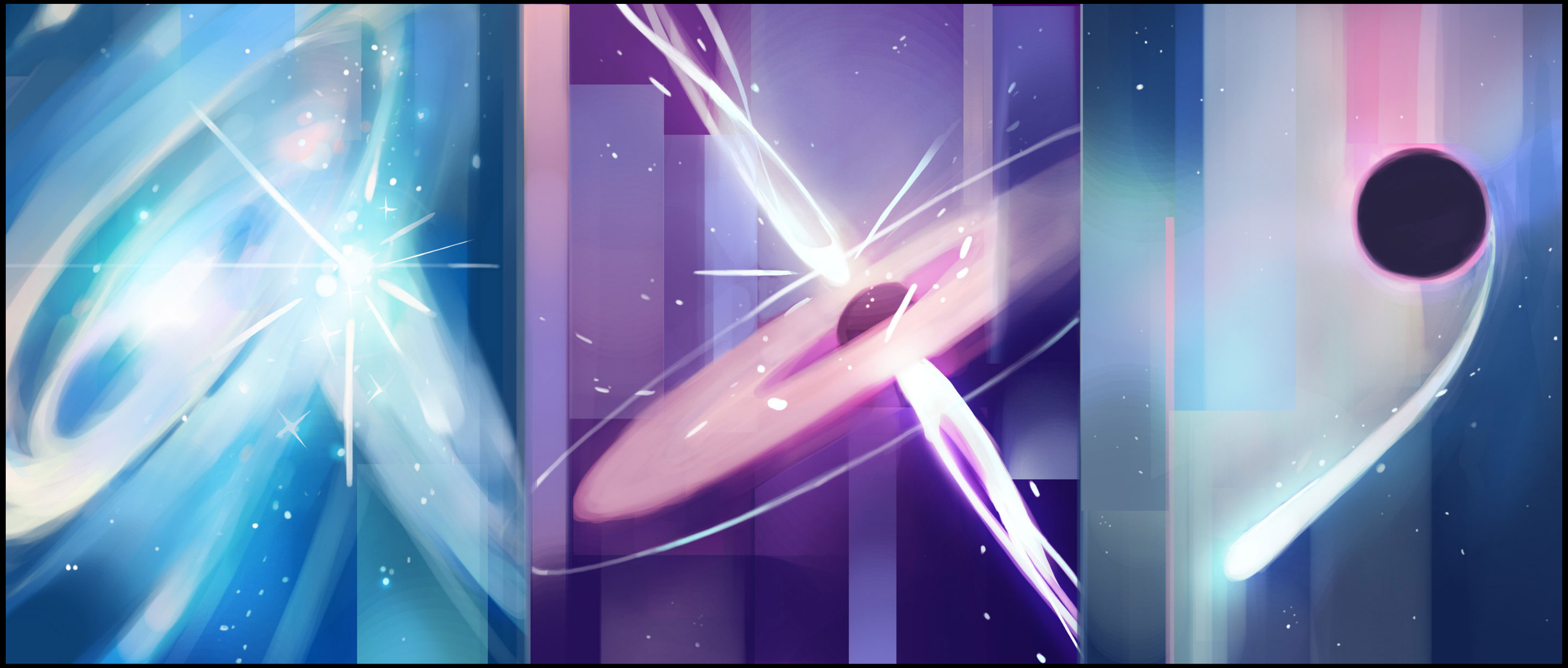
Image Credit: Daniel Chang for Quanta Magazine



The neutrino connection

Foteini Oikonomou with Egor Podlesnyi, Lena Saurenhaus, Francesca Capel, Andrii Neronov, Dmitry Semikoz

NTNU
Norwegian University of Science and Technology

Are neutrino sources transient?

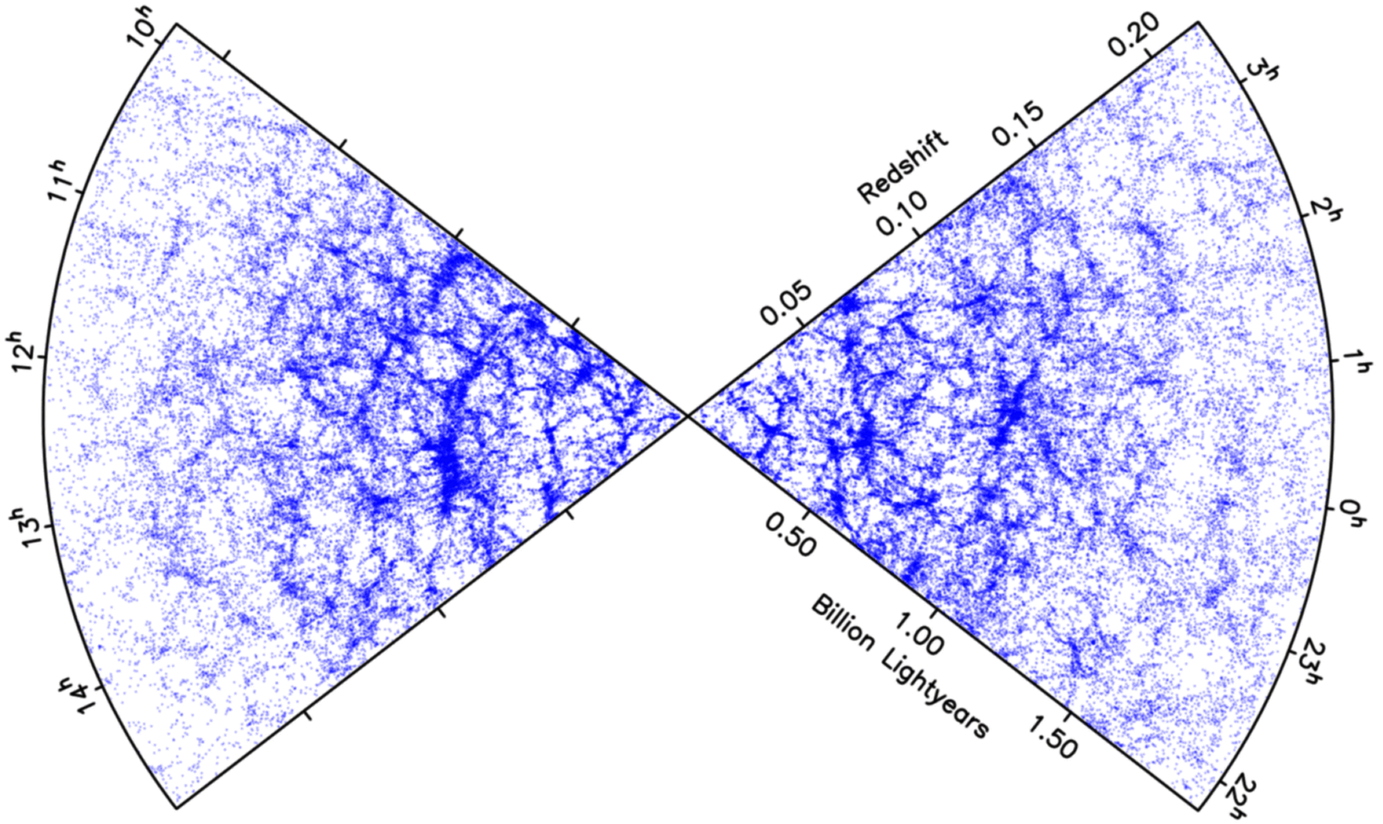
If YES:

- Lower cosmic background (better for establishing sources)

- Lower atmospheric neutrino background

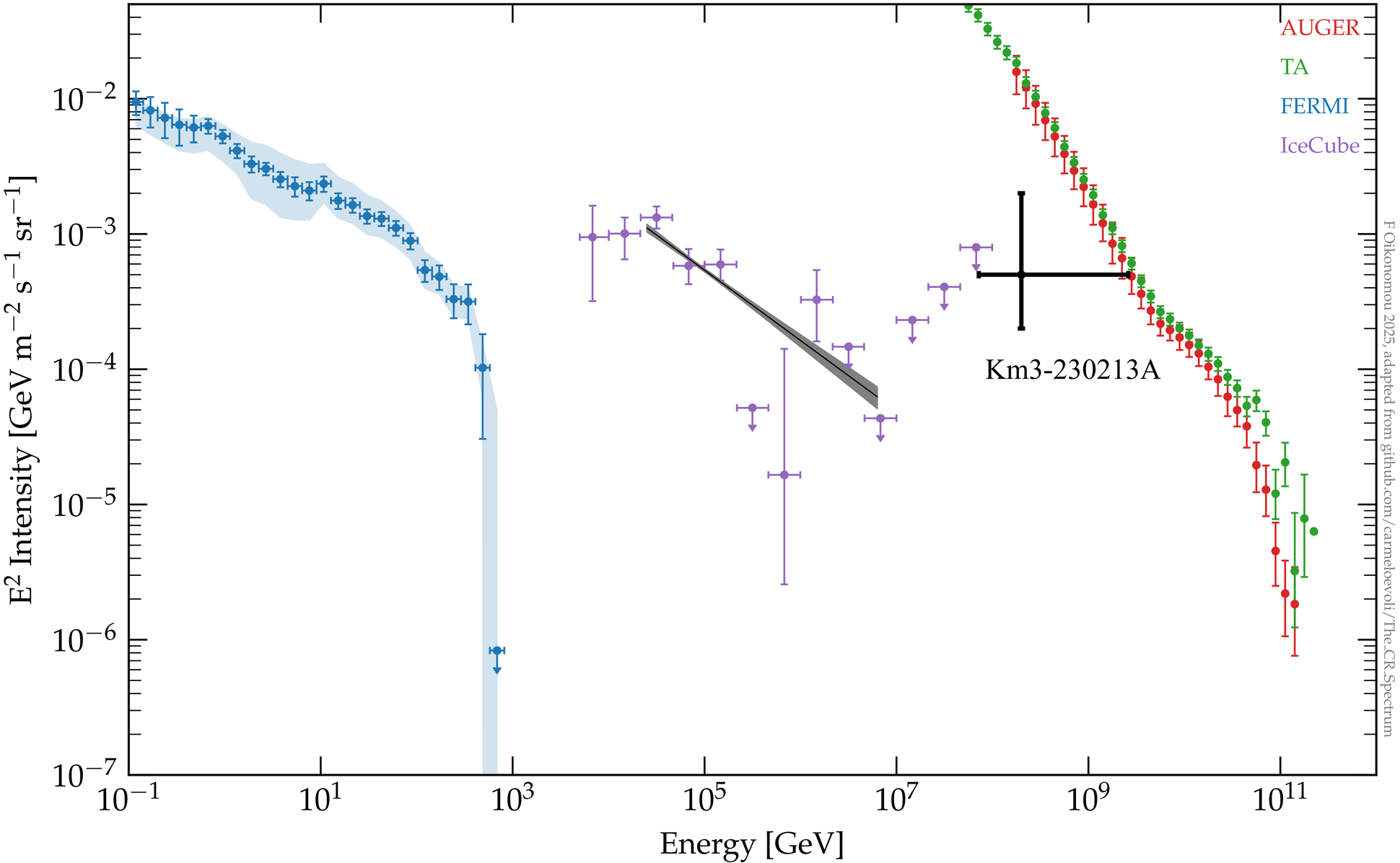
But:

-More time - more proton interactions

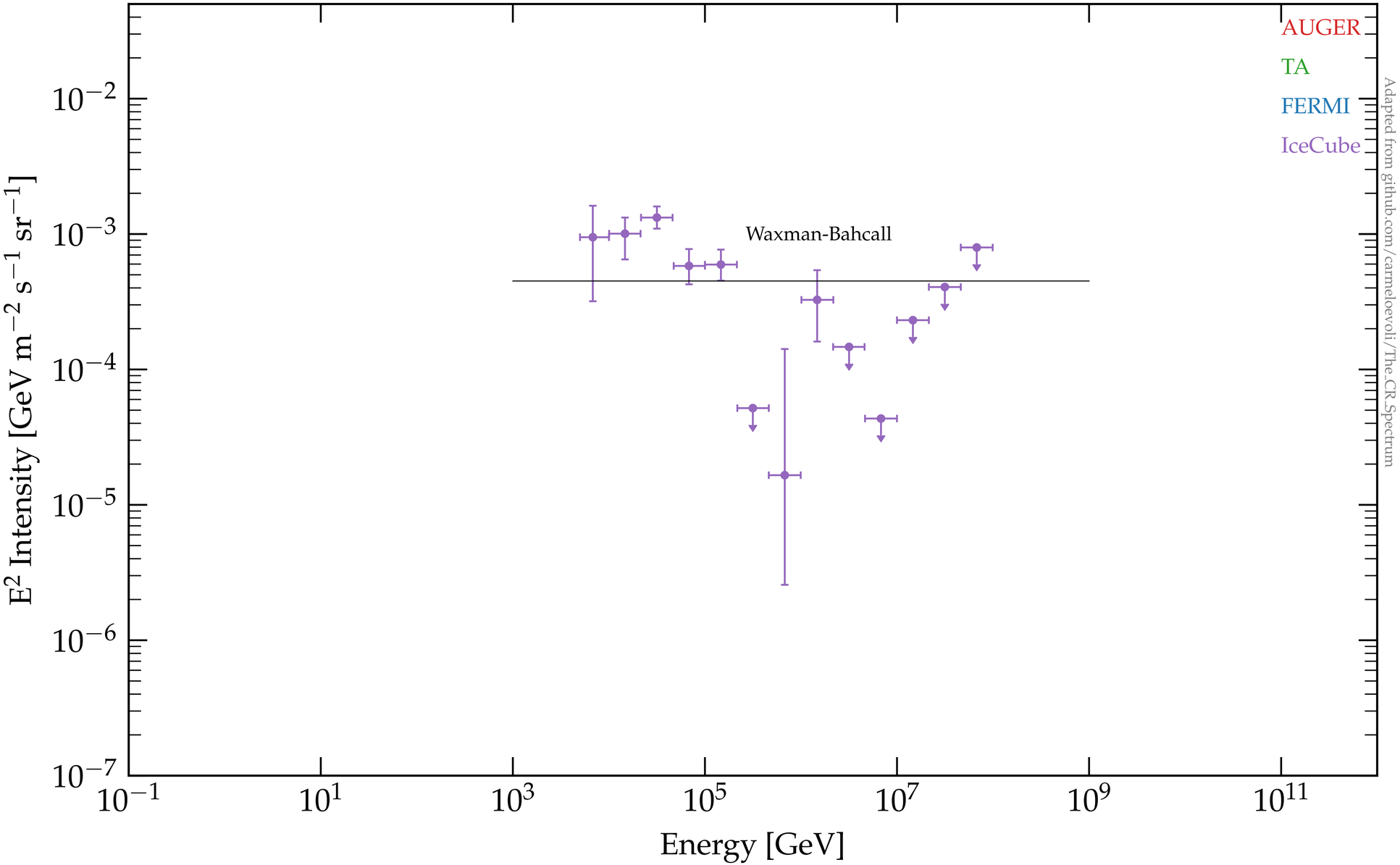


2dF Survey, Colless · 2001

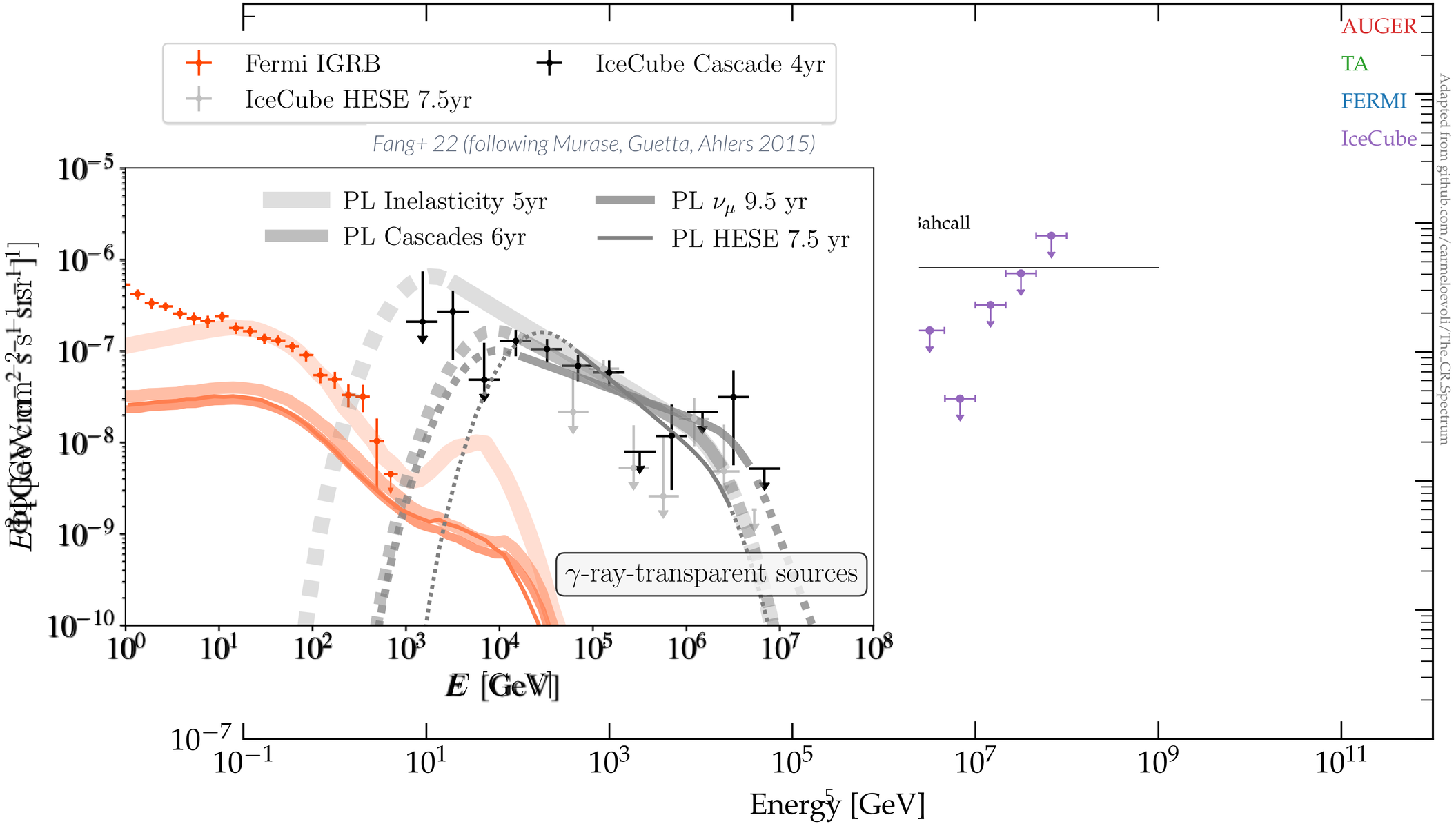
What we know so far



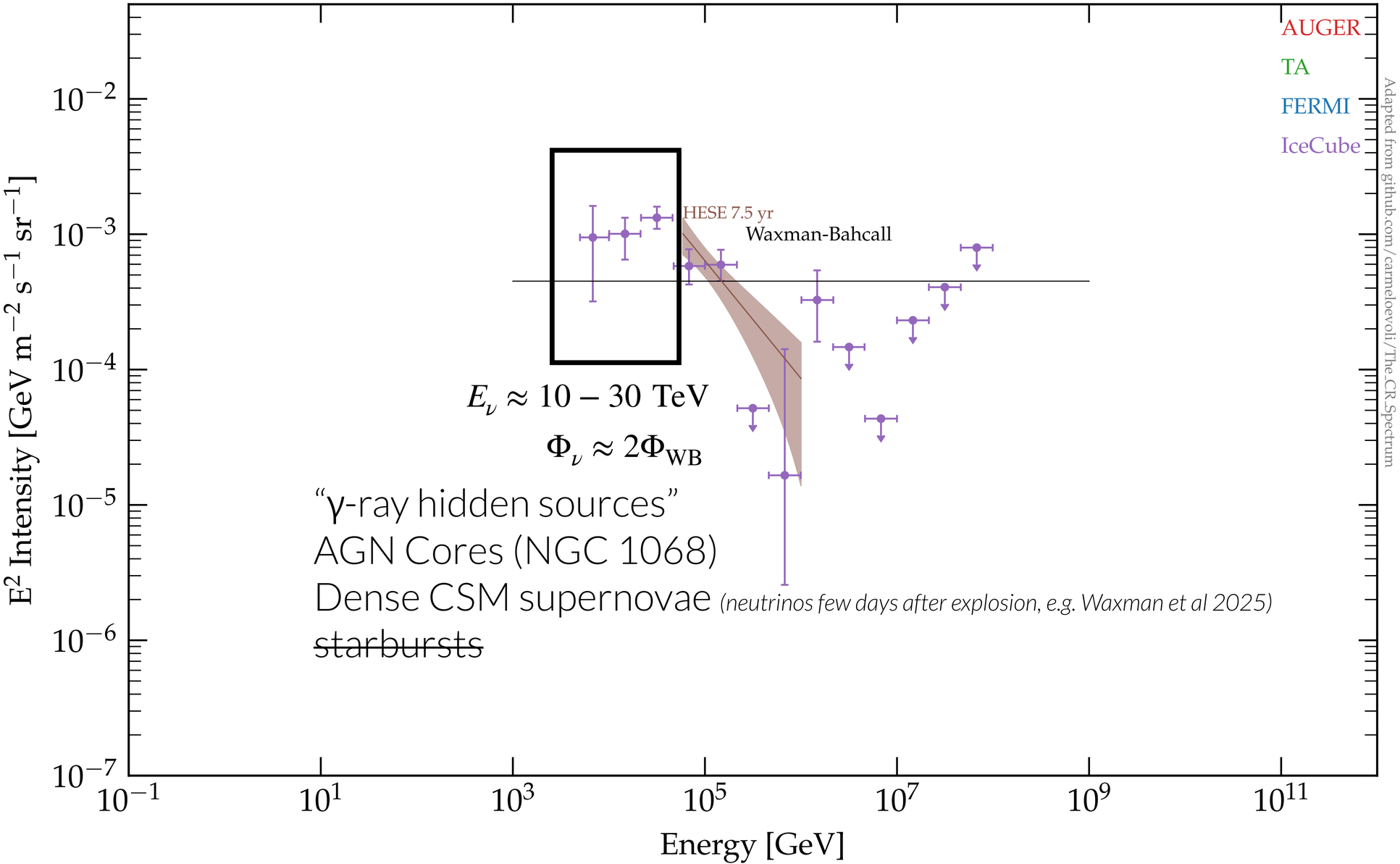
What we know so far



What we know so far

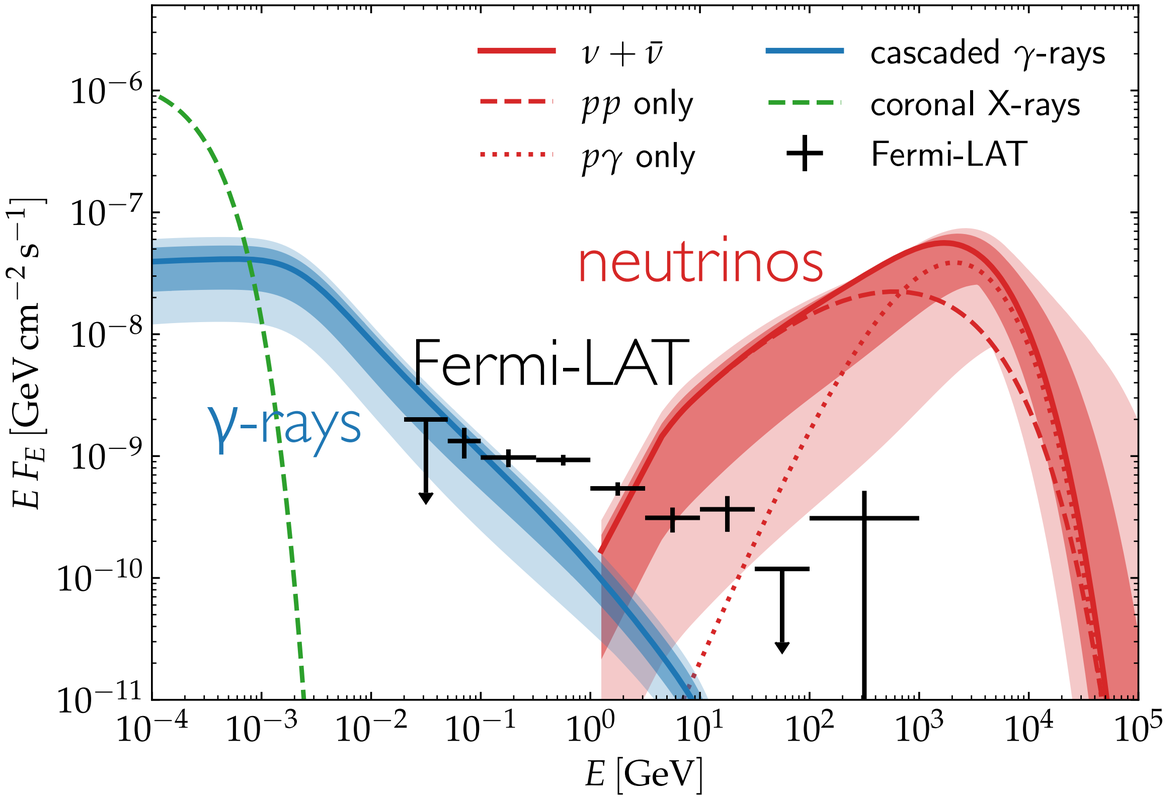


Medium-energy neutrinos



Neutrinos from AGN Coronae

Population model based on NGC 1068 and X-ray luminosity function of Seyferts

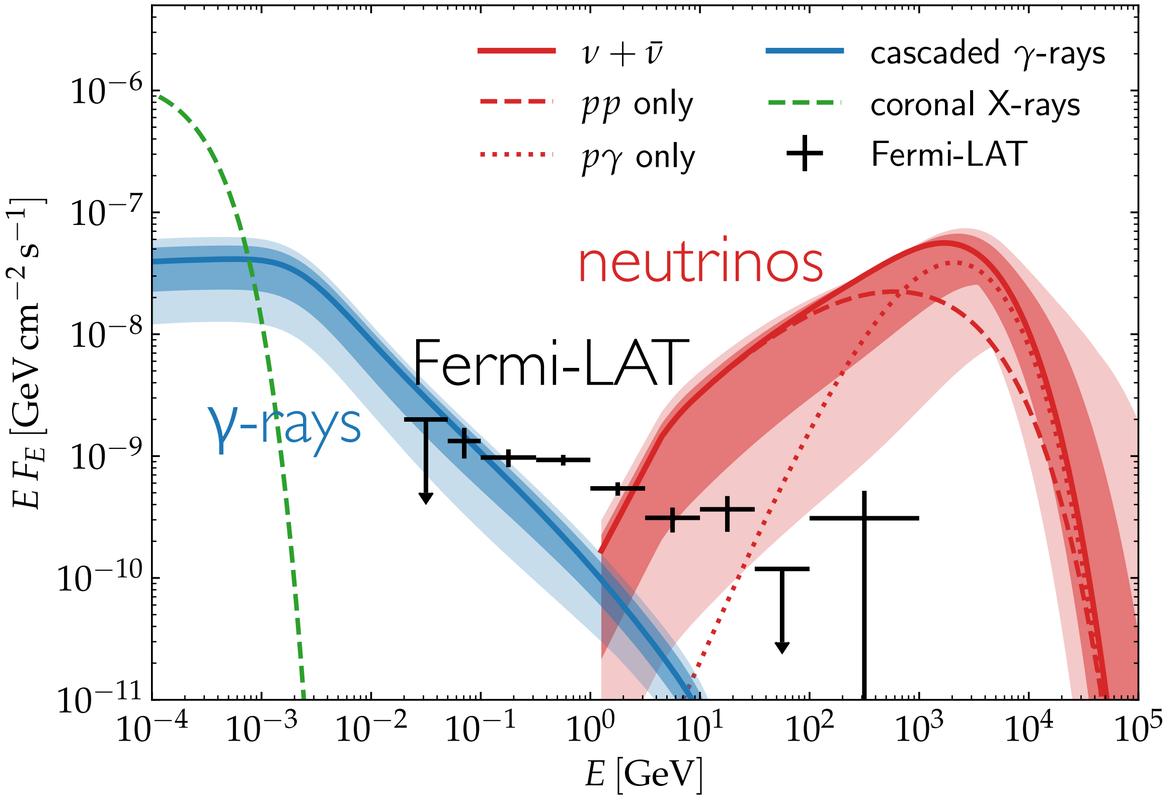


Population model based on Murase et al 2020 PRL (updated gamma-ray, neutrino observations).

$$L_\nu \propto L_X^{0.7}$$

Neutrinos from AGN Coronae

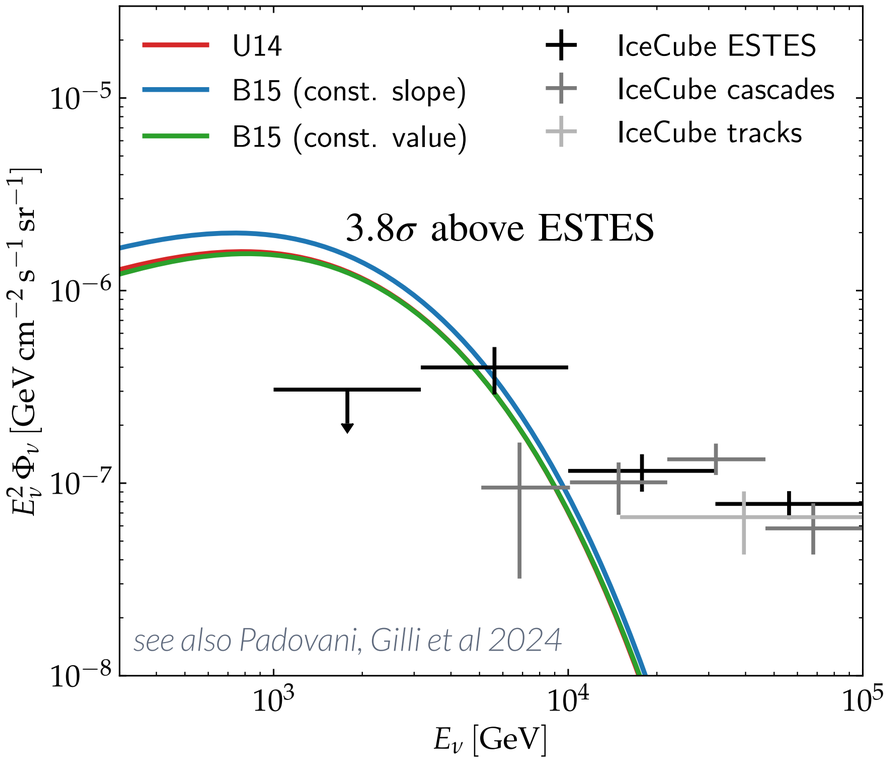
Population model based on NGC 1068 and X-ray luminosity function of Seyferts



Population model based on Murase et al 2020 PRL (updated gamma-ray, neutrino observations).

$$L_\nu \propto L_X^{0.7}$$

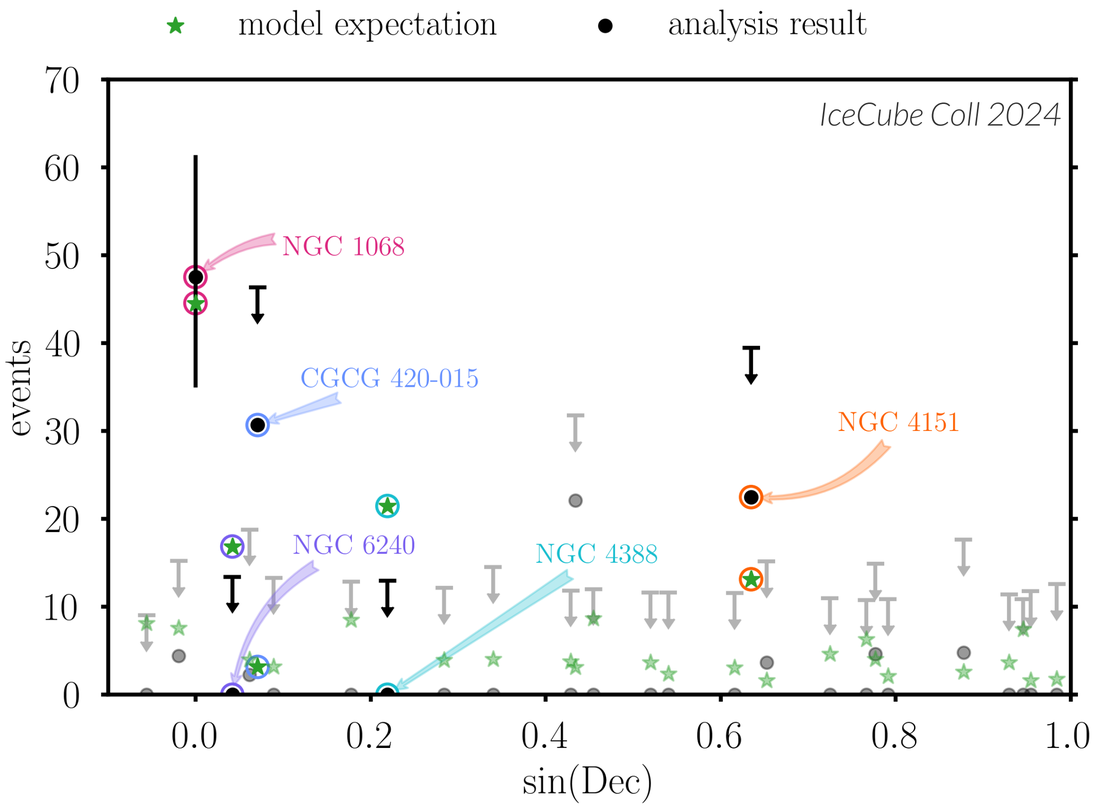
Saurenhaus, Capel, FO, Buchner, PRD, 2025



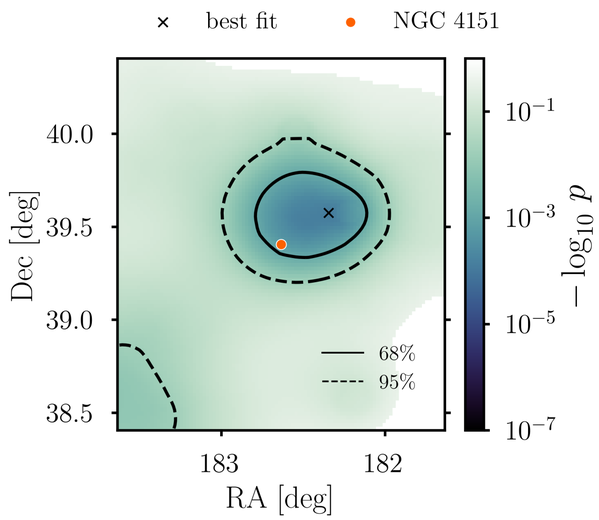
Neutrinos from AGN Coronae

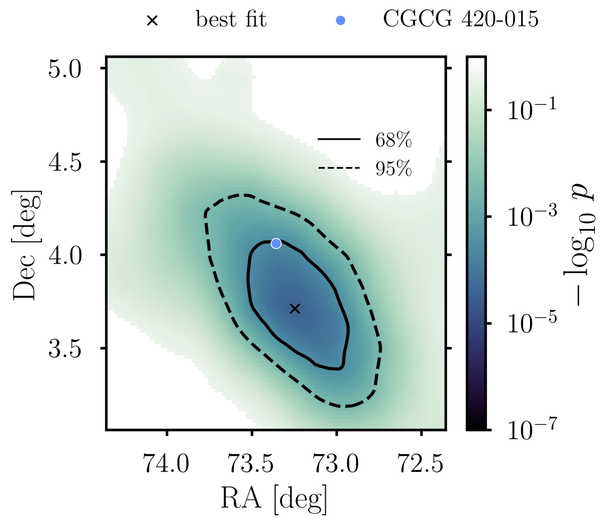
Population model based on NGC 1068 and X-ray luminosity function of Seyferts

Neronov et al 2024 : Hard X-ray selection: NGC 4151, NGC 3079 (3sigma), $L_\nu \propto L_X$



Search based on model of Murase et al 2020 PRL, Kheirandish et al 2021, $L_\nu \propto L_X$, NGC 4151 - 2.9σ signal



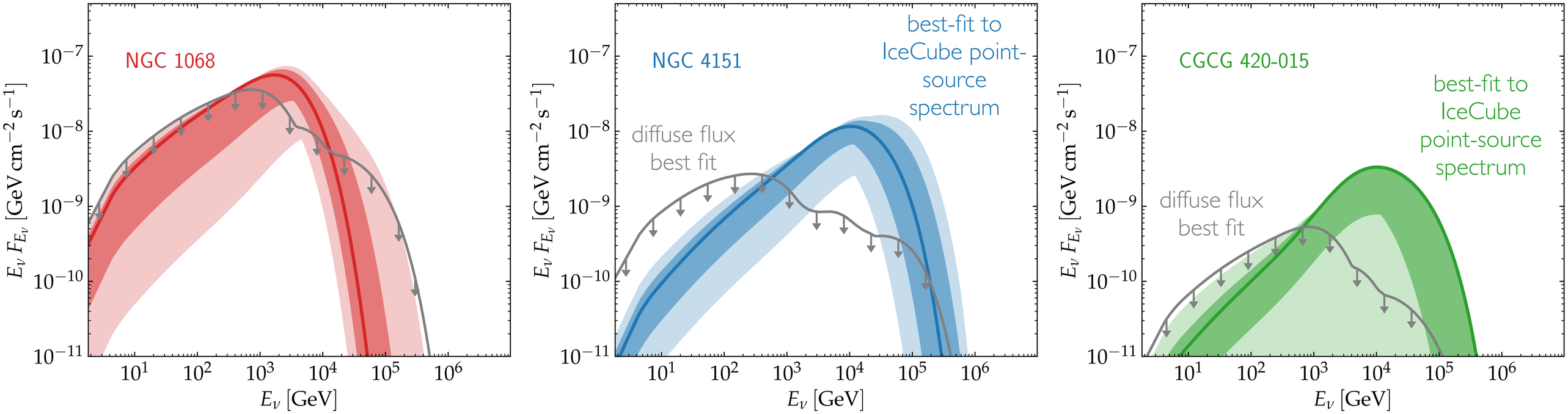


NGC4151: $N_{exp,model}$ =13.1, N_{obs} = 22.5, **CGCG 420-015:** N_{exp} =3.2, N_{obs} = 30.7, **NGC 4388:** N_{exp} =21.4, N_{obs} = 0,
NGC 6240: N_{exp} =16.8, N_{obs} = 0, **MCG+4-48-2:** N_{exp} = 3.1, N_{obs} = 22.1

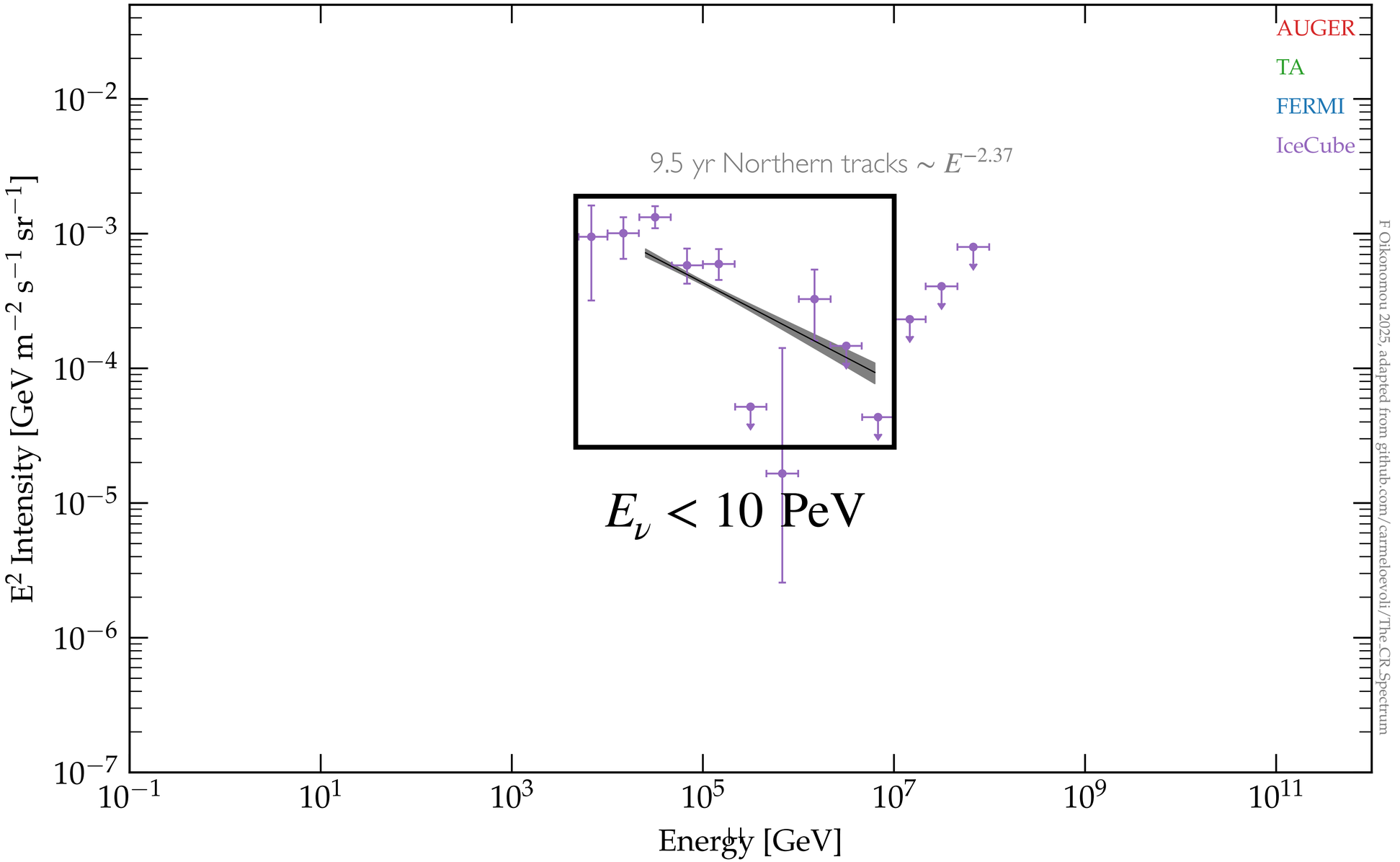
Neutrinos from AGN Coronae

Population model based on NGC 1068 and X-ray luminosity function of Seyferts

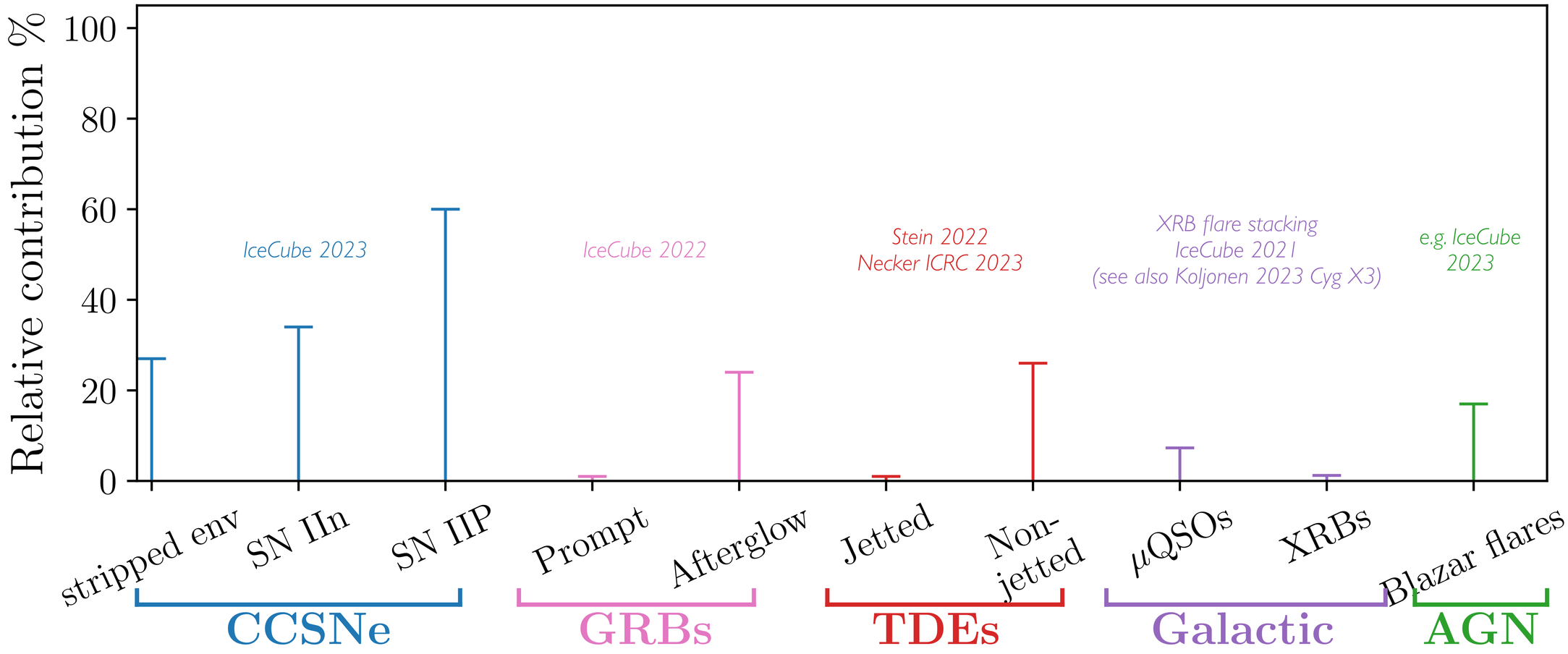
Saurenhaus, Capel, FO, Buchner, PRD, 2025



What we know so far



What we know so far: IceCube stacking + multiplet searches



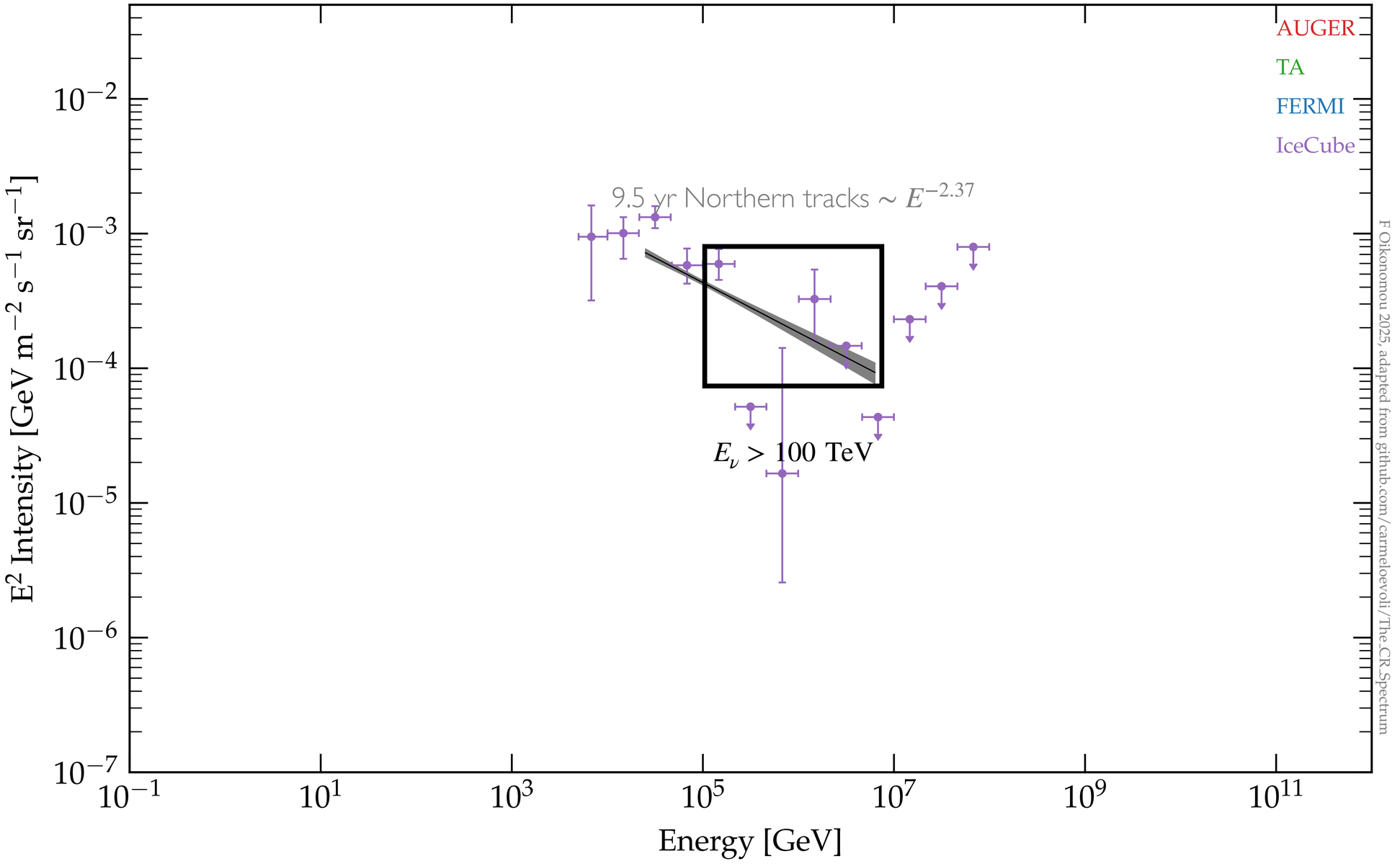
[-20, 1000] days optical

optical/ IR

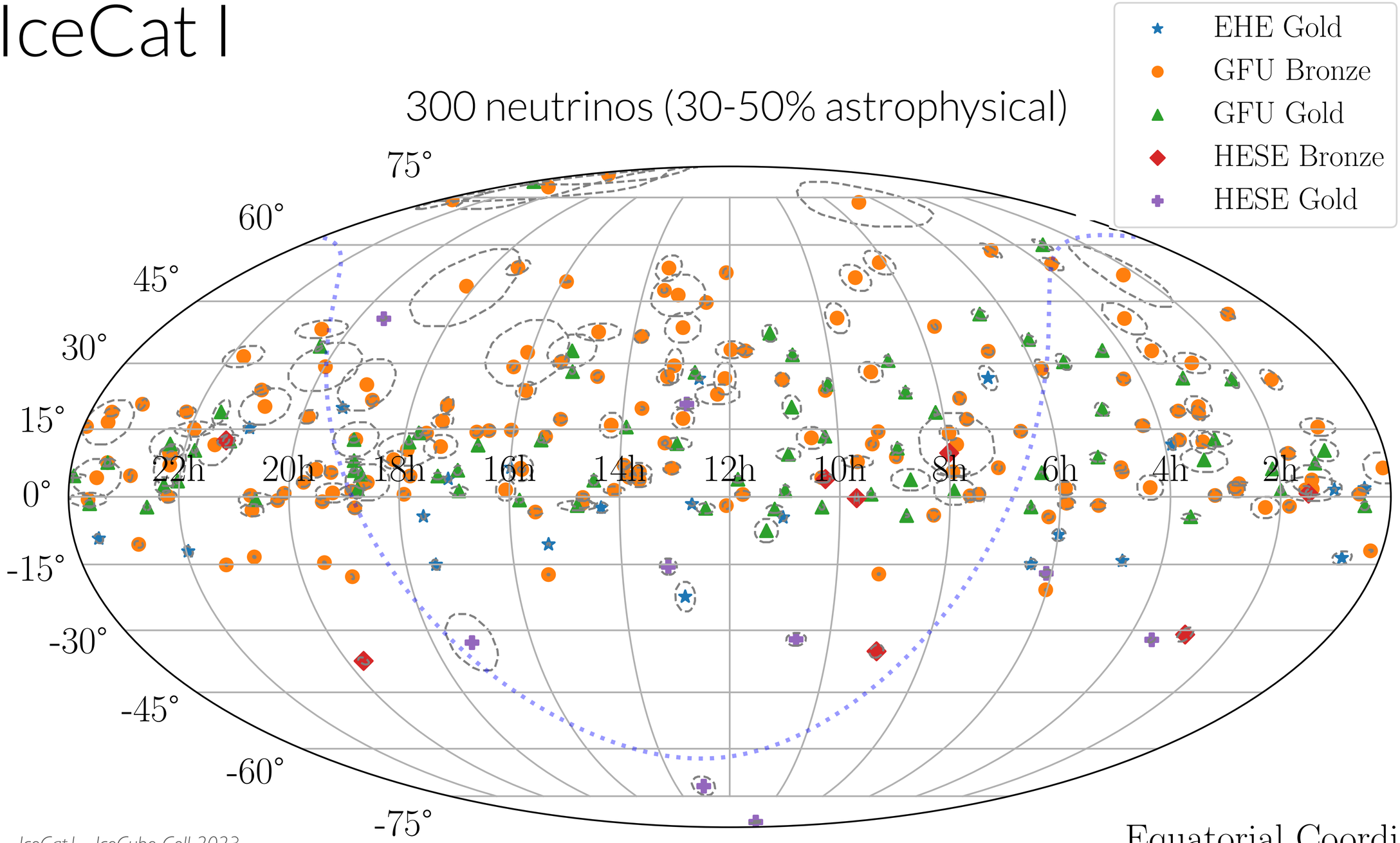
X-ray light curves

Fermi-LAT lightcurves

What we know so far



IceCat I


300 neutrinos (30-50% astrophysical)
EHE Gold
GFU Bronze
GFU Gold
HESE Bronze
HESE Gold
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
Equatorial Coordinates

IceCat 1

- Angular power spectrum /multiplet searches

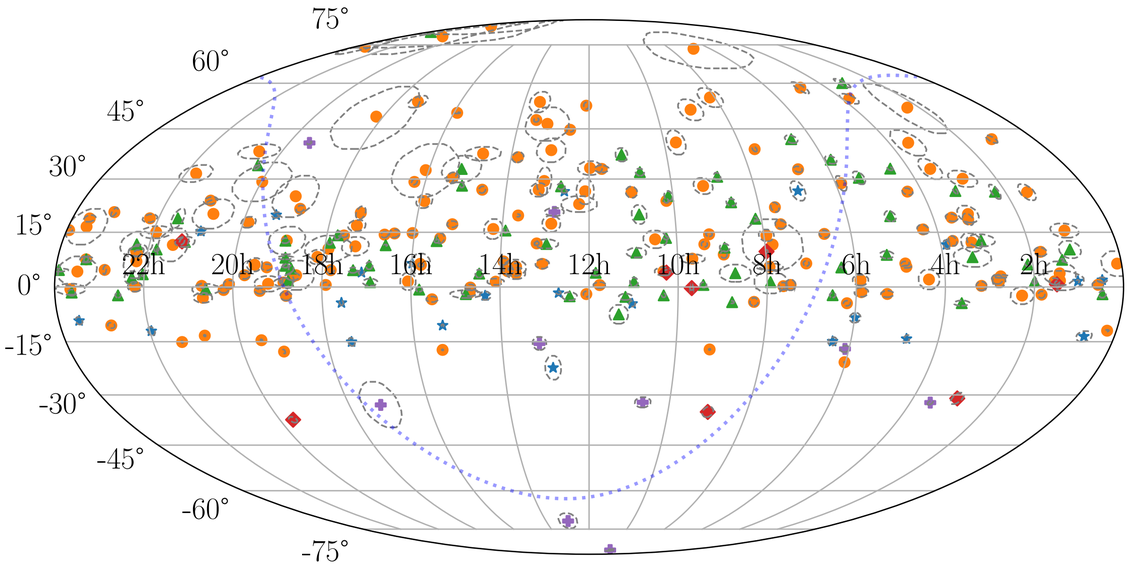
  Suggests that HE neutrino sources are not rare
  e.g. *Murase & Waxman 2014, Feyereisen et al 2018, Dekker et al 2020, IceCube Coll 2023, IceCube Coll 2025*

- *Spatial and temporal correlations with source populations*

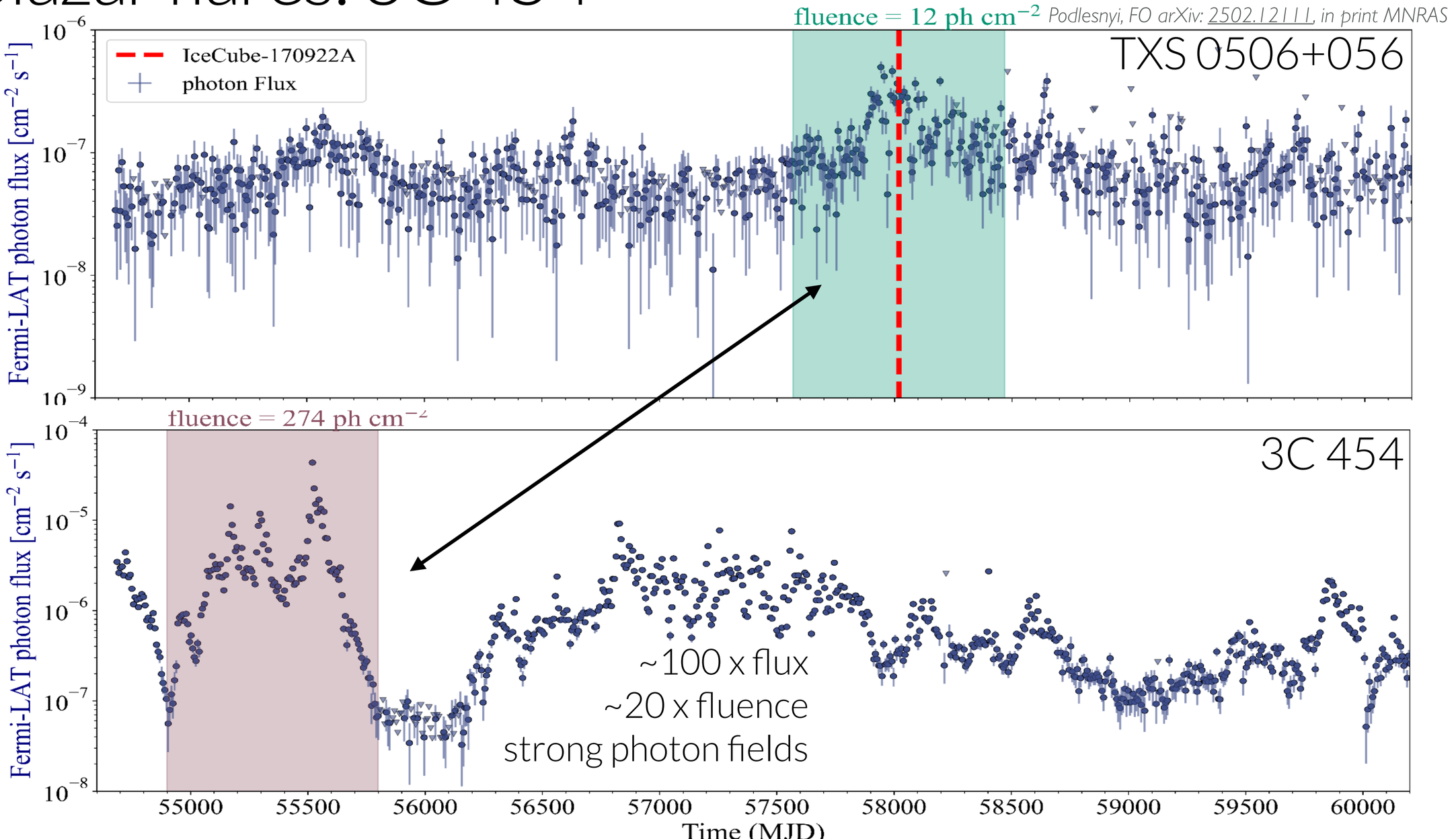
- 3.6σ signal from accretion flares *(Van Velzen et al 2024)*

- Blazars - not updated with IceCat 2

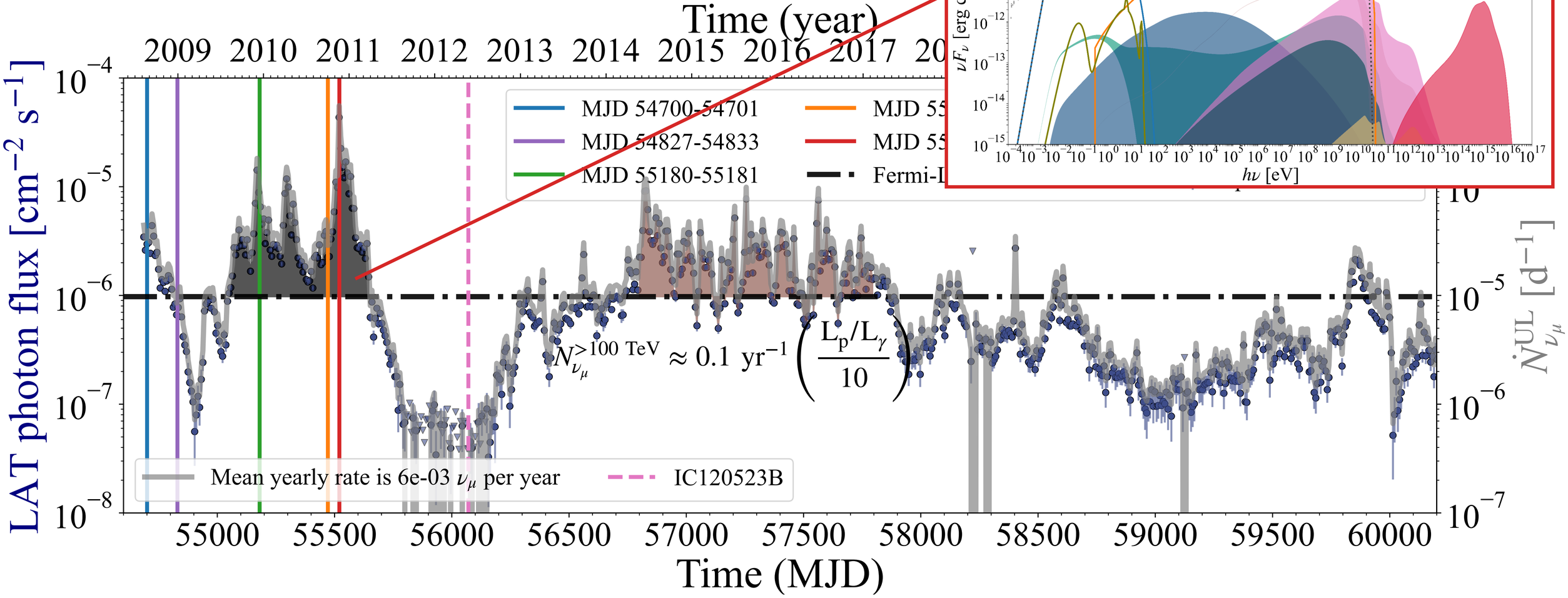
- Plavin et al 2024: 3.5σ (radio flares), IceCube Coll 2023 (gamma-ray flares) < 1%



Blazar flares: 3C 454



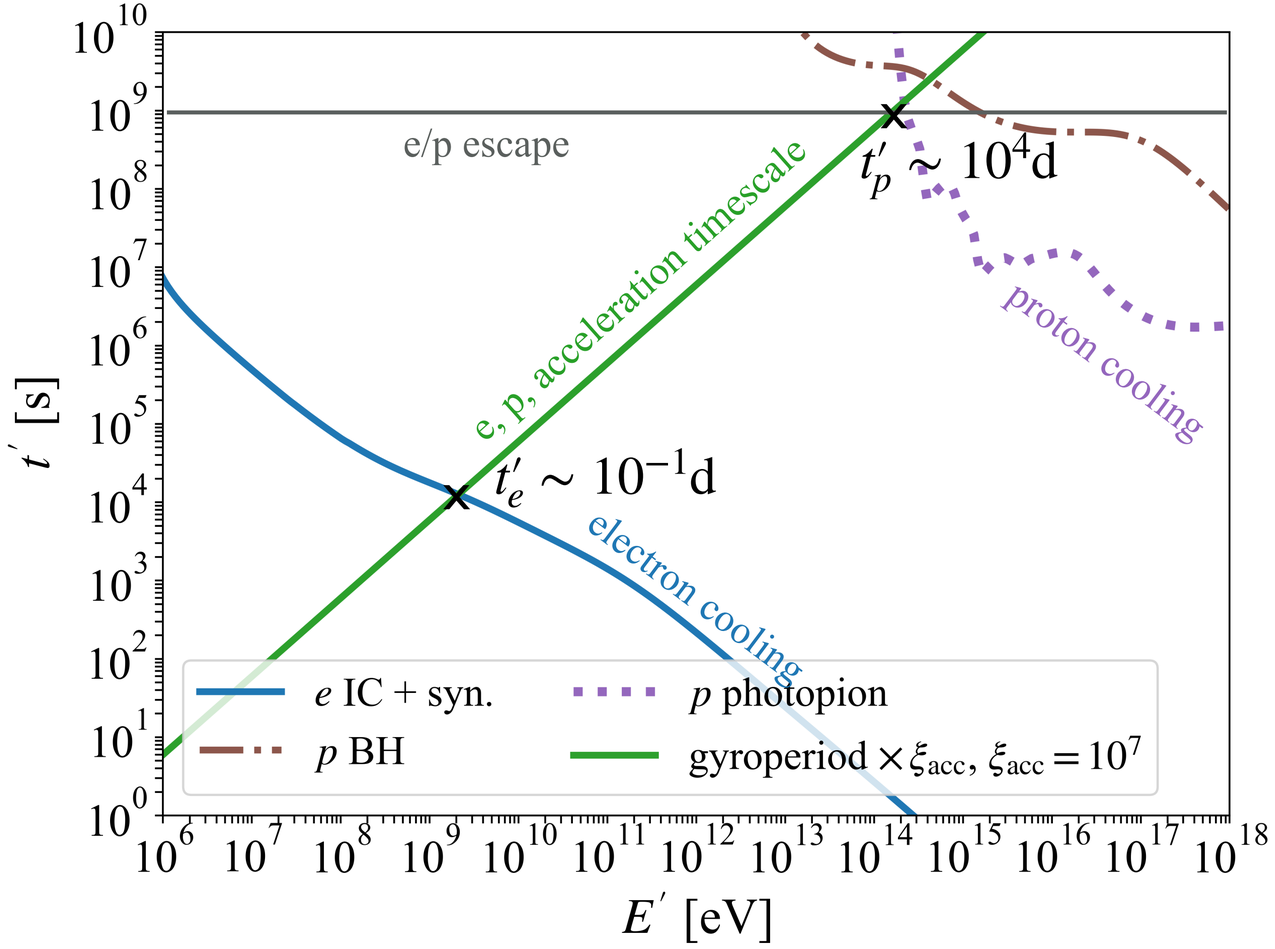
Blazar flares: 3C 454



IC120523A, with signalness 50% coincident with 3C454.3 during all time Fermi-LAT low

IceCube Coll ApJ 2023

Delayed neutrinos?



Fermi-LAT light curves from repository
Fermi-LAT Coll. (2023, ApJS, 265, 31)

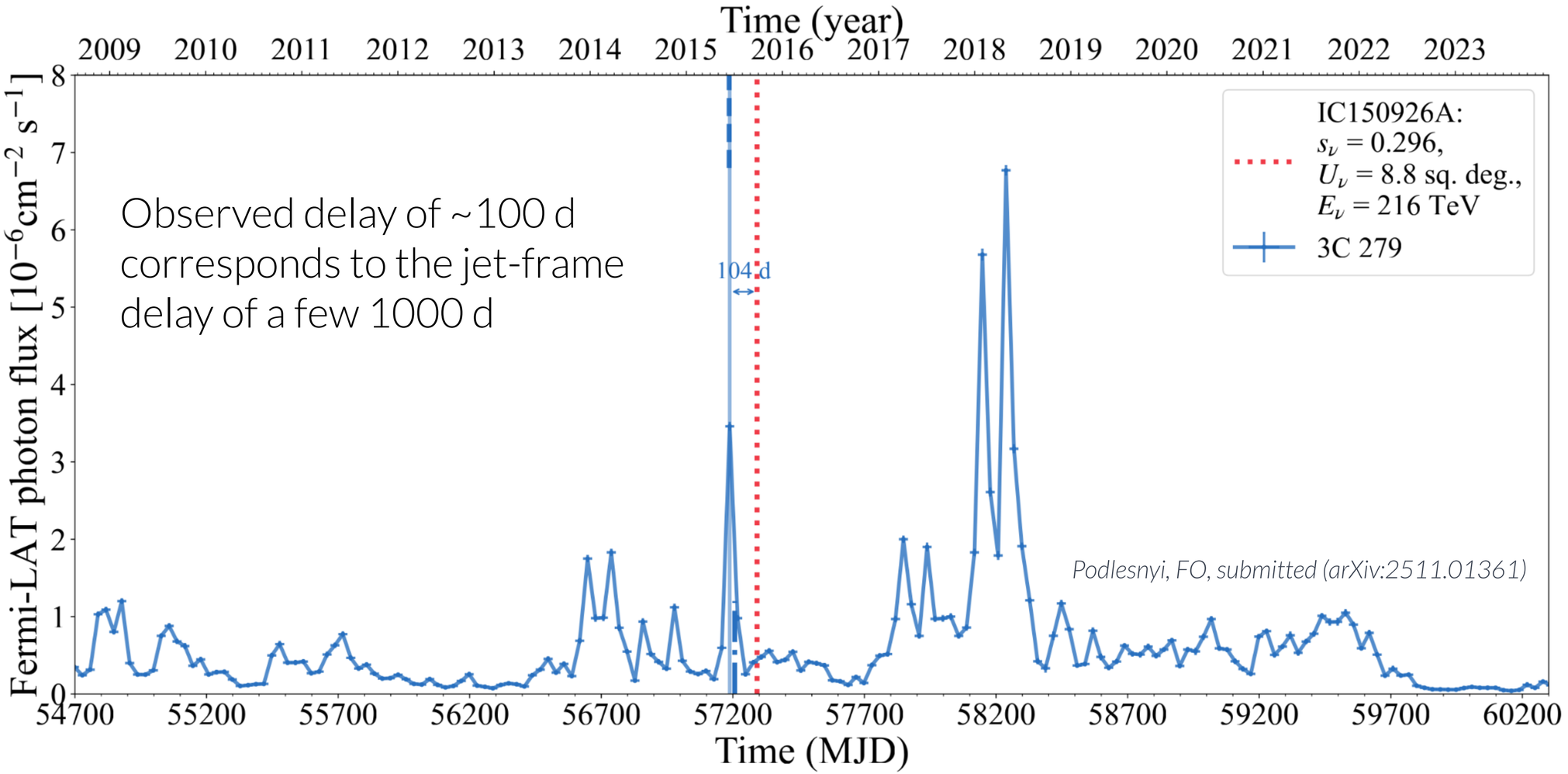
Neutrino alerts from IceCat-1
IceCube Coll. (2023, ApJS, 269, 25)

Doppler factors
Rodrigues+ (2024, A&A, 681, A119), Homan+ (ApJ, 2021, 923, 67)

295 blazars

Gaussian temporal weights centred at the anticipated prior maximum of the flare in the jet-frame

Delayed neutrinos?



Delayed neutrinos?

Scan over **jet-frame** delay

~2σ pre-trial @few x 10^3 d

~10% post-trial

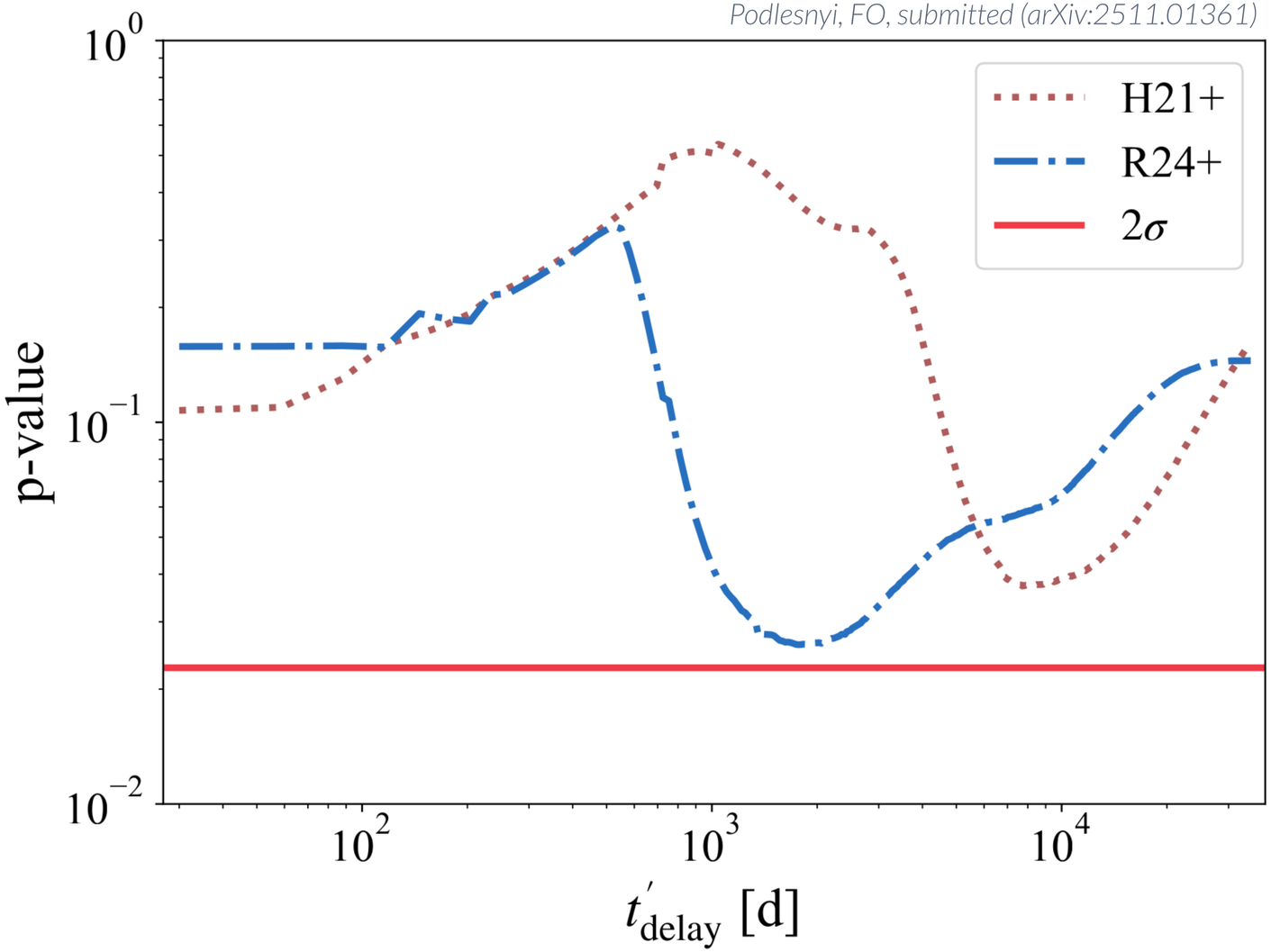
Too few associations? (4 found)

No universal jet-frame time delay?

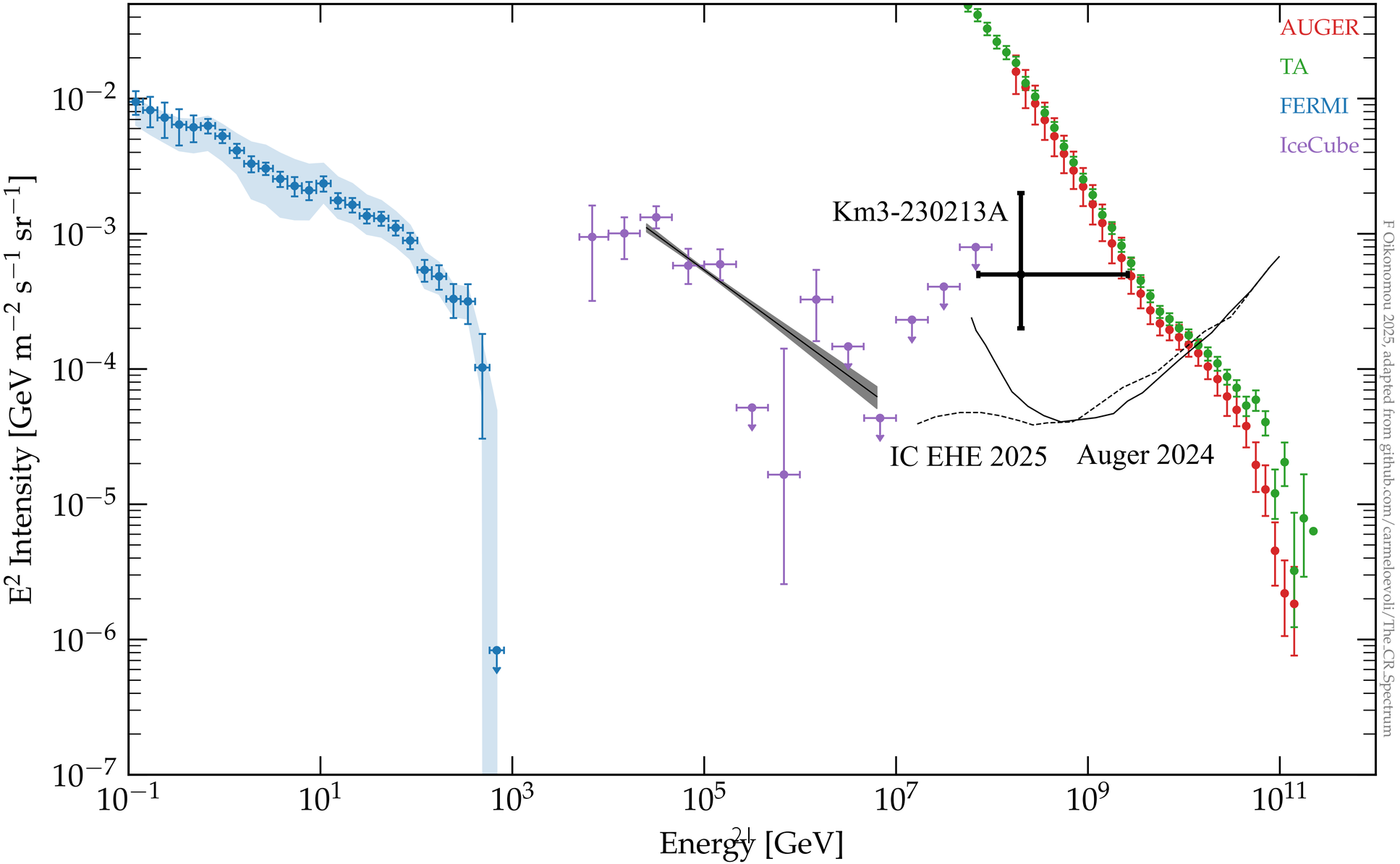
Too large Doppler factor uncertainty?

Proton and electron acceleration not correlated?

Podlesnyi, FO, submitted (arXiv:2511.01361)

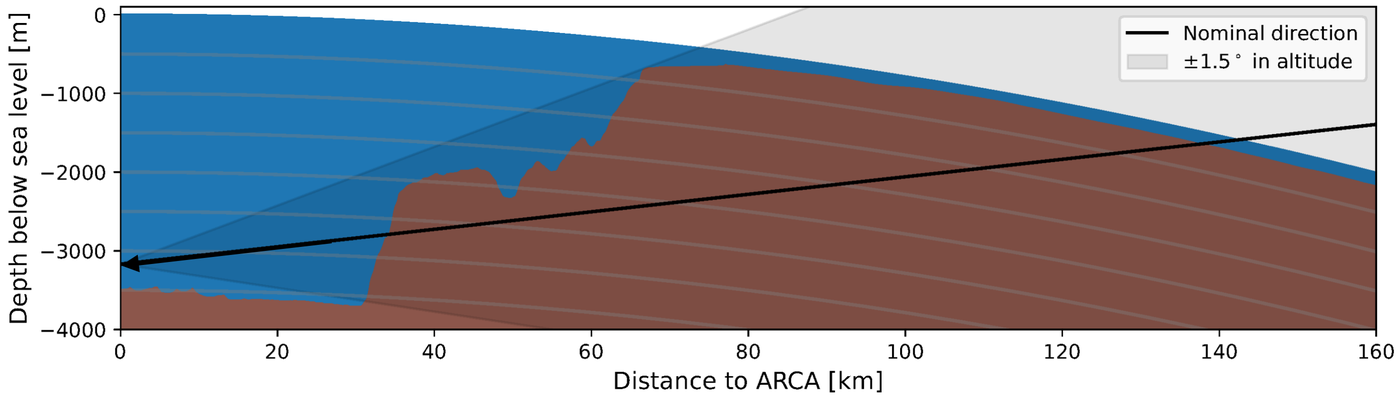


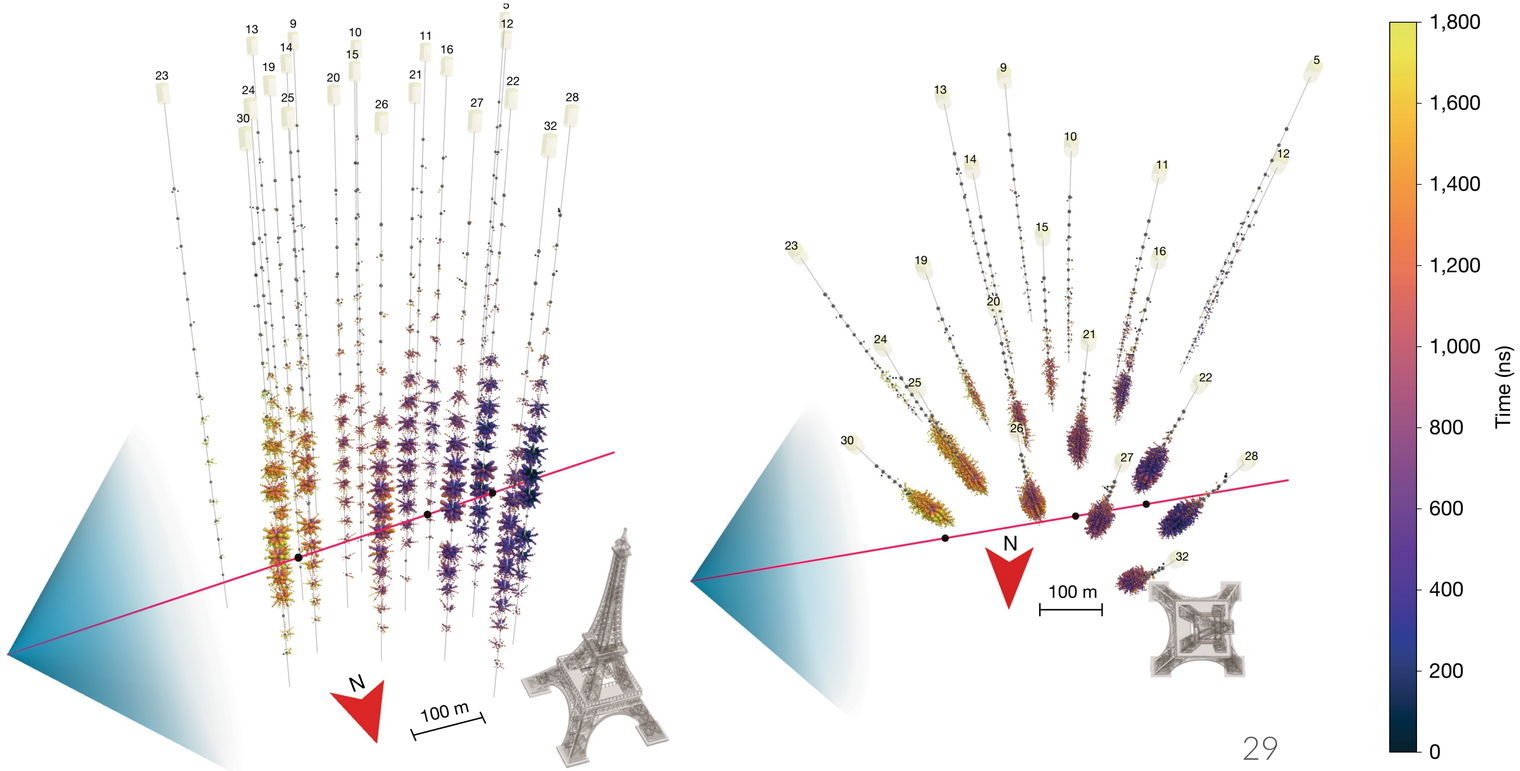
EHE-neutrinos



F Oikonomou 2025, adapted from github.com/carmeloevoli/The_CR_Spectrum

KM3-230213A





KM3NeT Coll, Nature, Vol 638 Issue 8050, 2025

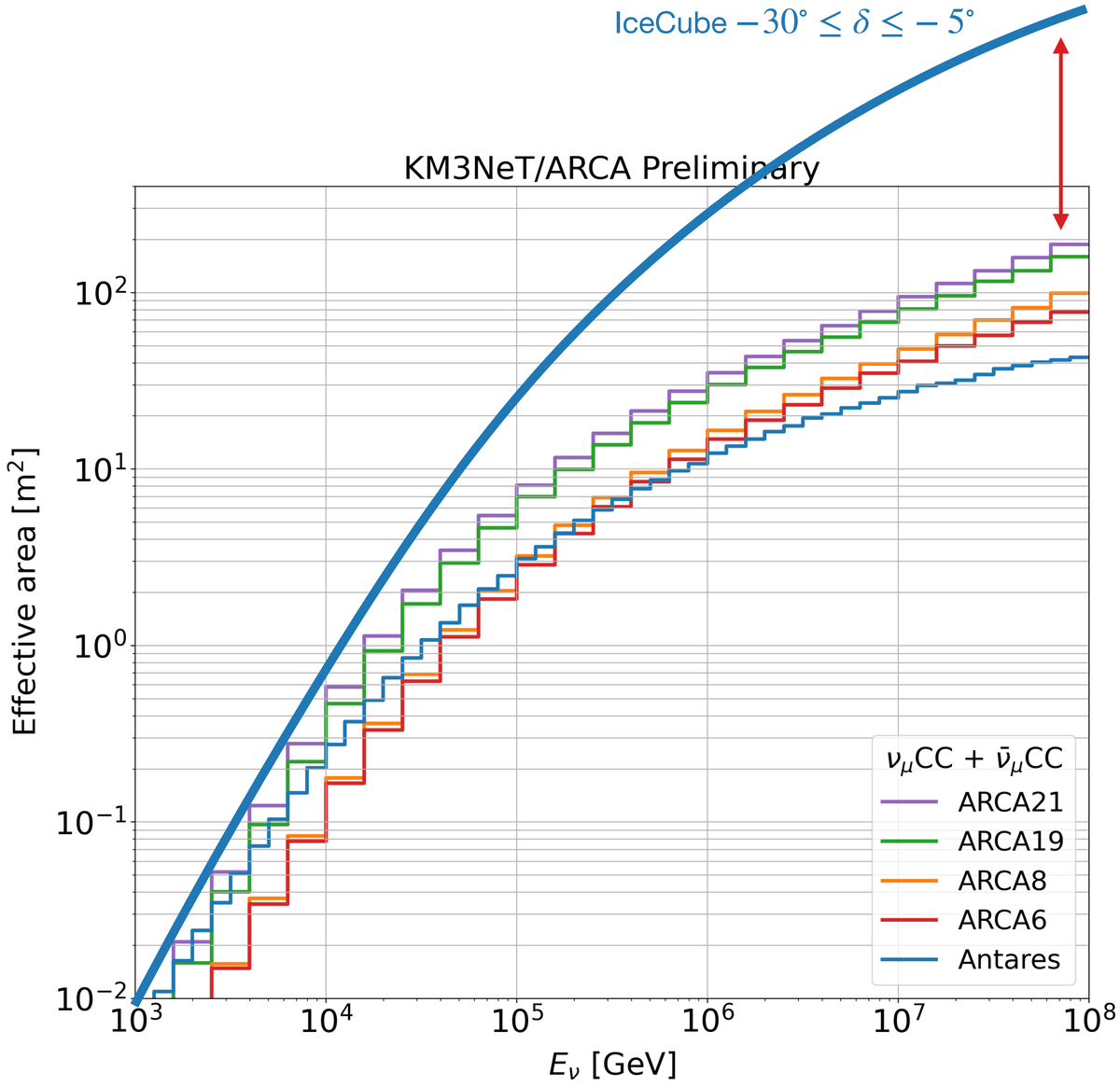
$7.2 \times 10^{16}\ \text{eV} \leq E_\nu \leq 2.6 \times 10^{18}\ \text{eV}$

$\text{RA} = 94.3^\circ,\ \delta = -7.8^\circ$

$R(68\%) = 1.5^\circ$

$R(99\%) = 3^\circ$

Why did IceCube not see it?



Neronov, FO, Semikoz, to appear in PRD, arXiv: 2502.12986

$$0.05 \leq N_\nu^{\mathrm{ARCA}} \leq 4.7 \ (90\,\%\ \mathrm{CL})$$

$$\mathrm{IC\ 1yr}: 1 \leq N_\nu \leq 94 \ (90\,\%\ \mathrm{CL})$$

$$\mathrm{IC\ 15yr}: 15 \leq N_\nu \leq 1410 \ (90\,\%\ \mathrm{CL})$$

**similar constraints from the Auger neutrino upper limits*

A neutrino from a year-long transient?

Neronov, FO, Semikoz, to appear in PRD, arXiv: 2502.12986

10-yr IceCube limit inconsistent with Km3NeT flux

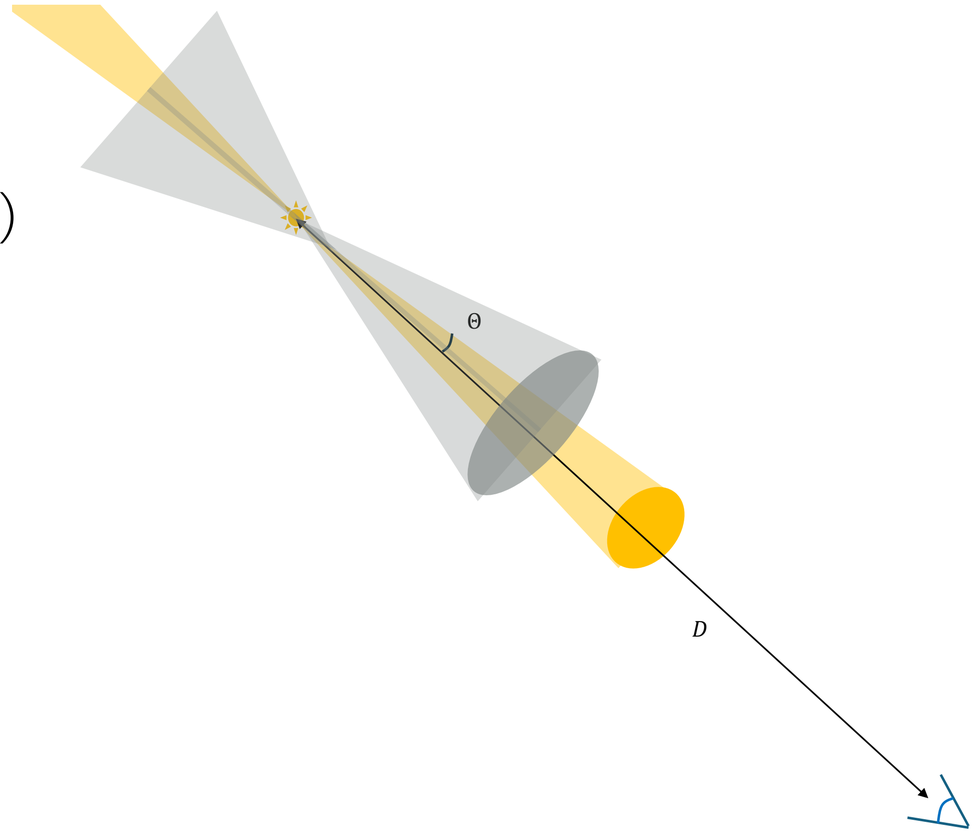
1-yr IceCube limit consistent with Km3NeT flux (within 90% CL)

Total neutrino energy

$$E_\nu = 4\pi D^2 \cdot \Delta T F_\nu = 10^{54} \left[\frac{\mathrm{D}}{1\ \mathrm{Gpc}}\right]^2 \mathrm{erg}$$

Compatible with GRB, jetted TDE, blazar flare, but must be rare
< 0.4 bursts / yr

EM counterpart? (neutrino beam?)



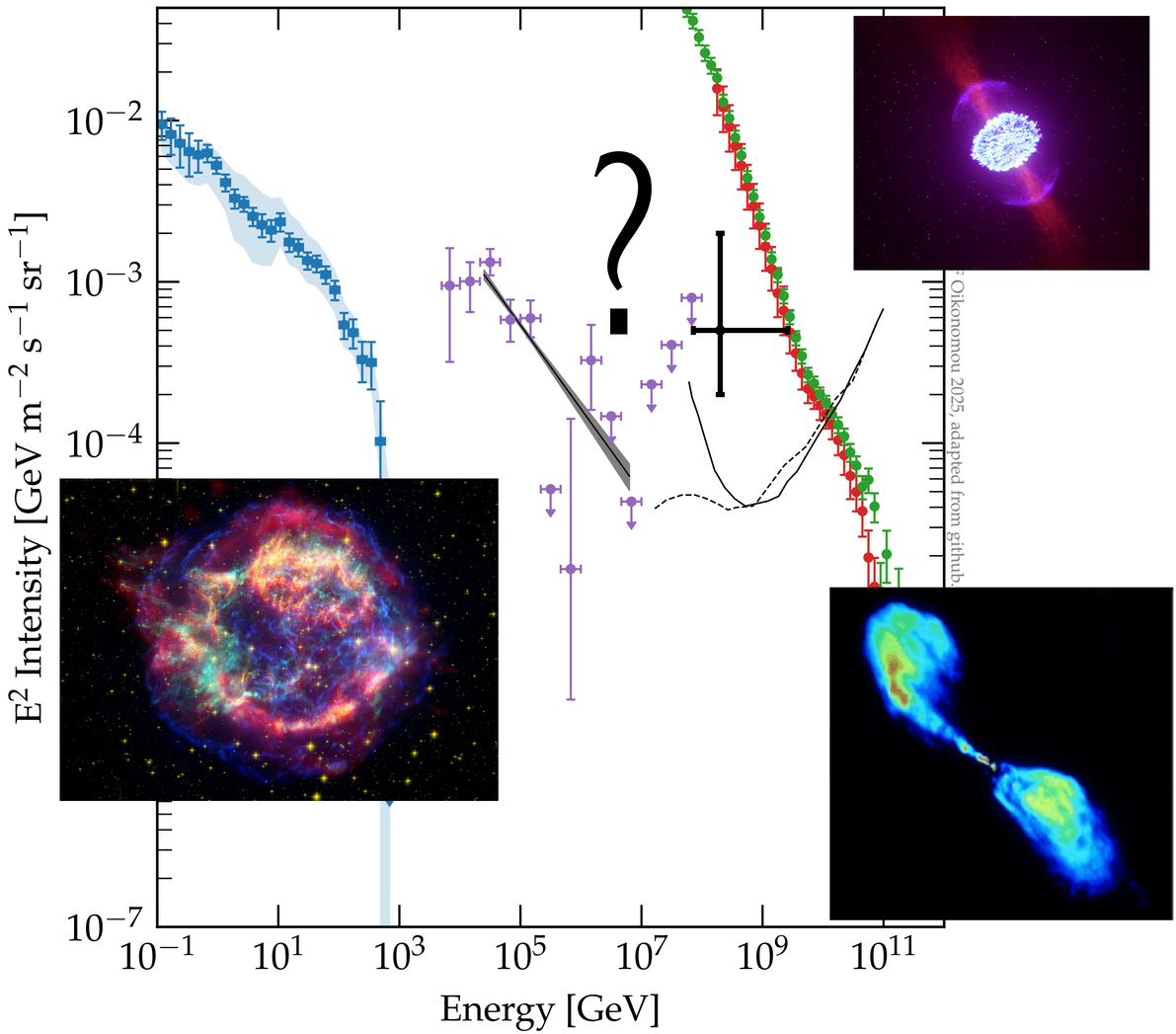
sketch by A. Neronov

Summary

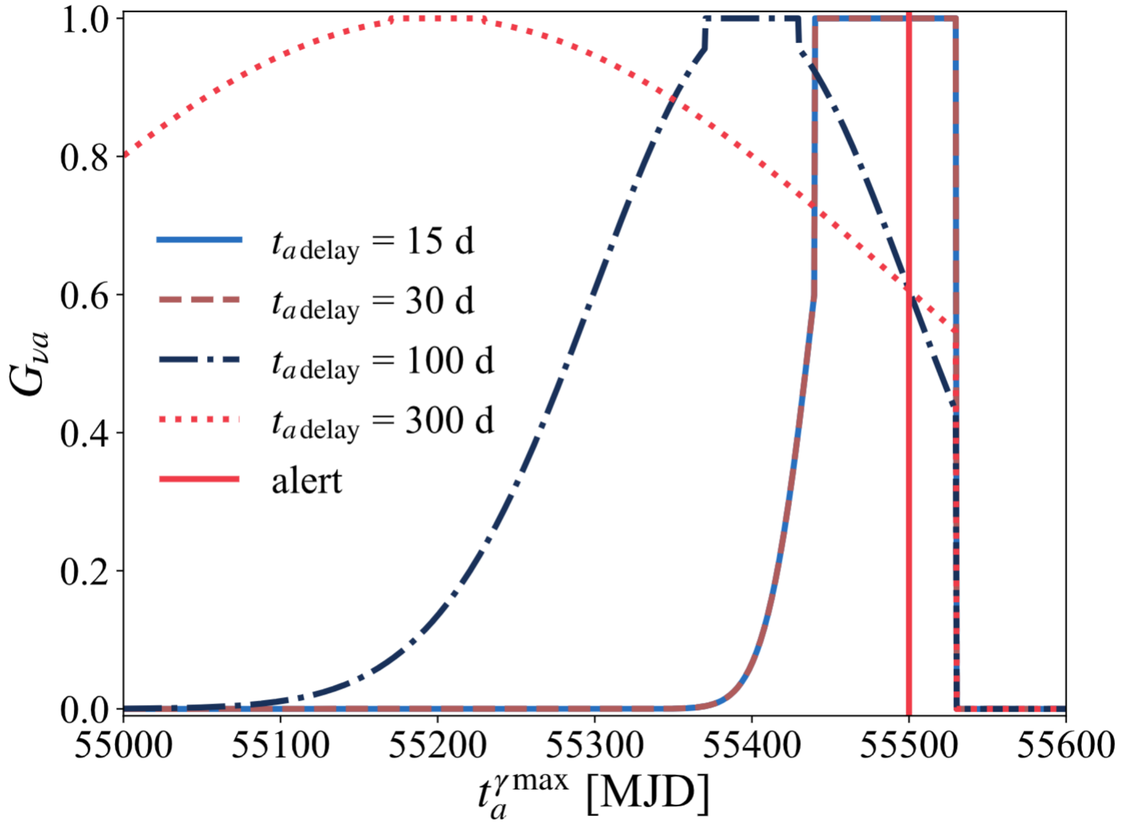
Rare Transients:
Not sources of the 10–300 TeV neutrinos
Only viable option for KM3-230213A

Supernovae and other not so rare transients:
Unconstrained - too many

Timing:
Neutrinos could be delayed



Delayed neutrinos?



Gaussian temporal weights with the centre at the anticipated prior maximum of the flare based on the neutrino arrival time and jet-frame delay

$$t_{a\,\mathrm{delay}}(t'_{\mathrm{delay}}, D_a, z_a) = \frac{1+z_a}{D_a} t'_{\mathrm{delay}}$$

$$w_\nu(t'_{\mathrm{delay}}) \propto G_{\nu a}(t_a^{\gamma\,\mathrm{max}}, t_\nu; t'_{\mathrm{delay}}, D_a, z_a) F_a^\gamma(t_a^{\gamma\,\mathrm{max}})$$

Delayed neutrinos?

Alert	Association	s_ν	E_ν [TeV]	U_ν [$^\circ{}^2$]	TS_ν	D	z
IC120523B	3C 454.3	0.490	168	47.2	0.0787	14.7	0.86
IC150926A	3C 279 †	0.296	216	8.8	0.0617	27.8	0.54
IC160814A	PKS 1313-333 †	0.607	263	26.3	0.0117	19.3	1.21
IC211208A	PKS 0735+17 †	0.502	171	25.1	0.0036	5.8	0.42
IC150812B	PKS 2145+06 †	0.831	508	6.5	0.0025	4.0	1.00
IC140927A	PKS 0336-01 †	0.481	182	37.2	0.0019	26.8	0.85
IC170427A	RX J0011.5+0058 † S3 0013-00	0.383	155	40.3	0.0018	17.3 15.0	1.49 1.58
IC120605A	OL 318 † B2 1015+35B †	0.385	107	21.1	0.0016	19.9 3.6	1.41 1.23
IC200614A	B2 0202+31	0.415	115	65.1	0.0015	20.5	1.47
IC220225A	PKS 0215+015 †	0.378	154	27.2	0.0015	14.6	1.72

Table 2. Top ten neutrino alerts with the highest values of their TS_ν in the test with the source list R24+ corresponding to the global minimum of $p(\hat{t}'_{\mathrm{delay}}) = 0.026$ reached at $\hat{t}'_{\mathrm{delay}} = 1.9 \times 10^3$ d. The sum TS for the whole dataset is 0.1734. The symbol † indicates associations requiring the extension of the original *IceCube* errors by $\Delta = 0.78^\circ$. Note the change of values for D w.r.t. Table 1 and that TXS 0506+056 is absent in R24+.

Delayed neutrinos?

Alert	Association	s_ν	E_ν [TeV]	U_ν [$^{\circ 2}$]	TS_ν	D	z
IC120523B	3C 454.3	0.490	168	47.2	0.1287	45.3	0.86
IC150926A	3C 279 †	0.296	216	8.8	0.0617	140.2	0.54
IC170922A	PKS 0502+049 †	0.631	264	7.1	0.0432	24.6	0.95
	TXS 0506+056					1.8	0.34
IC221223A	B2 2308+34 †	0.795	353	7.5	0.0181	22.8	1.82
IC180608A	PKS 0440-00 †	0.396	158	11.3	0.0168	3.5	0.45
IC160727A	4C +14.23 †	0.296	105	14.9	0.0082	13.9	1.04
IC181023B	TXS 0518+211 †	0.427	136	11.5	0.0071	2.7	0.11
IC131014A	MG1 J021114+1051 †	0.665	293	6.3	0.0071	6.3	0.20
IC190410A	PKS 2029+121	0.280	105	44.6	0.0050	28.3	1.22
	PKS 2032+107					9.7	0.60
IC120515A	OP 313	0.613	194	13.3	0.0039	24.2	1.00

Table 1. Top ten neutrino alerts with the highest values of their TS_ν in the test with the source list {H2+} corresponding to the local minimum of $p(\tilde{t}'_{\mathrm{delay}}) = 0.037$ reached at $\tilde{t}'_{\mathrm{delay}} = 7.7 \times 10^3$ d. The sum TS for the whole dataset is 0.3577. The symbol † indicates associations requiring the extension of the original *IceCube* errors by $\Delta = 0.78°$.

Comparison to Padovani 2024