Multimessenger emission from active galactic nuclei

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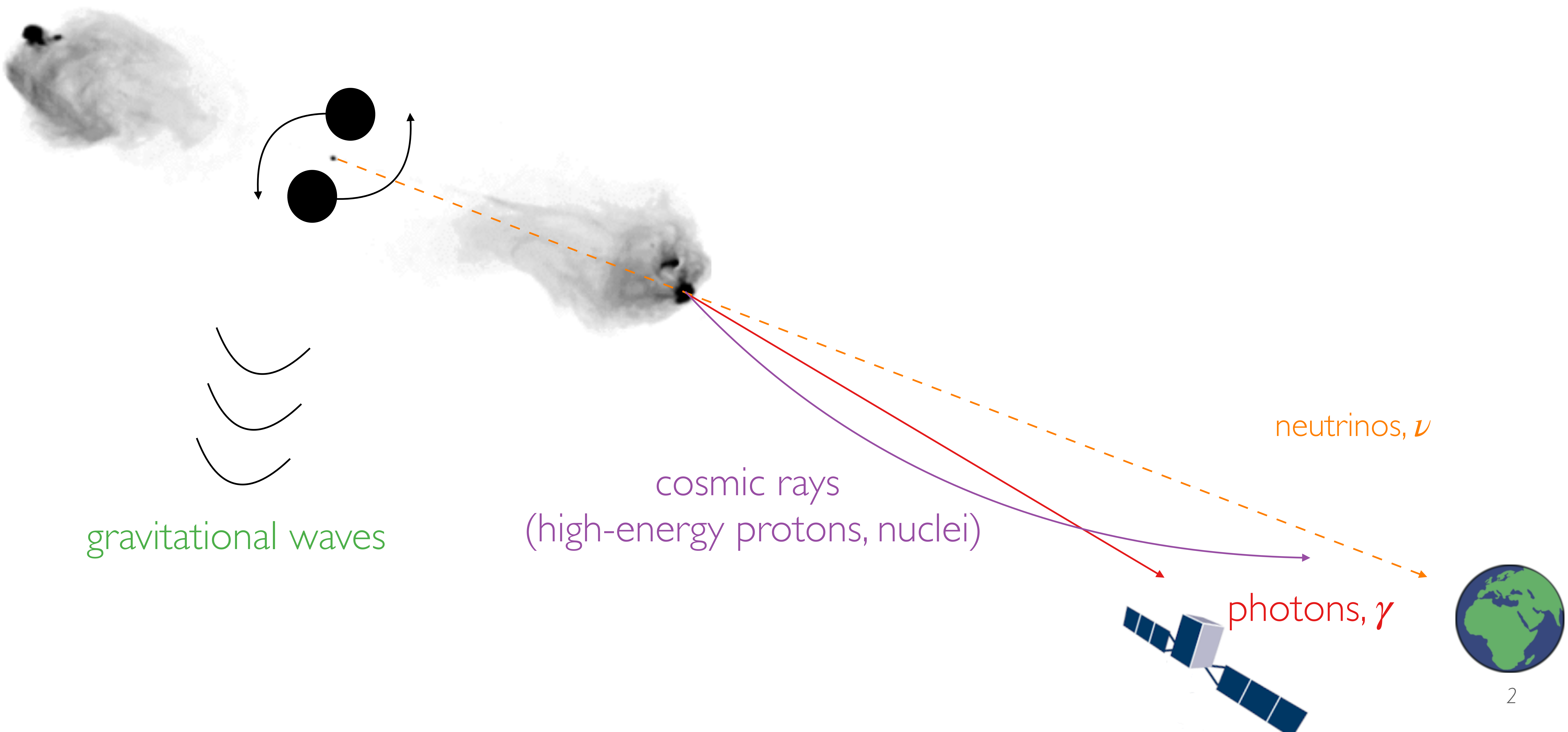
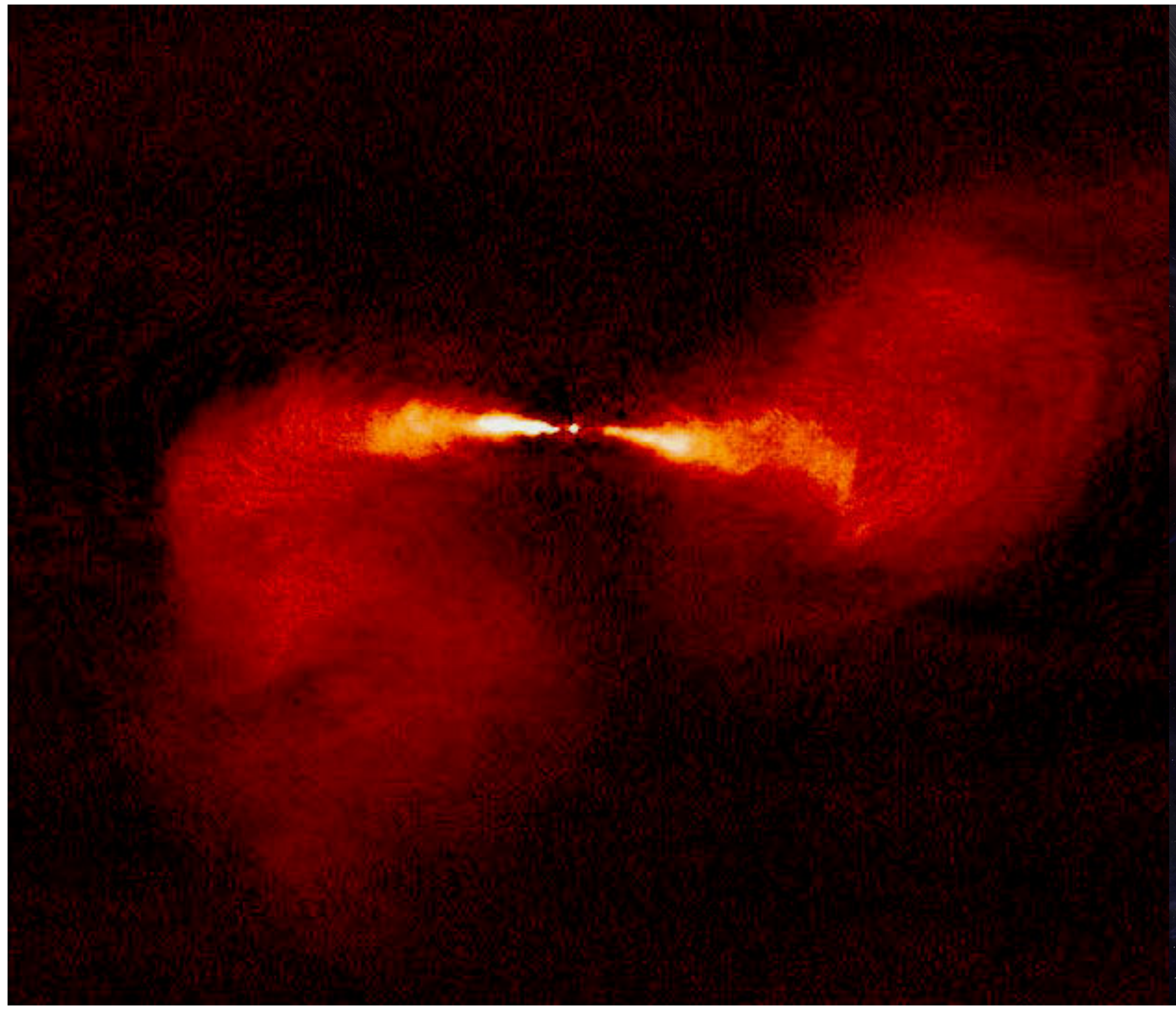
The most powerful long–lived astrophysical sources



This talk



Jetted AGN (10%)
Rare and extremely powerful

Non-jetted AGN (90%)

Tidal disruption events
jetted (~1%) and non-jetted

Requirements for multimessenger emission

Maximum particle energy

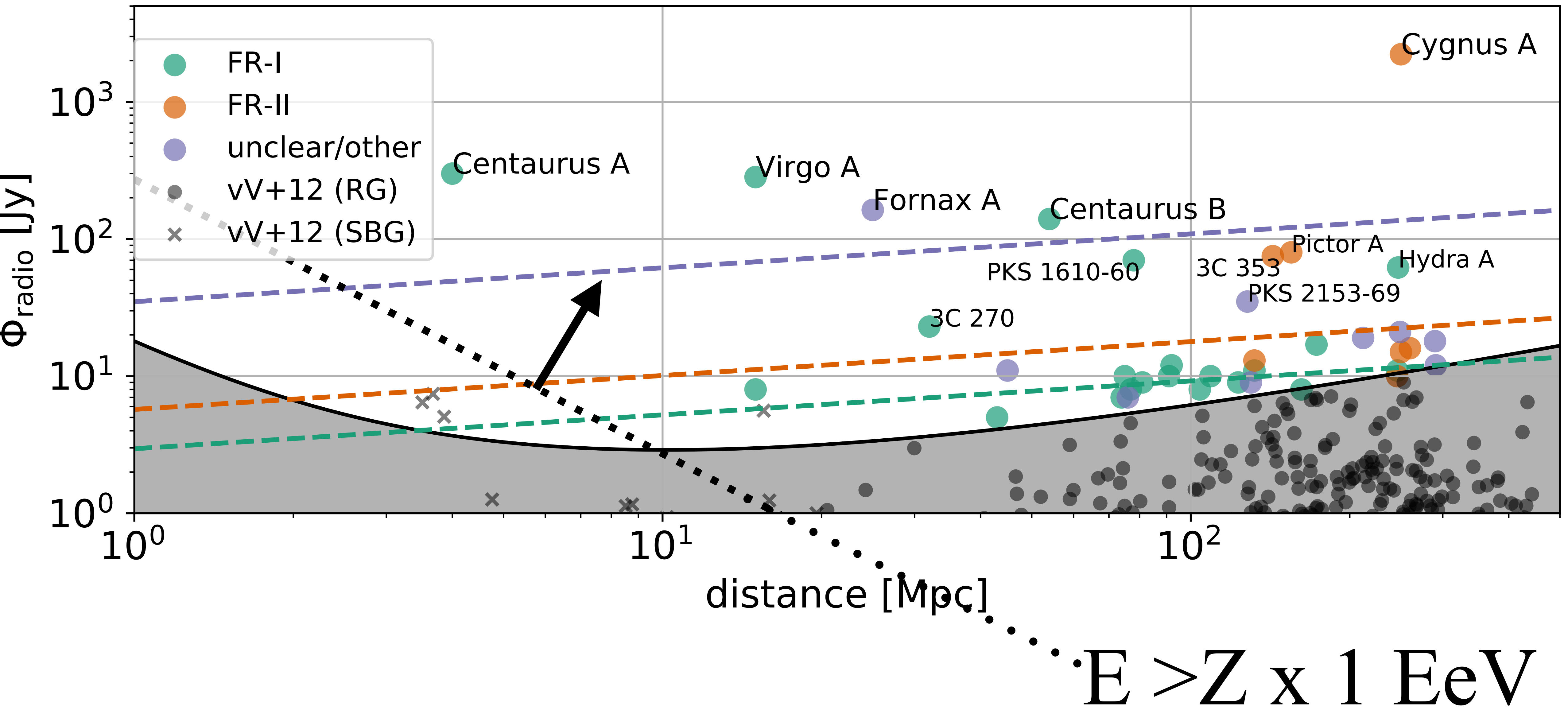
Sufficient emissivity

UHECRs: Fit to spectrum and composition

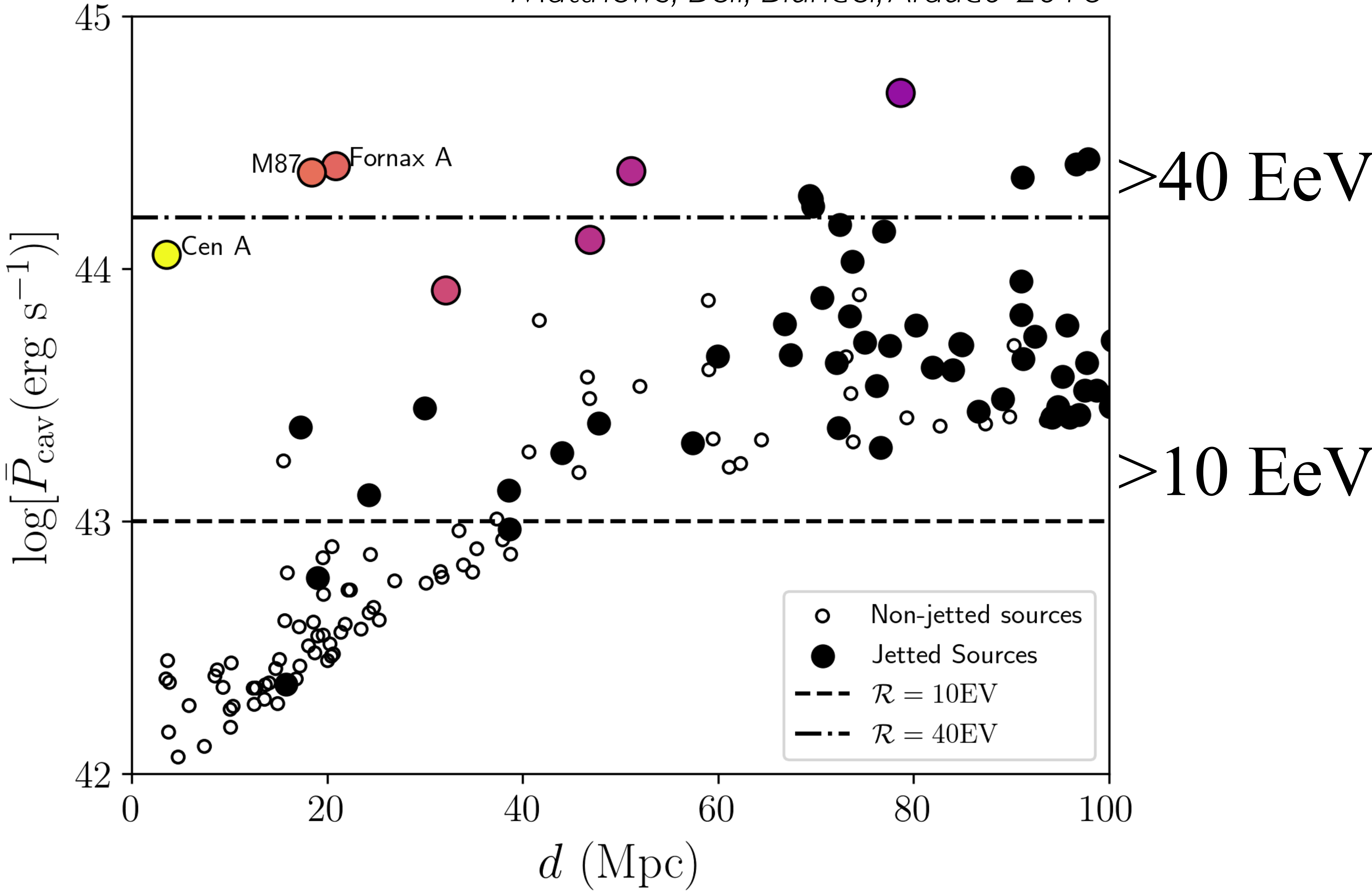
Neutrinos: Fit to the spectrum / stacking

Jetted AGN: Maximum energy

Eichmann, Kachelriess, FO 2022



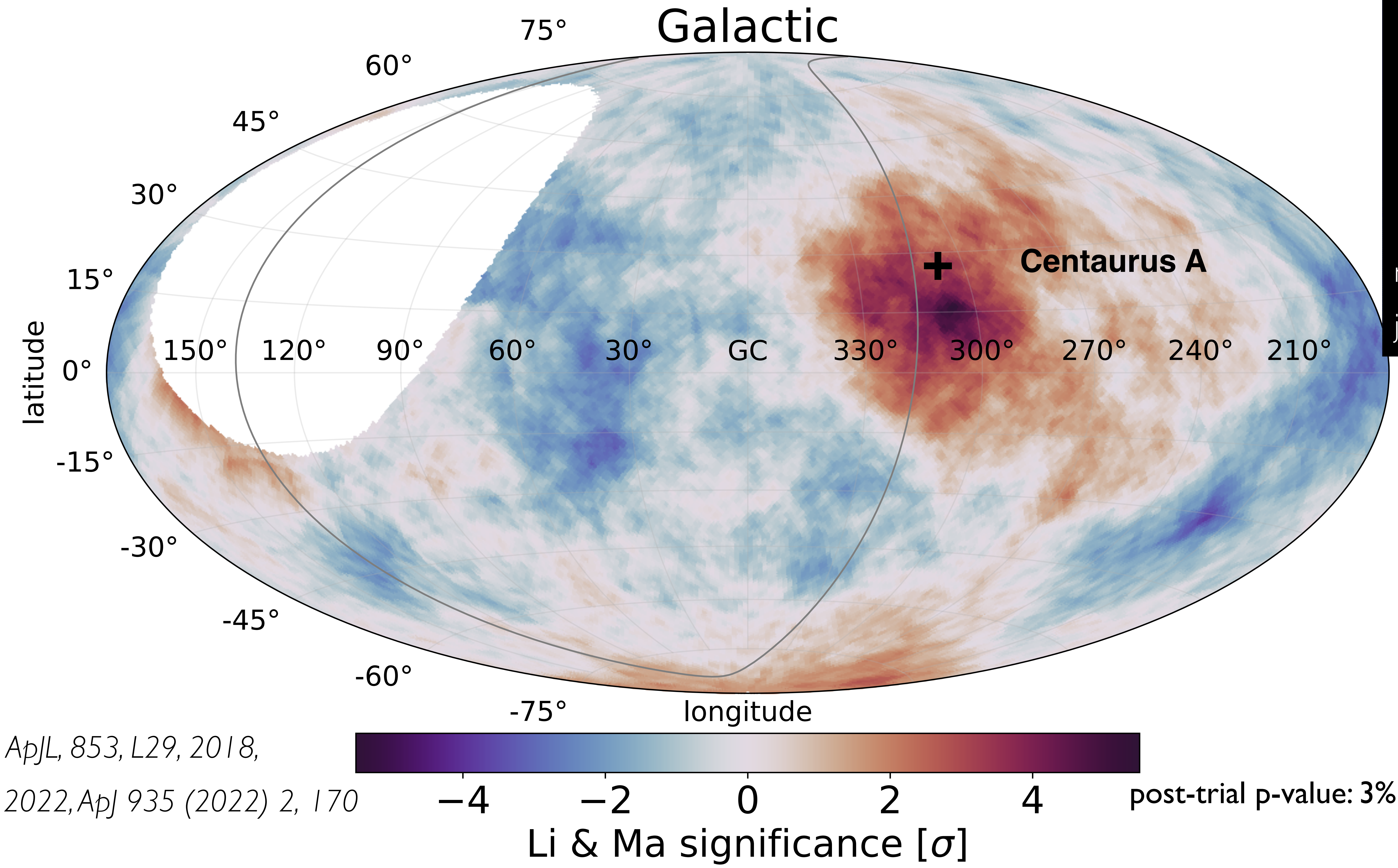
Matthews, Bell, Blundel, Araudo 2018



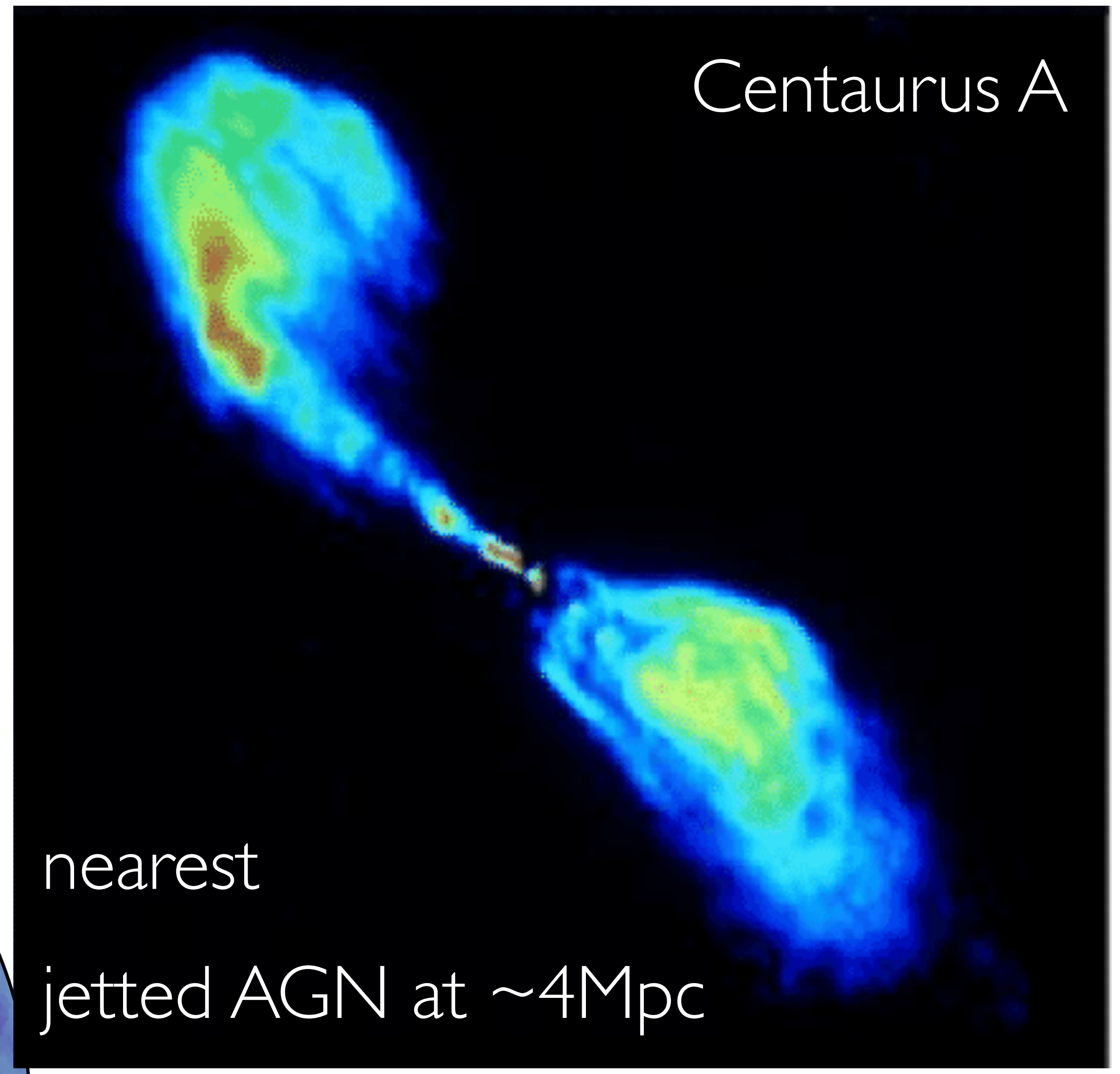
$$L \gtrsim L_B \sim B^2 R^2 \beta \sim \frac{10^{45.5}\ \mathrm{erg/s}}{\beta} \left(\frac{E}{100\ \mathrm{EeV}} \right)^2$$

Lovelace 1976, Waxman 1995, 2001, Blandford 2000, Lemoine & Waxman 2009

Arrival directions above 4 x 10^{19} eV



post-trial p-value: 3%



>Cen A region: 63 Excess events

E ≥38 EeV, angular radius: 27deg

post-trial significance: 4.1σ

>Jetted AGN (γ-ray flux weights)

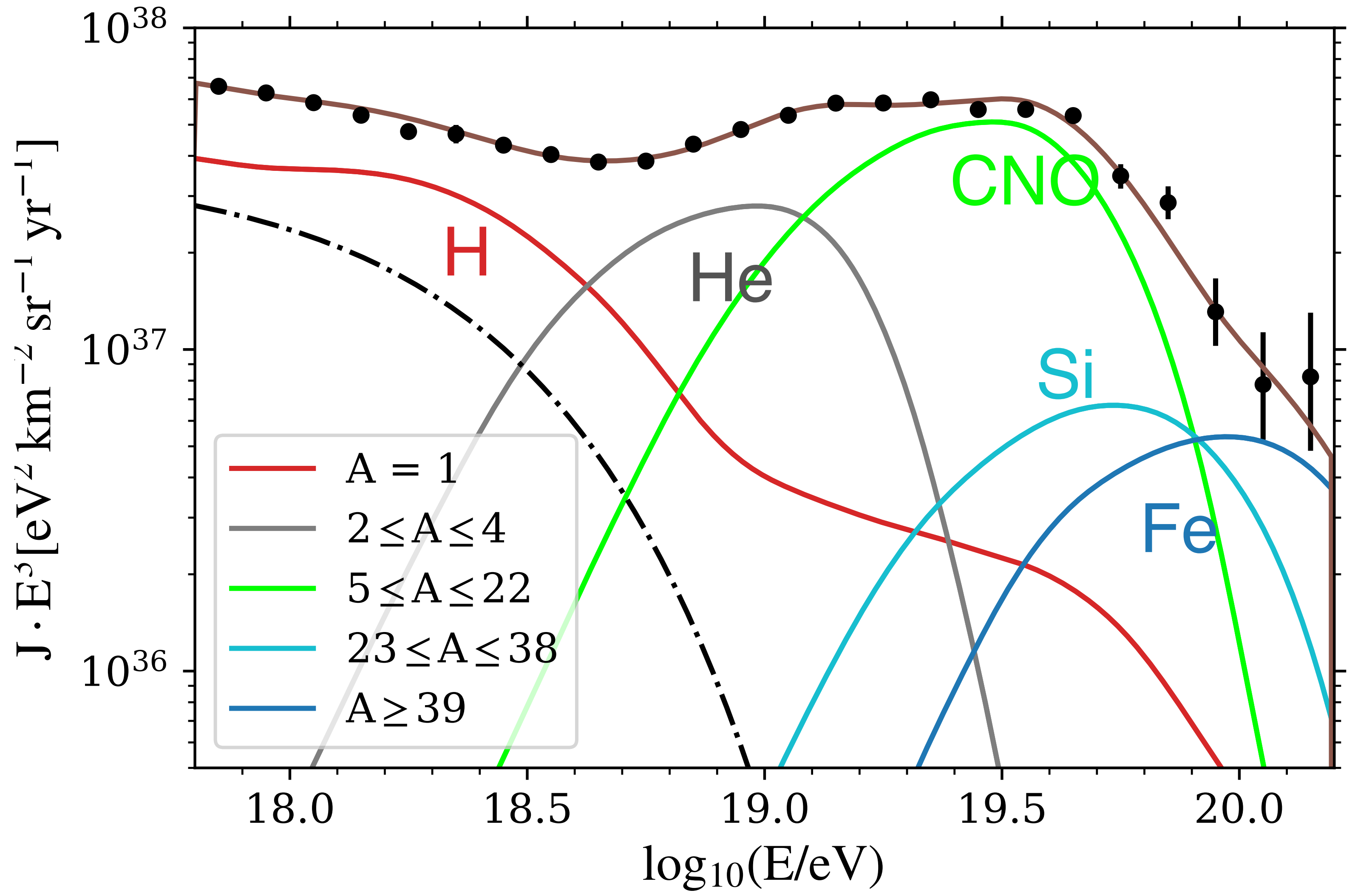
E ≥39 EeV, Flux fraction ~6%

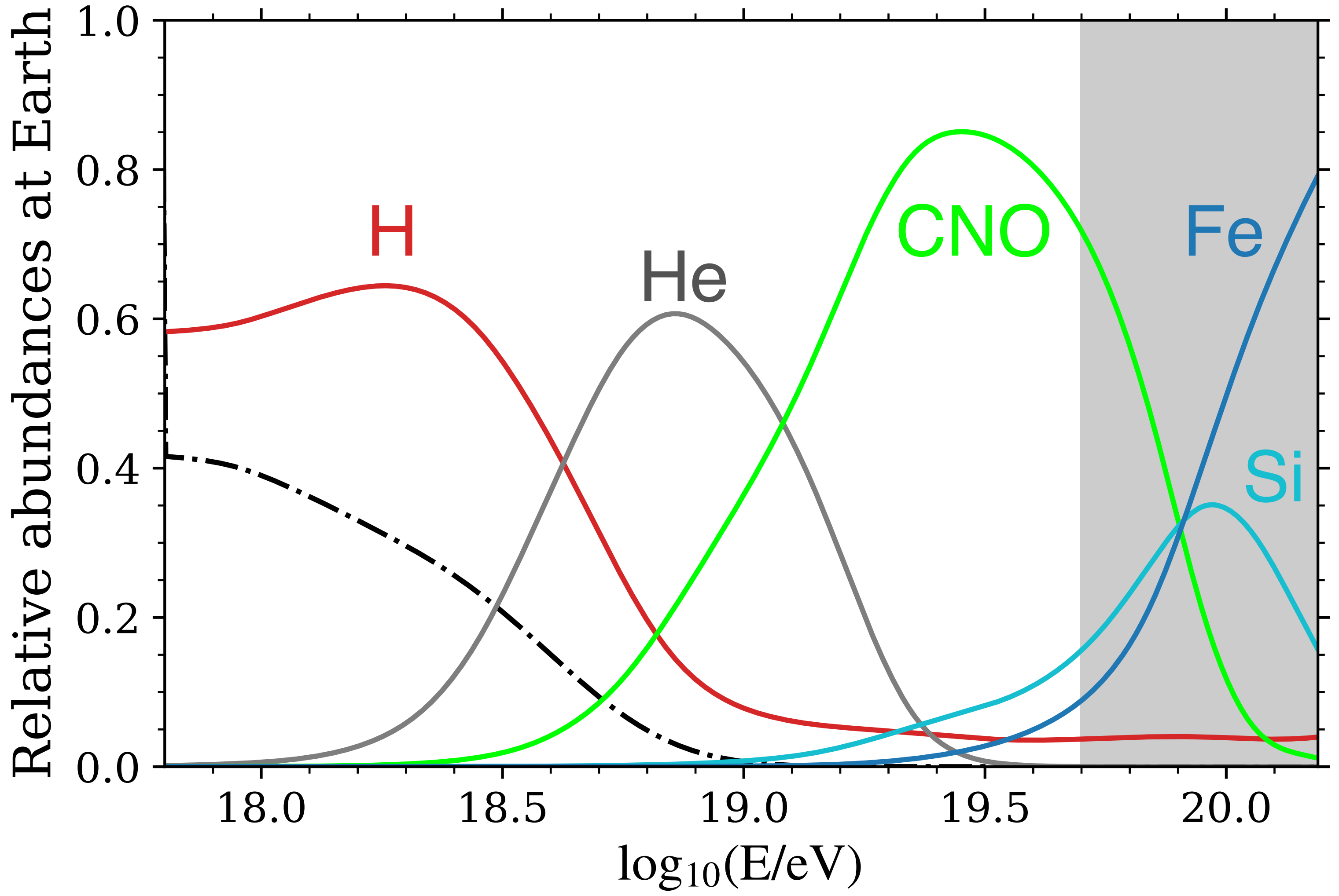
post-trial significance: 3.3σ

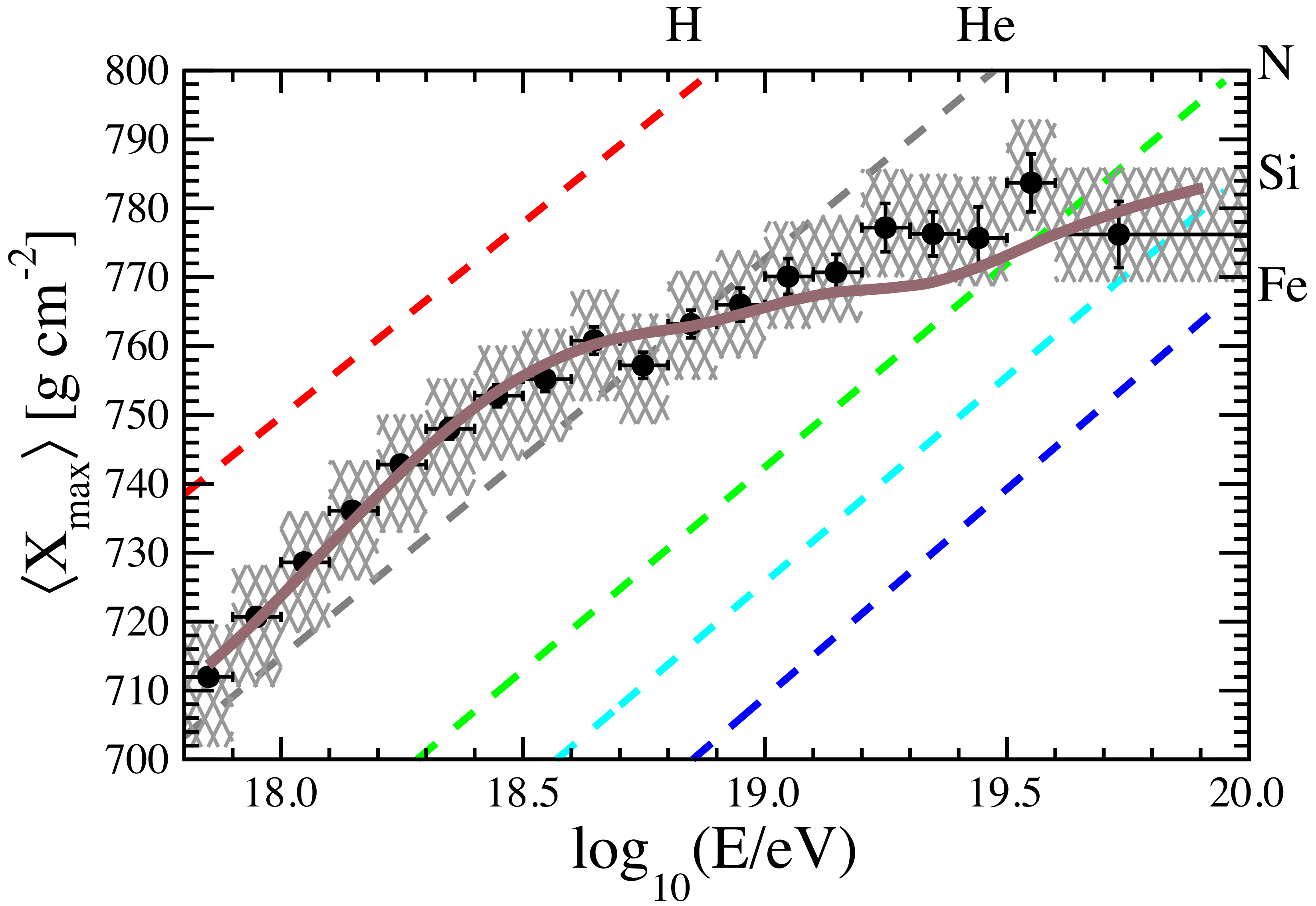
Auger Coll, ApJL, 853, L29, 2018,

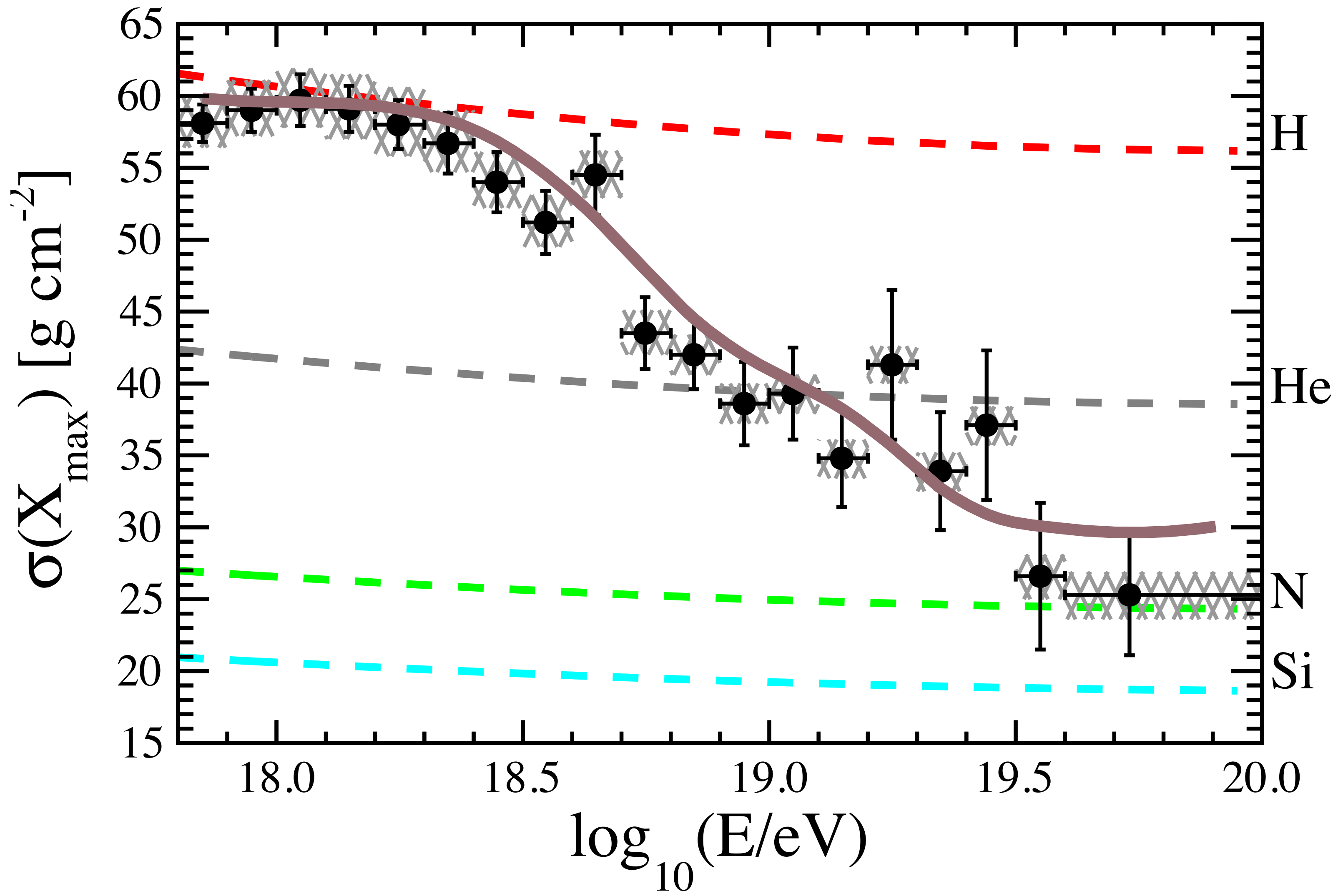
Auger Coll 2022, ApJ 935 (2022) 2, 170

Searching for the UHECR sources: Combined fit approach









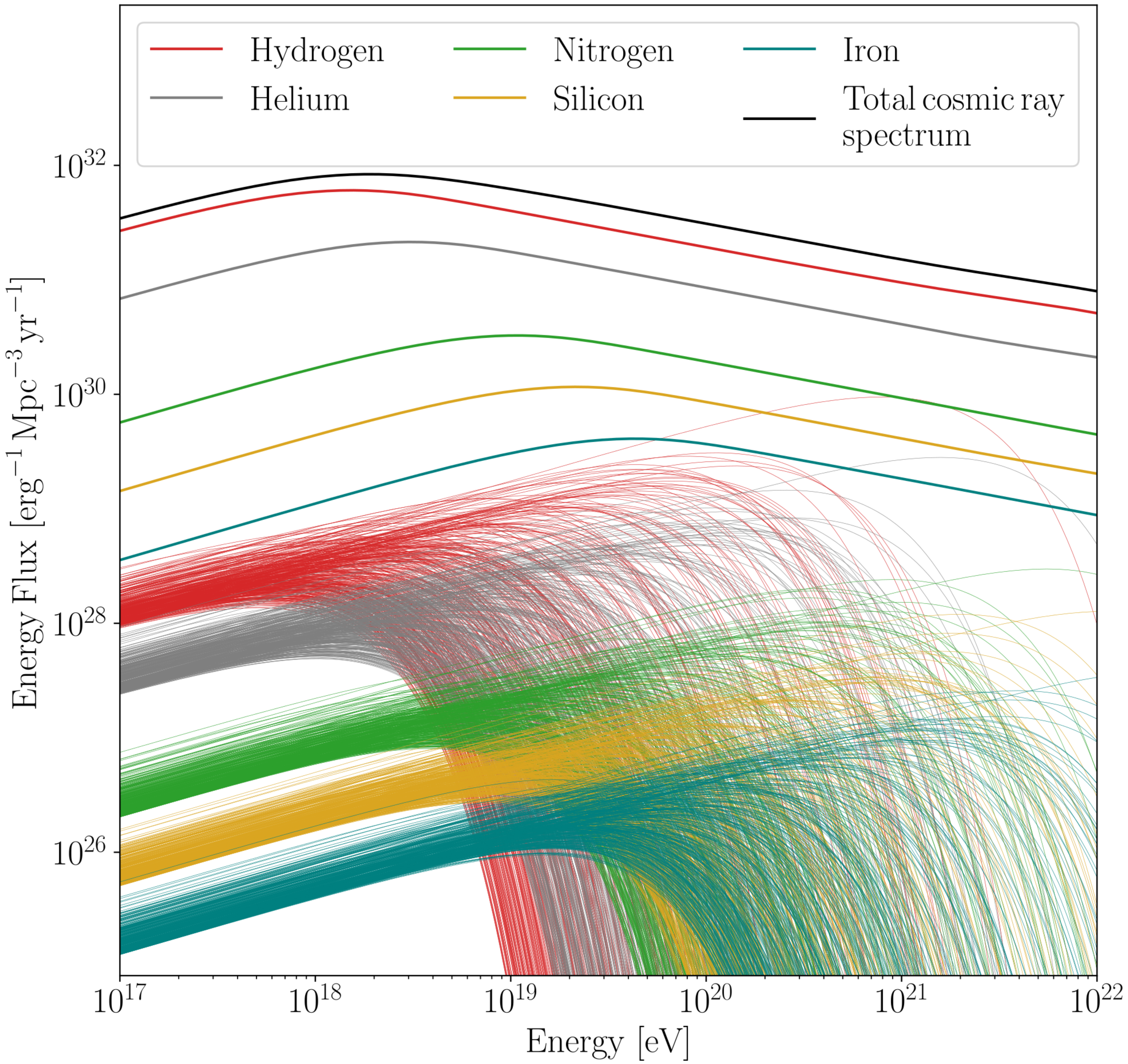
Generic Source Properties:
Allard et al 2007, 8, Hooper et al 2007, Unger et al 2015, Auger Coll 2016, Kachelriess et al 2017, Muzio et al 2019, 2022, Mollerach et al 2020, Das et al 2021.

Specific source classes:
Jetted AGN - *Eichmann et al 2017, 2022, Fang et al 2018, Kimura et al 2018, Rodrigues et al 2021*
GRBs - *Globus et al 2015, Biehl et al 2017, Zhang et al 2018, Boncioli et al 2018, 2019, Rudolf 2019,2022, Heinze et al 2020*
TDEs - *Biehl et al 2017, Guepin et al 2017, Zhang et al 2017*
Transrelativistic Supernovae - *Zhang & Murase 2019*
Starburst galaxies - *Condorelli et al 2022*

Sources generally assumed to be intrinsically identical

Distribution of maximum energies:
UHECR protons: *Kachelriess & Semikoz 2007*
Galactic sources: *Shibata et al 2010*
Discrete AGN: *Eichmann, Kachelriess, FO 2022*

UHECRs from a population with a range of maximum energies



Model maximum energy distributions constructed based on:

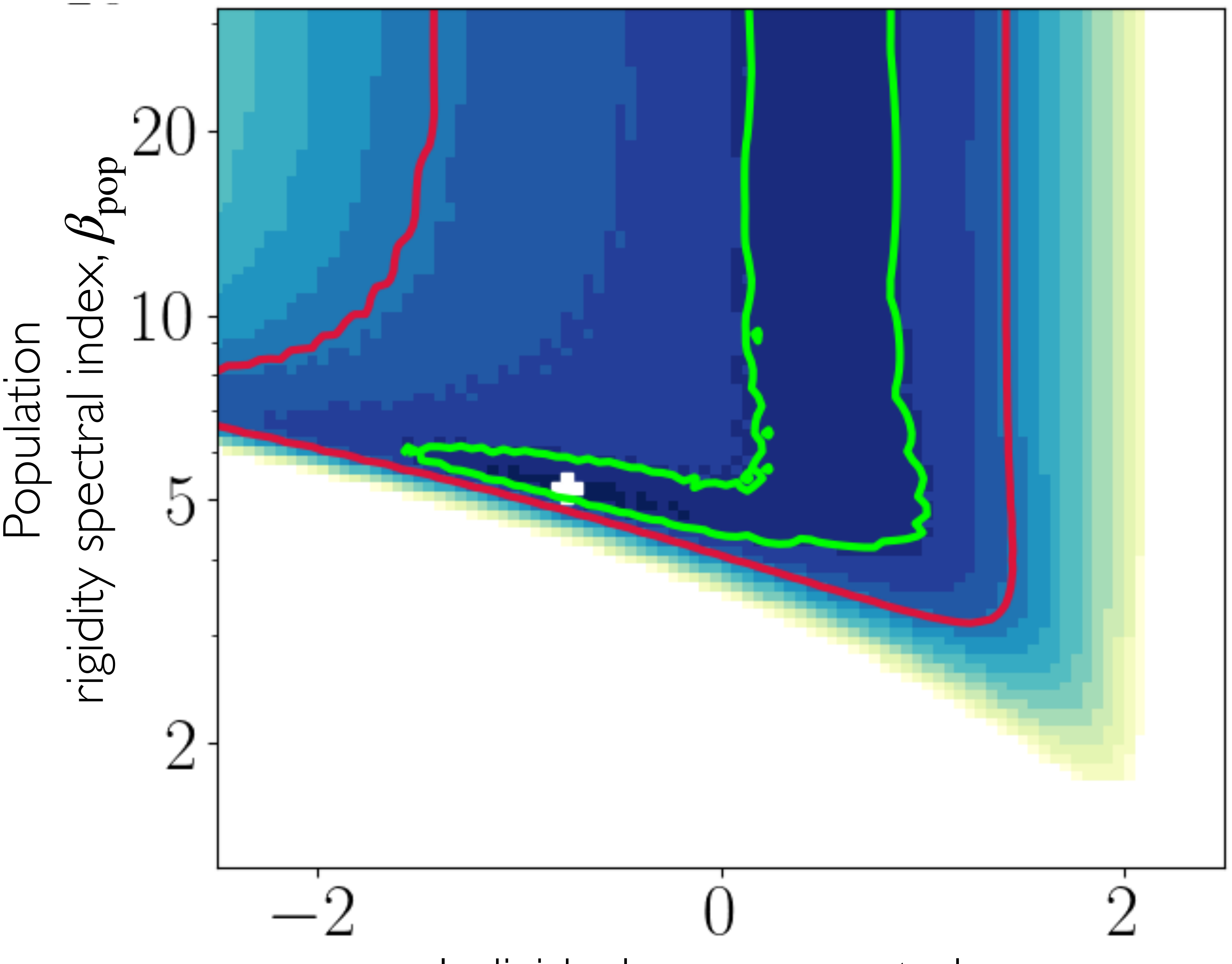
1. Extragalactic jet population **Lorentz factor distribution**

2. **Luminosity functions** (Seyfert galaxies, Tidal Disruption Events, Blazars, GRBs)

Compare to the Auger spectrum and composition data

Ehlert, FO, Unger, PRD 107 (2023) 10

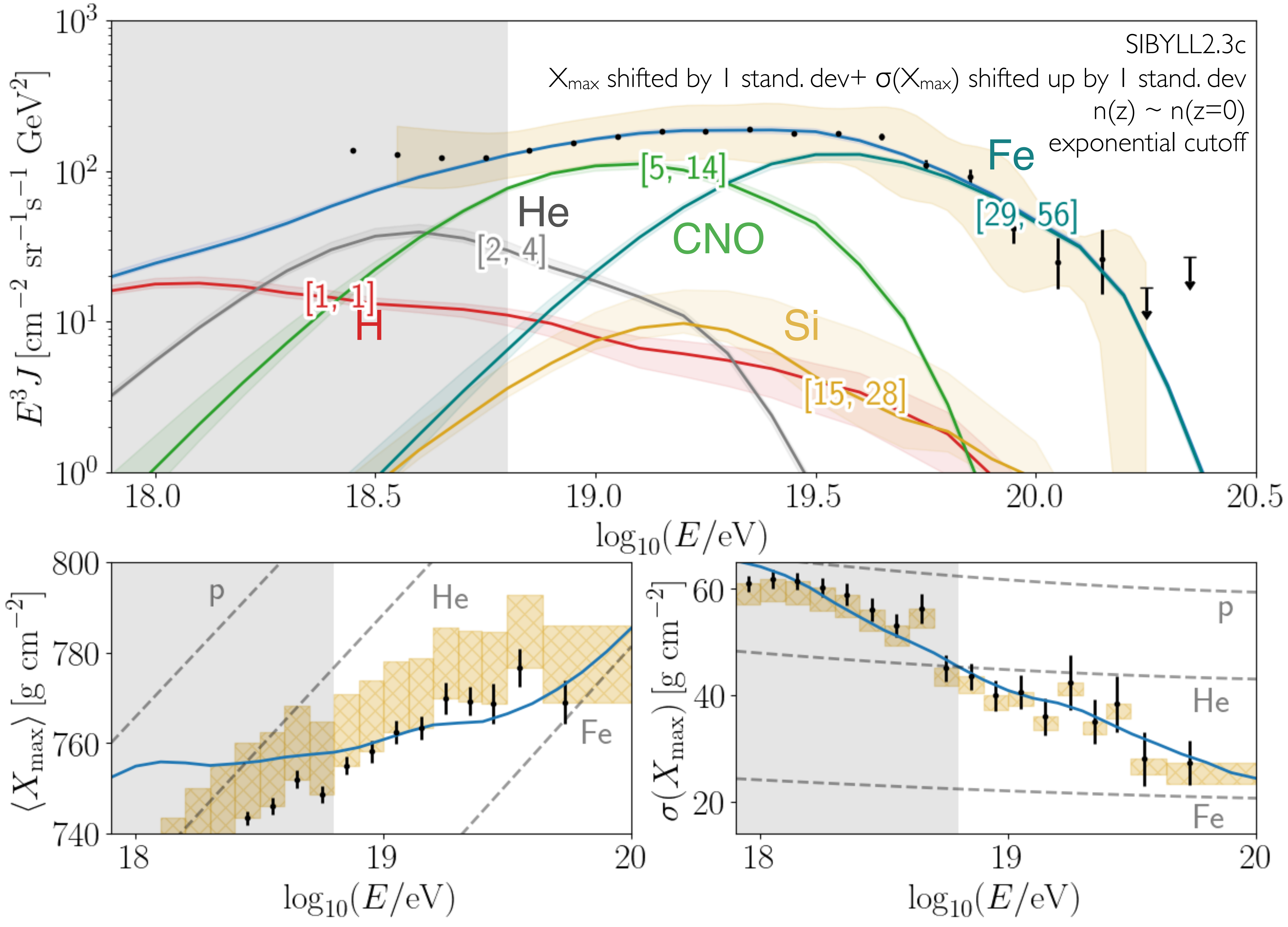
Jetted AGN: Variety problem?



Inverted Spectra

Individual energy spectral index, $\gamma_{\rm src}$

Shock Acceleration



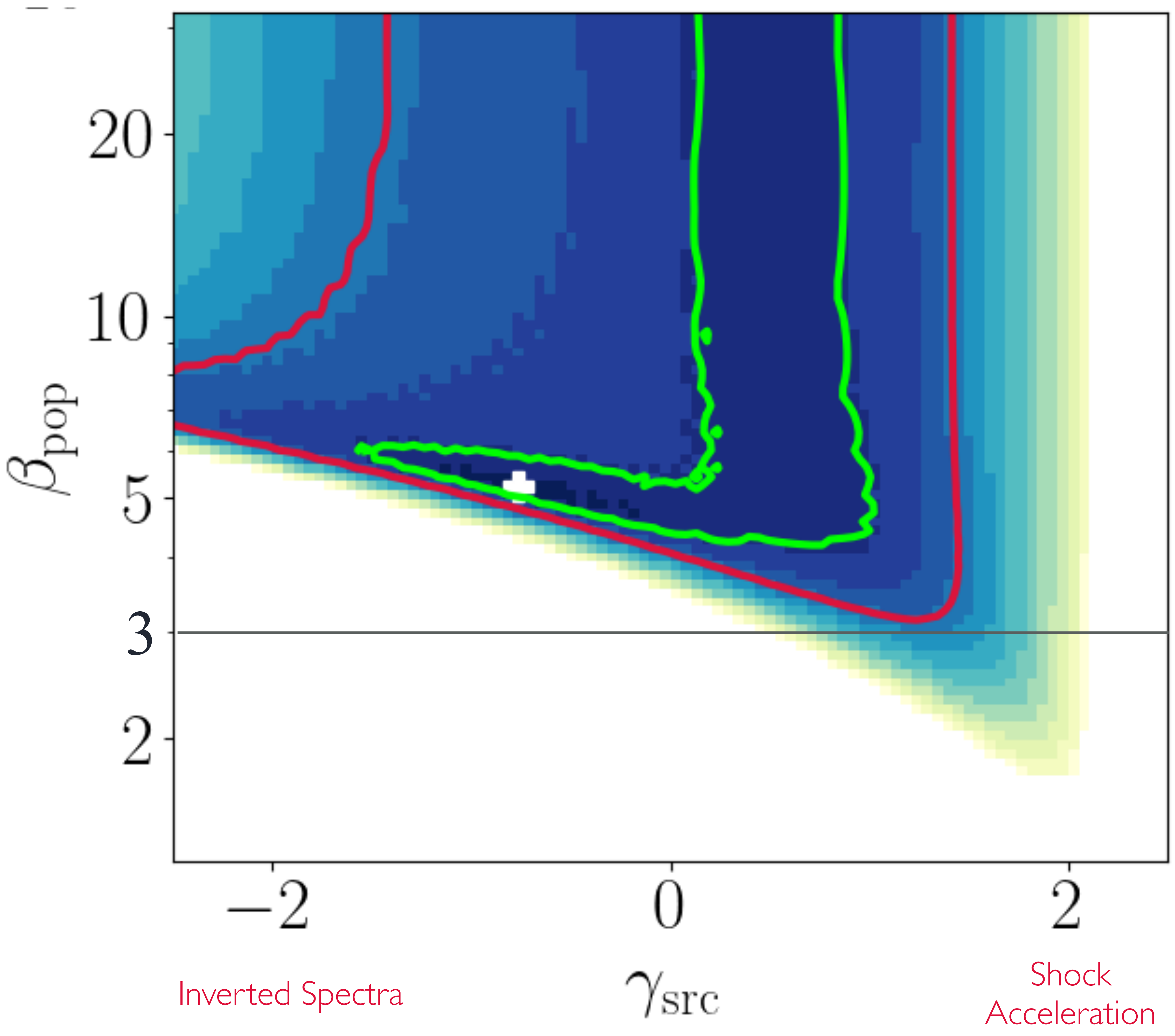
$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\rm src}}$$

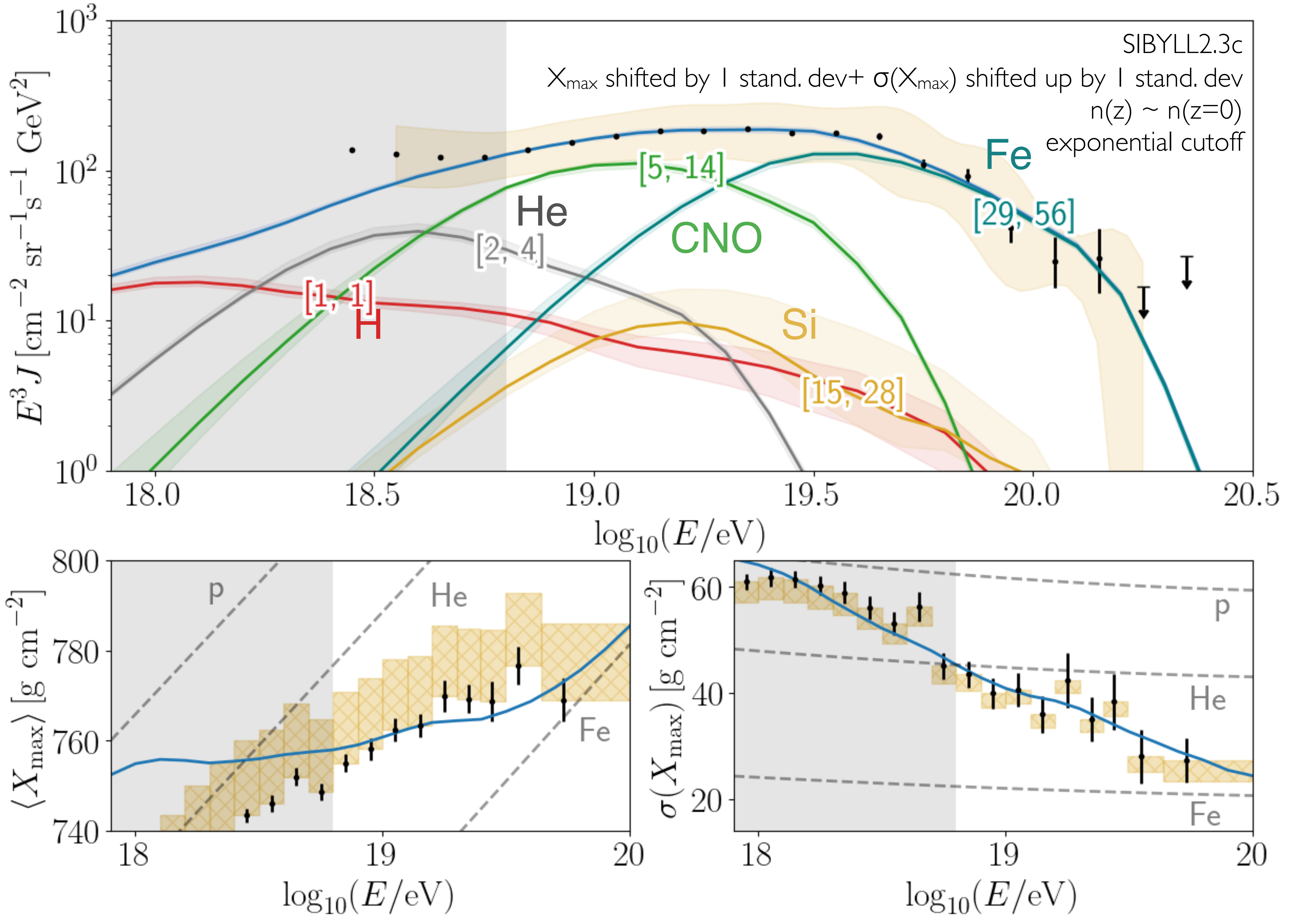
$$\frac{\mathrm{d}N}{\mathrm{d}R_{\rm max}} \propto R_{\rm max}^{-\beta_{\rm pop}}$$

$$\phi_{\rm pop} \propto \begin{cases} R^{-\gamma_{\rm src}} & R \ll R_0 \\ R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} & R \gg R_0 \end{cases}$$

Ehlert, FO, Unger, PRD 107 (2023) 10

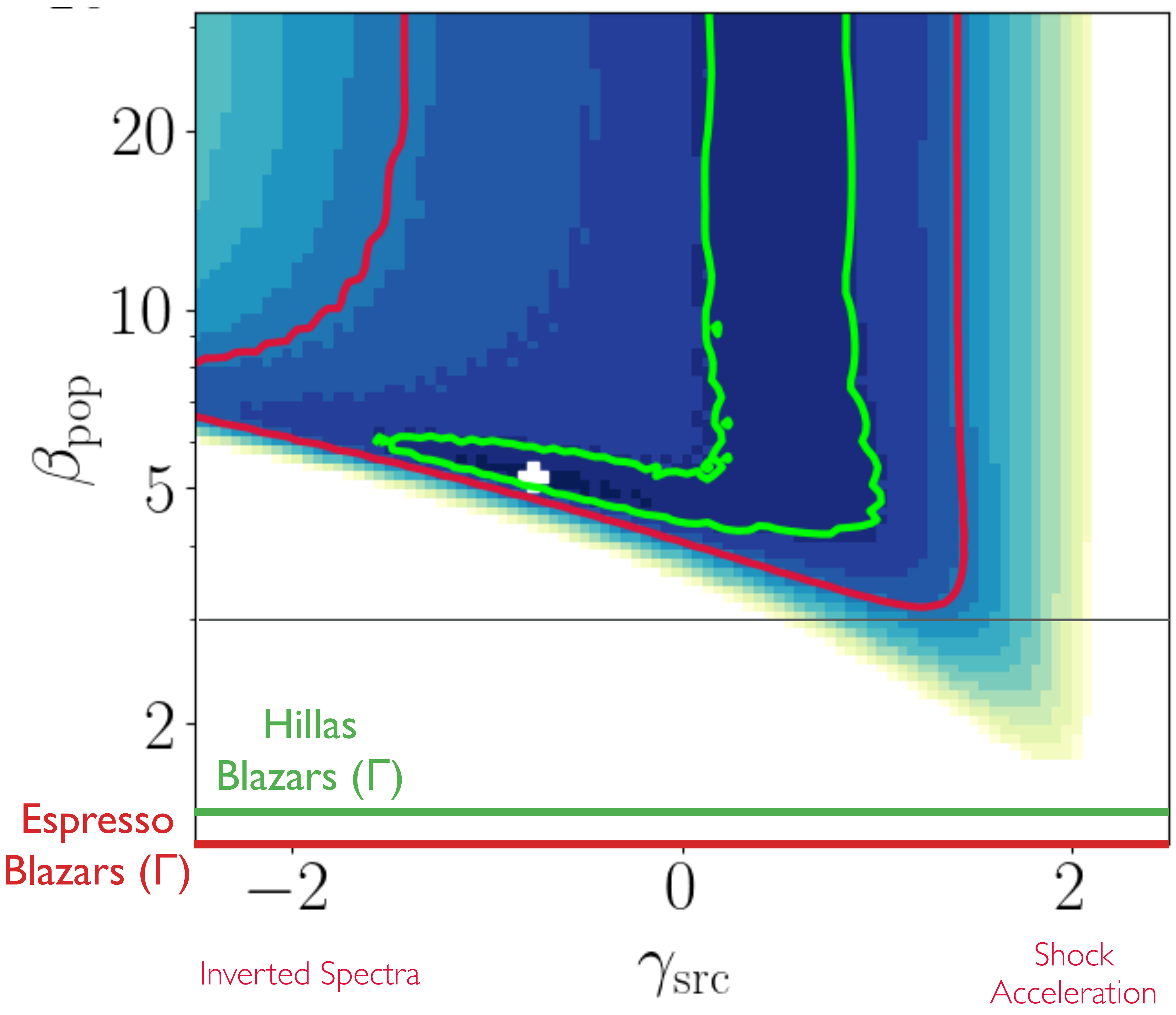
Jetted AGN: Variety problem?

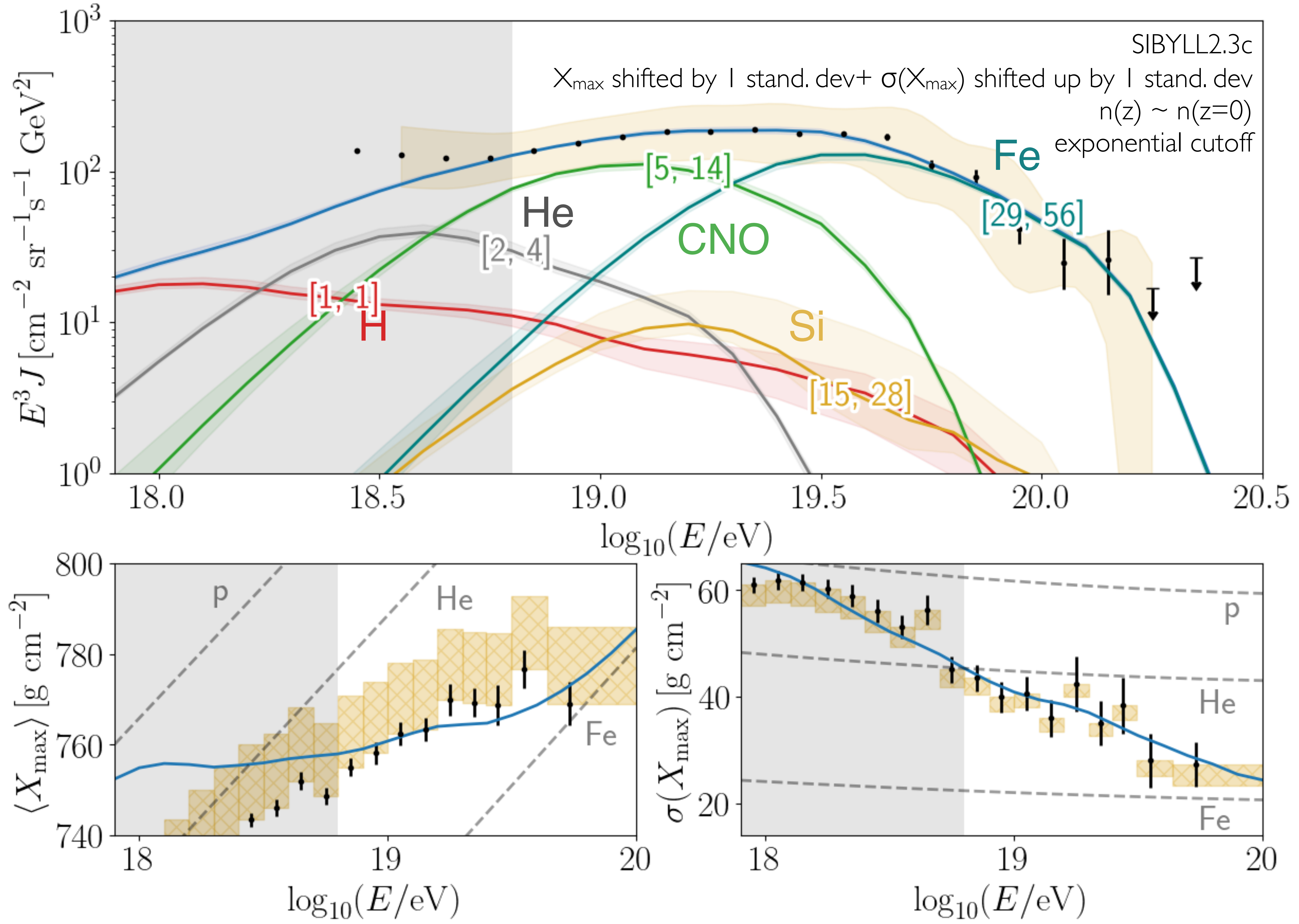




Ehlert, FO, Unger, PRD 107 (2023) 10

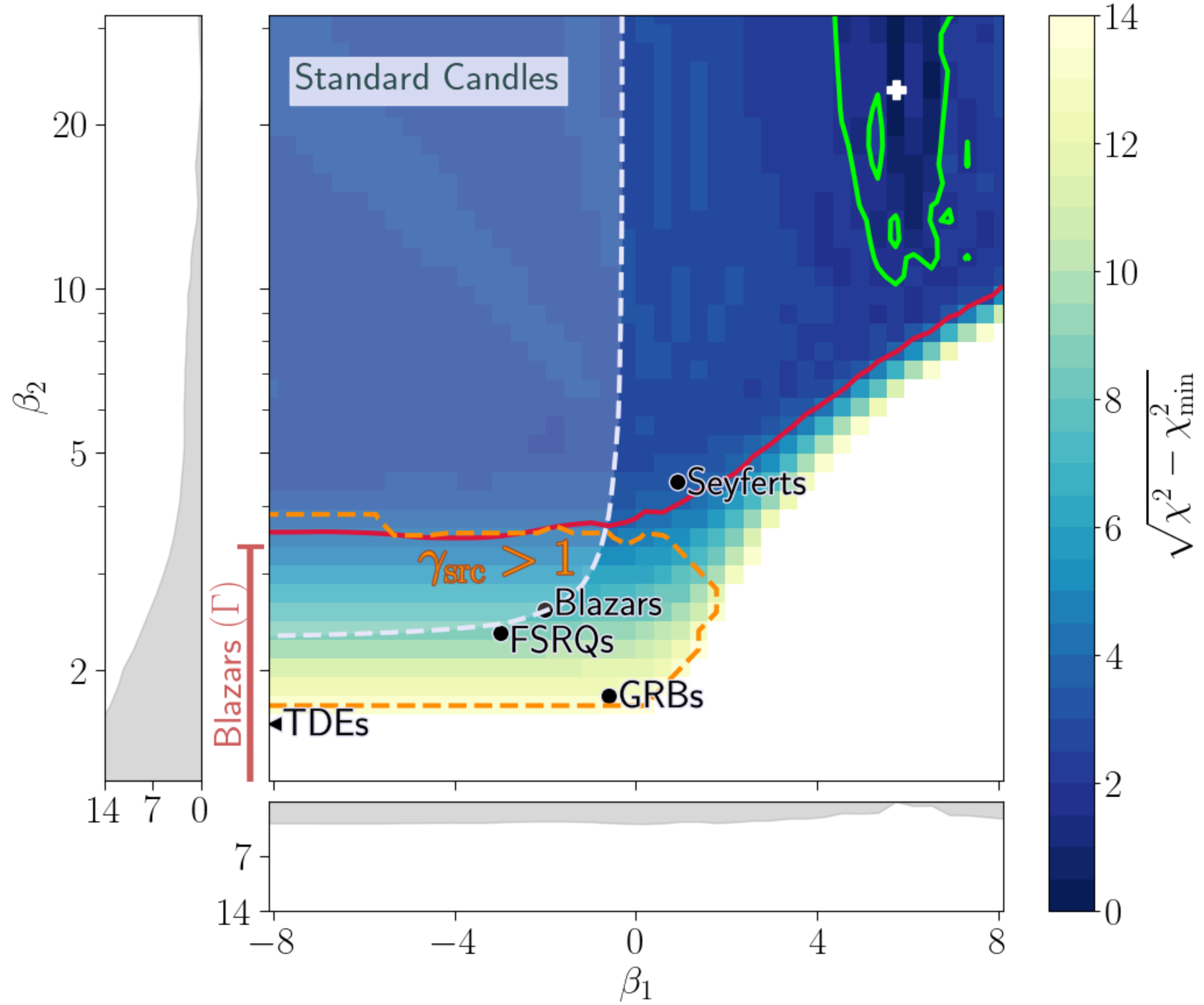
Jetted AGN: Variety problem?



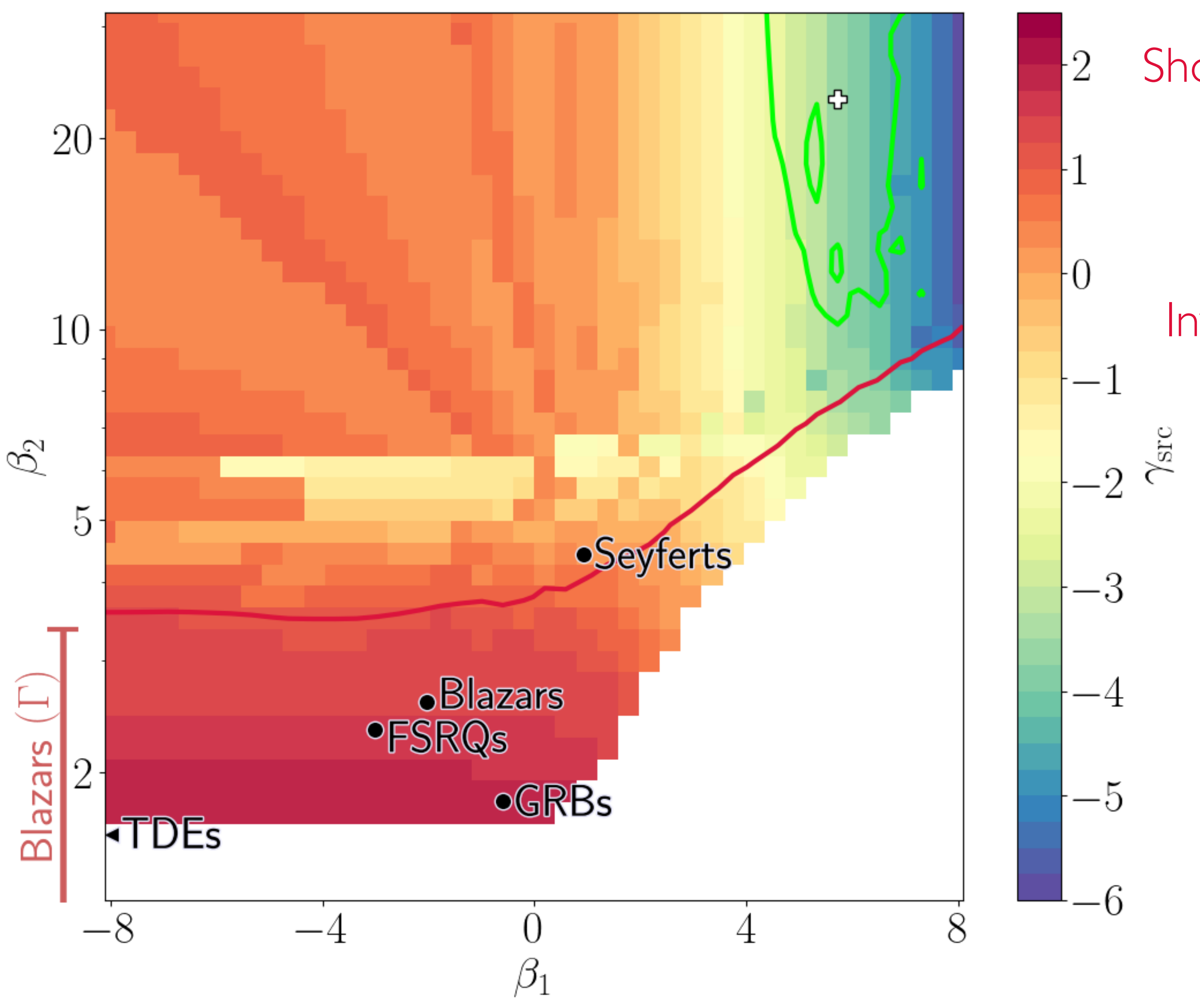


Ehlert, FO, Unger, PRD 107 (2023) 10

Jetted AGN: Variety problem?

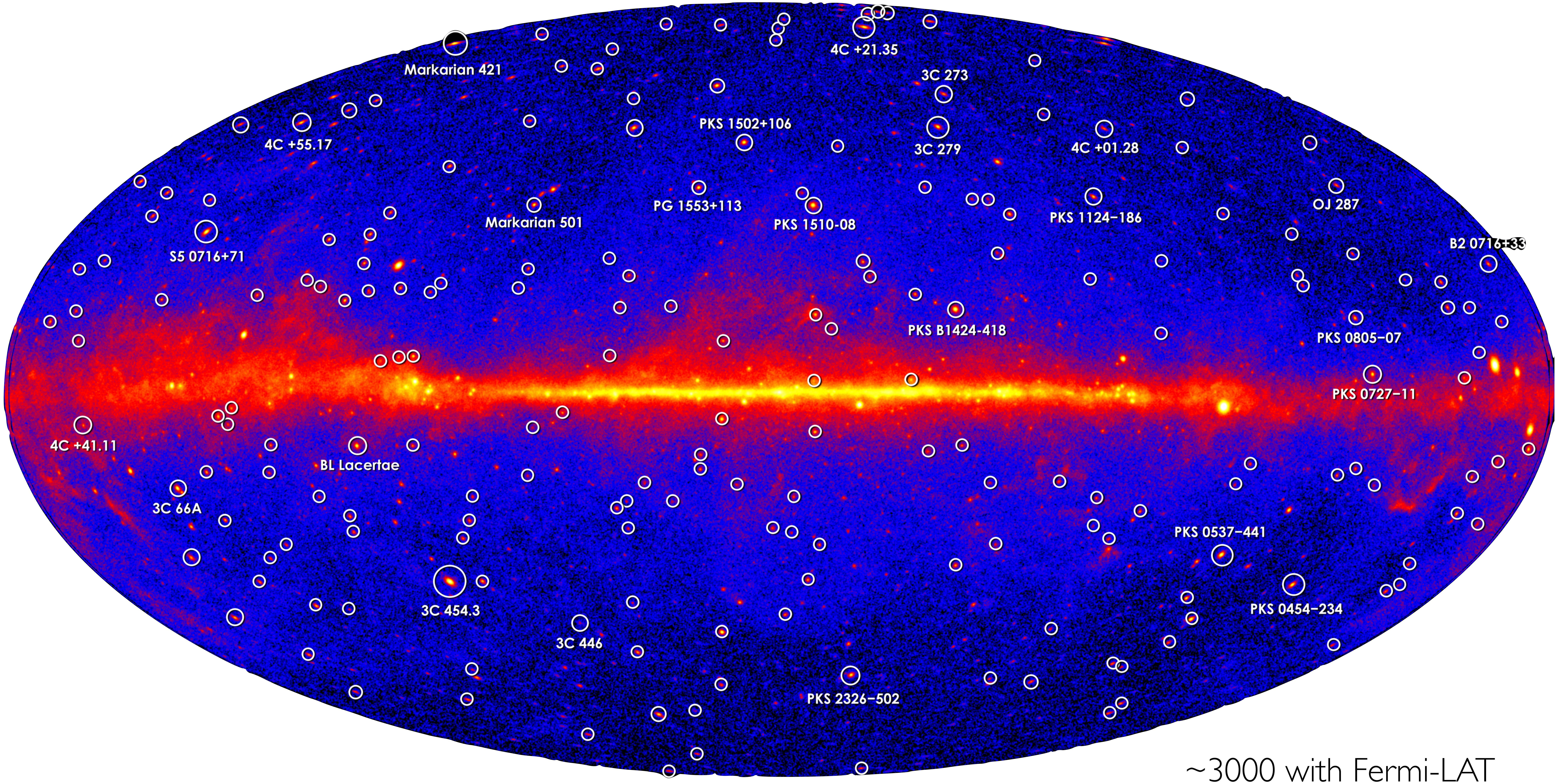


Individual source energy spectral index



$$\mathrm{d}N/\mathrm{d}R_{\max} \propto \begin{cases} \left(\frac{R_{\max}}{R_0}\right)^{-\beta_1} & R_{\max} < R_0 \\ \left(\frac{R_{\max}}{R_0}\right)^{-\beta_2} & R_{\max} > R_0 \end{cases}$$

Neutrinos from jetted AGN: Blazars

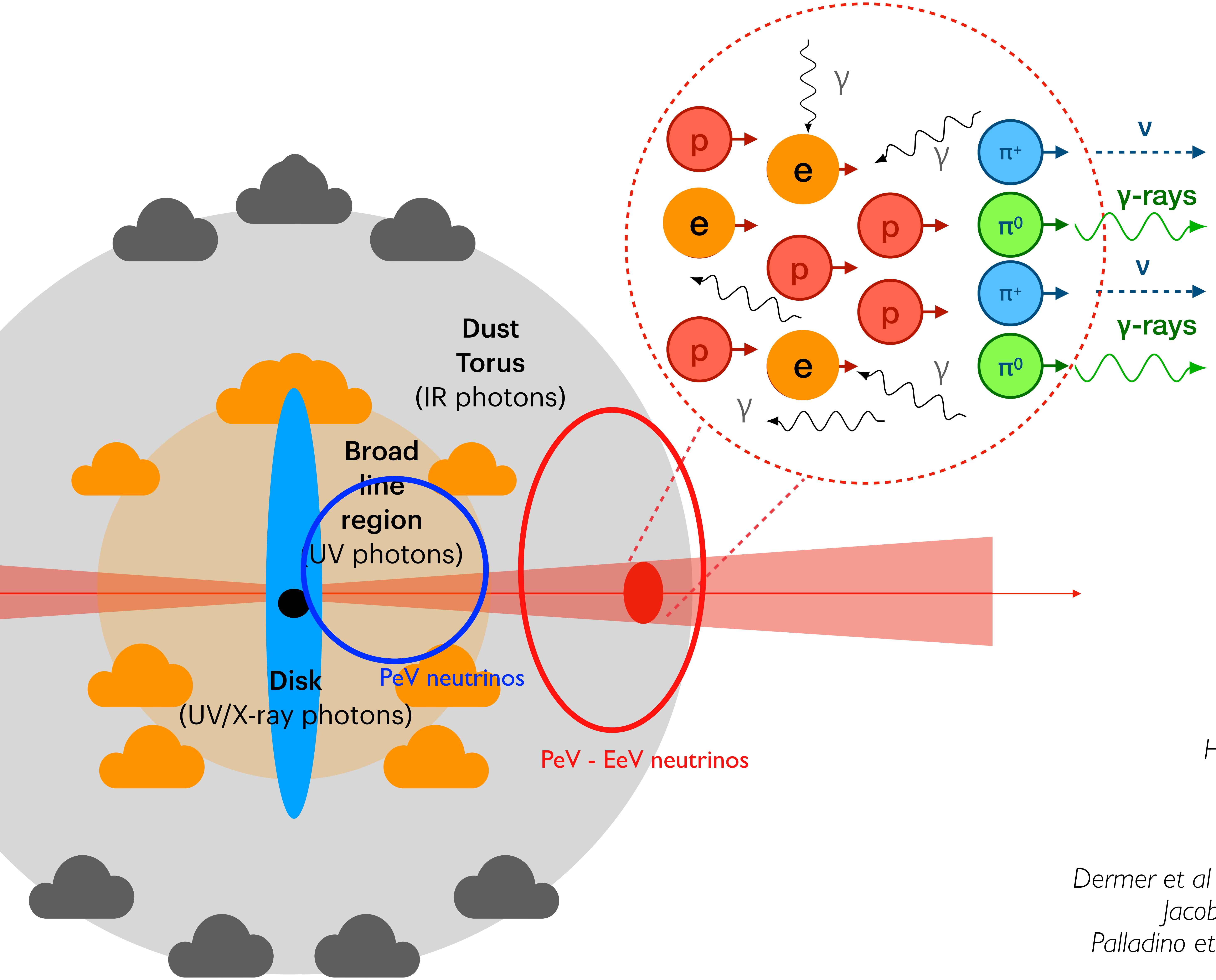


~3000 with Fermi-LAT

~10000 blazars detected with radio/IR surveys

Benefit from relativistic boost + flares (timing)

Neutrino production in blazars



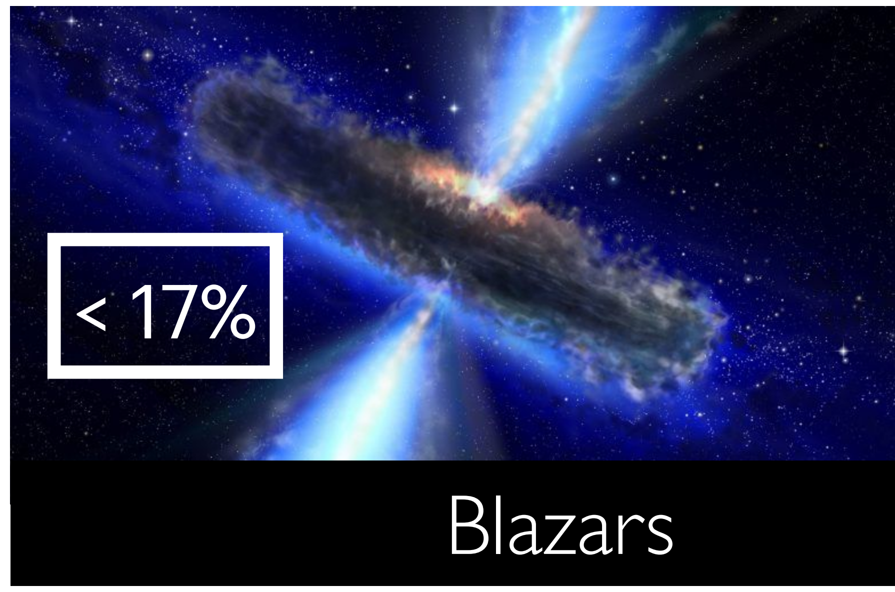
TXS 0506+056 observations:
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018,
MAGIC Coll. Astrophys.J. 863 (2018) L10
IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)

TXS 0506+056 modelling:
MAGIC Coll 2018, ApJ, 863, L10
Gao et al, 2019, Nat. Astron., 3, 88
Keivani et al. 2018, ApJ, 864, 84
Cerruti et al 2018, MNRAS, 483, 1
FO et al 2019, MNRAS, 489, 3

hadro-nuclear interactions: *Liu+19*
stellar disruption: *Wang+19*
multiple zones: *Xue+(inc FO)19*
neutron beam: *Zhang+(inc FO)19*
curved/double jet: *Britzen+19, Ros+19*
inefficient accretion flow: *Righi+19*
gamma-suppressed states: *Kun+21*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20, and more…!

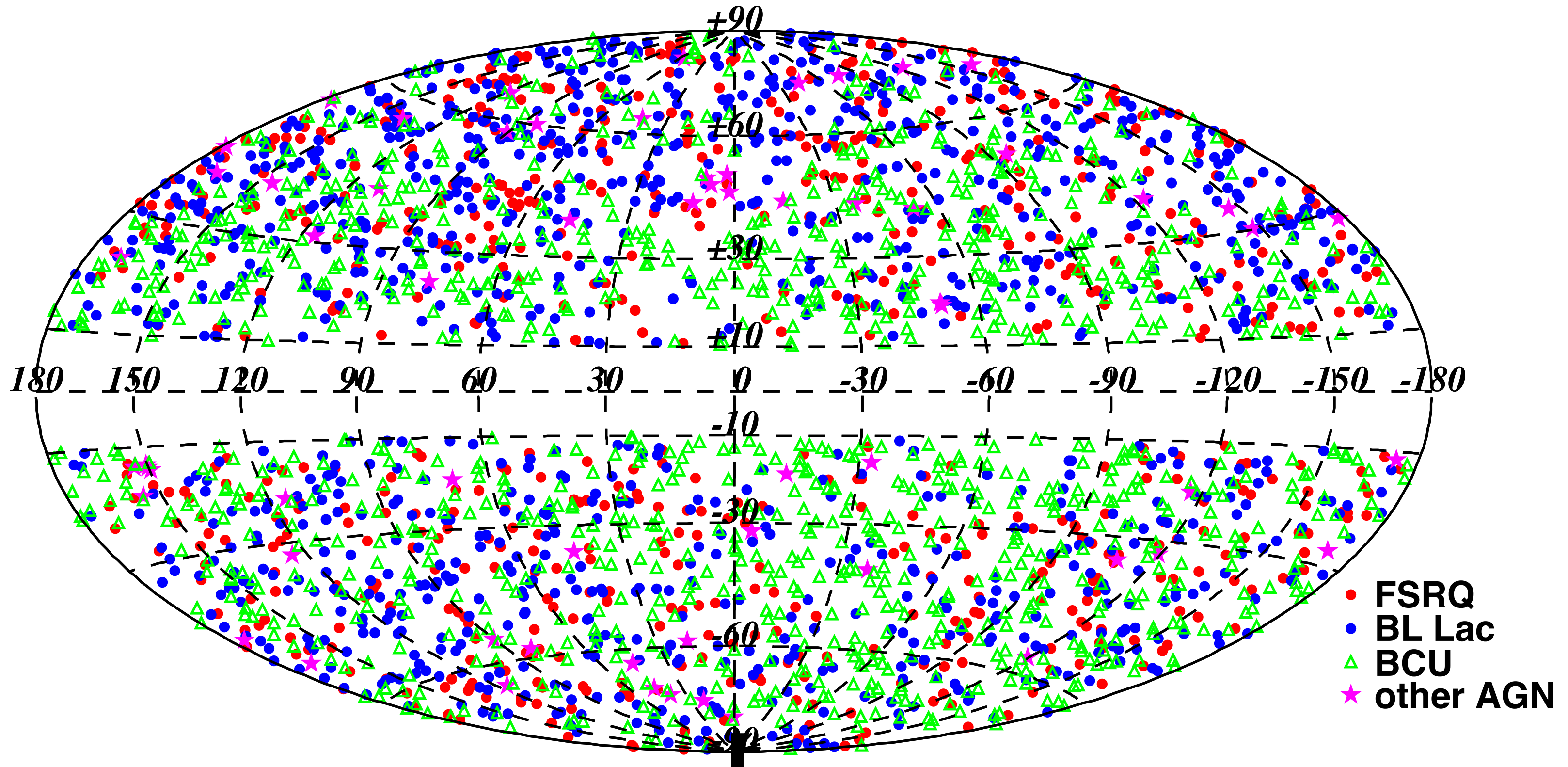
Neutrino production in blazars :
e.g. Mannheim 1991, 1993,
Halzen & Zas 1997, Mücke 2001, 2003, Atoyan & Dermer 2001, 2004,
Neronov, Semikoz 2002, Dermer et al 2006, Kachelriess et al 2009,
Neronov et al 2009, Böttcher 2013, Dermer, Cerruti 2013,
Cerruti et al 2013, Tchernin et al 2013, Murase et al. 2012, 2014,
Dermer et al 2014, Tavecchio et al 2014, 2015, Petropoulou et al 2014, 2015,2016,
Jacobsen 2015, Padovani 2015, Gao et al 2017, Rodrigues et al 2017, 2020,
Palladino et al. 2019, FO et al 2019 , 2021, Righi et al 2020, Rodrigues et al 2021

Blazar contribution to the cosmic-neutrino flux

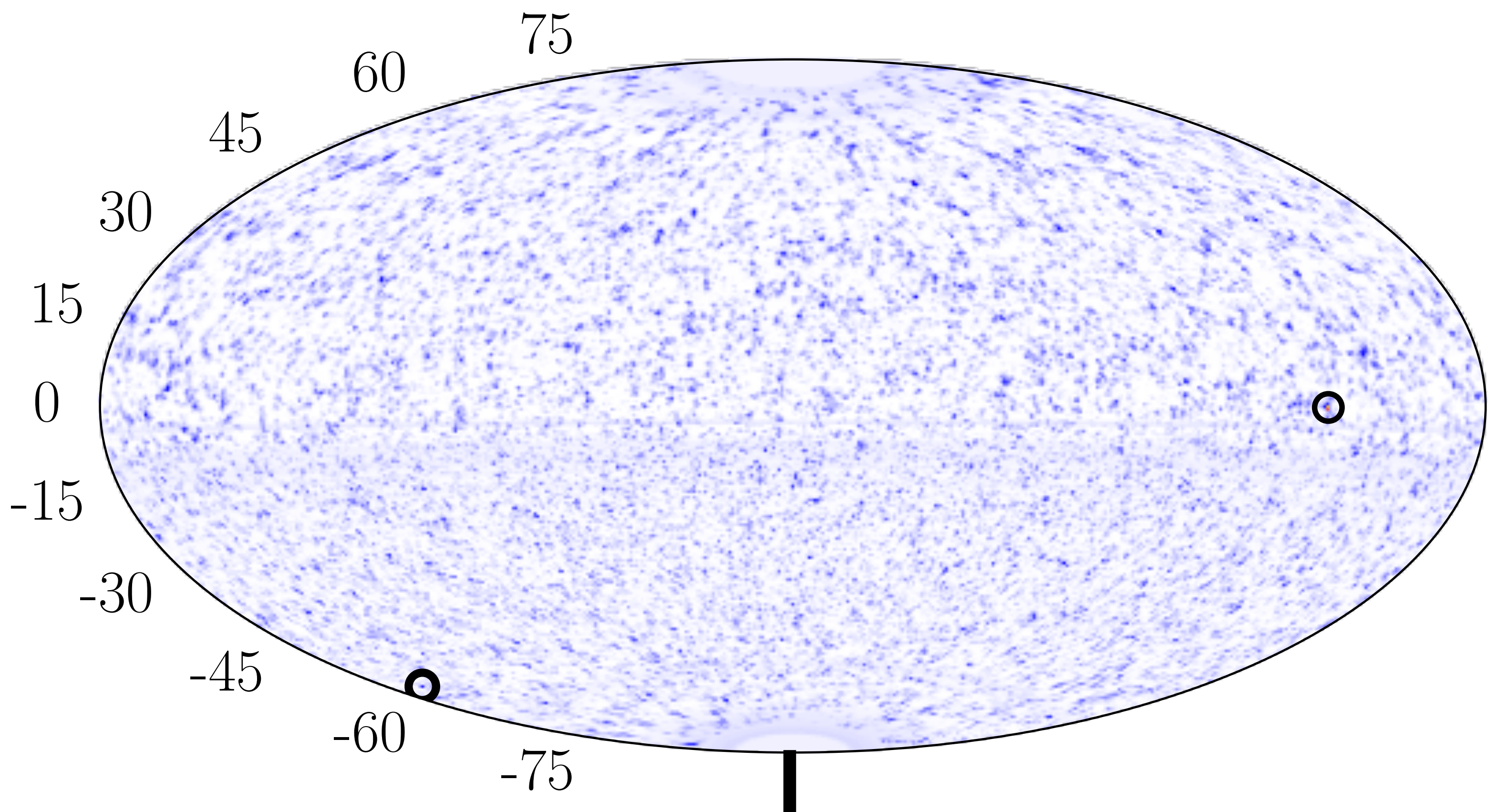


Stacked search for
neutrinos coincident with
2089 γ-ray selected blazars
3413 radio selected

Blazar sky-map



IceCube Point-Source Events



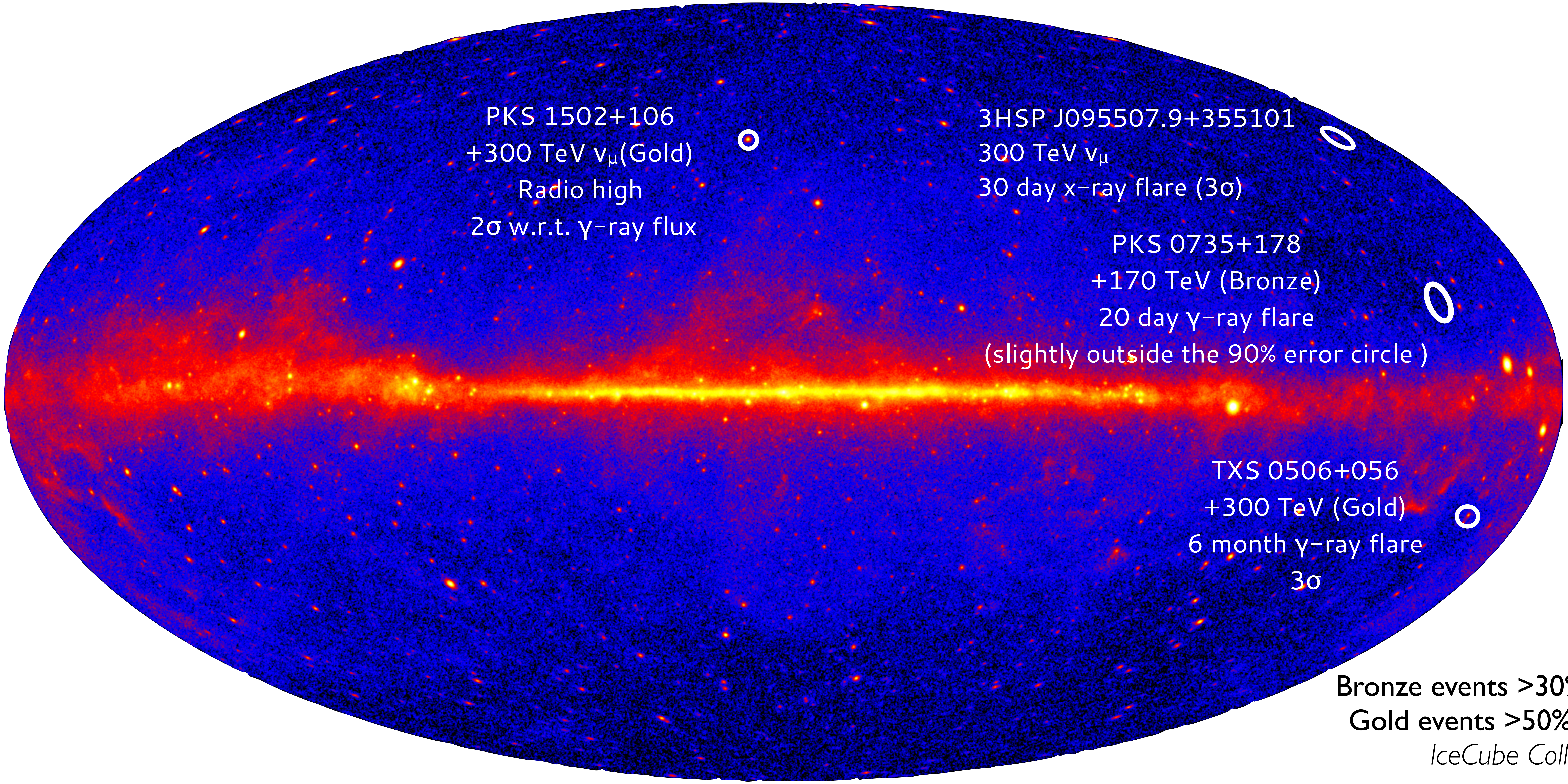
< 17% diffuse neutrino flux

See also:

IceCube Coll 10yr Point-Source Analysis (3 blazars),
Franckowiak et al ApJ 893 (2020),
Giommi et al MNRAS 497 (2020)
Hovatta et al A&A 650 (2021), Plavin et al ApJ 908 (2021), Buson et al ApJL (2022)

IceCube Coll PoS (ICRC 2019) 916
IceCube Coll arXiv: 2304.12675

Blazars coincident with high-energy neutrinos



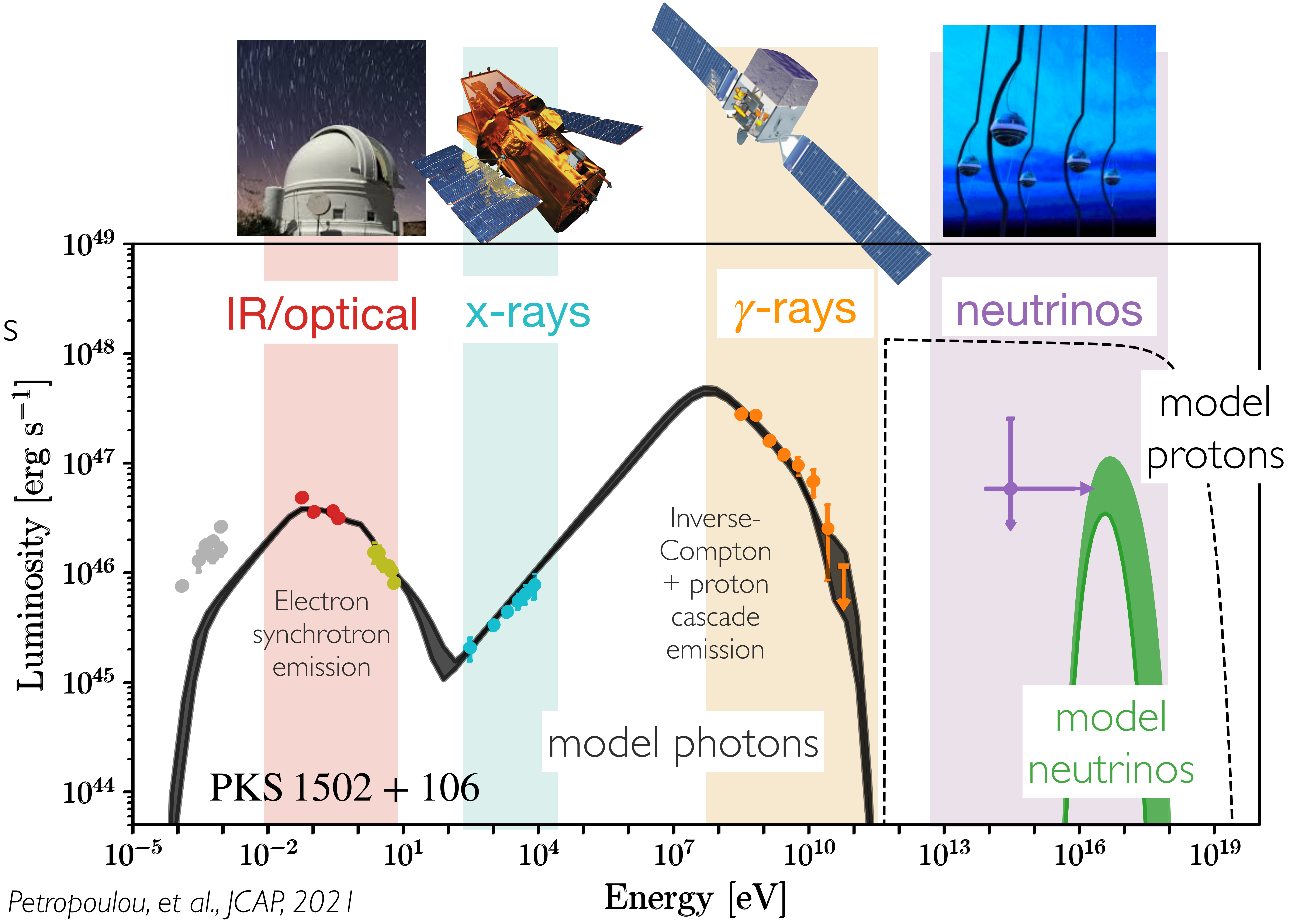
Bronze events >30% "signalness"
Gold events >50% "signalness"
IceCube Coll 2019

3HSP J095507.9+355101: *Petropoulou, FO et al. 2021, Paliya et al 2021*
PKS 1502+106: *Rodrigues et al 2021, Britzen et al 2021, FO et al 2021, Wang & Xue 2021, Kun et al ApJL 2021*

PKS B1424-418+IC35 *Kadler, Nat Phys 2016, Gao, Pohl, Winter, ApJ 843 2017, Kun et al ApJL 2021*
PKS 0735+178 + 211208A *Sahakyan et al MNRAS 2022, Fichet de Clairefontaine et al 2023*

The power of multimessenger modelling

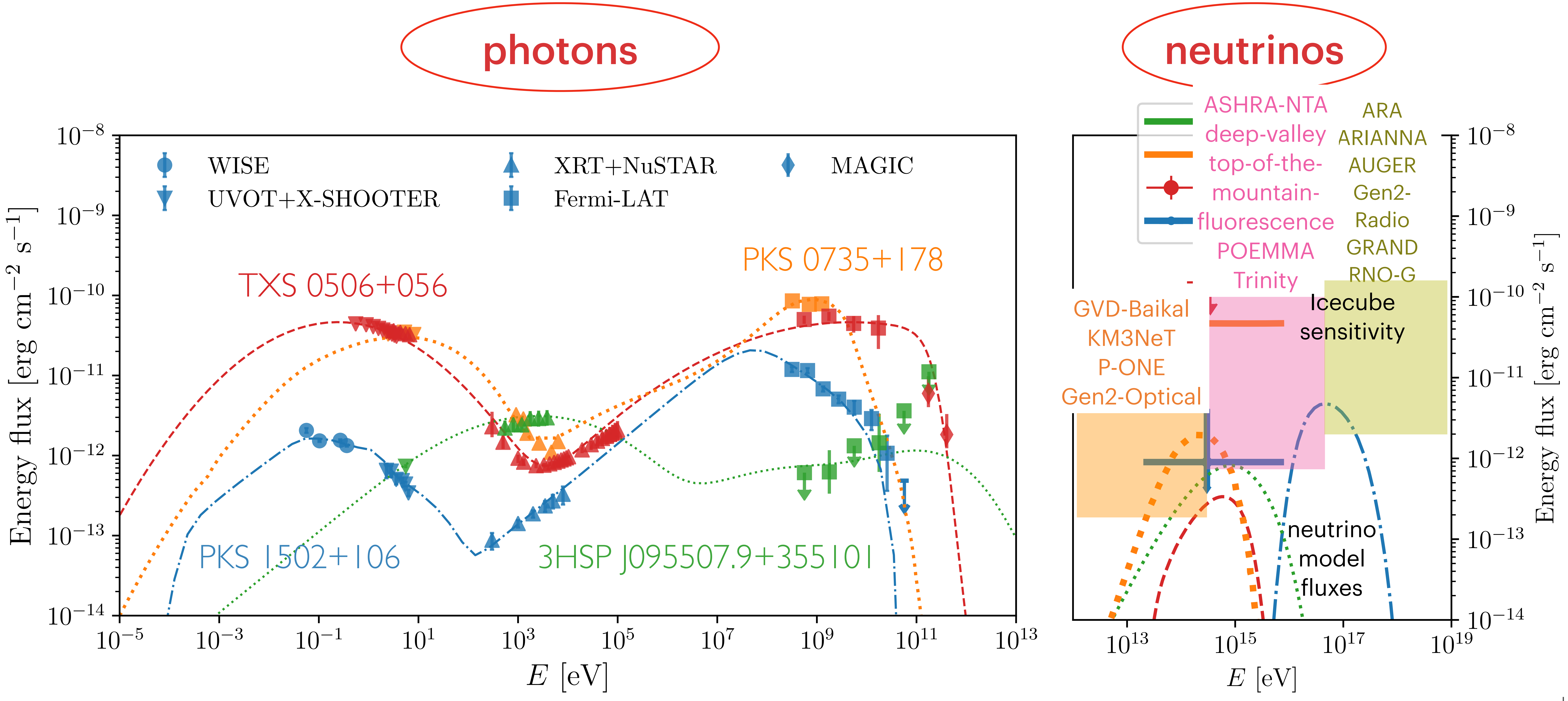
Radiation processes
+ particle interactions



FO, Petropoulou, et al., JCAP, 2021

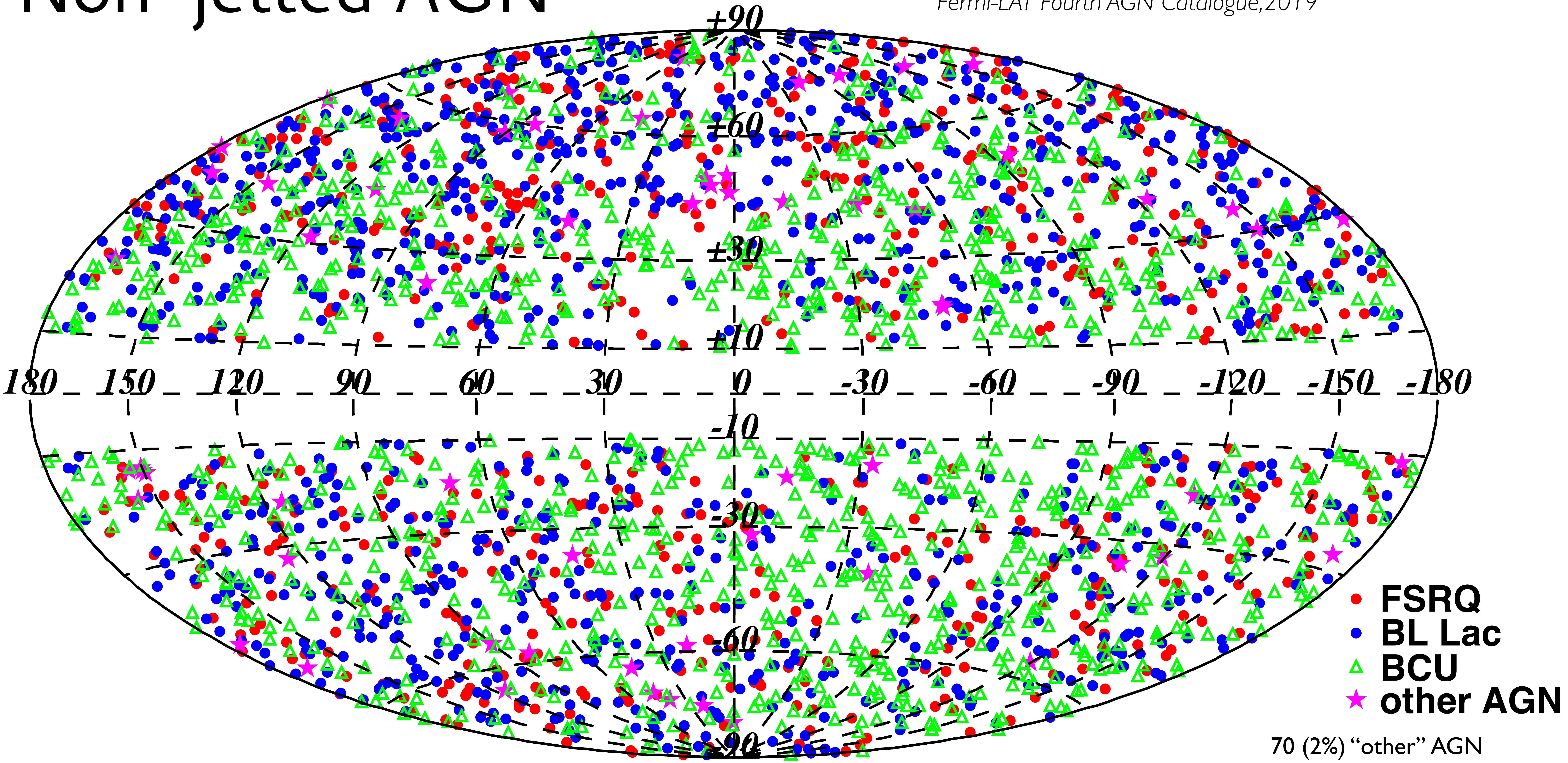
Blazars coincident with high-energy neutrinos

FO et al 2019
Petropoulou, FO et al 2021
FO et al 2021
Sahakyan et al 2022



Non-jetted AGN

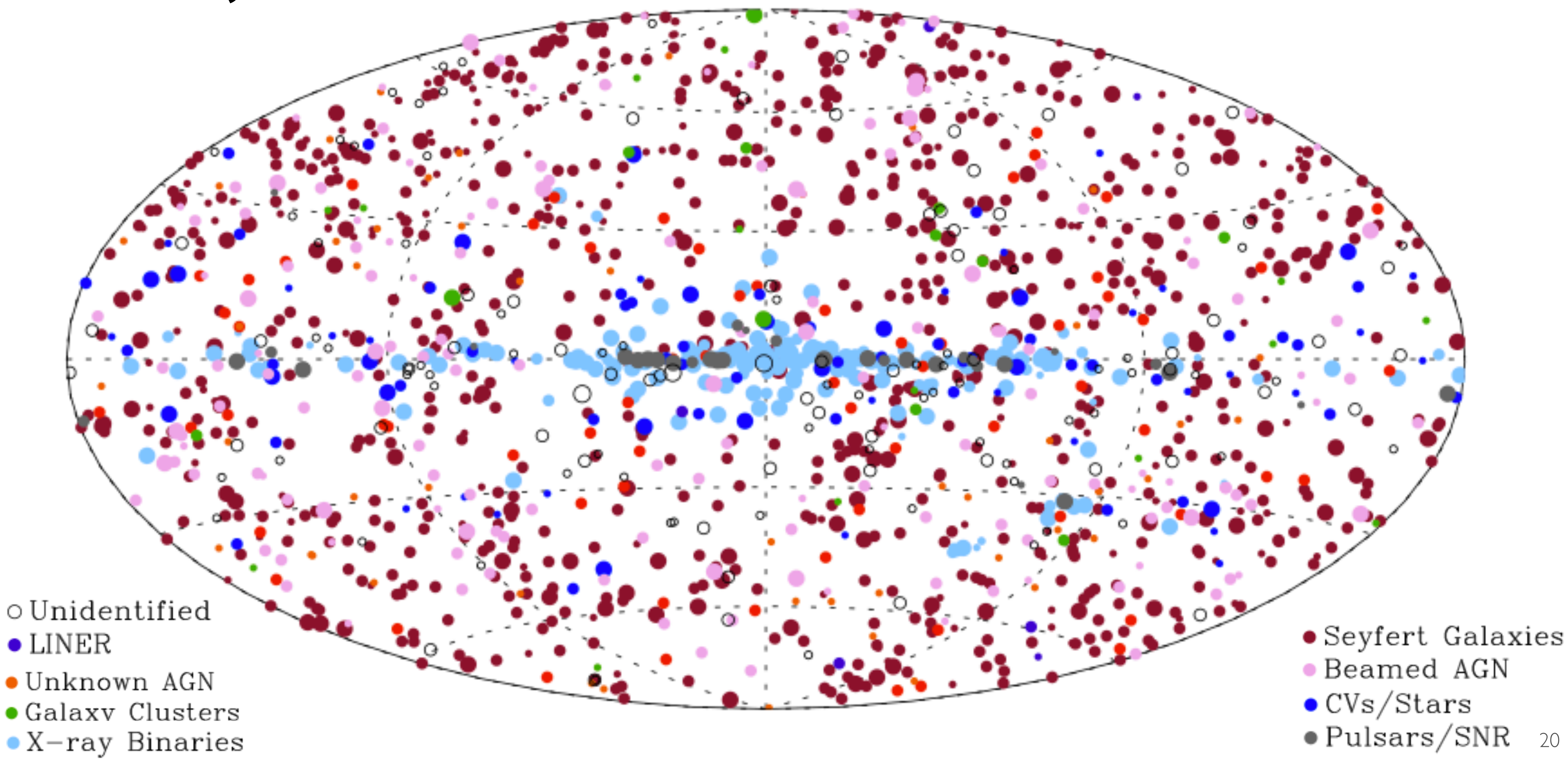
Fermi-LAT Fourth AGN Catalogue, 2019



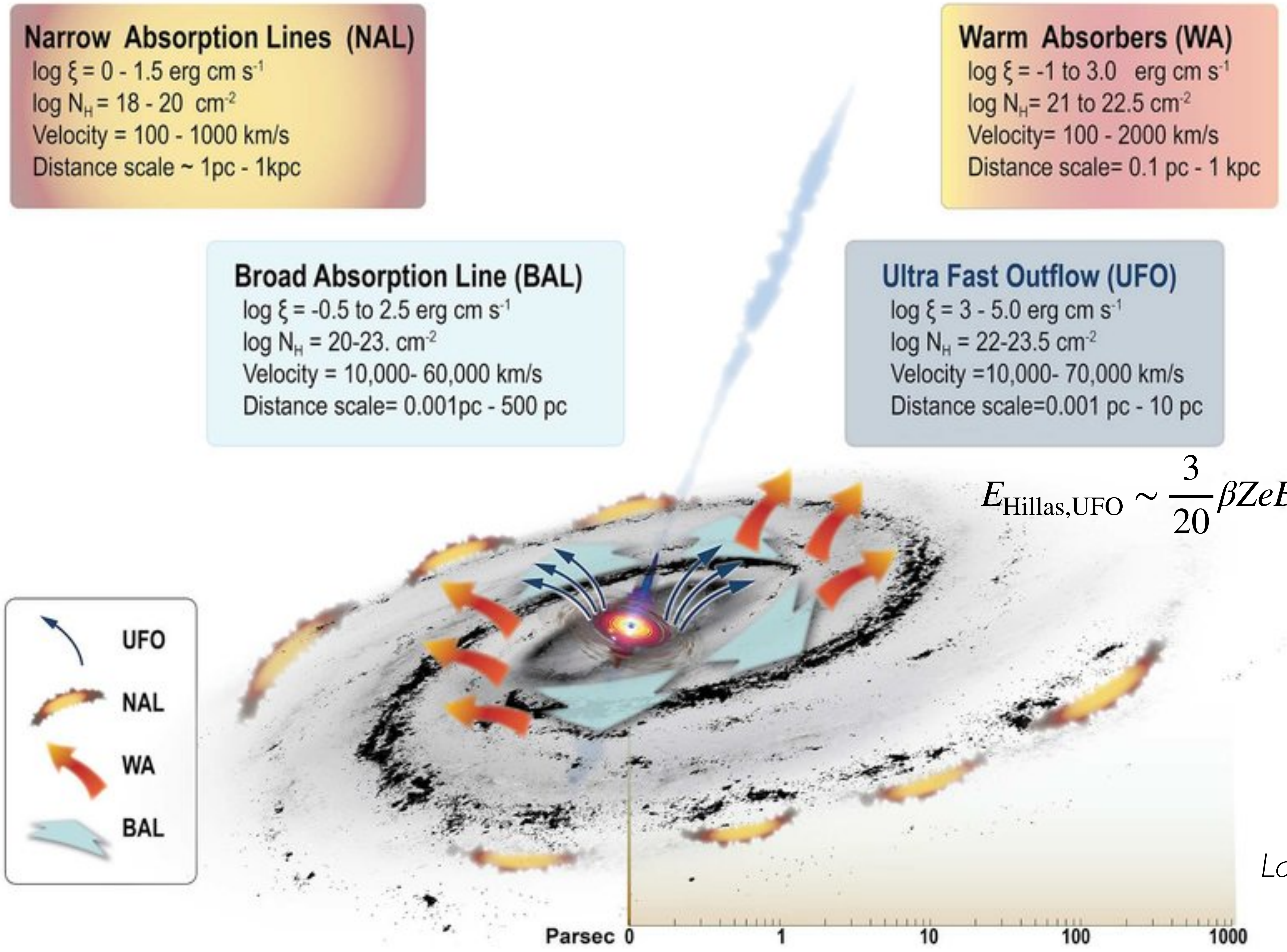
70 (2%) “other” AGN
~10 non-jetted AGN

Non-jetted AGN

Swift-BAT 105-month hard-X-ray catalogue 2018



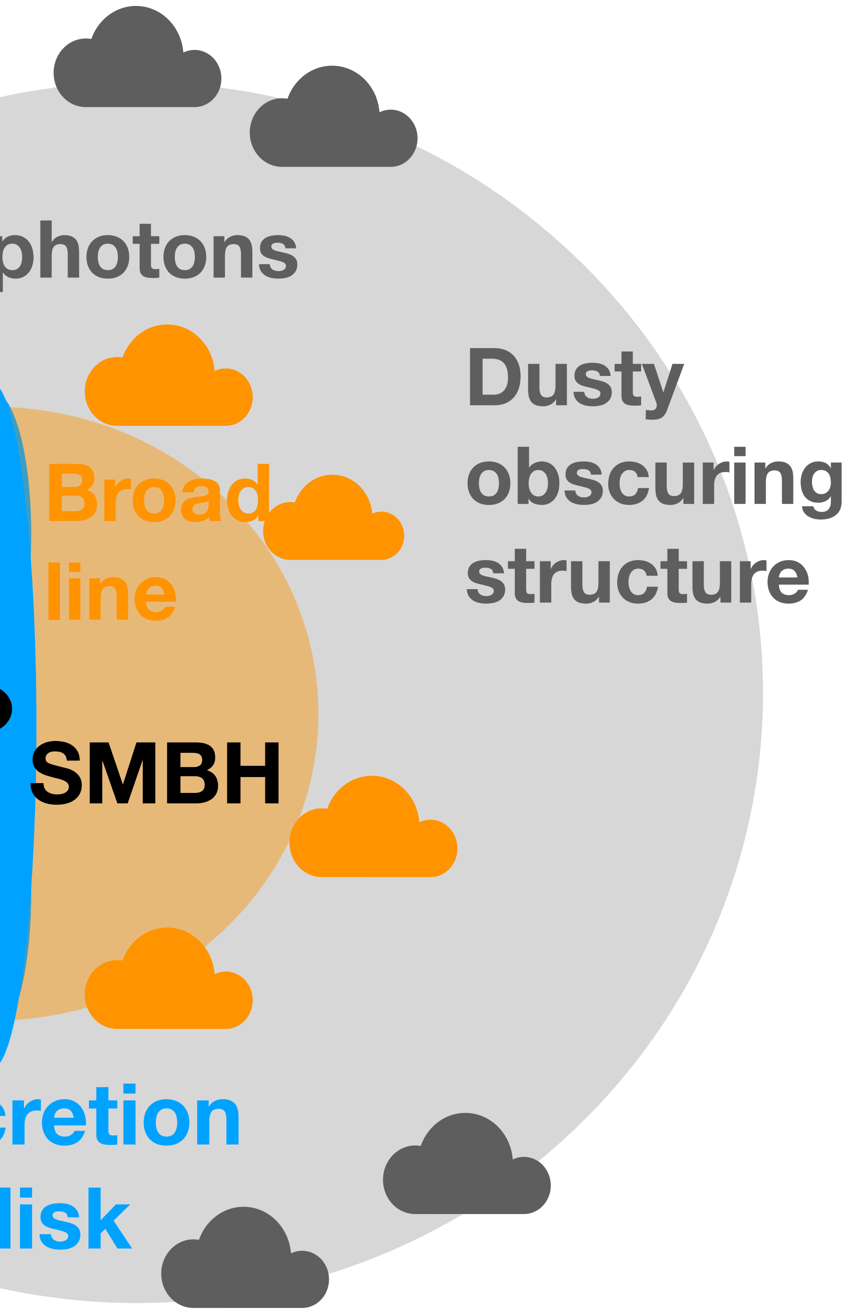
Cosmic ray acceleration in non–jetted AGN?



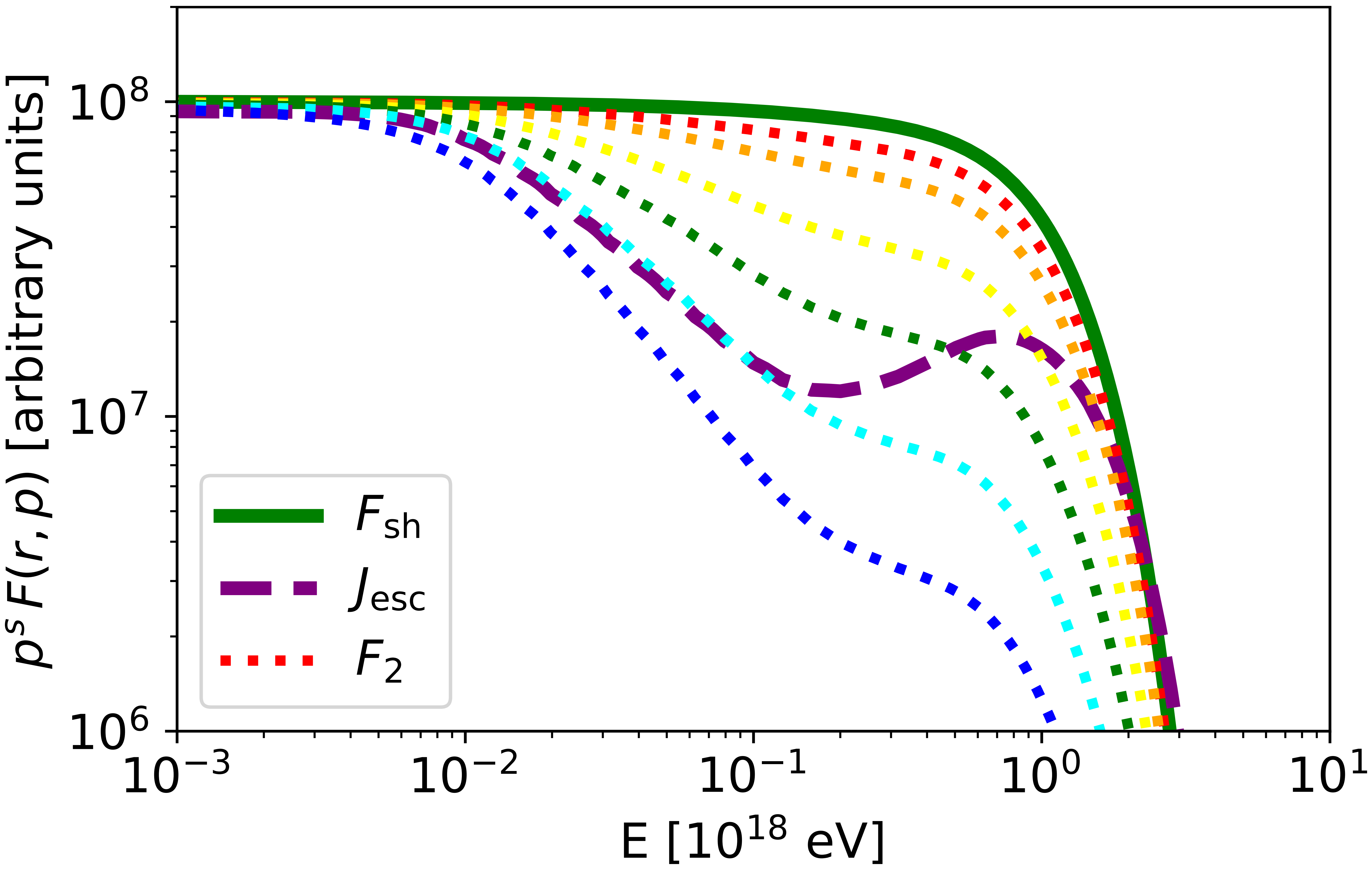
$$E_{\text{Hillas,UFO}} \sim \frac{3}{20}\beta ZeB'\Gamma R' \sim Z \cdot 10^{19}\ \text{eV}$$

Laha et al 2022

UFOs: Energy losses limit maximum energy



Peretti et al 2023

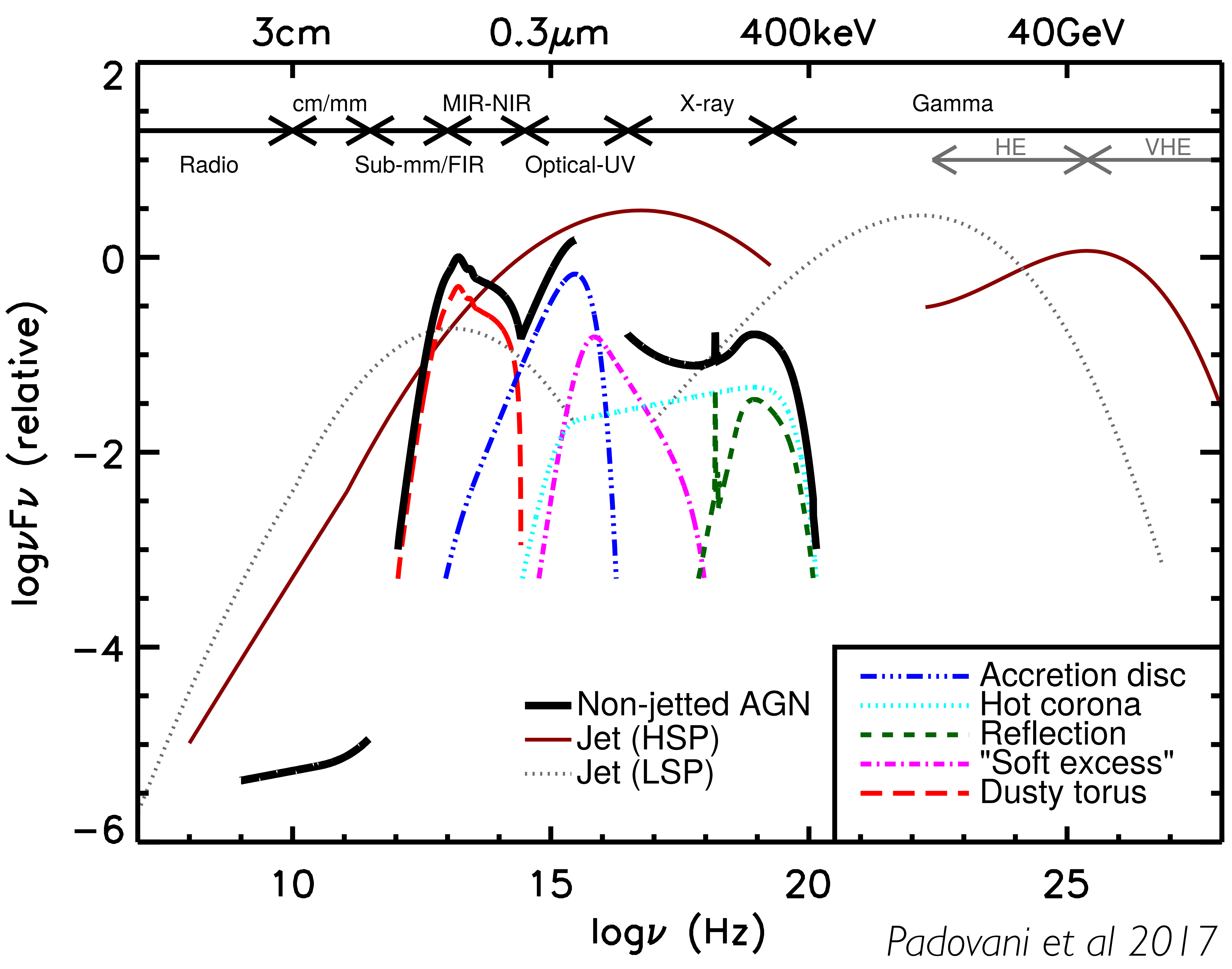


Nuclei could in principle reach

$$Z \times E_p \approx Z \times 10^{18} \text{ eV}$$

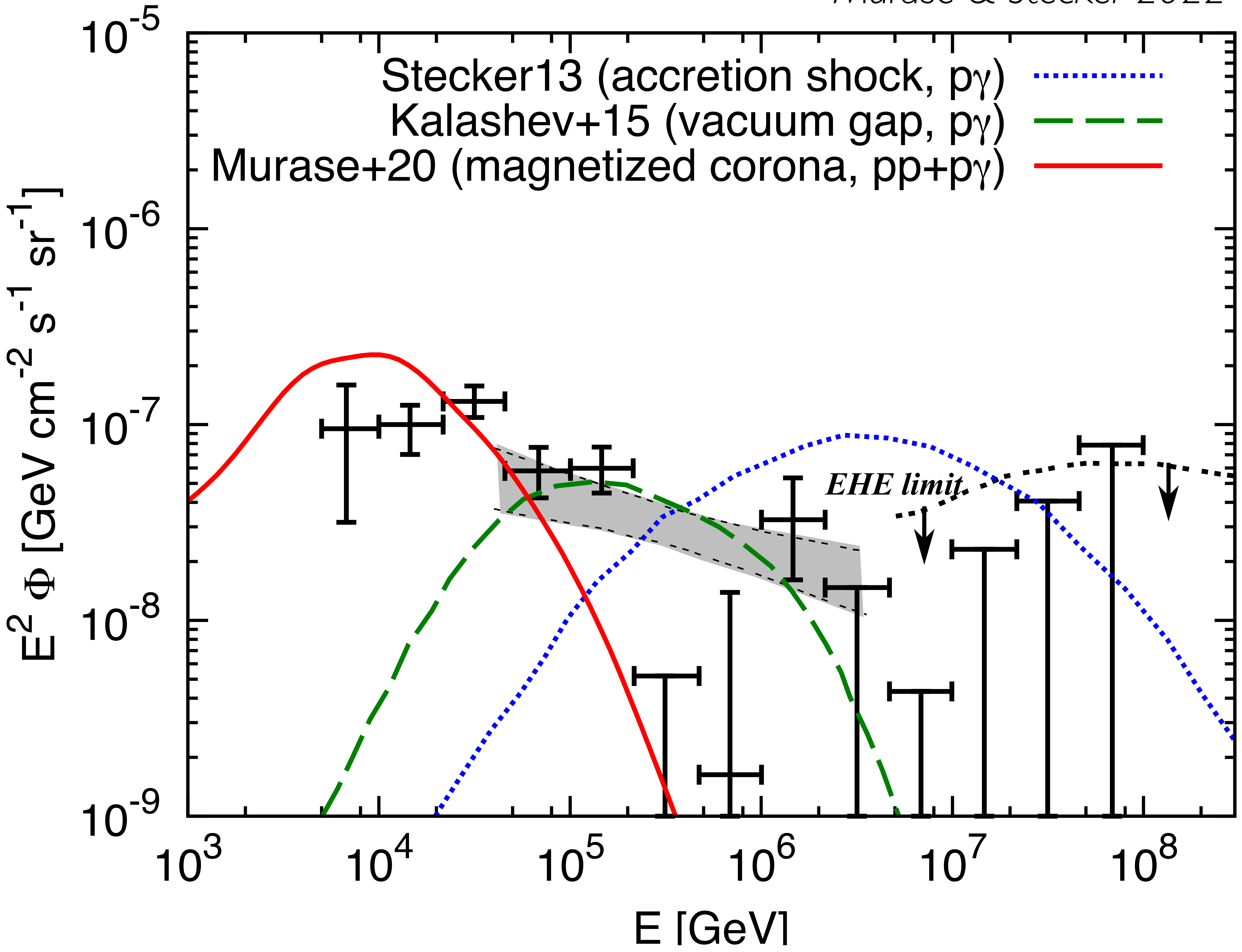
but are also limited by energy losses *(Ehlert, FO, Peretti in prep)*

High-energy neutrinos from Seyfert galaxies

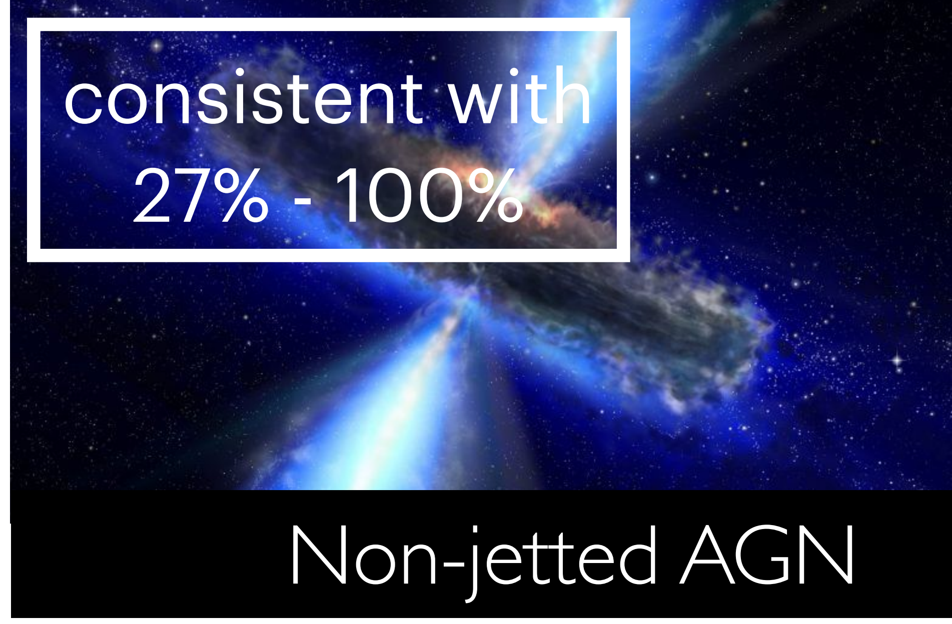


Padovani et al 2017

Murase & Stecker 2022



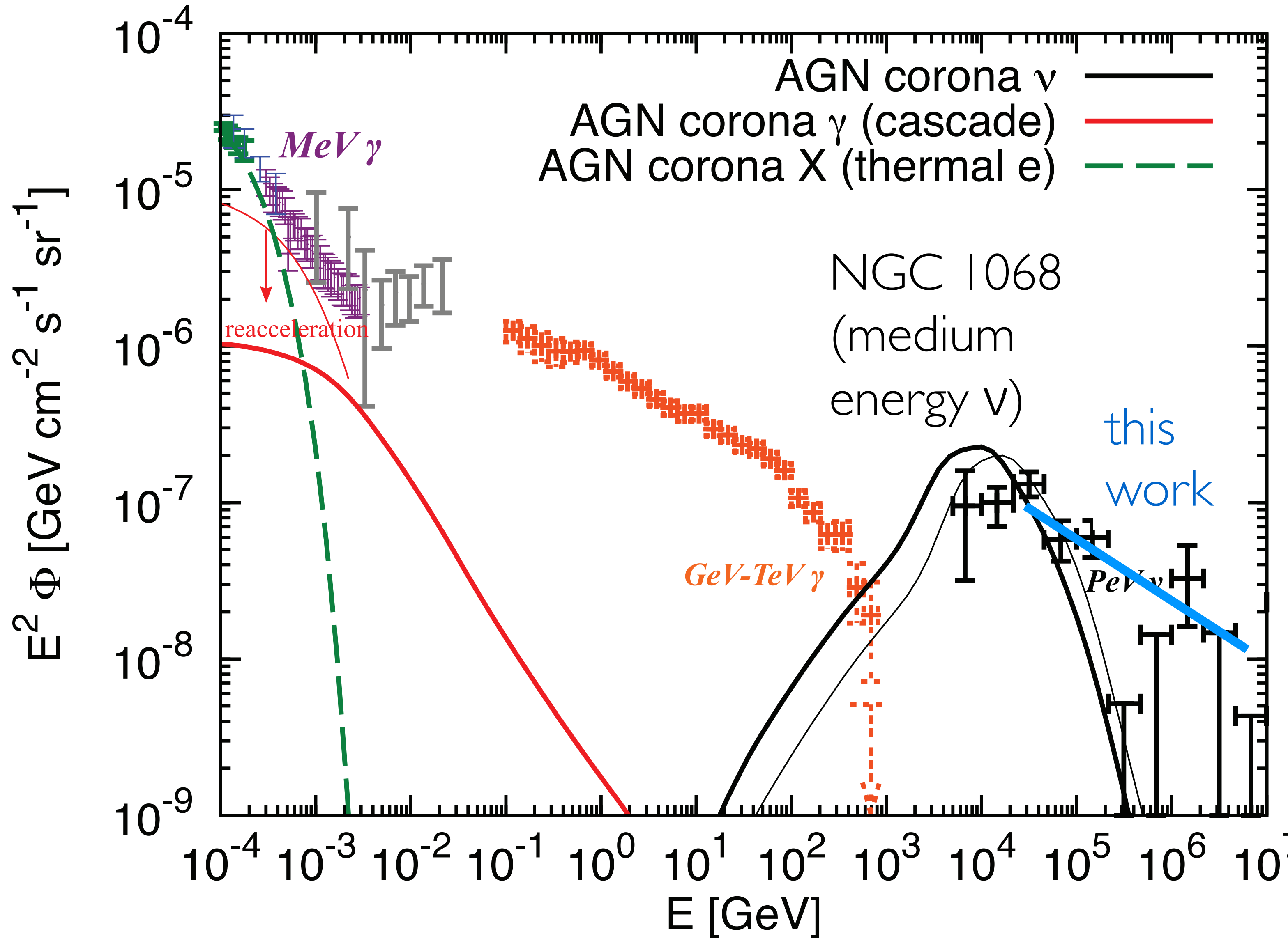
Non-jetted AGN contribution to the cosmic-neutrino flux



Infrared selected (ALLWISE) AGN with soft-X-ray weights ~ 32,249 AGN

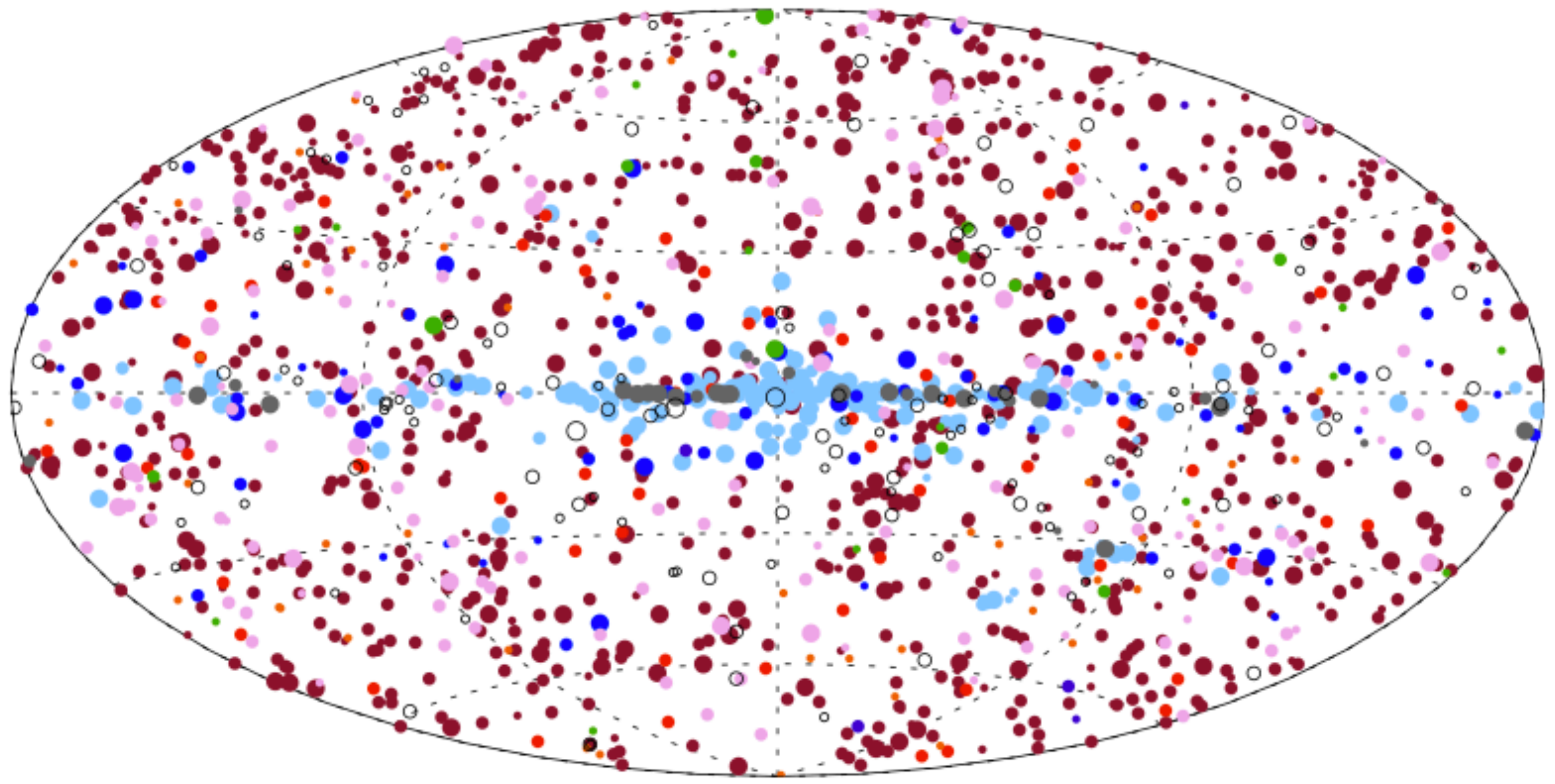
2.6σ excess w.r.t. background expectations

Best-fit spectral index $\frac{dN}{dE} \sim E^{-2}$

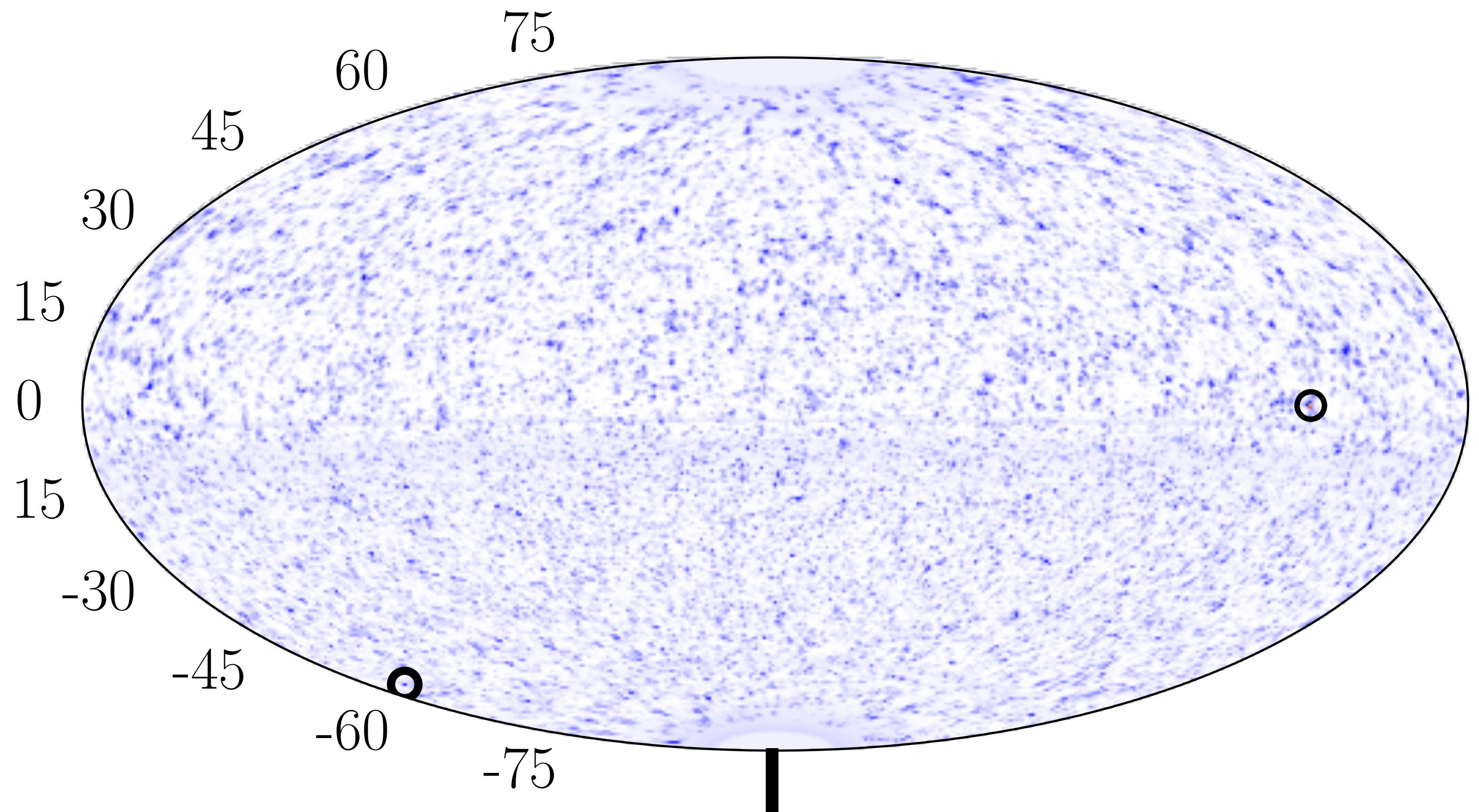


NB: Different energy range than NGC 1068

AGN sky-map



IceCube Point-Source Events

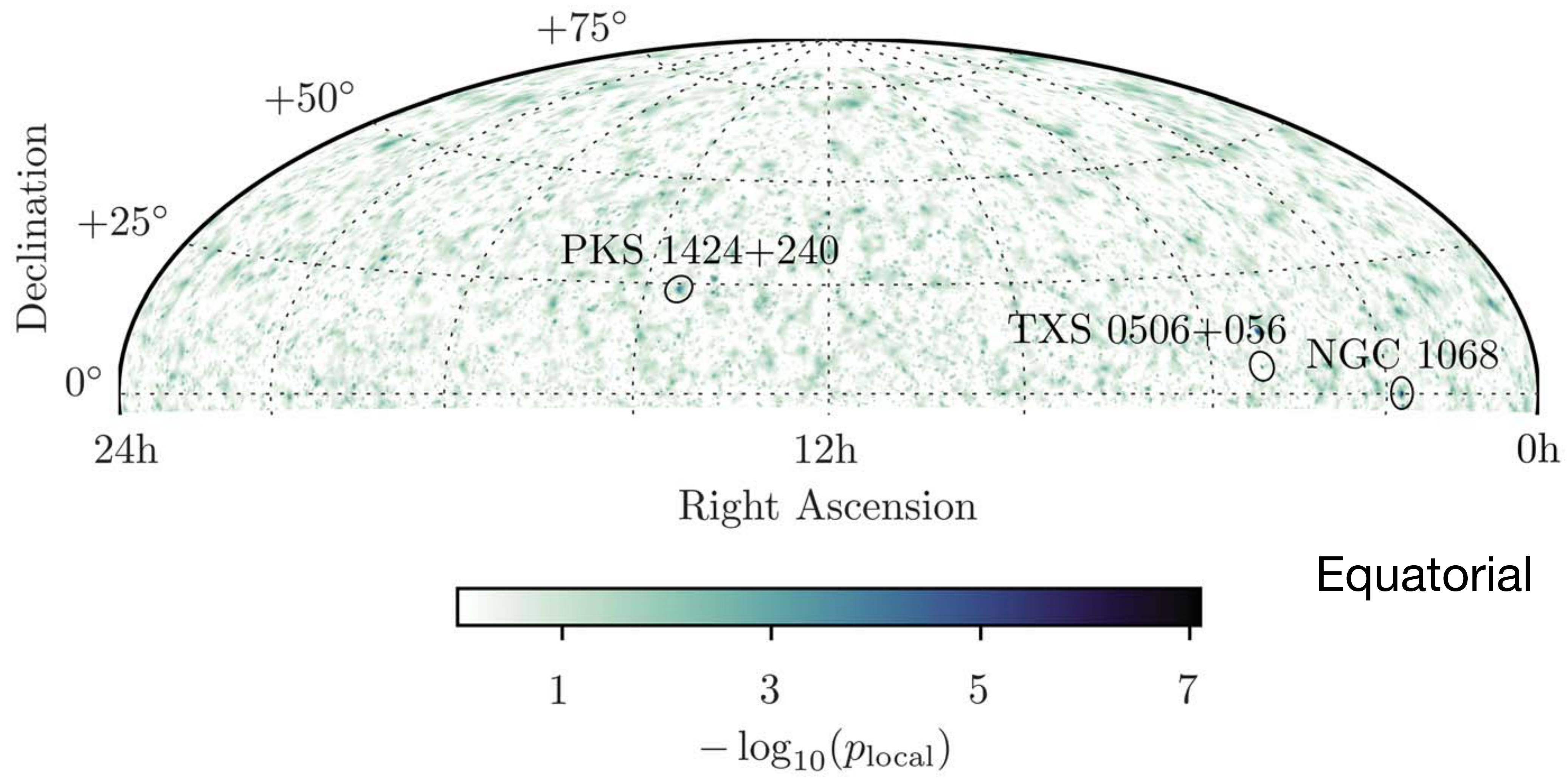


could account for 27-100% of diffuse neutrino flux at 100 TeV

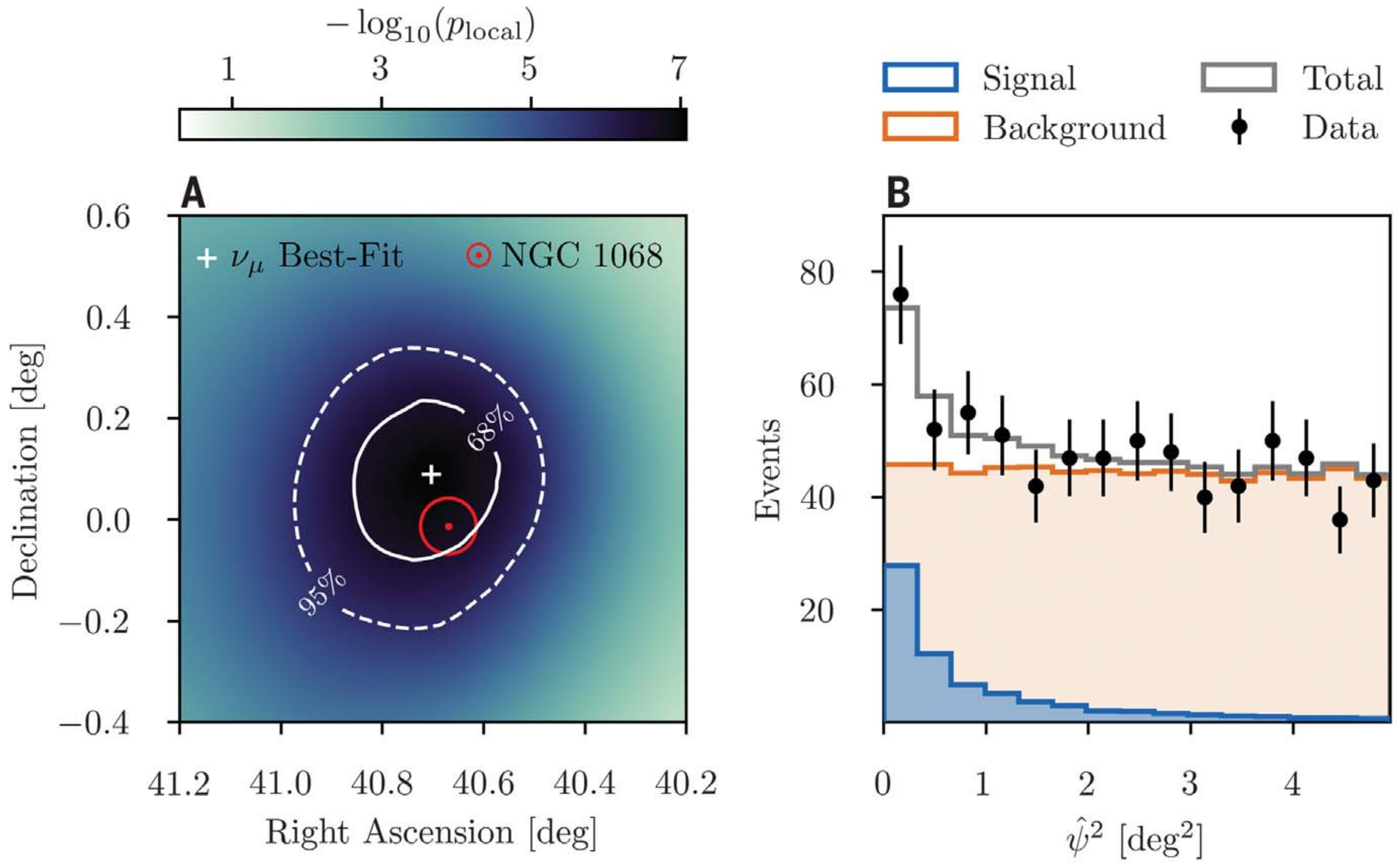
IceCube Coll 2022, PRD

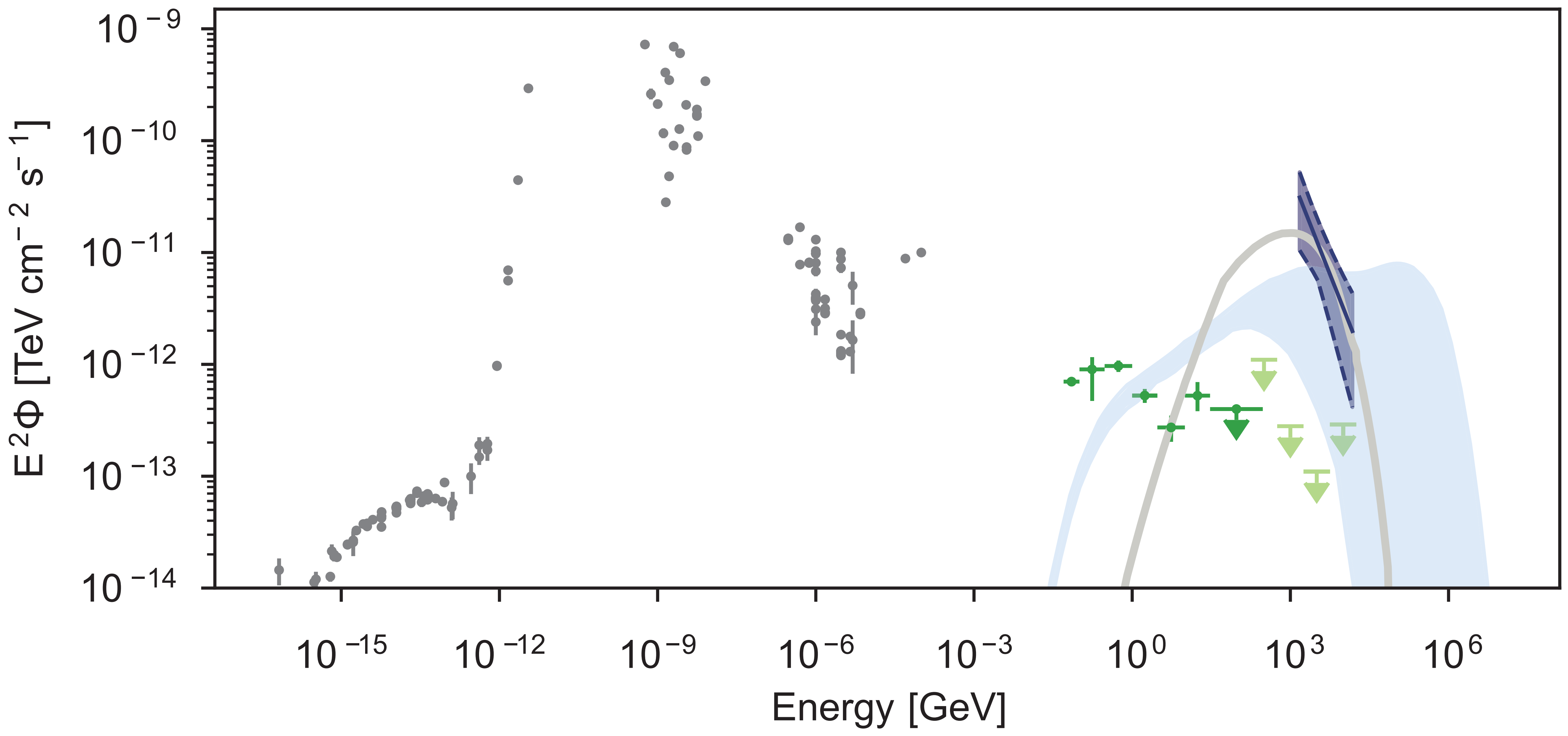
NGC 1068

Icecube Coll 2023 - Science



Test type	Pretrial *P* value, P_{local} (local significance)	Posttrial *P* value, P_{global} (global significance)
Northern Hemisphere scan	5.0×10^{-8} (5.3σ)	2.2×10^{-2} (2.0σ)
List of candidate sources, single test	1.0×10^{-7} (5.2σ)	1.1×10^{-5} (4.2σ)
List of candidate sources, binomial test	4.6×10^{-6} (4.4σ)	3.4×10^{-4} (3.4σ)

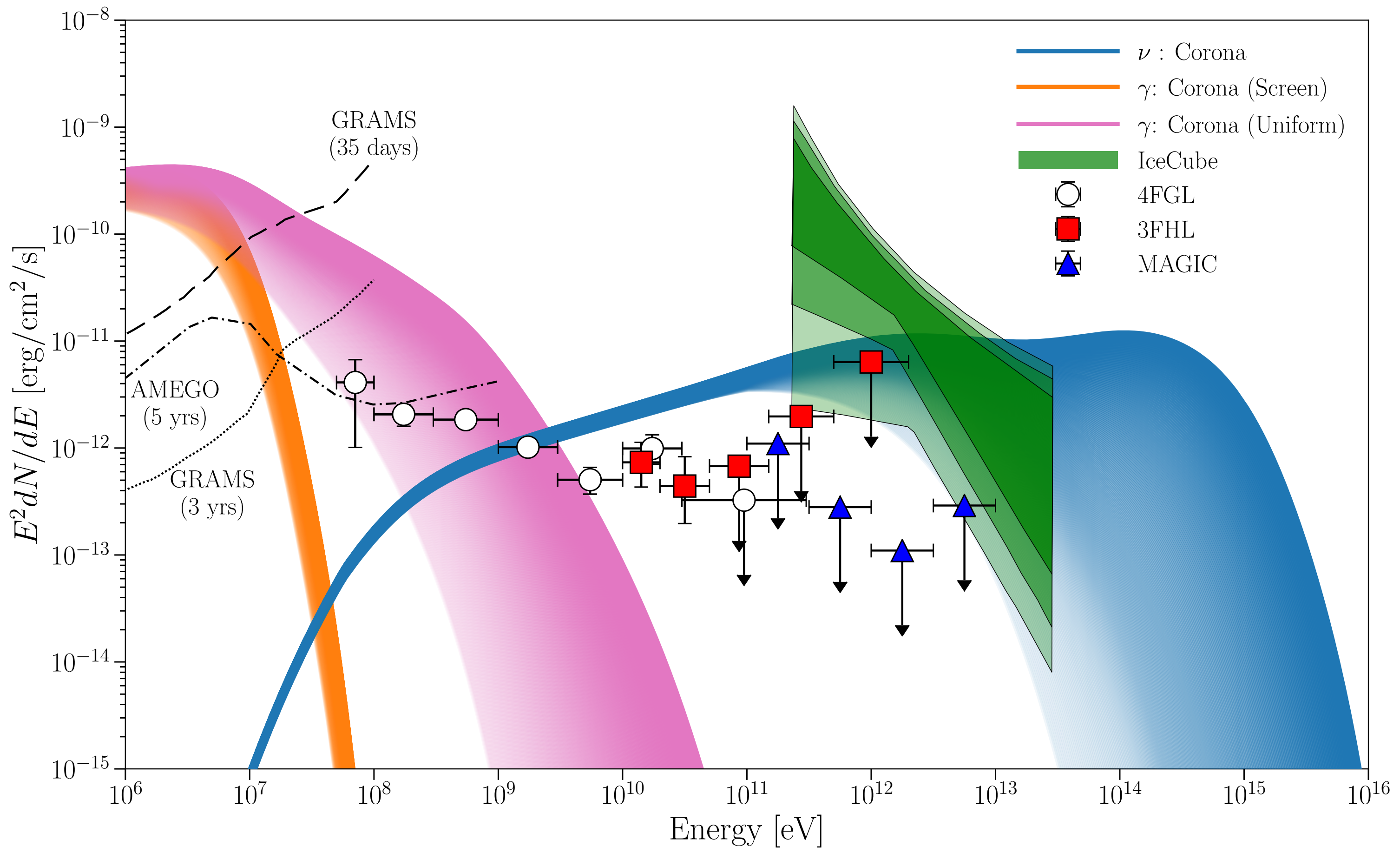




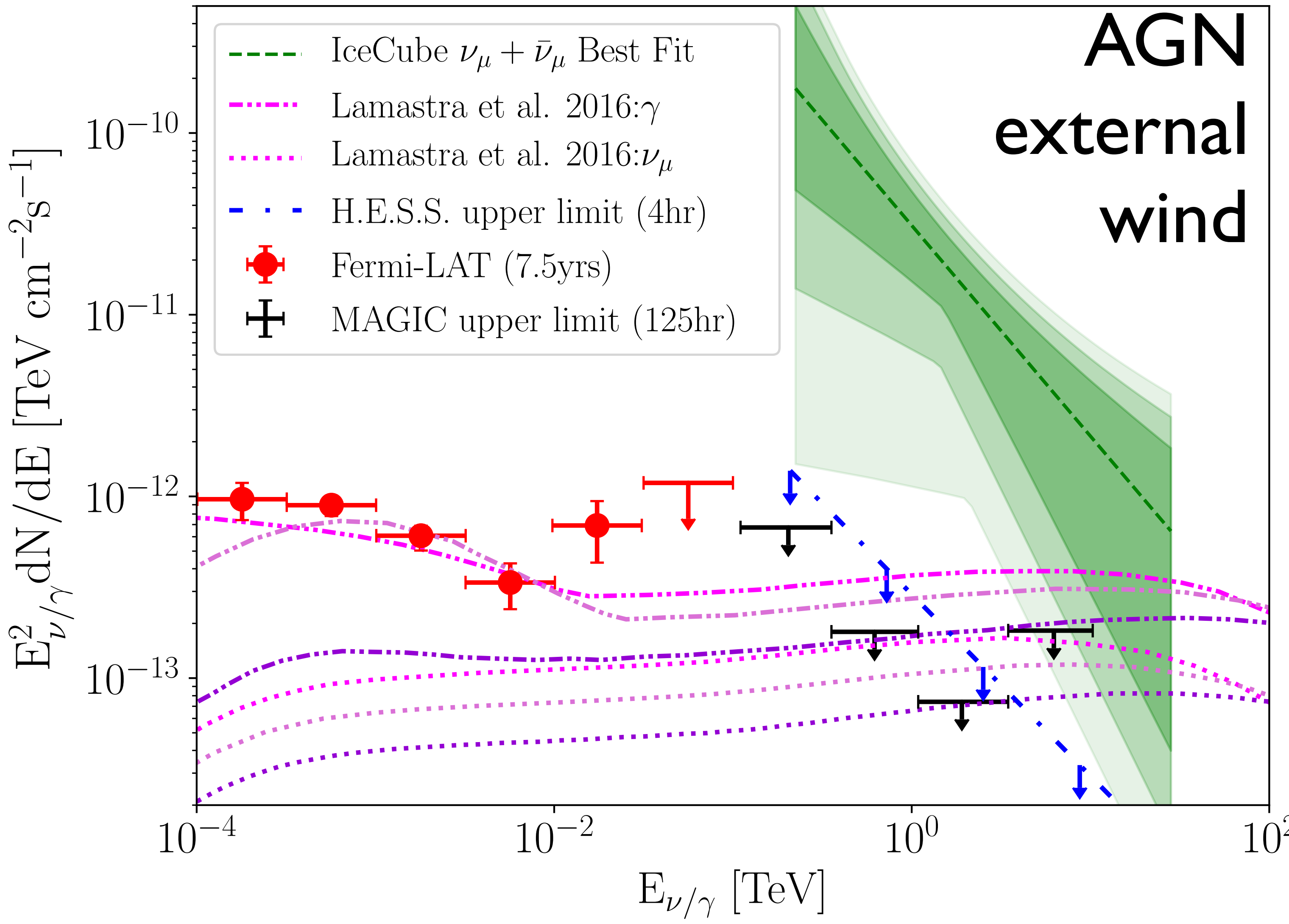
see also Kheirandish et al 2021
Anchordoqui et al 2021
Peretti et al 2023
Fang et al 2023
Salvatore et al 2023

Neutrino production in NGC 1068

AGN corona (low magnetisation) *Y. Inoue et al 2019*



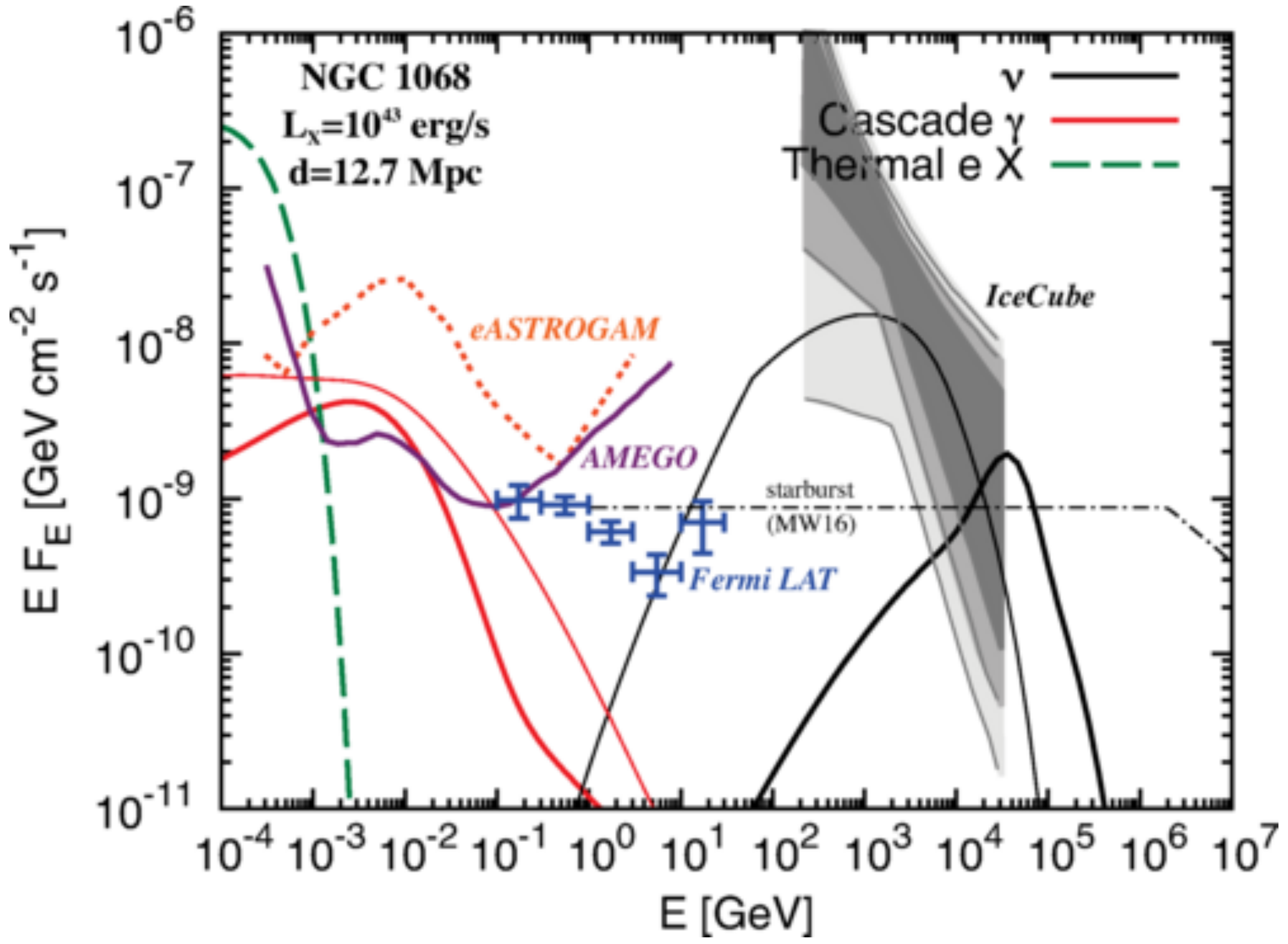
AGN external wind



Lamastra 2016, 2019

AGN corona (highly magnetised)

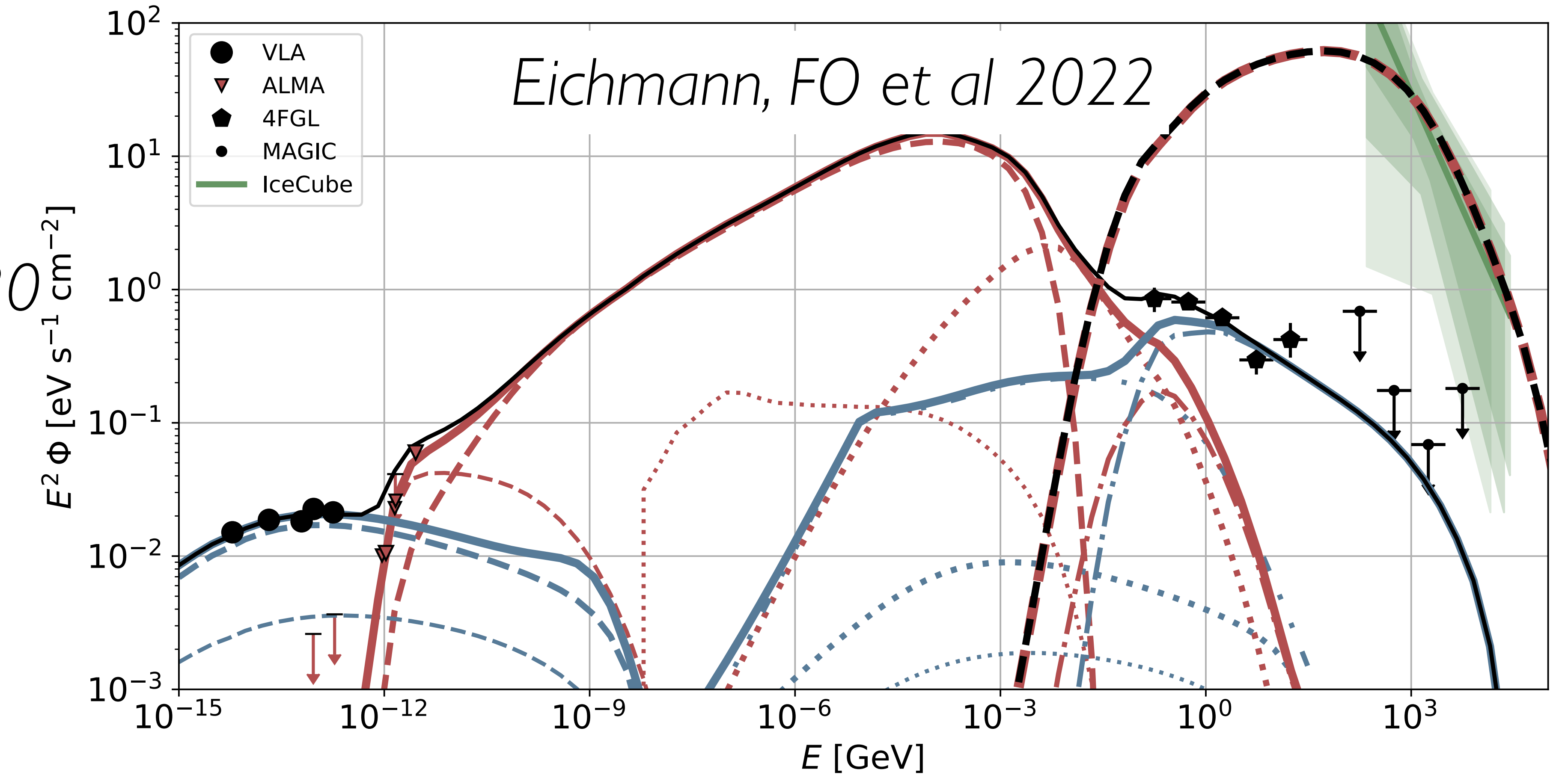
Murase et al 2020

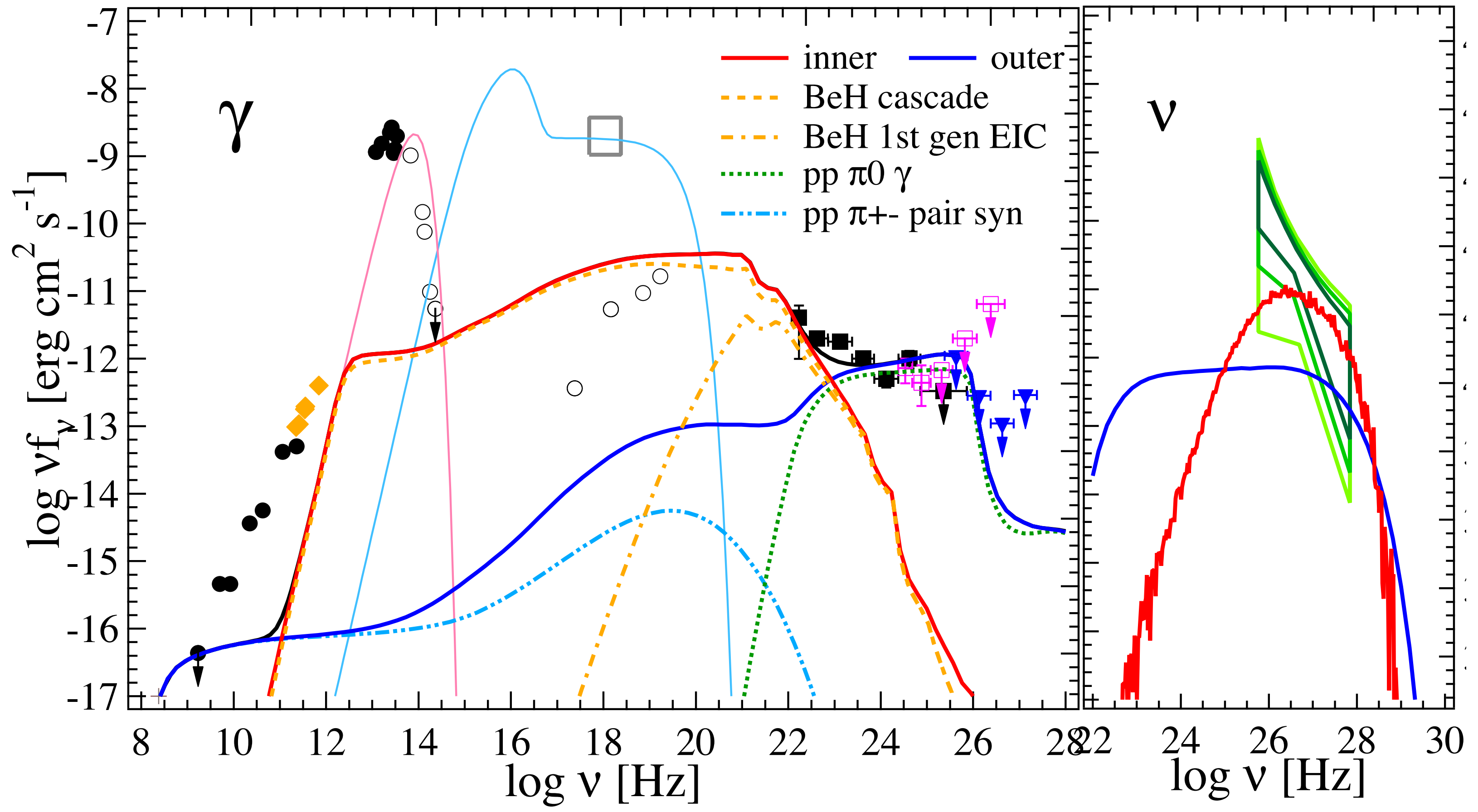


$$R_{\rm neutrinos} \leq 30 R_{\rm Sw}$$

Murase 2022
Halzen 2023

Starburst + AGN corona composite





AGN wind (pγ)

S. Inoue et al 2022

Tidal disruption events

X-ray observed TDEs

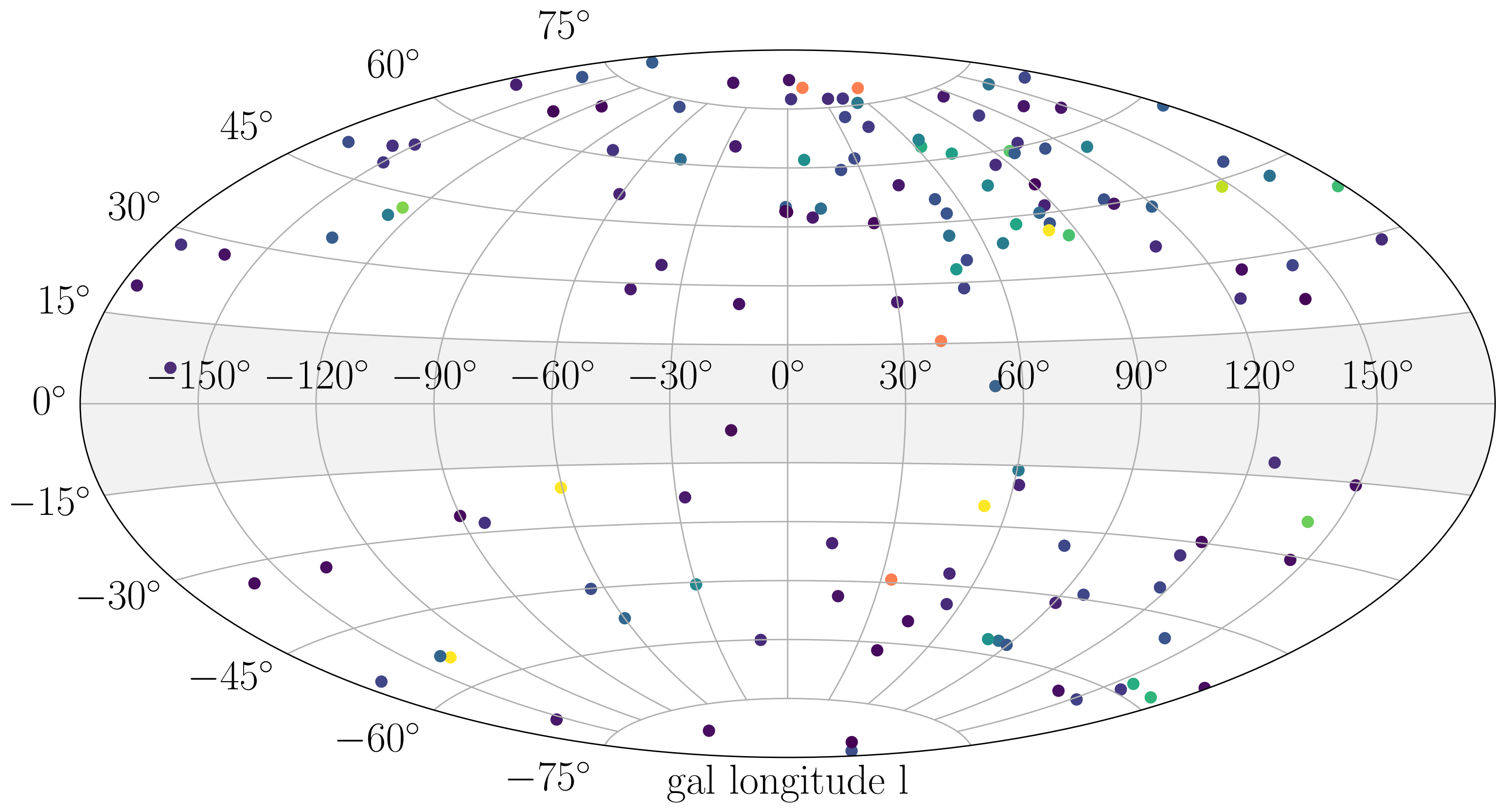
plot by D. Ehlert (based on catalogue of Goldtooth et al 2023)

TDE contribution to the cosmic-neutrino flux

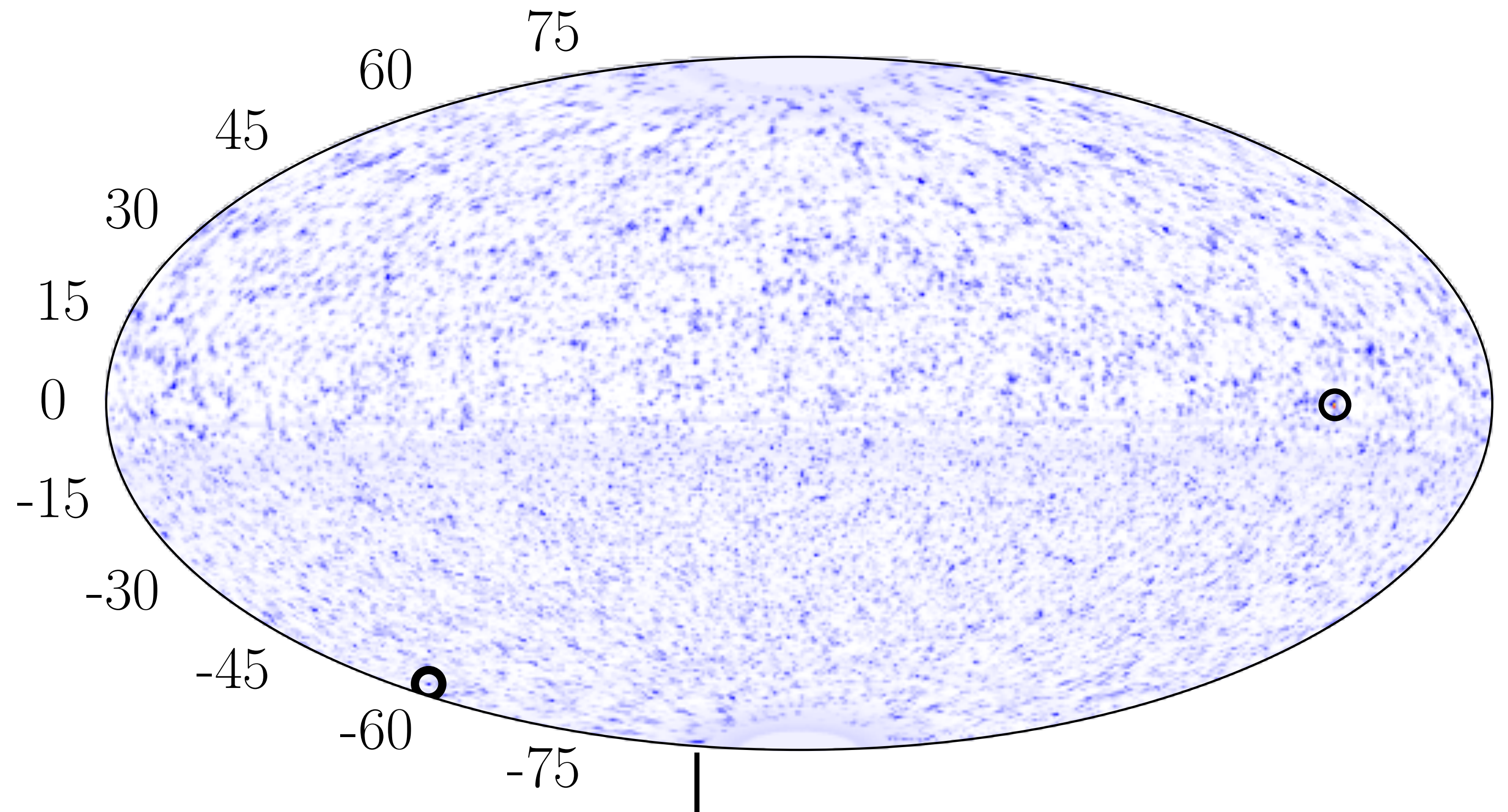
3 jetted TDEs
40 non-jetted TDEs (mixture of X-ray / UV / optical TDEs)

Updated search in 2022 ZTF TDEs with neoWISE flare (``dust echo'') Y. Necker TeVPA 2022 - No excess

TDE sky-map



IceCube Point-Source Events



IceCube Coll PoS ICRC 2019
Necker et al 2022 (ASAS-SN Coll)
Stein et al 2022 (ZTF Coll)

Jetted TDEs: < 3% diffuse neutrino flux

Non-jetted < 26%

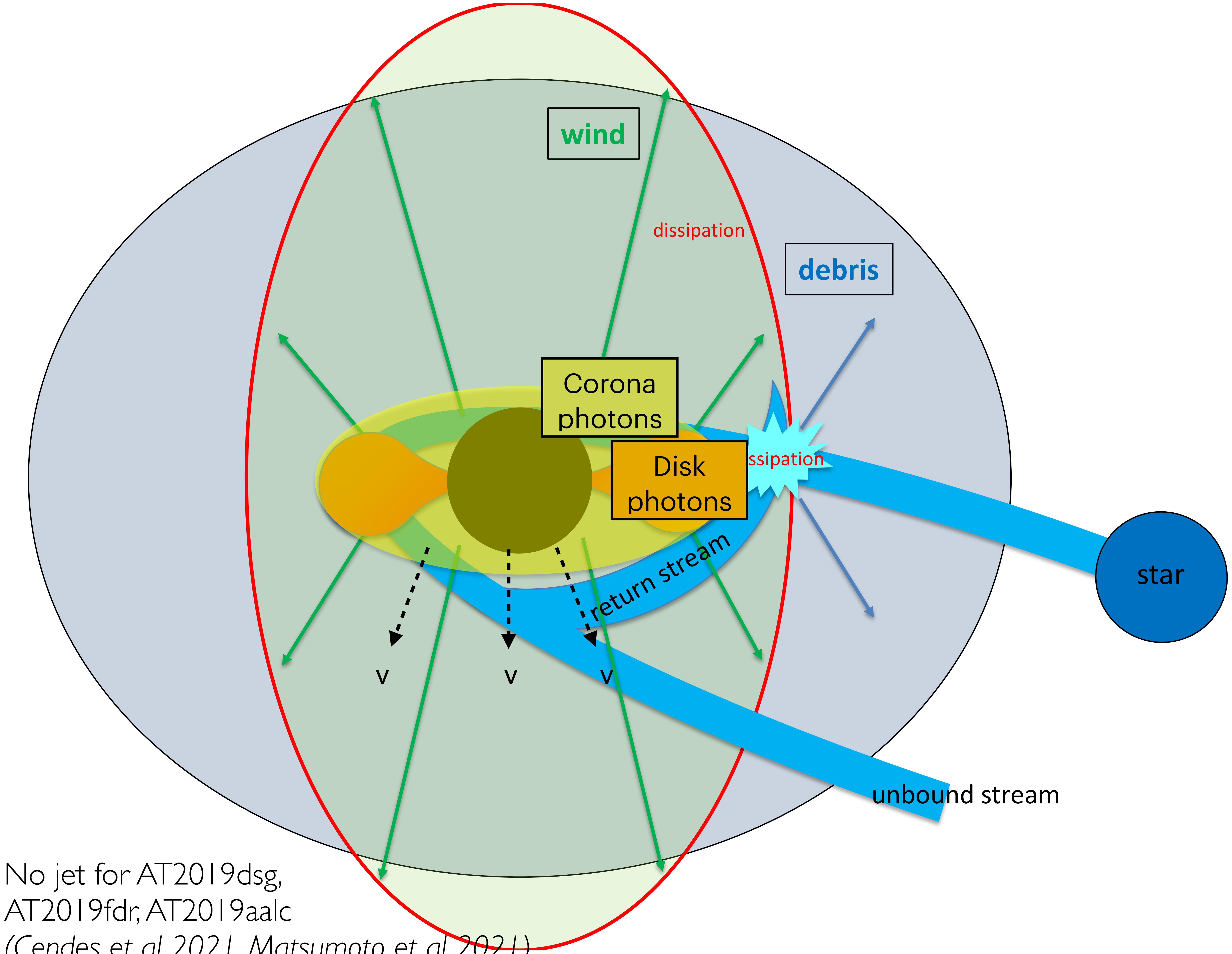
TDEs coincident with high-energy neutrinos

Stein et al 2021
Reutsch et al 2022
Van Velzen et al 2021
Albert et al 2021 (Antares)

combined significance: 3.7σ

Neutrino production in TDEs

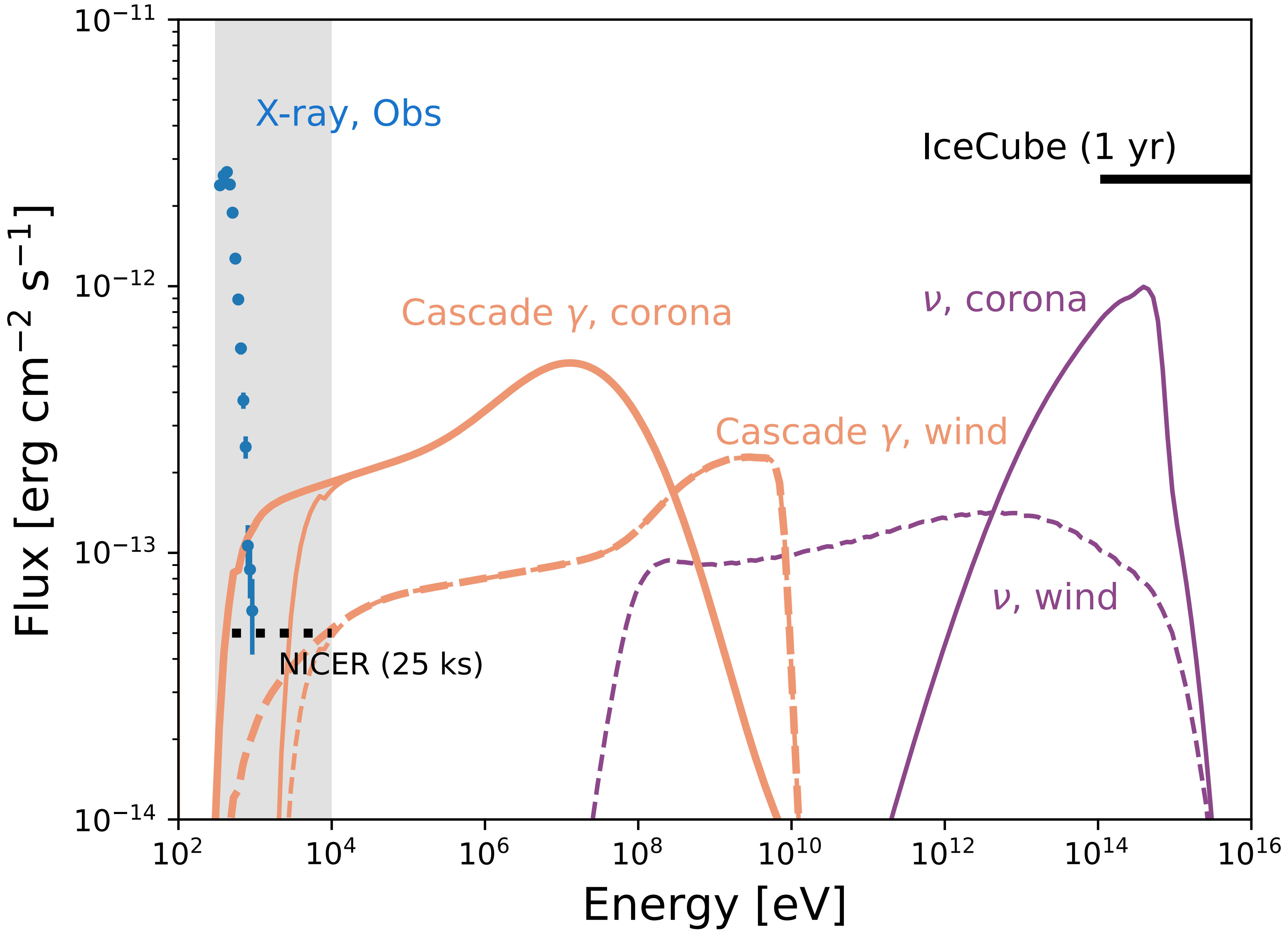
see also Hayasaki et al 2019
Winter, Lunardini 2020
Winter, Lunardini 2022
Banik & Bharda 2022



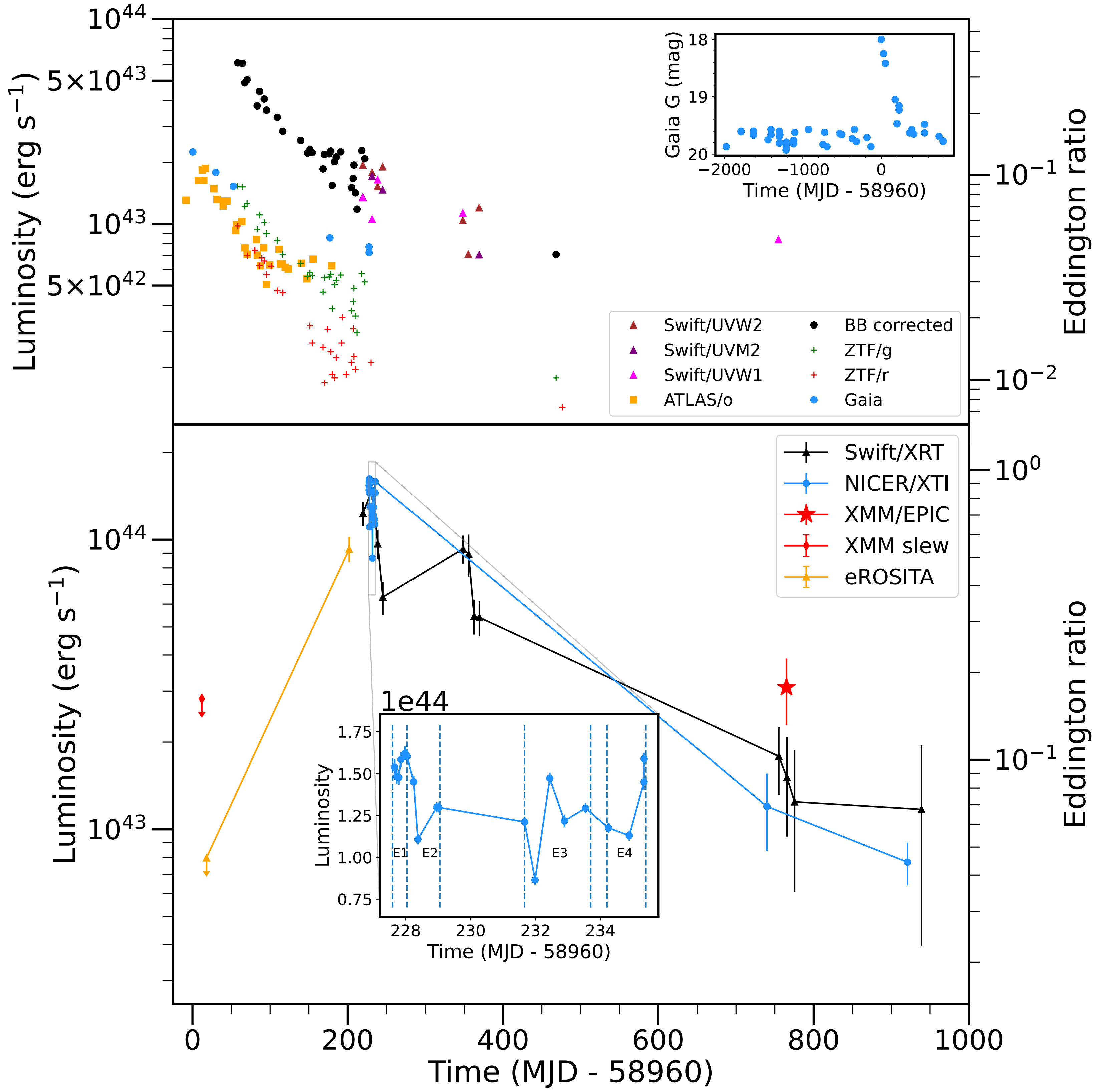
No jet for AT2019dsg, AT2019fdr, AT2019aalc
(Cendes et al 2021, Matsumoto et al 2021)

Example: AT2019dsg

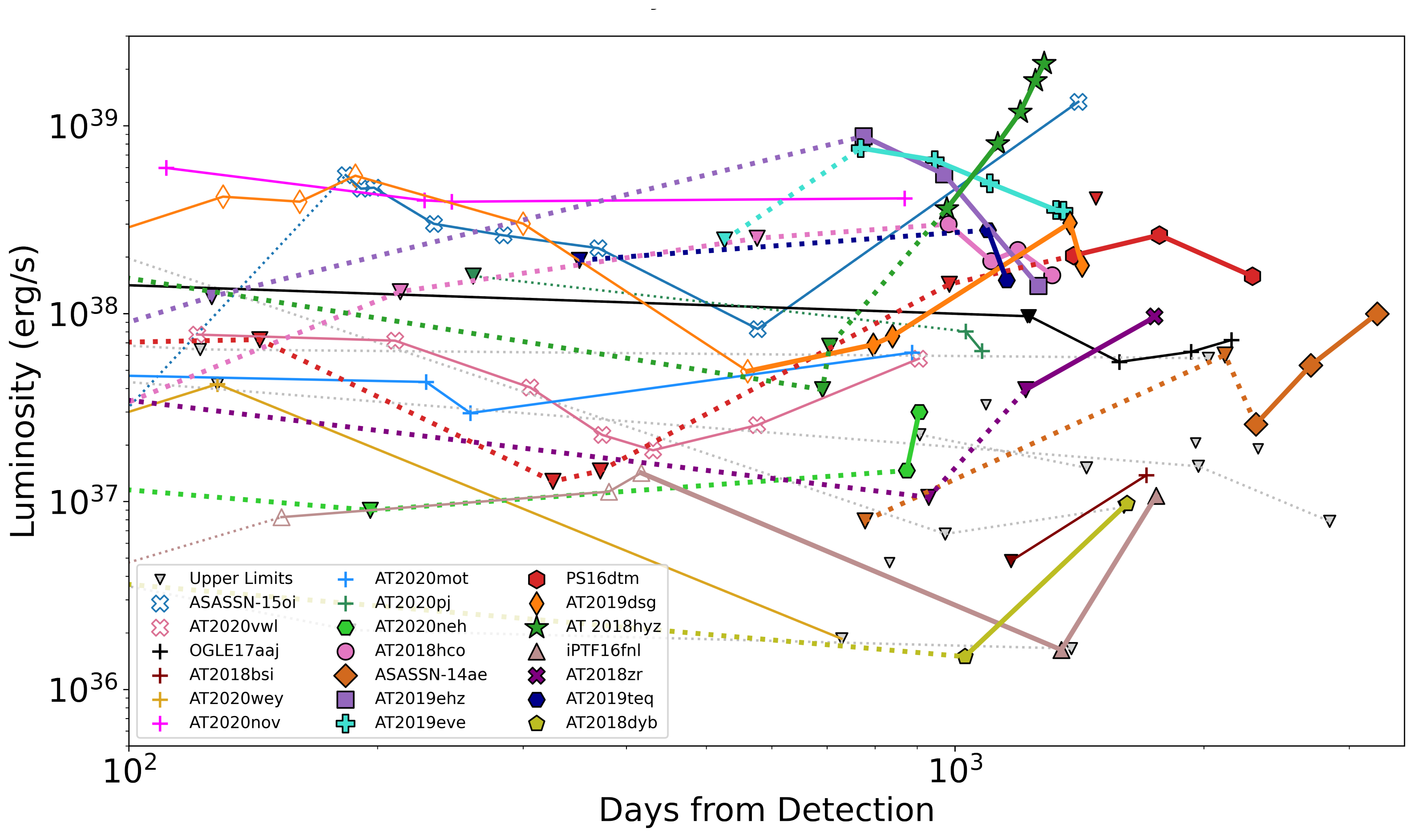
Murase, Zhang, Kimura, FO, Petropoulou 2020



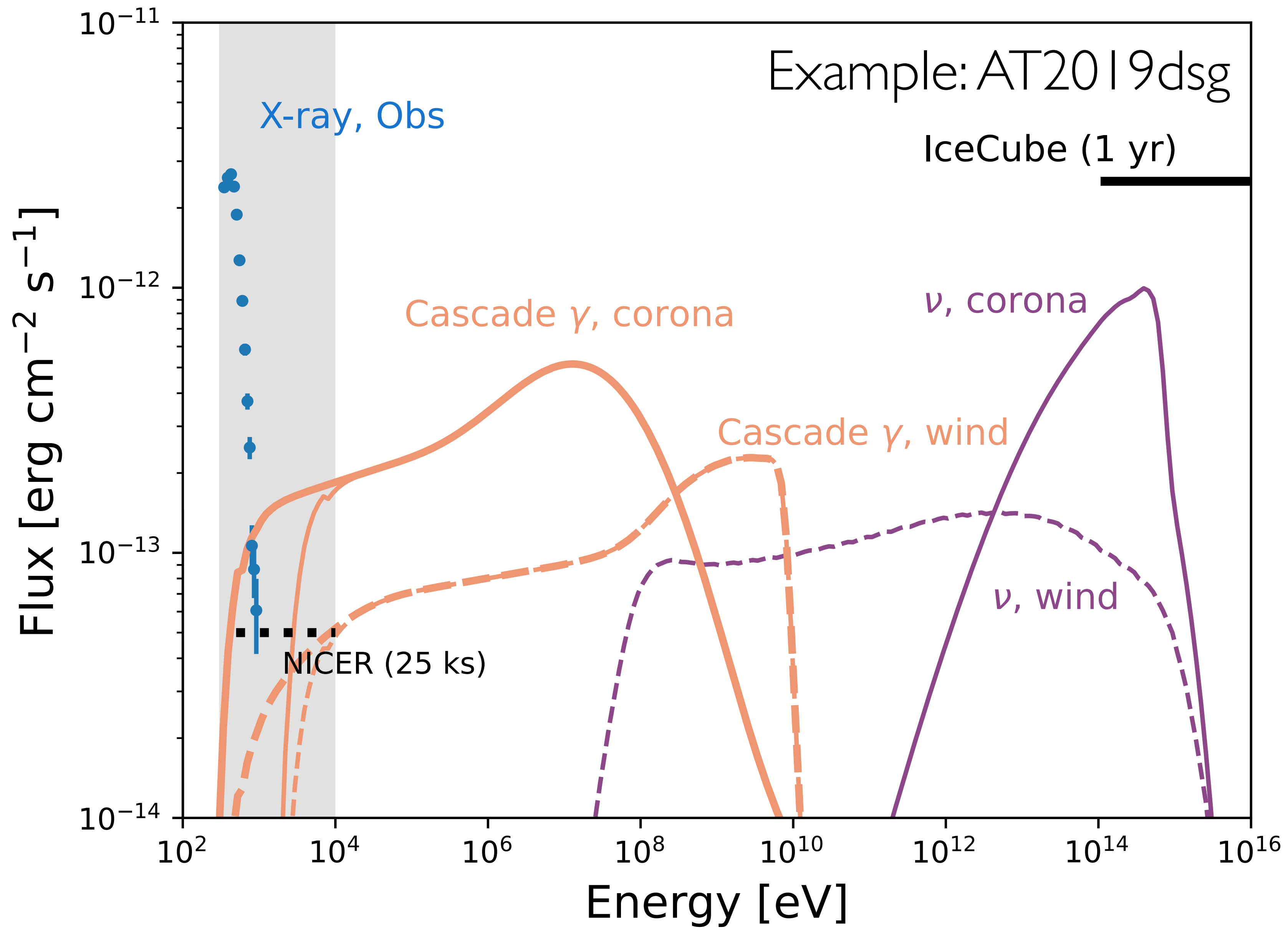
Interesting developments in TDE observations



X-ray rebrigthening after 200days in AT2020ksf.
(Wevers et al 2023)



Ubiquitous radio outflows up to 3000 days after TDE onset
(Cendes et al 2023)



NuStar followup of Gold neutrino alerts,
(Pasham, Murase, FO, Zhang)

Summary

Jetted AGN:

Most promising 100 EV UHECR candidates

Growing UHECR excess in direction of Cen A

Most promising $\geq 10\ \mathrm{PeV}$ neutrino point sources - transient (long) flare counterparts

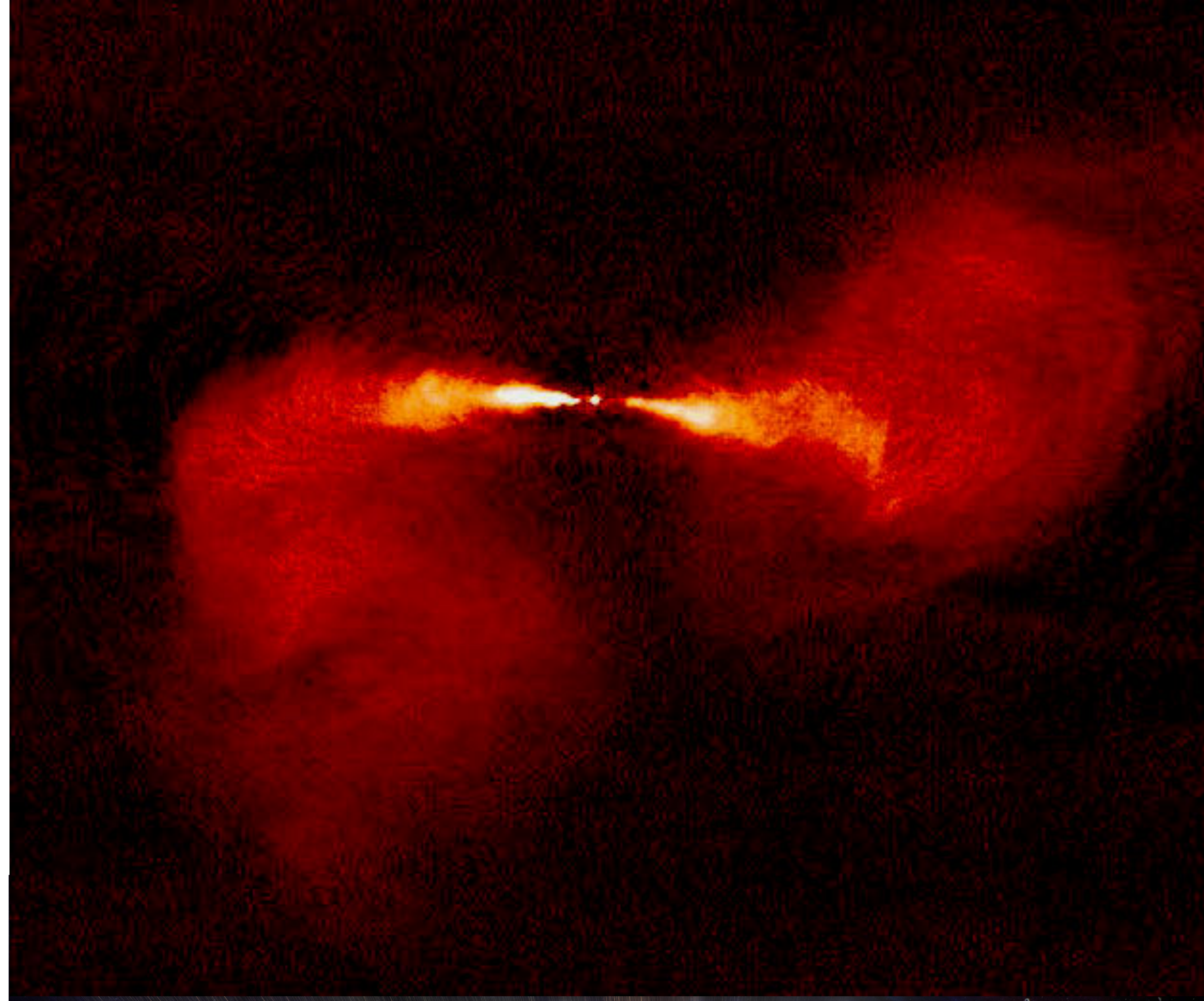
Non - jetted AGN:

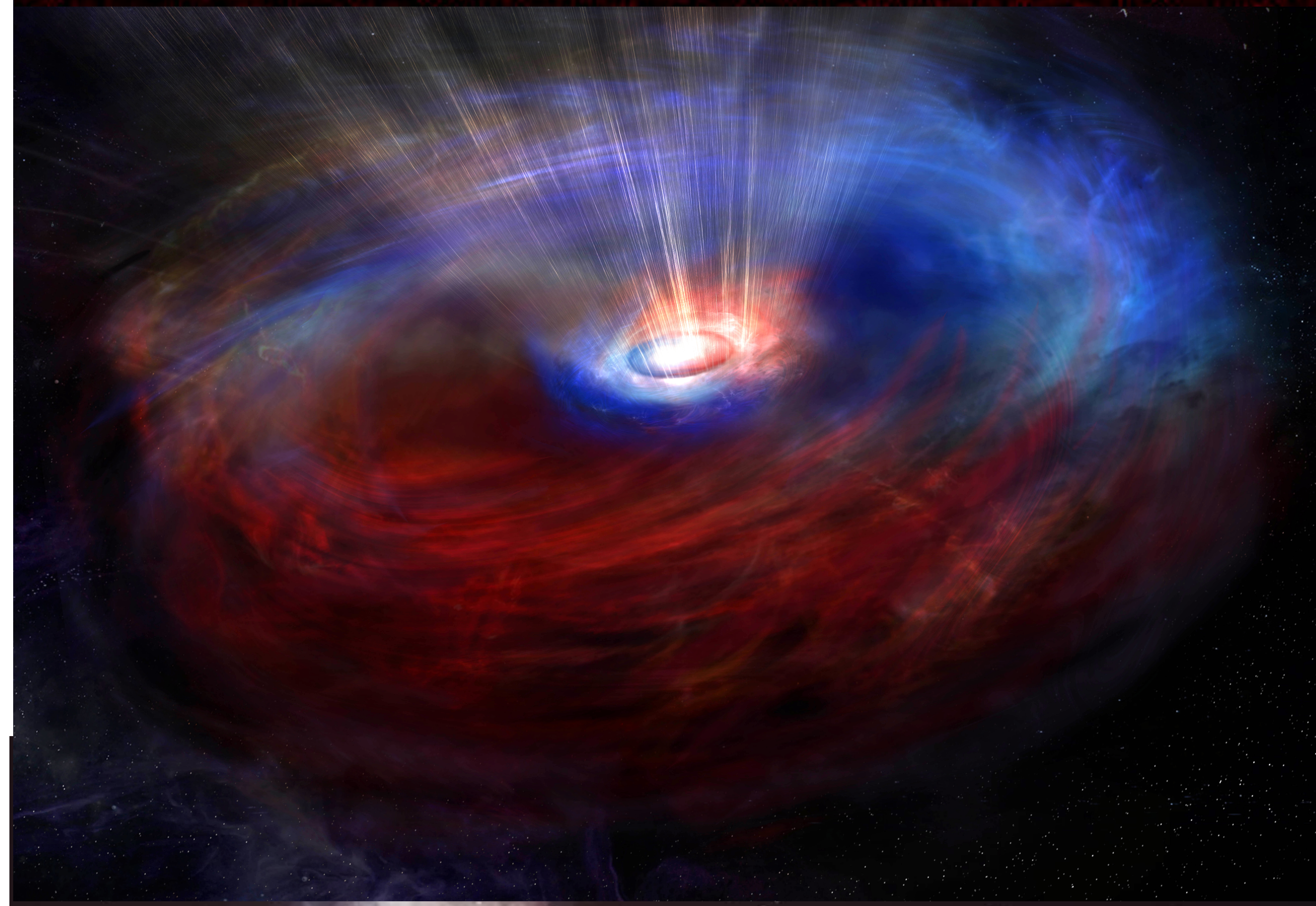
UHECRs: Don’t suffer from “variety” problem - but don’t seem to reach 100 EV due to energy losses

Could explain all IceCube neutrinos (medium and high) energy - usually steady emission

TDEs:

Interesting new observations suggest UFOs and long-lived radio outflows





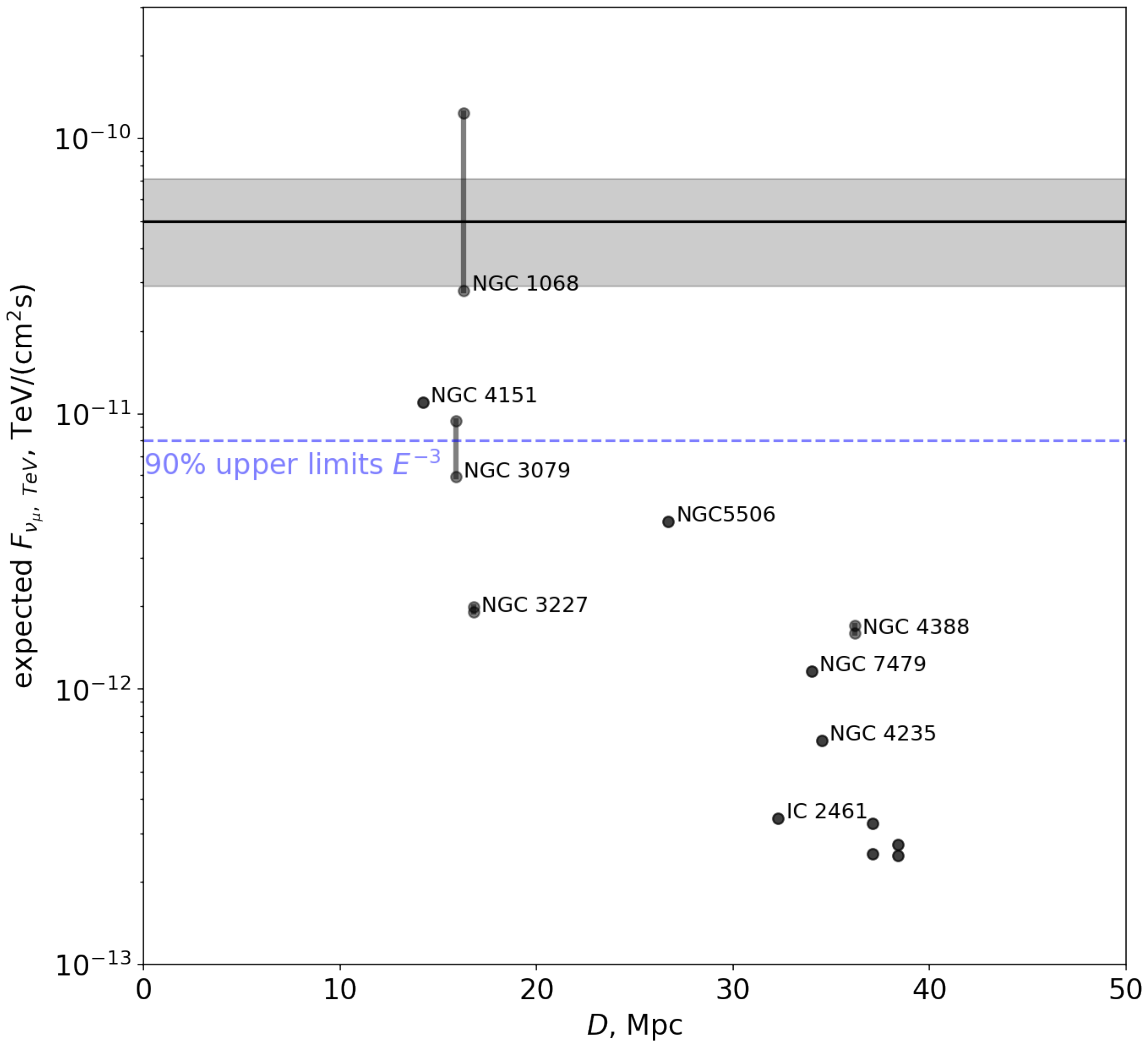
Back-up

Neronov, Savchenko, Semikoz arXiv: 2306.09018

Neutrino emission from additional Seyferts?

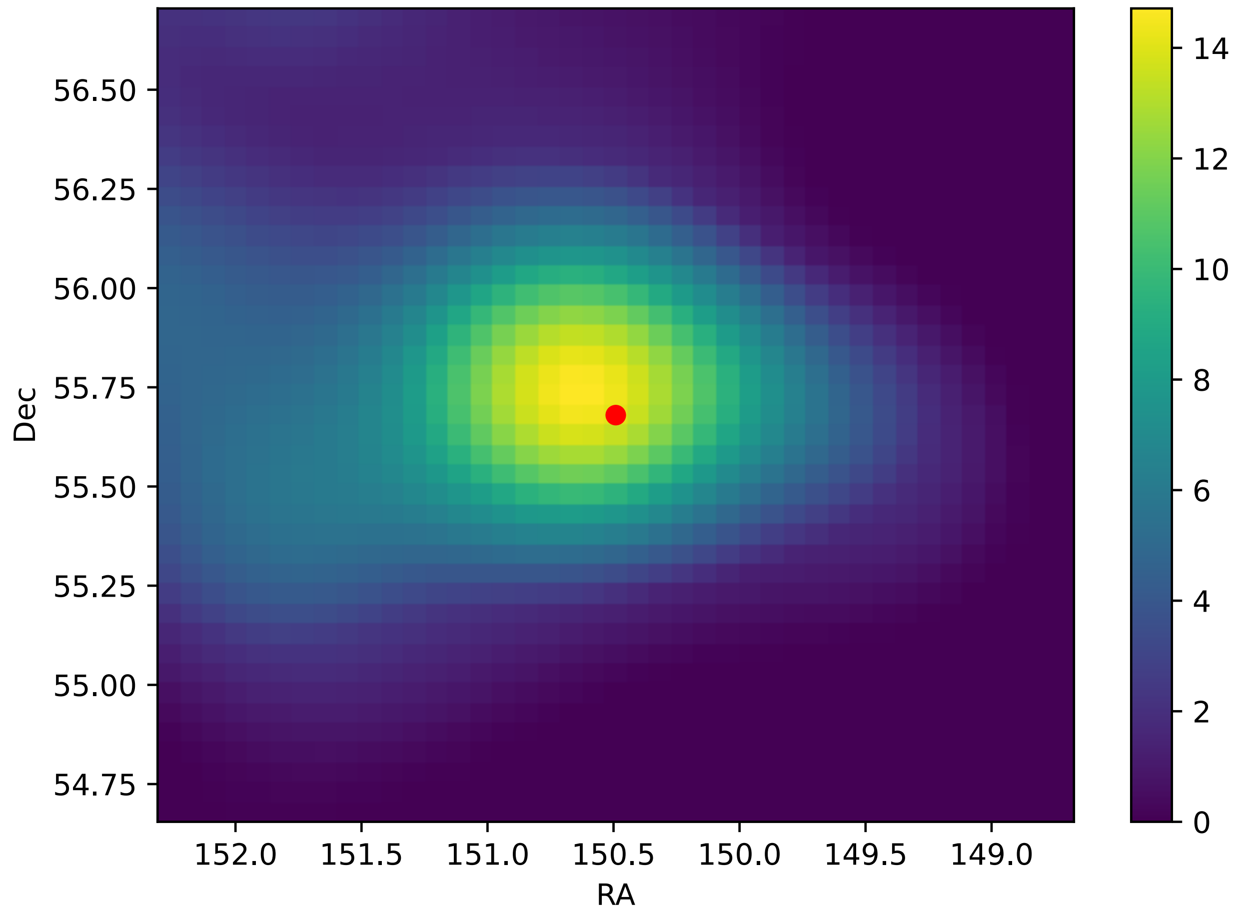
Swift-BAT selected Seyferts

Expected neutrino flux based on hard X-ray flux



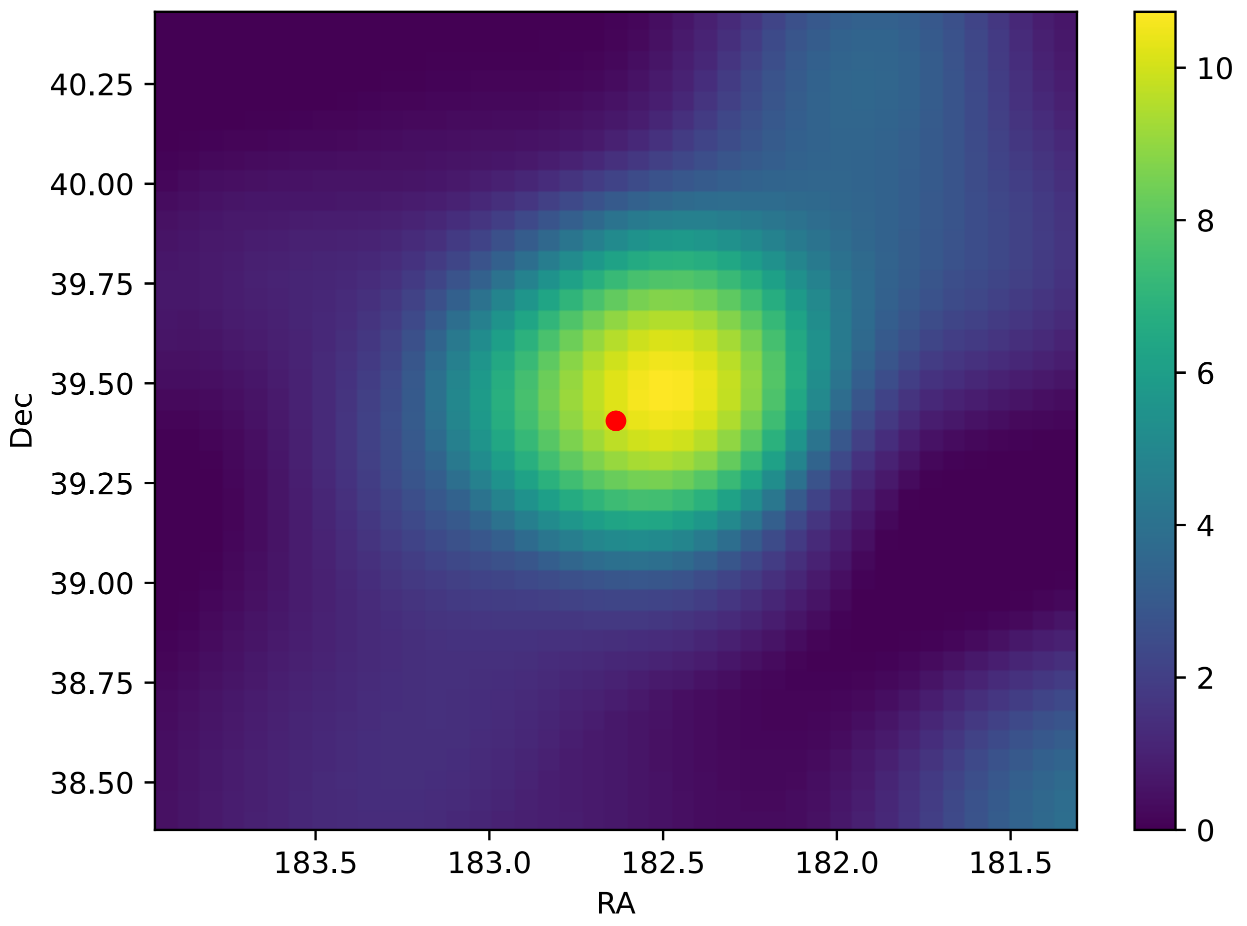
Neutrino excess in the 10 year IceCube Point Source sample

NGC 3079 $\delta = 55.7°$



$\mathrm{TS} = 14.1,\ p = 9.3 \times 10^{-5}$

NGC 4151 $\delta = 39.5°$



$\mathrm{TS} = 10,\ p = 2.7 \times 10^{-3}$

$p_{\mathrm{joint}} = 2.6 \times 10^{-7}$