Neutrinos from Outa Space – Recent Results from IceCube

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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Obertrubach-Bärnfels, 11.10.2014

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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Outline

- A century-old mystery and the cosmic-ray−neutrino connection
- How to detect high-energy neutrinos?
- IceCube − A neutrino observatory at the South Pole
- Recent astrophysical neutrino results from IceCube
- Cosmic-ray physics with IceCube and IceTop
- Looking into the future

1912: Discovery of cosmic rays (Victor Hess)

Observations before 1912:

- Electroscopes discharge due to natural radioactivity

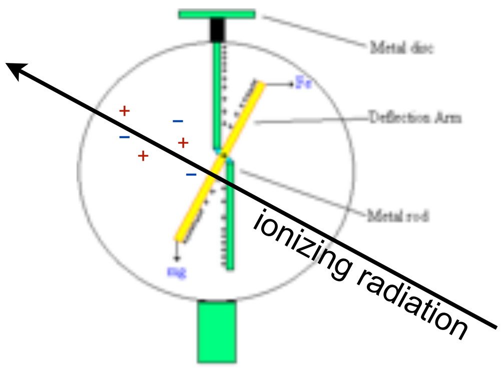
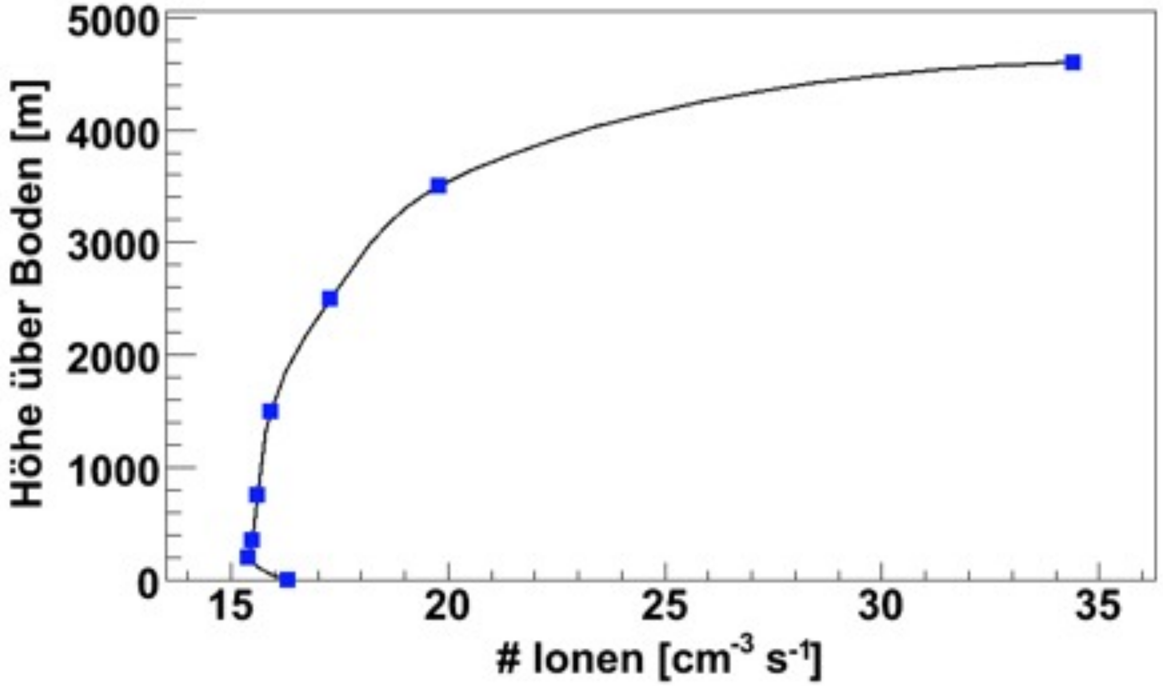


Figure 1: Electroscope

Balloon experiments since 1912: (Hess, Kolhörster)

- Discharge increases above ~1.5 km altitude
- Conclusion: ionizing radiation from outer space → “Cosmic Rays” (Millikan)

Measurements Victor Hess (1912)



. . . 101 years later

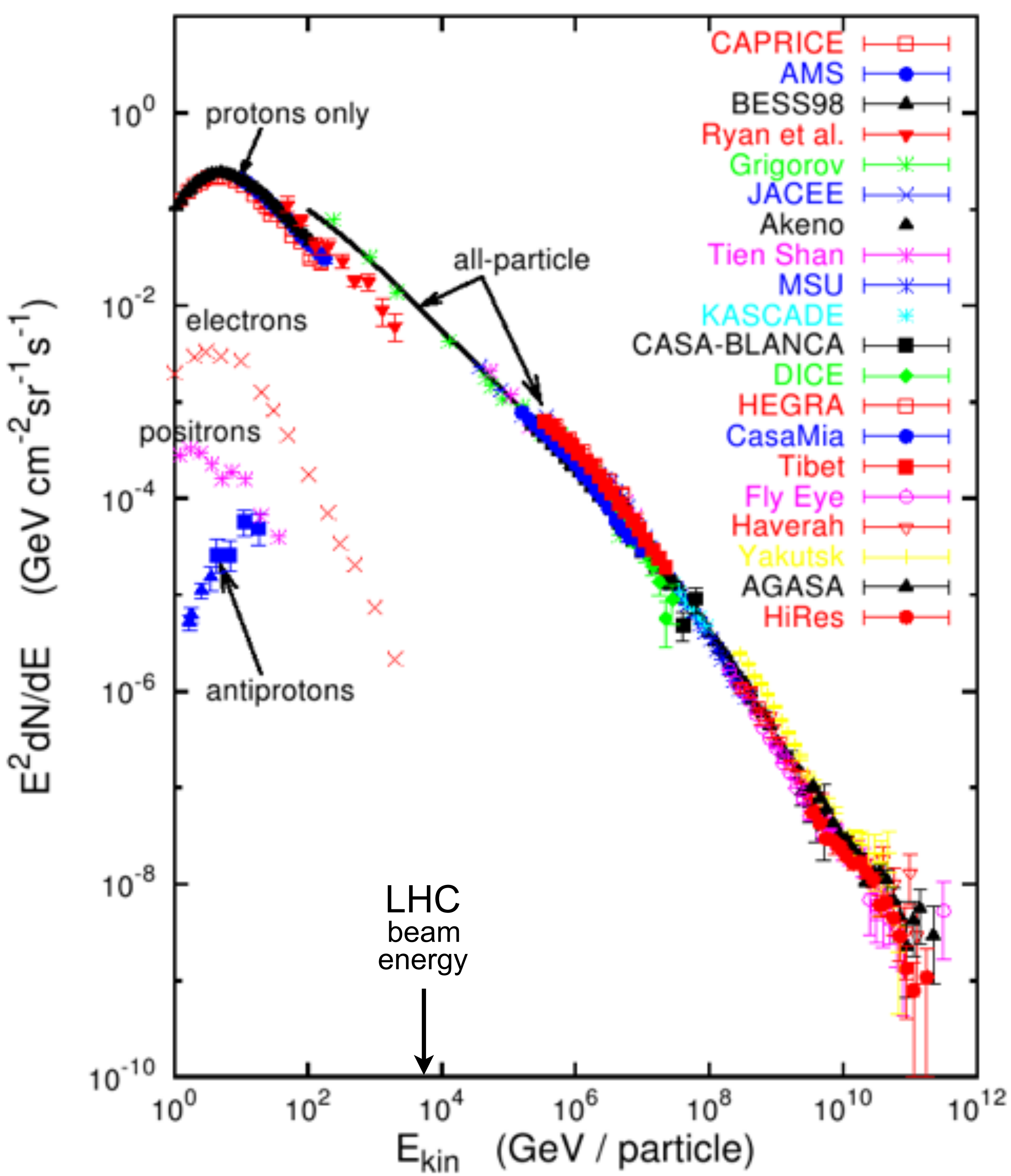
- Measured over 12 orders of magnitude in energy
- Consists of particles → dominated by protons at lower energies
- Power law spectrum (non thermal) with two breaks

  Interpretation:
  - Galactic sources ≲ 10^7 GeV
  - Extragalactic sources ≳ $5{\times}10^9$ GeV

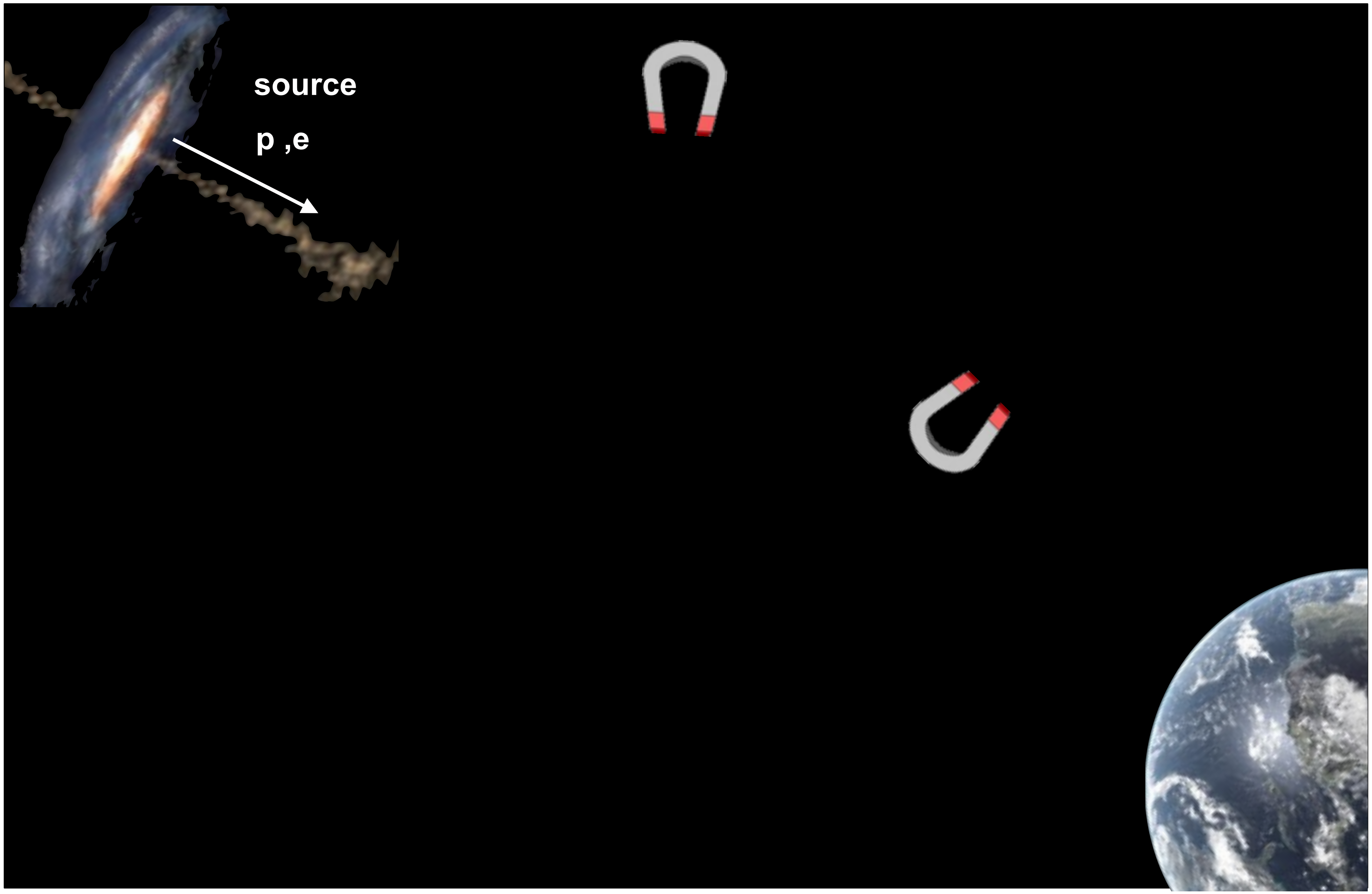
Questions:

- What is the composition and does it change with energy?
- What are the sources and how are particles accelerated?

Cosmic ray spectrum



What are the sources?



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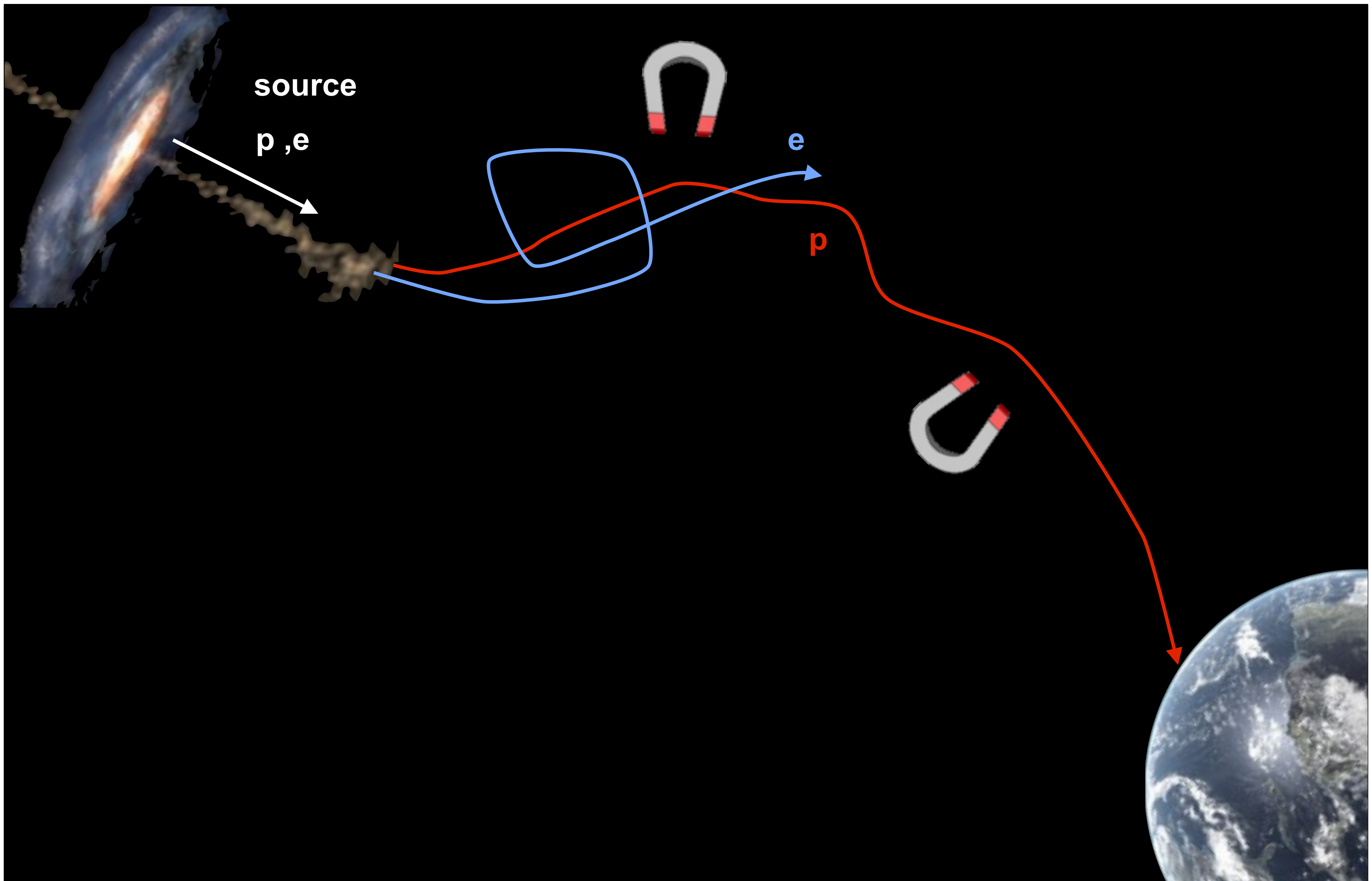
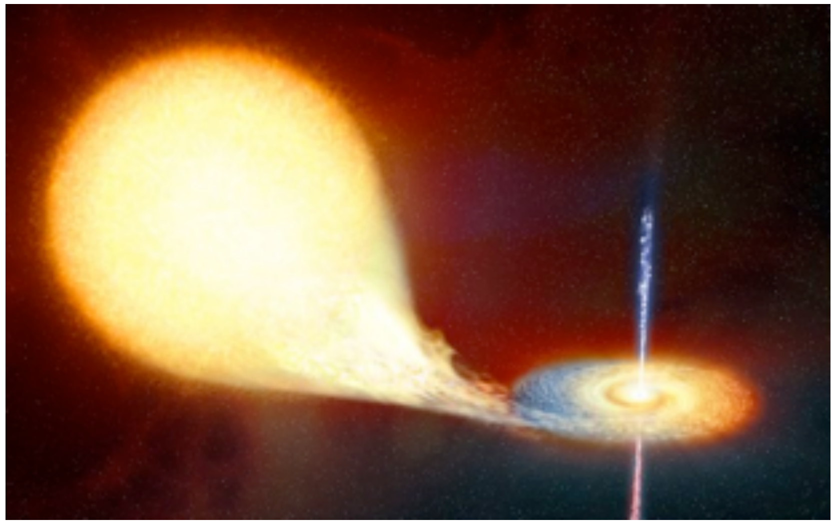


Examples of source candidates

Galactic

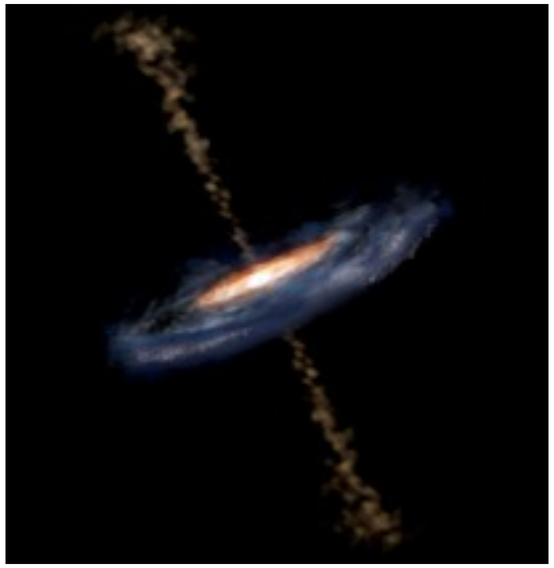
supernova remnants
(SN1006, optical, radio, X-ray)

binary
(artist's view)

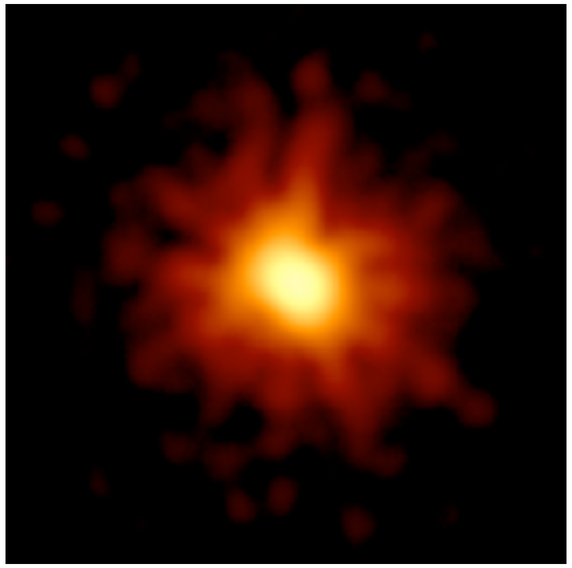


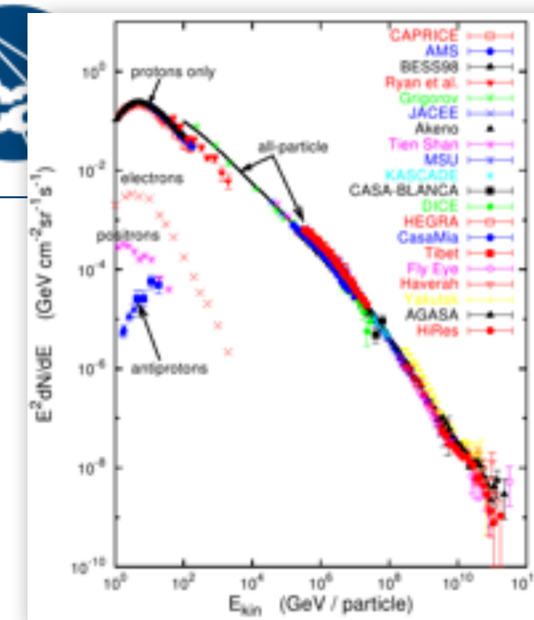
extragalactic

active galactic nuclei
(artist's view)



gamma-ray bursts
(GRB 080319B, X-ray, SWIFT)





Energy budget for cosmic rays

Galactic cosmic rays

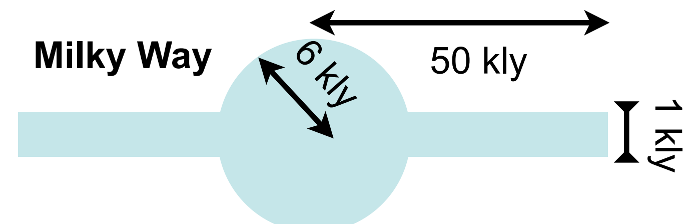
- energy density ~10^{-19} J cm^{-3}
  storage time in Milky Way ~3×10^6 yr

  } injection rate
  dE$_{CR}$/dt ~10^{-33} J cm^{-3} s^{-1}

- preferred candidates: supernovae

  released energy (no ν's) ~10^{44} J
  rate ~2−3 per century

  → **dE$_{SN}$/dt** ~ 10^{-32} J cm^{-3} s^{-1} **≈ 10 × dE$_{CR}$/dt**



volume ≈ 10^{67} cm^3

Extragalactic cosmic rays

- energy density above ankle (3 EeV) ~10^{-26} J cm^{-3}
  → injected energy over age of Universe (10^{10} yr) ~10^{37} J Mpc^{-3} yr^{-1}

- corresponds to ~10^{37} J s^{-1} per active galactic nuclei
  ~10^{45} J per gamma-ray burst

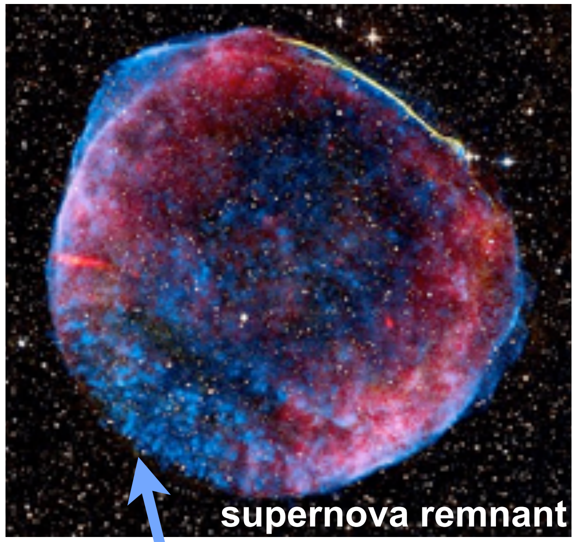
  } best (only) candidates

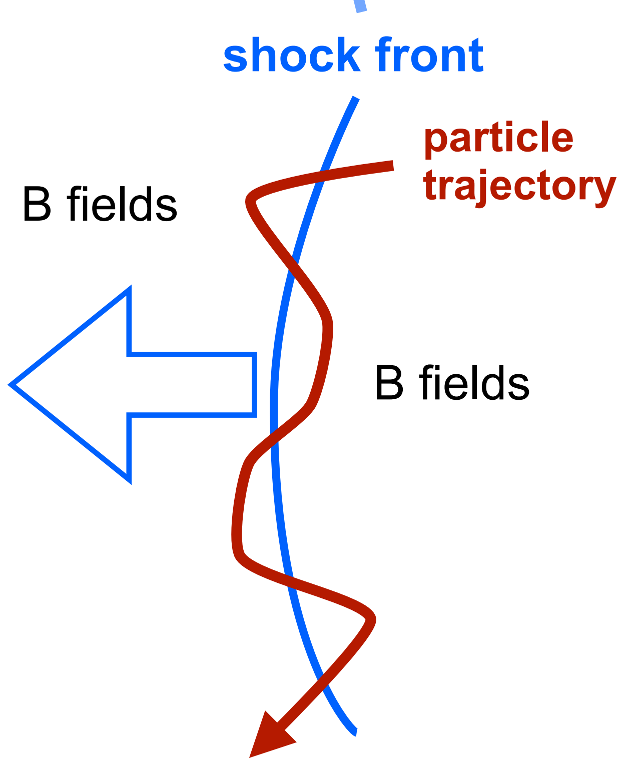
How are particles accelerated?

- Many cosmic objects involve **strong shocks** e.g. supernova remnants, micro-quasars, active galactic nuclei, gamma-ray bursts

- Fermi acceleration (circular process):
  - energy gain by “reflections” on magnetic fields
  - yields power law + required energies achievable

SN1006
(optical, radio, X-ray)





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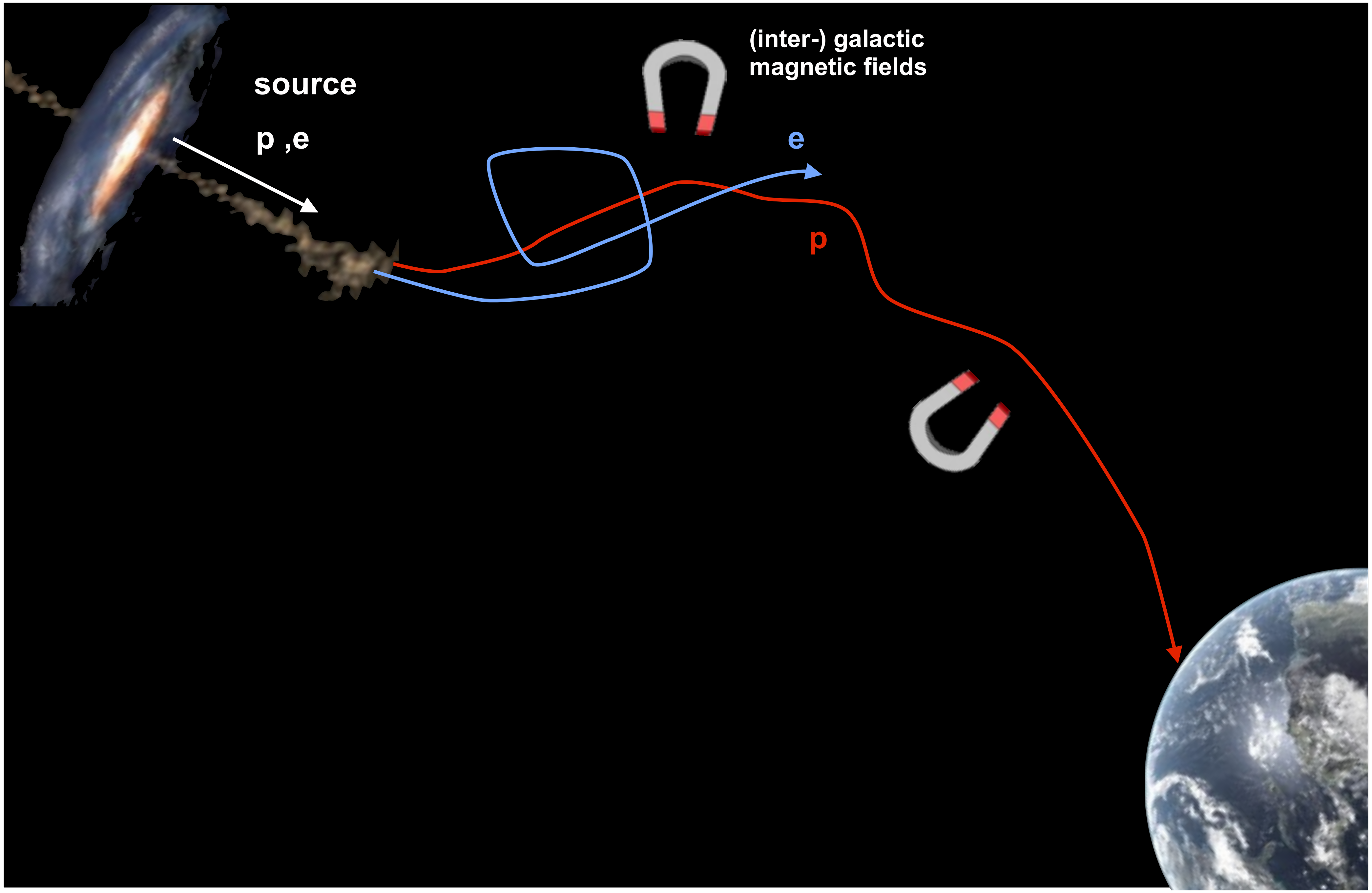

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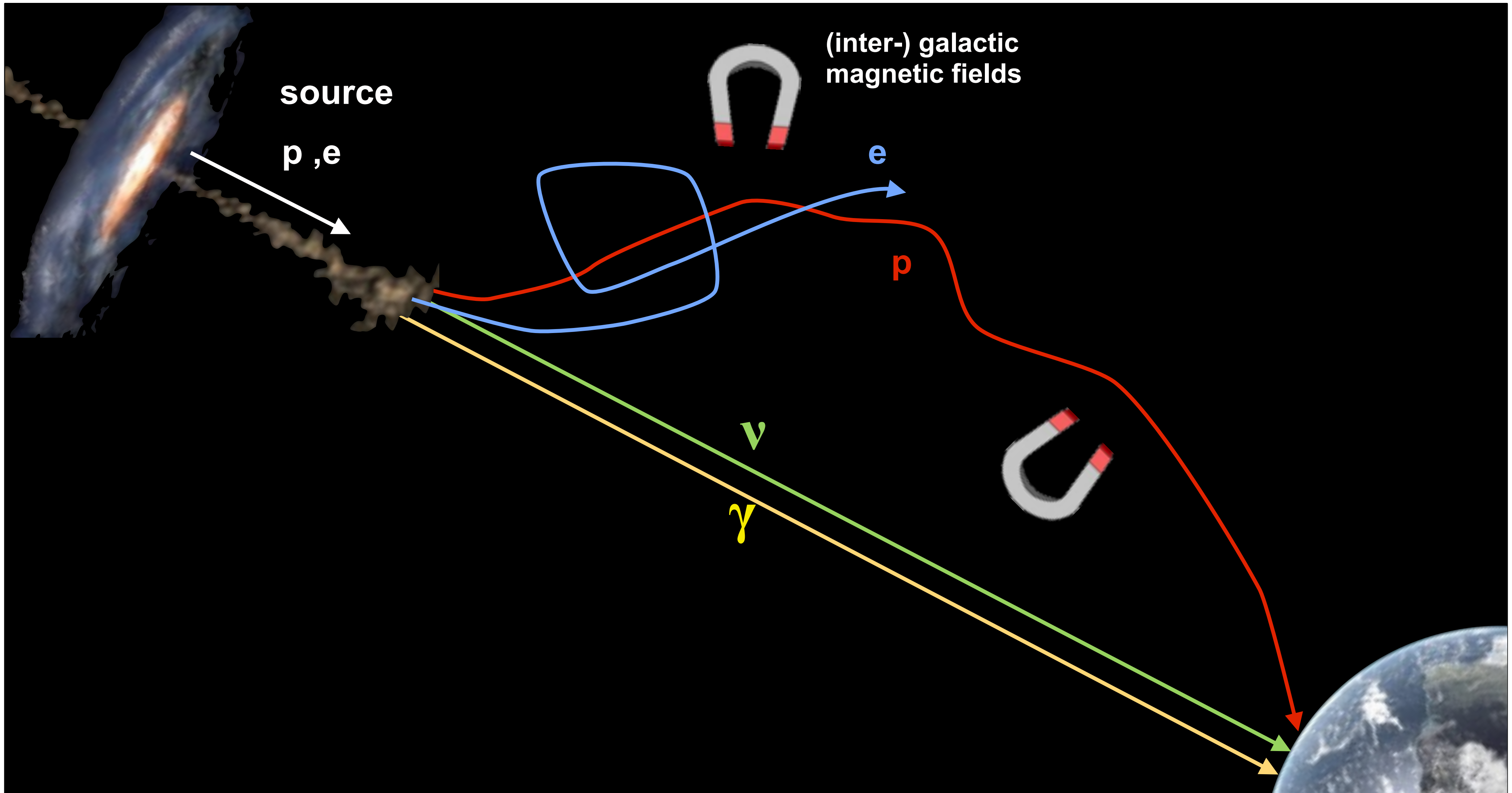


→ only two stable and neutral particles
- photons
- neutrinos

Production of high-energy photons and neutrinos

Interaction of accelerated particles with

- photon fields (cosmic microwave background, IR, star light)
- matter (star envelop, matter ejected by supernovae . . .)

→ production of secondary high-energy (> 0.1 TeV) particles

	with protons	**with electrons**
photons	$\overset{\text{CR}}{\downarrow}$ $p + p(\gamma) \rightarrow \pi^0 + X$ $\hookrightarrow \gamma + \gamma$	$e + \gamma_{\text{low-energy}} \rightarrow e + \gamma_{\text{high-energy}}$ (inverse Compton scattering)
neutrinos	$\overset{\text{CR}}{\downarrow}$ $p + p(\gamma) \rightarrow \pi^\pm + X$ $\hookrightarrow \mu^\pm + \nu_\mu$ $\hookrightarrow e^\pm + \nu_\mu + \nu_e$	

Why neutrinos?

- Neutrinos point back to their sources
- Neutrinos unambiguously prove acceleration of protons/nuclei, the main component of the cosmic rays
- Neutrinos escape even dense sources
- Neutrinos traverse cosmological distances
- Neutrino sky is terra incognita up to now

Expect surprises

Telescope	User	Date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi ...	1965	Sun, moon	Neutron start, accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	Military	1960?	Thermonuclear explosions	Gamma-ray bursts

What are the fluxes and how to detect high-energy neutrinos?

Source candidates: An example from our galaxy

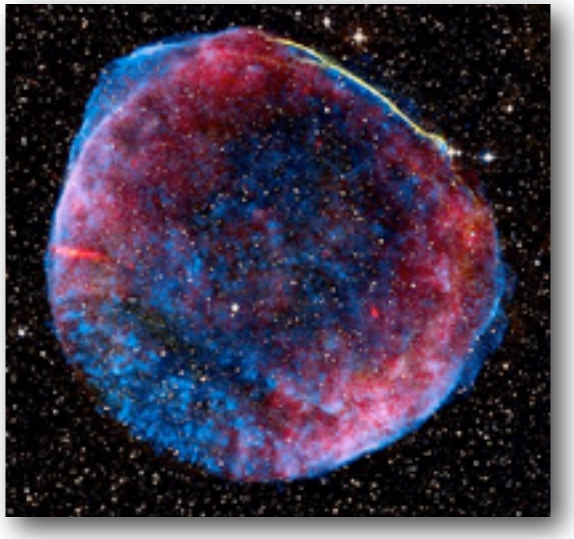
Supernova remnants:

- Expanding shell of ejected material
- Shock fronts at boundary to interstellar medium
  → acceleration of particles

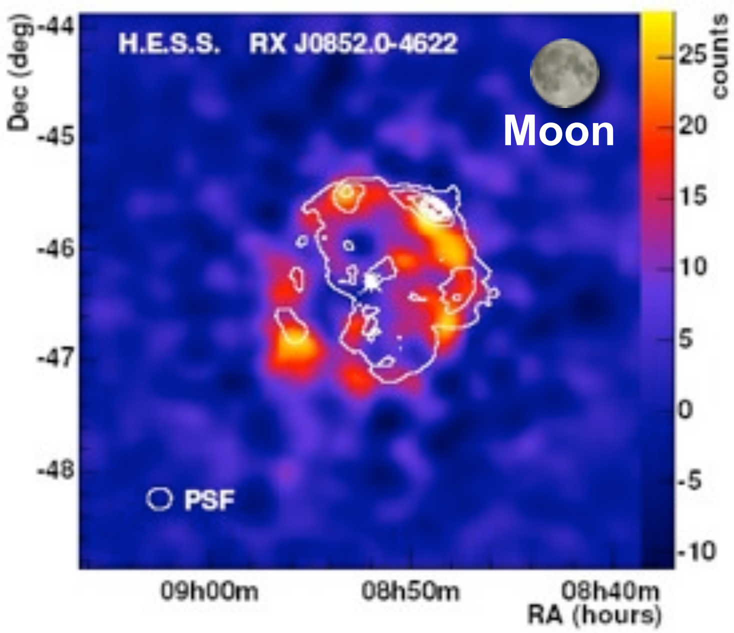
- High-energy particle acceleration in supernova remnants observed

. . . but are they proton accelerators?

SN1006
(optical, radio, X-ray)



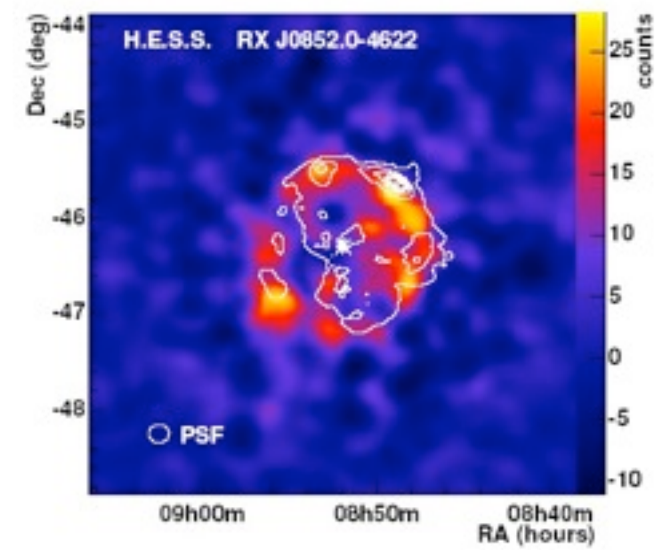
Vela Junior



What neutrino fluxes do we expect?

- Example:
  - supernova remnant Vela Junior
  - γ radiation up to 20 TeV (HESS Coll., A&A (2005))

    $\rightarrow$ particle acceleration beyond 20 TeV



- Assume hadronic mechanism via pion production:

$$p + p \rightarrow \pi^0 + X, \quad \pi^0 \rightarrow \gamma + \gamma$$

$$p + p \rightarrow \pi^\pm + X, \quad \pi^\pm \rightarrow \mu + \nu_\mu, \quad \mu \rightarrow e + \nu_\mu + \nu_e$$

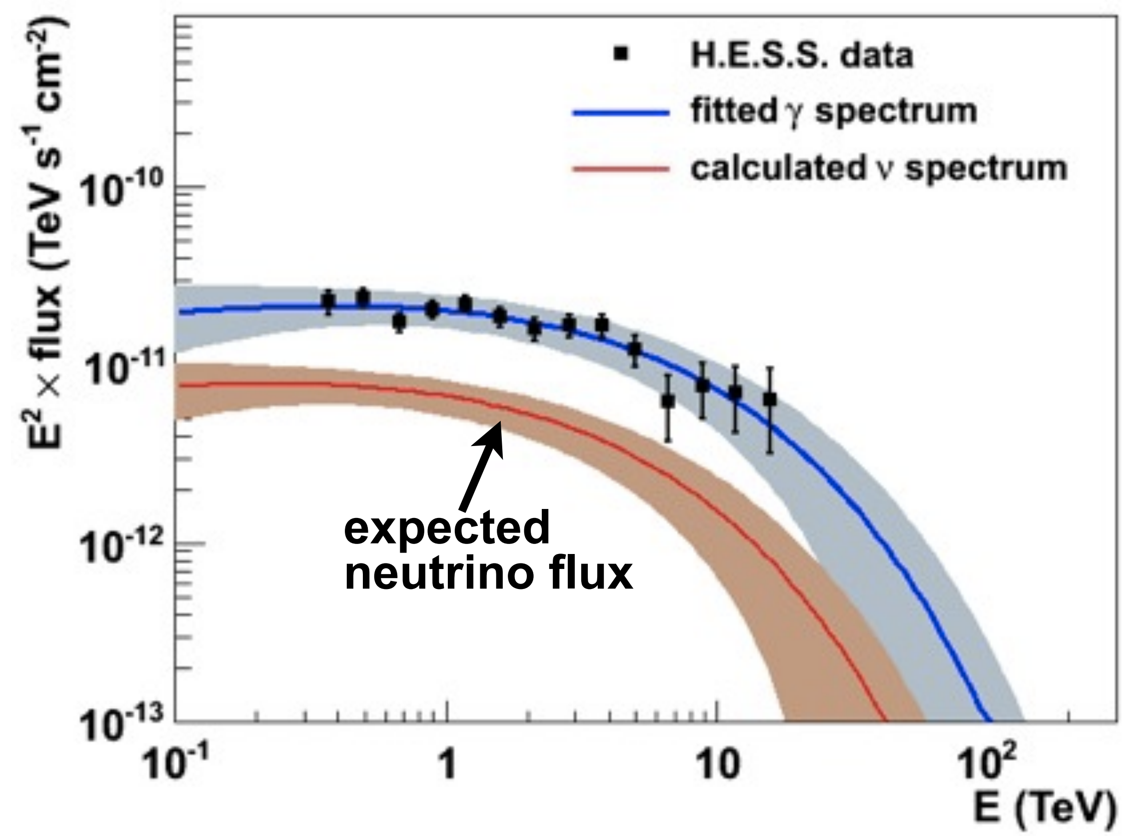
- Calculation of neutrino fluxes:

  For strong sources:

  $10^{-12} – 10^{-11}$ TeV^{-1} cm^{-2} s^{-1} @ 1 TeV

  Kappes, Hinton, Stegmann, Aharonian, ApJ (2006)
  Halzen, Kappes, O'Murchadha, PRD (2008)
  Kistler, Beacom, PRD (2006)
  . . .

Vela Junior (RX J0852–4622)



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What kind of detector do we need?

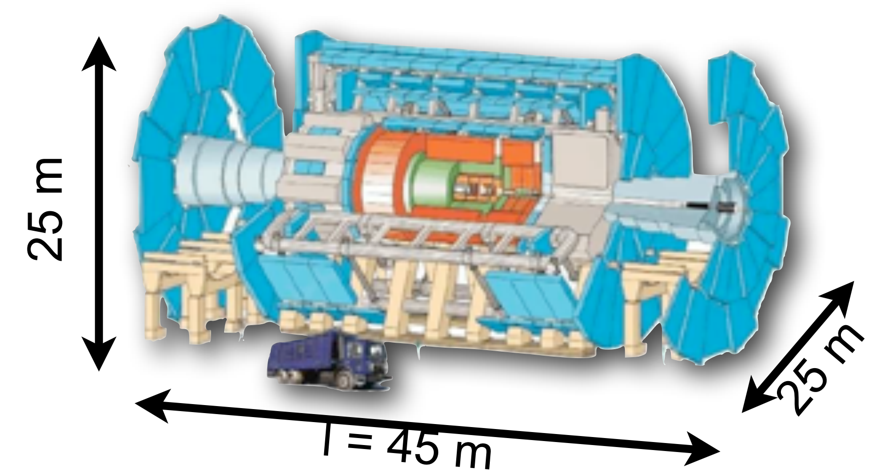
- Neutrino cross section:
  $\sigma \approx 10^{-35}$ cm^2 (at 1 TeV)

- Neutrino flux:
  $dN_\nu/dAdt = 10^{-12}$ cm^{-2} s^{-1} ($E_\nu > 1$ TeV)

- Rate in ATLAS detector:
  - $m_{ATLAS} = 7000$ t ; $m_{nucleon} \approx 1.7 \cdot 10^{-27}$ kg
    $\Rightarrow$ nucleons in ATLAS: $N_{ATLAS} \approx m_{ATLAS} / m_{nucleon} \approx 4 \cdot 10^{33}$
  - $R = N_{ATLAS} \cdot \sigma \cdot dN_\nu/dAdt = 4 \cdot 10^{-14}$ s^{-1}
    $\Rightarrow$ 800.000 years for 1 neutrino !

- For neutrino astronomy we need
  very large target masses
  $\mathcal{O}$(Gton) = $\mathcal{O}$(km^3) for ice/water

ATLAS



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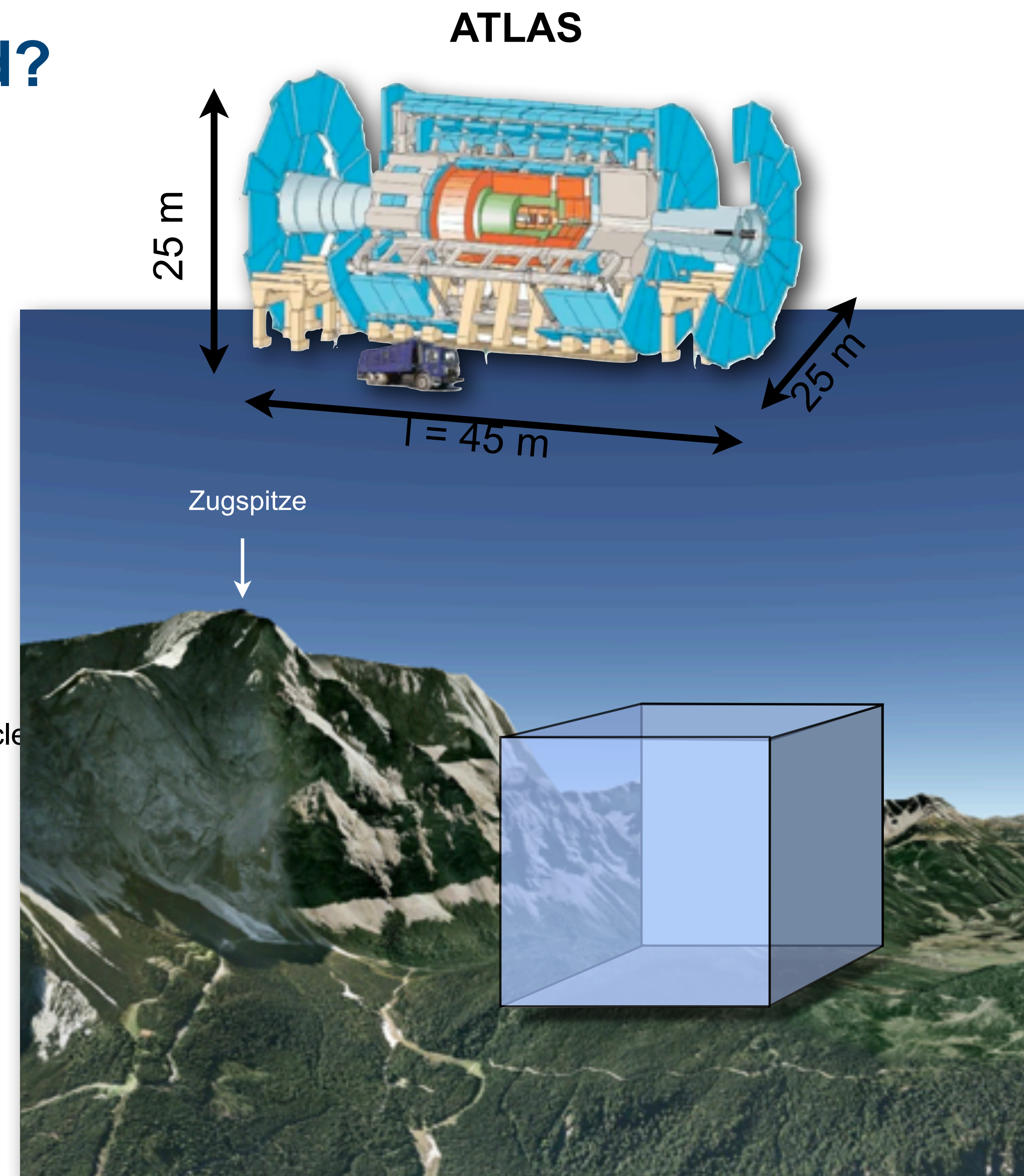

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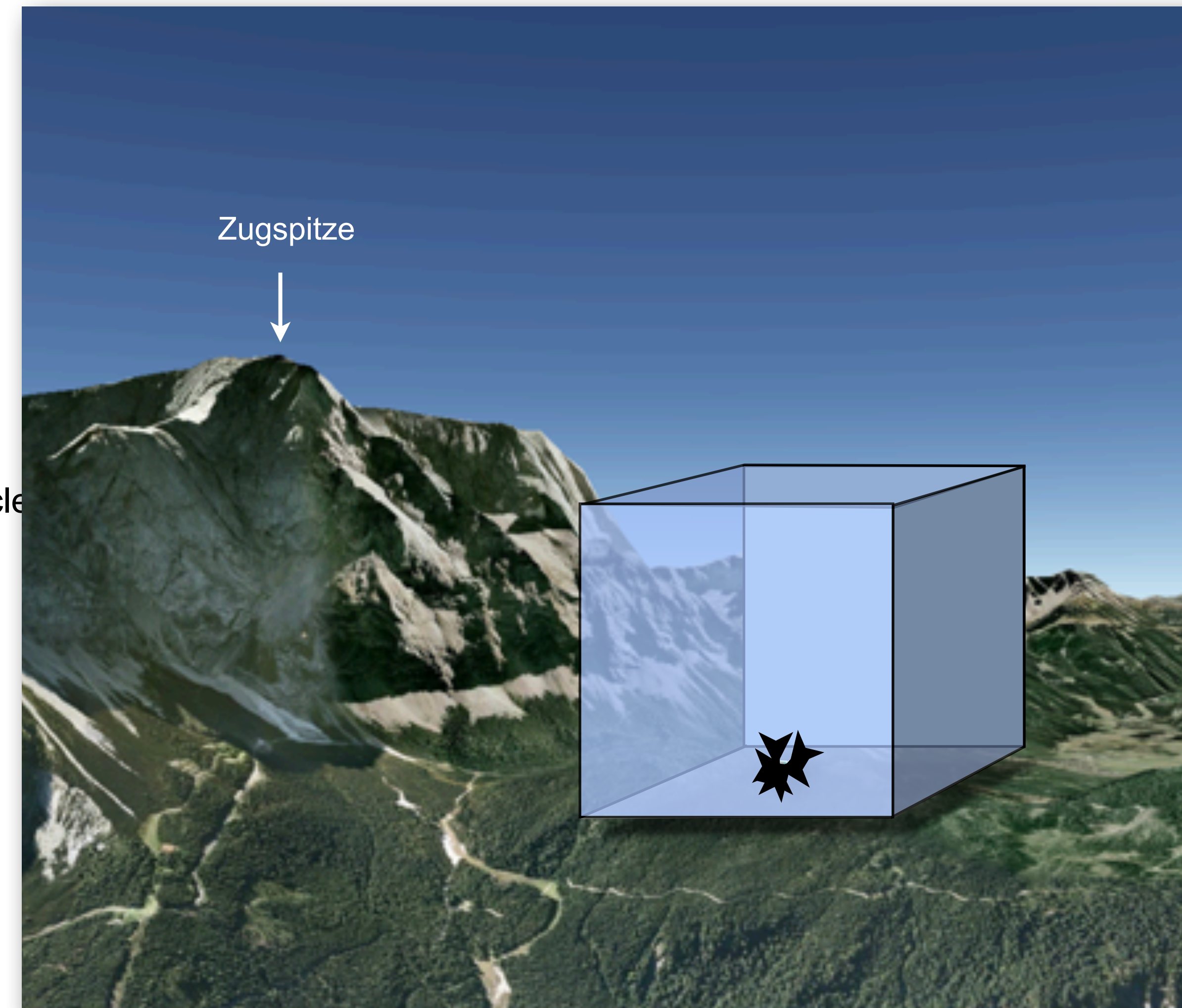

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Detection of cosmic neutrinos

- Detection & reconstruction via Cherenkov light of secondary particles
  → transparent detection media
- Huge detection volumes → natural

Time & position of hits

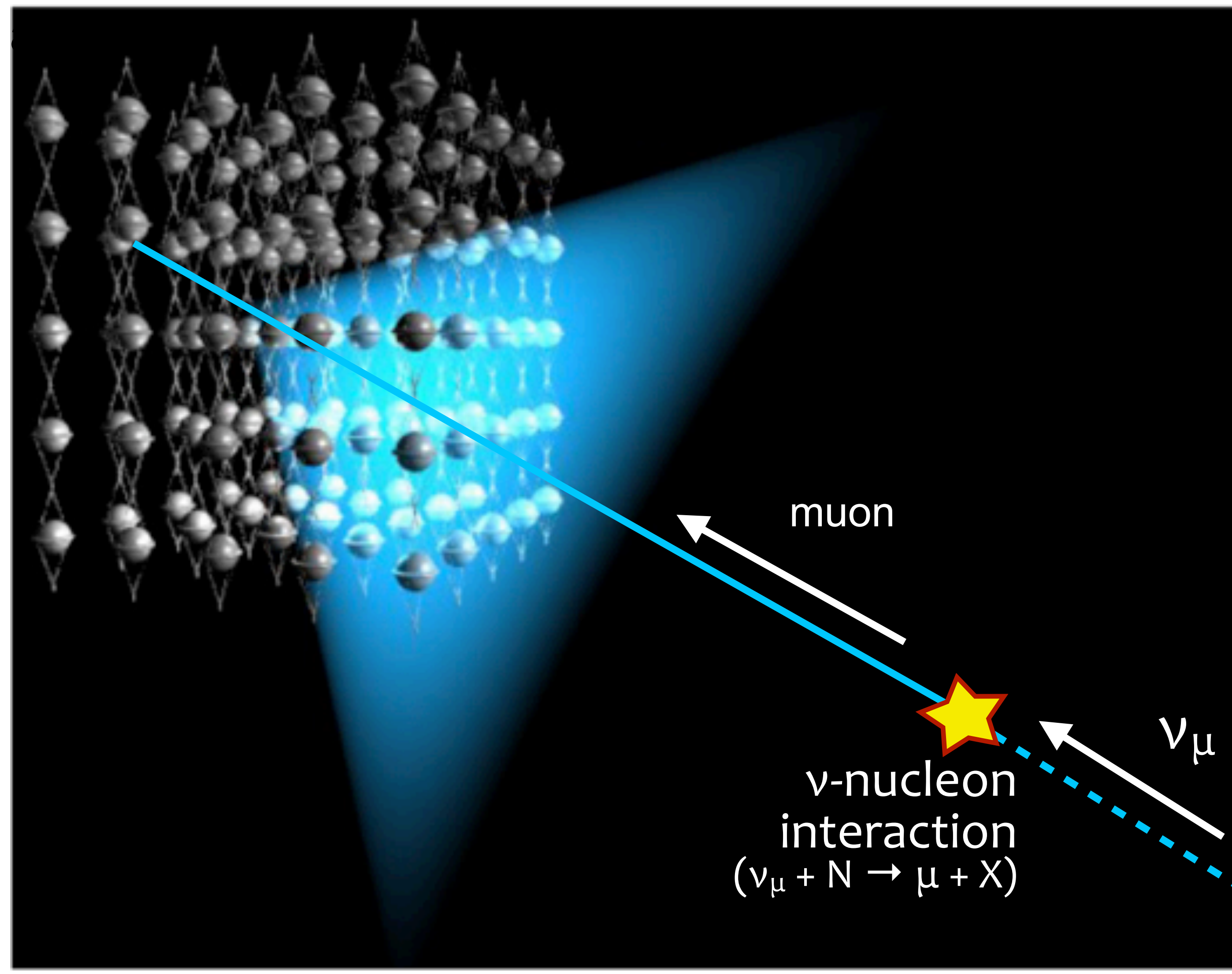
⬇

μ trajectory → ν trajectory

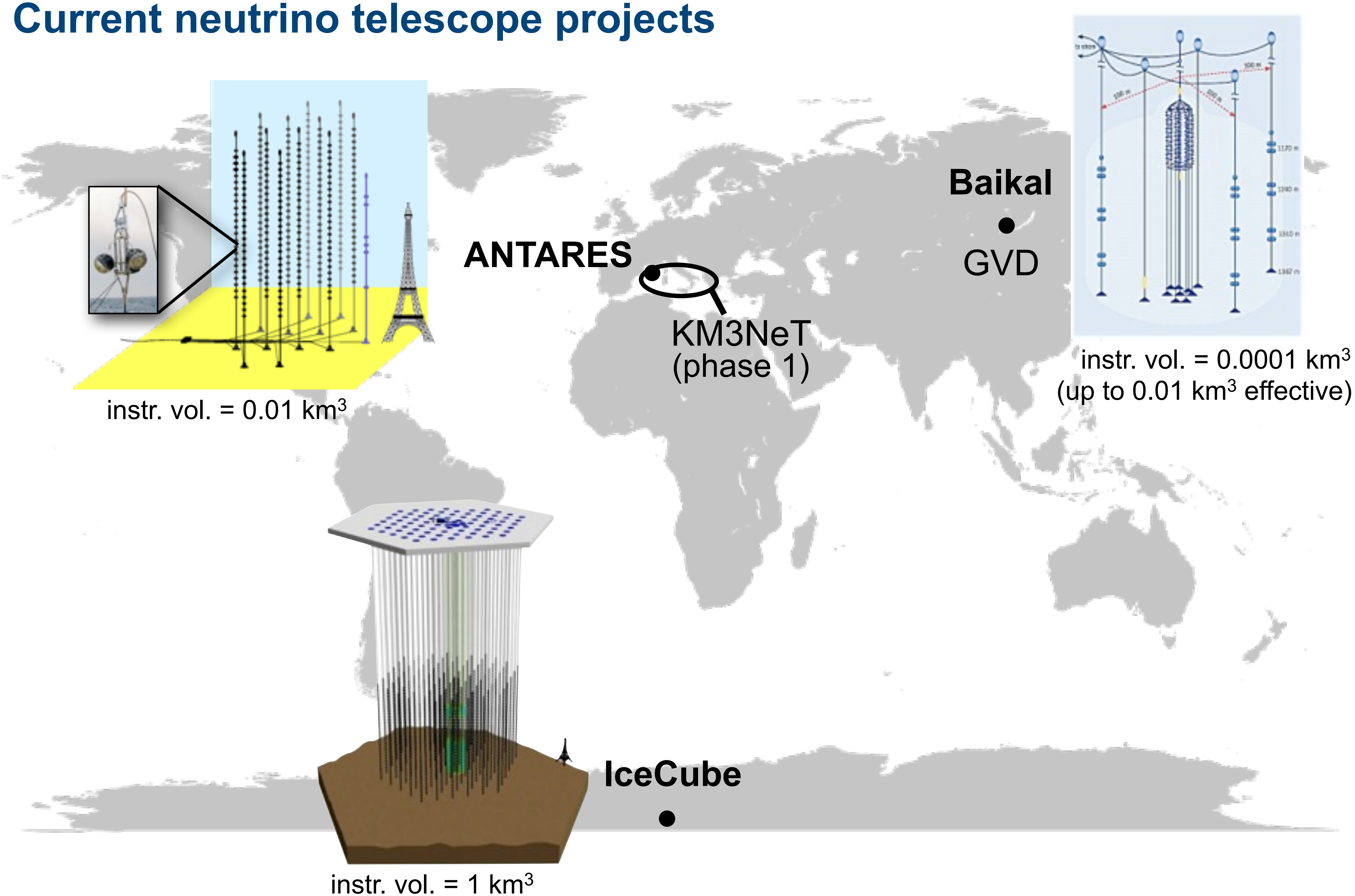
Light intensity

⬇

Energy



Current neutrino telescope projects



IceCube – a neutrino observatory at the South Pole

IceCube at the South Pole

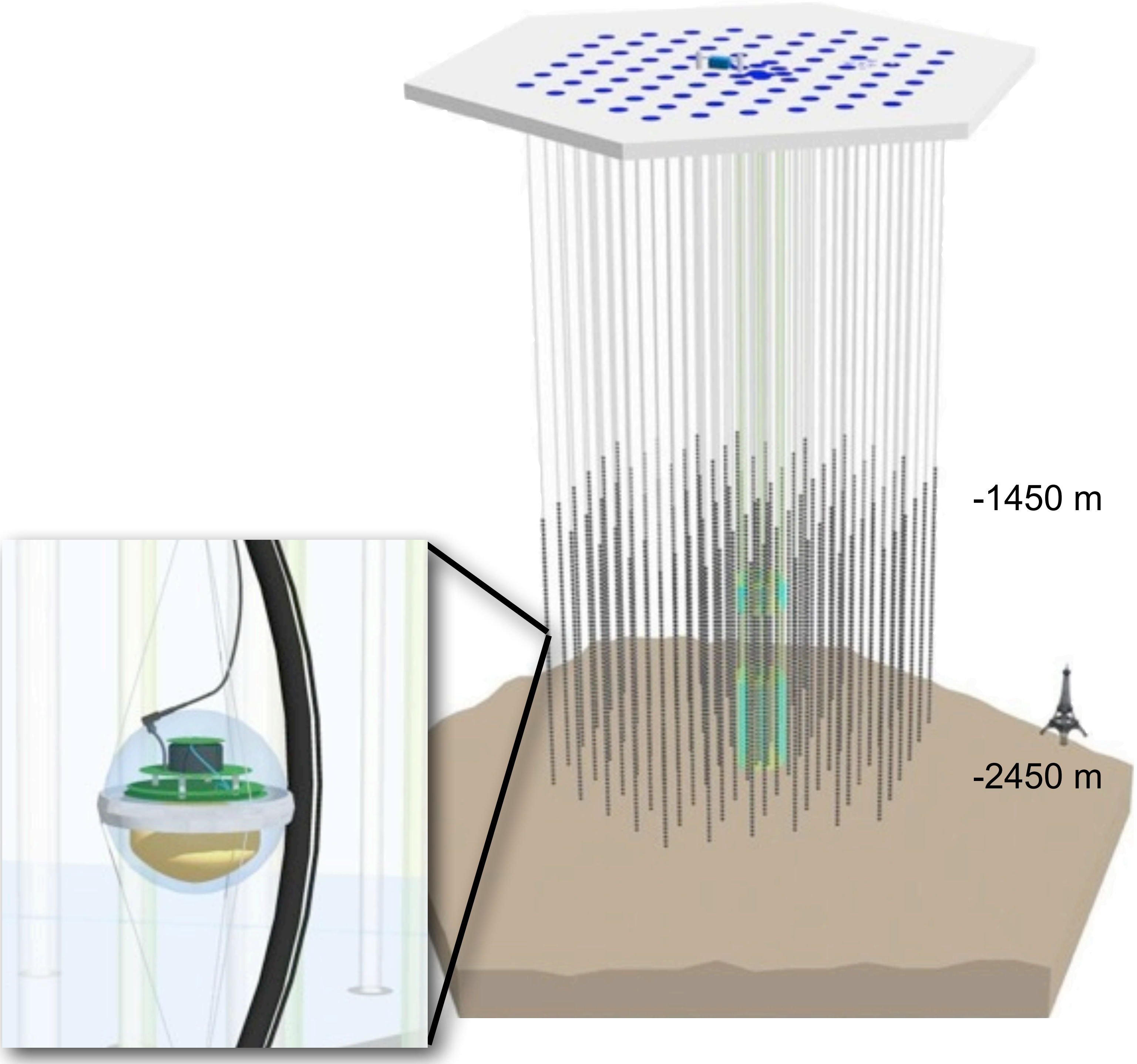
IceCube at the South Pole

⇒ **3 challenges:**

- Drilling of 86 holes
- Understanding the ice
- Muon/neutrino background

The IceCube Observatory

- IceTop: Air shower detector
- InIce: 86 strings (5160 PMTs)
  Instrumented volume: 1 km^3
- DeepCore
  densely instrumented
  central region (8 strings)
- Optical sensor
  10” photomultiplier (PMT)
  + in situ signal digitization
  in pressure glass sphere
- Completed since Dec. 2010
  (data taking since 2005)



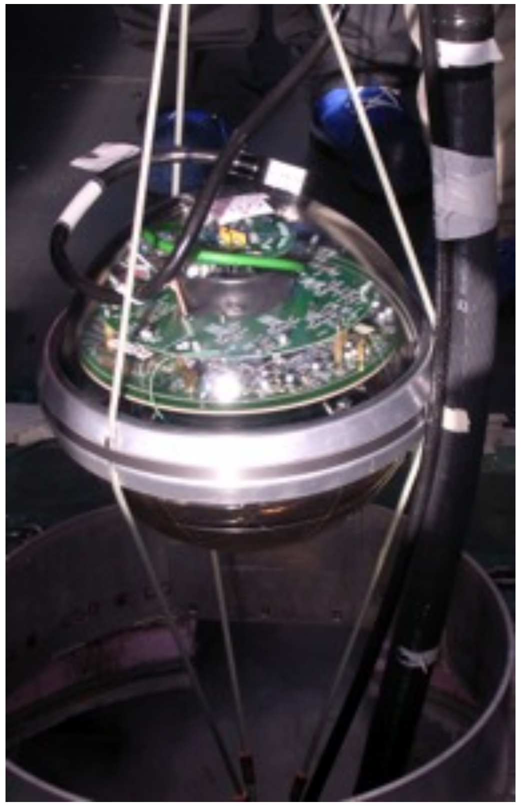
Life at the South Pole

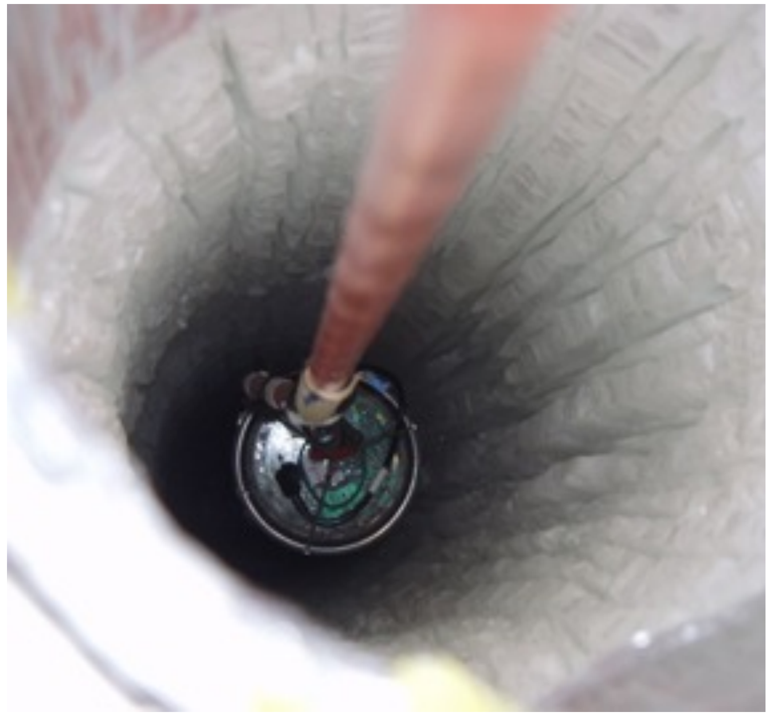
Drilling and deploying

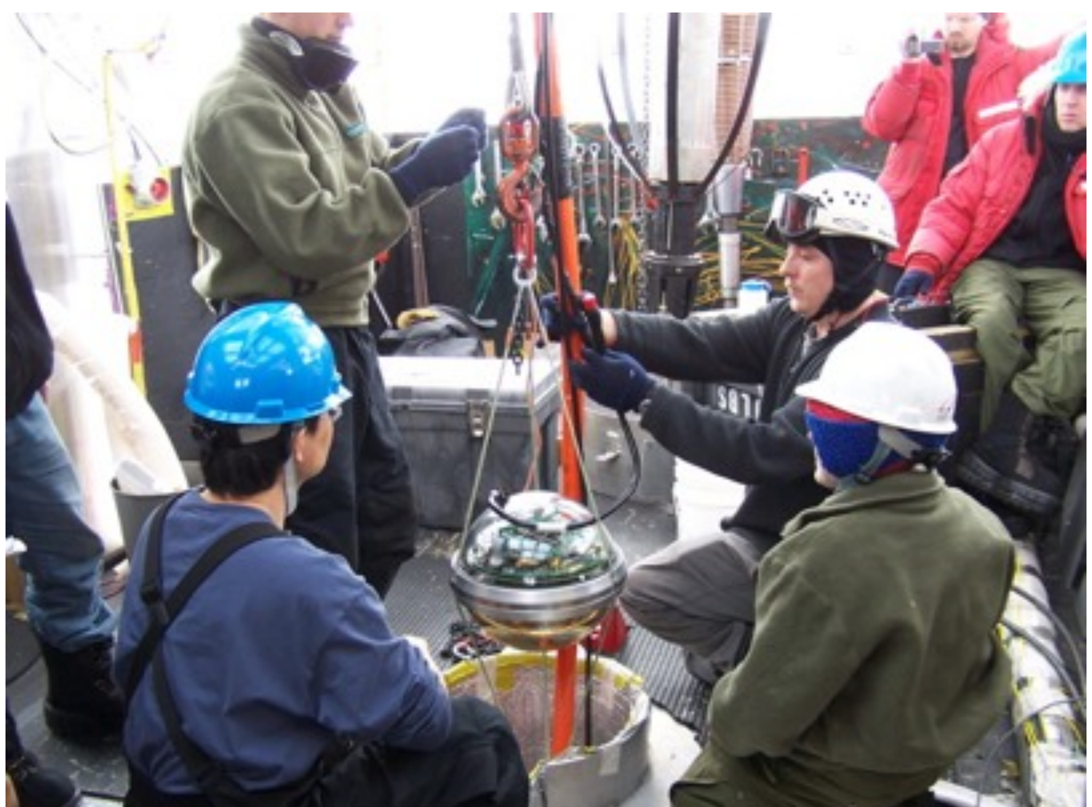
Nozzle delivers:
- 750 l per minute
- 90 degree C
- 70 bar

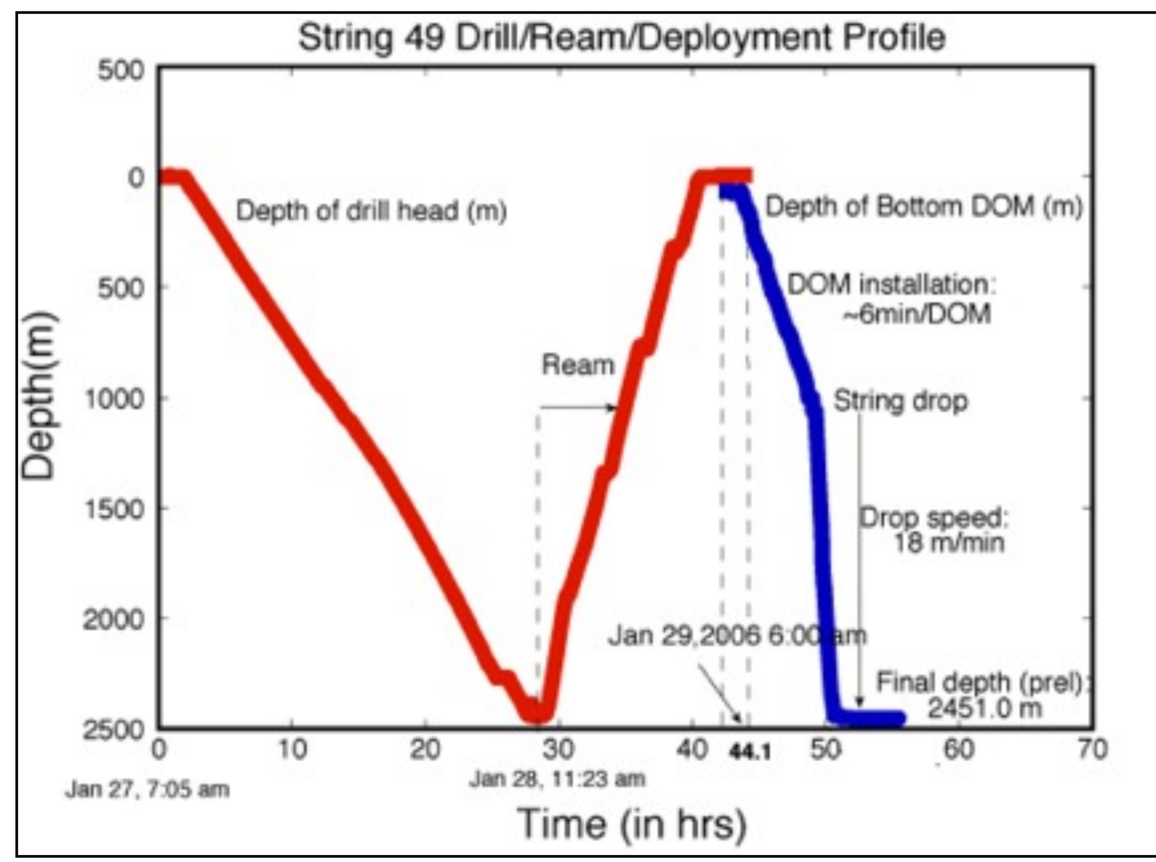
→ 4.8 MW heating plant

Drilling and deployment

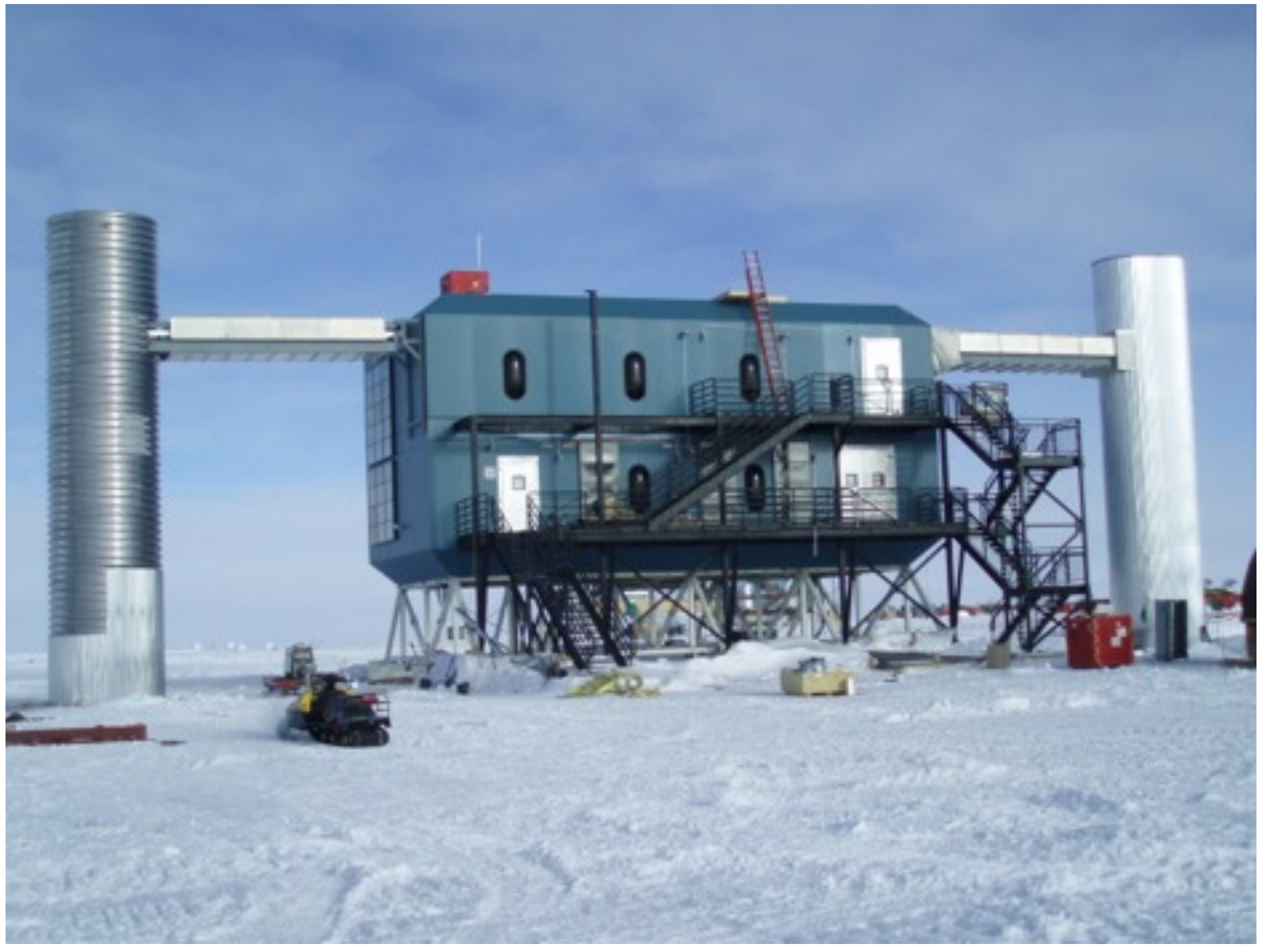








IceCube laboratory



- ICL is central data center for IceCube
- All cables and servers for IceCube DOMs, DAQ and online filtering
- All Level 1 filtering done at South Pole in real time and data sent north via satellite


The IceCube Collaboration
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University of Alberta–Edmonton
University of Toronto
USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
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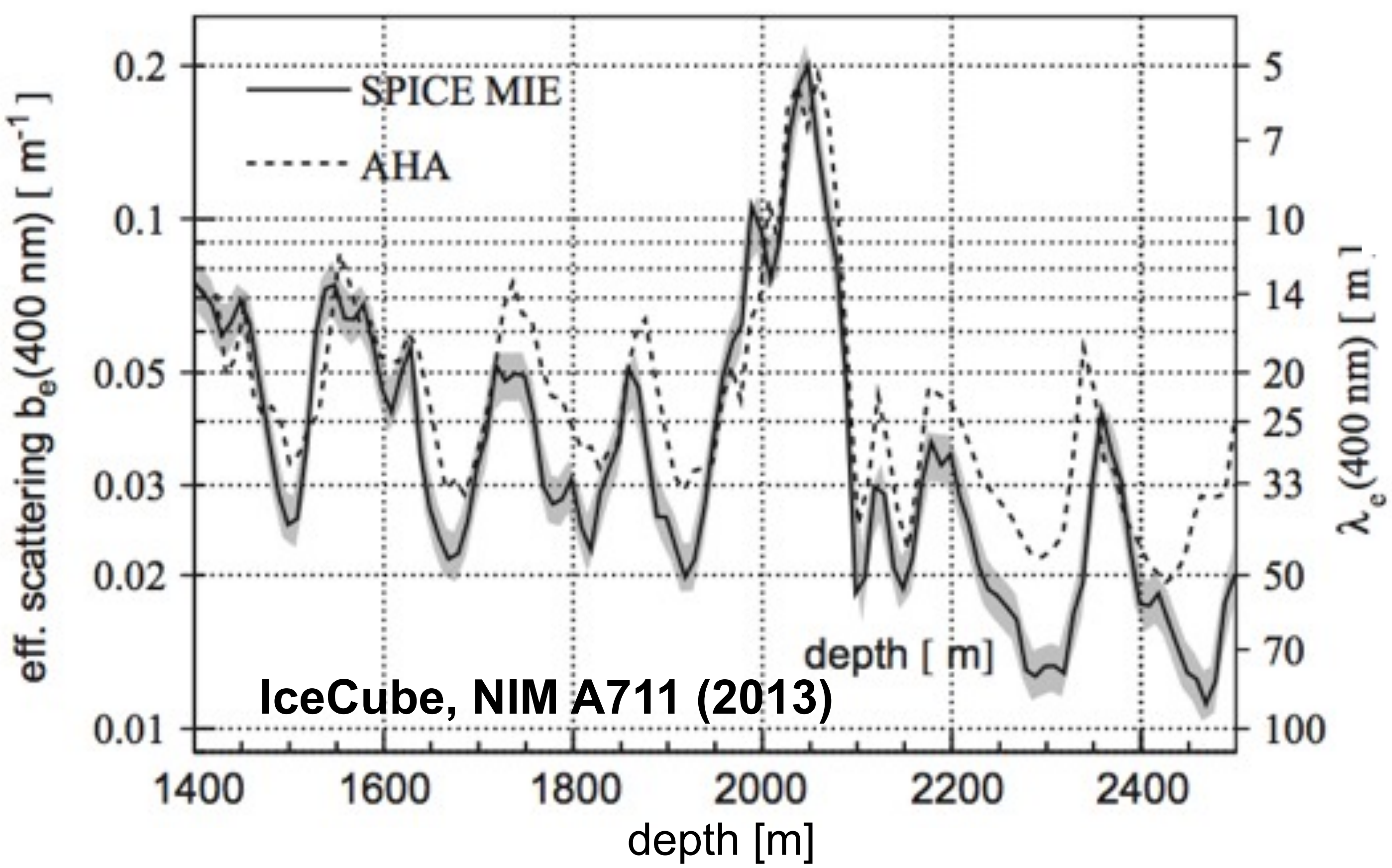
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
280 people from 44 institutes in 12 countries

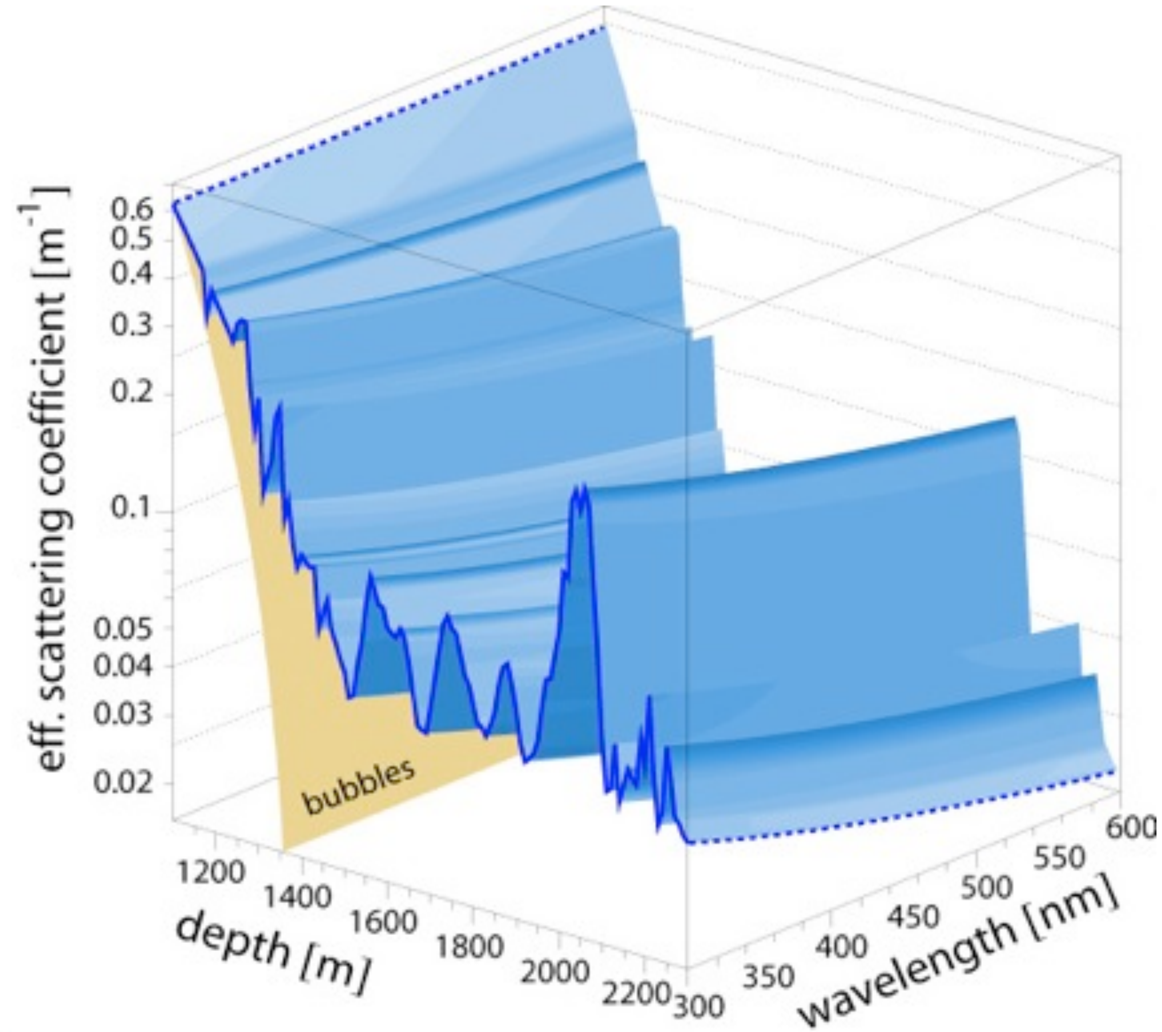
Understanding the ice

- Photon propagation in ice dominated by scattering

  λabs 50 – 300 m
  λ_{scat} 15 – 70 m

- Ice properties have to be very well measured





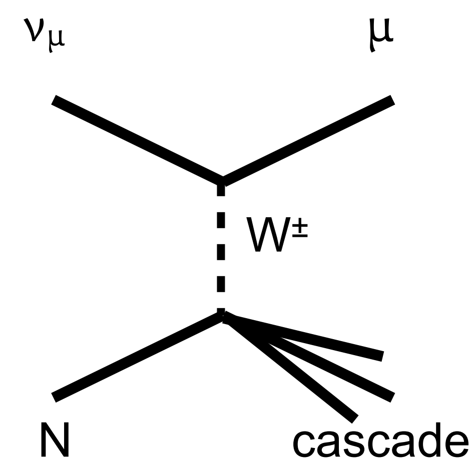
Neutrino signatures

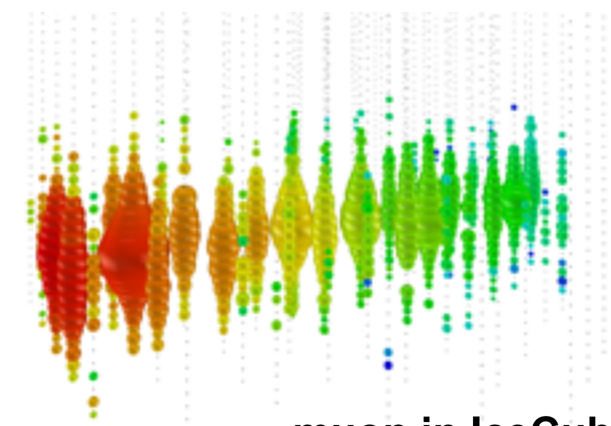
Track-like

- Good angular resolution
  in ice (IceCube) ~ 0.5° for E > 10 TeV
- Sensitive volume > instrumented volume

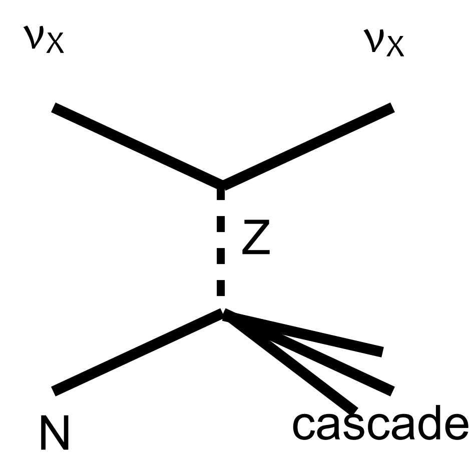
Cascade-like

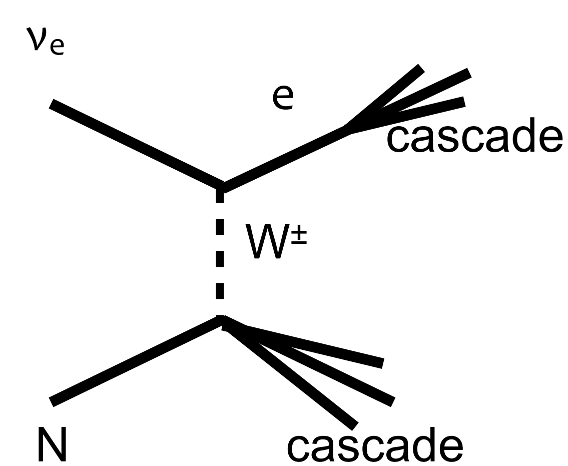
- Good energy resolution
  in ice (IceCube) < 10% for E > 10 TeV
- Reduced angular resolution
  in ice (IceCube) > $\mathcal{O}(10°)$
- Sensitive volume ≈ instrumented volume

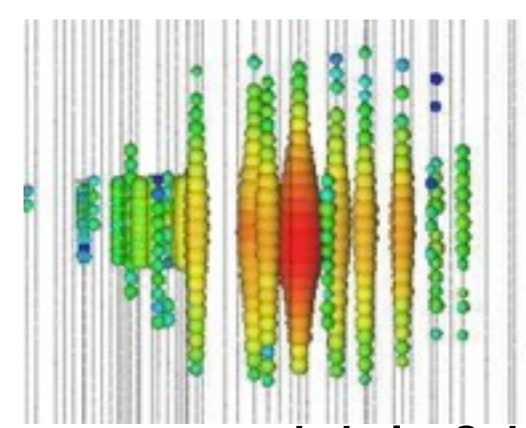




muon in IceCube

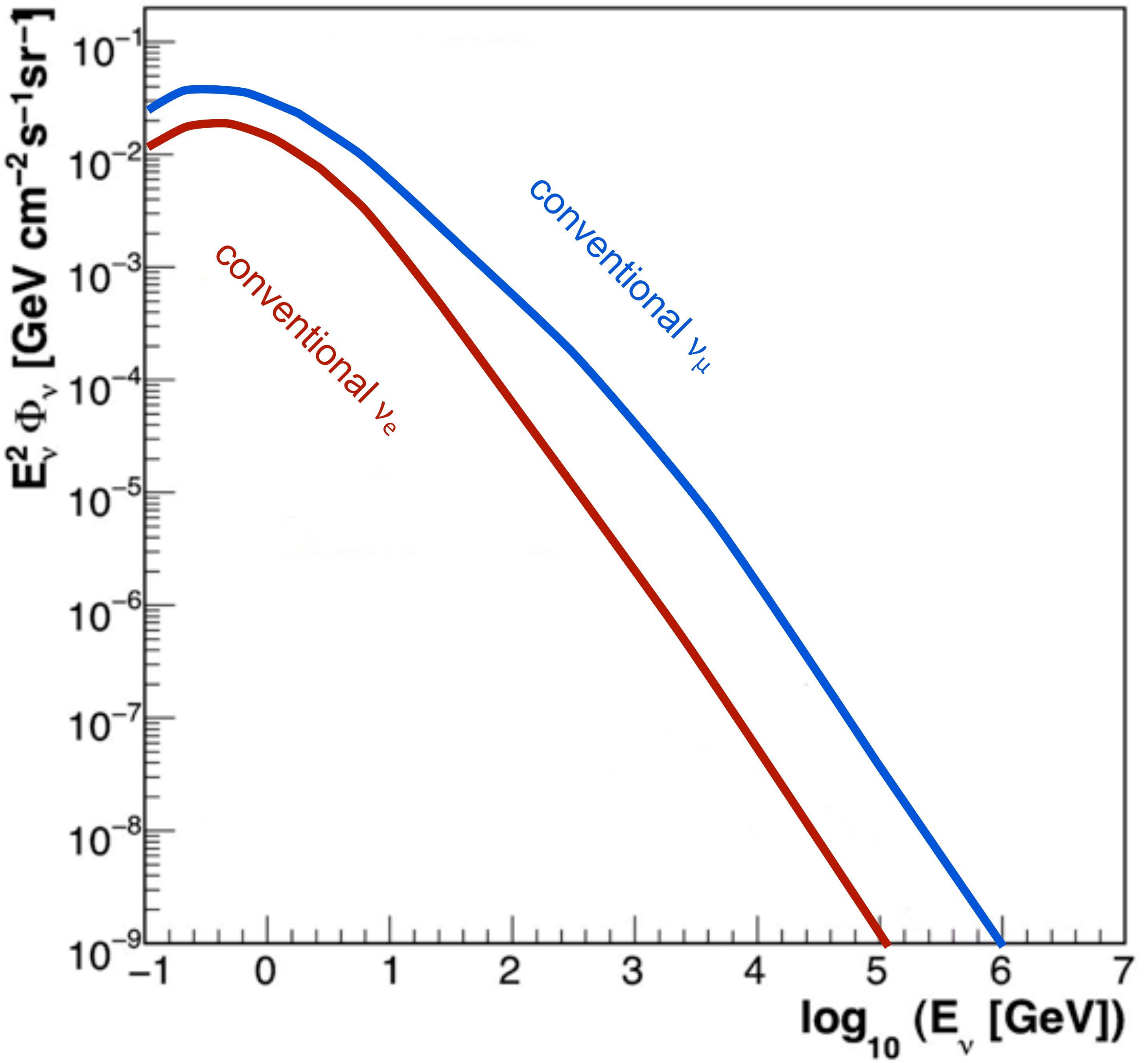


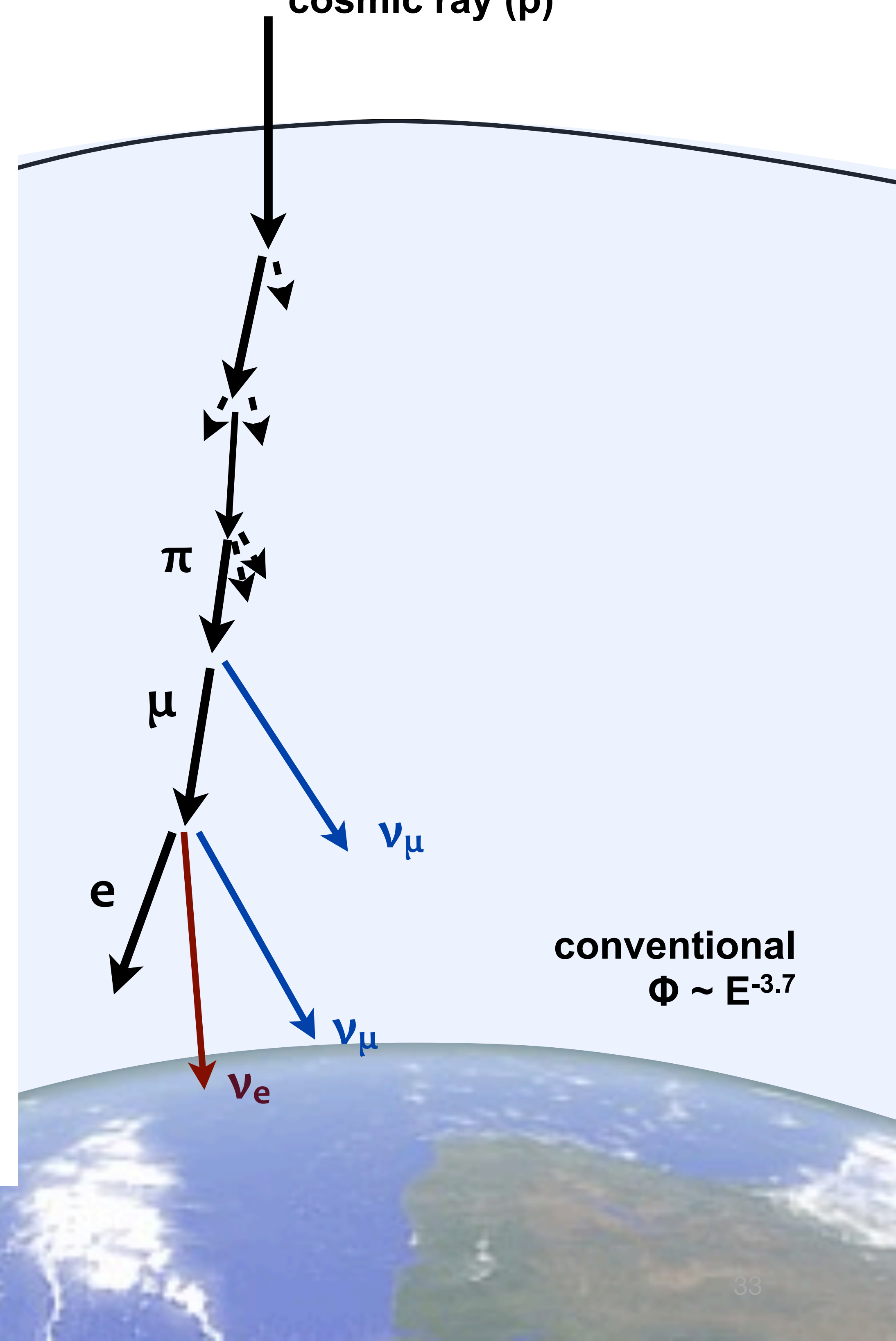




cascade in IceCube

Atmospheric muons and neutrinos





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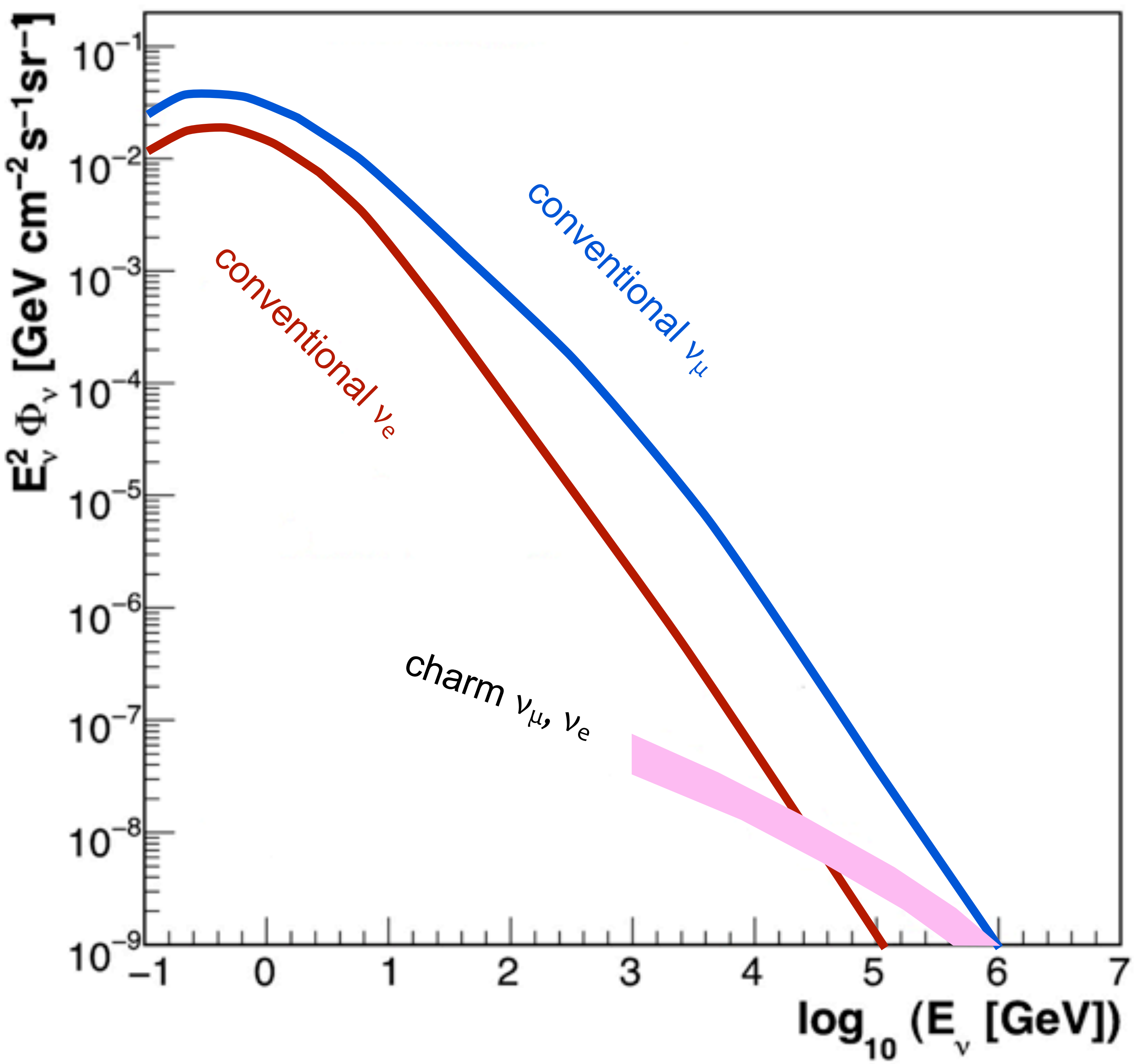

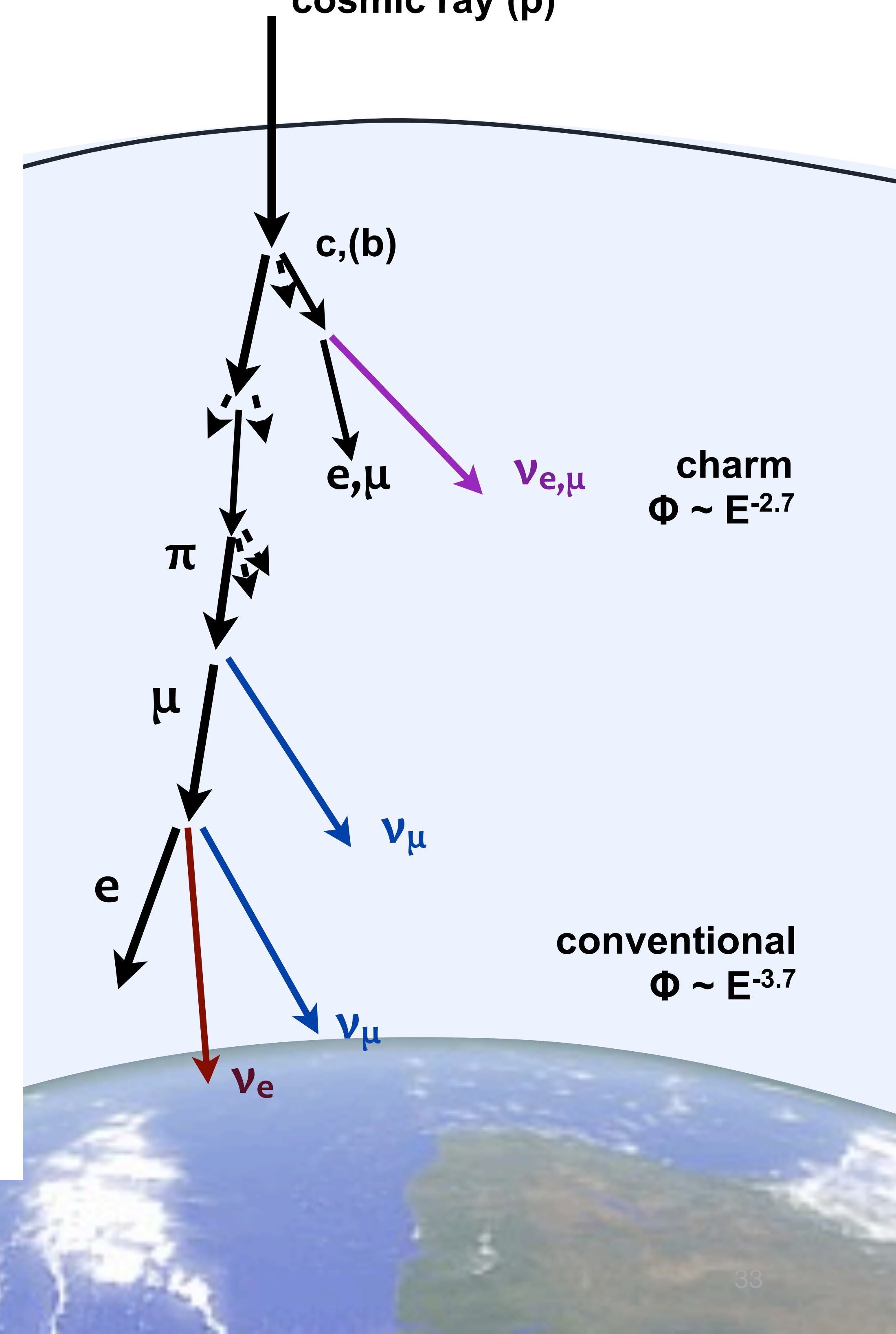

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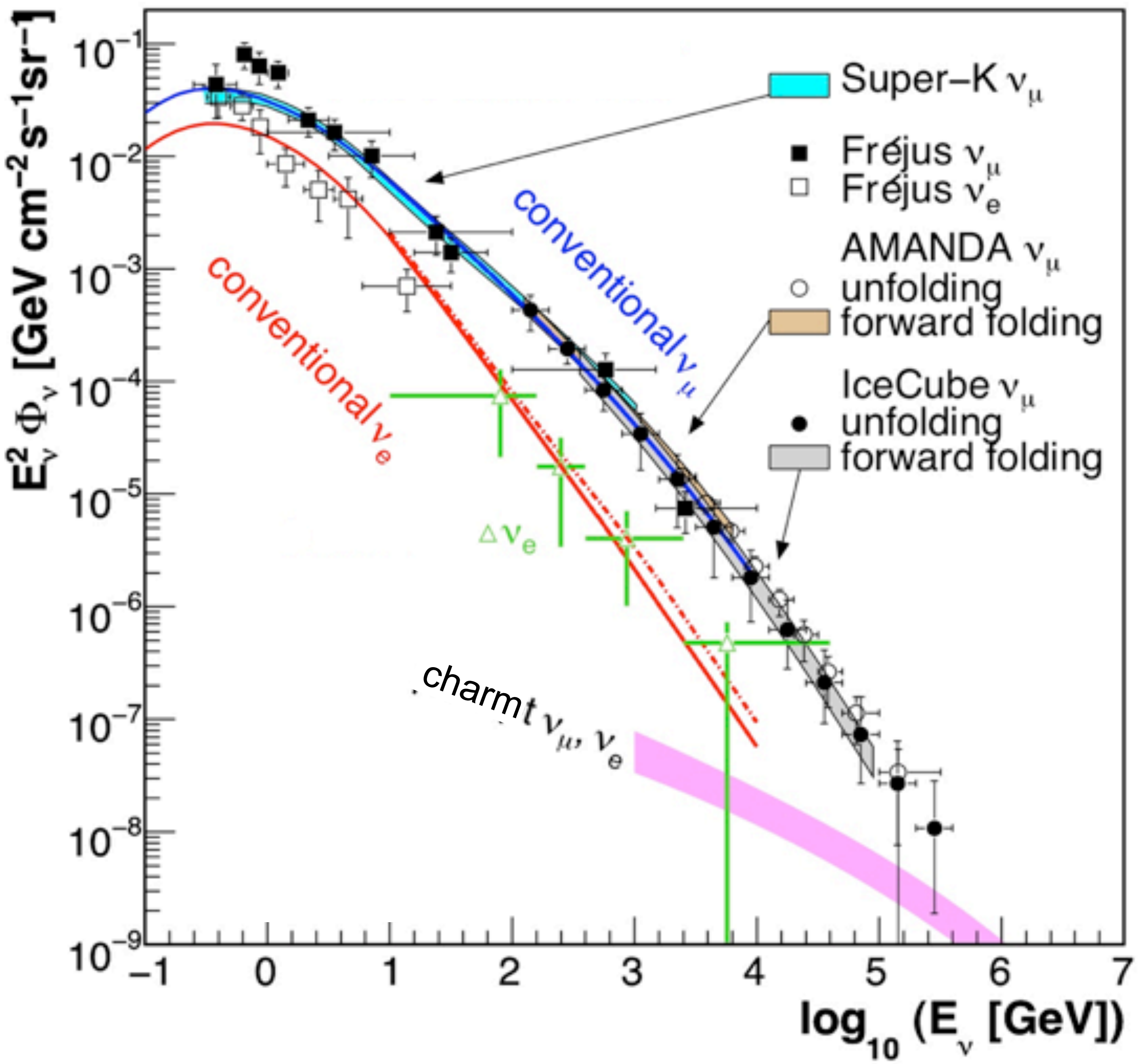

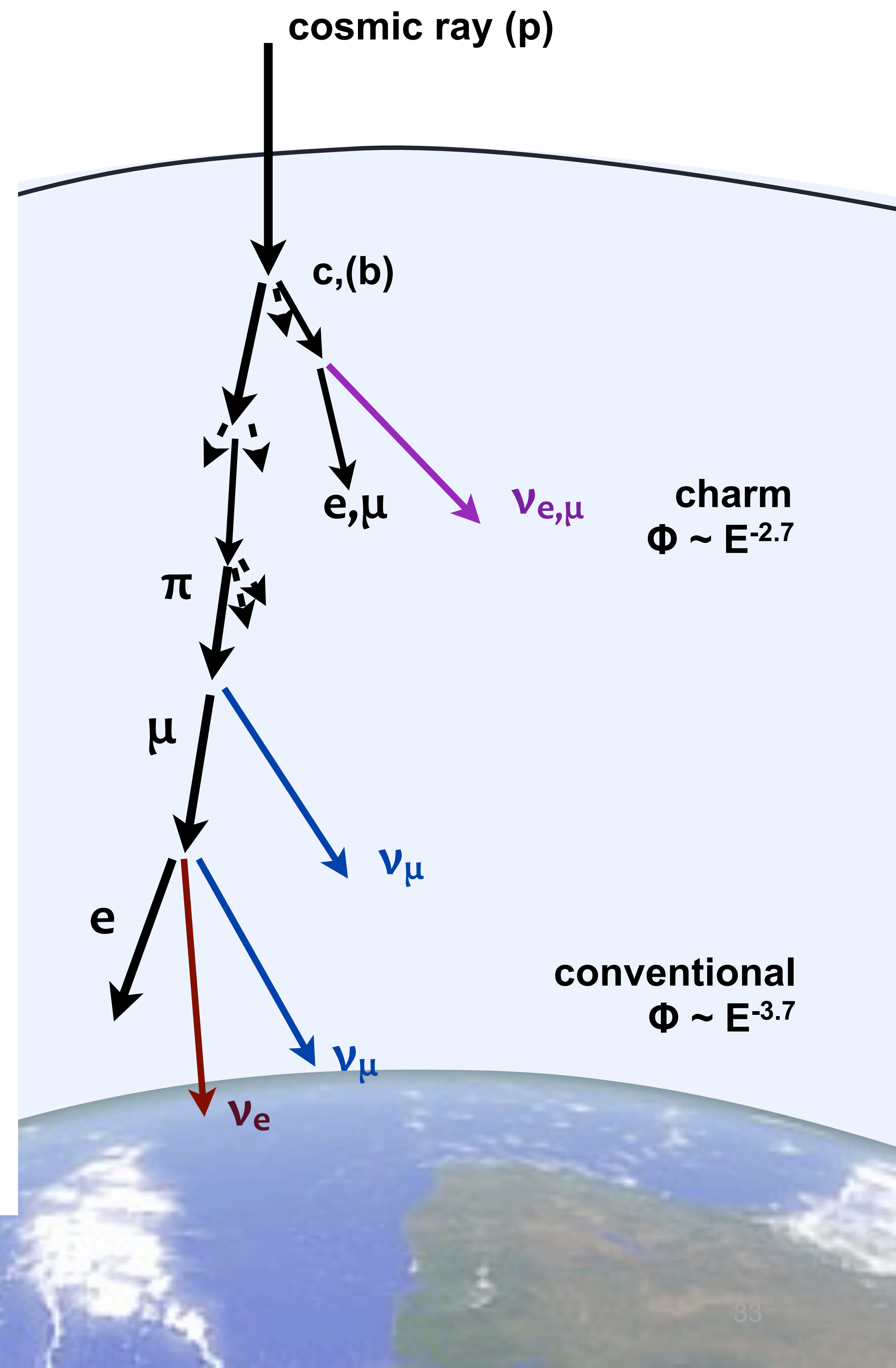

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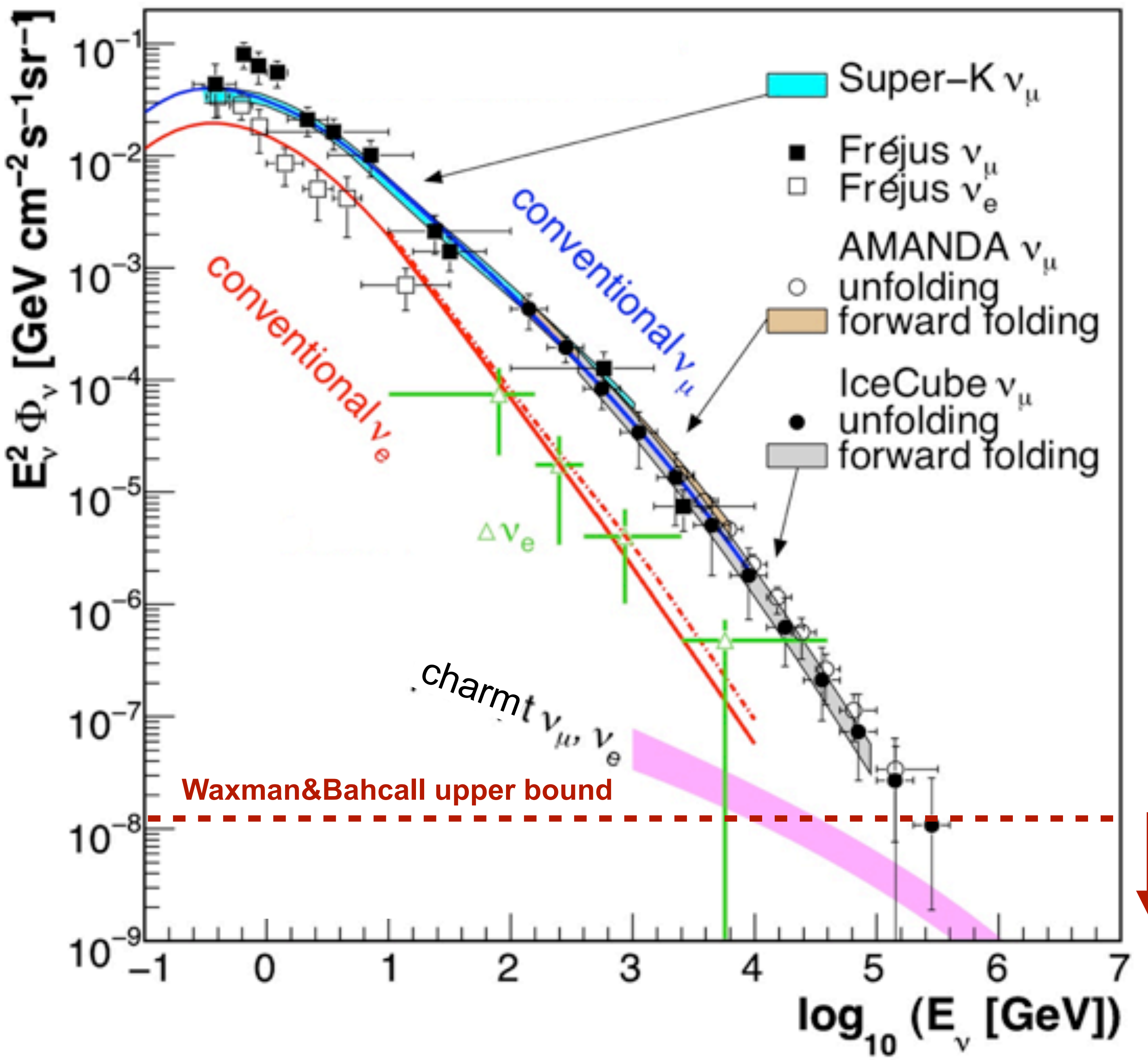
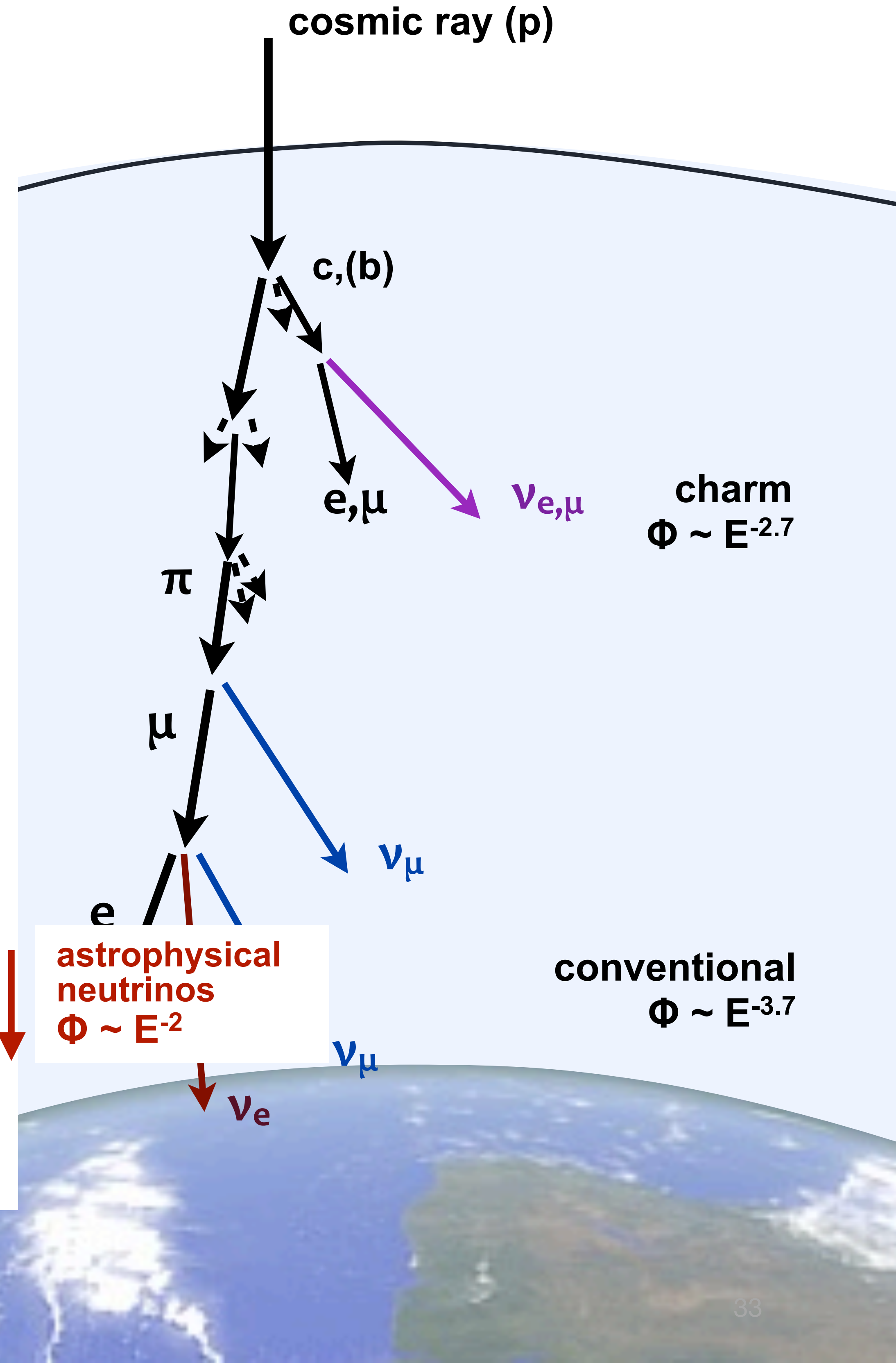
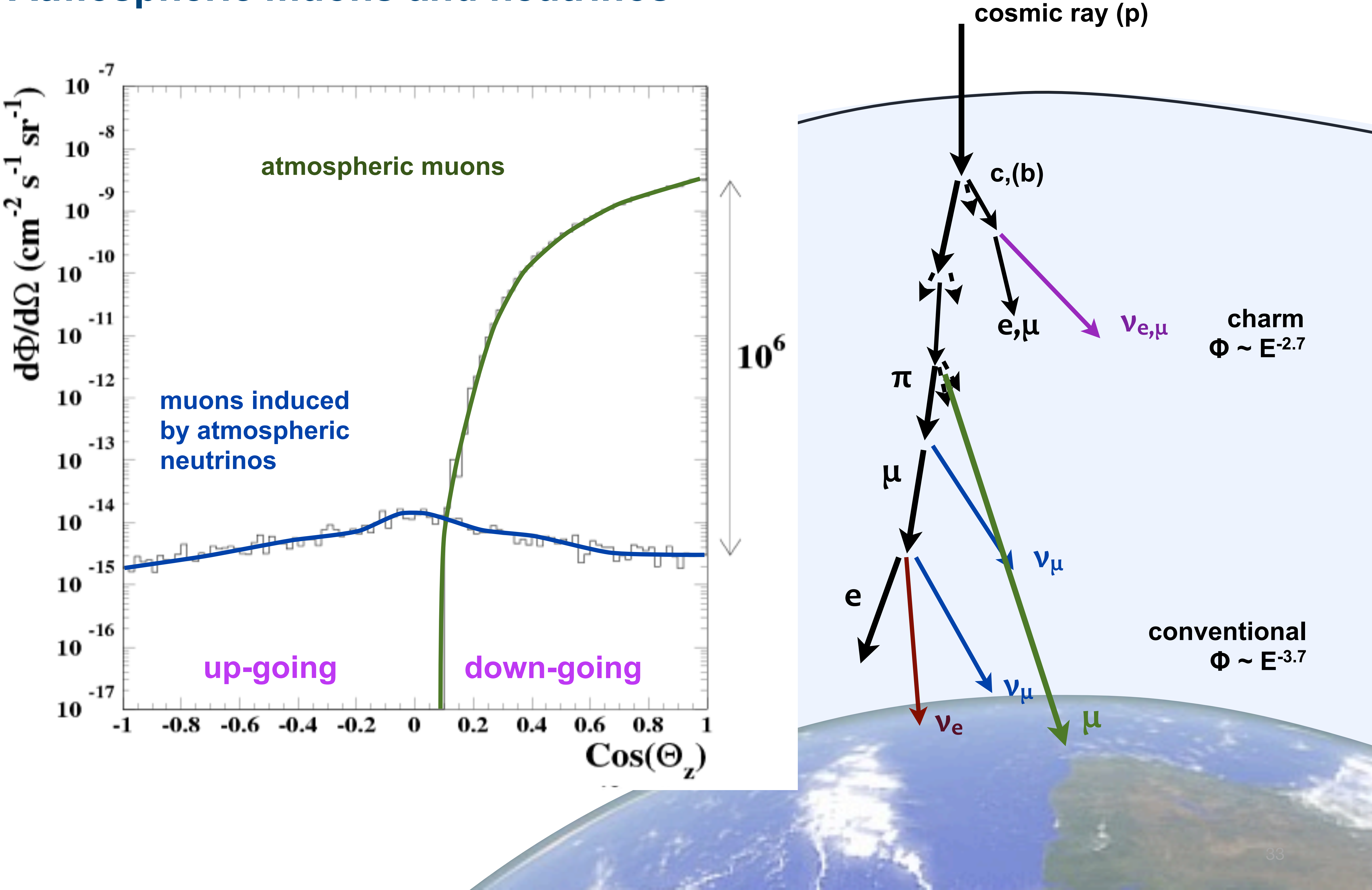




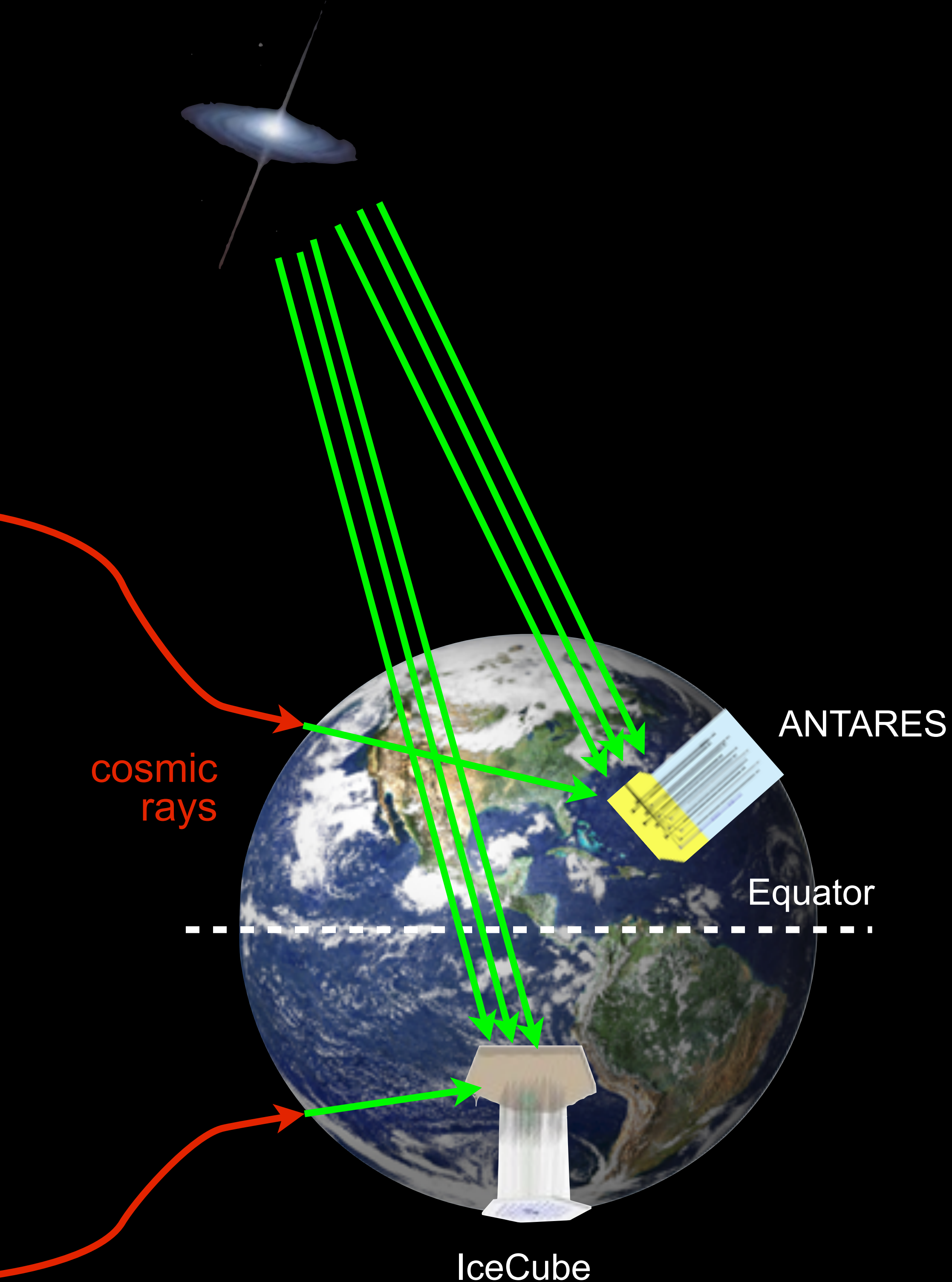
Atmospheric muons and neutrinos



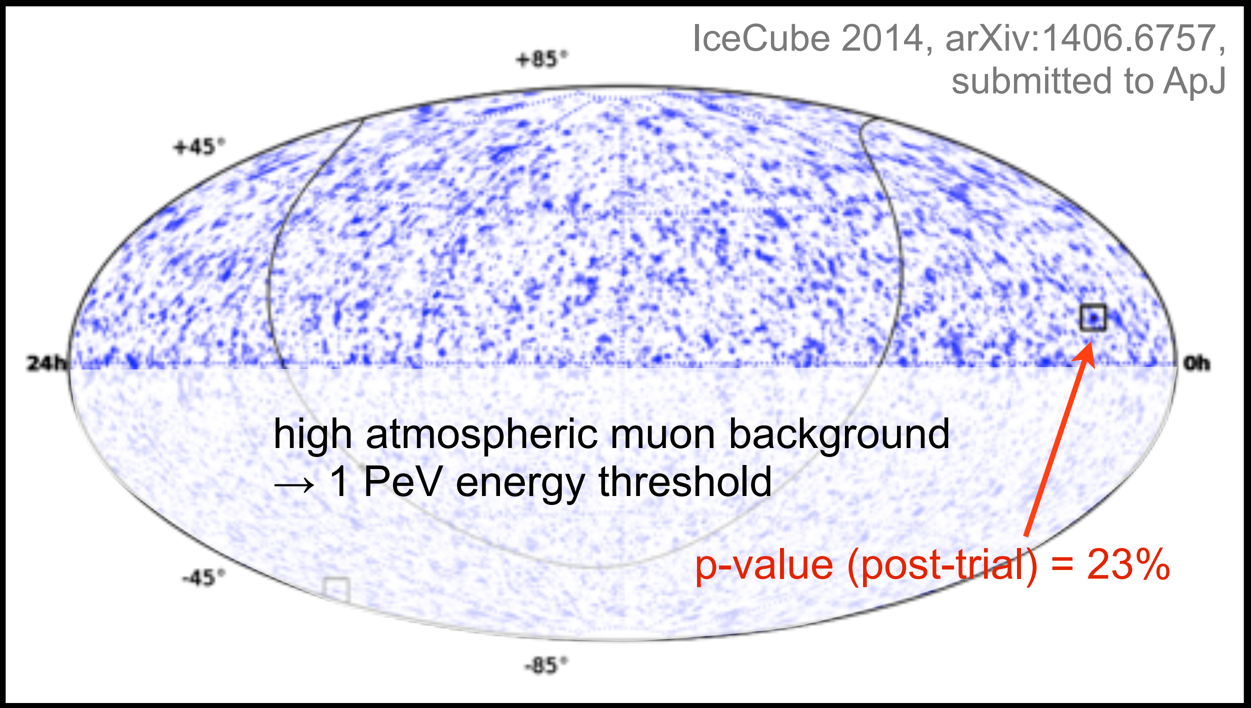
Recent astrophysical results from IceCube

“Classical” picture of neutrino astronomy

Search for point sources

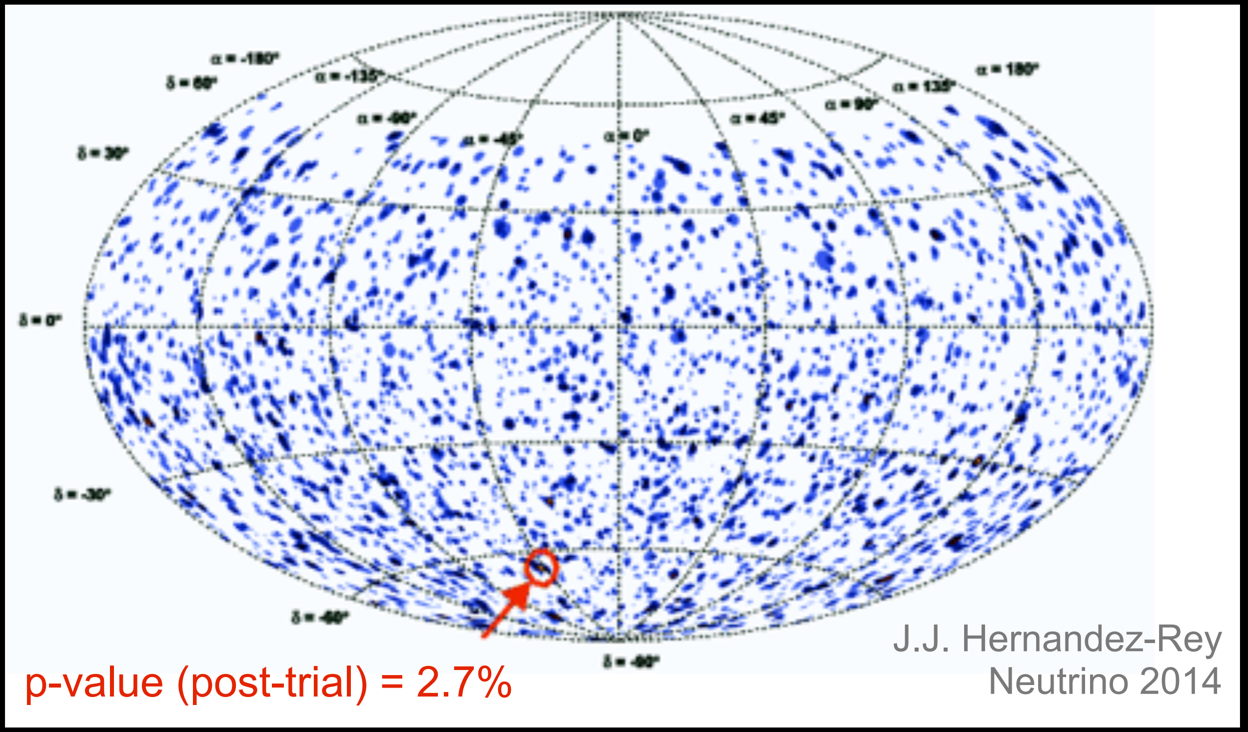


IceCube
1373 days
~180,000 ν
(up-going)

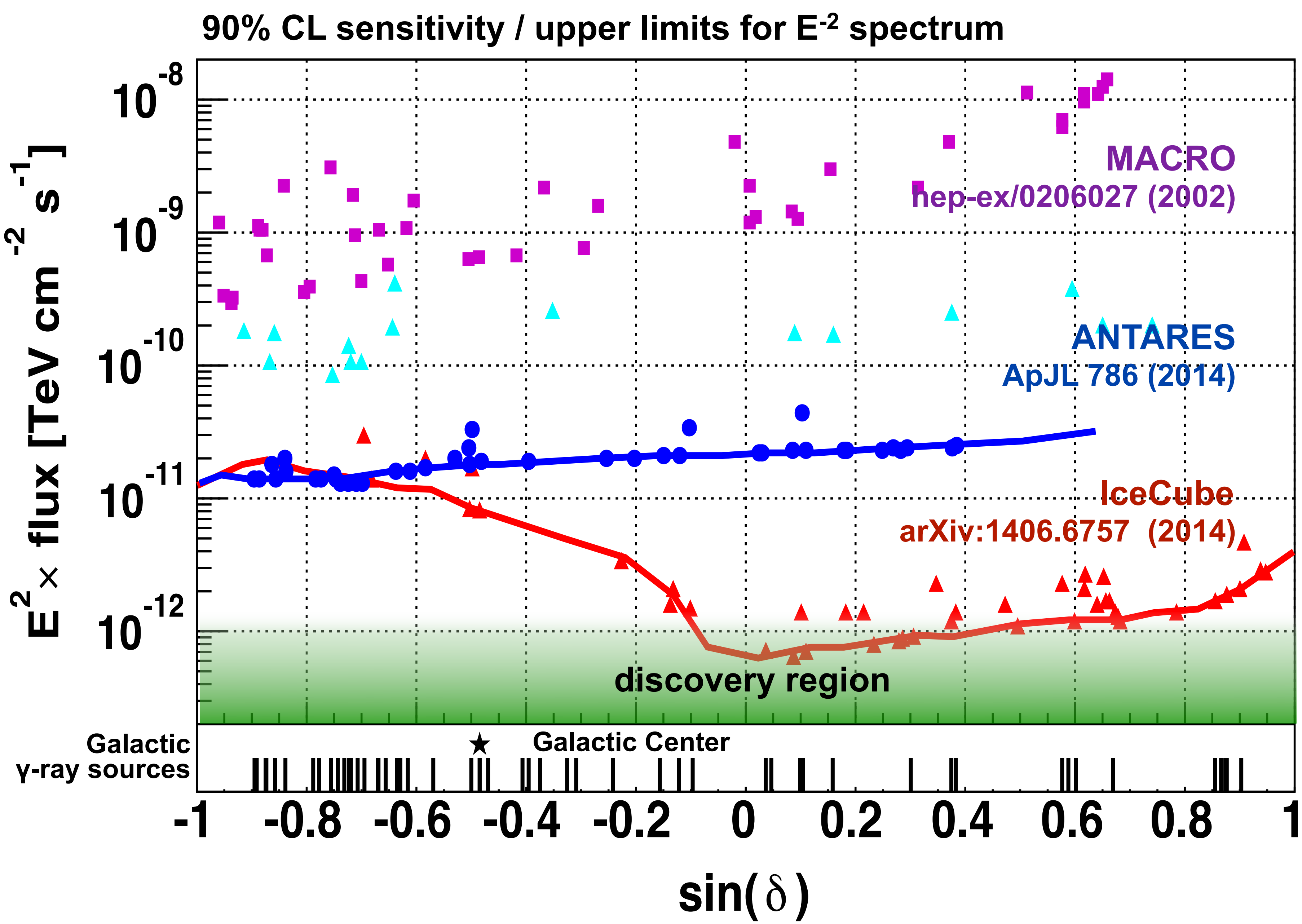


significance maps (equatorial coordinates)

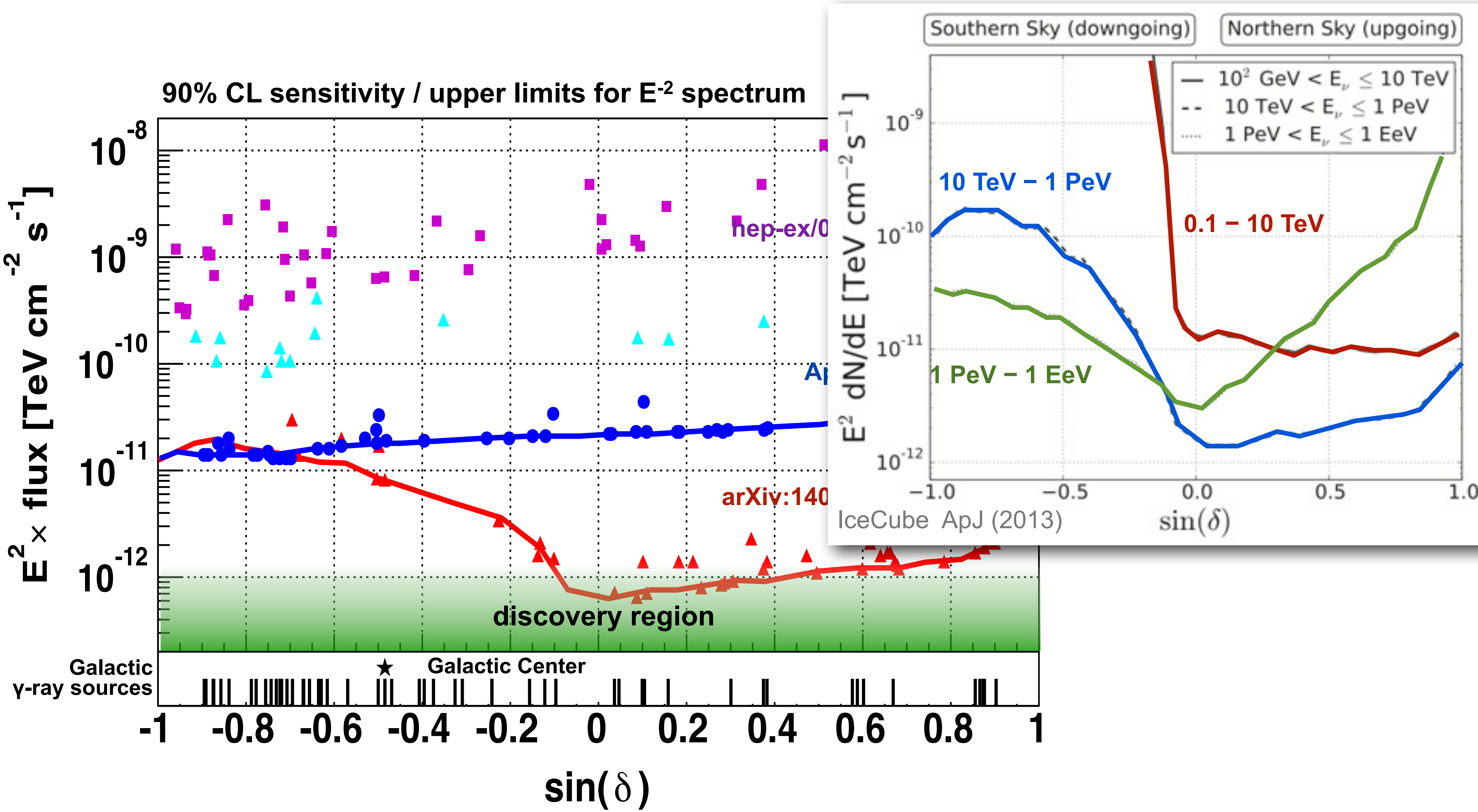
ANTARES
1338 days
~5500 ν
(up-going)



Point sources: Sensitivities & upper limits

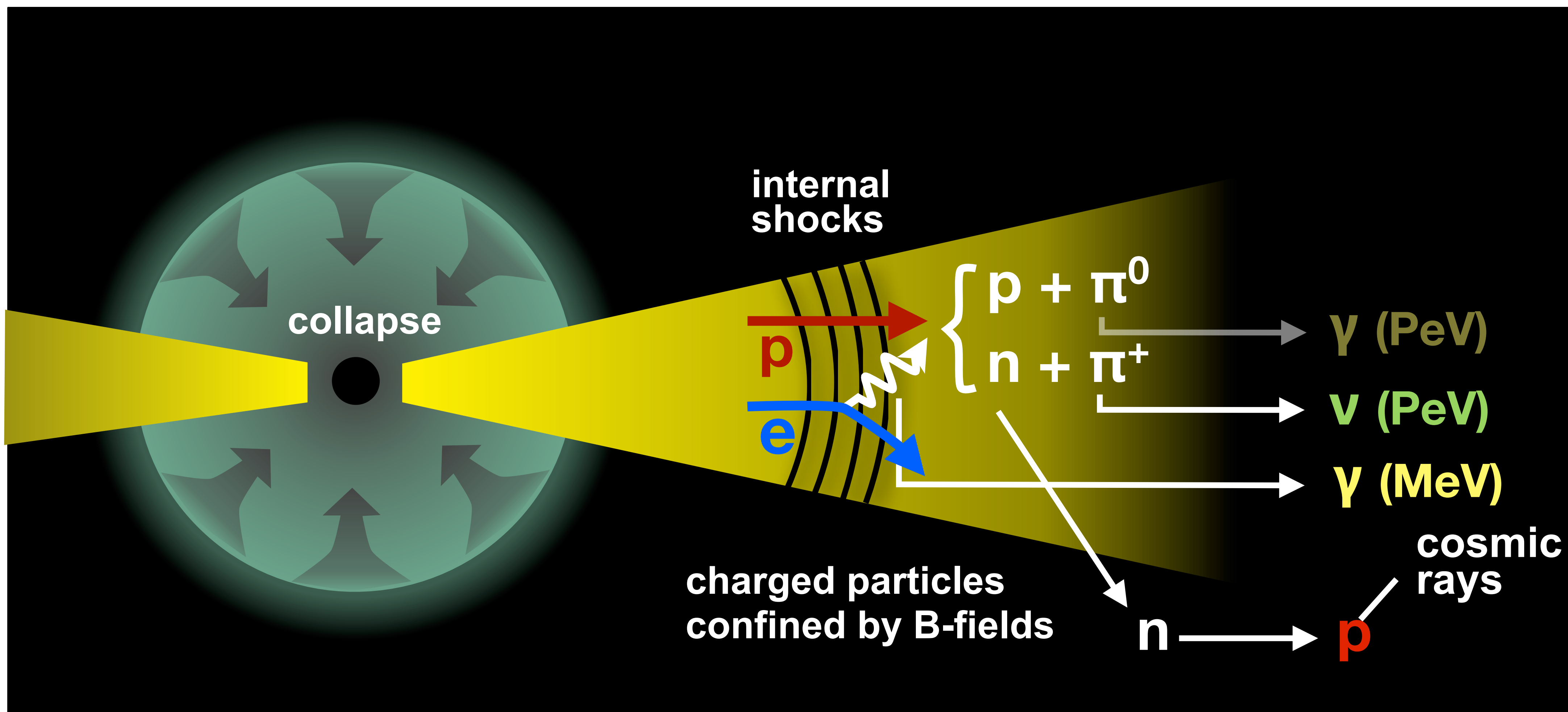


Point sources: Sensitivities & upper limits



Gamma-ray bursts (GRBs)

- Very intense flashes of γ radiation (keV-MeV) of short duration $\mathcal{O}(10\ \mathrm{s})$
- Eject material with Lorentz factor $\Gamma \gtrsim 300$
- One of few candidate source classes of ultra-high energy cosmic rays ($E > 10^{19}$ eV)



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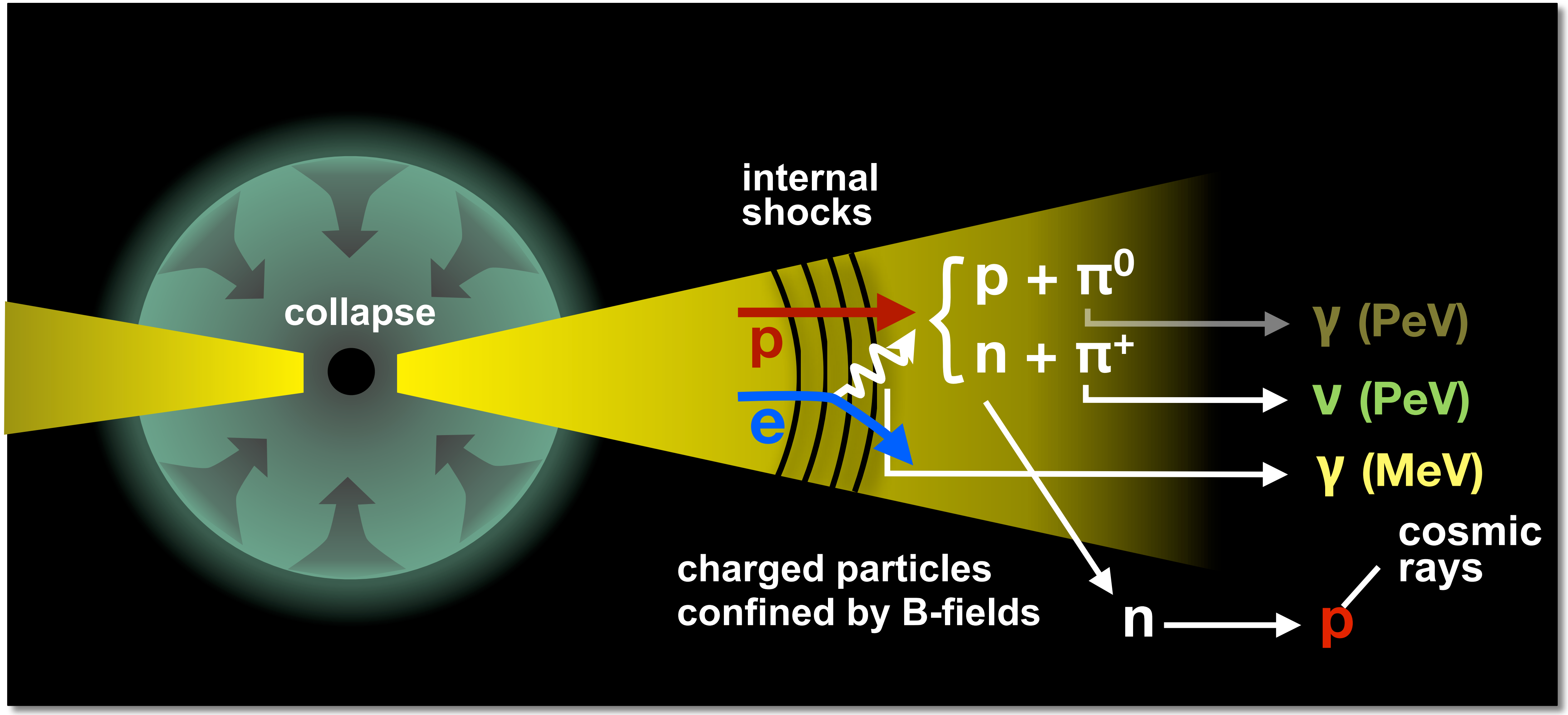
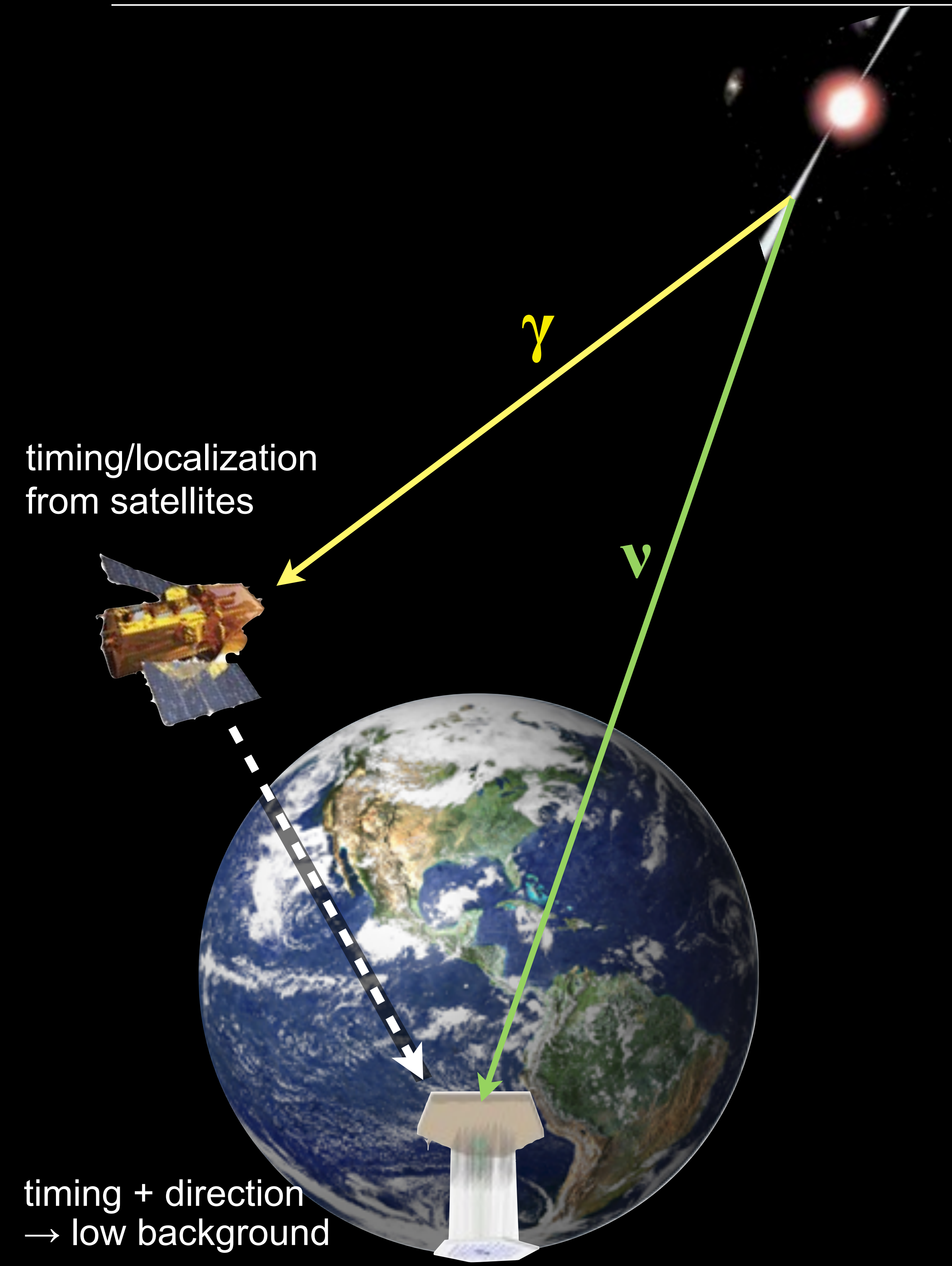
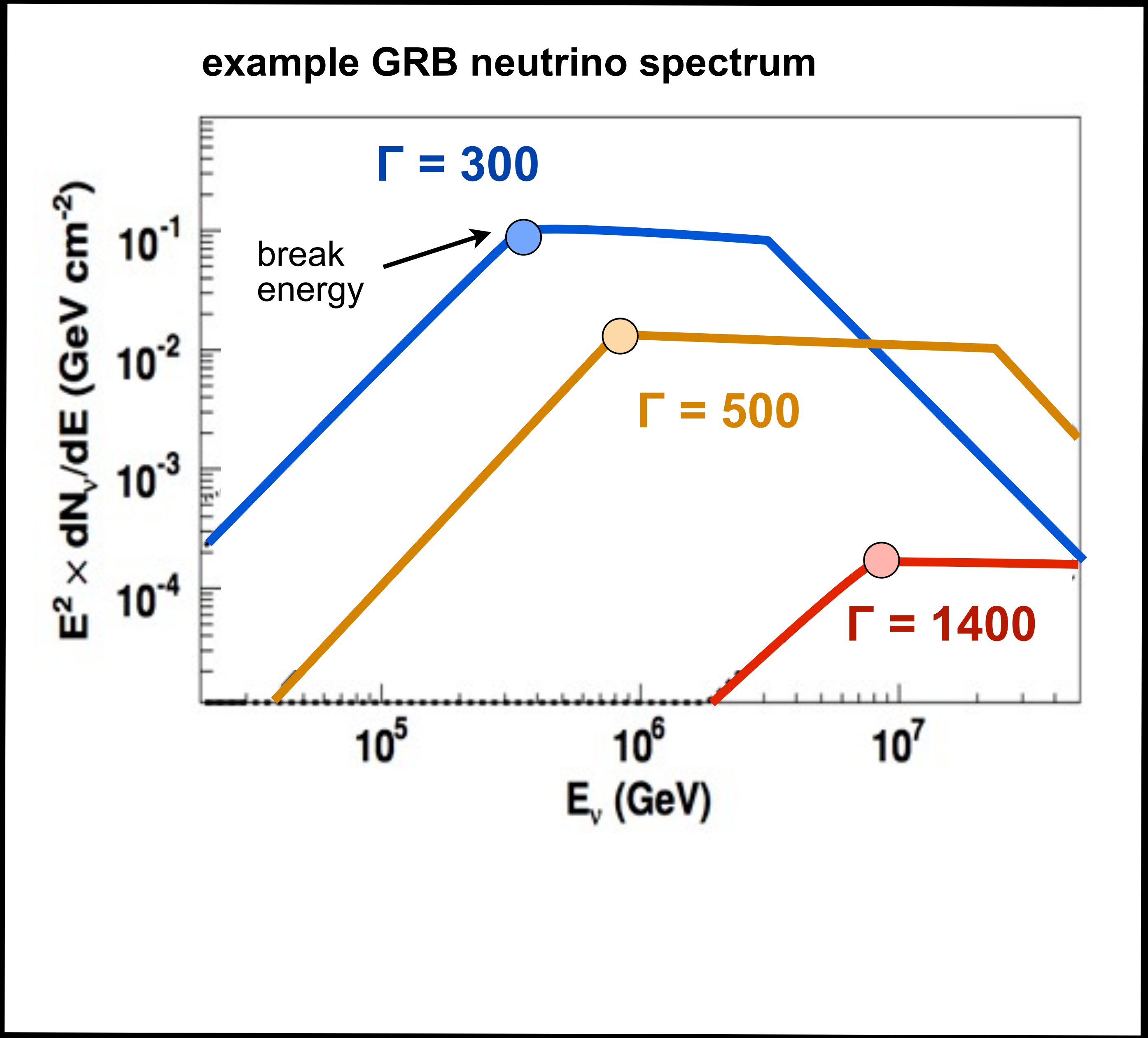


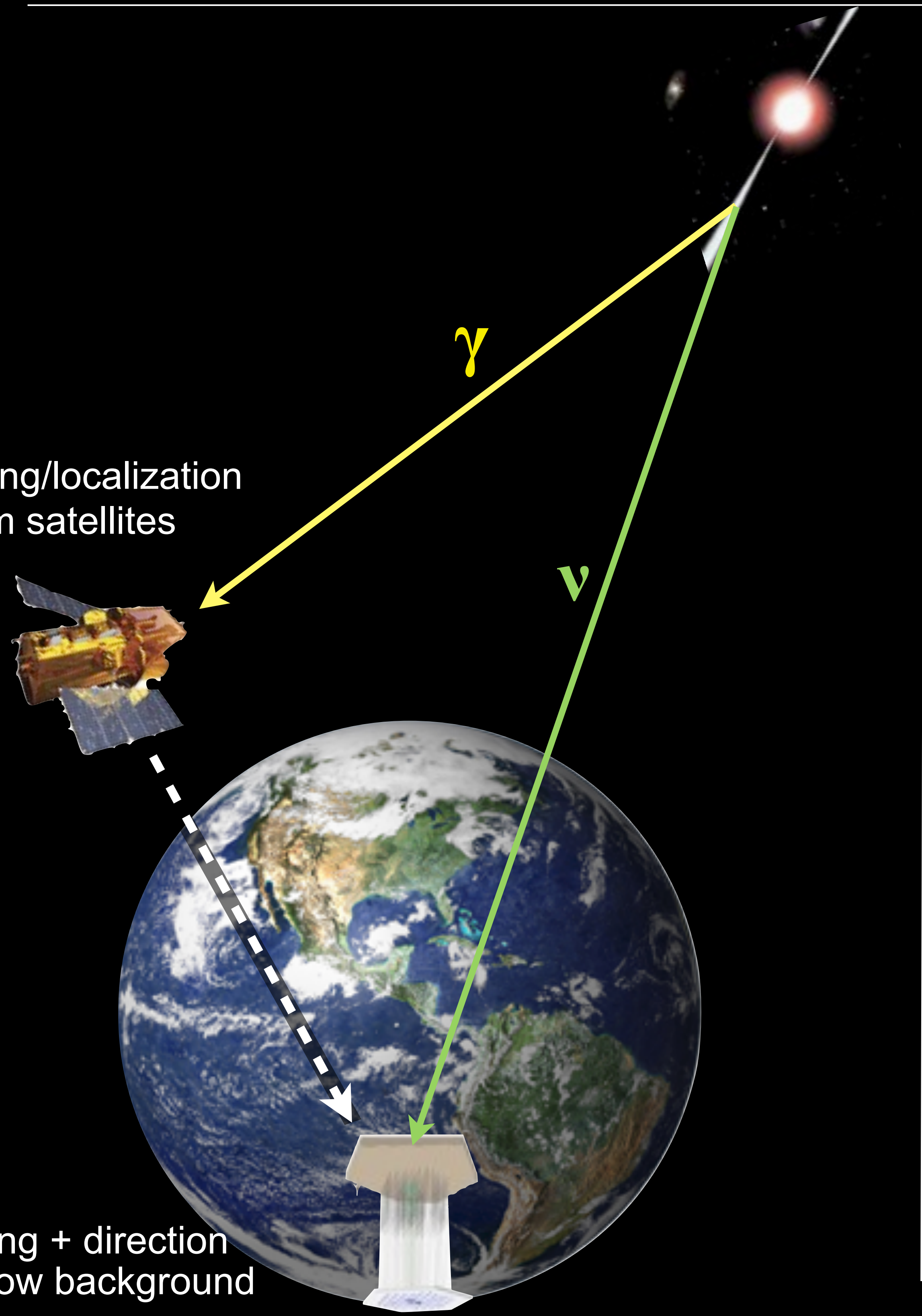
Neutrinos from gamma-ray bursts





Neutrinos from gamma-ray bursts

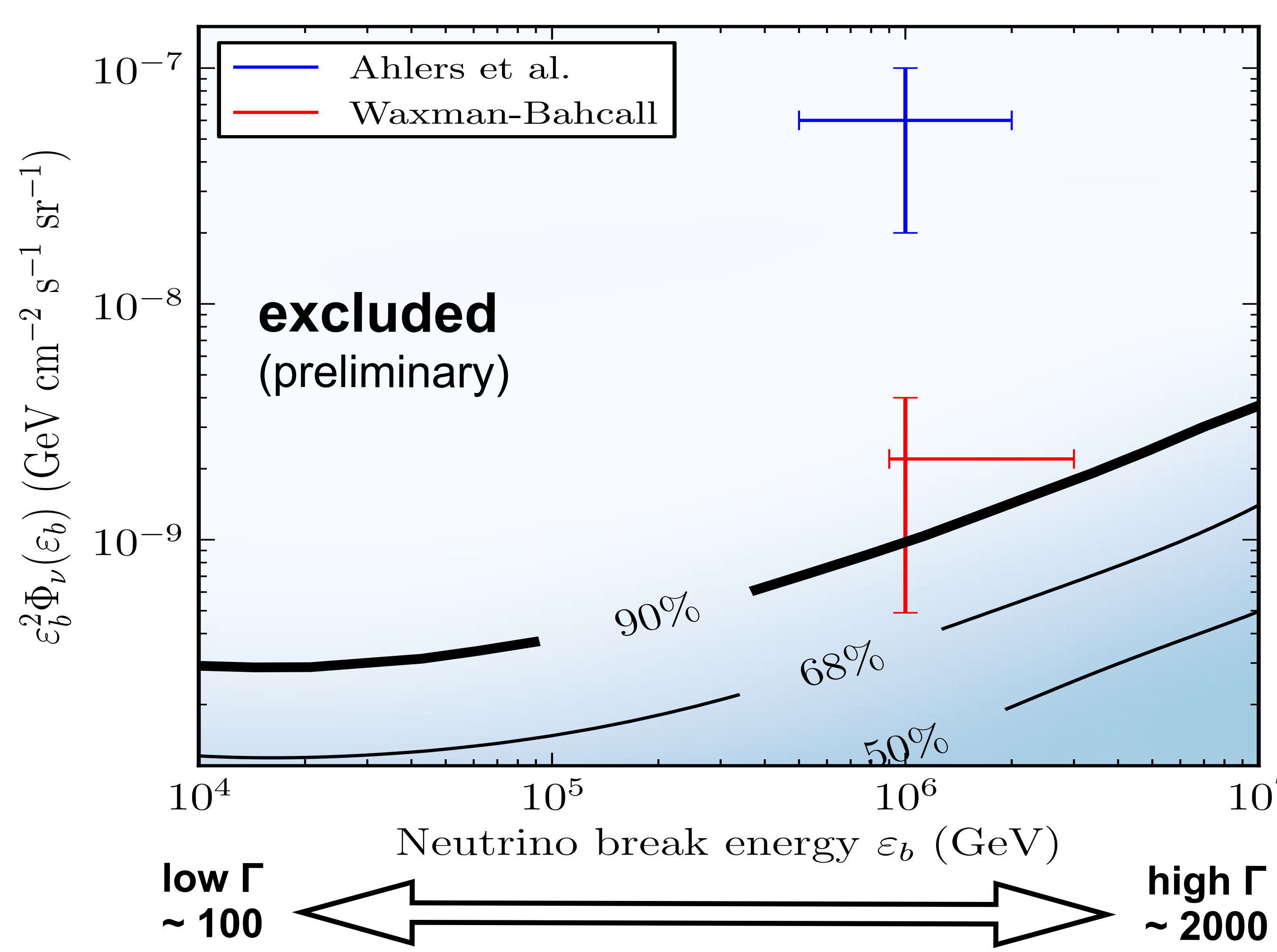
timing/localization
from satellites



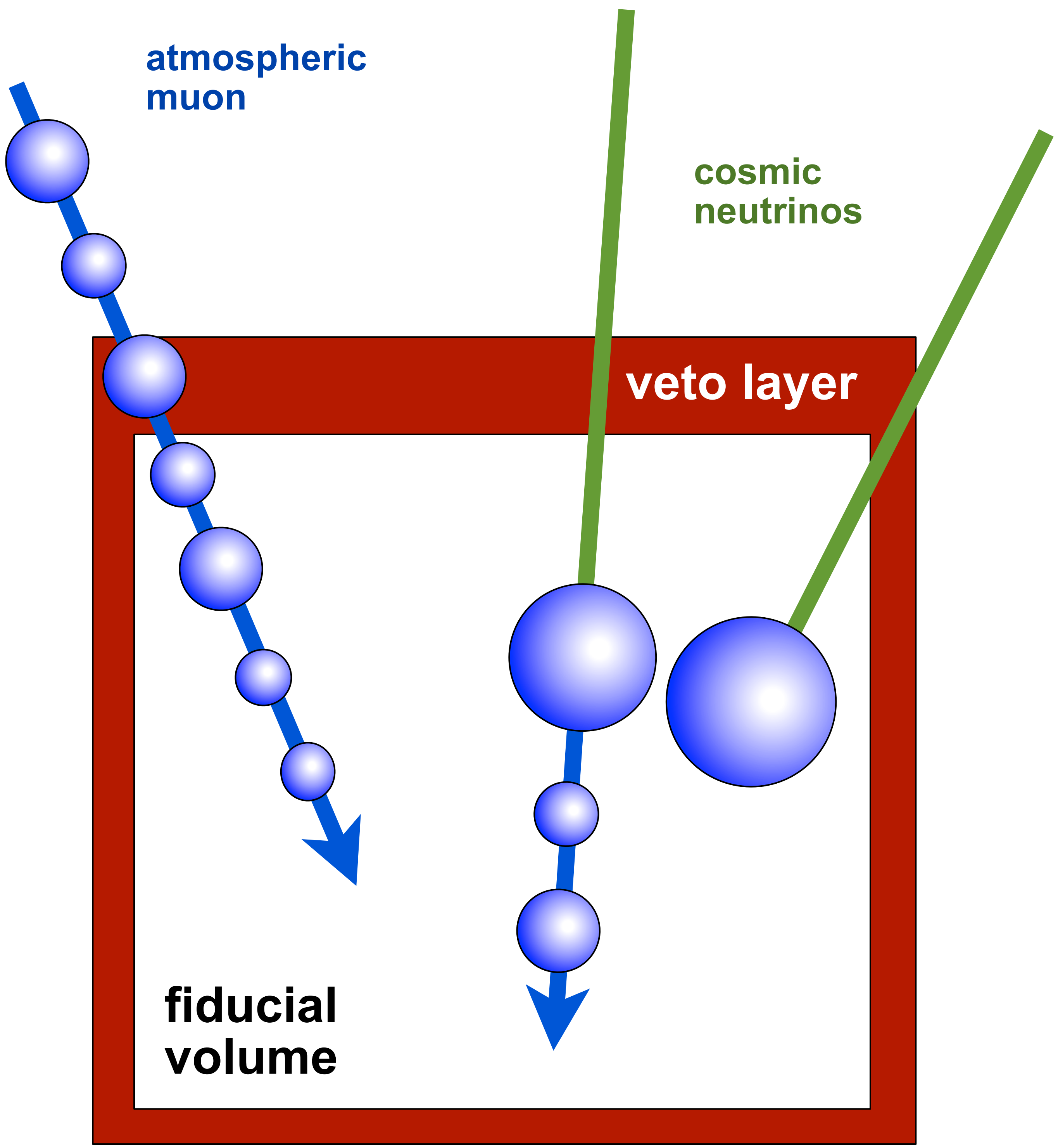
timing + direction
→ low background

IceCube: analysis of 506 GRBs → no correlation

Are GRBs really cosmic-ray sources?



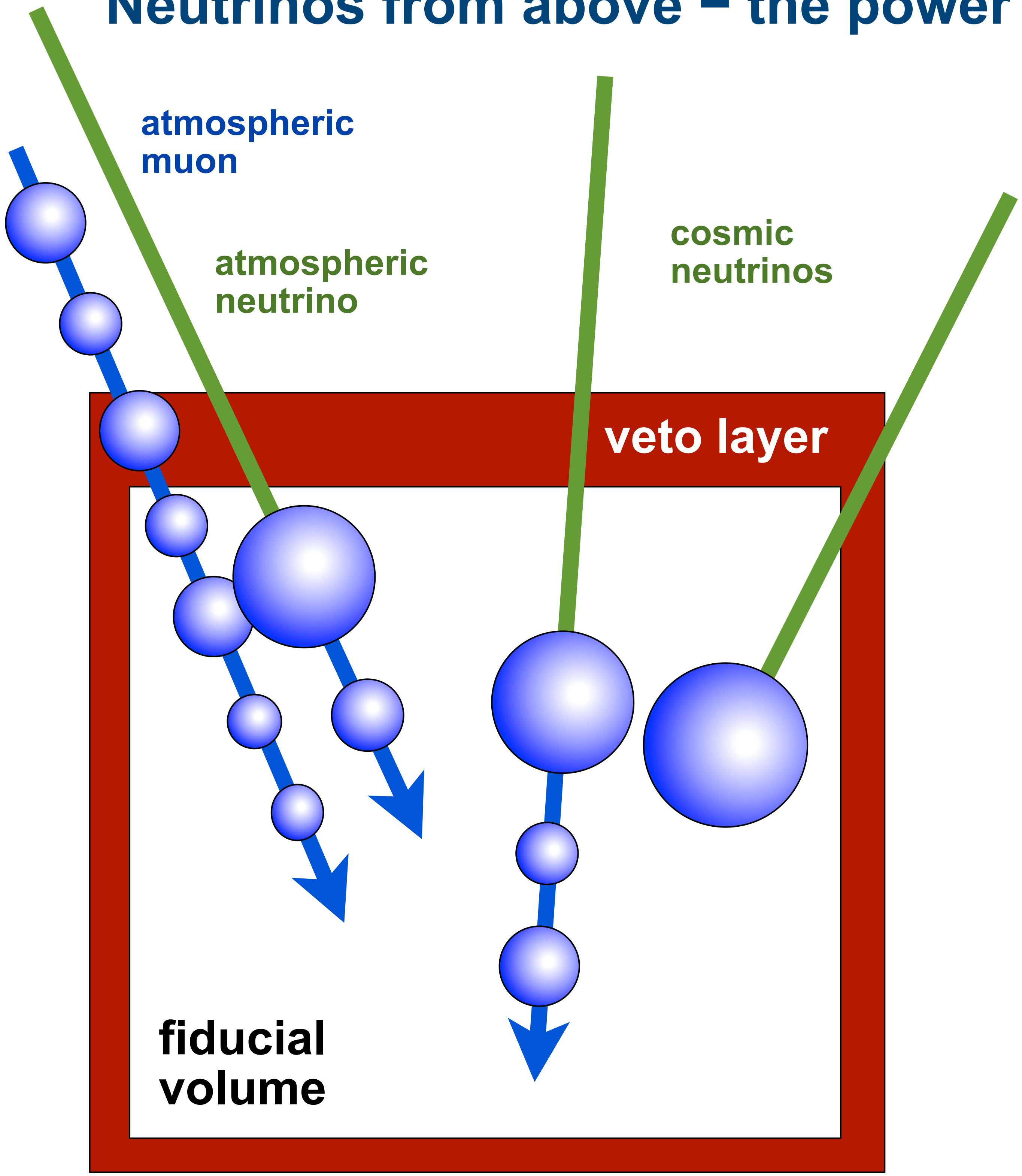
Neutrinos from above – the power of veto



First idea: Schönert et al., PRD (2009)

- Accept events with no light in veto layer
  + large signal in fiducial volume
  → cosmic neutrinos
- Reject events with light in veto layer
  → atmospheric muons

Neutrinos from above – the power of veto



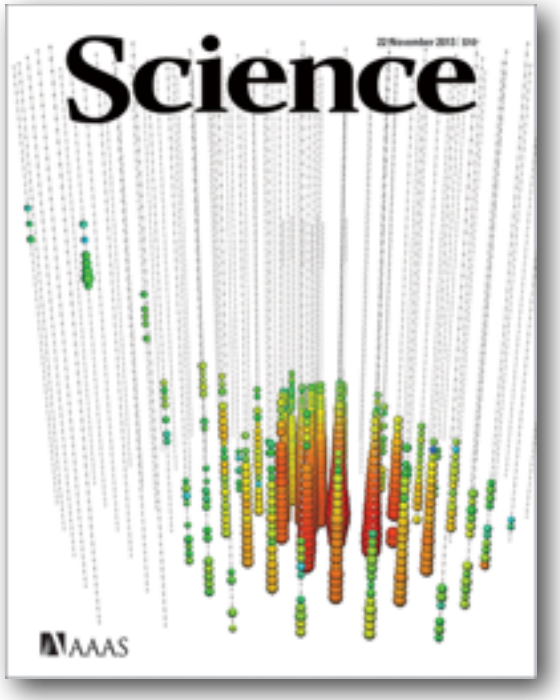
First idea: Schönert et al., PRD (2009)

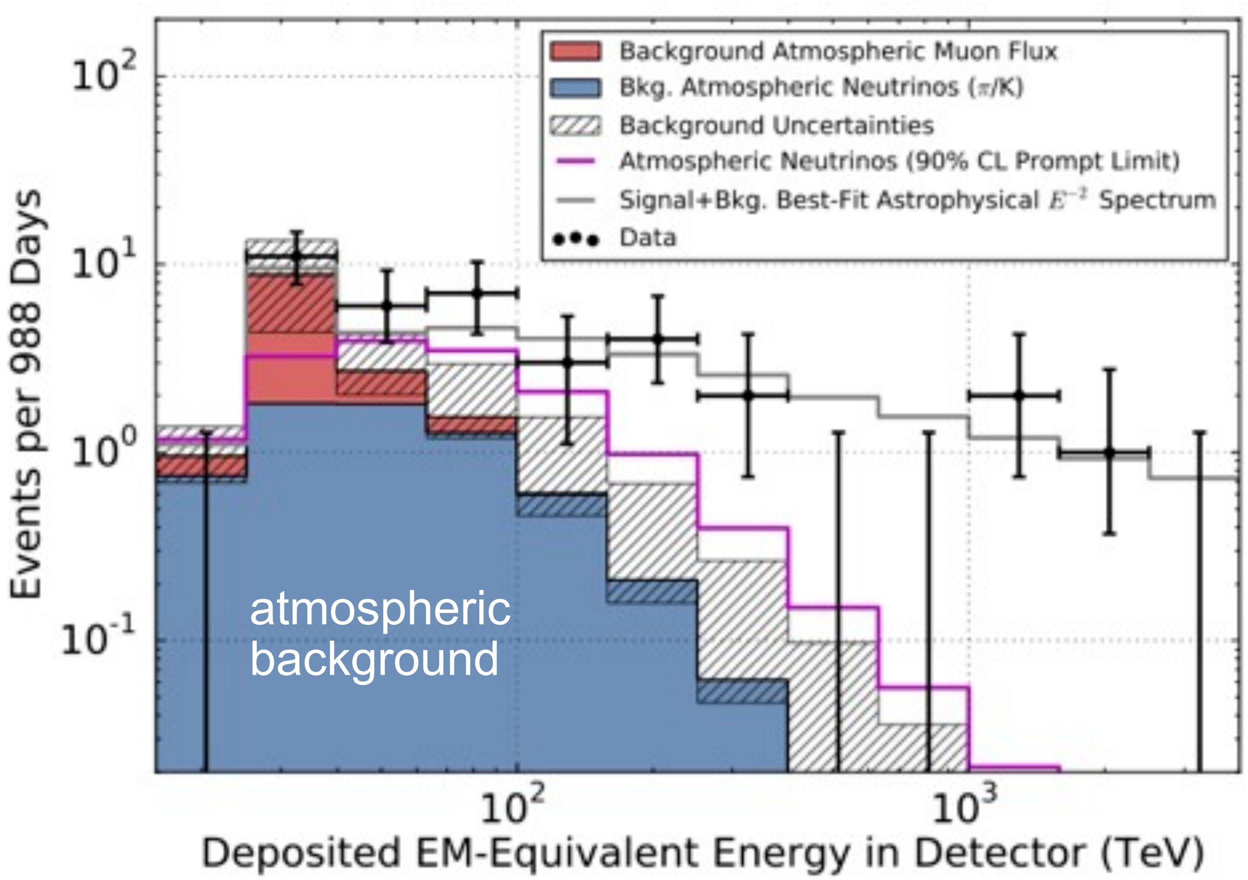
- Accept events with no light in veto layer + large signal in fiducial volume → cosmic neutrinos
- Reject events with light in veto layer → atmospheric muons
- Self-veto of atmospheric neutrinos through accompanying muons ! (muons can range out at low energies)

Discovery of cosmic neutrinos with IceCube

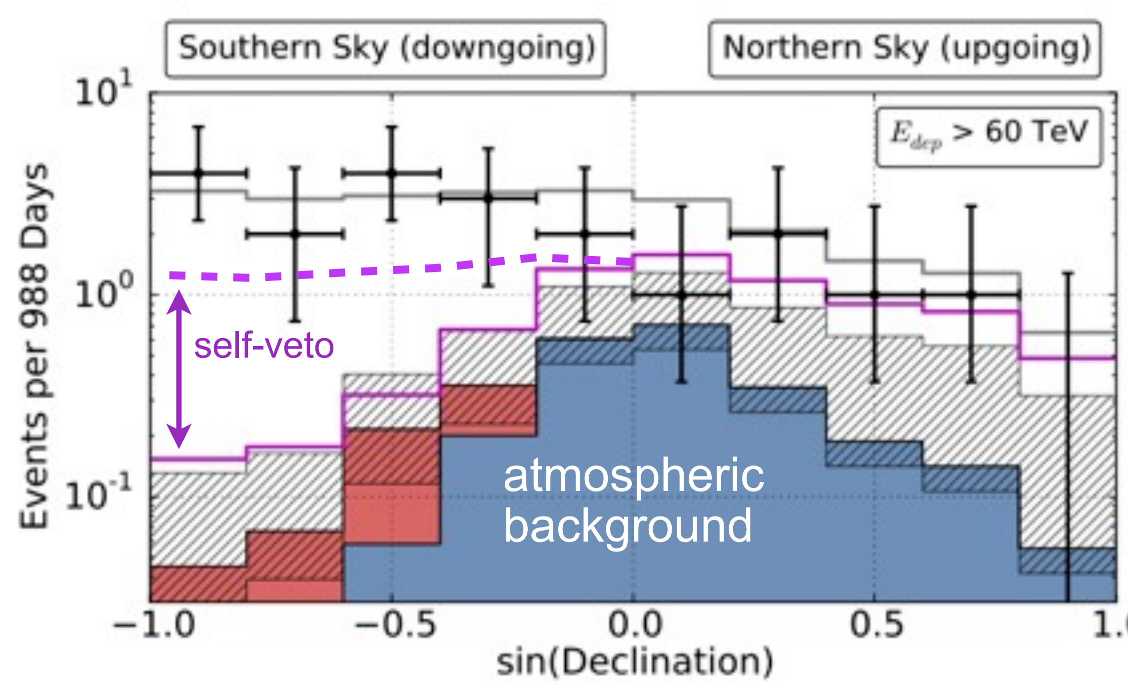
- Search for **H**igh-**E**nergy-**S**tarting **E**vents (HESE)
- 2 years data: 28 events observed (background $10.6^{+5.0}_{-3.6}$ → 4.2σ)
  → IceCube, Science (2013)

- 2+1 year data: observed 28+9 events (background $15.0^{+7.2}_{-4.5}$)
  - 2-d fit (zenith+energy) → 5.7σ rejection of atmospheric-only hypothesis
  - compatible with isotropic flux with flavor ratio (1:1:1)
  - best-fit astrophysical E^{-2} flux: $E^2\Phi \approx 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
    (best-fit slope $E^{-2.3}$)

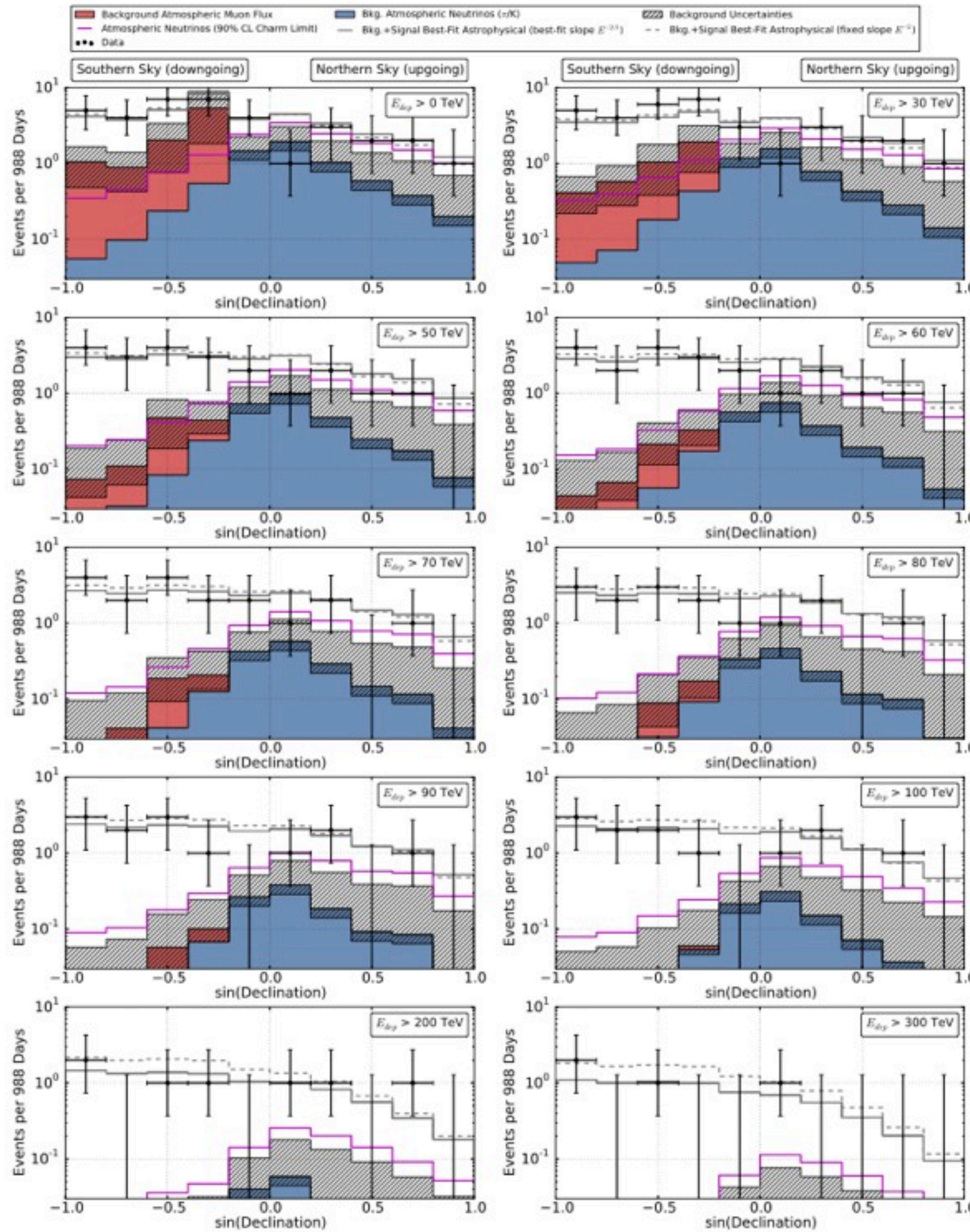




IceCube, arXiv:1405.5303 (2014)
accepted by PRL



Declination distribution for different energy cuts



Tracks vs. cascades

E_{dep} > 60 TeV IceCube, arXiv:1405.5303 (supplements)

	nom. atm. muons	nom. (best-fit) atm. neutrinos	cosmic neutrinos ($E^{-2.3}$ best-fit)	**sum nom. (best-fit)**	**data**
all events	~0.4	2.4 (1.4)	18.6	**21.4**	**20**
tracks	~0.4	1.7 (1.0)	3.5	**5.5 (4.8)**	**4**
cascades	~0	0.7 (0.4)	15.1	**15.8 (15.4)**	**16**
tracks/cascades	–	~2.5	~0.2	**~0.35 (~0.3)**	**~0.25**

- xsec(CC) ≈ 2 · xsec(NC)
  relative cross sections

	ν_e	ν_μ	ν_τ
NC	**1**	**1**	**1**
CC	**2**	**2**	**2**

cascades **tracks**

- (1 : 1 : 1) flavor ratio yields
  - 7/9 ≈ 80% cascades
  - 2/9 ≈ 20% tracks
- conv. atmospheric neutrinos > TeV mostly ν_μ
  - 1/3 ≈ 35% cascades
  - 2/3 ≈ 65% tracks

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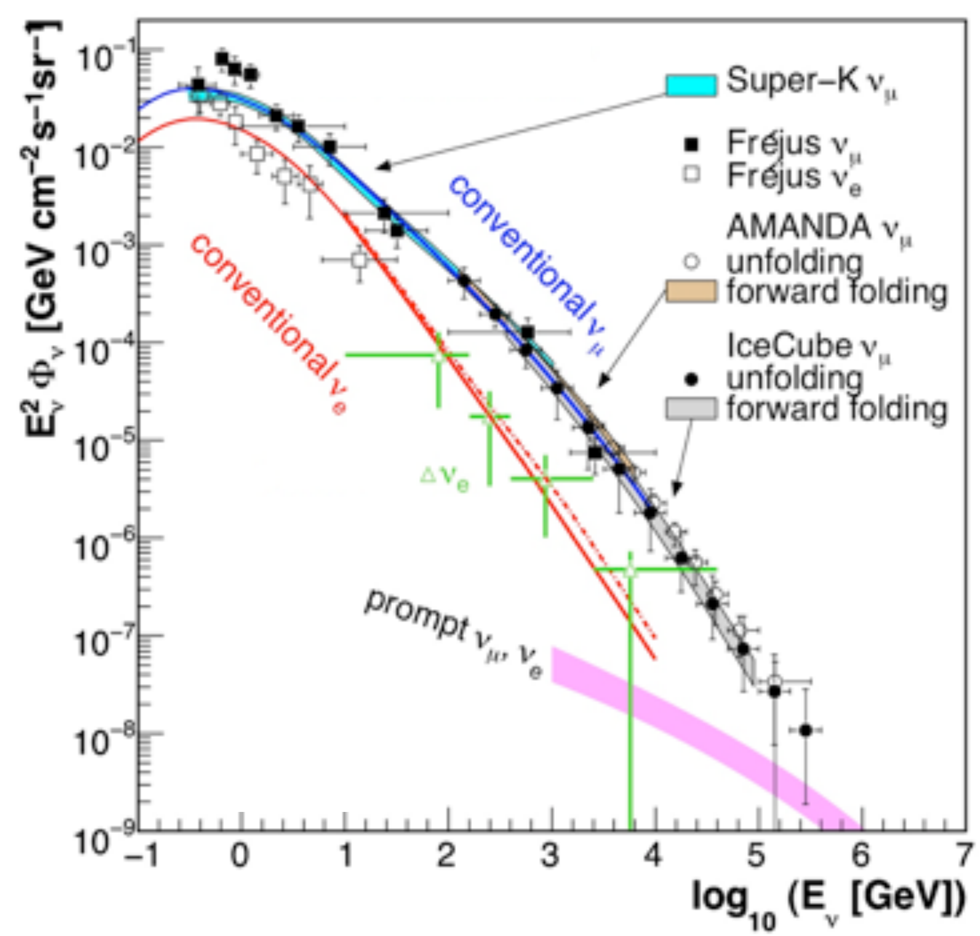
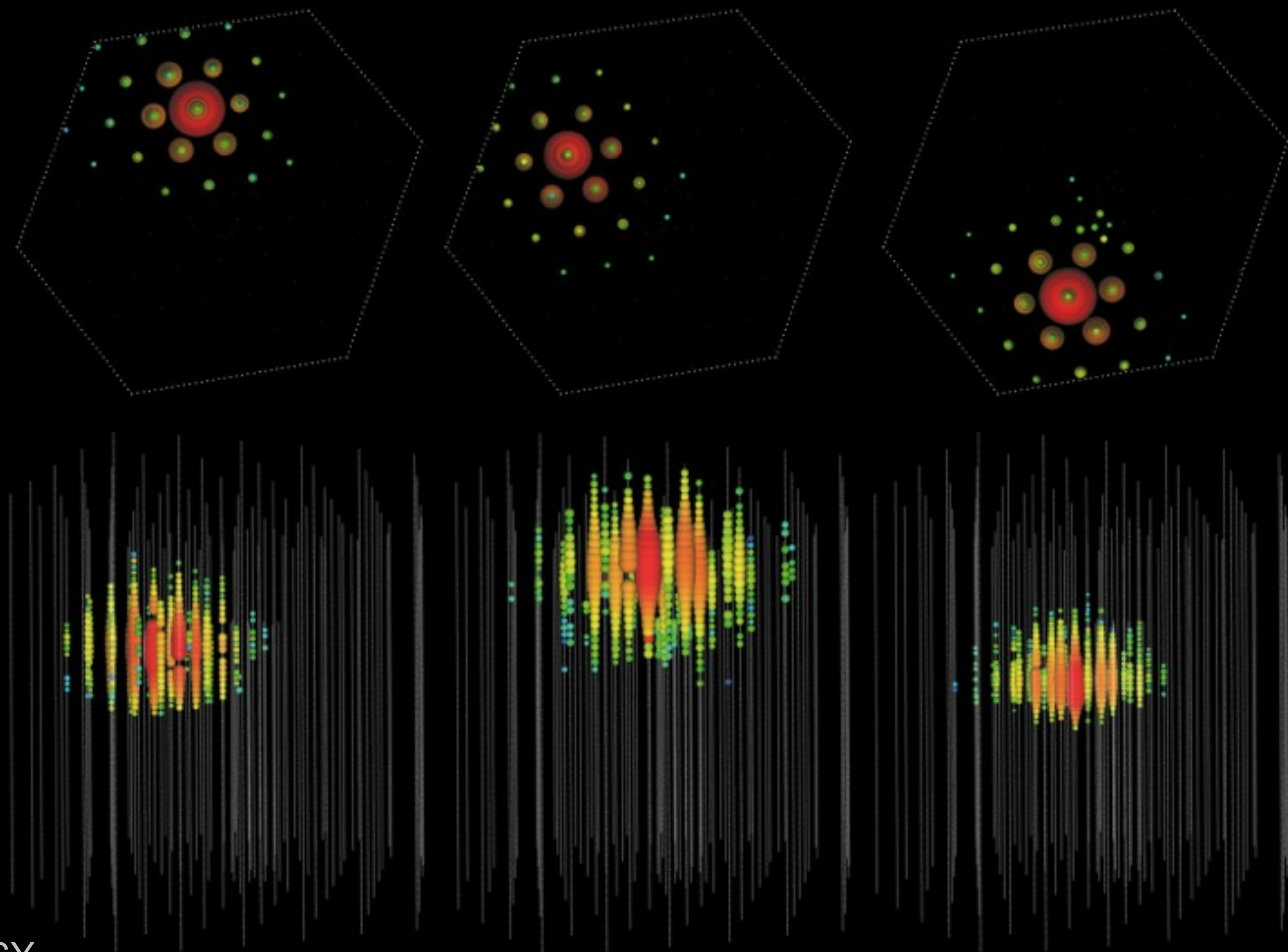


The PeV neutrinos

Ernie
E = 1.1 PeV, θ = 23º

Bert
E = 1.0 PeV, θ = 62º

Big Bird
E = 2.0 PeV, θ = 34º

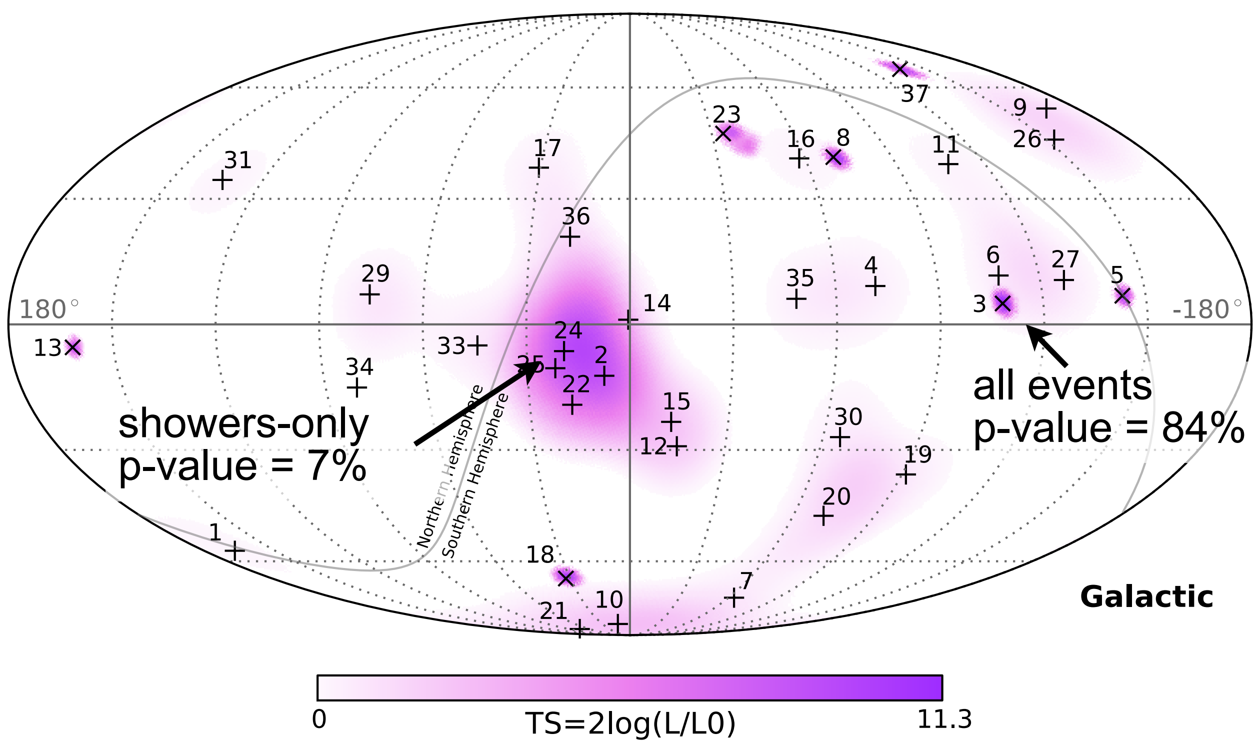


PETRA II accelerator DESY

Berlin television tower

Can we identify sources?

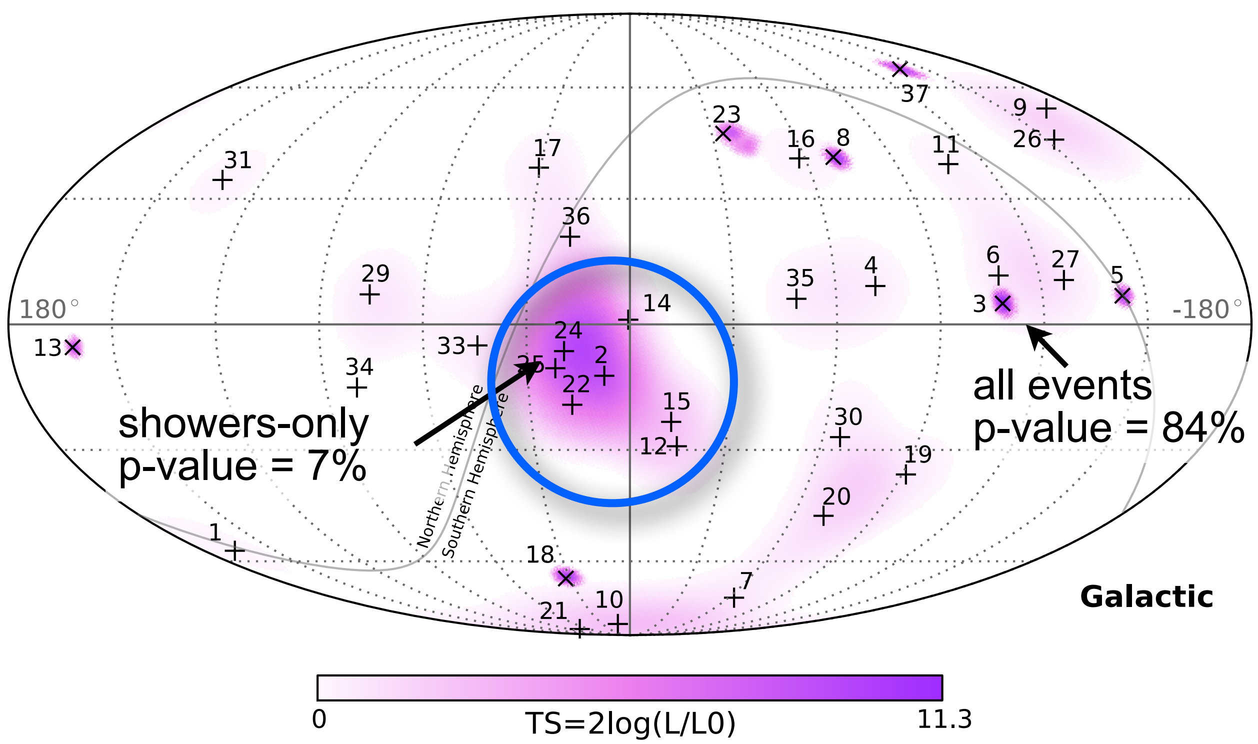
IceCube skymap



no indication for individual sources
no correlation with Galactic plane

Can we identify sources?

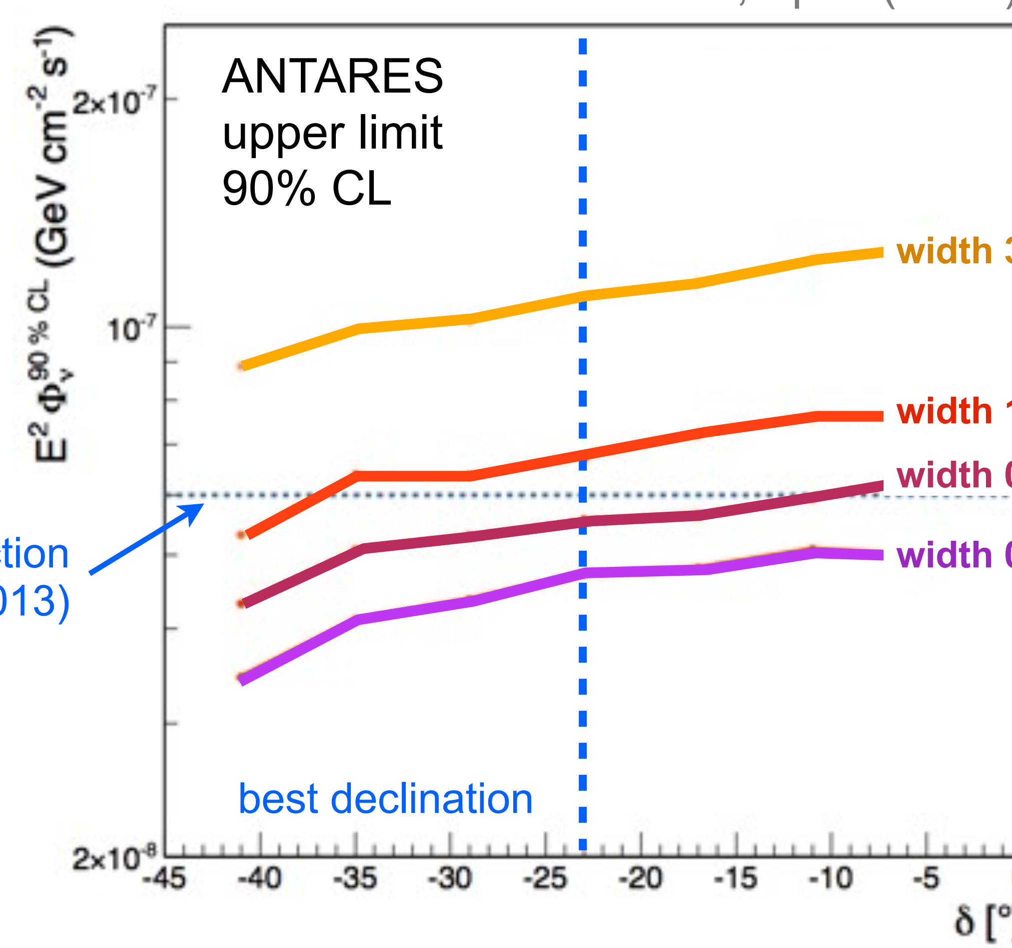
IceCube skymap



no indication for individual sources
no correlation with Galactic plane

- 7 cascades in “hot-spot”
  → low angular resolution
- ANTARES search for source with width 0° − 3°
  → source < 0.5° excluded

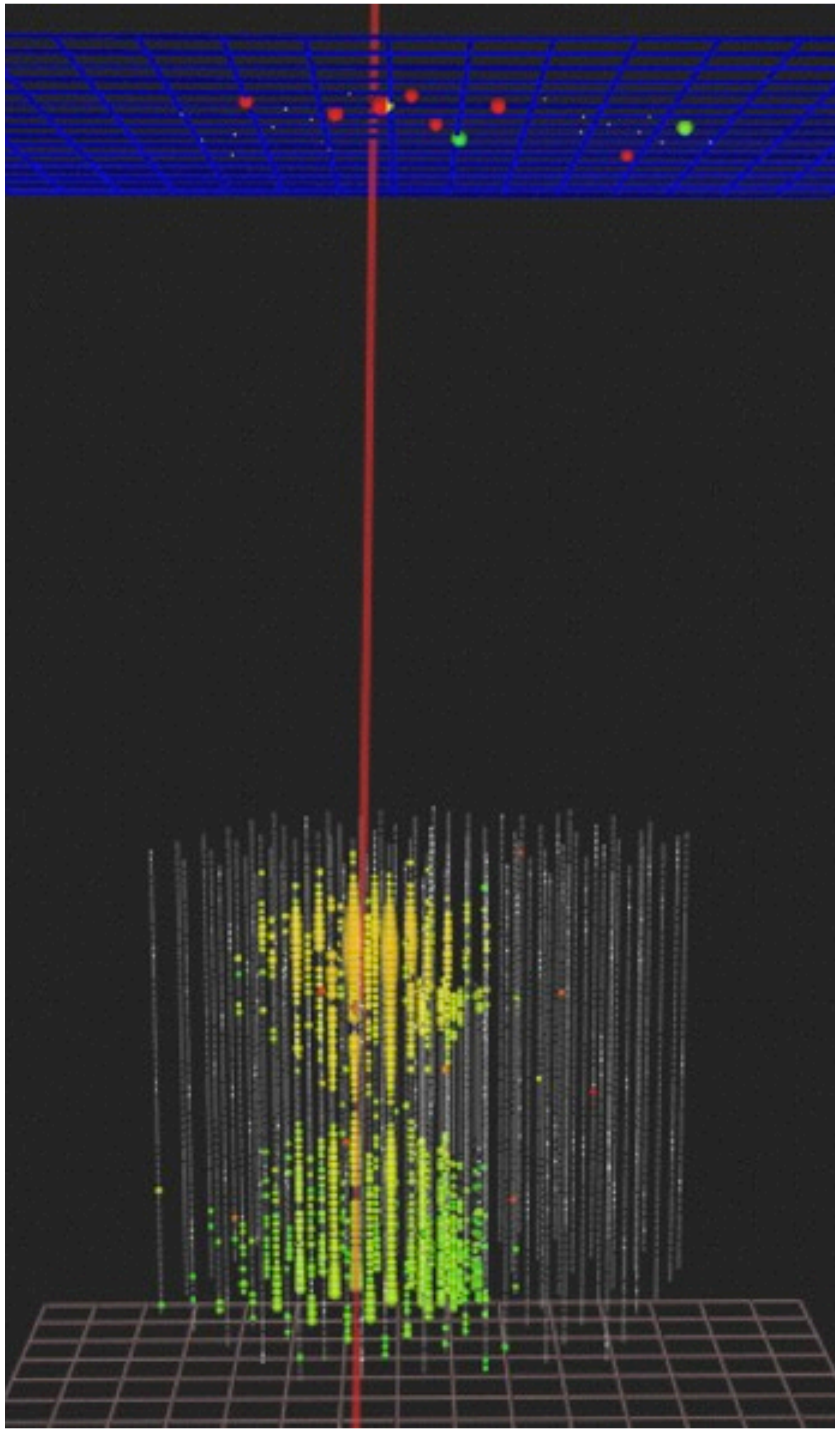
ANTARES, ApJL (2014)



hot-spot (7 events) flux prediction
Gonzalez-Garcia et al. (2013)

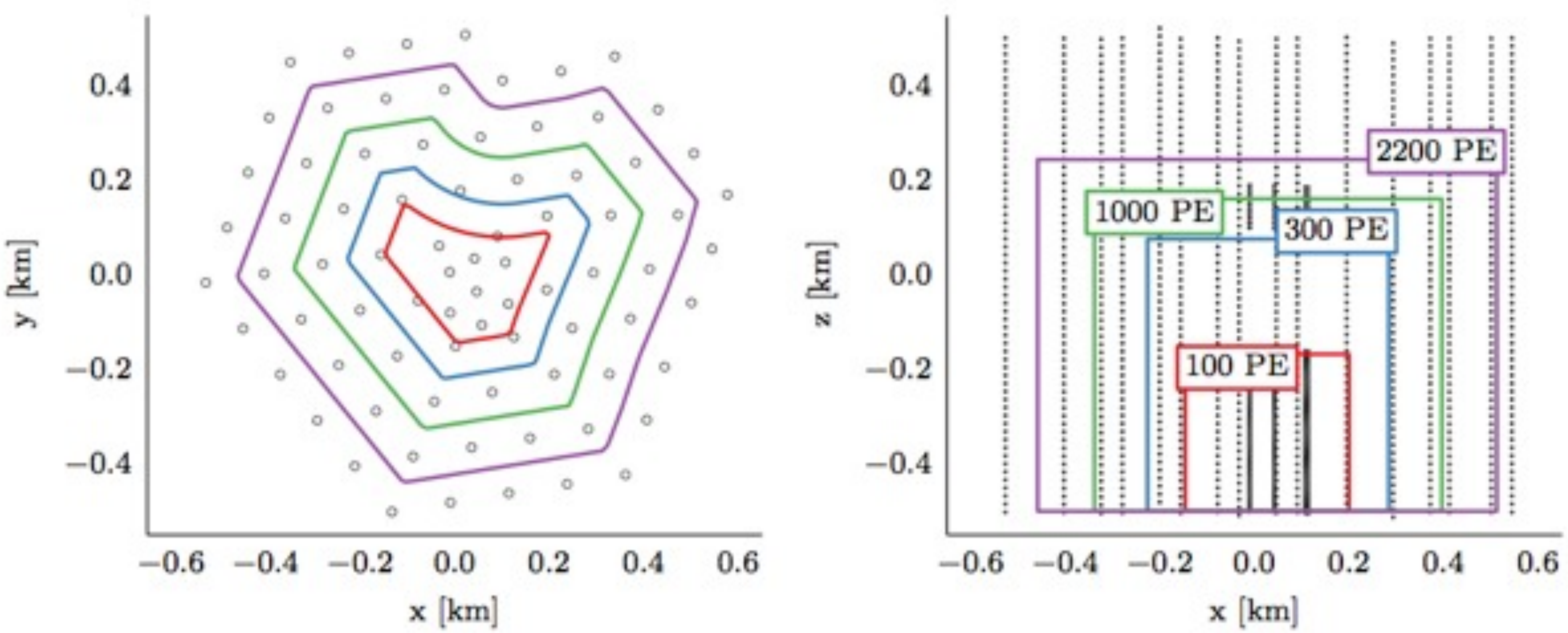
Latest news: 4th HESE year (IC86-II)

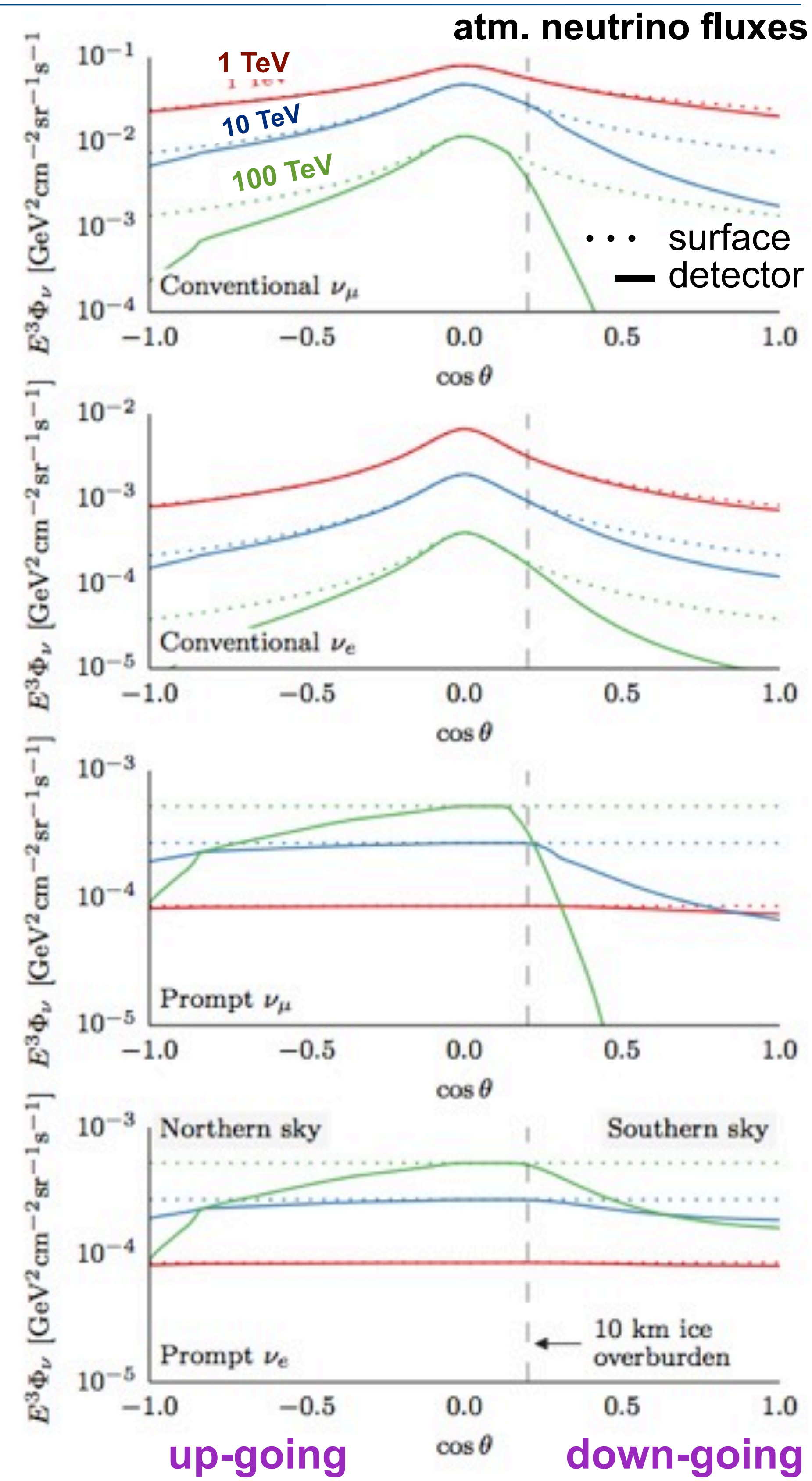
- 17 additional events above 30 TeV
  (no new Sesame Street characters)
- More information soon



Lowering the energy threshold

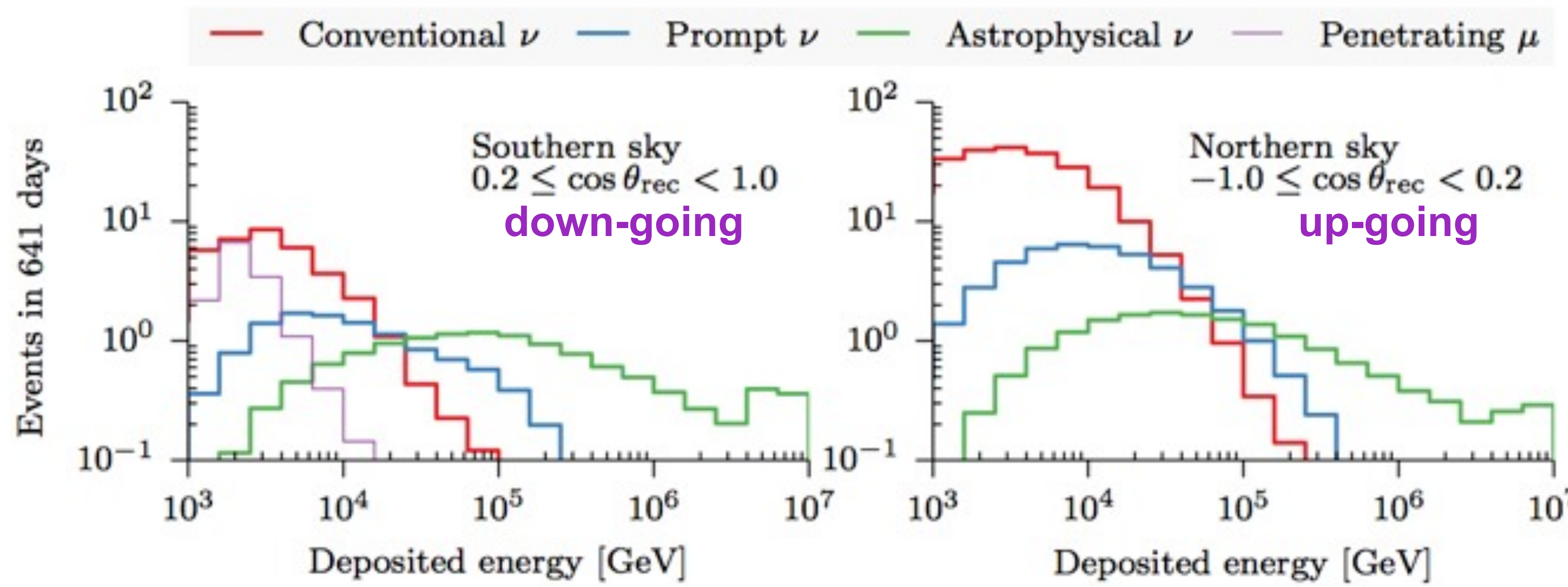
- **M**edium **E**nergy **S**tarting **E**vent (MESE) search
- Sliding veto region: grows with decreasing energy (≥ 2 hits associated with potential muon)
- Lowers threshold for cosmic neutrinos down to 10 TeV



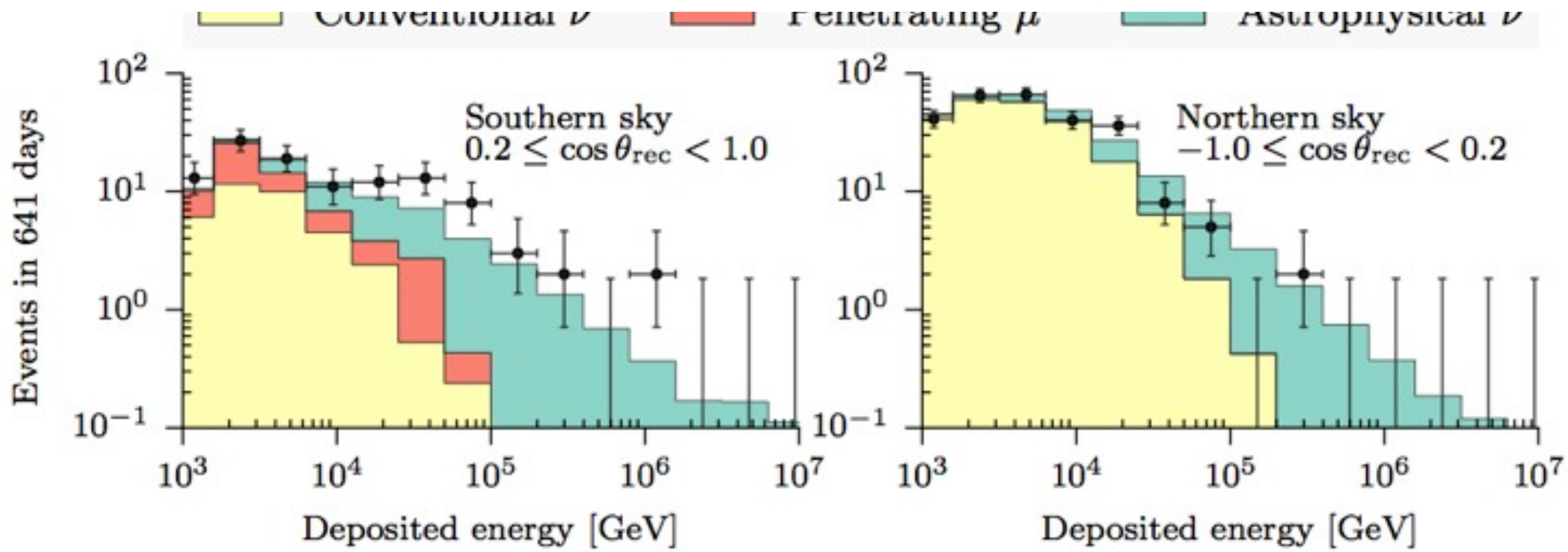


Multi-flavor, all-sky search in IC79+86-I

Nominal fluxes



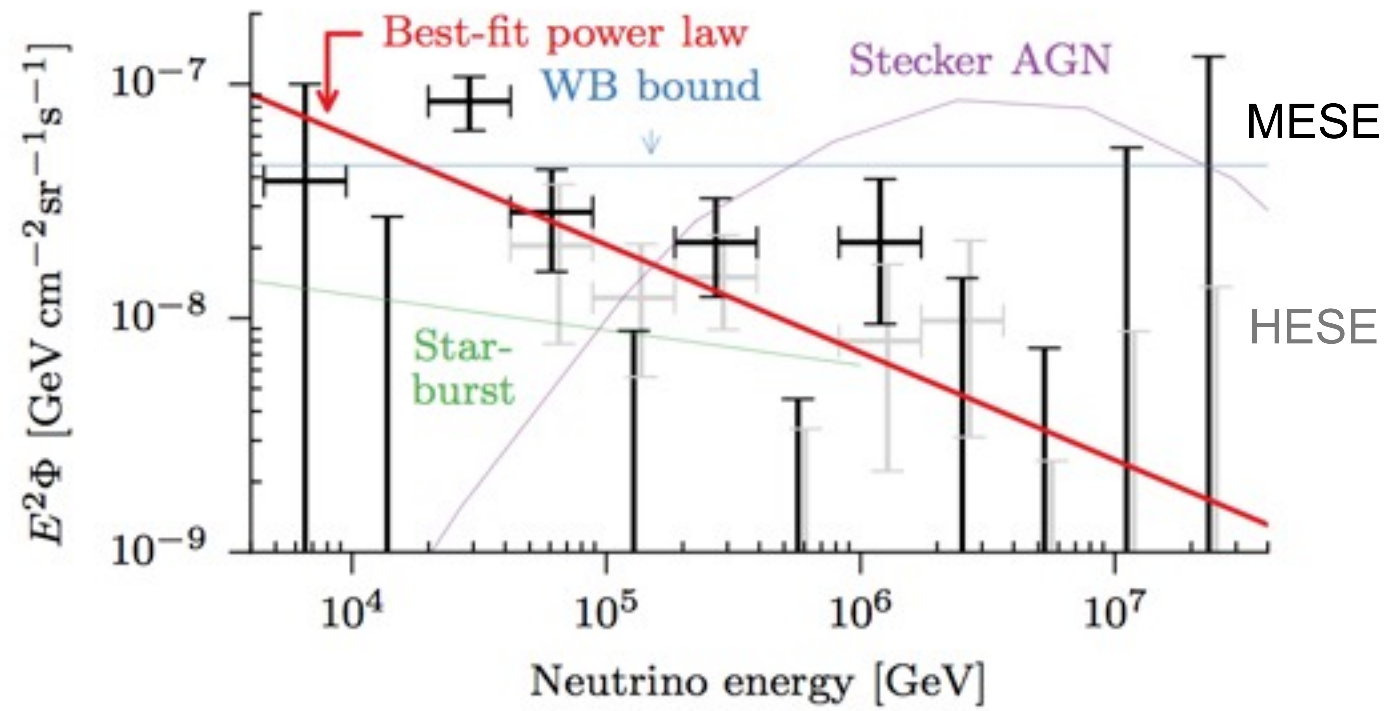
Best fit fluxes



Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\,\Phi_{\mathrm{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\,\Phi_{\mathrm{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\,\Phi_{\mathrm{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ $\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$	87^{+14}_{-10}
Astrophysical γ	-2.46 ± 0.12	

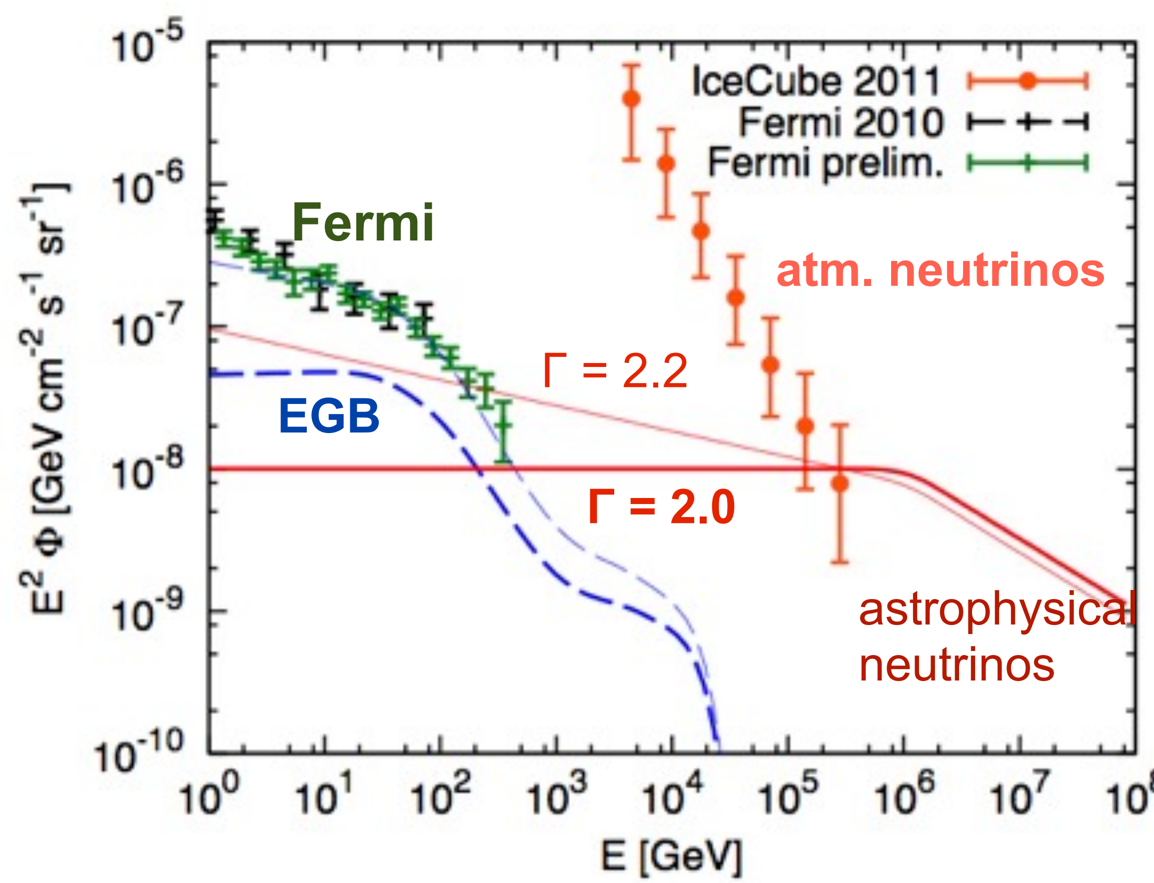
A steep spectrum

- Spectrum compatible with HESE
- Best fit index for single power law:
  Γ = 2.5±0.1



Implications:

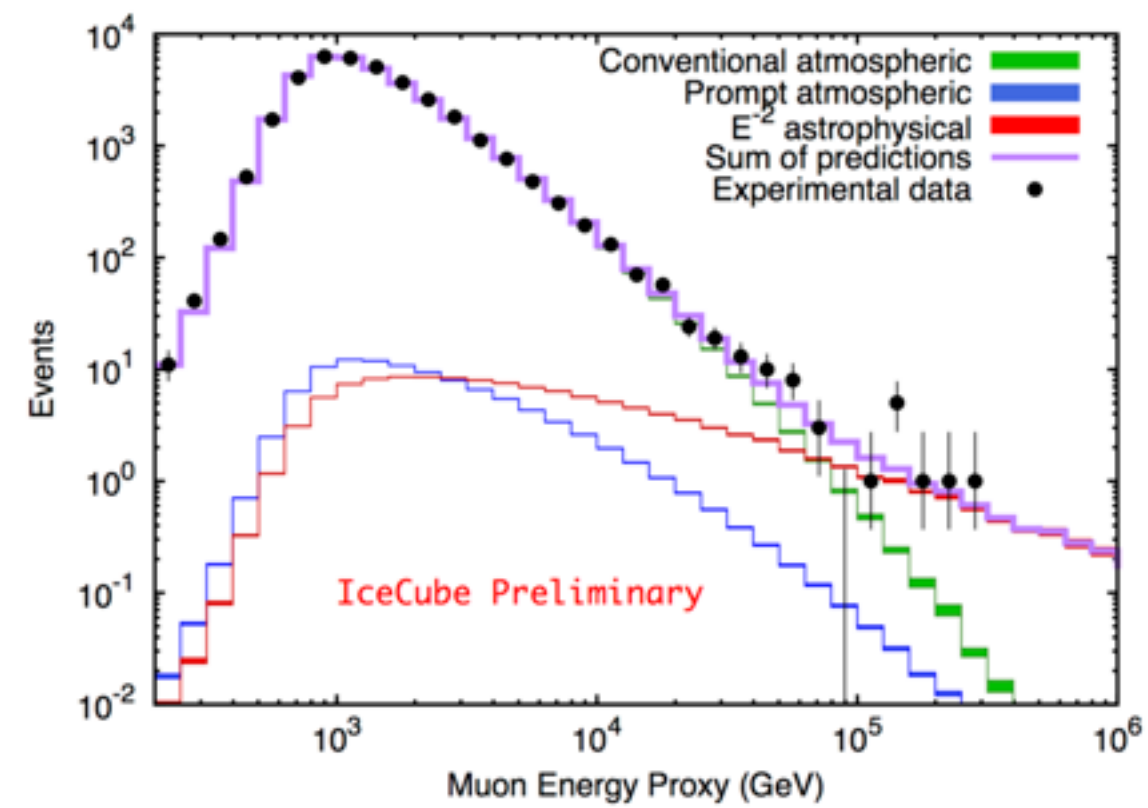
- for pp interactions, ν and γ spectra follow initial proton power-law spectrum
  → comparison of IceCube flux with GeV photons
- Extragalactic γ Background (EGB) measured by Fermi → Γ ≲ 2.2
  → pγ, sources optically thick, atm. flux @ $\mathcal{O}$(10 TeV) not understood ... ?

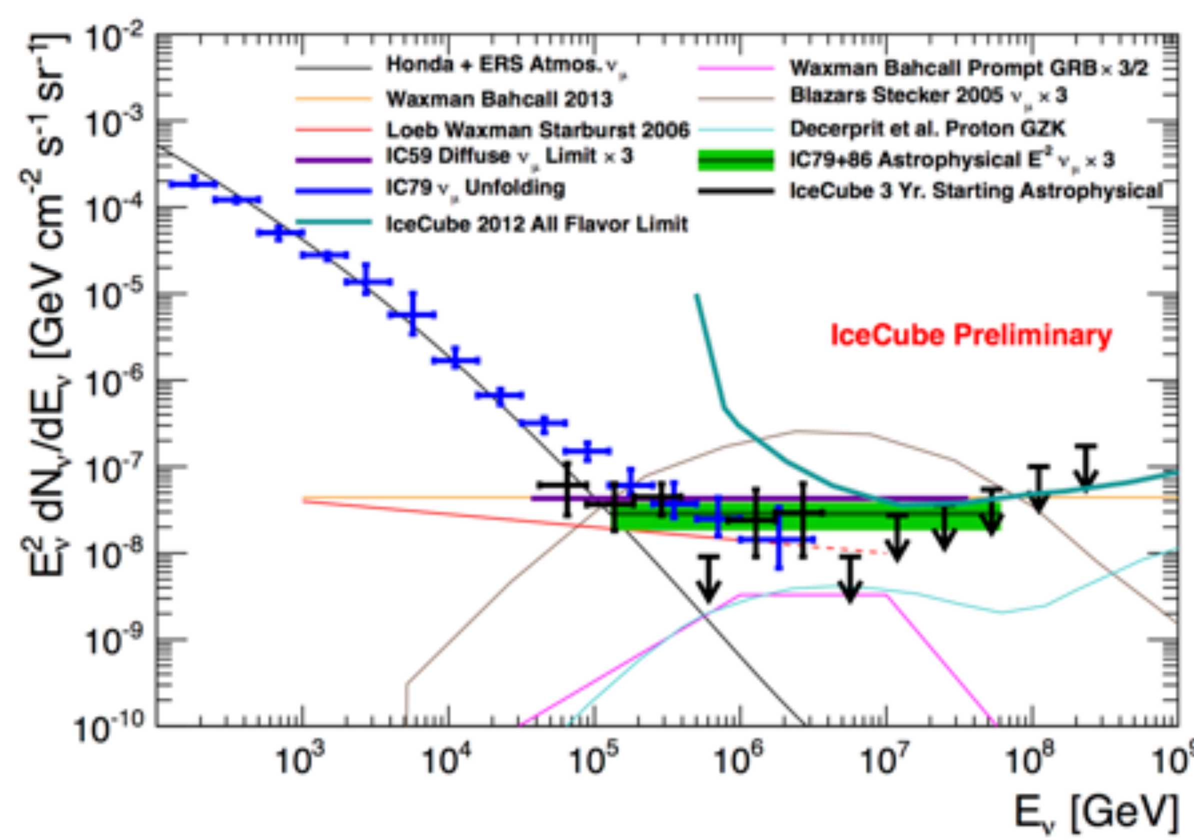


Murase et al., Phys.Rev. D88 (2013)

Upgoing neutrinos (IC79+86-I)

- Cosmic neutrino flux also visible in up-going neutrinos (3.9σ)
- Compatible with other measurements



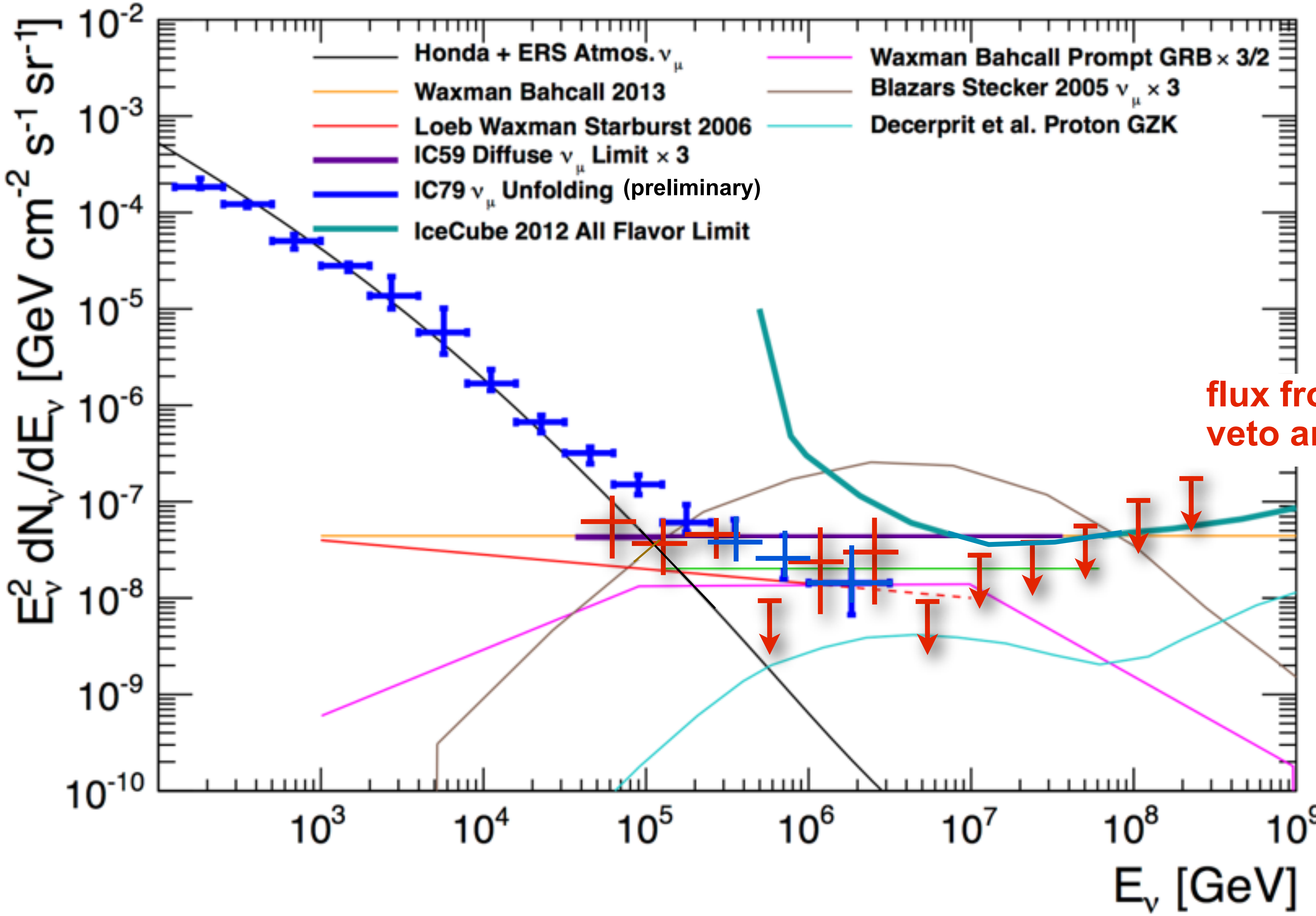


So what do we know about the astrophysical neutrinos flux?

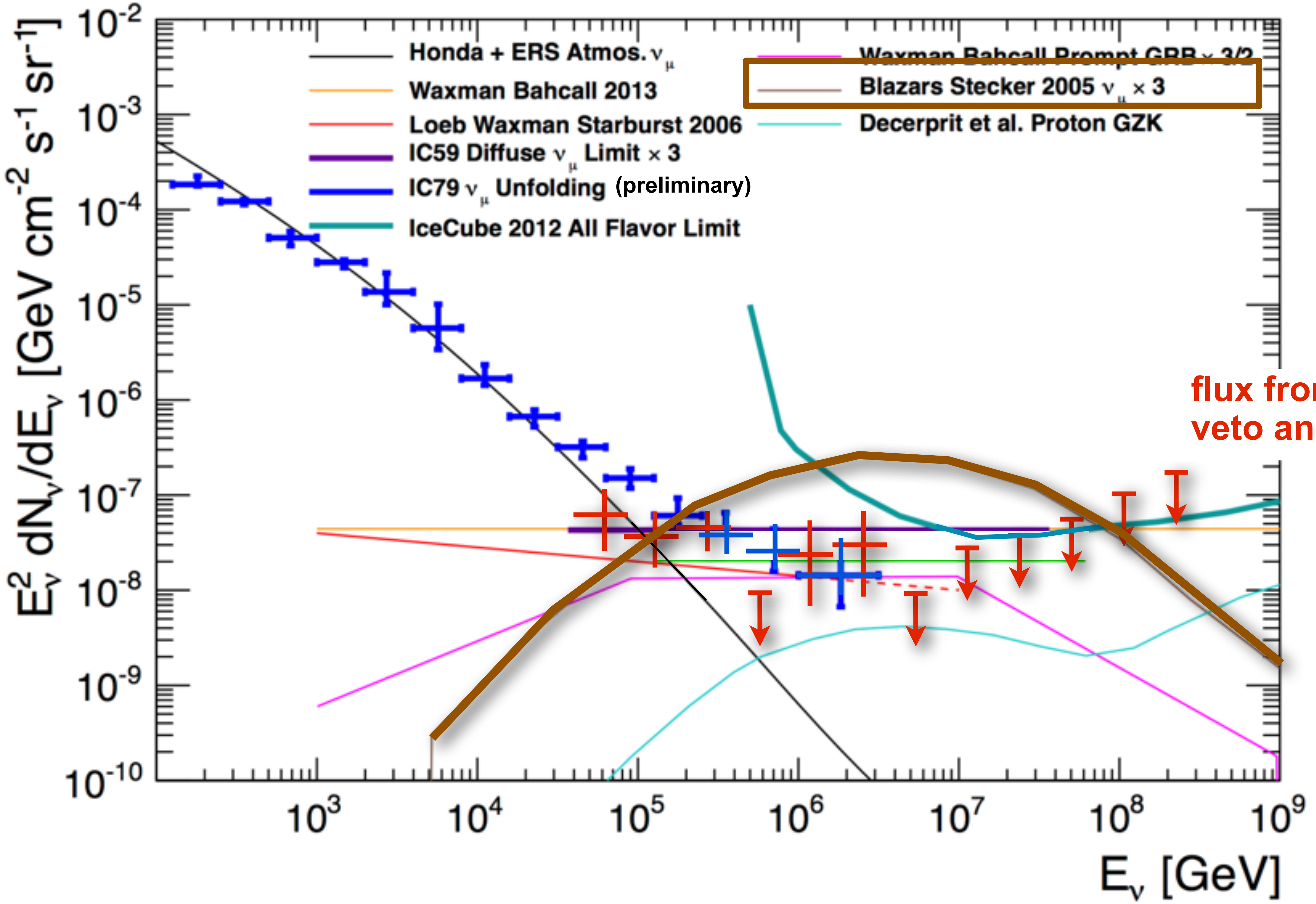
- Compatible with an isotropic cosmic neutrino flux (10 TeV − 3 PeV)
  - no correlation with Galactic plane
  - no correlation with specific sources

  → dominated by extragalactic sources (Milky Way halo might also be a possibility)
- Compatible with a (1 : 1 : 1) flavor ratio
- $E^{-2}\,\Phi \approx 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} per flavor
- Can be fit reasonably well with a single power law (index varies between 2.3−2.5 depending on energy range)
- For $\Gamma \gtrsim 2.3$, non visibility of Glashow resonance at 6.3 PeV does NOT require a cutoff at PeV energies

Source candidates



Source candidates



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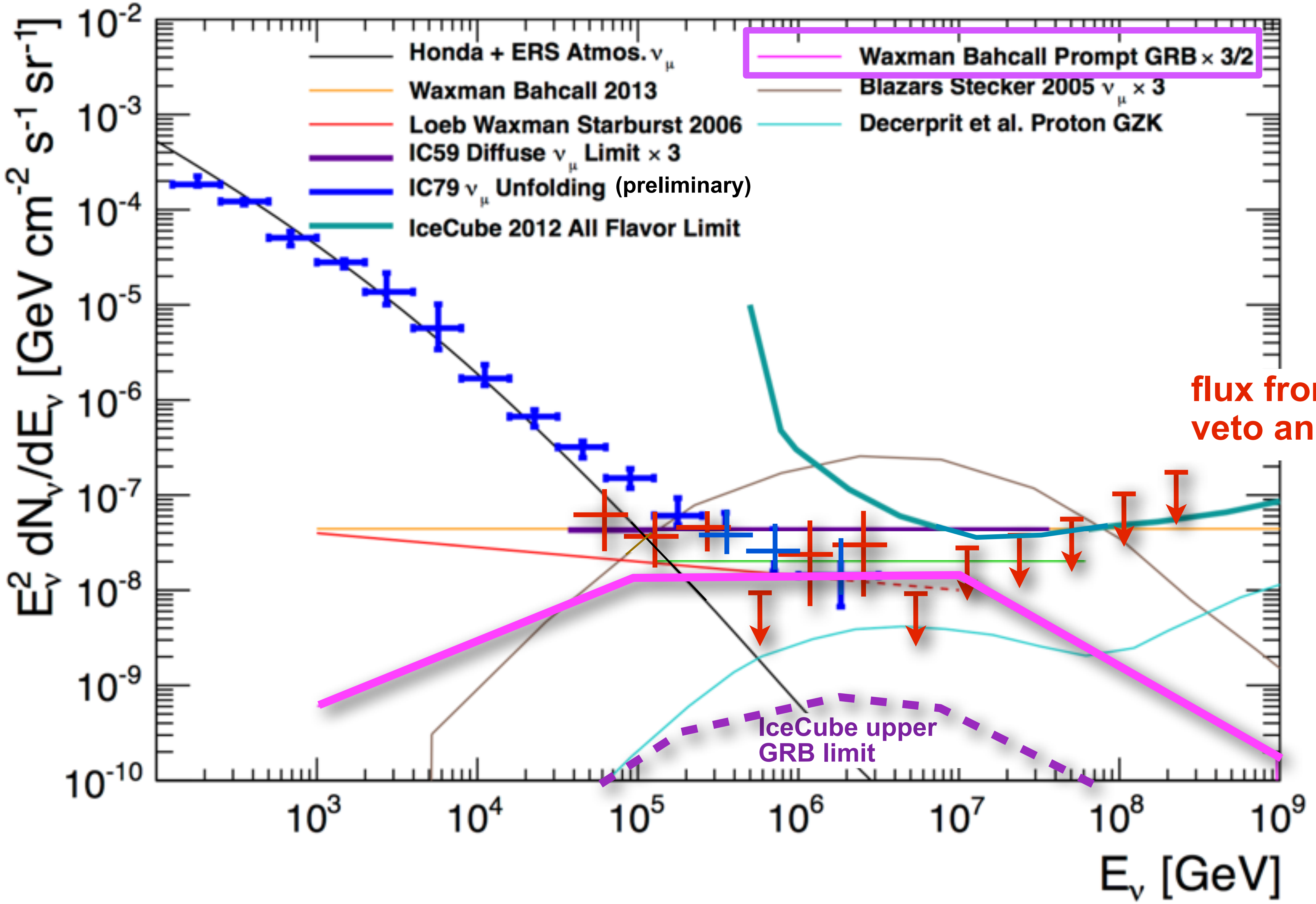

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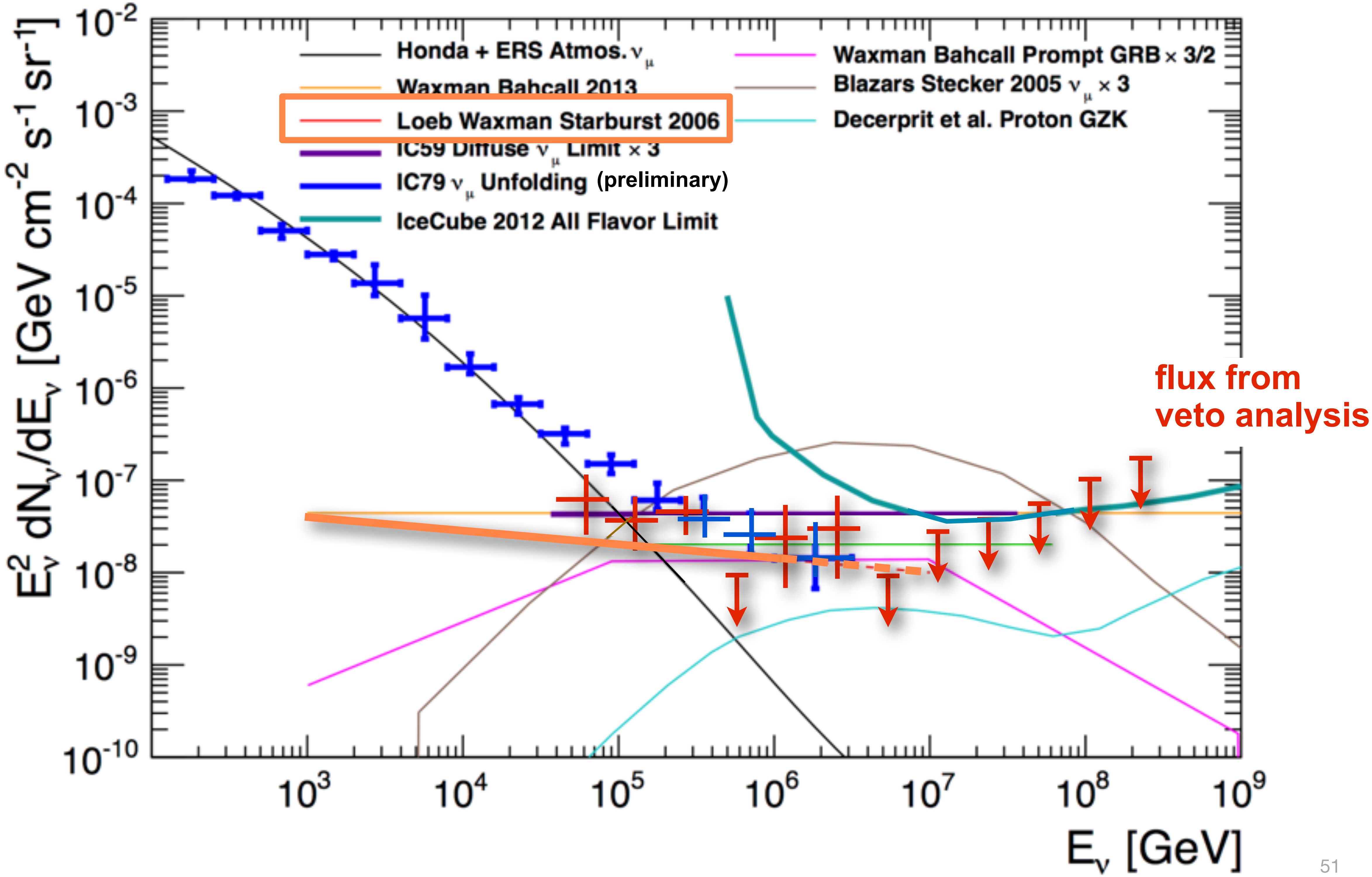
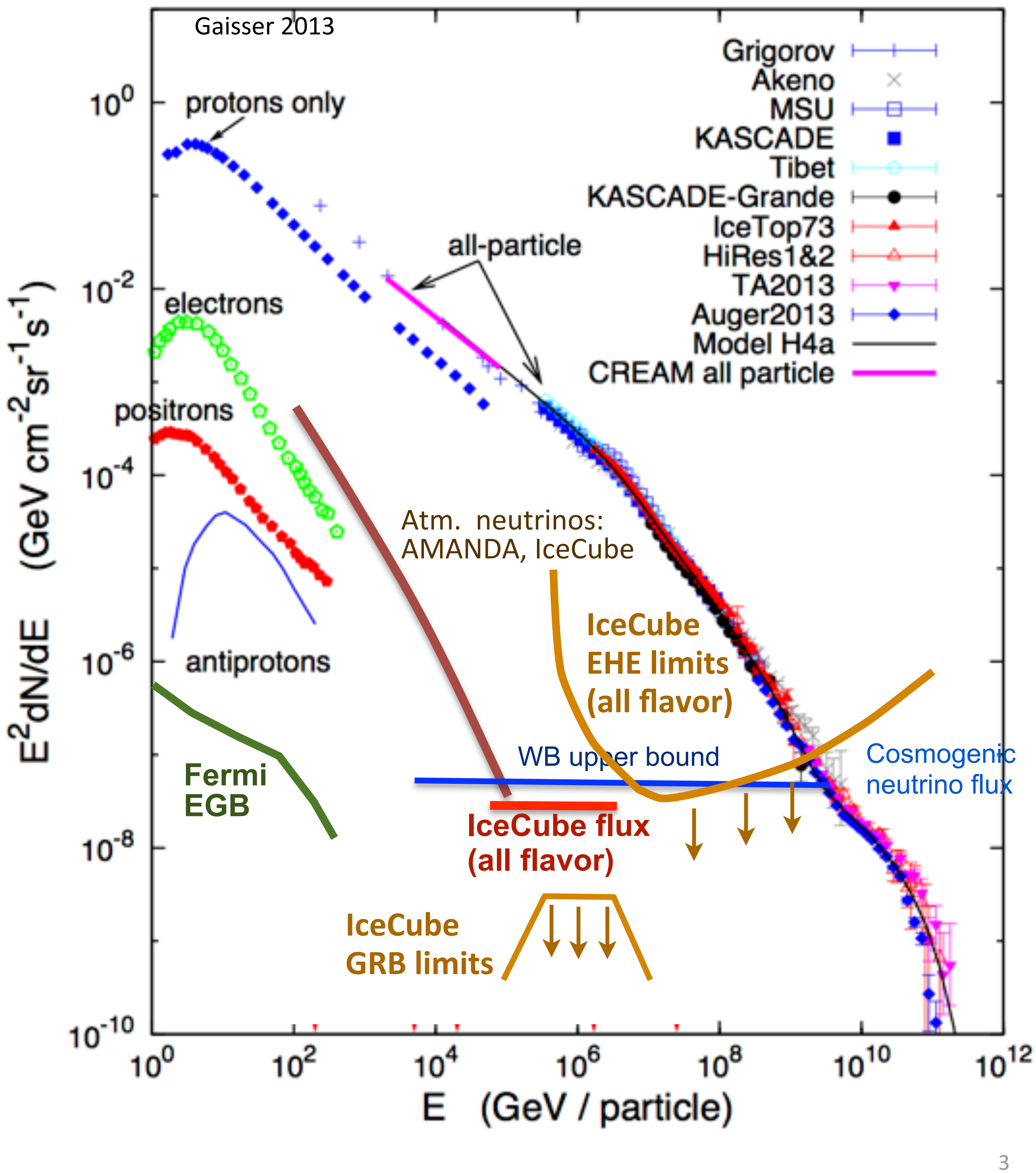


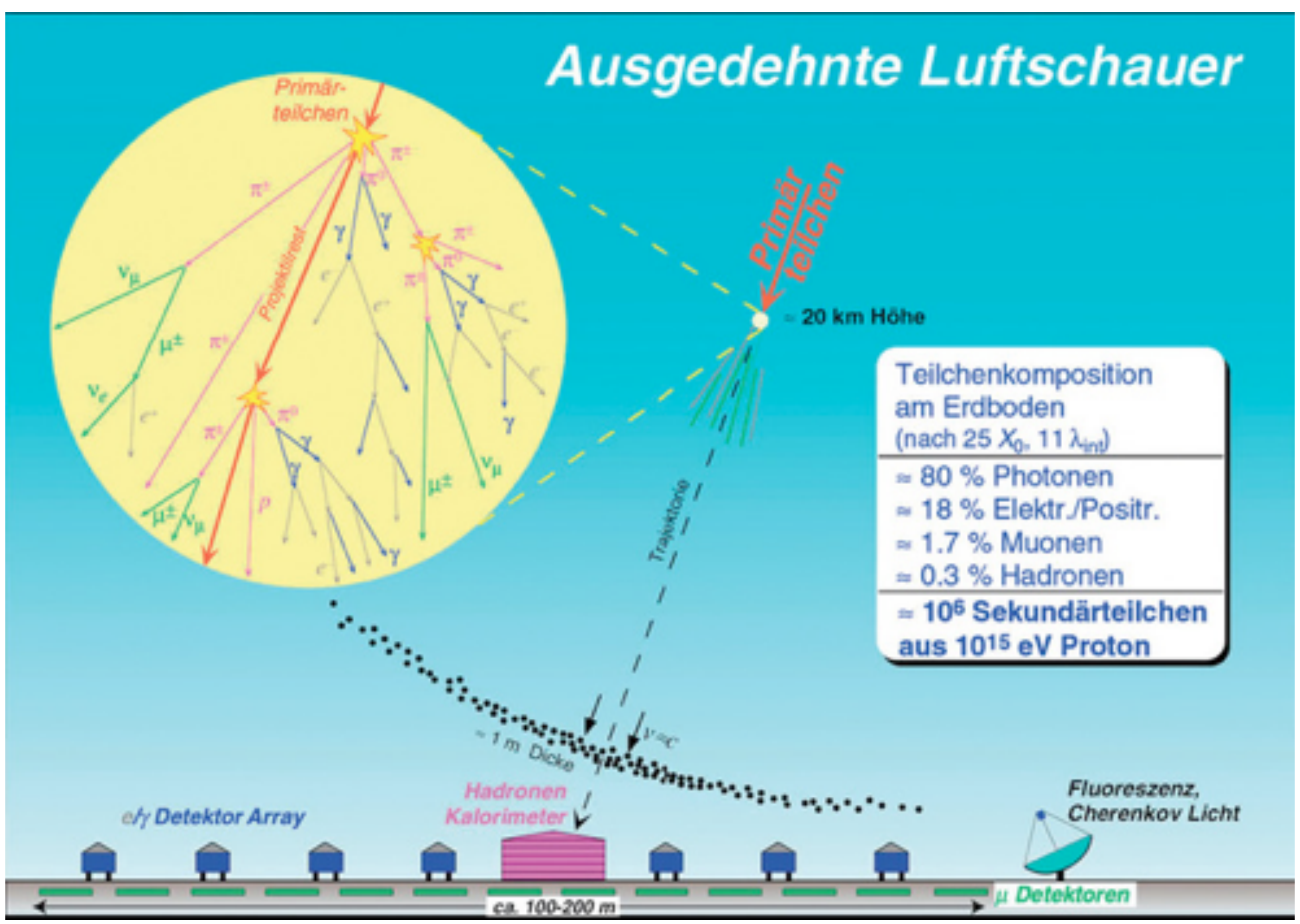
The big picture

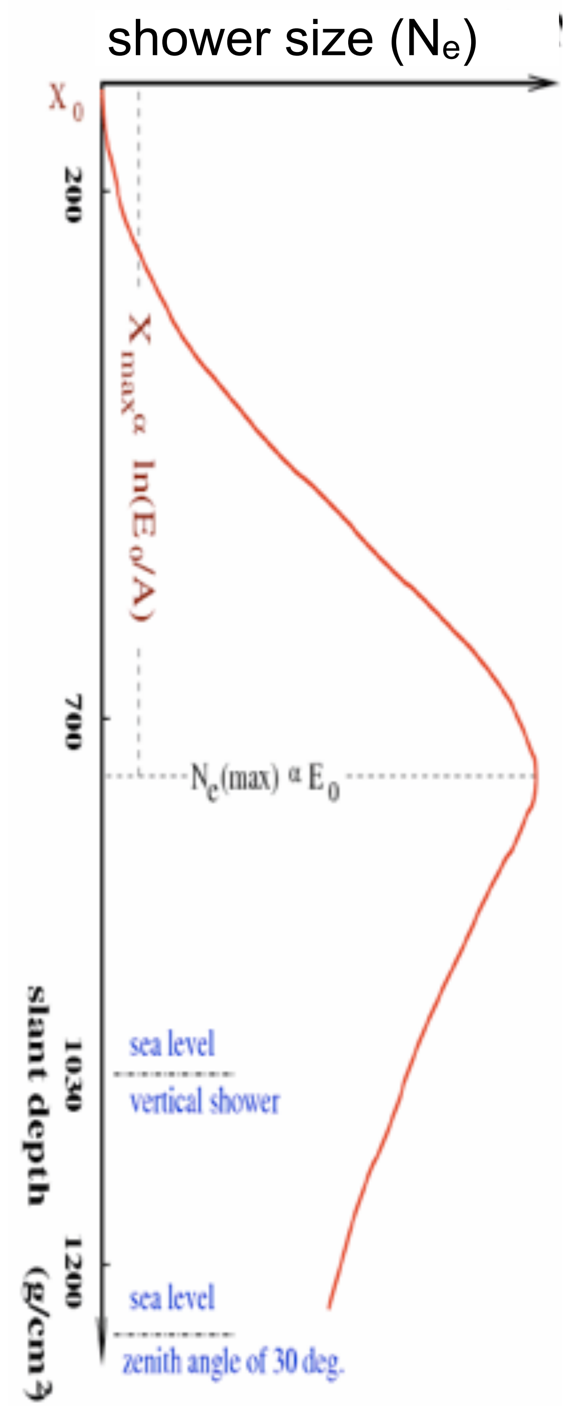


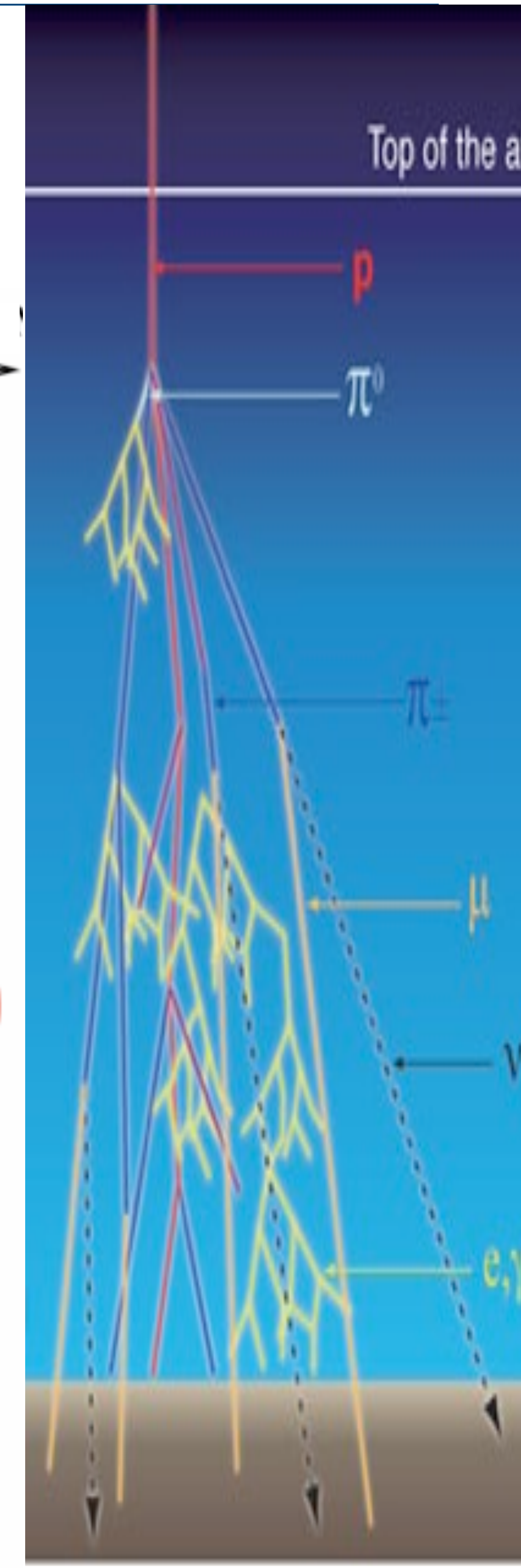
Cosmic-ray physics with IceCube and IceTop

Cosmic-ray air showers

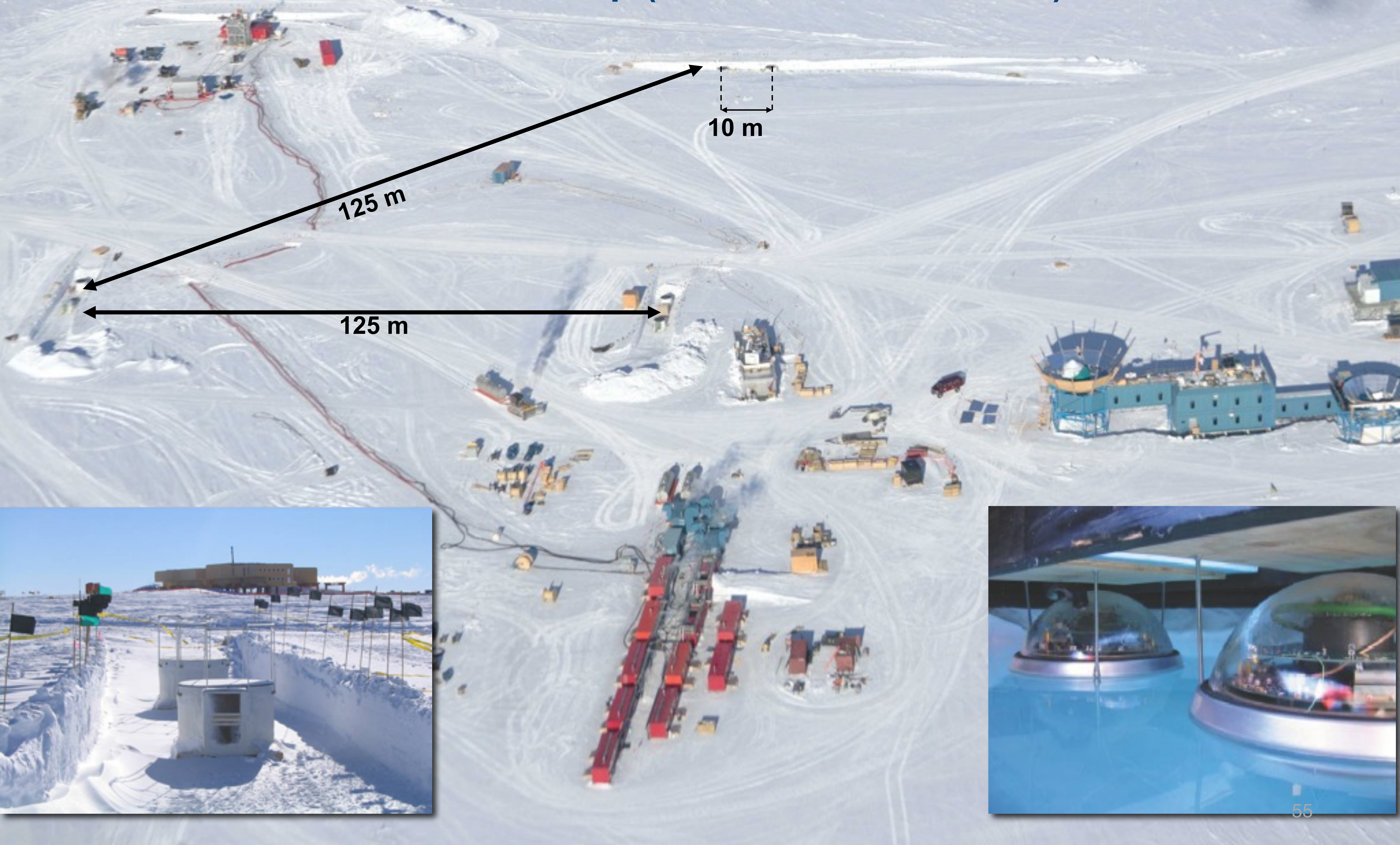
- Use atmosphere as target for cosmic rays
  → particle shower
- Ground detectors measure shower components
  - charged particles: muons, electrons (hadrons)
  - fluorescence light
  - Cherenkov light





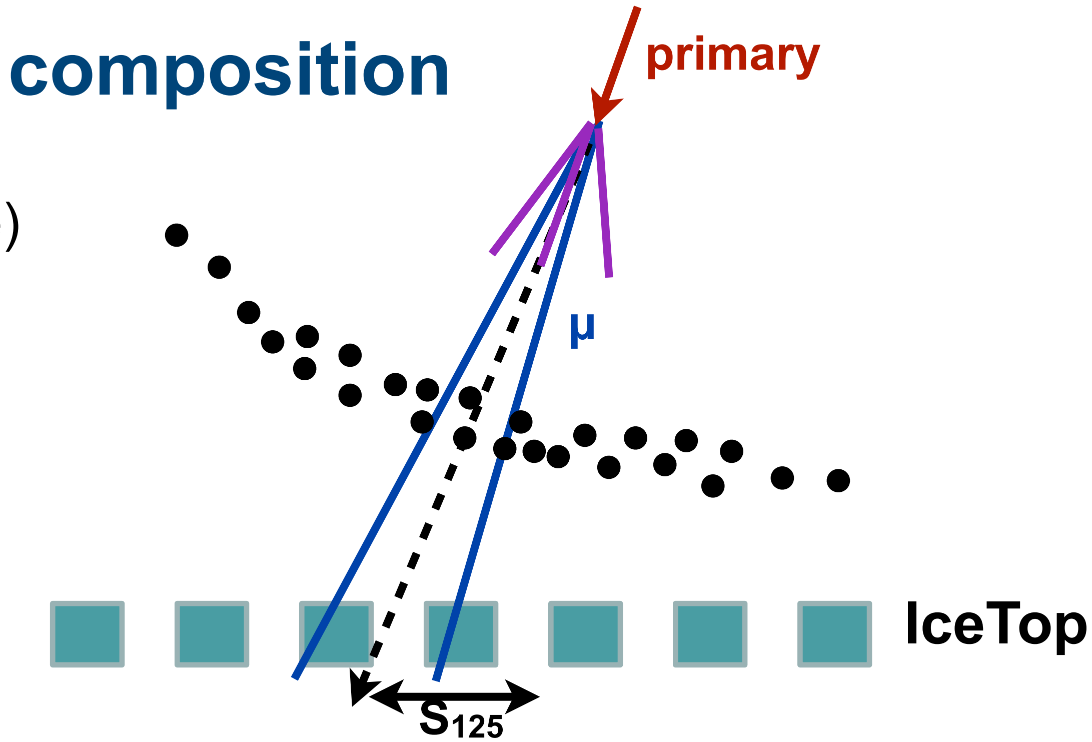


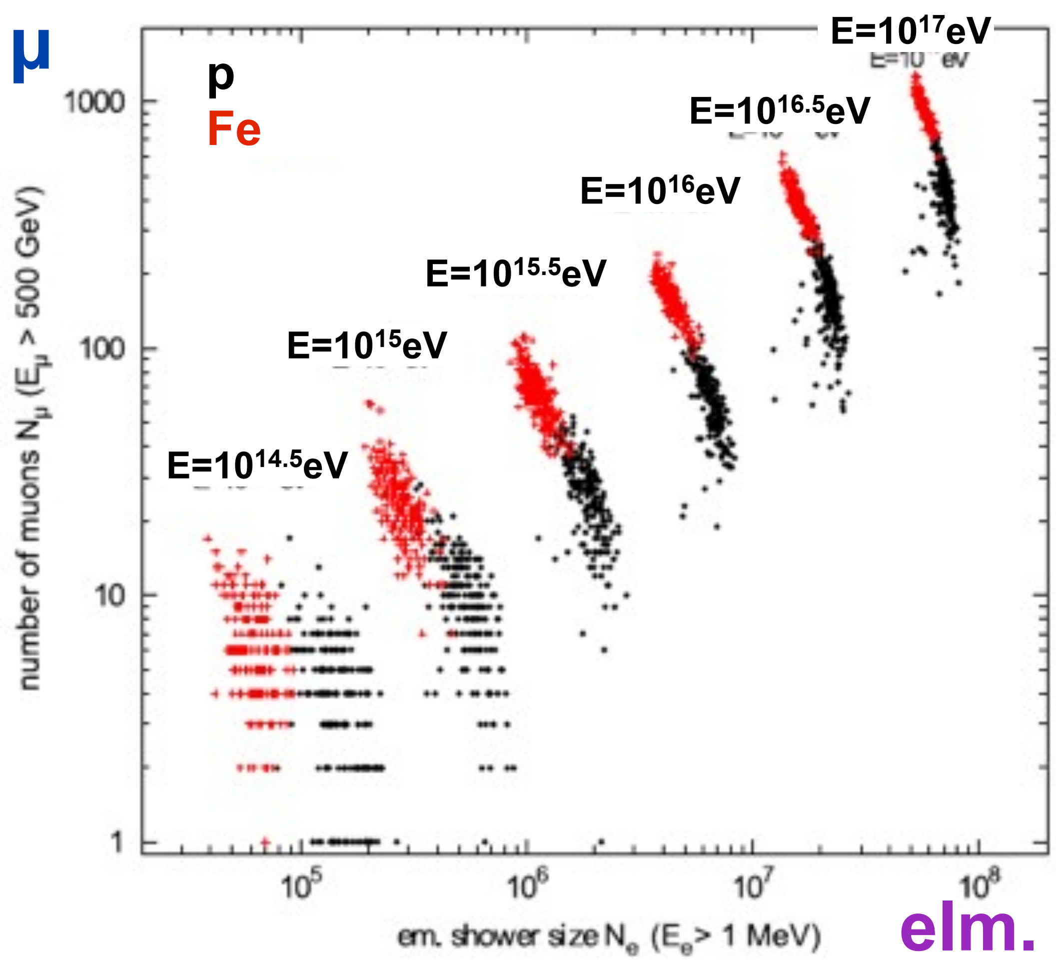
Aerial view of IceCube/IceTop (81 stations, 162 tanks)

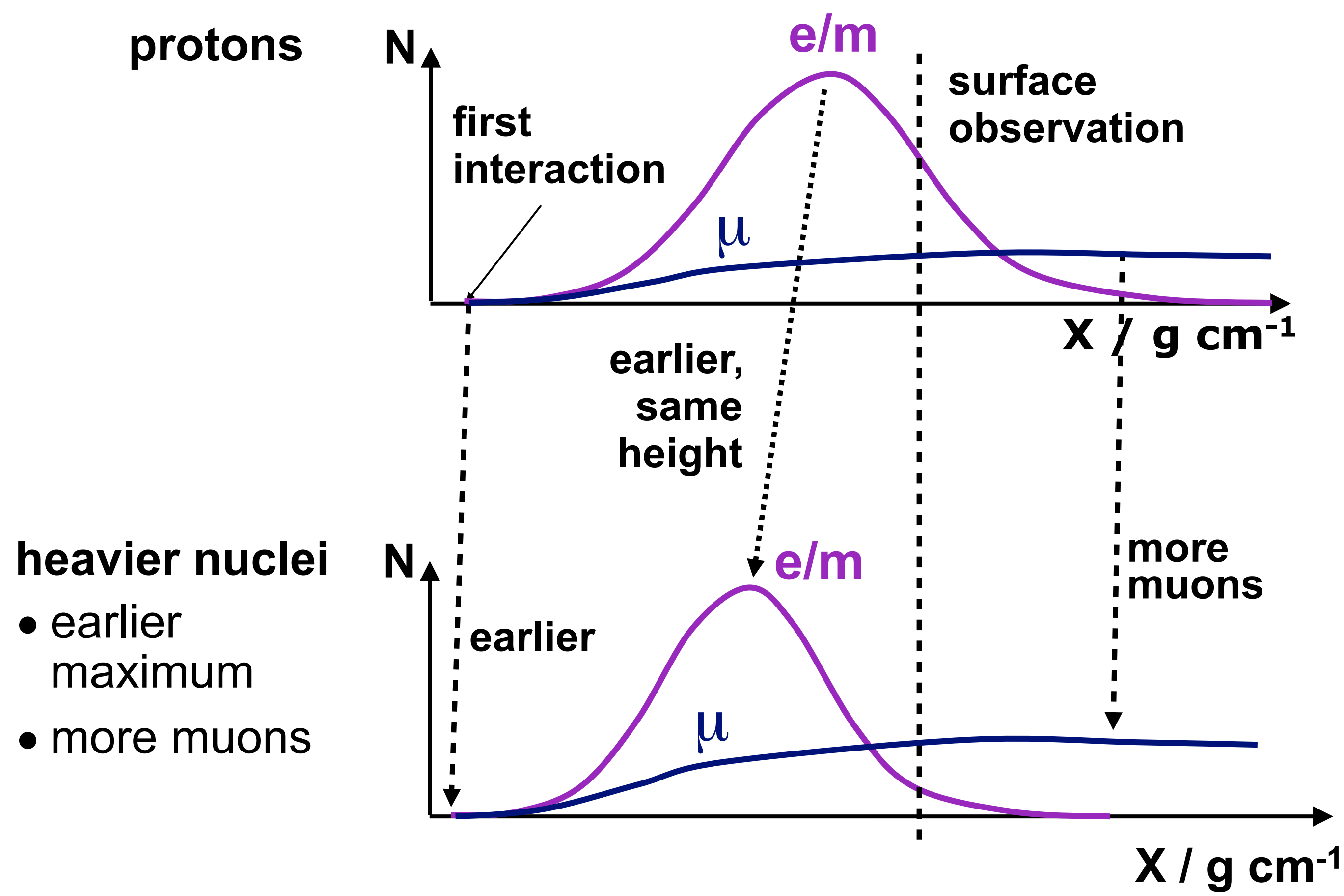


IceTop and cosmic rays - Spectrum and composition

- IceTop 2835 m above sea-level (692 g cm^{-2} atmosphere) → close to shower maximum
- Shower energy measured from signal 125 m from shower core (S_{125})
- Measured spectrum depends on assumed composition

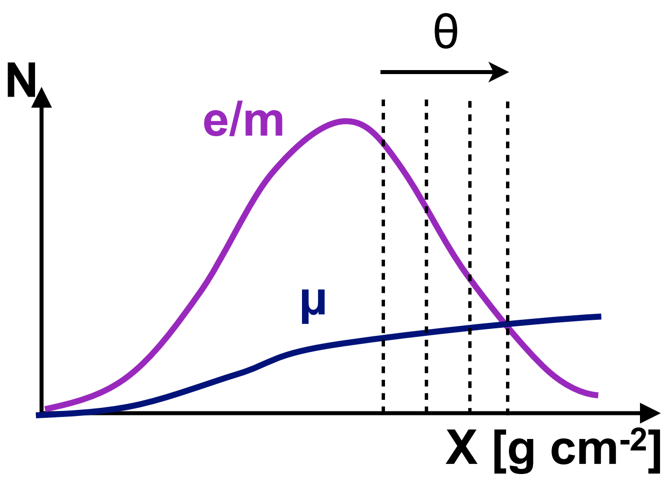




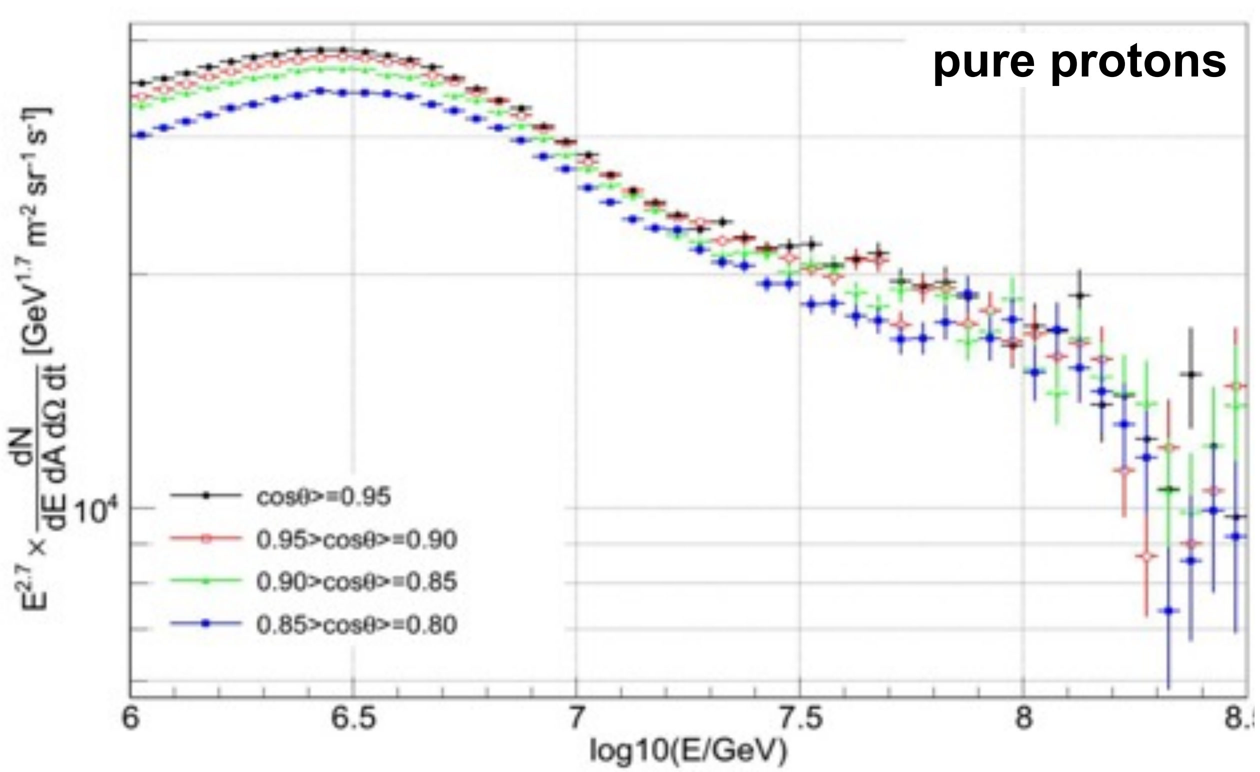


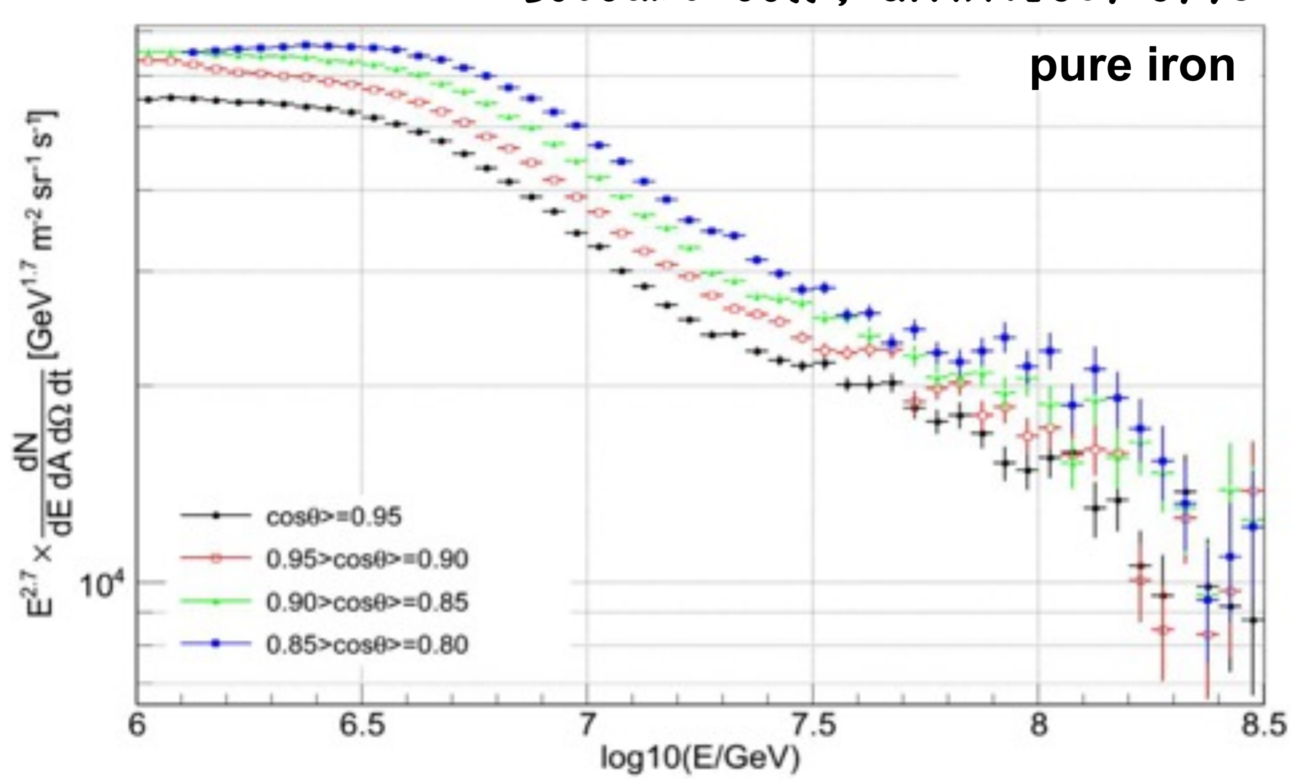
IceTop and cosmic rays - Spectrum and composition

- Atmosphere (slant) depth depends on zenith angle
  $X(\theta) = X(0) / \cos(\theta)$
- Flux not isotropic for pure proton or iron assumption
  → mixed composition needed
  → composition sensitivity with IceTop only



IceCube Coll., arXiv:1307.3795





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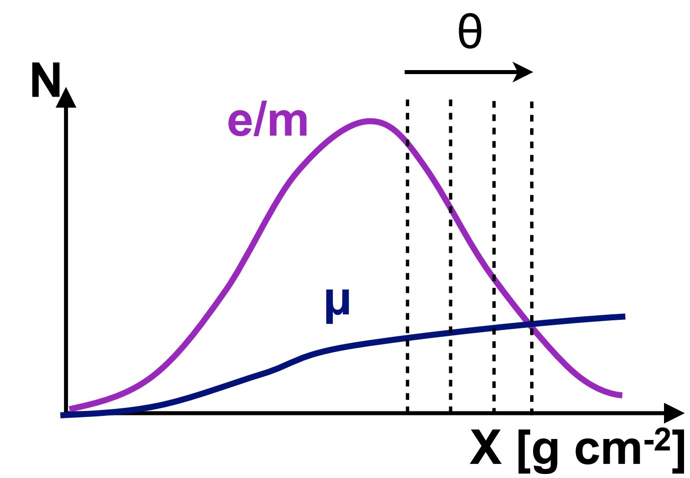
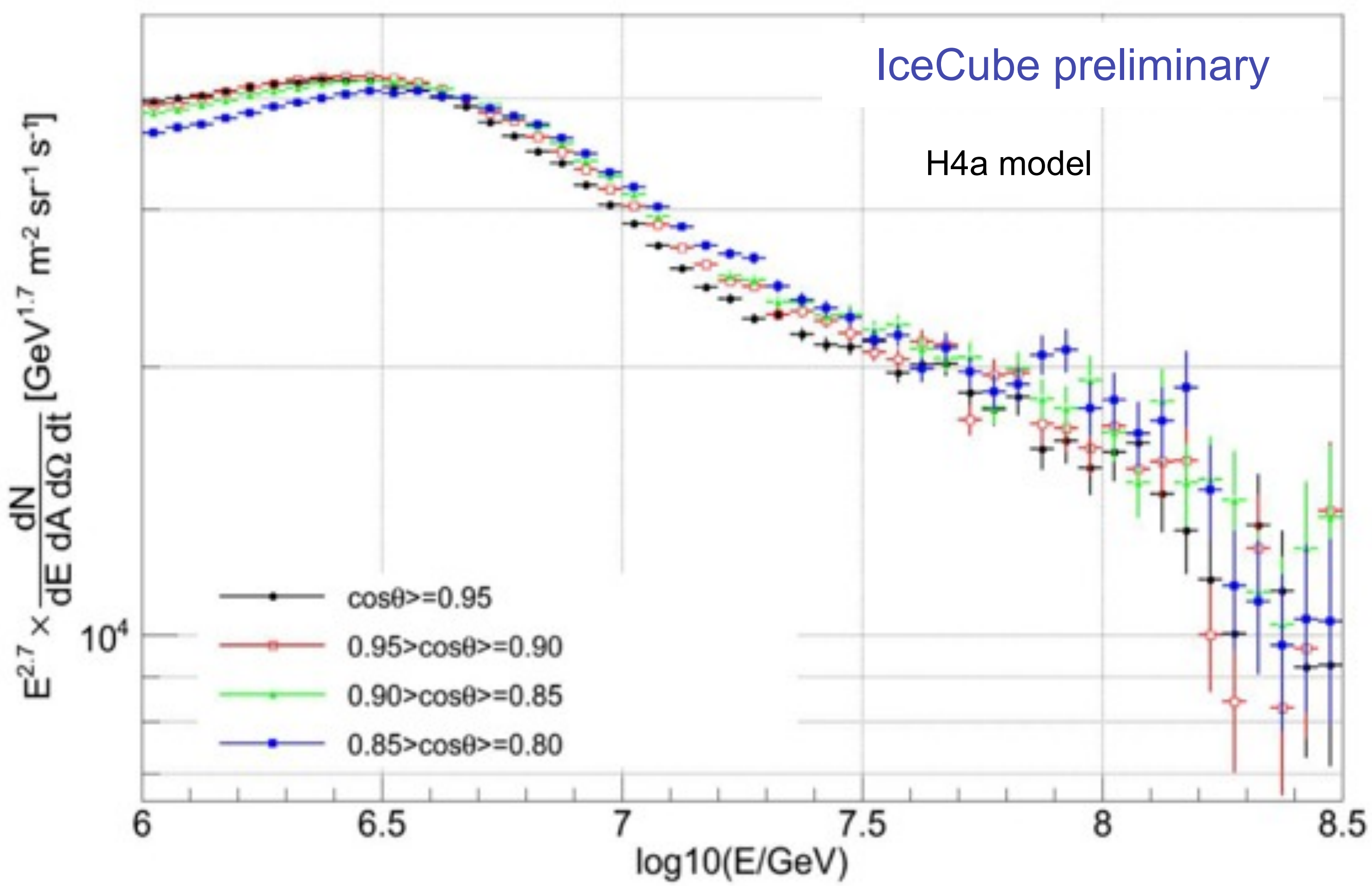
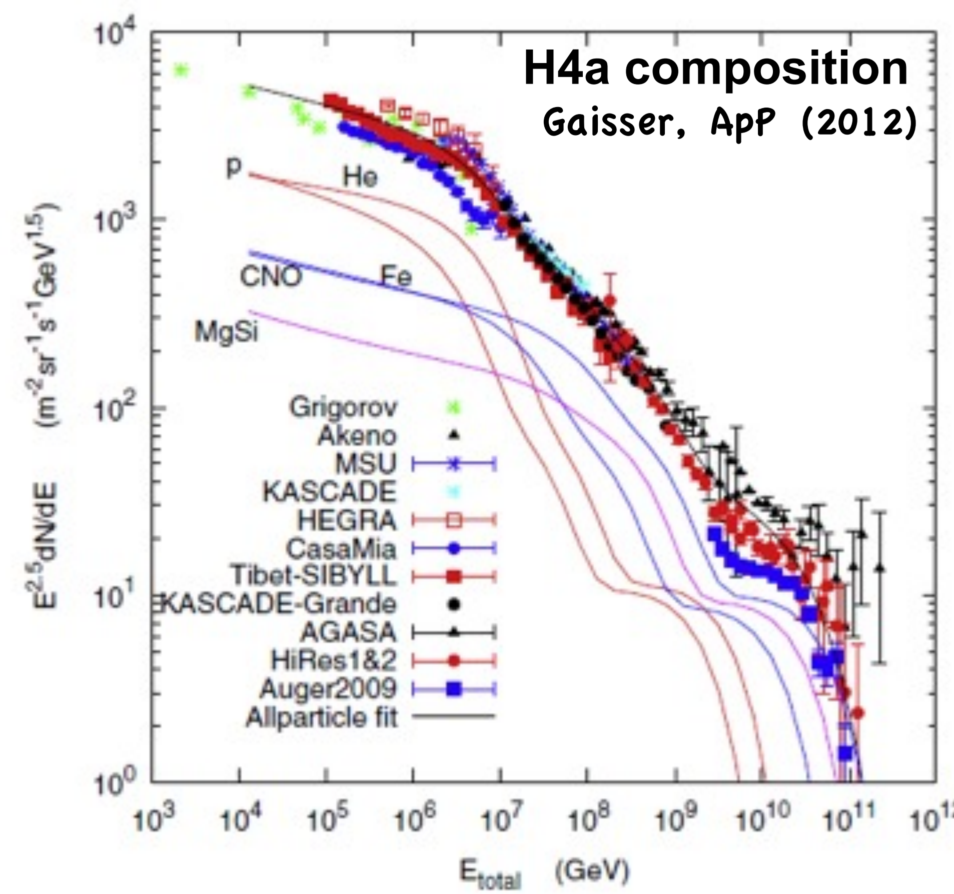
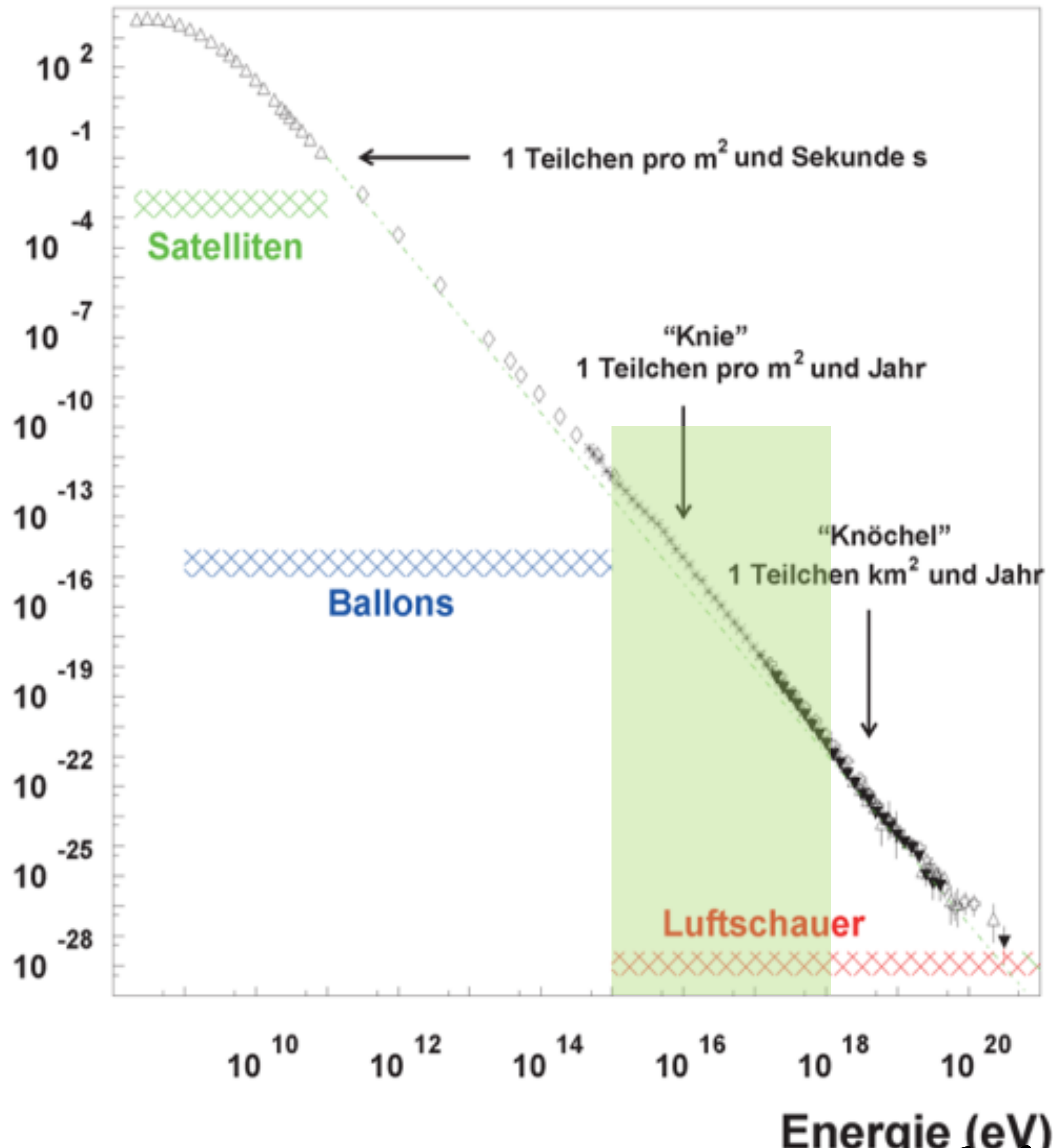




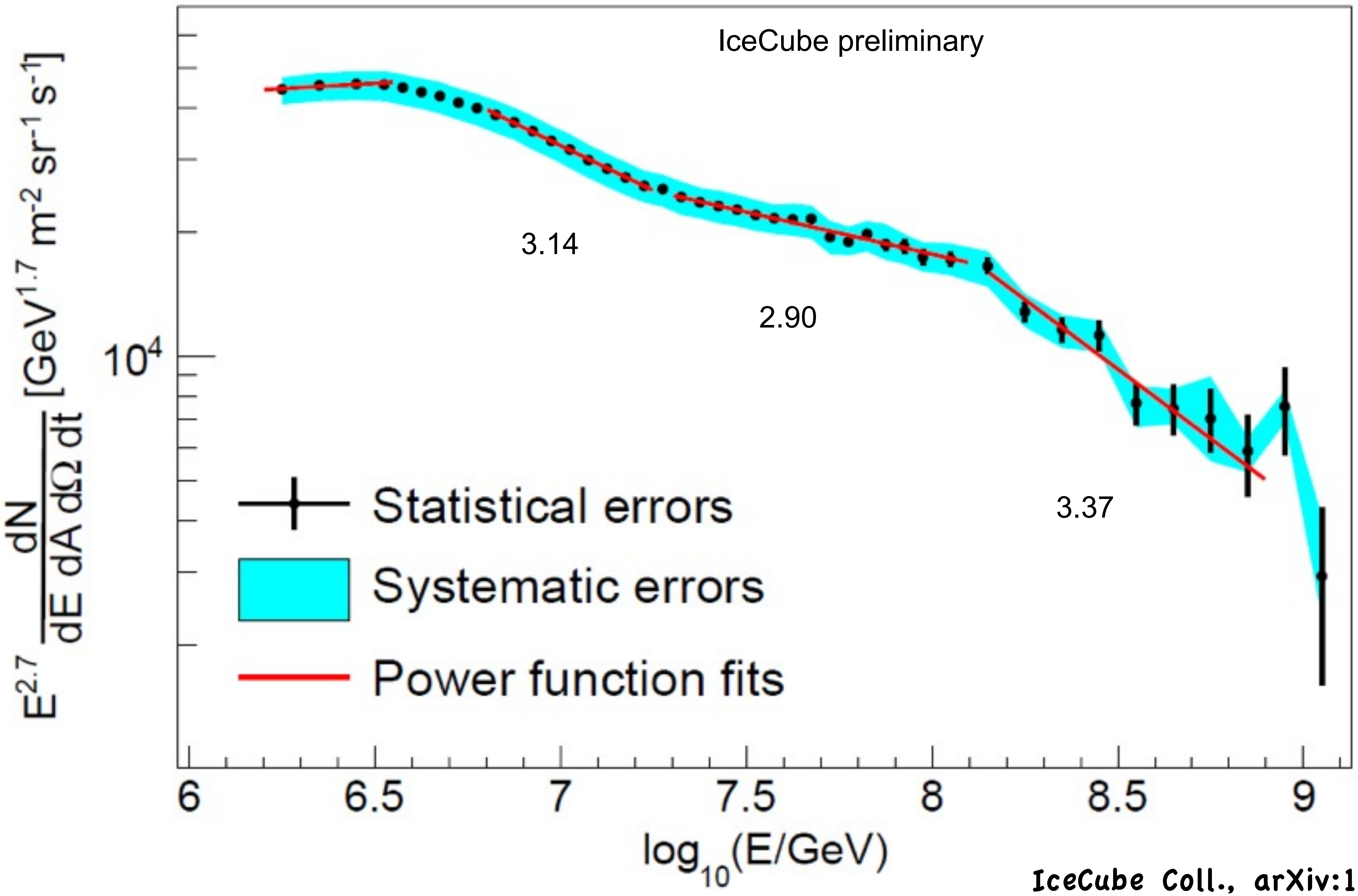


IceTop and cosmic rays - The fine-structure of the spectrum



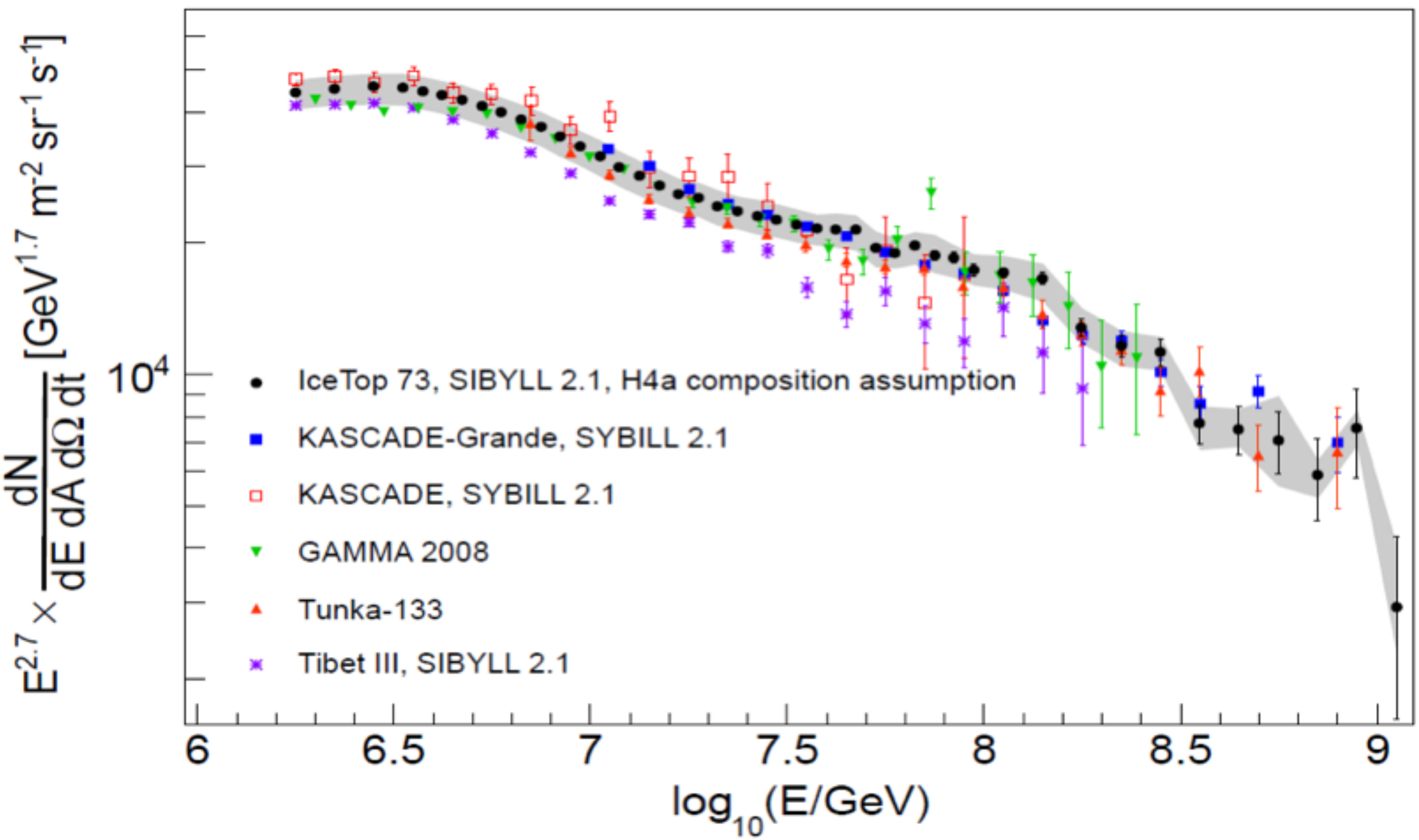
IceCube Coll., arXiv:1307.3795

IceTop and cosmic rays - The fine-structure of the spectrum



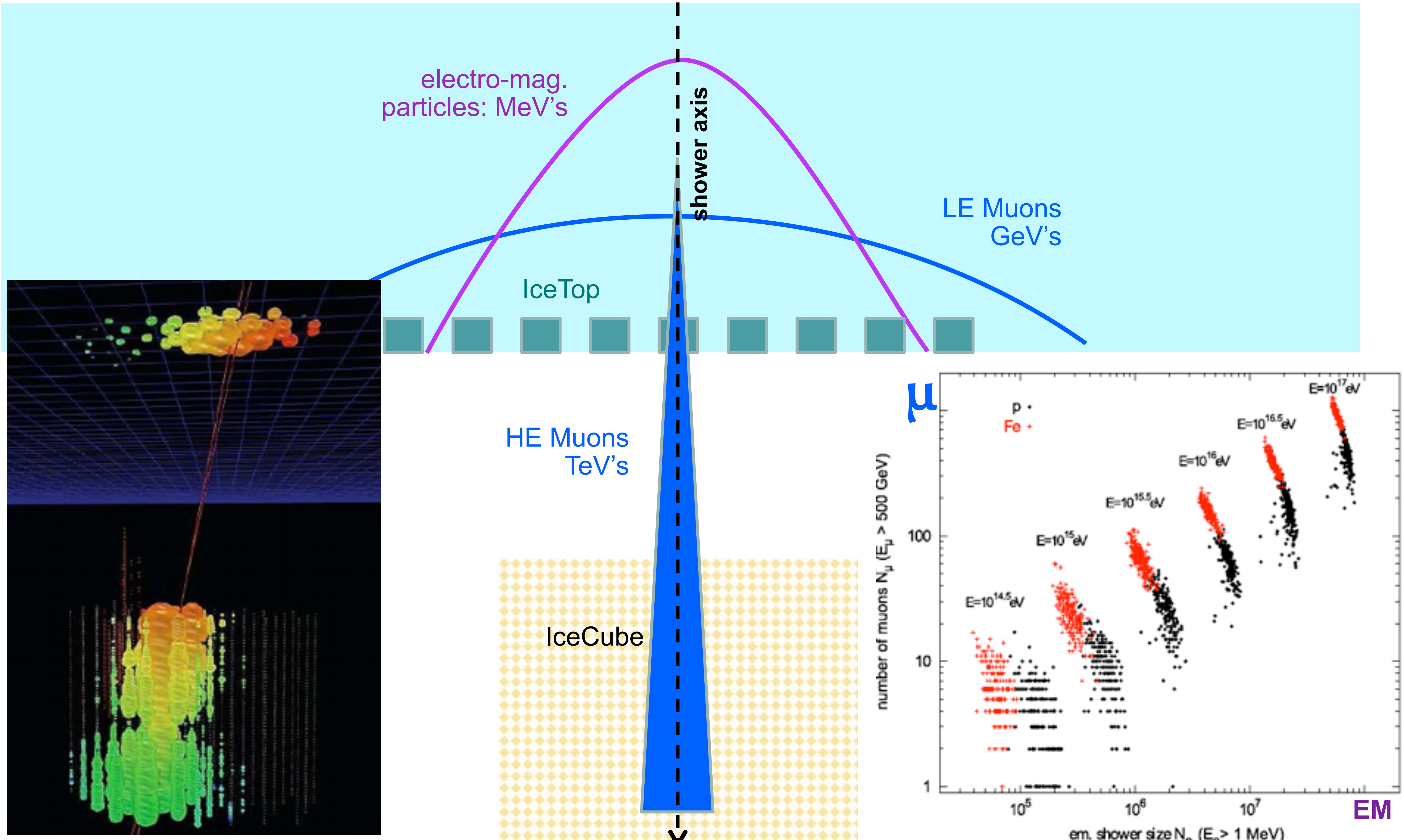
IceCube Coll., arXiv:1307.3795

IceTop and cosmic rays - The fine-structure of the spectrum

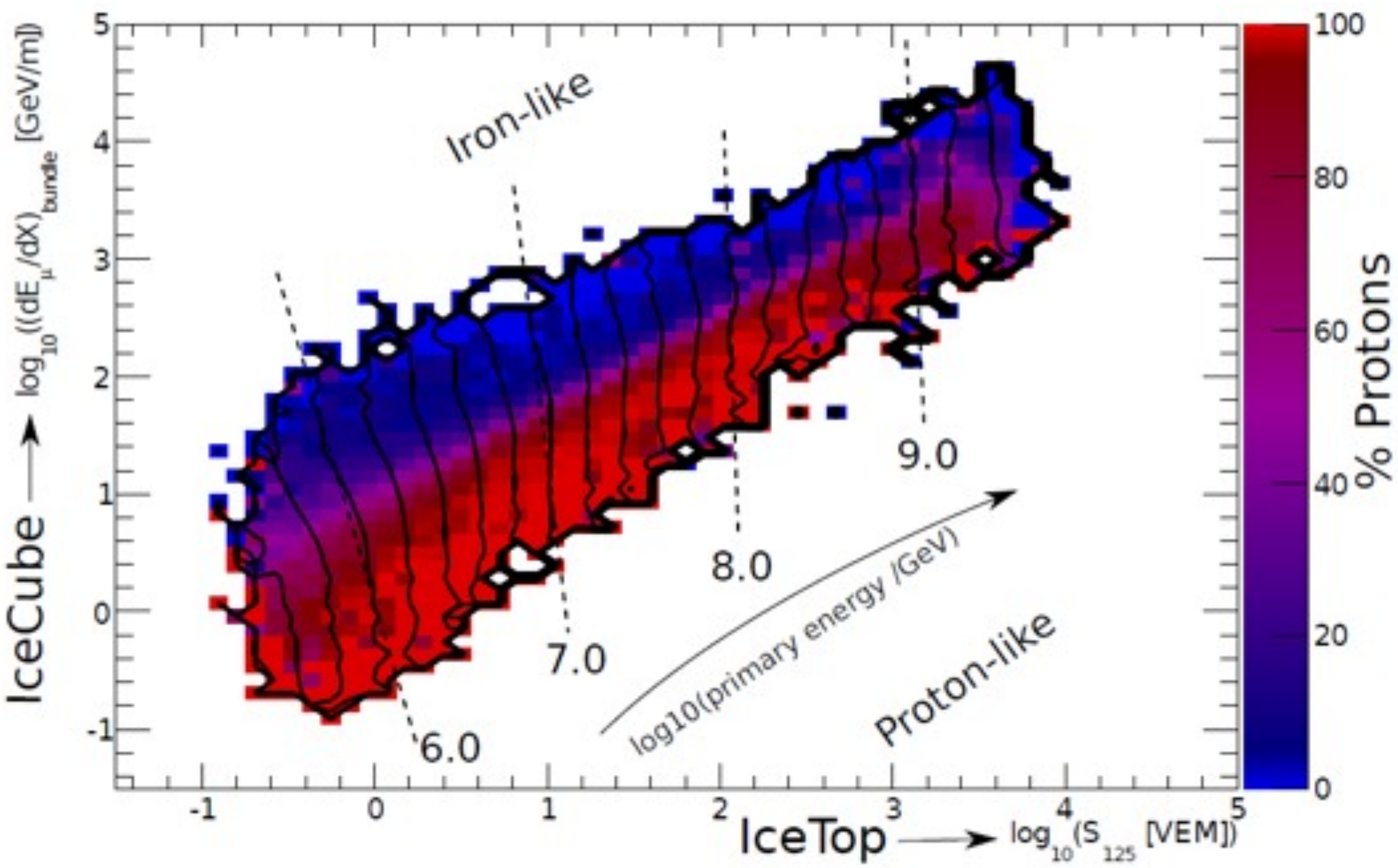


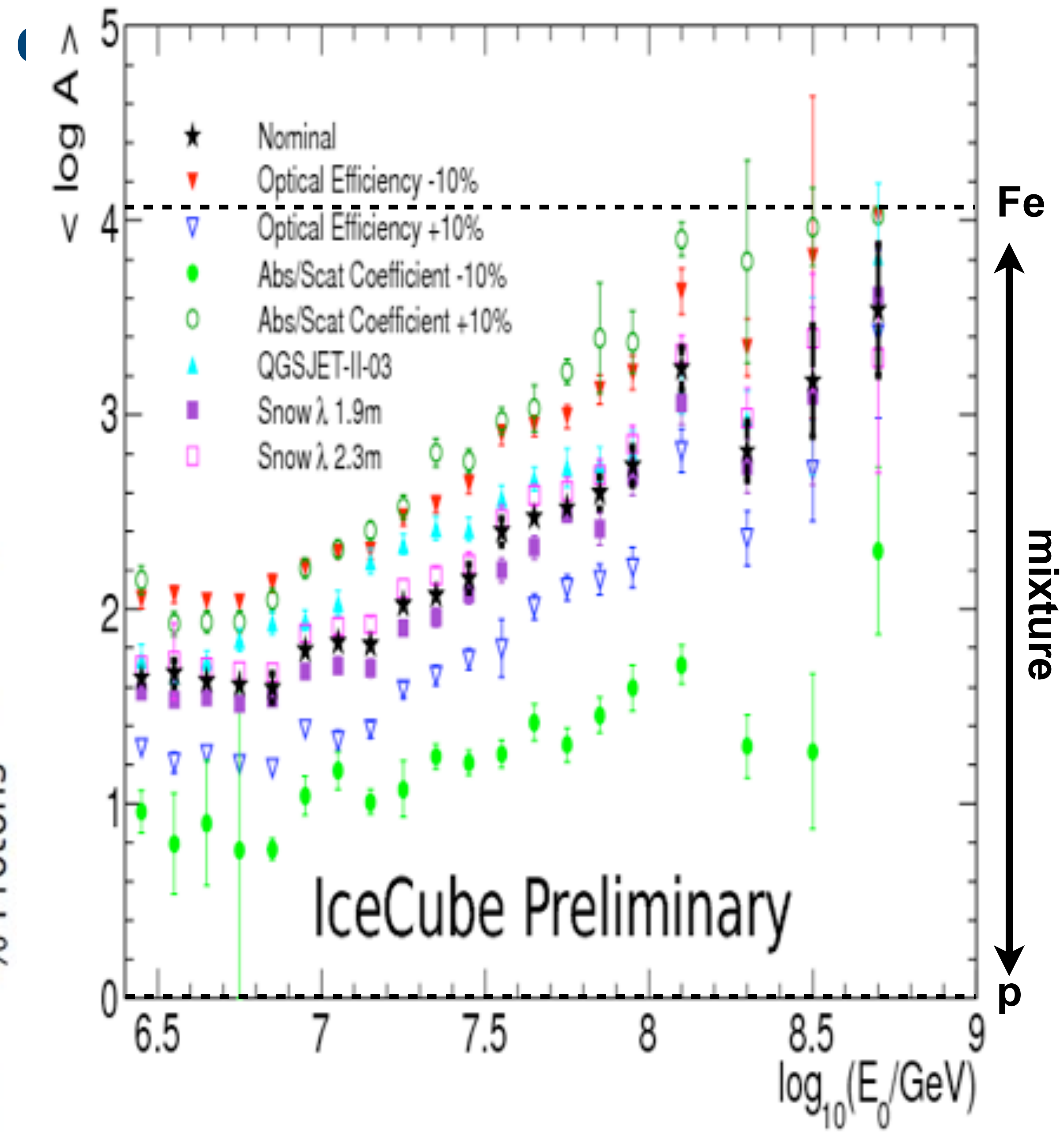
IceCube Coll., arXiv:1307.3795

Cosmic rays composition - Combing IceCube and IceTop



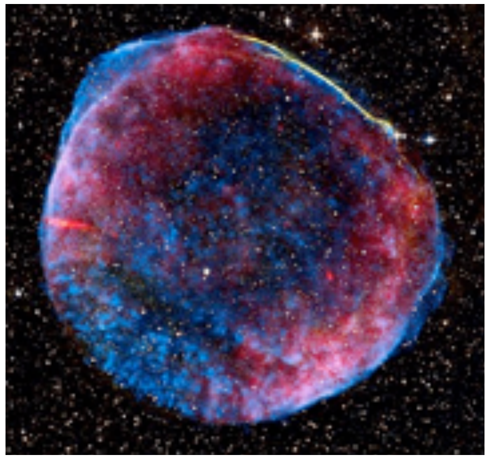
- Ratio of high-energy muons (IceCube, dE/dx) to air shower energy (IceTop, S_{125}) depends on composition (+ zenith angle)
- Observe increasing "heaviness" of composition with increasing energy



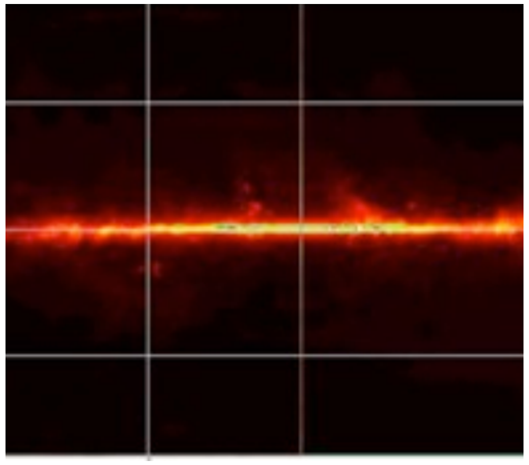


Physics with neutrino telescopes

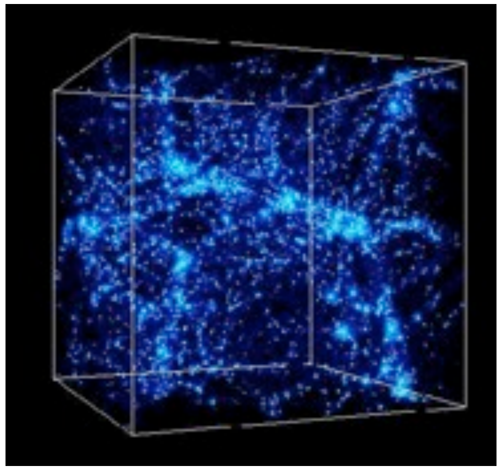
Cosmic accelerators



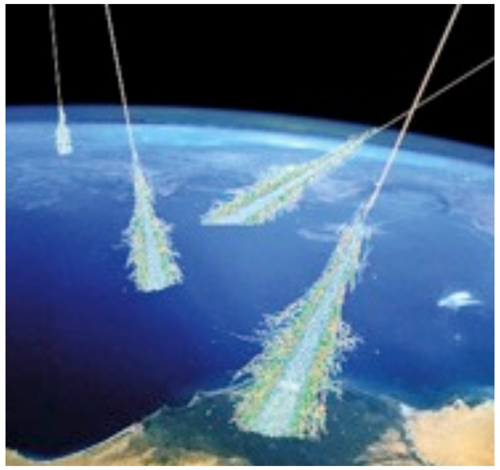
Diffuse fluxes



Dark Matter & Exotic Physics

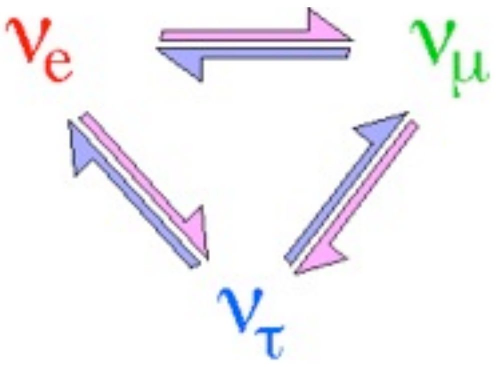


Cosmic rays



Supernovae

Neutrino Properties & Particle Physics



Physics with neutrino telescopes

Cosmic accelerators

- Point-like sources (SNRs, Binaries ...)
- Extended sources
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes
- Galactic plane
- Extended structures (e.g. Fermi-Bubbles)

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls
- Lorentz invariance violation

Cosmic rays

- Spectrum around “knee” (10^{15}–10^{17} eV)
- Composition
- Anisotropy

Supernovae

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

Neutrino Properties & Particle Physics

- Neutrino oscillations
- Charm in showers
- K/π ratio in showers
- Cross sections at very high energies

Looking into the future

The road ahead

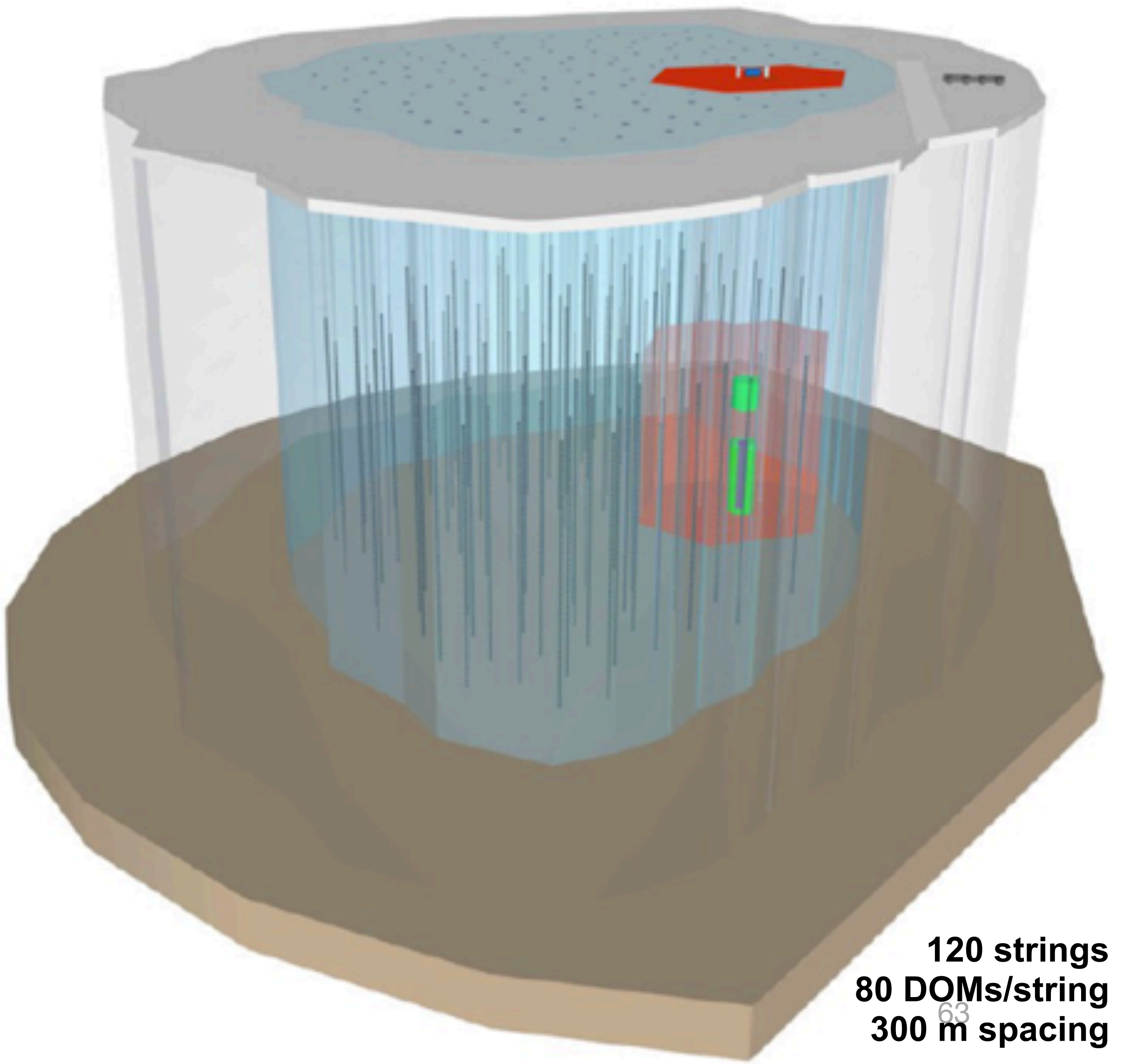
After 10 years of IceCube data-taking

- Muon neutrinos (point source searches)
  - ~90 astrophysical ν_μ above 100 TeV
- Cascade events (energy spectrum/flavor composition)
  - ~100 events above 60 TeV
  - ~10 events above 1 PeV

→ need significantly more events

Plans for a next-generation IceCube

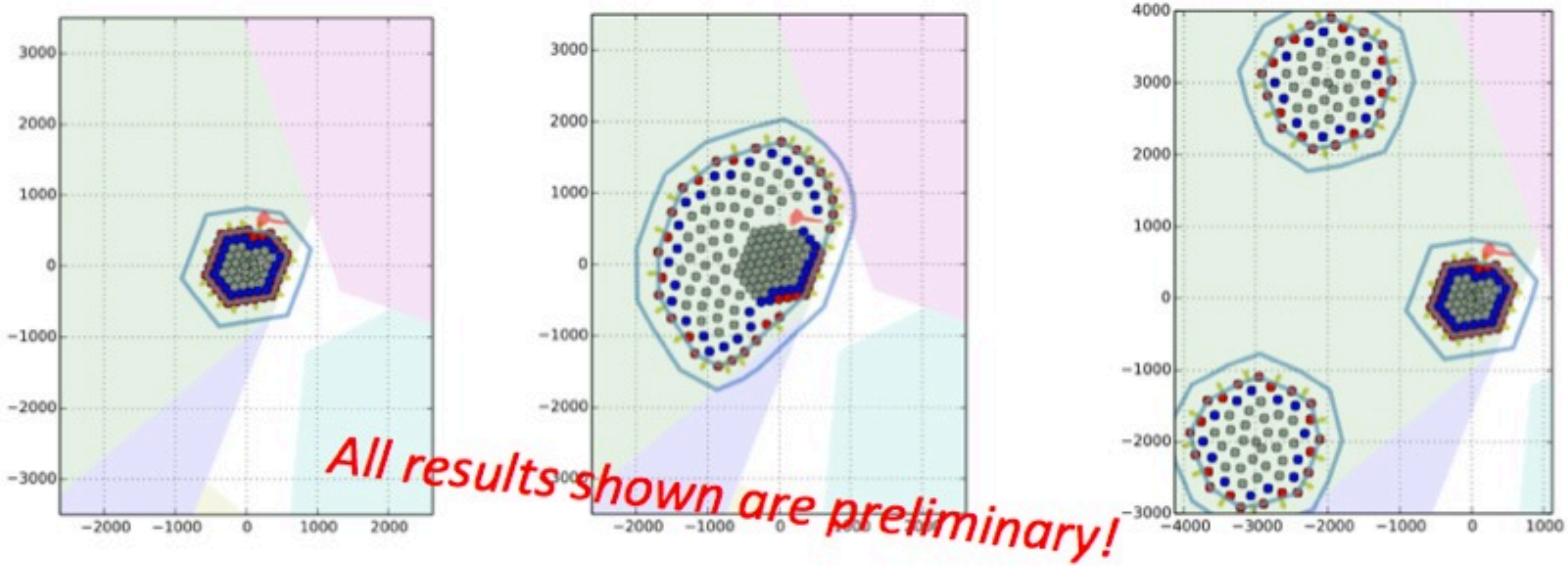
- In-ice detector of 5−10 km^3
- Extended surface veto to reject atmospheric showers (muons/neutrinos)
- Requires development of new hardware (out-dated electronics, power consumption ...)



120 strings
80 DOMs/string
300 m spacing

Different possible configurations

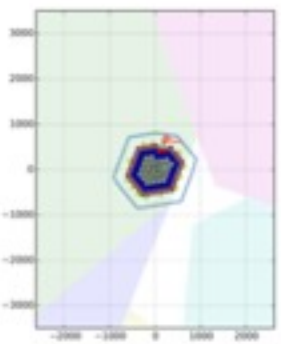
IceCube | Sunflower 96 | Supercluster

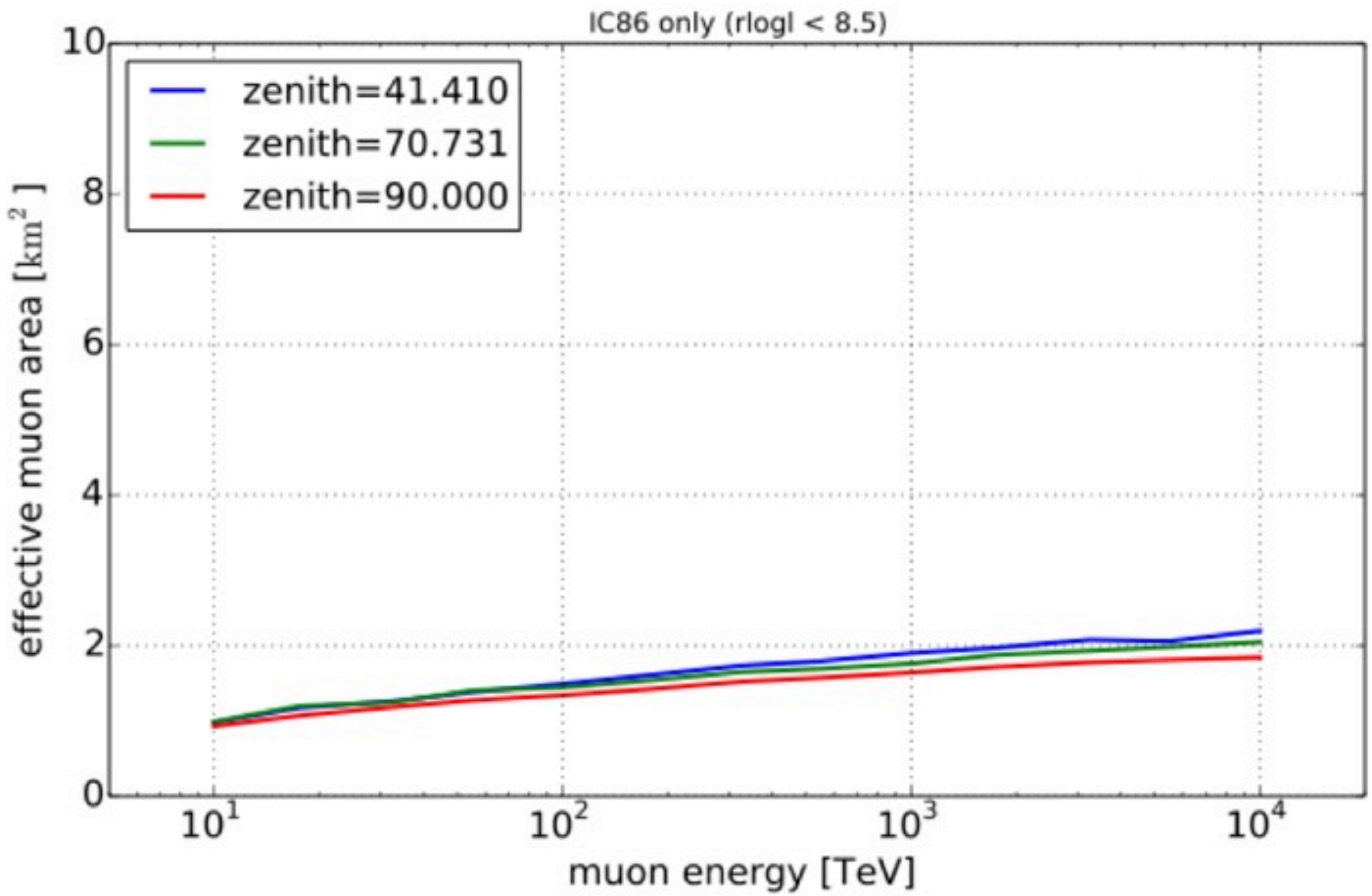


IceCube	Sunflower 96	Supercluster
Top area (instrumented+60m border): 0.9 km^2	top area (instrumented+60m border): 5.3 km^2	top area (instrumented+60m border): 5.6 km^2
Volume: 0.9 km^3	Volume: 6.9 km^3	Volume: 7.3 km^3
Strings: IC86 spacing: ~125m	Strings: IC86+96 spacing: ~240m	Strings: IC86+2x60 spacing: ~240m

Karle, Neutrinos Beyond IceCube, Arlington, April 2014

First studies: effective muon area (loose cuts)





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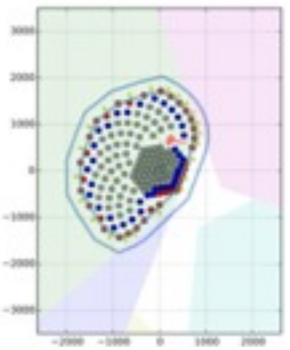

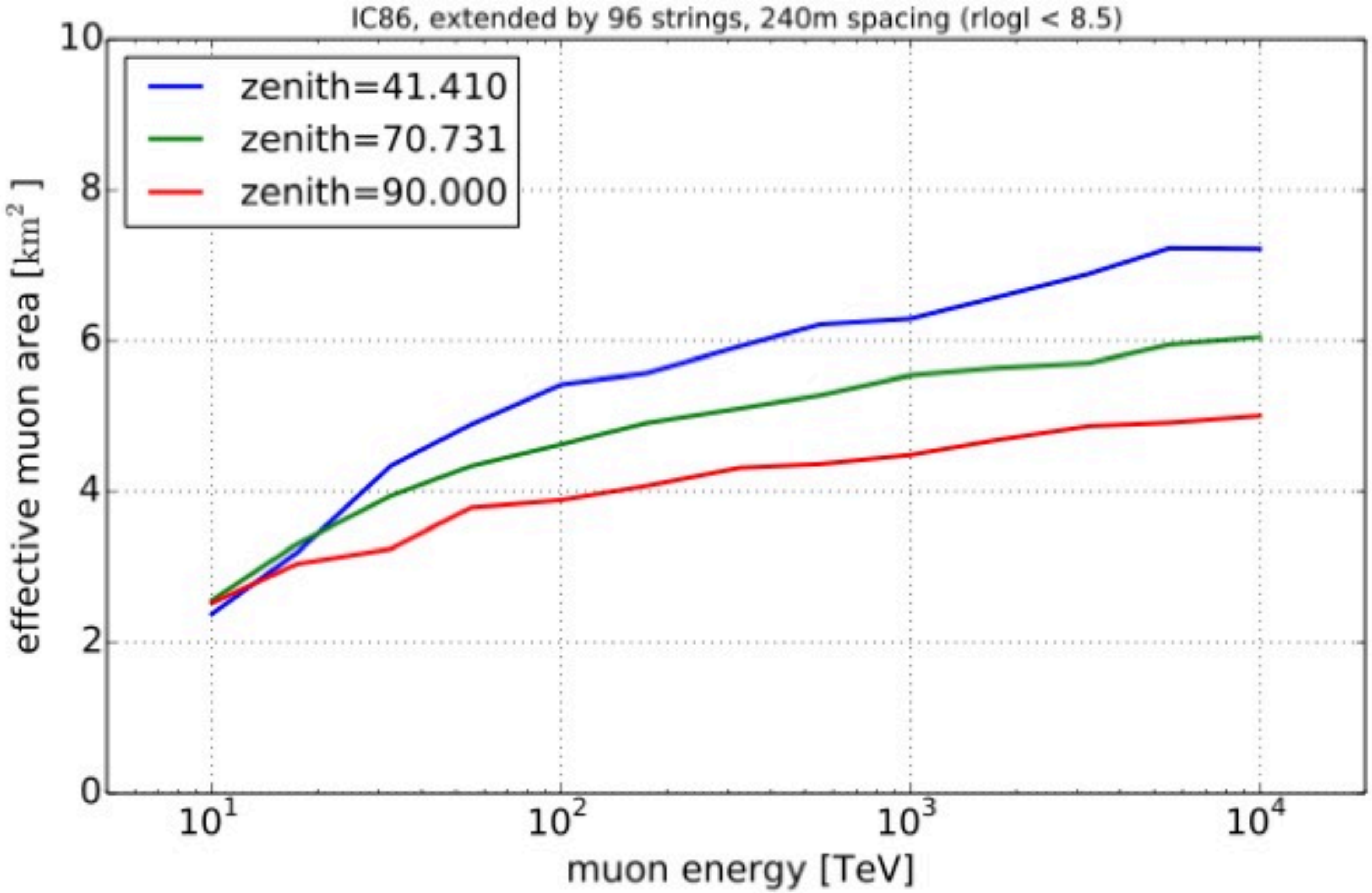

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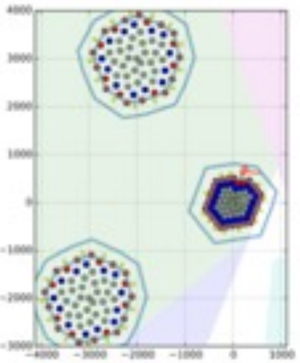
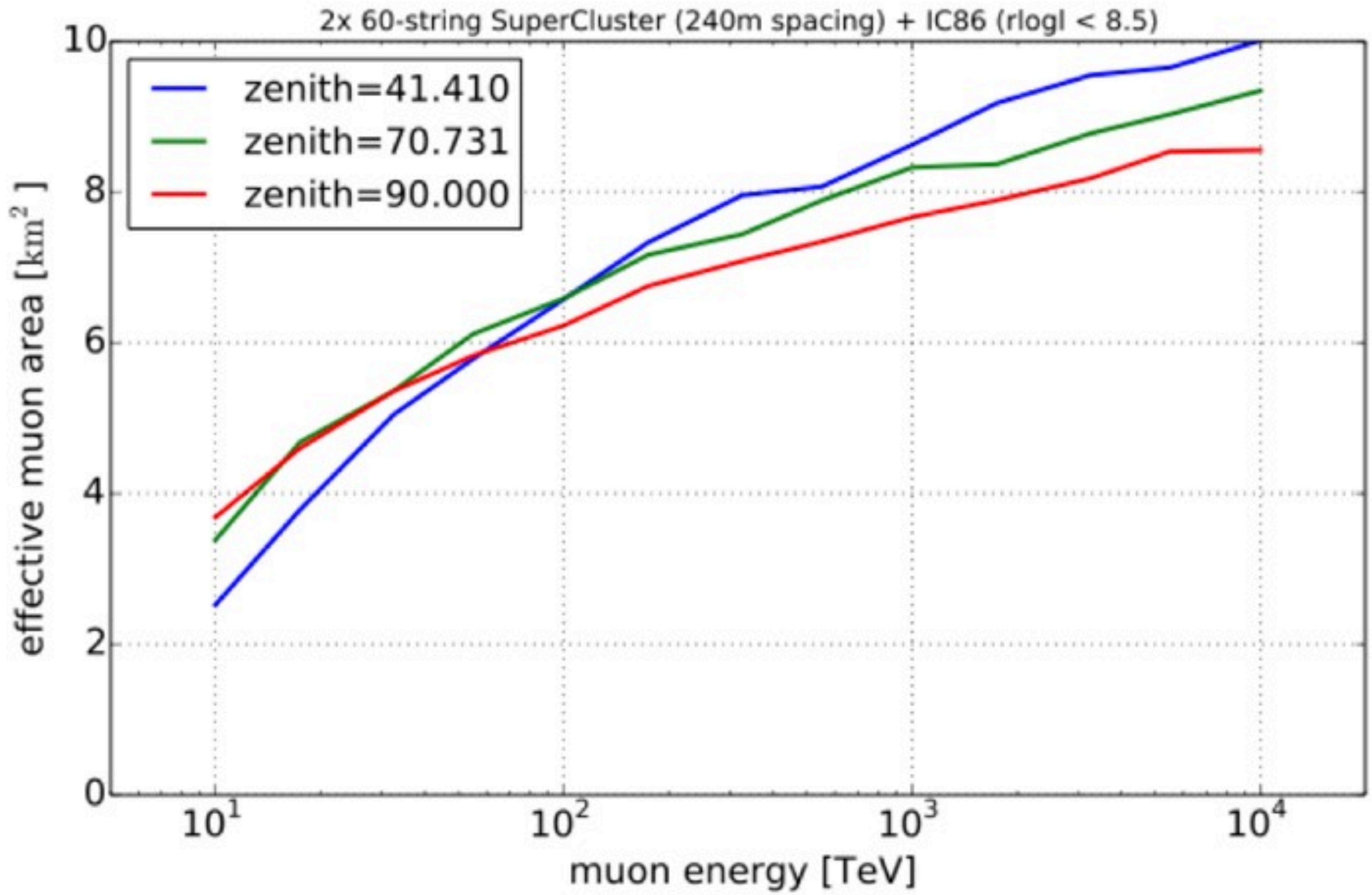
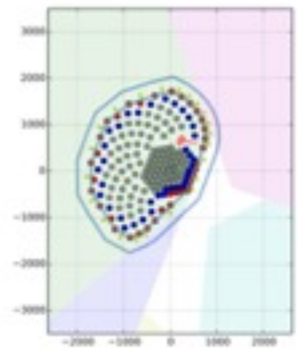


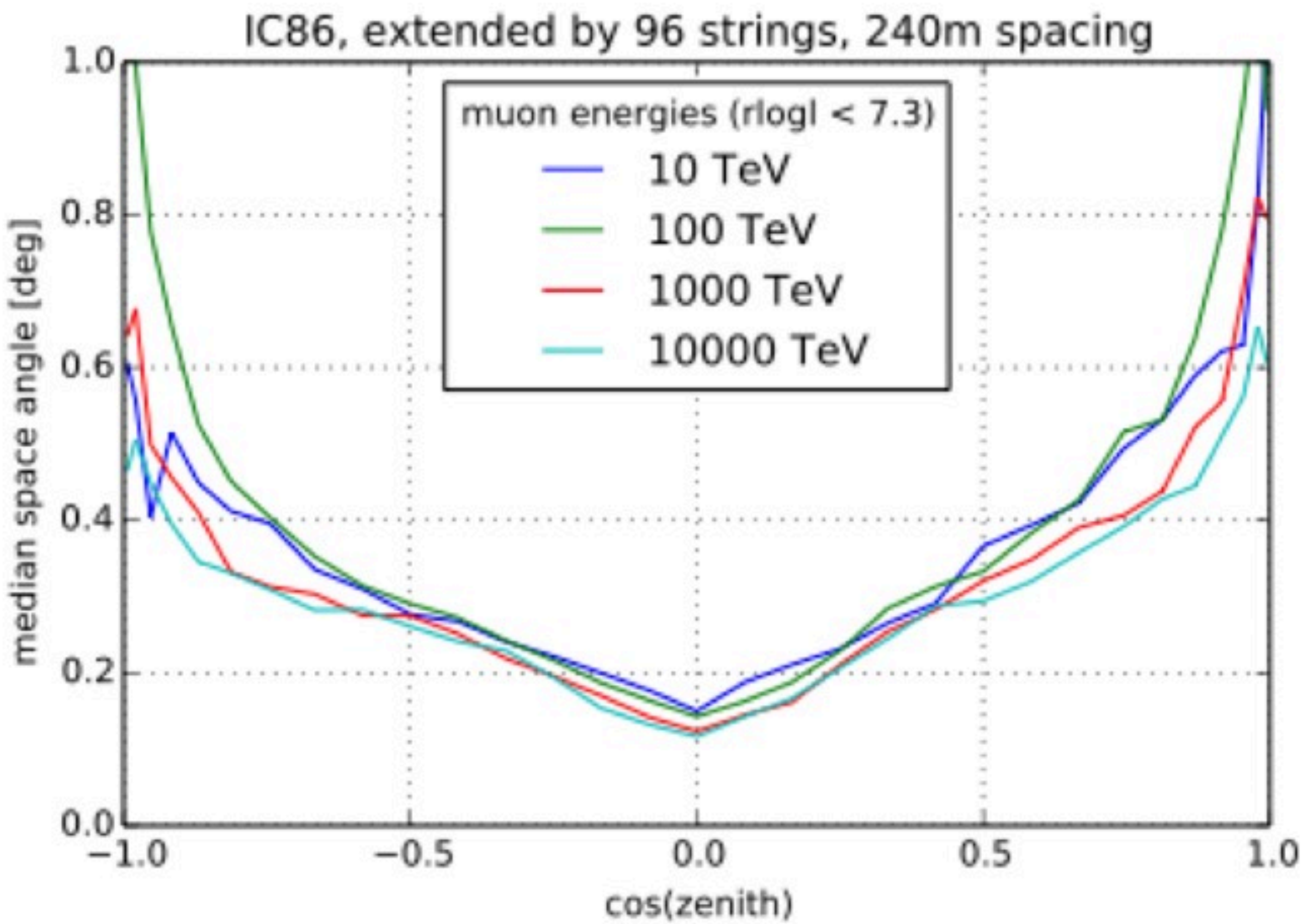


Karle, Neutrinos Beyond IceCube, Arlington, April 2014

First studies: angular resolution



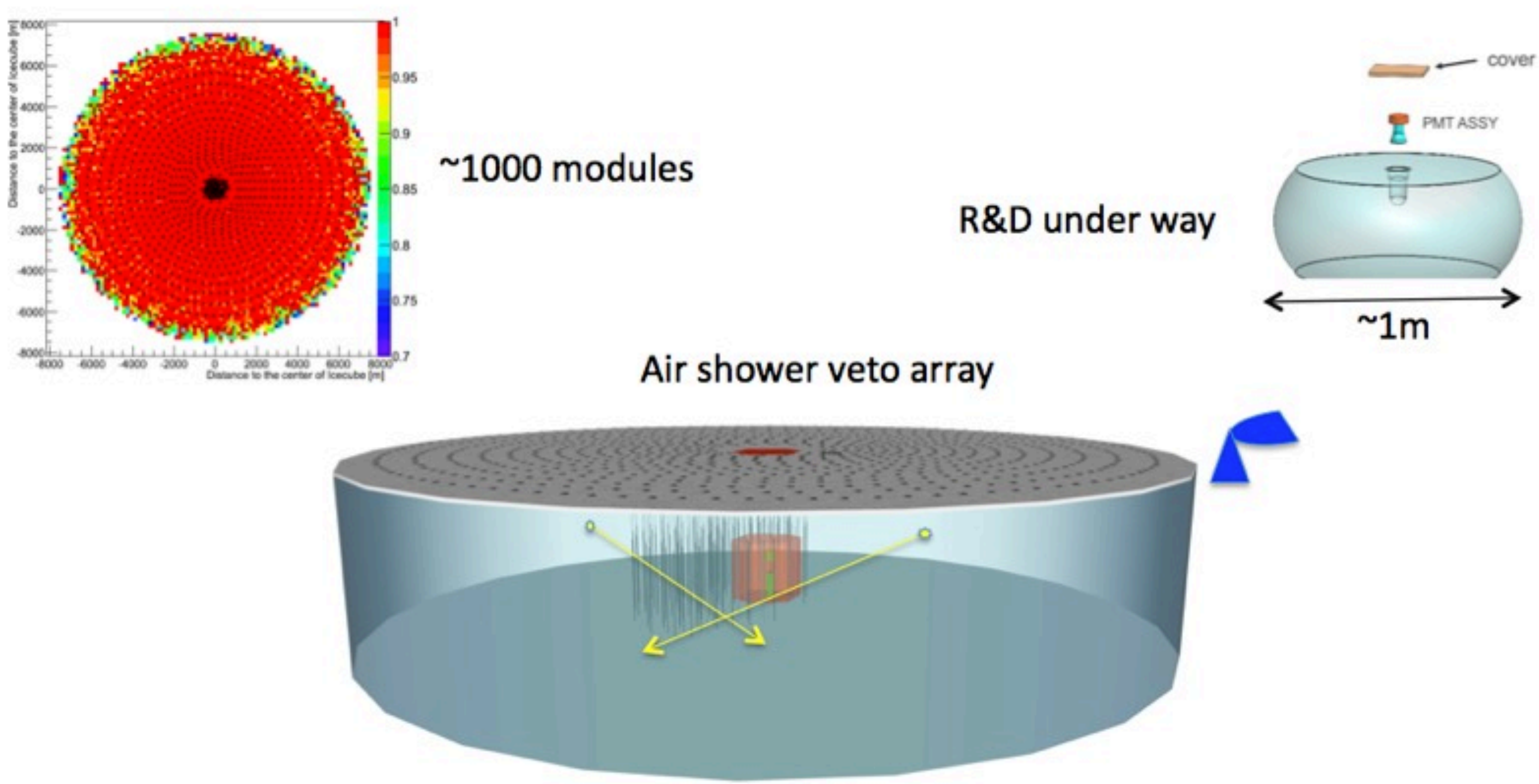
angular resolution (hard cuts)



Karle, Neutrinos Beyond IceCube, Arlington, April 2014

Expanded surface veto

- A surface veto above 1 PeV (cosmic primary) could reject most atmospheric muon AND neutrino background above 100 TeV.
- An efficient surface veto, 100 km^2, for 3 – 5 sr background free cosmic and some cascade detection



Karle, Neutrinos Beyond IceCube, Arlington, April 2014

Gain in muon signal events with surface veto (100% effective for primaries ≥ 1 PeV)

CURRENT IceCube detector