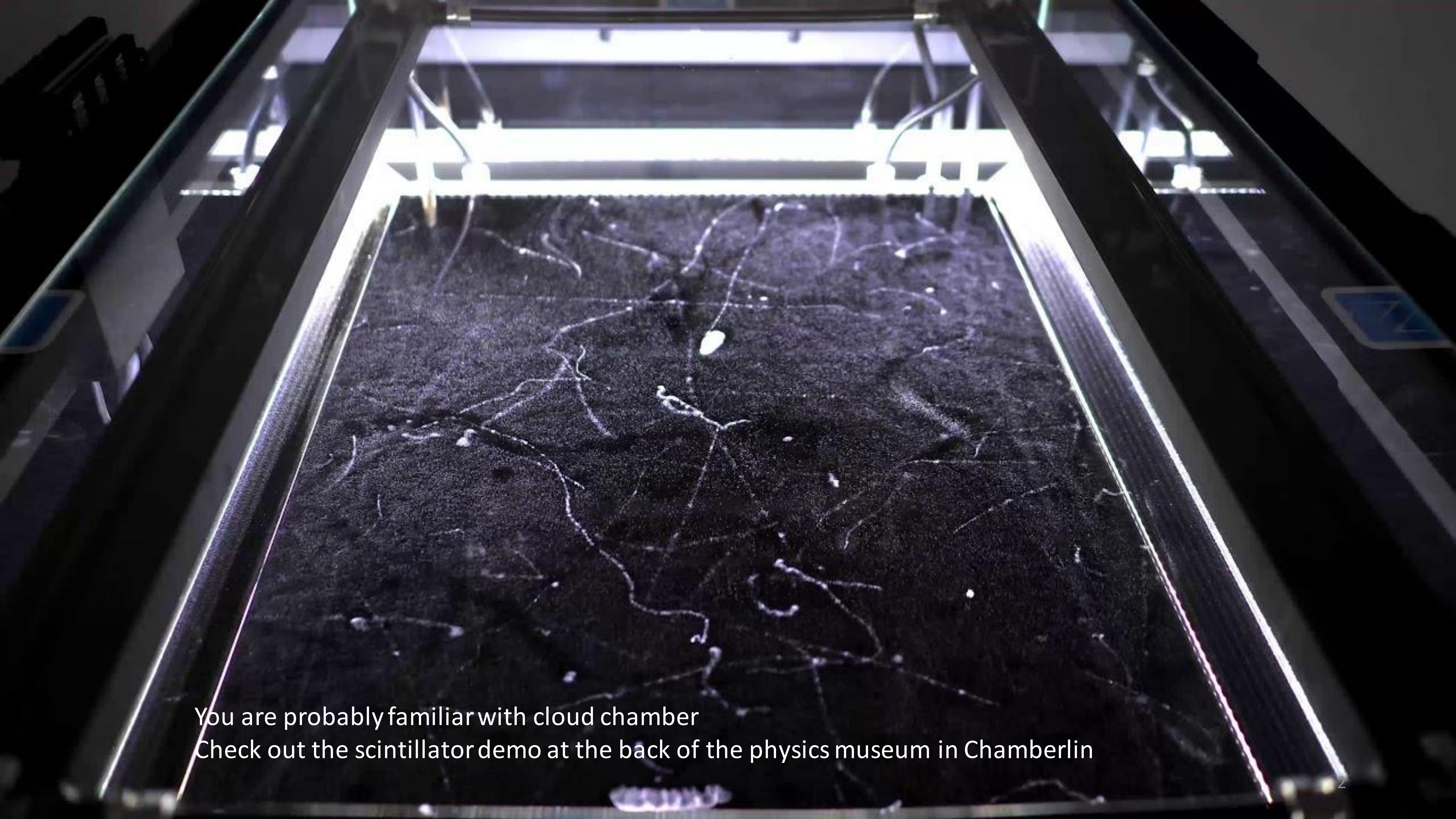
Diffuse neutrinos from 1 TeV to 1 EeV

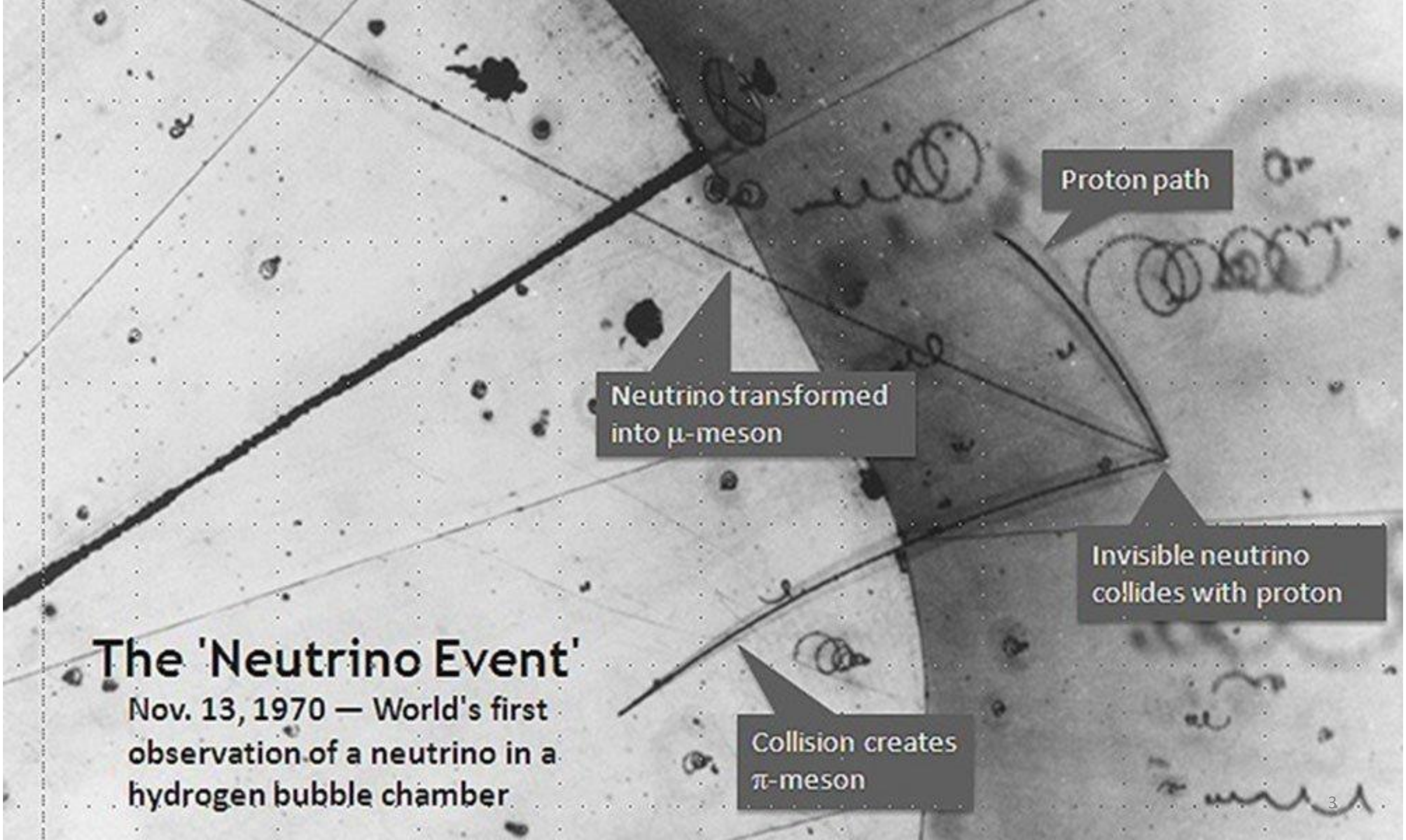
Lu Lu

University of Wisconsin-Madison

Bootcamp 2022



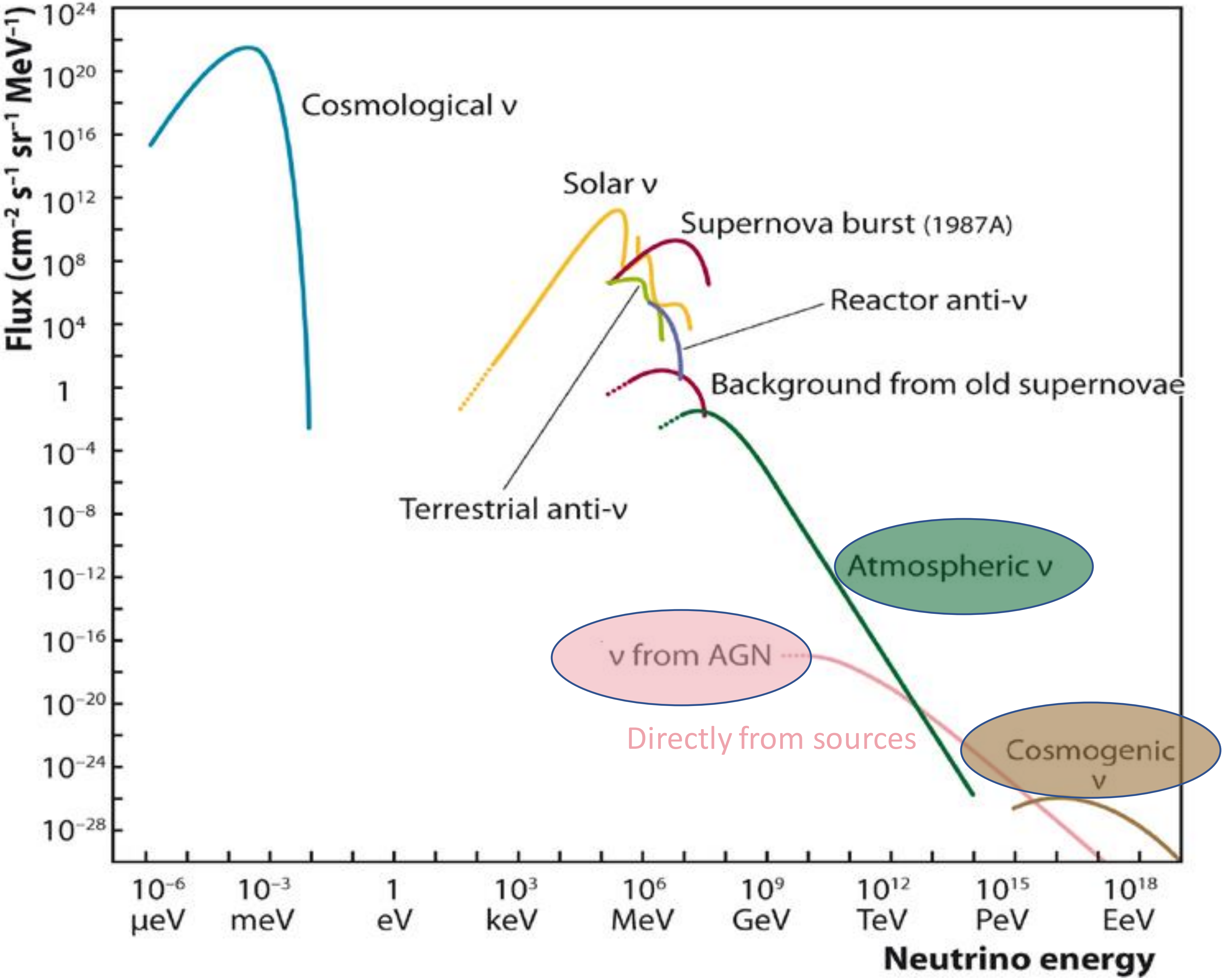
You are probably familiar with cloud chamber
Check out the scintillator demo at the back of the physics museum in Chamberlin

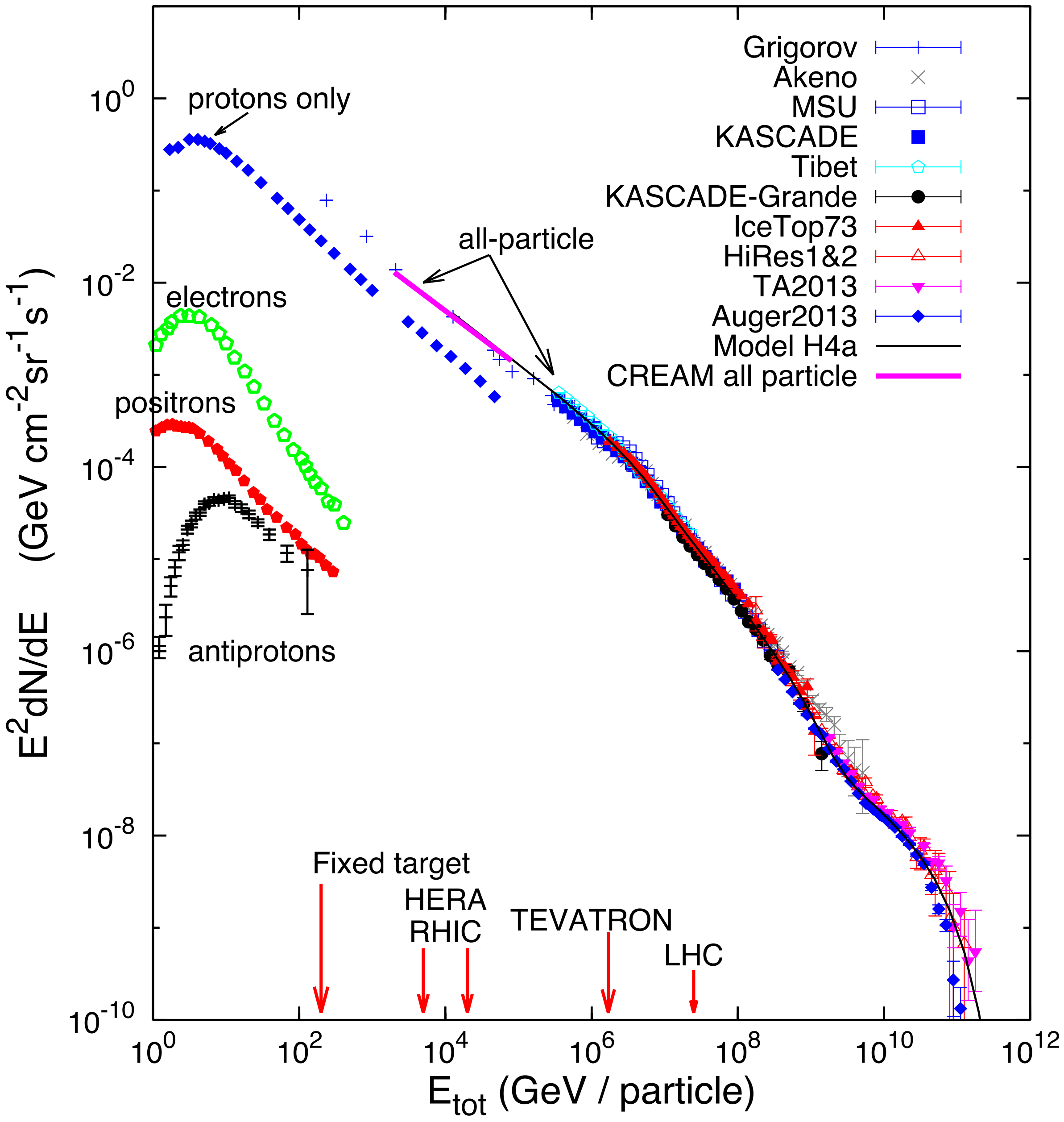


The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Diffuse flux





See Paolo's talk on cosmic rays

Cosmogenic neutrinos

- 1956 discovery of neutrinos
- 1962 discovery of UHECR 10^20 eV
- 1964 discovery of CMB
- 1969 theory cosmogenic neutrinos

$$p + \gamma_{\rm CMB} \to p + \pi^0 \to p + \gamma\gamma, \text{ and}$$
$$p + \gamma_{\rm CMB} \to n + \pi^+ \to p + \nu_{e,\mu}.$$

Atmospheric nu

$\pi^{\pm}\ K^{\pm} \rightarrow\ \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu)$ **(63.5% for K)**

$\quad \hookrightarrow e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$

→ E_ν ~ 100/cosθ GeV

$K^{\pm} \rightarrow \pi^0 e \nu_e$ **(5%)**

$K_L^0 \rightarrow \pi e \nu_e$ **(40%)**

Conv.

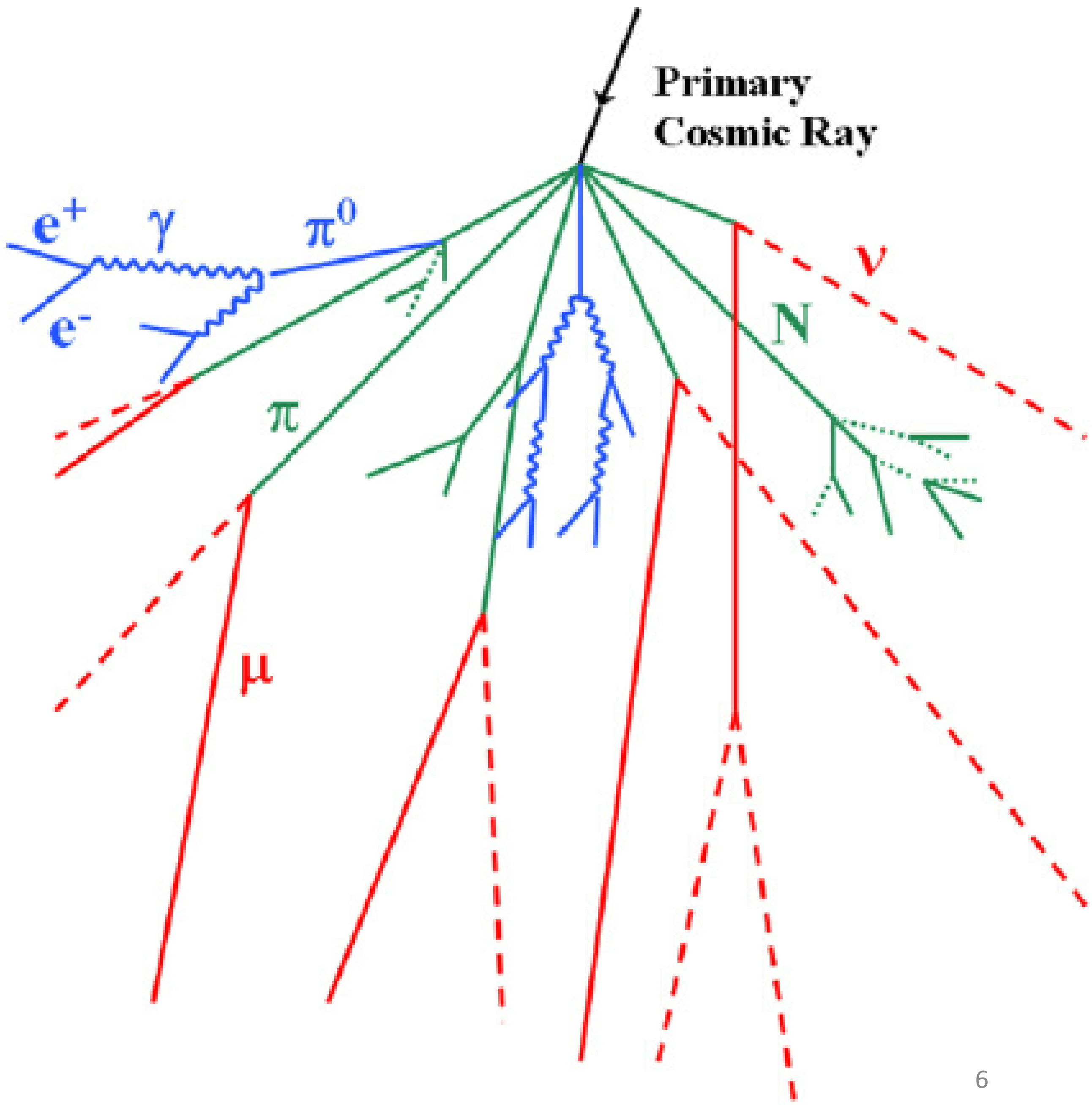
→ E_ν ~ 100/cosθ TeV

$K_S^0 \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) **(0.07%)**

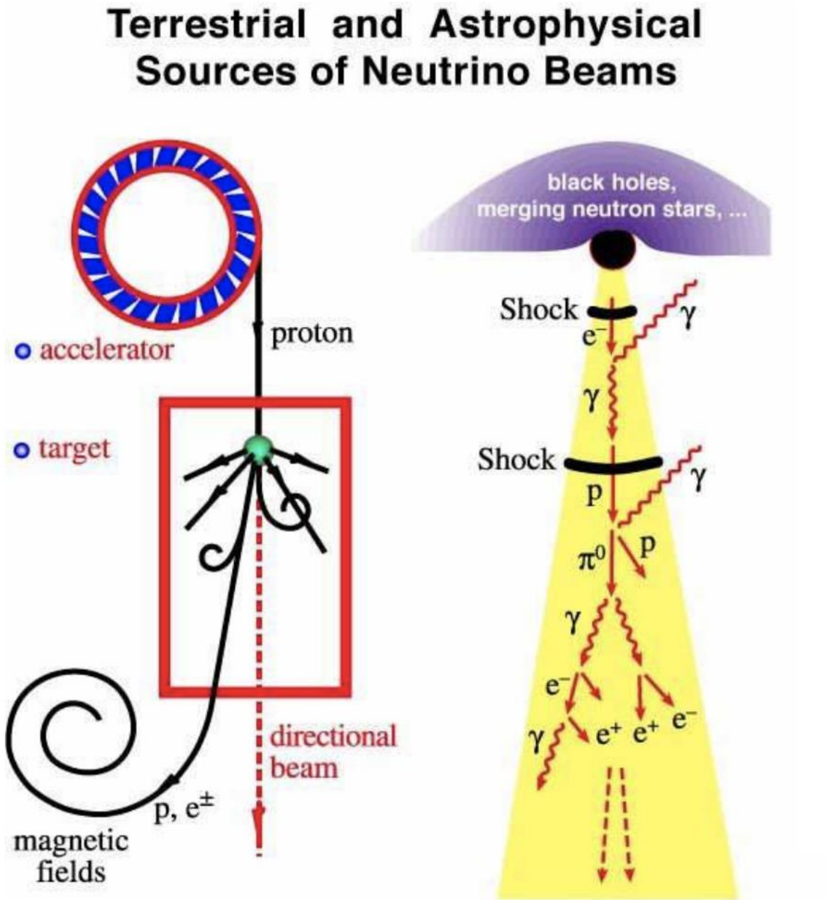
prompt

$D, \Lambda_c \rightarrow \ell + \nu_\ell + \ldots$ **(order %)**

$\eta, \eta' \rightarrow \mu^+ \mu^-$



Astrophysical neutrinos



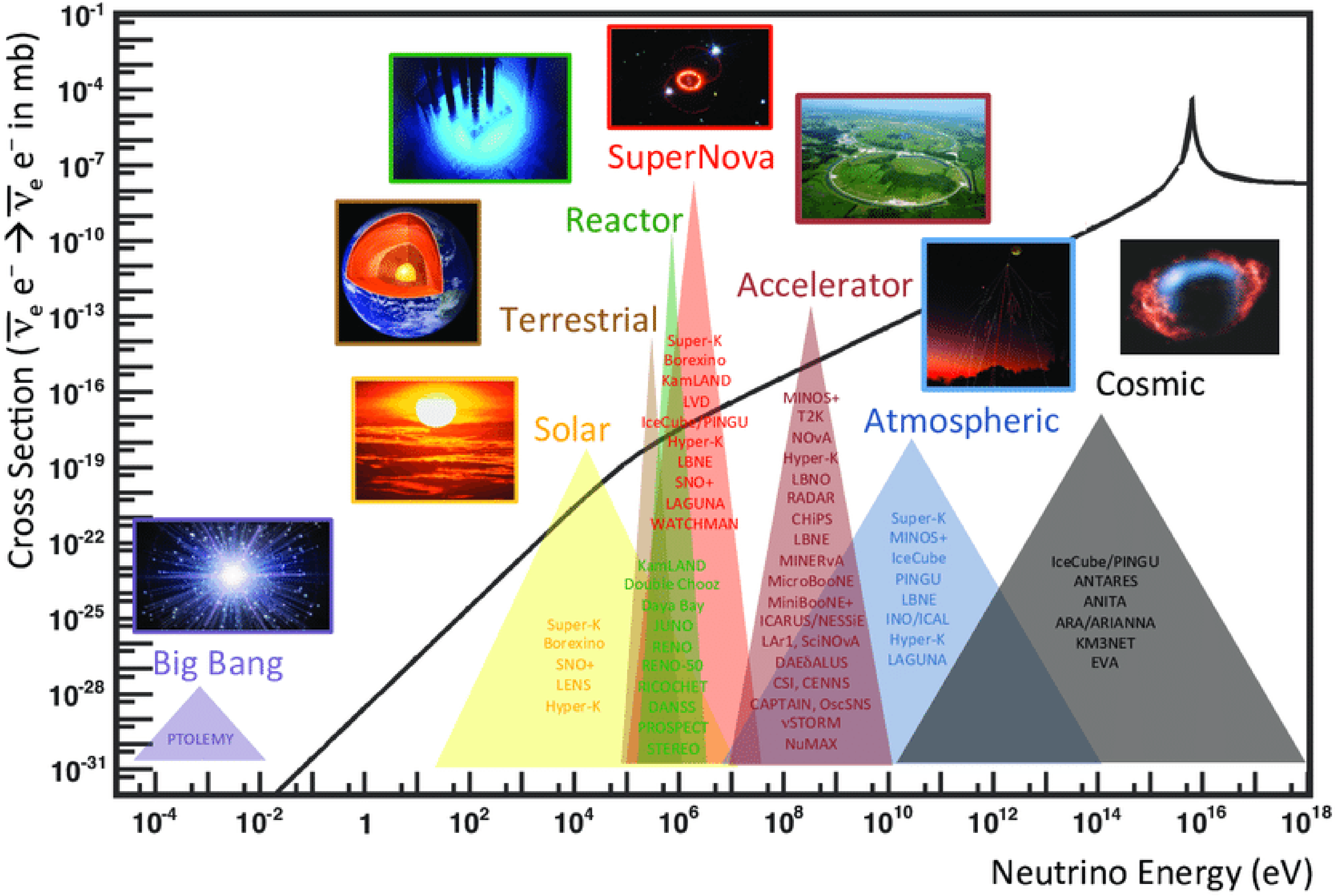
Neutrinos are produced in astrophysical shock fronts in proton–photon and/or proton–proton interactions via pion production. The dominant channels are

$$p\,\gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} p\,\pi^0, & \text{fraction } 2/3 \\ n\,\pi^+, & \text{fraction } 1/3 \end{cases}$$

$$pp \rightarrow \pi^+\pi^-\pi^0.$$

$$\pi^+ \rightarrow \mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\overline{\nu}_\mu\,\nu_\mu$$

$$\pi^- \rightarrow \mu^-\,\overline{\nu}_\mu \rightarrow e^-\,\overline{\nu}_e\,\nu_\mu\,\overline{\nu}_\mu$$


Cross Section ($\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ in mb)
Neutrino Energy (eV)
Big Bang
PTOLEMY
Solar
Super-K
Borexino
SNO+
LENS
Hyper-K
Terrestrial
Reactor
KamLAND
Double Chooz
Daya Bay
JUNO
RENO
RENO-50
RICOCHET
DANSS
PROSPECT
STEREO
SuperNova
Super-K
Borexino
KamLAND
LVD
IceCube/PINGU
Hyper-K
LBNE
SNO+
LAGUNA
WATCHMAN
Accelerator
MINOS+
T2K
NOvA
Hyper-K
LBNO
RADAR
CHIPS
LBNE
MINERvA
MicroBooNE
MiniBooNE+
ICARUS/NESSiE
LAr1, SciNOvA
DAEδALUS
CSI, CENNS
CAPTAIN, OscSNS
vSTORM
NuMAX
Atmospheric
Super-K
MINOS+
IceCube
PINGU
LBNE
INO/ICAL
Hyper-K
LAGUNA
Cosmic
IceCube/PINGU
ANTARES
ANITA
ARA/ARIANNA
KM3NET
EVA

The above discussion is summarized in Fig. 3.

IceCube design report 2001

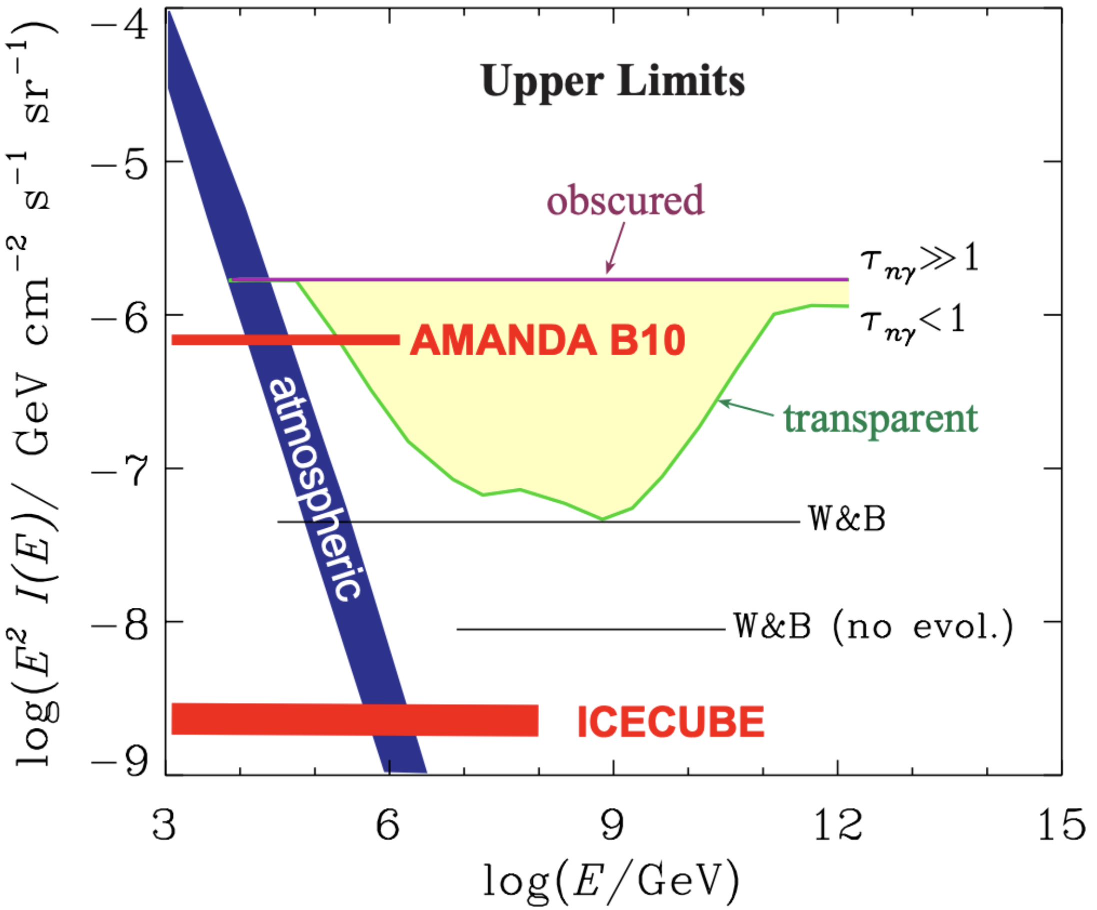
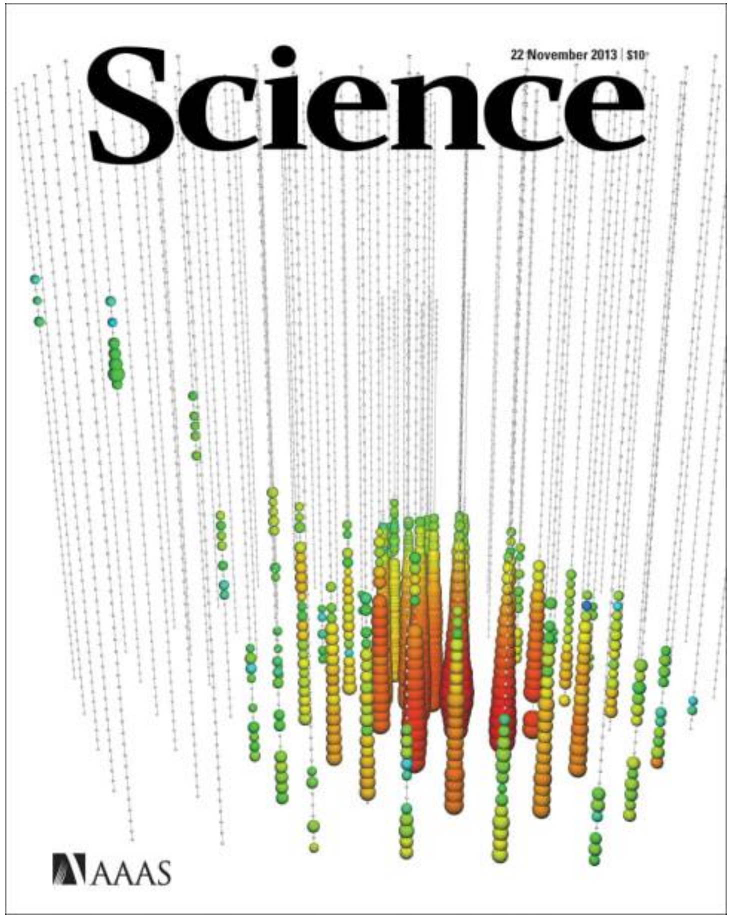


Figure 3: Cosmic-ray bounds on extragalactic neutrino fluxes. The generic bound obtained by Mannheim, Protheroe and Rachen [18] for the optically thin ($\tau_{n\gamma} < 1$) and thick case ($\tau_{n\gamma} \gg 1$) are shown together with the limit inferred from Waxman and Bahcall [8] with and without source evolution. They are compared to the present AMANDA limit and to the limit expected from three years of IceCube operation.

2013 - when the discoveries began



RESEARCH ARTICLE

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

ICECUBE COLLABORATION*

SCIENCE • 22 Nov 2013 • Vol 342,Issue 6161 • DOI: 10.1126/science.1242856

Extraterrestrial Neutrinos

Neutrinos are thought to be produced in astrophysical sources outside our solar system but, up until recently, they had only been observed from one supernova in 1987. **Aartsen *et al.*** (10.1126/science.1242856; see the cover) report data obtained between 2010 and 2012 with the IceCube neutrino detector that reveal the presence of a high-energy neutrino flux containing the most energetic neutrinos ever observed, including 28 events at energies between 30 and 1200 TeV. Although the origin of this flux is unknown, the findings are consistent with expectations for a neutrino population with origins outside the solar system.

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- No significant point sources
- -> diffuse measurement

(all sky 4pi)

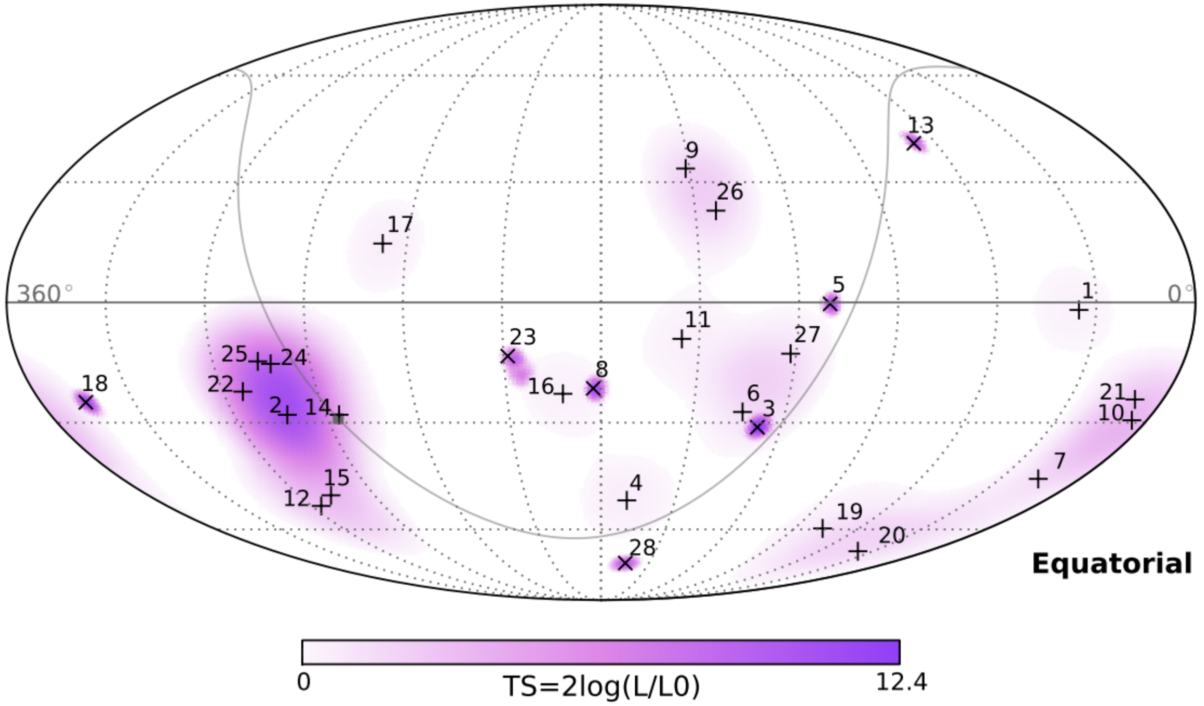


FIG. 5. Skymap in equatorial coordinates of the Test Statistic value (TS) from the maximum likelihood point-source analysis. The most significant cluster consists of five events—all showers and including the second-highest energy event in the sample—with a final significance of 8%. This is not sufficient to identify any neutrino sources from the clustering study. The galactic plane is shown as a gray line with the galactic center denoted as a filled gray square. Best-fit locations of individual events (listed in Table I) are indicated with vertical crosses (+) for showers and angled crosses (×) for muon tracks.

* More recent point-source results see talk from Francis (hint: many since 2013!)

Fast forward… key diffuse results from the past decade

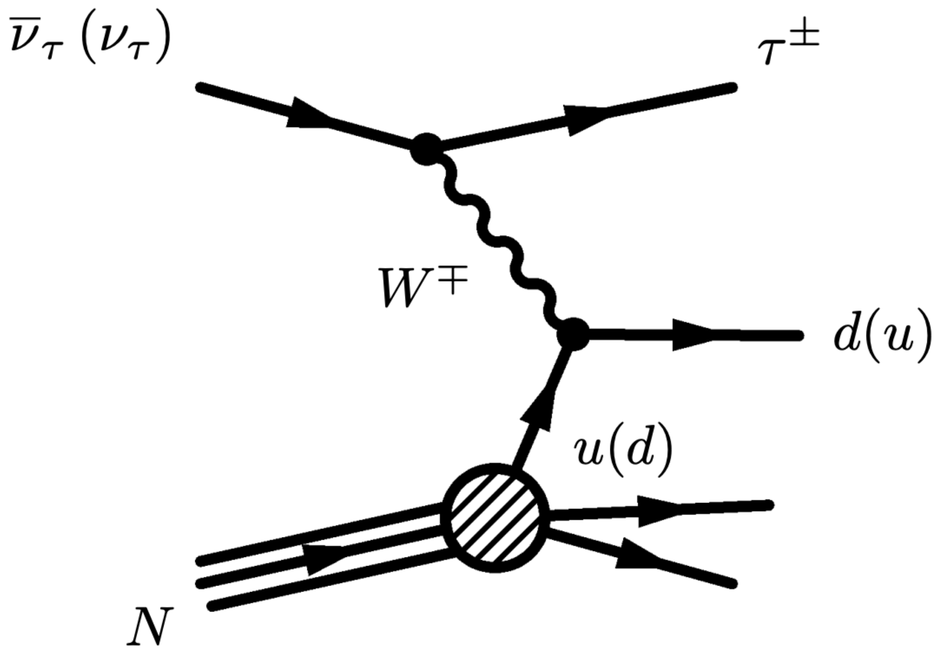
- Astrophysical diffuse spectrum
- Atmospheric nu flux, seasonal variations
- Galactic plane diffuse flux
- Cosmogenic limits
- Flavour measurement
- Cross section
- Inelasticity
- Glashow resonance (nu/nubar)

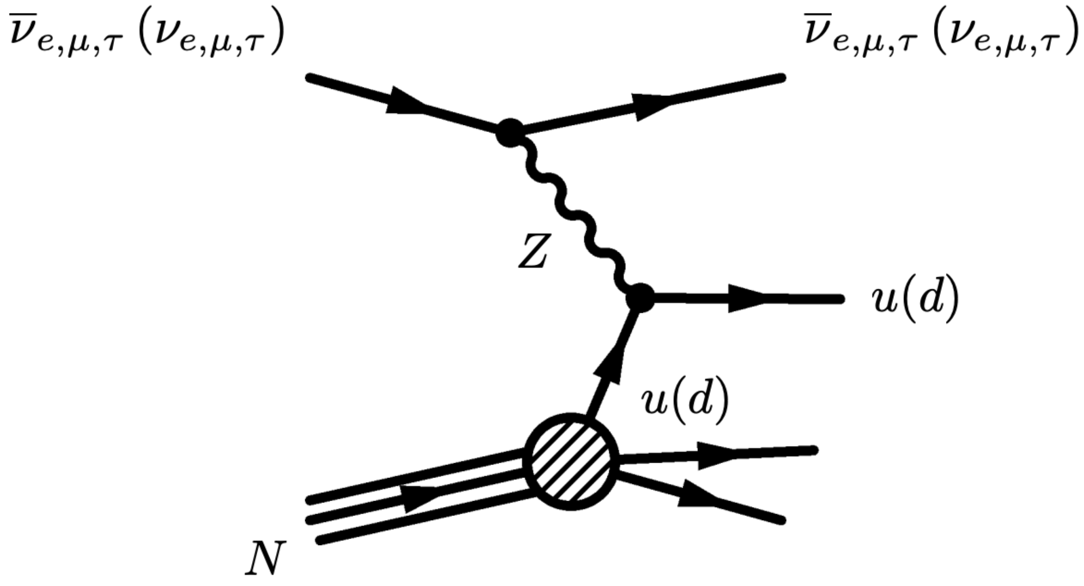
- Wishlist: earth tomography (on-going) / charm detections / CC vs NC…

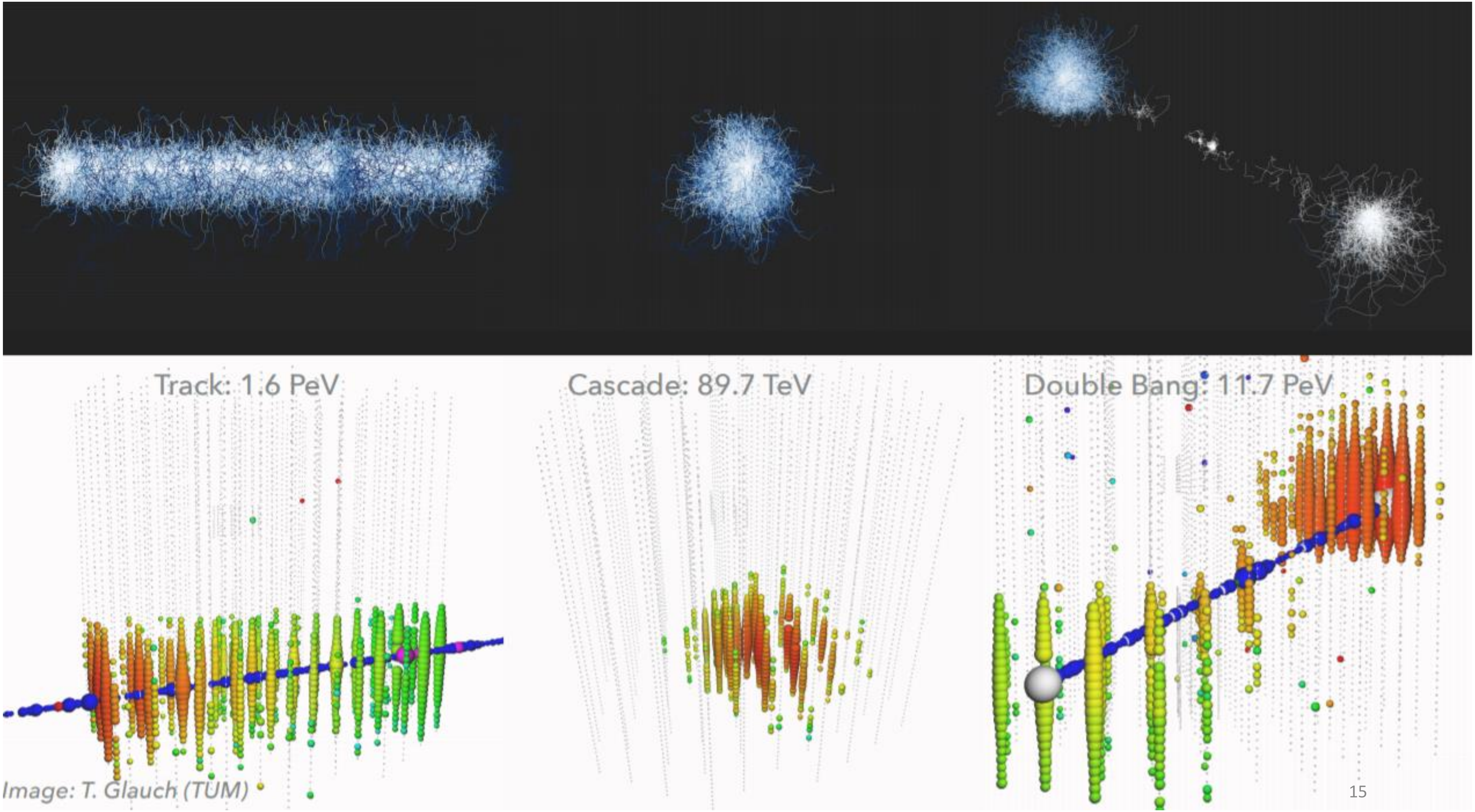
What we observe – secondaries of neutrino interactions with matter

Deep inelastic neutrino-nucleon scattering

- Charged current and neutral current interactions

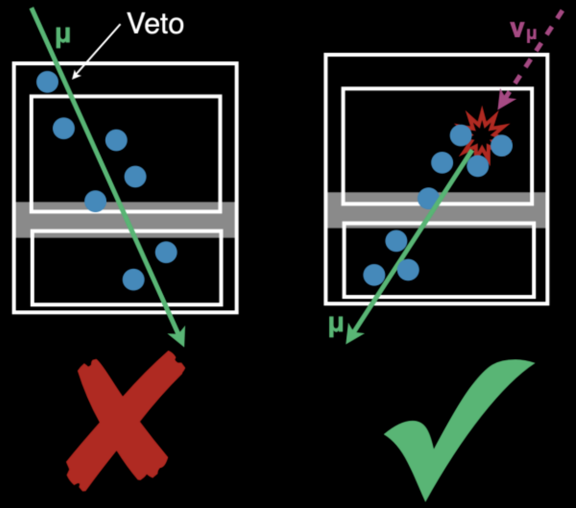





Track: 1.6 PeV
Cascade: 89.7 TeV
Double Bang: 11.7 PeV
Image: T. Glauch (TUM)

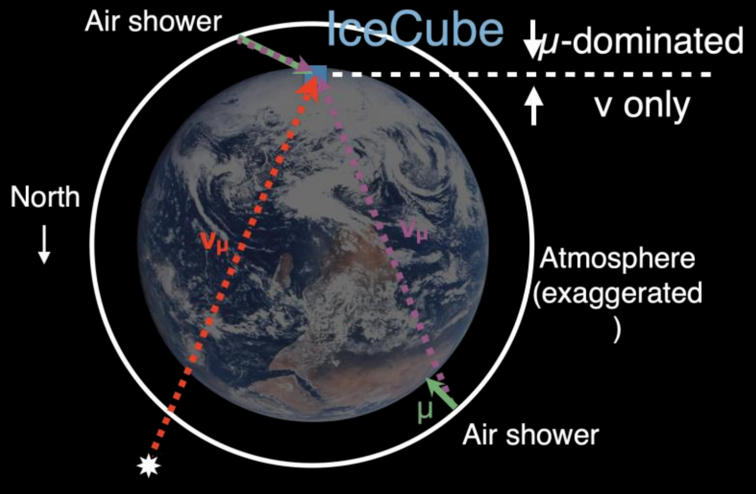
Signal:Background~1:10million

Active veto



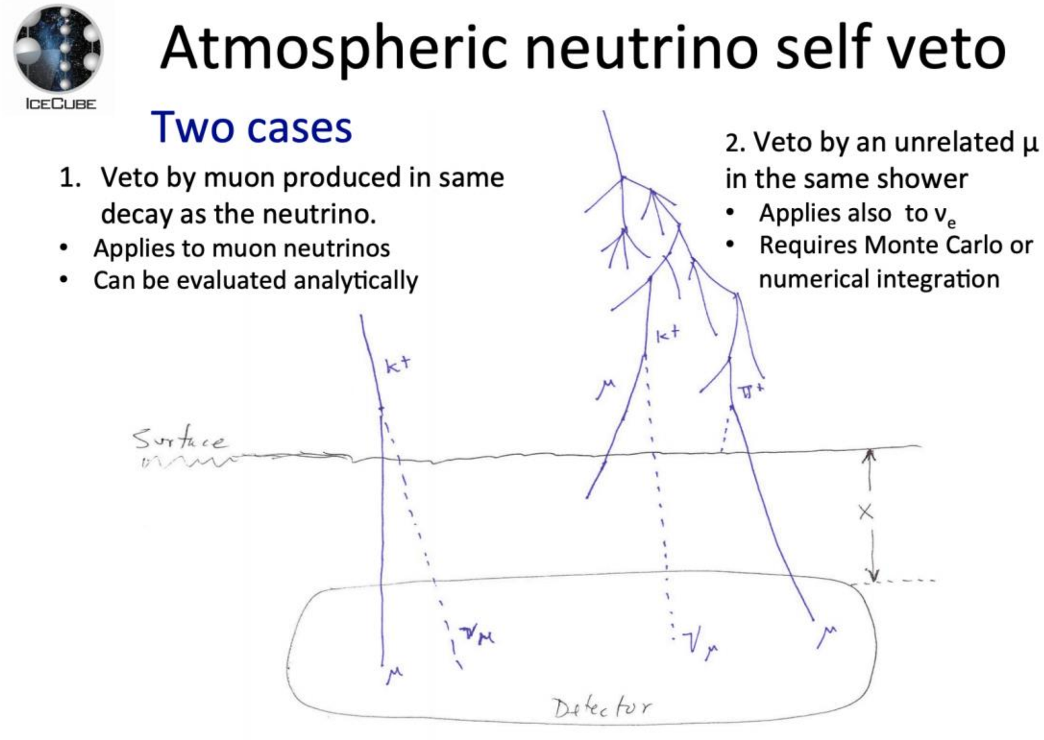
Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

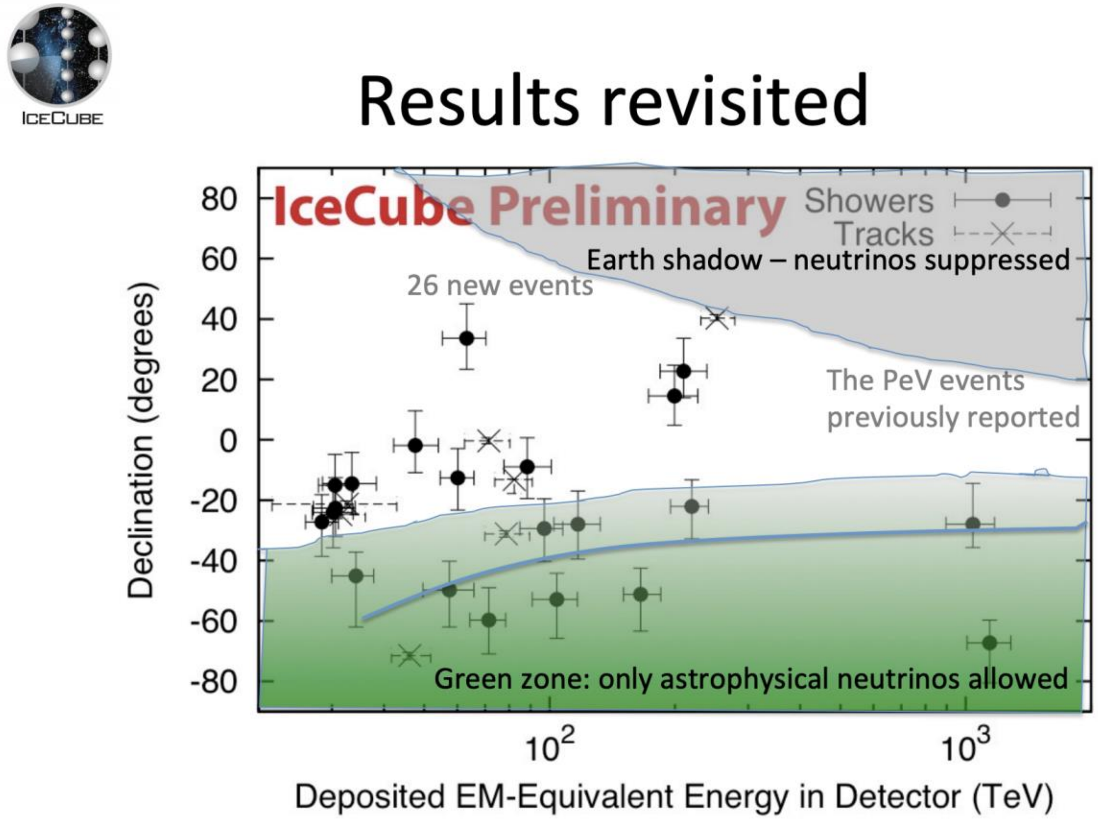
Up-going tracks



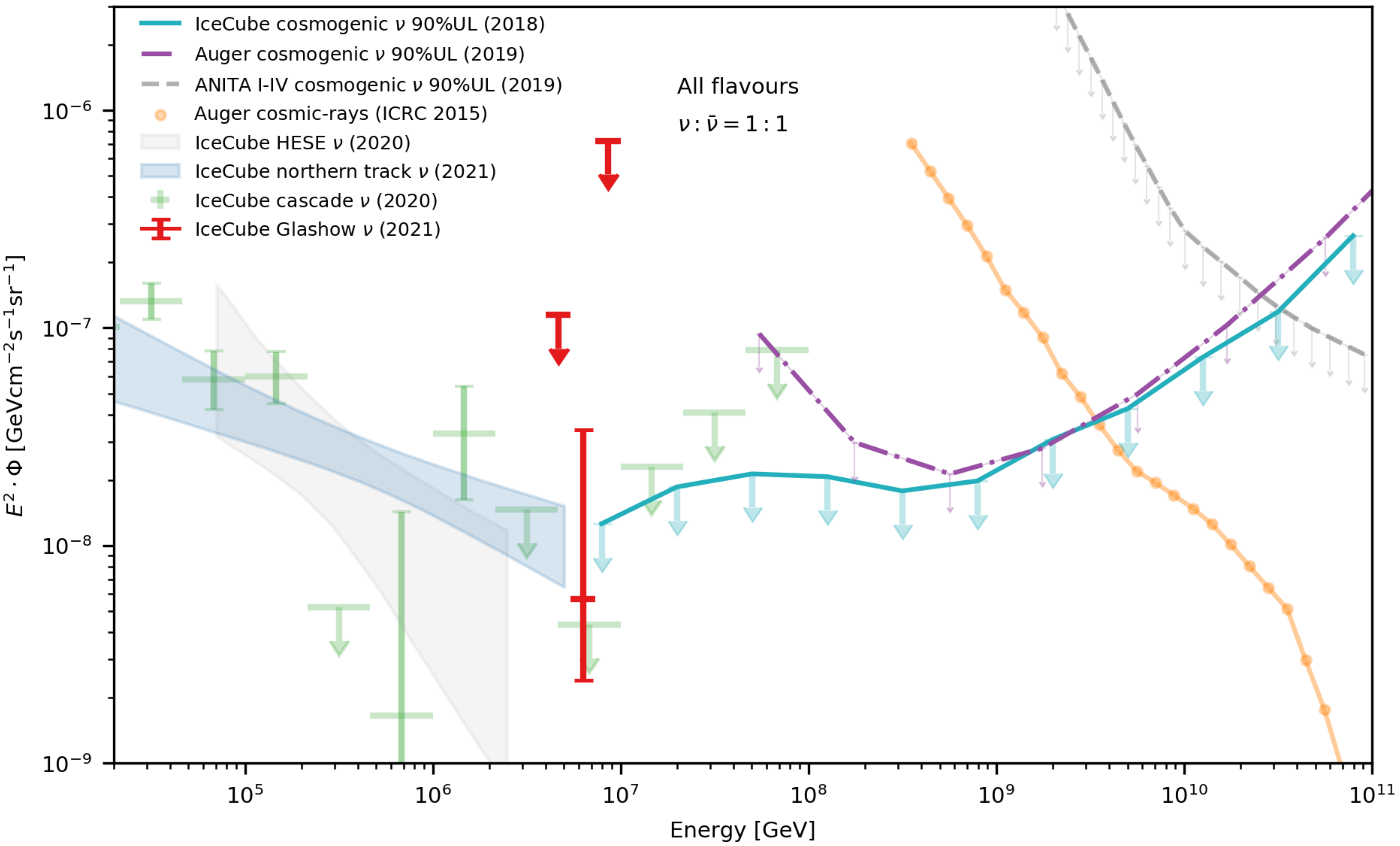
Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to “half” the sky

Southern sky advantage: self-veto (slide stolen from Tom Gaisser)

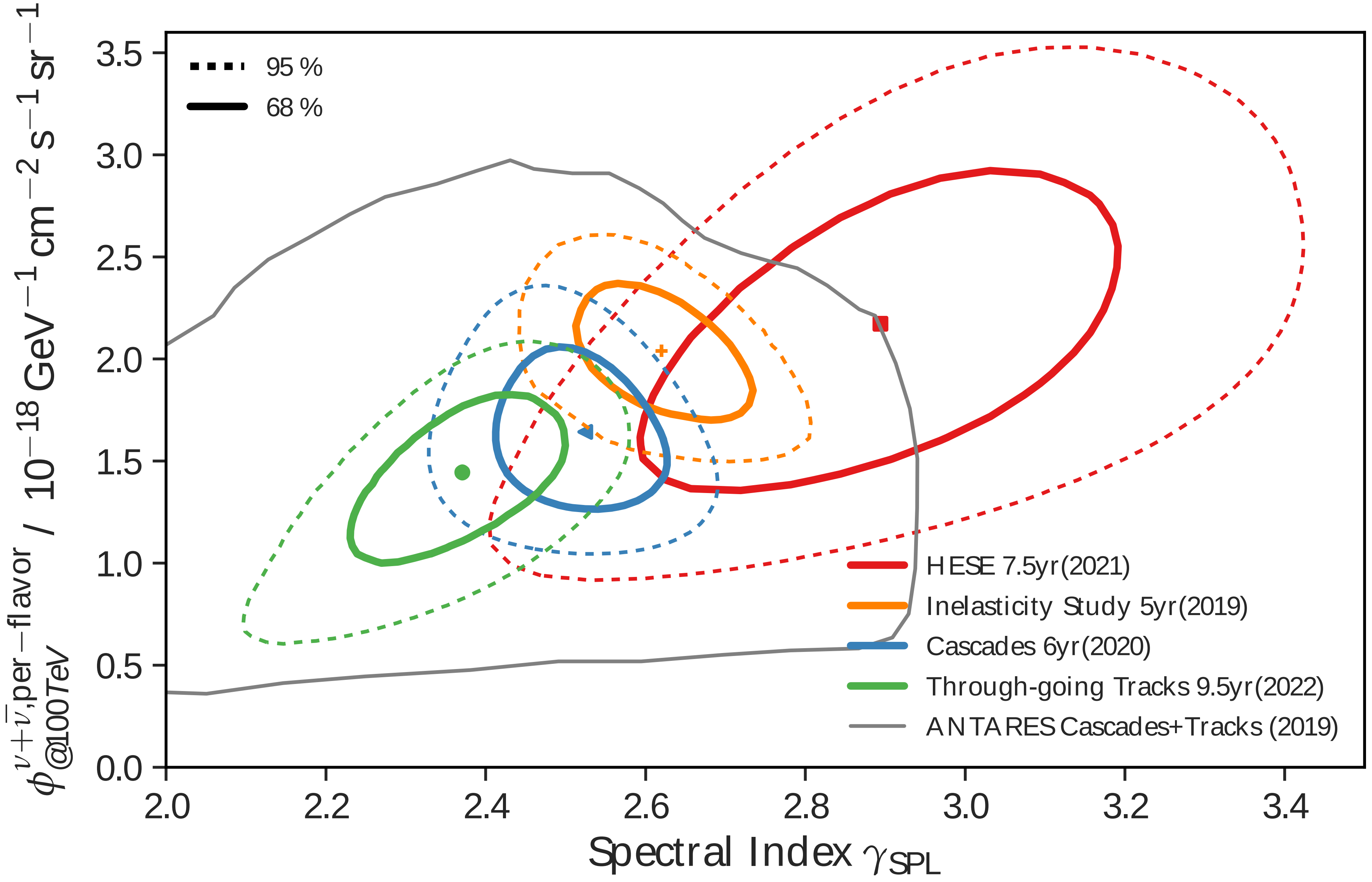




Argument applied to HESE, MESE, ESTES, cascade etc diffuse measurements

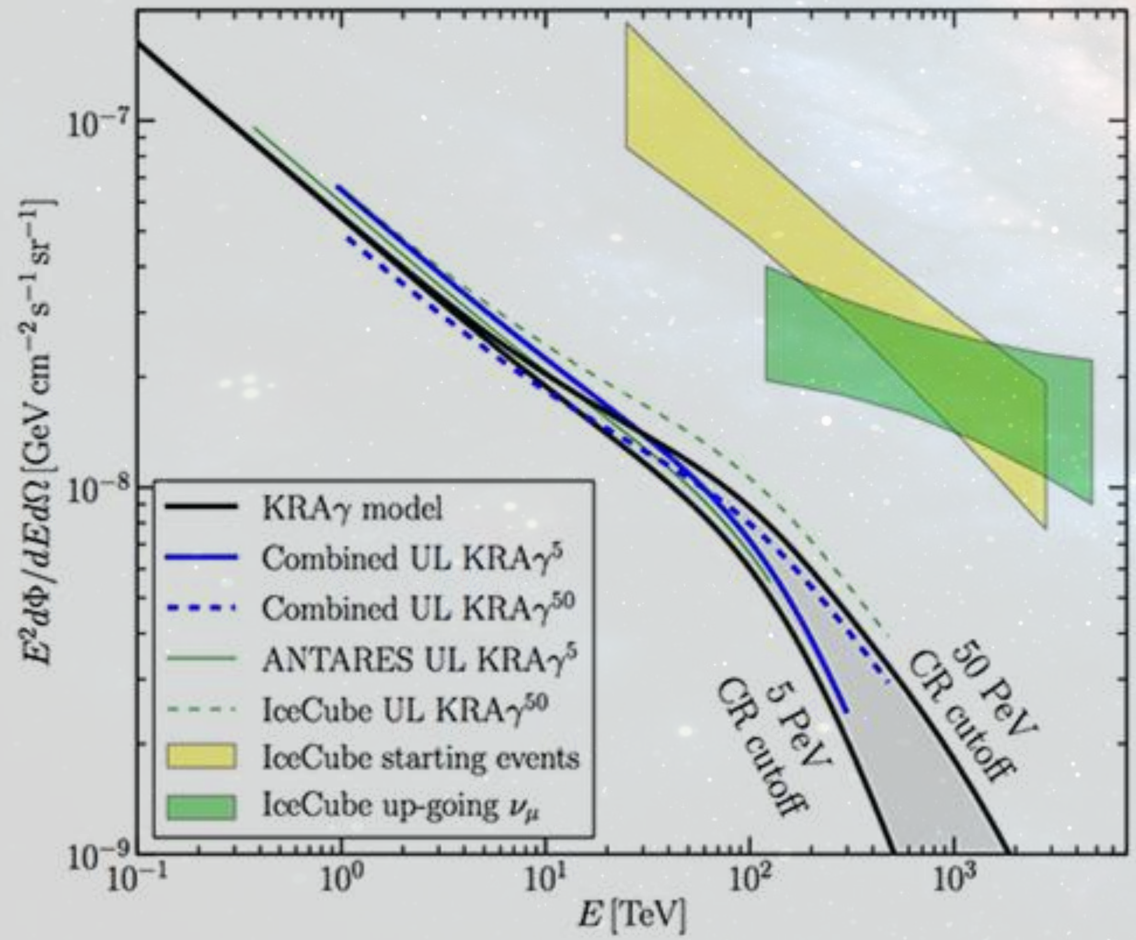


IceCube cosmogenic ν 90%UL (2018)
Auger cosmogenic ν 90%UL (2019)
ANITA I-IV cosmogenic ν 90%UL (2019)
Auger cosmic-rays (ICRC 2015)
IceCube HESE ν (2020)
IceCube northern track ν (2021)
IceCube cascade ν (2020)
IceCube Glashow ν (2021)
All flavours
$\nu : \bar{\nu} = 1 : 1$
$E^2 \cdot \Phi$ [$\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$]
Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

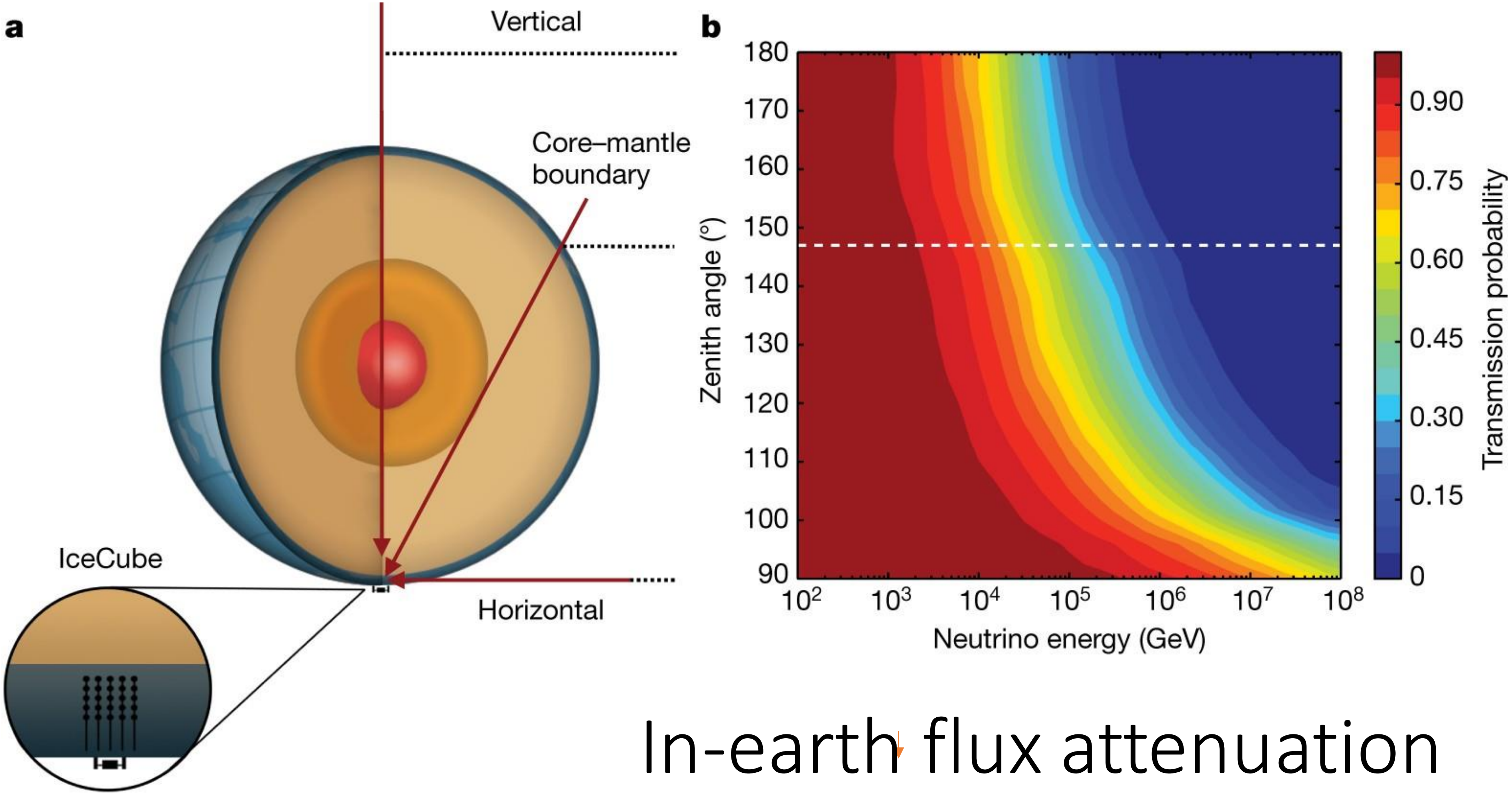


95 %
68 %
HESE 7.5yr(2021)
Inelasticity Study 5yr(2019)
Cascades 6yr(2020)
Through-going Tracks 9.5yr(2022)
ANTARES Cascades+Tracks (2019)
Spectral Index γ_{SPL}
$\phi^{\nu+\bar{\nu},\mathrm{per-flavor}}_{@100TeV}$ / $10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

Galactic plane



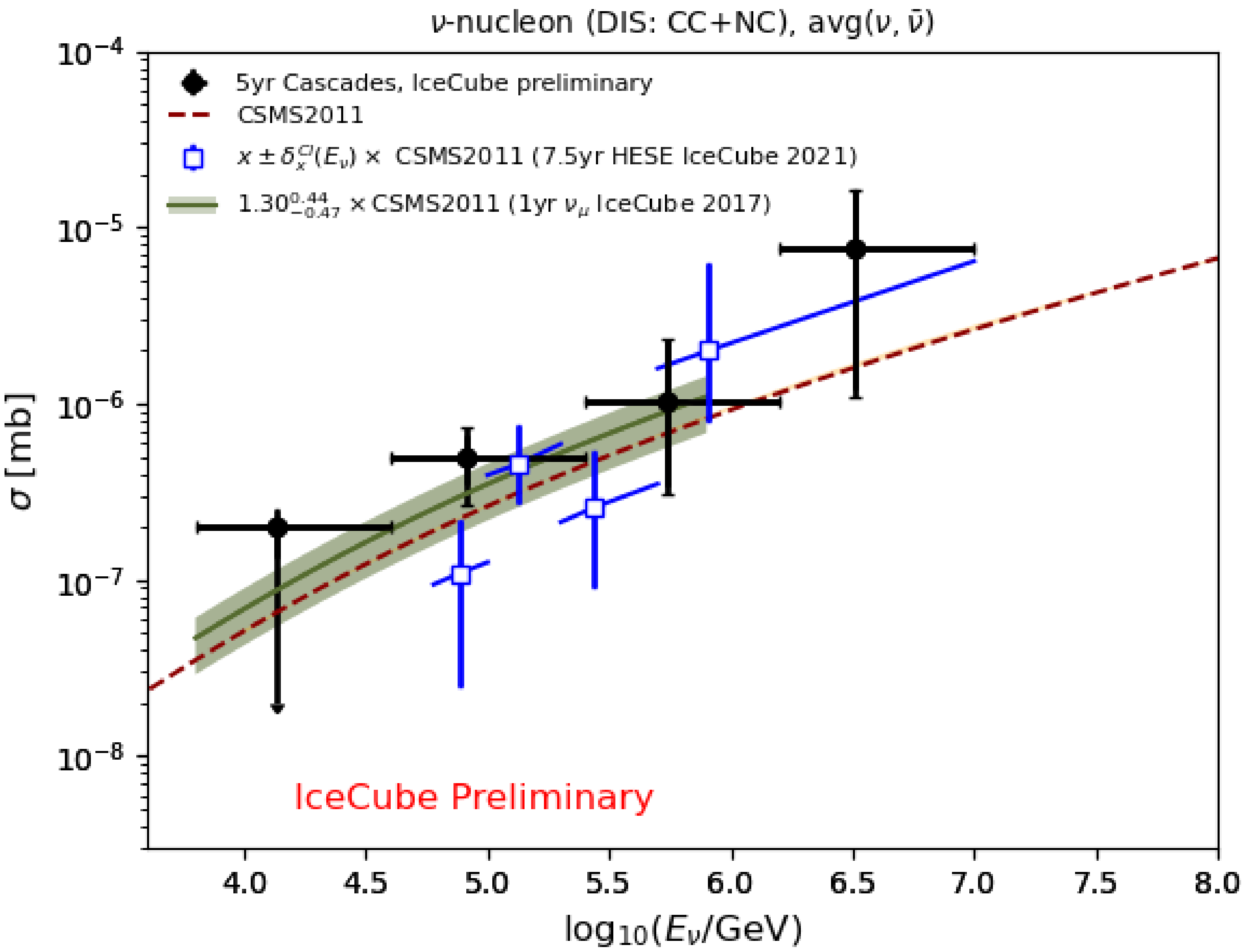
Cross section measurement using Earth as the target



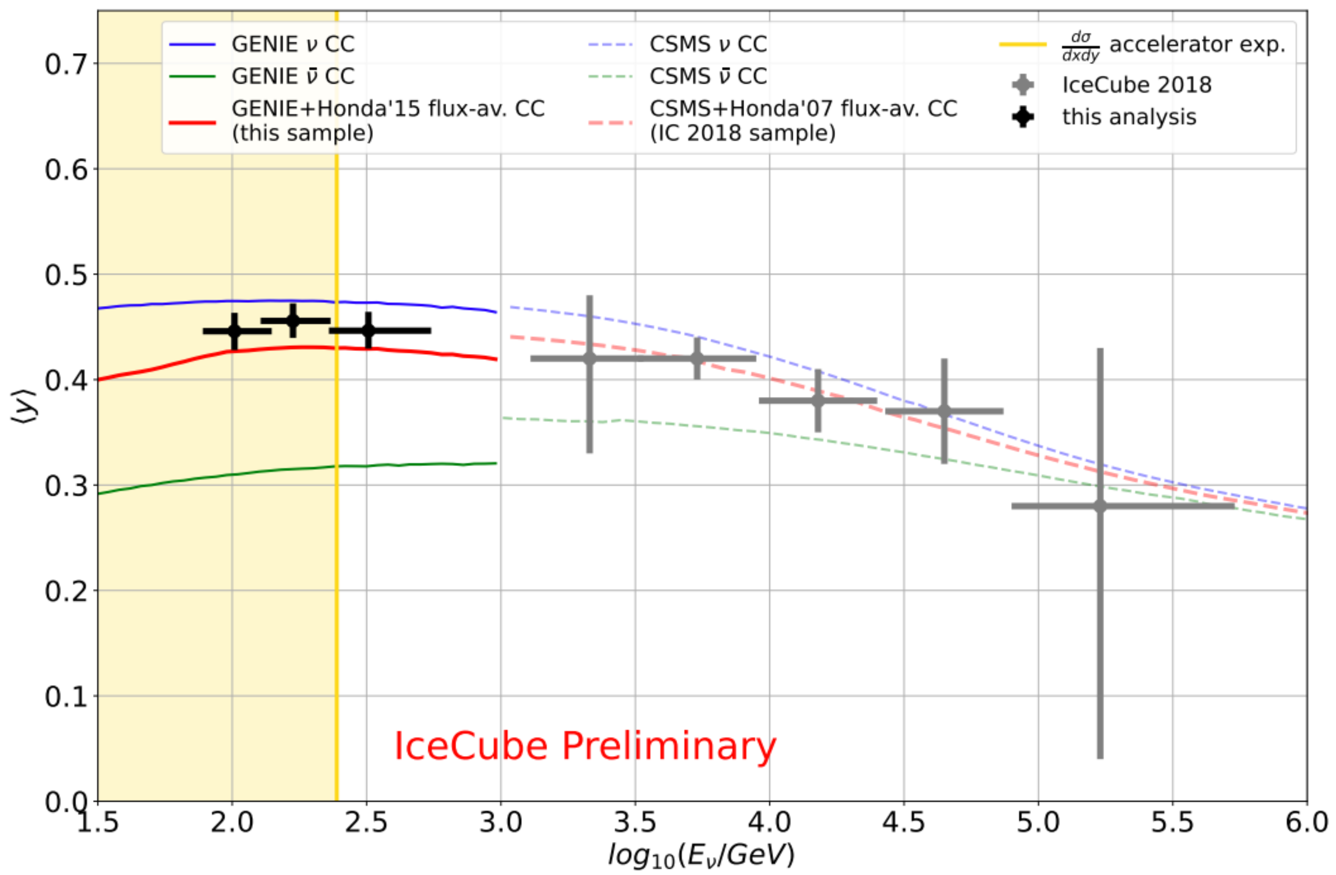
In-earth flux attenuation

Cross section

- Both tracks and cascades
- Reaching energies beyond accelerators



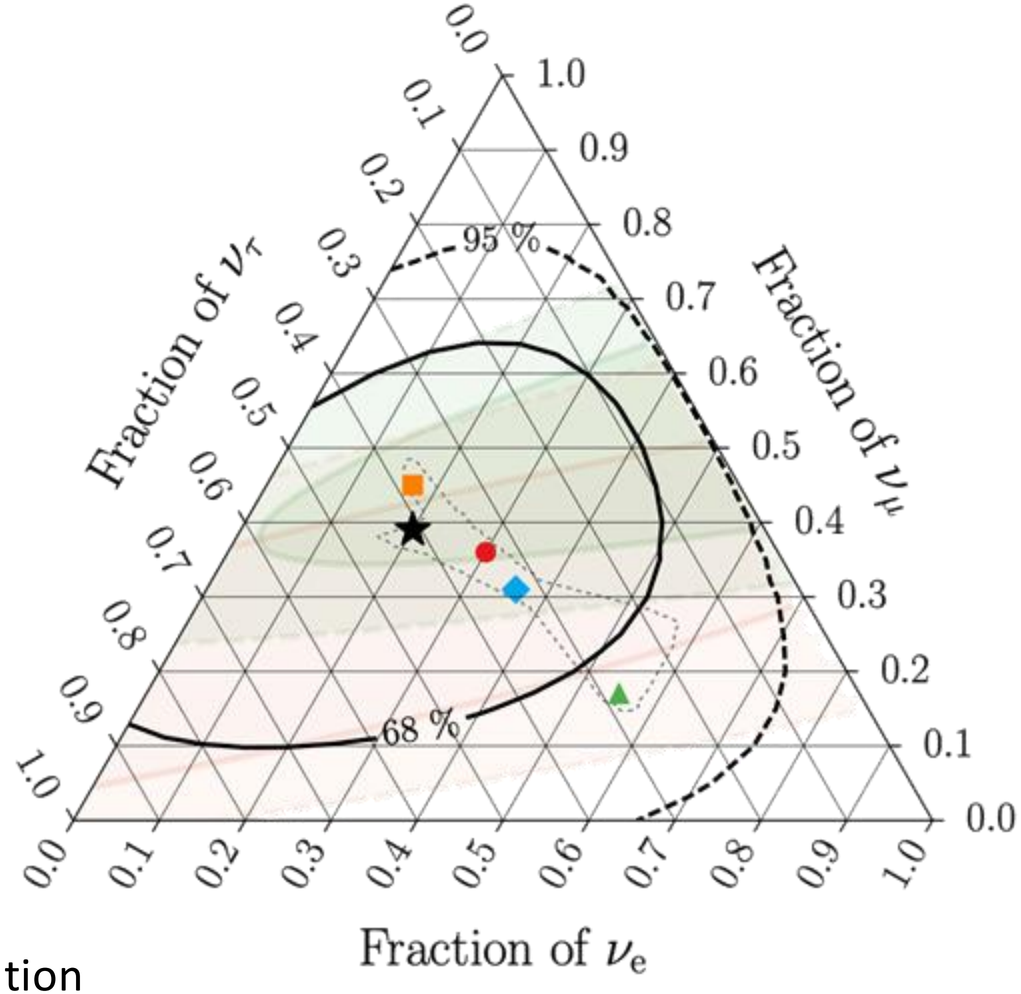
Inelasticity



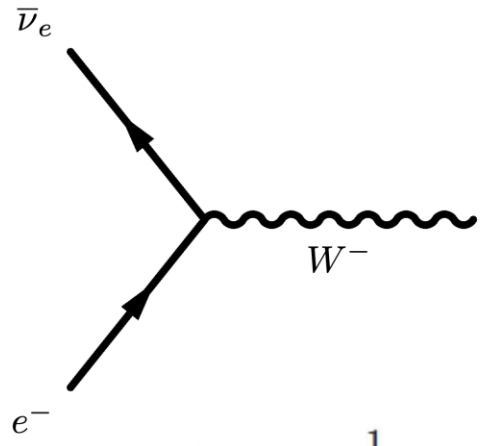
Neutrino oscillations over cosmic baselines

- For the first time tau candidates in data

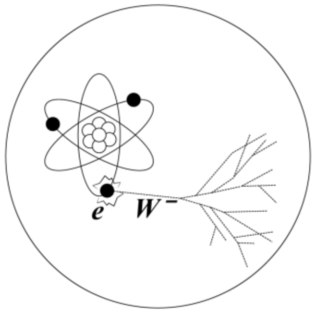
- Observed high-energy tau neutrinos mainly due to neutrino oscillations through astronomical distances.
- Sensitive probe for physics beyond the Standard Model



https://arxiv.org/abs/2011.03561, publication in preparation



Neutrino-electron scattering



at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

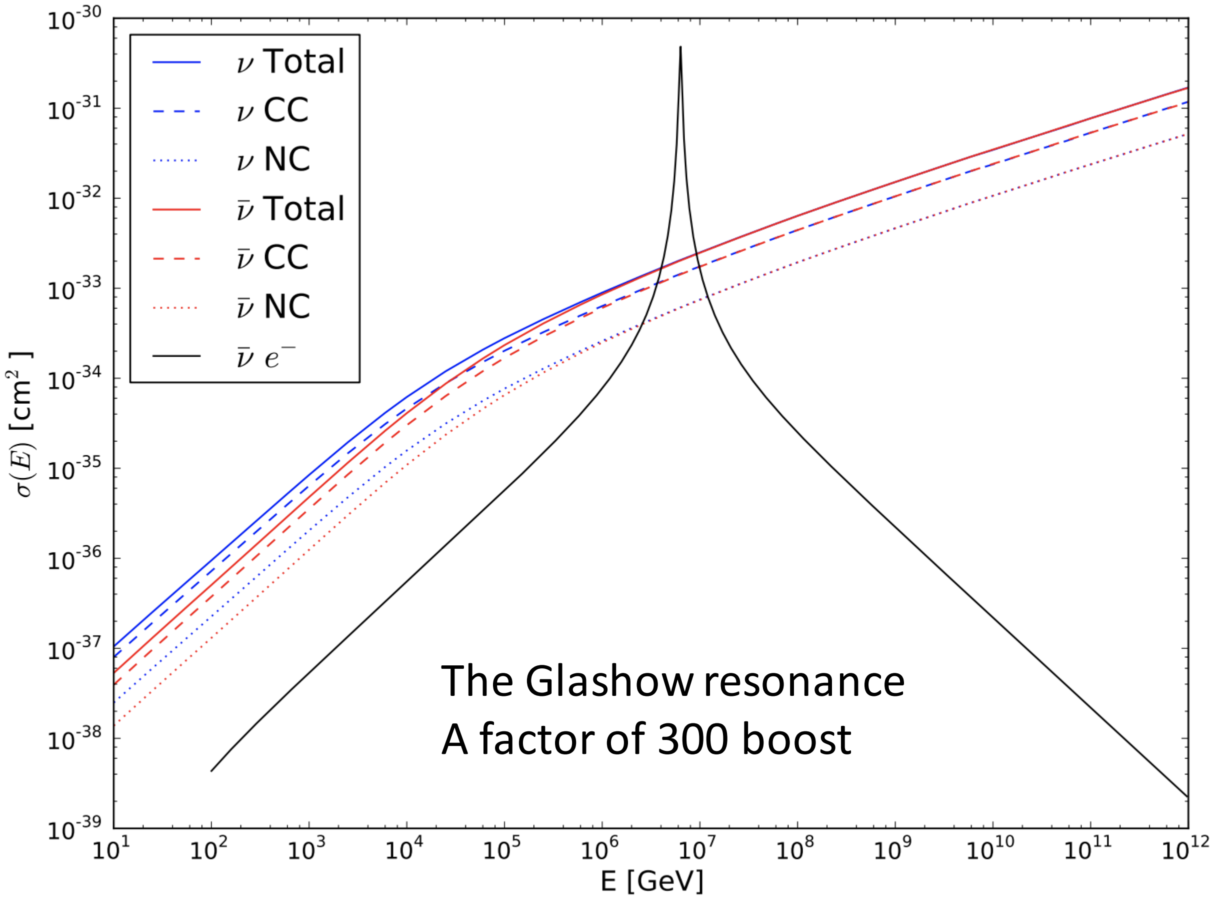
$$\lambda_{\bar{\nu}_e} \sim \frac{1}{n_e\, \sigma_{\rm Res}^{\rm peak}} \sim \begin{cases} 110\,{\rm km} \ \ \text{in mantle rock}\,, \\ 310\,{\rm km} \ \ \text{in ice}\,. \end{cases}$$

$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^-\to\bar{\nu}_e+e^-} \frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2 M_W^2}$$

$$\overline{\nu_e} + e \ \rightarrow W^- \rightarrow \ \overline{\nu_l} + l$$

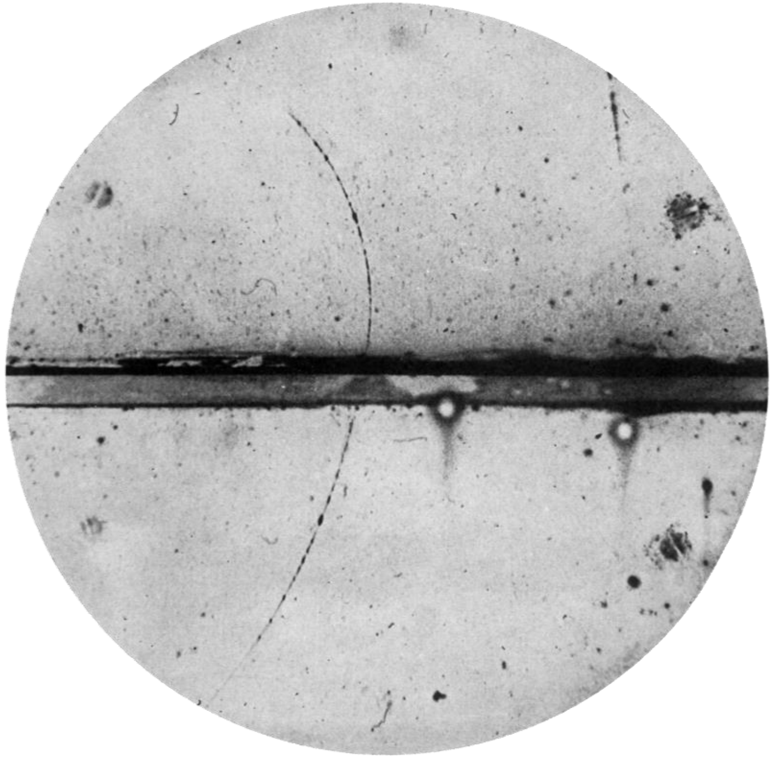
$$\overline{\nu_e} + e \ \rightarrow W^- \rightarrow \ X \quad ,$$

$$E_{\rm R} = M_W^2/(2m_e) = \ 6.32{\rm PeV}$$

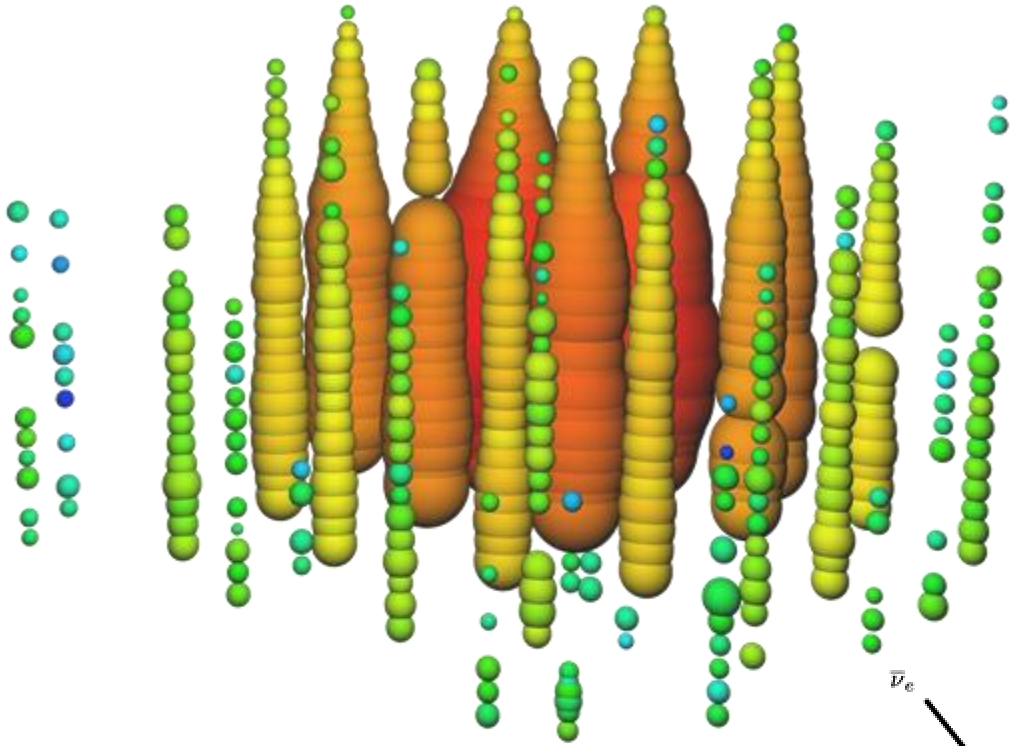


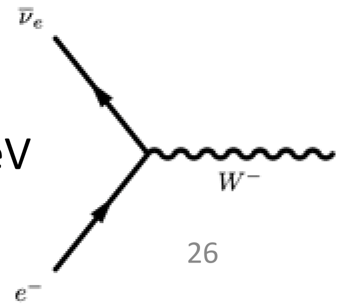
W boson (Glashow) resonance – first hint of electron anti-neutrino

Nature **591,** 220–224 (2021)



Discovery of antimatter, positron
Carl Anderson via cloud chamber, 1932

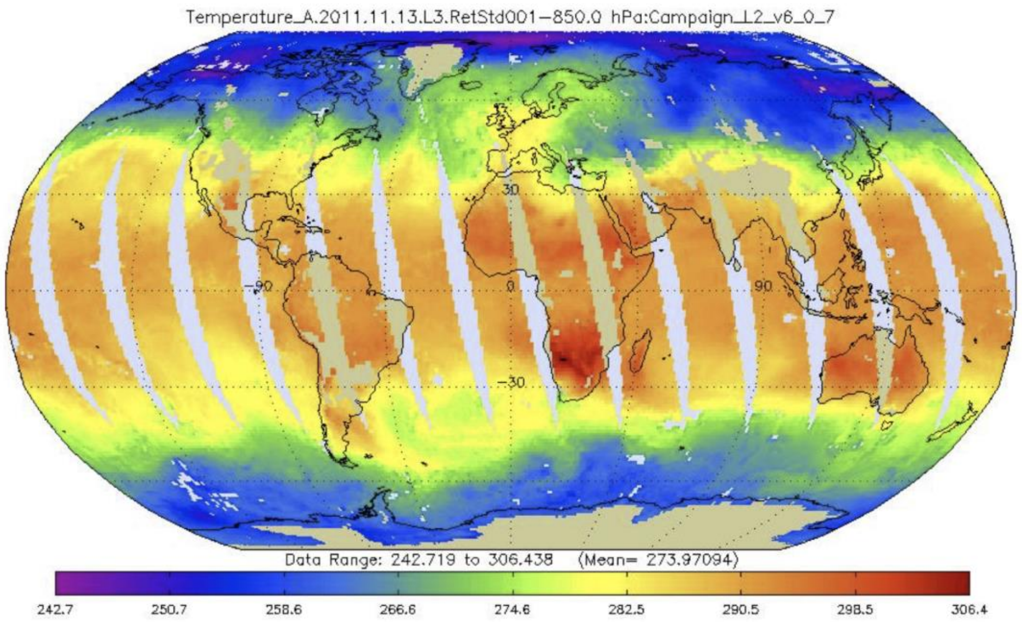


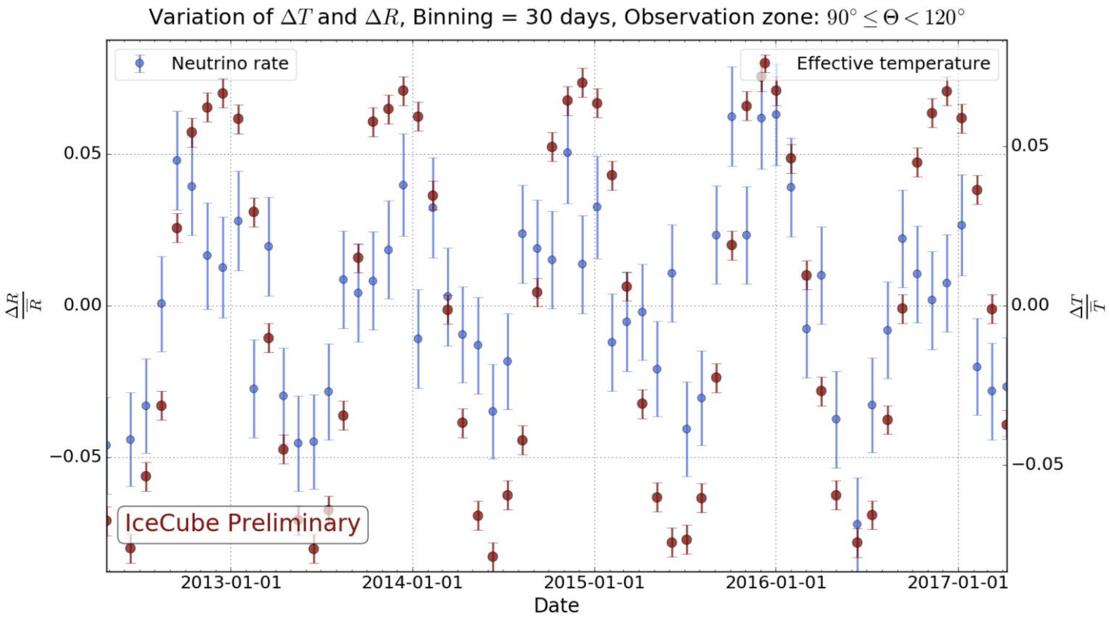


W boson resonance , nuebar 6.3 PeV
IceCube, 2021

(atmospheric) Neutrino weather!

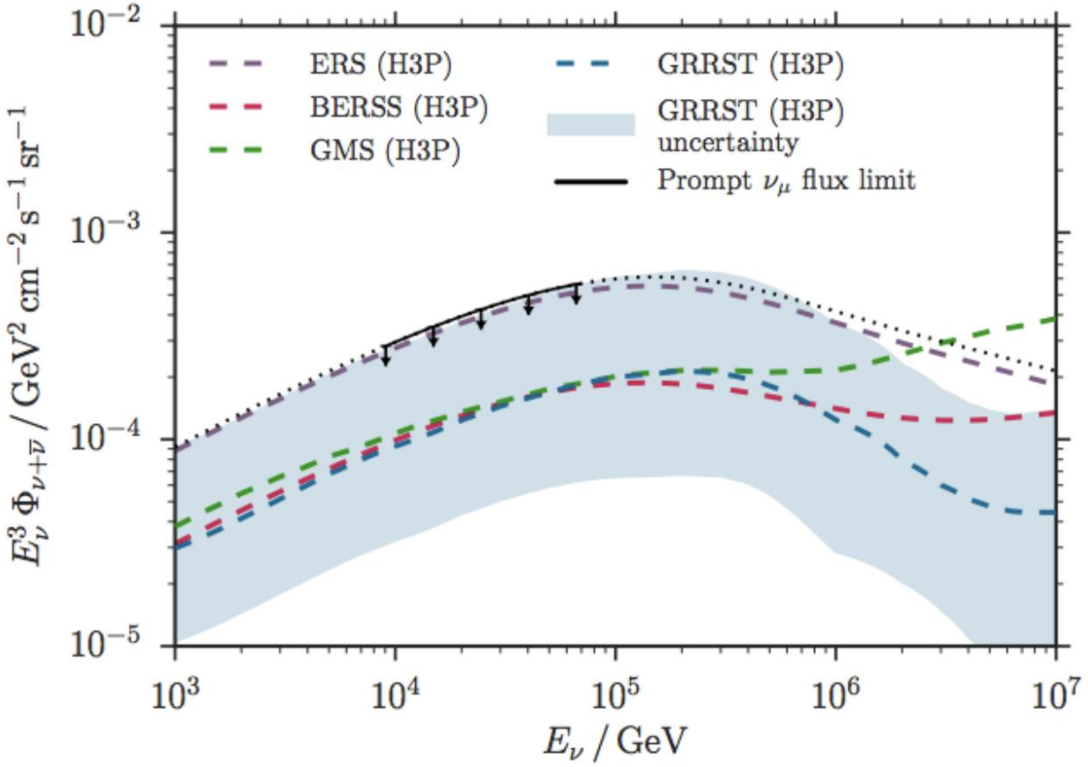
Lead by Aachen group





Charm-on going searches

Produced in the atmosphere



Produced in the ice through DIS

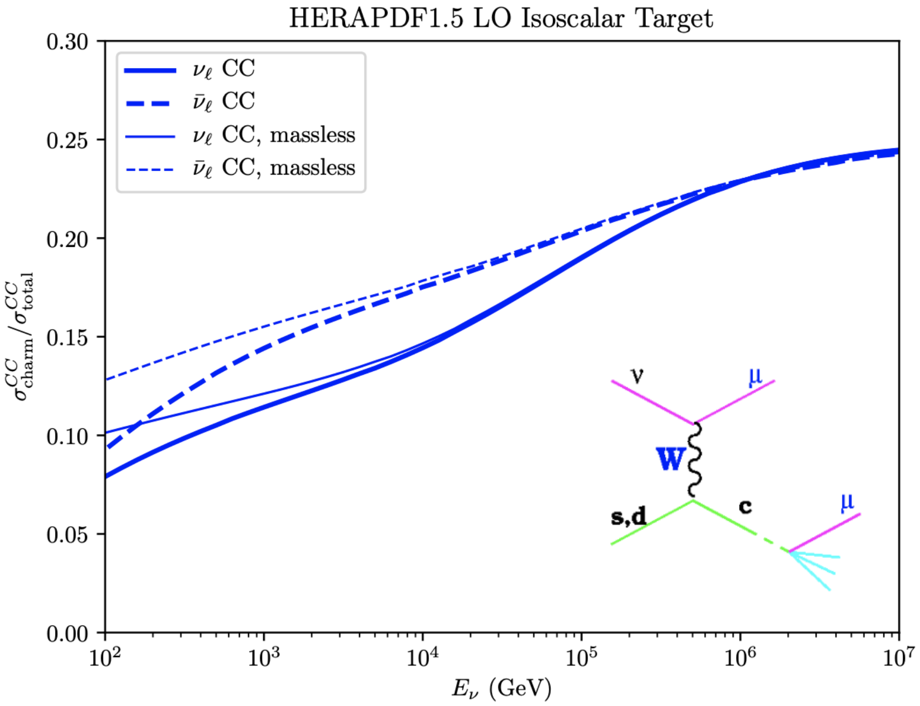
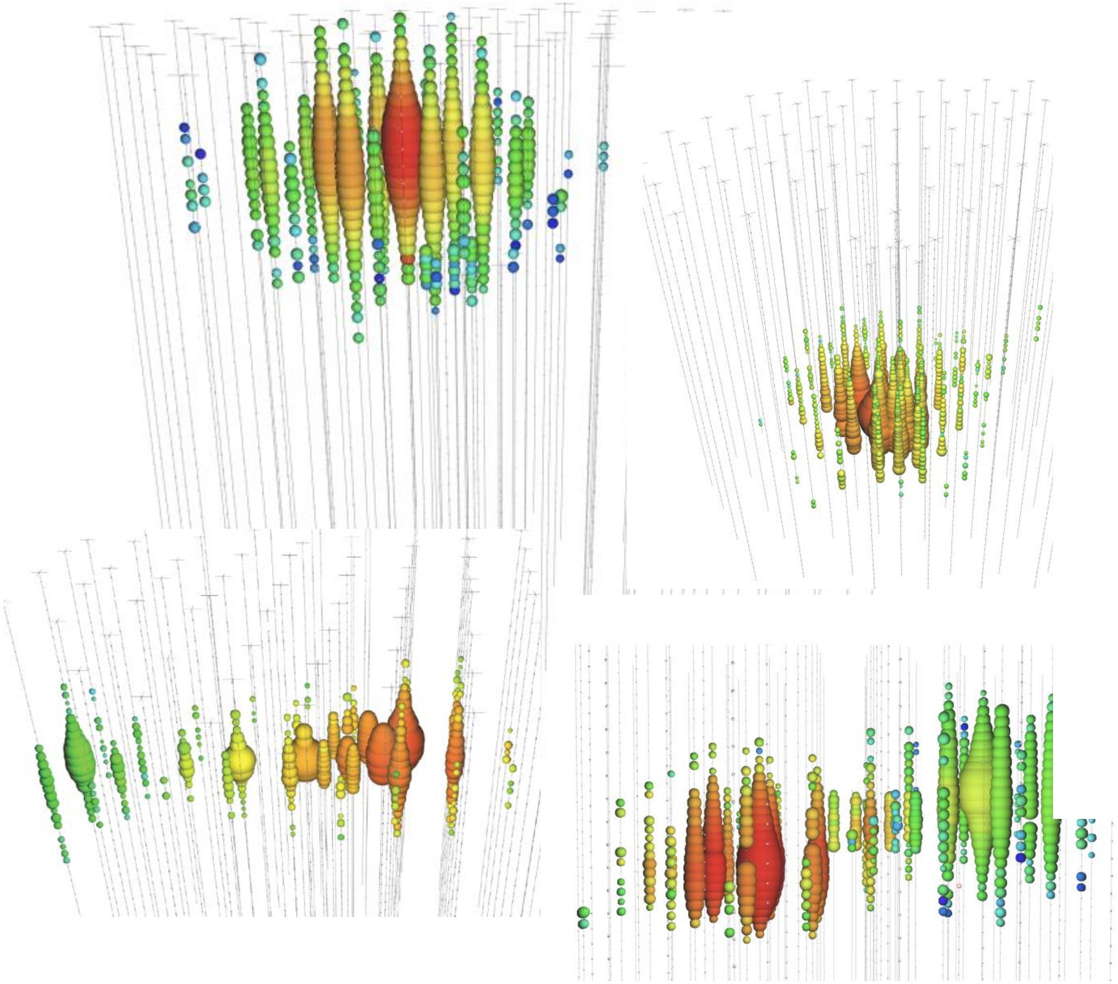
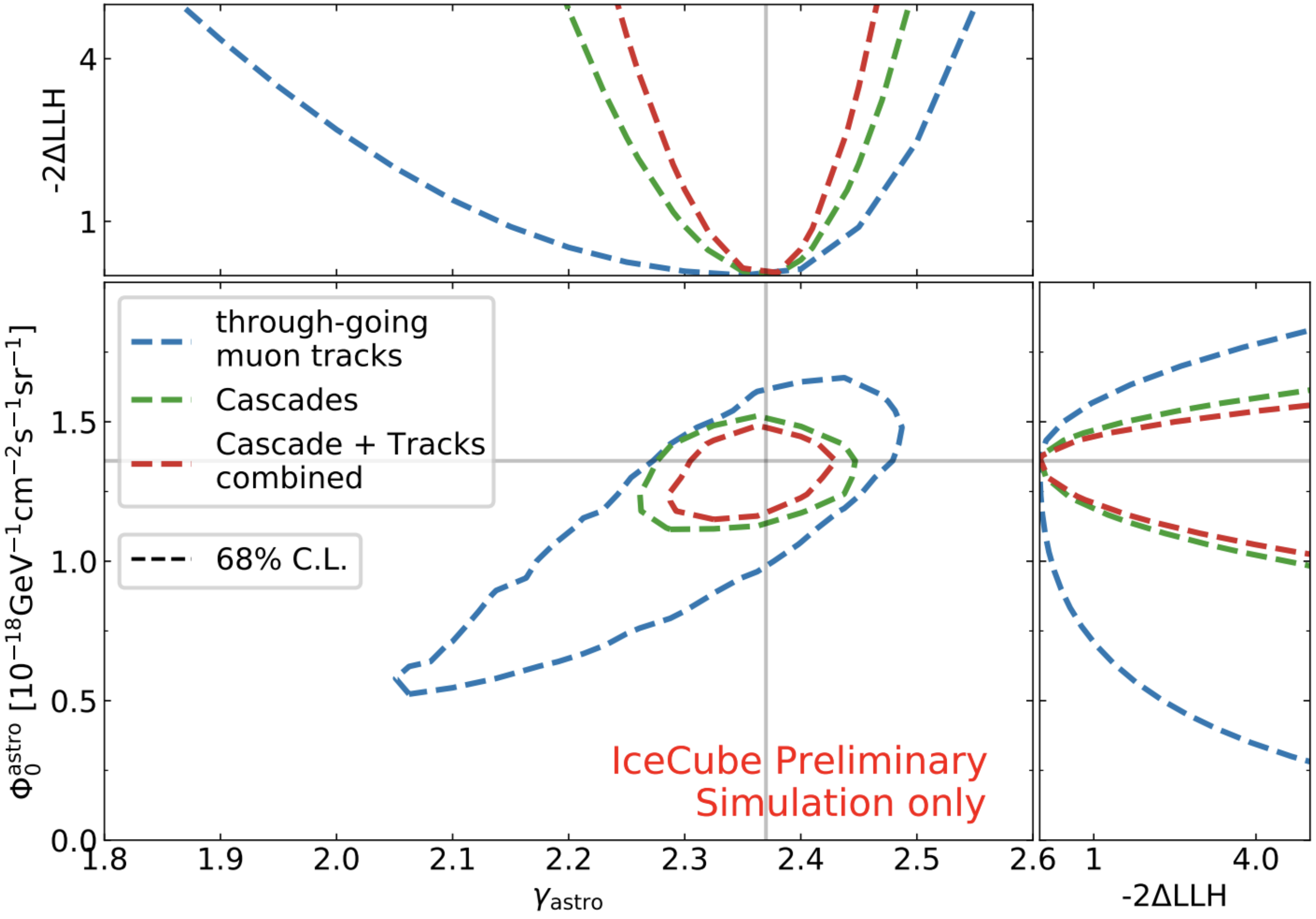


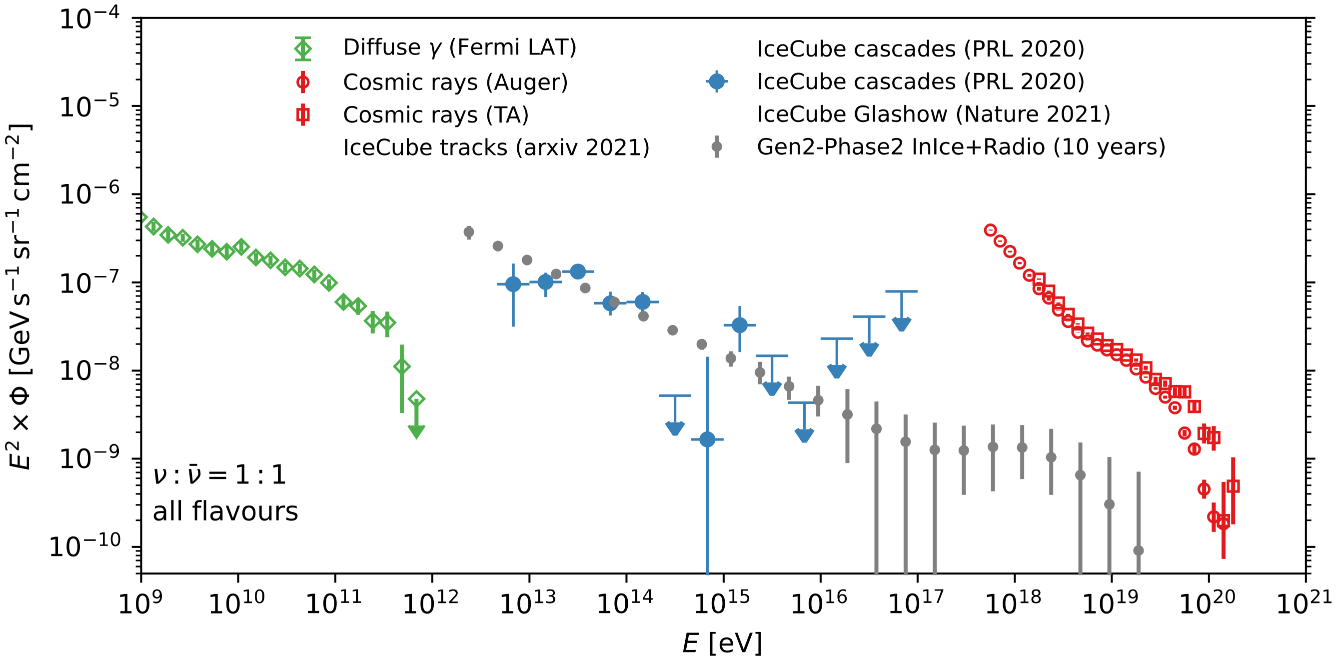
Figure 2.9: LO calculation of the charm production fraction by neutrinos (solid) and antineutrinos (dashed). Calculations using the slow-rescaling model with $m_c = 1.4\,\text{GeV}$ are shown with thick lines and the massless approximation is shown with thin lines. The massless approximation works well for energies above 1 TeV.

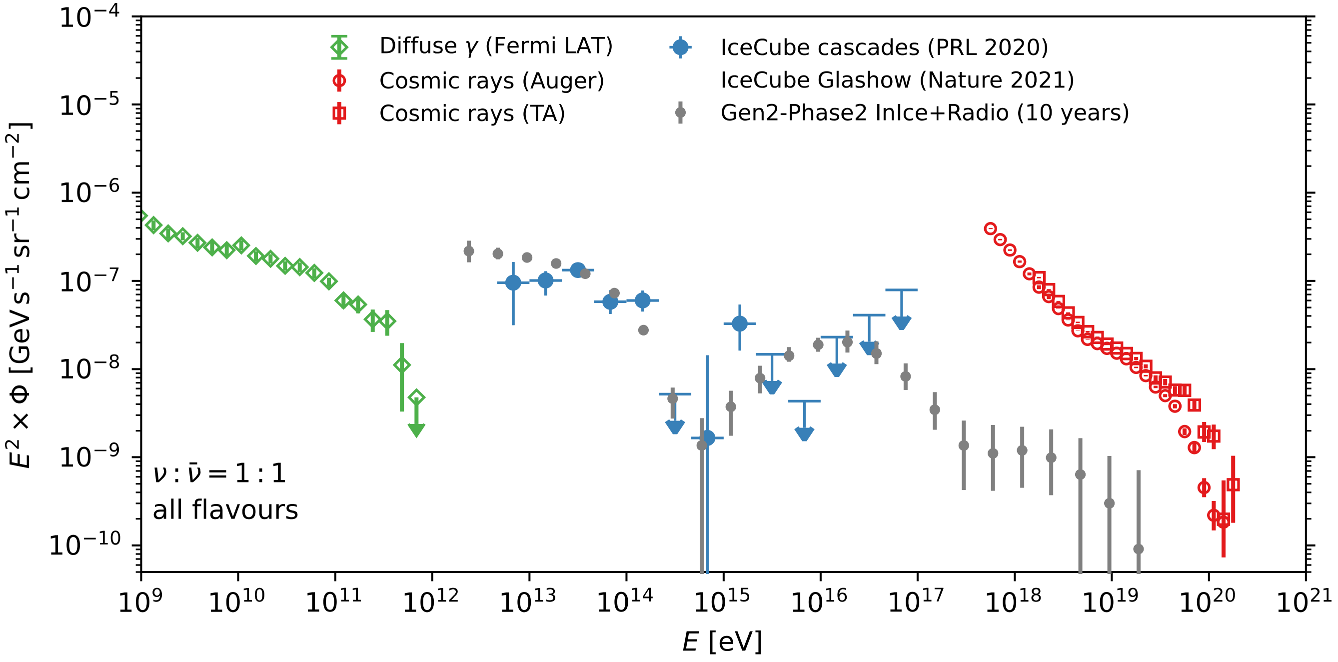
The global fit





Gen2 Diffuse see talk from Albrecht





Conclusions

Discovered diffuse flux

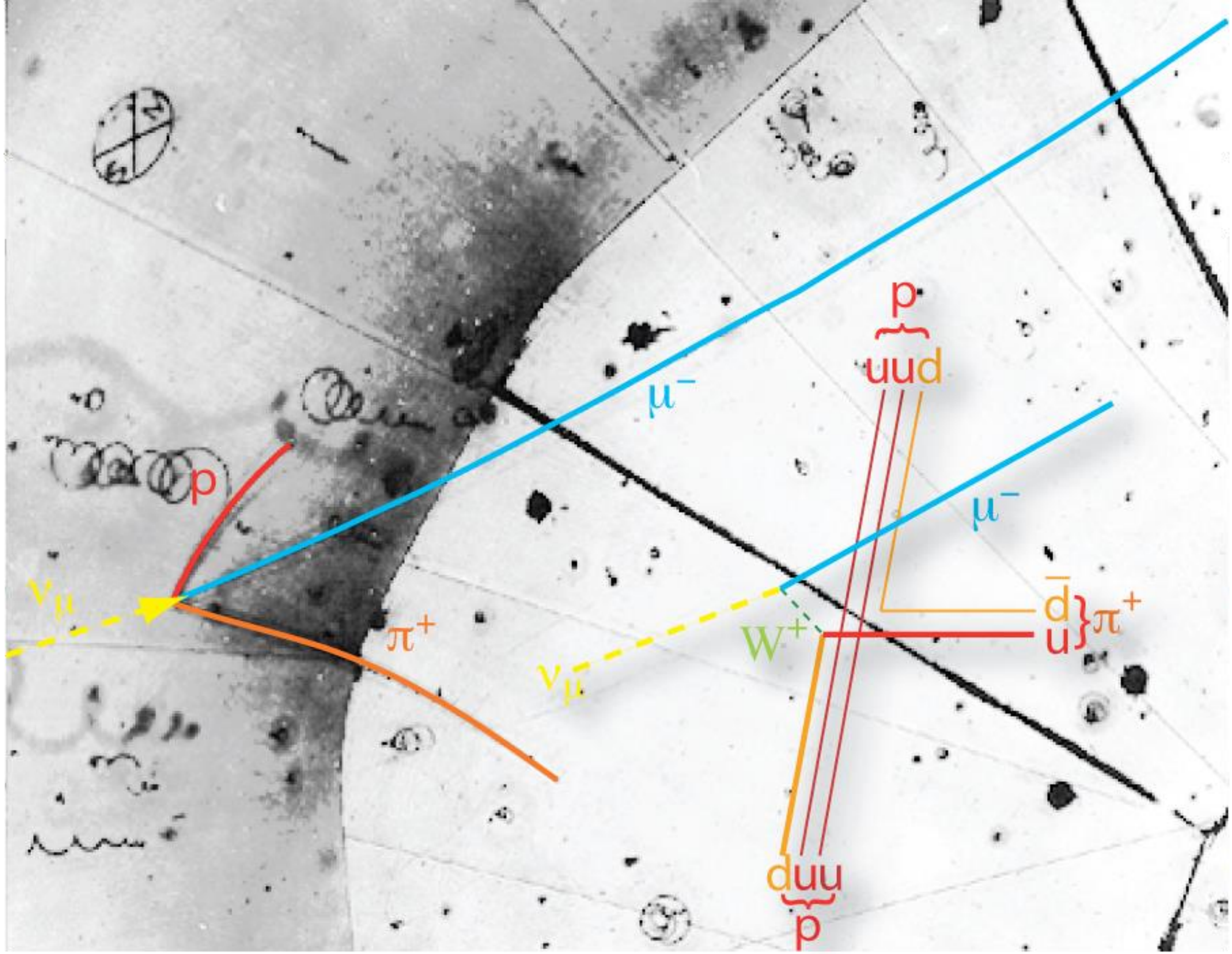
Are there energy/flavour dependent features?

Tau and Glashow started to show up

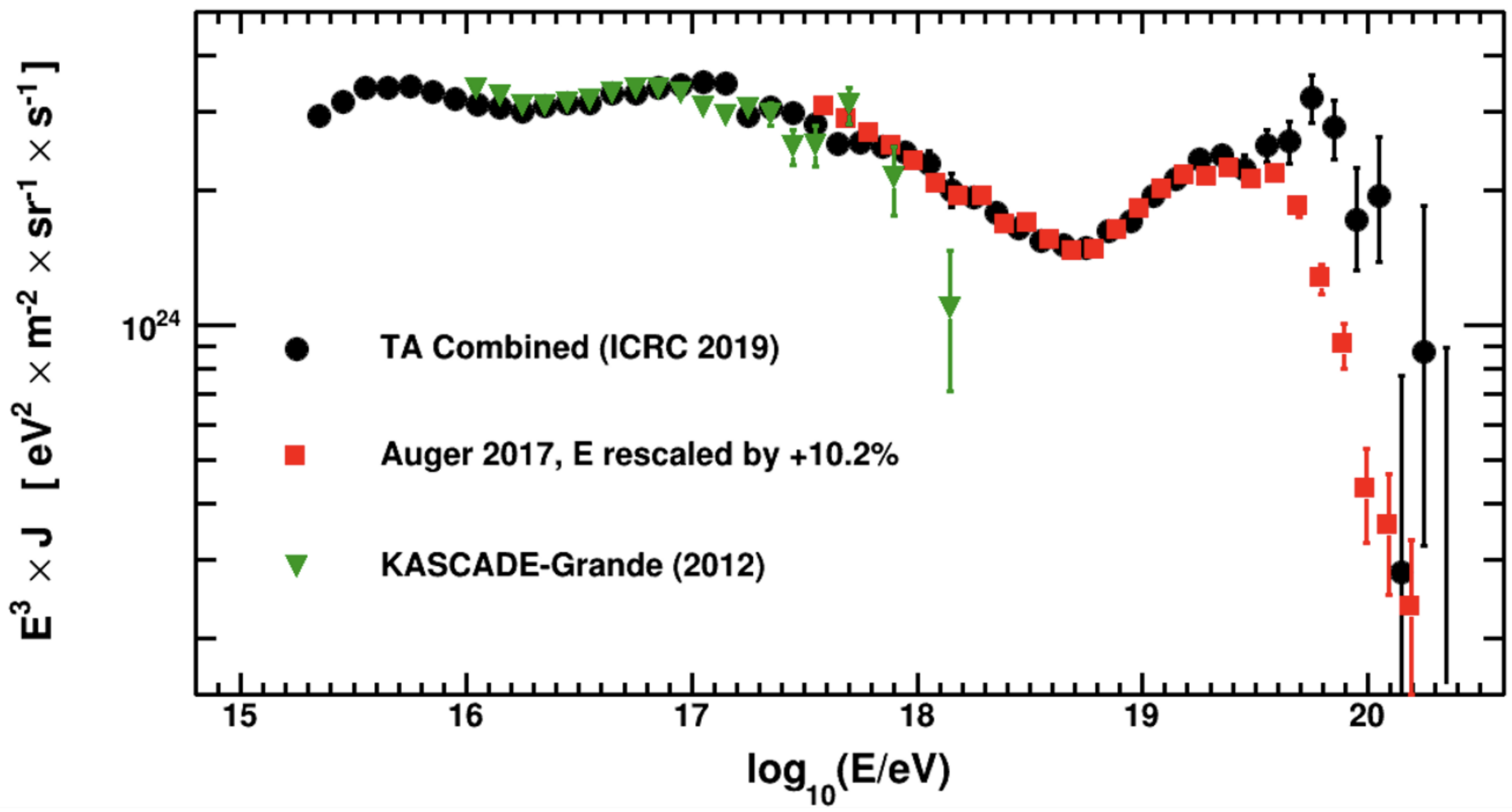
Particle physics measurement

Future: global fit and combine all samples together

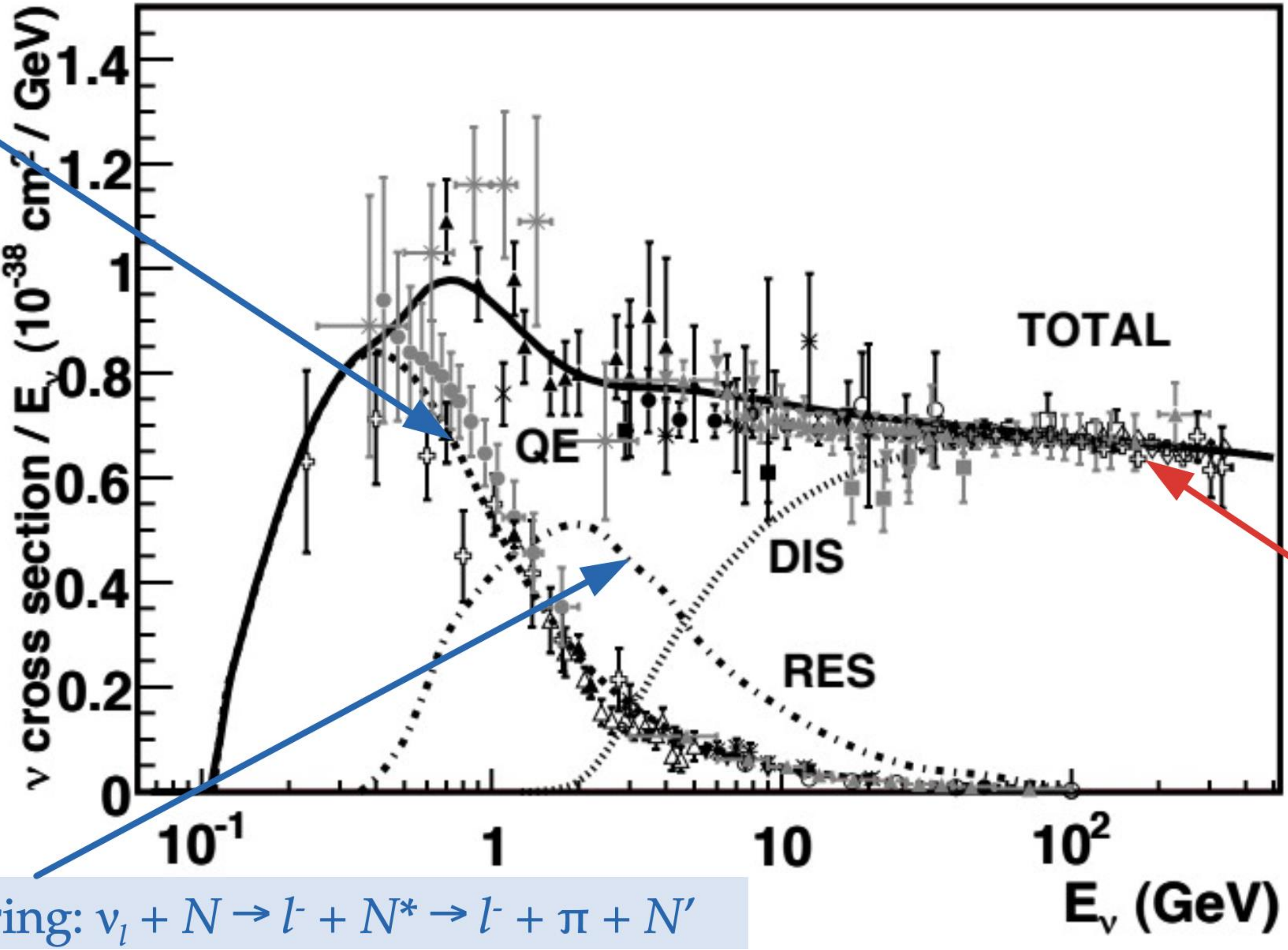

AMC
McCHORD
88193

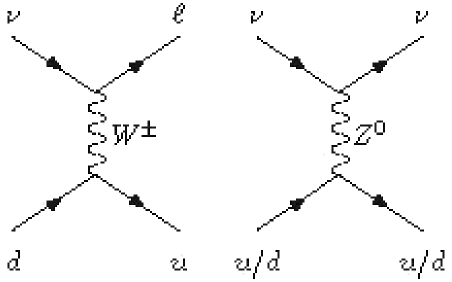

p
uud
μ^-
μ^-
p
ν_μ
π^+
$\bar{d}$ } π^+
u
W^+
ν_μ
duu
p

		$(\nu_e : \nu_\mu : \nu_\tau)$
$\pi^\pm\ K^\pm \rightarrow\ \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$ **(63.5% for K)** $\hookrightarrow e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$ → **E_ν ~ 100/cosθ GeV** $K^\pm \rightarrow \pi^0 e \nu_e$ **(5%)** $K_L^0 \rightarrow \pi e \nu_e$ **(40%)**	**conventional**	$(1 : 2 : 0)$ $(1 : 20 : 0)$
→ **E_ν ~ 100/cosθ TeV** $K_S^0 \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) **(0.07%)** $D, \Lambda_c \rightarrow \ell + \nu_\ell + \ldots$ **(order %)** $\eta, \eta' \rightarrow \mu^+ \mu^-$	**prompt**	$(1 : 1 : 1/10)$


$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
TA Combined (ICRC 2019)
Auger 2017, E rescaled by +10.2%
KASCADE-Grande (2012)
15
16
17
18
19
20
$\log_{10}(E/eV)$

Quasi-elastic scattering:
$\nu_l + n \rightarrow l^- + p$
$\bar{\nu}_l + p \rightarrow l^+ + n$





Deep inelastic scattering:
$\nu_l + N \rightarrow l^- + X$
$\bar{\nu}_l + N \rightarrow l^+ + X$

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

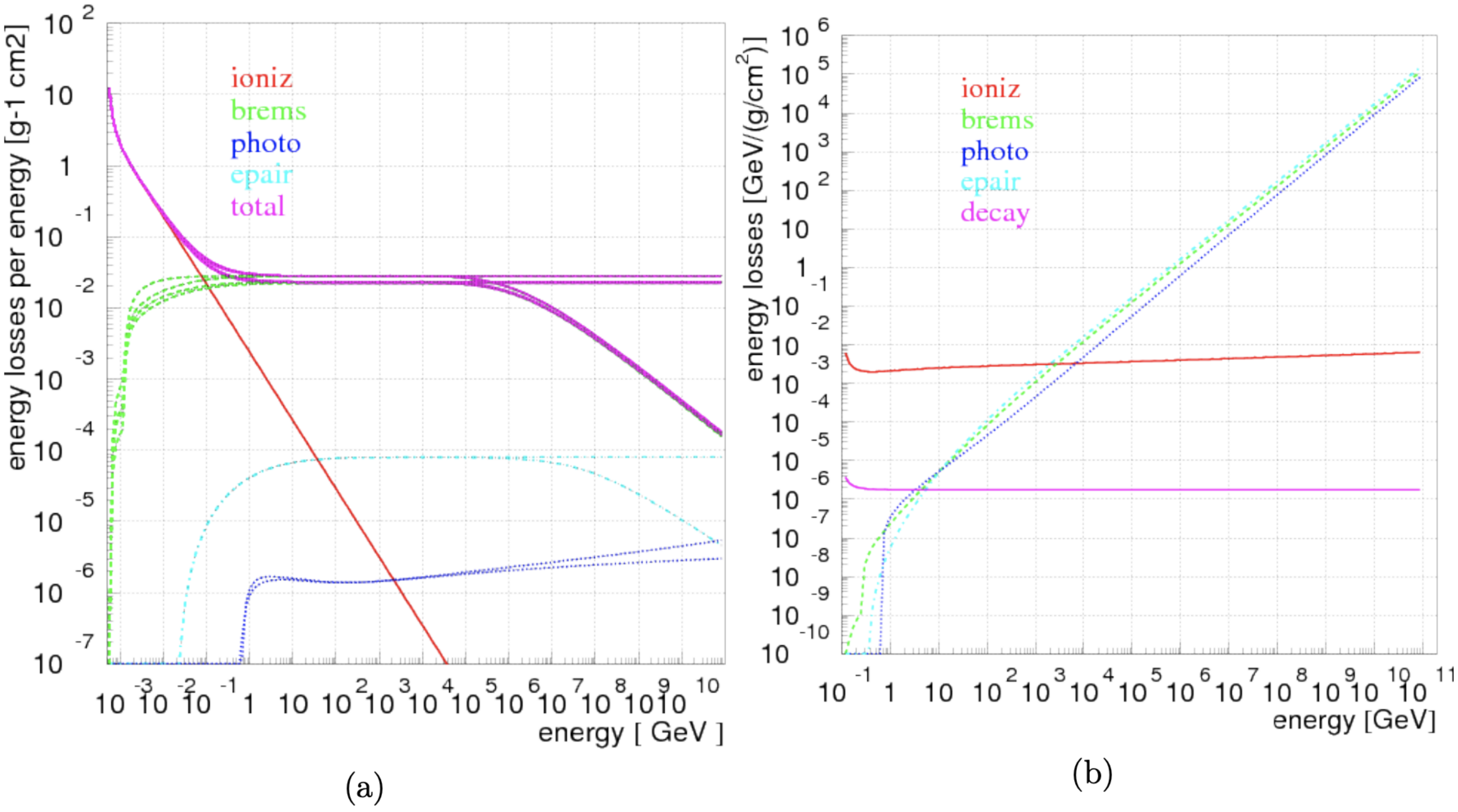
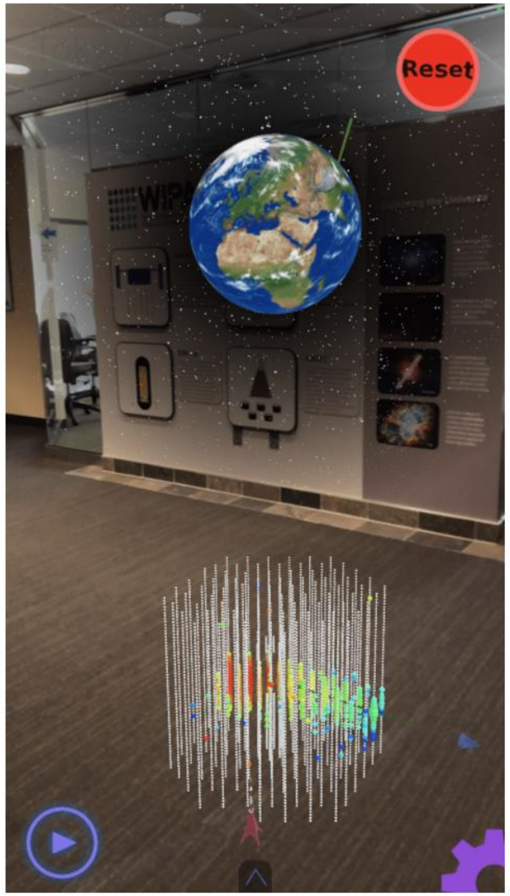


Figure 4.2: Left: The average energy loss rate divided by energy, $-\frac{1}{E}\frac{dE}{dX}$, for electrons in ice showing the contributions from ionization, bremsstrahlung, photonuclear interactions, and pair production from [152]. Right: The average energy loss rate, $-\frac{dE}{dX}$, for muons in ice showing the contributions from ionization, bremsstrahlung, photonuclear interactions, pair production, and decay from [152].

From outer space, to the South Pole, to your phone: A new AR app for IceCube

Posted on October 8, 2020 by Madeleine O'Keefe



A screenshot from the IceCubeAR app.

Located in the frigid desert that is the South Pole, the IceCube Neutrino Observatory isn't your typical telescope. It doesn't have an observatory dome or satellite dish. In fact, if you were standing at the South Pole looking at IceCube, you would see nothing but a small building in a vast, barren, snowy landscape.

That's because the IceCube detector is *underground*. It comprises an array of 5,160 optical sensors that are frozen beneath a cubic kilometer of ice a mile beneath the surface. These sensors pick up signals left behind by mysterious particles called neutrinos.

Now, thanks to a new augmented reality (AR) app, anyone in the world can see what's happening under the ice at the South Pole. And when a neutrino candidate sails through the detector, users will find out in real time!

Introducing IceCubeAR, aka IceBear.

Neutrinos are fundamental particles that travel through the cosmos. They come from myriad sources on Earth and in our solar system—but many are from outside our galaxy, known as astrophysical neutrinos, and

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