keV sterile neutrino detection with KATRIN

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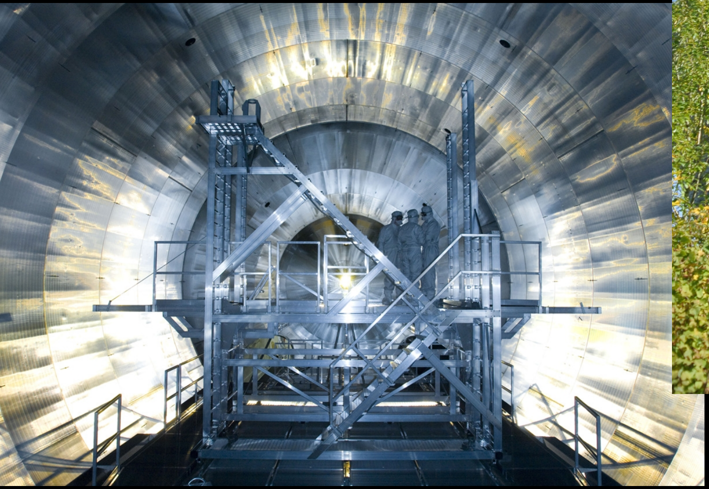
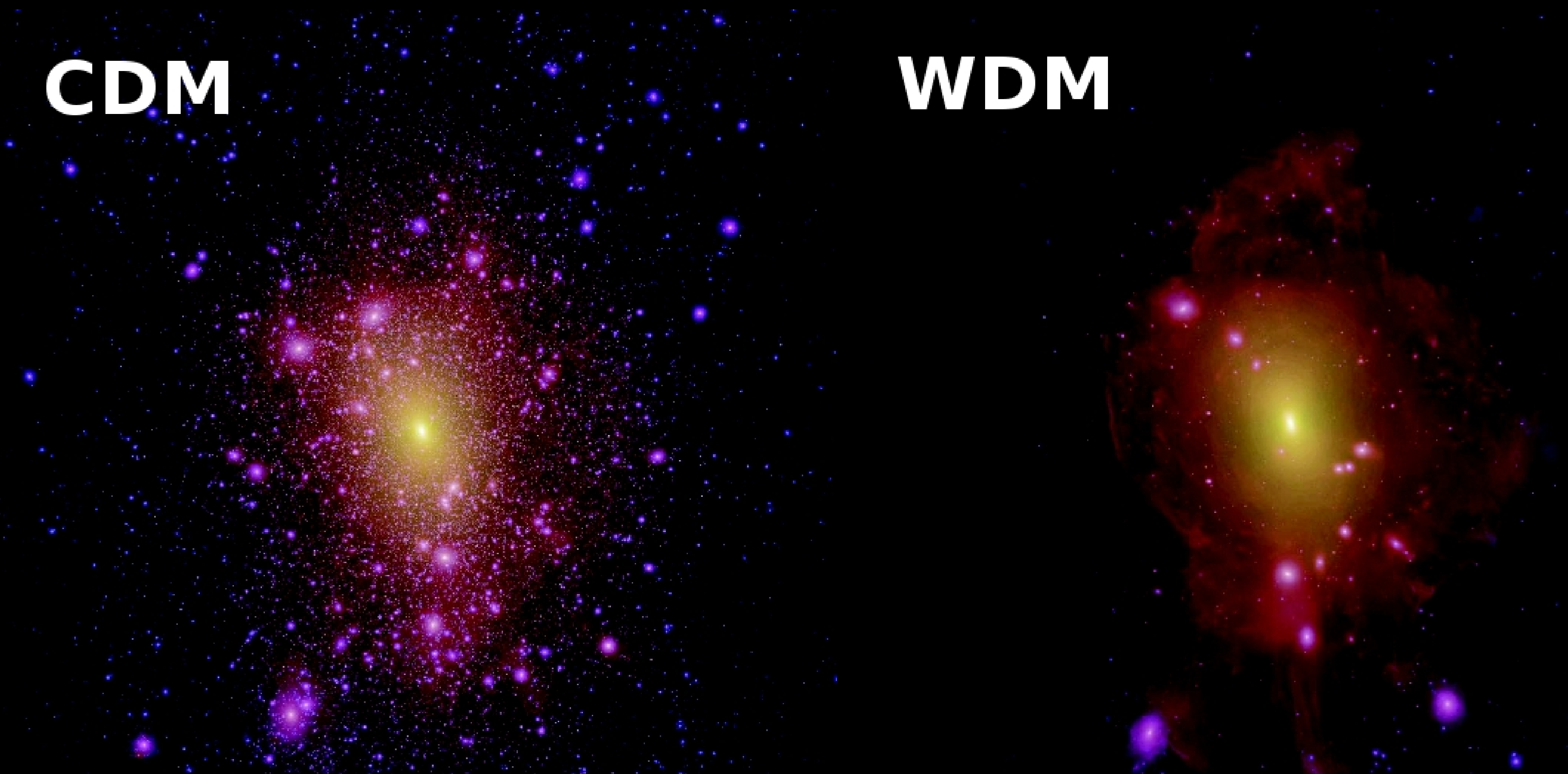


Schule für Astroteilchenphysik 2013
Obertrubach-Bärnfels

Is dark matter neither hot nor cold, but warm (WDM)?

Cold dark matter (CDM) predicts too much substructure

e.g. Anderhalden et al. 2013, http://arxiv.org/abs/1212.2967



Possible DM candidate: **sterile neutrino with ~ keV mass**

Picture: Lovell et al., CIAS Meudon Workshop 2012

Non trivial ν mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Active ν flavours | Unitary mixing matrix | Mass states

3 active ν plus a sterile ν

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & 0 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

New "flavour" state ν_s:
Right handed
No coupling to W and Z

3x3 sub-matrix
still unitary

4^{th} mass state
Identical to ν_s

Non vanishing mixing between active and sterile ν

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3x3 sub-matrix
not unitary any longer

=> oscillation between $\nu_{e/\mu/\tau}$ and ν_s possible

=> new mass state ν_4 mixes with active flavour states

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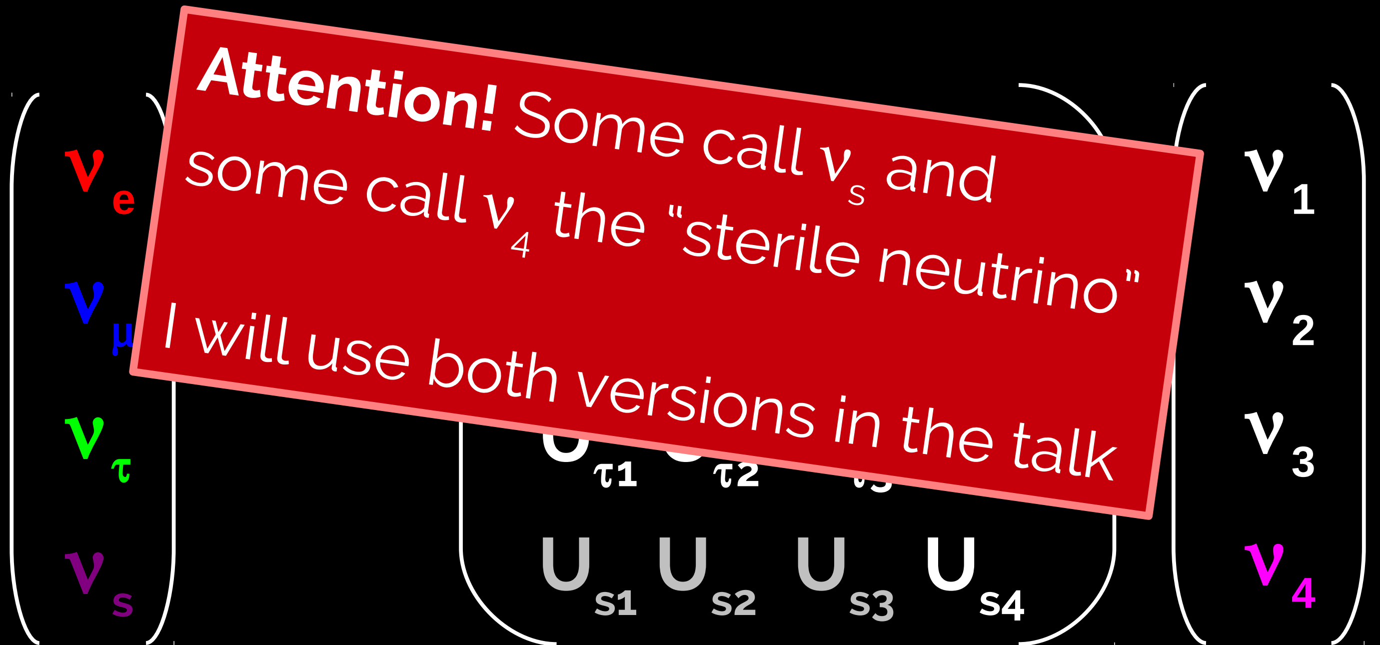

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Sterile ν mass scales

- **eV**:
  - favored for explaining reactor ν / LSND / MiniBoone anomalies
- **keV:**
  - favored as dark matter candidate
- **above:**
  - leptogenesis, GUT...

Example of model with 3 sterile ν:
Canetti, Drewes, Frossard, Shaposhnikov Phys. Rev. D 87, 093006 (2013), arXiv: 1208.4607

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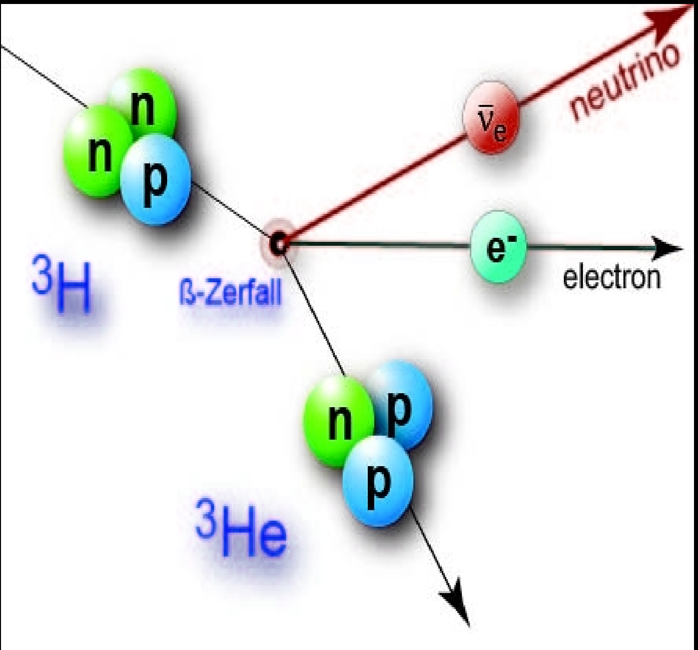
The tritium β spectrum

$$\frac{dR}{dE}(E) = N \frac{G_F^2}{2\pi^3 \hbar^7 c^5} \cos^2(\theta_C)|M|^2 \; F(E, Z')\cdot$$

$$p \cdot (E + m_e c^2) \cdot (E_0 - E) \cdot \sum_i^3 U_{ei} \sqrt{(E_0 - E)^2 - m(\nu_i)^2 c^4}$$



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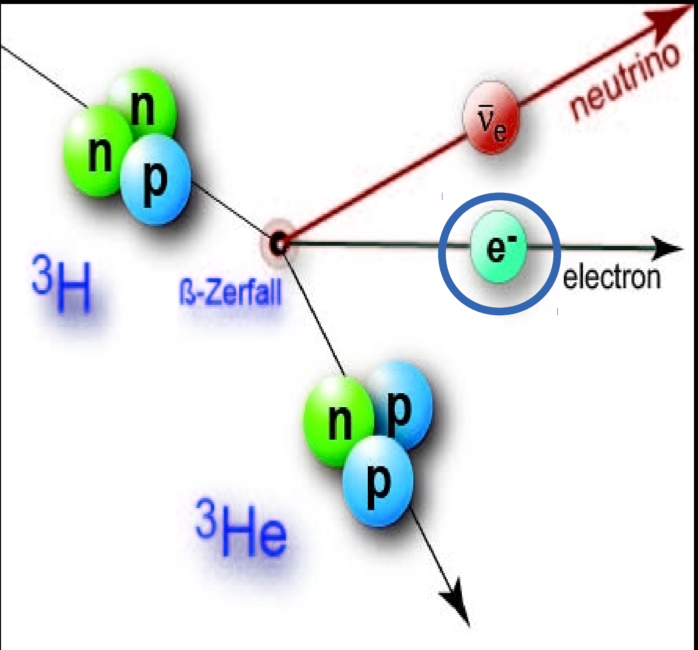

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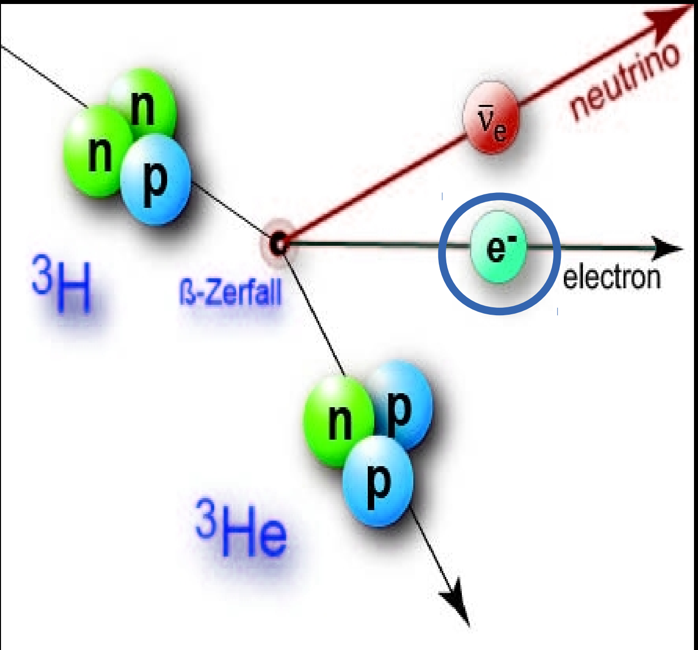
Def.: "electron neutrino mass"

$$m(\nu_e)^2 = \sum_i^3 |U_{ei}^2| m_i^2$$

$$\approx \sqrt{(E_0 - E)^2 - m(\nu_e)^2 c^4}$$



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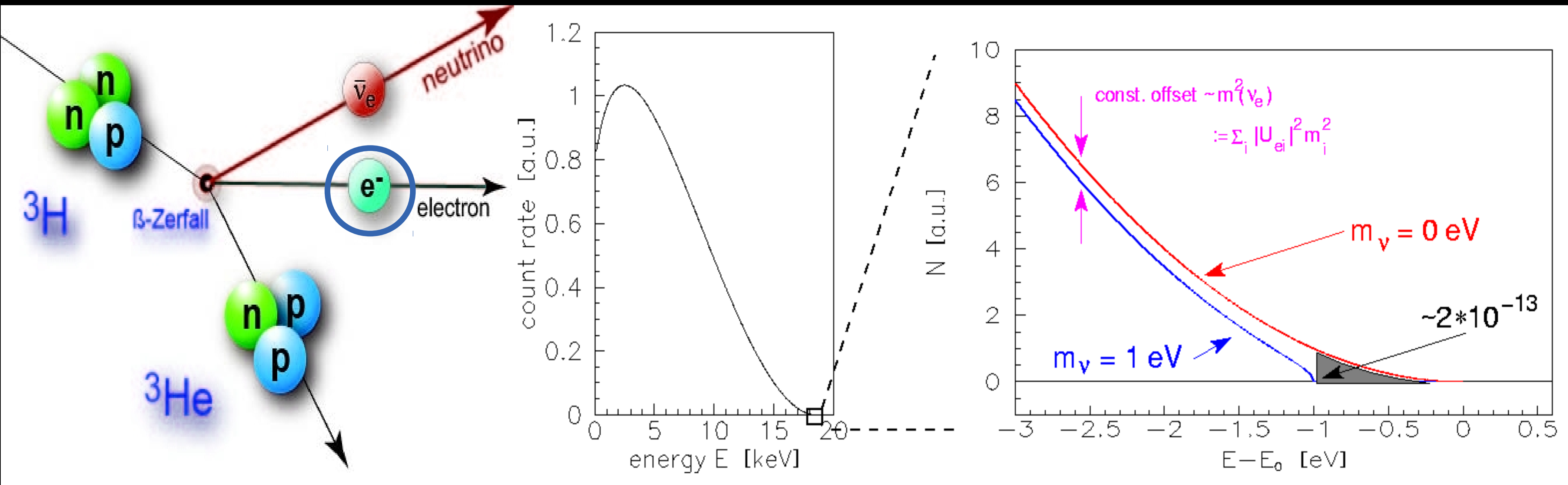
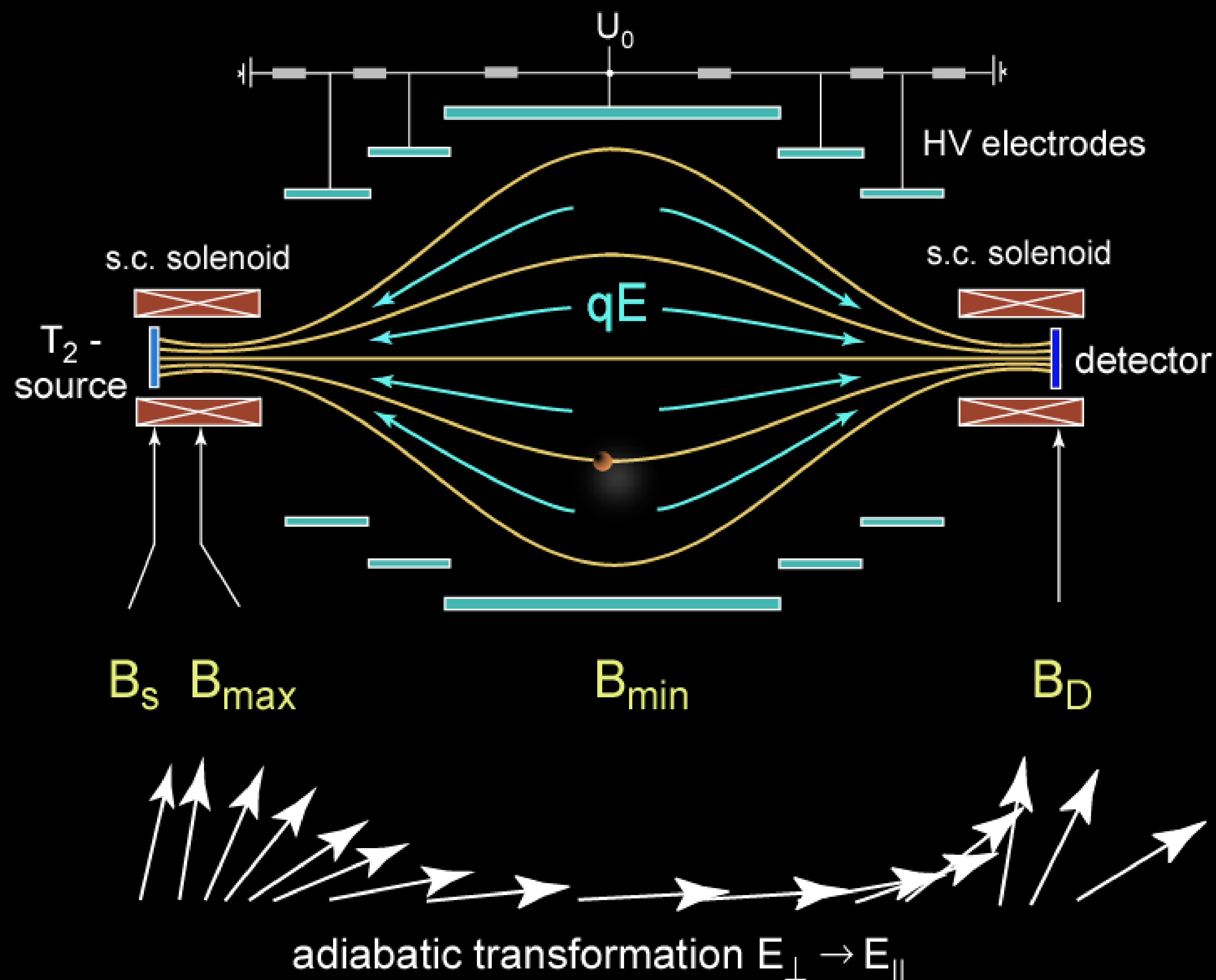


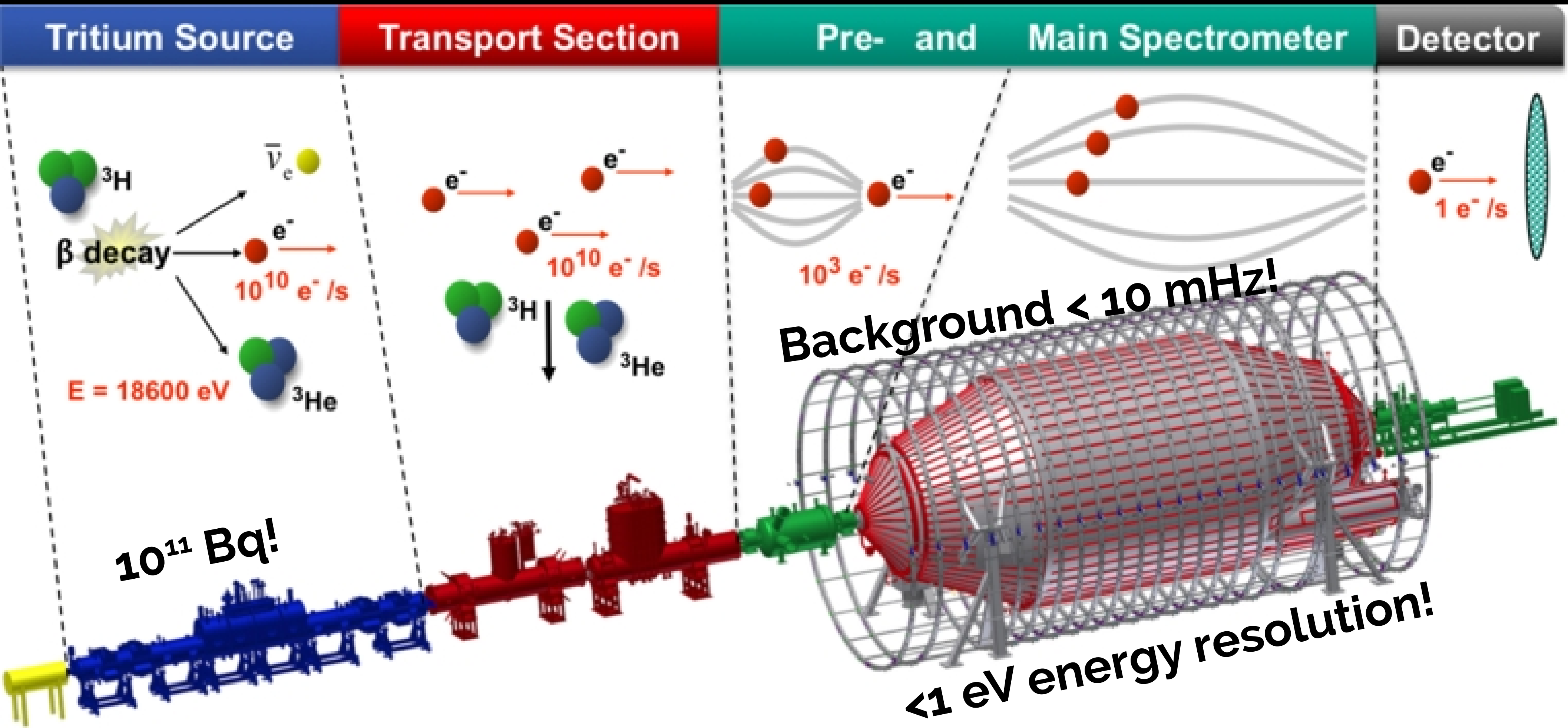
KATRIN

Design goal:
Measurement of $m(\nu_e)$ with
< 0.2 eV sensitivity (90% C.L.)

Measure endpoint region of β spectrum by electrostatic high pass filter (MAC-E-Filter)



KATRIN Components



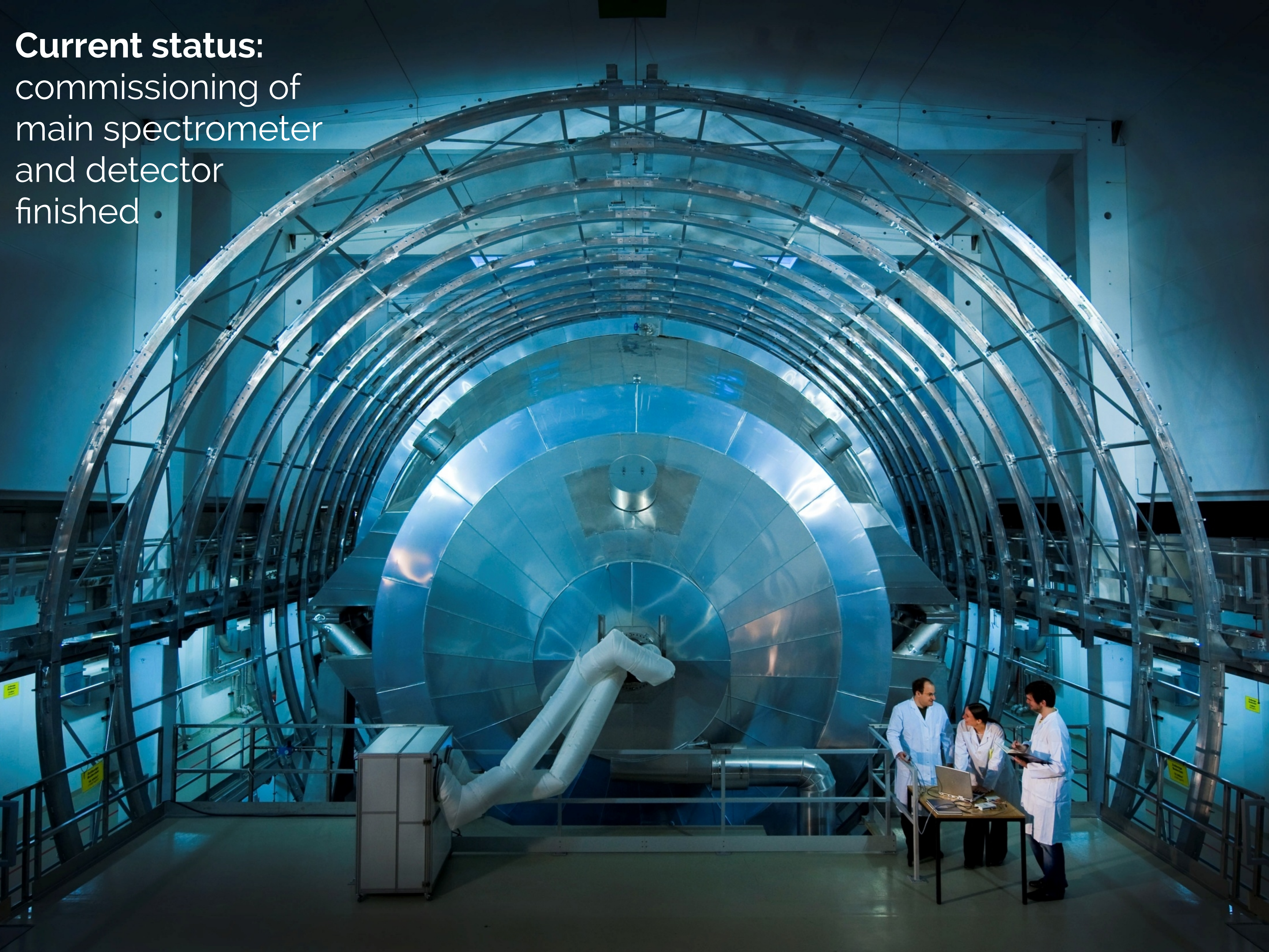
Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Current status:
commissioning of
main spectrometer
and detector
finished



β spectrum with 4th mass state

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$$\approx \cos\theta_4\sqrt{(E_0-E)^2-m(\nu_e)^2c^4}$$
$$+\sin\theta_4\sqrt{(E_0-E)^2-m(\nu_4)^2c^4}$$

θ_4: mixing angle between $\nu_{1/2/3}$ and ν_4

→ Linear combination of classic β spectrum and β spectrum with "heavy neutrino"

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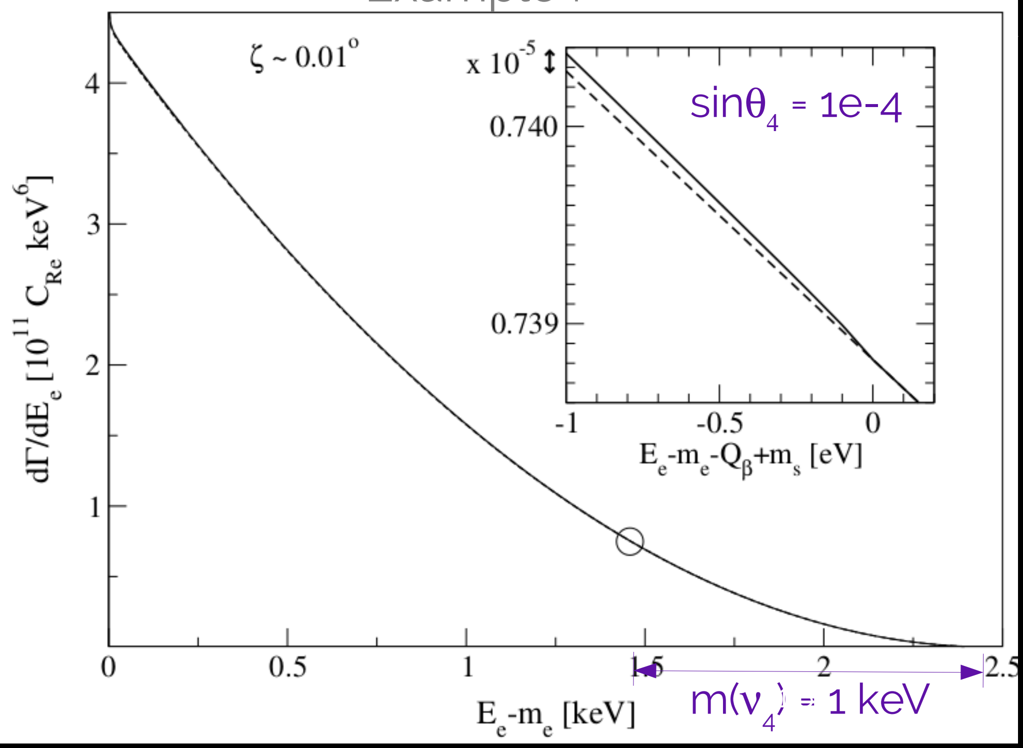
Example*:



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*) for ^{187}Re->^{187}Os,
de Vega et al., Nucl. Phys. B866 177-195 (2013), arXiv: 1109.3452

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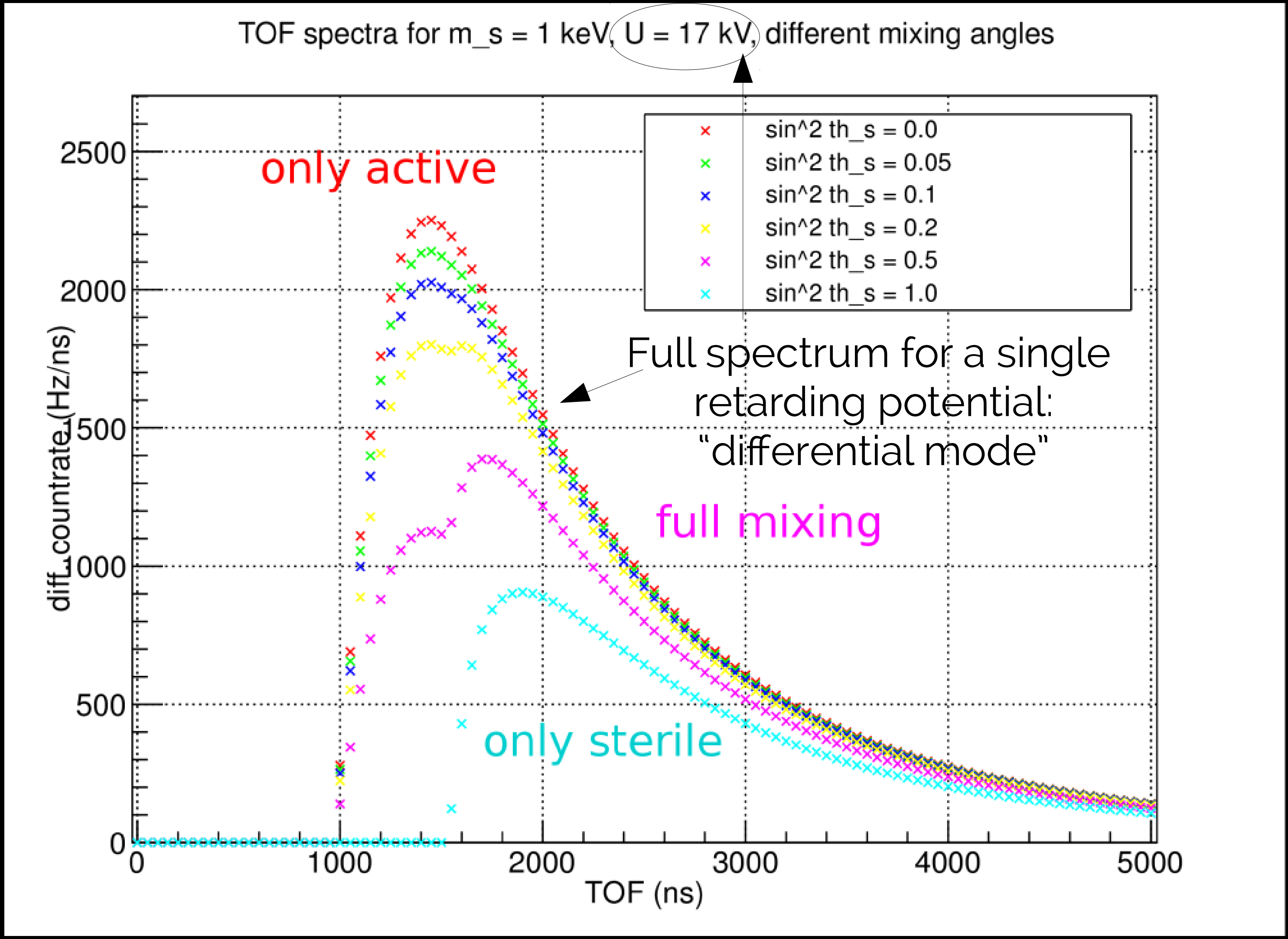
=> New stategy necessary!

Idea: Time-Of-Flight (TOF) mode

TOF function of energy <=> TOF spectrum function of β spectrum

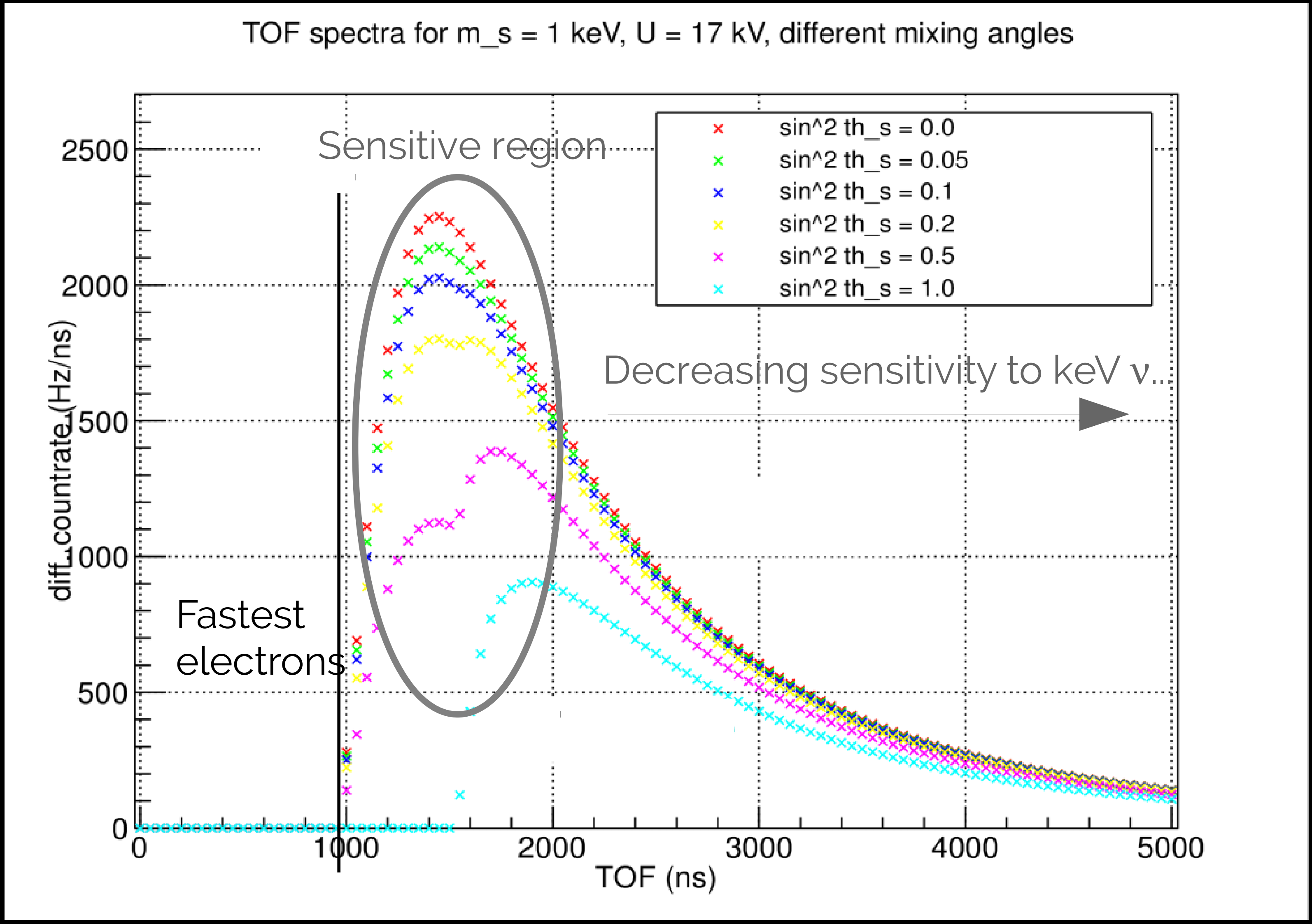


For active ν: potential mass sensitivity improvement (stat) up to factor 2!

(NSt, Christian Weinheimer et al., 2013, arXiv:1308.0532, submitted to NJP)

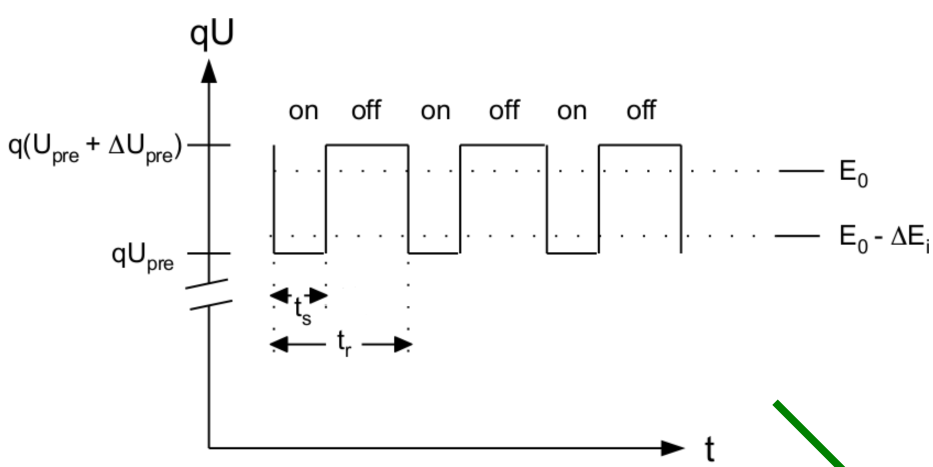
'Band pass' like behavior of TOF

Can distinguish ν_4 sensitive parts from higher energy parts!



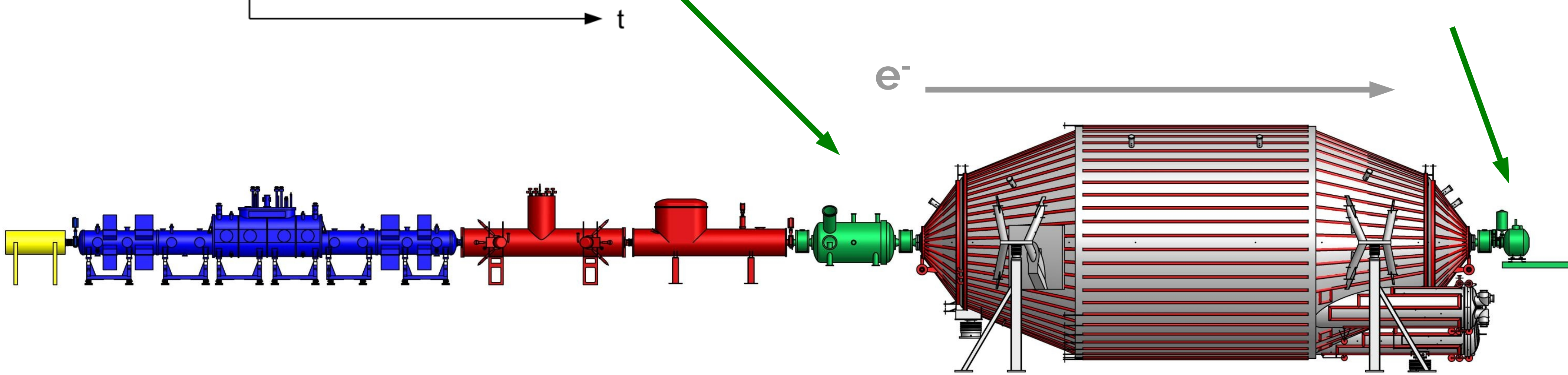
TOF measurement: gated filter

1) Pulse pre-spectrometer potential with narrow duty cycle
→ e^- pass during 'on' cycles



Disadvantage:
Loss of count rate.
But statistics no problem
(S. Mertens et al., t.b.p.)

2) Measure time-of-arrival at detector



MC simulations needed!

Systematics...

Parameter optimization...

Statistics...

Sensitivity of KATRIN-TOF to keV sterile ν

Conclusion

- Sterile keV neutrino is DM candidate
- KATRIN may be sensitive to indirect detection
- TOF mode may improve sensitivity
- Sensitivity to be simulated

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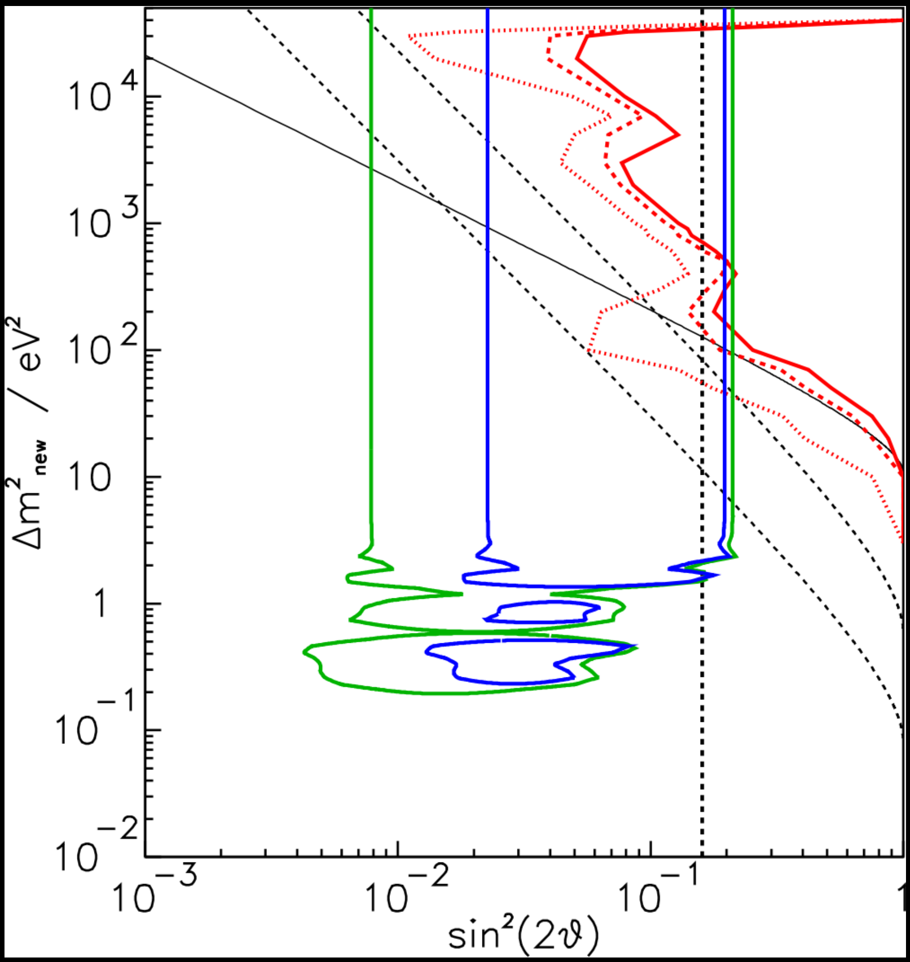
Backup Slides

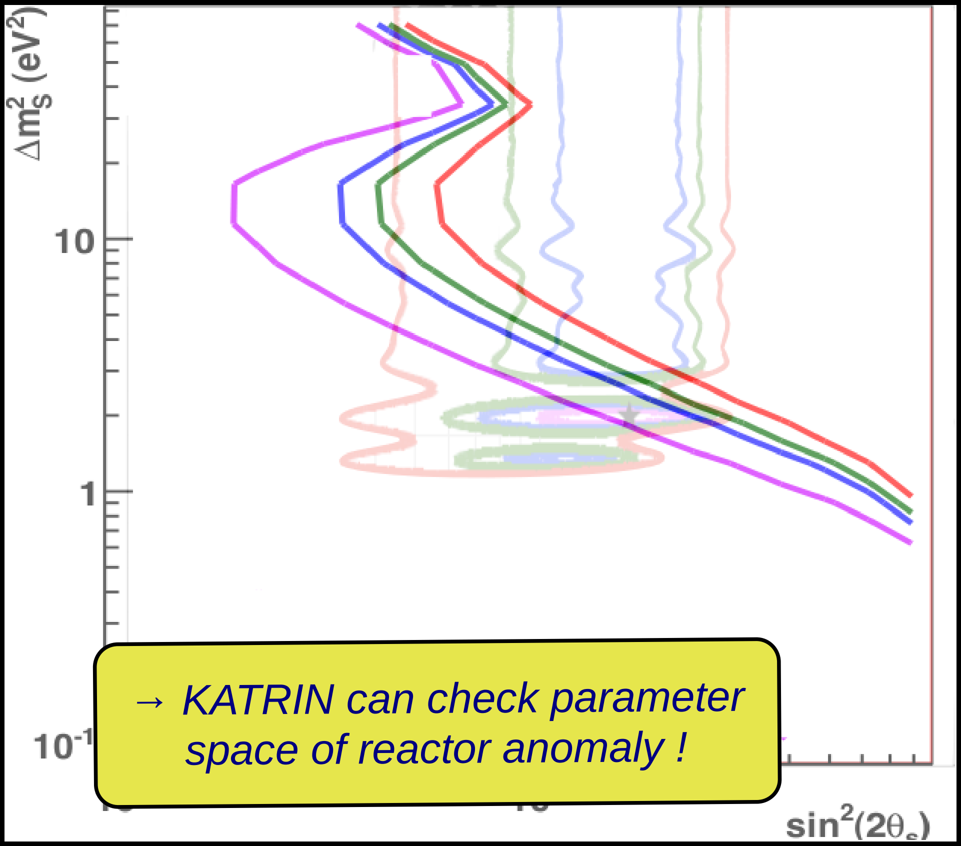
Sensitivity to light sterile ν

MAINZ



Ch. Kraus, A. Singer, K. Valerius, C. Weinheimer, arXiv.1210.4194, Eur. Phys. J. C73 (2013)

KATRIN



J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

Classic integrated vs. differential spectrum

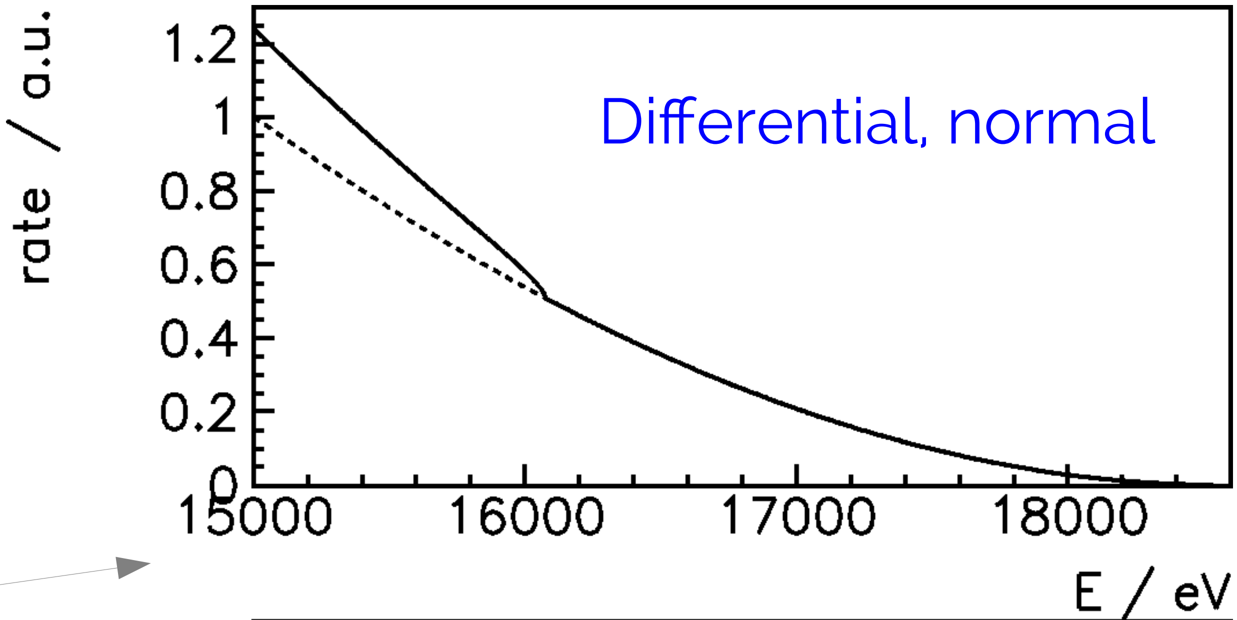
→ Obviously much better signal-to-background-ratio for differential β-spectrum w.r.t. integrated β-spectrum

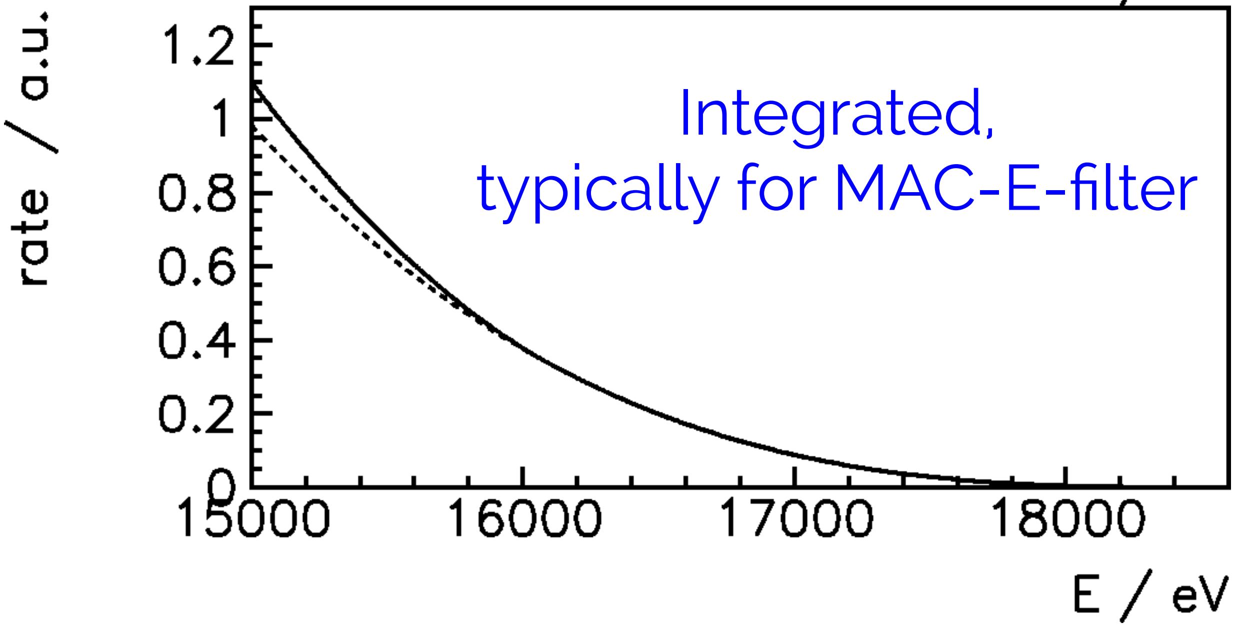
Example:

$m(\nu_s) = 2.5$ keV

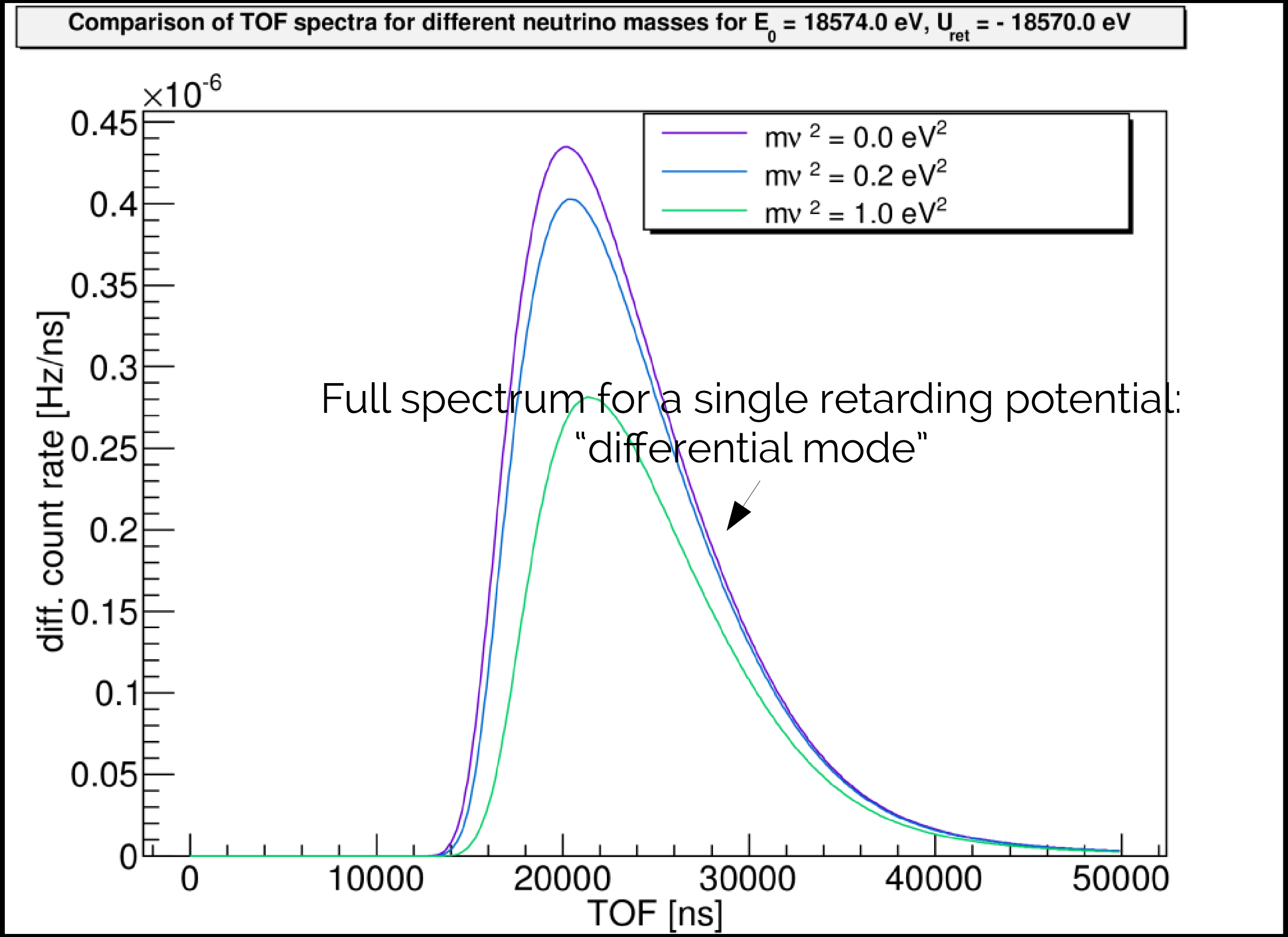
$\sin^2(\theta) = 0.25$

(unrealistic!)





Neutrino mass dependence of TOF mode



Potential mass sensitivity improvement (stat) up to factor 2!
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