Neutrino Astrophysics: *A Theory Perspective*

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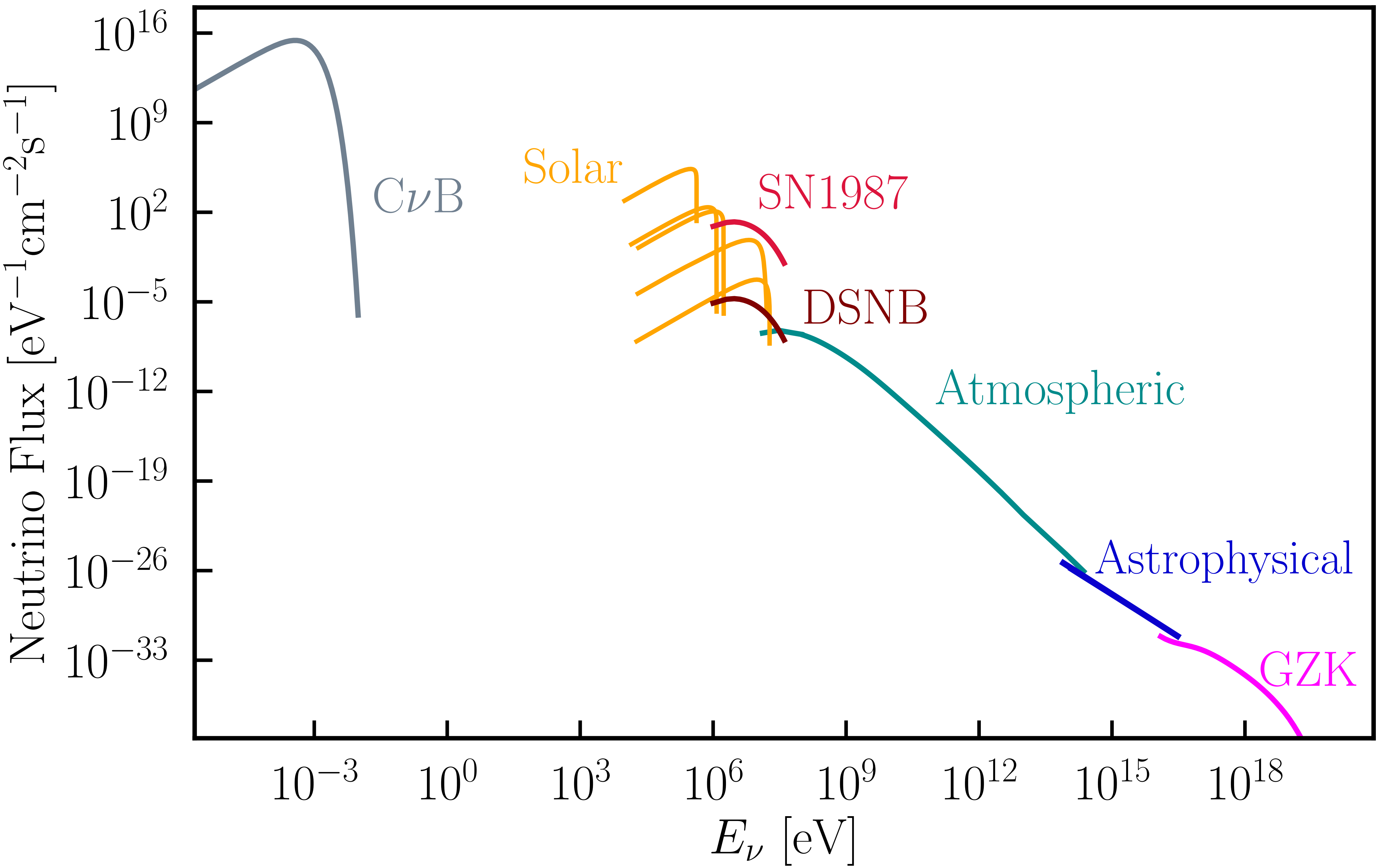
University of Nevada, Las Vegas

CIPANP 2022, Orlando, Florida

UNLV
NCfA

The Universe in Neutrinos



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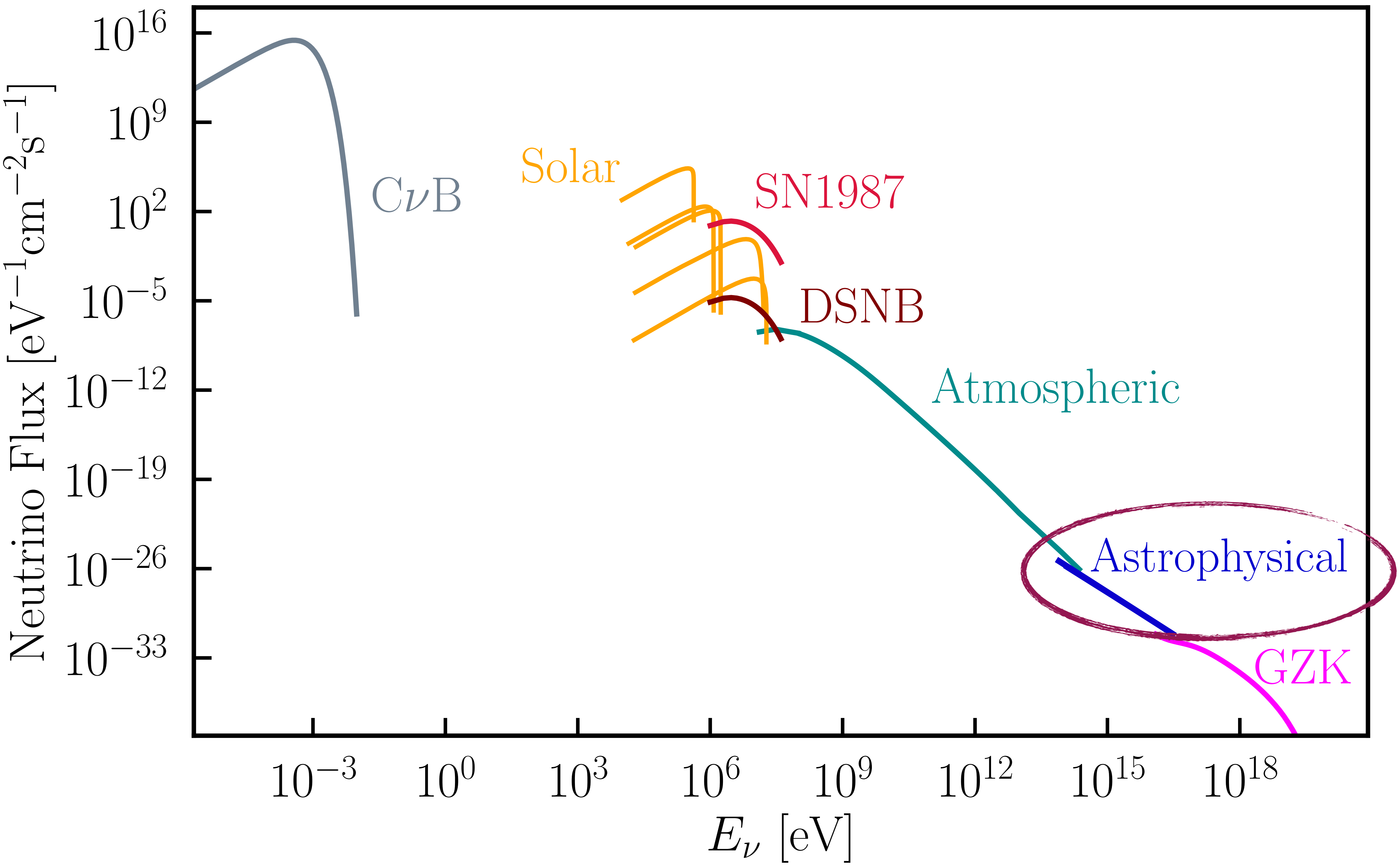
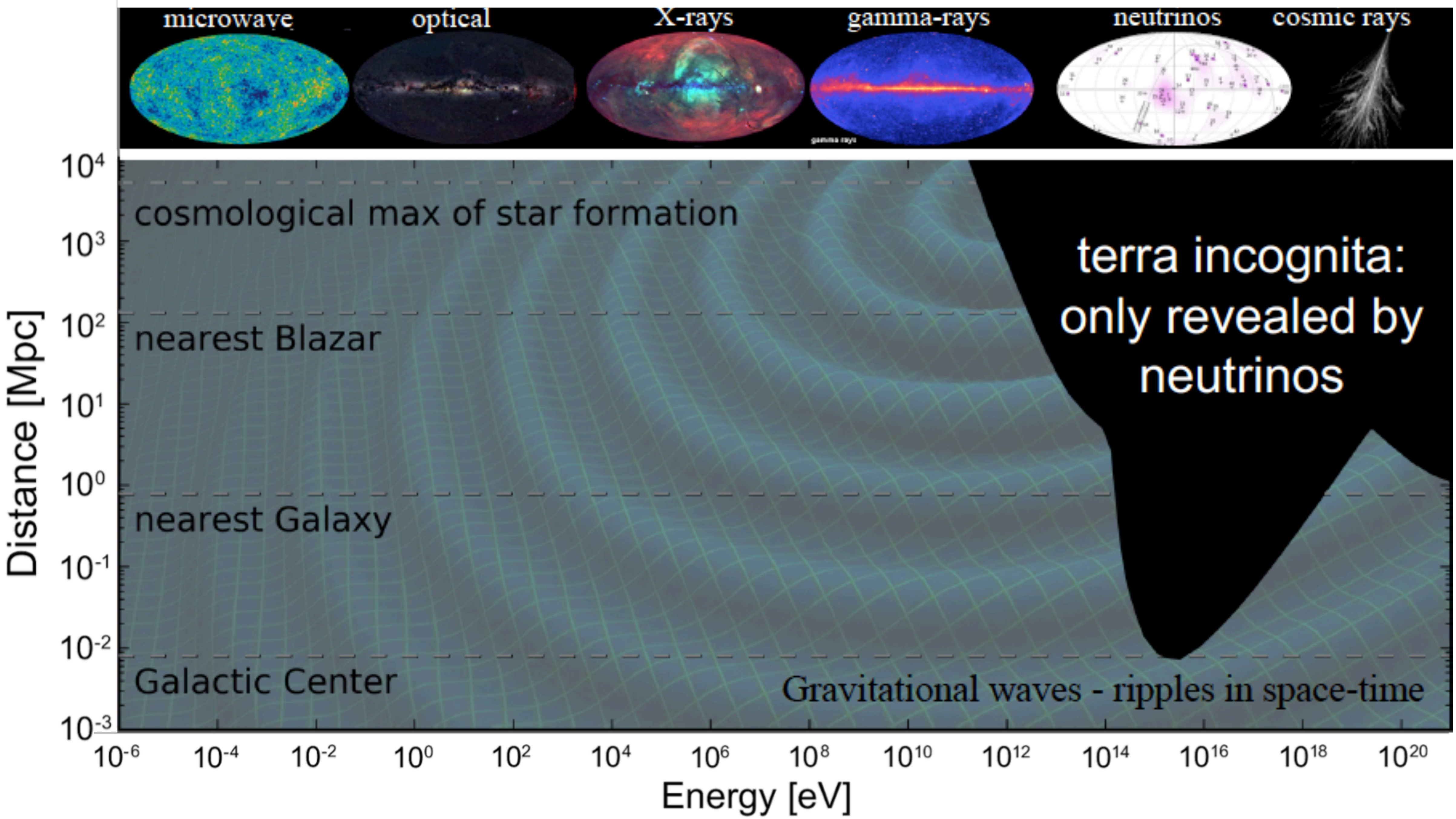


Observable Universe

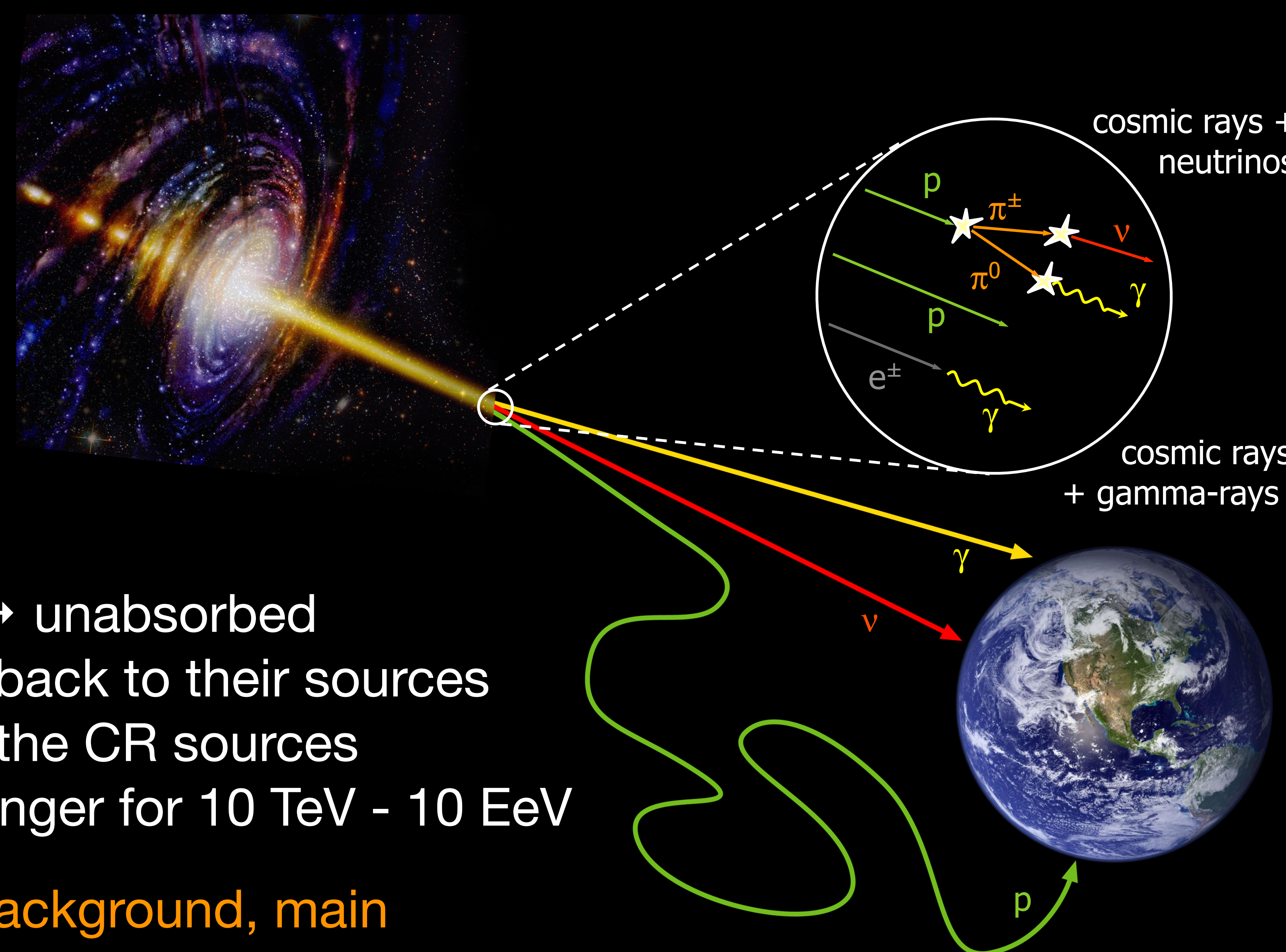


- 20% of the Universe is opaque to the EM spectrum
- Non-thermal Universe powered by cosmic accelerators, probed by gravitational waves, neutrinos and cosmic rays

Neutrino Astrophysics

- Soon after discovery it was realized neutrinos are ideal cosmic messengers.

Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



- Neutrinos:
  - ✓ Hardly interact → unabsorbed
  - ✓ Neutral → point back to their sources
  - ✓ Smoking gun of the CR sources
  - ✓ Exclusive messenger for 10 TeV - 10 EeV

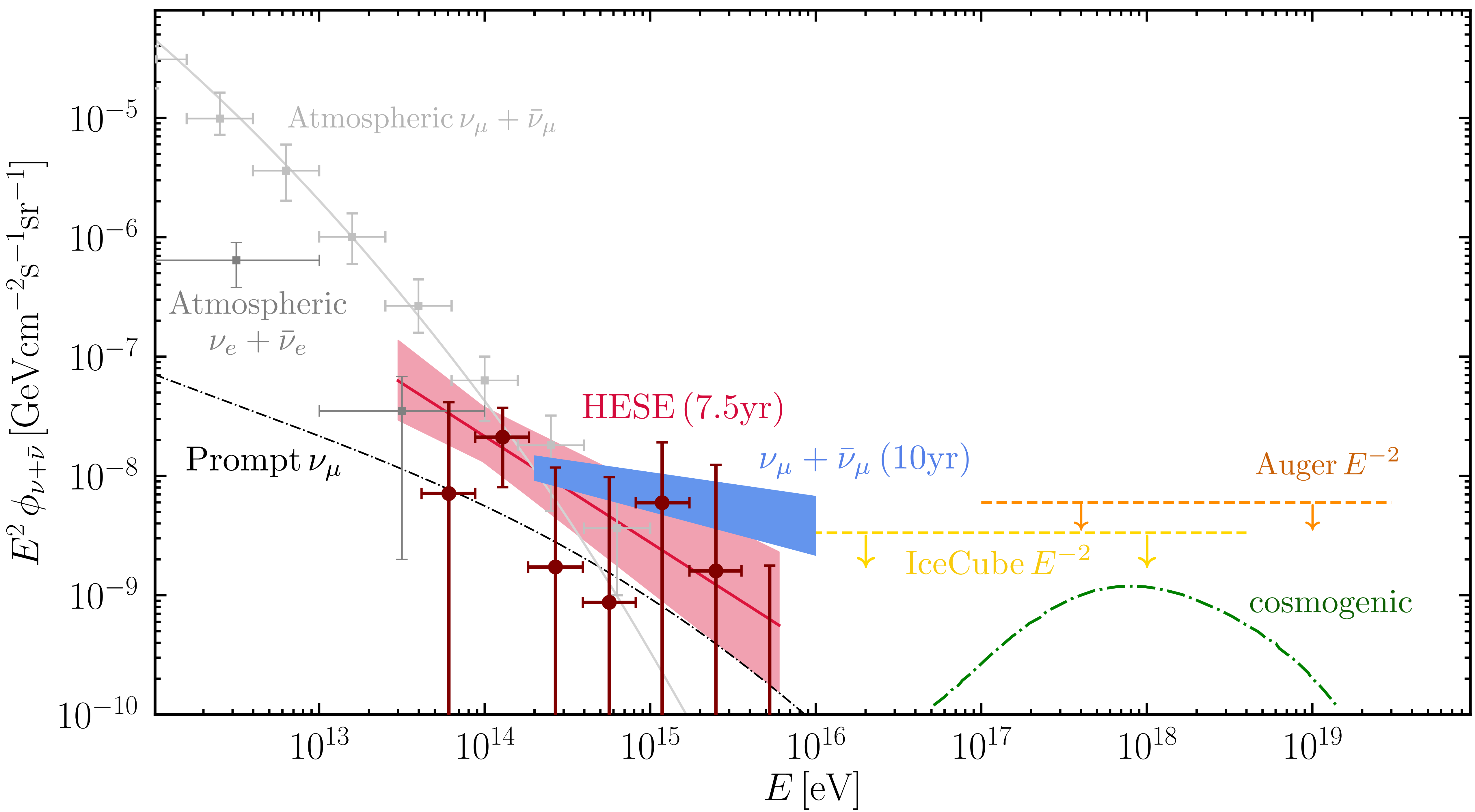
Low statistics and large background, main challenges for neutrino astronomy.

10 years of IceCube Observation

- What have we learned about the **nature cosmic neutrino flux**?
- What have we learned about the **origin(s) of the cosmic neutrinos**?
- How we can use high-energy cosmic neutrino flux observables to **study neutrino**?

  - For the highlights on the latest IceCube results, see James DeLaunay talk tomorrow.

High-Energy Neutrino Flux



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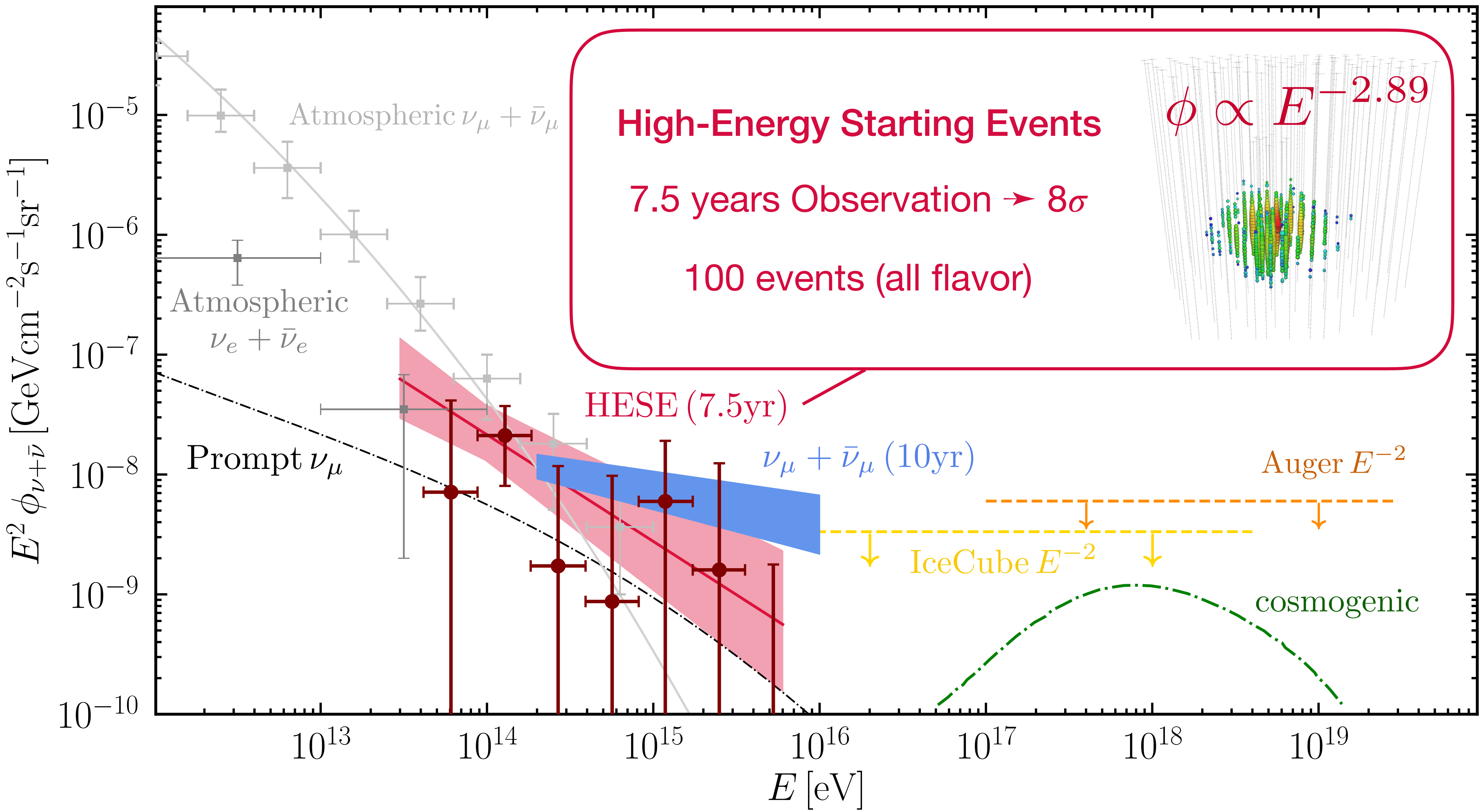

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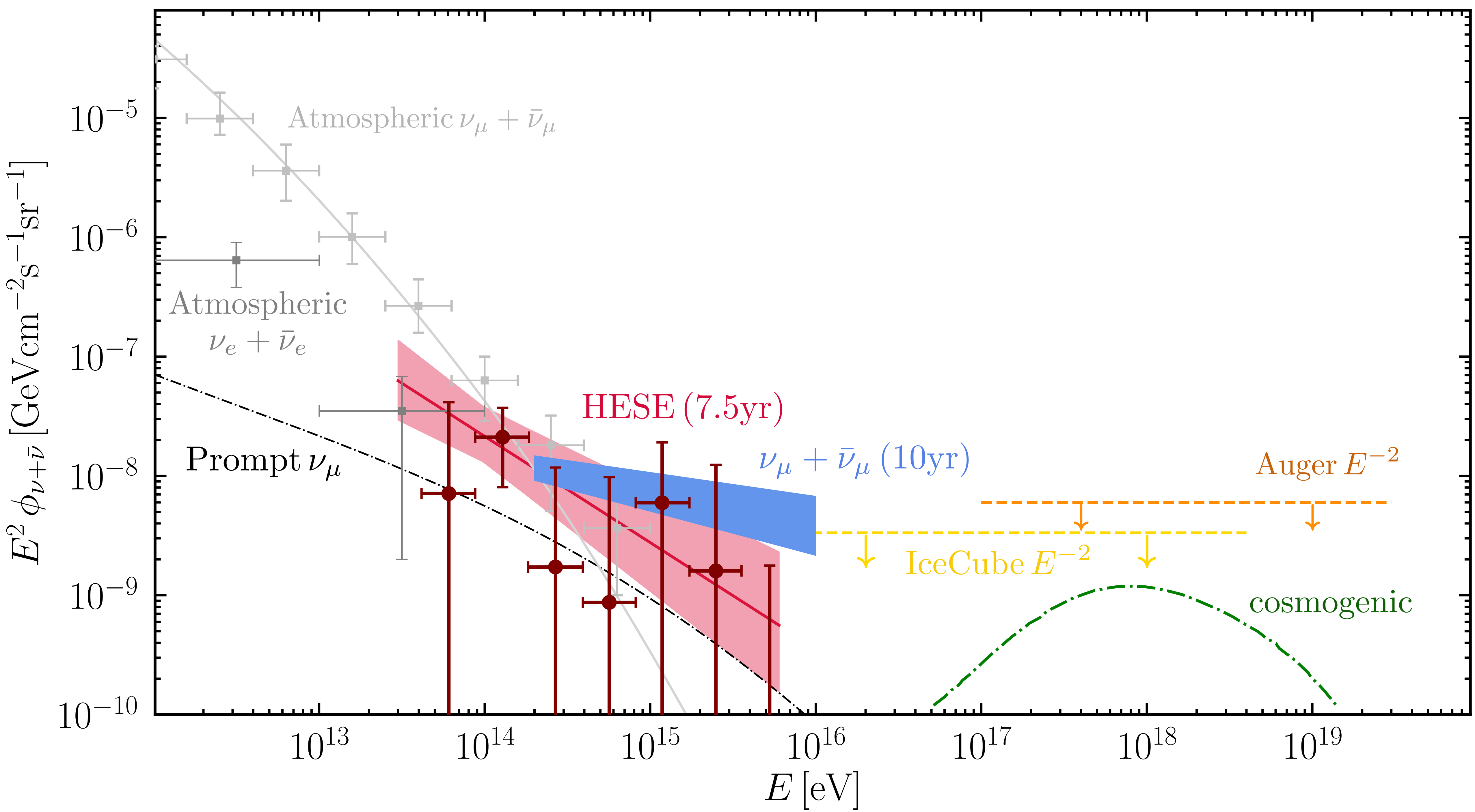

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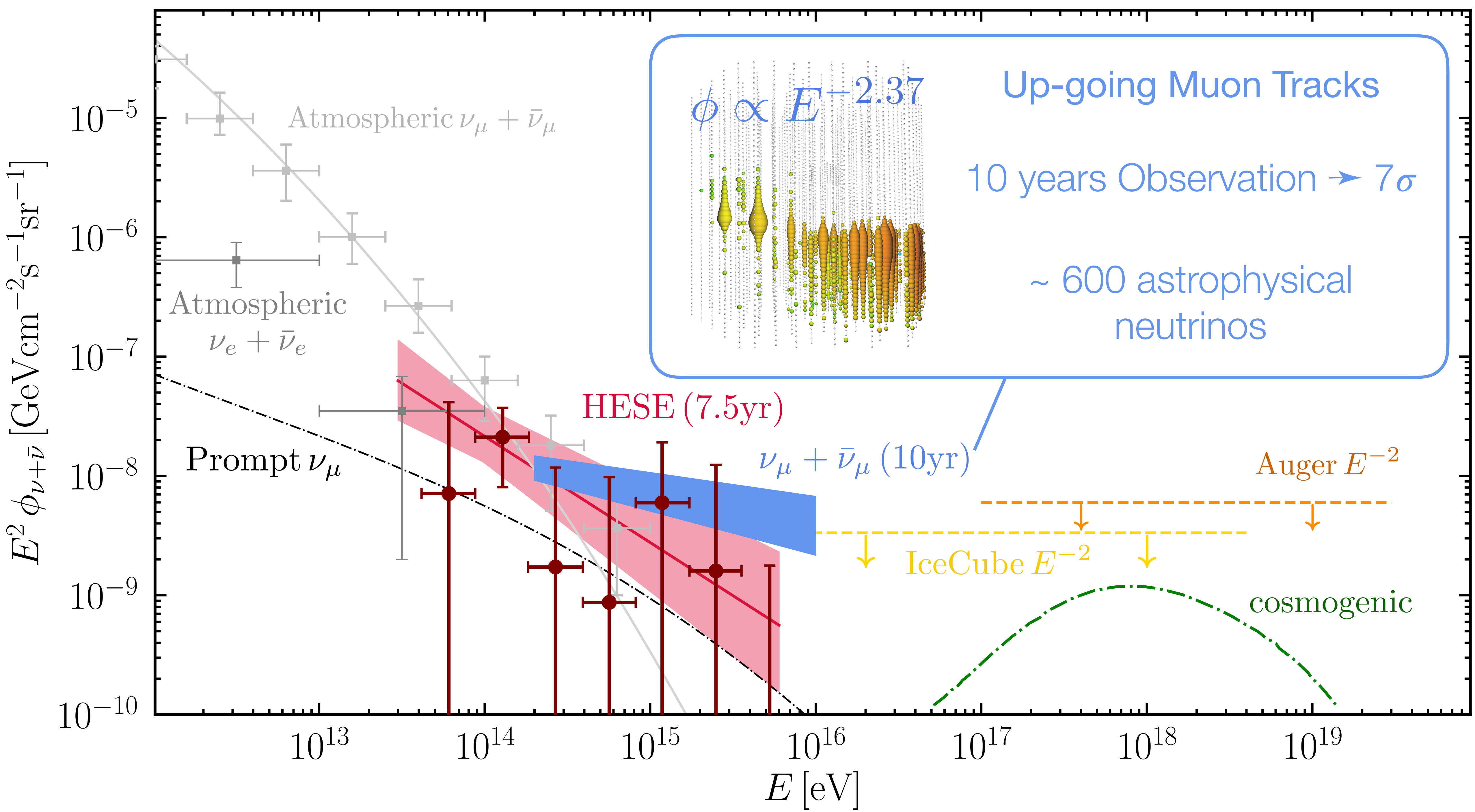

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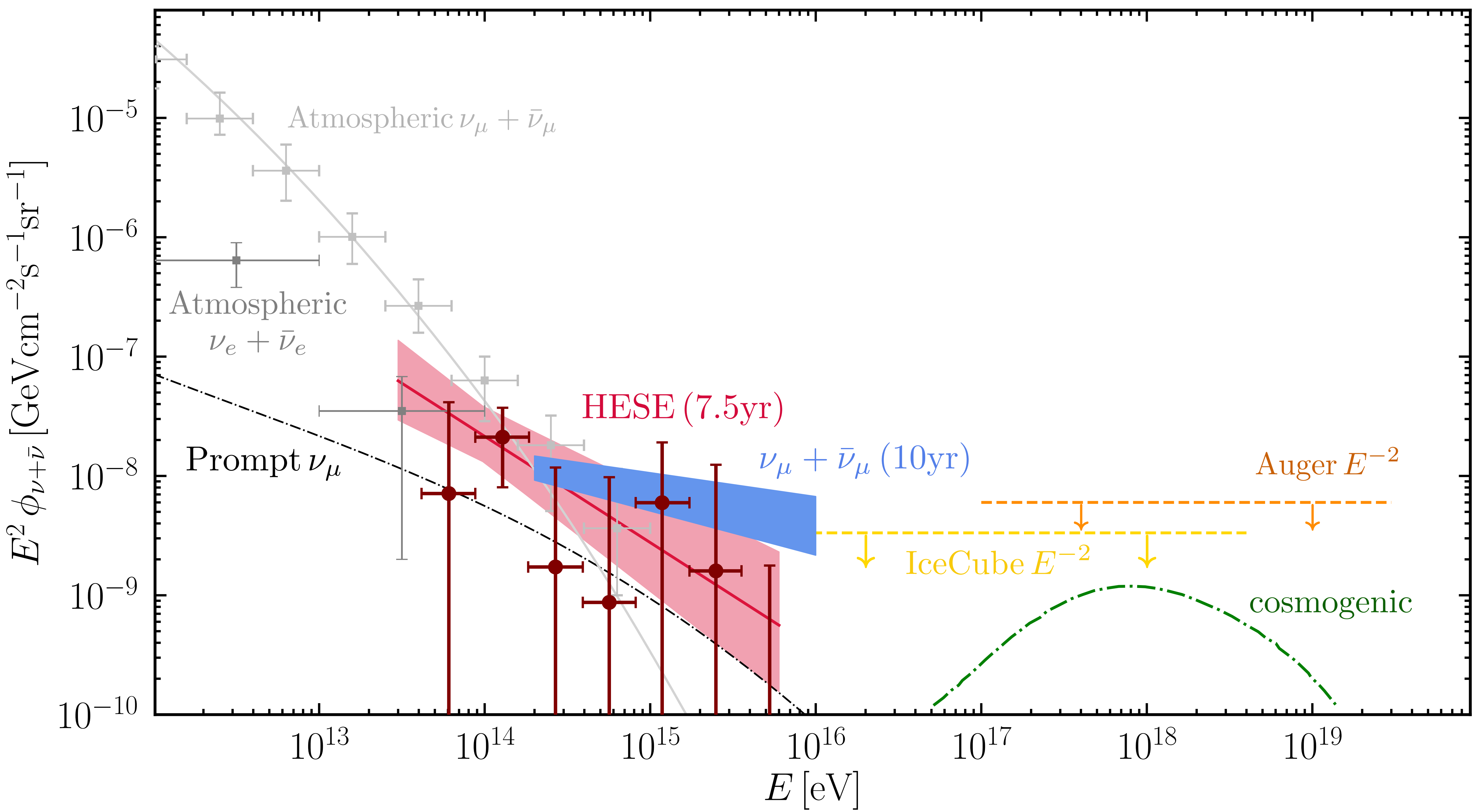

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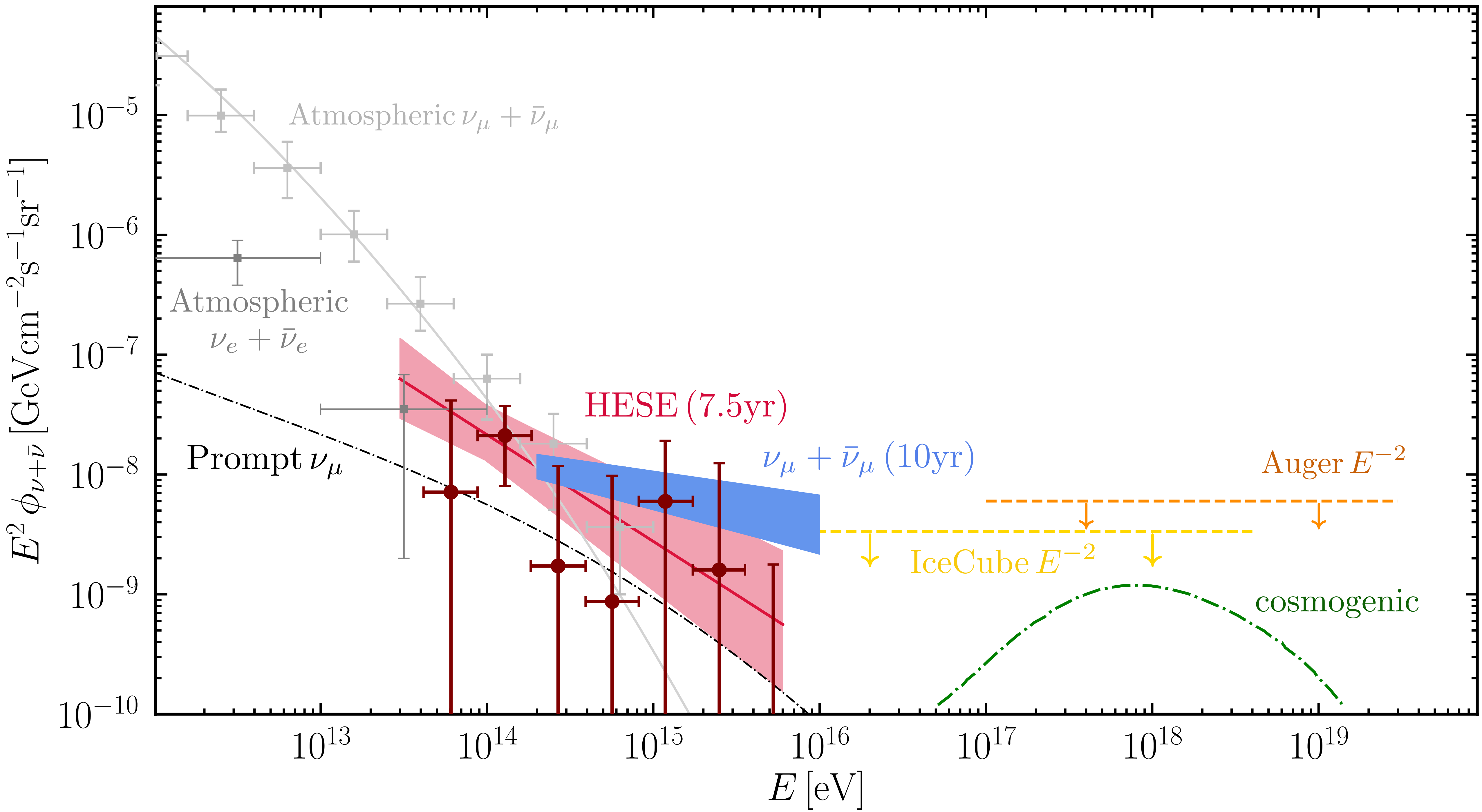
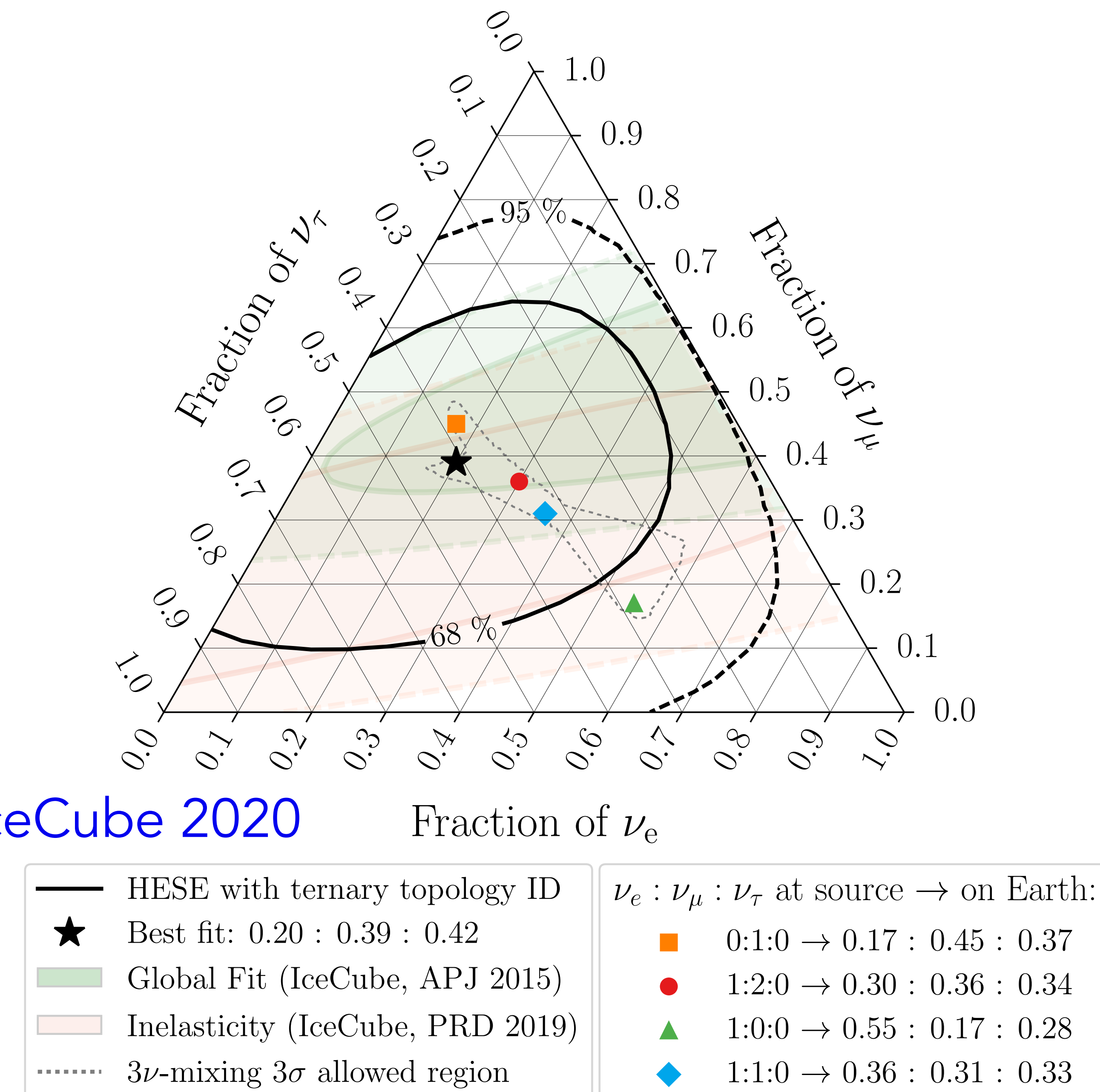


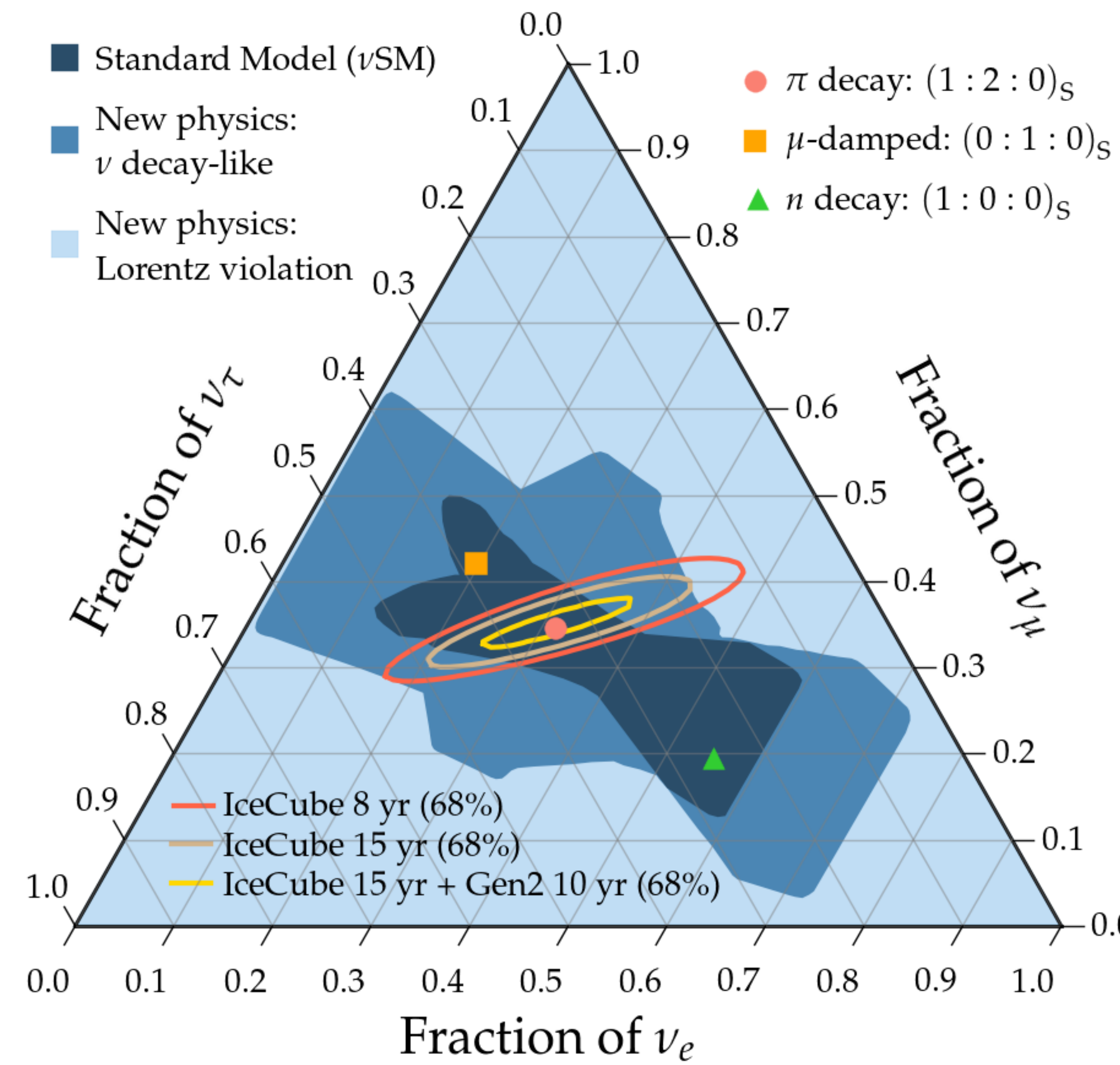
- Fluxes are compatible in common energy range.
- Features in high-energy neutrino flux can point to different source properties.

Flavor Composition

- Standard Expectation: equal proportion of each flavor
- Flavor composition compatible with equal proportion of each flavor.
- **Any deviation from the equal proportion indicate new physics!**



IceCube 2020



IceCube-Gen2 2020

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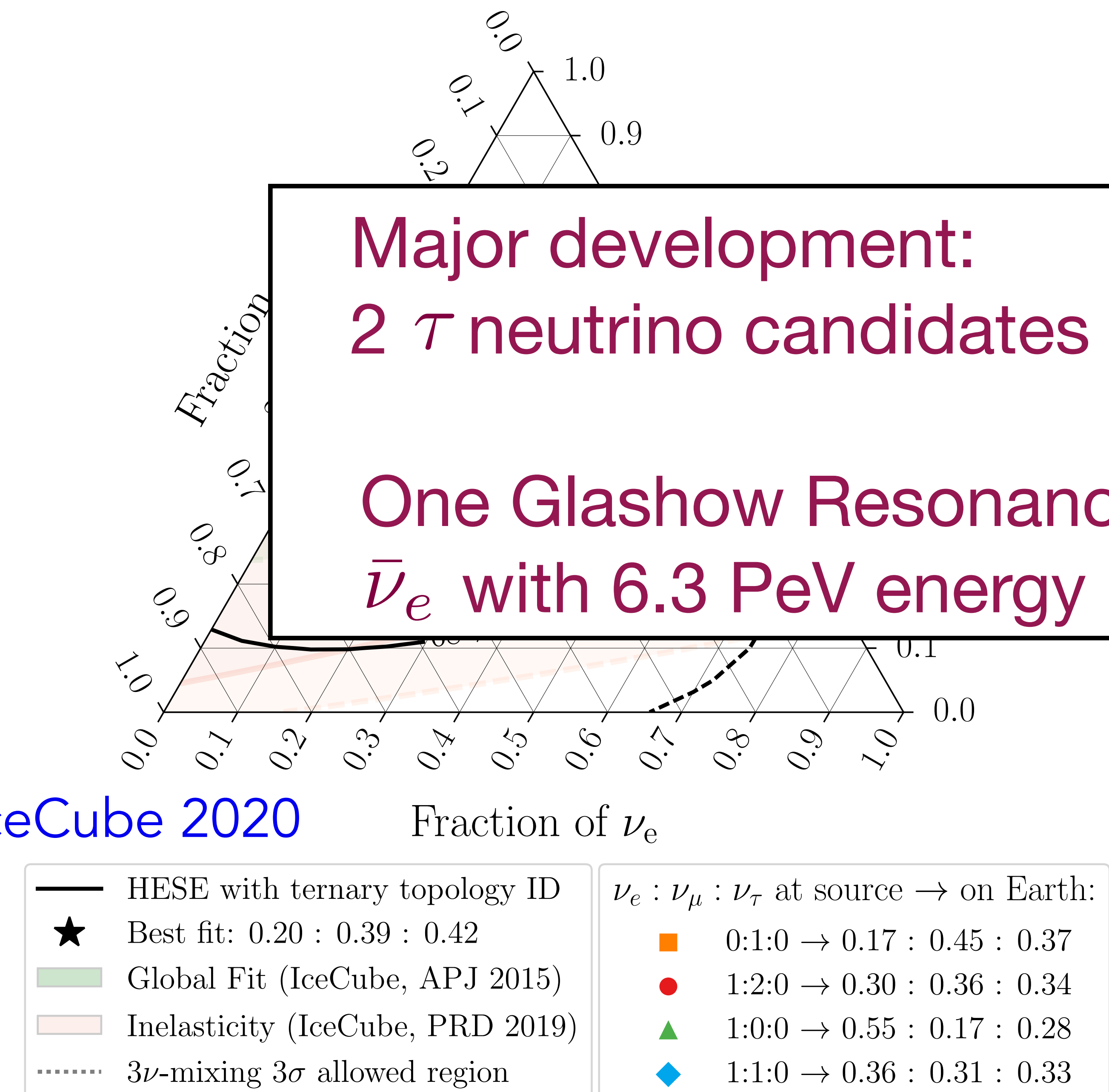
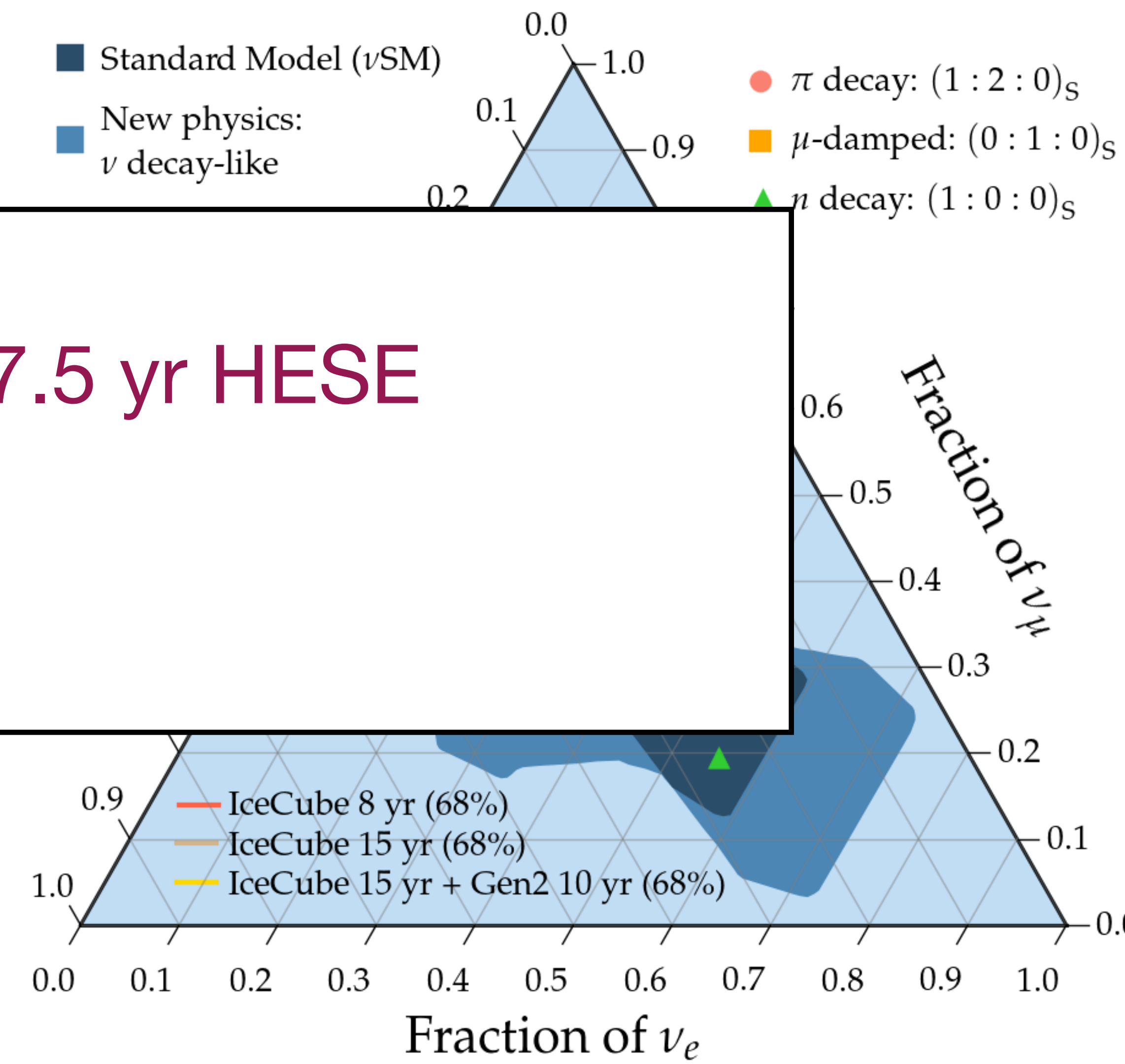


IceCube 2020

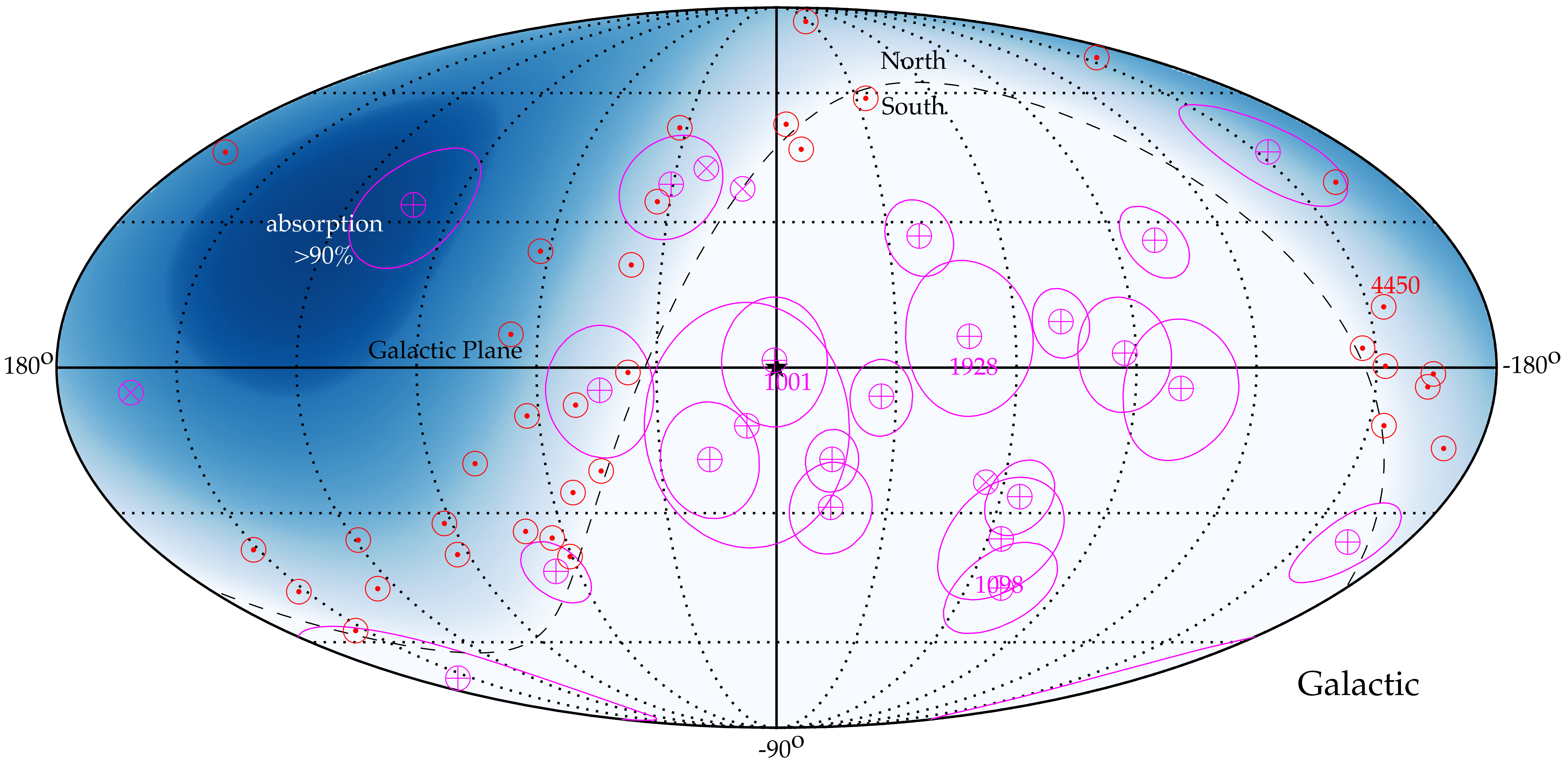
Major development:
2 τ neutrino candidates in 7.5 yr HESE

One Glashow Resonance:
$\bar{\nu}_e$ with 6.3 PeV energy



IceCube-Gen2 2020

Arrival Direction of the Most Energetic Neutrinos

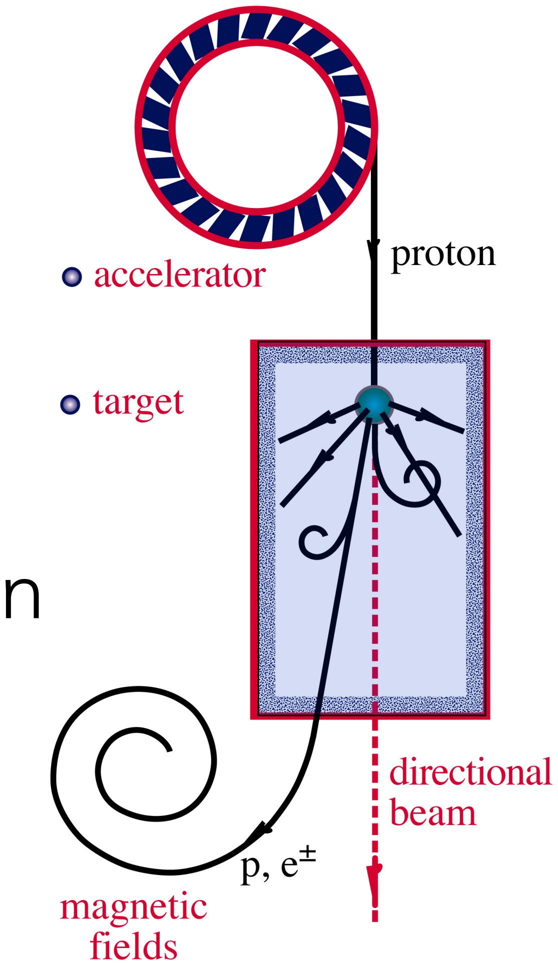


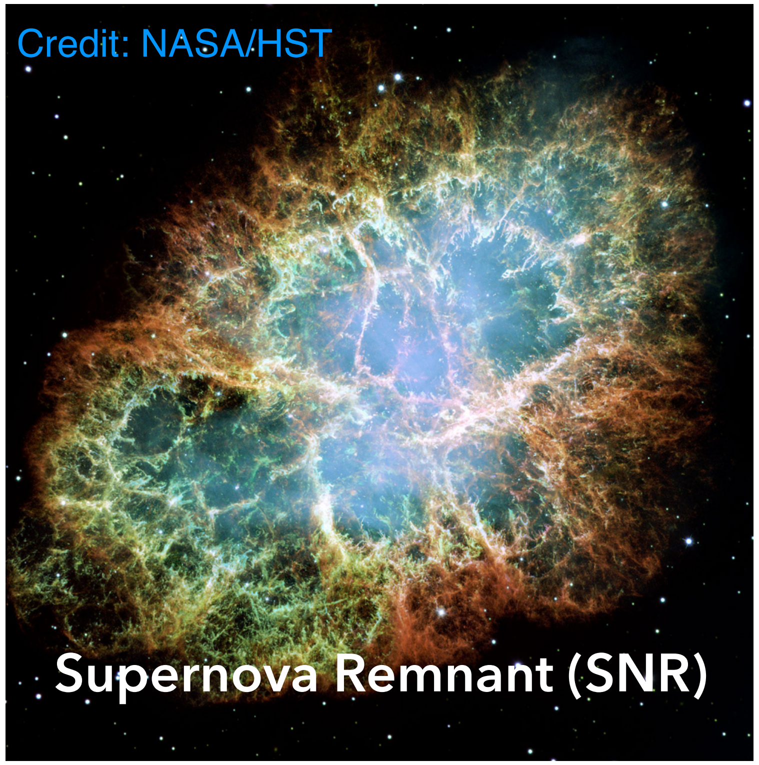
predominantly extragalactic origin

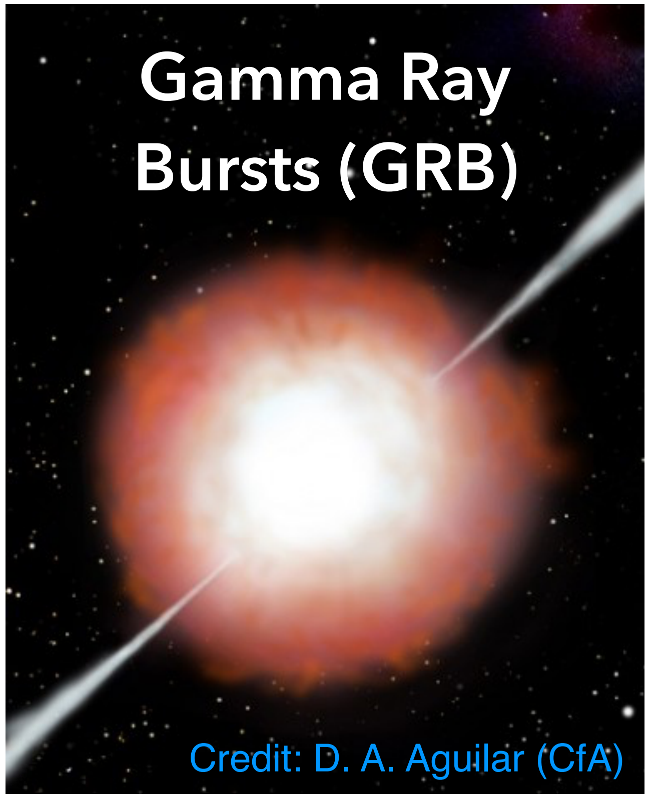
Possible Sources

Sources of TeV - PeV cosmic neutrinos should

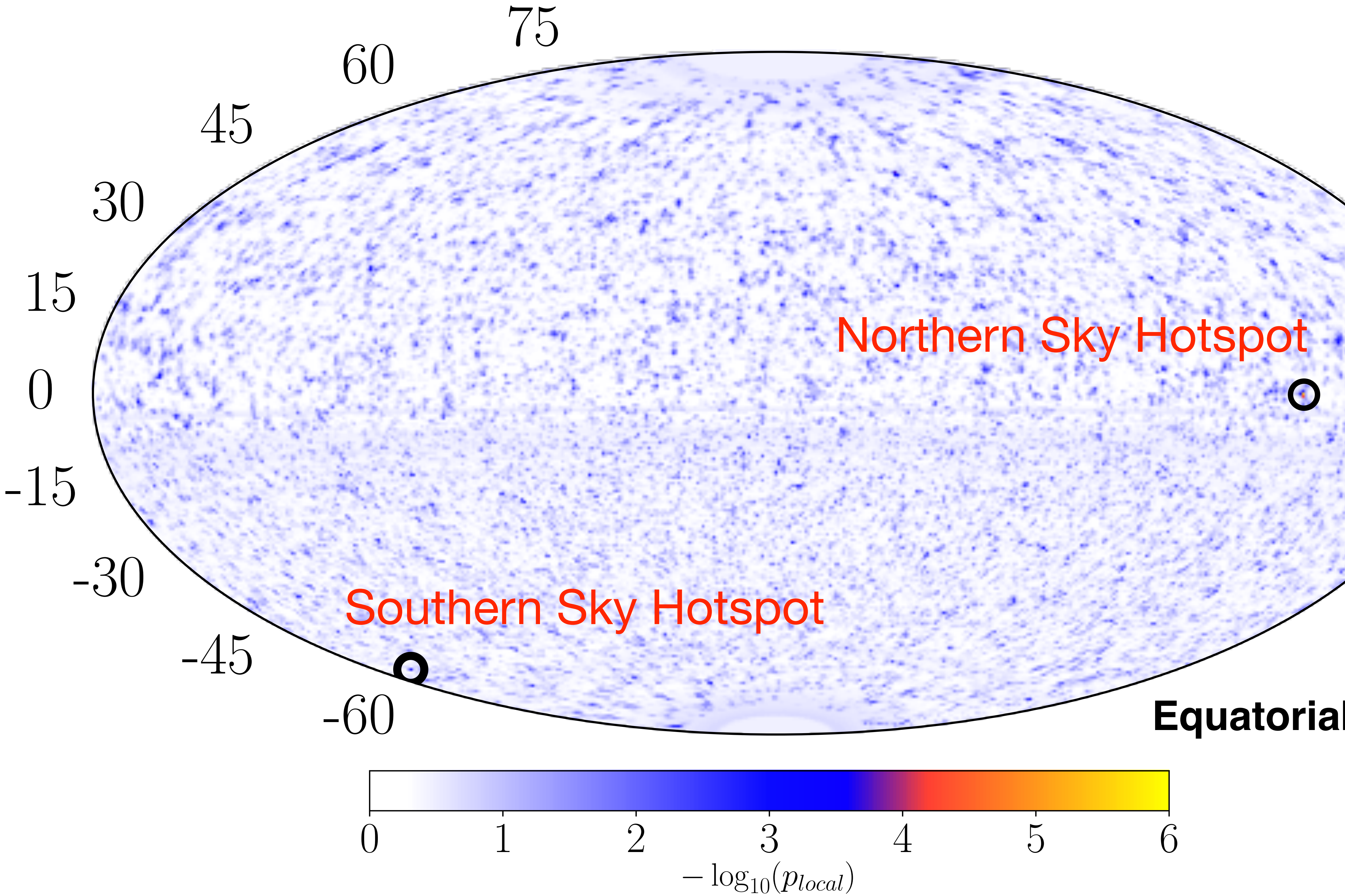
- Accelerate Cosmic Rays to > PeV energies
    - sources of VHE & UHE CRs
- Poses beam dumps that facilitate CR interaction
    - environment that can provide gas and radiation with enough density







Neutrino Sky-IceCube 10 yr



[IceCube, PRL 2020]

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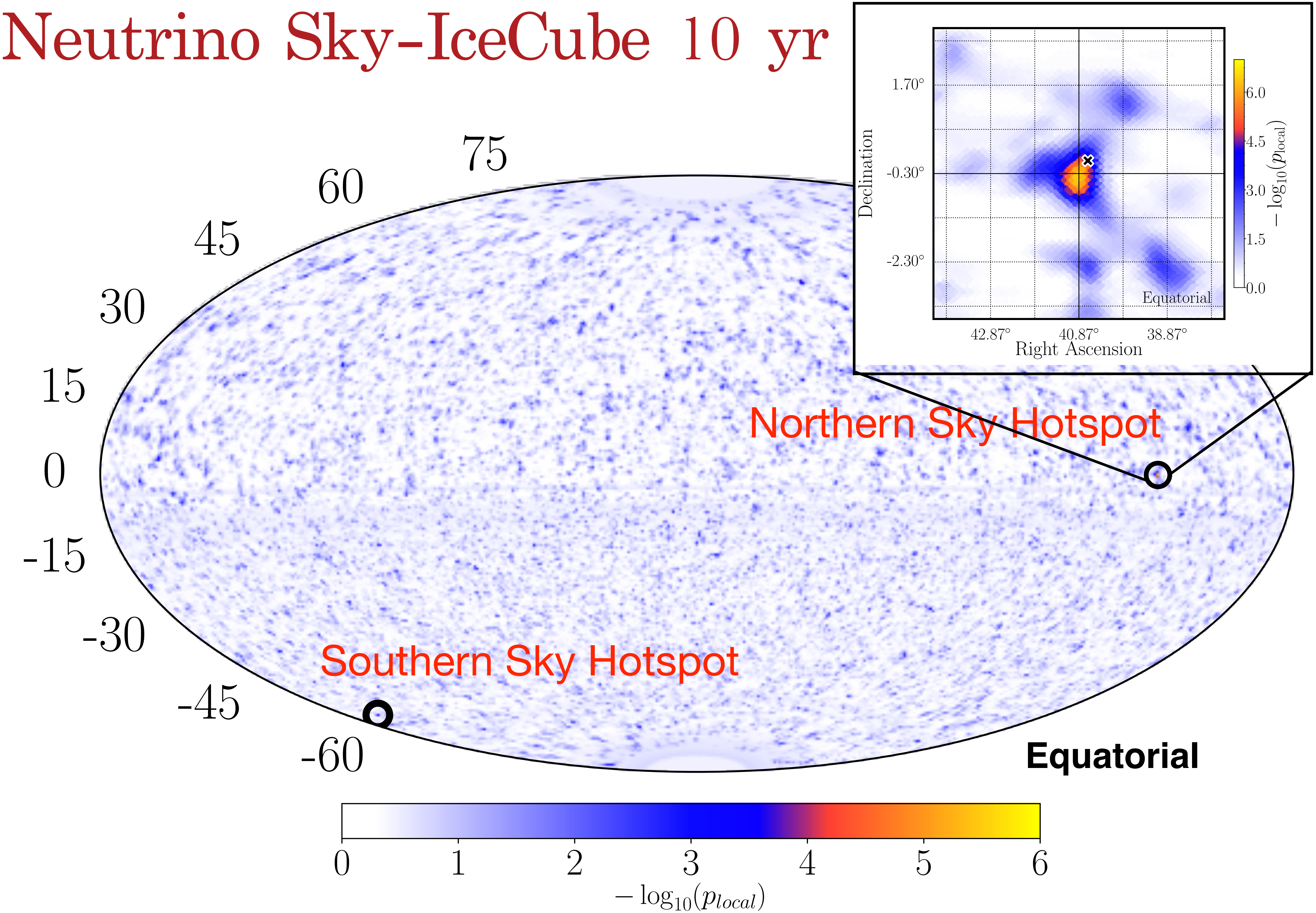

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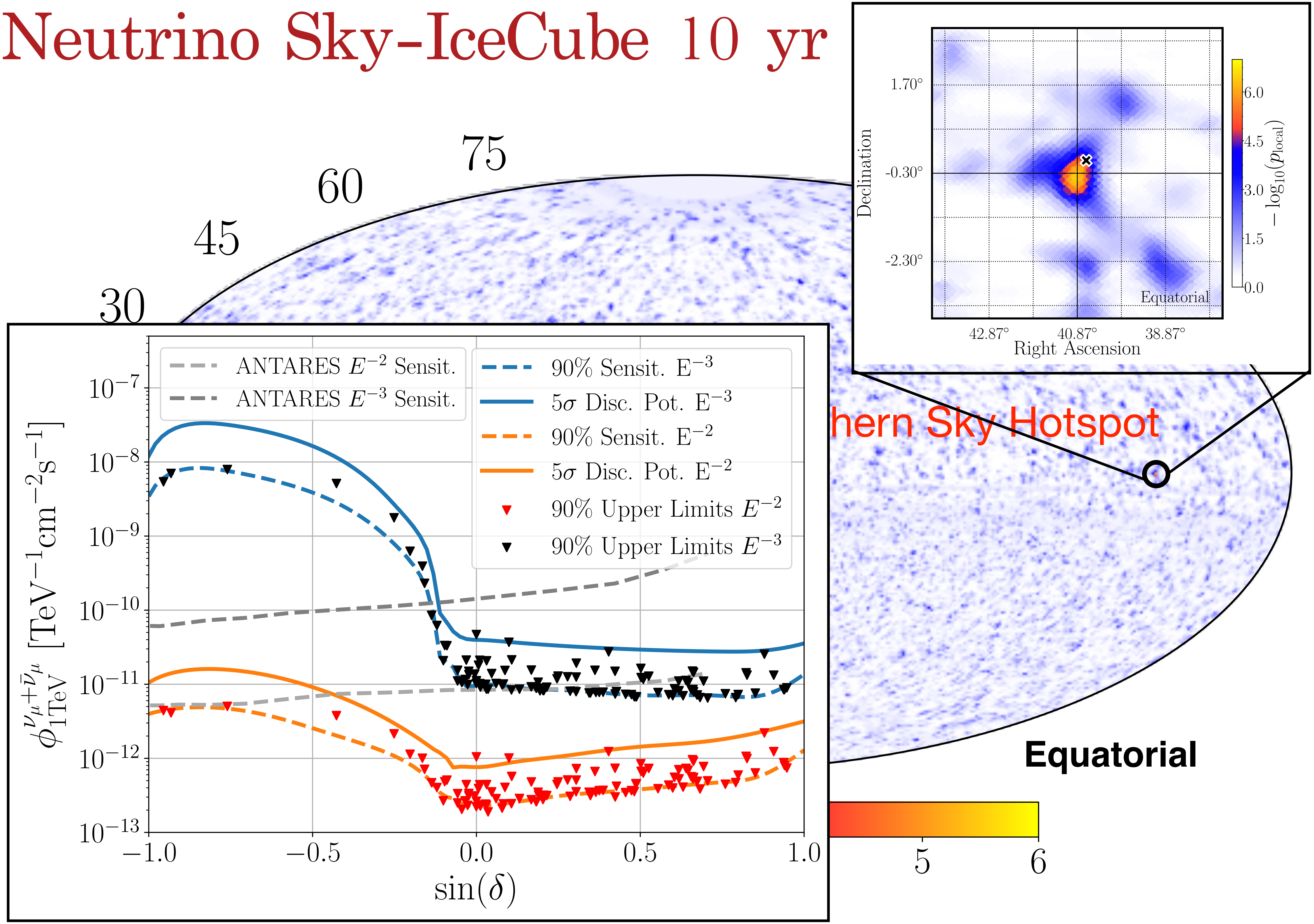

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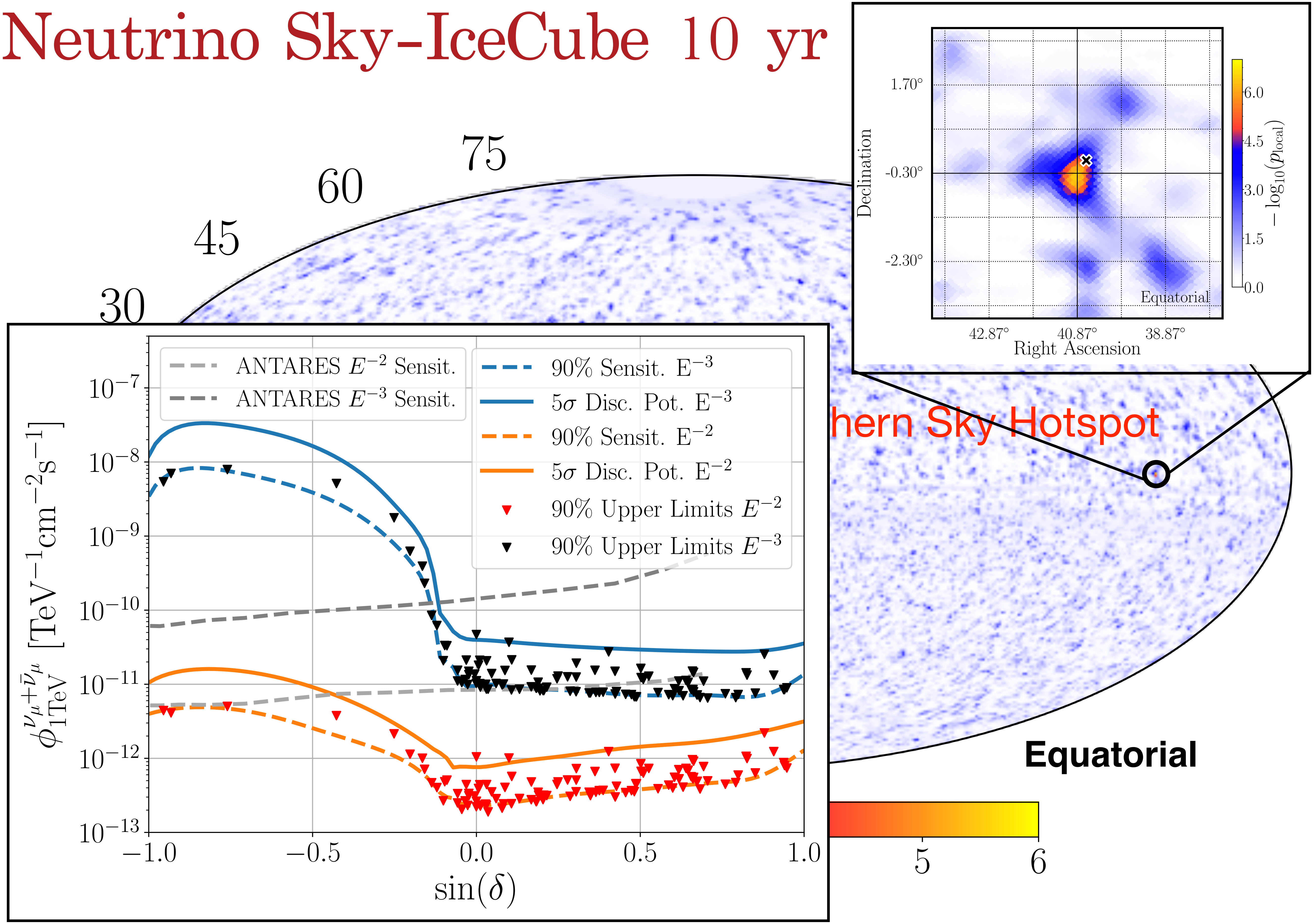

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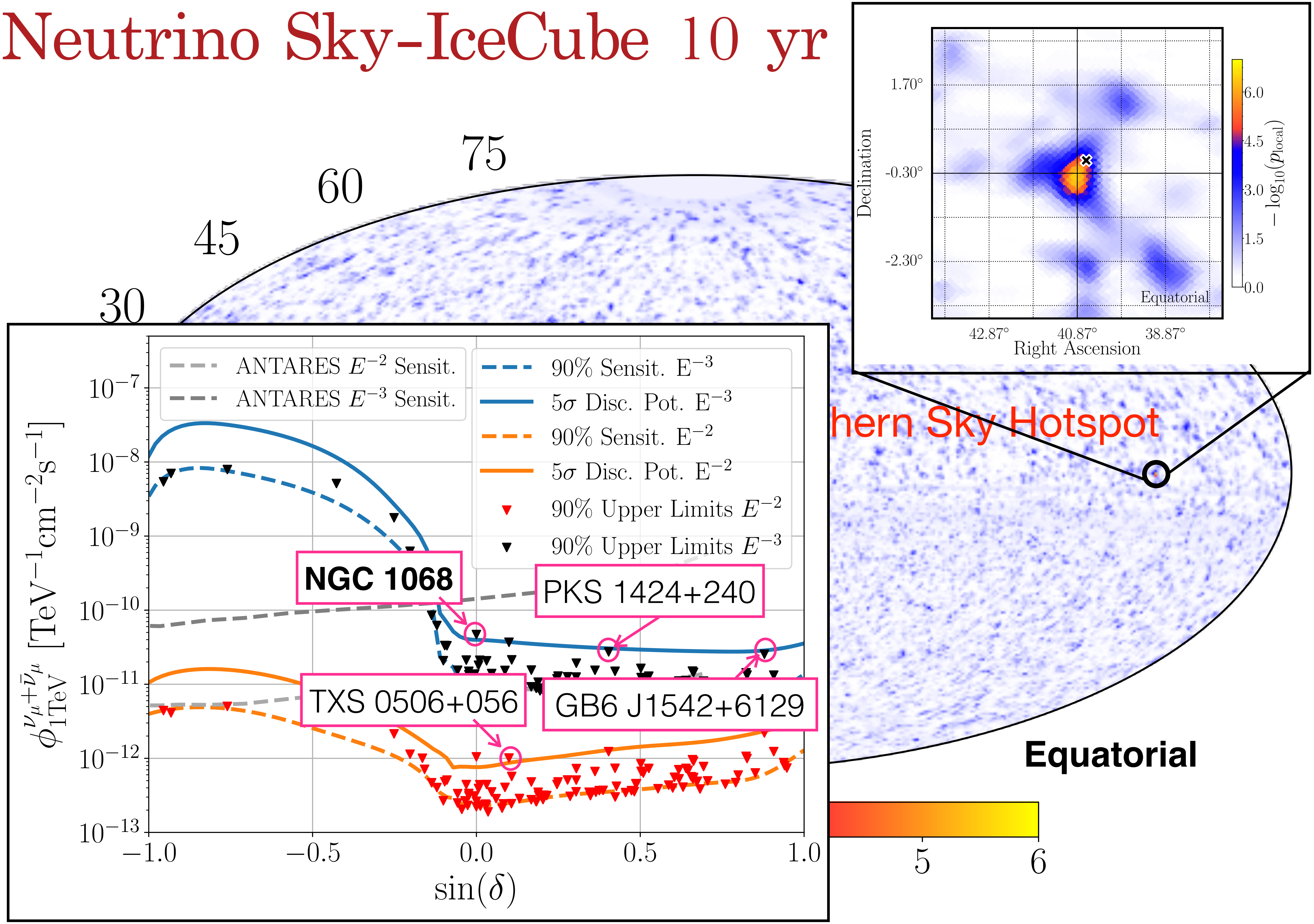
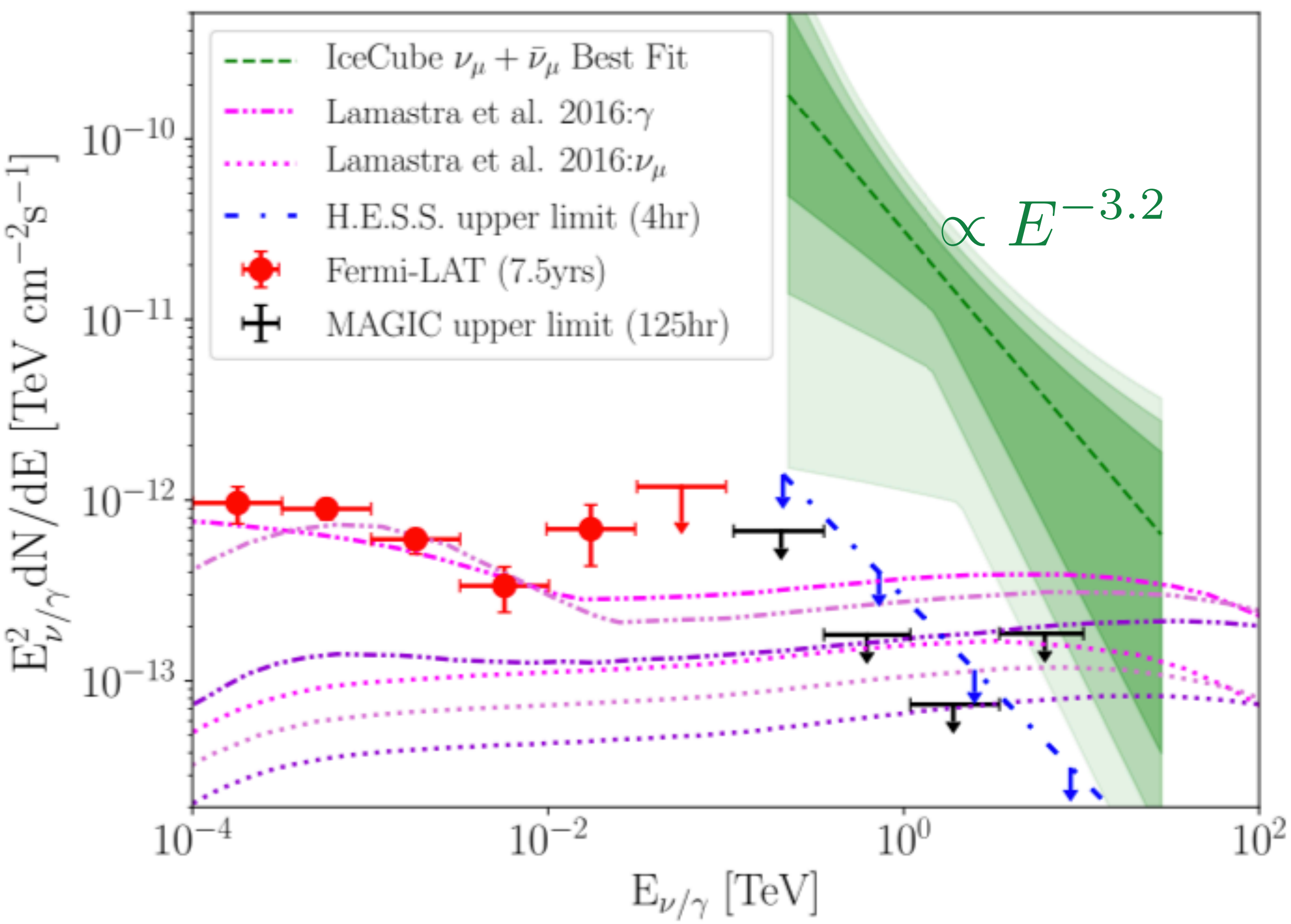
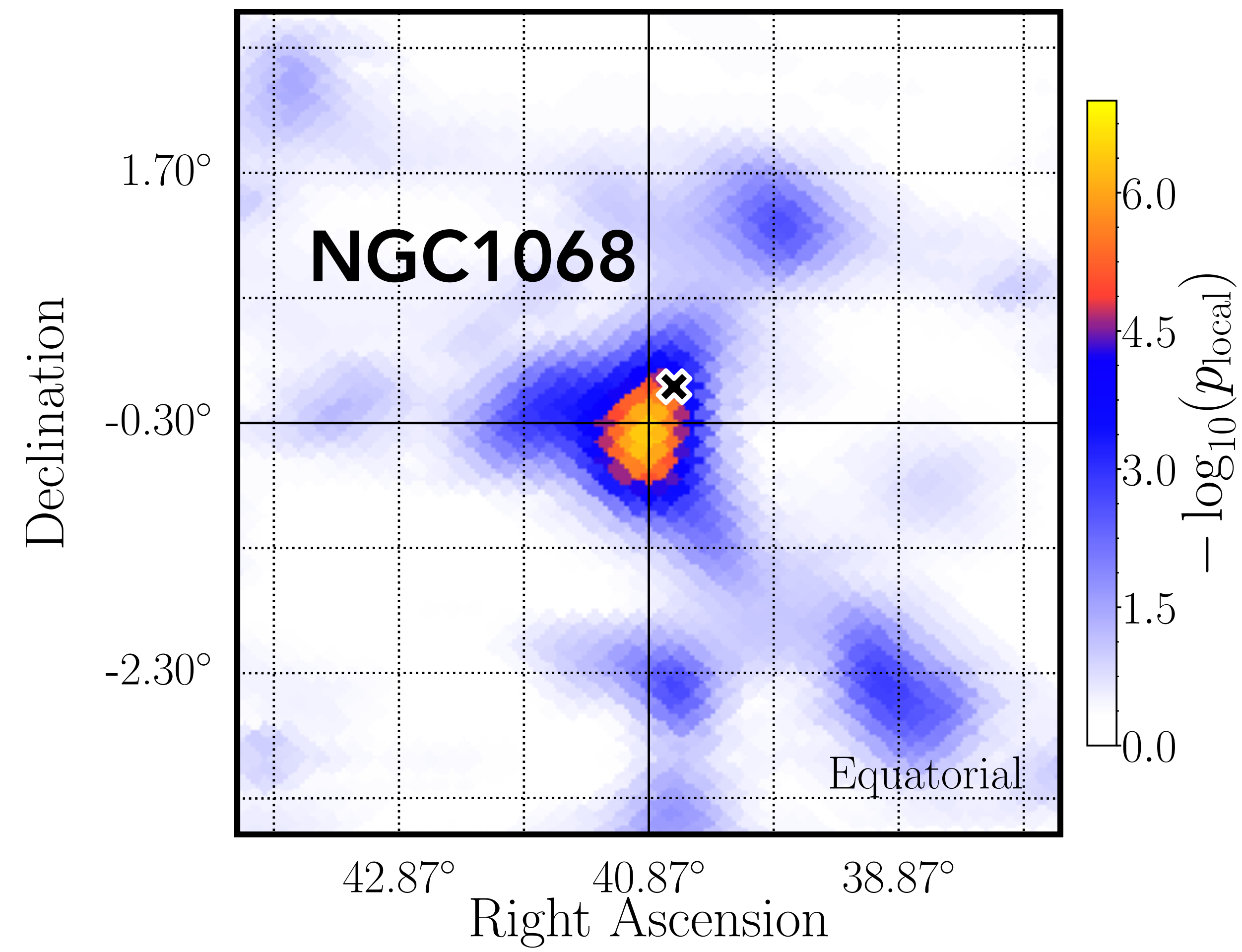


[IceCube, PRL 2020]

NGC 1068





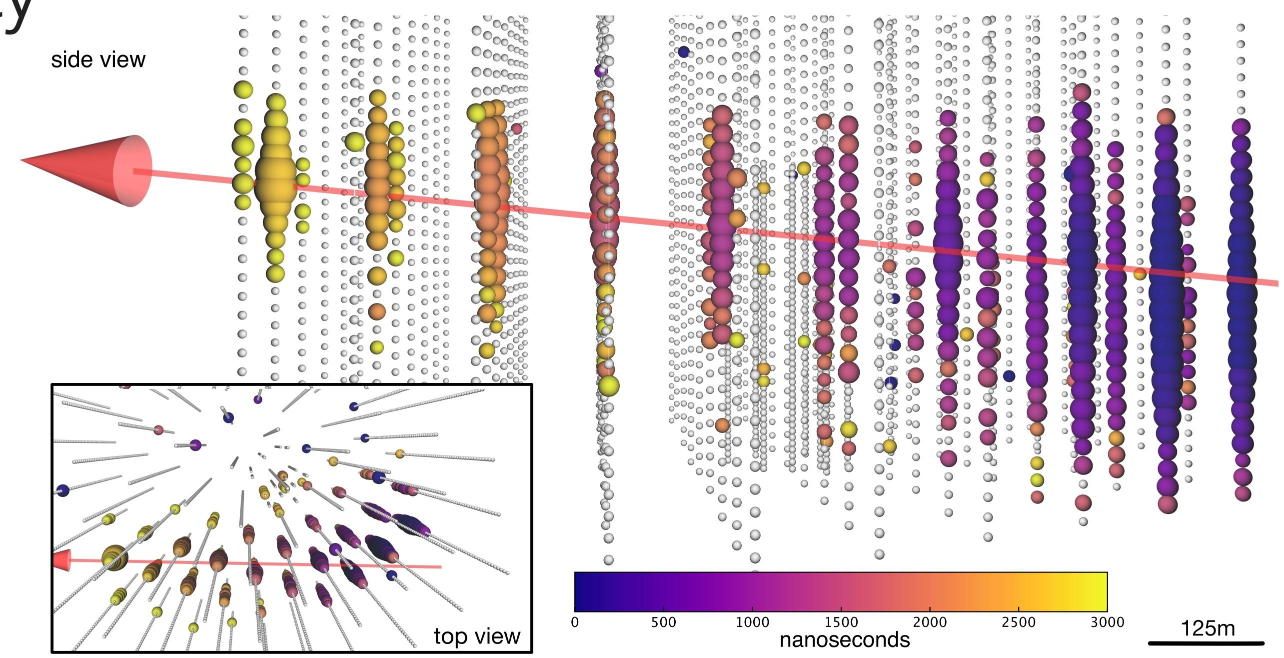
IceCube, PRL2020

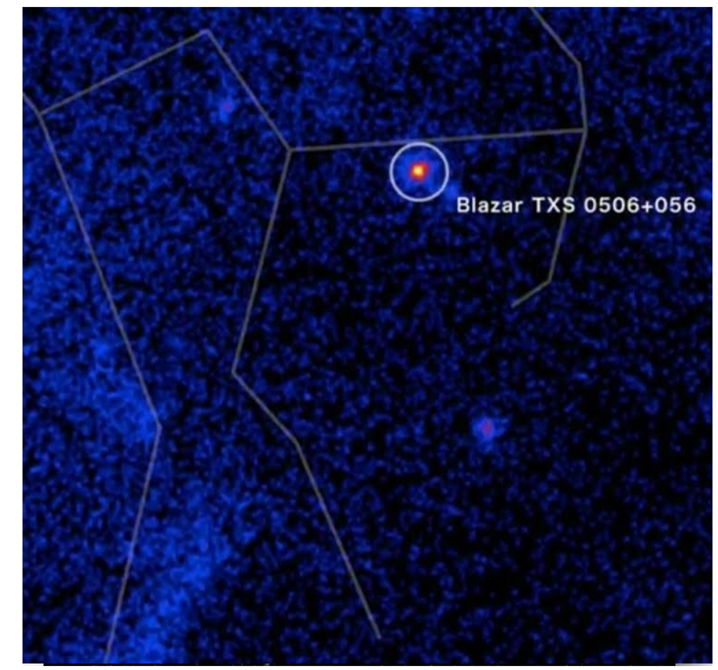
Hottest spot in the all-sky scan coincides with the direction of NGC 1068!
NGC 1068 is the most significant source in IceCube source list with a local pre-trial p-value of 1.8×10^{-5} (2.9σ Post trial).

- 51 signal neutrinos in the direction of NGC 1068, with a soft spectrum.

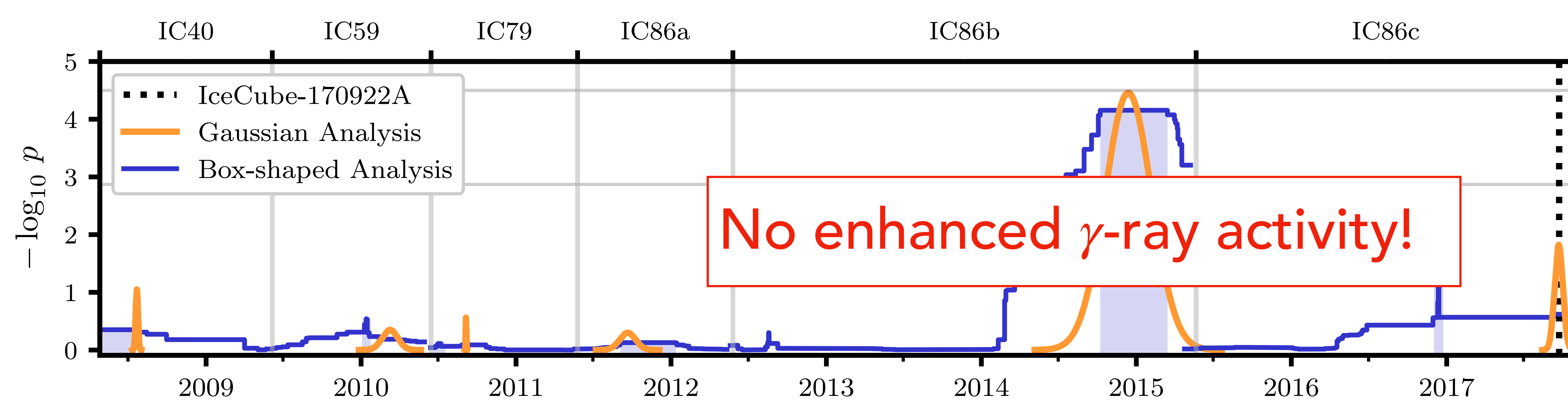
TXS 0506+056

- 290 TeV neutrino in Sep. 2107 found in coincidence with enhanced γ-ray activity



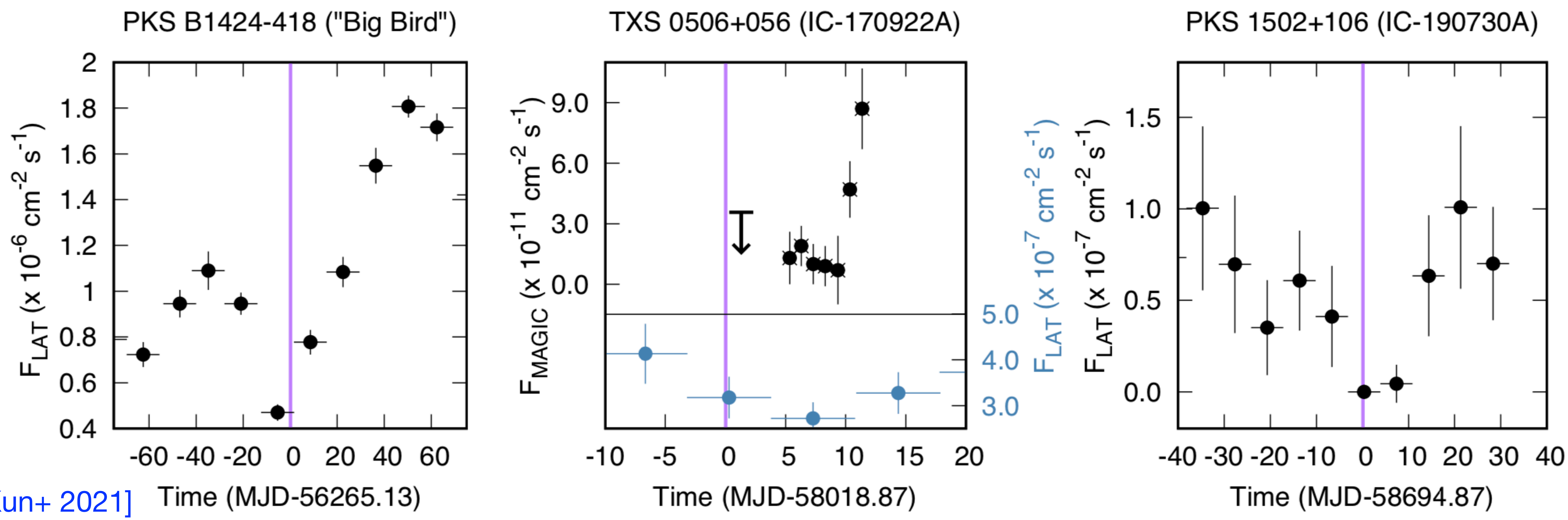


Time-dependent search in the direction of TXS 0506+056 revealed a neutrino flare in December 2014 that dominates neutrino emission in 10 years.



The emerging picture

- The neutrino sky is no longer anisotropic. Early evidences point to AGN as the primary source of high-energy cosmic neutrinos.



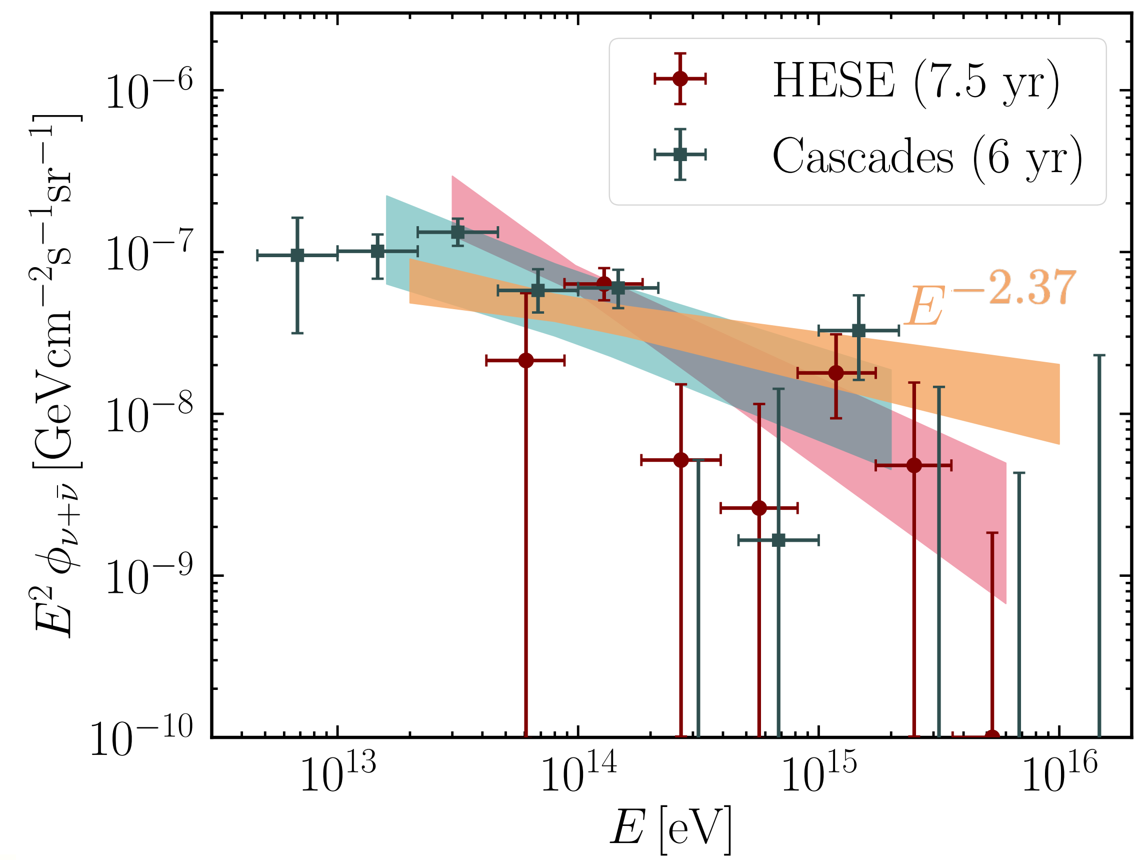
[Kun+ 2021]

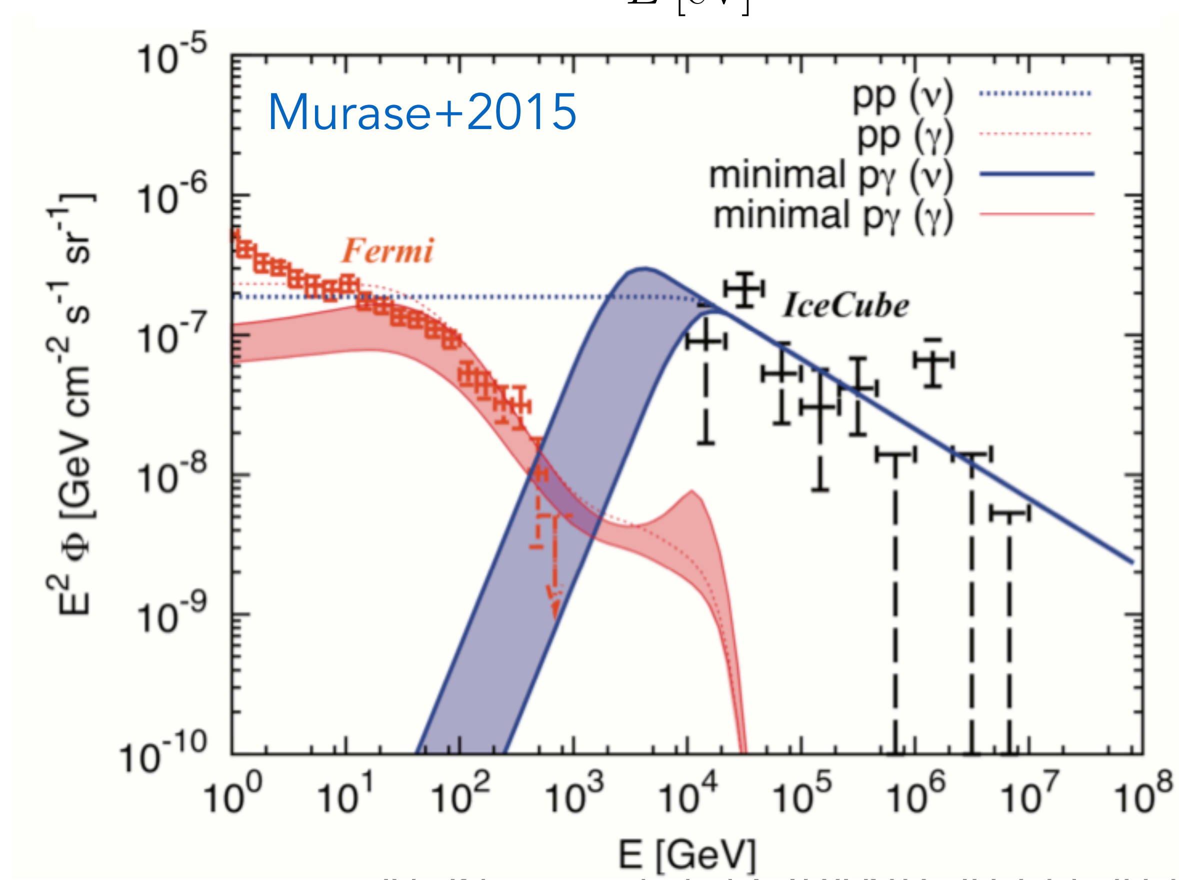
- Sources found to be in quiet mode in γ-rays at the time of a neutrino alert detection.
  - Efficient neutrino emission: dense target
  - Neutrino-gamma ray connection more complicated than anticipated
  - Canonical One zone models cannot explain the multimessneger interface

[Halzen & AK 2020, Fang+ 2022, Murase+ 2019, …]

Medium Energy Flux

- Different slopes hint at structure in the flux of high-energy cosmic neutrinos.
- The magnitude of the flux at ~10 TeV energies is found to be higher than the flux at >100 TeV energies.
- Multimessenger connection dictates extragalactic sources of the high-energy neutrino flux at medium-energies to be "obscured" to GeV γ-rays.





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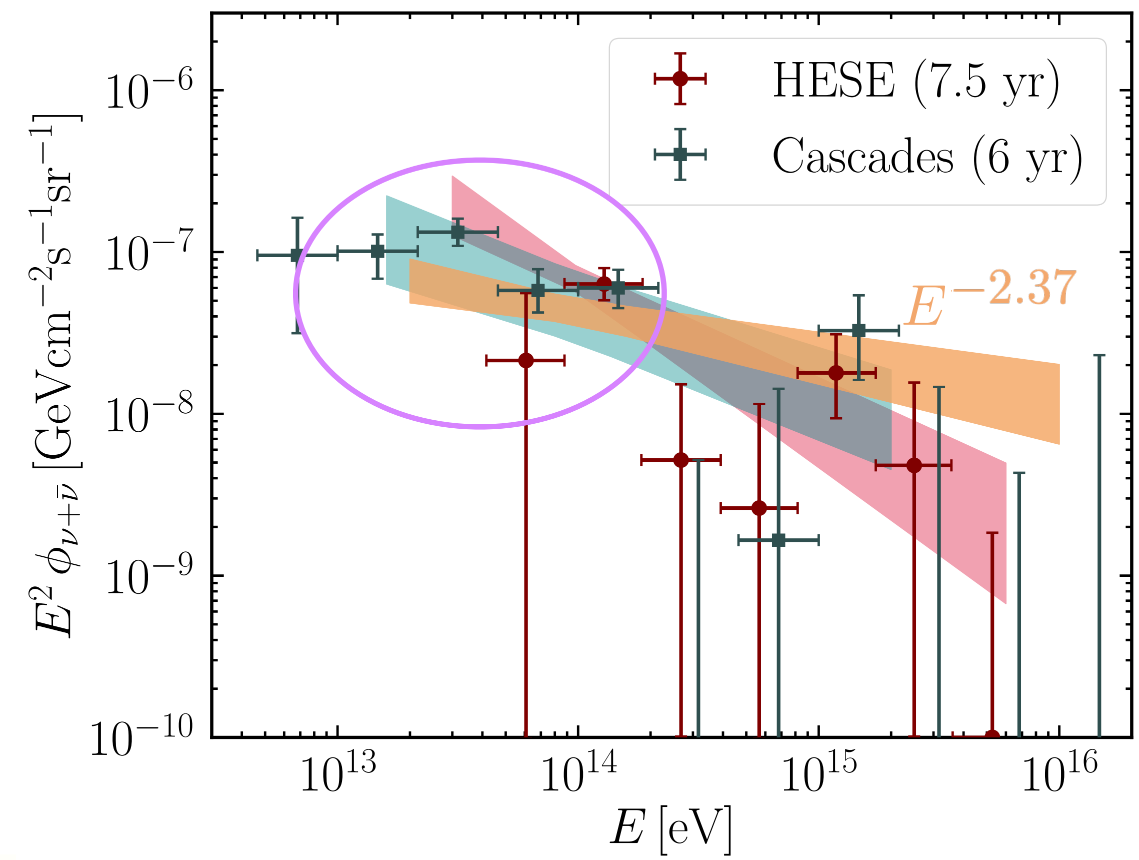
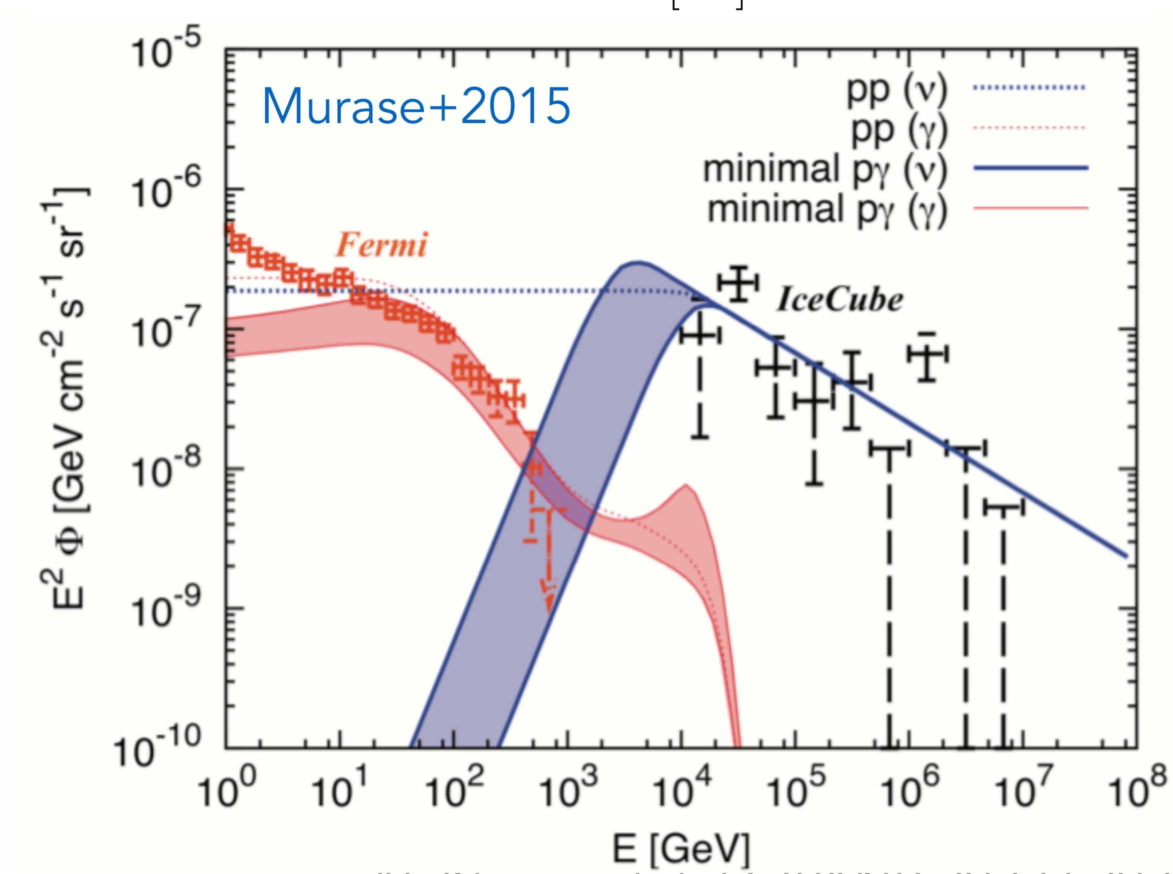
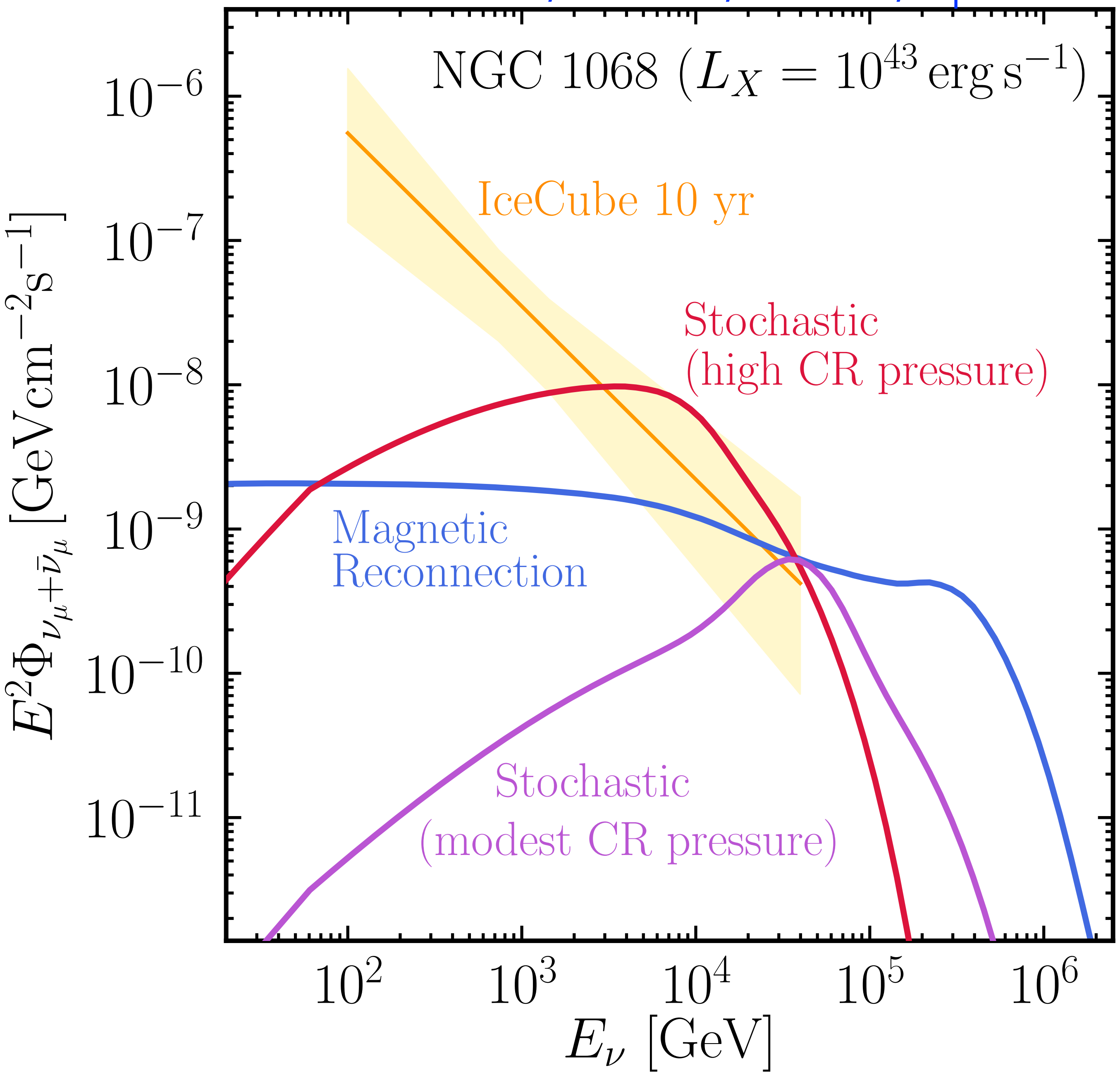




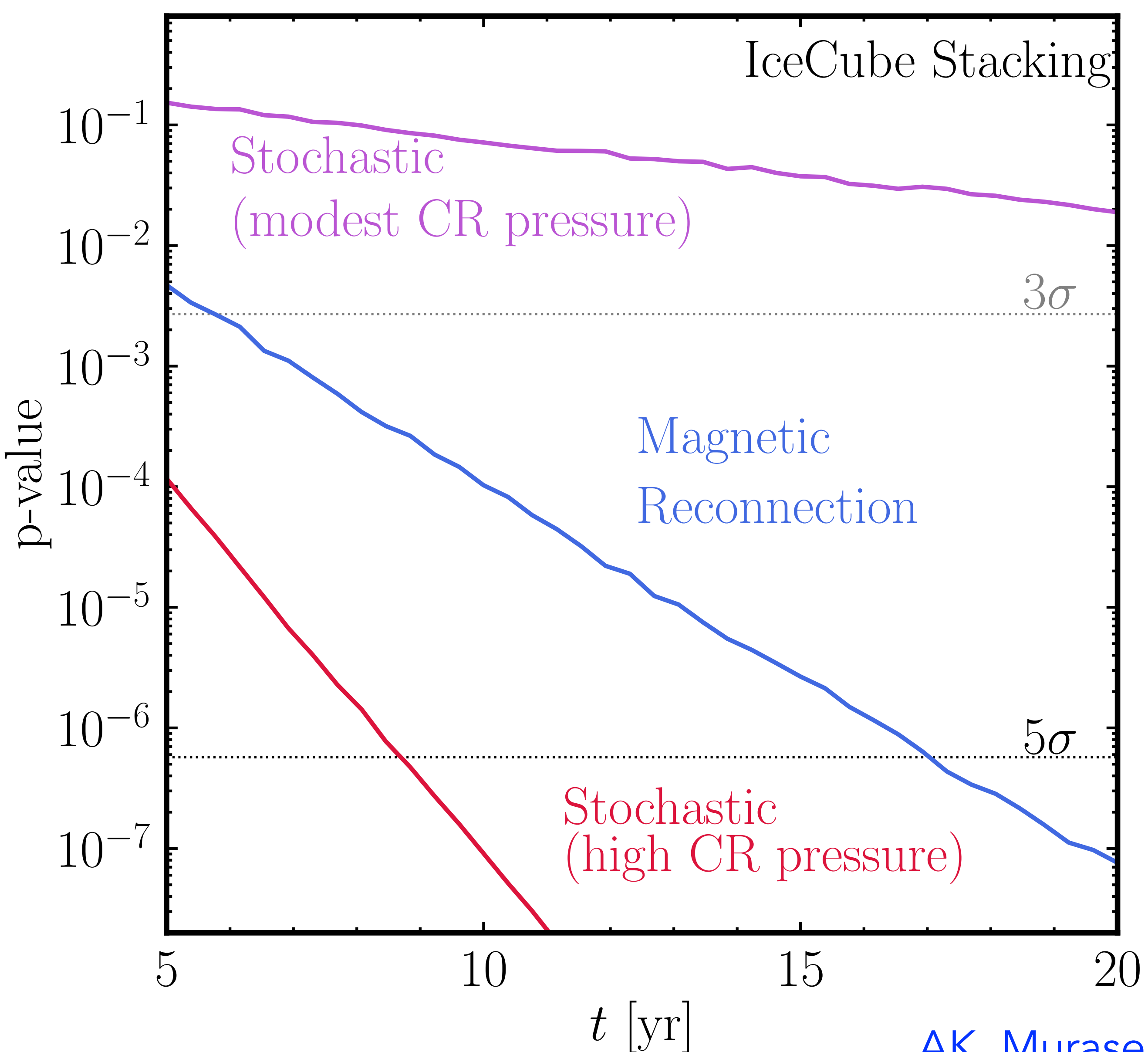
NGC 1068 in AGN-Corona Model

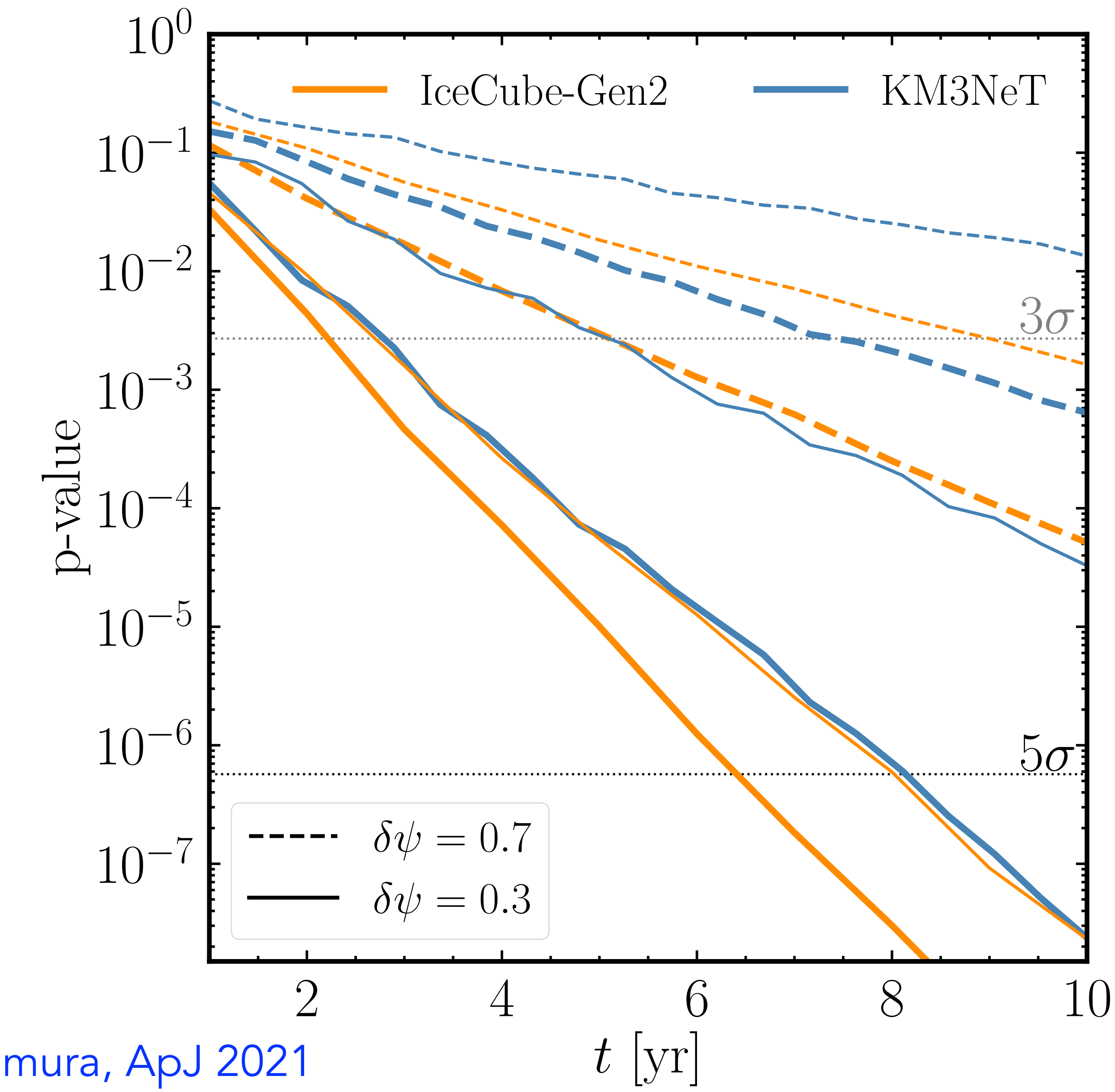
- **Cores** of the AGN, which are optically thick for GeV-TeV γ-rays, are one of the best candidates as the source of the high-energy neutrinos.
- Accretion dynamics and magnetic dissipation will form a magnetized **corona** above the disk.
- The **disk-corona** model HE neutrino emission can successfully accommodate the flux of neutrinos at ME in the 10-100 TeV range. [Murase+, PRL 2020]

AK, Murase, Kimura, ApJ 2021



Bright Seyfert Galaxies: Prospects

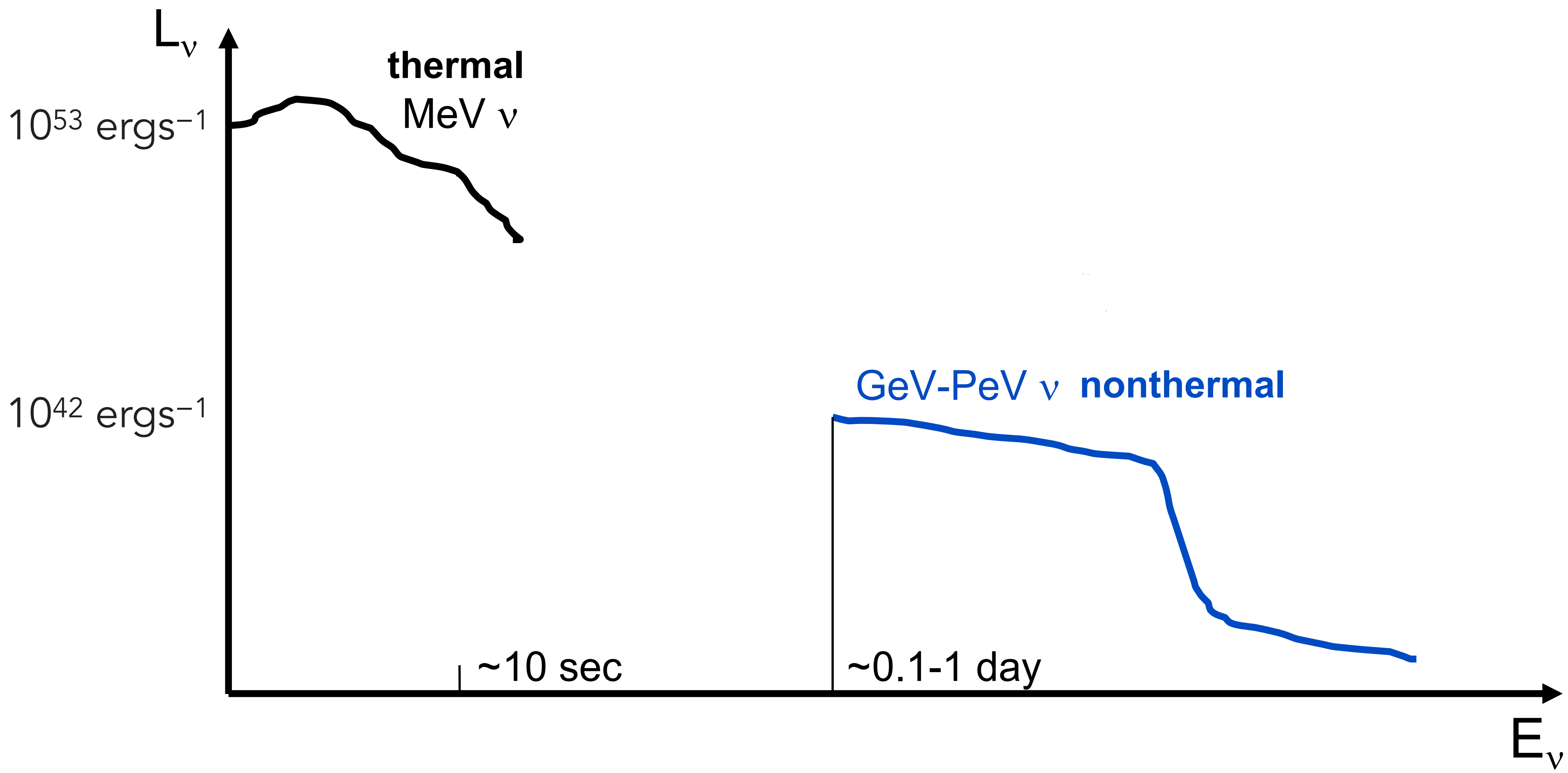




AK, Murase, Kimura, ApJ 2021

- The optimum scenarios for neutrino emission from bright seyferts, consistent with NGC 1068, should be seen with addition of data in IceCube.
- Neutrinos from bright Seyfert galaxies could be confirmed with operation of next generation of neutrino telescopes.

Neutrinos from Core Collapse Supernovae



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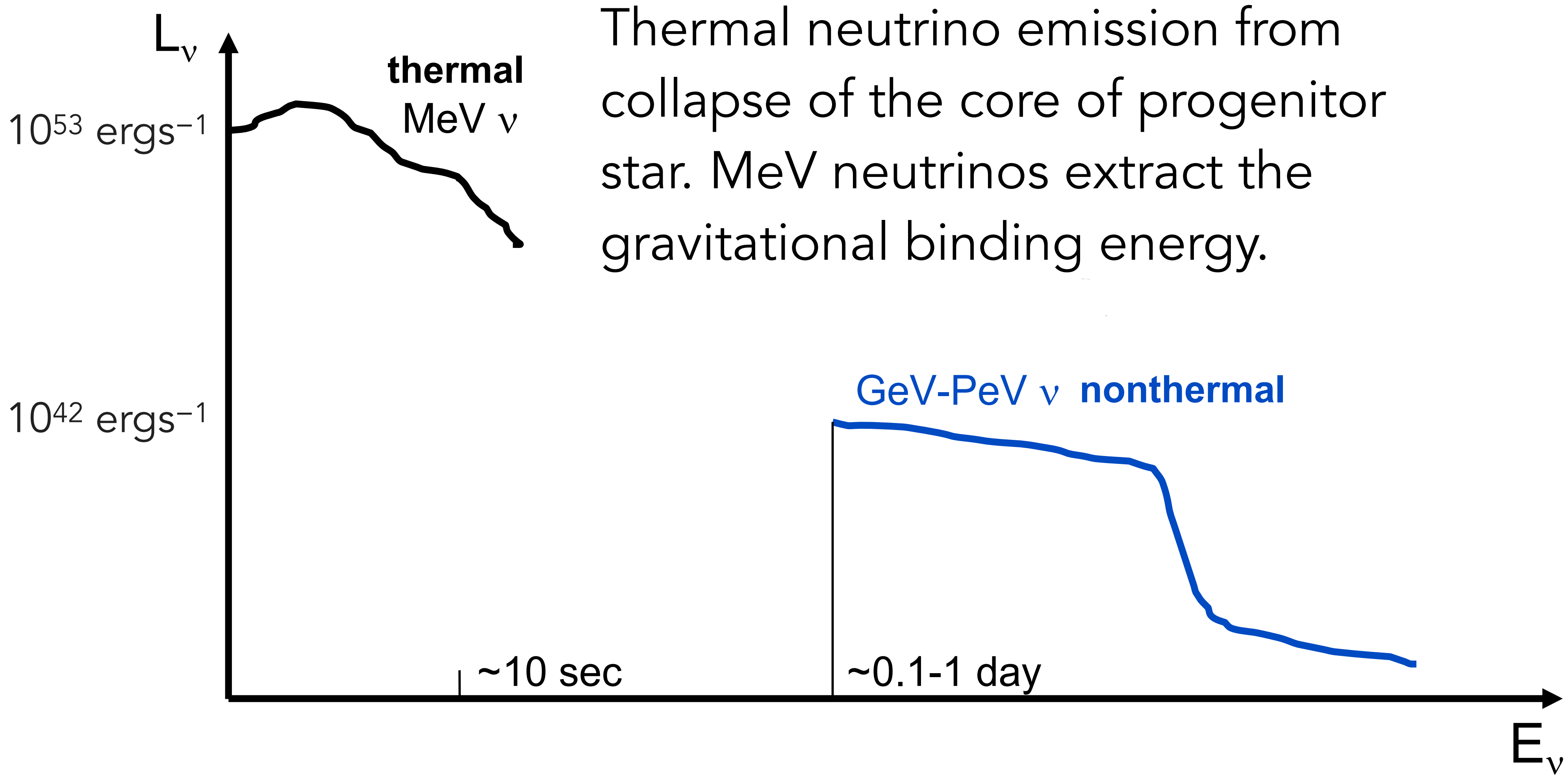
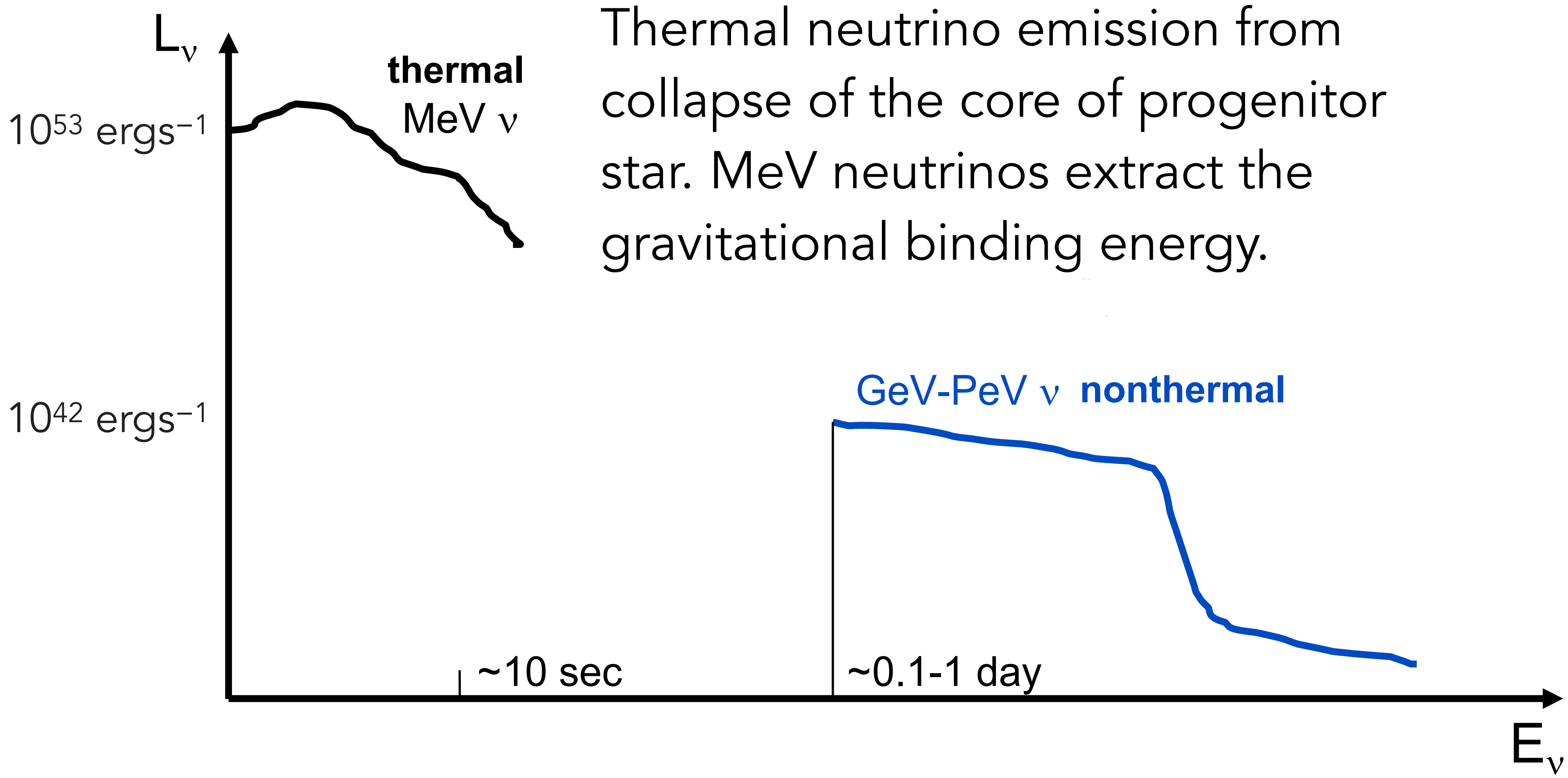


Thermal neutrino emission from collapse of the core of progenitor star. MeV neutrinos extract the gravitational binding energy.

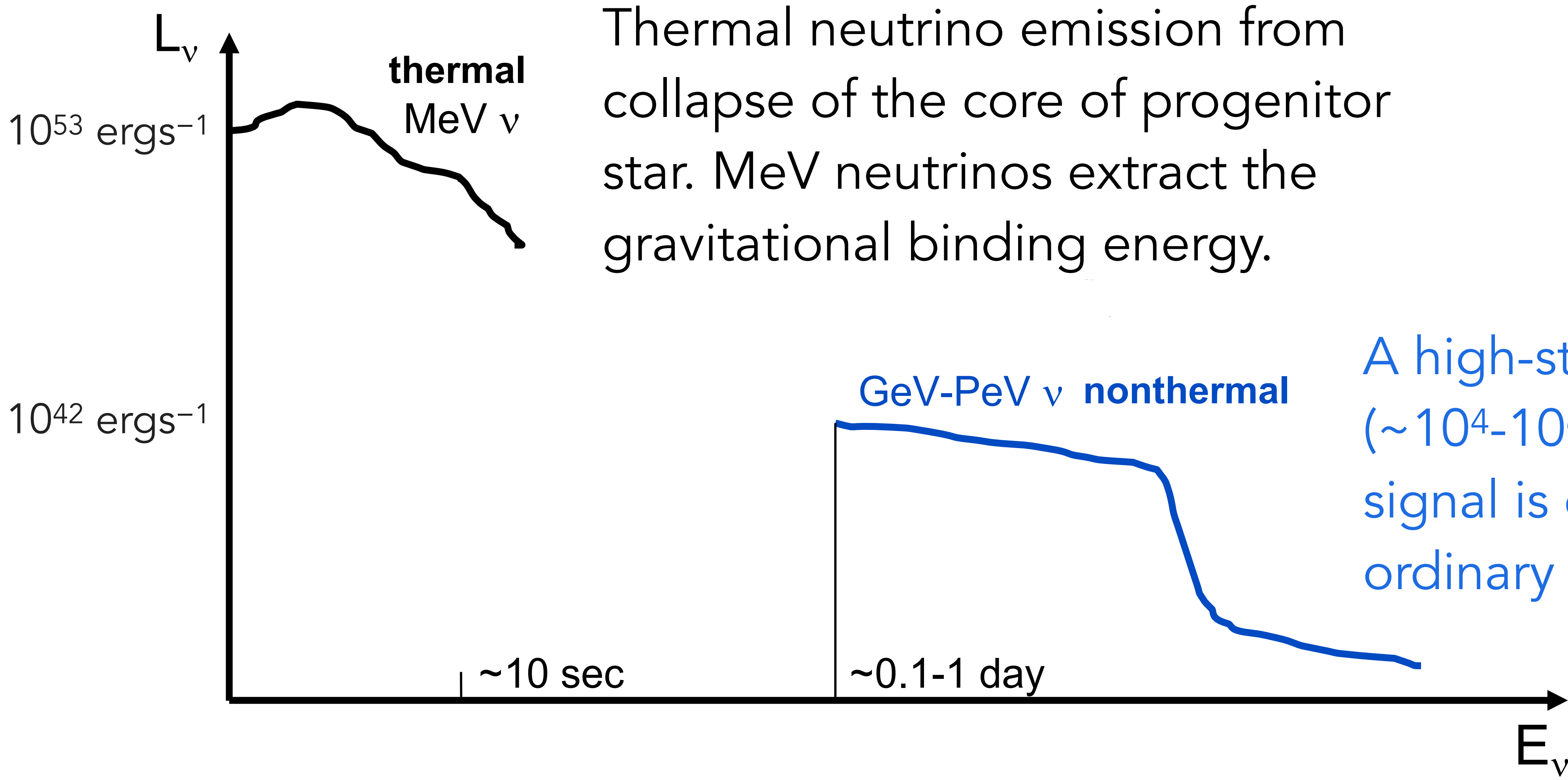
Neutrinos from Core Collapse Supernovae



Thermal neutrino emission from collapse of the core of progenitor star. MeV neutrinos extract the gravitational binding energy.

- Observation of extragalactic SNe showed **rapid significant mass loss** in SN progenitor which leads to shock **interaction with dense circumstellar material (CSM)**.
    - Shock interaction with CSM results in production of HE neutrinos!

Neutrinos from Core Collapse Supernovae

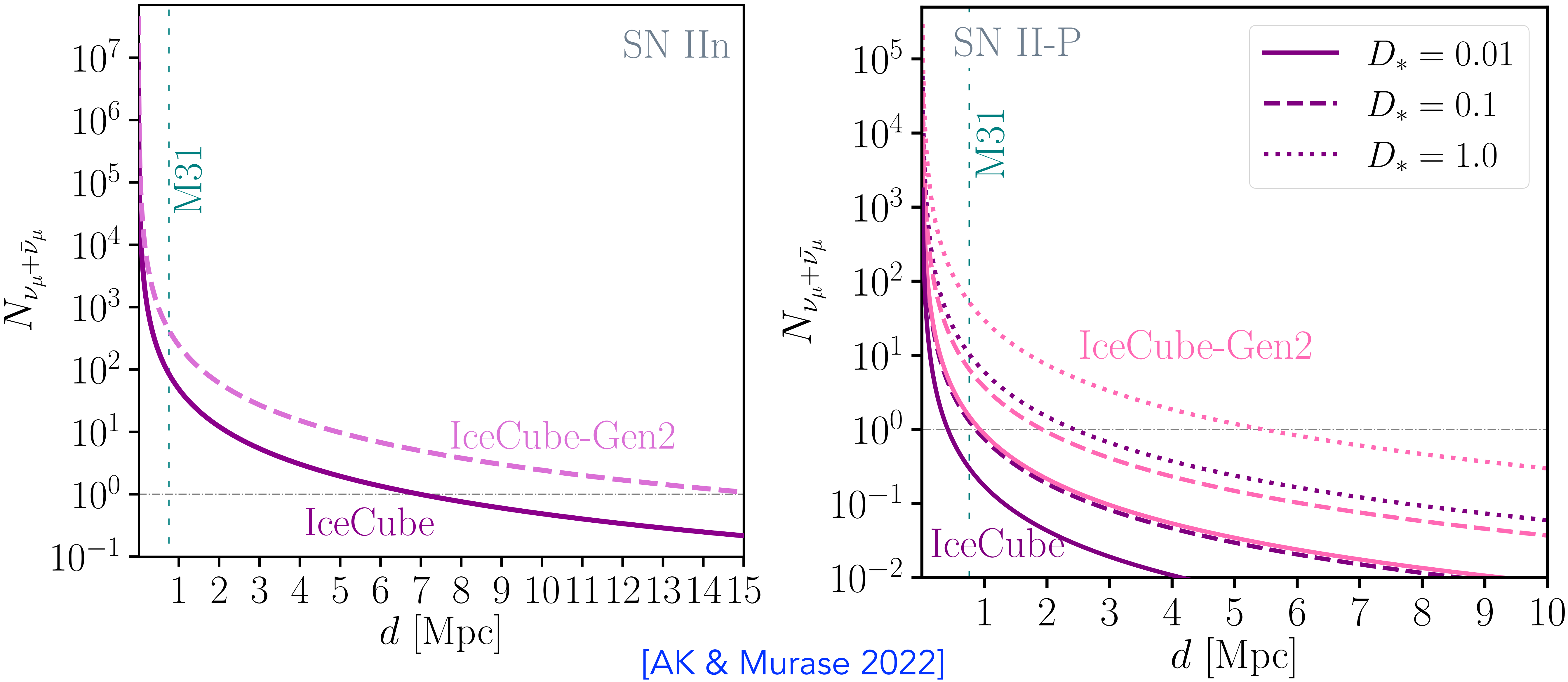


Thermal neutrino emission from collapse of the core of progenitor star. MeV neutrinos extract the gravitational binding energy.

A high-statistics (~10^4-10^6) TeV neutrino signal is expected for an ordinary Galactic SN.

- Observation of extragalactic SNe showed **rapid significant mass loss** in SN progenitor which leads to shock **interaction with dense circumstellar material (CSM)**.
  - Shock interaction with CSM results in production of HE neutrinos!

HE Neutrino Emission from CCSNe



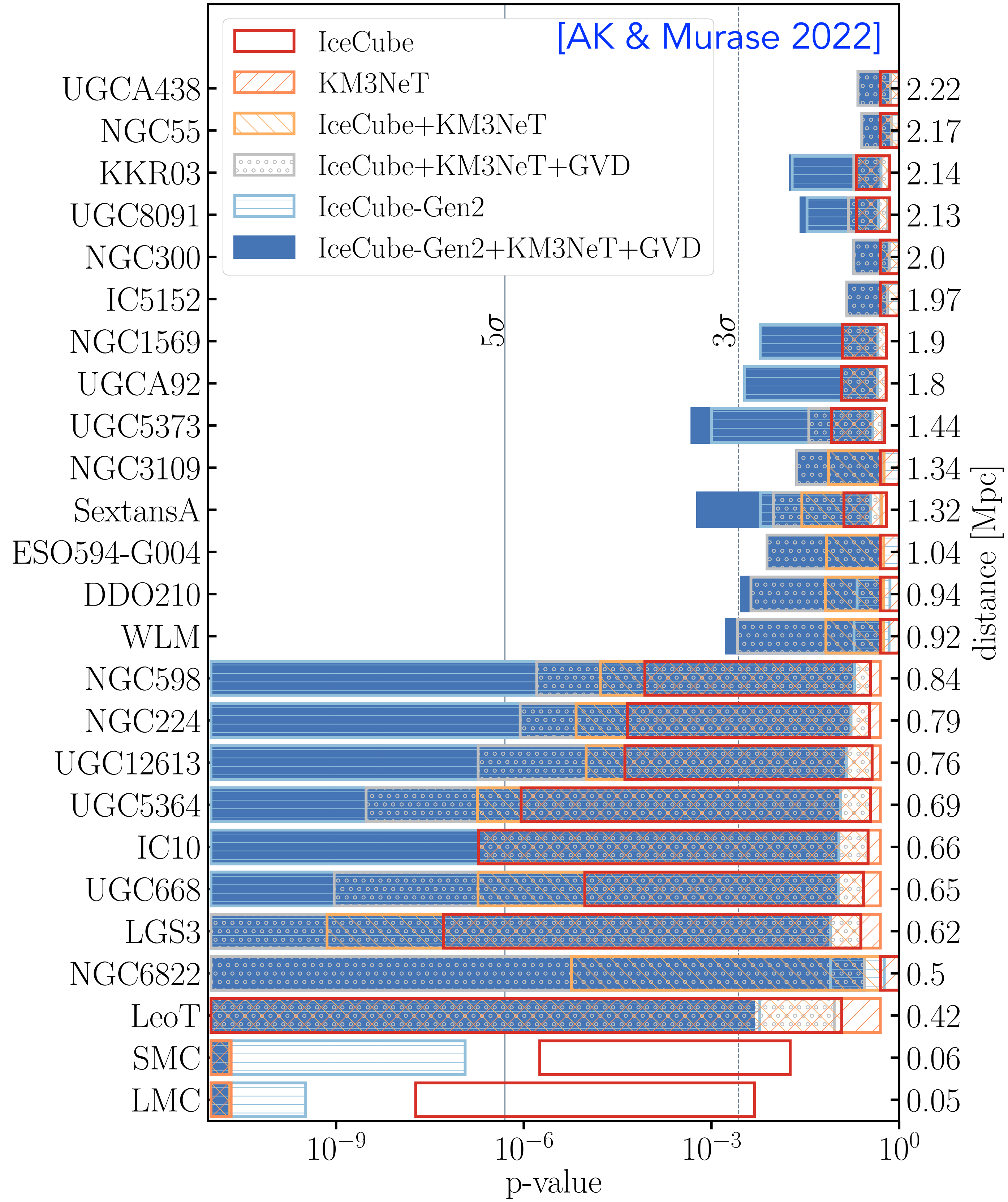
[AK & Murase 2022]

- Occurrence of SNe inside Milky Way would overwhelm neutrino telescopes with > 10^7 neutrinos within a year.
- The horizon for observation of neutrinos from SNe extends beyond our Galaxy.

HE Neutrino emission from SN II-P

Local Galaxies

- HE neutrinos from close by sources (e.g. LMC & SMC) can be identified in current detectors.
- Joint analysis of data from upcoming neutrino telescopes in the Northern hemisphere will boost the sensitivity.
- Next generation of neutrino telescopes will push the horizon for identification of HE neutrinos from SN II-P to more than 2 Mpc.



Cosmic Neutrinos as Probes of New Physics

Symmetry Magazine

New Physics Search with HE Neutrinos

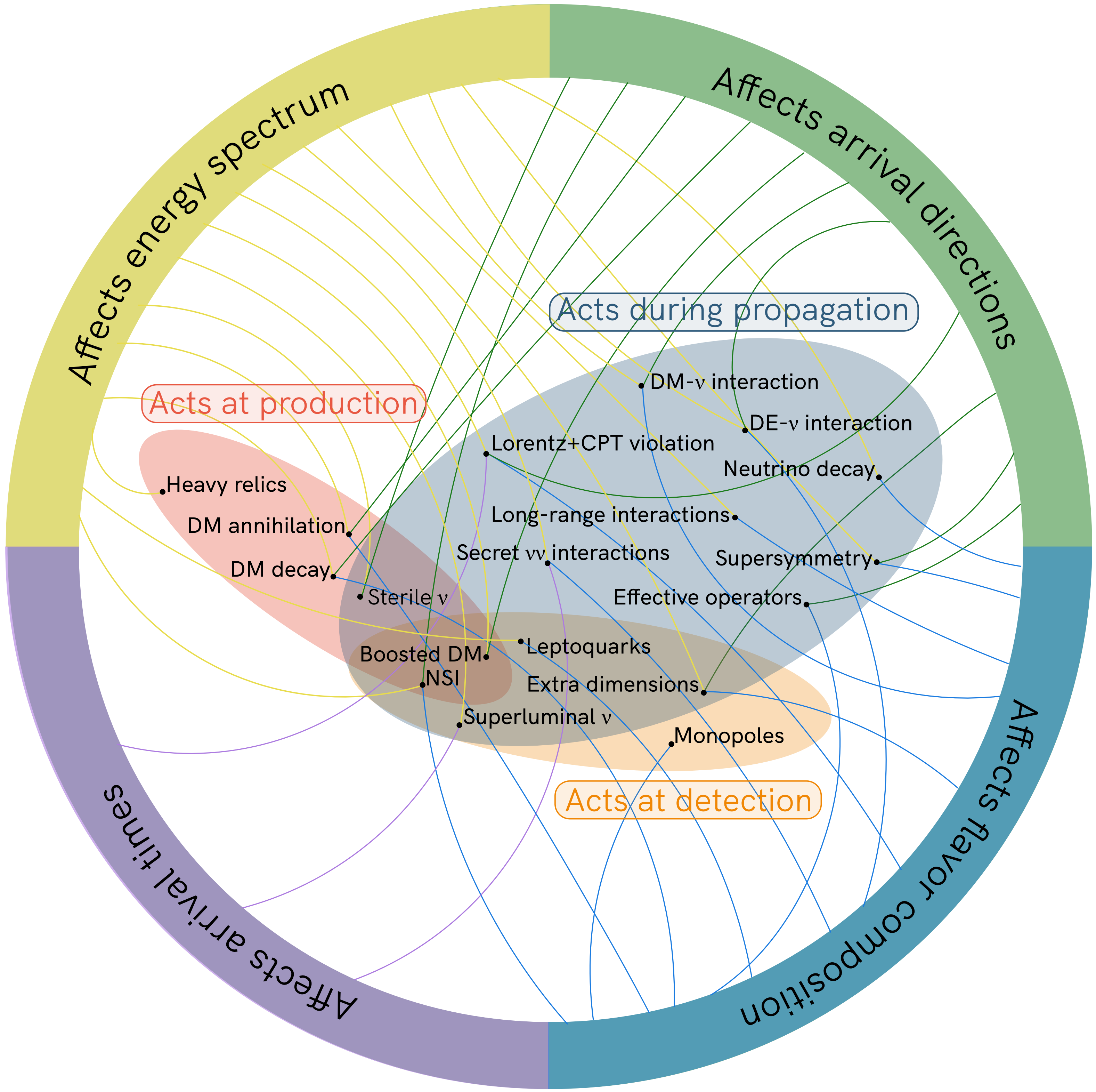
1. They have the highest energies (TeV-10s of PeV)
   ⇝ Probe physics at new energy scales

2. They have long baseline (diameter of the Eath-~Gpc)
   ⇝ Tiny effects can accumulate and become observable

3. They are weakly interacting & have unique quantum number (flavor)
   ⇝ Powerful tool to probe for new effects

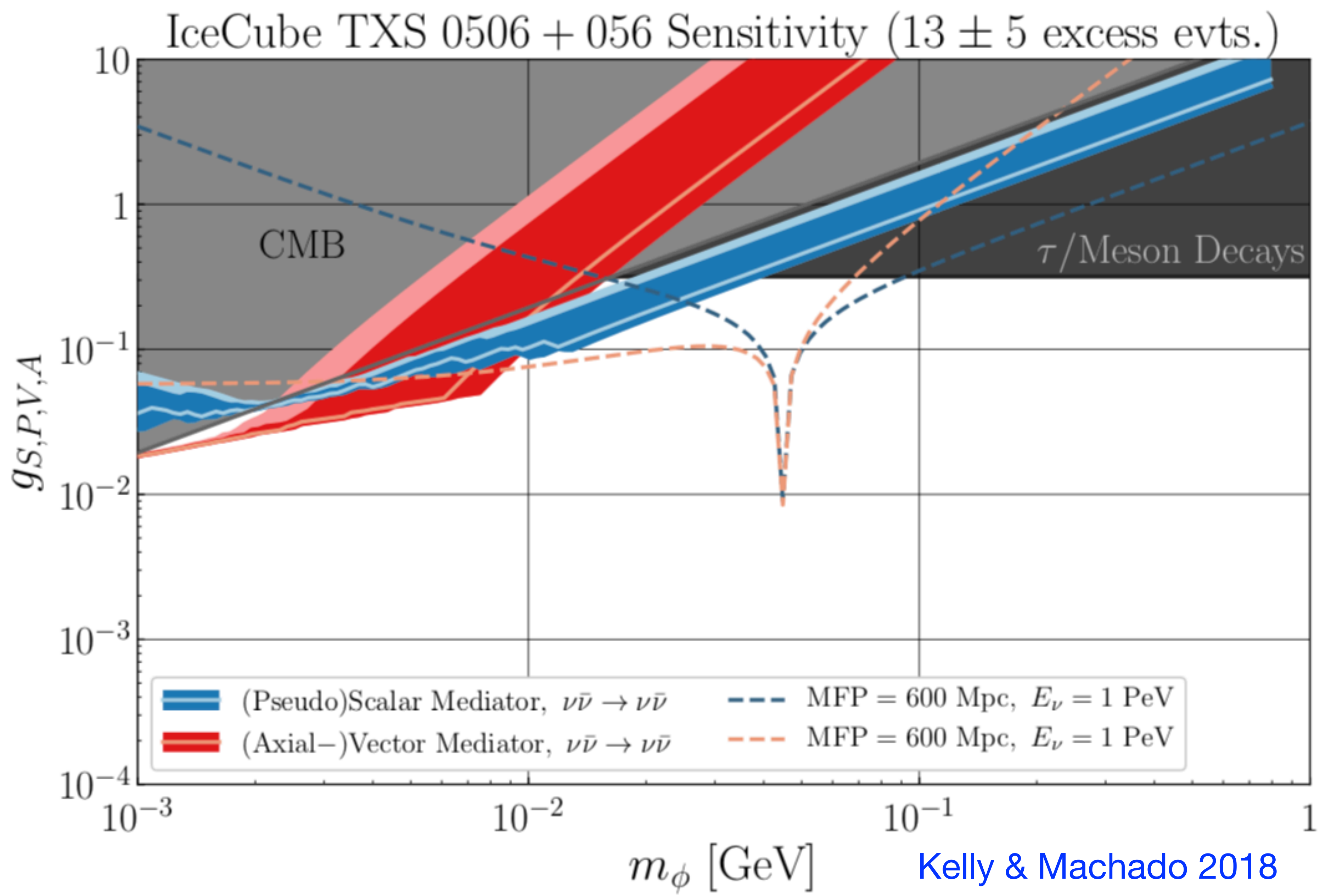
Understanding the origin of HE neutrinos offers unique opportunities to probe for new physics!

New Physics Search



Argüelles, Bustamante, **AK,** Palomares-Ruis, Vincent, 2019

Non-Standard Neutrino Interactions

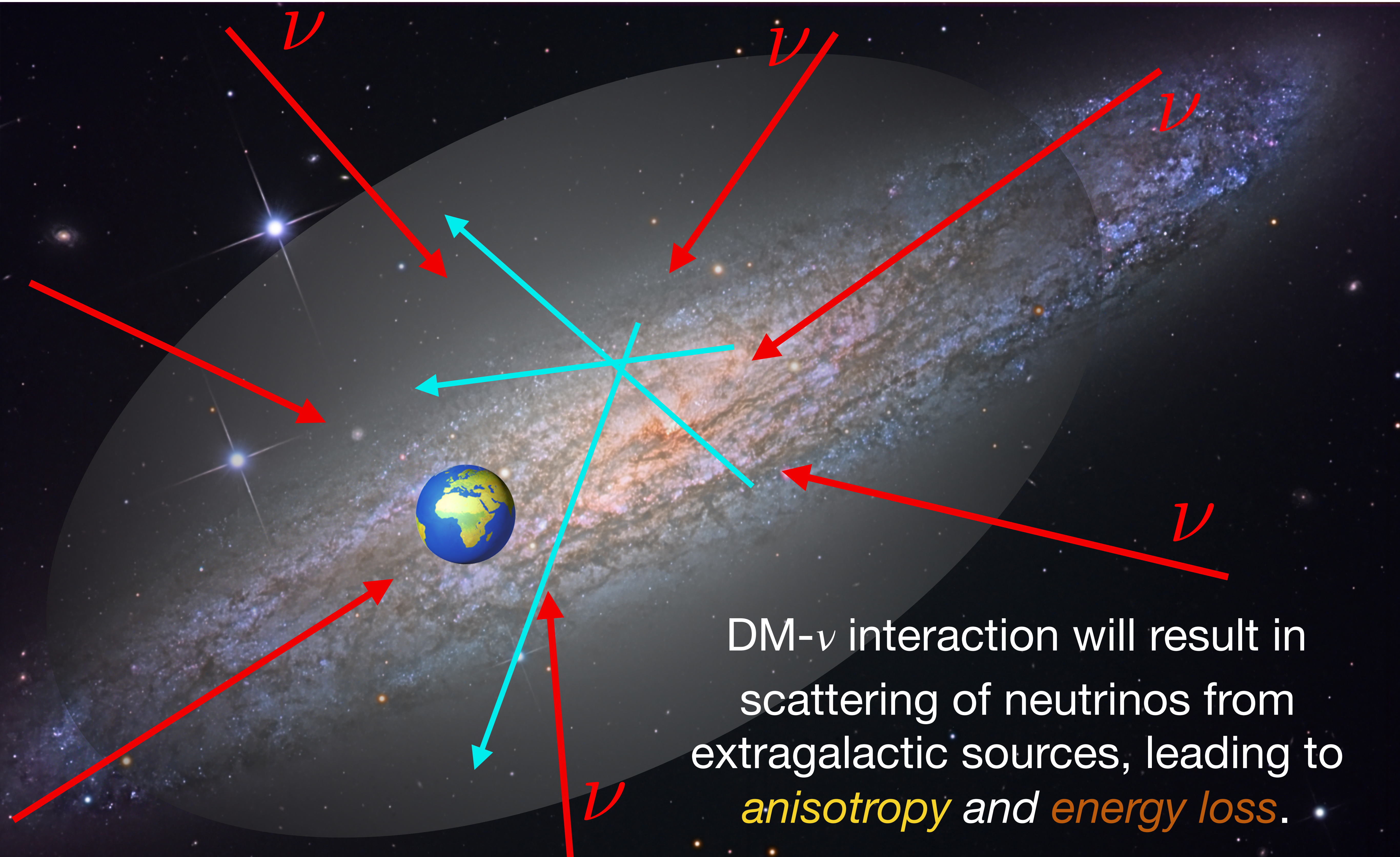


Kelly & Machado 2018

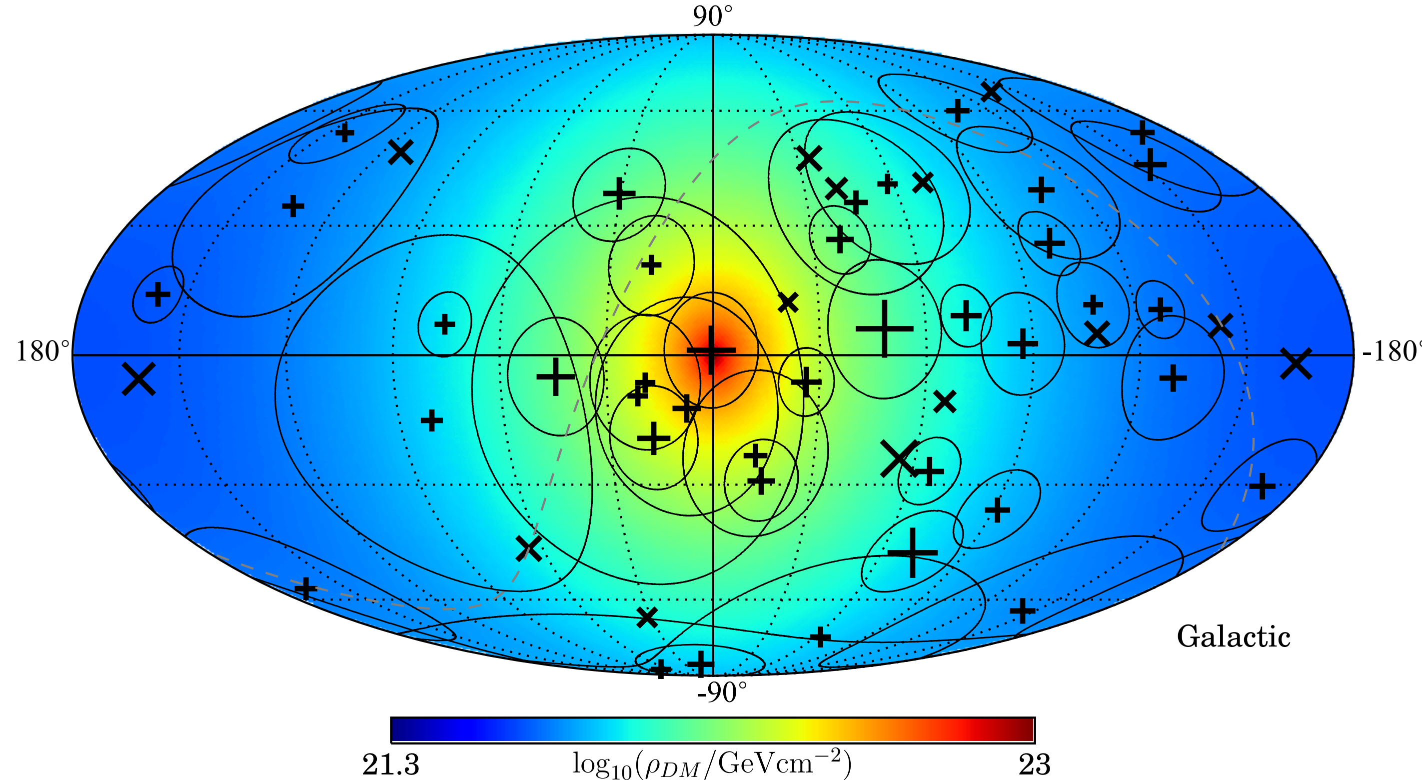
Multimessenger observations imply the neutrino mean free path > 1.3 Gpc.

! Limits depend on source models

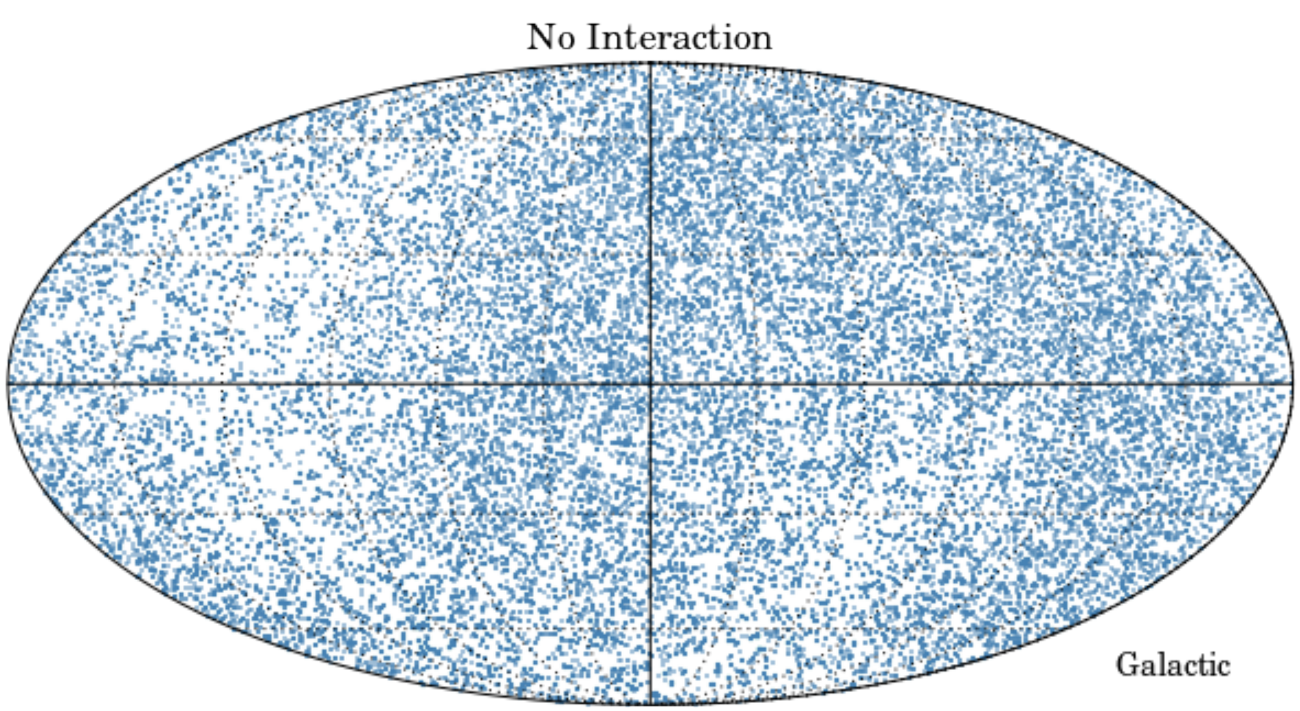
Dark Matter-Nu Interaction

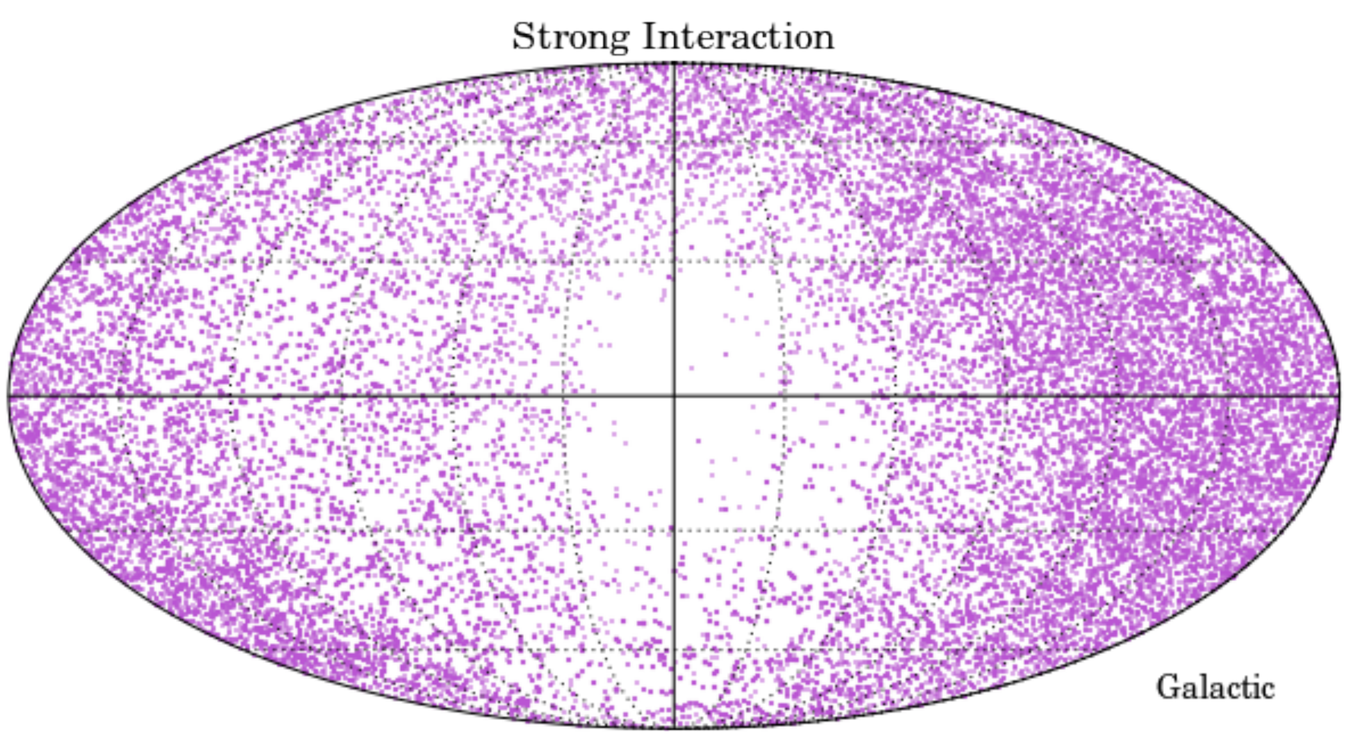


Dark matter column density* seen from Earth



Simulation including effects of detector, Earth

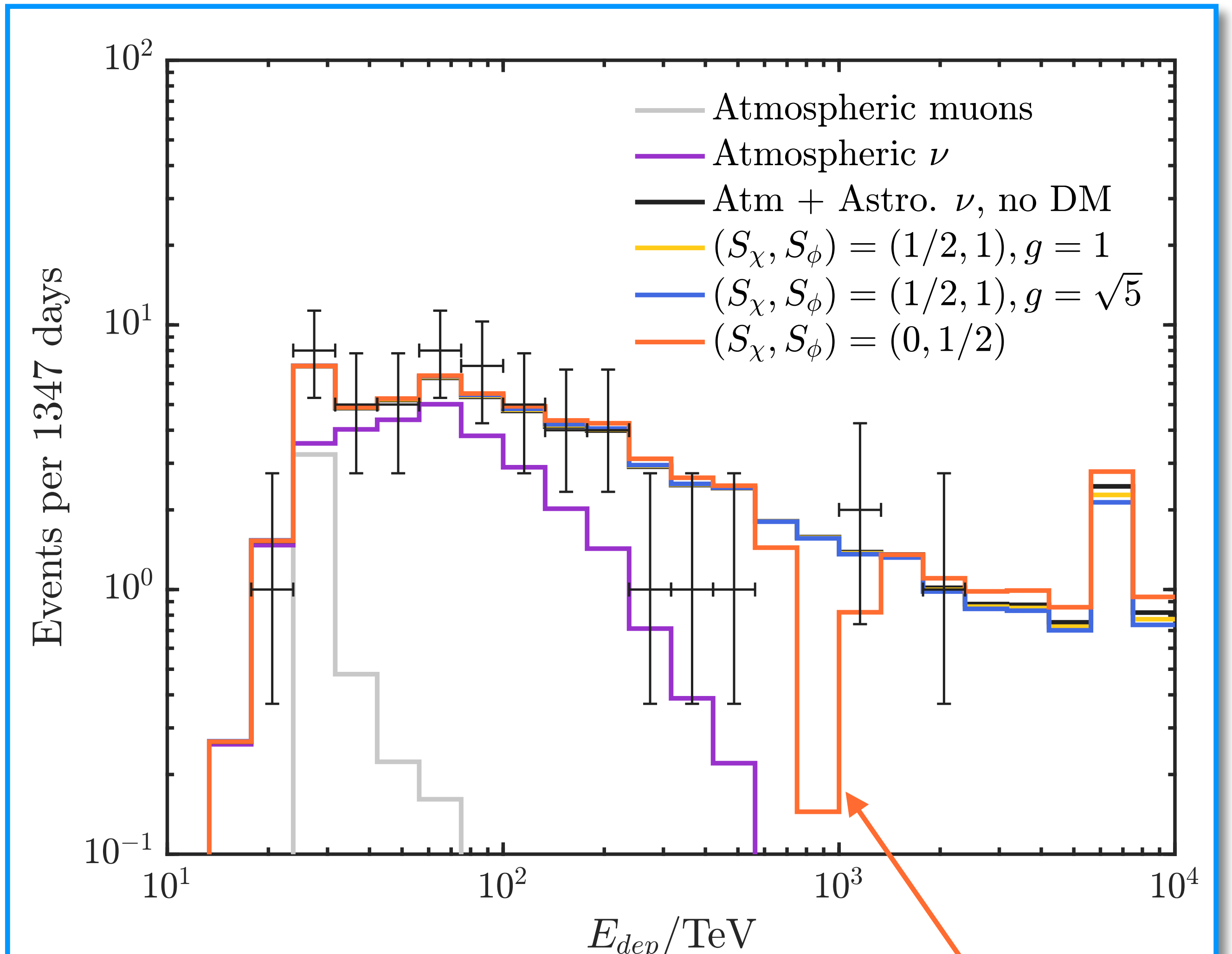




* *Einasto*

Energy & Morphology

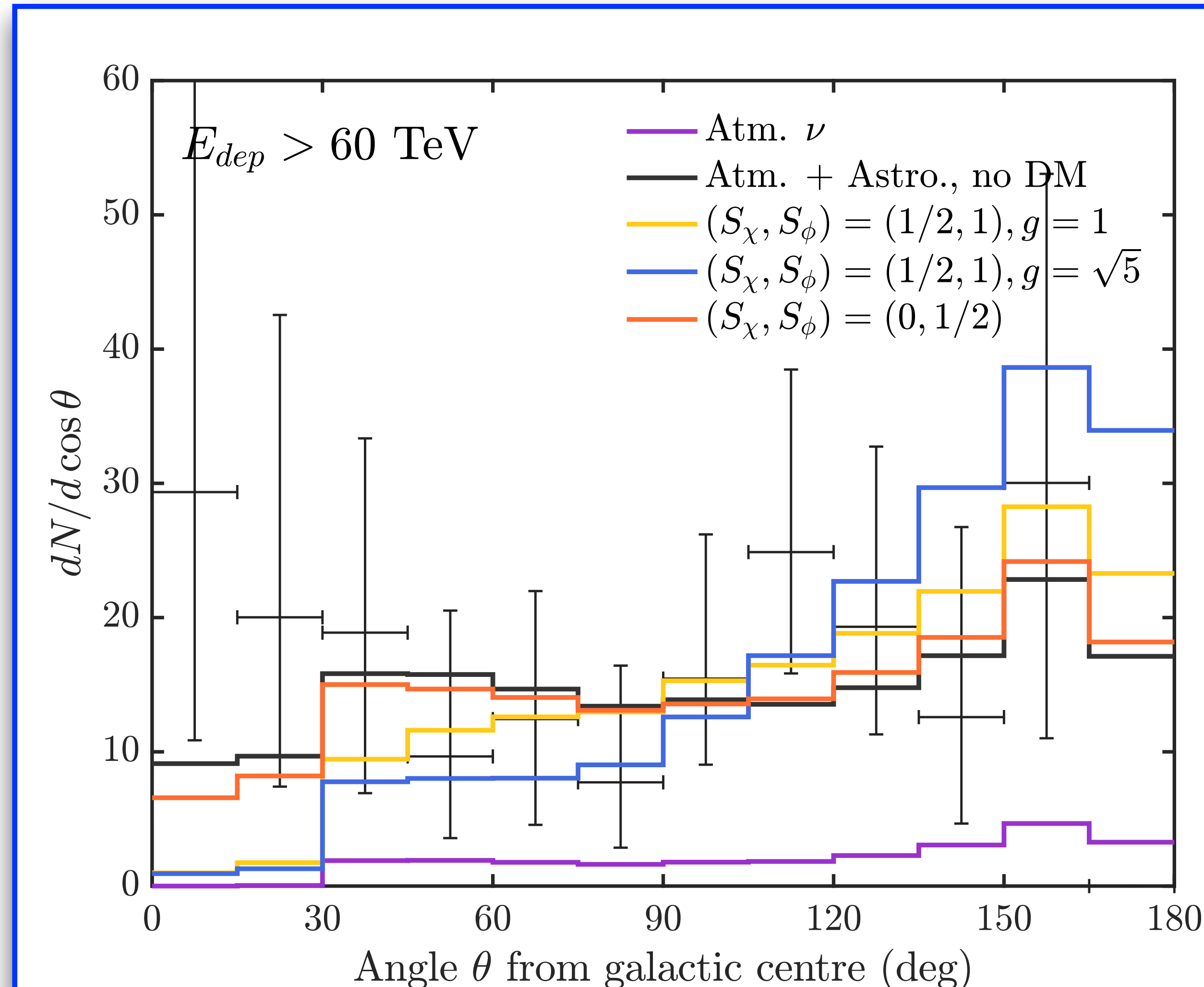
Energy Distribution



Resonance @ 810 TeV

Neutrino-DM interactions creates features in the energy spectrum (e.g. Dips, cut-off, softening)

Angular Distribution

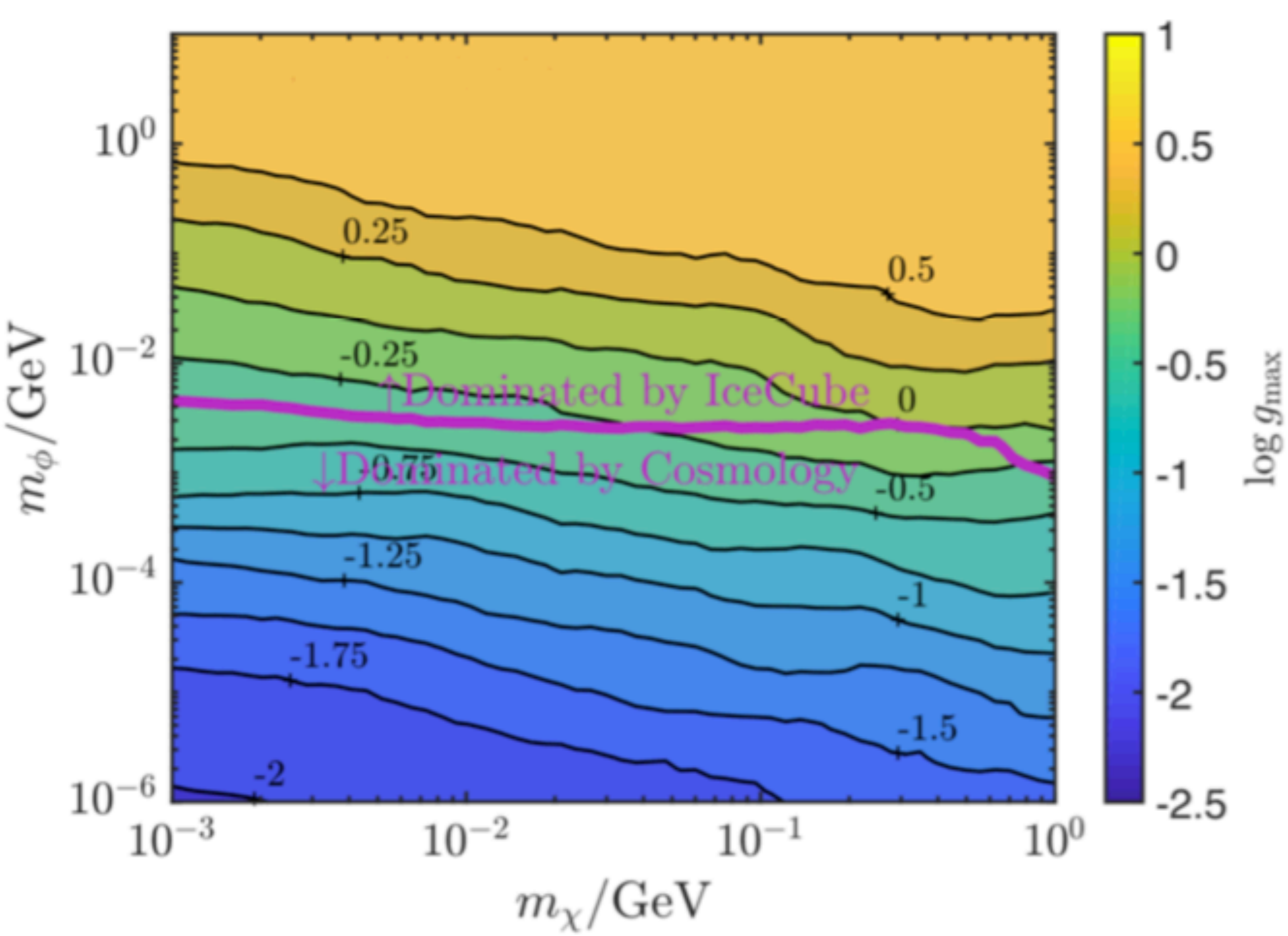


IceCube HESE

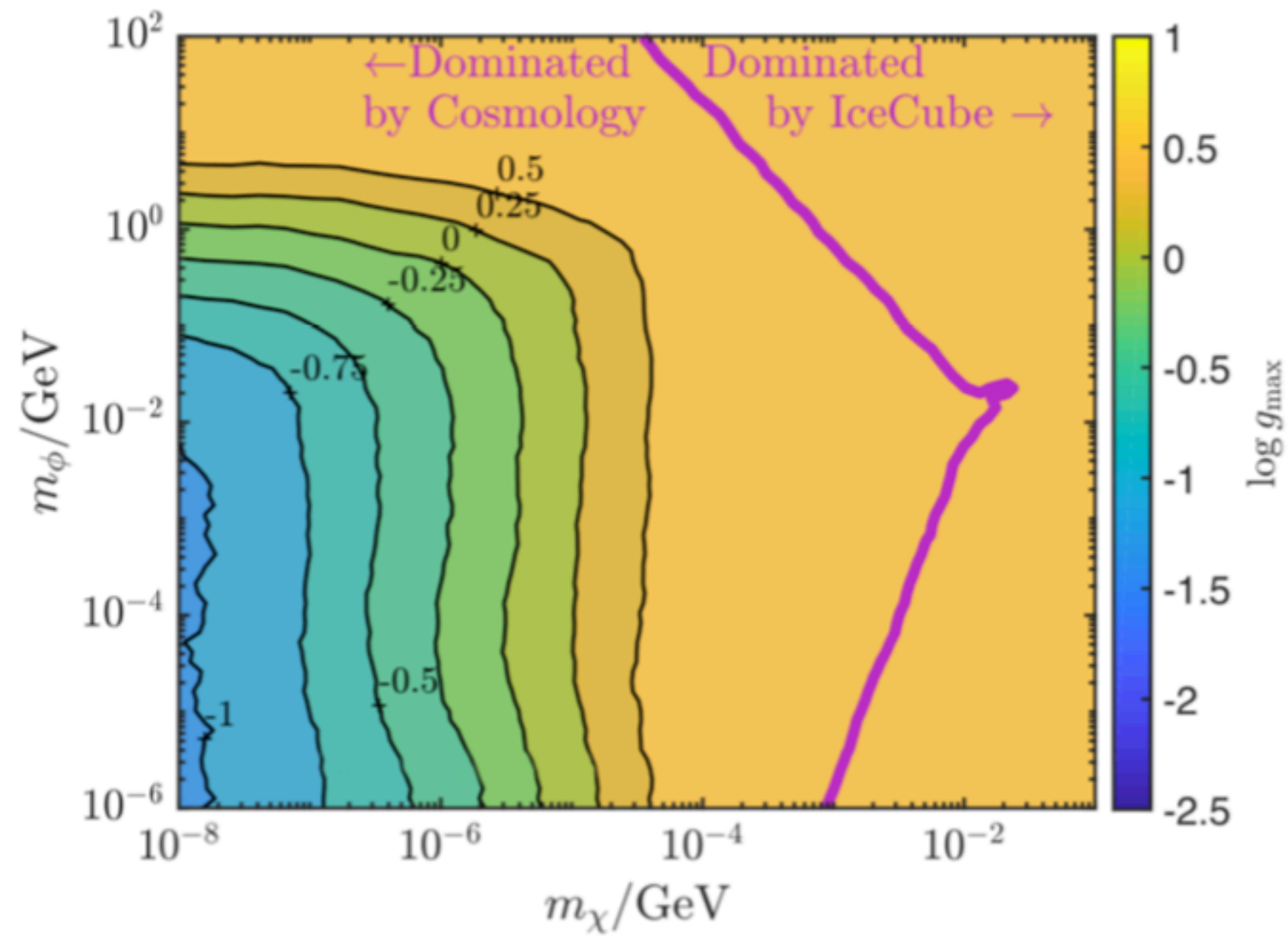
Neutrino-DM interaction leads to the deficit towards Galactic center

Constraints on DM-Nu Interaction

Fermionic DM
Vector Mediator



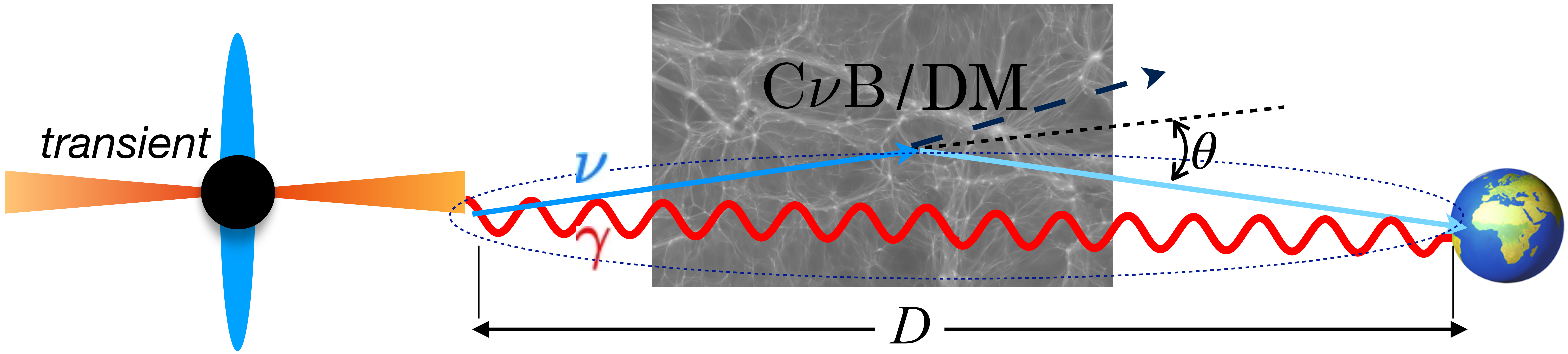
Scalar DM
Fermionic Mediator

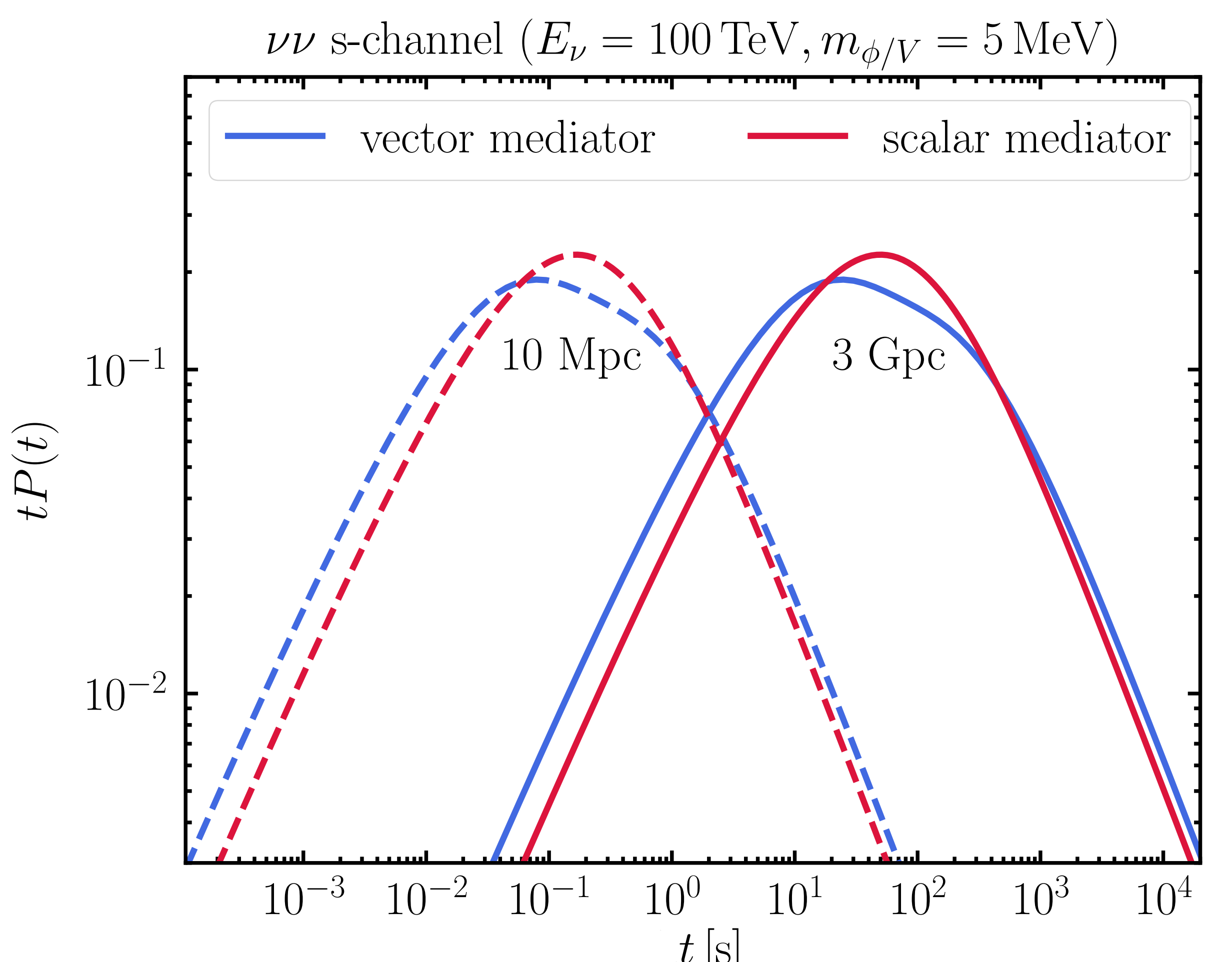


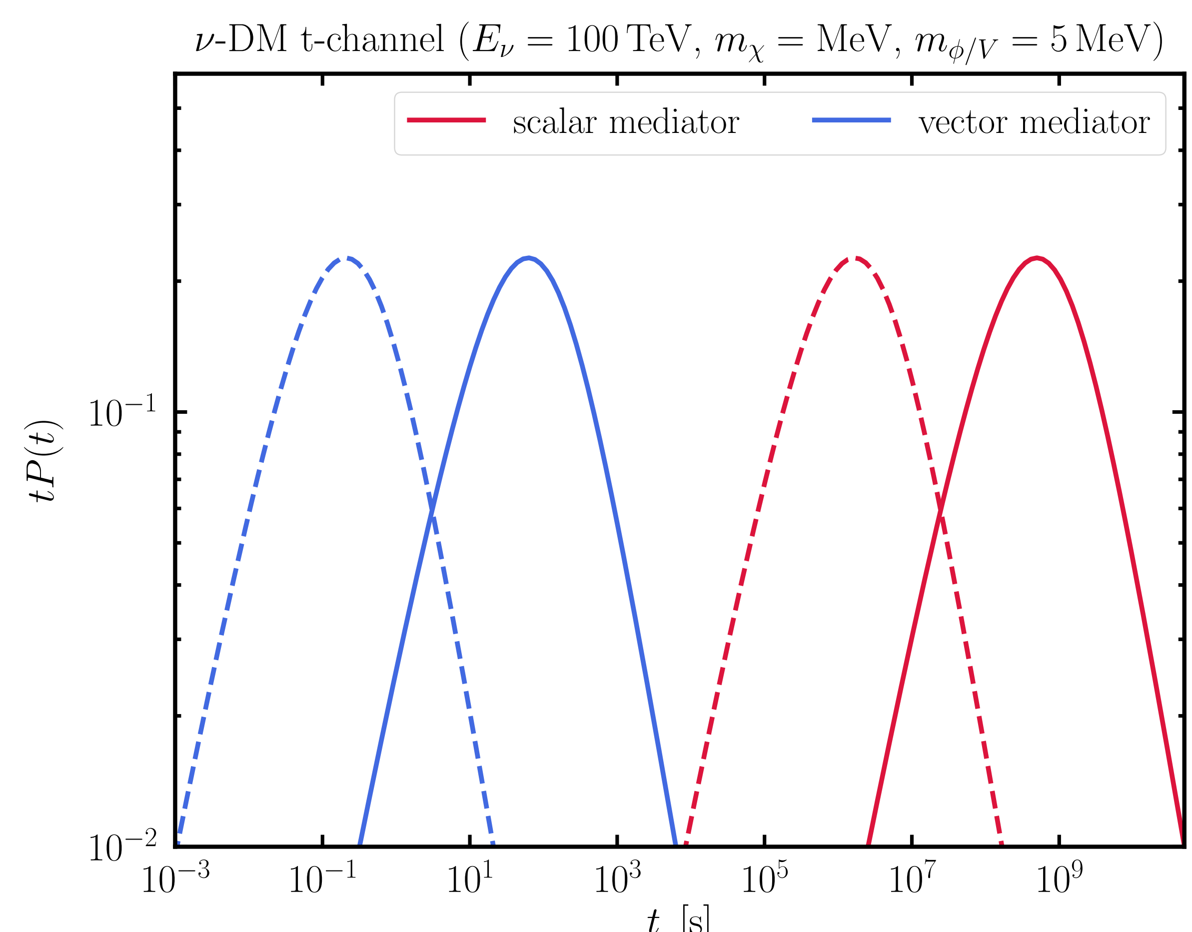
Competitive limits compared to cosmological constraints!

[Argüelles, AK, Vincent 2017, IceCube 2022]

BSM-induced Time Delay



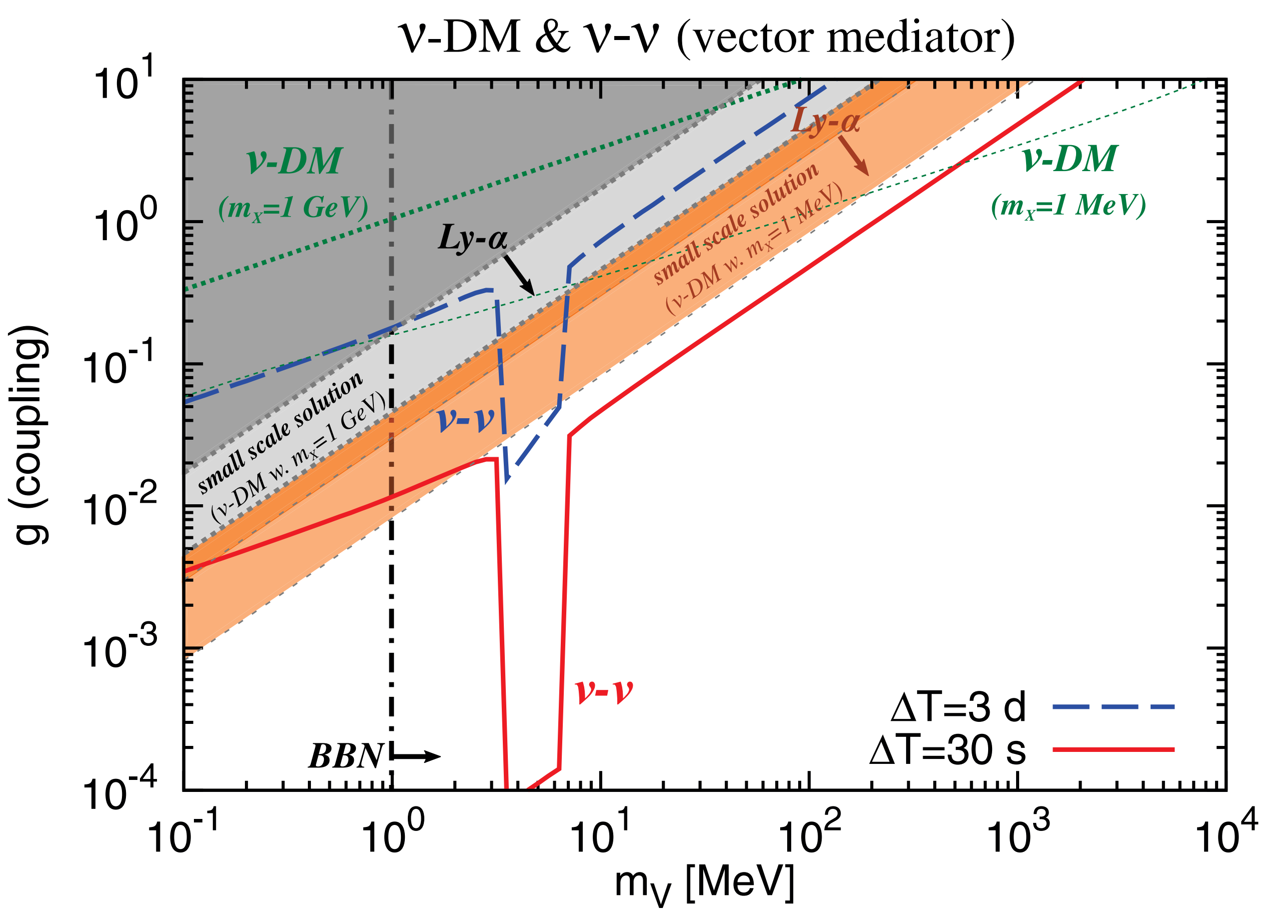




Eskenasy, AK, Murase, 2022

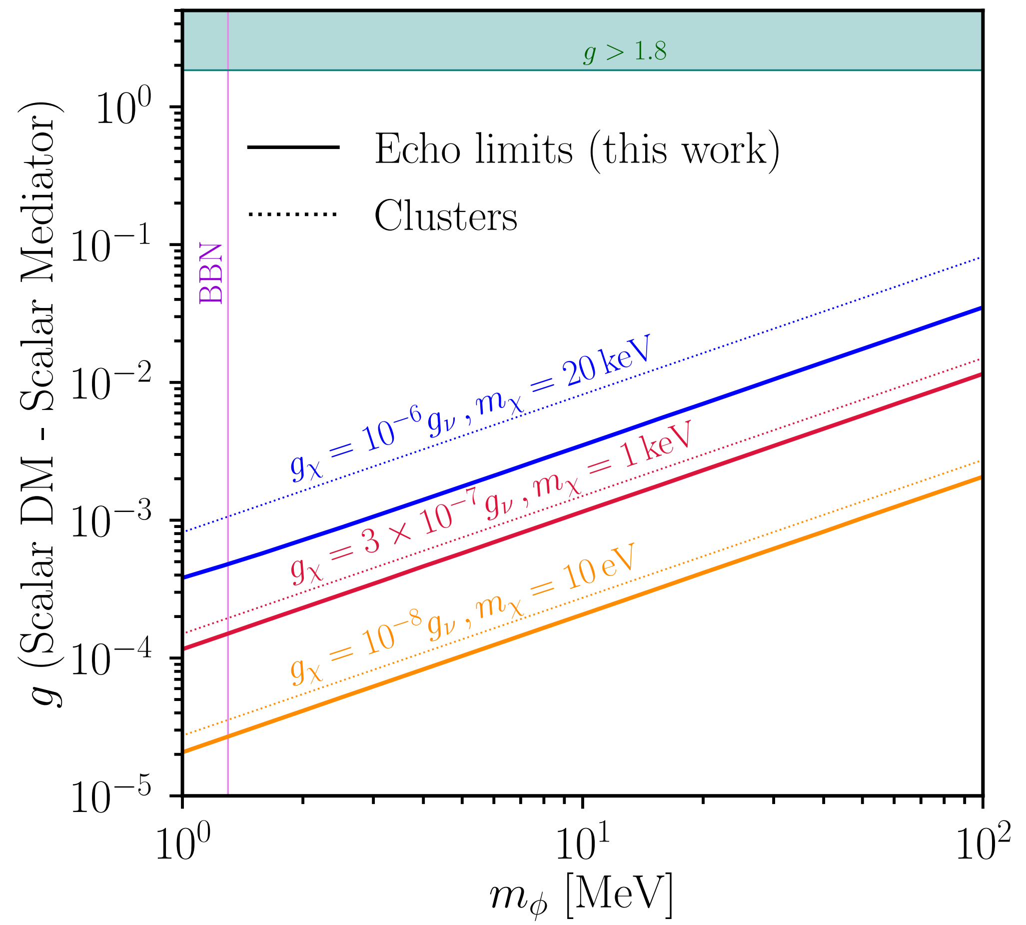
Constraining nu interactions

Blazar flares
100 TeV neutrinos
IceCube



Murase & Shoemaker 2019

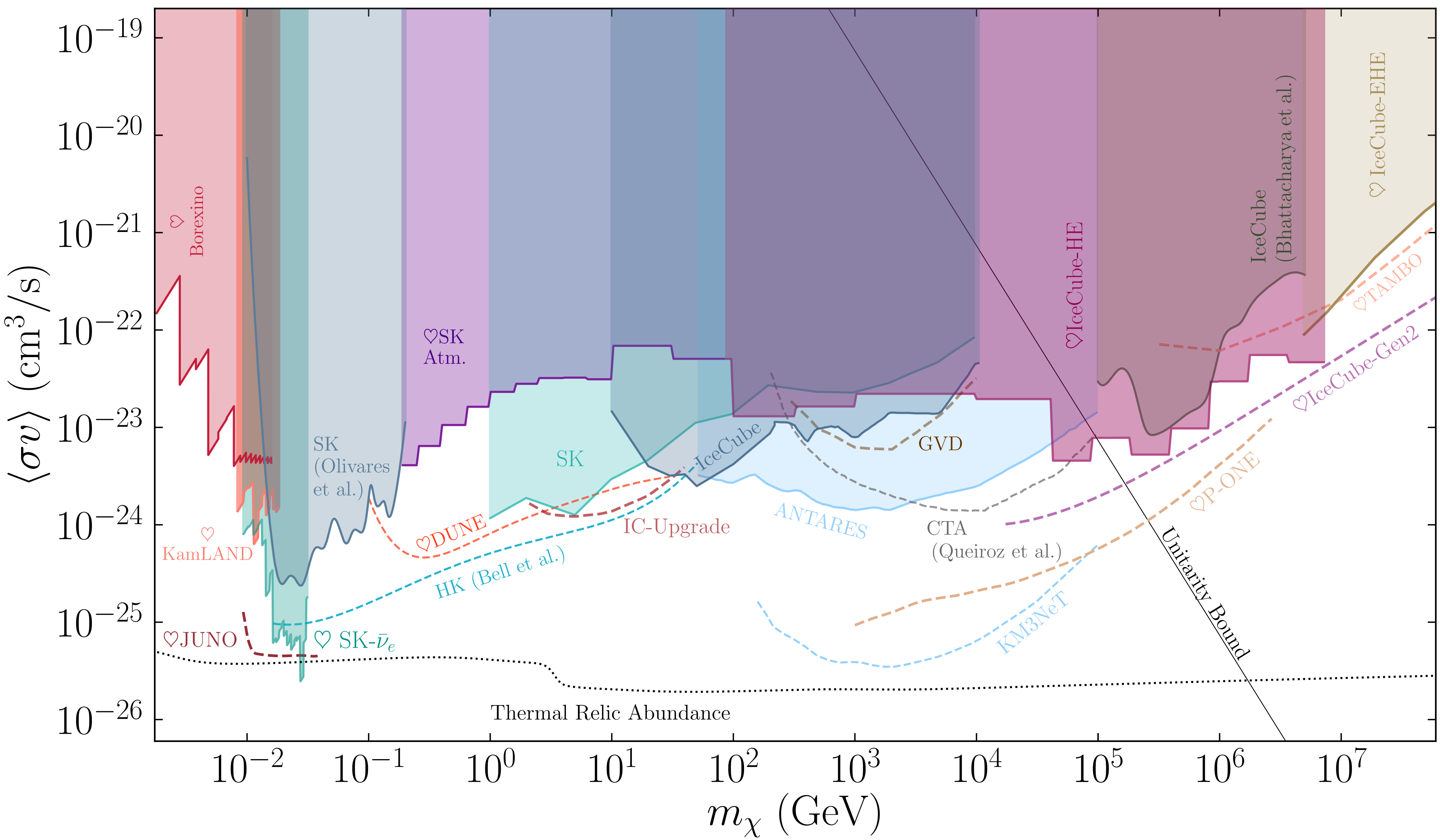
Core Collapse SN
15 MeV neutrinos
Hyper-K



Carpio, AK, Murase 2022

Dark Matter Annihilation

[Argüelles, Diaz, **AK**+ Rev. Mod. Phys. 2022.]



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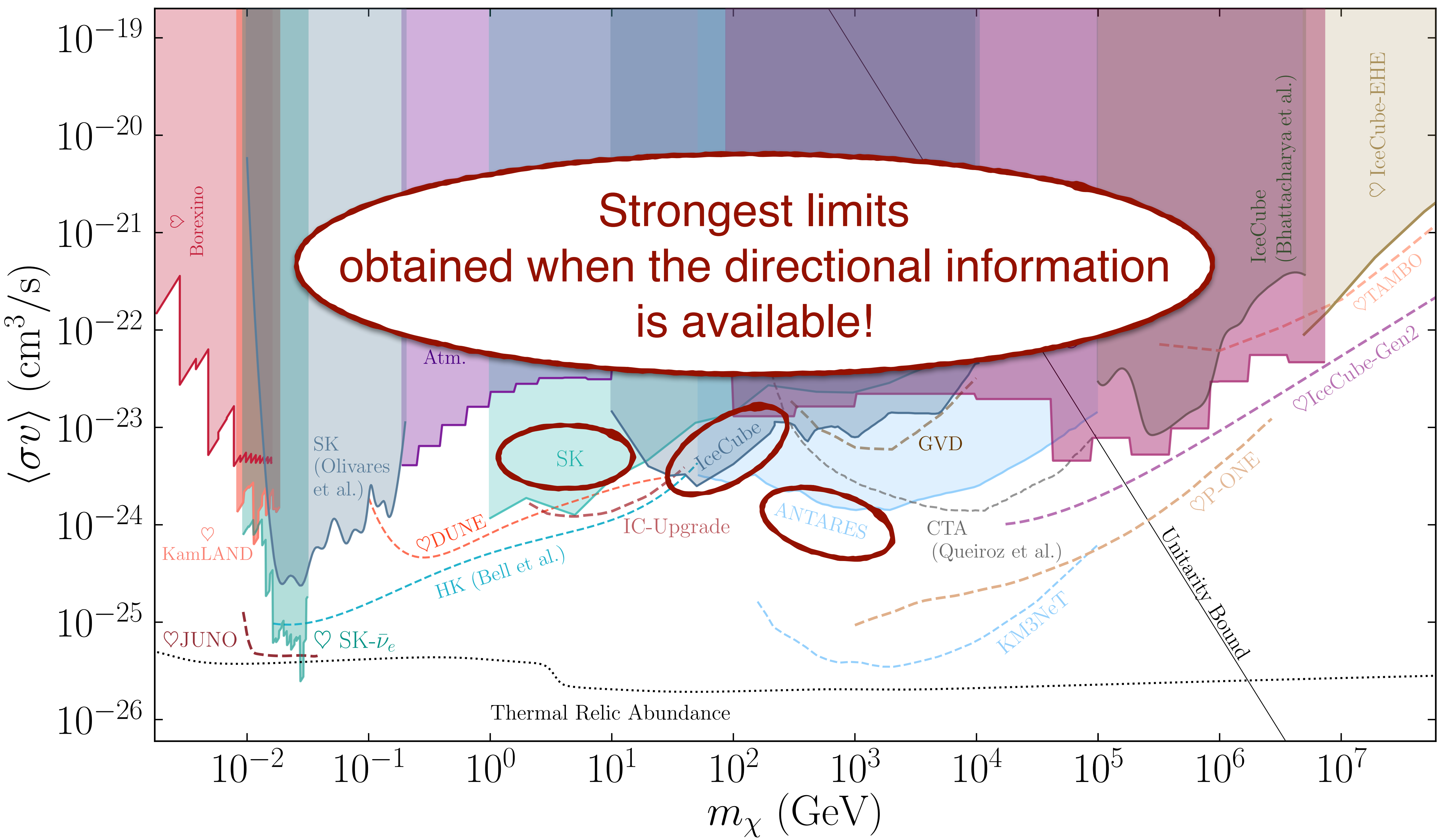
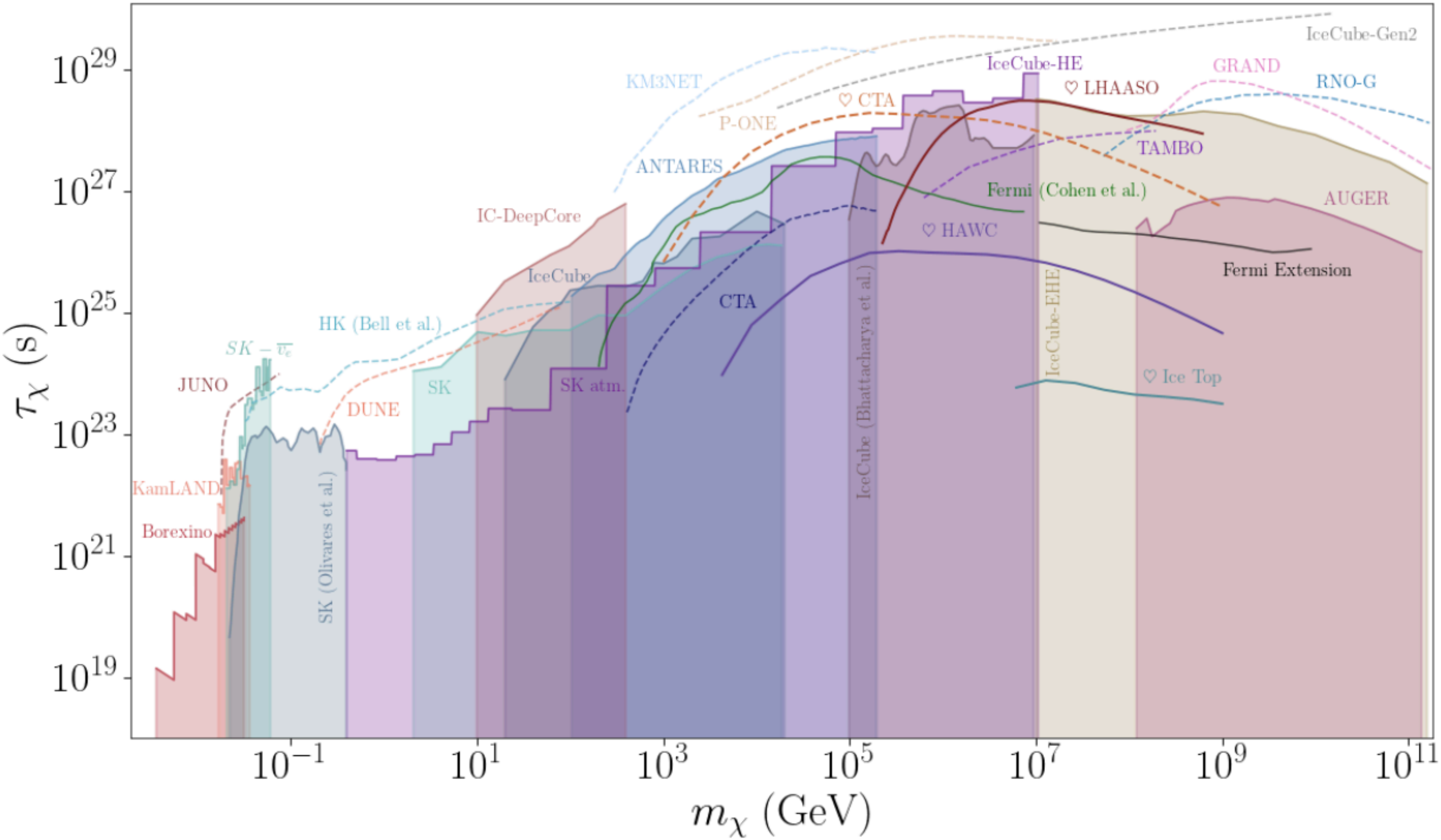
[Argüelles, Diaz, **AK**+ Rev. Mod. Phys. 2022.]



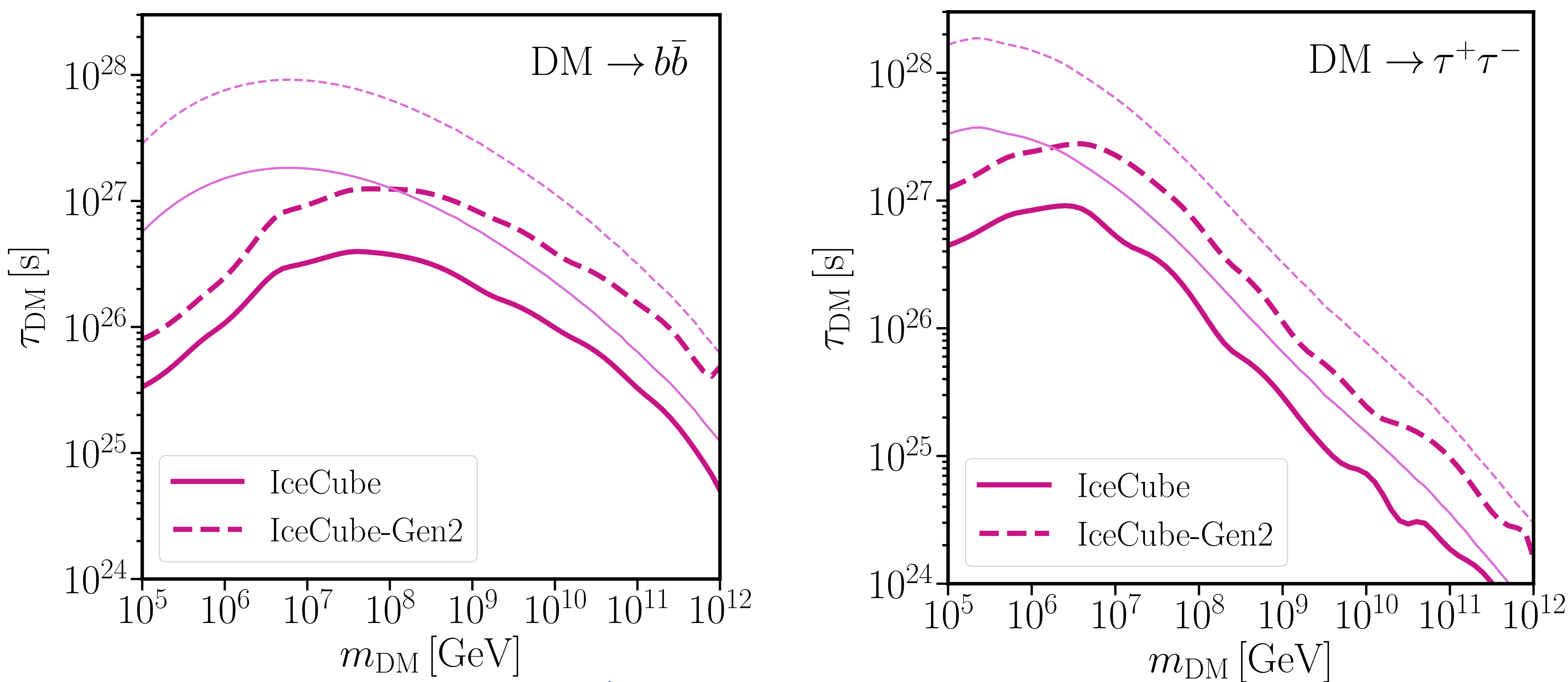
Dark Matter Decay

[Argüelles, Delgado Lopez, Friedlander, **AK**, Safa, White, Vincent, *in prep.*]



DM Signal from Galaxy Clusters

▸ Virgo Cluster

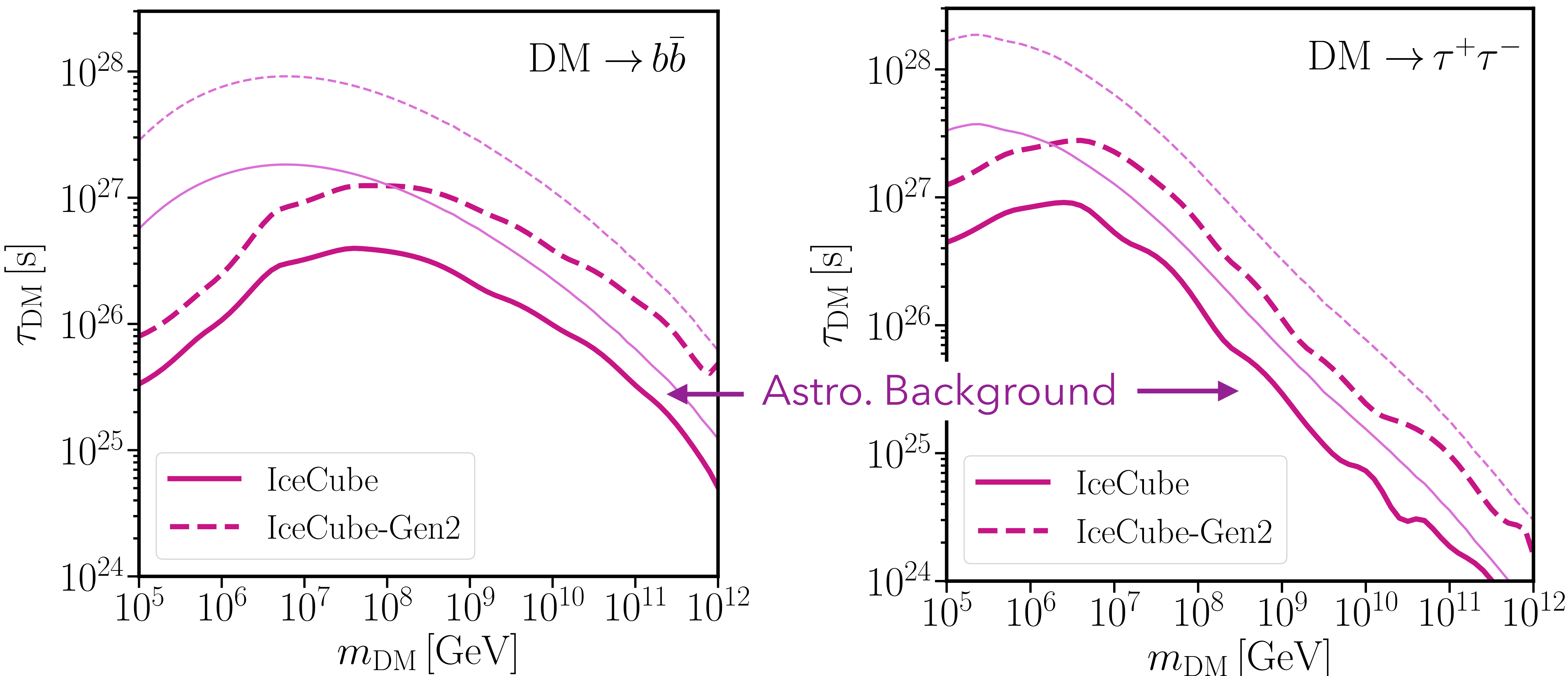


[Chianese, **AK**, Murase, in prep.]

In the Gen2-era, stacking with more clusters can overcome diffuse limits.

DM Signal from Galaxy Clusters

‣ Virgo Cluster



[Chianese, **AK**, Murase, in prep.]

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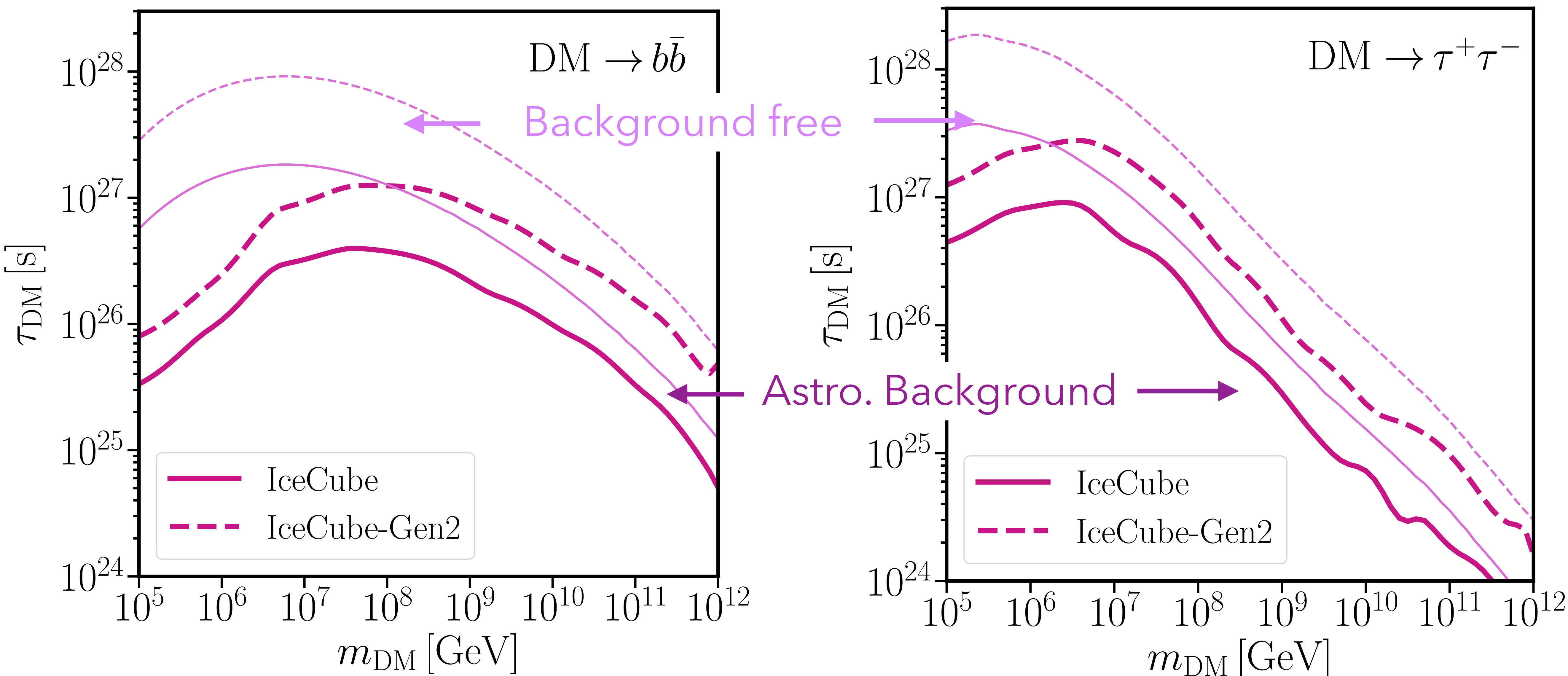


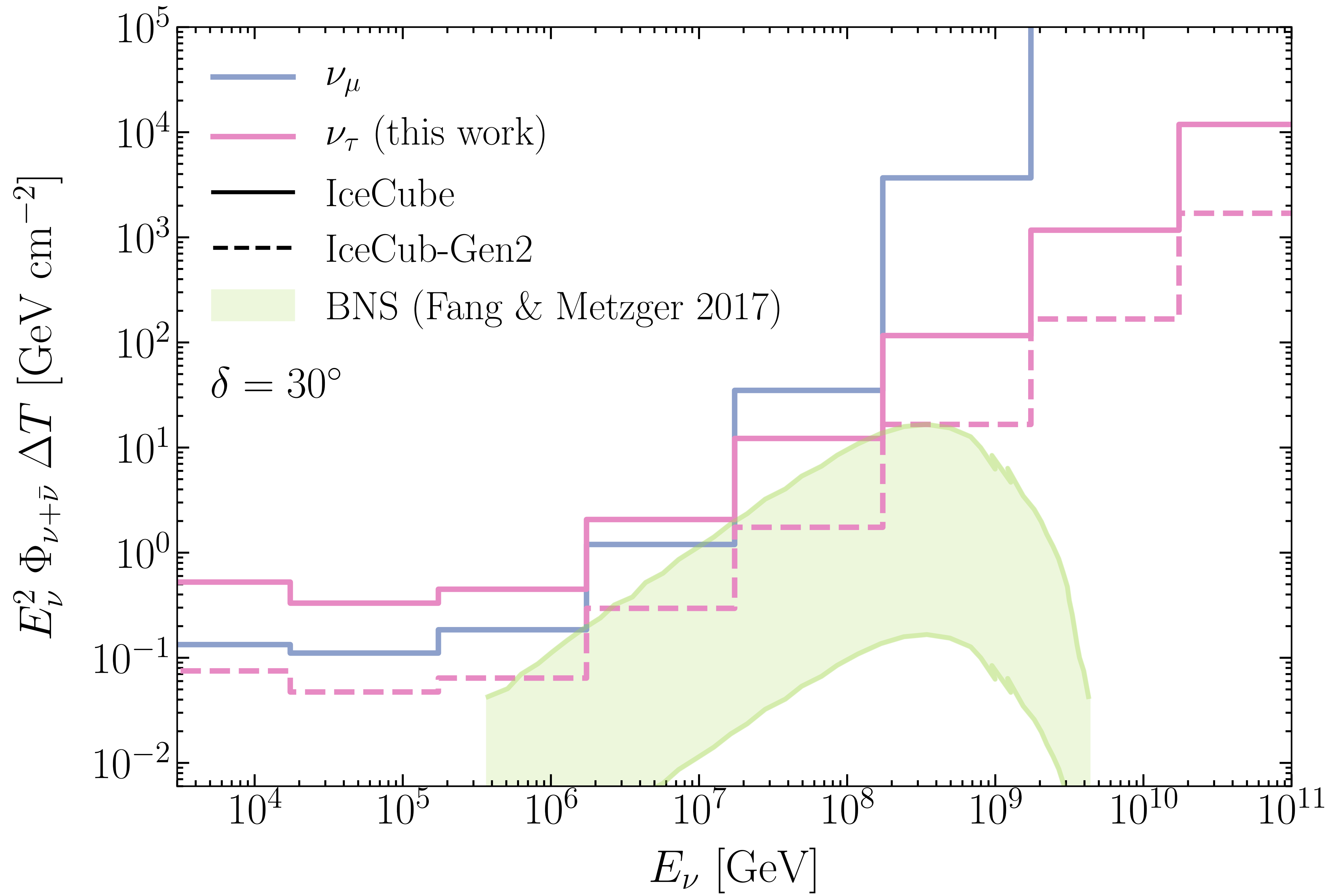
[Chianese, **AK**, Murase, in prep.]

In the Gen2-era, stacking with more clusters can overcome diffuse limits.

UHE Regime

- Tau PeV Neutrinos

[Argüelles, Halzen, AK, Safa 2022]

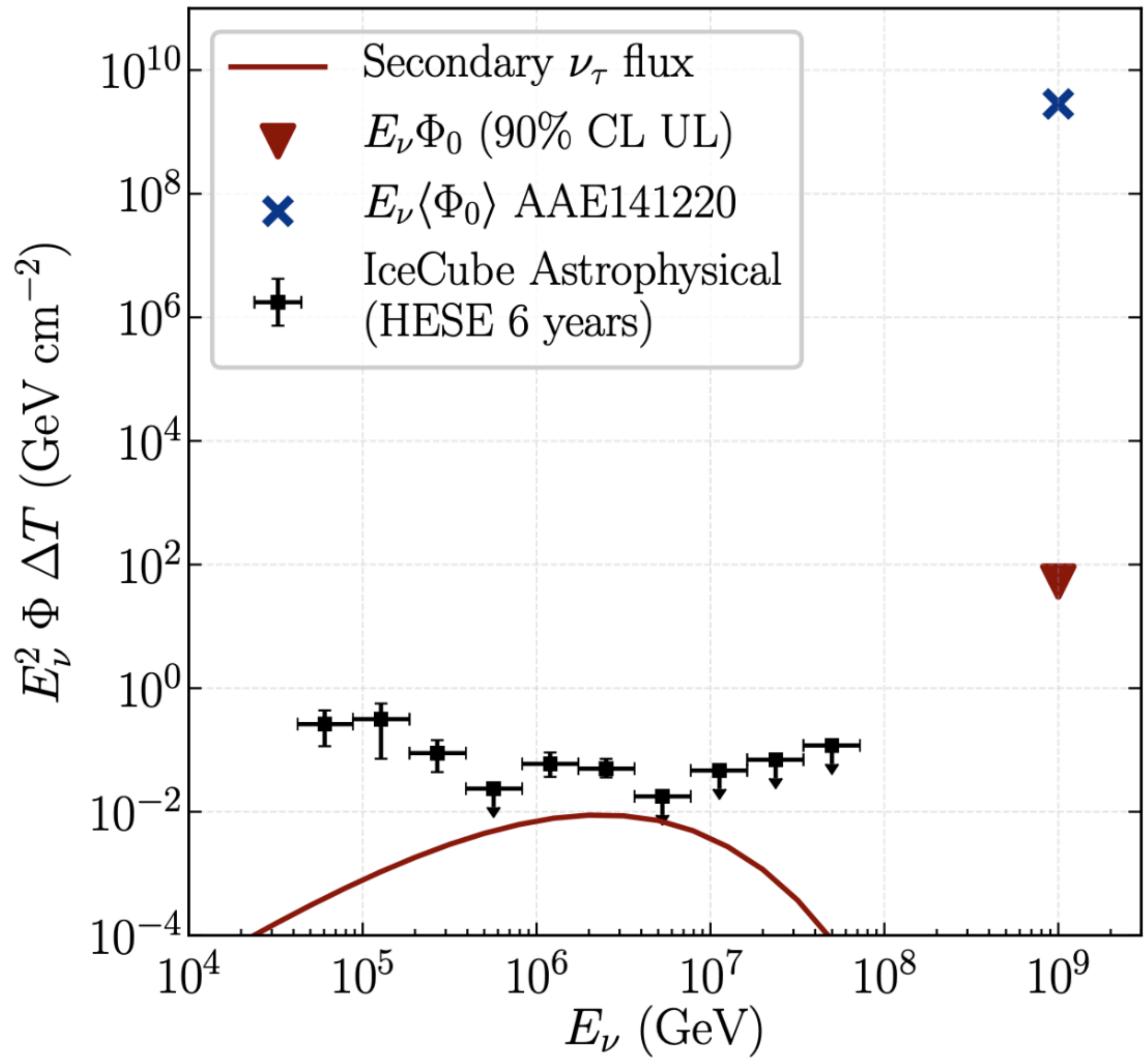


ANITA Anomalous Event

The 3rd flight of ANITA identified an up-going tau shower initiated by a tau-neutrino interaction in the ice.

The corresponding isotropic flux (within the Standard Model) is in tension with cosmogonic flux limits.

Could discrete emission avoid the tension?



Constraints from regenerated flux at PeV energies disapproves localized emission in the direction of the anomalous event!

[Safa, Pizzuto, Argüelles, Halzen, Hussain, **AK**, Vandenbroucke 2019]

Outlook

- After a decade of observation, signs of anisotropy are emerging in IceCube data.
    - Early indications points to active galactic nuclei as primary source of high-energy cosmic neutrinos.
- Identification of the origin of HE cosmic neutrinos will bring insight into the working of cosmic accelerators.
- The HE neutrino beam provided by cosmic accelerators offers unique opportunities to study neutrinos.
- Cosmic neutrinos provide complementary tests of physics beyond the Standard Model in the neutrino sector.