Prospects for Identifying Bright Seyfert Galaxies in Current & Future Neutrino Telescopes

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with K. Murase & S. S. Kimura, arXiv: 2102.04475

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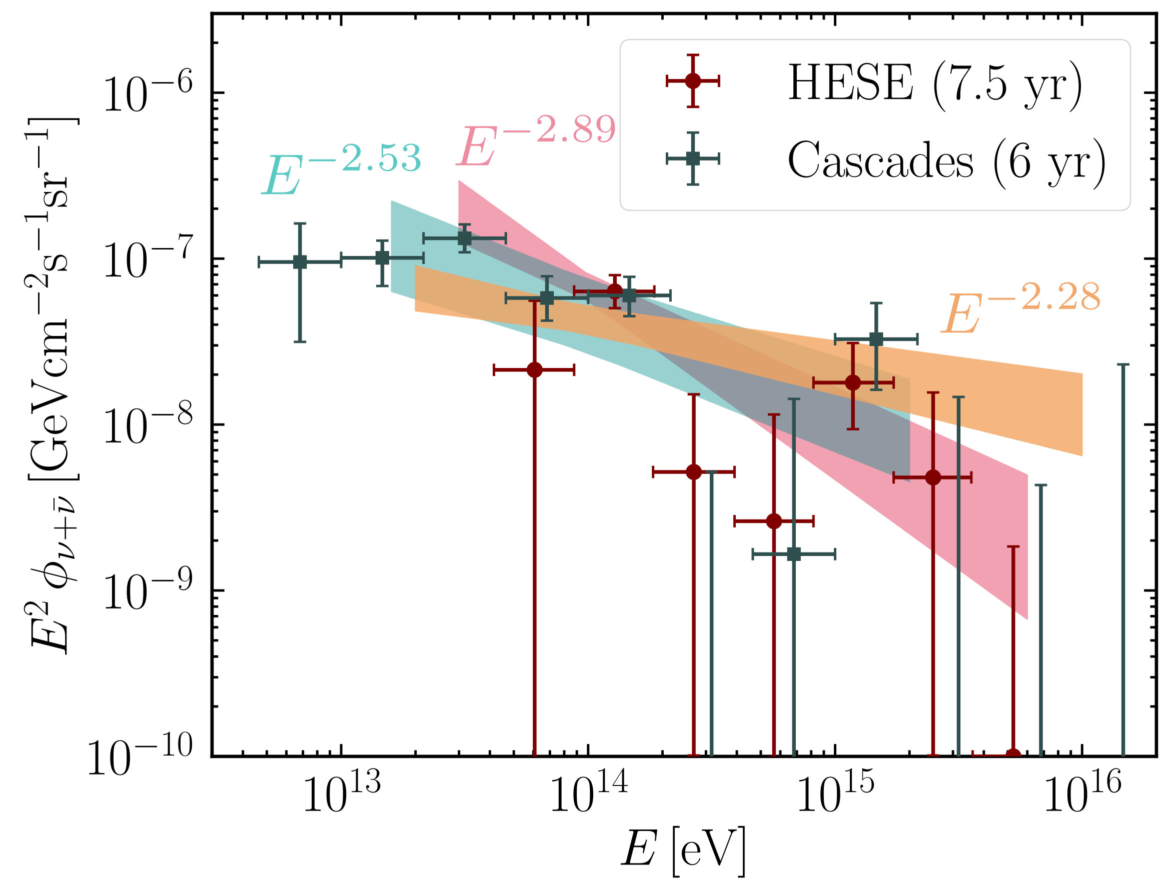
High-Energy Neutrino Flux

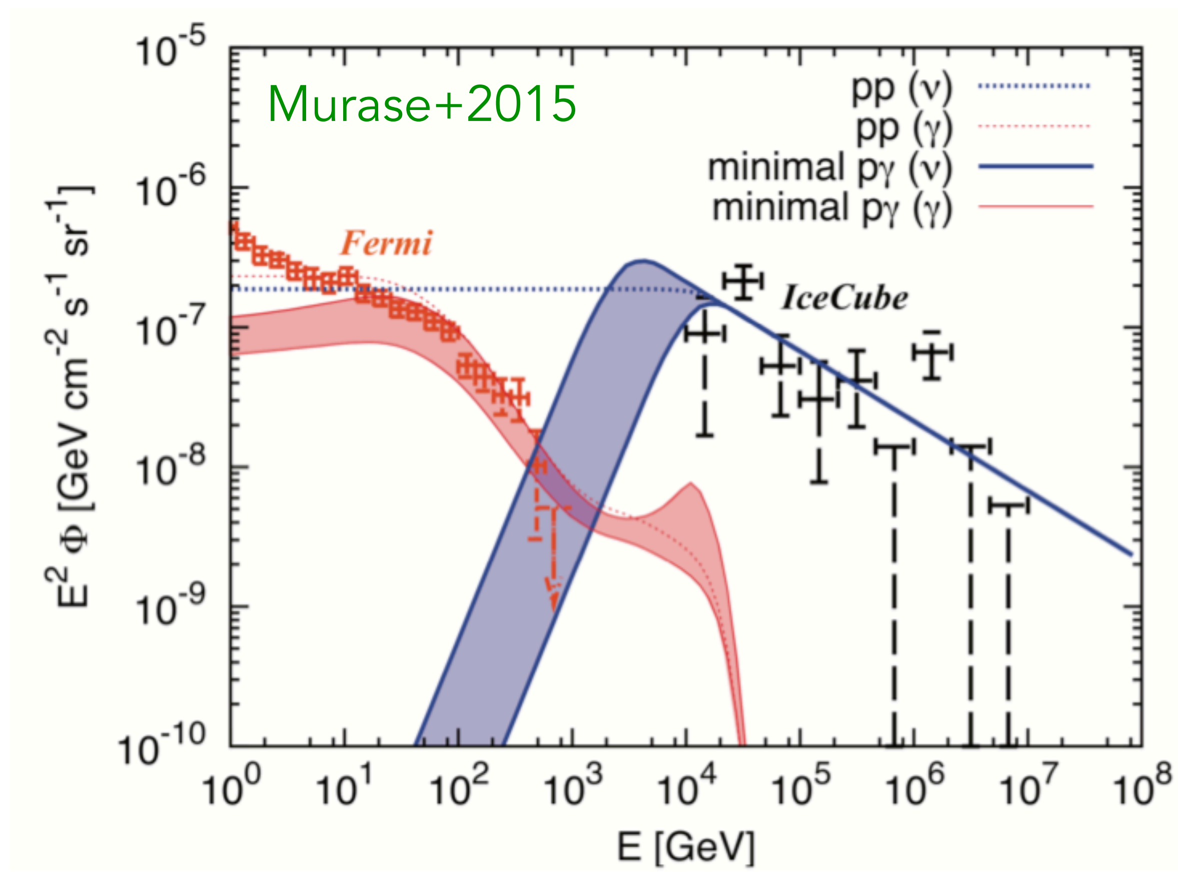
Observation of the high-energy cosmic neutrino flux has been established in multiple channels in IceCube.

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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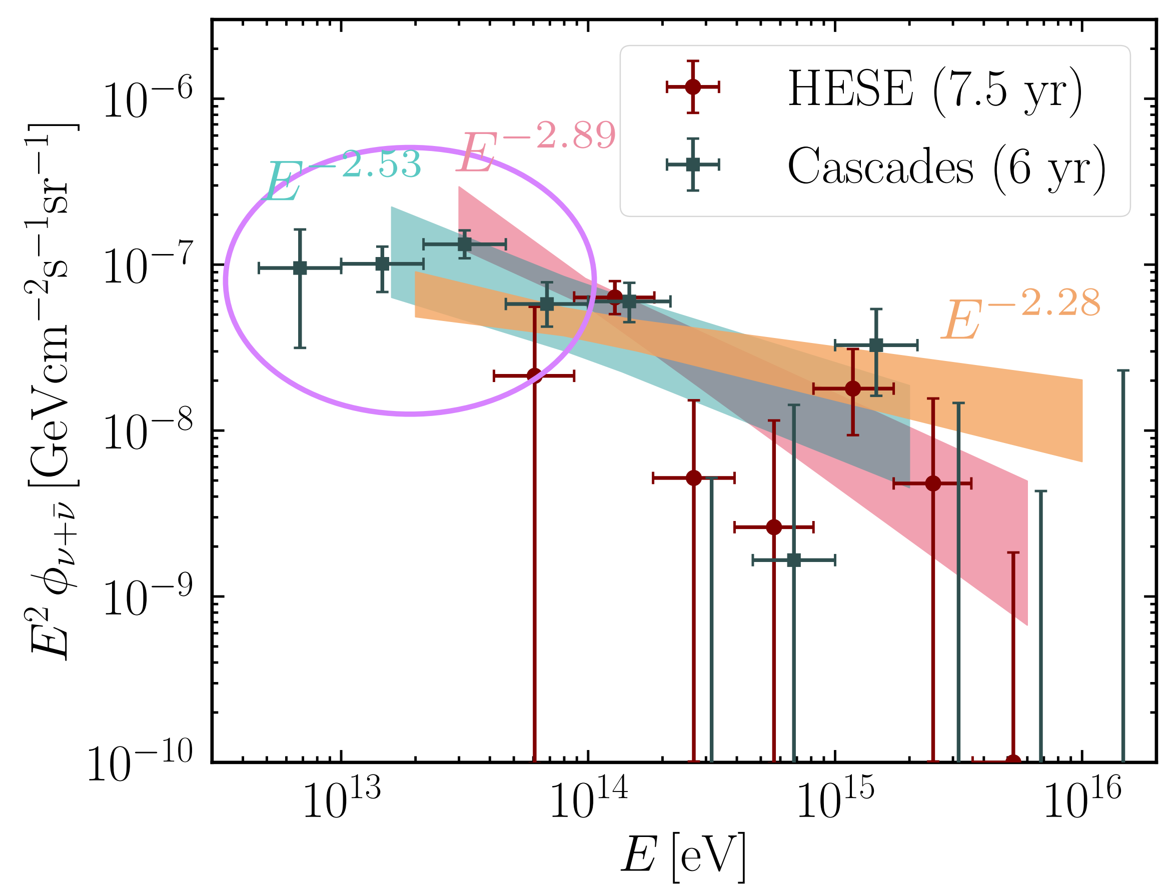
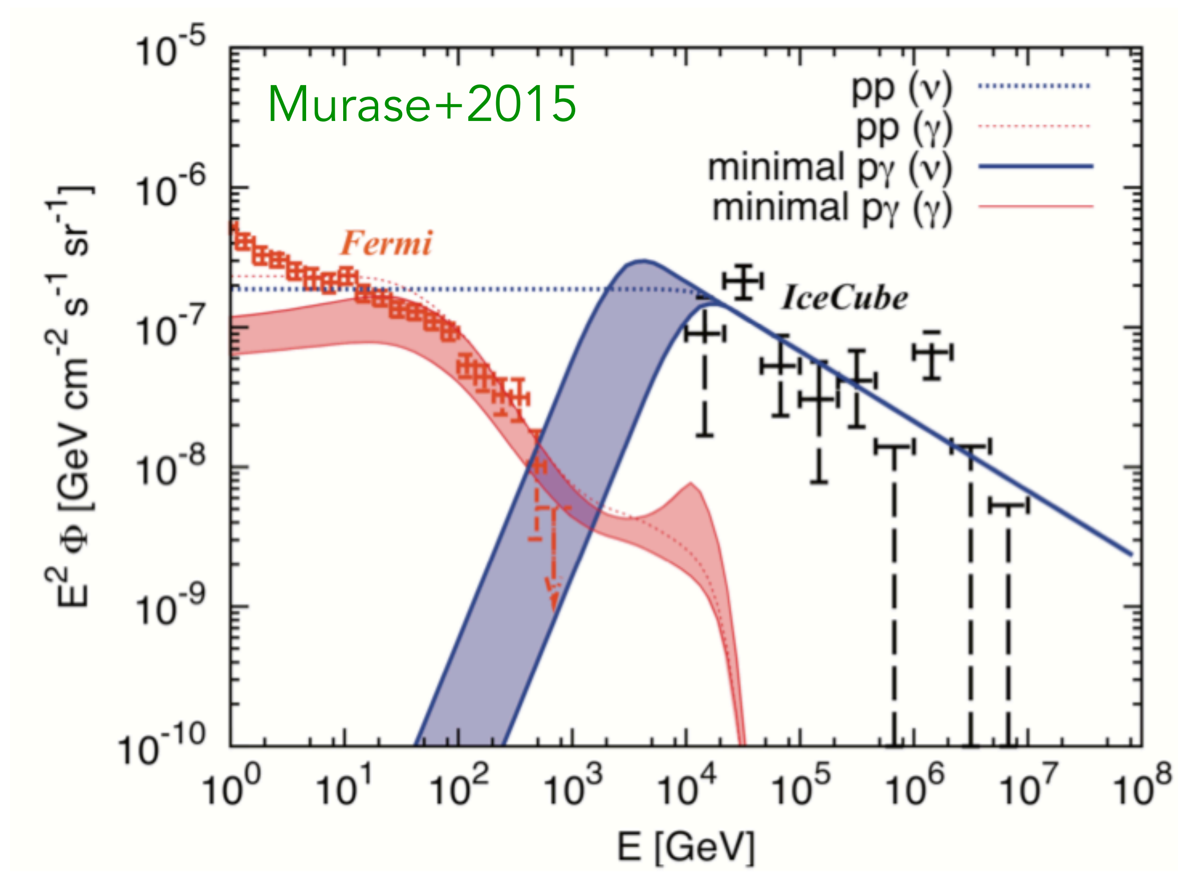
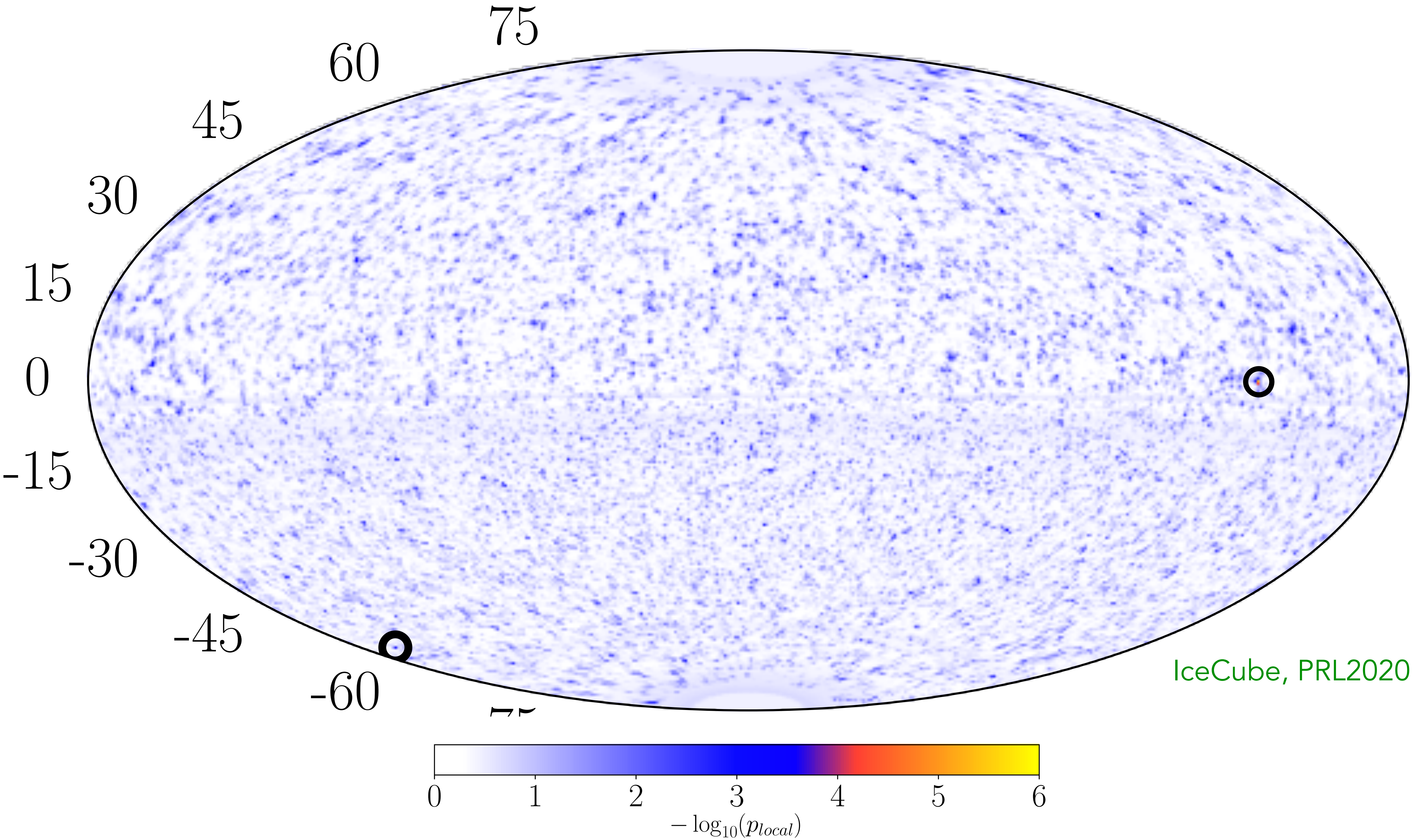




Neutrino Sky - IceCube 10 yr



IceCube, PRL2020

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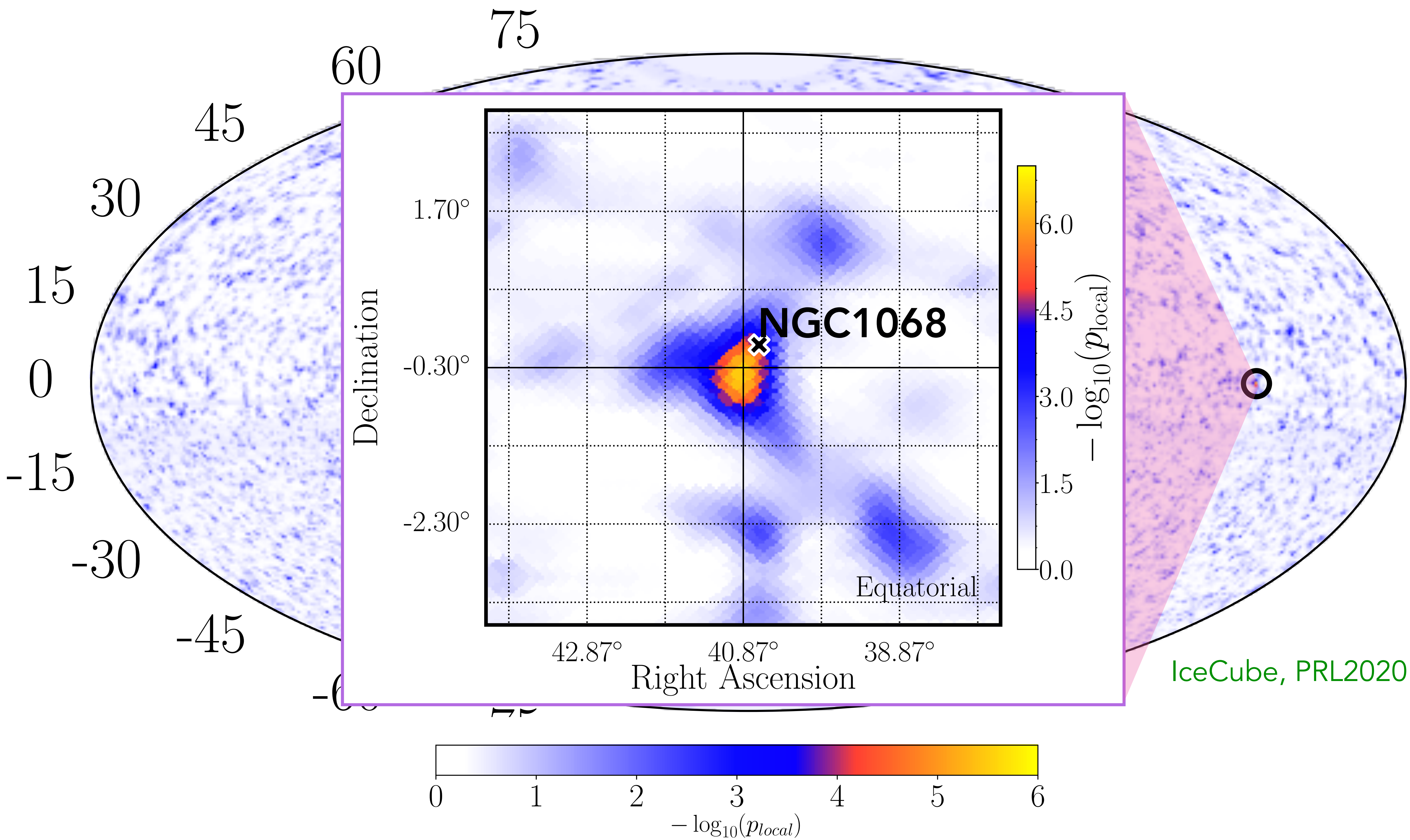

IceCube, PRL2020

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 $1.8\mathrm{x}10^{-5}$ (2.9σ Post trial).

NGC 1068 & the Neutrino Signal

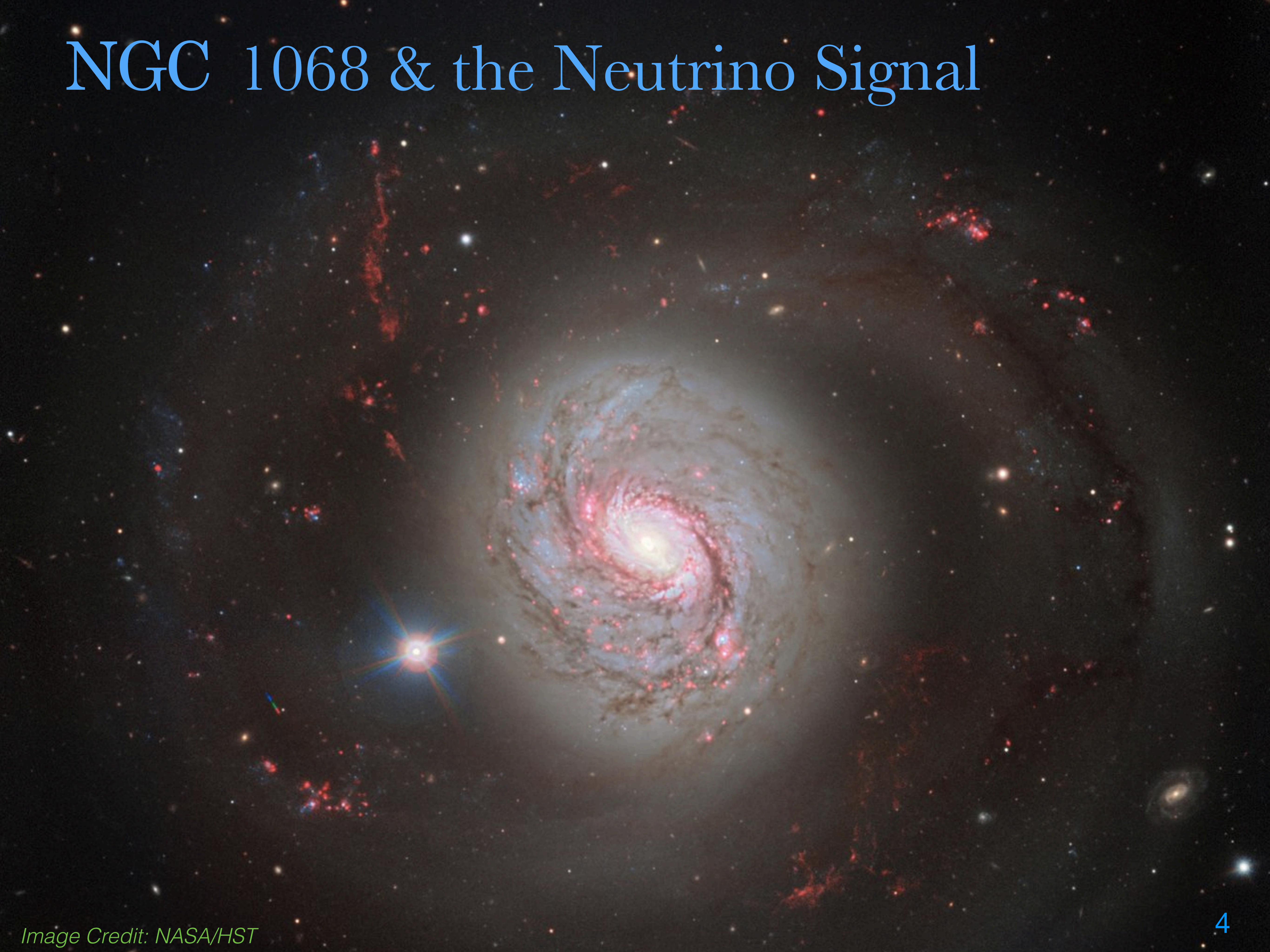

Image Credit: NASA/HST

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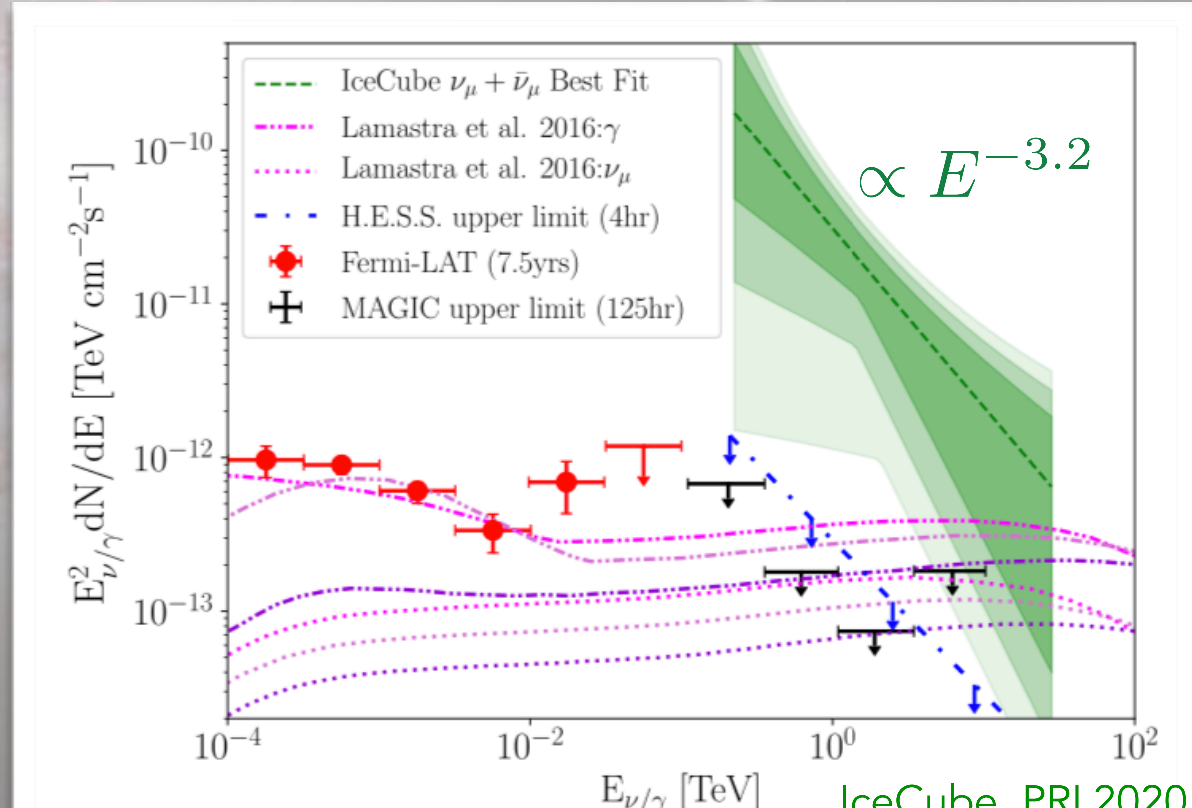
- IceCube 10 yr time-integrated search found **51 neutrinos** in the direction of NGC 1068, with a soft spectrum.
- The neutrino flux much higher than the observed γ-ray flux by *Fermi*.
- Models built on measured γ-ray flux by Fermi cannot accommodate the neutrino flux.
- **Obscuring** necessary in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



IceCube, PRL2020

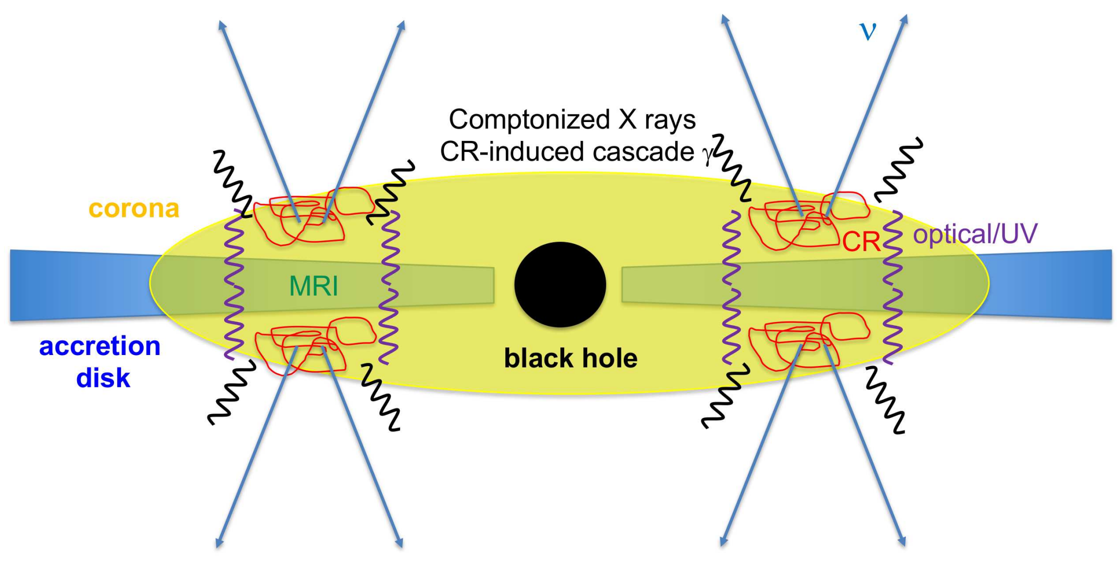
Image Credit: NASA/HST

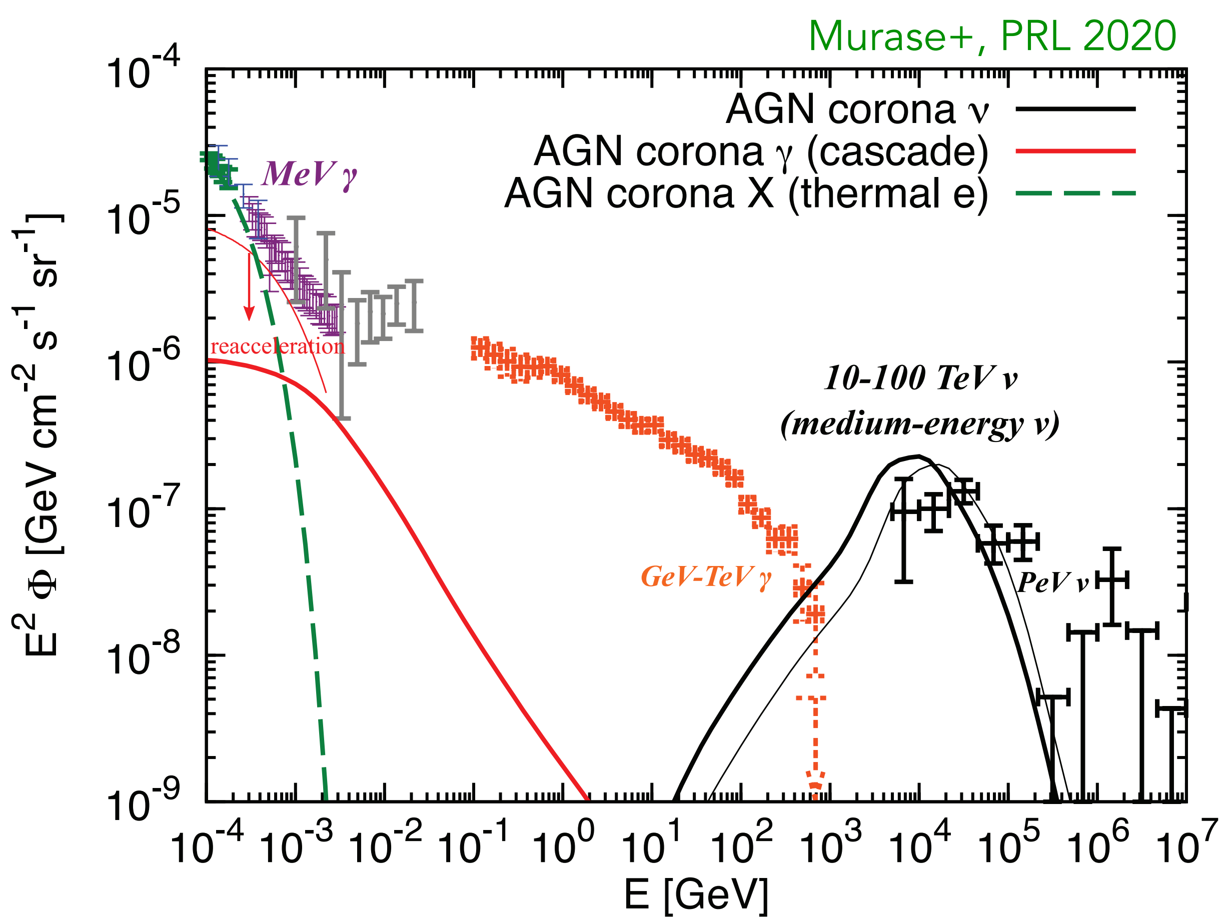
Neutrino Production in AGN Coronae

- **Cores** of the active galactic nuclei (AGN), which are optically thick for GeV-TeV γ-rays are one of the best candidates as the source of the high-energy neutrinos.

- In **Seyfert galaxies**, accretion dynamics and magnetic dissipation will form a magnetized **corona** above the disk.

- The **disk-corona** model for high-energy neutrino emission from the core of AGNs can successfully accommodate the flux of cosmic neutrinos at medium energies in the 10-100 TeV range.





Magnetized Corona Model

- The **corona** above the optically thick accretion disk is *hot*, *magnetized*, and *turbulent*.
  - Acceleration of ions via stochastic &/or magnetic reconnection processes

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- Solve diffusion equation

CR injection function

$$\dot{\mathcal{F}}_{p,\mathrm{inj}} = \frac{f_{\mathrm{inj}} L_X \delta(\varepsilon_p - \varepsilon_{\mathrm{inj}})}{4\pi(\varepsilon_{\mathrm{inj}}/c)^3 \mathcal{V}}$$

injection fraction

injection energy

volume of the corona

Diffusion coefficient

$$D_{\varepsilon_p} \propto \varepsilon_p^q$$

q=5/3
(Kolmogorov turbulence)

- Input parameters

$\frac{P_{\mathrm{CR}}}{P_{\mathrm{th}}}$ CR to thermal pressure ratio

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Solve transport equation

injection term $\dot{N}_{\varepsilon_p,\mathrm{inj}} \propto \varepsilon_p^{-s}$

$$\int \dot{N}_{\mathrm{inj}} \varepsilon_p d\varepsilon_p = \epsilon_{\mathrm{CR}} \dot{M} c^2$$

accretion rate

Cutoff energy of the injection spectrum is given by the balance between cooling & acceleration.

Input parameters

ϵ_{CR} energy fraction carried by CRs

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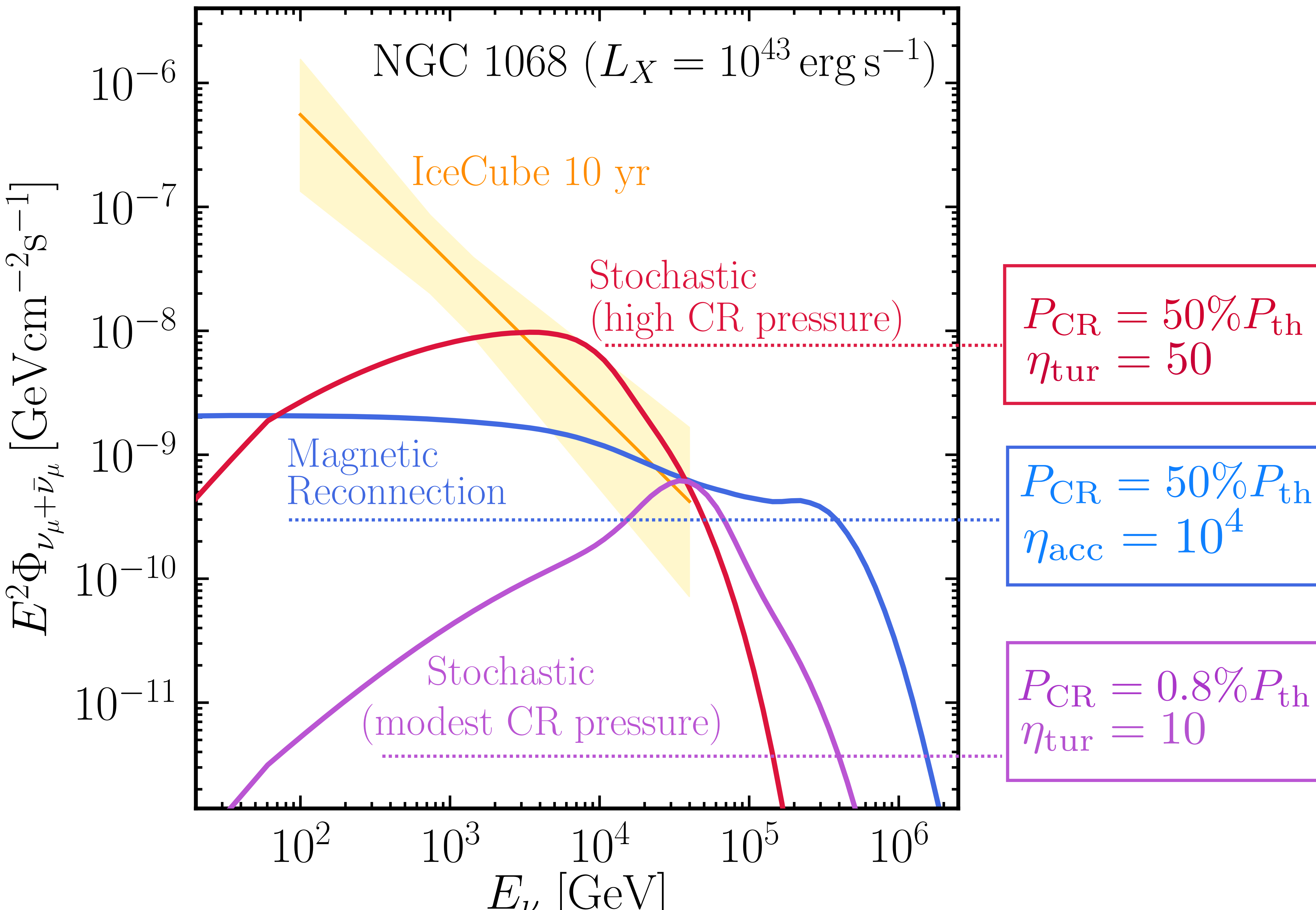
processes: *pp, pγ, Bethe-Heitler*

NGC 1068 in AGN-Corona Model

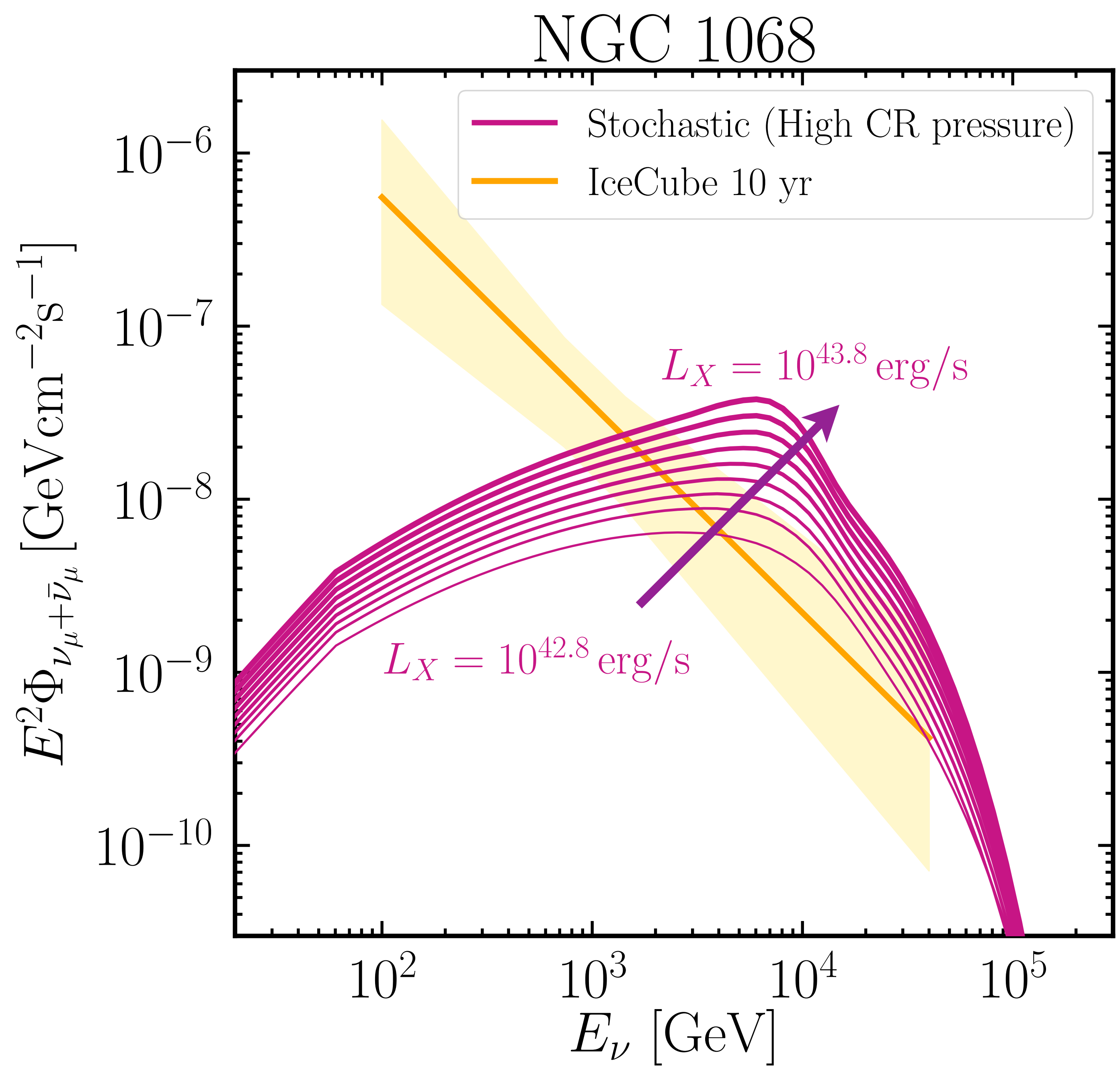
Adopting parameters compatible with IceCube 10 year source search



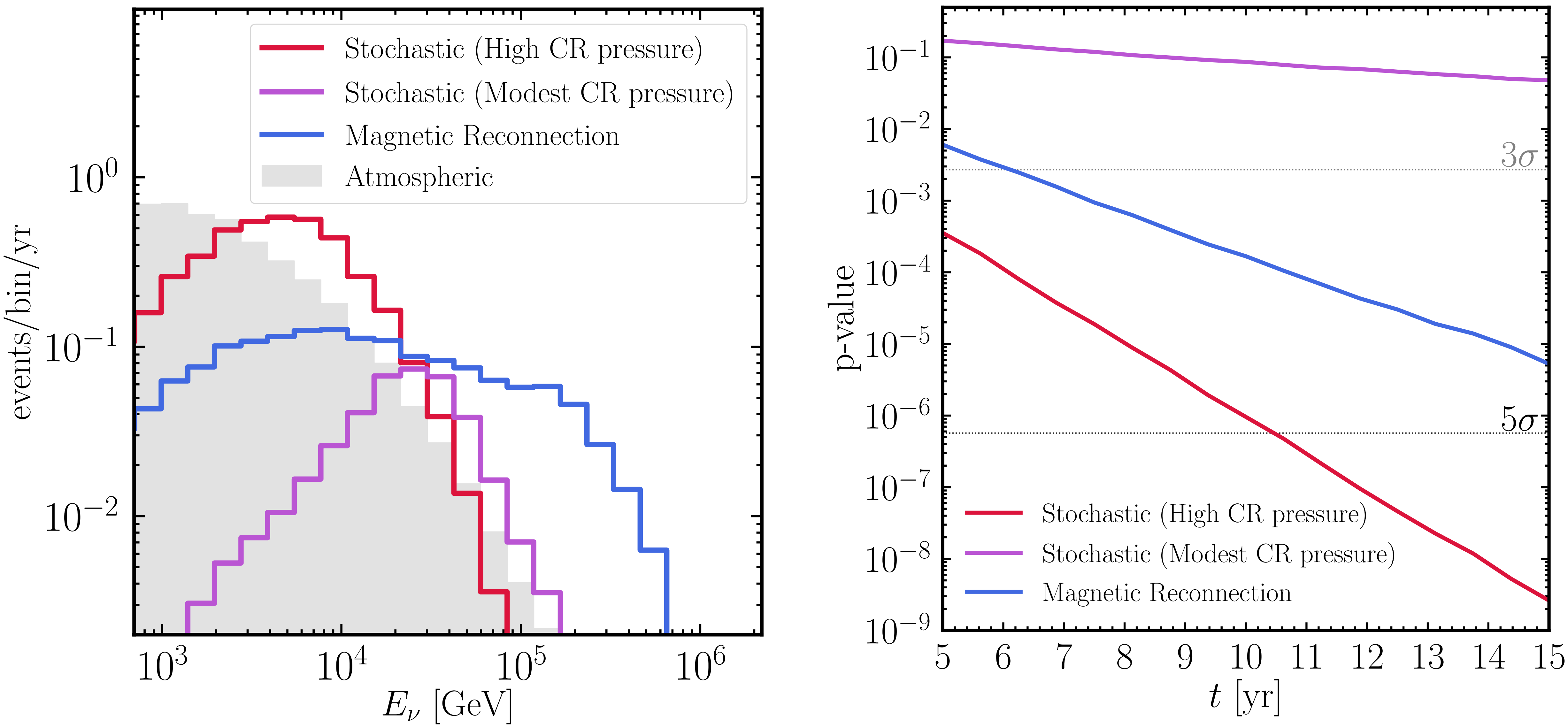
Neutrino flux & X-ray Measurements

- The high level of column density for NGC 1068 makes measuring the intrinsic X-ray luminosity challenging.
  - Estimated intrinsic X-ray luminosity carry large uncertainties.

- NuSTAR and XMM-Newton monitoring campaigns have reported $L_X \simeq 7^{+7}_{-4} \times 10^{43}\mathrm{erg/s}$ [Marinucci+2015]



Likelihood for Identifying NGC 1068



- Stochastic acceleration with high CR pressure will be the most likely scenario for identification in IceCube.
- Magnetic reconnection scenario would be identified.
  - hard spectrum is in tension with IceCube best fit spectrum.

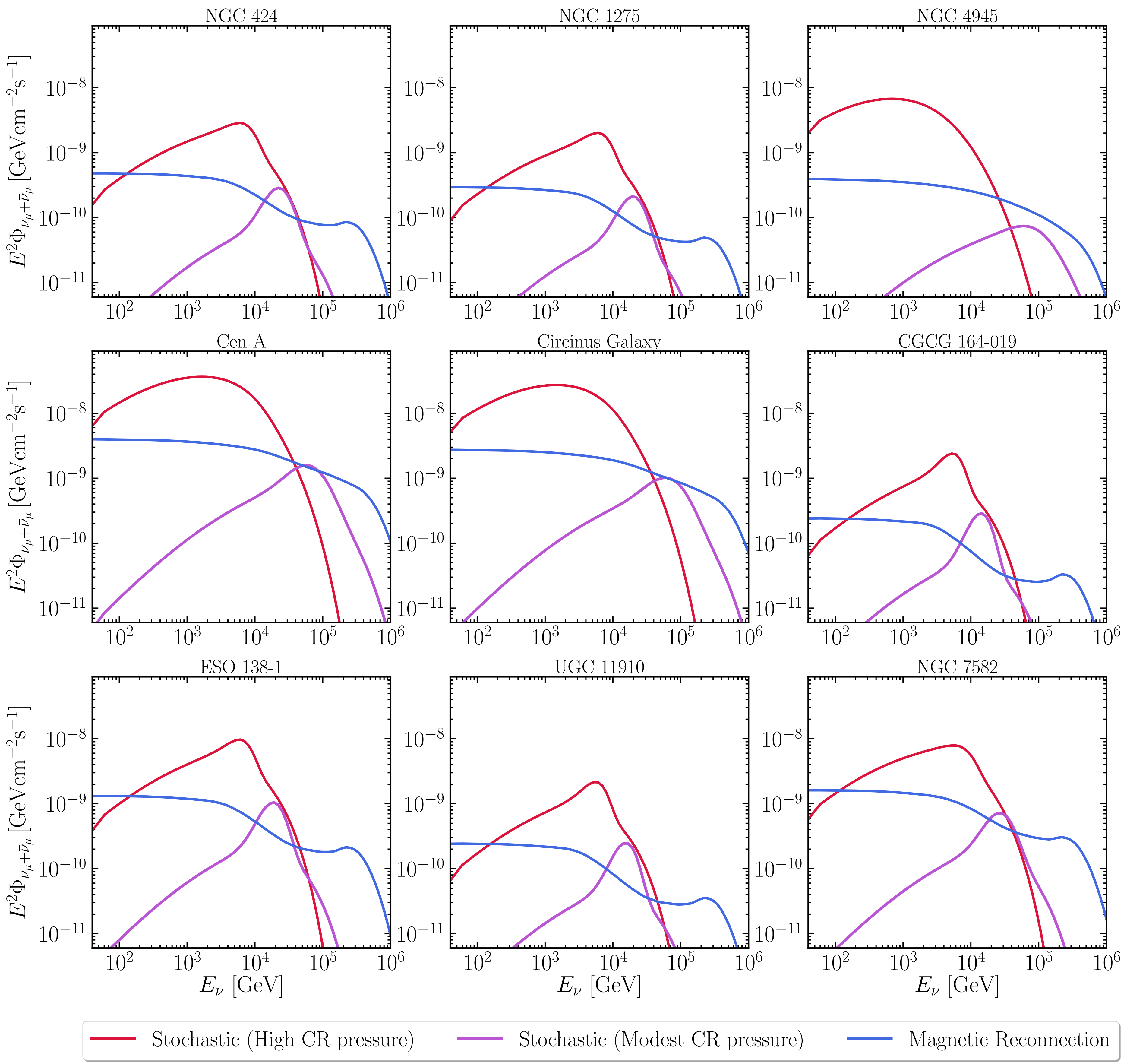
Neutrino Flux from Bright Nearby Seyferts

From BAT AGN Spectroscopic Survey (BASS), we select the **10** sources that are classified as ***Seyfert*** galaxies and pose the **highest intrinsic X-ray flux.**

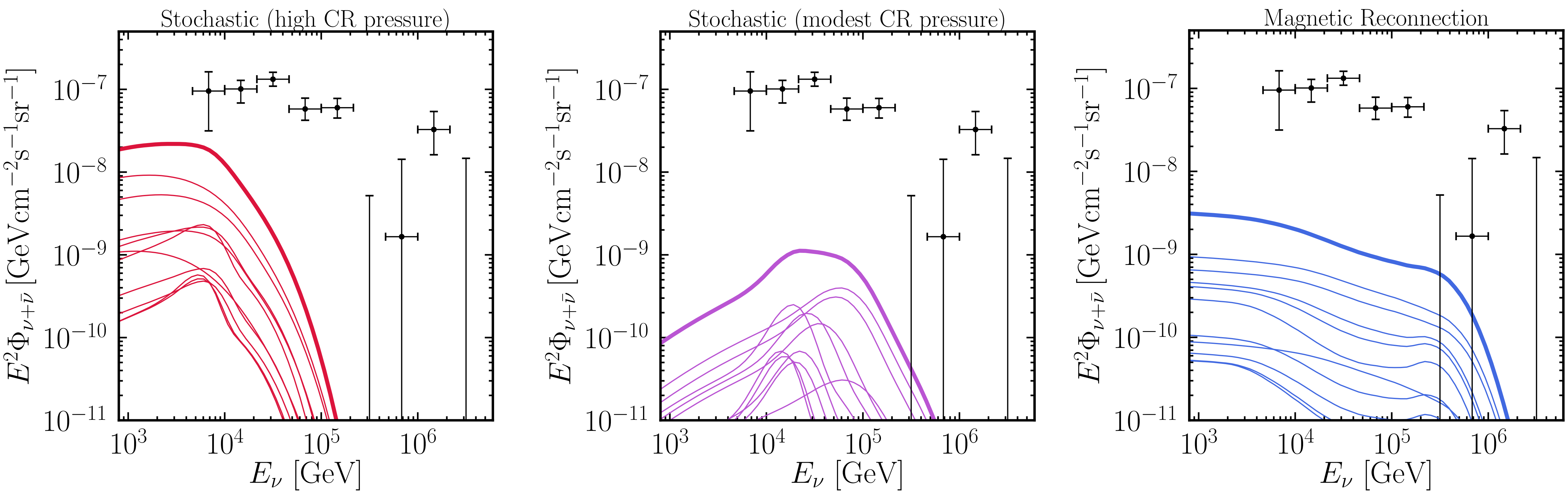
Source	Declination [deg]	z	d_{L} [Mpc]	Intrinsic flux [10^{-12}erg cm^{-2} s^{-1}]	log(Intrinsic luminosity) [erg s^{-1}]
Circinus Galaxy	-65.34	0.0014	$4.2^{\star}$	984.4	42.31
ESO 138-1	-59.23	0.0091	39.2	671.3	44.09
NGC 7582	-42.37	0.0052	22.4	507.6	43.48
Cen A	-43.02	0.00136	$3.8^{\star}$	347.3	42.39
NGC 1068	-0.013	0.00303	13.0	268.3	42.93
NGC 424	-38.08	0.0118	51.0	188.1	43.77
CGCG 164-019	27.03	0.0299	131.0	179.5	44.57
UGC 11910	10.23	0.0267	116.7	157.5	44.41
NGC 4945	-49.47	0.0019	$3.6^{\star}$	149.4	41.36
NGC 1275	41.51	0.0176	76.4	132.8	43.98

- We incorporate intrinsic X-ray luminosities & NGC 1068 model parameters to estimate the neutrino flux from nearby bright sources.

Neutrino flux from Bright Nearby Sources



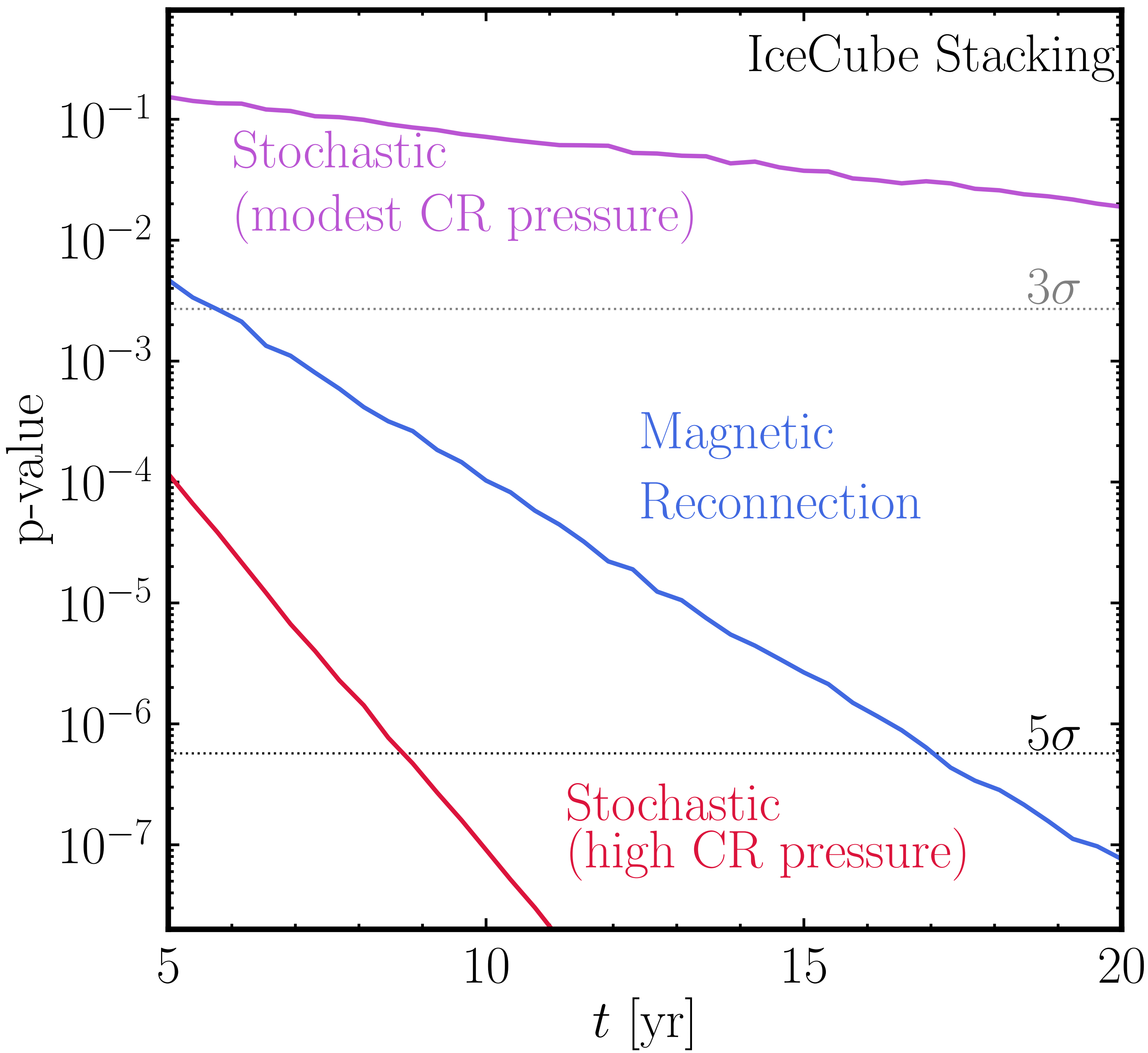
Neutrinos from Bright Sources



- The aggregated flux from individual sources contribute 2-10% to the total flux at medium-energies.

- Besides NGC 1068, identification of other bright nearby Seyferts is not likely in IceCube
    - **Stacking analysis** have a better sensitivity for identifying signal from collective neutrino emission

Prospects for Stacking Neutrinos from Bright Sources in IceCube



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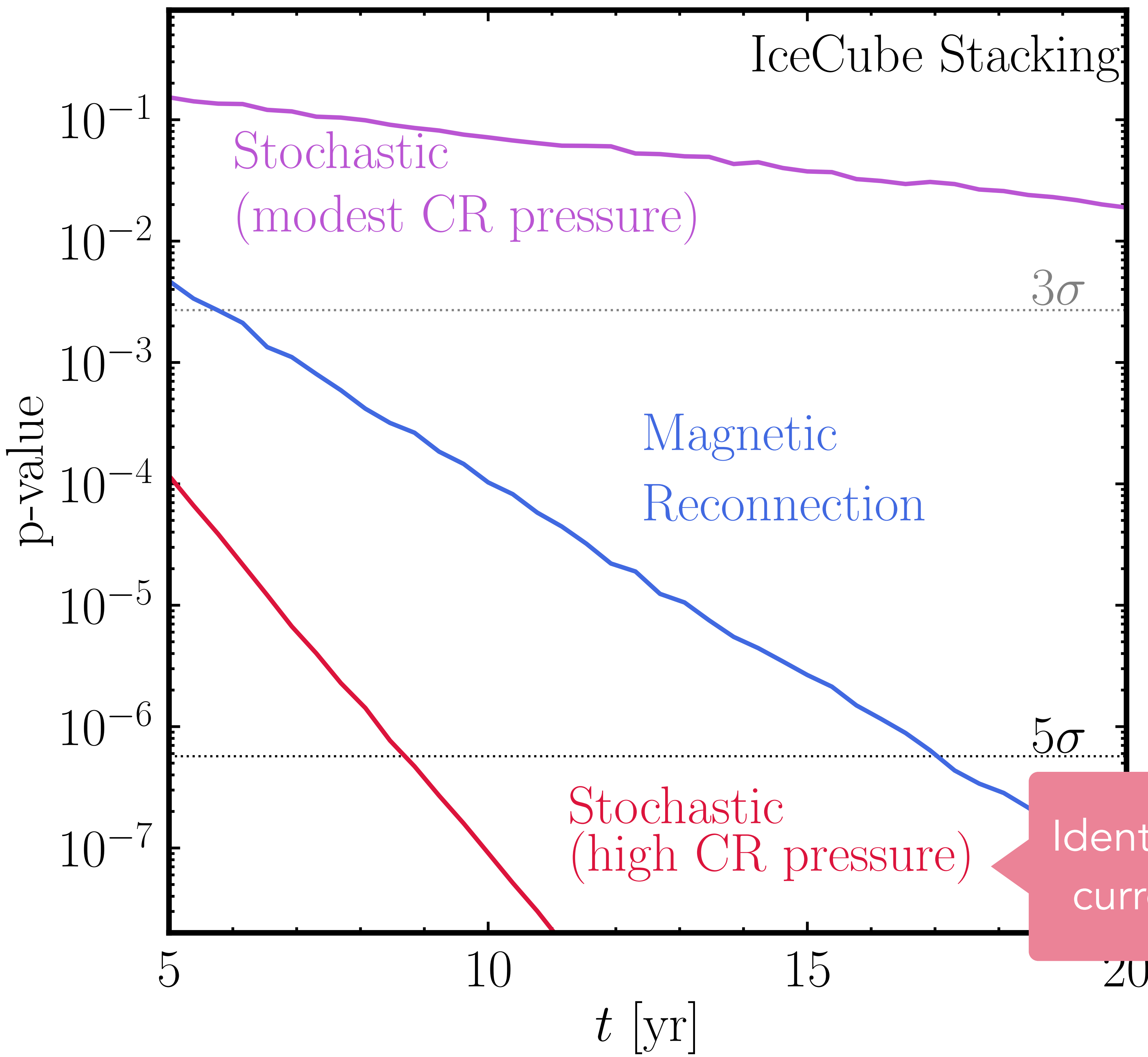

Identification is likely in current IceCube data

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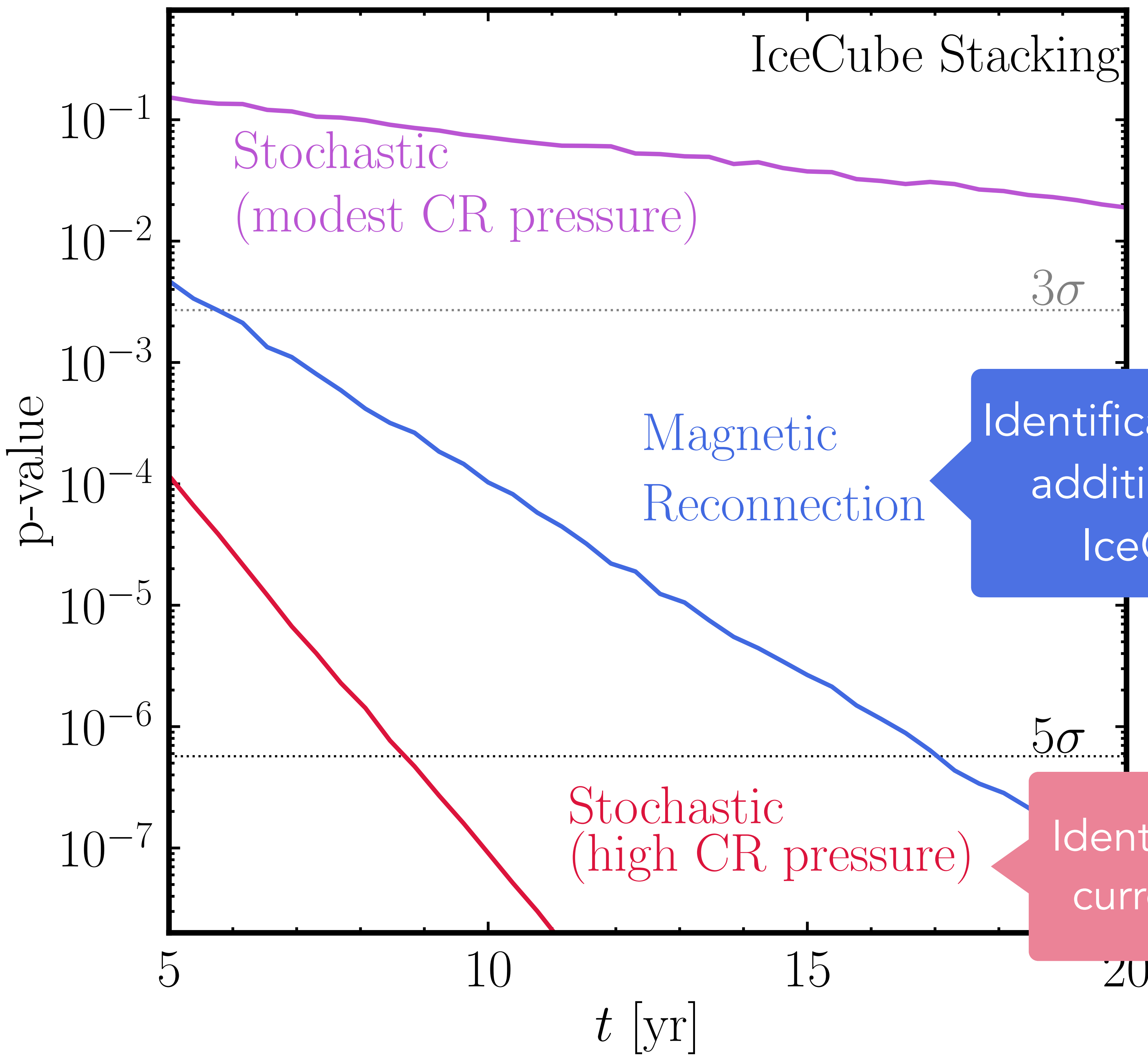

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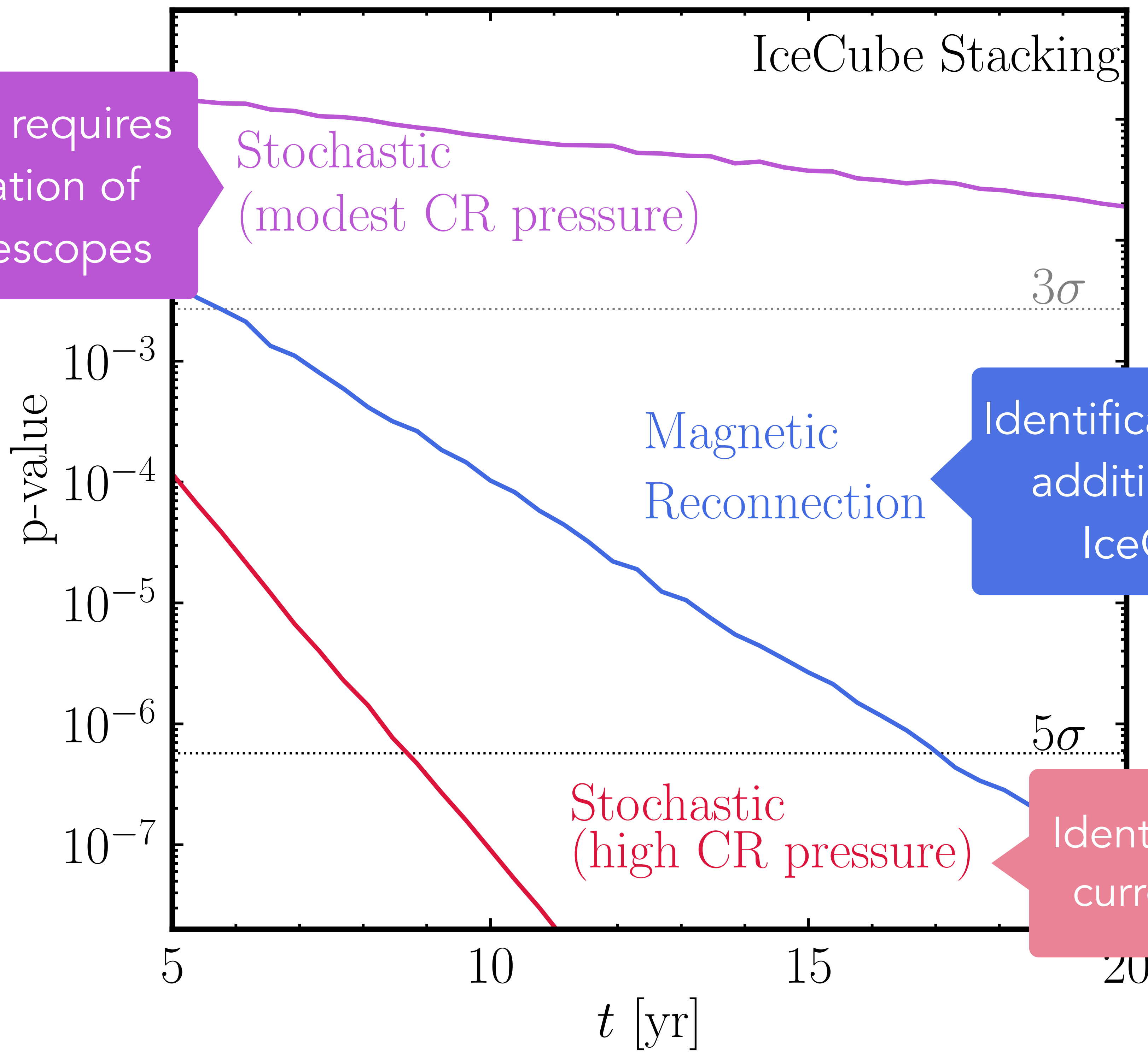


Identification requires next generation of neutrino telescopes

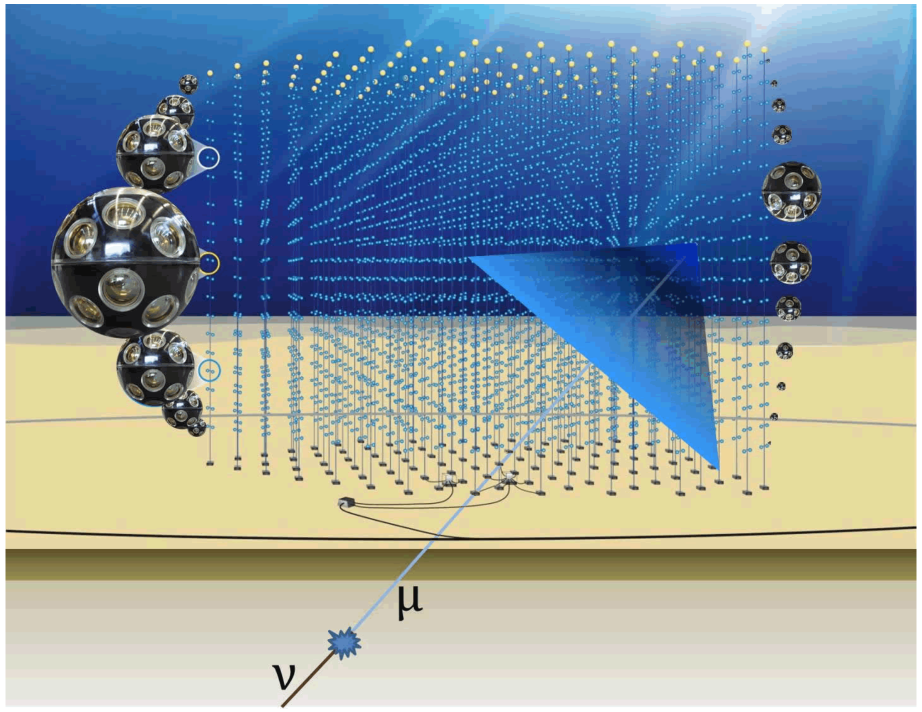
Identification is likely in additional years of IceCube data

Identification is likely in current IceCube data

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.

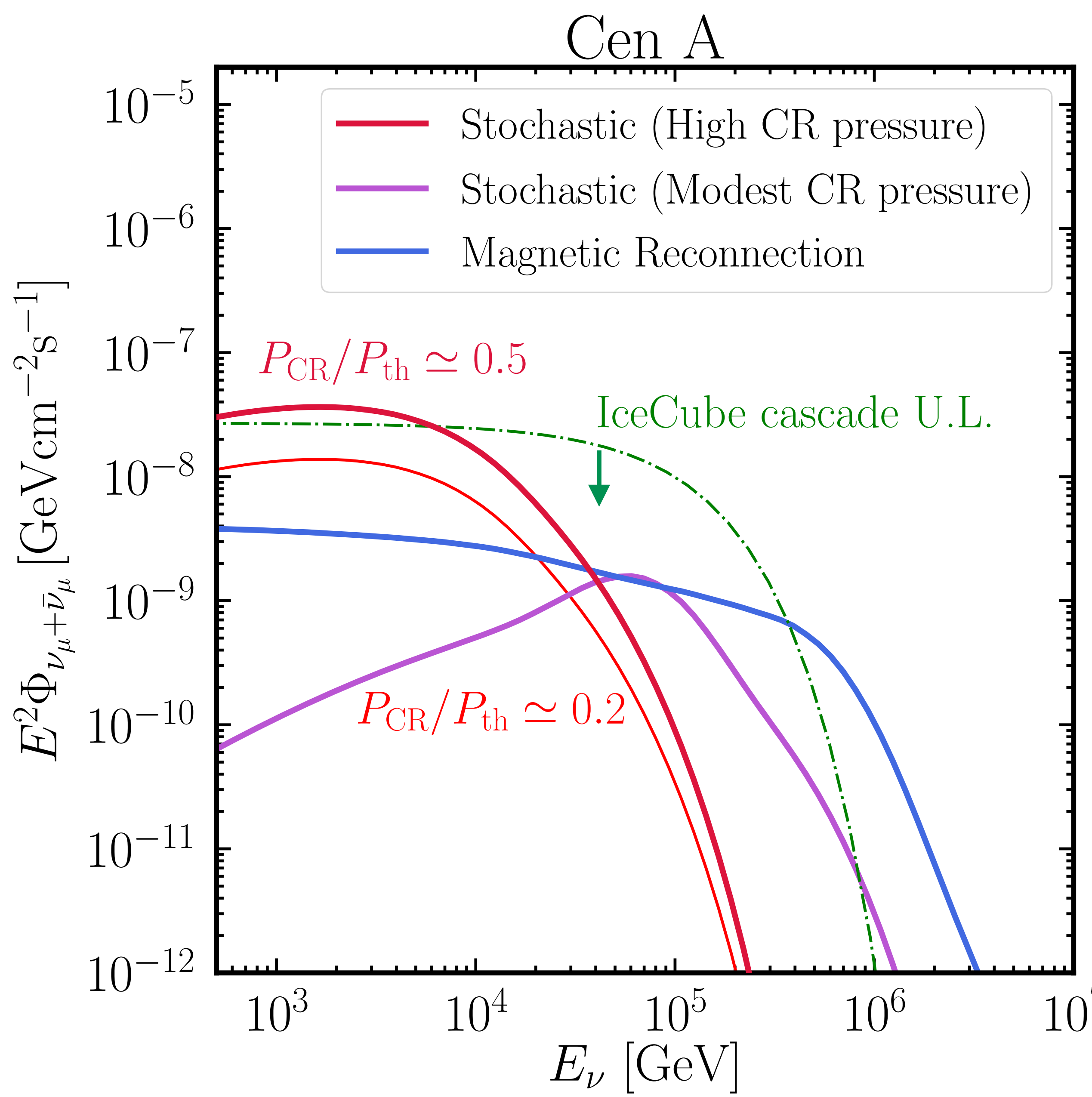


		p-value 1 yr (3 yr)		
Source	Visibility	Stochastic (high CR pressure)	Stochastic (Modest CR pressure)	Magnetic Reconnection
Cen A	0.7	0.001 (9.3×10^{-8})	0.2 (0.07)	0.1 (0.01)
Circinus Galaxy	1.0	0.008 (1.9×10^{-5})	0.2 (0.09)	0.1 (0.02)
ESO 138-1	1	0.1 (0.02)	0.4 (0.3)	0.4 (0.3)
NGC 7582	0.7	0.2 (0.04)	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)

Cen A & the Jet Activity

- Among the list of bright Seyfert galaxies, Cen A & NGC 1275 are seen with high jet activity.
  - X-ray emission could be from the jet?

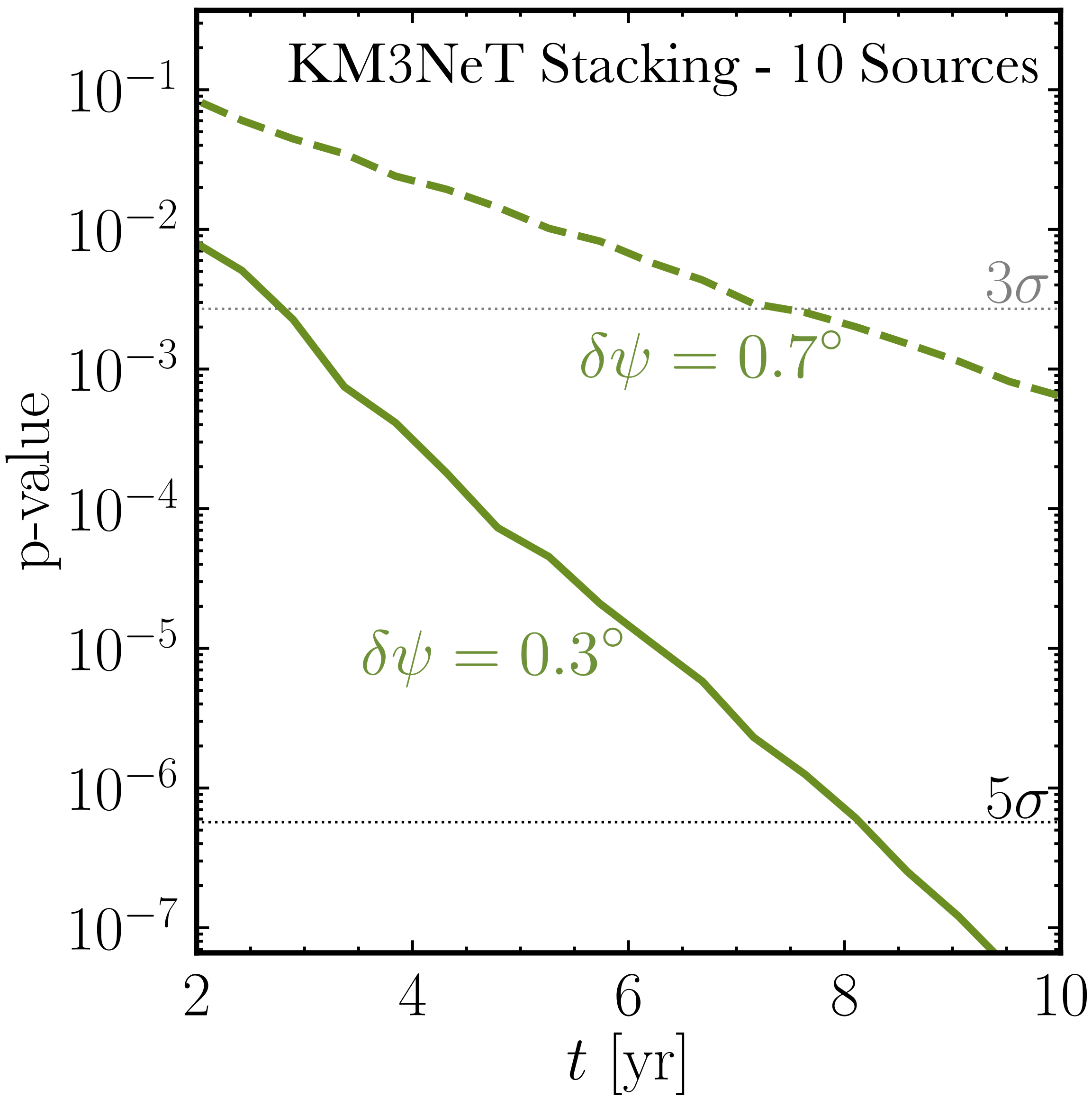
- X-ray emission features from Cen A are difficult to explain with 1-zone models that attribute HE emission to the jet.
  - Observed soft lags X-rays from Cen A may indicate a coronal origin!

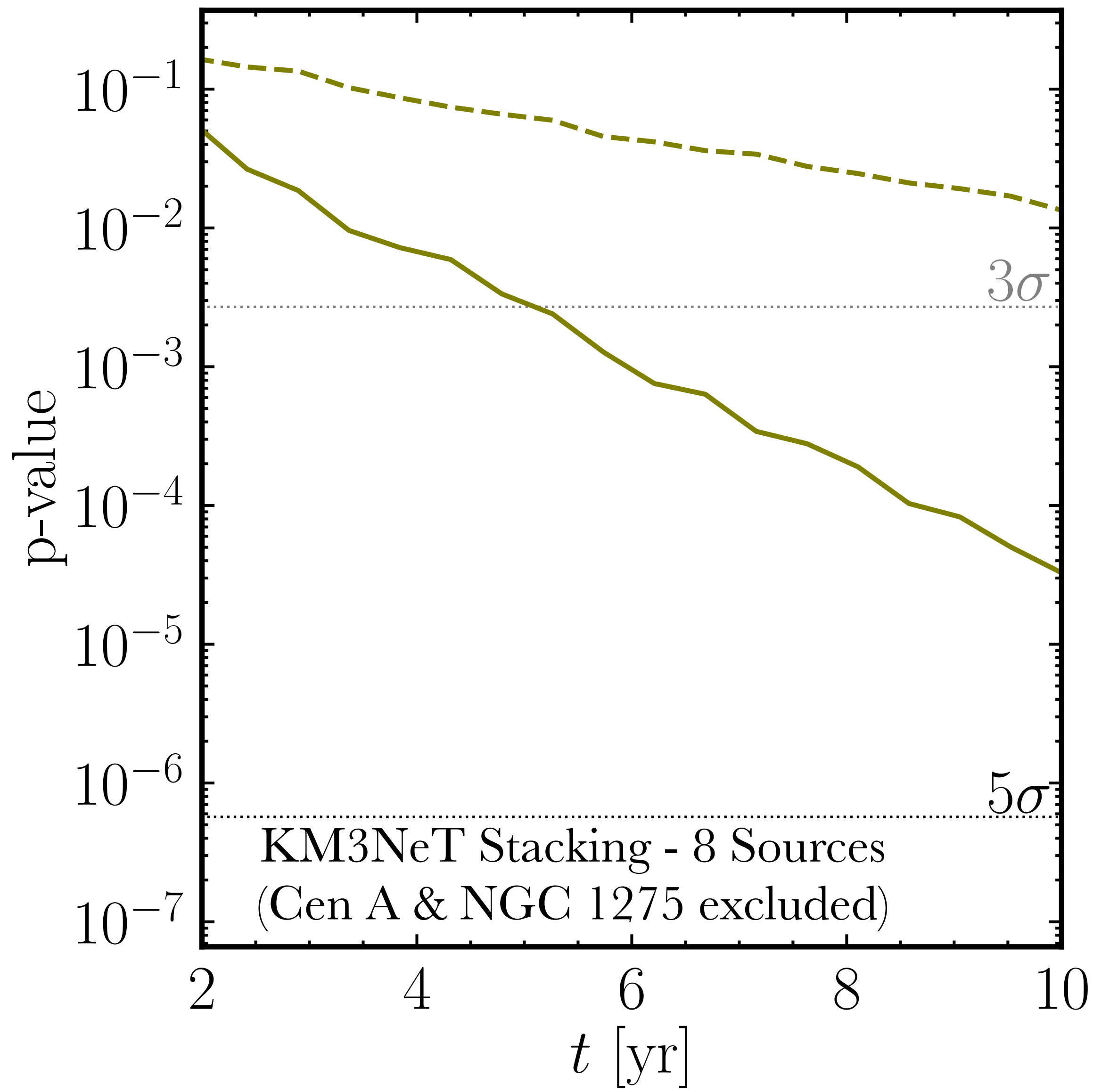


- The modeled neutrino flux is compatible with current upper limits!

KM3NeT & Stacking Search

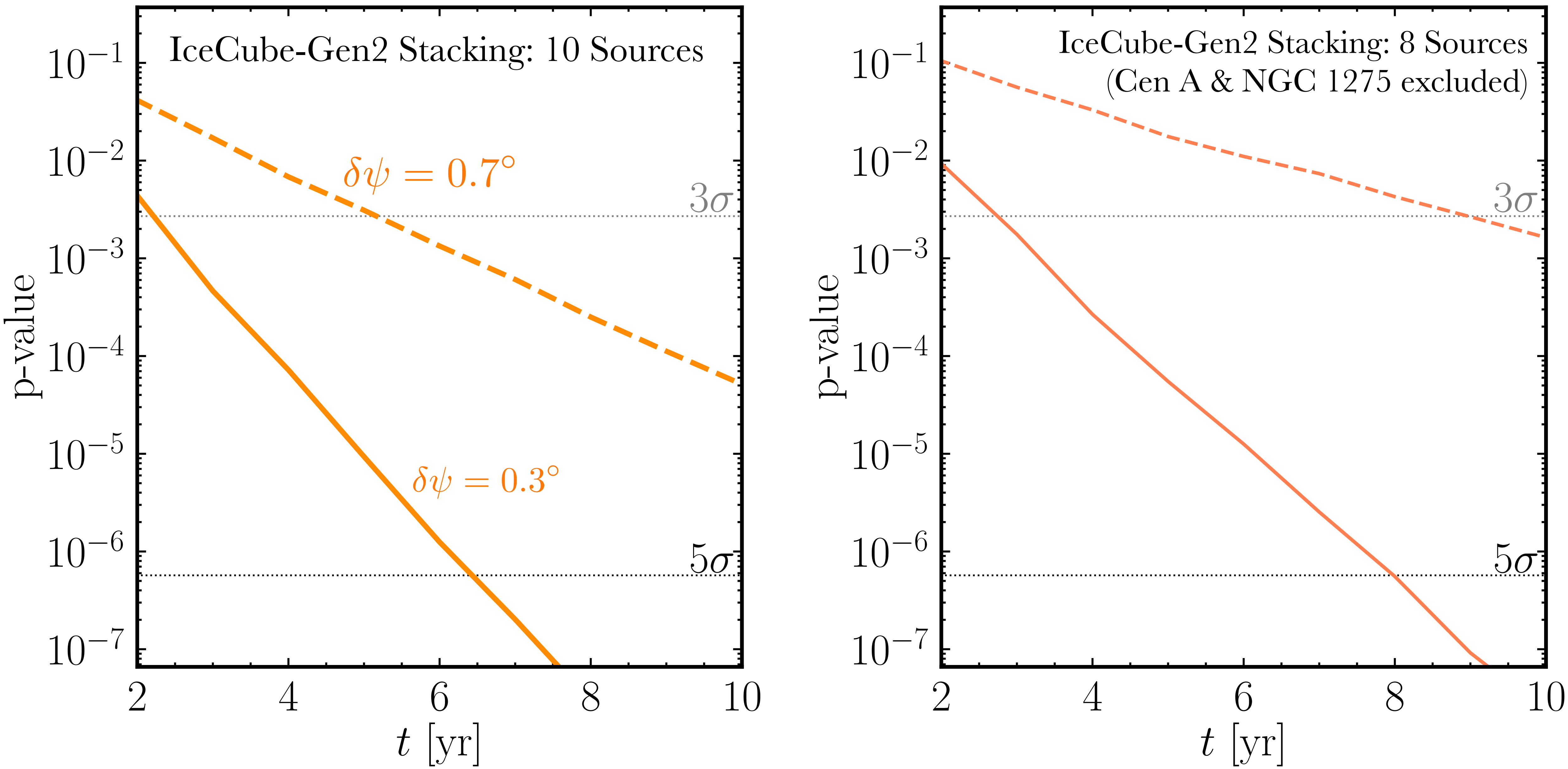
‣ Stochastic acceleration with Modest CR pressure





- Collective neutrino emission in Stochastic acceleration with modest CR pressure from nearby bright Seyfert galaxies could be confirmed with less than 10 years of KM3NeT operation.
  - Cen A dominates the signal. The likelihood for observation will decrease if the nonthermal emission is not originated in the corona.

Bright Seyferts in IceCube-Gen2

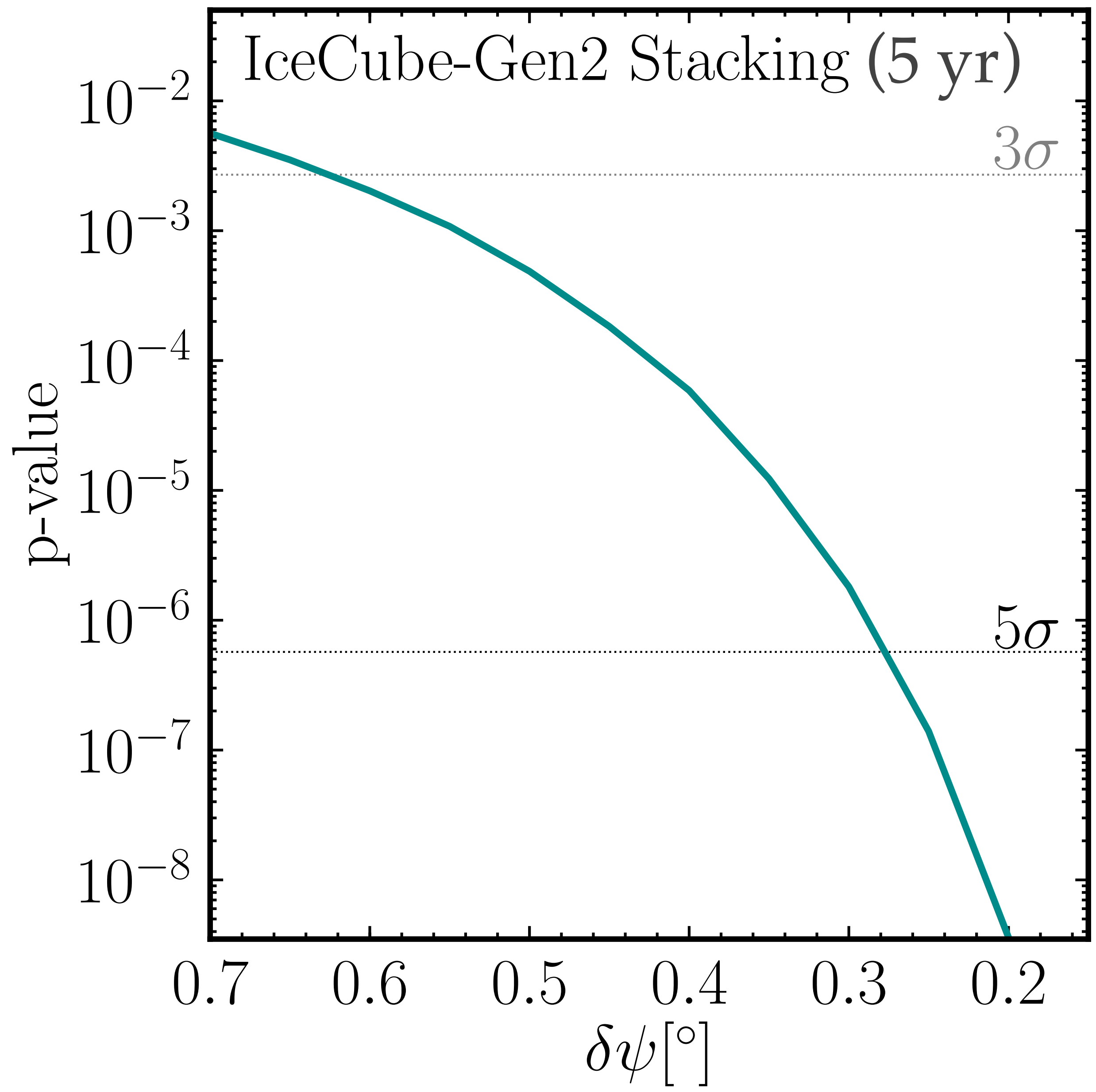


- IceCube-Gen2 will be able to test stochastic acceleration scenario
  - Even most conservative scenario that excludes potential neutrino flux from NGC 1275 & Cen A.

Prospects vs Resolution

- Prospects for identification of bright nearby Seyfert galaxies depend on the angular resolution of future telescopes in ~ 10 TeV range.

- 5σ observation could be achieved for resolution better than 0.4 deg.



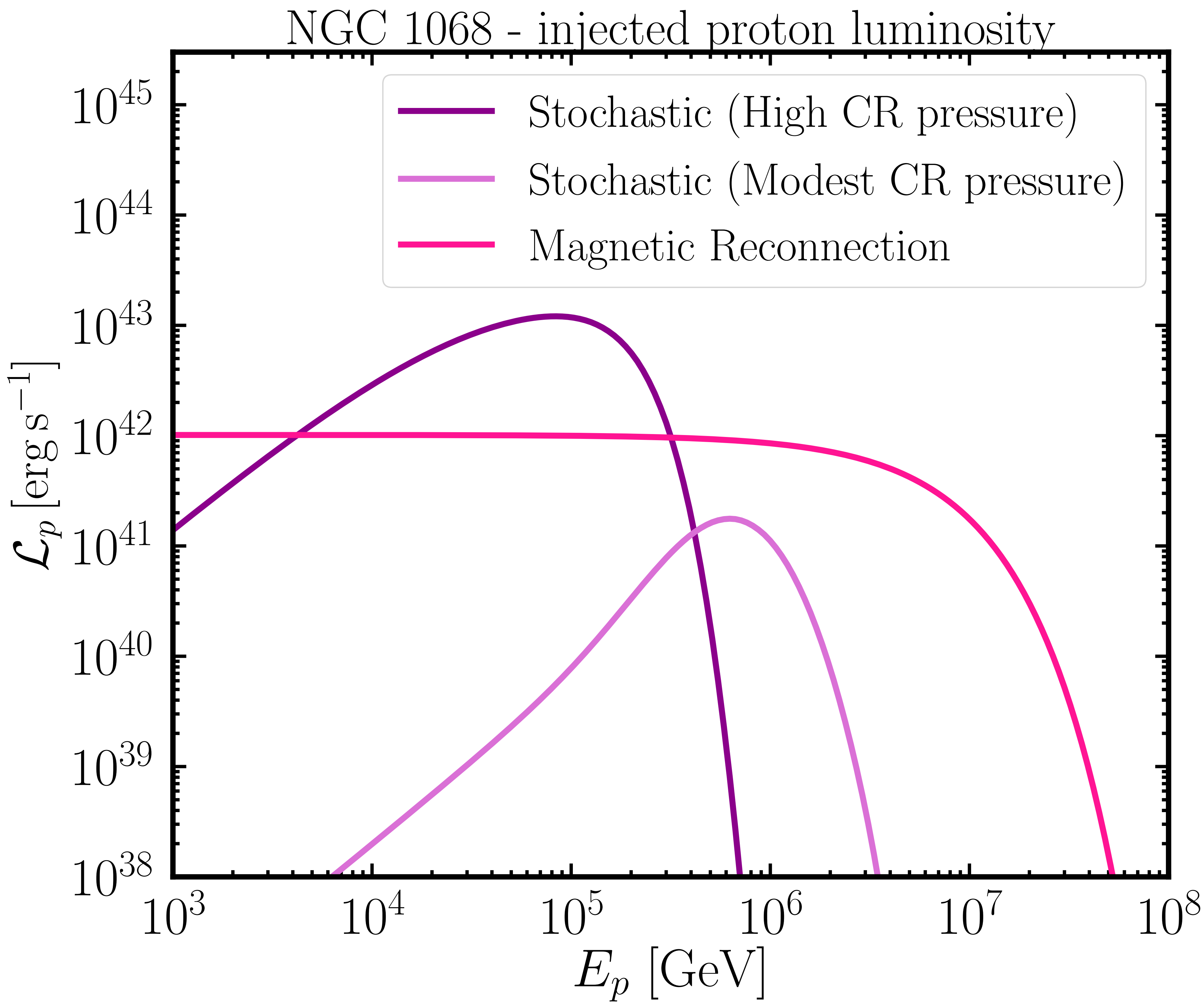
Summary

- For the 1st time since the discovery of high-energy cosmic neutrinos, first signs of anisotropy are emerging the high-energy neutrino sky
- Identification of neutrino emission in the direction of NGC 1068 with 2.9σ and high-level of neutrino emission hints at efficient neutrino production and suppression of pionic gamma-rays
- The disk-corona model leads to production of high-energy neutrinos and soft gamma-rays
    - High-level of CR pressure can explain the measured neutrino flux
    - Bright nearby Seyfert galaxies based on X-ray surveys present a testable scenario for *current* and *future* neutrino telescopes

Thanks!

Back up Slides

Cosmic-Ray Differential Luminosity



Magnetic Reconnection Scenario

▷ Varying the injected CR spectral index