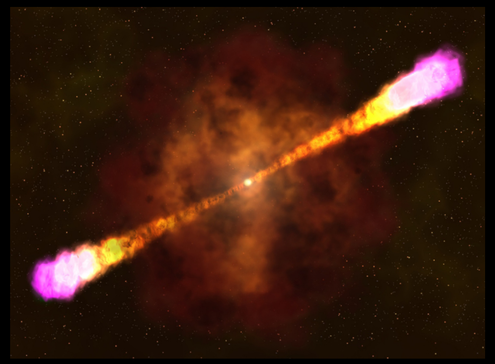
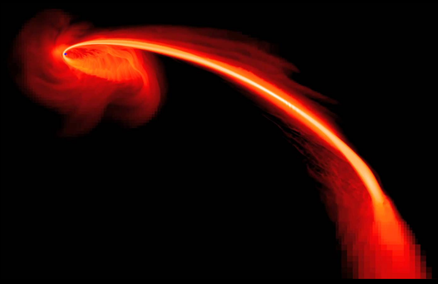
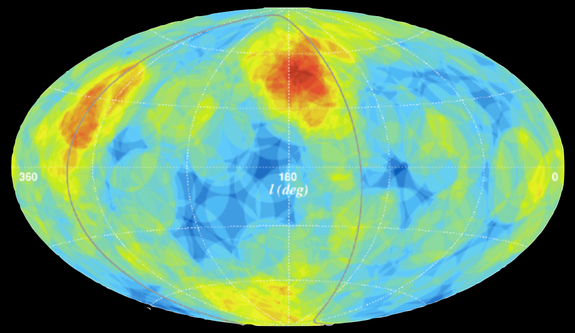
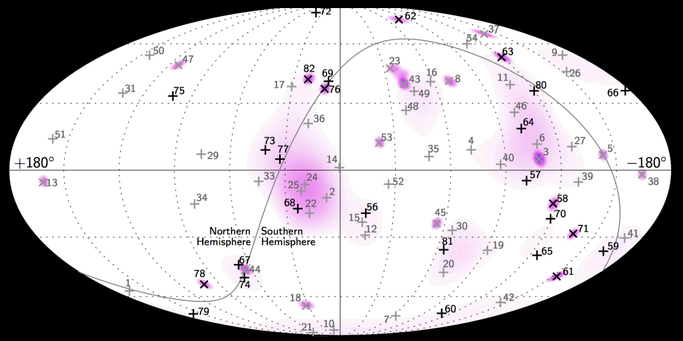
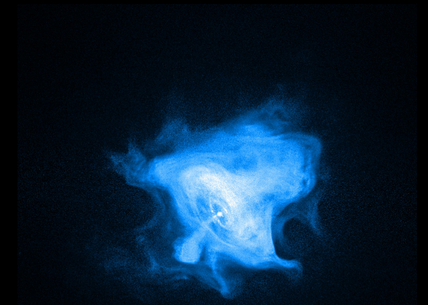








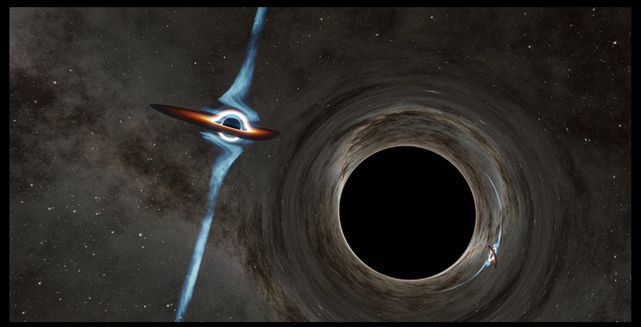


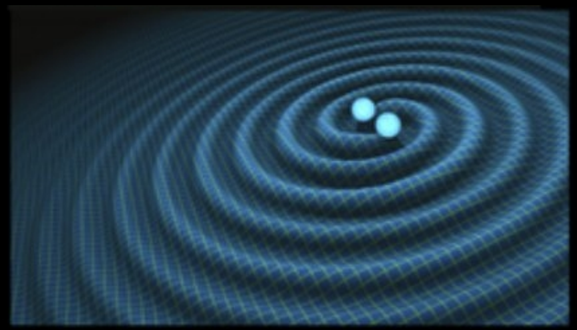
MULTIMESSENGER ASTROPHYSICS

ECRS 2022

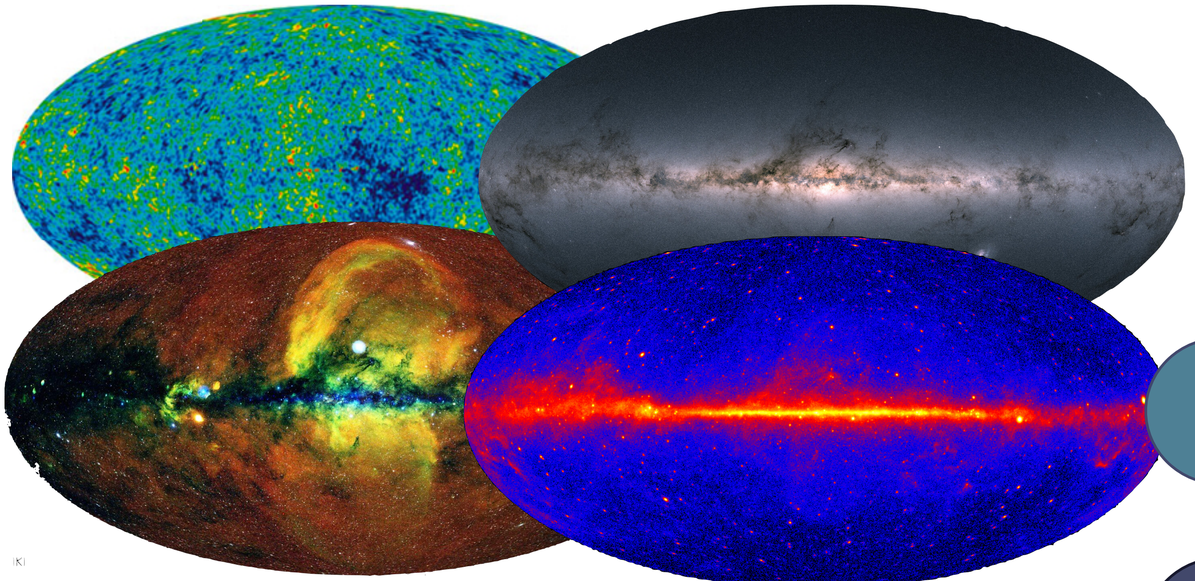
Foteini Oikonomou, 27 July 2022

NTNU
Norwegian University of Science and Technology



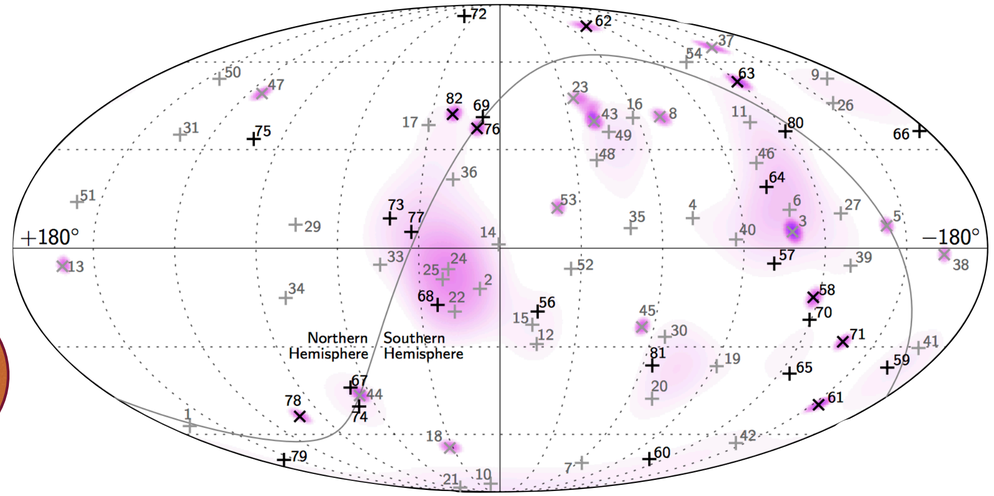


The Universe through multiple messengers



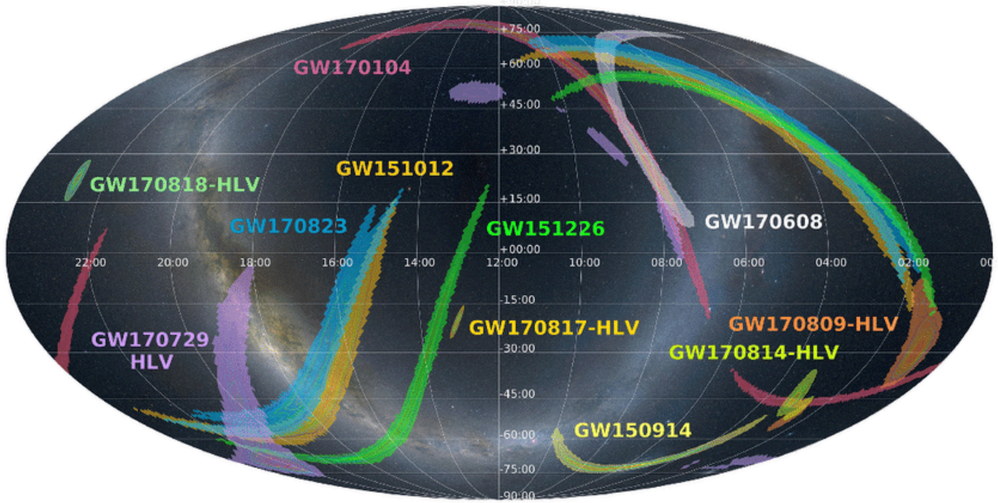
γ

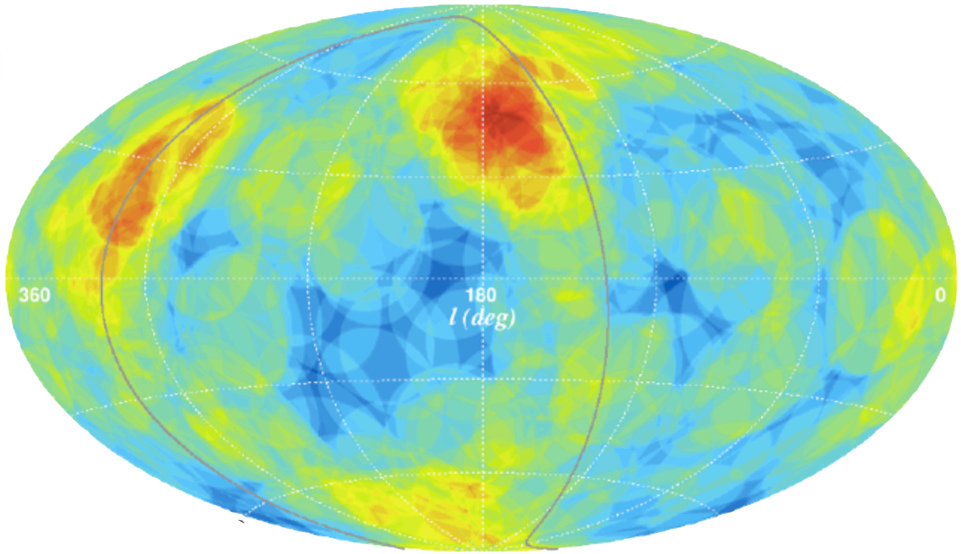
ν



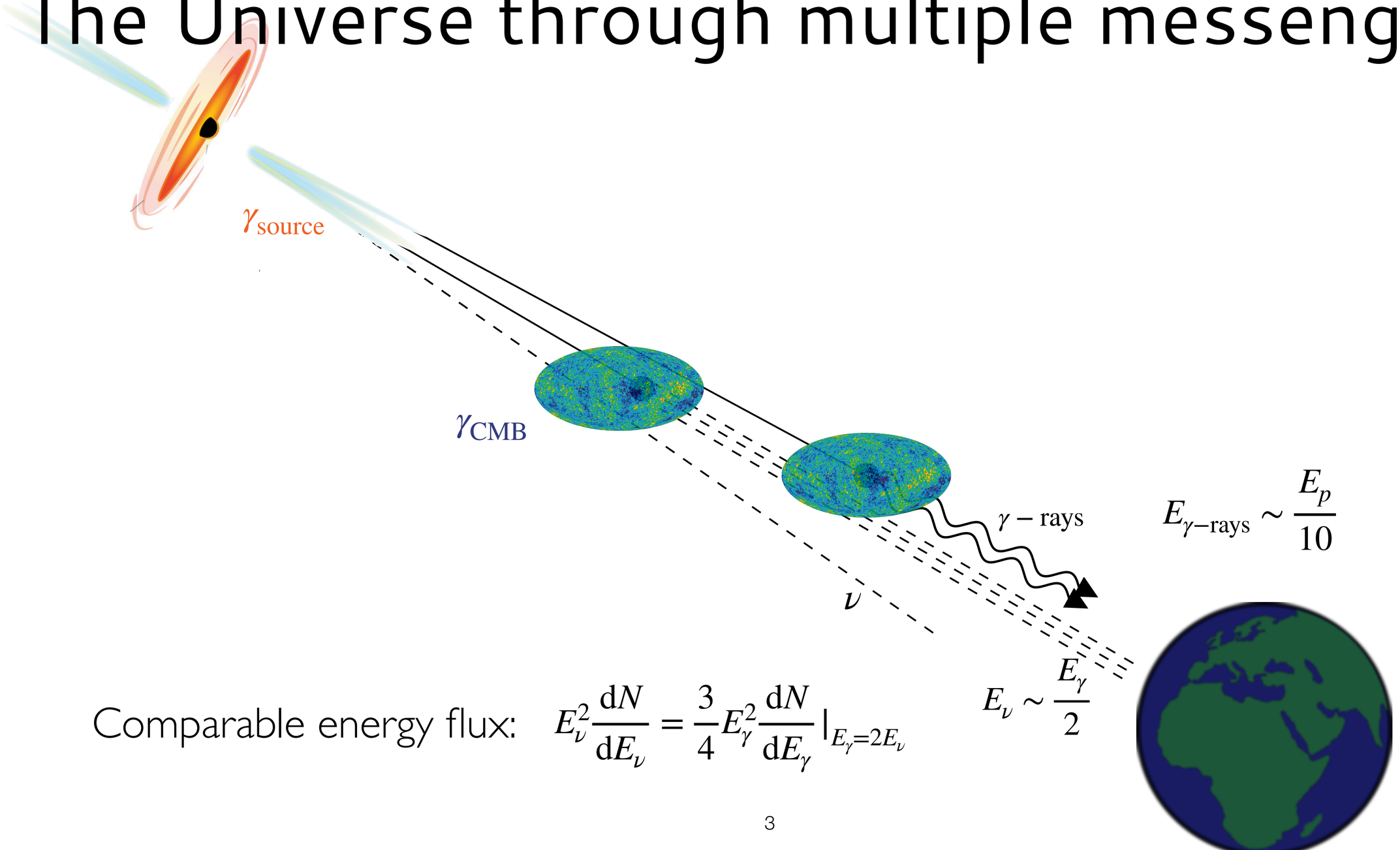
GW

CR



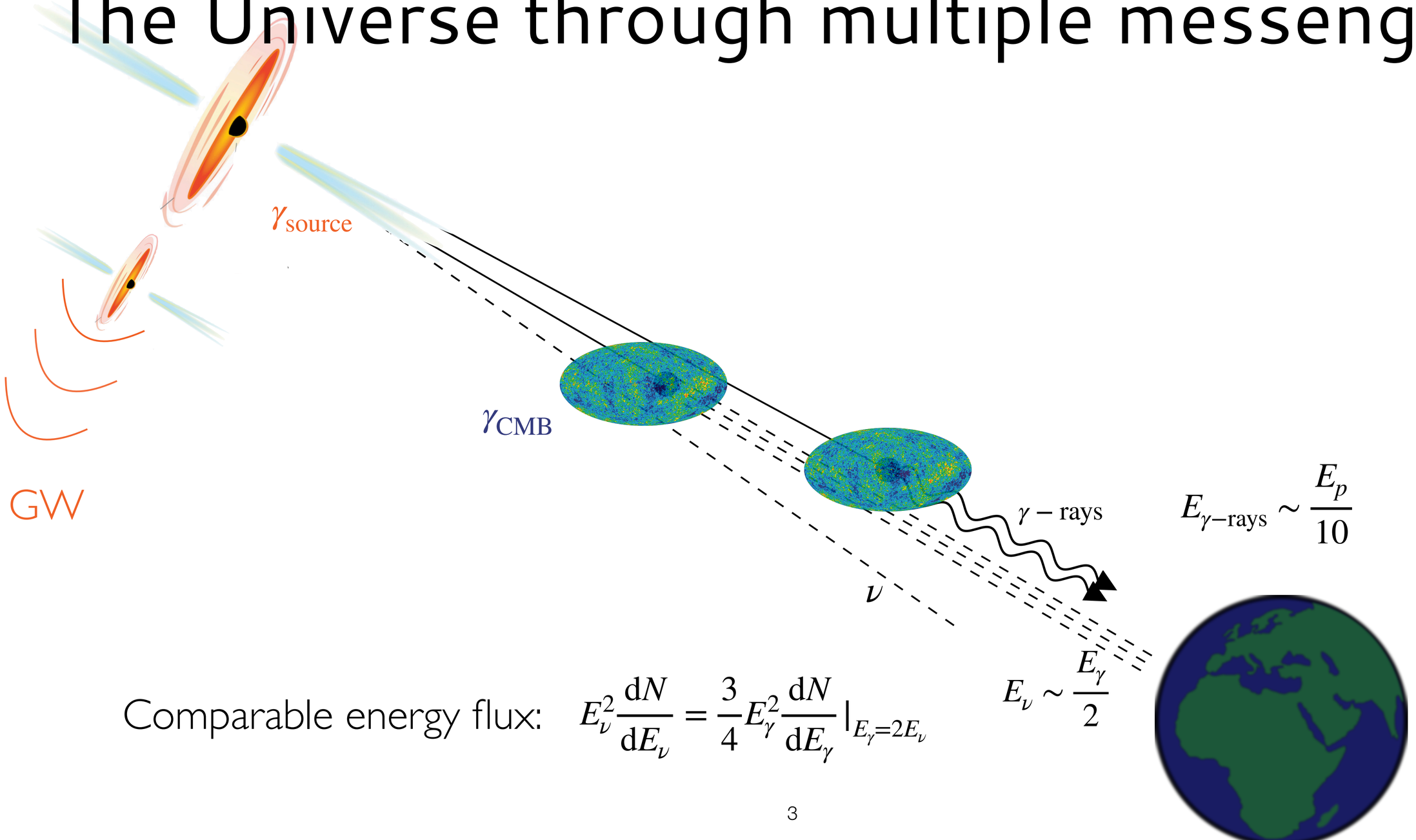


The Universe through multiple messengers



Comparable energy flux: $E_\nu^2 \frac{\mathrm{d}N}{\mathrm{d}E_\nu} = \frac{3}{4} E_\gamma^2 \frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\Big|_{E_\gamma = 2E_\nu}$

The Universe through multiple messengers



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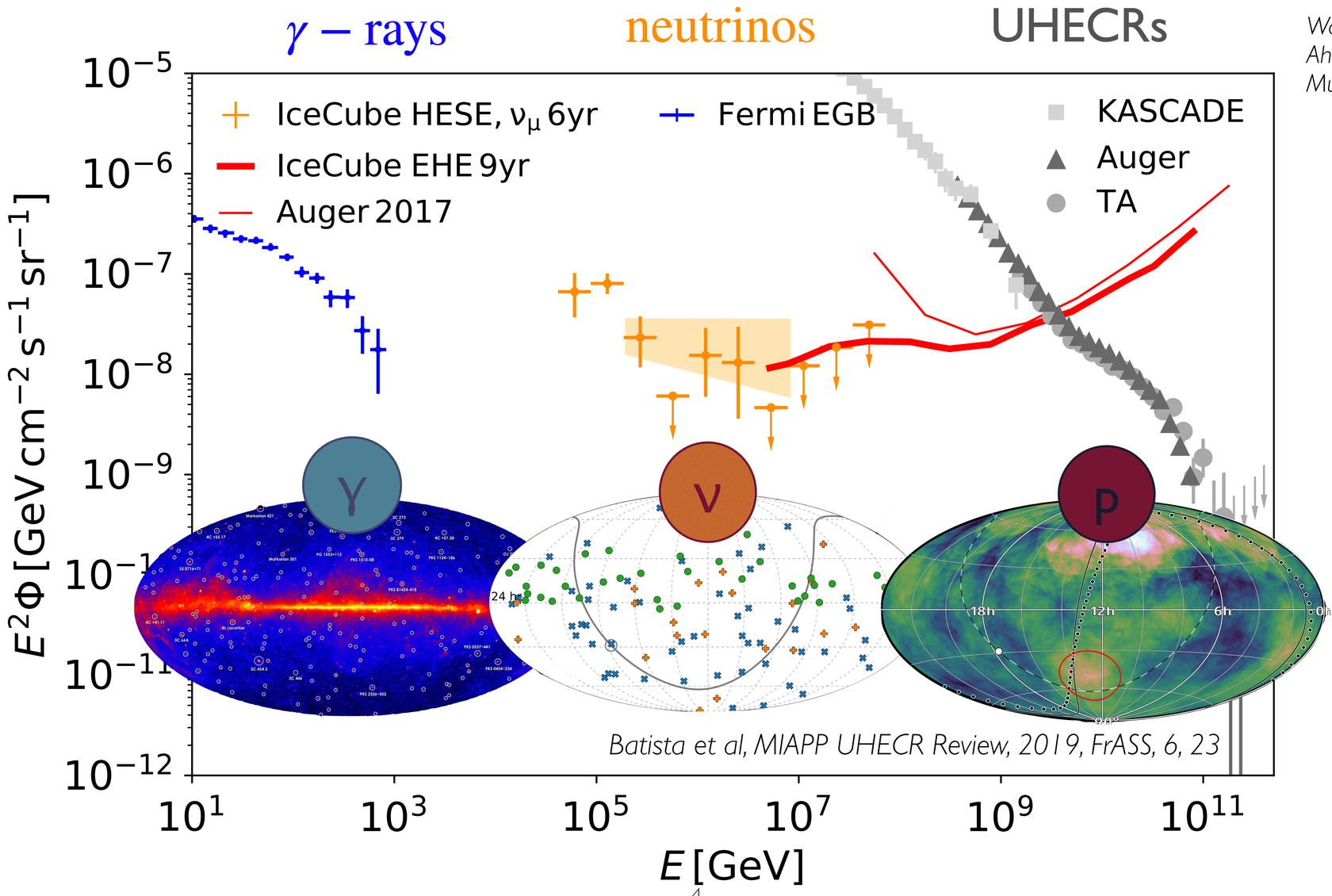
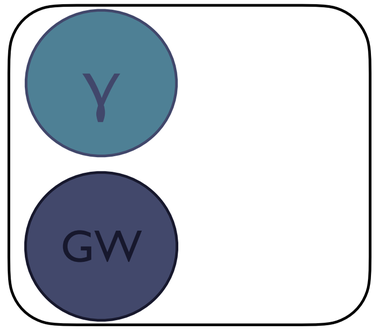
The Universe through multiple messengers



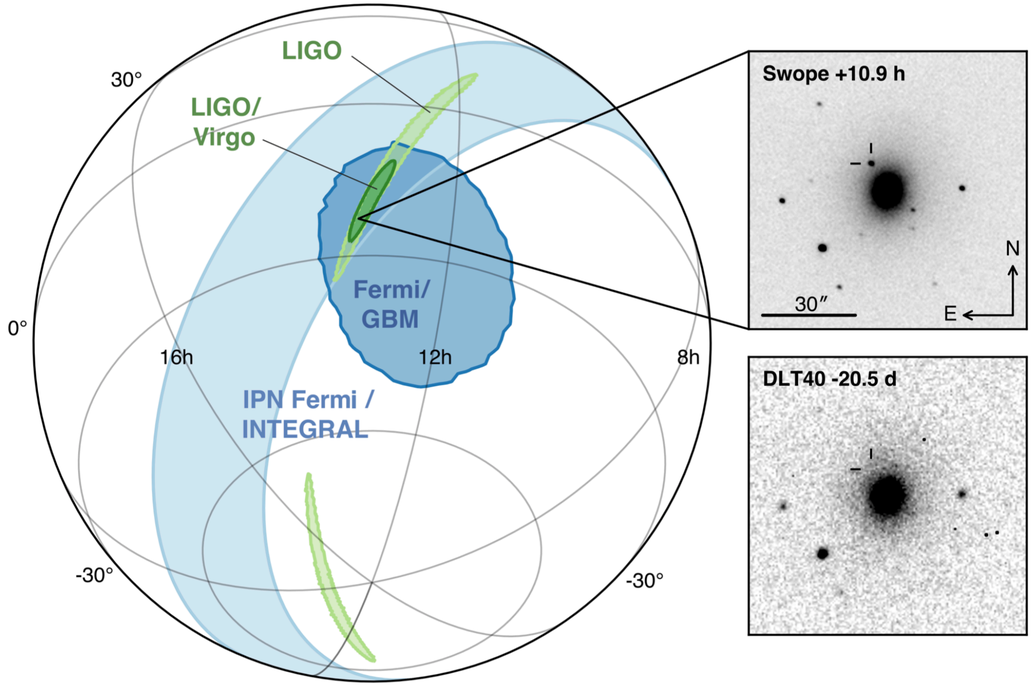
Batista et al, MIAPP UHECR Review, 2019, FrASS, 6, 23

Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018

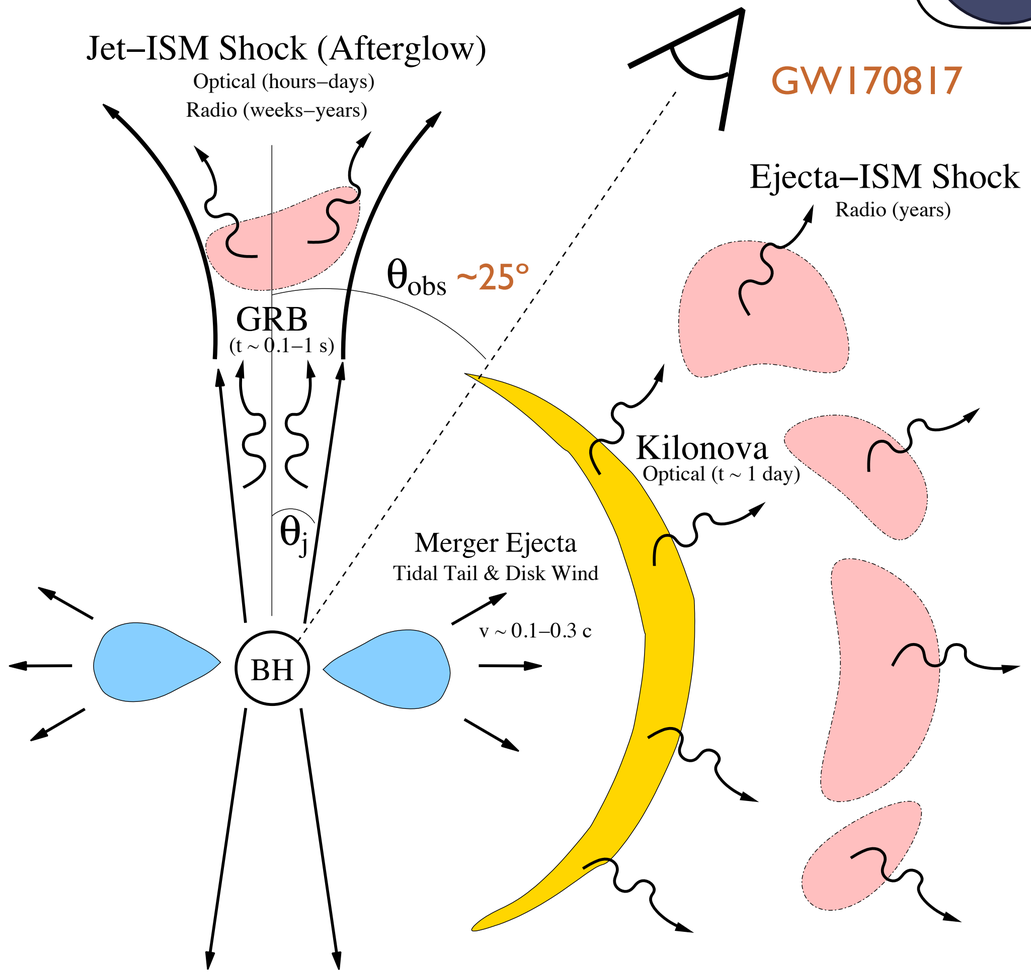
Binary neutron star mergers: GW170817



LIGO, Virgo, Fermi Coll+ many others, Astrophys.J. 848 (2017) no.2, L12

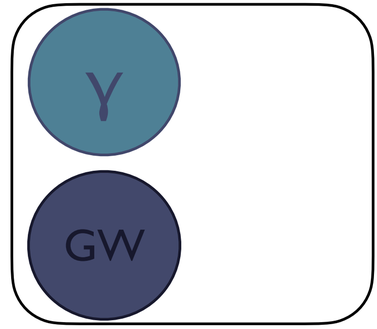


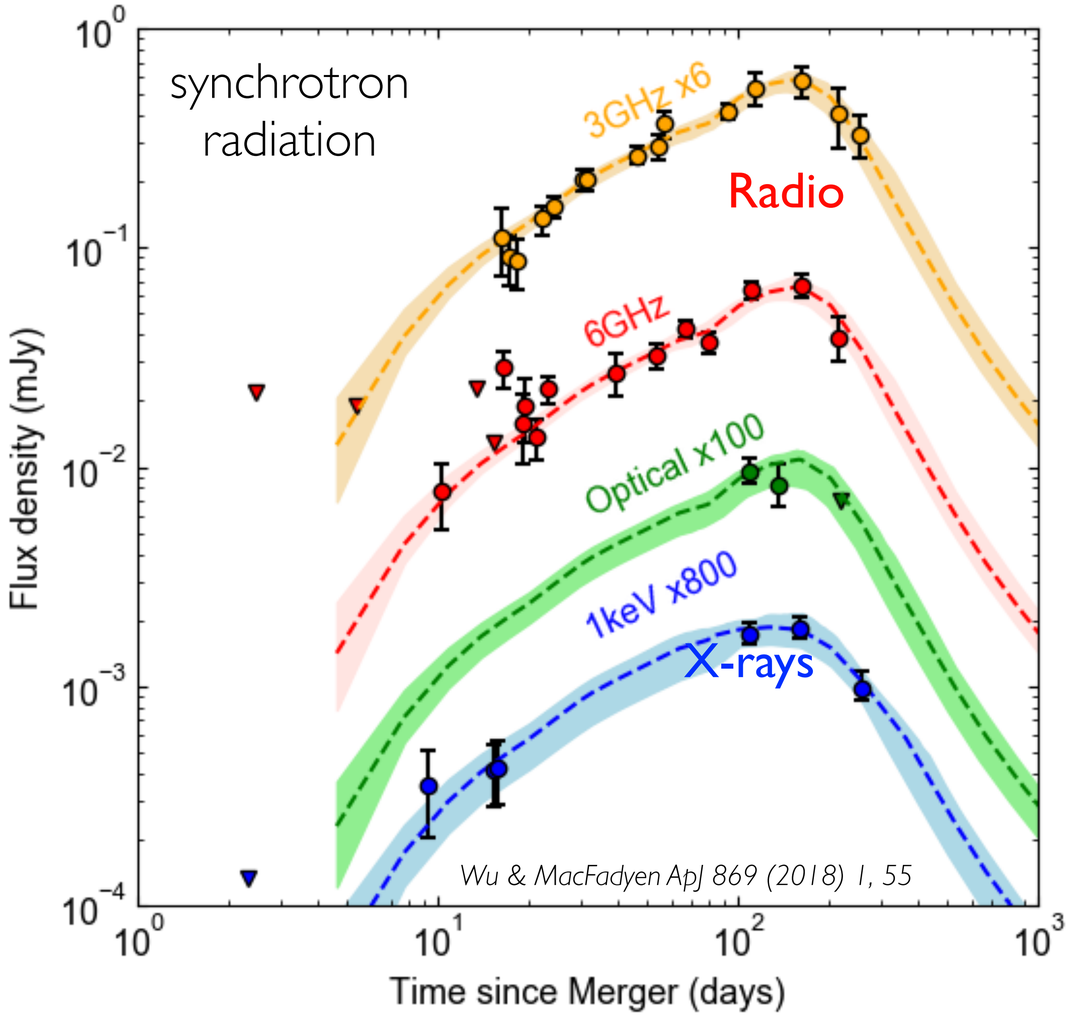
NGC 4993, at distance ~ 40 Mpc



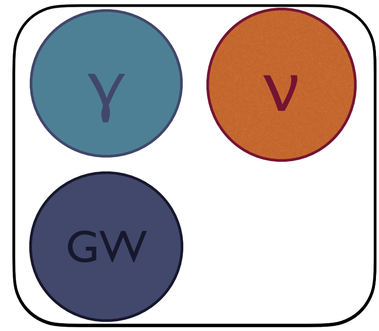
Metzger & Berger, ApJ, 746 (2012) 48, 1

Binary neutron star mergers: GW170817

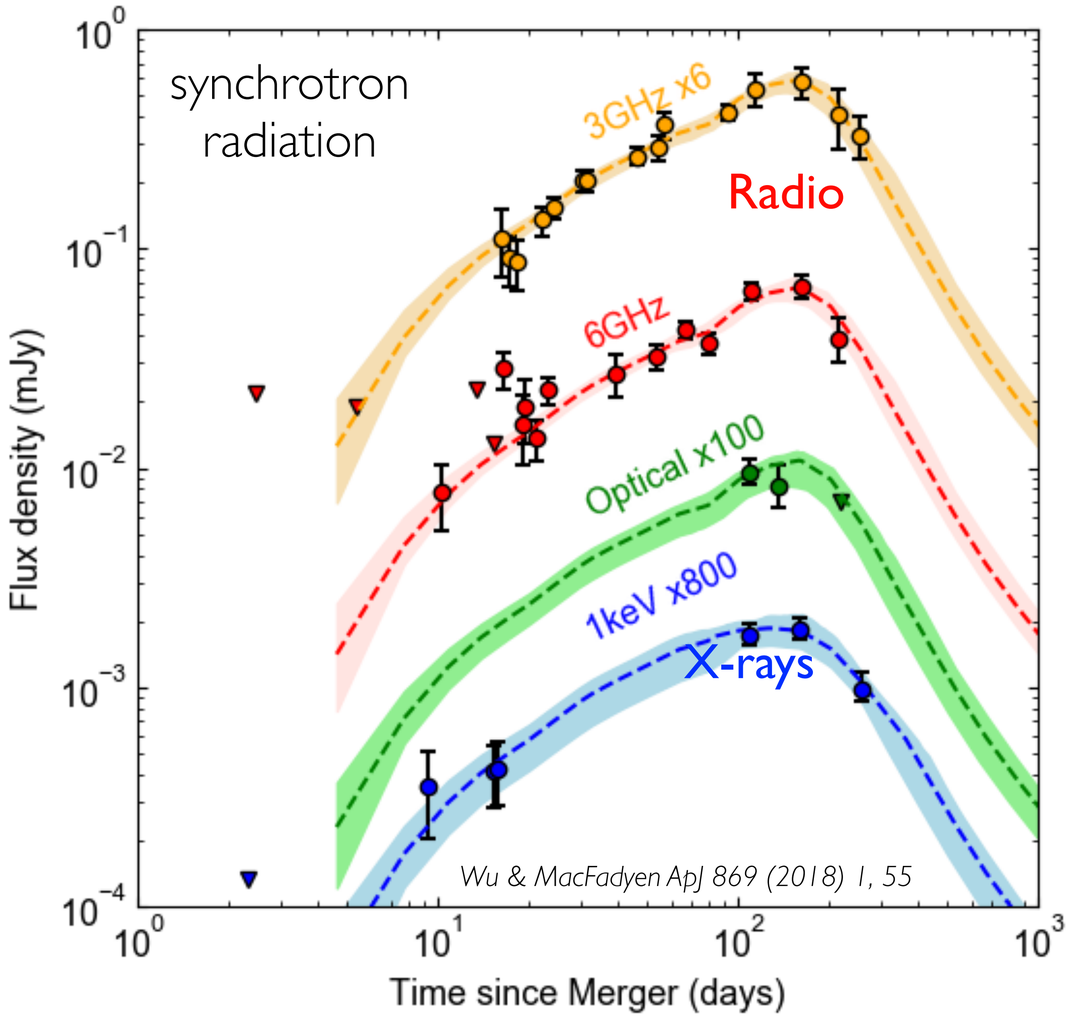


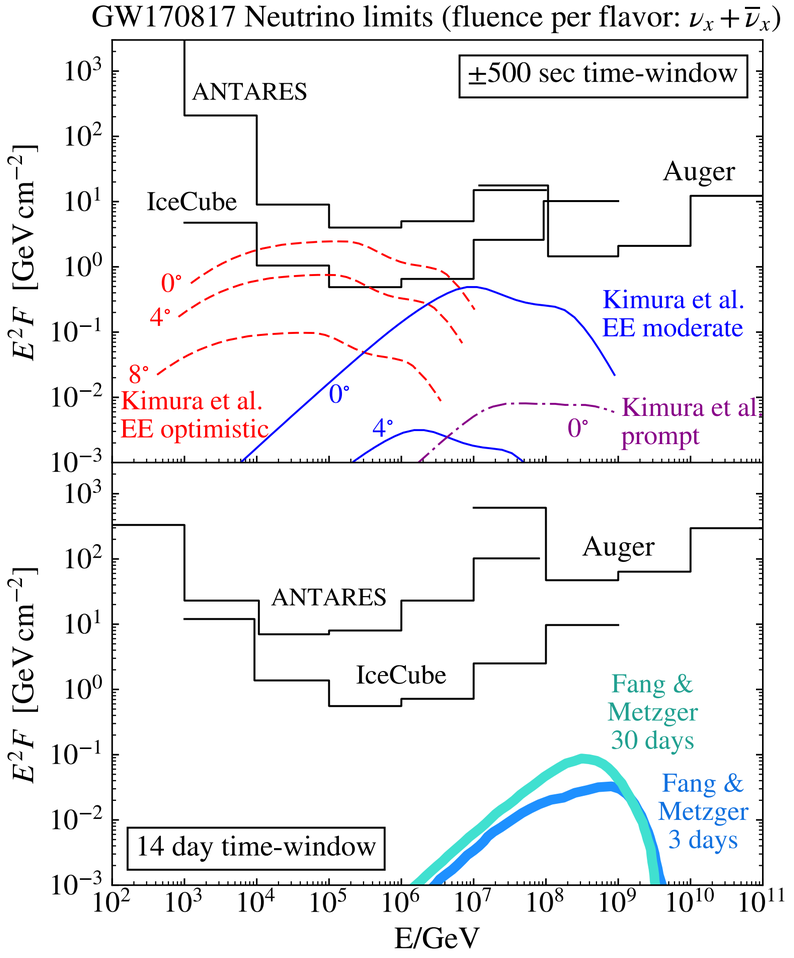


Binary neutron star mergers: GW170817



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

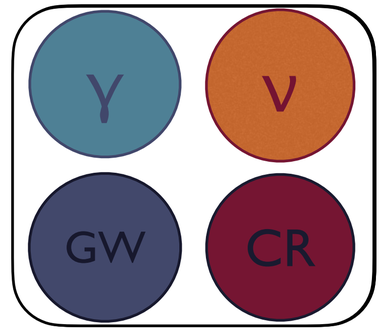




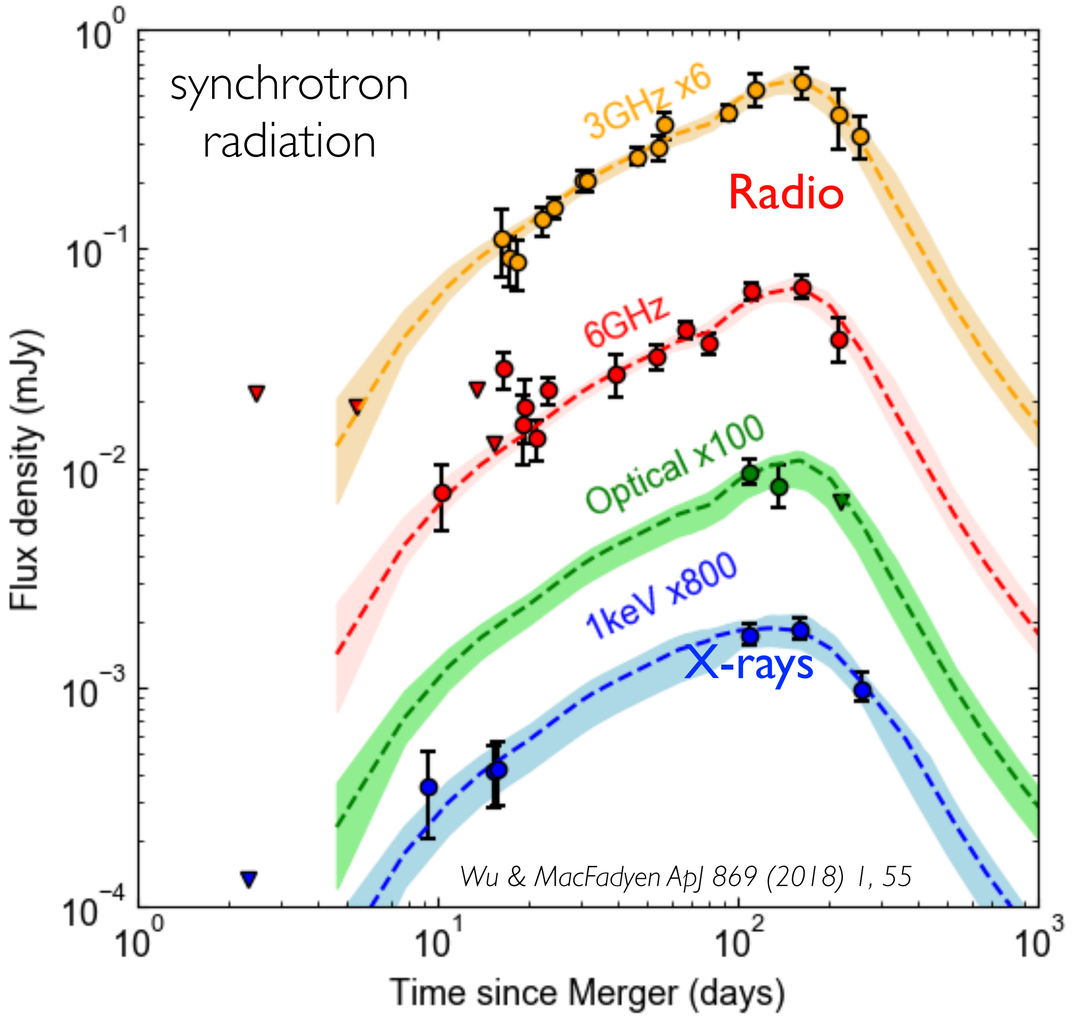
neutrinos from the GRB

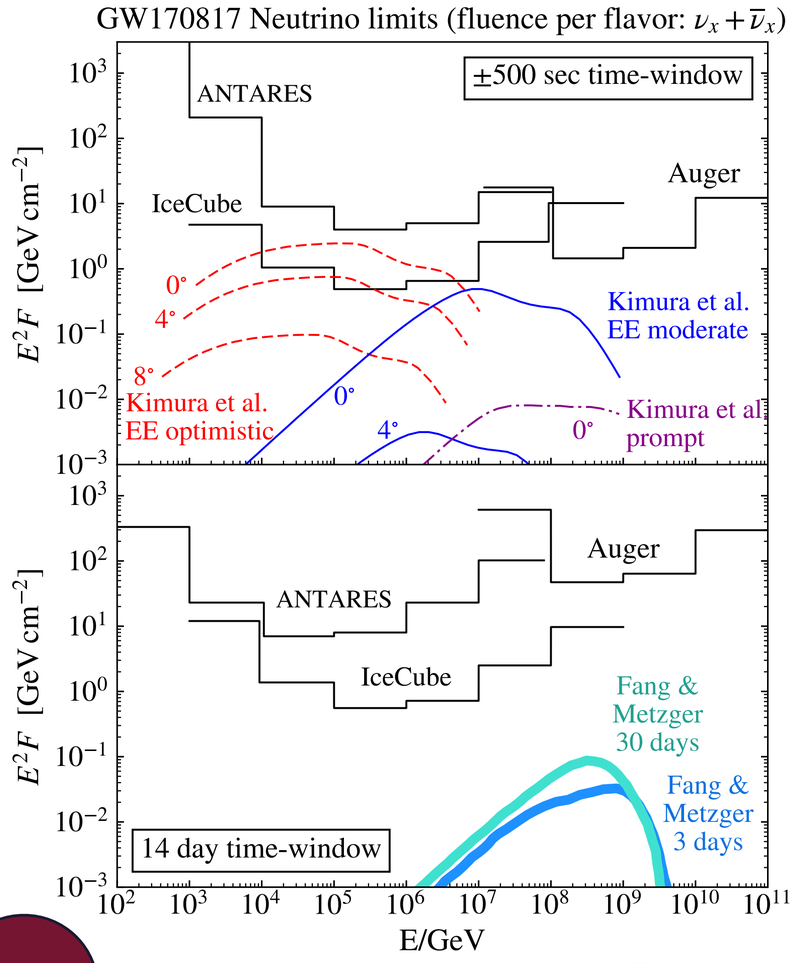
neutrinos from magnetar nebula

Binary neutron star mergers: GW170817



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





neutrinos from the GRB

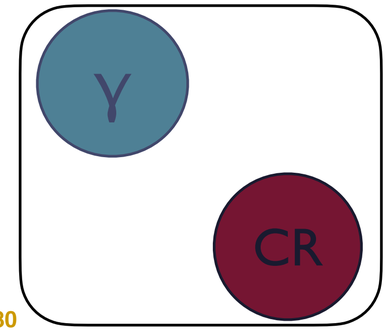
neutrinos from magnetar nebula

\+ CR could sources of CRs up to the ankle

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

Arrival directions

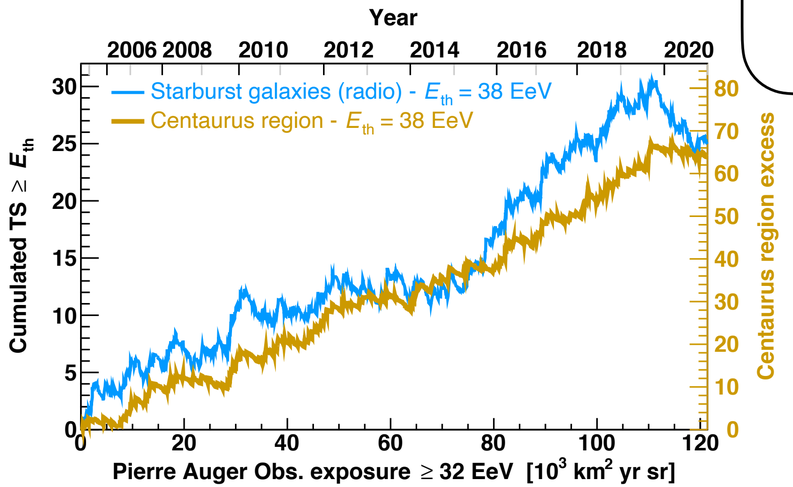
plenary talk by Claudio Galleli tomorrow

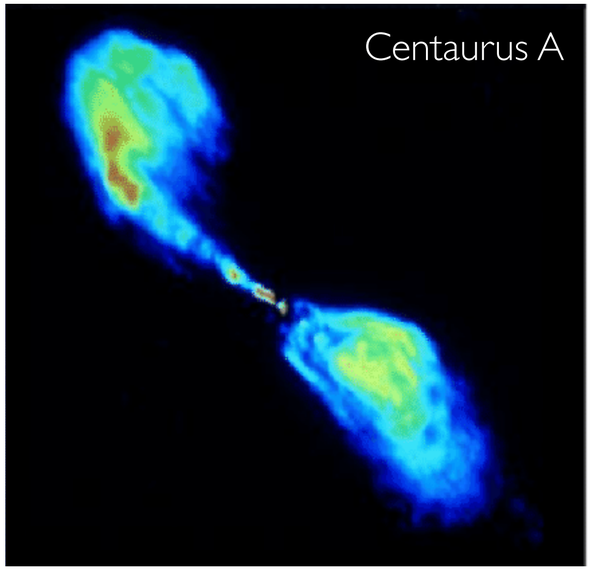


Starburst galaxies (radio flux weights)

E ≥38 EeV, Flux fraction ~10%

post-trial significance: 4.2σ





Jetted AGN (γ-ray flux weights)

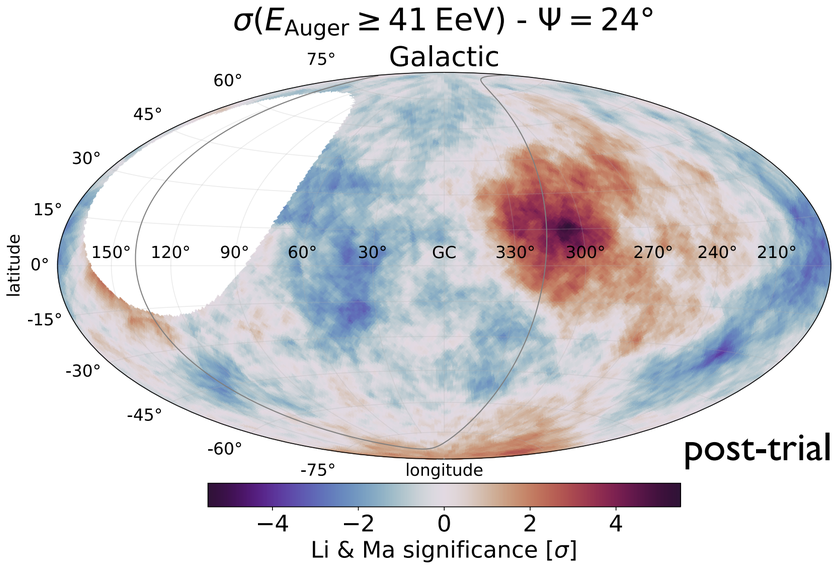
E ≥39 EeV, Flux fraction ~6%

post-trial significance: 3.3σ

Cen A region: 63 Excess events

E ≥38 EeV, angular radius: 27deg

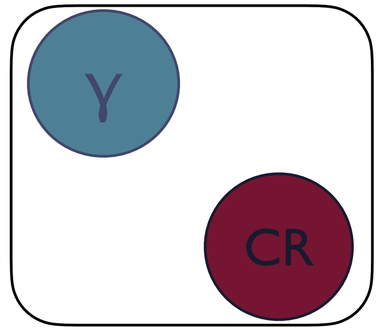
post-trial significance: 4.1σ



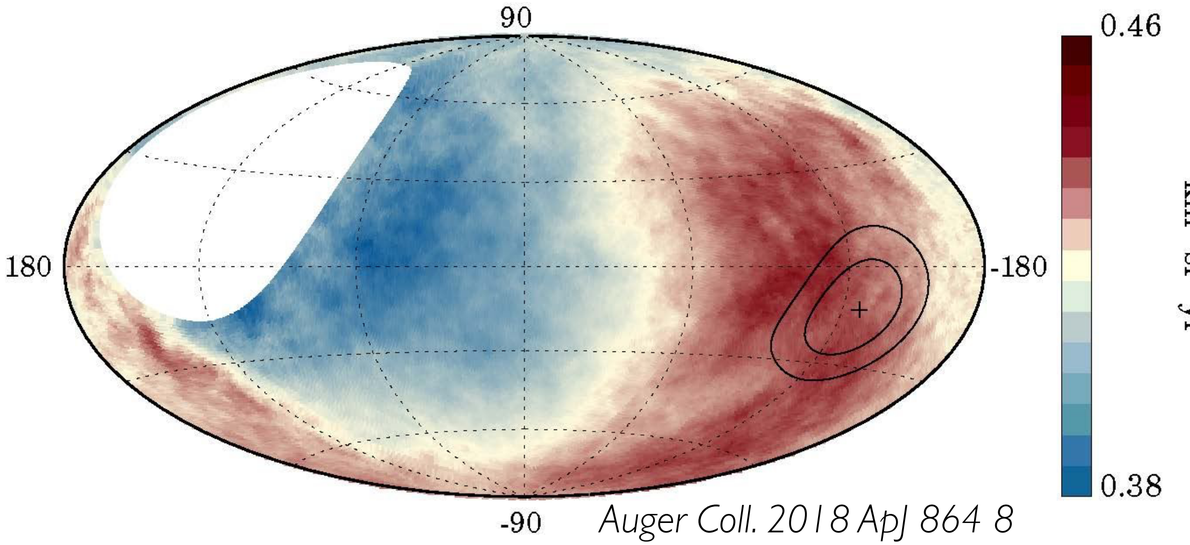
post-trial p-value: 3%

Auger Coll, ApJL, 853, L29, 2018, Auger Coll 2022, arXiv:2006.13492

Arrival directions



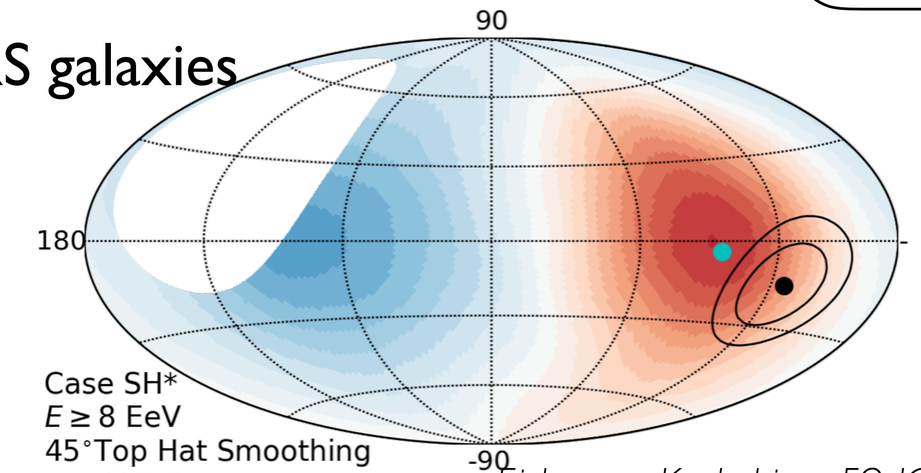
Auger Coll. 2017 Science 357 6357



Auger Coll. 2018 ApJ 864 8
de Almeida PoS(ICRC2021) 335

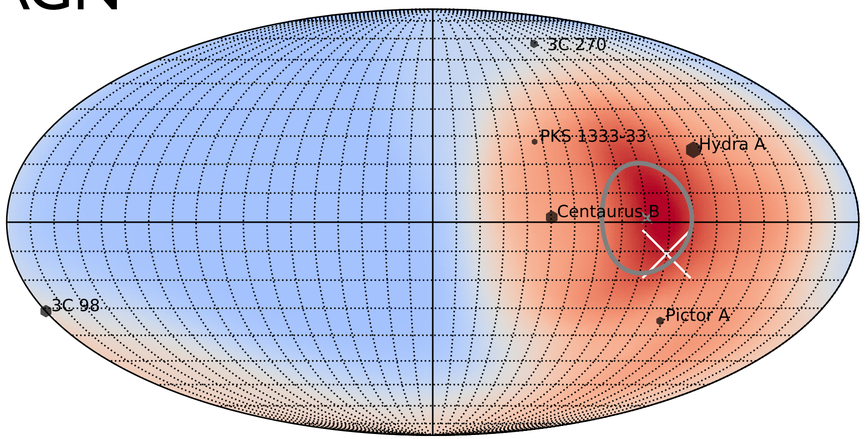
Ding, Globus, Farrar, ApJL 913 (2021) 1
(see also Allard, Aublin, Baret, Parizot 2021)

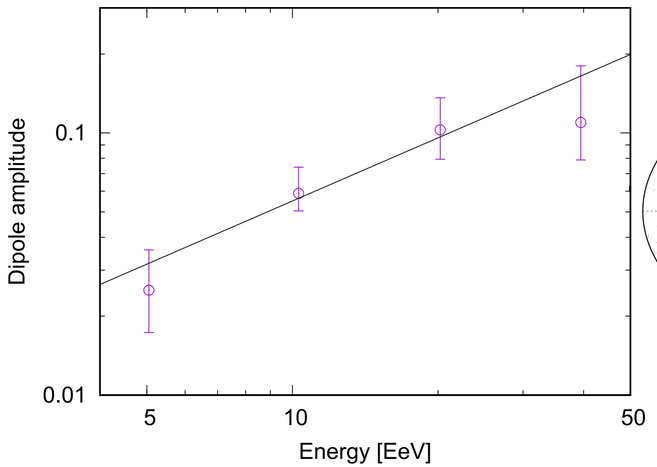
2MRS galaxies

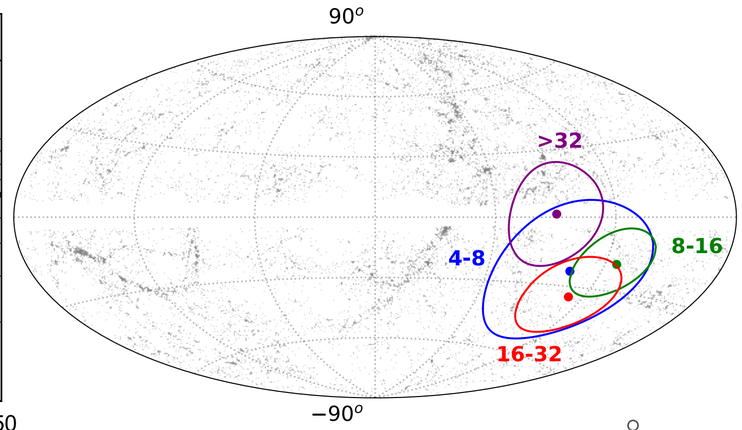


Eichmann, Kachelriess, FO, JCAP07(2022)06

Jetted AGN

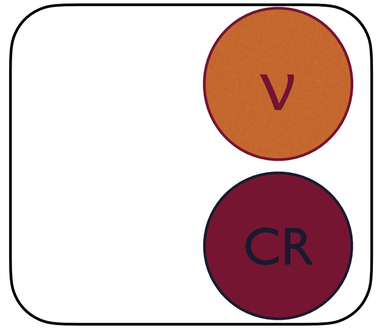




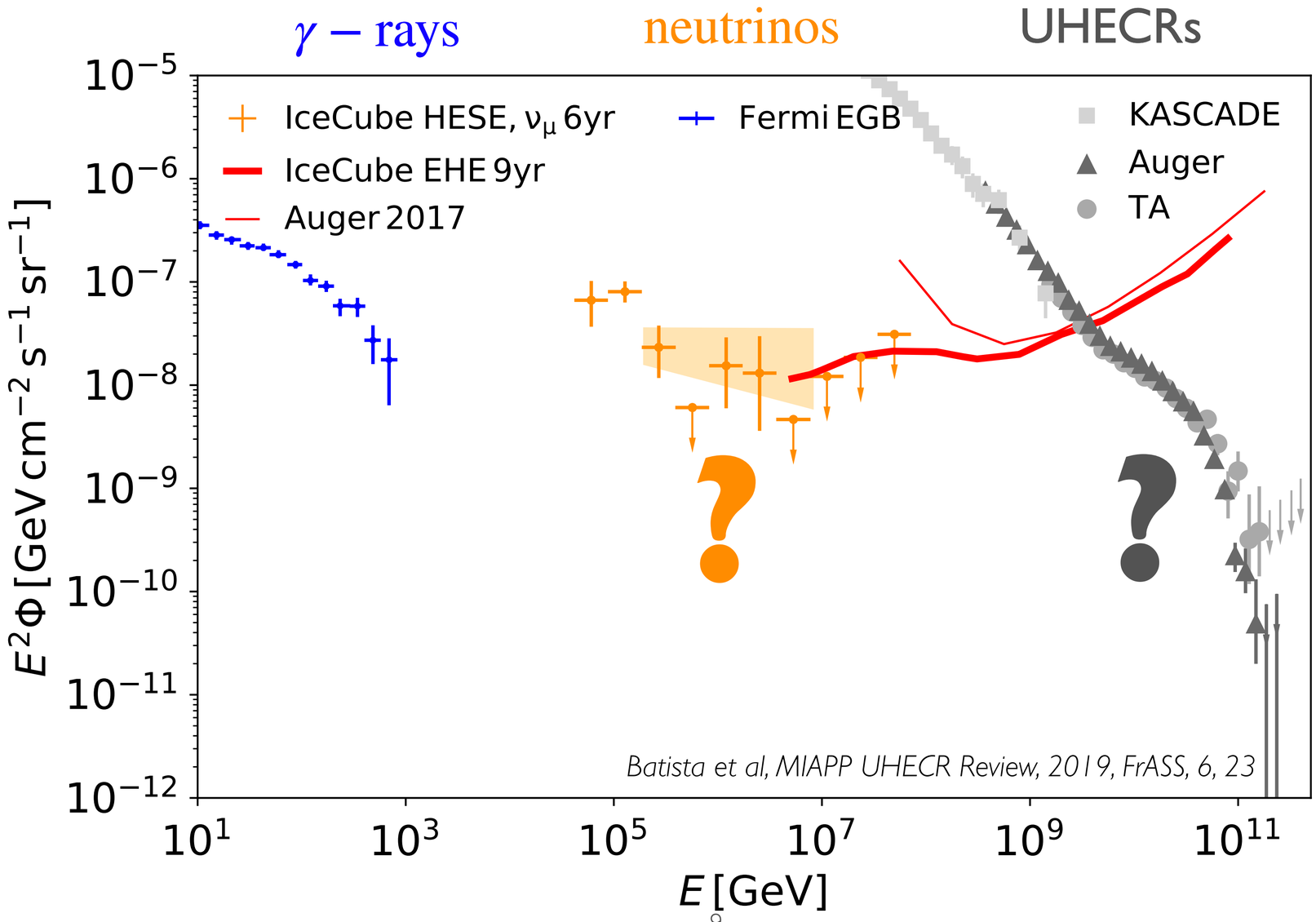


or a single source e.g. Cen A [+ M82] (Harari et al 2016, Mollerach et al 2019, Mollerach & Roulet 2022)

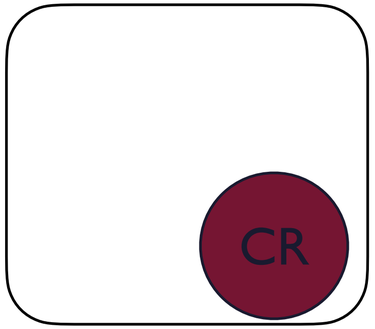
A common origin?



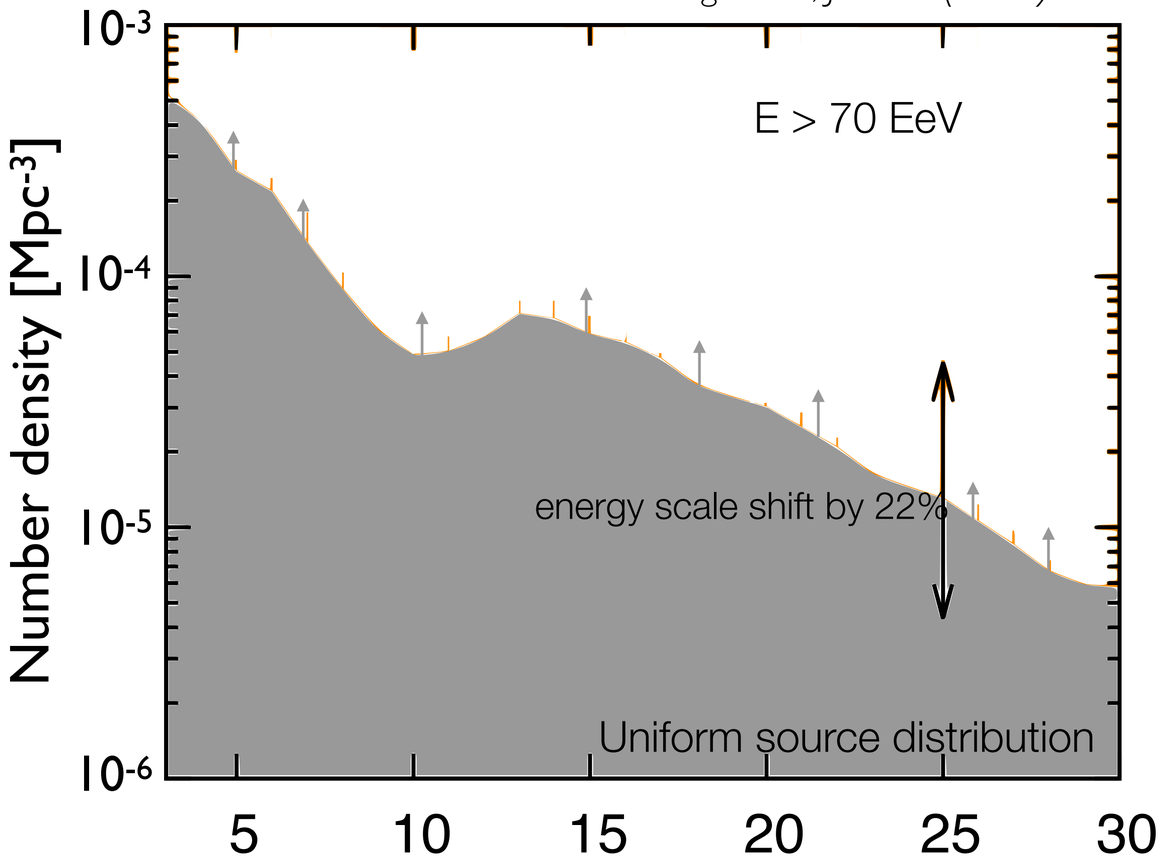
Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018



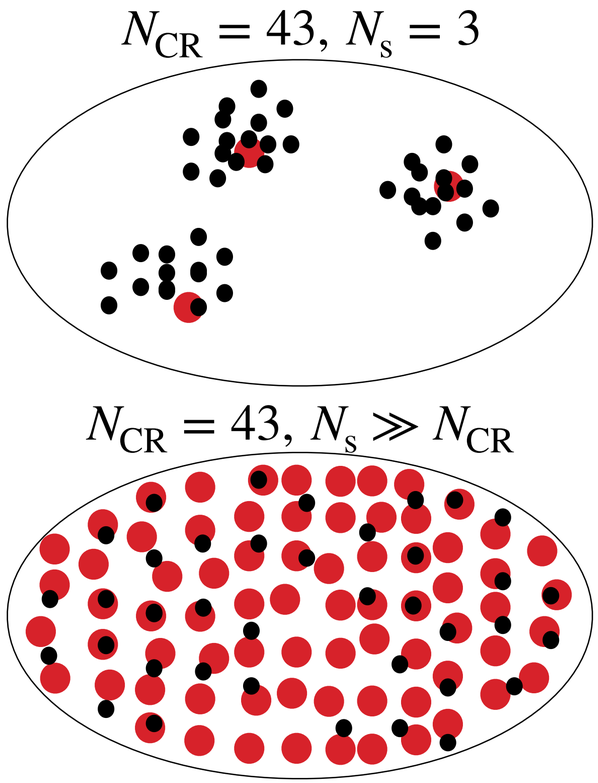
Source number density of UHECRs



Auger Coll, JCAP05(2013)009



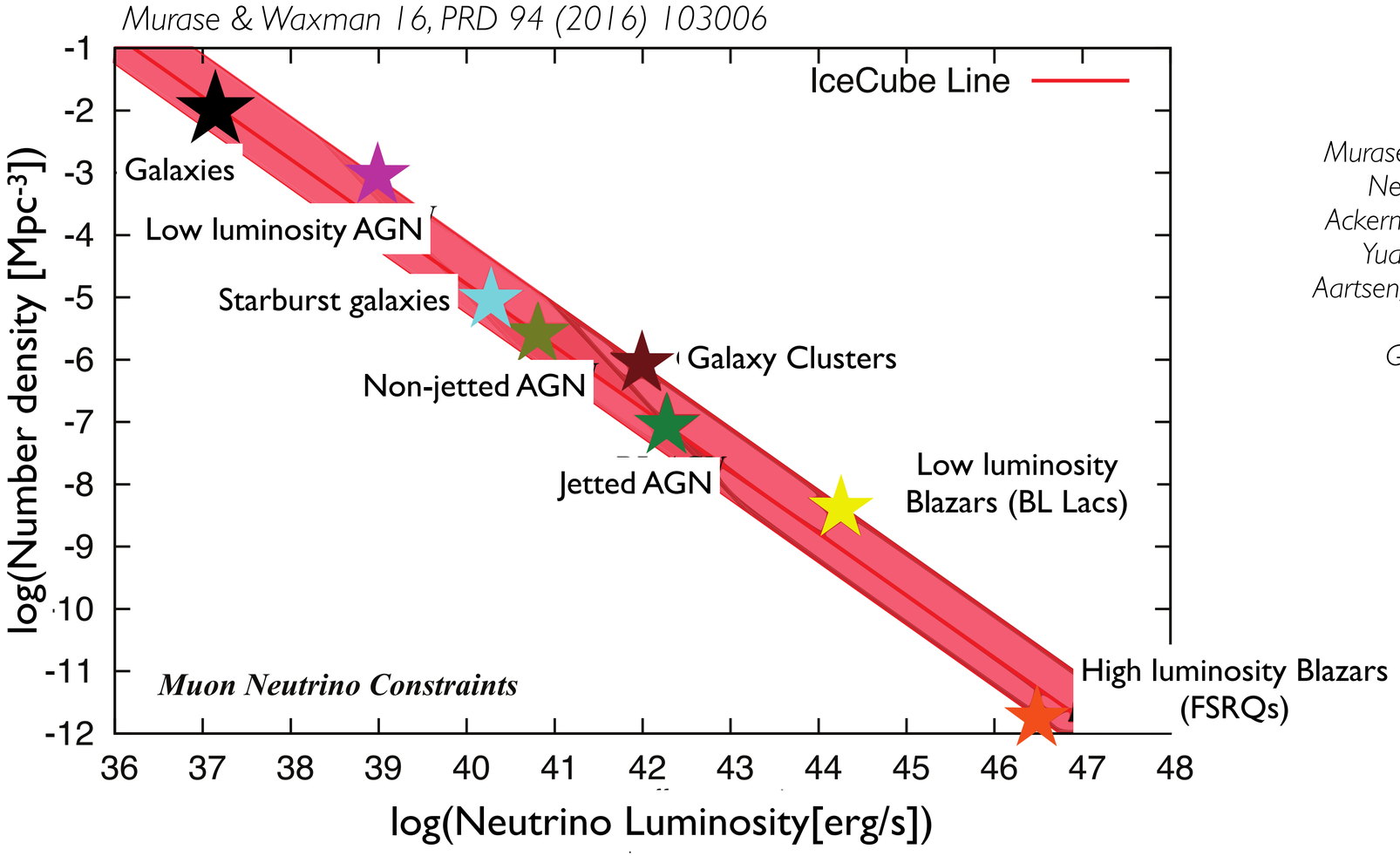
$E_{\rm thres} = 70$ EeV Average deflection Angle [deg]



Galaxies - 10^{-2} Mpc^{-3}
Non jetted AGN - 10^{-3} Mpc^{-3}
Starbursts - 10^{-4} Mpc^{-3}
Jetted AGN - 10^{-4} Mpc^{-3}
BL Lacs - 10^{-6} Mpc^{-3}
Flat Spectrum Radio Quasars - 10^{-9} Mpc^{-3}
GRBs - 10^{-9} Mpc^{-3}
Jetted TDEs ~ 10^{-10} Mpc^{-3}

as well as Waxman, Fisher, Piran , ApJ 1997
Dubovski, Tinyakov, Tkachev, PRL85(2000)1154
Takami & Sato, Astrop.Phys.30 (2009) 306
FO, Connolly et al JCAP05(2013)015

Source number density of high-energy neutrinos



as well as Lipari 2008
Ahlers & Halzen 2014
Kowalski 2014,
Murase, FO, Petropoulou 2018
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan, Meszaros et al 2019
Aartsen, Ackermann et al 2019
Fiorillo et al 2022
Guepin, Kotera, FO 2022

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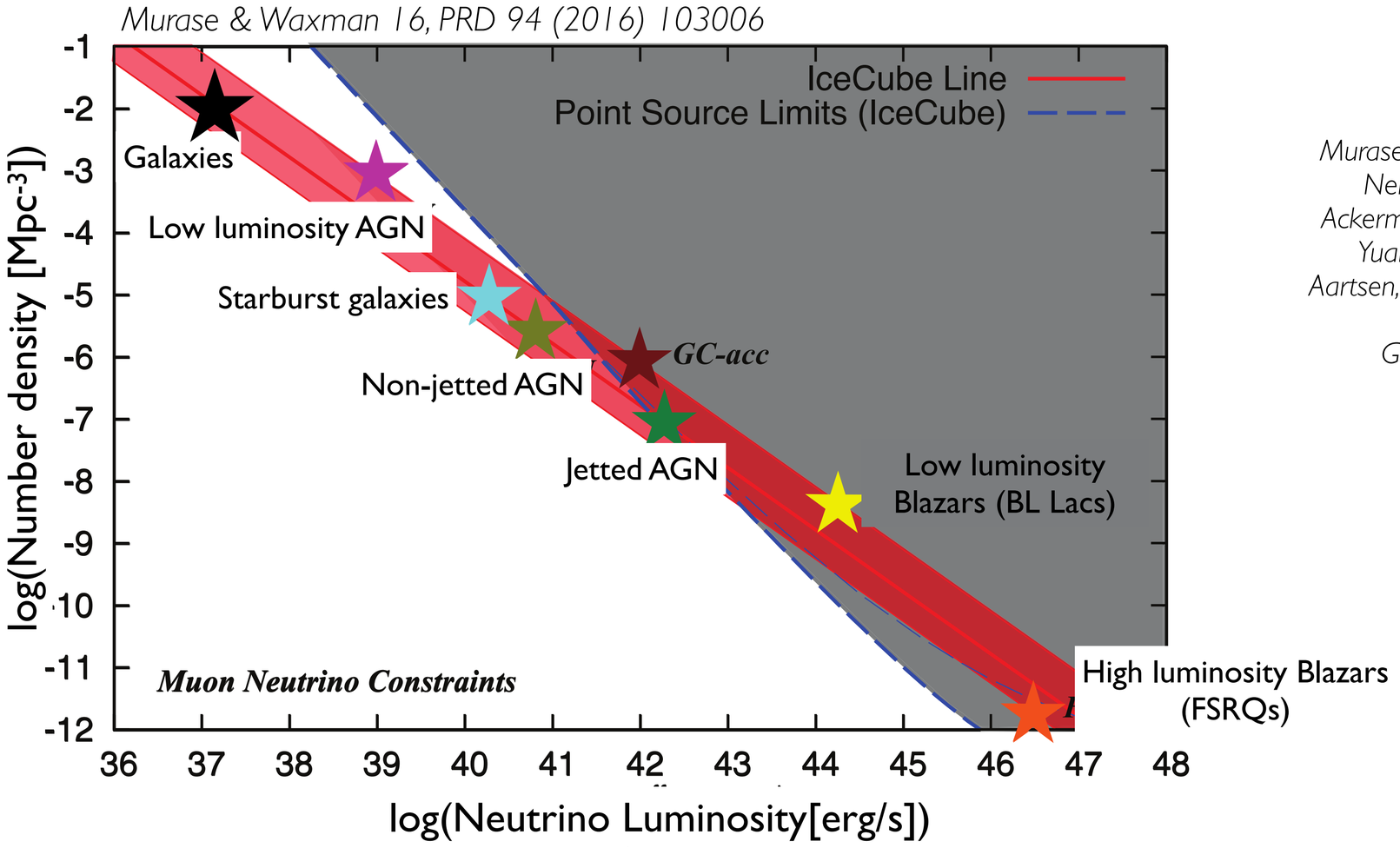

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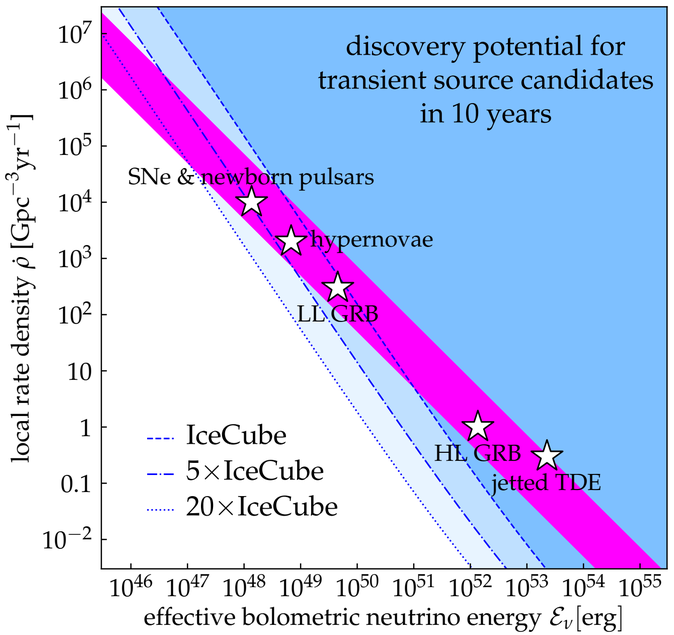
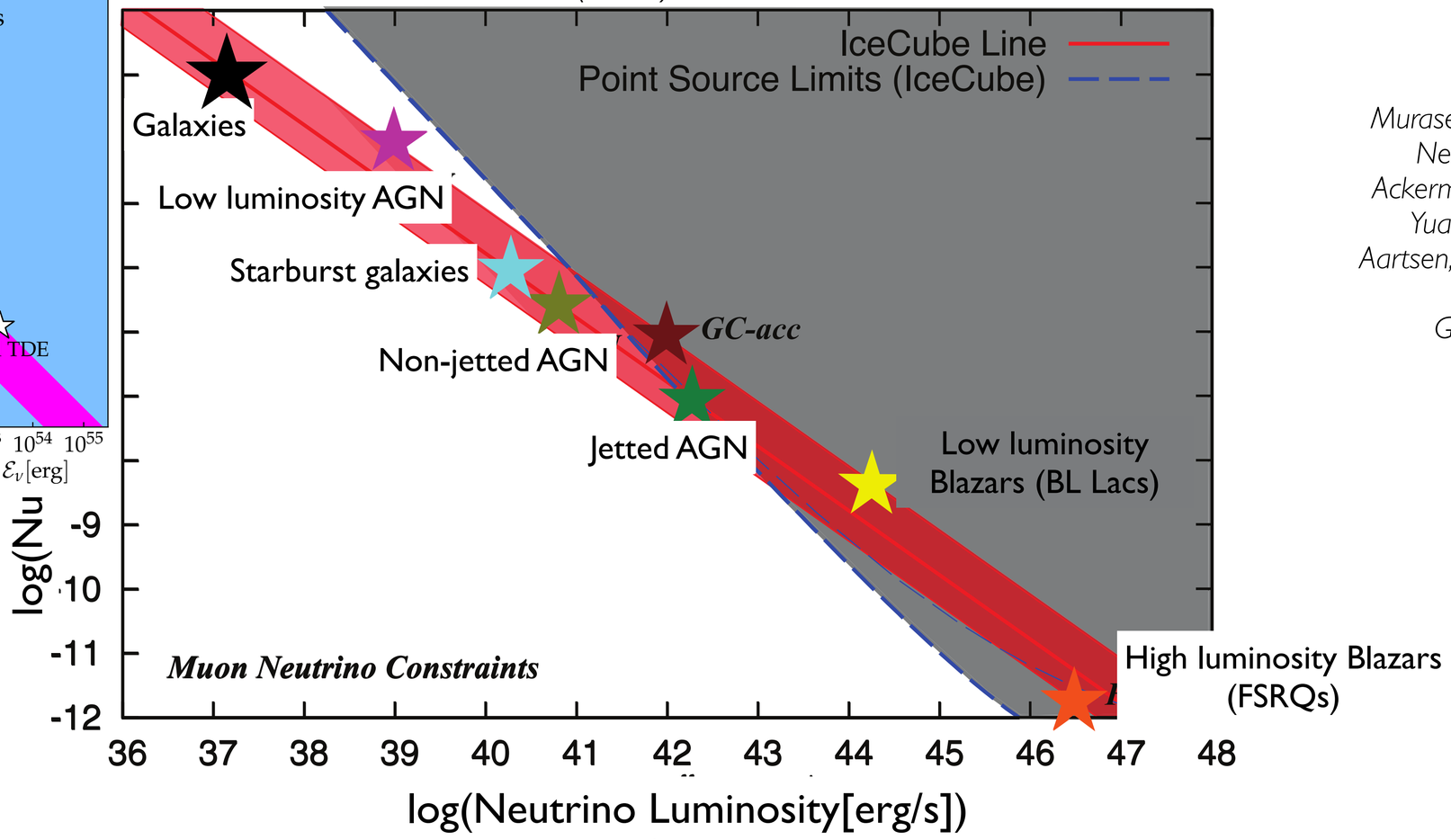
Source number density of high-energy neutrinos

Ackermann, Ahlers et al. ASTRO2020



Murase & Waxman 16, PRD 94 (2016) 103006



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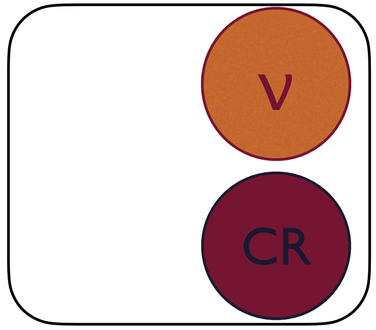
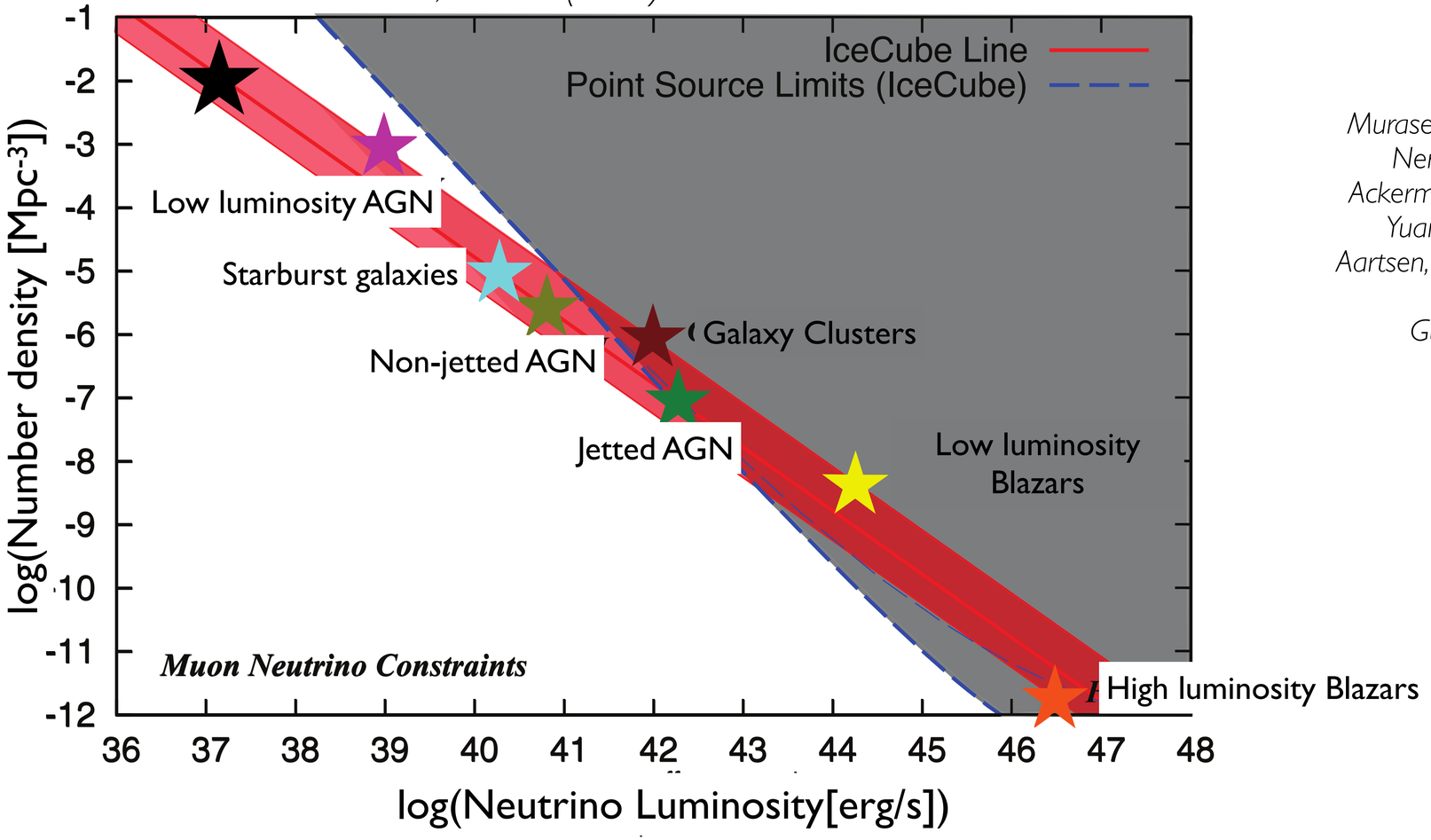


Murase & Waxman 16, PRD 94 (2016) 103006



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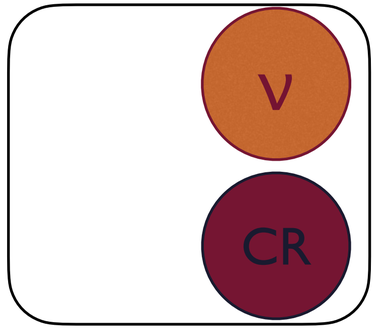

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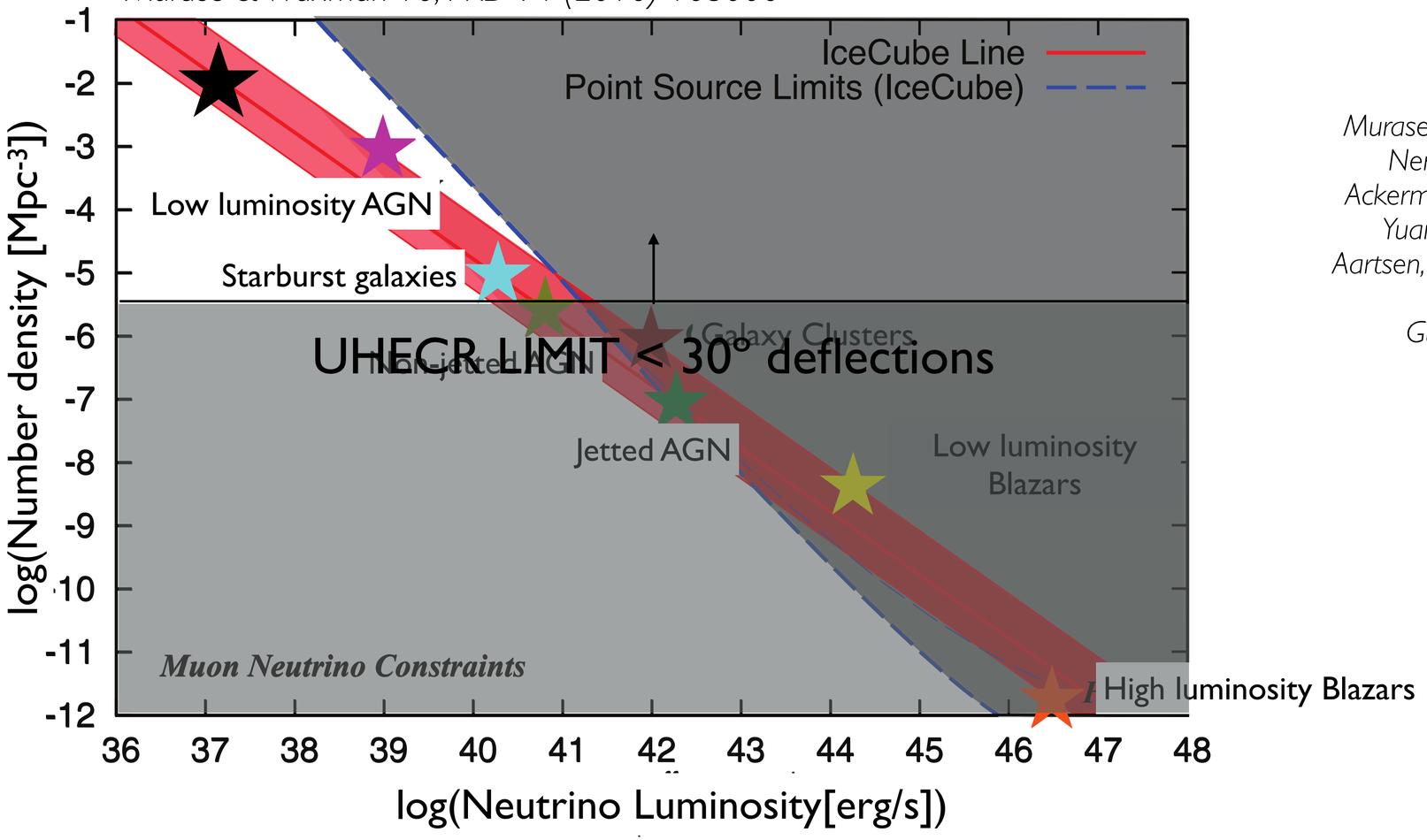

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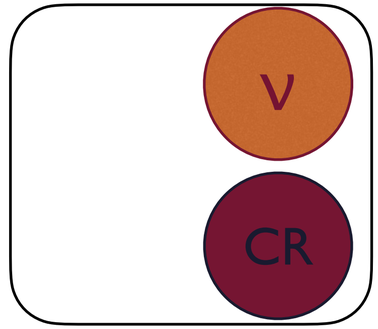
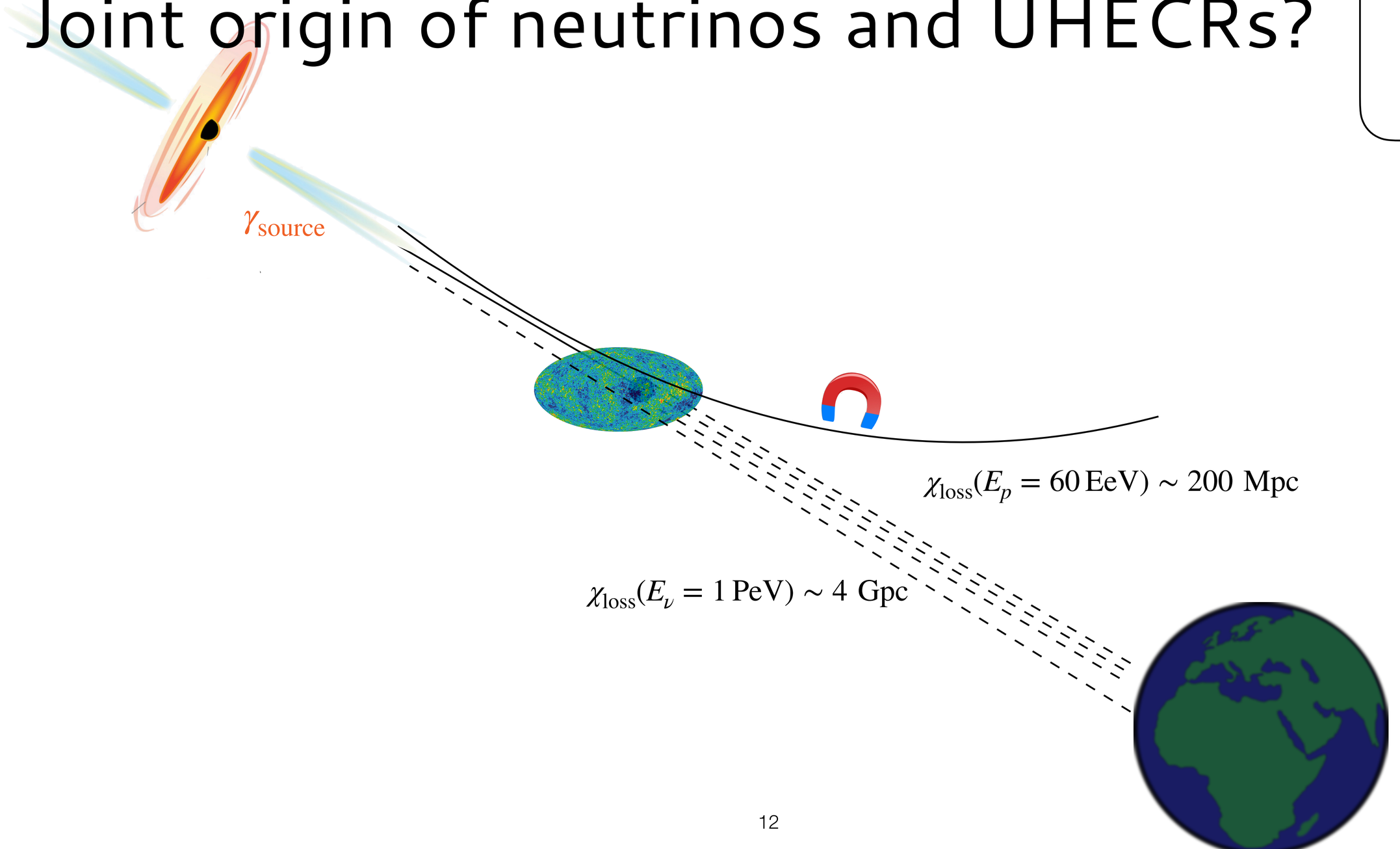
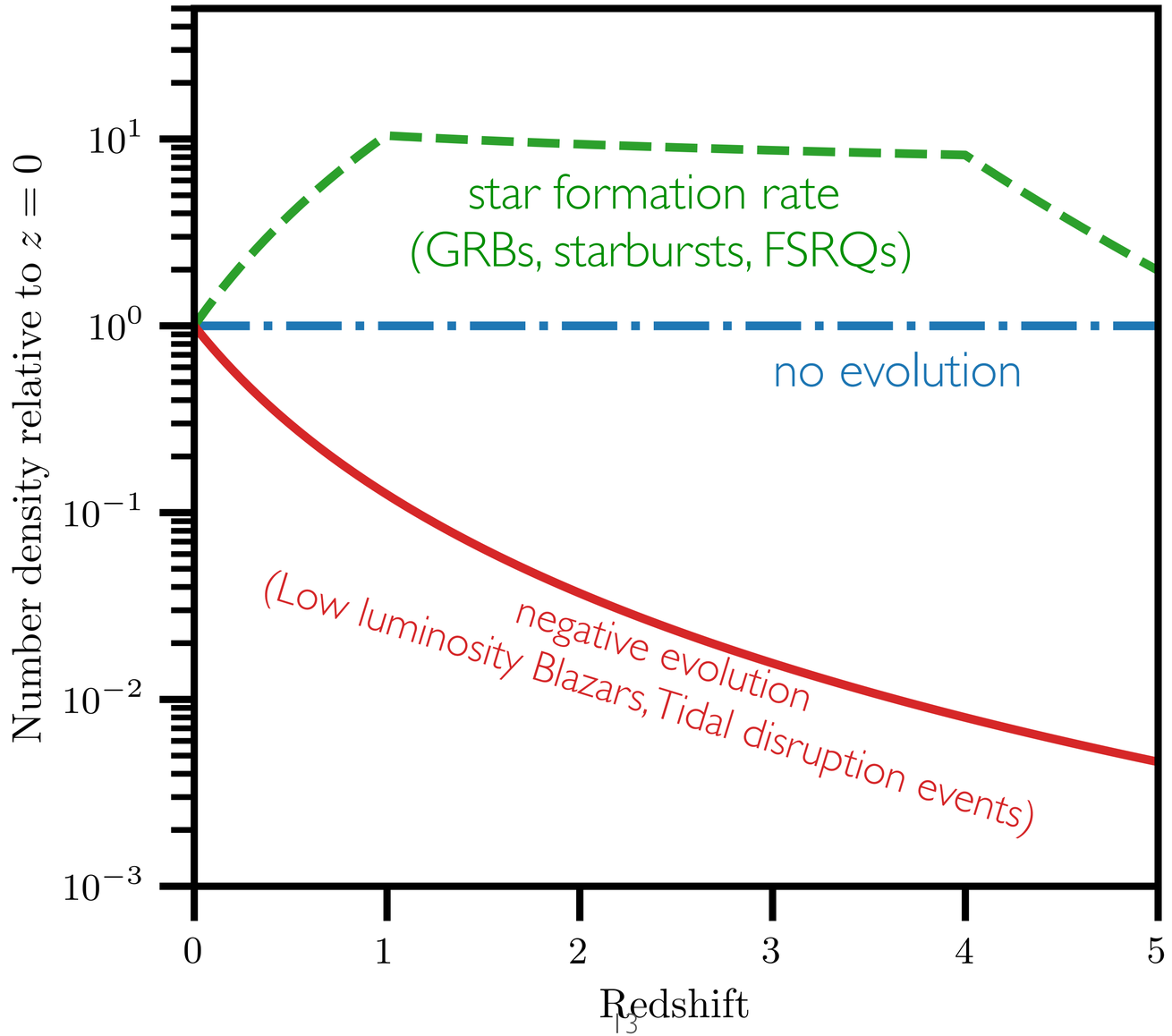
Guepin, Kotera, FO 2022

Joint origin of neutrinos and UHECRs?

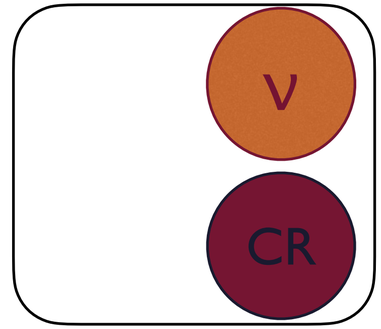




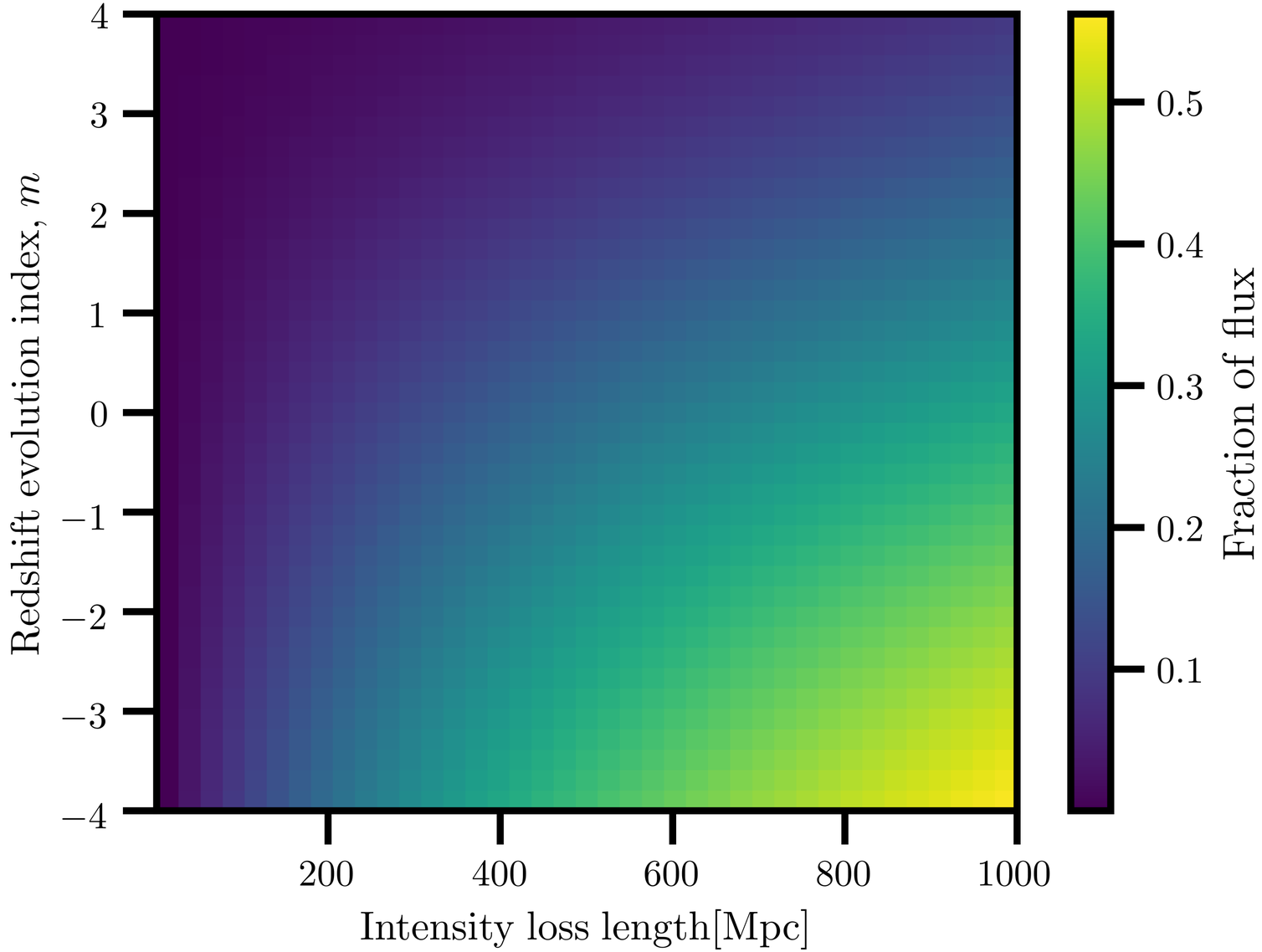
Redshift evolution of astrophysical sources



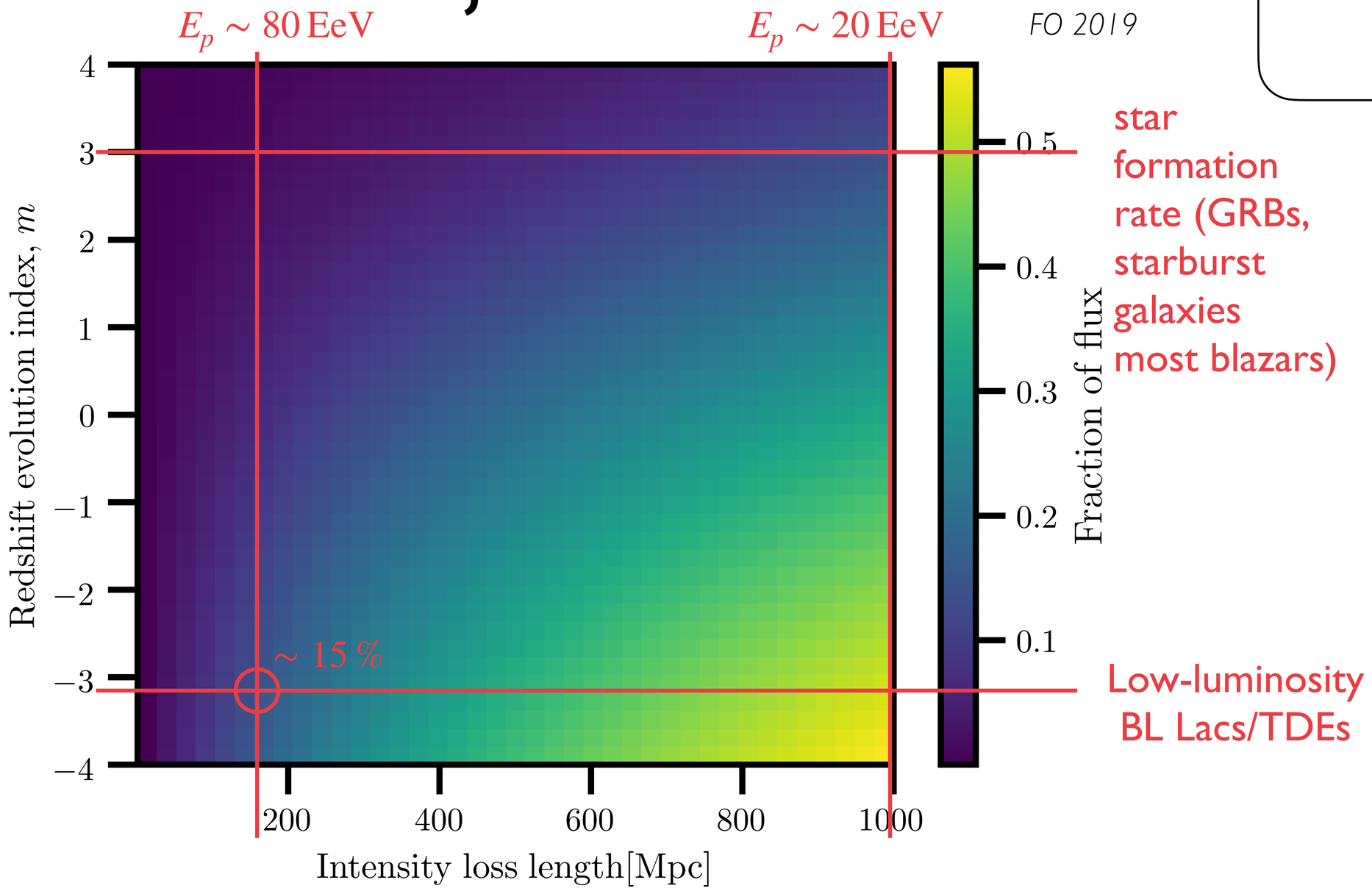
UHECR–neutrino joint horizon

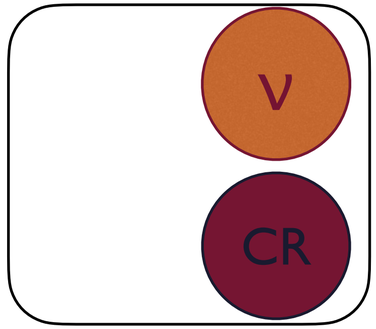


FO 2019



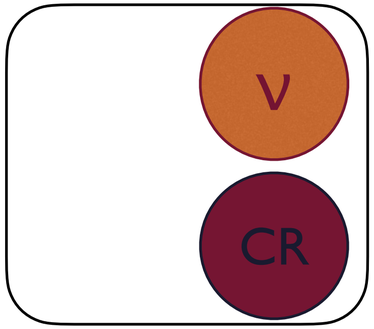
UHECR–neutrino joint horizon

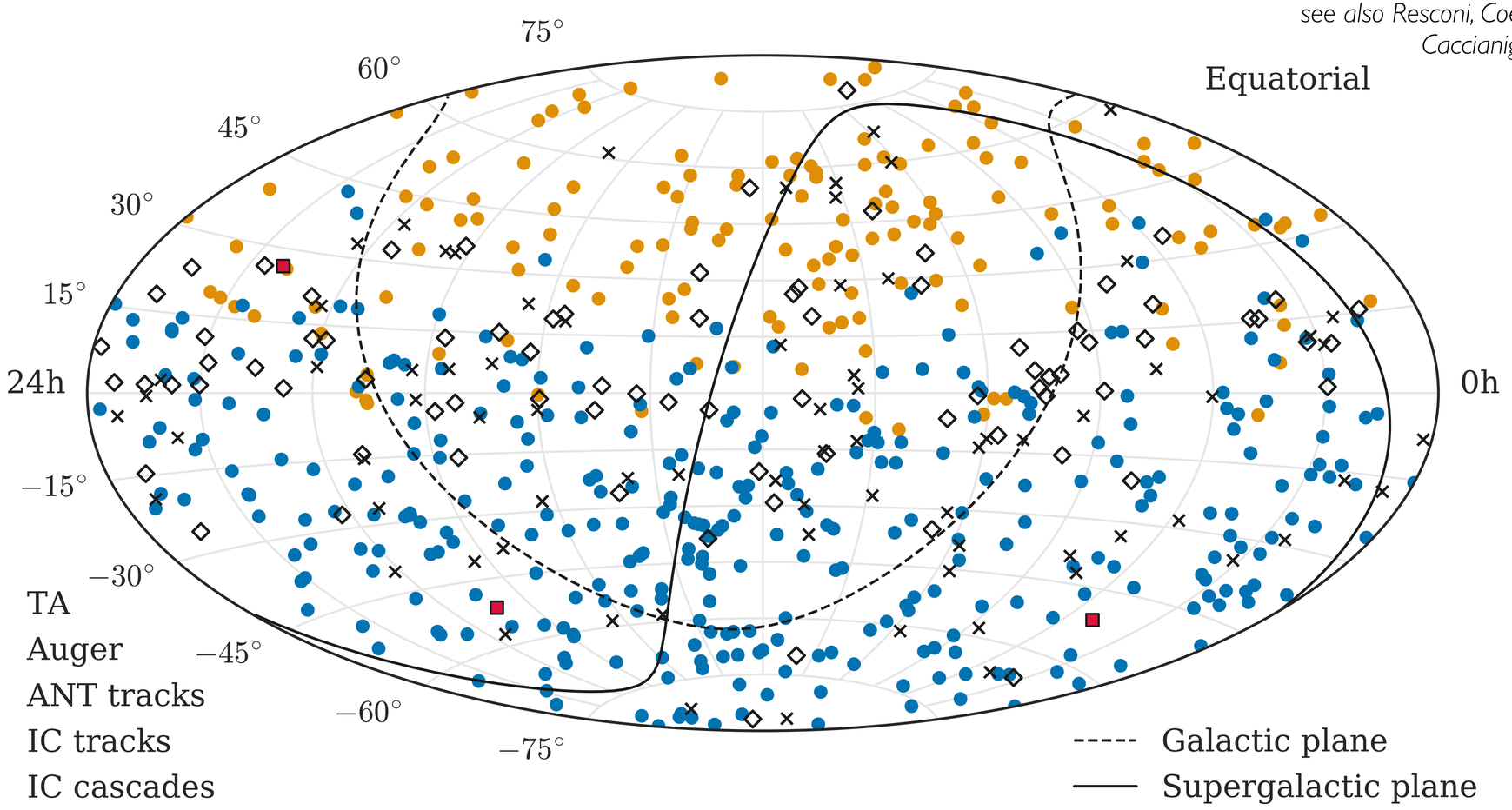


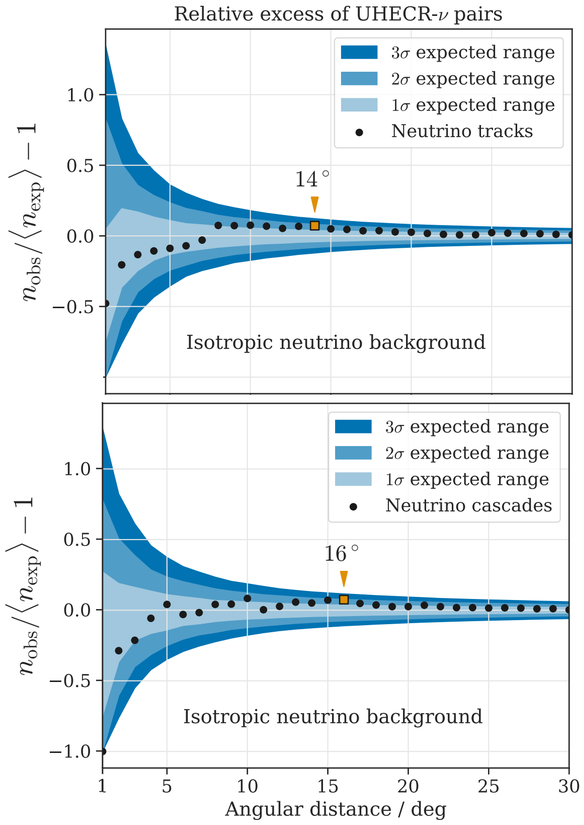


Arrival direction analysis

ANTARES, IceCube, Auger, TA Collaborations:
M. G. Aartsen et al., JCAP 1601 (2016) 037
Al Samarai et al, PoS(ICRC2017)961
Caccianiga et. al.,
EPJ Web Conf., 210 (2019)
Schumacher, L. et al.,
EPJ Web Conf., 207 (2019)
Barbano et al 2019 PoS(ICRC2019)1177
Albert et al 2022 arXiv:2201.07313
see also Resconi, Coenders, Padovani, Giommi, Caccianiga, MNRAS, 468, 1, 2017



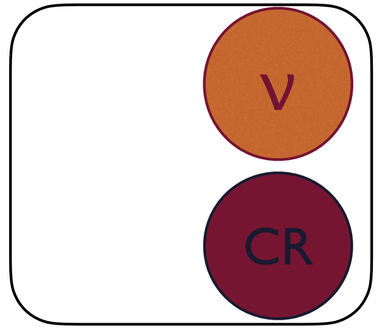


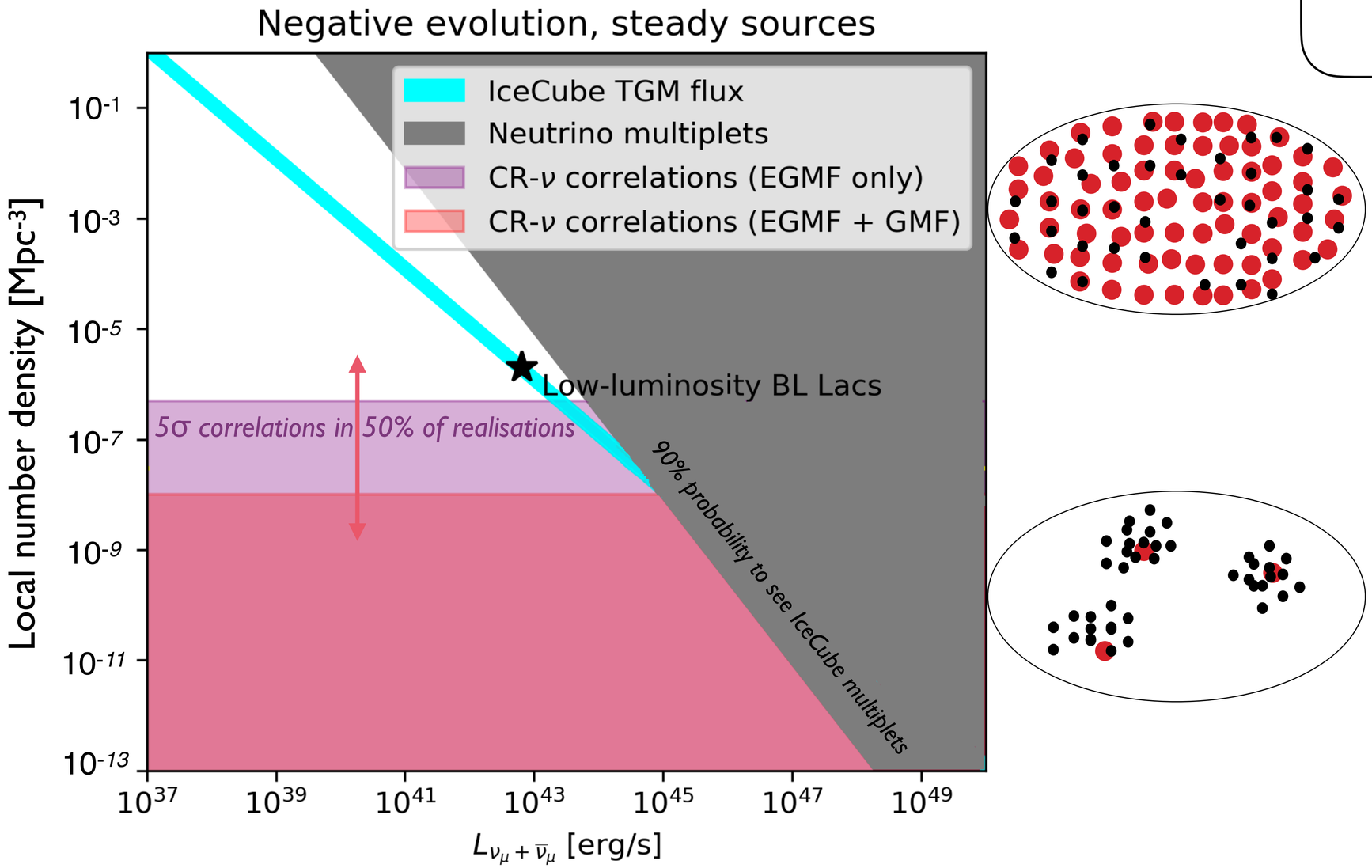


Tracks: p-value 0.23 (post-trial)
Cascades: 0.15 (post-trial)

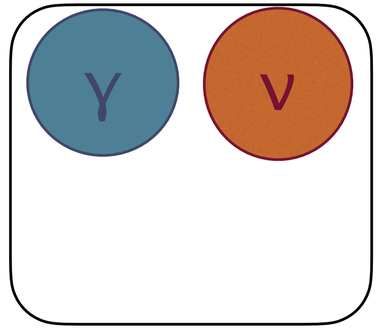
Can neutrino arrival directions trace the origin of UHECRs?

Palladino, Van Vliet, Winter, Franckowiak, 2019

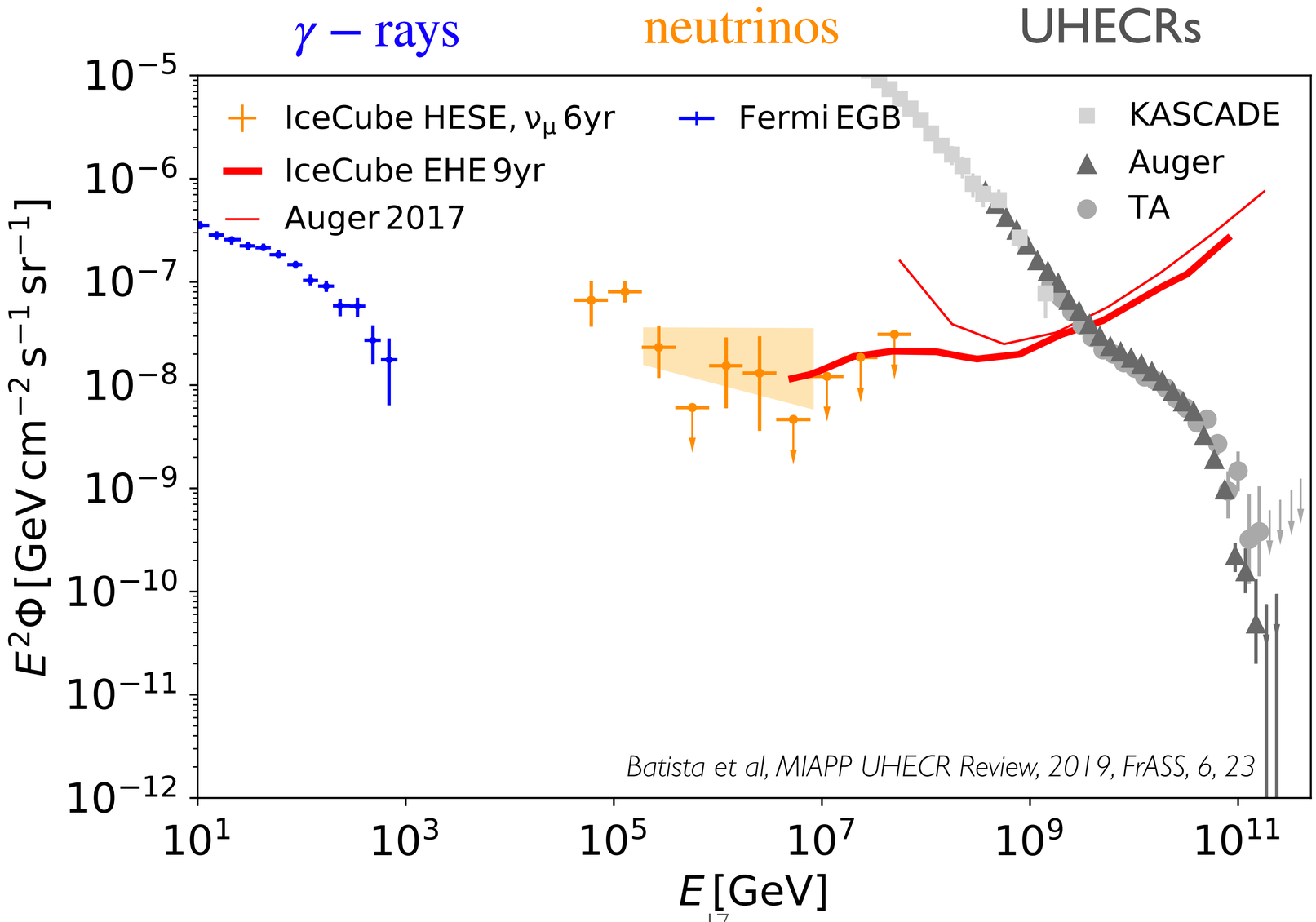




A common origin?



Waxman 2013
Ahlers & Halzen PPNP 2018
Murase & Fukugita 2018



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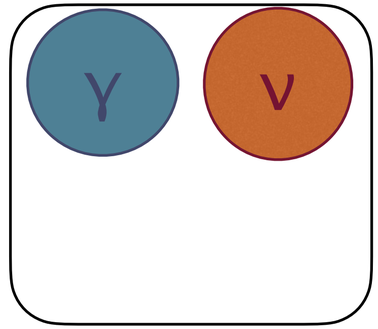

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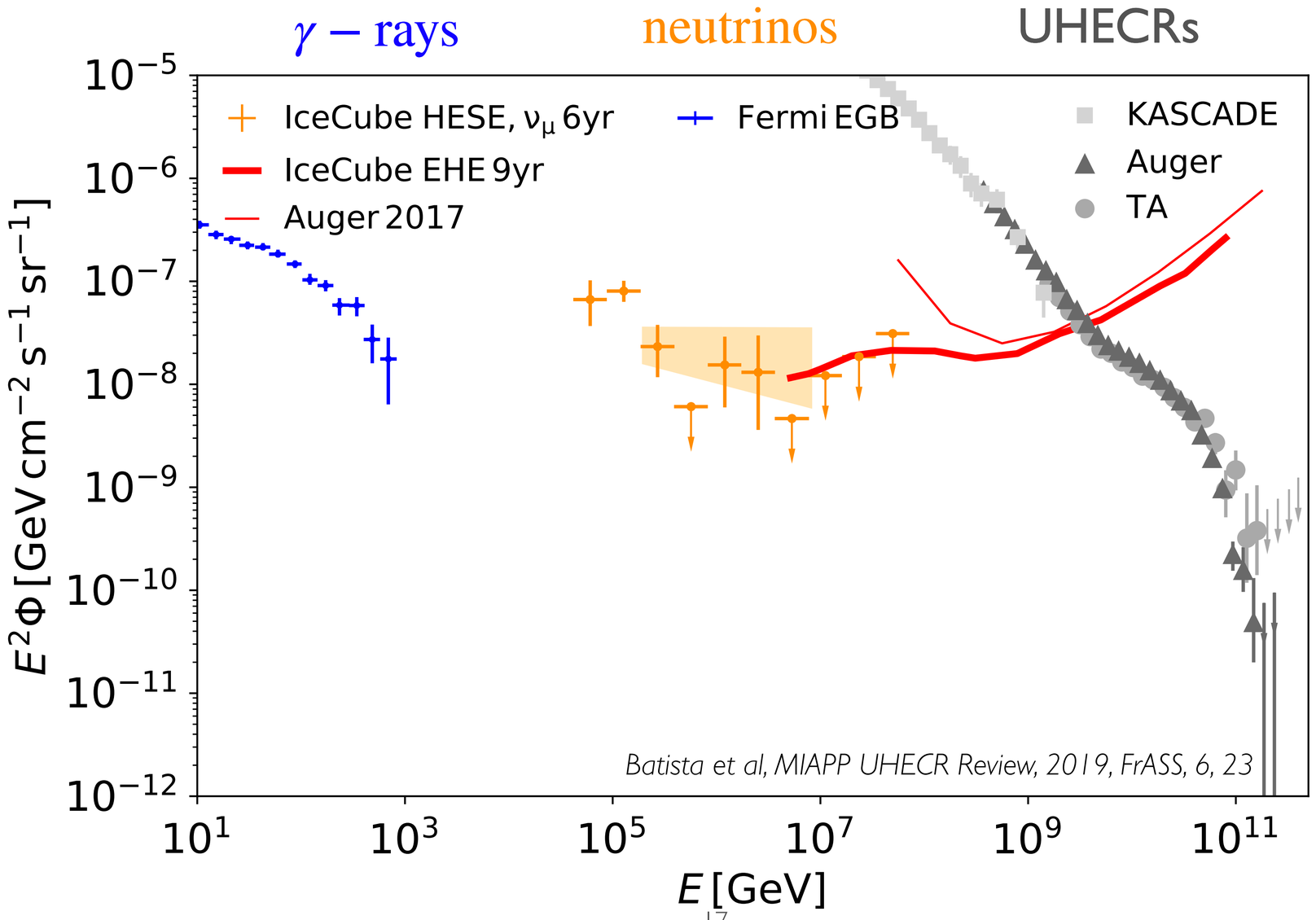

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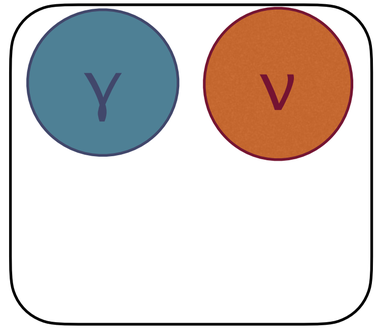

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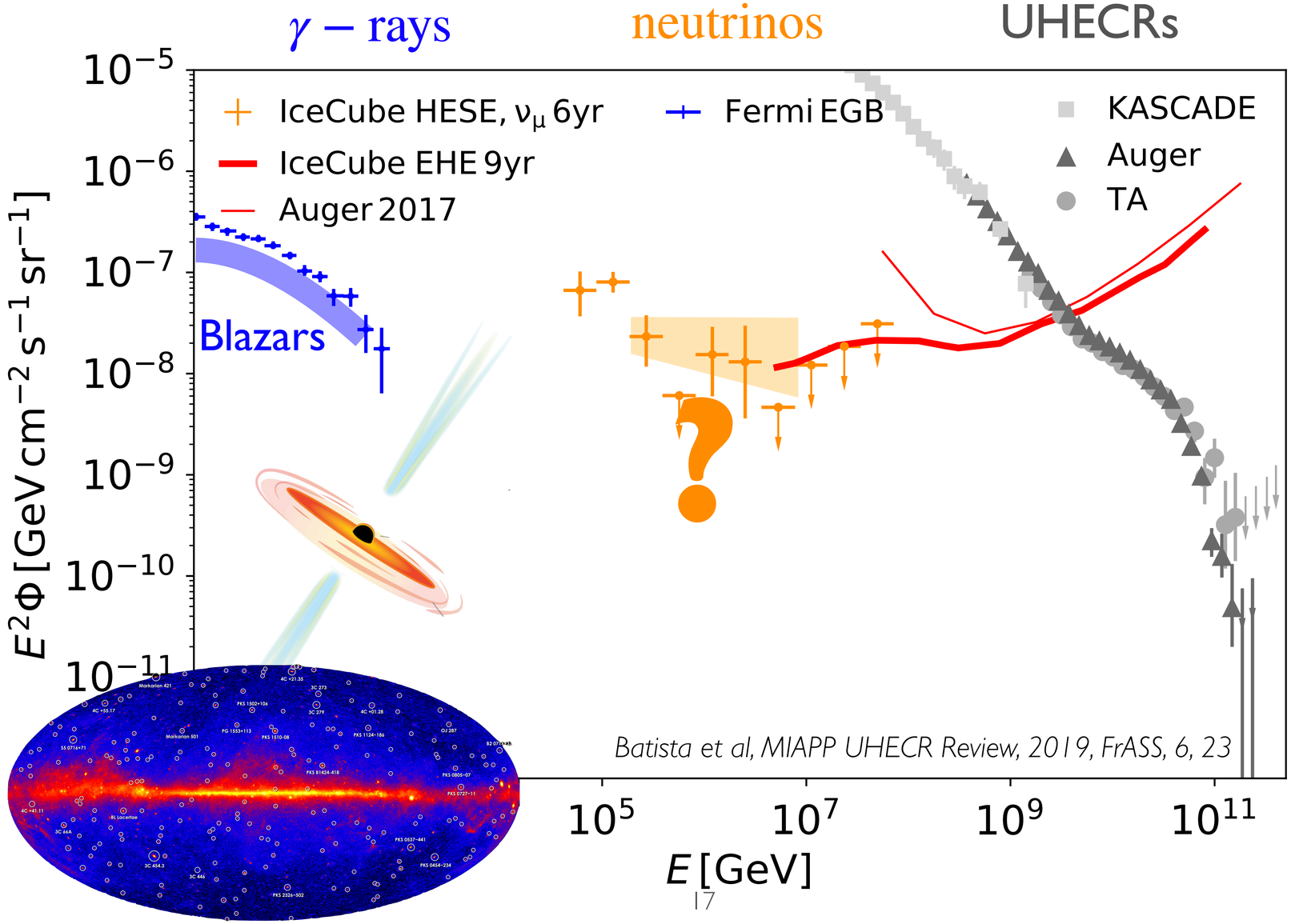
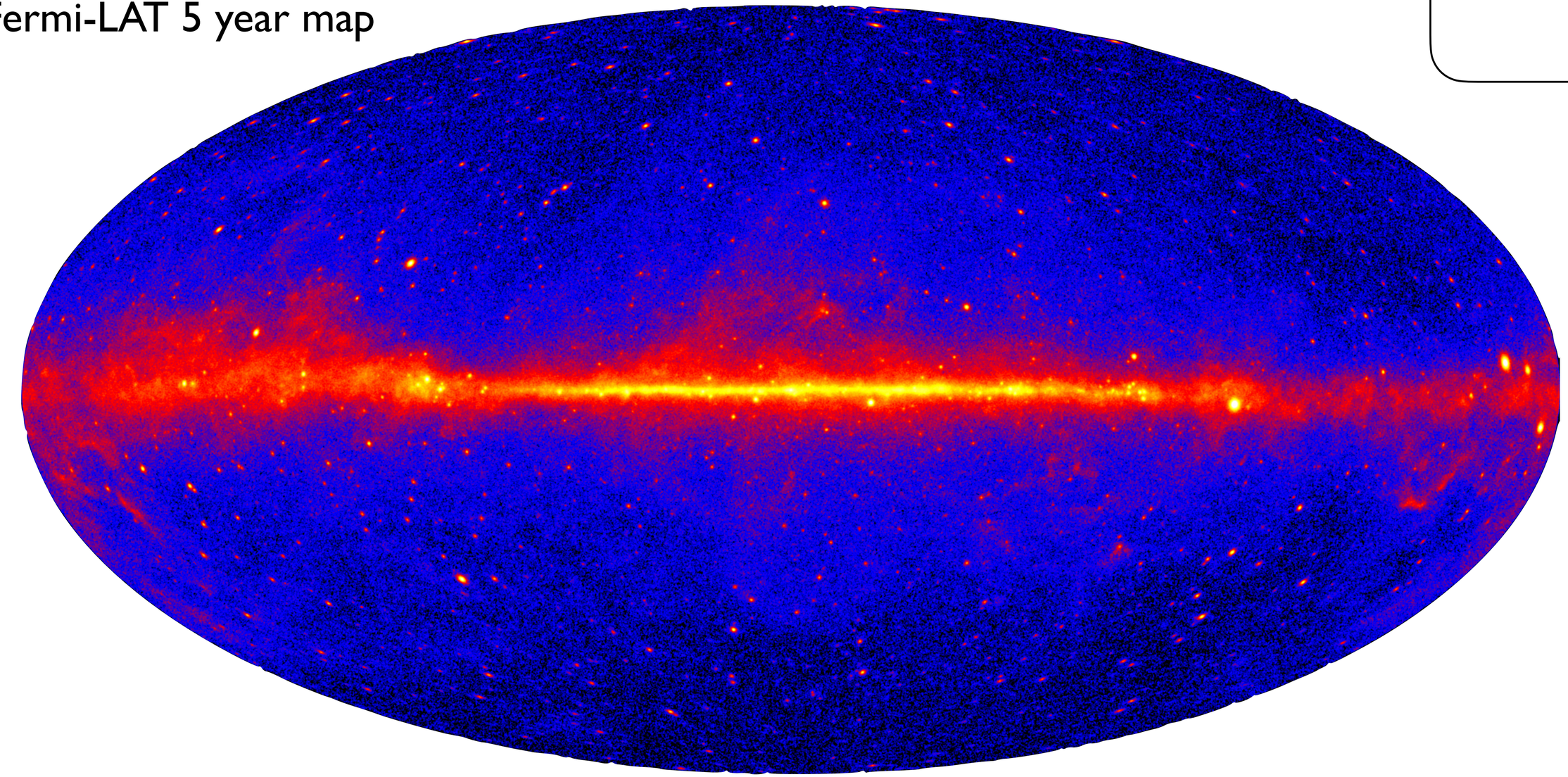
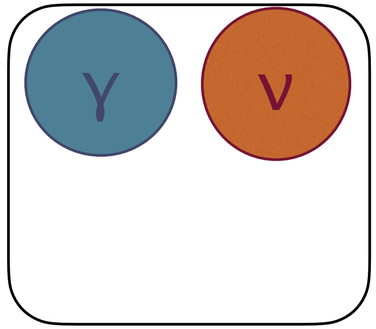


Blazars

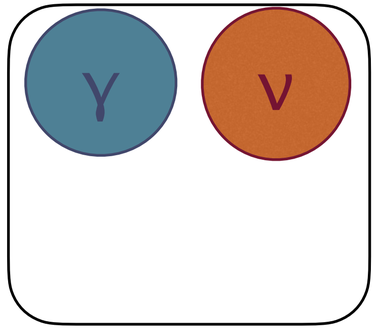
Fermi-LAT 5 year map

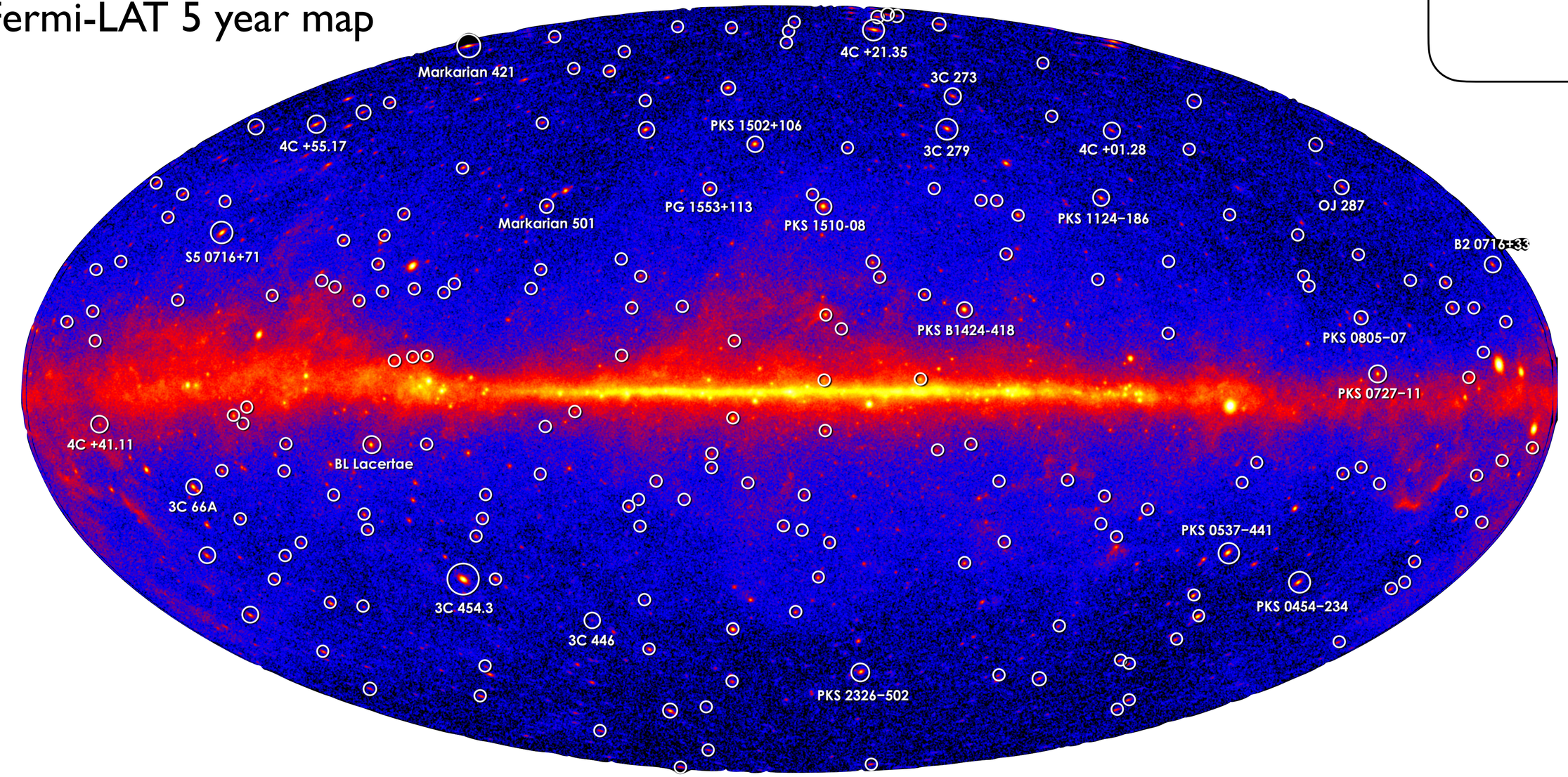




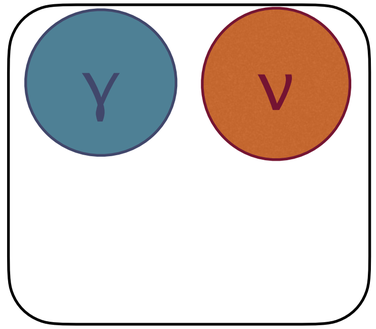
Blazars

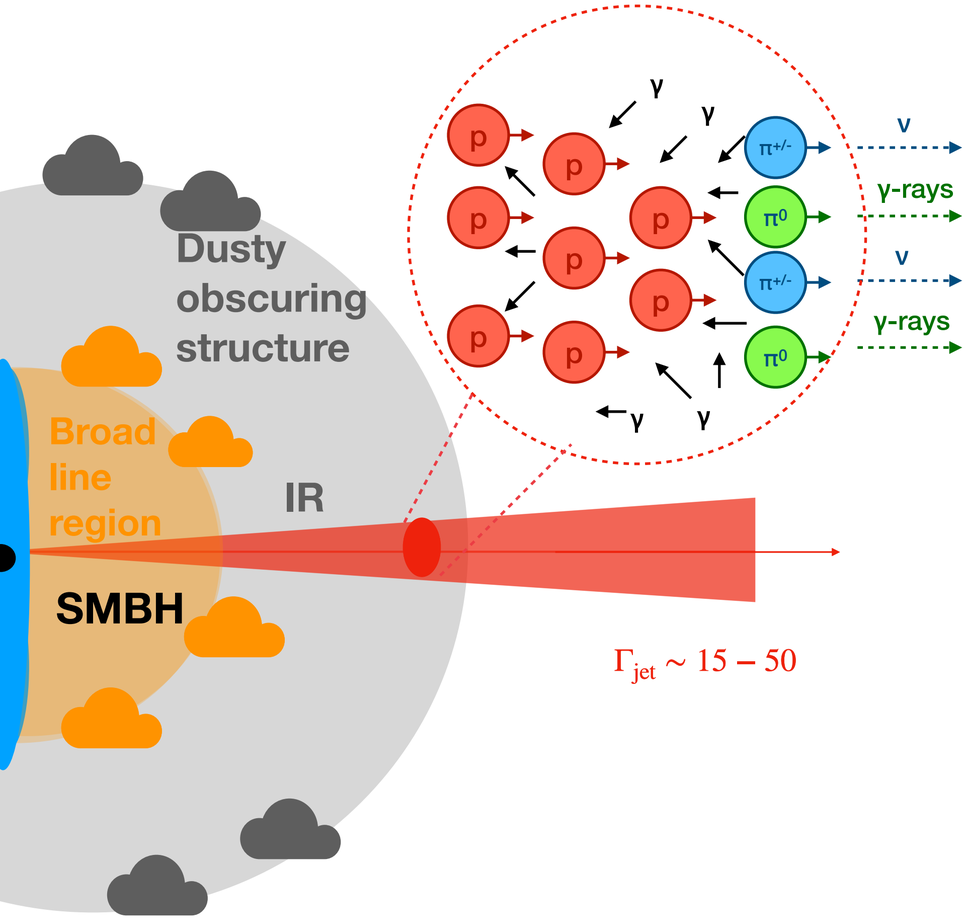
Fermi-LAT 5 year map

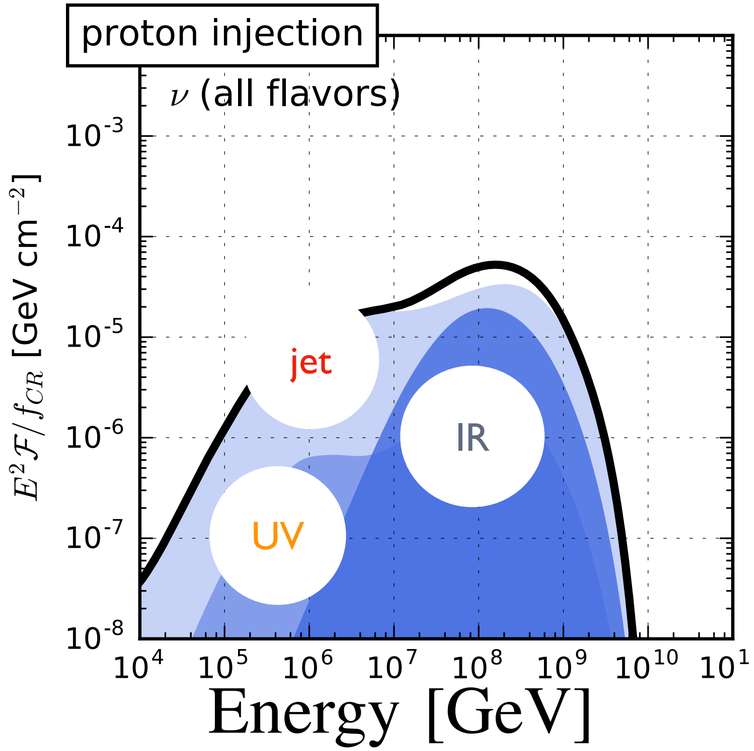




Neutrino production in blazars

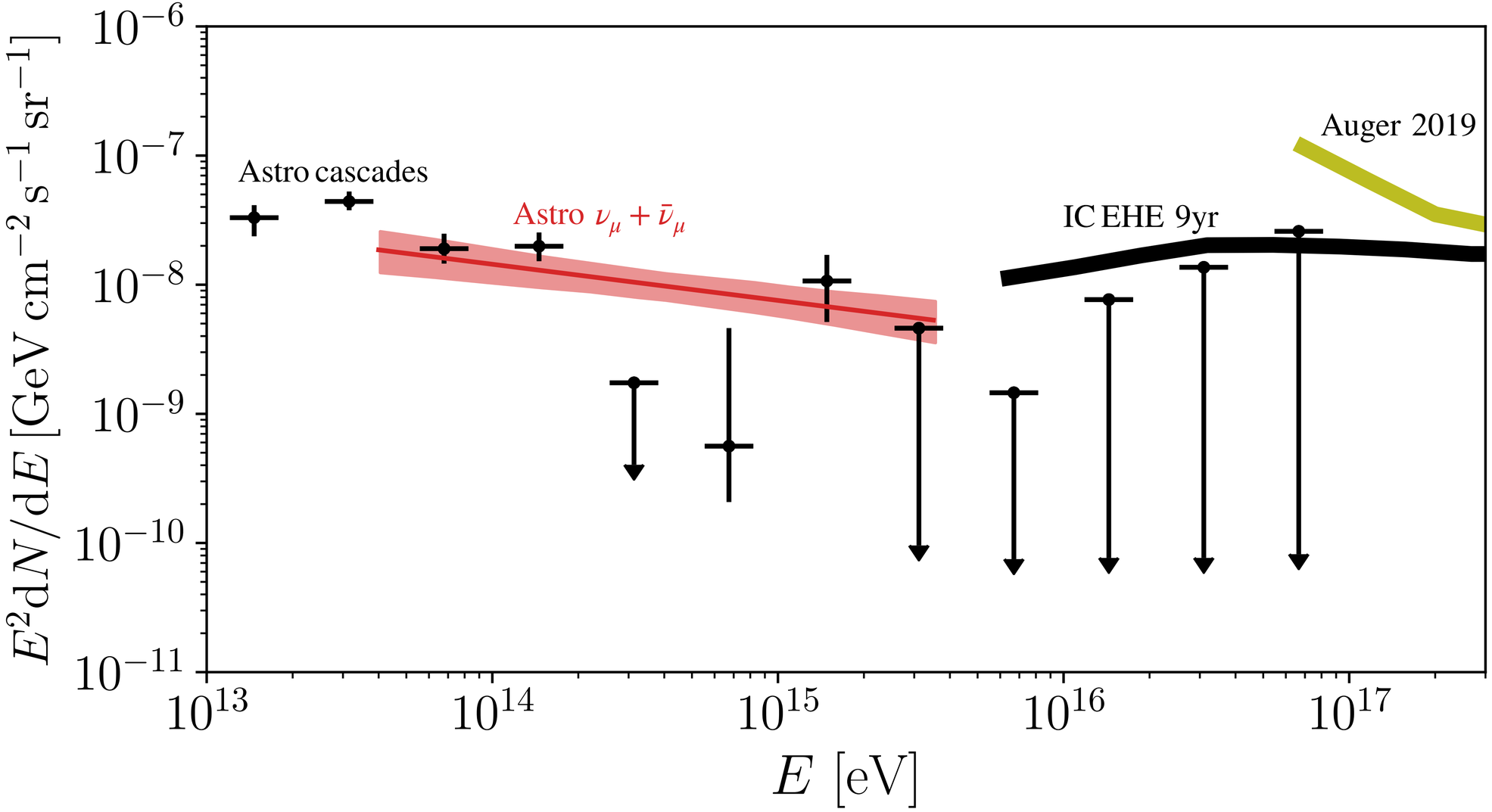




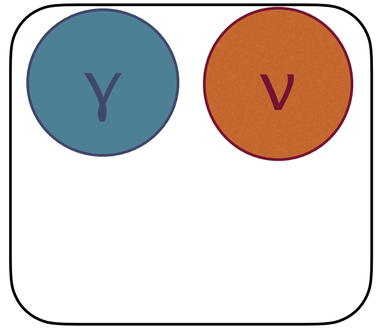


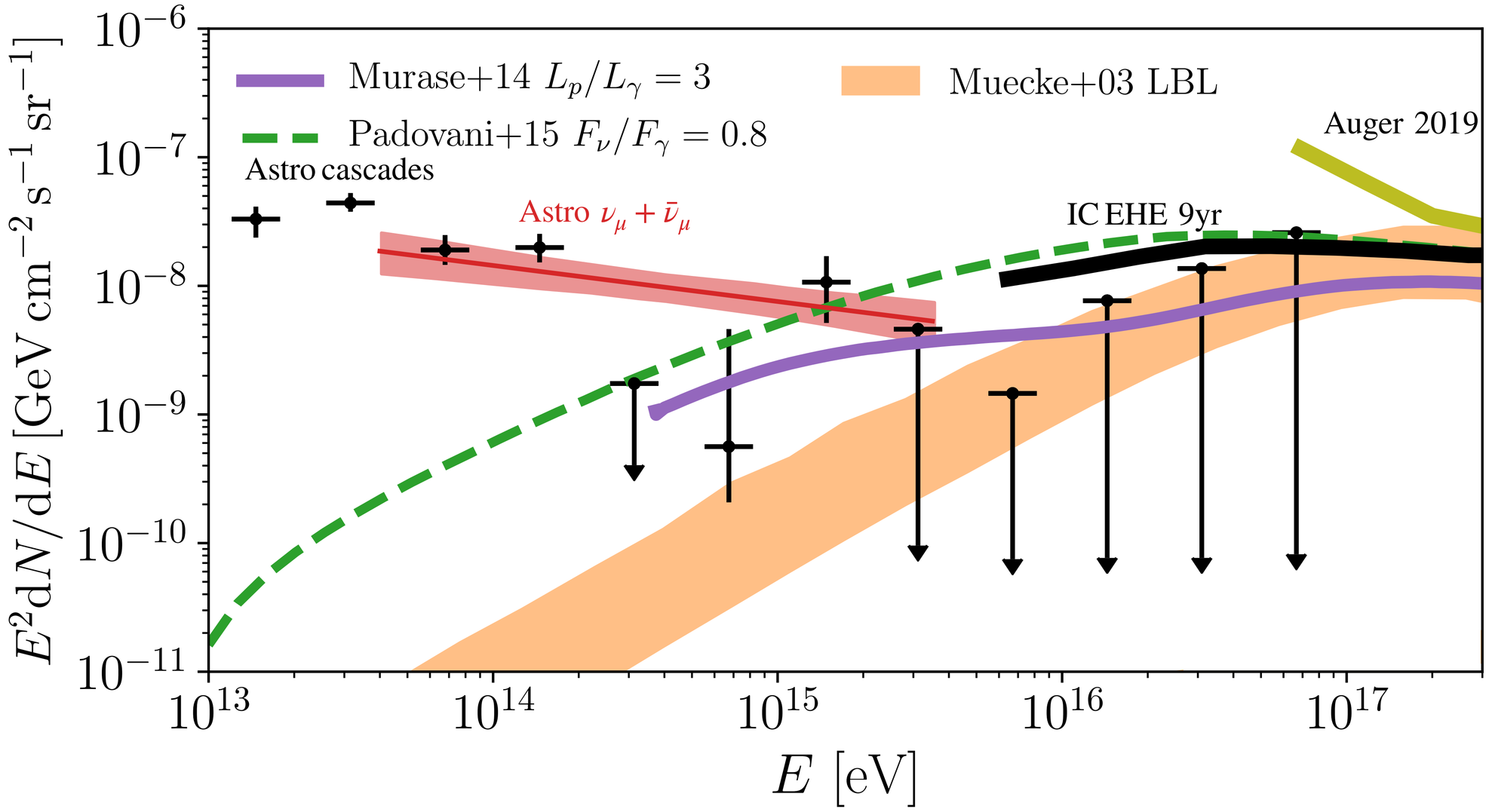
e.g. Mannheim 1991, 1993, Halzen & Zas 1997, Mücke 2001, 2003, Atoyan & Dermer 2001, 2004, Neronov, Semikoz 2002, Dermer et al 2006, Kachelriess et al 2009, Neronov et al 2009, Böttcher 2013, Dermer, Cerruti 2013, Cerruti et al 2013, Tchernin et al 2013, Murase et al. 2012, 2014, Dermer et al 2014, Tavecchio 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, Righi et al 2020, Rodrigues et al 2021

Blazar contribution to the diffuse neutrino flux

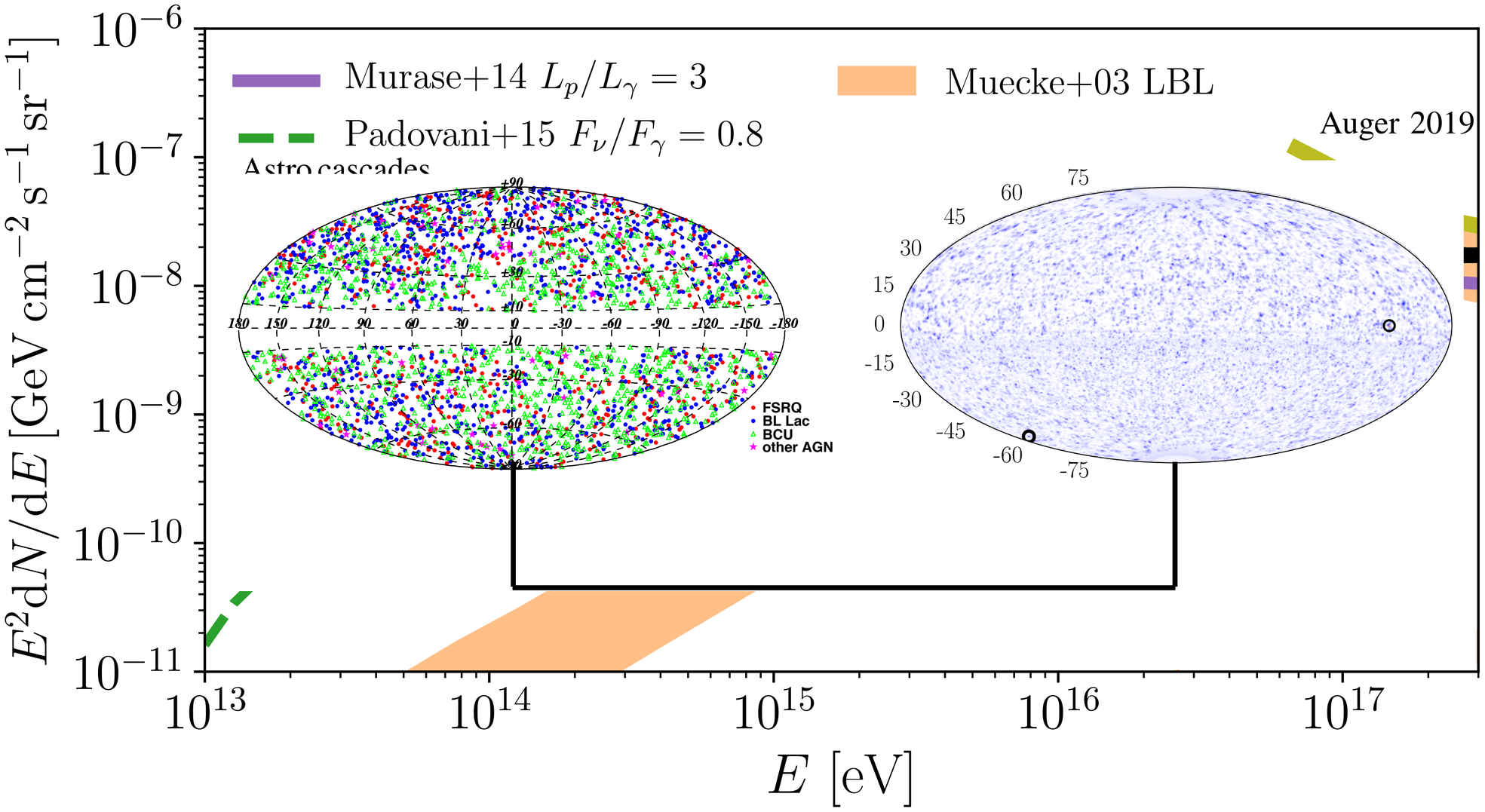


Blazar contribution to the diffuse neutrino flux

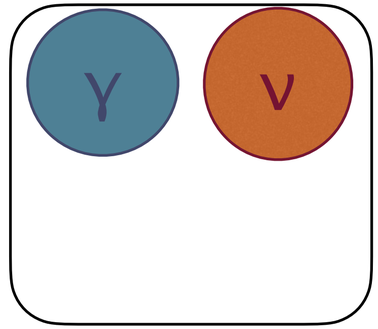


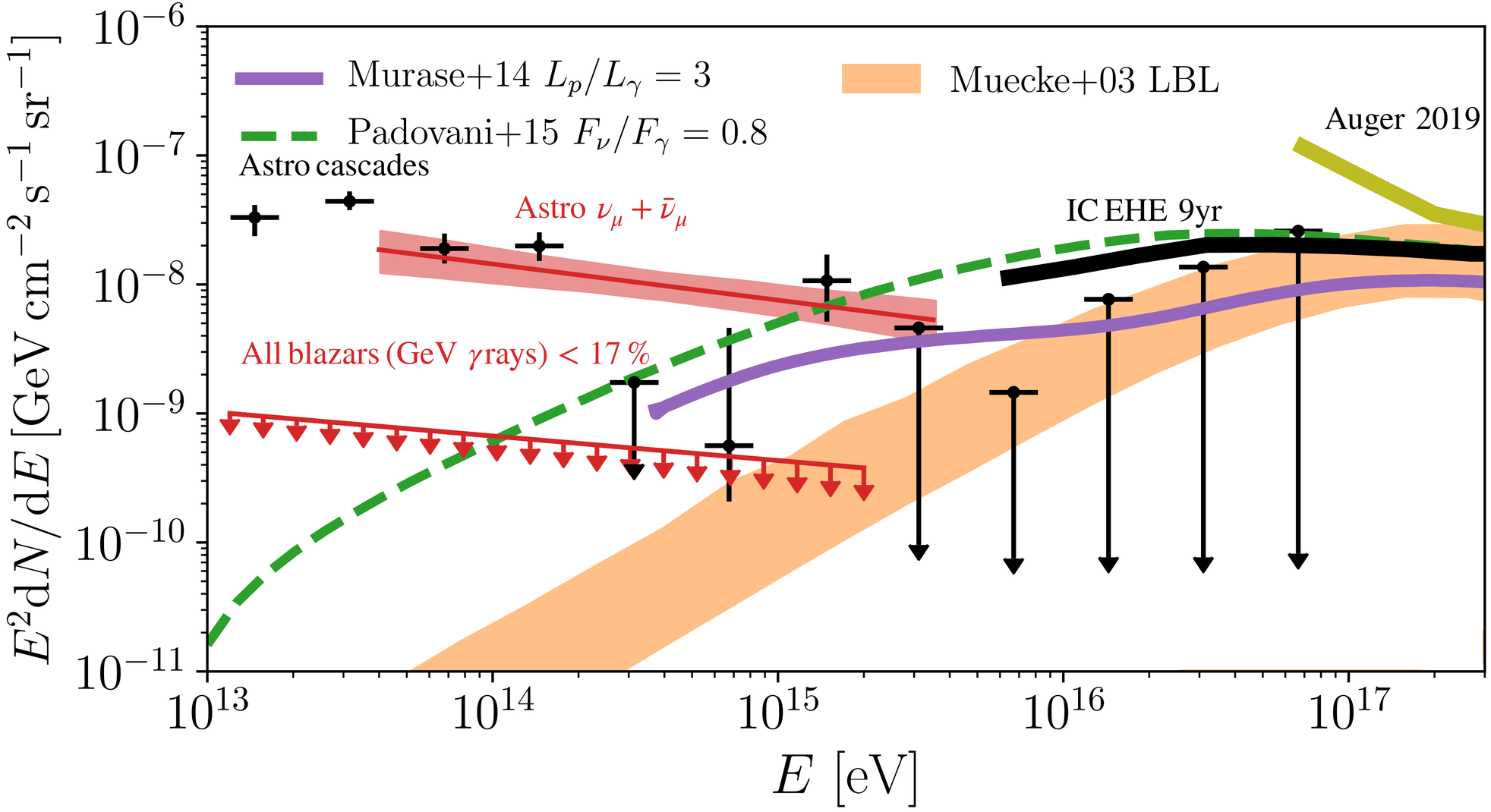


Blazar contribution to the diffuse neutrino flux



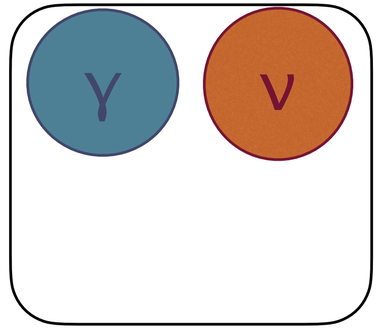
Blazar contribution to the diffuse neutrino flux

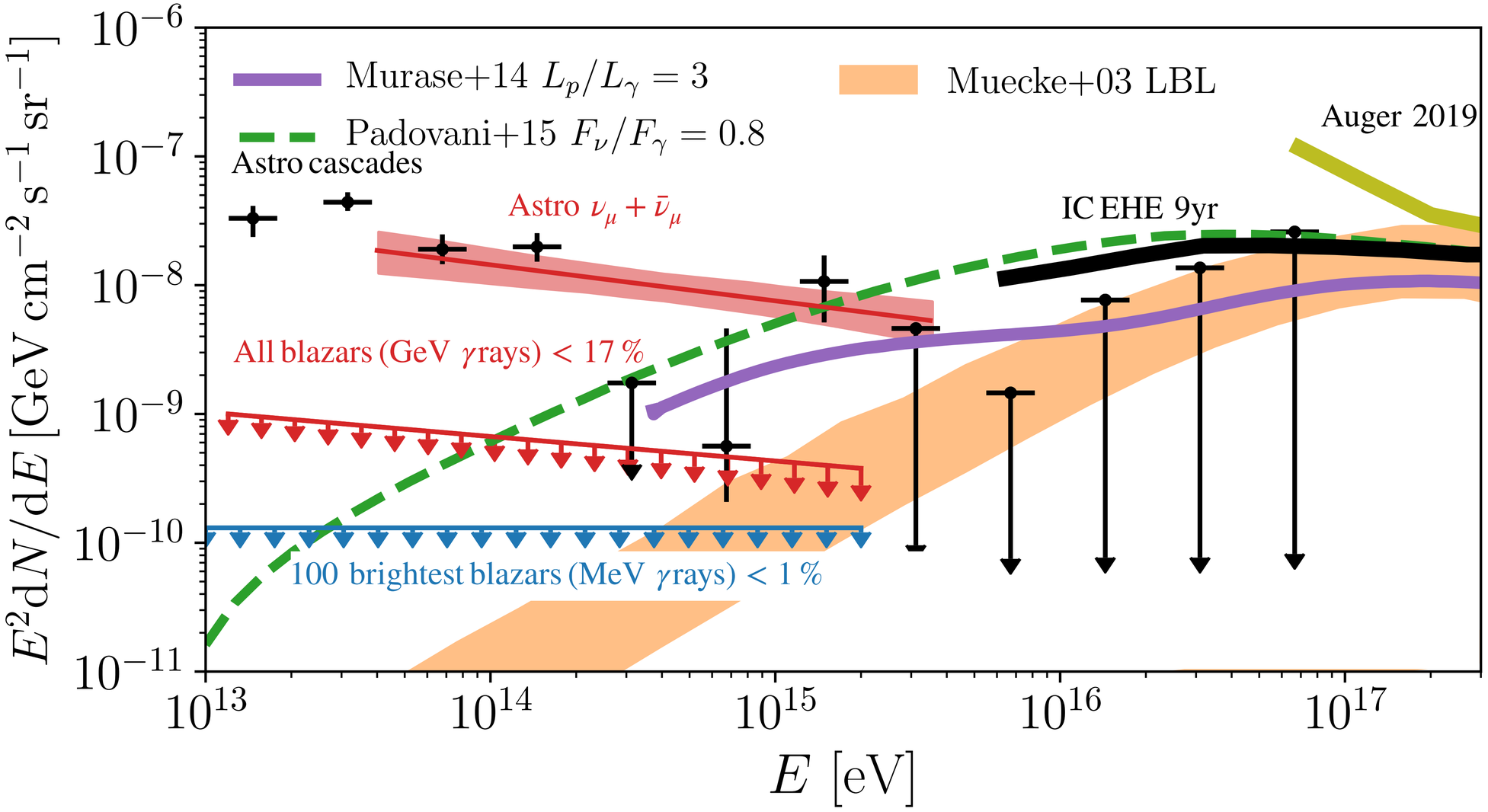




Huber for IceCube Coll PoS (ICRC 2019) 916. Limits also apply to infrared selected blazars, ≲27% with spectral templates: IceCube Coll PoS (ICRC2017) 994

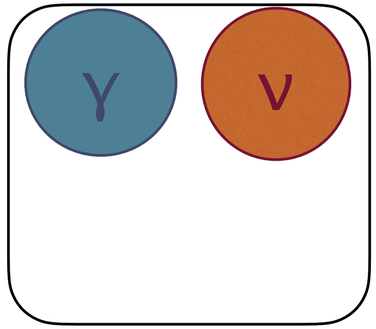
Blazar contribution to the diffuse neutrino flux

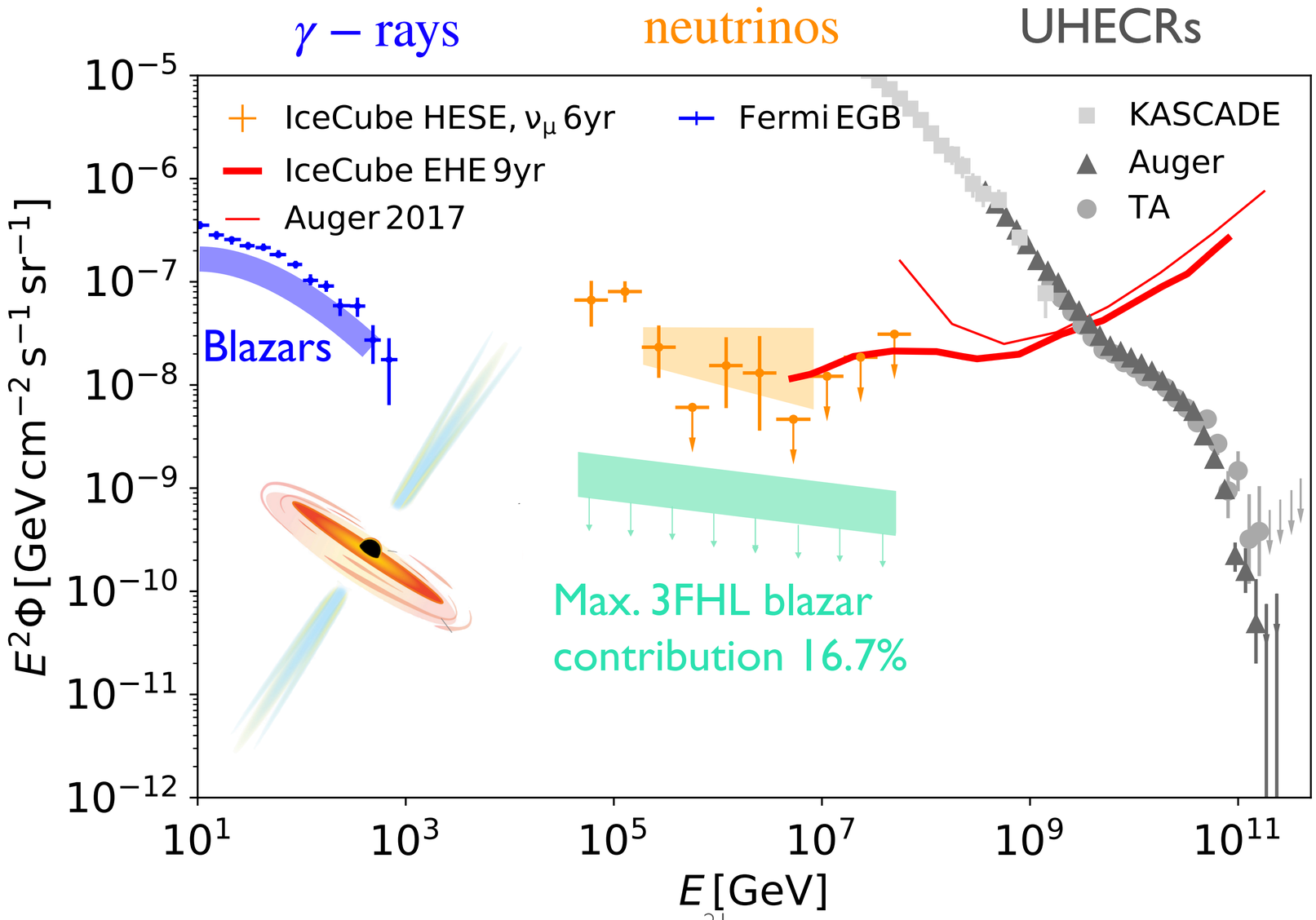




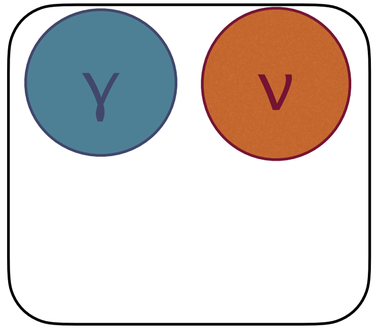
Abbasi et al (IceCube Coll), 2022, Based on 1FLE blazar catalogue

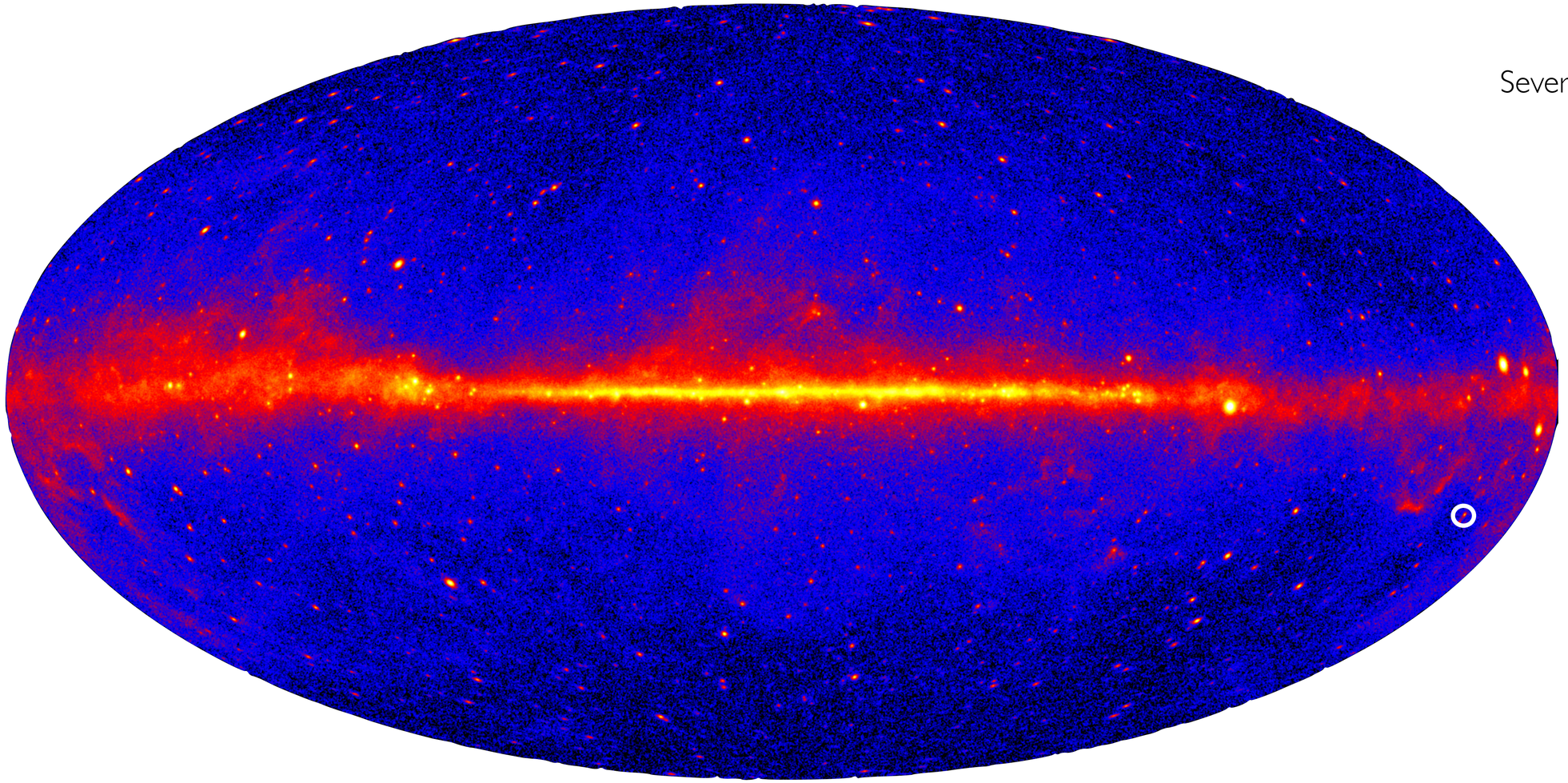
Joint origin disfavoured





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)
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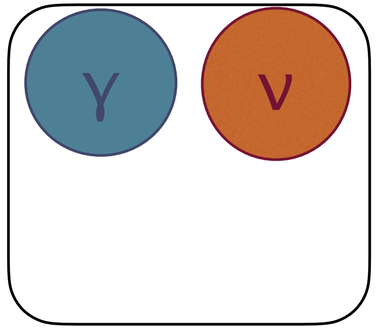

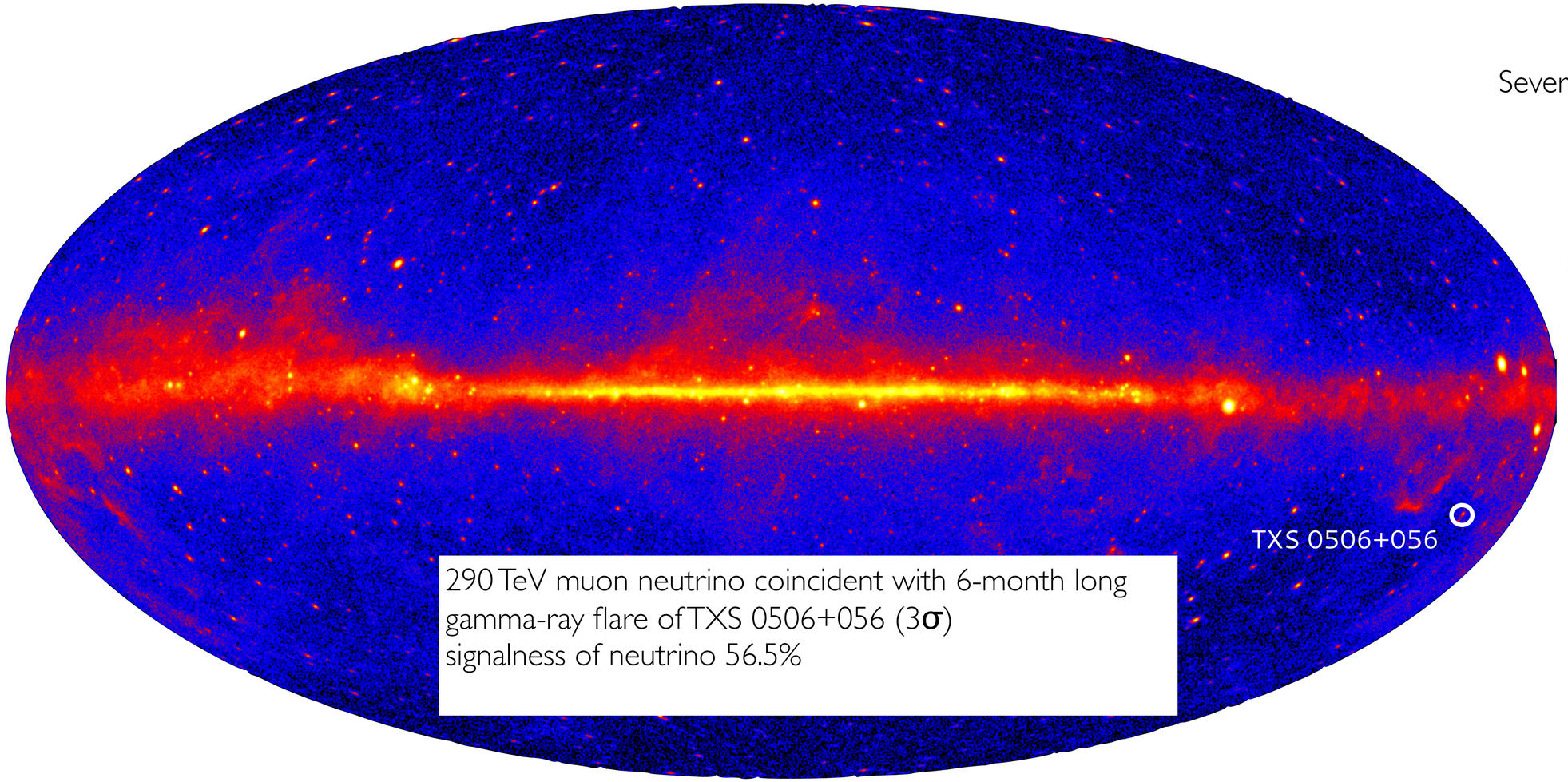

290 TeV muon neutrino coincident with 6-month long gamma-ray flare of TXS 0506+056 (3σ)
signalness of neutrino 56.5%

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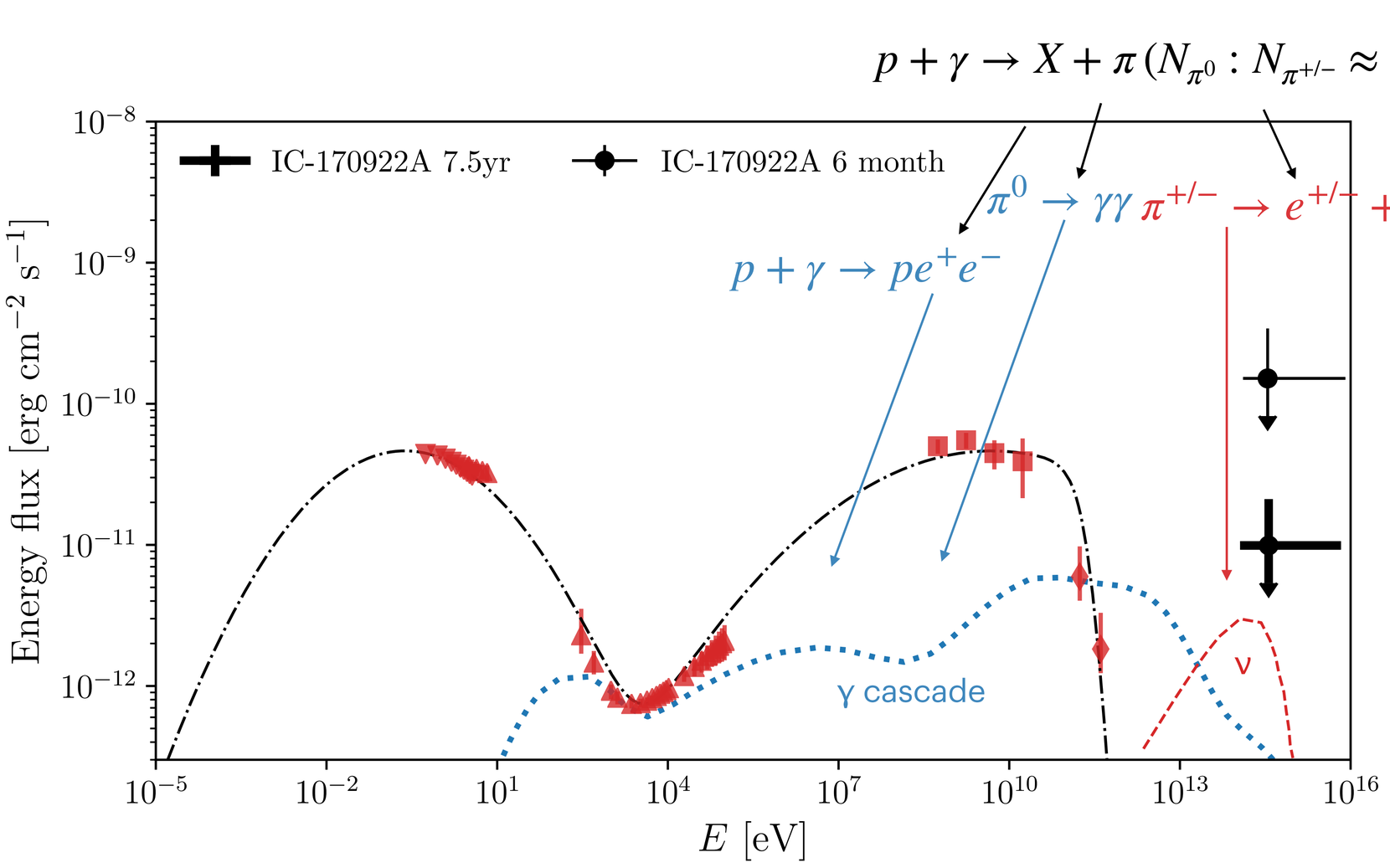
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018,

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

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

See also:

hadro-nuclear interactions: *Liu+19*
stellar disruption: *Wang+19*
multiple zones: *Xue+(inc FO)19*
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curved/double jet: *Britzen+19, Ros+19*
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and more…!

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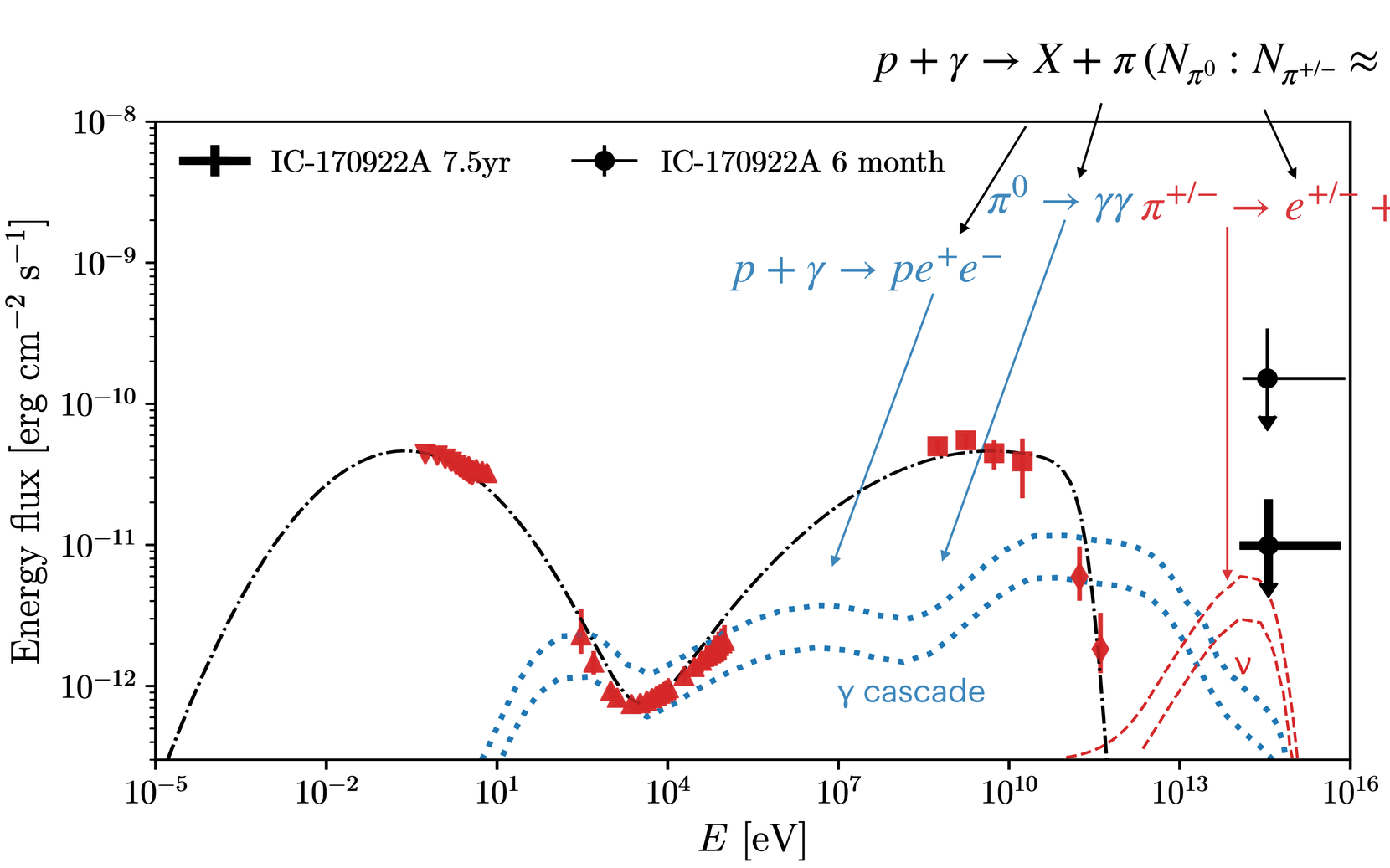

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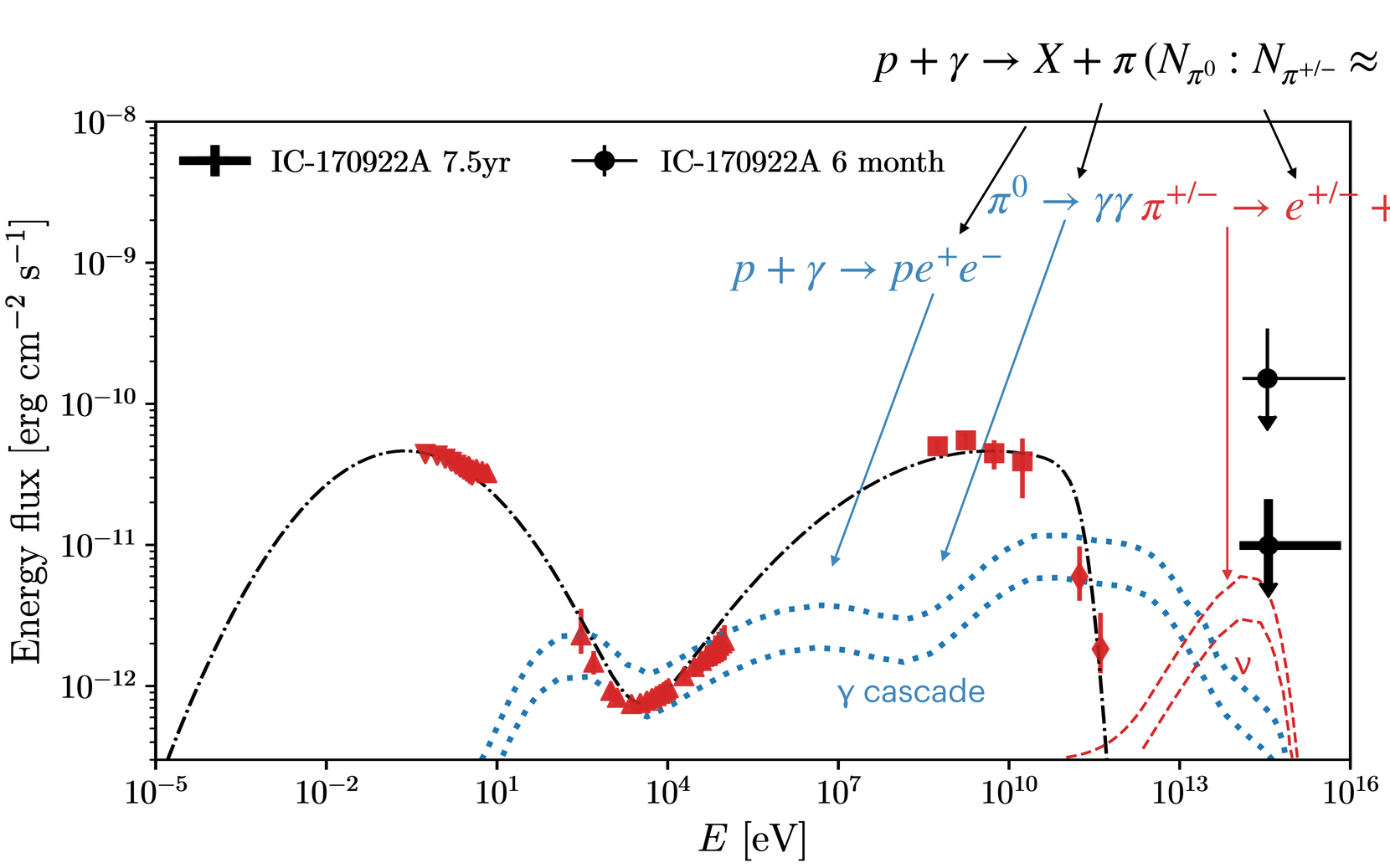

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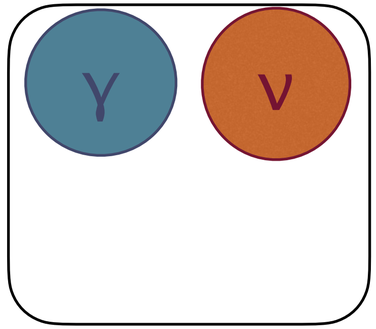

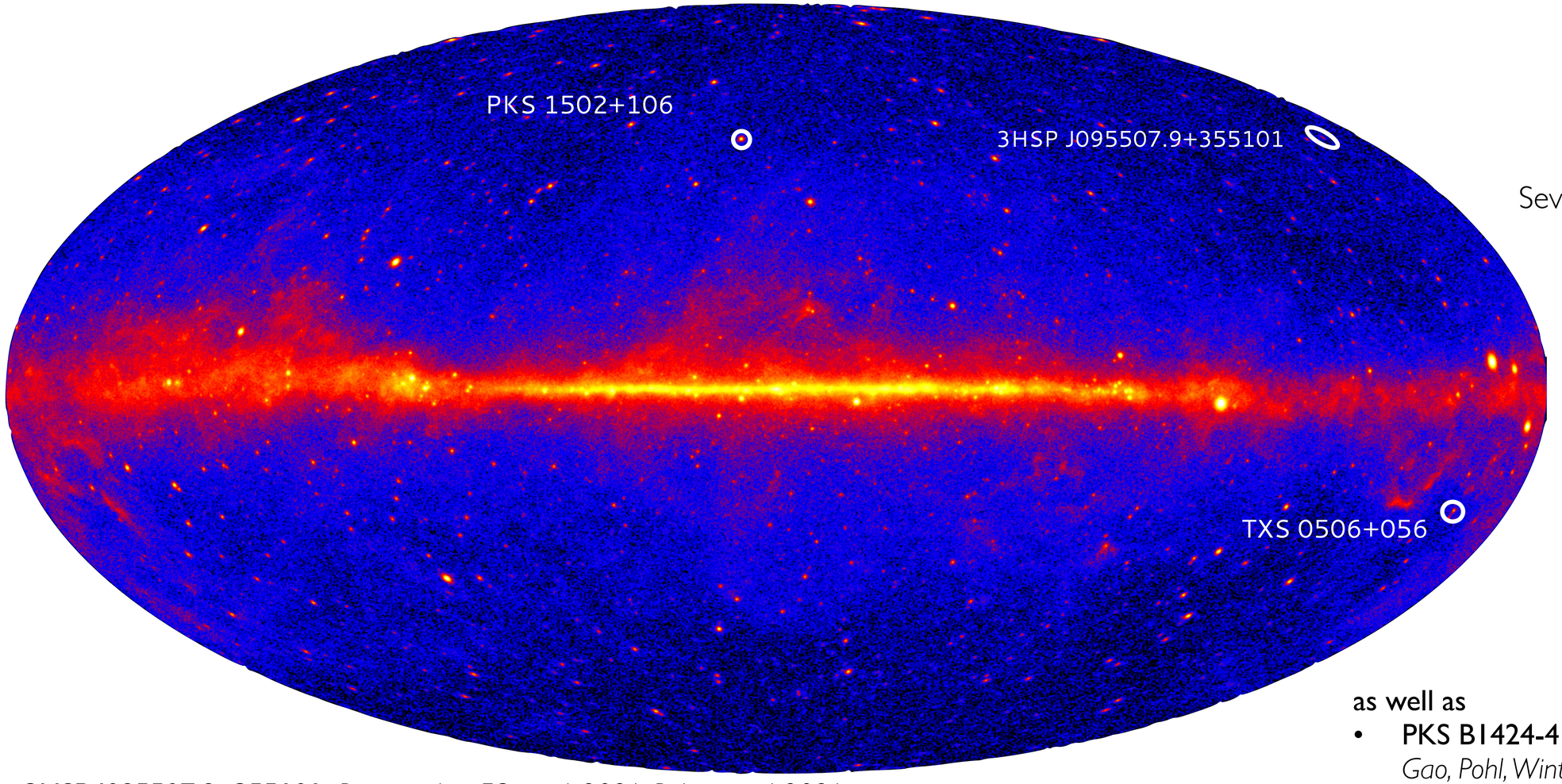

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Buson et al ApJL (2022)

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*

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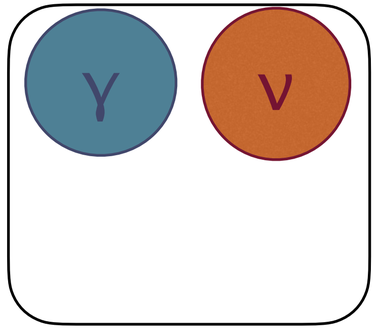
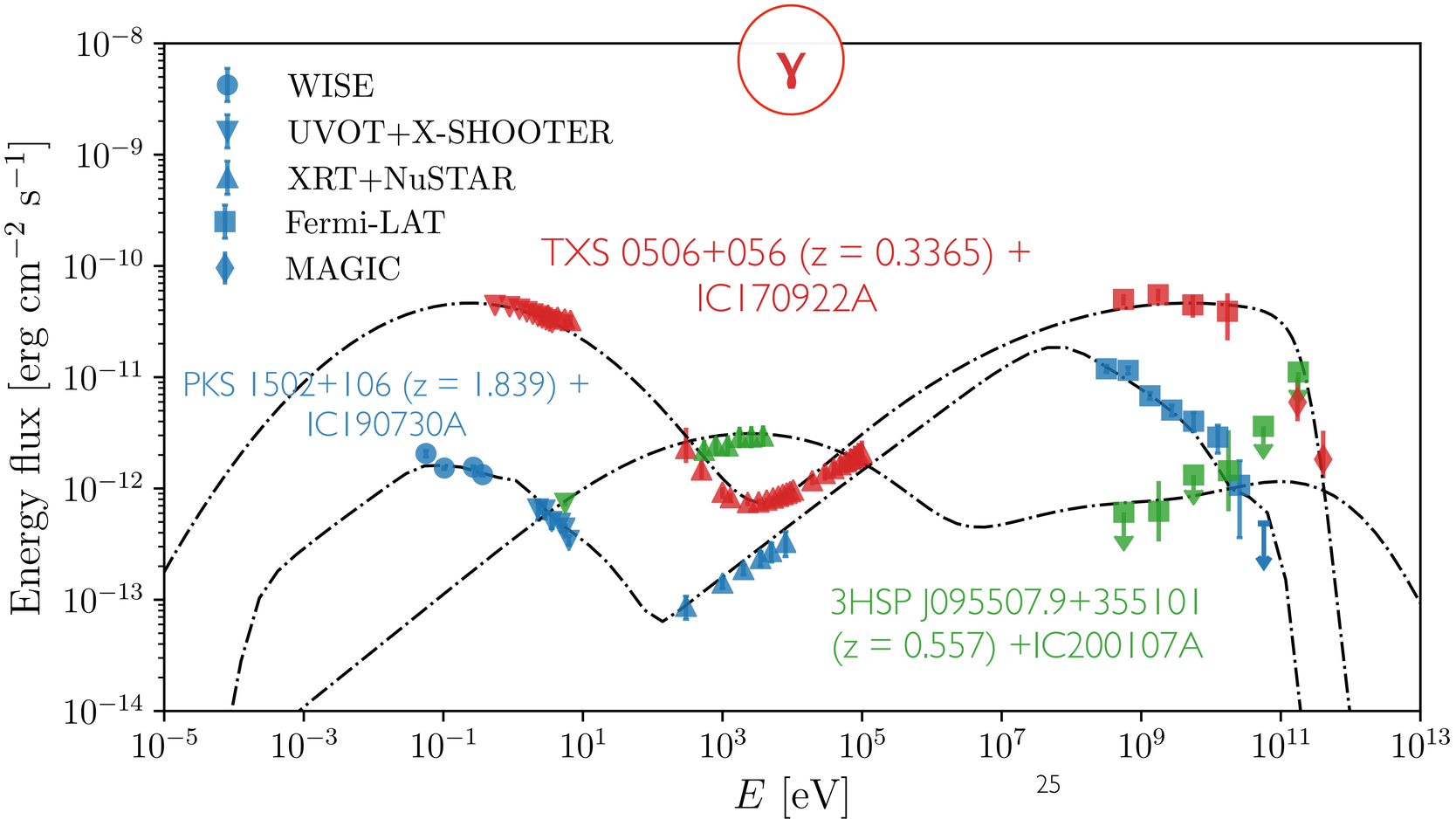
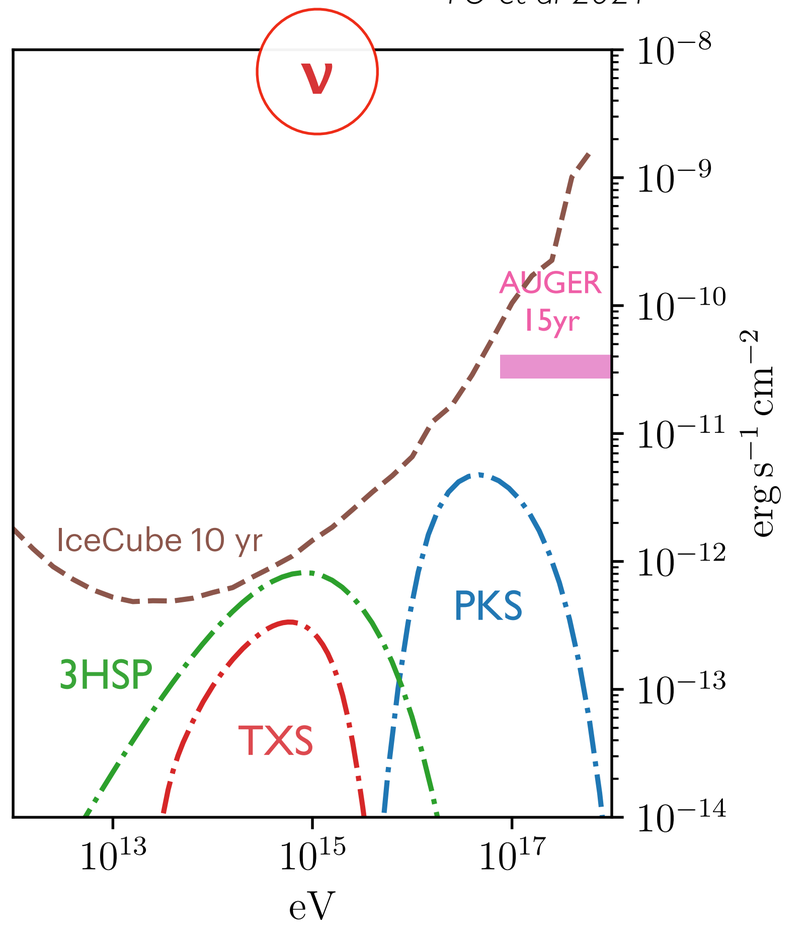


Models consistent (statistically) with the detection of the neutrinos

but generally require high proton content

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

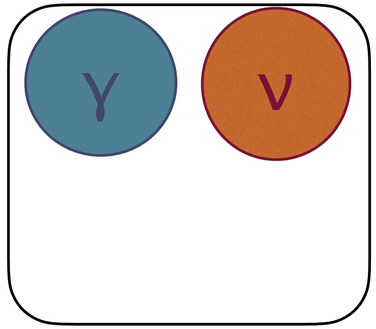


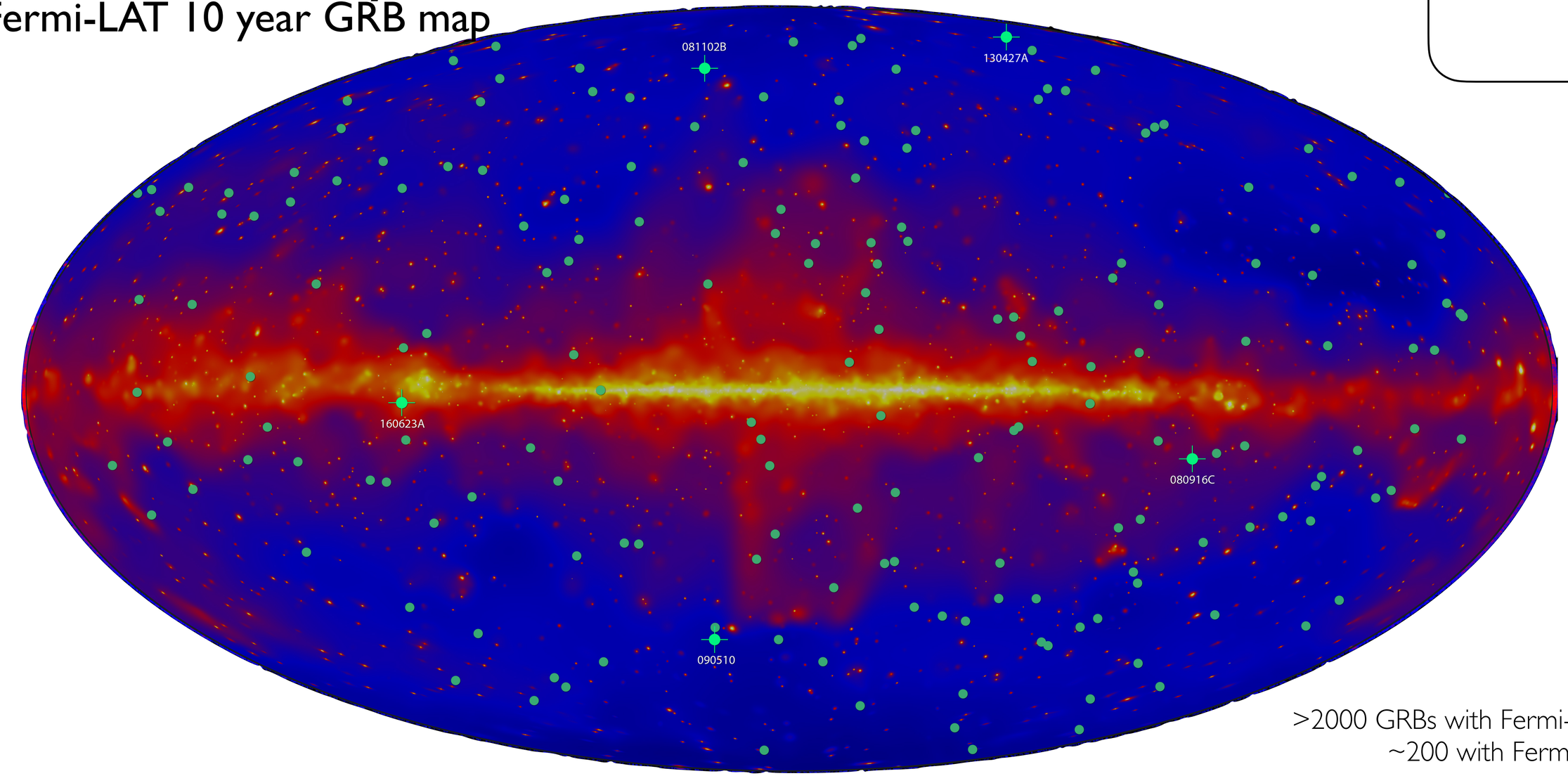


Gamma-ray bursts

Fermi-LAT 10 year GRB map

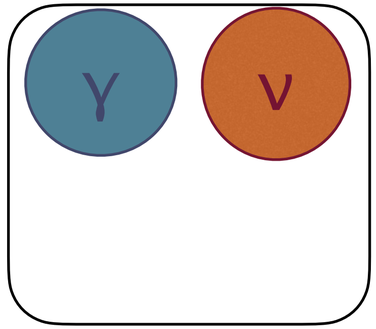
Fermi-LAT 2nd GRB Catalogue,2019

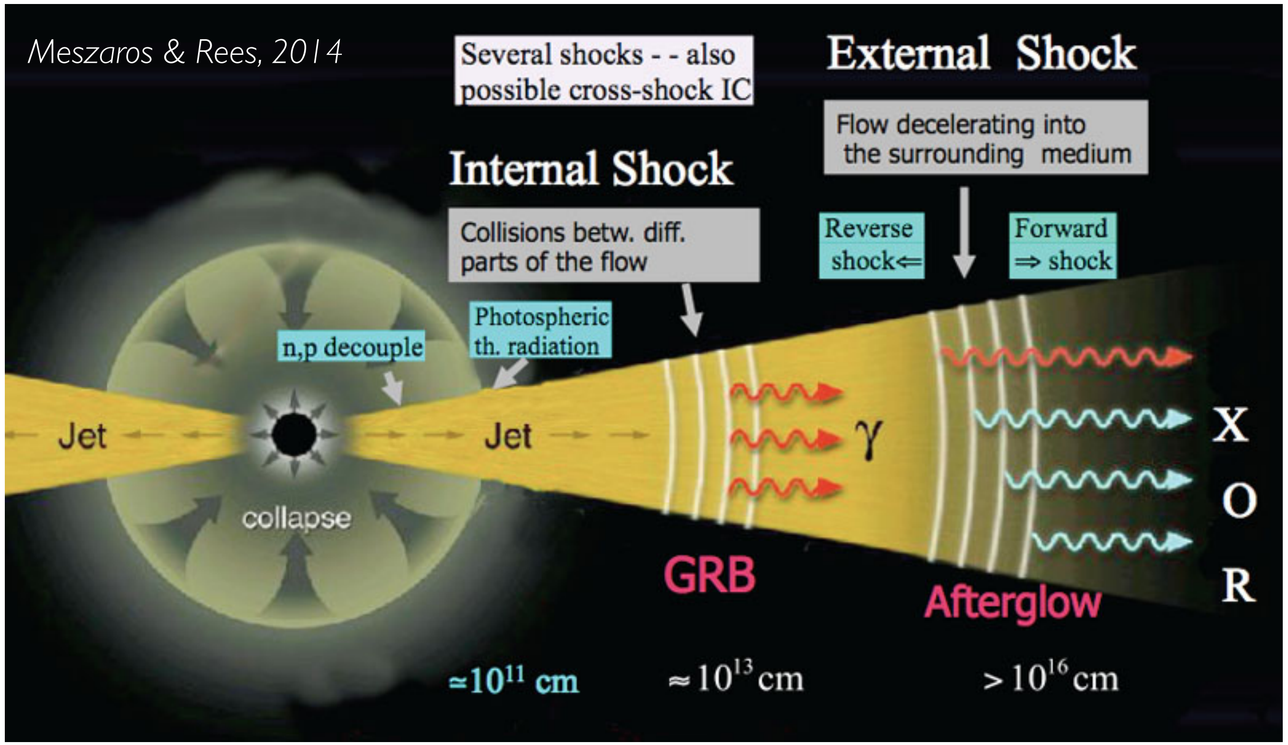




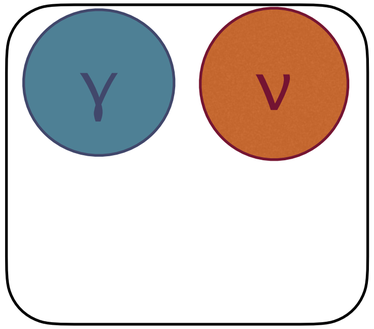
>2000 GRBs with Fermi-GBM
~200 with Fermi-LAT

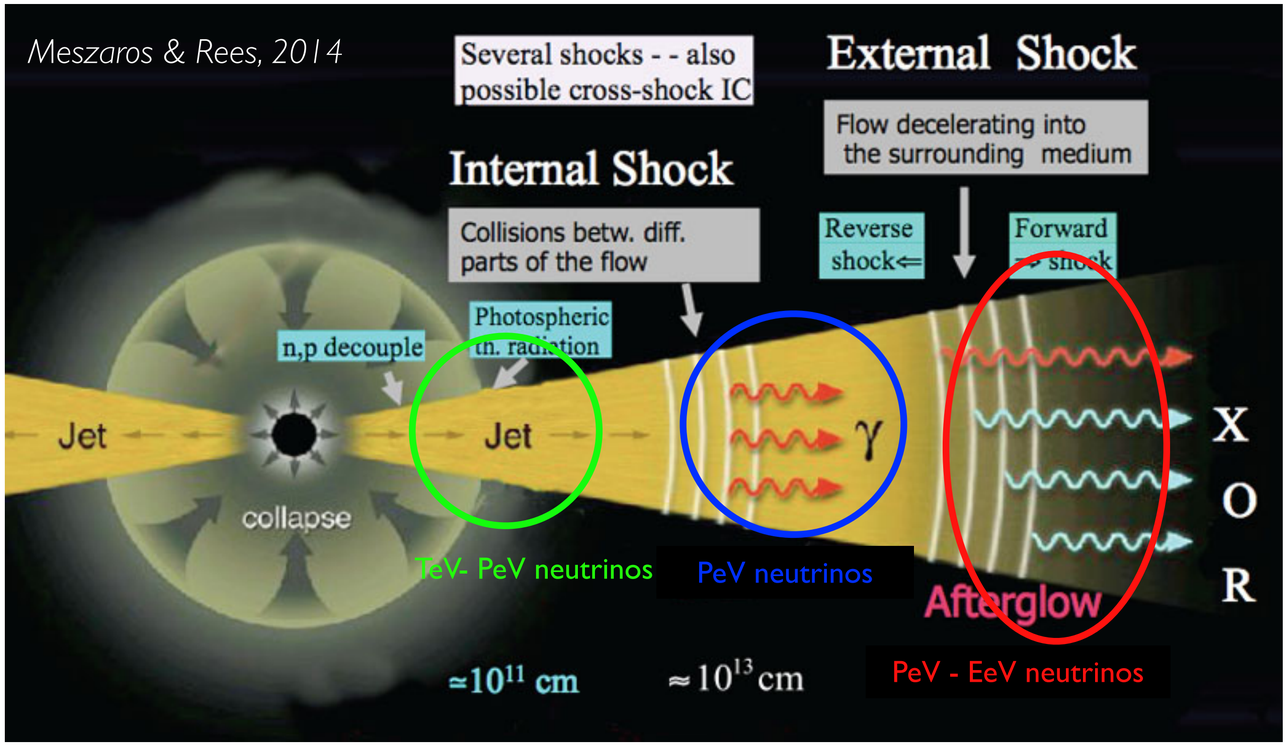
Neutrino production in gamma-ray bursts



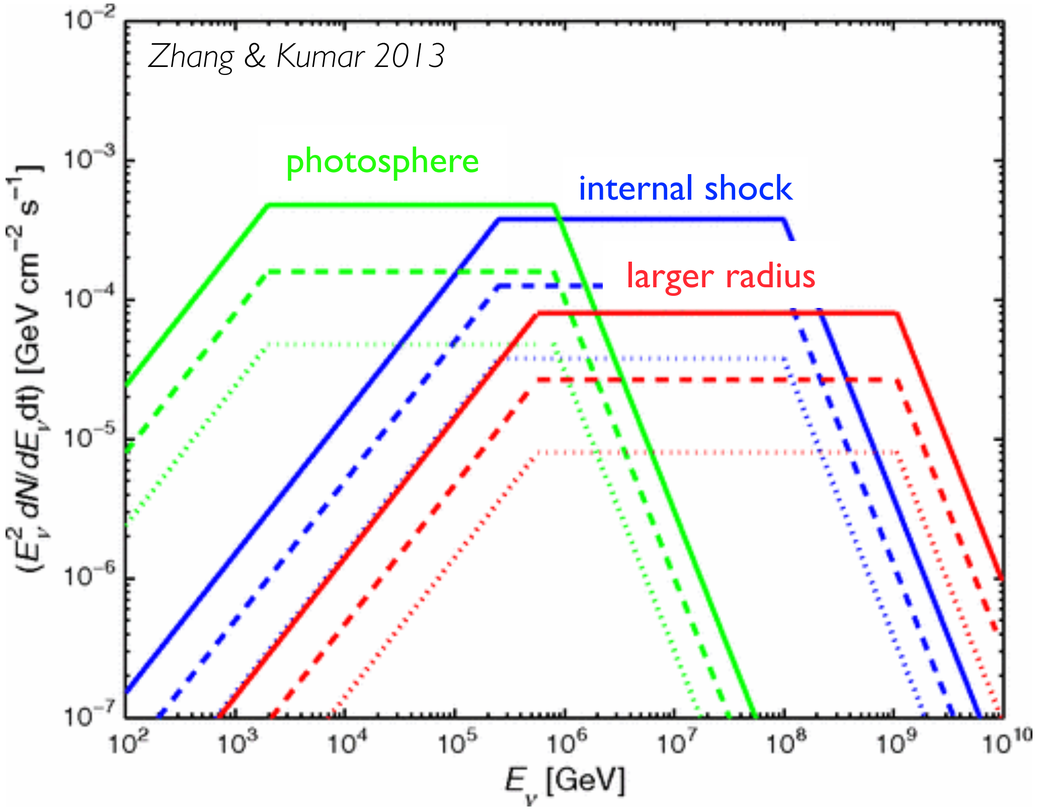


Neutrino production in gamma-ray bursts



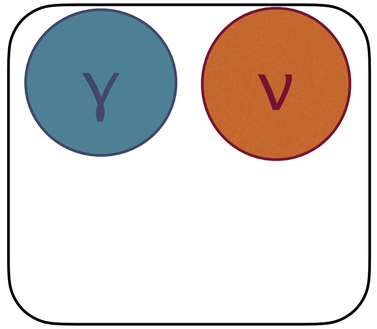


possible neutrino production sites

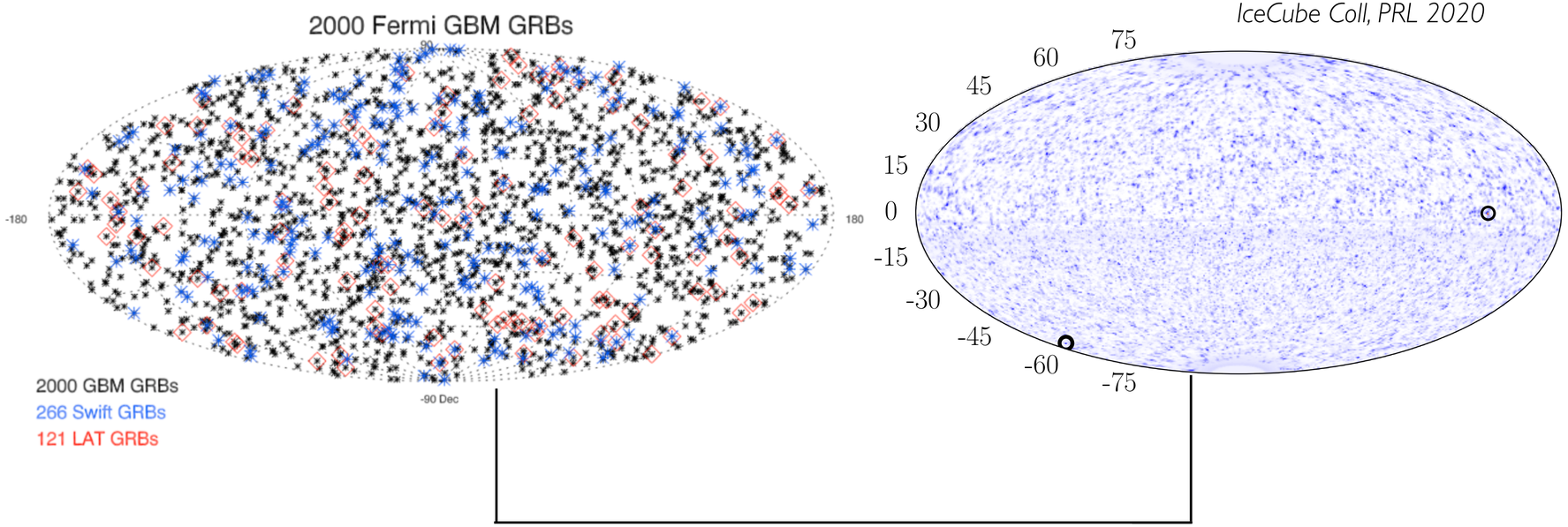


>100 publications on theoretical expectations:
see e.g. review "Neutrinos from GRBs" (Kimura 2022)

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

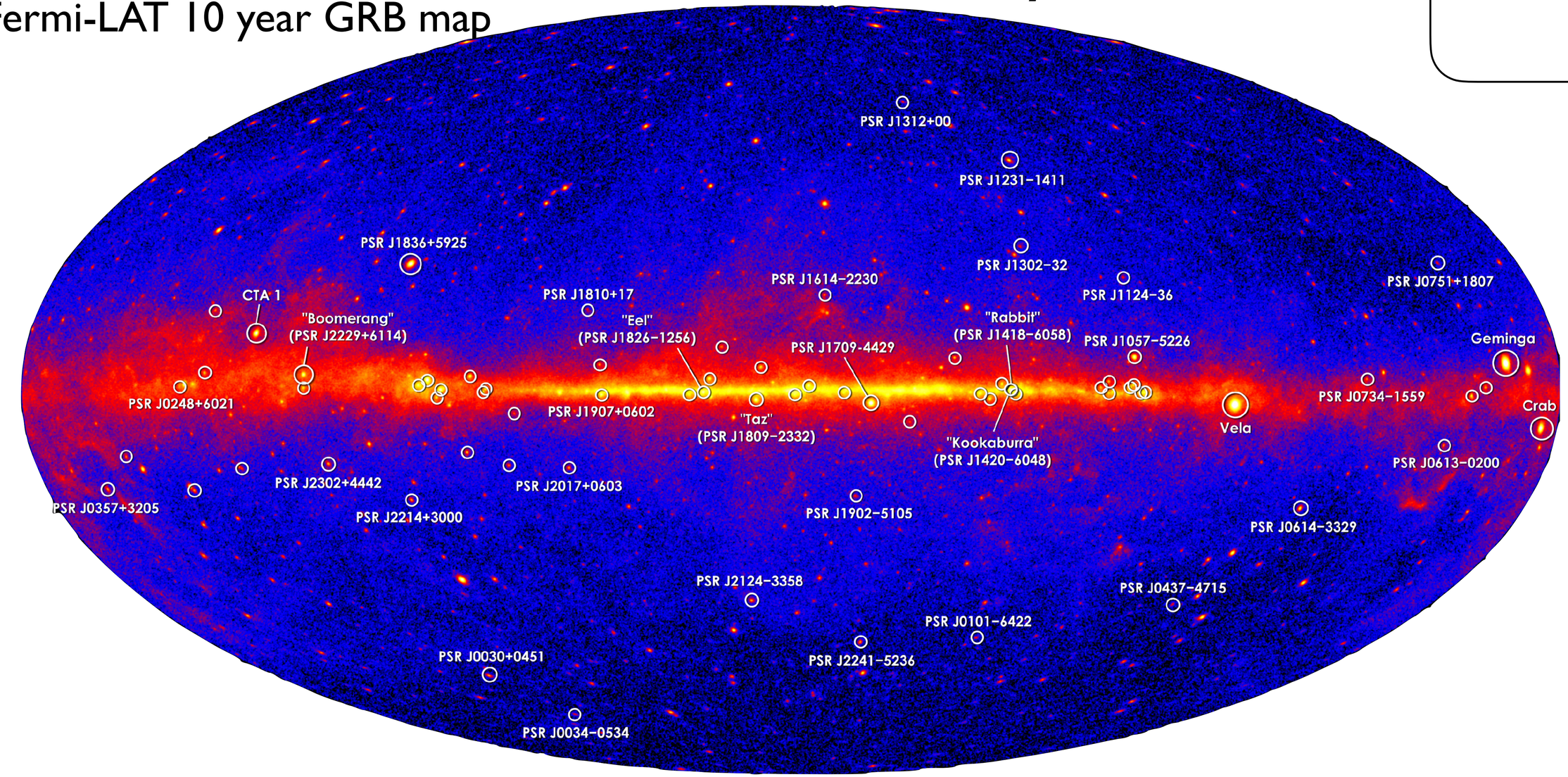


IceCube Coll, ApJ 843 (2017) 112
IceCube Coll., Fermi GBM Coll. 2022 ApJ in press

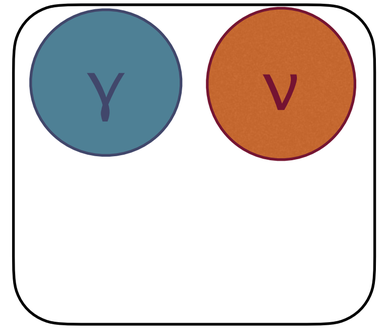
Prompt (ΔT_{promt} ~1-100s): < 1% diffuse neutrino flux
Precursor/Afterglow ($\Delta T_{afterglow}$ ± 14d): < 24% diffuse neutrino flux

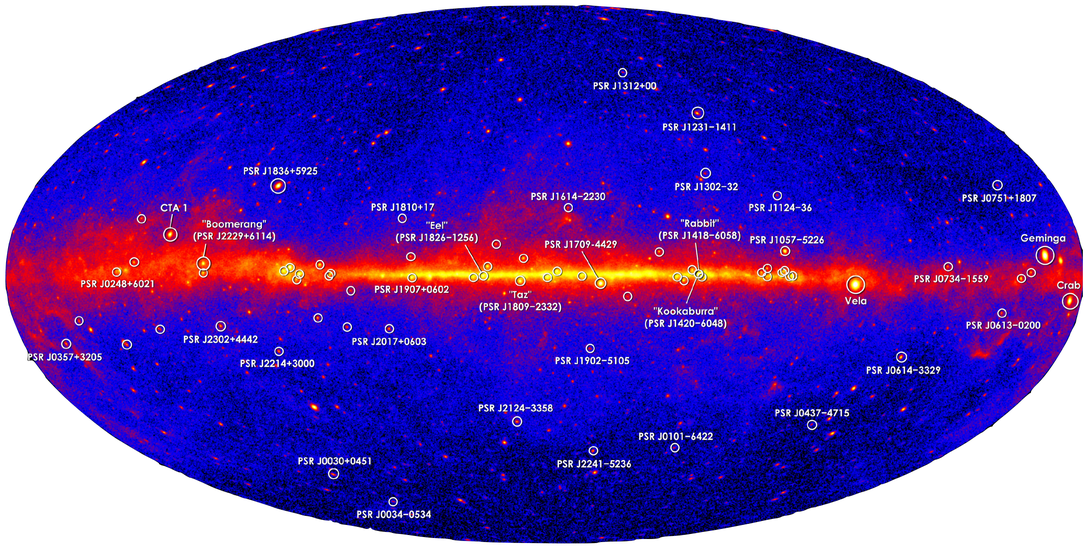
Pulsars and Galactic cosmic rays

Fermi-LAT 10 year GRB map

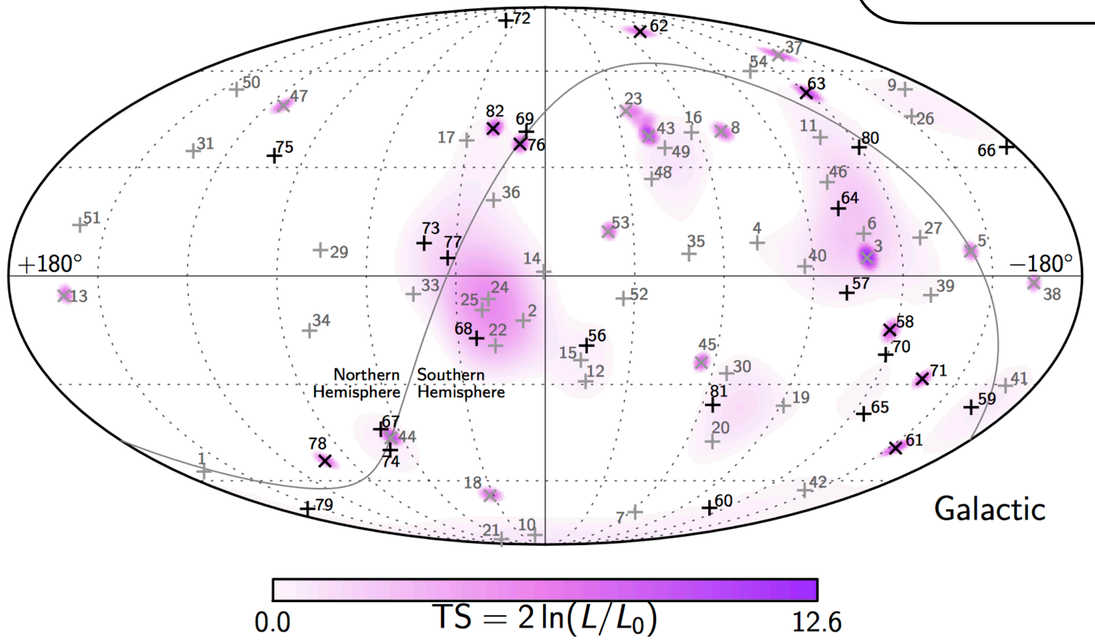


Pulsars and Galactic cosmic rays





IceCube Coll. PoS(ICRC2017)981

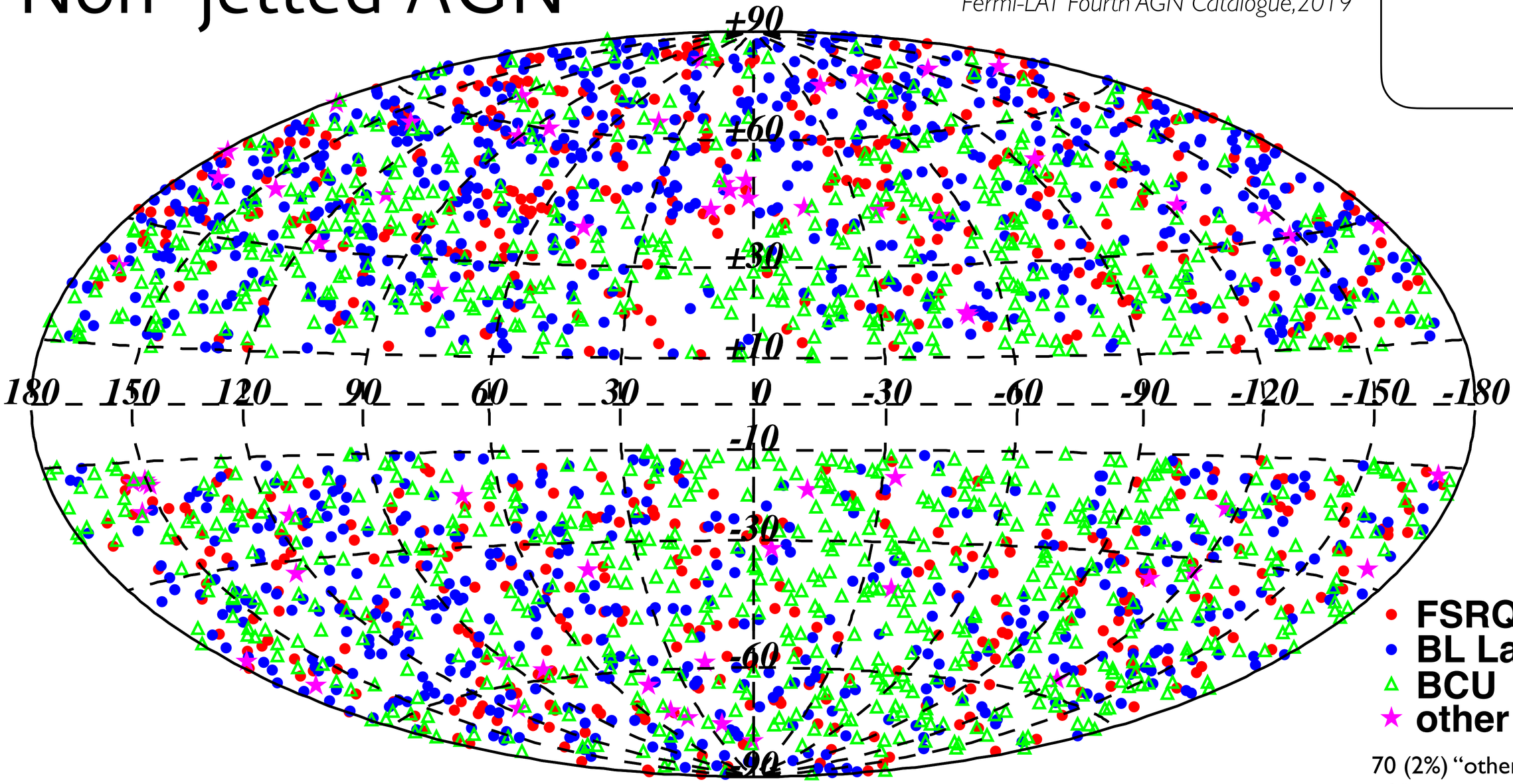


Galactic CRs ≤ 14%
Galactic TeV emitting pulsars ≤ 4%
Galactic X-ray binaries ≤ 1%
Galactic microquasars ≤ 7%

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

Fermi-LAT Fourth AGN Catalogue, 2019

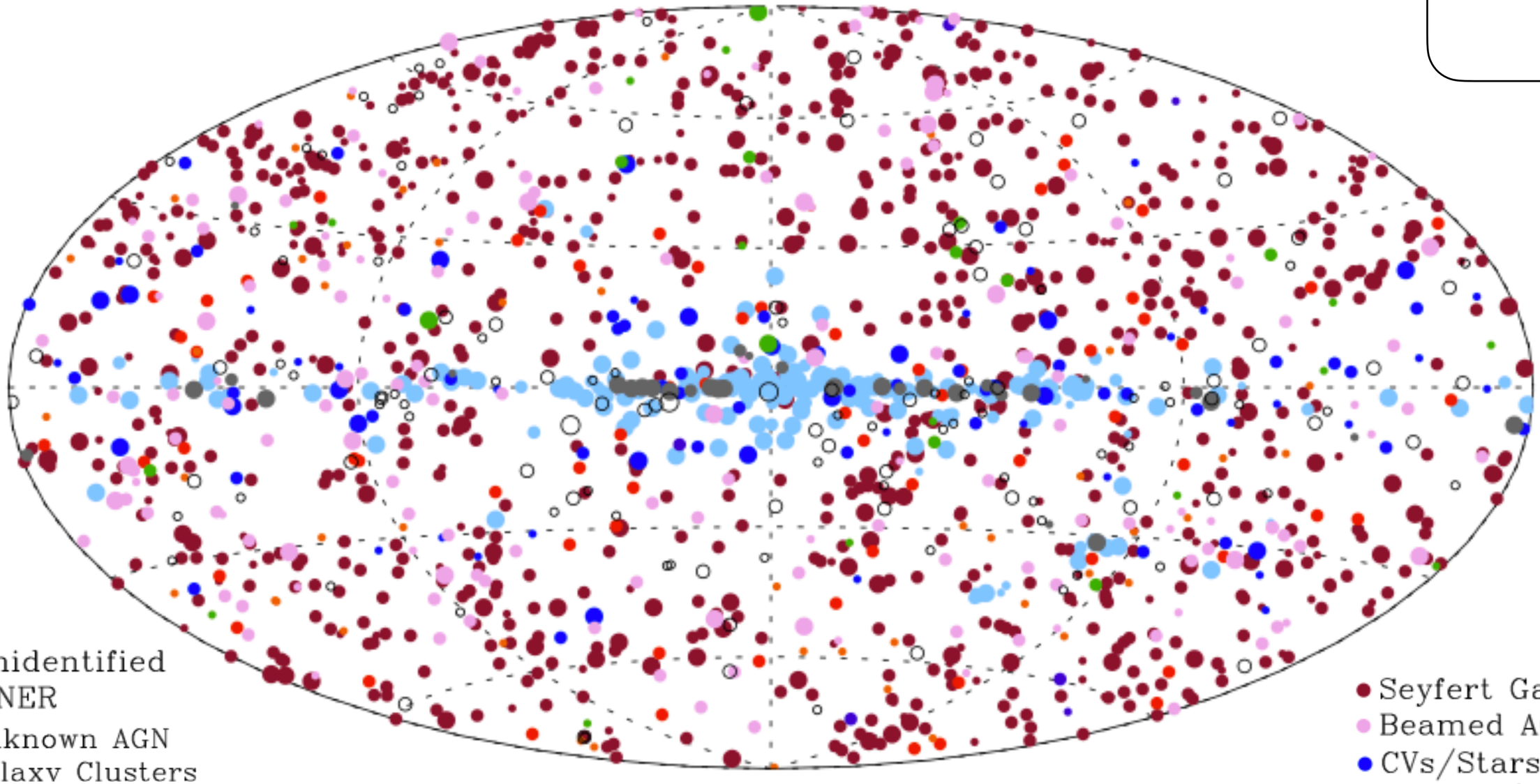


FSRQ
BL Lac
BCU
other AGN

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

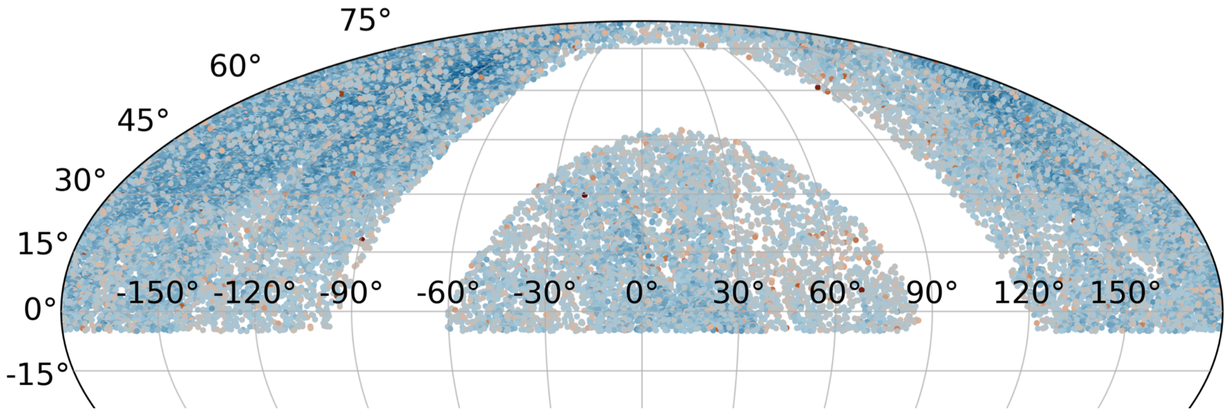
Non-jetted AGN

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

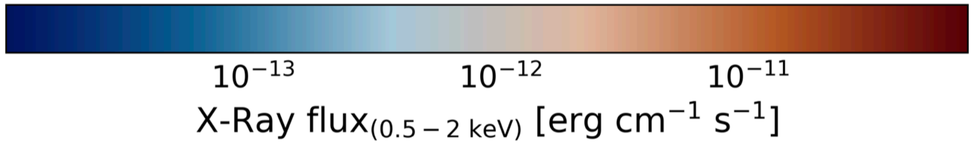


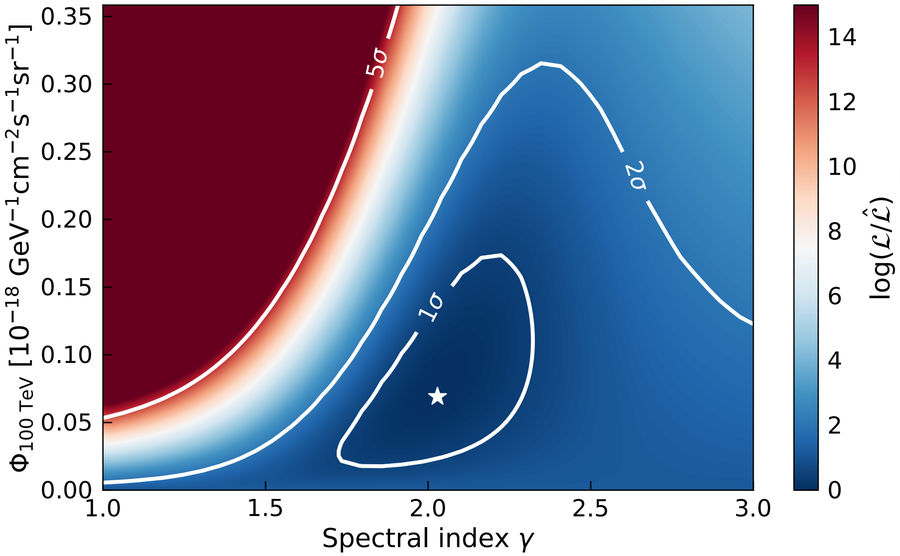
Non-jetted AGN

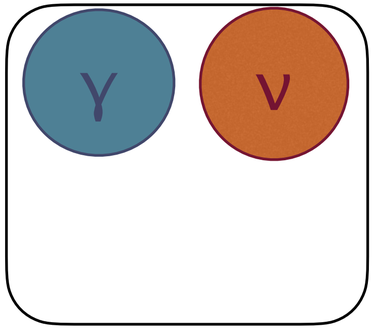
IceCube Coll in press. arXiv: 2111.10169

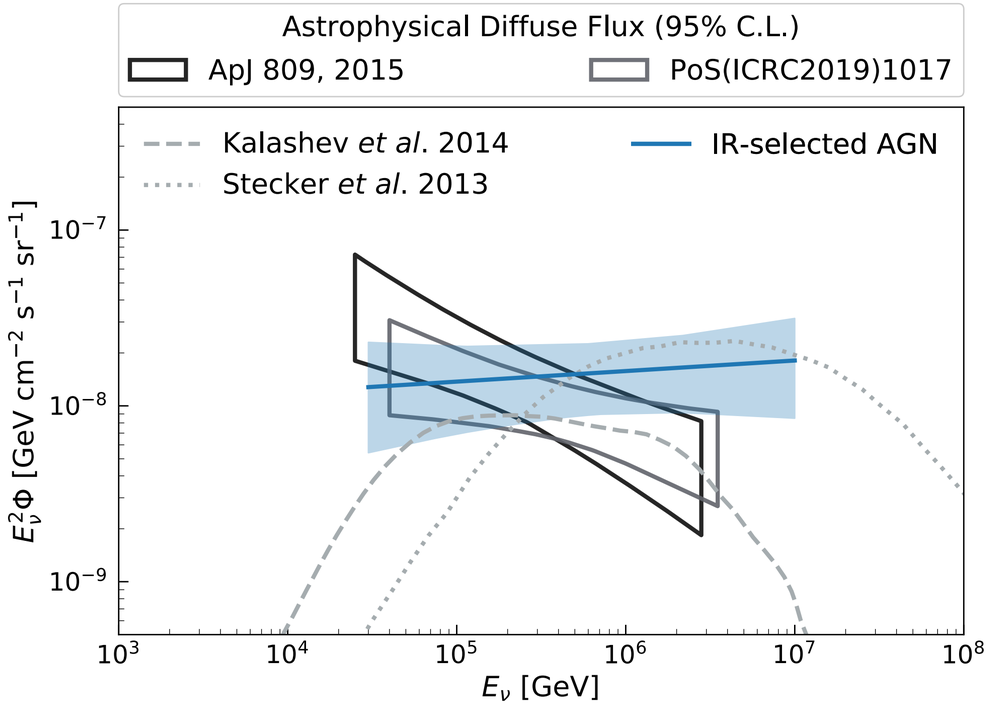


Equatorial



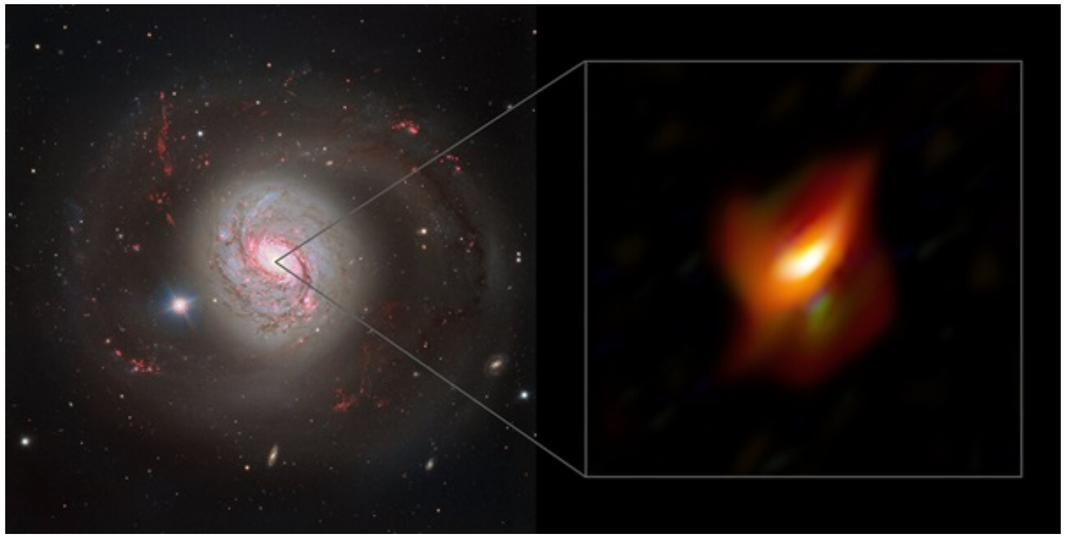


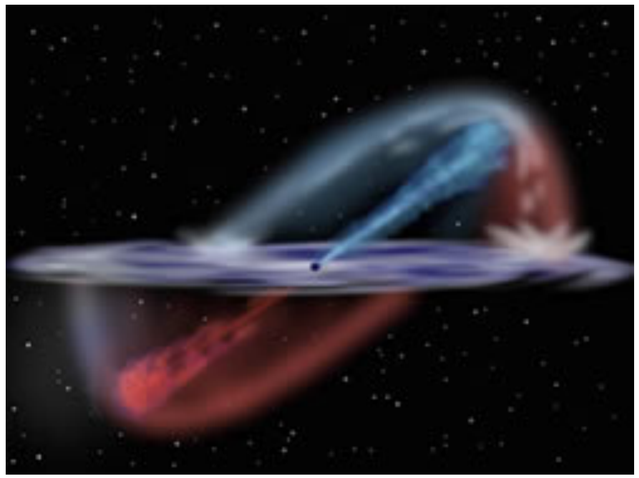




Infrared selected (A$_{\mathrm{LL}}$WISE) AGN with soft-X-ray weights could account for 27-100 % of neutrino flux at 100 TeV (2.6σ excess w.r.t. background expectations) with ~E^{-2} spectrum.

NGC 1068 (M77)

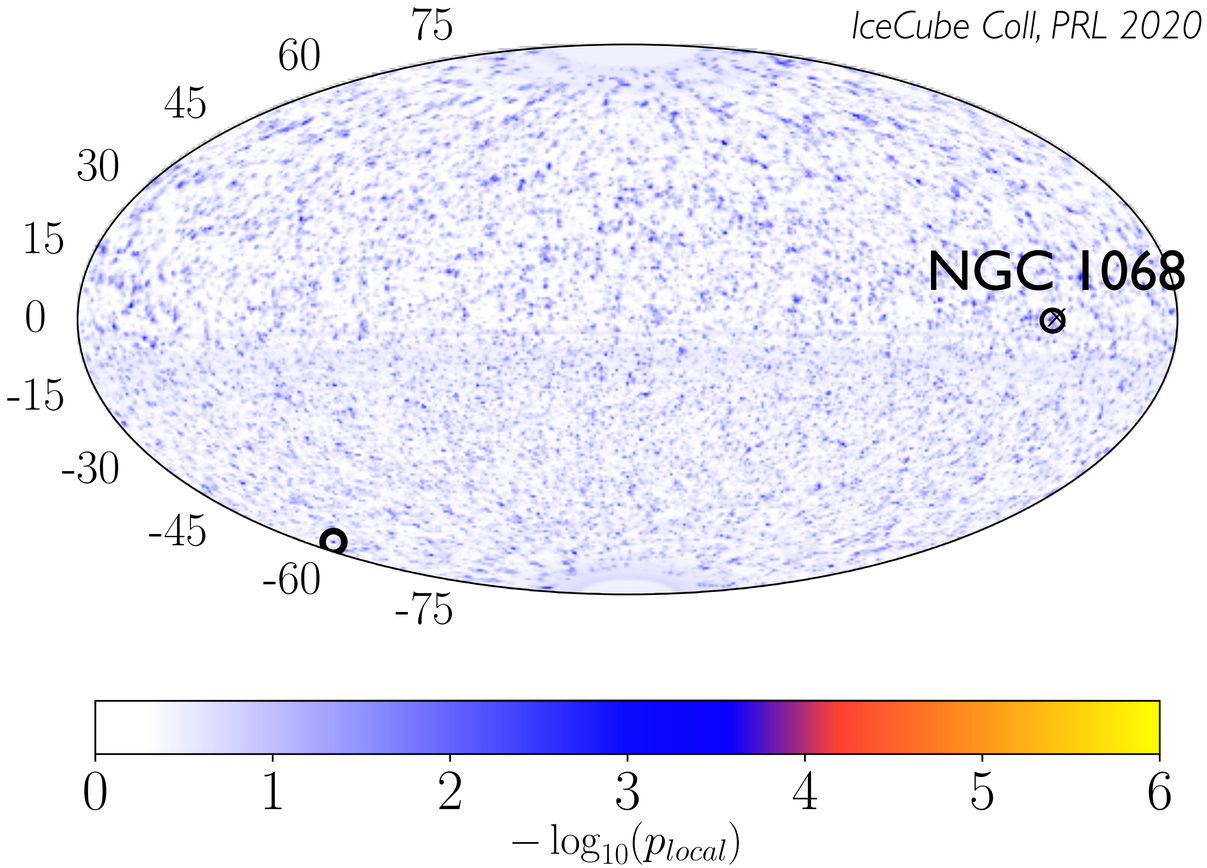




Seyfert 2 galaxy with heavily obscured nucleus

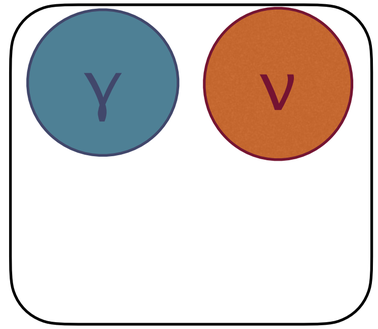
Prototypical nearby Seyfert 2 (14.4 Mpc)

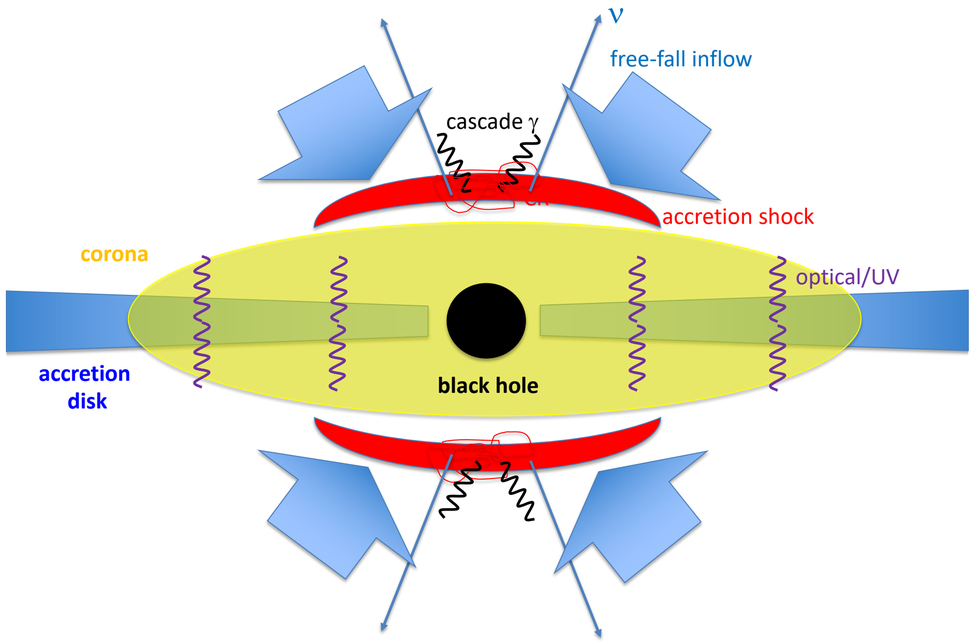
High infrared luminosity: high-level of star formation



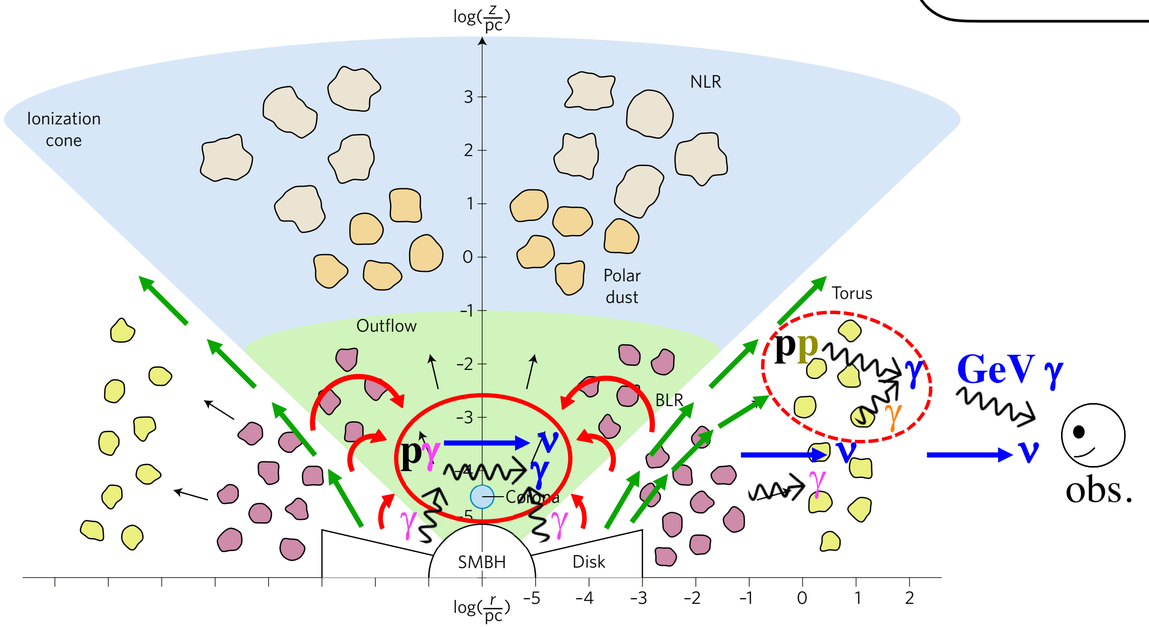
dN/dE ~ $E^{-3.2}$, $N_{\text{source neutrinos}}$ =50.4, E > 1 TeV,
post-trial significance: 2.9σ

Possible sites of neutrino production in non-jetted AGN





K. Murase, F. Stecker "Neutrino Physics & Astrophysics" 2022

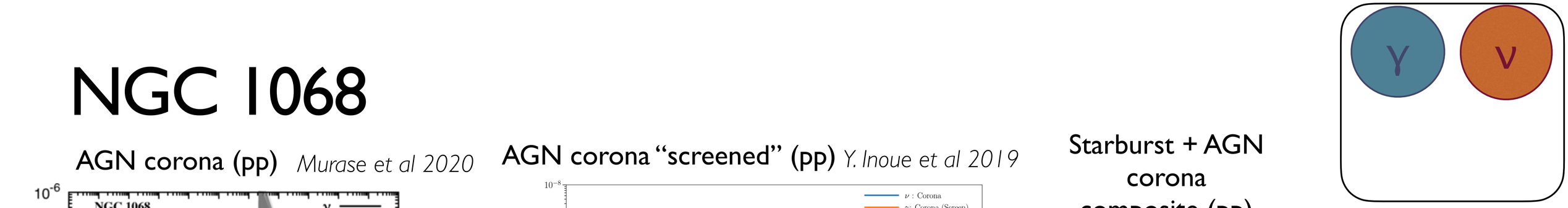


Inoue, Cerruti, Murase, Liu, 2022

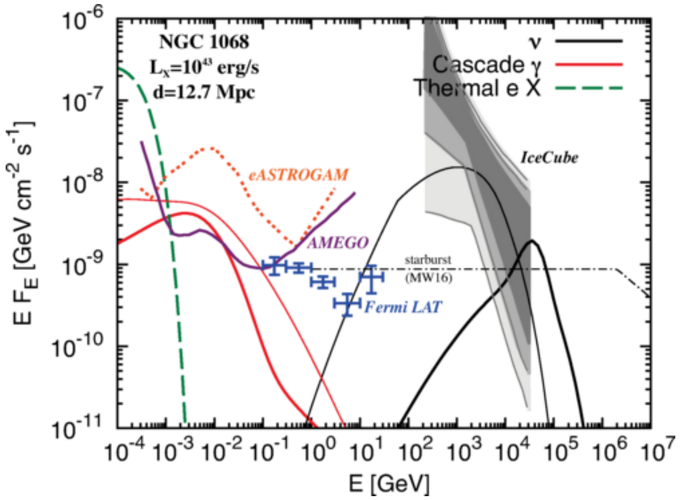
theory talk by Enrico Peretti this afternoon

Stecker et al. 1991
Stecker 2013
Kalashev et al. 2015
Wang & Loeb 2017
Liu et al 2018
Padovani et al 2018
Kimura et al 2019, 2021
Y. Inoue et al 2020
Murase et al 2020
Kheirandish et al 2021
Anchordoqui et al 2021
Eichmann, FO et al 2022
S. Inoue 2022

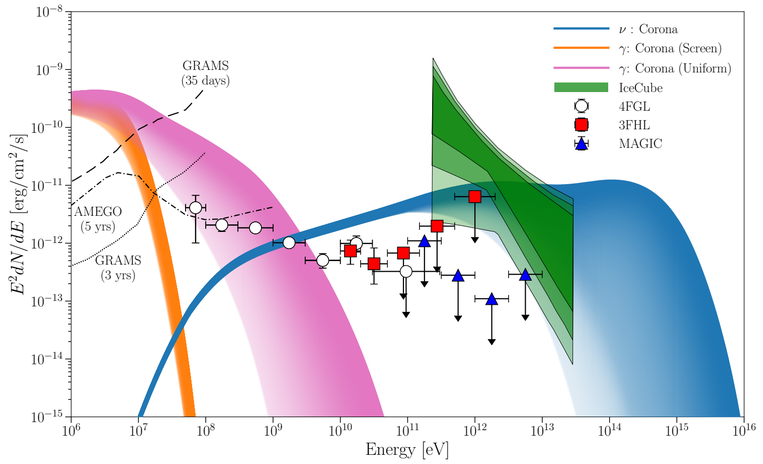
NGC 1068



AGN corona (pp) *Murase et al 2020*

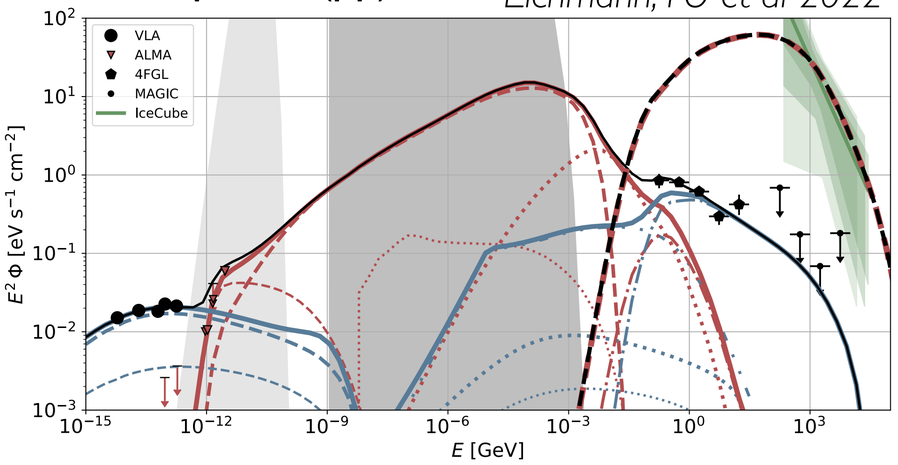


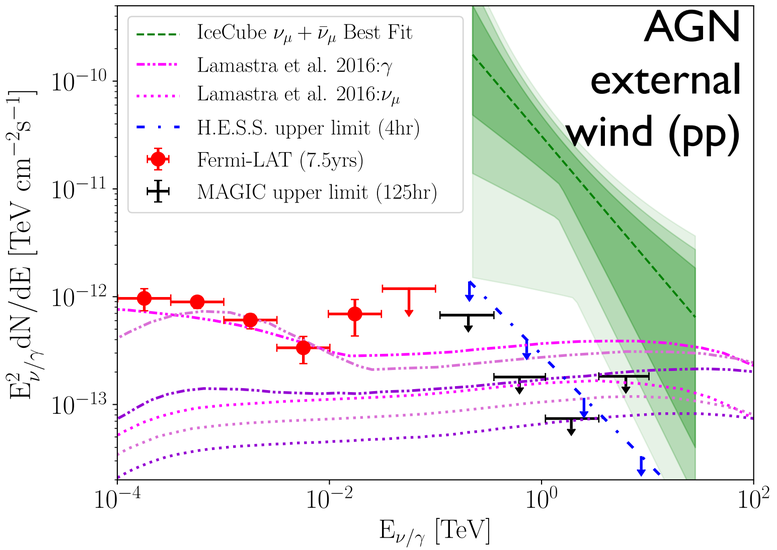
AGN corona "screened" (pp) *Y. Inoue et al 2019*



Starburst + AGN corona composite (pp)

Eichmann, FO et al 2022



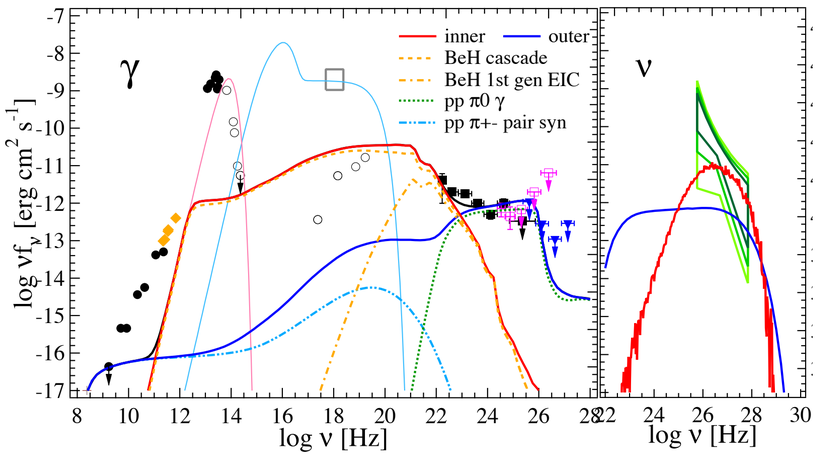


based on Lamastra 2016 see also Lamastra 2019

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

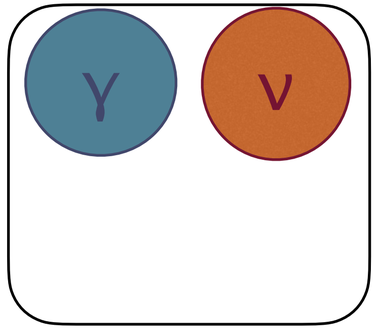
see also Kheirandish et al 2021
Anchordoqui et al 2021

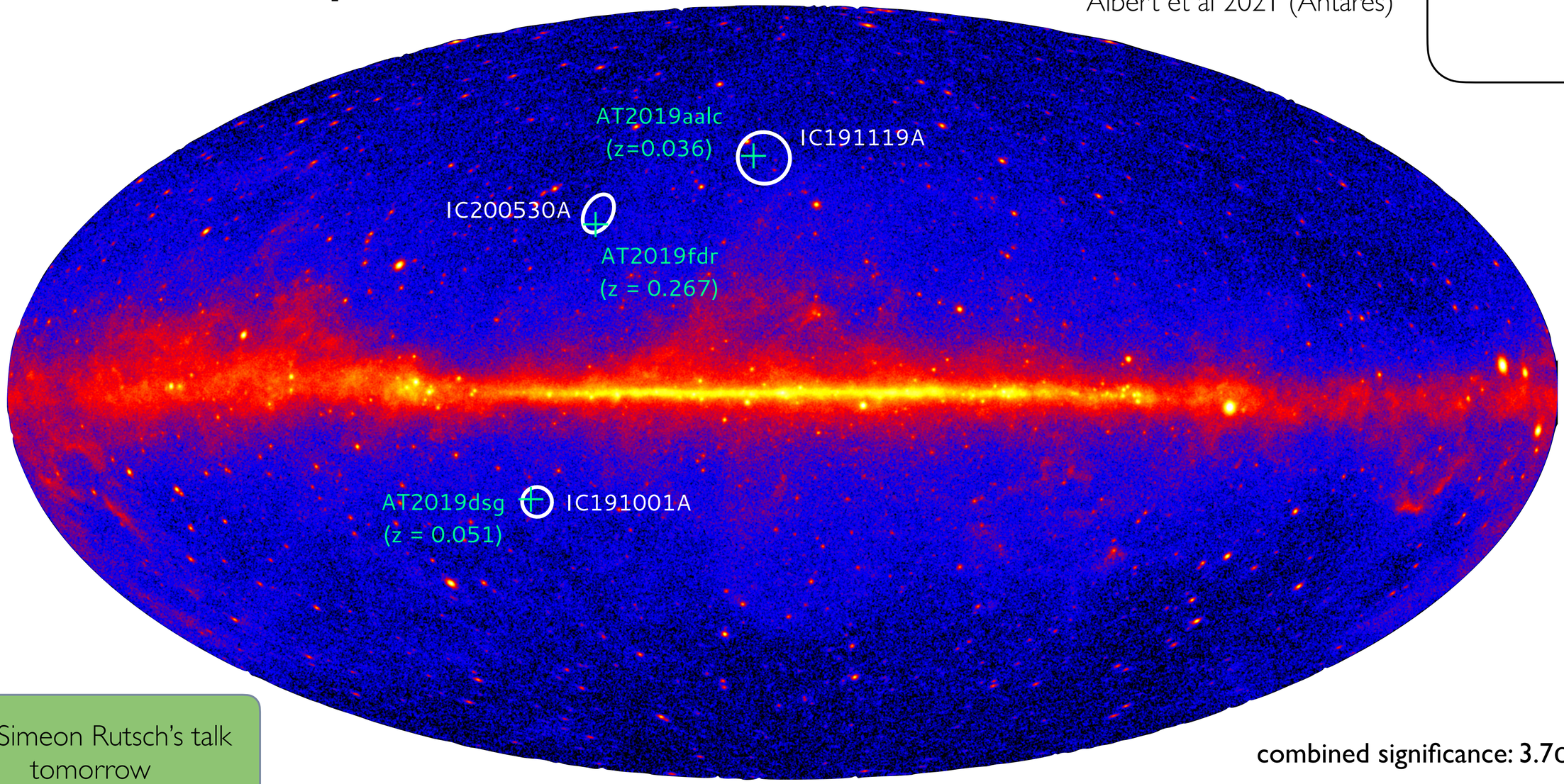


AGN internal wind (pγ) *S. Inoue et al 2022*

Tidal disruption events

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





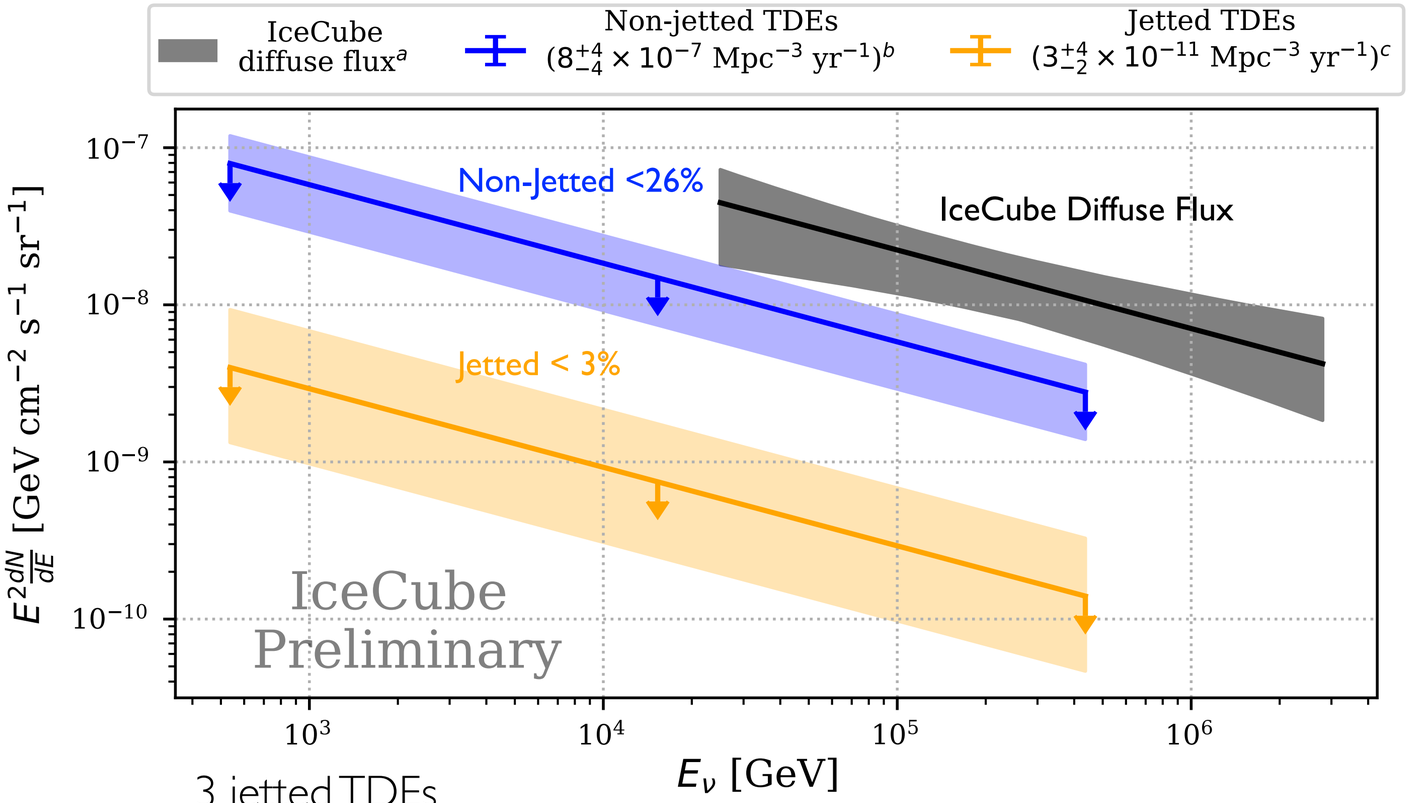
see Simeon Rutsch's talk tomorrow

combined significance: 3.7σ

Tidal disruption events

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

R. Stein for IceCube Coll PoS ICRC 2019

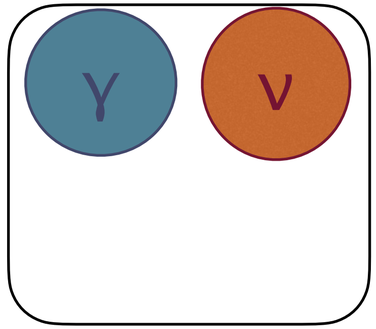


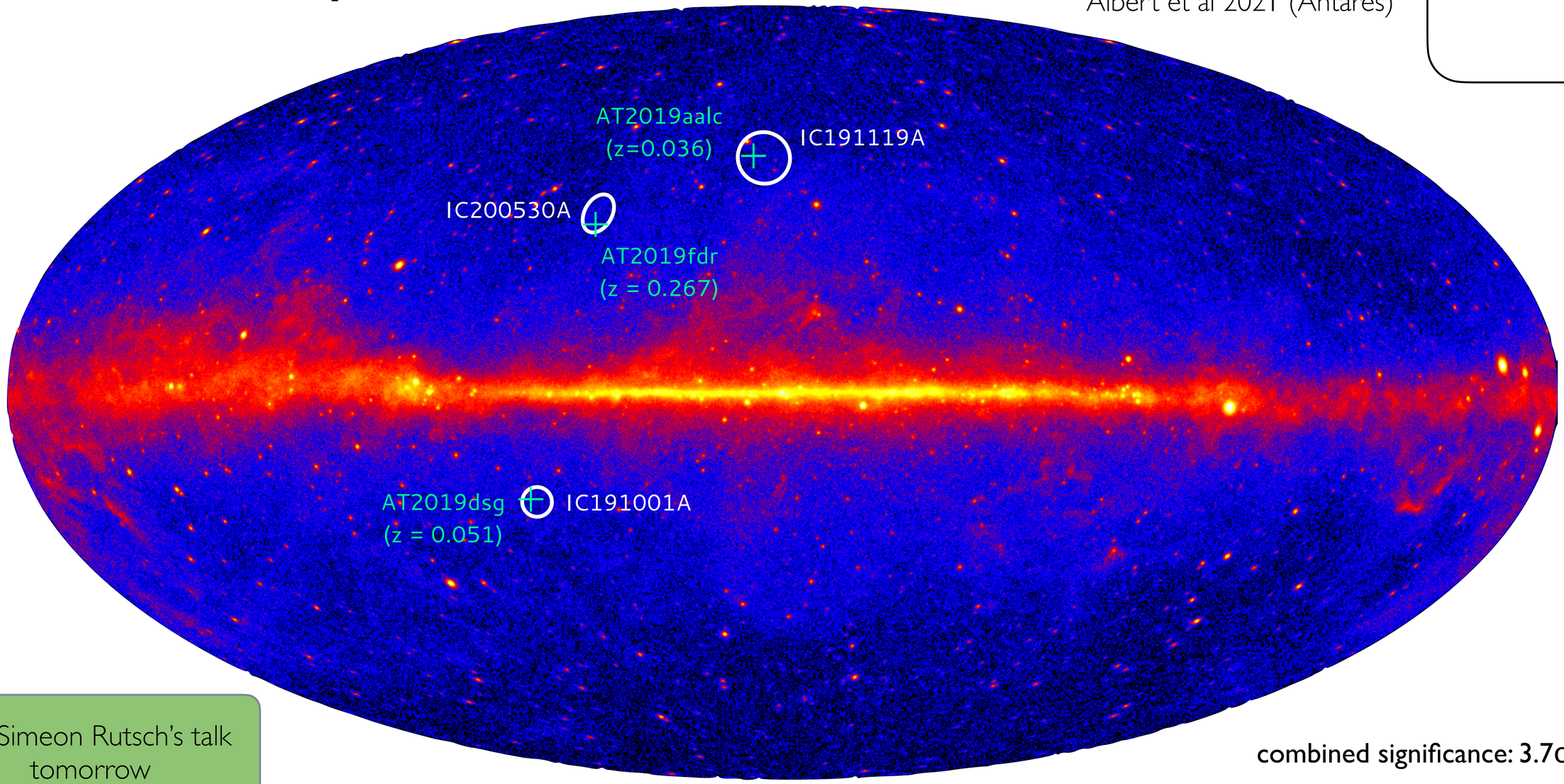
3 jetted TDEs
40 non-jetted TDEs

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

Tidal disruption events

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





see Simeon Rutsch's talk tomorrow

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Stein et al 2021
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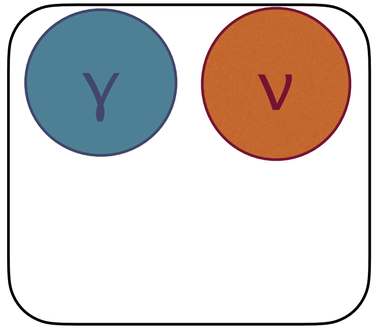
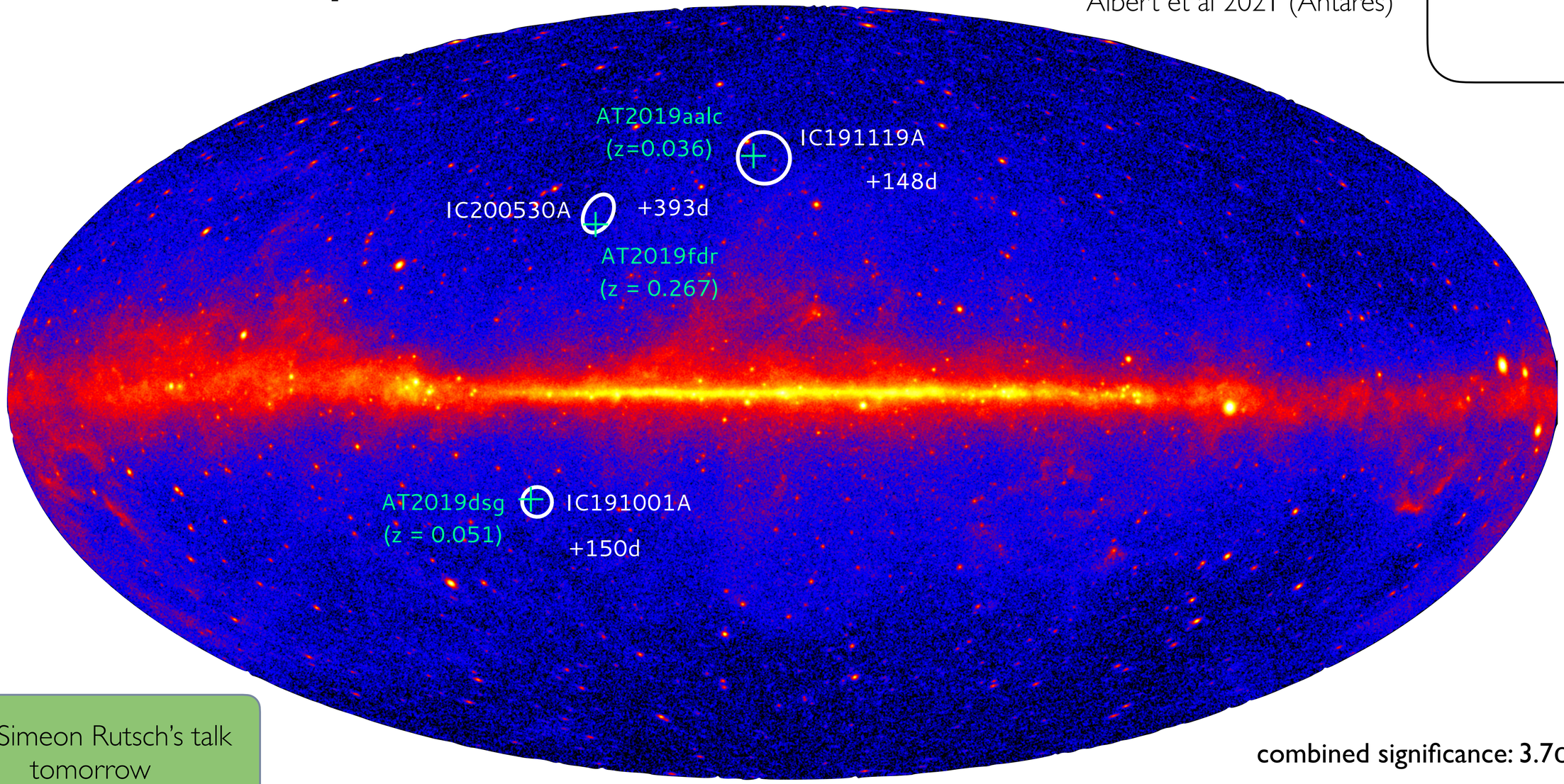


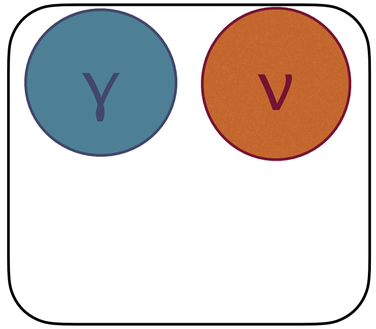


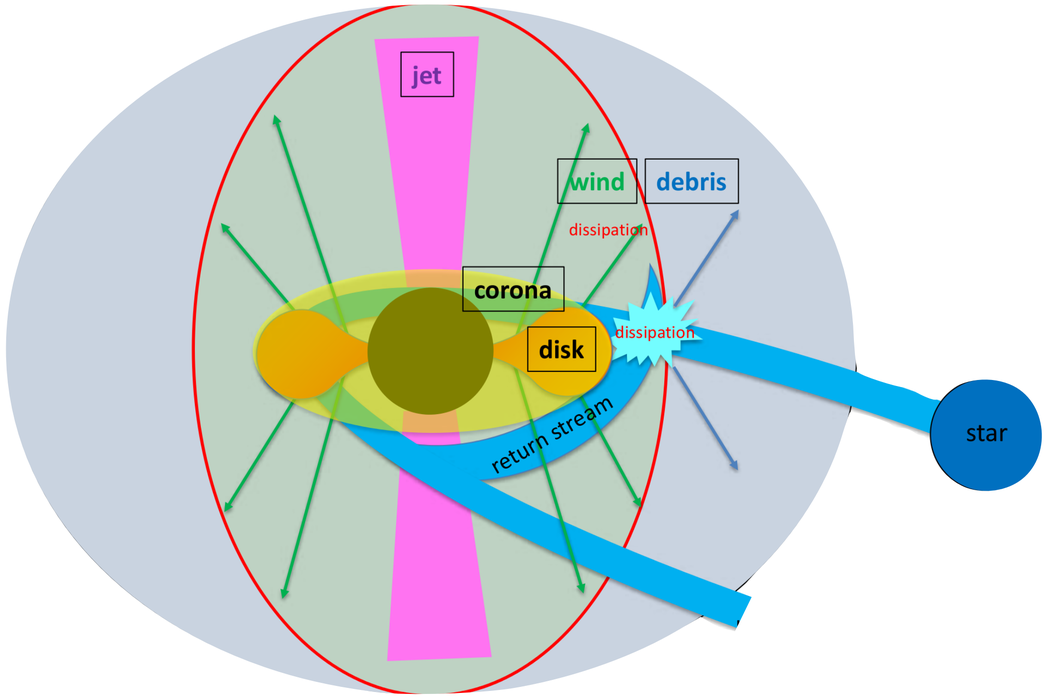
see Simeon Rutsch's talk tomorrow

combined significance: 3.7σ

Tidal disruption events

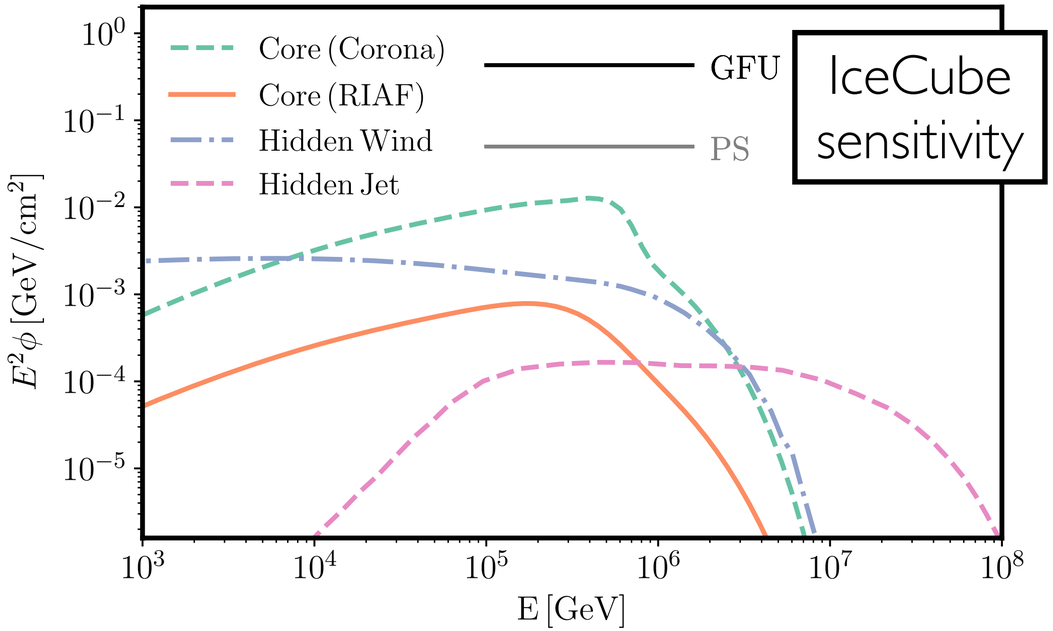
see also Hayasaki et al 2019
Winter, Lunardini 2020
Winter, Lunardini 2022
Banik & Bharda 2022





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

Murase, Zhang, Kimura, FO, Petropoulou 2020

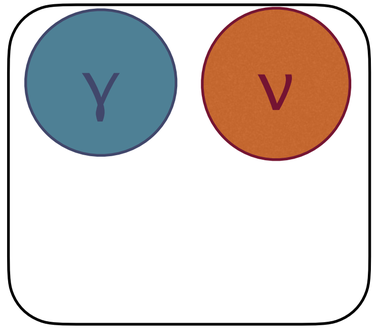


Similar neutrino production mechanism to AGN cores possible

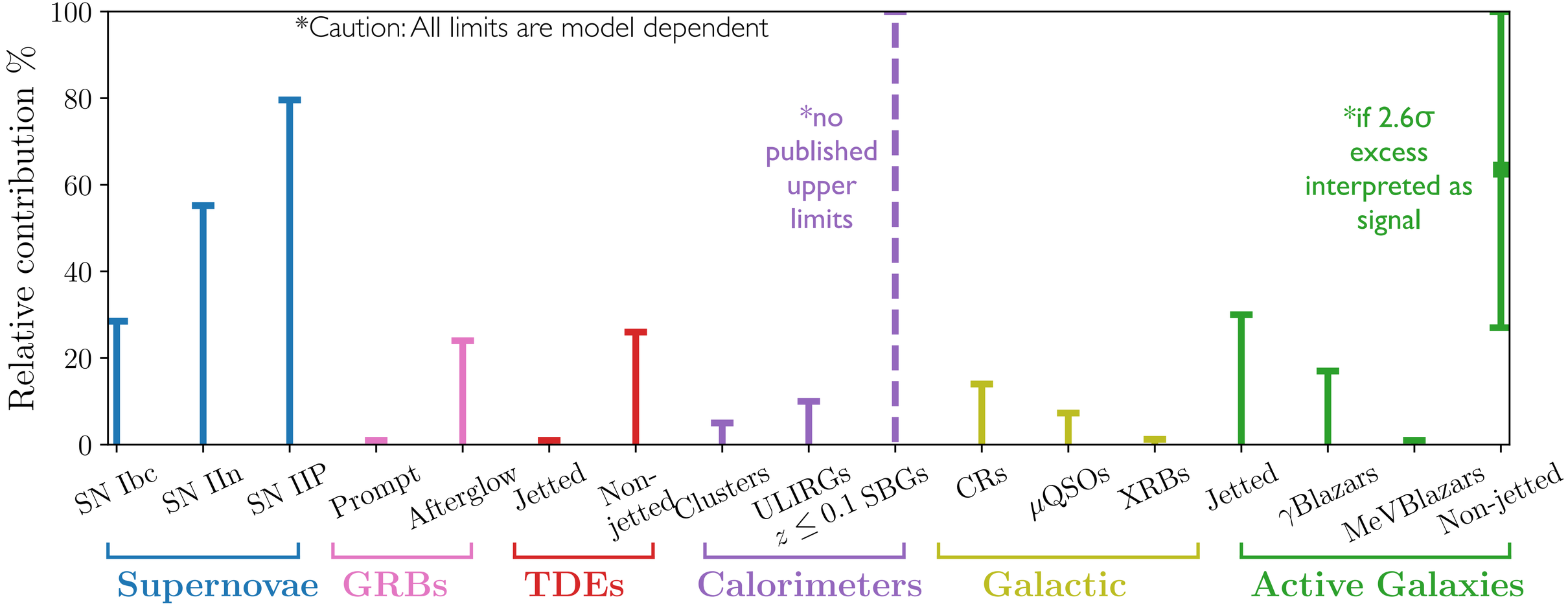
Models consistent with the detection of a neutrino (statistically)

but require protons with super-Eddington luminosities

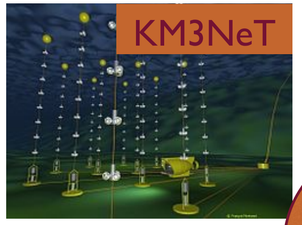
The current landscape: Stacking upper limits

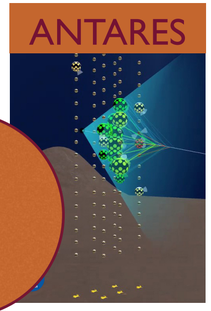


summary of IceCube stacking analyses results, list of references in
FO PoS ICRC2021 (2022) 030, arXiv:2201.05623

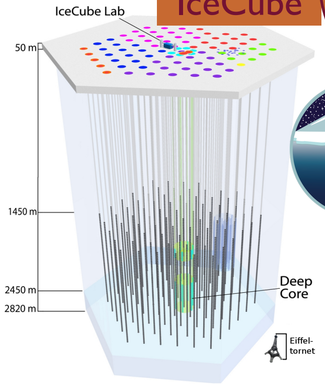


Waiting for the next multimessenger alert

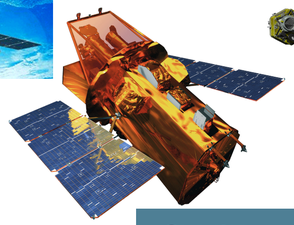


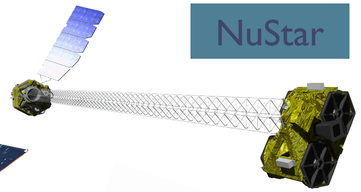


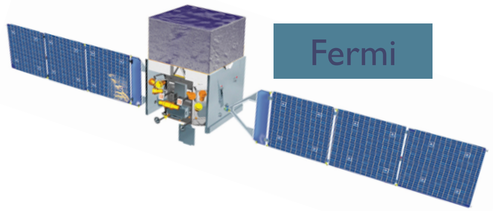
ν

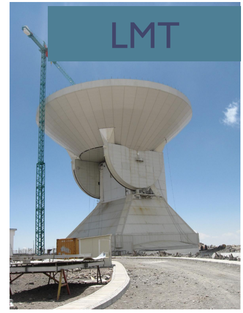


BAIKAL-GVD

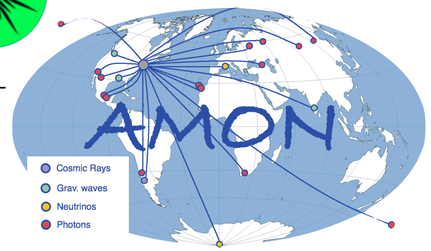




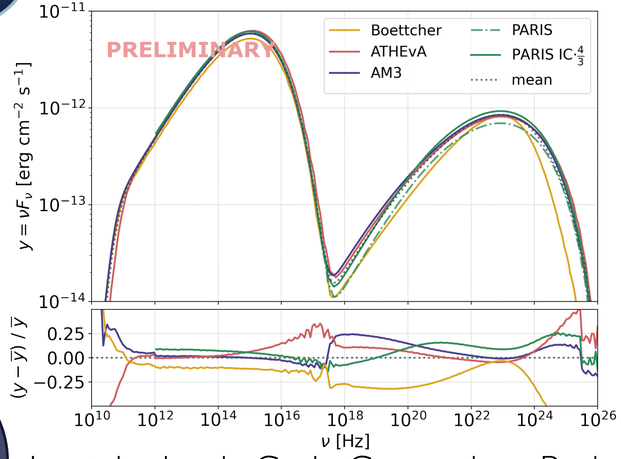




AMPEL

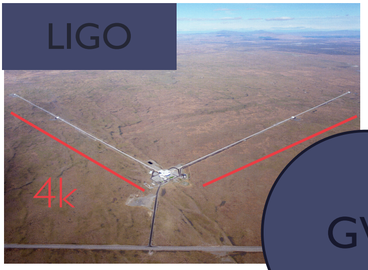


Astro-COLIBRI



Leptohadronic Code Comparison Project

Cerruti et al PoS 979 ICRC 2021



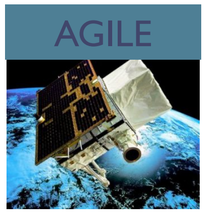
GW

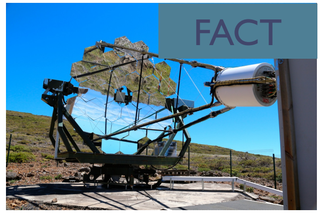
CR

γ

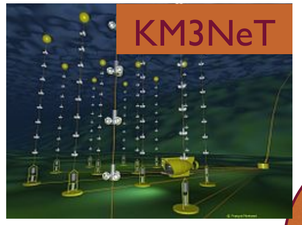
ALPACA

MASTER





Multimessenger astrophysics in the 2030s



P-ONE

SWGO

SVOM

cta

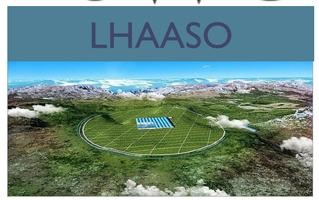
ν

TRIDENT

TRINITY

ASHRA-NTA

Transient Astrophysics Probe (TAP)



STROBE-X

ATHENA

BAIKAL-GVD

ICECUBE GEN2

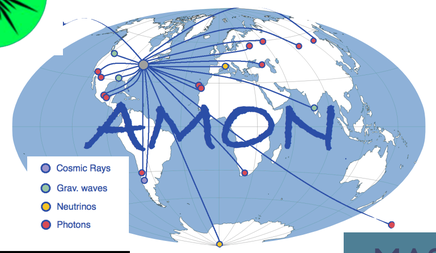
PUEO

ARA

ARIANNA

GRAND

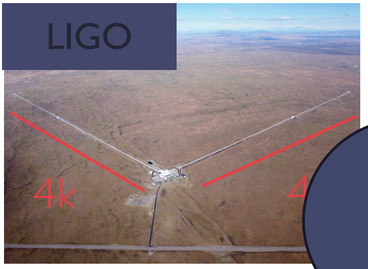
RNO-G



SKA
SQUARE KILOMETRE ARRAY

VERA C. RUBIN OBSERVATORY

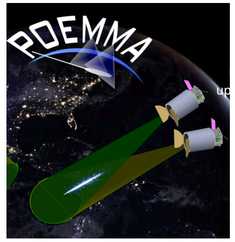
γ



GW

Einstein Telescope

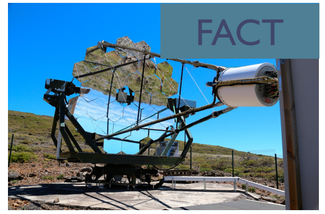
CR



JEM-EUSO

MASTER

ALPACA

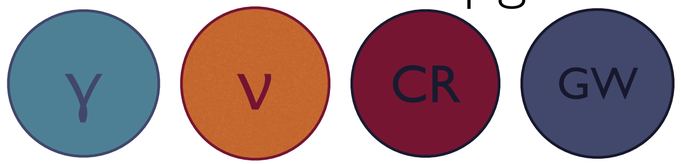


[non-exhaustive]
for timelines and sensitivities see e.g.
Guepin, Kotera, FO, Nature Phys. Reviews 2022

Summary

UHECR and neutrino sources appear to be numerous

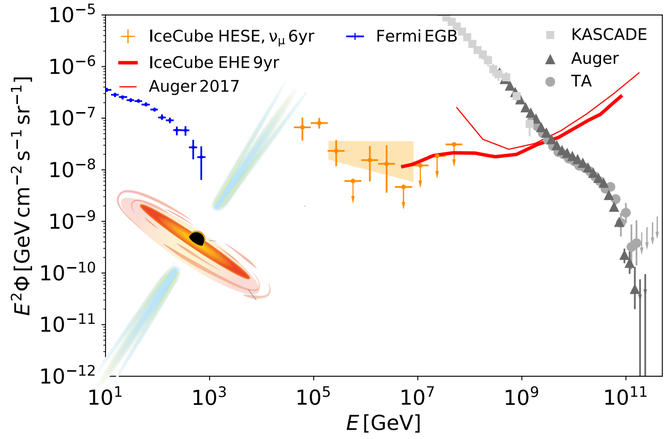
New facilities and sensitive upgrades being deployed

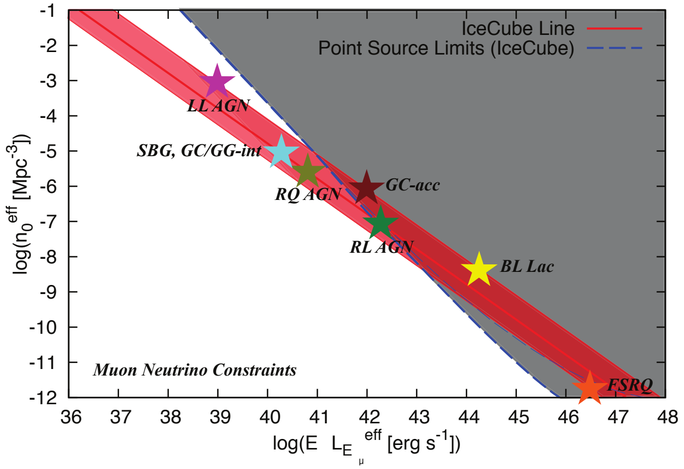


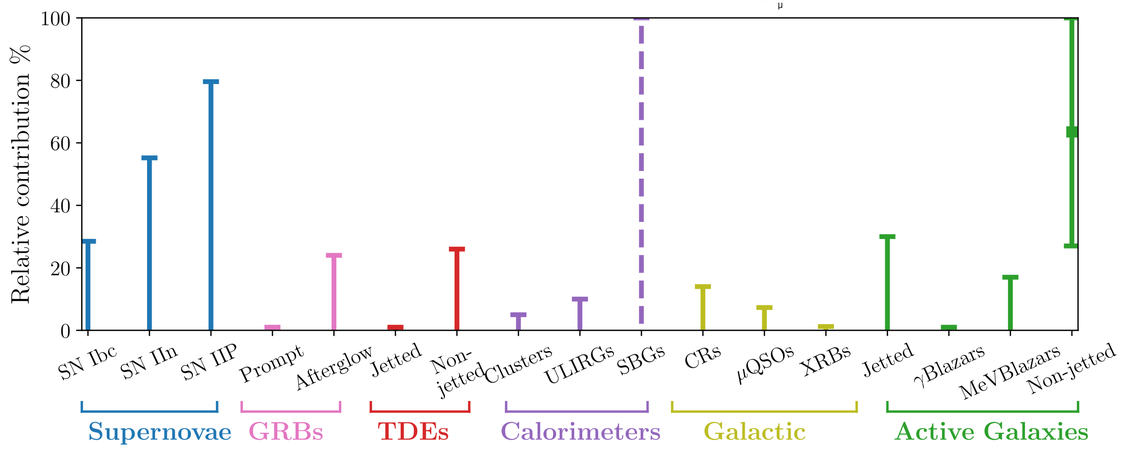
Multimessenger monitoring+phenomenology: Scrutinise every alert

Waiting for the next multimessenger events!

Many thanks to Jörg and to the organising committee for the invitation!







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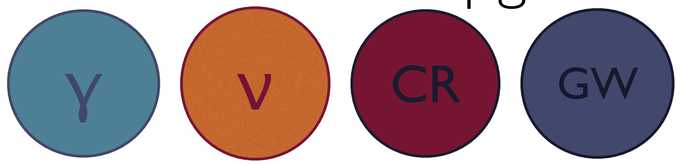

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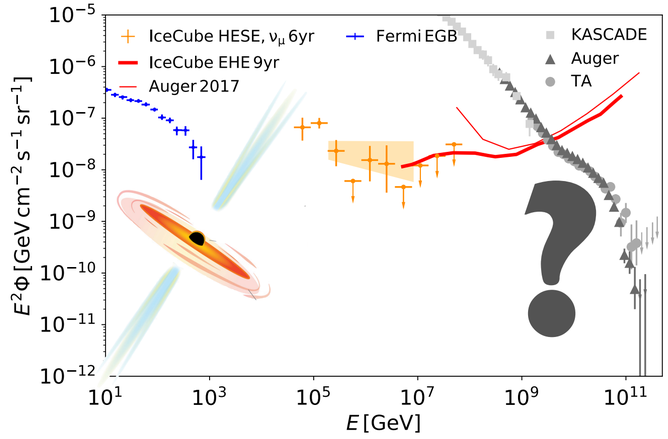

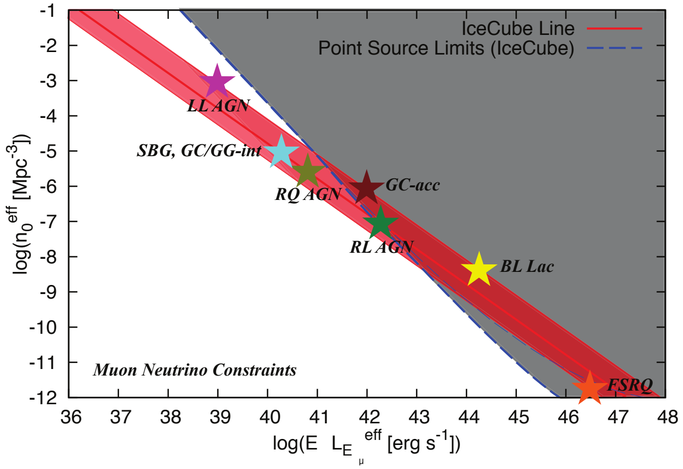

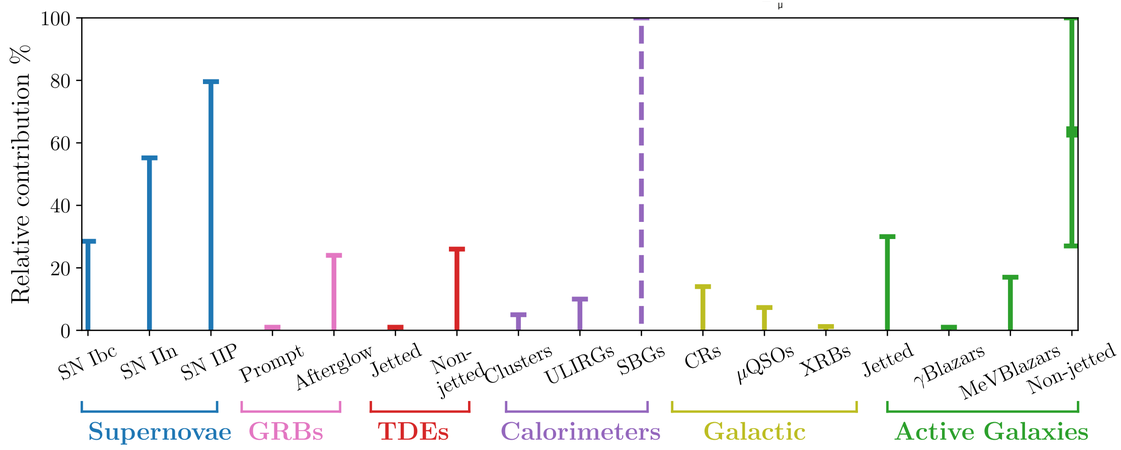

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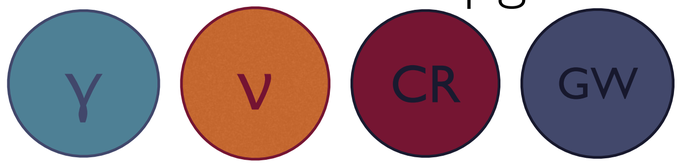

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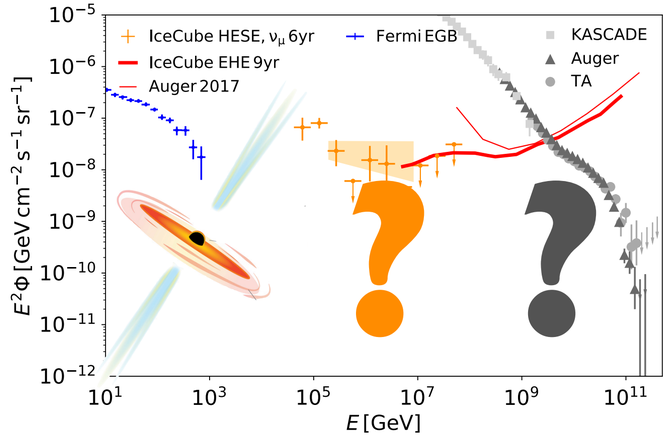

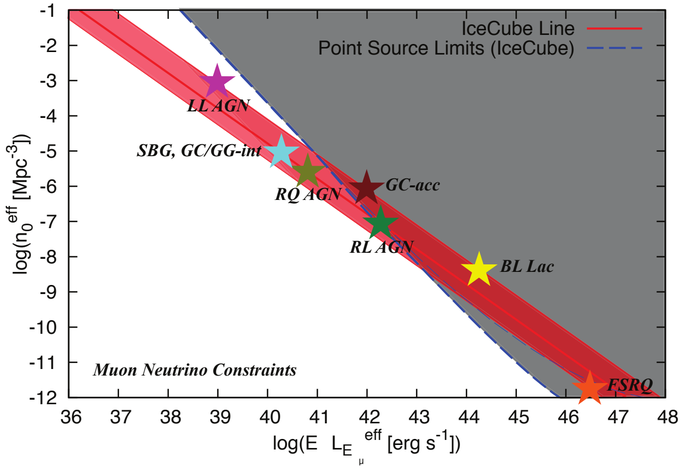

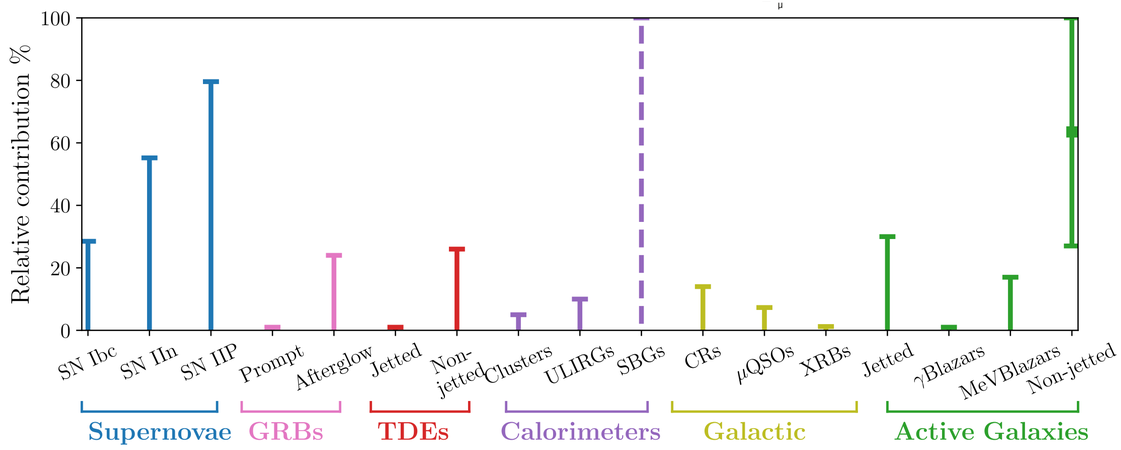

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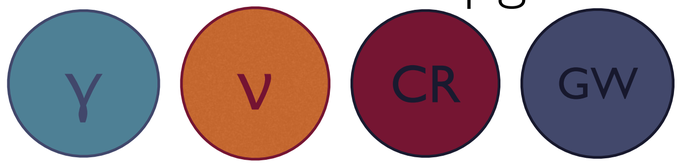

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