On the Origins of High-Energy Neutrinos

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Interdisciplinary Developments in Neutrino Physics
KITP, UC Santa Barbara
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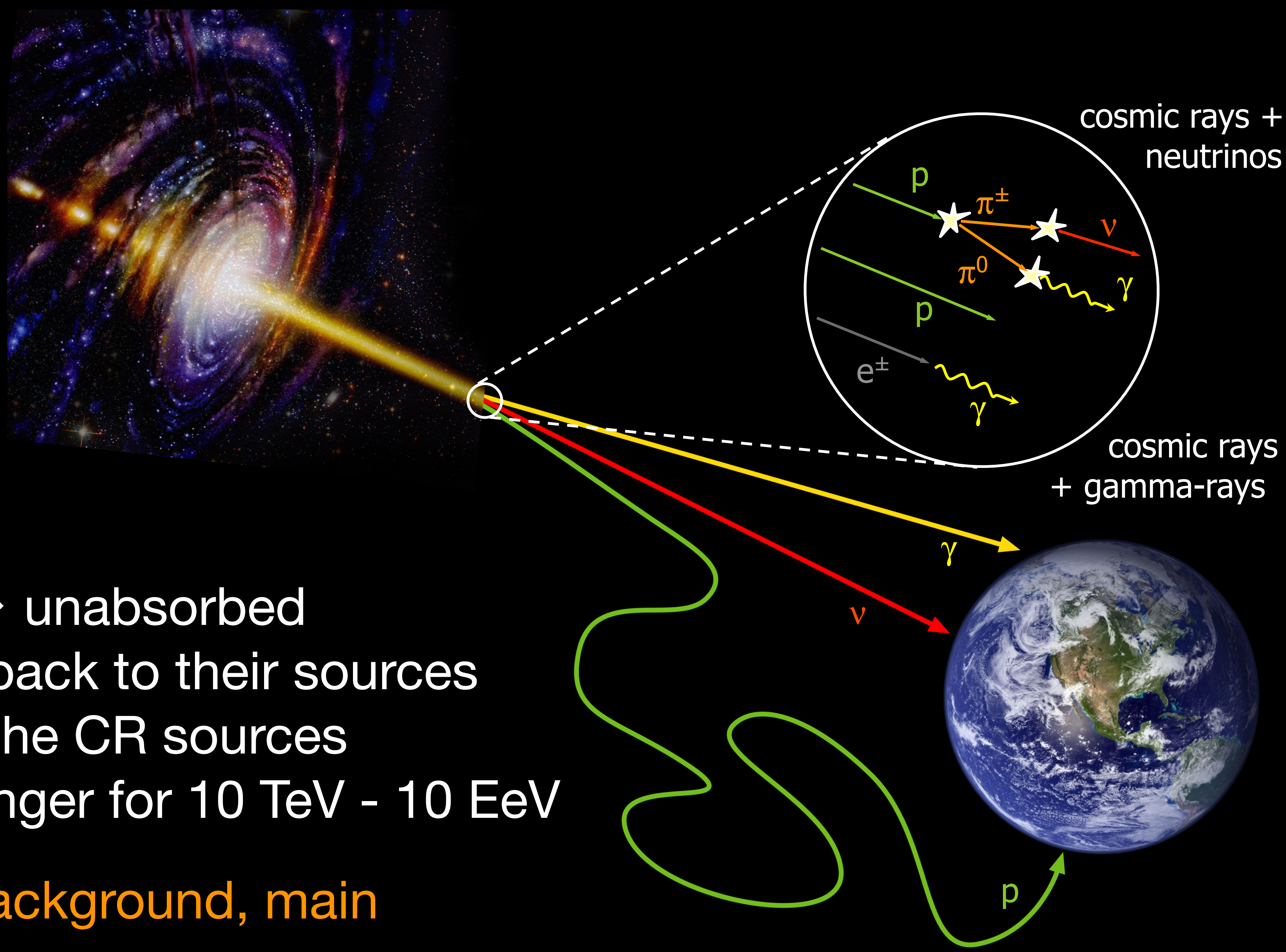
Neutrino Astronomy

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

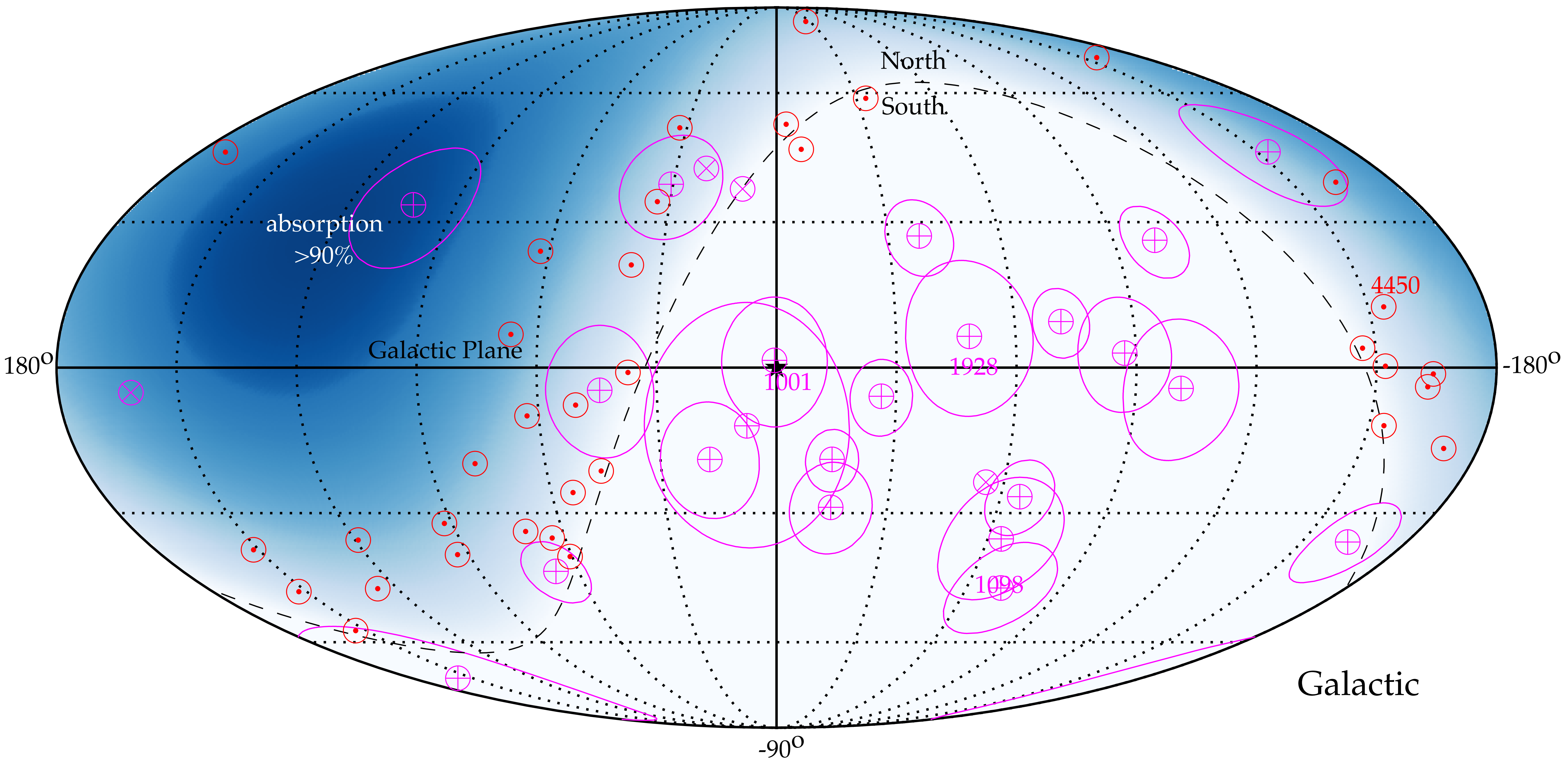
Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



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

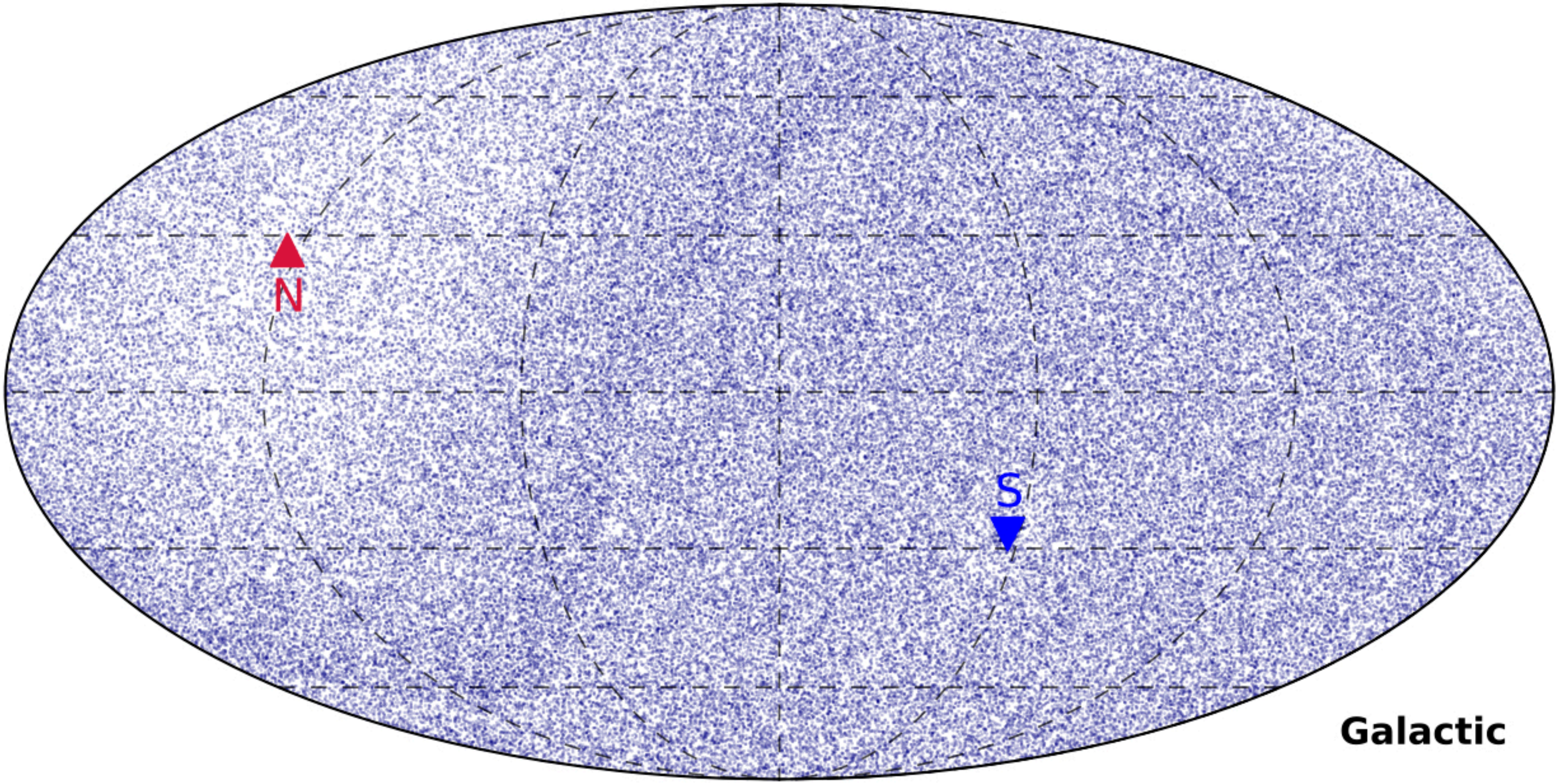
Low statistics and large background, main challenges for neutrino astronomy.

Arrival Direction of the Most Energetic Neutrinos



predominantly extragalactic origin

Spatial Distribution

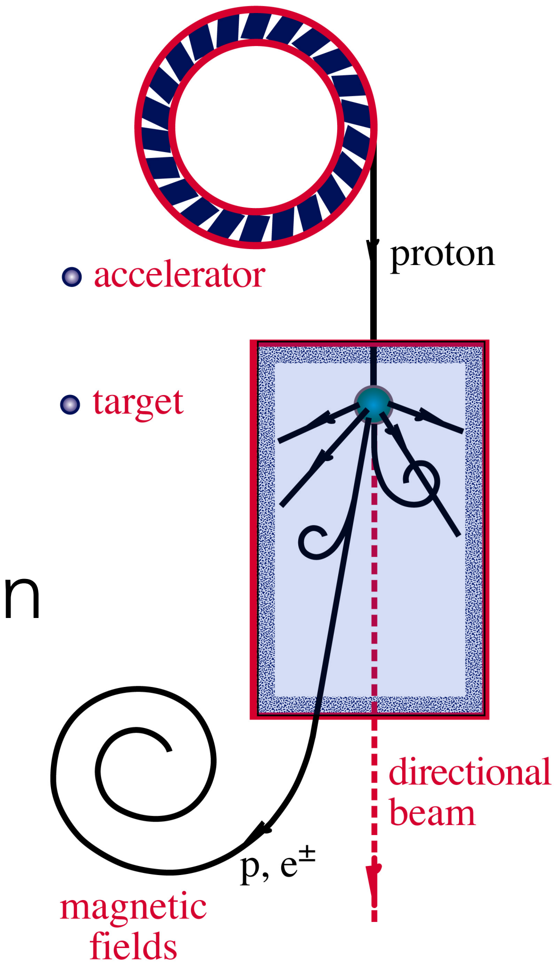


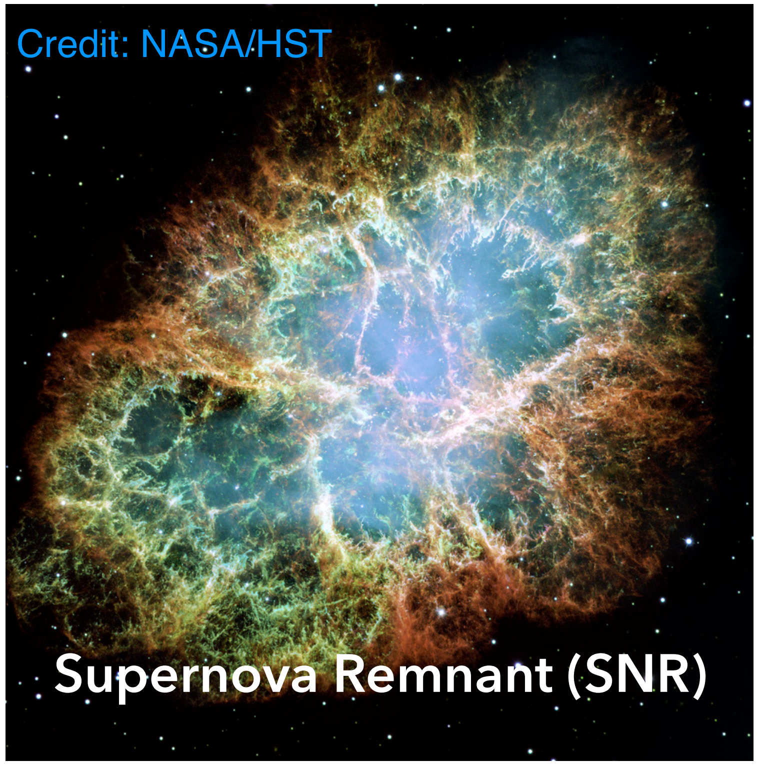
138322 neutrino candidates in one year

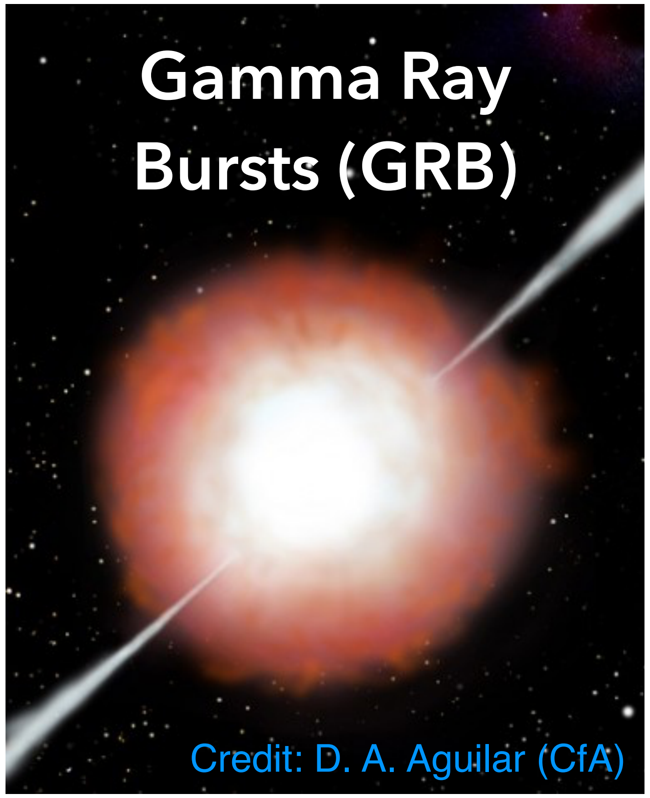
Possible Sources

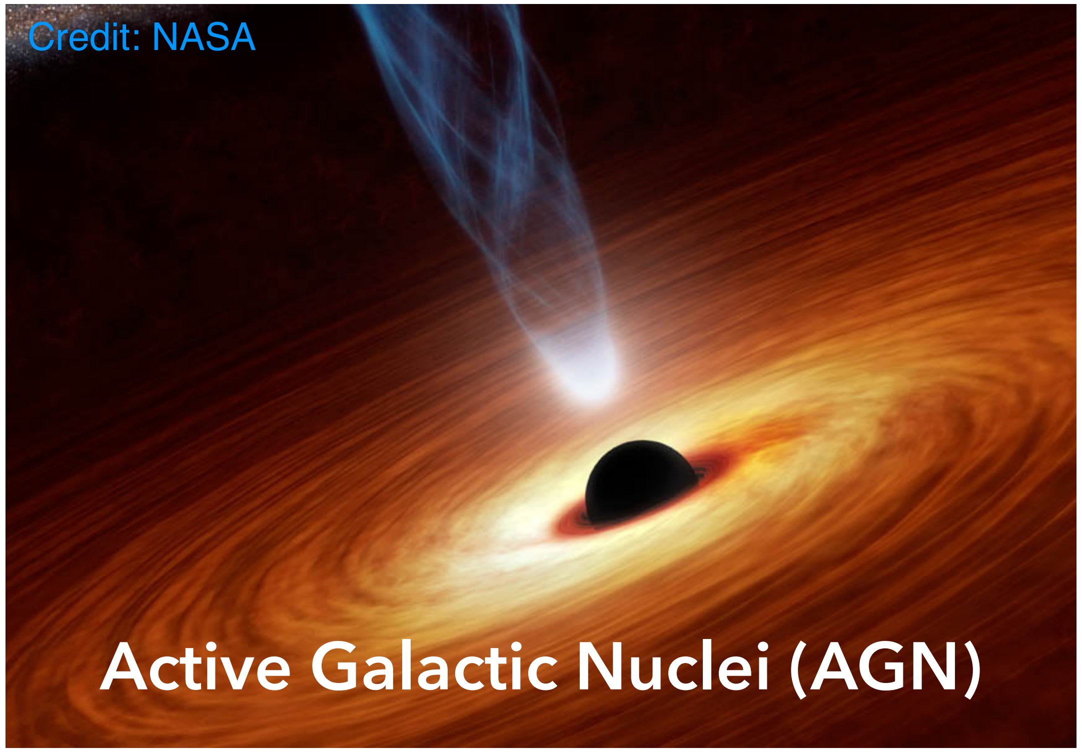
Sources of TeV - PeV cosmic neutrinos should

- 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





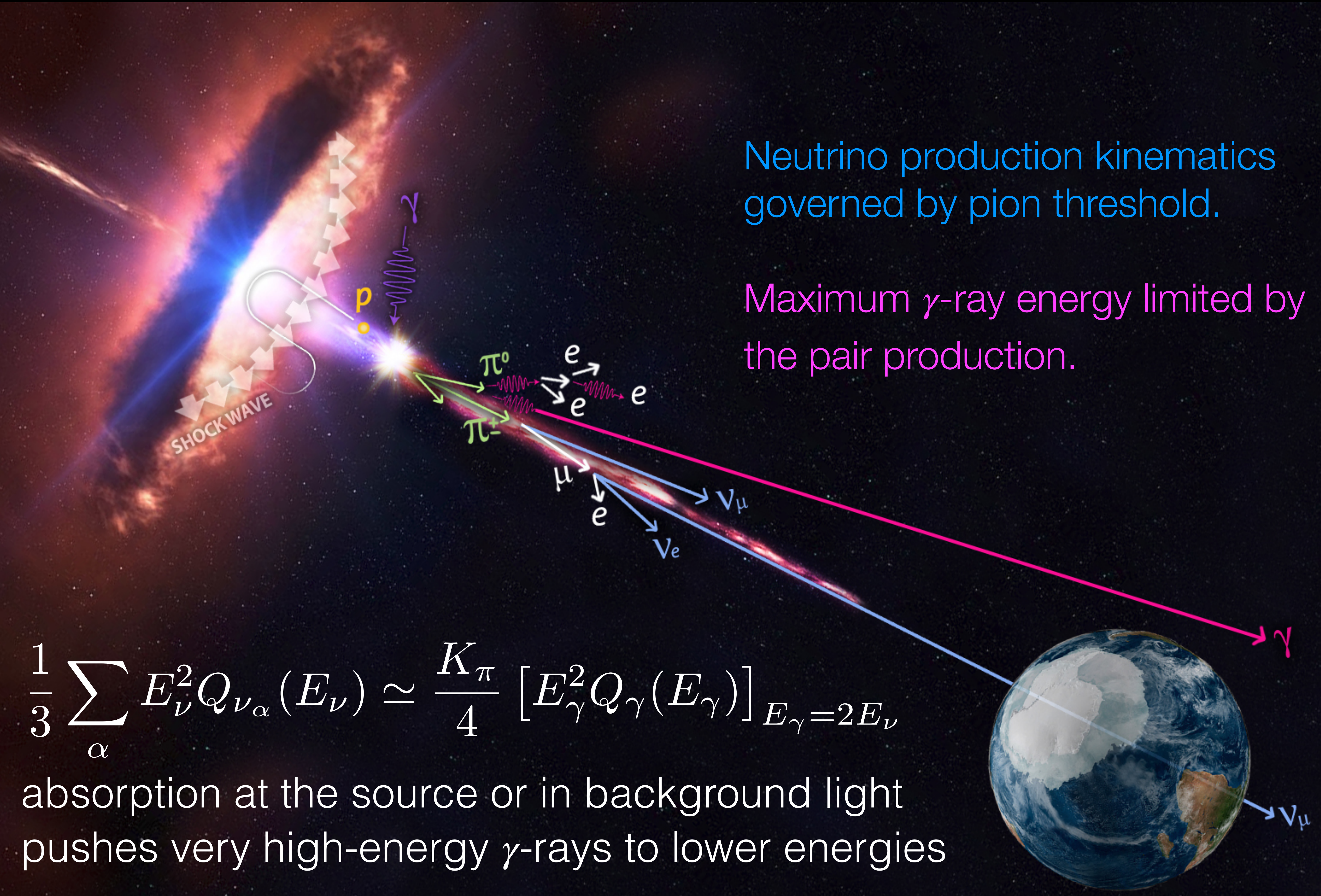




The Neutrino γ-ray Connection

Neutrino production kinematics governed by pion threshold.

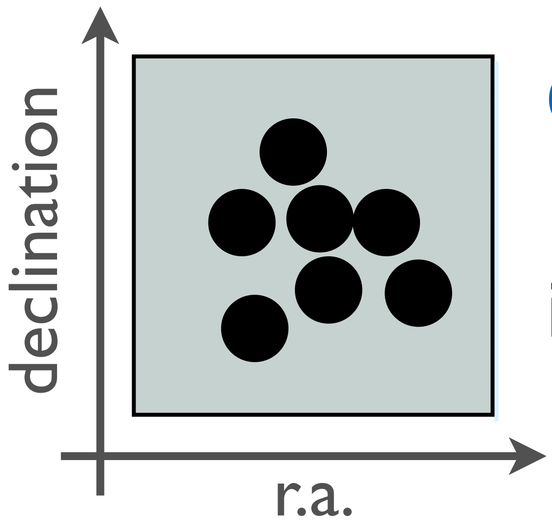
Maximum γ-ray energy limited by the pair production.



$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma=2E_\nu}$$

absorption at the source or in background light pushes very high-energy γ-rays to lower energies

Point Source Searches

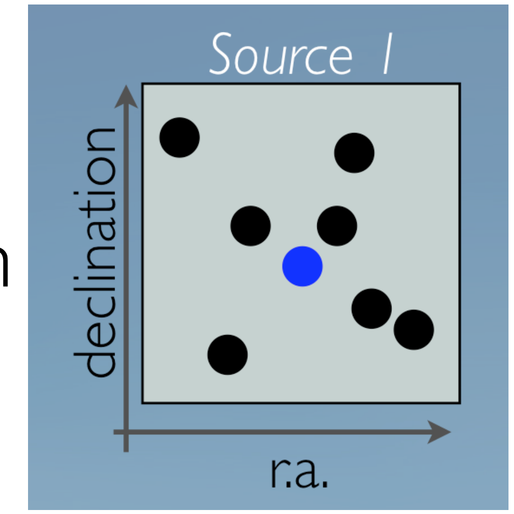


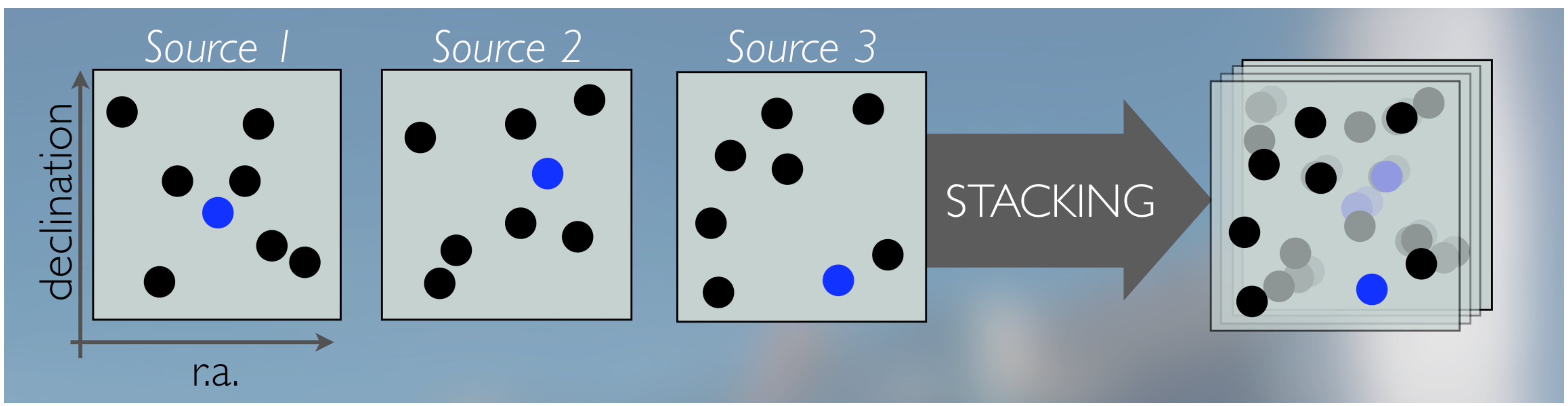
clustering

- Untriggered search in space & time

source search

- Triggered search for pre-identified locations



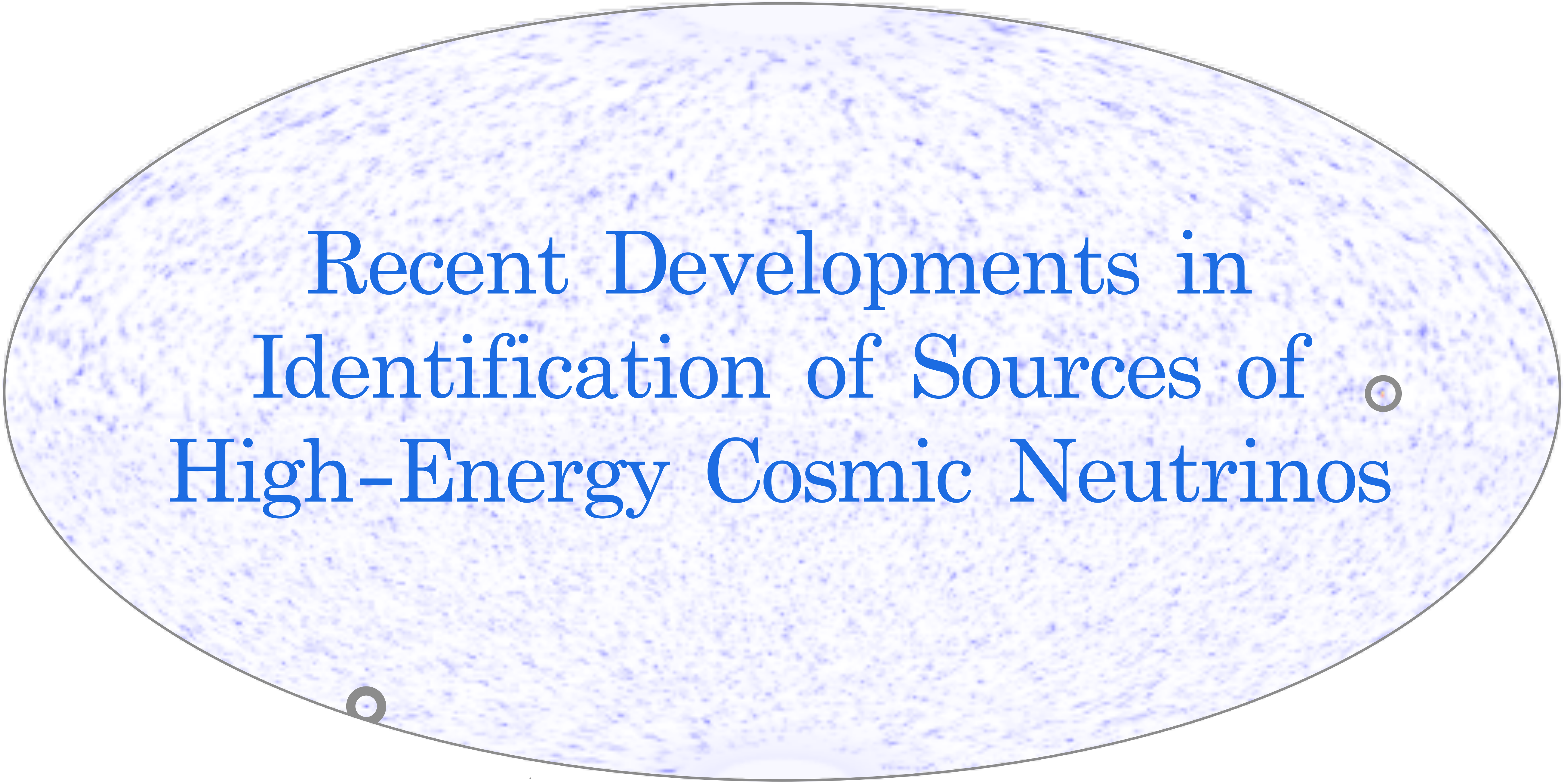


Stacking Search

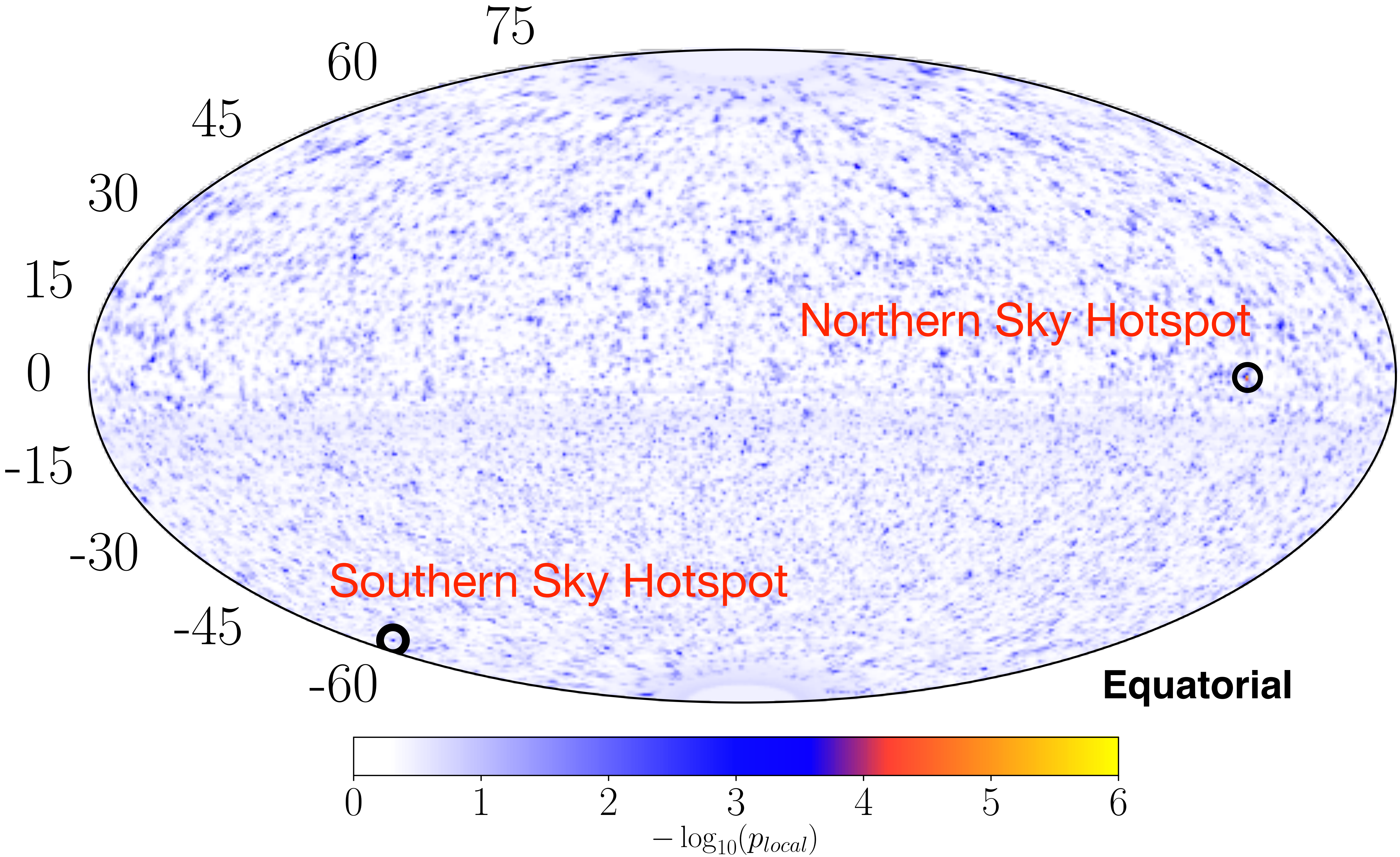
- Search for collective neutrino emission from a catalog/class of sources

+ *Realtime analysis and Neutrino alerts…*

Recent Developments in Identification of Sources of High-Energy Cosmic Neutrinos



Neutrino Sky-IceCube 10 yr



[IceCube, PRL 2020]

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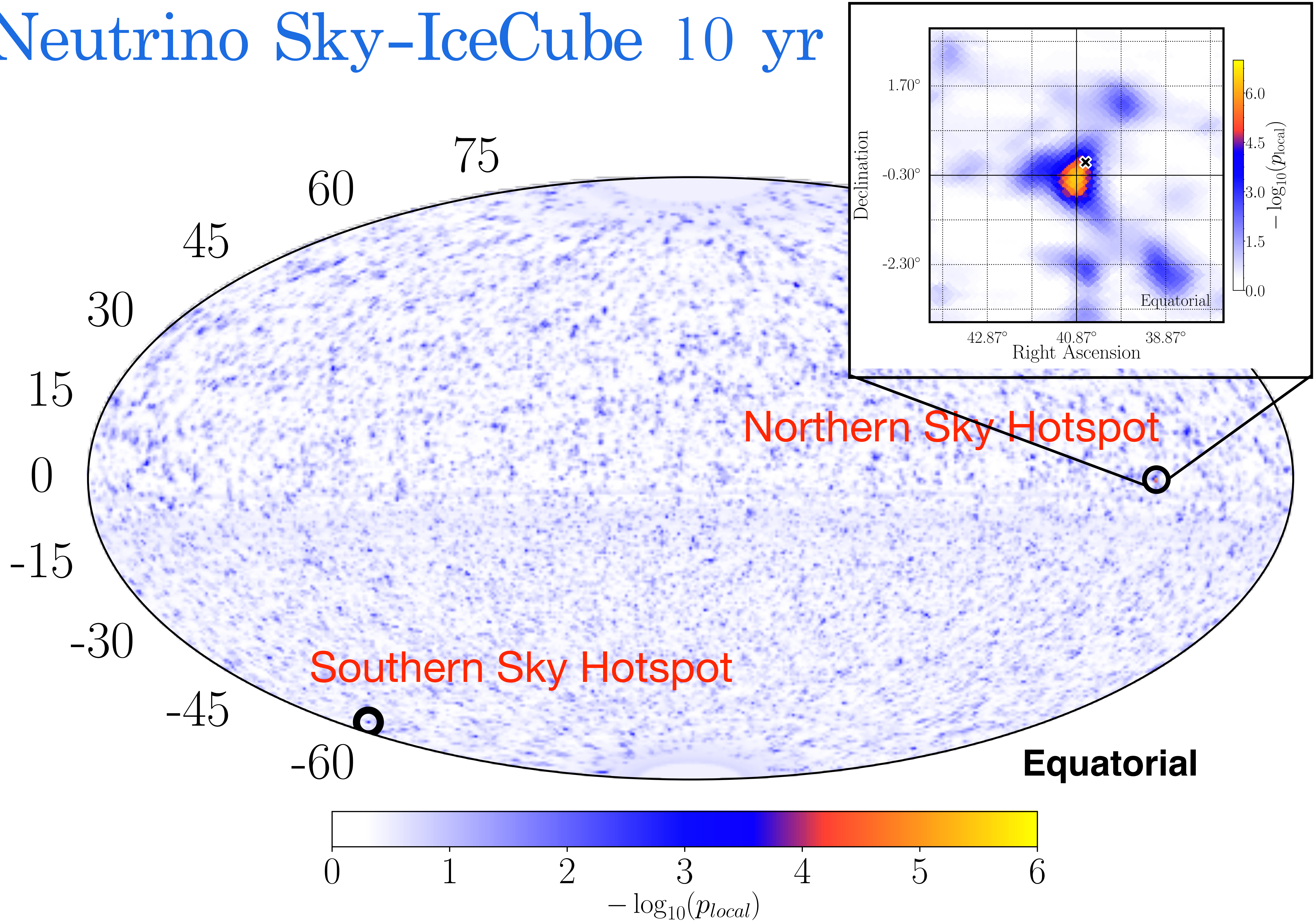

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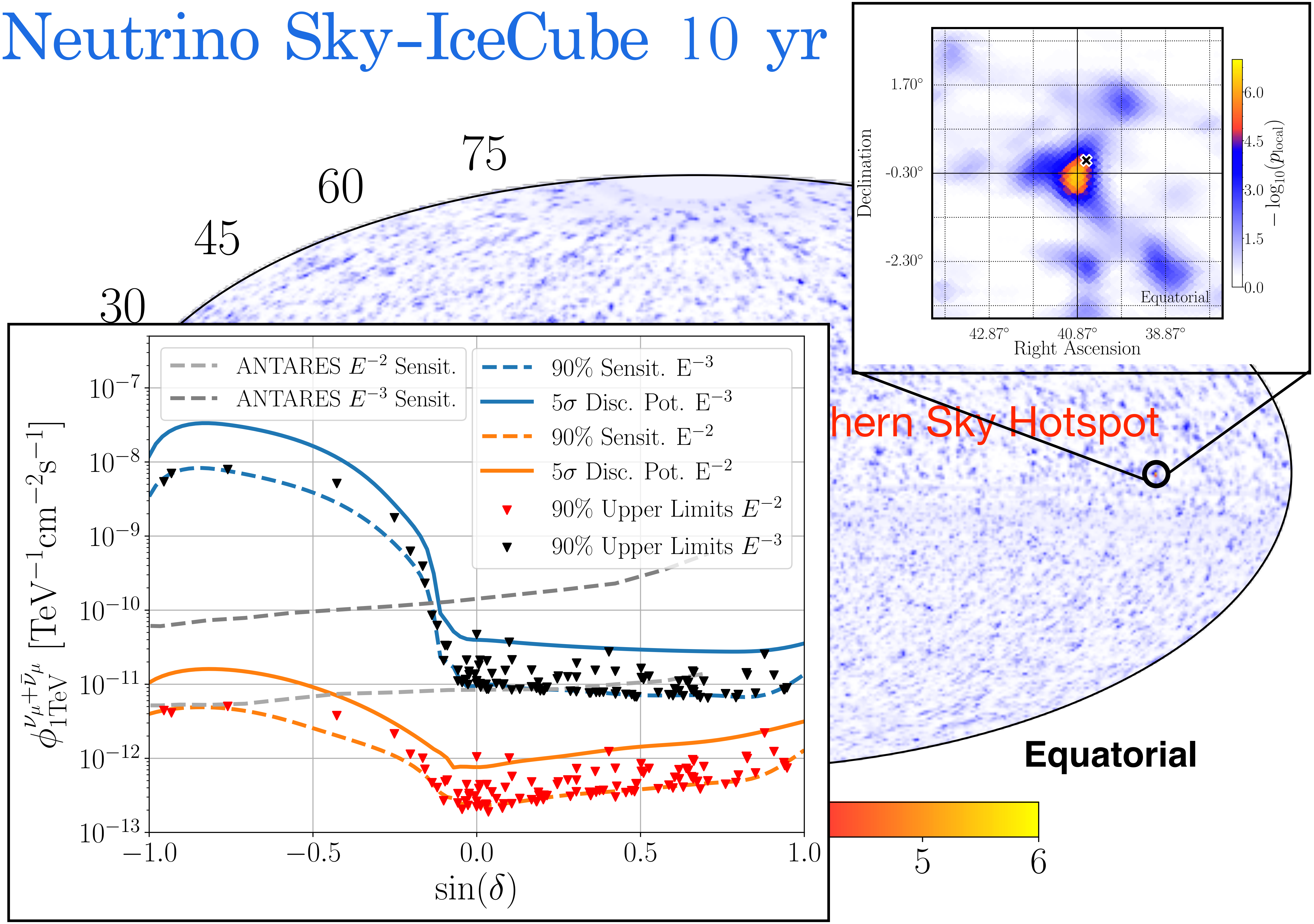

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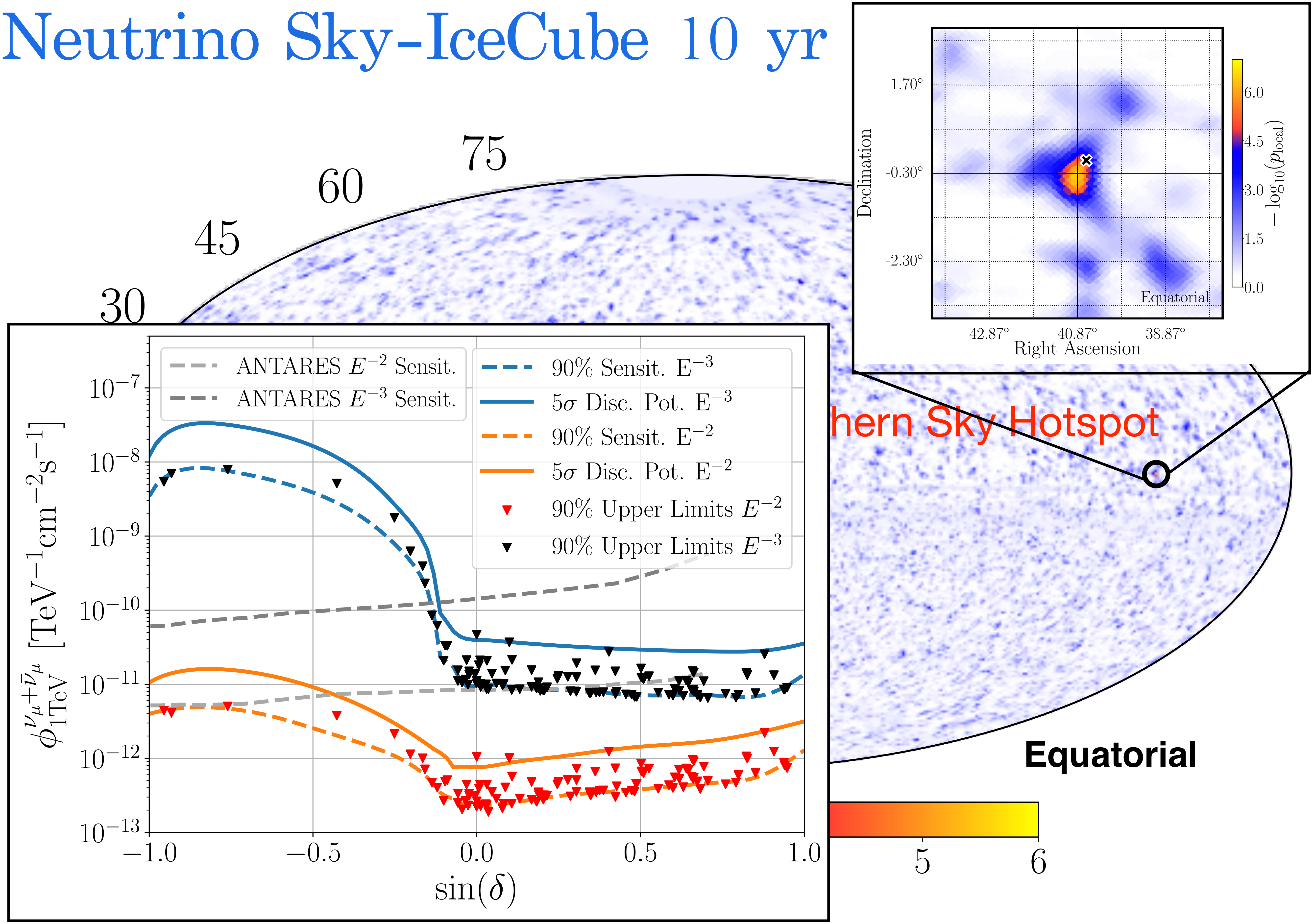

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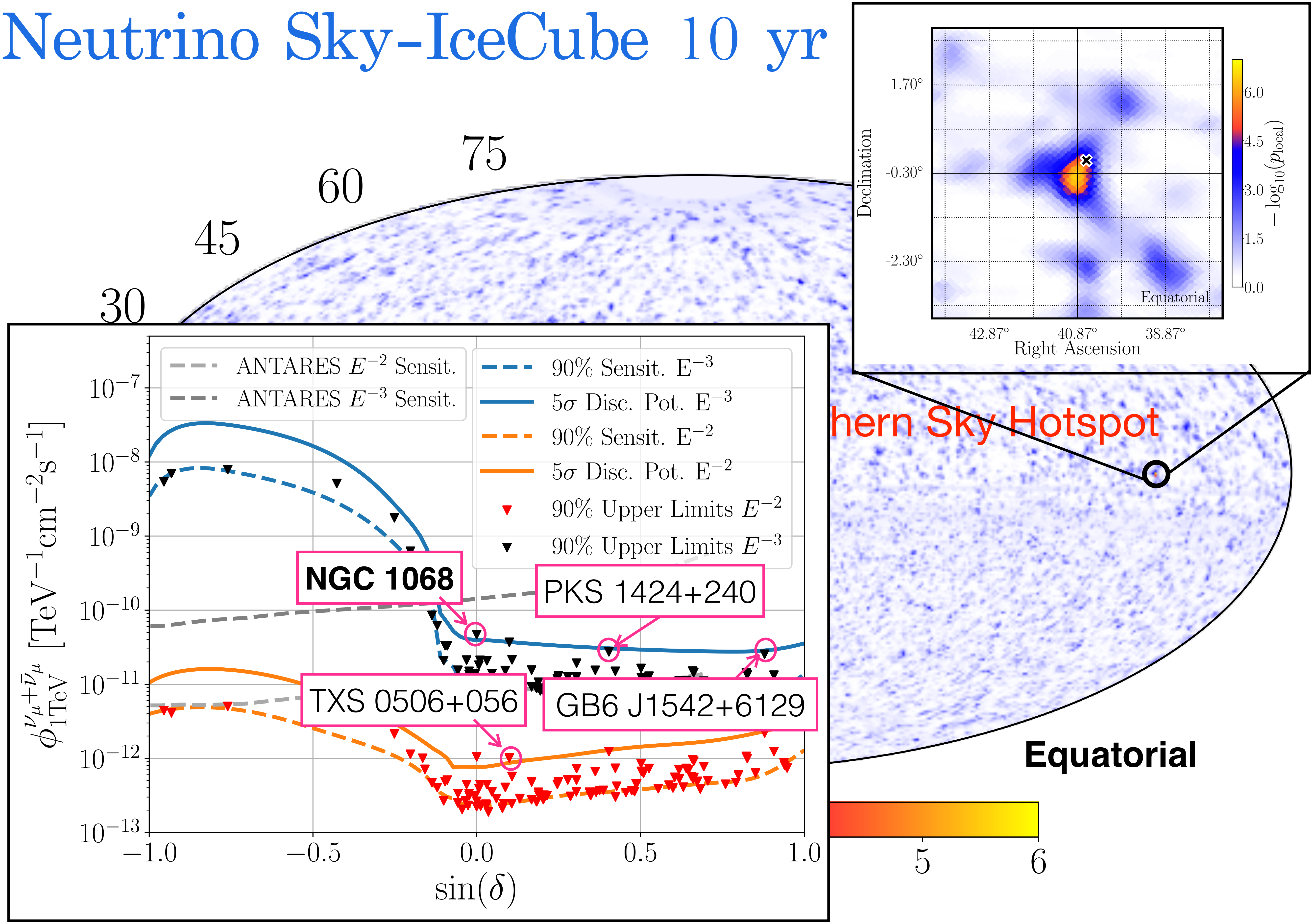
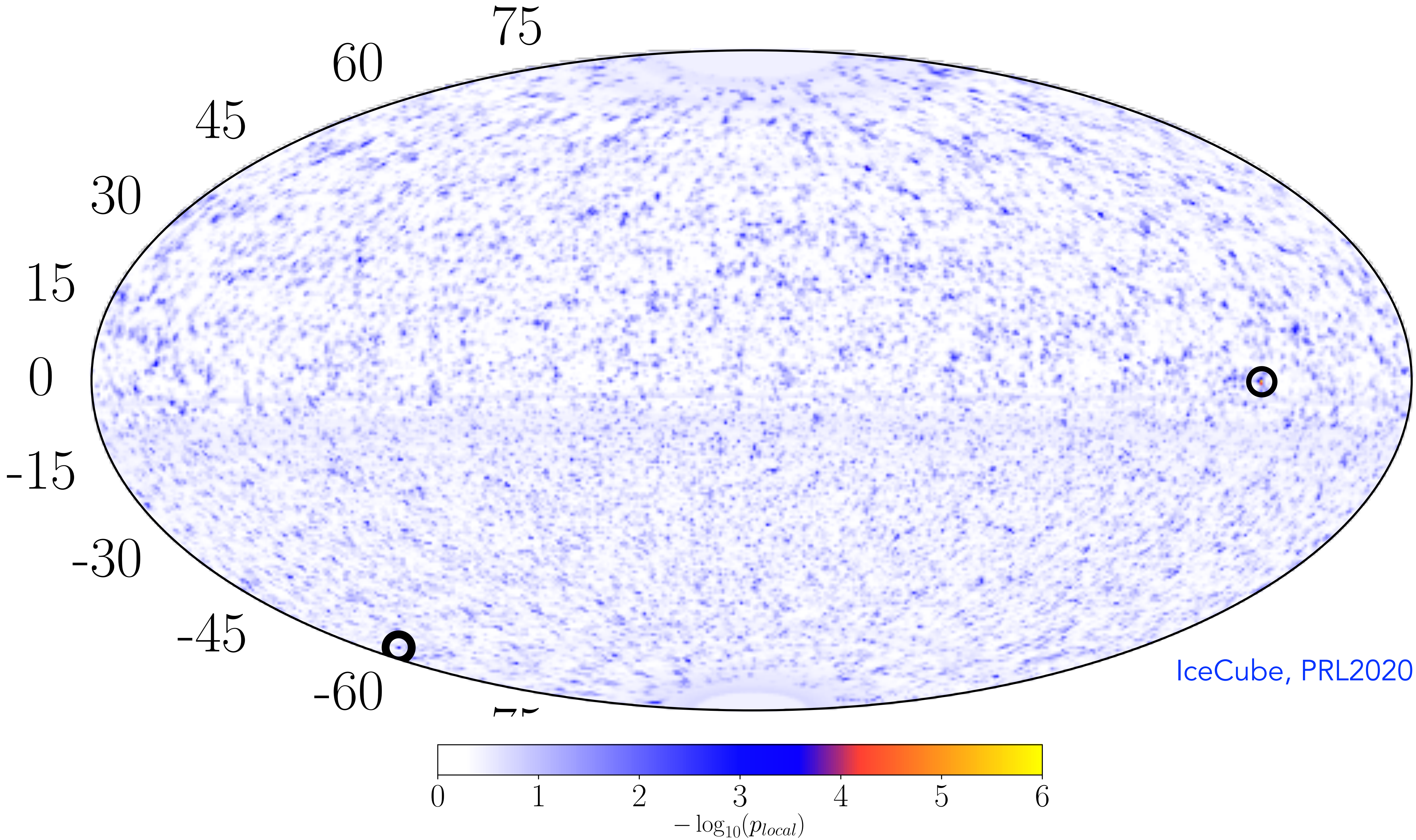


[IceCube, PRL 2020]

Hottest Spot ↔ Hottest Source



IceCube, PRL2020

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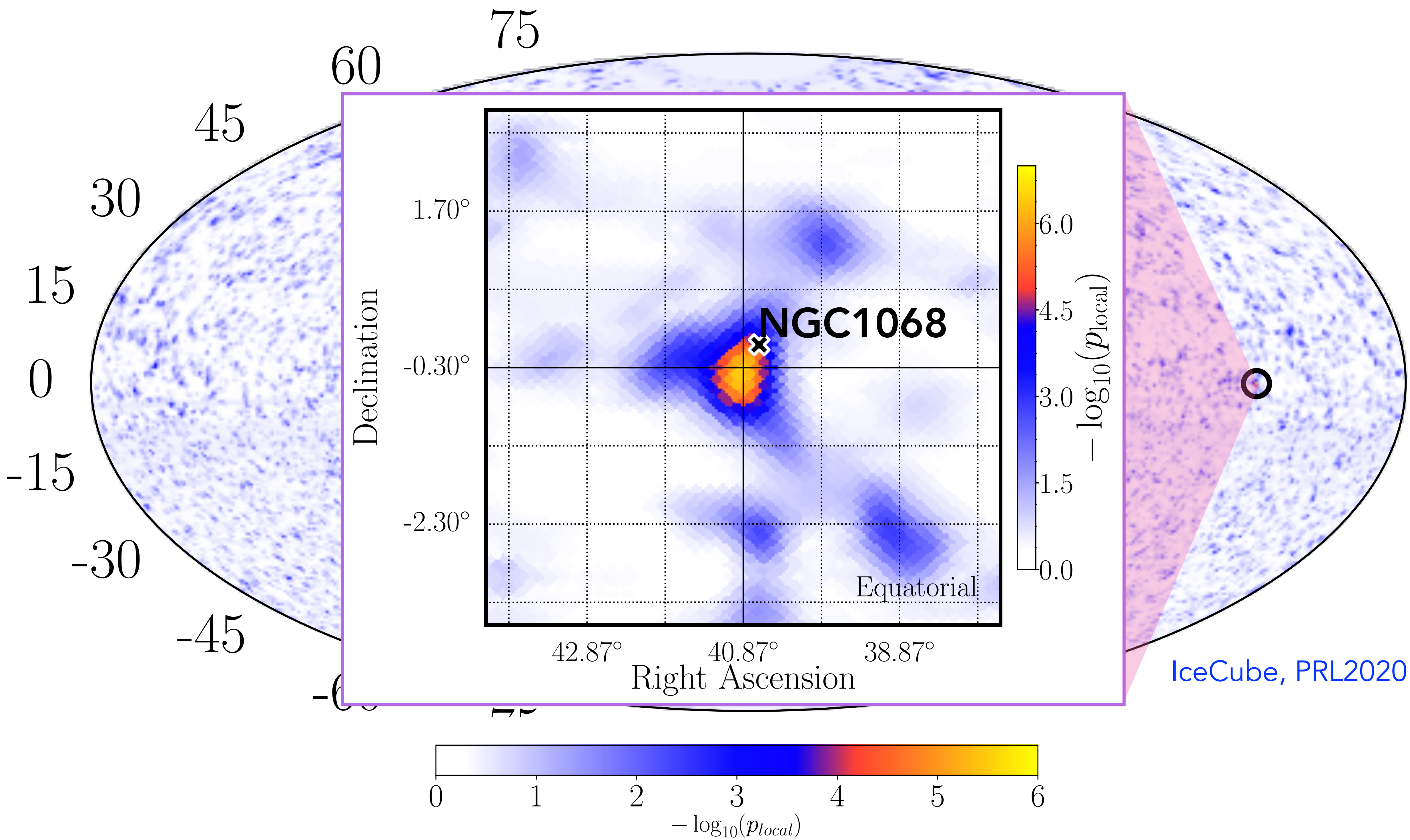

IceCube, PRL2020

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).

NGC 1068 & the Neutrino Signal

Image Credit: NASA/HST

NGC 1068 & the Neutrino Signal

- NGC 1068, aka M77, is a Seyfert 2 galaxy with a heavily obscured nucleus
- One of the best studied AGN, which played a major role in AGN unification scheme
- Compton thick environment with Column density ~ 10^{25} cm^{-2}
- Bright in X-ray, and high infrared luminosity indicating high level of star formation

Image Credit: NASA/HST

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  ▸ *Historically considered as a promising cosmic-ray accelerator.*

Image Credit: NASA/HST

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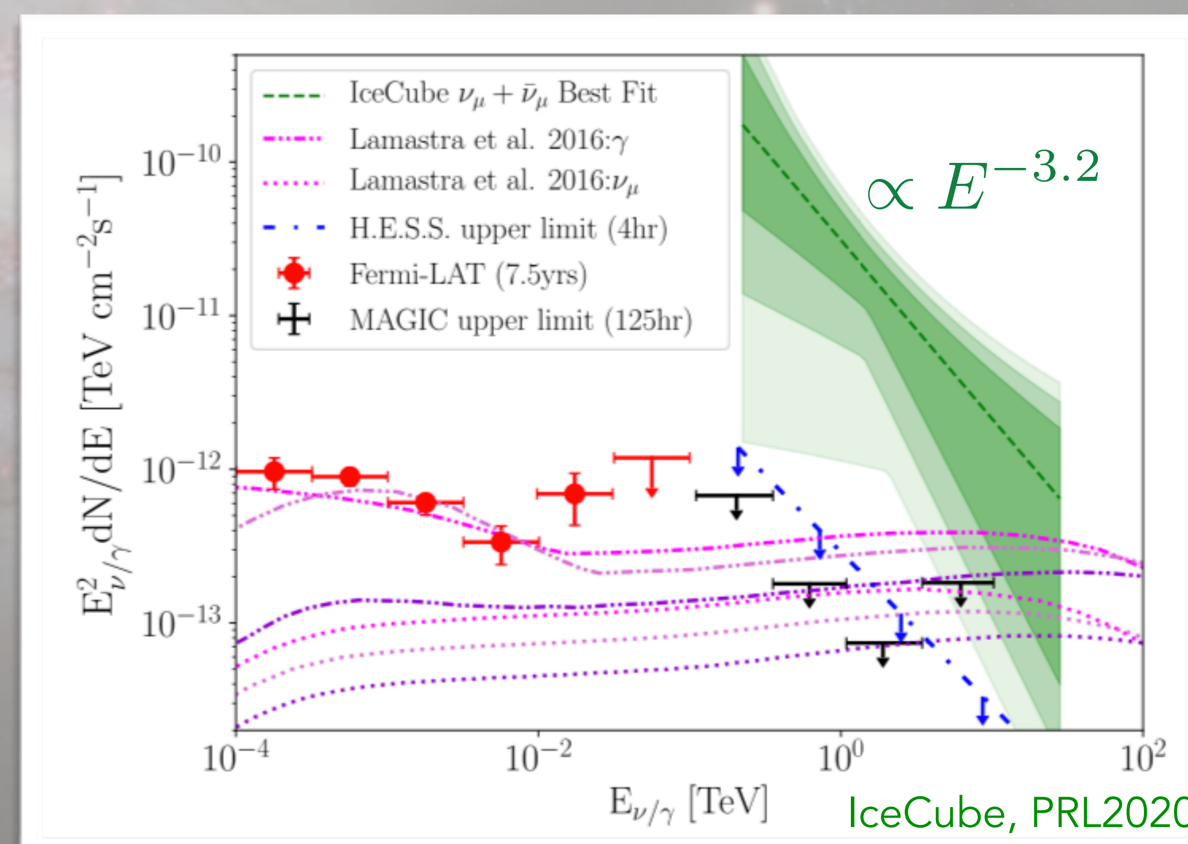
- IceCube 10 yr time-integrated search found 51 neutrinos in the direction of NGC 1068, with a soft spectrum.
- The neutrino flux much higher than the observed γ-ray flux by *Fermi*.
- Models built on measured γ-ray flux by Fermi cannot accommodate the neutrino flux.
- **Obscuring** necessary to absorb the pionic γ-ray accompanying neutrinos.

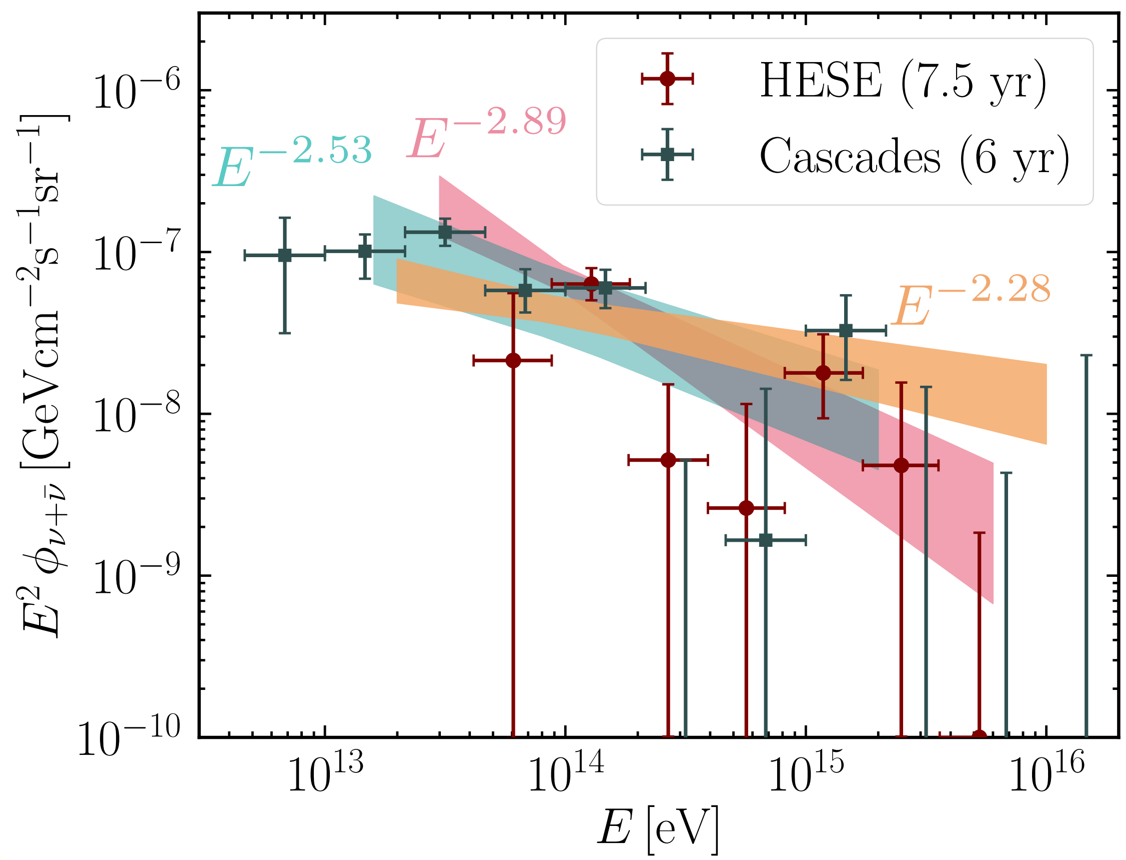


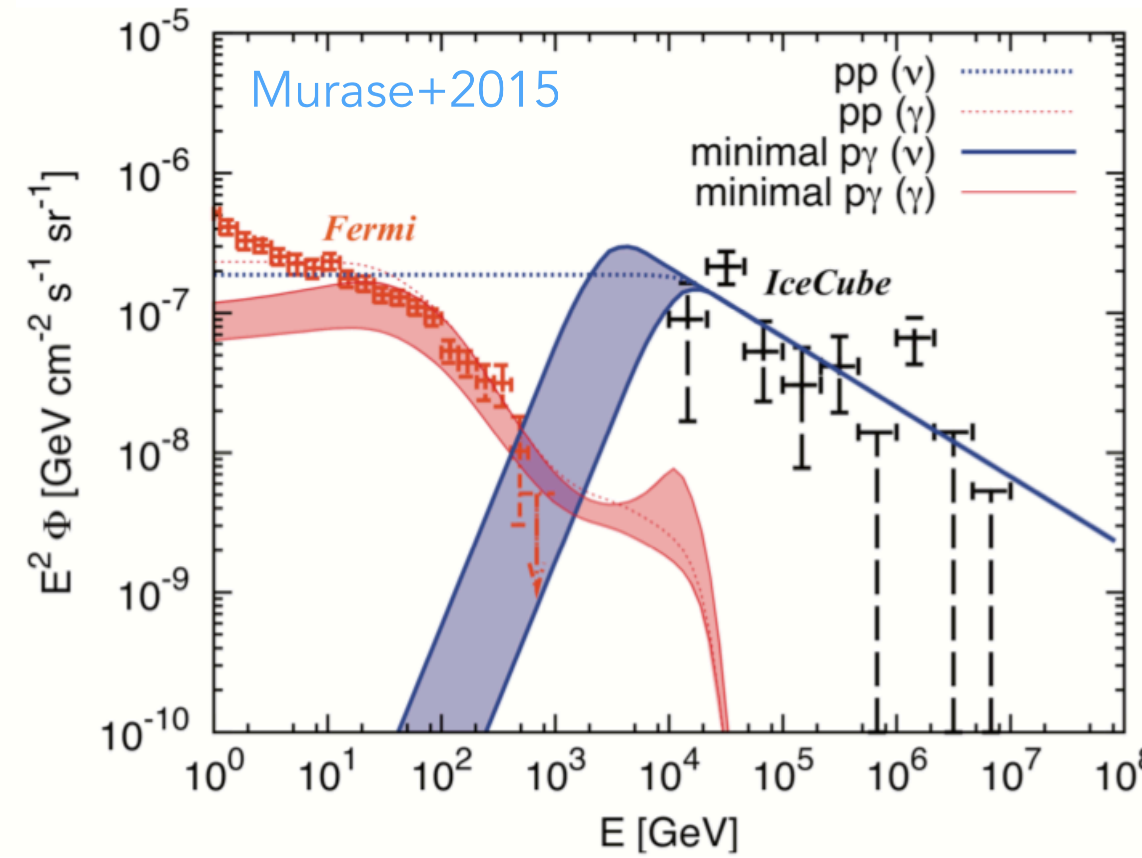
IceCube, PRL2020

Image Credit: NASA/HST

Medium-Energy Excess in Neutrino 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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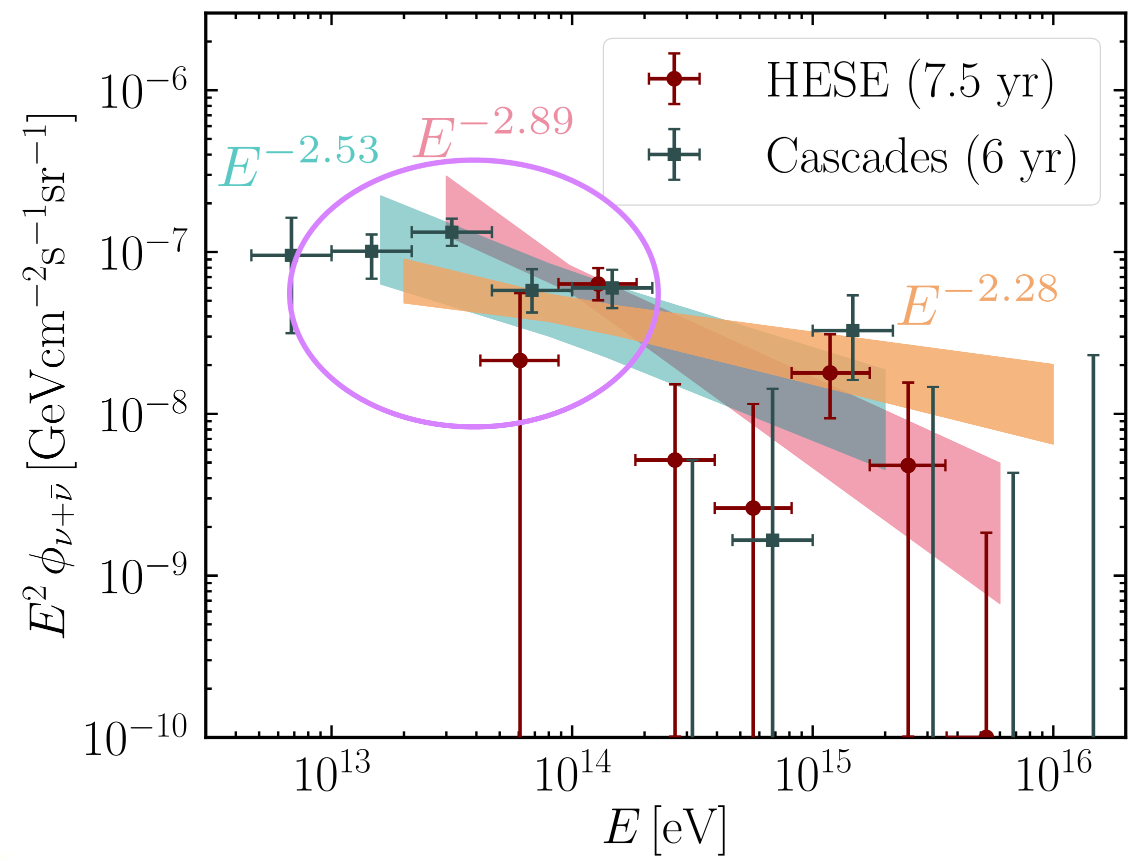
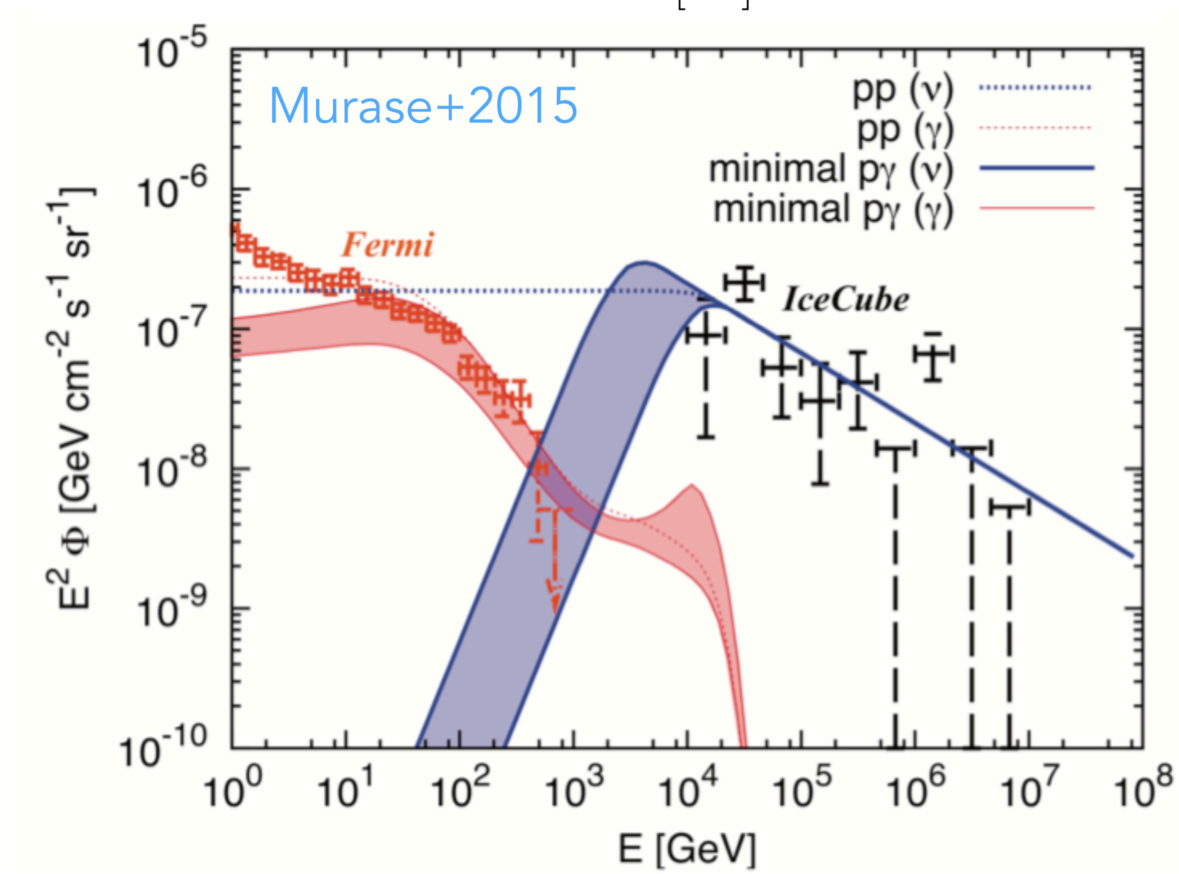




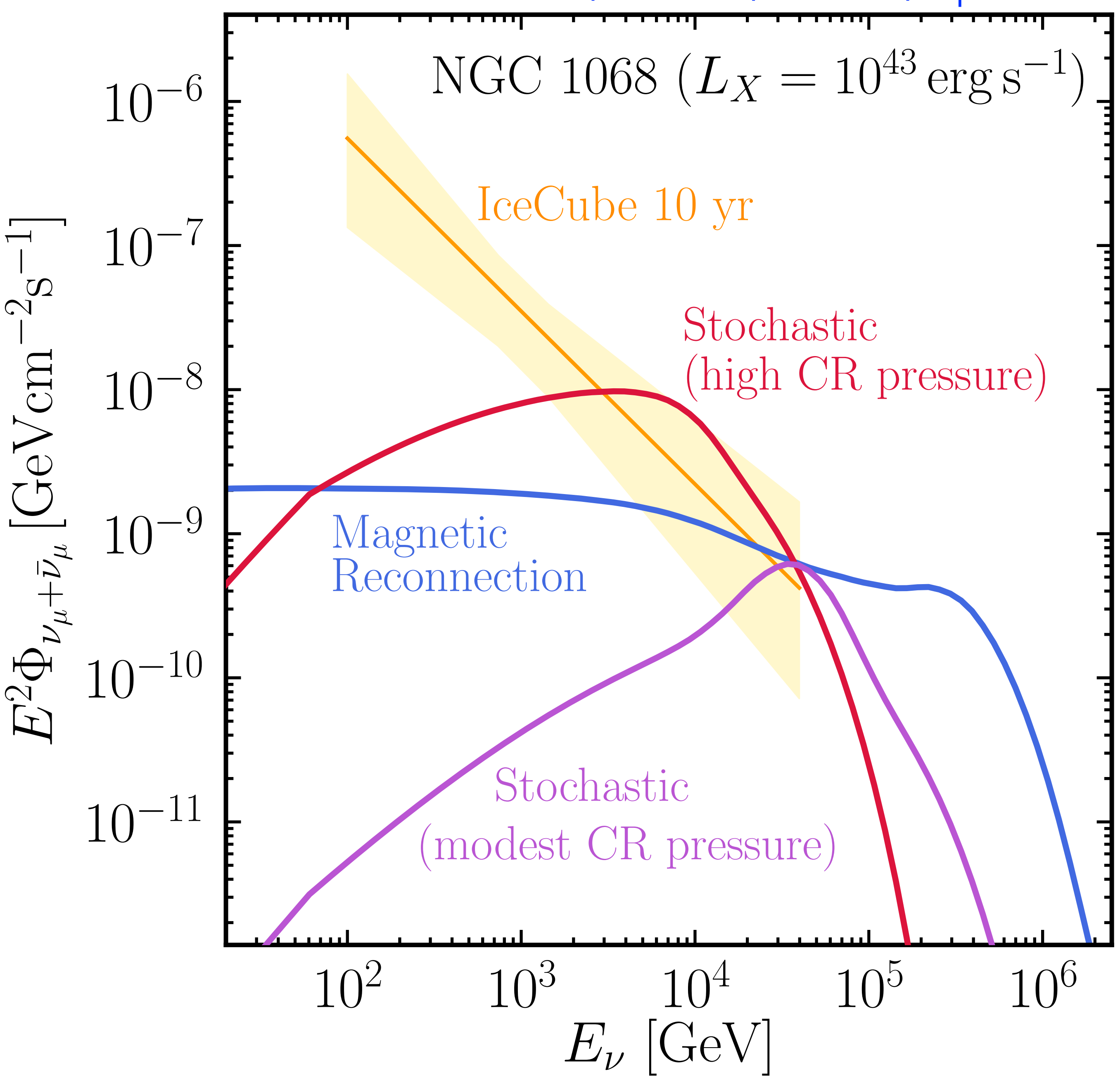
NGC 1068 in AGN-Corona Model

- **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.

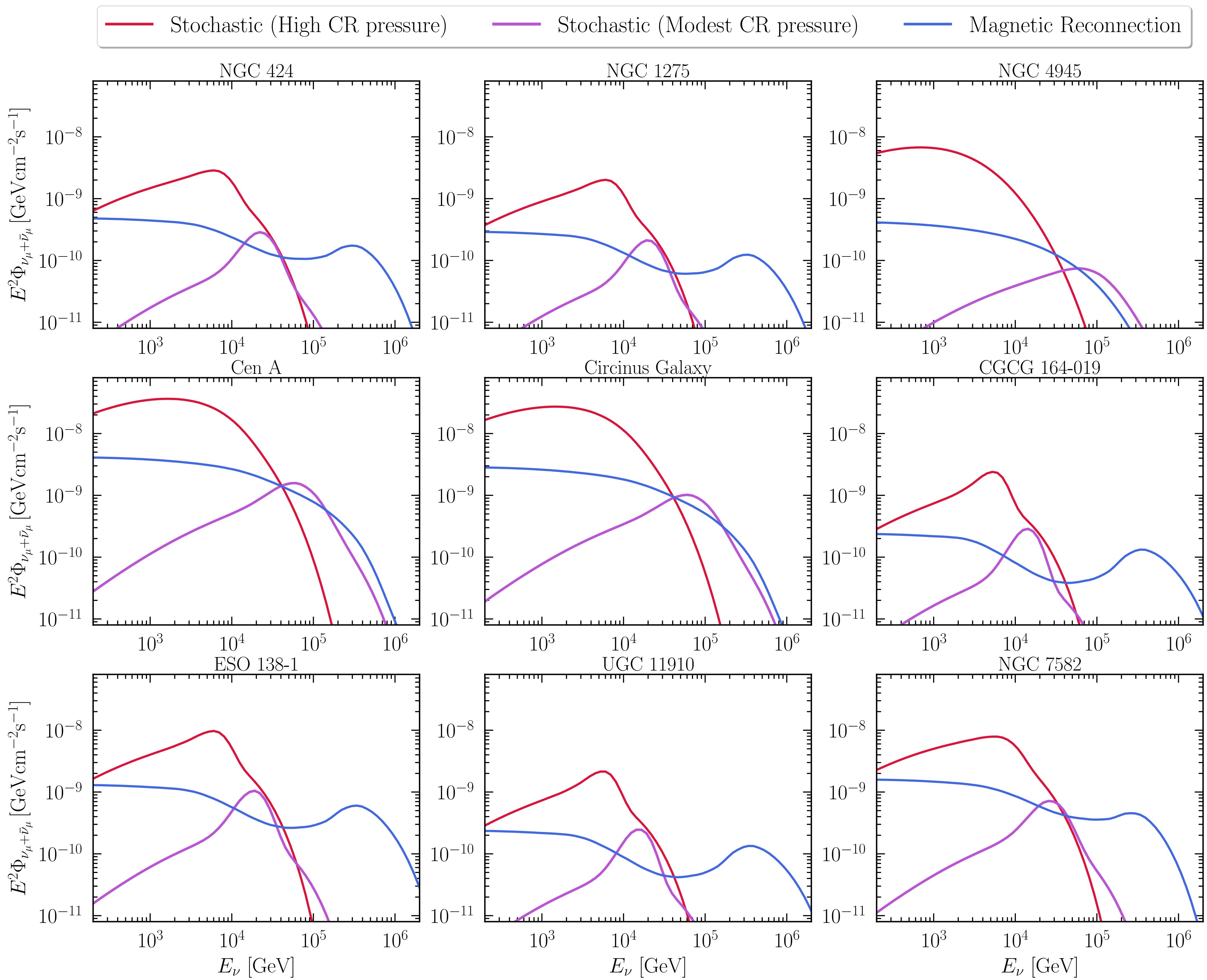
- Accretion dynamics and magnetic dissipation will form a magnetized **corona** above the disk.

- 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



Neutrino flux from Bright Nearby Sources



AK, Murase, Kimura, ApJ 2021

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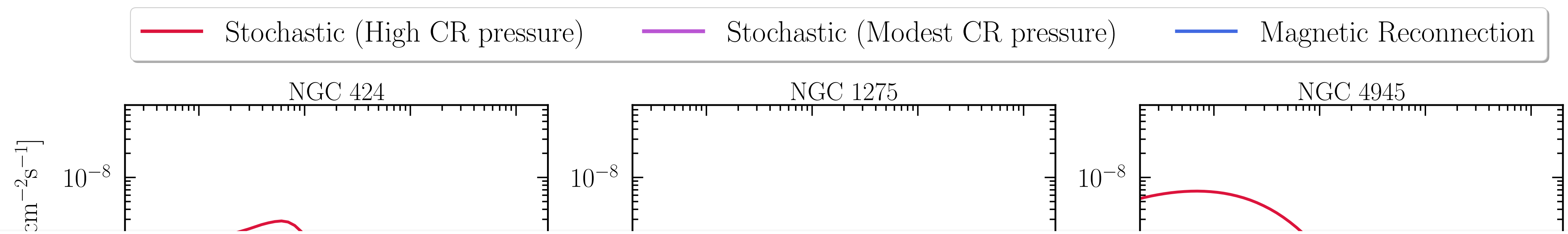
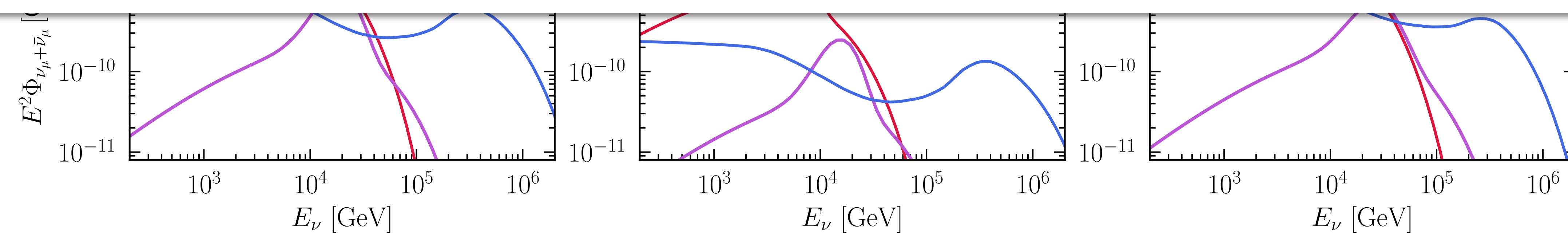


- **NGC 1068 is the brightest source in IceCube.**

Source	p-value Stochastic (High CR pressure)	Stochastic (Modest CR pressure)	Magnetic reconnection
NGC 1068	10^{-6}	0.09	1.8×10^{-4}
NGC 1275	0.03	0.3	0.1
CGCG 164-019	0.04	0.3	0.1
UGC 11910	0.1	0.4	0.09
Cen A	0.5	0.2	0.2
Circinus Galaxy	0.5	0.3	0.3
NGC 7582	0.5	0.5	0.1
ESO 138-1	0.5	0.5	0.09
NGC 424	0.5	0.5	0.5
NGC 4945	0.5	0.5	0.5

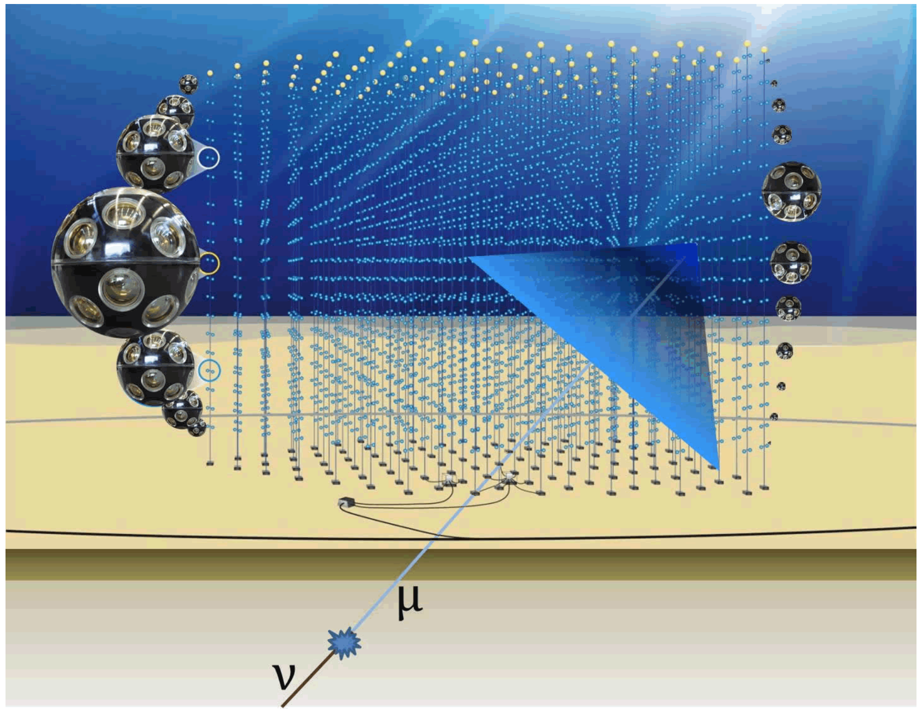


AK, Murase, Kimura, ApJ 2021

KM3NeT & the Bright Nearby Seyferts

- Located in the Northern hemisphere, KM3NeT has a good sensitivity for nearby bright Seyferts, which are mostly located in the Southern sky.

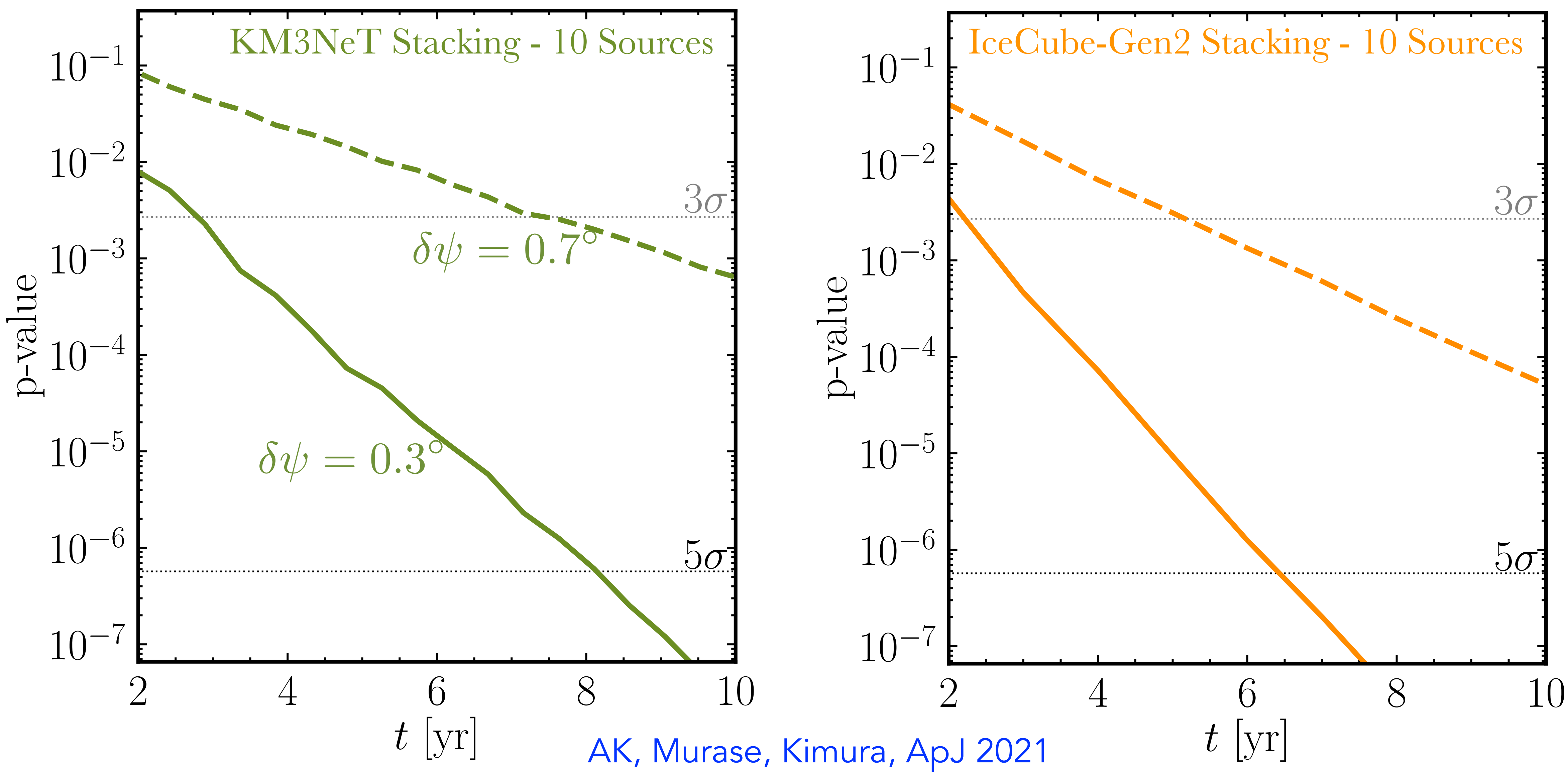
- Cen A and Circinus Galaxy, because of their high flux, proximity, and high degree of visibility are likely to be identified in KM3NeT.



		p-value 1 yr (3 yr)		
Source	Visibility	Stochastic (high CR pressure)	Stochastic (Modest CR pressure)	Magnetic Reconnection
Cen A	0.7	0.001 (9.3×10^{-8})	0.2 (0.07)	0.2 (0.05)
Circinus Galaxy	1.0	0.008 (1.9×10^{-5})	0.2 (0.09)	0.2 (0.07)
ESO 138-1	1	0.1 (0.02)	0.4 (0.3)	0.3 (0.08)
NGC 7582	0.7	0.2 (0.04)	0.4 (0.3)	0.4 (0.2)
NGC 1068	0.5	0.2 (0.05)	0.4 (0.4)	0.4 (0.2)
NGC 4945	0.8	0.5 (0.2)	0.5 (0.4)	0.5 (0.4)
NGC 424	0.7	0.4 (0.2)	0.5 (0.4)	0.5 (0.4)
UGC 11910	0.5	0.4 (0.4)	0.5 (0.5)	0.5 (0.5)
CGCG 164-019	0.4	0.4 (0.3)	0.5 (0.5)	0.5 (0.5)
NGC 1275	0.3	0.4 (0.4)	0.5 (0.5)	0.5 (0.5)

Future Neutrino Telescopes

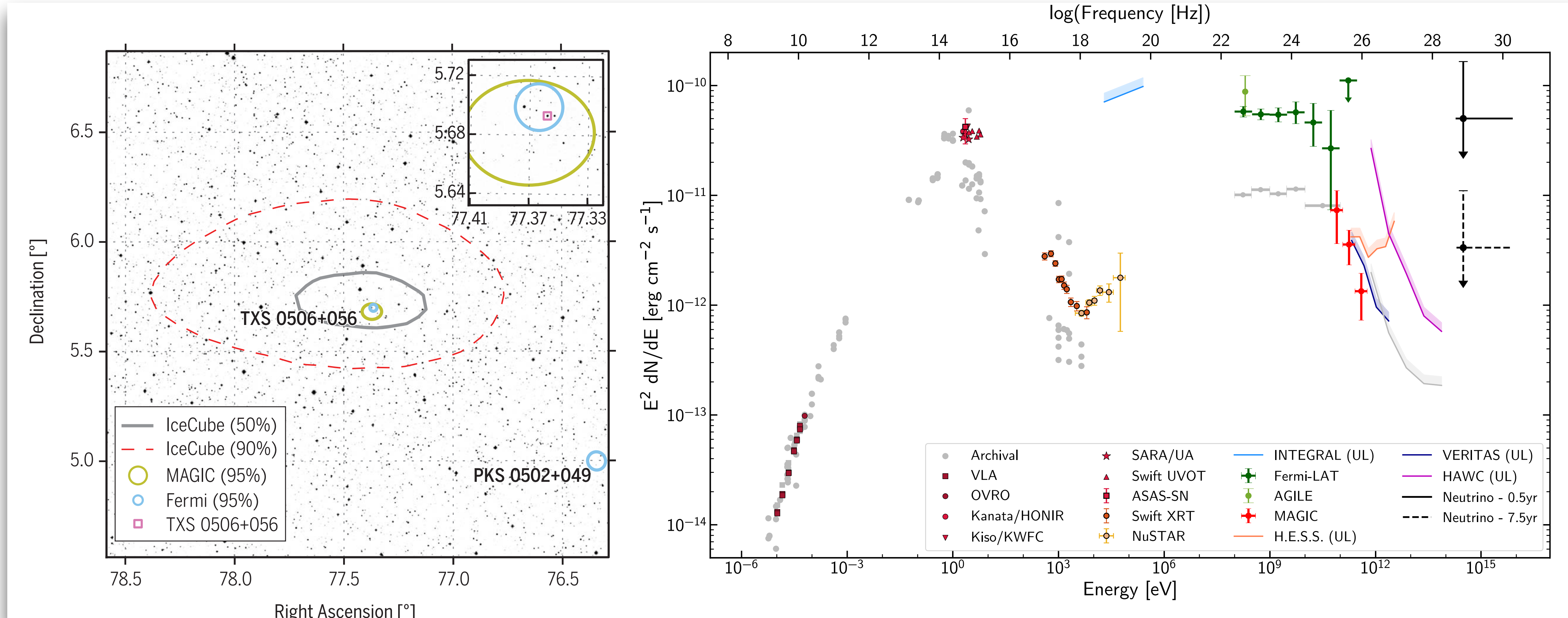
- Stochastic acceleration with Modest CR pressure



AK, Murase, Kimura, ApJ 2021

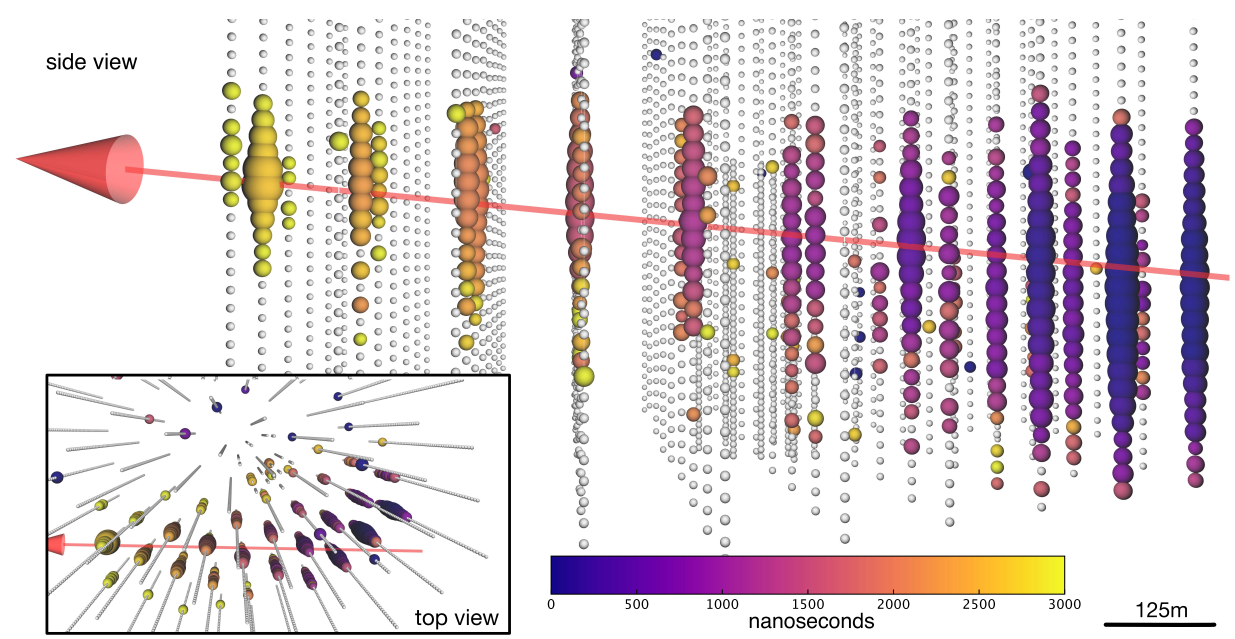
- Collective neutrino emission in Stochastic acceleration with modest CR pressure from nearby bright Seyfert galaxies could be confirmed with operation of next generation of neutrino telescopes.

Multimessenger Observation of TXS 0506+056



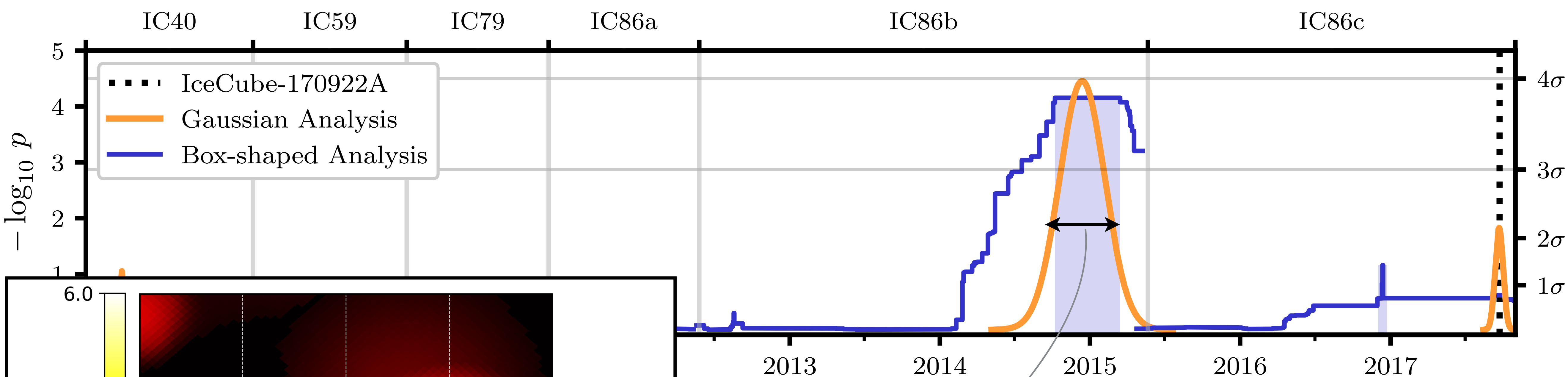
[IceCube, Science 2018]

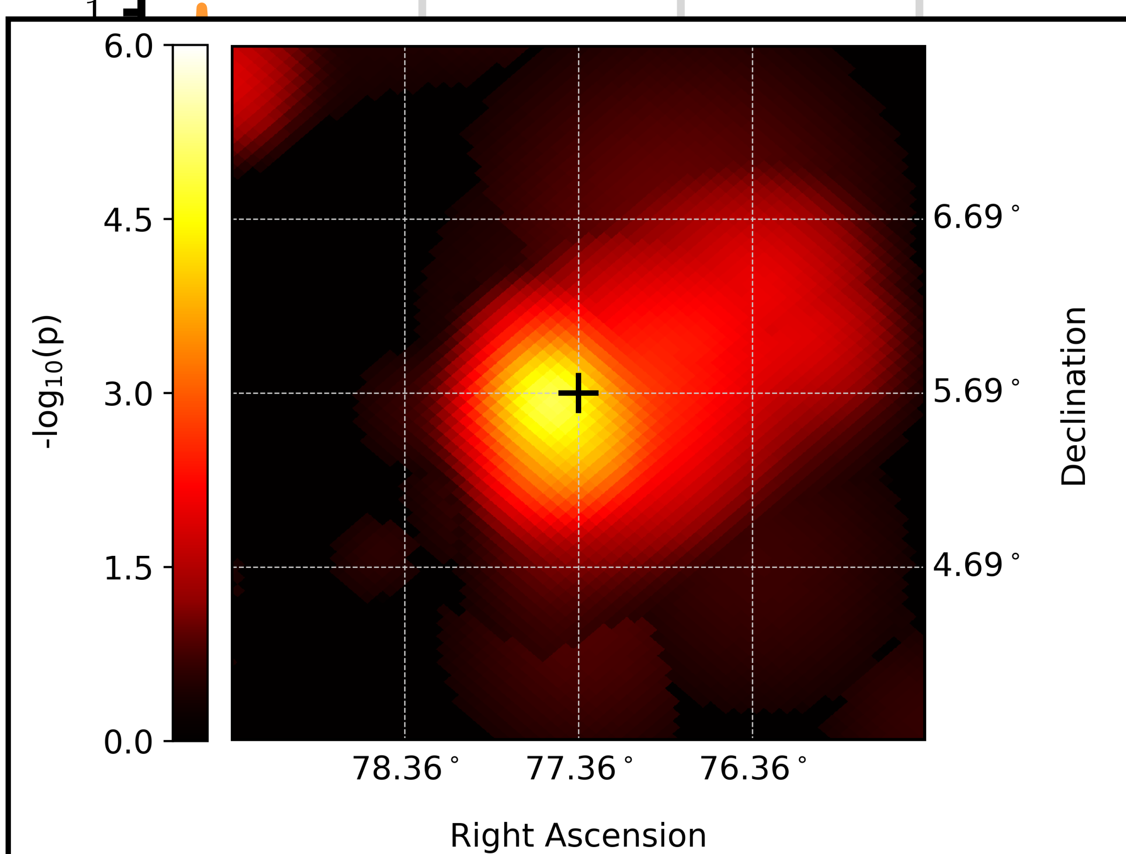
- Up-going track observed on September 22, 2017 from 5.7° below horizon with best fit neutrino energy of ~300 TeV for E^{-2} Spectrum.
- Coincidence with enhanced γ-ray activity, chance correlation rejected at the level of 3σ.



Neutrino Flare in 2014-15

Time-dependent search in the direction of TXS 0506+056 revealed a **neutrino flare** in December 2014.





$$T_{\mathrm{W}} = 110^{+35}_{-24} \text{ days}$$

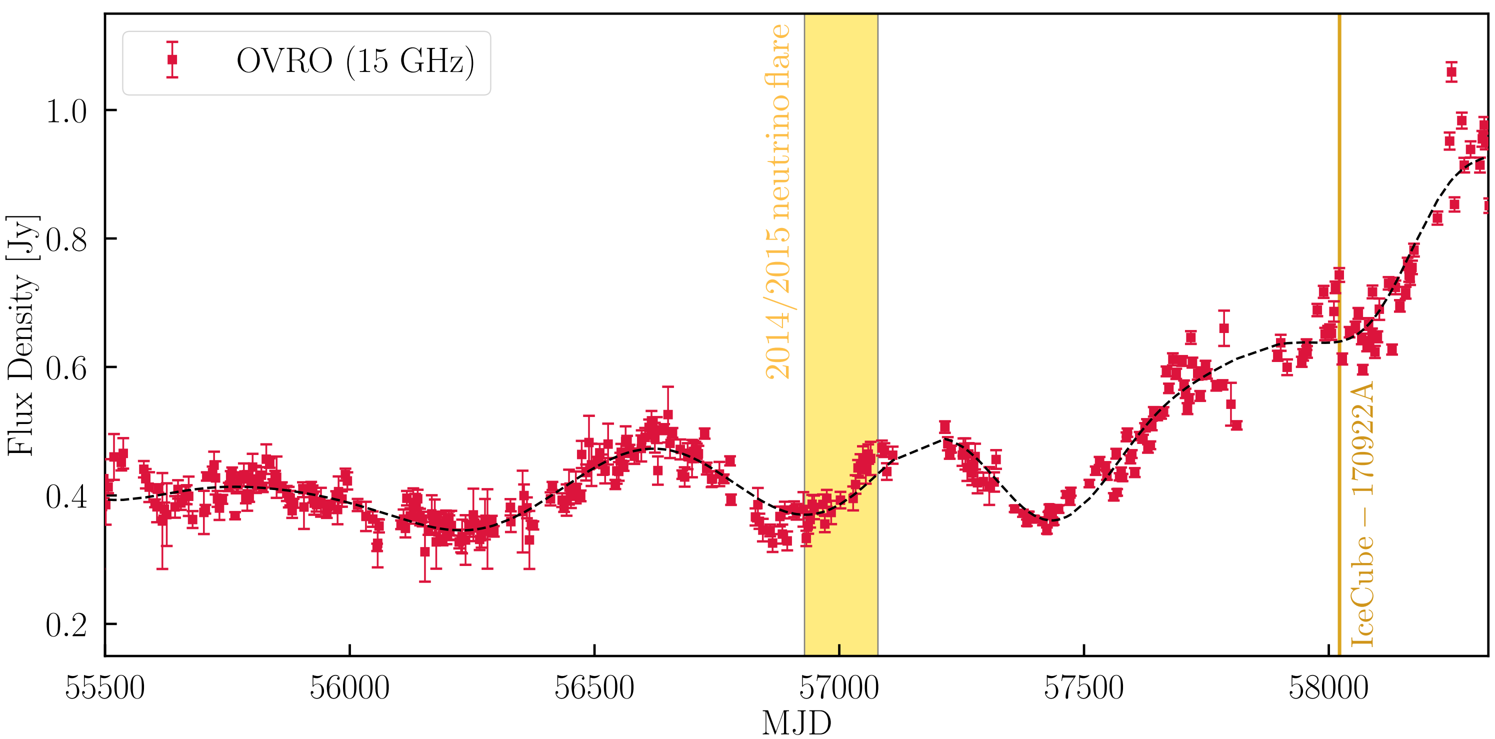
$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15} \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

13±5 signal events rejecting background hypothesis at 3.5σ

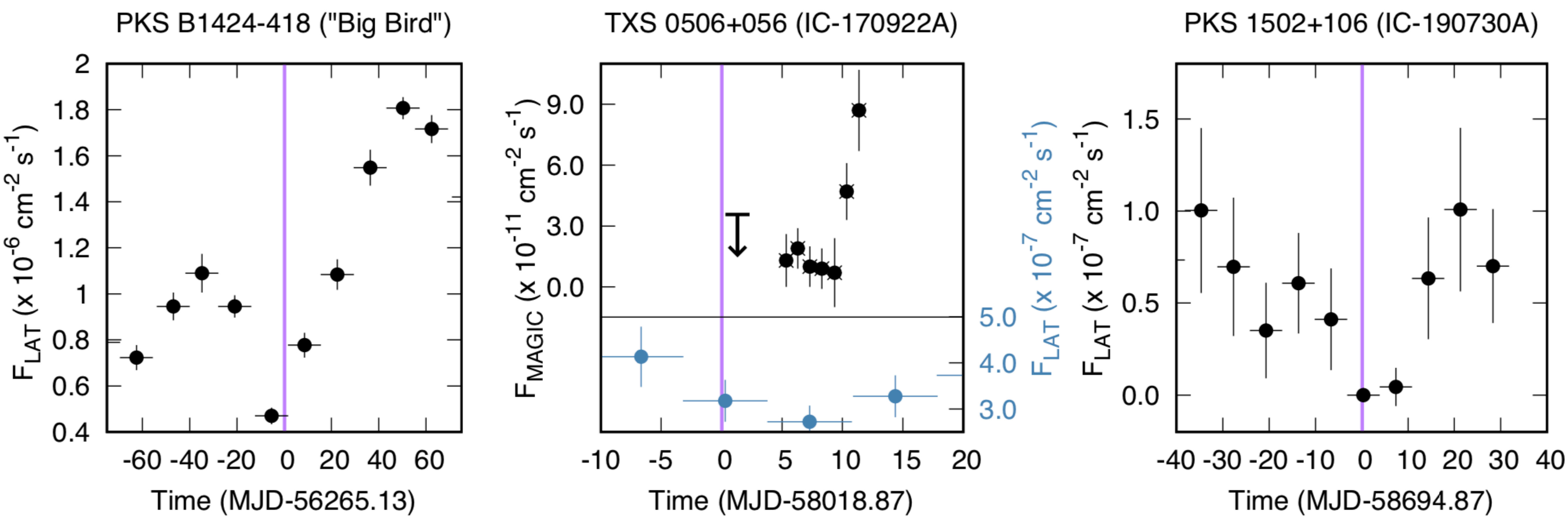
[IceCube, Science 2018]

γ–Neutrino Connection

- The 10 year averaged flux of neutrinos from TXS 0506+056 is dominated by the 2014 burst.
- Contrary to IC 170922A, No enhanced γ-ray activity for the neutrino burst in 2014. May be hardening of the spectrum [Padovani+, 2018] although no significant slope change [Garrappa+2019].
- Explaining broadband spectrum of the source during neutrino burst is challenging with single zone models. [Reimer+2018, Murase+2018, Gao+2019]
- Suppression inside the source, EBL absorption, and large intergalactic magnetic filed makes it difficult to observe the possible enhancement for such sources. [Halzen, AK+, APJ Lett 2018]
- Enhanced Radio emission and possible jet structure demonstrates a potentially more complicated picture. [Kun+ 2018, Britzen+2019, de Brujin+2020]
- Accommodating the flux without overshooting X-ray flux is challenging [Murase+ 2018, Petrupoulue+2020]



Emerging Feature: γ-ray Suppression

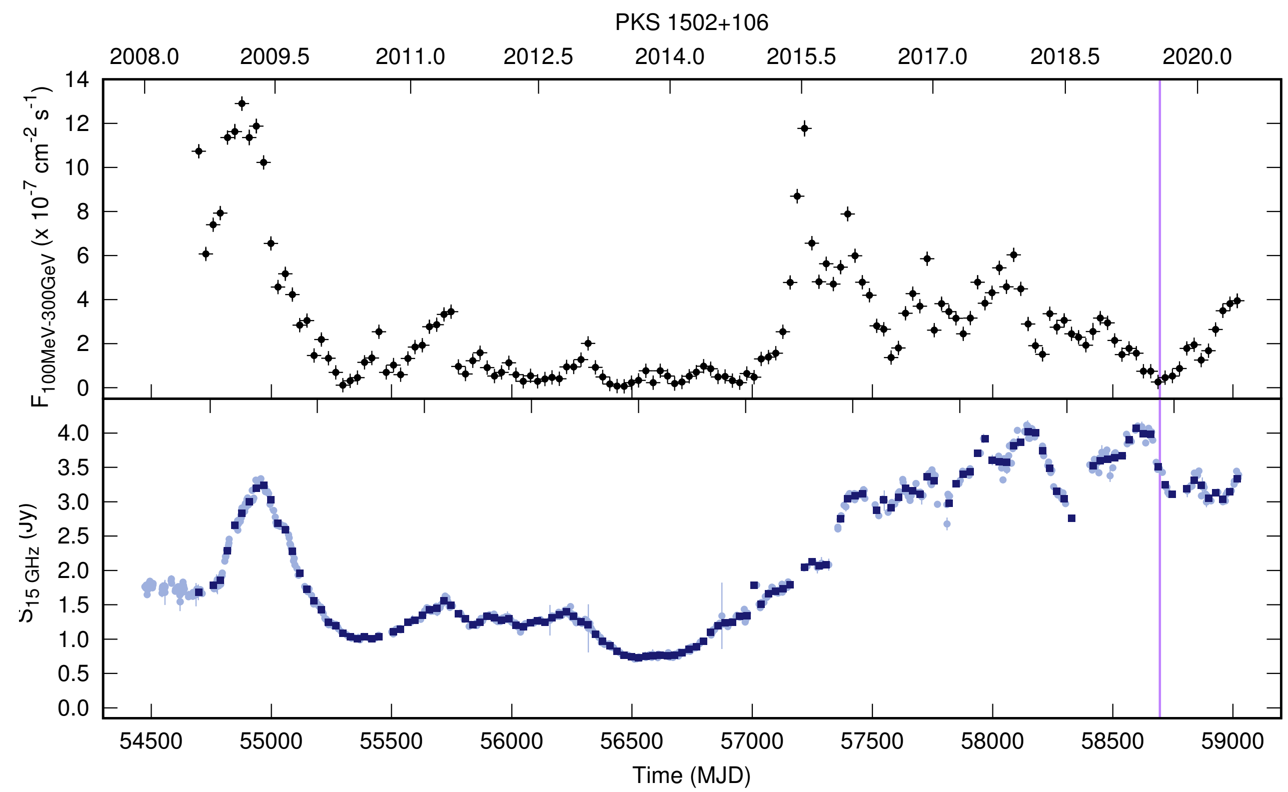


[Kun+ 2021]

Sources found to be in quiet mode in gamma-rays at the time of a high-energy neutrino alert detection.

More Coincidences

- Additional coincidences
  - IC 190730 with PKS 1502+106
  - IC 200107 and 3HSP J095507.9 +355101
  - Coincidence with radio enhancement [Hovatta+ 2020]



- Coincidence with Tidal Disruption Events (TDEs): AT 2019fdr [Reusch+ 21], AT 2019dsg [Stein+ 2021]

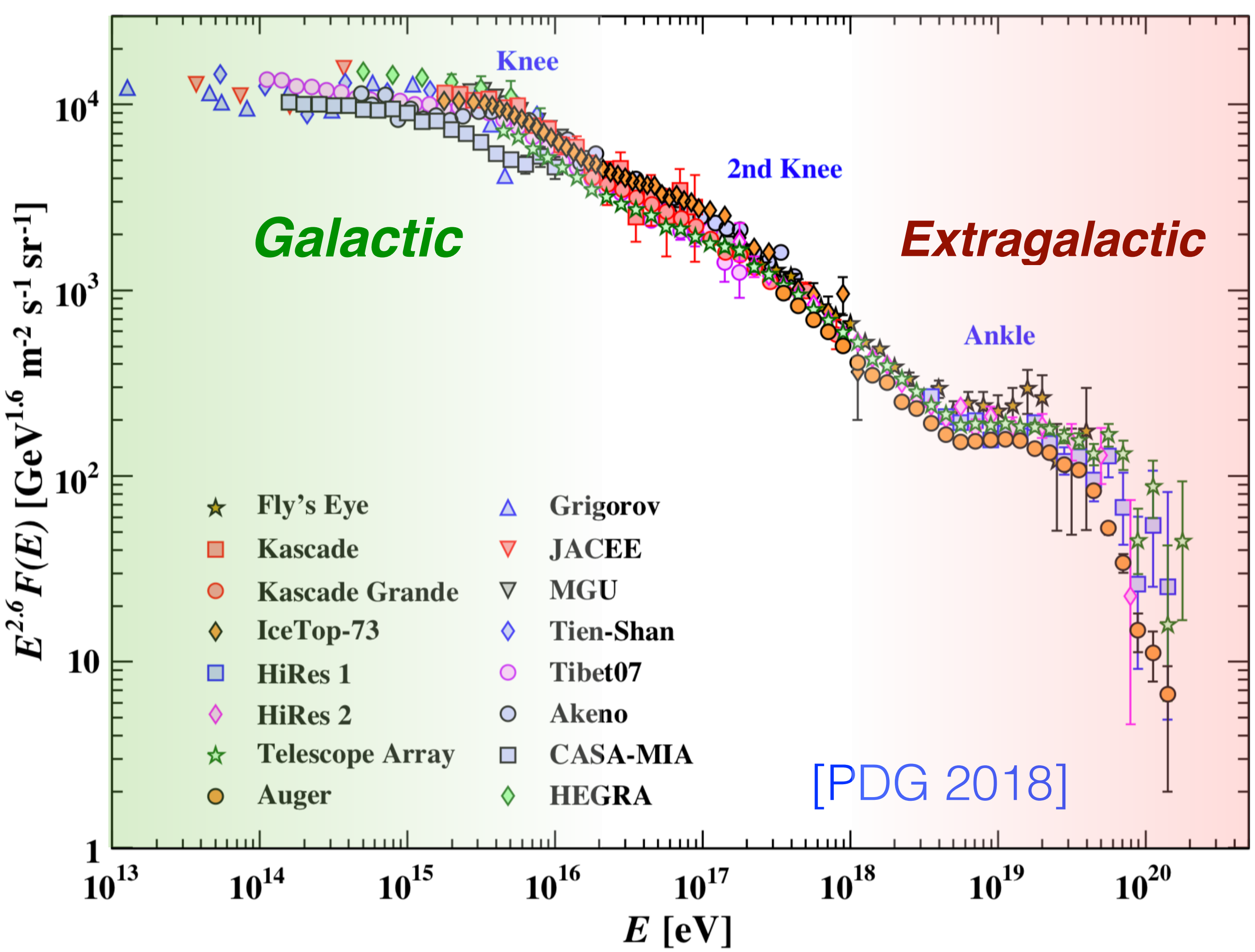
- Studies suggest common mechanism between TDEs and AGN neutrino emission [Murase+ 2020]

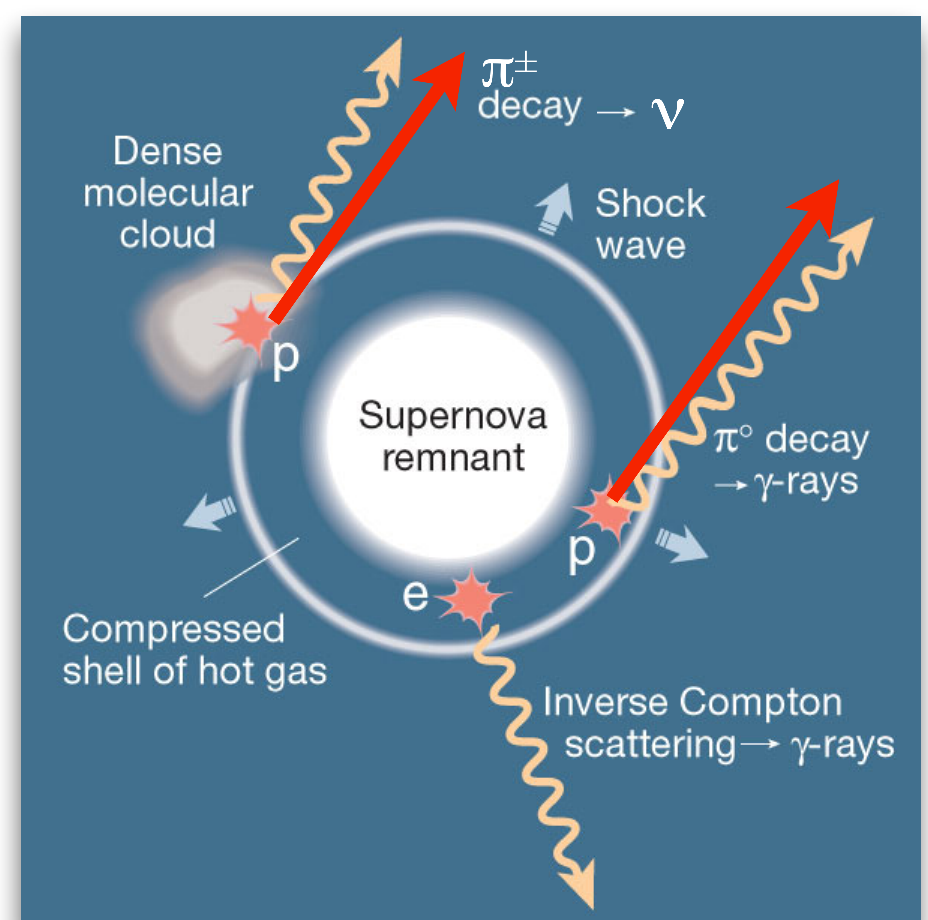
- More data required for a more coherent picture.

Credit: DESY, Science Communications Lab

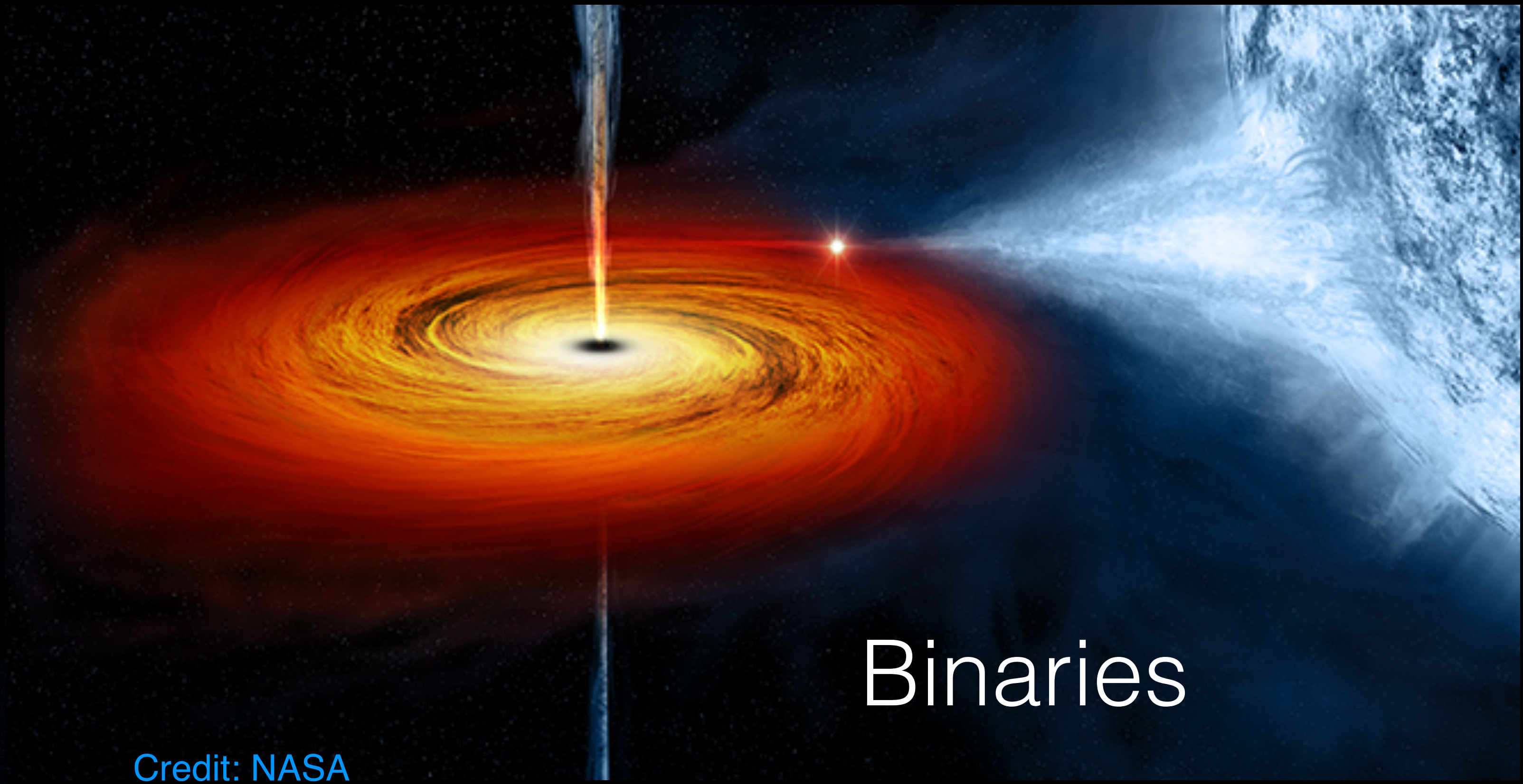
Galactic Cosmic Ray Accelerators

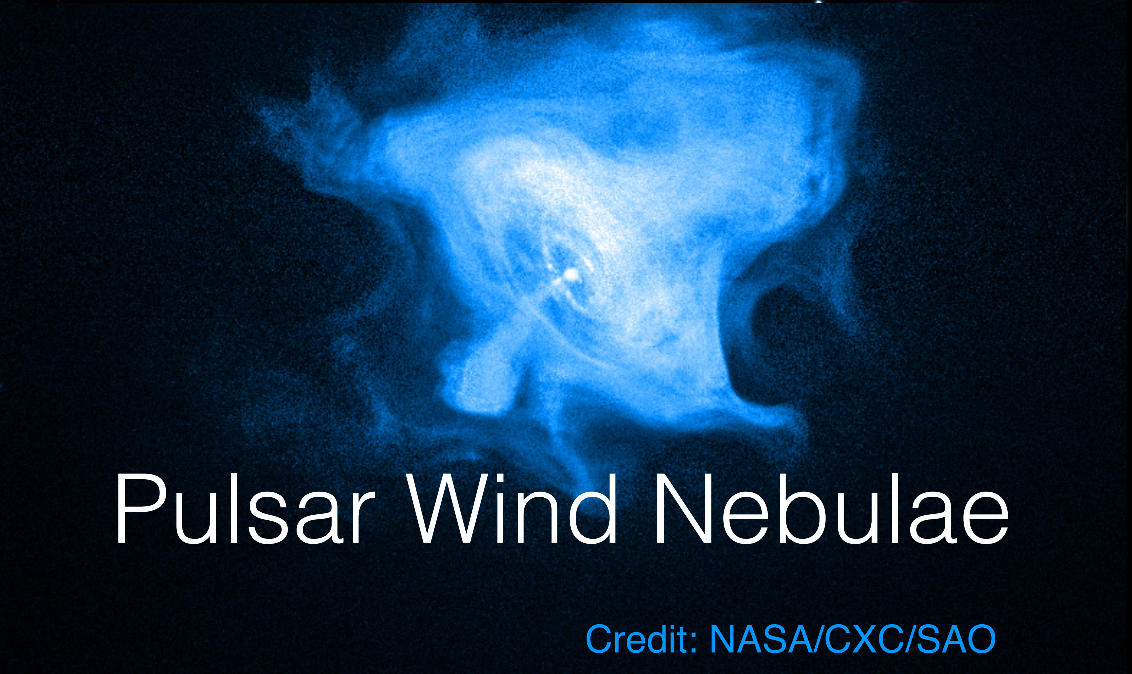
- The search for Galactic cosmic neutrino sources concentrates on the search for "Pevatrons" which have the required energetics to produce cosmic rays up to the knee in the spectrum.
- ``Pevatrons" will produce pionic γ-rays whose spectrum extends to several hundred TeV without cut-off.
- Supernova remnant meet such condition.
- TeV γ-rays should be accompanied by TeV neutrinos, observable at IceCube.

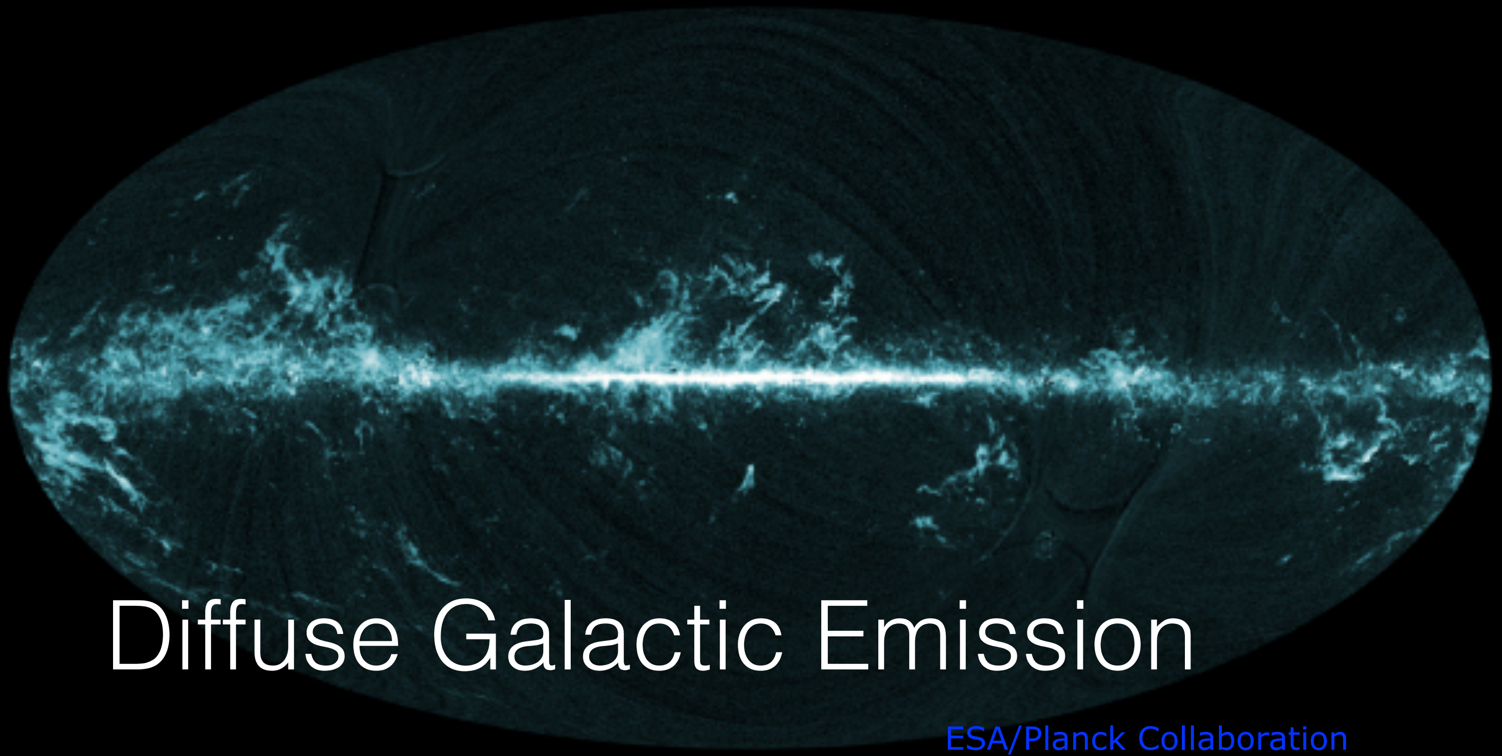




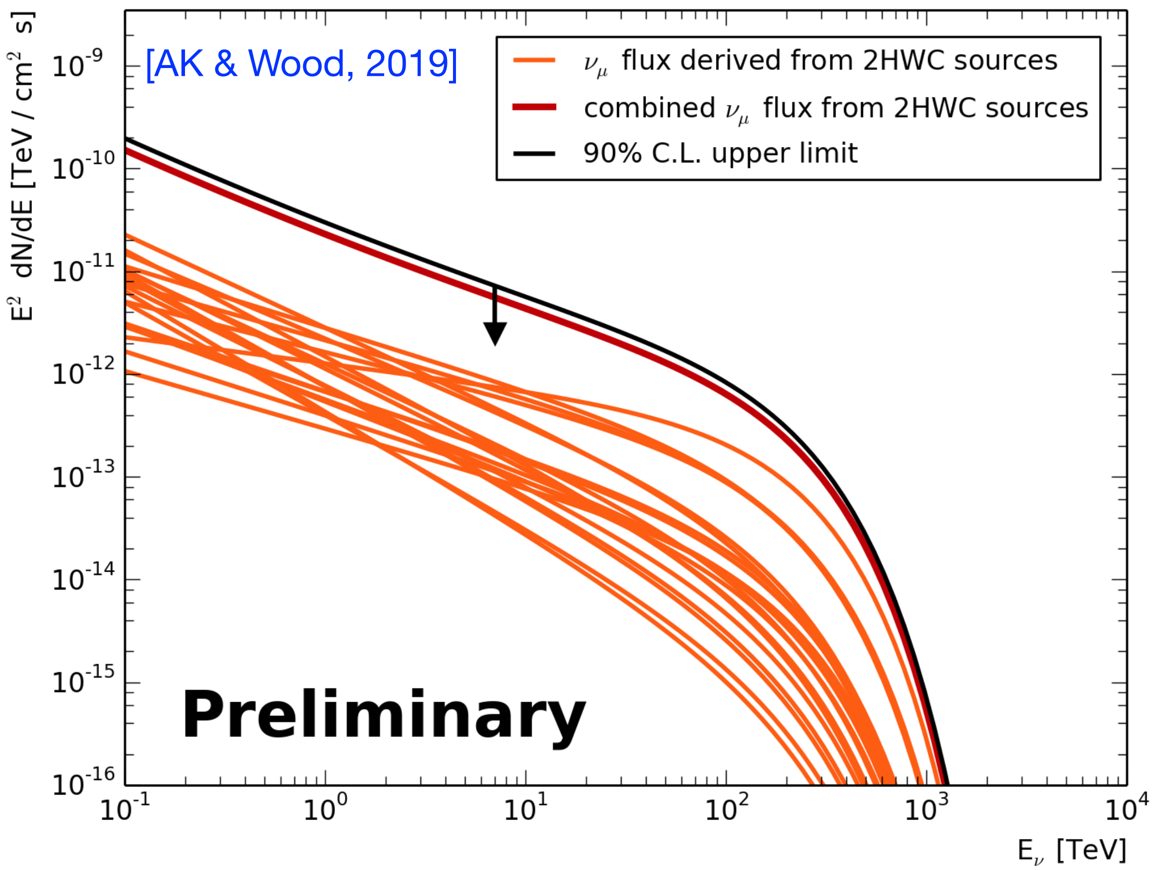
Potential Galactic Sources



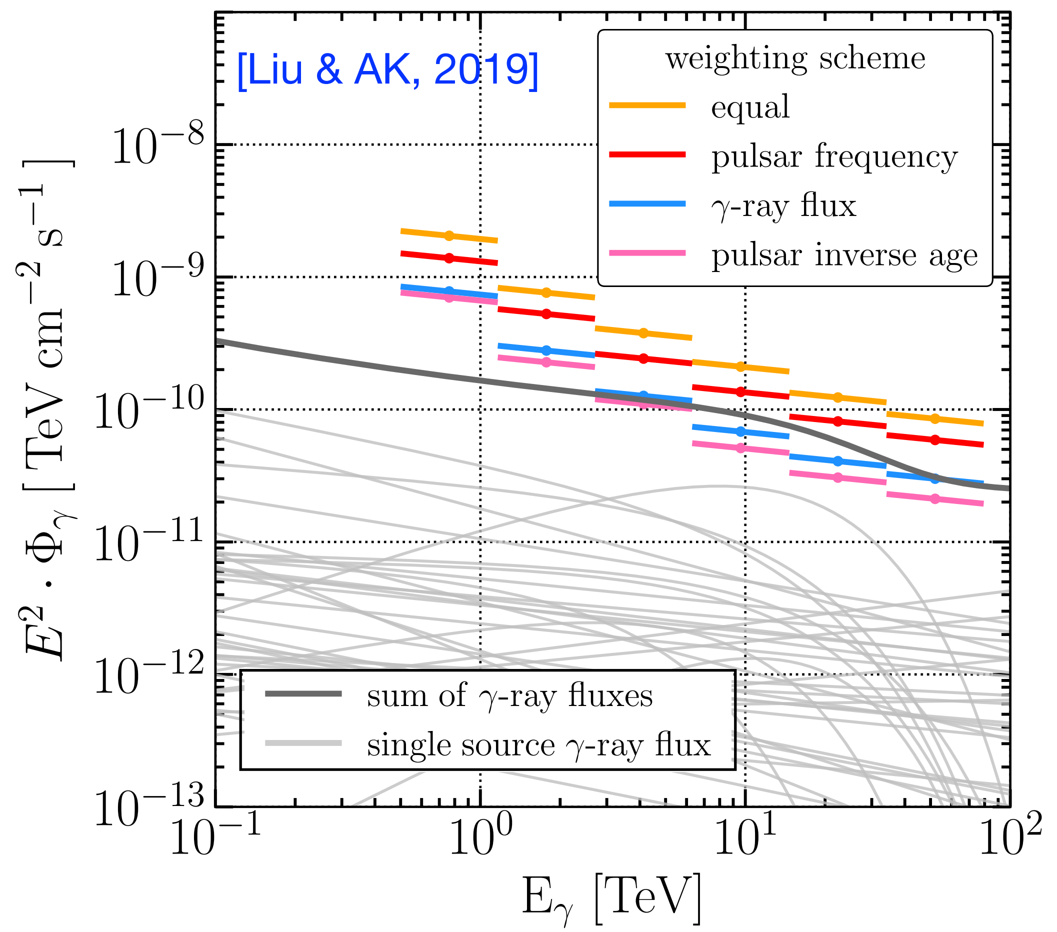




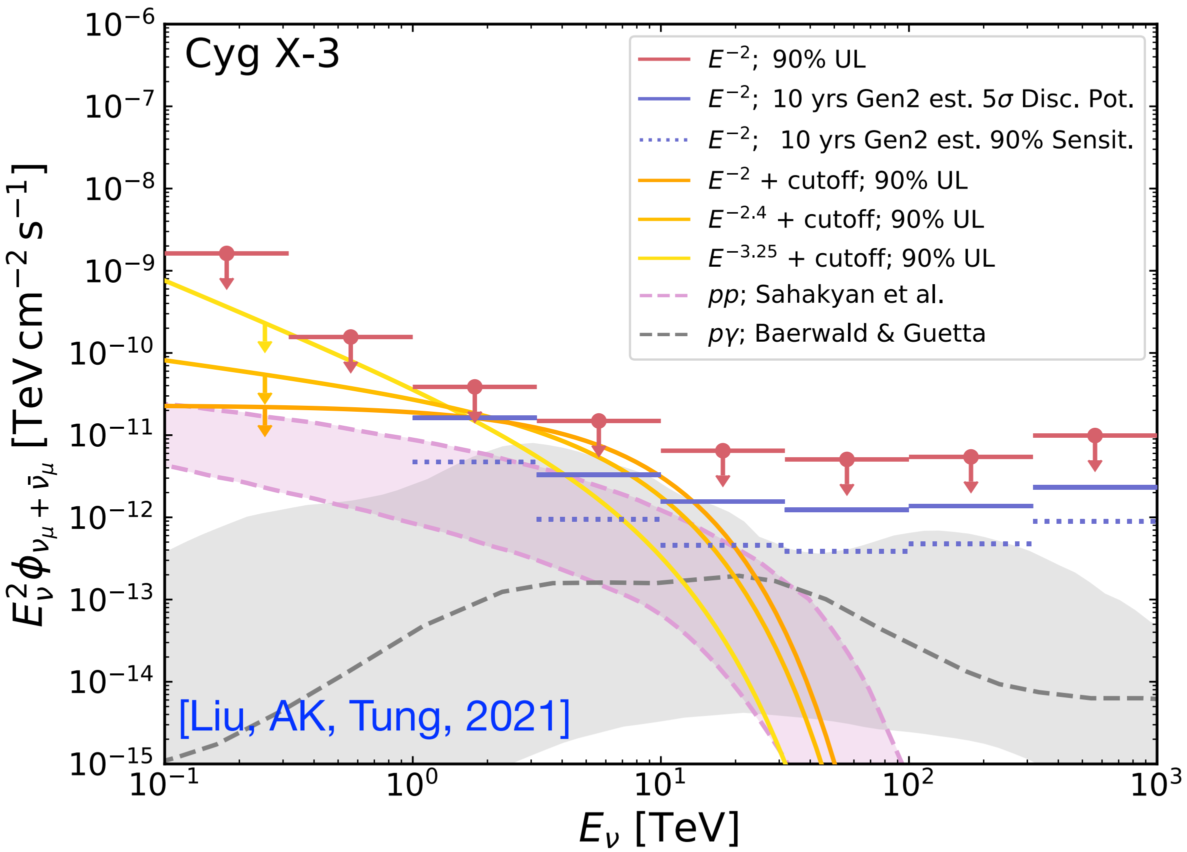
Supernova Remnants



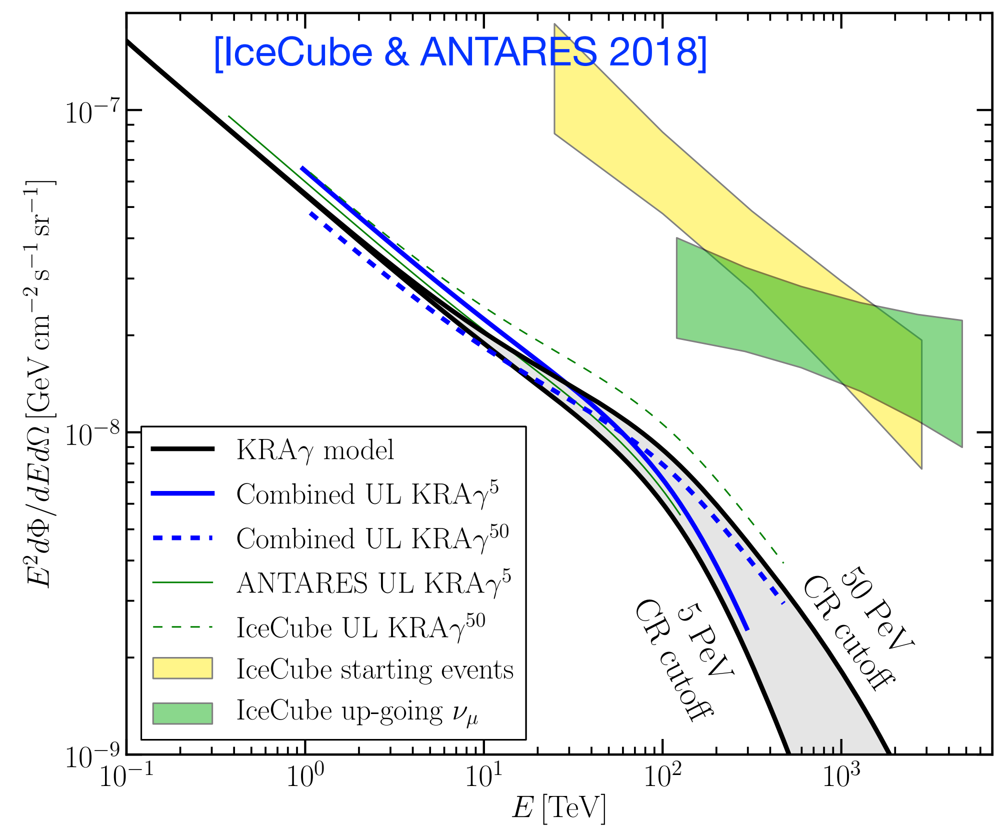
Pulsar Wind Nebulae



Binaries

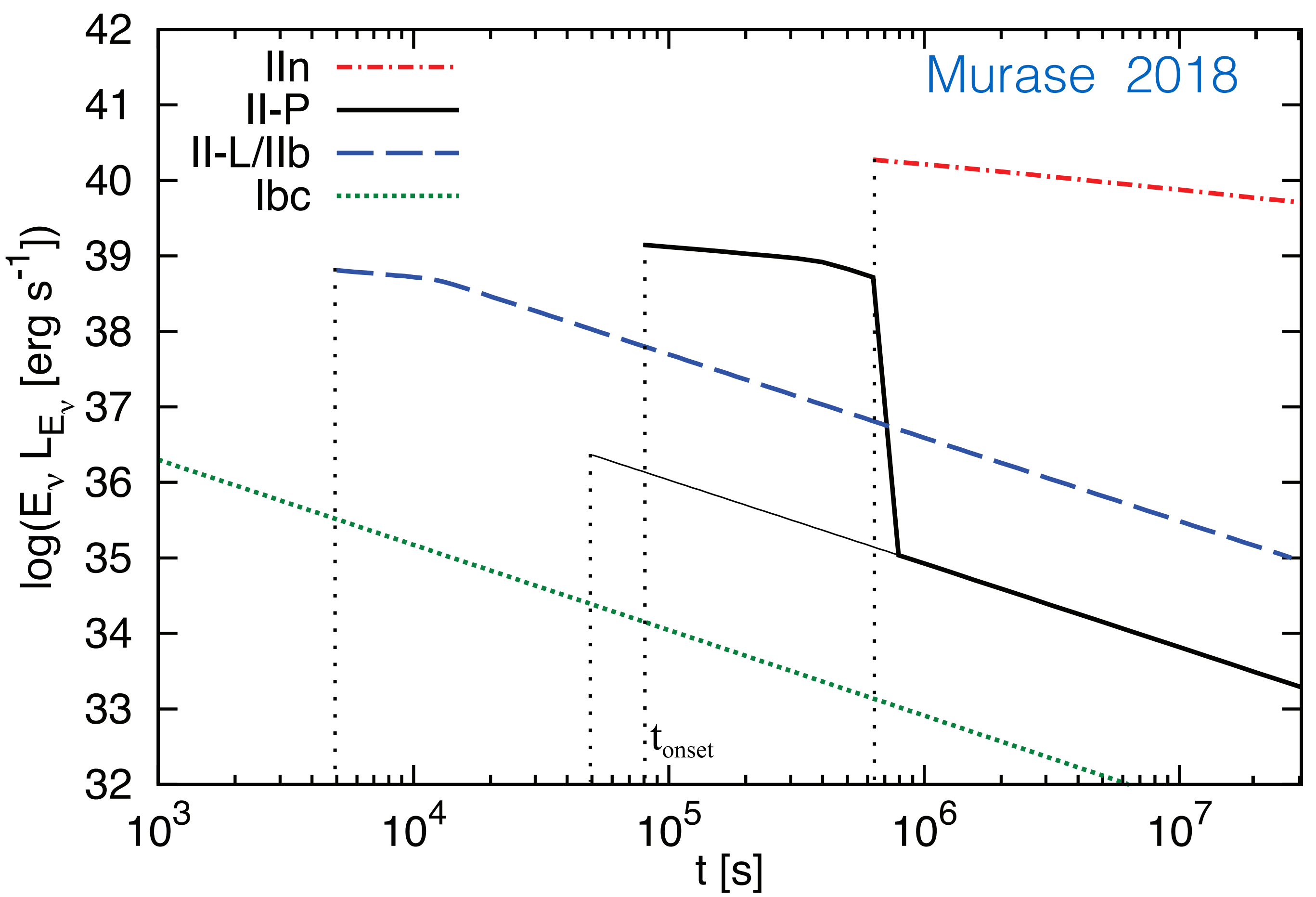


Diffuse Galactic Emission



HE Neutrino Emission from CCSNe

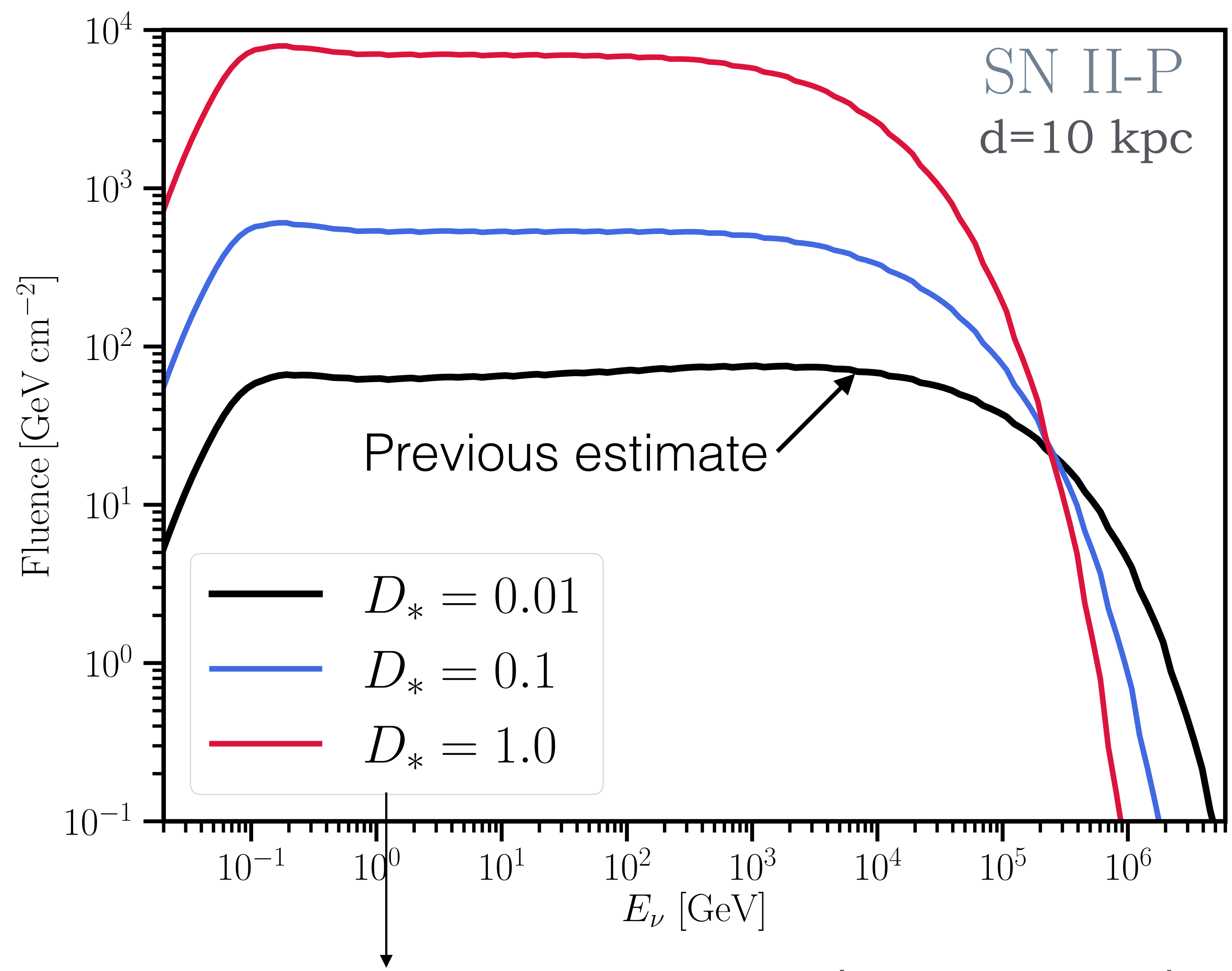
- A core-collapse SN (CCSN) with MeV neutrino luminosity of $L_\nu \sim 10^{53}$ $ergs^{-1}$ will be accompanied by HE neutrino emission with a bolometric luminosity of $L_\nu \sim 10^{37} - 10^{42}$ $ergs^{-1}$.
- Growing evidence from observation of extragalactic SNe shows **rapid significant mass loss** in SN progenitor which leads to shock **interaction with dense circumstellar material (CSM)**.
- After the shock breakout from a progenitor star, the SN ejecta starts to interact with a CSM.



~ 0.1 – 10 days after detections of MeV neutrinos and gravitational waves, a high-statistics TeV neutrino signal is expected for an ordinary Galactic SN.

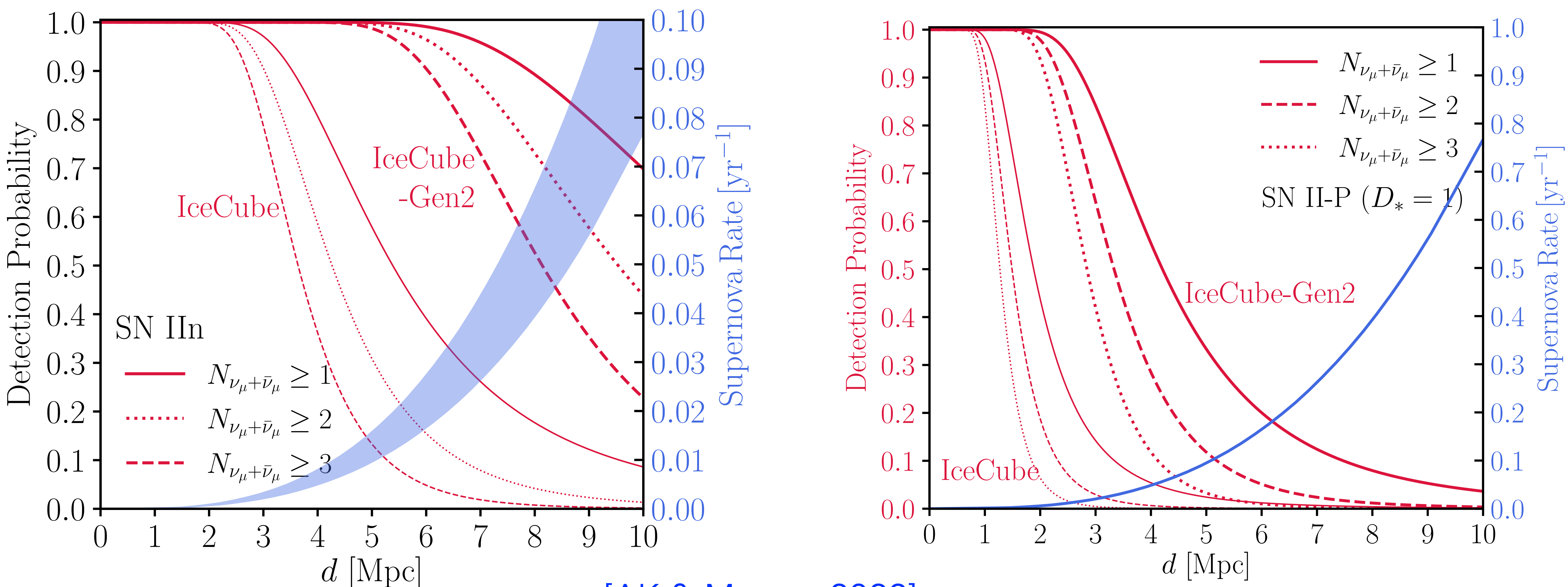
HE Neutrinos from SN II-P

- SN II-P is the most common type of core-collapse SN
- Progenitors are Red Super Giants.
- The level of the neutrino emission is generally lower than SN IIn but the higher rate increases the chance for observation.
- Recent observations have revealed that mass ejections is larger than previous estimates. [MOROZOVA+ 2018]
  - *Observation is more likely!*



D* parameterizes mass loss rate and wind velocity and is directly correlated with neutrino emission.

HE Neutrinos from CCSNe



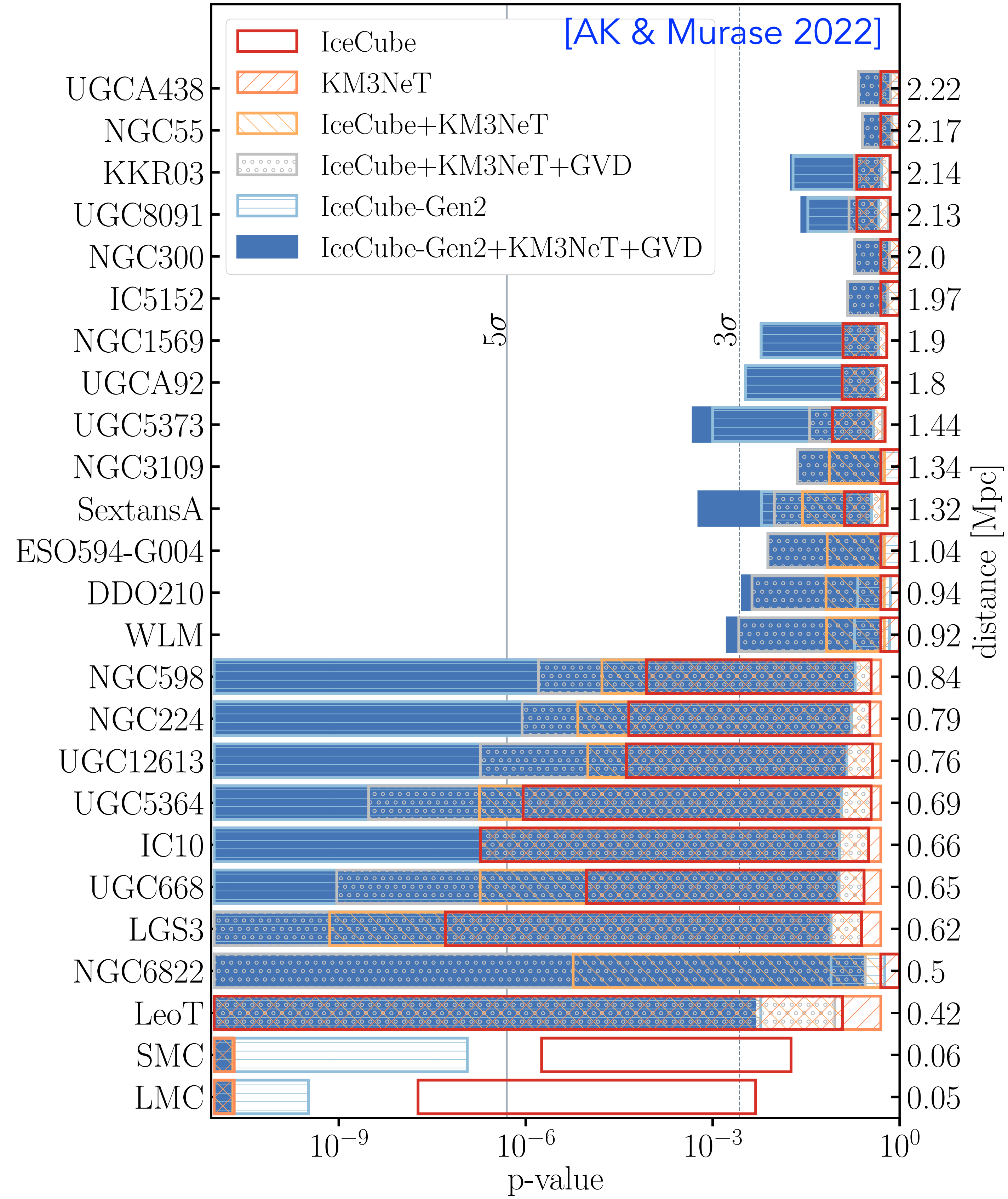
[AK & Murase 2022]

The next generation of neutrino telescopes will extend the horizon for observation of multiple neutrinos from extragalactic SN IIn.

HE Neutrino emission from SN II-P

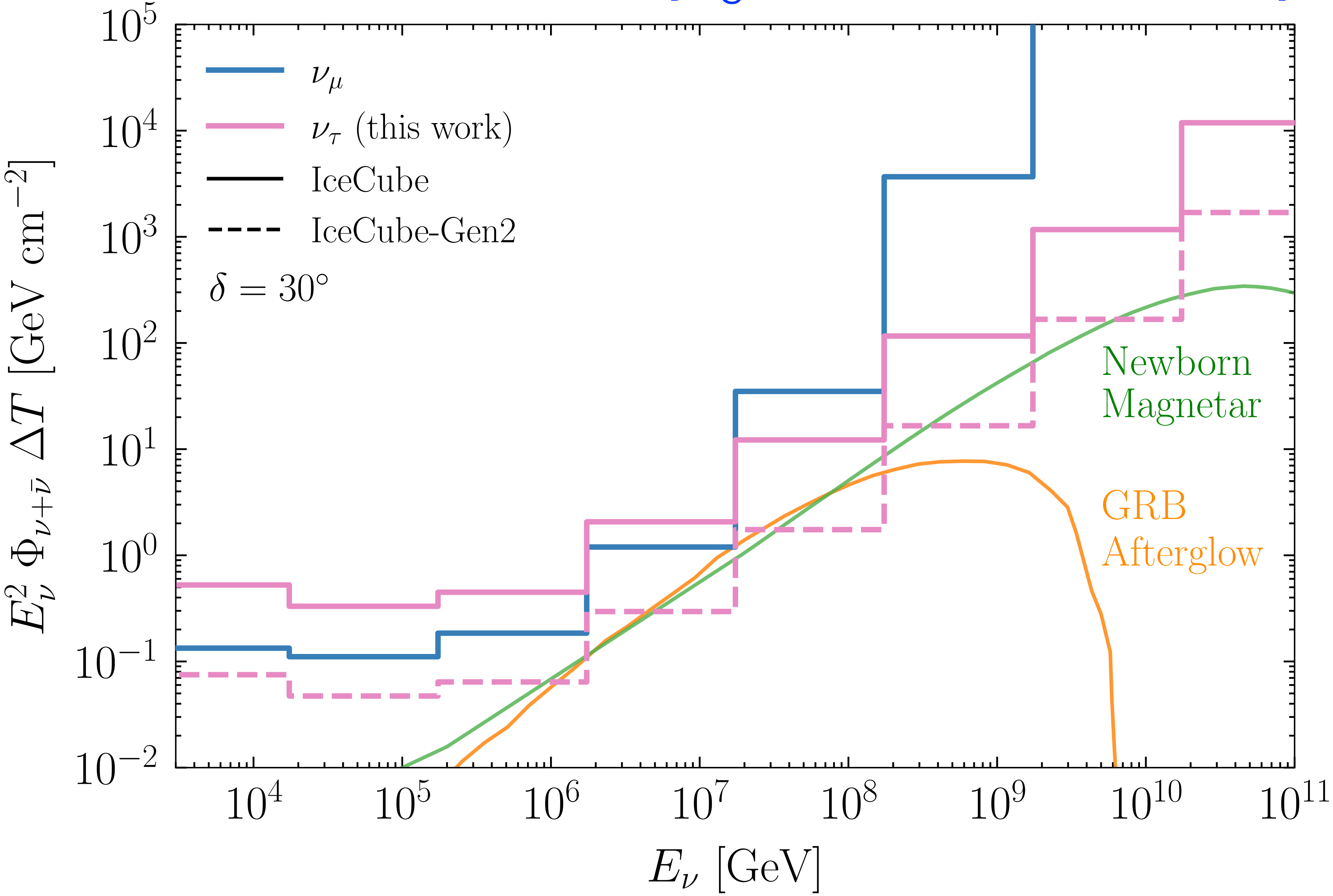
Local Galaxies

- 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.



Tau Neutrinos & UHE Sources

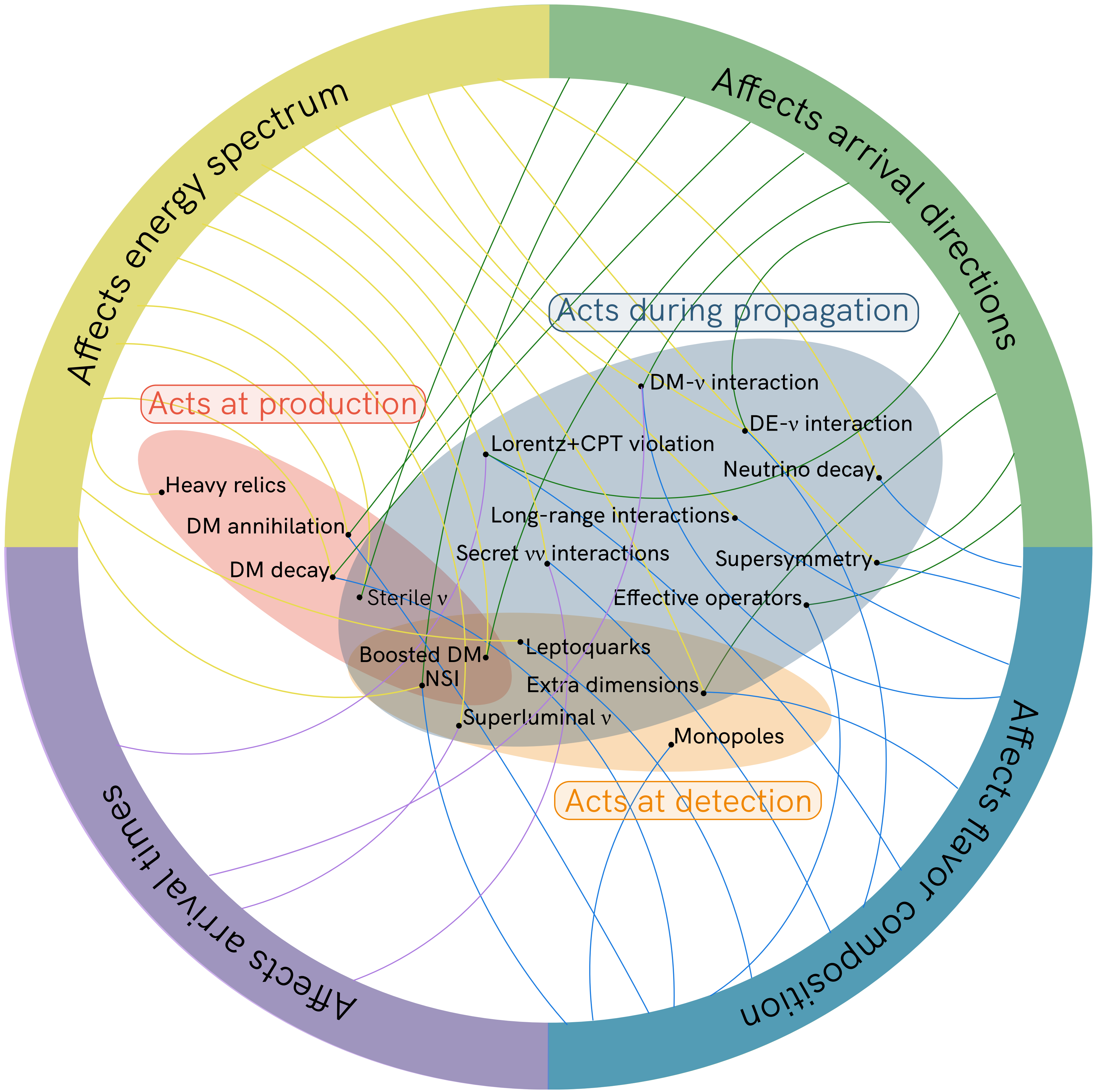
[Argüelles, Halzen, AK, Safa 2022]



PeV tau neutrinos improve the sensitivity for Cherenkov telescopes to identify sources with EeV emission.

Cosmic Neutrinos as Probes of New Physics

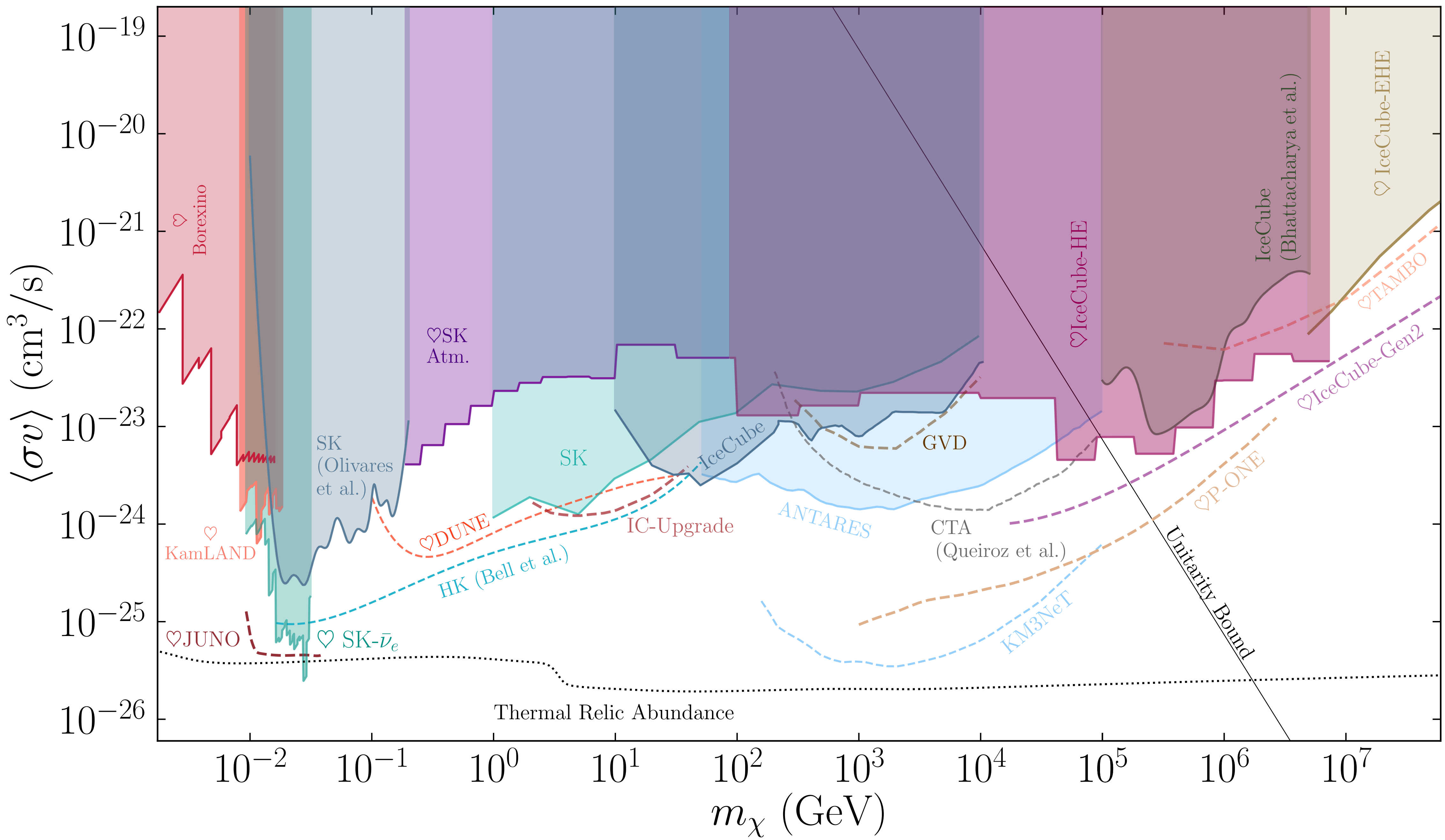
Symmetry Magazine



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

Dark Matter Annihilation

[Argüelles, Diaz, AK, Olivares Del Camp, Safa, Vincent, RMP 2022.]

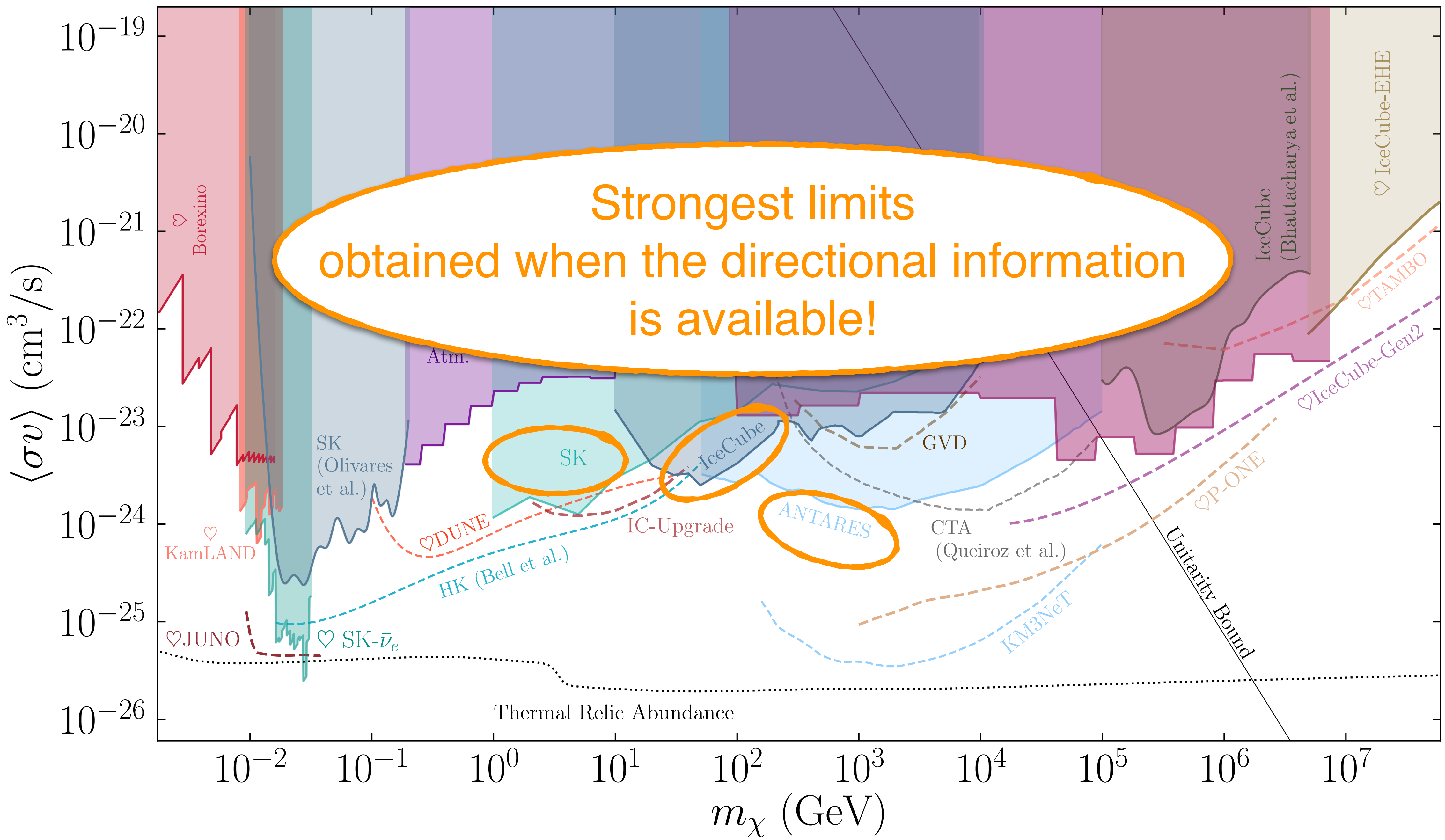


Neutrino portal: *the most invisible channel*, hardest to detect, difficult to rule out!

Upper limit on DM annihilation to neutrinos serves as an upper bound to DM annihilation to SM [Beacom+2007].

Dark Matter Annihilation

[Argüelles, Diaz, AK, Olivares Del Camp, Safa, Vincent, RMP 2022.]



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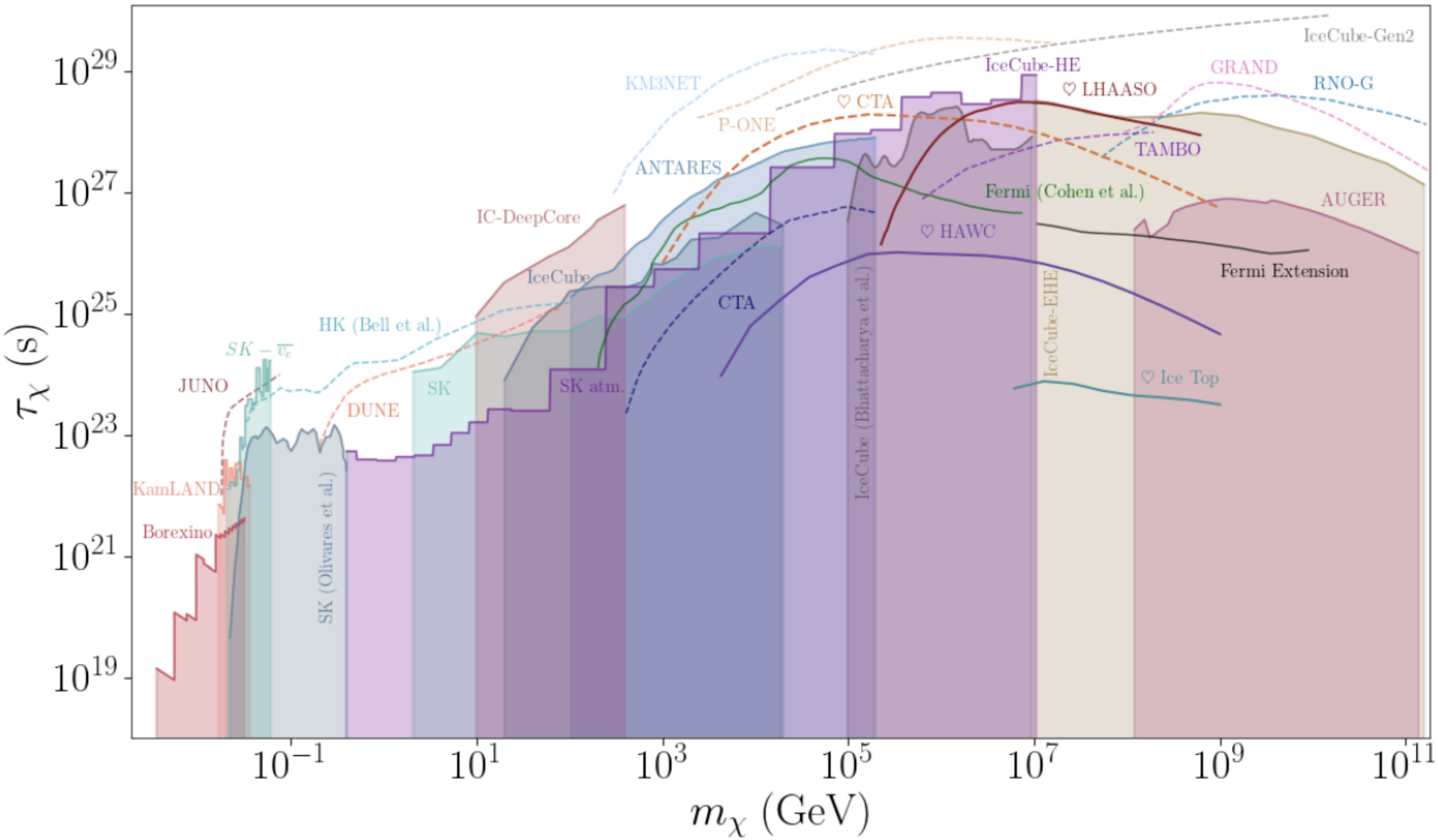
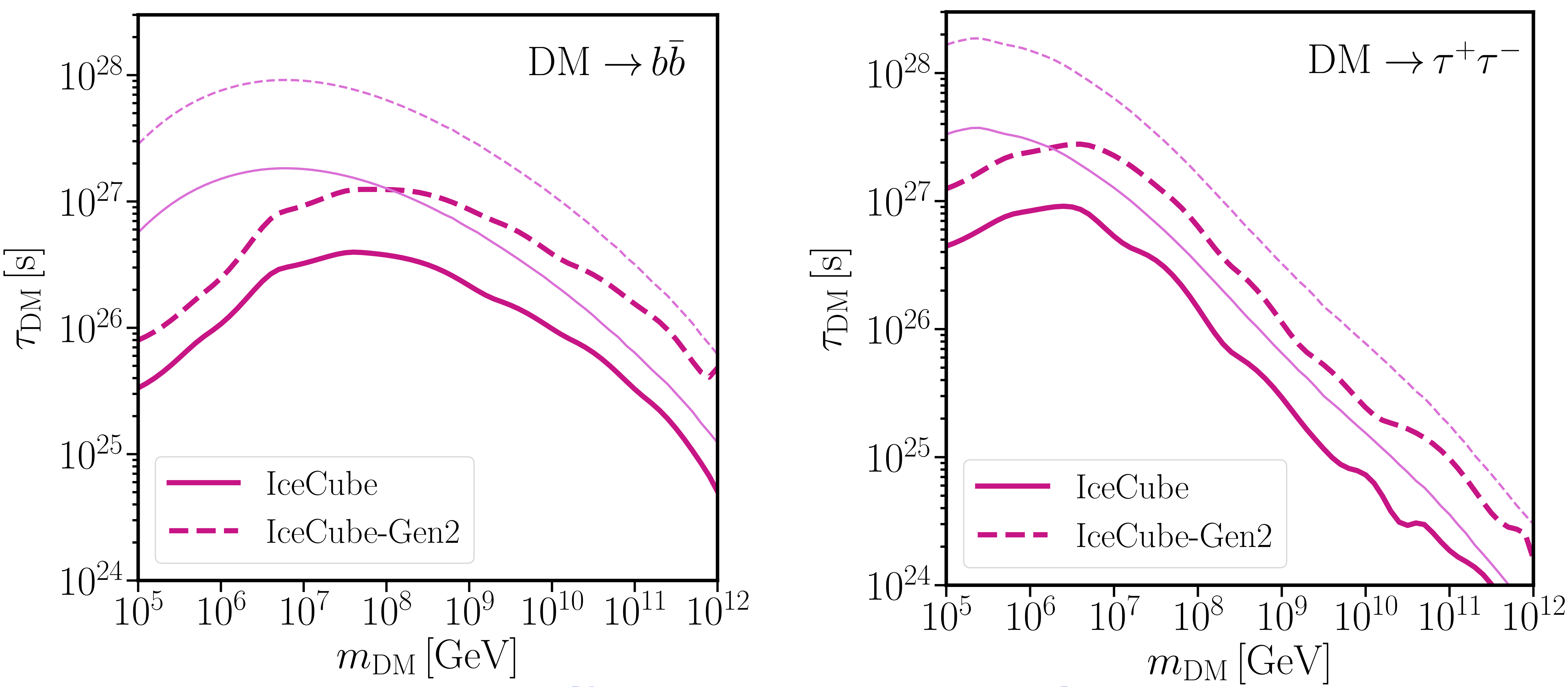
Dark Matter Decay



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

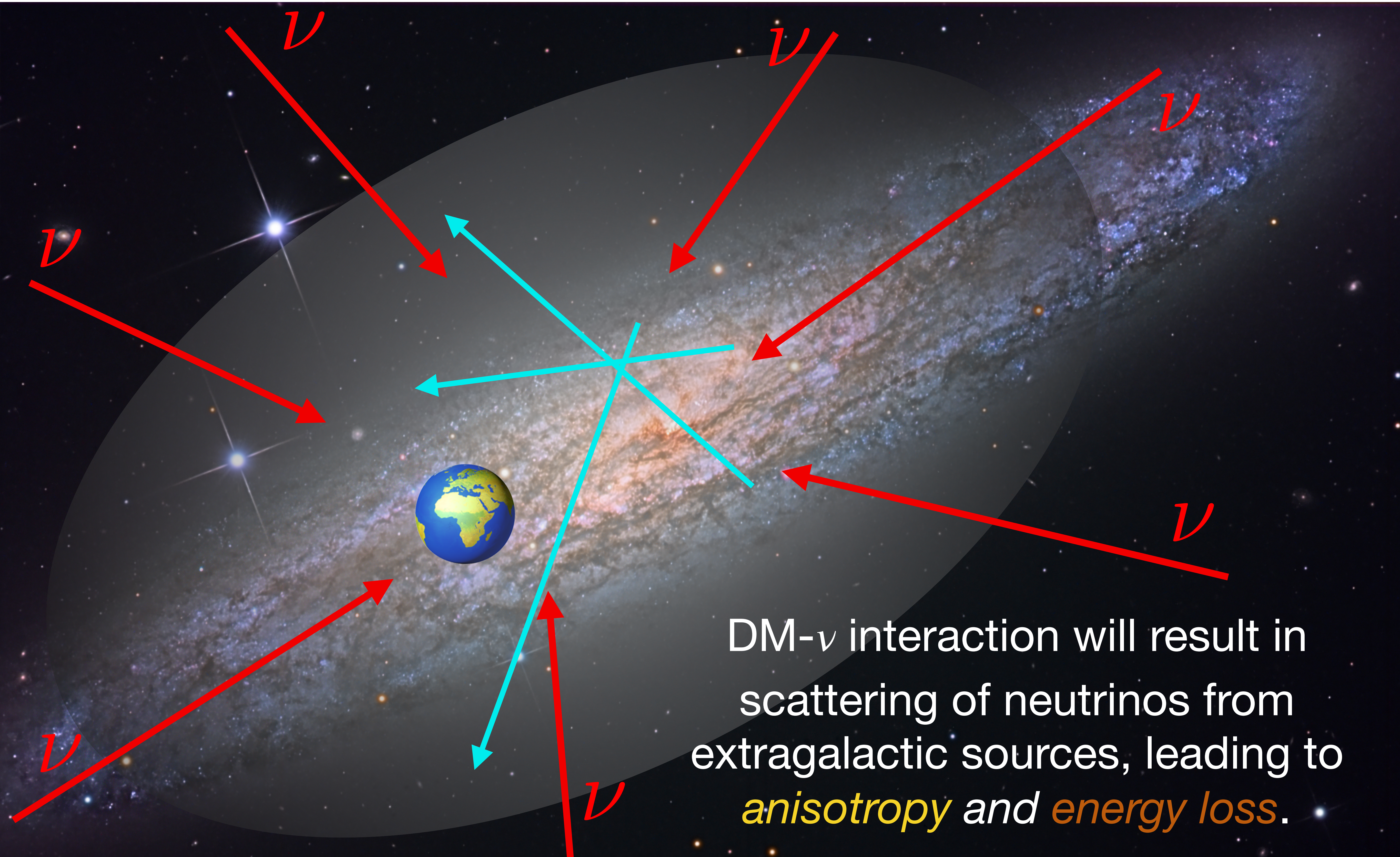
DM Signal from Galaxy Clusters



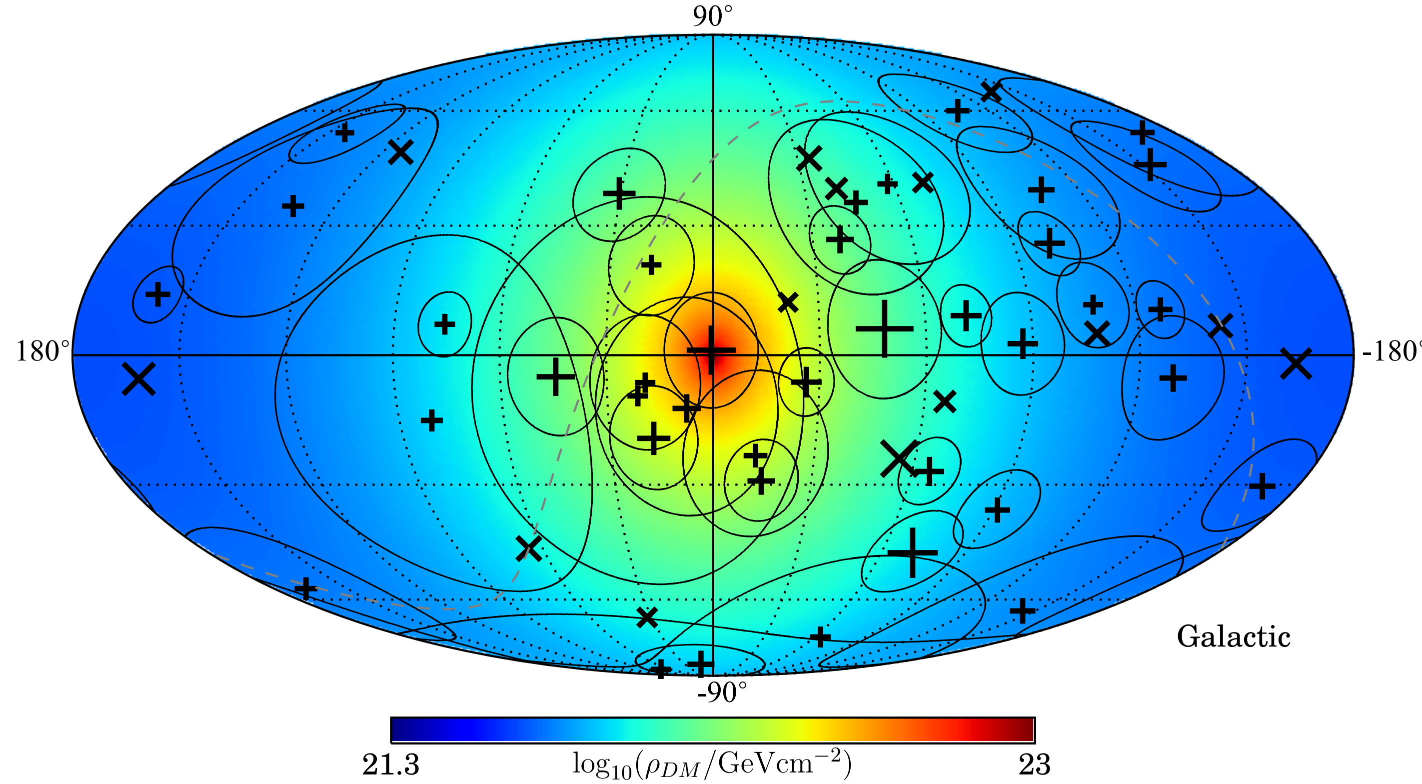
[Chianese, AK, Murase, in prep.]

In the Gen2-era, stacking with more clusters may overwhelm diffuse limits

Dark Matter-Neutrino Interaction

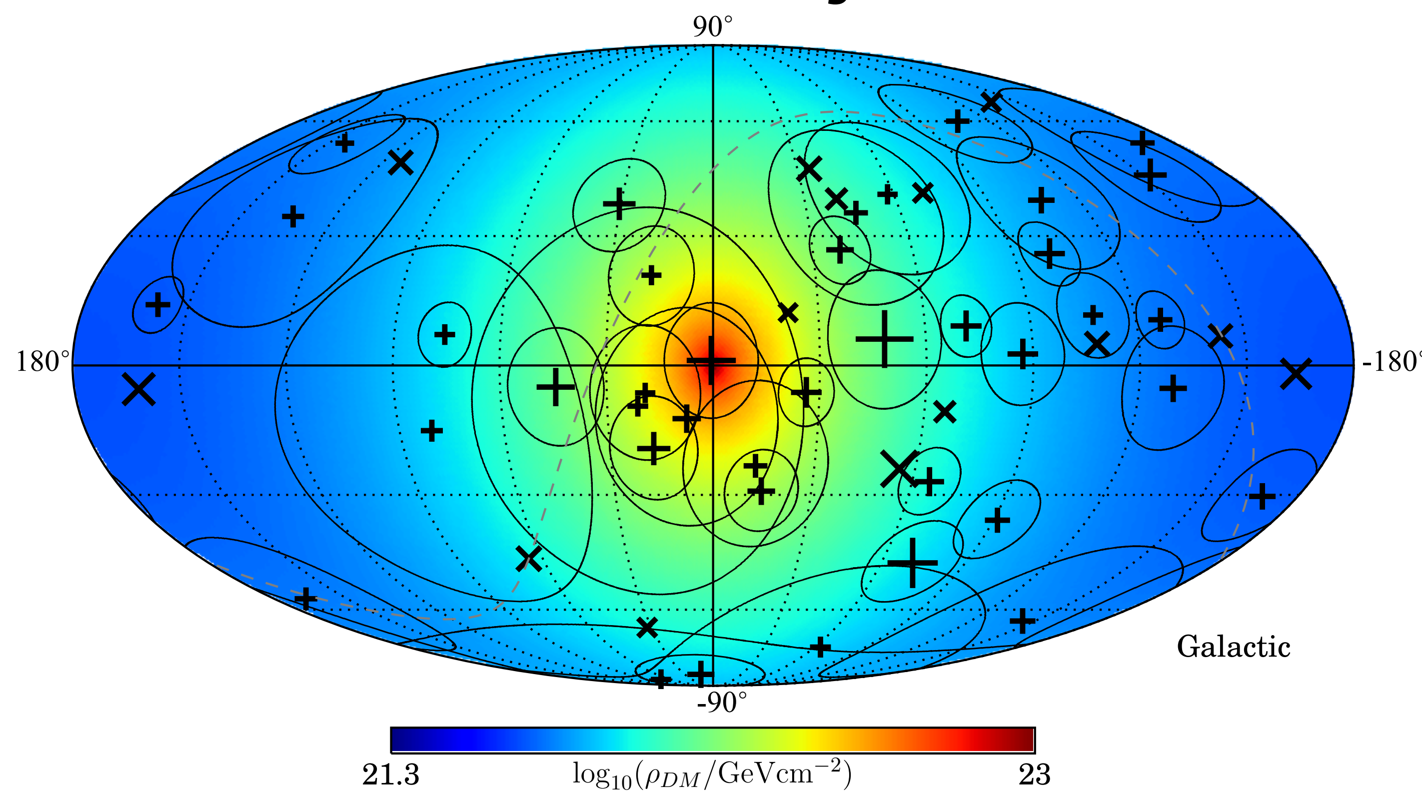


Dark matter column density* seen from Earth



* *Einasto*

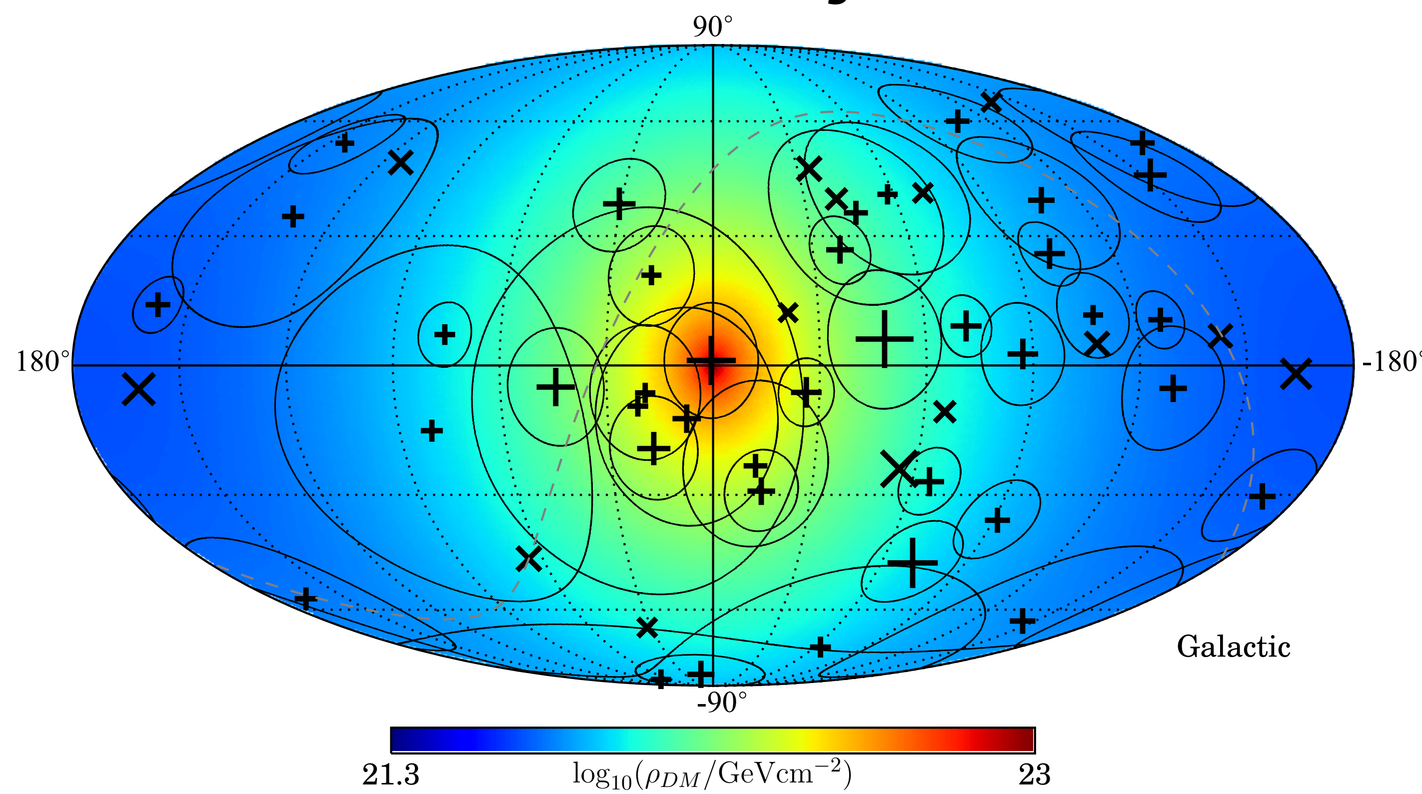
Dark matter column density* seen from Earth



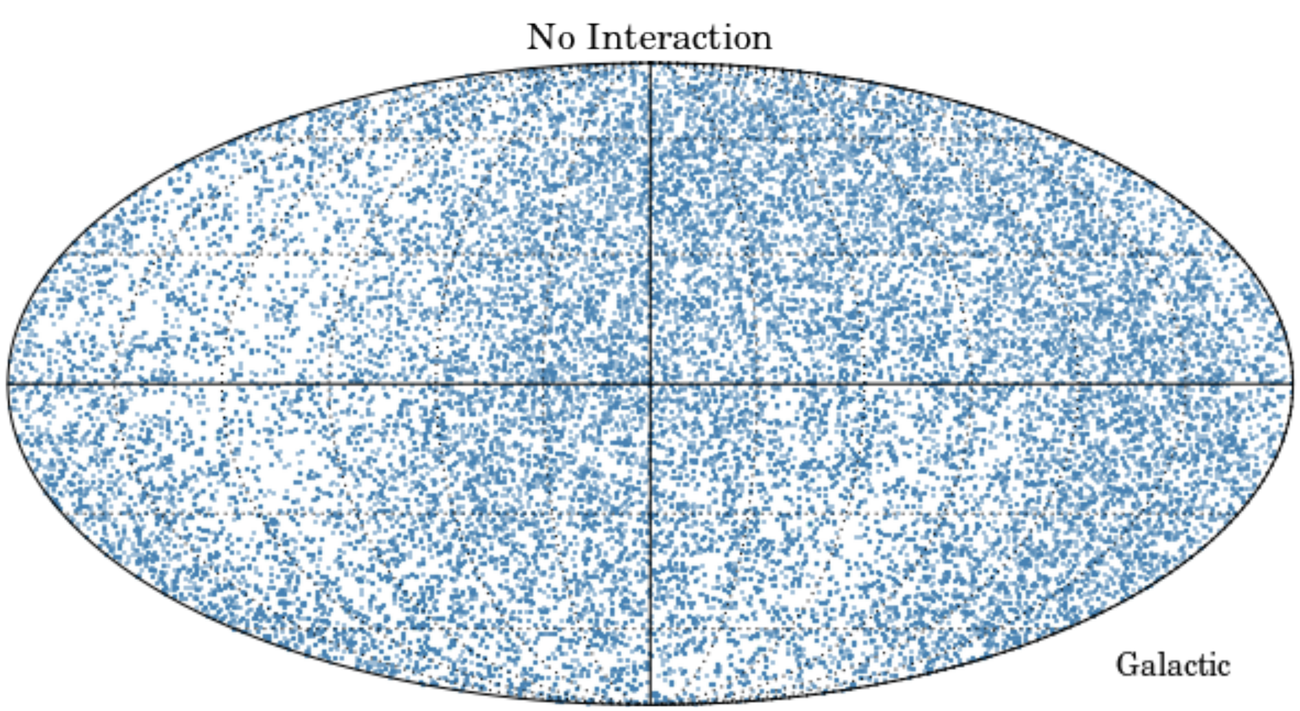
Simulation including effects of detector, Earth

* *Einasto*

Dark matter column density* seen from Earth

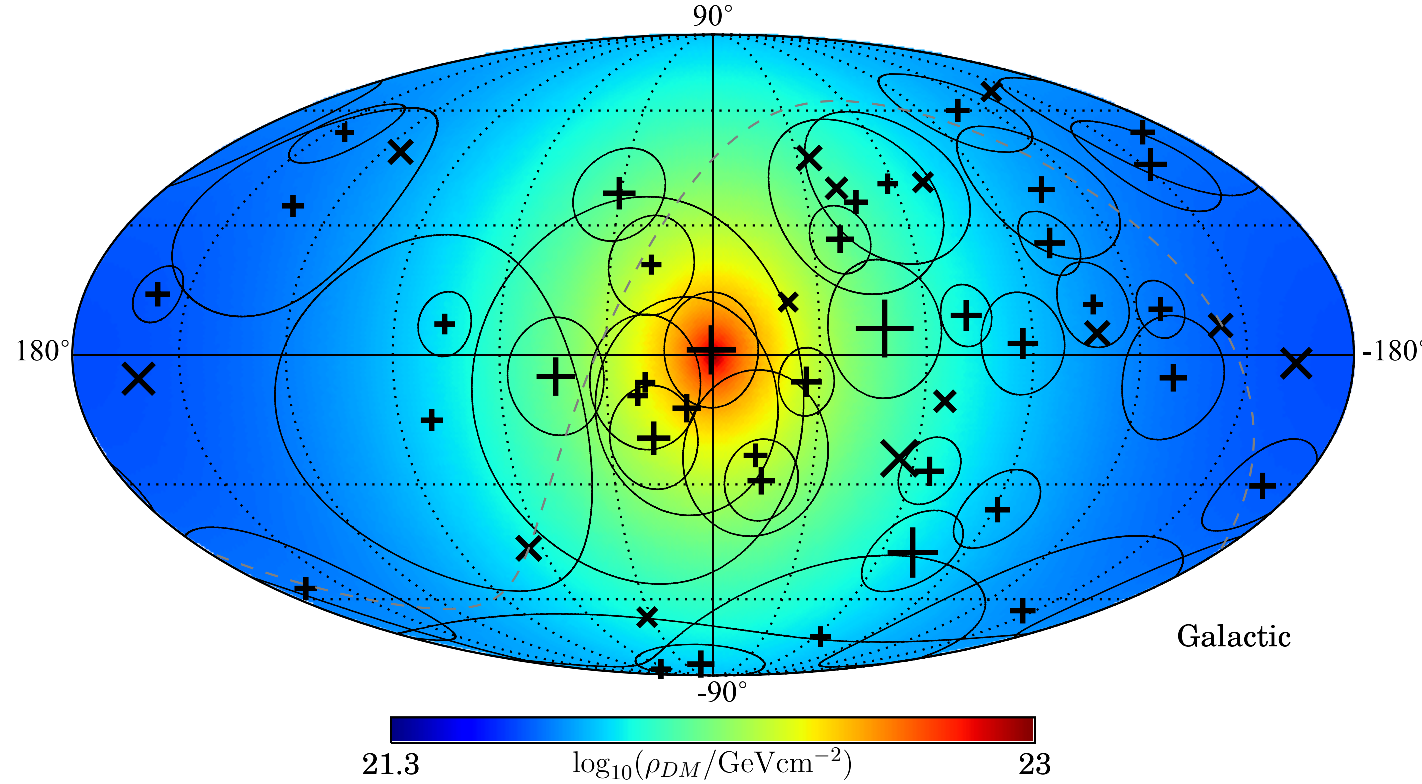


Simulation including effects of detector, Earth

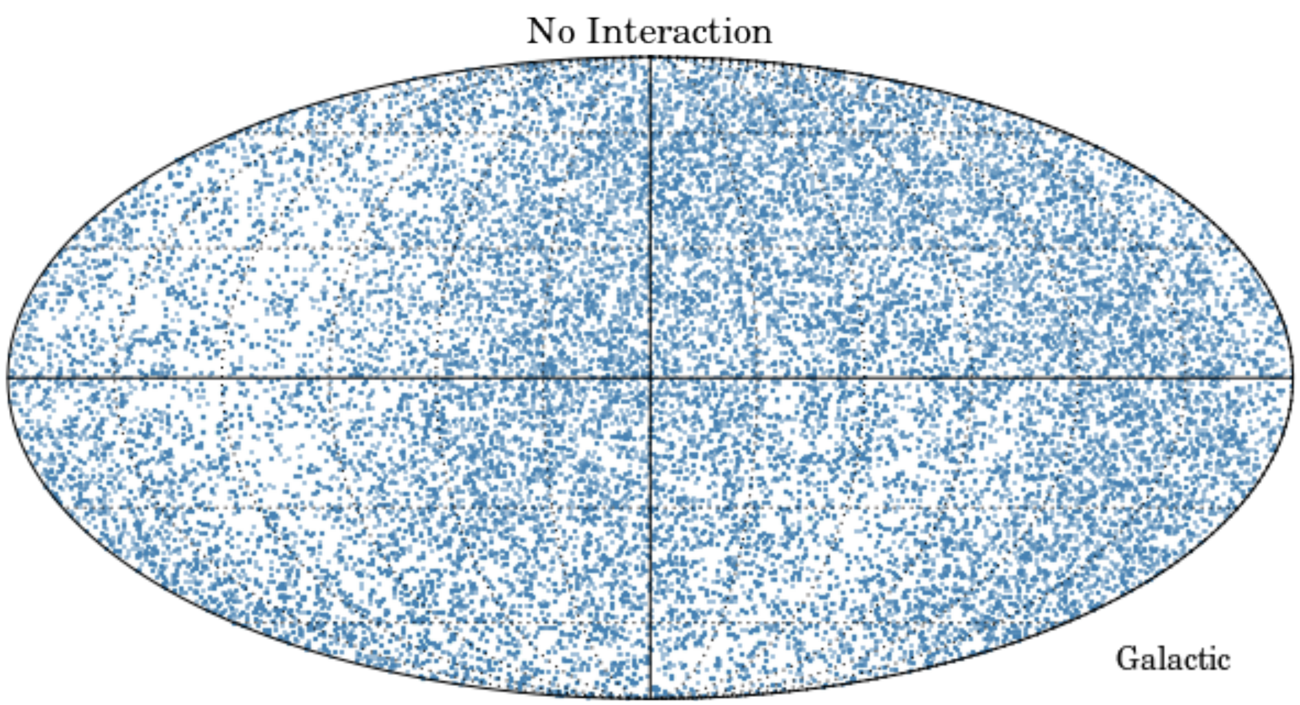


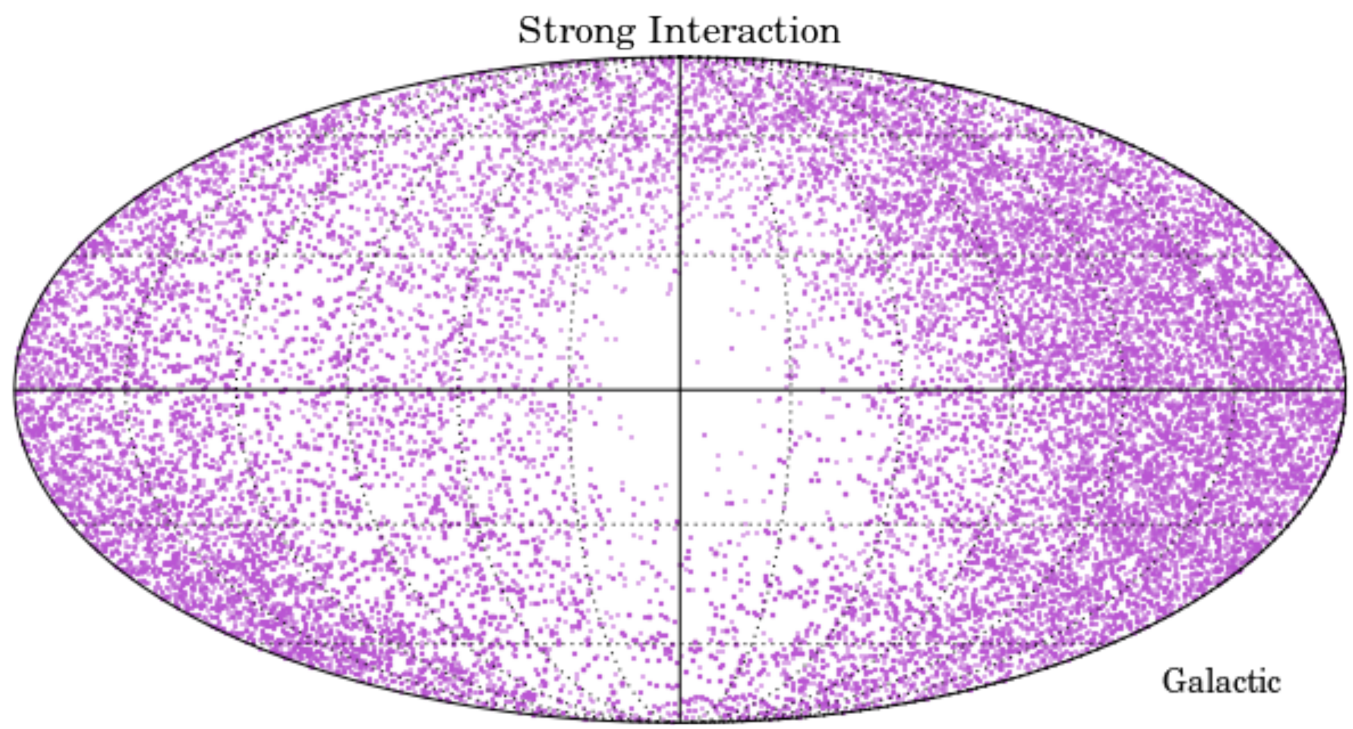
* *Einasto*

Dark matter column density* seen from Earth



Simulation including effects of detector, Earth

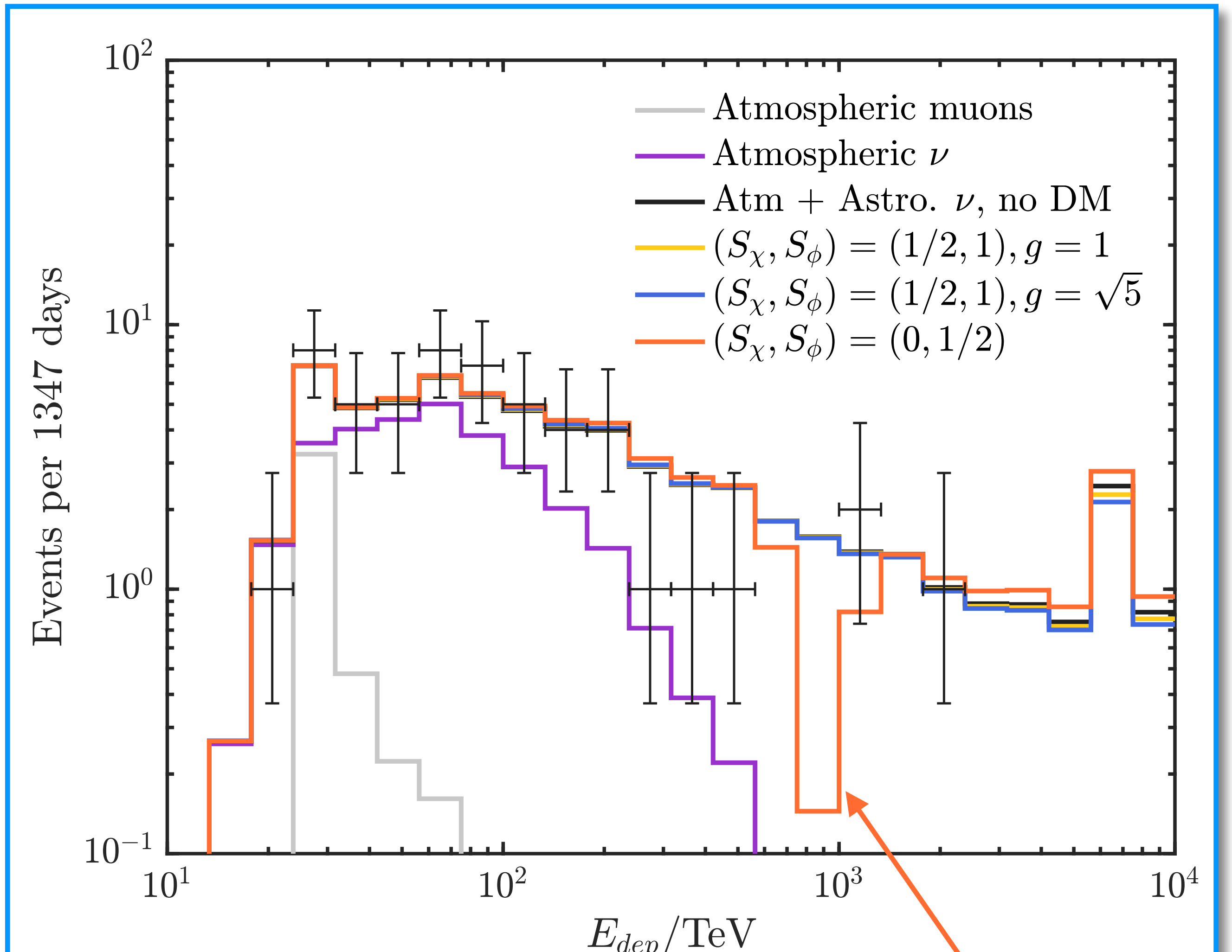




* *Einasto*

Energy & Morphology

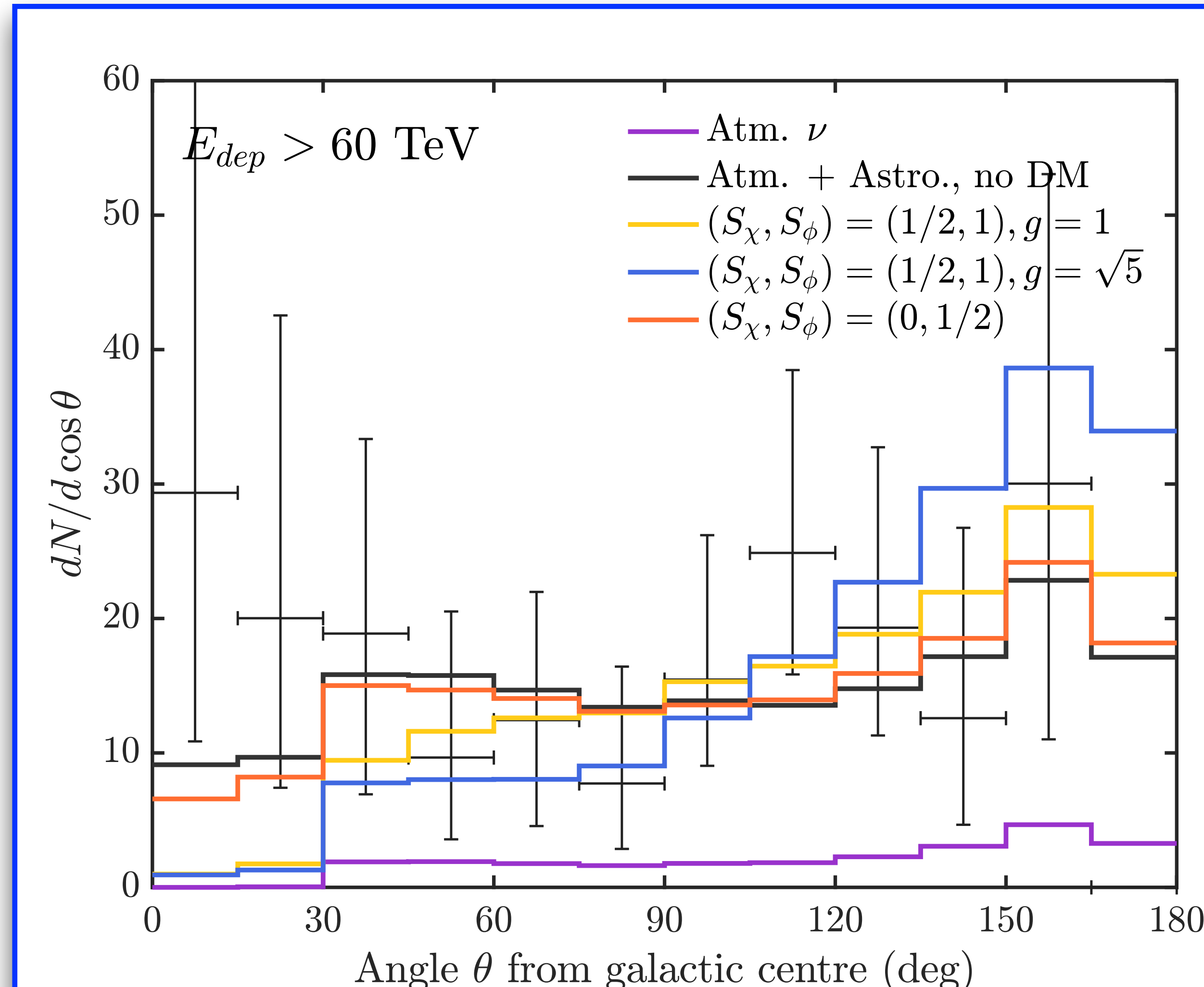
Energy Distribution



Resonance @ 810 TeV

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

Angular Distribution

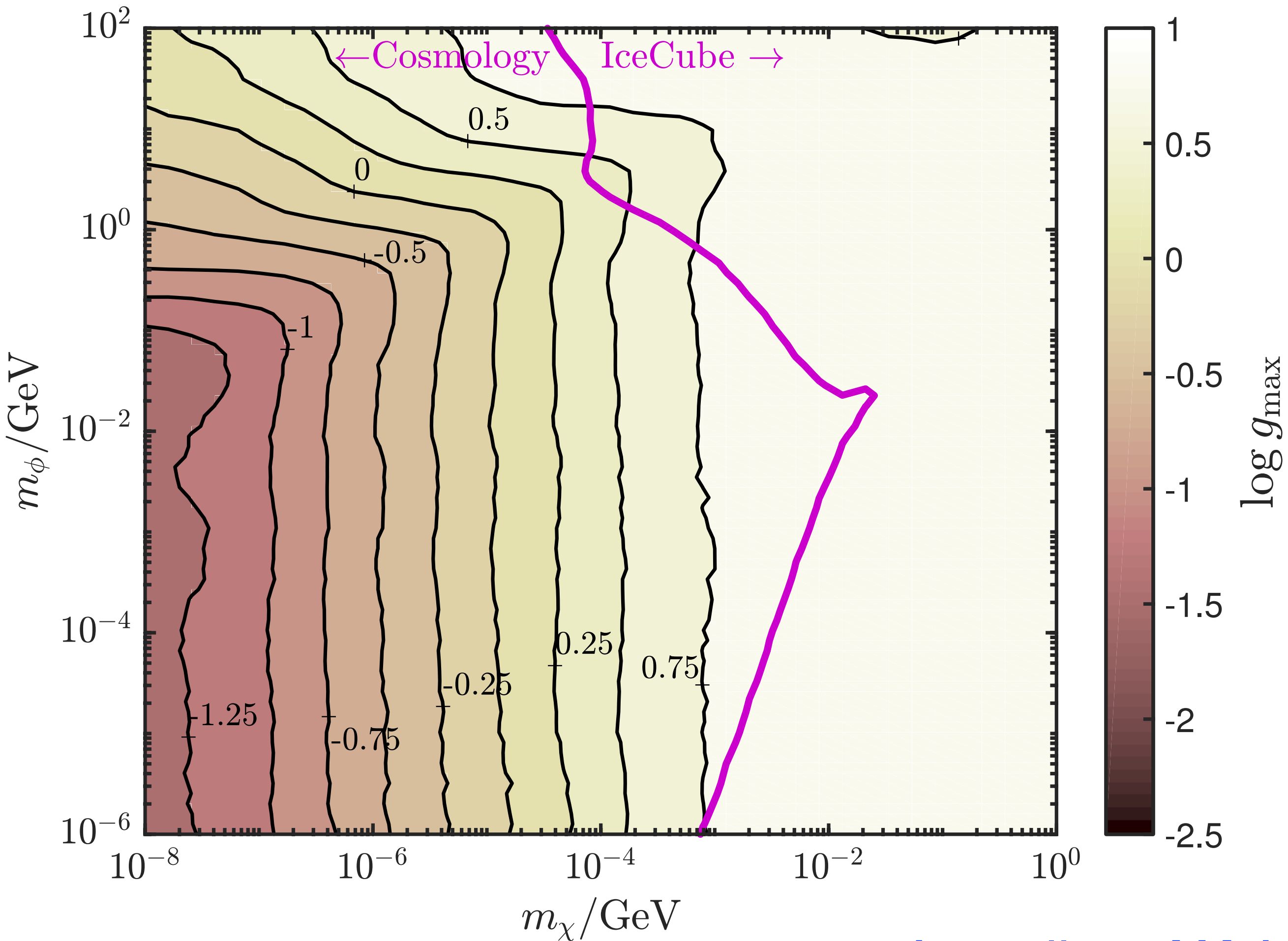


IceCube HESE

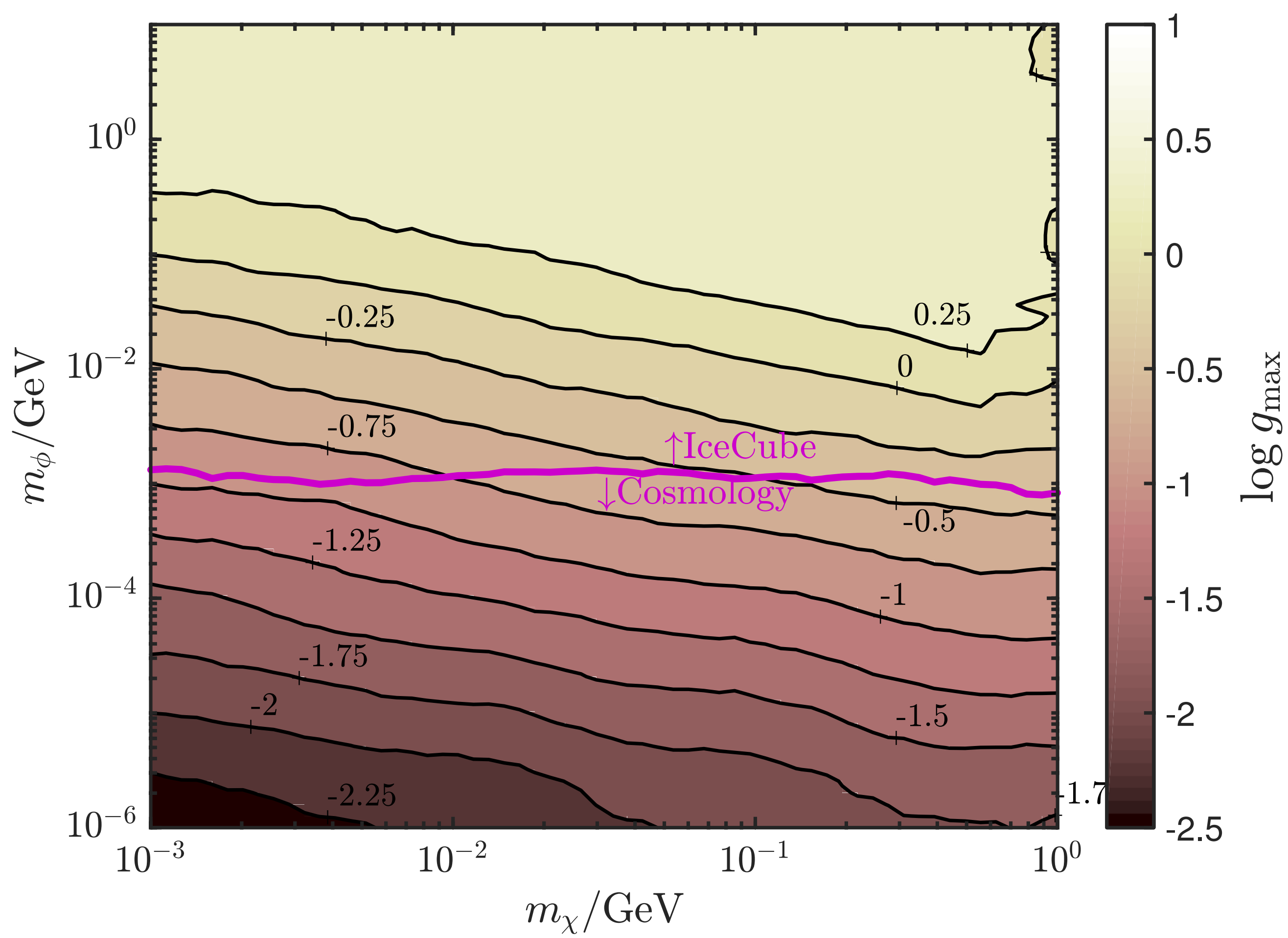
Neutrino-DM interaction leads to the deficit towards Galactic center

Constraints on DM-Nu Interaction

Scalar DM
Fermionic Mediator



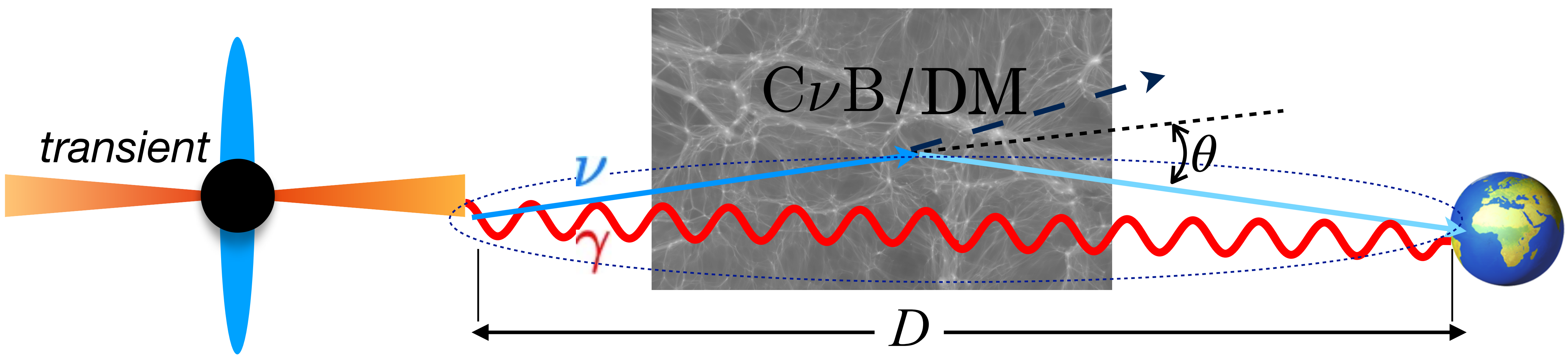
Fermionic DM
Vector Mediator

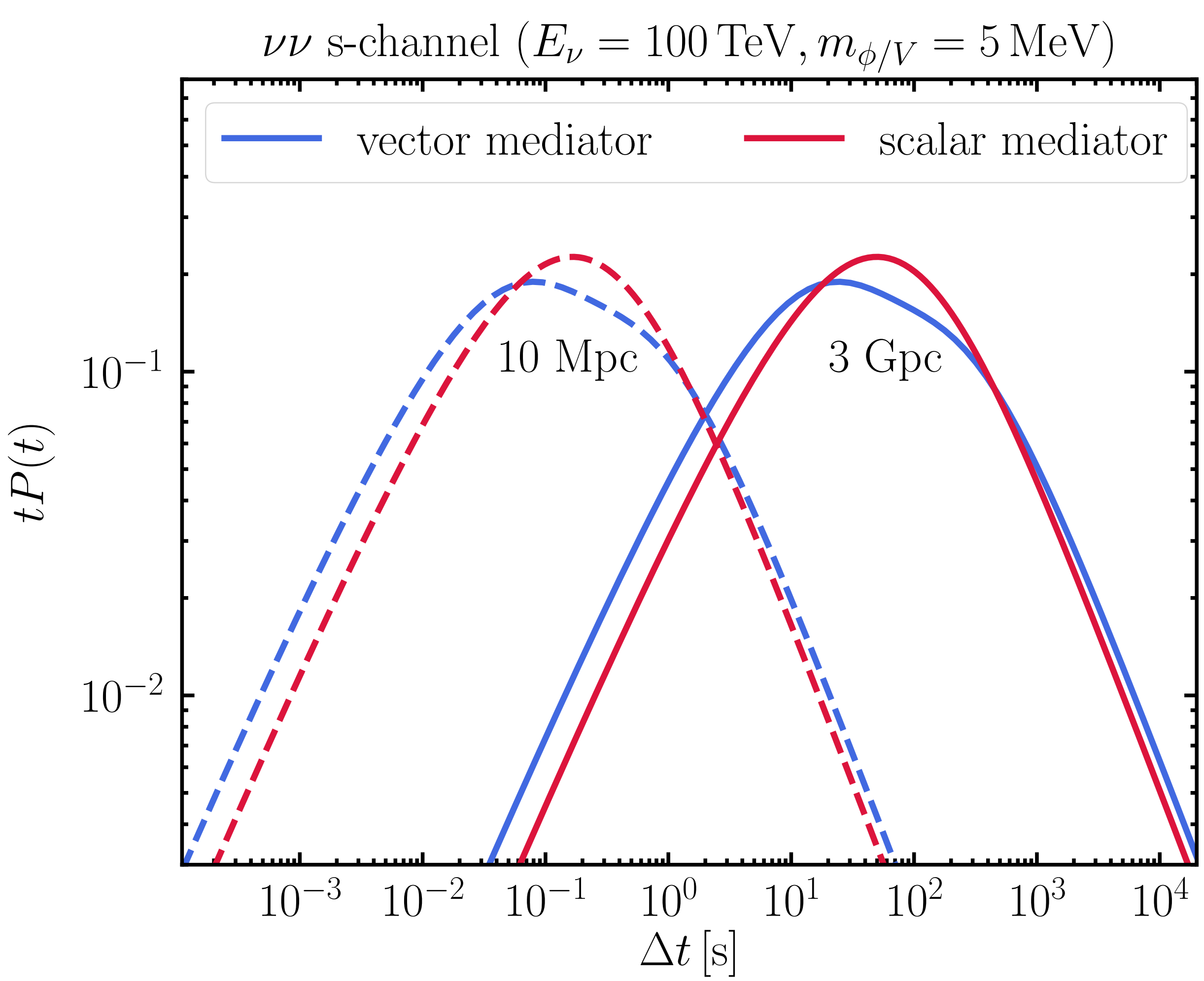


Argüelles, **AK**, Vincent, PRL 2017

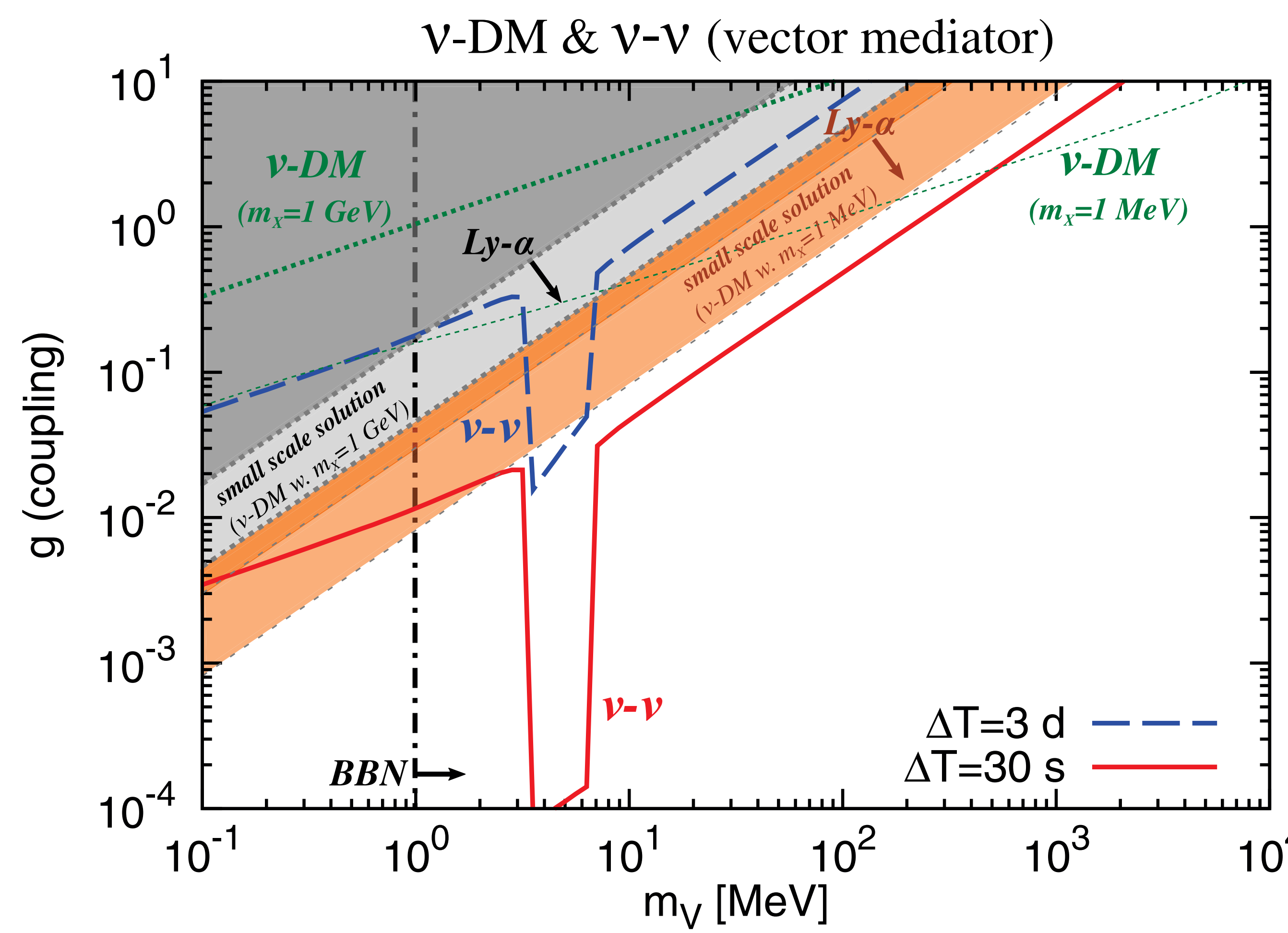
Competitive limits compared to cosmological constraints!

BSM-induced Time Delay





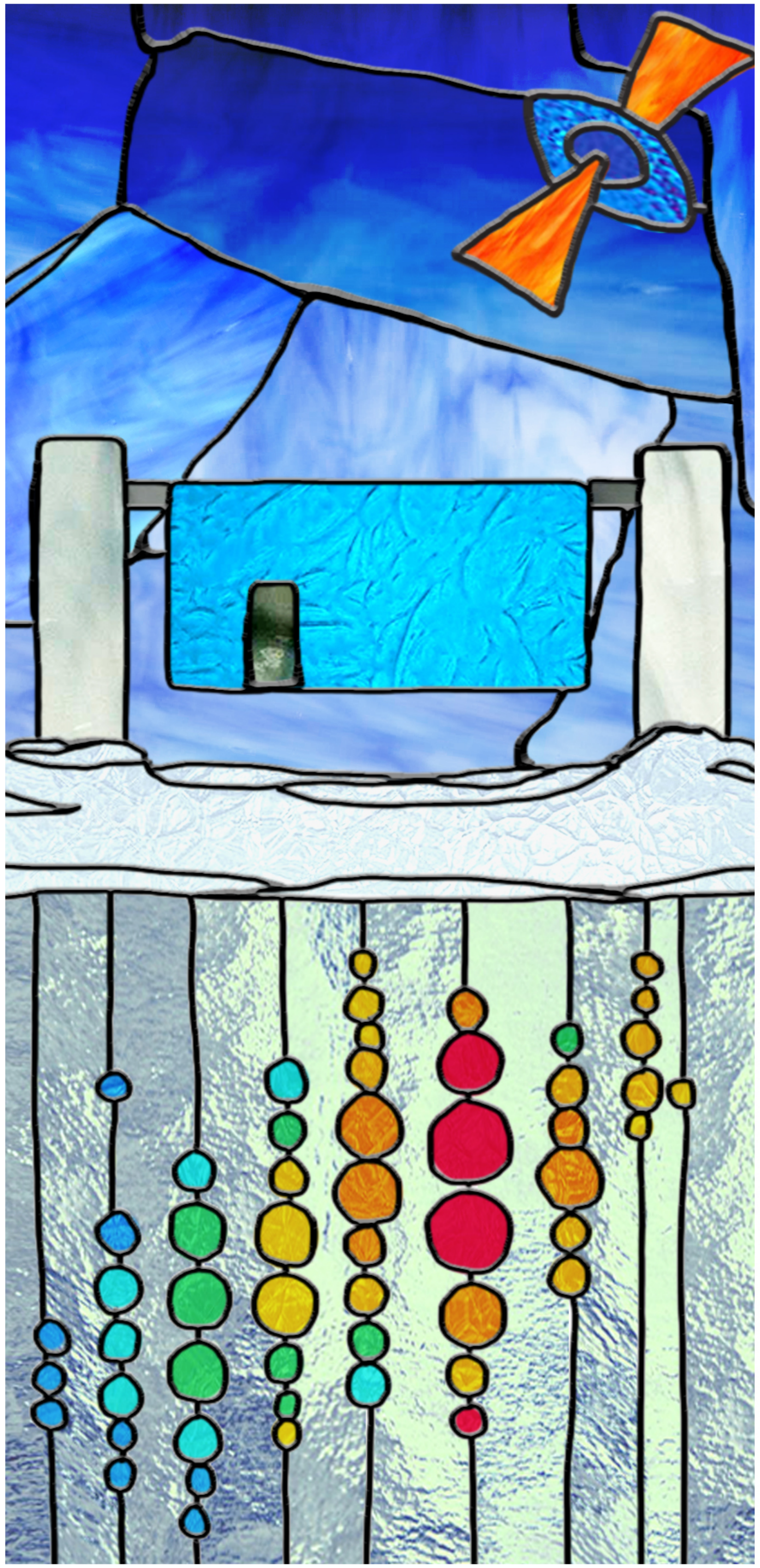
Eskenasy, AK, Murase, 2022



Murase & Shoemaker, PRL 2019

Summary

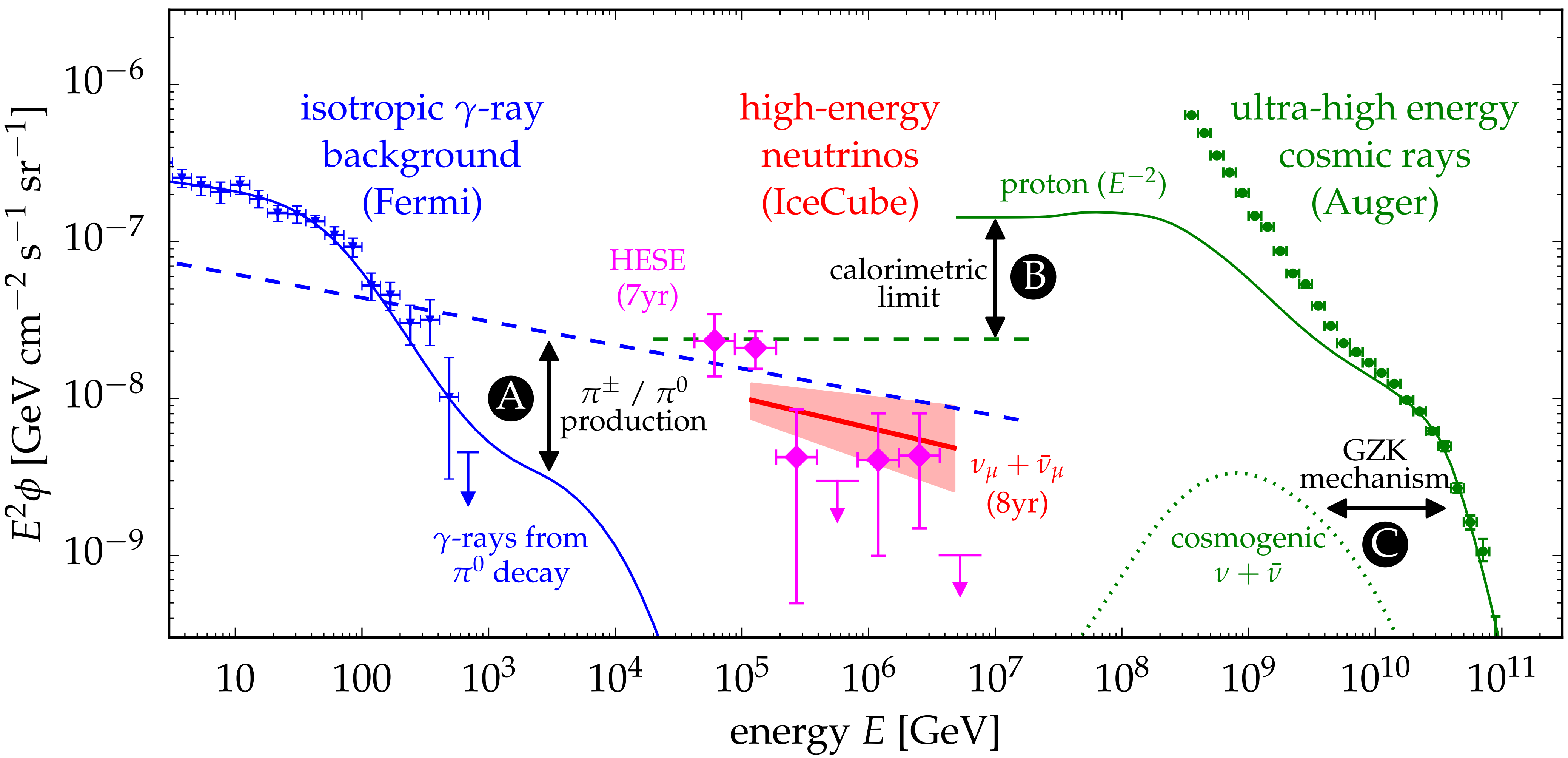
- After a decade of observation, signs of anisotropy are emerging in IceCube data.
  - Early indications points to active galactic nuclei as primary source of high-energy cosmic neutrinos.
  - Neutrino Telescopes are closing in on the Galactic sources of HE neutrinos.
  - Core collapse supernovae can contribute to the cosmic neutrino flux and identification of HE neutrinos from them can provide realtime probe of particle acceleration.
- Cosmic neutrinos provide complementary tests of physics beyond the Standard Model in the neutrino sector.
  - **Identification of the sources will boost the power to probe for new physics with HE neutrinos.**



Thanks!

Back up Slides

Multimessenger Interfaces

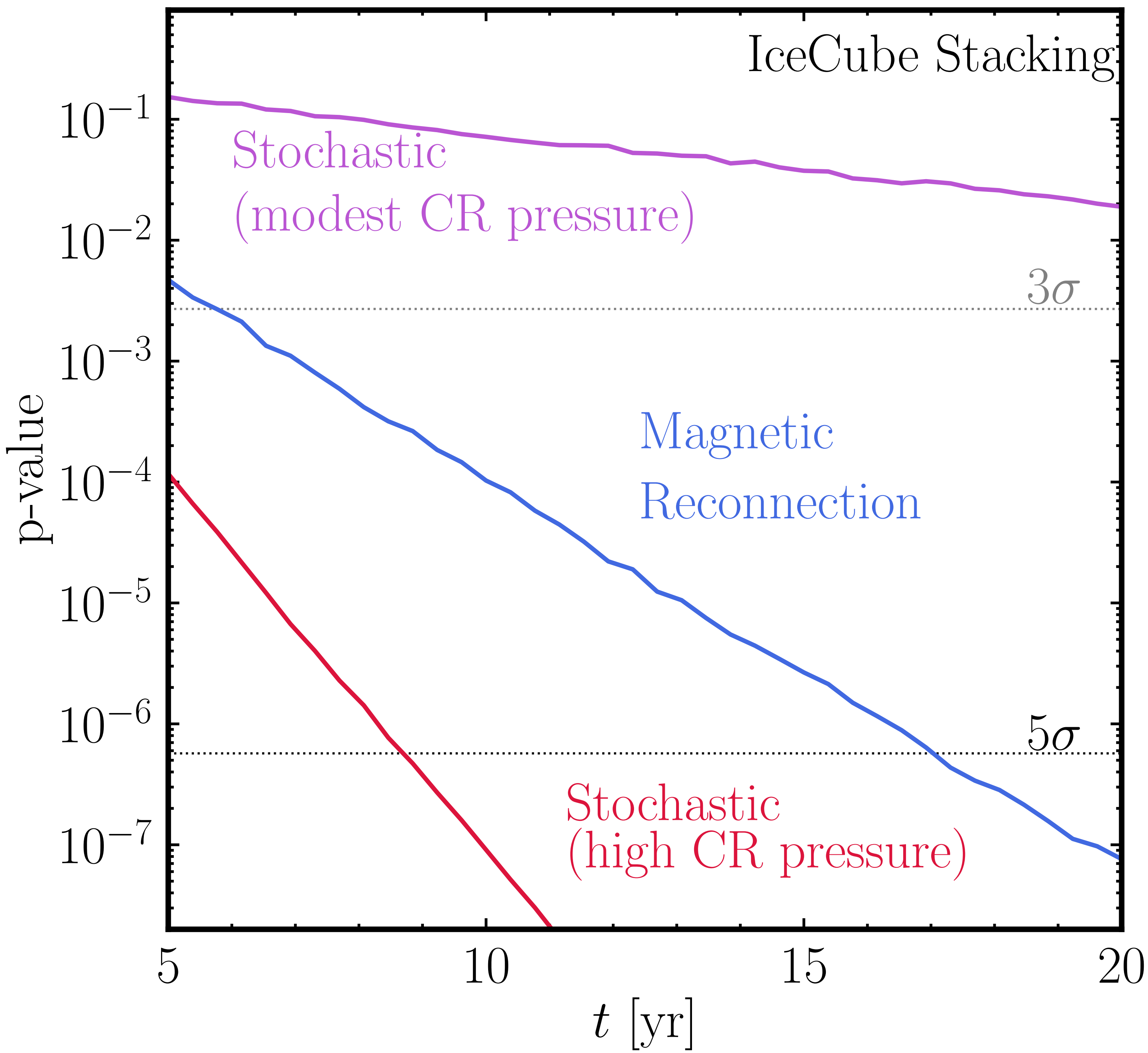


- Similar energy in the γ-rays, neutrinos and cosmic rays suggest common origin [Ahlers 2015, Murase+ 2014, Kowalski 2014]

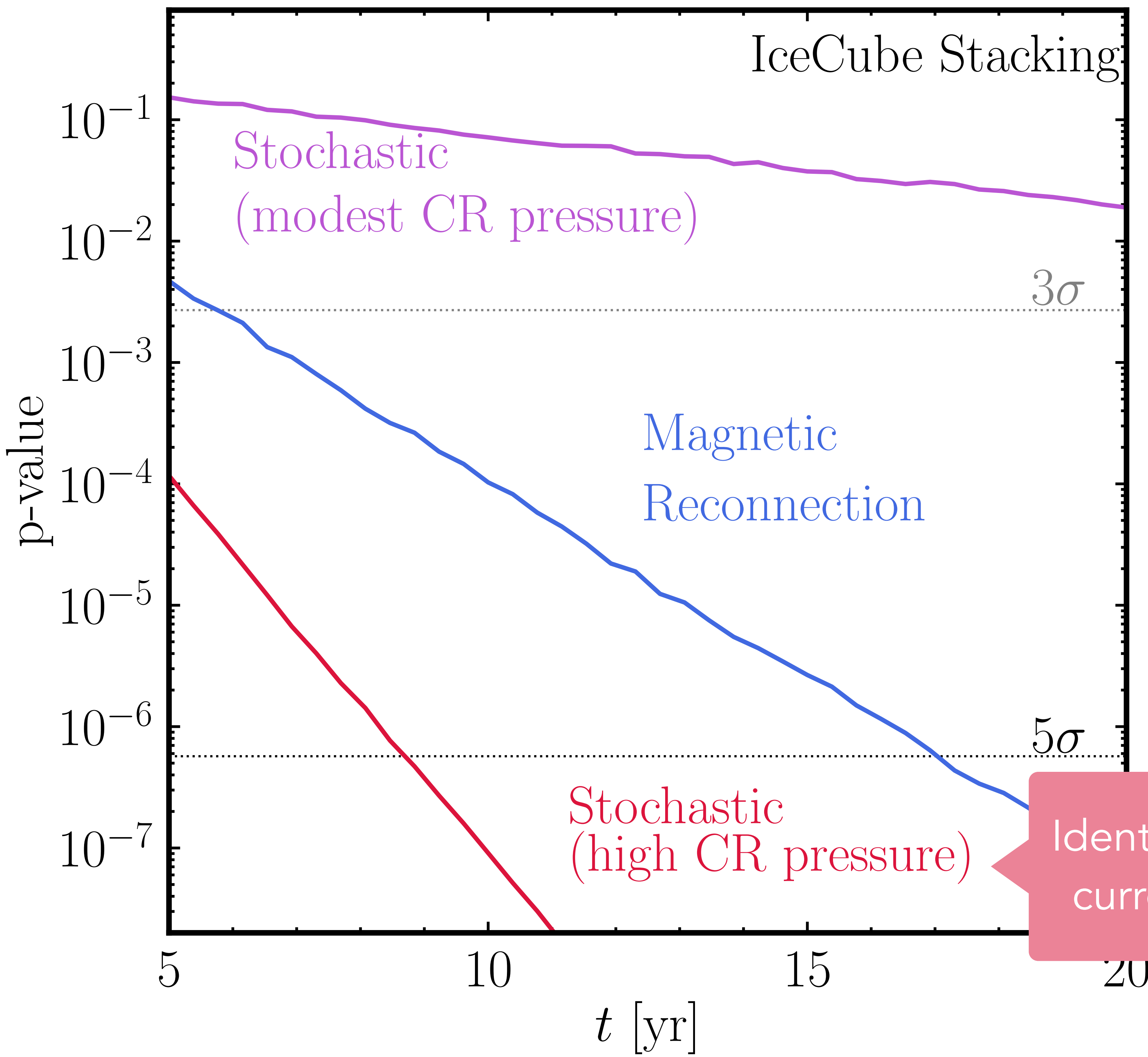
- Pionic gamma rays associated with high-energy neutrinos cascade in EBL and contribute to IGRB below 100 GeV → upper limit on neutrino spectrum.

    - Cosmic neutrino flux above 100 TeV saturates this limit.
    - Excess at lower energies suggest opaque sources

Prospects for Stacking Neutrinos from Bright Sources in IceCube

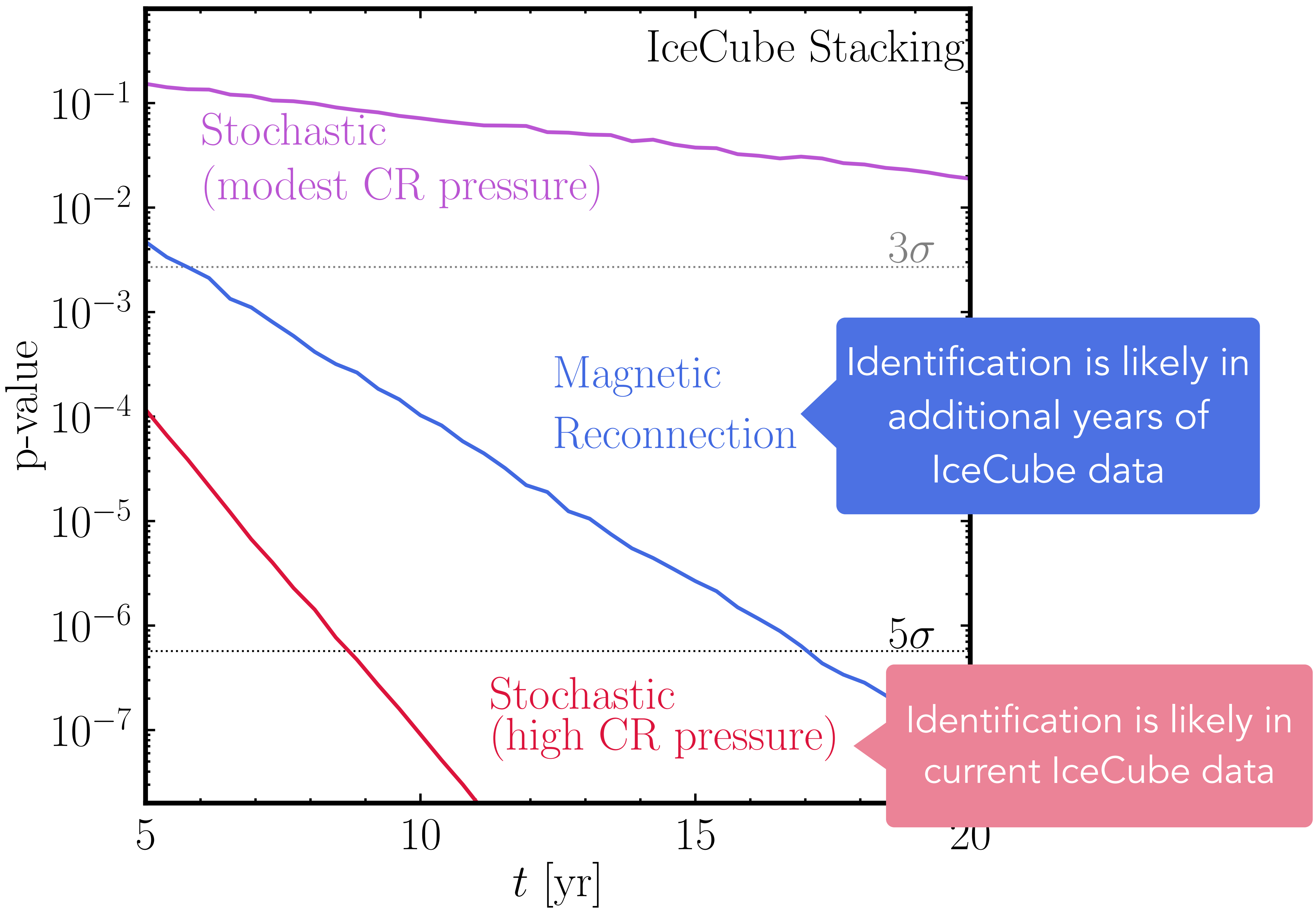


Prospects for Stacking Neutrinos from Bright Sources in IceCube

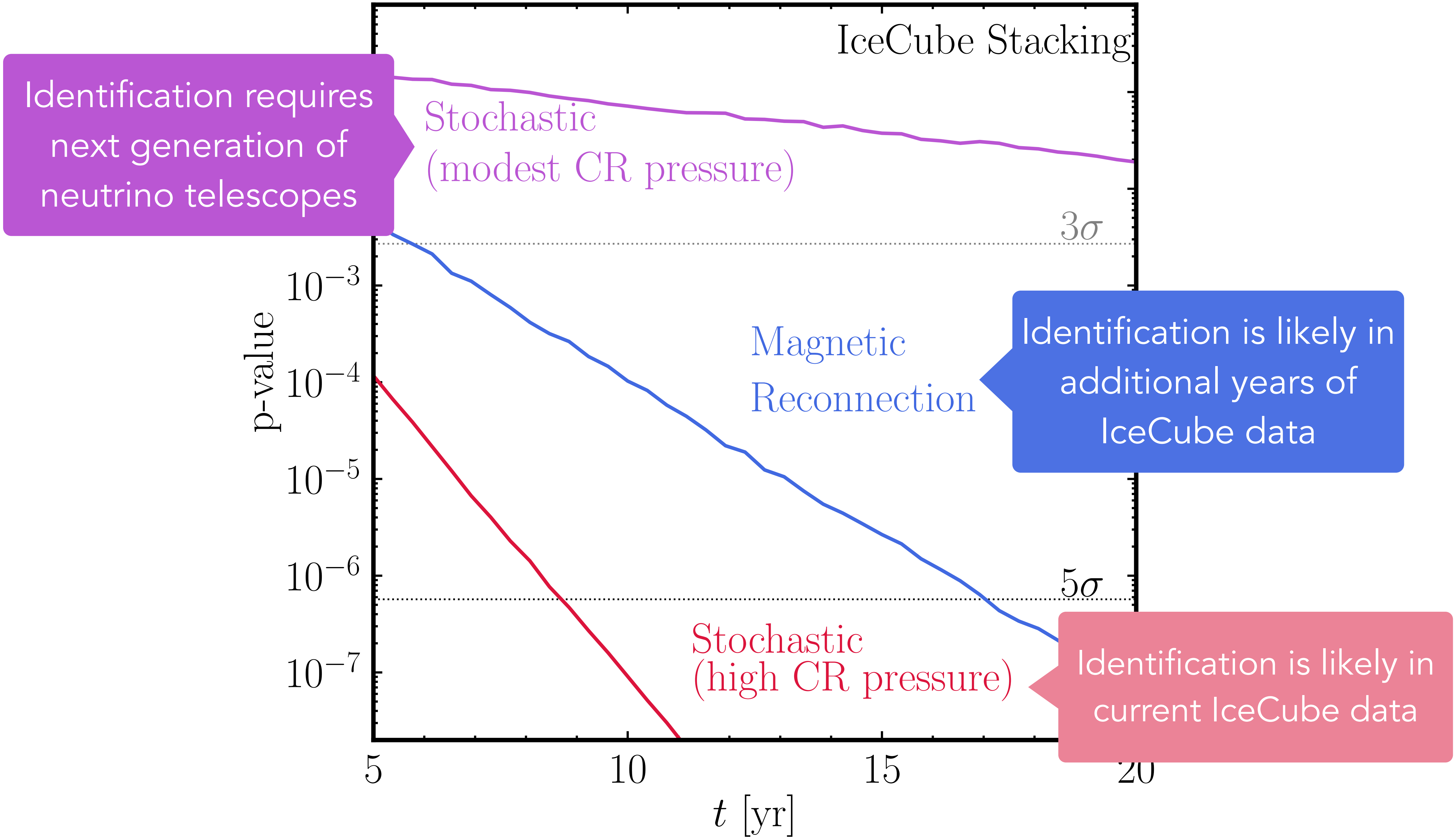


Identification is likely in current IceCube data

Prospects for Stacking Neutrinos from Bright Sources in IceCube

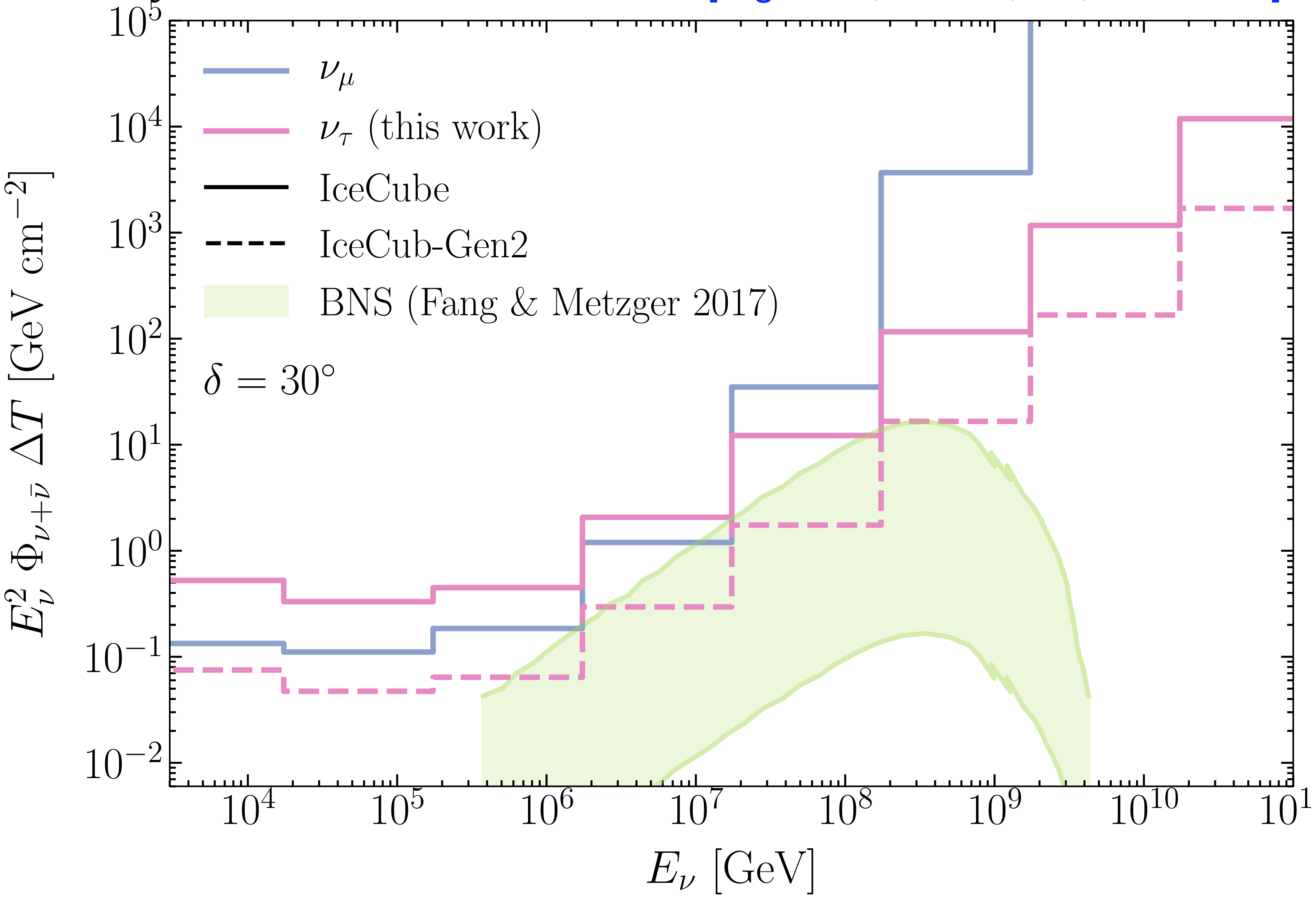


Prospects for Stacking Neutrinos from Bright Sources in IceCube

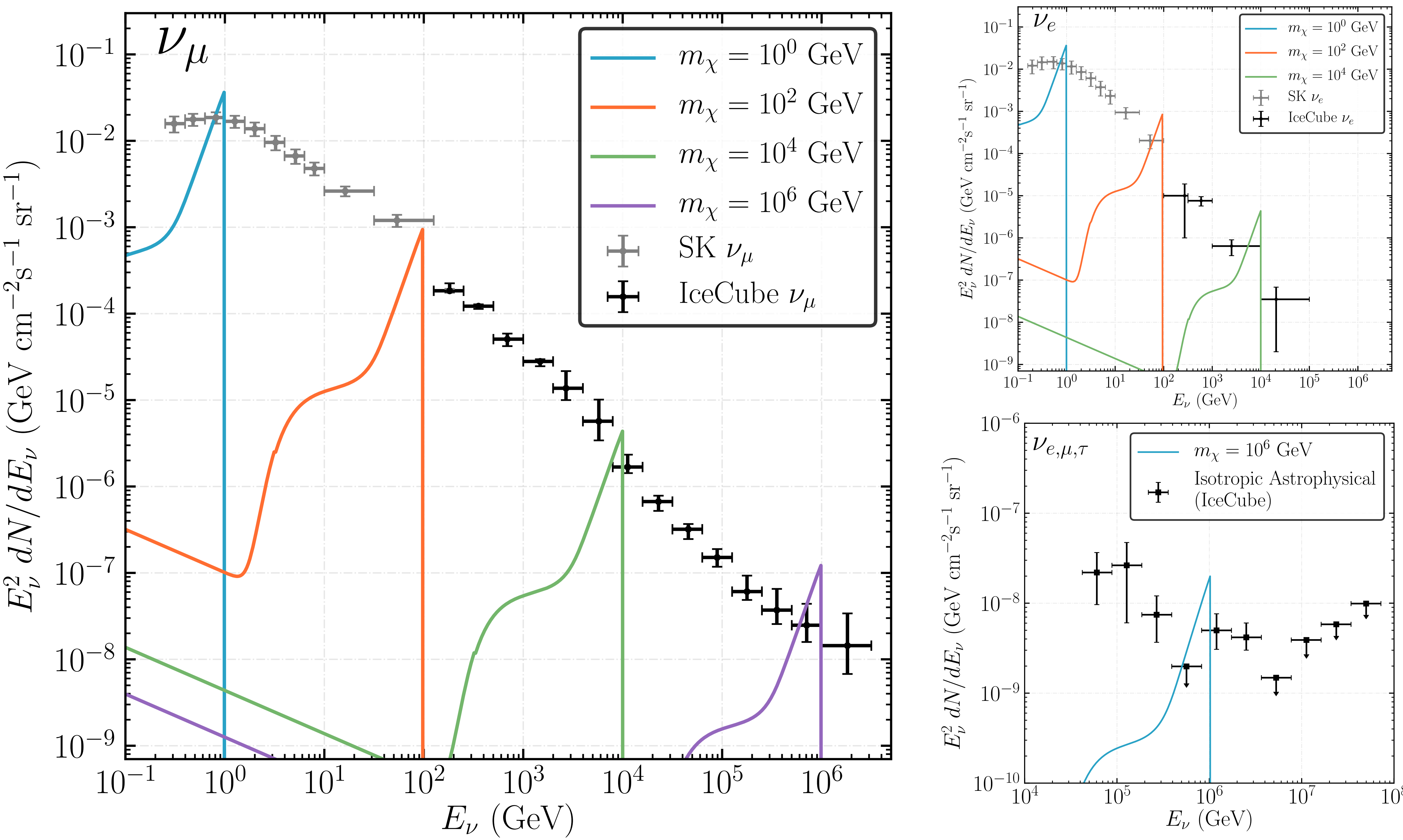


Tau PeV Neutrinos & UHE Emission

[Argüelles, Halzen, AK, Safa 2022]

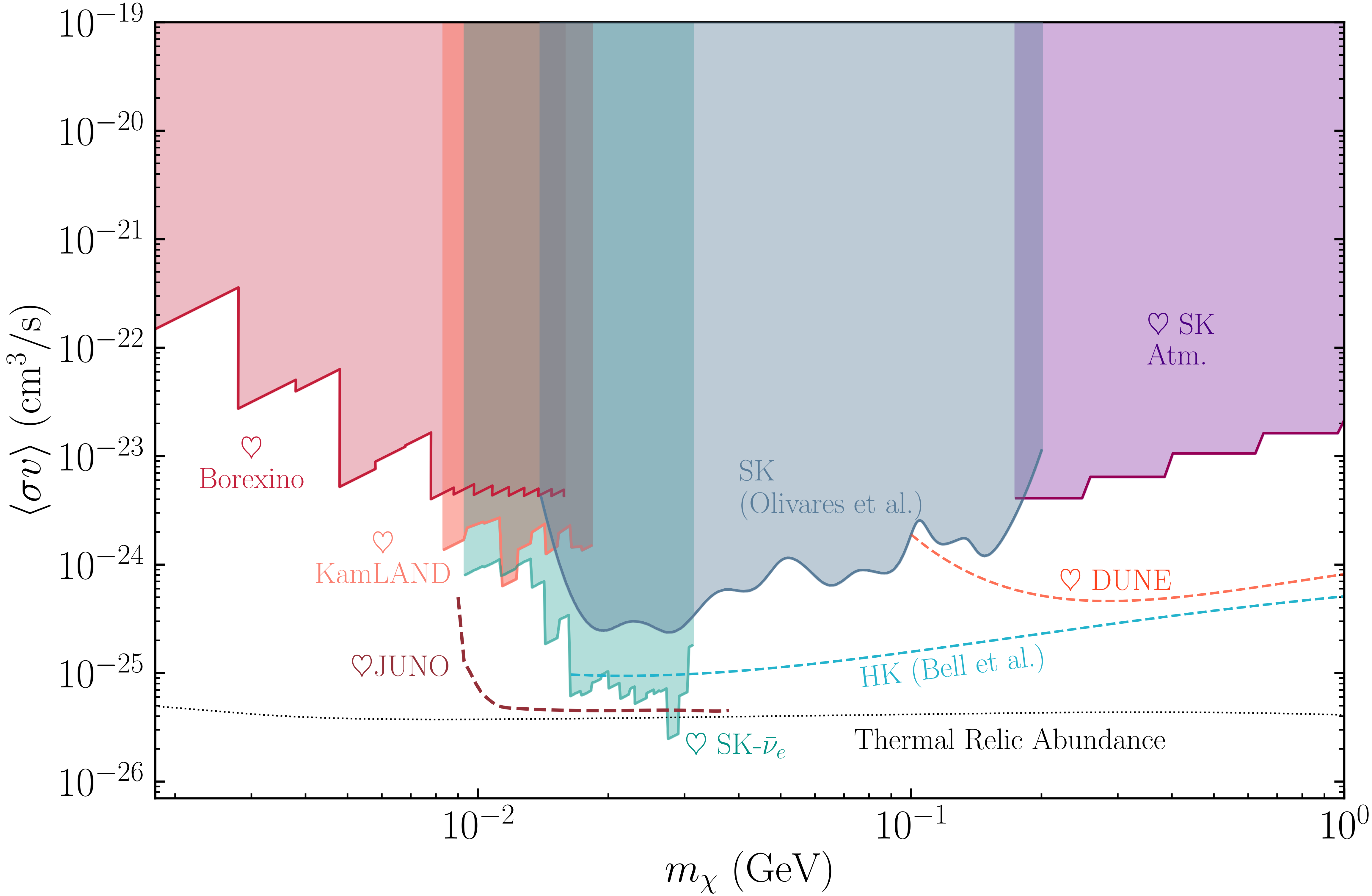


Neutrinos Signal from DM Annihilation

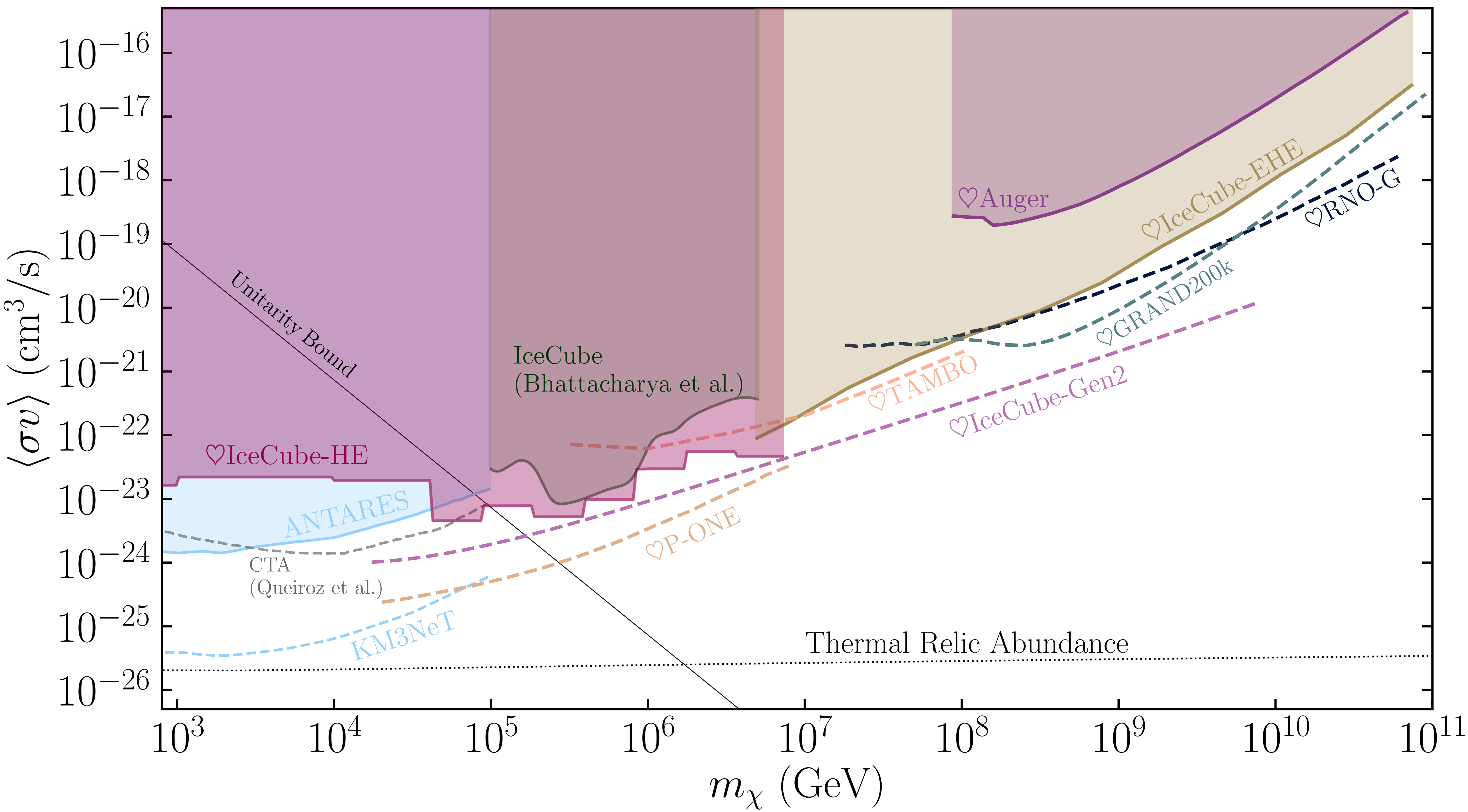


Direct DM annihilation to neutrinos would create spikes in atmospheric and cosmic neutrino flux

Constraining the DM parameter space
‣ Low Mass

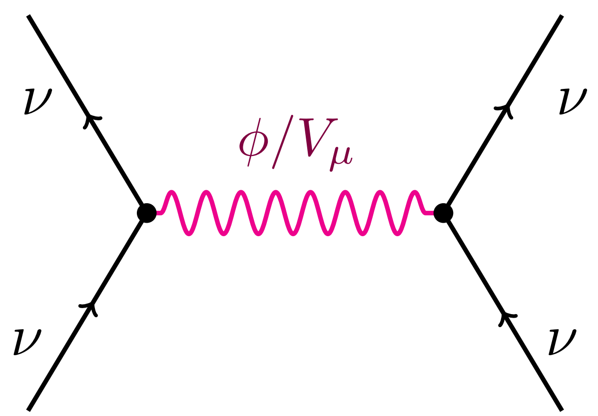


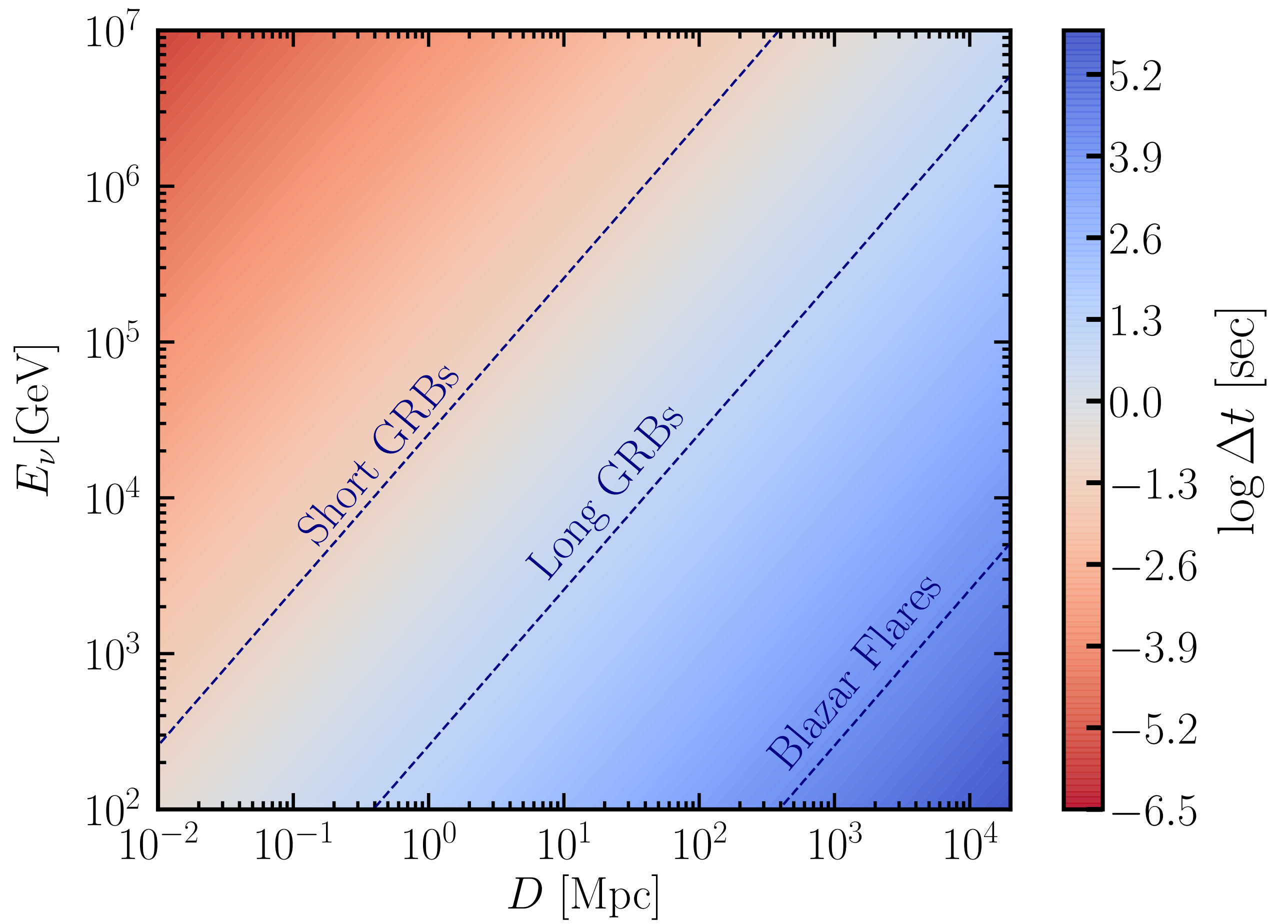
Constraining the DM parameter space
▸ High Mass (only accessible to neutrinos)



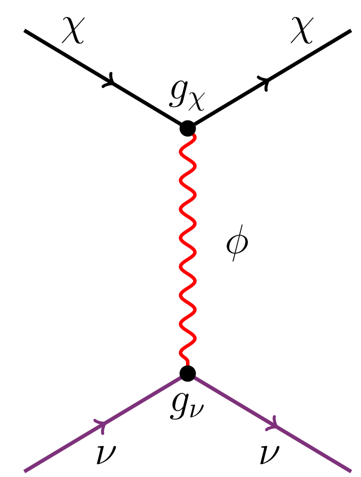
Delay via BSM Neutrino Interactions Induced

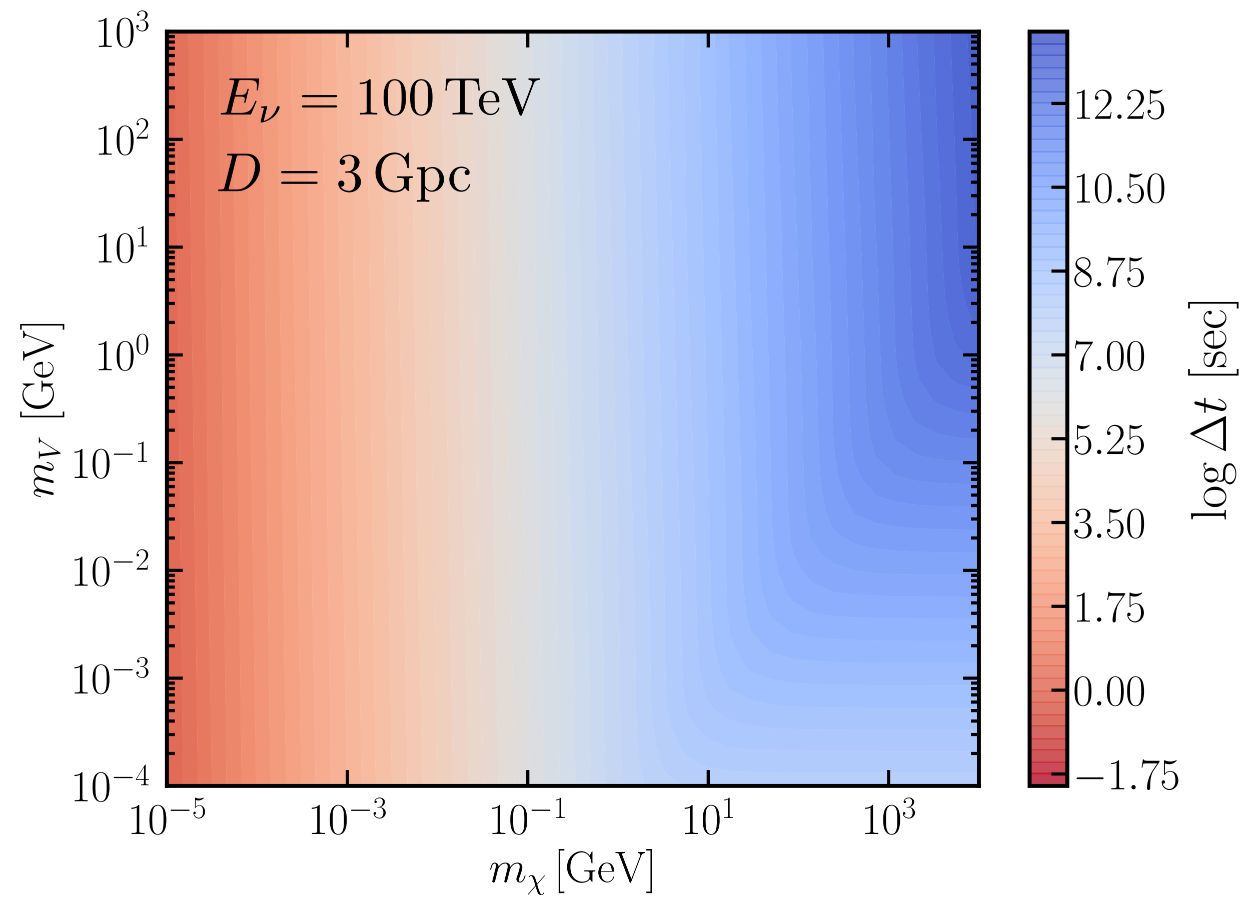
- *Secret* self neutrino interaction



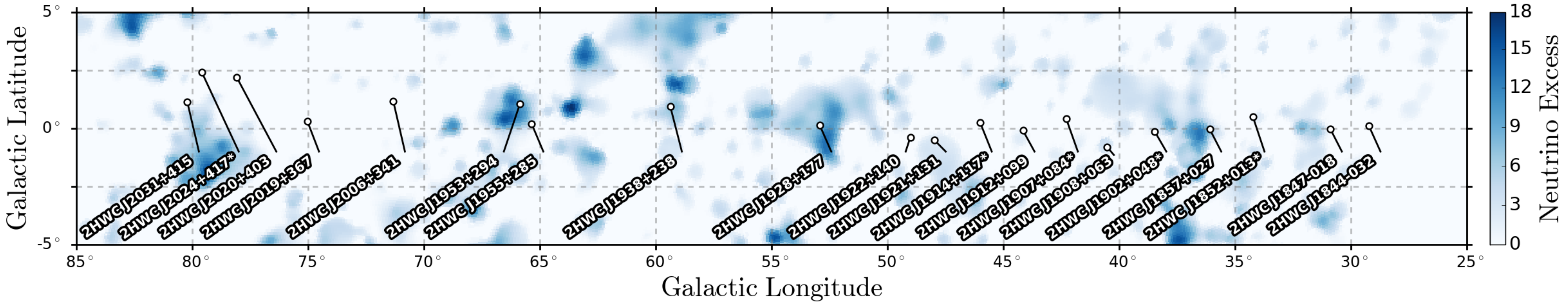


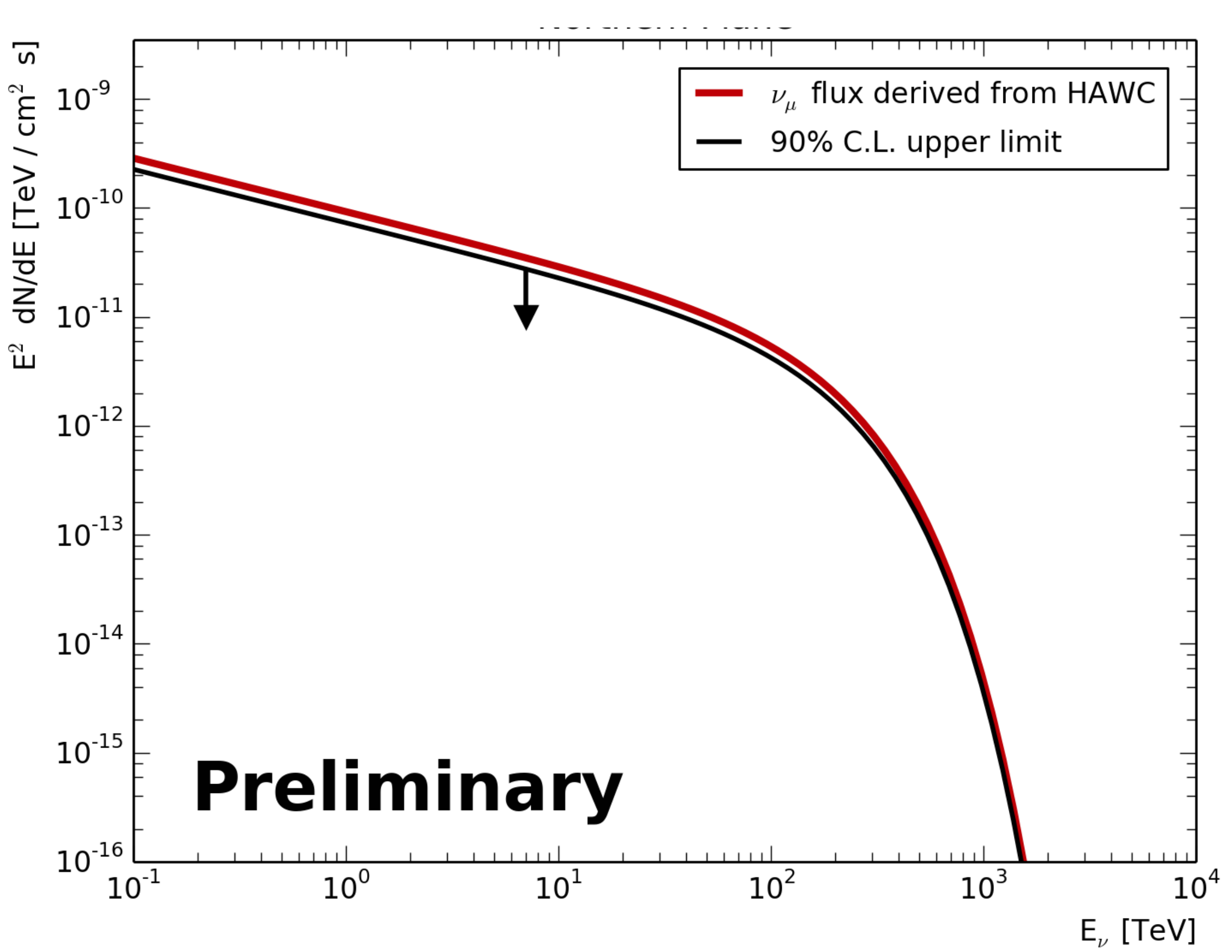
- DM-ν interactions

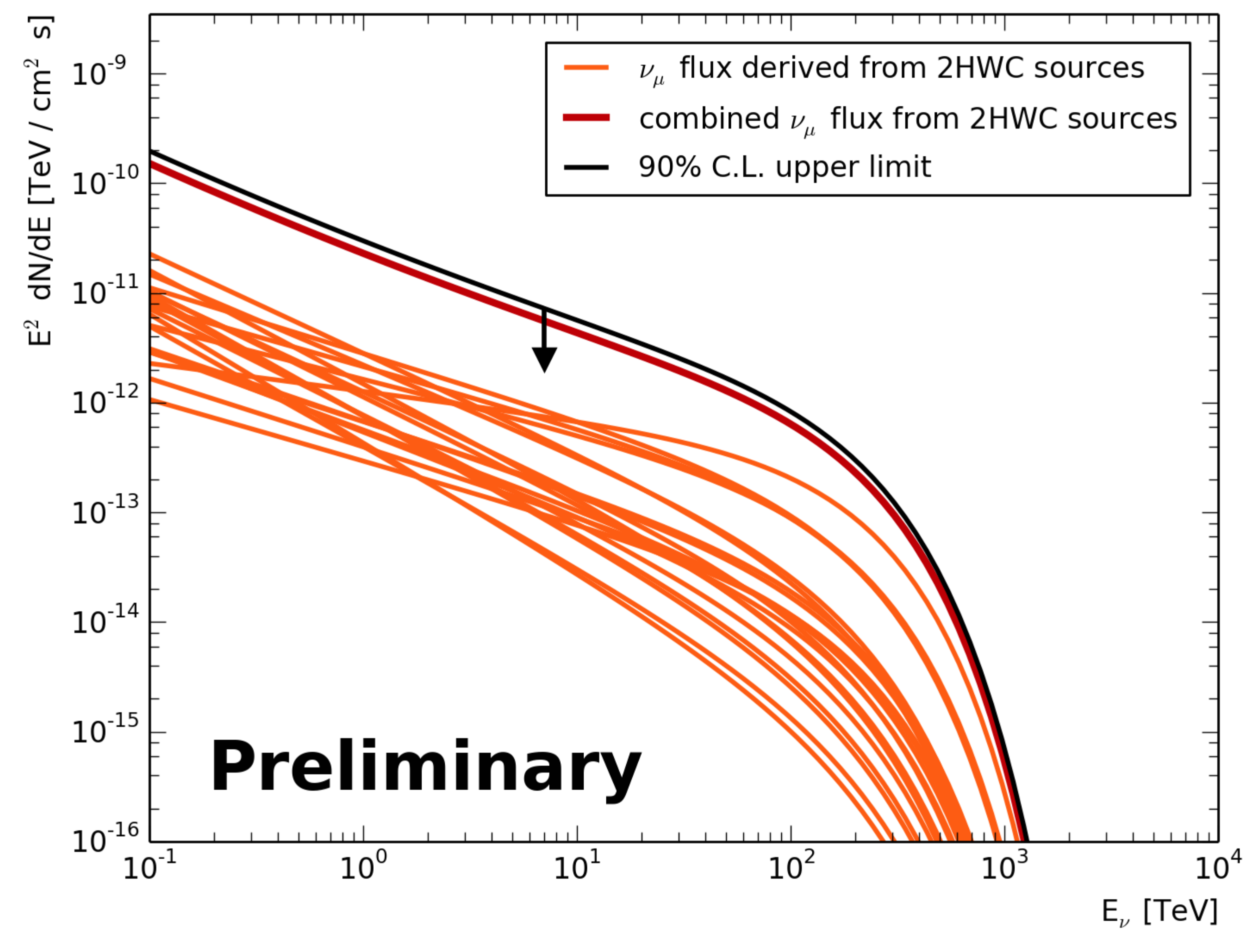




IceCube-HAWC Joint Search





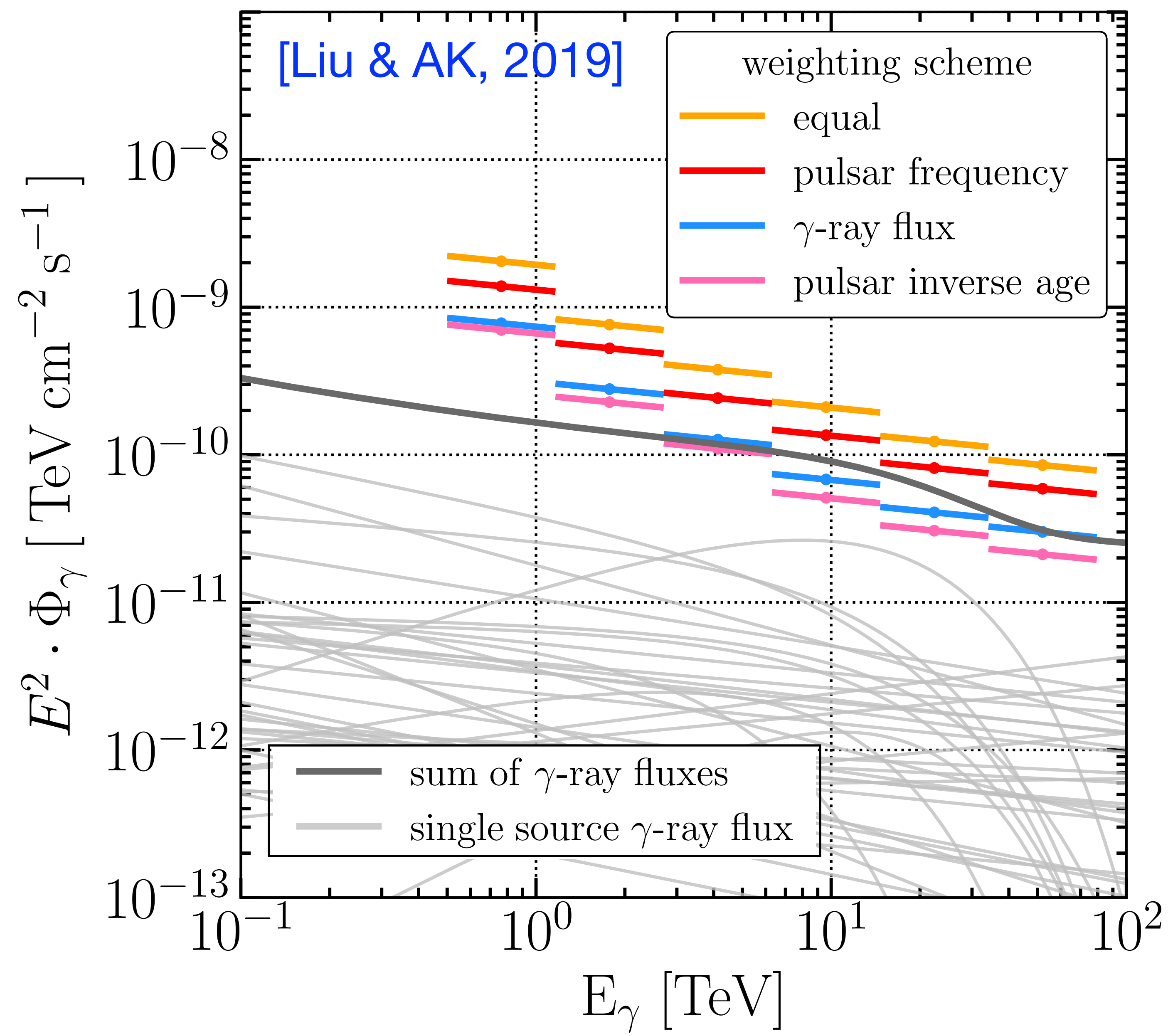


[AK & Wood, 2019]

Pulsar Wind Nebulae

- PWN: major Galactic sources at very high energies.
- Leptonic scenarios favored but caveats exist.
- Hadronic component cannot be ruled out [Amato+ 2003, Guetta+ 2007, Palma+ 2017]

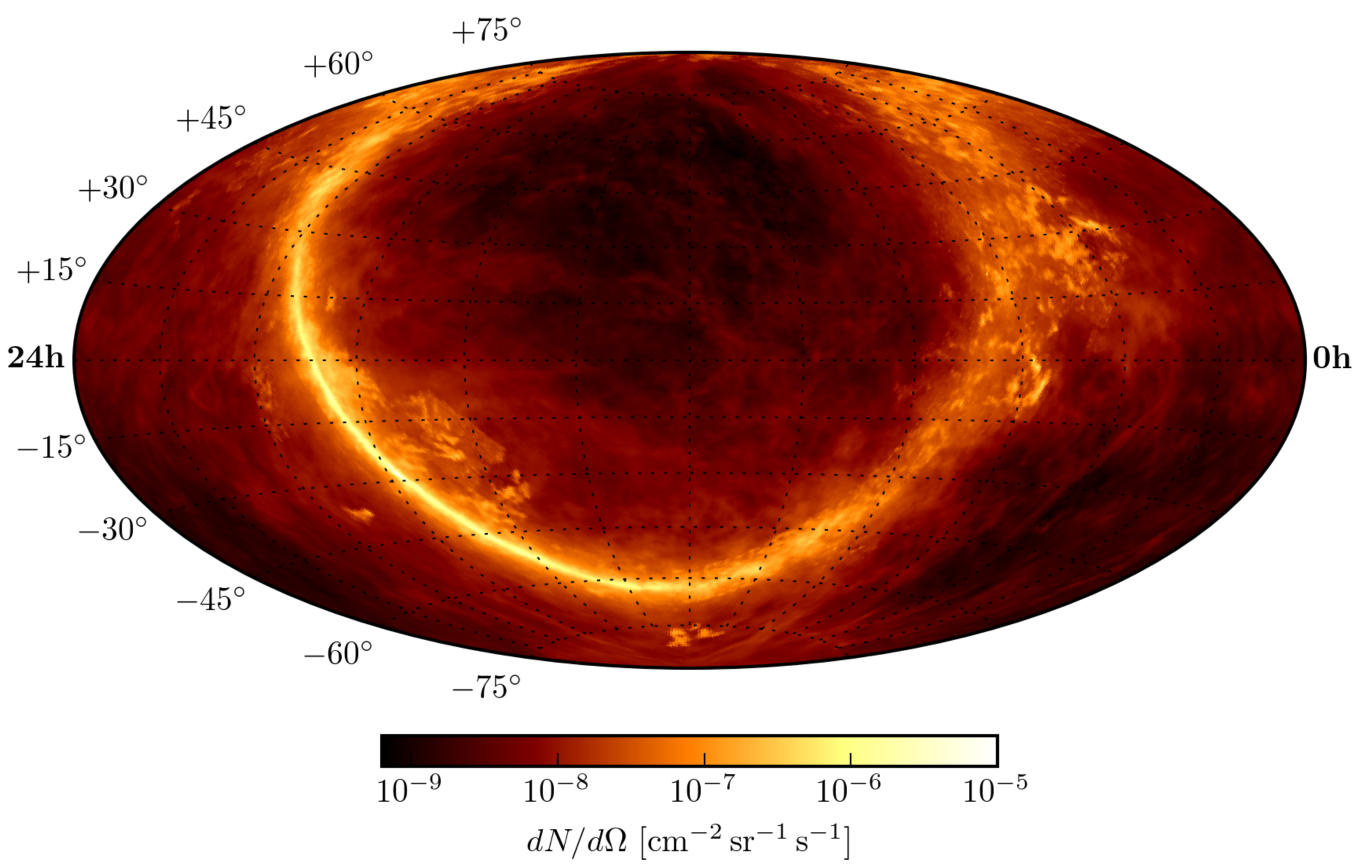
Upper limits on the pionic gamma-ray emission

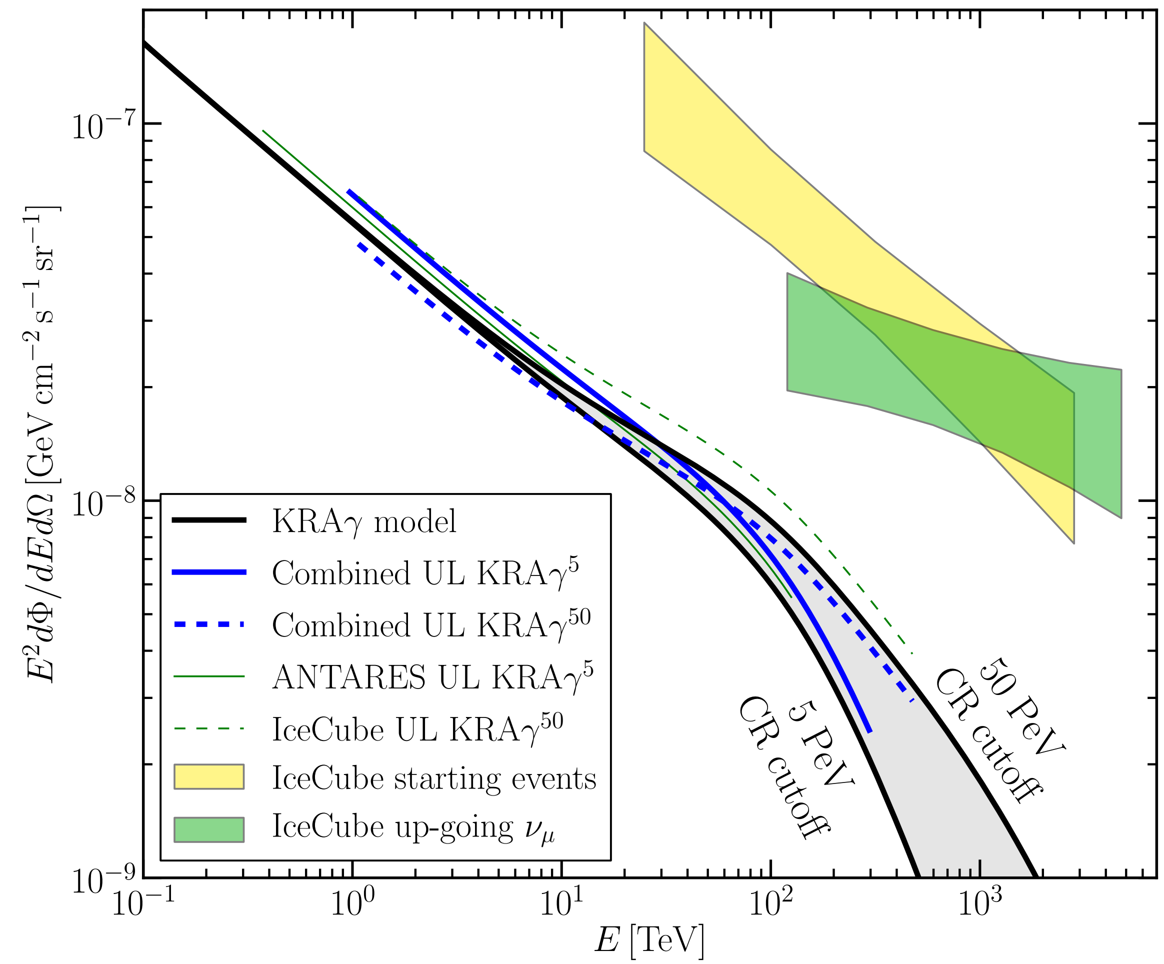


Diffuse Galactic Neutrino Emission

- Interaction of Galactic CR with dense environments in the Miky Way:
  - Guaranteed flux of HE neutrinos

[IceCube & ANTARES ApJLett 2018]





- Extended emission from the Milky Way at high energies
- Upper limits closing in on the predicted flux