IceCube Experiment
&
Particle & Astroparticle Phenomenology

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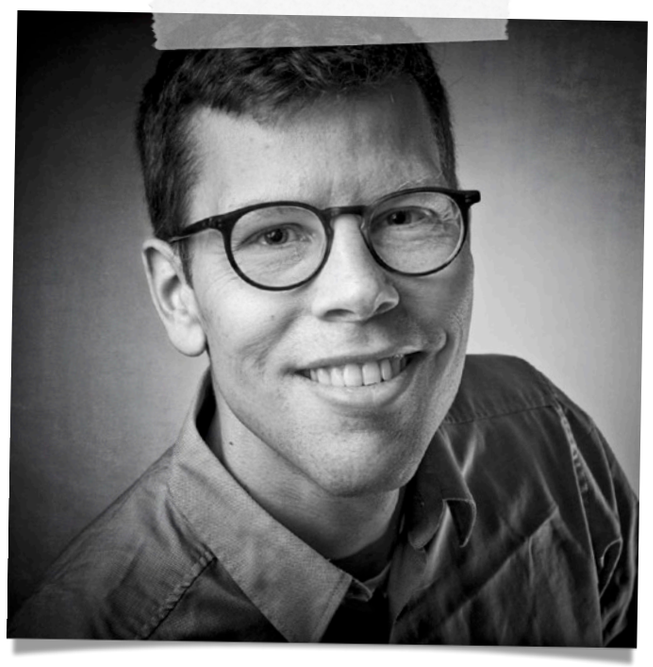

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The Elusive Neutrino

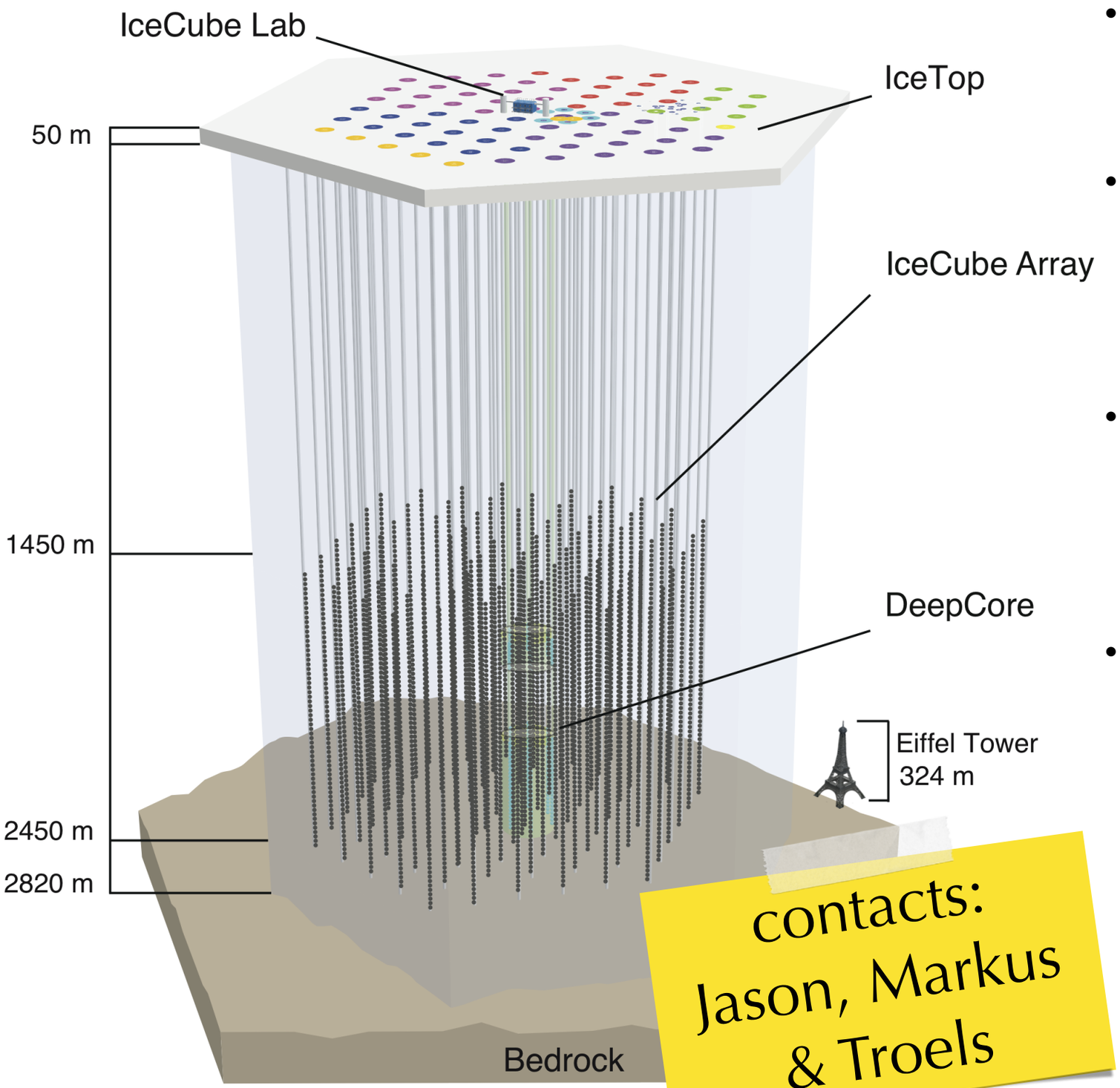
- **three neutrino flavours**
- very small masses *(unknown origin)*
- large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **unique probe of high-energy astrophysics**

Standard Model of Particle Physics

1968: SLAC **u** up quark	1974: Brookhaven & SLAC **c** charm quark	1995: Fermilab **t** top quark	1979: DESY **g** gluon
1968: SLAC **d** down quark	1947: Manchester **s** strange quark	1977: Fermilab **b** bottom quark	1923: Washington γ photon
19[illegible]: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1897: Cavendish [illegible] e electron	1937: Caltech & Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson

(+ Higgs boson)

IceCube Observatory

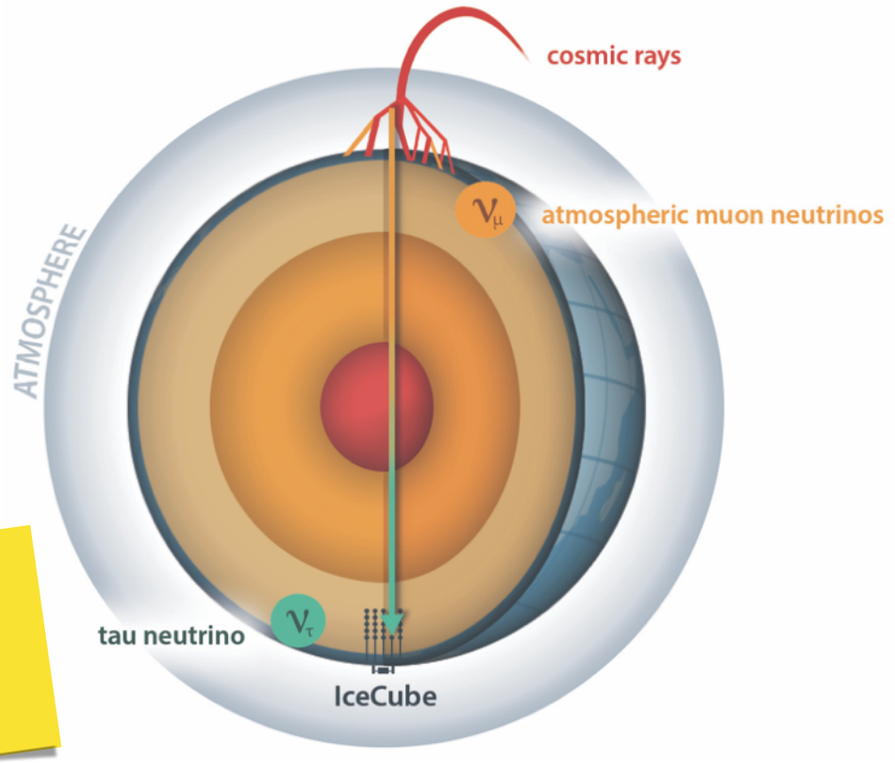


contacts:
Jason, Markus
& Troels

- **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*
  - *non-standard ν phenomena*
  - ***IceCube Upgrade*** *(from '25)*

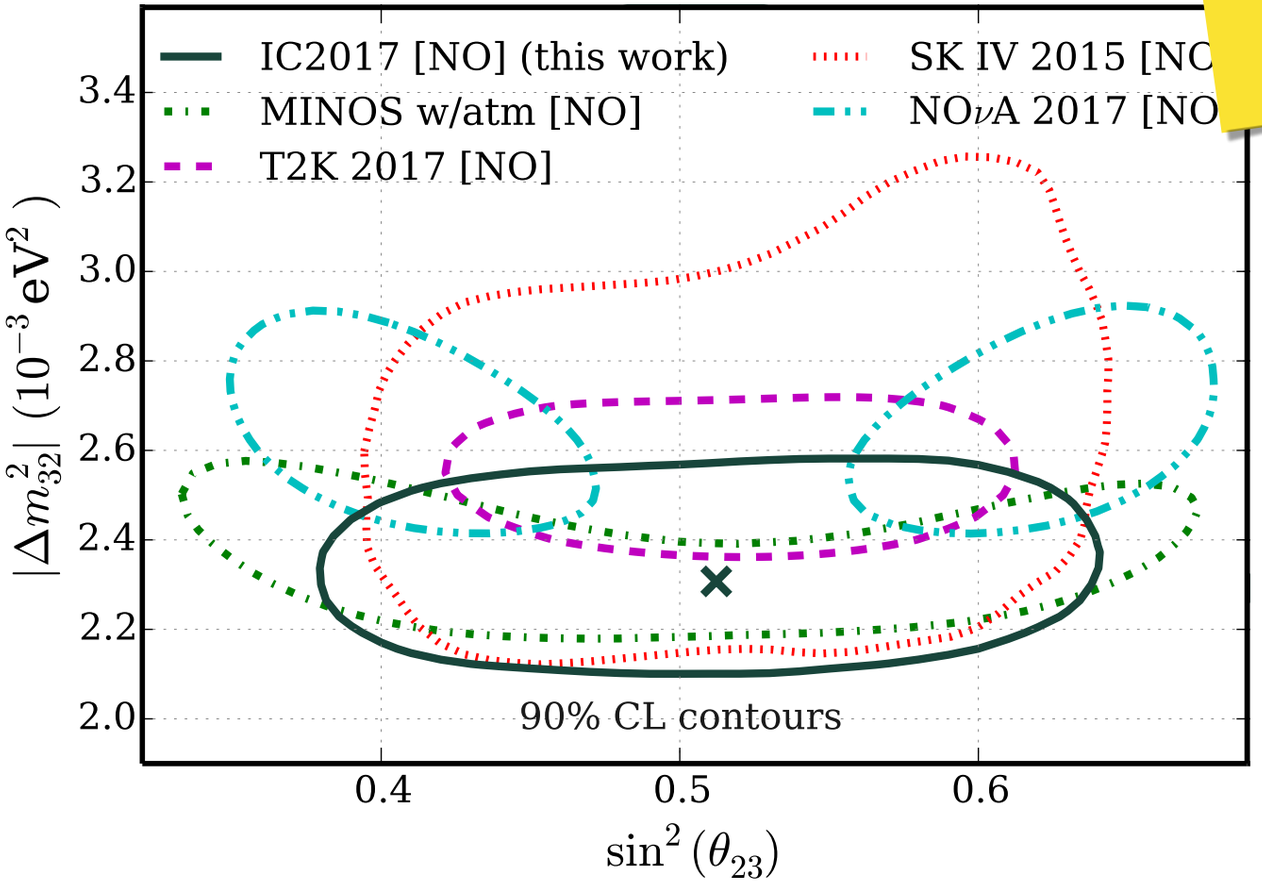
Atmospheric Neutrino Oscillations

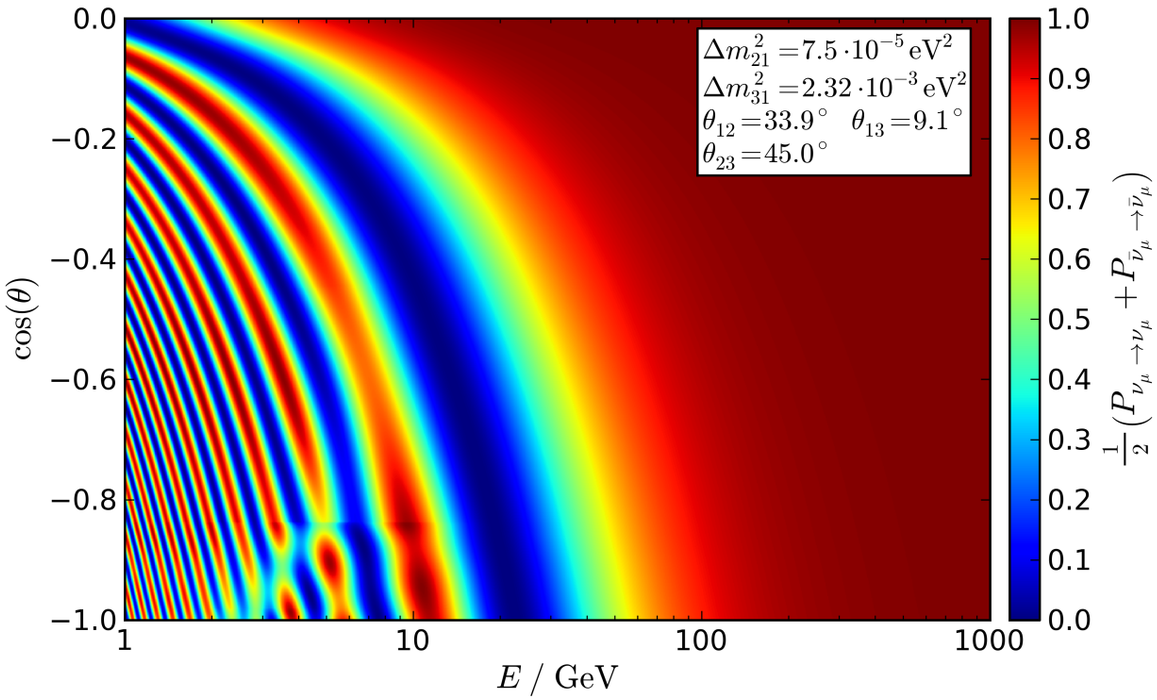
- **Muon neutrino disappearance** in the 1-100 GeV range allows for precision measurement of atmospheric mixing parameters.
- **IceCube @ NBI** leads the current generation of oscillation analyses with DeepCore data.



contact: Jason

[IceCube, PRL 120 (2018) 7]

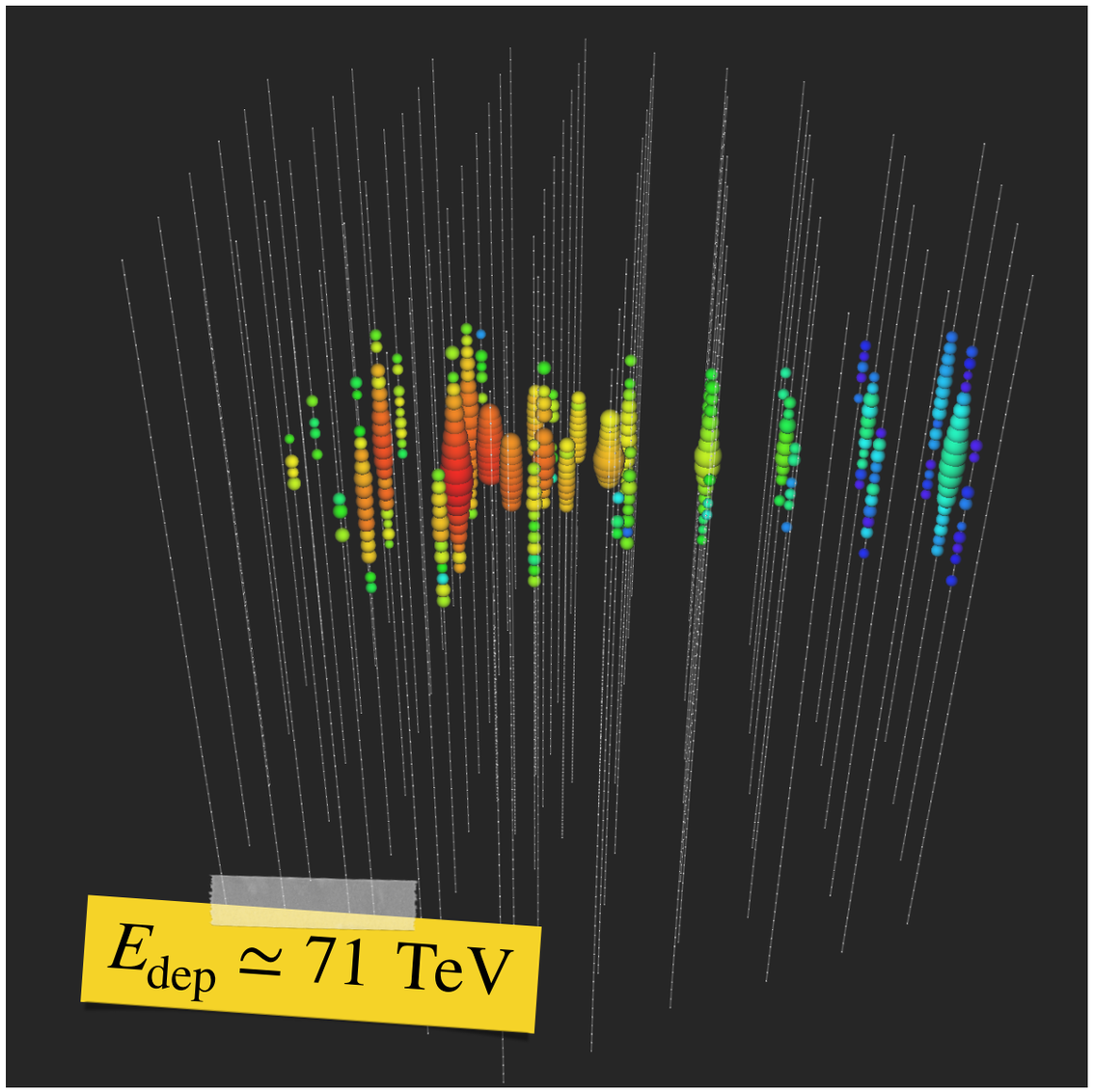




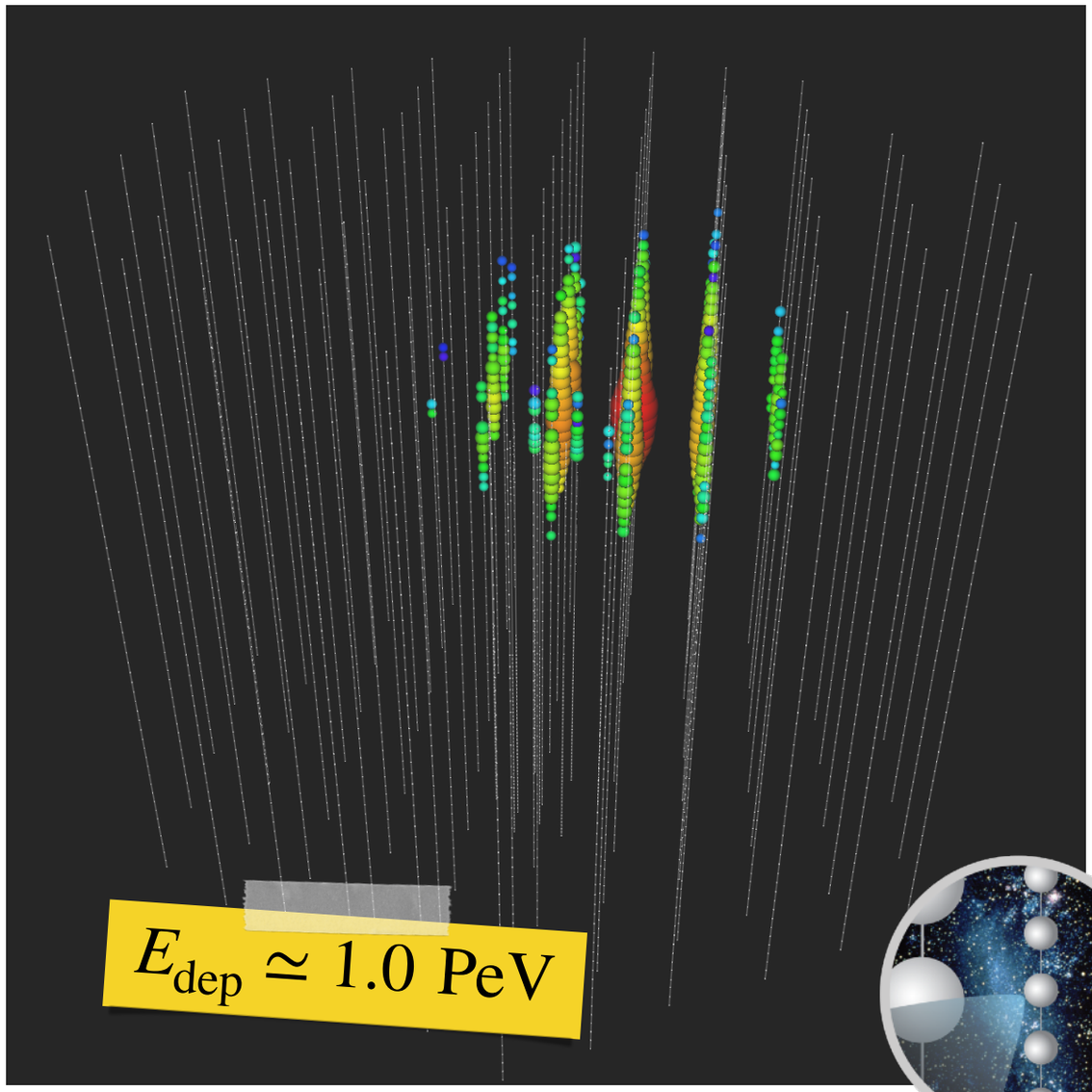
Astrophysical Neutrinos

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)



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

Event Reconstructions

contact: Troels

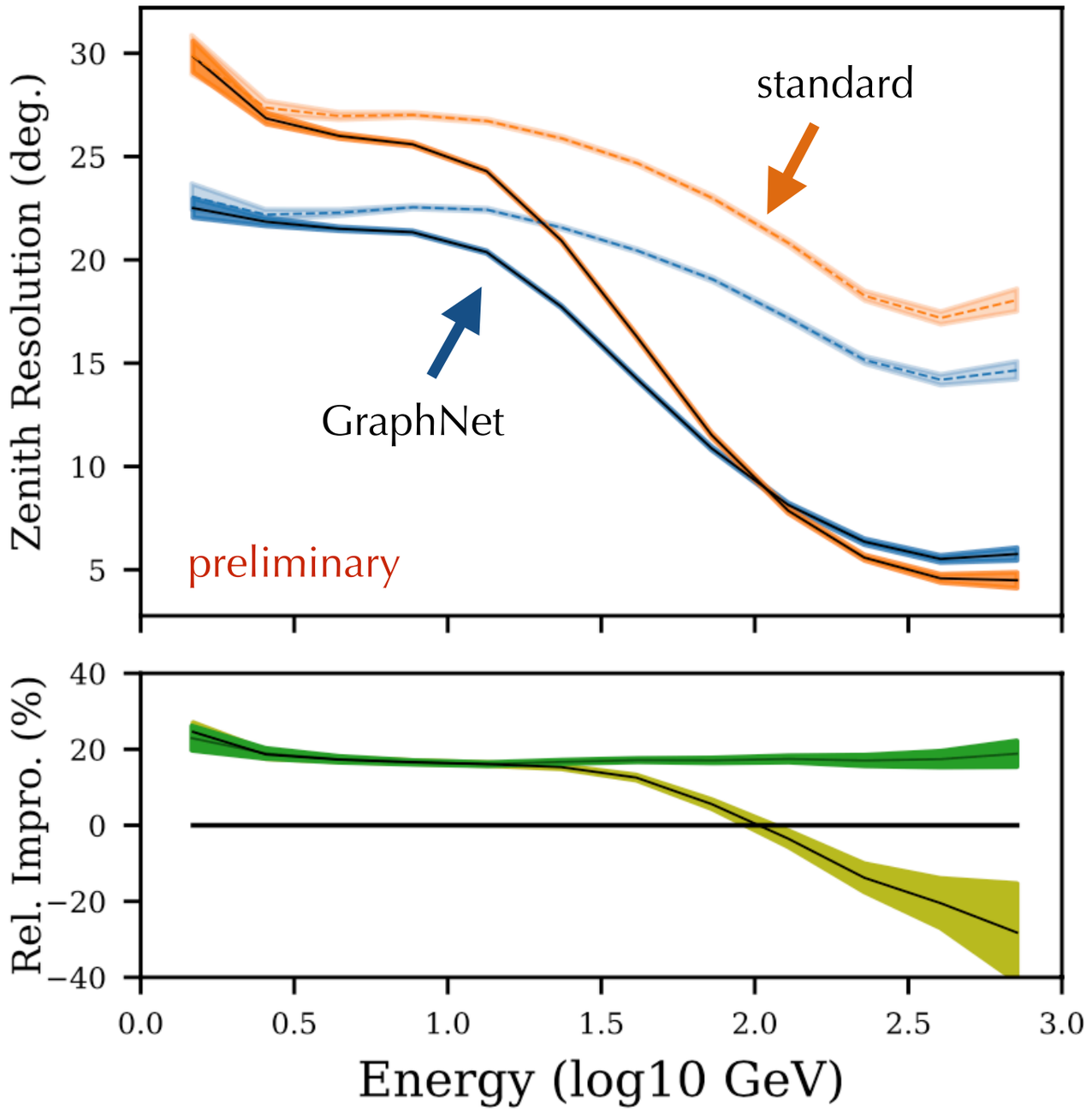
- Improved angular and energy reconstructions are a key to improve sensitivities of neutrino telescopes.
- **Machine-learning tools**, *e.g.* based on graph neural networks are paving the way for future analyses with DeepCore data and IceCube-Upgrade.

GraphNeT

Graph Neural Networks for Neutrino Telescope Event Reconstruction

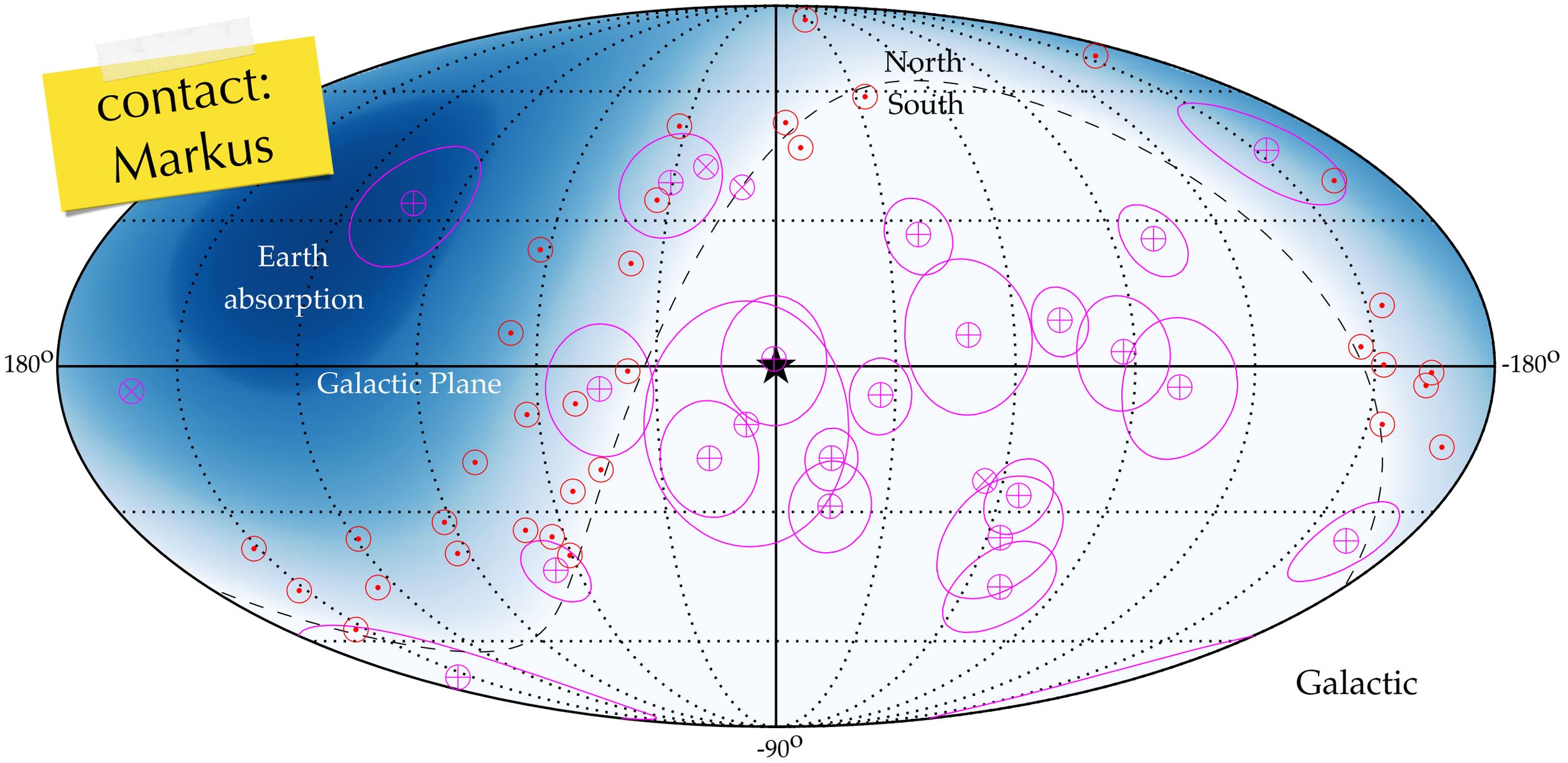
https://github.com/icecube/graphnet/

Angular reconstructions with **GraphNet**



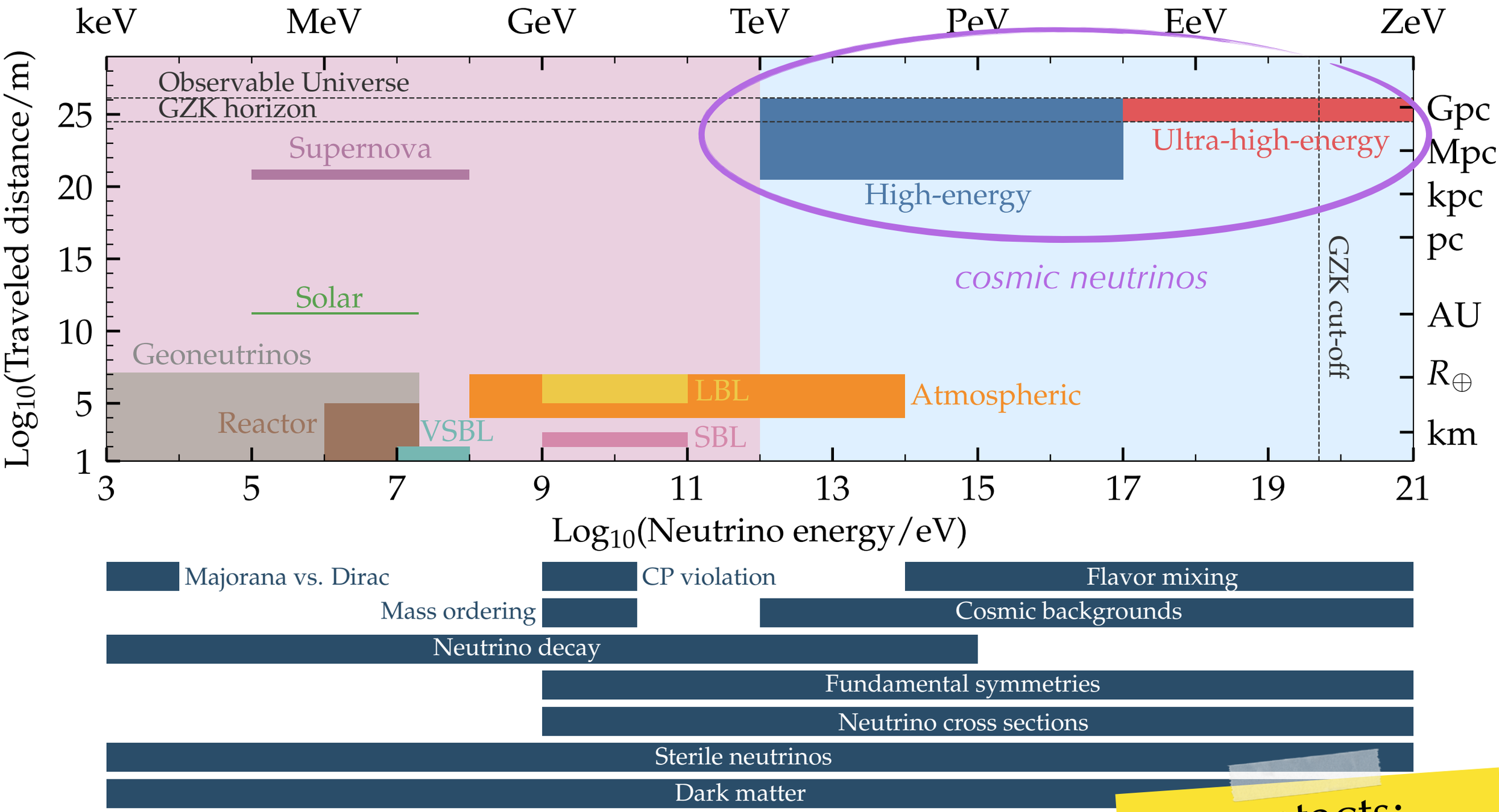
Neutrino Astrophysics

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



No significant steady or transient emission from known Galactic and extragalactic high-energy sources (*except for one candidate*).

Probe of Fundamental Physics

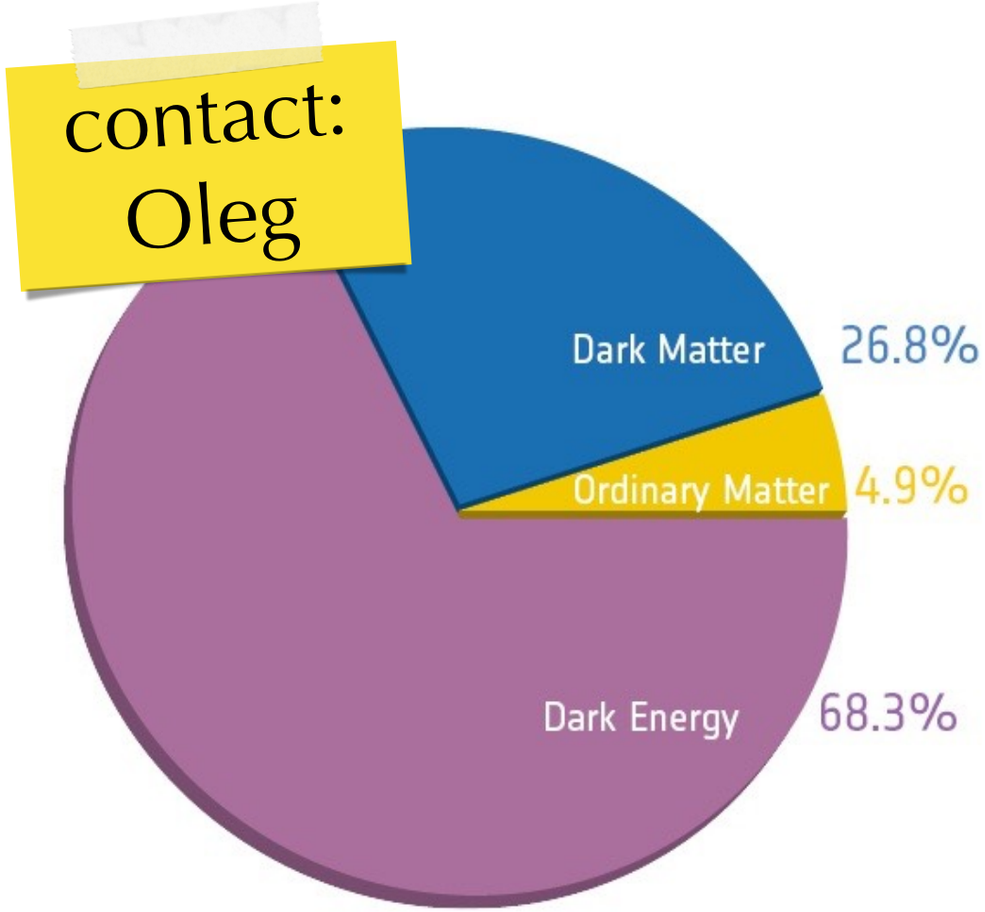


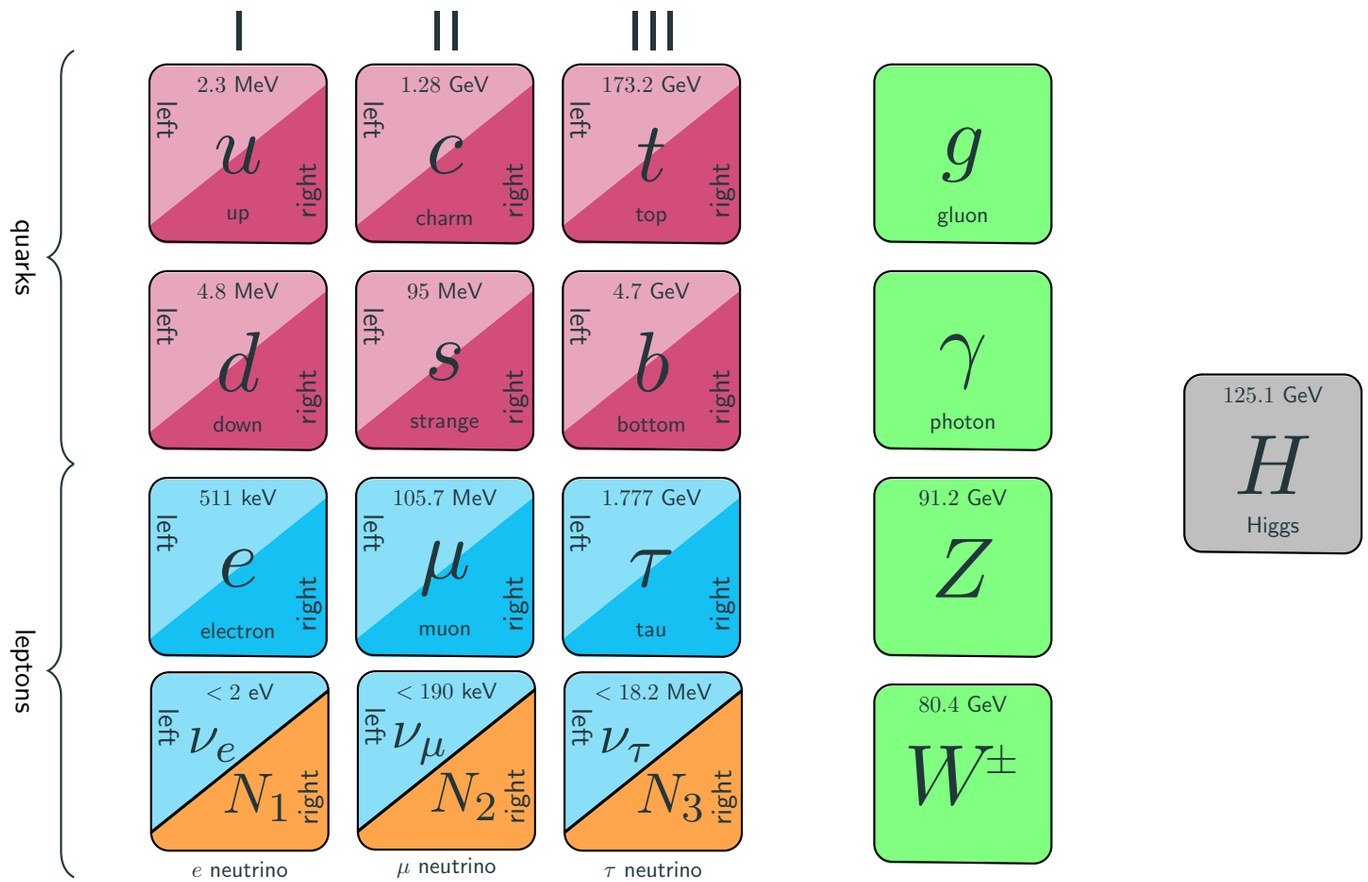
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al.*, Bull. Am. Astron. Soc. 51 (2

contacts:
Markus & Jason

Heavy Neutral Leptons

- also known as "right-handed neutrinos" or "heavy sterile neutrinos"
- candidates for (warm) dark matter and/or mediators of leptogenesis
- *possible astrophysical signatures:* X-ray emission, Lyman-α forest
- *phenomenology of direct experimental searches:* SHiP, ATLAS @ CERN

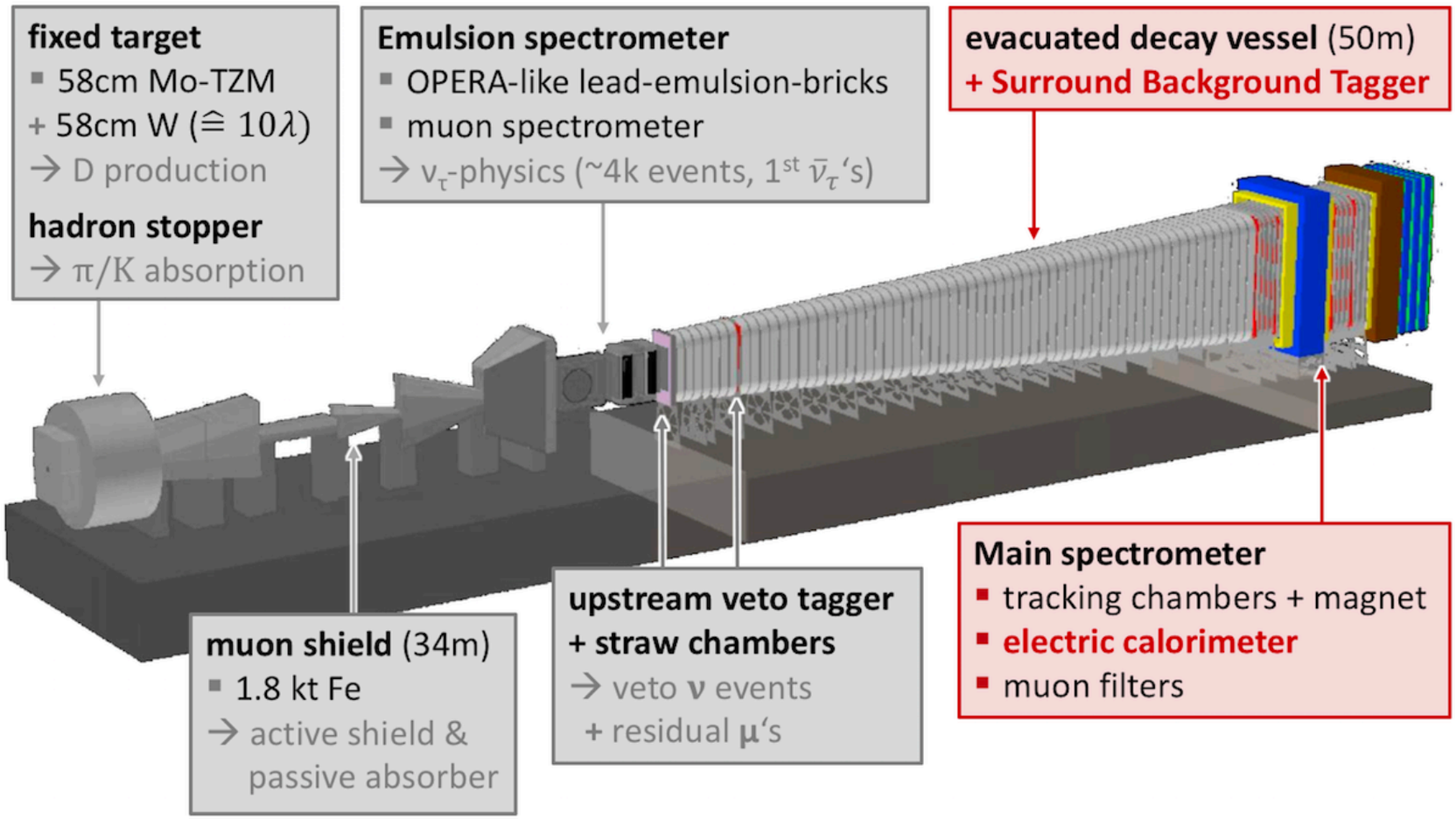


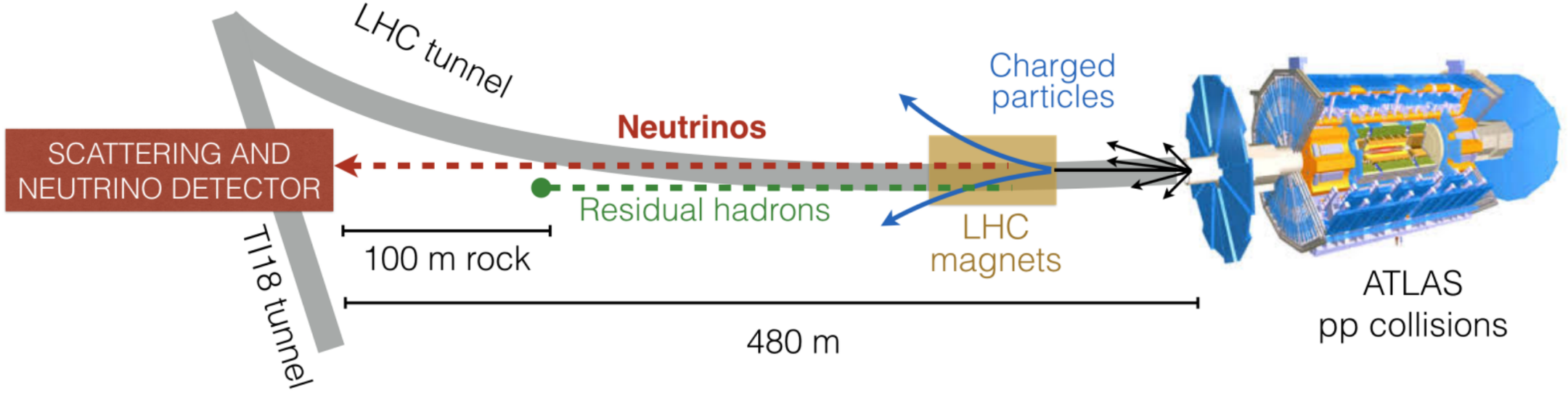


[Boyarsky, Drewes, Lasserre, Mertens & Ruchayskiy, Prog.Part.Nucl.Phys. 104 (2019)]

Search for Hidden Particles (SHiP)

contact: Oleg

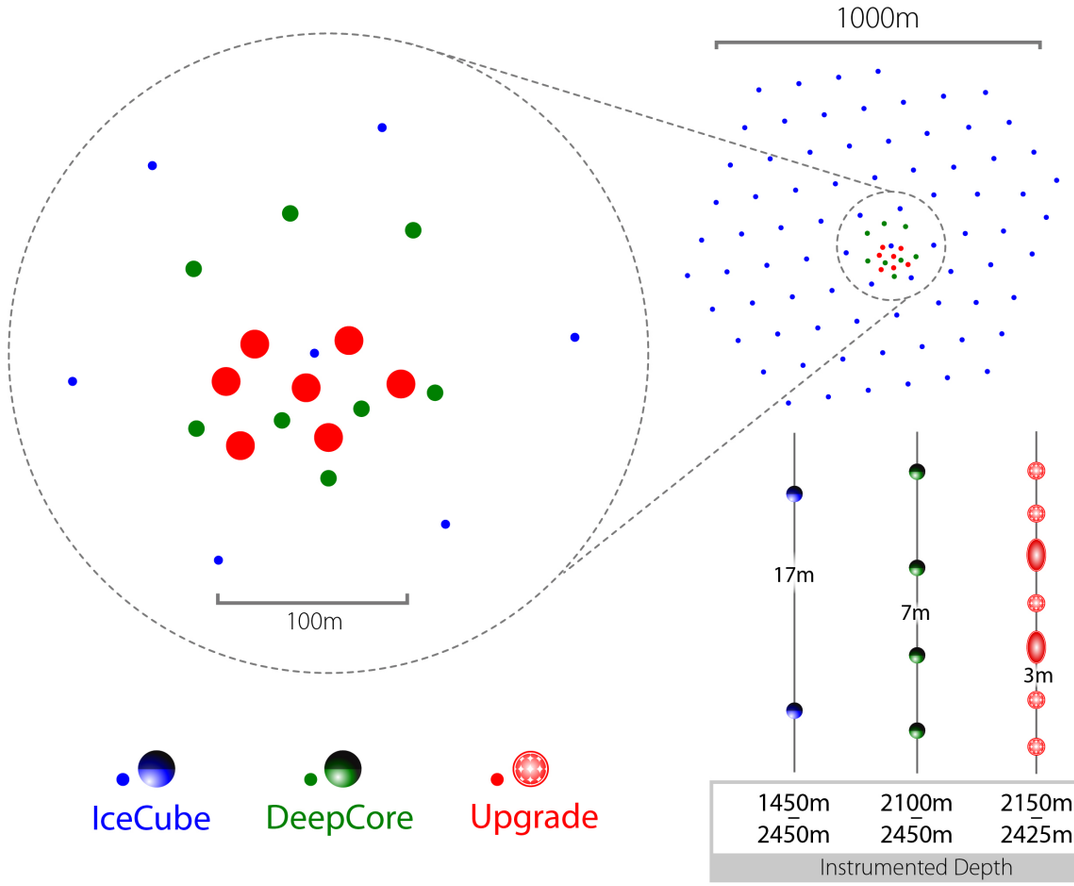


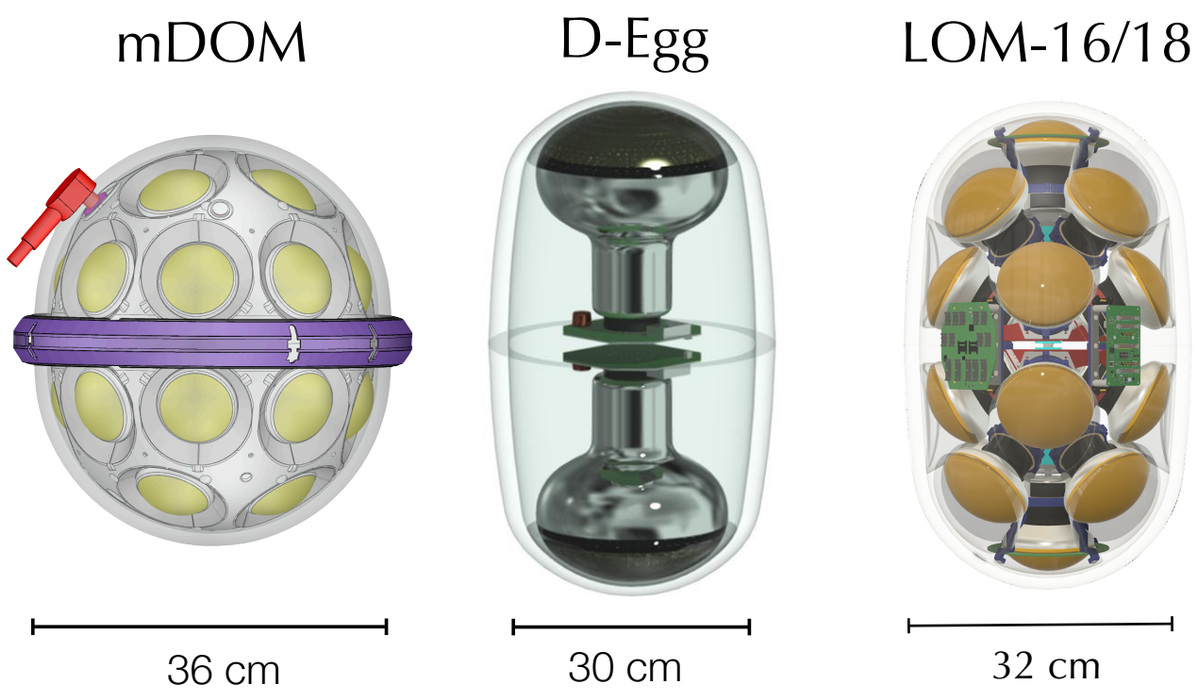


Backup Slides

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.
- **Scheduled deployment in 2025/26**

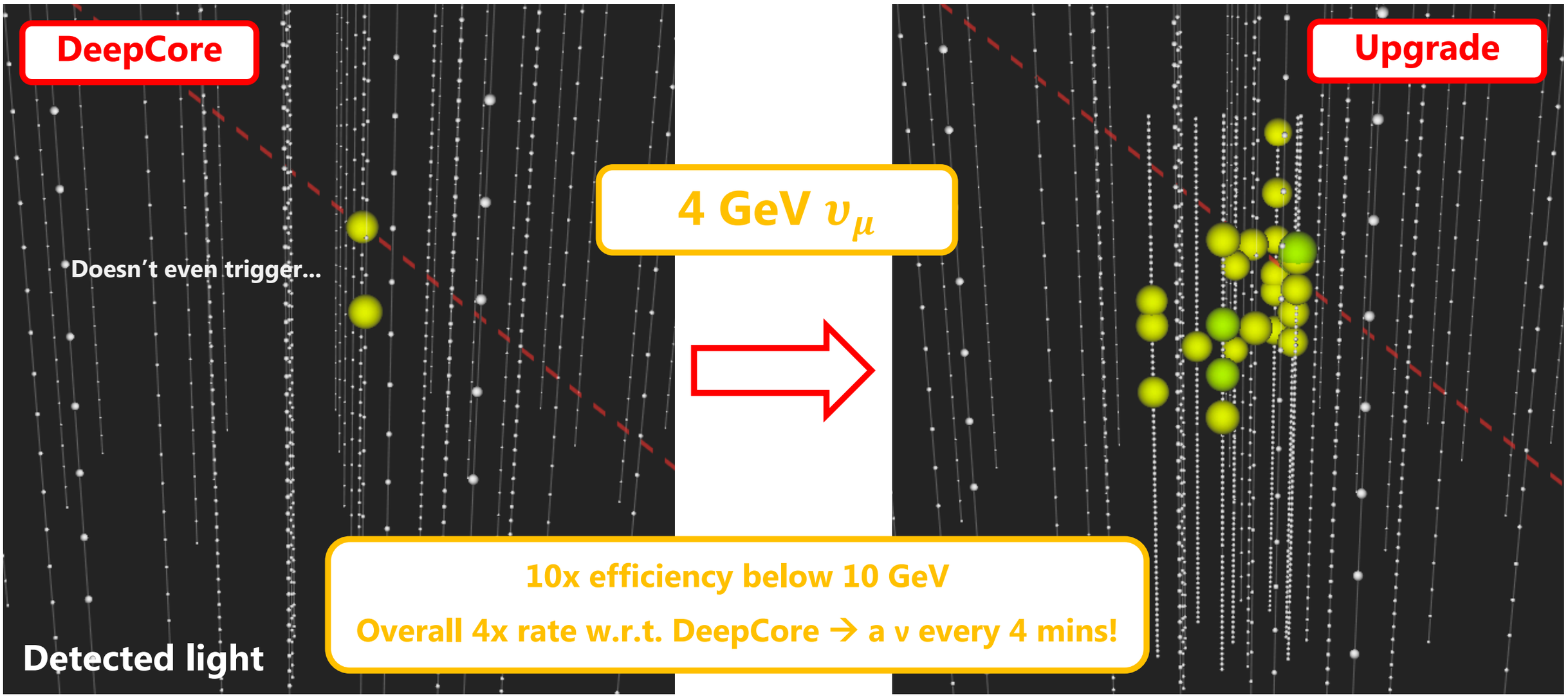




IceCube Upgrade Simulation

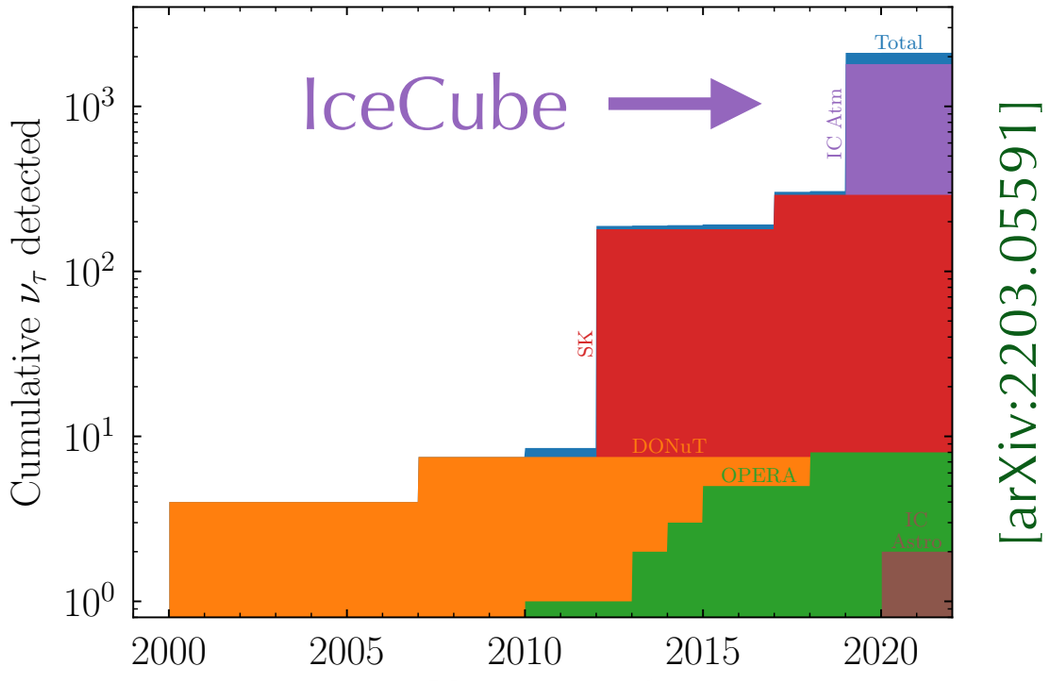
Improved low-energy detection efficiency with IceCube Upgrade

[courtesy of **Tom Stuttard**]

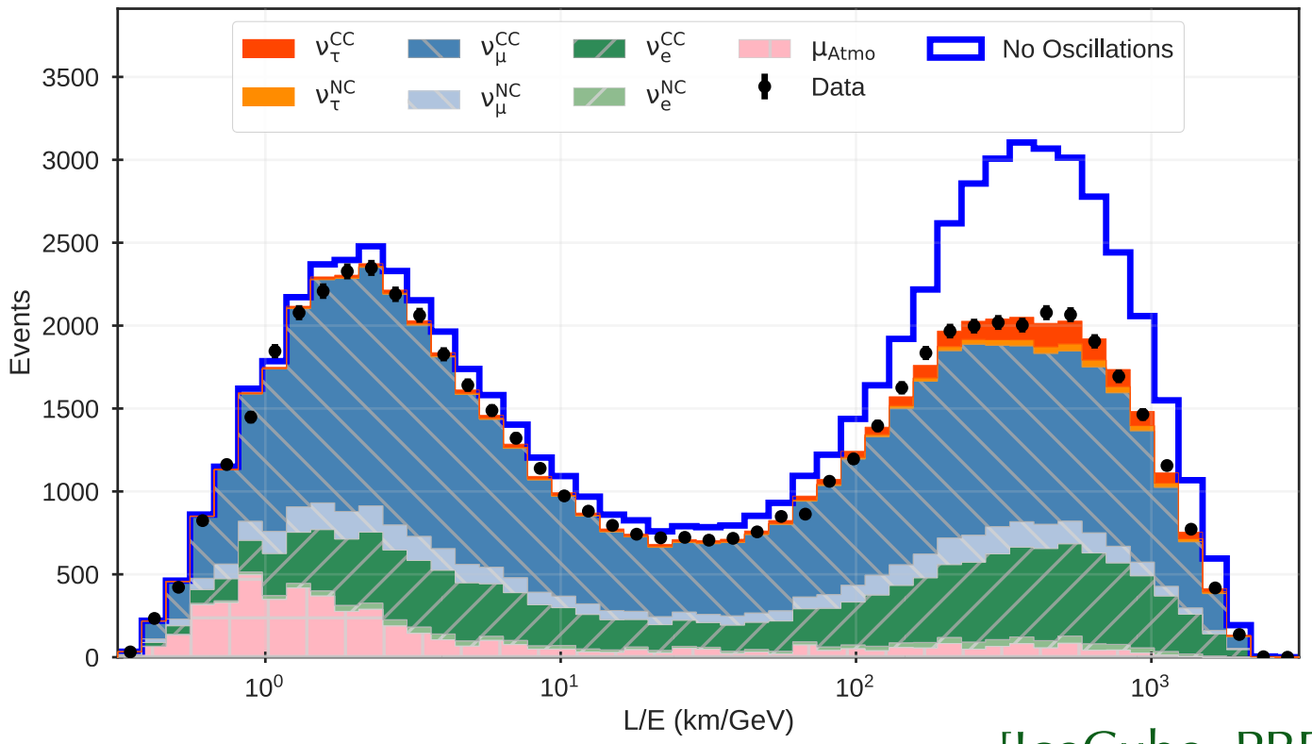


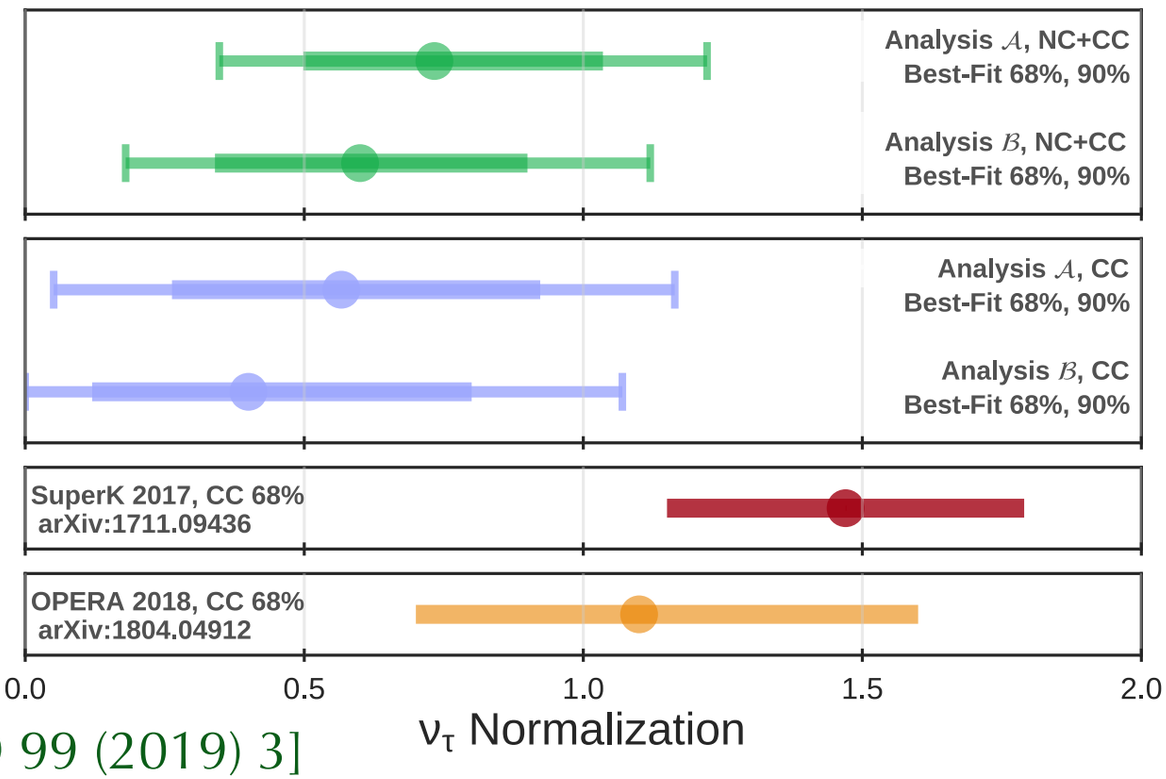
Tau Neutrino Appearance

- 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**.



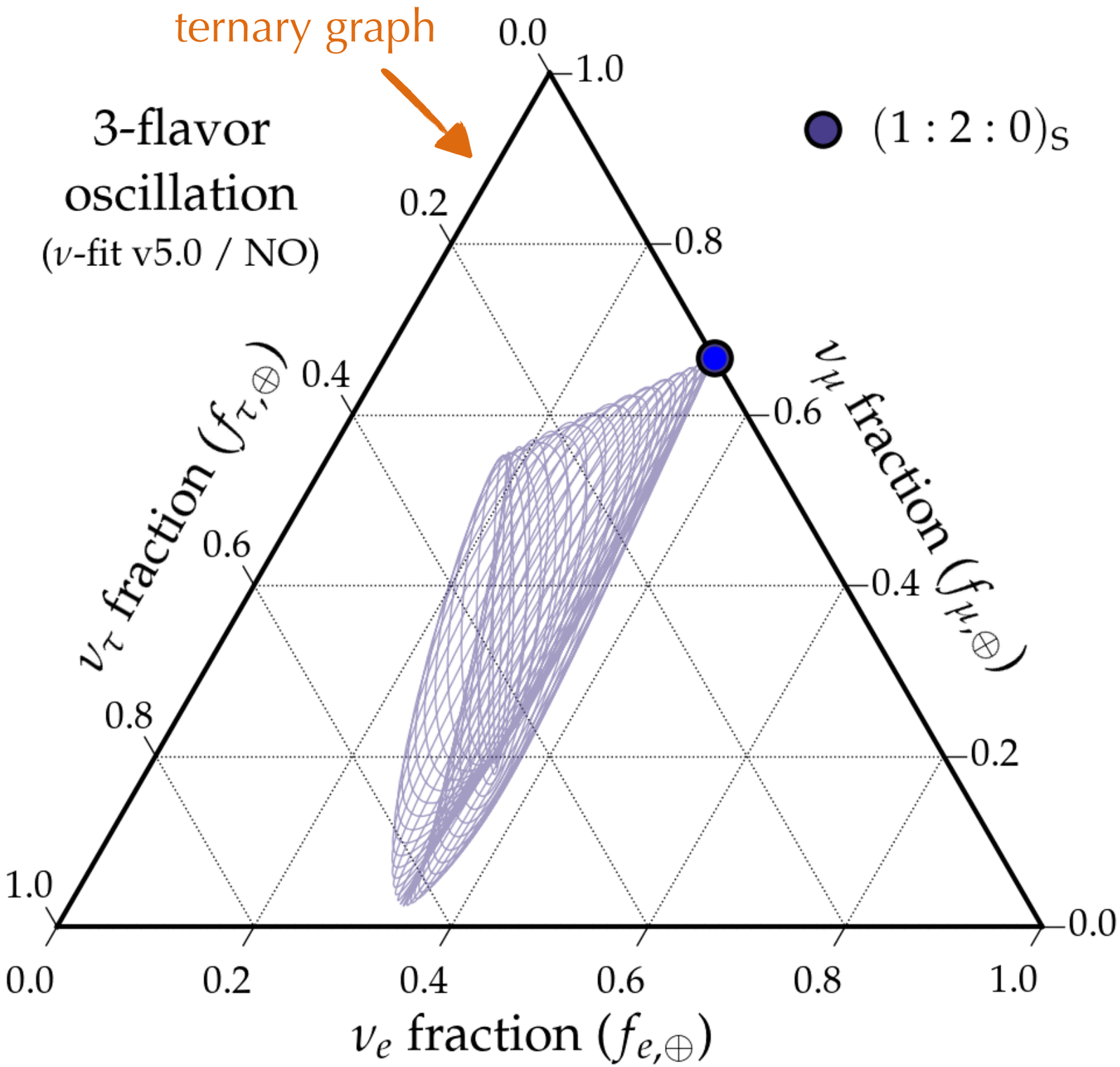
[arXiv:2203.05591]



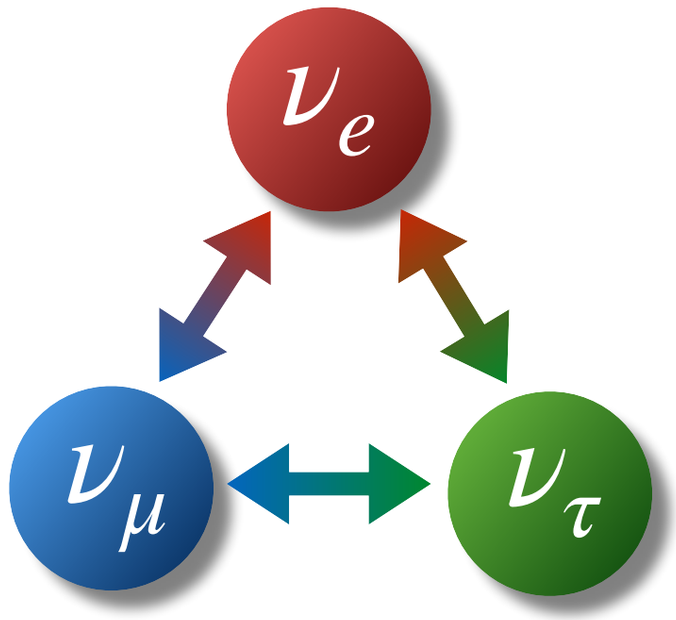


[IceCube, PRD 99 (2019) 3]

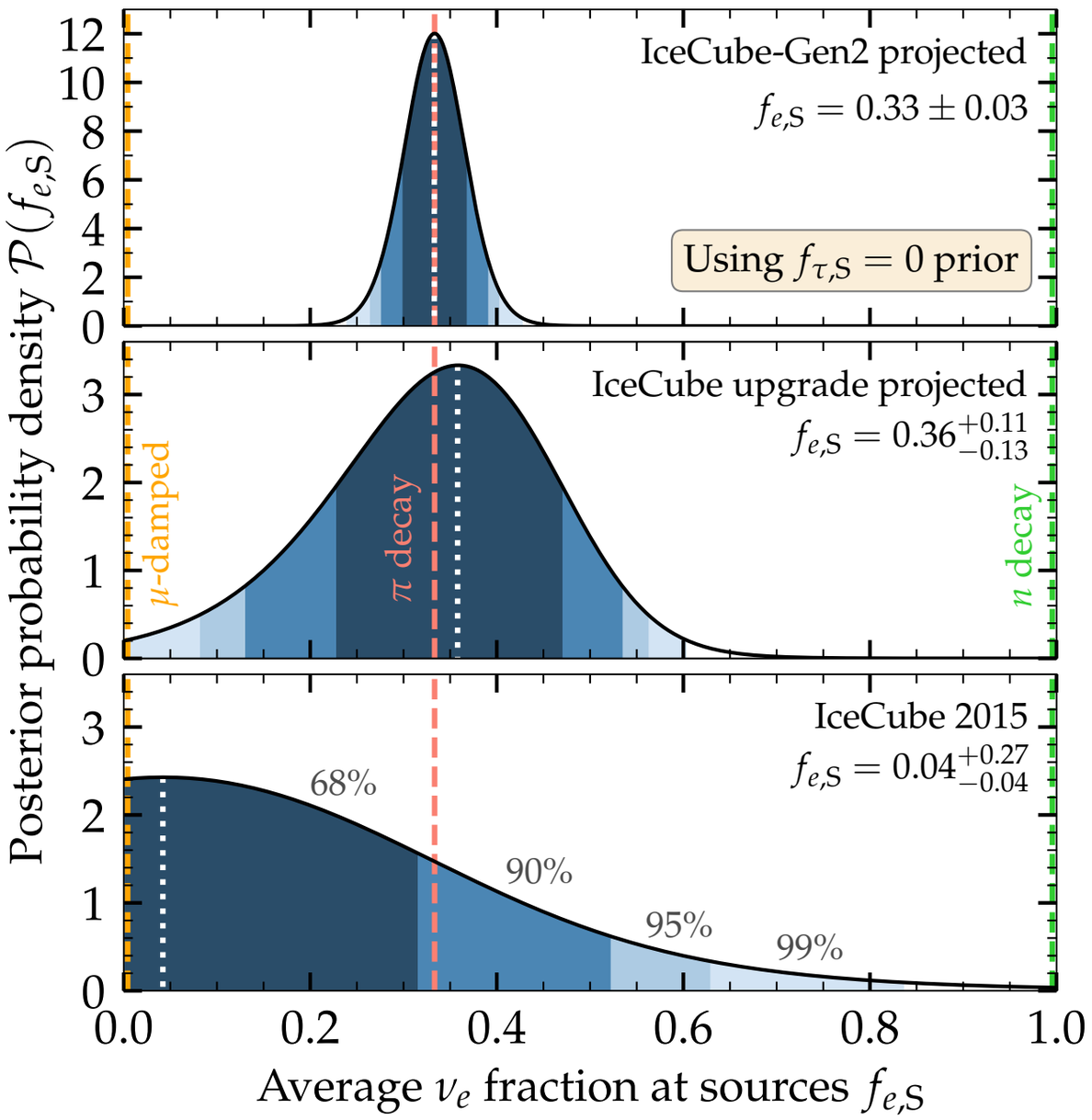
Astrophysical Flavours



Superposition of flavor and mass states induce oscillations.

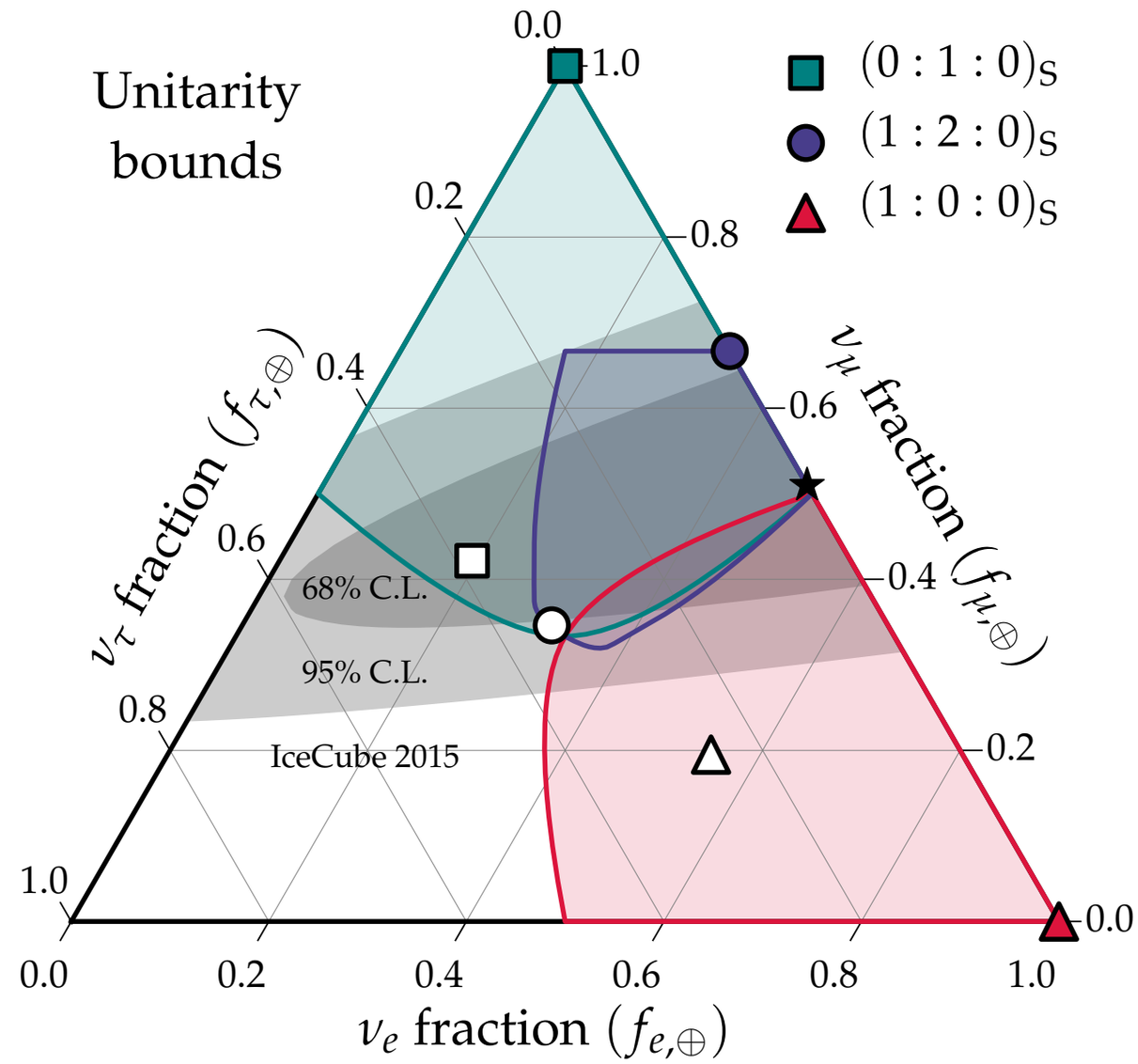


Probe of Particle (Astro-)Physics



"Inferring the flavor of high-energy astrophysical neutrinos at their sources"

[Bustamante & MA, **PRL** 122 (2019)]



"Unitarity Bounds of Astrophysical Neutrinos"

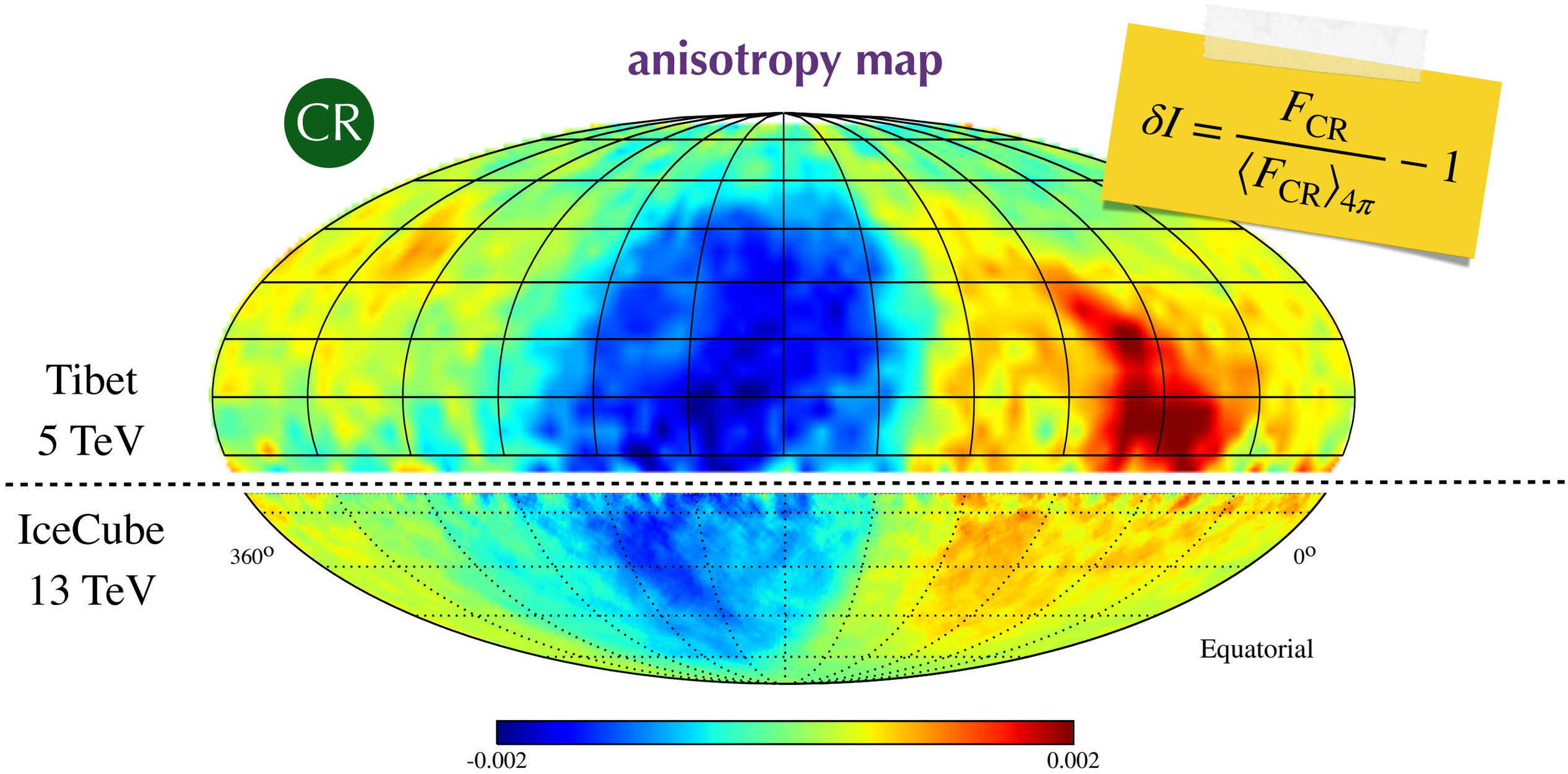
[MA, Bustamante & Mu, **PRD** 98 (2018)]

"Flavors of astrophysical νs with active-sterile mixing"

[MA, Bustamante & Willesen, **JCAP** 07 (2021)]

Galactic Cosmic Rays Anisotropy

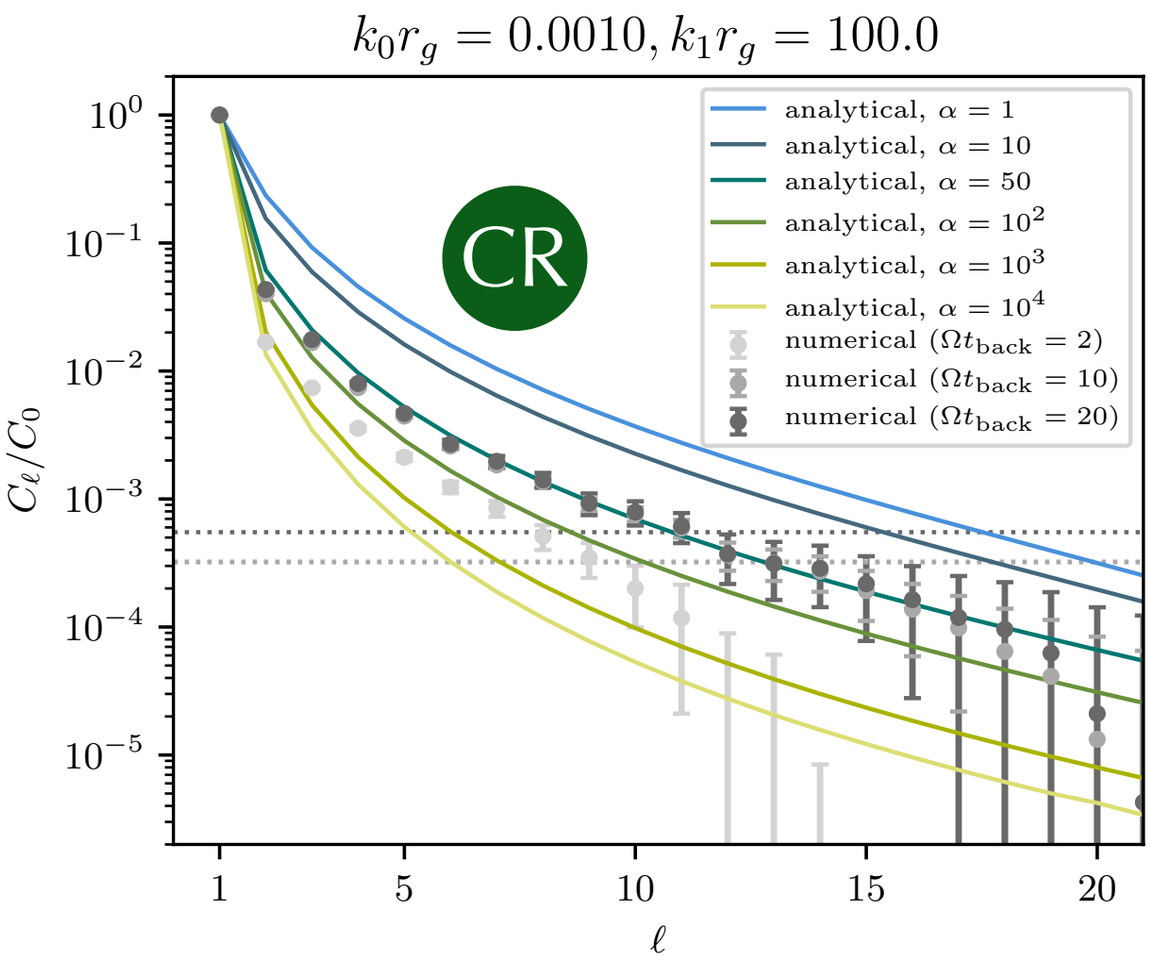
Cosmic ray anisotropies up to the level of **one-per-mille** at various energies



"*Origin of Small-Scale Anisotropies in Galactic Cosmic Rays*"

[MA & P. Mertsch, **PPNP** 94 (2017)]

Cosmic Ray Anisotropy

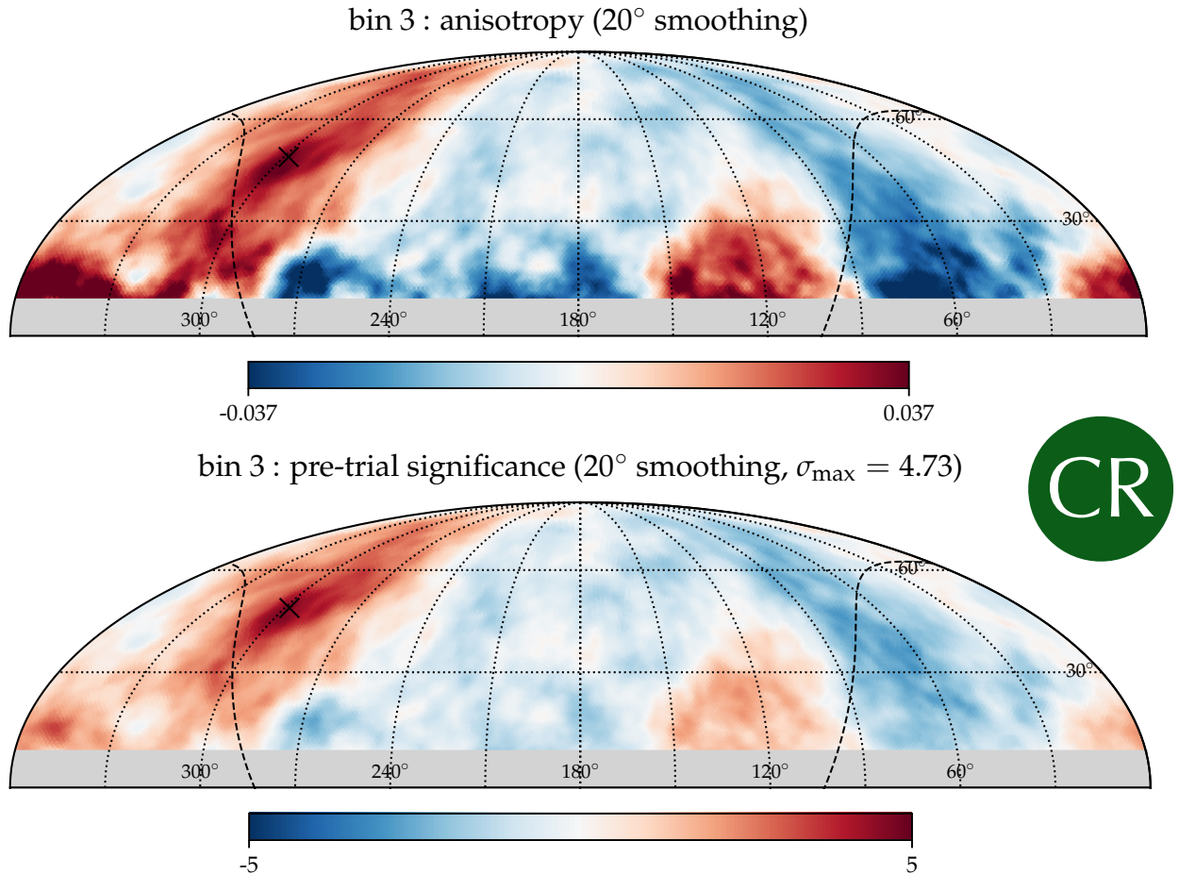


"*Cosmic ray small-scale anisotropies in quasi-linear theory*"

[P. Mertsch & MA, **JCAP** 11 (2019)]

"*Small-Scale Anisotropies of Cosmic Rays from Relative Diffusion*"

[MA & P. Mertsch, **ApJL** 815 (2015)]



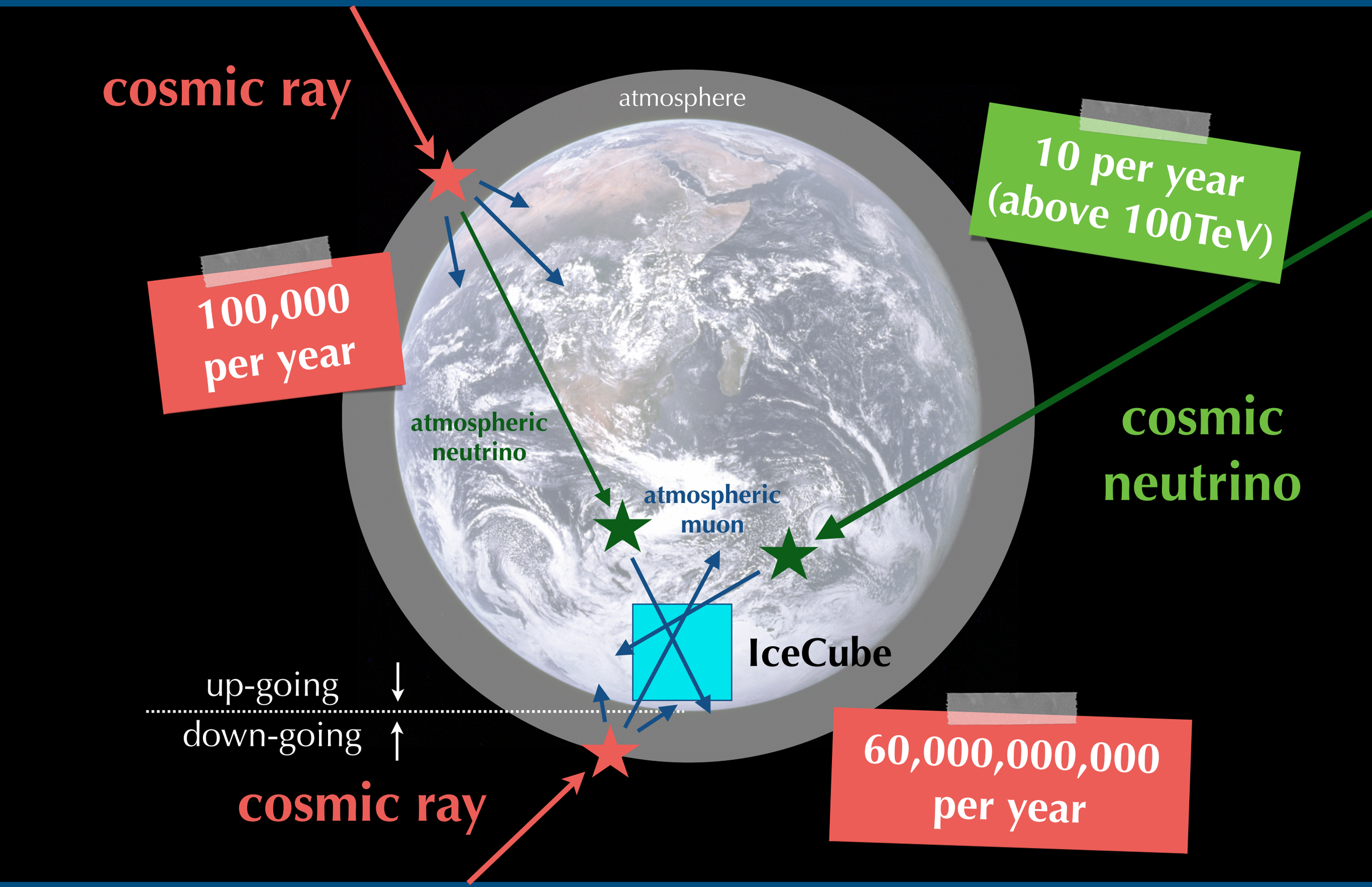
"*Large- and Medium-Scale Anisotropies in the Arrival Directions of Cosmic Rays observed with KASCADE-Grande*"

[MA, **ApJL** 886 (2019)]

"*Searching for All-Scale Anisotropies in the Arrival Directions of CRs above the Ankle*"

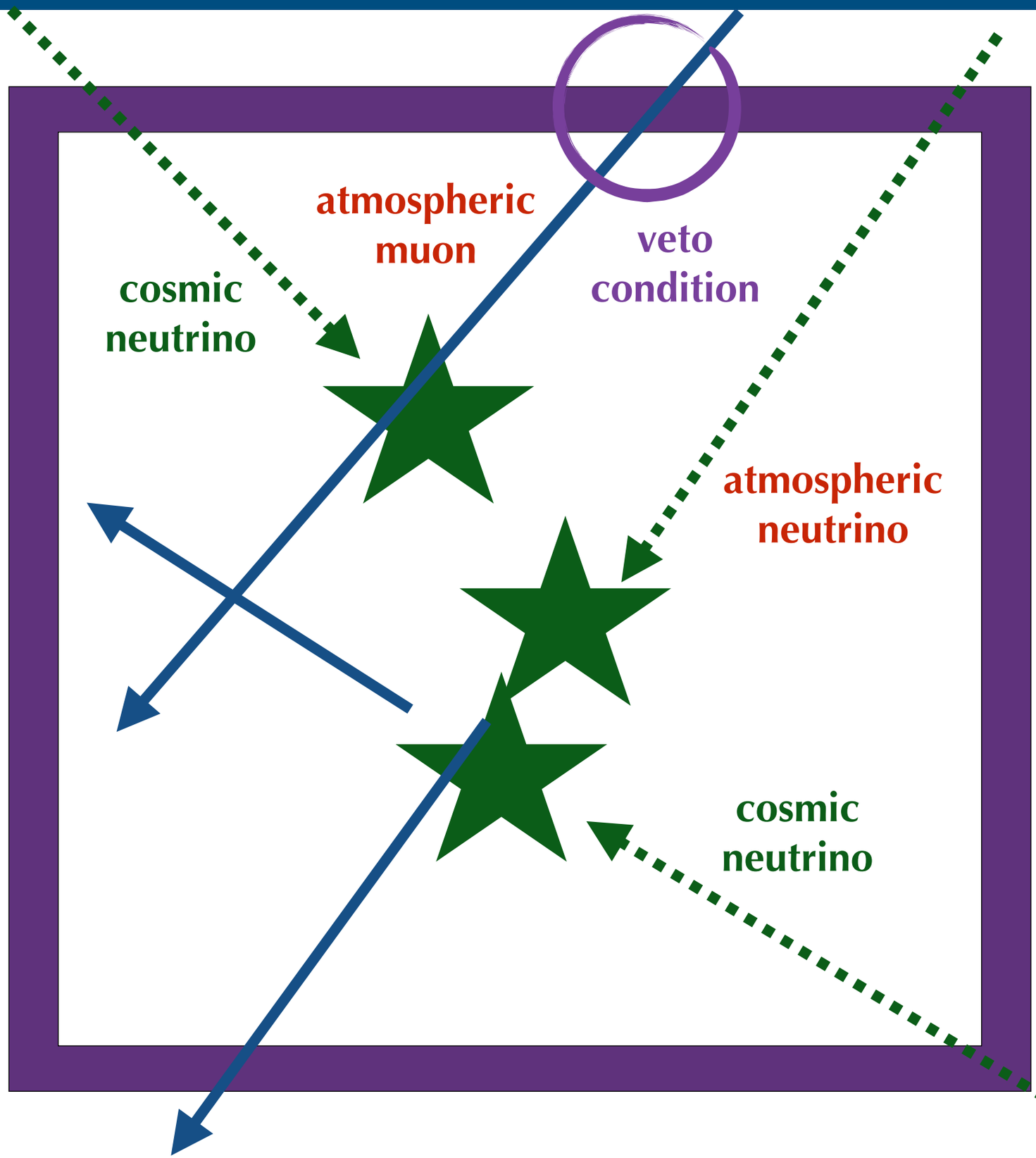
[MA, **ApJ** 863 (2018)]

Neutrino Selection I



Neutrino Selection II

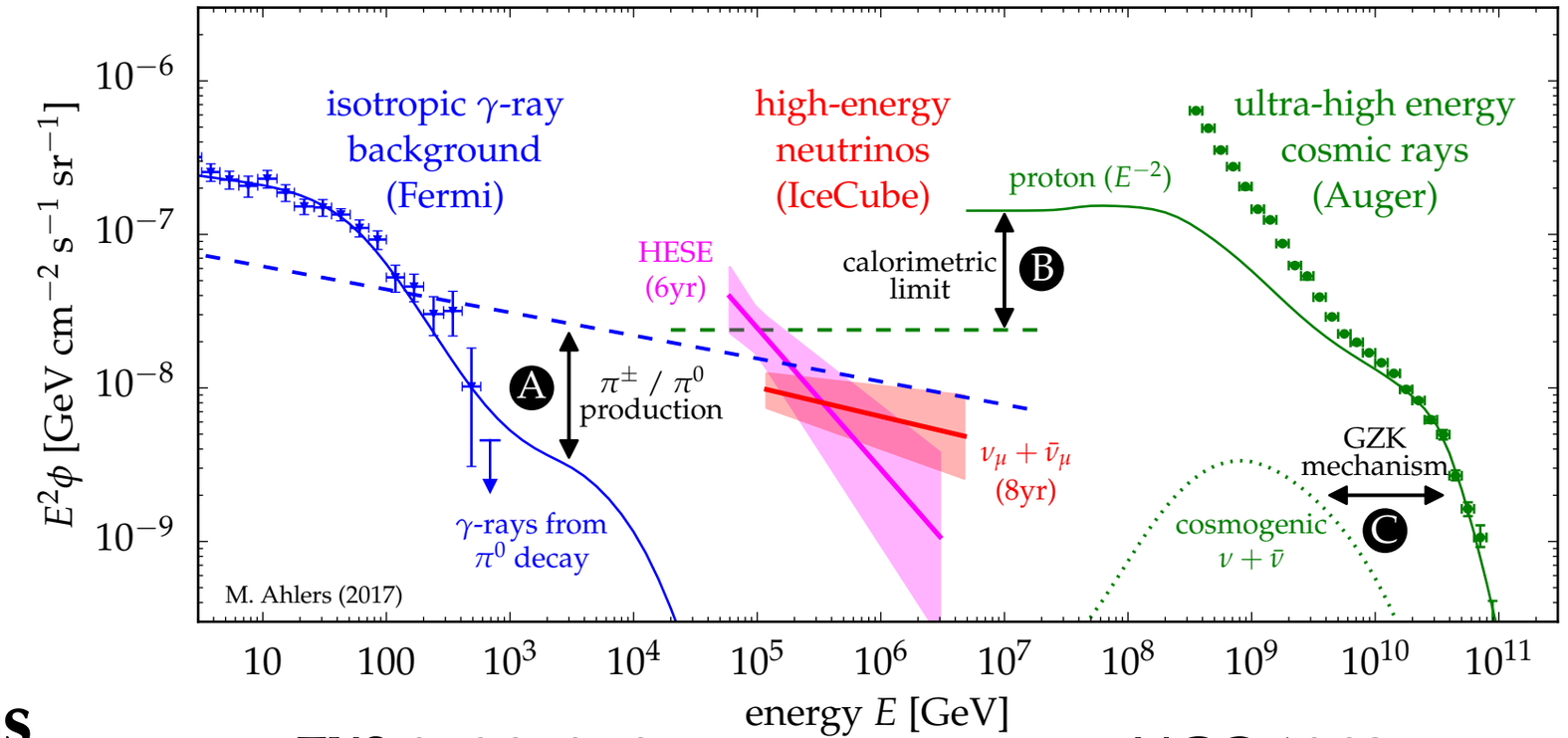
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



Status of Neutrino Astronomy

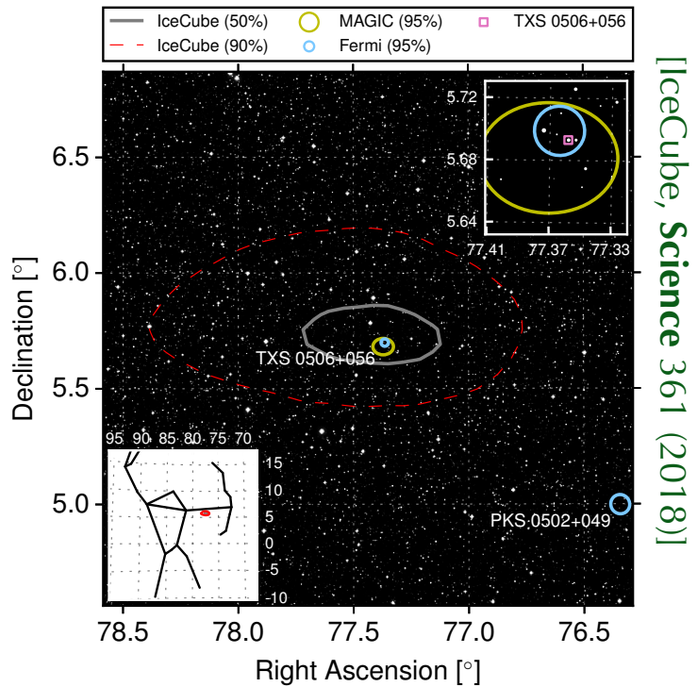
- **High neutrino intensity** compared to other cosmic backgrounds.
- **Open questions**:
  - ⋆ origin?
  - ⋆ spectral features?
  - ⋆ consistent MM emission?
- **Some strong indications for individual sources:**
  - ⋆ blazar TXS 0506+056
  - ⋆ Seyfert II galaxy NGC 1068
  - ⋆ Galactic plane
- **Many interesting (but weak) correlations** with other candidate sources.

multi-messenger interfaces



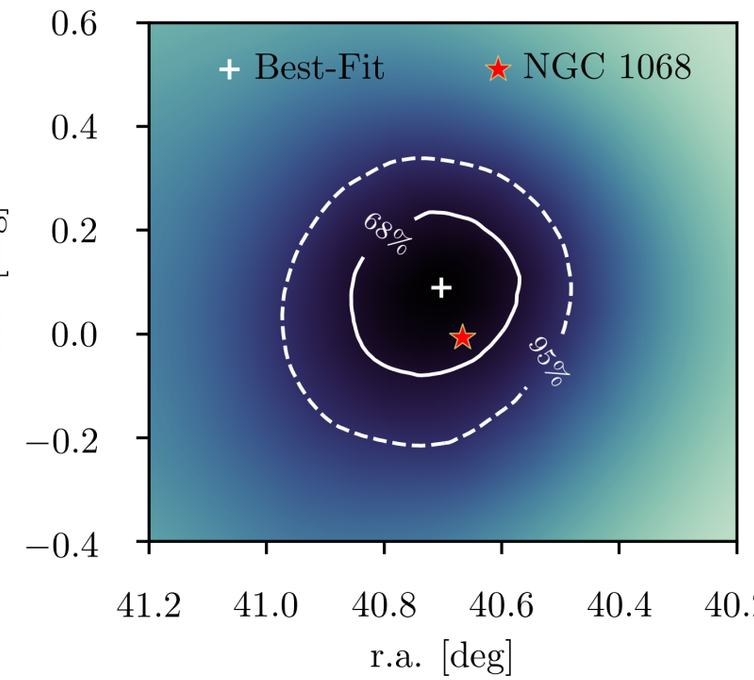
[MA & Halzen, **PPNP** 102 (2018)]

TXS 0506+056



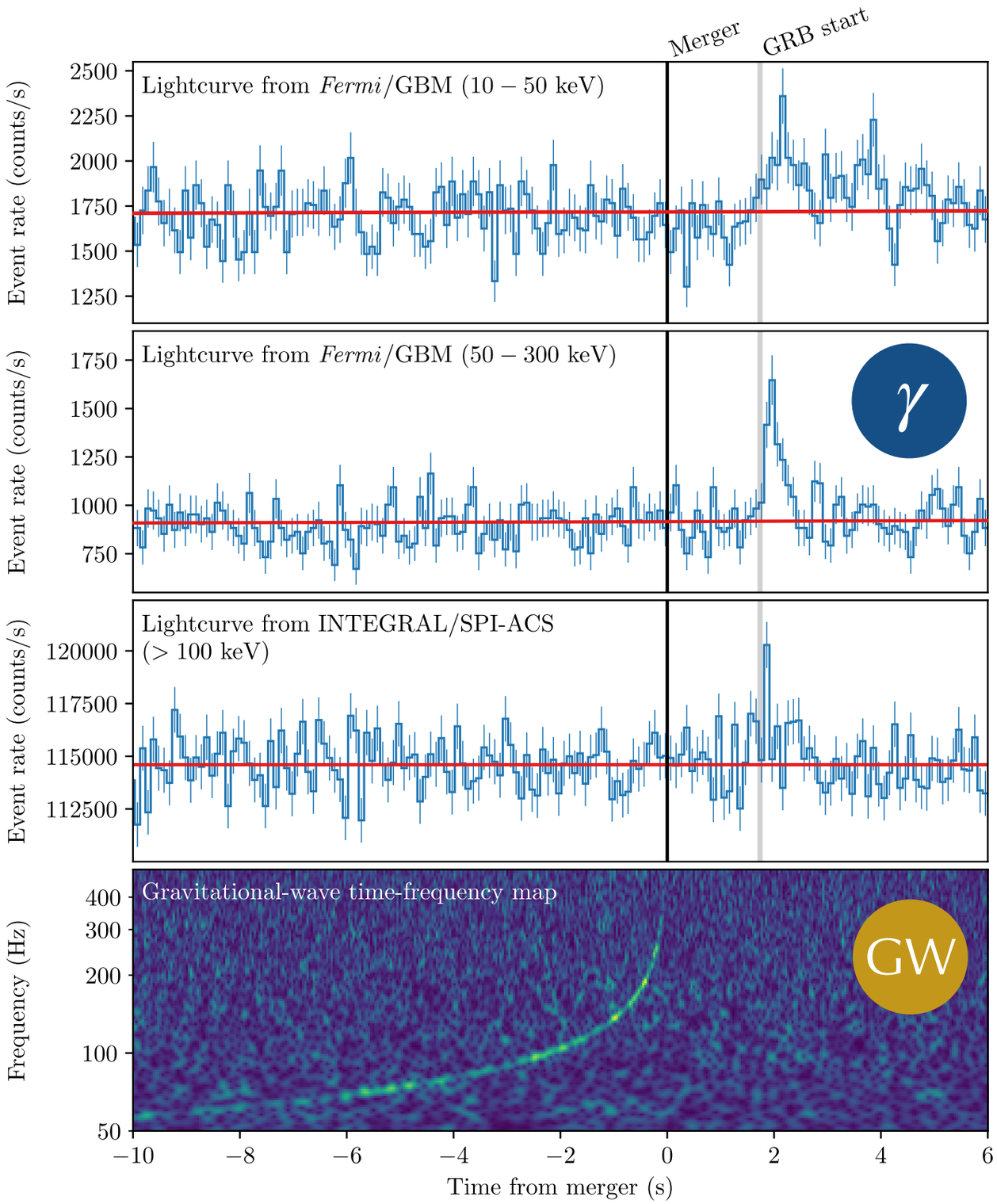
[IceCube, **Science** 361 (2018)]

NGC 1068

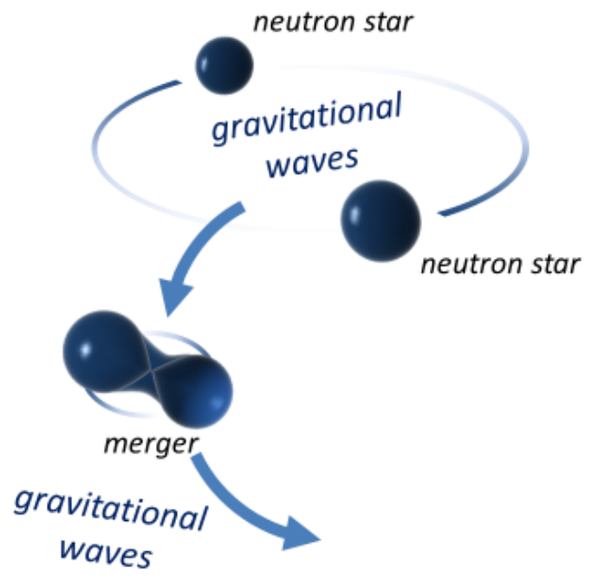


[IceCube, **Science** 378 (2022)]

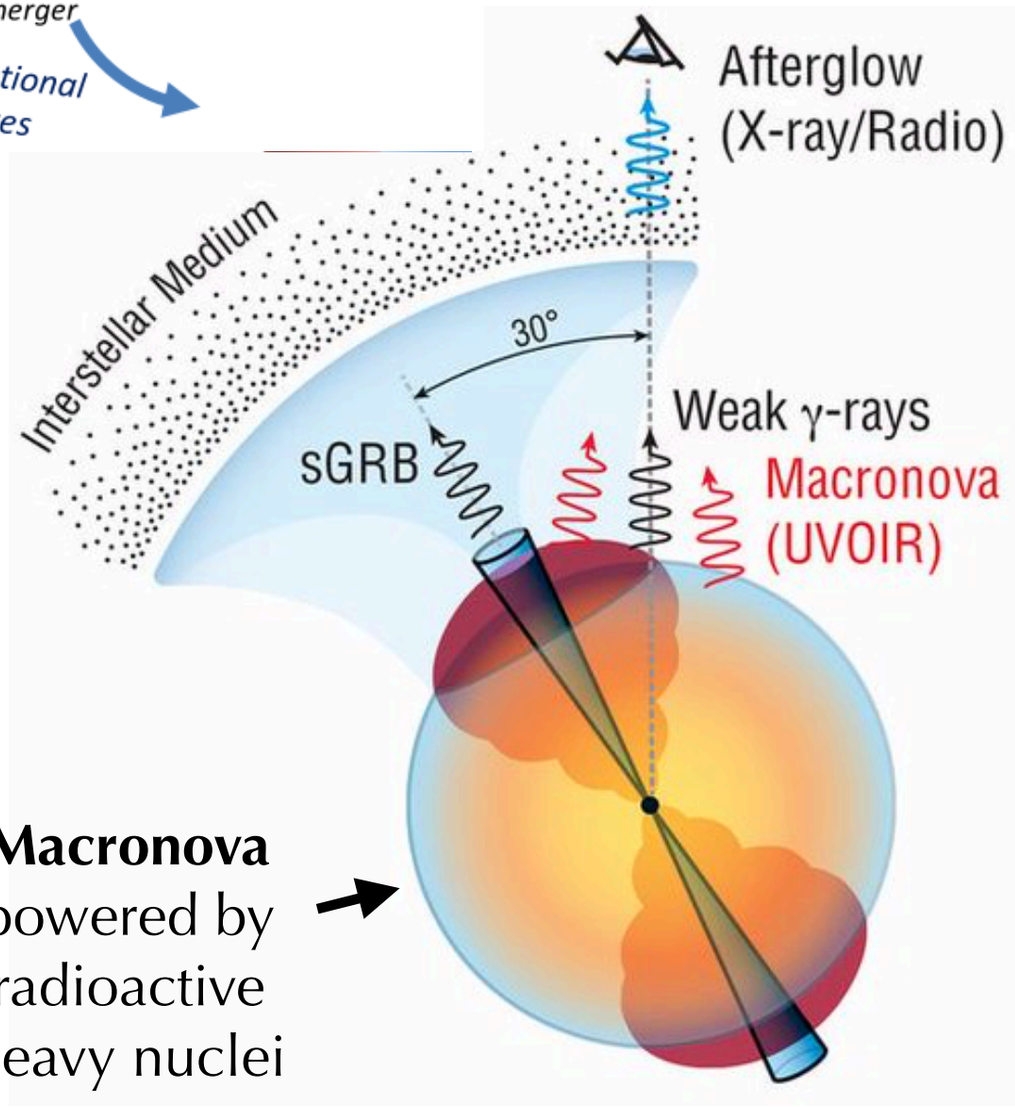
GRBs as Multi-Messenger Sources



[LVD, Fermi & INTEGRAL, **ApJ** 848 (2017) no.2, L13]

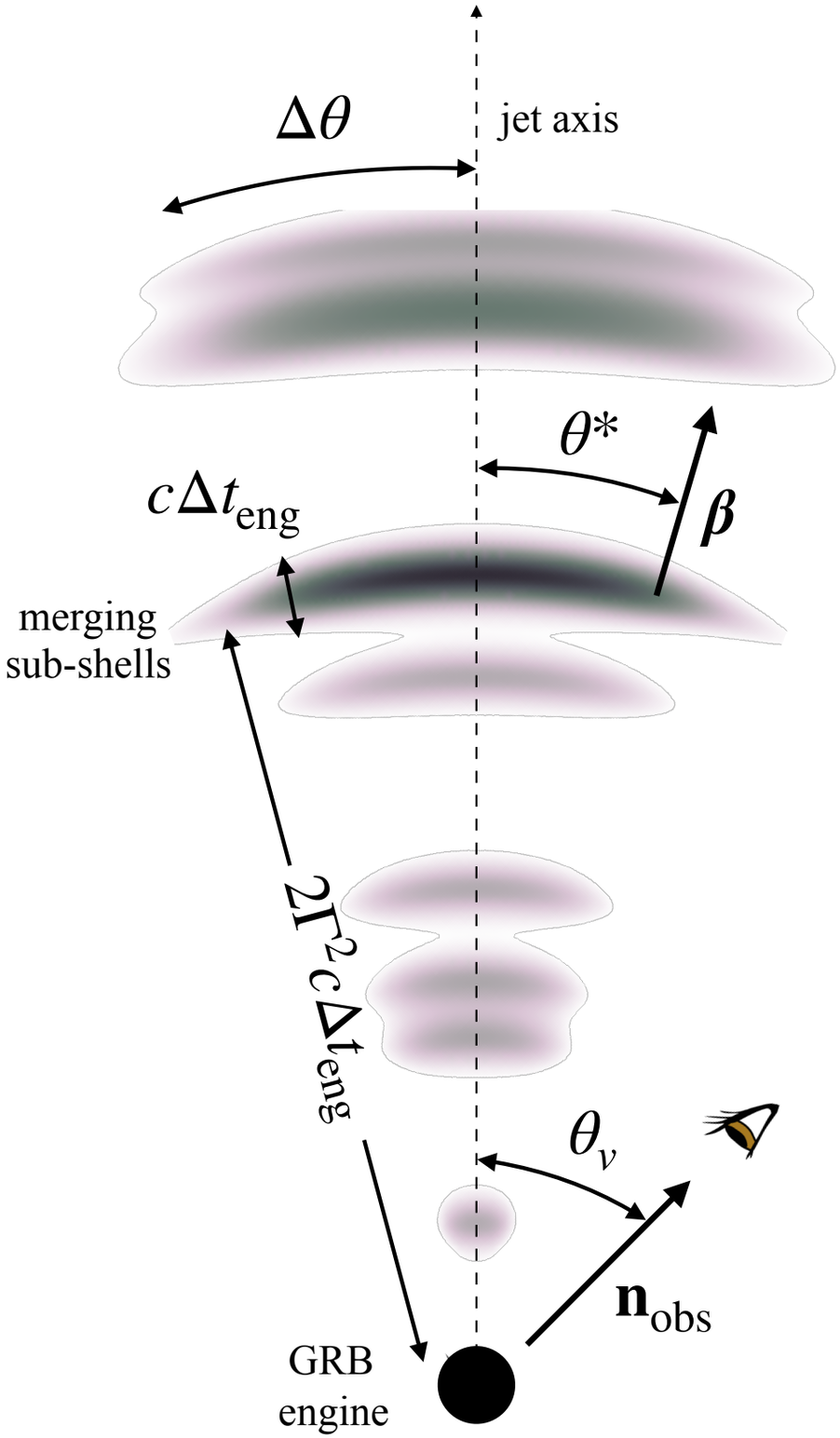


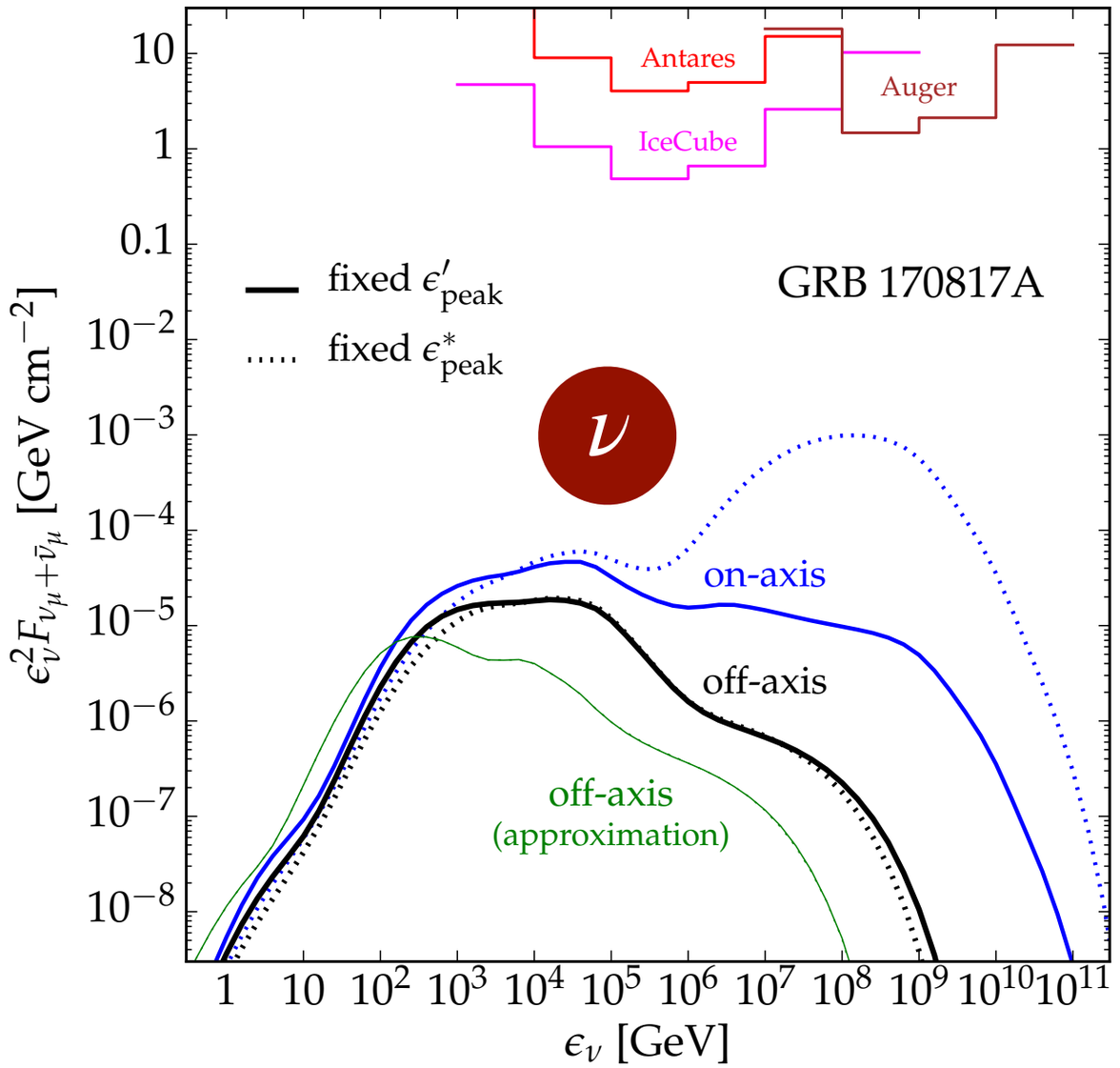
GW 170817
&
GRB 170817A



Macronova
powered by
radioactive
heavy nuclei

GRBs as Multi-Messenger Sources





"Neutrino Fluence from Gamma-Ray Bursts: Off-Axis View of Structured Jets"

[MA & Halser **MNRAS** 490 (2019)]

[see also Biehl, Heinze & Winter, **MNRAS** 476 (2018)]