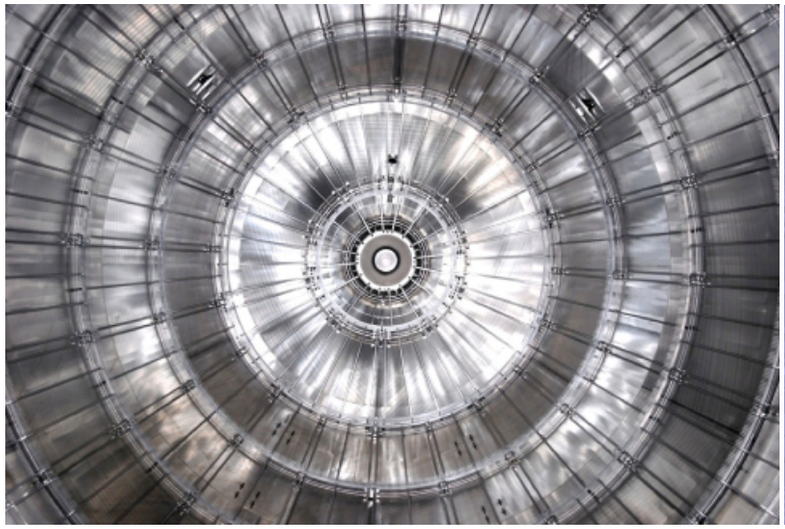
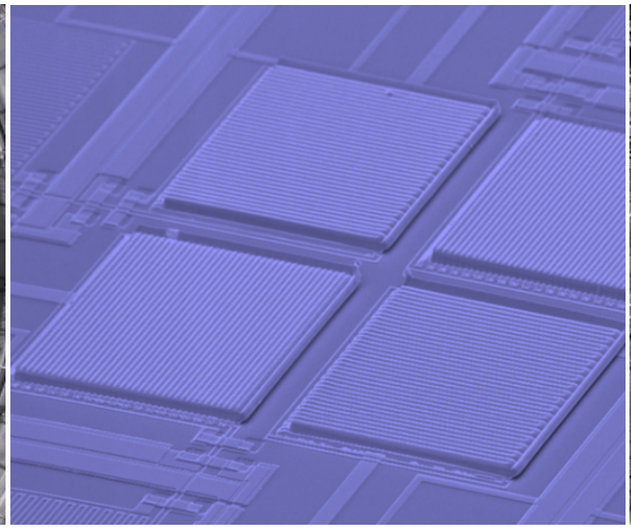
Karlsruhe Institute of Technology

Astroparticle Physics School 2015 // Obertrubach-Bärnfels

Neutrino mass measurements

Kathrin Valerius

KIT Center for Elementary Particle and Astroparticle Physics


4 Nobel Prizes for Neutrino Physics

1988



Leon M. Lederman
Prize share: 1/3



Melvin Schwartz
Prize share: 1/3



Jack Steinberger
Prize share: 1/3

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.

1995

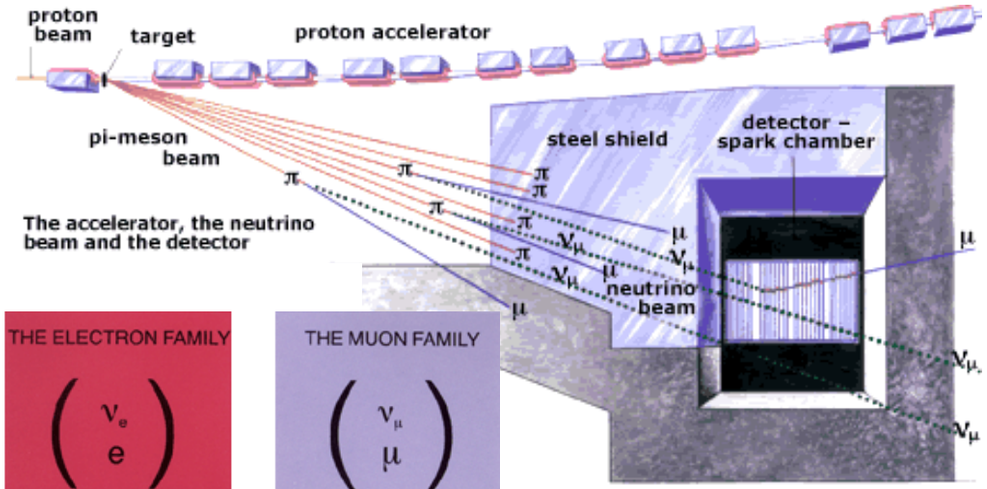


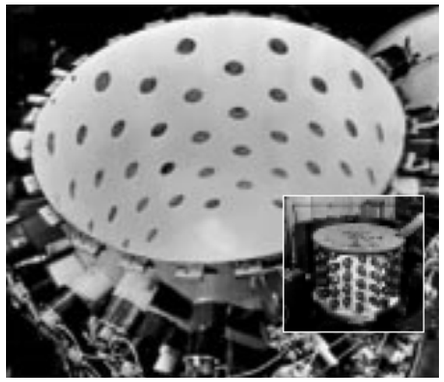
Martin L. Perl
Prize share: 1/2



© University of California Regents
Frederick Reines
Prize share: 1/2

The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.







“Herr Auge”

4 Nobel Prizes for Neutrino Physics

2002



Raymond Davis Jr.
Prize share: 1/4



Masatoshi Koshiba
Prize share: 1/4



Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

2015



Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

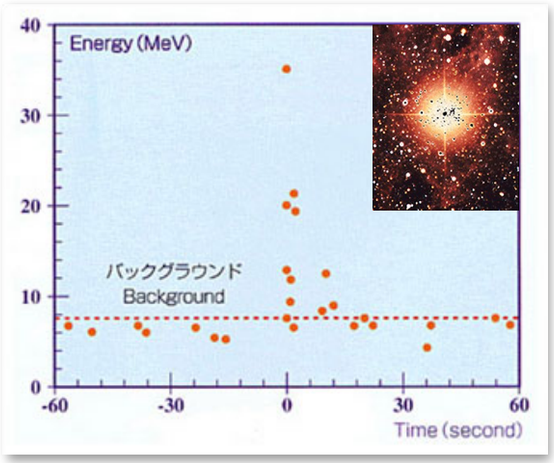


Photo: K. MacFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

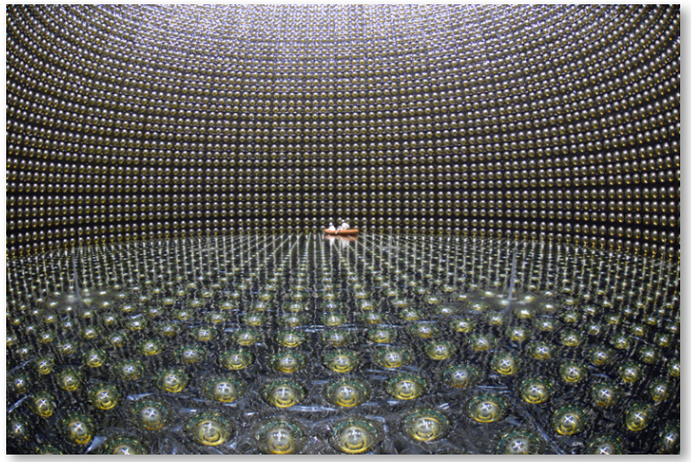
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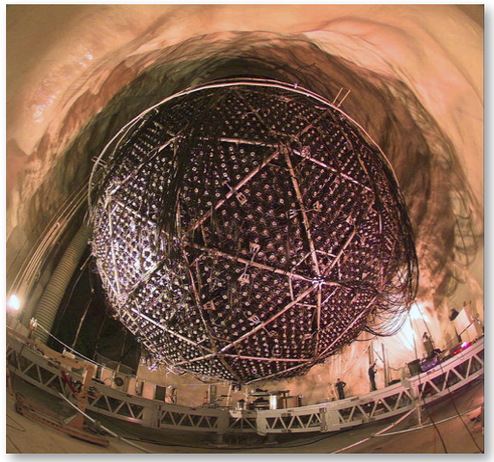
Homestake



KamiokaNDE



Super-KamiokaNDE



SNO

4 Nobel Prizes for Neutrino Physics

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Raymond Davis Jr.
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2015



Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2



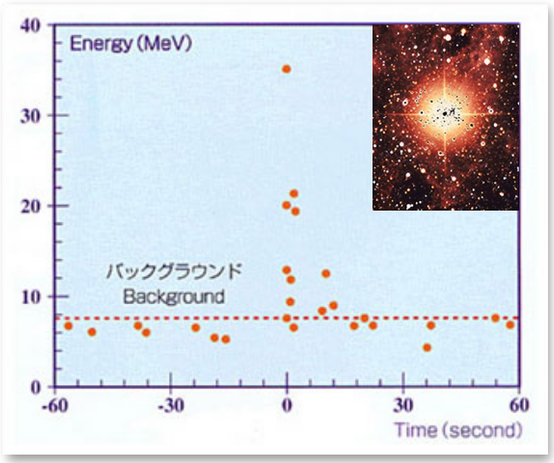
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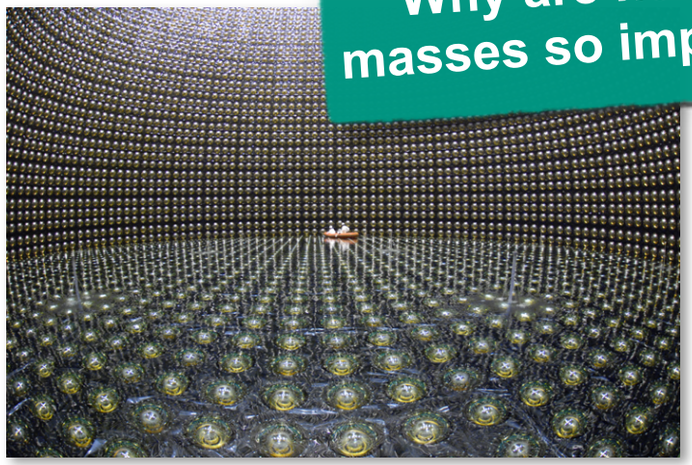
Why are neutrino masses so important?



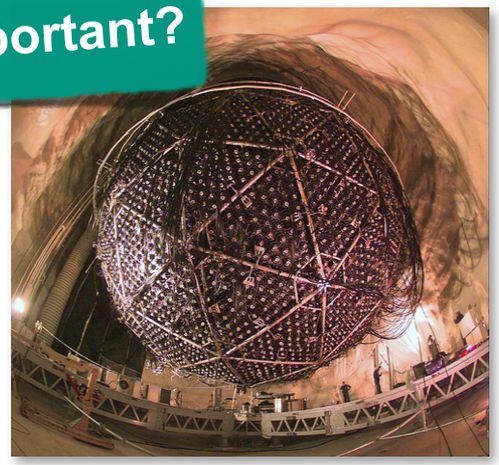
Homestake



KamiokaNDE



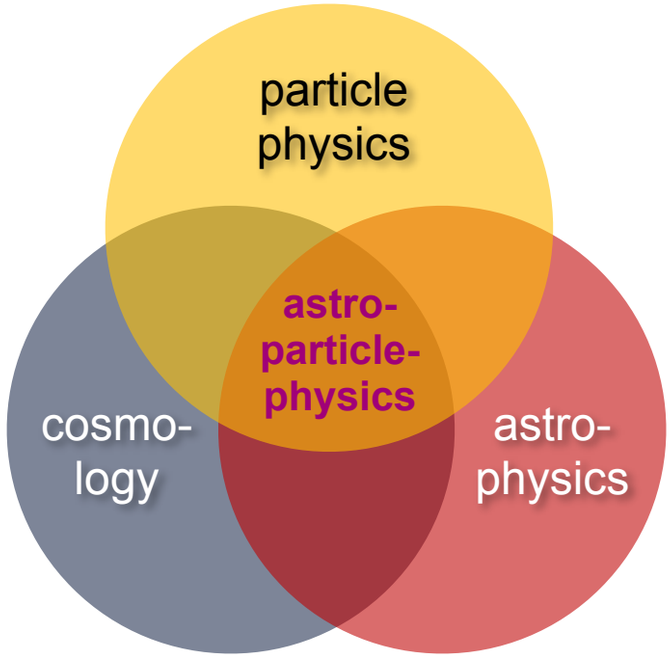
Super-KamiokaNDE



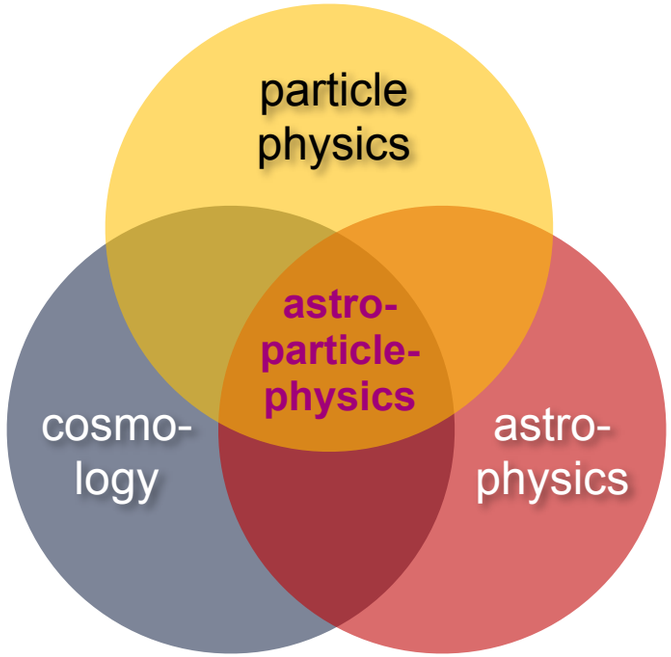
SNO

Massive neutrinos in astroparticle physics

Connecting the micro- and the macro-cosmos:



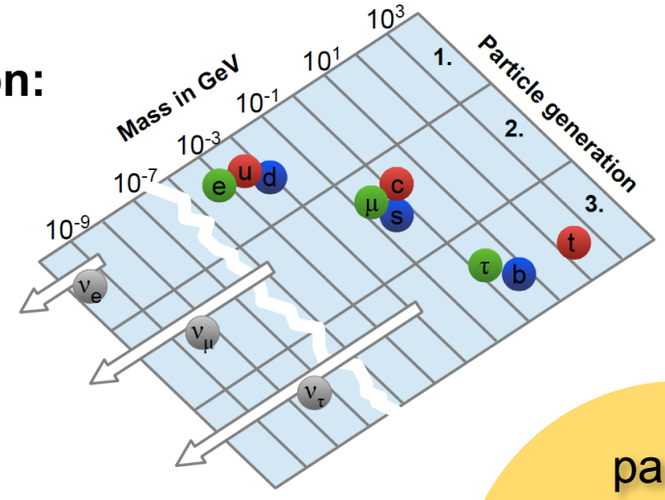
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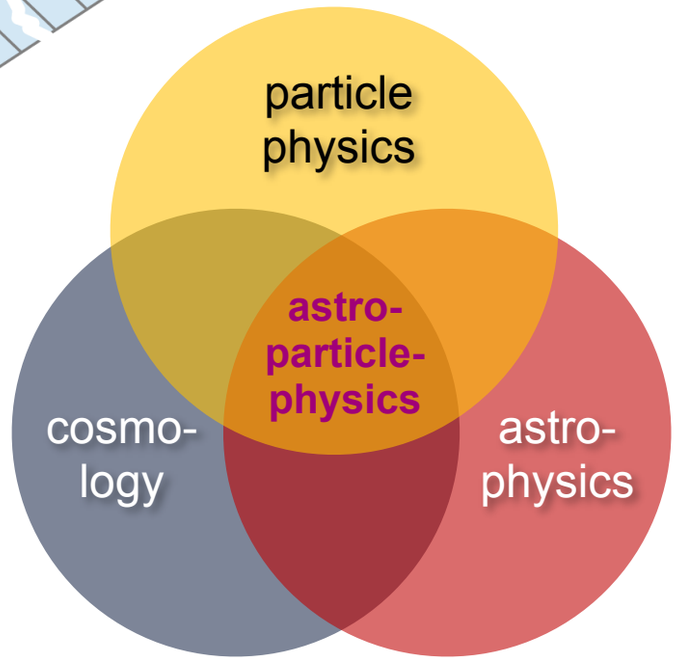


Massive neutrinos in astroparticle physics

mass generation:
new concepts



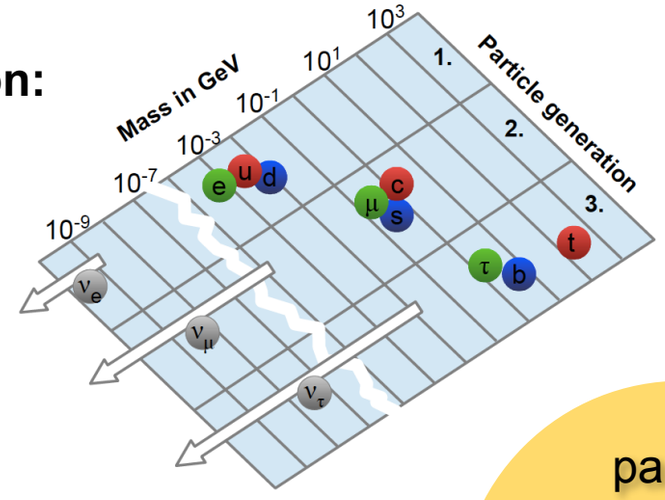




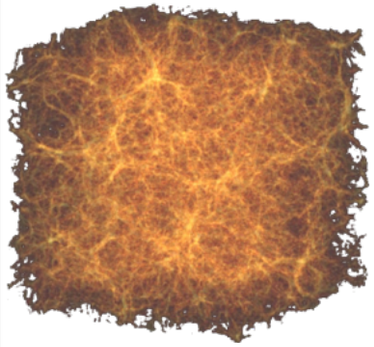
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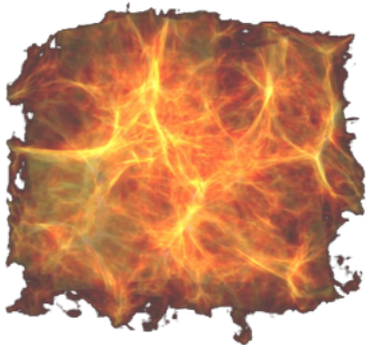




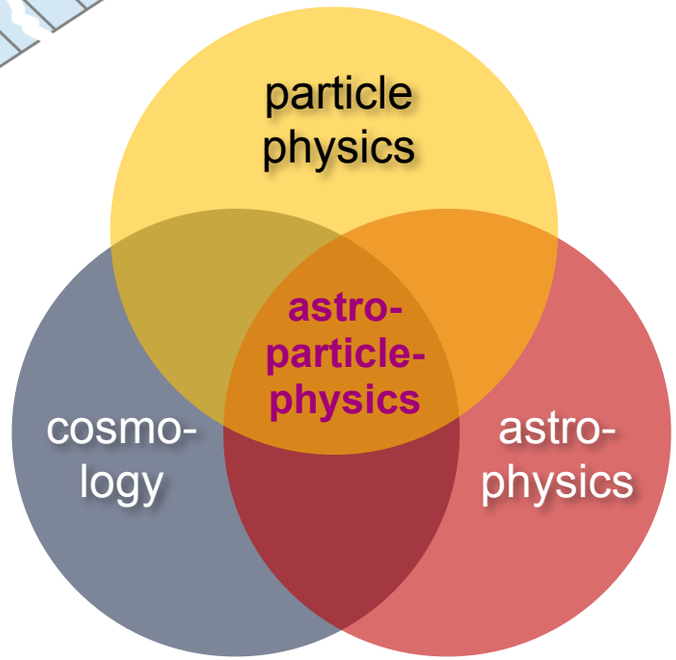
massive neutrinos as
"cosmic architects"



Σm_ν = **0 eV**



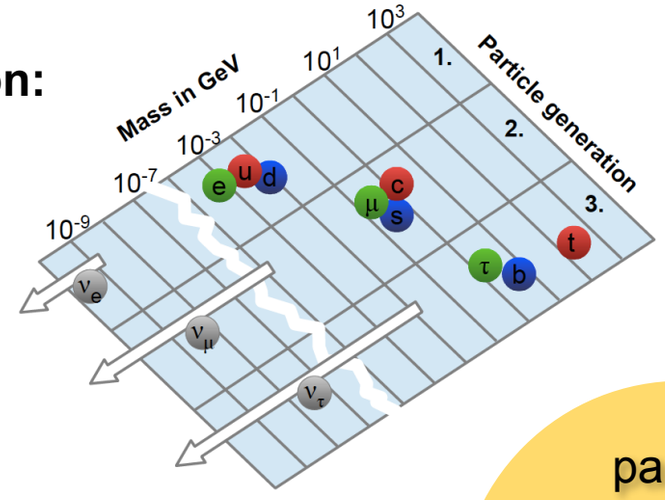
6.9 eV



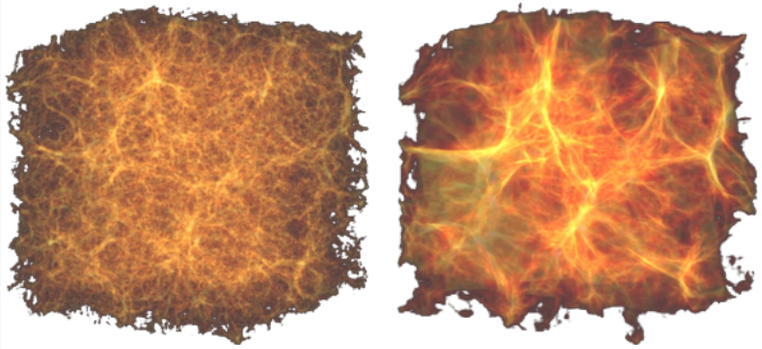
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mass generation: new concepts



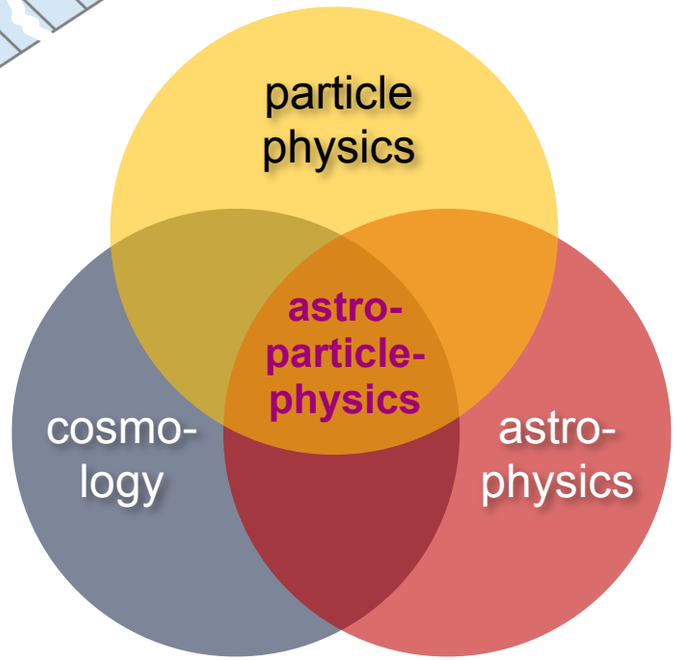


massive neutrinos as "cosmic architects"



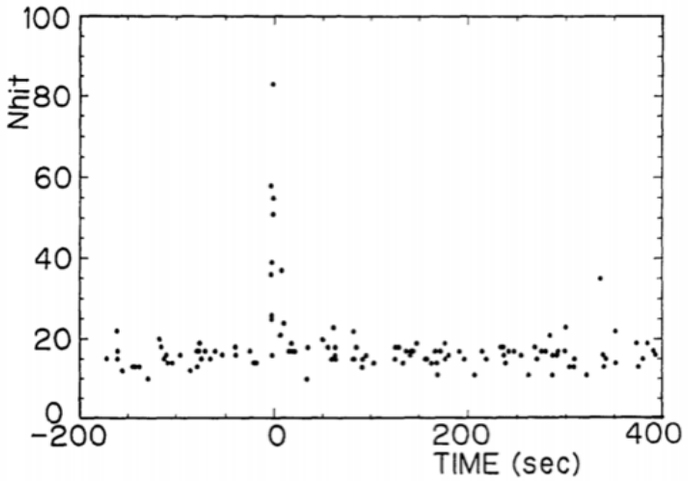
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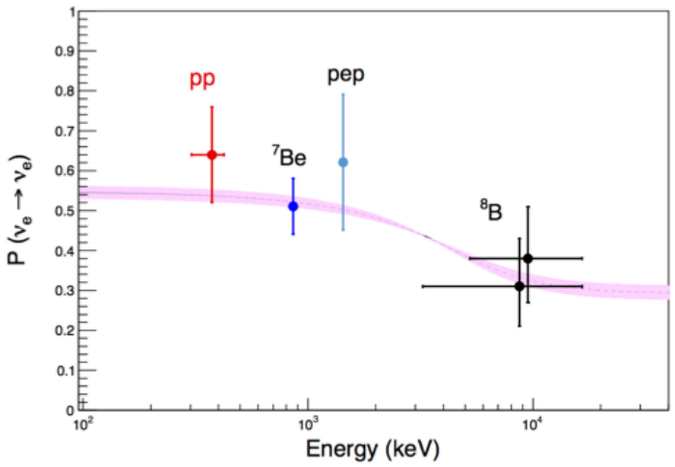


understanding astrophysical processes

Neutrino burst from SN 1987a



Matter effects in the sun



What's on the menu today?

- Motivation: Massive neutrinos in cosmology
- Neutrino mass searches with lab experiments
  - Neutrinoless double beta decay
  - Direct kinematical searches
- New ideas and developments



Neutrino mixing and mass scheme

RECAP
Lectures M. Wurm

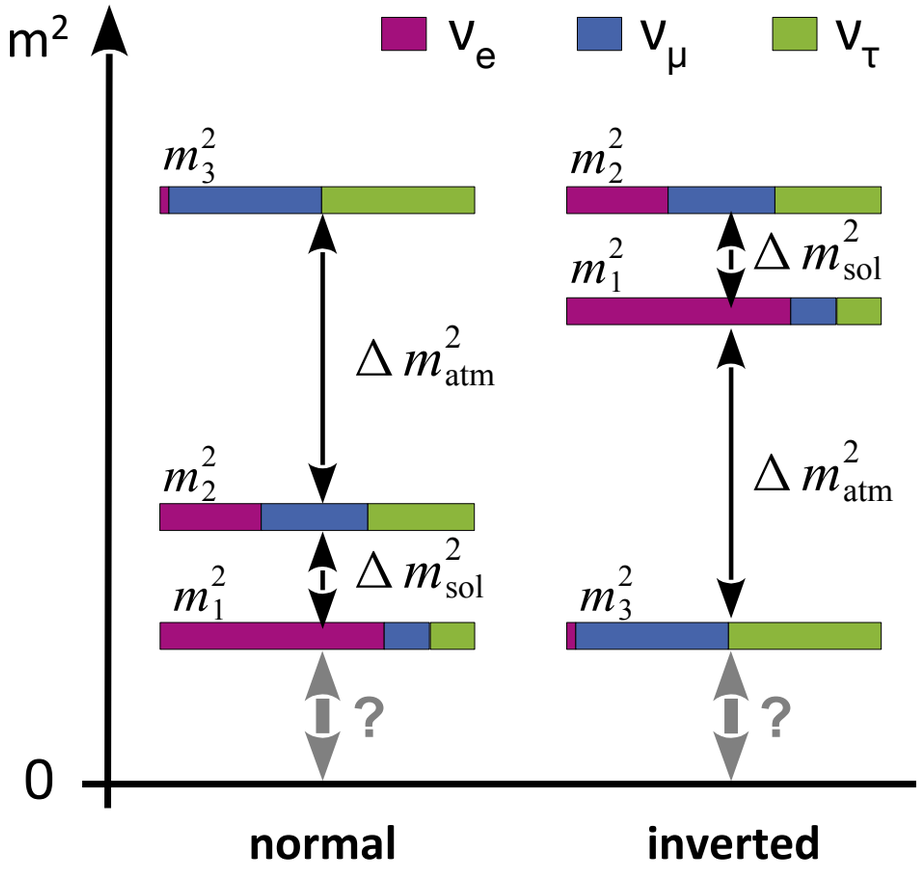
Wealth of ν oscillation data:

- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$ established

New!
BSM physics!

$$\theta_{12} \approx 34^\circ$$
$$\theta_{23} \approx 45^\circ$$
$$\theta_{13} \approx 9^\circ$$

$$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$$
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Neutrino mixing and mass scheme

RECAP
Lectures M. Wurm

Karlsruhe Institute of Technology

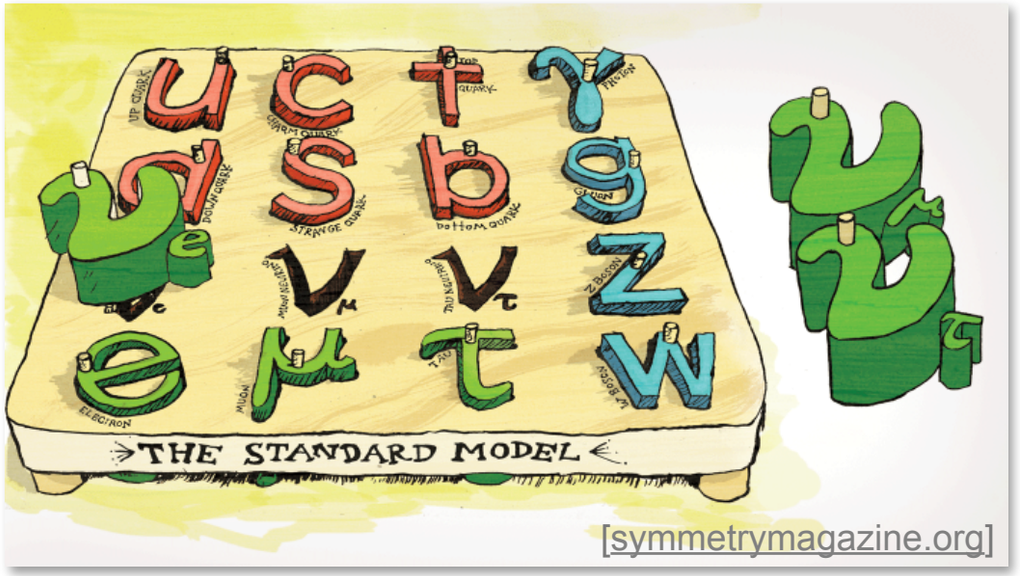
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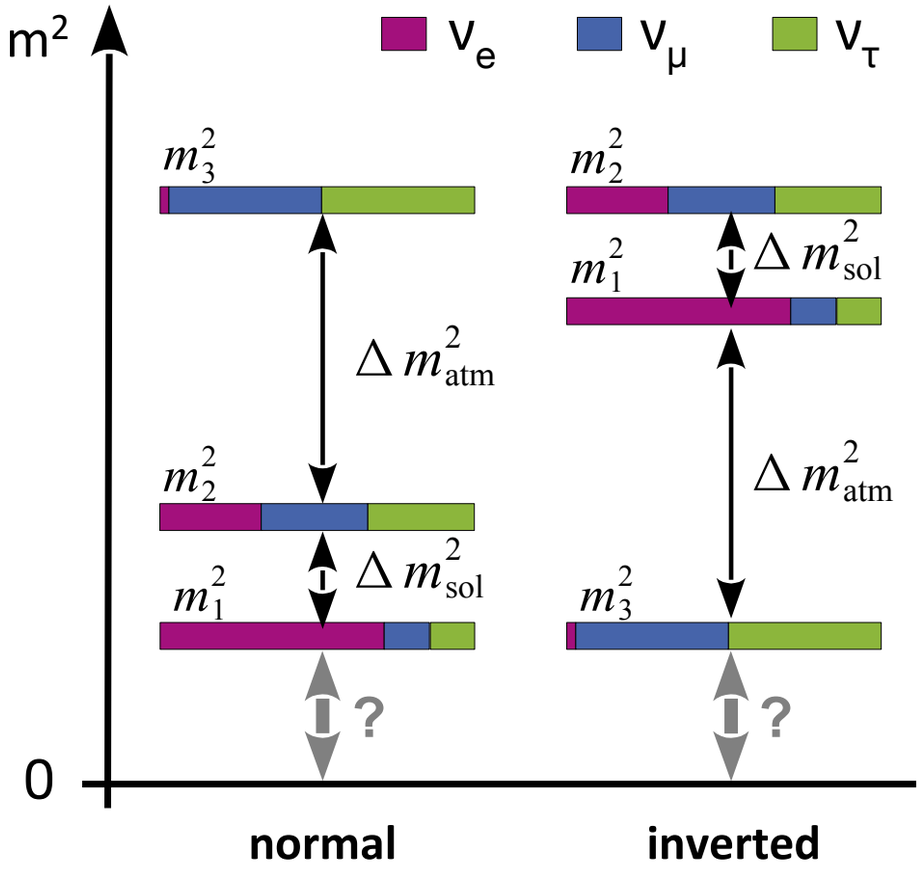
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[symmetrymagazine.org]



Neutrino mixing and mass scheme

RECAP
Lectures M. Wurm

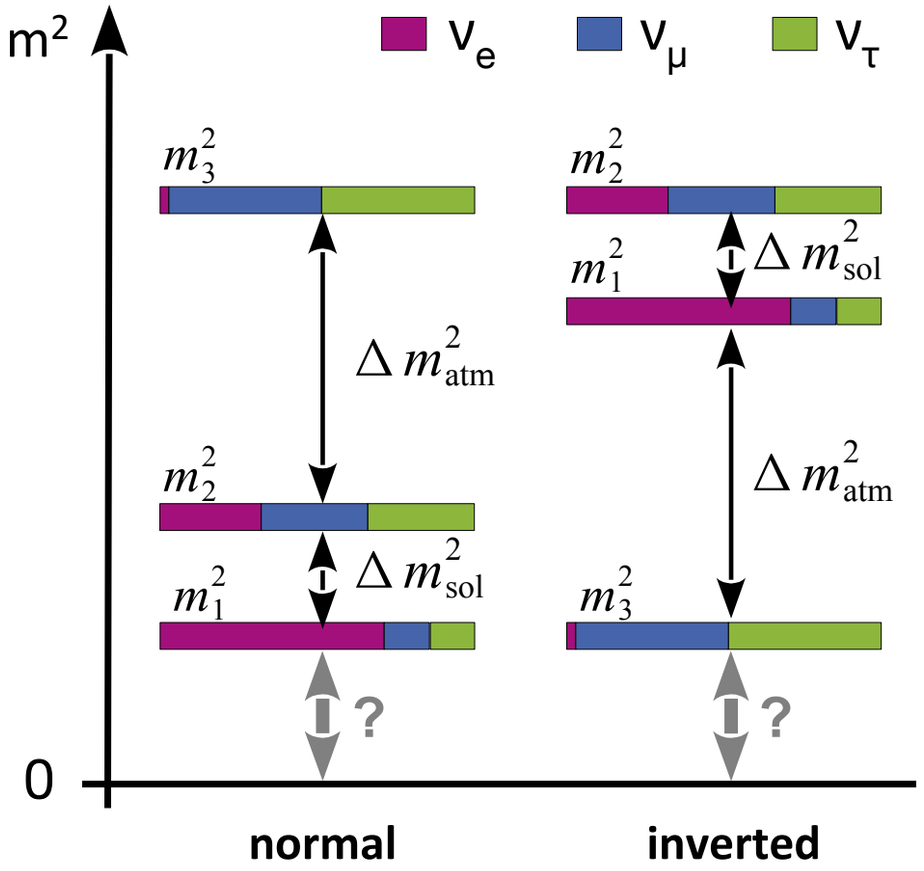
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- Oscillation experiments: only interferometric measurement, no absolute values
- *Which mass ordering (normal, inverted)?*
- ***What is the absolute ν mass scale?***



So far: only **upper** (< 2 eV) and **lower bounds** (>0.01 resp. >0.05 eV)

Neutrino mixing and mass scheme

RECAP
Lectures M. Wurm

Wealth of ν oscillation data:

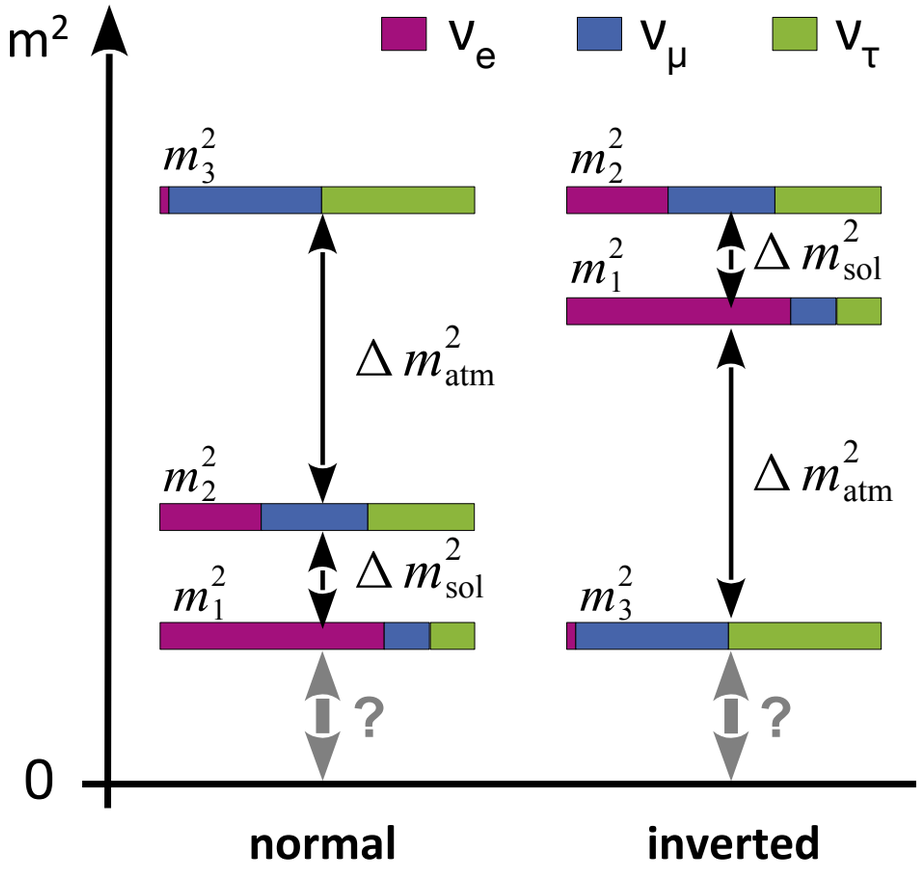
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Well, then, how to determine the neutrino mass scale?

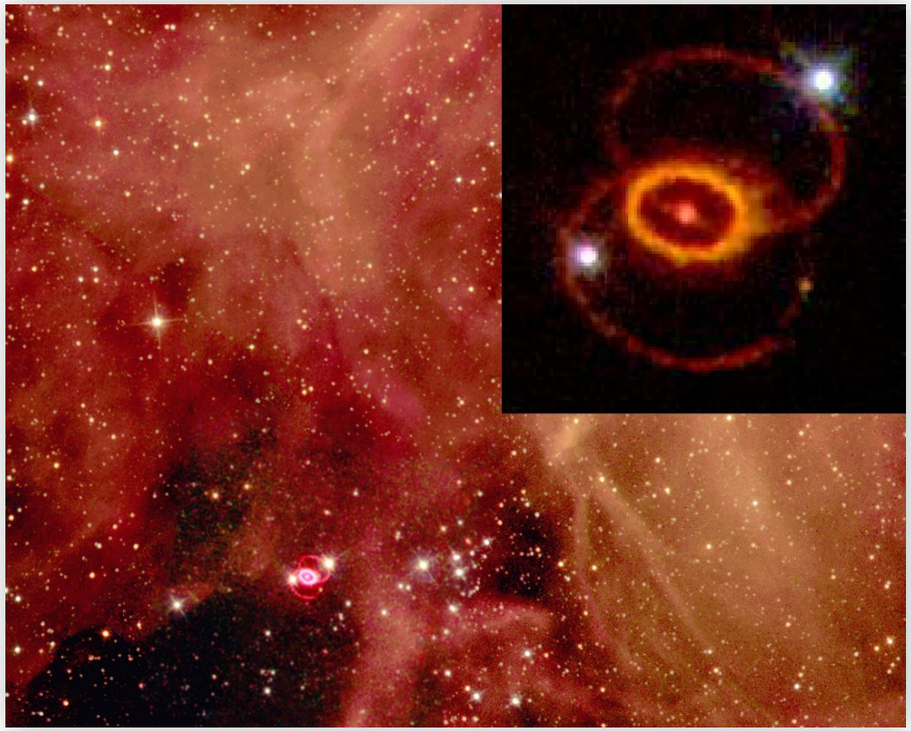
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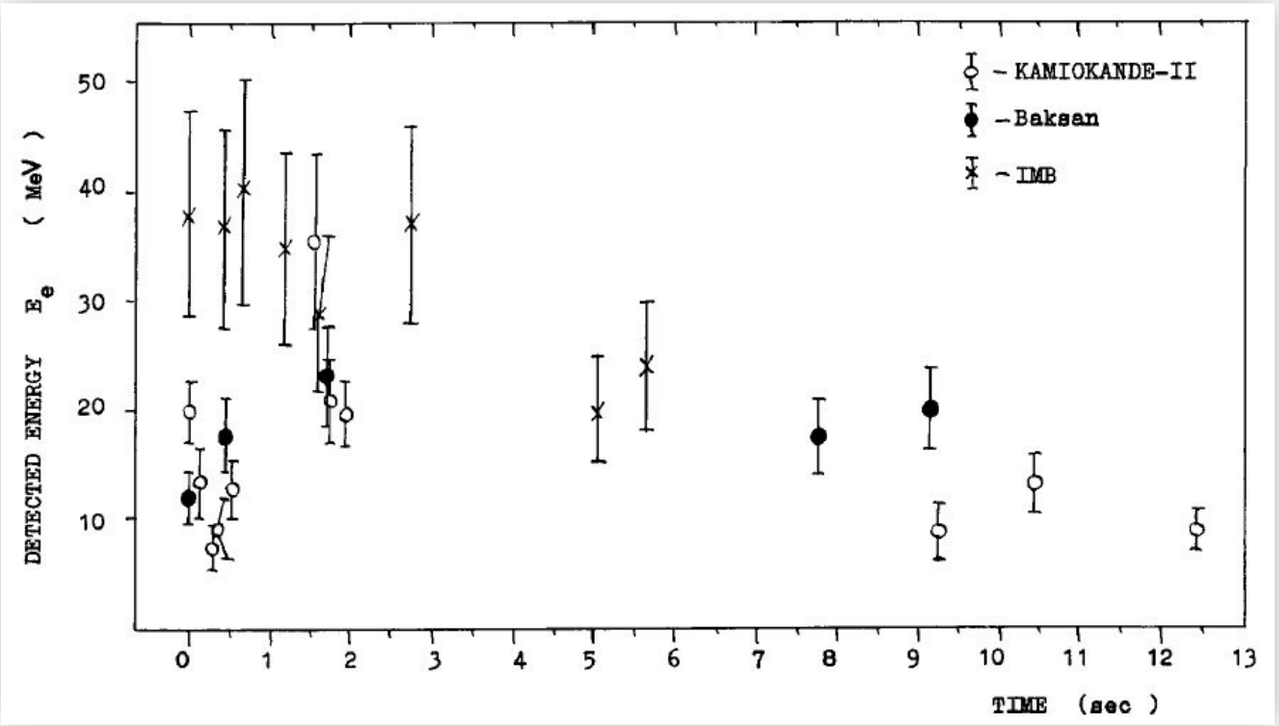
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Core-collapse SN 1987a in LMC

today



24. Feb. 1987

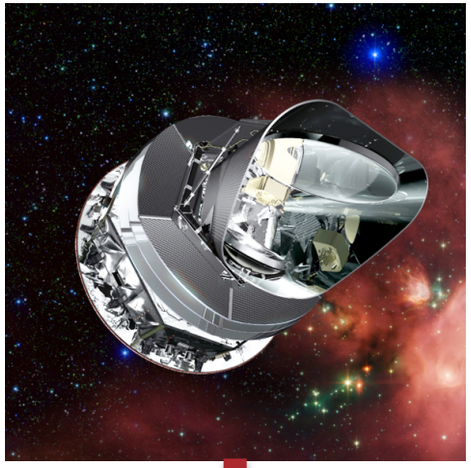


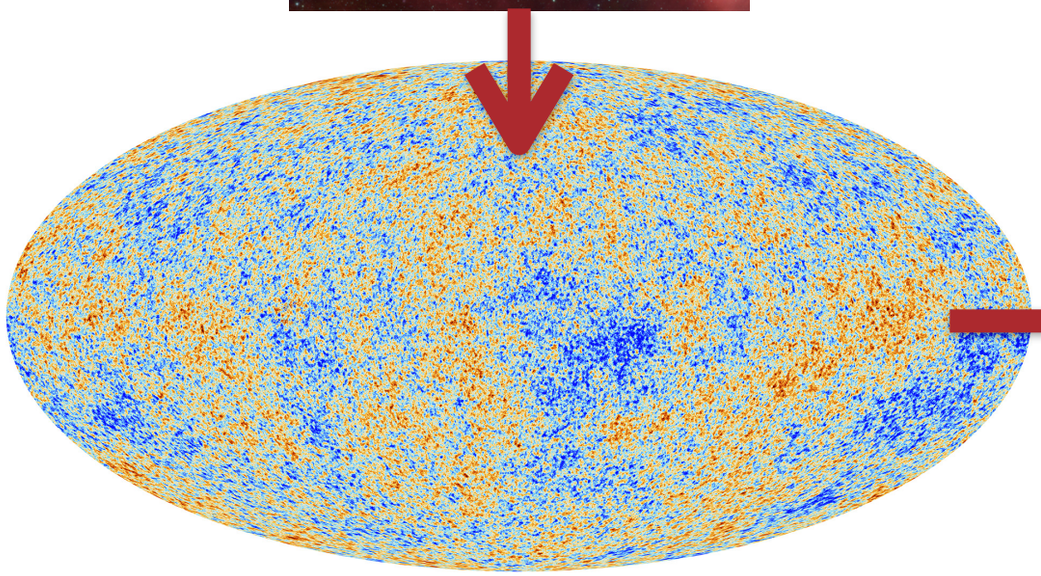
➡ Estimate ν mass from energy-dependent time of flight. Current limit: $m(\nu_e) < 5.7$ eV.

➡ Purely kinematical. Main difficulties: (a) rare! (b) emission model! [Loredo et al., 2005]

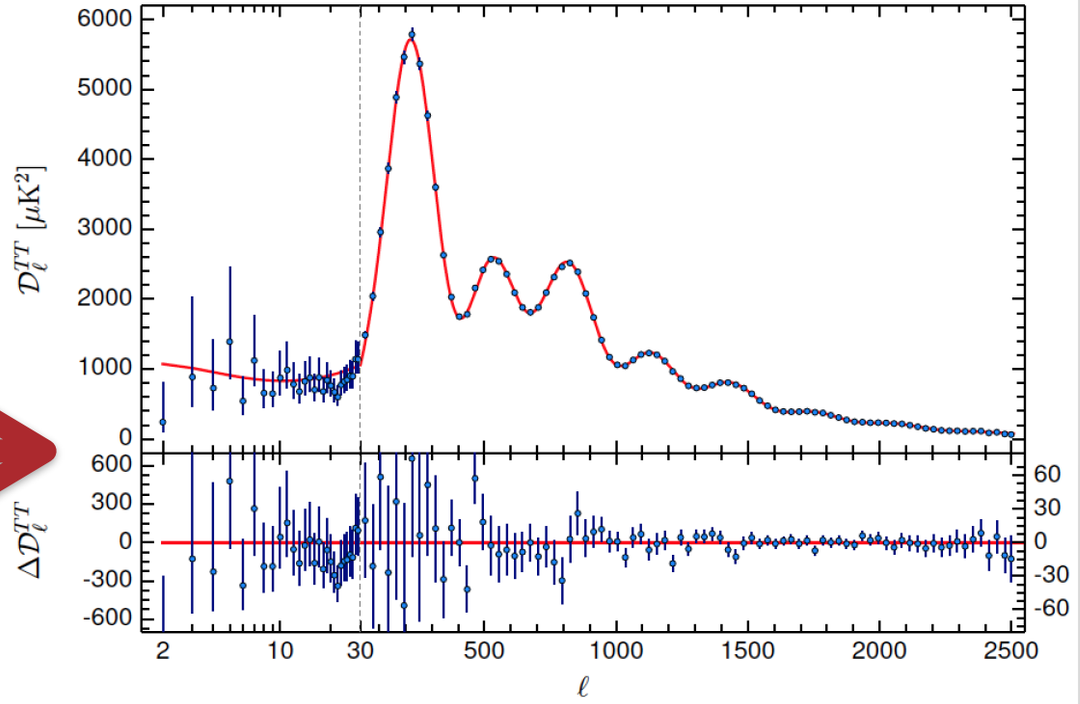
Well, then,
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Cosmologist's answer: Use excellent cosmological data!

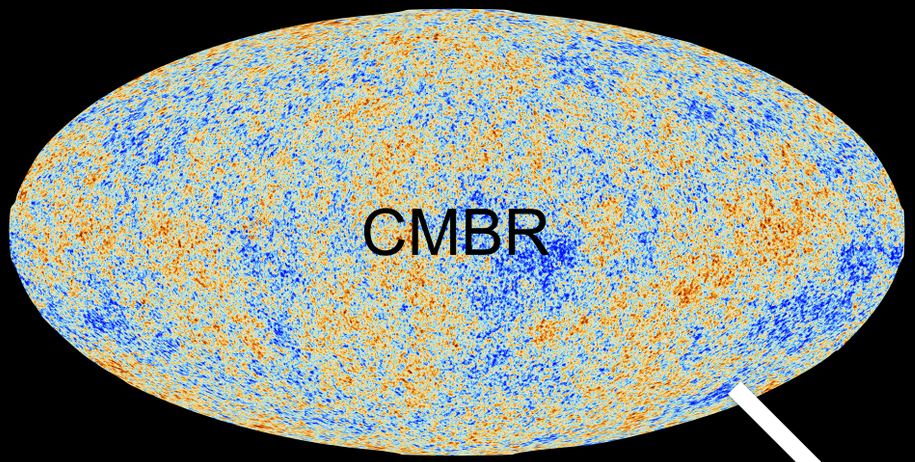




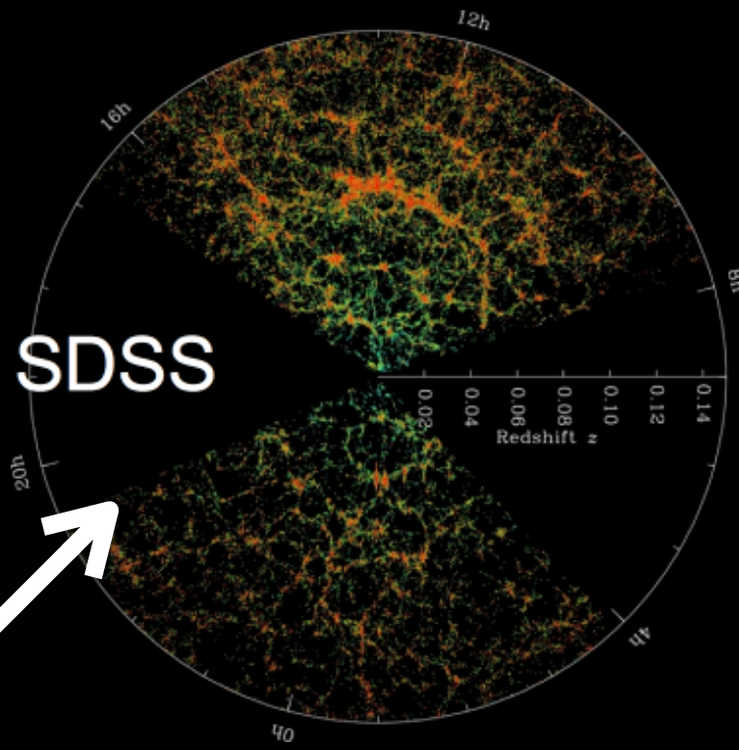
Ade et al. (Planck Coll.), arXiv:1502.01589



Neutrino mass from cosmology

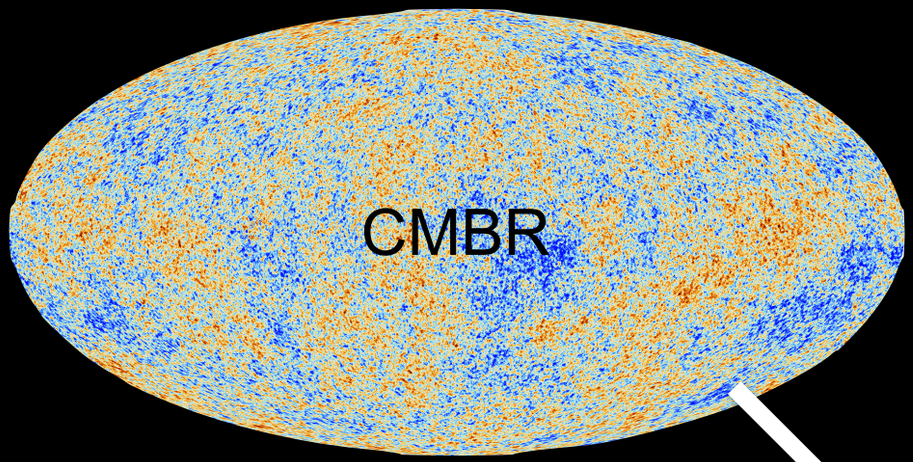


relic neutrino density: 336 ν /cm^3

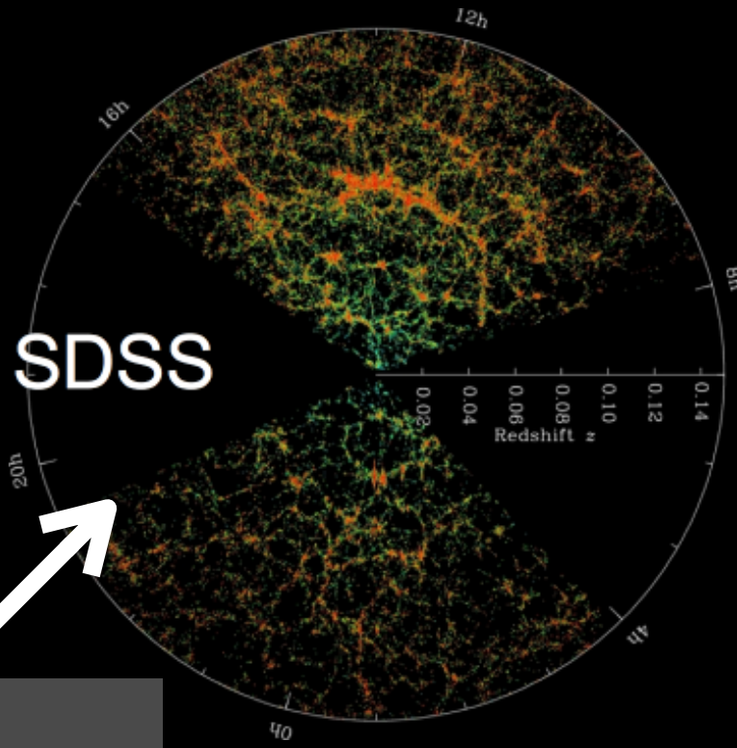


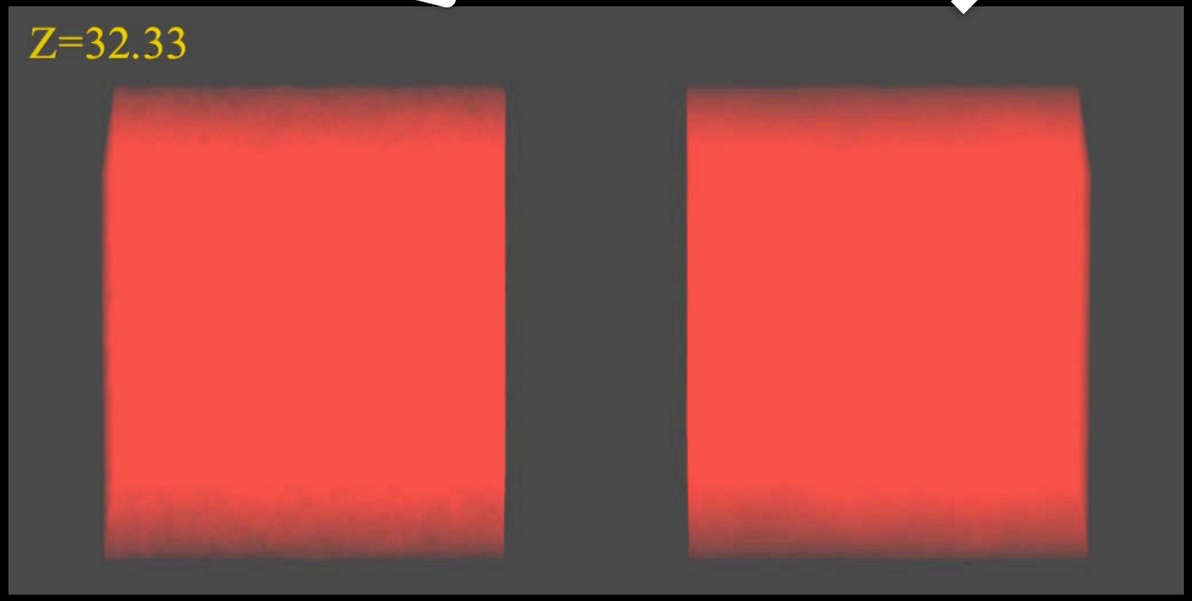
[T. Haugbølle, Univ. of Aarhus]

Neutrino mass from cosmology



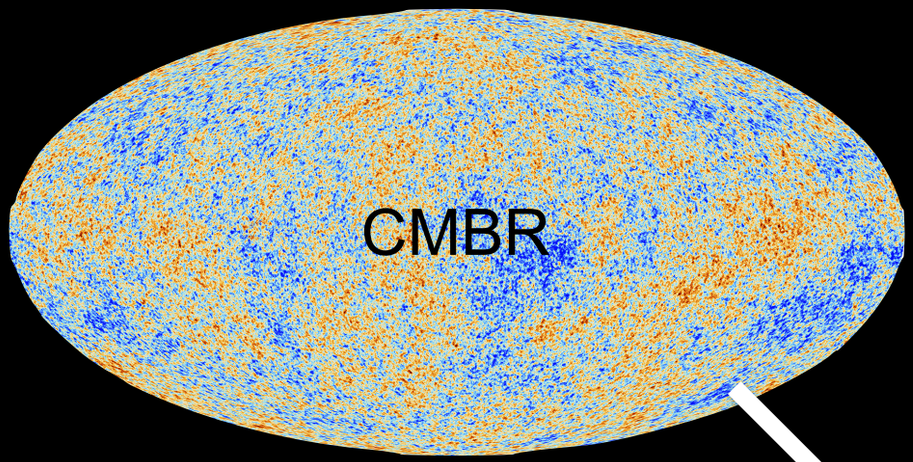
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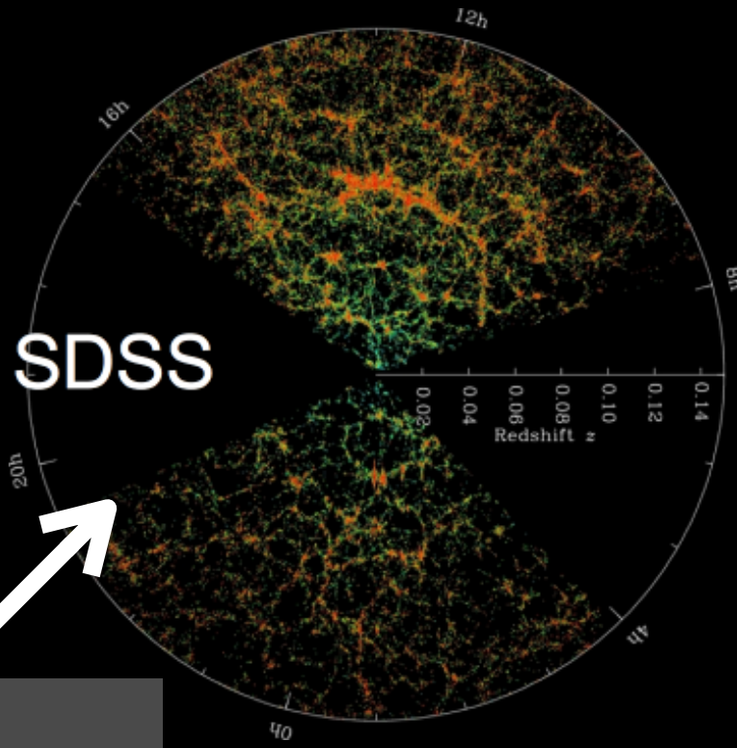


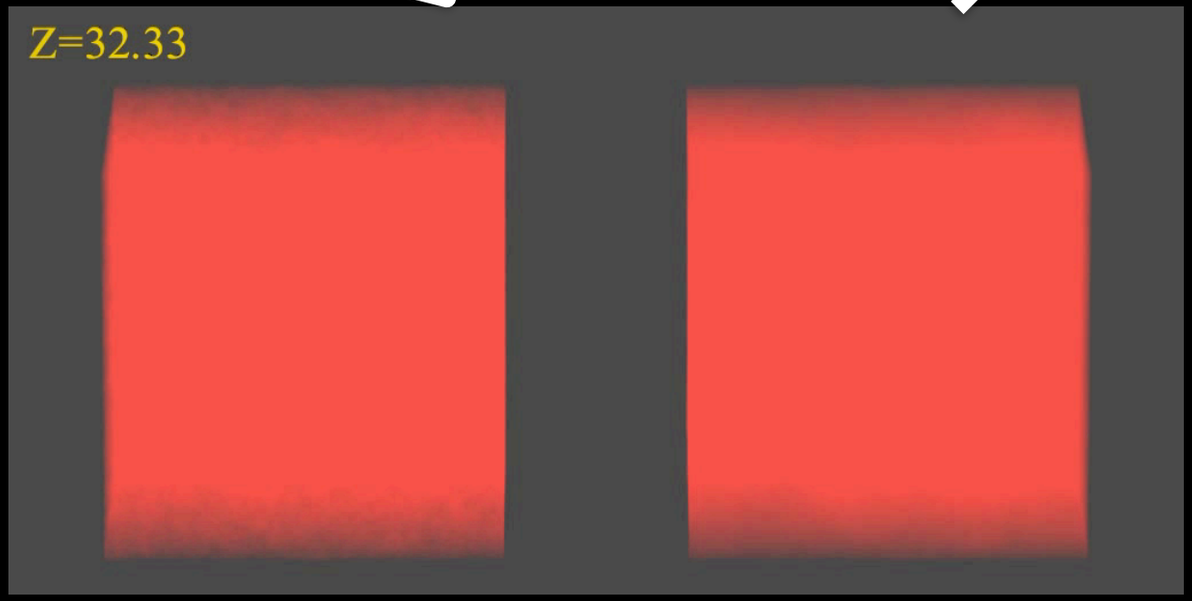
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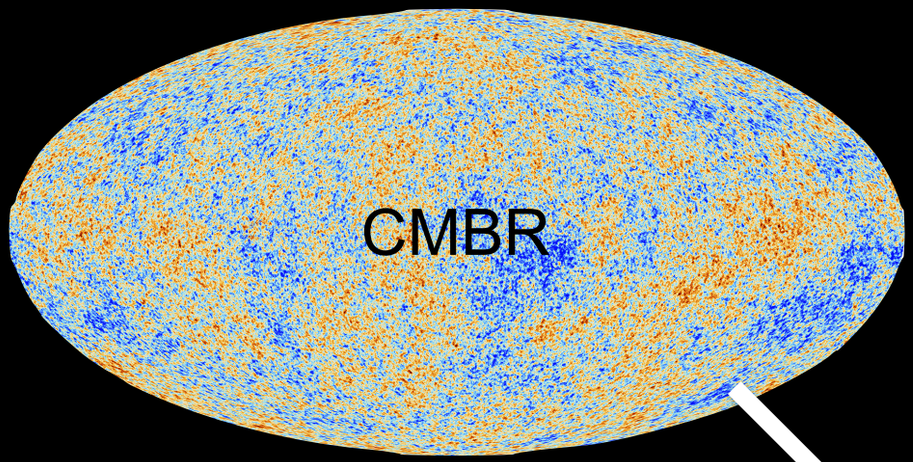
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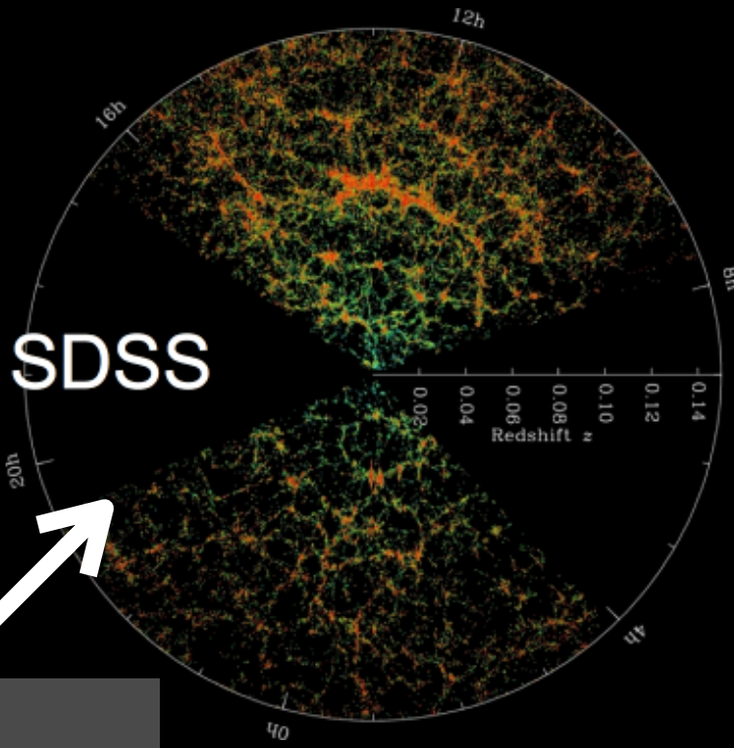


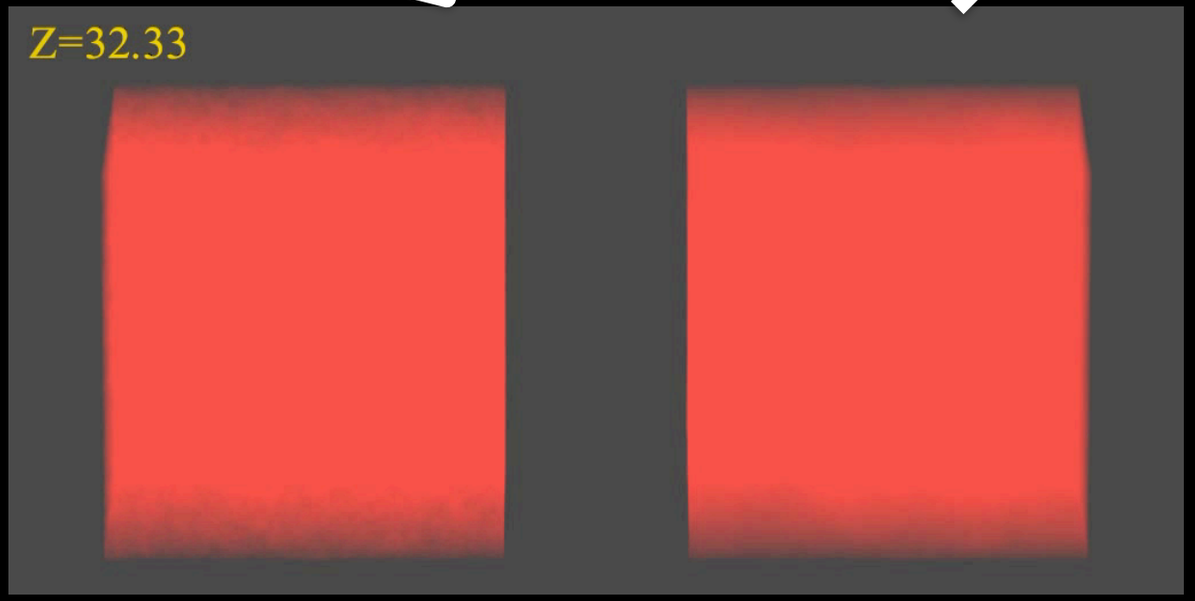
[T. Haugbølle, Univ. of Aarhus]

Neutrino mass from cosmology



relic neutrino density: 336 ν /cm³



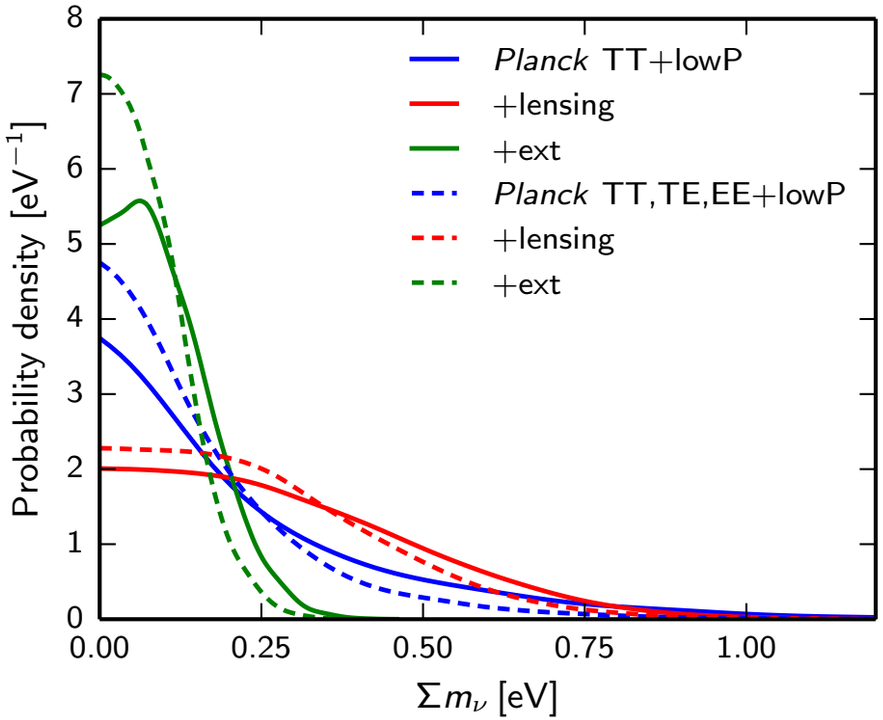


Σm_ν = **0 eV** **6.9 eV ***

[T. Haugbølle, Univ. of Aarhus]

Neutrino mass from cosmology

arXiv:1502.01589

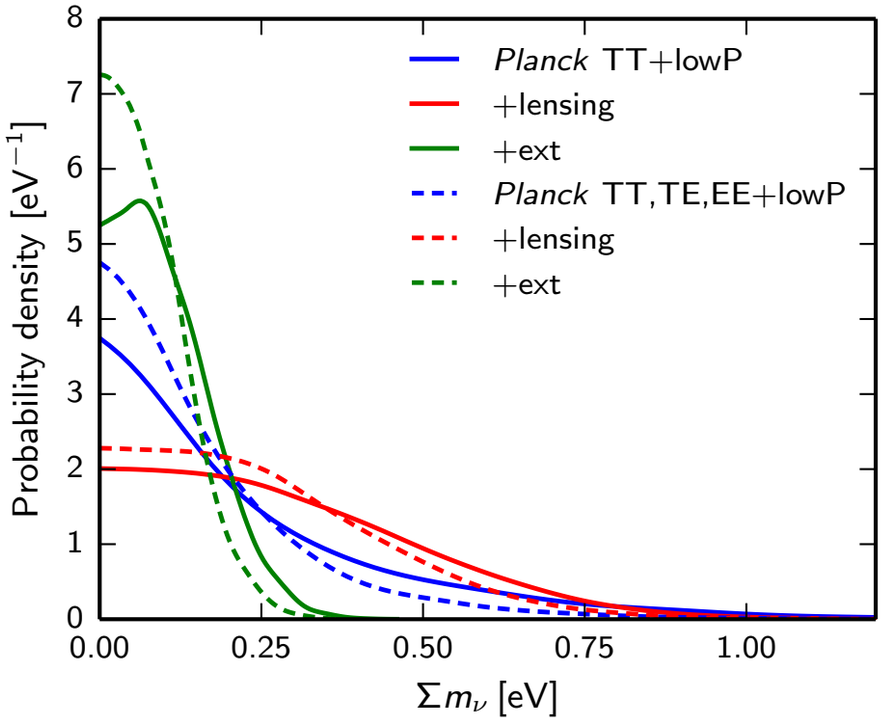


$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck}\ \text{TT, TE, EE+lowP};$$
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6 + 2 parameter ΛCDM model

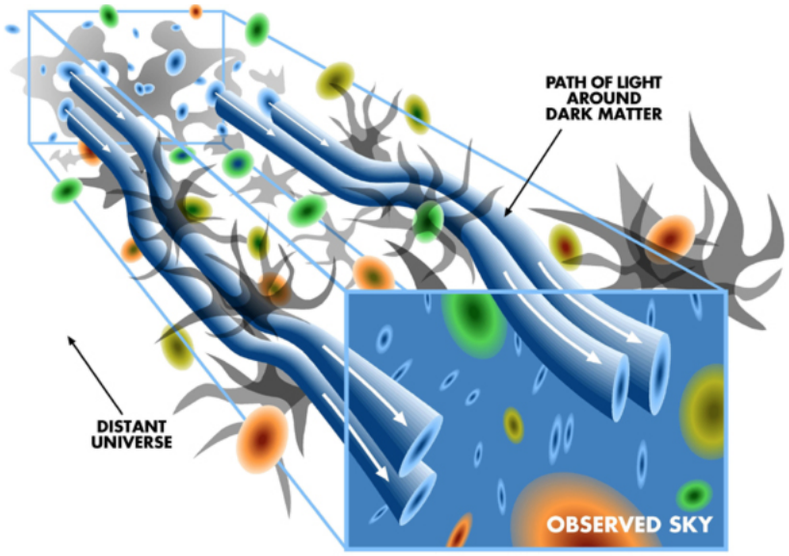
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$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP};$$
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6 + 2 parameter ΛCDM model



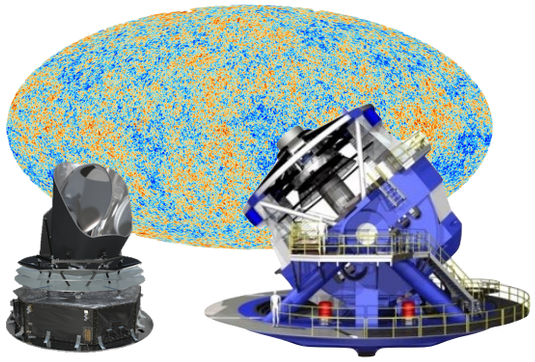
Future EUCLID mission (ESA): grav. lensing & galactic power spectrum

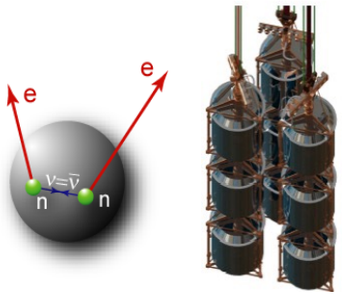
*"… Euclid will very likely provide a **positive detection** of neutrino mass …, the exact nature of the neutrino mass spectrum remains out of its reach …"*

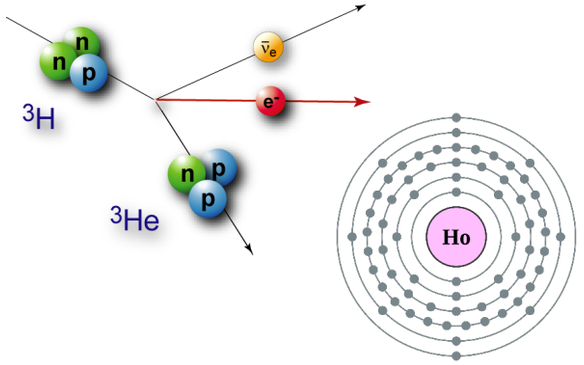
[Hamann, Hannestad, & Wong, JCAP 11 (2012) 52]

Well, then, how to determine the neutrino mass scale?

Experimentalist's answer:
3 complementary paths!







Tool	Cosmology CMB + LSS + ...	Neutrinoless double β-decay	β-decay endpoint and EC
Observable	$\sum m_\nu = \sum_{i=1}^{3} m_i$	$\langle m_{\beta\beta} \rangle = \left\| \sum_{j=1}^{3} \lvert U_{ej} \rvert^2 \, m_j \, e^{i\alpha_j} \right\|$	$m_\beta^2 = \sum_{i=1}^{3} \lvert U_{ei}^2 \rvert \, m_i^2$
Present upper limit	0.2 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	20 – 50 meV	20 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana vs. Dirac - phase cancellations possible - nucl. matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

Lab experiments, part I:

Search for neutrinoless double beta decay

Double β-decay: 2νββ & 0νββ modes

RECAP
Lectures M. Wurm

Karlsruhe Institute of Technology

Double beta decay with neutrino emission (2νββ):

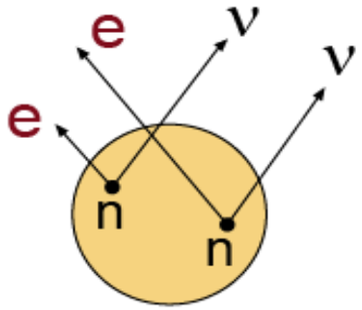
2nd-order weak interaction process

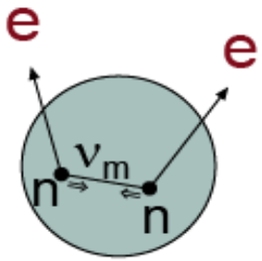
↳ extremely small transition rates & long half-lifes: $T_{1/2} \sim 10^{19} - 10^{21}$ years

↳ energy E_0 shared by 4 leptons, observed in 12 isotopes so far

2νββ

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- + \bar{\nu}_{e,1} + \bar{\nu}_{e,2}$$





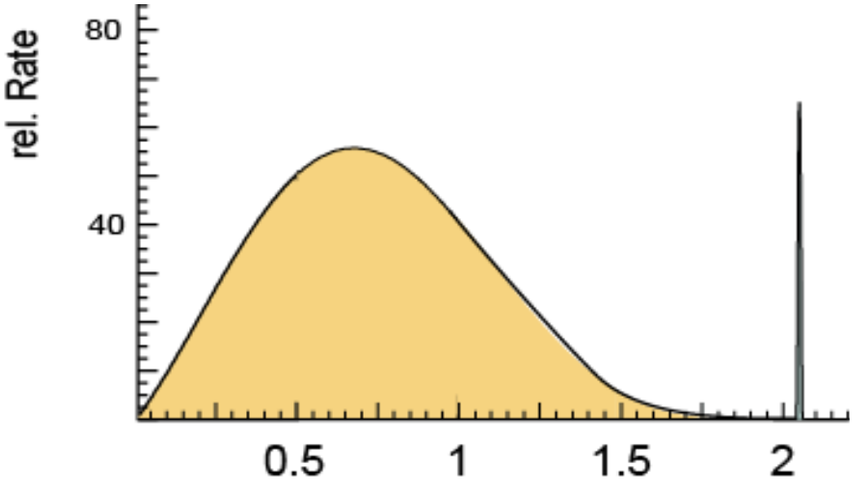
0νββ

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^-$$

first description:



M. Goeppert-Mayer (1935)



first description:





G. Racah (1937) E. Majorana

Double β-decay & Majorana mass $m_{\beta\beta}$

effective Majorana mass $m_{\beta\beta}$ is **not** identical with $m(\nu_e)$ from β-decay

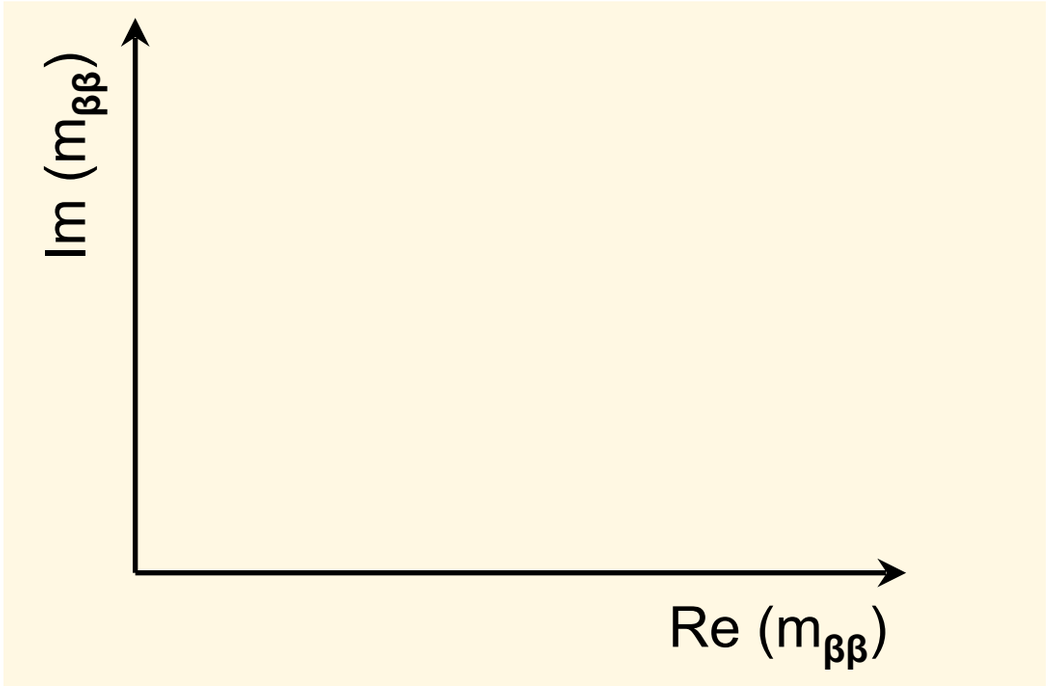
coherent sum over three ν–mass eigenstates m_1, m_2, m_3

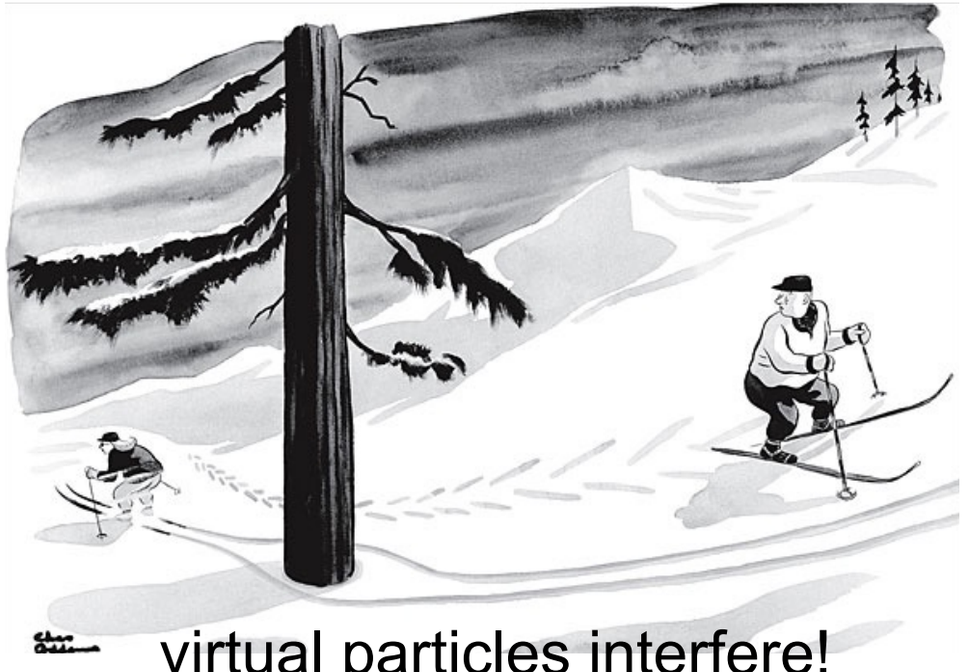
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} |U_{e,i}|^2 m_i \cdot e^{i\alpha_i} \right|$$

2 independent Majorana CP-phases α_i

↳ **mutual cancellations are possible**

if $\alpha_i \neq n \cdot \pi$ ↳ CP violation





virtual particles interfere!

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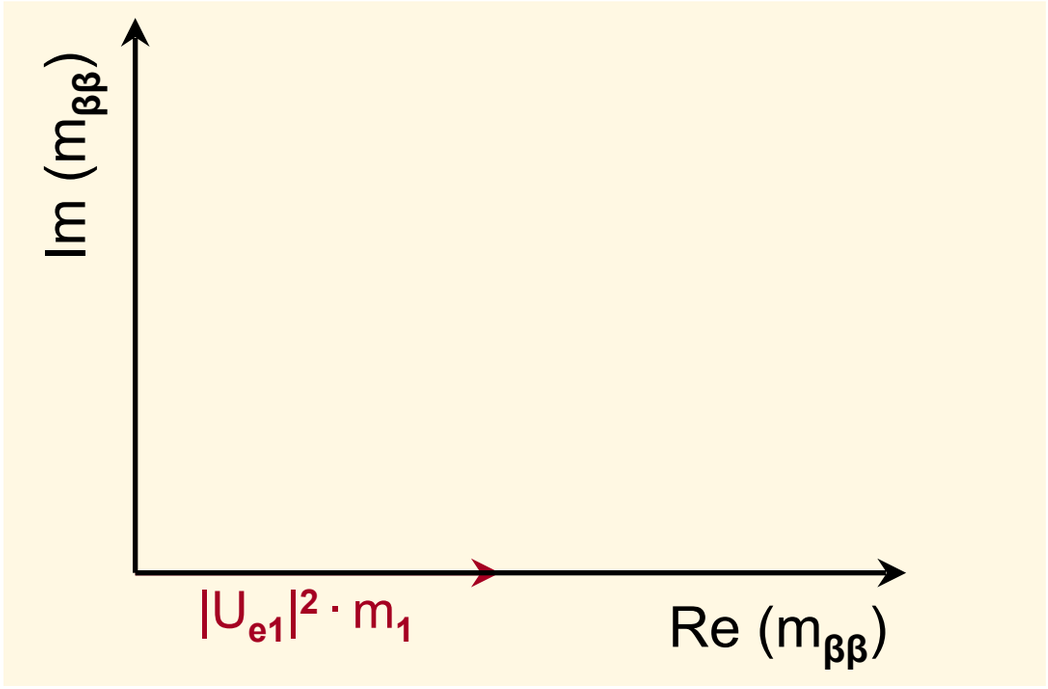
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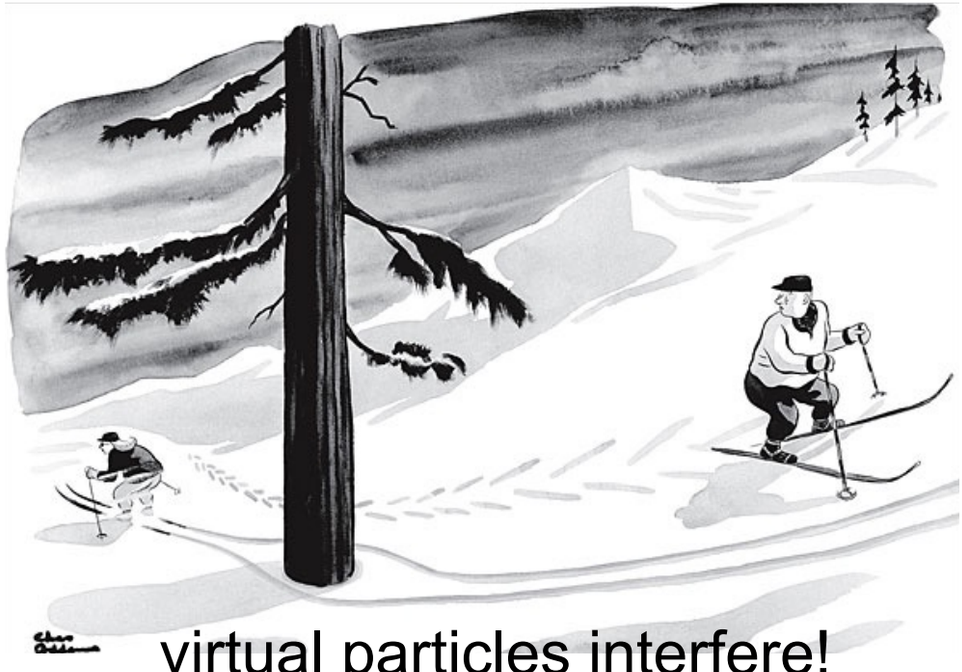
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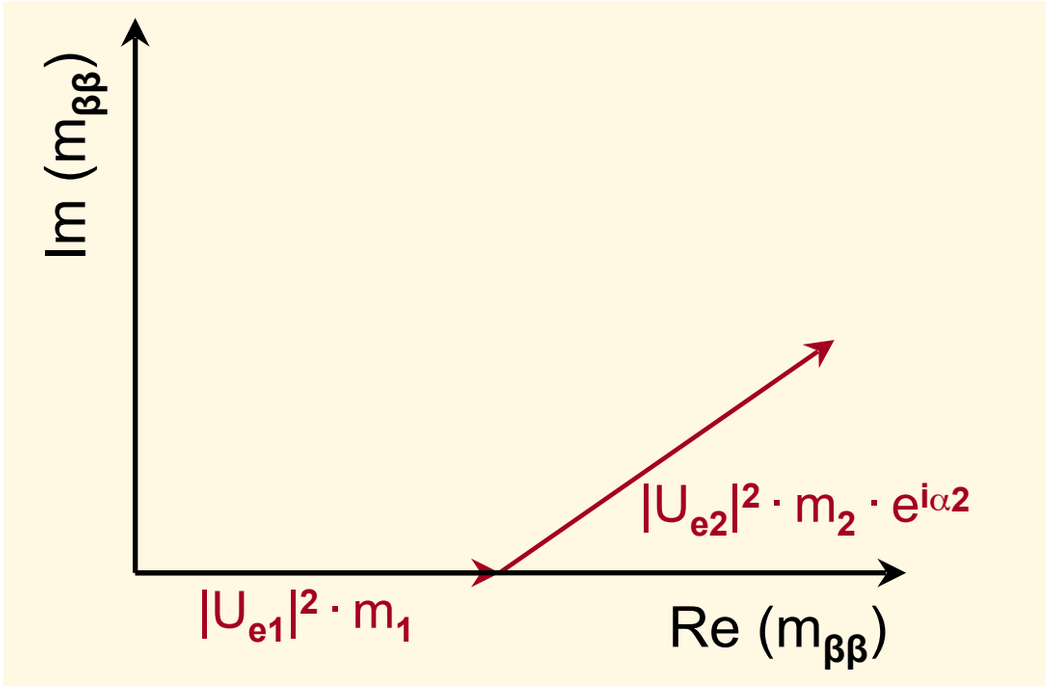
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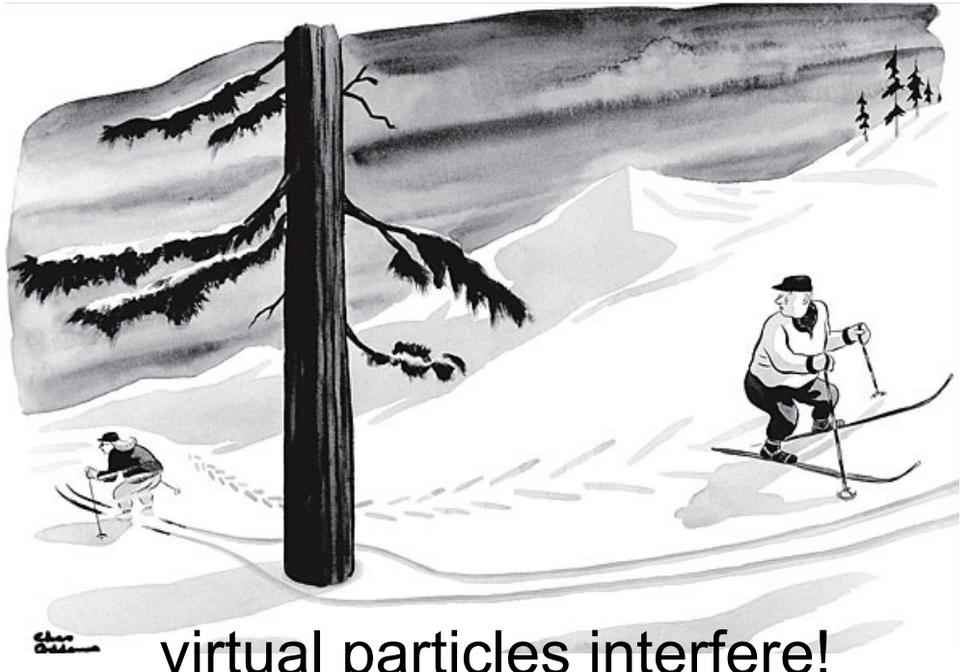
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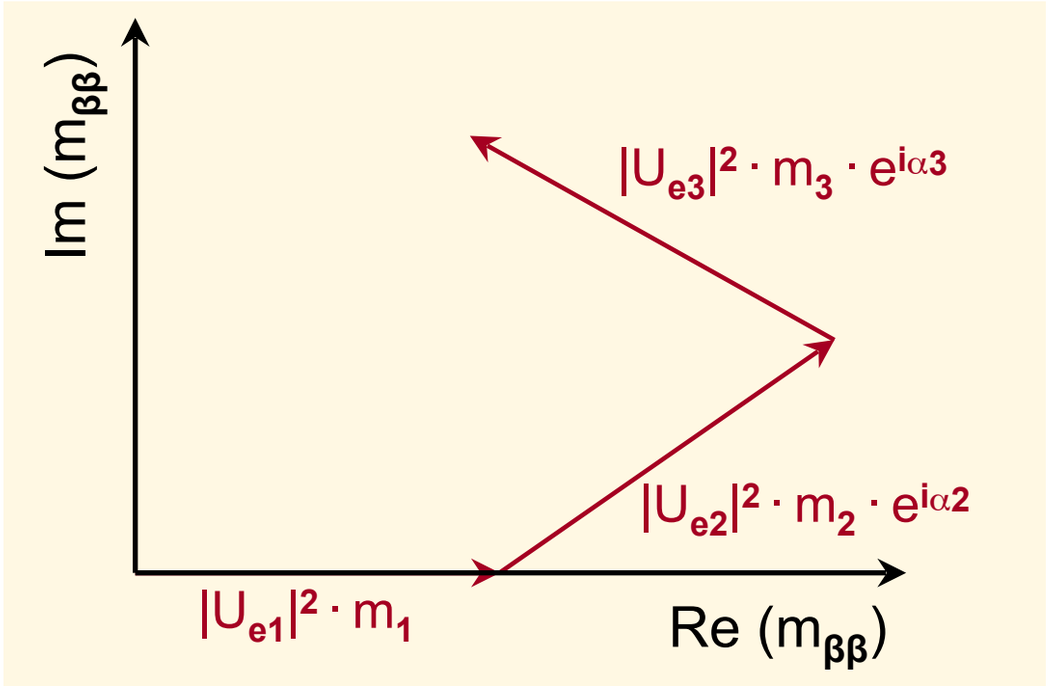
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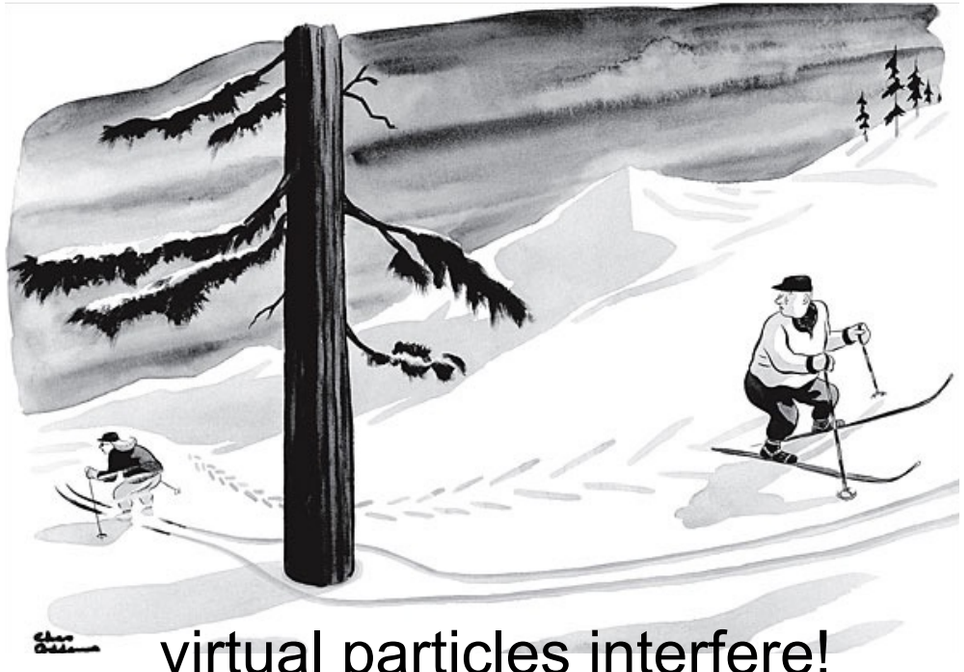
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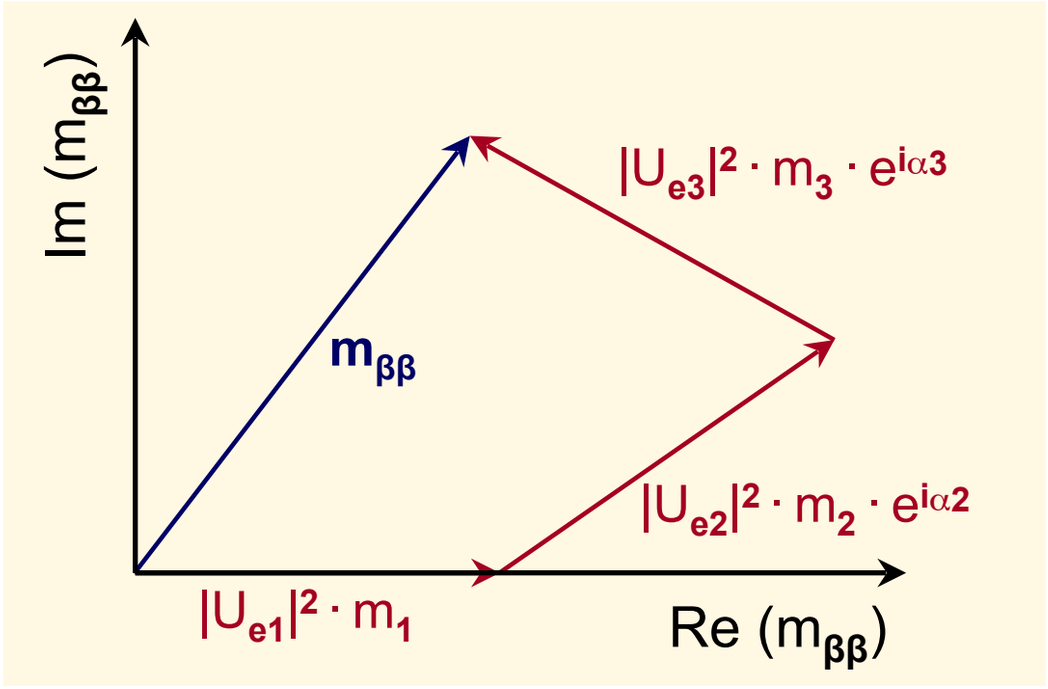
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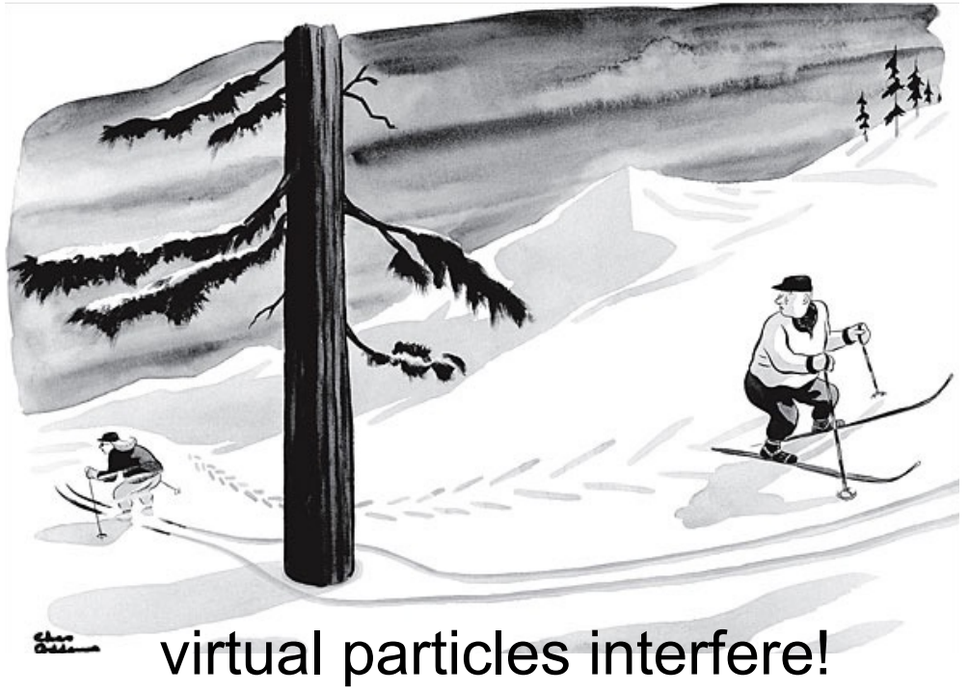
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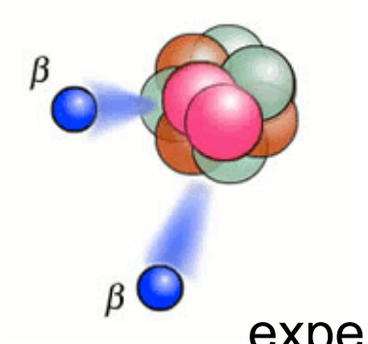




virtual particles interfere!

Double β-decay & Majorana mass $m_{\beta\beta}$

determination of **effective Majorana mass $m_{\beta\beta}$** from $0\nu\beta\beta$ half-life $T_{1/2}$



$$\left\langle m_{\beta\beta} \right\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \cdot G^{0\nu\beta\beta}(E_0, Z) \cdot \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

experimental value of $0\nu\beta\beta$ **half-life**

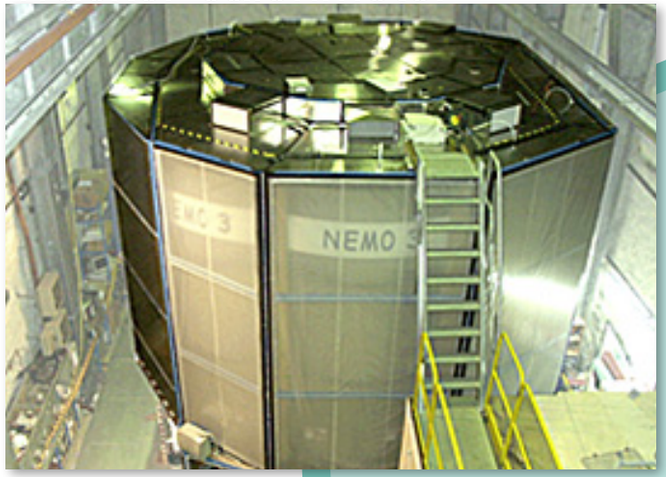
phase space factor

nuclear matrix element
M_{GT}: Gamov-Teller
M_F: Fermi

- **experimental observable: $T_{1/2}$**
  - ↳ $0\nu\beta\beta$ event number (N), measuring time (t), number of target nuclei (mol), experimental efficiency (ε)
- **weak interaction (phase space factor): $G^{0\nu\beta\beta}$**
  - ↳ ββ-endpoint energy
- **nuclear physics (matrix elements): $M^{0\nu\beta\beta}$**
  - ↳ shell model calculations, large uncertainties ~200-300%

Experimental techniques

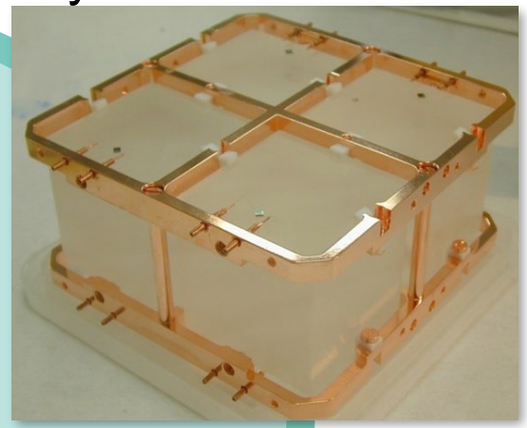
Tracker-calorimeter

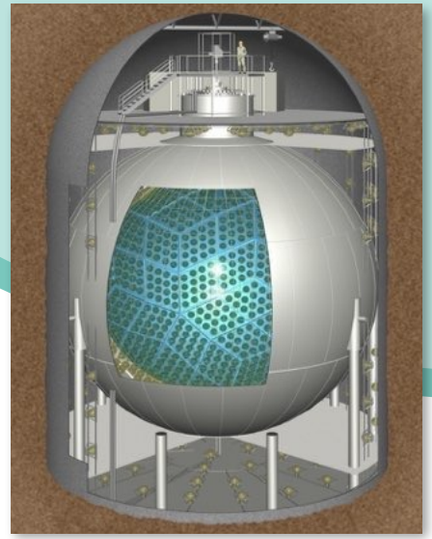




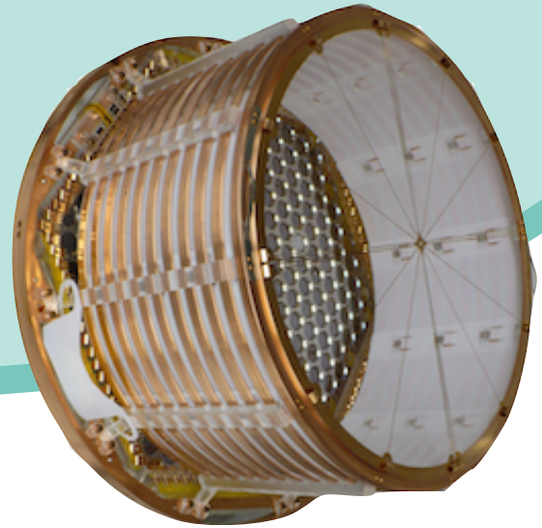
Ge diodes

Cryo-bolometer





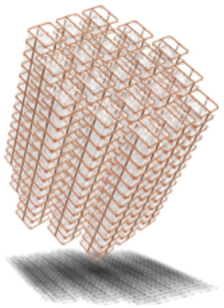
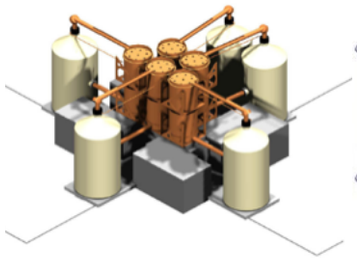
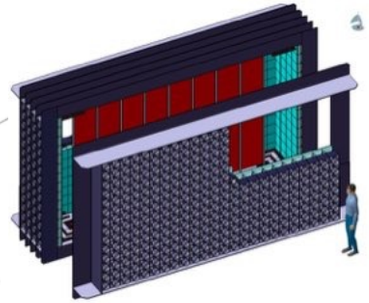
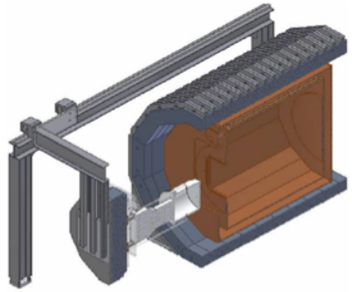
Liquid scintillator

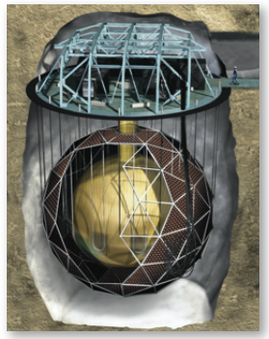
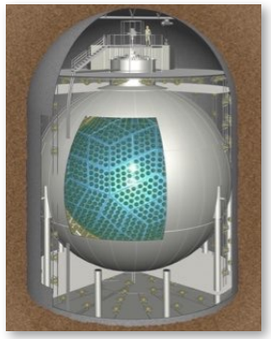


Liquid noble gas TPC

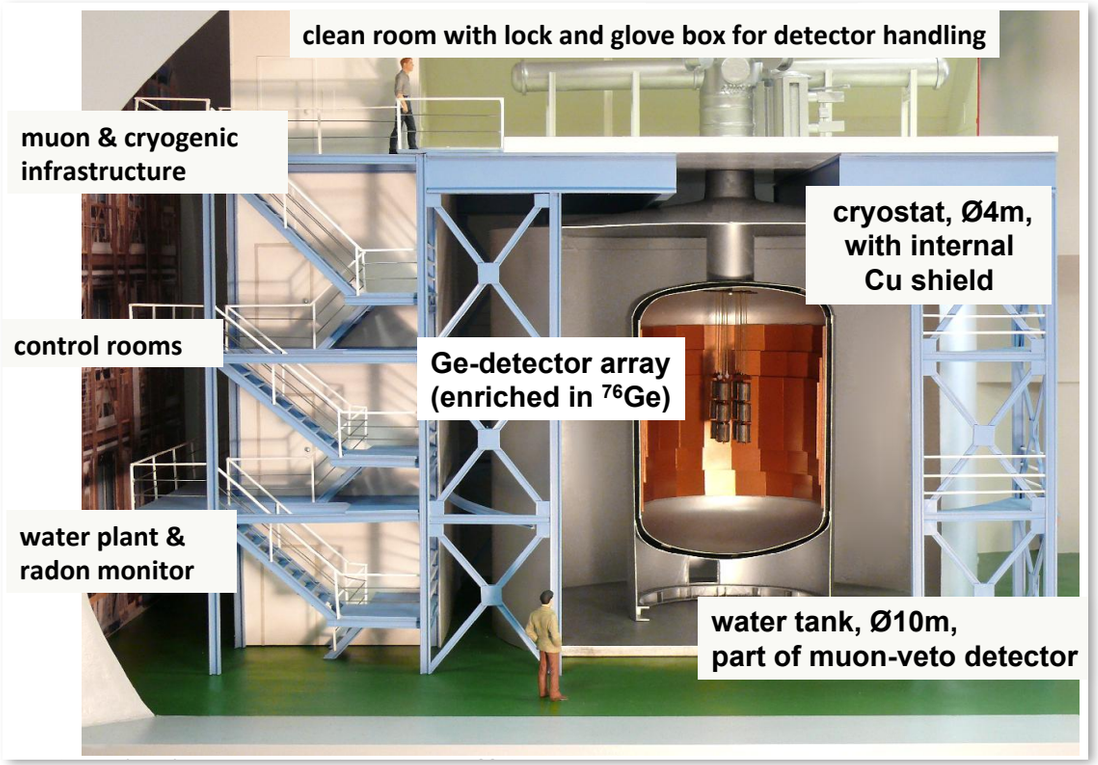
0νββ experiments – a (non-inclusive) overview

experiment	*ββ emitter*	*method*	*ββ mass [kg]*	*laboratory*	*status/start*
Cuoricino	^{130}Te	*bolometer*	*40.7*	*LNGS*	*finished*
NEMO-3	$^{100}Mo/^{82}Se$	*tracko-calorimeter*	*6.9*	*LSM*	*finished*
CUORE	^{130}Te	*bolometer*	*200*	*LNGS*	*2013/14*
GERDA	^{76}Ge	*ionisation*	*18/40/(500)*	*LNGS*	*2011, 2015*
EXO	^{136}Xe	*liquid-TPC*	*200*	*WIPP*	*2011*
Super-NEMO	^{82}Se	*tracko-calorimeter*	*~100*	*LSM*	*>2013*
MAJORANA	^{76}Ge	*ionisation*	*30/(500)*	*DUSEL*	*2013/14*
SNO+	^{150}Nd	*scintillation*	*56*	*SNOlab*	*2013/14*
KamLAND-Zen	^{136}Xe	*scintillation*	*250-400*	*Kamioka*	*2012*

GERDA phase I results

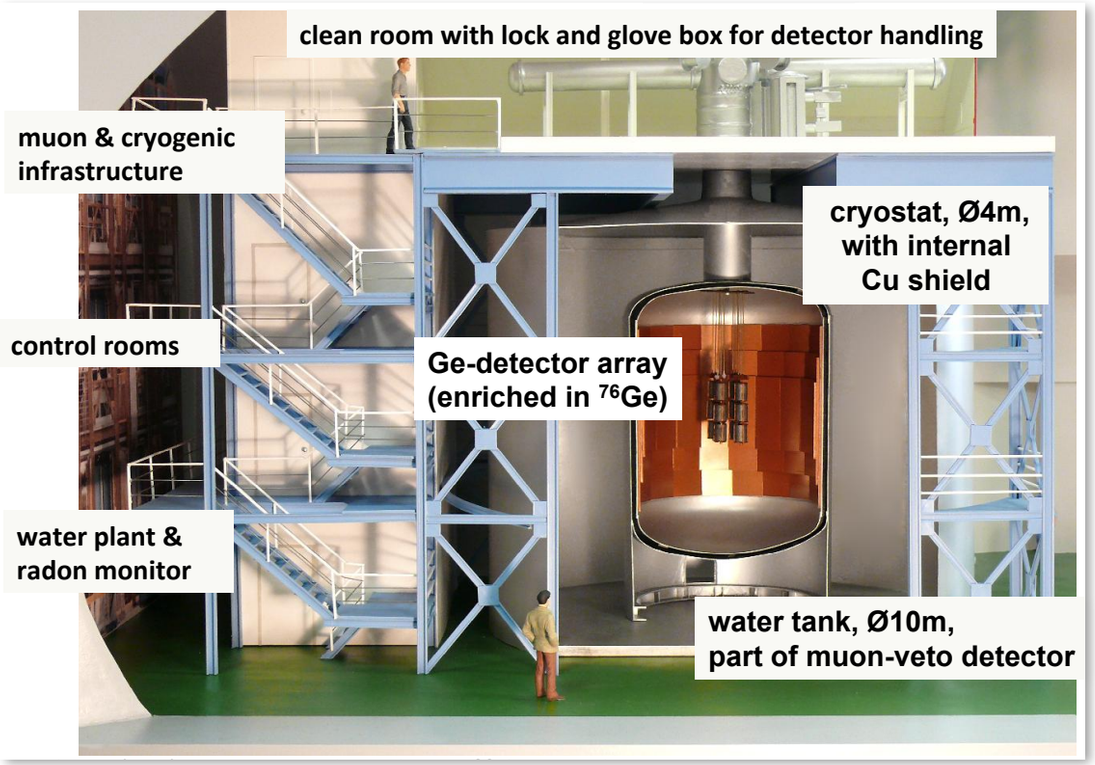


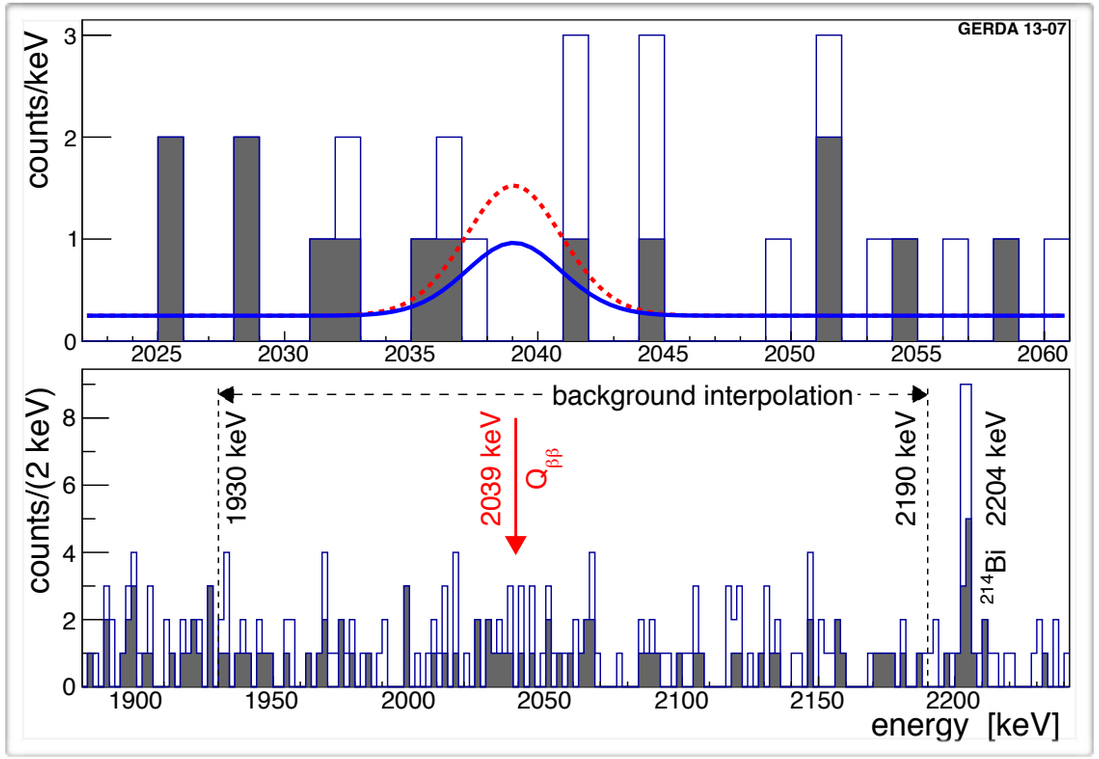
Gran Sasso underground lab

18 kg enriched crystals in LAr

expected $0\nu\beta\beta$ event rate:
< 1 / year / kg

GERDA phase I results



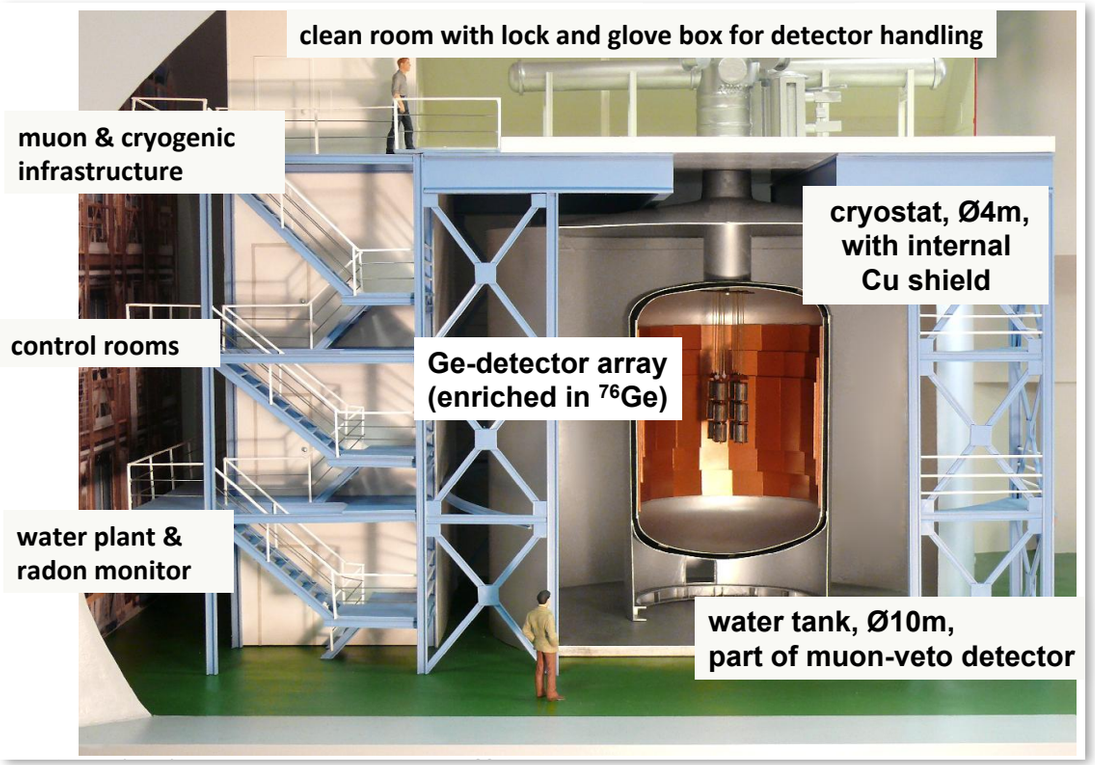


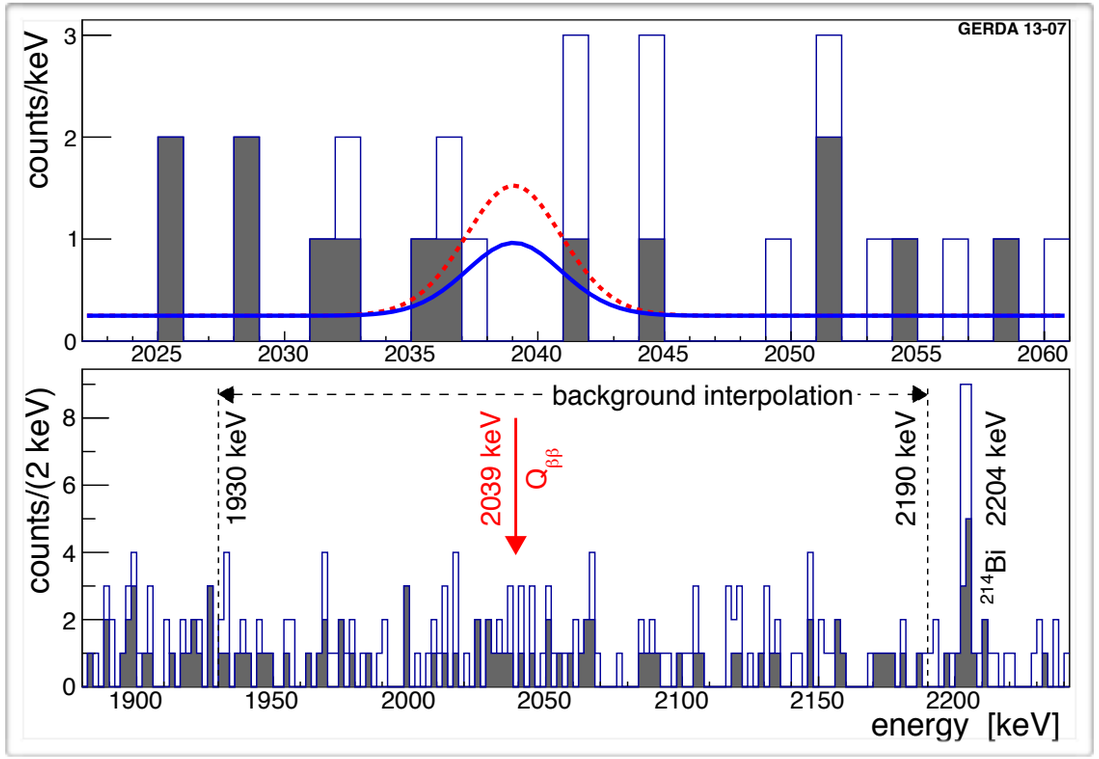
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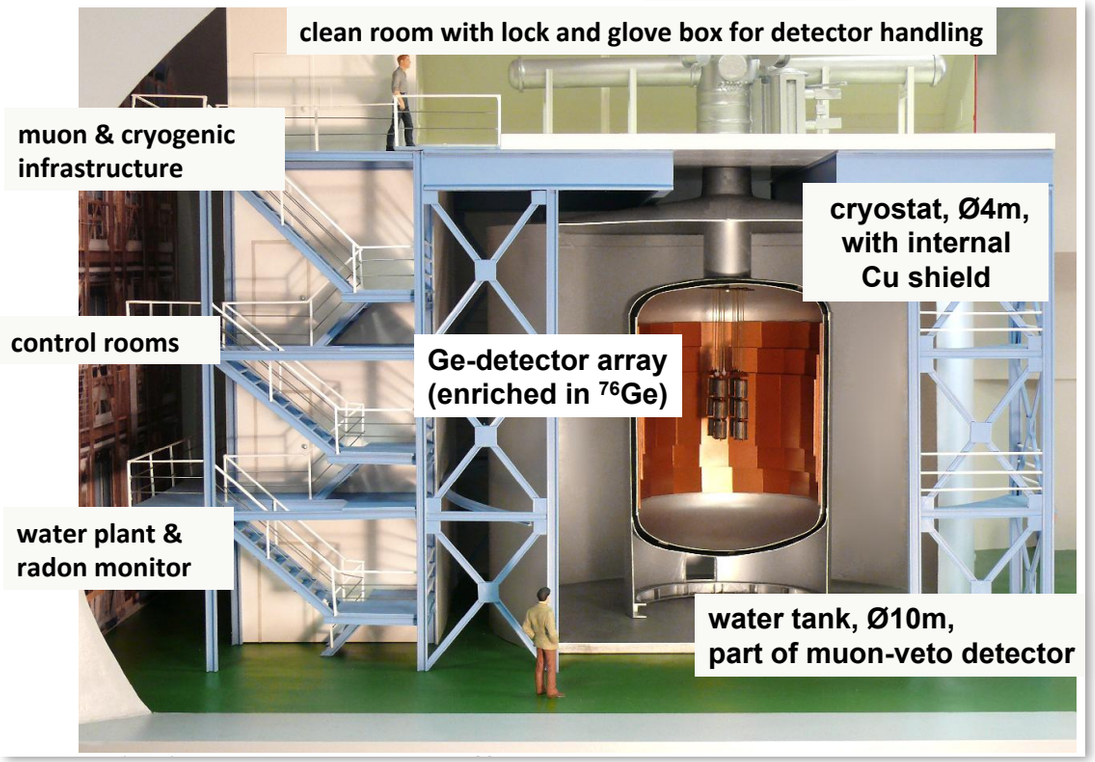
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GERDA phase I + IGEX + HdM (all ^{76}Ge):

$T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr (90% C.L.)

$m_{\beta\beta} < 0.2 - 0.4$ eV

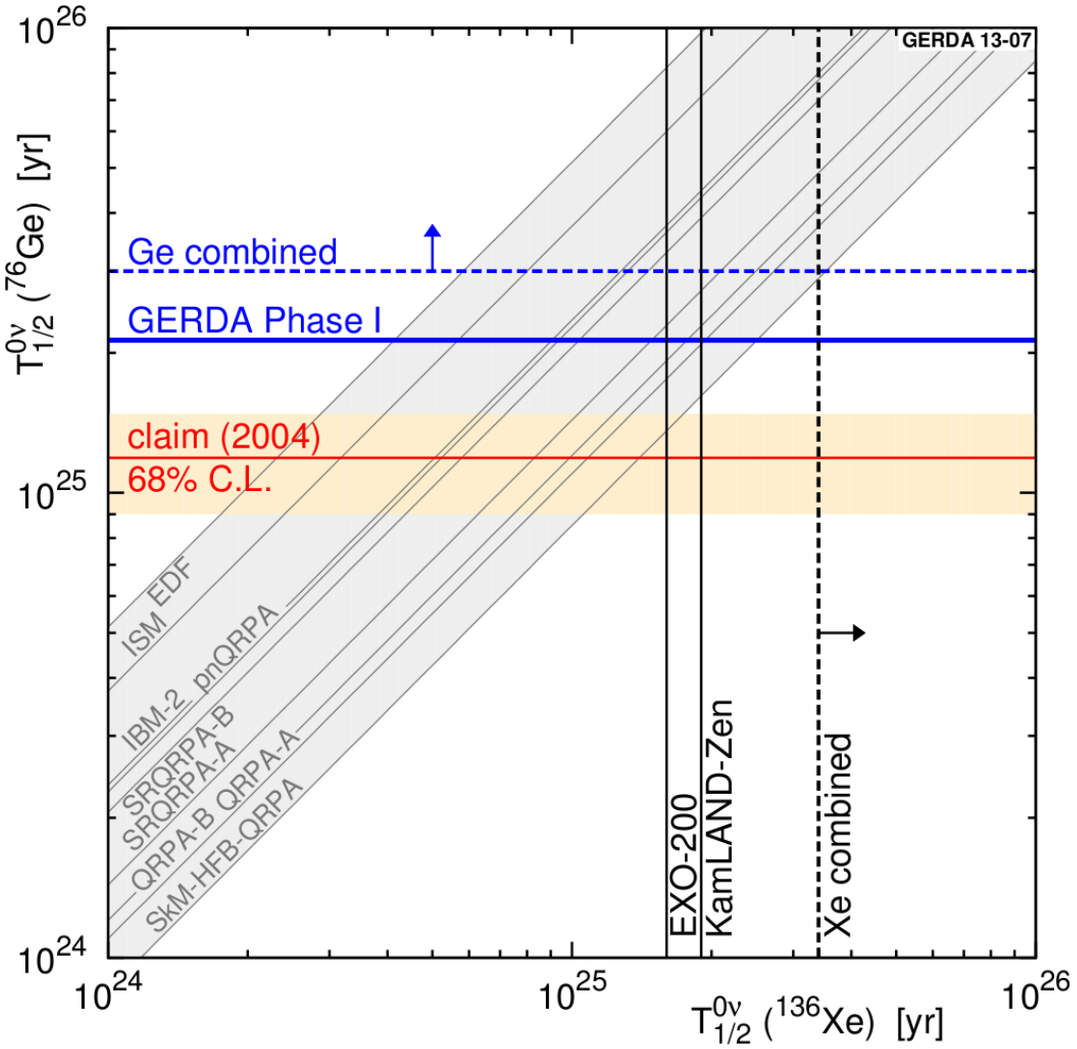
GERDA phase I results



Gran Sasso underground lab

18 kg enriched crystals in LAr

expected 0νββ event rate:
< 1 / year / kg



➜ former claim strongly disfavoured

Current and future 0νββ experiments

EXO-200 (WIPP):
^{136}Xe
175 kg LXe TPC
ionisation & scintillation signals
(similar to DM experiments)



Current and future 0νββ experiments

Karlsruhe Institute of Technology

Pushing towards $T_{1/2} > 10^{26}$ yr sensitivity ($m_{\beta\beta} < 100$ meV)

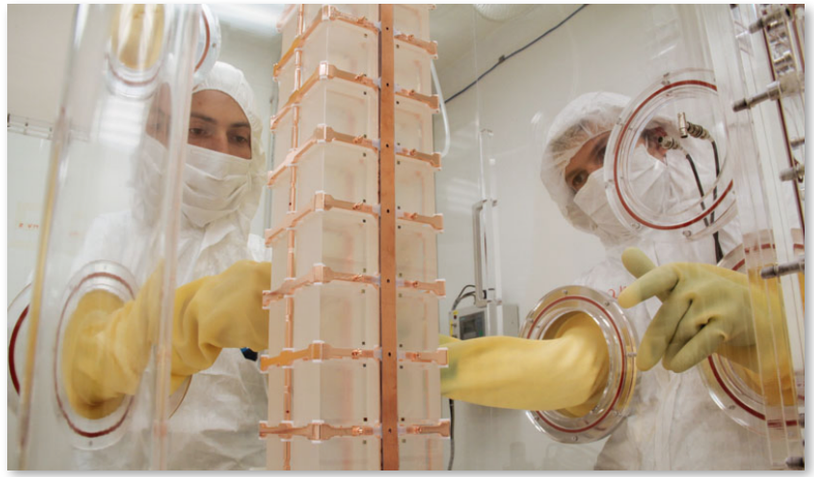
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GERDA II (LNGS):
18+20 kg, better BEGe detectors
lower bg rate due to active veto

Majorana demonstrator (Sanford Lab):
^{76}Ge, similar goal as GERDA II

CUORE (LNGS) under commissioning:
^{130}Te, reached < 10 mK & bg goal

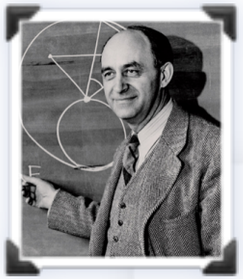


Lab experiments, part II:

Kinematics of weak decays

(“direct” ν mass search)

β decay and neutrino mass



Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

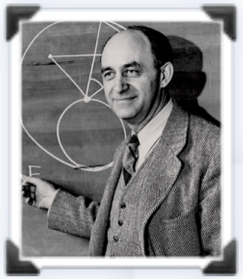
Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

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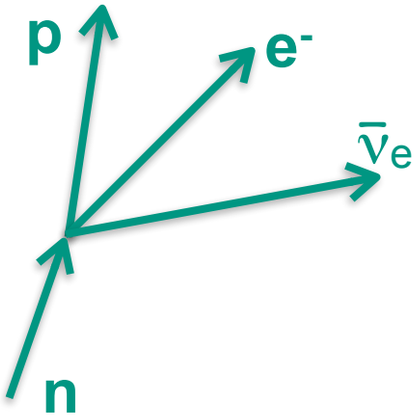
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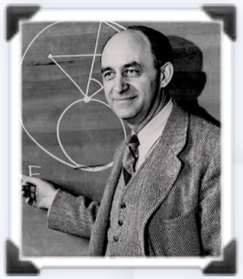
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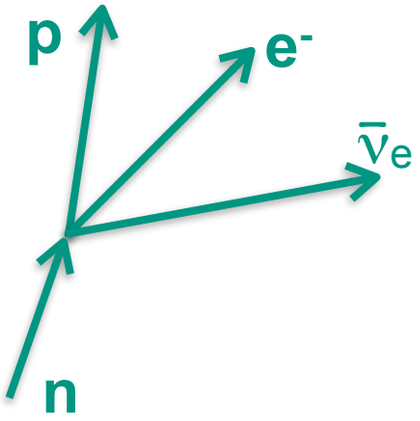
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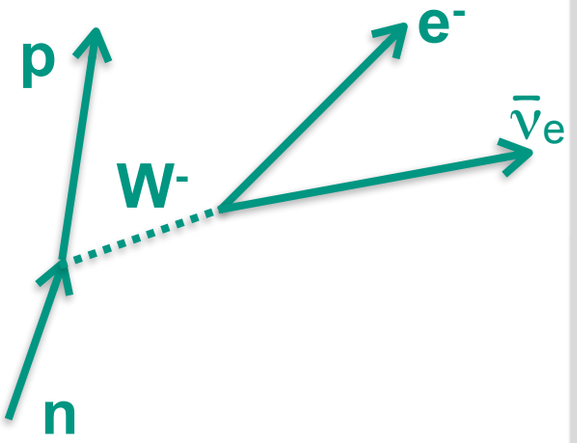
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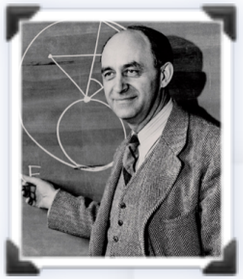


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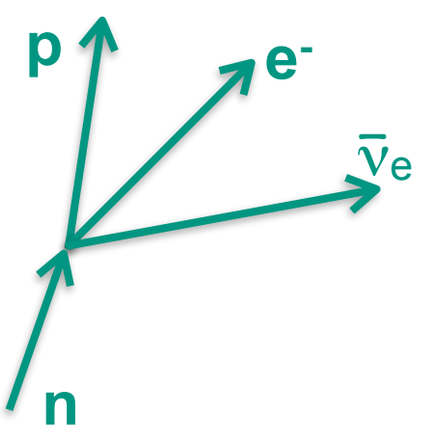
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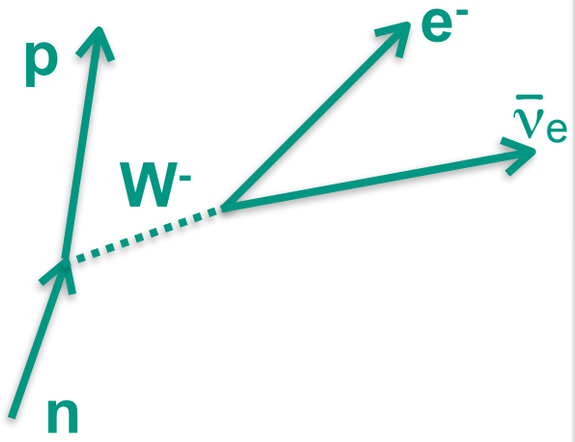
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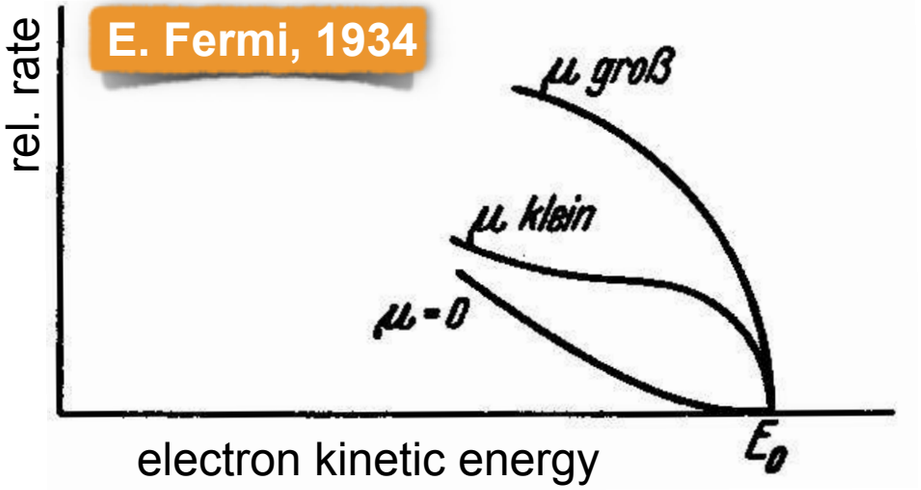
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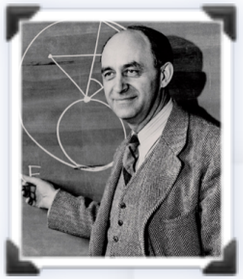
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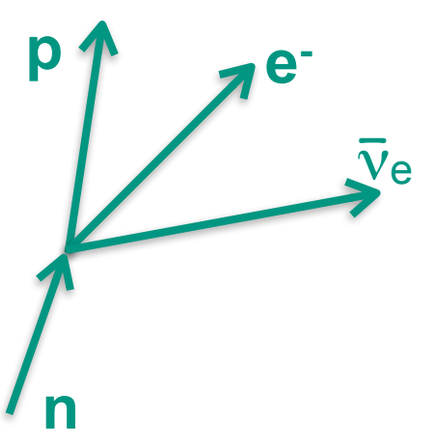
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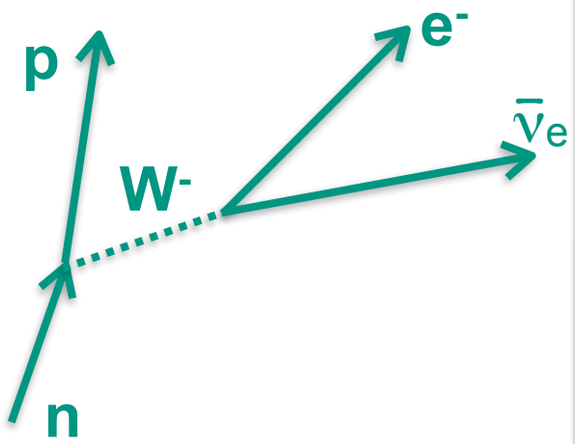
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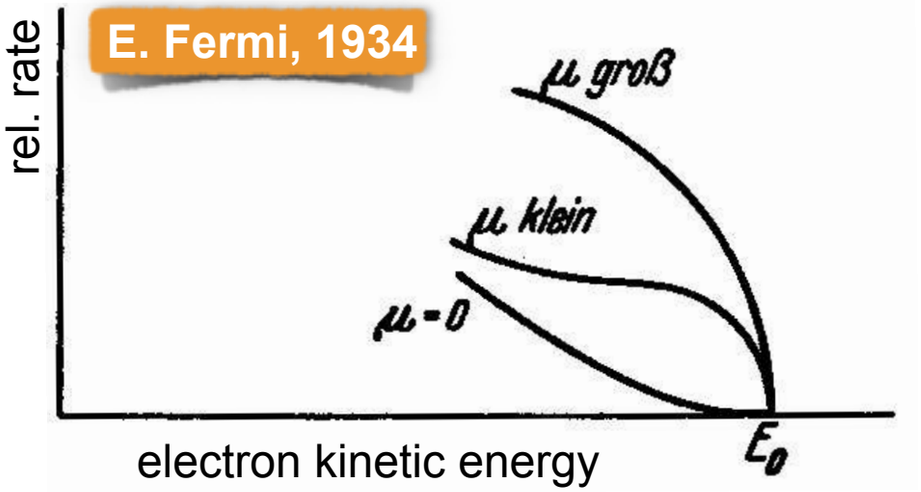
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- Model independent neutrino mass measurement:
  based solely on **kinematic variables** (E_0, E_e, p_e, m_e) and **energy conservation**
- Elusive neutrino escapes undetected, only electron energy is measured

Direct neutrino mass measurement

Imprint of m_ν on endpoint region of β spectrum (similar for EC):

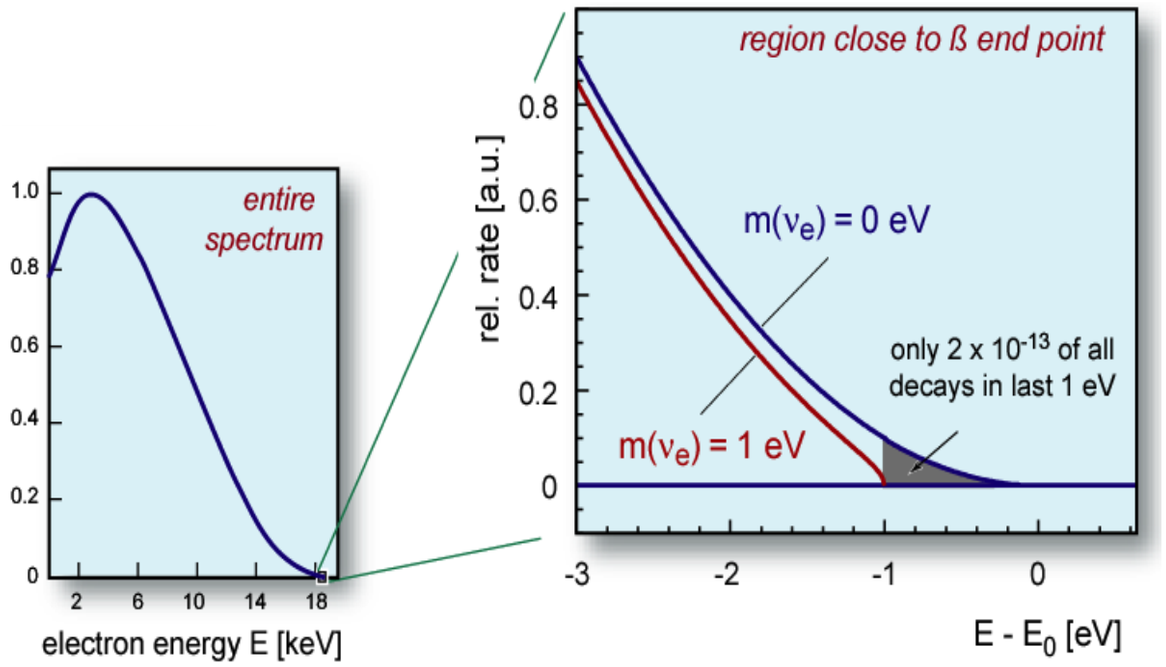
$$\frac{dN}{dE} = C \cdot F(Z,E) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m^2(\nu_e)}$$

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

observable: effective squared mass

Key requirements

- Source isotope:
  - Low spectral endpoint Q
  - Large decay rate (short $T_{1/2}$)
- Instrument:
  - Excellent energy resolution
  - Very low background



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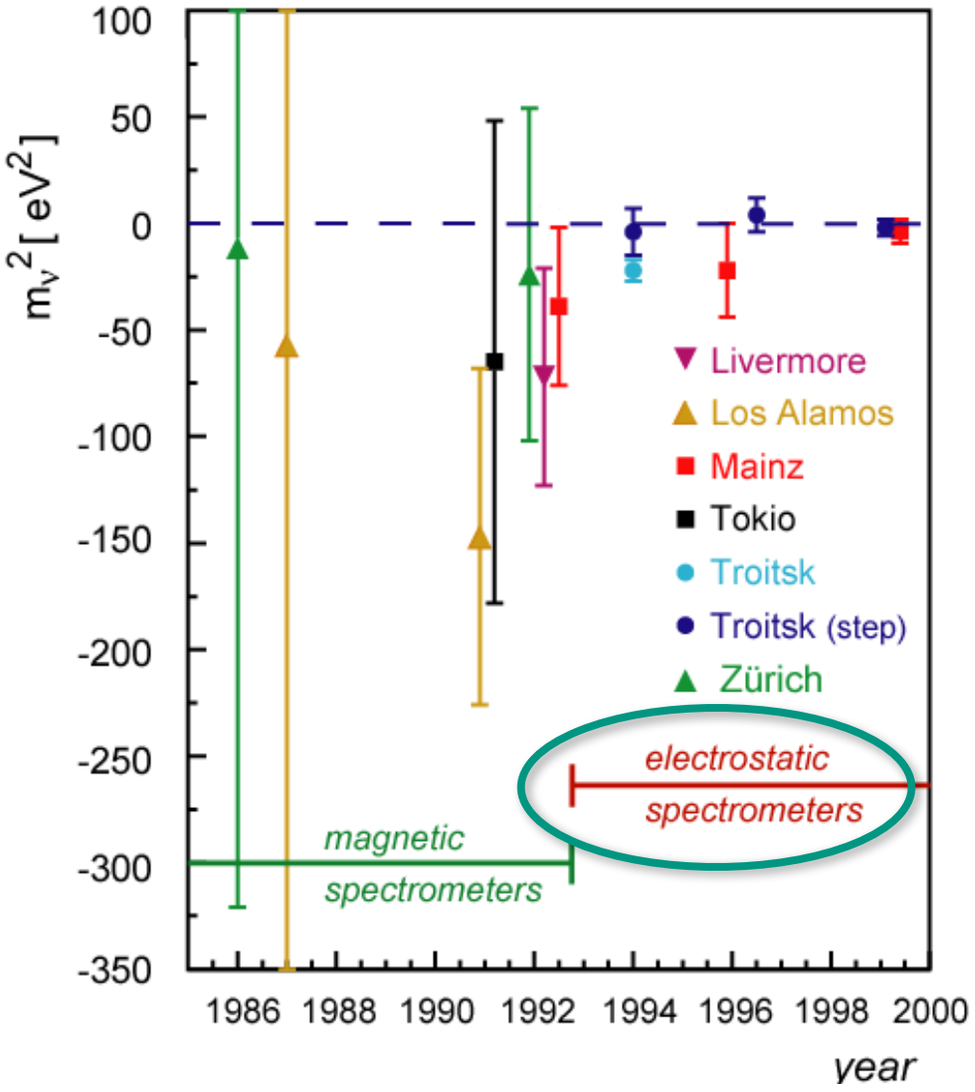
Experimental options

	^{3}H (β)	^{187}Re (β)	^{163}Ho (EC)
Q value	18.6 keV	2.5 keV	~2.5 keV
$T_{1/2}$	12.3 yr	41 Gyr	4.5 kyr
technique	spectrometer	cryogenic micro-calorimeter	
	source ≠ det.	source *within* detector	
present m(ν) sens.	**< 2 eV** **Mainz, Troitsk ~2004**	< 15-30 eV Milan, Genoa ~2004	< 225 eV Livermore 1987
	$\bar{\nu}_e$	$\bar{\nu}_e$	ν_e

History of tritium β-decay experiments

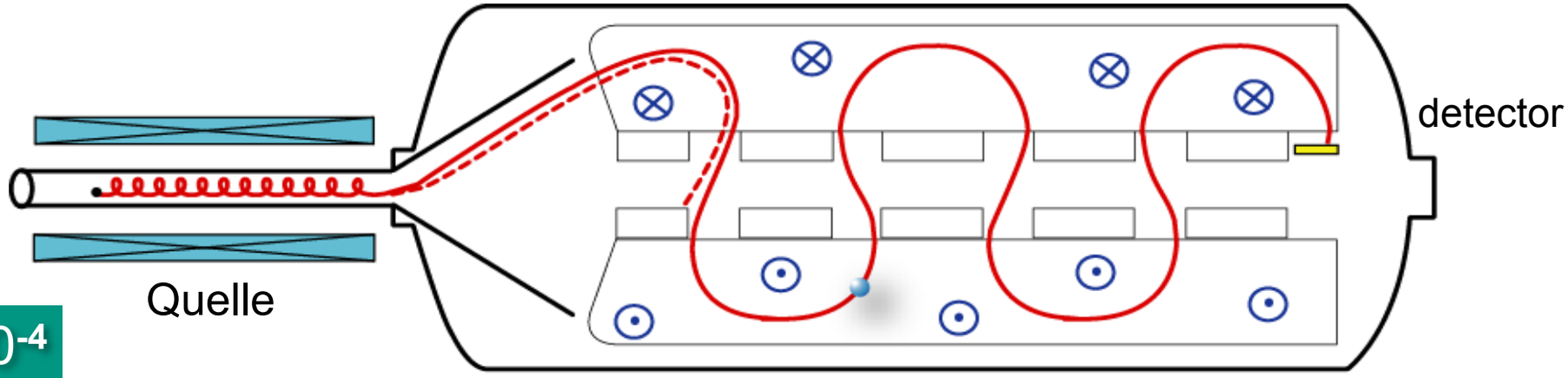
	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer* **Mainz (1994-today)** *frozen T_2 - source* *electrostat. spectrometer*	**< 2 eV**

experimental results for m_ν^2



Magnetic vs. electrostatic spectrometers

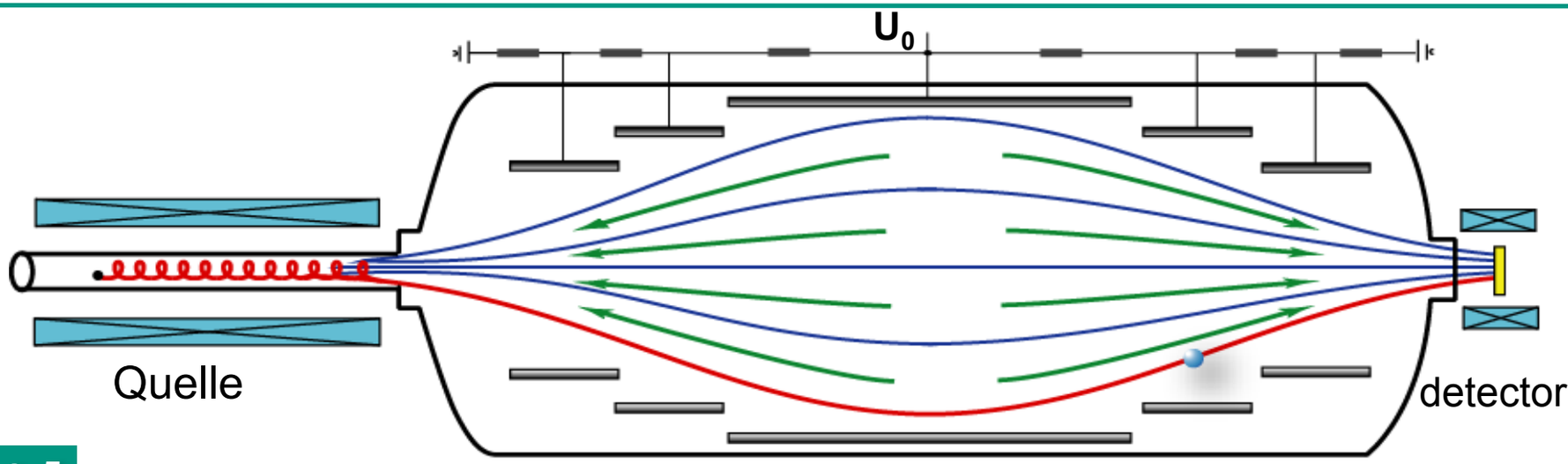
magnetic



$\Delta p/p = 7 \times 10^{-4}$
$\delta\Omega = 10^{-3}$

Principle: magnetic guiding, **momentum analysis**

electrostatic

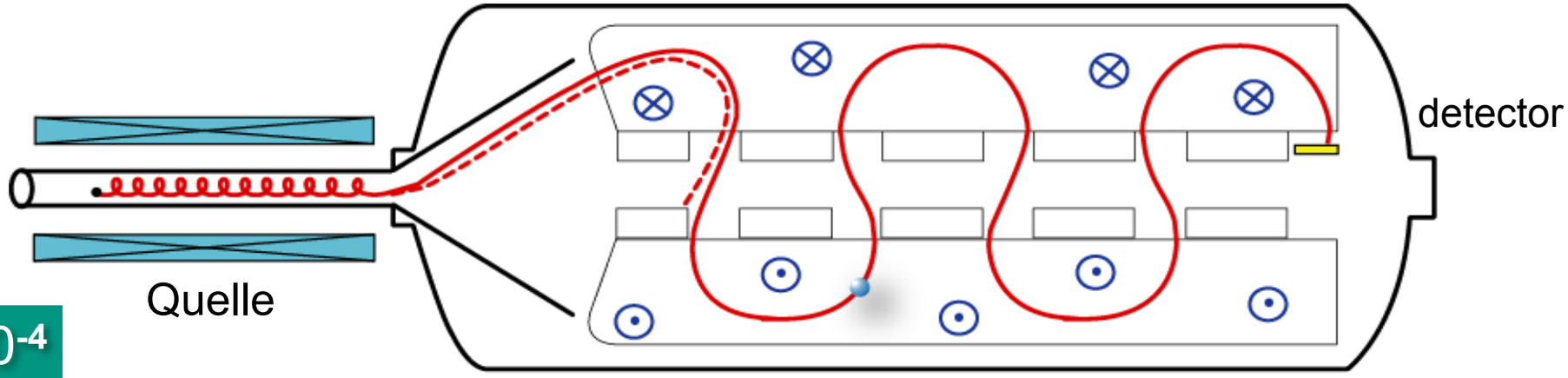


$\Delta E/E = 1 \times 10^{-5}$
$\delta\Omega \sim 2\pi$

Principle: magnetic guiding, transformation cycl. -> long. energy, **energy analysis** by retardation potential

Magnetic vs. electrostatic spectrometers

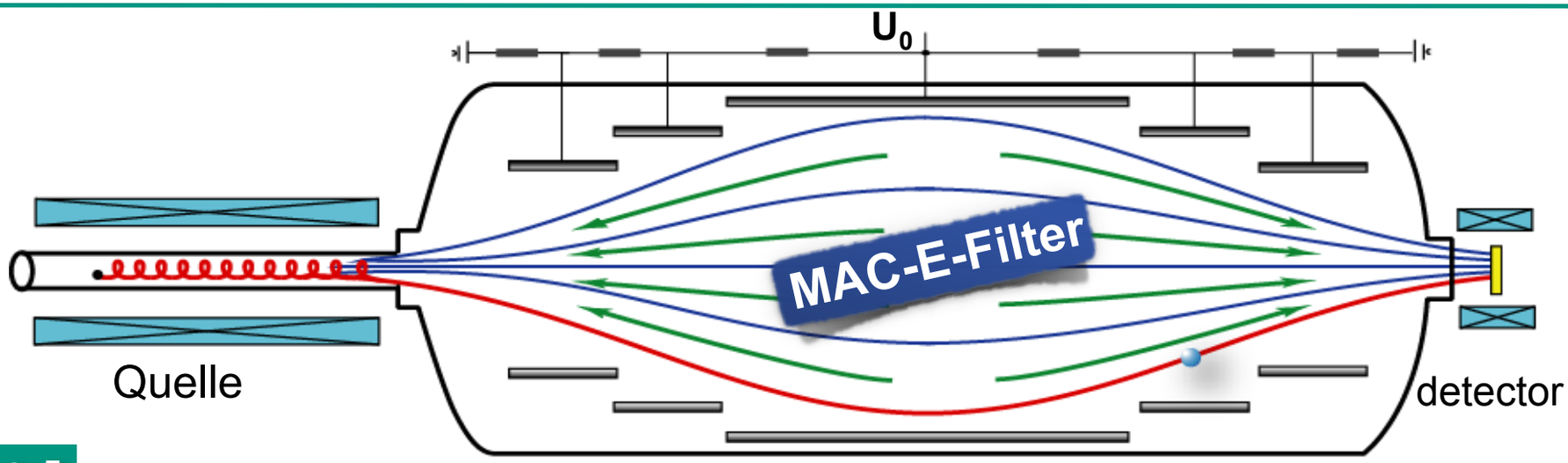
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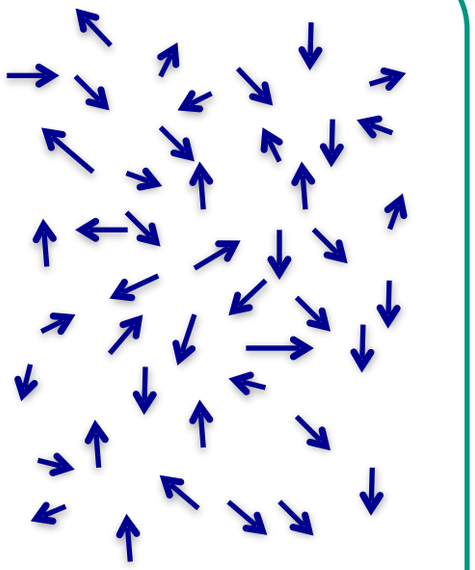


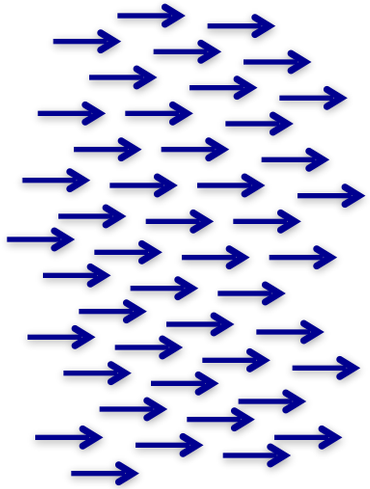
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MAC-E principle: Mainz, Troitsk, KATRIN

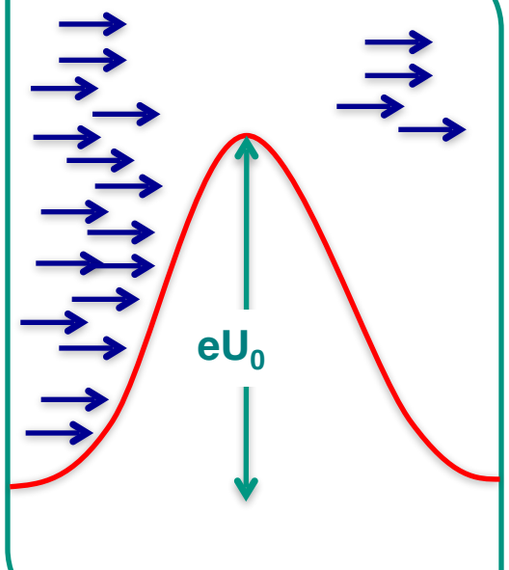
isotropic emission of e^-

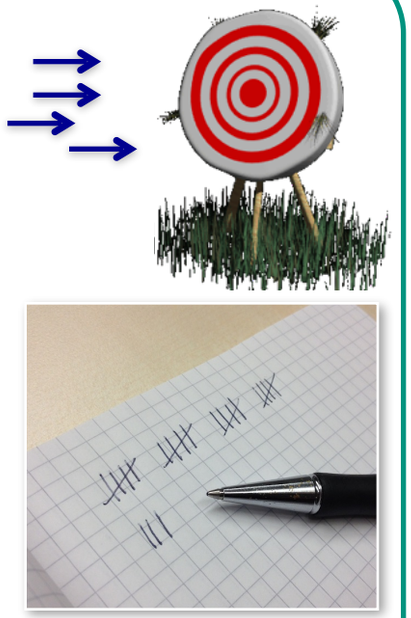




magnetic guiding
& adiabatic collimation

electrostatic filtering





counting

$$\mu = \frac{E_\perp}{B} = \text{const.}$$

$$E_\perp \longrightarrow E_\parallel$$

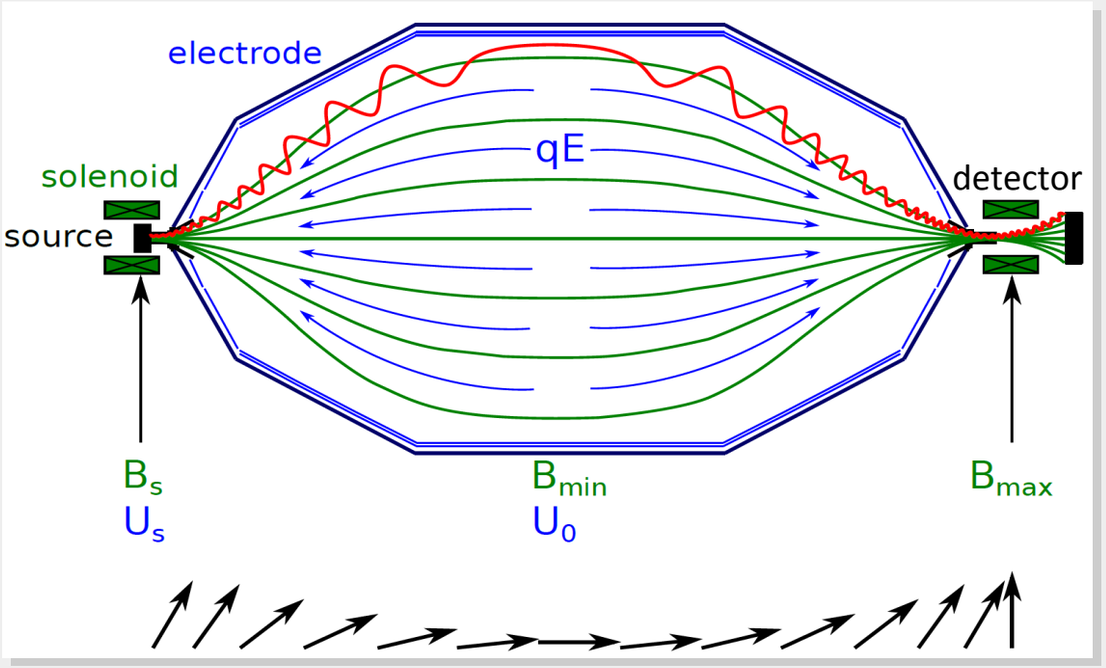
$$E_\parallel > eU_0$$

adapted from T. Thümmler

Spectroscopic technique for tritium β-decay

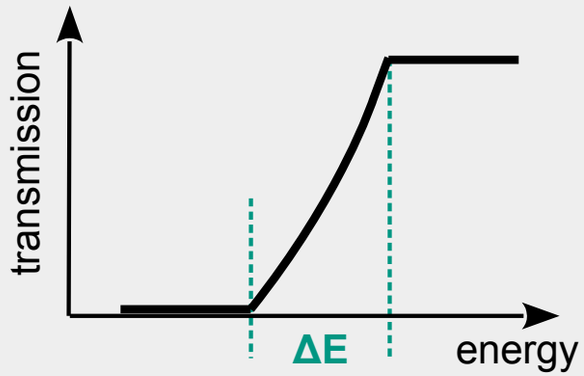
MAC-E filter technique

Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



$$\mu = \frac{E_\perp}{B} = \text{const.}$$

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

Combination of high luminosity and high energy resolution:

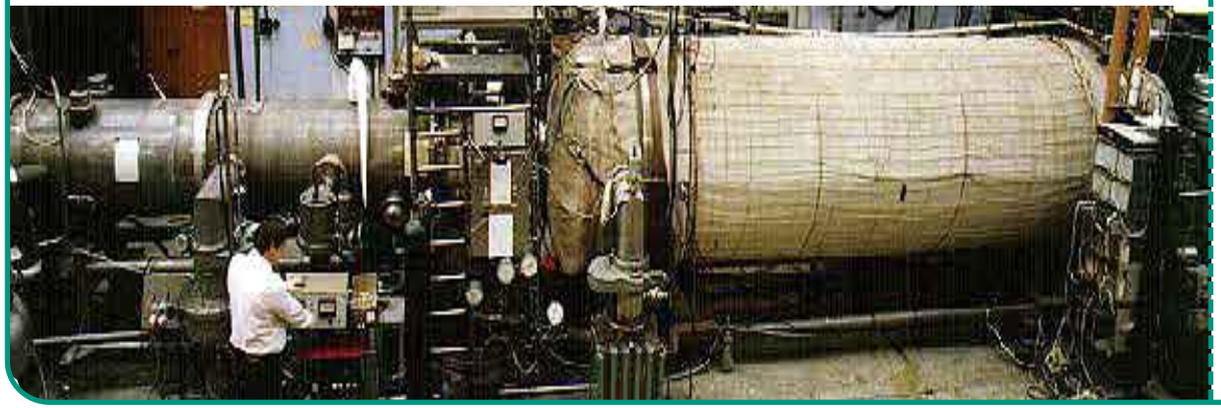
$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}} = \frac{1}{20000}$$

(at KATRIN)

Spectroscopic technique for tritium β-decay

Troitsk experiment

- windowless gaseous tritium source



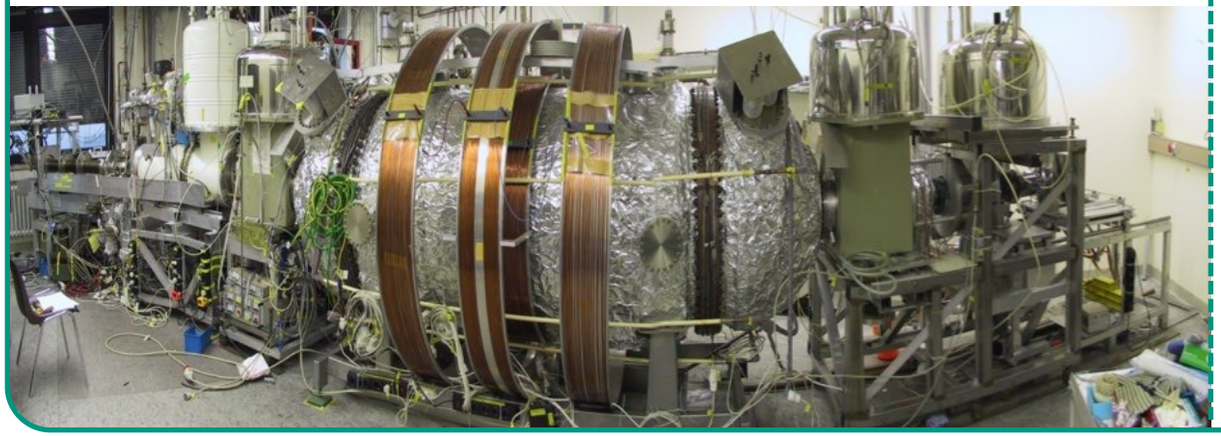
$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

$$m(\nu_e) < 2.05\ eV$$

V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003

Mainz experiment

- quench condensed tritium source



$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ eV^2$$

$$m(\nu_e) < 2.3\ eV$$

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

Next-generation experiment: KATRIN

Aim: Enhance sensitivity on m(ν_e) by one order of magnitude:

$2\ eV/c^2 \rightarrow 0.2\ eV/c^2$

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Drastic improvements w.r.t. predecessor experiments of same kind:

1) Statistics (source luminosity) **x100**
2) Systematics **÷100**
3) Scaled-up linear dimensions (at roughly same background level)

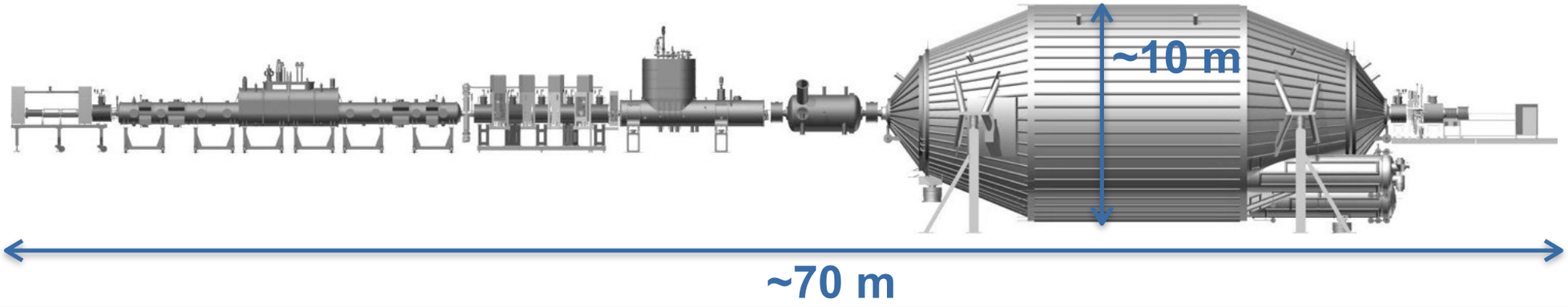
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Looks good on paper, but …

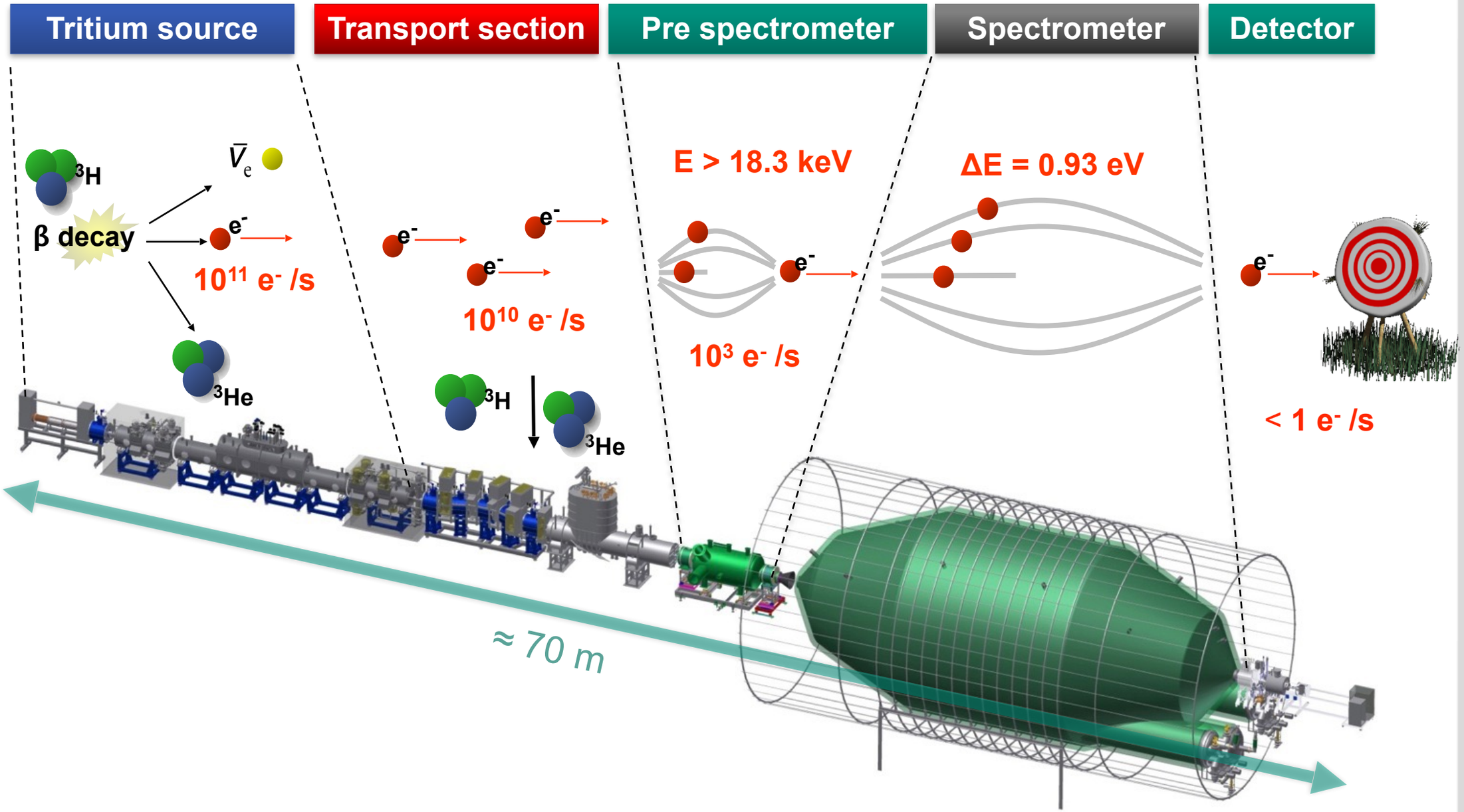



Looks good on paper, but …
tagesschau
Galileo
tv total
2DF heute
BBC Pictures of the Year 2006

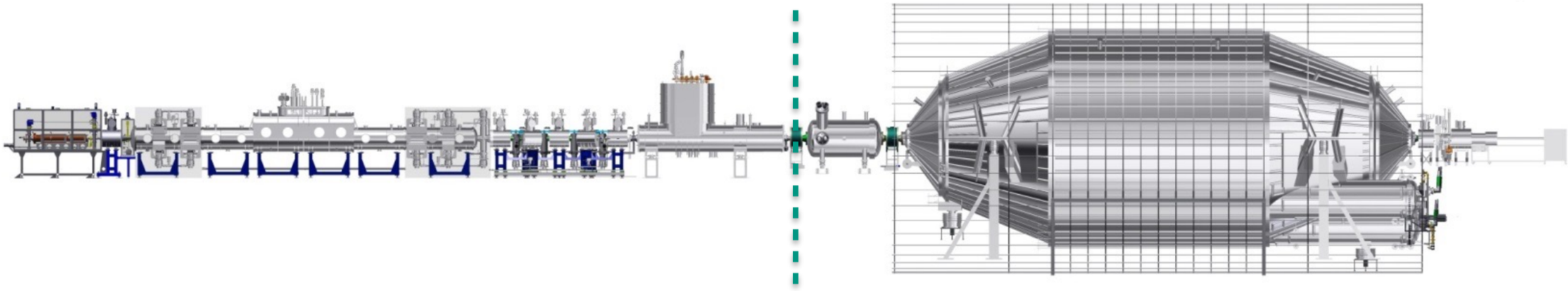
KATRIN in a nutshell



Karlsruhe Institute of Technology



Experimental challenges



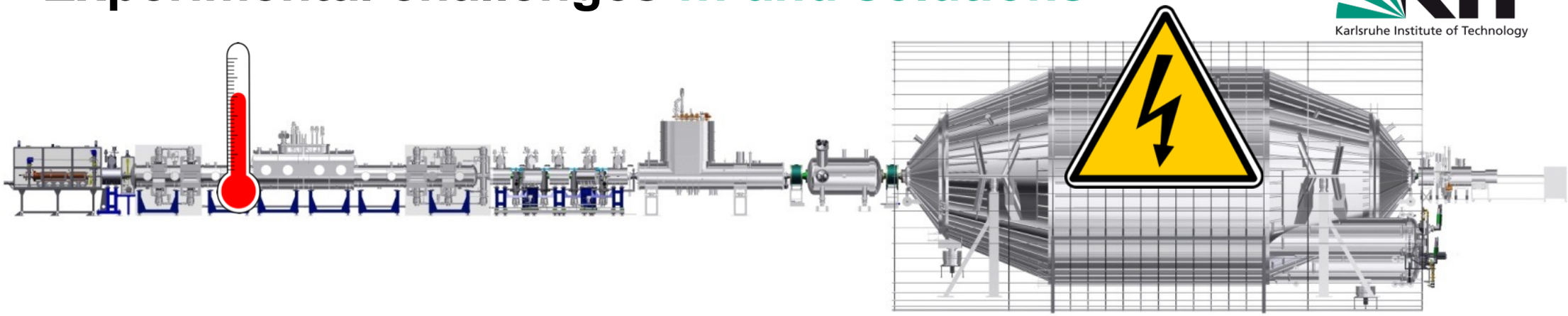
Source and Transport Section

- Windowless gaseous tritium source
  - Intensity (10^{11} decays/s)
  - Stability (10^{-3} h^{-1})
  - Isotopic purity (> 95%)
- Tritium retention (factor > 10^{14})
- Adiabatic transport of electrons

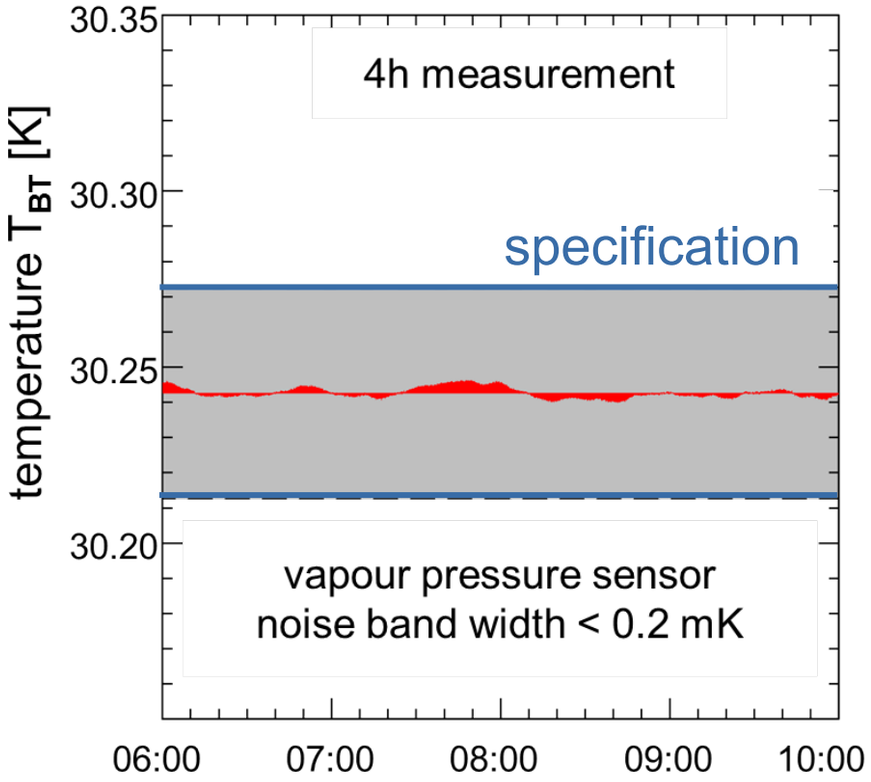
Spectrometer and Detector Section

- Spectrometer UHV ($p < 10^{-11}$ mbar)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (sub-ppm/month)
- High detection efficiency (10^{-3}-10^{3} cps)
- Low background rate (10^{-2} cps)

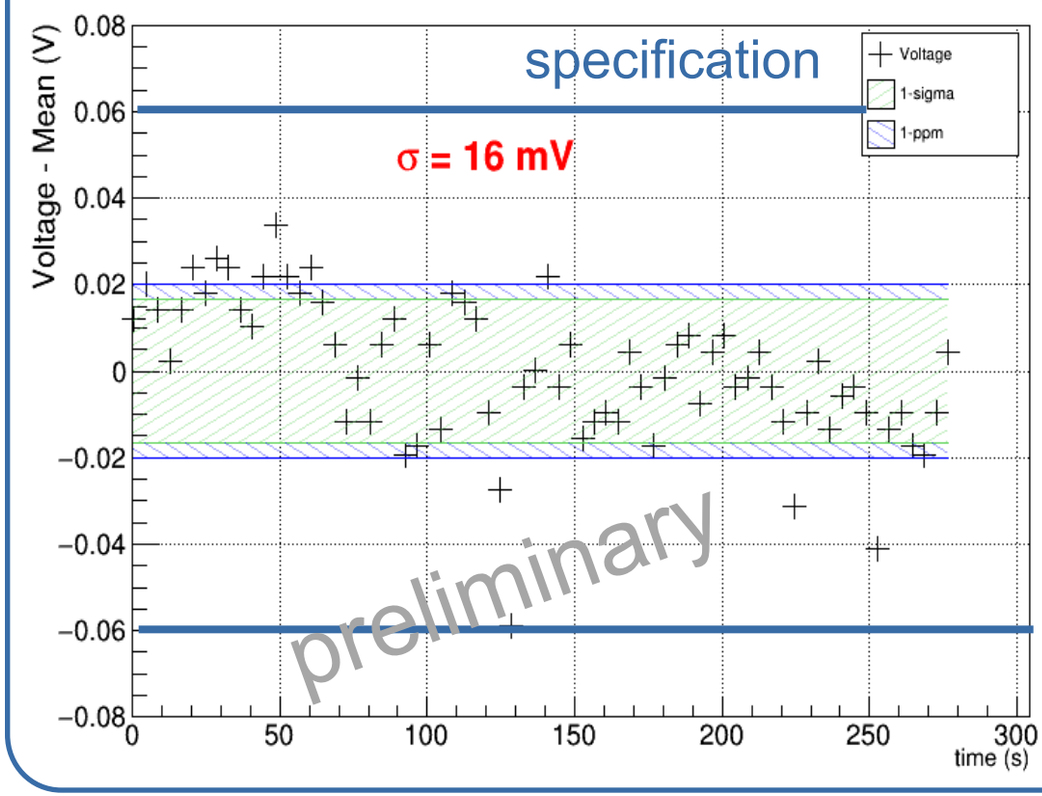
Experimental challenges … and solutions



Source demonstrator: $\Delta T/T \sim 10^{-4}$



SDS2: HV post-regulation: $\Delta U \sim 1$ ppm



[S. Grohmann et al., Cryogenics 55–56 (2013) 5]

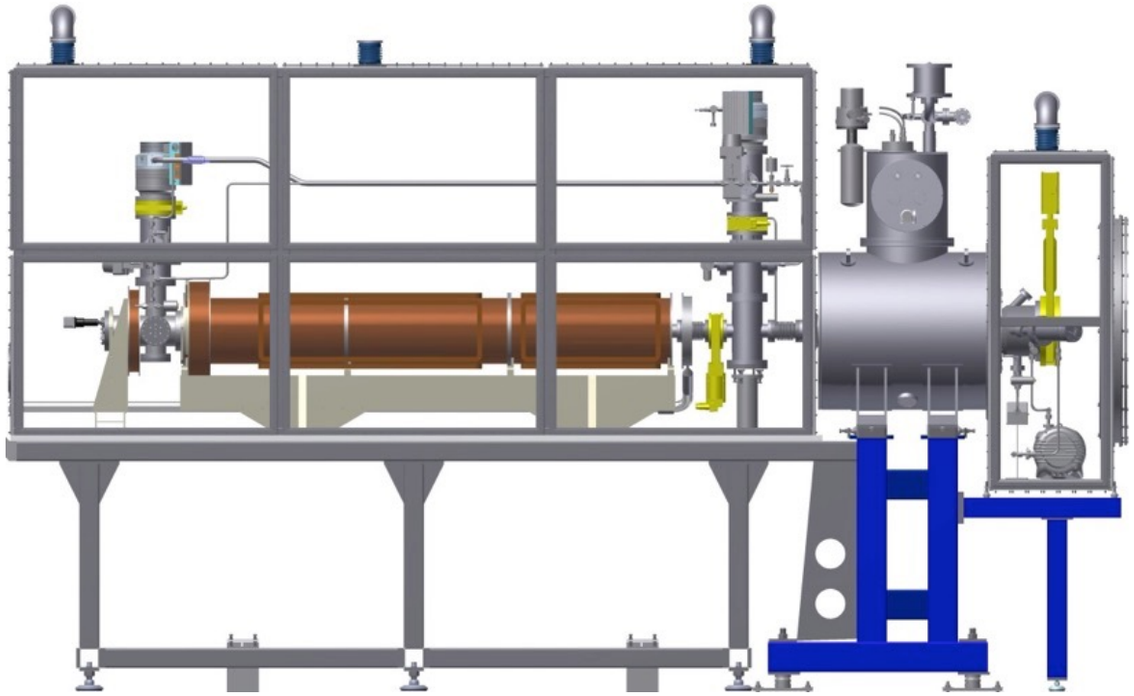
[M. Erhard et al., in prep.]

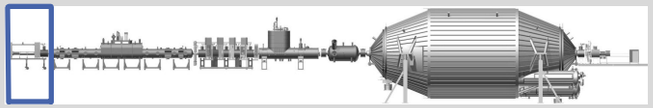
Rear Section – design and assembly

Major importance for systematics:

Presentations H. Seitz-Moskaliuk, F. Heizmann

- **Precision e^- source:**
  column density monitoring
  and determination of energy loss
  function (scattering)



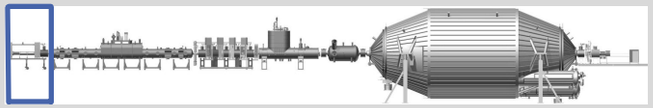


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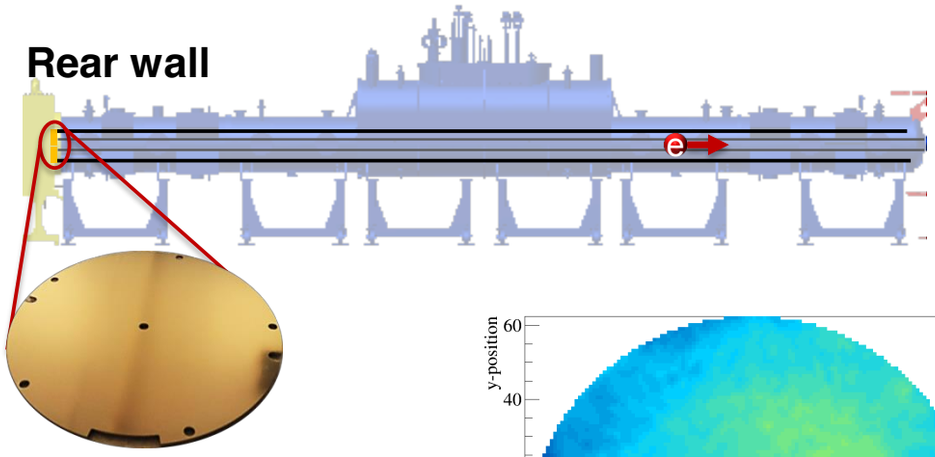
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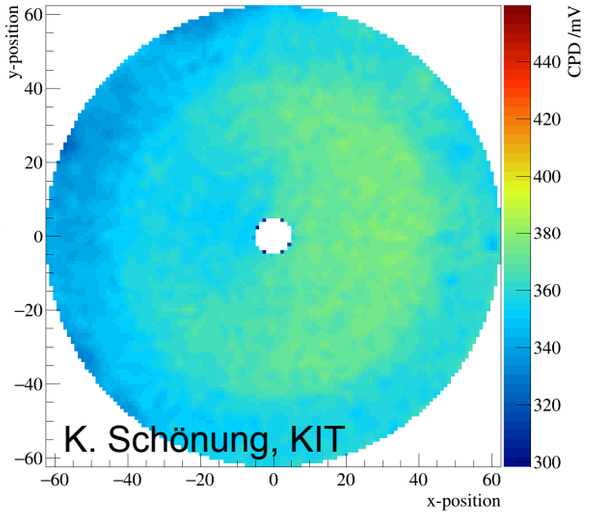


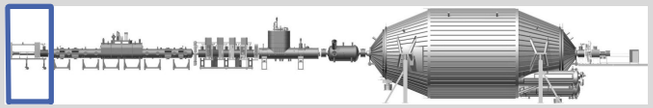
- **Rear Wall:**
  stable and homogeneous
  electrostatic potential in the
  source plasma



⌀15 cm gold surface
for homogeneity

work function test
of smaller sample



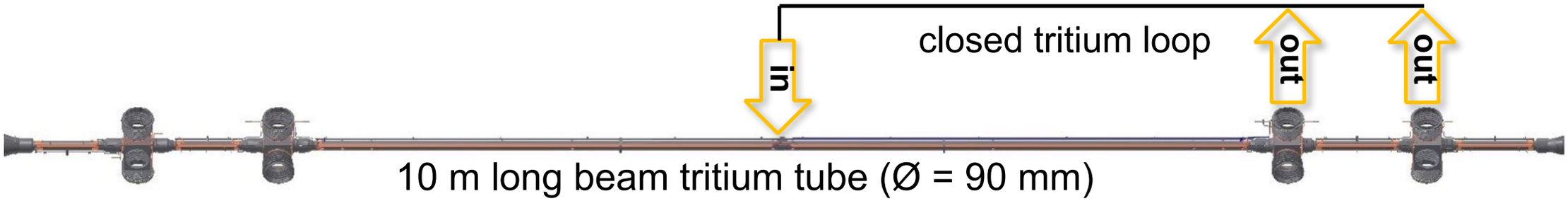


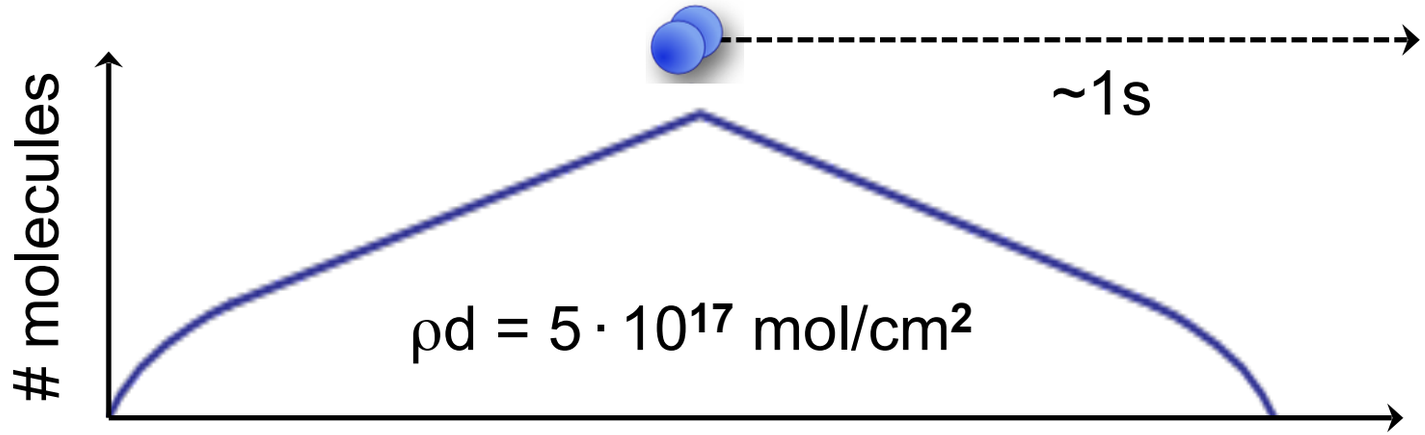
WGTS – windowless gaseous source

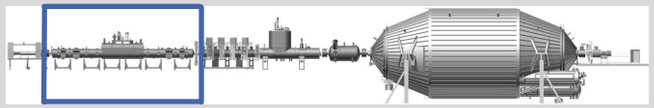
Closed-loop processing of molecular T_2:

- isotopic purity > 90%
- 10^{11} β decays / s
- 40% no-loss electrons
- stability at level 10^{-3}
- extensive control of systematics

Presentations M. Hackenjos, F. Heizmann







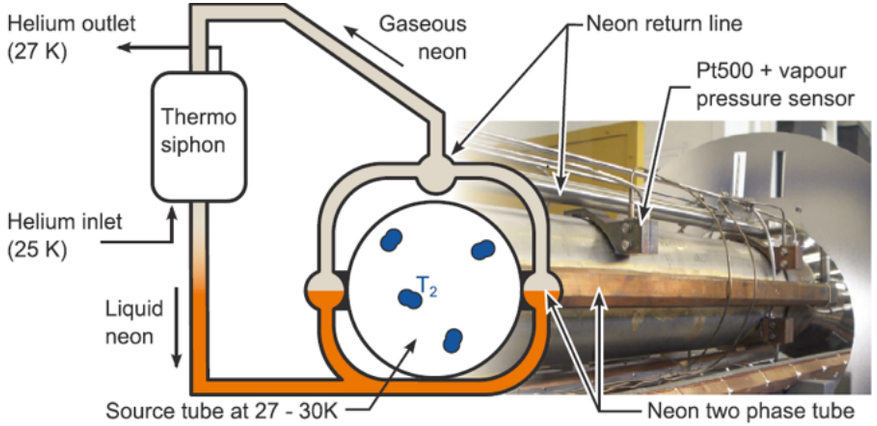
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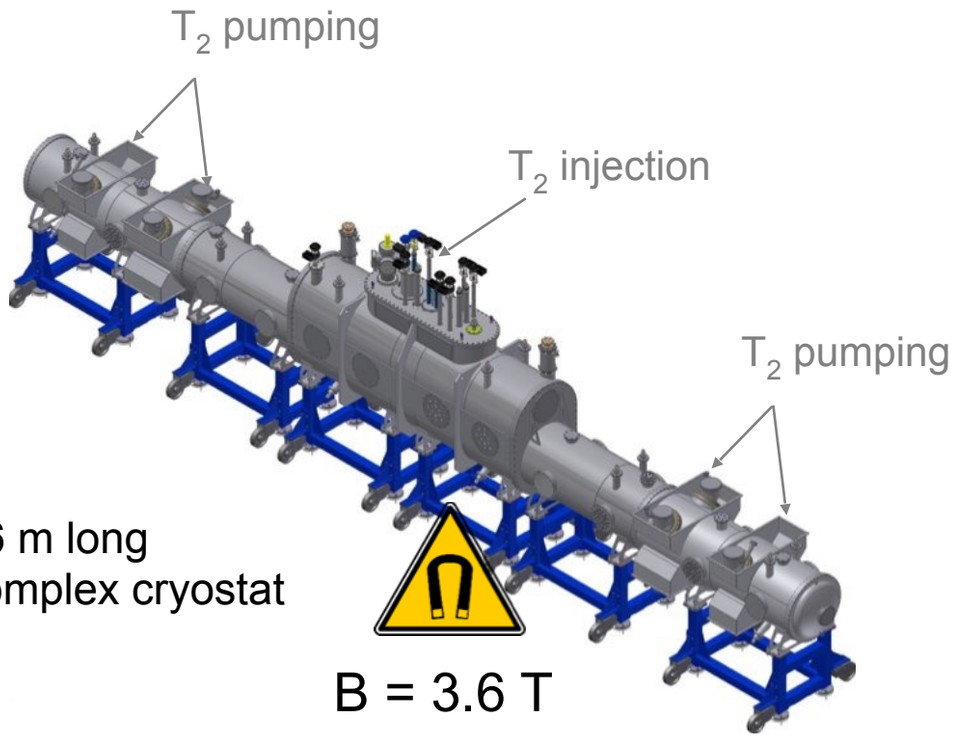
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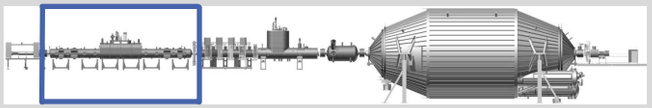
Presentation M. Hackenjos

novel 2-phase neon cooling concept



[S. Grohmann et al., Cryogenics 55–56 (2013) 5]





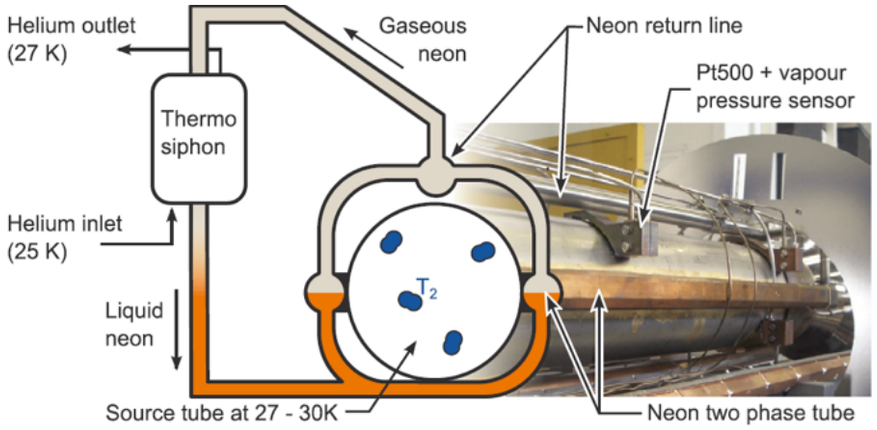
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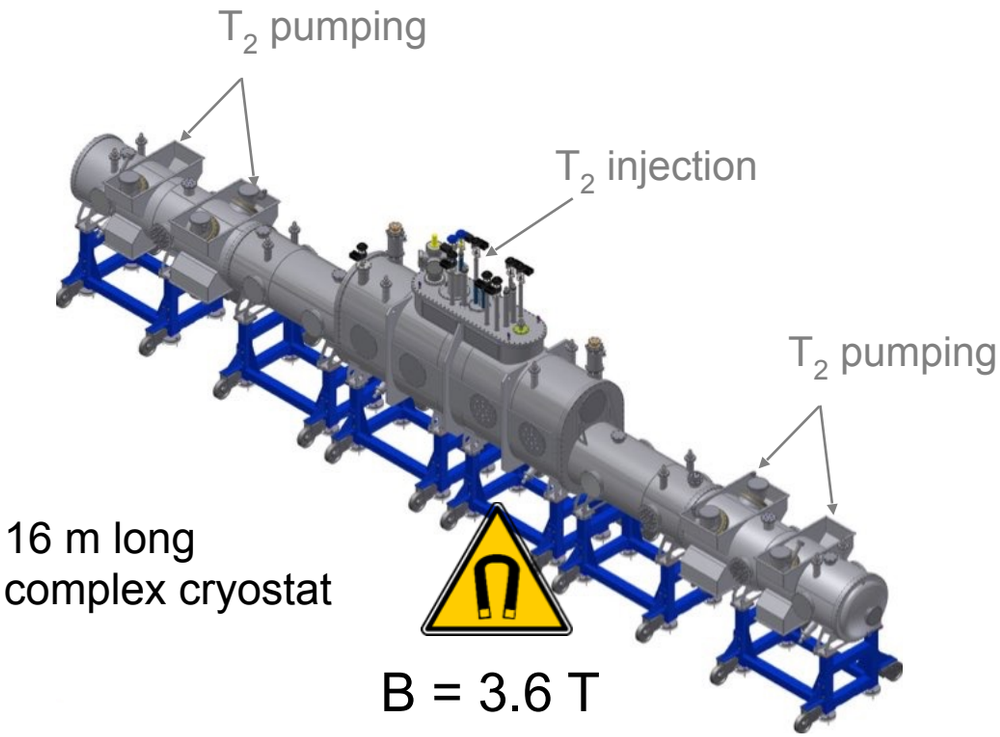
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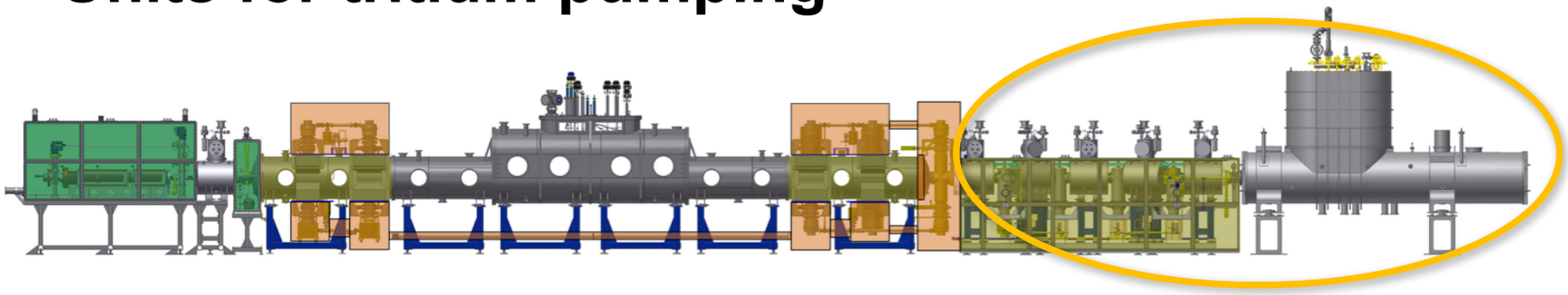


[S. Grohmann et al., Cryogenics 55–56 (2013) 5]





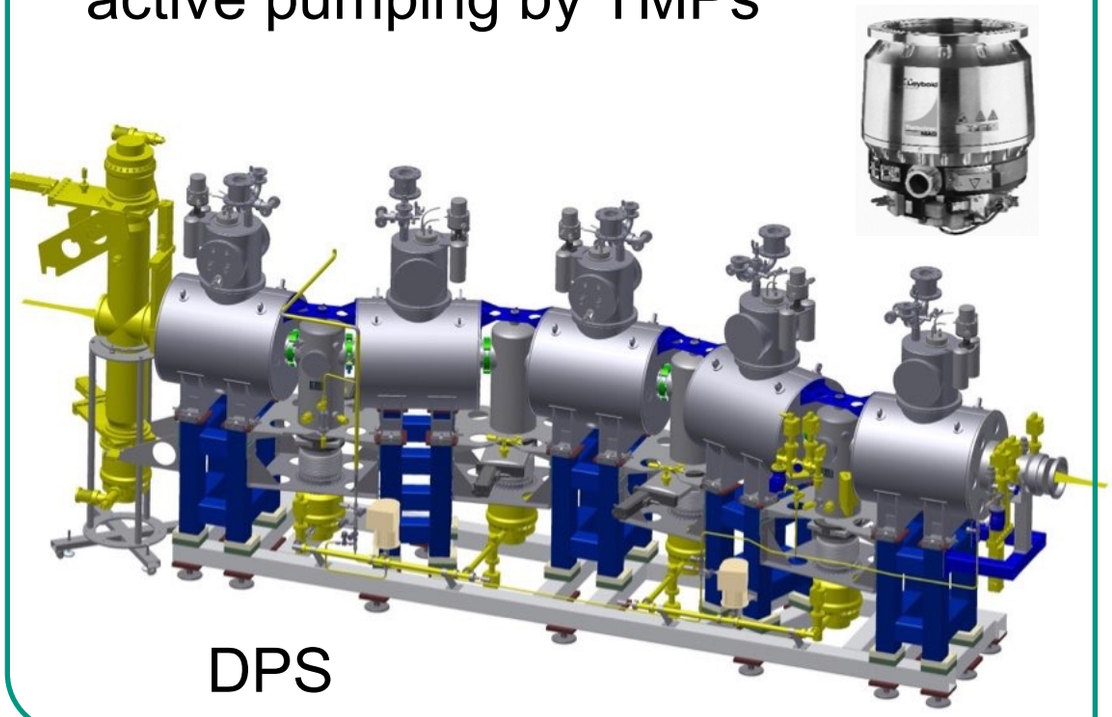
Units for tritium pumping



tritium free

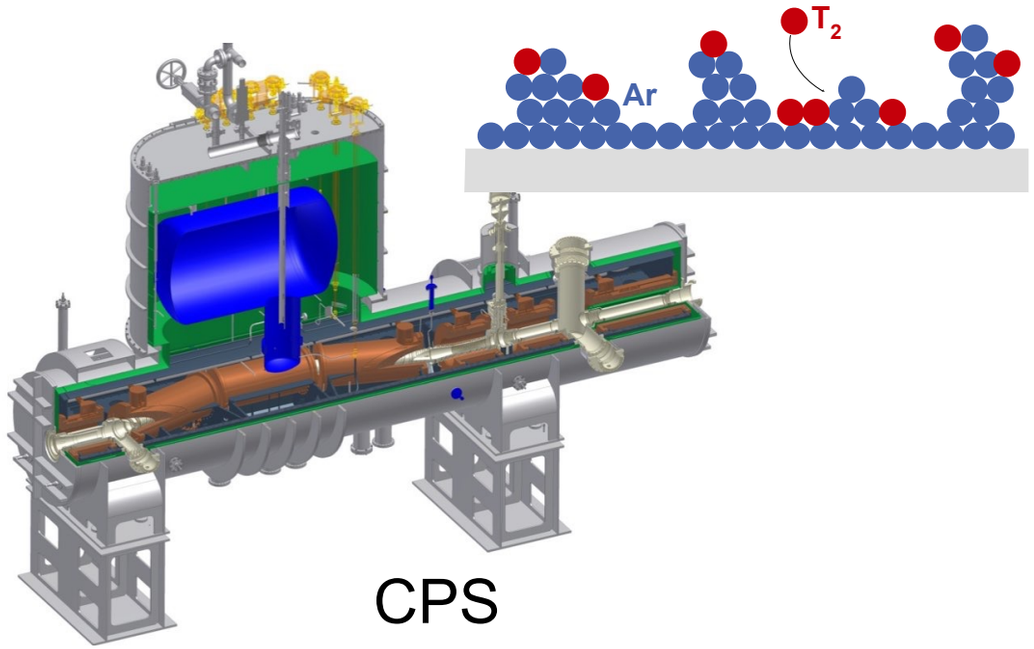
Two large cryostat systems for overall tritium retention **factor > 10^{14}**

- **Differential Pumping Section DPS**
  active pumping by TMPs

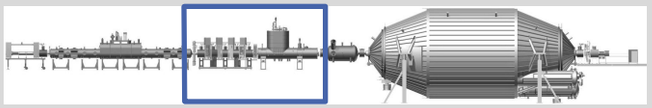


DPS

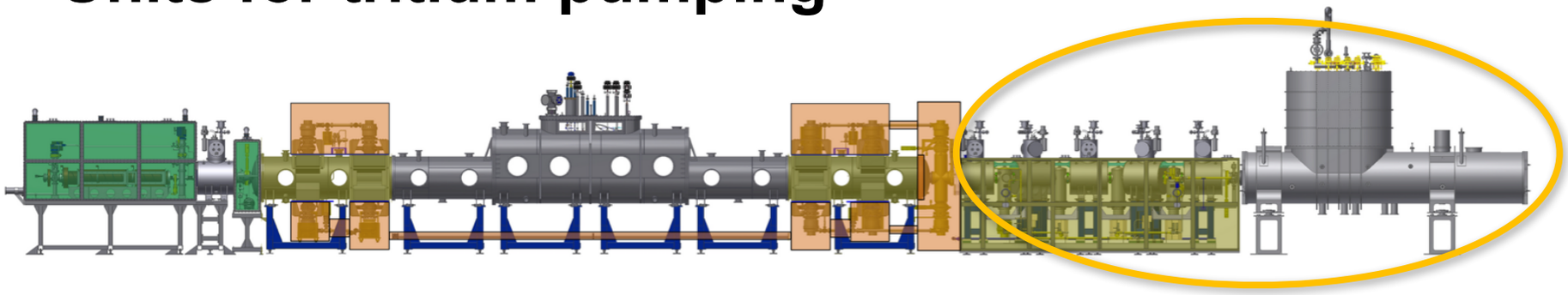
- **Cryogenic Pumping Section CPS**
  cryosorption on Ar-frost at 3-4 K



CPS



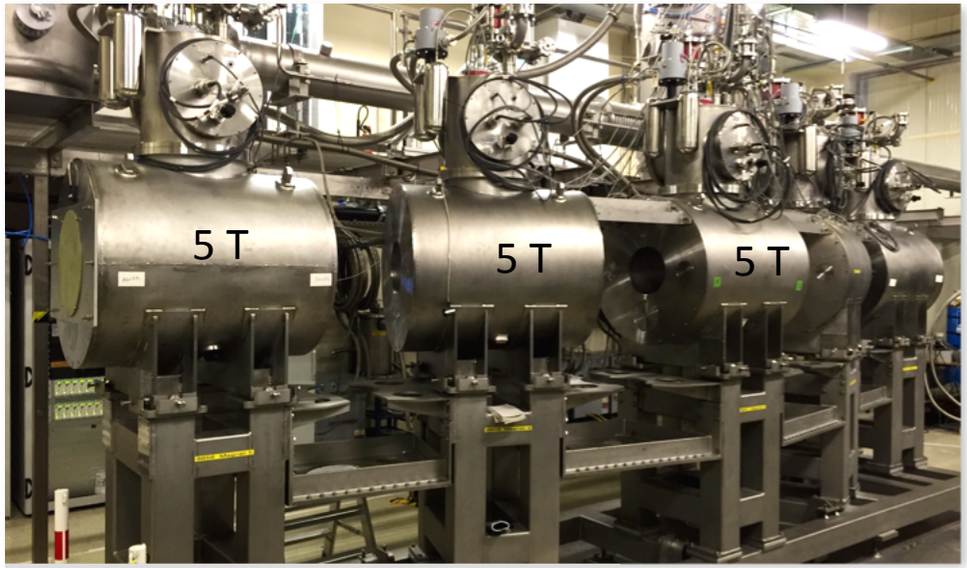
Units for tritium pumping



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Two large cryostat systems for overall tritium retention **factor > 10^{14}**

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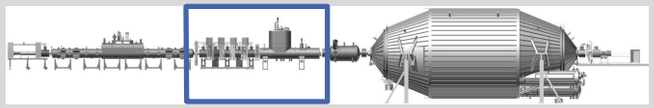


DPS site acceptance tests at KIT almost completed

▪ Cryogenic Pumping Section CPS



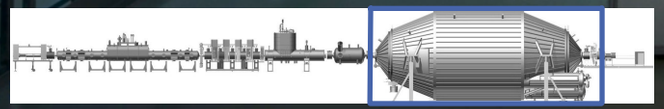
Delivered to KIT 07/2015
Installation started



LFCS
low-field fine-tuning

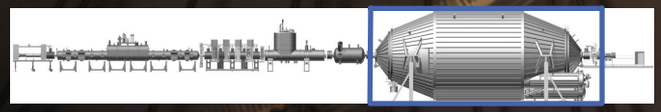
EMCS
earth field compensation

Ø = 12.7 m



2011: fully commissioned large Helmholtz coil system

January 2012:
Inner electrode system
(24.000 wires in 2 layers!)
completely mounted
(precision: 200 µm)

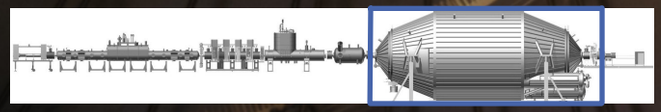




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Inner electrode system
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Bake-out at 300 (200)°C
to achieve UHV conditions
$p < 10^{-11}$ mbar





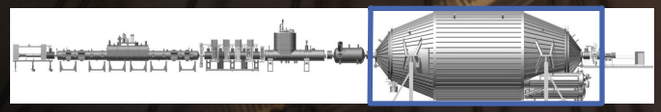


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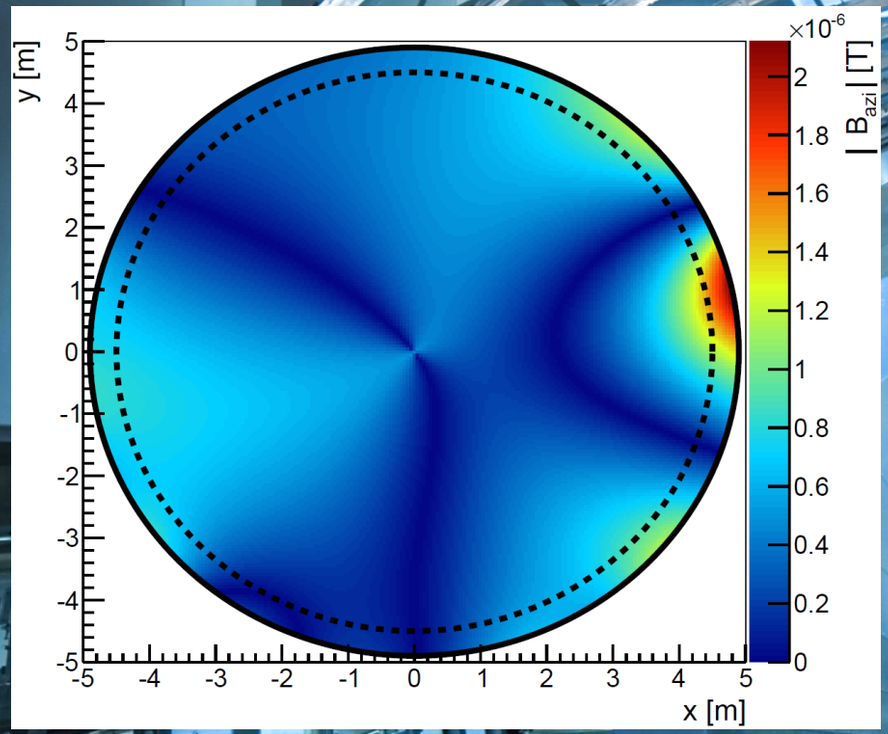
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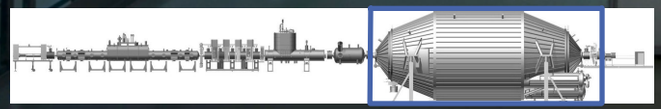


Trivia question:
UHV recipient — LHC vs. KATRIN?

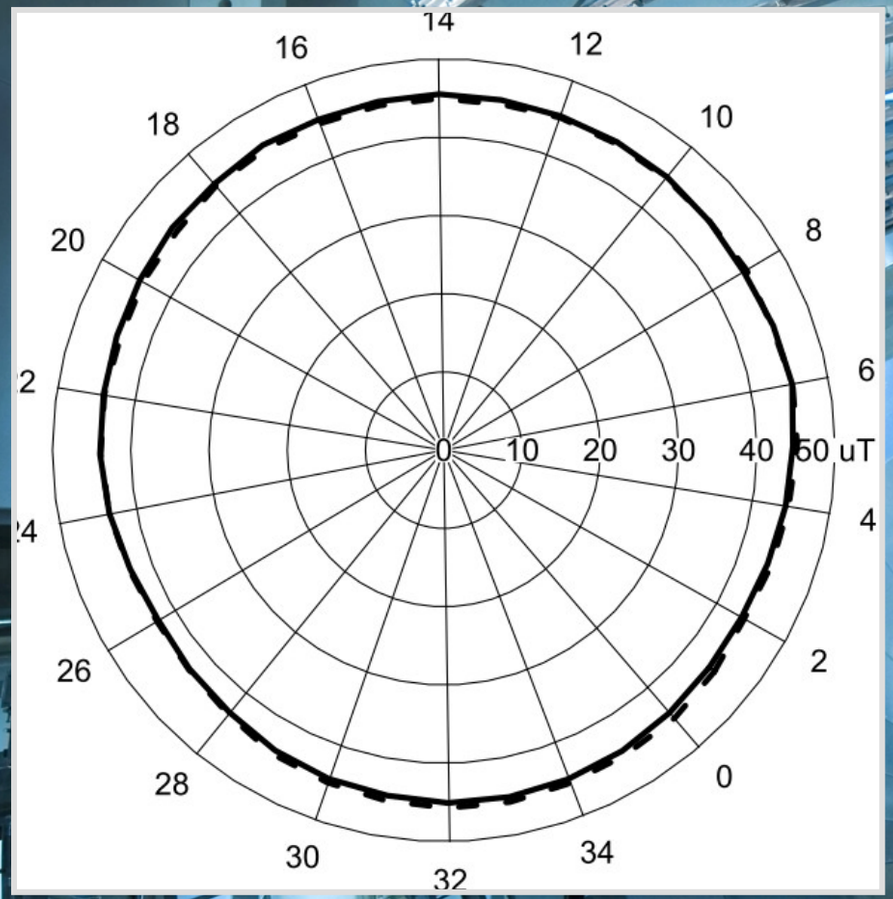






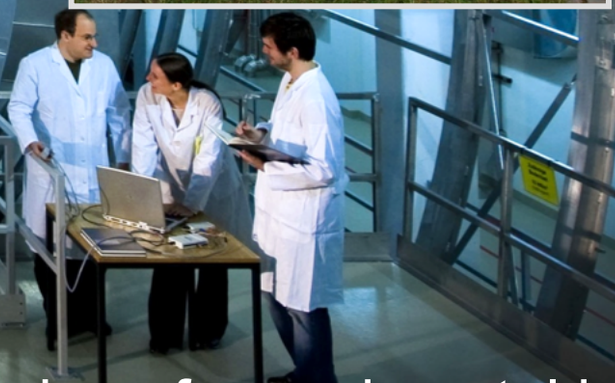


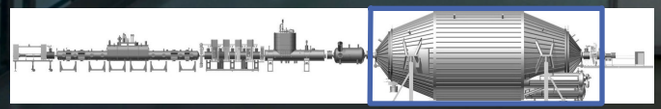
9/2014: successfull de-gaussing of experimental hall









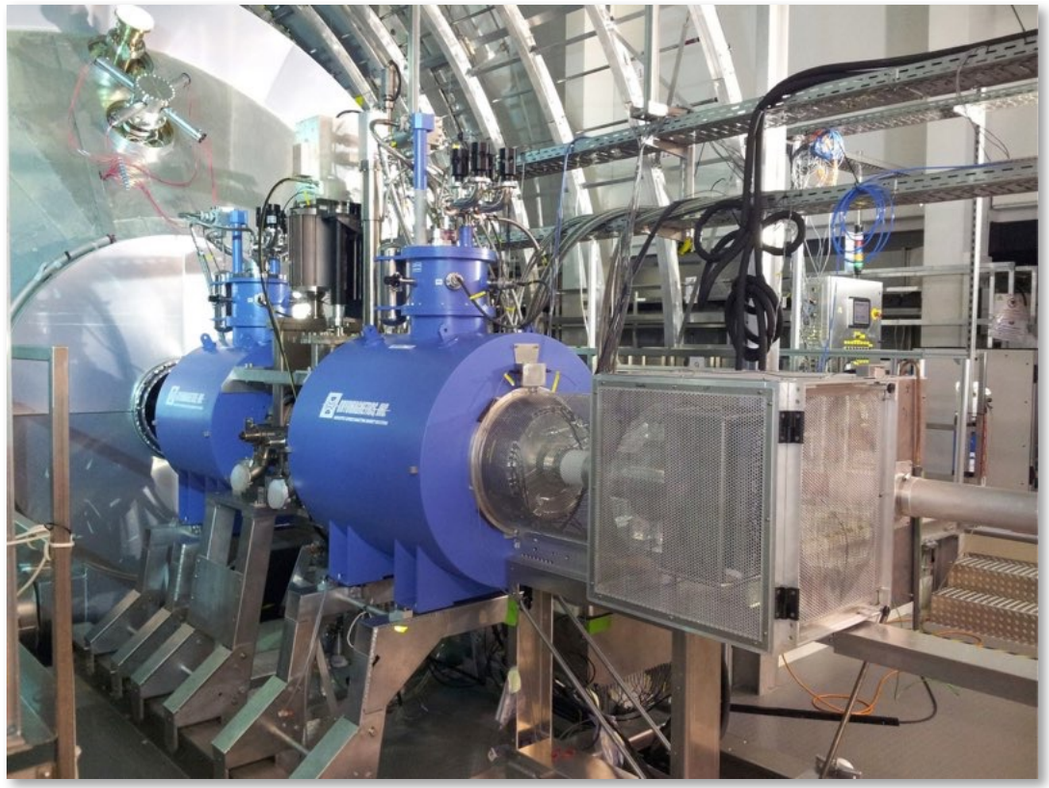


9/2014: successfull de-gaussing of experimental hall

Detector system

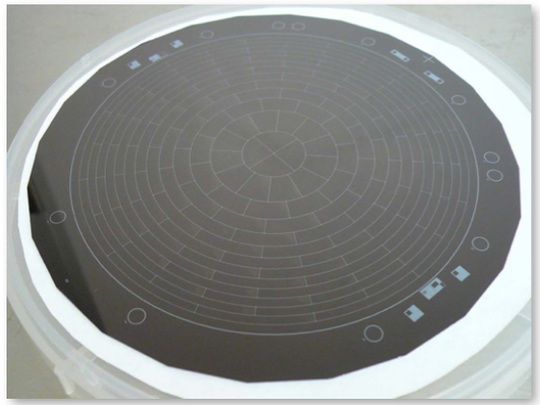
Requirements:

- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  - ➜ passive and active shielding
  - ➜ post-acceleration (10-30 kV)
- good energy resolution (~1 keV)

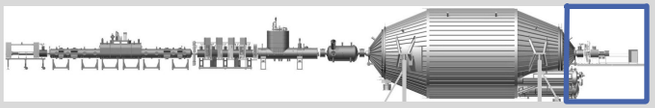


Characteristics:

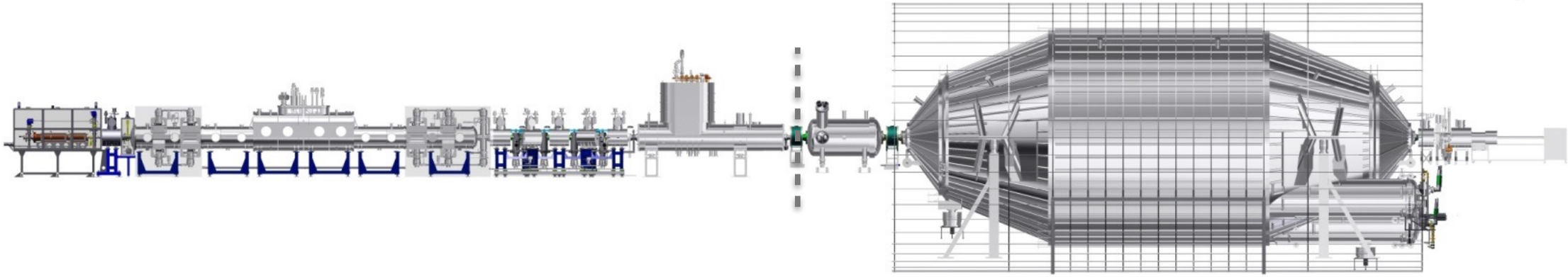
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- segmented wafer (148 pixels)
  - ➜ compensate field inhomogeneities
  - ➜ radial-dependent background
  - ➜ investigate systematic effects
- detector magnet 3 - 6 T



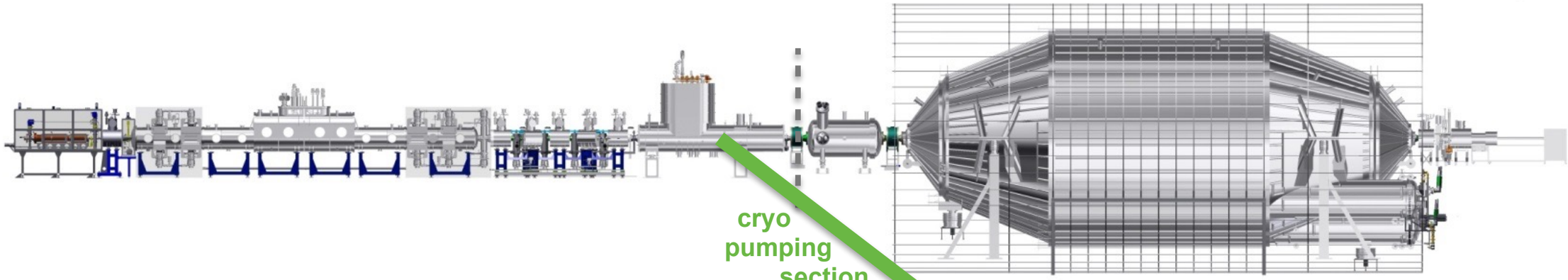




Status of system integration and commissioning



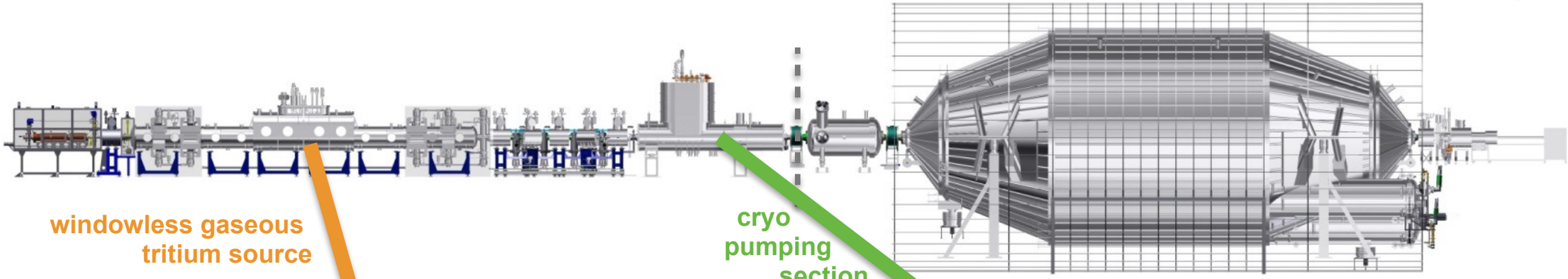
Status of system integration and commissioning



cryo pumping section



Status of system integration and commissioning



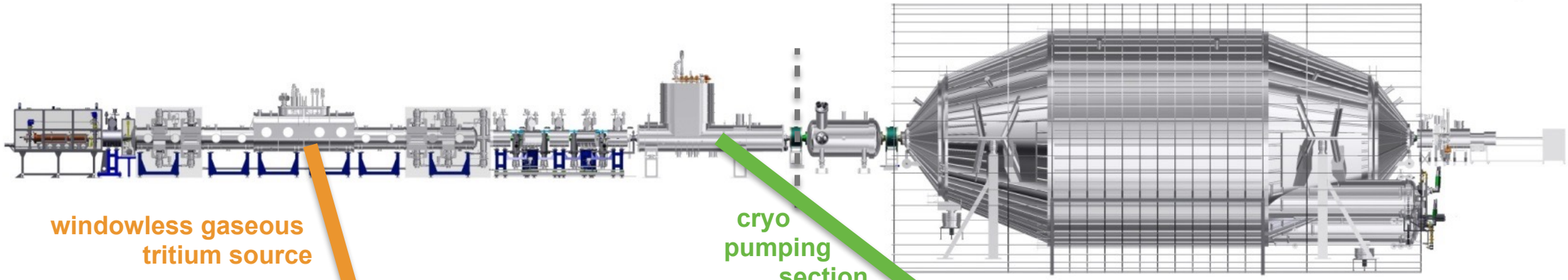
windowless gaseous tritium source

cryo pumping section





Status of system integration and commissioning



windowless gaseous tritium source

cryo pumping section

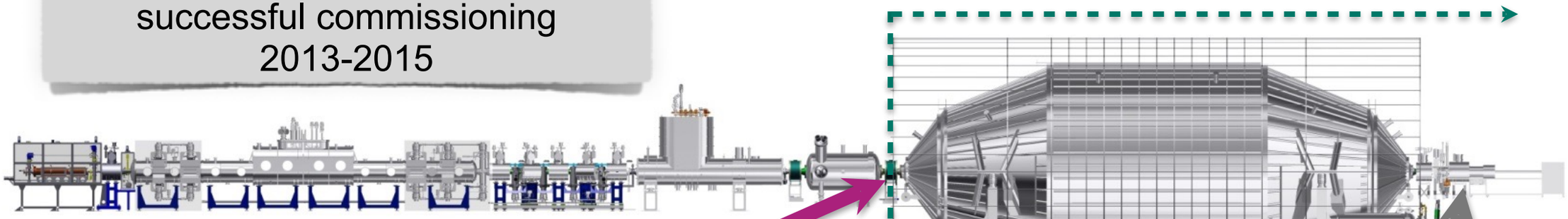




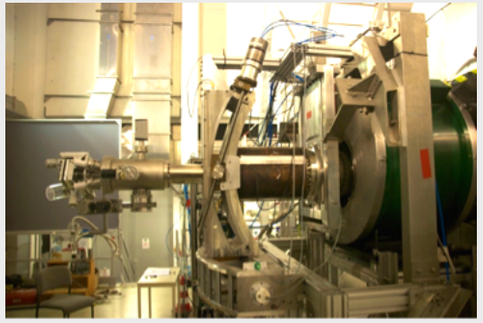
Summer 2015:
Arrival of last two major system components on site

Status of system integration and commissioning

Spectrometer & detector:
successful commissioning
2013-2015



electron gun
well-defined, sharp energy and angle



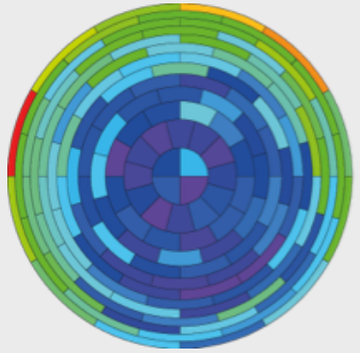
magnetic fields
- s.c. magnets
- field-shaping air coil systems

precision high voltage
vessel + wire electrode at separate HV

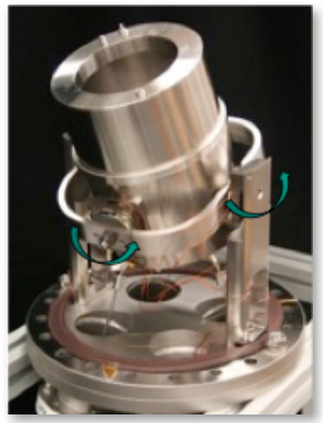
vacuum system
- TMPs
- 3 x 1 km NEG strips, 10^6 ℓ/s (+ LN_2-cooled baffles)



148-pix detector
spatial & timing info



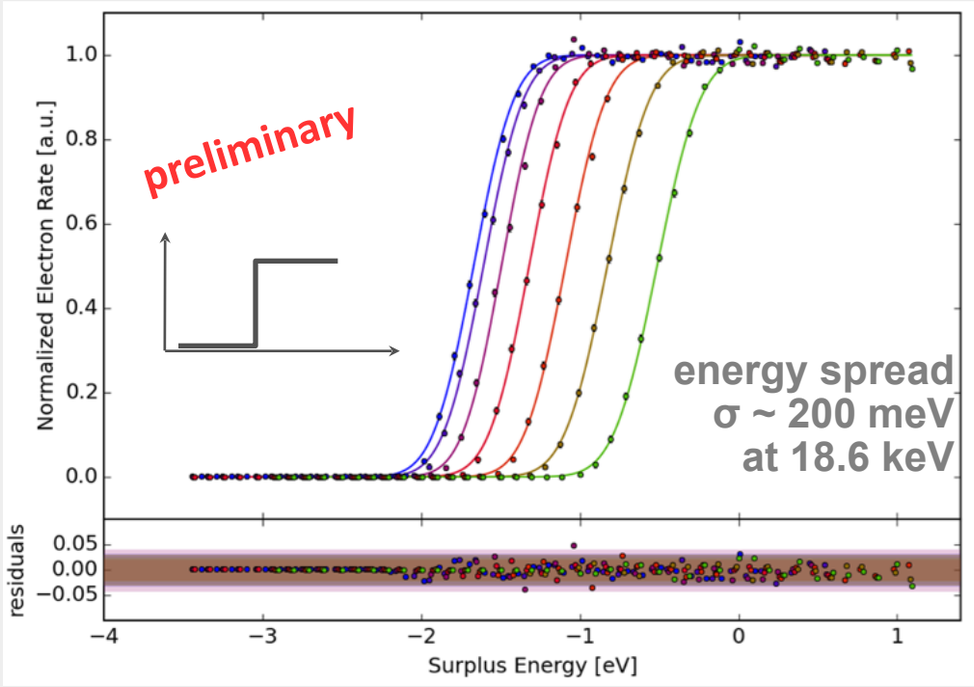
Spectrometer & detector commissioning



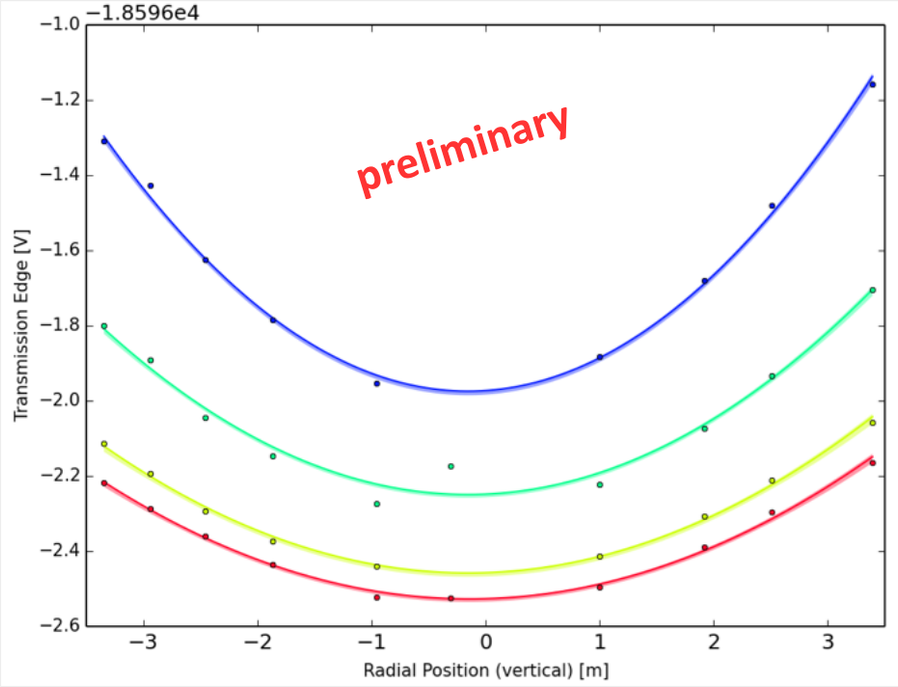
Characterisation of spectrometer transmission

using precision electron source:
mono-energetic, point-like, angular selective

Transmission characteristics of main spec.
as expected (limited by e-gun systematics ...)



Radial dependence of retardation potential
as expected (precision mapping by e-gun)

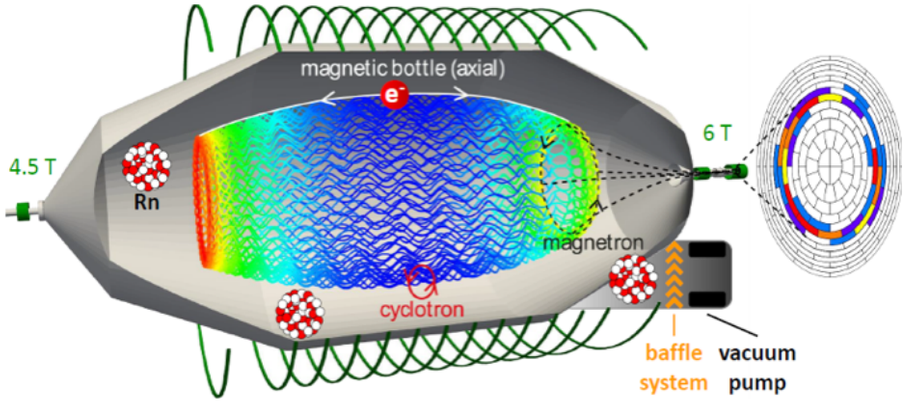


Spectrometer & detector commissioning

Characterisation of backgrounds

- Very efficient magnetic & electrostatic shielding, but only for charged particles ($\mathbf{e}^-$ and H^-)
- Neutral, unstable atoms ($^{219,\,220}\mathbf{Rn}$, H*) can penetrate into inner flux tube

  → further measures required, e.g. passive shielding against Rn-induced secondaries

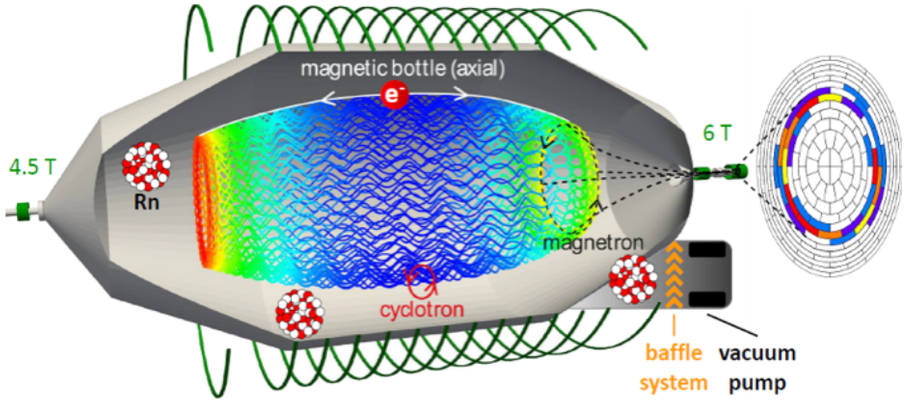


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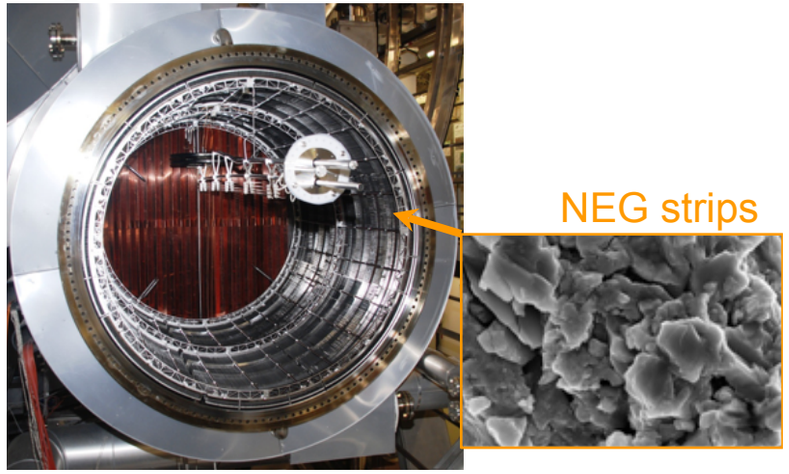
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LN_2-cooled baffles

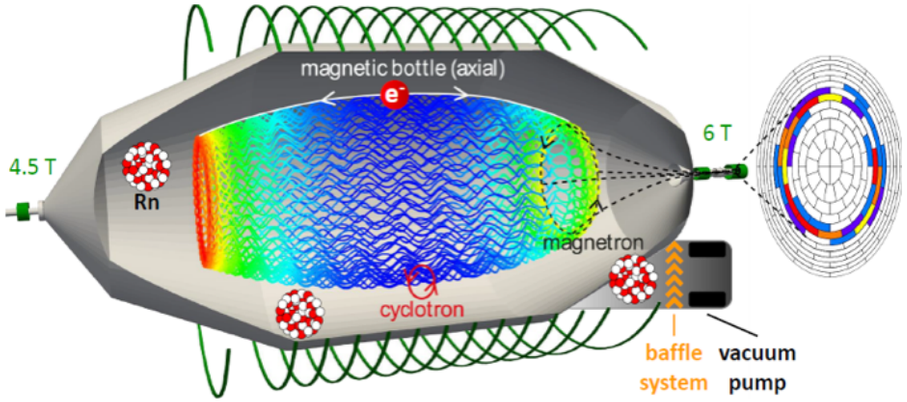


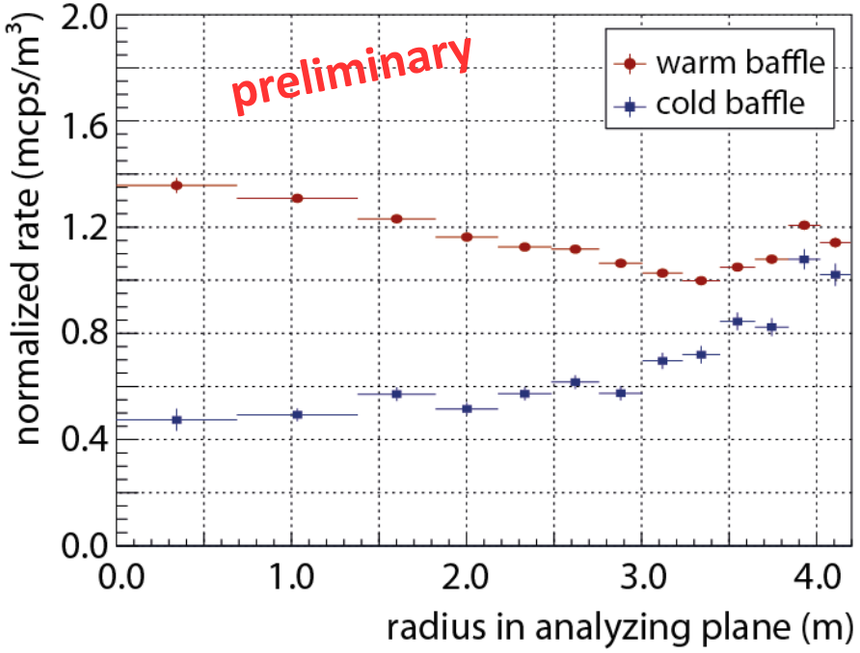
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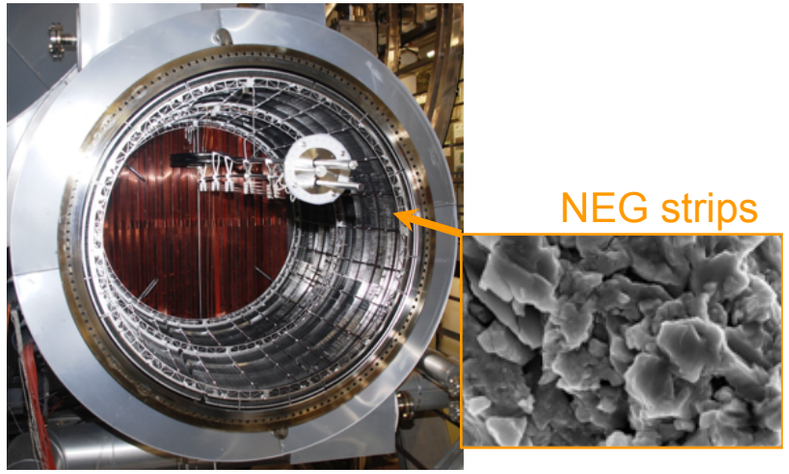
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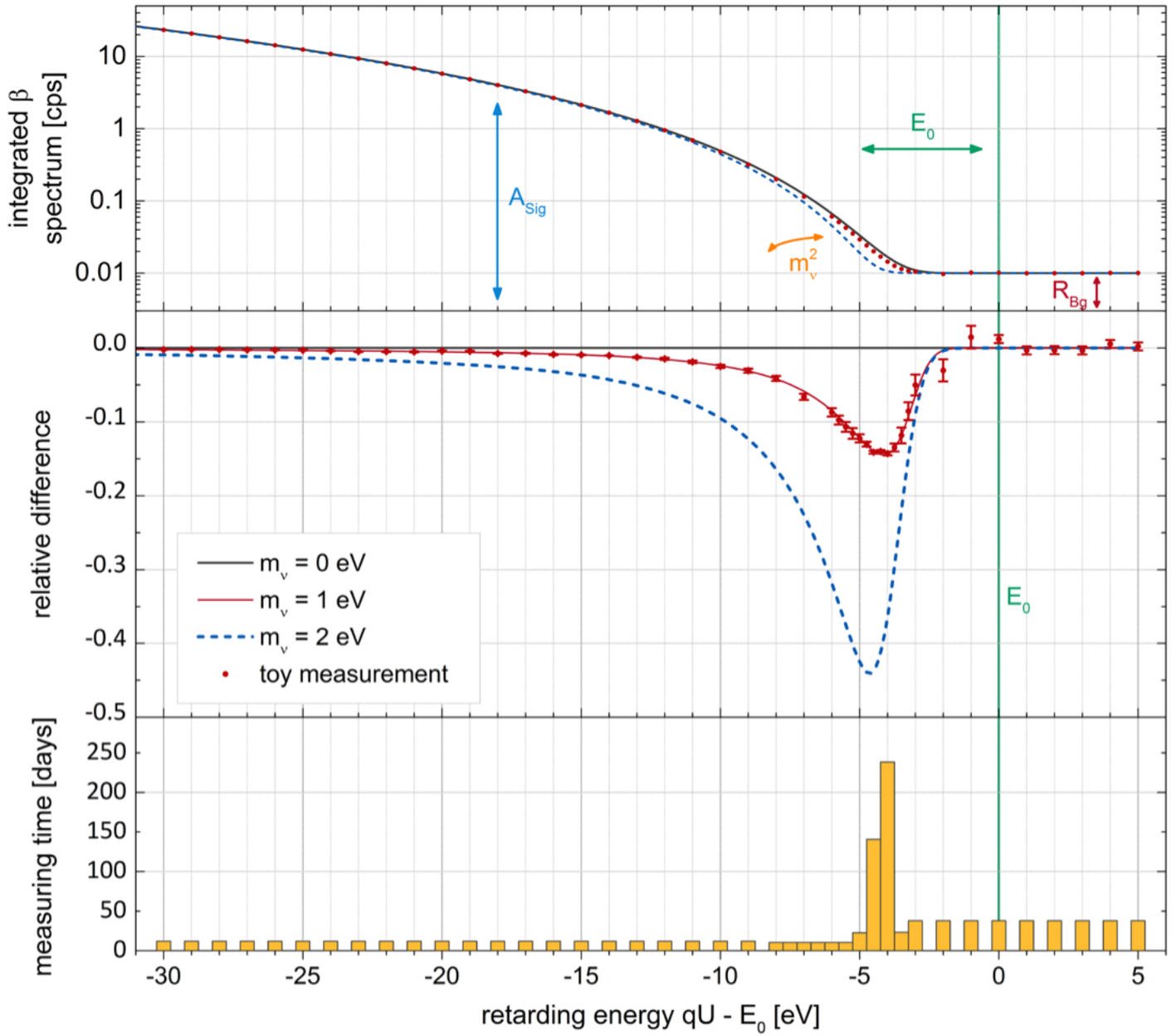
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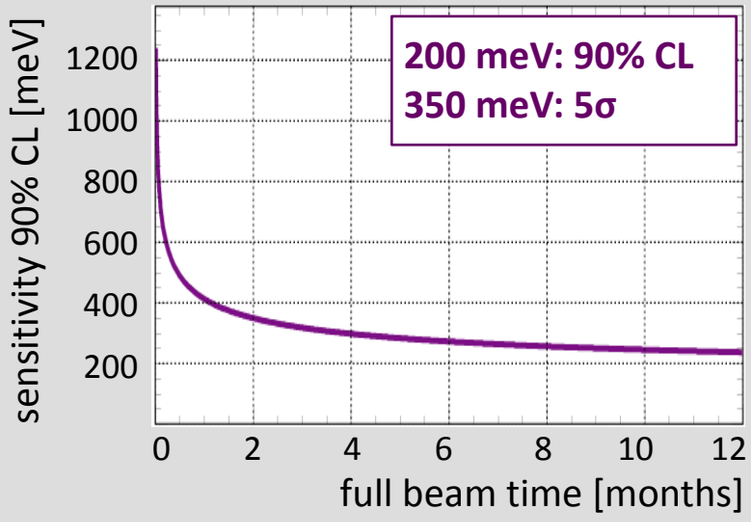
preliminary

477 ± 3 mcps background level achieved

KATRIN: ν-mass sensitivity



- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters:
  m_ν^2 , E_0 , A_S , R_{Bg}
- After **3 yrs** of data (~5 cal. yrs): balance of statistics and systematics



Intermediate summary





Karlsruhe Institute of Technology

- Discovery of neutrino masses ➜ **incompleteness** of the Standard Model
- **Mass scale** & **pattern** remain to be uncovered!
- Increasingly stringent bounds from cosmology ➜ LCDM paradigm
- Quest for 0νββ detection continues ➜ **Majorana/Dirac** nature of neutrinos?
- Next-gen. direct ν mass experiment KATRIN in commissioning phase
  ➜ start by end of 2016

Stay tuned!

New developments

New developments

How can we improve the sensitivity of direct neutrino mass experiments even further?

Problems:

New developments

How can we improve the sensitivity of direct neutrino mass experiments even further?

Problems:

MAC-E technique does not scale further

- energy resolution
- source luminosity



⌀100 m spectrometer ???

New developments

How can we improve the sensitivity of direct neutrino mass experiments even further?

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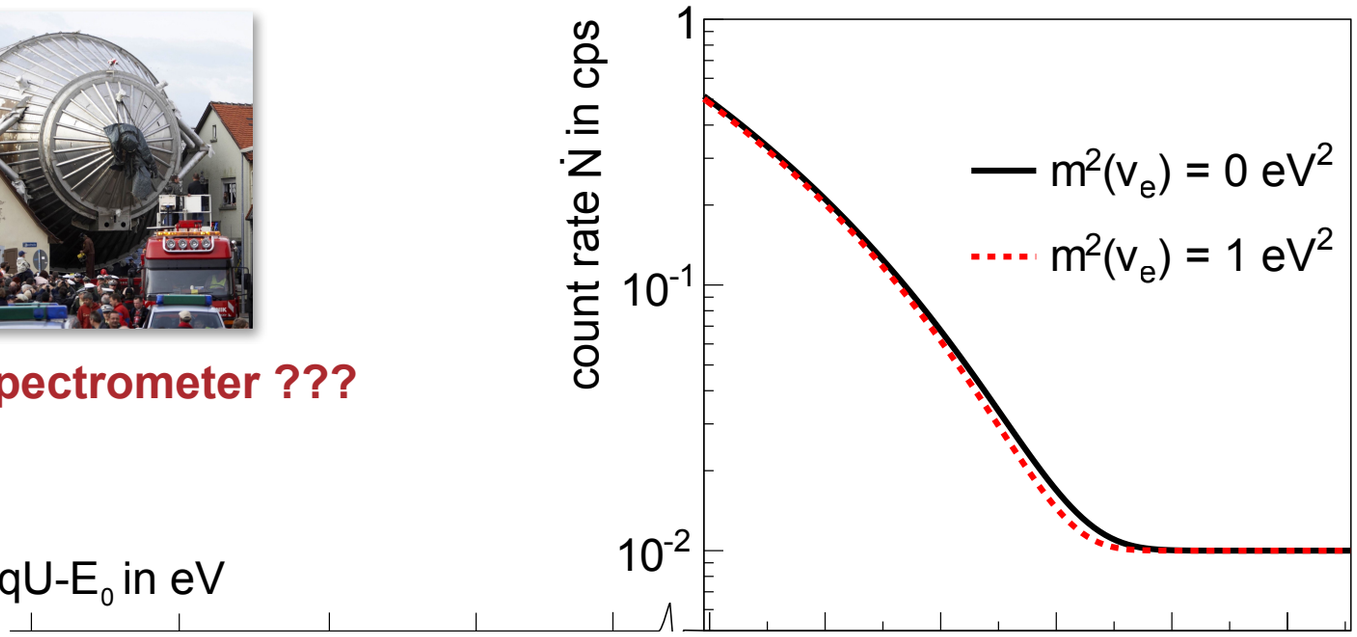
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Integrated β spectrum: loss of information



New developments

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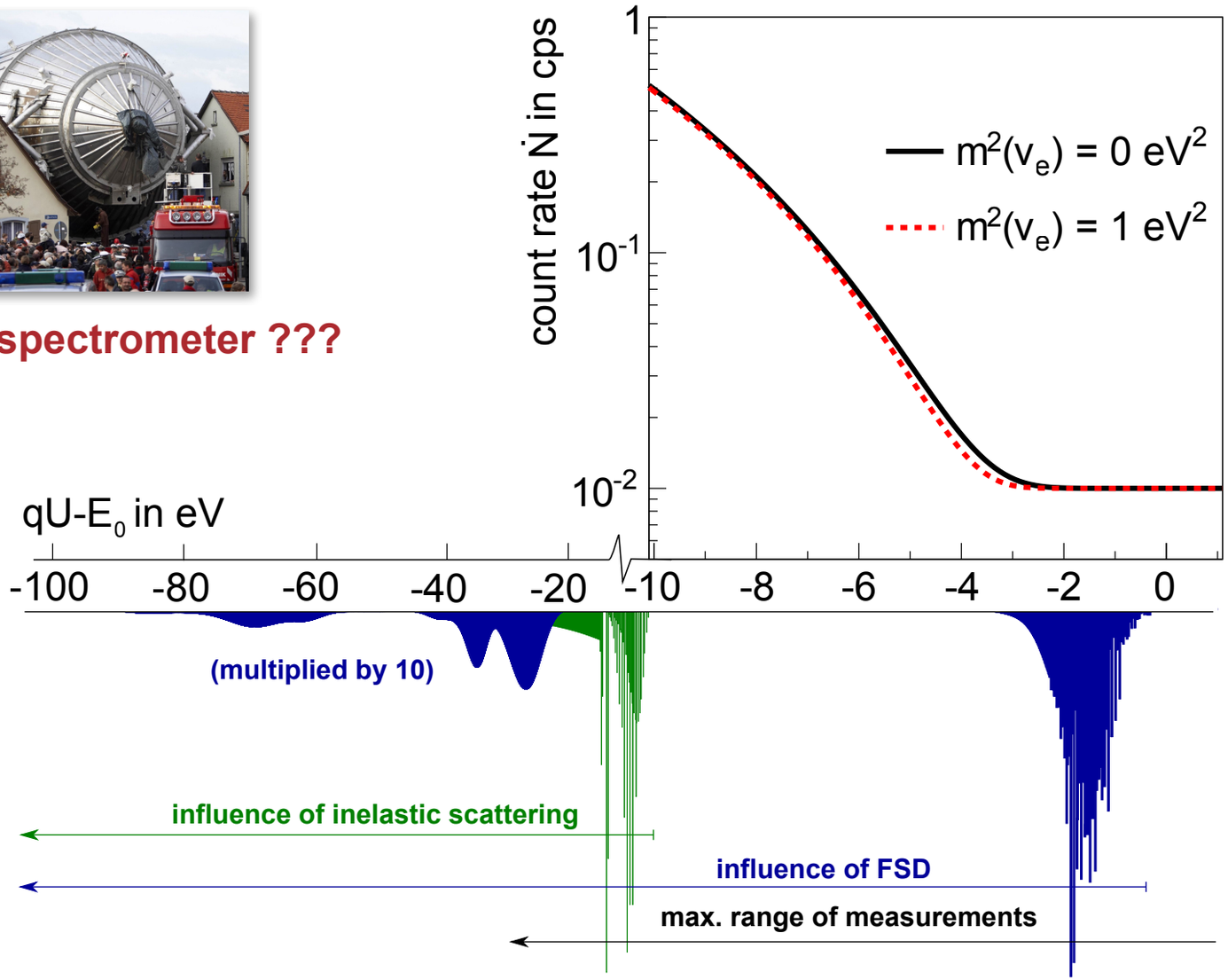
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⌀100 m spectrometer ???



Integrated β spectrum: loss of information

Final state uncertainty in molecular T_2

New developments

Several avenues towards improvement



New developments

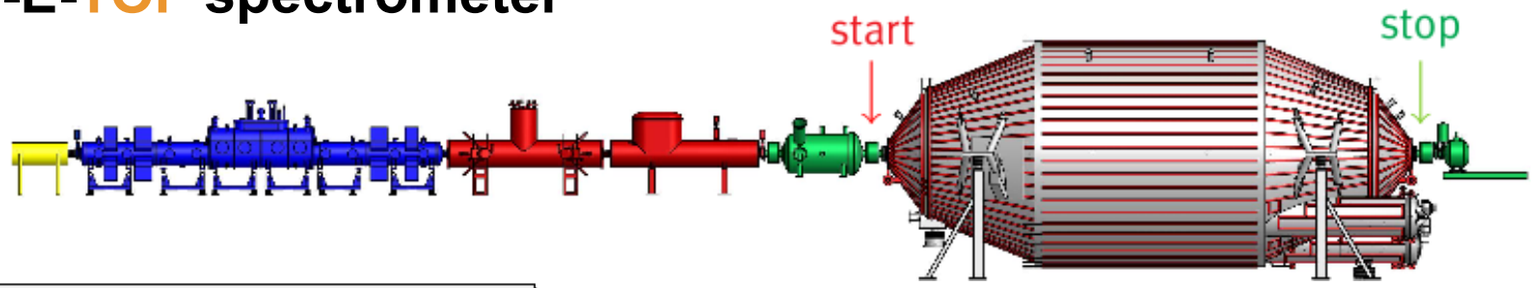
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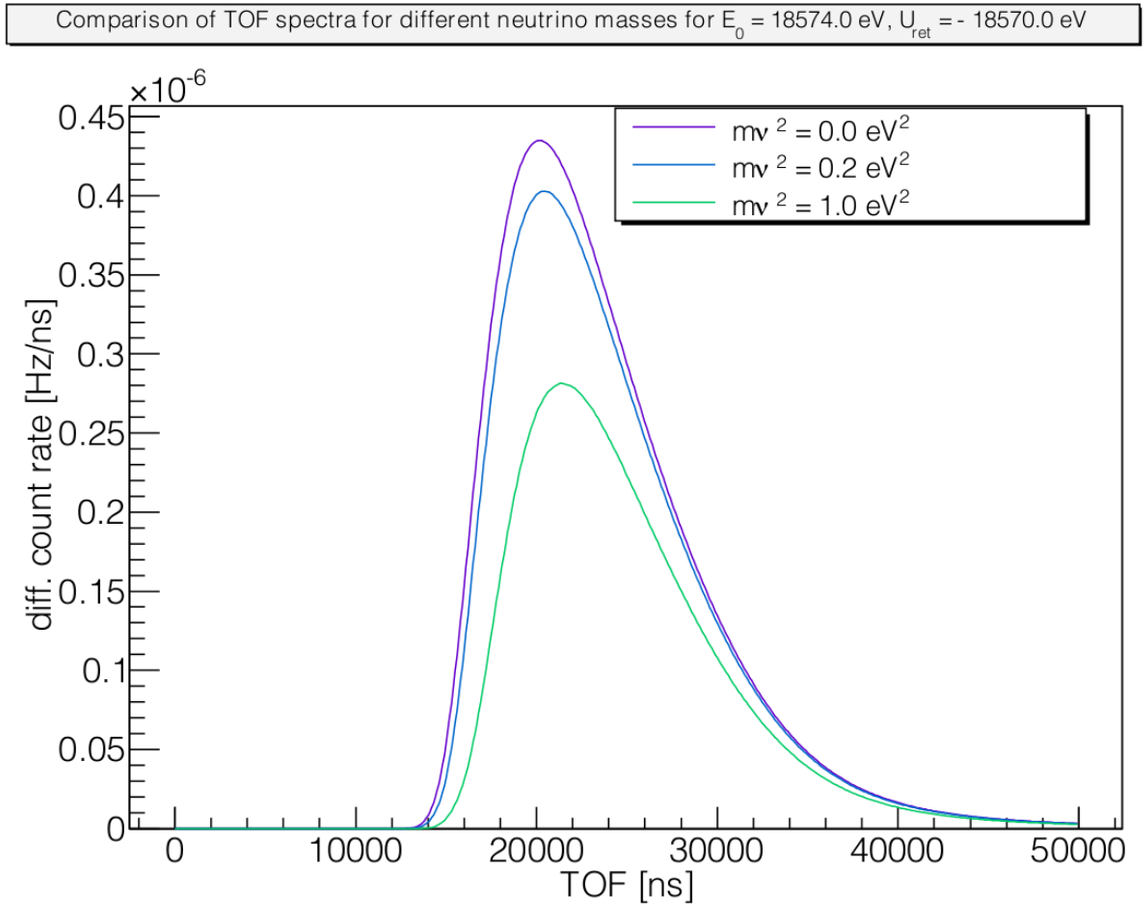
Several avenues towards improvement



1st avenue: exploit differential β spectrum

Idea: Upgrade to MAC-E-TOF spectrometer





Spectrometer as 24 m long “delay line”
➜ very sensitive to small differences in surplus energy

TOF spectrum records full β spectrum
➜ save meas. time by using only few voltage settings of MAC-E filter

Coincidence requirement
➜ add. background suppression

Technical realization?
(a) pre-spectrometer as gated filter
(b) radio frequency tagger

[Bonn et al. (1999), Steinbrink et al. (2013), Robertson et al. (in prep.)]

2nd avenue: alternative spectroscopic technique



2nd avenue: alternative spectroscopic technique



Idea: Cyclotron Radiation Emission Spectroscopy (CRES)

[Formaggio & Monreal, PRD 80 (2009) 051301(R)]

$$\omega(\gamma) = \frac{\omega_c}{\gamma} = \frac{eB}{E_{kin} + m_e}$$

Energy measured via **cyclotron frequency** of single electrons in B field

2nd avenue: alternative spectroscopic technique



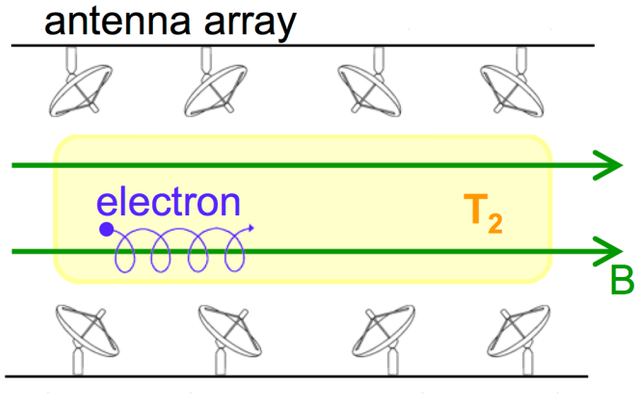
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B ~1 T,
E ~18.6 keV
➜ **ω ~27 GHz**

2nd avenue: alternative spectroscopic technique



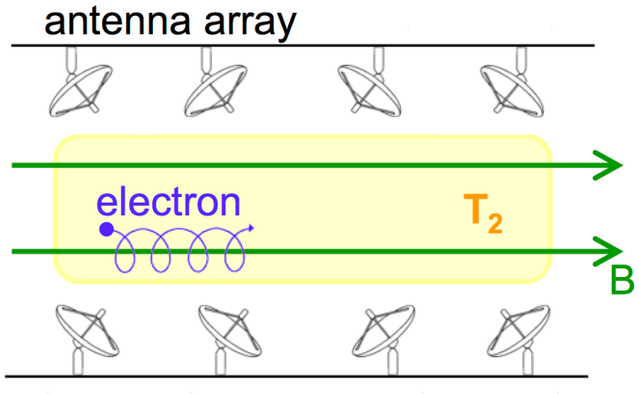
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"KATRIN"-like gaseous source:
uniform B-field and low-pressure T_2 gas

2nd avenue: alternative spectroscopic technique



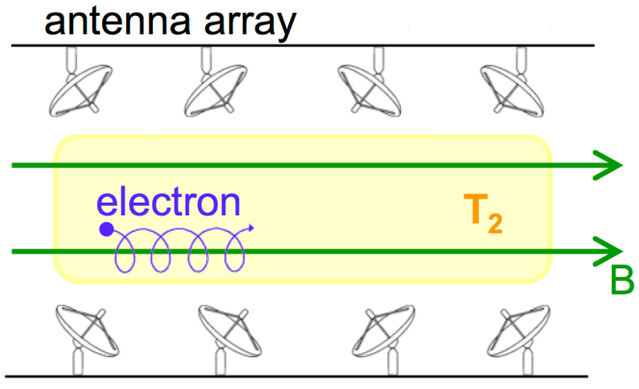
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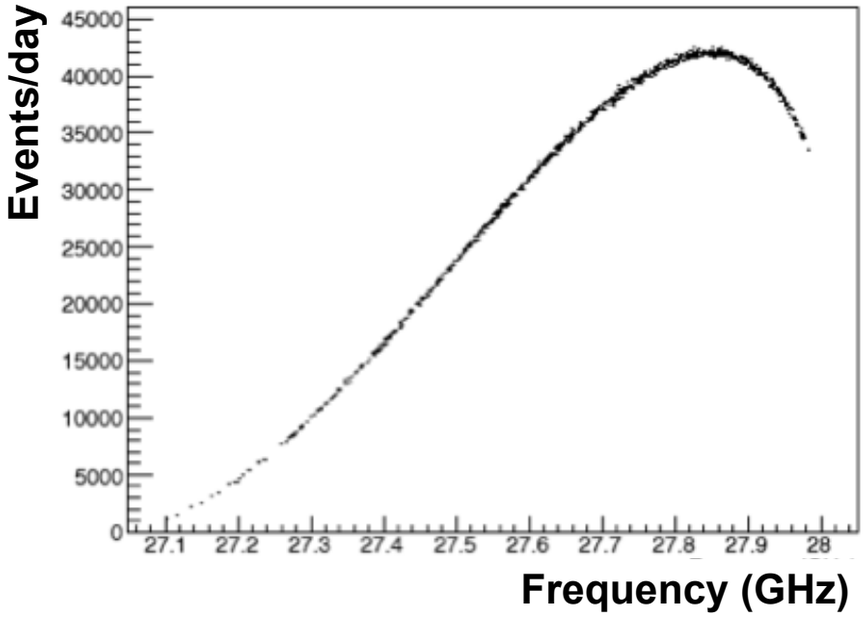
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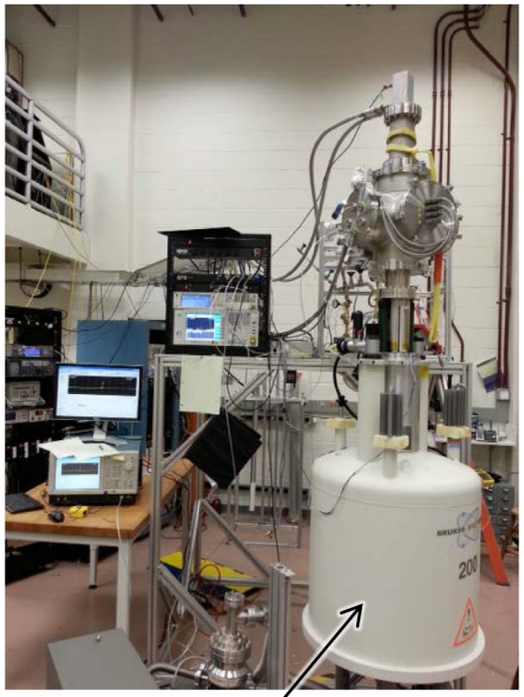
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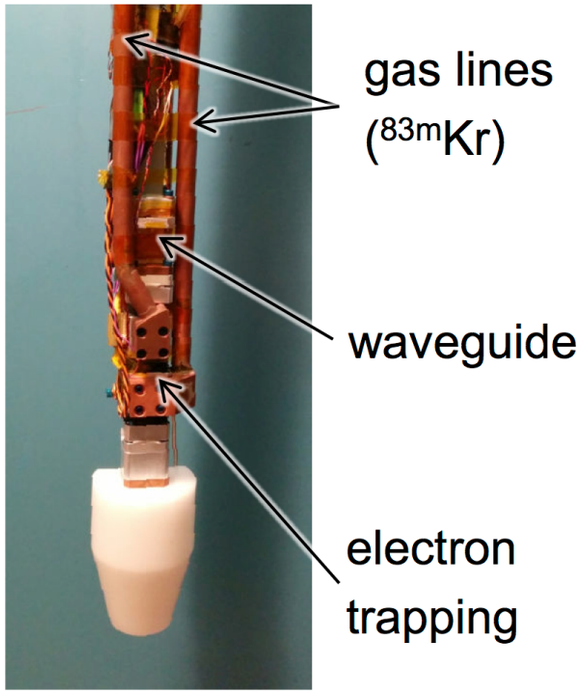


"KATRIN"-like gaseous source:
uniform B-field and low-pressure T_2 gas

Project 8 – phase I

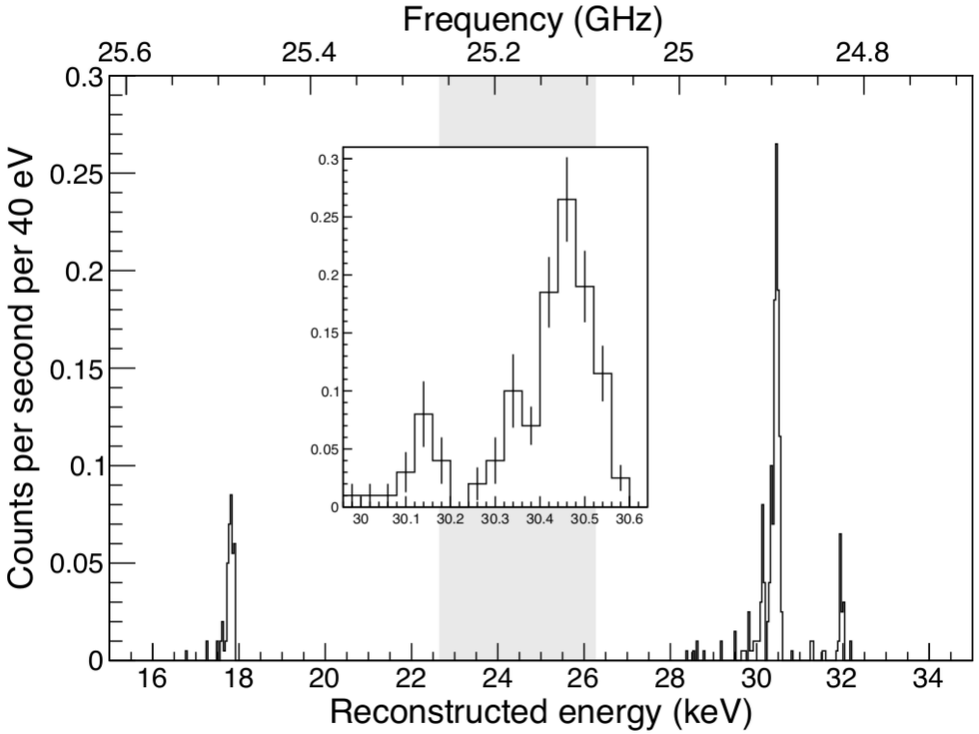
Successful measurements with prototype system at UW/Seattle





[courtesy J Formaggio, RGH Robertson]

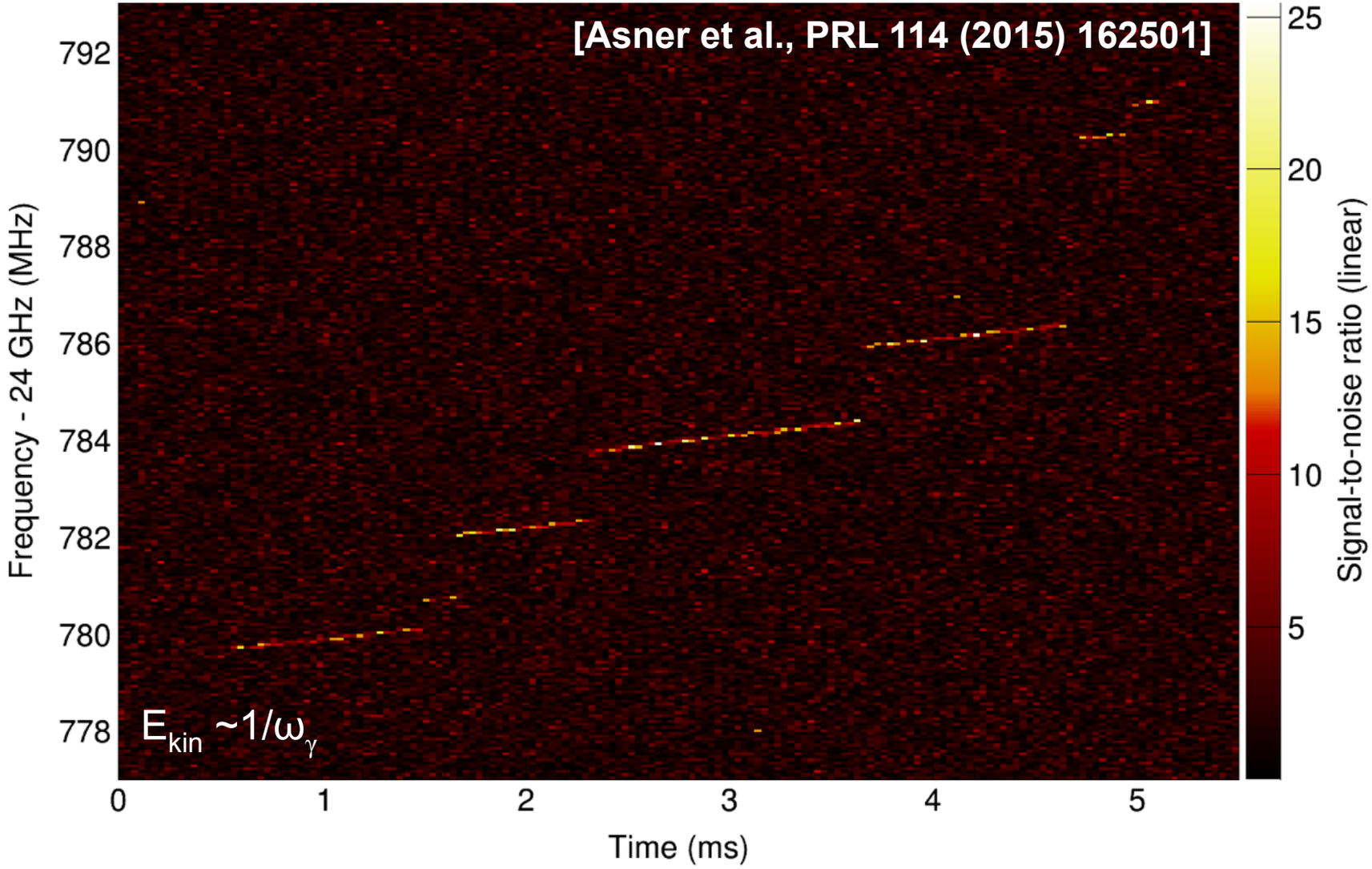
Proof-of-principle goal: detect single electrons from ^{83m}Kr



[Asner et al., PRL 114 (2015) 162501]

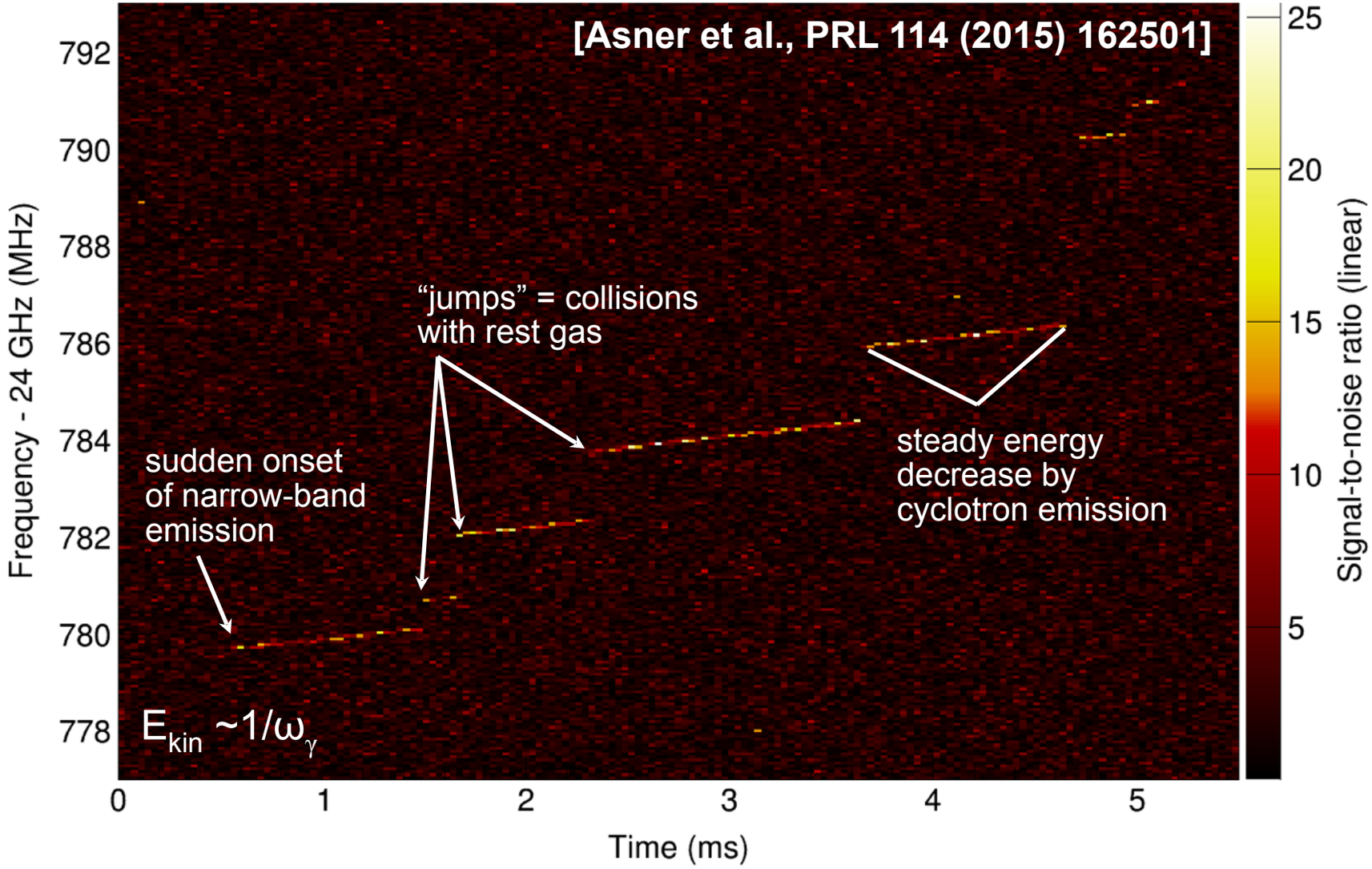
Project 8 – phase I results

First observation of cyclotron radiation from single electrons



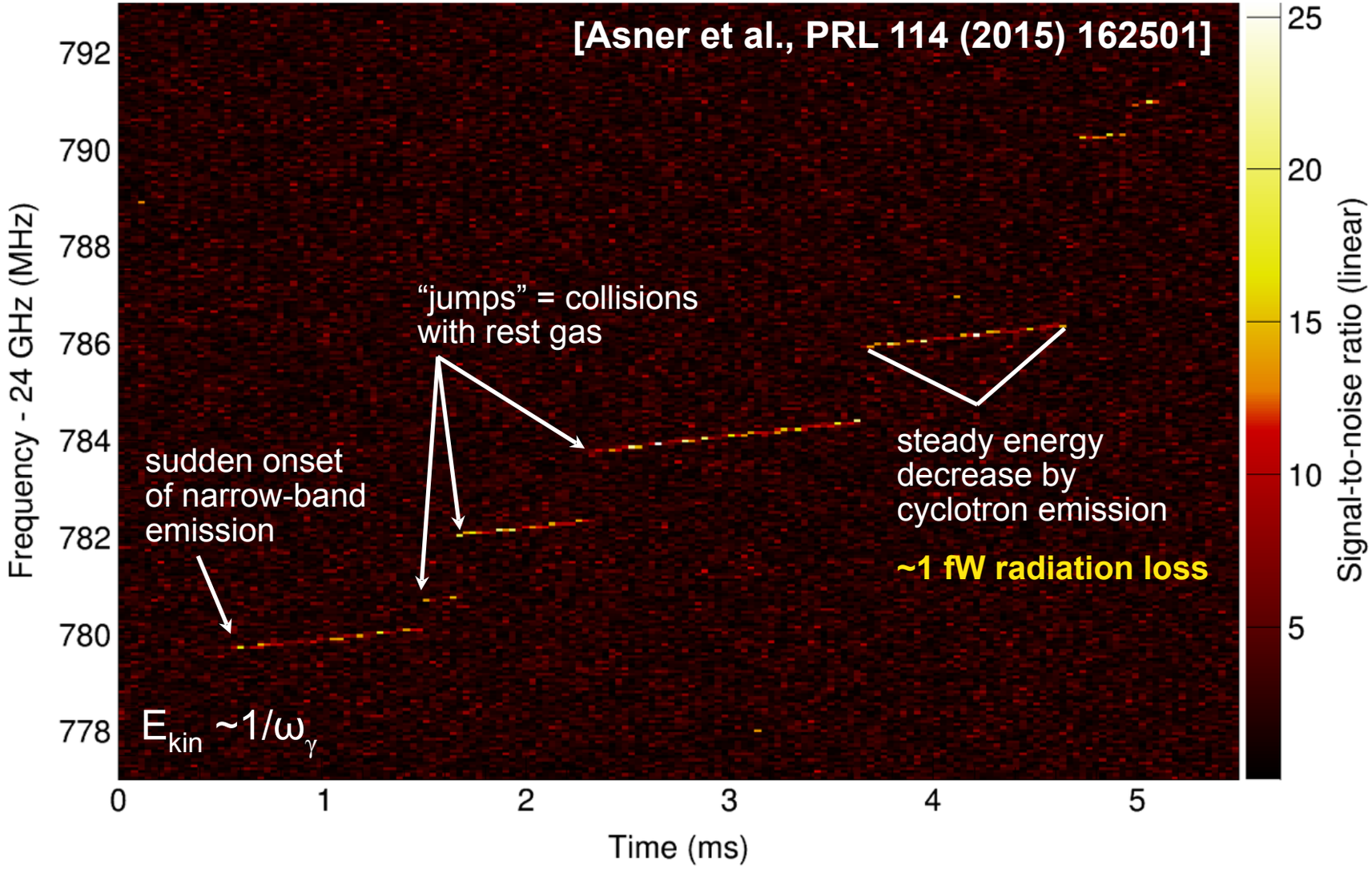
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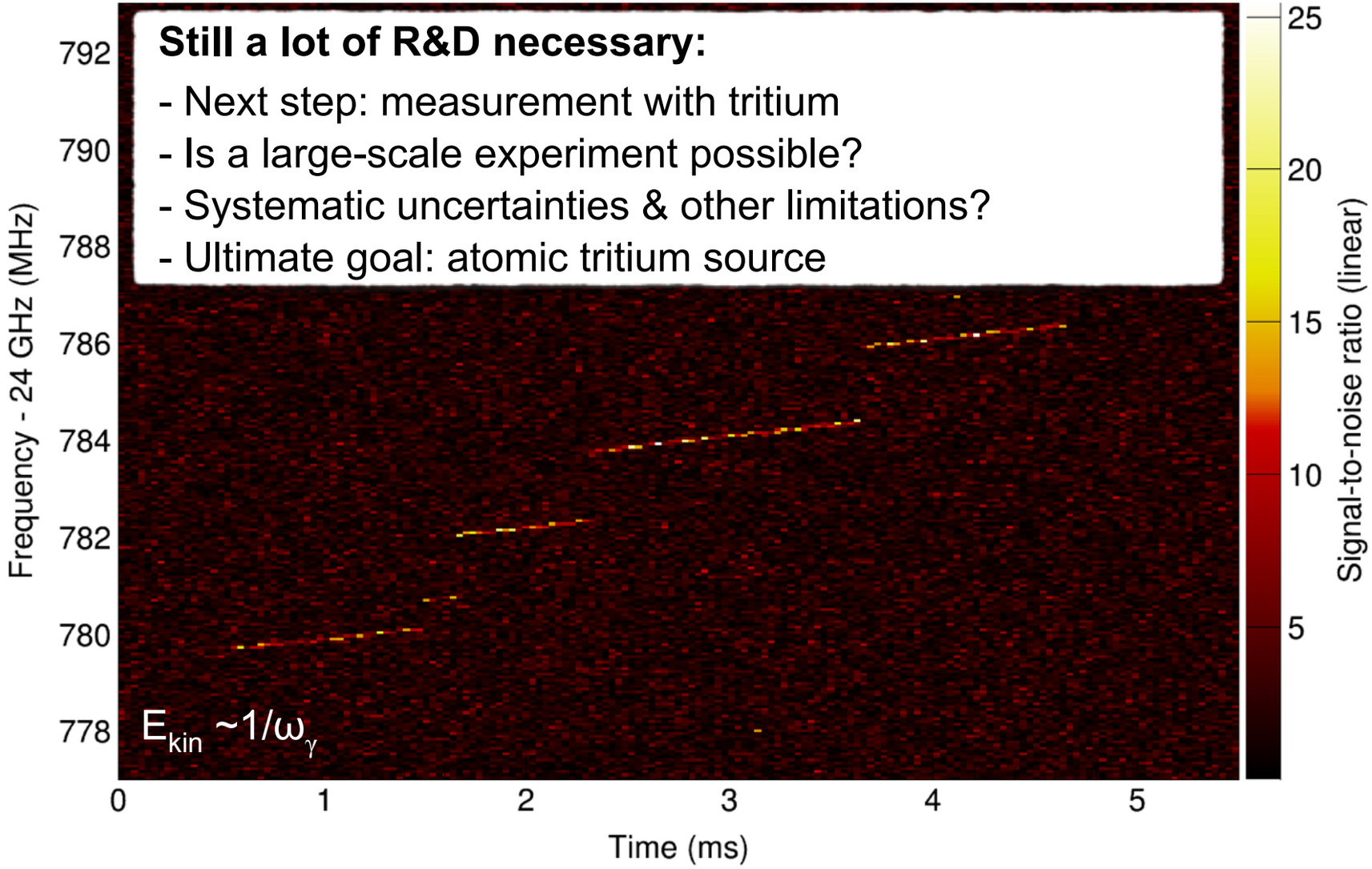
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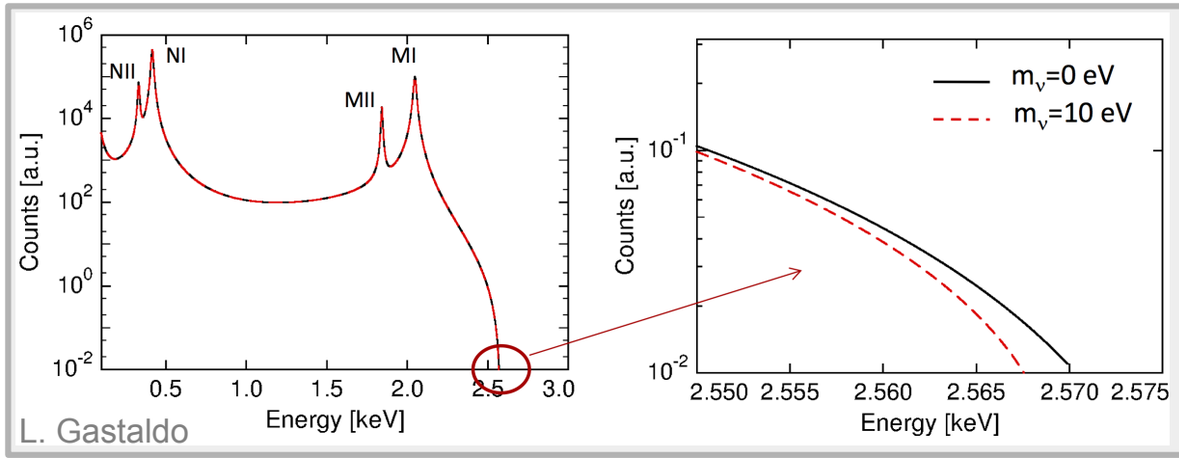


3rd avenue: use electron capture & calorimetry

Idea: Source inside detector (“single final state”)

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Idea: Source inside detector ("single final state")



$^{163}Ho \rightarrow {}^{163}Dy^* + \nu_e$:

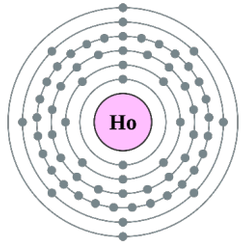
lowest Q_{EC} ~2.5 keV

short $T_{1/2}$ ~ 4570 a

Atomic de-excitation of $^{163}Dy^*$:

- X-rays
- Electrons (Auger, Coster-Kronig)

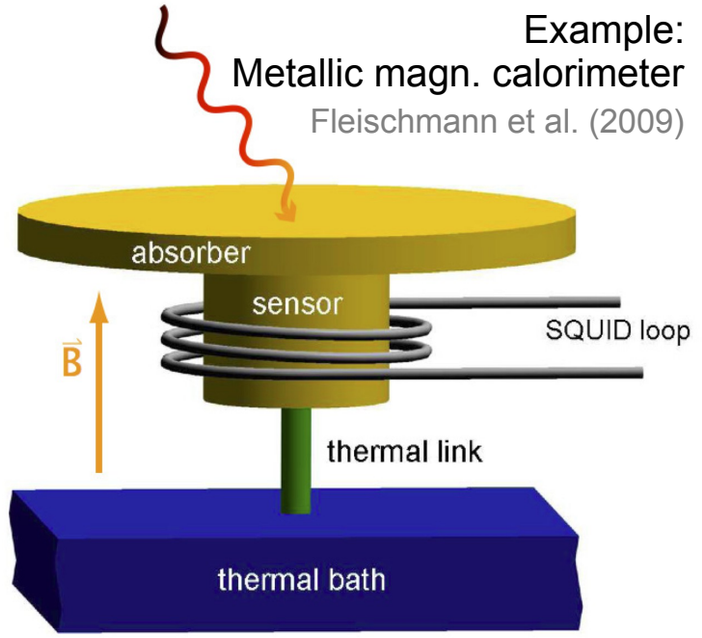
→ **Cryogenic calorimetric measurement**



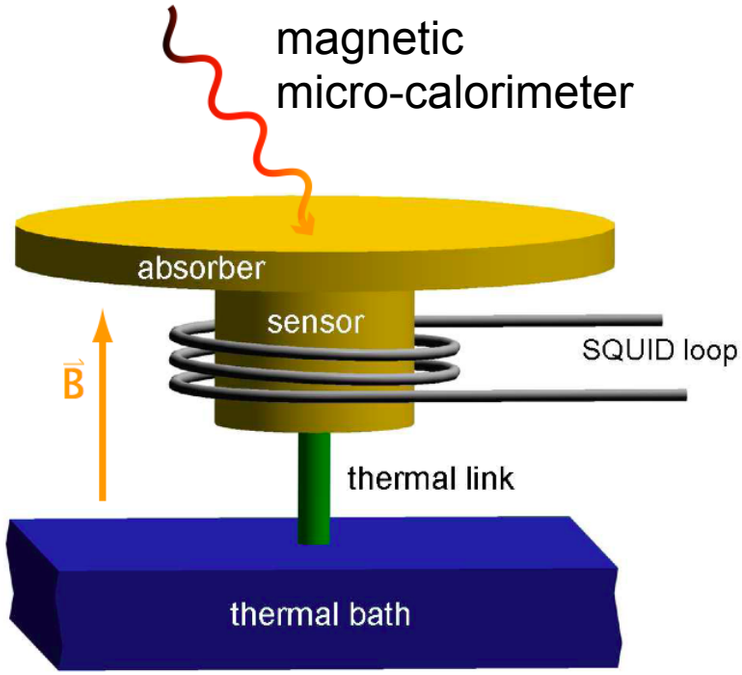
$$\Delta\Phi_s \propto \frac{\partial M}{\partial T} \cdot \underbrace{\frac{E}{C_{sensor} + C_{absorber}}}_{\Delta T}$$

T < 100 mK

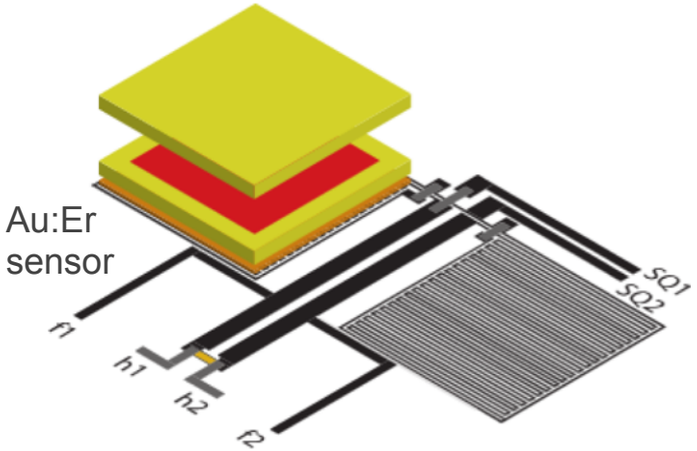
Example:
Metallic magn. calorimeter
Fleischmann et al. (2009)



^{163}Ho-based electron capture experiments

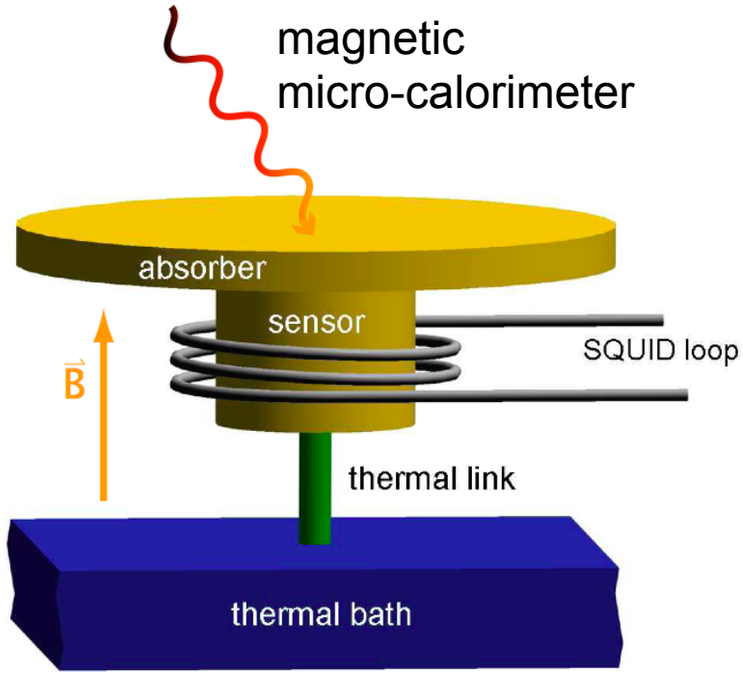


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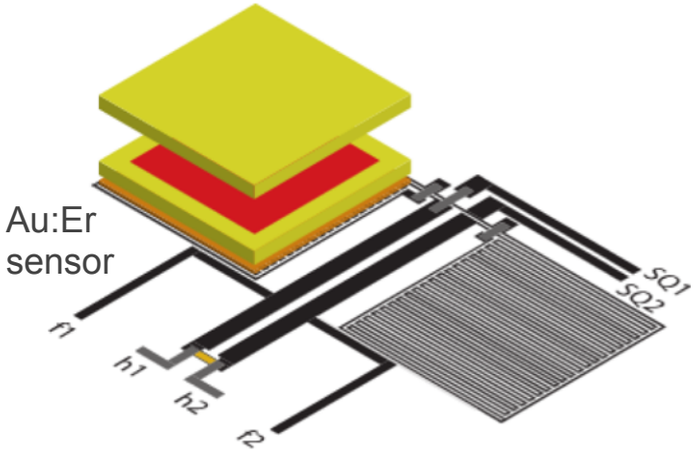


[Ranitzsch et al. 2012, Gastaldo et al. 2013]

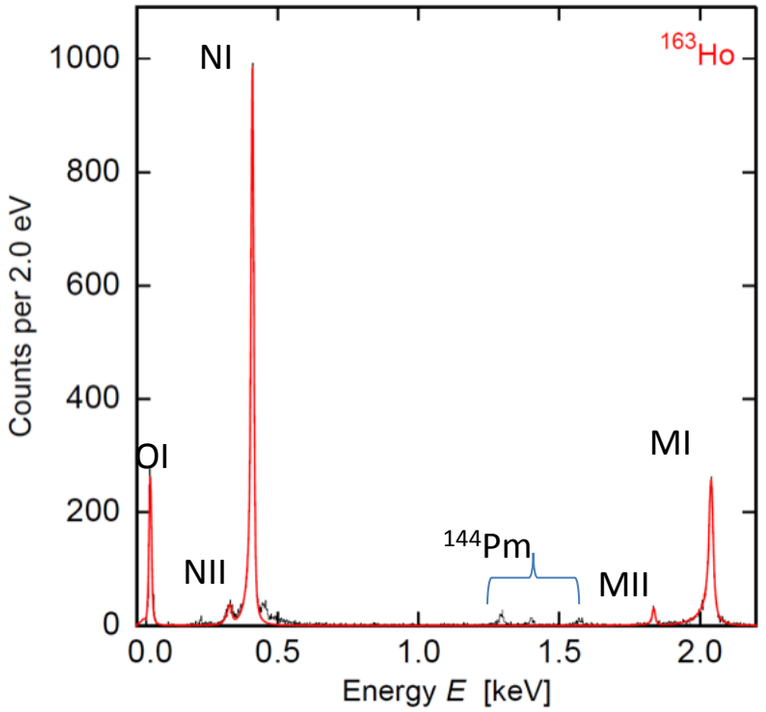
^{163}Ho-based electron capture experiments



[Fleischmann et al. 2009]



[Ranitzsch et al. 2012, Gastaldo et al. 2013]

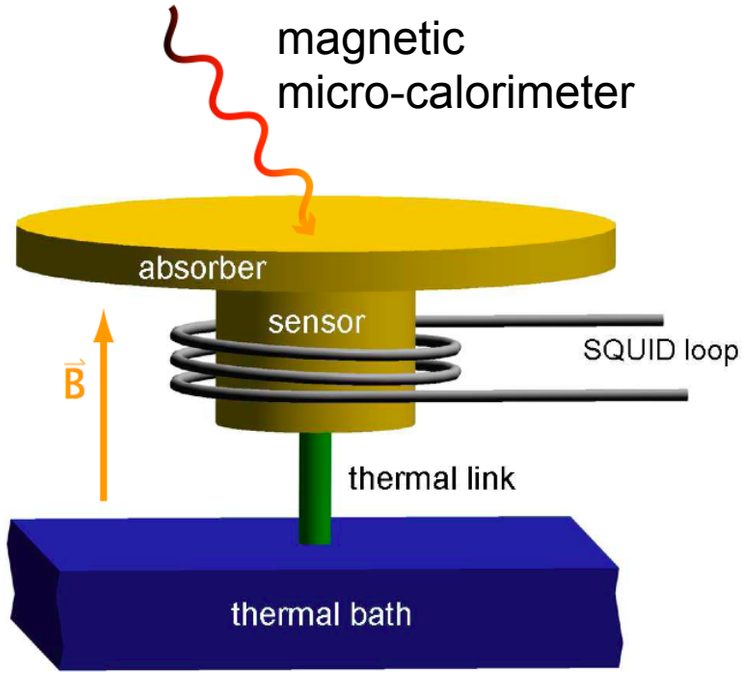


ECHo Collaboration, 2014

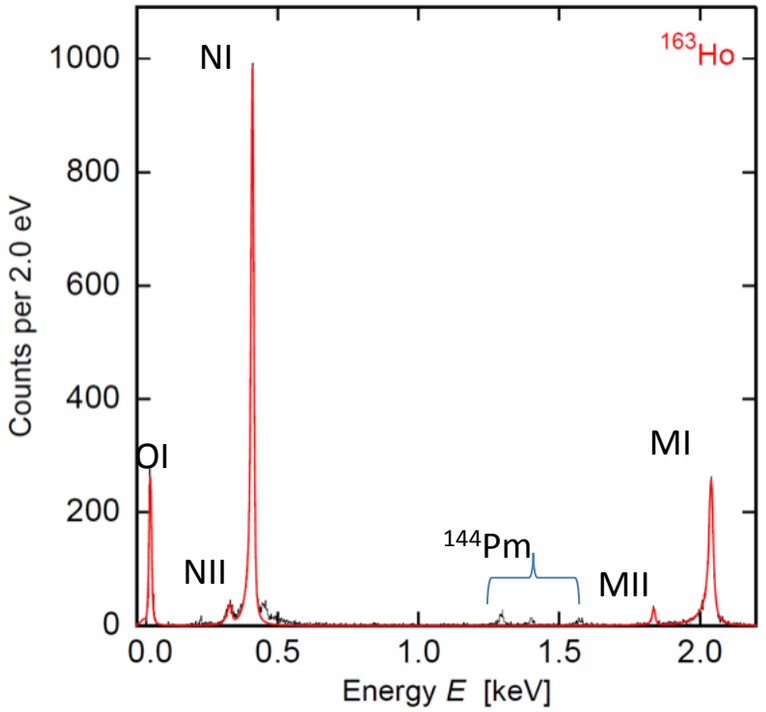
remarkable precision on ^{163}Ho EC spectrum achieved!

NEW (2015):
no prometium any more

^{163}Ho-based electron capture experiments



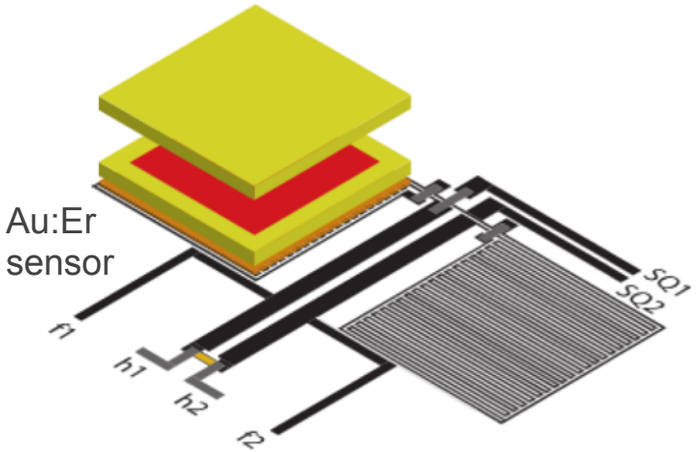
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ECHo Collaboration, 2014

remarkable precision on ^{163}Ho EC spectrum achieved!

NEW (2015):
no prometium any more



[Ranitzsch et al. 2012, Gastaldo et al. 2013]

- **Phase I: ECHo-1k (2015 - 2018)**
  - 1000 Bq
  - 1 year meas. time

  sensitivity m(ν_e) < 10 eV
  prove scalability
- **Phase II (>2018)**
  - 1 MBq
  - 3 years meas. time

  large multiplexed arrays
  sub-eV sensitivity

^{163}Ho-based experiments: overview

ECHo

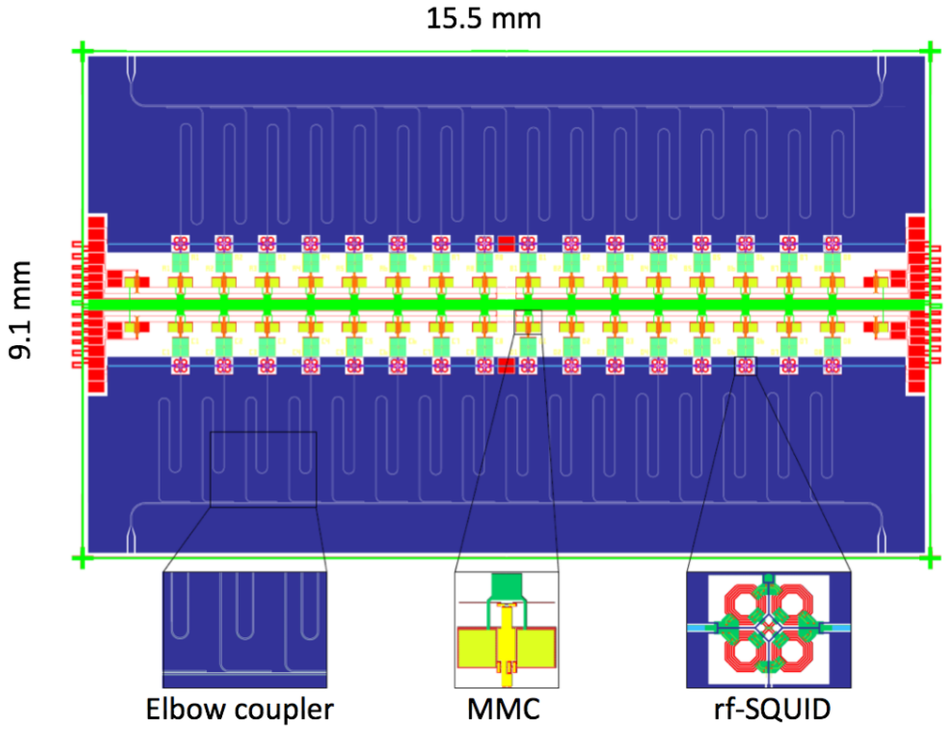
since ~2011
technology: MMC

HOLMES

since ~2013
technology: TES

NuMECS

since ~2011
technology: TES

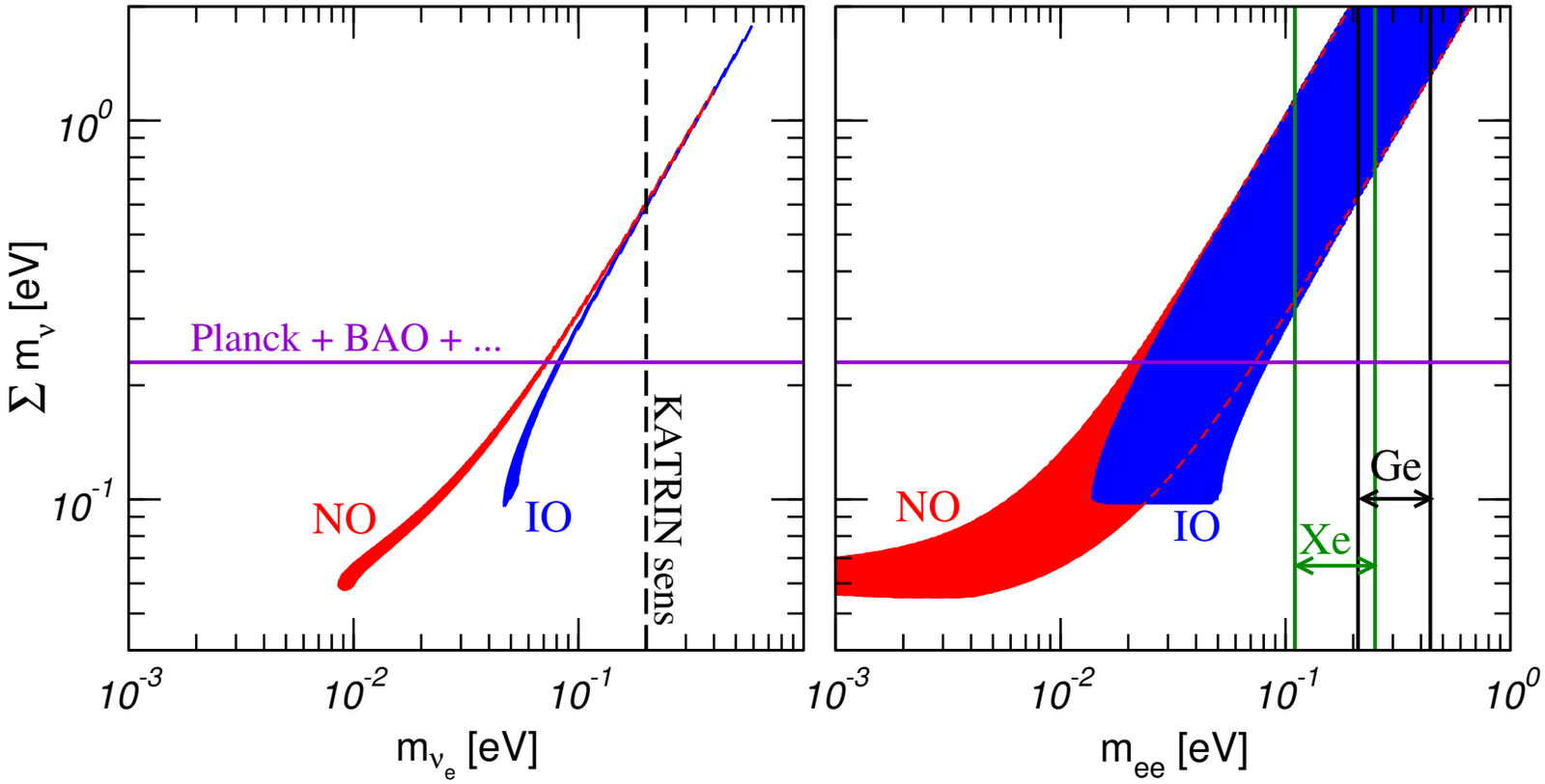


Cryo-calorimetric multipixel detectors

- **Starts to become scalable**
- But: many orders of magnitude to go for required statistics and background!
- Systematics and show stoppers on the way?

128 pixels: microwave SQUID multiplexing

Wrap-up: complementarity paths towards neutrino masses



$0\nu\beta\beta$: Ge: GERDA + HDM + IGEX, Xe: KamLAND-Zen + EXO
ranges due to NME compilation from Dev et al., 1305.0056
cosmology: Planck Dec. 2014

[compilation from T. Schwetz-Mangold]

Summary & outlook





Karlsruhe Institute of Technology

- Discovery of neutrino masses ➜ **incompleteness** of the Standard Model
- **Mass scale** & **pattern** remain to be uncovered!
- Increasingly stringent bounds from cosmology ➜ LCDM paradigm
- Quest for 0νββ detection continues ➜ **Majorana/Dirac** nature of neutrinos?
- Next-gen. direct ν mass experiment KATRIN in commissioning phase
  ➜ start by end of 2016
- Direct ν mass experiments can also probe for “new physics”, investigate sterile on eV - keV scales
- Many novel concepts and new projects emerging
- Big challenges ahead of us. :)





Bonus material:

Other fun physics with precision β spectroscopy

KATRIN: ν-mass sensitivity … and more:

Karlsruhe Institute of Technology

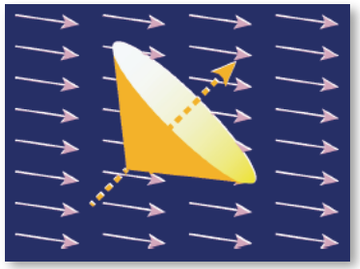
Explore physics potential

- **close to the spectral endpoint E_0:**

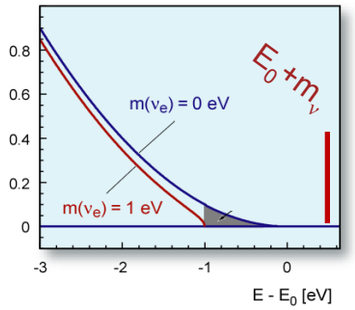
standard operation mode for KATRIN

RH currents
Bonn et al. (2011)

Violation of Lorentz symmetry
e.g. Blasone et al. (2005)
Diaz, Kostelecky & Lehnert (2013)

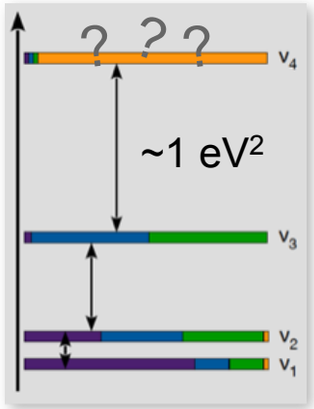


Constraining local CνB
e.g. Kaboth & Formaggio (2010), Fässler et al. (2013)



capture of relic ν on β-instable nuclei

Search for eV-scale sterile ν
e.g. Formaggio & Barrett (2011)



- **and further away from E_0:**

  search for keV-mass scale sterile ν as WDM candidates

  Mertens et al. (2015); see also Barry, Heek & Rodejohann (2014)

non-standard operation, novel detector concepts

Why sterile neutrinos?



Hints of eV-scale sterile neutrinos?

Hints of keV-scale sterile neutrinos?

Why sterile neutrinos?



Hints of eV-scale sterile neutrinos?

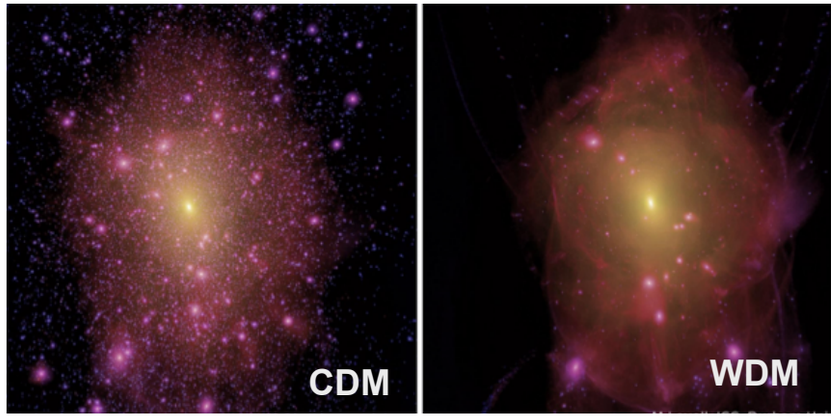
Hints of keV-scale sterile neutrinos?

Pure (Λ)CDM scenario:

- Missing satellites problem
- Too-big-to-fail problem
- “Core” vs. “cusp” problem

see Lectures R. Lang

KeV-scale sterile ν as viable WDM candidate

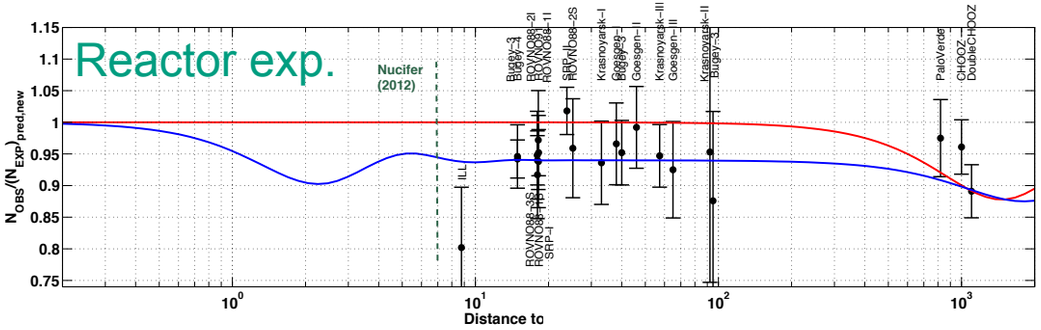


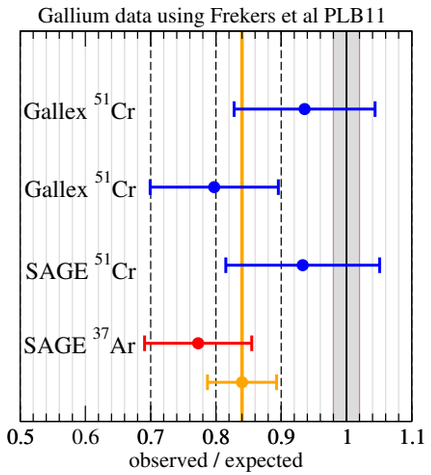
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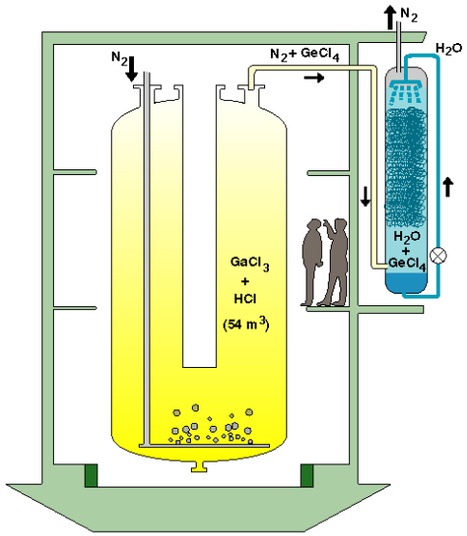


Hints of eV-scale sterile neutrinos?

May explain anomalous short-baseline oscillation results:







Gallium experiments

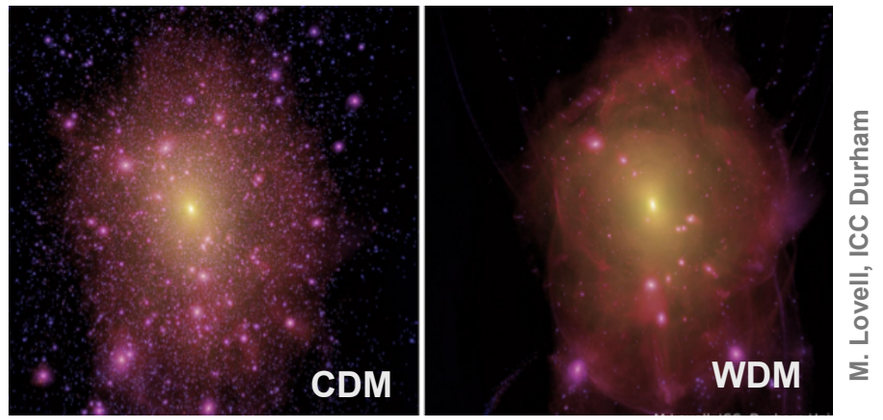
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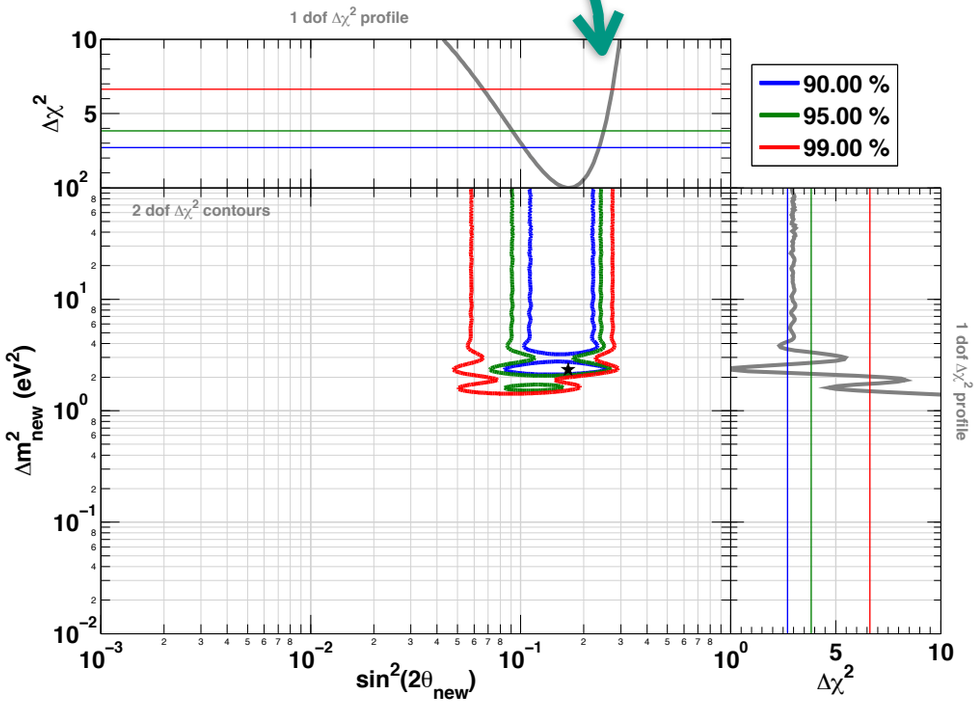


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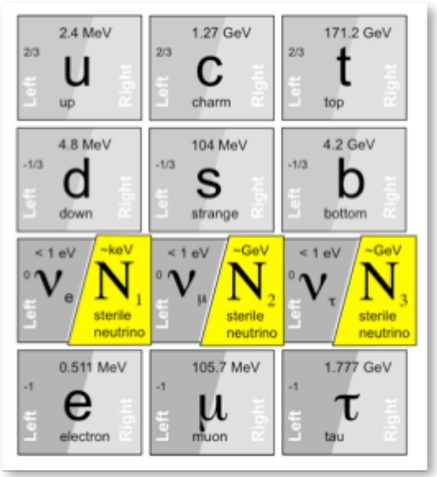
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[G. Mention et al. (2011), updated in White Paper (2014)]

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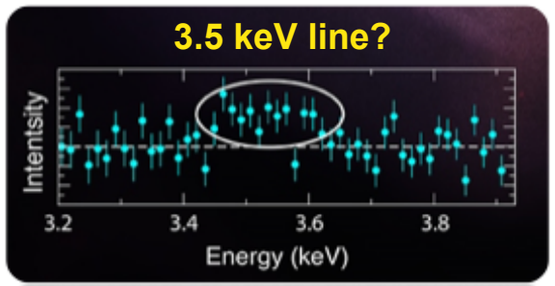
Well motivated as natural extension of Standard Model (νMSM)

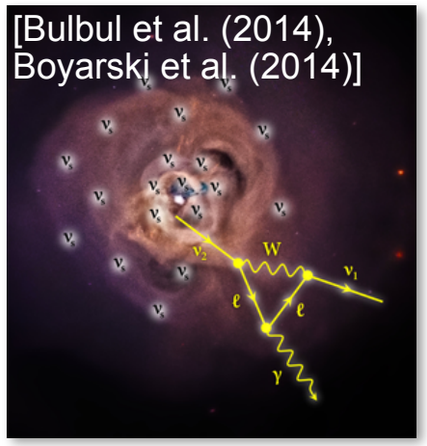


[e.g., Canetti, Drewes, Shaposhnikov (2013)]

In agreement with cosmological observations from small to large scales [e.g., Shi & Fuller (1999)]

Recent indirect hints from X-ray astronomy?



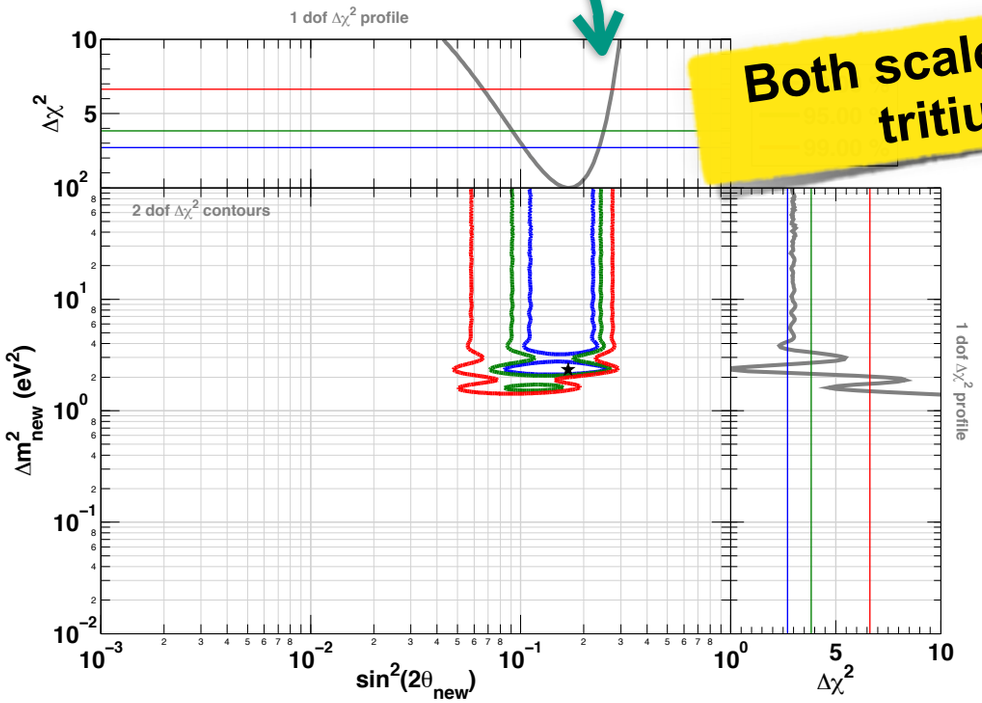


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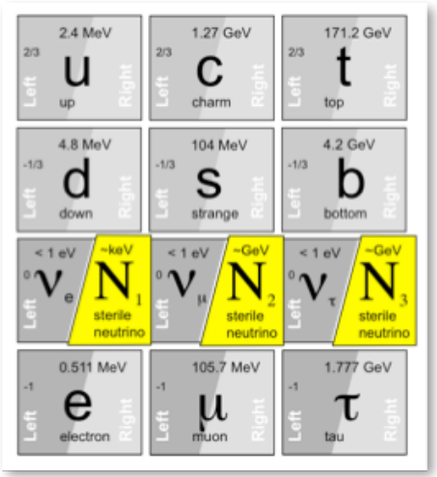


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Both scales accessible in tritium β decay

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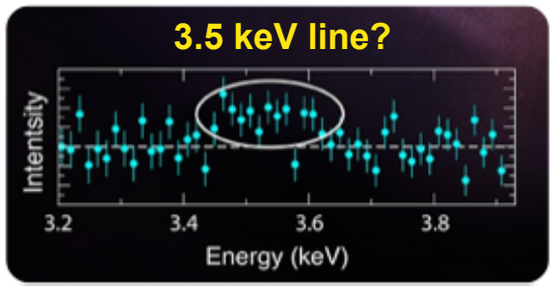
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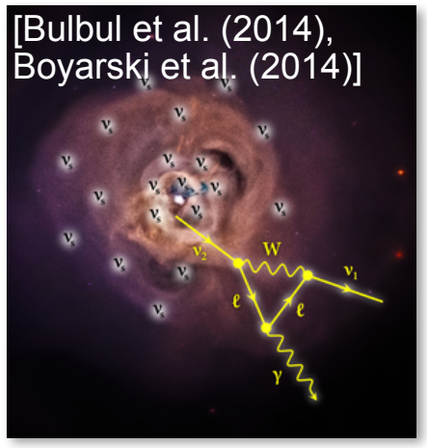


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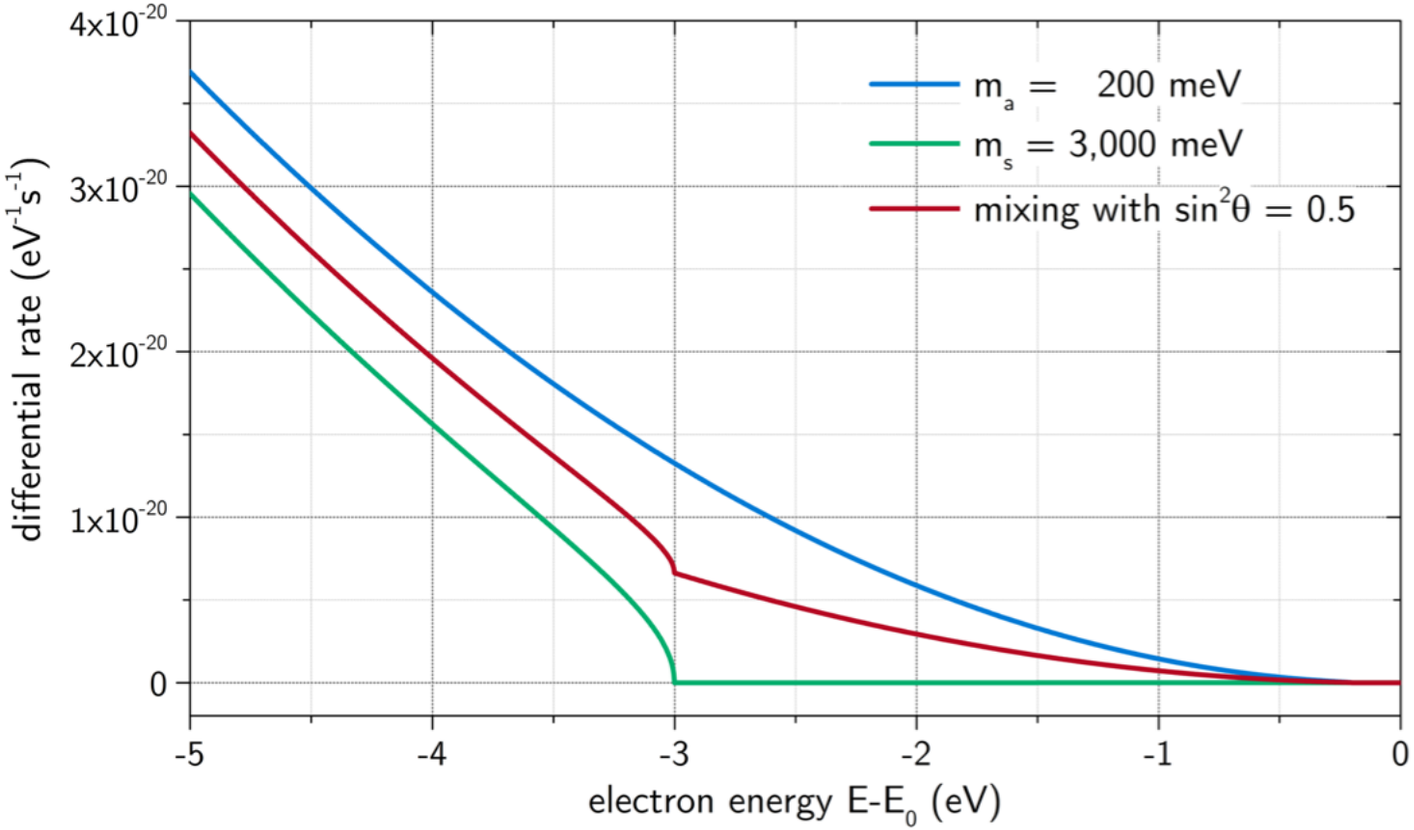
Imprint of sterile neutrinos on β spectrum

Shape modification below E_0 by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

$$\frac{dN}{dE} = \cos^2\theta_s \frac{dN}{dE}(m_a^2) + \sin^2\theta_s \frac{dN}{dE}(m_s^2)$$

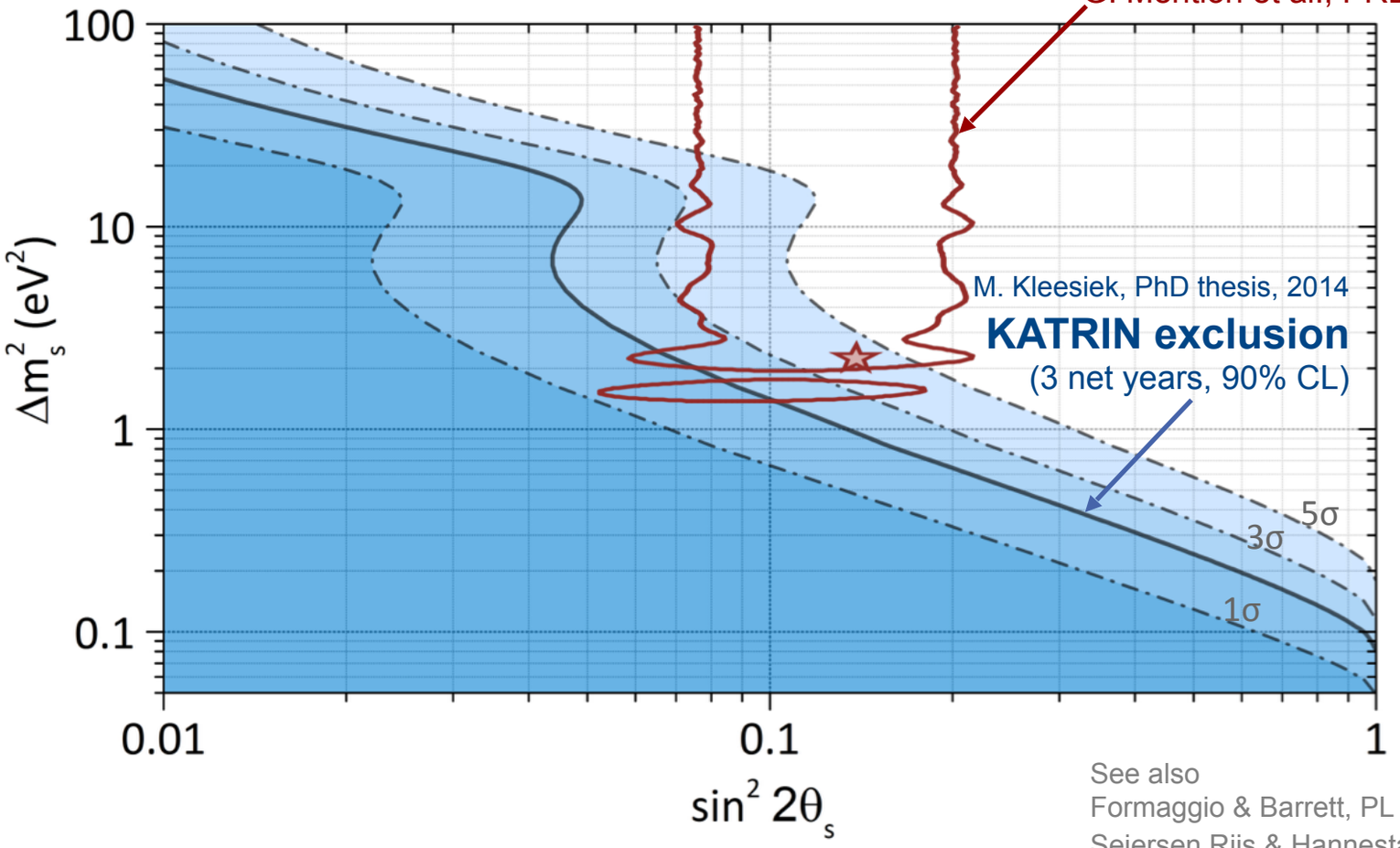
⇒ additional kink in β spectrum at $E = E_0 - m_s$

example:
light sterile ν
m_s = 3 eV



Search for eV-scale sterile ν with KATRIN

- "Reactor antineutrino anomaly": $|\Delta m_s^2| > 1.5\ \mathrm{eV}^2, \quad \sin^2(2\theta_s) = 0.14 \pm 0.08 \quad (95\%\,\mathrm{CL})$
- Favoured parameter space can be probed by KATRIN:



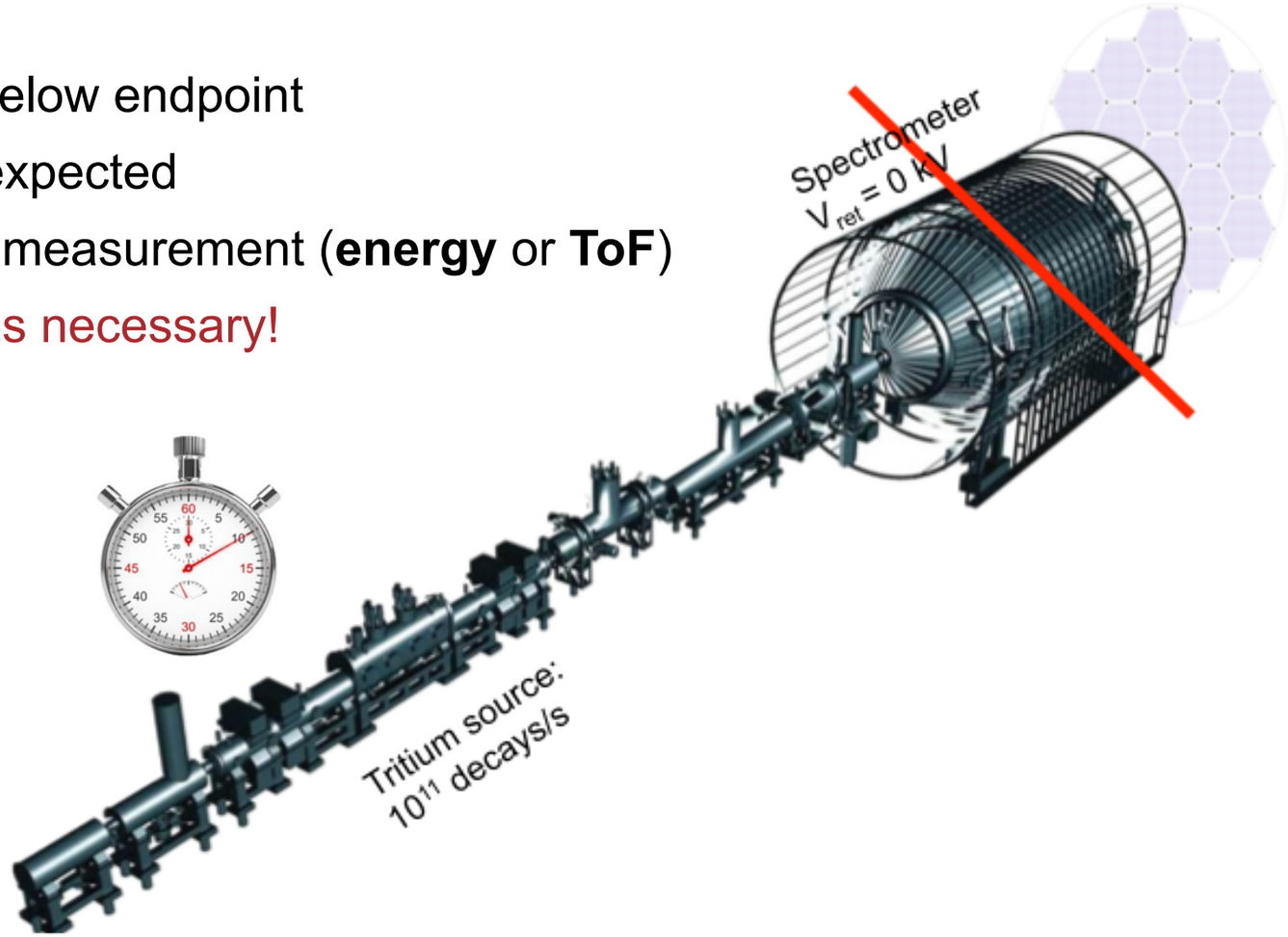
See also
Formaggio & Barrett, PL B706 (2011) 68;
Sejersen Riis & Hannestad, JCAP02 (2011) 011;
Esmaili & Peres, PR D85 (2012) 117301

Search for keV-scale sterile ν with KATRIN

The challenge:

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for **differential** measurement (**energy** or **ToF**)

➡ Development of new techniques necessary!



*) **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing

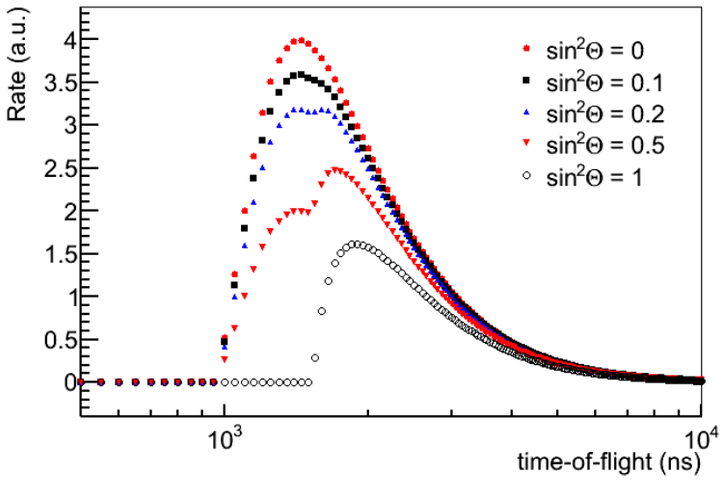
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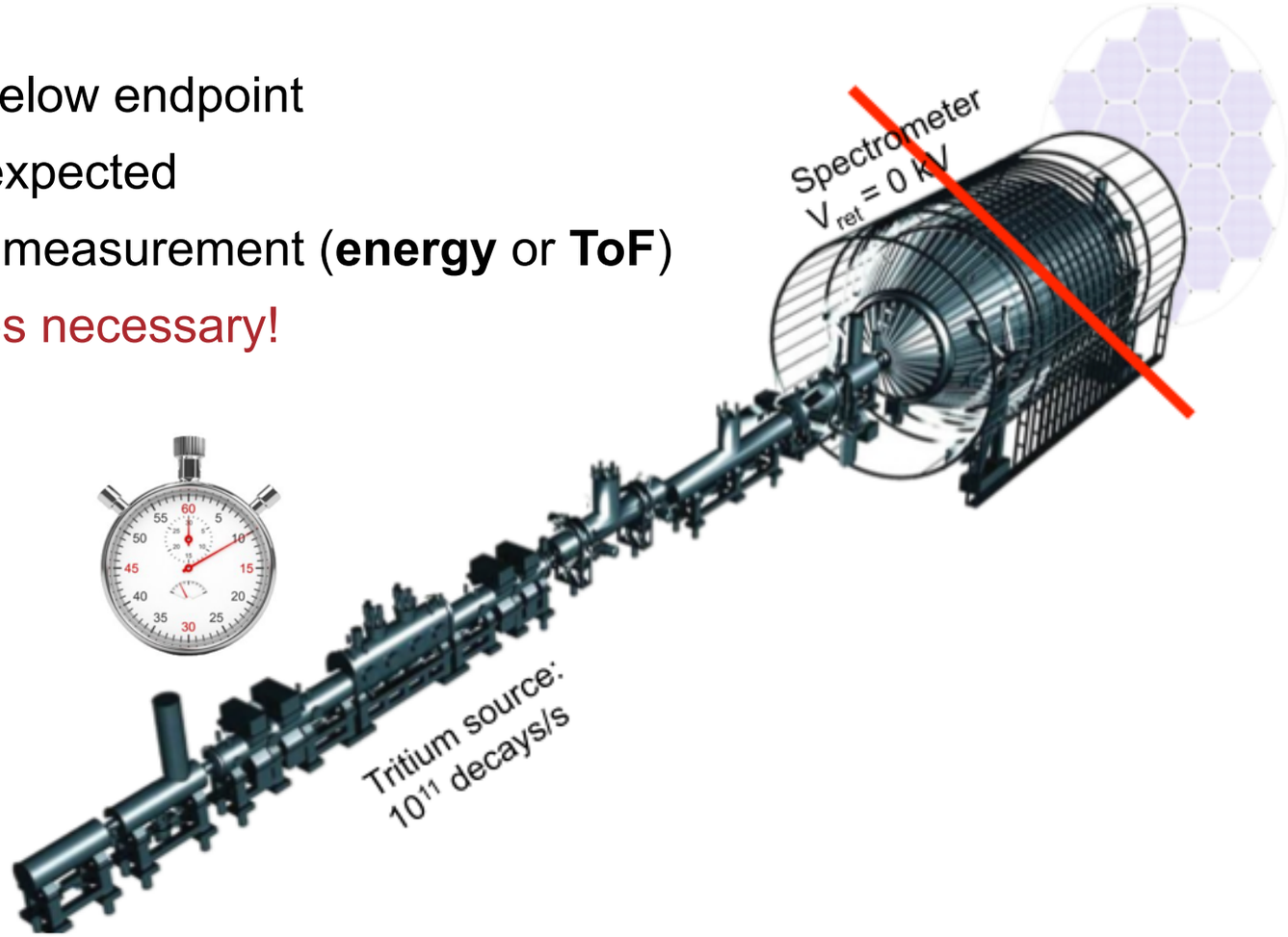
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ToF option:
electron tagger required





[Steinbrink et al. (2013), Robertson et al. (in prep.)]

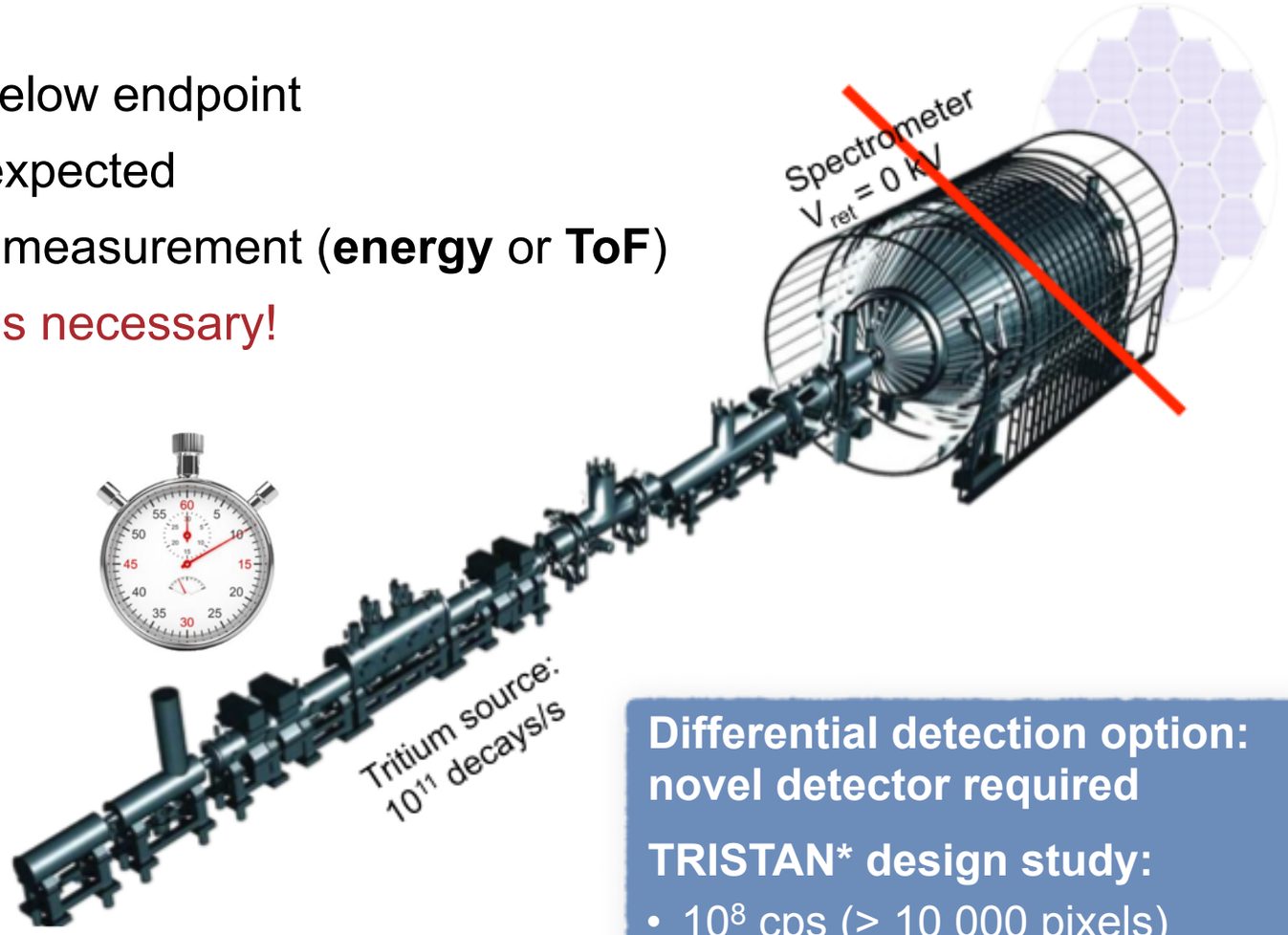
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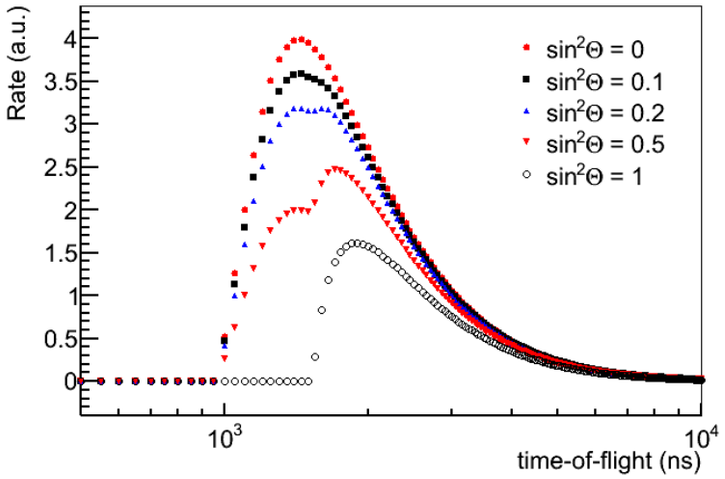
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Differential detection option:
novel detector required

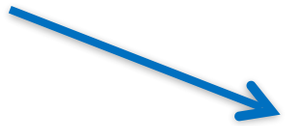
TRISTAN* design study:

- 10^8 cps (> 10 000 pixels)
- FWHM 300 eV @ 20 keV
- > 20 cm diameter

[Mertens et al. (2015)]

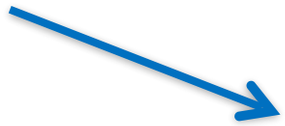
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Search for keV-scale sterile ν with KATRIN



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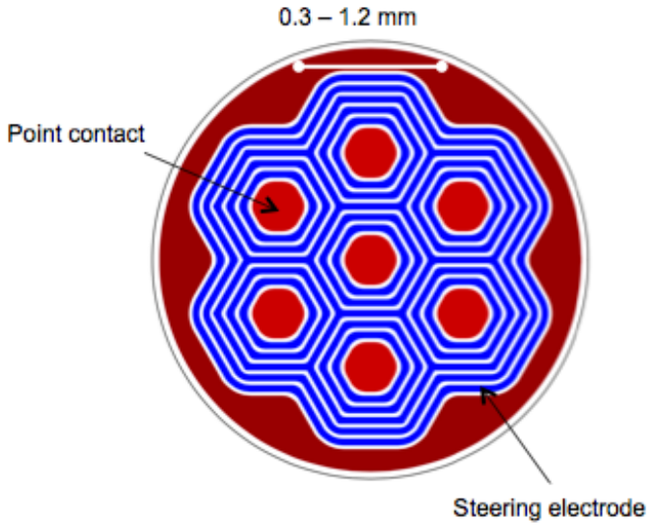
- First measurements with KATRIN “baseline” set-up at reduced source strength
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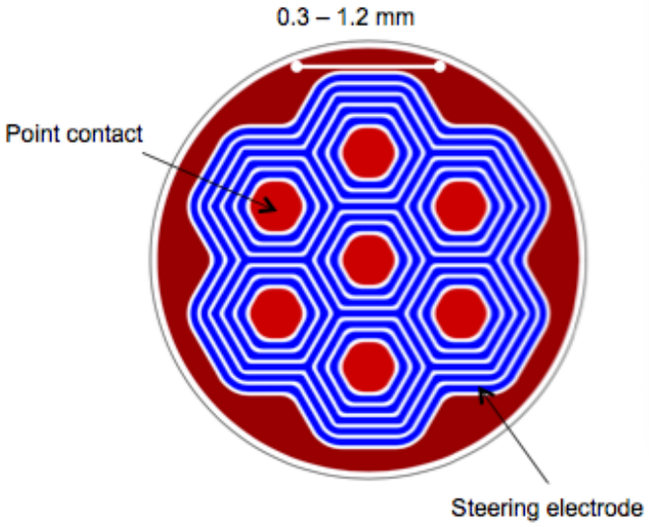
TRISTAN prototype (10/2015):
characterize pile-up, backscattering, charge-sharing, etc.

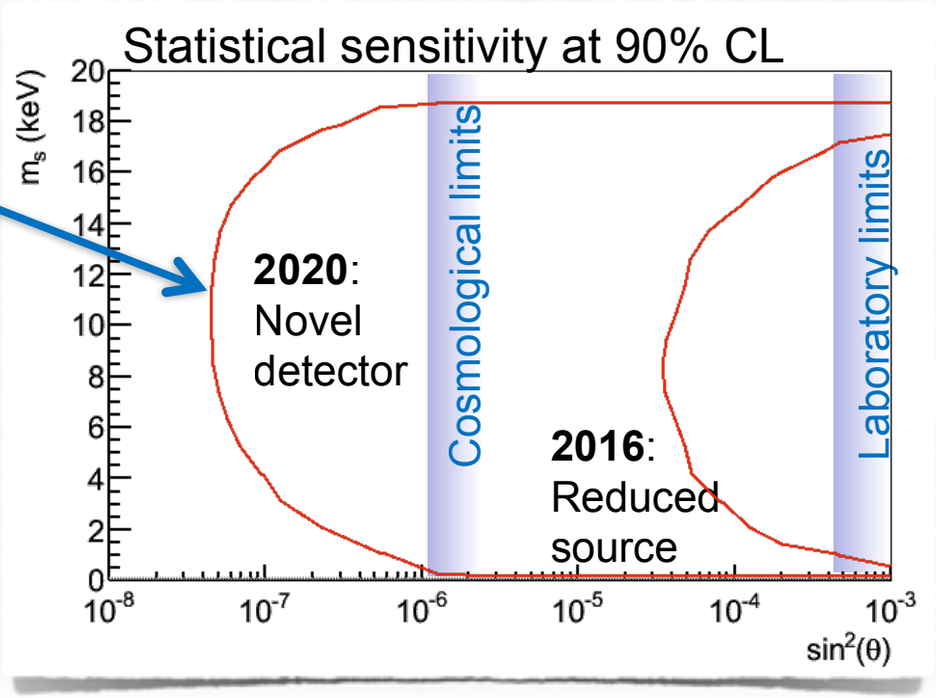


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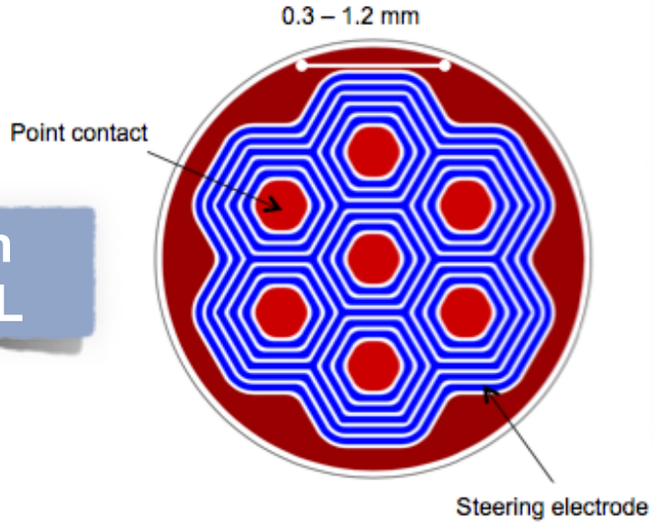


courtesy S. Mertens

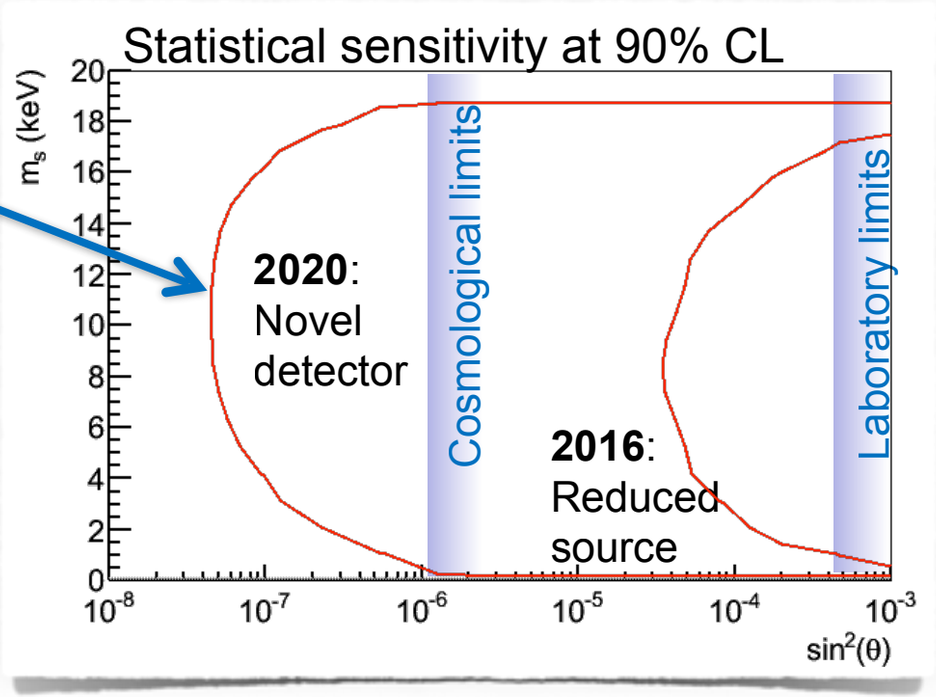
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Collaboration with HLL Munich, LBNL

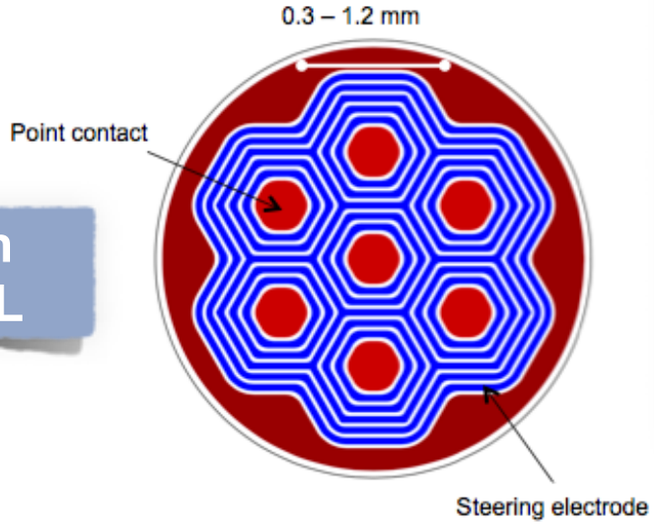


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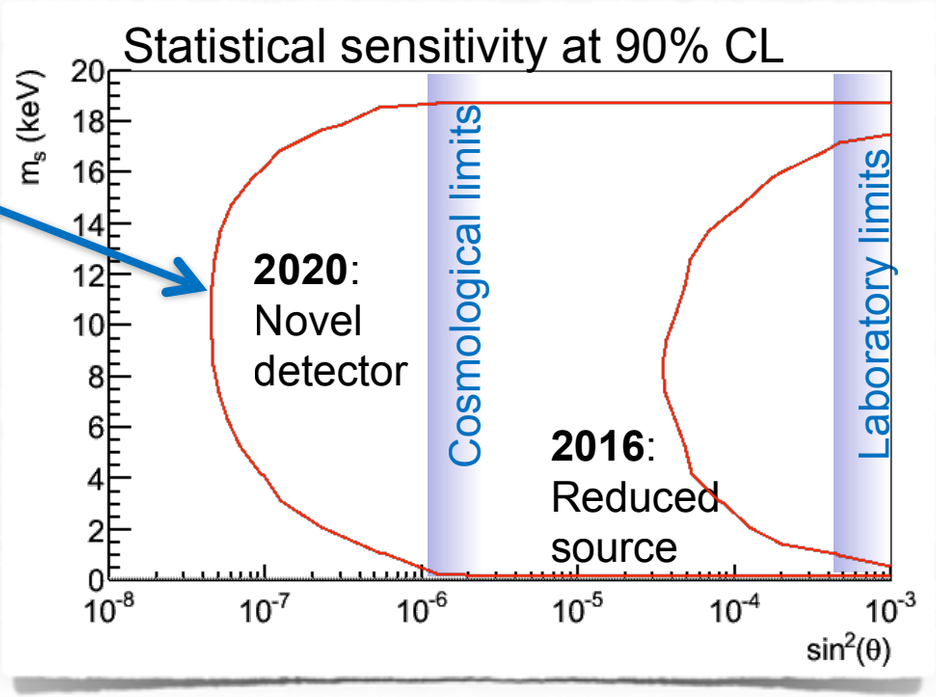
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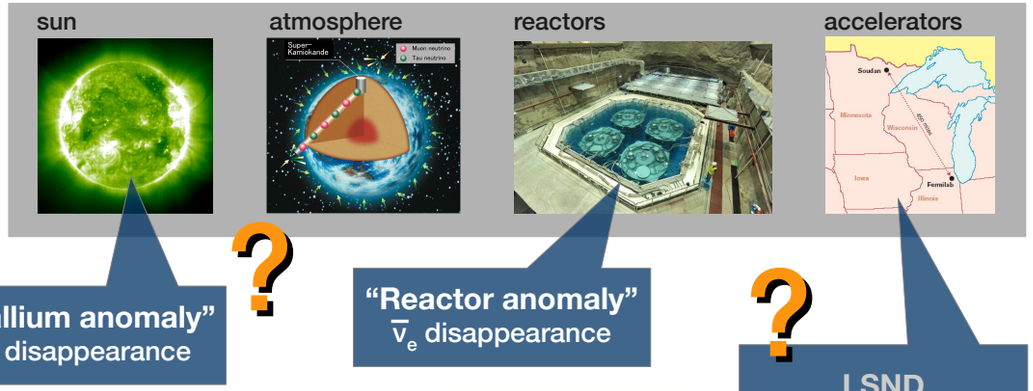
courtesy S. Mertens

➜ High-sensitivity keV sterile ν search probing cosmologically allowed parameter space after the ν-mass measurement with KATRIN


THE END

Summary & outlook

Is there room (and is there evidence)
for a 4th, **sterile neutrino?**

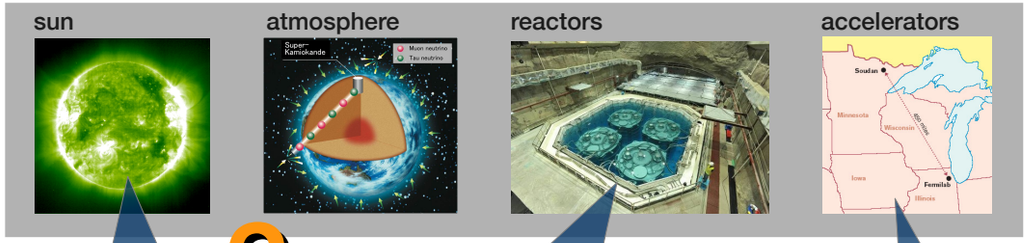


If "anomalous ν oscillations":
invoke extra mass splitting
→ extra (sterile) neutrino state



Summary & outlook

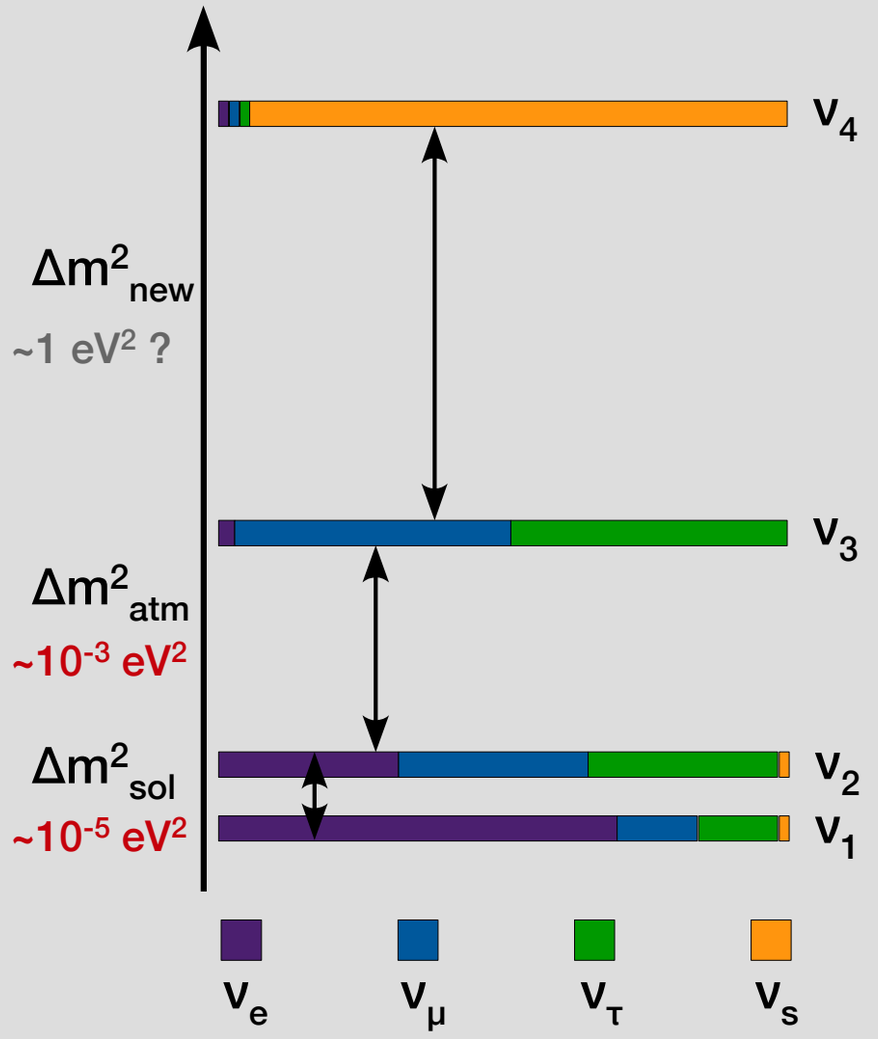
Is there room (and is there evidence) for a 4th, **sterile neutrino?**



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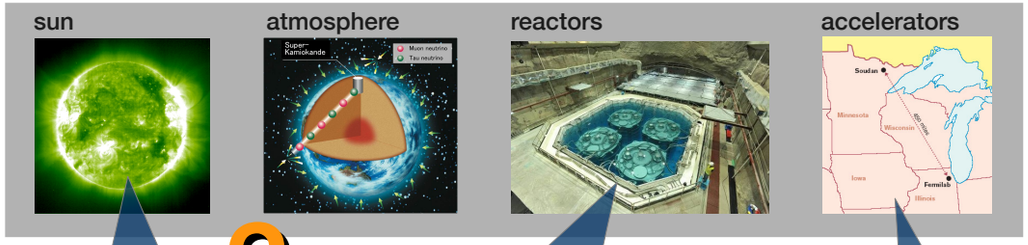


Simplest (3+1) extension:



Summary & outlook

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"Gallium anomaly"
ν_e disappearance

?

"Reactor anomaly"
$\bar{\nu}_e$ disappearance

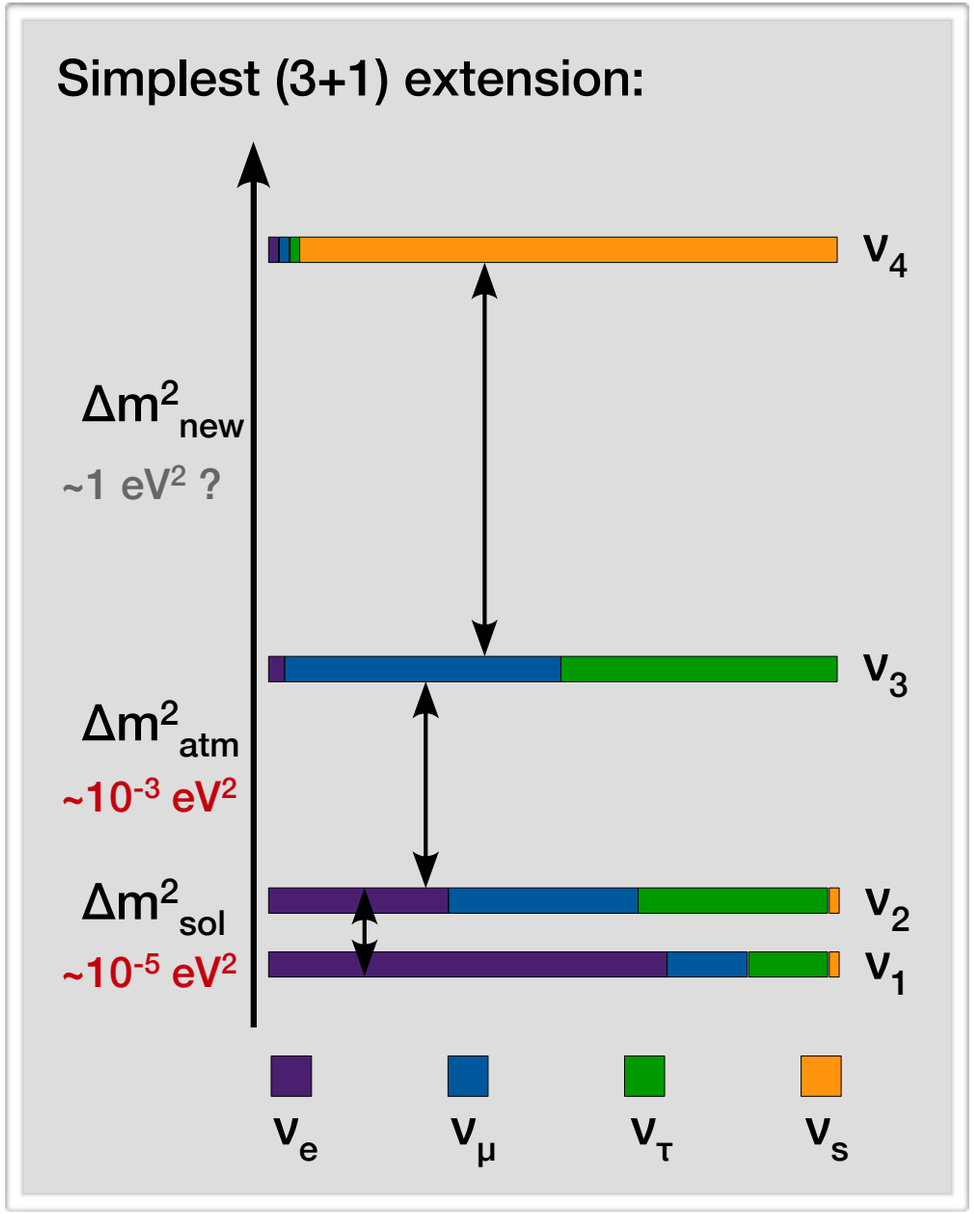
?

LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
MiniBooNE
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_e$ appearance

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What about **keV sterile** neutrinos as Warm Dark Matter candidates?



Stay tuned for news from neutrinos in astroparticle physics!

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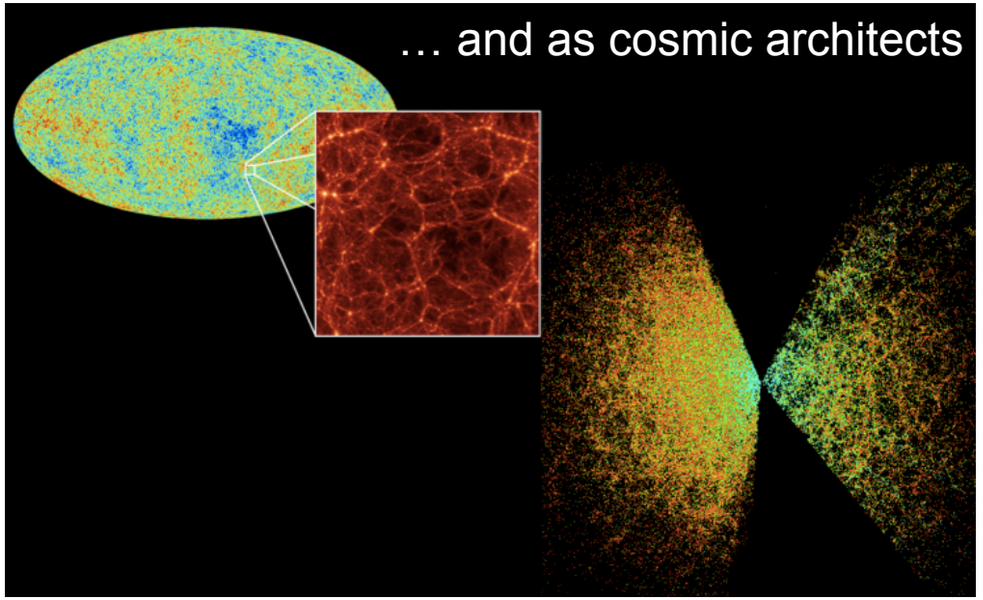
Massive neutrinos in the lab …



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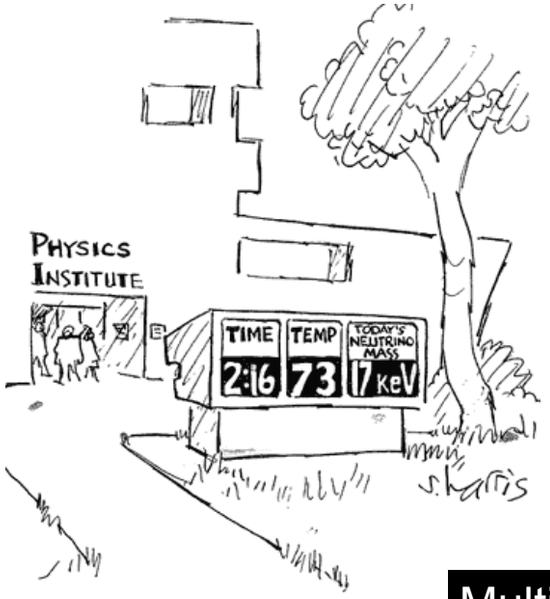
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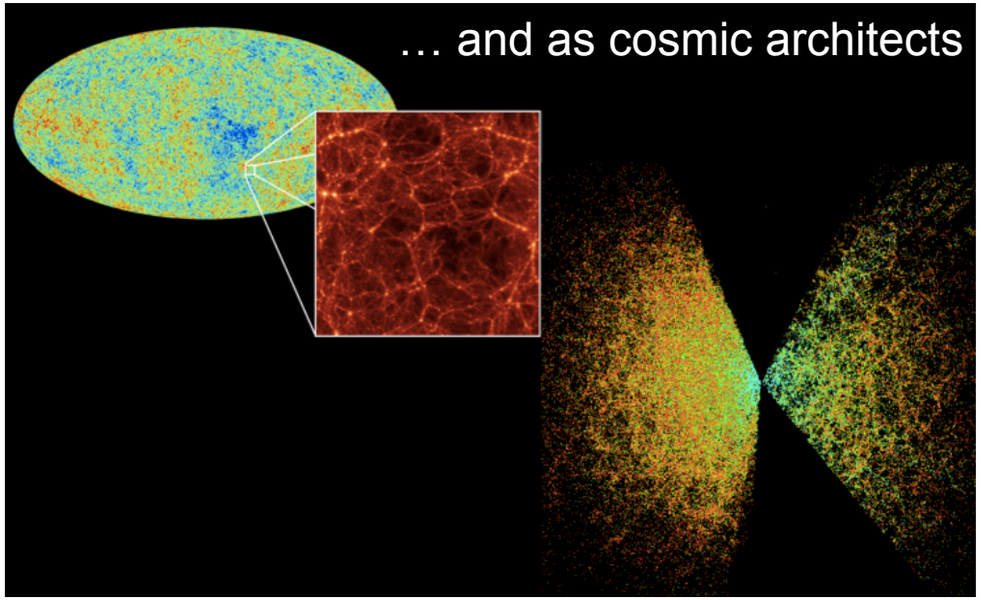


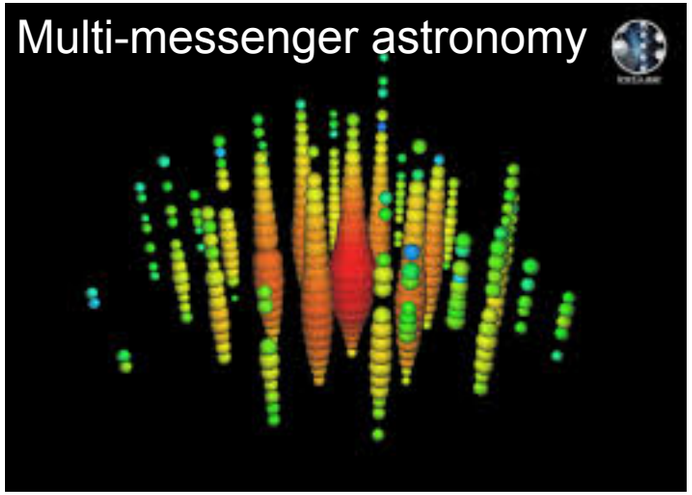


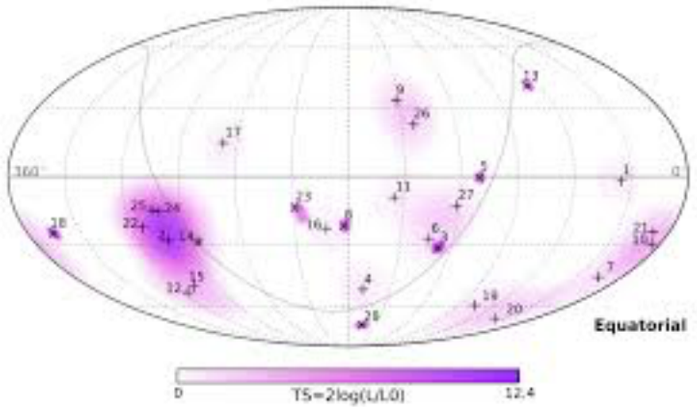
Stay tuned for news from neutrinos in astroparticle physics!

Massive neutrinos in the lab …





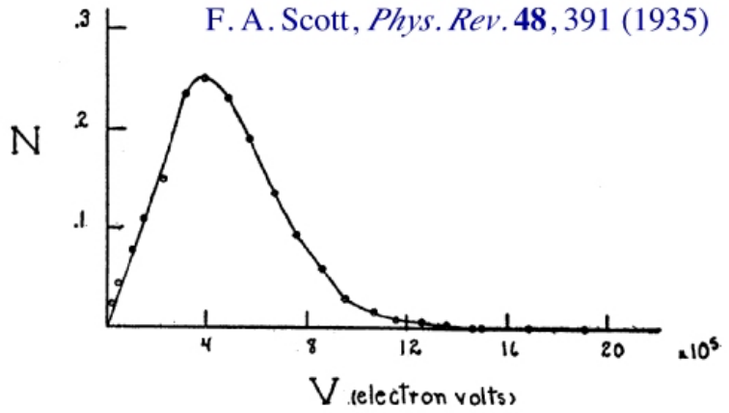




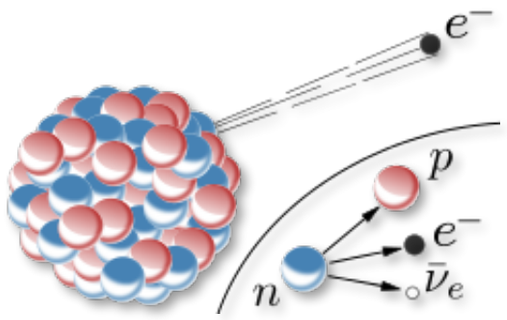
β decay and neutrino mass

1930: Wolfgang Pauli's "desperate remedy" to solve the problem of apparent violation of energy & momentum conservation in β-decay

postulation of **new particle**: neutral, spin ½, weak interaction



Energy distribution curve of the beta-rays.




W. Pauli

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

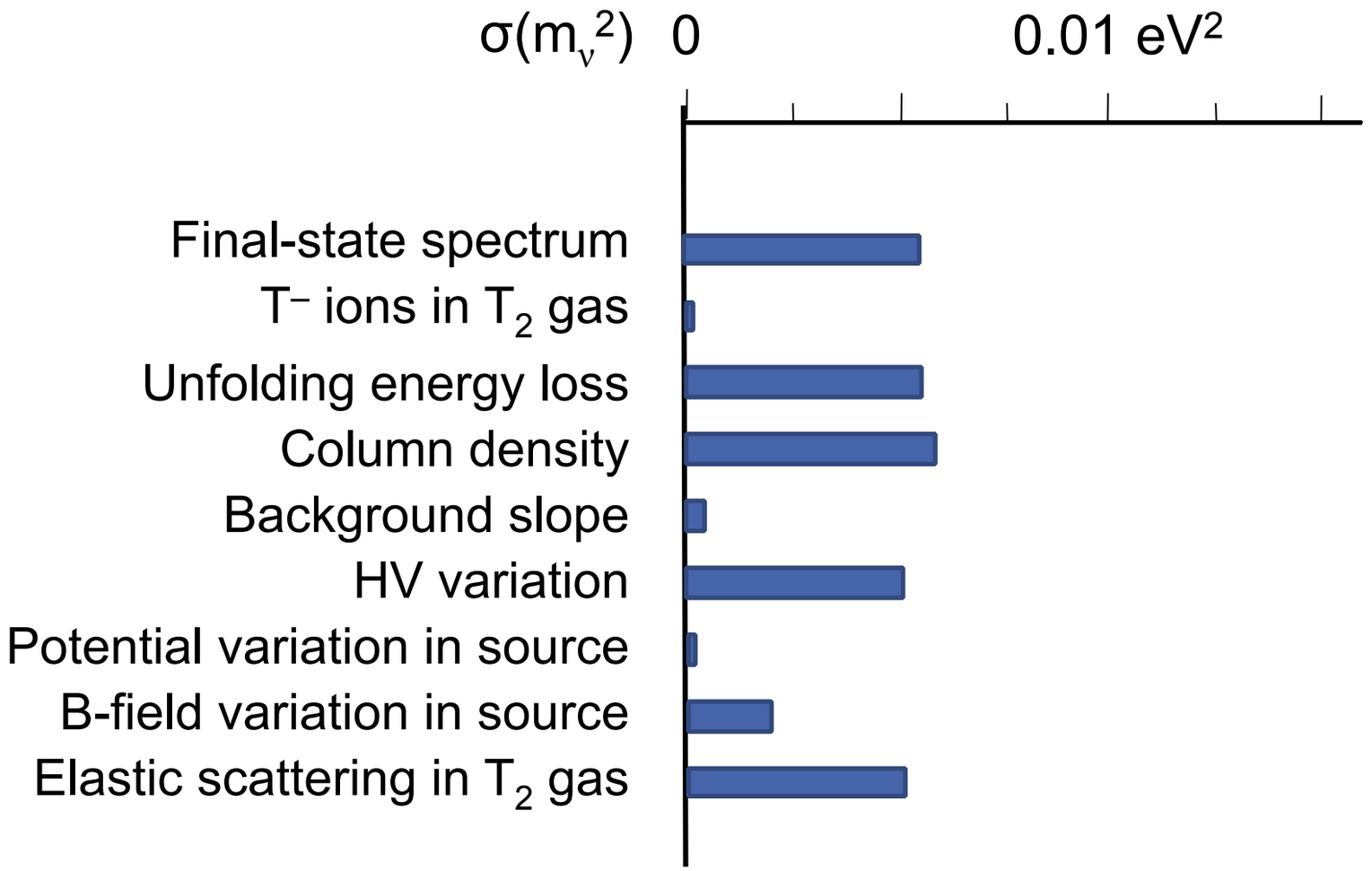
Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

KATRIN systematics “budget”

How to read this table?

(b) sorted by magnitude of individual contributions

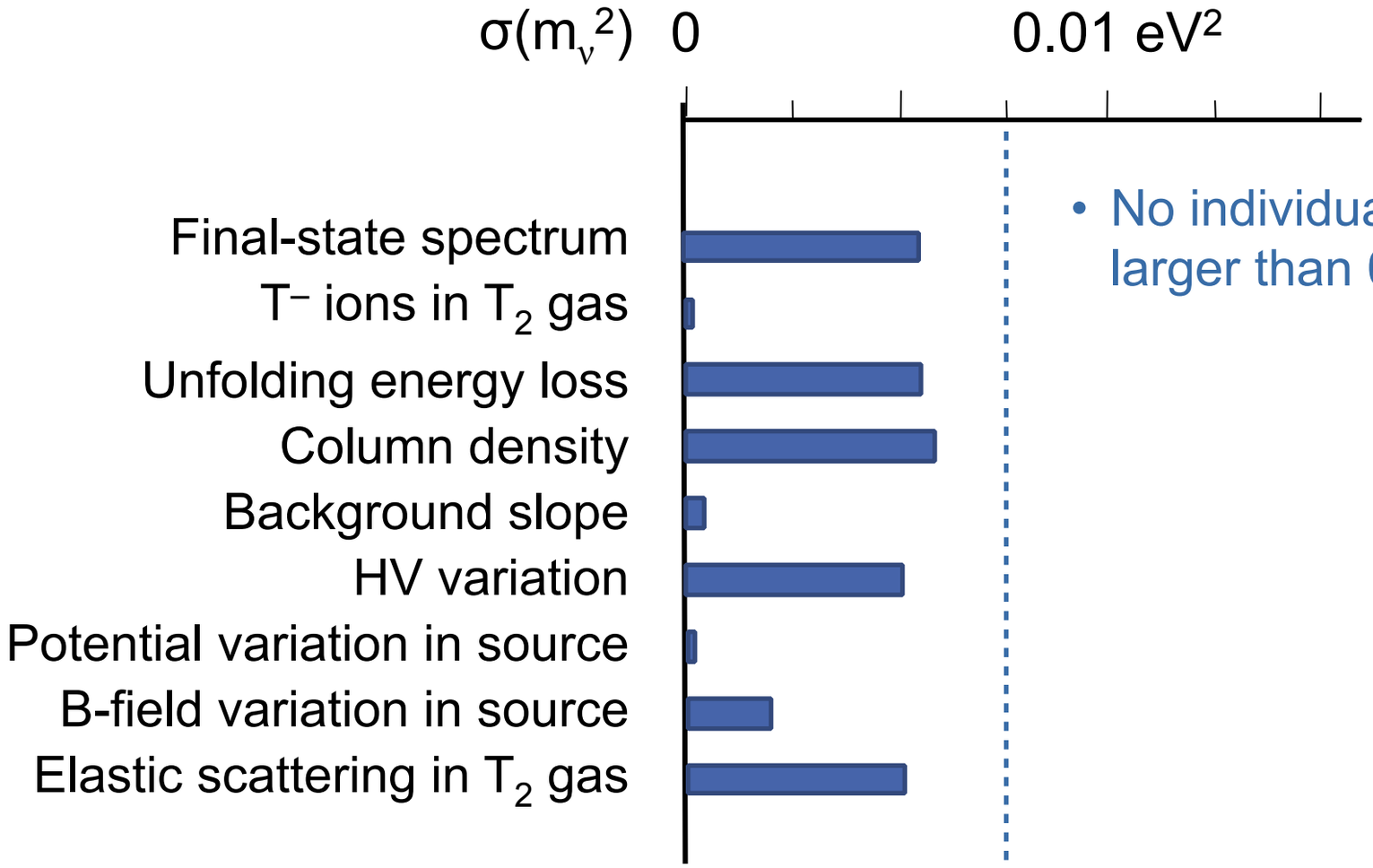


visualization courtesy R.G.H. Robertson

KATRIN systematics “budget”

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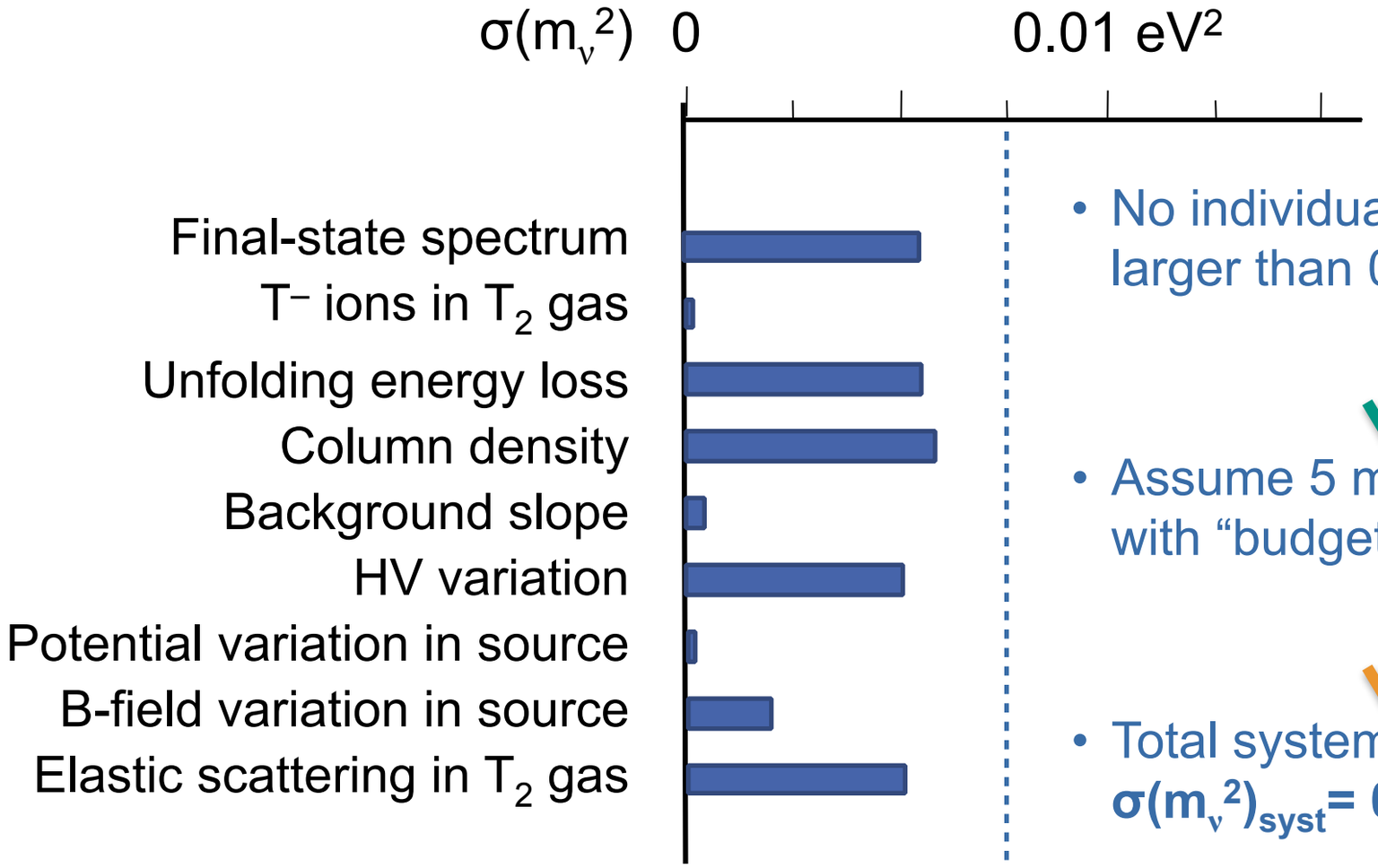
- No individual contribution larger than 0.0075 eV^2 expected

visualization courtesy R.G.H. Robertson

KATRIN systematics “budget”

How to read this table?

(b) sorted by magnitude of individual contributions



- No individual contribution larger than 0.0075 eV^2 expected

conservative estimate

- Assume 5 main systematics with “budget” of 0.0075 eV^2 each

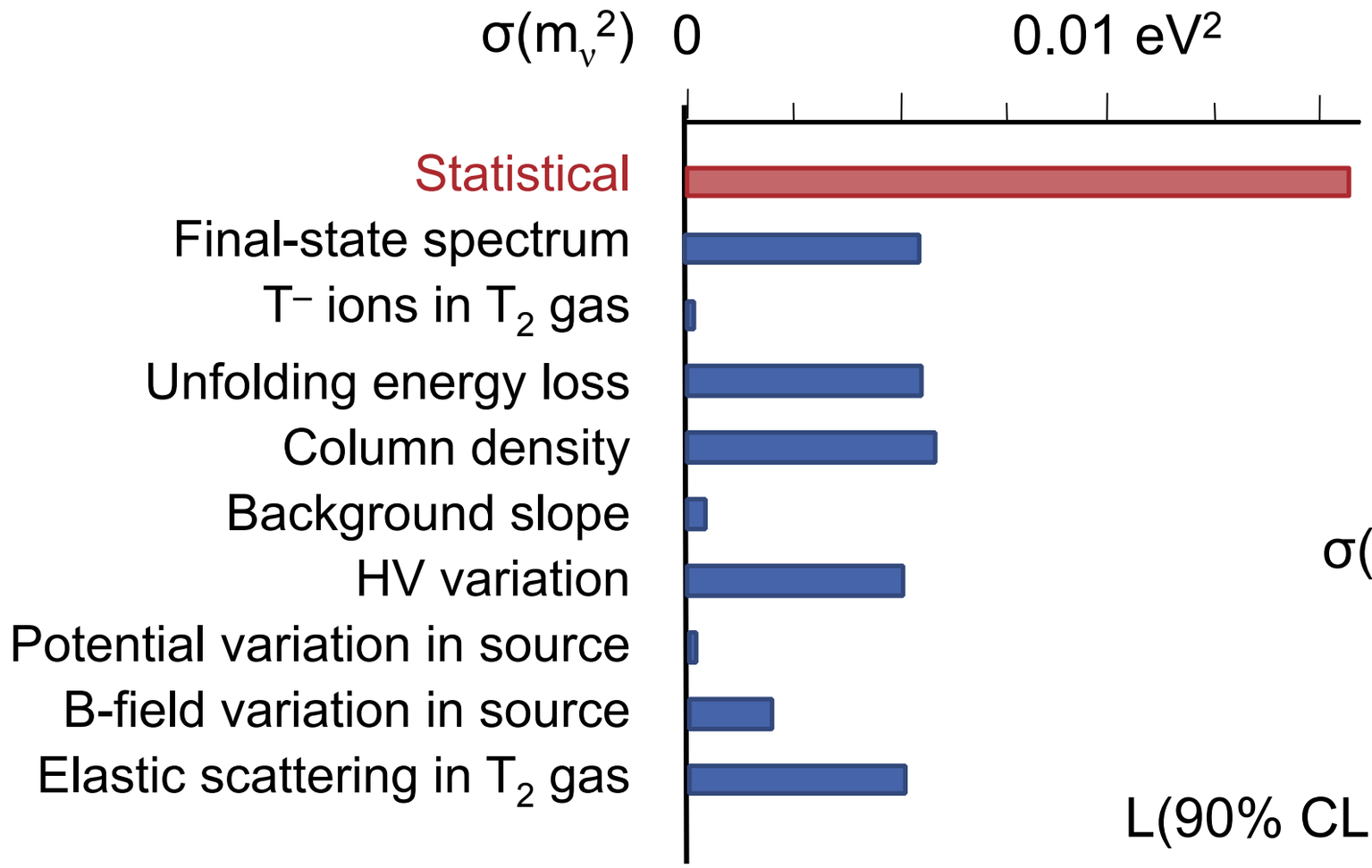
adding in quadrature

- Total systematic uncertainty: **$\sigma(m_\nu^2)_{syst} = 0.017$ eV^2**

visualization courtesy R.G.H. Robertson

KATRIN sensitivity in a nutshell

A simple sensitivity estimate from combining (conservative) **systematics** budget with **statistical** uncertainty (3 net years of data):



$\sigma(m_\nu^2)_{stat} = 0.018\ eV^2$

$\sigma(m_\nu^2)_{syst} = 0.017\ eV^2$

adding in quadrature

$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

unified approach
Feldman & Cousins, 1998

$L(90\%\ CL) = \sqrt{1.64 * \sigma(m_\nu^2)_{total}}$

$m_\nu < 200$ meV (90% CL)

visualization courtesy R.G.H. Robertson

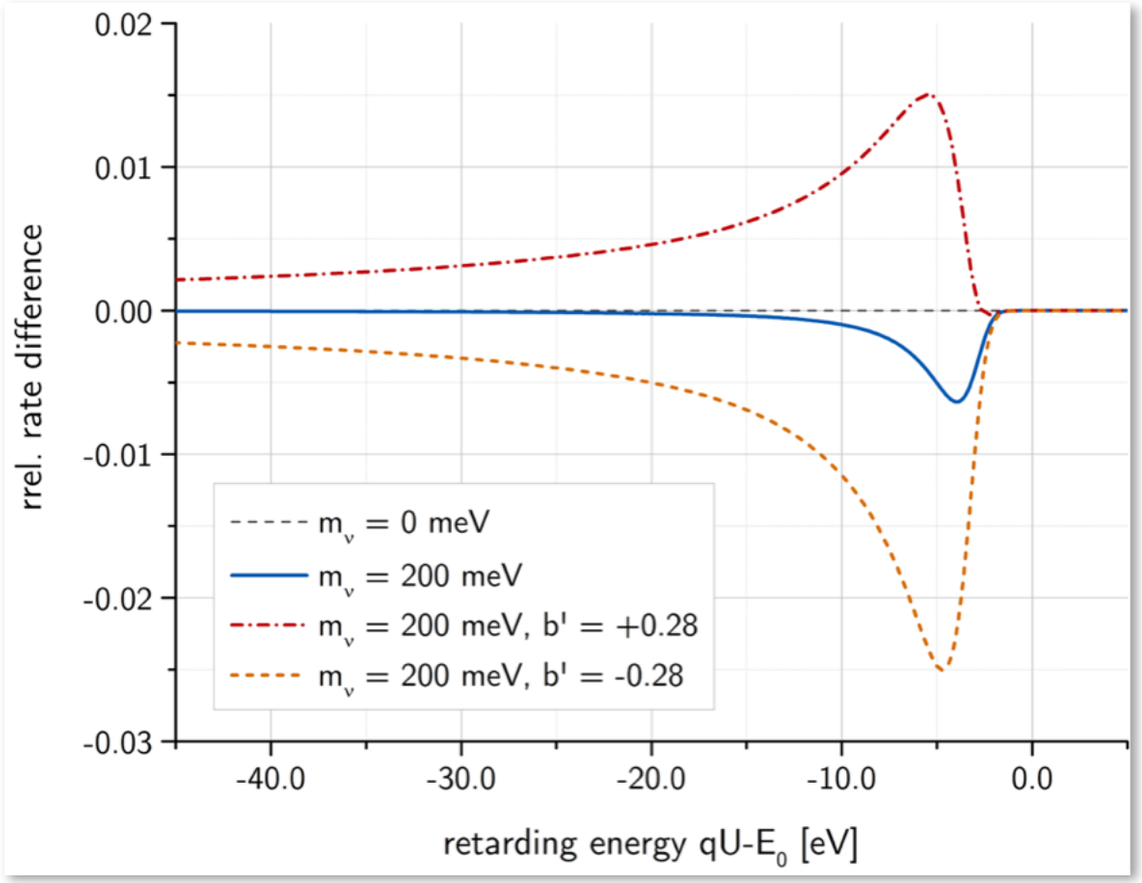
Effect of RH current contributions

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E\,\mathrm{d}t} \propto E_\nu \sqrt{E_\nu^2 - m_\nu^2} \left(1 + b' \frac{m_\nu}{E_\nu}\right)$$

[J. Bonn et al., *Phys. Lett. B* 703 (2011) 310]

Fierz-like parameter *b'* enters differential rate

$$b' \approx -2\,\frac{\mathfrak{Re}(L_V R_V^* + L_V R_S^*)|\mathcal{M}_F|^2 + \mathfrak{Re}(L_A R_A^* + L_A R_T^*)|\mathcal{M}_{GT}|^2}{|L_V|^2|\mathcal{M}_F|^2 + |L_A|^2|\mathcal{M}_{GT}|^2}$$



Imprint on integrated spectrum:

- Only small sensitivity on *b'* if endpoint E_0 left free in fit
  ➜ good for determination of $m^2(\nu_e)$
- Improvement of present bounds on *b'* with KATRIN for small $m(\nu_e)$ if
  - external E_0 value with accuracy < 50 meV as input*
  - absolute energy scale in KATRIN $U_{spec} - U_{source}$ known to same accuracy of < 50 meV

Figure: M. Kleesiek

*) 70 meV accuracy:
E. G. Myers et al., *PRL* 114 (2015) 013003

Probing Lorentz invariance in β decay

[Kostelecky & Mewes (2004, 2009)]

Standard Model Extension (SME) framework:

Neutrinos satisfy Dirac-like equation

$$(i\mathbf{\Gamma}^{\alpha}\partial_{\alpha} - \mathbf{M})\,\psi = 0$$

with $\mathbf{\Gamma}$, $\mathbf{M}$ including momentum-dependent coefficients

[review: Diaz (2014)]

Experimental searches:

- Neutrino oscillations
- Neutrino velocity (ToF)
- Weak decays

probe oscillation-free parameters

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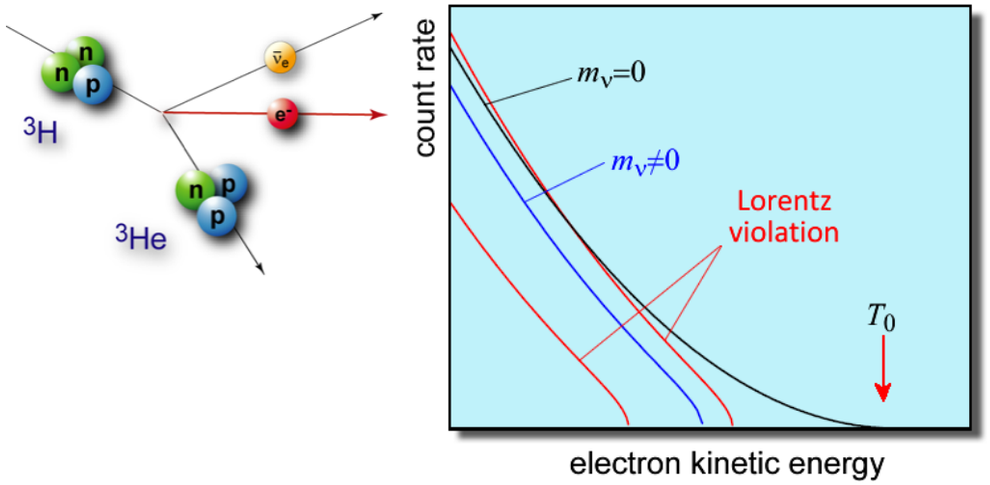
[review: Diaz (2014)]

Experimental searches:

- Neutrino oscillations
- Neutrino velocity (ToF)
- Weak decays

probe oscillation-free parameters

Tritium β decay:



[Diaz, Kostelecky, & Lehnert (2013)]

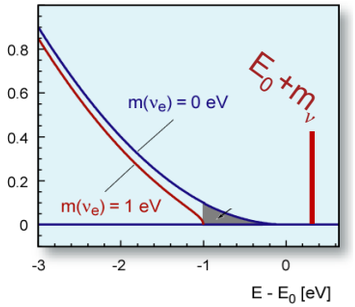
- Modified energy dependence of decay rate
- Spectral shape dependent on sidereal time and experiment orientation
- Effective dim-3 coefficient:
  osc. shift of endpoint $T_{0,\mathrm{eff}}$ with $\omega_{\mathrm{sidereal}}$
- Effective dim-2 coefficient:
  osc. of m^2 parameter (can mimic tachyonic ν)

Constraining local CνB density with KATRIN

About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background' — Peter Fisher

ν capture on β-instable nuclei:

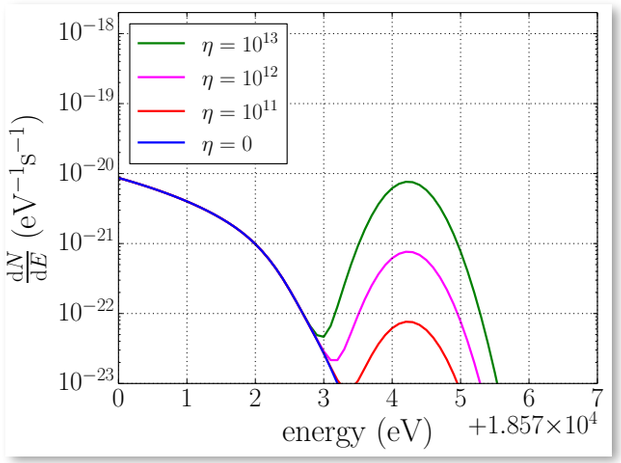
$$^{A}_{Z}N + \nu_e \rightarrow {}^{A}_{Z+1}N' + e^-$$

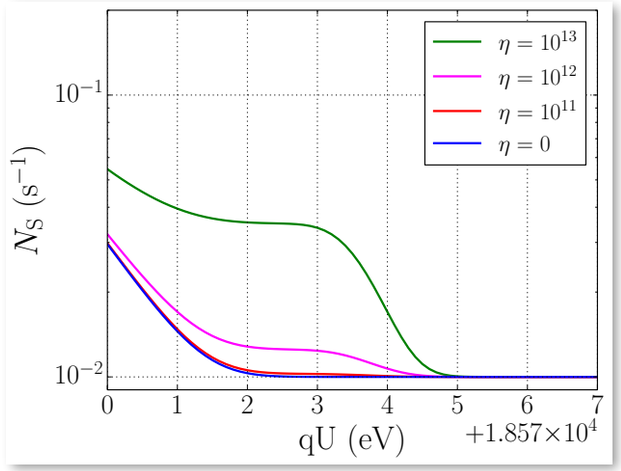


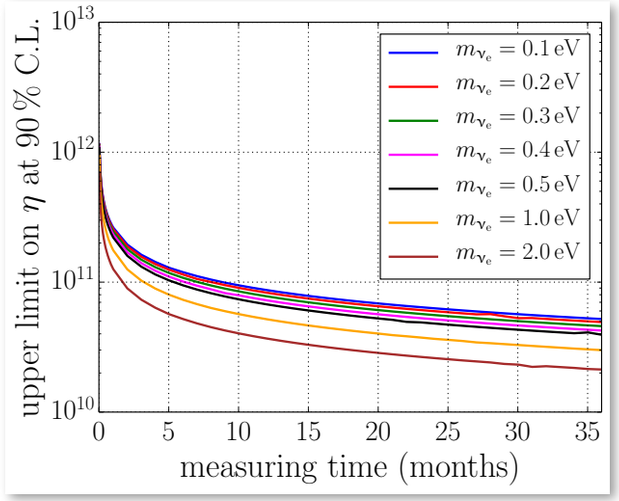
Threshold-free, but tiny cross section O(10^{-45} cm^2)

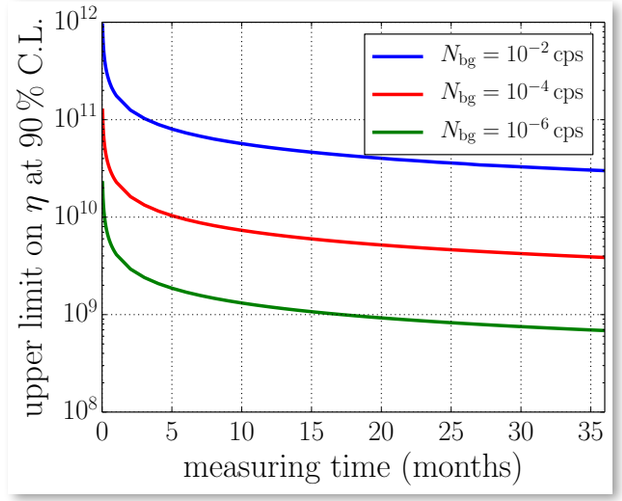
KATRIN reference setup only sensitive to local overdensity:

$$\eta = \frac{n_\nu}{\langle n_\nu \rangle}$$









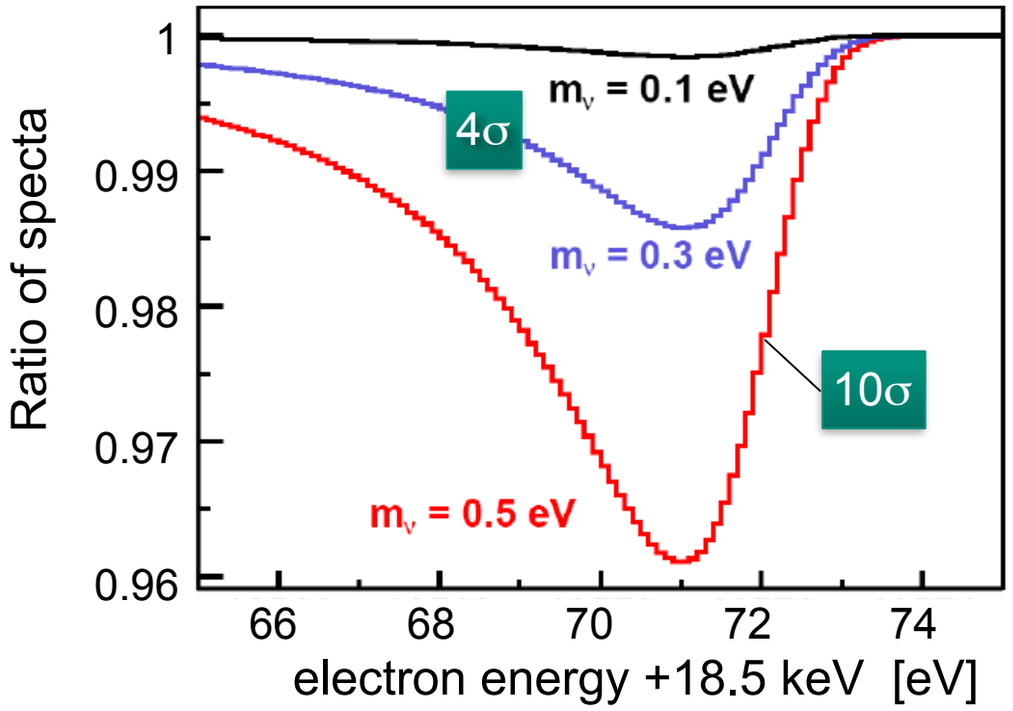
[F. Heizmann, Master's thesis (2015); see also: Kaboth & Formaggio (2010), Fässler et al. (2013)]

KATRIN sensitivity

- **reference ν-mass sensitivity**
  for 3 ´full beam´ years:
  - statistical & systematic errors contribute equally:
    statistics σ_{stat} = 0.018 eV²
    systematics σ_{syst} < 0.017 eV²

sensitivity m(ν) = 200 meV (90% CL)

350 meV (5σ)

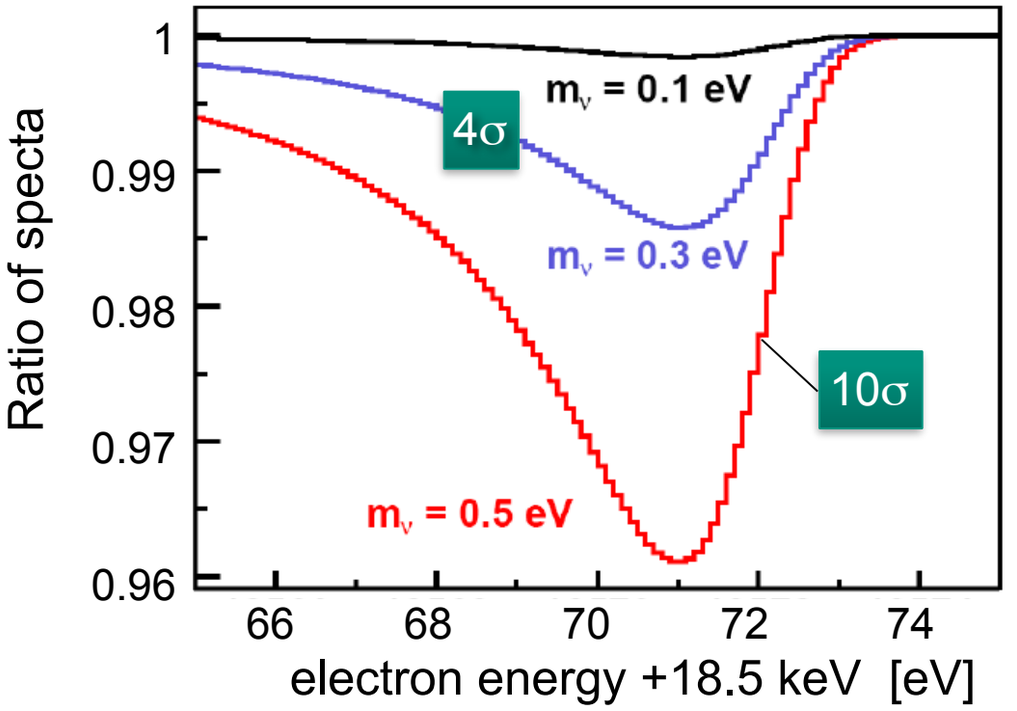


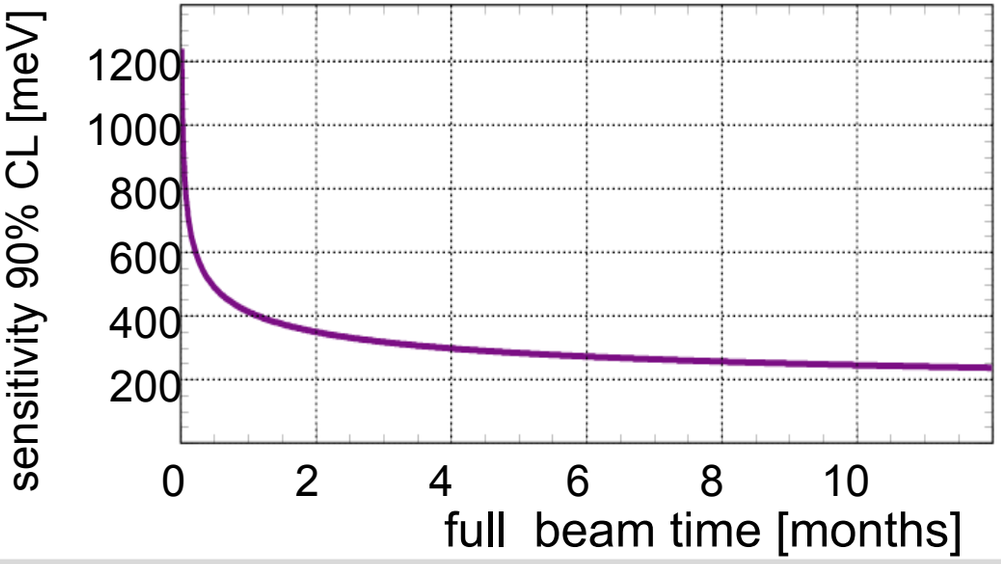
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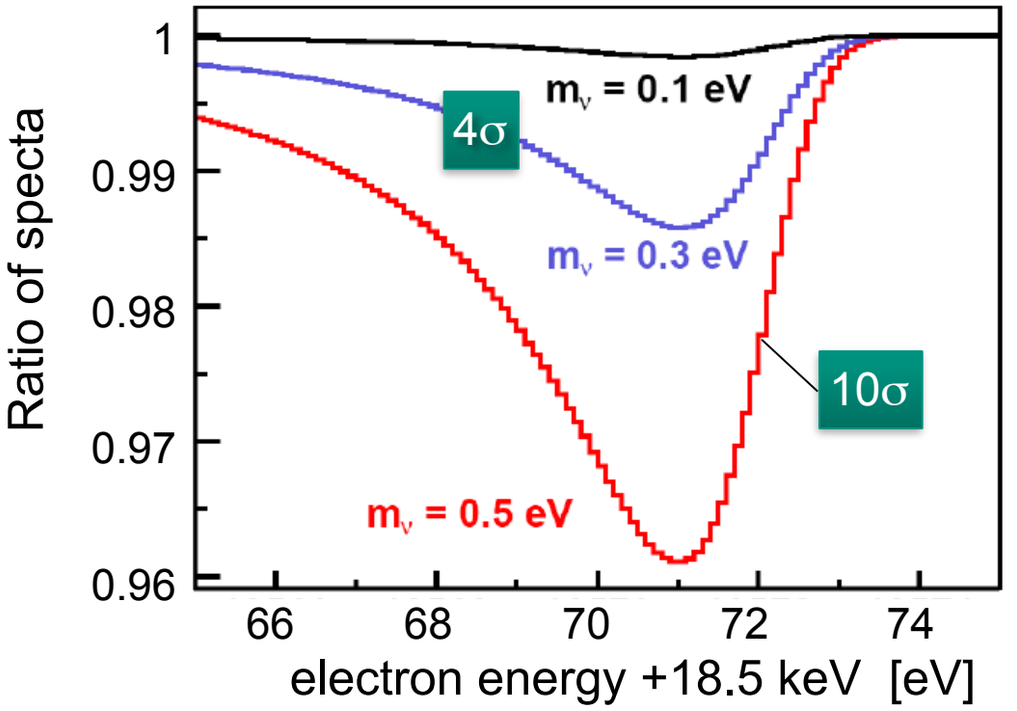


KATRIN sensitivity

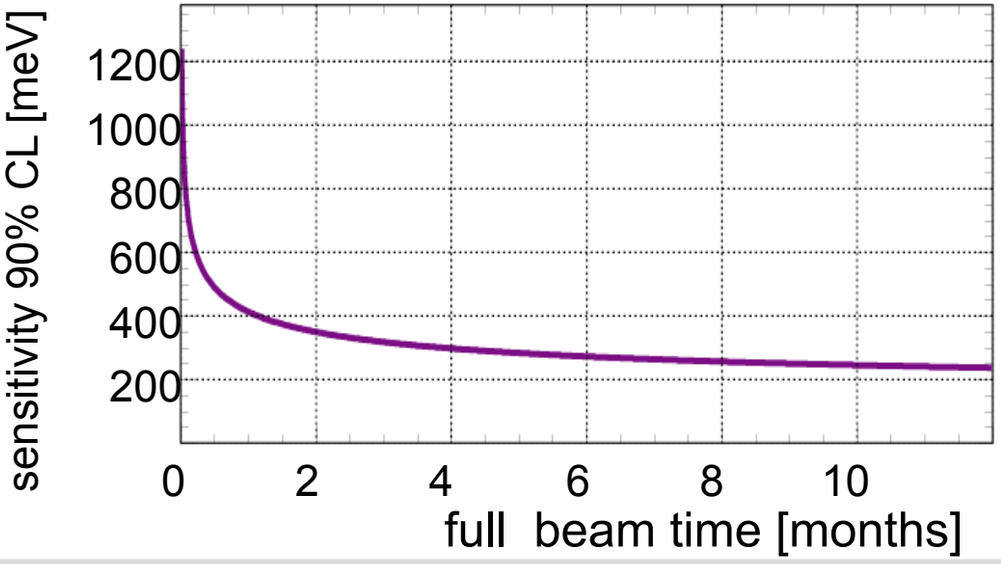
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sensitivity m(ν) = 200 meV (90% CL)

350 meV (5σ)



- **plans for a later KATRIN phase II:**
  - differential ß-energy spectrum:
    cryo-bolometer array with ΔE ~ 1eV?
    synchrotron emission (GHz-range)?
  - precision external value end point E_0
  - atomic tritium source?



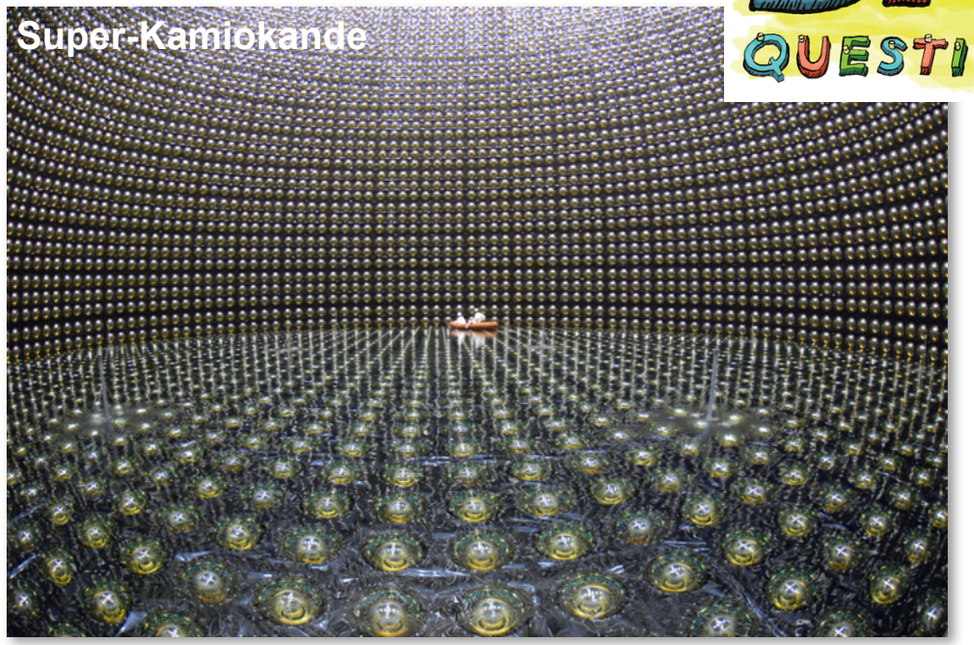
“Neutrino physics is driven by experiments”

— Boris Kayser, theoretician



Karlsruhe Institute of Technology

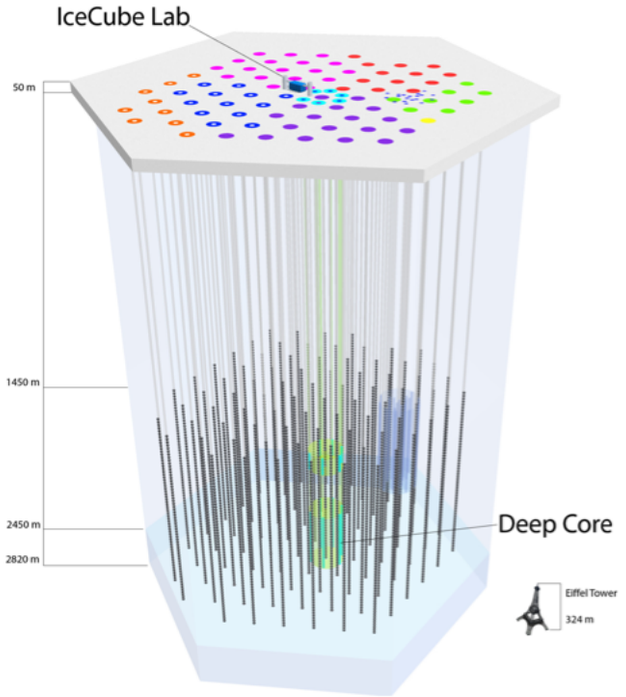












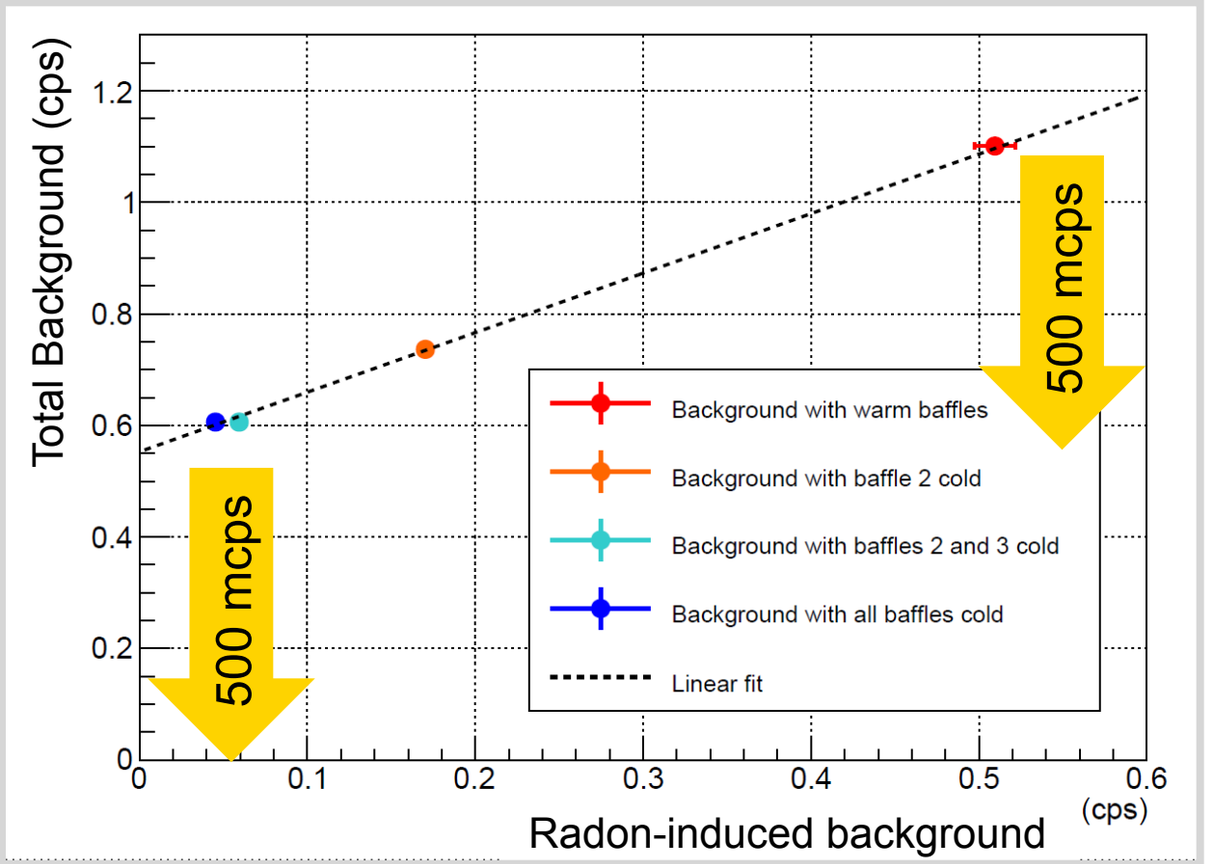
Background characterization

2015: 2nd phase of commissioning measurements completed

> Spectrometer works as MAC-E filter

> LN2-cooled baffles eliminate Radon-induced background with efficiency of (97 ± 2)%

> Remaining background still under investigation



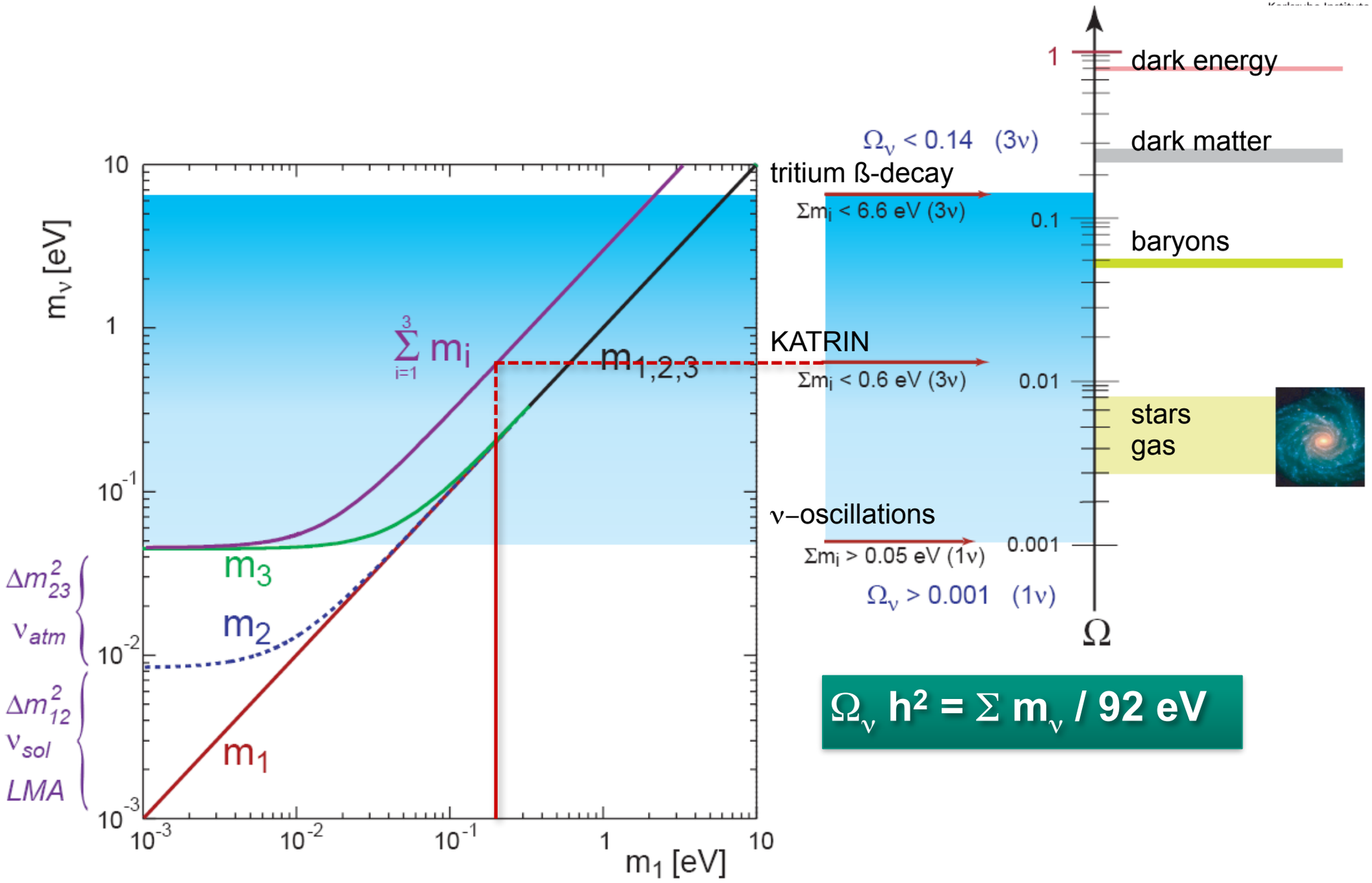
$$B_{total} = S_{Rn} + C_{Rn} + R$$

$$S_{Rn} = \alpha \cdot C_{Rn}$$

$$B_{total} = (\alpha+1) \cdot C_{Rn} + R$$

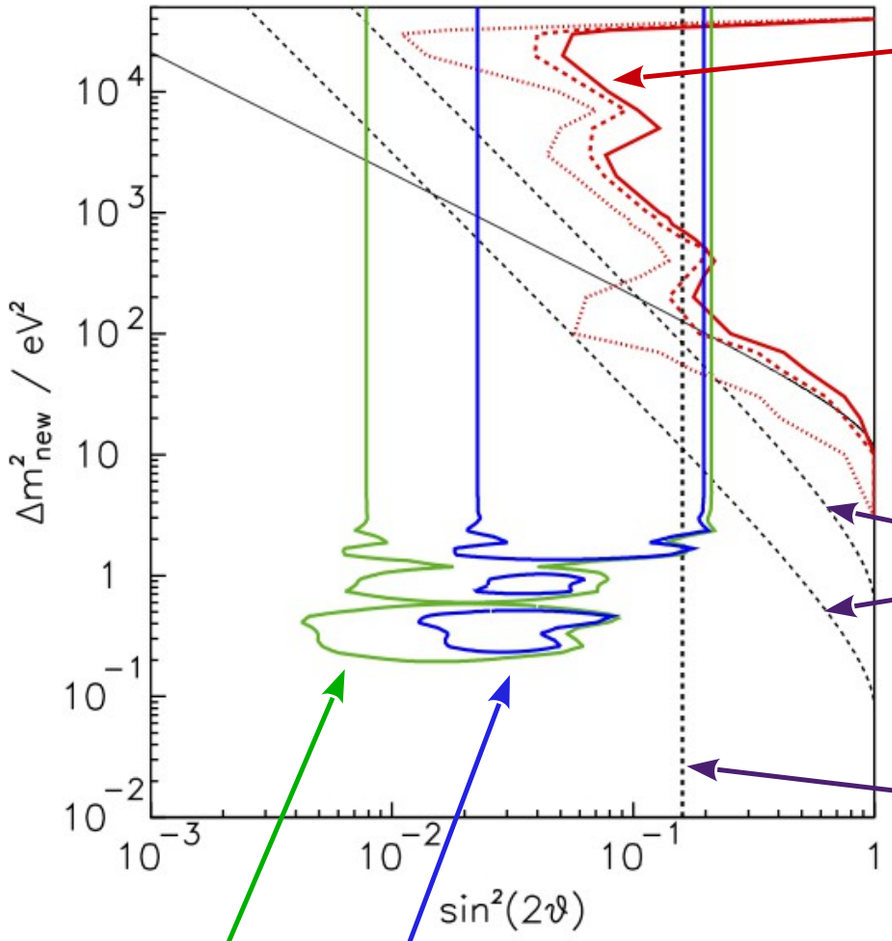
B_{total} : Total background rate
S_{Rn} : Radon-induced single event rate
C_{Rn} : Event rate in Radon-induced clusters
R : Non-Radon-induced bg rate

Neutrino masses in astroparticle physics



$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$

Search for eV-scale sterile ν: Mainz data



68%, 90%, 95% C.L.
Mainz exclusion region

EXO-200 data

solar + KamLAND osc. analysis

95% and 90% C.L. favoured regions, reactor ν anomaly

G. Mention et al., Phys. Rev. D 83 (2011) 073006

C. Kraus, A. Singer, KV, & C. Weinheimer, Eur. Phys. J C 73 (2013) 2323

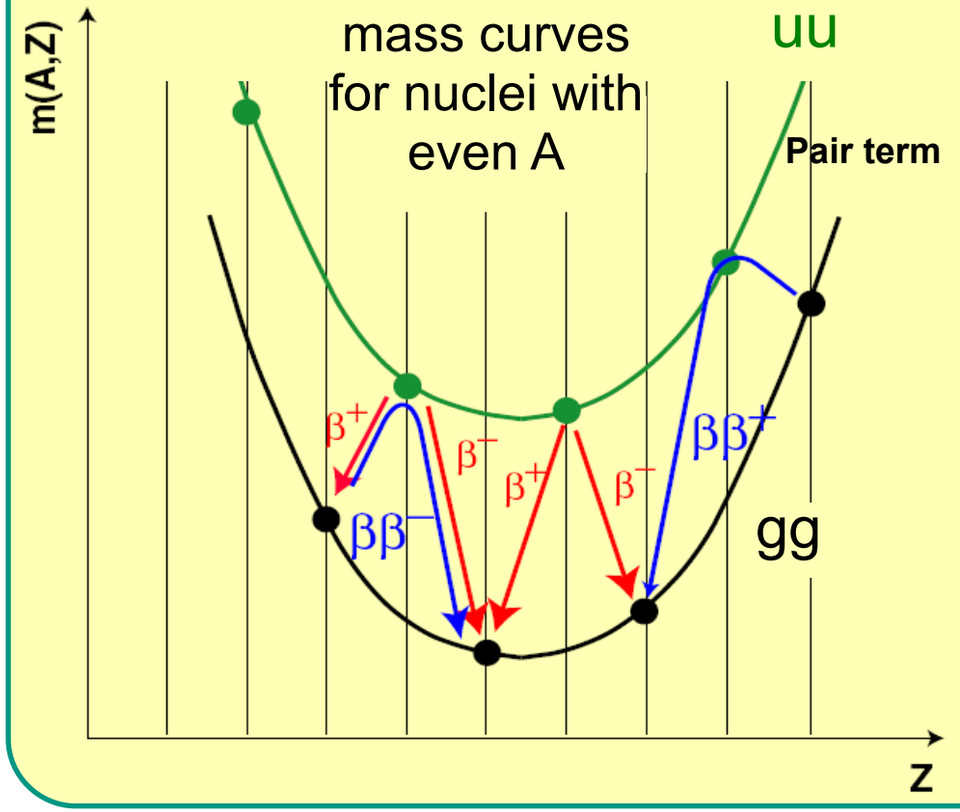
0νββ – nuclear physics aspects

Double beta-decay (2νββ & 0νββ): **only in even-even-nuclei**
where single β-decay energetically not possible
11 $\beta^-\beta^-$ isotopes with Q > 2 MeV are viable for 0νββ experiments

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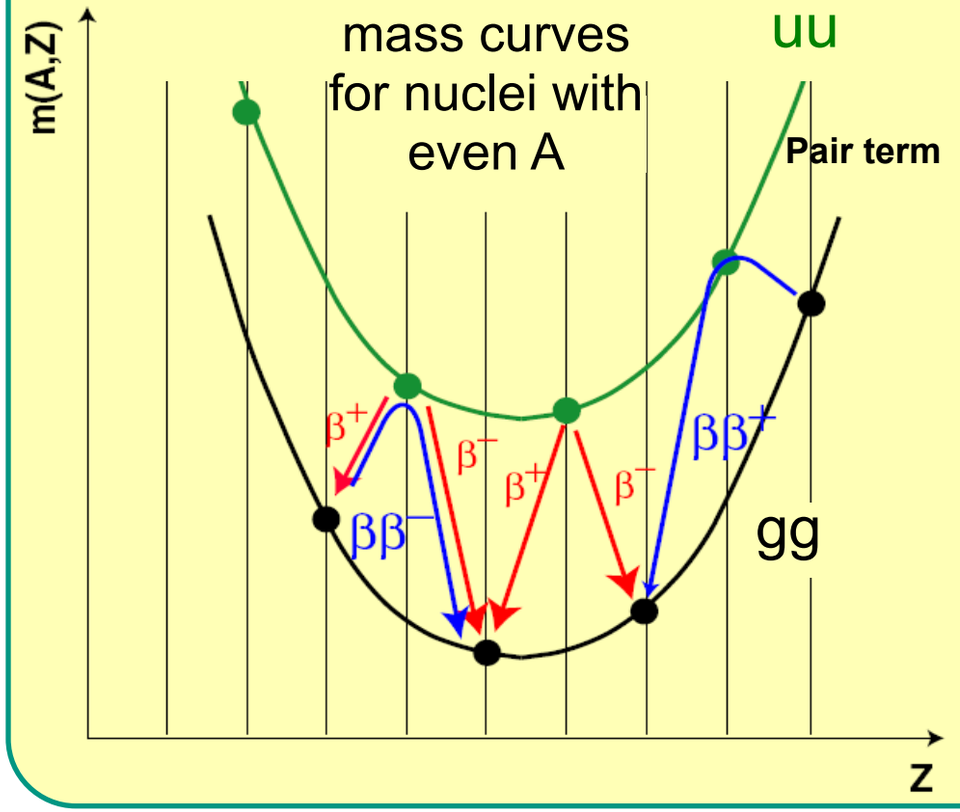
shell model: mass parabola for gg and uu nuclei (pair-term)



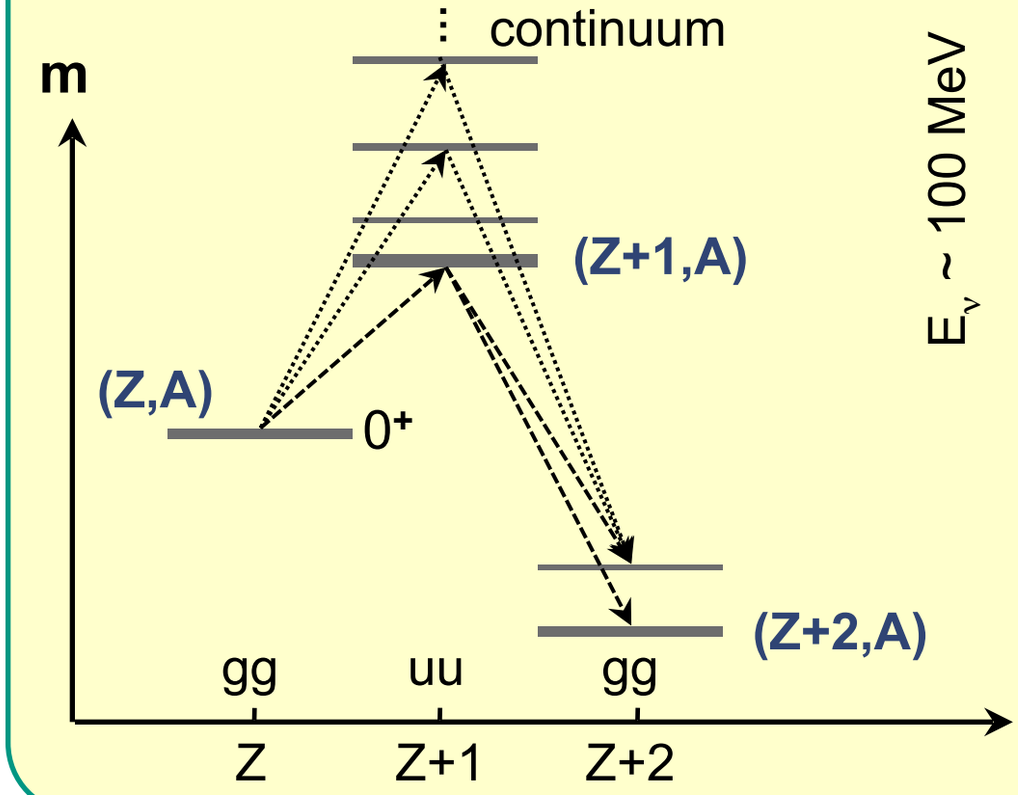
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excitation of nuclear levels in the virtual, intermediate (Z+1,A) level



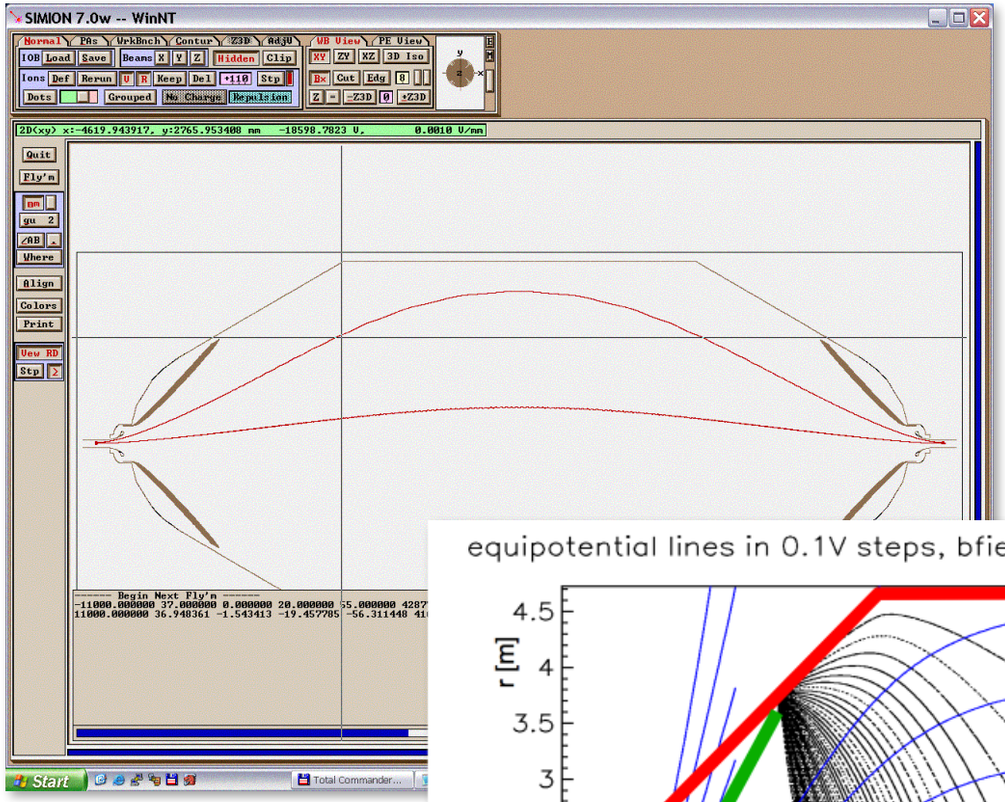


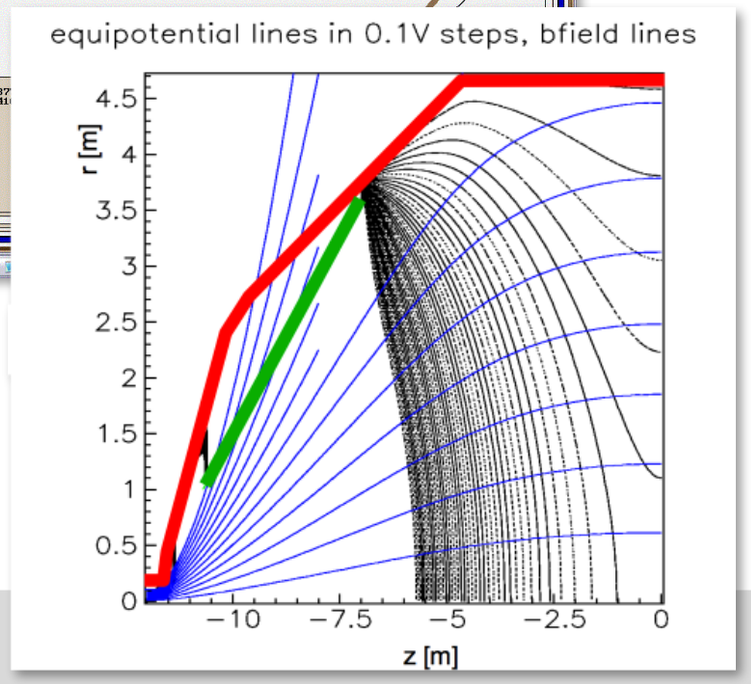
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REWIND

Astroteilchen-schule 2004

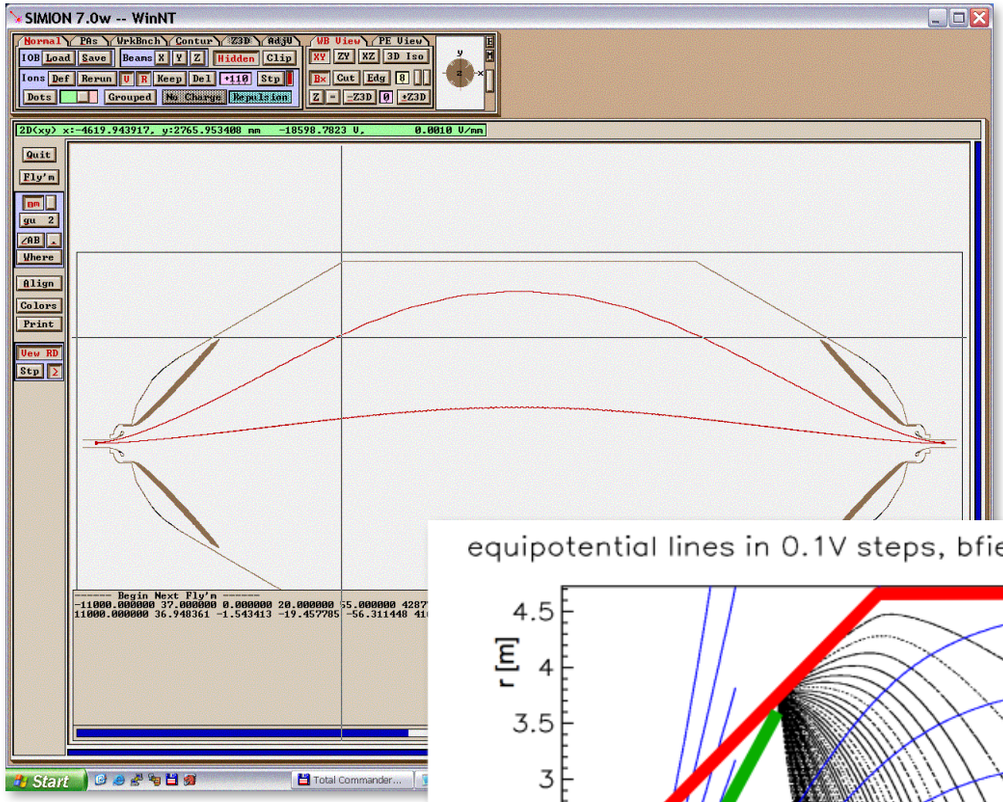
Karlsruhe Institute of Technology

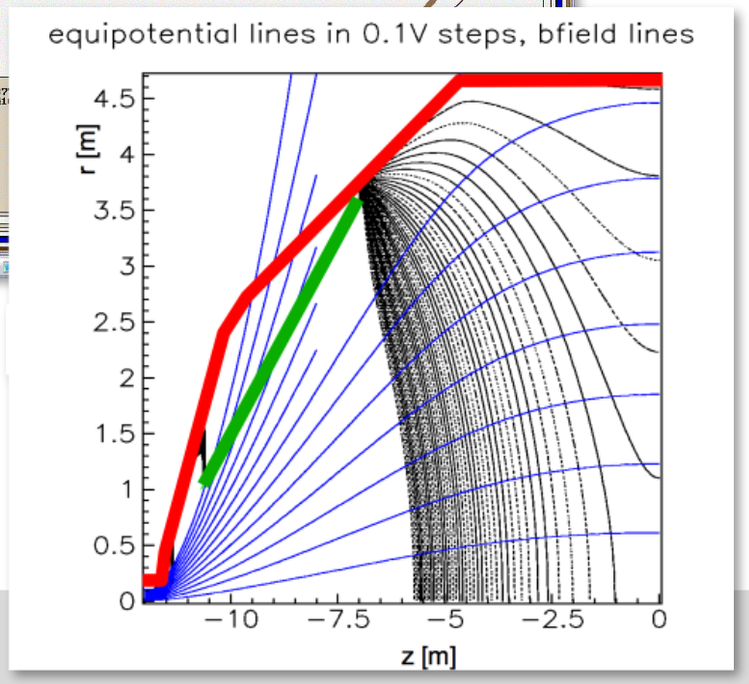




REWIND

Astroteilchen-schule 2004





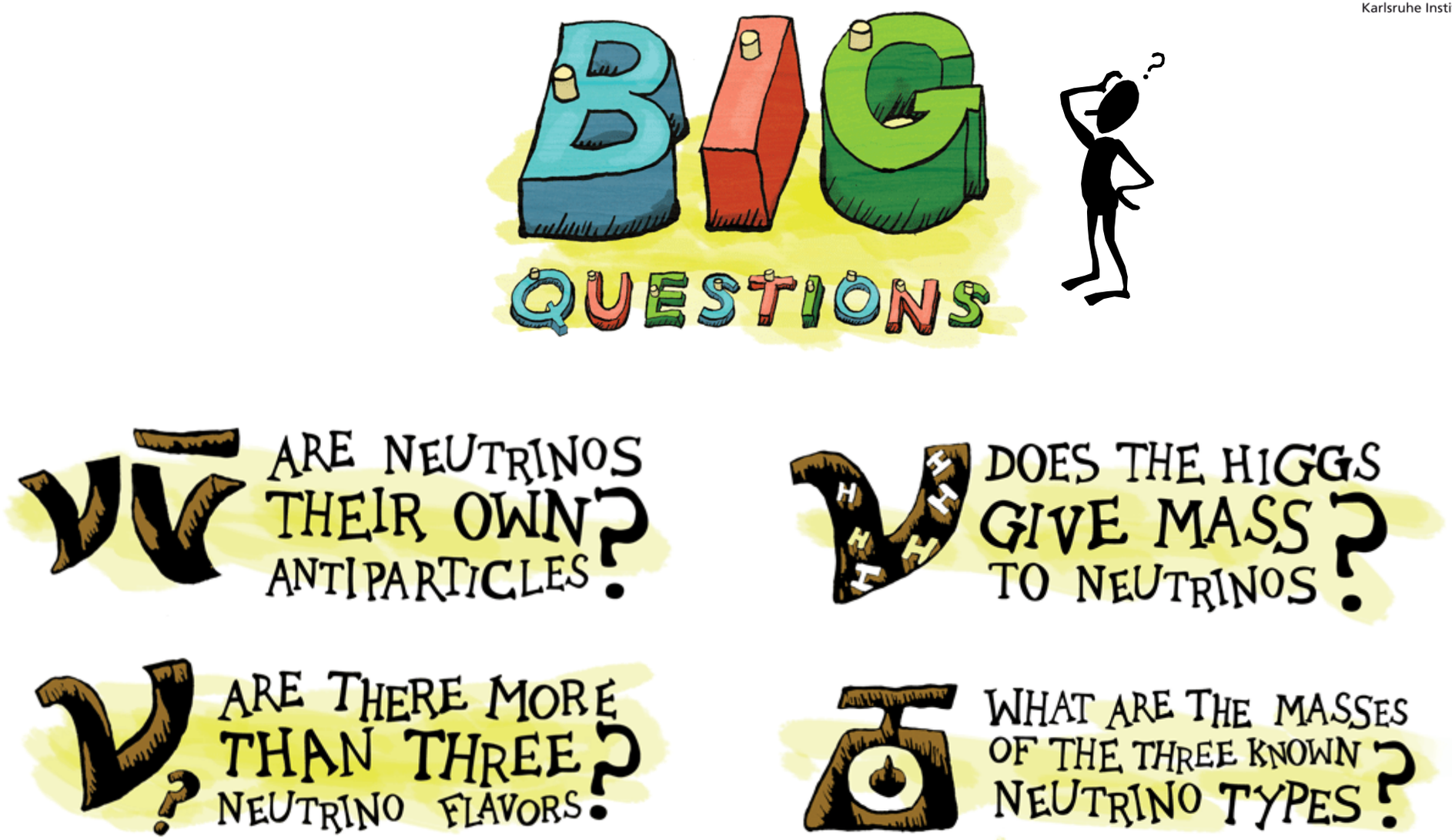
Astroteilchen-schule 2006





During Astroteilchenschule 2006:





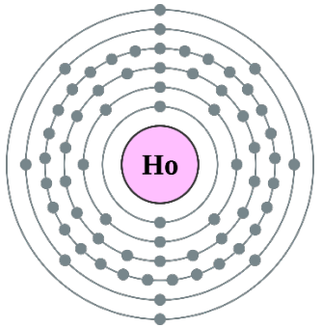
[symmetrymagazine.org]

Neutrino mass determination in EC: ^{163}Ho

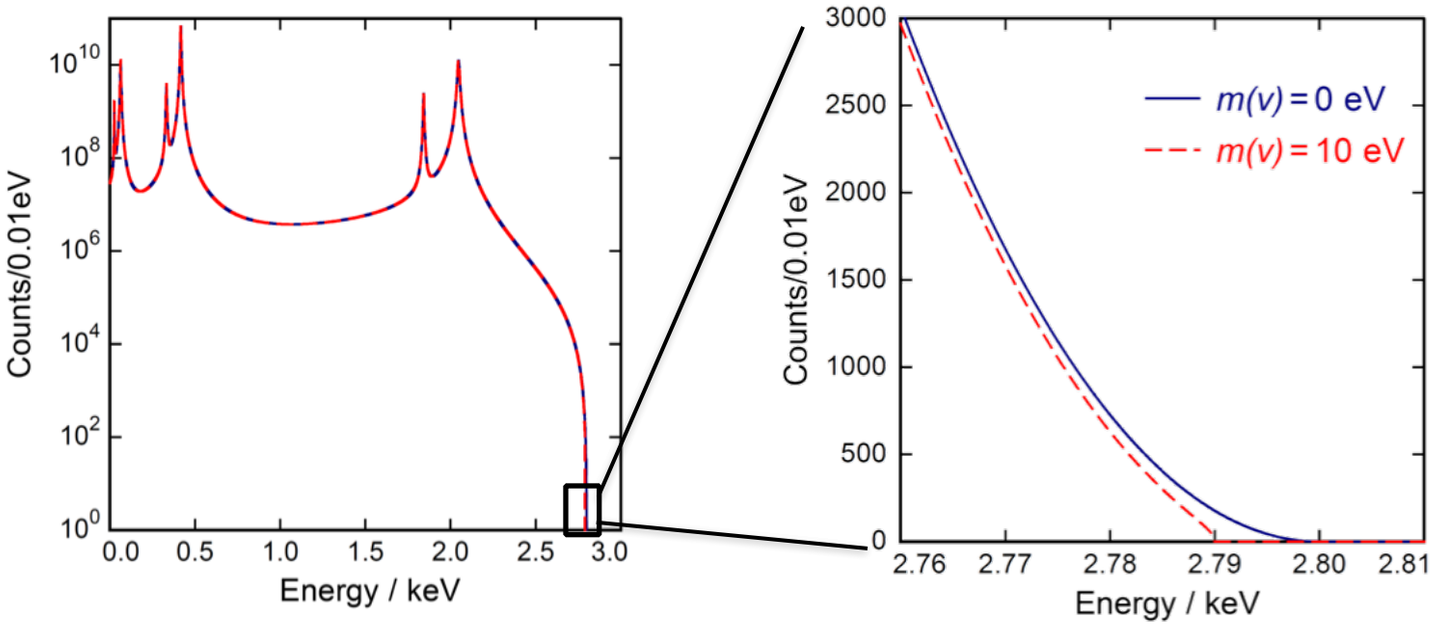
$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



- short $\tau_{1/2} \approx 4570$ a
- low $Q_{EC} \approx$ 2.3 … 2.8 keV
  (rec.: 2.555 ± 0.016 keV)

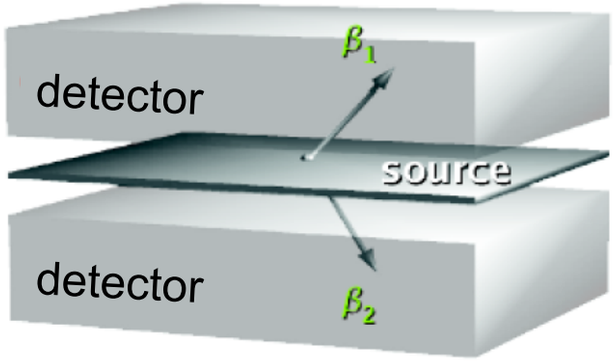


- **Non-zero m_ν** imprinted in de-excitation spectrum
- Atomic de-excitation (X-rays, Auger, Coster-Kronig) best measured by **calorimetry**

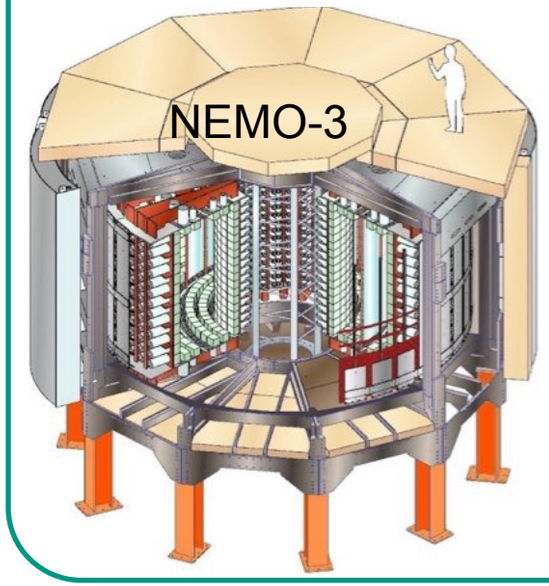
Experimental techniques

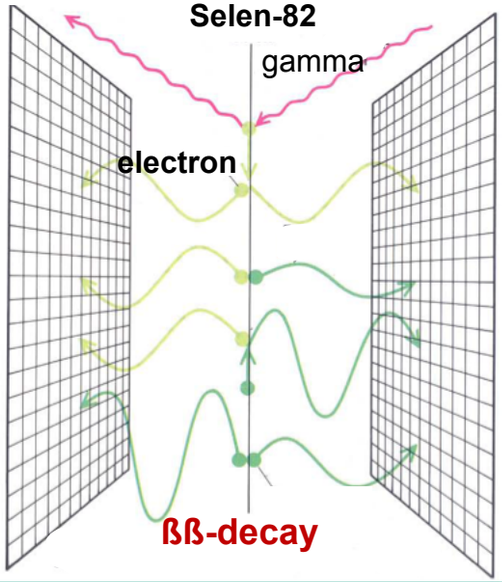
two generic techniques to detect 0νββ / 2νββ:

passive target: source ≠ detector

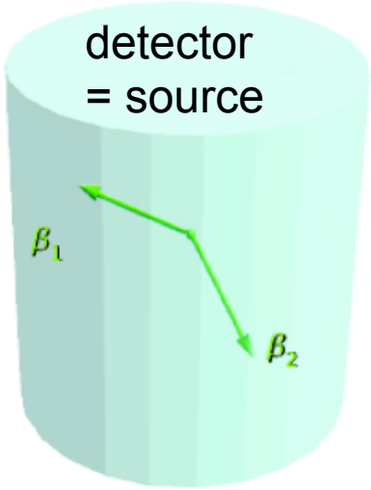


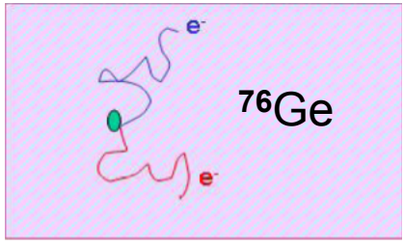
ββ-emitter
in thin foils





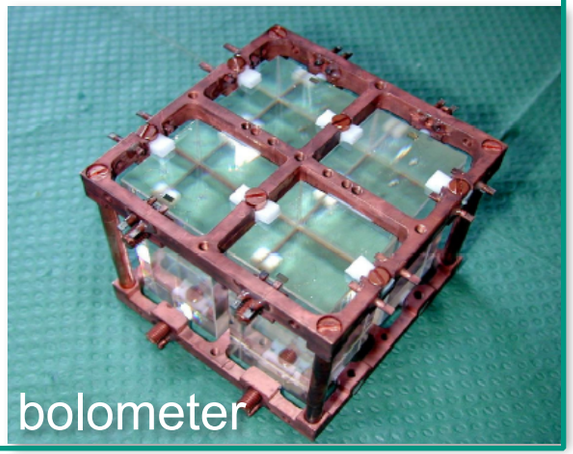
active target: source = detector





Ge-
diode



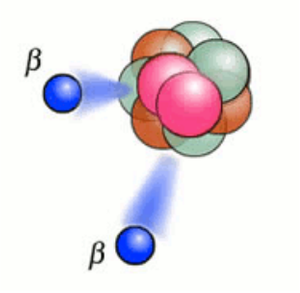


0νββ & Majorana mass $m_{ββ}$

$$\left\langle m_{\beta\beta} \right\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \cdot G^{0\nu\beta\beta}(E_0, Z) \cdot | M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} |^2 \right)^{-1}$$

experimental observable: $\mathbf{T_{1/2}}$ for 0νββ

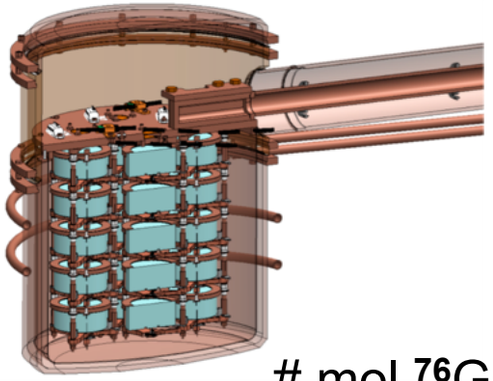
need: number of detected 0νββ events (N), live time (t),
number of 0νββ nuclei (mol), detection efficiency



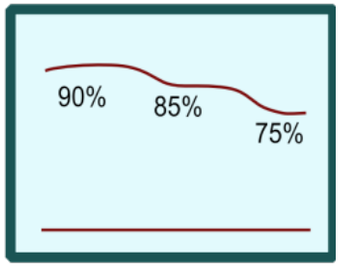
0νββ



live days



mol ^{76}Ge



ε efficiency (0 … 1)

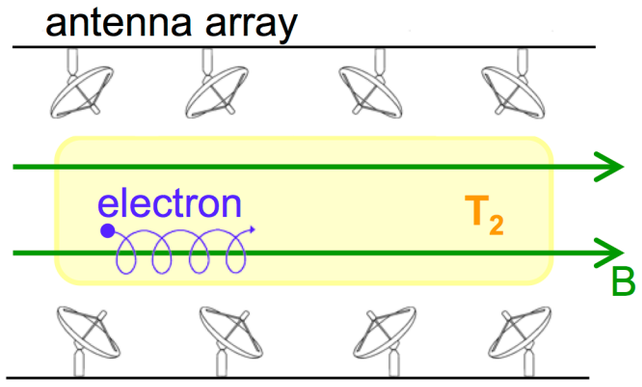
Cyclotron Radiation Emission Spectroscopy (CRES)



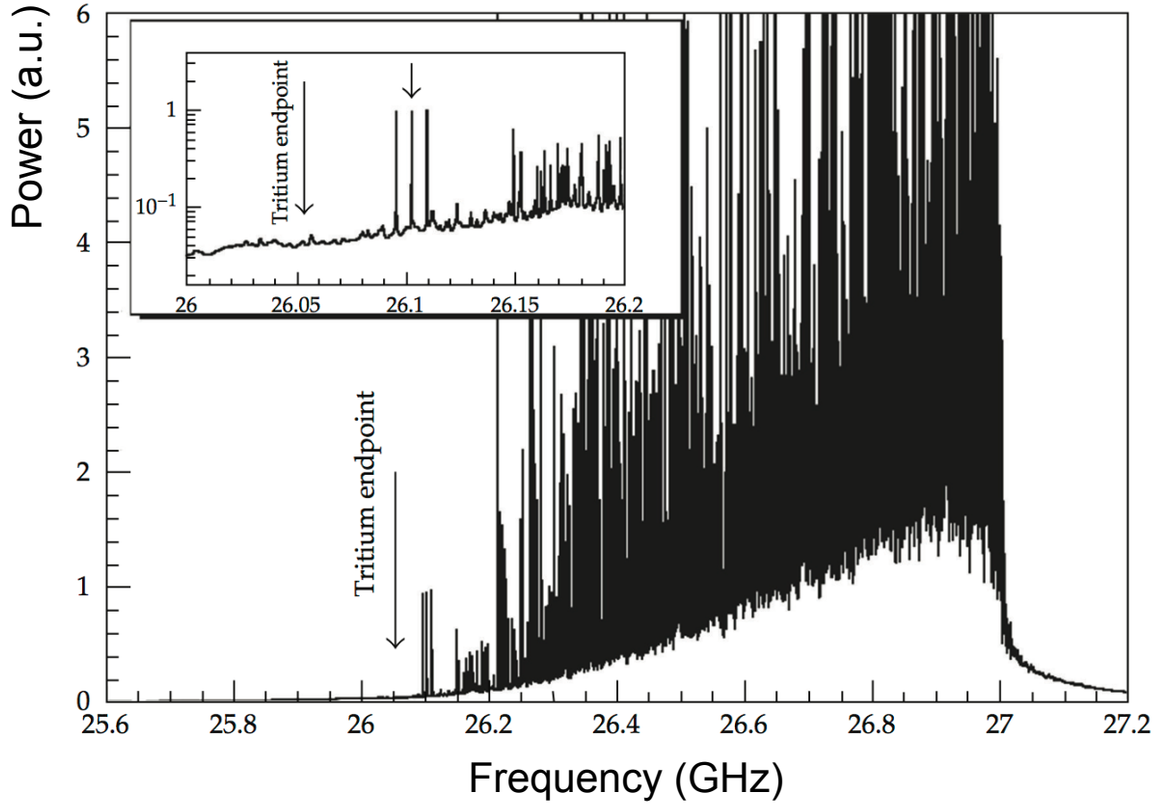
Energy measured via **cyclotron frequency** of single electrons in B field:

$$\omega_\gamma = \frac{\omega_c}{\gamma} = \frac{eB}{E_{kin} + m_e}$$

single electron
in trapping volume



β spectrum
10^5 simulated decays, B = 1 T



Formaggio & Monreal,
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