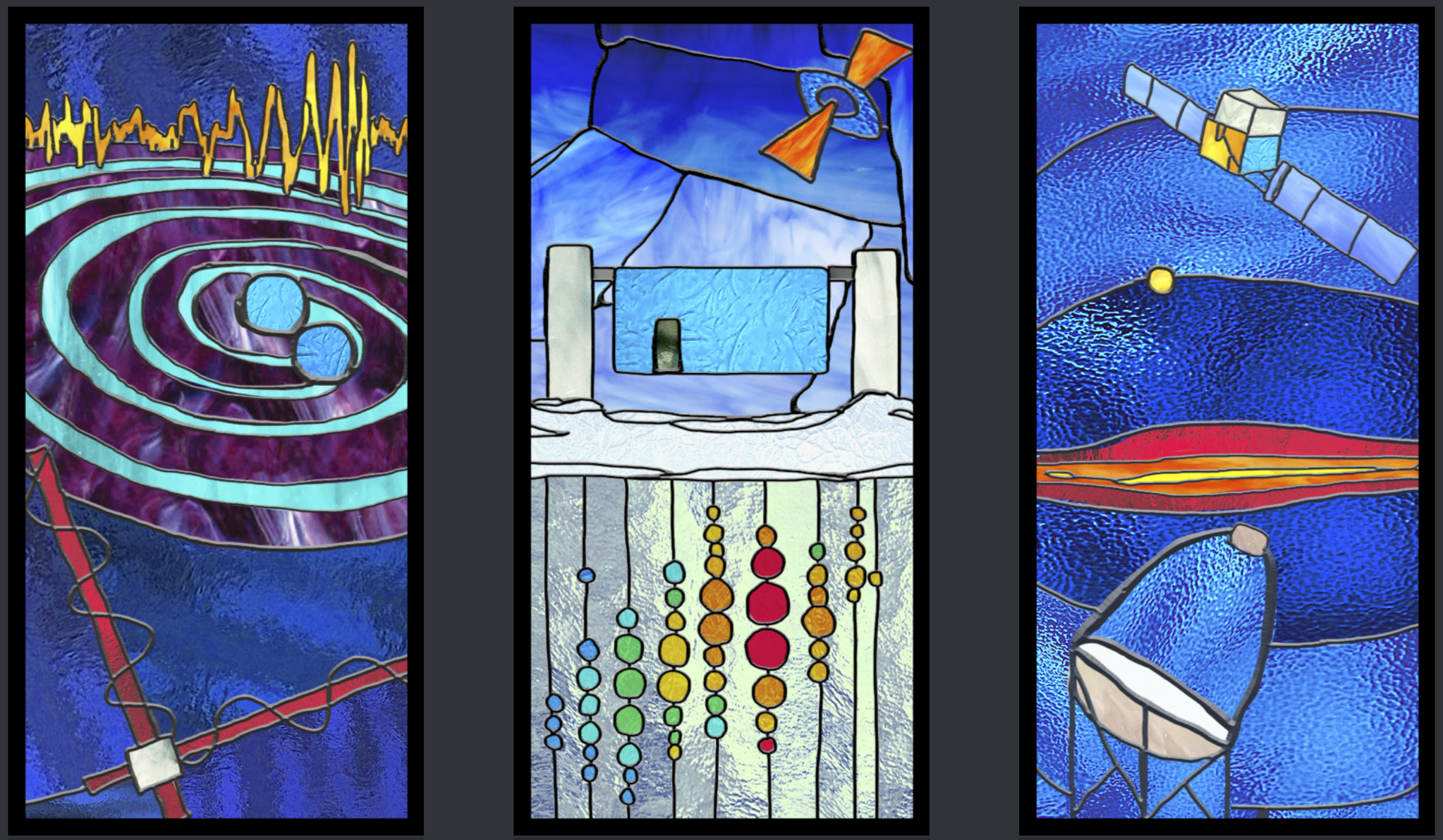


IceCube

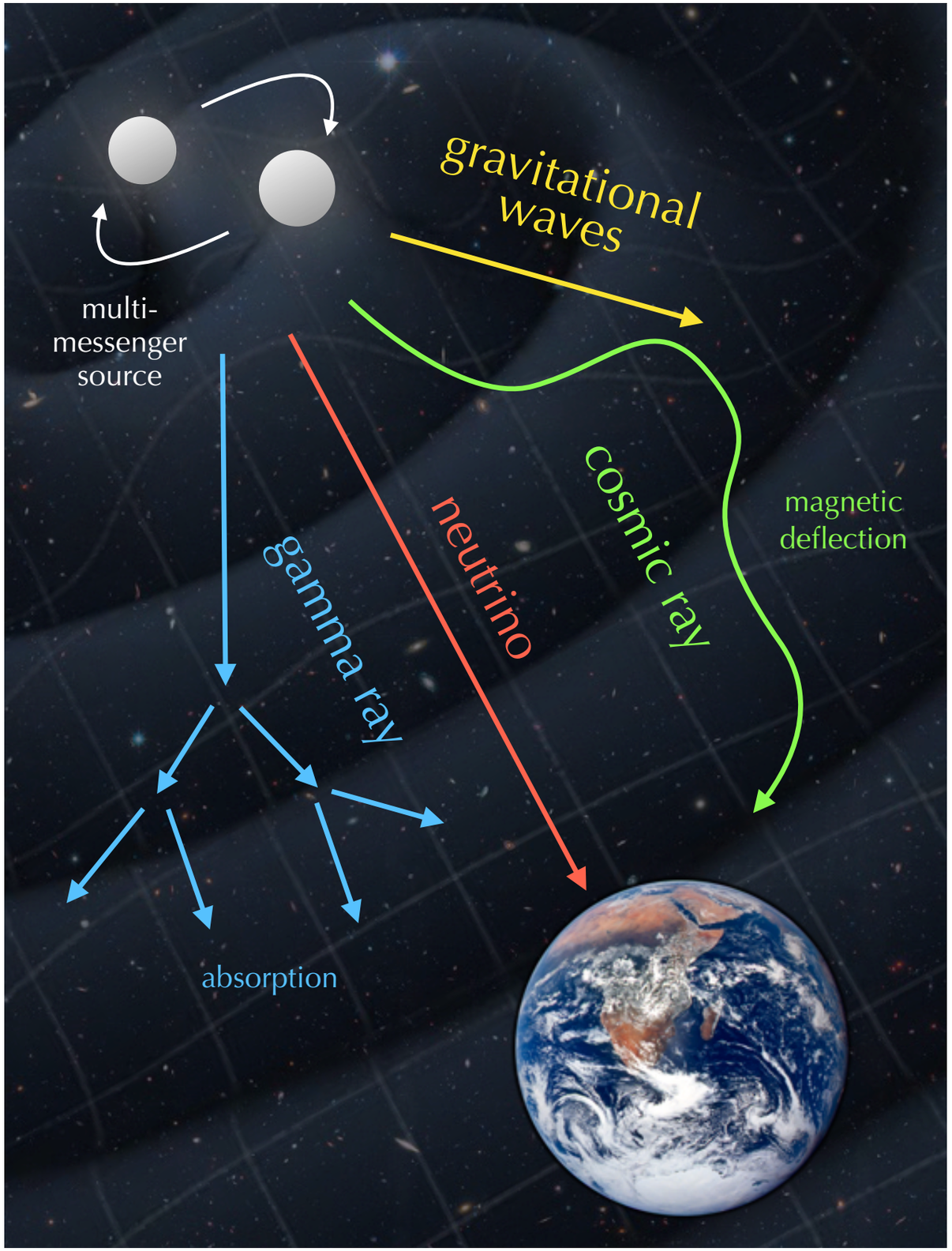
Markus Ahlers (NBI)

Danish PANP Meeting 2022

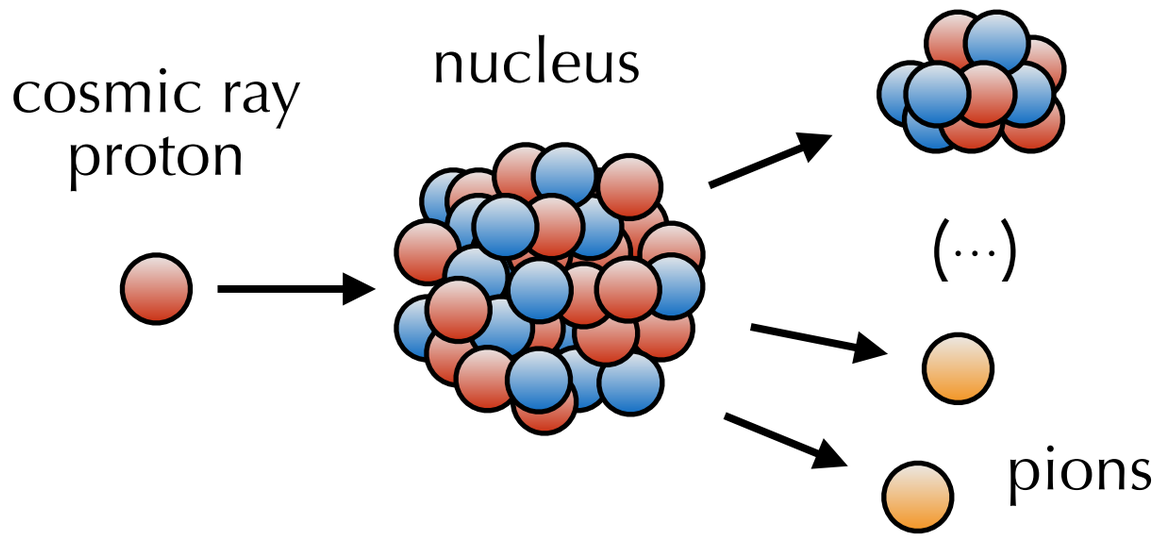
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Multi-Messenger Paradigm



Acceleration of **cosmic rays** - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

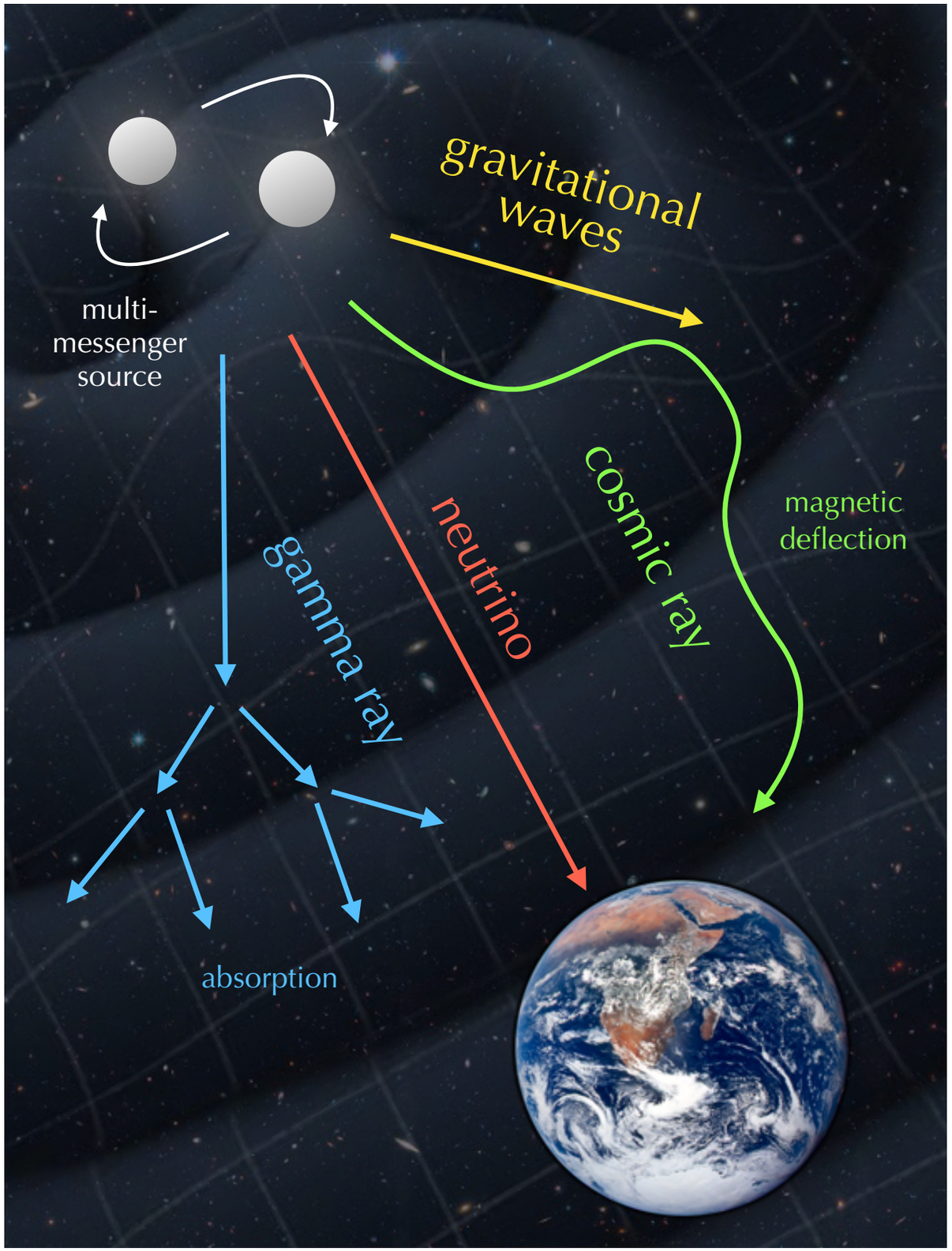


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

Optical Cherenkov Telescopes

P-ONE

(proposed)

Antares

Baikal-GVD

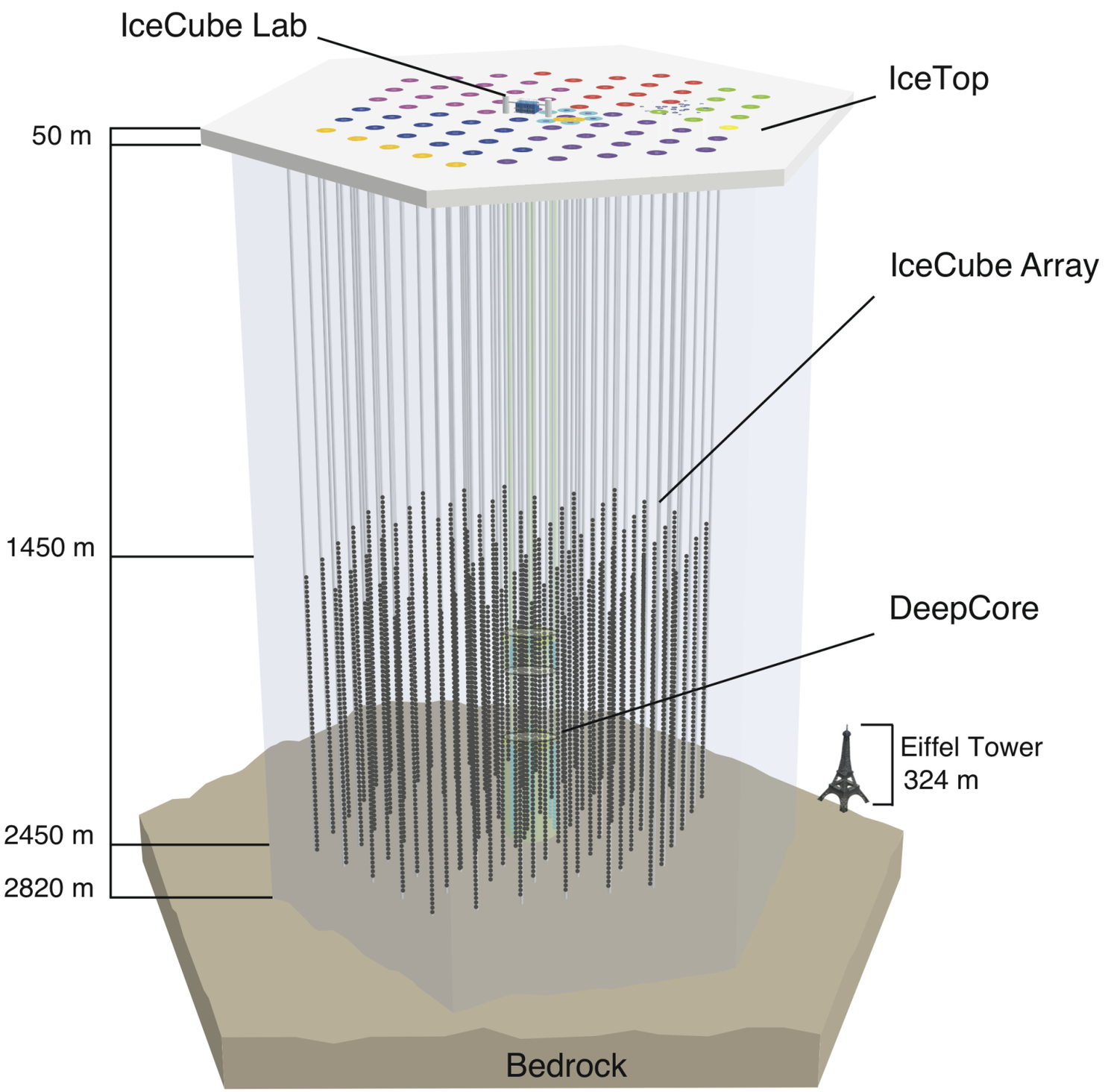
KM3NeT

IceCube

Markov 1960:

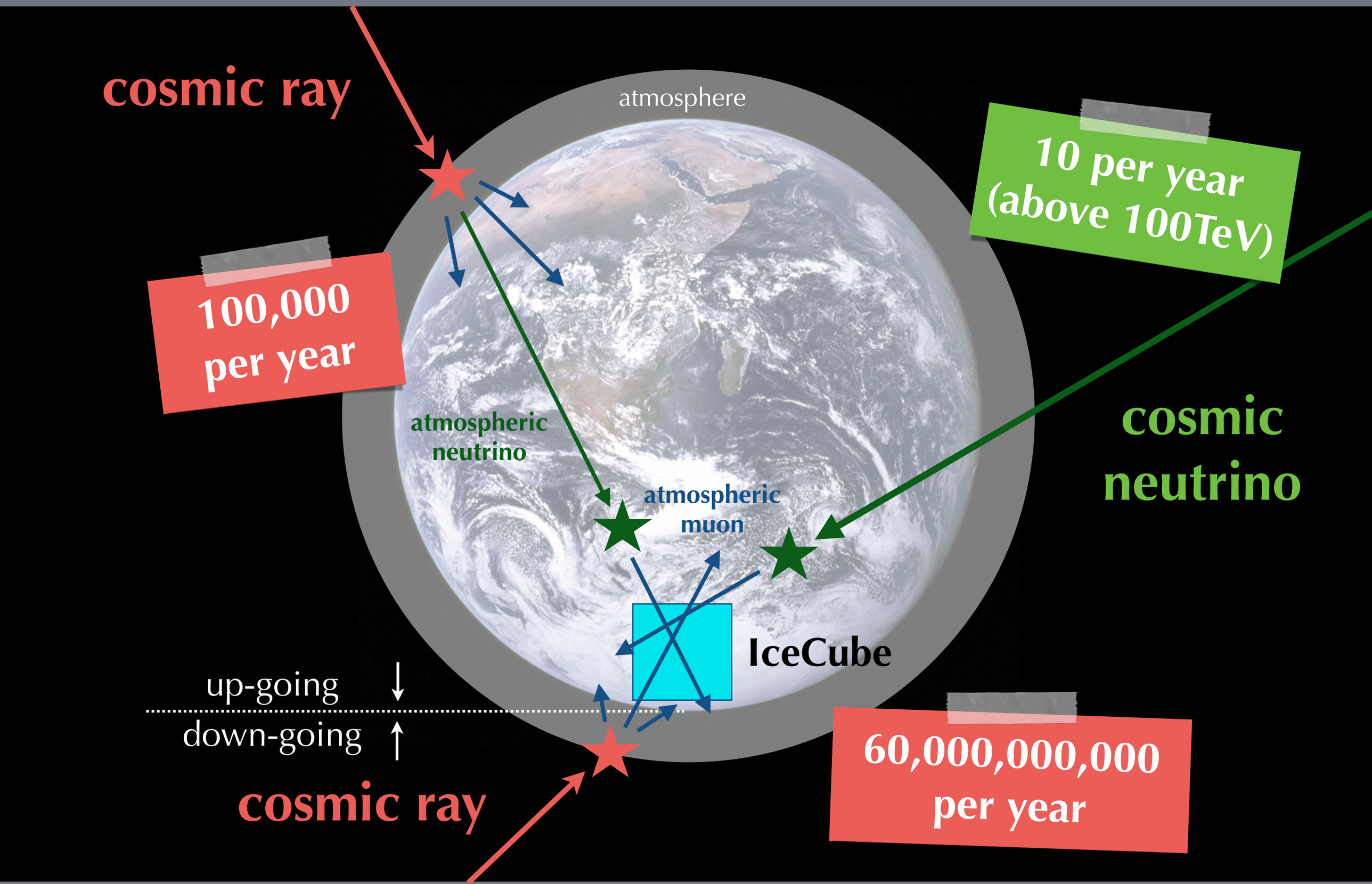
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by **Cherenkov radiation**."

IceCube Observatory



- **Giga-ton optical Cherenkov telescope at the South Pole**
- Optical modules attached to strings instrumenting **1 km³ of clear glacial ice**
- Collaboration of more than 300 scientists at 56 institutions in 14 countries.
- **Research focus @ NBI :**
  - ⋆ *low-energy event selections, reconstructions & systematics*
  - ⋆ *tau neutrino appearance*
  - ⋆ *multi-messenger analyses*
  - ⋆ *IceCube Upgrade*
  - ⋆ *non-standard ν phenomena*

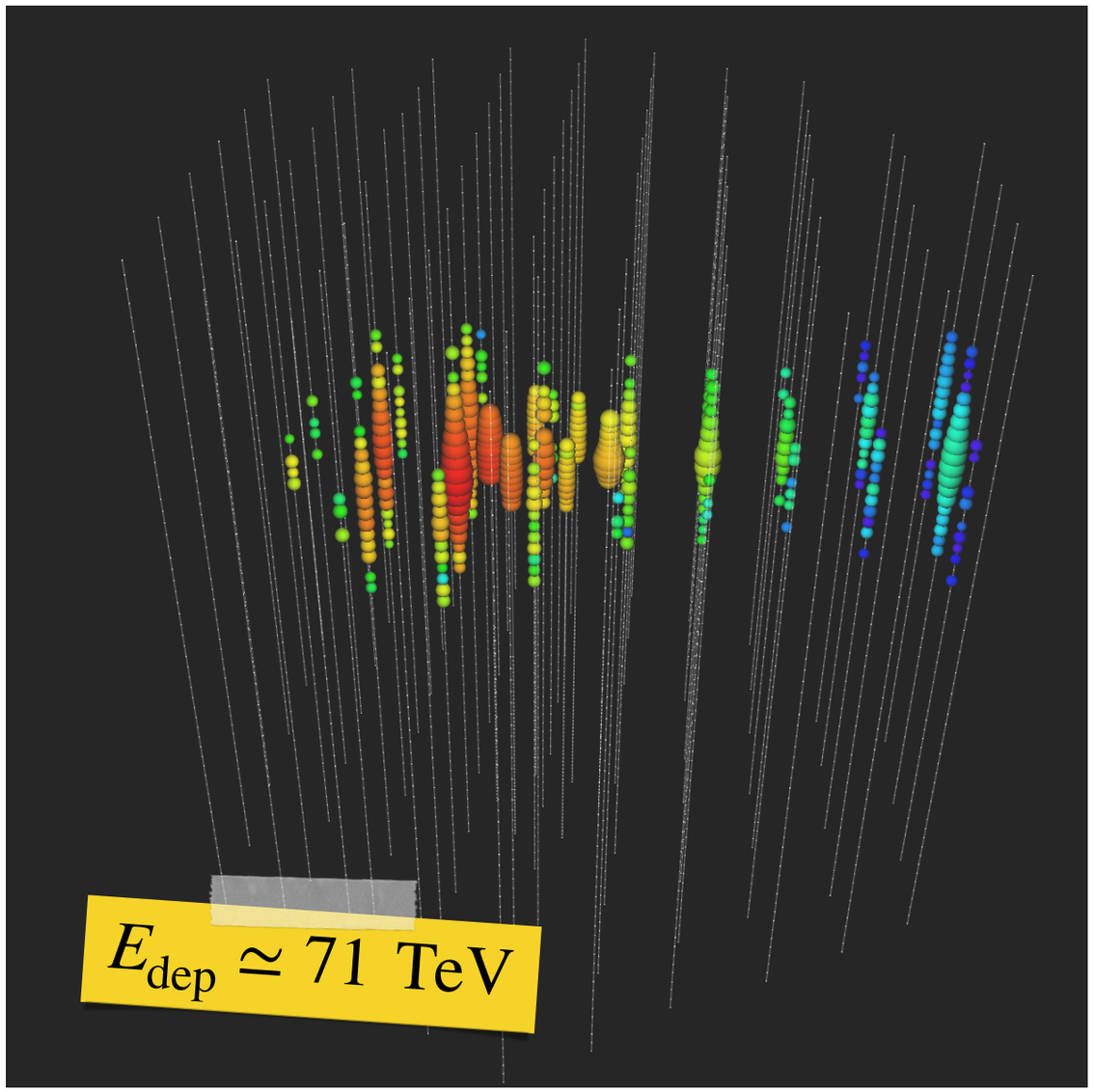
Neutrino Selections



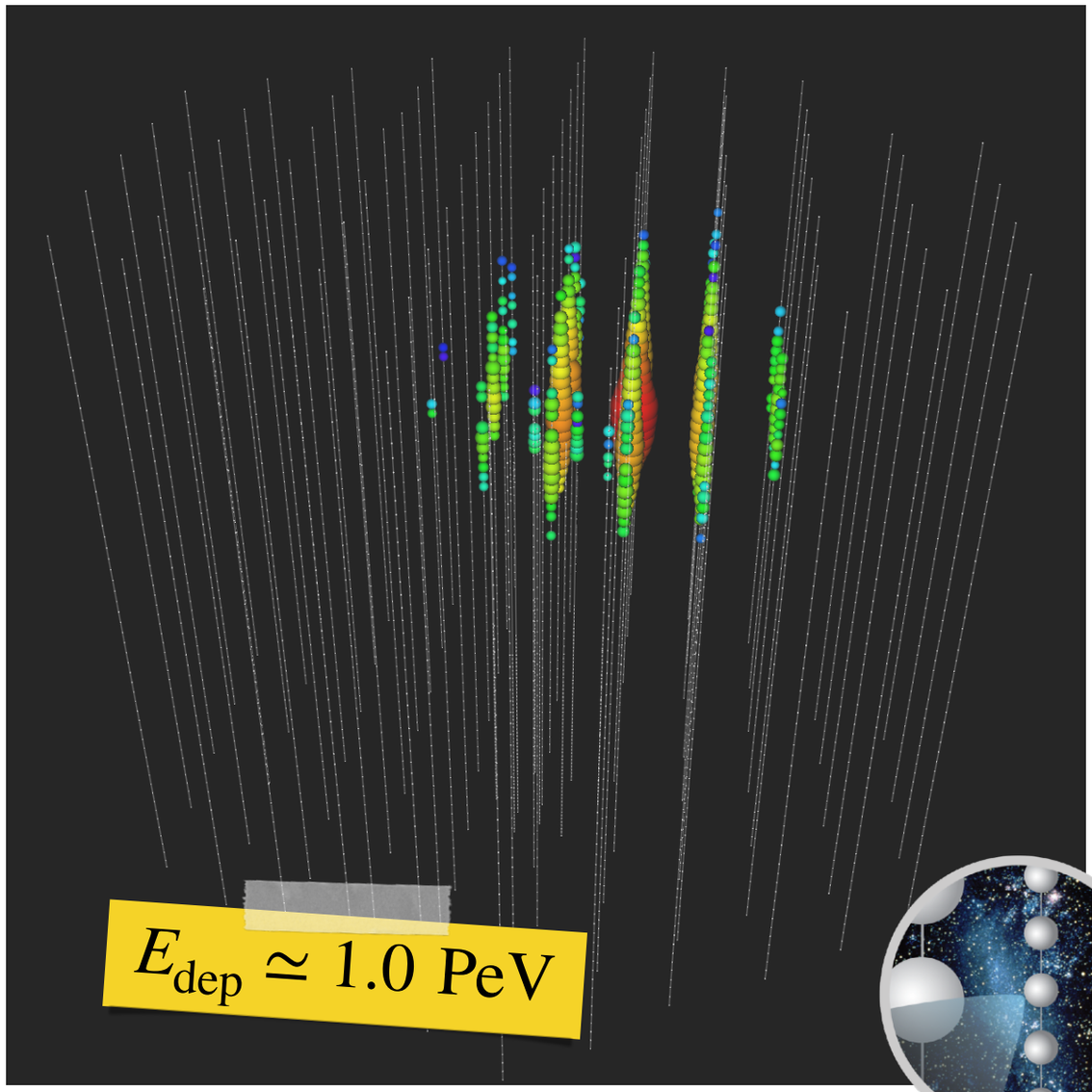
High-Energy Neutrinos

First observation of high-energy astrophysical neutrinos by IceCube in 2013.

"track event" (e.g. ν_μ CC interactions)



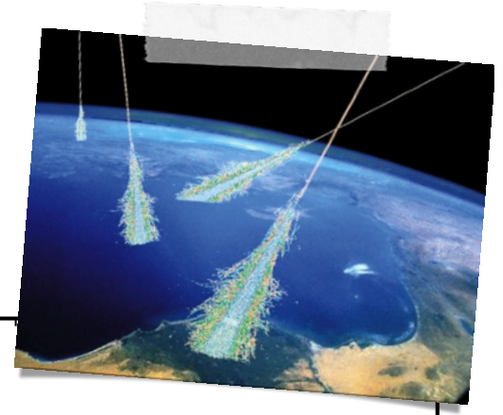
"cascade event" (e.g. NC interactions)

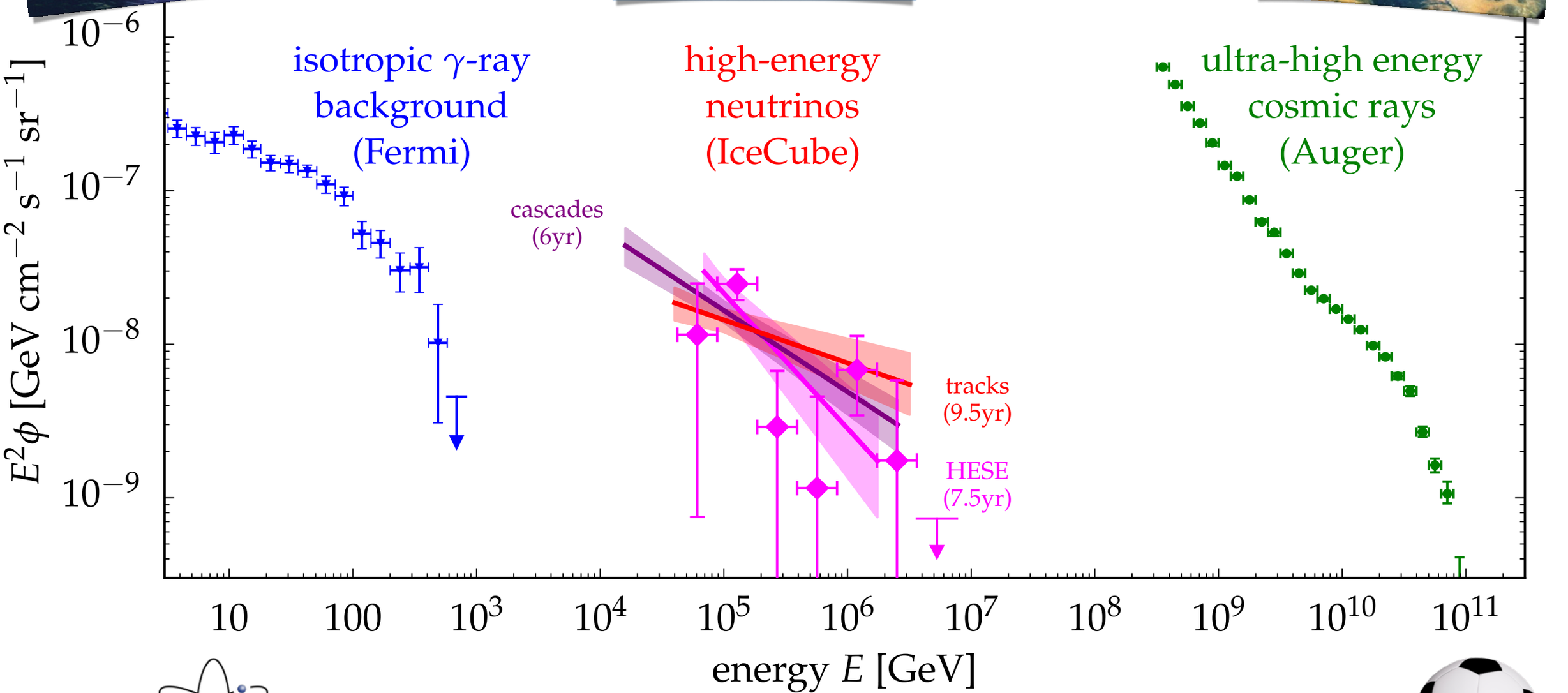


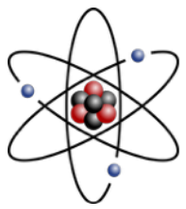
ICECUBE

(colours indicate arrival time of Cherenkov photons from **early** to **late**)

Diffuse TeV-PeV Neutrinos



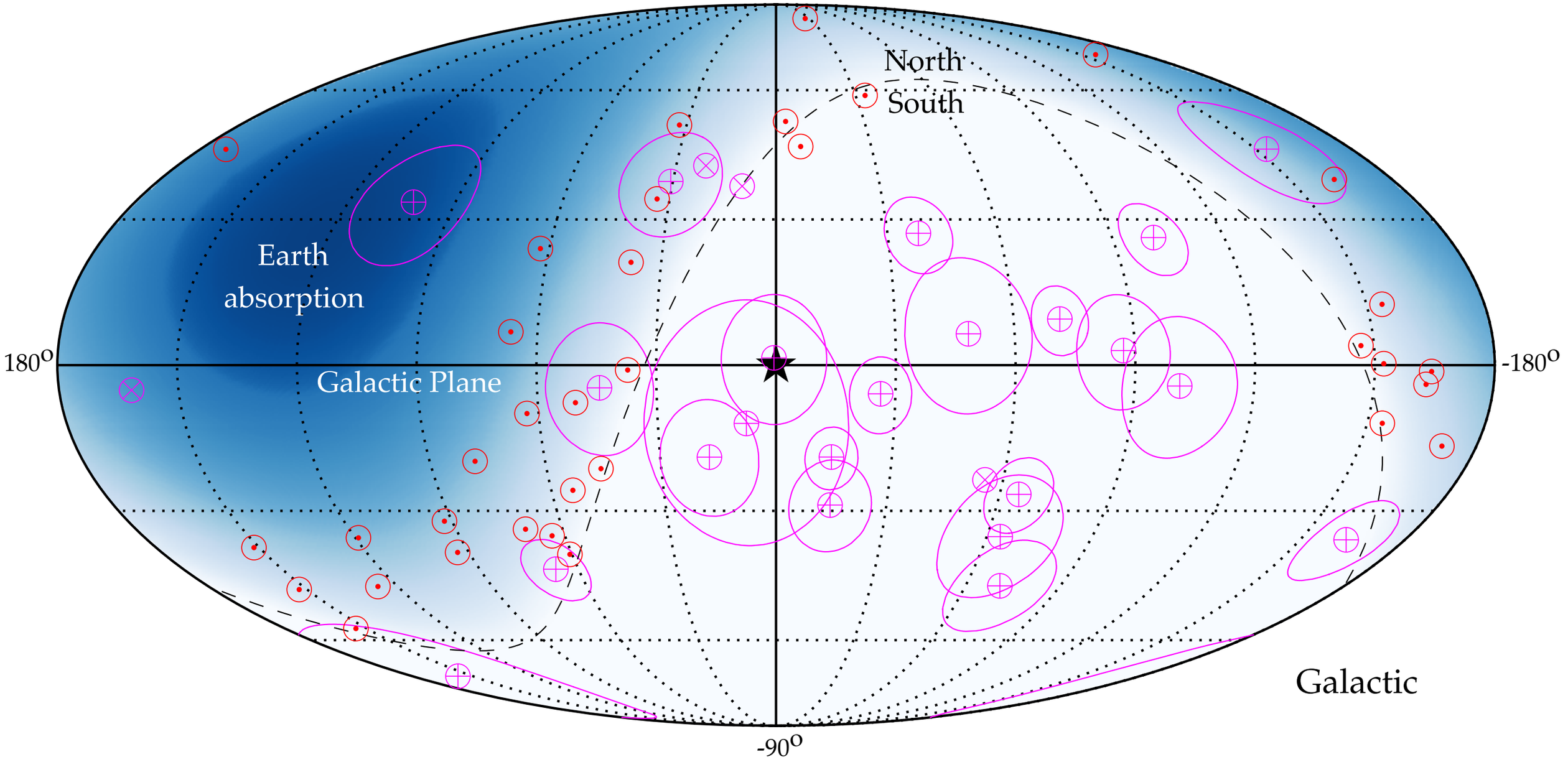




[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Status of Neutrino Astronomy

Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))

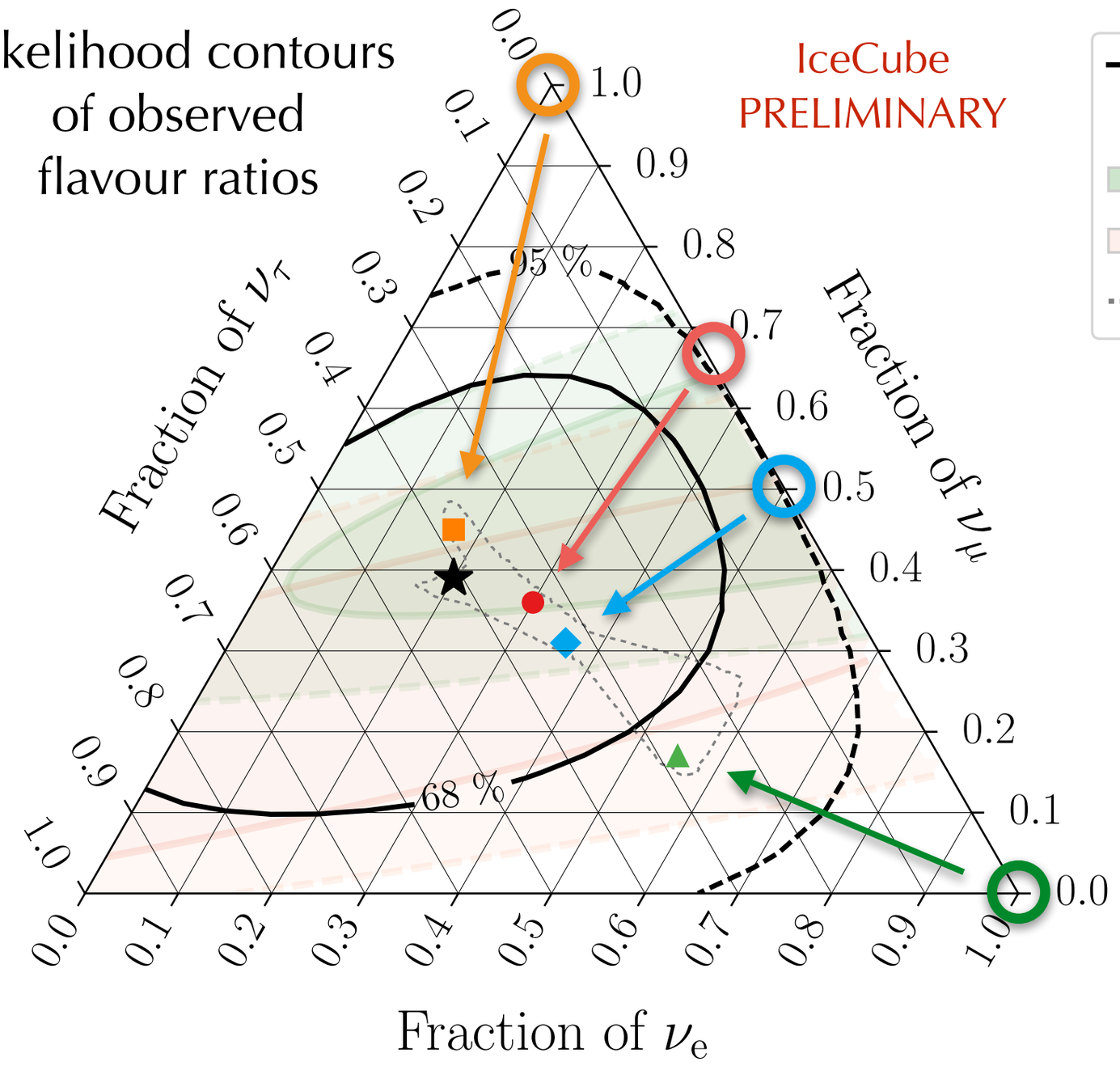


No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.

Likelihood contours of observed flavour ratios



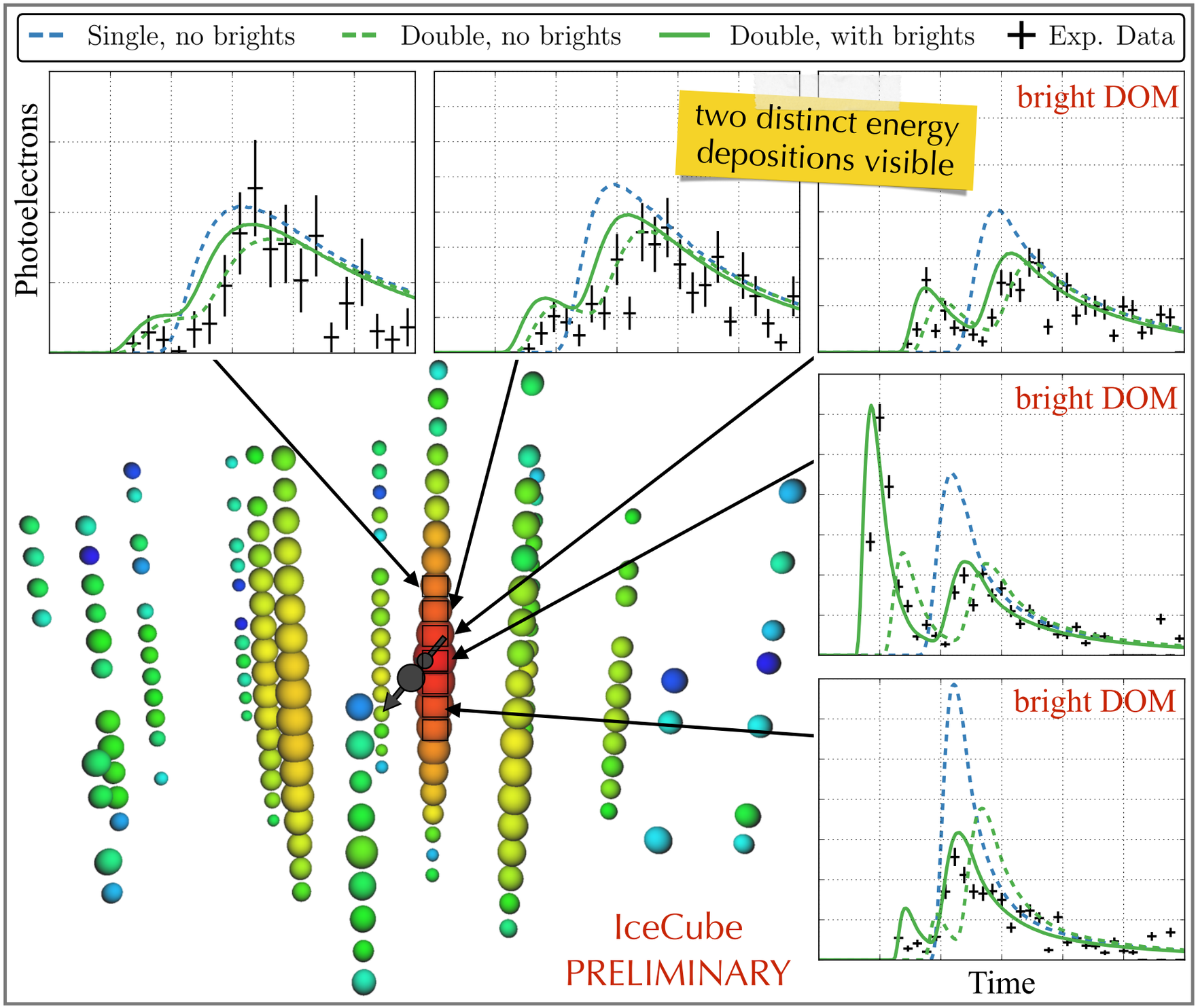
- HESE with ternary topology ID
- ★ Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- 3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:

- ■ 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
- ● 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
- ▲ 1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
- ◆ 1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

[IceCube, arXiv:2011.03561]

Astrophysical Flavours



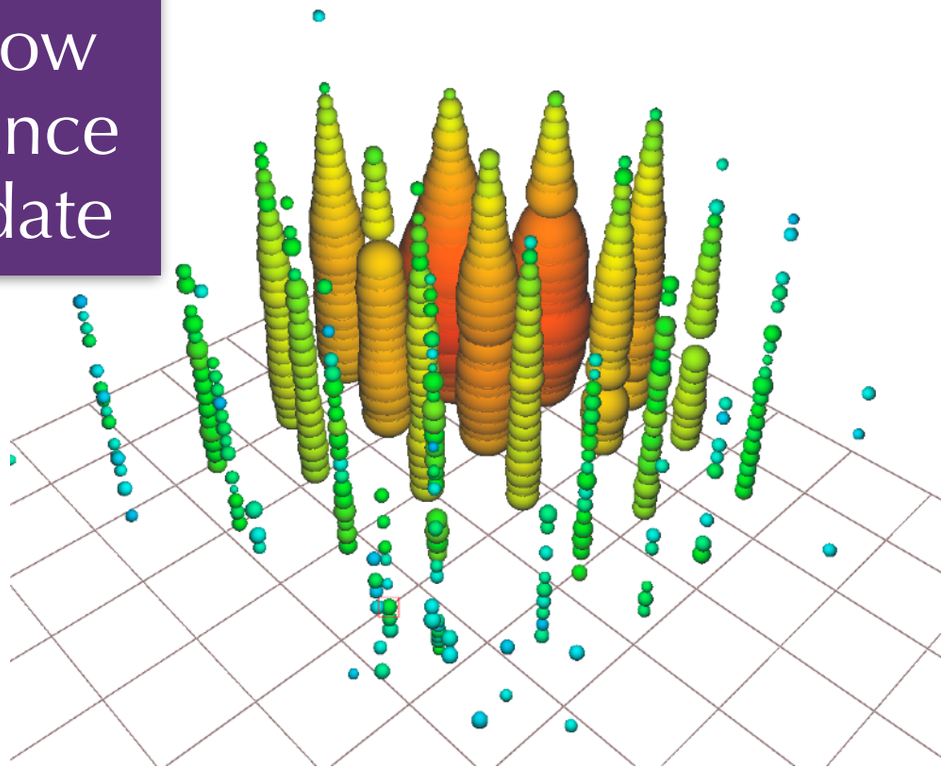
[IceCube, arXiv:2011.03561]

tau neutrino candidate

- **Tau neutrino** charged current interactions can produce delayed hadronic cascades from tau decays.
- Arrival time of Cherenkov photons is visible in individual DOMs.

Astrophysical Flavours

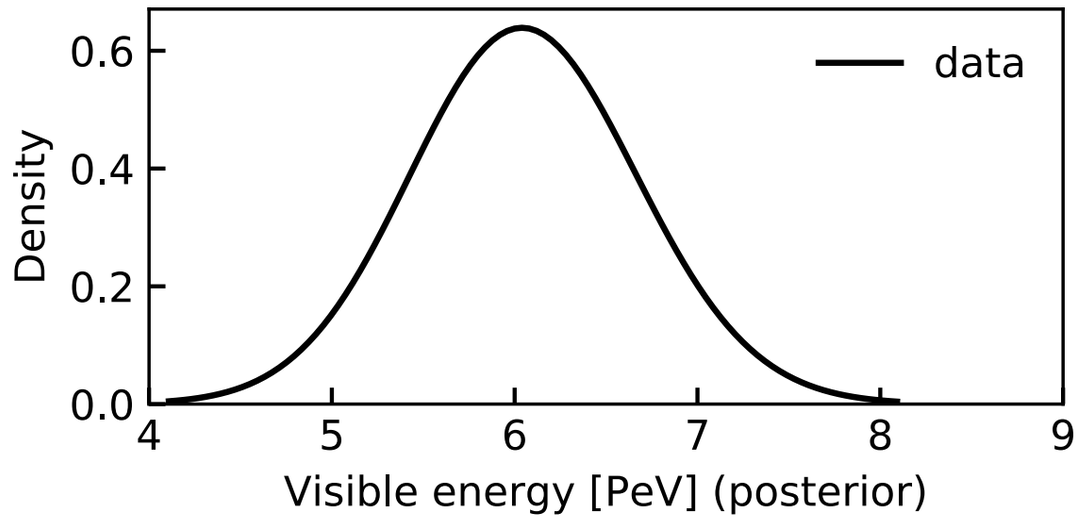
Glashow resonance candidate

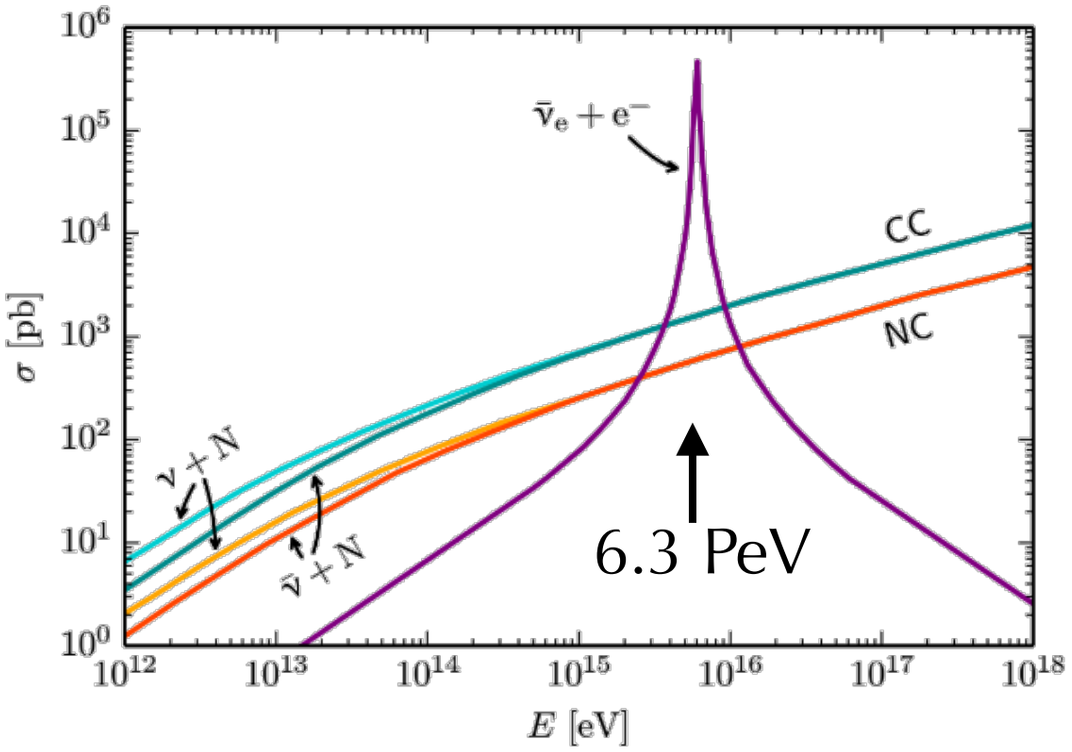


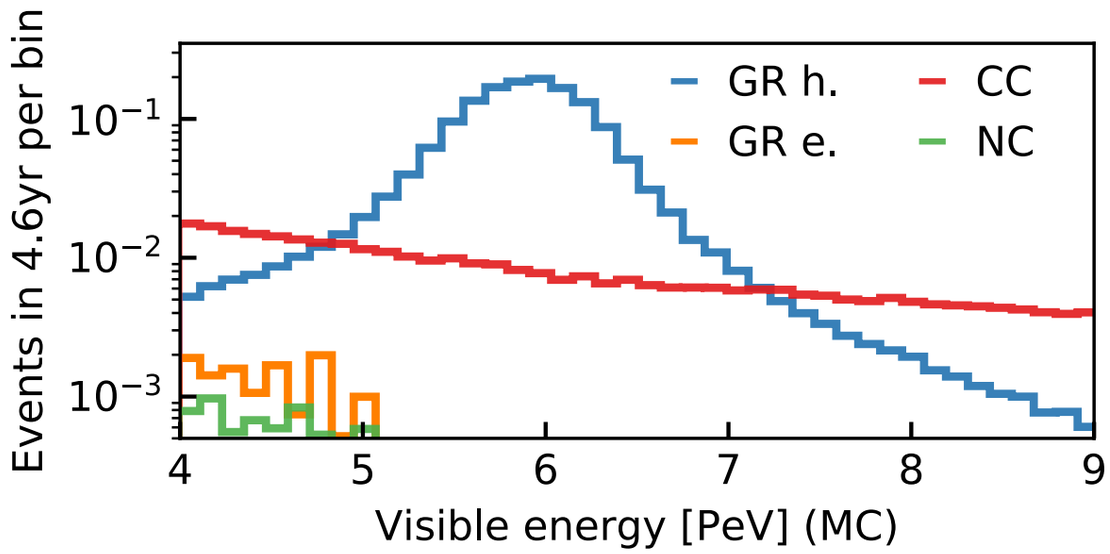
IceCube

Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$



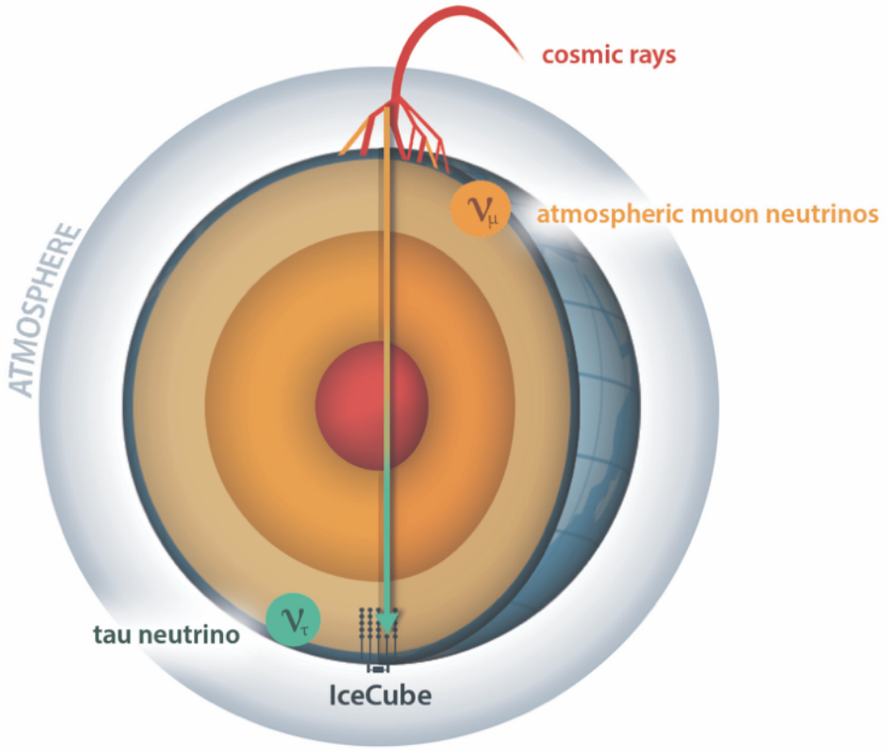




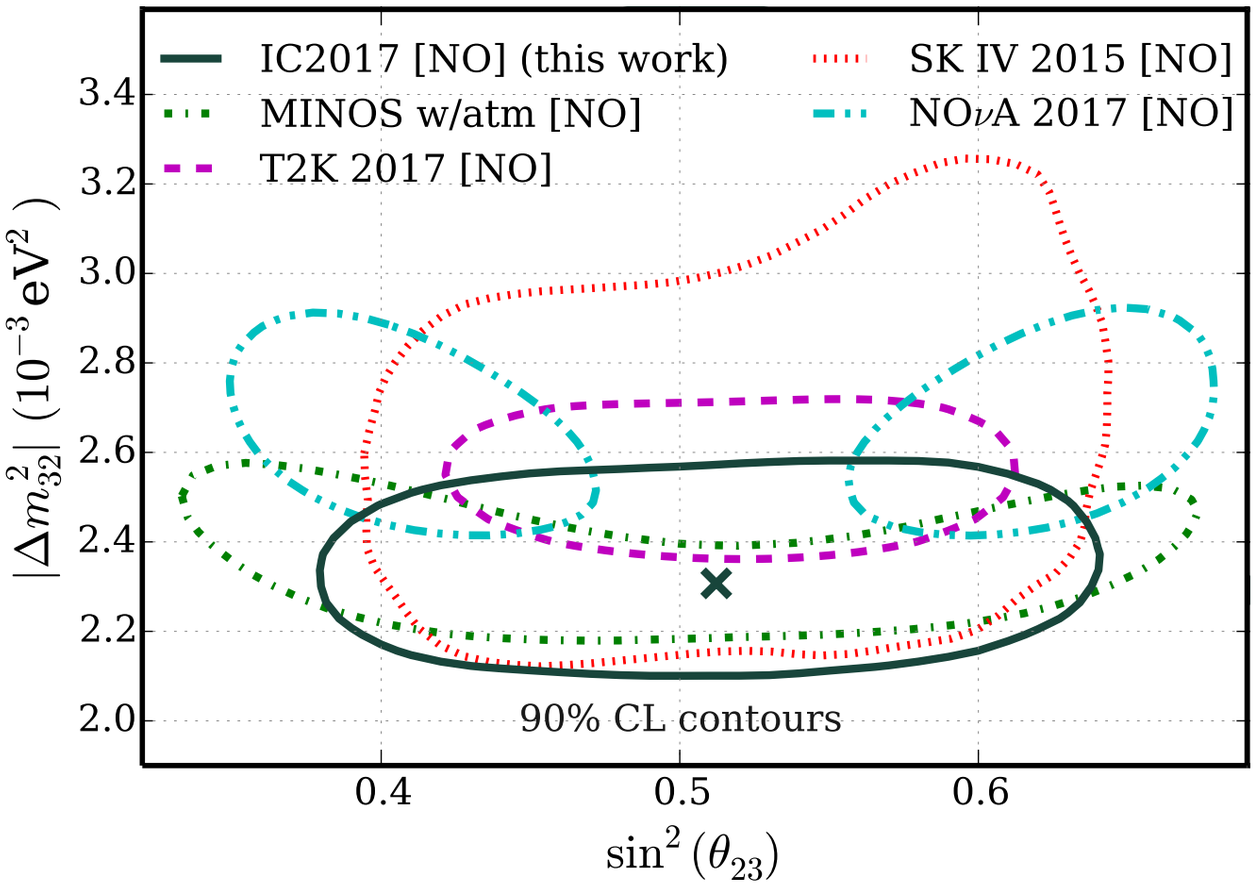
[IceCube, Nature 591 (2021) 220-224]

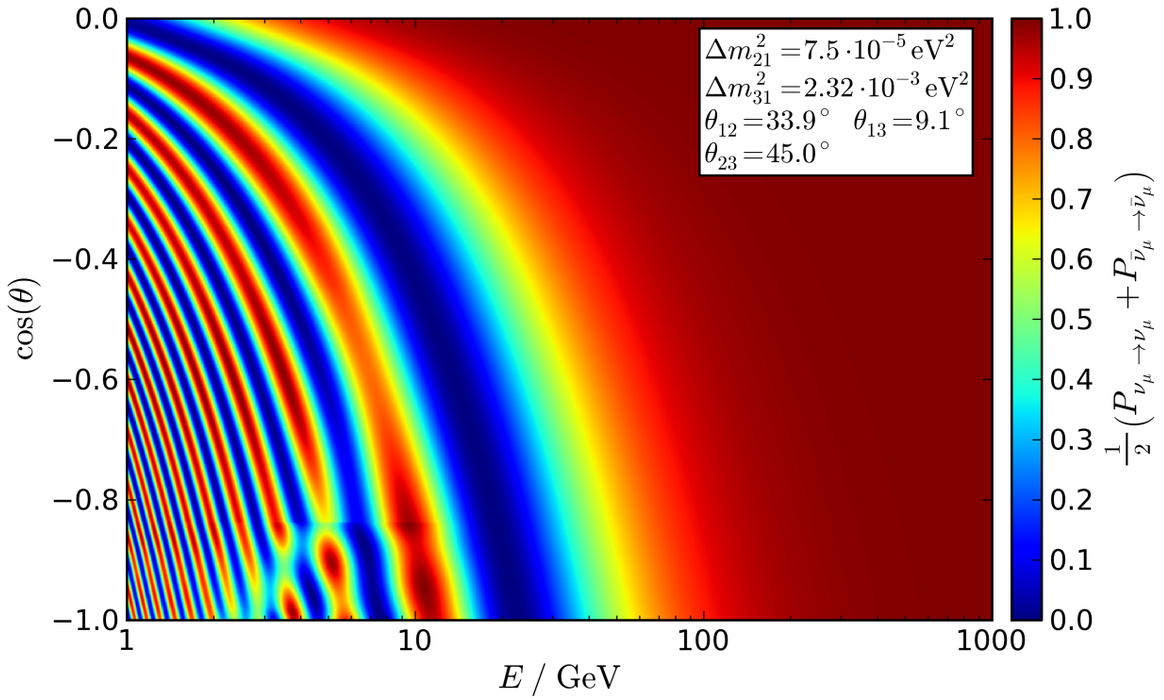
Atmospheric Neutrino Oscillations

- **Muon neutrino disappearance** in the 1-100 GeV range allows for precision measurement of atmospheric mixing parameters.
- **IceCube @ NBI** leads the current generation of oscillation analyses with DeepCore data.



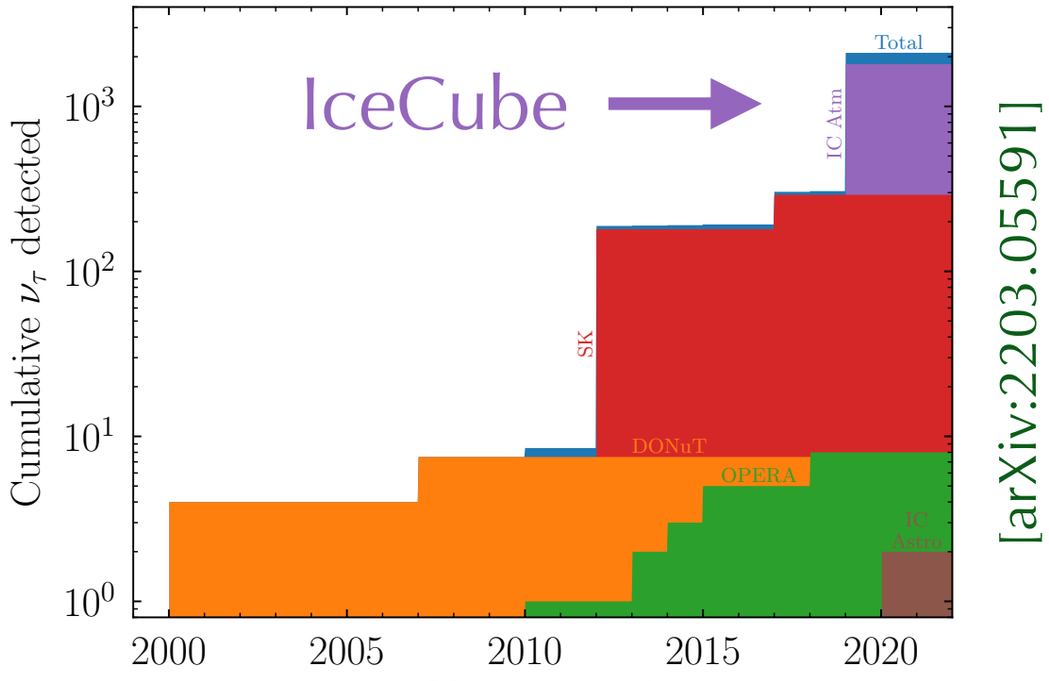
[IceCube, PRL 120 (2018) 7]



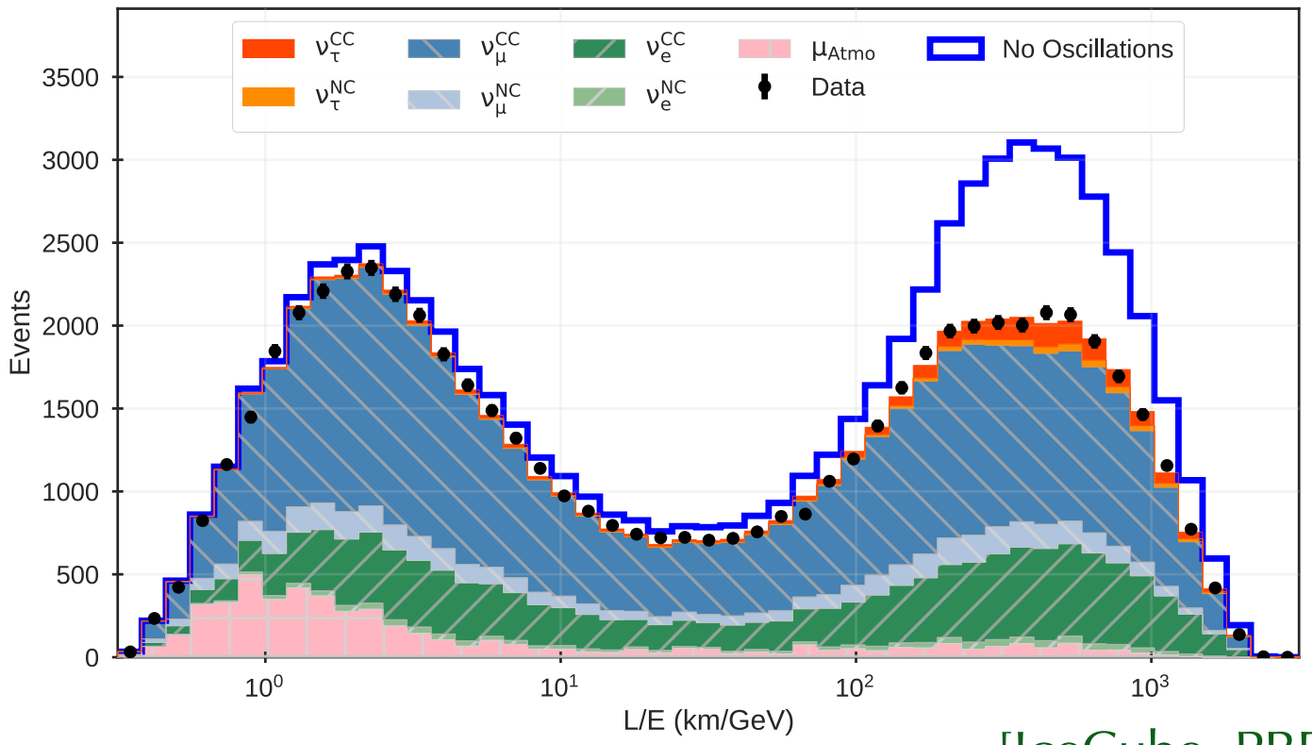


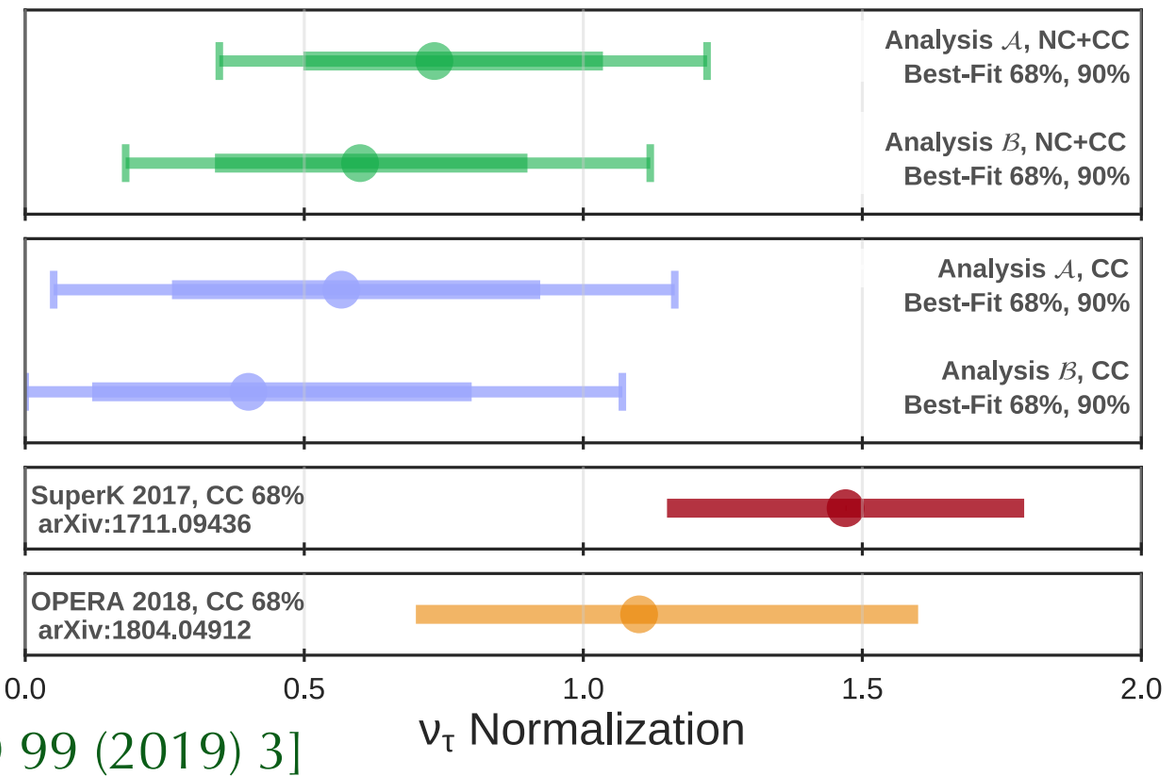
Tau Neutrino Appearance

- 86% of ν_τ global data from IceCube
- High statistics of ν_τ allow to make **precision tests** of the 3-flavour oscillation paradigm.
- Current analyses efforts led by NBI will **increase the data by a factor 4-5**.



[arXiv:2203.05591]





[IceCube, PRD 99 (2019) 3]

Machine-Learning Tools

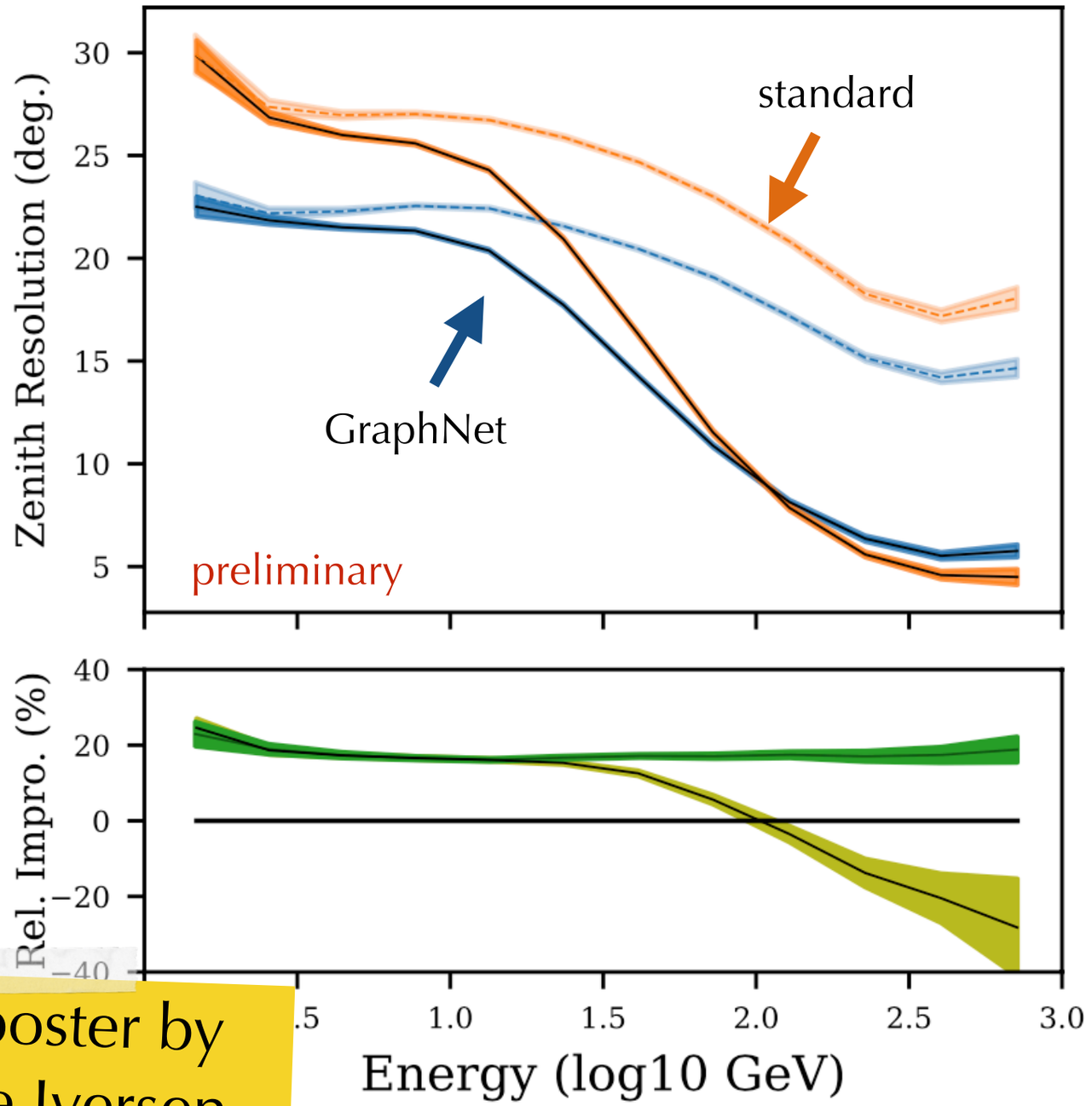
- Improved angular and energy reconstructions are a key to improve sensitivities of neutrino telescopes.
- **Machine-learning tools**, *e.g.* based on graph neural networks are paving the way for future analyses with DeepCore data and IceCube-Upgrade.

GraphNeT

Graph Neural Networks for
Neutrino Telescope Event Reconstruction

https://github.com/icecube/graphnet/

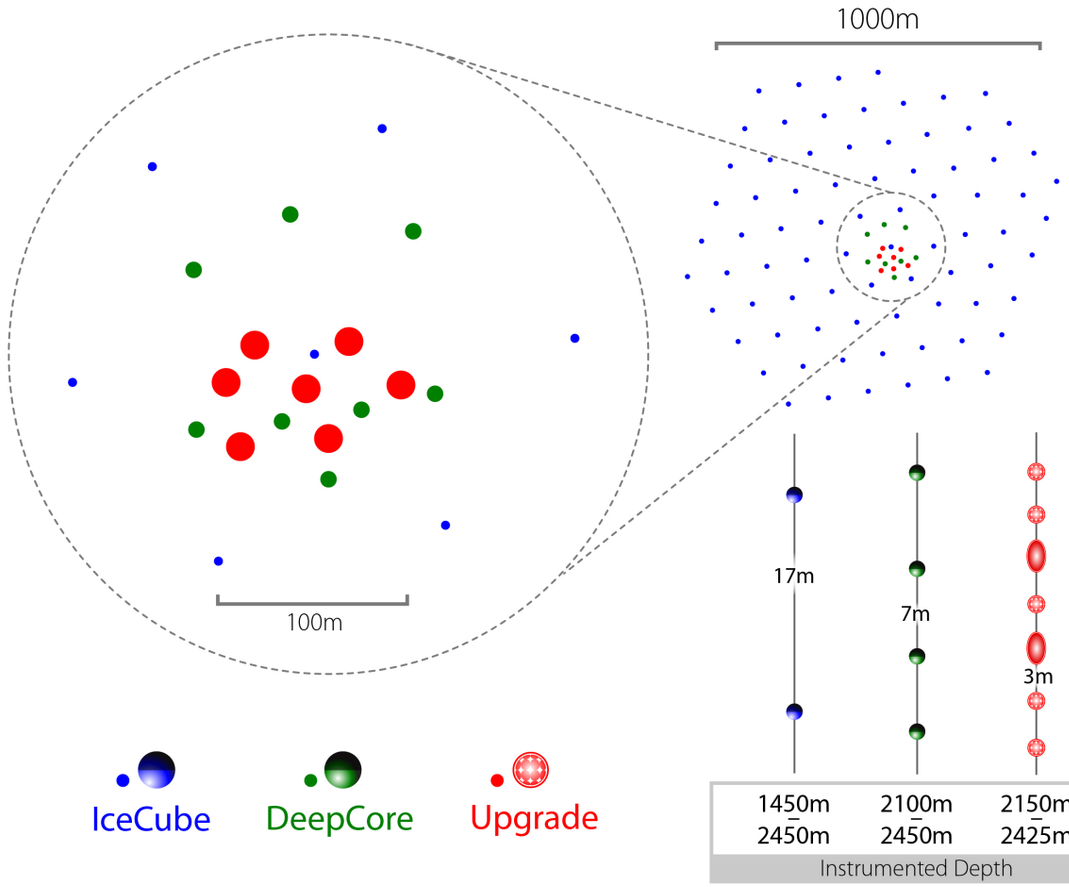
Angular reconstructions with **GraphNet**
[courtesy of **Troels C. Petersen** *et al.*]

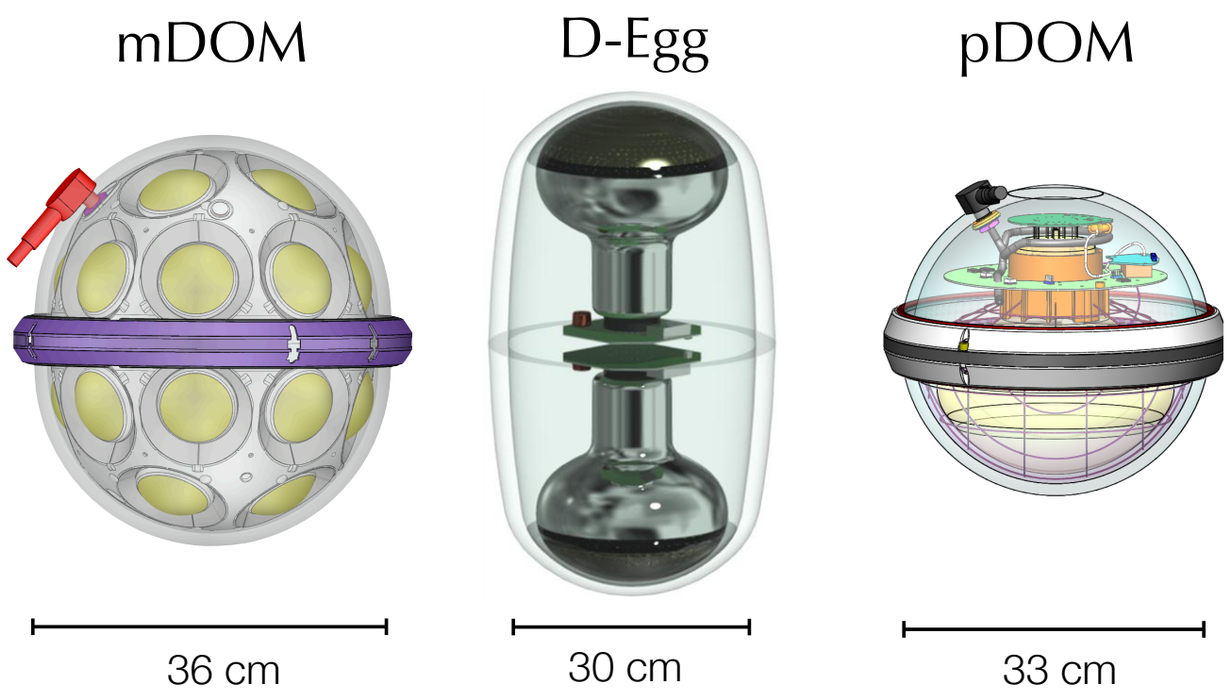


see poster by
Kaare Iversen

Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Aim: deployment in 2025/26**

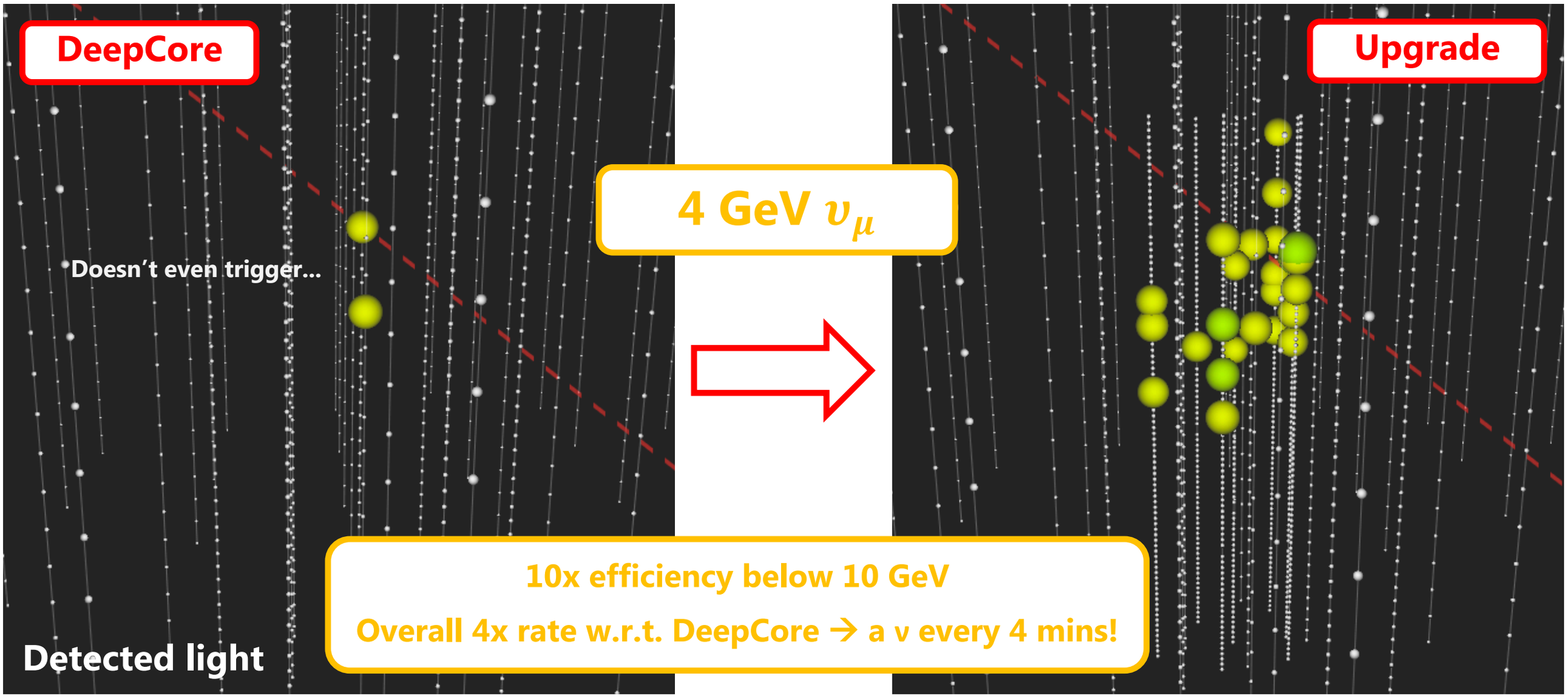




Outlook: IceCube Upgrade

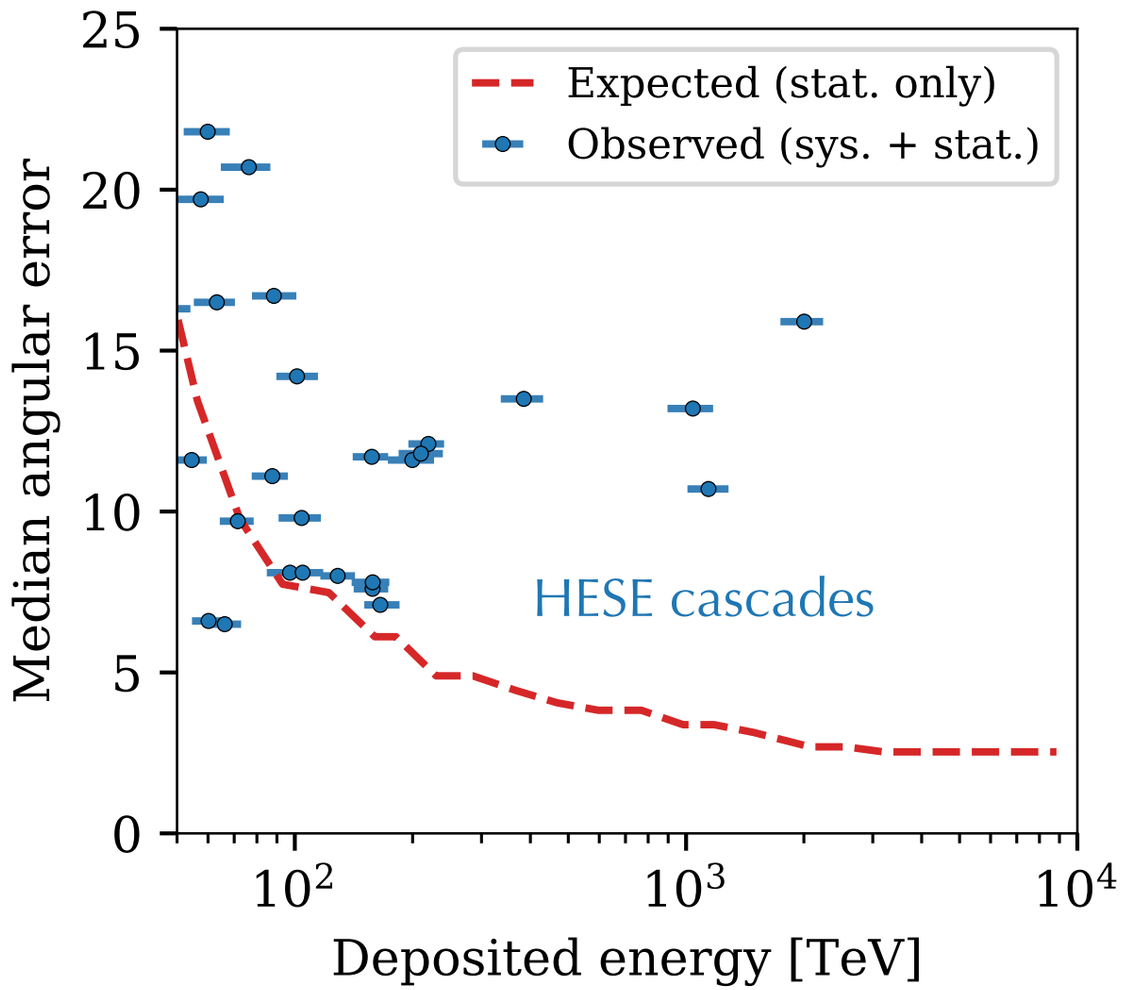
Improved low-energy detection efficiency with IceCube Upgrade

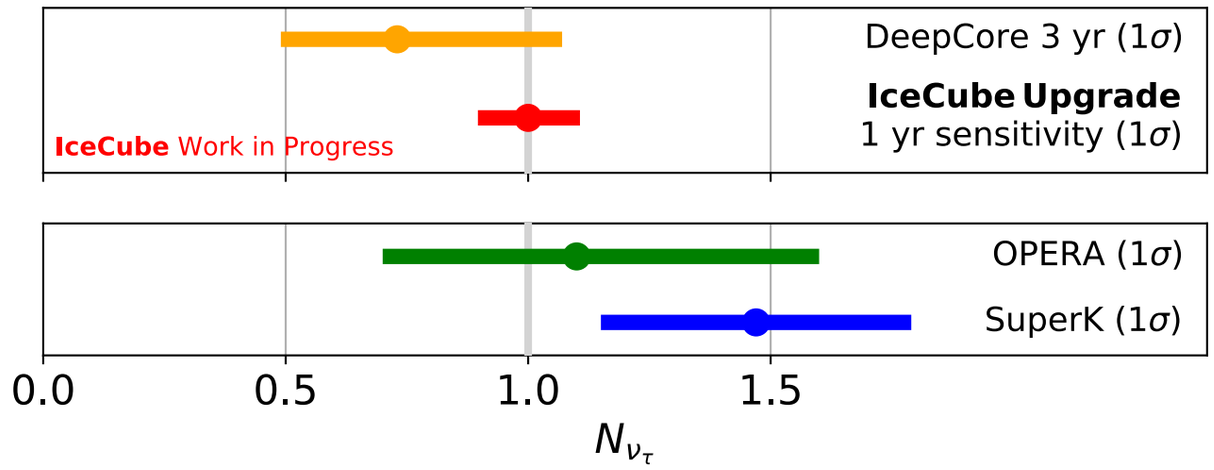
[courtesy of **Tom Stuttard**]

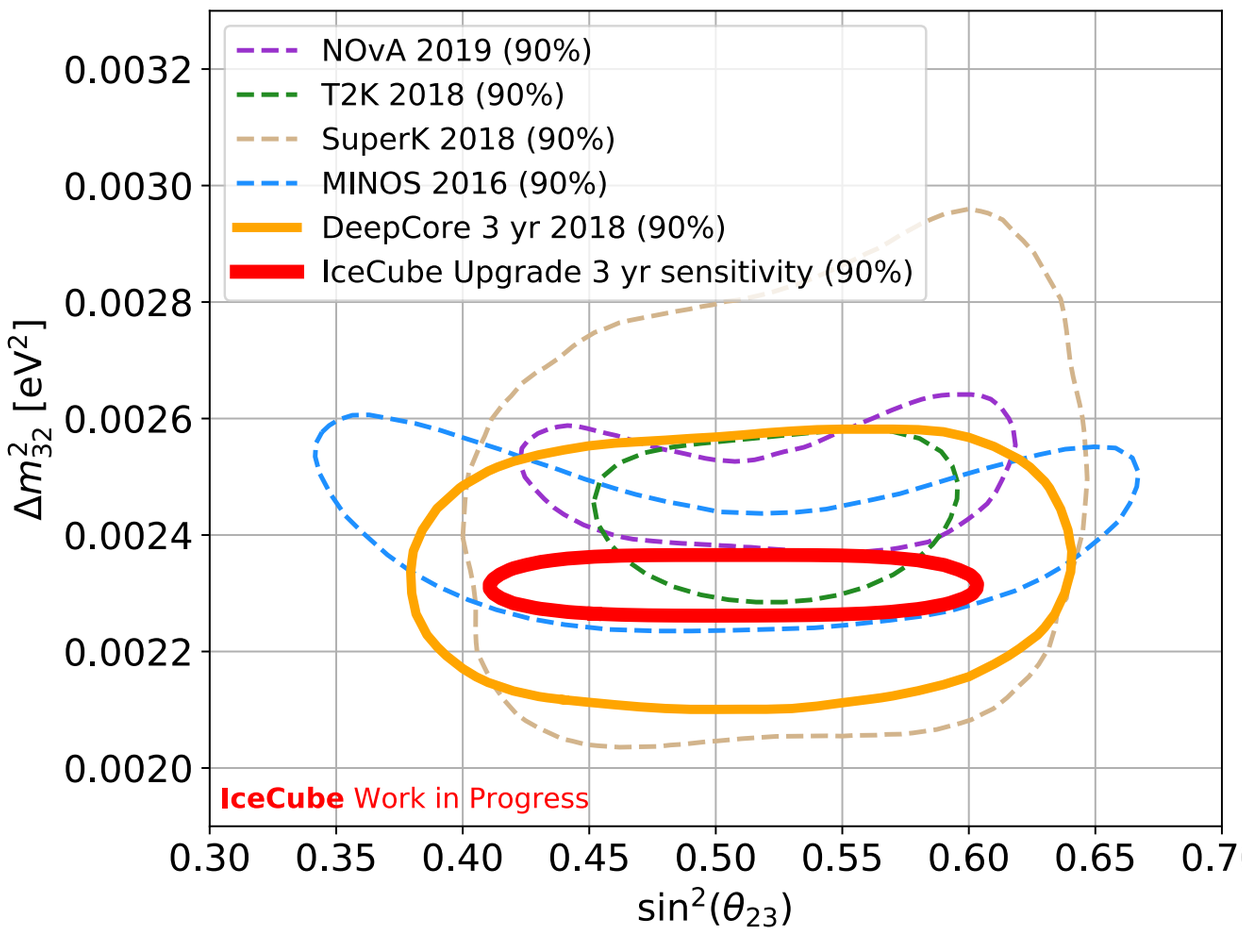


Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance
- **Improved energy and angular reconstructions** of IceCube data



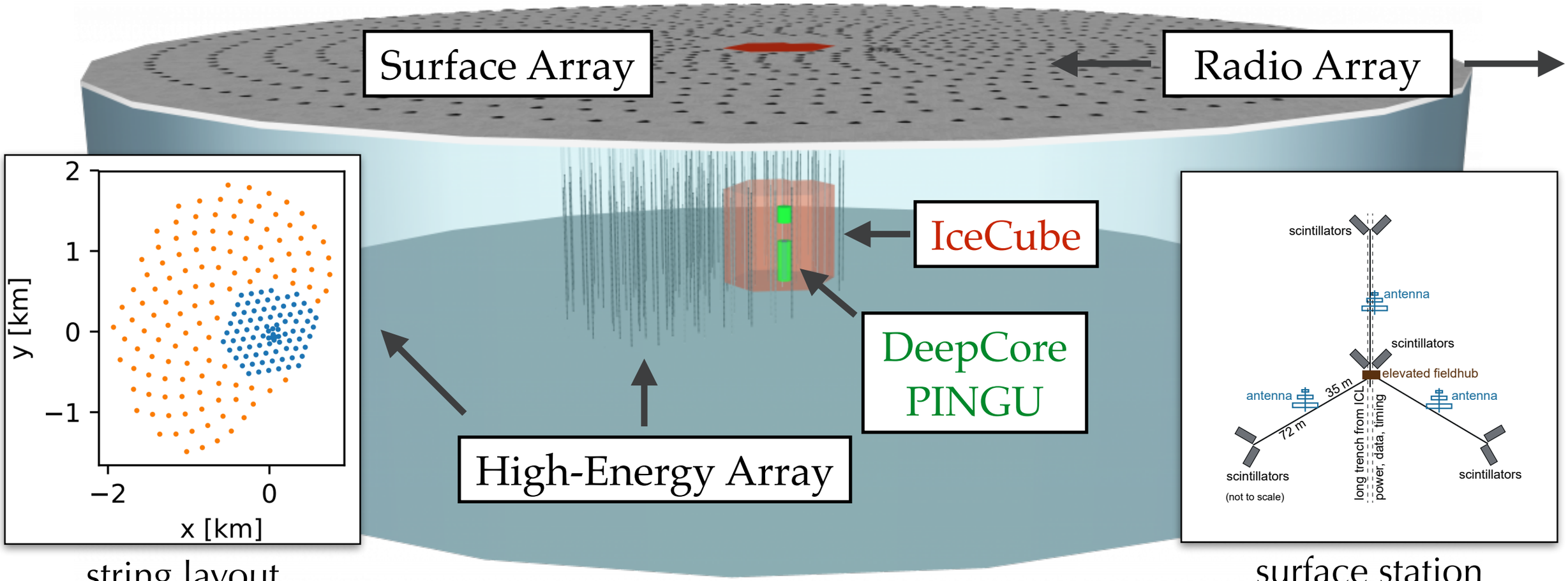




[IceCube, PoS (ICRC2019) 1031]

Vision: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10PeV neutrino detection

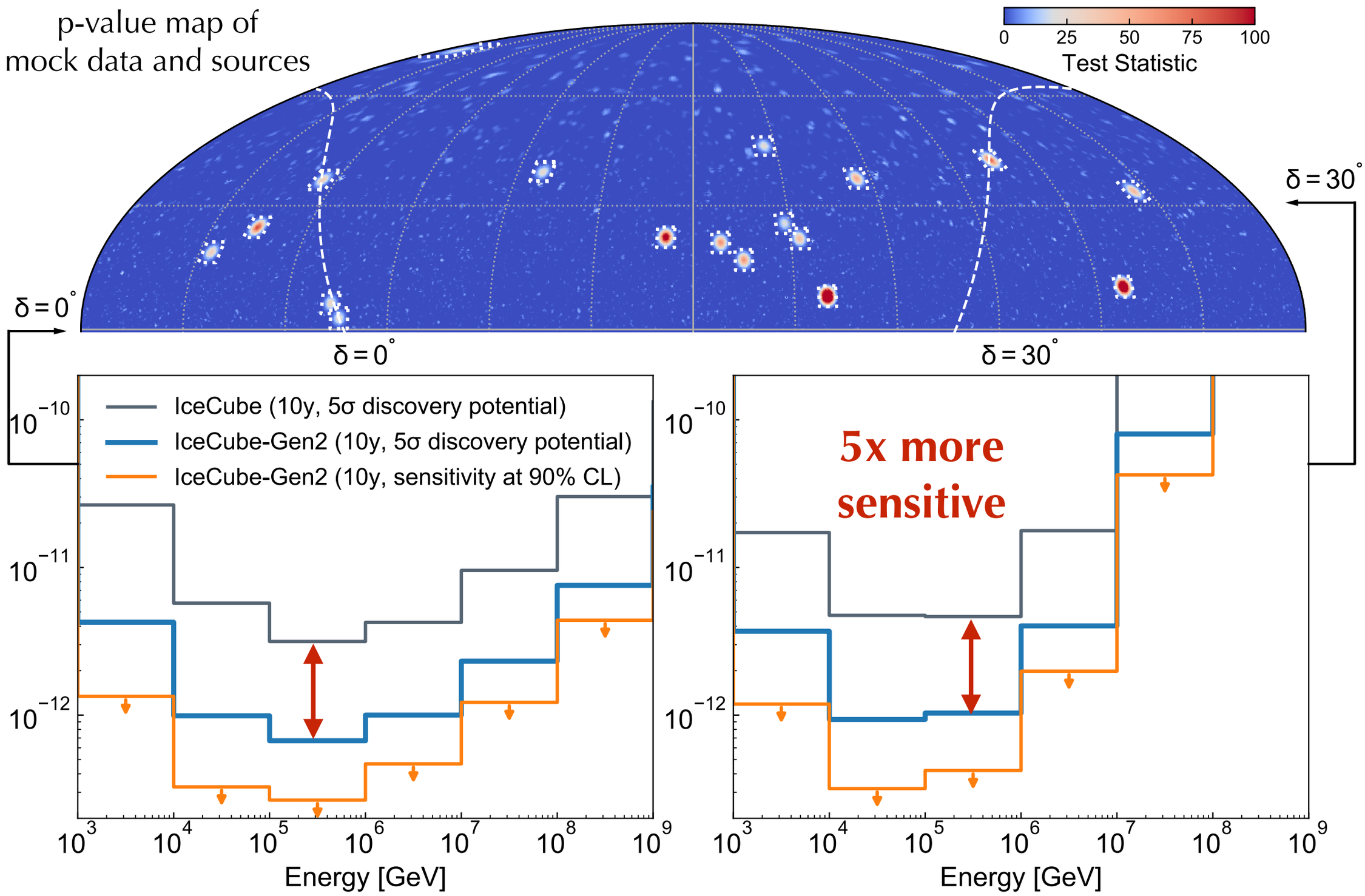


string layout

surface station

[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Vision: IceCube-Gen2



[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Summary

- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**

- So far, **no significant** point sources, but many **interesting candidates**.

  (TXS 0506+056, NGC 1068,TDE AT2019dsg, ...)

- In parallel, neutrino telescopes are potent and unique **particle physics laboratories.**

  (high statistics, broad energy range, broad range of baselines, all flavour, ...)

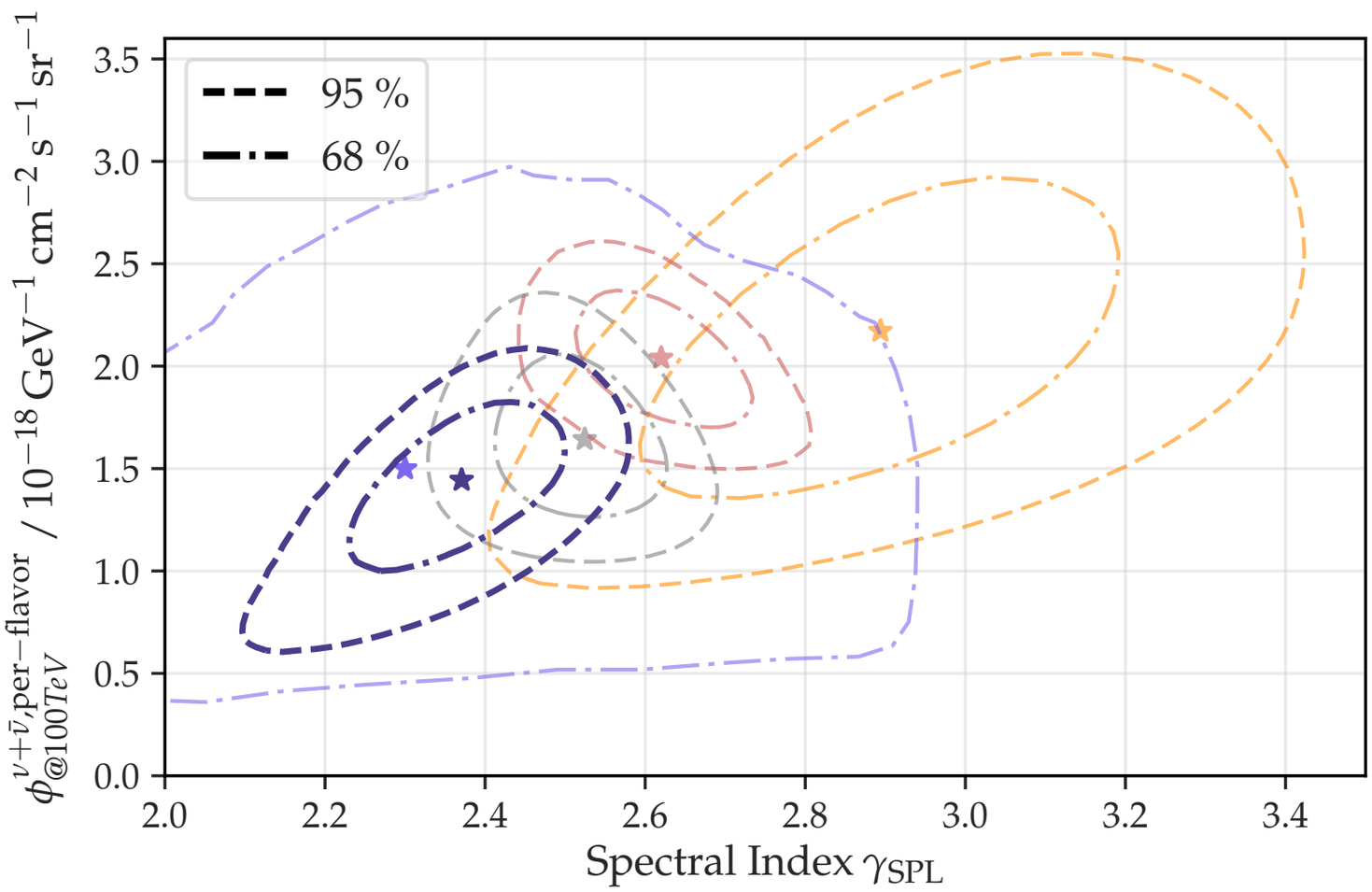
- Broad neutrino oscillation program with **competitive atmospheric mixing parameter measurements** and **world-leading ν_τ data**.

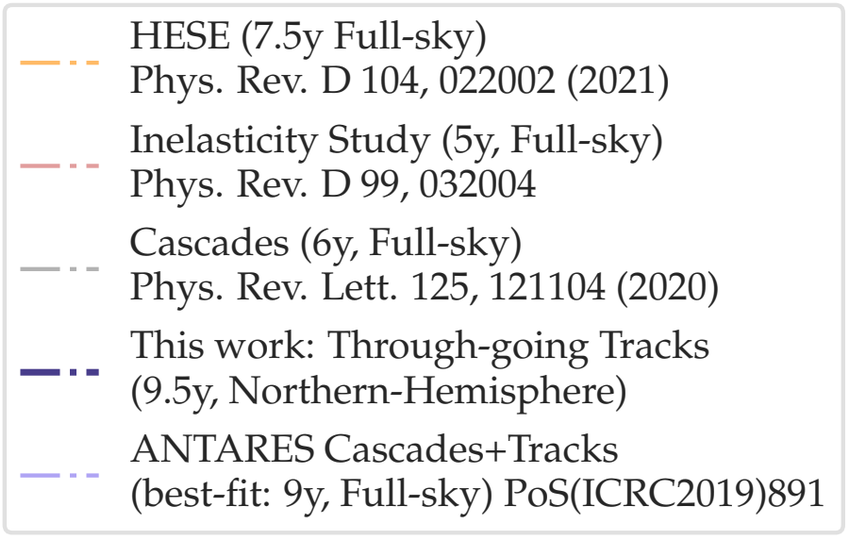
- Development of **neutrino telescopes for the next decade** with complementary FoV and/or increased sensitivity and energy coverage.

  (IceCube-Upgrade, Baikal-GVD, KM3NeT, P-ONE, RNO-G, IceCube-Gen2, ...)

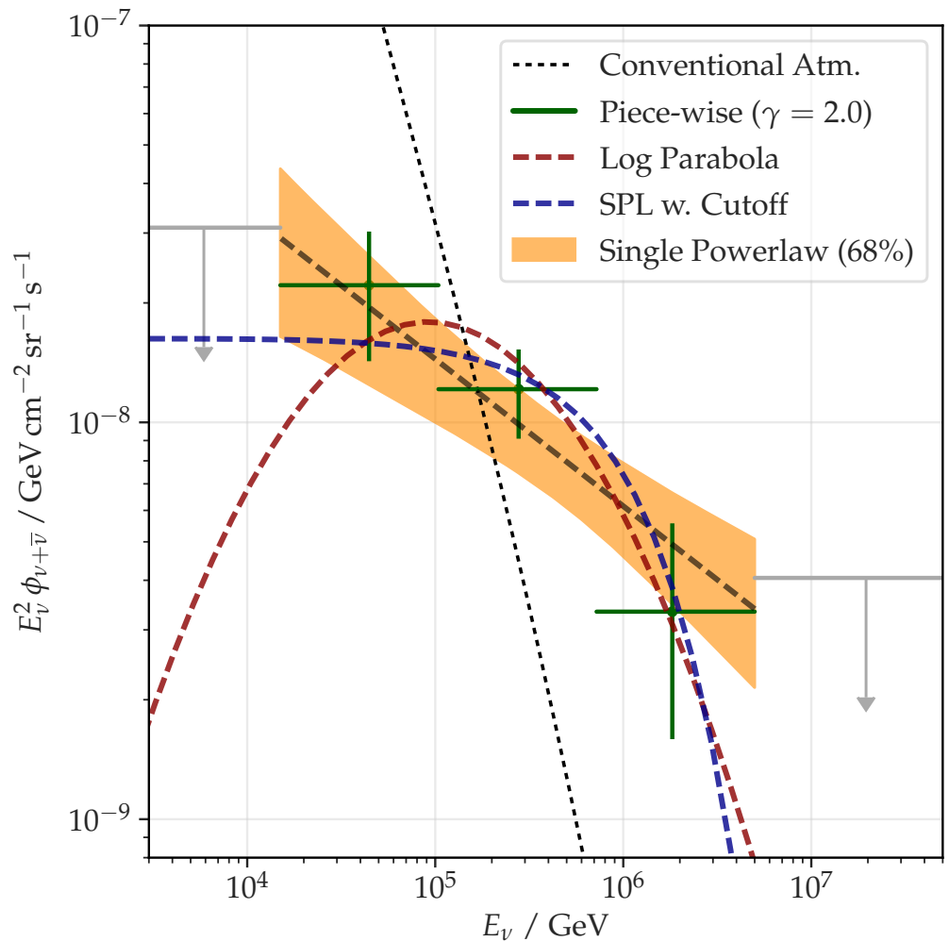
Backup Slides

Isotropic Diffuse Flux





[IceCube, ApJ (2022) 928]



- Diffuse **flux level agrees** across analyses (*within their overlapping energy regions*).
- However, **mild tension between spectral index** for a "vanilla" single power-law flux.

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

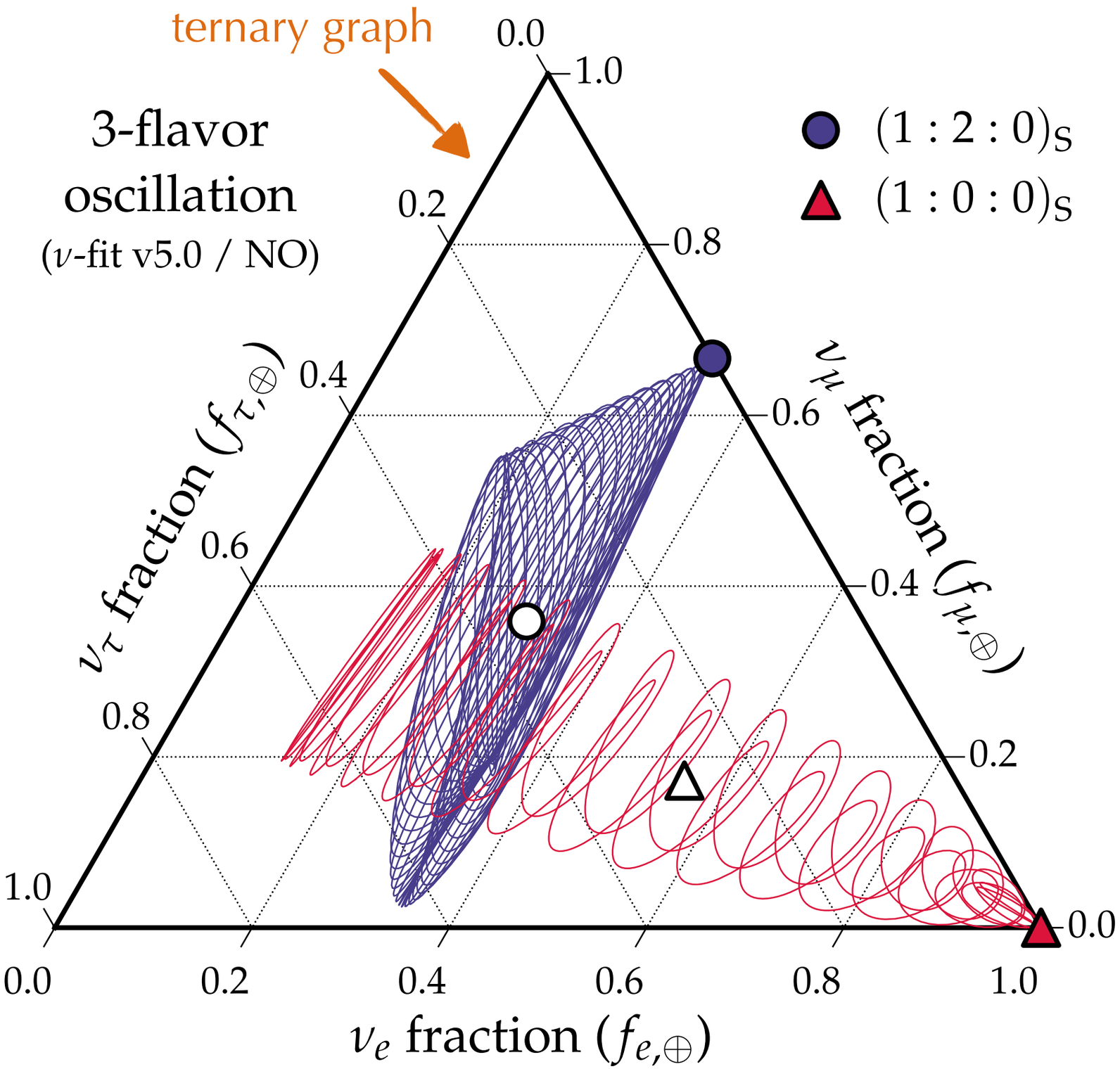
"atmospheric"	~~CP~~ Dirac phase	"solar"	~~CP~~ Majorana
mixing	$\propto \sin\theta_{13}$	mixing	phases

flavour transition probability (in vacuum):

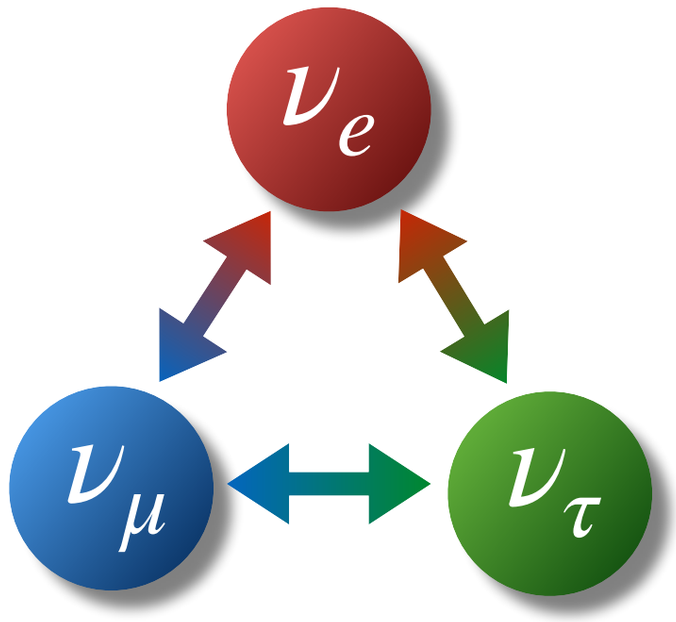
$$P_{\nu_\alpha \to \nu_\beta}(\ell) = \sum_{i=1}^{3}\sum_{j=1}^{3} U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j} \exp\left(i\frac{\Delta m^2_{ij}\ell}{2E_\nu}\right)$$

notation: $c_{ij} \equiv \cos\theta_{ij}$ & $s_{ij} \equiv \sin\theta_{ij}$ & $\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Astrophysical Flavours



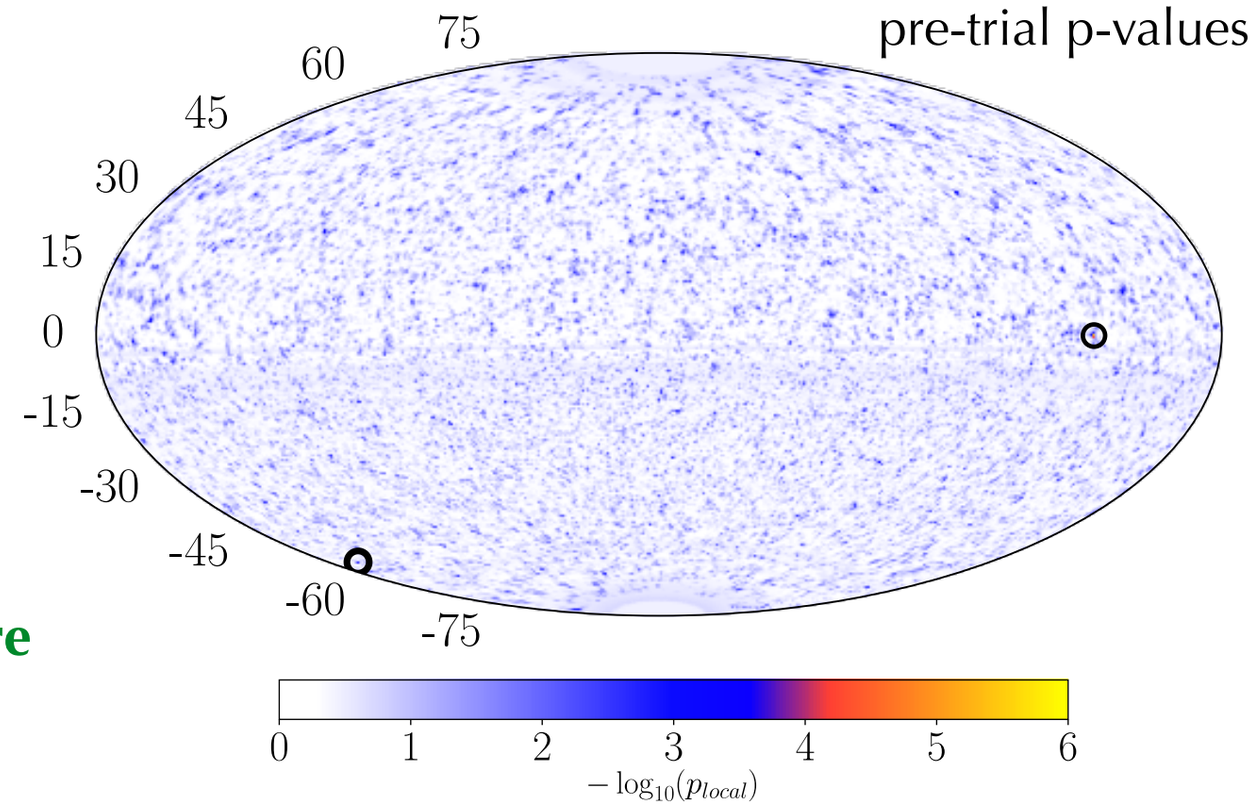
Superposition of flavor and mass states induce oscillations.



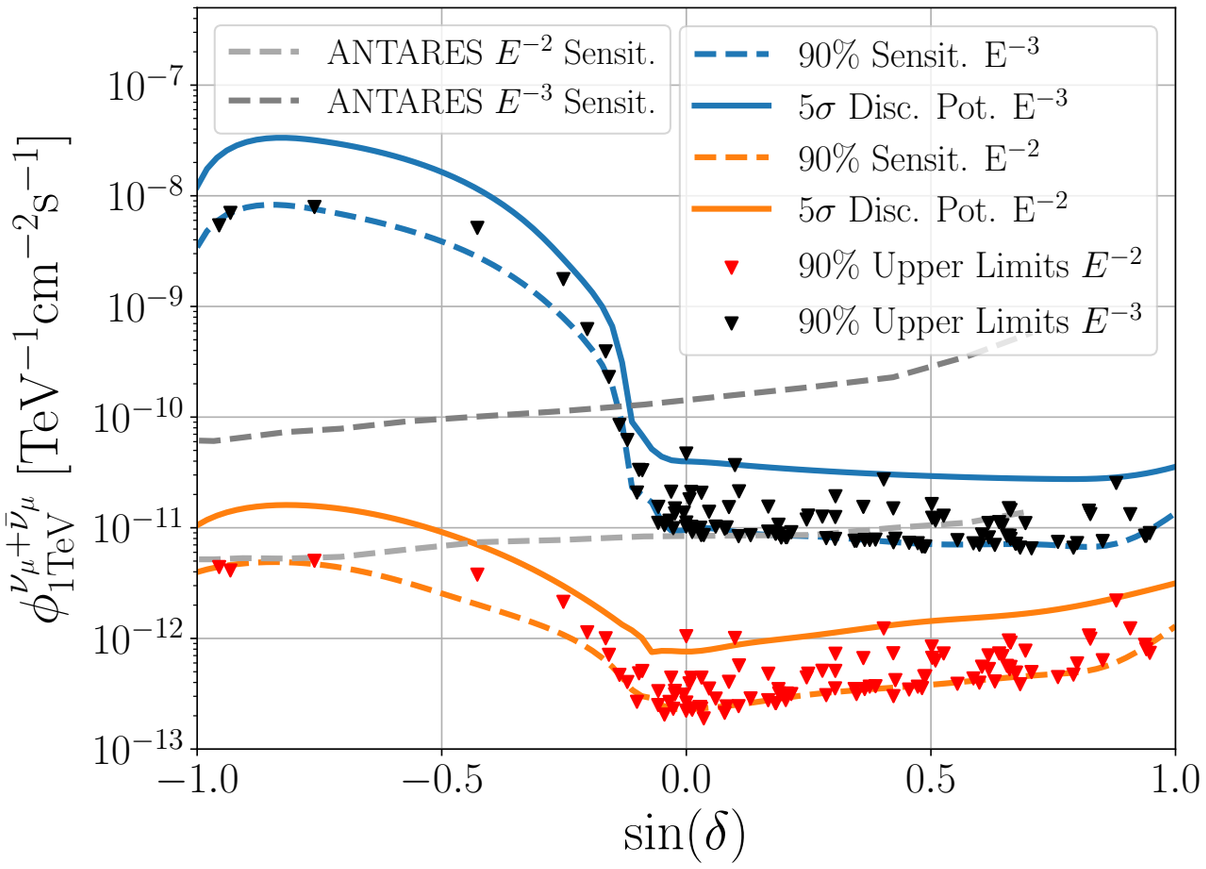
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT
with complementary field of views.

Southern Hemisphere | Northern Hemisphere

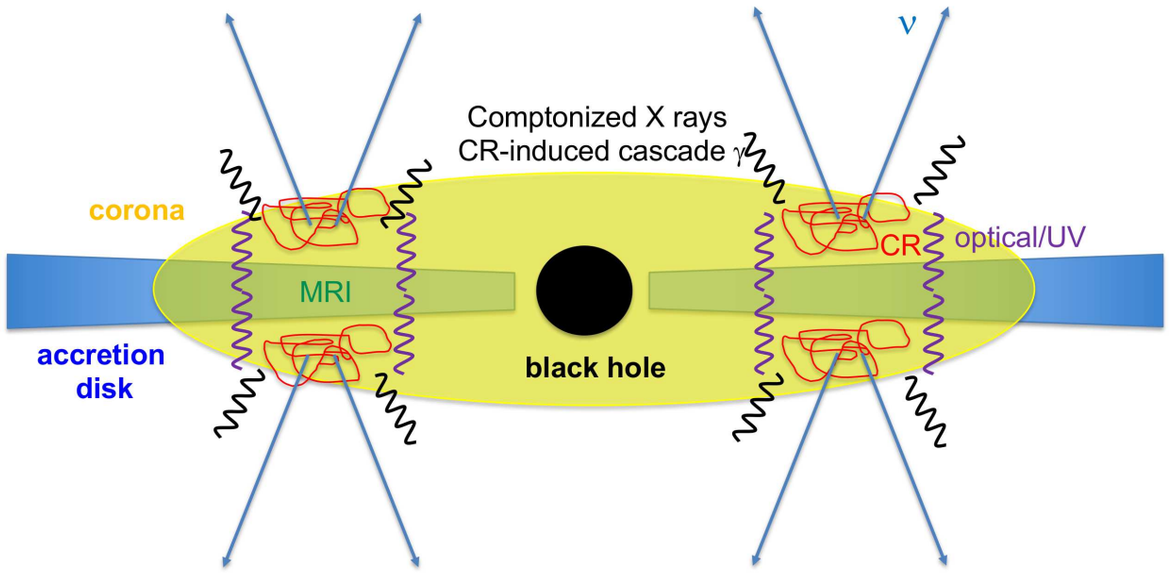


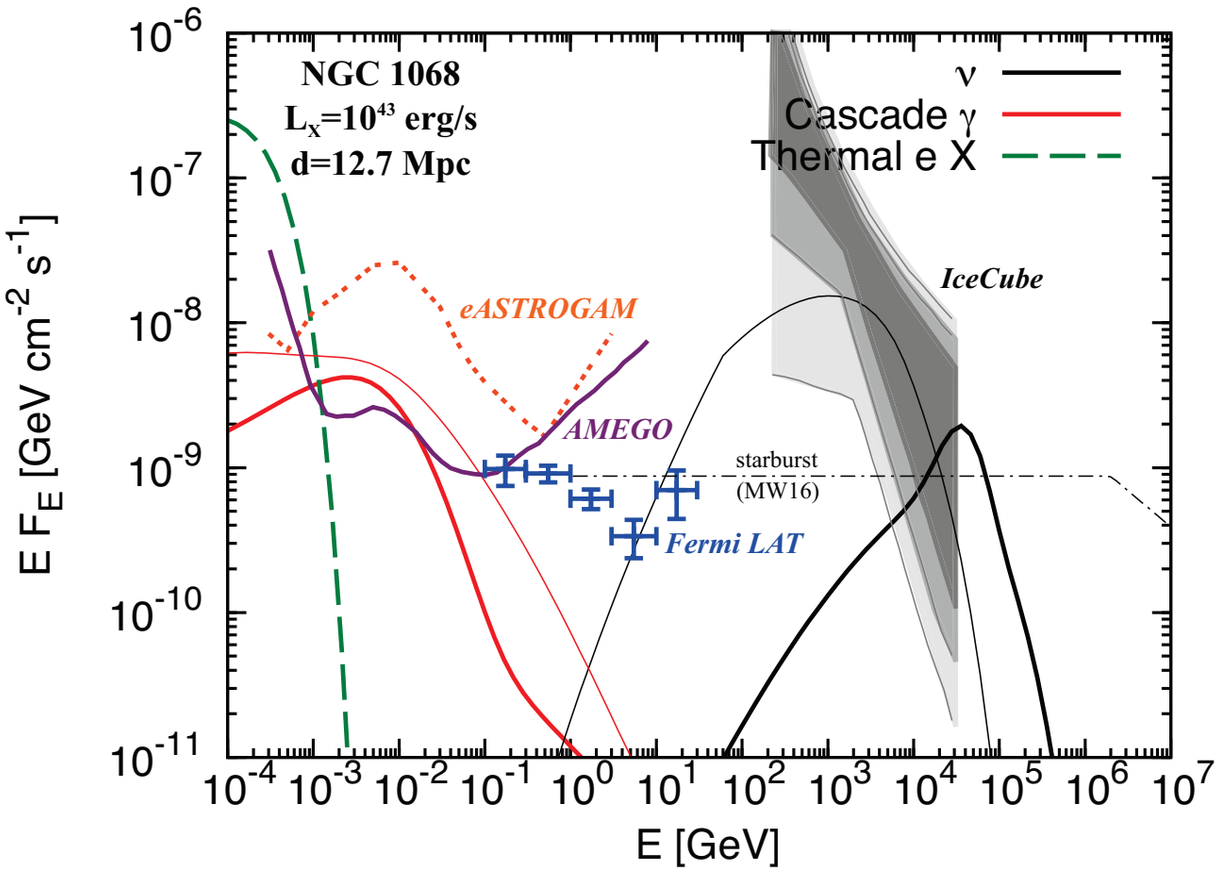
[IceCube, PRL 124 (2020) 5]



- **No significant** time-integrated point sources emission in all-sky search.
- **No significant** time-integrated emission from known Galactic and extragalactic high-energy sources, but interesting candidates, *e.g.* NGC 1068.

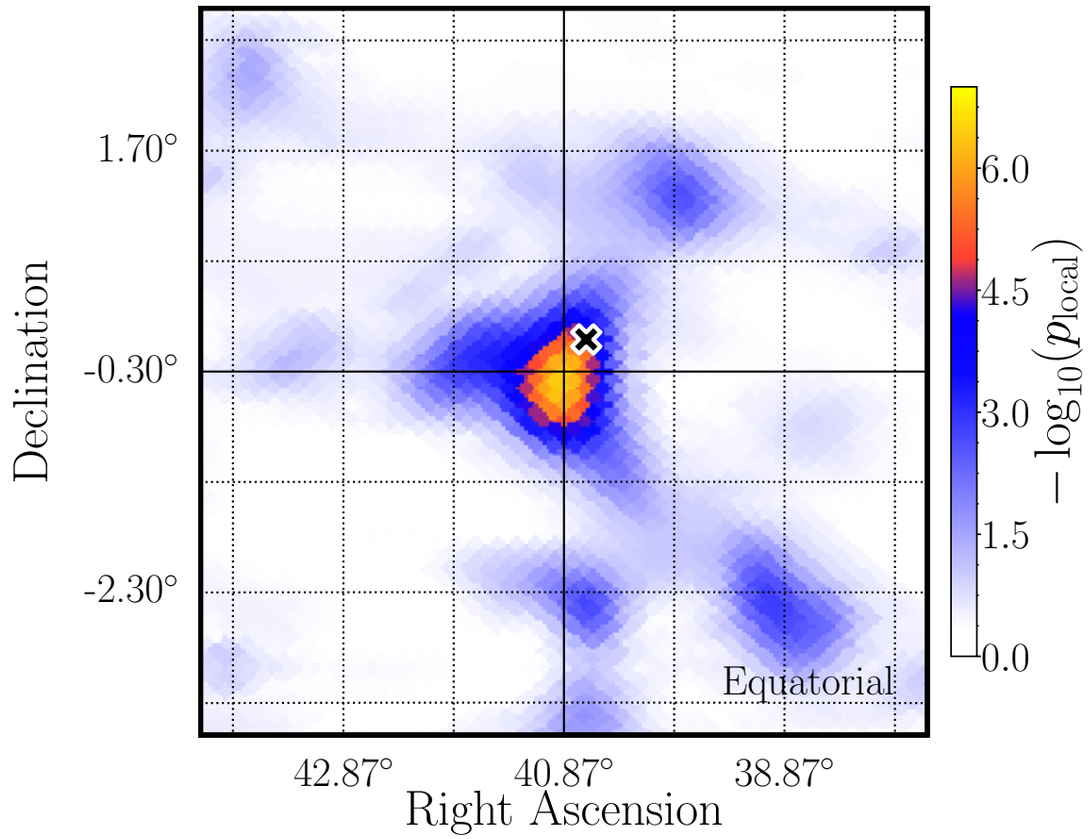
Northern Hot Spot





[Murase, Kimura & Meszaros, PRL 125 (2020)]

- Northern hot spot in the vicinity of the AGN **NGC 1068** has a **significance of** 3.3σ
- Emission can be modelled via stochastic **CR acceleration in AGN coronae.**

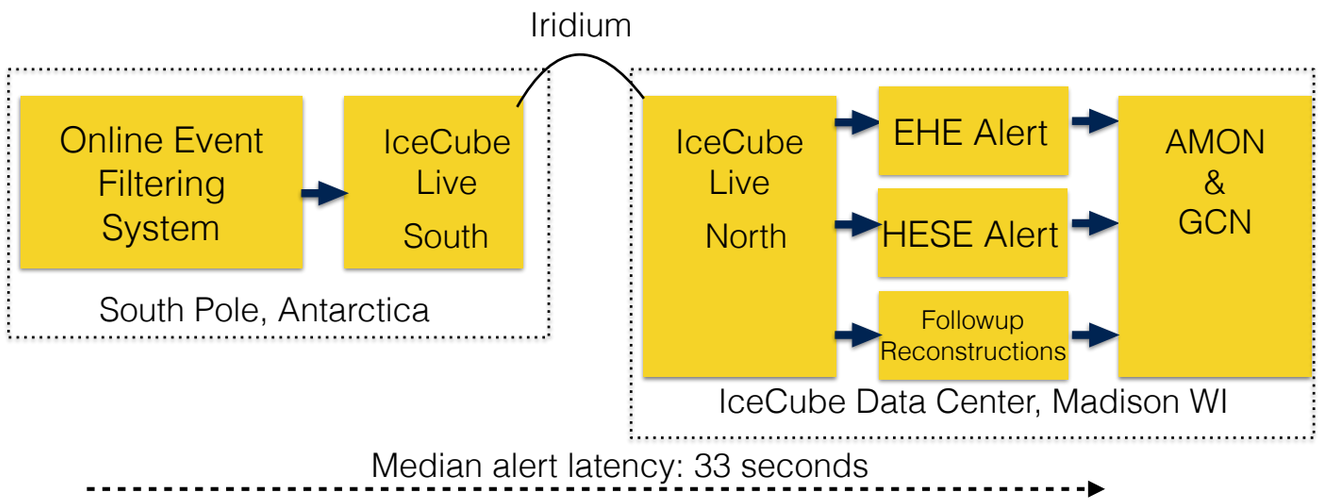


[IceCube, PRL 124 (2020) 5]

Realtime Neutrino Alerts

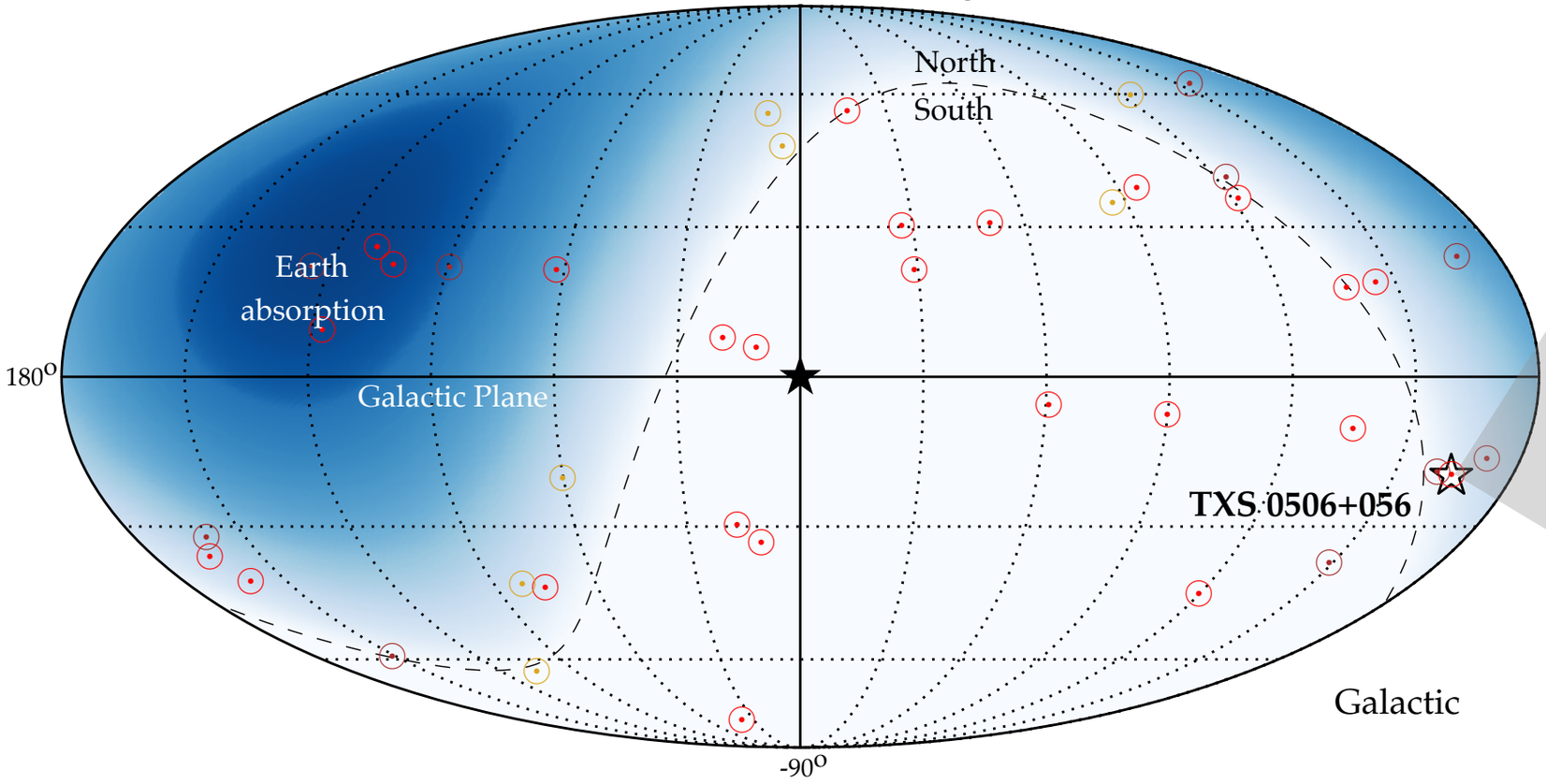
Low-latency (<1min) **public neutrino alert system** established in April 2016.

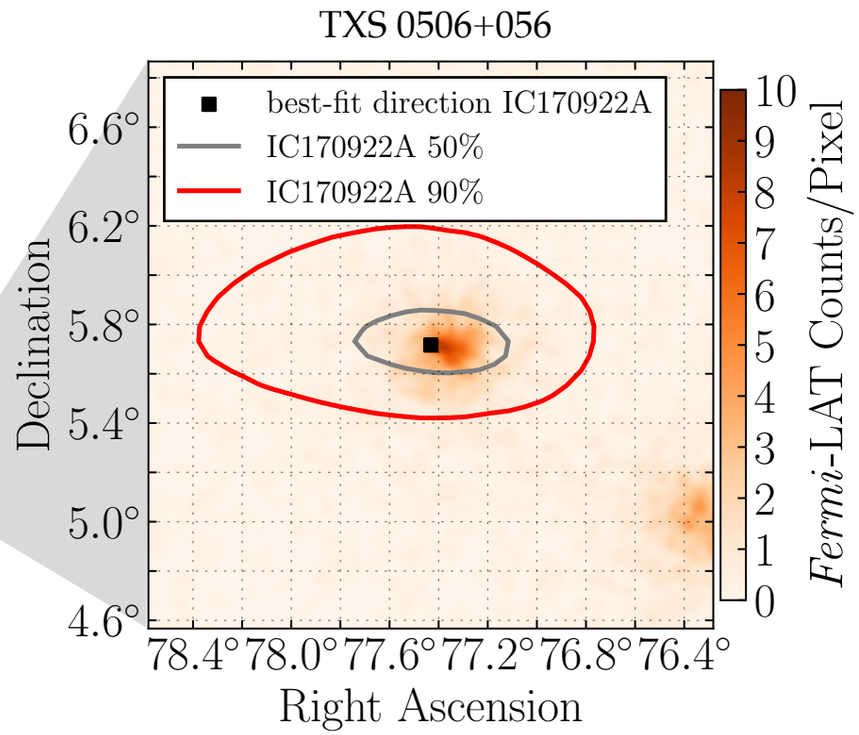
- **Gold alerts:** ~10 per year
  >50% signalness
- **Bronze alerts:** ~20 per year
  30-50% signalness



[IceCube, PoS (ICRC2019) 1021]

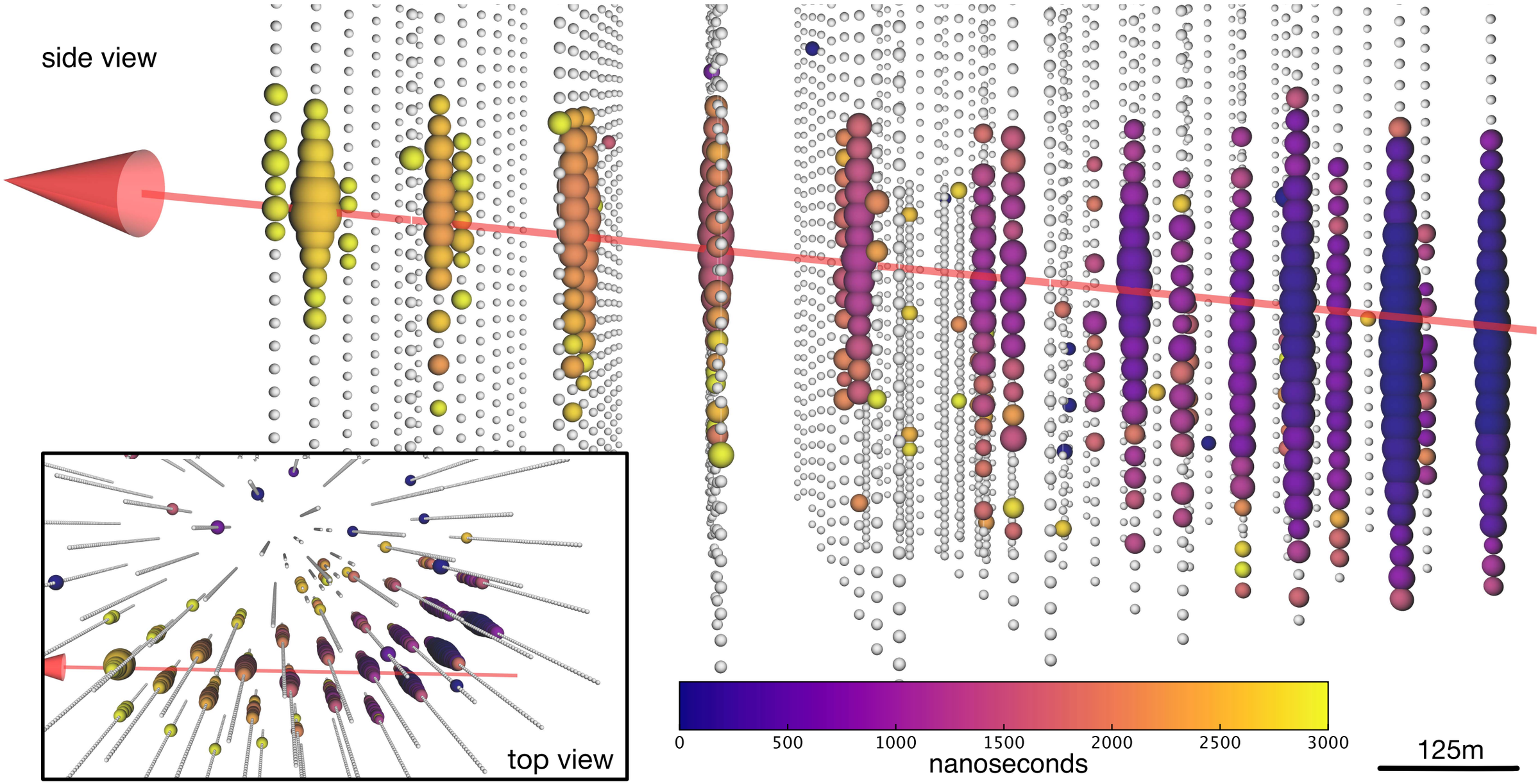
Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))





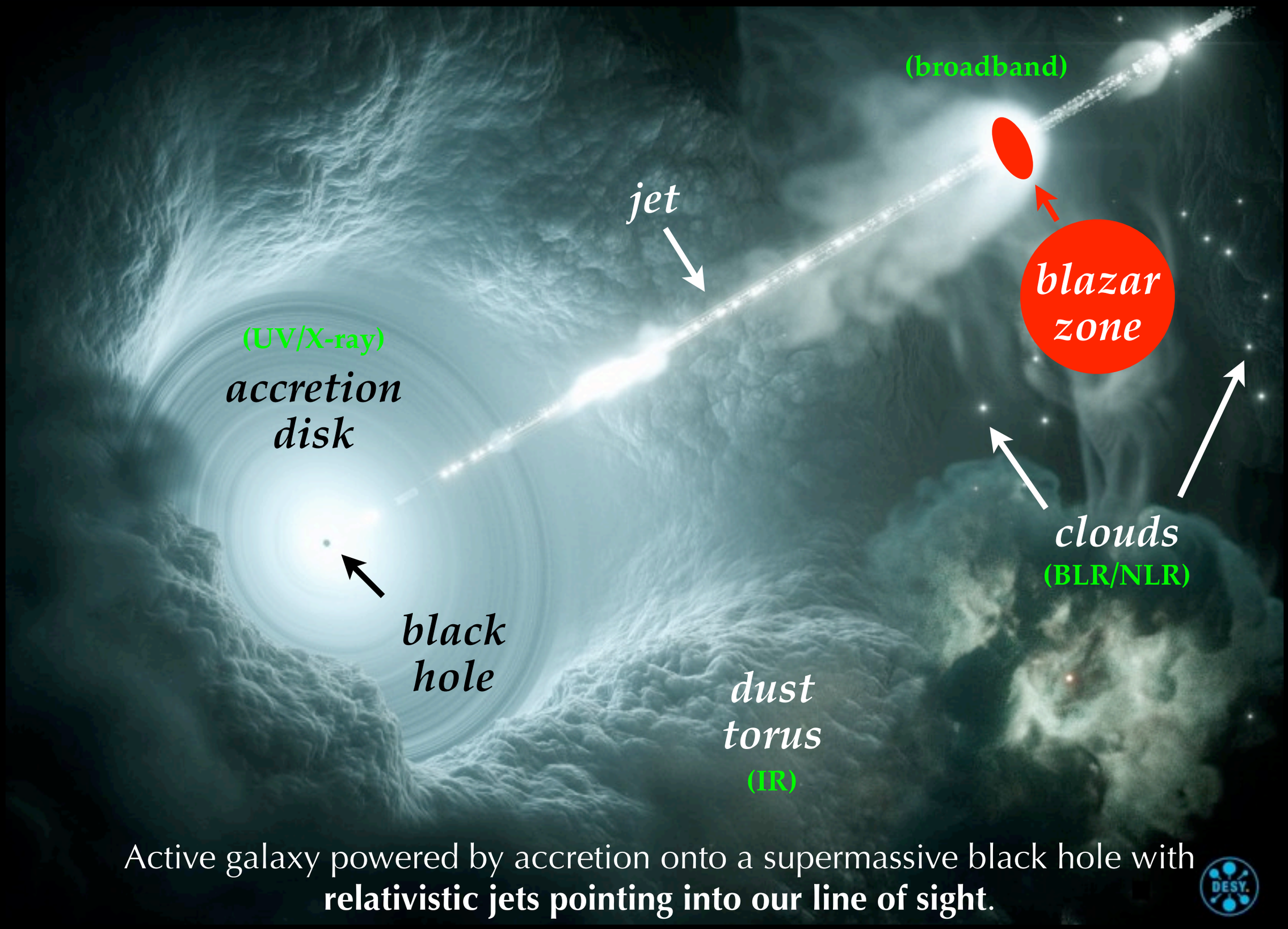
Realtime Neutrino Alerts

IC-170922A



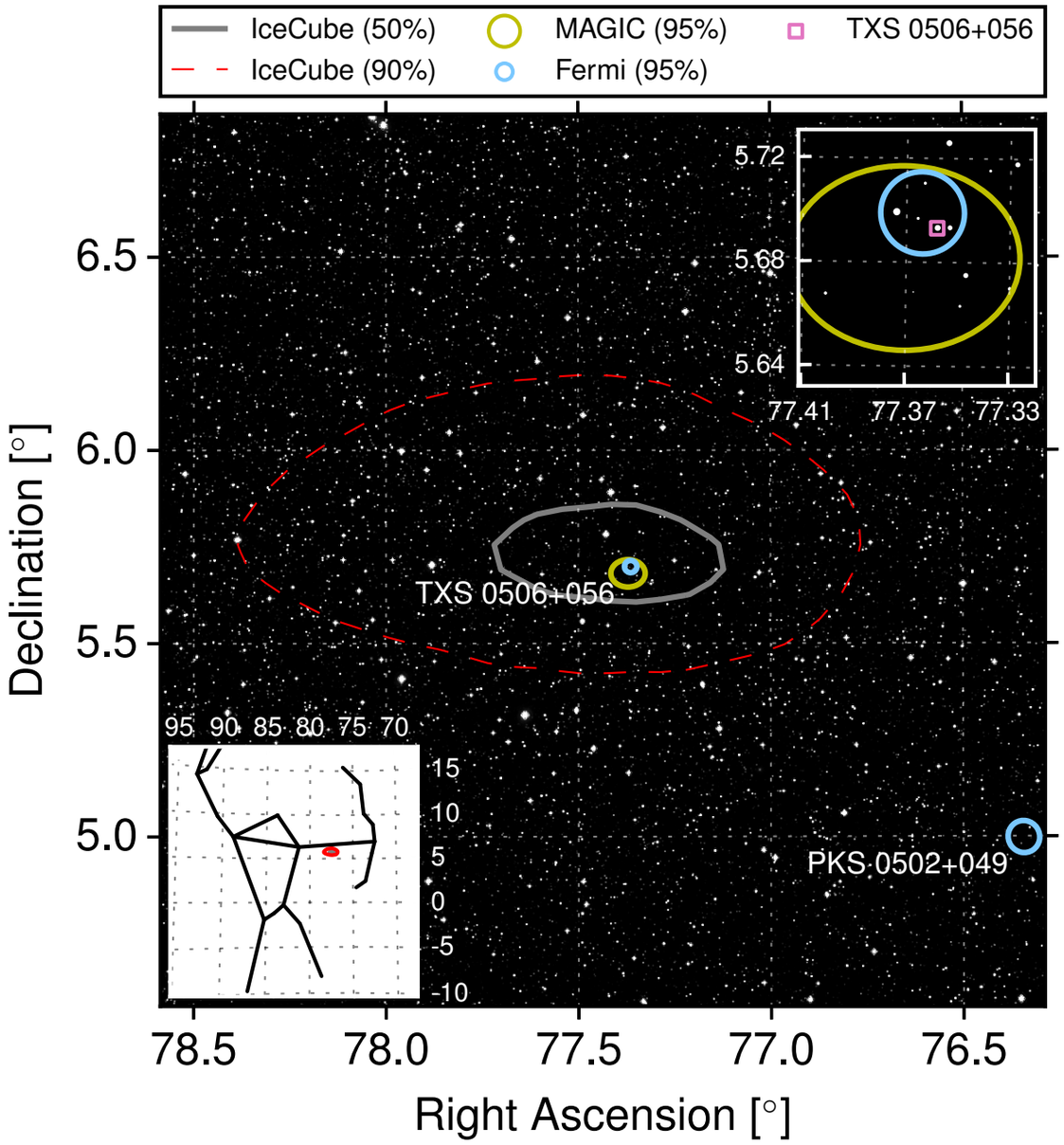
up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

Blazars



Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

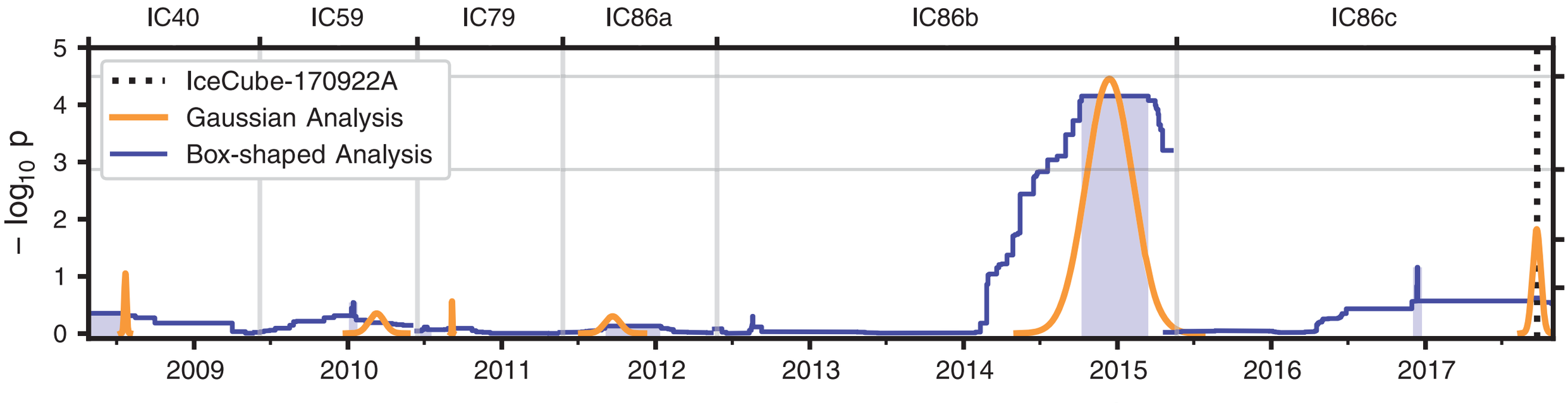
TXS 0506+056



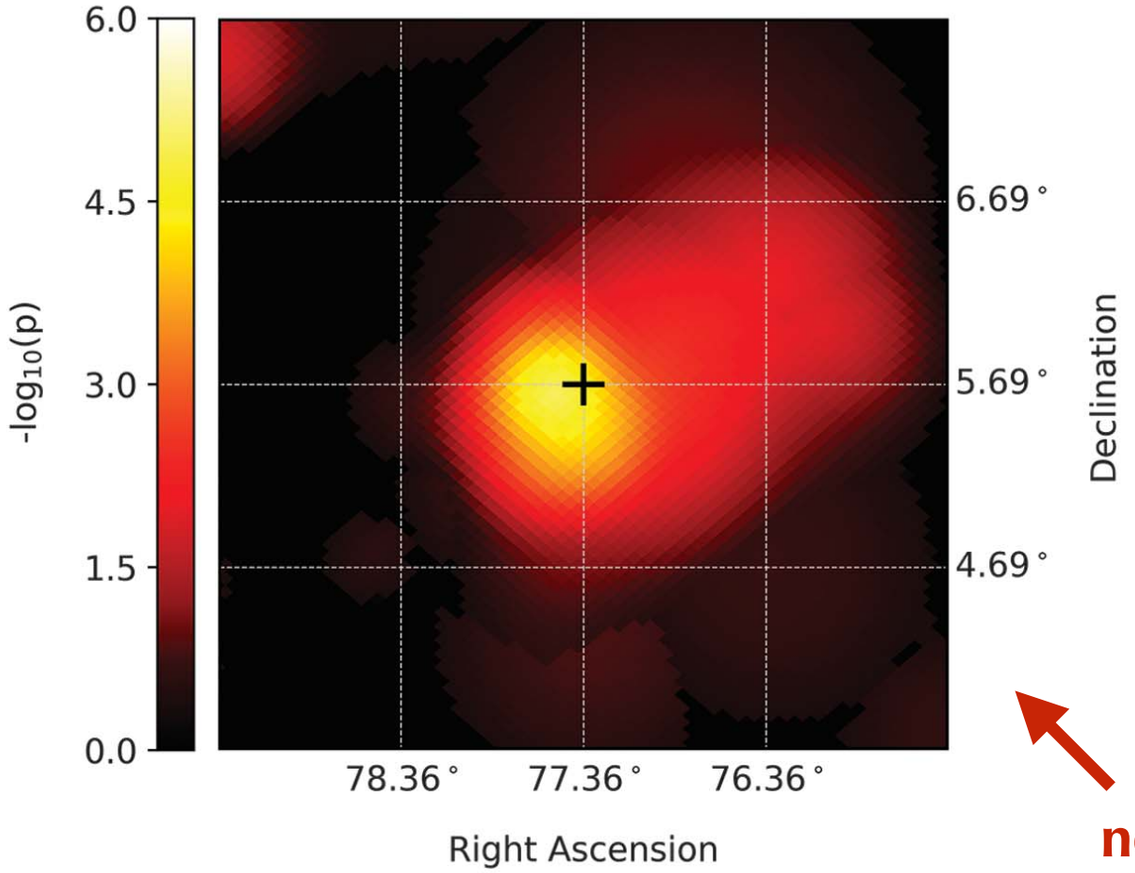
[IceCube++, Science 361 (2018) 6398]

- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Neutrino Flare in 2014/15



[IceCube, Science 361 (2018) 6398]

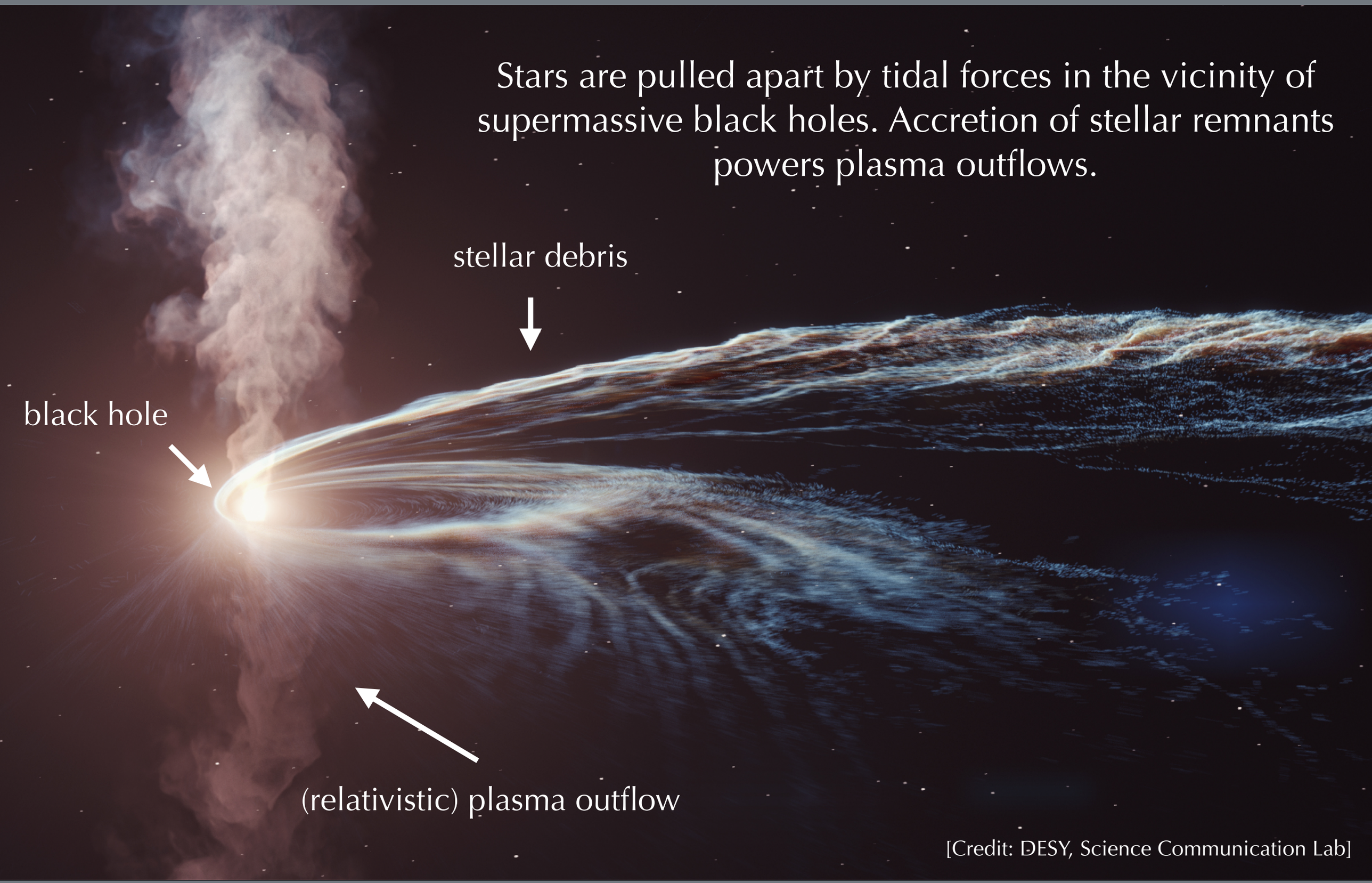


- Independent 3.5σ evidence for a **neutrino flare** (13±5 excess events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of Fermi-LAT γ-rays**.

neutrino "morphology" of 2014/15 flare

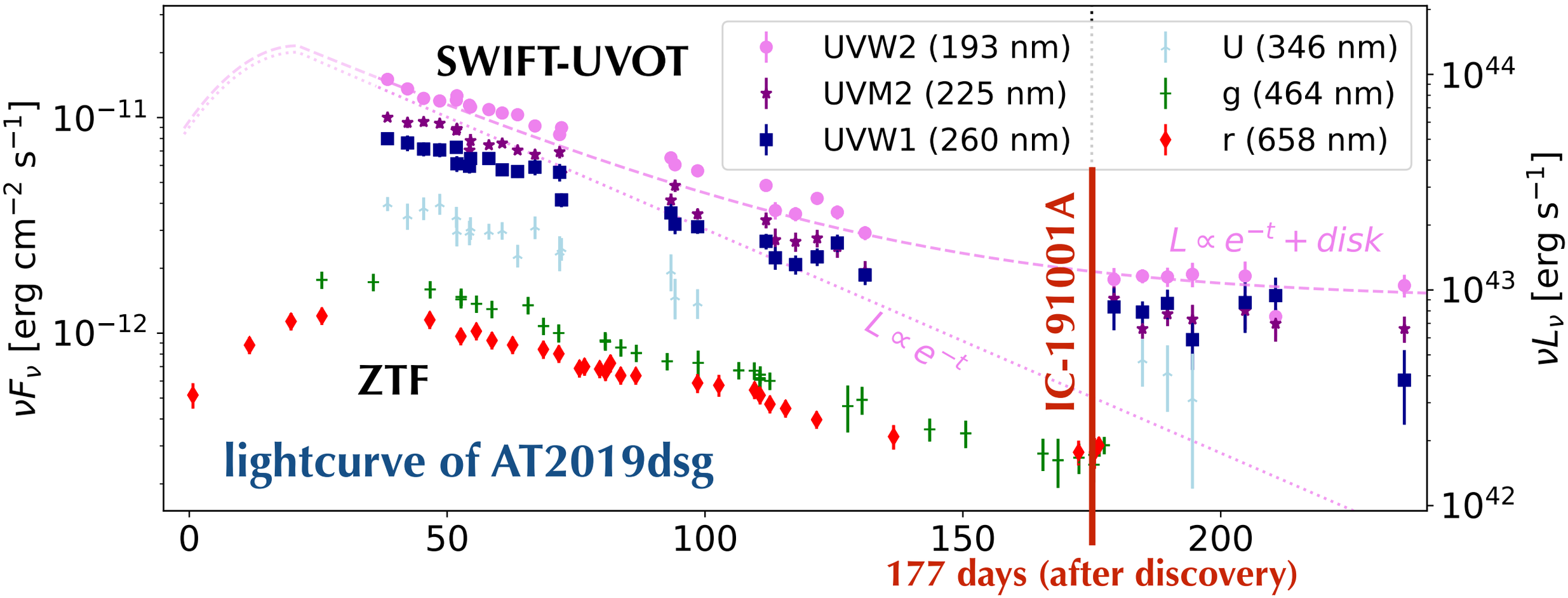
Tidal Disruption Events

Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants powers plasma outflows.



[Credit: DESY, Science Communication Lab]

Tidal Disruption Events

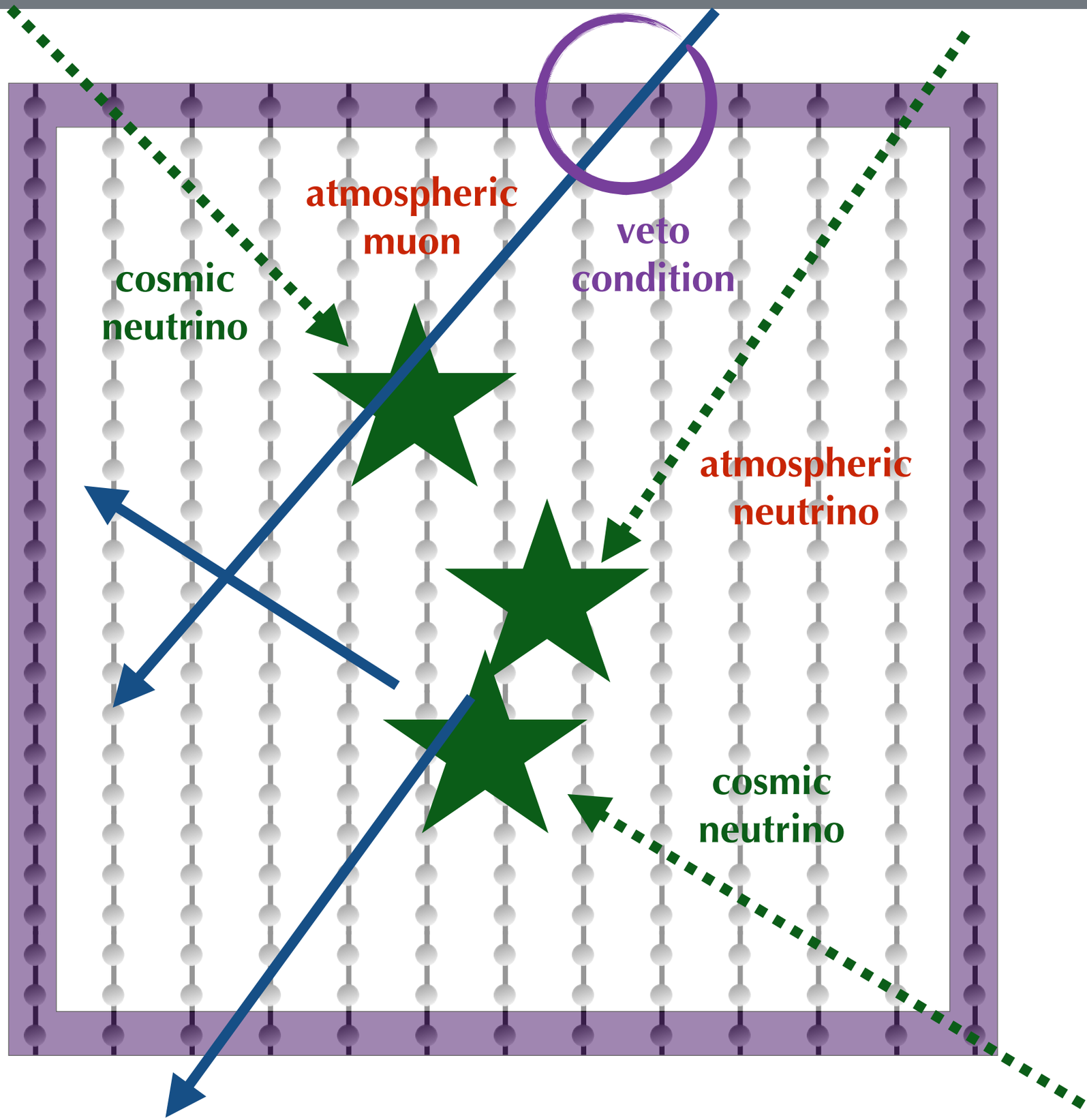


- Association of IC-191001A with TDE AT2019dsg and IC-200530A with AT2019fdr.
- Plot shows optical/UV data from Zwicky-Transient Facility (ZTF) and SWIFT-UVOT for AT2019dsg
- Combined **chance for random correlation** of TDEs and IceCube alerts is **0.034%**.

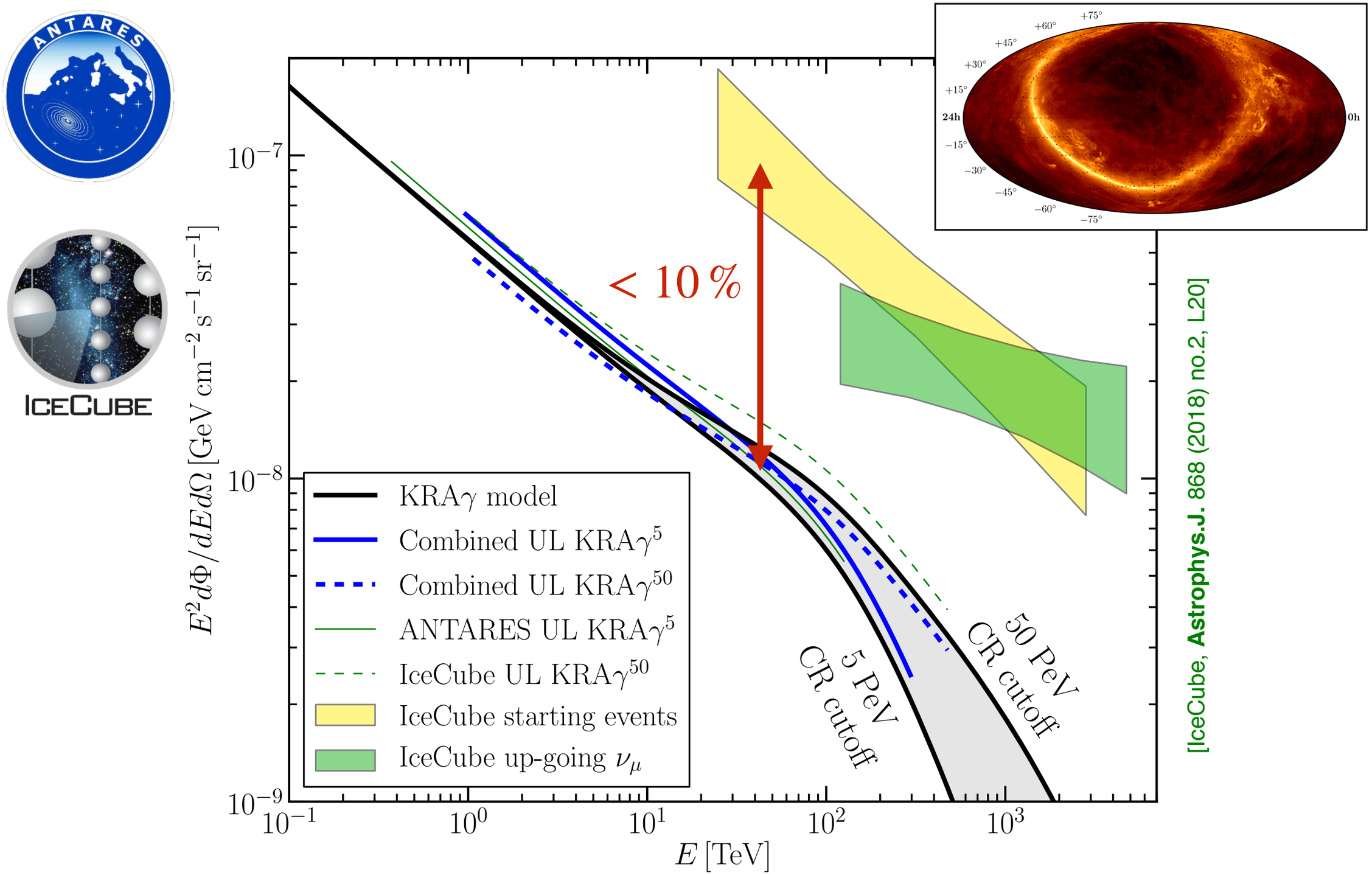
[Stein et al. Nature Astron. 5 (2021) 5; Reusch et al. arXiv:2111.09390]

Neutrino Selection II

- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis

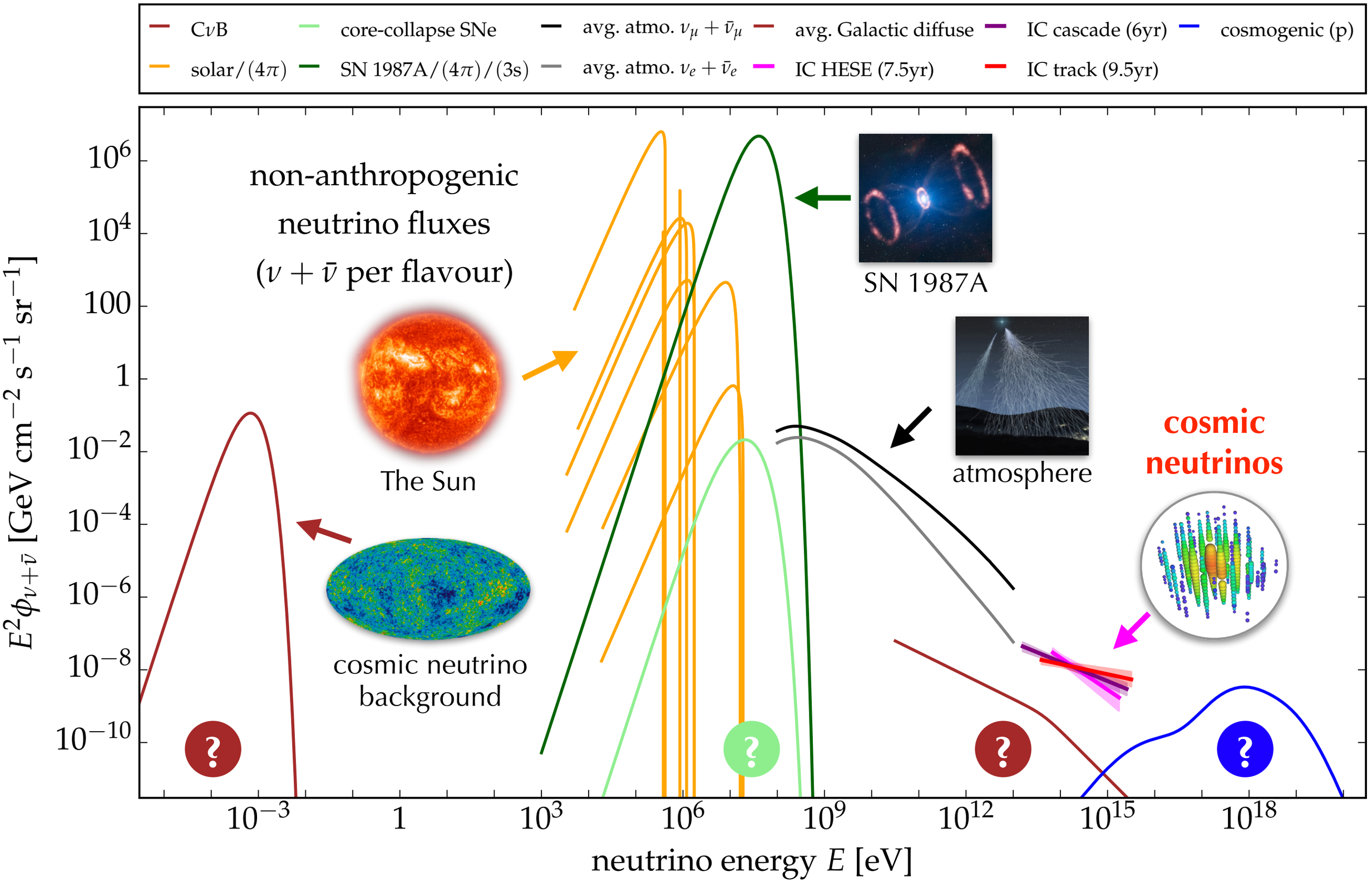


Galactic Neutrino Emission

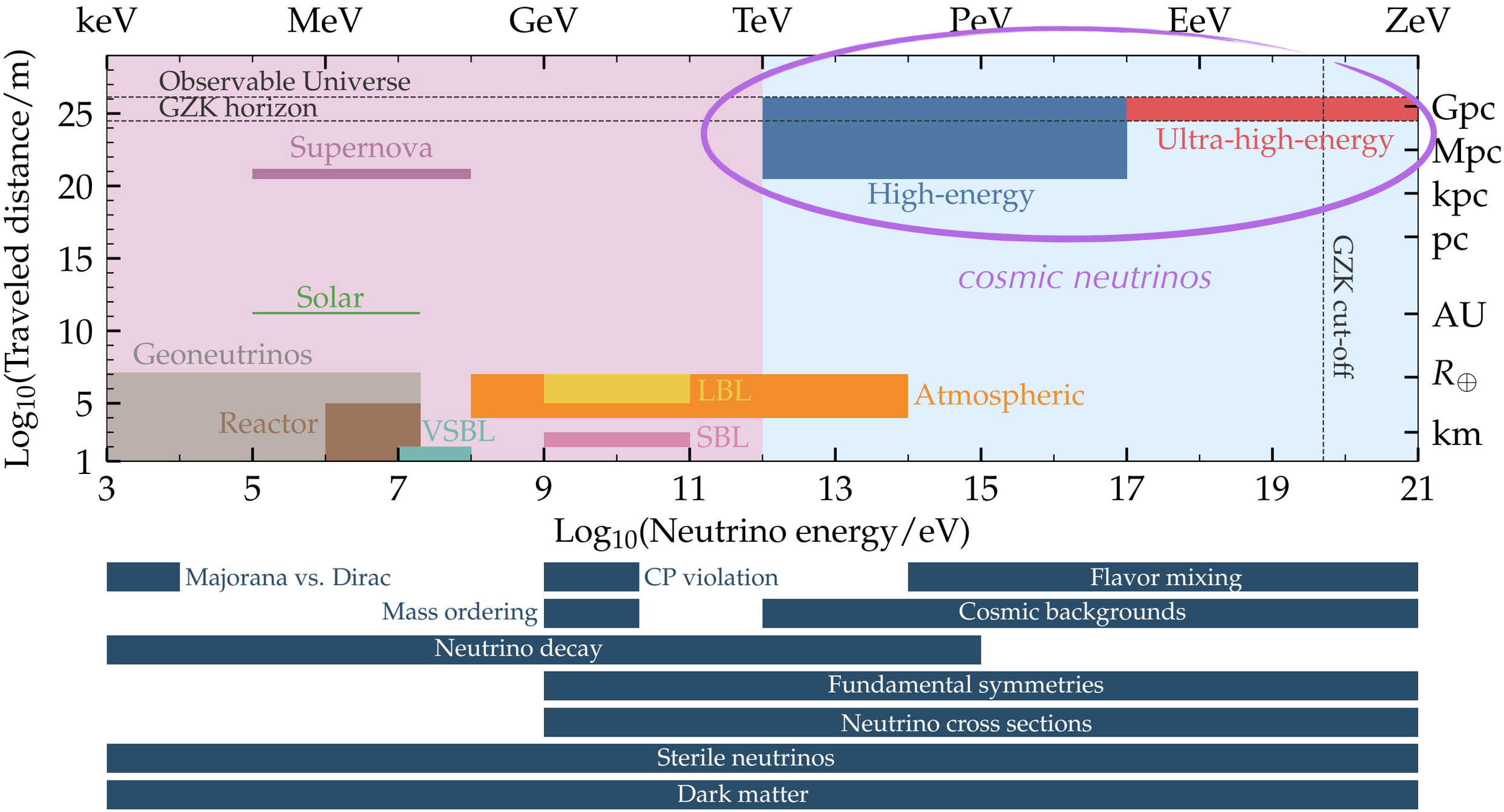


Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Astrophysical Neutrino Fluxes



Probe of Fundamental Physics



[Ackermann, MA, Anchordoqui, Bustamante *et al., Astro2020* arXiv:1903.04334]