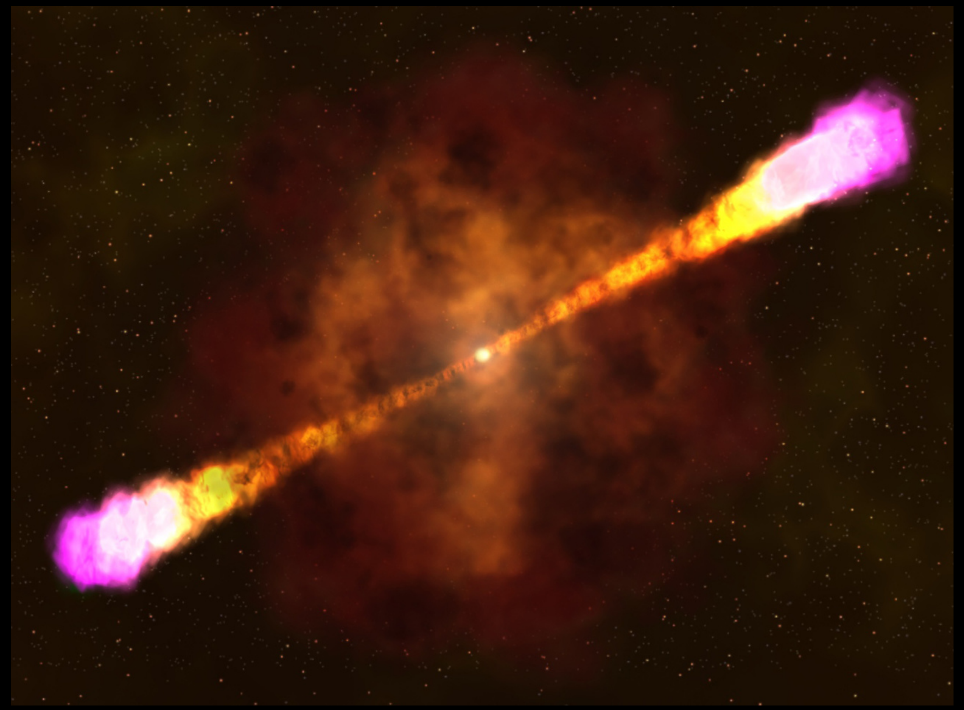
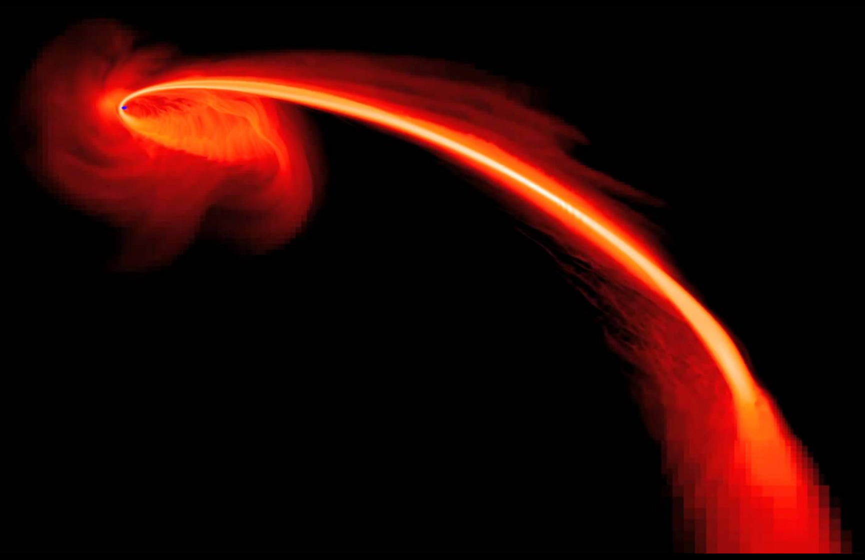
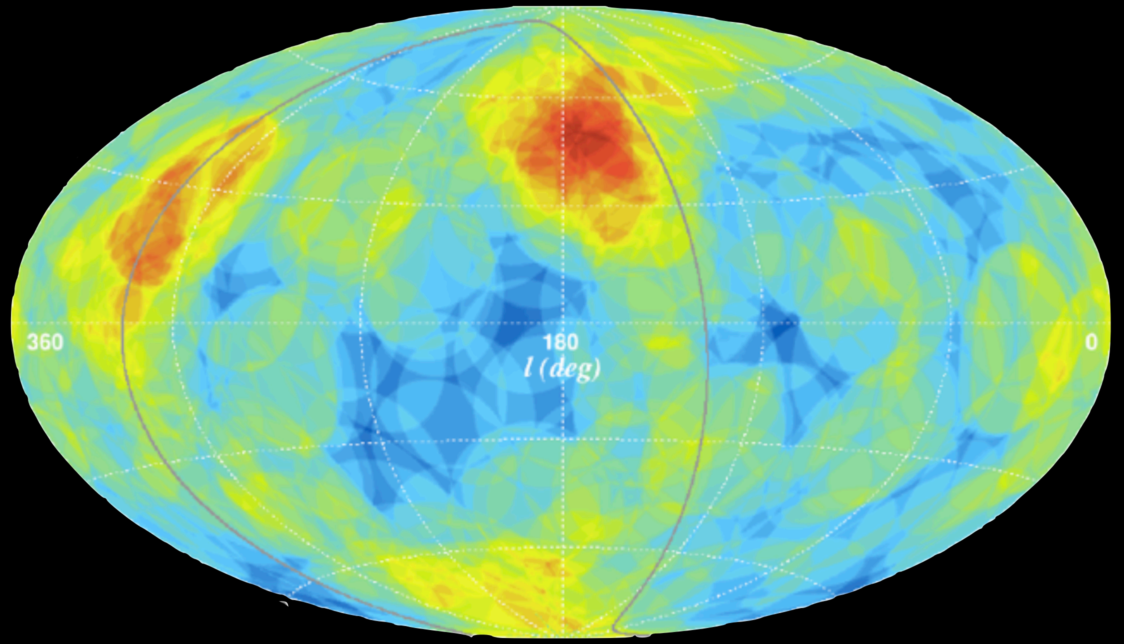
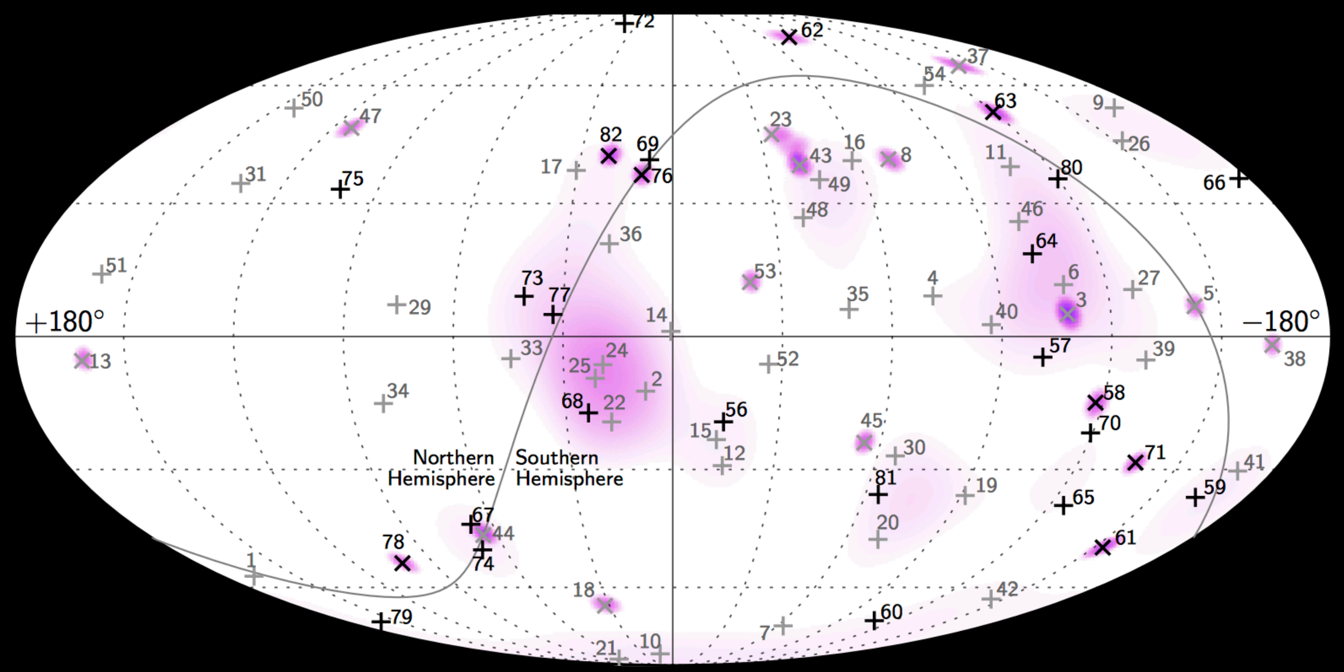
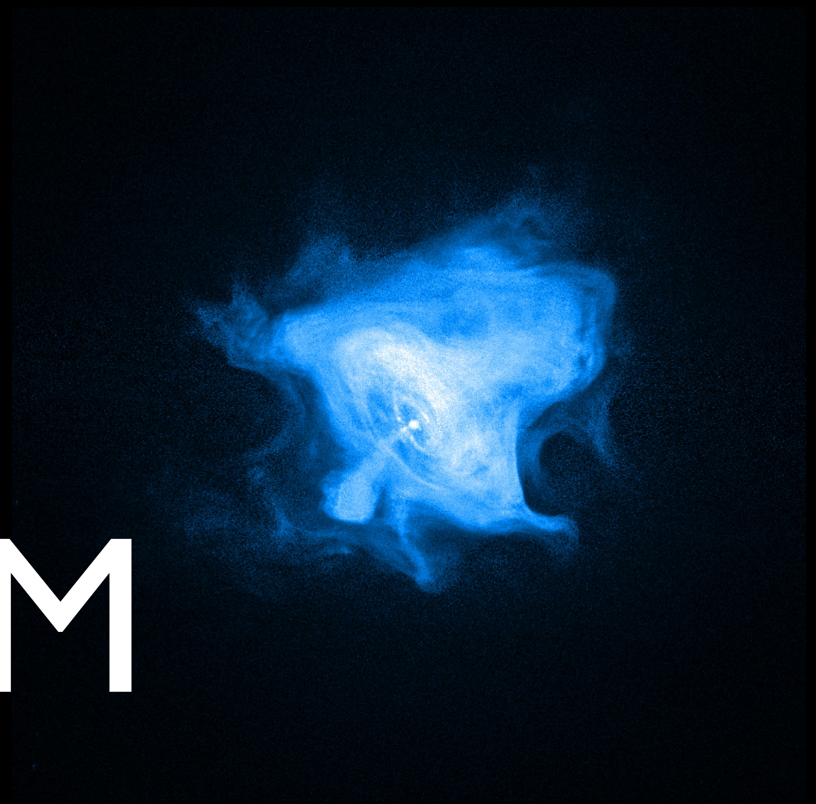








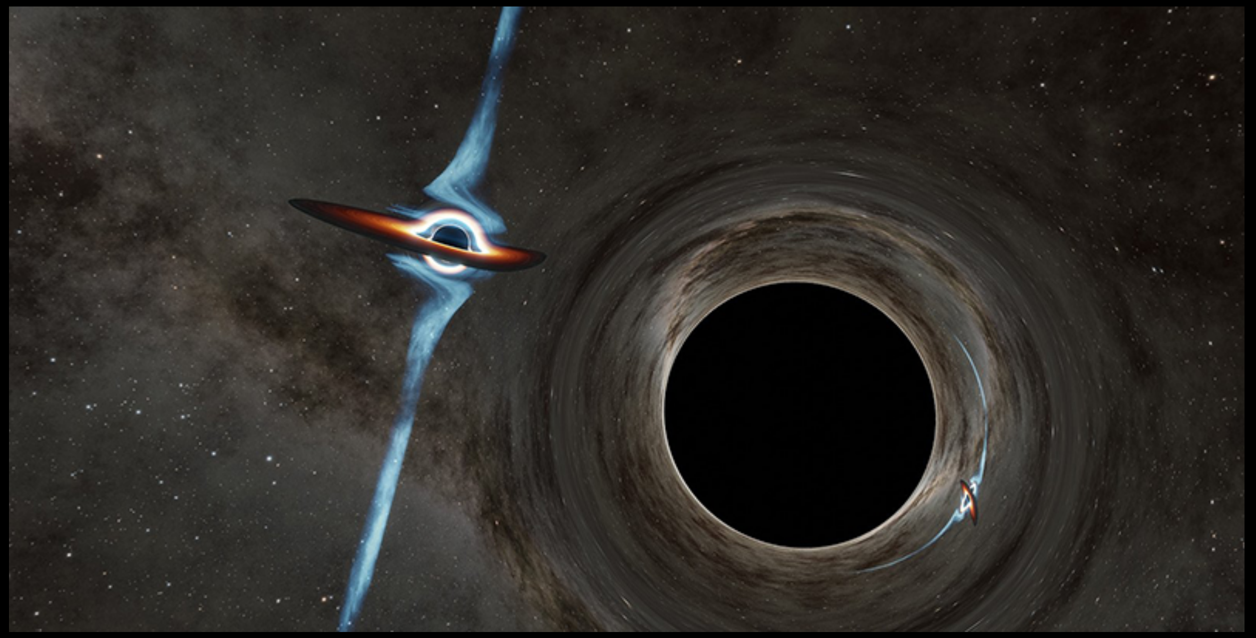


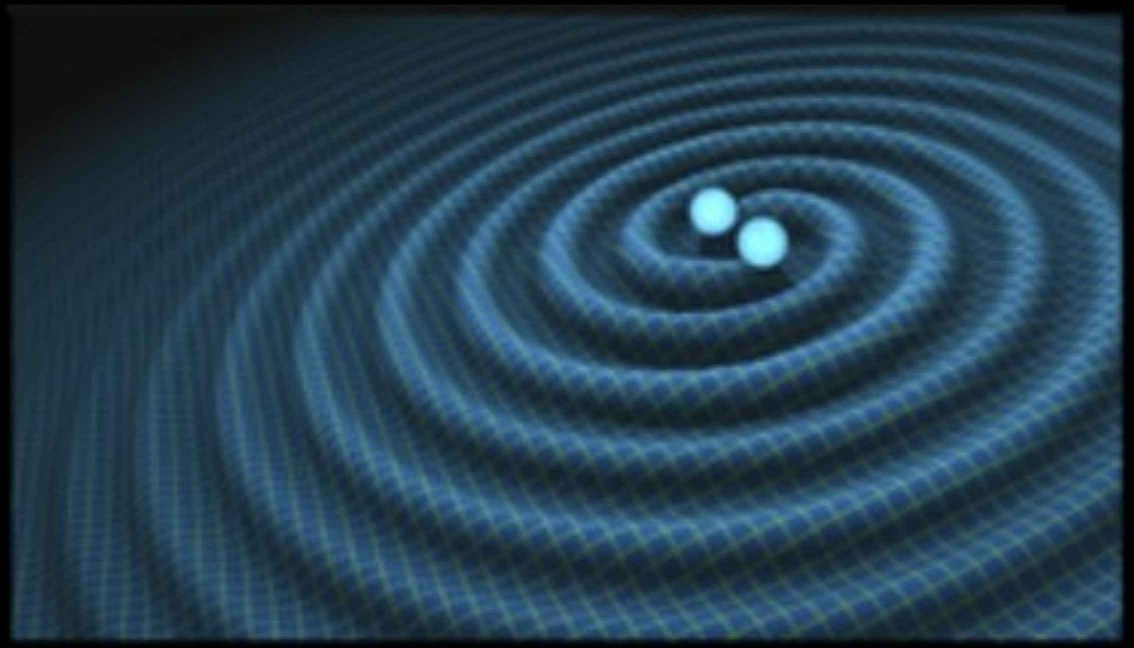
MULTIMESSENGER EMISSION FROM TRANSIENT SOURCES

Astro-COLIBRI Workshop

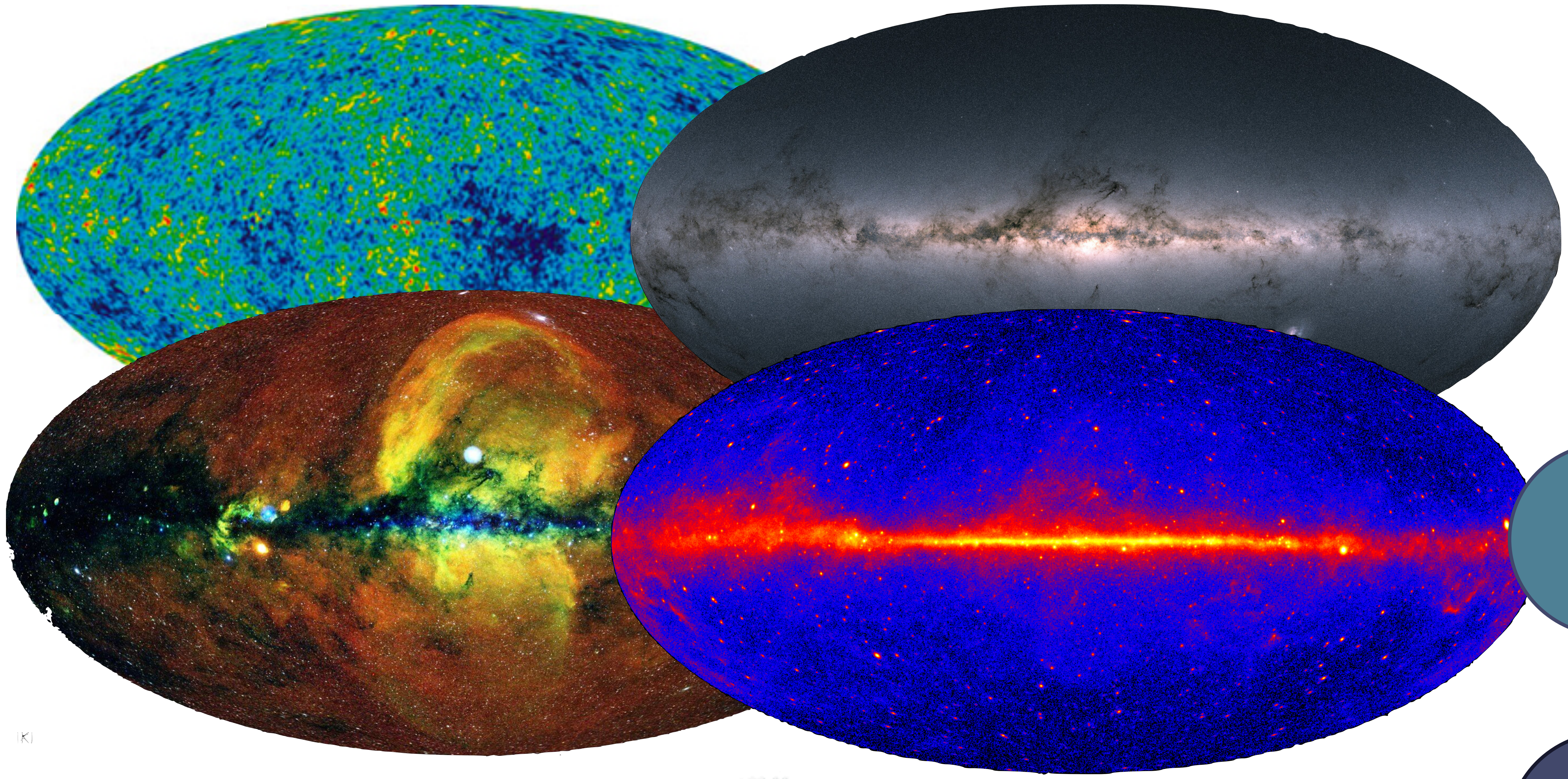
Foteini Oikonomou, 26 September 2022

NTNU
Norwegian University of Science and Technology



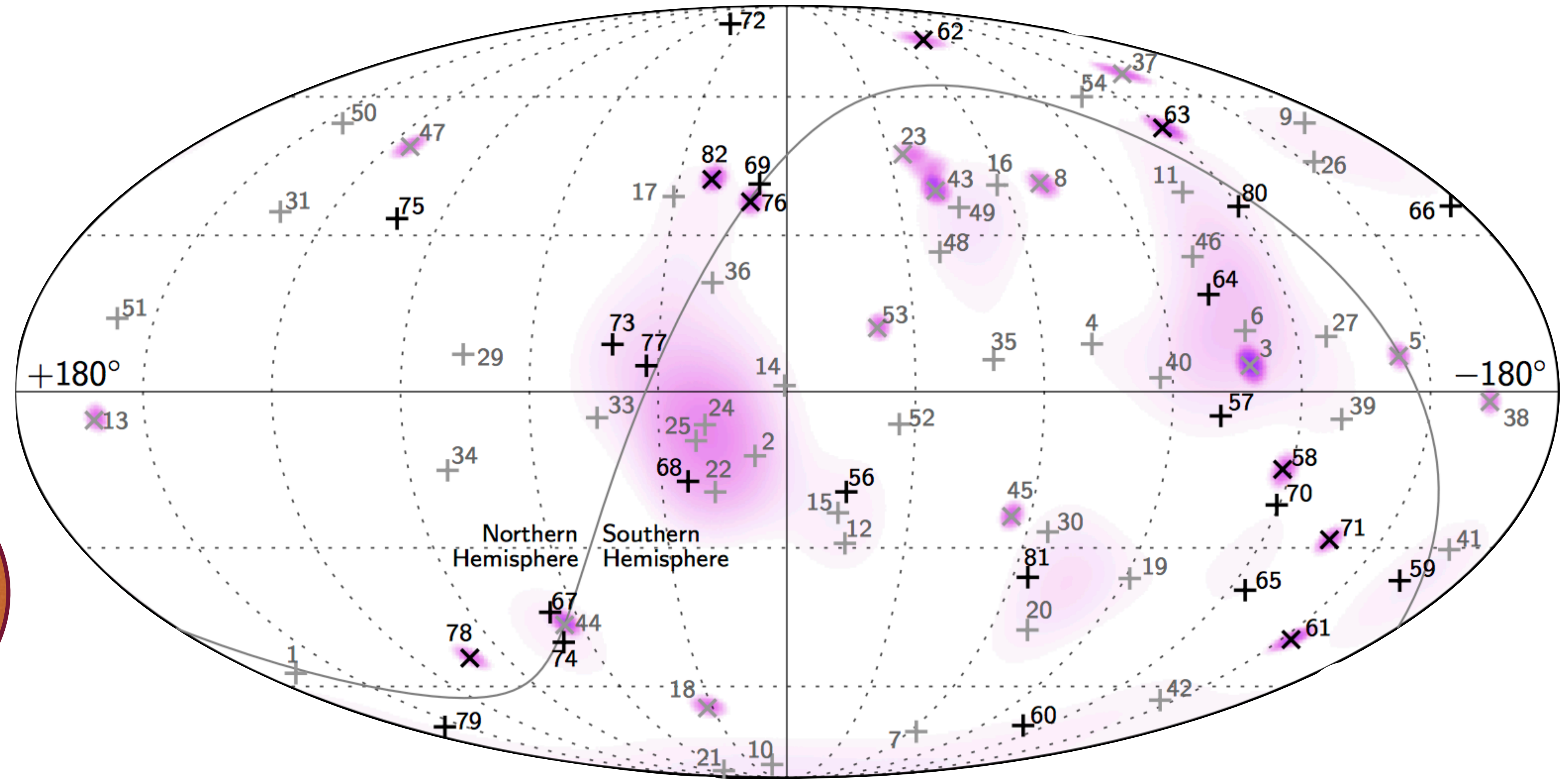


The Universe through multiple messengers



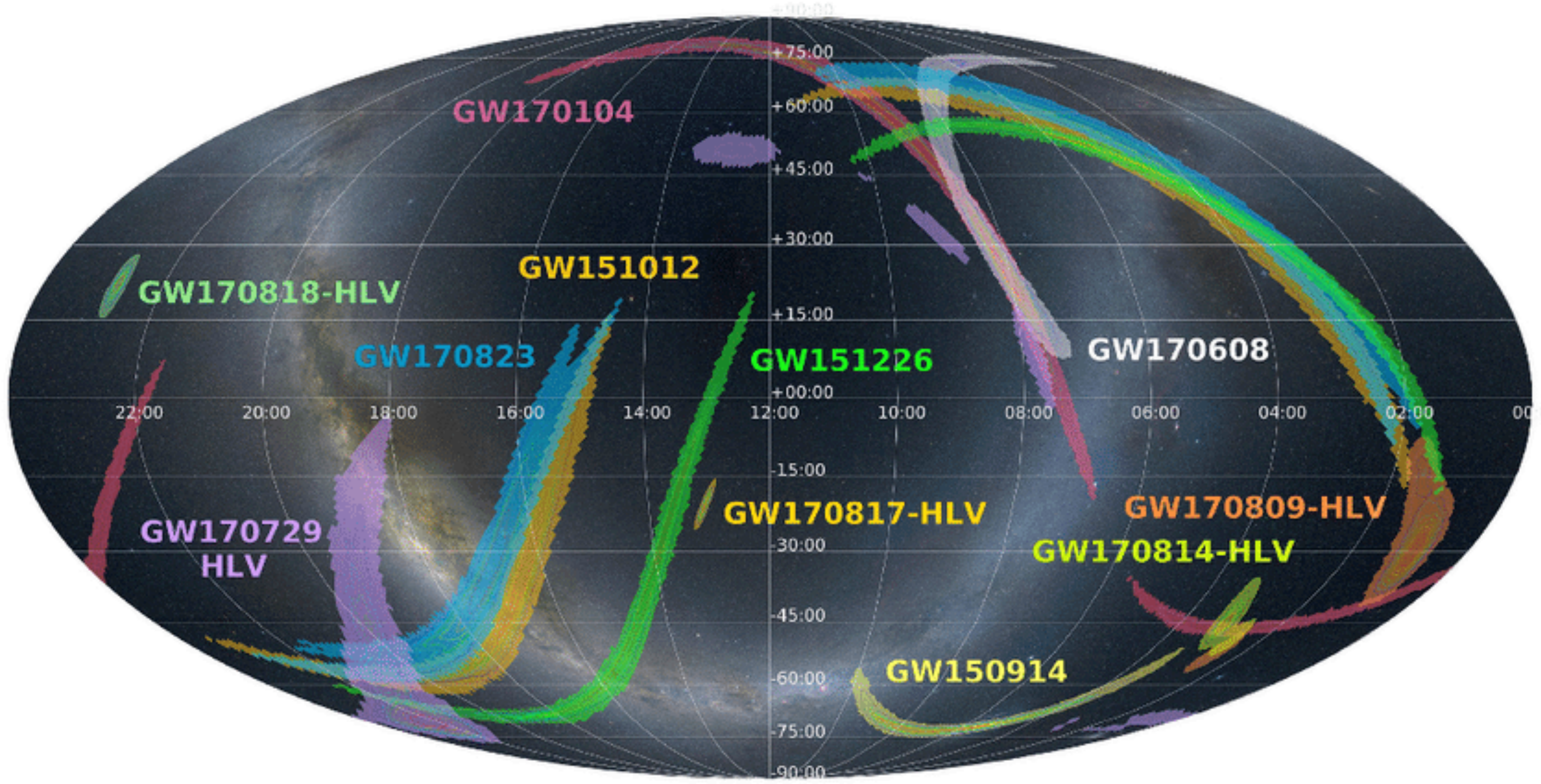
γ

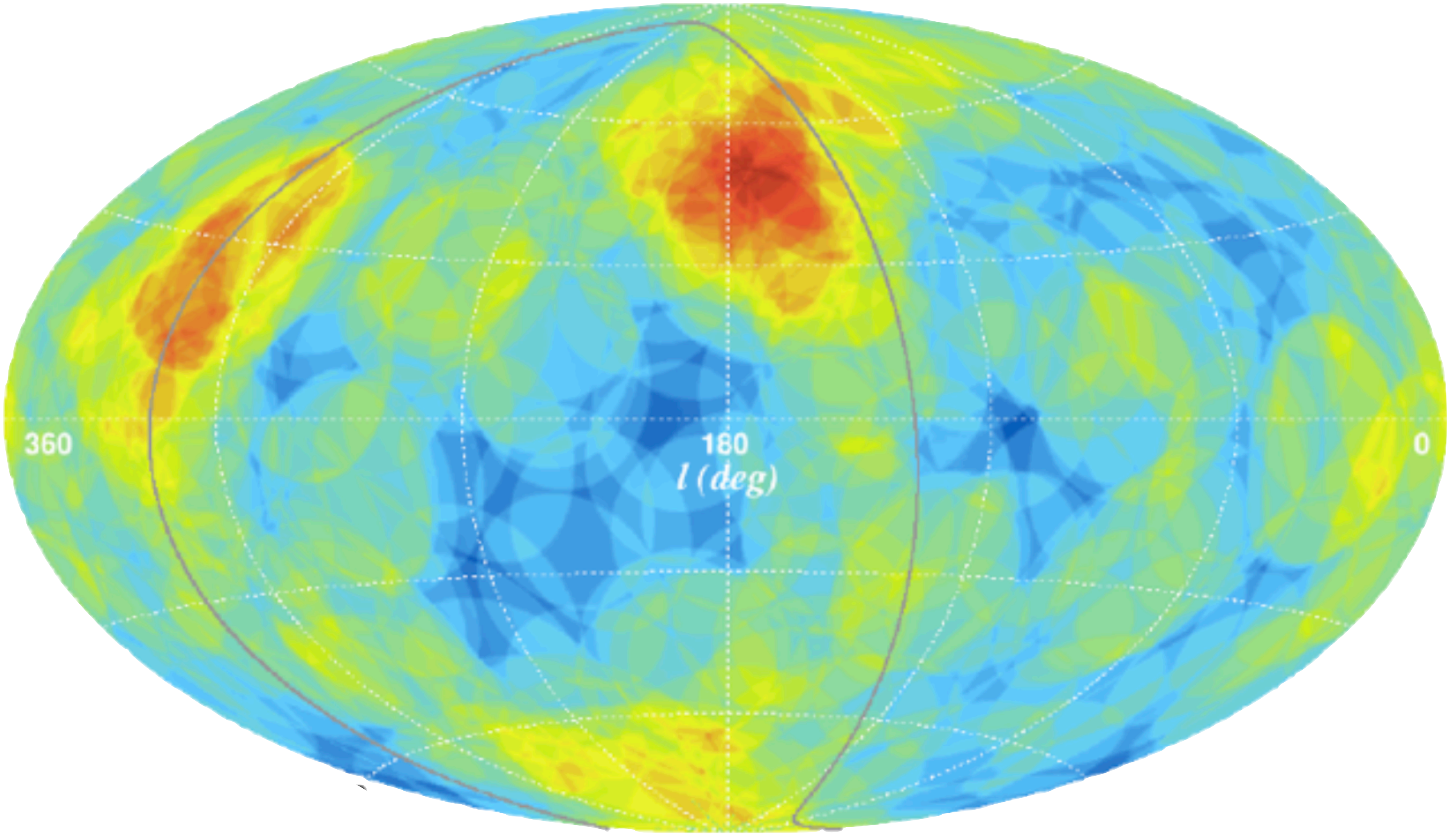
ν



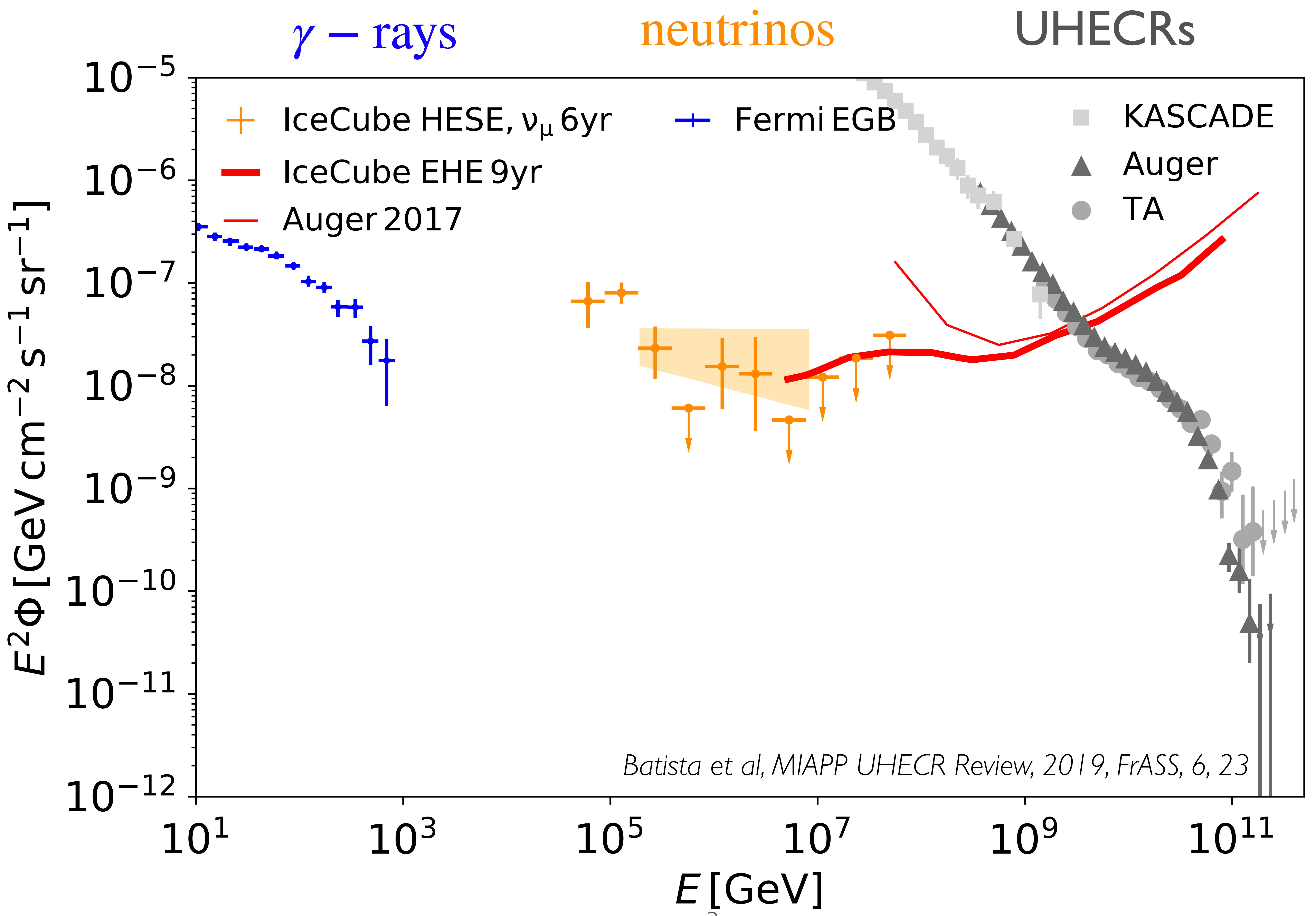
GW

CR



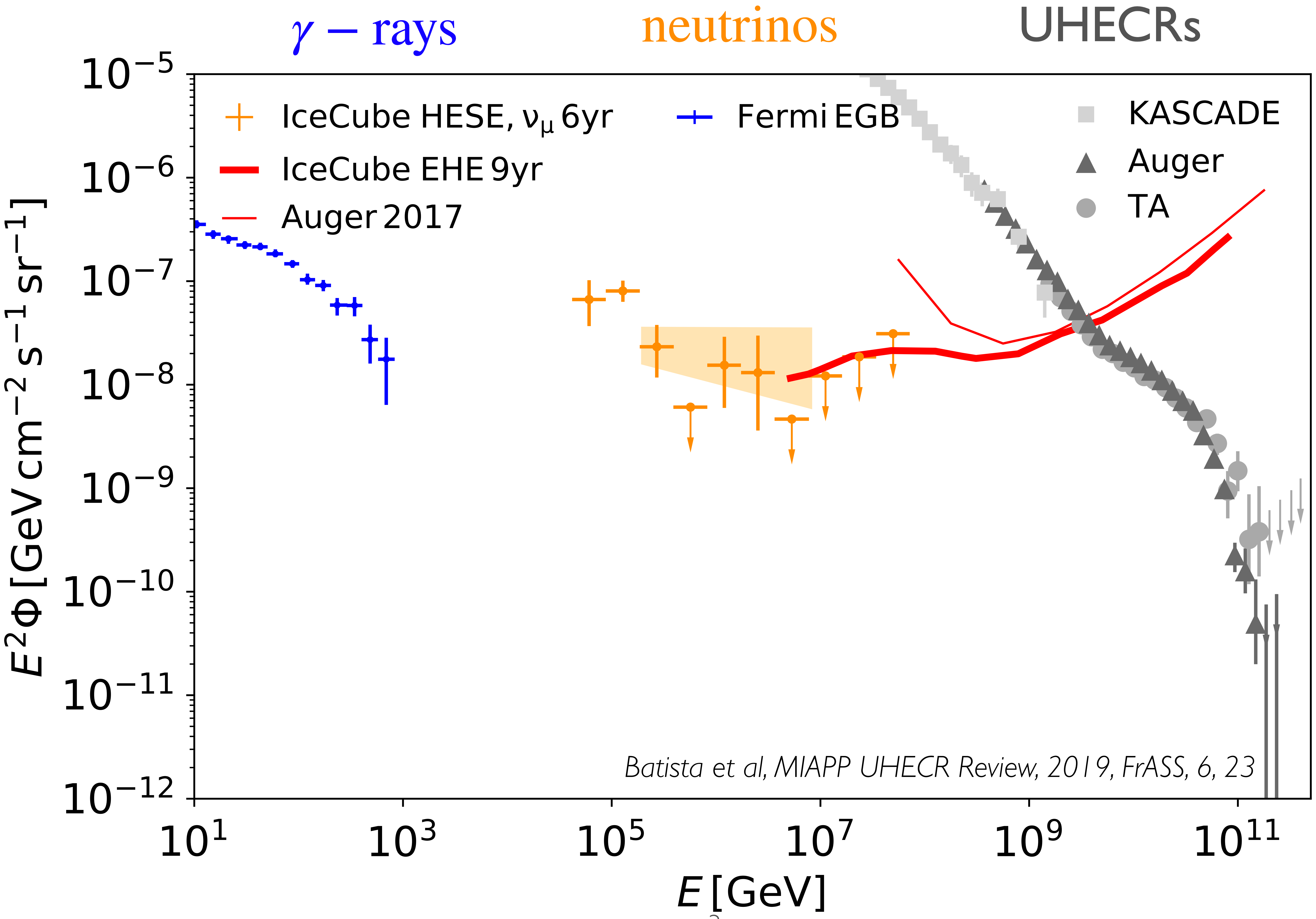


A common origin?



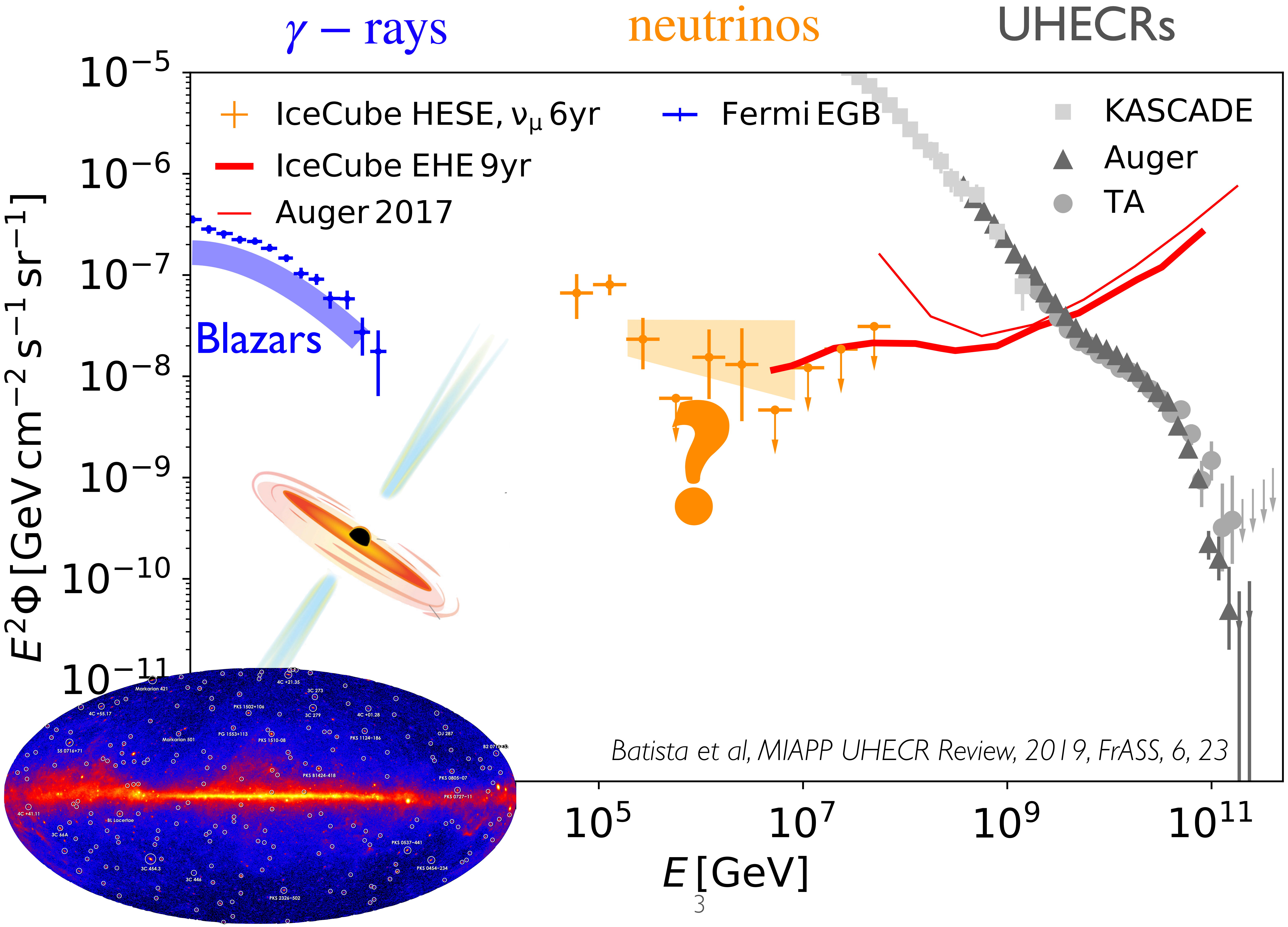
Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018

A common origin?



Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018

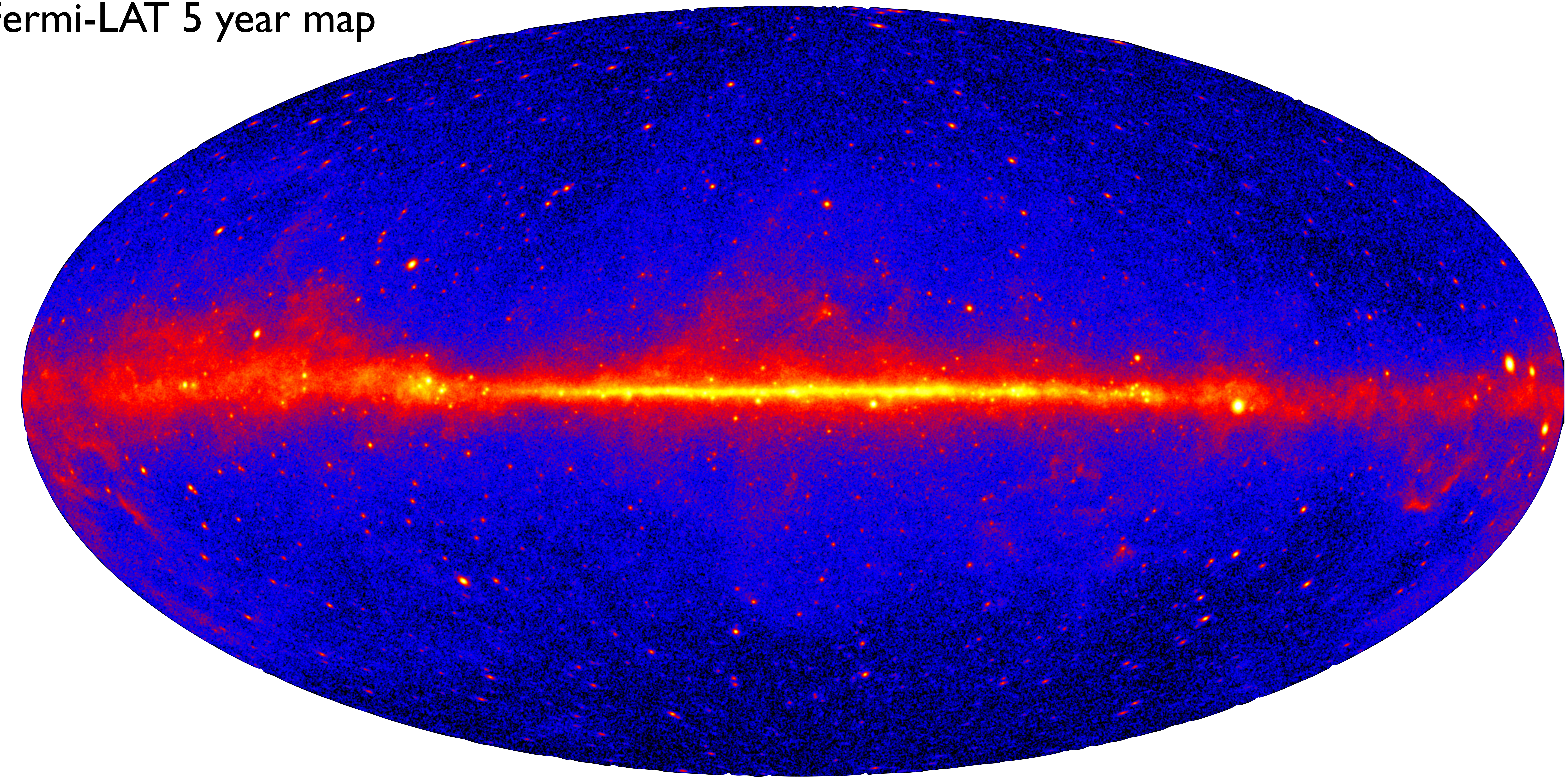
A common origin?



Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018

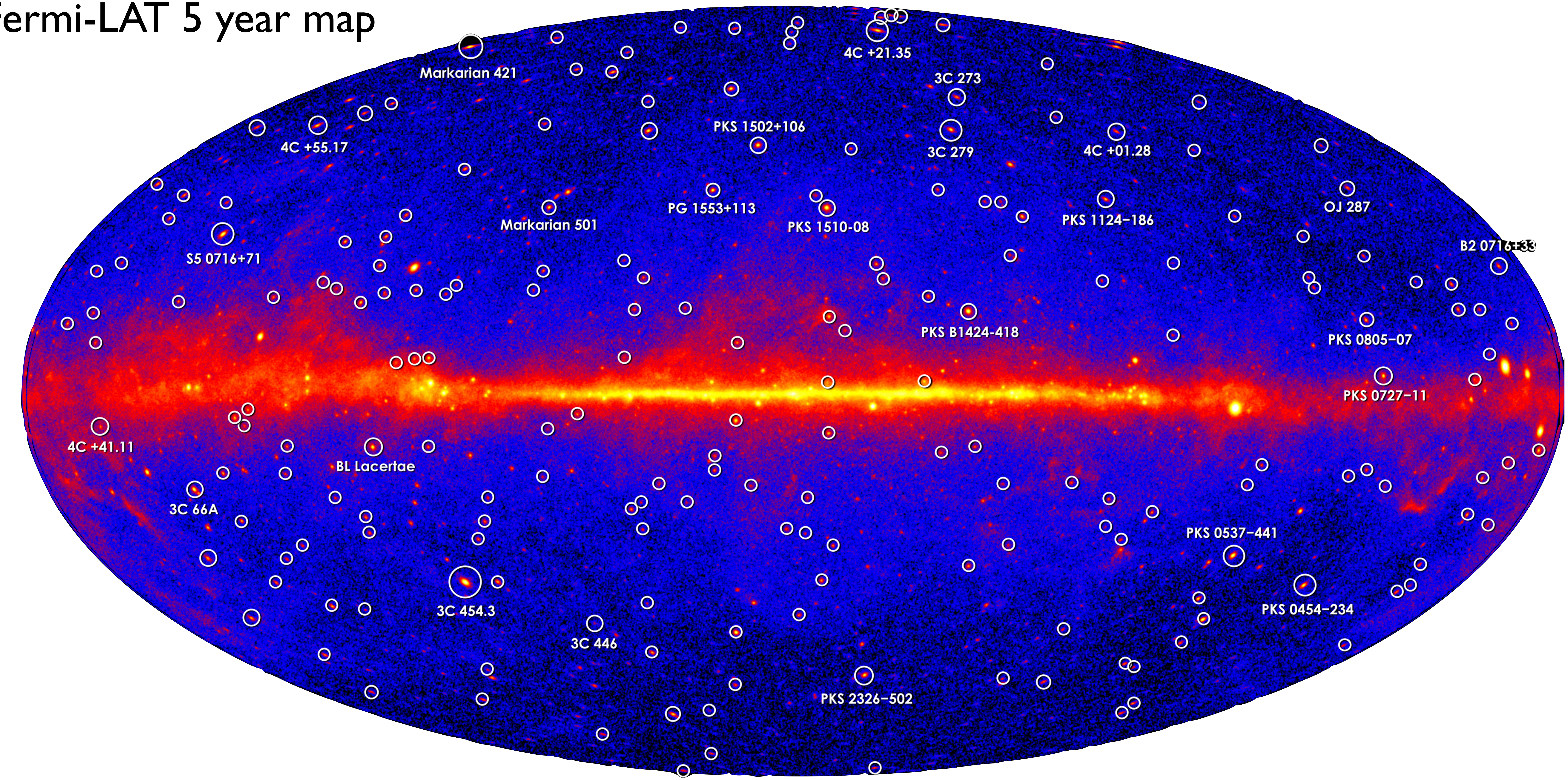
Blazars

Fermi-LAT 5 year map

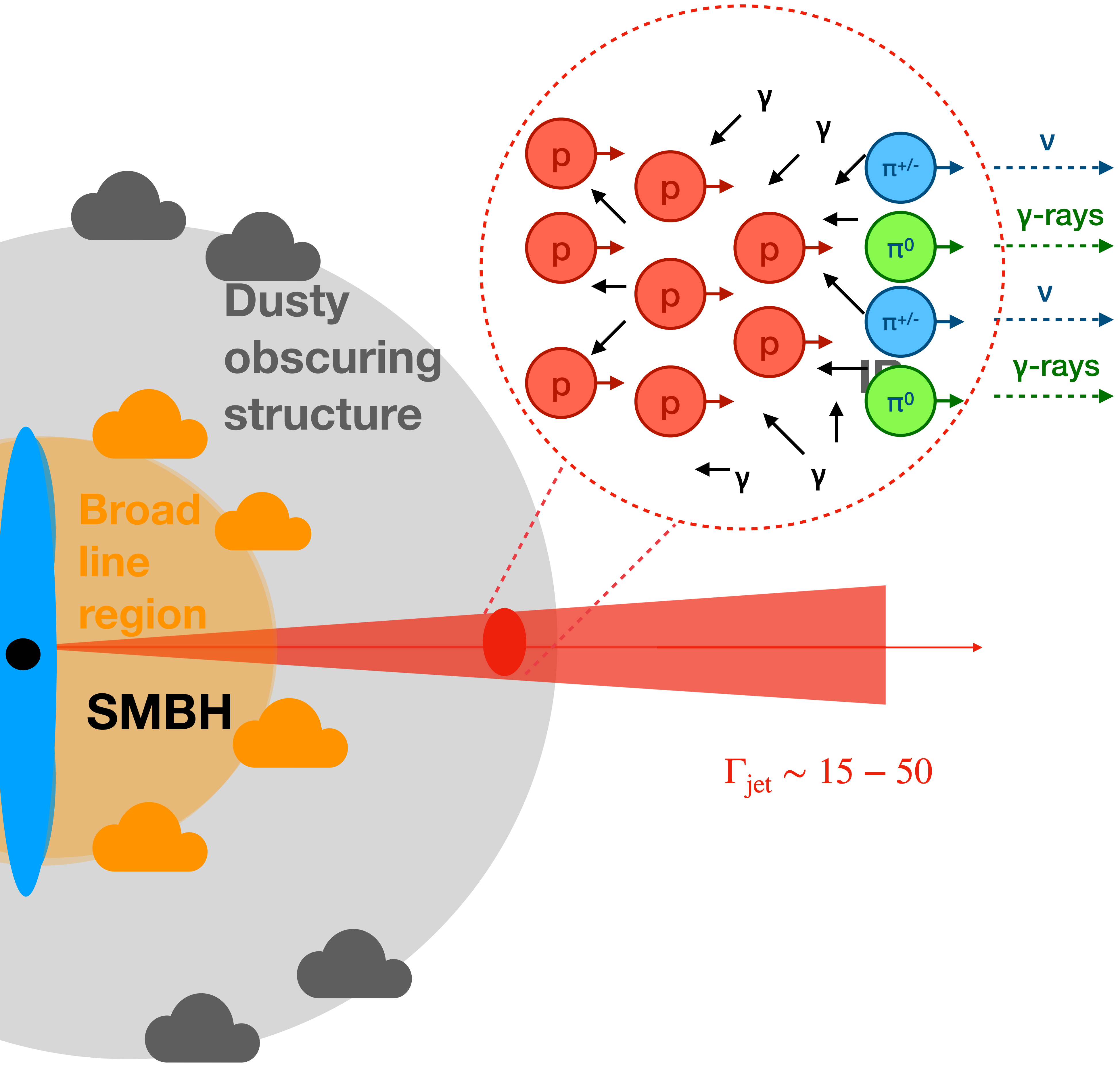


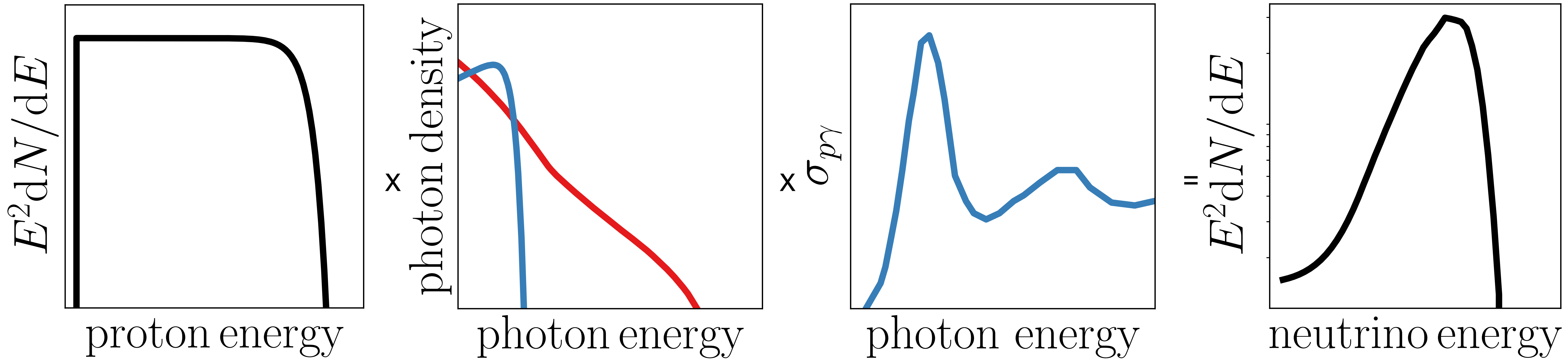
Blazars

Fermi-LAT 5 year map



Neutrino production in blazars





$$E_{\rm BLR} = 10.2 \text{ eV}$$

$$E_{\rm dust\ torus} = 0.1 \text{ eV}$$

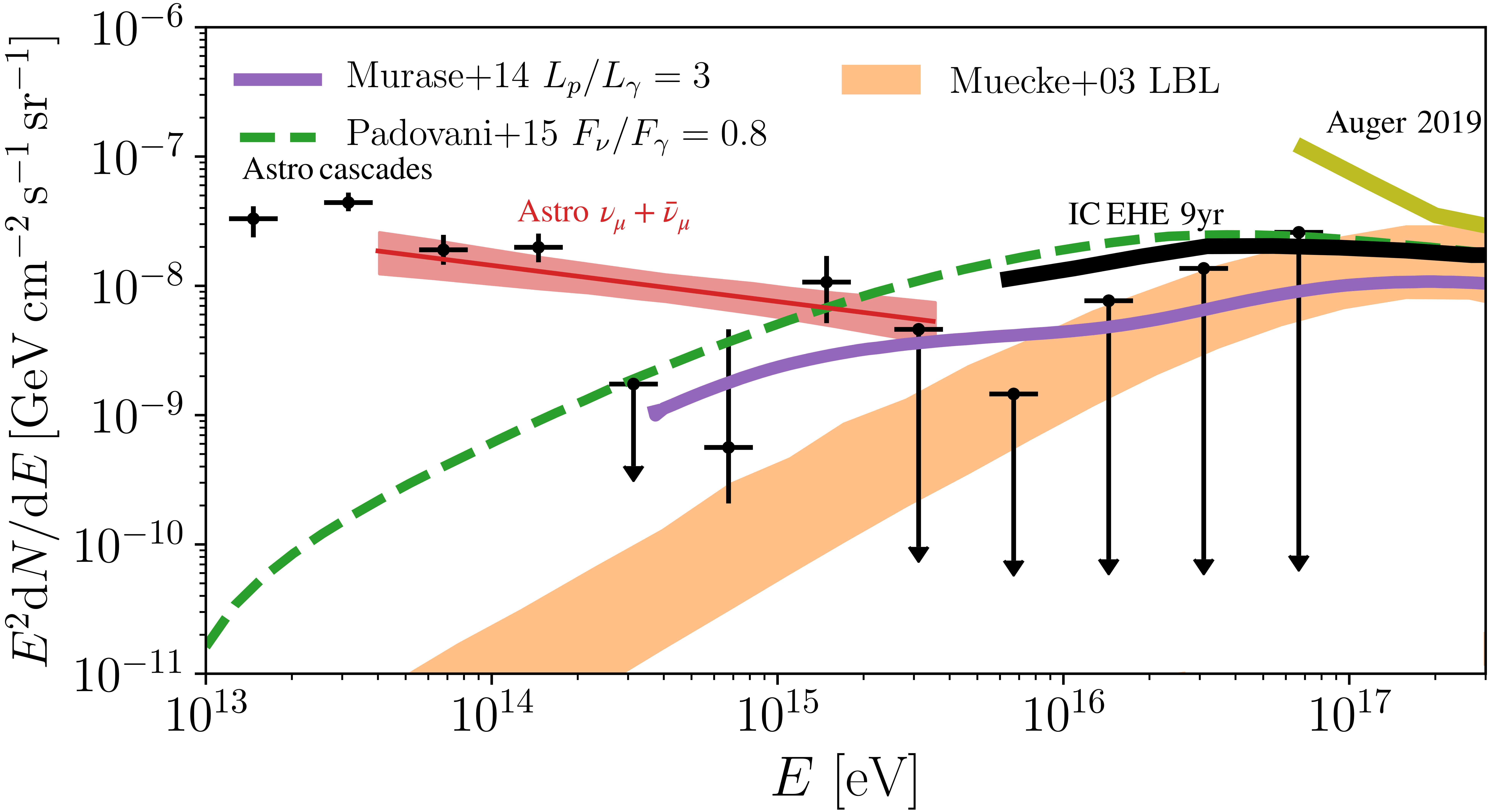
Neutrino typical energy:

$$E_{\nu,\rm BLR} = \frac{80 \text{ PeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \frac{10 \text{ eV}}{E_\gamma}$$

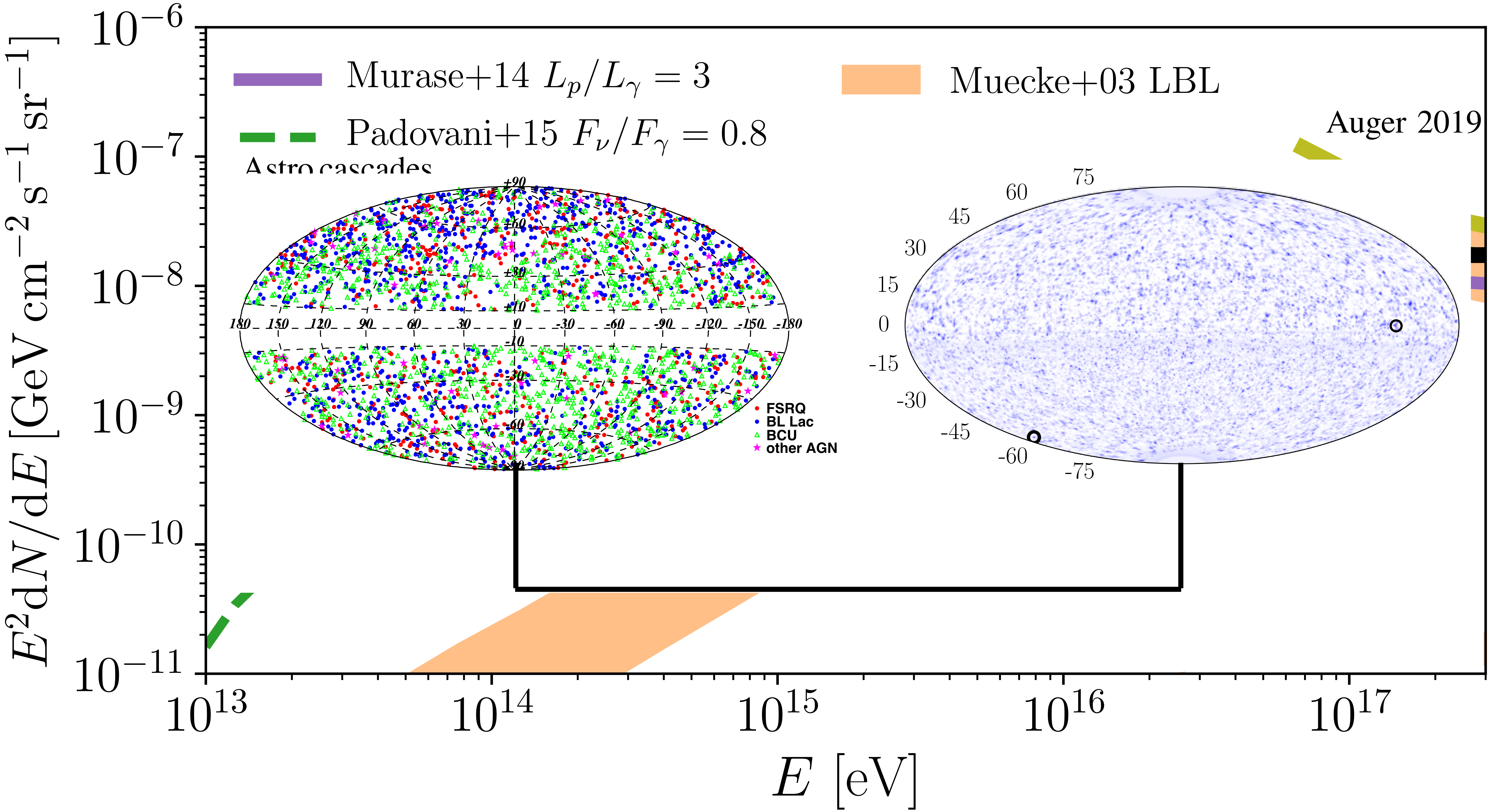
$$E_{\nu,\rm IR} = \frac{8 \text{ EeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \frac{0.1 \text{ eV}}{E_\gamma}$$

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, Righi et al 2020, Rodrigues et al 2021

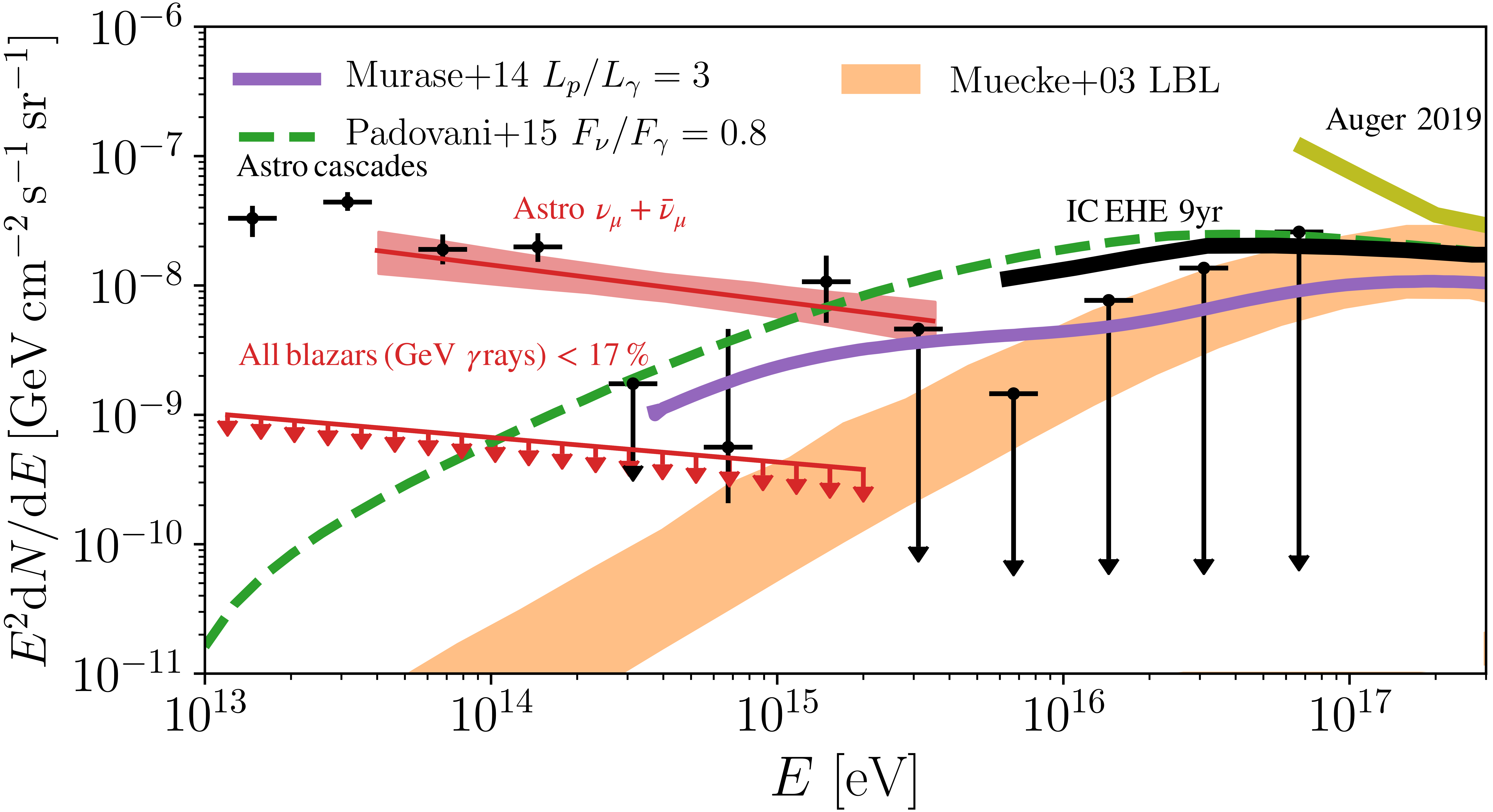
Blazar contribution to the diffuse neutrino flux



Blazar contribution to the diffuse neutrino flux

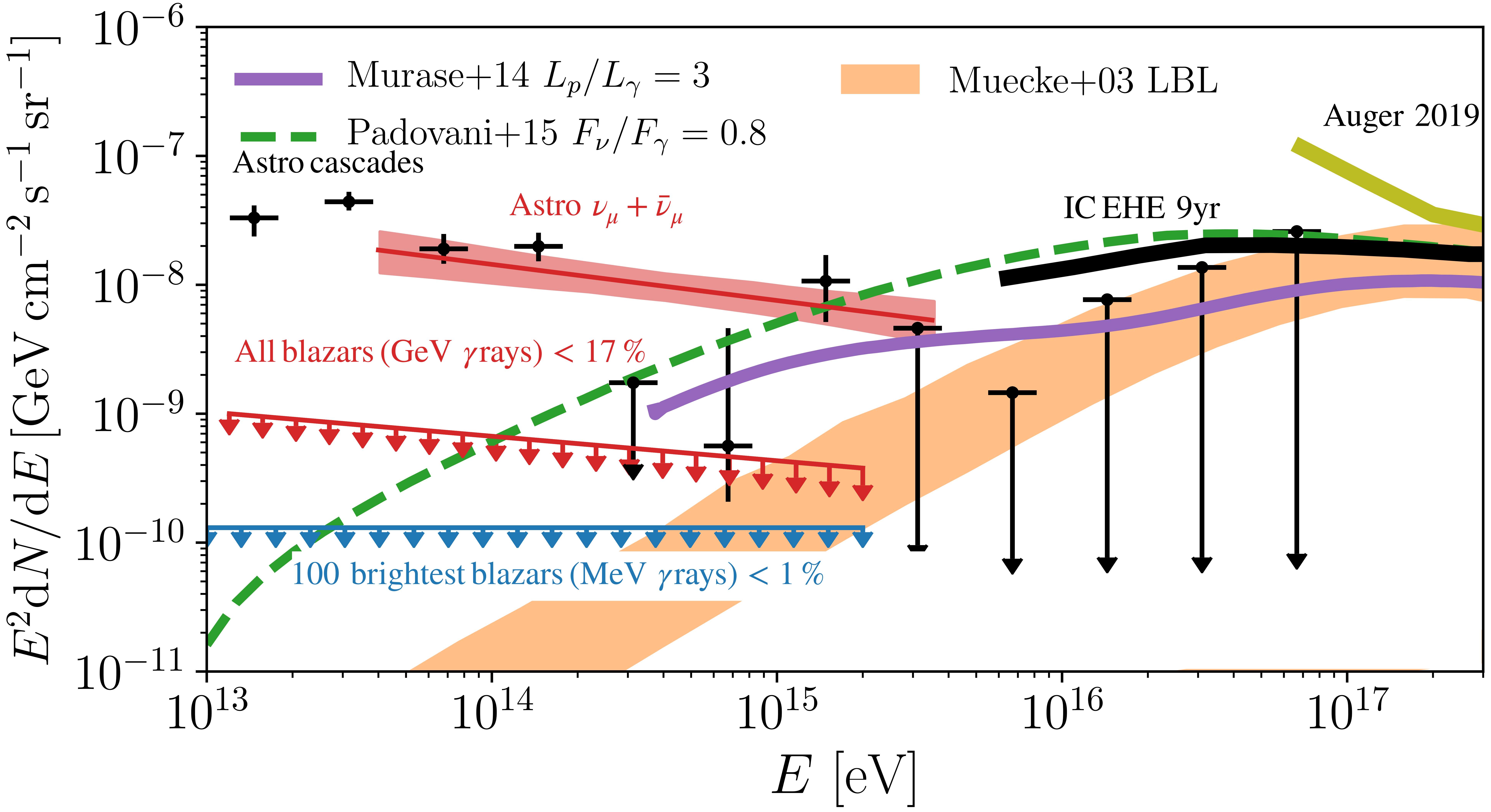


Blazar contribution to the diffuse neutrino flux



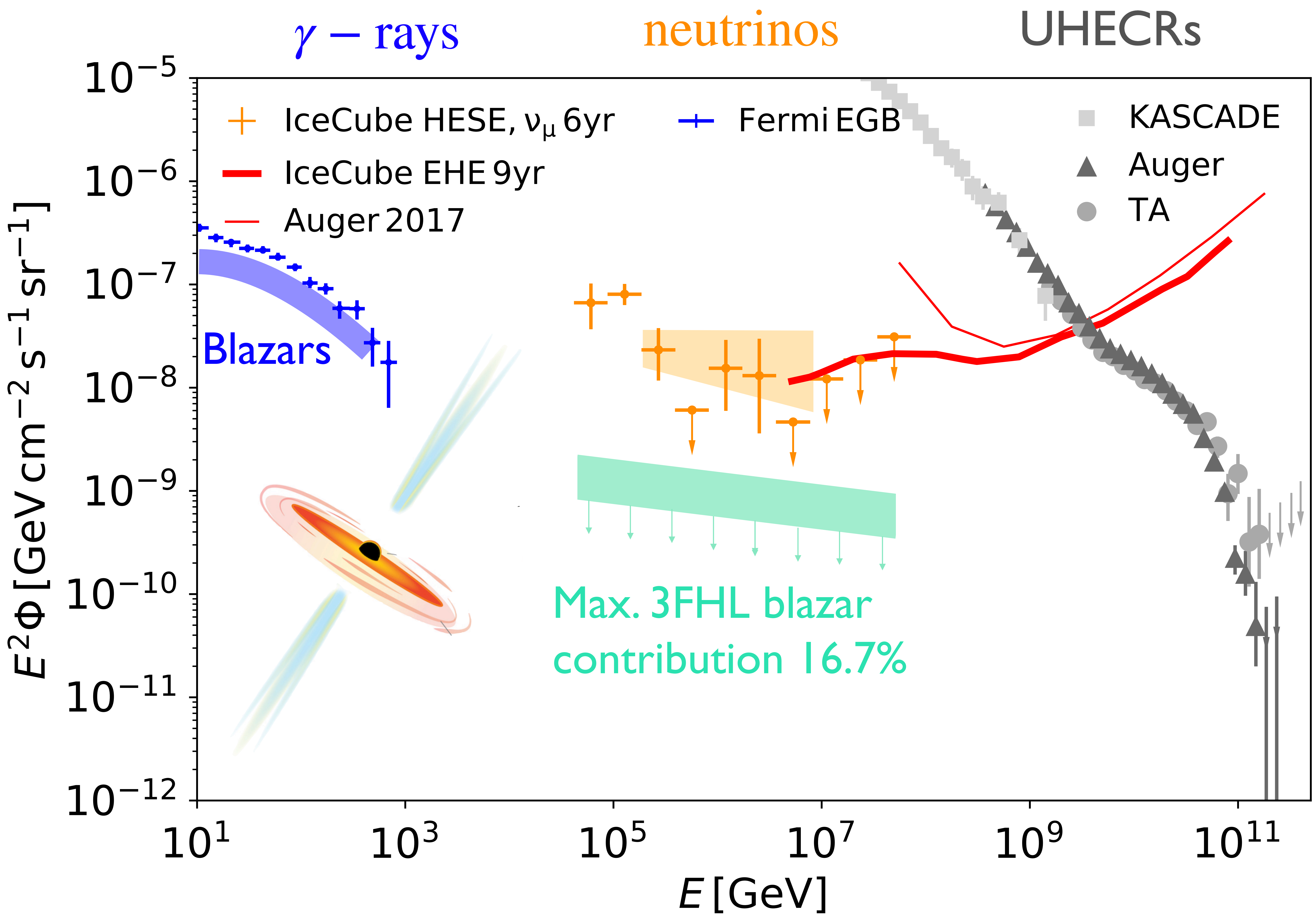
Huber for IceCube Coll PoS (ICRC 2019) 916. Limits also apply to infrared selected blazars, ≲27% with spectral templates: IceCube Coll PoS (ICRC2017) 994

Blazar contribution to the diffuse neutrino flux

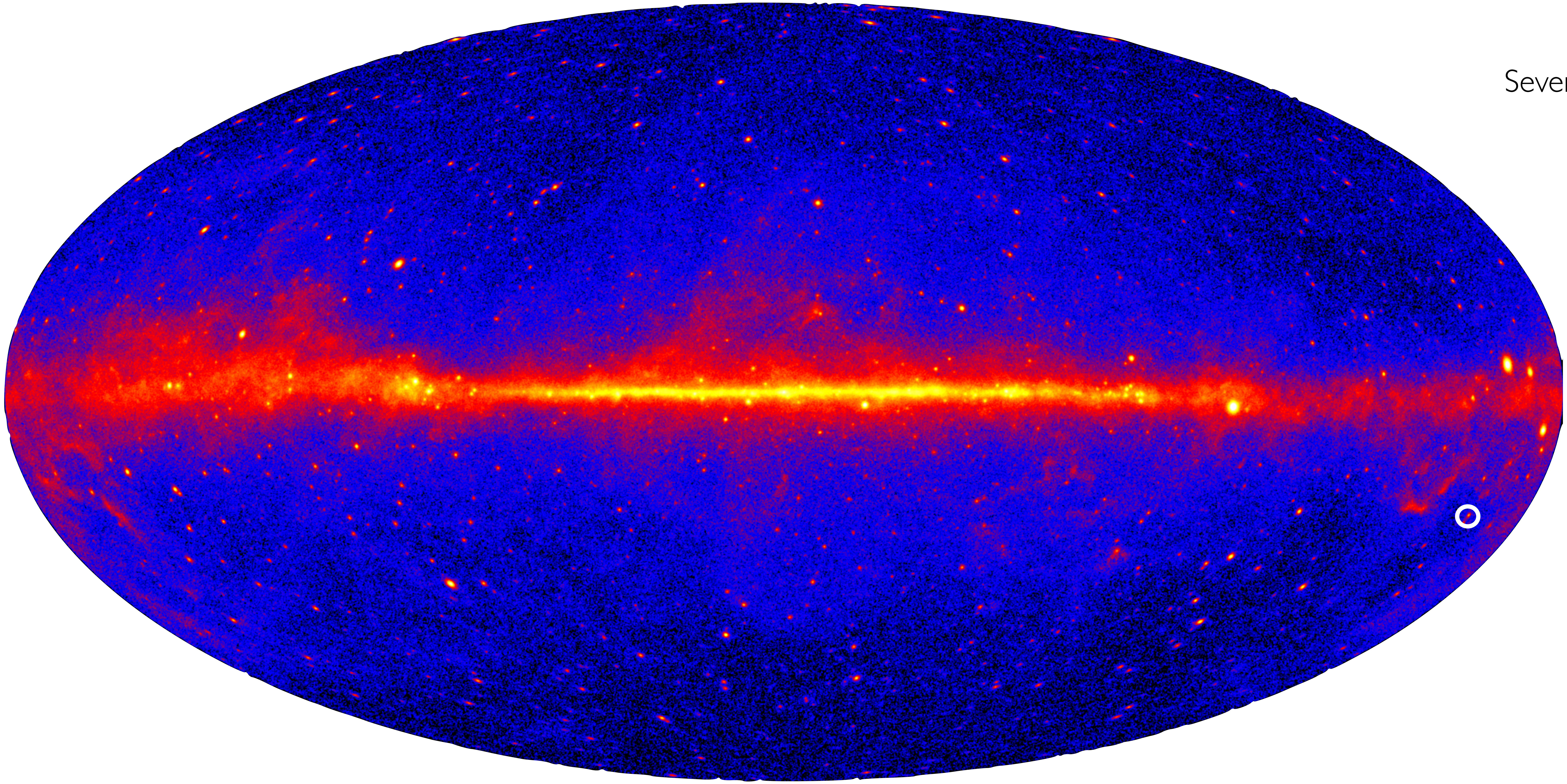


Abbasi et al (IceCube Coll), 2022, Based on 1FLE blazar catalogue

Joint origin disfavoured



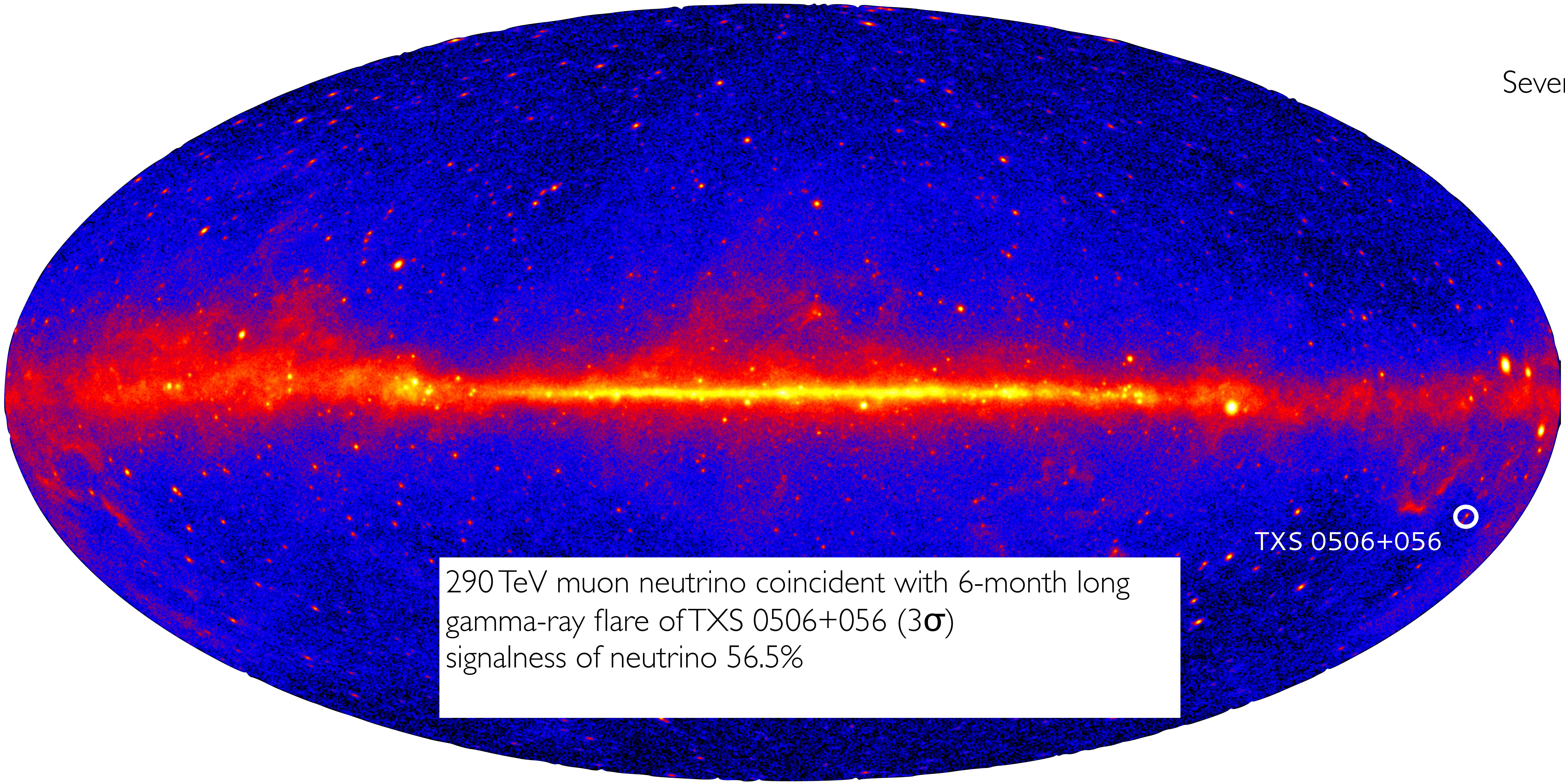
Blazars coincident with high-energy neutrinos



Several dozen associations so far ≥ 3σ:

3.3σ 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)
de Menezes et al ICRC 2021
Buson et al ApJL (2022)

Blazars coincident with high-energy neutrinos



290 TeV muon neutrino coincident with 6-month long gamma-ray flare of TXS 0506+056 (3σ)
signalness of neutrino 56.5%

Several dozen associations so far ≥ 3σ:

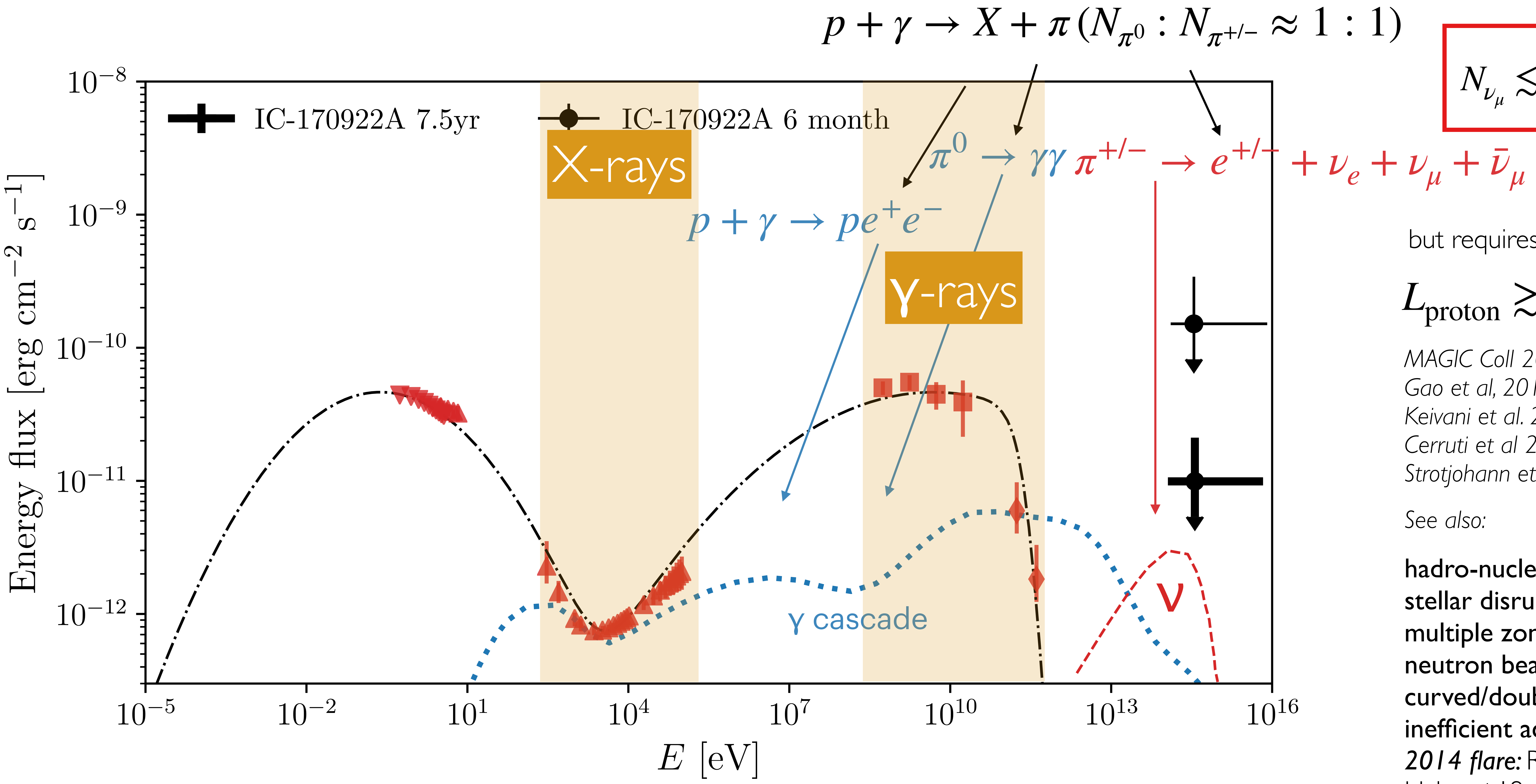
3.3σ IceCube Coll 10yr
Point-Source Analysis (3 blazars)
Franckowiak et al ApJ 893 (2020)
Giommi et al MNRAS 497 (2020)
Hovatta et al A&A 650 (2021)
Plavin et al ApJ 908 (2021)
de Menezes et al ICRC 2021
Buson et al ApJL (2022)

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 + IC170922A



$N_{\nu_\mu} \lesssim 0.05/6$ months

but requires atypically high proton luminosity

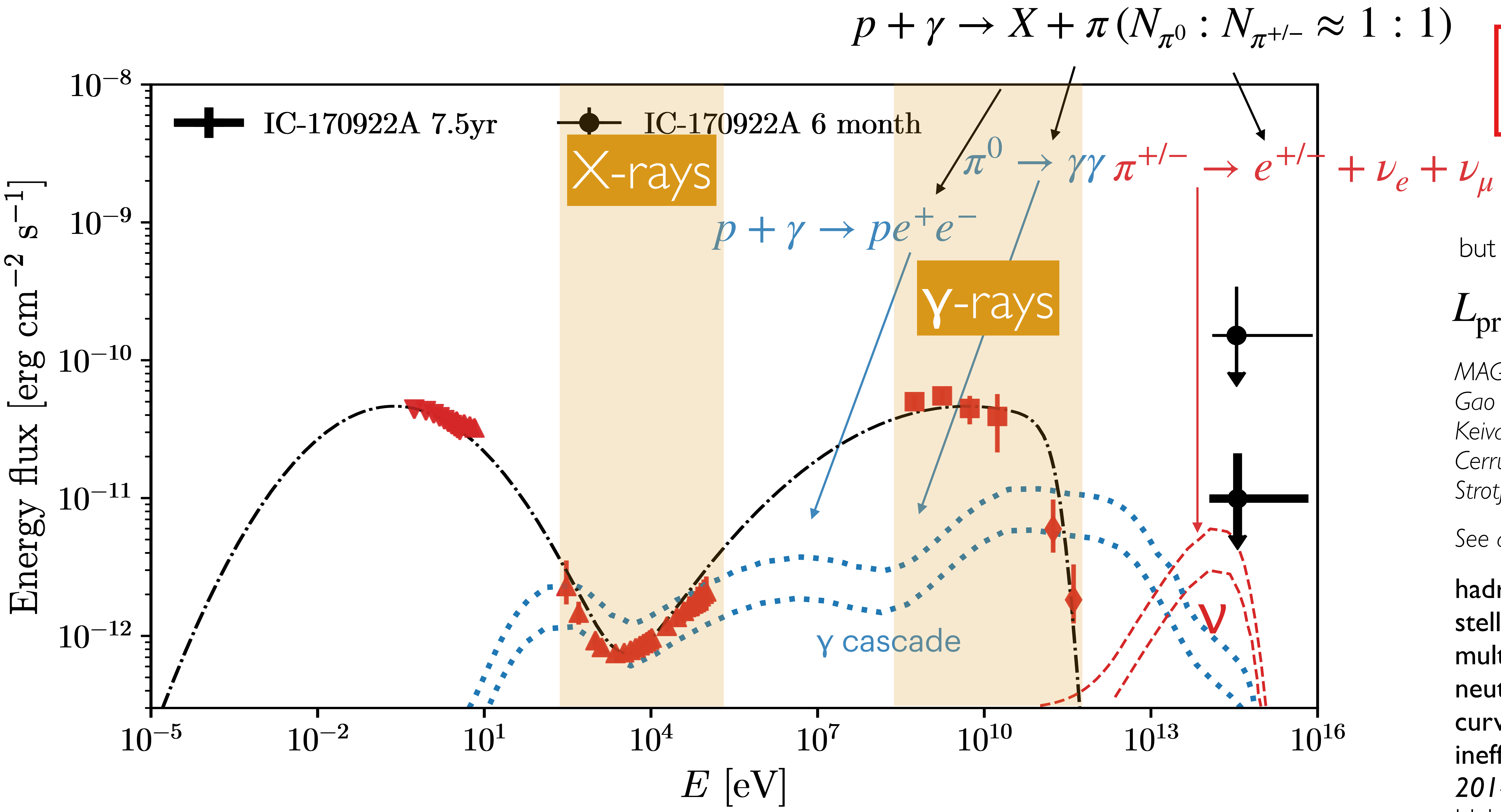
$L_{\text{proton}} \gtrsim 10 - 100\ L_{\text{Eddington}}$

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,
Strotjohann et al 2019, A&A, 622, L9

See also:

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*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20,
and more…!

TXS 0506+056 + IC170922A



$N_{\nu_\mu} \lesssim 0.05/6$ months

but requires atypically high proton luminosity

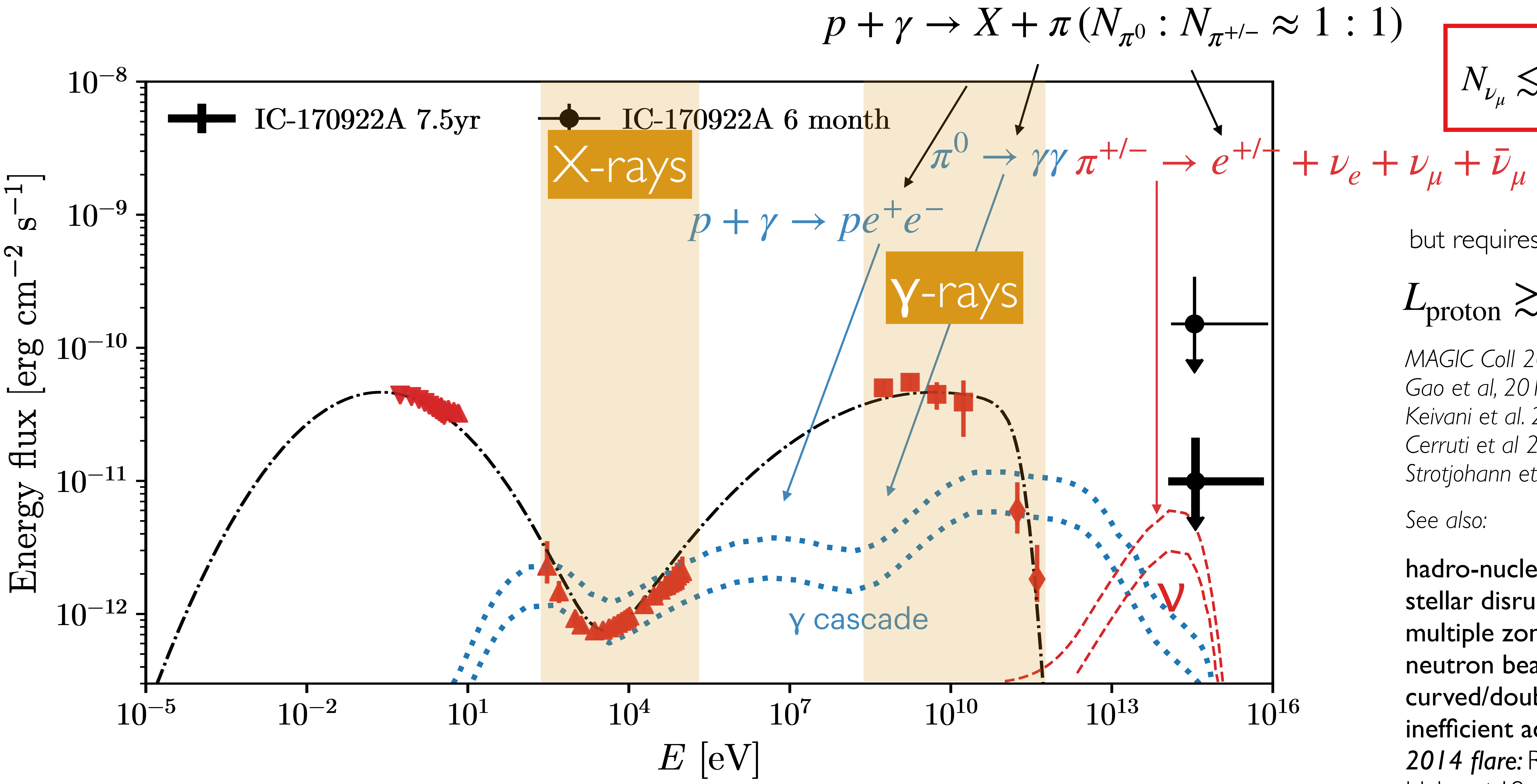
$L_{\rm proton} \gtrsim 10 - 100 \; L_{\rm Eddington}$

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,
Strotjohann et al 2019, A&A, 622, L9

See also:

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*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20,
and more…!

TXS 0506+056 + IC170922A



$N_{\nu_\mu} \lesssim 0.05/6$ months

but requires atypically high proton luminosity

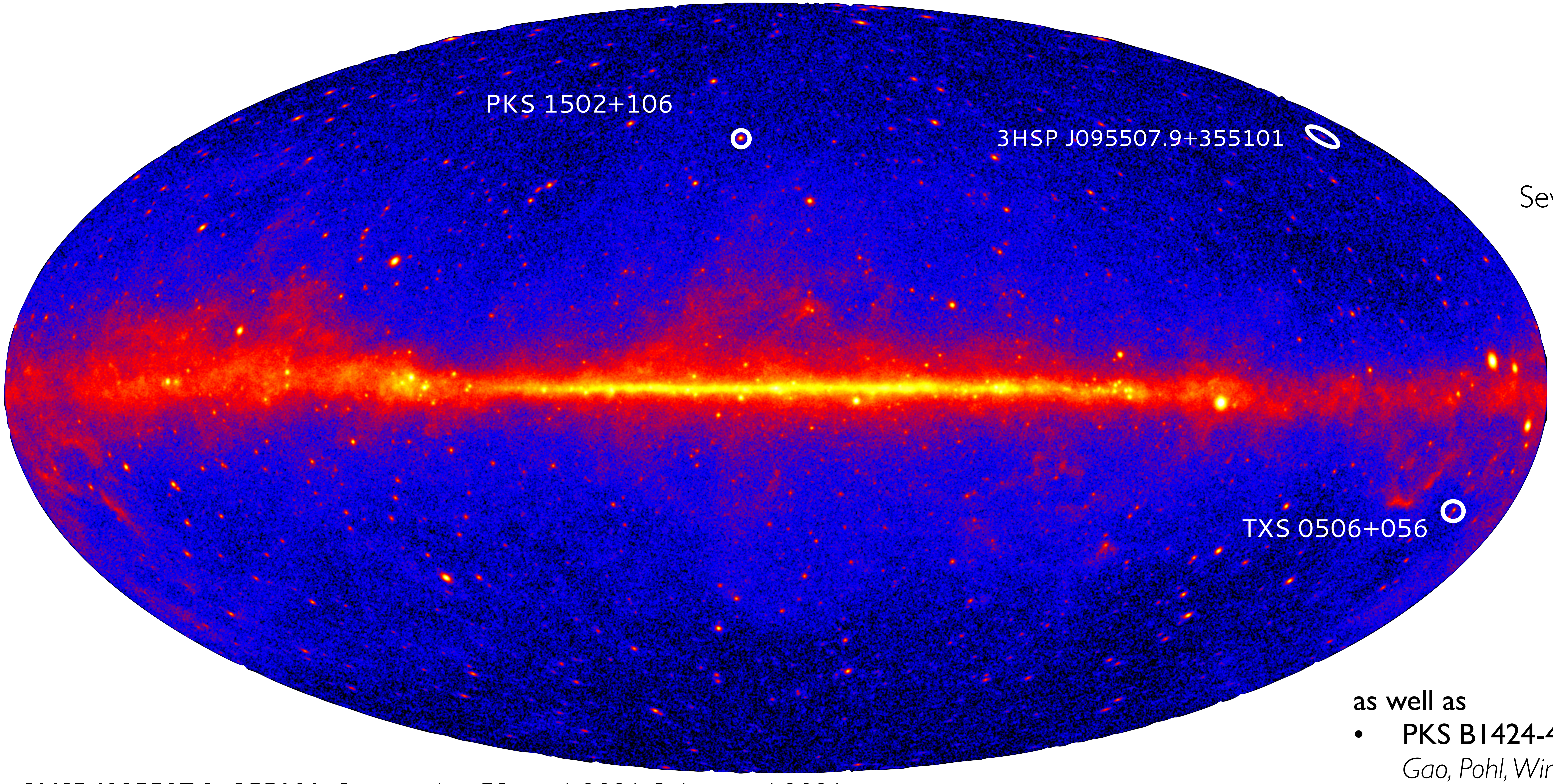
$L_{\mathrm{proton}} \gtrsim 10 - 100\ L_{\mathrm{Eddington}}$

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,
Strotjohann et al 2019, A&A, 622, L9

See also:

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*
2014 flare: Reimer+19, Rodrigues+19, Halzen+19, Petropoulou+20,
and more…!

Blazars coincident with high-energy neutrinos



Several dozen associations so far ≥ 3σ:

3.3σ 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)
de Menezes et al ICRC 2021
Buson et al ApJL (2022)

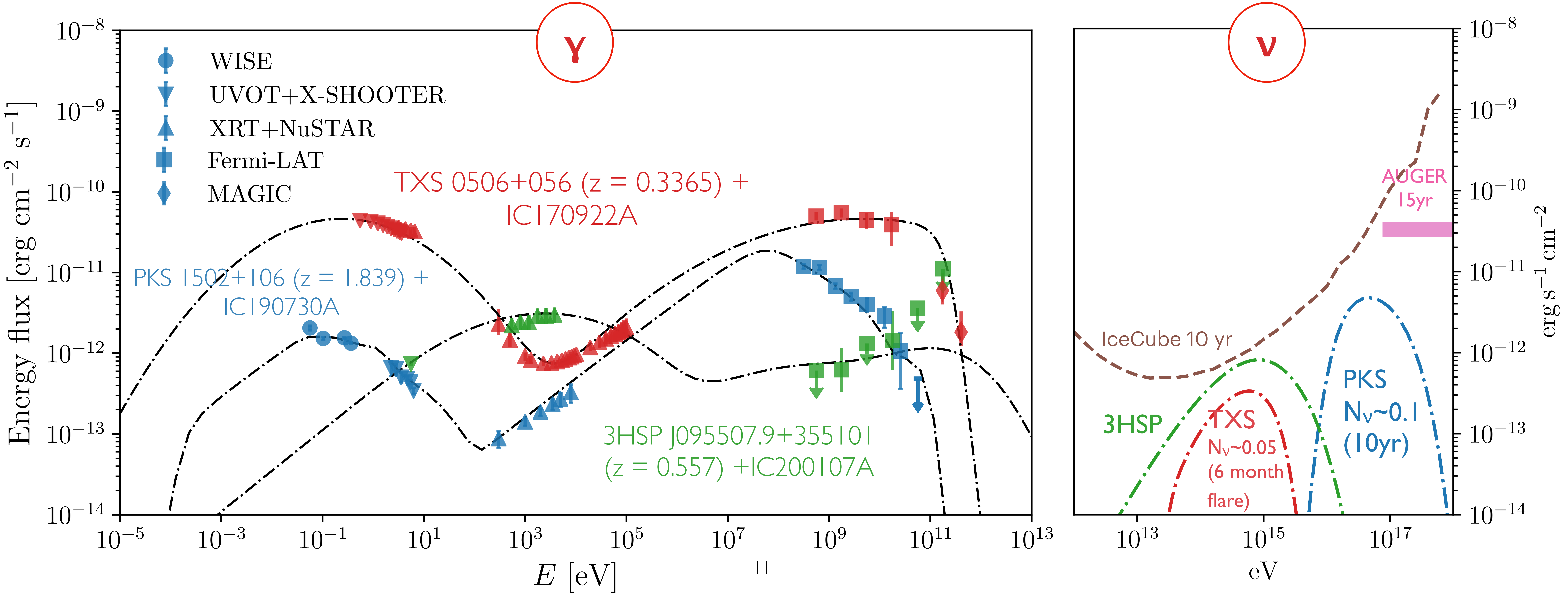
3HSP J095507.9+355101: *Petropoulou, FO et al. 2021, Paliya et al 2021*
PKS 1502+106: *Rodrigues et al 2021, Britzen et al 2021, FO et al 2021, Wang & Xue 2021*

as well as
- **PKS B1424-418+IC35** *Kadler, Nat Phys 12 (2016), Gao, Pohl, Winter, ApJ 843 (2017)*
- **PKS 0735+178 + 211208A** *Sahakyan et al 2022 arXiv:2204.05060v1*

Blazars coincident with high–energy neutrinos

- Models consistent (statistically) with neutrino detection for **> month long** flares but require atypically high proton content
- High-luminosity FSRQs ok with more conservative parameters

FO et al 2019
Petropoulou et al 2021
FO et al 2021

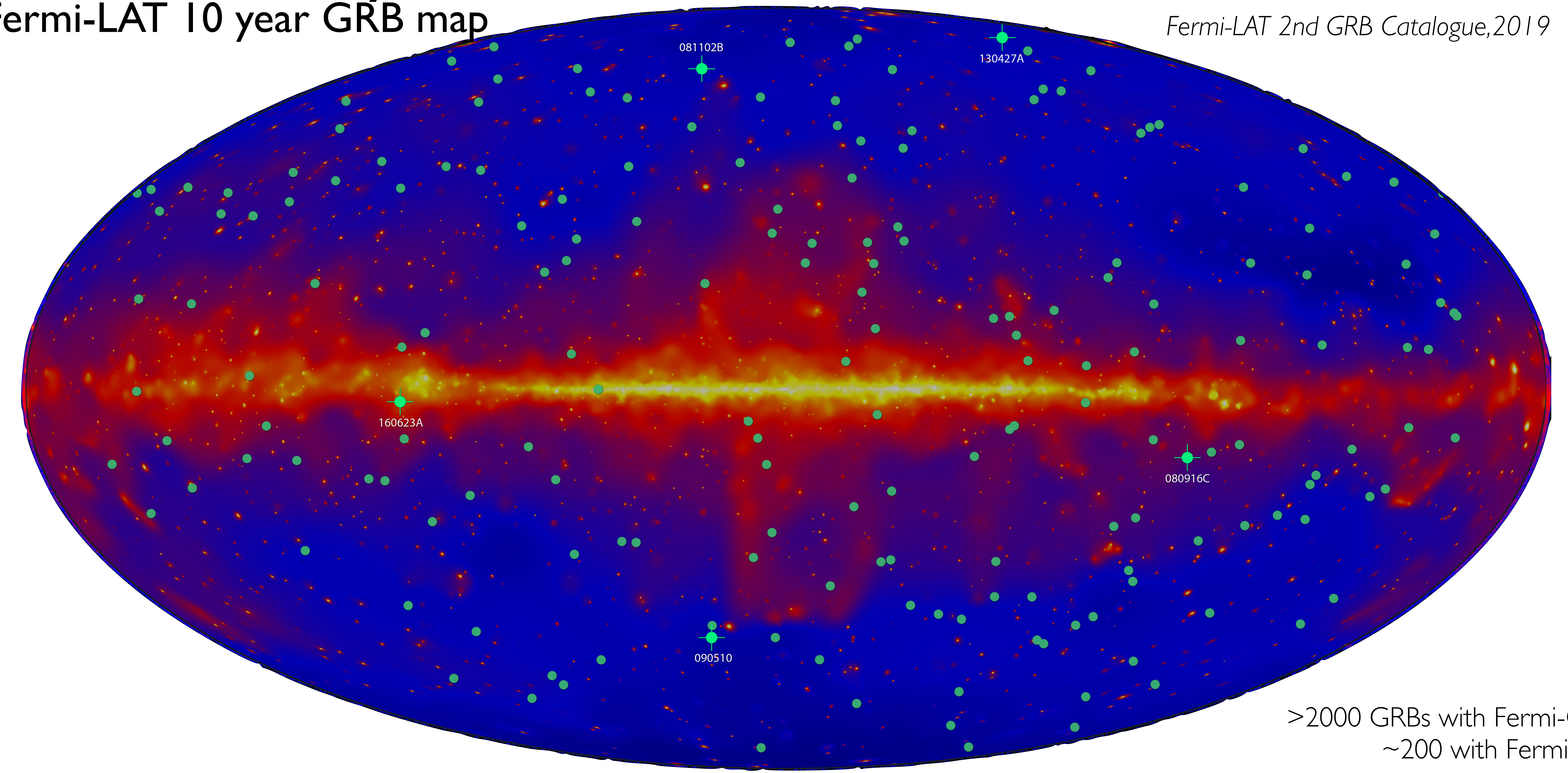


11

Gamma-ray bursts

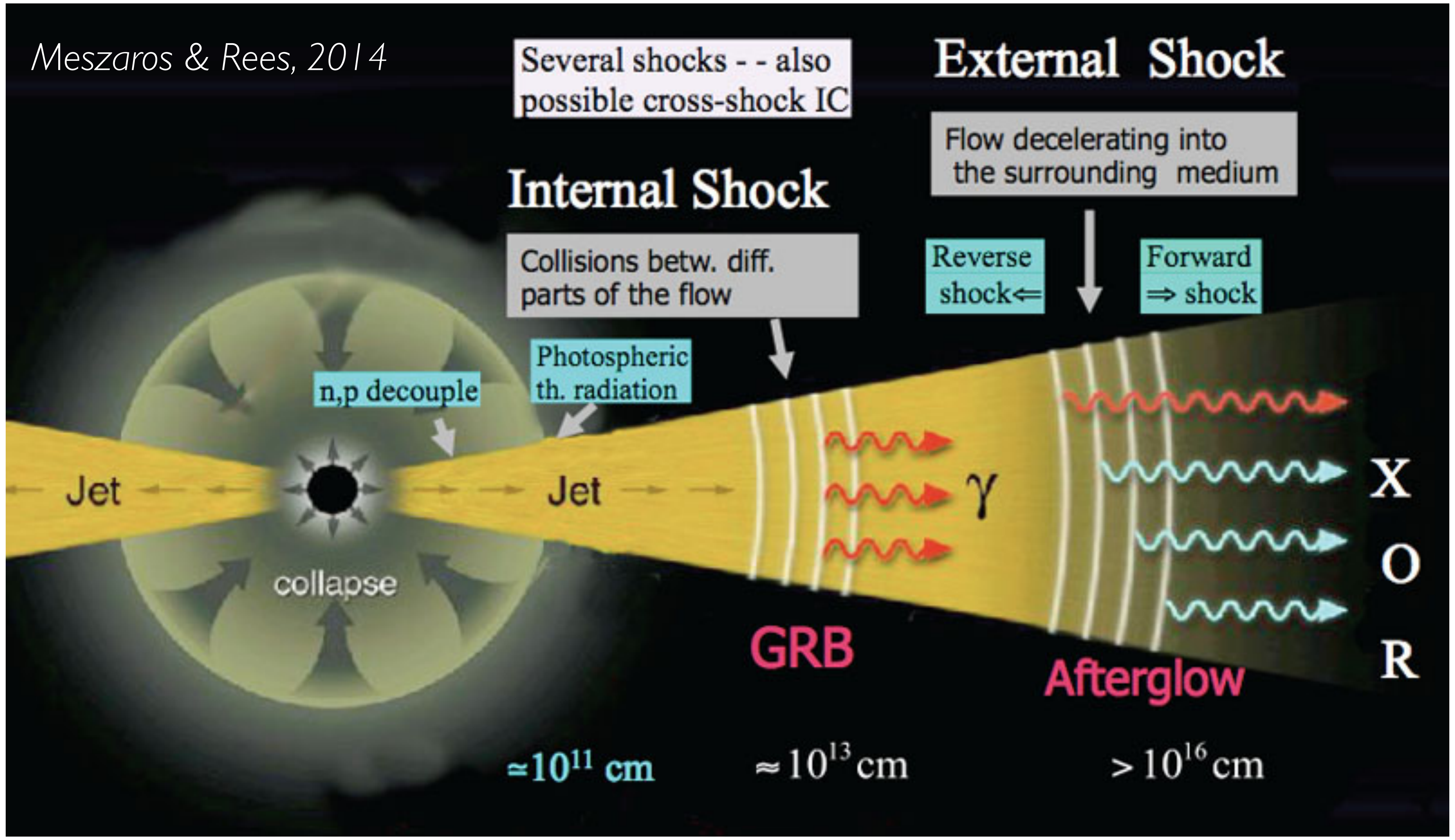
Fermi-LAT 10 year GRB map

Fermi-LAT 2nd GRB Catalogue, 2019

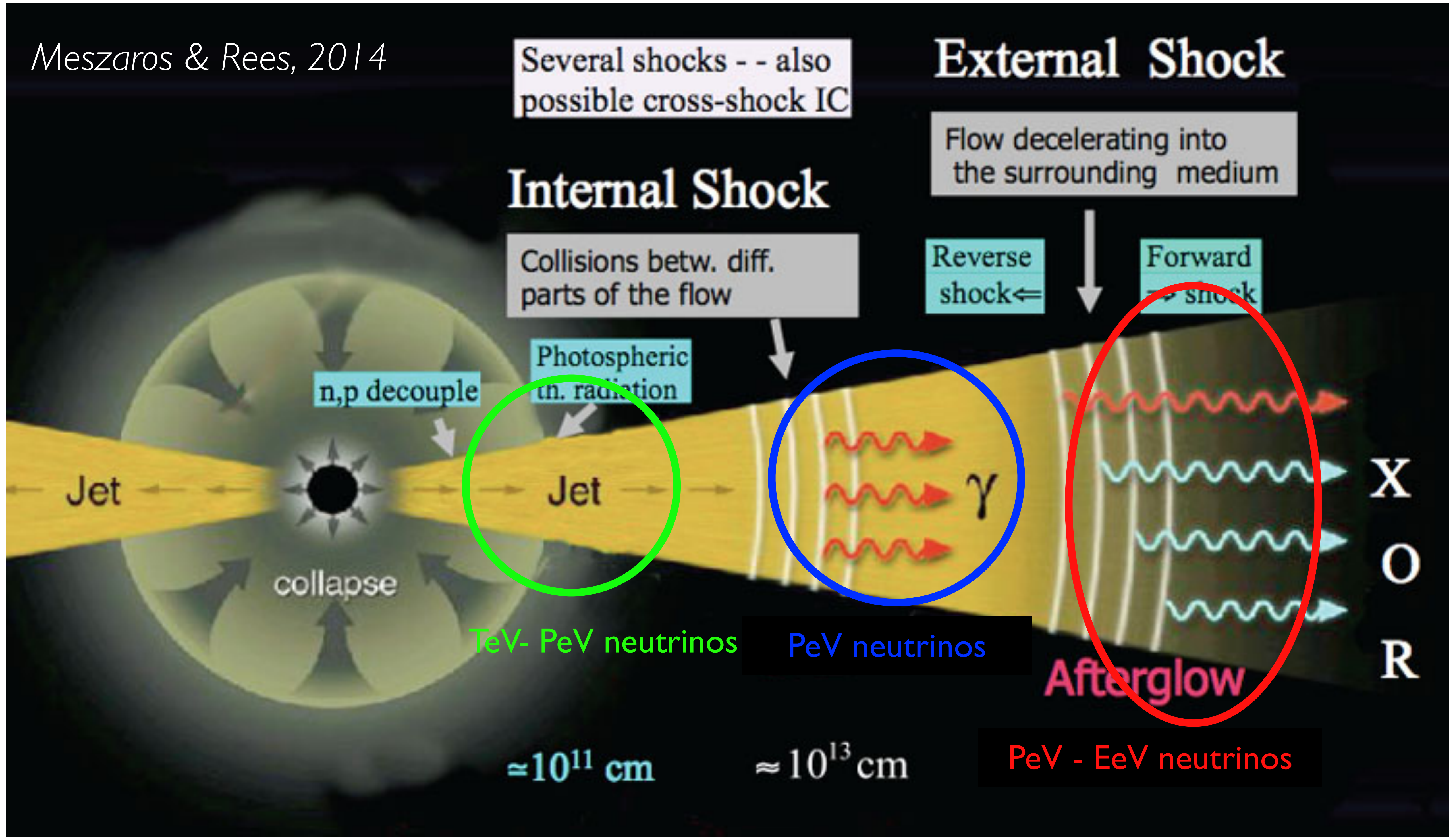


>2000 GRBs with Fermi-GBM
~200 with Fermi-LAT

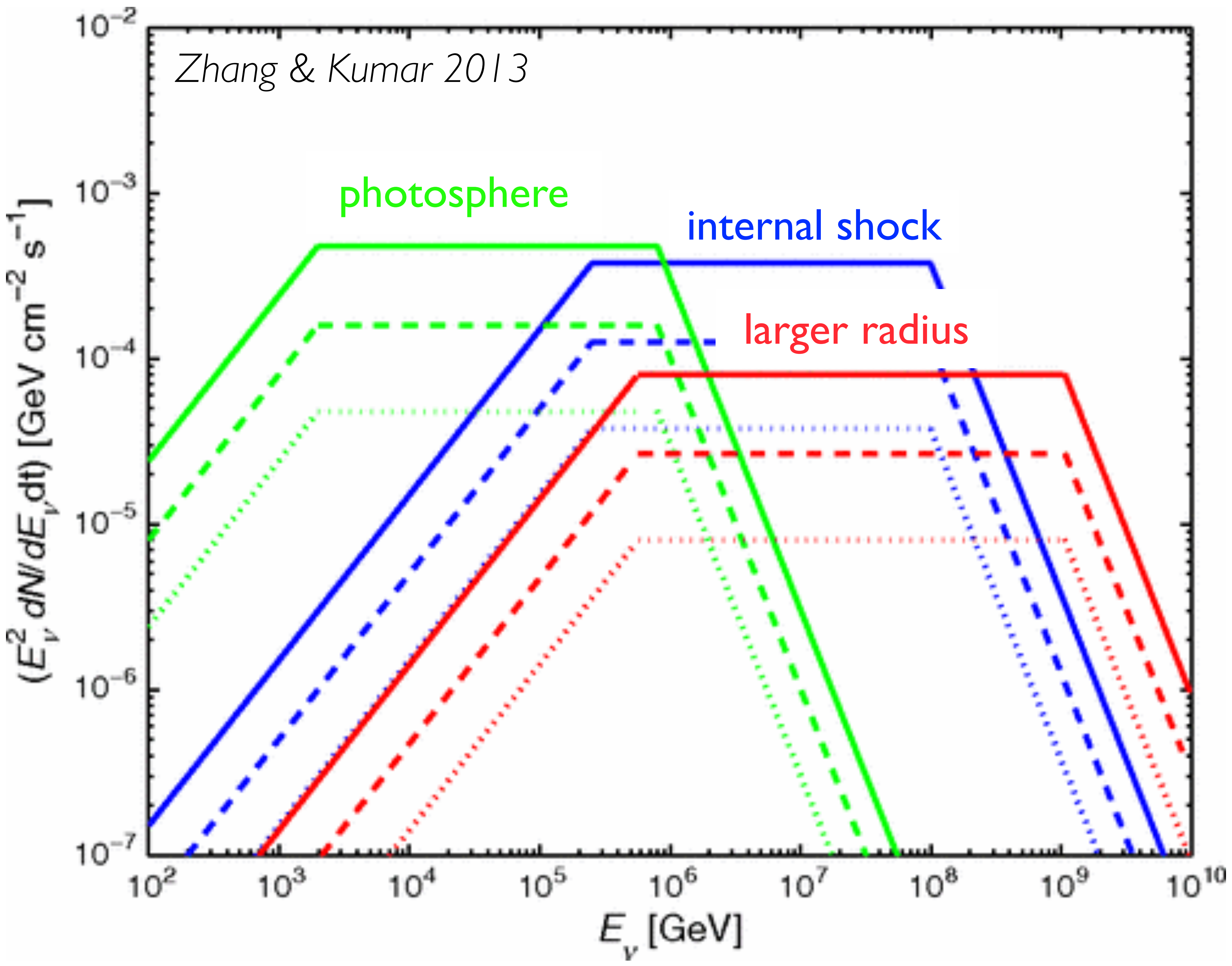
Neutrino production in gamma-ray bursts



Neutrino production in gamma-ray bursts



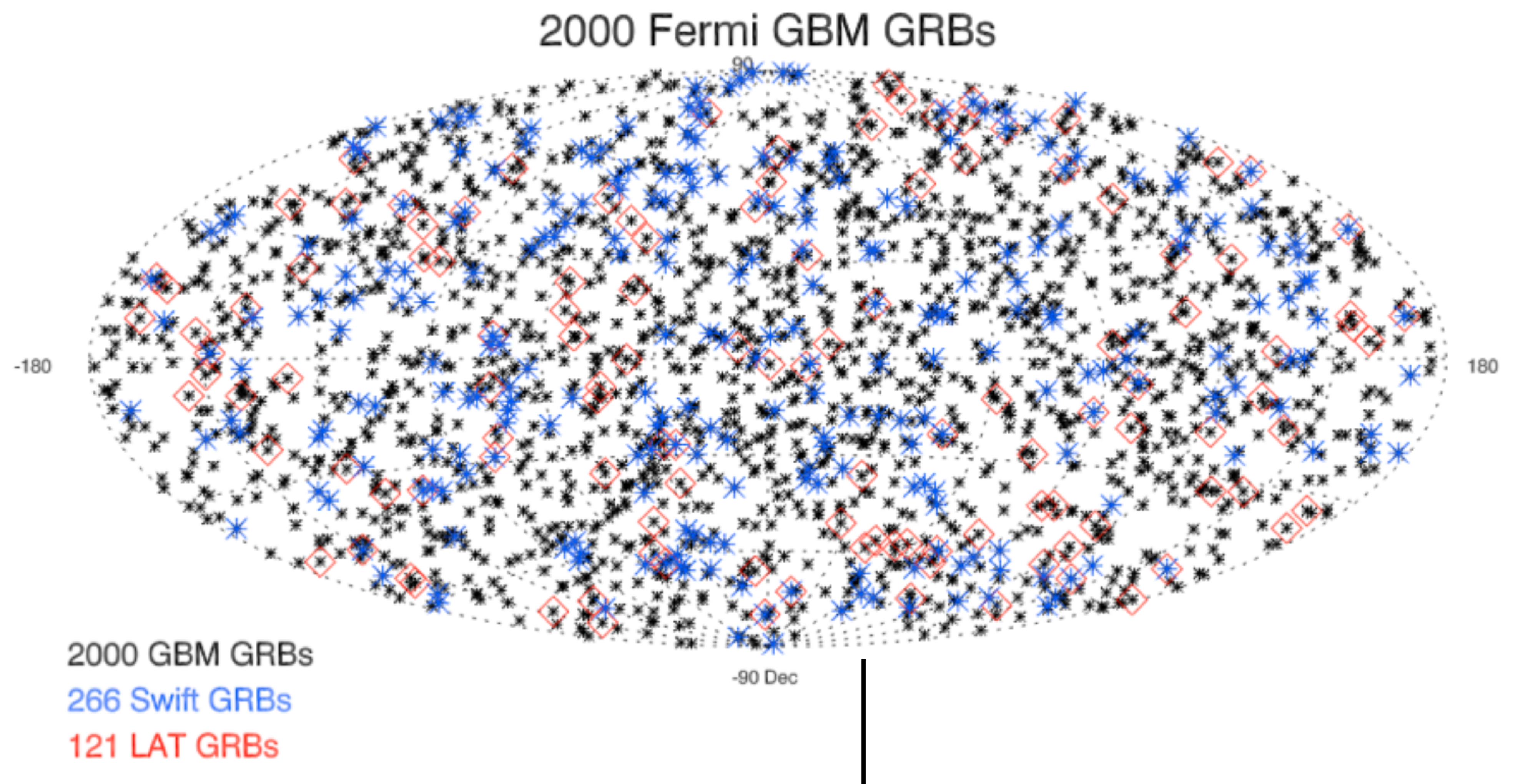
possible neutrino production sites



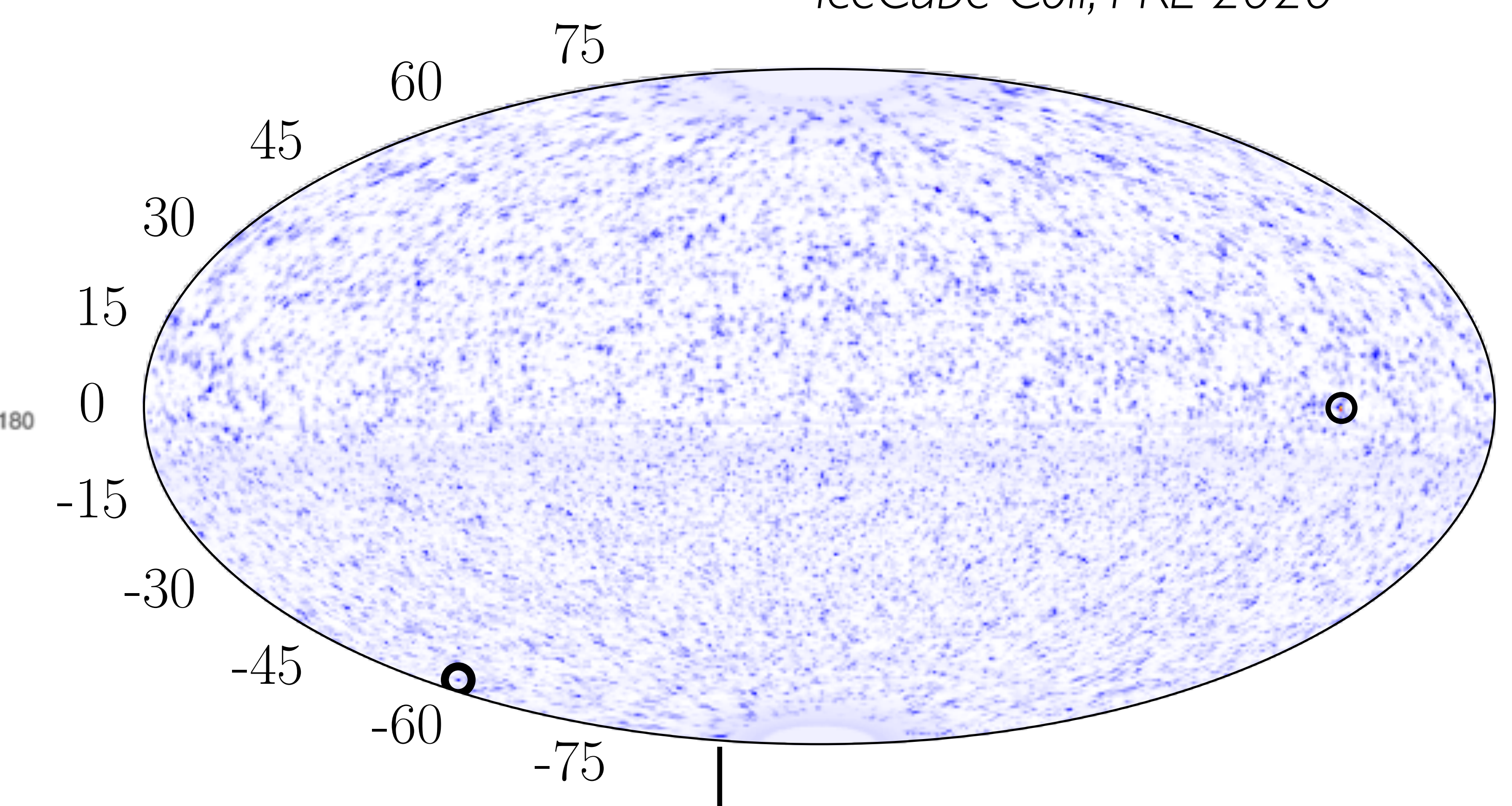
>100 publications on theoretical expectations:
see e.g. review "Neutrinos from GRBs" (Kimura 2022)

GRB contribution to the cosmic neutrino flux

A stacked search for neutrinos coincident with prompt GRB emission by IceCube (now a total of 2091 GRBs) has led to limits on the neutrino production in GRBs



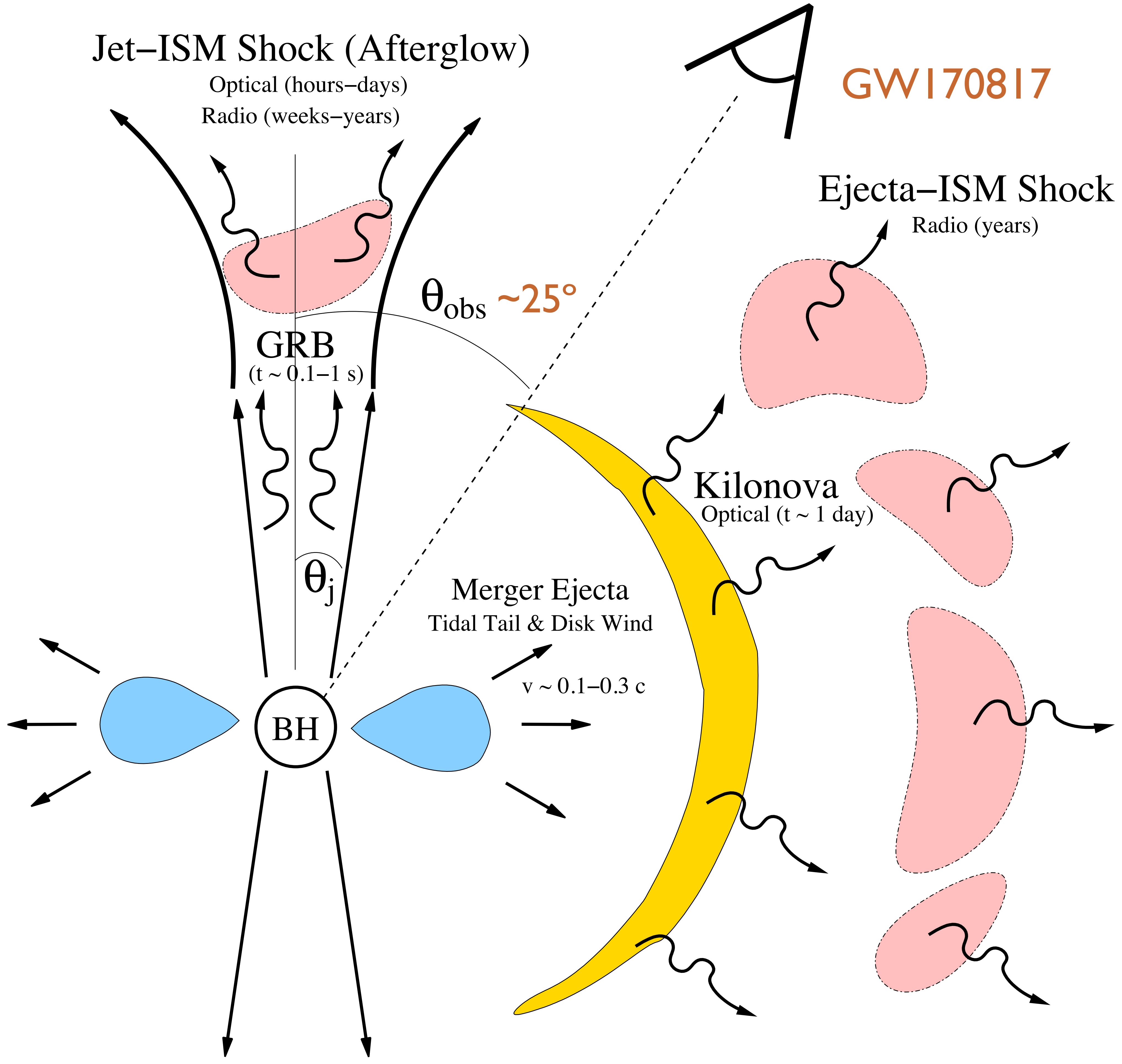
IceCube Coll, PRL 2020



IceCube Coll, ApJ 843 (2017) 112
IceCube Coll., Fermi GBM Coll. 2022 ApJ in press

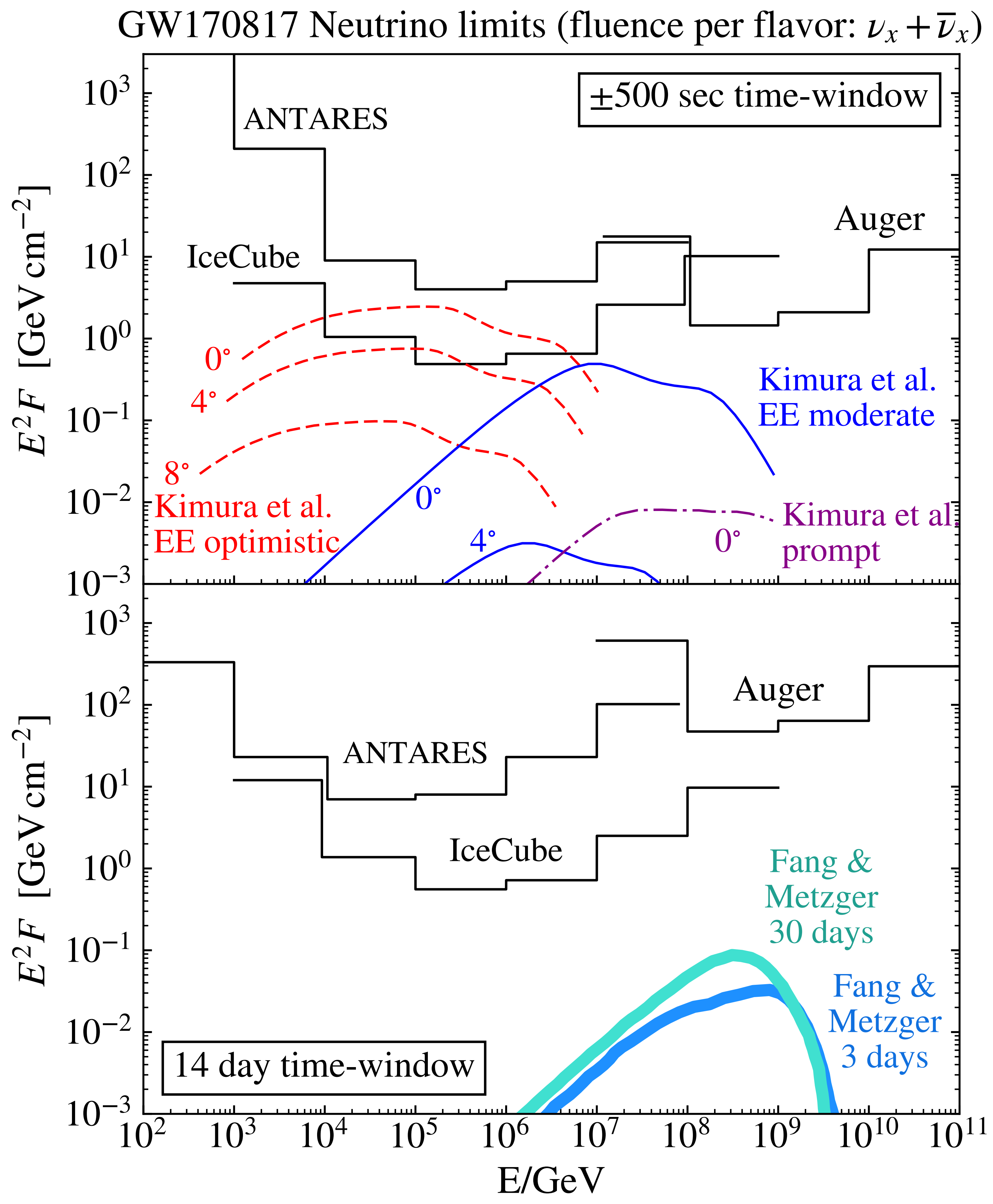
Prompt (ΔT_{promt} ~1-100s): < 1% diffuse neutrino flux
Precursor/Afterglow ($\Delta T_{afterglow}$ ± 14d): < 24% diffuse neutrino flux

Binary neutron star mergers: GW170817



Metzger & Berger, ApJ, 746 (2012) 48, 1

ANTARES, AUGER, ICECUBE, LIGO & VIRGO Coll., ApJ 850 (2017) 2, L35



neutrinos from the GRB

neutrinos from magnetar nebula

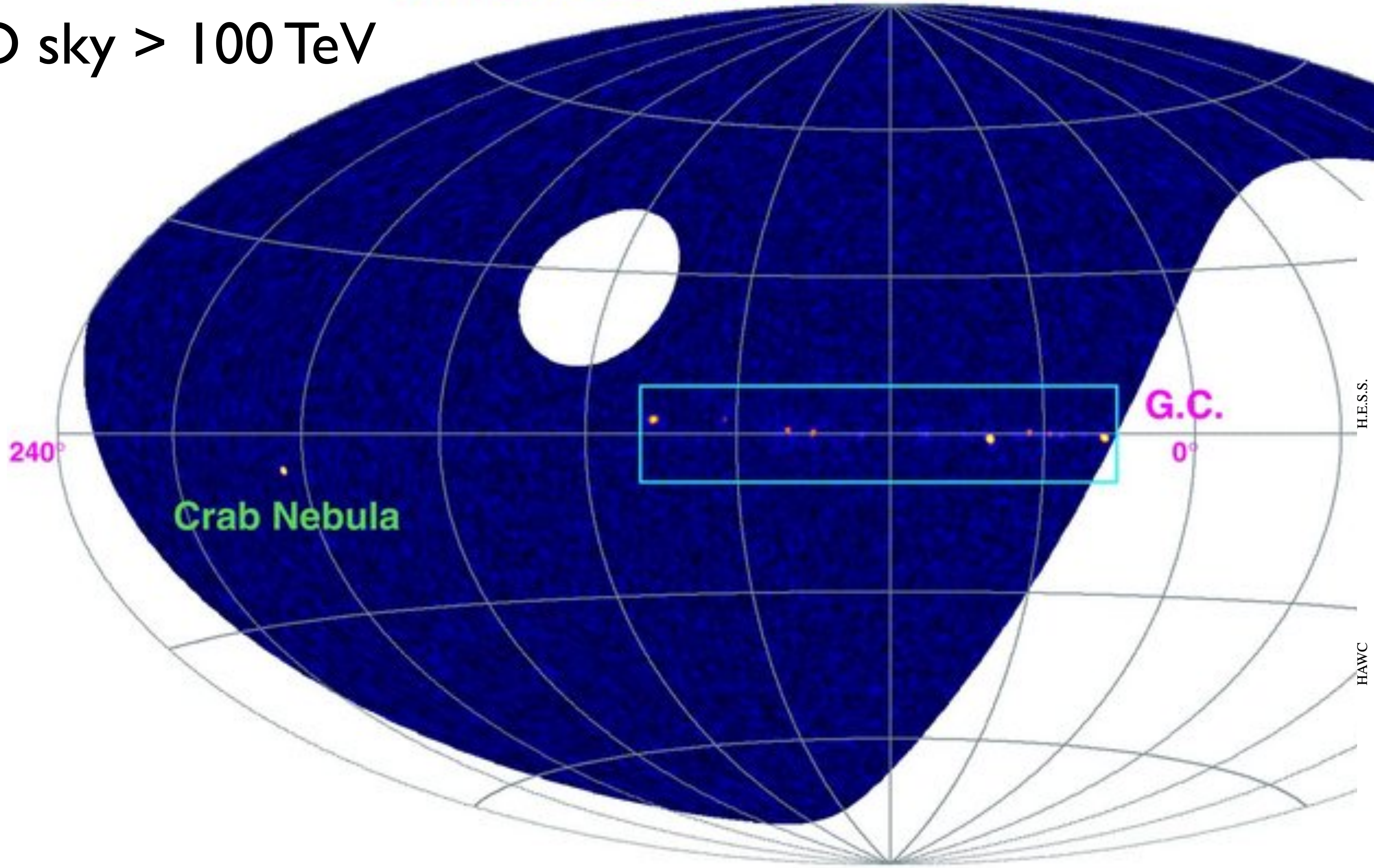
Could be sources of CRs up to the ankle

Rodrigues, Biehl, Boncioli, Taylor 2018, Kimura, Murase, Meszaros 2018

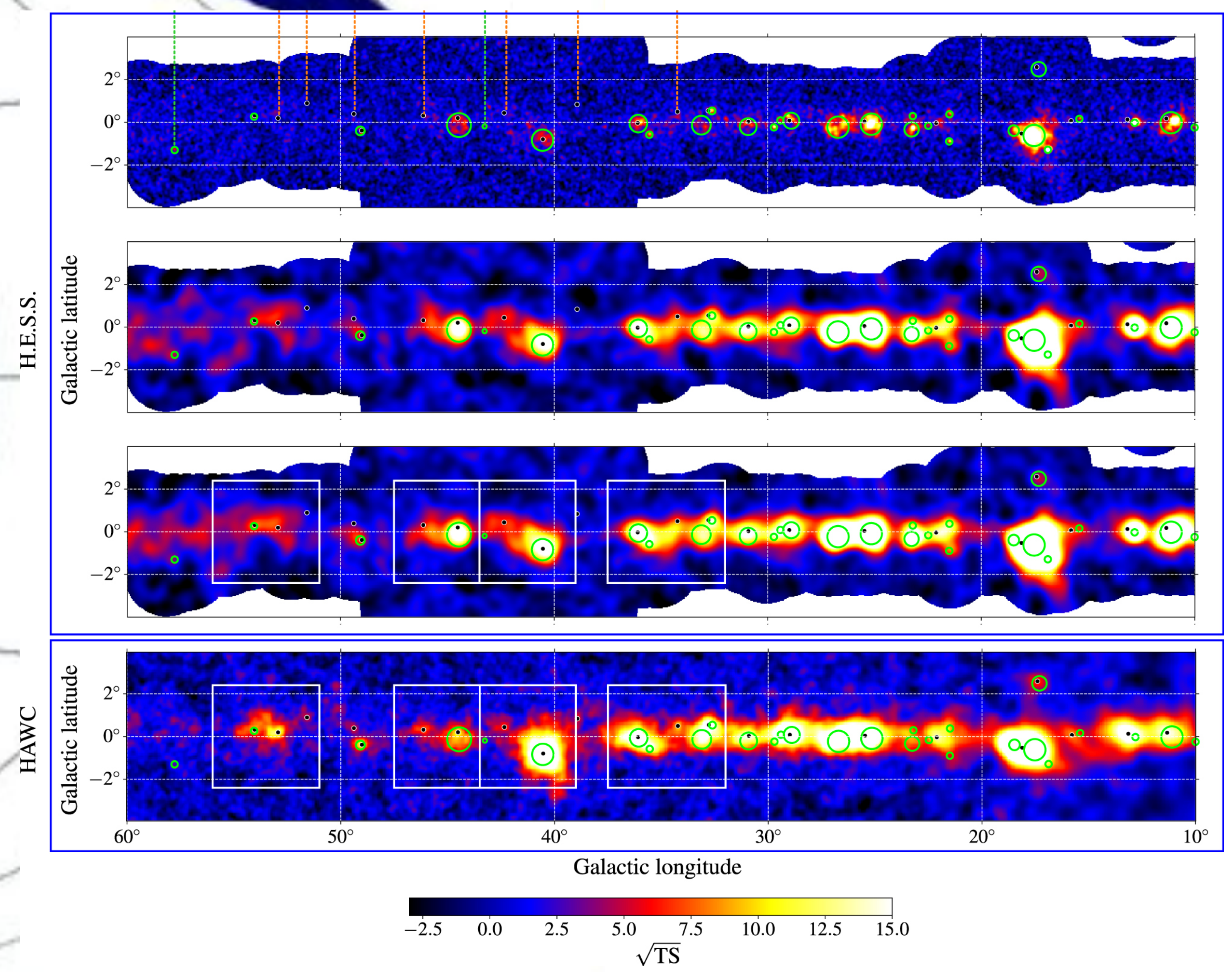
Galactic transients

LHAASO sky > 100 TeV

LHAASO Coll 2021 Nature ***594*** *6*

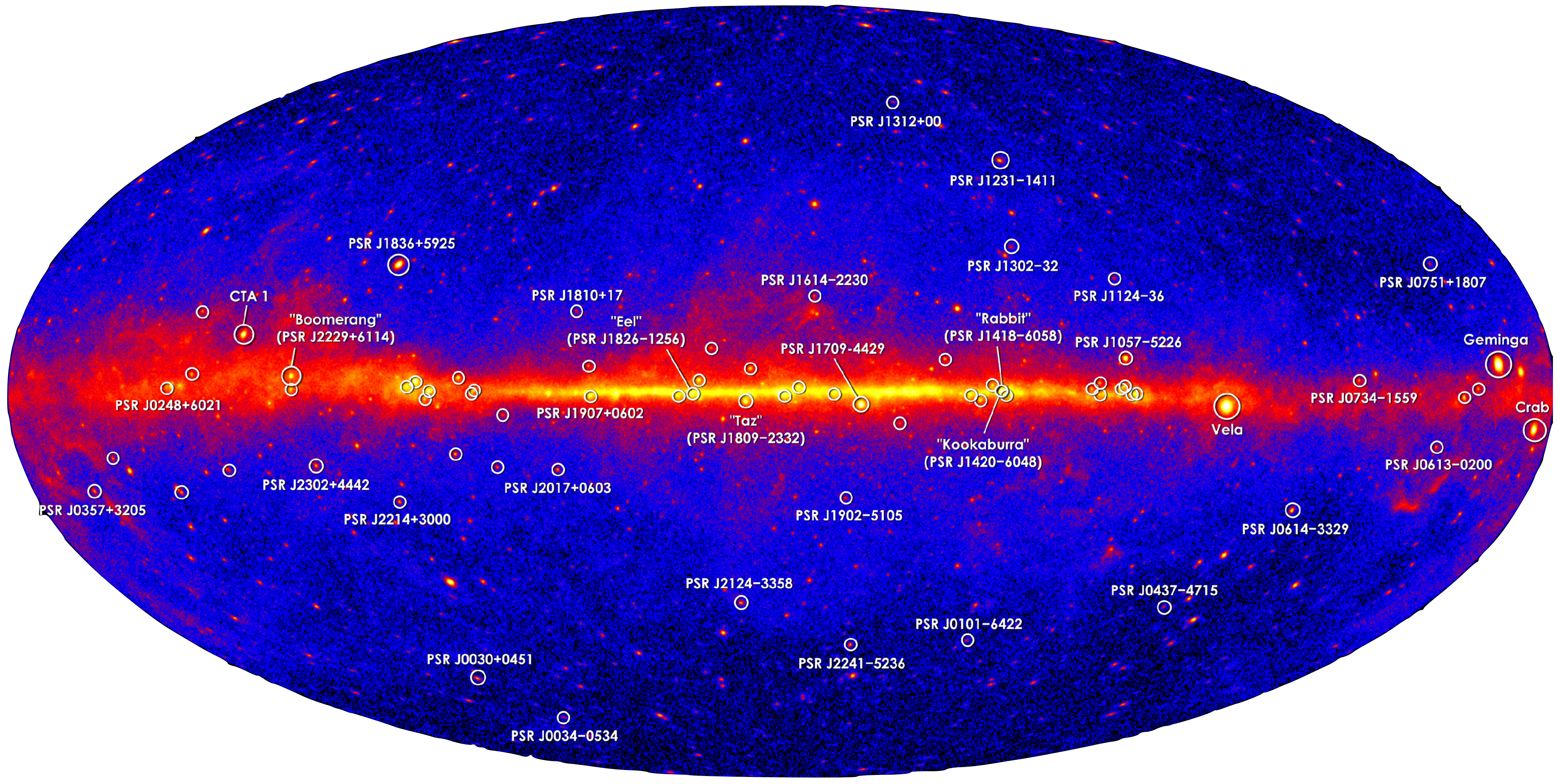


HAWC & H.E.S.S. Collaborations 2021 ApJ ***917*** *6*

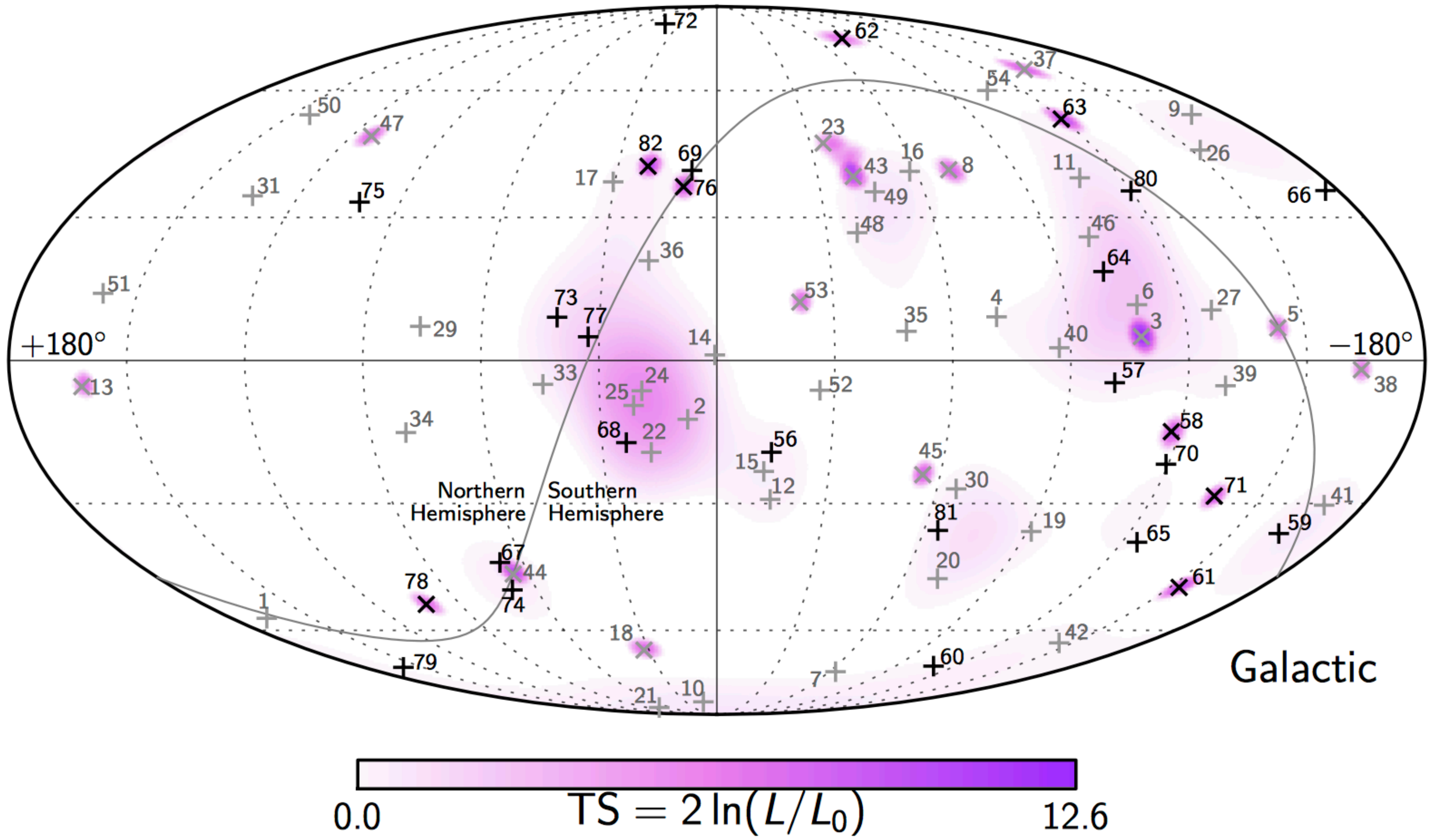


Microquasars: Photopion (synchrotron photons. e.g. Levinson & Waxman 2001; Distefano et al. 2002; Romero & Vila 2008) or hadronic (jet/cloud interactions) neutrino production e.g. Aharonian & Atoyan 1991; Romero et al. 2003; Bednarek 2005.
X-ray Binaries: Periodic/episodic, hadronic neutrino production (e.g. Gaisser & Stanev 1985, Berezynski 1985, Anchordoqui et al. 2003)
Young pulsars: Plausible CR acceleration sites, neutrinos from interactions with pulsar wind (e.g. Blasi et al. 2000, Bednarek 2003, Fang et al 2016)

Galactic transients



IceCube Coll. PoS(ICRC2017)981

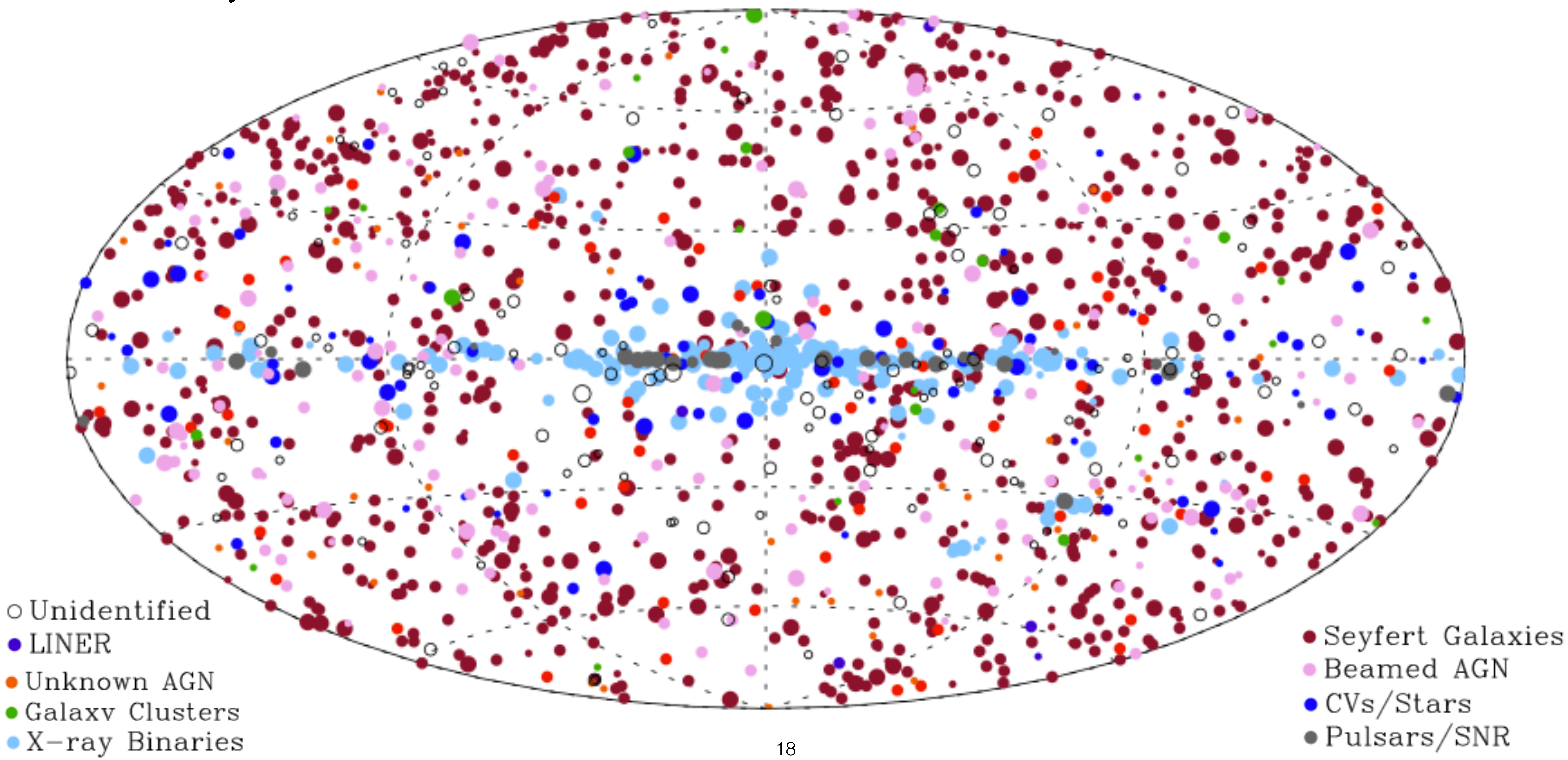


Galactic CRs ≤ 14% (time integrated)
Galactic TeV emitting pulsars ≤ 4% (time integrated)
Galactic X-ray binaries ≤ 1%
Galactic microquasars ≤ 7%

IceCube Coll ApJ 849 (2017)
Antares Coll, IceCube Coll, ApJL 868 (2018)
IceCube Coll, ApJ 898 (2020)
IceCube Coll, ApJL 930 (2022)

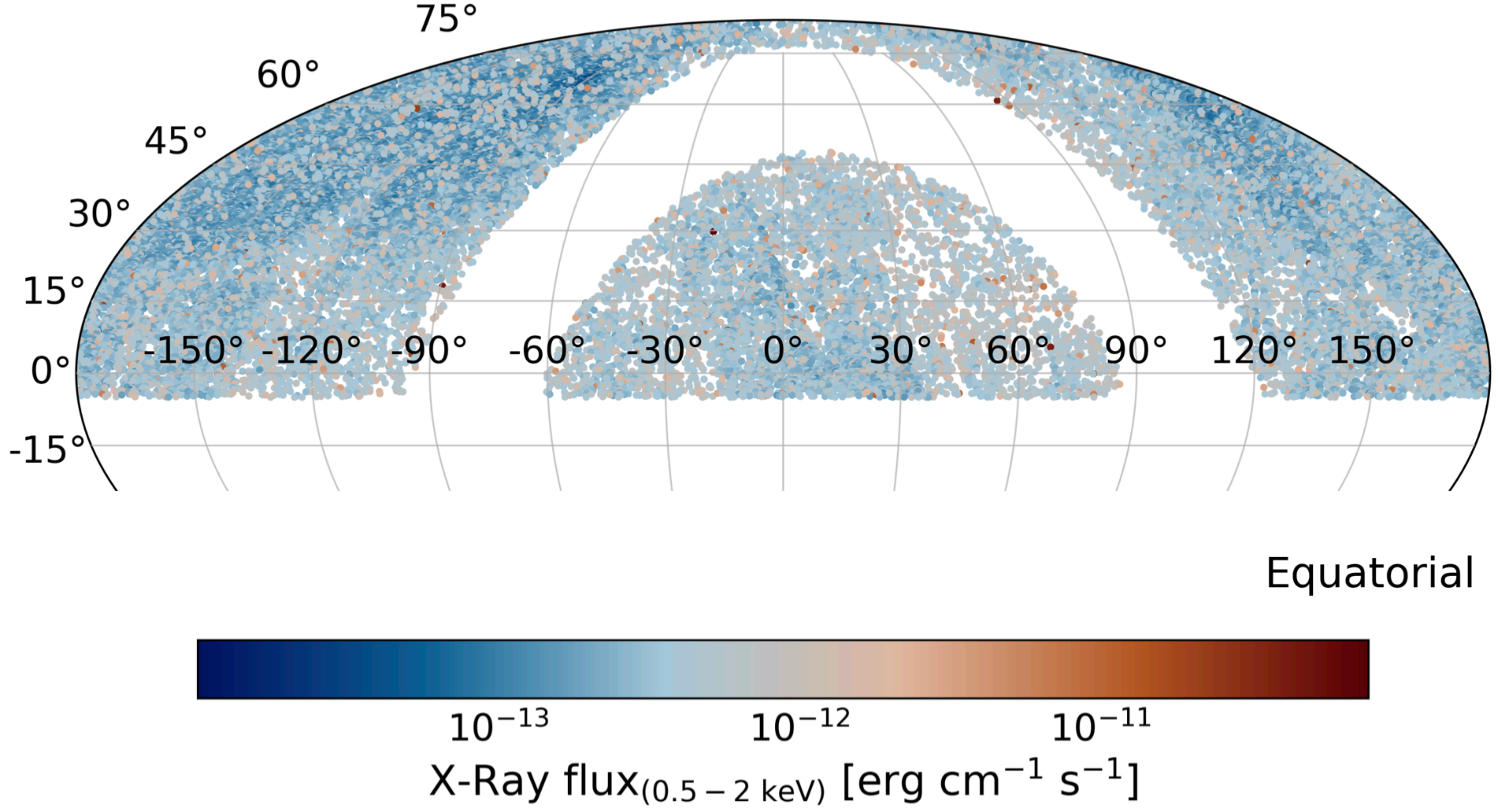
Non-jetted AGN

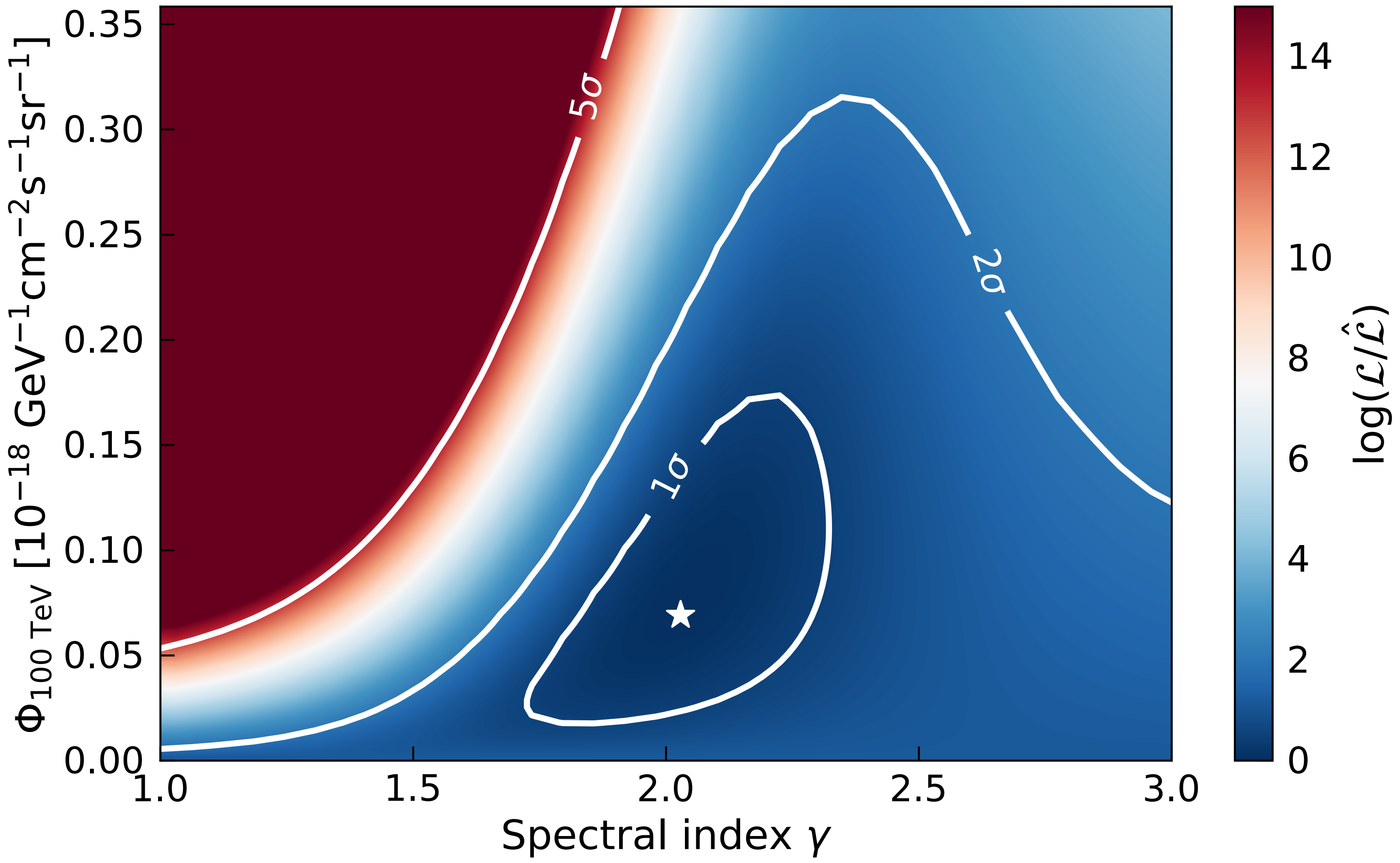
Swift-BAT 105-month hard-X-ray catalogue 2018

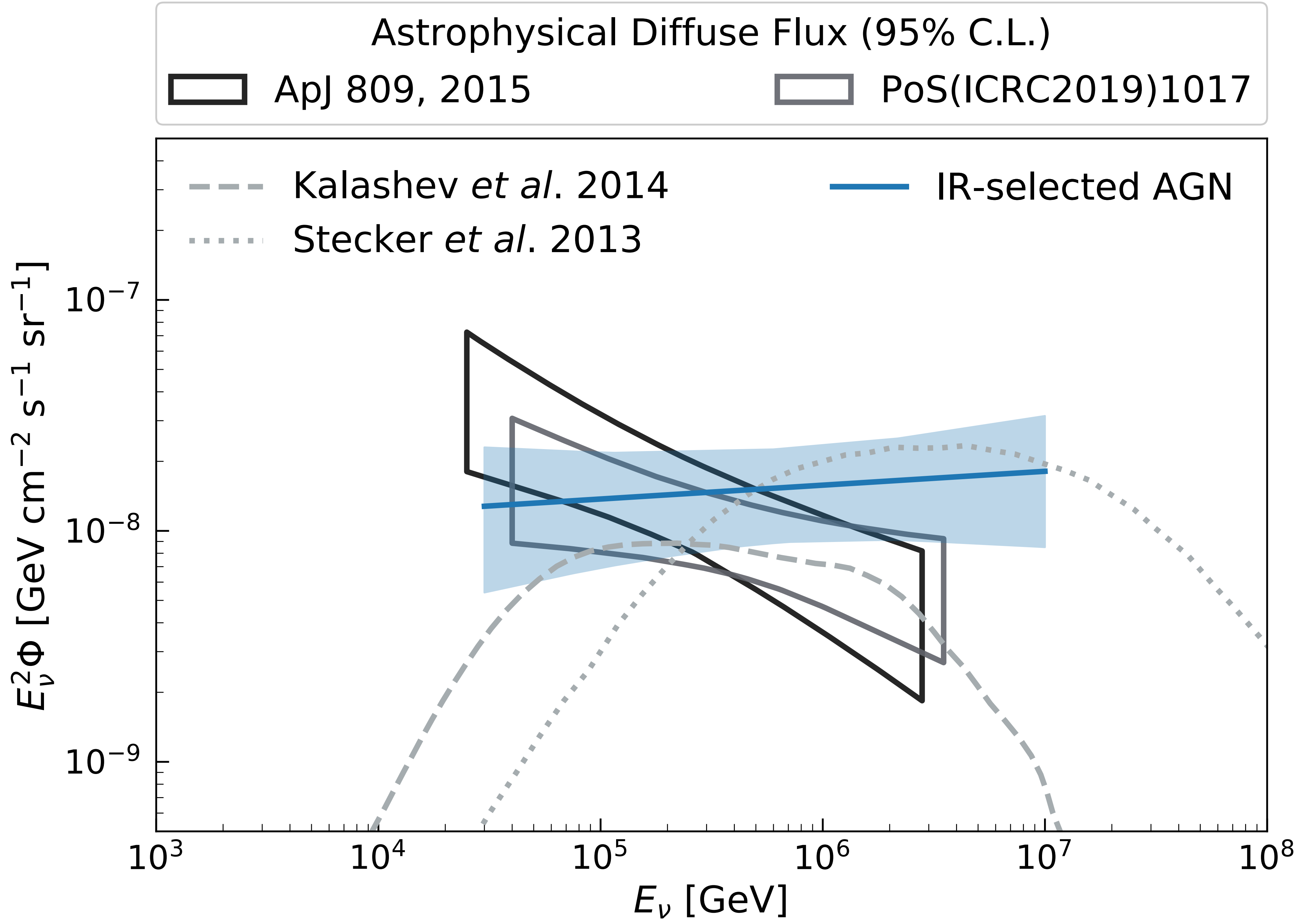


Non-jetted AGN

IceCube Coll 2022, PRD ***106****, 022005*

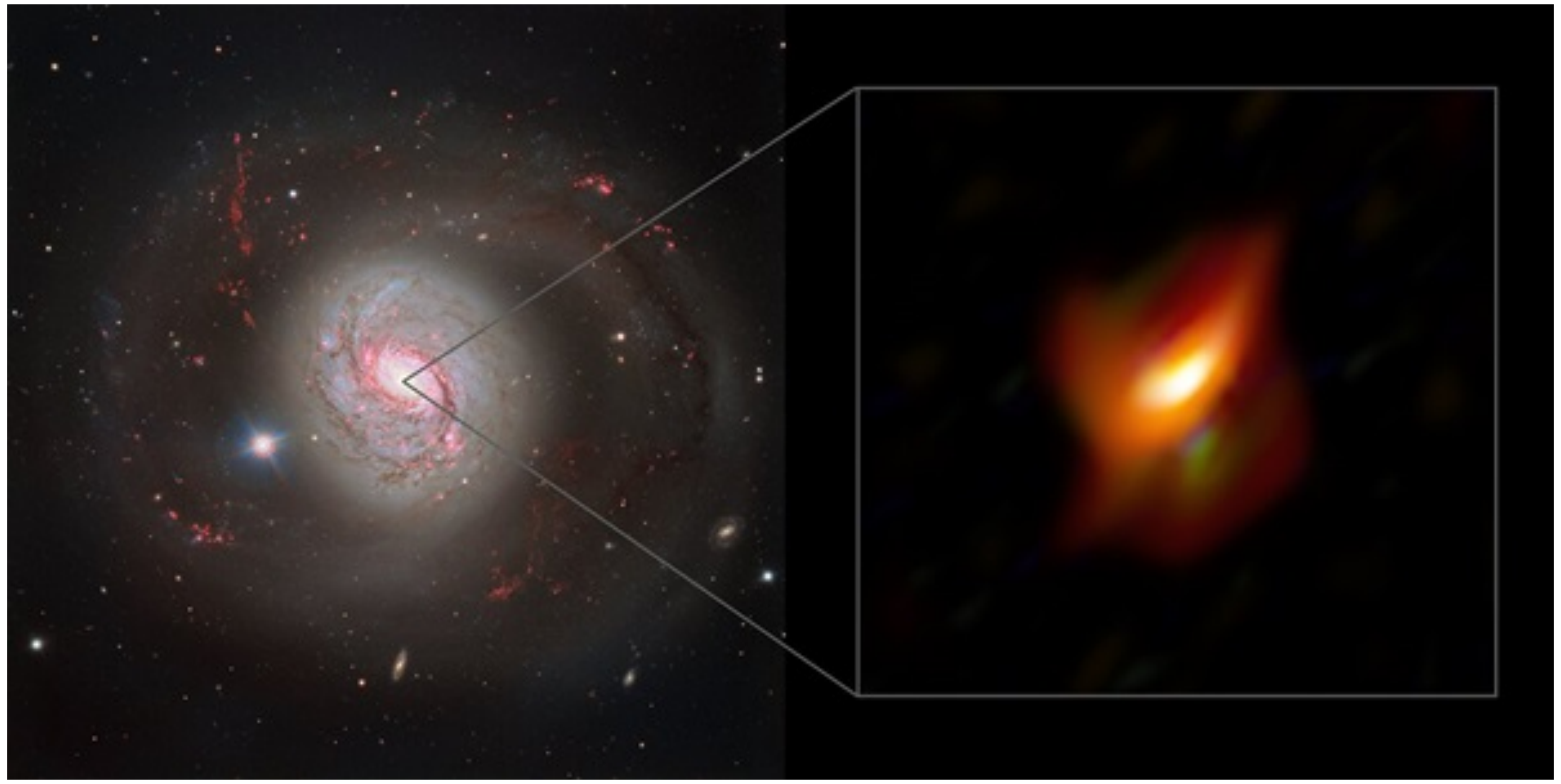


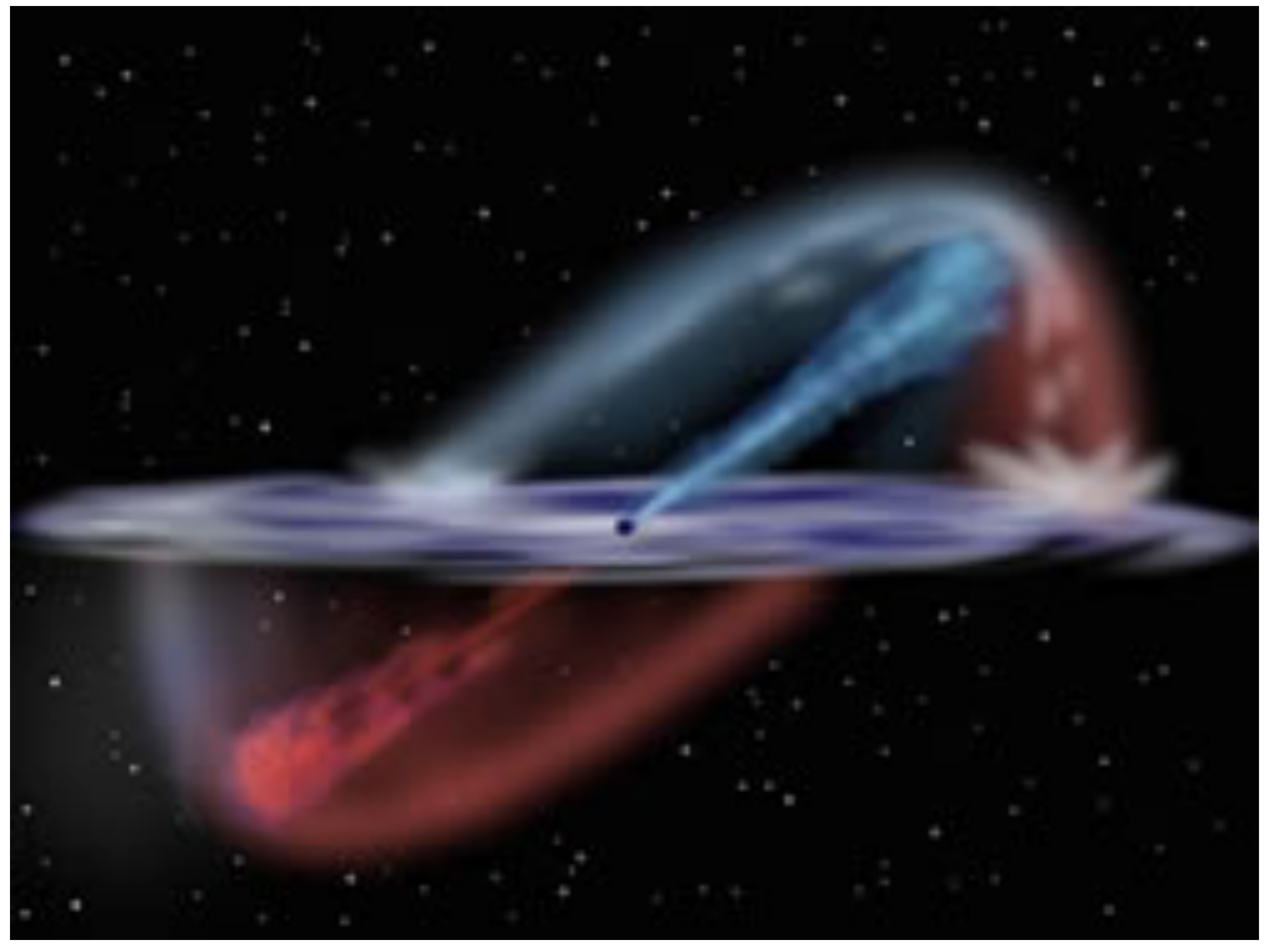




Infrared selected (ALLWISE) AGN with soft-X-ray weights could account for 27-100 % of neutrino flux at 100 TeV (2.6σ excess w.r.t. background expectations) with ~E^{-2} spectrum.

NGC 1068 (M77)



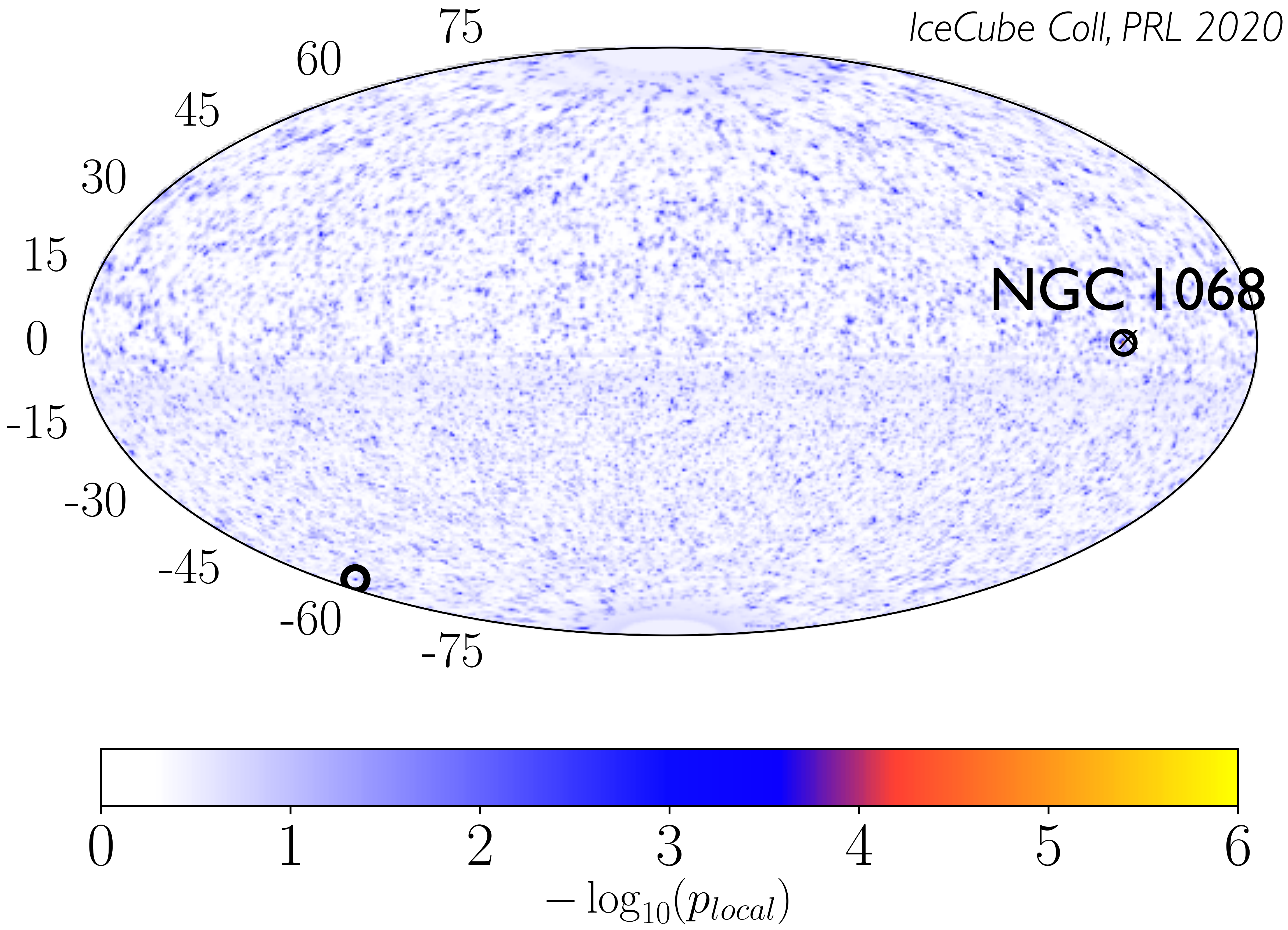


Seyfert 2 galaxy with heavily obscured nucleus

Prototypical nearby Seyfert 2 (14.4 Mpc)

High infrared luminosity: high-level of star formation

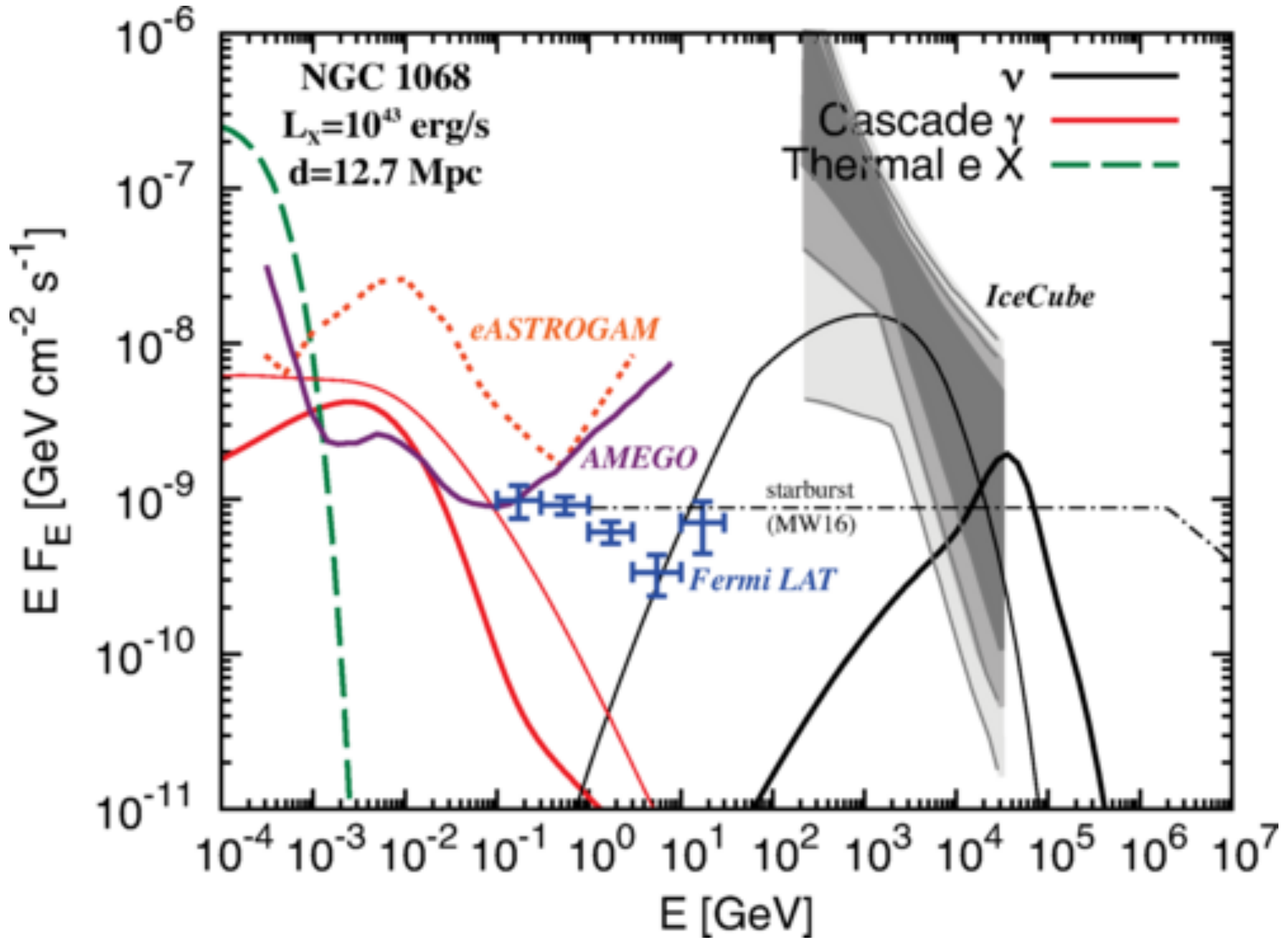
IceCube Coll, PRL 2020



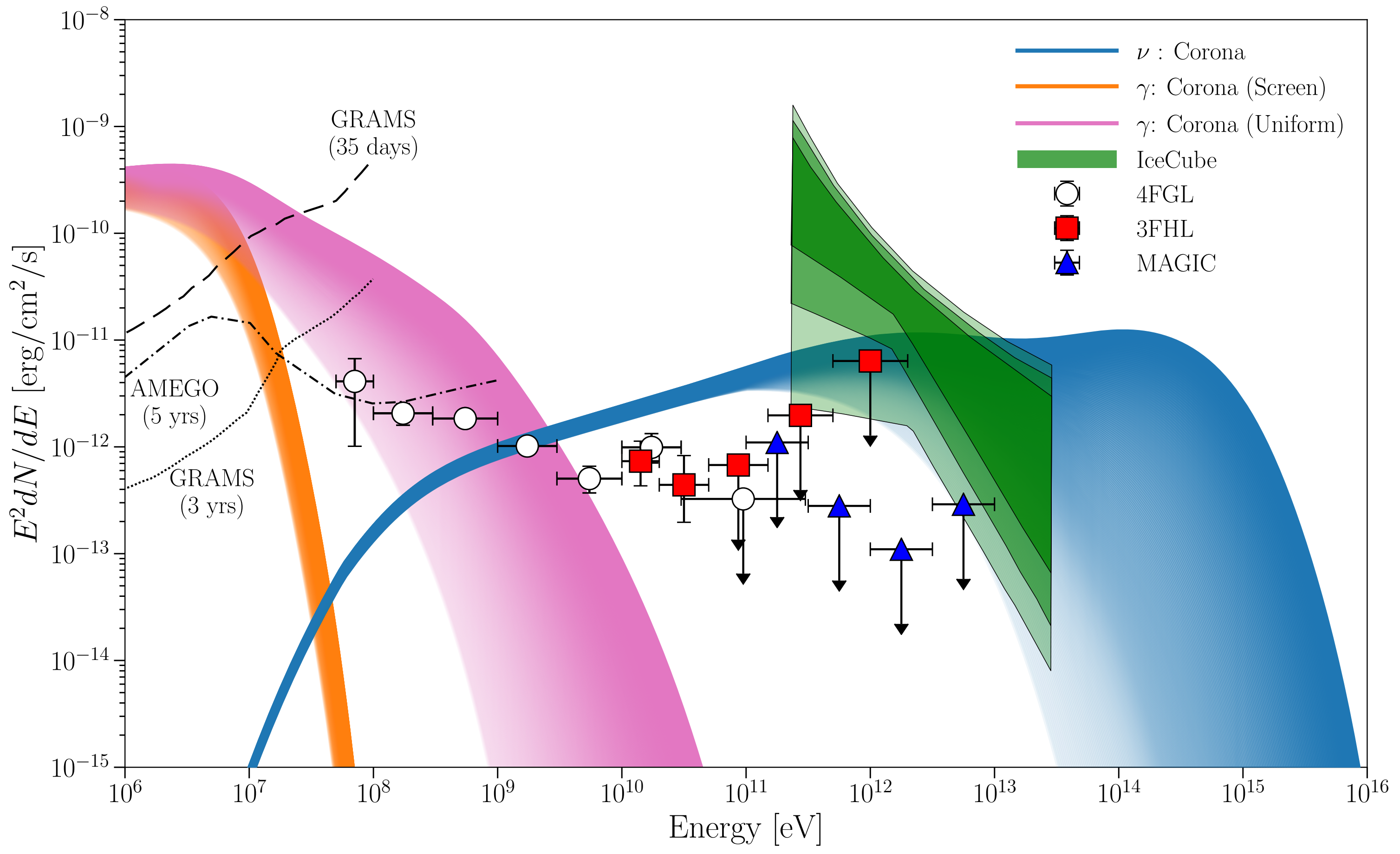
dN/dE ~ $E^{-3.2}$, $N_{source\ neutrinos}$ =50.4, E > 1TeV,
post-trial significance: 2.9σ

NGC 1068

AGN corona (pp) *Murase et al 2020*

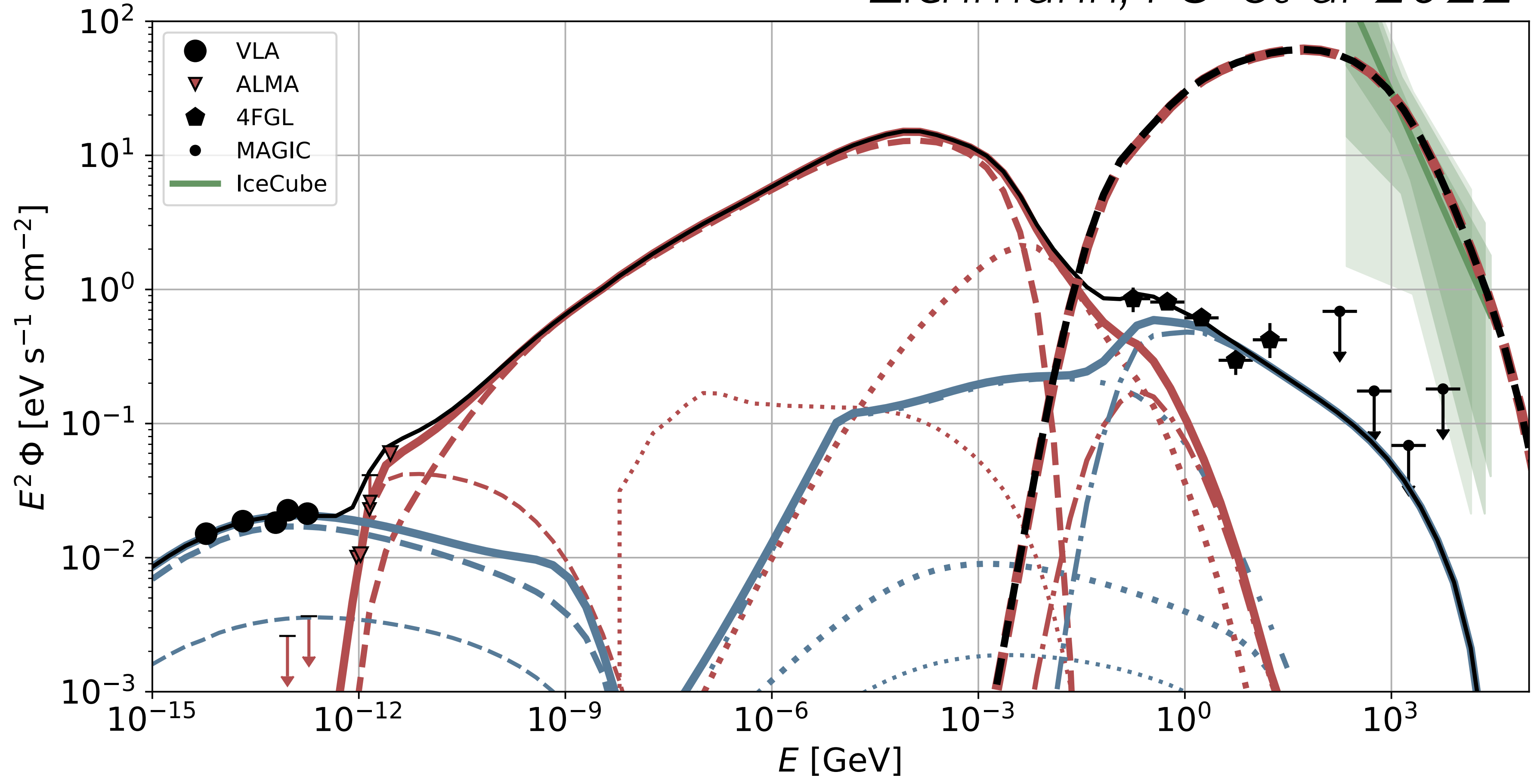


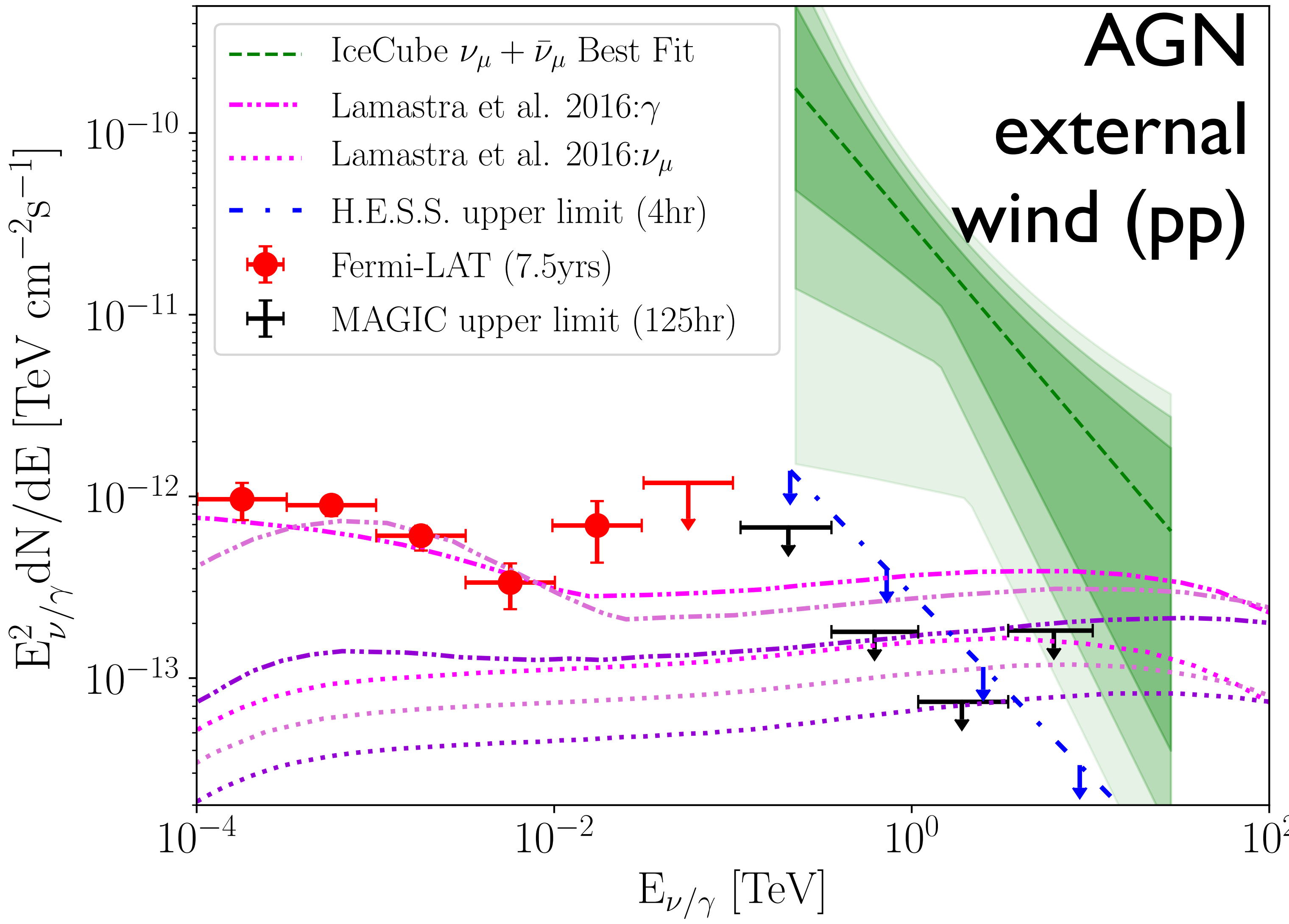
AGN corona "screened" (pp) *Y. Inoue et al 2019*



Starburst + AGN corona composite (pp)

Eichmann, FO et al 2022





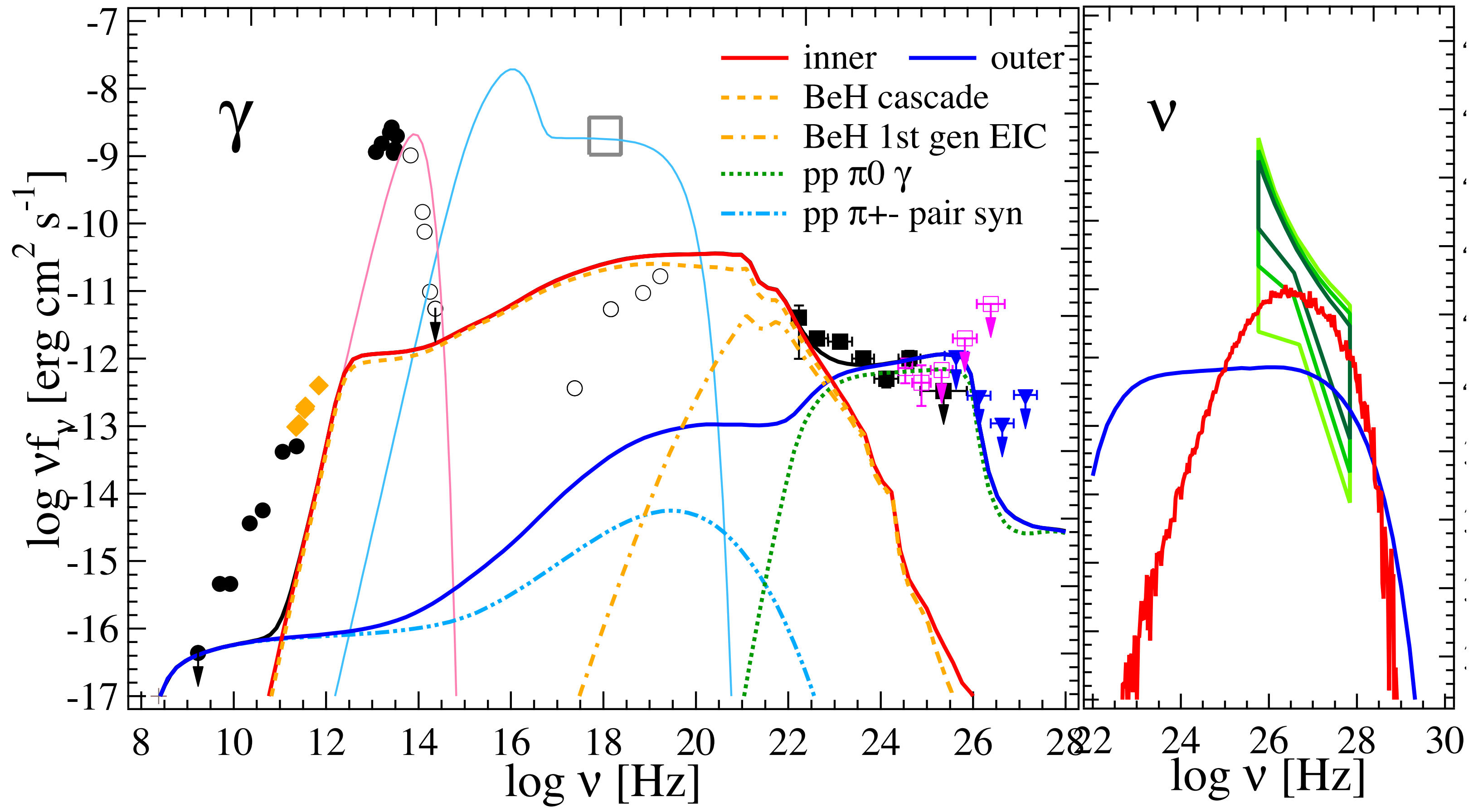
AGN external wind (pp)

based on Lamastra 2016 see also Lamastra 2019

Possible to explain IceCube signal if neutrinos produced in inner AGN regions

Bur CR content must be much higher than in the rest of the AGN population

see also Kheirandish et al 2021
Anchordoqui et al 2021



AGN internal wind (pγ) *S. Inoue et al 2022*

Tidal disruption events

Some TDEs form jets (Swift 1644+57)
Burrows et al 2011, Nat, 476, 421

$$E_{\text{CR, jet, max}} \sim 10^{17}\ \text{eV}\,\Gamma_{\text{jet}} \frac{ZBR}{10^{16}\ \text{G cm}}$$

Farrar & Piran 2014

Neutrinos from (mostly) photopion interactions *(Wang et al 2011, 2016, Senno et al 2017, Dai & Fang 2017, Lunardini & Winter 2017)*

Tidal disruption events

Some TDEs form jets (Swift 1644+57)

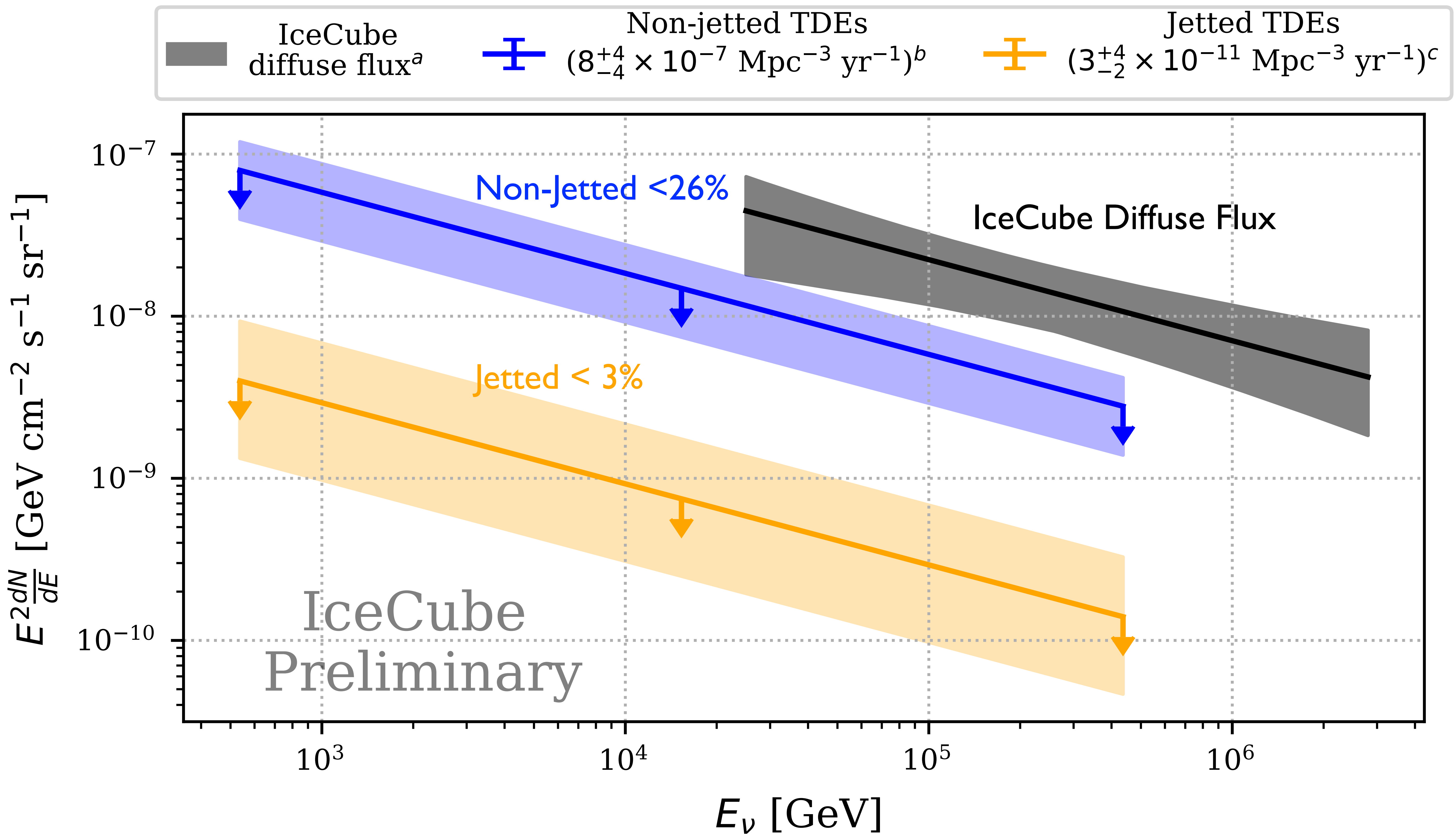
Burrows et al 2011, Nat, 476, 421

$$E_{\mathrm{CR,\ jet,\ max}} \sim 10^{17}\ \mathrm{eV}\,\Gamma_{\mathrm{jet}} \frac{ZBR}{10^{16}\ \mathrm{G\ cm}}$$

Farrar & Piran 2014

Neutrinos from (mostly) photopion interactions *(Wang et al 2011, 2016, Senno et al 2017, Dai & Fang 2017, Lunardini & Winter 2017)*

R. Stein for IceCube Coll PoS ICRC 2019



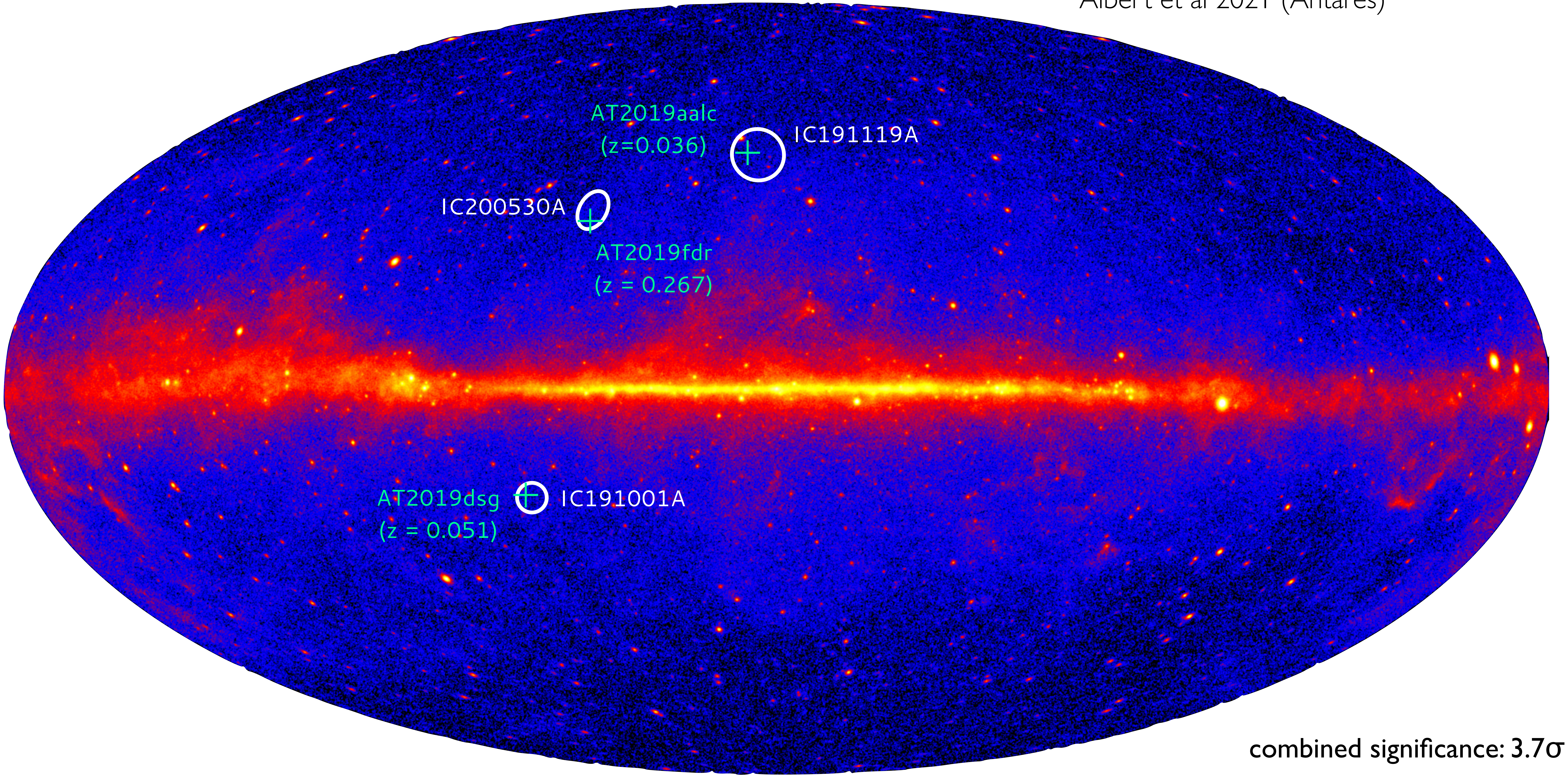
3 jetted TDEs

40 non-jetted TDEs

(up to 1 year before and 100 days after the TDE)

Non-jetted TDEs

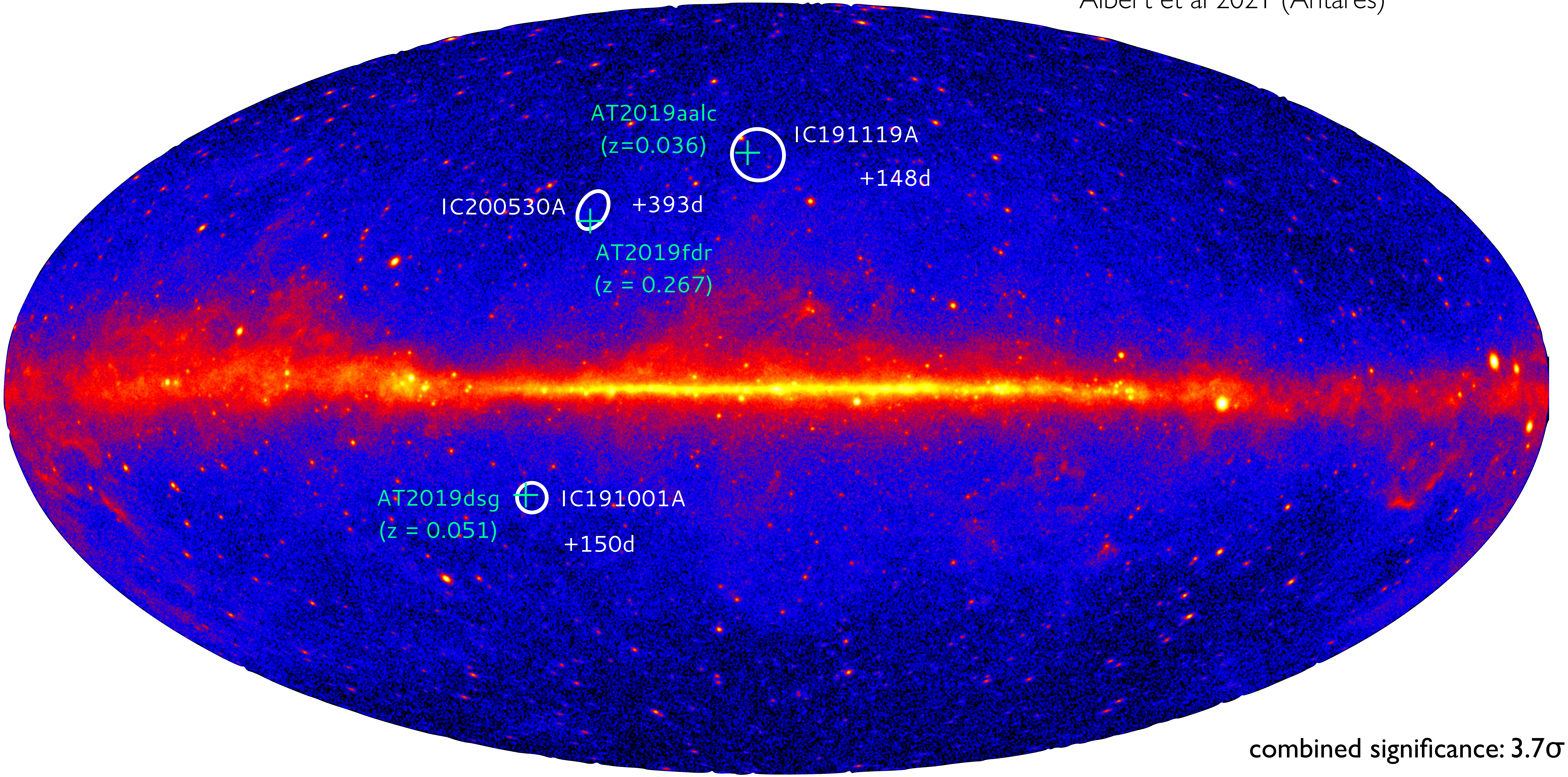
Stein et al 2021
Reutsch et al 2022
Van Velzen et al 2021 arXiv:2111.0939
Albert et al 2021 (Antares)



combined significance: 3.7σ

Non–jetted TDEs

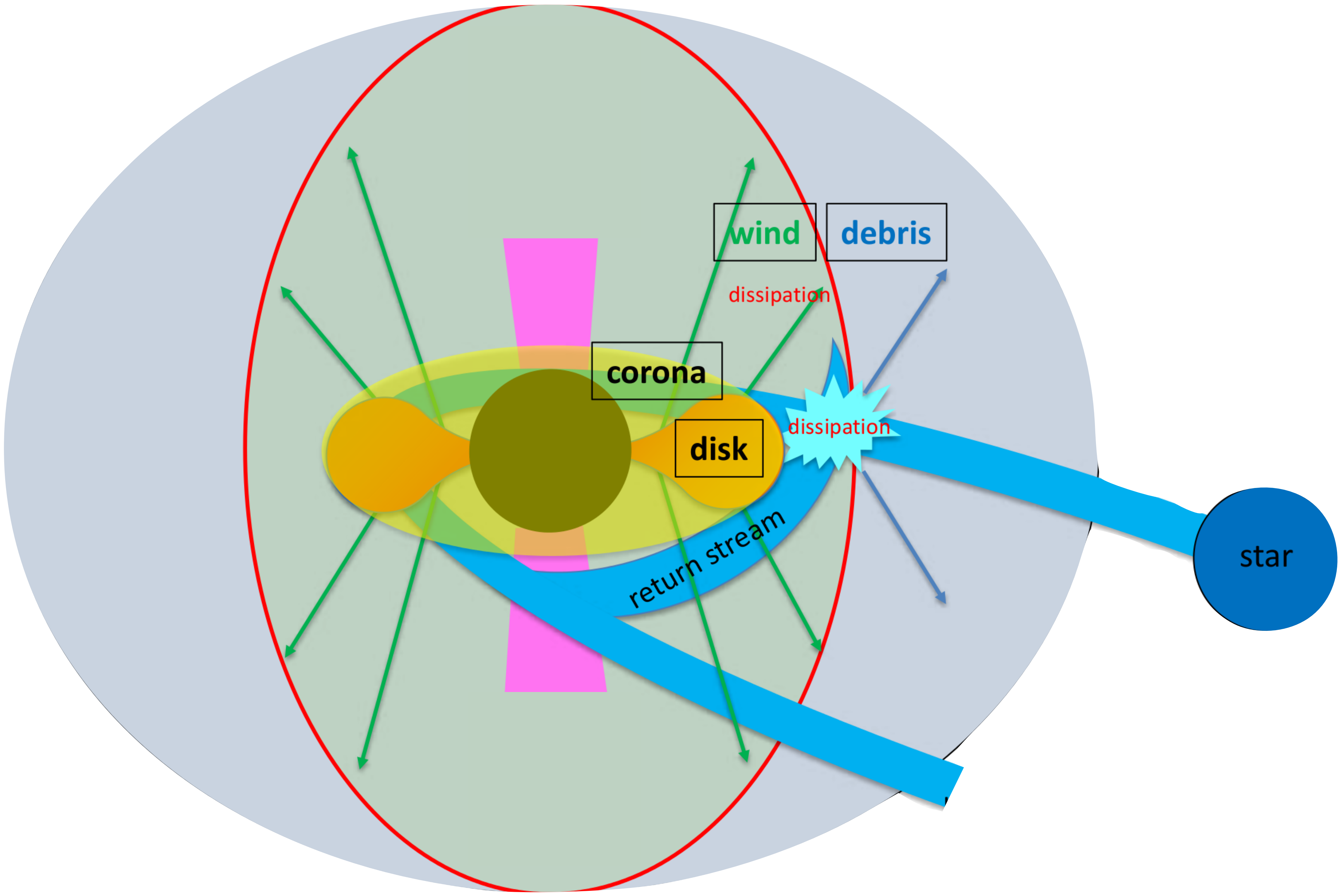
Stein et al 2021
Reutsch et al 2022
Van Velzen et al 2021 arXiv:2111.0939
Albert et al 2021 (Antares)



combined significance: 3.7σ

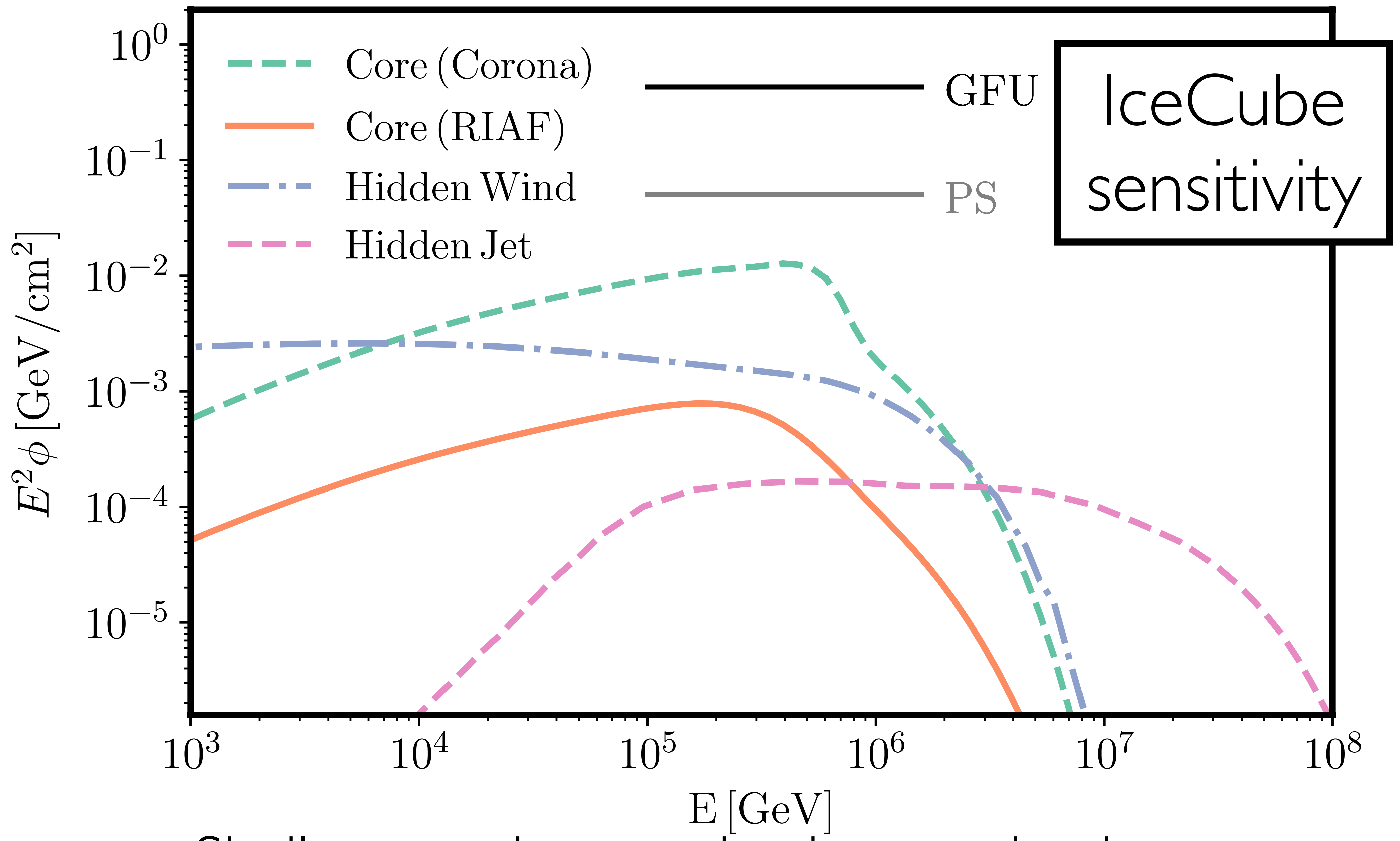
Non-jetted TDEs

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)

Murase, Zhang, Kimura, FO, Petropoulou 2020



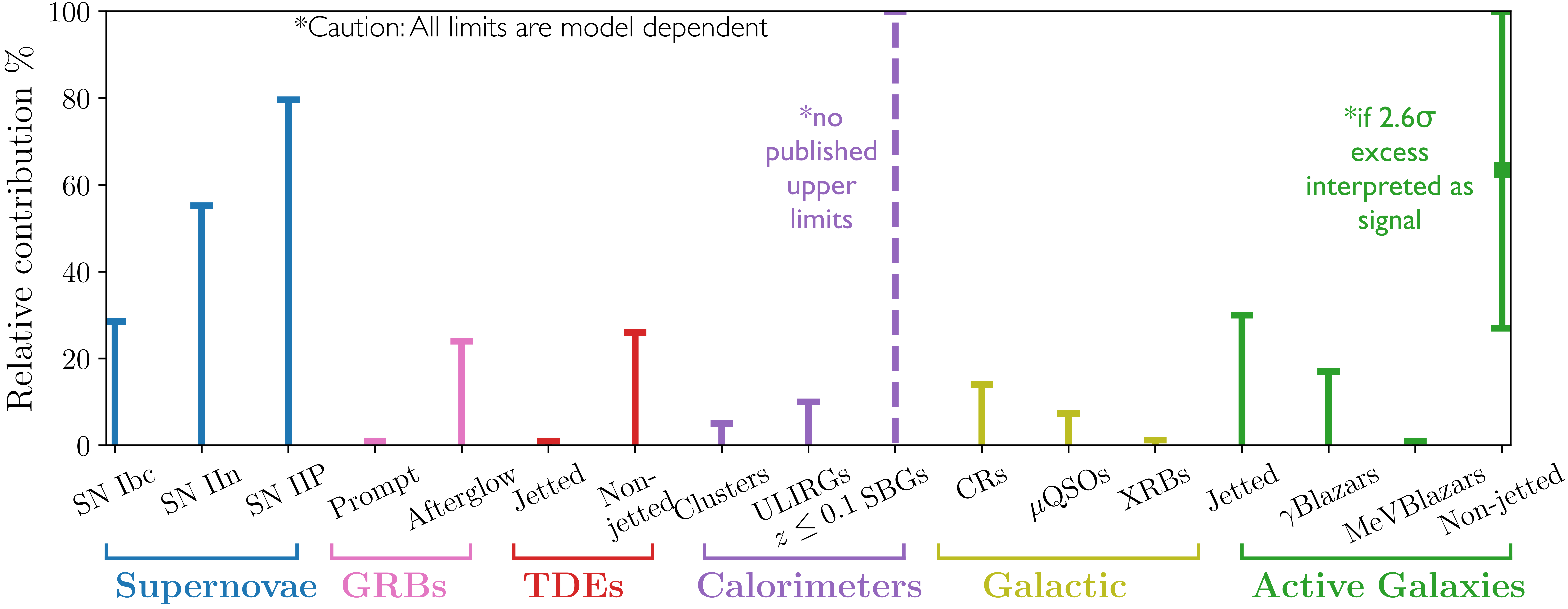
Similar neutrino production mechanism to AGN cores possible

Models consistent with the detection of a neutrino (statistically)

But require protons with $L_p \sim 100\ L_{\rm Edd}$ for ~year-long timescales

The current landscape: Stacking upper limits

summary of IceCube stacking analyses results, list of references in
FO PoS ICRC2021 (2022) 030, arXiv:2201.05623



Summary

Neutrino emission from rare transient and steady sources constrained by IceCube analyses

Currently no theoretical model why TXS 0506+056, AT2019dsg detected first

Good transients for follow up: High-luminosity, low redshift, long-duration transients,
X-ray and MeV-GeV γ-ray counterparts (proton cascade emission)