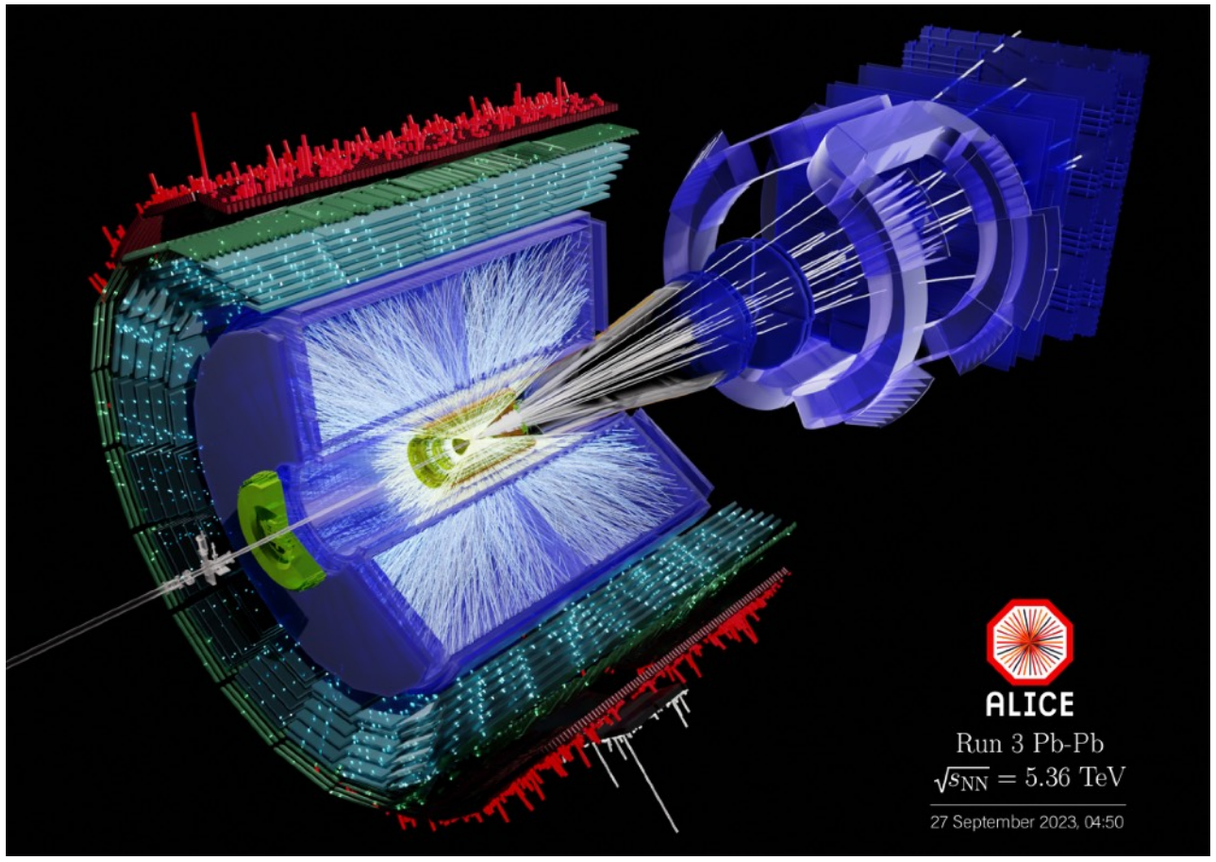
Find Your Supervisor

Subatomic Physics Group

nbi.ku.dk/subatomic_projects_2025



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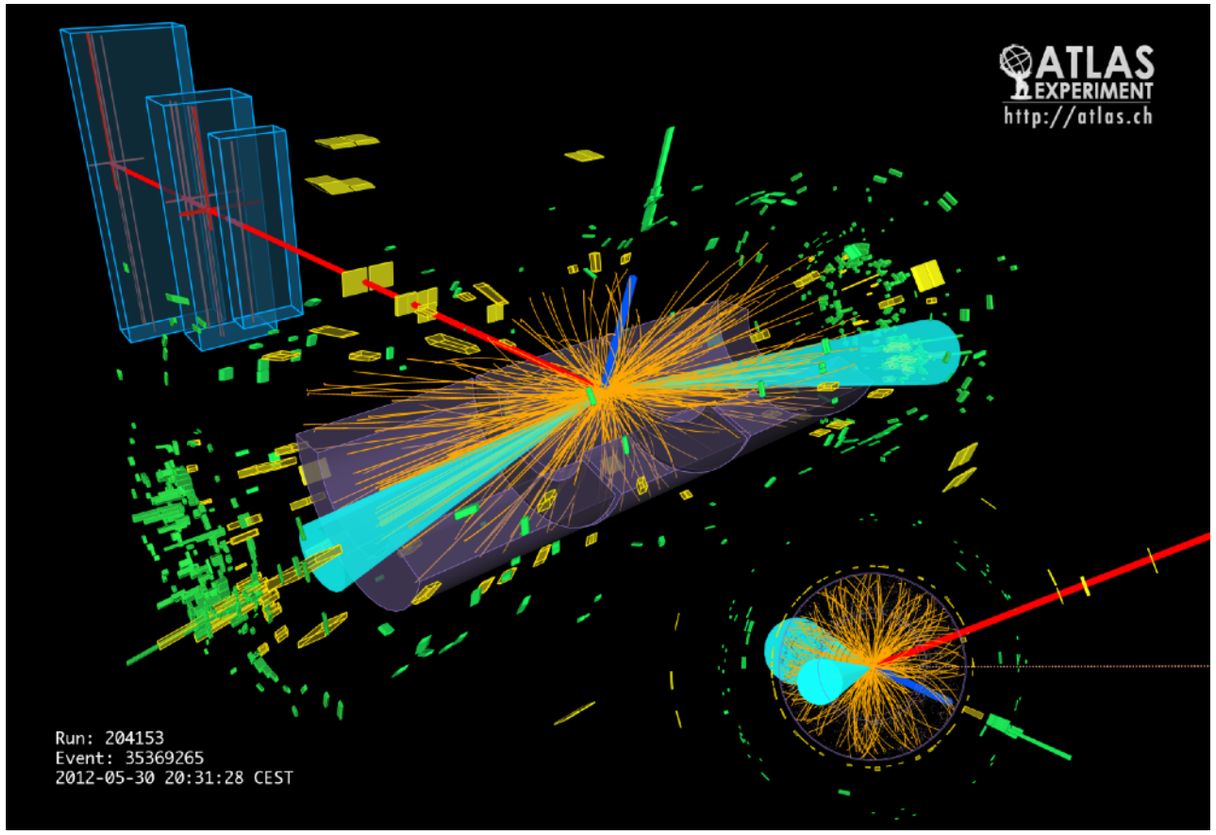

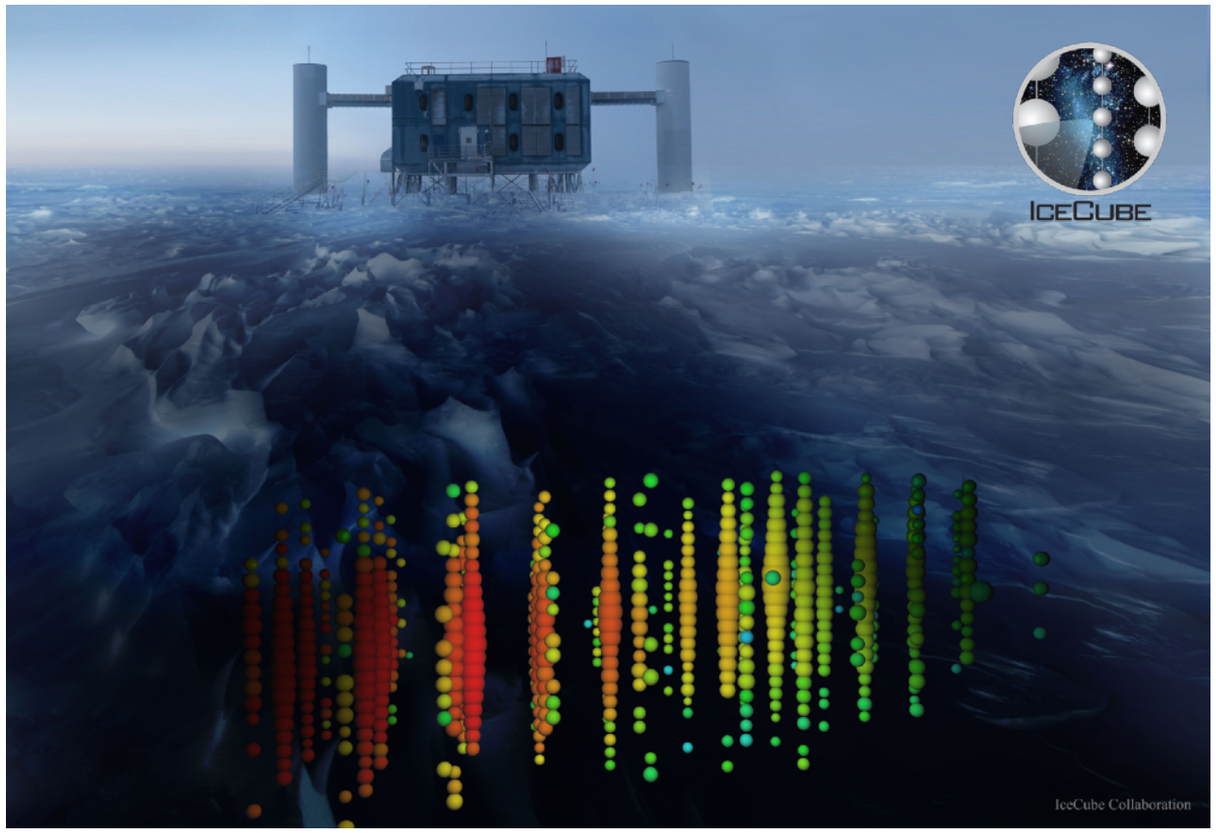

ALICE Experiment

The ALICE detector exploits the unique physics potential of nucleus-nucleus collisions at LHC energies. Our aim is to study the physics of strongly interacting matter at the highest energy densities. Under these conditions, an extreme phase of matter - the quark-gluon plasma - is formed. The Universe is thought to have been in such a primordial state for the first few millionths of a second after the Big Bang. The NBI group is leading studies of collective flow effects in collisions and in the Forward Calorimeter (FoCal) upgrade.

ATLAS Experiment

The main goal of the ATLAS detector is to discover new properties of elementary particles and forces in the head-on collisions of protons of extraordinarily high energy. The ATLAS group at the Niels Bohr Institute is active in several areas of the experiment: data analysis and theoretical interpretations of the results; silicon detector, trigger and data acquisition system design upgrades for the High-Luminosity LHC (HL-LHC); transition radiation detector operation; machine-learning tools in new physics searches.

IceCube Experiment

The IceCube experiment is the world's largest and most sensitive telescope for high-energy neutrinos. IceCube members at NBI have a broad science portfolio: from searches for high-energy neutrinos from the most violent astrophysical phenomena in the Universe to probes of fundamental neutrino physics revealed in neutrino flavour oscillations. We are leading the simulation development of the IceCube Upgrade in 2025/26 and actively work on improved neutrino event reconstructions using modern machine-learning tools.

Particle & Astroparticle Phenomenology

The scientific knowledge generally advances in two ways: "top-down" and "bottom-up." Phenomenological particle physics is a bottom-up theoretical research. Our group is searching for new particles at both accelerator and cosmic frontiers. We explore the hypothesis that new particles are light, and very feebly interacting. In particular we search for heavy neutral leptons, such as sterile neutrinos - particles that may be responsible for some (maybe even all) beyond-the-Standard-Model phenomena.

Future Circular Collider (FCC)

The NBI group is active in ongoing design studies of the FCC, a next-generation high-performance collider at CERN following the LHC. A new tunnel of 91 km circumference would initially house the FCC-ee, an electron–positron collider for precision measurements offering a 15-year research programme from the mid-2040s. A second machine, the FCC-hh, installed in the same tunnel, aims to reach collision energies of 100 TeV, colliding protons and also heavy-ions, and running until the end of the 21st century.

SHiP Experiment

SHiP is a future CERN experiment to search for "hidden" particles as predicted by a large number of Standard Model extensions that are capable of explaining, for instance, dark matter, neutrino oscillations, and the origin of the baryon asymmetry in the Universe. The experiment is designed to search for any type of feebly interacting long-lived particles, among which are found heavy neutral leptons, dark photons, dark scalars, axion-like particles, light supersymmetric particles, as well as certain types of dark matter.

Find Your Supervisor

Subatomic Physics Group

IceCube Experiment &
(Astro-)Particle Phenomenology

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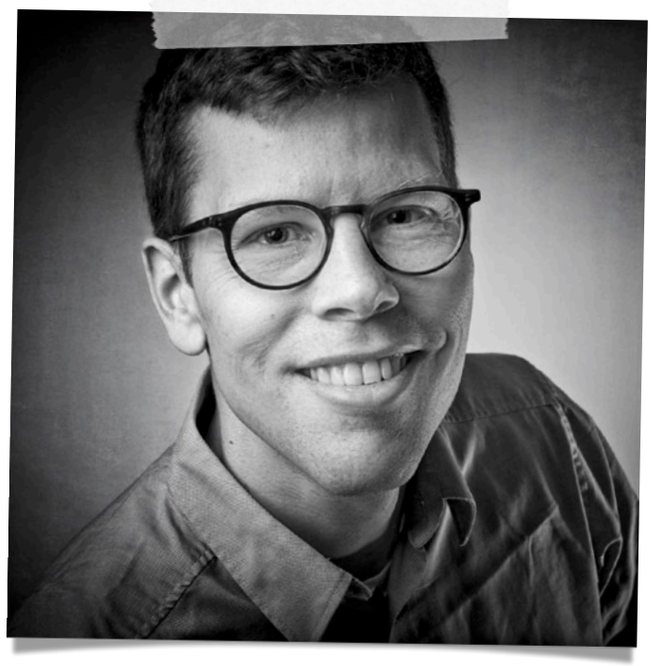

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The Elusive Neutrino

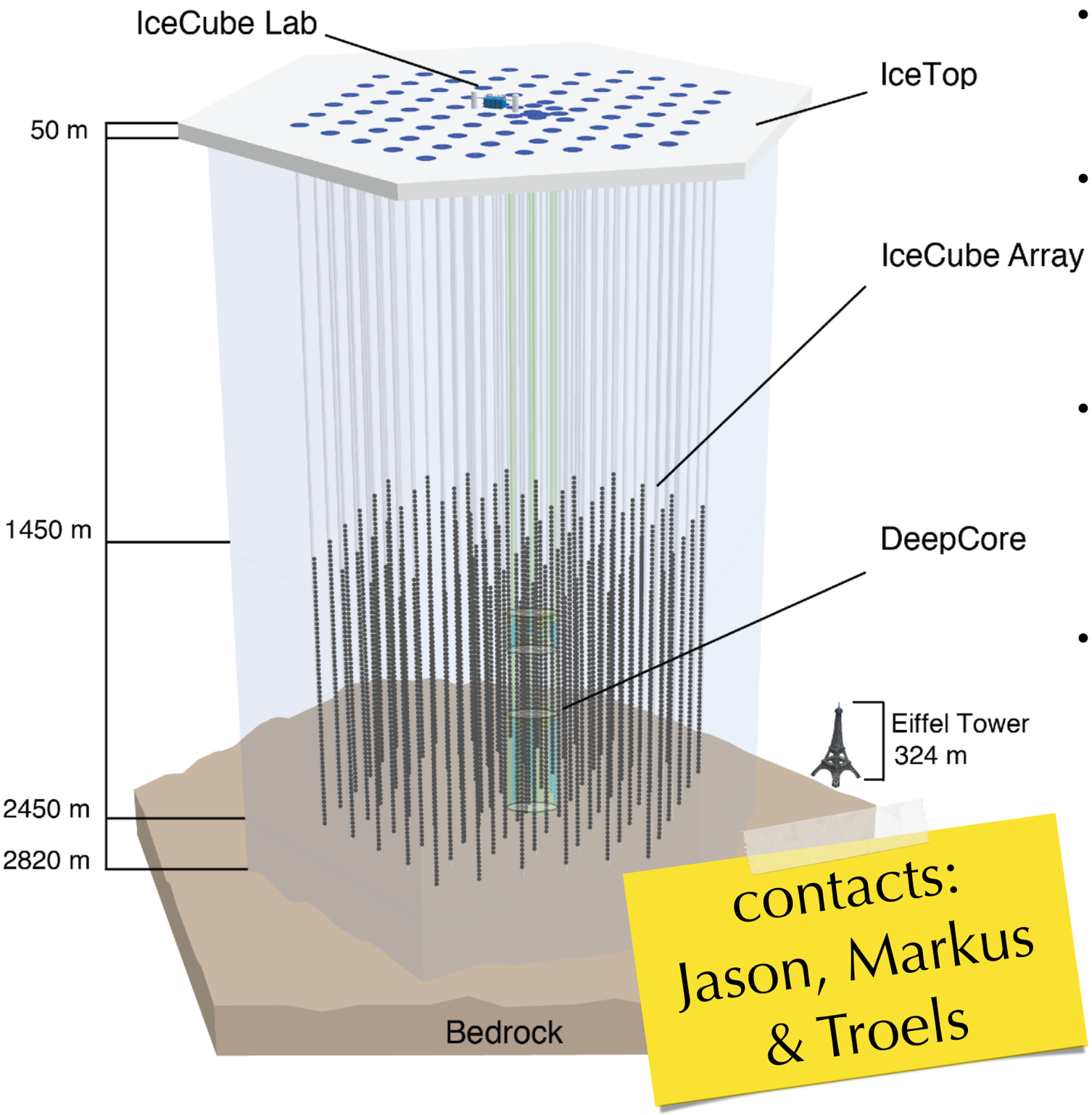
- **three neutrino flavours**
- very small masses *(unknown origin)*
- large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **unique probe of high-energy astrophysics**

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

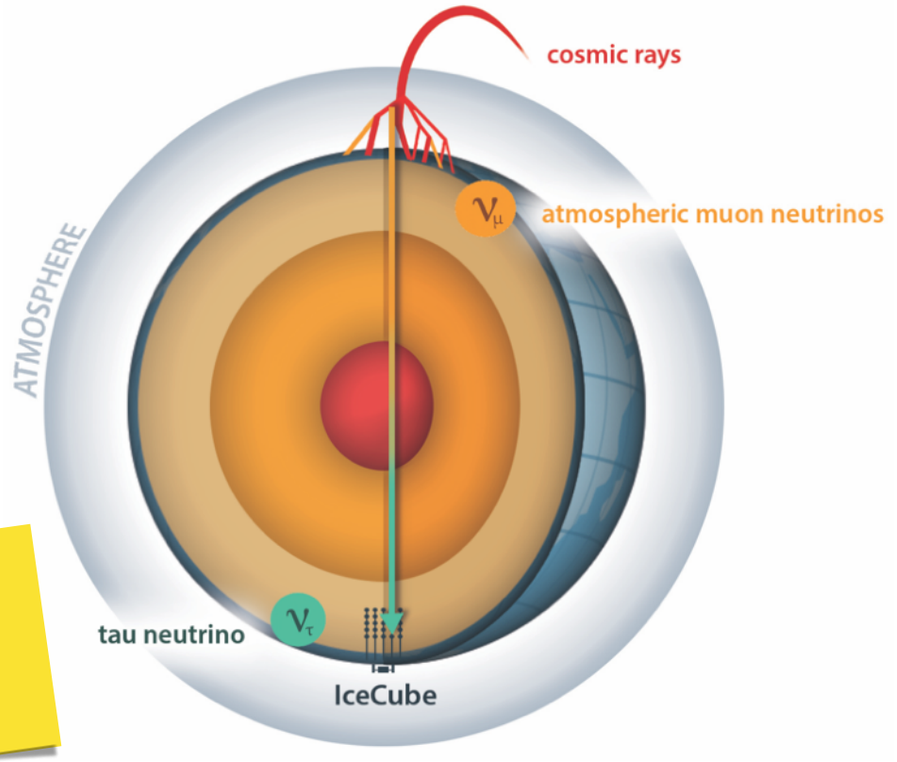


contacts:
Jason, Markus
& Troels

- **Giga-ton optical Cherenkov telescope at the South Pole**
- Optical modules attached to strings instrumenting **1 km³ of clear glacial ice**
- Collaboration of 450+ scientists at 58 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)*

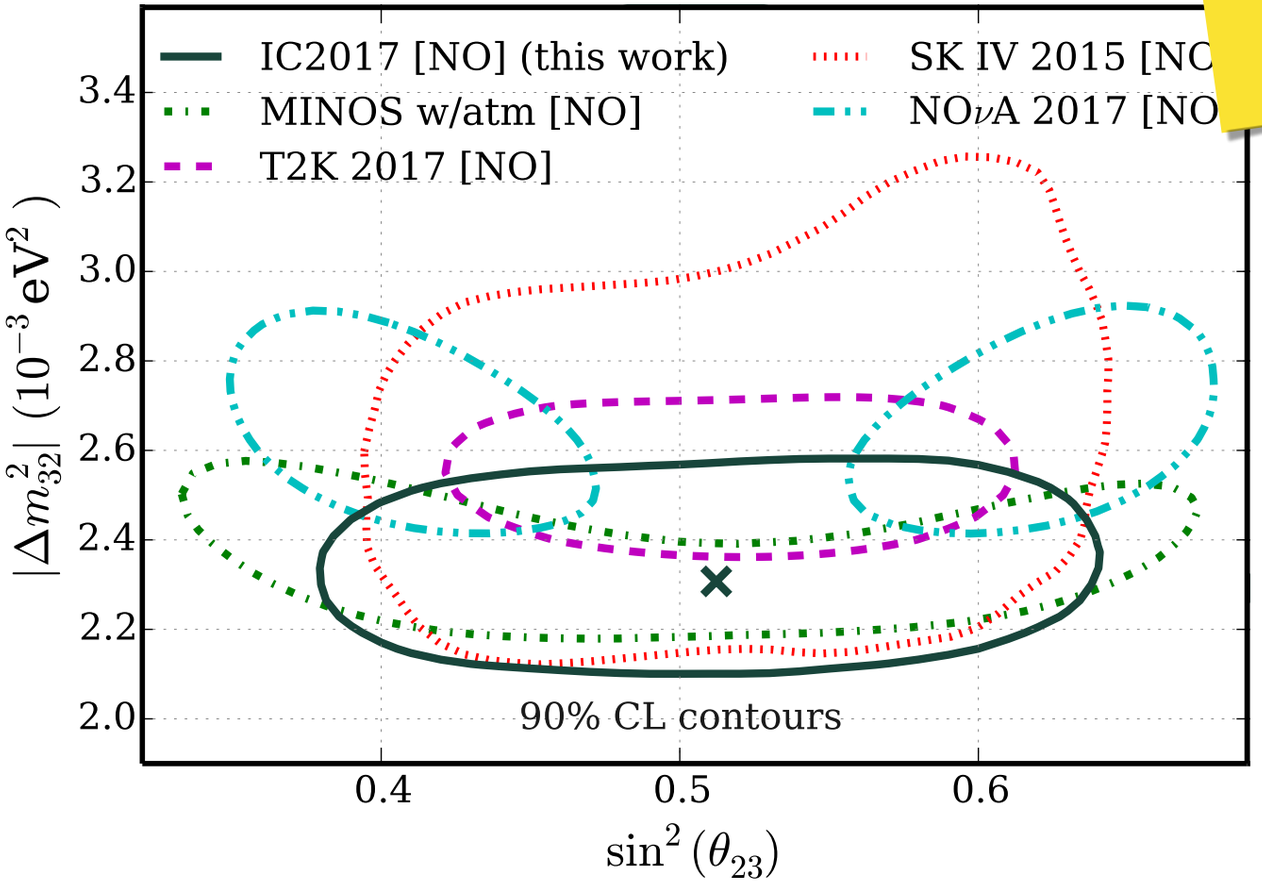
Atmospheric Neutrino Oscillations

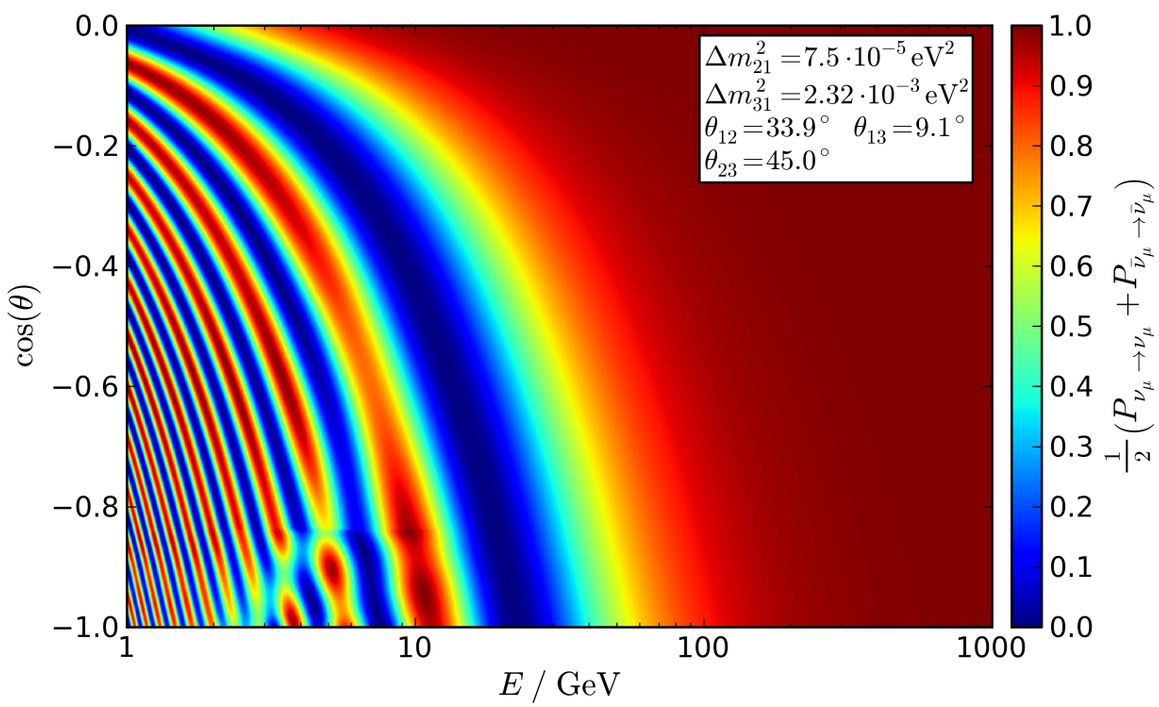
- **Muon neutrino disappearance** in the 1-100 GeV range allows for precision measurement of atmospheric mixing parameters.
- **IceCube @ NBI** leads the current generation of oscillation analyses with DeepCore data.



contact: Jason

[IceCube, PRL 120 (2018) 7]

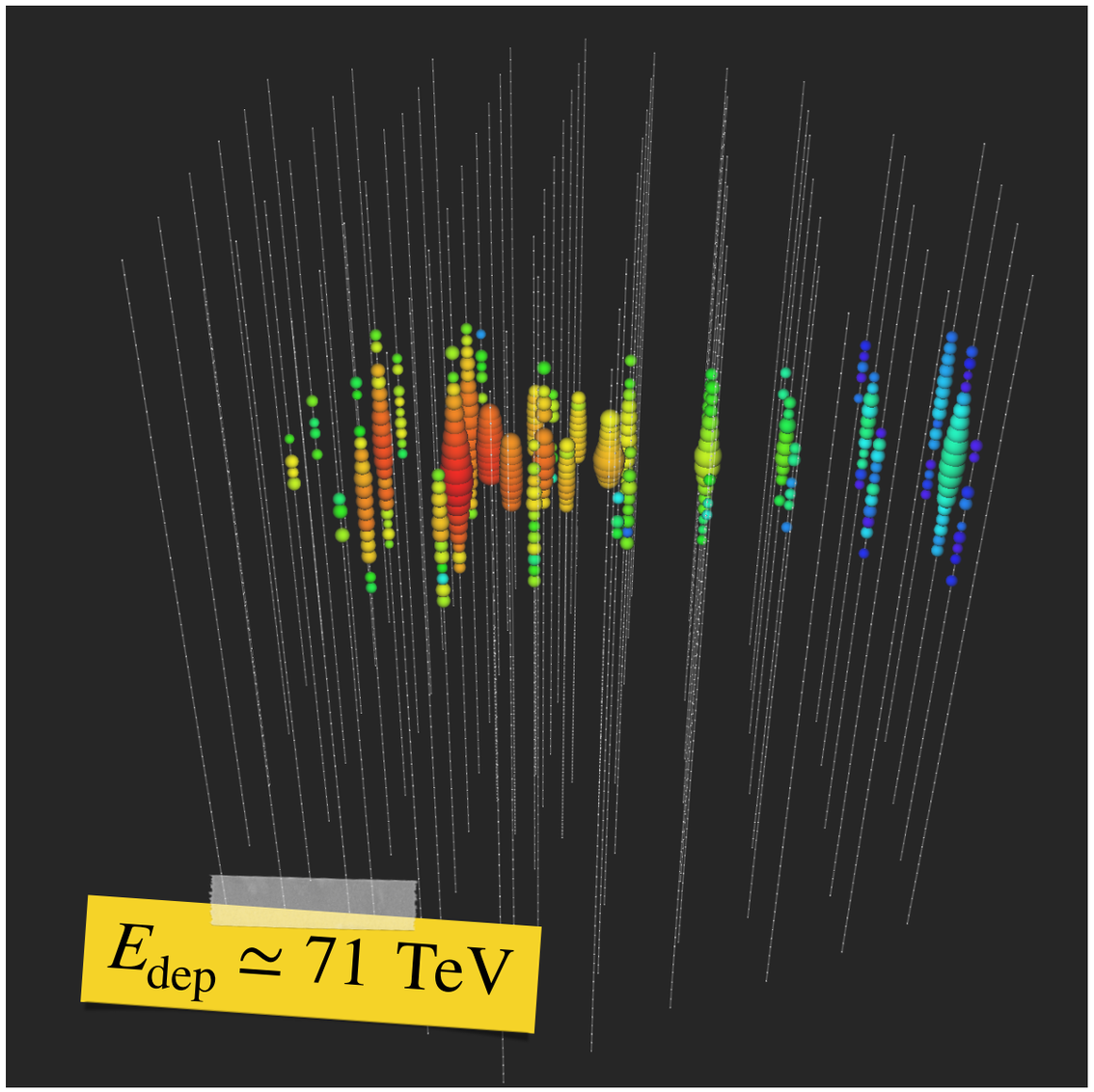




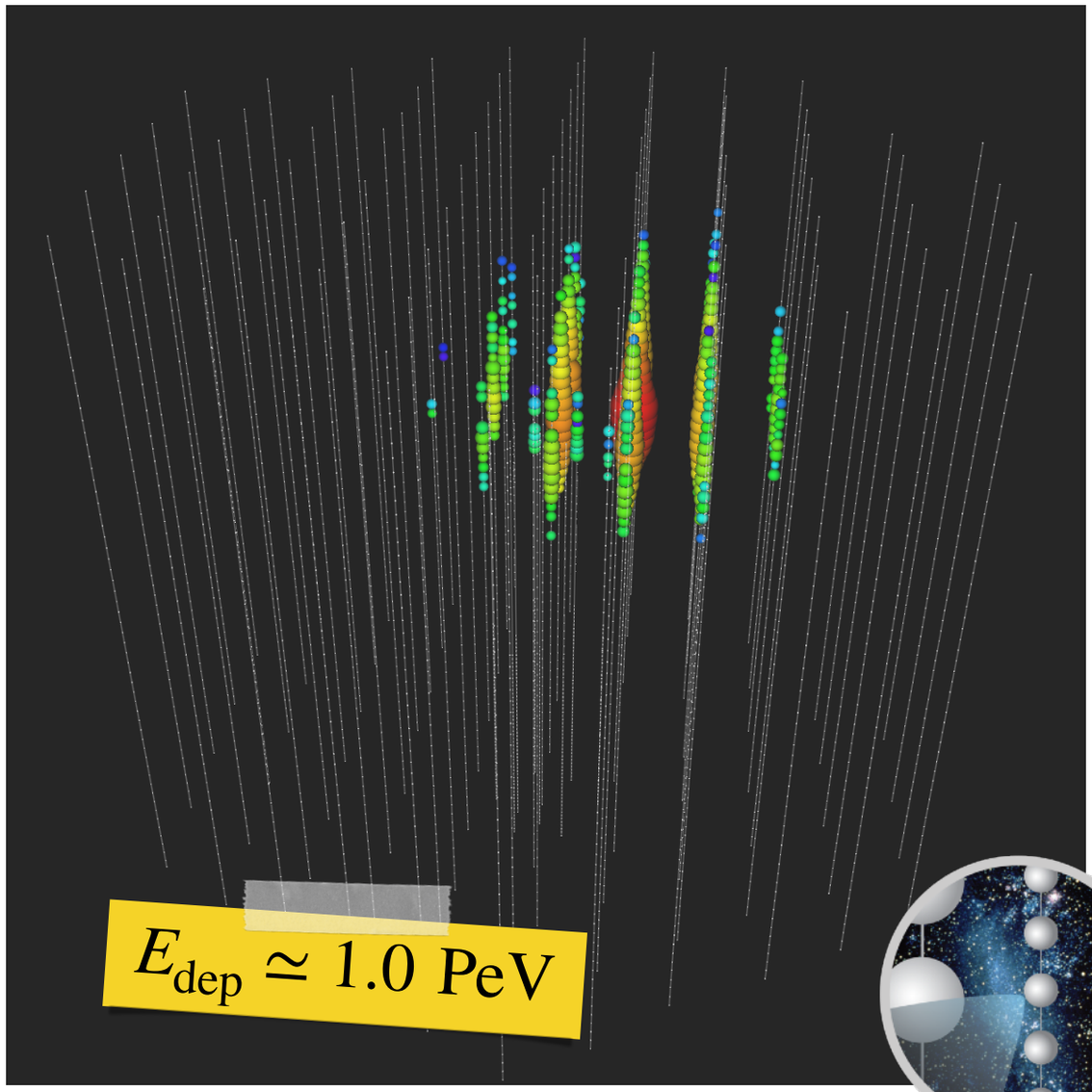
Astrophysical Neutrinos

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**)

ICECUBE

Event Reconstructions

contacts: Troels & Jason

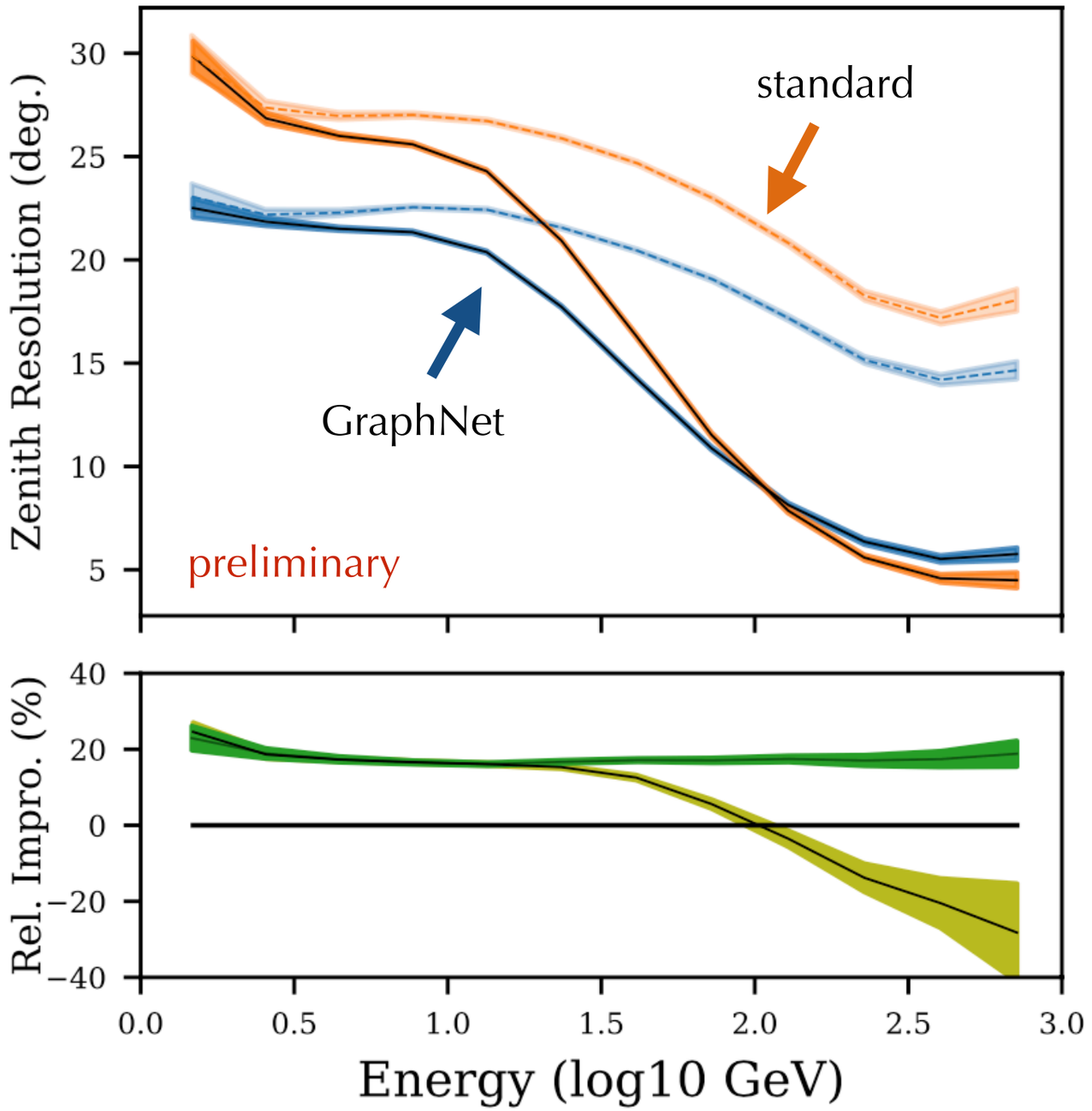
- Improved angular and energy reconstructions are a key to improve sensitivities of neutrino telescopes.
- **Machine-learning tools**, *e.g.* based on graph neural networks are paving the way for future analyses with DeepCore data and IceCube-Upgrade.

GraphNeT

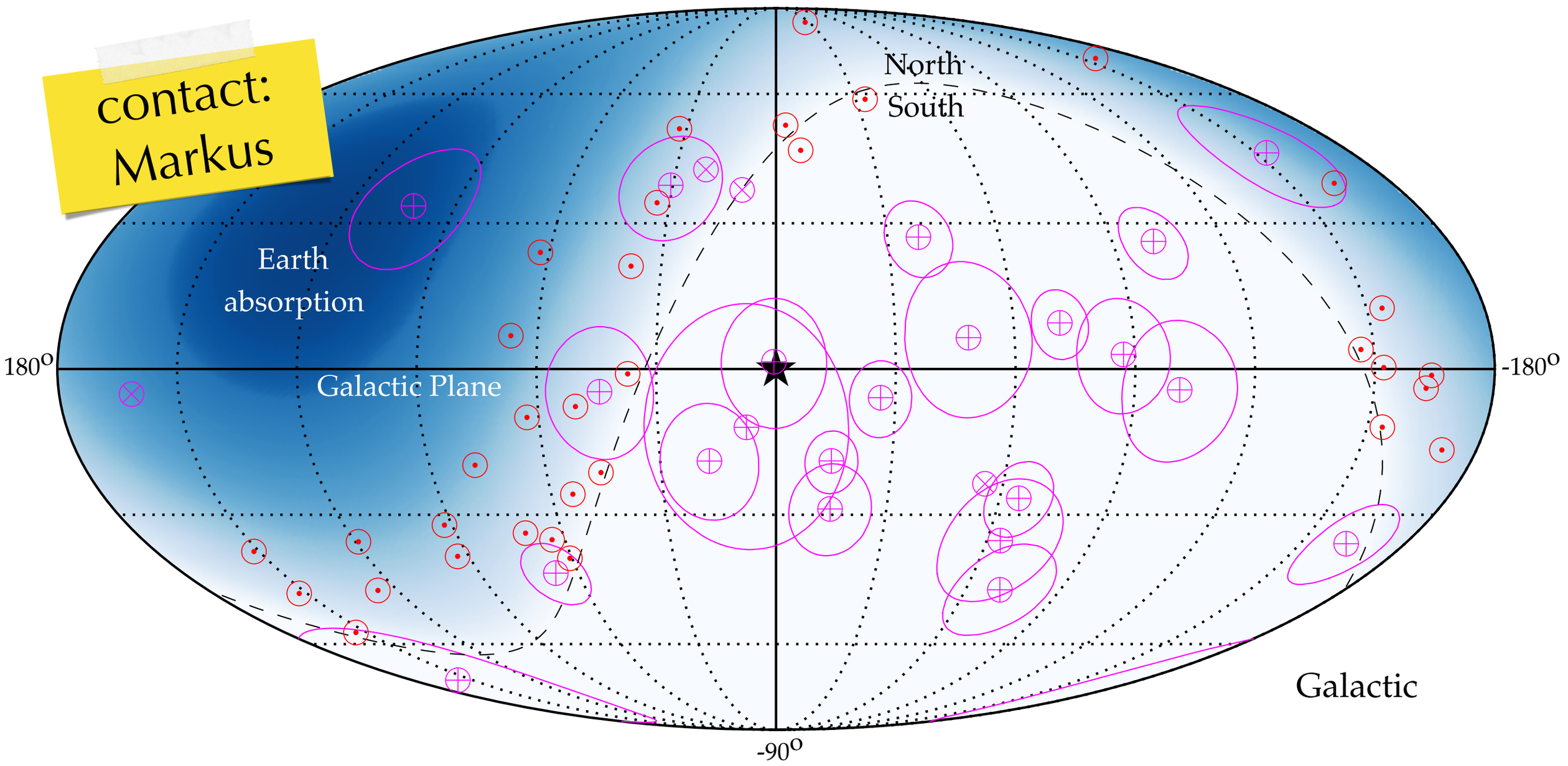
Graph Neural Networks for Neutrino Telescope Event Reconstruction

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

Angular reconstructions with **GraphNet**

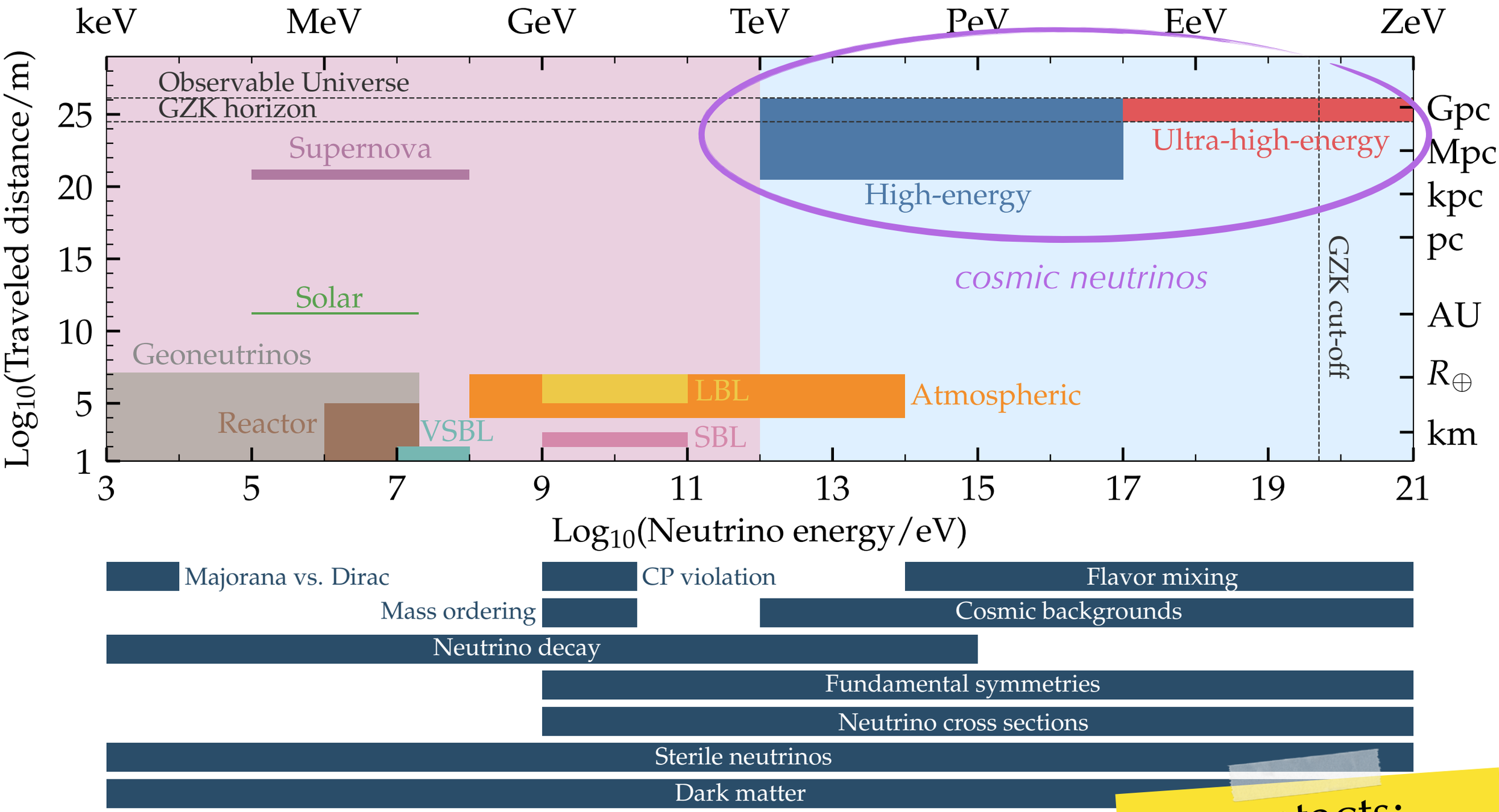


Neutrino Astrophysics



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

Probe of Fundamental Physics



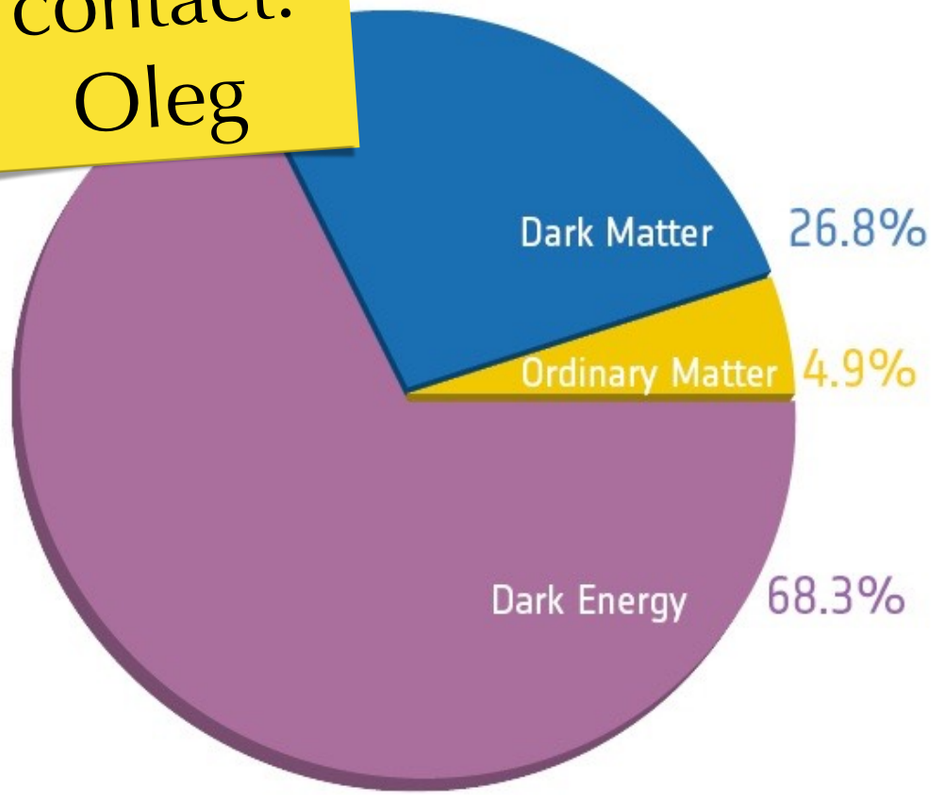
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al.*, Bull. Am. Astron. Soc. 51 (2

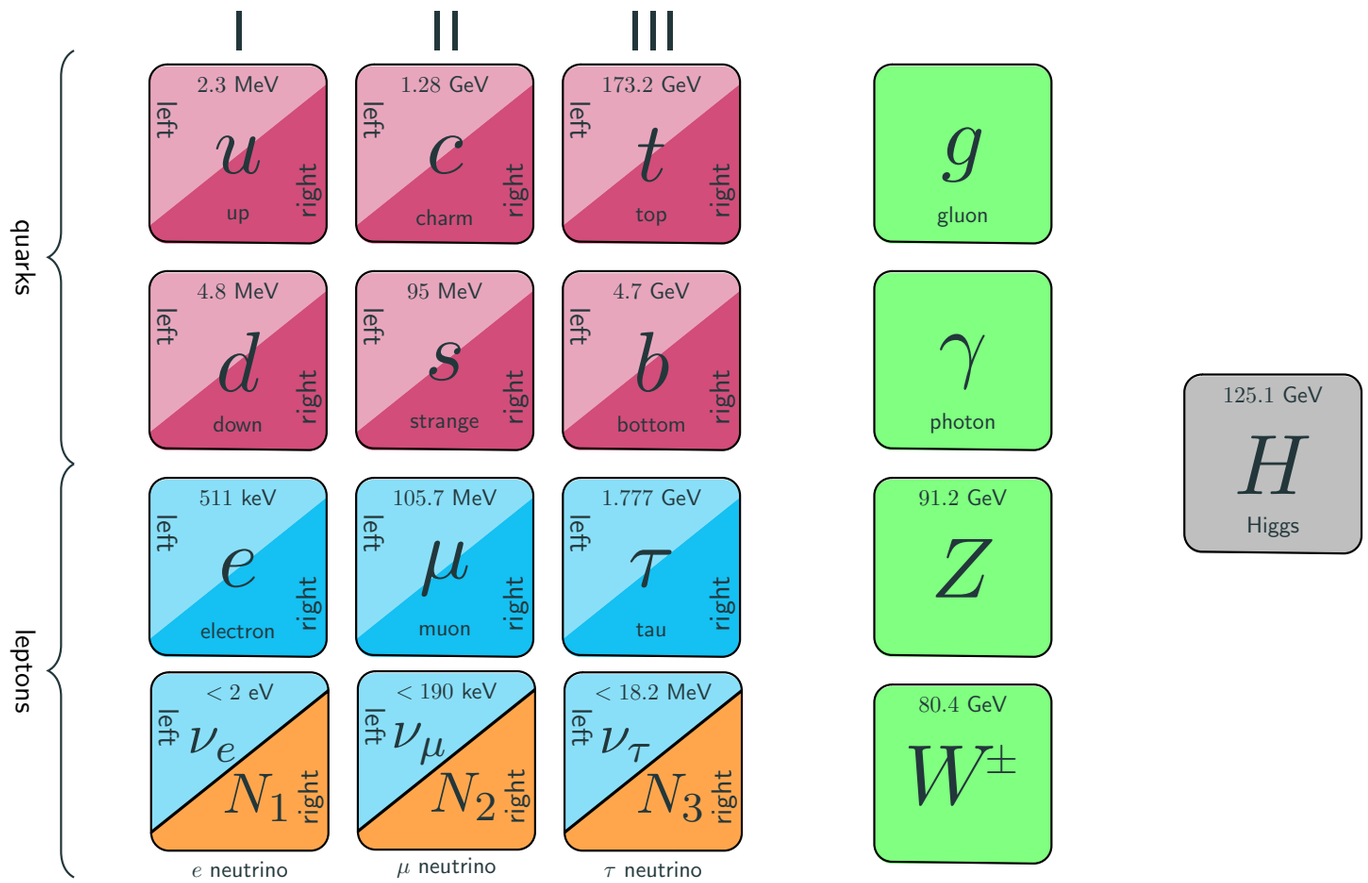
contacts:
Markus & Jason

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

contact: Oleg

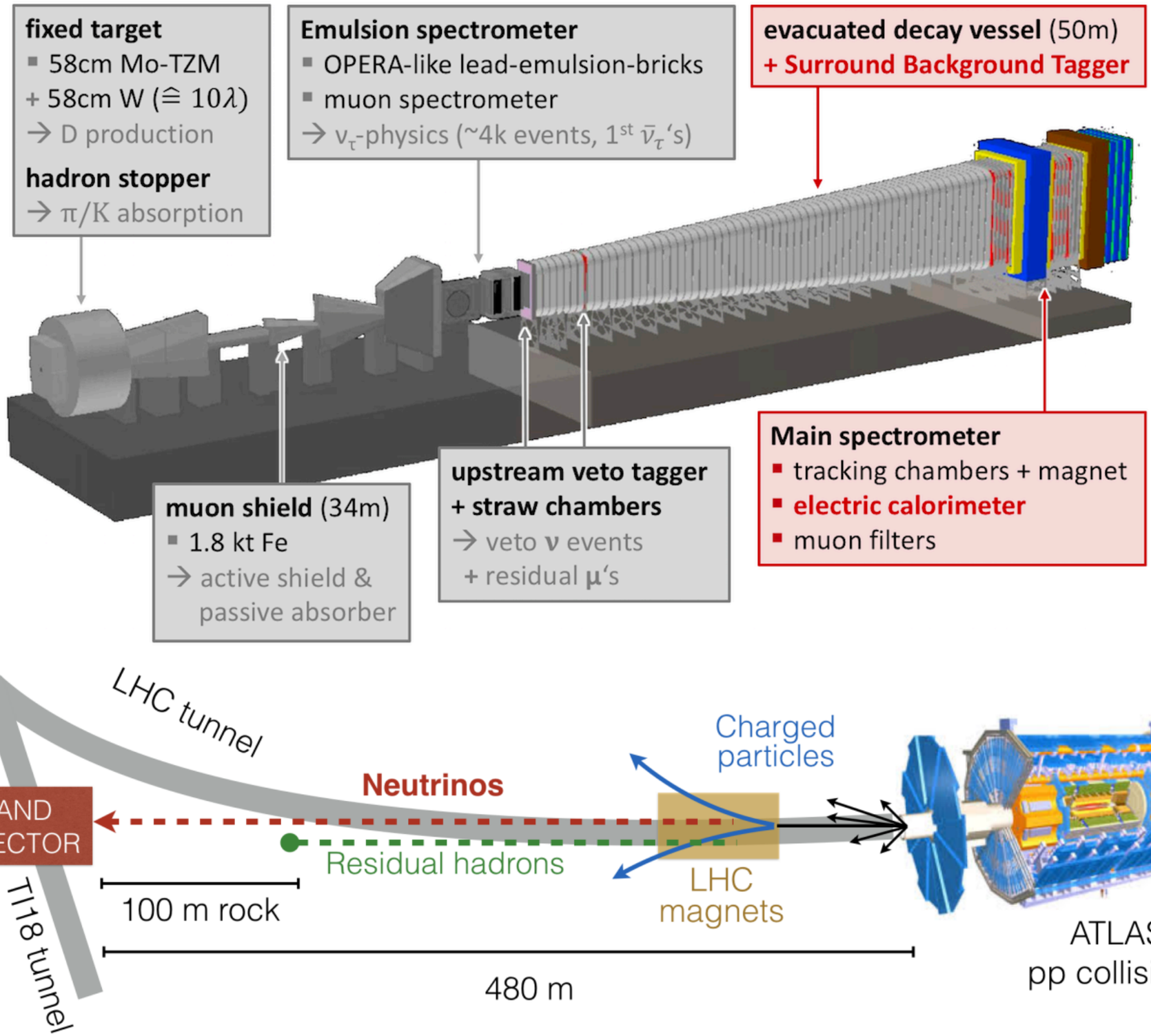




[Boyarsky, Drewes, Lasserre, Mertens & Ruchayskiy, Prog.Part.Nucl.Phys. 104 (2019)]

Search for Hidden Particles (SHiP)

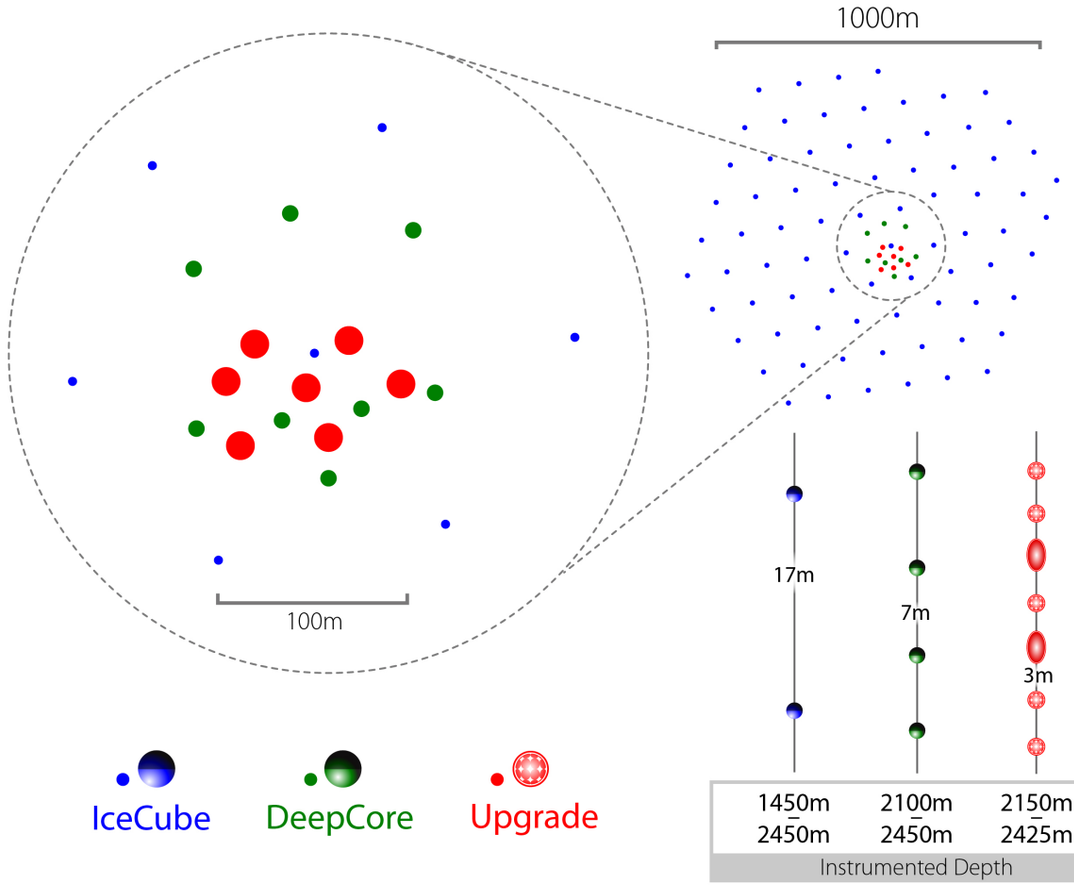
contact: Oleg

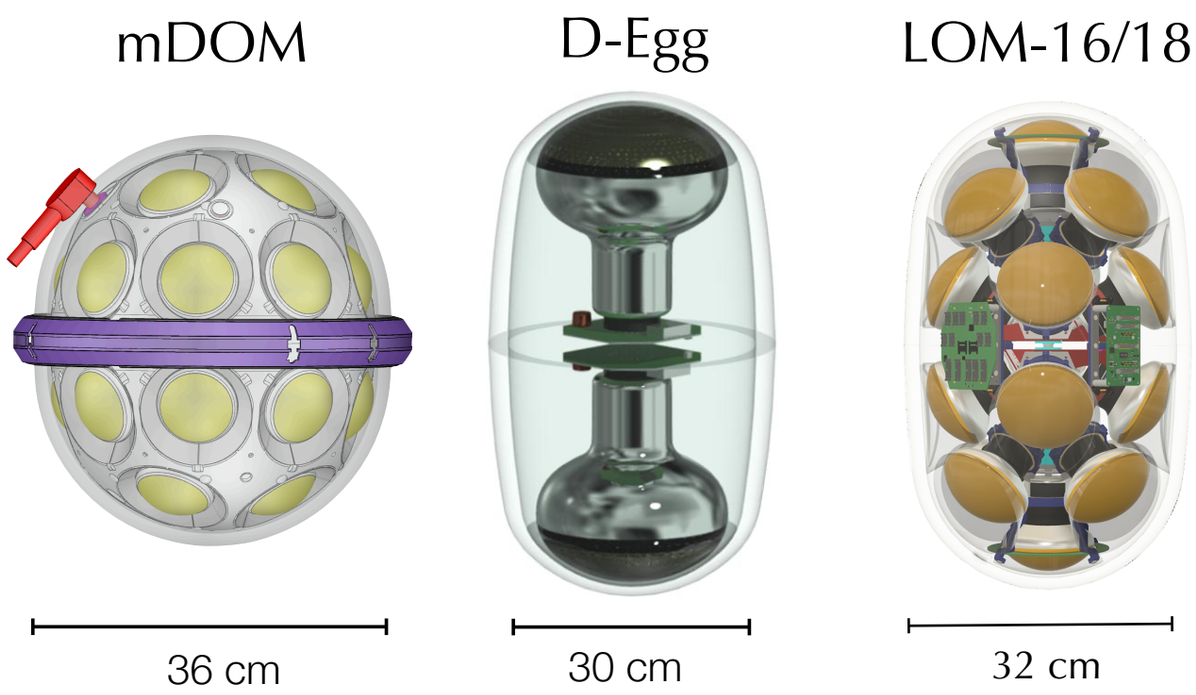


Backup Slides

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.
- **Deployment in 2025/26**

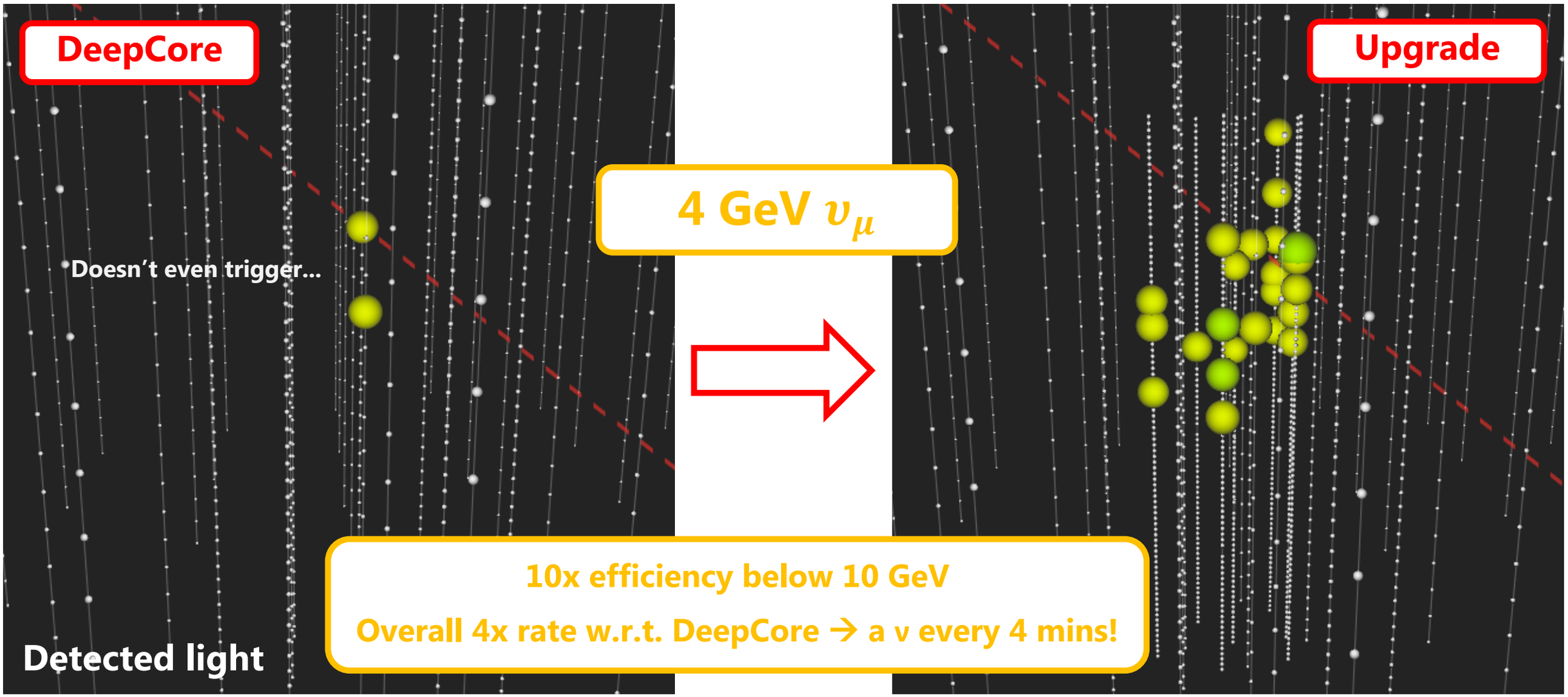




IceCube Upgrade Simulation

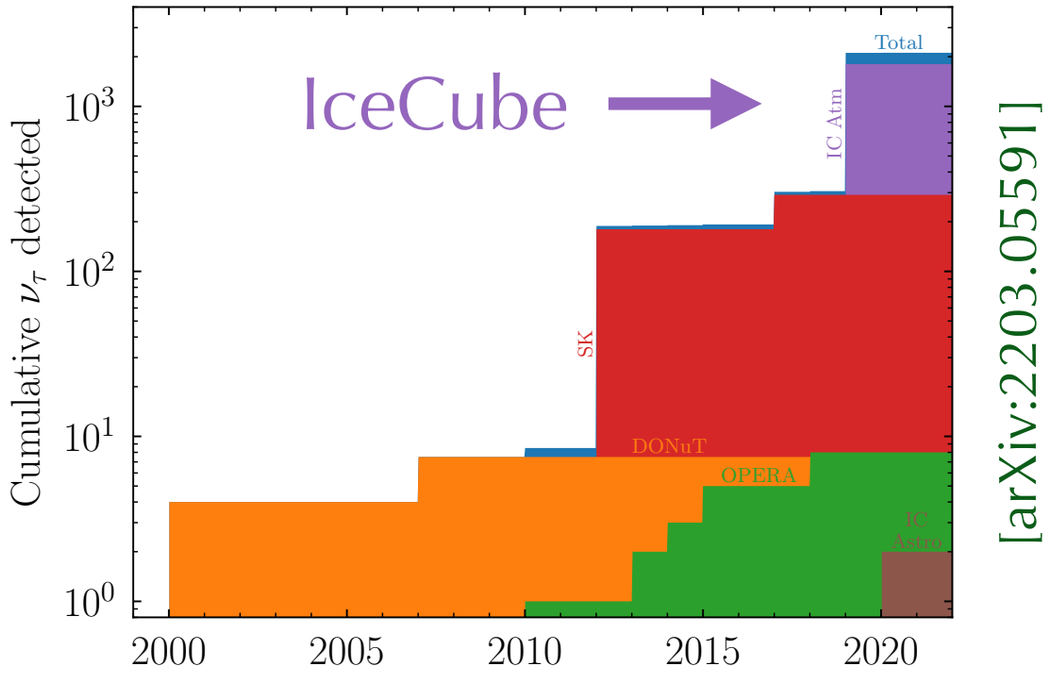
Improved low-energy detection efficiency with IceCube Upgrade

[courtesy of **Tom Stuttard**]

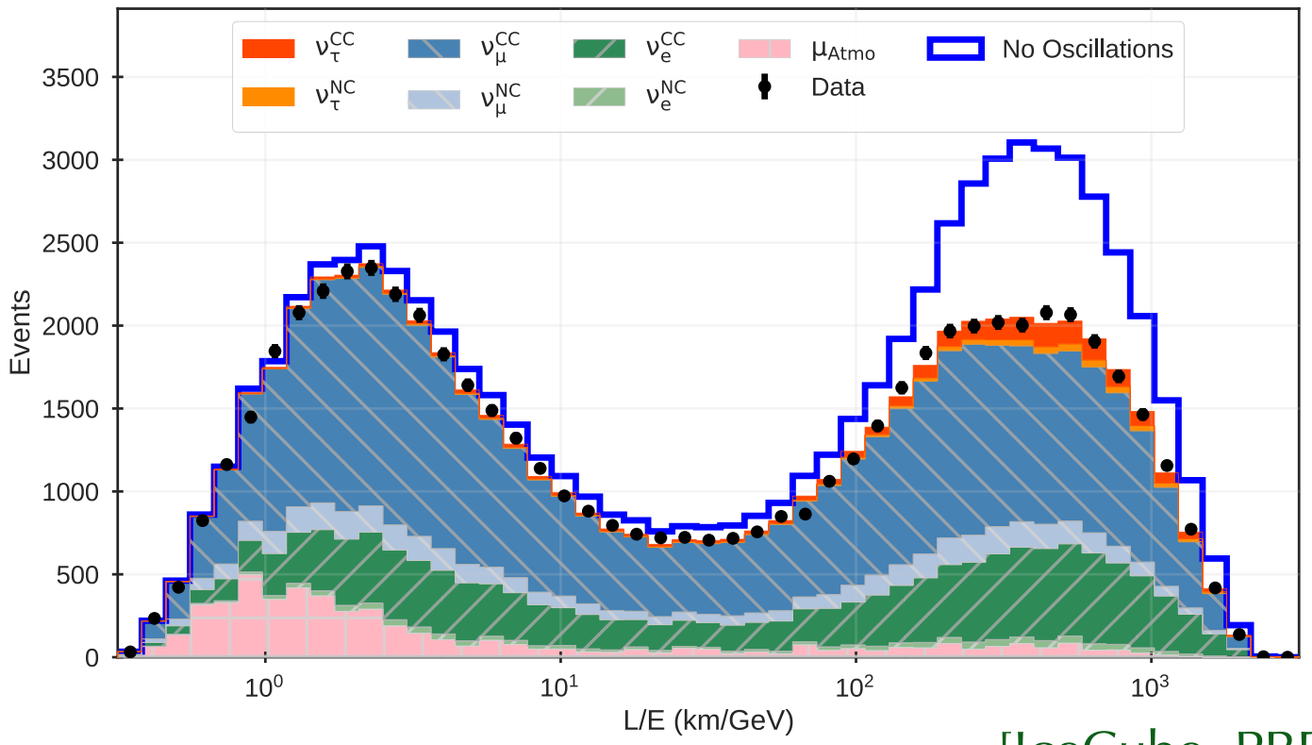


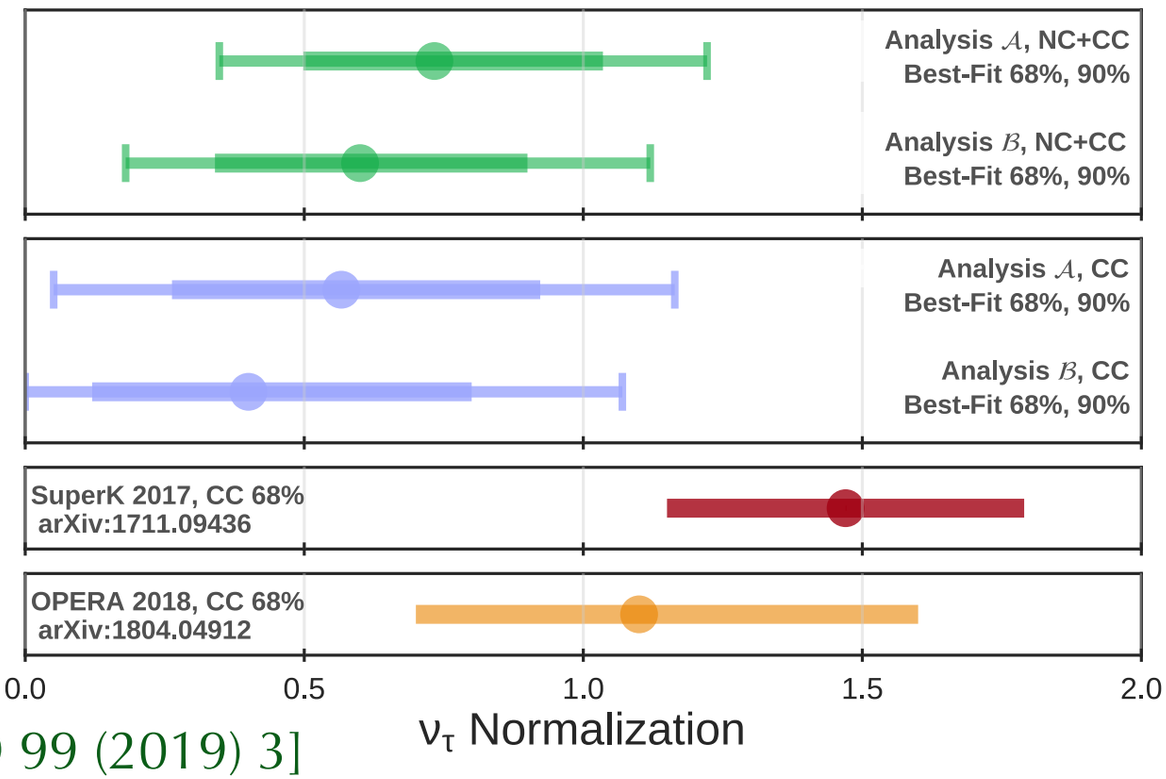
Tau Neutrino Appearance

- 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**.



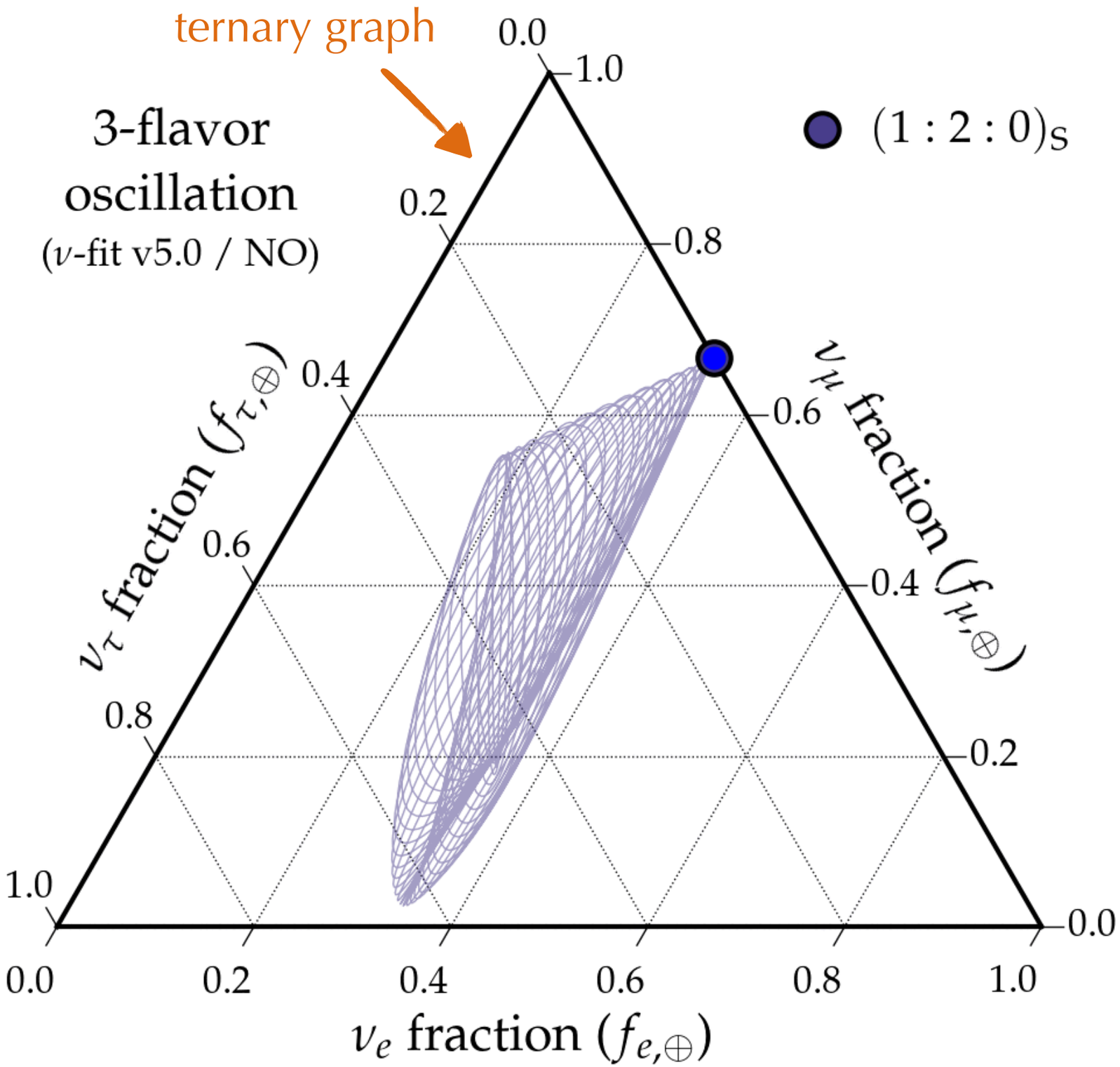
[arXiv:2203.05591]



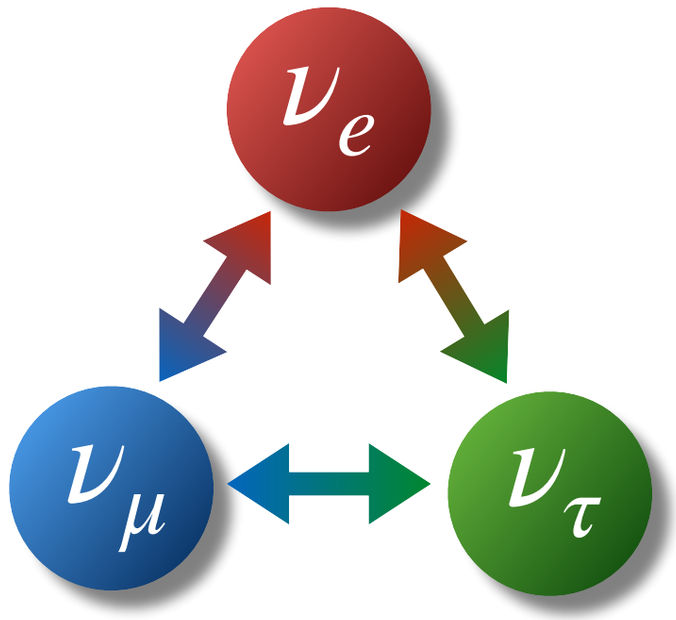


[IceCube, PRD 99 (2019) 3]

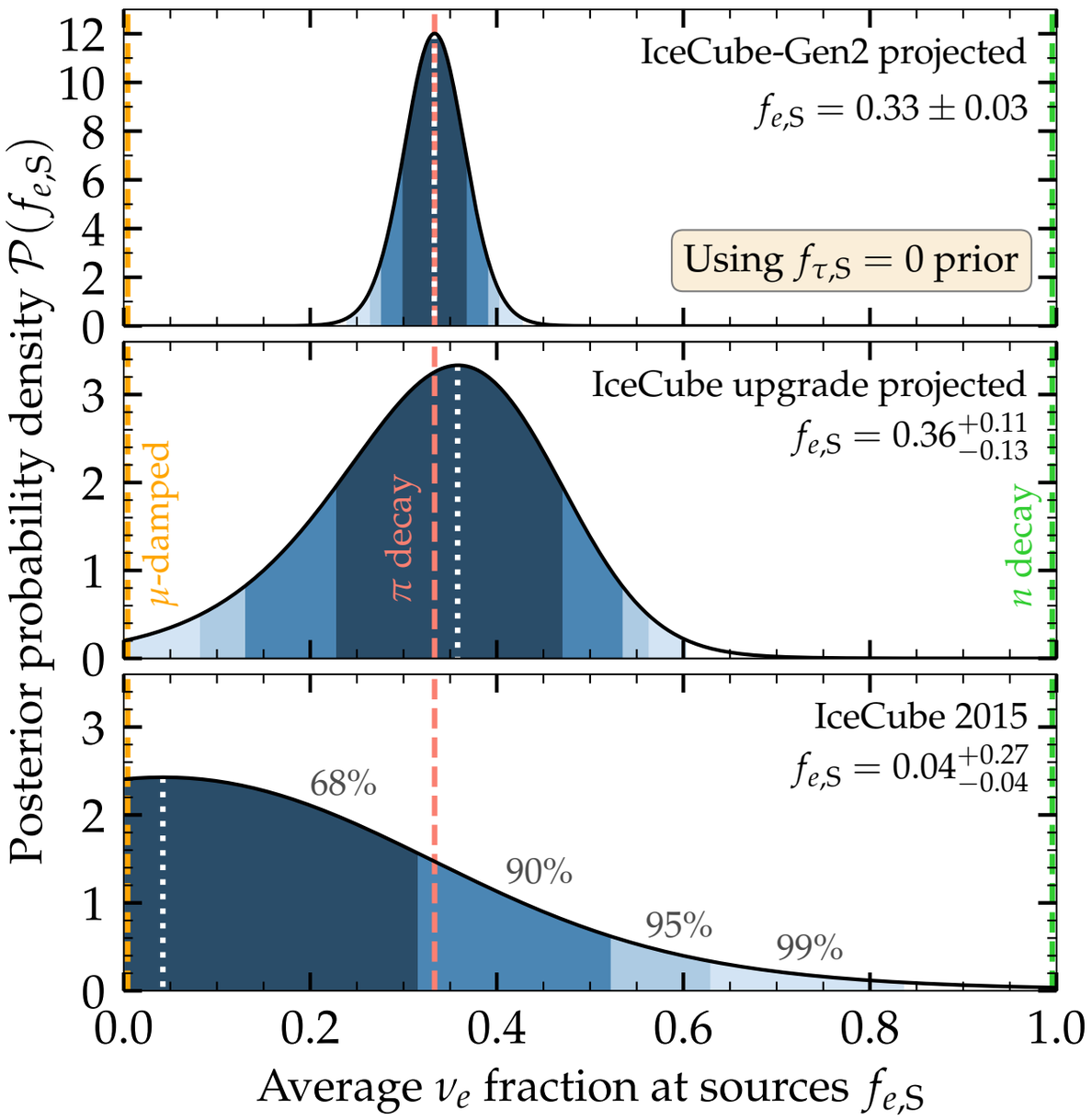
Astrophysical Flavours



Superposition of flavor and mass states induce oscillations.

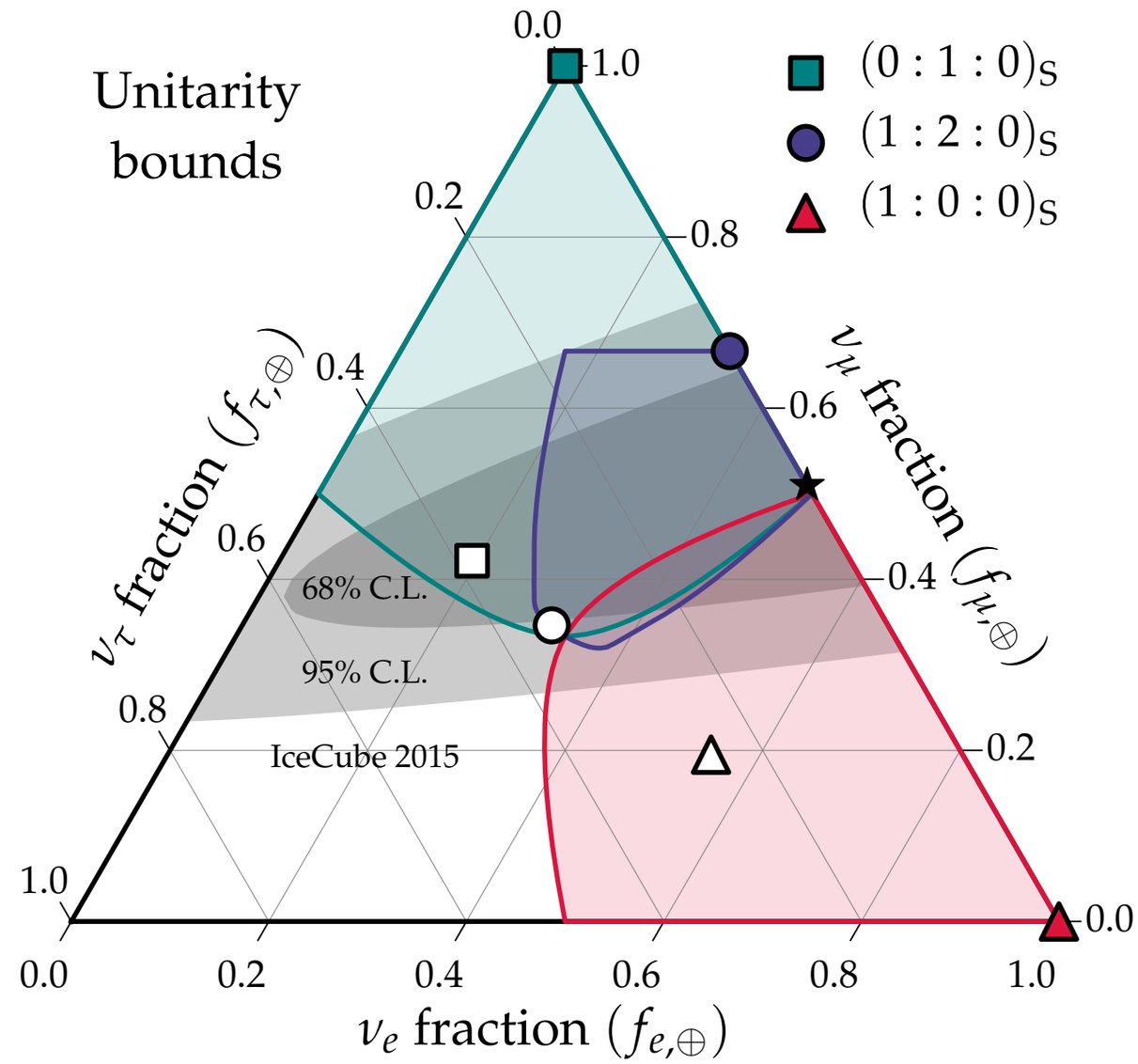


Probe of Particle (Astro-)Physics



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

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



"Unitarity Bounds of Astrophysical Neutrinos"

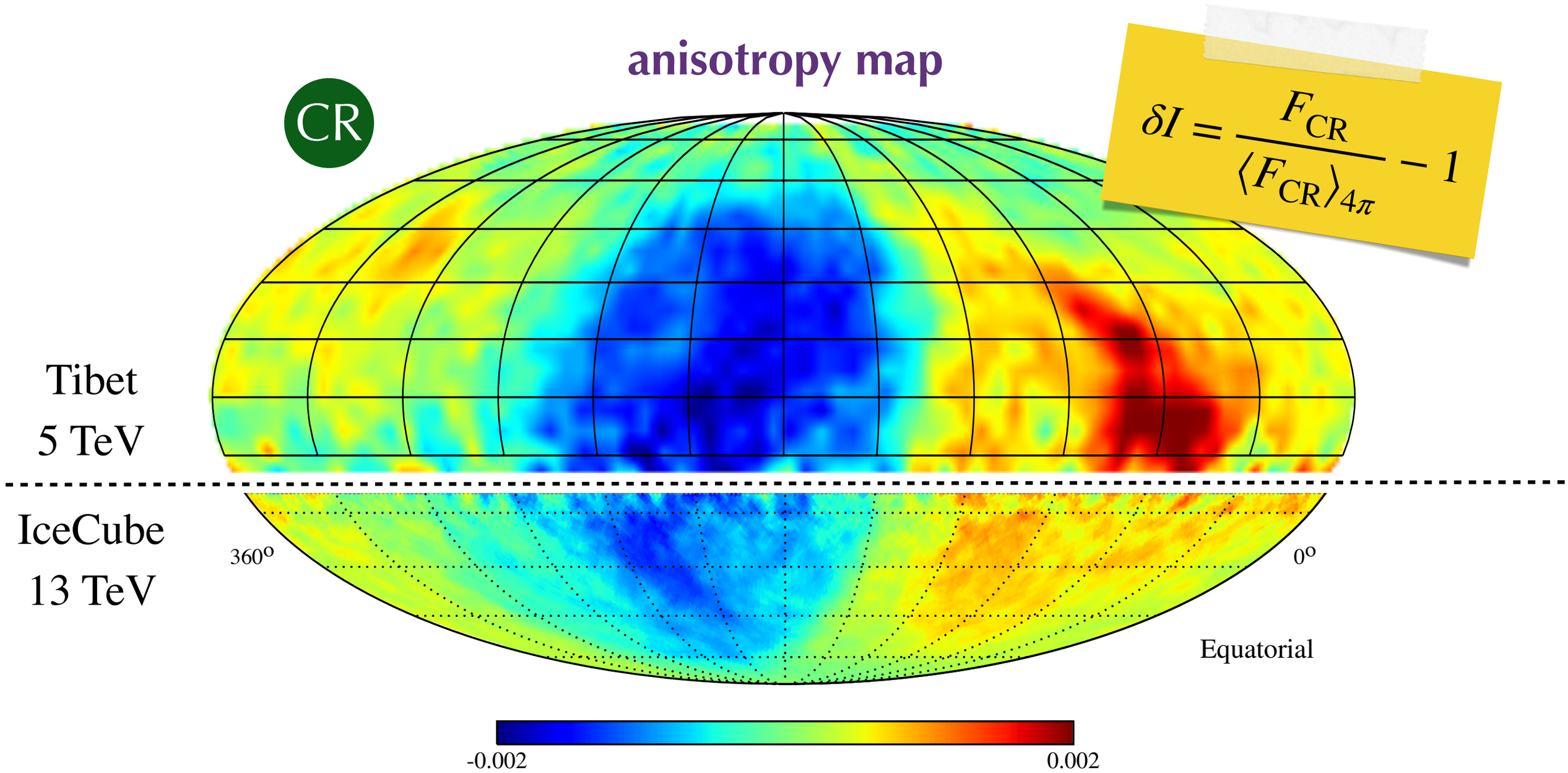
[MA, Bustamante & Mu, **PRD** 98 (2018)]

"Flavors of astrophysical νs with active-sterile mixing"

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

Galactic Cosmic Rays Anisotropy

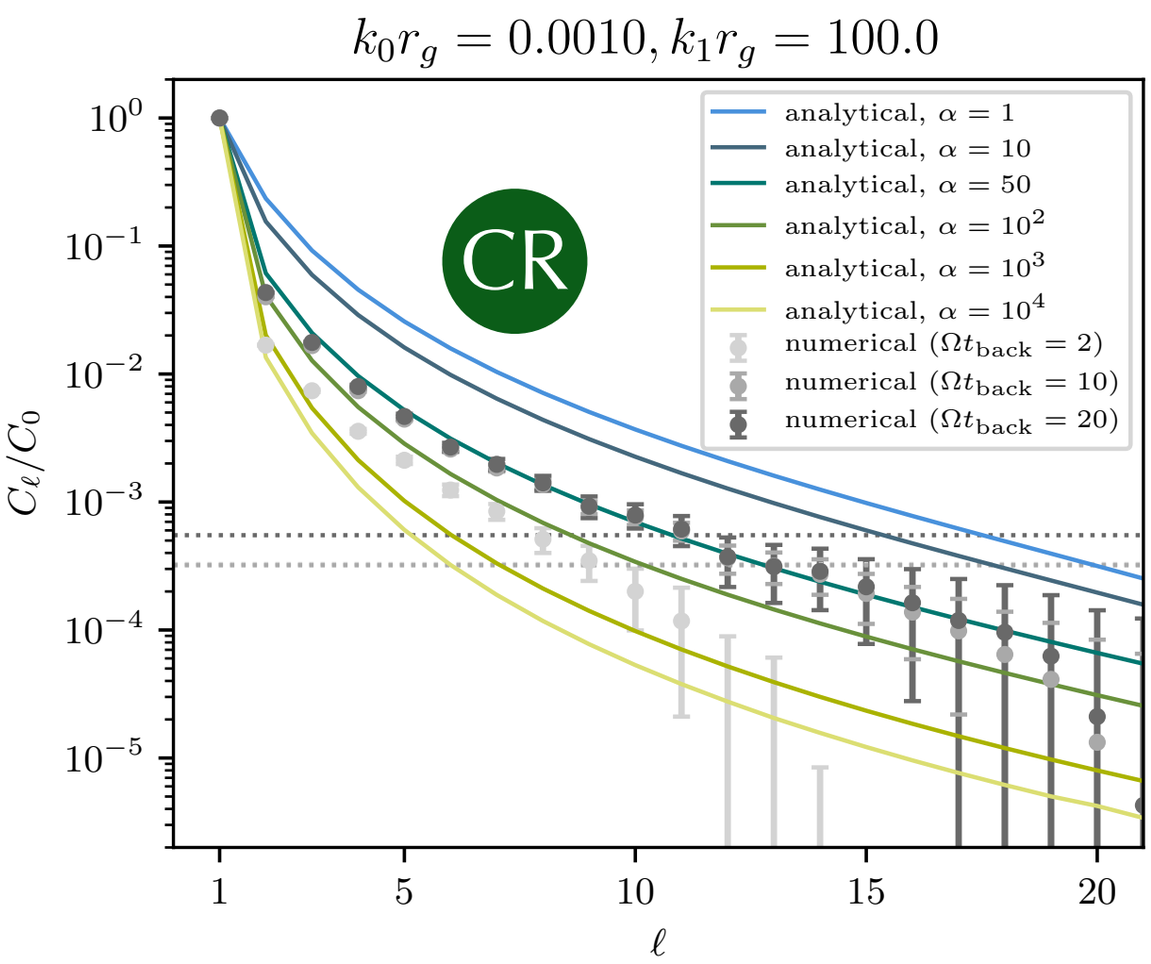
Cosmic ray anisotropies up to the level of **one-per-mille** at various energies



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

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

Cosmic Ray Anisotropy

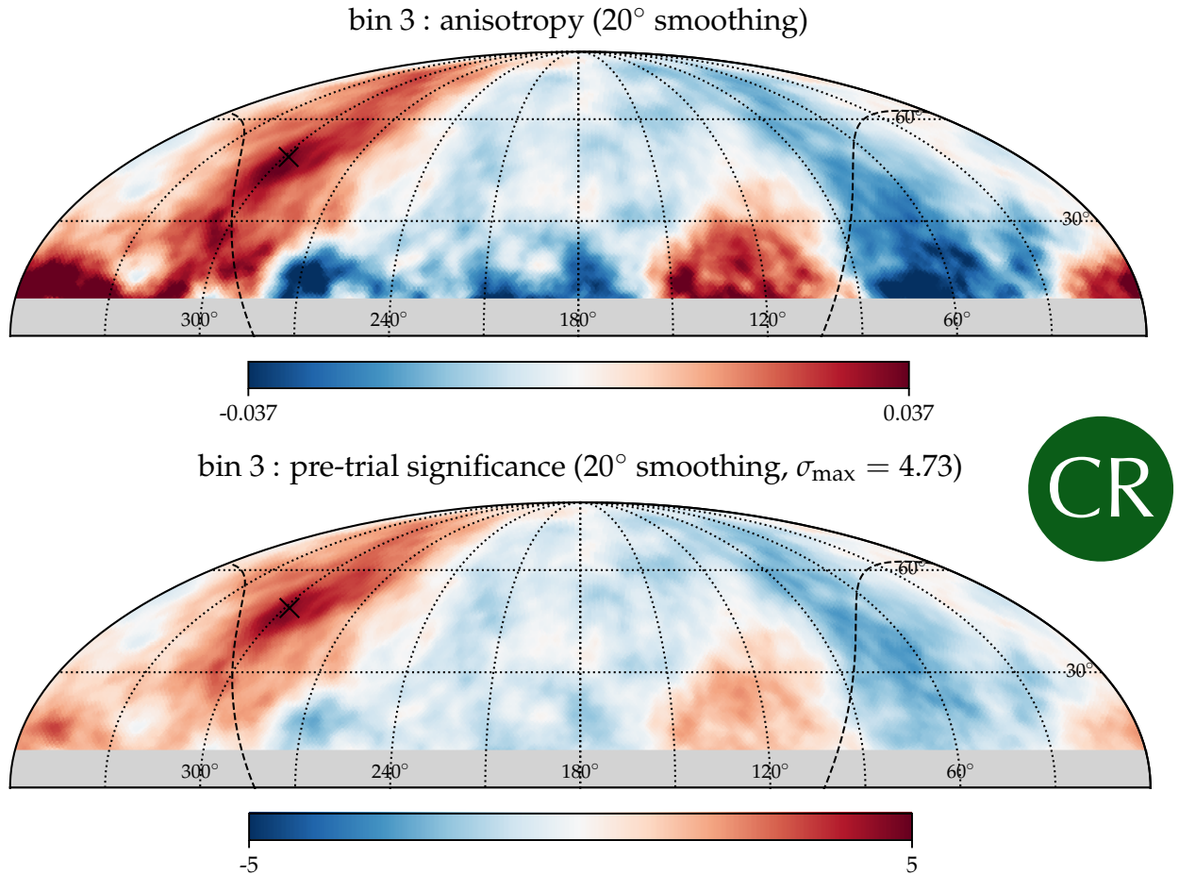


"*Cosmic ray small-scale anisotropies in quasi-linear theory*"

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

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

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



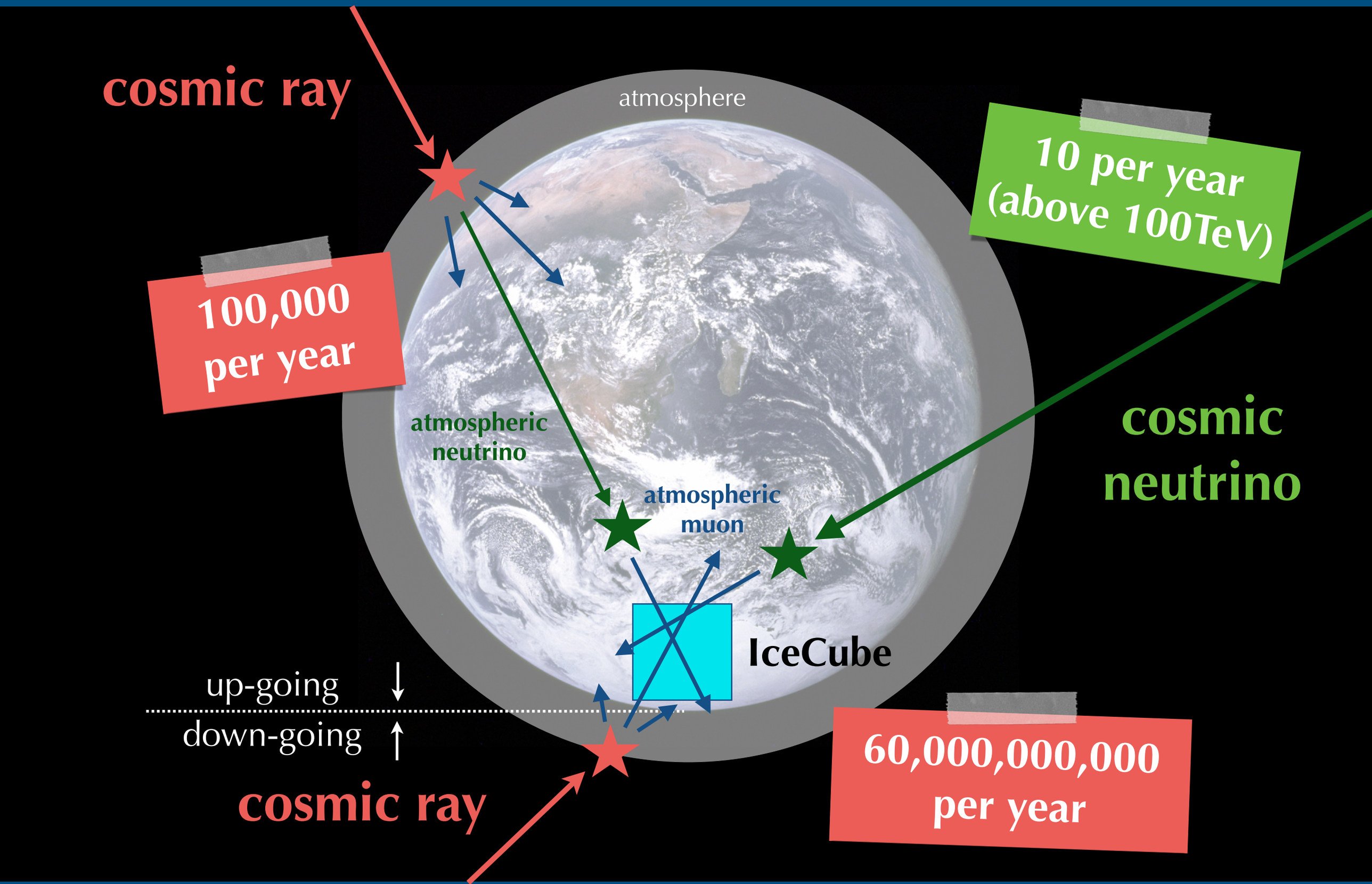
"*Large- and Medium-Scale Anisotropies in the Arrival Directions of Cosmic Rays observed with KASCADE-Grande*"

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

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

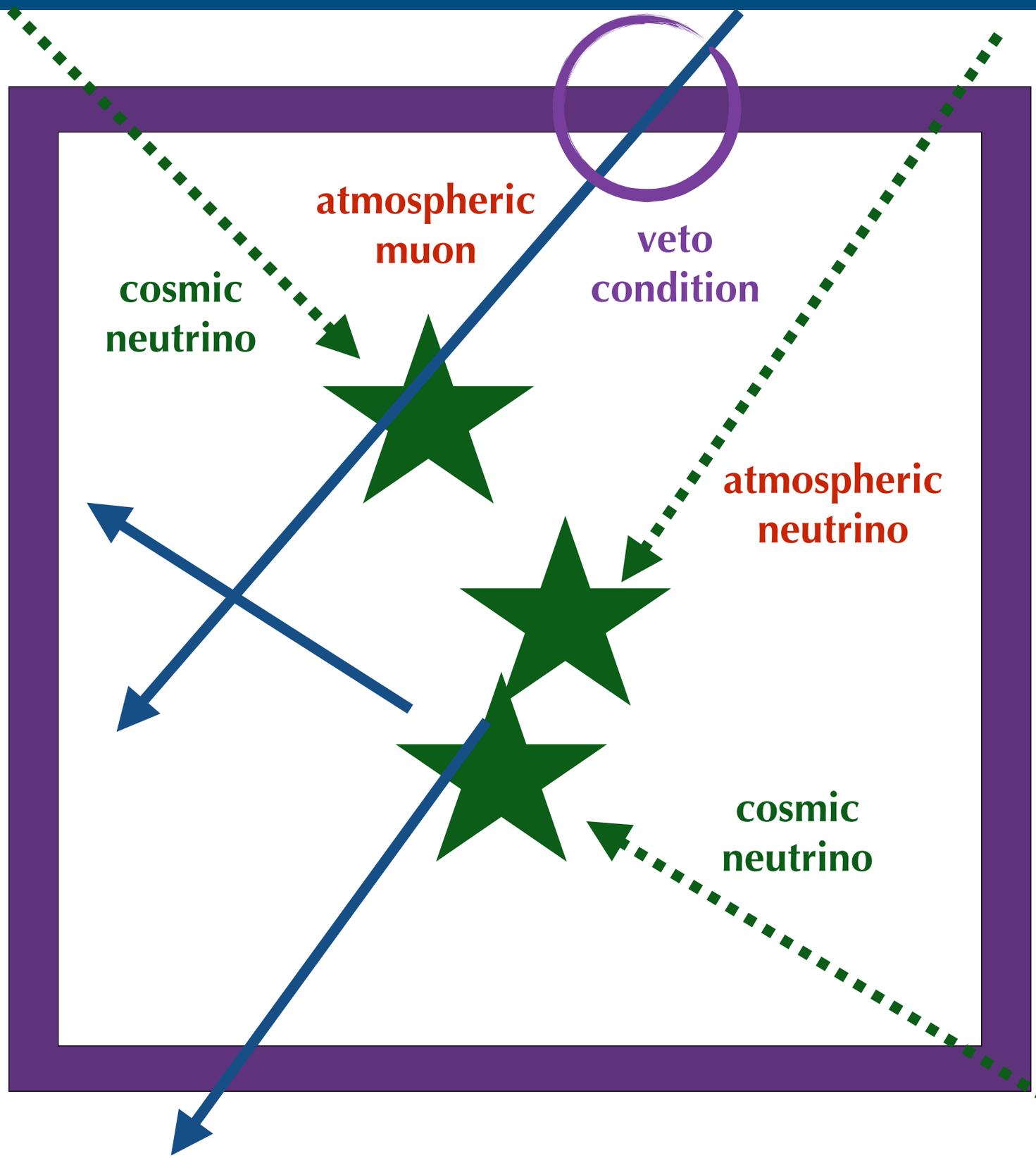
[MA, **ApJ** 863 (2018)]

Neutrino Selection I



Neutrino Selection II

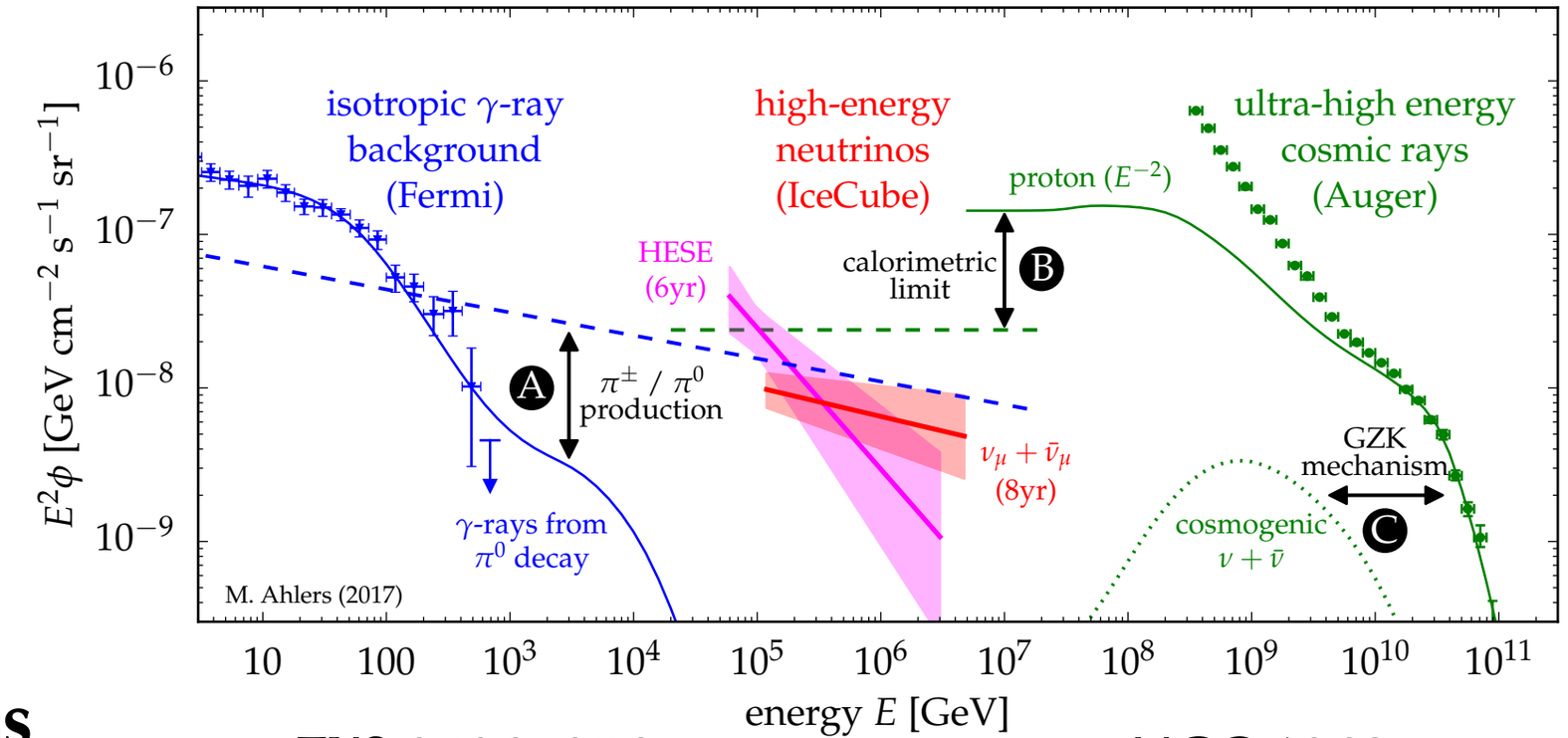
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



Status of Neutrino Astronomy

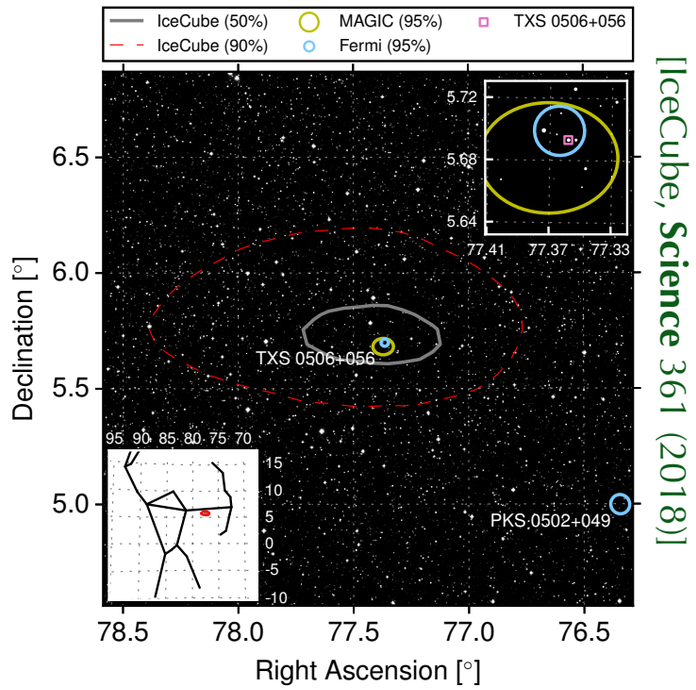
- **High neutrino intensity** compared to other cosmic backgrounds.
- **Open questions**:
  - ⋆ origin?
  - ⋆ spectral features?
  - ⋆ consistent MM emission?
- **Some strong indications for individual sources:**
  - ⋆ blazar TXS 0506+056
  - ⋆ Seyfert II galaxy NGC 1068
  - ⋆ Galactic plane
- **Many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

multi-messenger interfaces



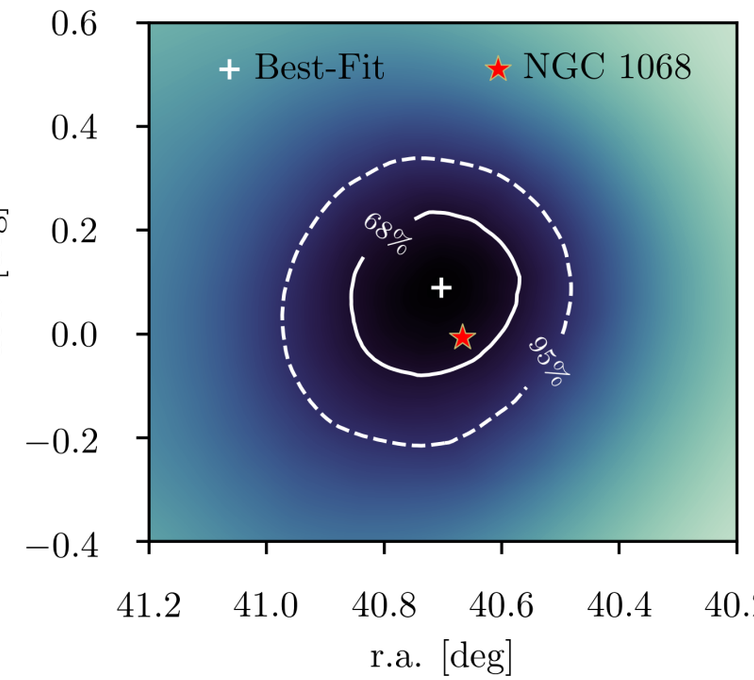
[MA & Halzen, **PPNP** 102 (2018)]

TXS 0506+056



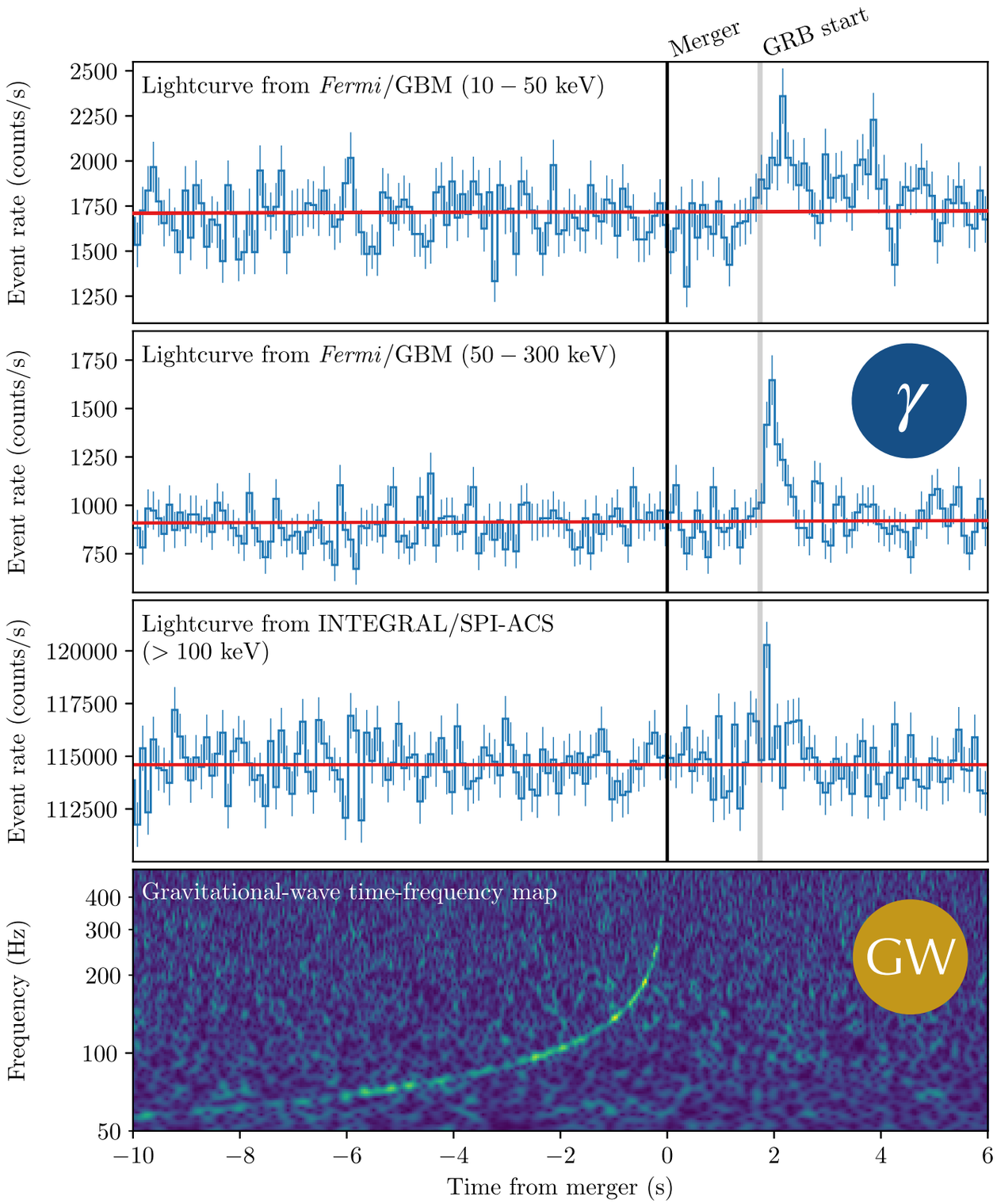
[IceCube, **Science** 361 (2018)]

NGC 1068

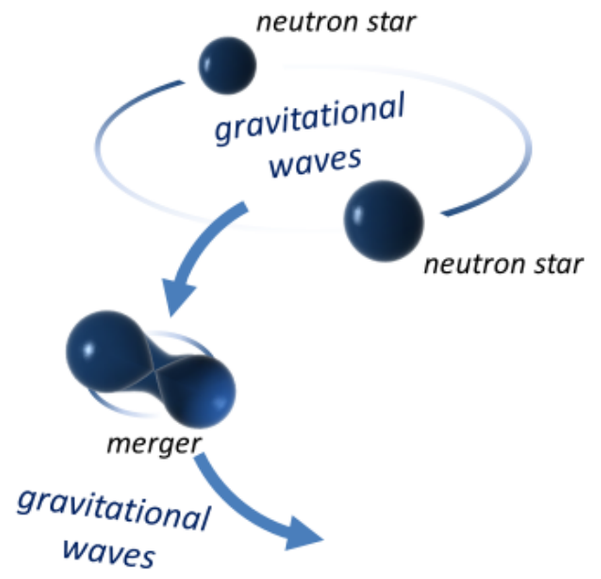


[IceCube, **Science** 378 (2022)]

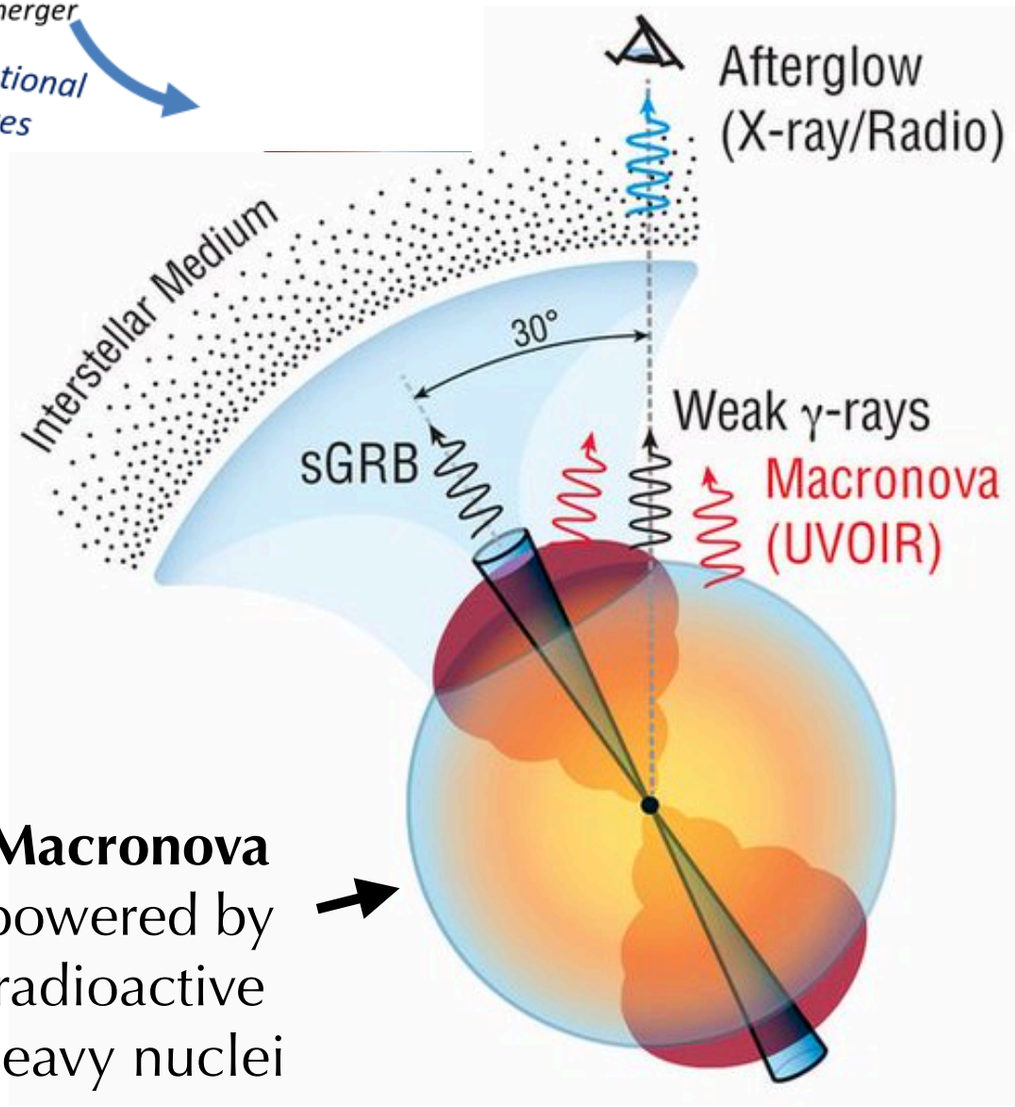
GRBs as Multi-Messenger Sources



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

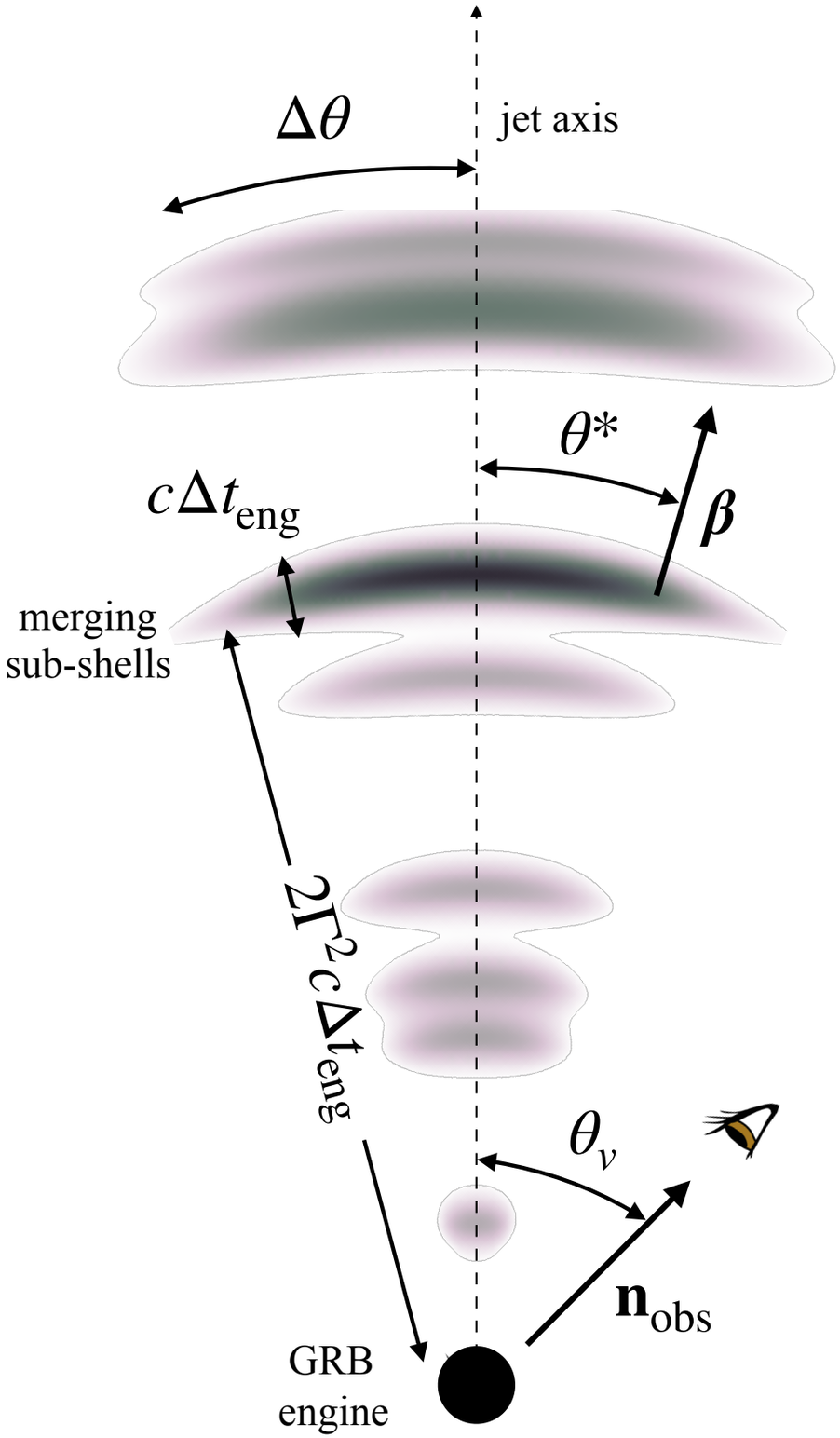


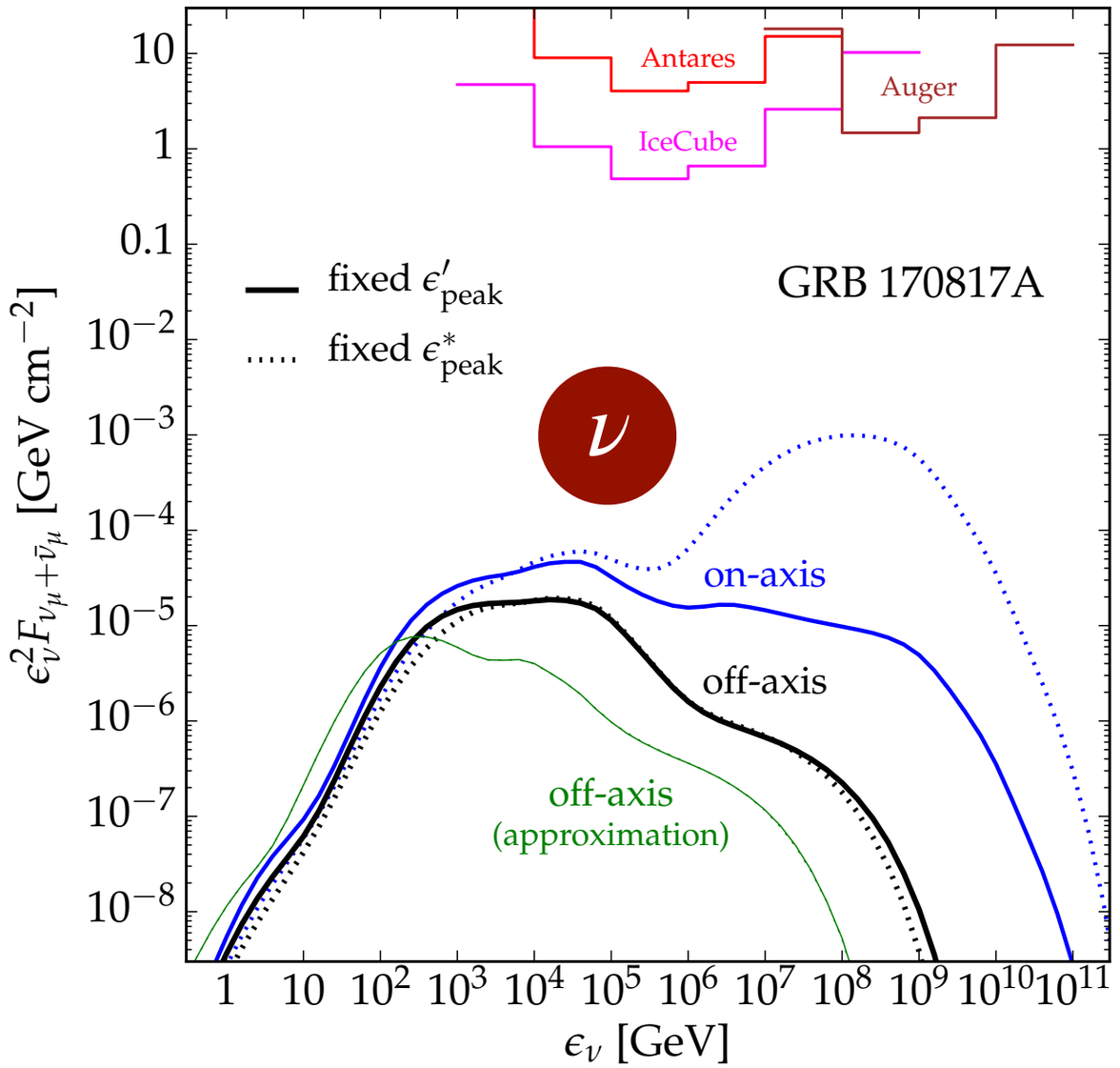
GW 170817
&
GRB 170817A



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)]