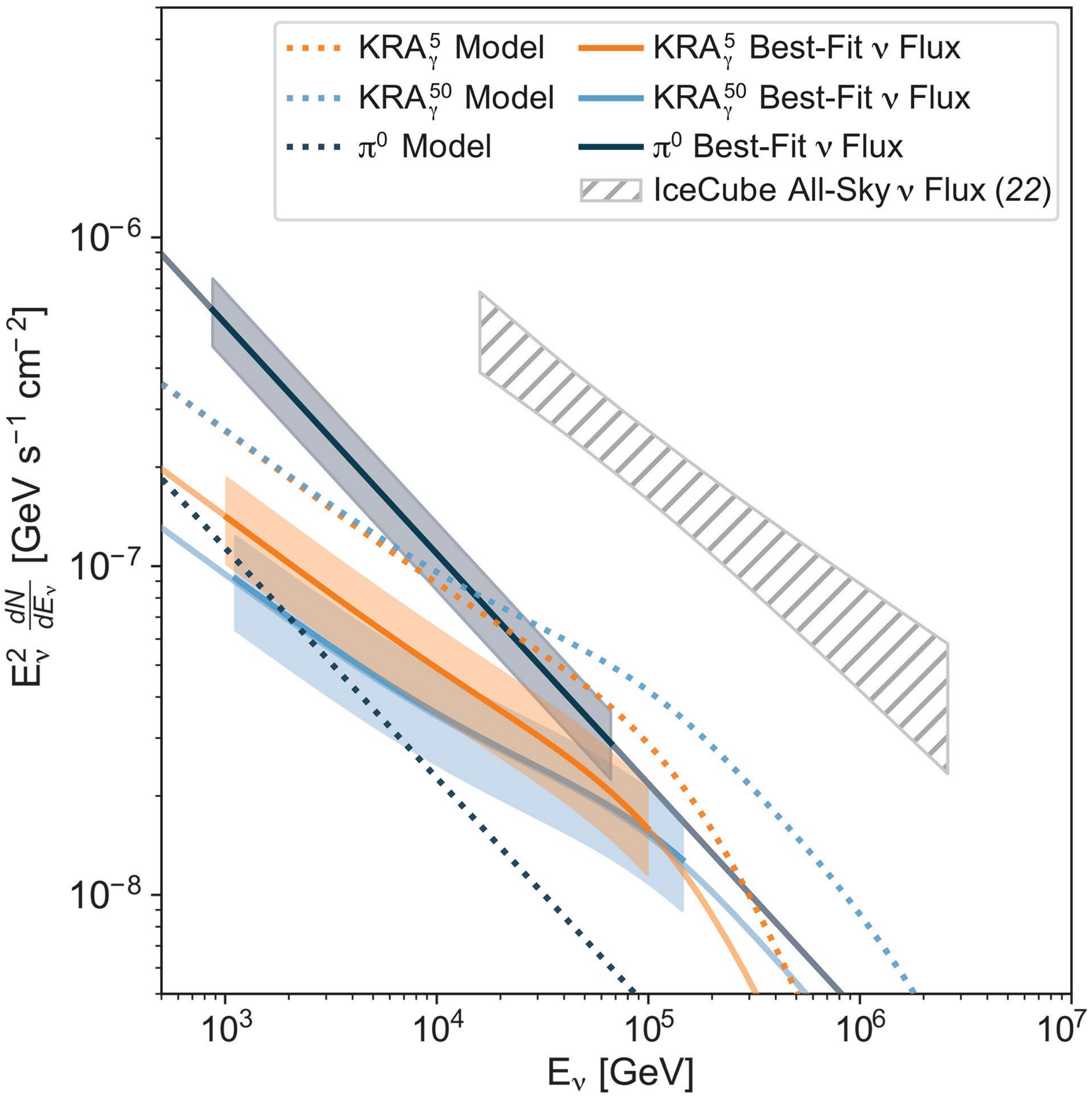
How to…

High-energy neutrino astronomy

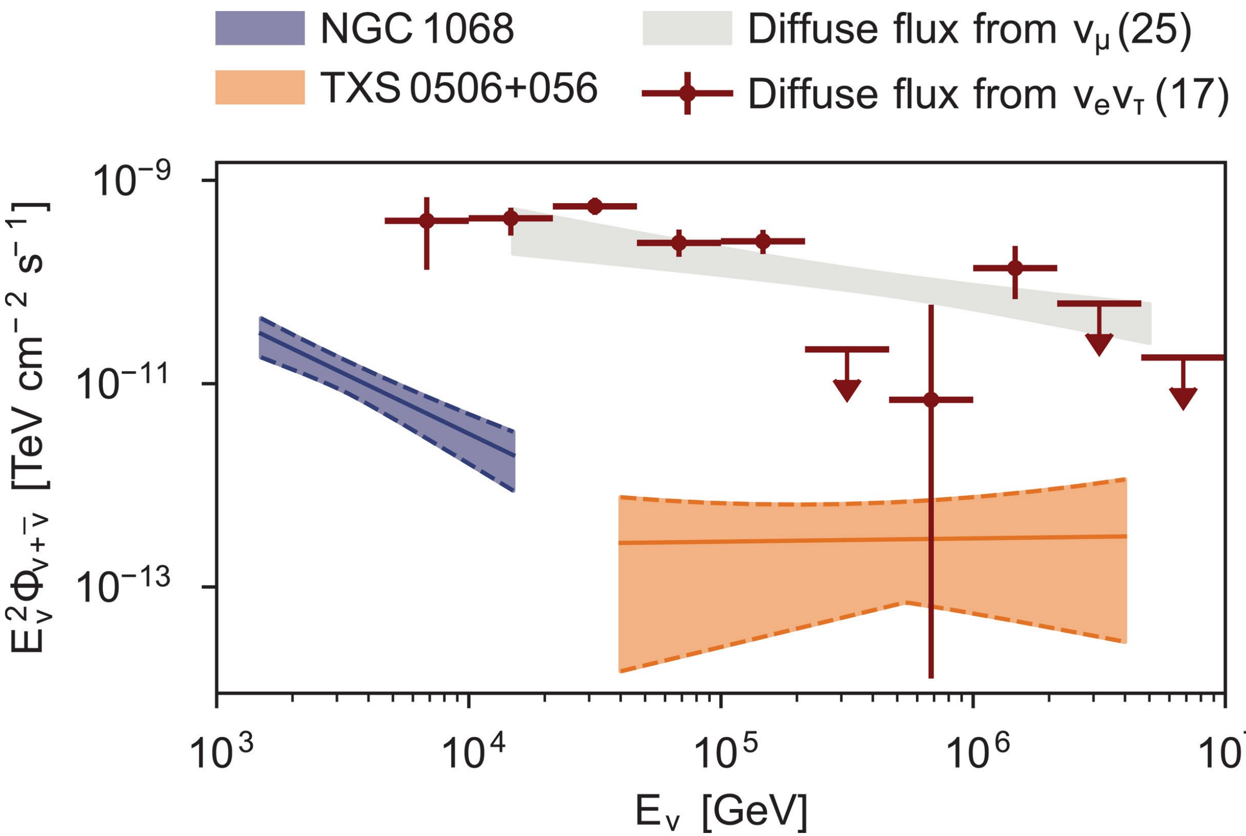
Lisa Schumacher, Erlangen Centre for Astroparticle Physics (ECAP)

Astroparticle School 2024

Outline



KRA$_\gamma^5$ Model
KRA$_\gamma^{50}$ Model
π^0 Model
KRA$_\gamma^5$ Best-Fit ν Flux
KRA$_\gamma^{50}$ Best-Fit ν Flux
π^0 Best-Fit ν Flux
IceCube All-Sky ν Flux (22)
$E_\nu^2 \frac{dN}{dE_\nu}$ [GeV s^{-1} cm^{-2}]
E_ν [GeV]

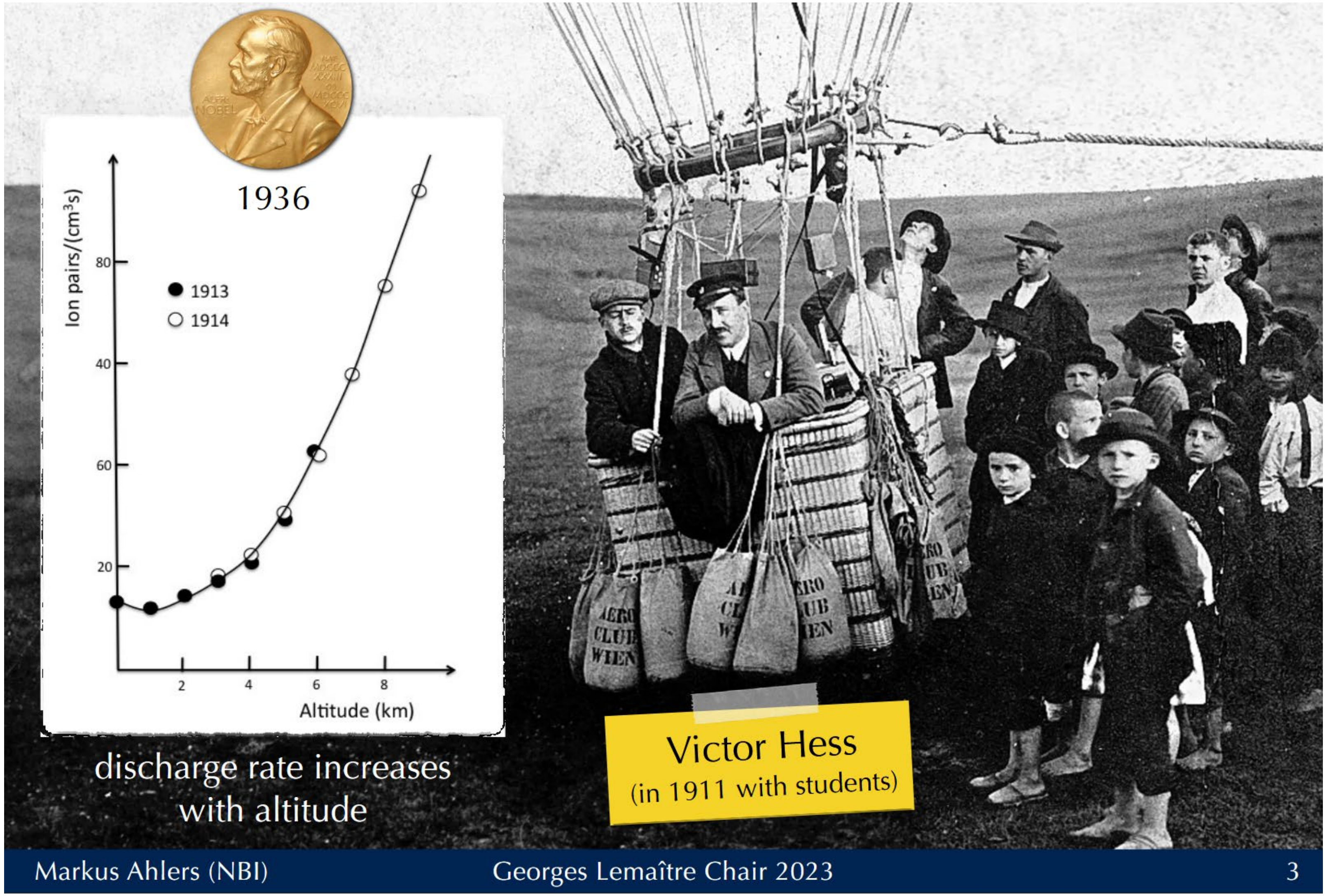


NGC 1068
TXS 0506+056
Diffuse flux from ν_μ (25)
Diffuse flux from $\nu_e\nu_\tau$ (17)
$E_\nu^2\Phi_{\nu+\bar{\nu}}$ [TeV cm^{-2} s^{-1}]
E_ν [GeV]

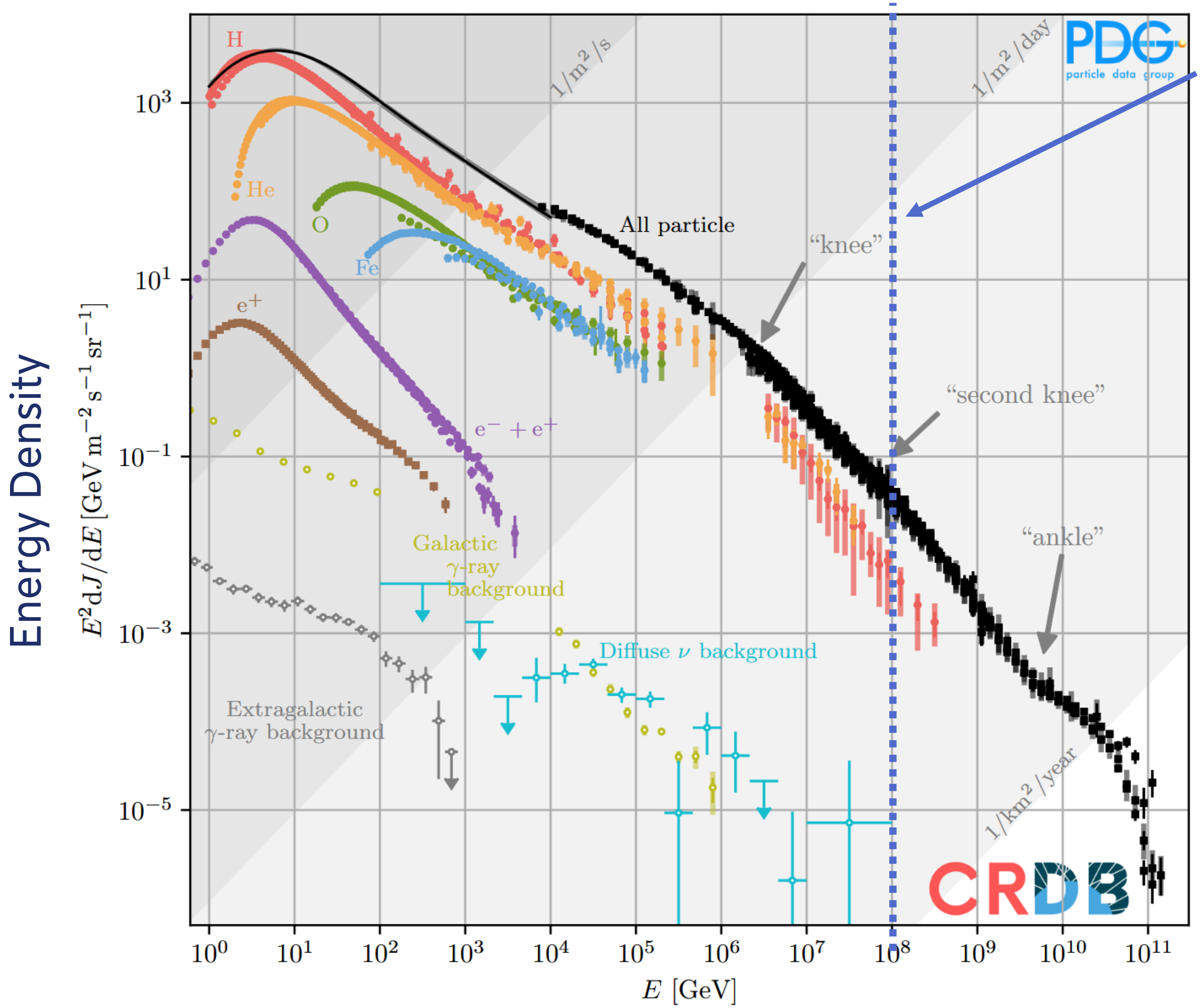
Outline

1) Why is neutrino astronomy interesting?
2) How are high-energy neutrinos detected?
3) Recent results from IceCube
4) What’s the future of the field?

Cosmic radiation – a century-old puzzle

Credit: 

The Cosmic Ray Puzzle



Center of mass energy at LHC (pp) 14 TeV ≈ 10^{17}eV

Where and how are cosmic rays accelerated?

Where and how are neutrinos produced?

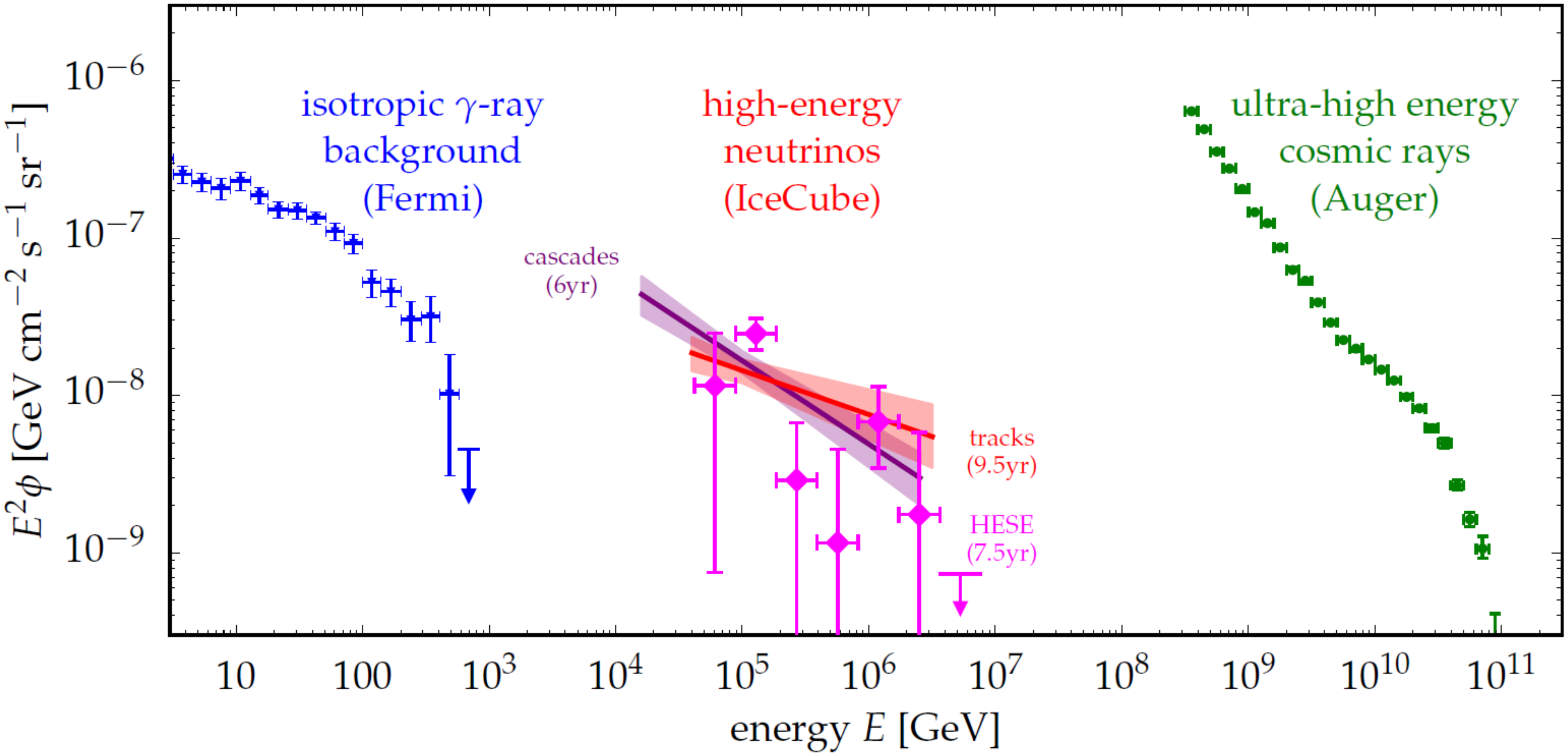
PDG review – Cosmic Rays (2024) Fig. 30.1

Overview over highest-energy particle spectra

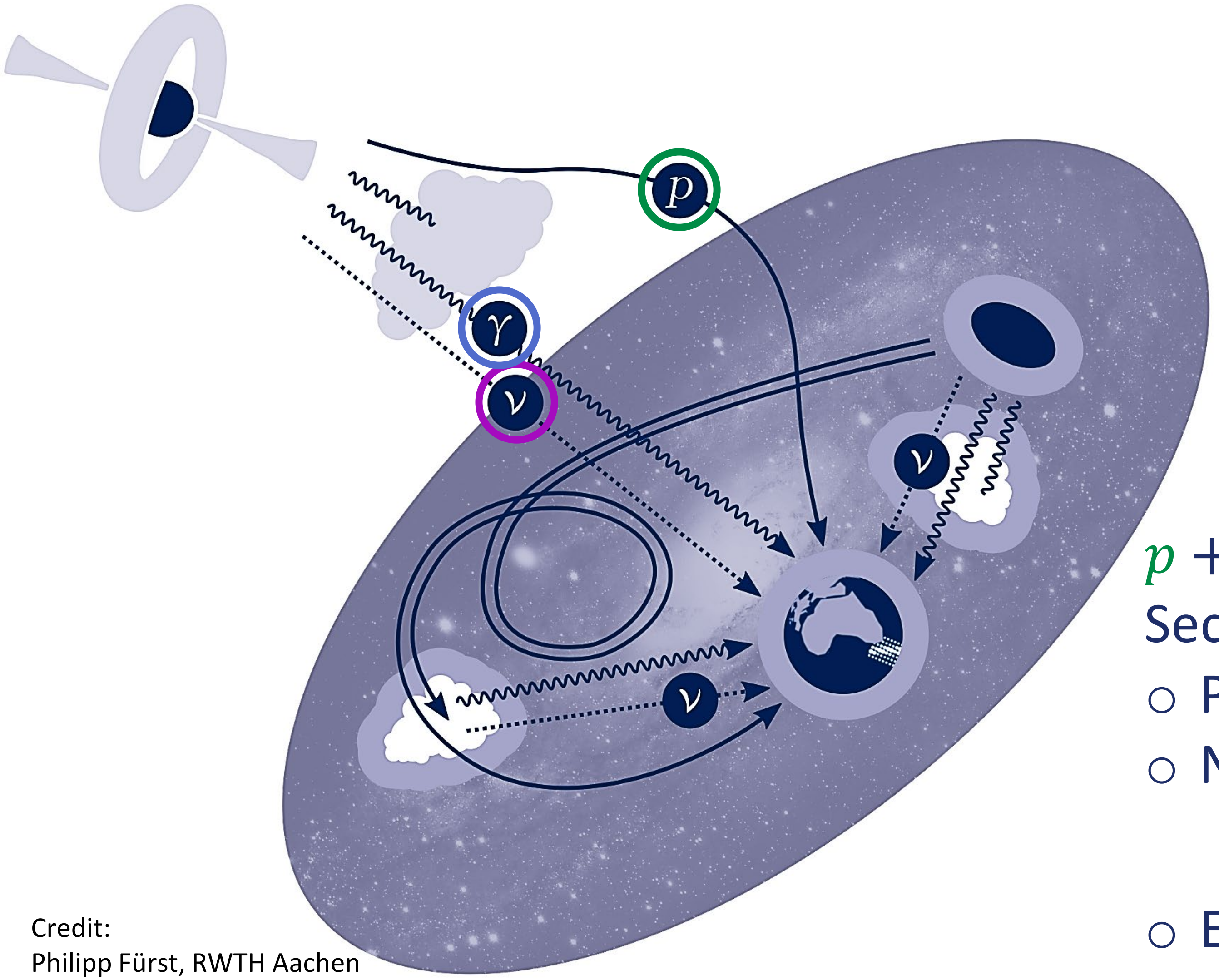
Almost constant energy budget $\left(E^2 \frac{d\Phi}{\mathrm{dE}}\right)$ of neutrinos with $E_\nu = 0.1 - 1\mathrm{PeV}$

$\rightarrow$ same as of UHECRs $\mathrm{E_{CR}} > 10^{19}\mathrm{PeV}$, as implied by Waxman-Bahcall bound

About 30% of gamma-ray background is attributed to non-blazar sources



Multimessenger puzzle



Credit:
Philipp Fürst, RWTH Aachen

- Protons and nuclei (charged CRs) accelerated by the central engine of astrophysical objects
- CRs produce photons and neutrinos via interactions with ambient photons/protons

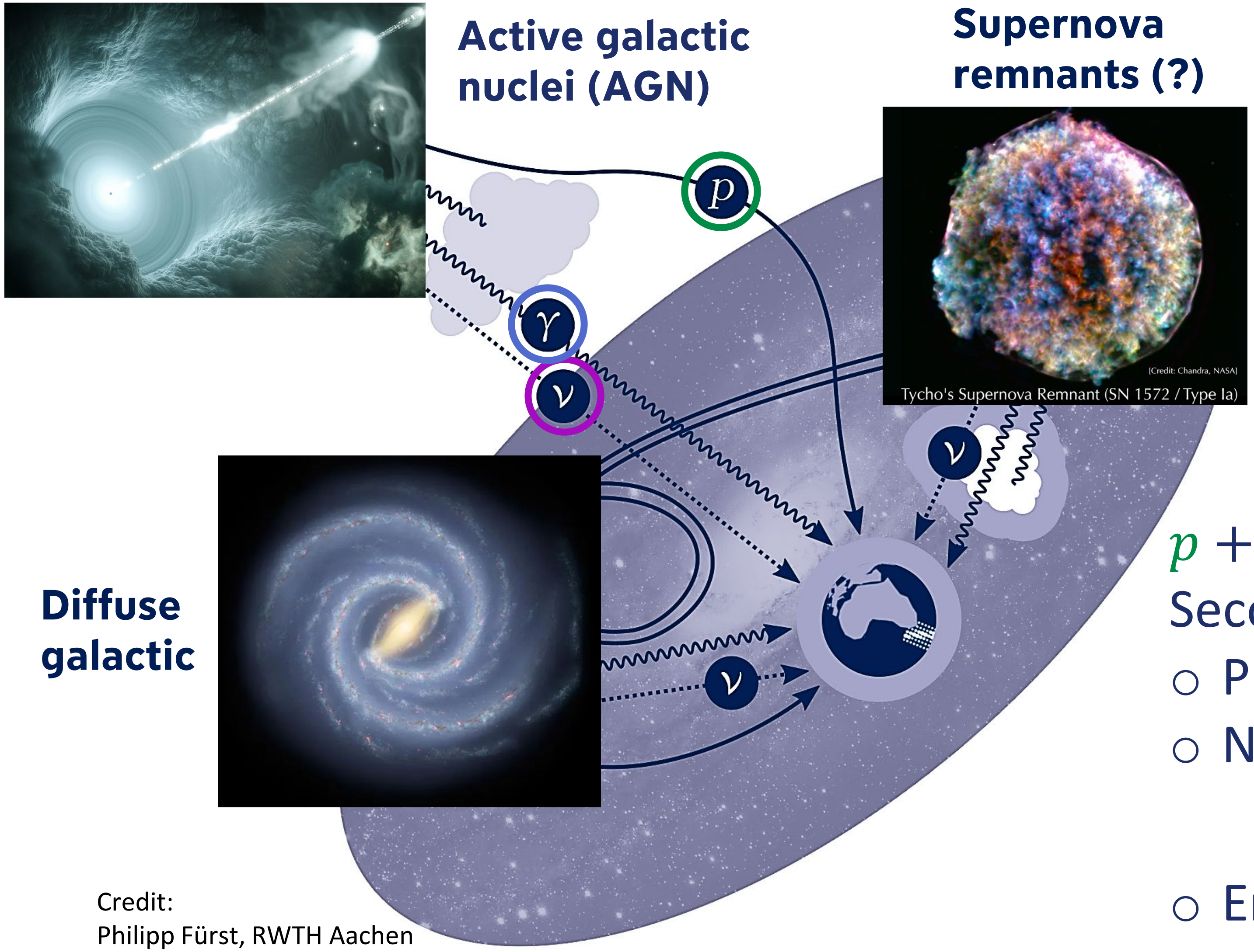
$p + p$ or $p + \gamma \rightarrow X + \pi^0, \pi^\pm$

Secondary decay:

- Photons: $\pi^0 \rightarrow \gamma\gamma$
- Neutrinos: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

  $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Energy: $E_\nu \approx \frac{1}{2} E_\gamma \approx \frac{1}{20} E_N$

Multimessenger puzzle



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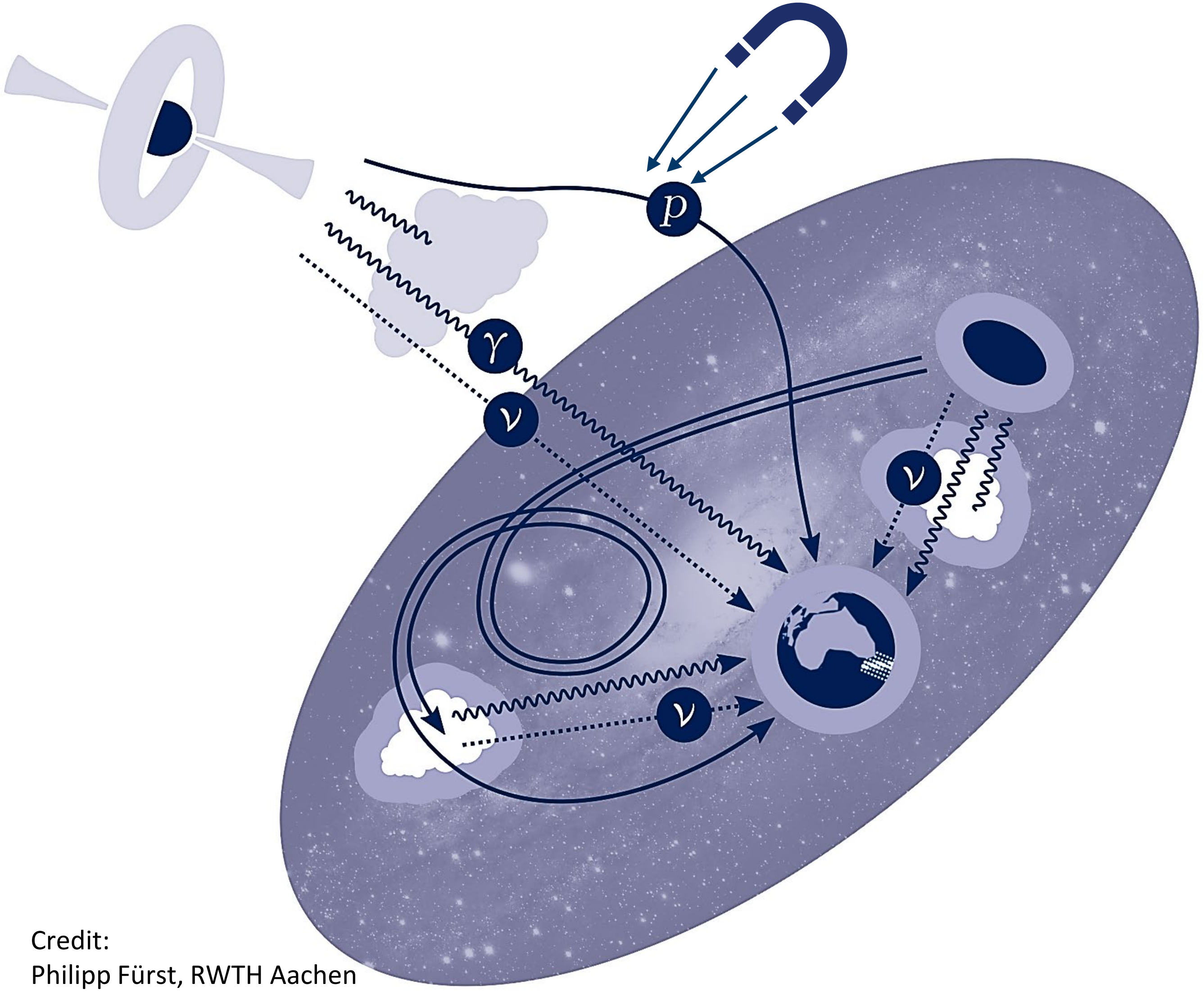


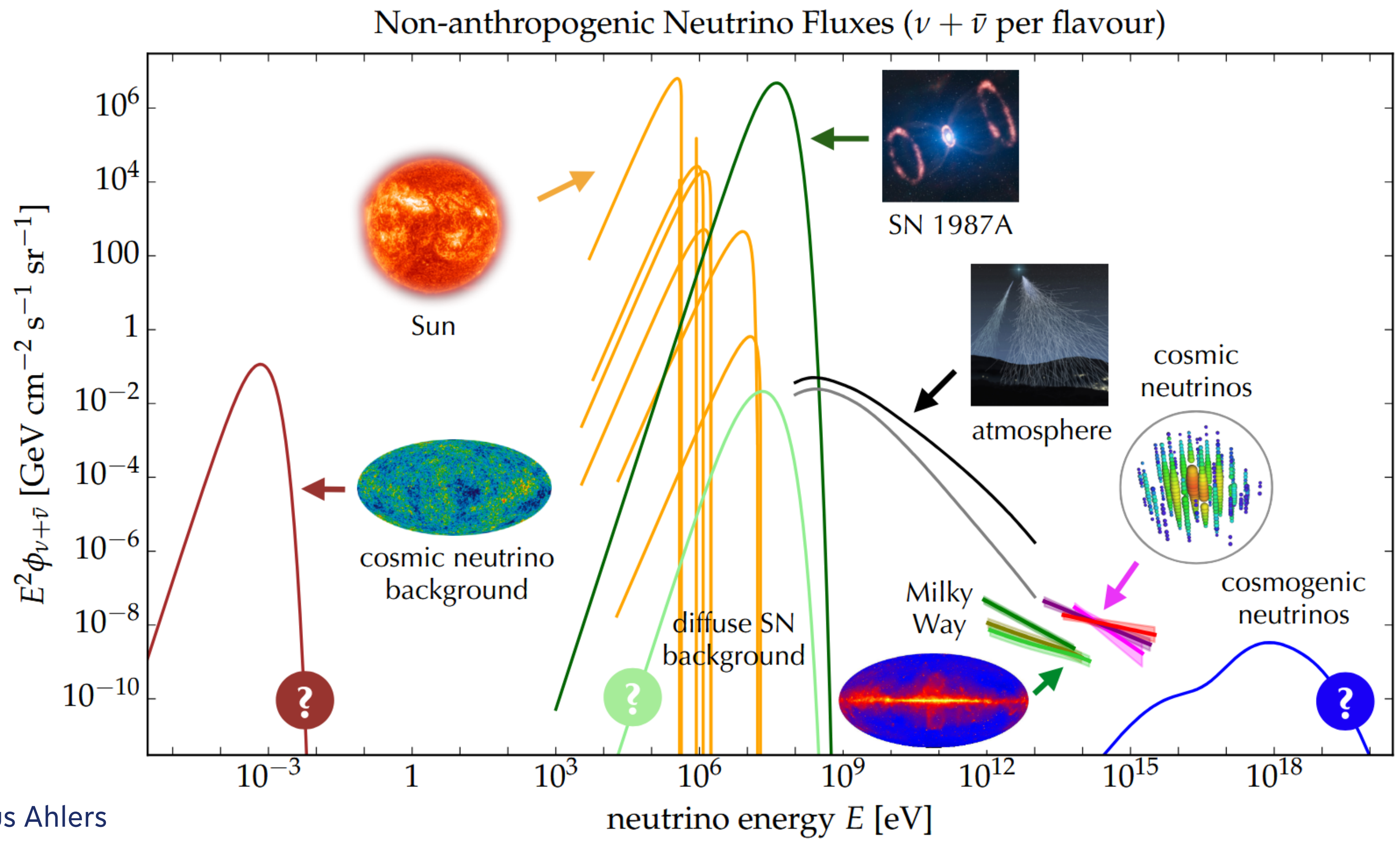
Credit:
Philipp Fürst, RWTH Aachen

What can these extreme environments tell us about particle physics at the highest energies?

Why are neutrinos interesting?

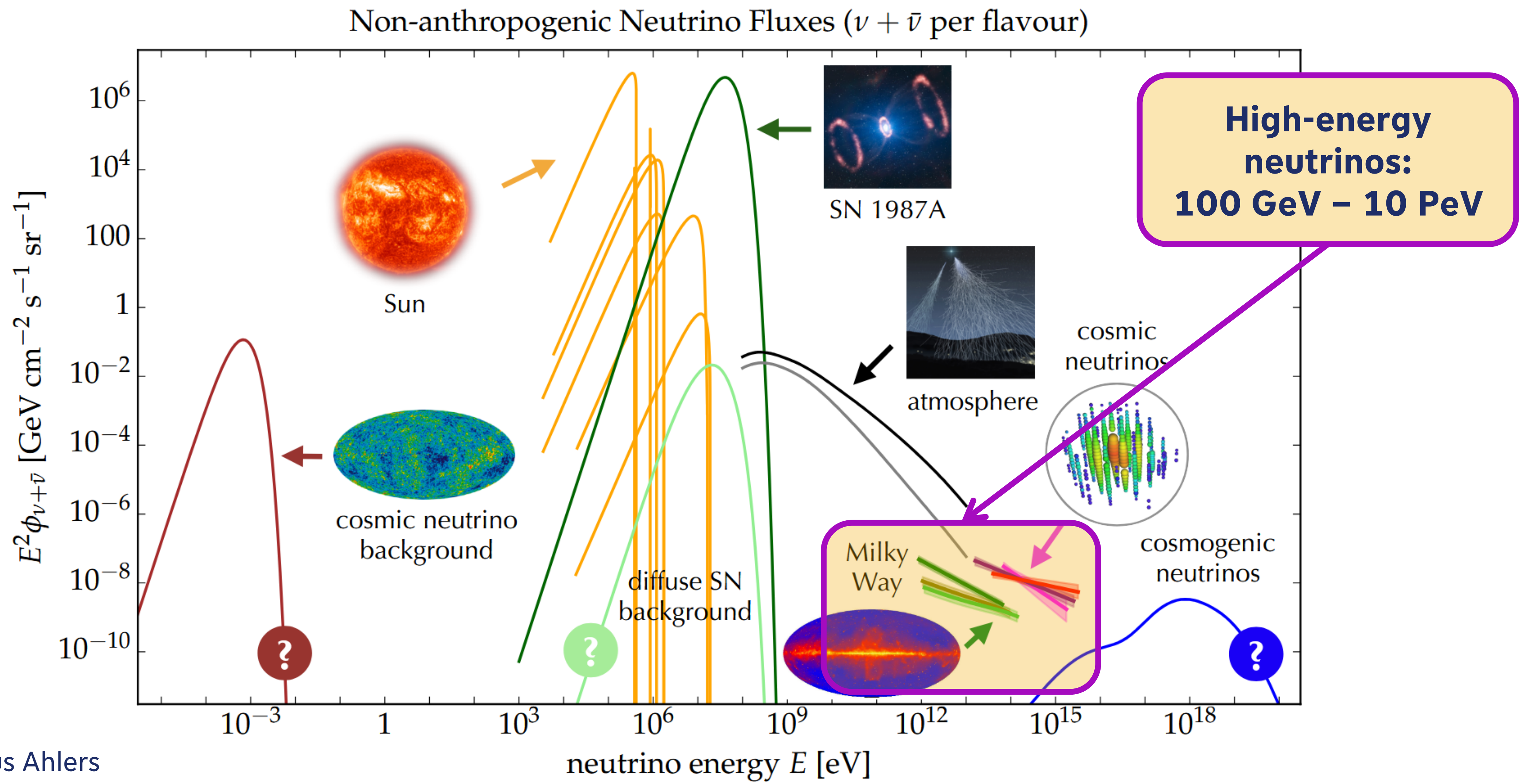
1) Neutrinos are unambiguous tracers of hadronic processes of CRs
2) Neutrinos can travel cosmological distances and through dense environments unimpeded
3) Non-zero neutrino masses already point to physics beyond the standard model – what else are they hiding?

Astrophysical neutrino fluxes



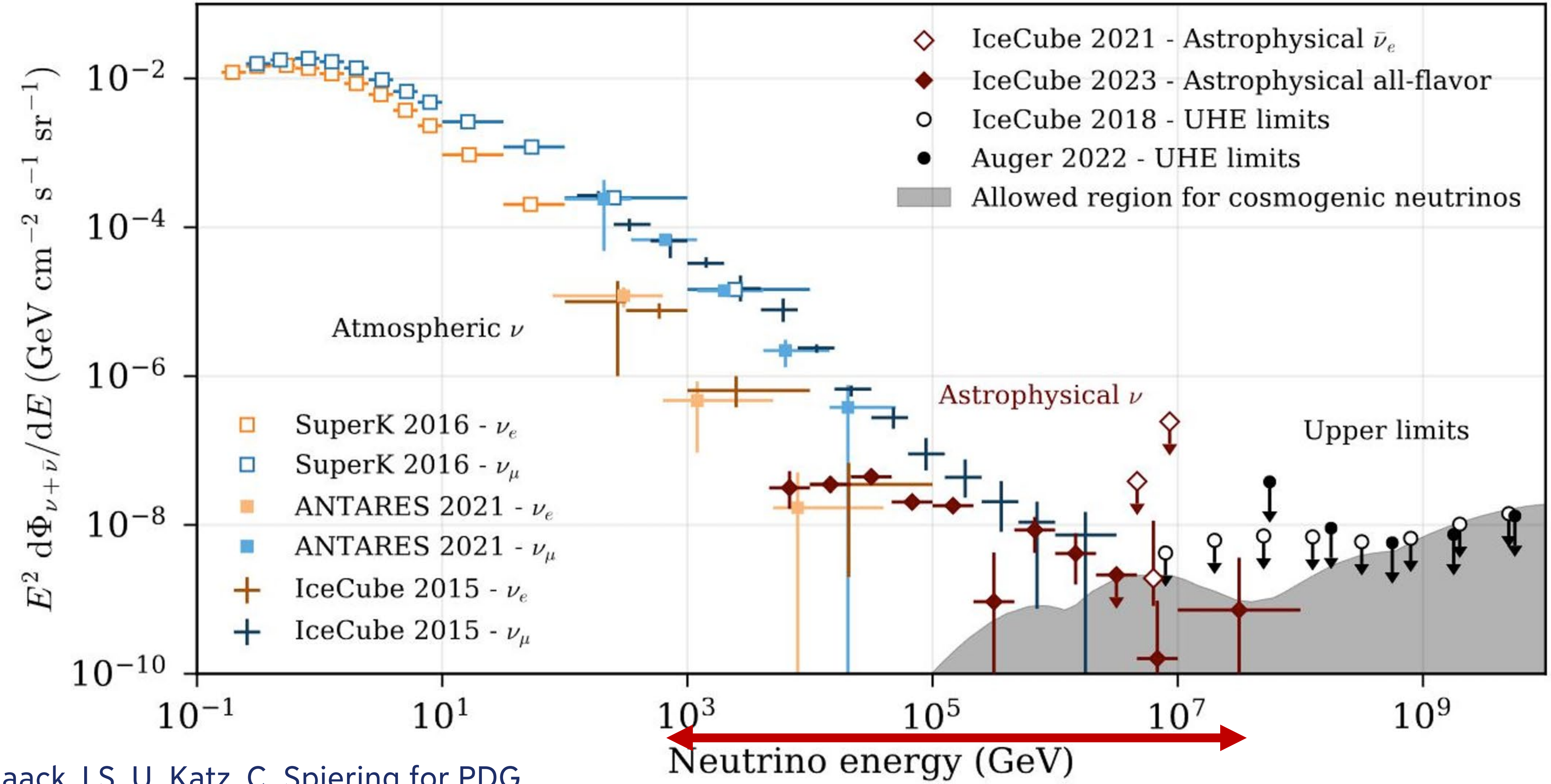
Credit: Markus Ahlers

Astrophysical neutrino fluxes



Credit: Markus Ahlers

“High-energy” / “cosmic” neutrino flux



C. Haack, LS, U. Katz, C. Spiering for PDG

How to detect high-energy neutrinos

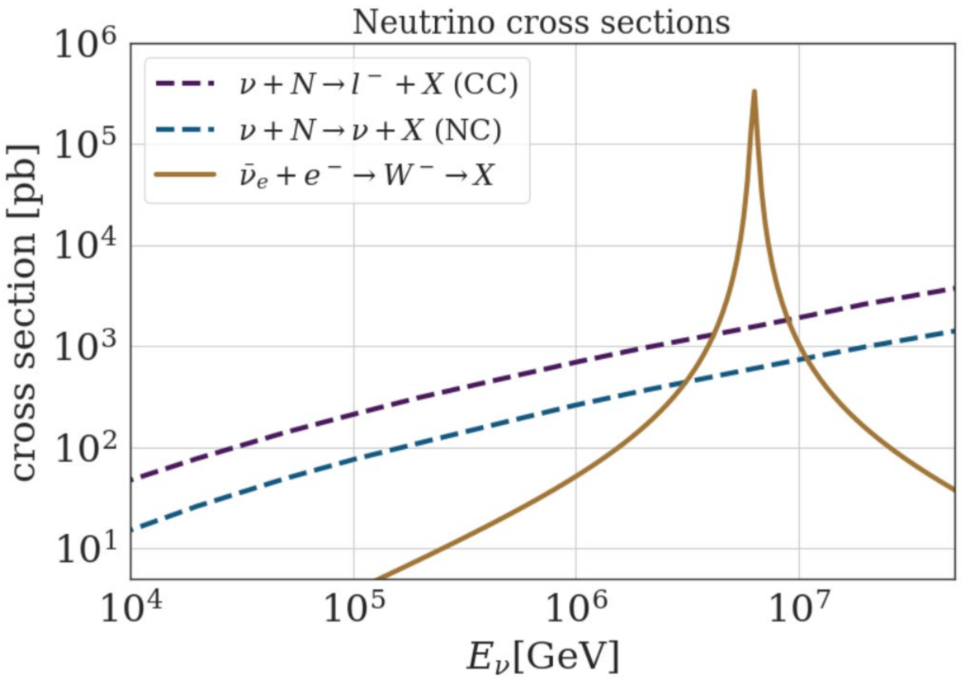
Three challenges:

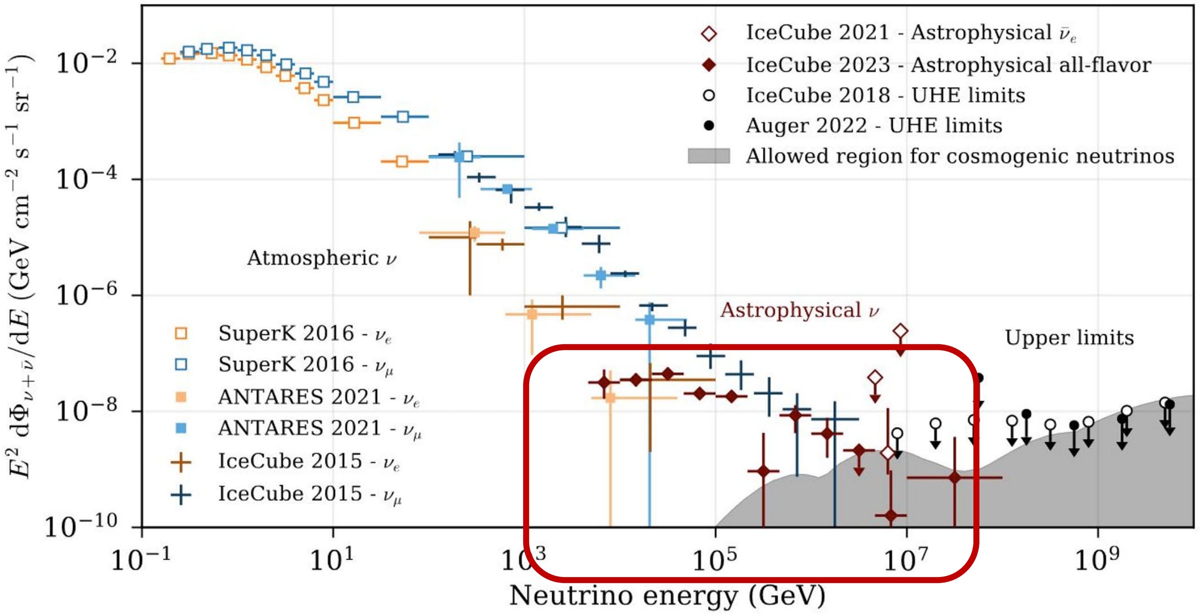
1. Tiny cross sections $\sim 10^{-34}\,\mathrm{cm}^2$
2. Low flux at TeV-PeV energies
3. Background for astrophysical neutrinos: atmospheric Muons and neutrinos

Need km³-sized detectors

$$\frac{dN}{dEdAdtd\Omega}(E = 100\ \mathrm{TeV}) \sim \frac{10^{-18}}{\mathrm{GeV\ cm^2 s\ sr}}$$

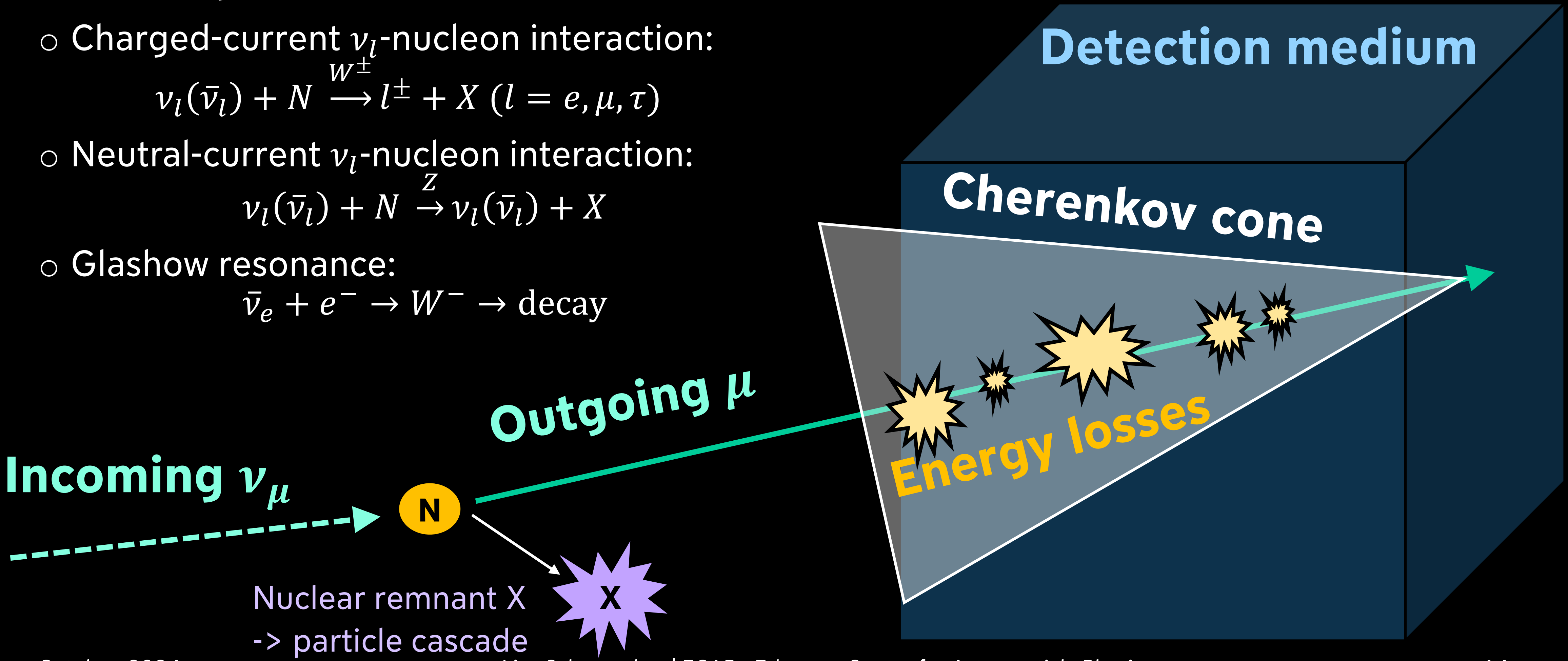
Vitagliano et al. arXiv:1910.11878v3



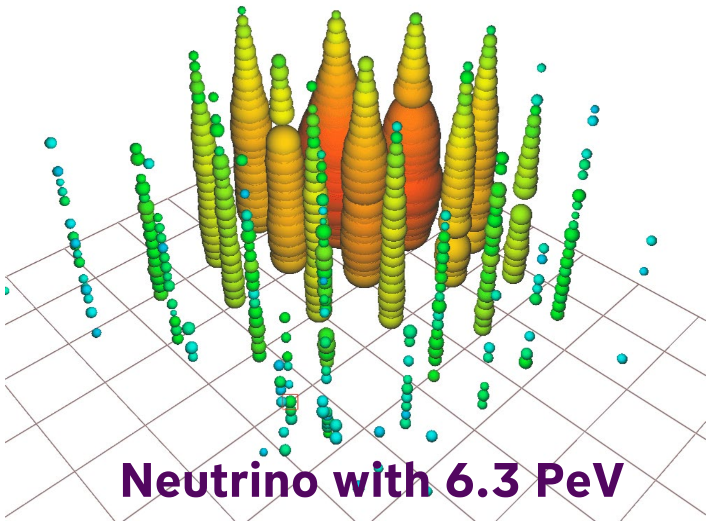


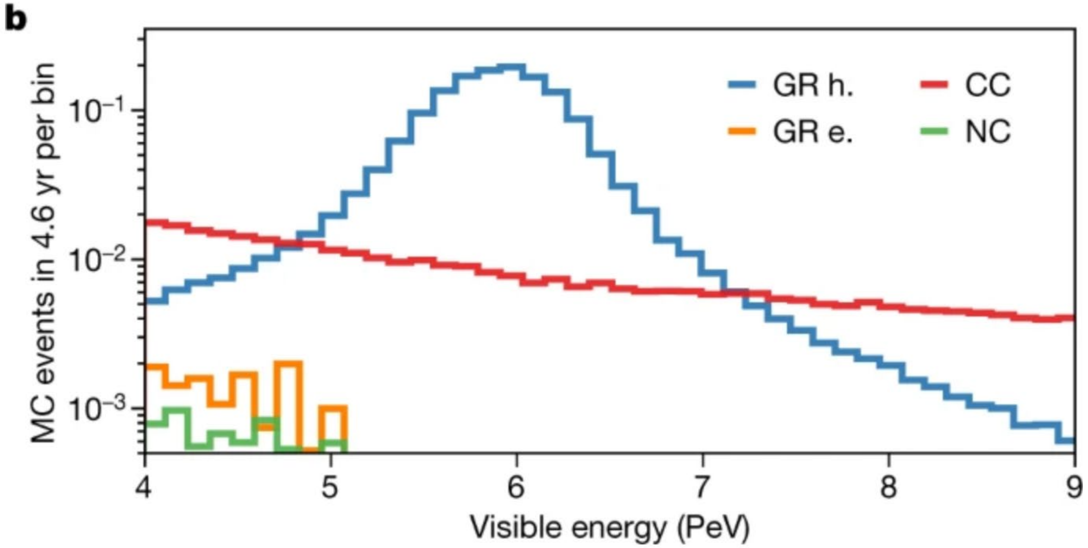
Neutrino interactions

- Main detection channel: deep inelastic scattering (DIS)
- Charged-current ν_l-nucleon interaction:
$$\nu_l(\bar{\nu}_l) + N \xrightarrow{W^\pm} l^\pm + X \ (l = e, \mu, \tau)$$
- Neutral-current ν_l-nucleon interaction:
$$\nu_l(\bar{\nu}_l) + N \xrightarrow{Z} \nu_l(\bar{\nu}_l) + X$$
- Glashow resonance:
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{decay}$$



Glashow resonance: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{decay}$





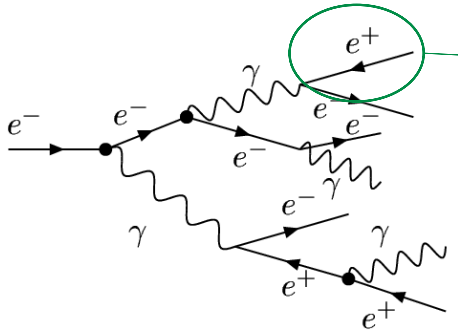
https://www.nature.com/articles/s41586-021-03256-1

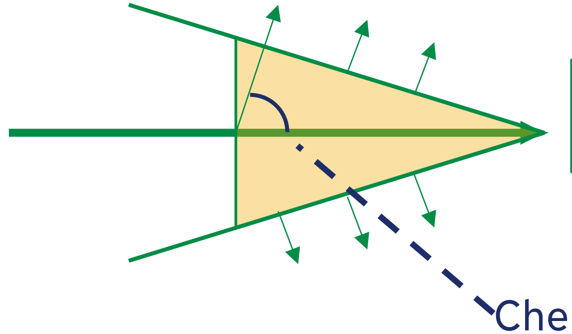
W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)	Conf
Γ_1	$\ell^+\nu$	⟵ 1/3	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$			(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$			(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$			(11.38 ± 0.21) %	
Γ_5	hadrons	⟵ 2/3		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$			$< 7 \times 10^{-6}$	
Γ_7	$D_s^+\gamma$			$< 1.3 \times 10^{-3}$	
Γ_8	cX			(33.3 ± 2.6) %	
Γ_9	$c\bar{s}$			$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible		[b]	(1.4 ± 2.9) %	
Γ_{11}	$\pi^+\pi^+\pi^-$			$< 1.01 \times 10^{-6}$	

Cherenkov Light Yield for EM Cascades



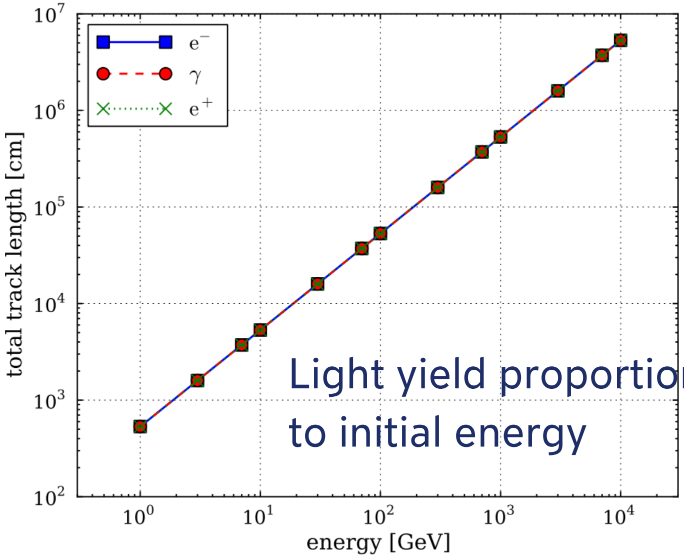


~250 photons / cm between 300nm and 500nm

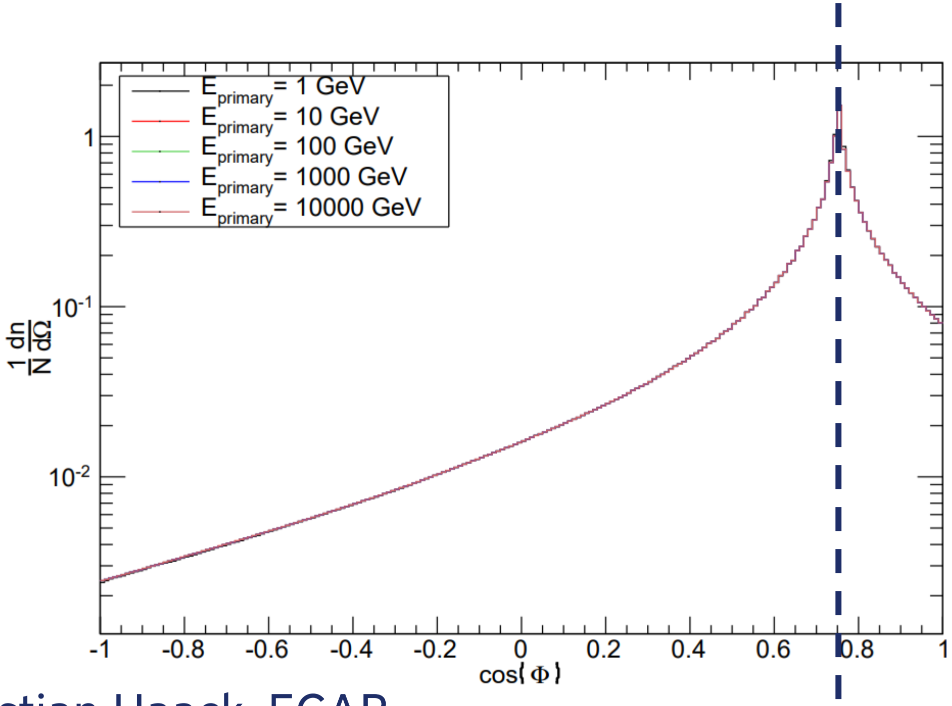
Cherenkov angle $\cos\theta = \frac{1}{n\beta}$

Cascade → Sum of Cherenkov „tracks"

Light Yield



Light yield proportional to initial energy



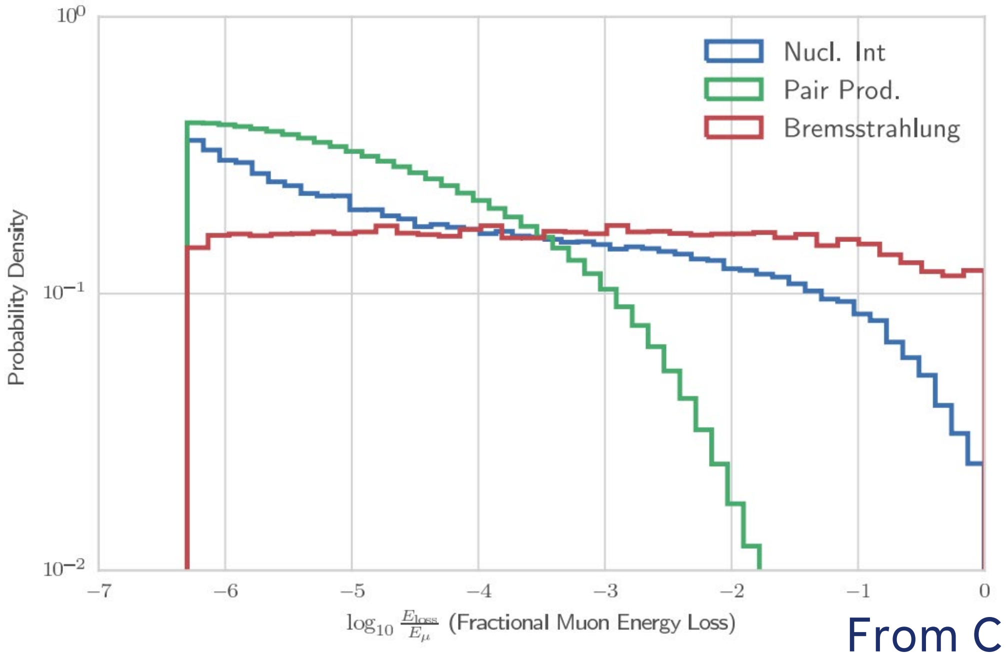
From Christian Haack, ECAP

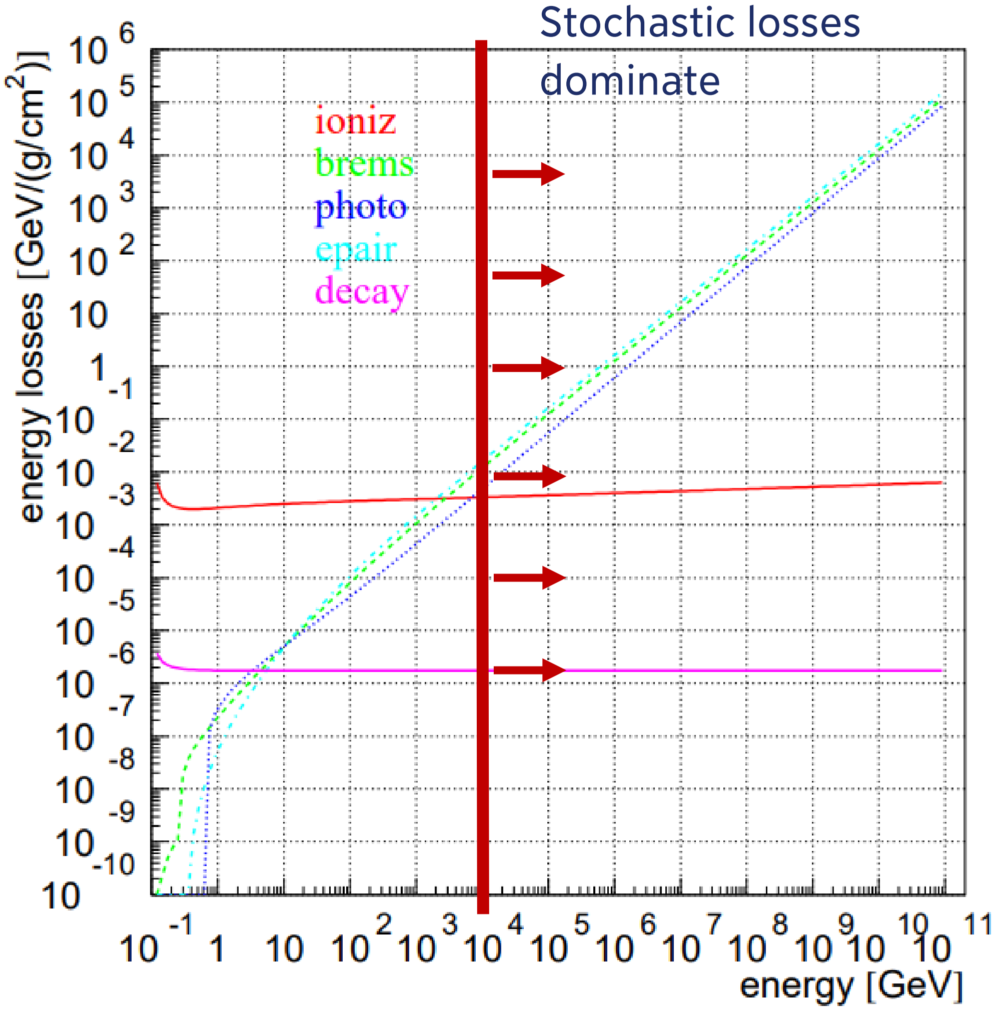
Energy Losses of High-Energy Muons

$$\frac{dE}{dX} = a + b(E) * E$$

Continuous Losses (Ionization)

Stochastic Losses (Bremsstrahlung, Photohadronic, Pair Production)





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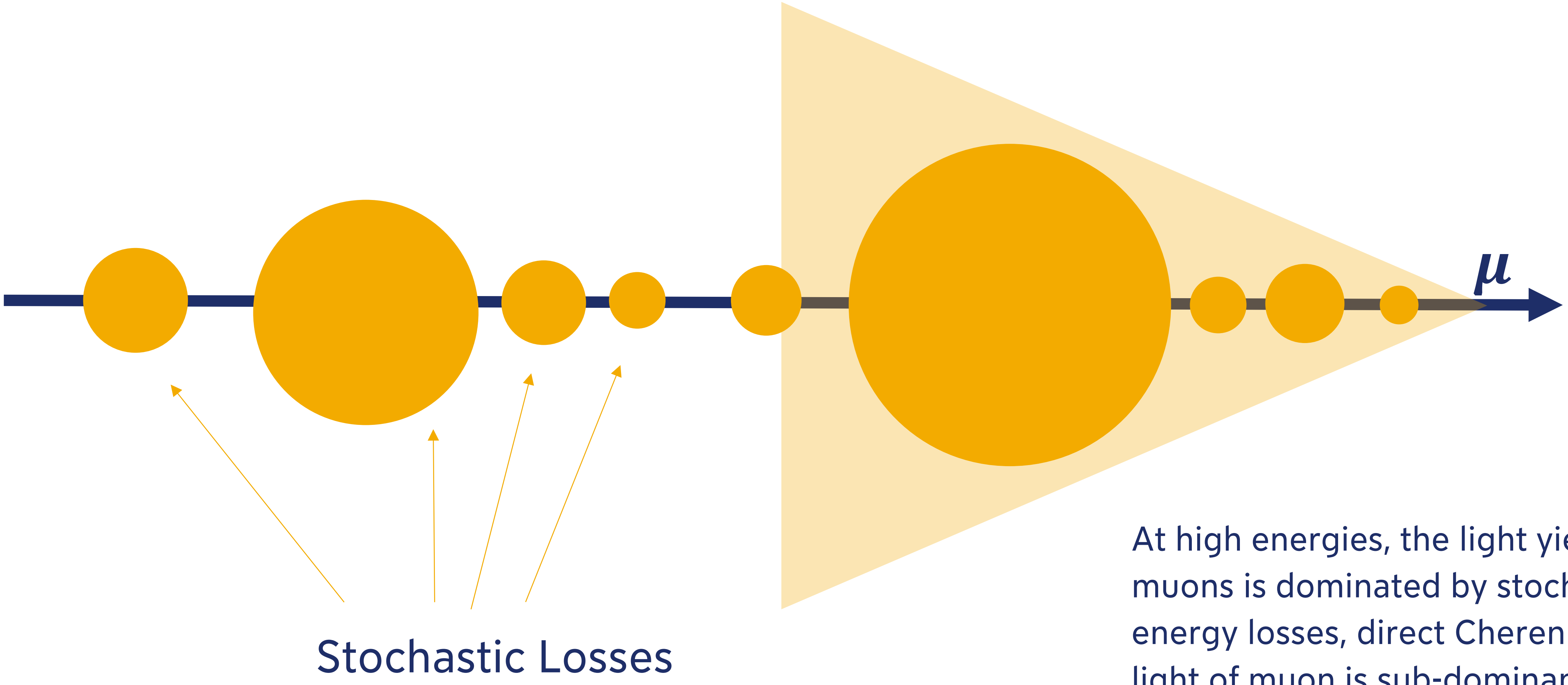
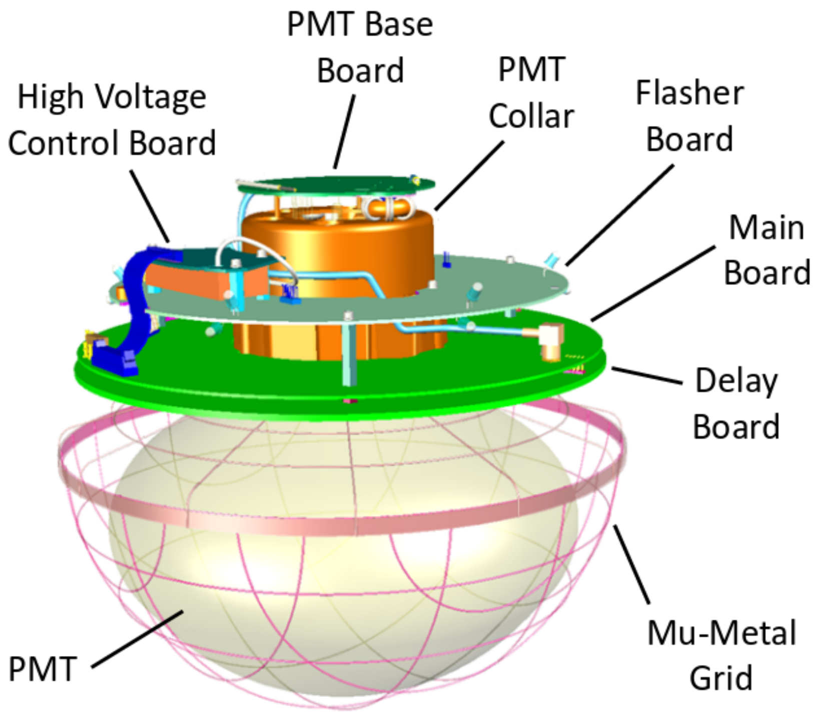
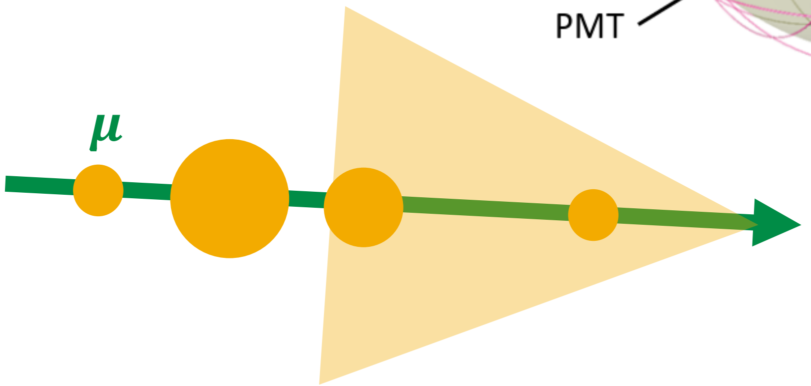


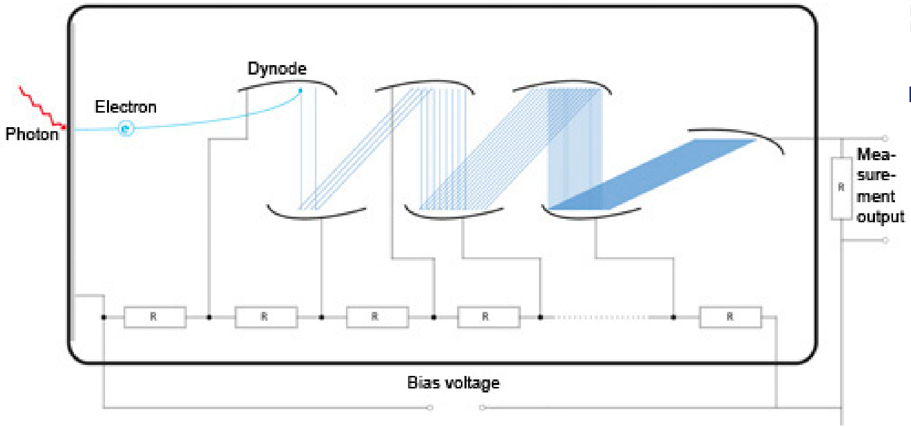
At high energies, the light yield of muons is dominated by stochastic energy losses, direct Cherenkov light of muon is sub-dominant

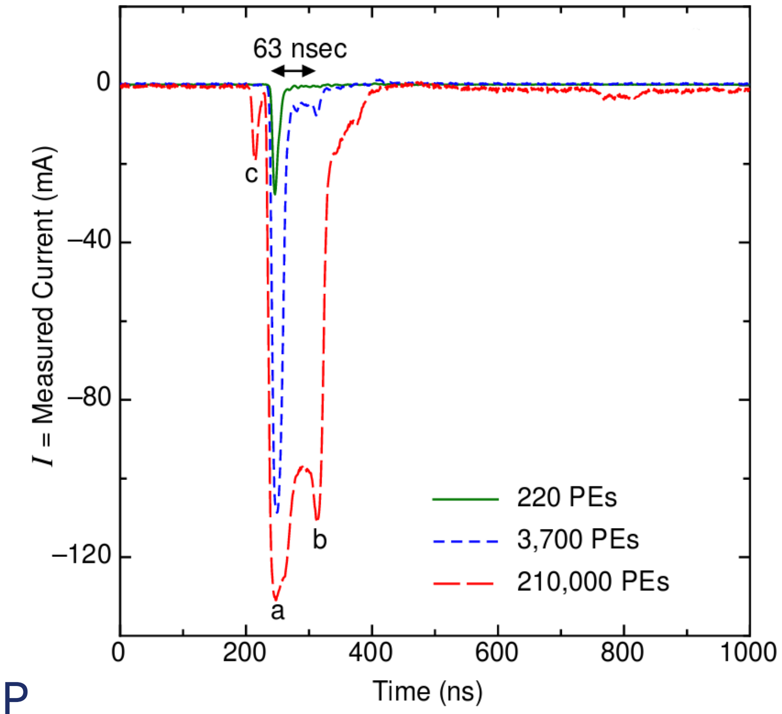
From Christian Haack, ECAP

What do optical modules measure?



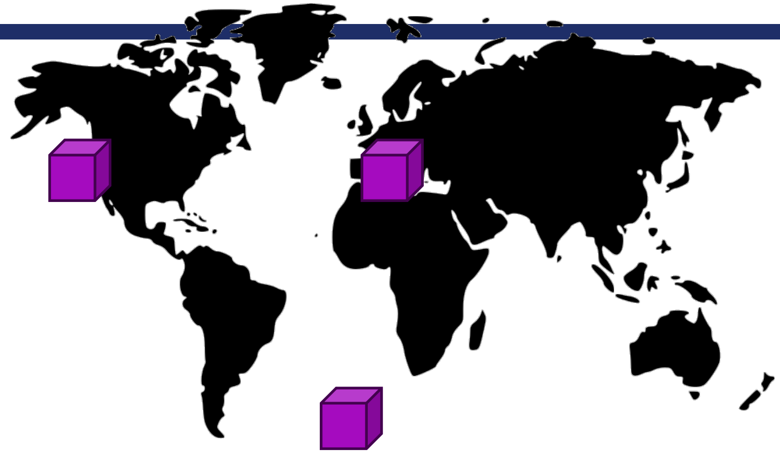


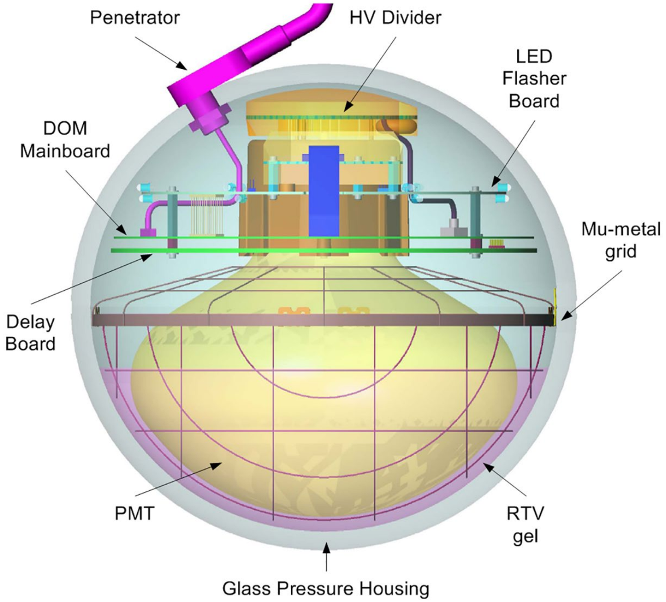




From Christian Haack, ECAP

Different types of optical modules



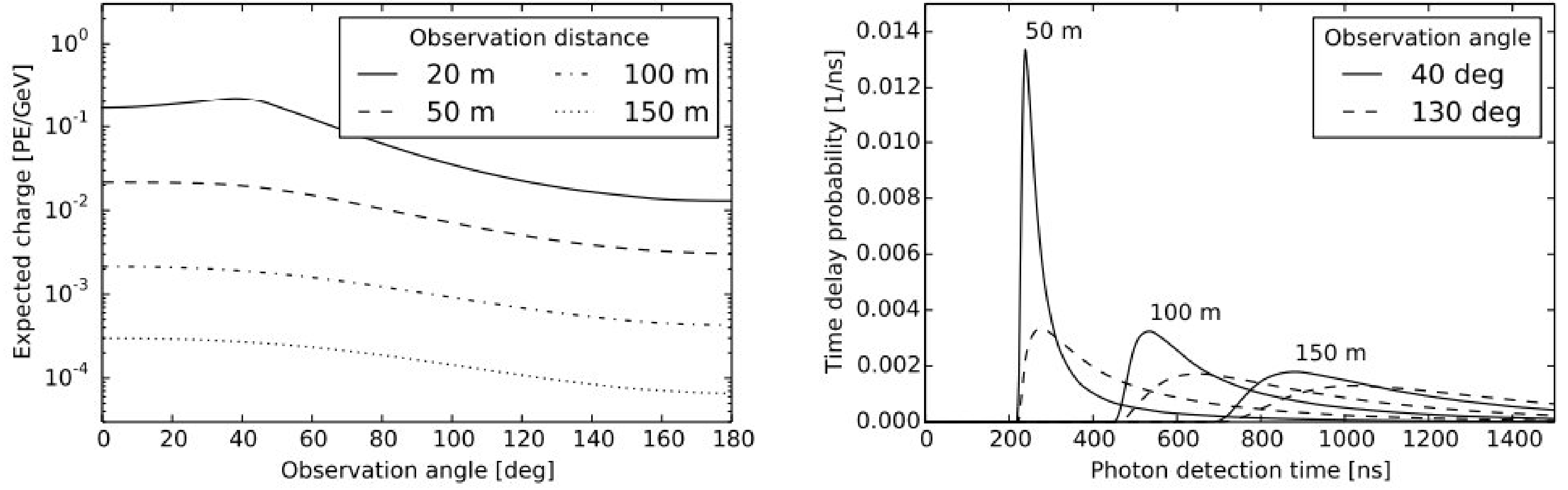


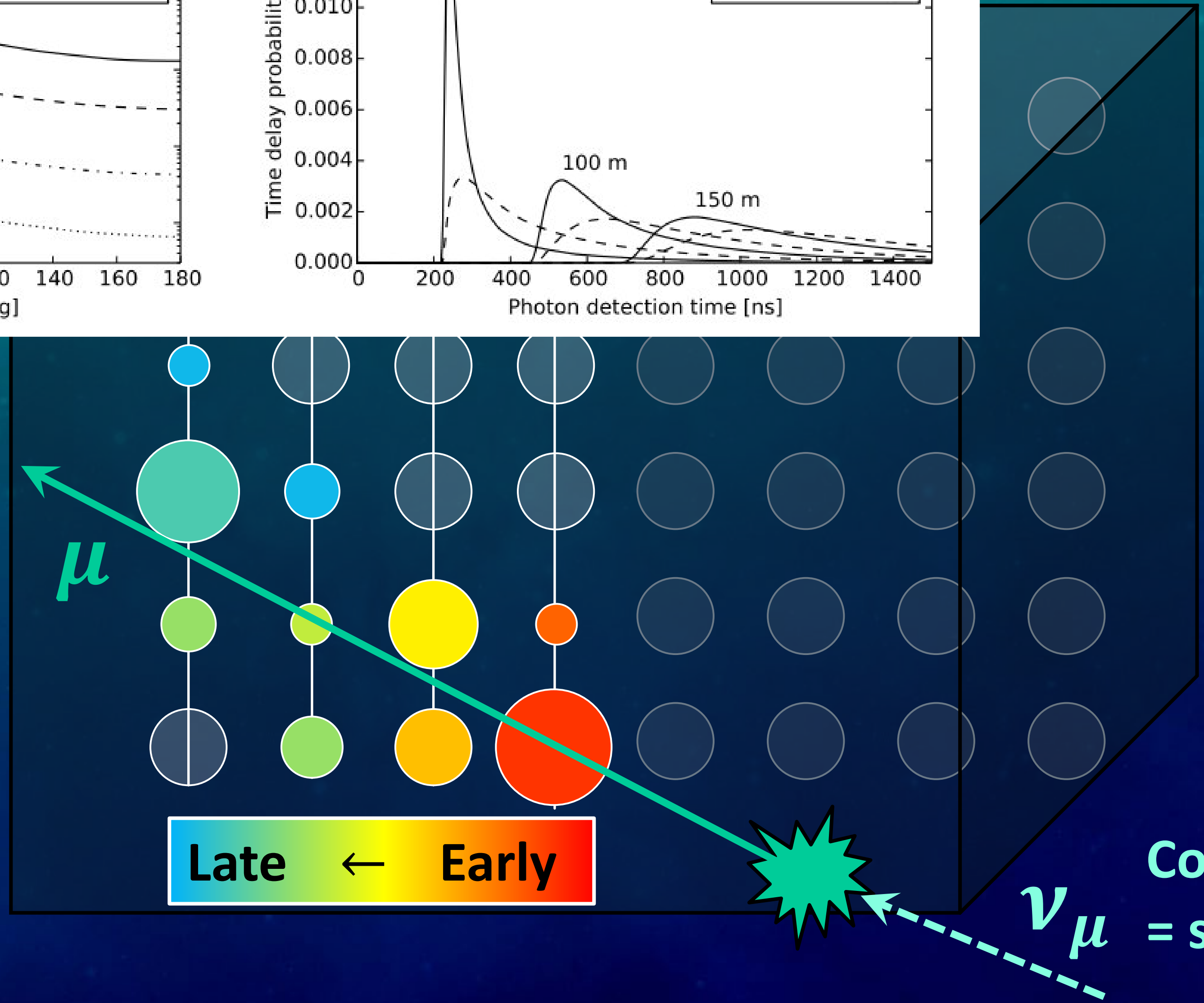
IceCube at the South Pole

KM3NeT – under construction in the Mediterranean Sea

P-ONE – to be deployed in Pacific Ocean near Vancouver Island

1 GeV EM Cascade





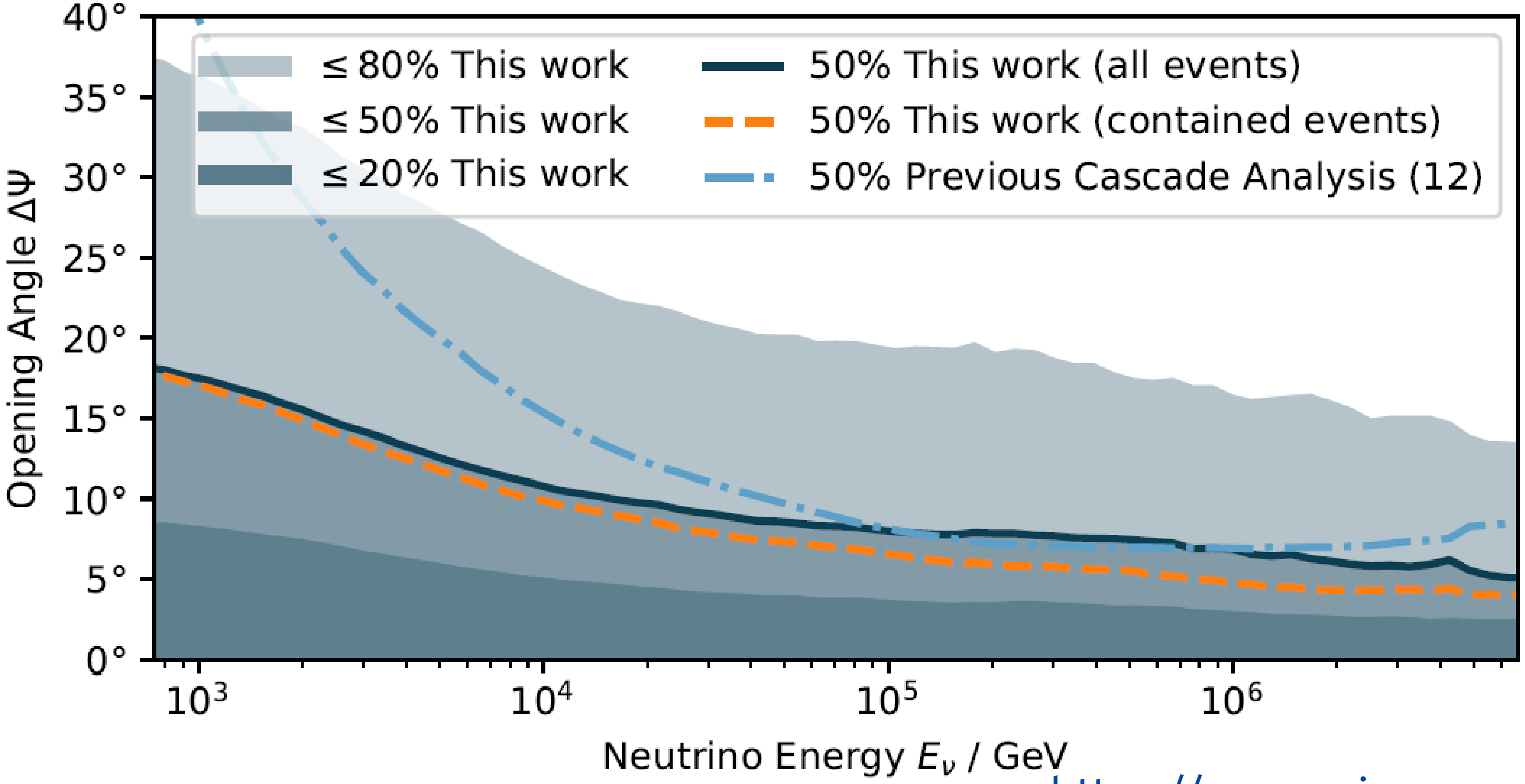
Detection medium: ice

3D array of optical modules

Cosmic neutrino = signal

Event reconstruction

- Likelihood-based or Machine Learning – or a mixture of both
- All based on photon arrival times and overall number of photons detected



Cascades reconstructed with Convolutional neutral network

https://www.science.org/doi/10.1126/science.adc9818

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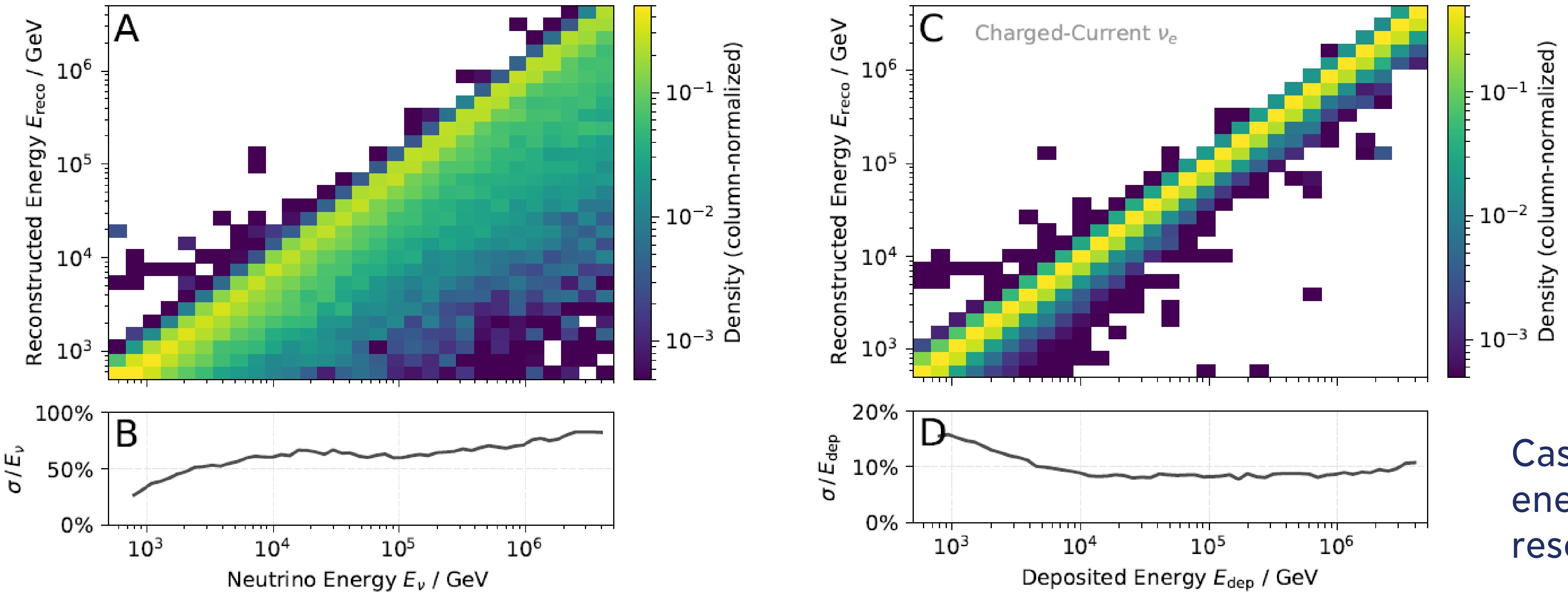

Cascades – energy resolution

https://www.science.org/doi/10.1126/science.adc9818

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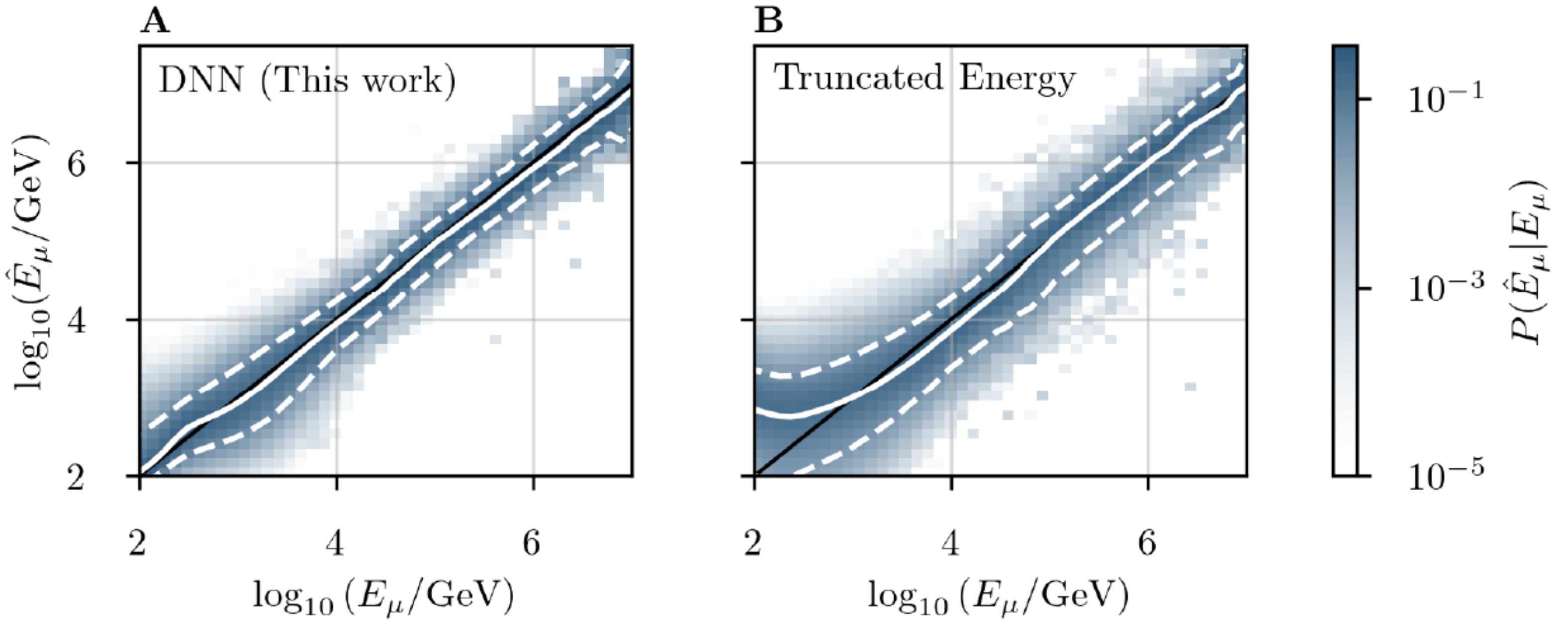
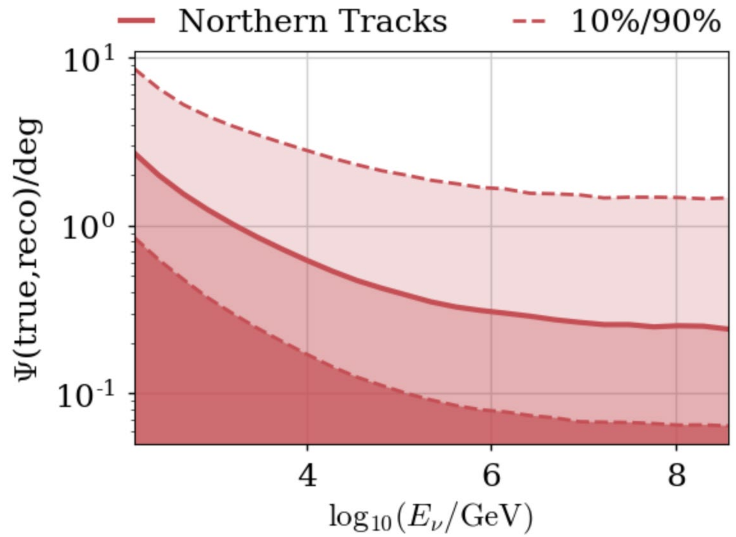


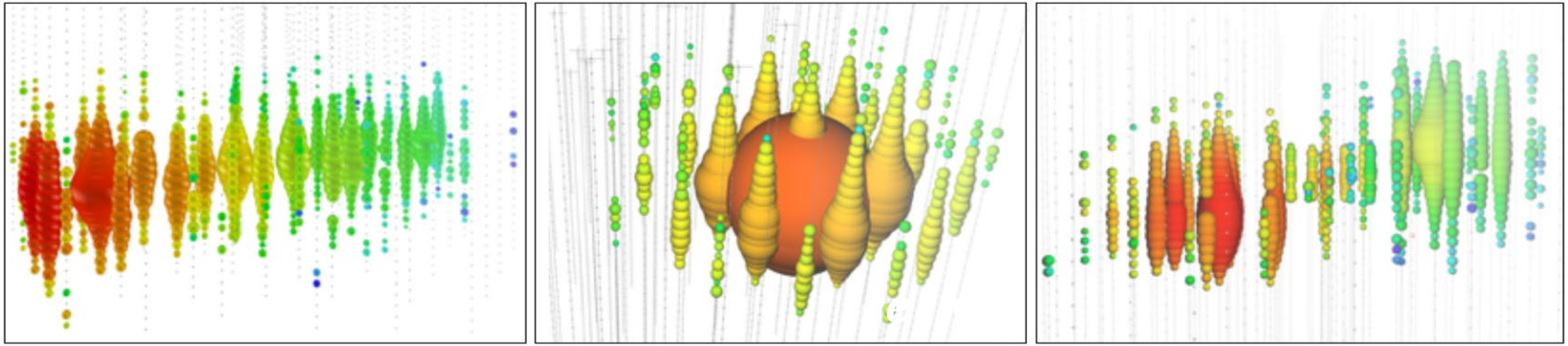


https://www.science.org/doi/10.1126/science.abg3395

Muon tracks – energy and angular resolution

Neutrino signatures - summary

IceCube-Gen2
arXiv:2008.04323v1



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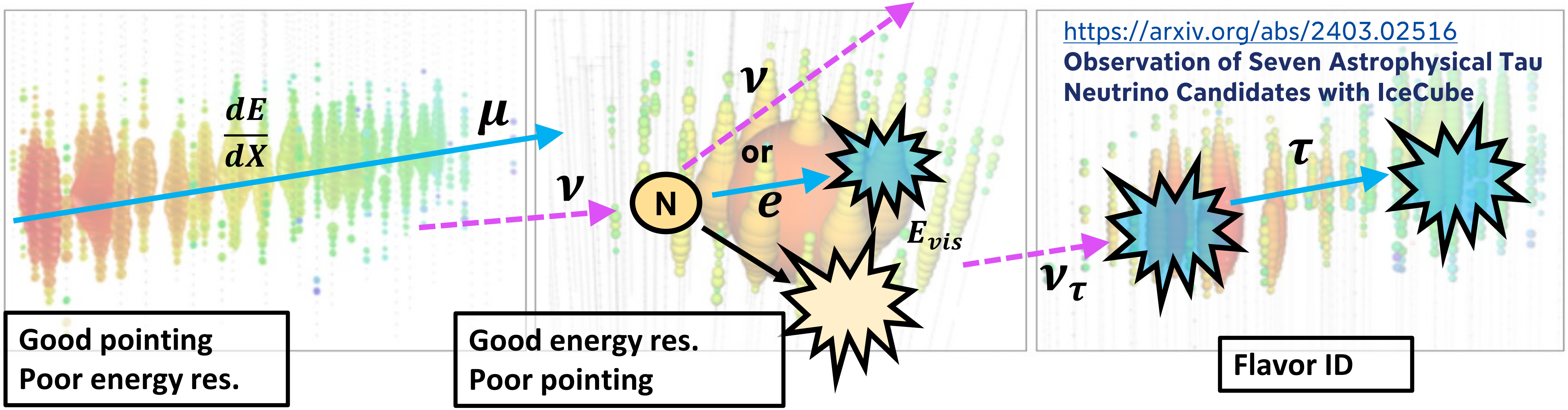
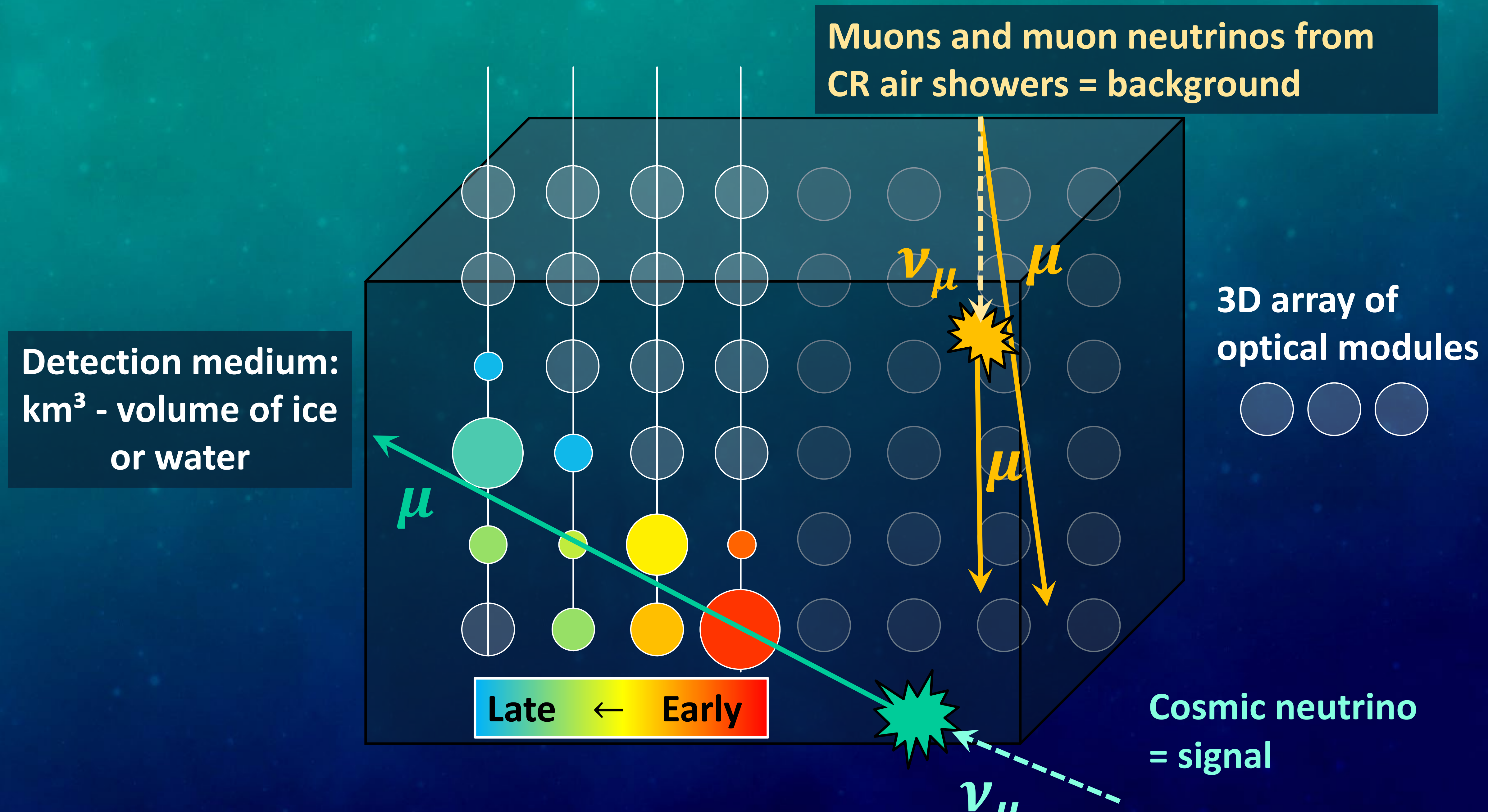


"**Tracks**":
- Good directional resolution $< 1°$
- Poor energy resolution via $\frac{dE}{dX}$ of muon

"**Cascades**":
- CC ν_e & ν_τ interactions + NC all-flavor
- Directional resolution $\sim 5 - 15°$
- Good resolution of visible energy: $\sim 10\%$ for CC ν_e

"**Double Bang**":
- CC ν_τ interactions + τ decay
- Only resolvable at high energies with distance between cascades

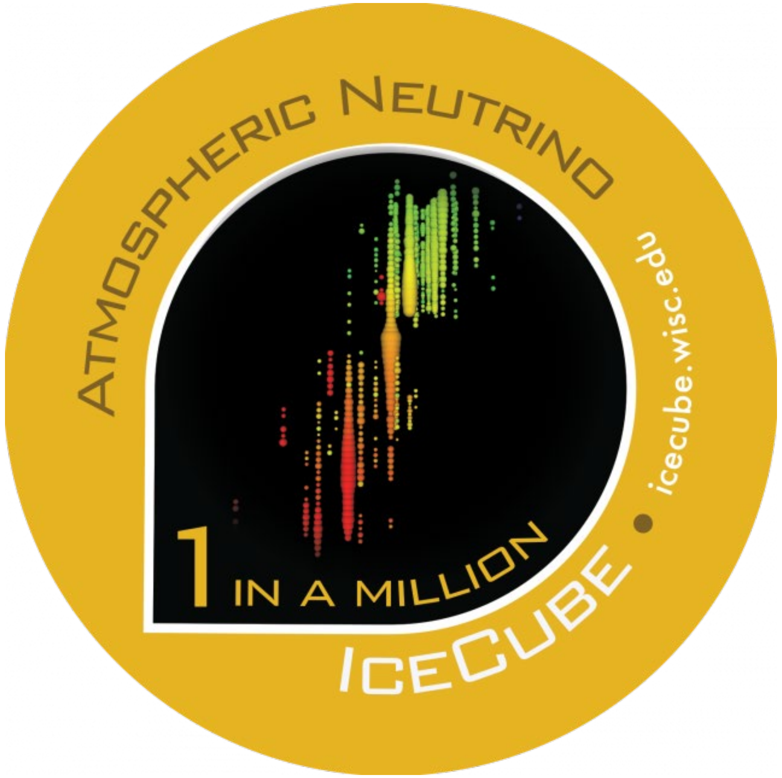
$$\sim 50\text{m} \cdot \left(\frac{E}{\text{PeV}}\right)$$



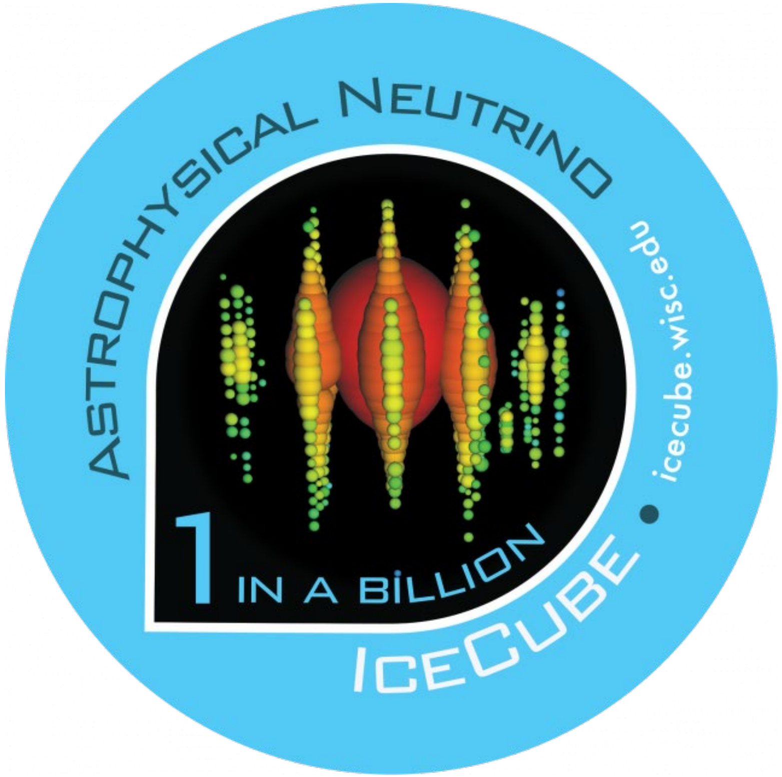
Muons and muon neutrinos from CR air showers = background
ν_μ
μ
μ
3D array of optical modules
Detection medium: km³ - volume of ice or water
μ
Late ← Early
Cosmic neutrino = signal
ν_μ

Needle in a haystack

3000 atmospheric μ
per second
Trigger level



10 atmospheric ν
per hour
Cleaned data

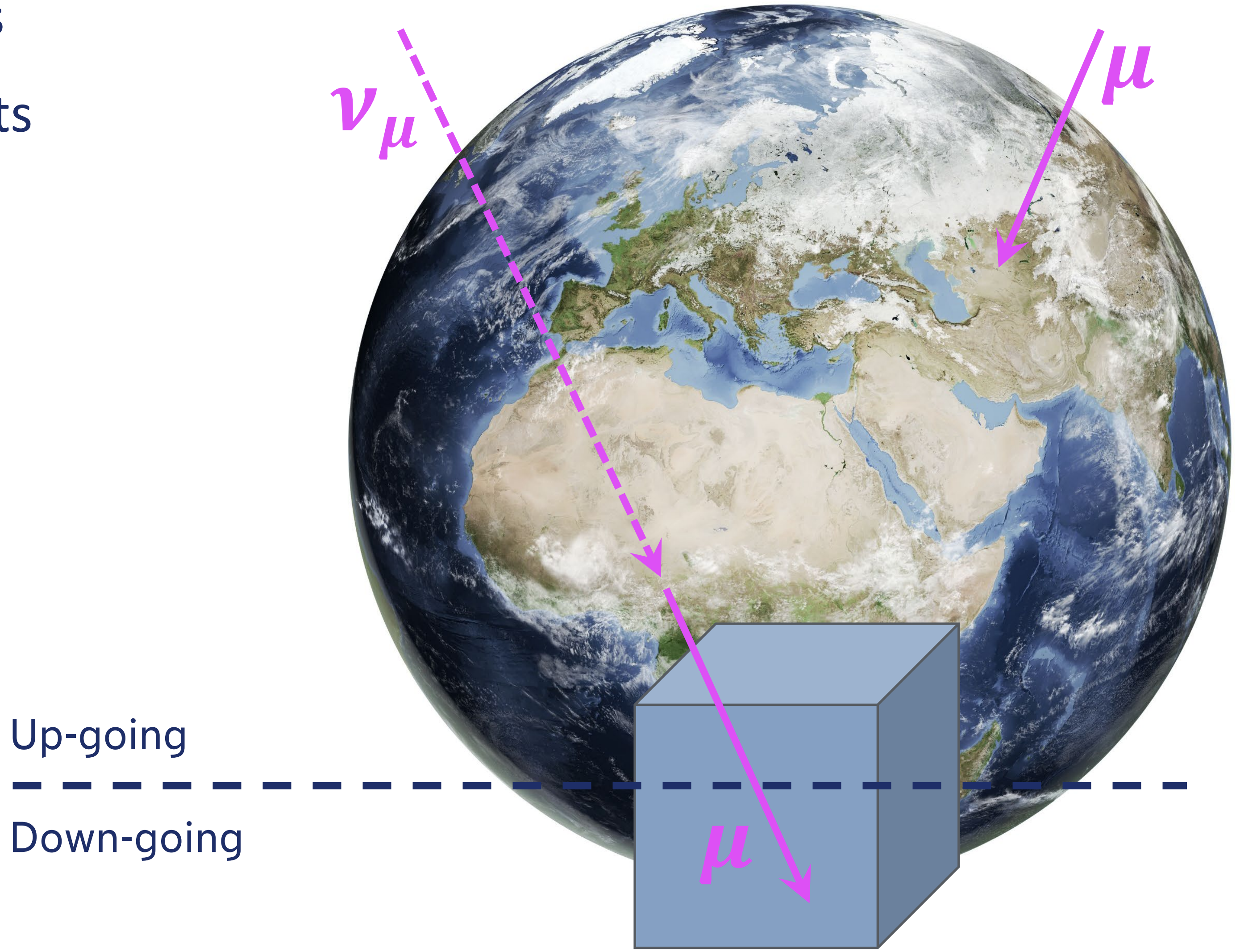


100 astrophysical ν
per year
Cleaned data

Neutrino selection

a) Select “up-going” events

b) Select “contained” events



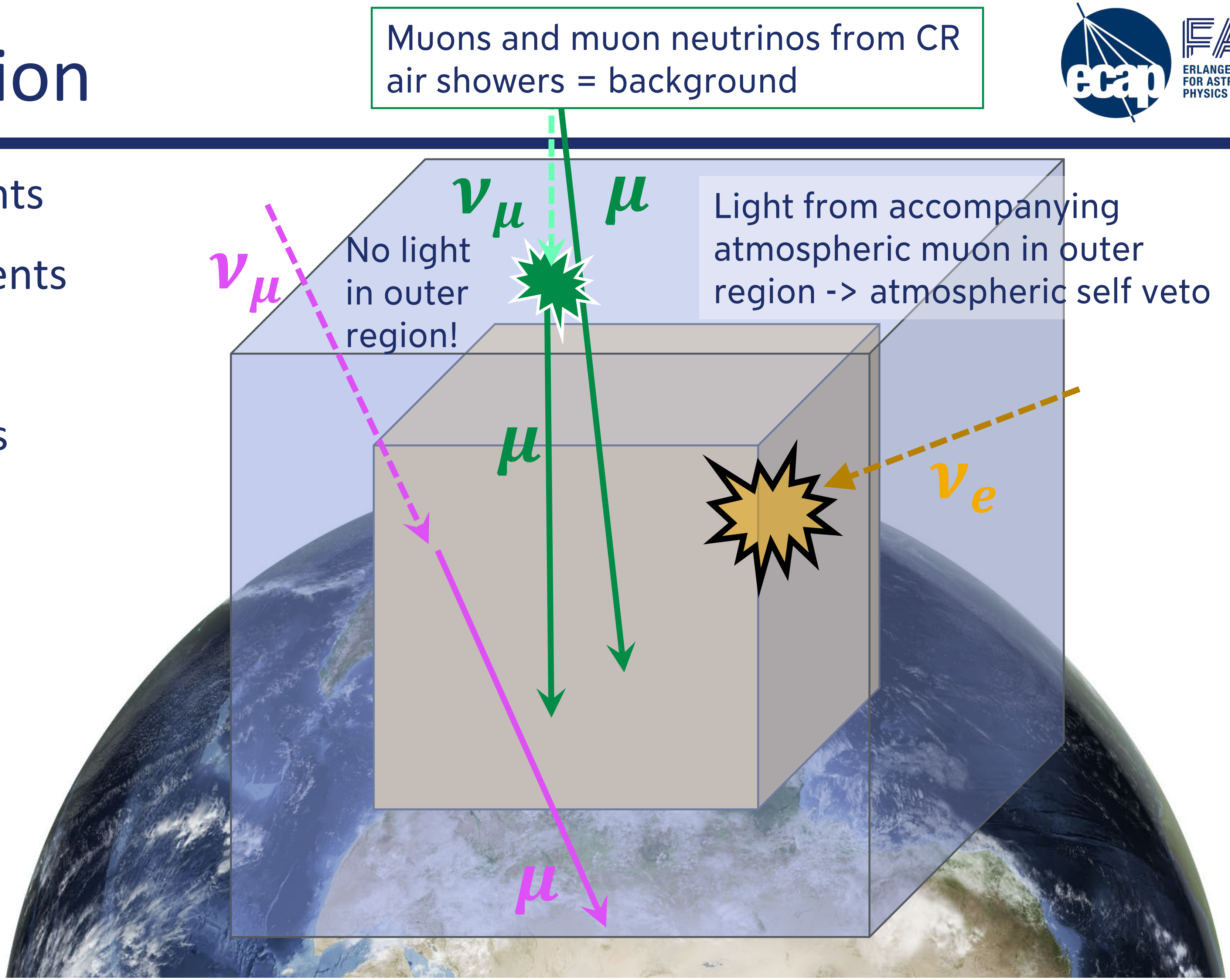
Neutrino selection

a) Select "up-going" events

b) Select "contained" events

  a) Starting events

  b) Contained cascades



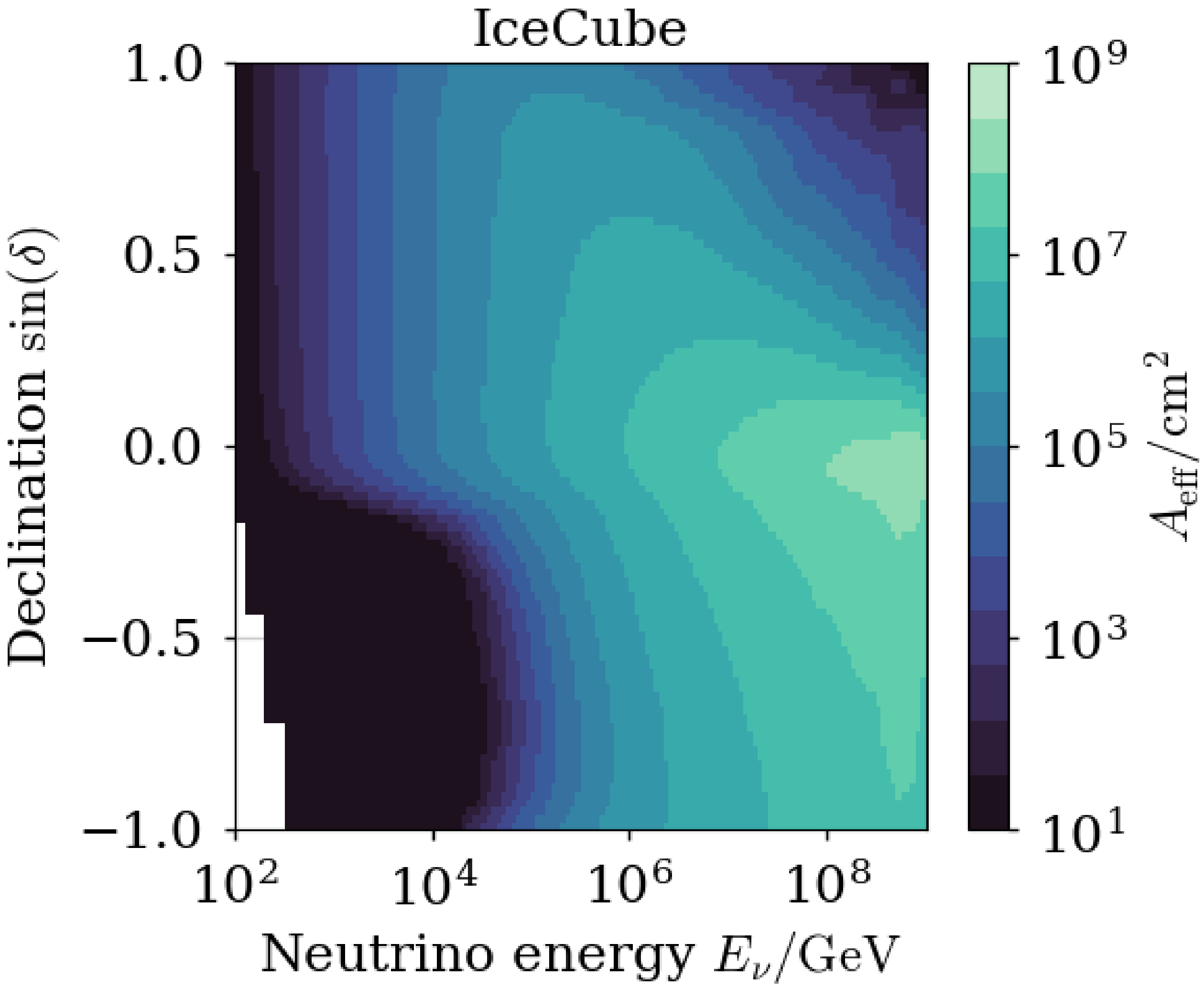
Effective area – what's that?

- "Effective area" is the imagined detection area (perpendicular to the neutrino direction) a detector with 100% efficiency would need to have to match the neutrino flux to the observed event rate

$$N_\nu(\sin(\delta_{\mathrm{src}})) = T_{\mathrm{live}} \cdot \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \mathrm{d}E\, A_{\mathrm{eff}}\left(E, \sin(\delta_{\mathrm{src}})\right) \cdot \frac{\mathrm{d}\Phi_{\mathrm{src}}}{\mathrm{d}E}$$

- Fold in transmission and interaction probability, selection efficiency and geometric area (usually MC-based)

$$A_{\mathrm{eff}}(E,\vec{\Omega}) = T_{\mathrm{Earth}}(E_\nu,\vec{\Omega}) \otimes P_{\nu\to\mu}(E_\nu, E_\mu, R) \otimes \epsilon_{\mathrm{select}}(E_\mu,\vec{\Omega}) \otimes A_{\mathrm{geo}}(\vec{\Omega})$$



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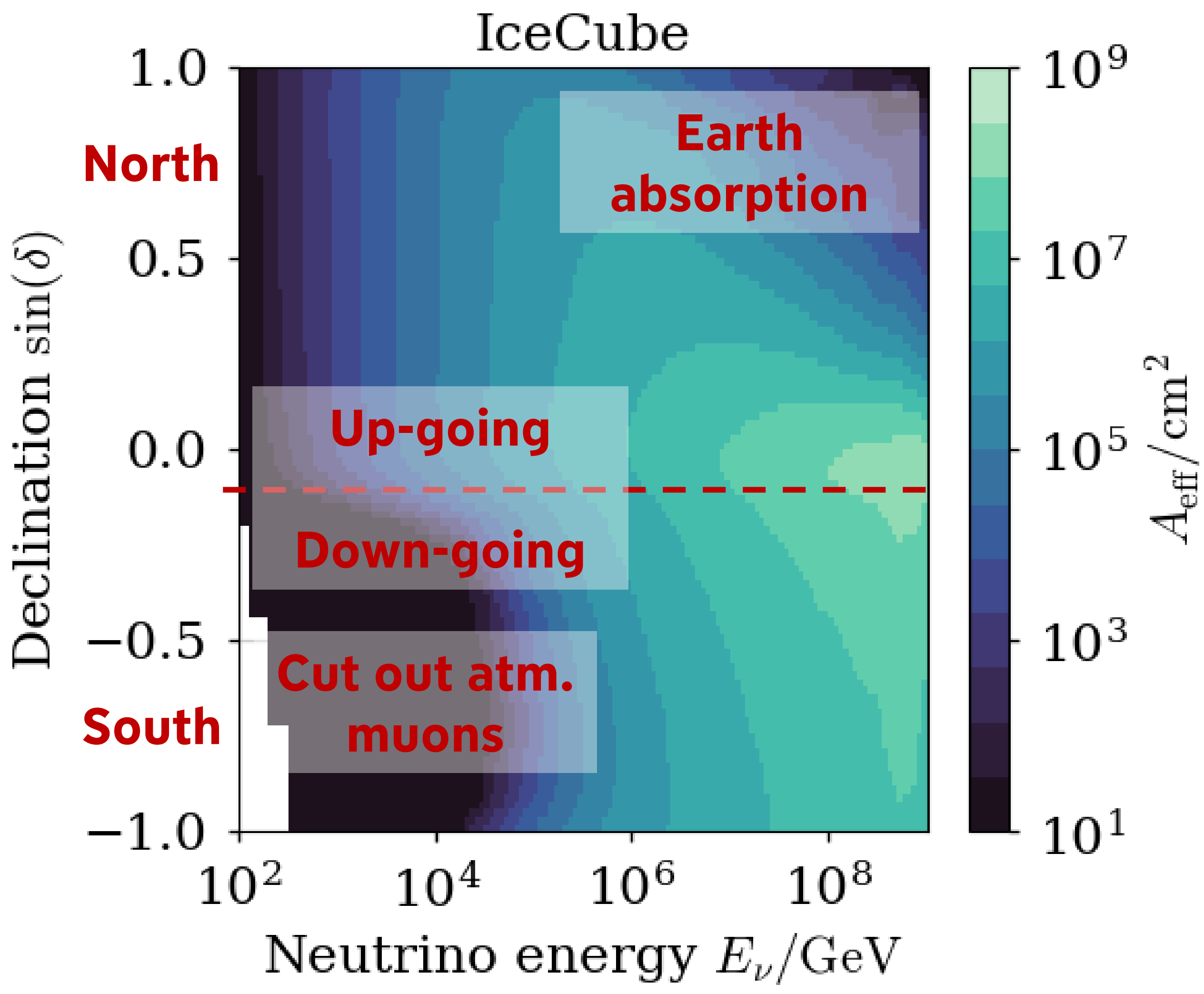
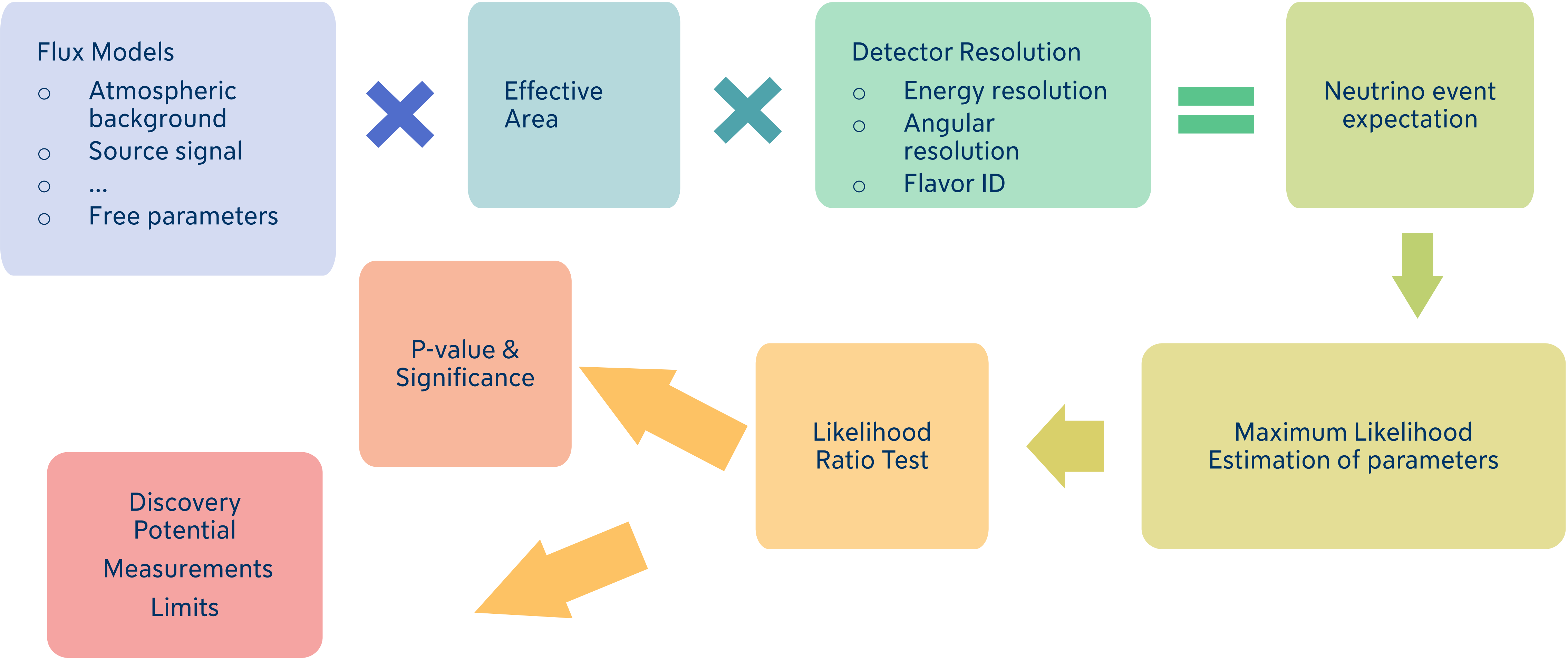
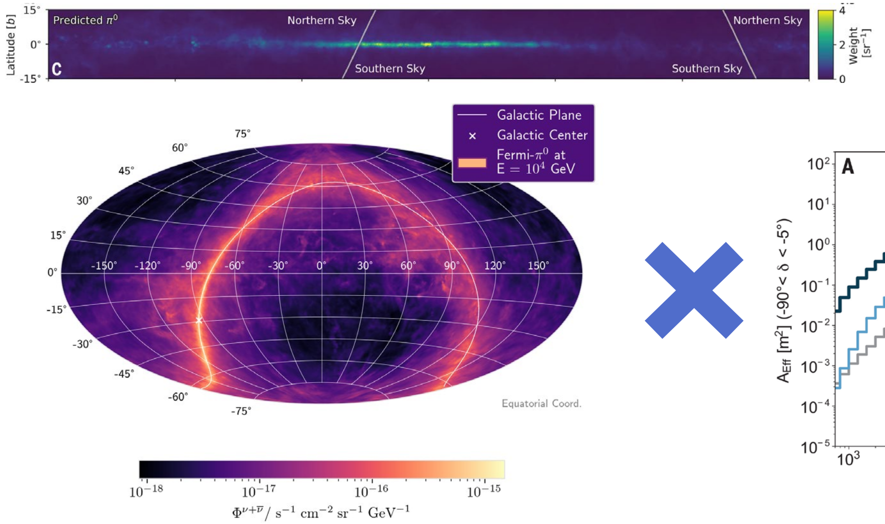
Muon tracks

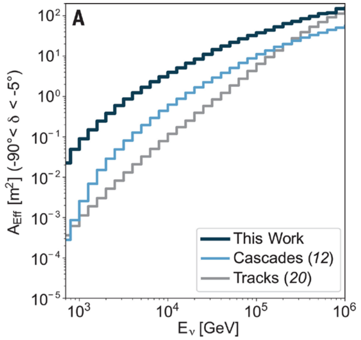


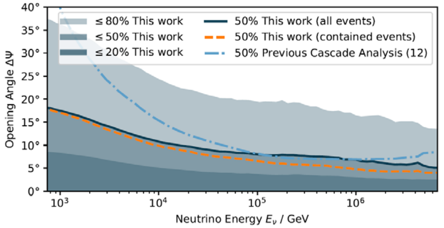
Generic analysis method

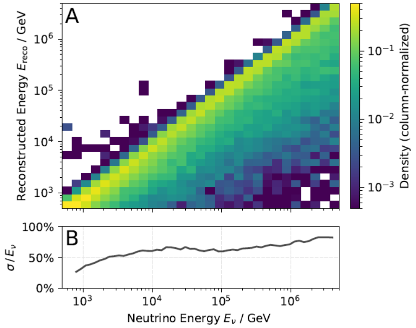


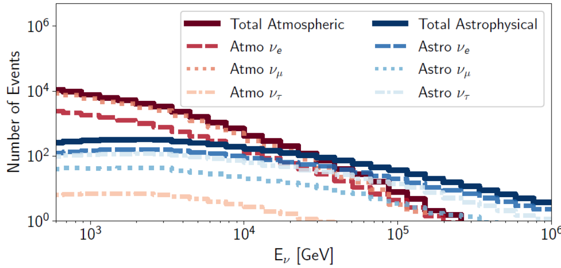
Galactic plane - analysis method (cascades)

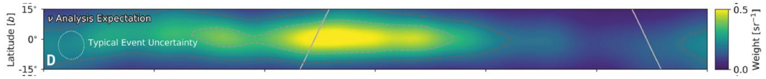












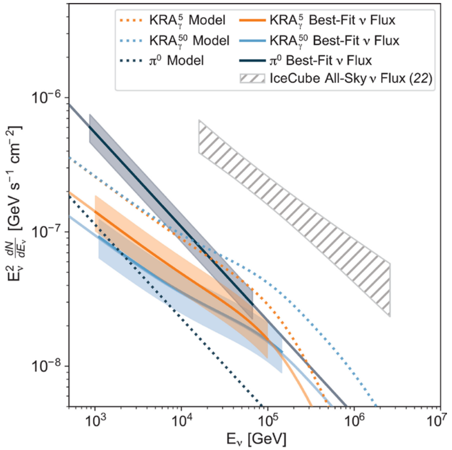
4.5 sigma (trial corrected)

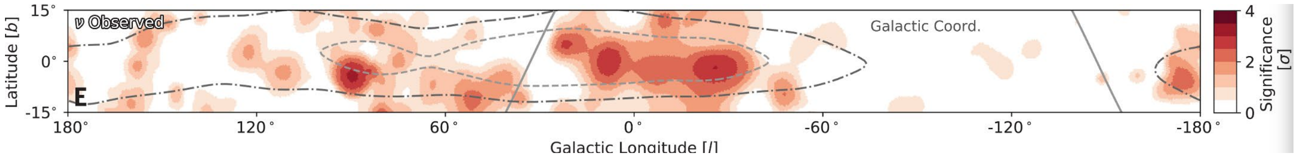
Likelihood Ratio Test

Maximum Likelihood Estimation of parameters

	2.9 x CRINGE
	4.7 x Fermi-π^0
	0.7 x KRA-γ-50
	1.1 x KRA-γ-5

(Tracks)

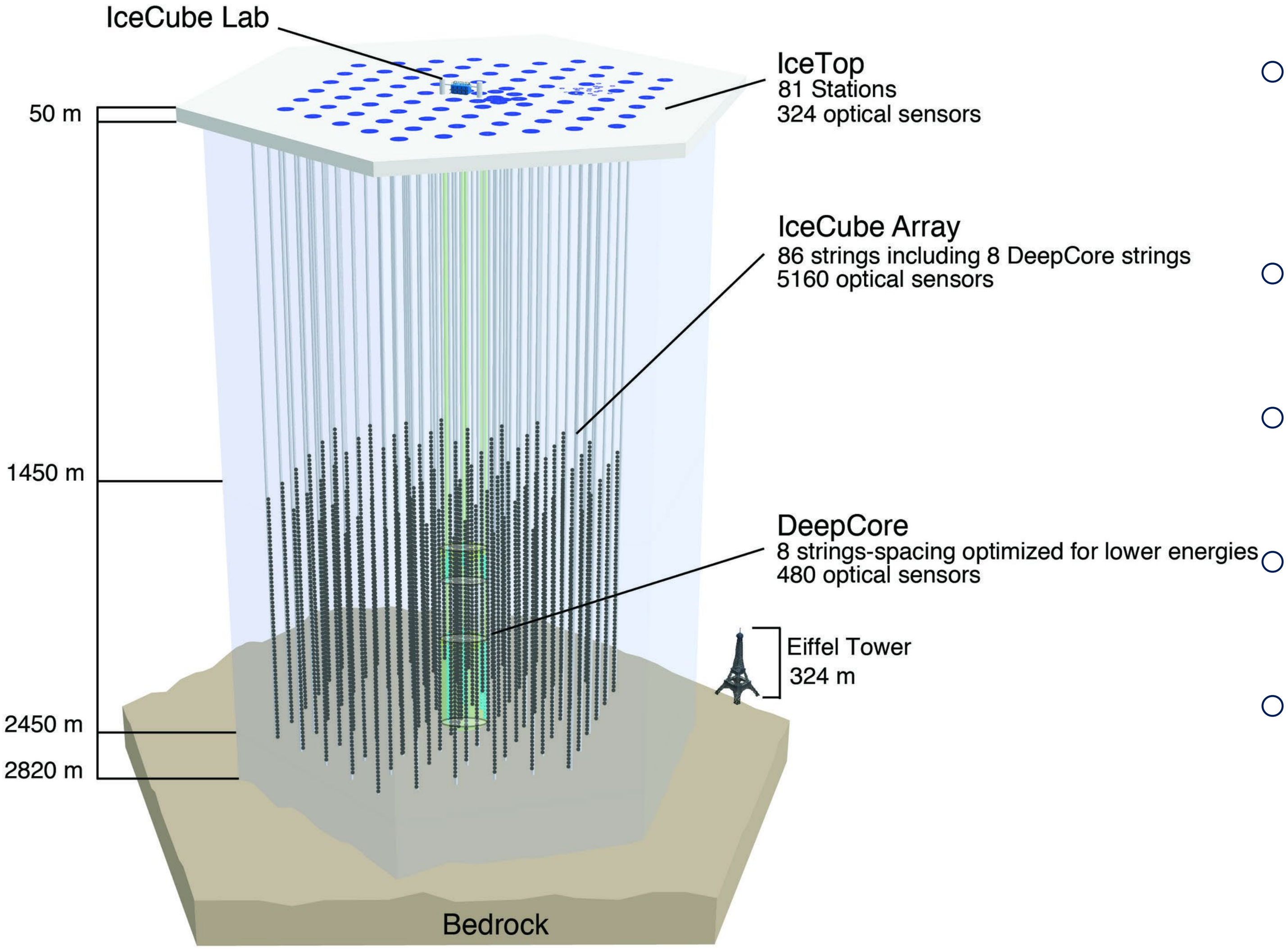




Recent results from IceCube

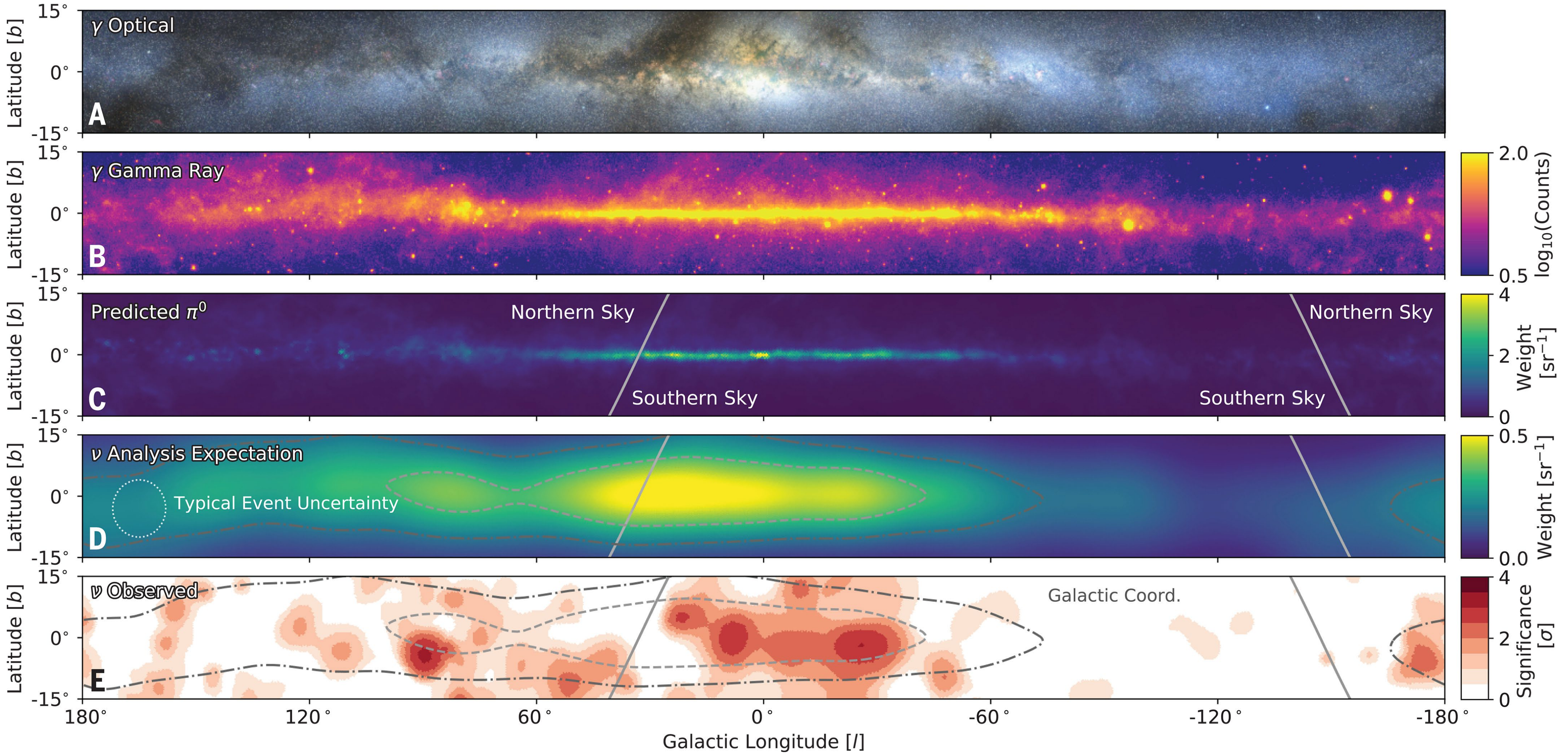
A very incomplete selection

The IceCube Neutrino Observatory



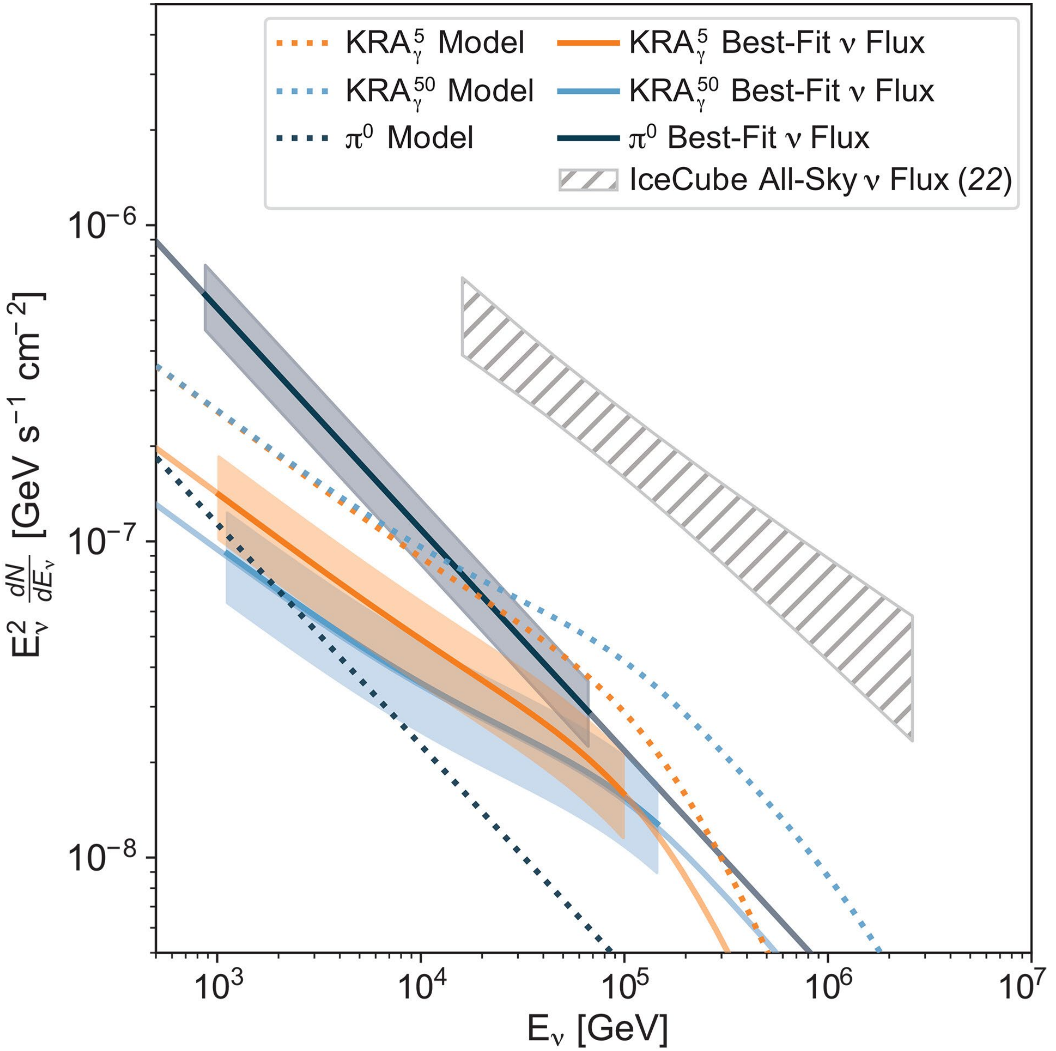
- Located at the geographic south pole 1.45-2.45 km deep in the ice with an instrumented volume of 1 km³
- 86 Strings with 60 Digital Optical Modules (DOMs) = 5160 DOMs in total
- Sparse instrumentation! 17m vertical & 125m horizontal spacing
- Full configuration running with >99% uptime since 2011
- Multi-purpose instrument for neutrino astronomy, neutrino physics, particle physics, physics beyond the standard model, …

Galactic neutrinos



Galactic plane – diffuse emission

https://doi.org/10.1126/science.adc9818

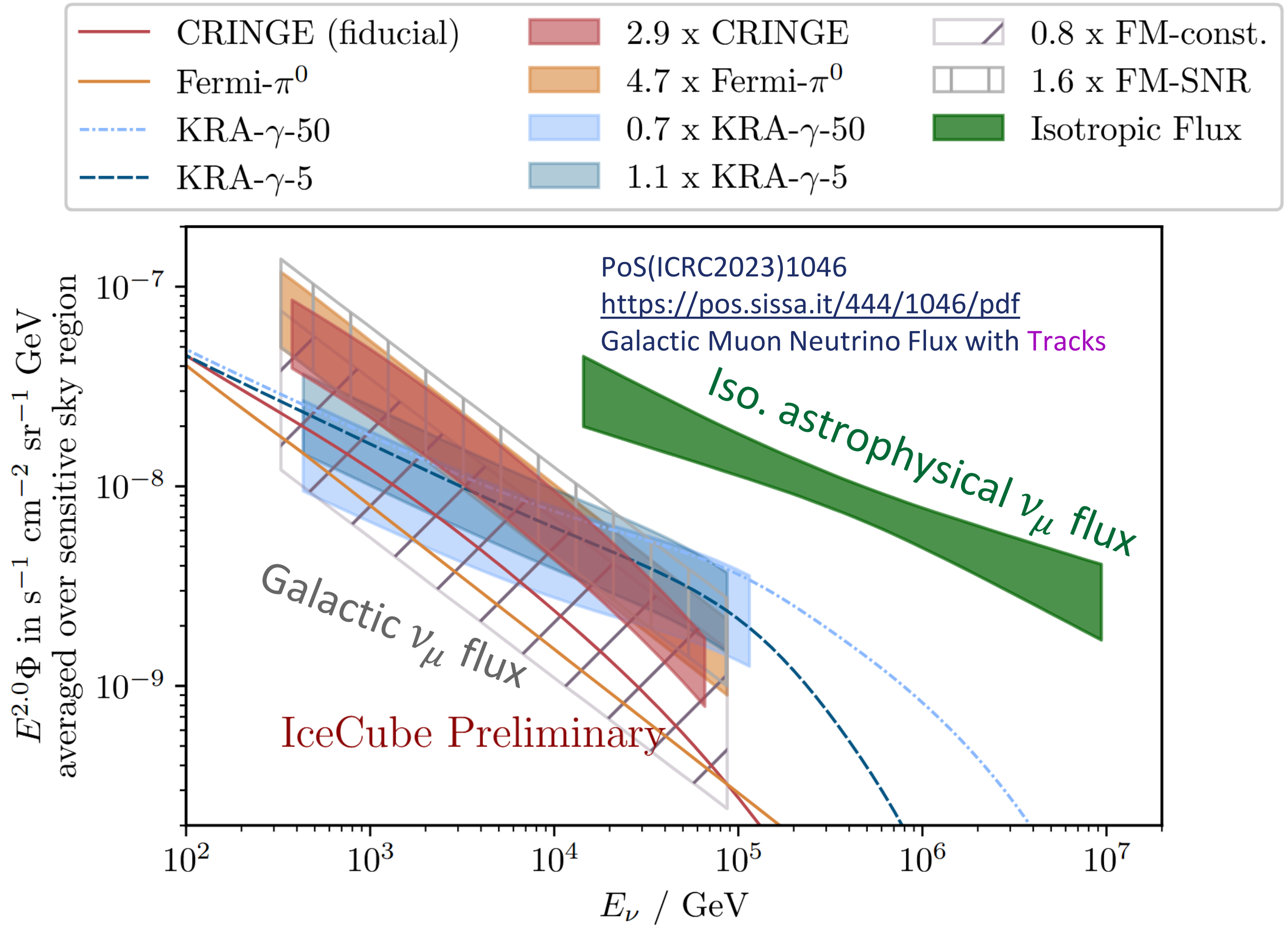


- Observation of Neutrinos from the Galactic Plane with a novel machine-learning reconstruction of Cascades - **Significance: 4.5σ**
- Galactic Muon Neutrino Flux with Tracks **Significance: 2.7σ**

- View of our Galaxy at highest energies & complementary to Fermi and LHAASO gamma rays
- Results using tracks are not yet significant, but are compatible with cascades
- Work ongoing for combining these independent data sets

What we (don't) know

http://dx.doi.org/10.3847/1538-4357/acc1e2 CRINGE as baseline model



Tested models differ in underlying model assumptions
-> different energy spectrum & spatial distribution

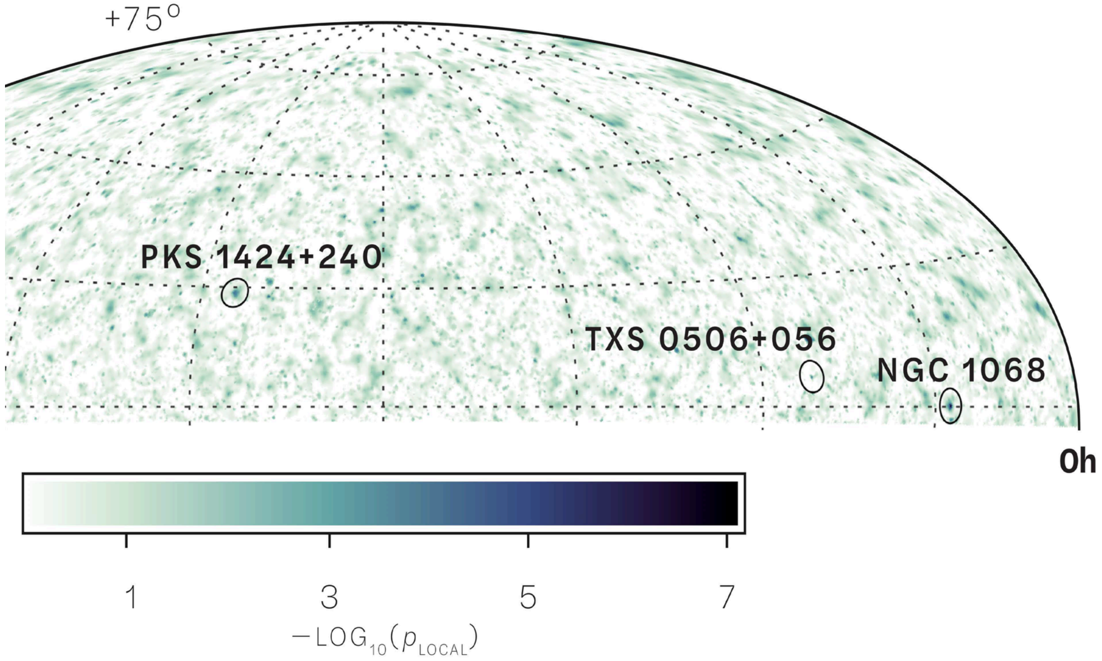
Galactic Muon Neutrino Flux with Tracks
Significance: 2.7σ

✓ About 6-13% of total astrophysical neutrino flux comes from GP (based on simultaneous fit of both components)

- ❑ Multiple diffuse neutrino emission models were tested, but no clear preference yet
- ❑ Normalization larger than expected could hint at sources in addition to diffuse emission, but still speculative

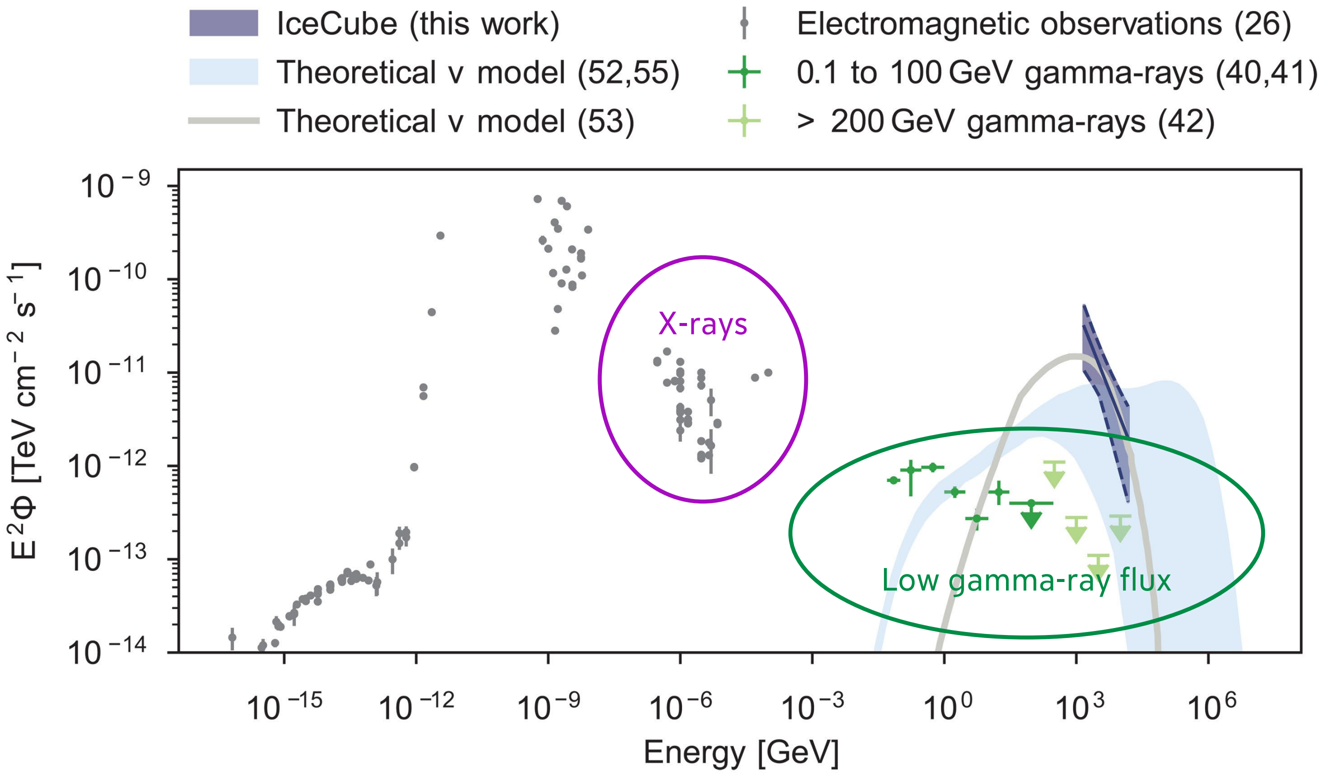
NGC 1068

- Evidence for neutrino emission from NGC 1068 with significance of 4.2σ using tracks
- Significance based on pre-defined list of 110 gamma-ray sources – local significance $> 5\sigma$



https://doi.org/10.1126/science.abg3395

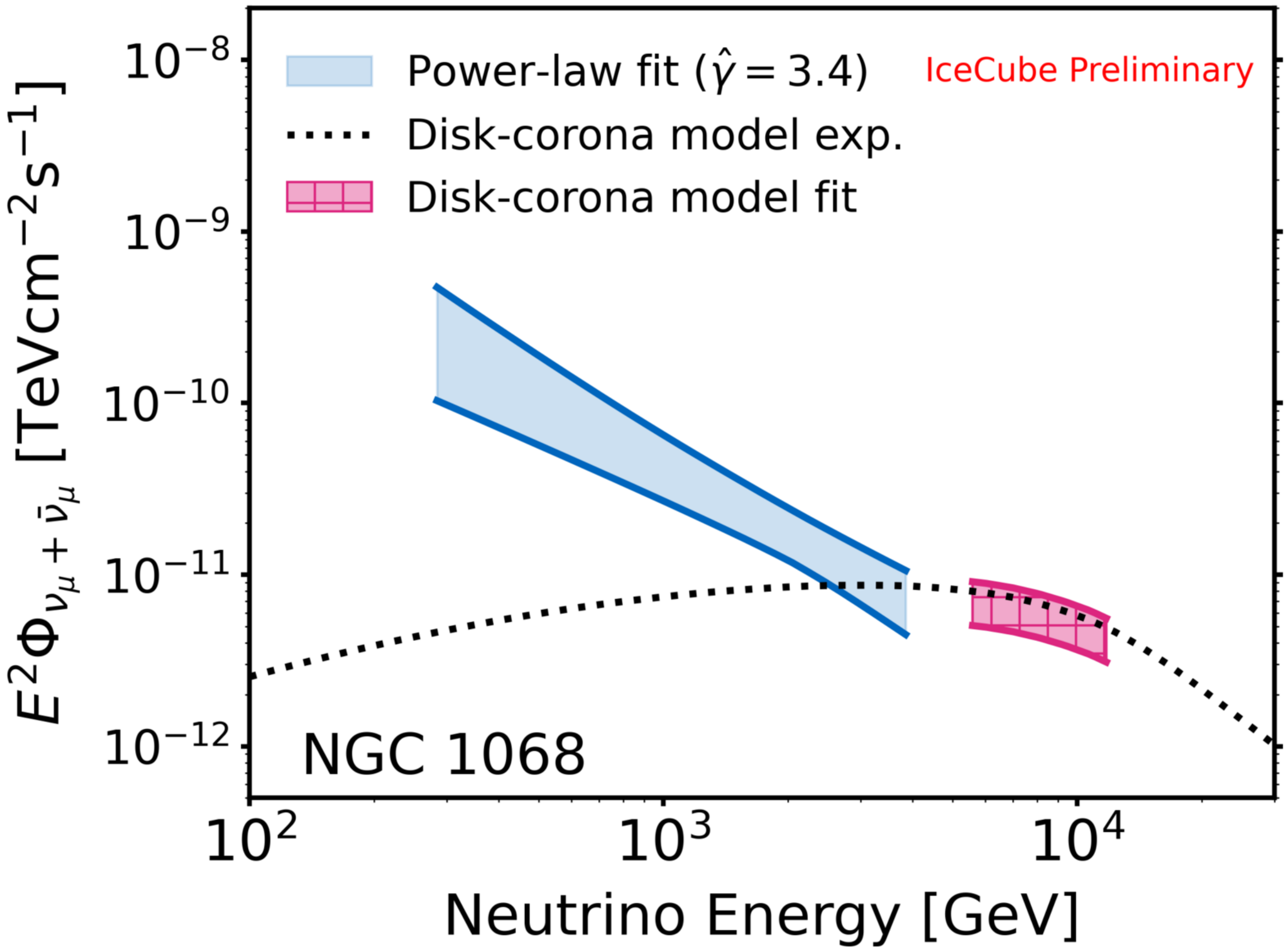
- Seyfert II galaxy at a distance of 14.4 Mpc (very close by!) with Compton-thick AGN
- X-Ray corona around accretion disk may enable neutrino production & gamma-ray absorption



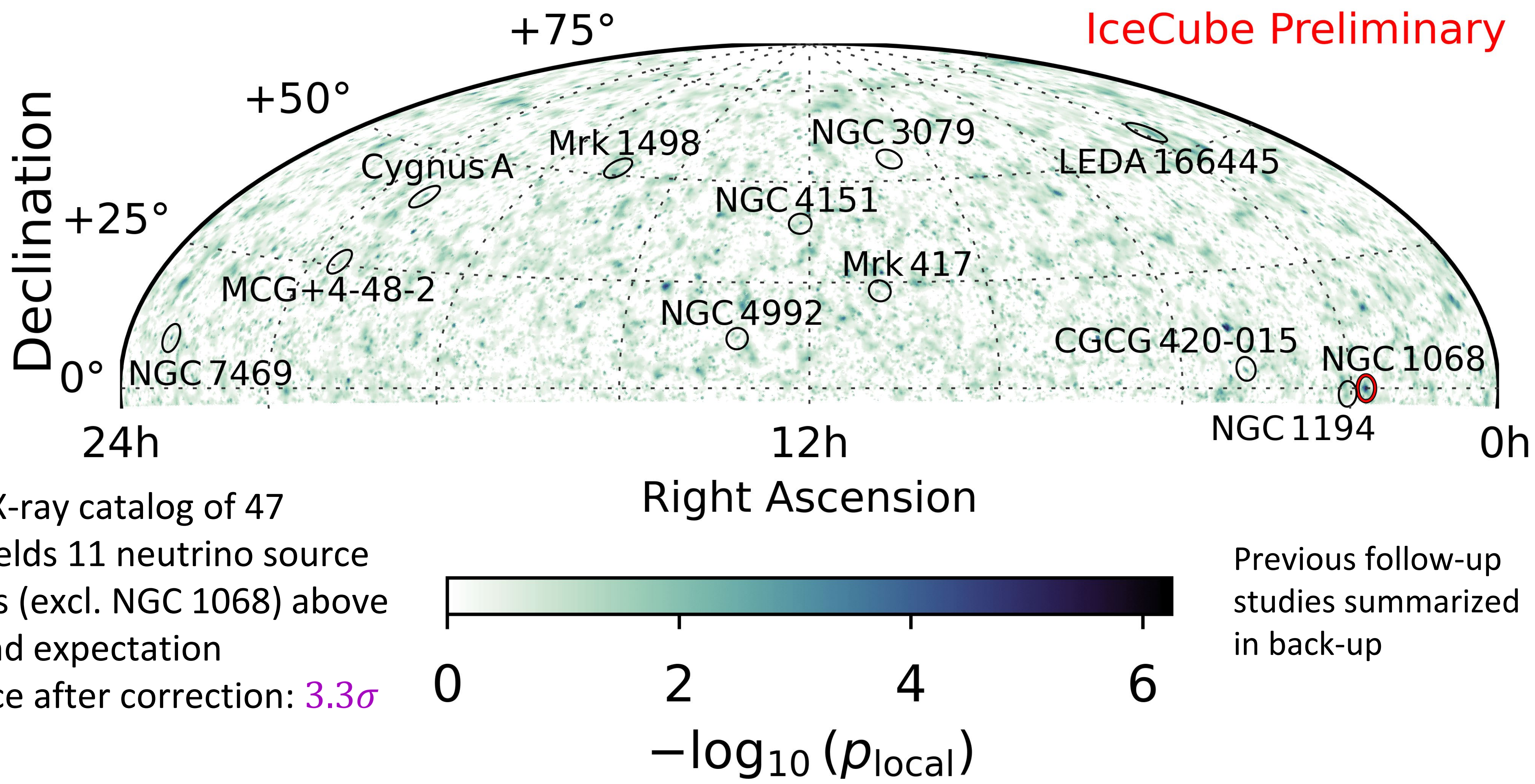
New results on NGC 1068

Disk-corona model based on
https://doi.org/10.3847/1538-4357/ac1c77

- Spectrum became softer - $E^{-\gamma}$ with $\gamma = 3.2 \rightarrow 3.4$
- Model prediction similarly significant, but fundamentally different spectral shape – further investigations needed!



Newest addition to x-ray/neutrino puzzle

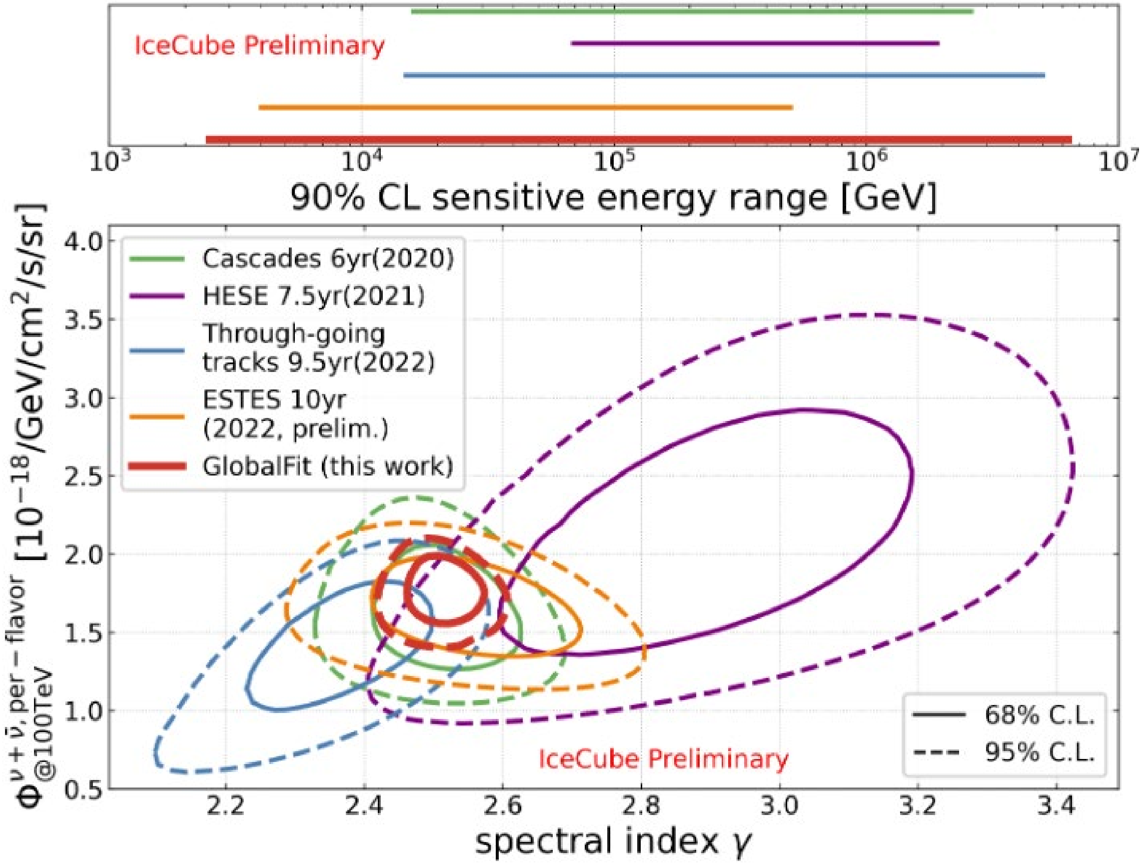


- Seyfert – X-ray catalog of 47 sources yields 11 neutrino source candidates (excl. NGC 1068) above background expectation
- Significance after correction: 3.3σ

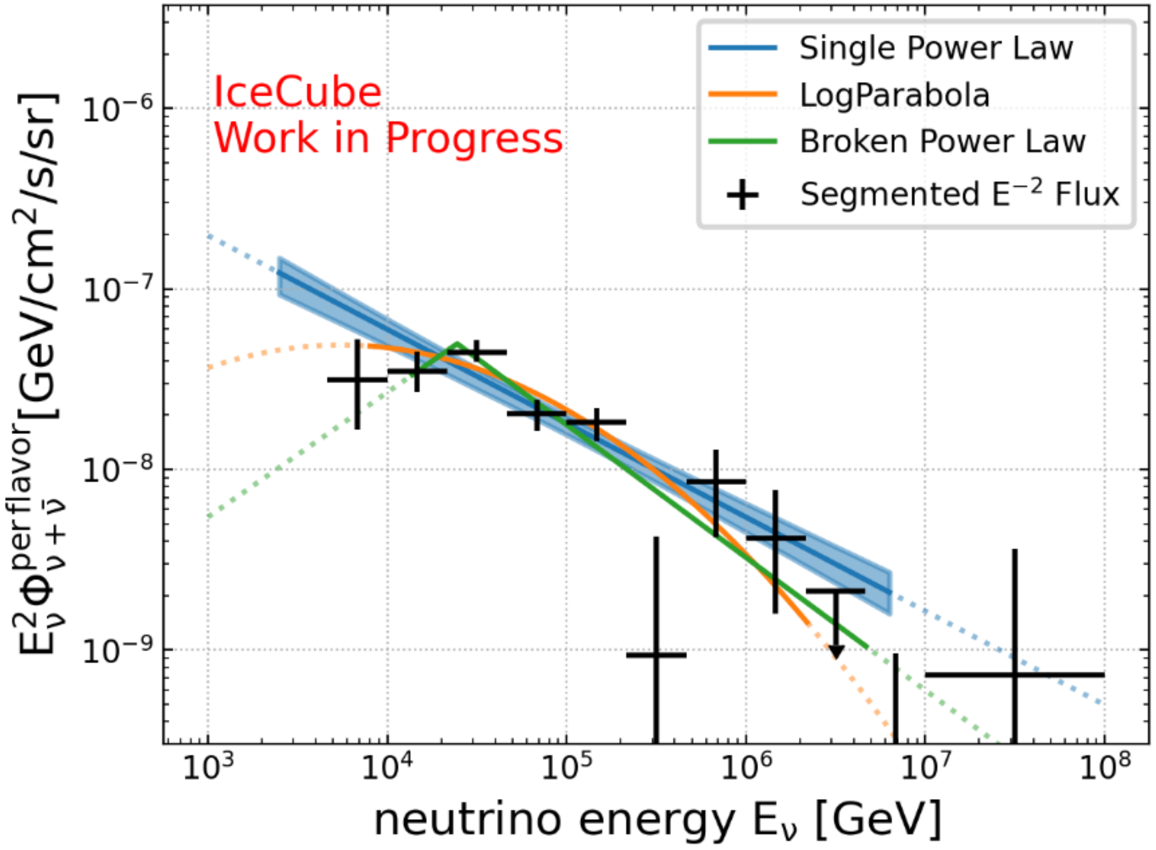
Previous follow-up studies summarized in back-up

First indication for flux beyond power law

Measurements of the diffuse astrophysical neutrino flux (all flavors)



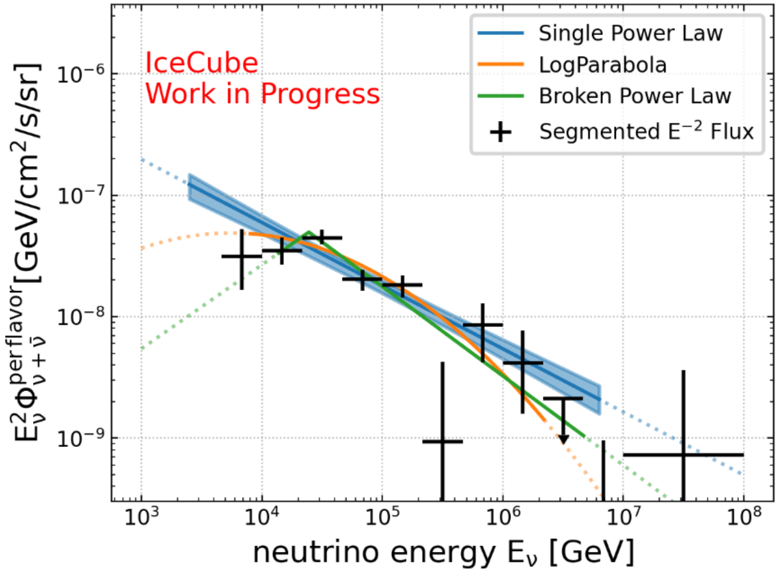
First hint of spectral features in the diffuse astrophysical neutrino flux



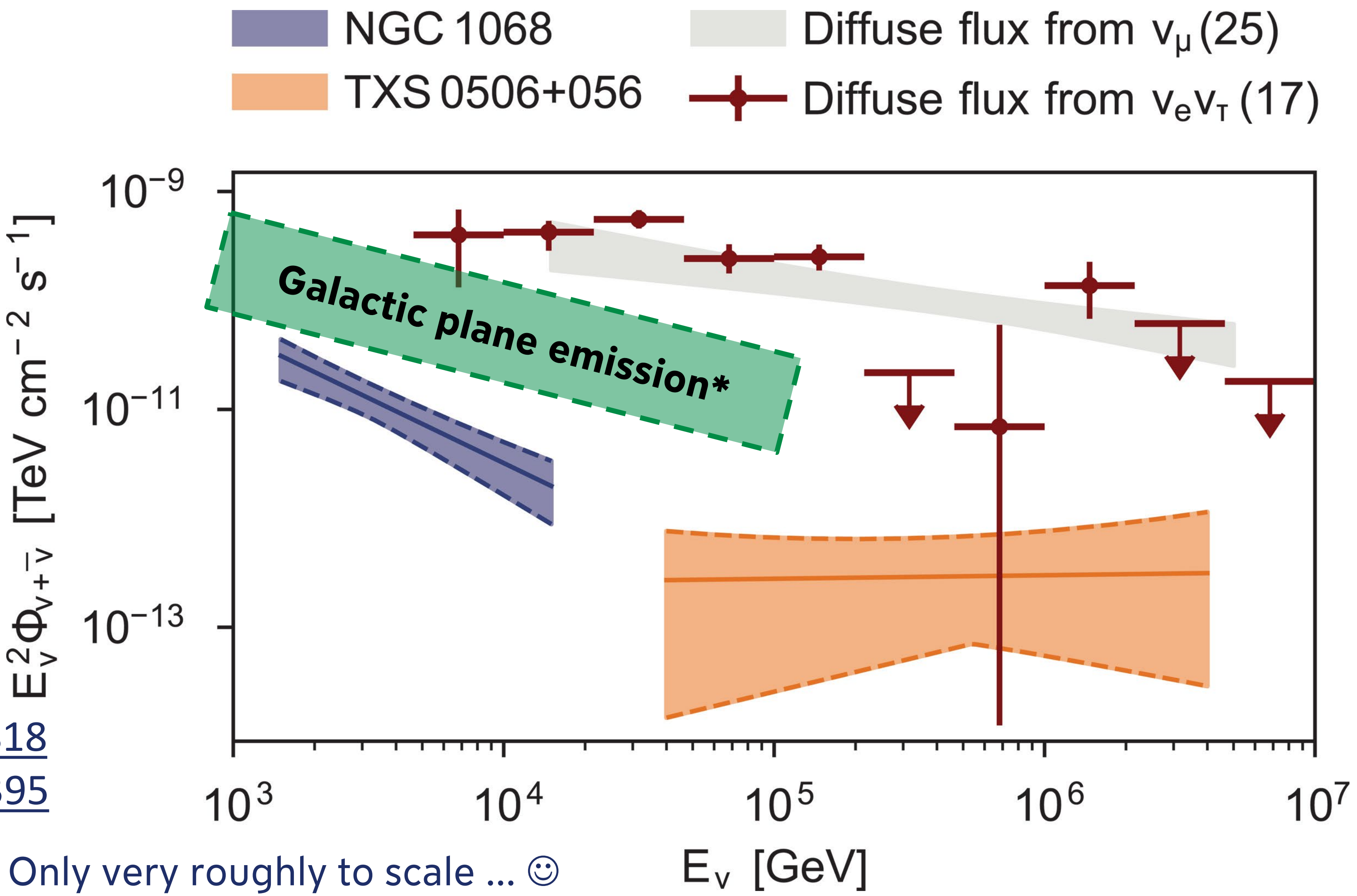
https://doi.org/10.22323/1.444.1064 (ICRC'23) - Full publication in progress

The road so far

First hint at spectral features in diffuse flux



https://doi.org/10.1126/science.adc9818
https://doi.org/10.1126/science.abg3395



* Only very roughly to scale … ☺

Open Questions

- Are TXS056+056 and NGC1068 just the brightest sources of an entire population of similar sources? Or are they special in another way?
- Are there other source populations?
- How does CR acceleration and neutrino production work in these sources?
- Is the Galactic-Plane emission truly diffuse or are there also smaller-scale sources?

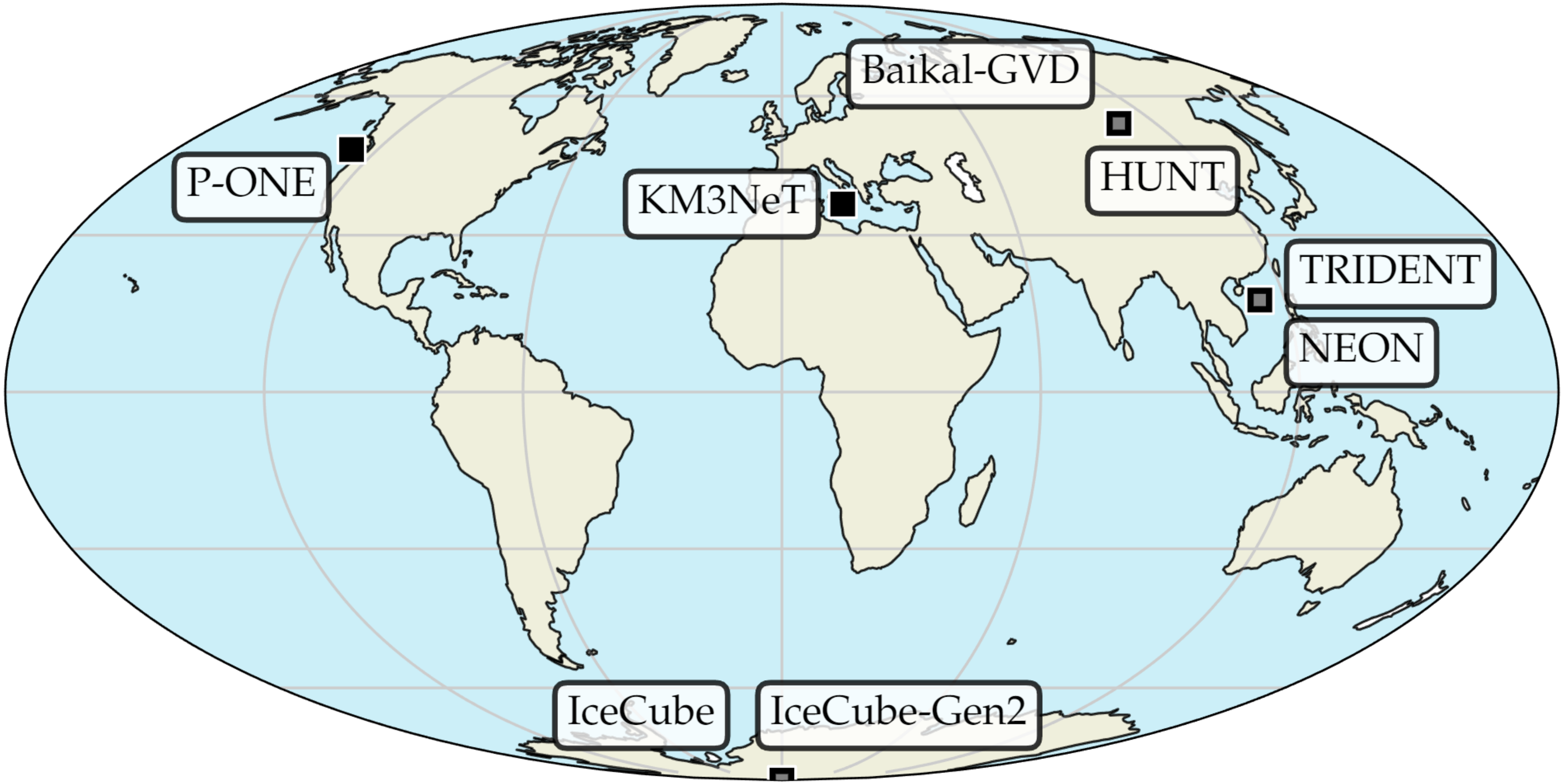
Open Questions

- Are TXS056+056 and NGC1068 just the brightest sources of an entire population of similar sources? Or are they special in another way?
- Are there
- How does hese sources?
- Is the Gal maller-scale sour

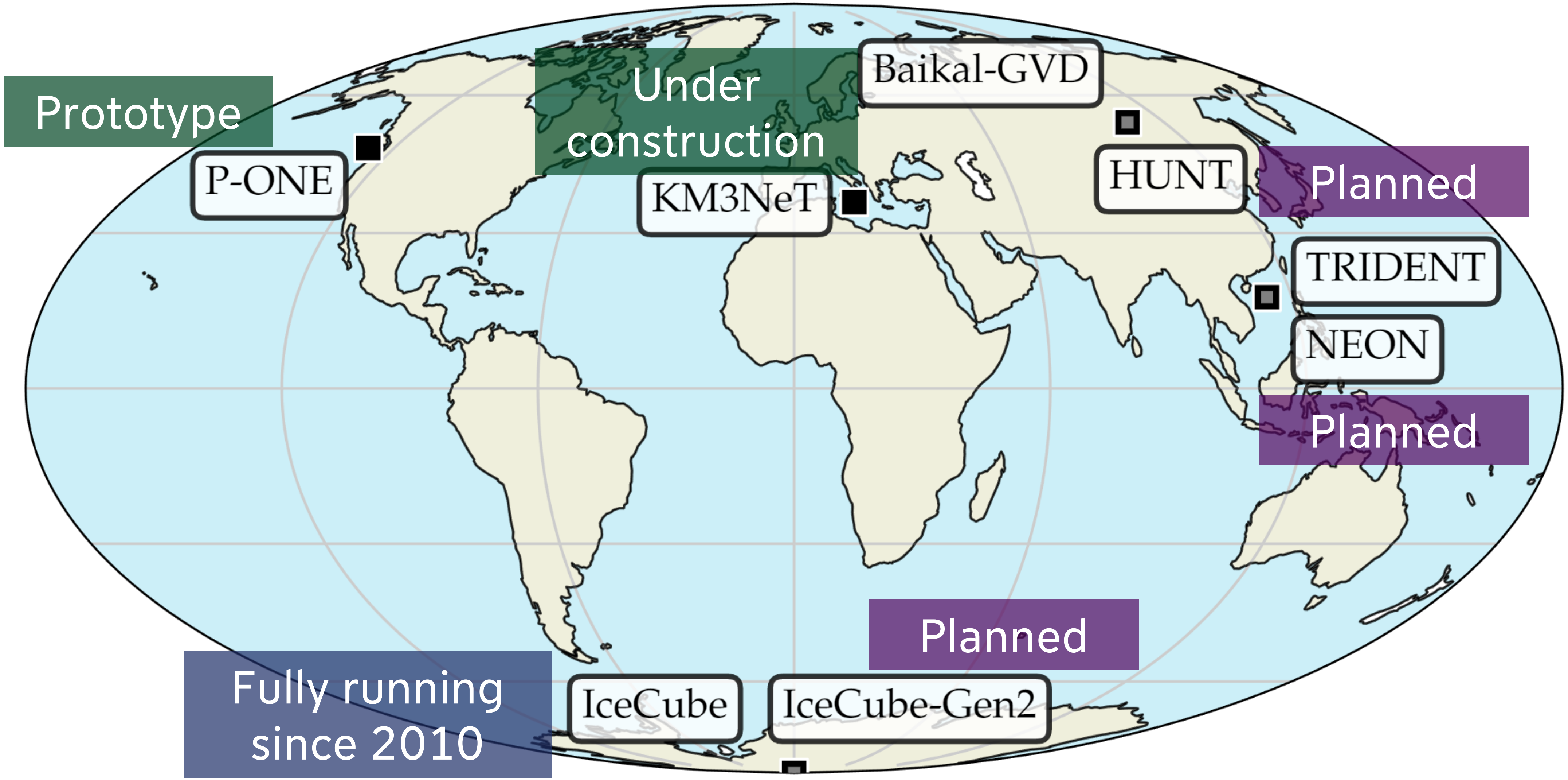
IceCube gathered data for more than a decade and progress based on livetime alone will slow down

We need more telescopes!

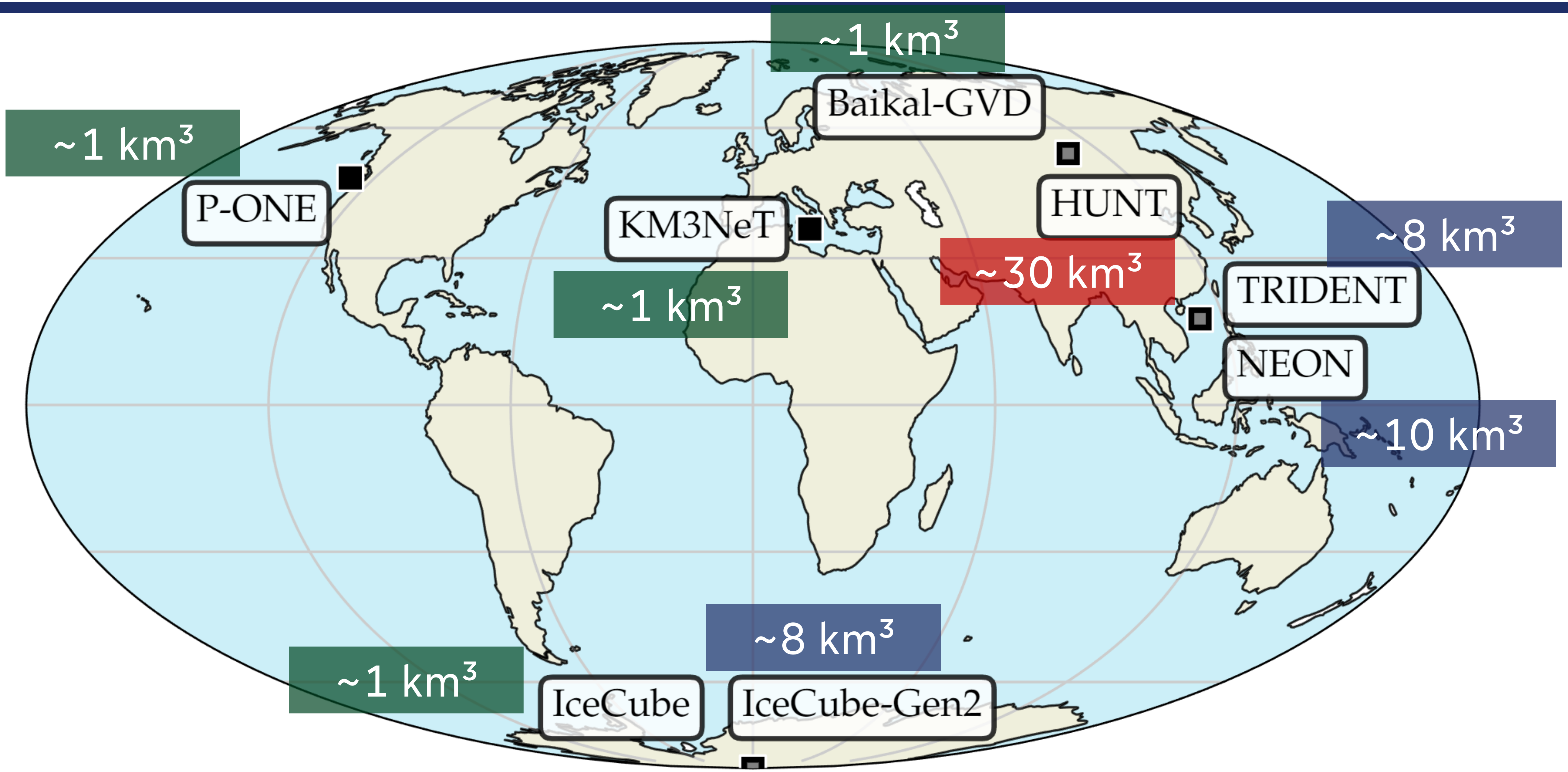
Current & future neutrino telescopes



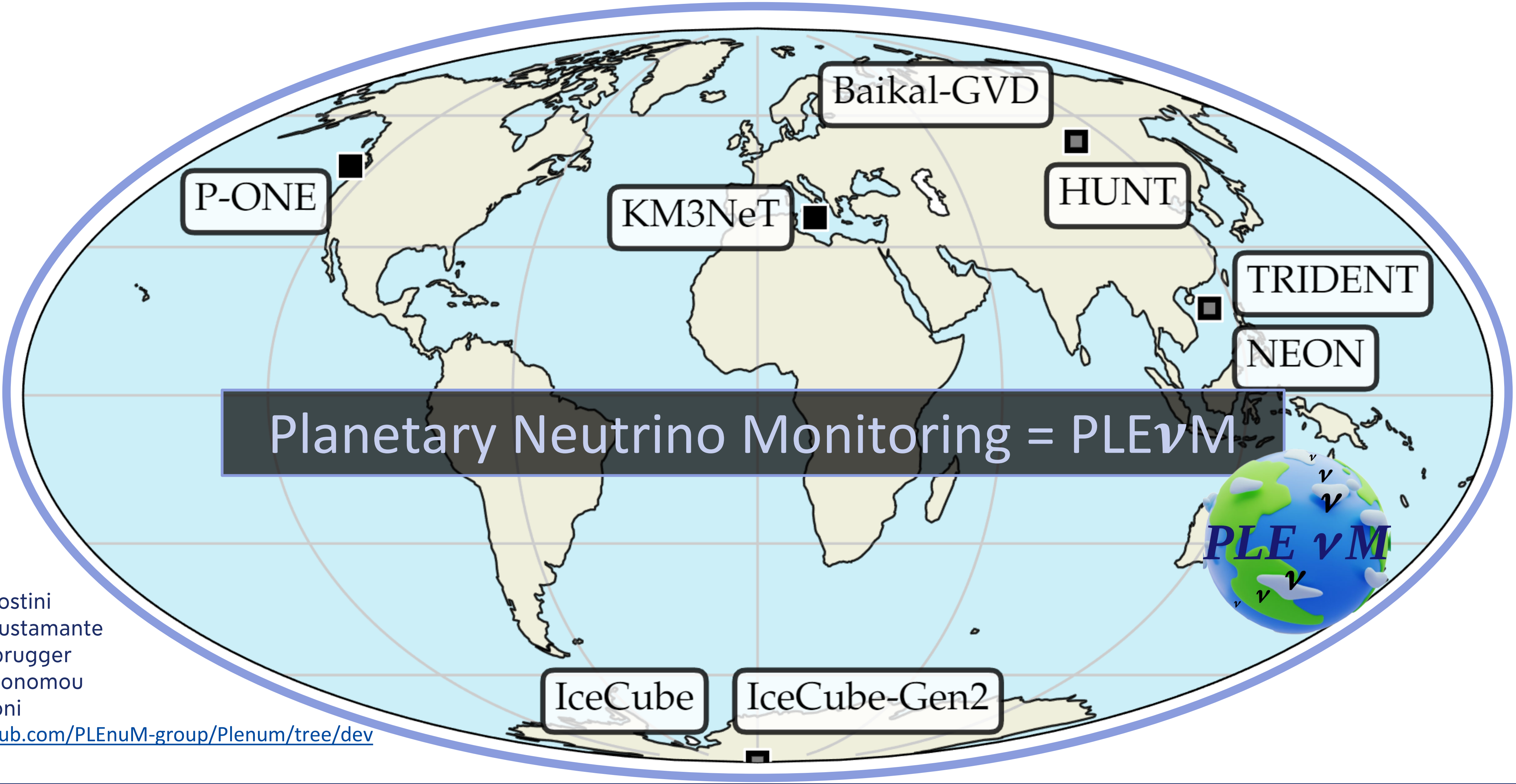
Current & future neutrino telescopes



Current & future neutrino telescopes

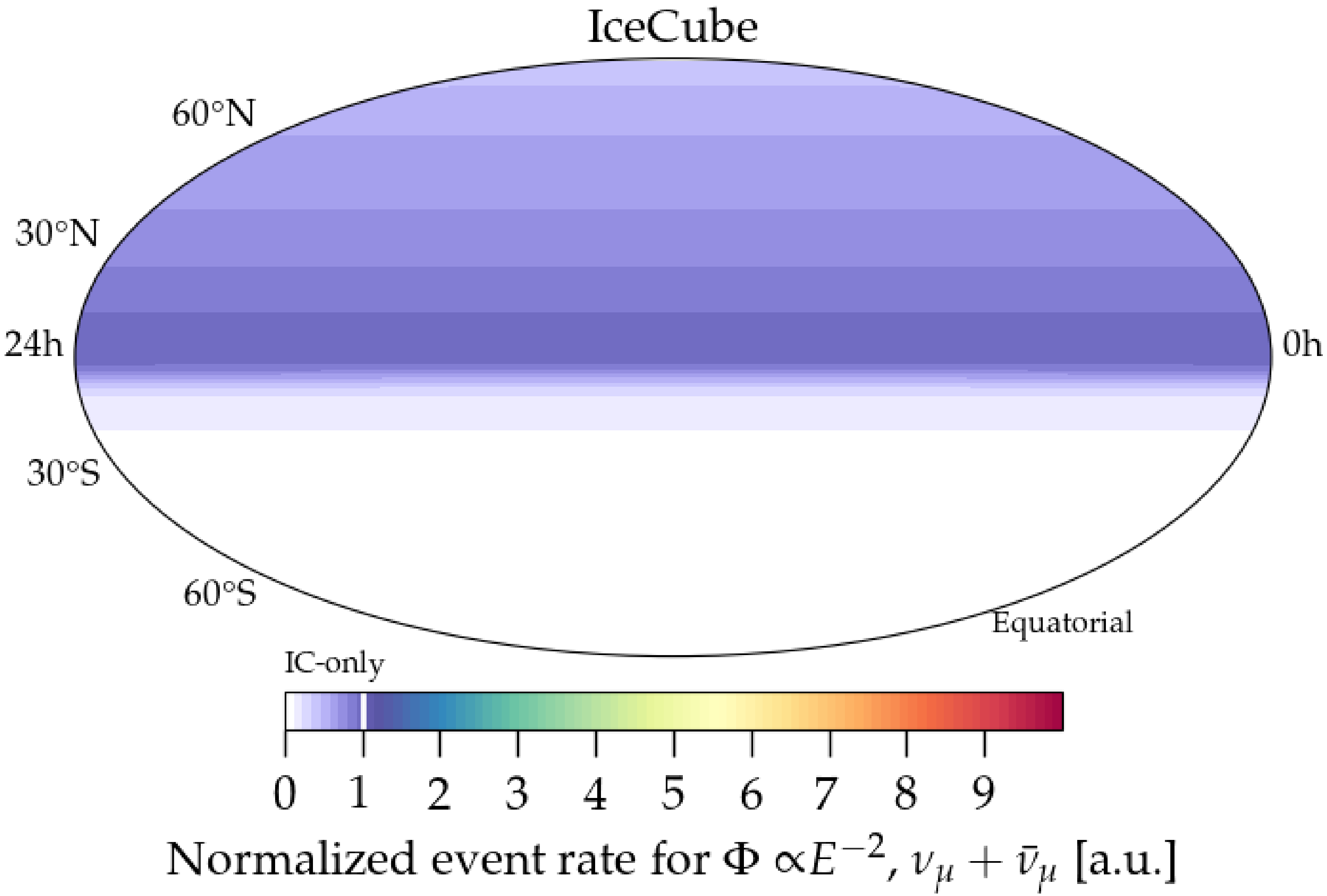


Current & future neutrino telescopes

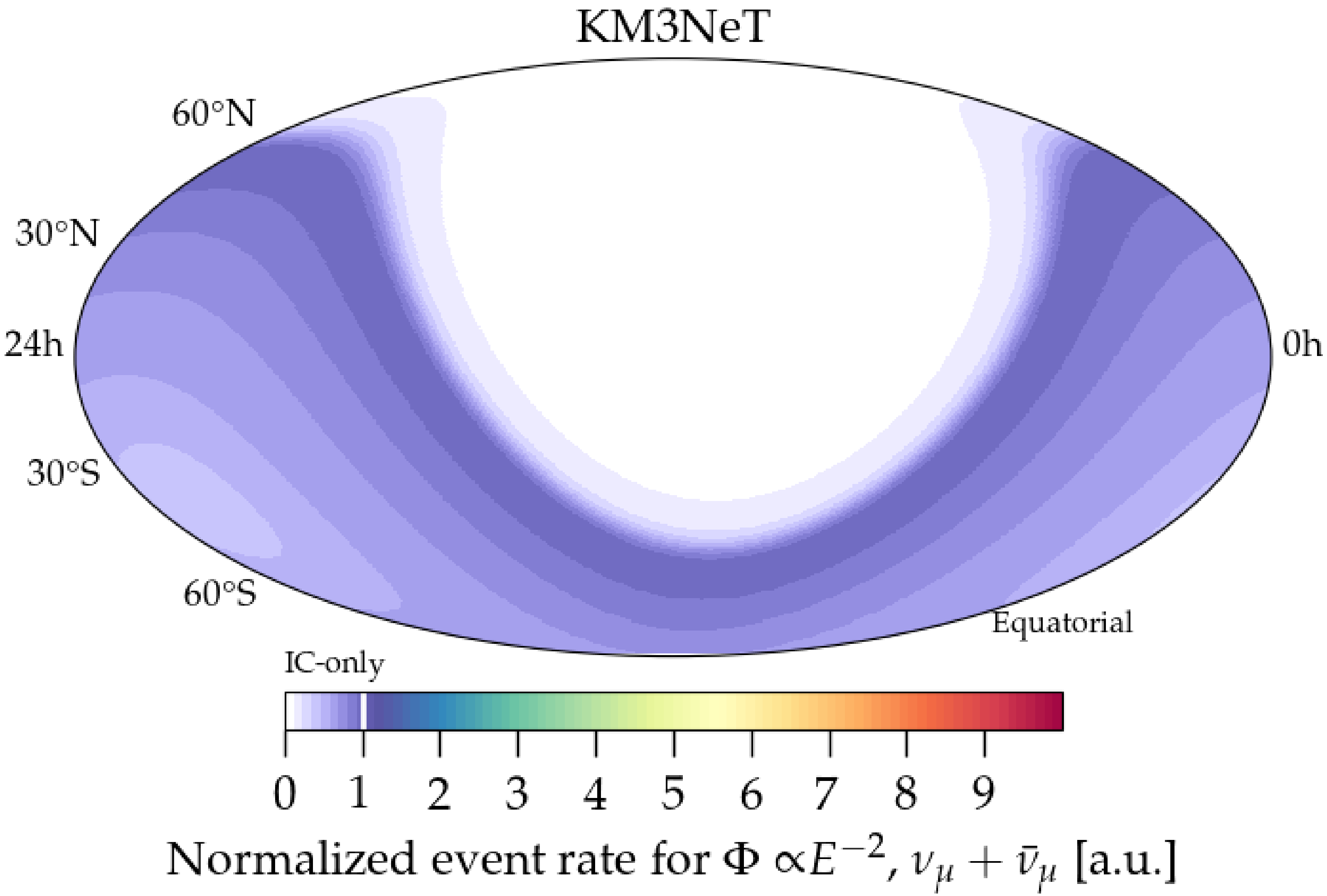


Matteo Agostini
Mauricio Bustamante
Anke Mosbrugger
Foteini Oikonomou
Elisa Resconi
https://github.com/PLEnuM-group/Plenum/tree/dev

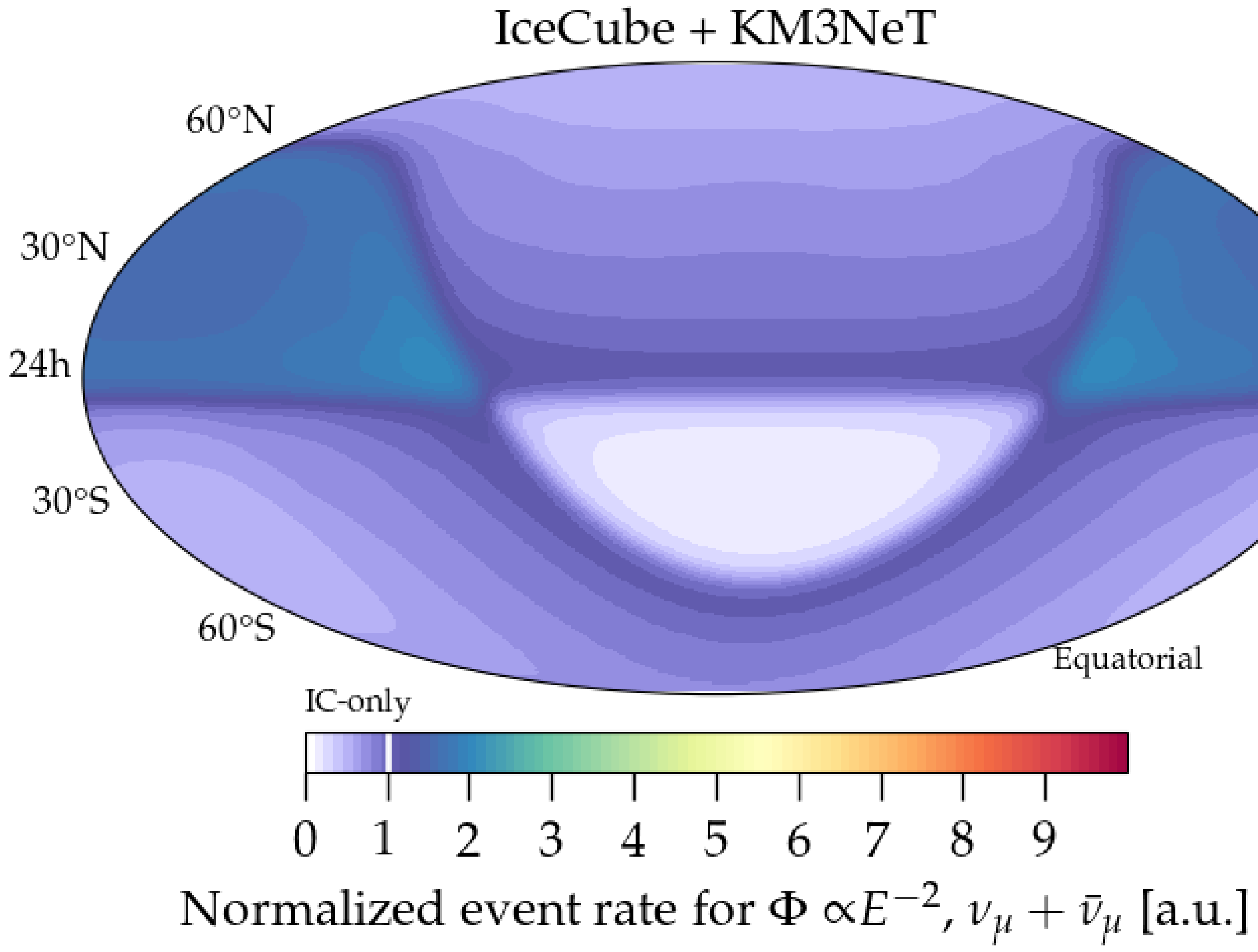
Instantaneous detection efficiency



Instantaneous detection efficiency

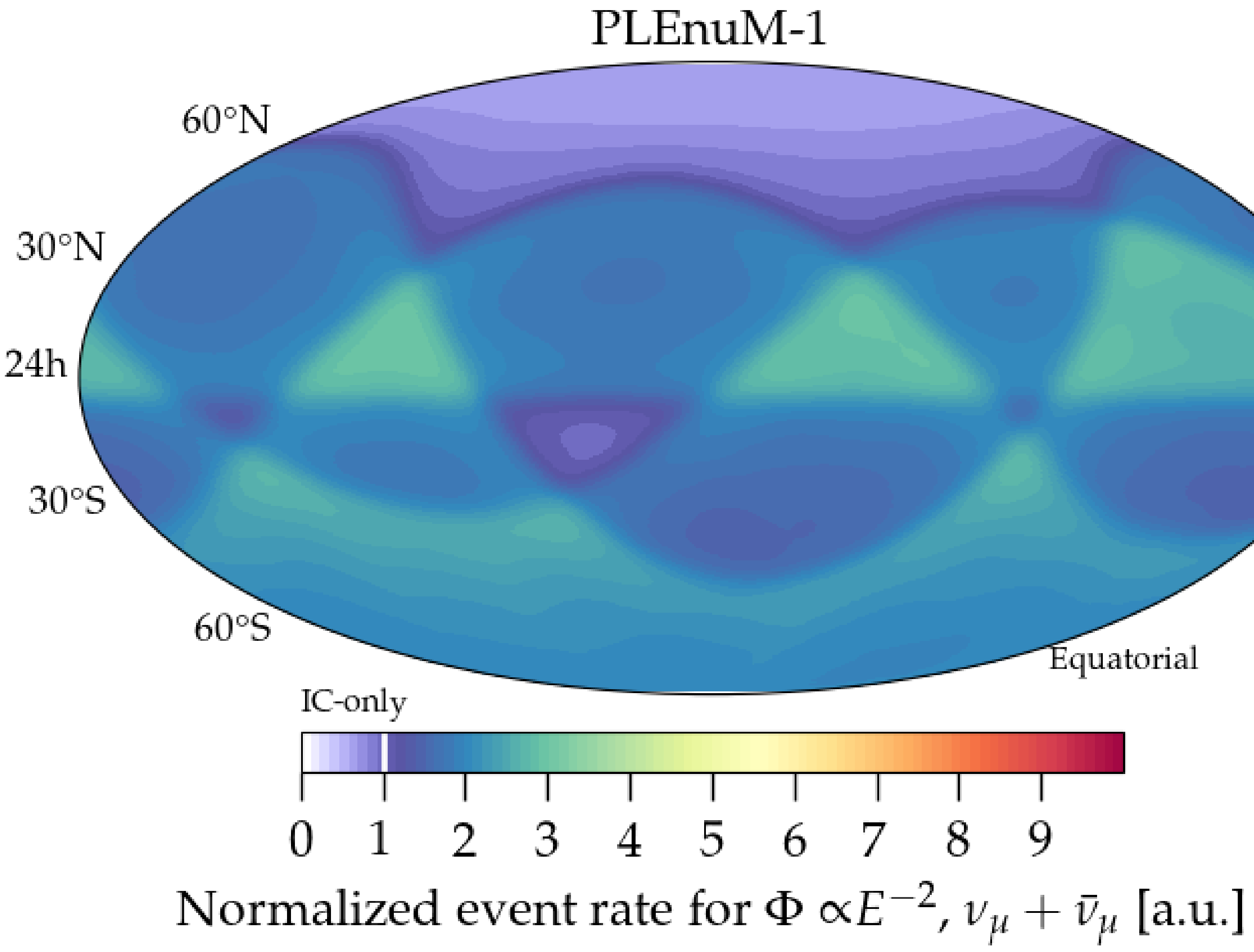


Instantaneous detection efficiency



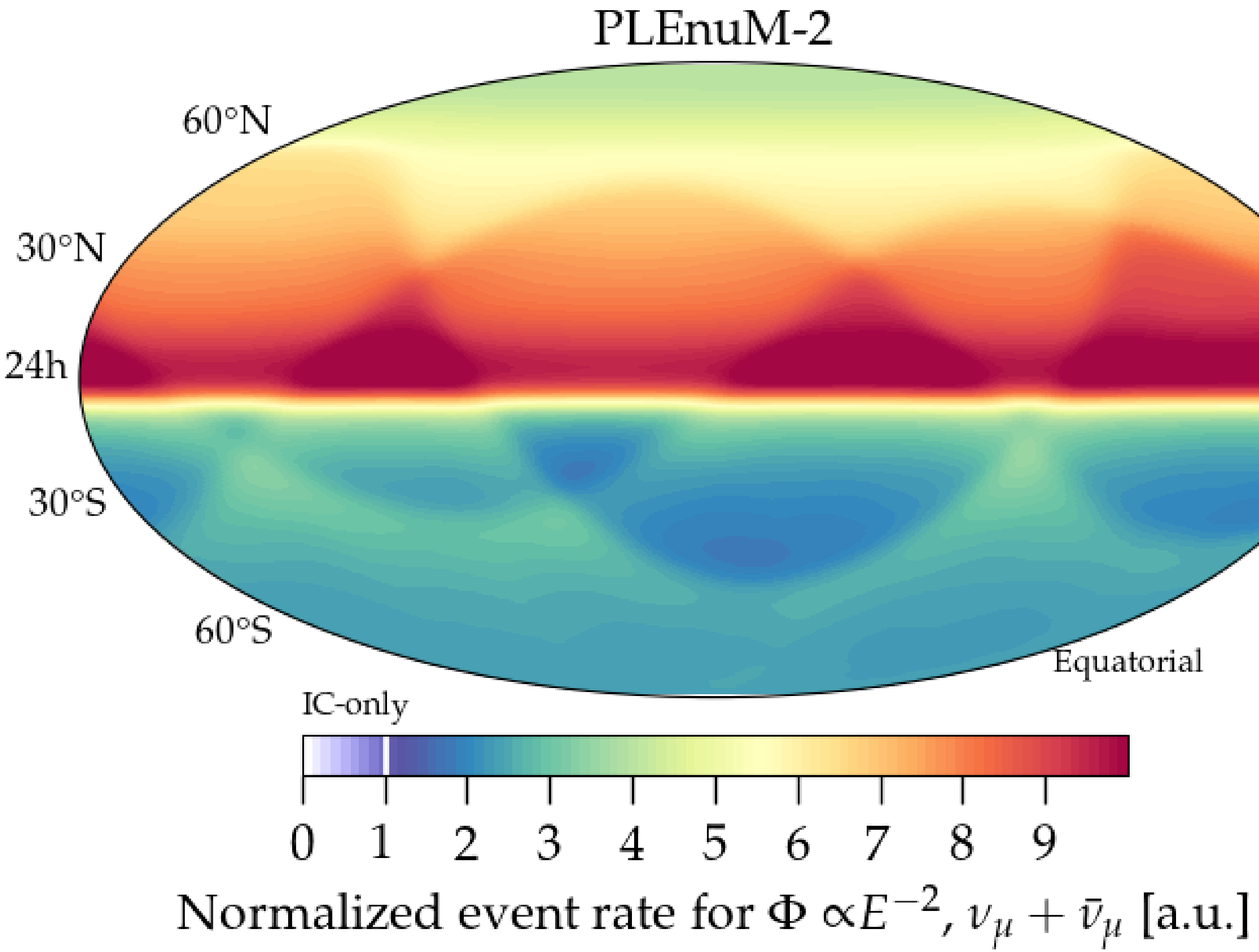
Instantaneous detection efficiency

IceCube
+ KM3NeT
+ P-ONE
+ Baikal-GVD



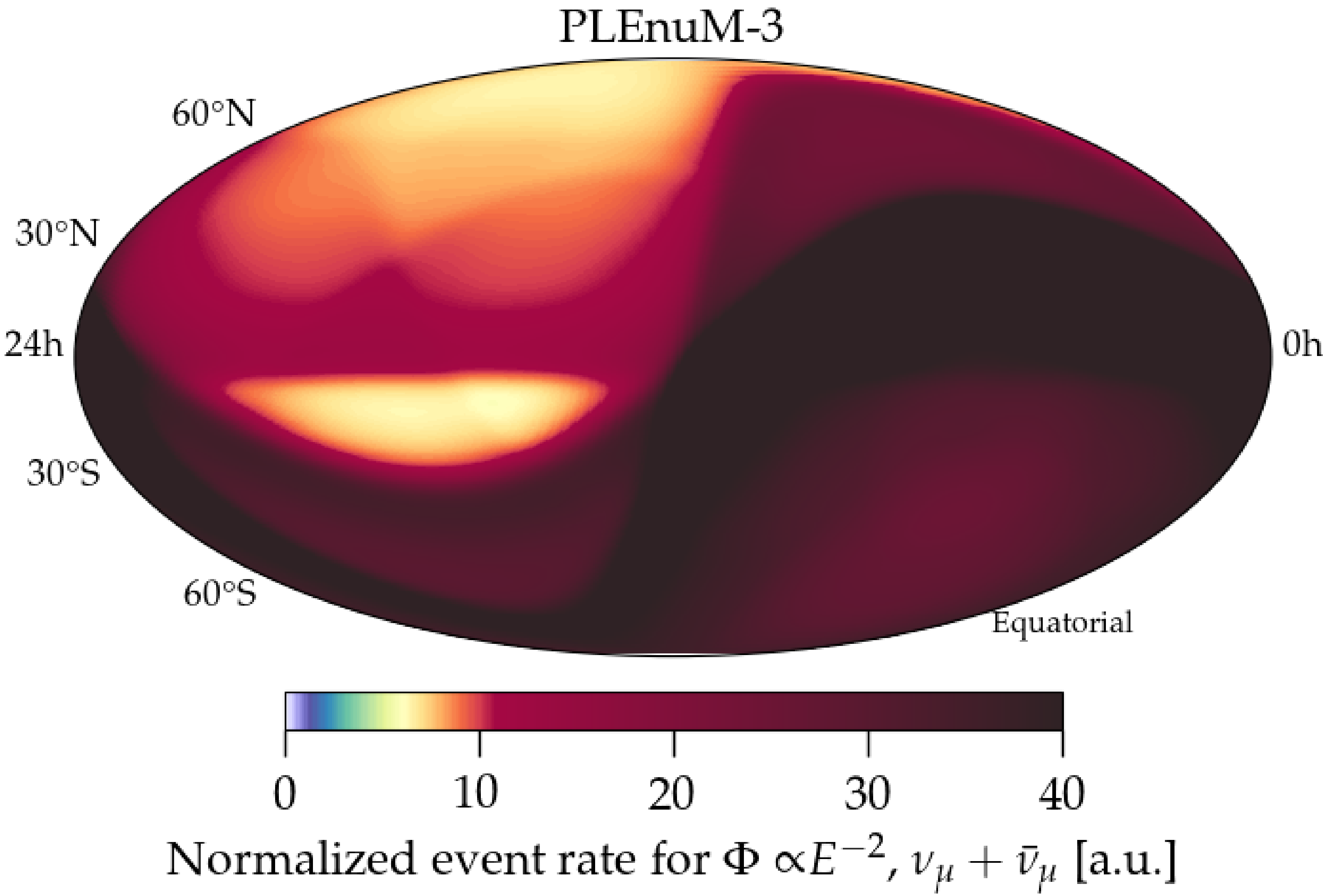
Instantaneous detection efficiency

IceCube
+ KM3NeT
+ P-ONE
+ Baikal-GVD
+ IceCube-Gen2 (IC x 7.5)



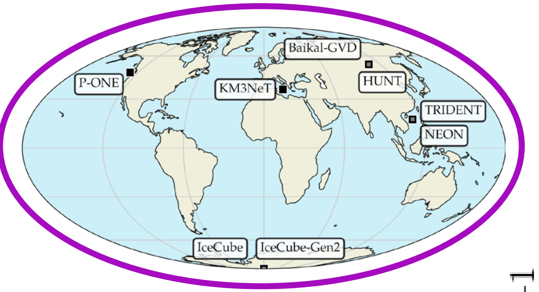
Instantaneous detection efficiency

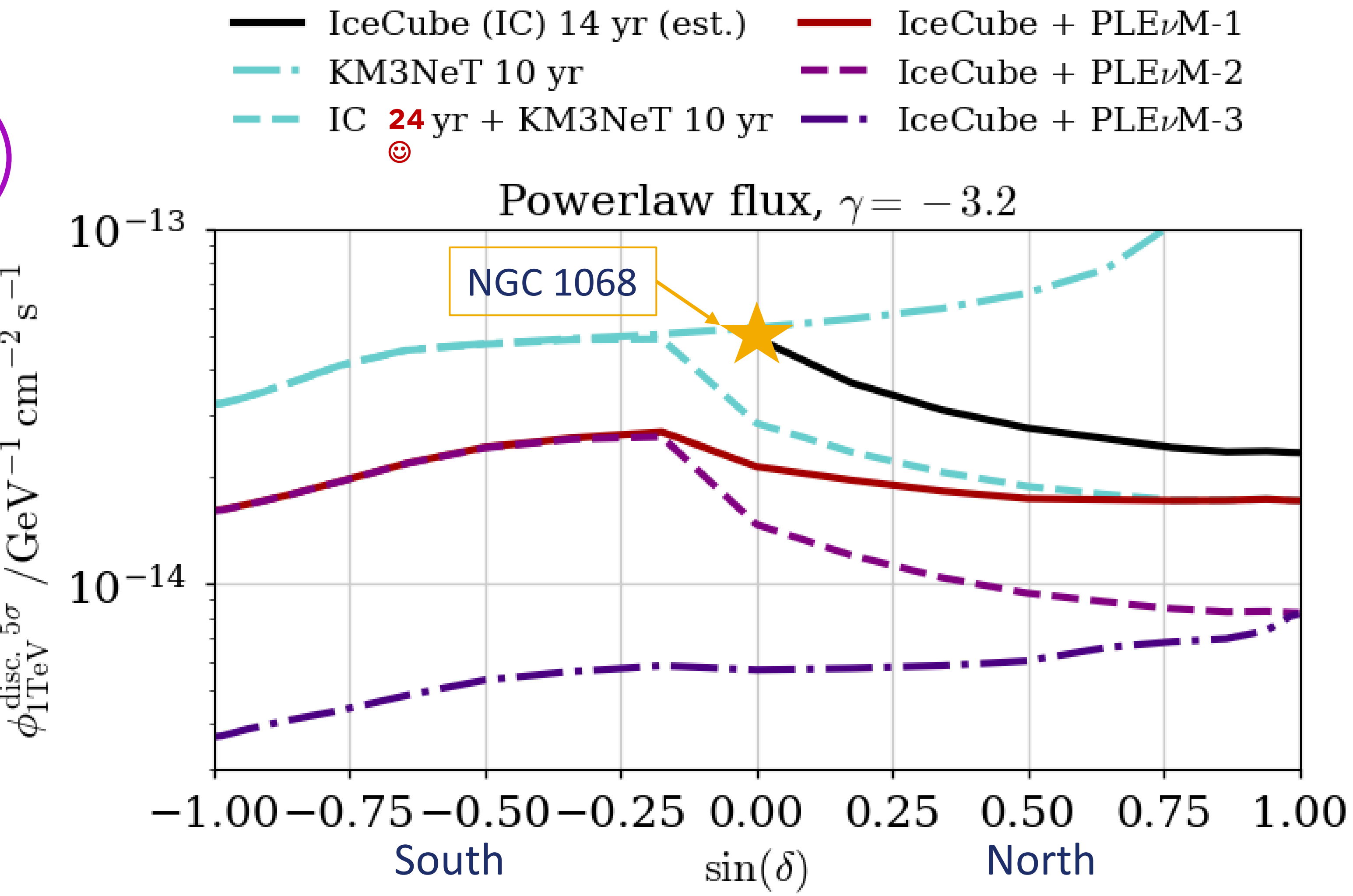
IceCube
+ KM3NeT
+ P-ONE
+ Baikal-GVD
+ IceCube-Gen2
+ TRIDENT (IC x 7.5)
+ NEON (IC x 10)
+ HUNT (IC x 30)



Discovery potential for point sources

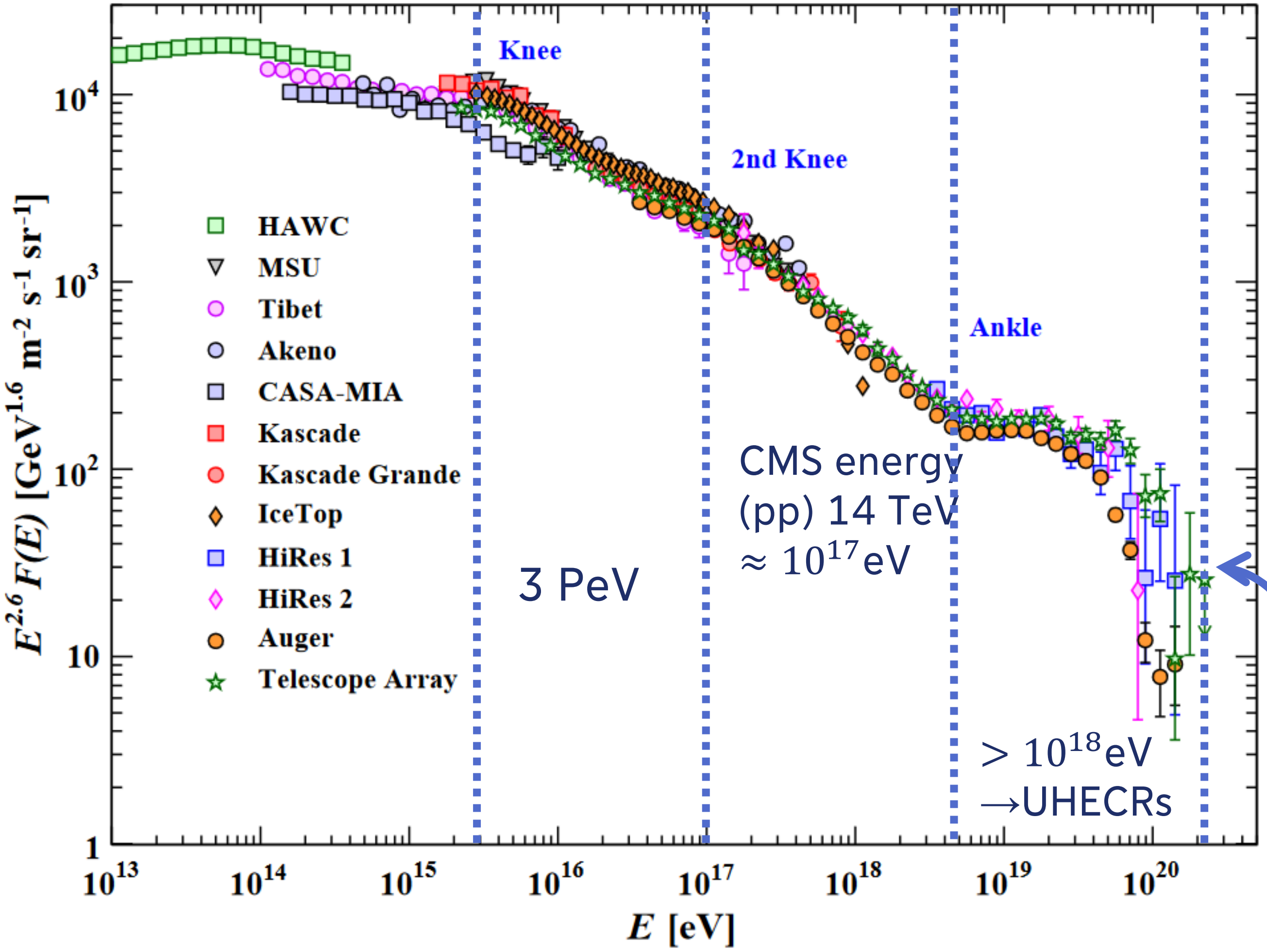
… as function of declination for NGC 1068-like sources

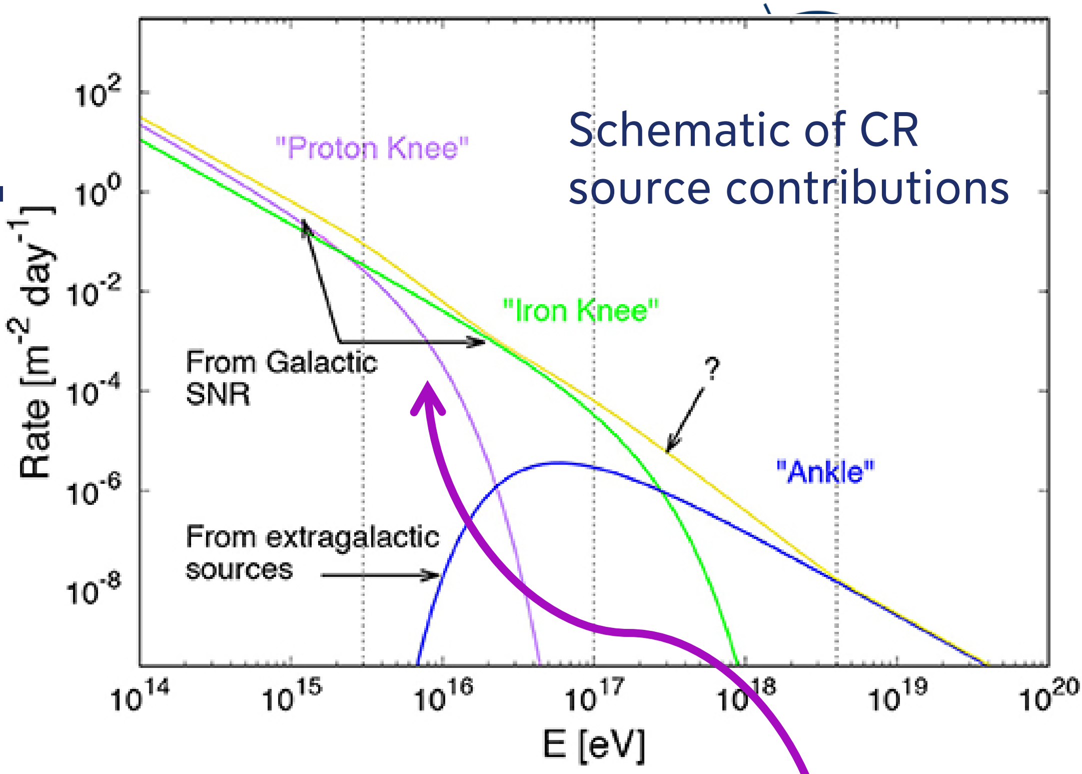




Back up

Cosmic rays: Galactic and extragalactic



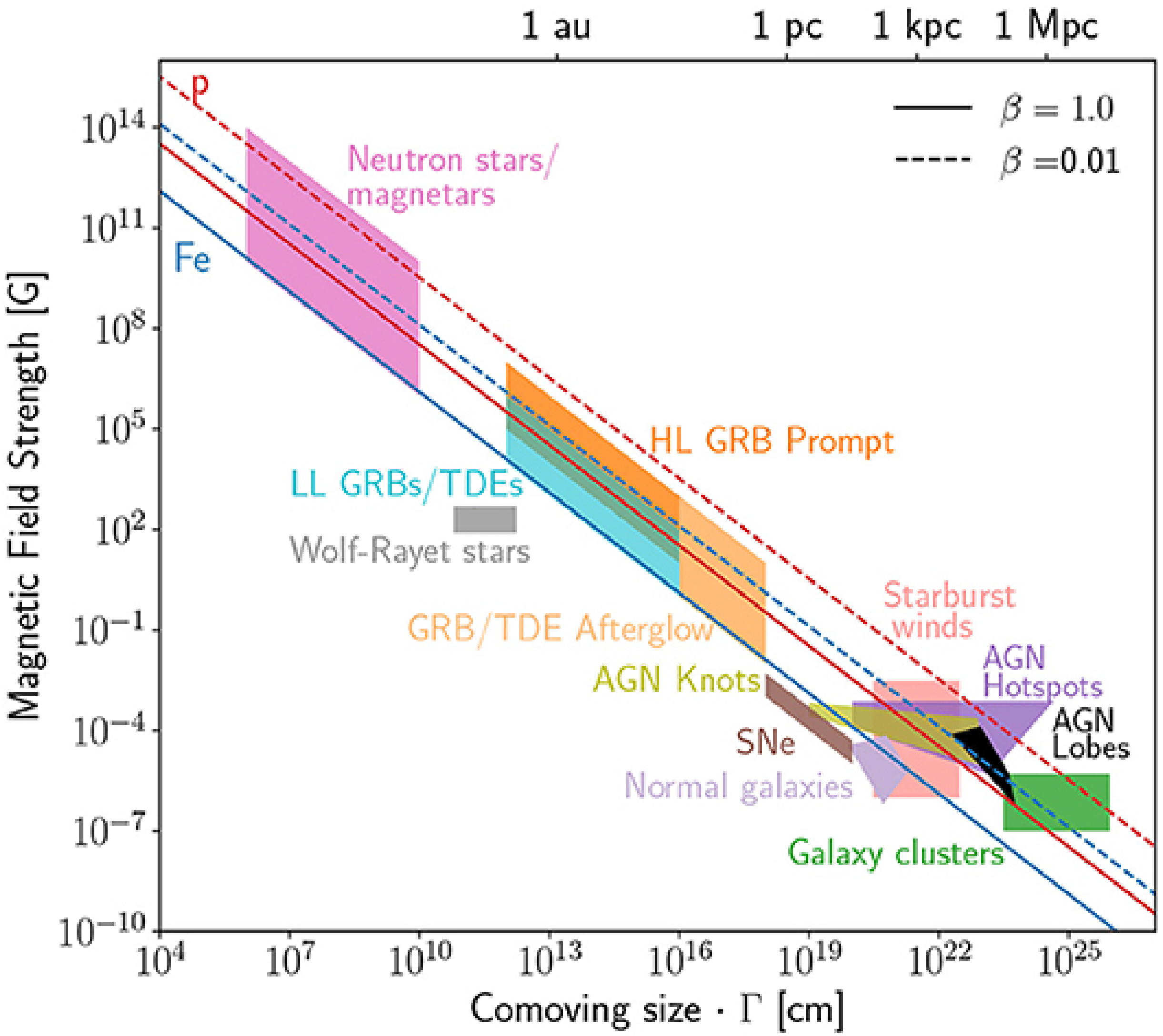


Oh-my-god particle, presumably first UHECR detected above 10^{20} eV "… equivalent to a 142-gram baseball travelling at about 26 m/s…"*

"Guaranteed galactic neutrino flux" – measured by now!

*https://en.wikipedia.org/wiki/Oh-My-God_particle
arXiv:astro-ph/9410067

Required source characteristics: Maximum energy



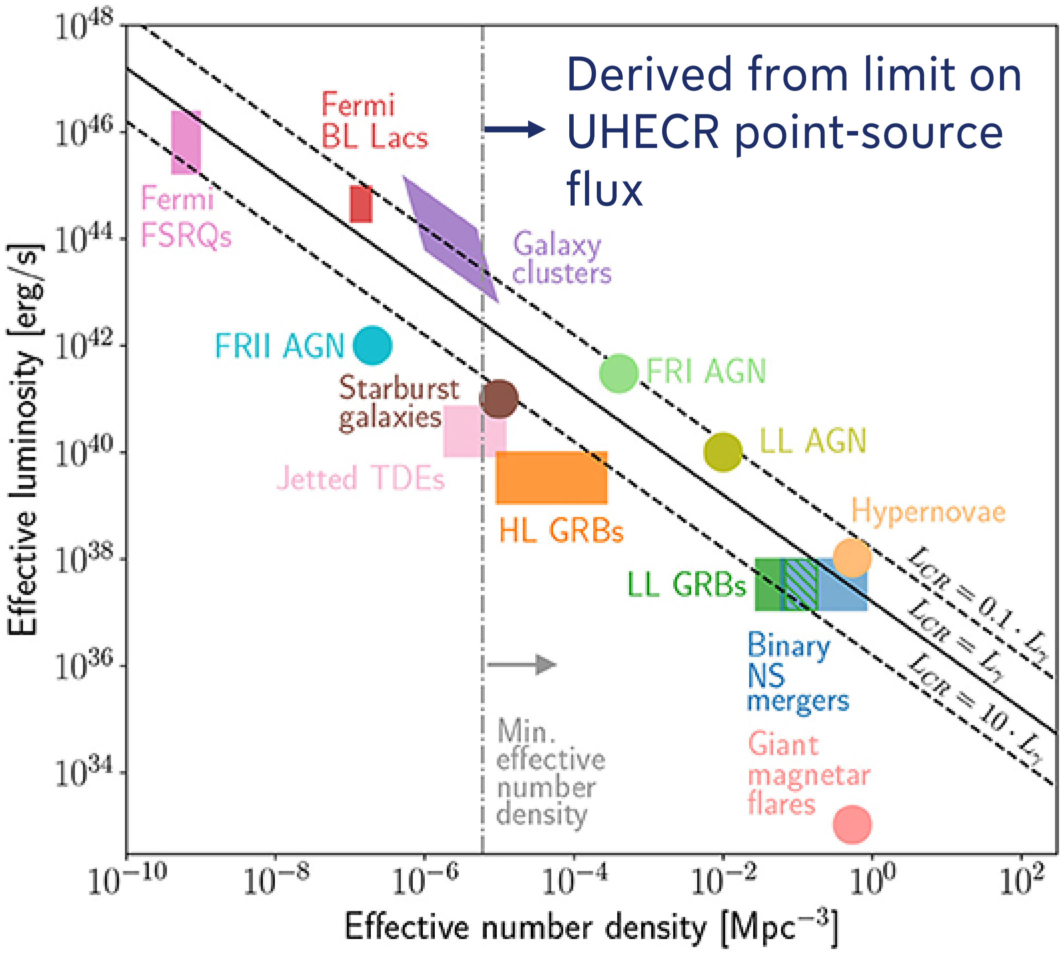
- Hillas diagram connects the maximum possible CR energy (here 10^{20} eV = UHECR) to source size and magnetic field strength
- Requirement: Gyroradius needs to be equal to source size (Γ) to enable acceleration up to corresponding energy

$$B \propto \frac{E\beta}{q} \cdot \frac{1}{\Gamma}$$

- Depends on CR-charge, B-field strength and outflow speed

https://doi.org/10.3389/fspas.2019.00023

Required source characteristics: Energy budget

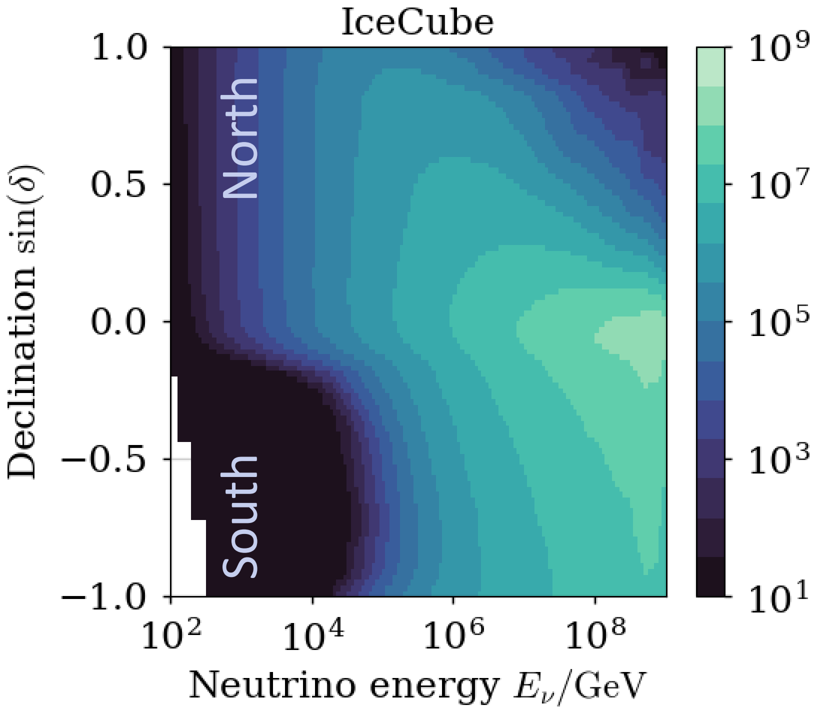


- Energy budget inferred from UHECR spectrum constrains source luminosity and number density
- Scenario of few, strong sources disfavored
- Multi-messenger analyses needed to constrain source models and individual sources
- Does one source class dominate the UHECR production or do many classes contribute?
  Which processes accelerate particles to highest energies of PeV to over 100 EeV?
  Can this be explained with today's knowledge of physics?
  Can these processes (in small scales) be applied to future accelerator experiments?

https://doi.org/10.3389/fspas.2019.00023

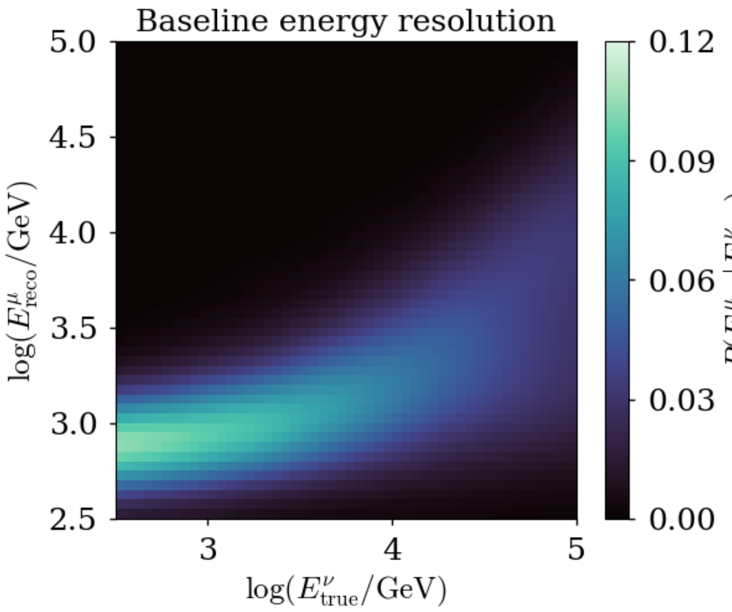
What input is needed for PLEnuM?

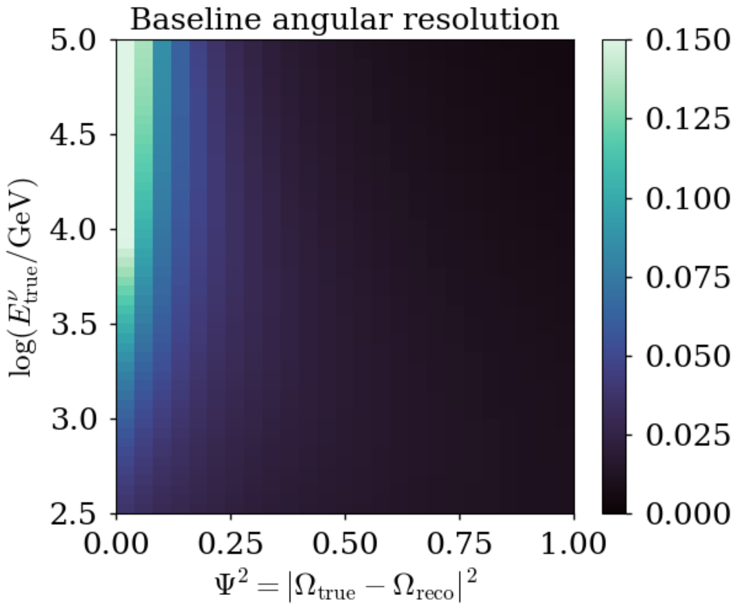
$$A_{\mathrm{eff}}(E,\vec{\Omega}) = T_{\mathrm{Earth}}(E_\nu,\vec{\Omega}) \otimes P_{\nu\to\mu}(E_\nu, E_\mu, R) \otimes \epsilon_{\mathrm{select}}(E_\mu,\vec{\Omega}) \otimes A_{\mathrm{geo}}(\vec{\Omega})$$



$$N_\nu(\sin(\delta_{\mathrm{src}})) = T_{\mathrm{live}} \cdot \int_{E_{\min}}^{E_{\max}} \mathrm{d}E\, A_{\mathrm{eff}}\left(E, \sin(\delta_{\mathrm{src}})\right) \cdot \frac{\mathrm{d}\Phi_{\mathrm{src}}}{\mathrm{d}E}$$

- **Effective area:** rotated from local zenith to declination for other detectors based on IceCube's effective area
- **Energy resolution**
- **Angular resolution**



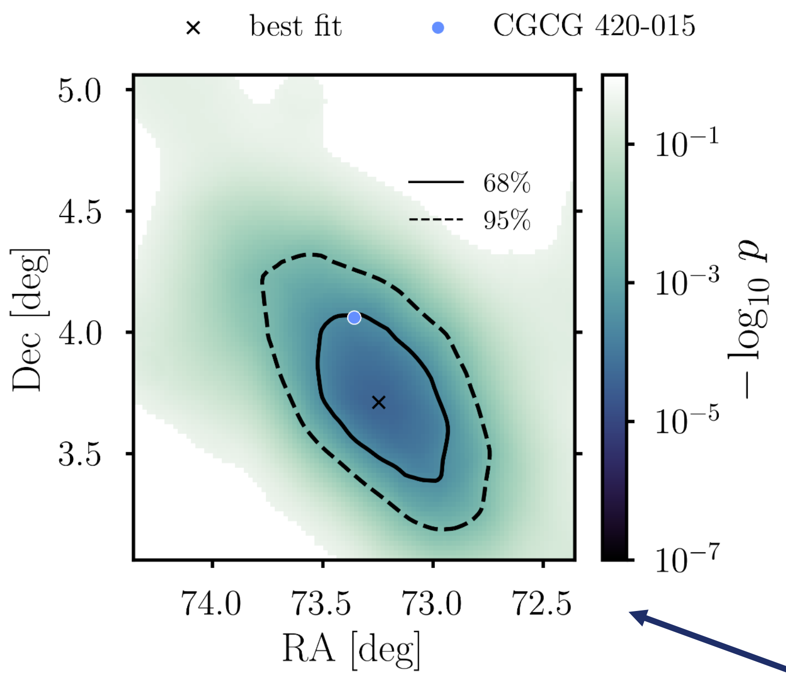


Important: currently everything is based on IceCube's data release of 10yr muon tracks http://doi.org/DOI:10.21234/sxvs-mt83

Seyfert Galaxies & X-ray bright AGN

- Excess of neutrinos associated with two sources, NGC 4151 and CGCG 420-015 @ 2.7σ significance
- Results constrain the collective neutrino emission from chosen source catalogue

- Search for high-energy neutrino emission from hard X-ray AGN
- Confirmed emission of NGC 1068 and found NGC 4151 @ 2.9 σ significance



- Overlapping data sets and source catalogues → not independent results
- Open questions remain about neutrino production mechanism in source candidates
- Further studies on-going!

Publications submitted to ApJ:
https://arxiv.org/abs/2406.07601
https://arxiv.org/abs/2406.06684