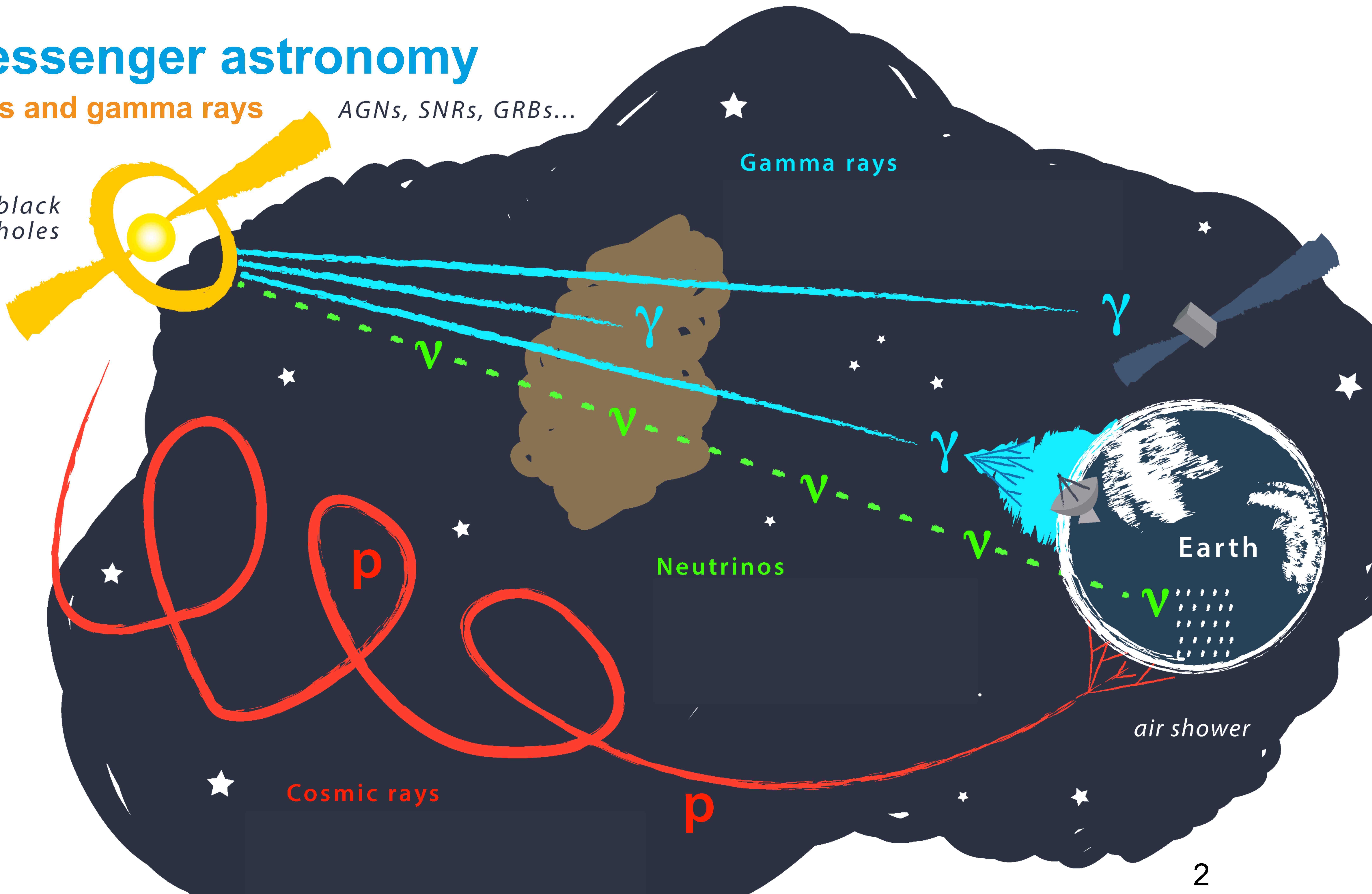
Multi-messenger astrophysics

with neutrinos and gamma rays

Markus Ackermann
Clues to the Mysterious Universe, Humboldt Kolleg, Kitzbühel, 29.06.22

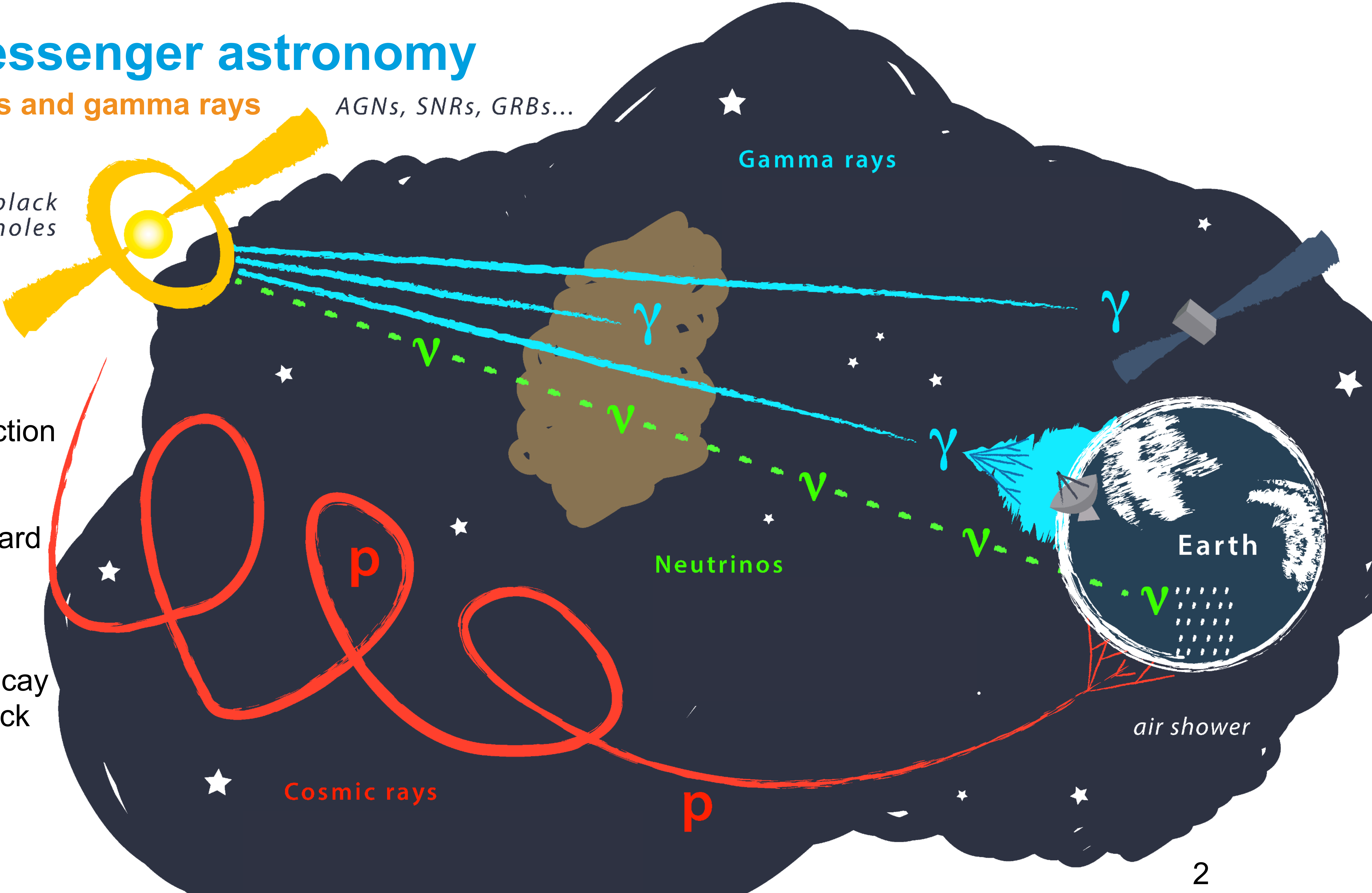
Multi-messenger astronomy

With neutrinos and gamma rays



Multi-messenger astronomy

With neutrinos and gamma rays

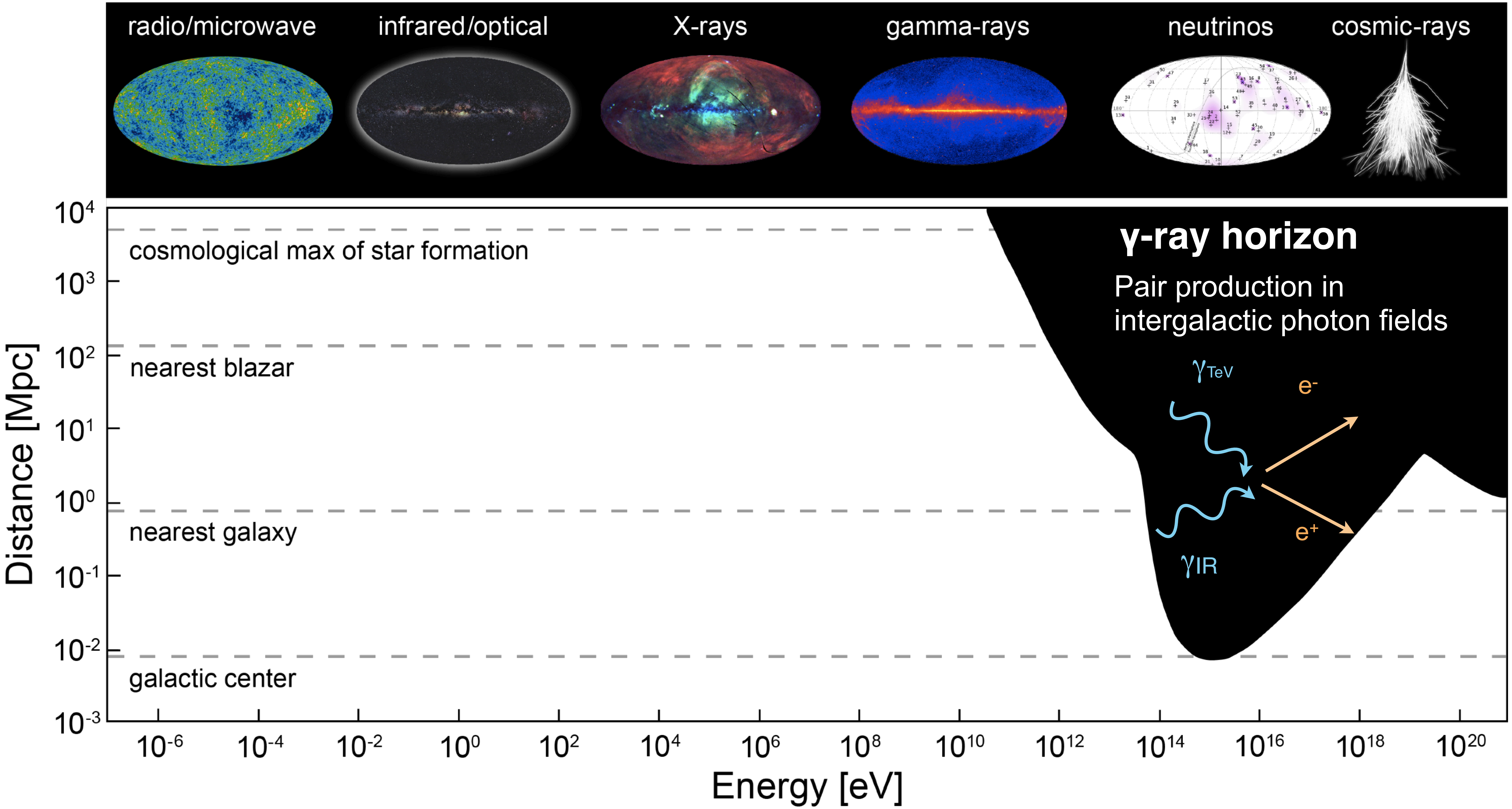


+ potential production of neutrinos and gamma rays in beyond the standard model processes:

- Dark matter annihilation / decay
- Evaporating black holes
- …

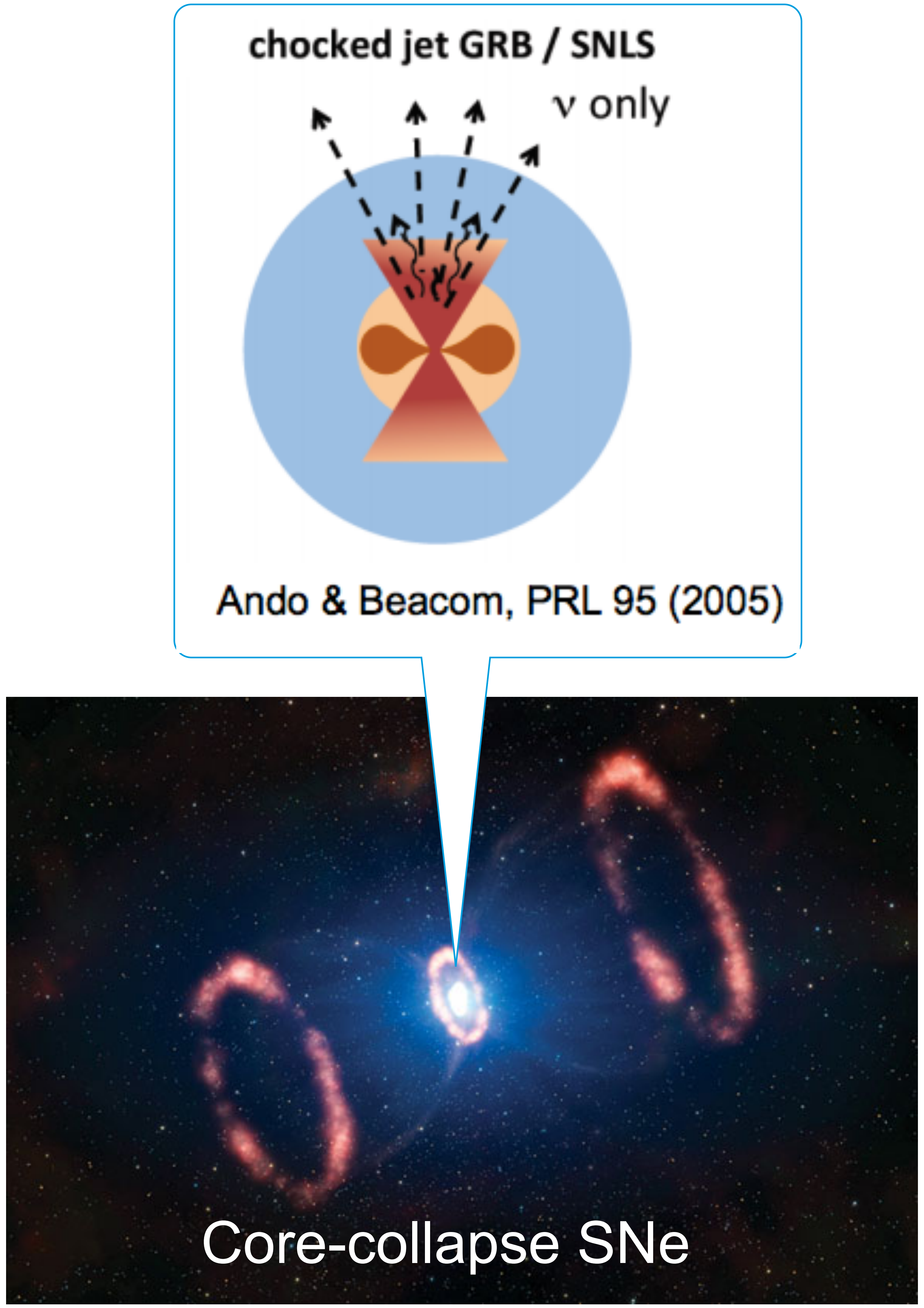
The photon and the neutrino domain

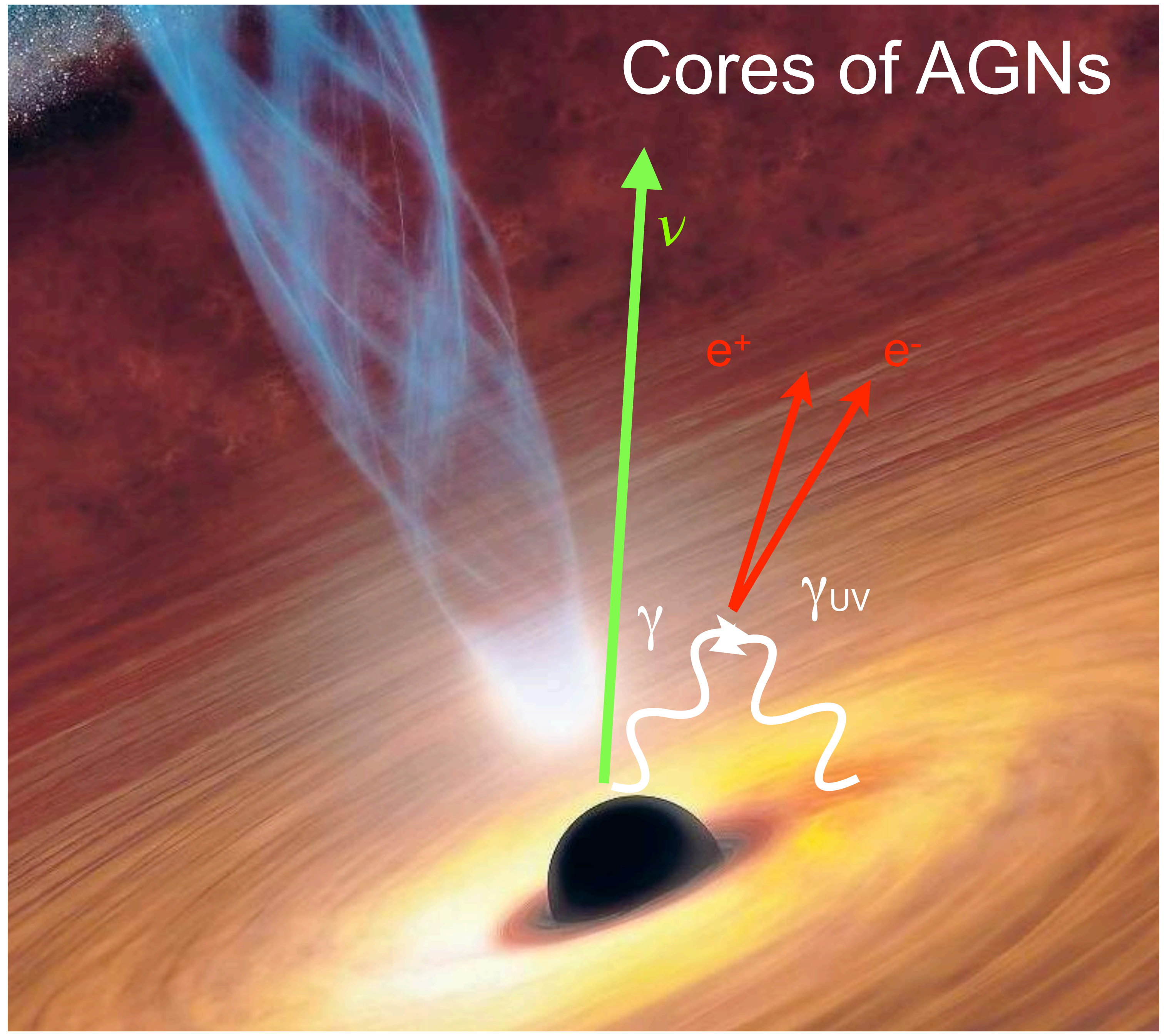
- **Neutrinos** allow us to observe the universe that is opaque to electromagnetic radiation.
- **(Extragalactic) astronomy at PeV energies** can only be done with neutrinos !

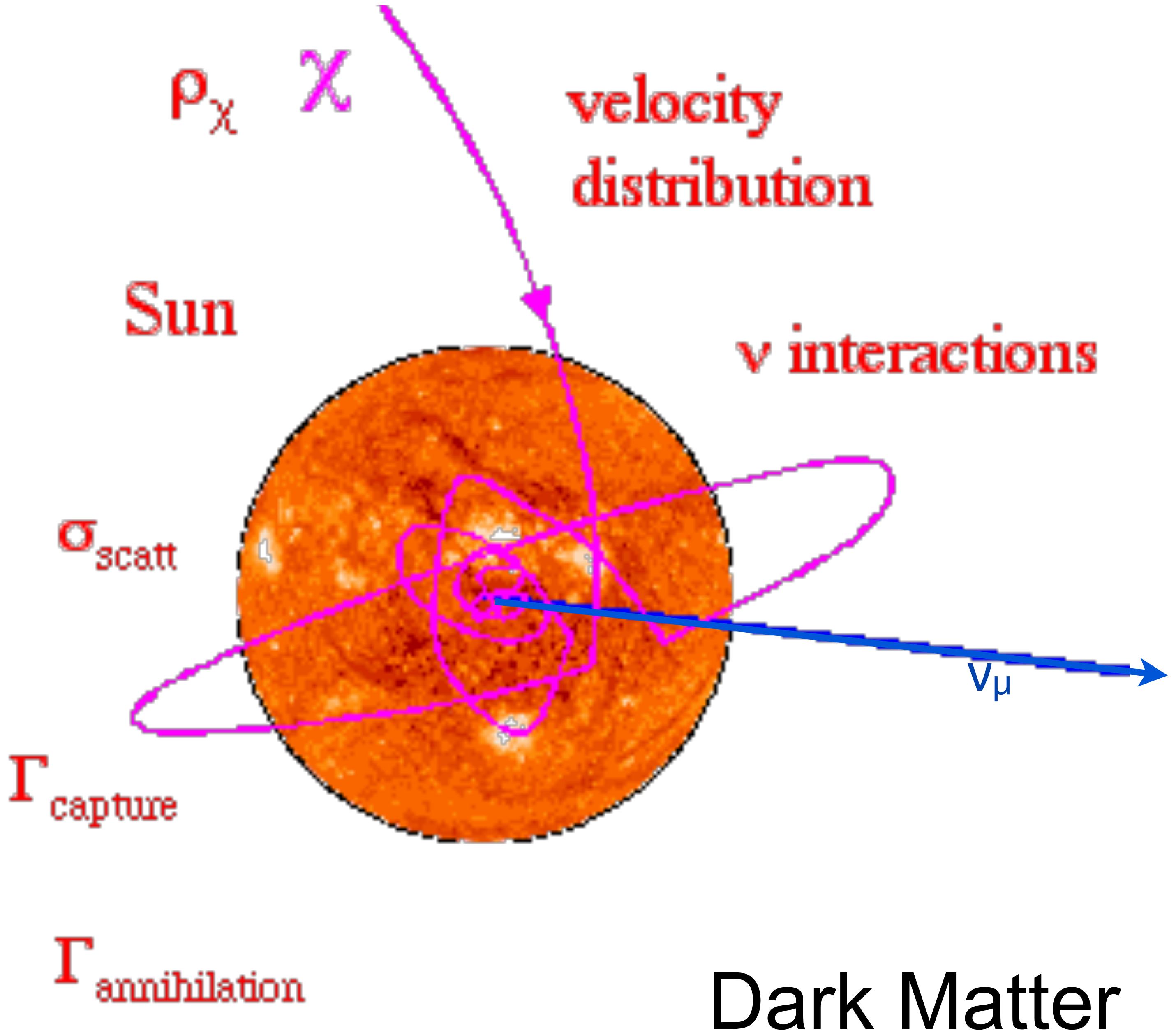


Astrophysical environments opaque to EM radiation …

… can only be observed in neutrinos





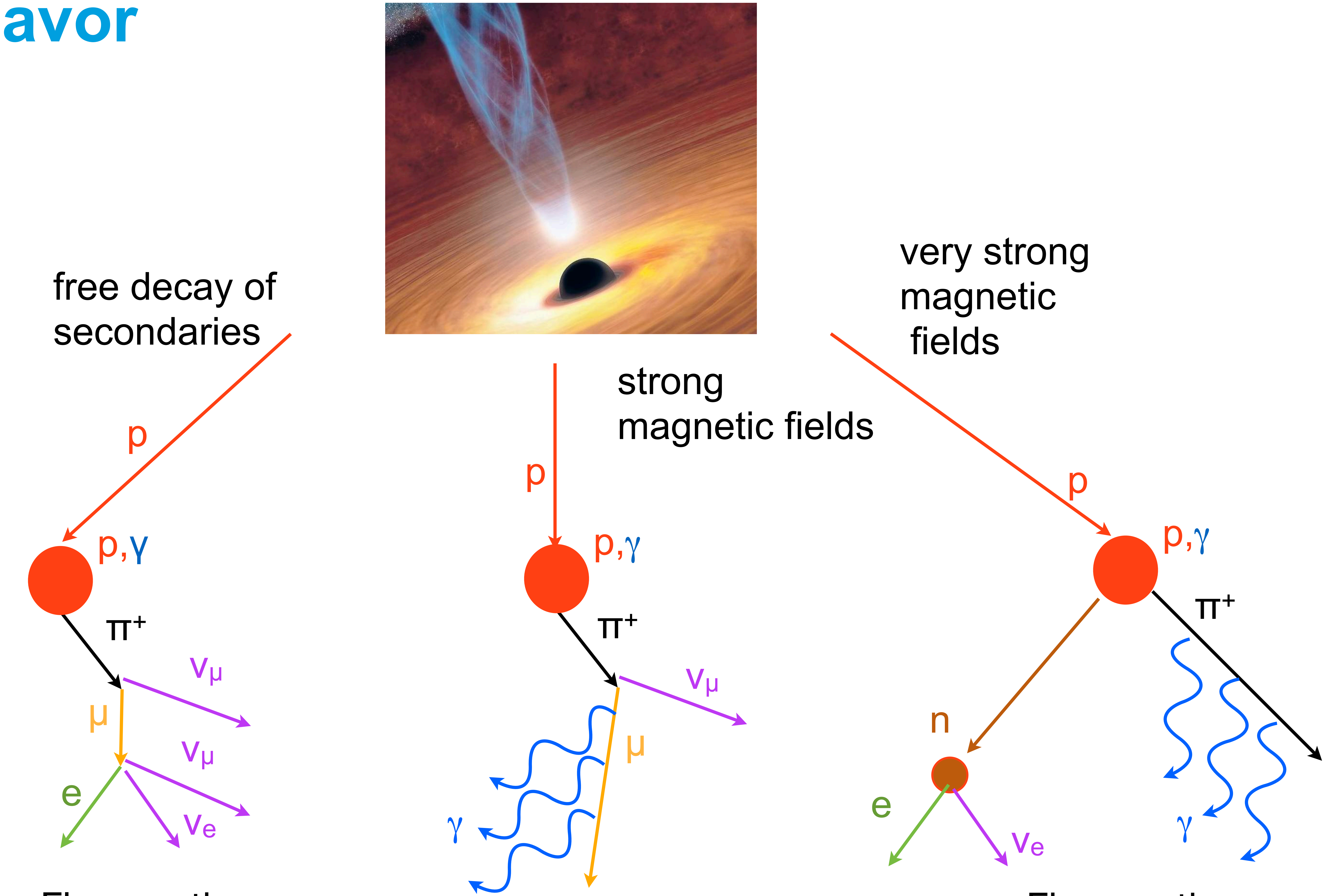


Dark Matter annihilation in the sun

- Intense radiation fields / high matter densities absorb high-energy photons in some astrophysical environments

Neutrinos carry flavor

- Study of flavor ratios can help to distinguish production processes and environments
- Flavor ratios at Earth different to flavor ratios at source due to neutrino oscillations.

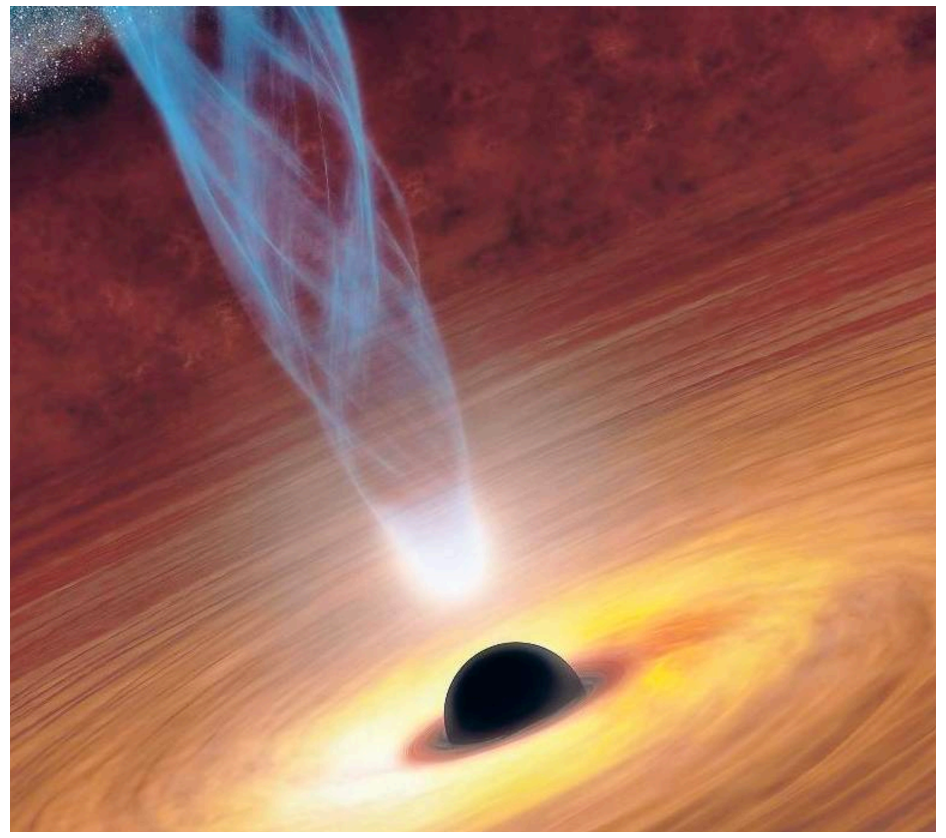


Flavor ratio $\nu_e : \nu_\mu : \nu_\tau$	Flavor ratio $\nu_e : \nu_\mu : \nu_\tau$	Flavor ratio $\nu_e : \nu_\mu : \nu_\tau$
1 : 2 : 0	**0 : 1 : 0**	**1 : 0 : 0**

Neutrino oscillations

over cosmic baselines

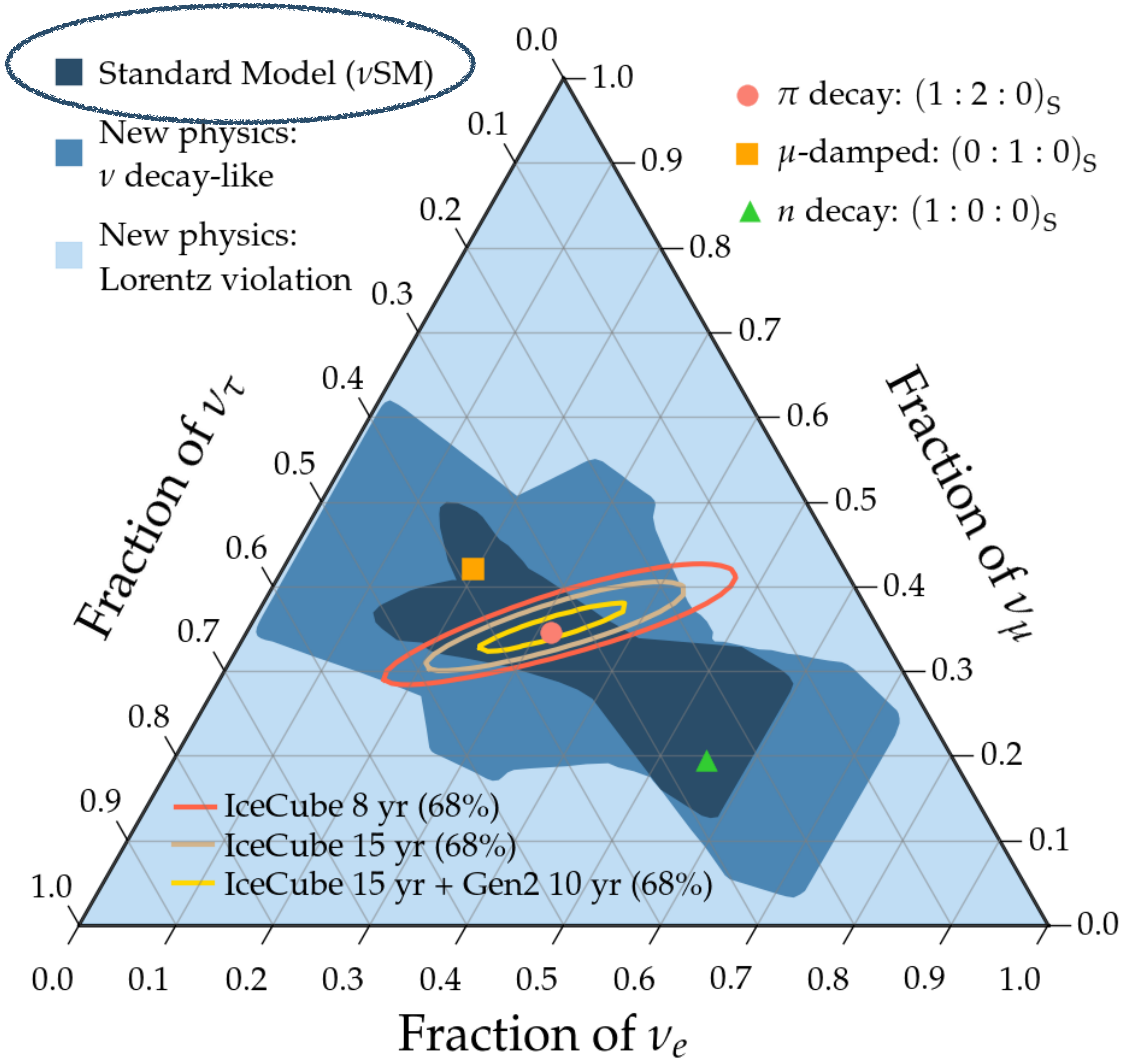
- A unique window into non-standard model physics



Propagation over Mpc — Gpc

1 : 2 : 0
0 : 1 : 0
1 : 0 : 0

Flavor composition at source

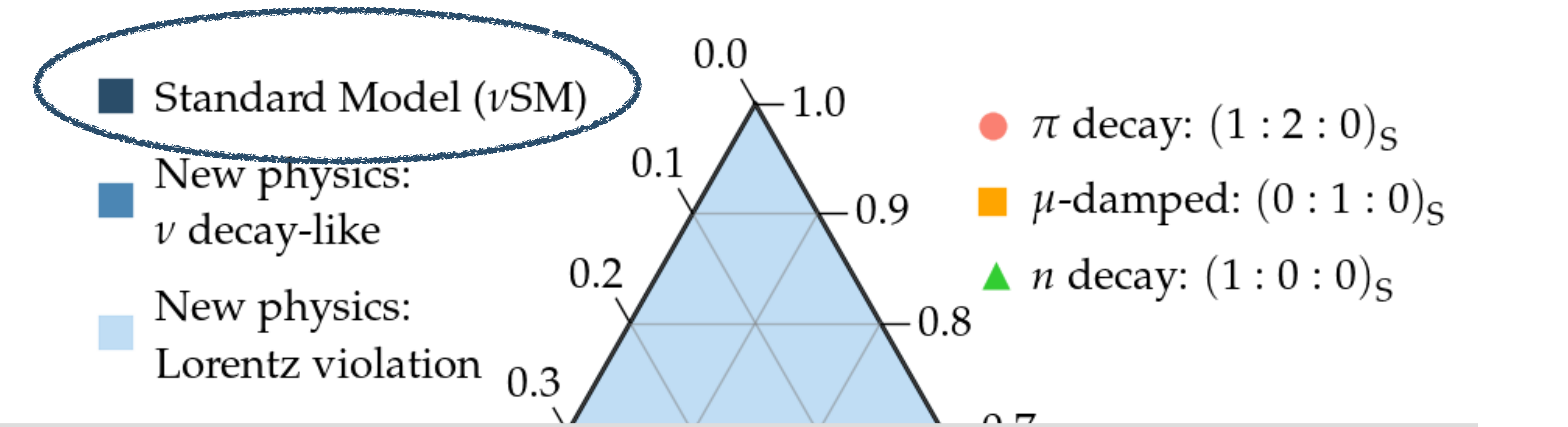


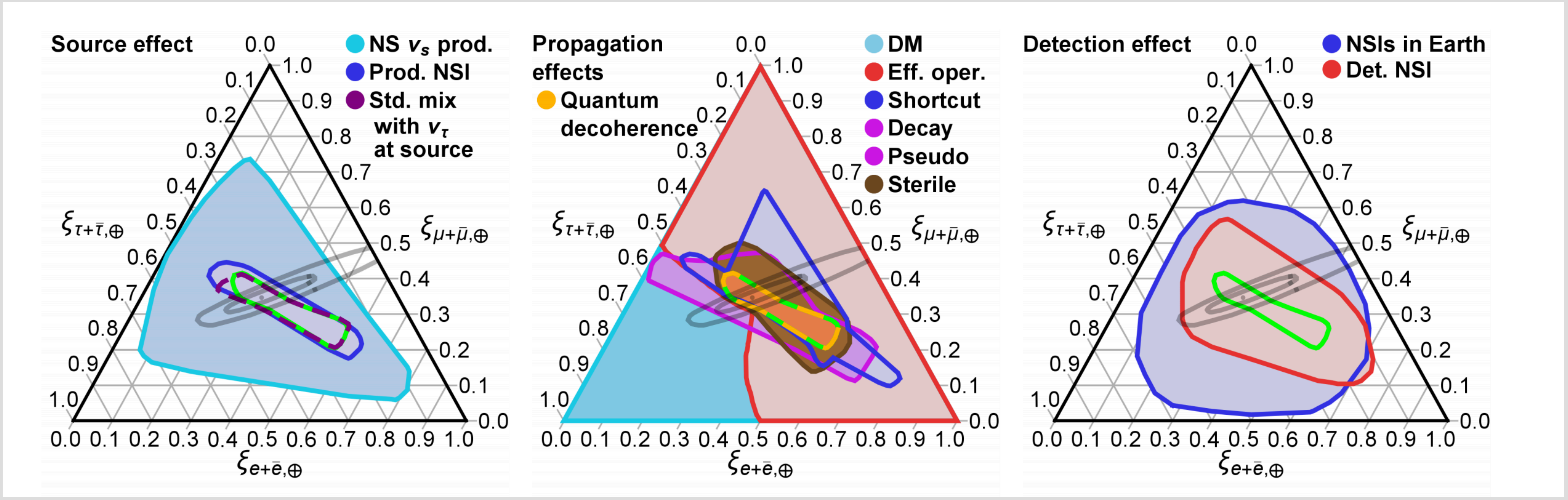
Flavor composition at Earth

Neutrino oscillations

over cosmic baselines

- A unique window into non-standard model physics





Flavor composition at source

Flavor composition at Earth

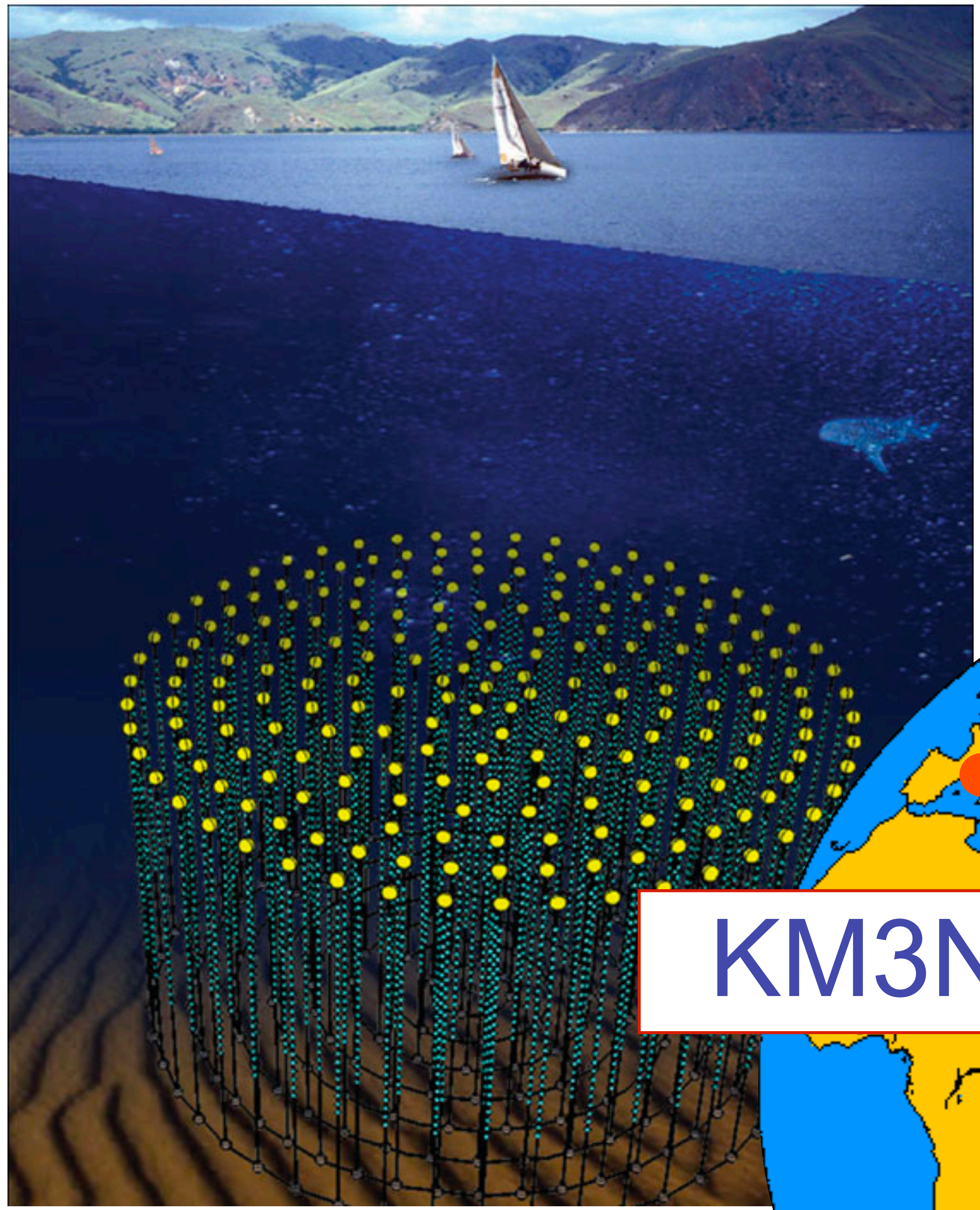
Neutrino telescopes

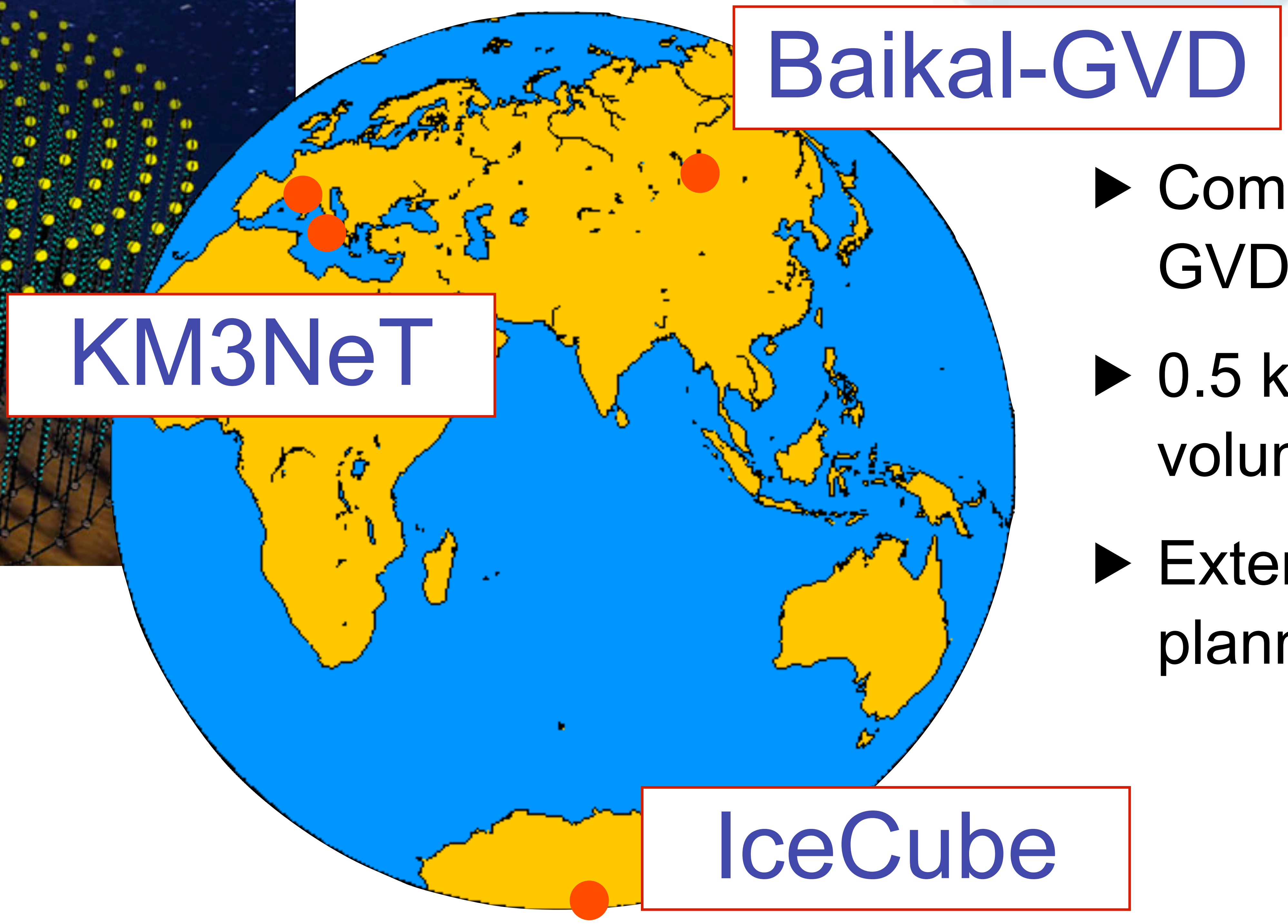
■ Detect Cherenkov light from secondaries produced in neutrino interactions

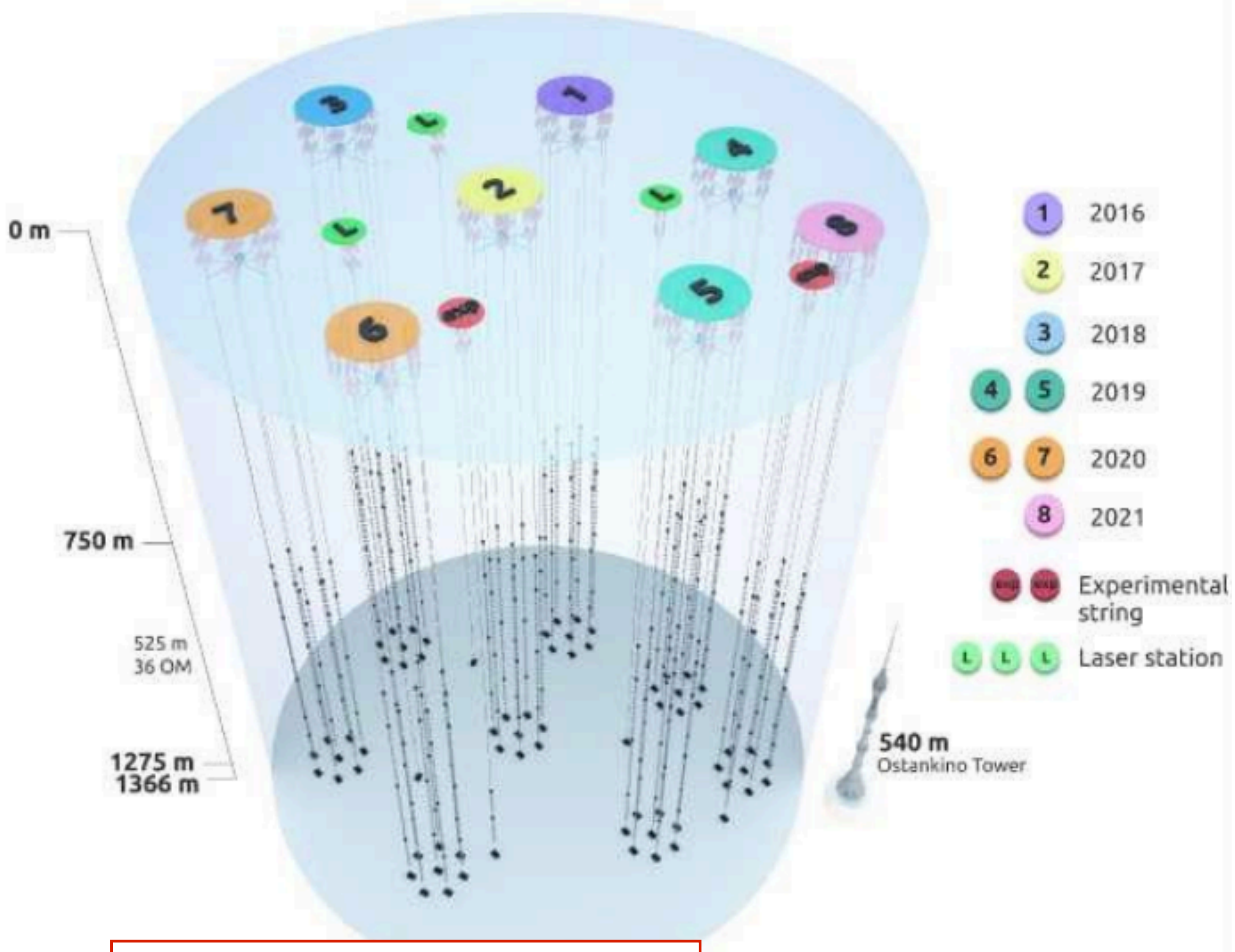
▶ Under construction

▶ 19 strings deployed (ARCA)

▶ Goal: O(1 km^3) instrumented volume in two-block configuration





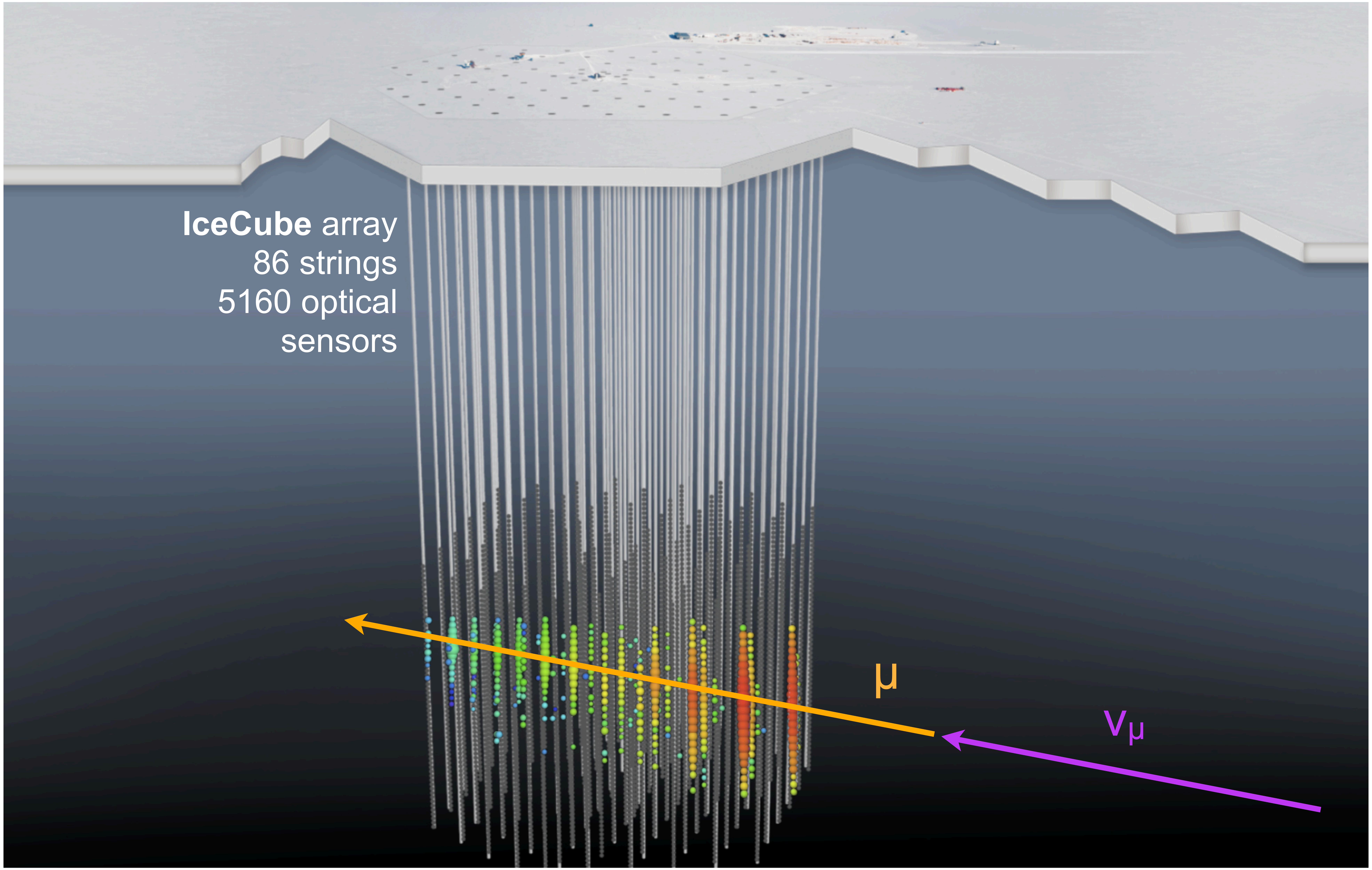


▶ Completed in 2021 in GVD-I configuration

▶ 0.5 km^3 instrumented volume

▶ Extension to 1 km^3 planned

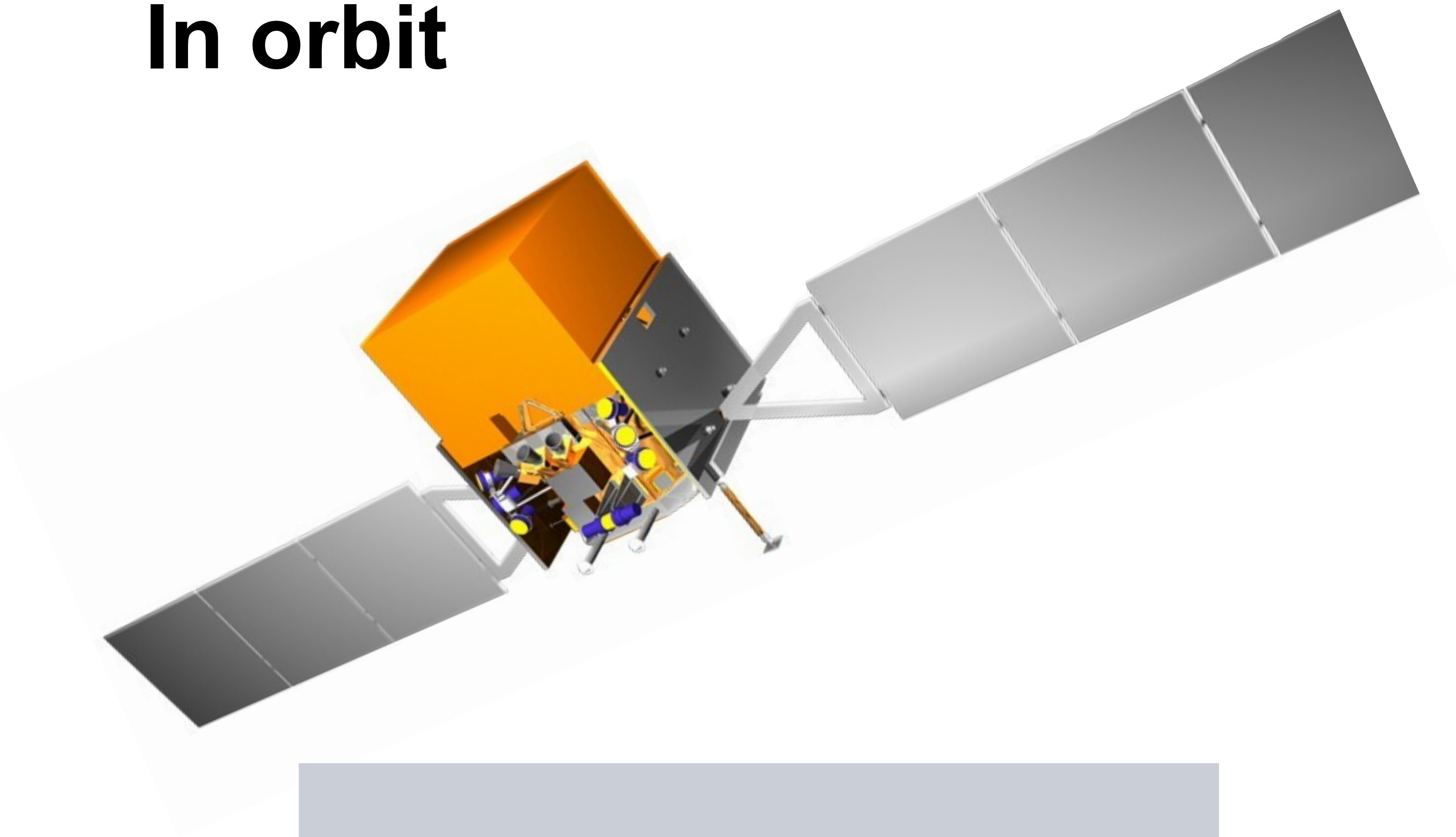
Neutrino telescopes — IceCube



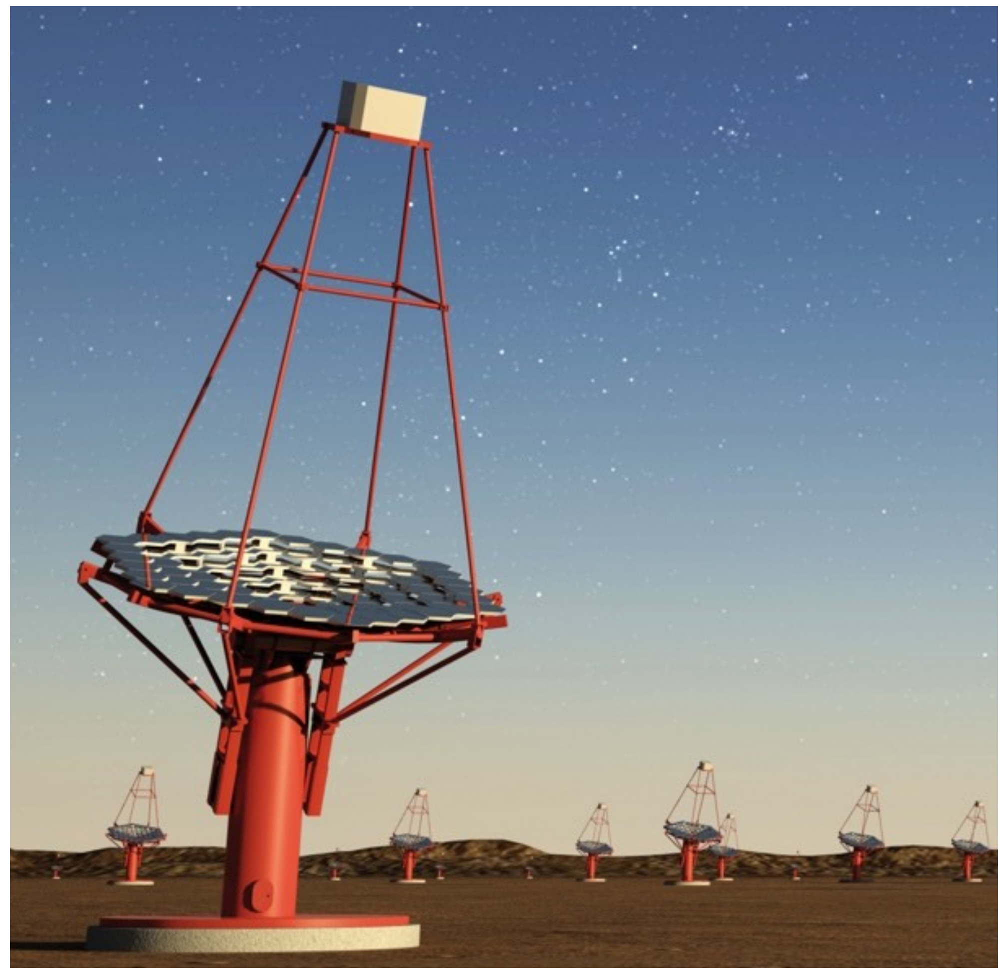
- Completed in 2010
- 1 km^3 instrumented volume

Gamma-ray telescopes

In orbit



On the ground

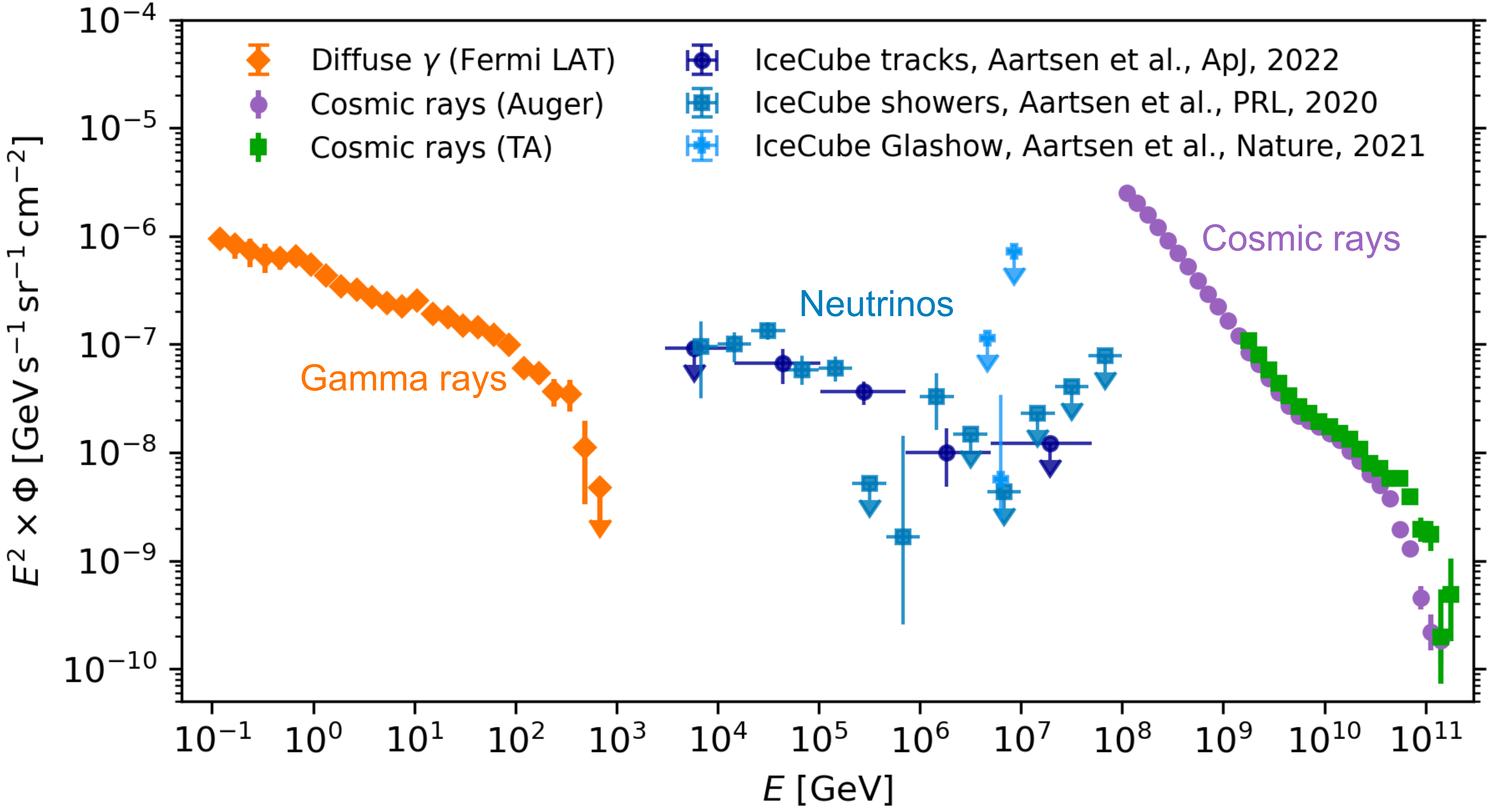


Fermi LAT	Instruments	HESS, MAGIC, Veritas
30 MeV - 1 TeV	**Energy range**	50 GeV - 100 TeV
20% of the sky	**Field-of-view**	~ 0.02% of the sky
~1 m^2	**Effective area**	~10000 m^2
85% of the year	**Duty cycle**	10% of the year

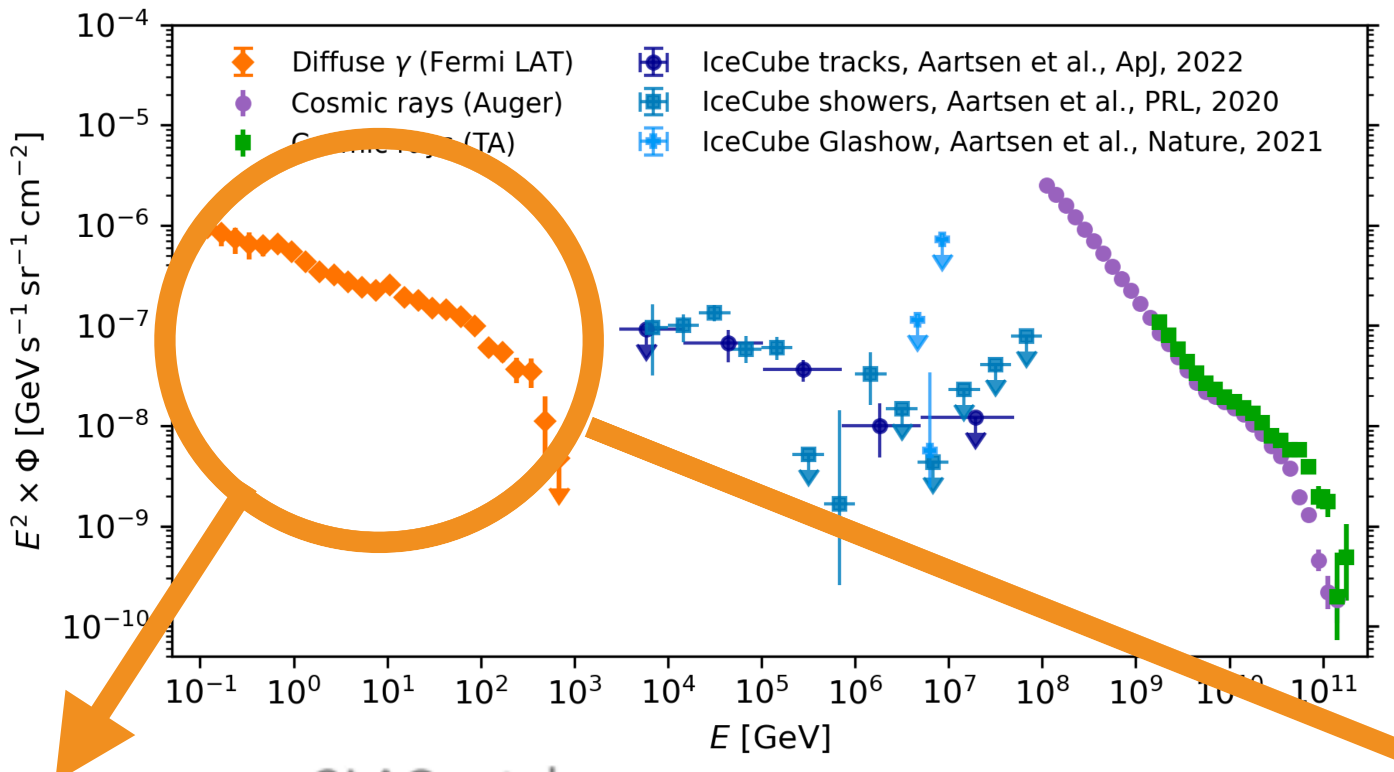
The extragalactic gamma-ray and neutrino flux

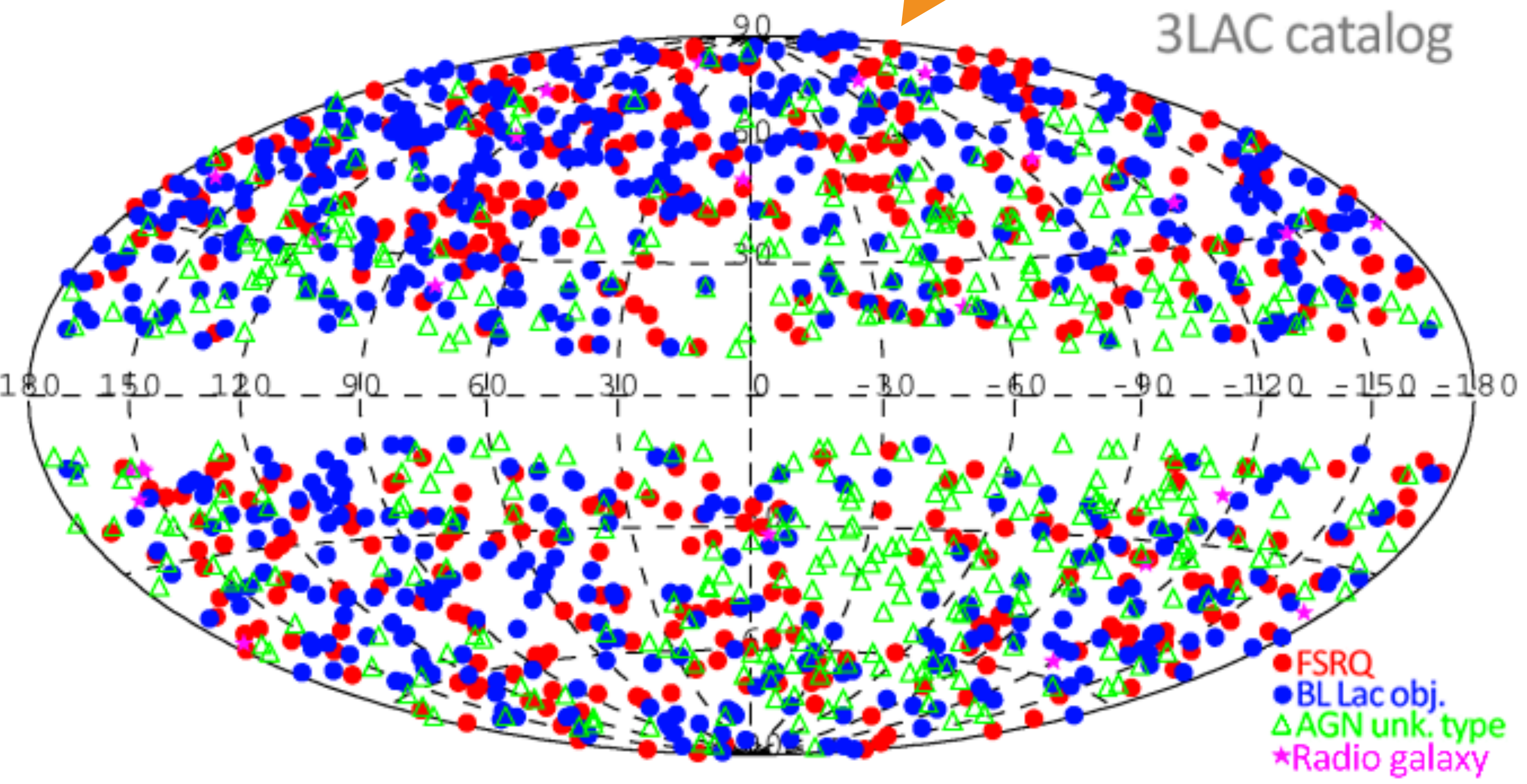
The extragalactic gamma-ray and neutrino flux

- Cumulative extragalactic particle flux (astrophysical sources and other contributions…)

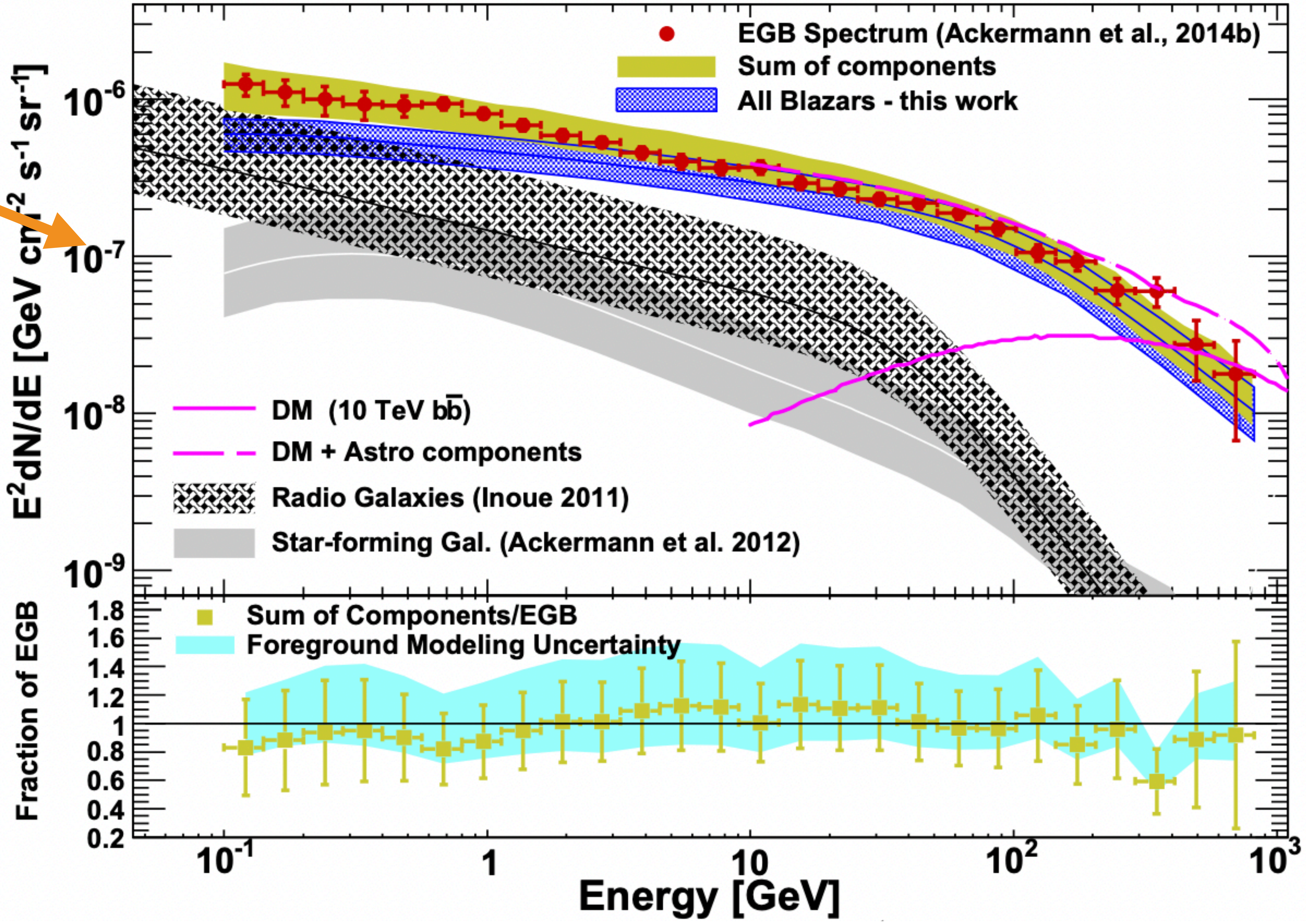


The extragalactic gamma-ray background (EGB) spectrum



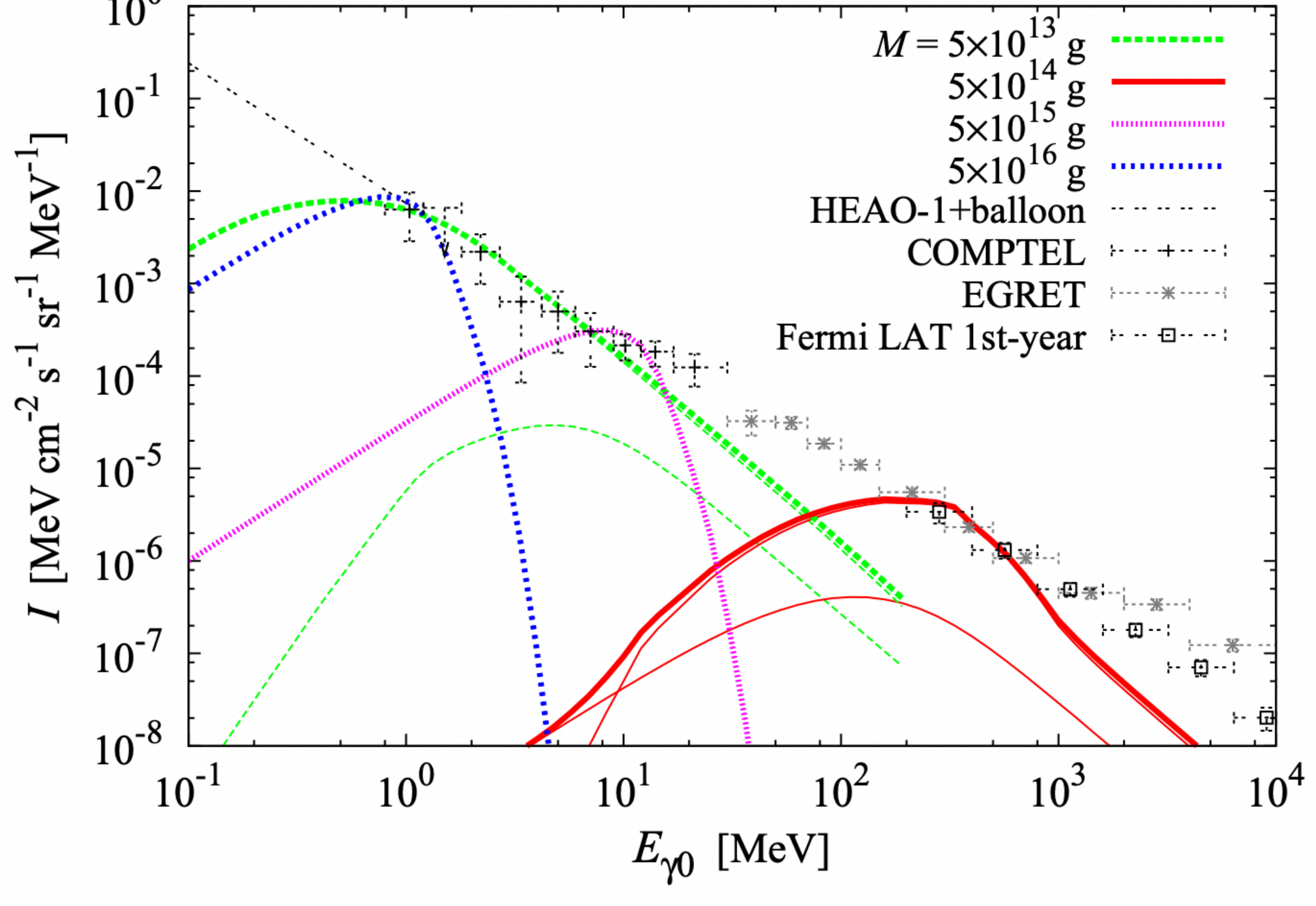


Ajello et al., ApJL, 2015



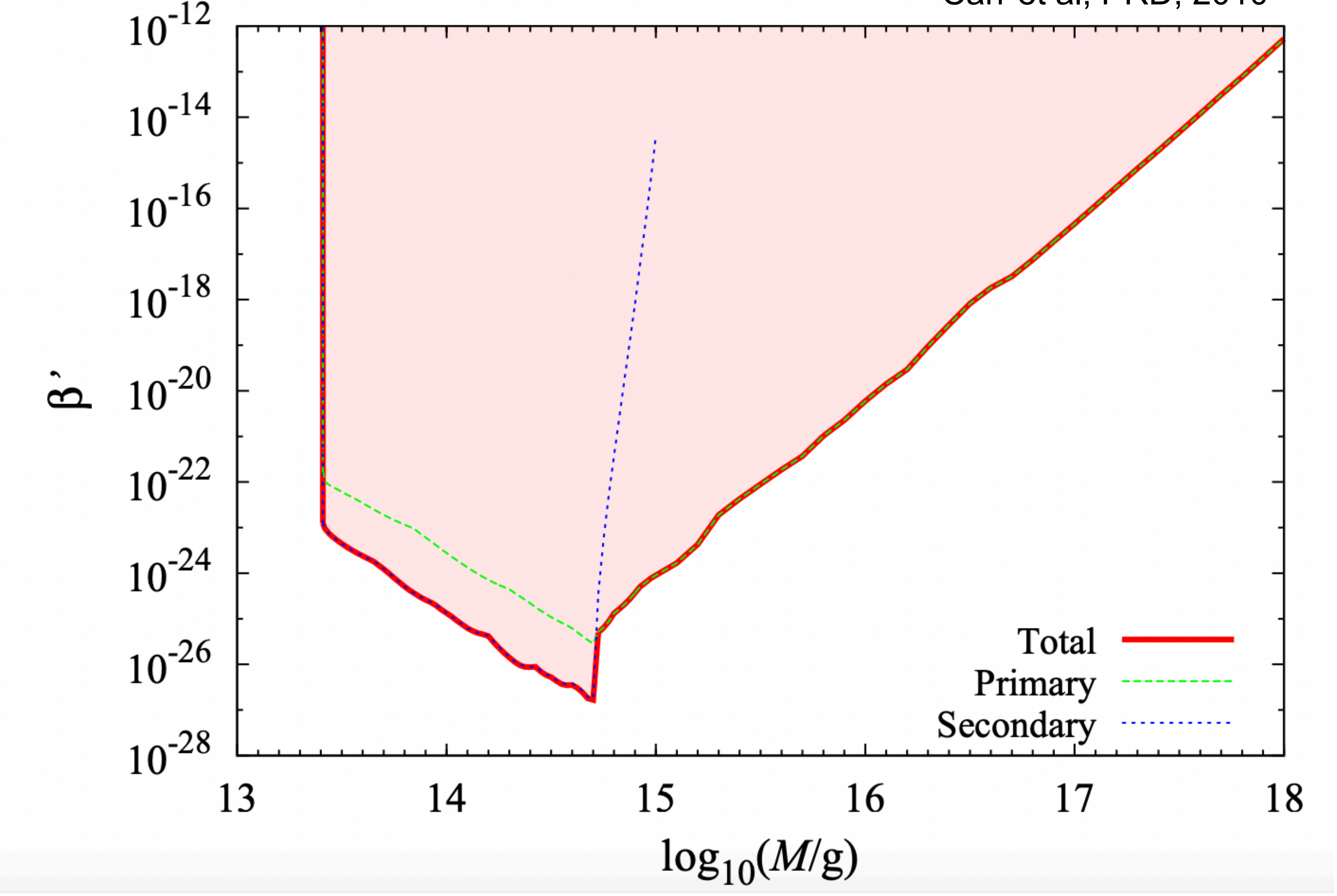
- Most of the extragalactic gamma rays can be attributed to resolved and unresolved sources.
- Important constraint on gamma-ray yield from any exotic physics process

The EGB and primordial black holes



- For a mass range from ~10^{13} g to ~10^{16} g the EGB captures the integrated radiation of all primordial black holes (PBH) in the universe
- Measured intensity constrains PBH intensity

- Black holes radiate with a temperature inversely proportional to their mass

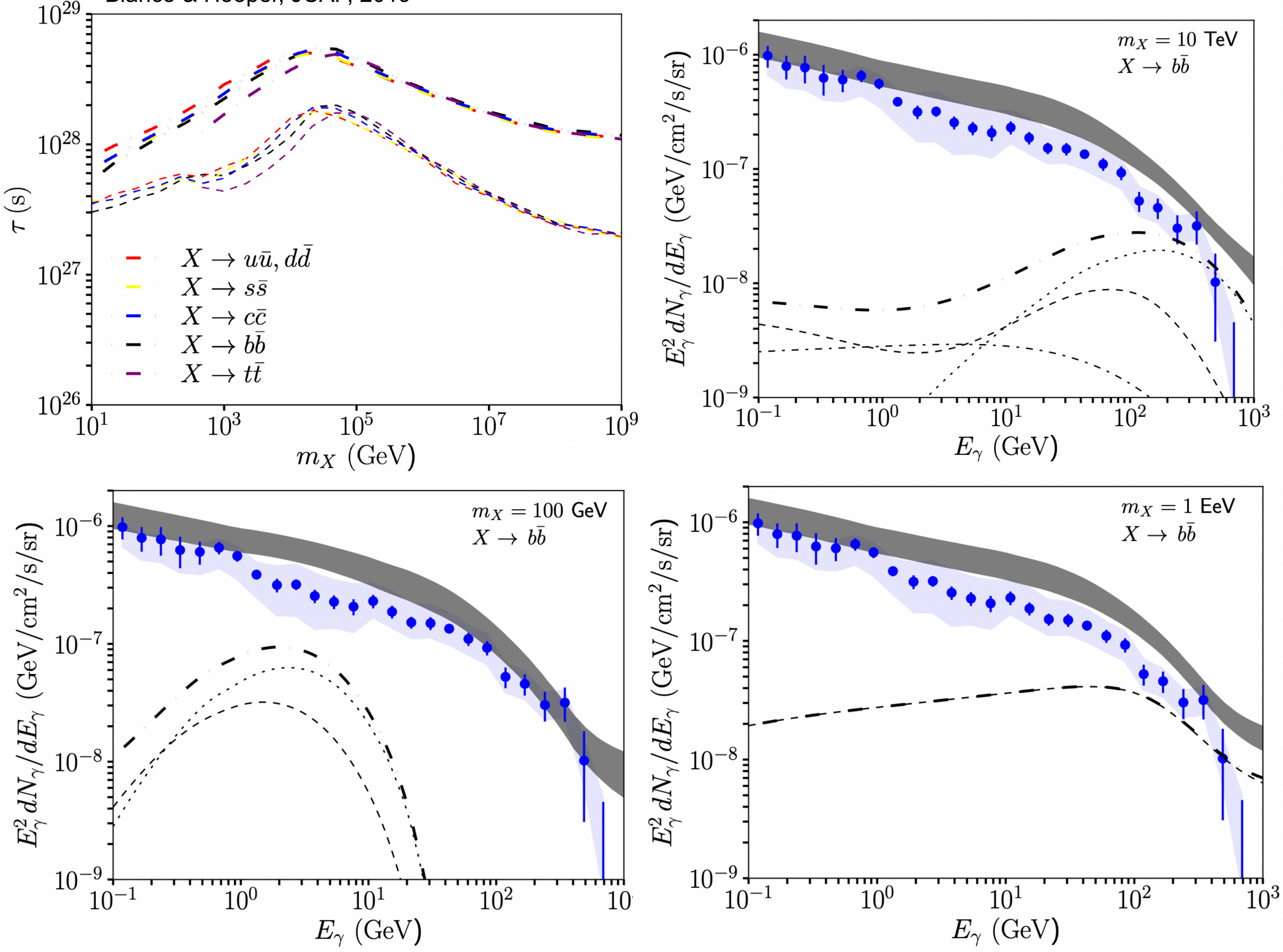


DESY.

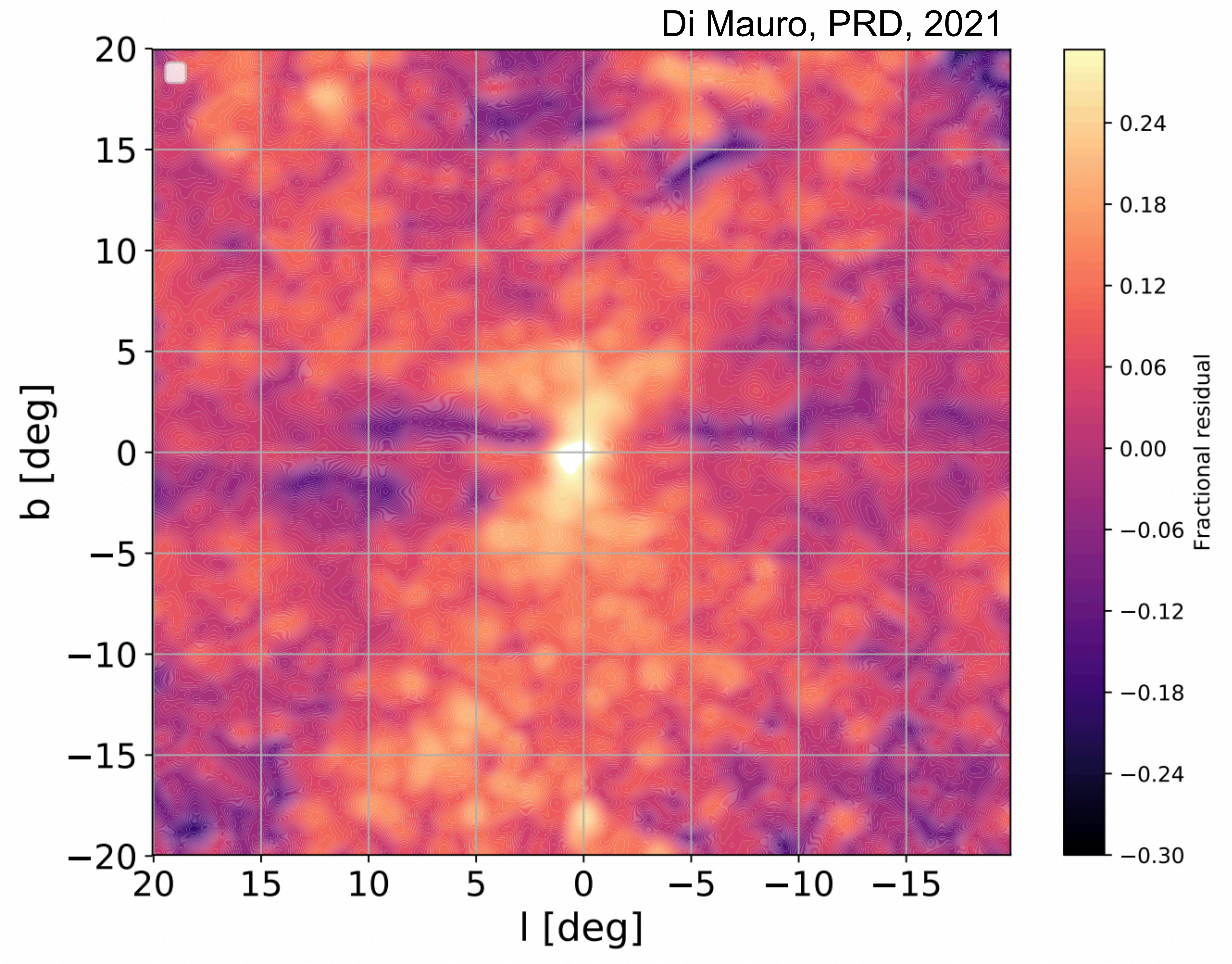
Decaying DM

- EGB provides most stringent limits on dark matter lifetime over a very wide energy range
- High-energy photons produced in the decay are reprocessed to GeV energies by intergalactic radiation fields
- Additional contributions from inverse Compton radiation of electrons

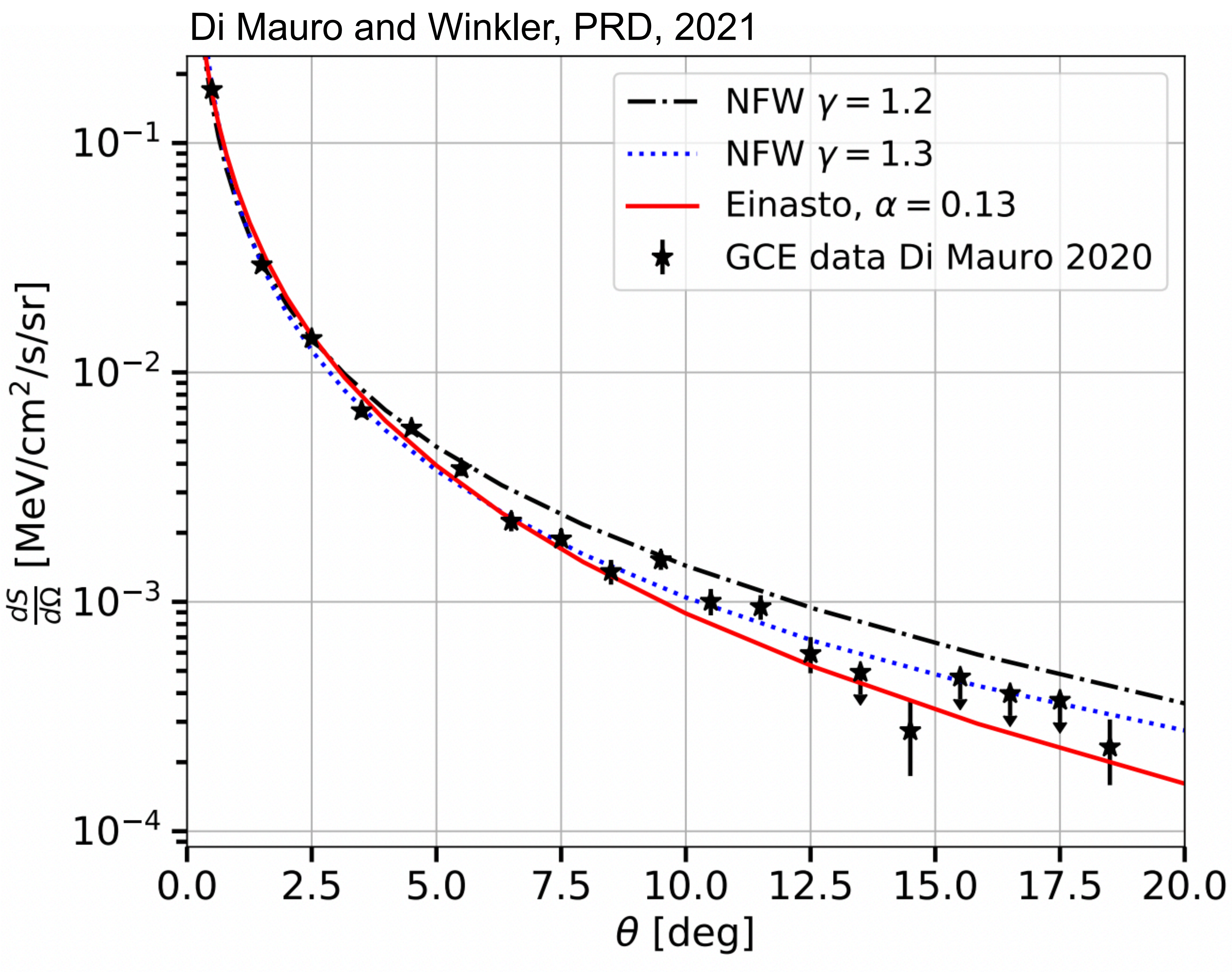
Blanco & Hooper, JCAP, 2019



(Annihilating) DM constraints from Galactic gamma-ray emission



1 - 10 GeV
Residual emission:
(LAT data) - (Well known astrophysical emission)



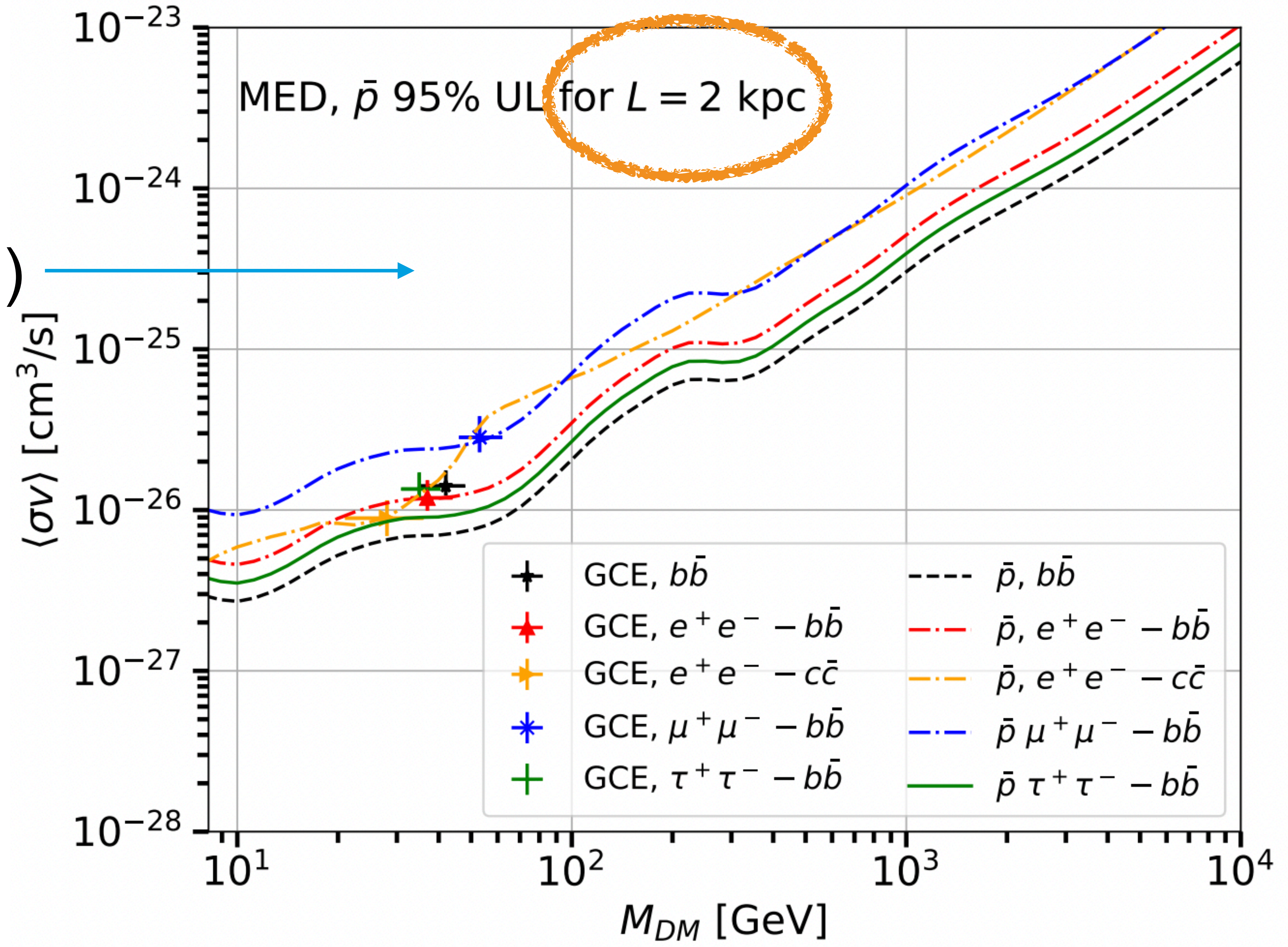
- Compatible with expected DM density profile
- But also compatible with unresolved astrophysical sources, e.g., millisecond pulsars

DM constraints

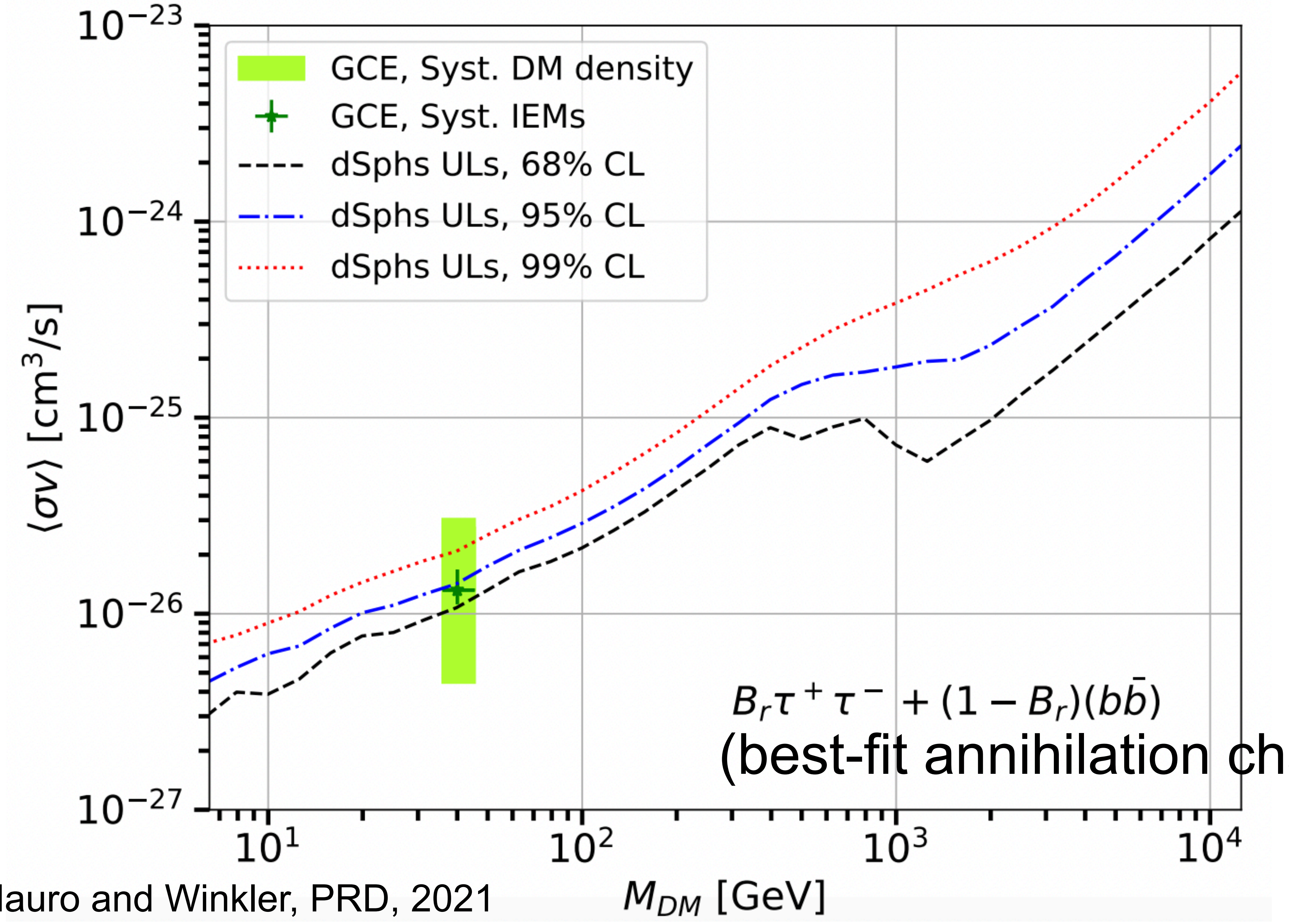
...continued

- Compatible with non-observation of Dwarf Galaxies
- Not compatible with antiproton flux at Earth for measured CR halo size of ~ 4 +/- 1 kpc

Limits from observed antiproton flux (AMS-02)

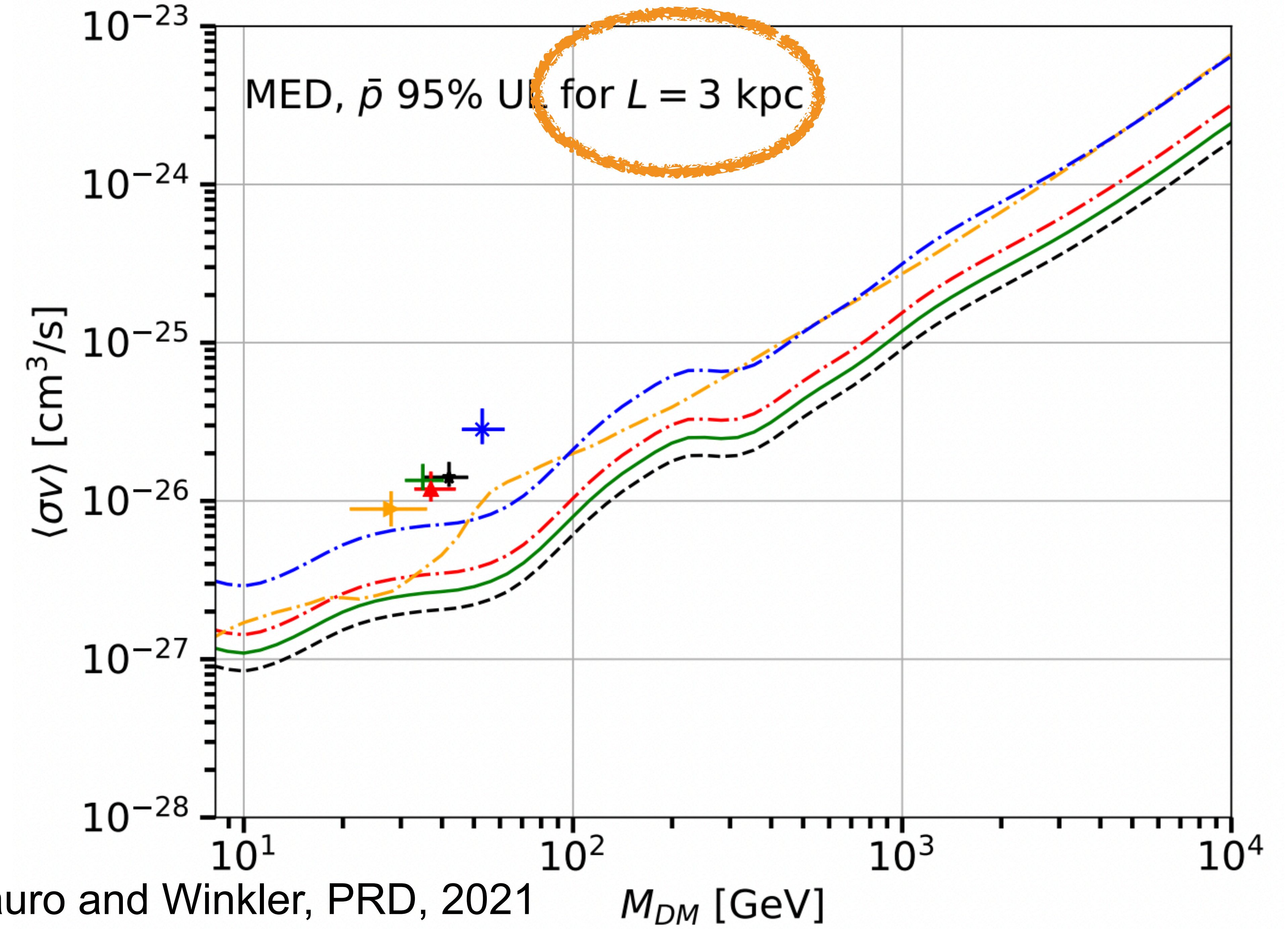


Limits from non-observation of Dwarf Galaxies



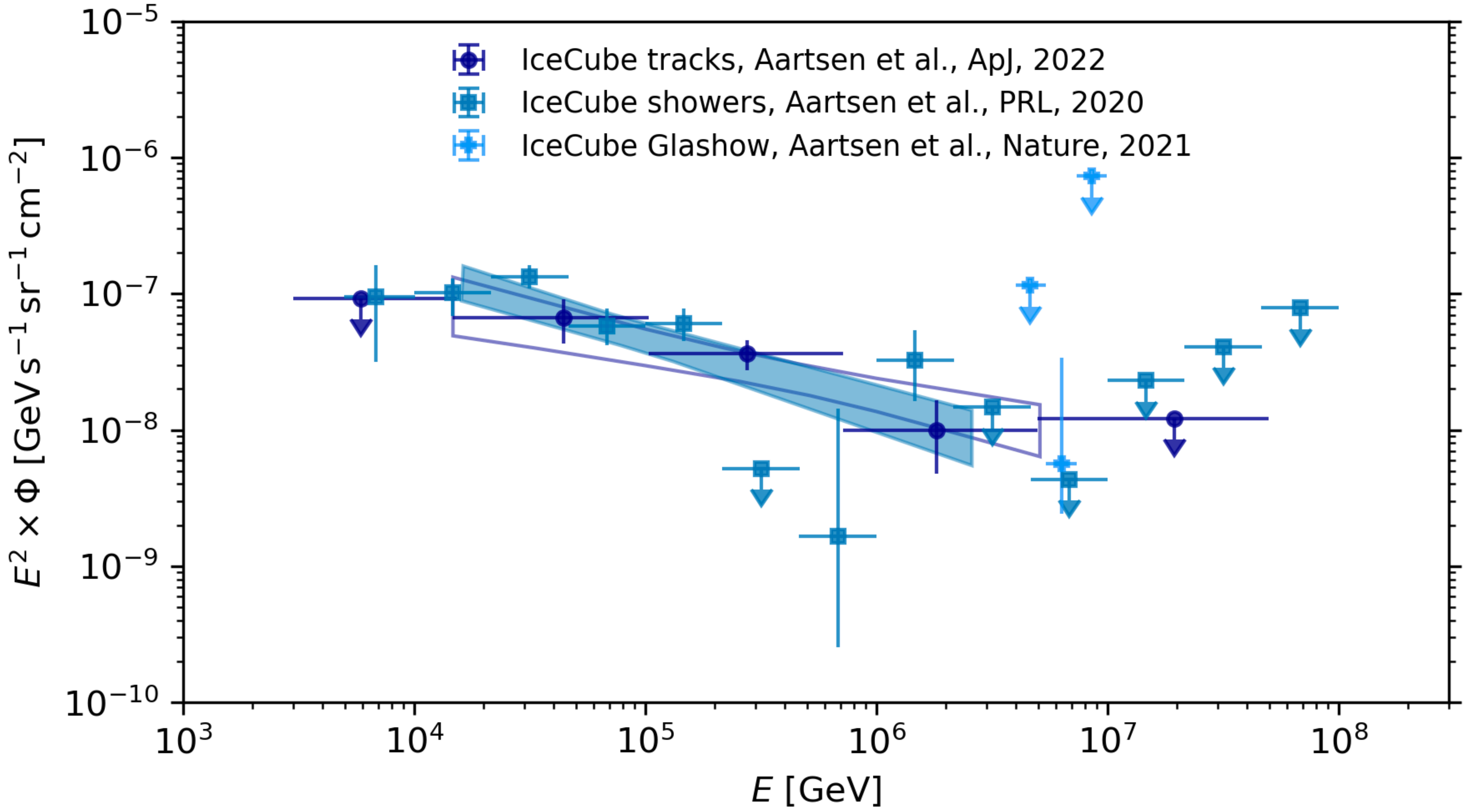
(best-fit annihilation channel)

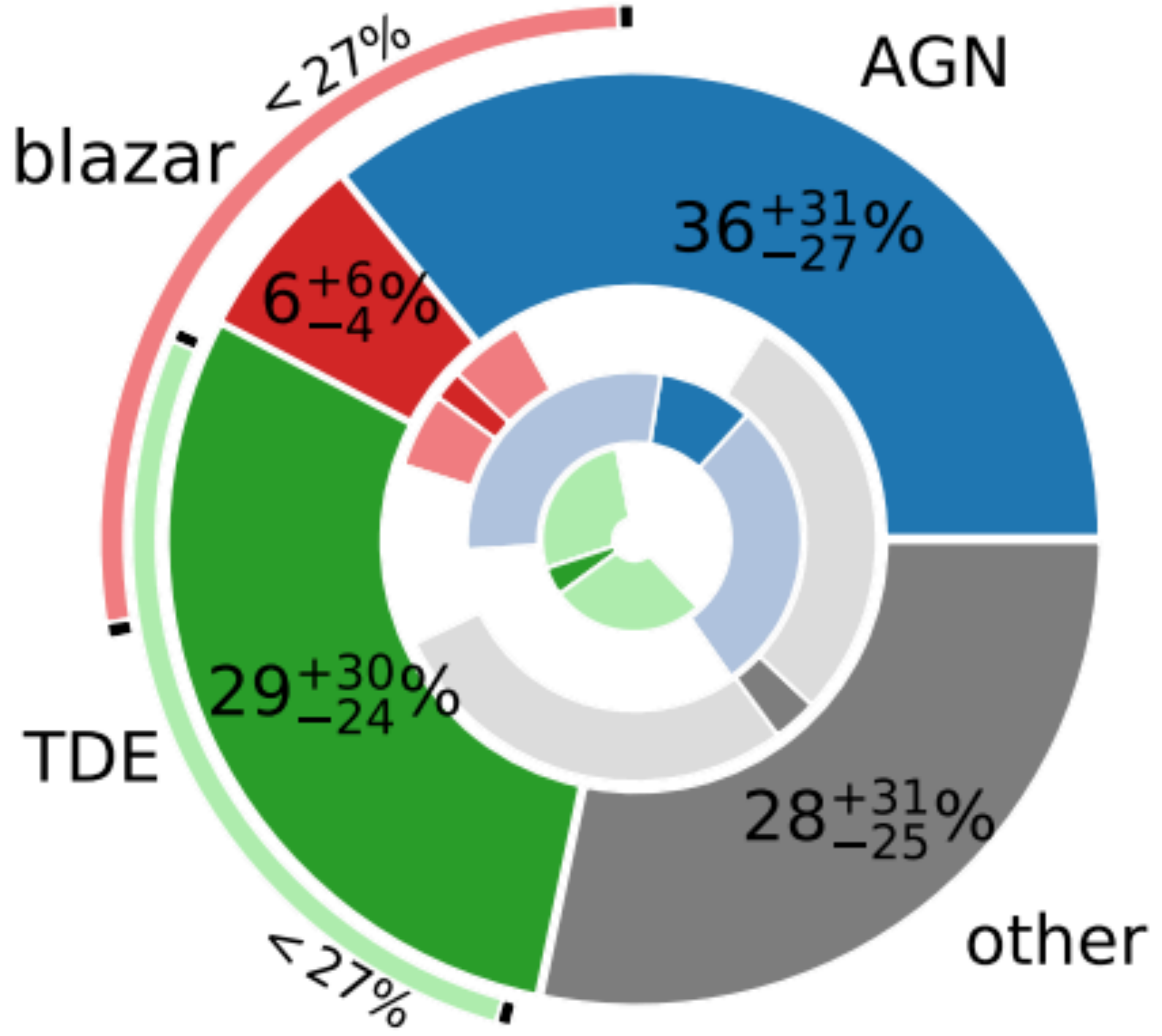
Di Mauro and Winkler, PRD, 2021



Di Mauro and Winkler, PRD, 2021

The cosmic neutrino spectrum and flavor composition

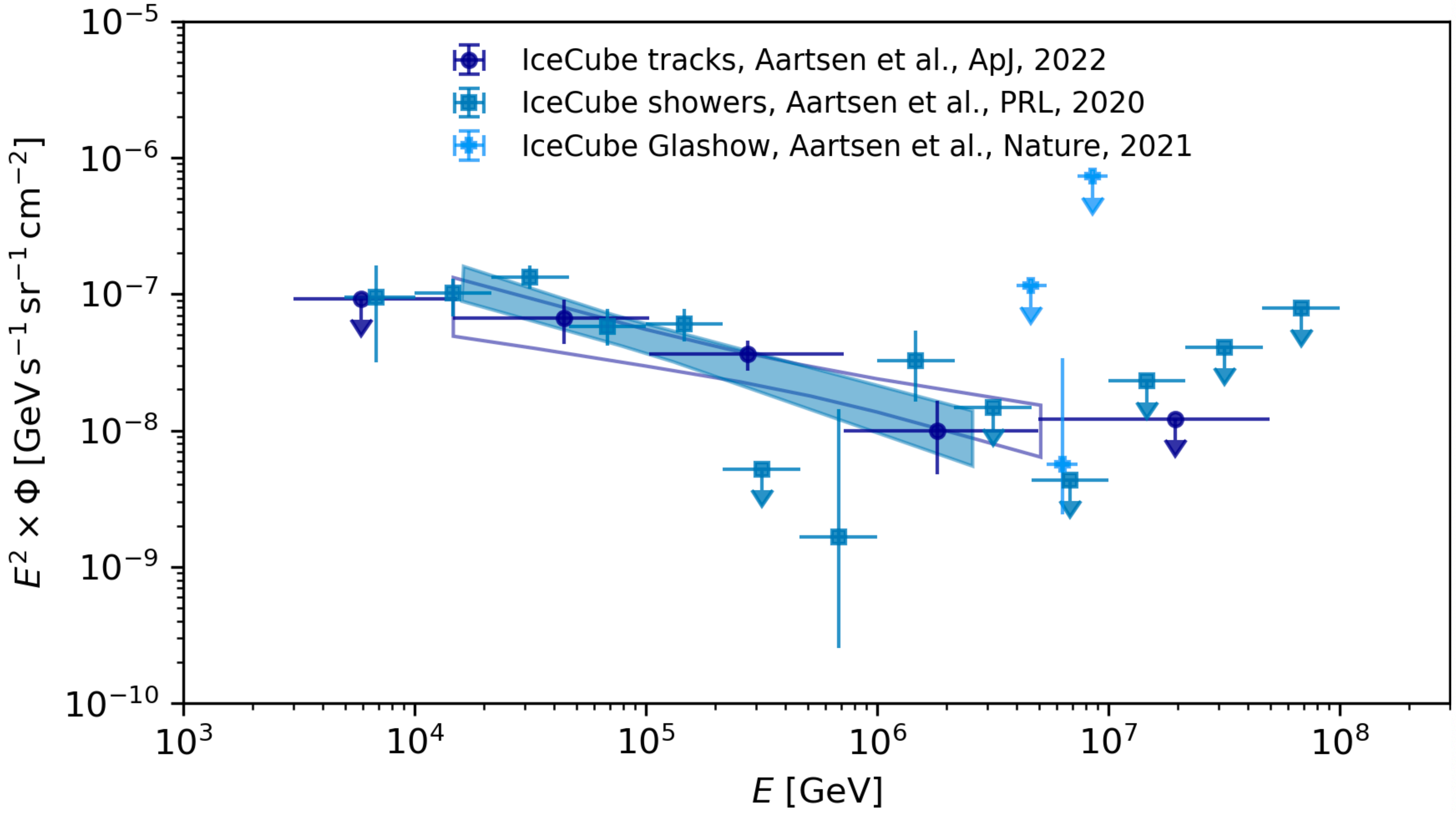


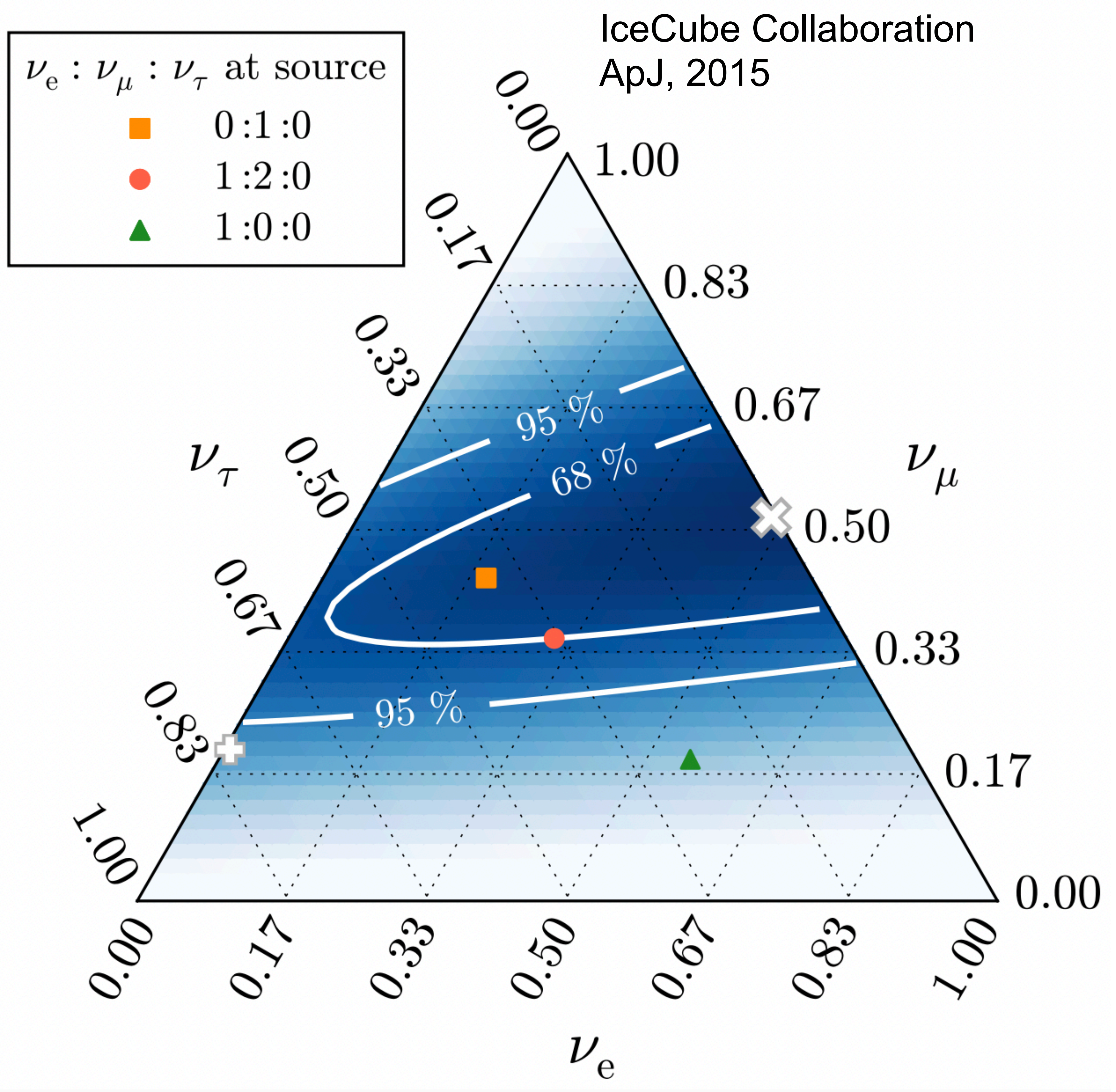


Bartos et al., arXiv 2105.03792

- Independent results from shower-like (all flavors, CC + NC), track-like events (nu-mu CC), and Glashow events (resonant nu-e scattering)
- Spatial distribution of events consistent with isotropic distribution

The cosmic neutrino spectrum and flavor composition

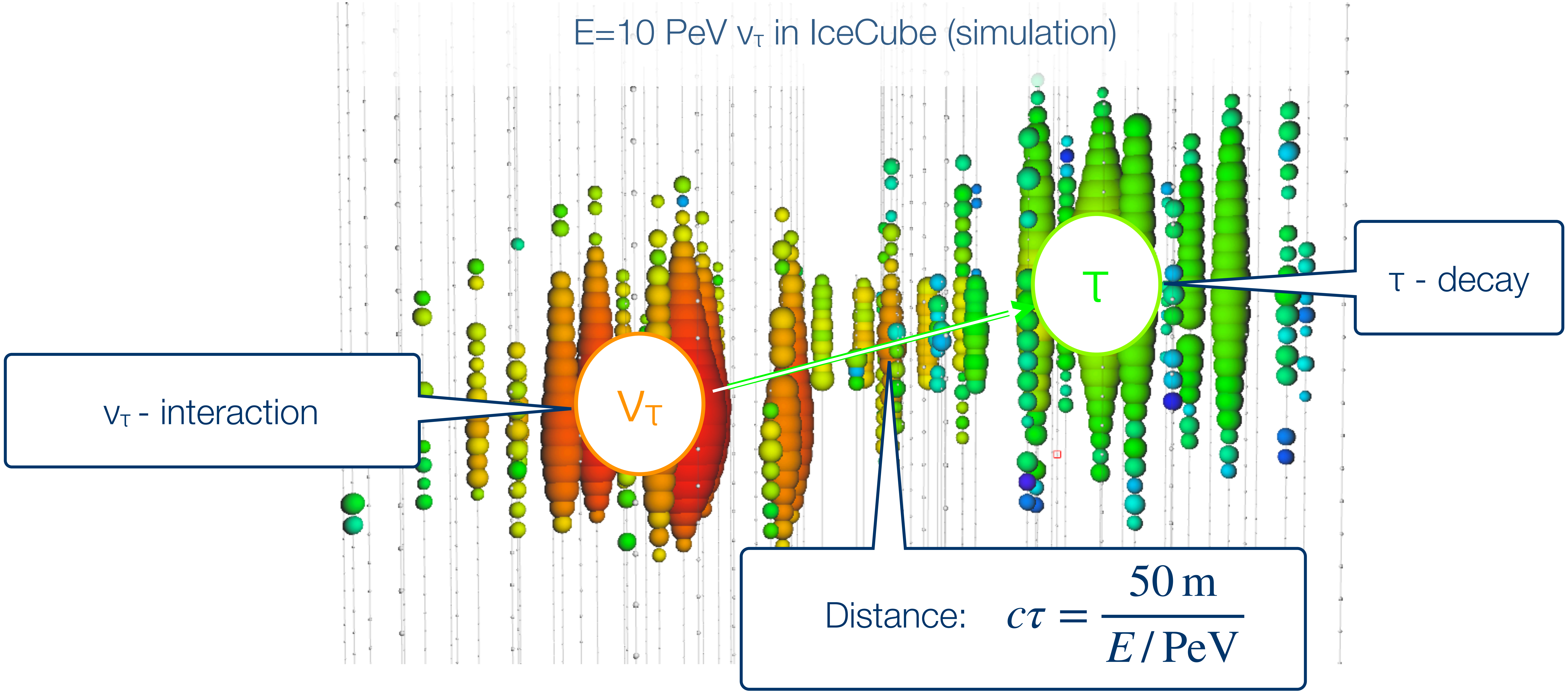




- Independent results from shower-like (all flavors, CC + NC), track-like events (nu-mu CC), and Glashow events (resonant nu-e scattering)
- Spatial distribution of events consistent with isotropic distribution

Flavor composition of cosmic neutrinos

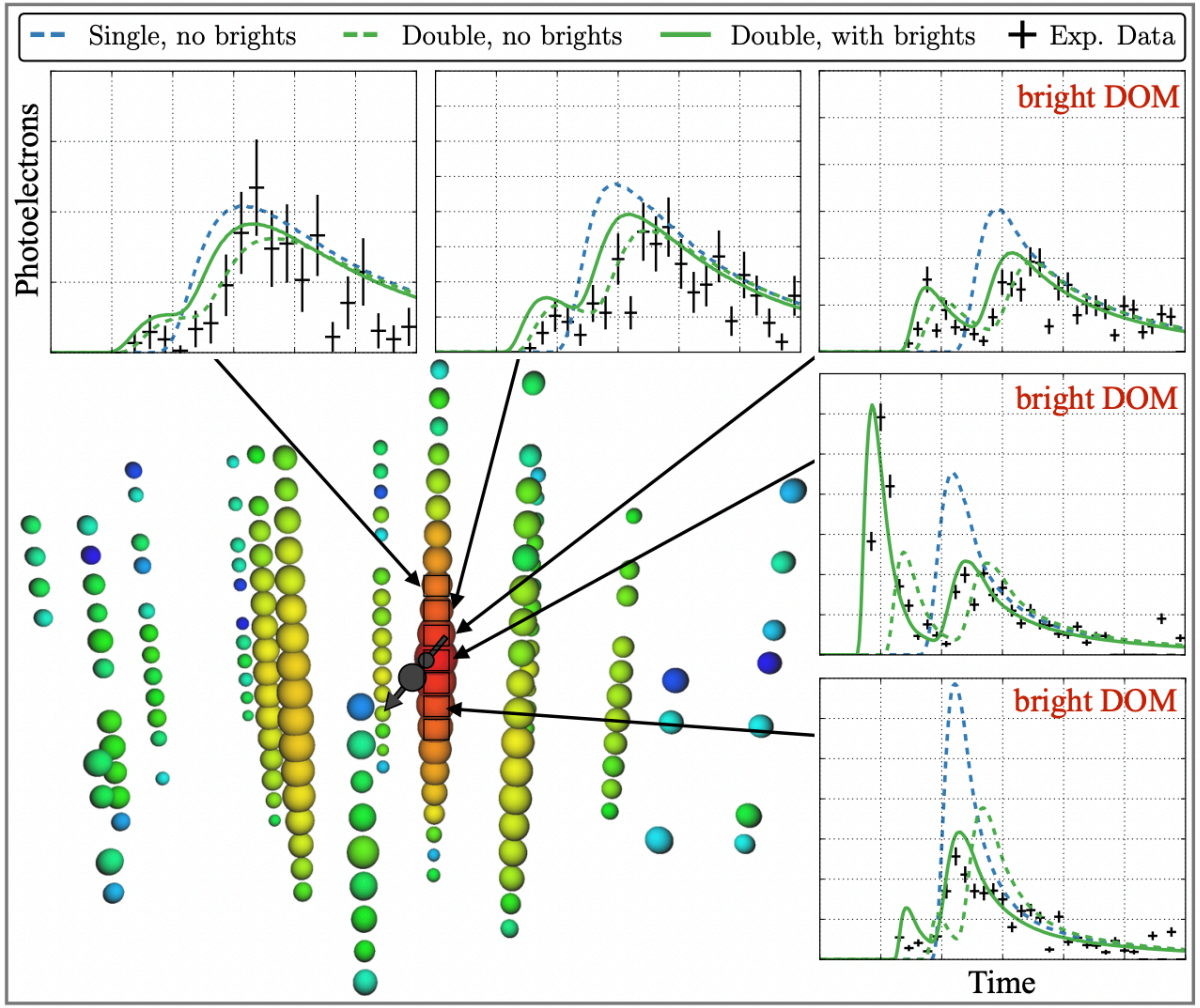
- **Tau neutrinos with** E> 100 TeV can be identified based on **special signatures** in IceCube.

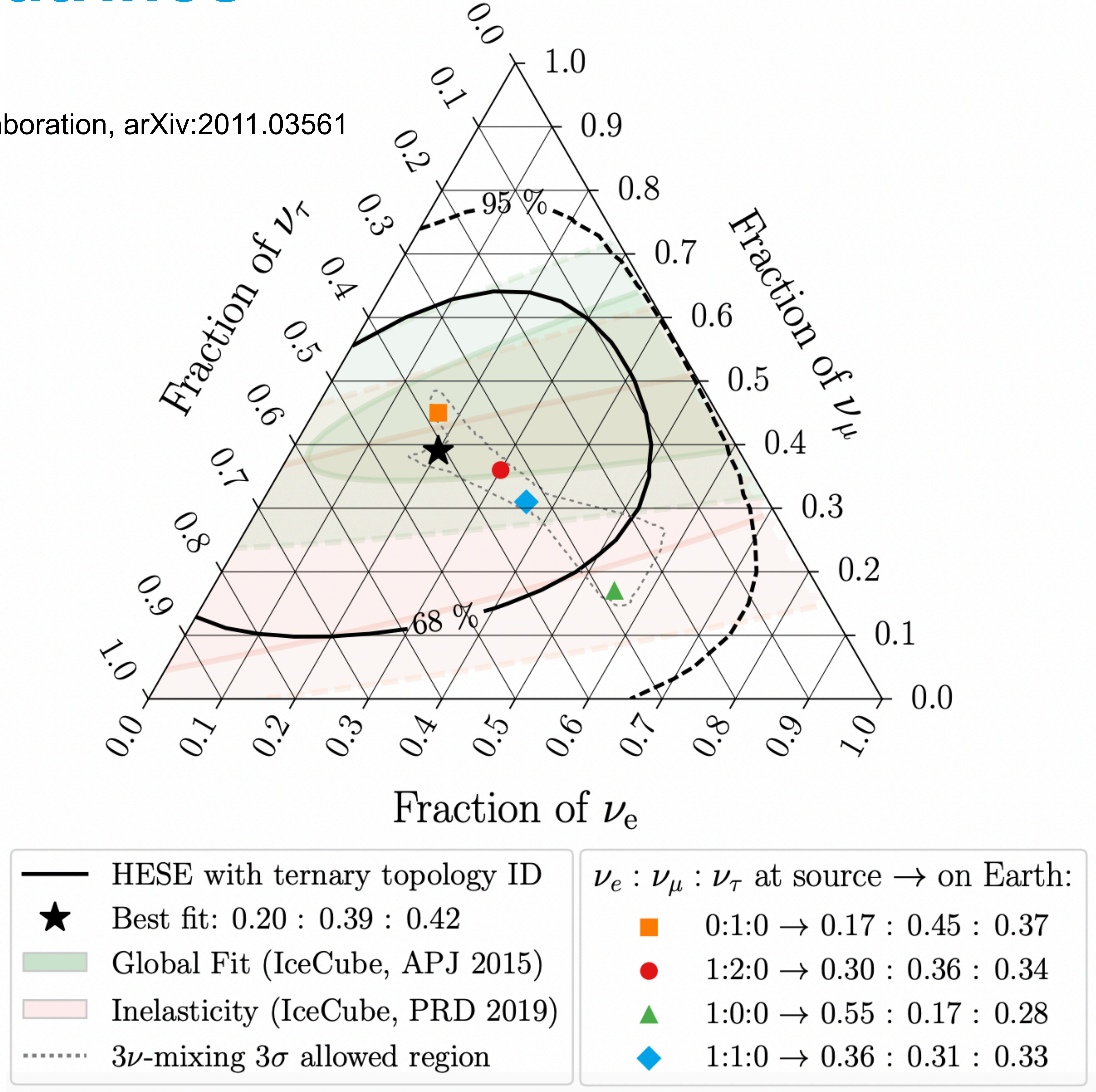


Flavor composition of cosmic neutrinos

The first tau neutrino candidates

IceCube Collaboration, arXiv:2011.03561





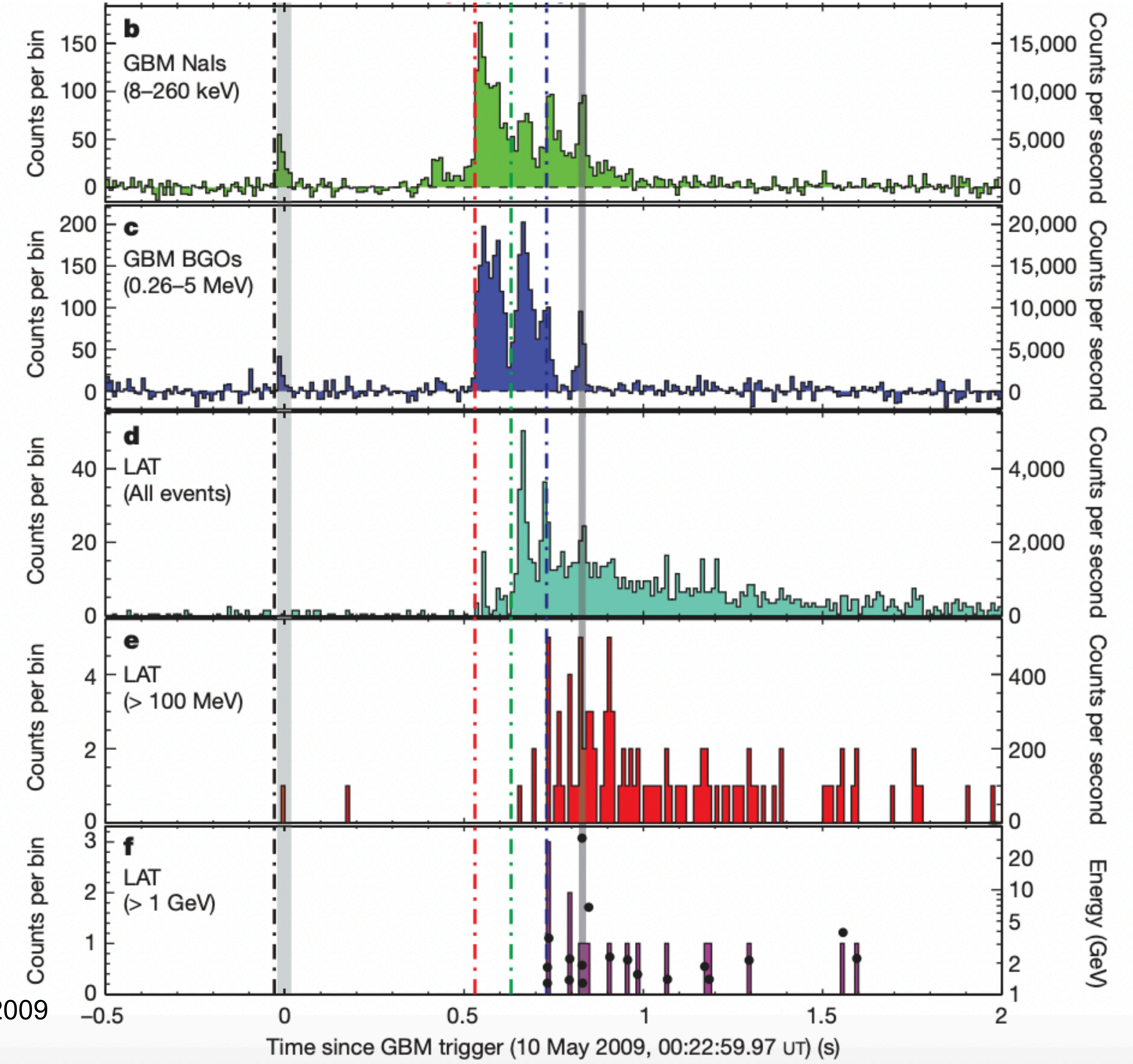
Transient sources

Transient sources and Lorentz Invariance Violation Constraints

Modified dispersion relation:

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{\mathrm{QG},n}} \right)^n$$

- Short Gamma-ray burst at redshift z=0.9 (10 billion light years)
- 0.82s between first 8 keV photon and a 30 GeV photon
- Limit on $M_{QG} > 1.2\ M_{Planck}$ (for n=1)

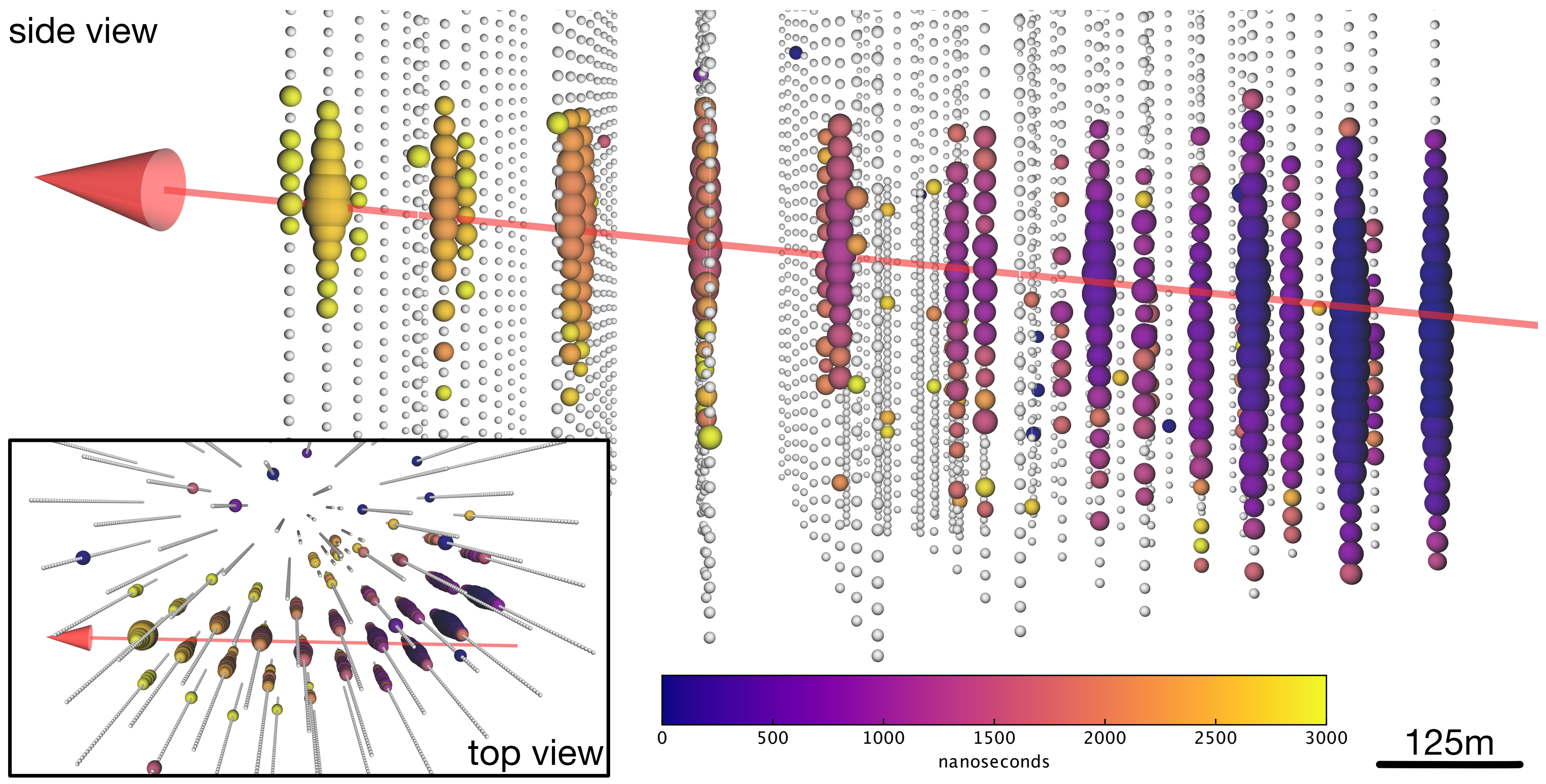


Fermi LAT collaboration, Nature, 2009

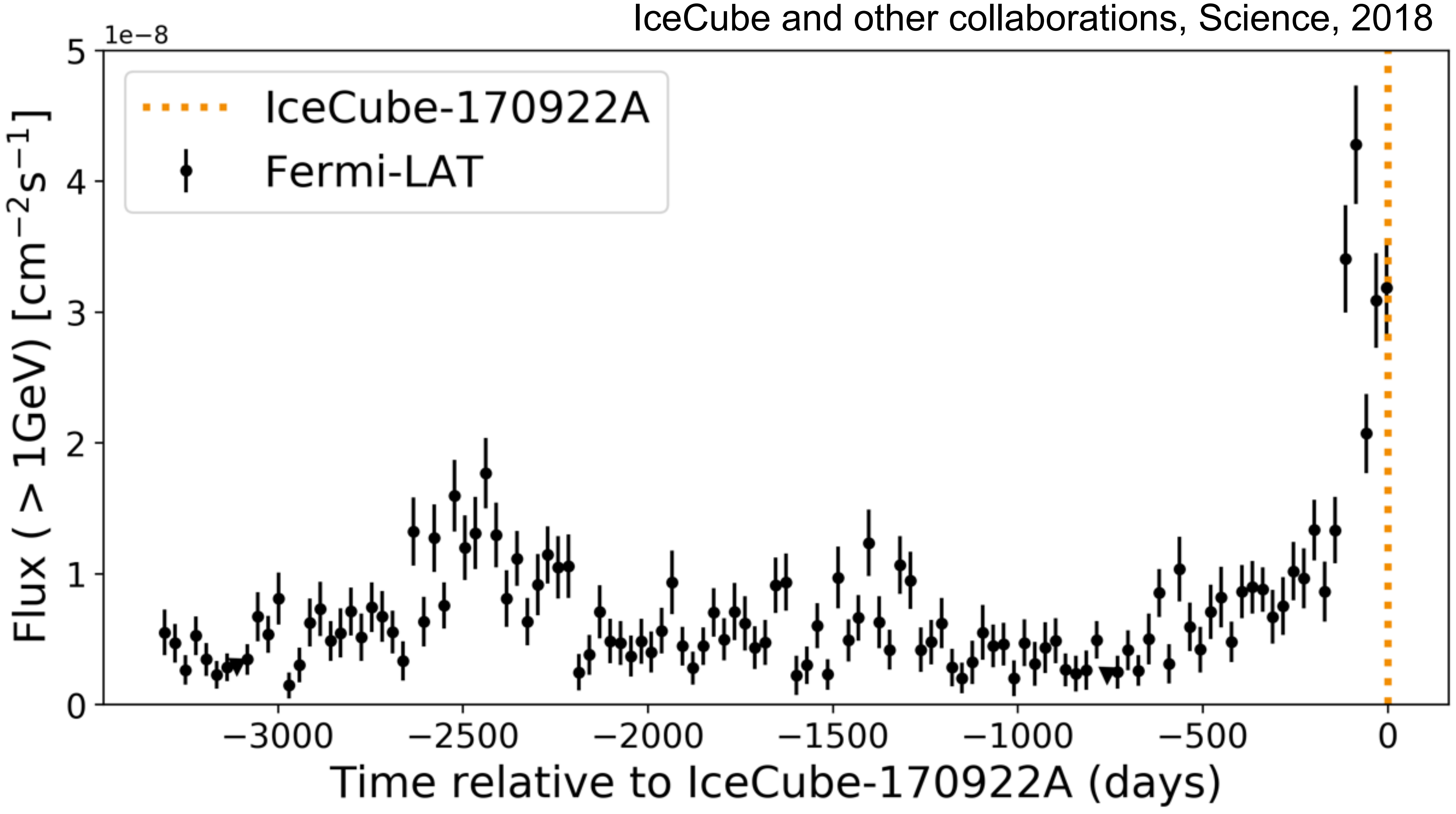
TXS0506+056: The first candidate neutrino source

and its relation to Lorentz invariance violation constraints

- TXS0506+056 is an Active Galaxy at a distance of z=0.34
- Neutrino energy >= 200 TeV
- In case of Lorentz invariance violation, energy loss process of neutrinos during propagation in vacuum could be allowed (Cohen and Glashow, PRL 2011)
- Pair creation of electron/positrons would be dominant energy loss
- Limit on M_{QG} > 100 M_{Planck} (for n=1) (Wang et al., PRD 2020)



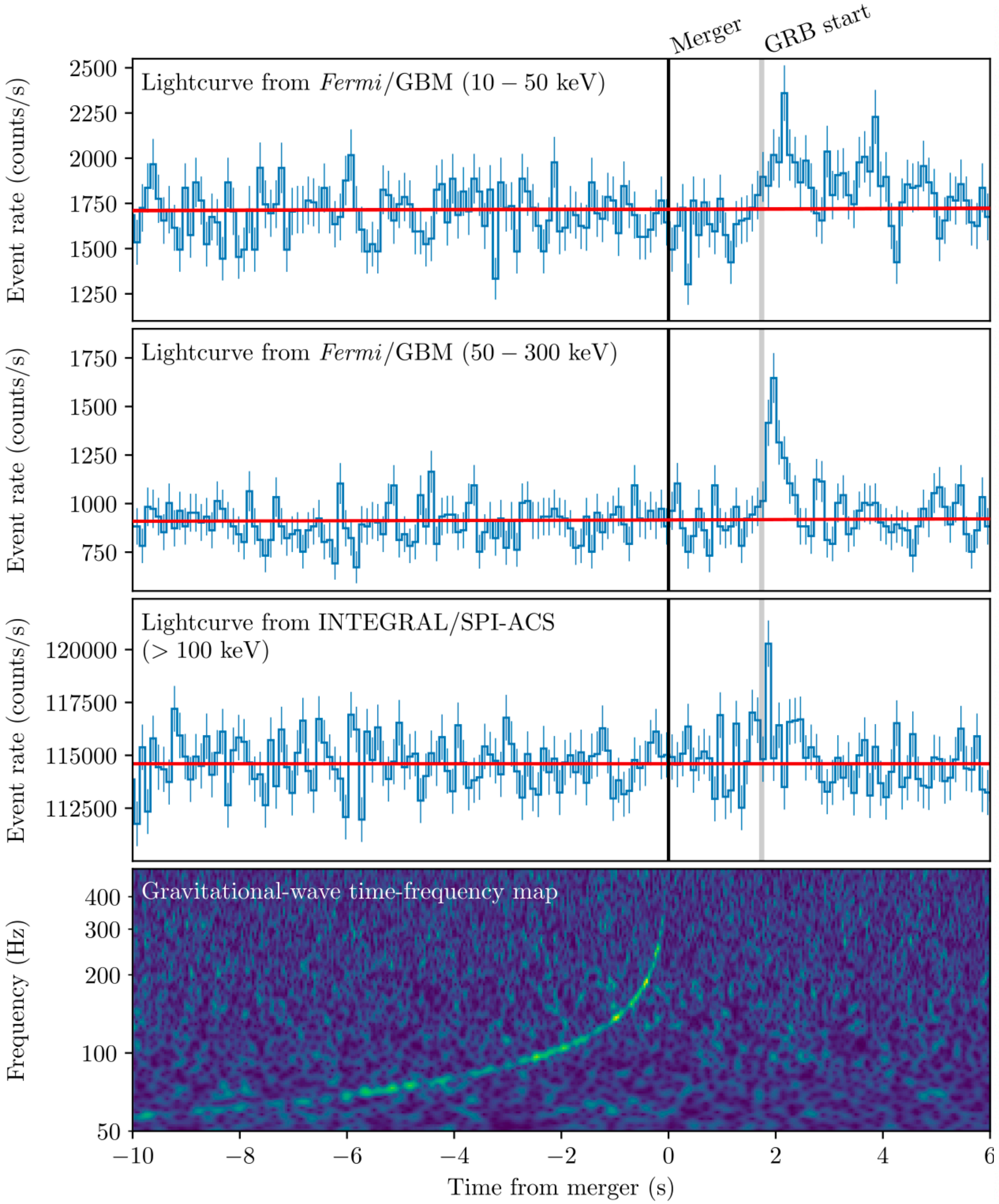
IceCube and other collaborations, Science, 2018

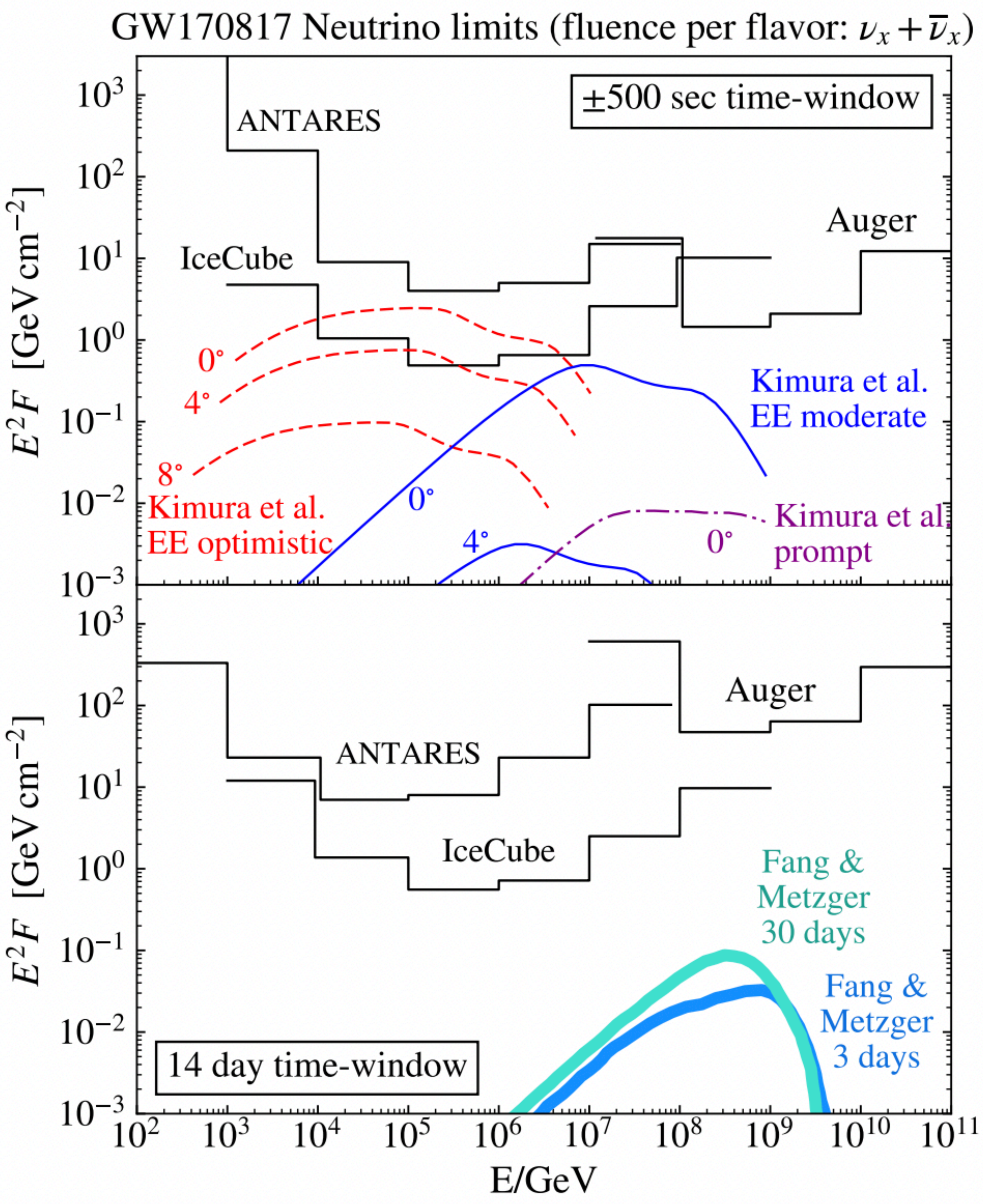


Gamma rays and neutrinos from binary neutron star mergers

- GW170817 resolved several longstanding questions in astrophysics in a single instant

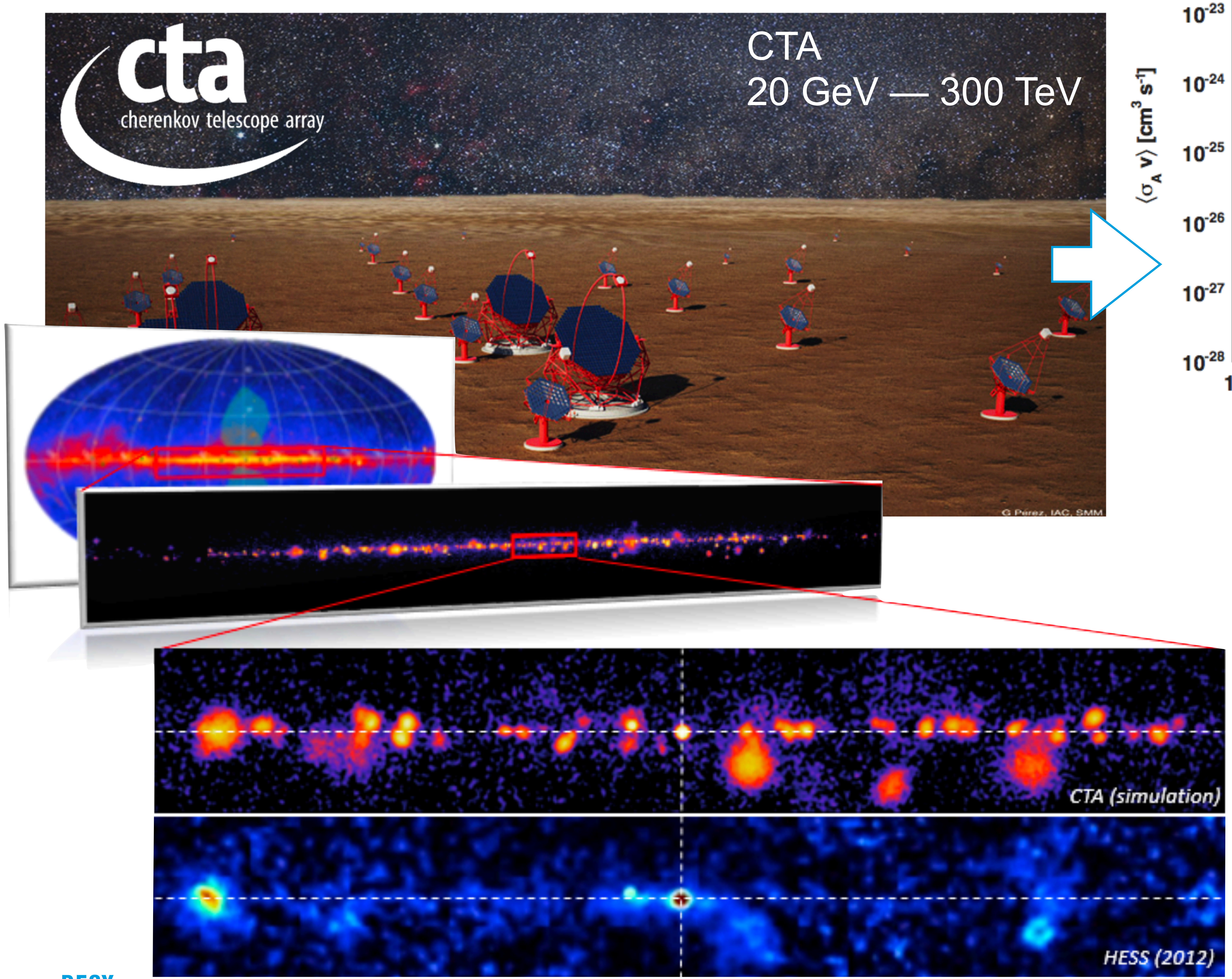
- Neutrino production expected but not observed with current instruments



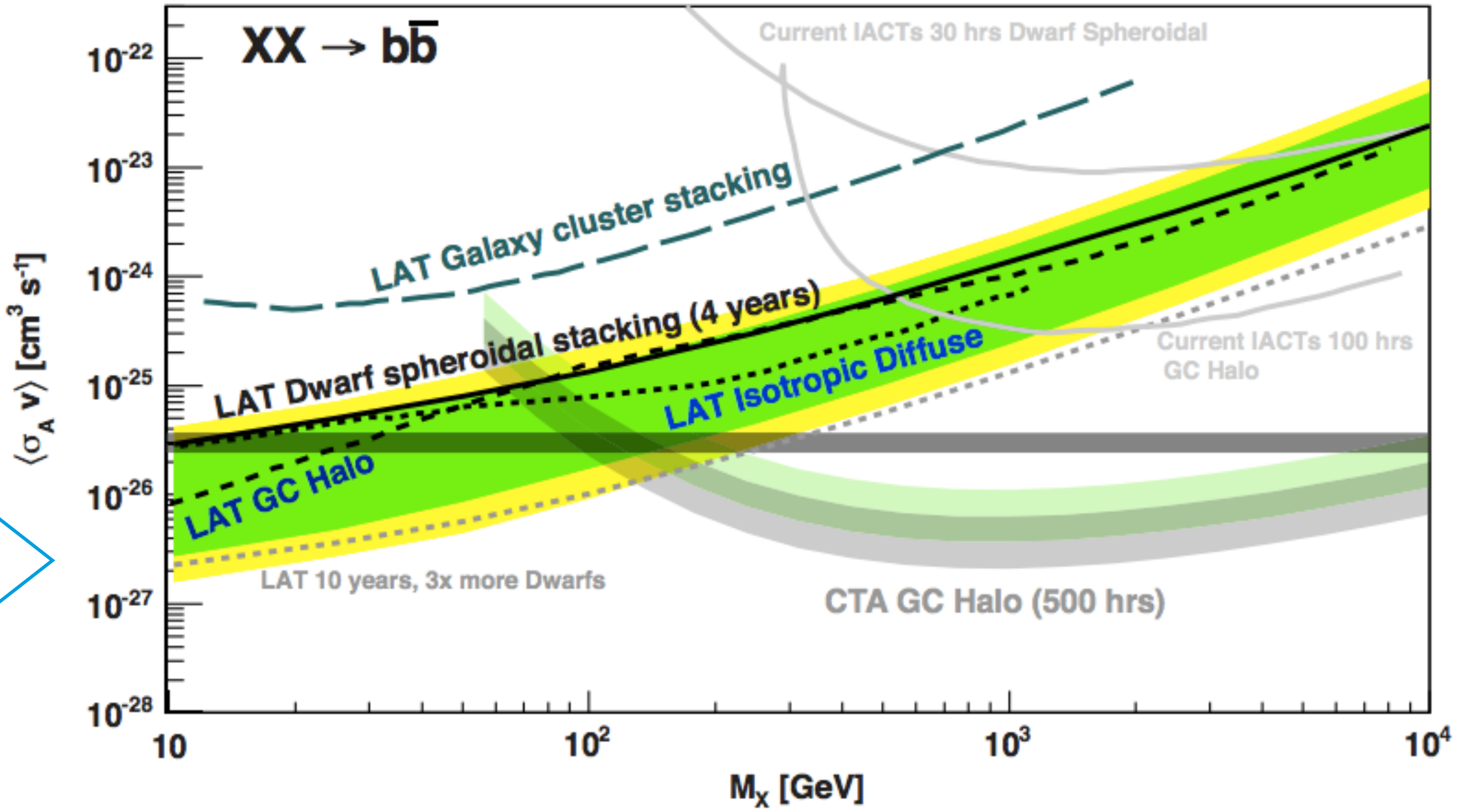


Future instruments

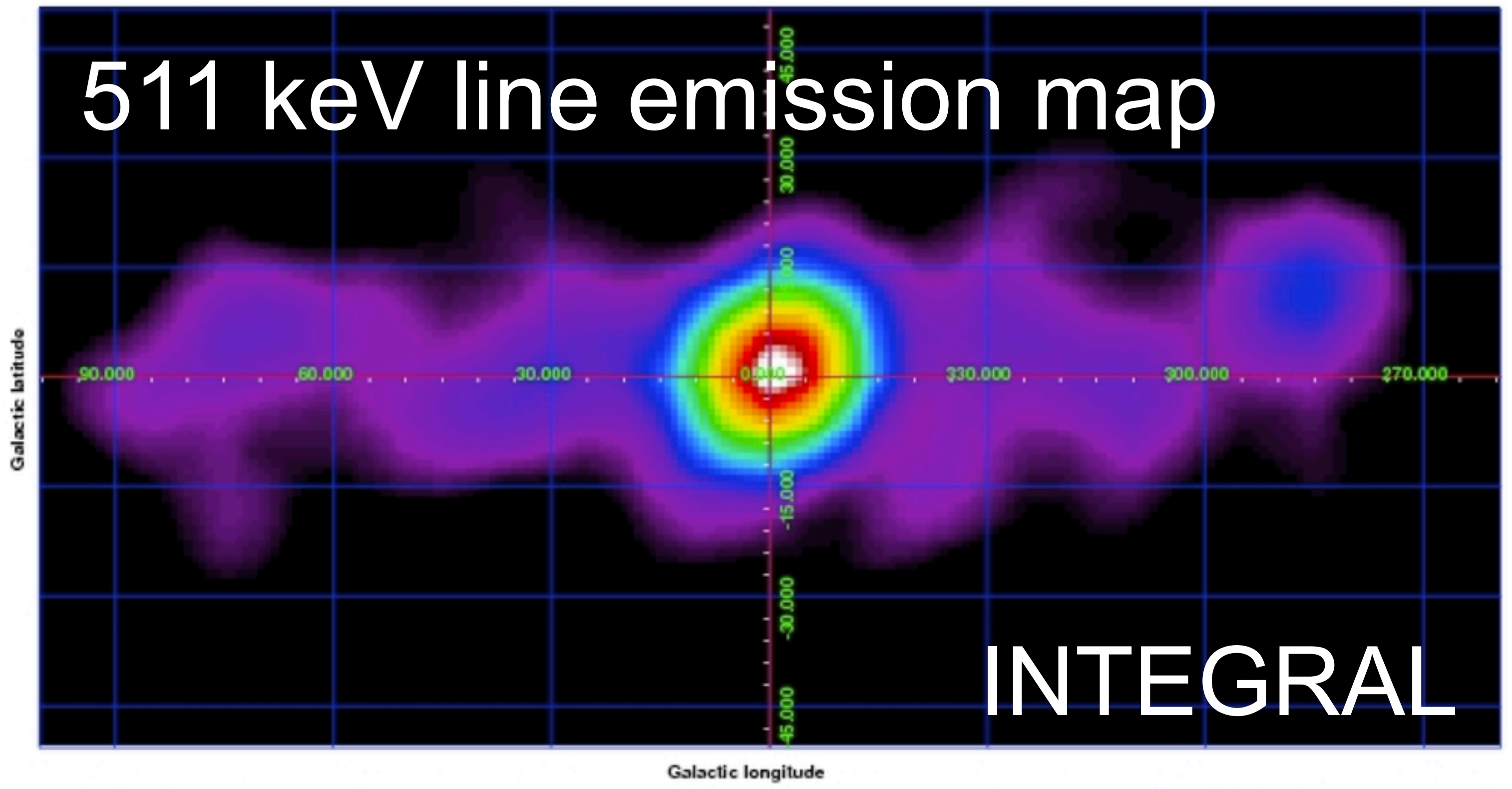
Gamma-ray telescopes



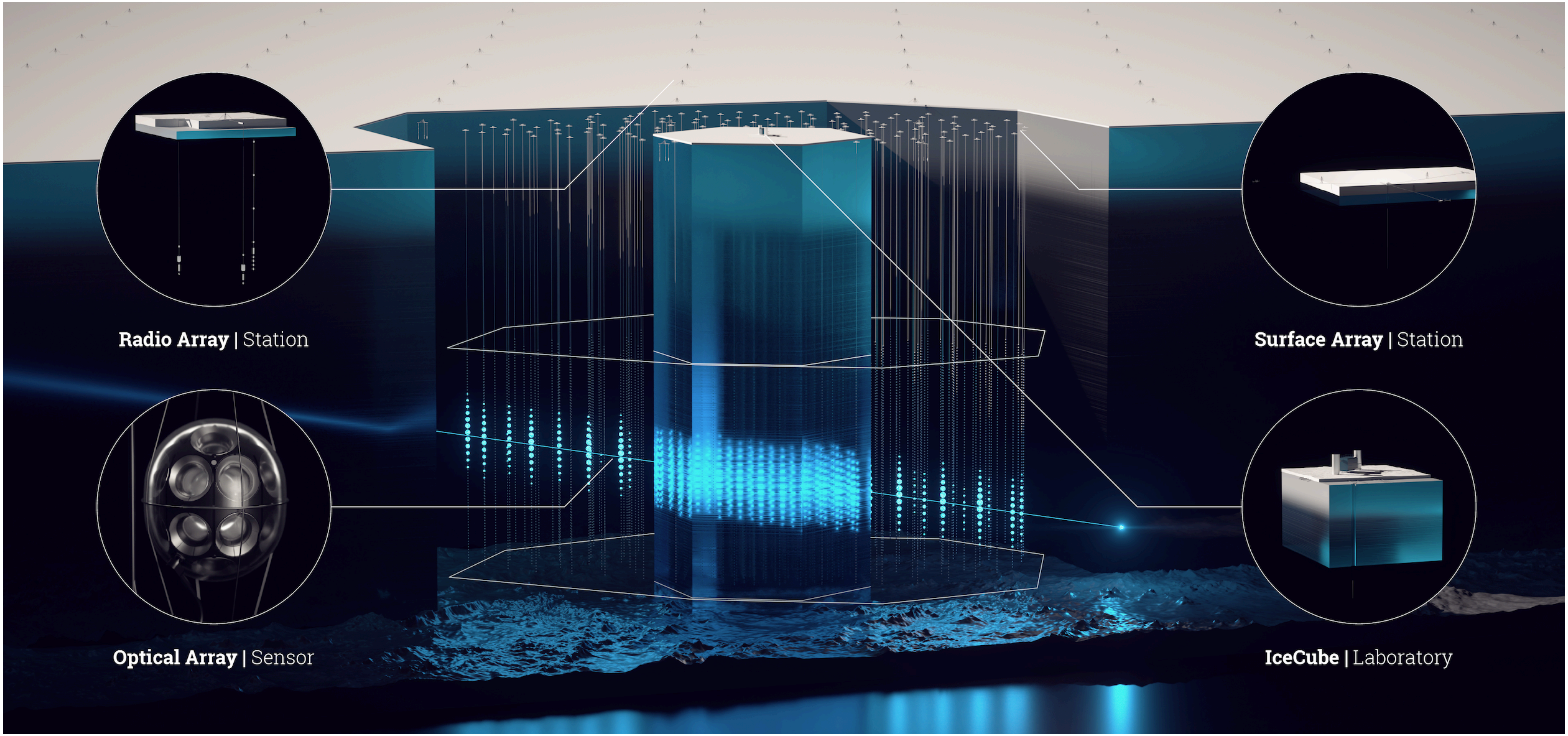
Funk, 2013



COSI
0.2 — 5 MeV



IceCube Upgrade and IceCube-Gen2



DESY.

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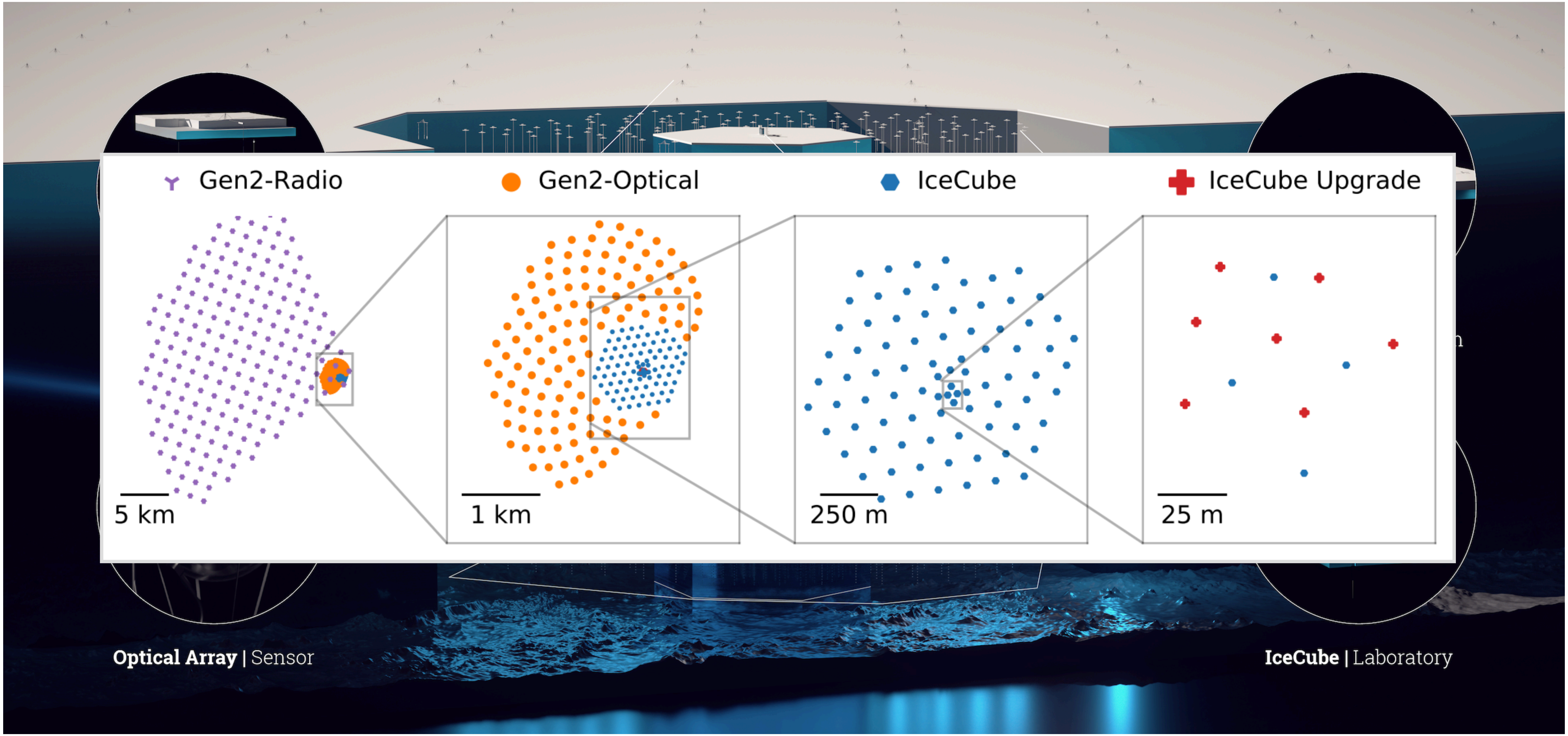
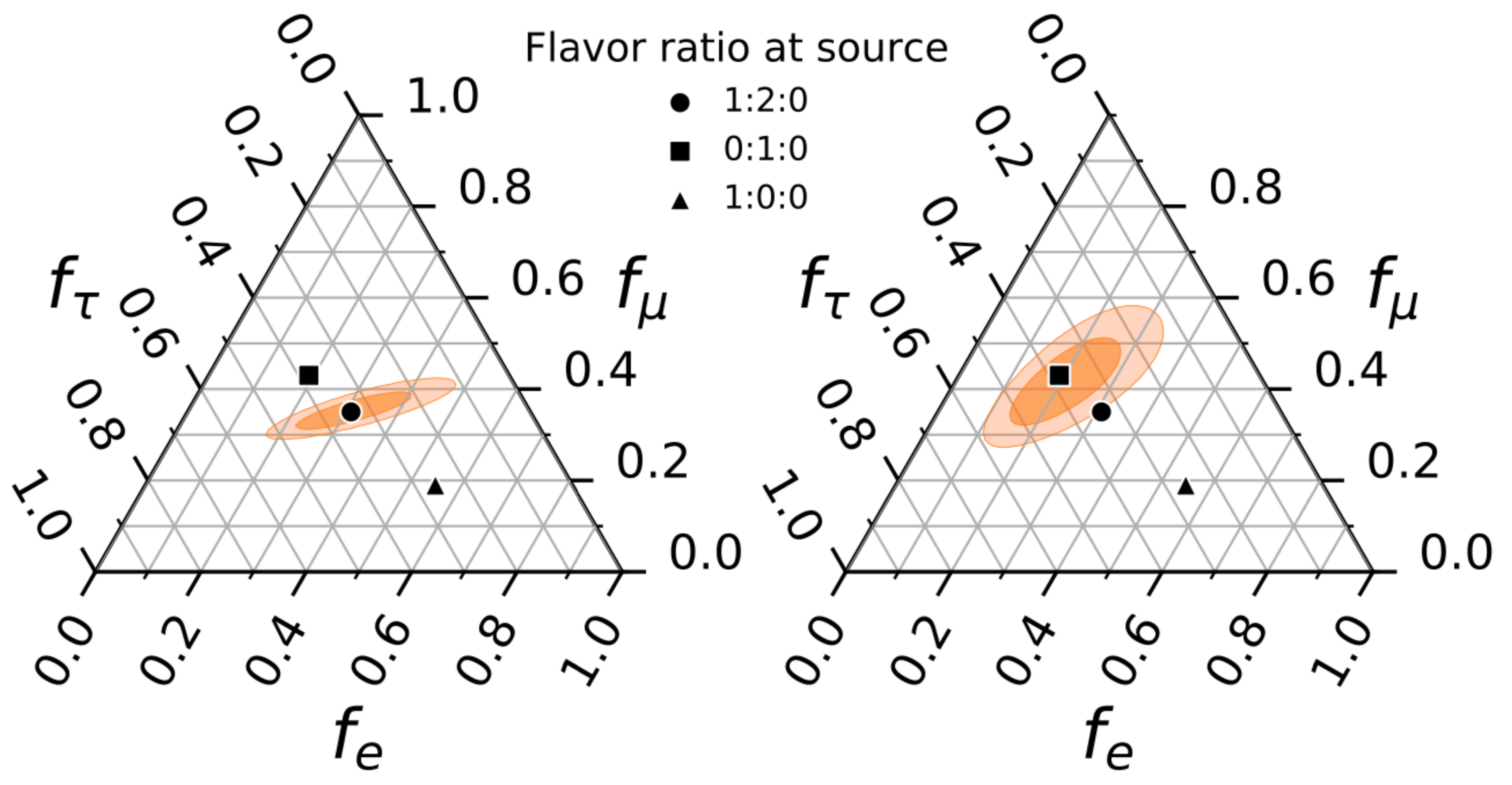
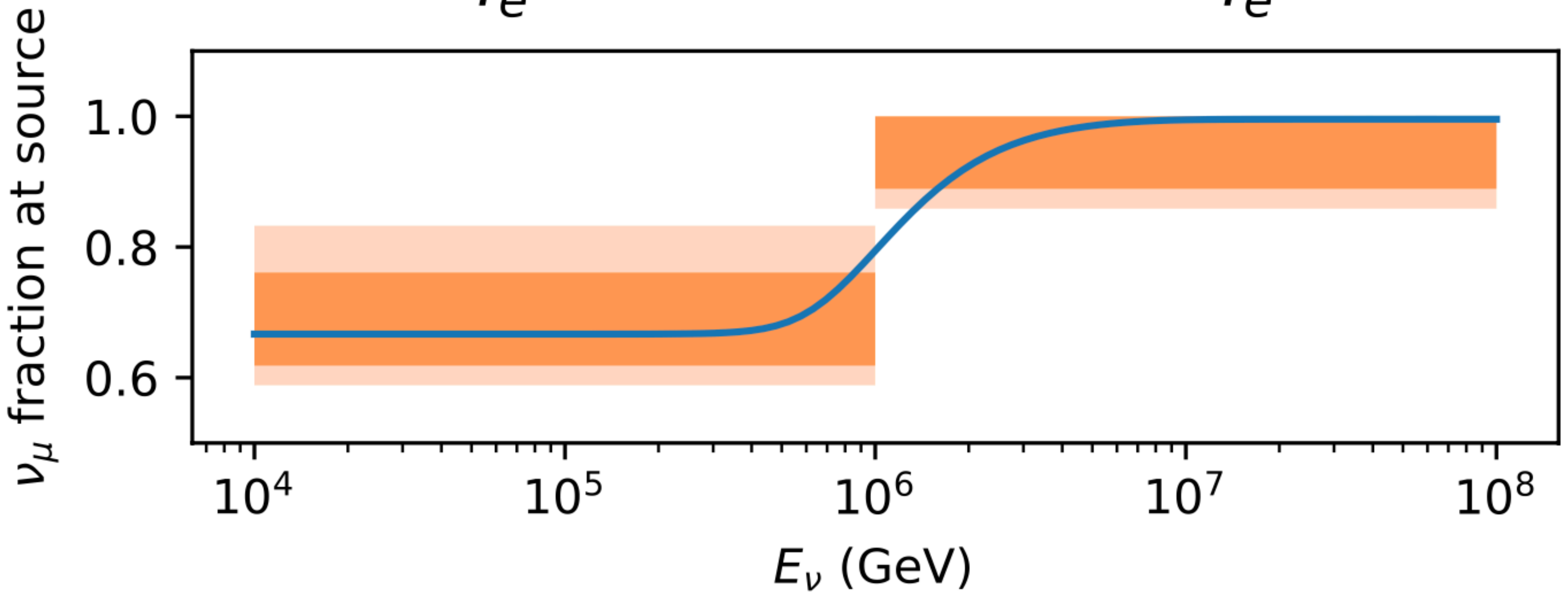
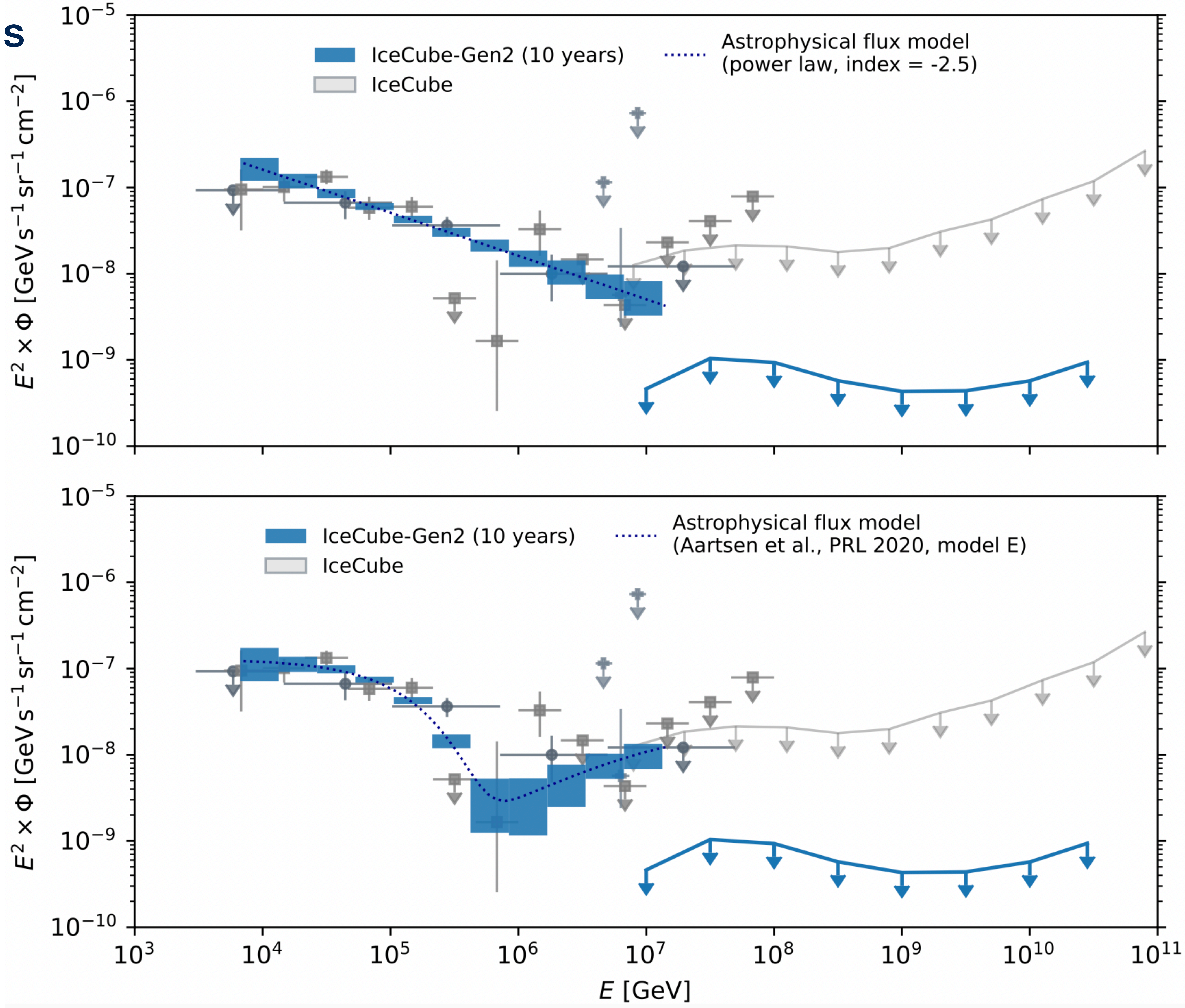


IceCube-Gen2 — Expected performance

- Flavor composition measurements in energy bands
- High-precision spectral shape measurements
- >1 transient / year







Summary

- Multi-messenger observations are a valuable tool not only for astrophysics, but also for particle physics.

- Gamma-ray and neutrino observations yield leading constraints on
  - Dark matter annihilation cross section / lifetime
  - Primordial black hole density in the universe
  - Lorentz Invariance Violation

- Measurement of the flavor composition of astrophysical neutrinos is unique:
  - Study of neutrino propagation over baselines of billions of light years
  - Sensitive to many new physics effects

- Future instruments will not only be great for astrophysics, but also significantly extend the phase space of BSM physics that can be tested.