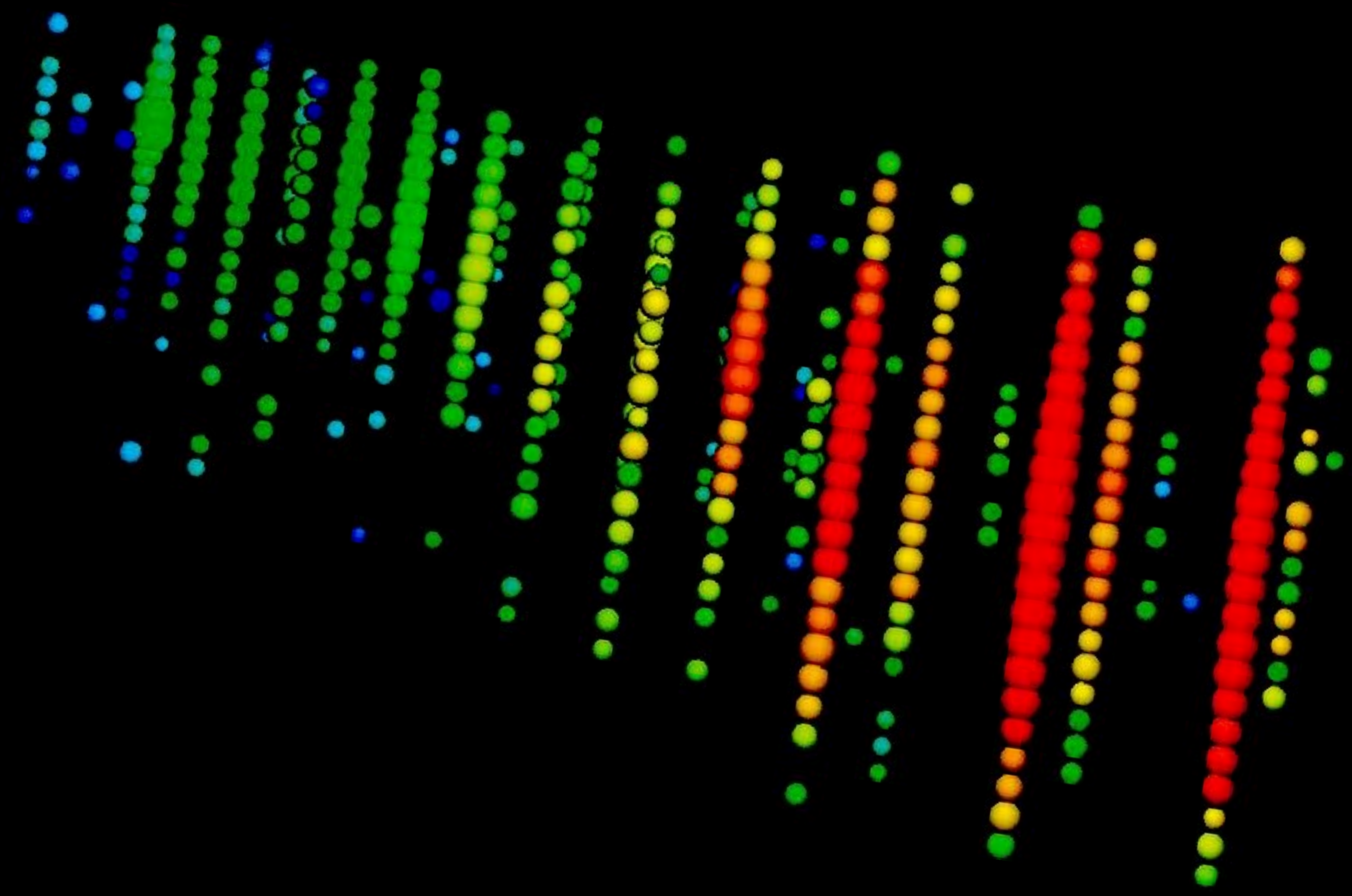


Multimessenger Astroparticle Physics

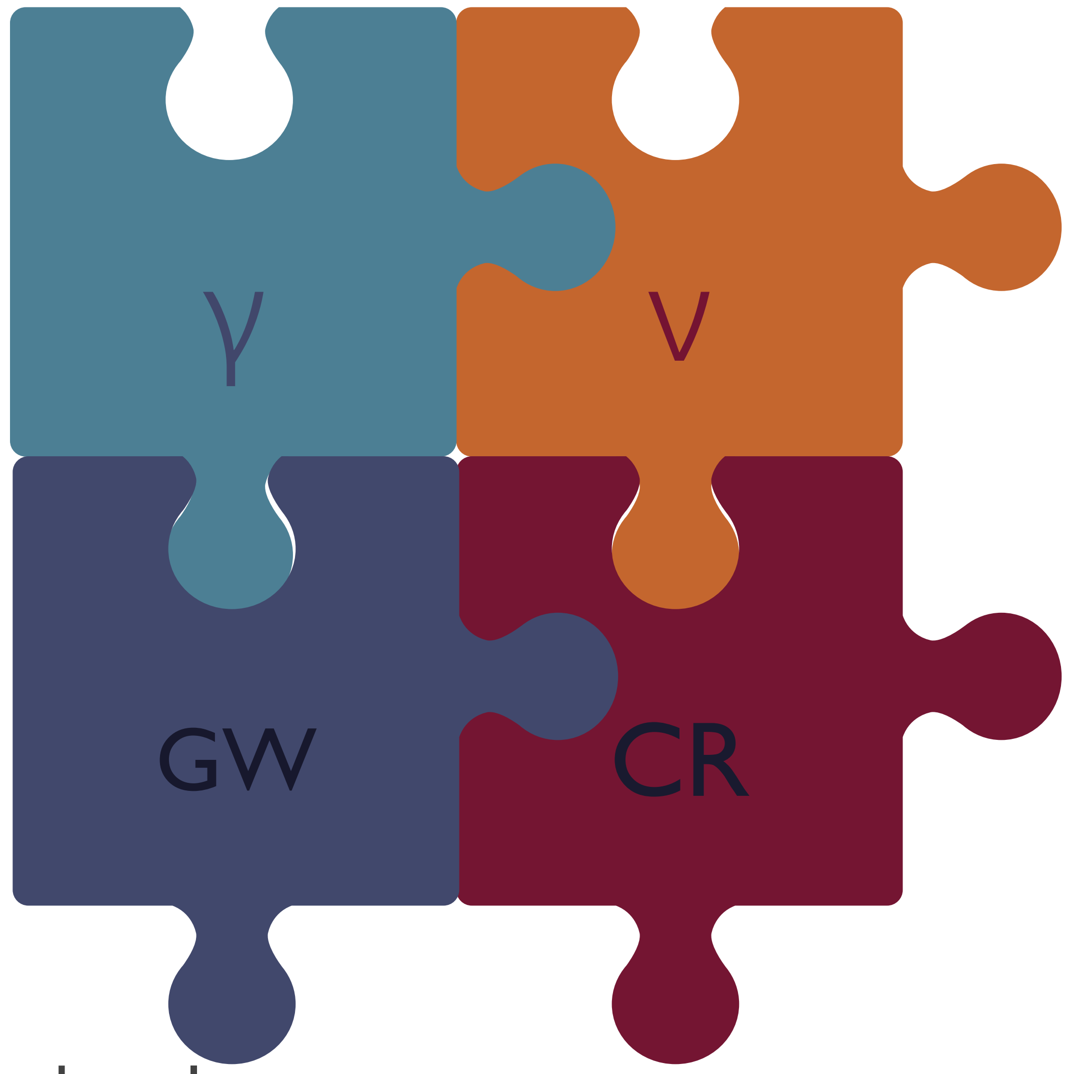
ISCRA Erice 2024

Foteini Oikonomou

July 24th 2024

NTNU
Norwegian University of
Science and Technology

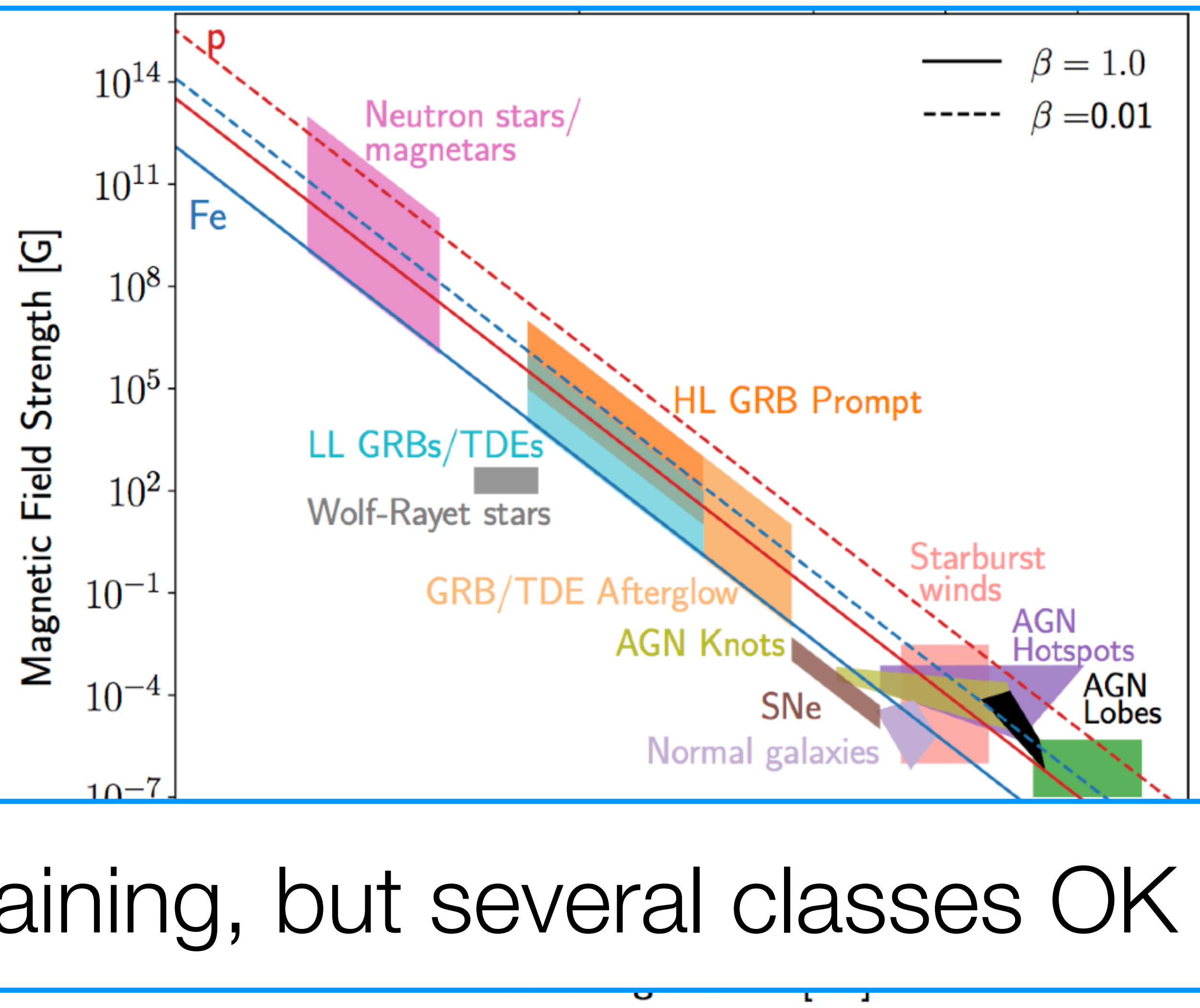
Lecture plan



- Focus on: UHECRs, neutrinos and EM counterparts
- **Monday**: Generic source properties (Requirements for astrophysical accelerators of high-energy cosmic rays/high-energy neutrinos)
- **Tuesday/Wednesday:** Overview of candidate multimessenger sources
  - **Tuesday:** (Jetted) Active Galactic Nuclei
  - **Wednesday:** Non-jetted AGN/Starburst Galaxies/Gamma-ray bursts/Pulsars/Tidal Disruption Events

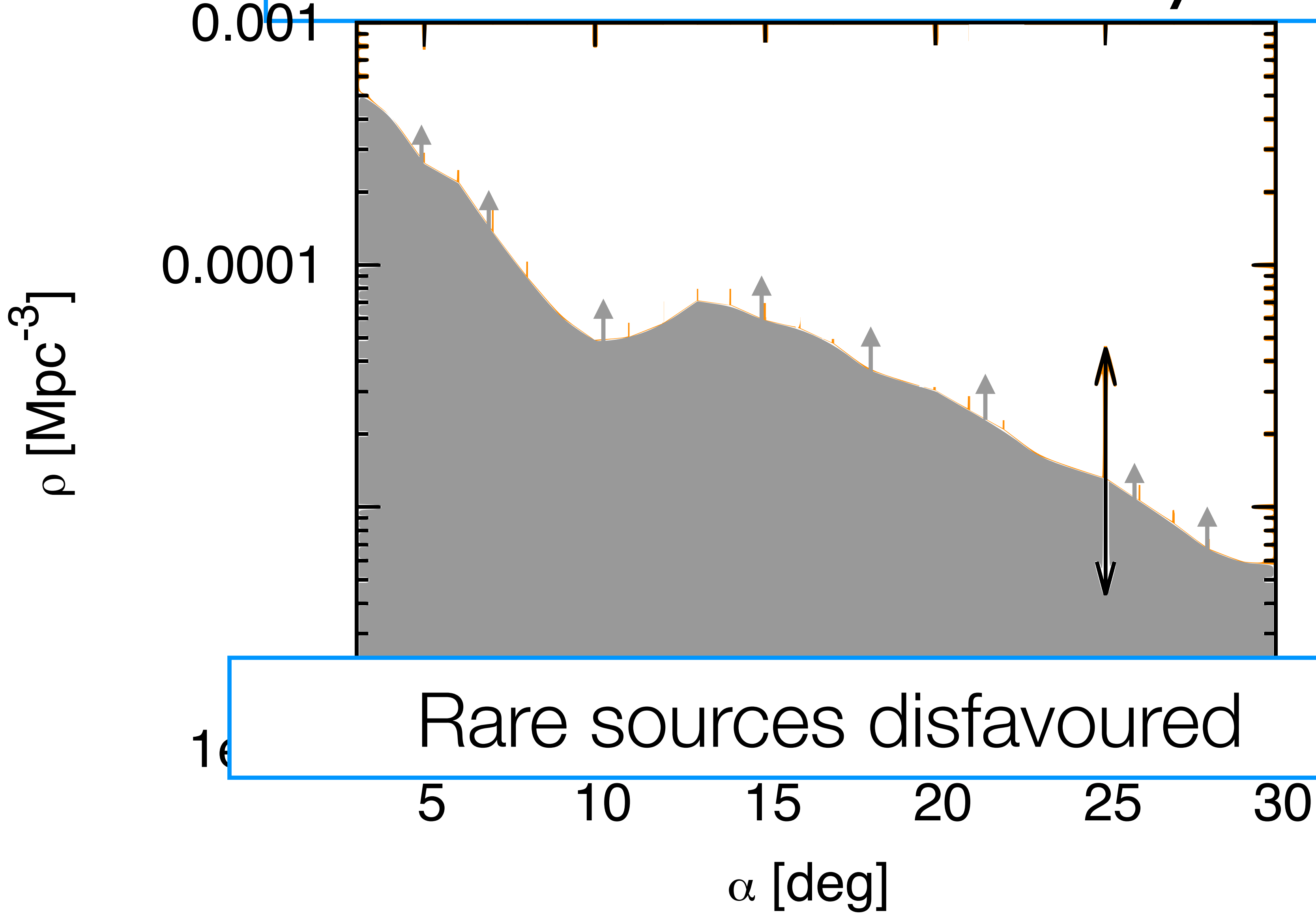
Recap of Monday’s lecture

UHECR Maximum Energy



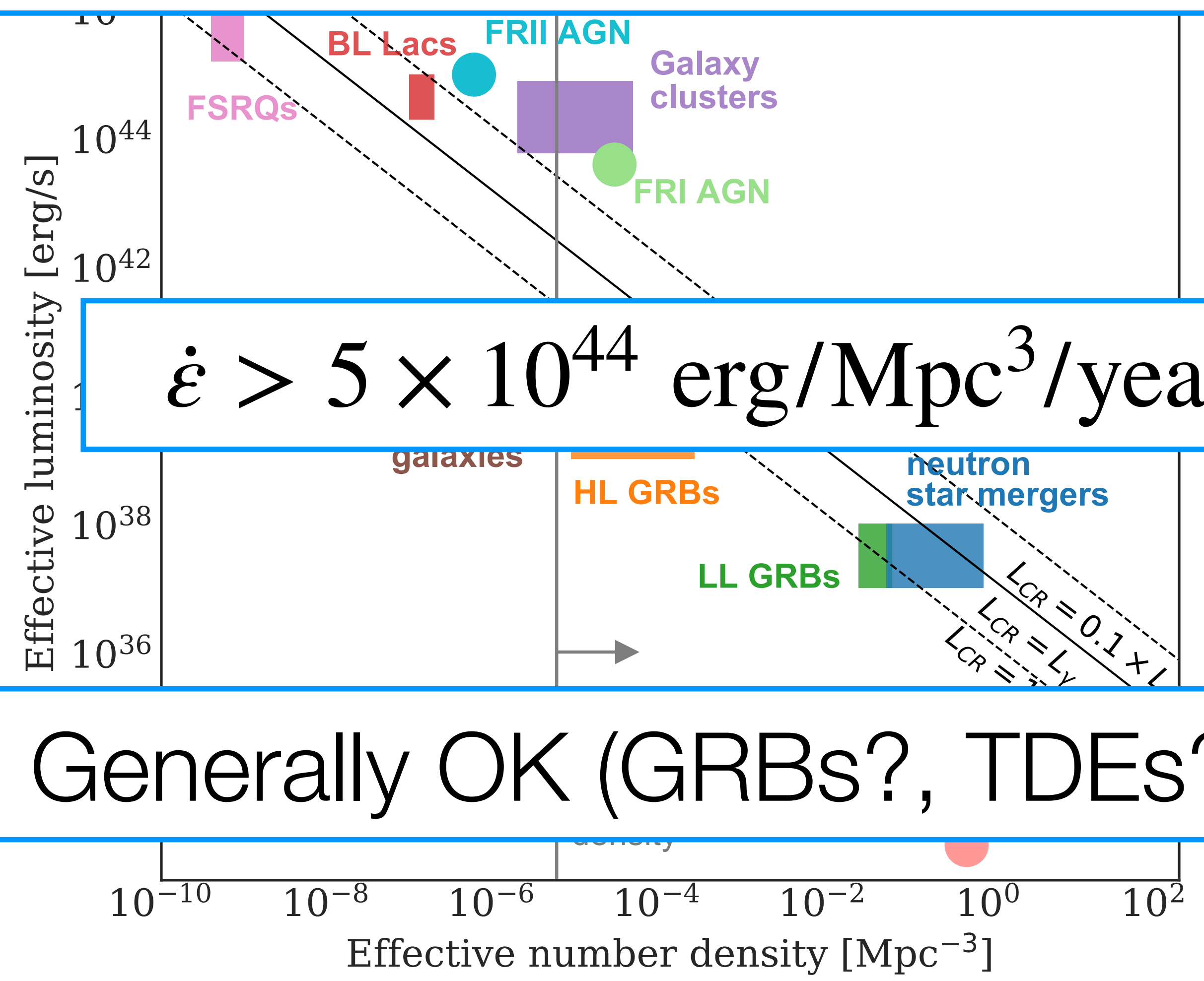
constraining, but several classes OK for nuclei

UHECR number density



Rare sources disfavoured

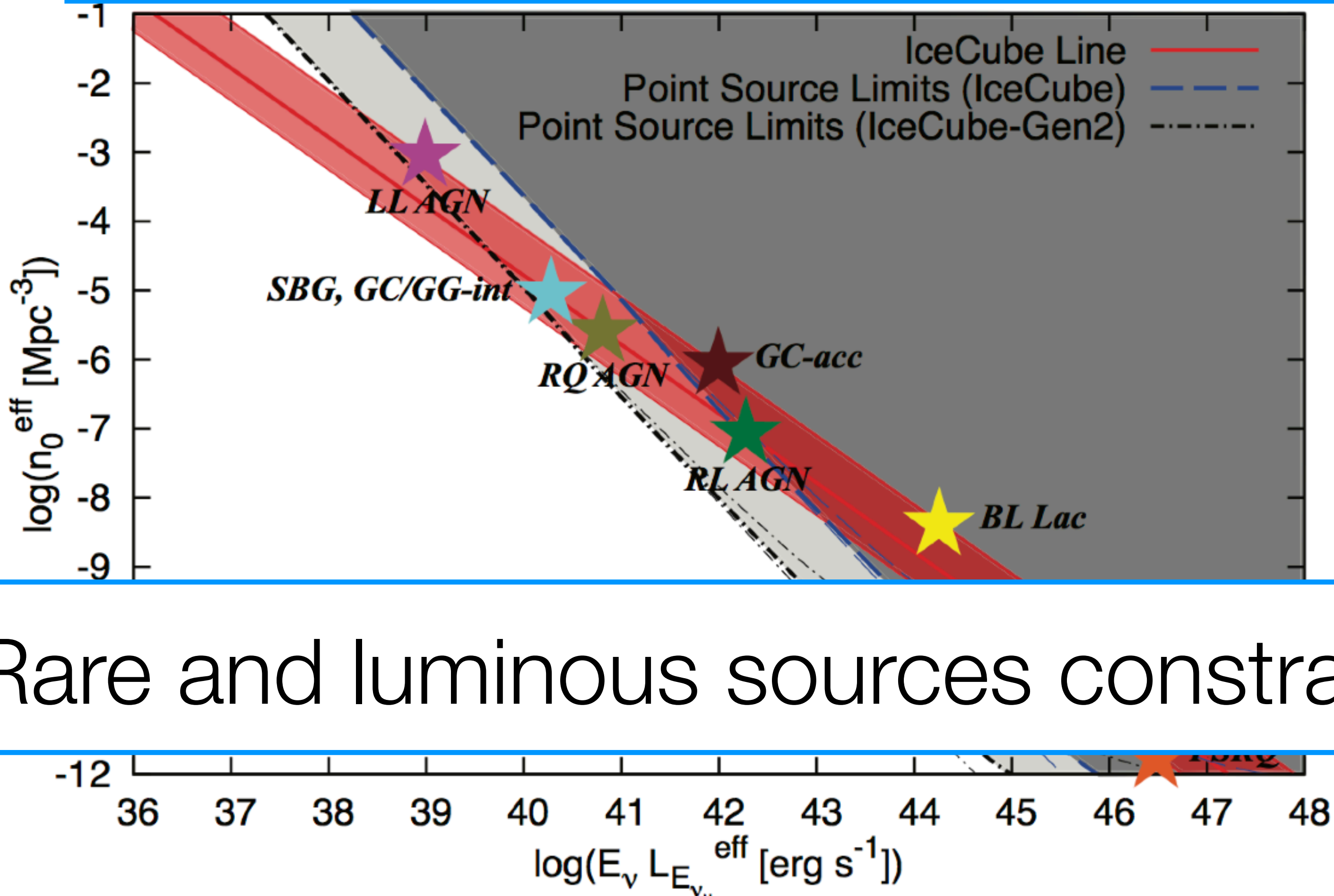
UHECR Emissivity



$$\dot{\varepsilon} > 5 \times 10^{44}\ \mathrm{erg/Mpc^3/year}$$

Generally OK (GRBs?, TDEs?)

Neutrino clustering constraints

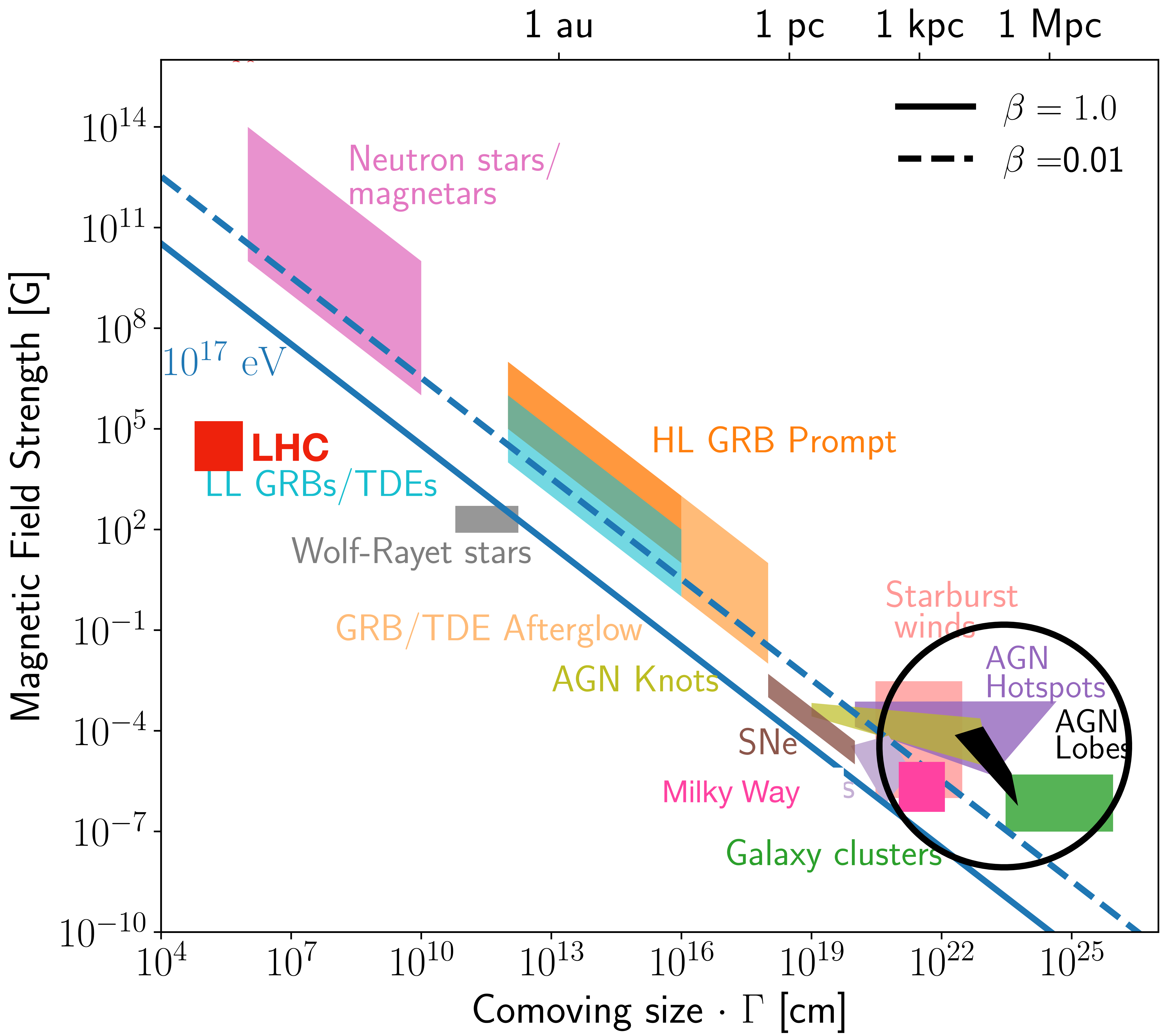


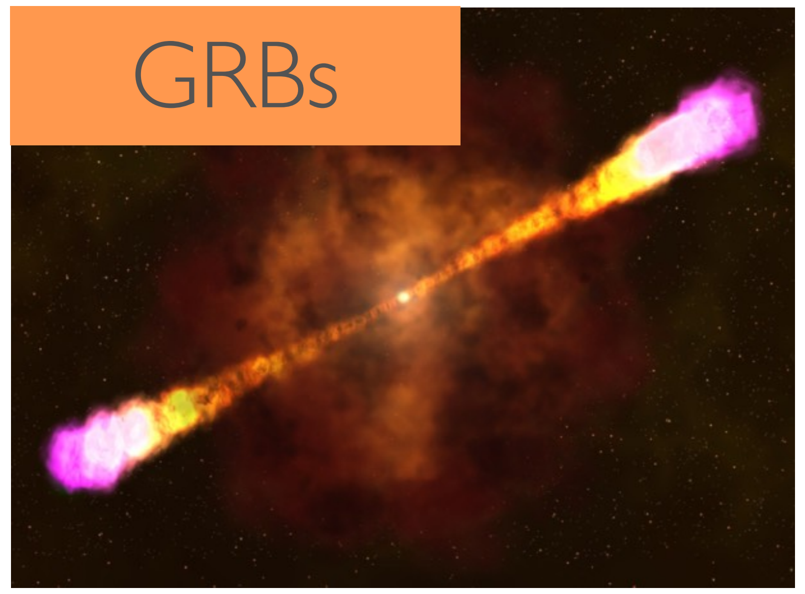
Rare and luminous sources constrained

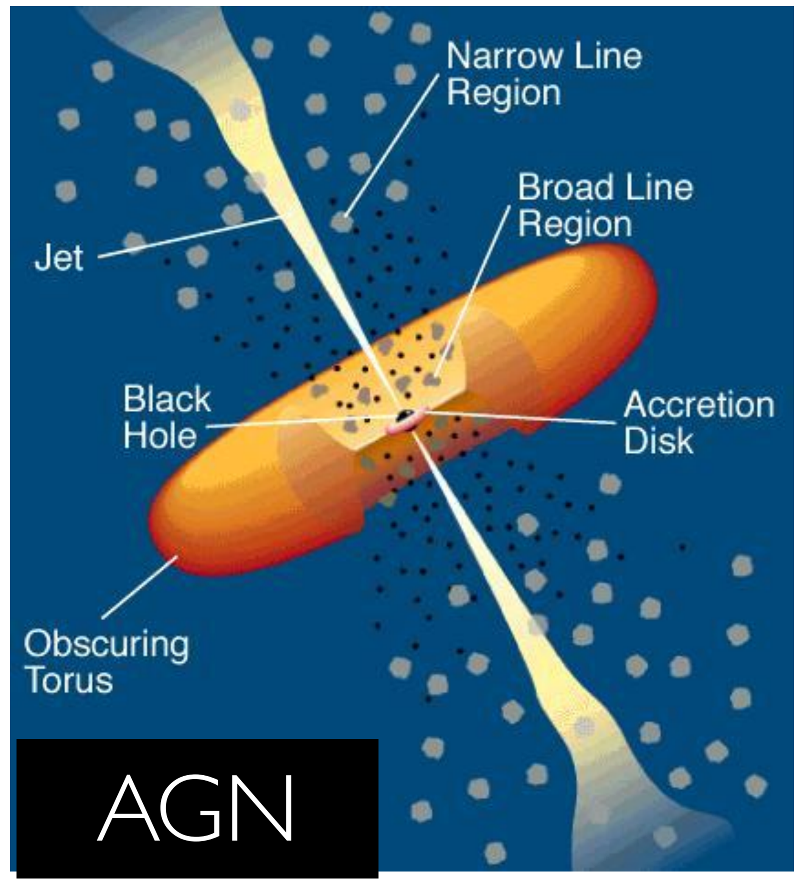
Scorecard

	$E_{\max}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_ν	Stacking UL
BL Lacs	😀	😞	😀	😞	≲20%
FSRQs	😀	😞	😀	😞	≲20%
FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN					
Starburst galaxies					
HL GRBs					
LL GRBs					
Pulsars					
TDEs					

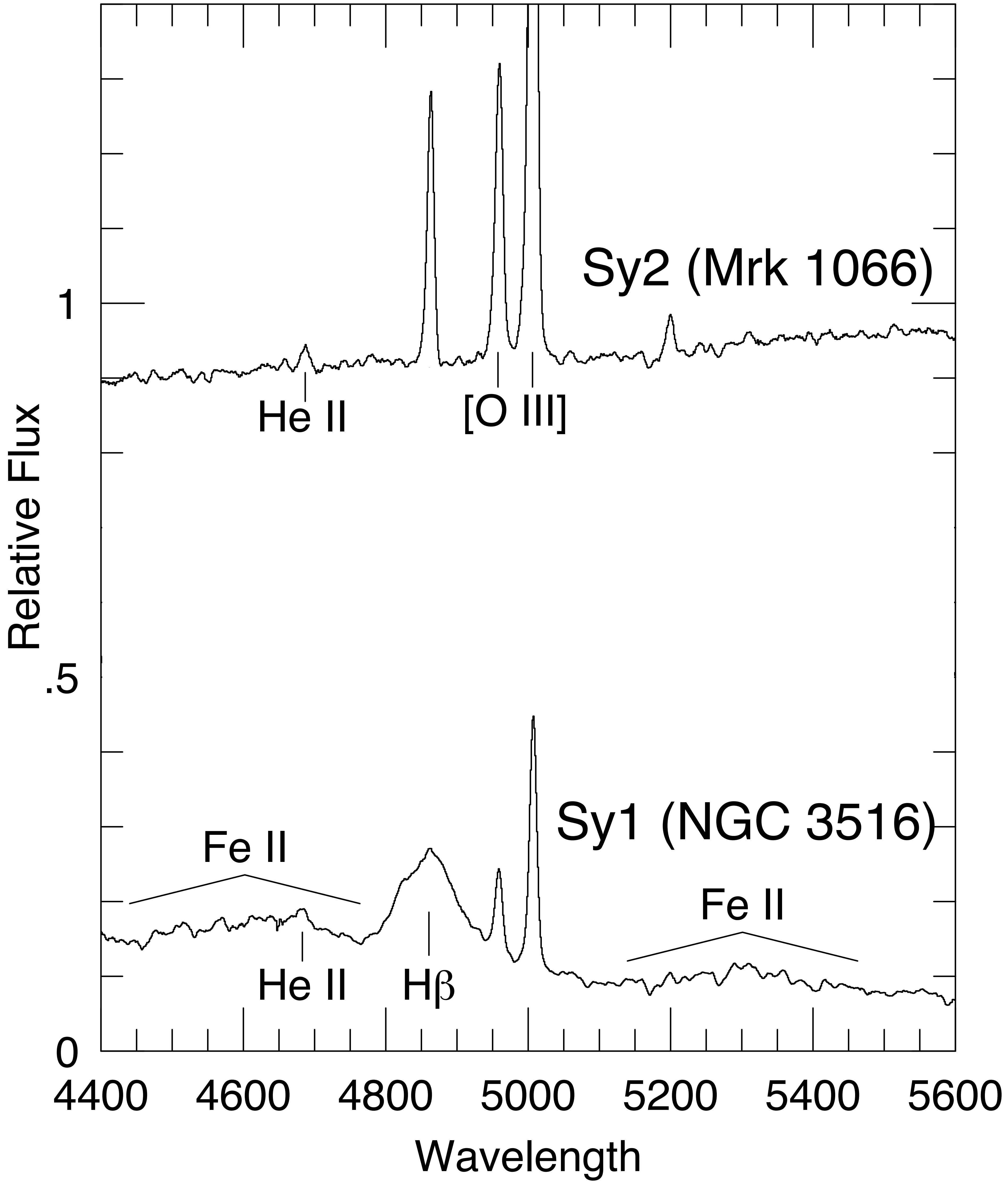
Cosmic-ray accelerators that satisfy the confinement r

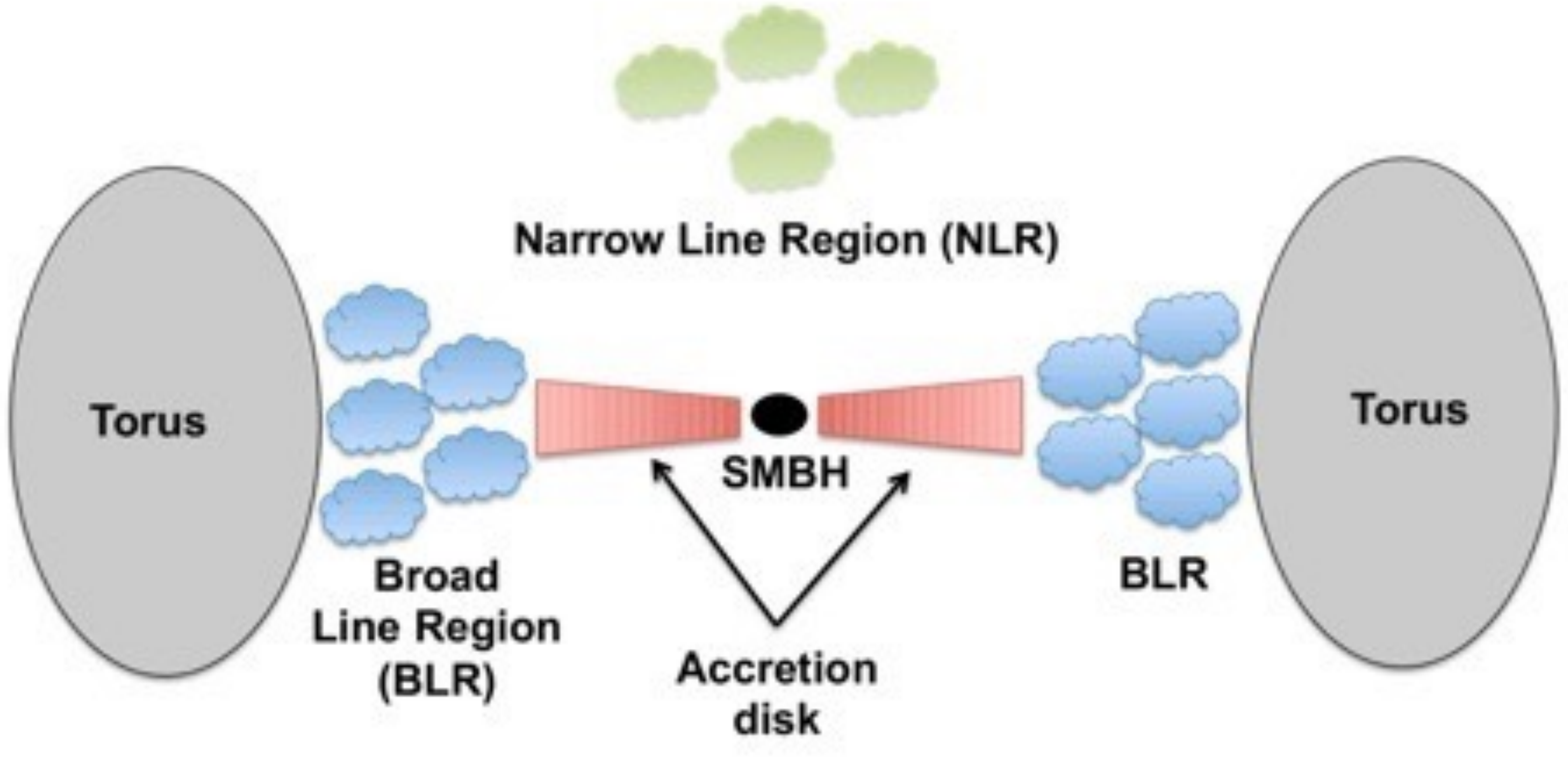


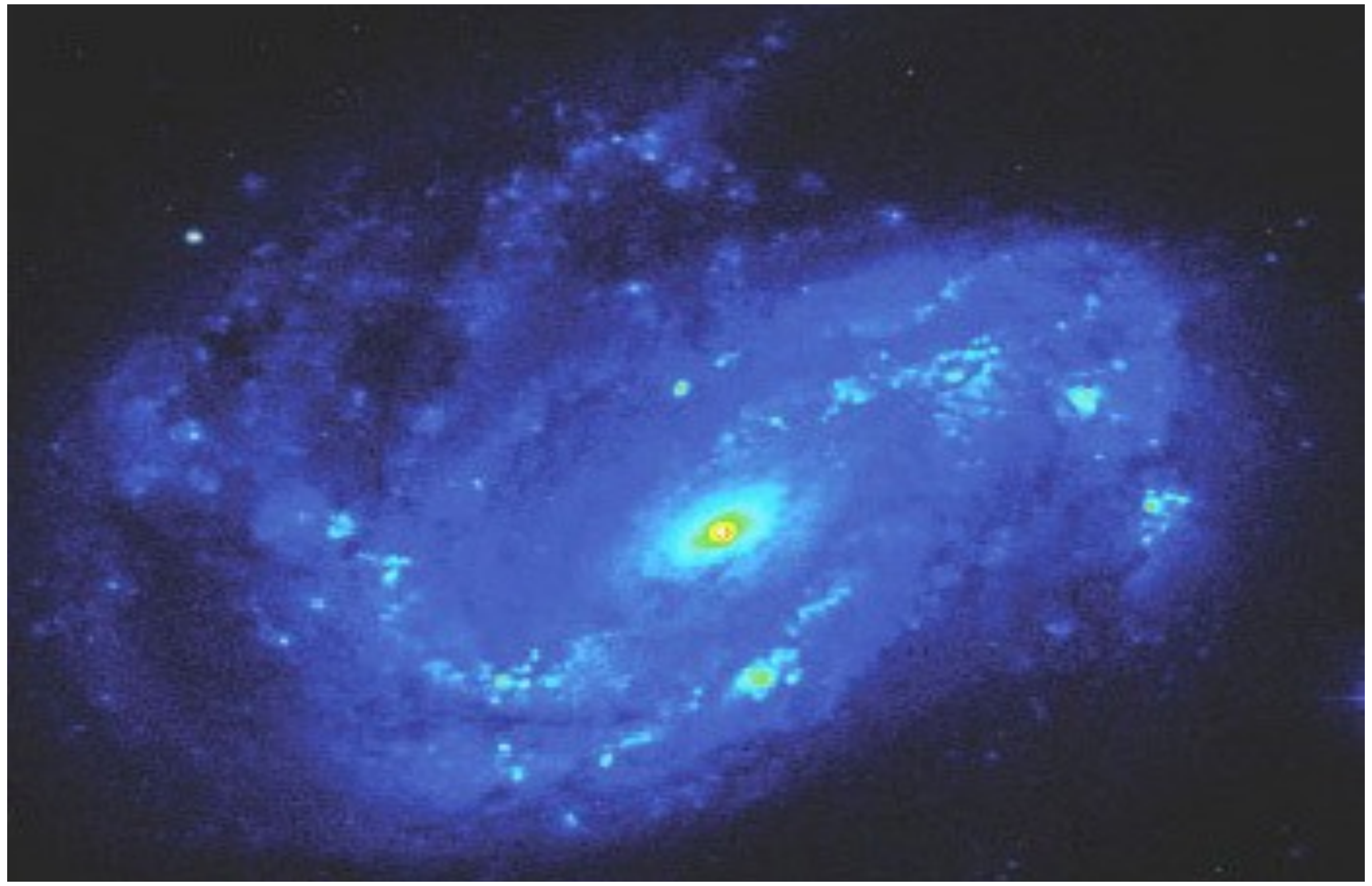




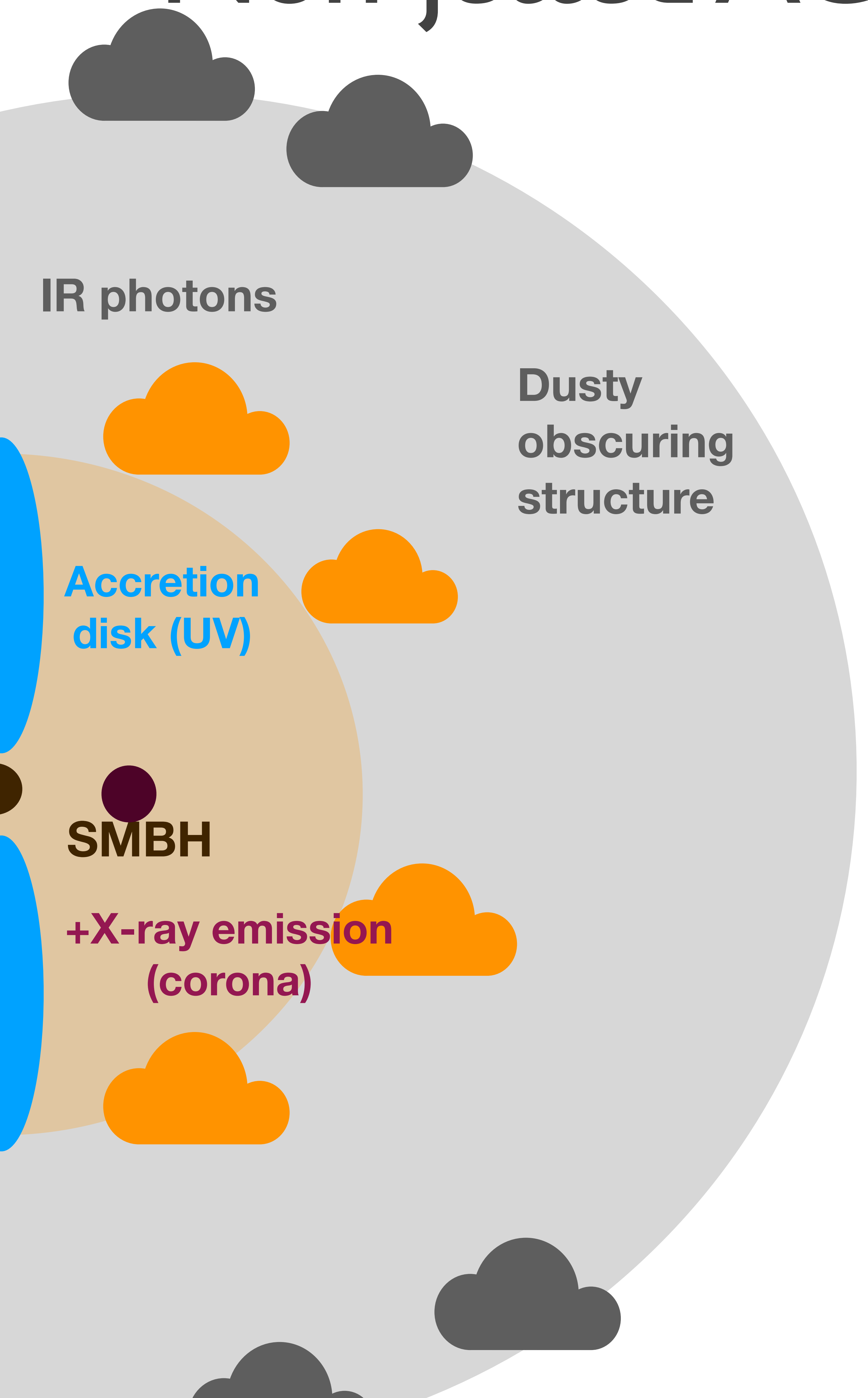
Non-jetted AGN

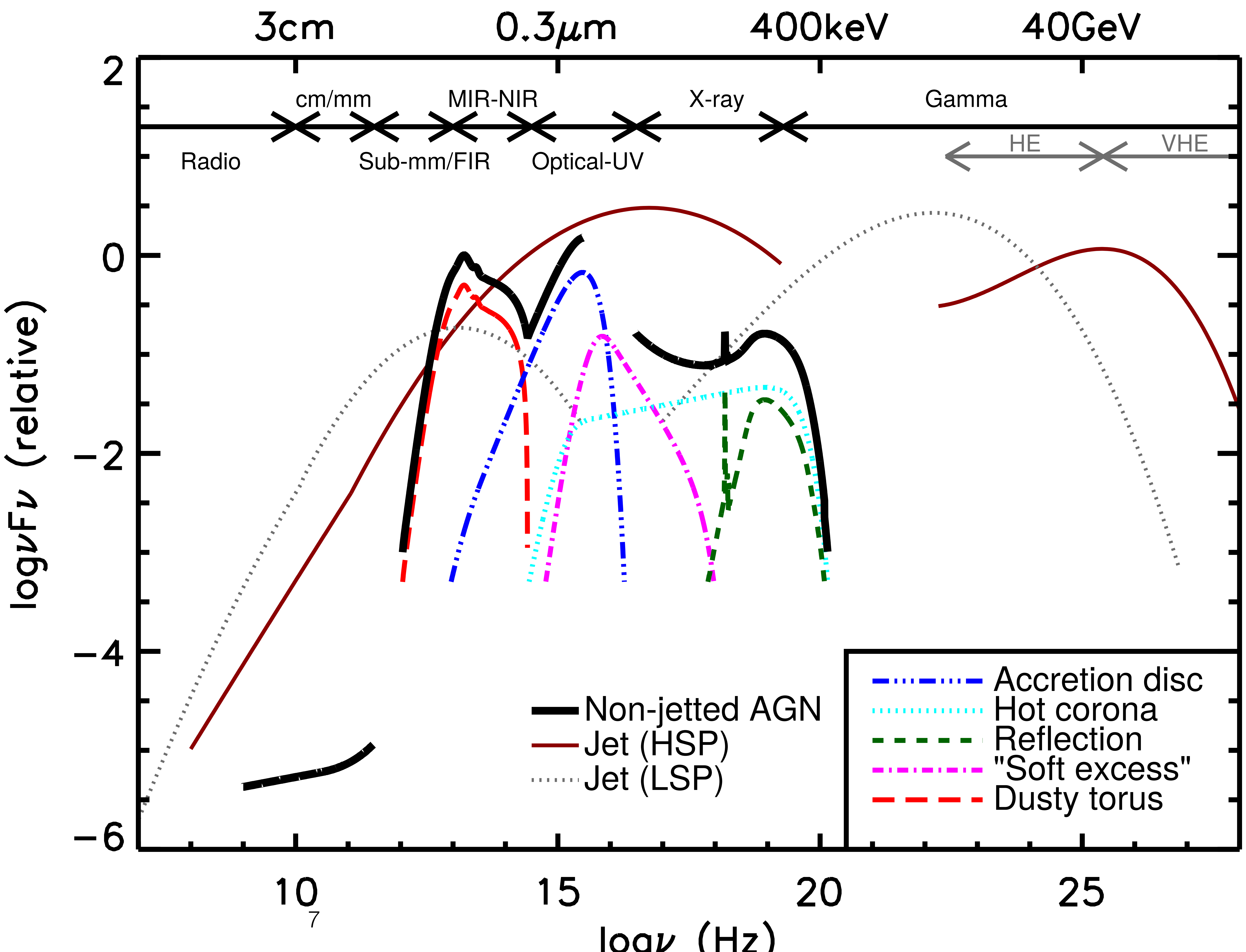






Non-jetted AGN

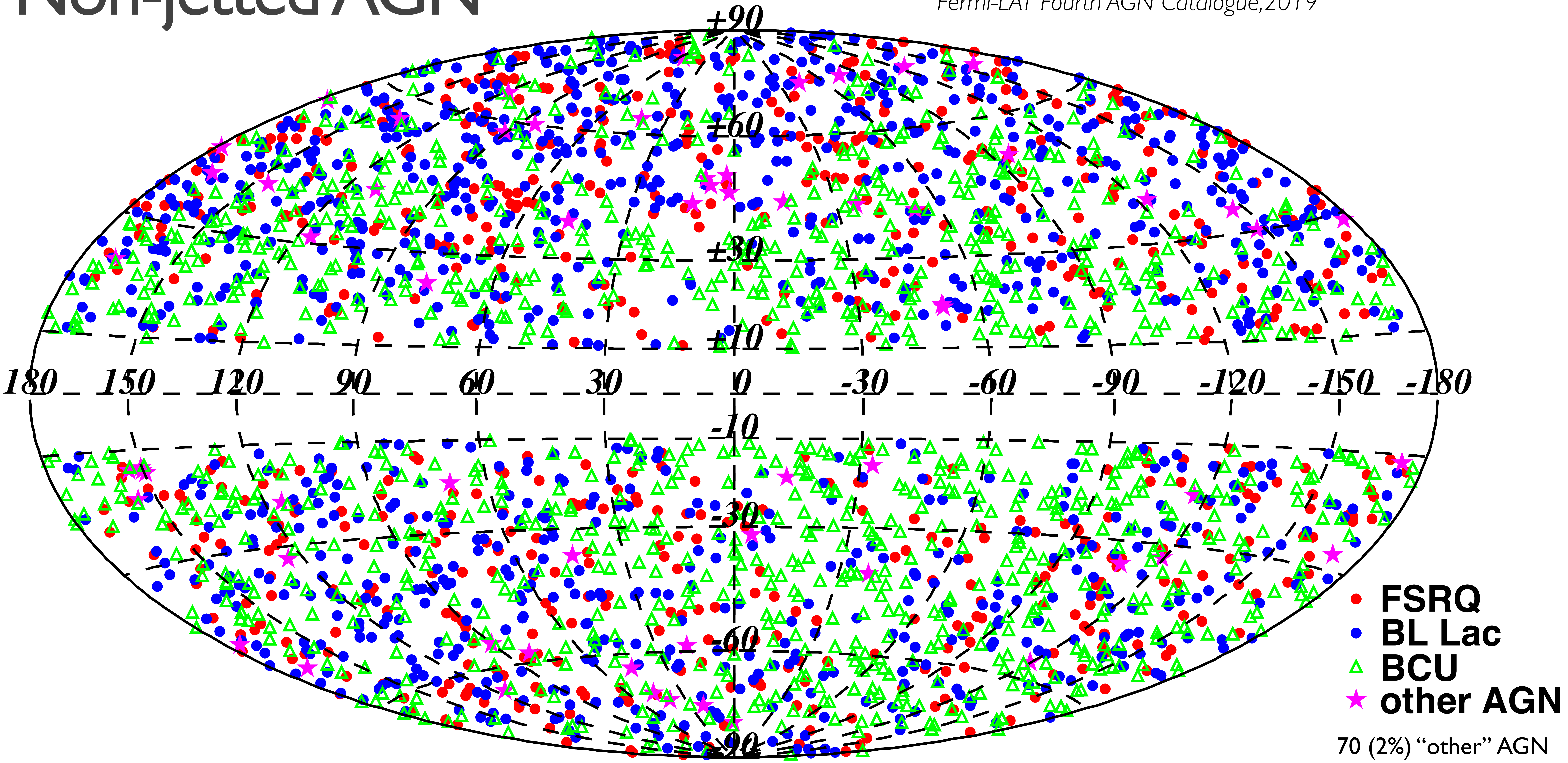




Padovani et al 2017 AGN: What's in a name?

Non-jetted AGN

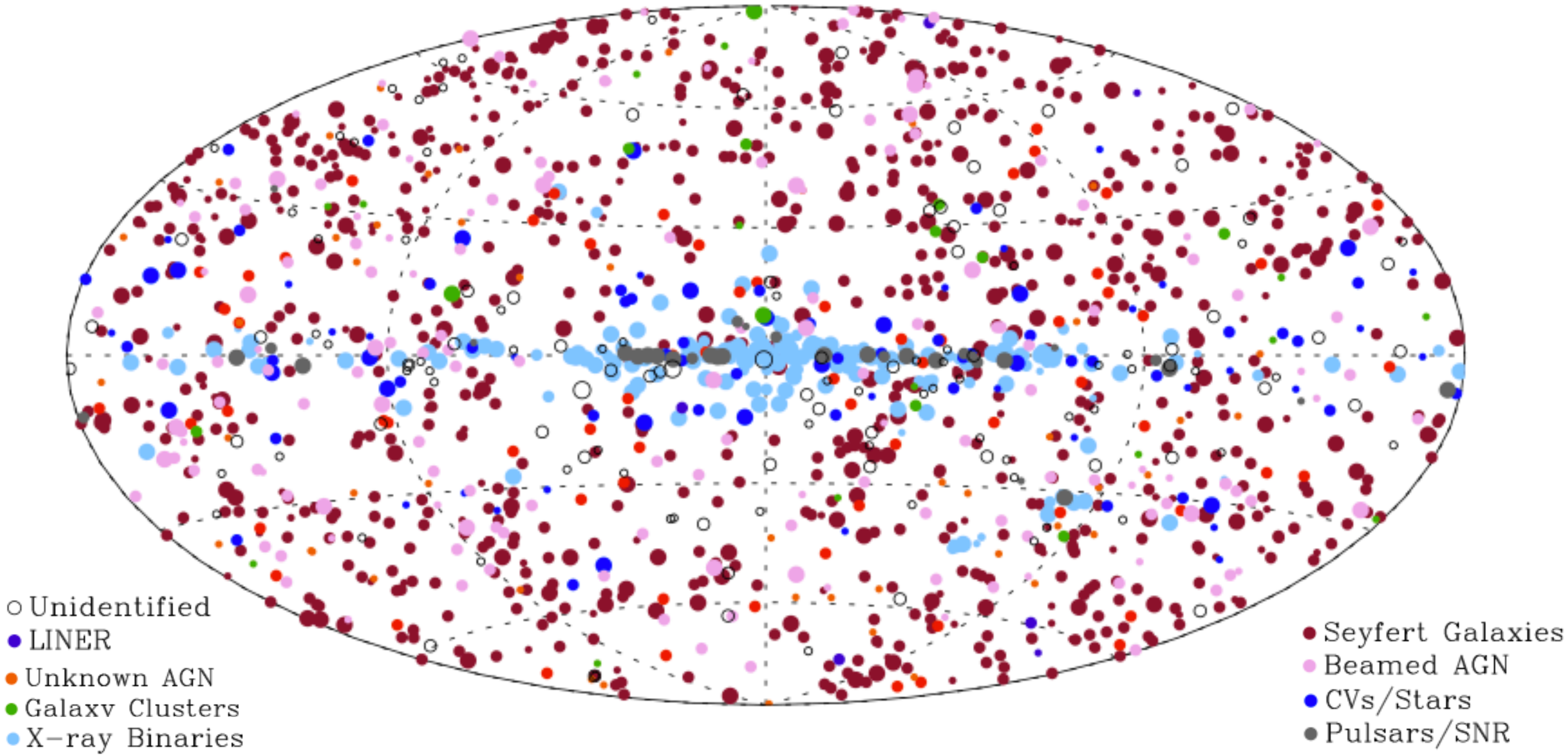
Fermi-LAT Fourth AGN Catalogue,2019



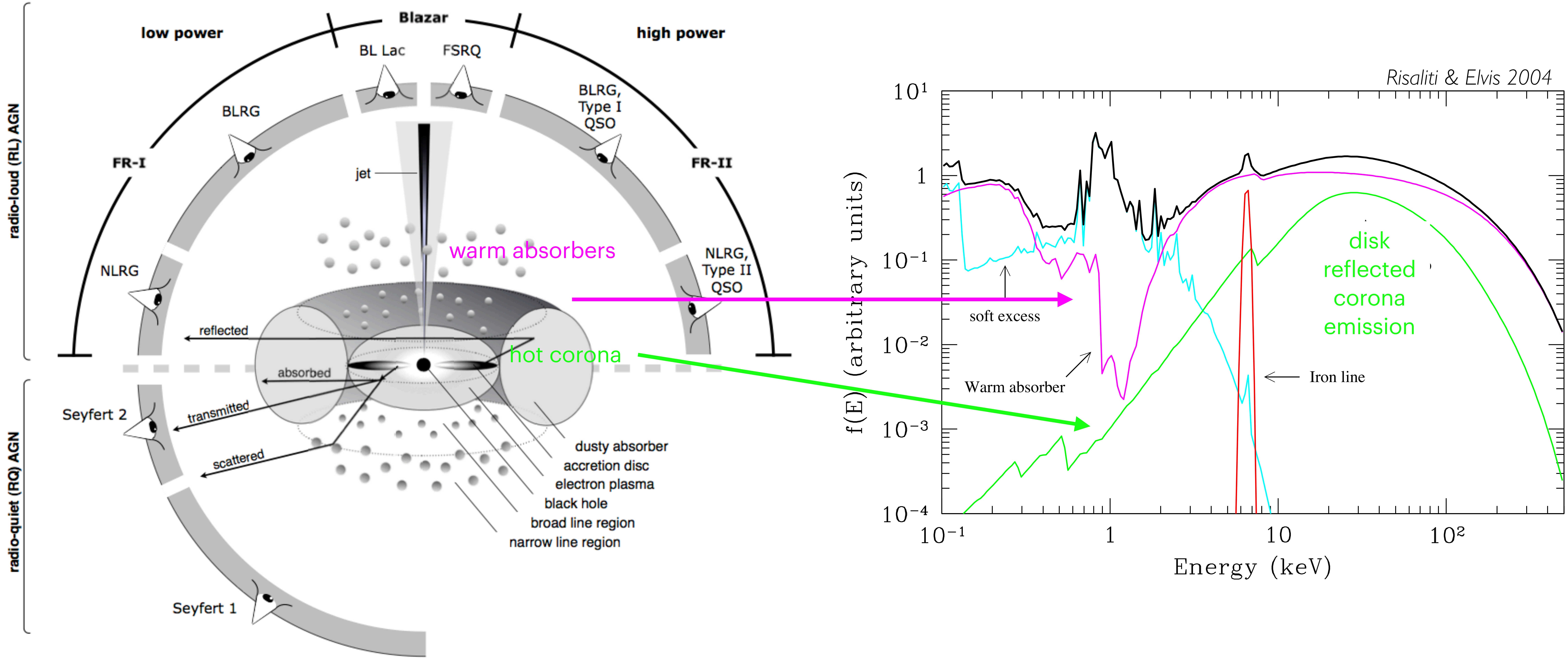
70 (2%) "other" AGN
~10 non-jetted AGN

Non-jetted AGN

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

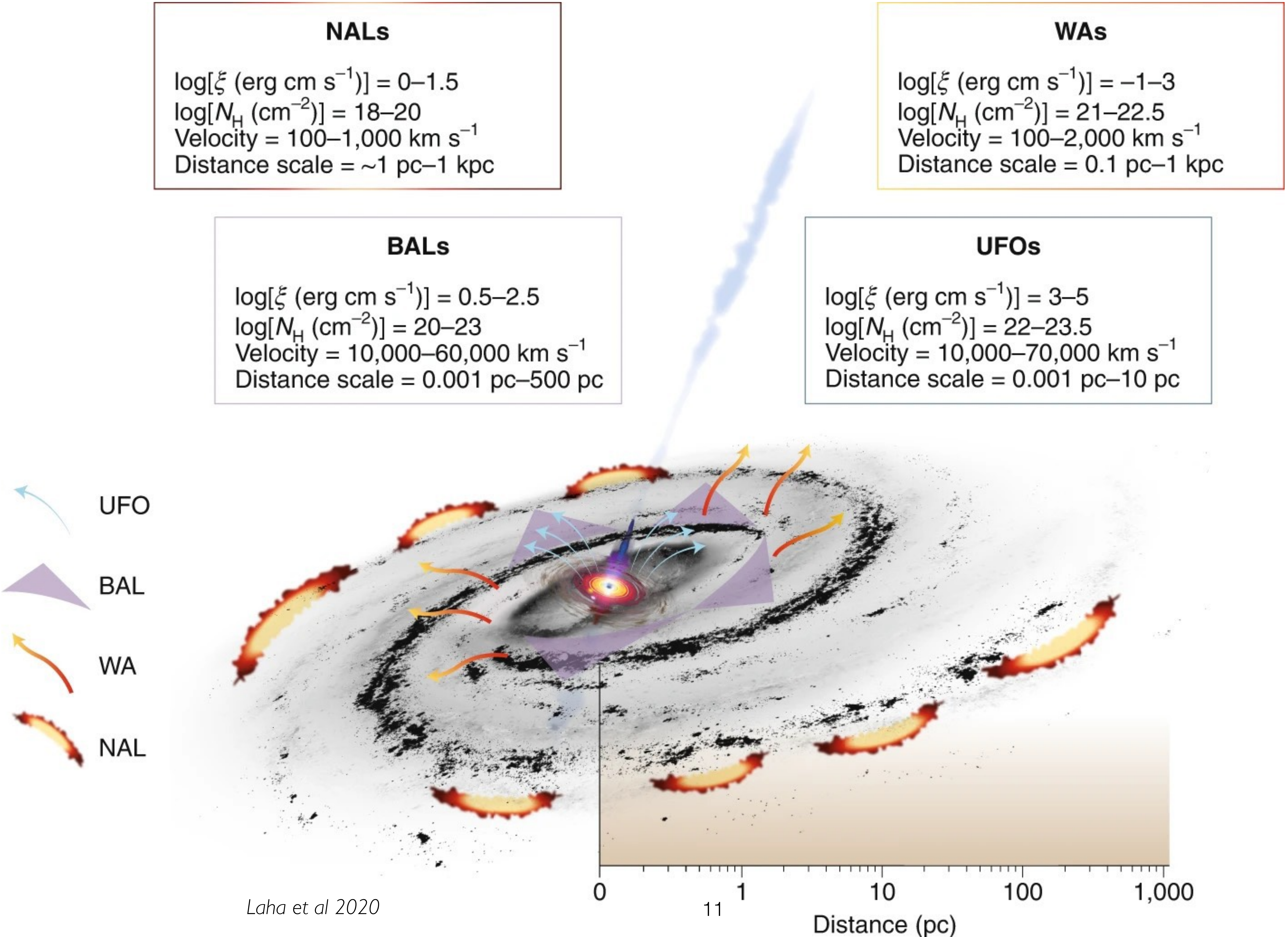


X-ray absorbers in AGN



Risaliti & Elvis 2004

Beckmann & Shrader 2012



NALs

$\log[\xi \text{ (erg cm s}^{-1})] = 0–1.5$
$\log[N_H \text{ (cm}^{-2})] = 18–20$
Velocity = 100–1,000 km s^{-1}
Distance scale = ~1 pc–1 kpc

WAs

$\log[\xi \text{ (erg cm s}^{-1})] = -1–3$
$\log[N_H \text{ (cm}^{-2})] = 21–22.5$
Velocity = 100–2,000 km s^{-1}
Distance scale = 0.1 pc–1 kpc

BALs

$\log[\xi \text{ (erg cm s}^{-1})] = 0.5–2.5$
$\log[N_H \text{ (cm}^{-2})] = 20–23$
Velocity = 10,000–60,000 km s^{-1}
Distance scale = 0.001 pc–500 pc

UFOs

$\log[\xi \text{ (erg cm s}^{-1})] = 3–5$
$\log[N_H \text{ (cm}^{-2})] = 22–23.5$
Velocity = 10,000–70,000 km s^{-1}
Distance scale = 0.001 pc–10 pc

Observed in ~50% of Seyfert I

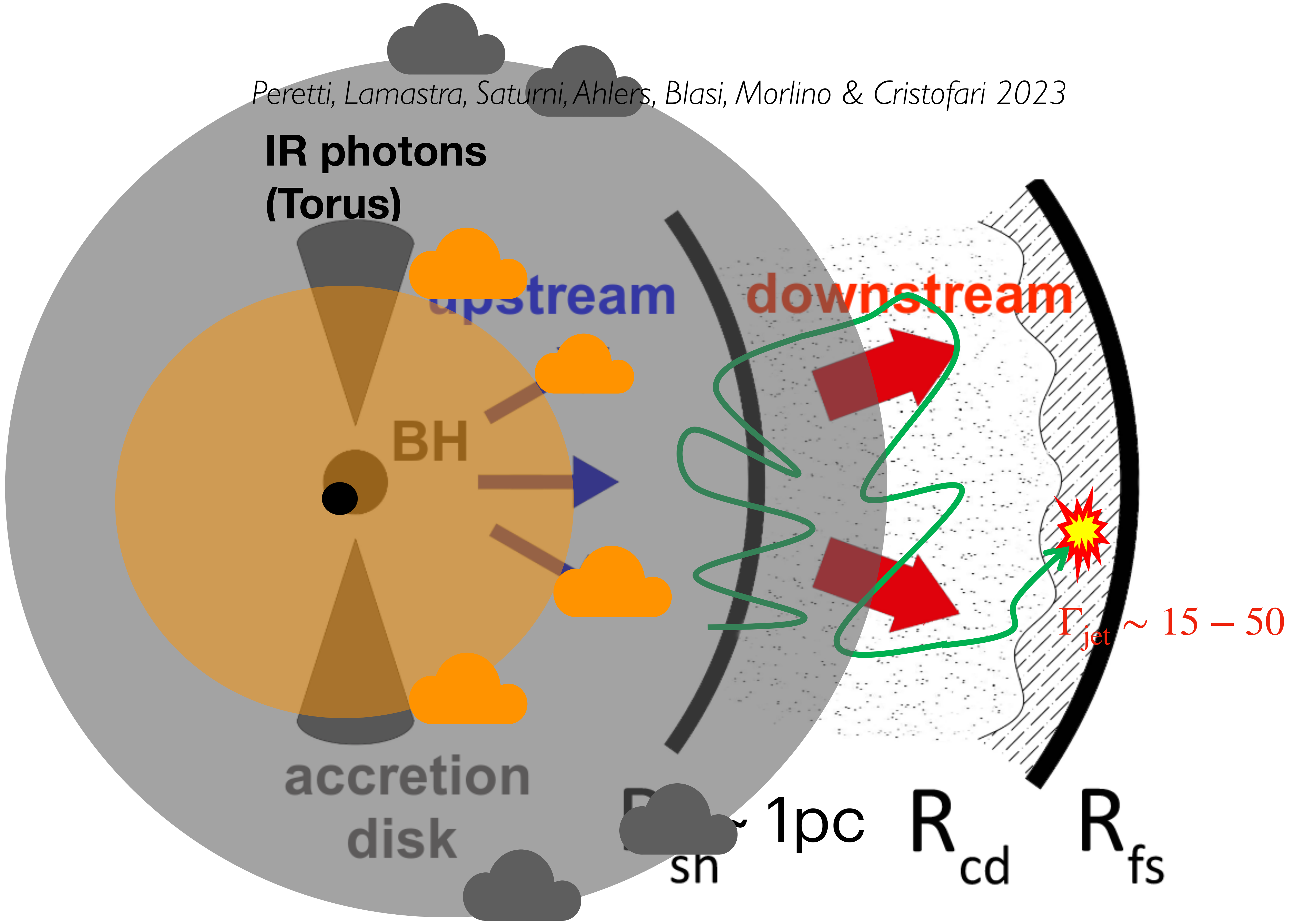
Observed in ~40% of radio loud and radio quiet AGN

v ~ 0.03 - 0.3 c

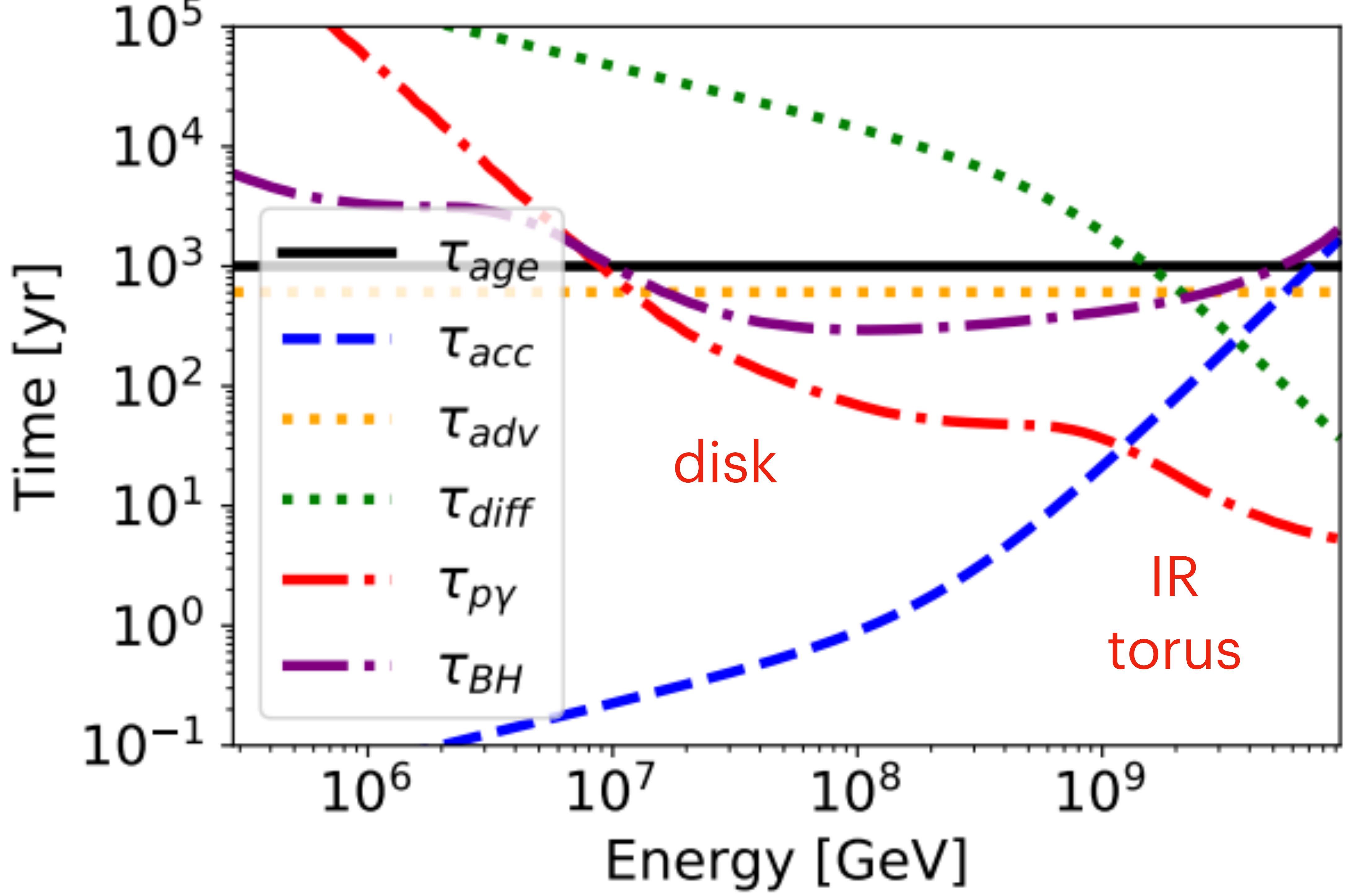
(Tombesi et al 2010,2011, 2012, 2014)

Laha et al 2020

Can UFOs accelerate protons to UHE?


Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023

Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023

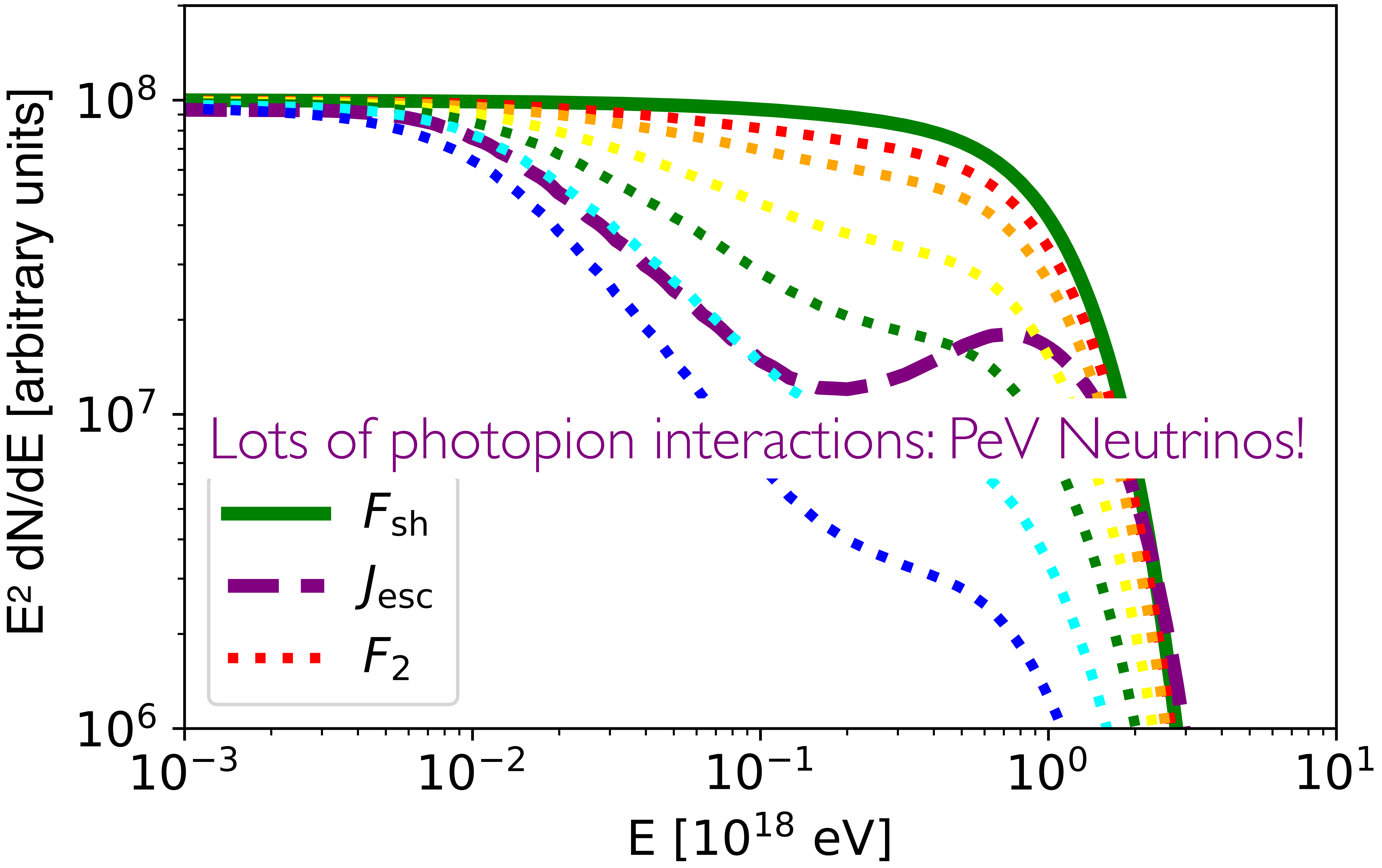


IR torus $L_{\rm IR} \sim 0.5 L_{\rm disk}$

$$R_{\rm IR} \sim 1 \ {\rm pc} \cdot \left(\frac{L_{\rm disk}}{10^{45} \ {\rm erg/s}} \right)^{1/2}$$

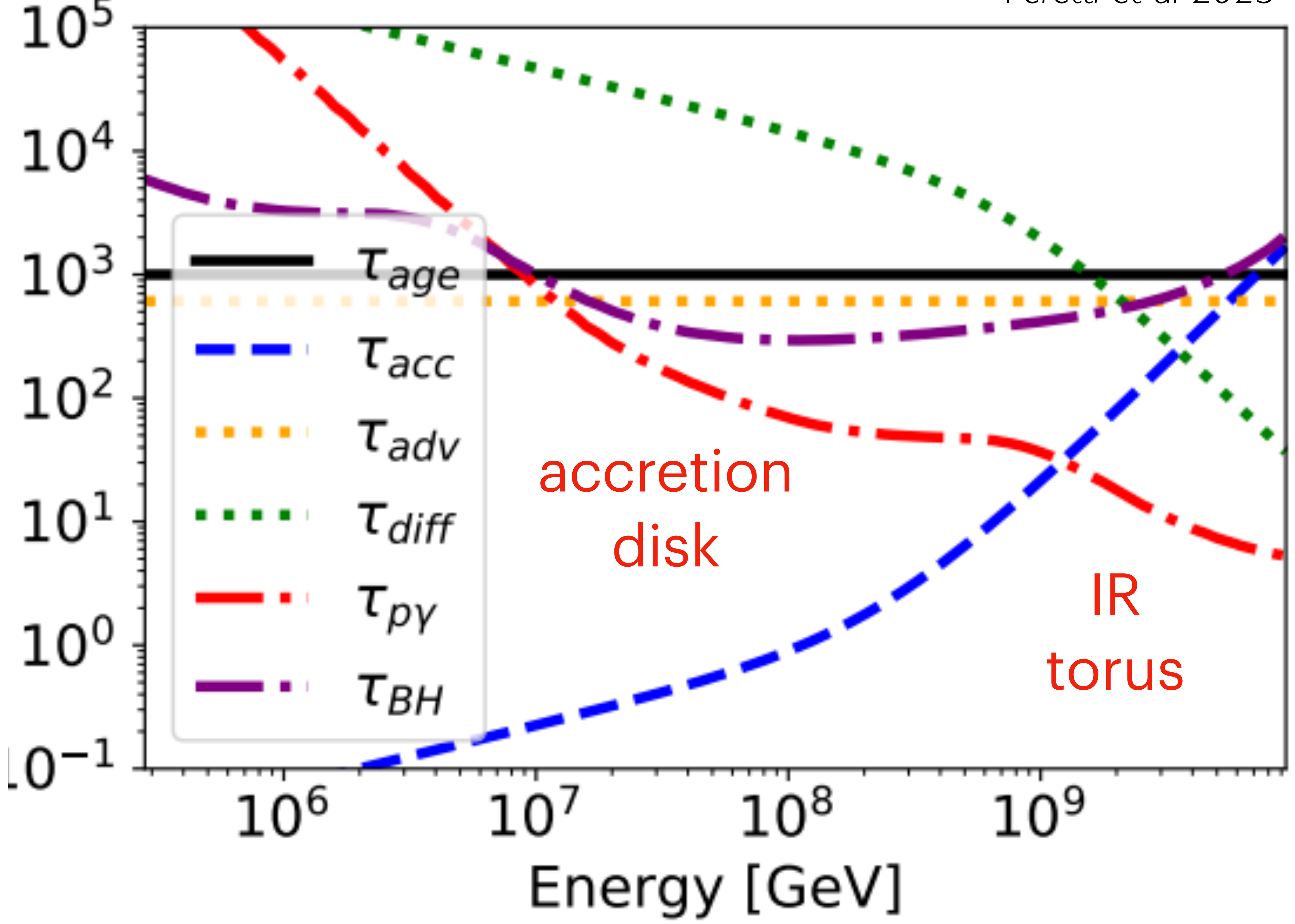
$$E_{p,{\rm max}} \sim 1 \ {\rm EeV} \left(\frac{\epsilon_B}{5 \ \%} \frac{M}{0.1 \ M_\odot \ {\rm yr}^{-1}} \frac{1 \ {\rm pc}}{R_{\rm shock}} \right)^{1/2} \frac{v_{\rm UFO}}{0.2c}$$

Can UFOs accelerate protons to UHE?



Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023

Lots of photopion interactions: PeV Neutrinos!



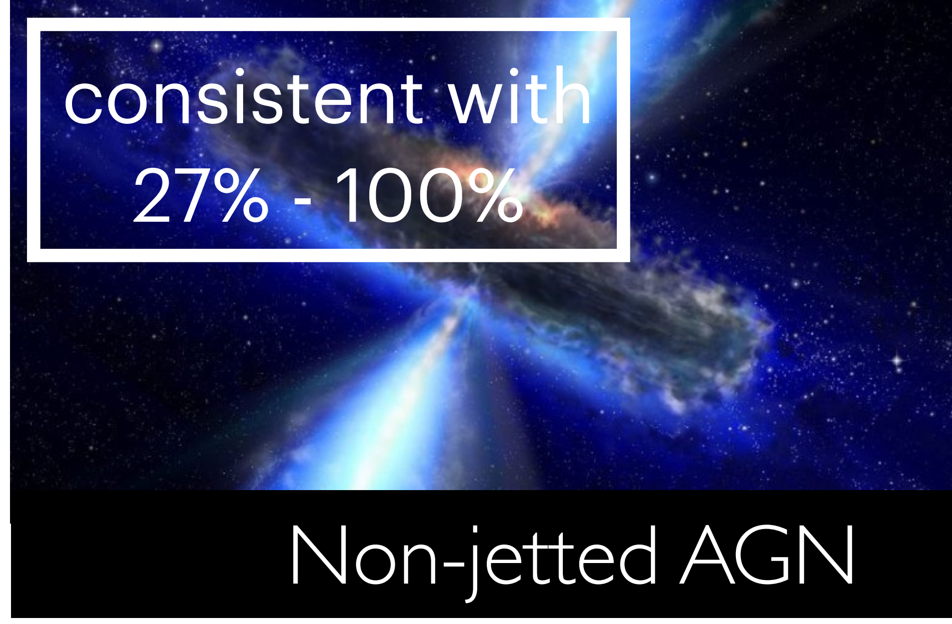
Peretti et al 2023

accretion disk

IR torus

$$E_{p,\max} \sim 1\ \mathrm{EeV} \left(\frac{\epsilon_B}{5\ \%} \frac{M}{0.1\ M_\odot\ \mathrm{yr}^{-1}} \frac{1\ \mathrm{pc}}{R_{\mathrm{shock}}} \right)^{1/2} \frac{v_{\mathrm{UFO}}}{0.2c}$$

Non-jetted AGN contribution to the cosmic-neutrino flux



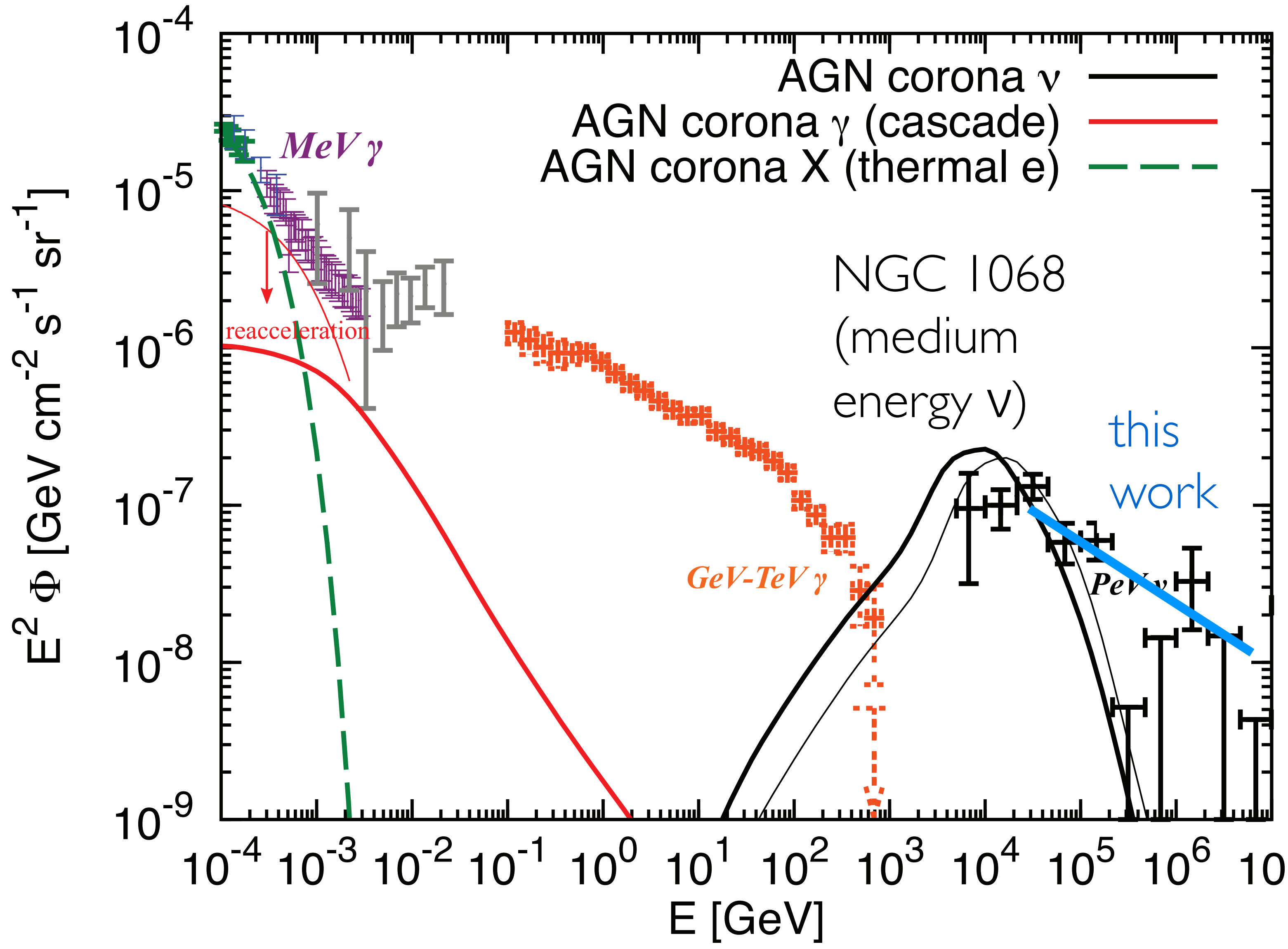
consistent with 27% - 100%

Non-jetted AGN

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

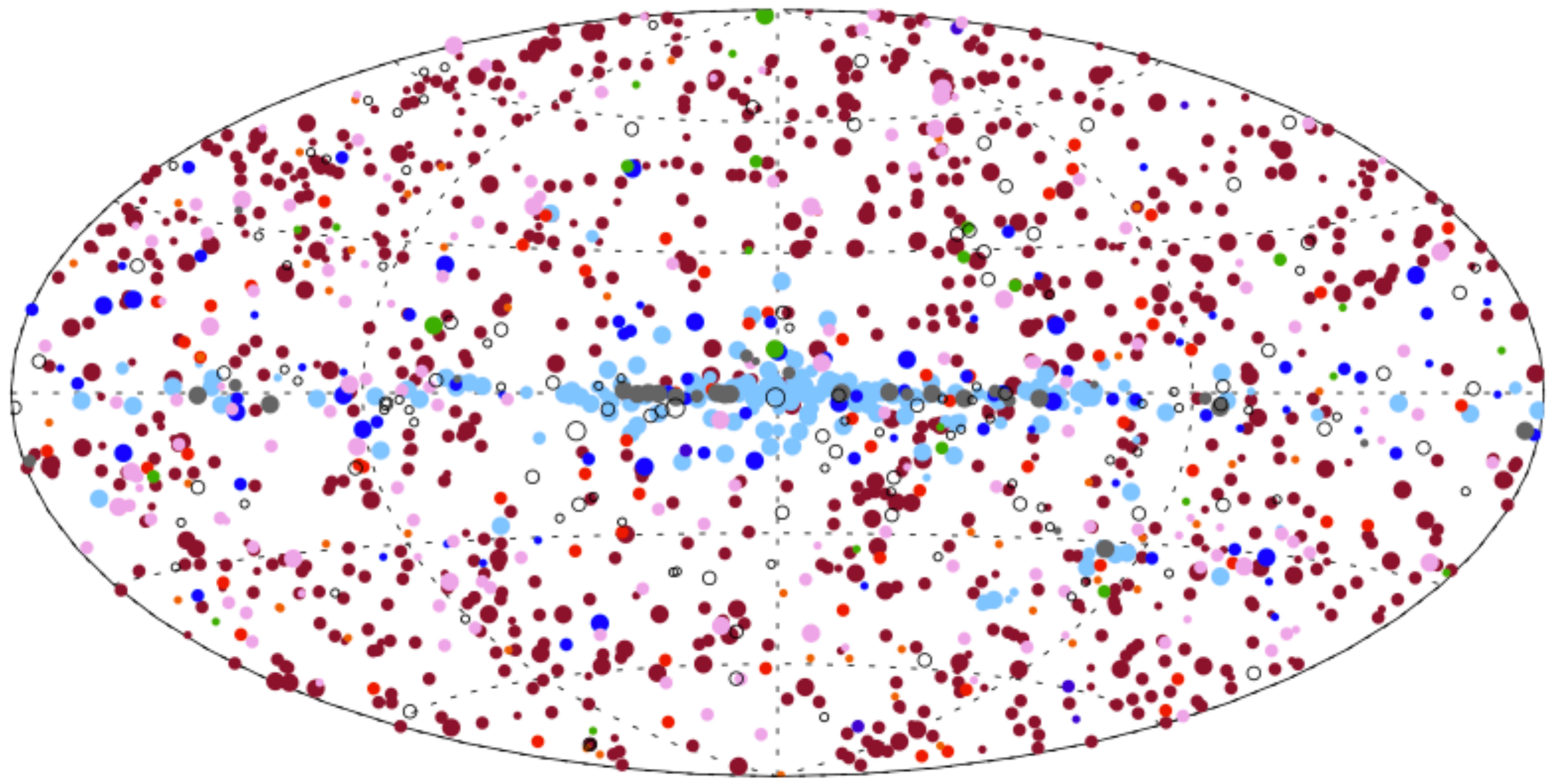
2.6σ excess w.r.t. background expectations

Best-fit spectral index $\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-2}$

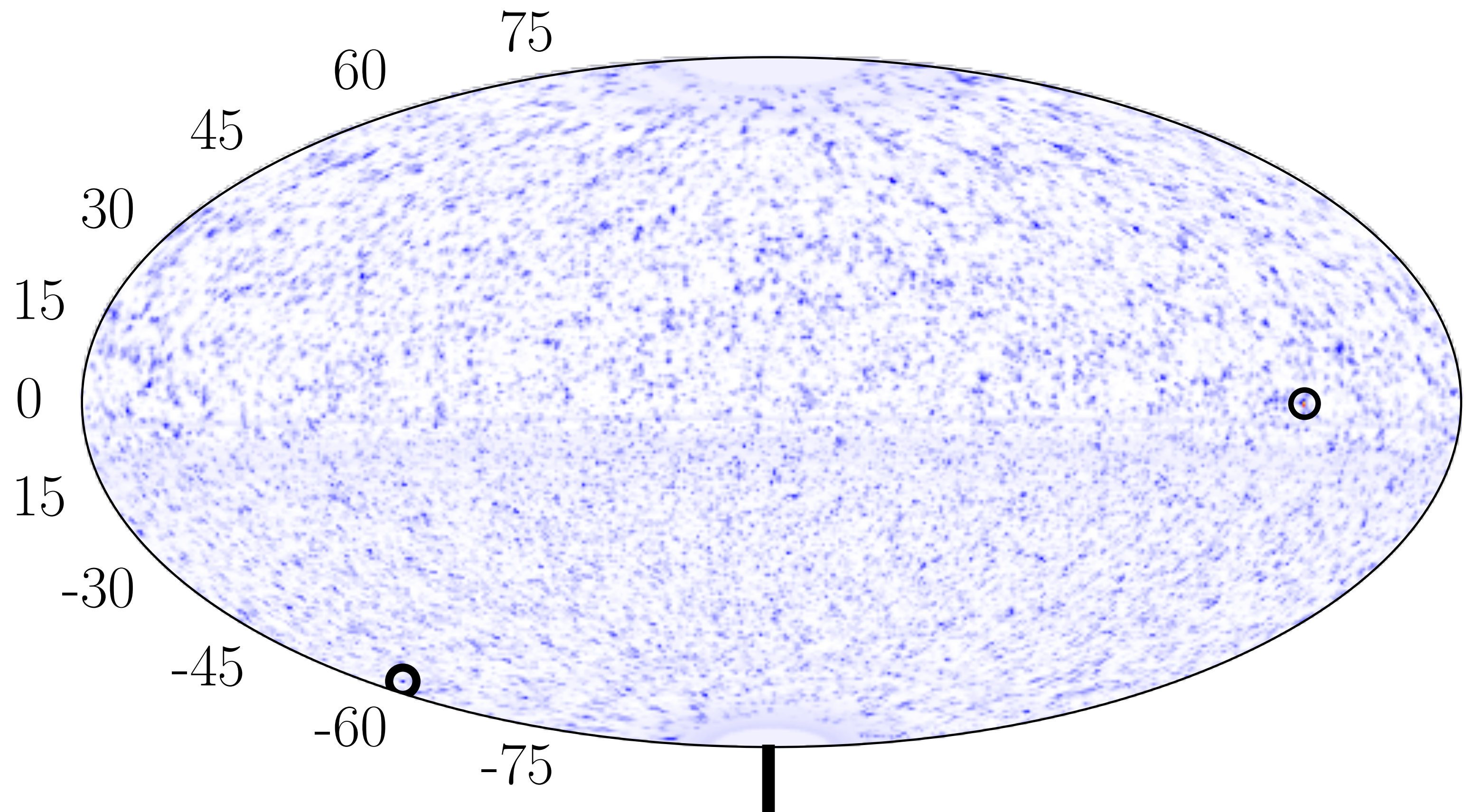


NB: Different energy range than NGC 1068

AGN sky-map



IceCube Point-Source Events

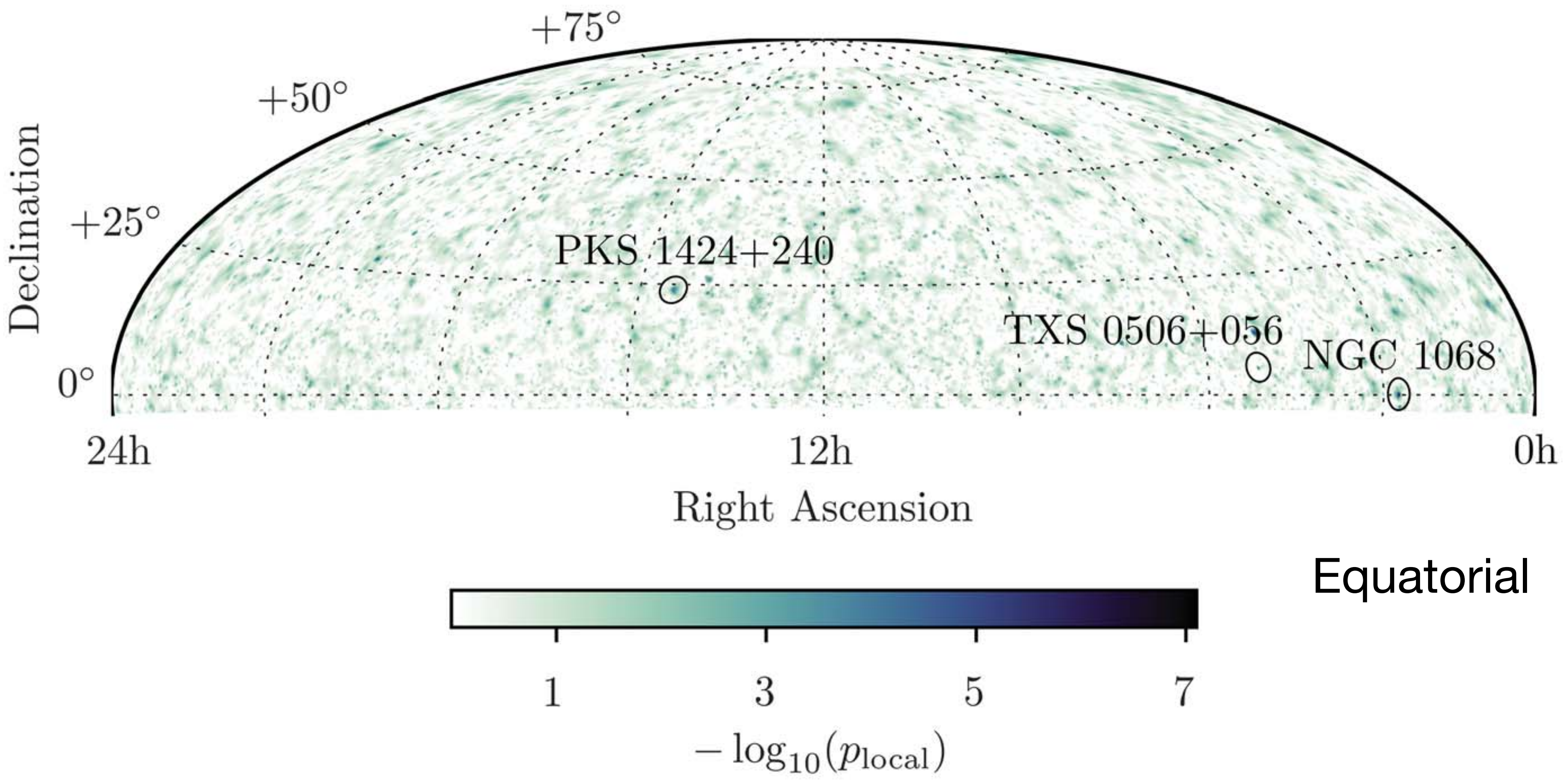


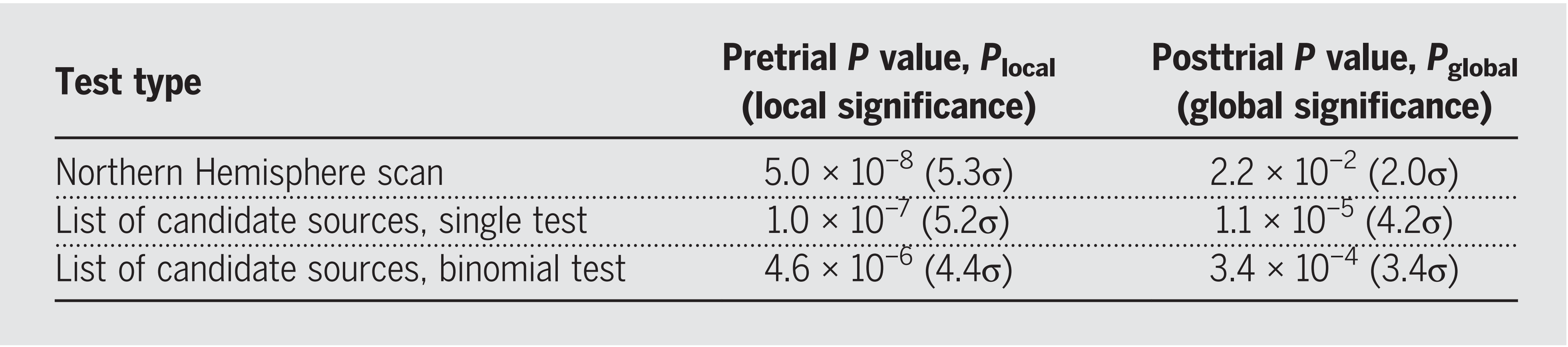
could account for 27-100% of diffuse neutrino flux at 100 TeV

IceCube Coll 2022, PRD

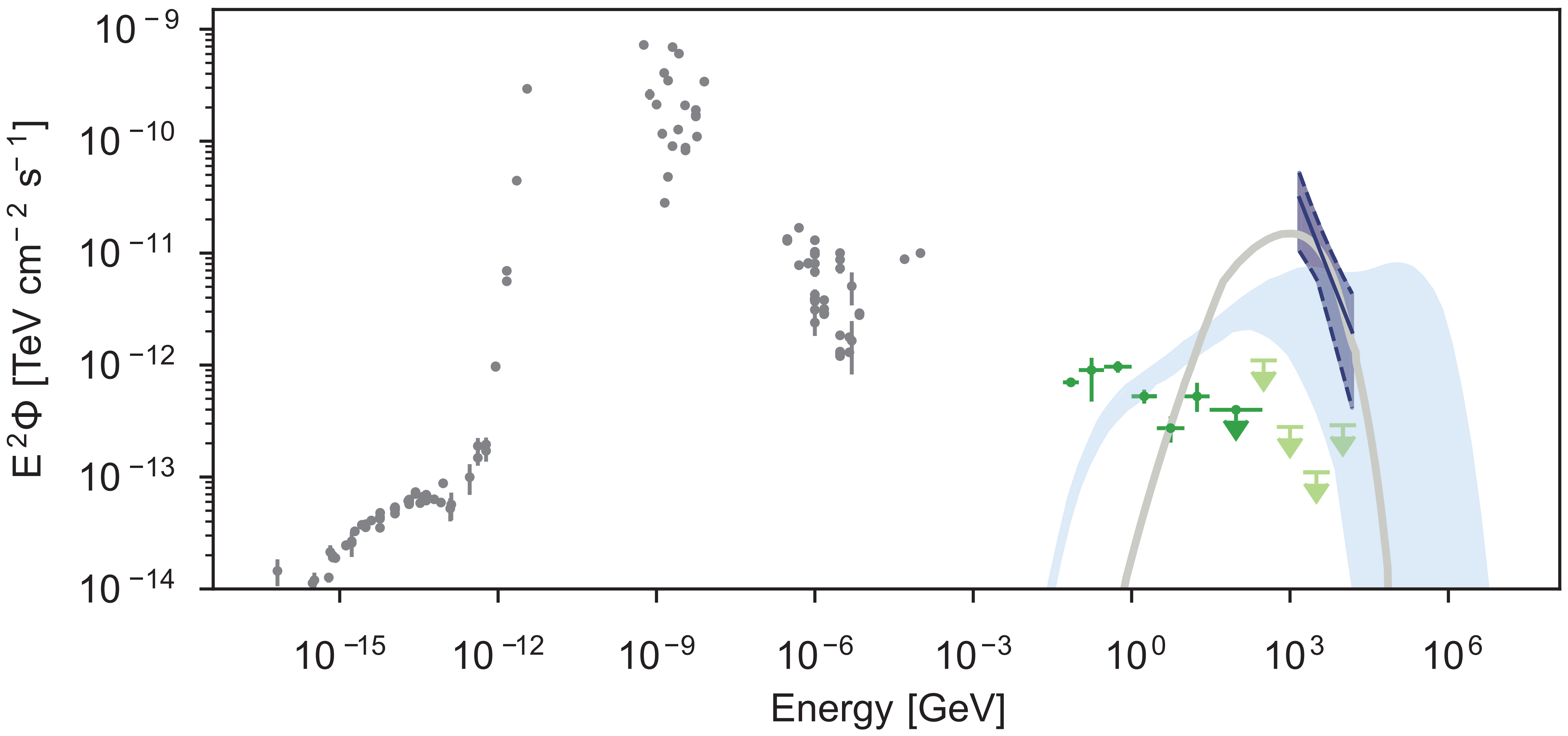
NGC 1068

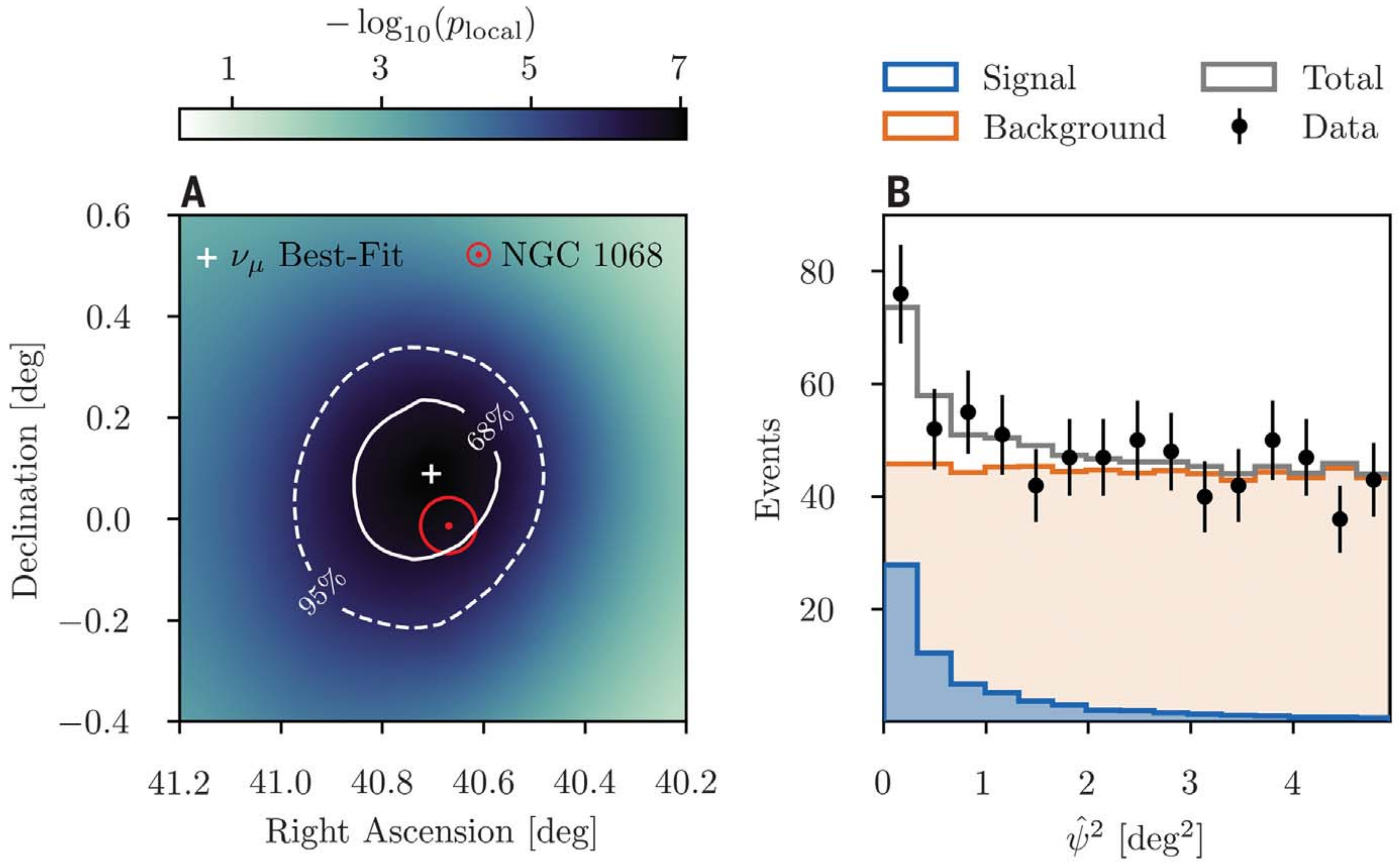
Icecube Coll 2023 - Science





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)

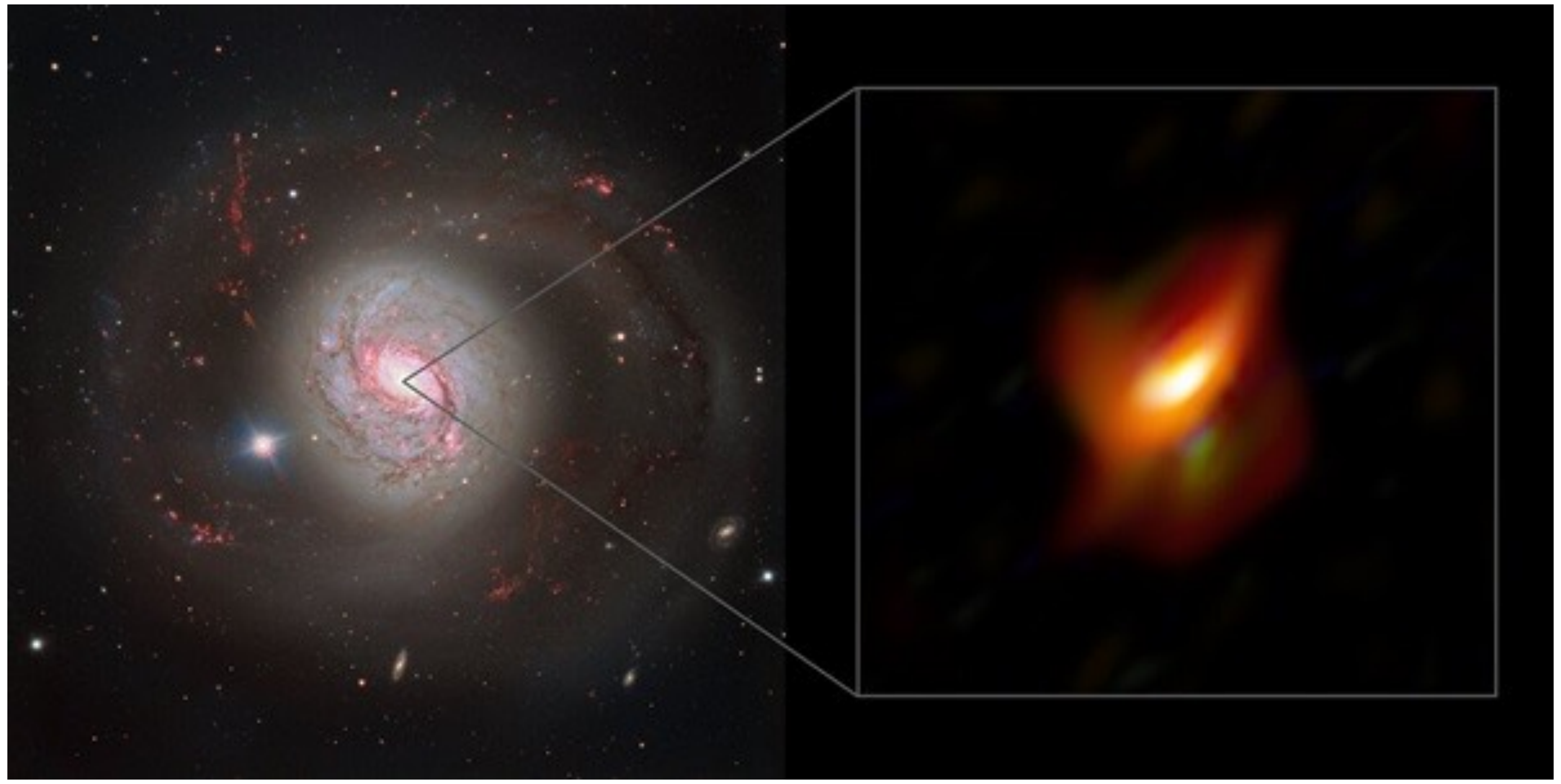


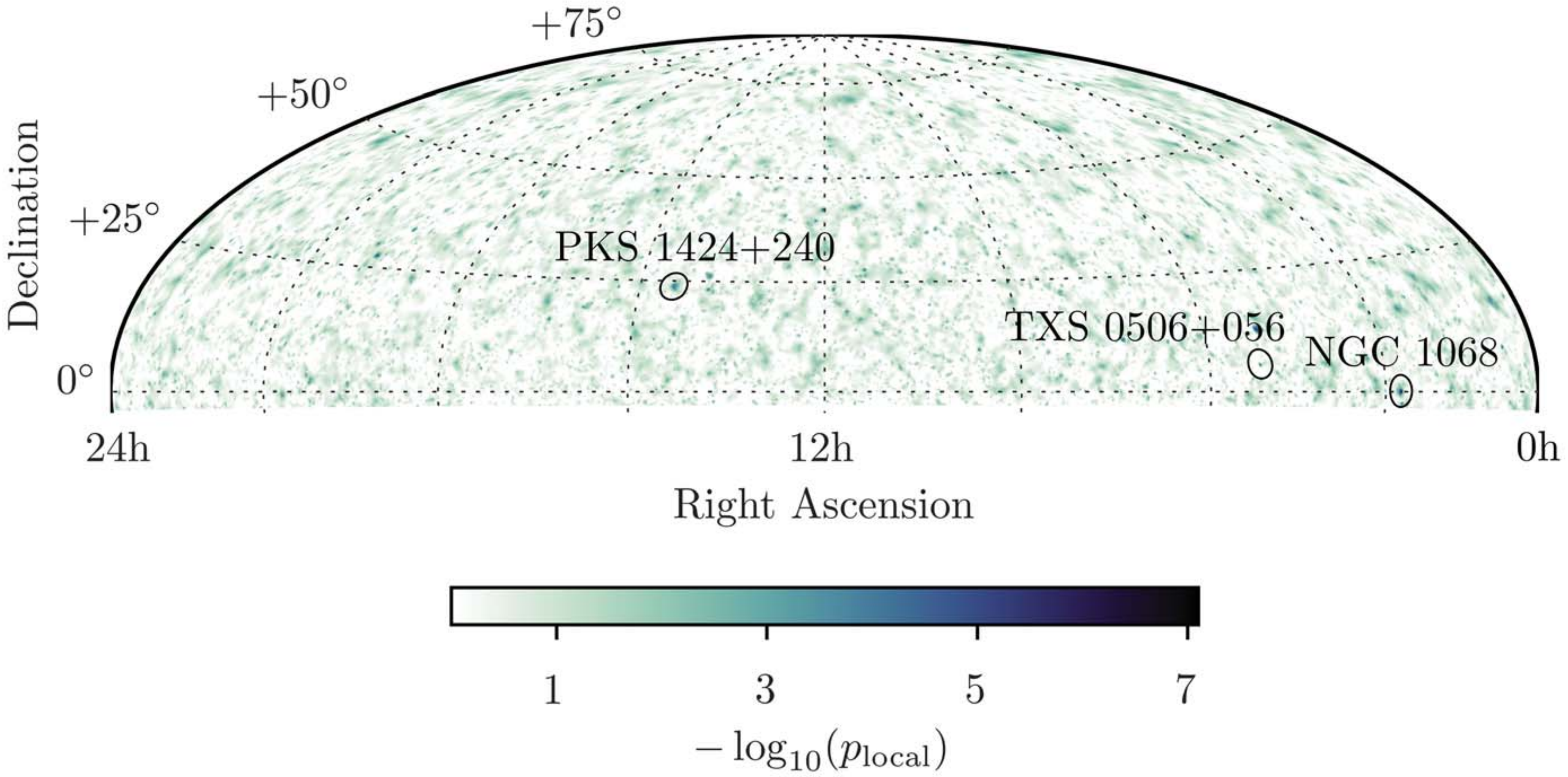


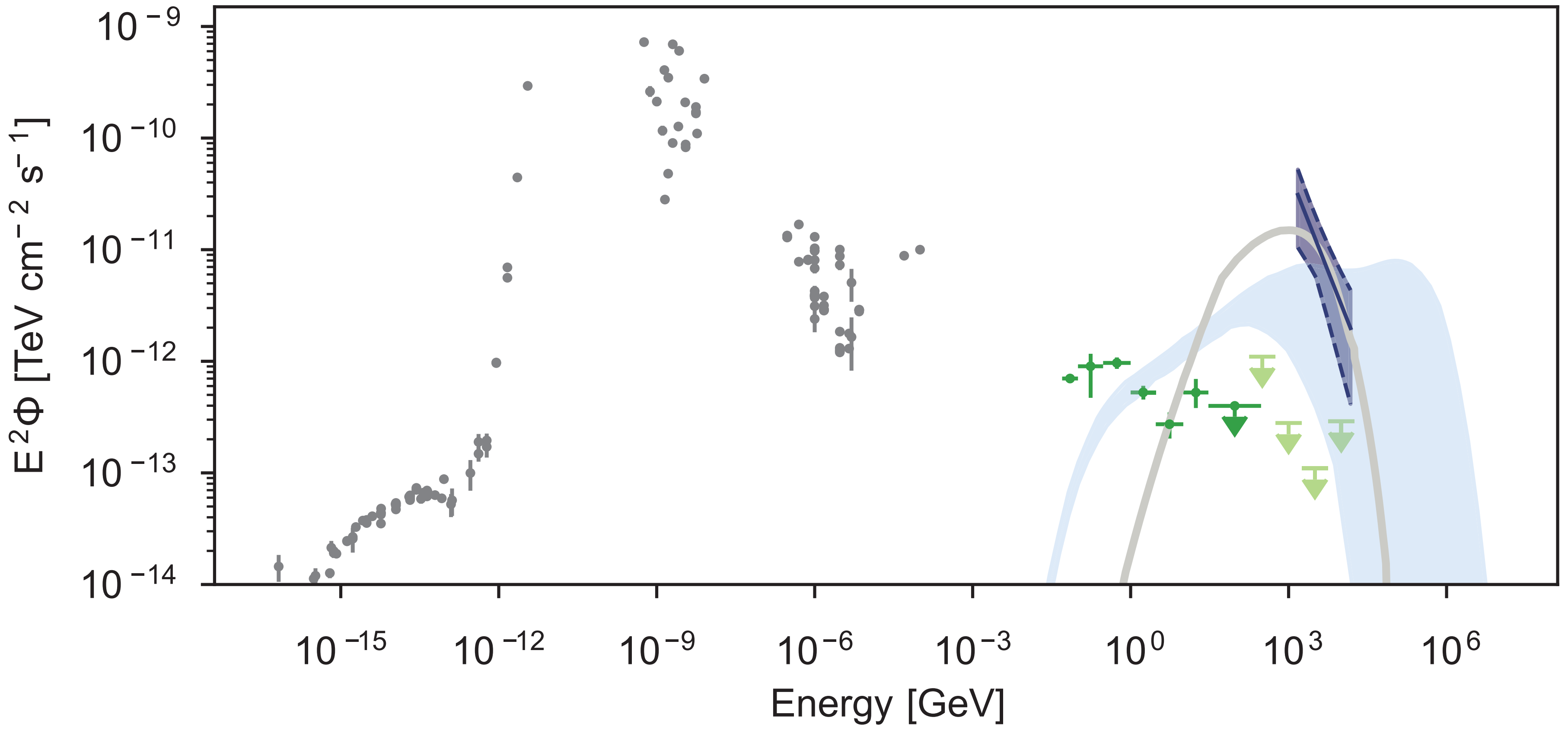
NGC 4151, CGCG 420-015 ~ 3σ

NGC 1068

Icecube Coll 2023 - Science







Seyfert 2 galaxy with heavily obscured nucleus

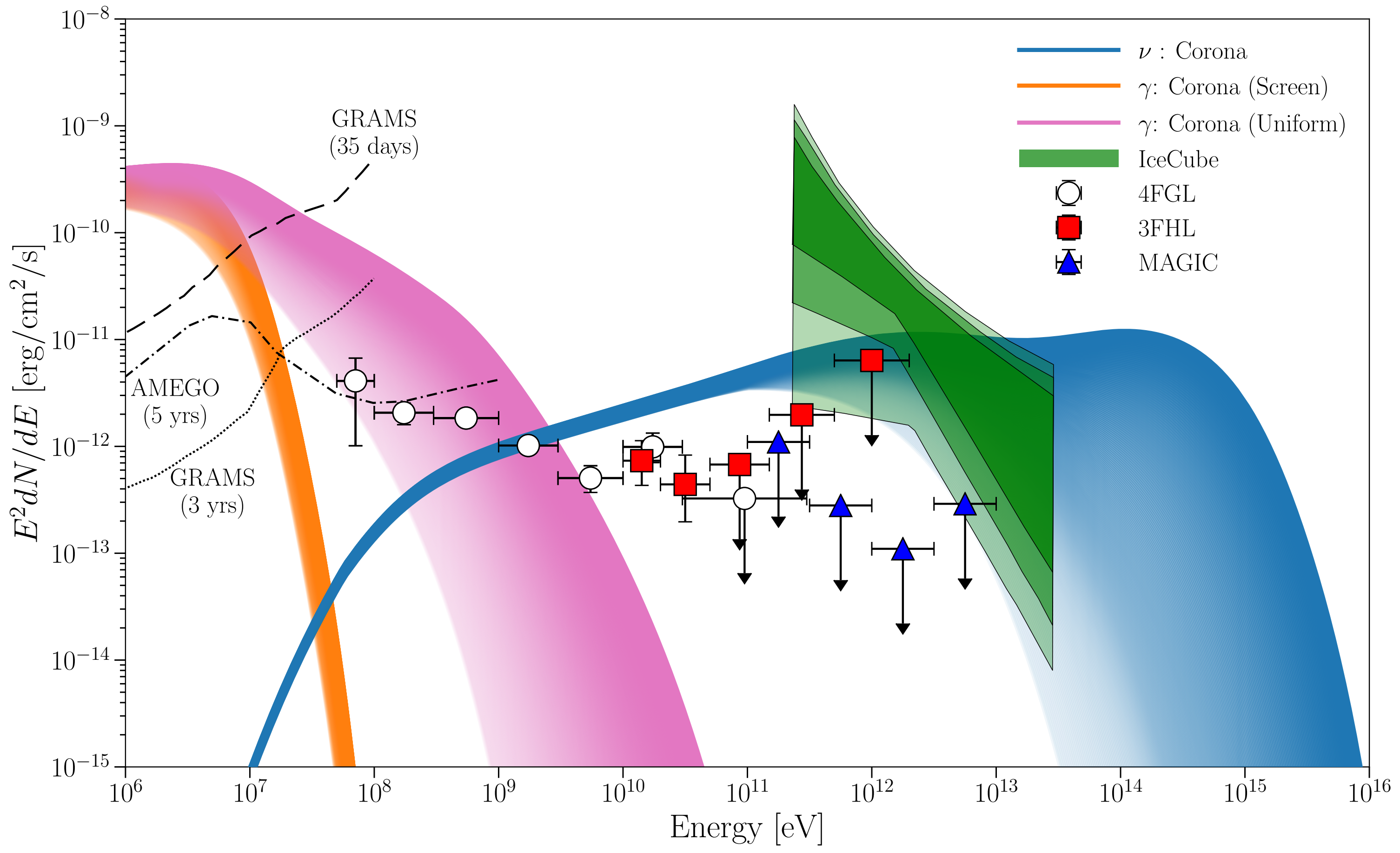
Prototypical nearby Seyfert 2 (14.4 Mpc)

High infrared luminosity: high-level of star formation

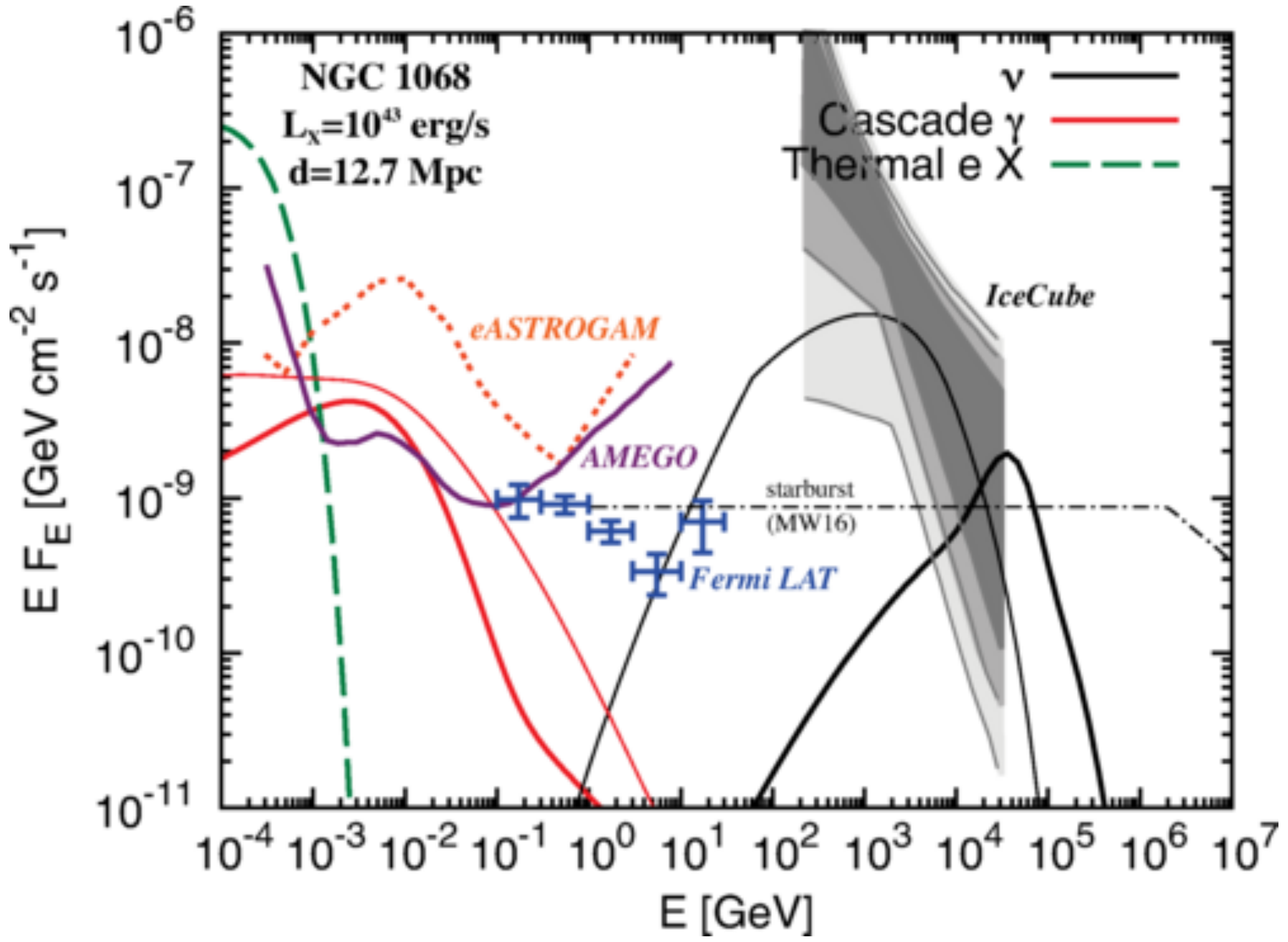
Neutrino production in NGC 1068

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

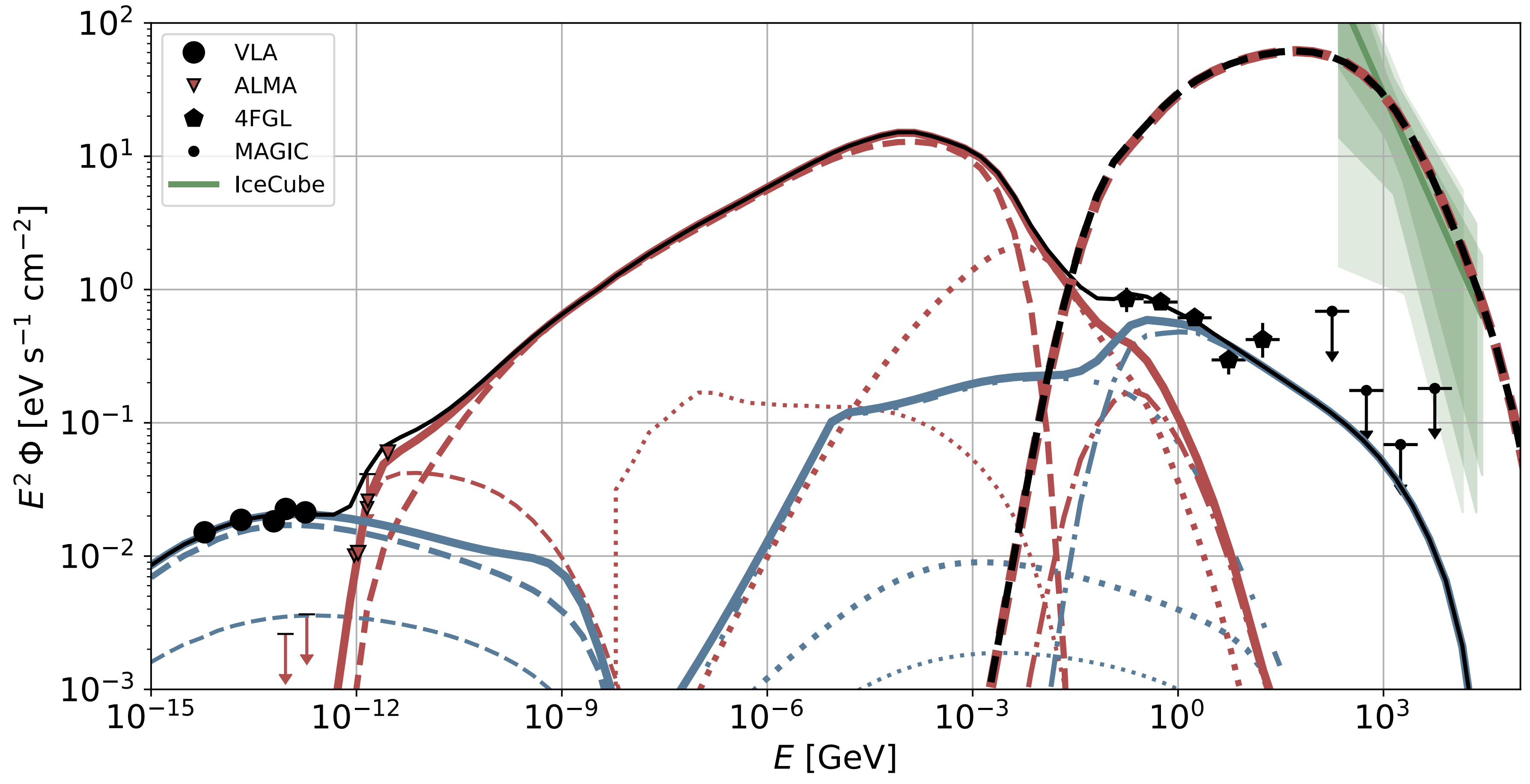
Y. Inoue et al 2019

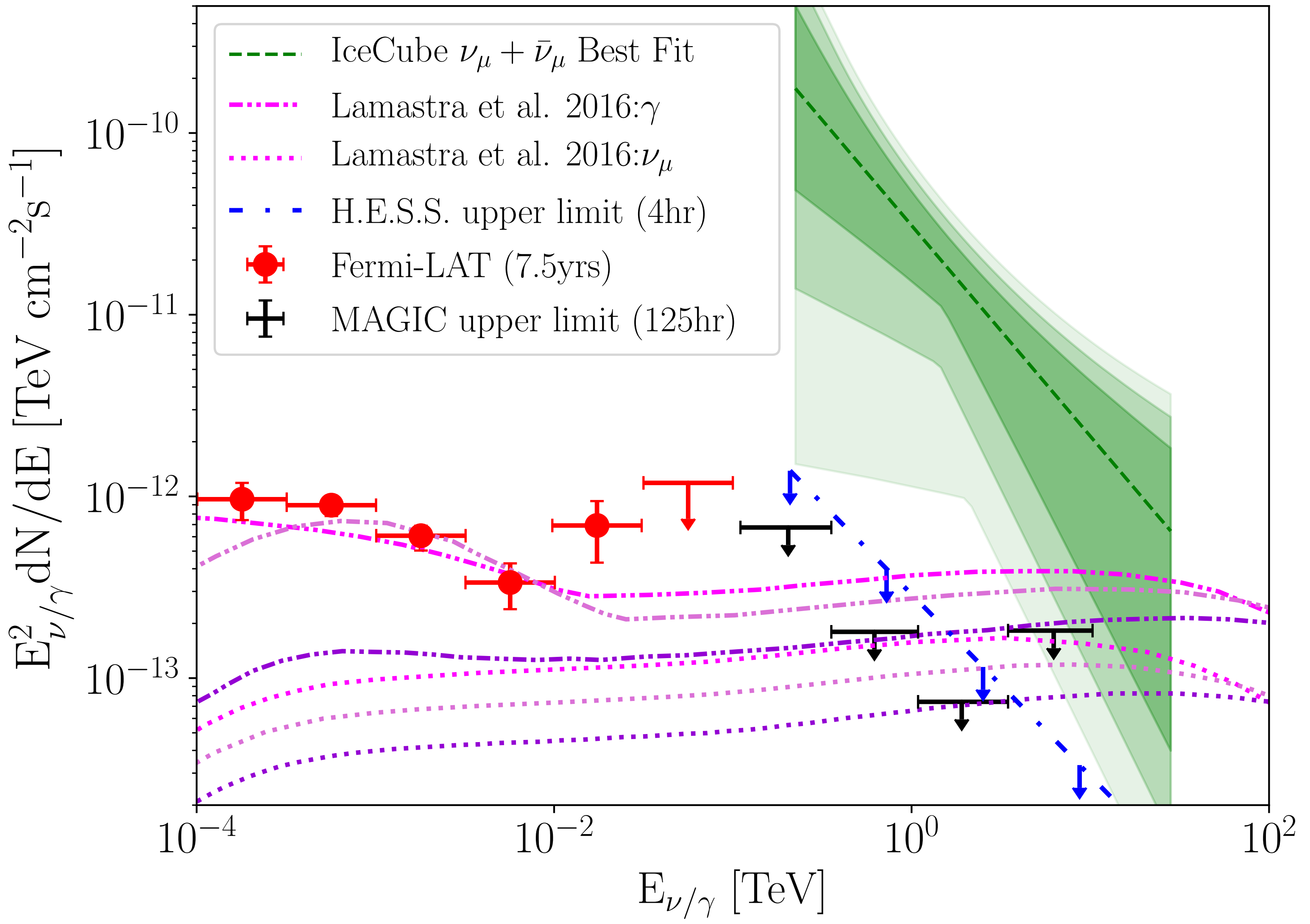


Murase et al 2020

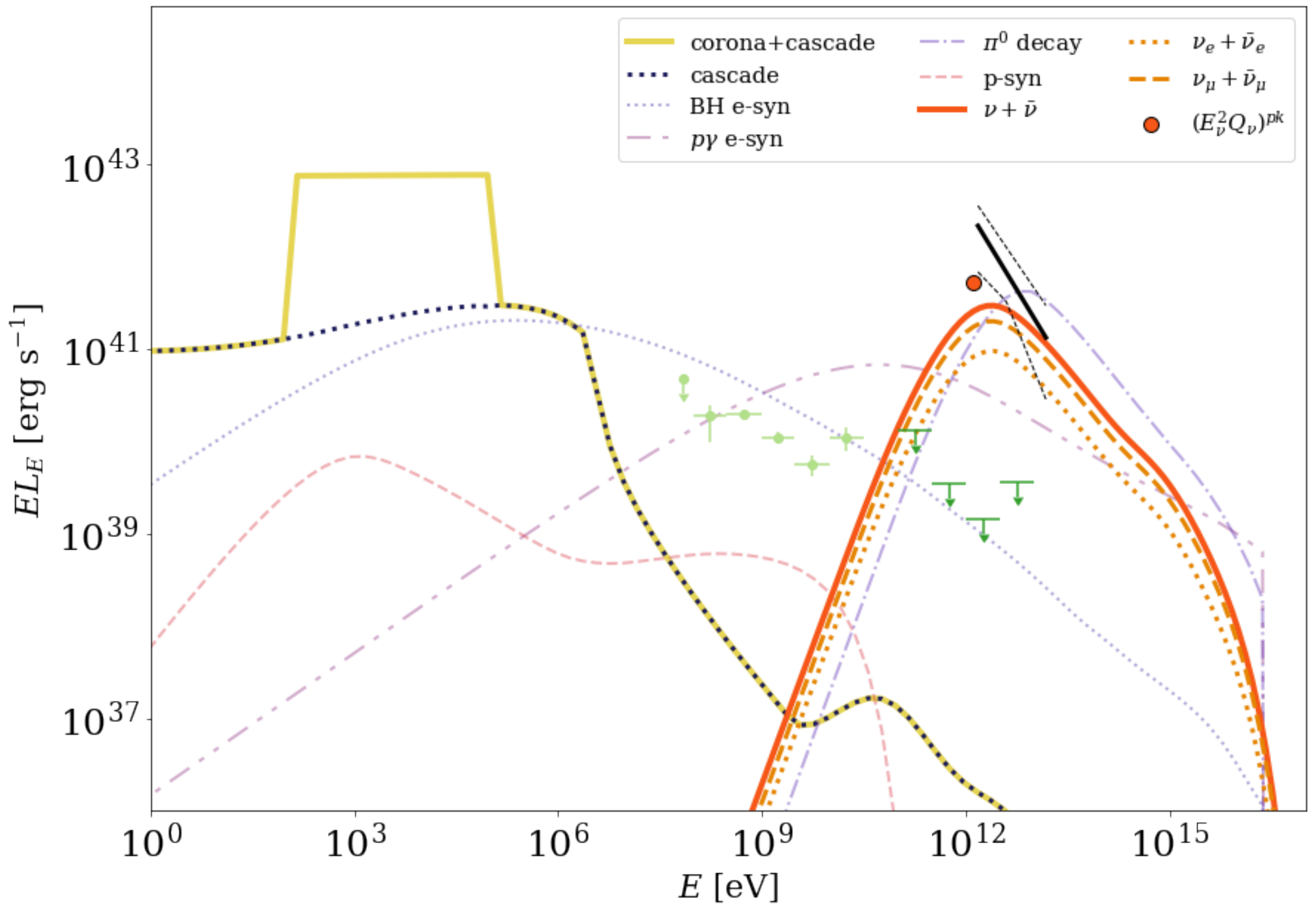


Eichmann, FO et al 2022

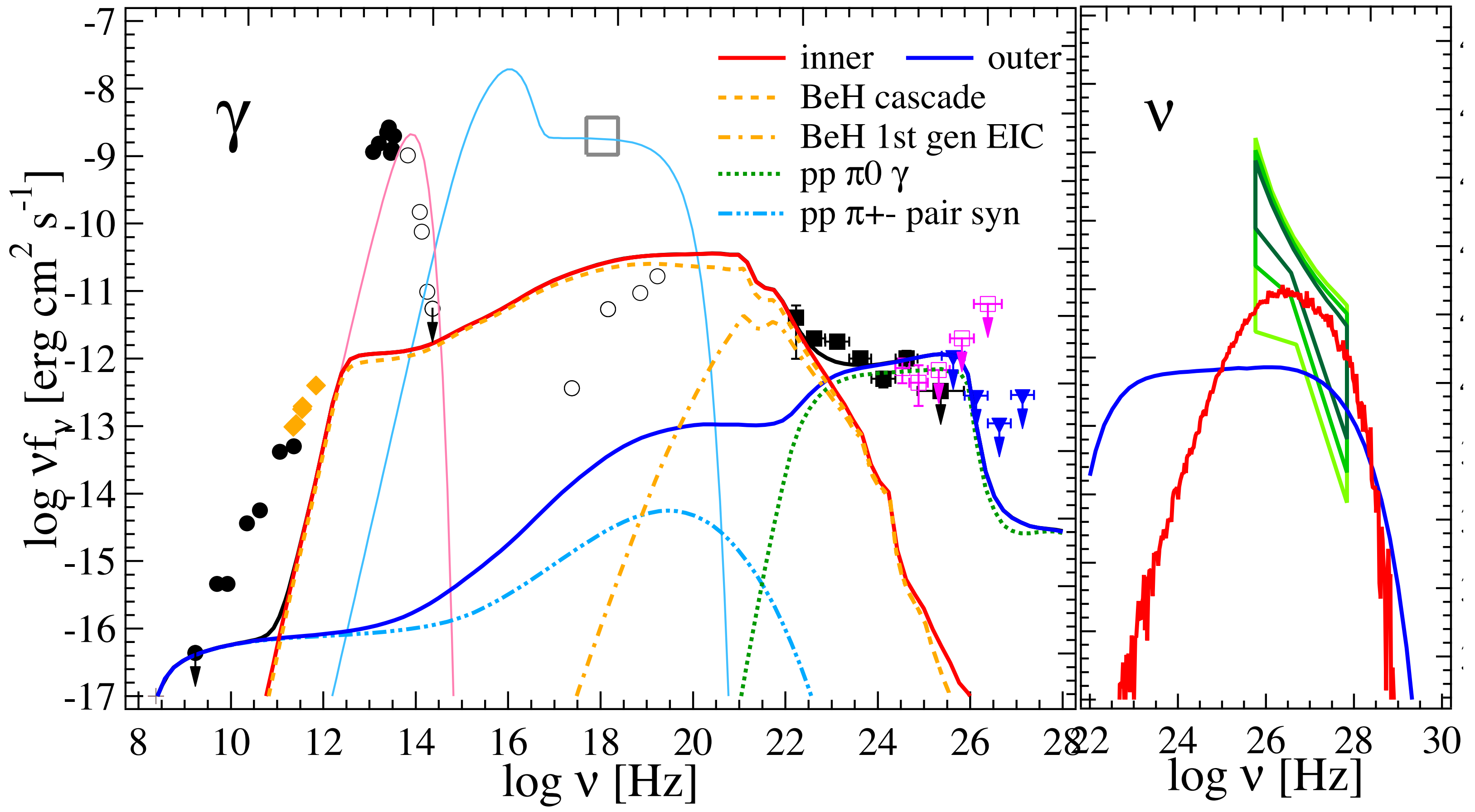




Lamastra 2016, 2019



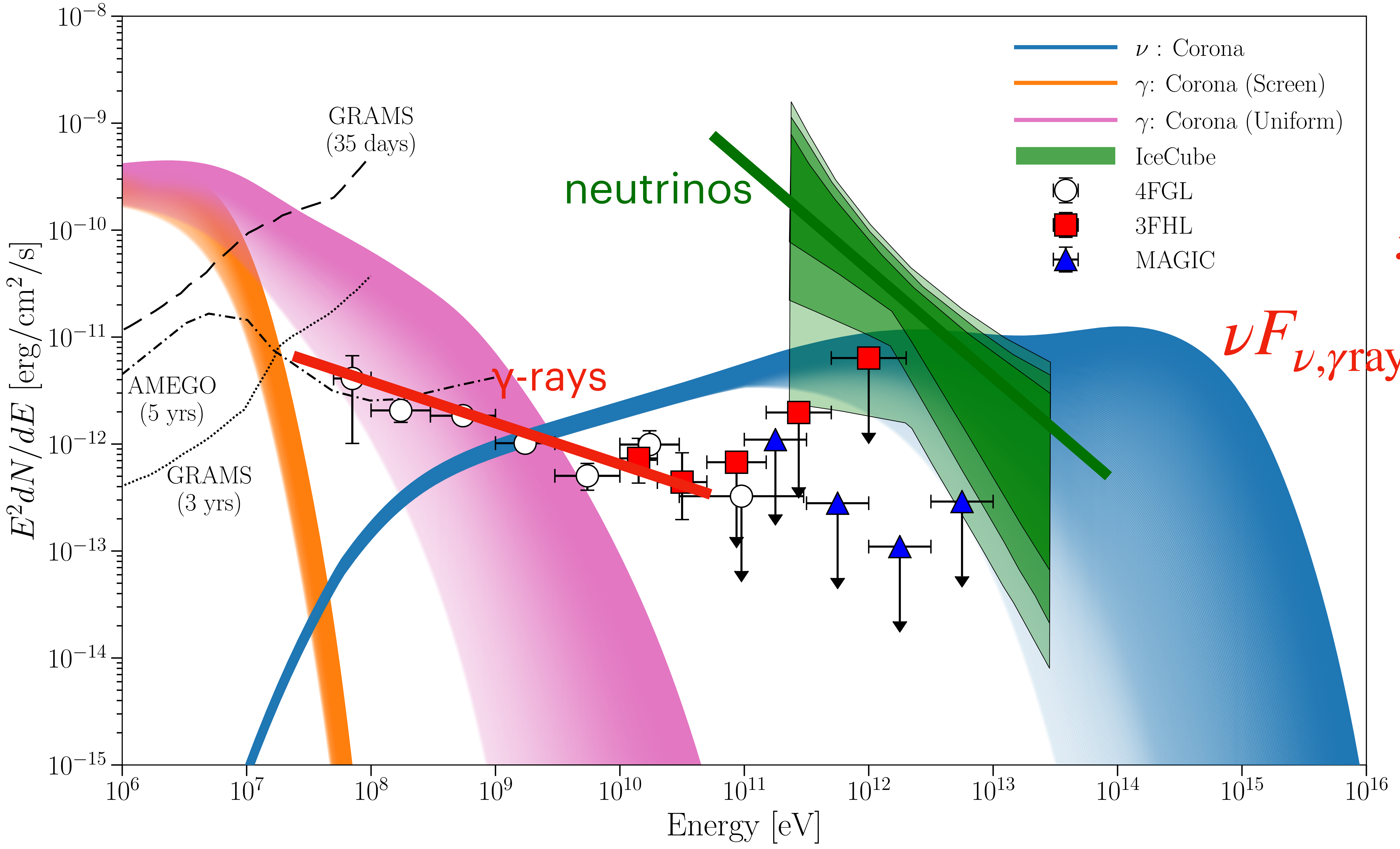
Fiorillo et al 2024a,b



S. Inoue et al 2022

Neutrino production in NGC 1068

Y. Inoue et al 2019



$$\pi^0 \rightarrow \gamma\gamma : \pi^{+/-} \rightarrow \nu_e \nu_\mu \bar{\nu}_\mu$$

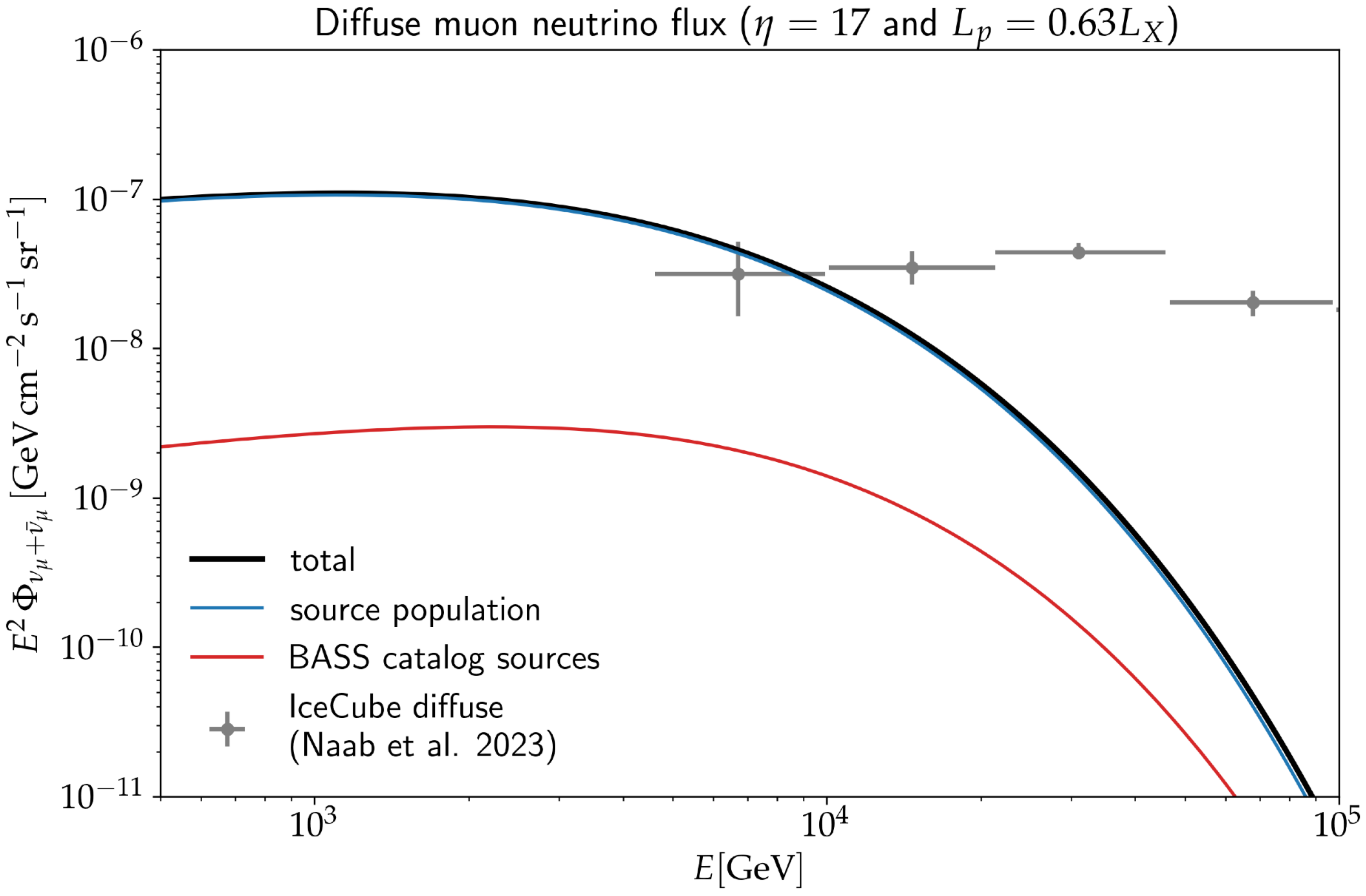
$$\nu F_{\nu,\gamma\text{rays}} \big|_{E_\gamma=2E_\nu} \sim \nu F_{\nu,\text{neutrinos}}$$

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

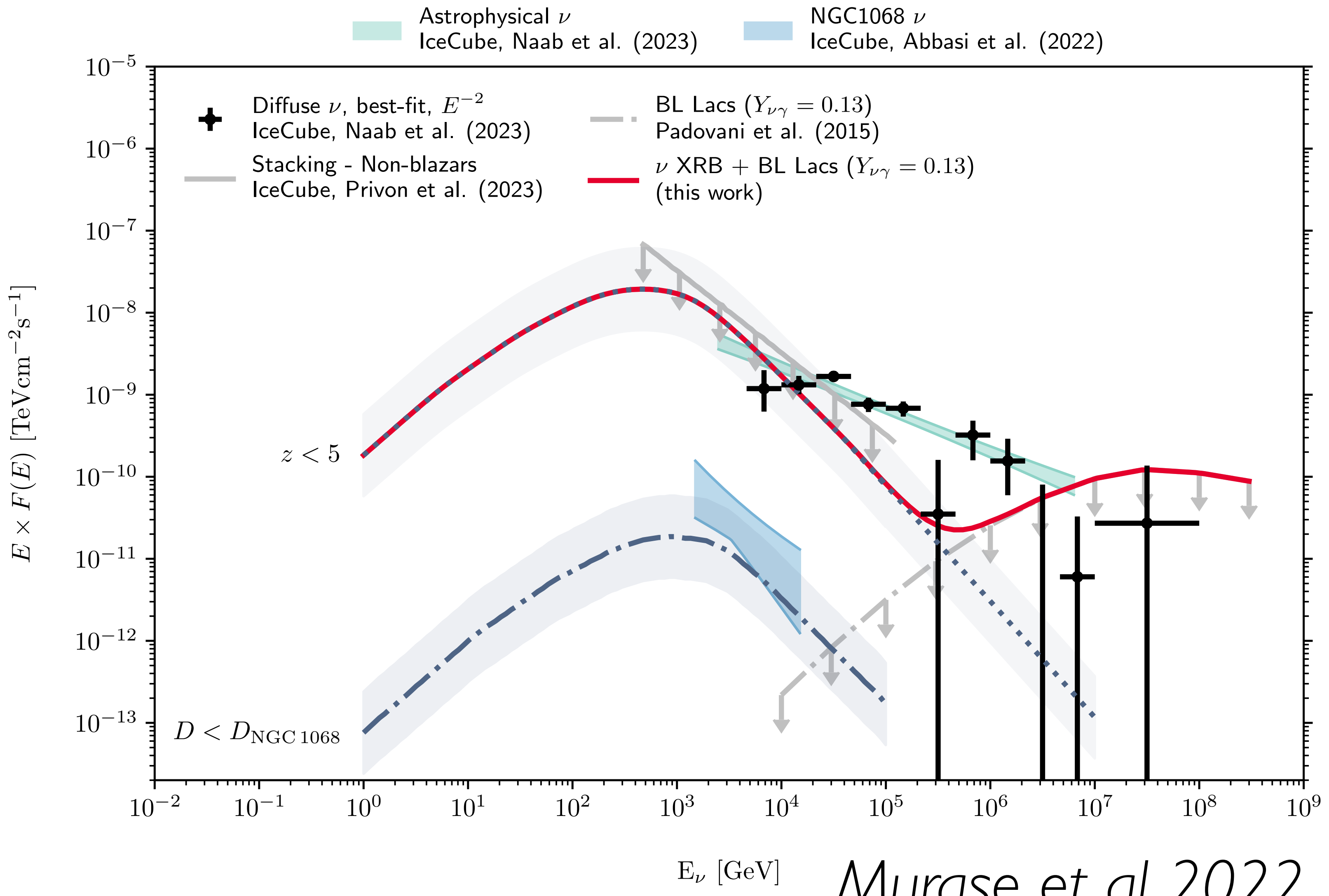
Murase 2022
Halzen 2023

Neutrino production in the cores of AGN

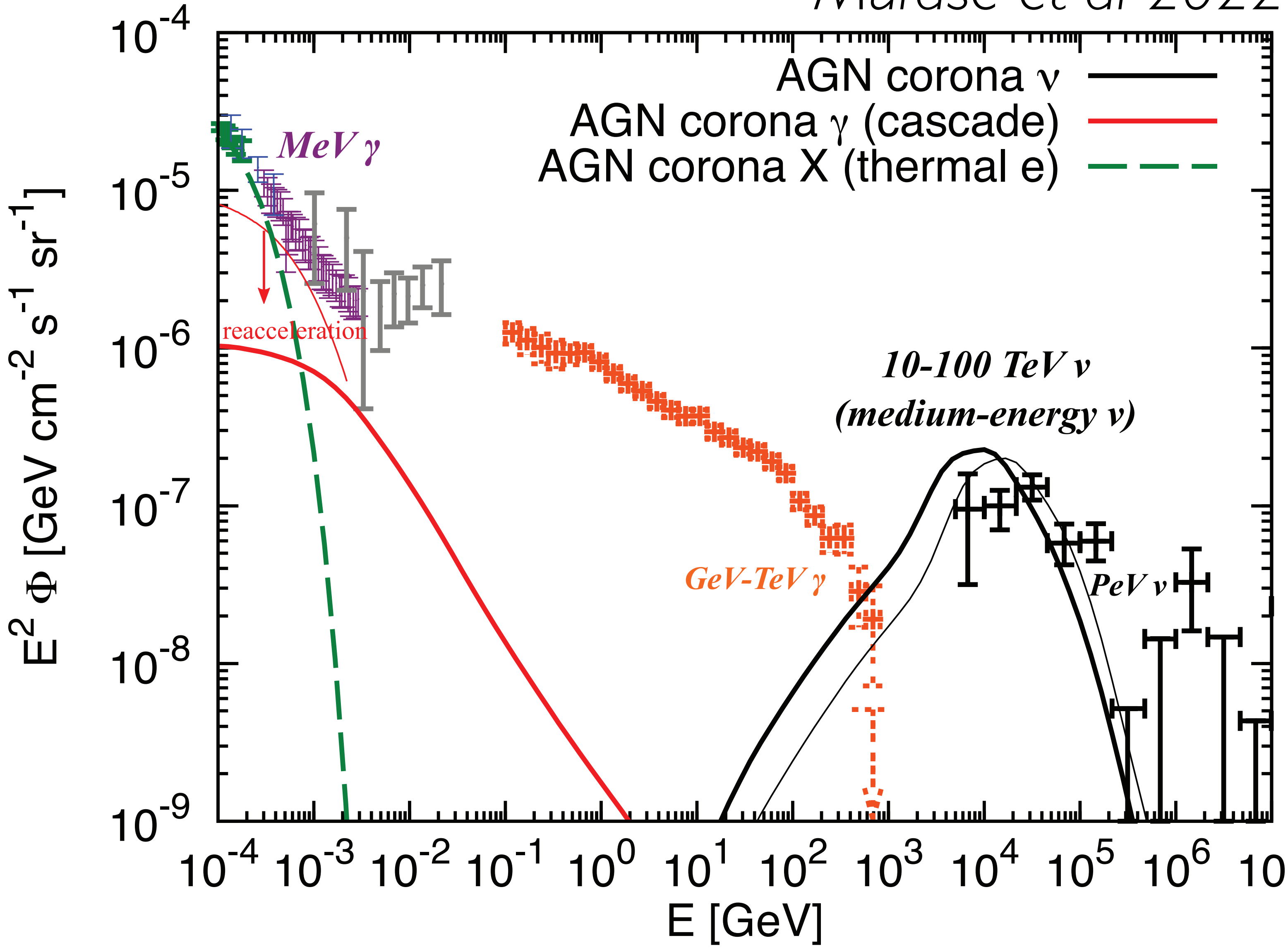
Saurenhaus, Capel, FO, in prep



Padovani etl al 2024



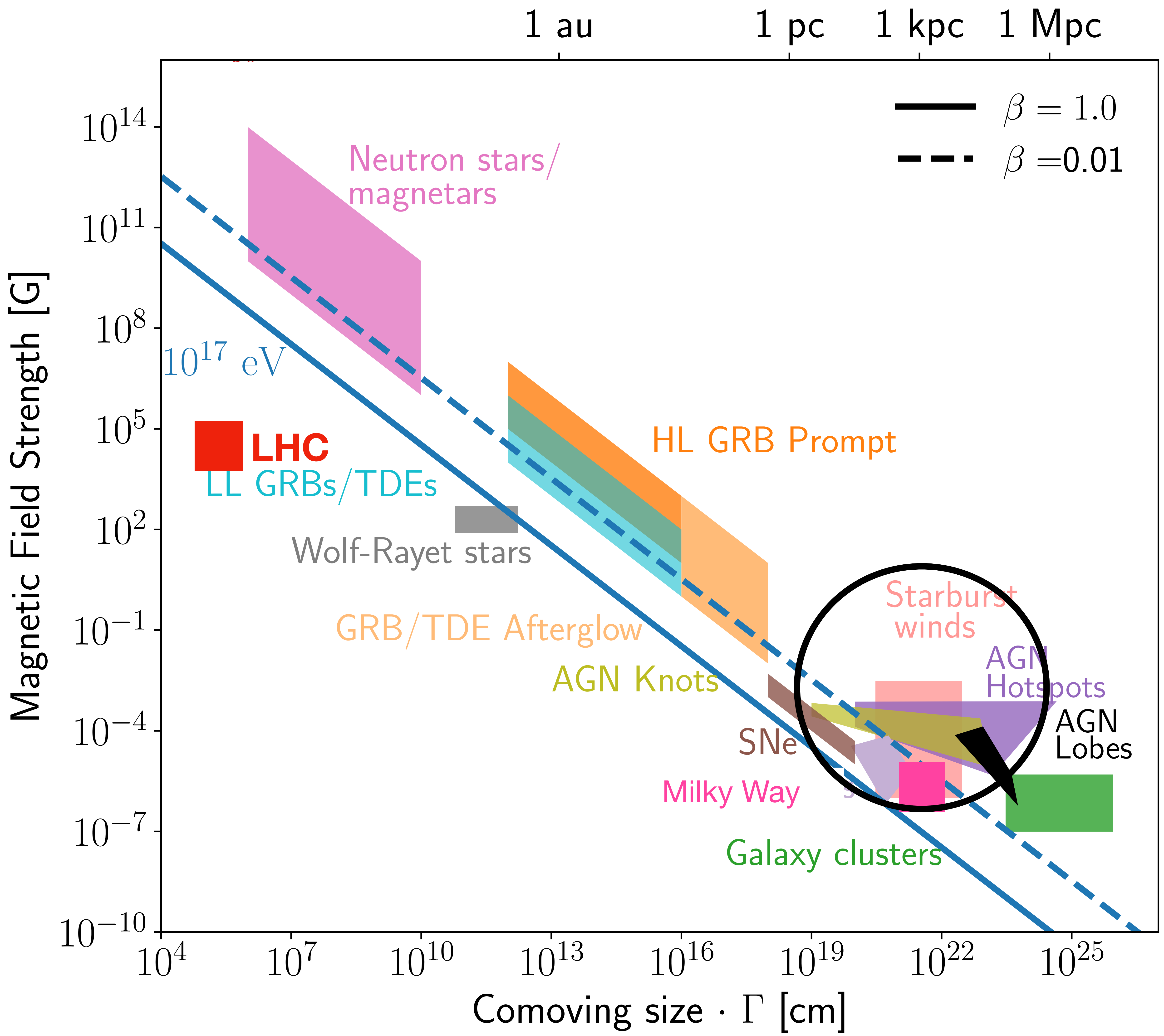
Murase et al 2022



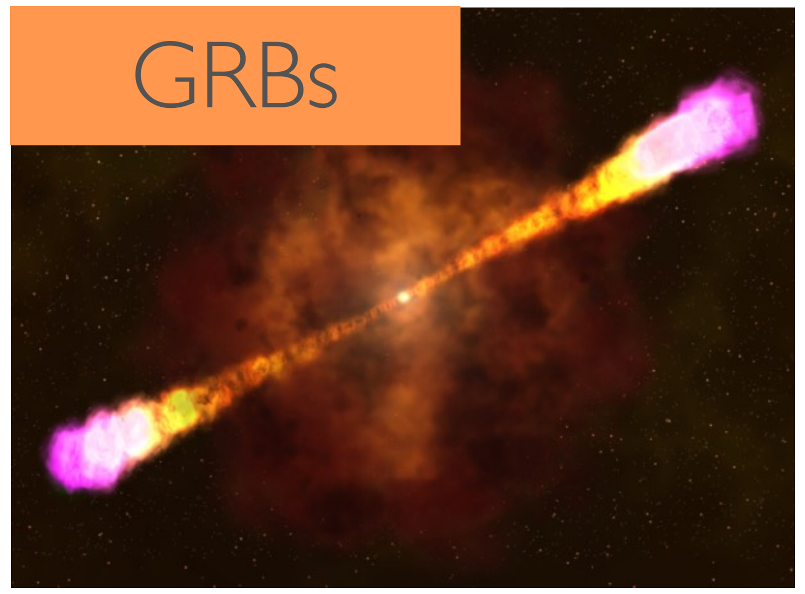
Scorecard

	$E_{\mathrm{max}}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_{ν}	Stacking UL
BL Lacs	😀	😞	😀	😞	$\lesssim 20\%$
FSRQs	😀	😞	😀	😞	$\lesssim 20\%$
FR I	😀	😀	😀	😀	$\lesssim 20\%$
FR II	😀	😀	😀	😀	$\lesssim 20\%$
Non-jetted AGN	😐	😀	😀	😀	$\lesssim 100\%$
Starburst galaxies					
HL GRBs					
LL GRBs					
Pulsars					
TDEs					

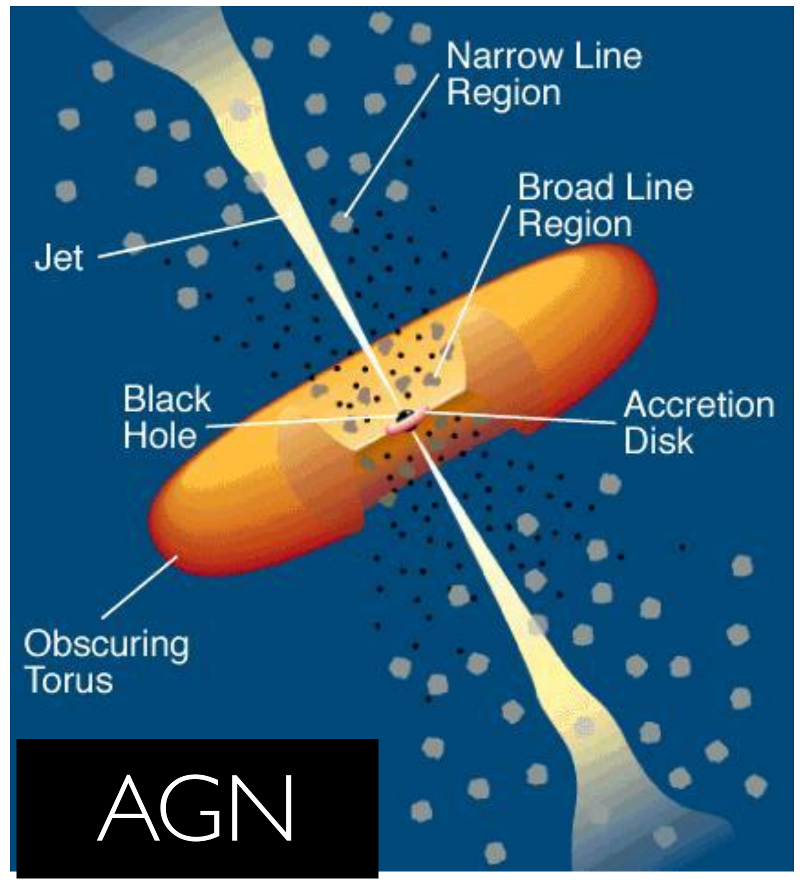
Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)




Neutron stars

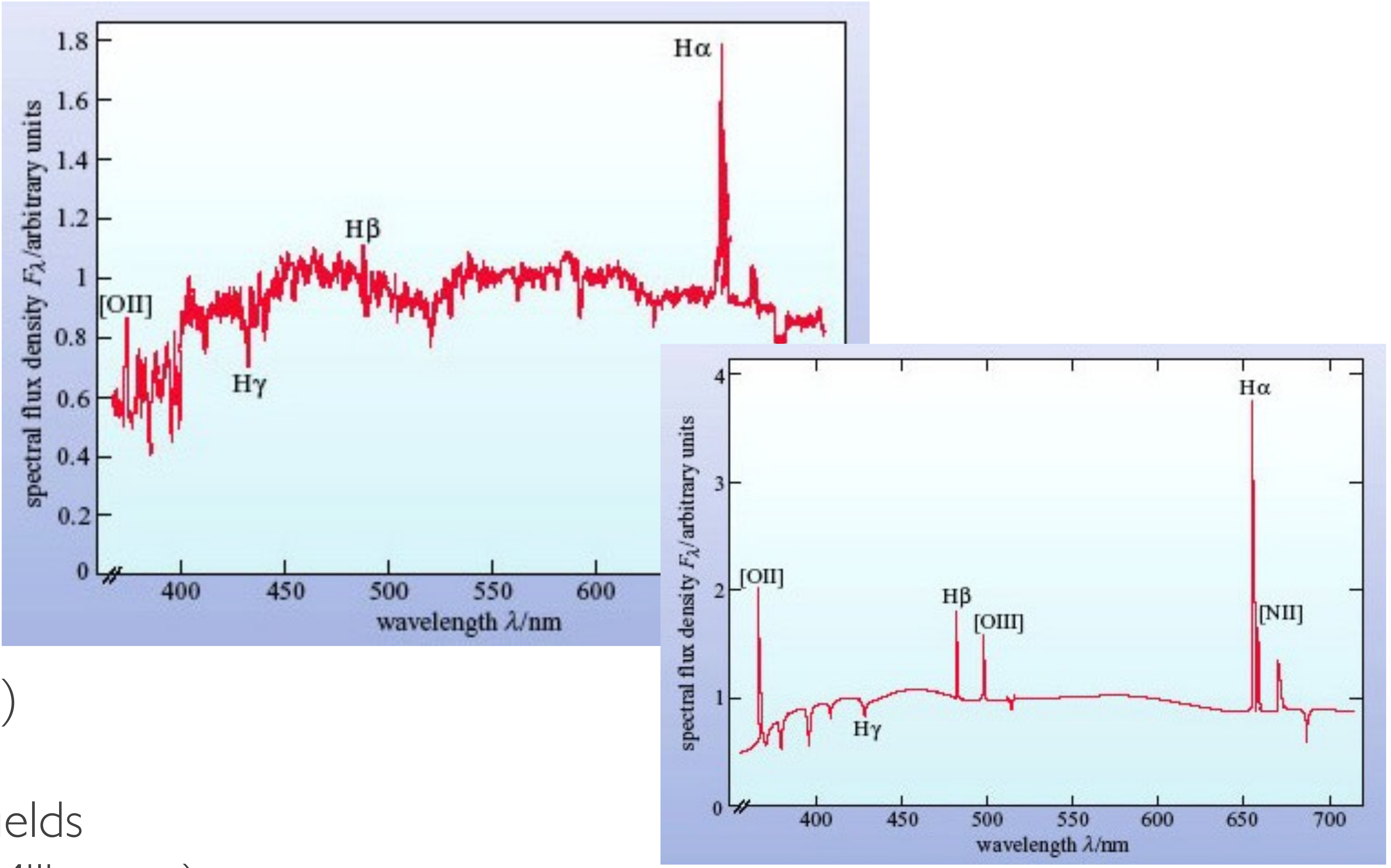

GRBs


Starbursts



AGN

Starburst galaxies



High star-formation rate (> 100 x Milky Way)

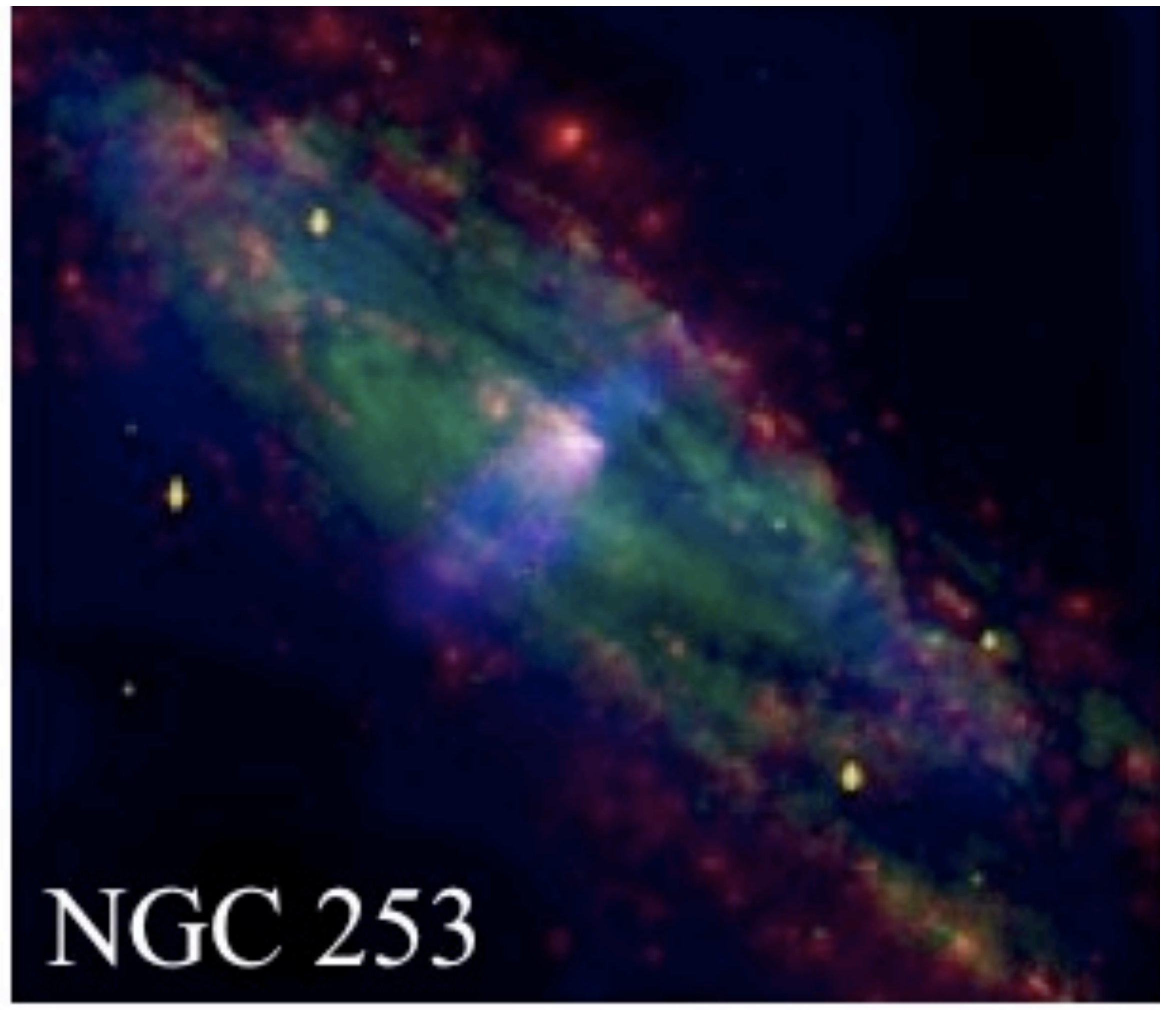
Starburst episodes are short-lived (<10^8 yrs)

Centrally driven strong outflows (``superwinds'')

Column densities $\Sigma_g > 0.1 \mathrm{g/cm^2}$ and magnetic fields B ~ 1 mG (cf $\Sigma_g \approx 0.003 \mathrm{g/cm^2}$, B ~ 5μG in the Milky way)

TeV gamma-ray detections from NGC 253 (~3 Mpc) & M82 (~4 Mpc) - consistent with point like at VHE

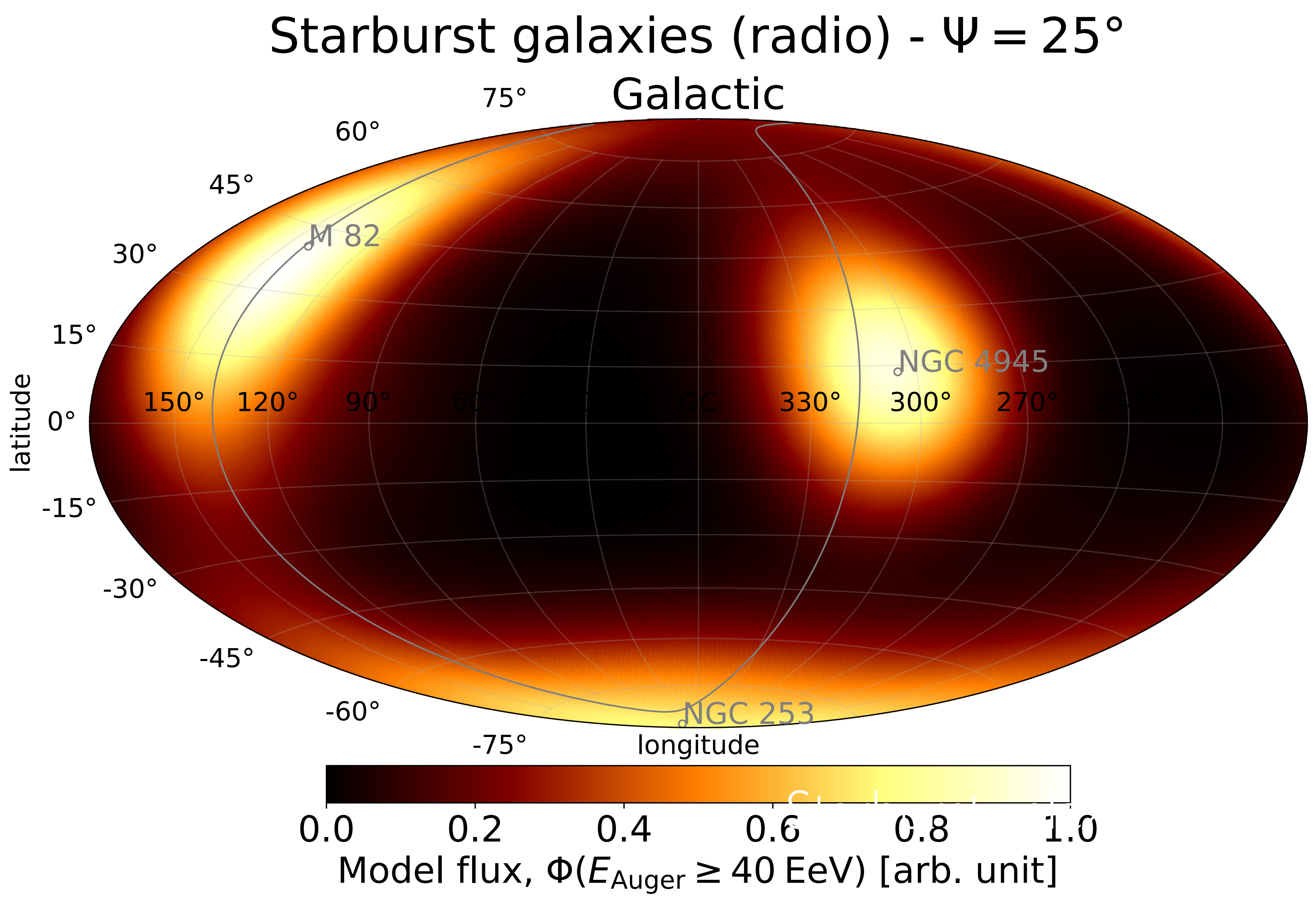
And a handful more in GeV gamma-rays (NGC4945, NGC1068, Circinus, Arp 220)



UHECRs from starburst galaxies?

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

Auger Coll, ApJL, 853, L29, 2018, Auger Coll 2022, ApJ 935 (2022) 2, 170



Starburst galaxies (radio flux weights)

E ≥38 EeV, Flux fraction ~10%

post-trial significance: 4.2σ

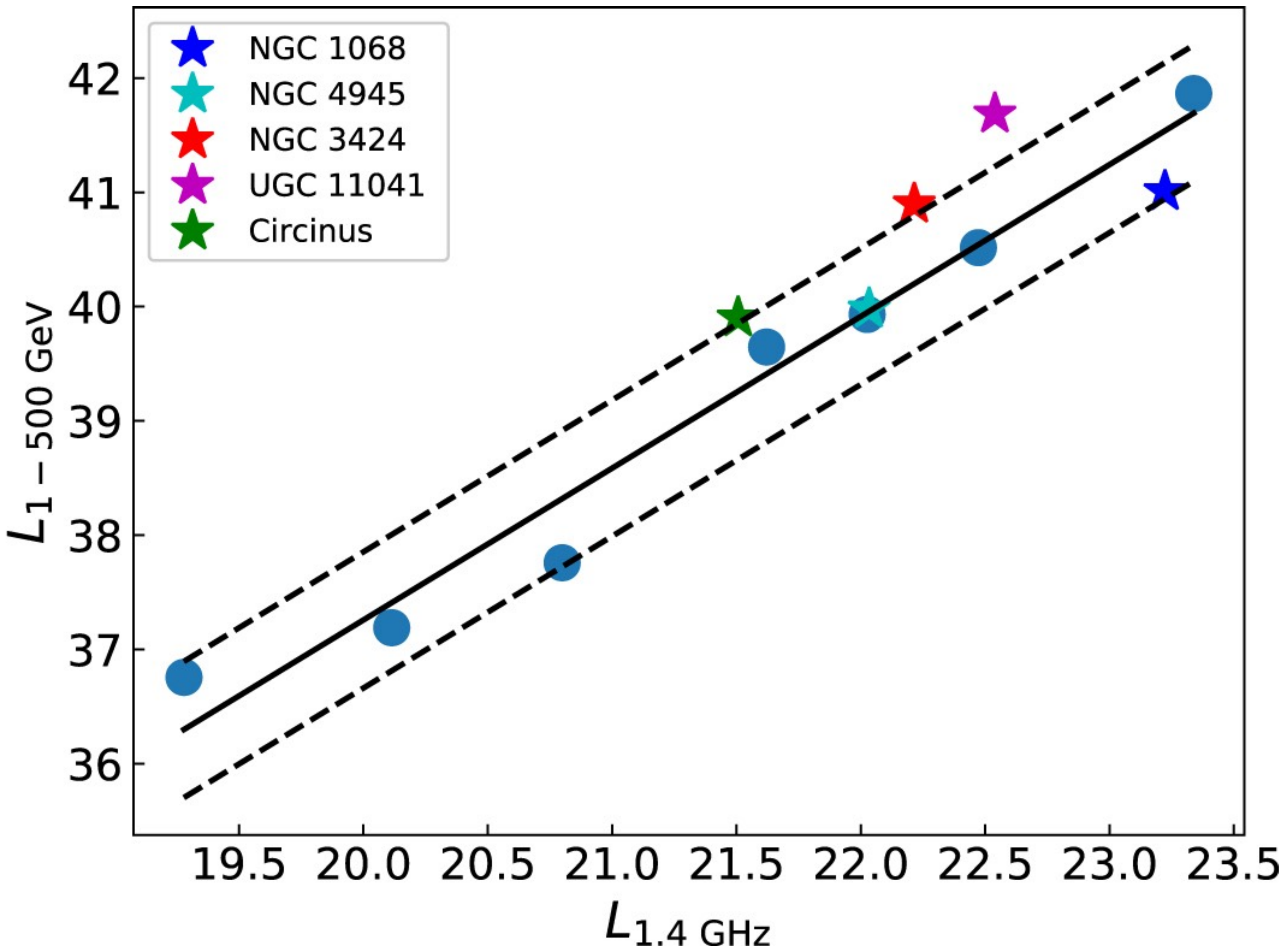
Correlation could be related to transients

inside the starburst (GRBs etc)

$$L \gtrsim L_B \sim \frac{U_B \cdot \mathrm{Volume}}{t} \sim B^2 R^2 \beta c$$

$$L_{\min} \sim 10^{45}\ \mathrm{erg/s} \cdot \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^2 \left(\frac{Z}{10}\right)^{-2} \left(\frac{u}{10^{-3} c}\right)^{-1}$$

Peng et al 2019



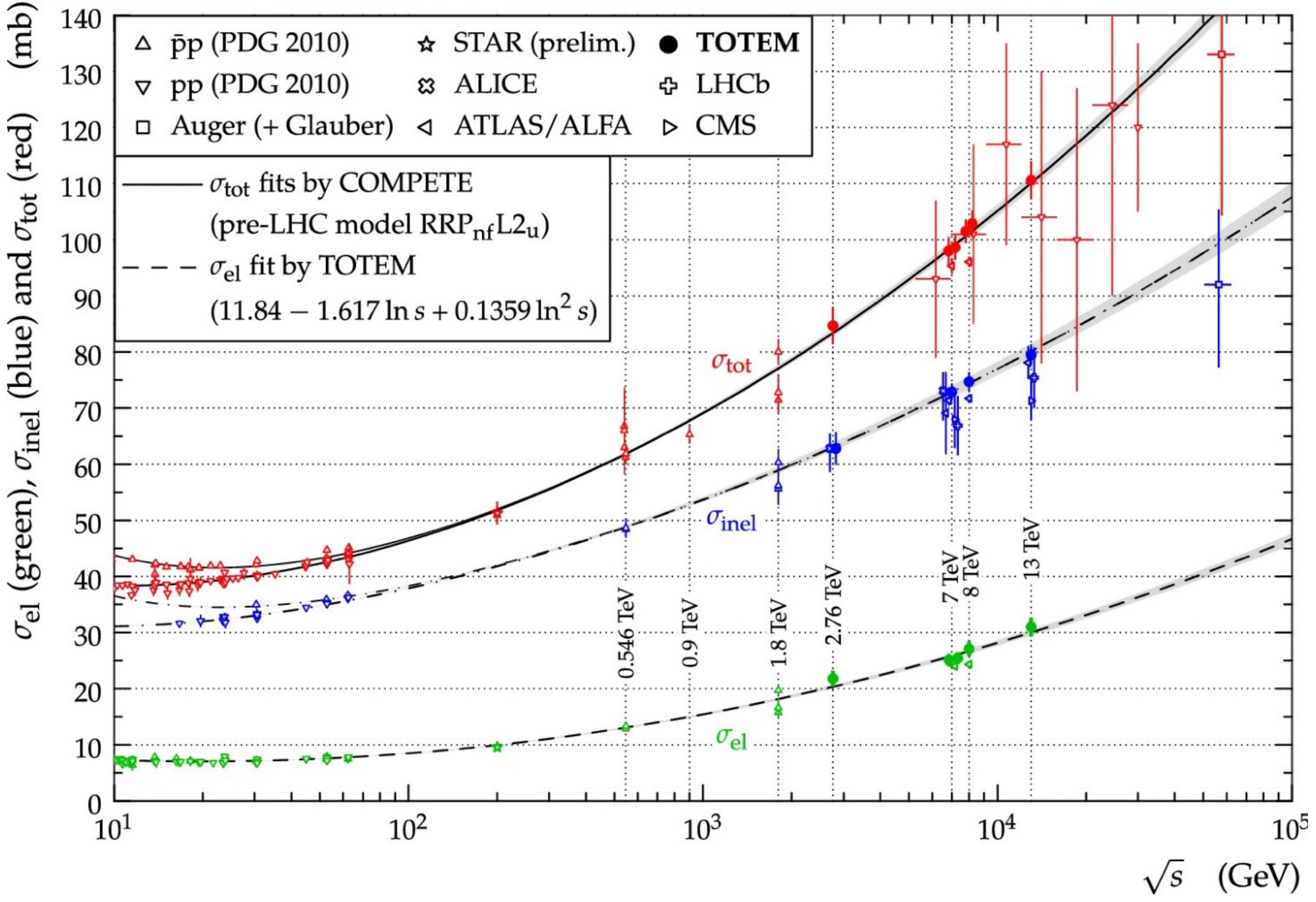
Neutrino production in proton-proton interactions

Gas reservoirs (Starburst galaxies, Galaxy Clusters…)

$$p + p \rightarrow p + p + N\pi^{+} + N\pi^{-} + N\pi^{0}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e} \ldots$$

TOTEM Coll. Eur.Phys.J.C 79 (2019) 103



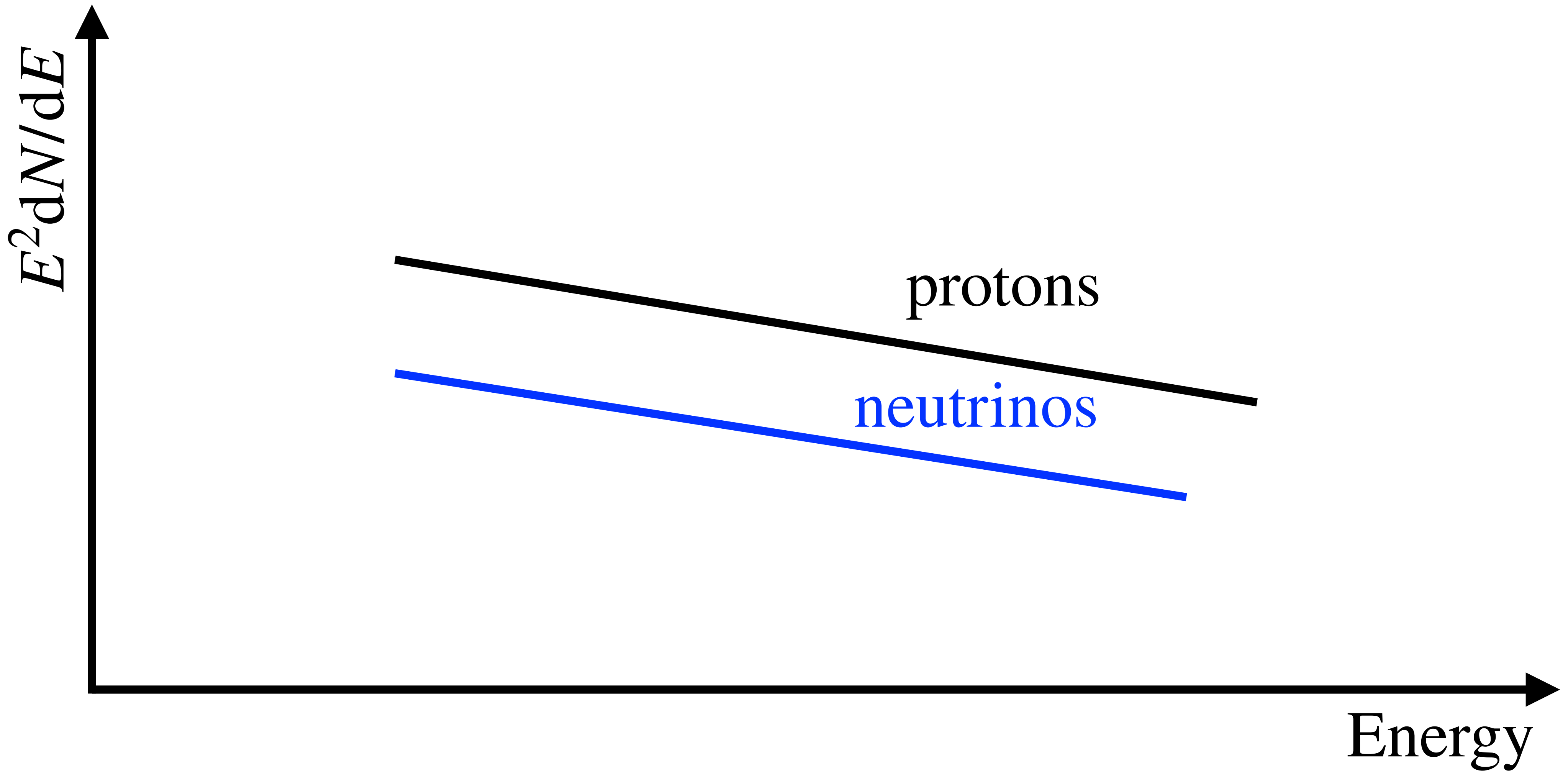
Since interaction length $\lambda(E) \propto 1/\sigma(E) \approx \text{const}.$

and meson production spectra

$$f(E_\pi, E_p) \approx f(E_\pi / E_p)$$

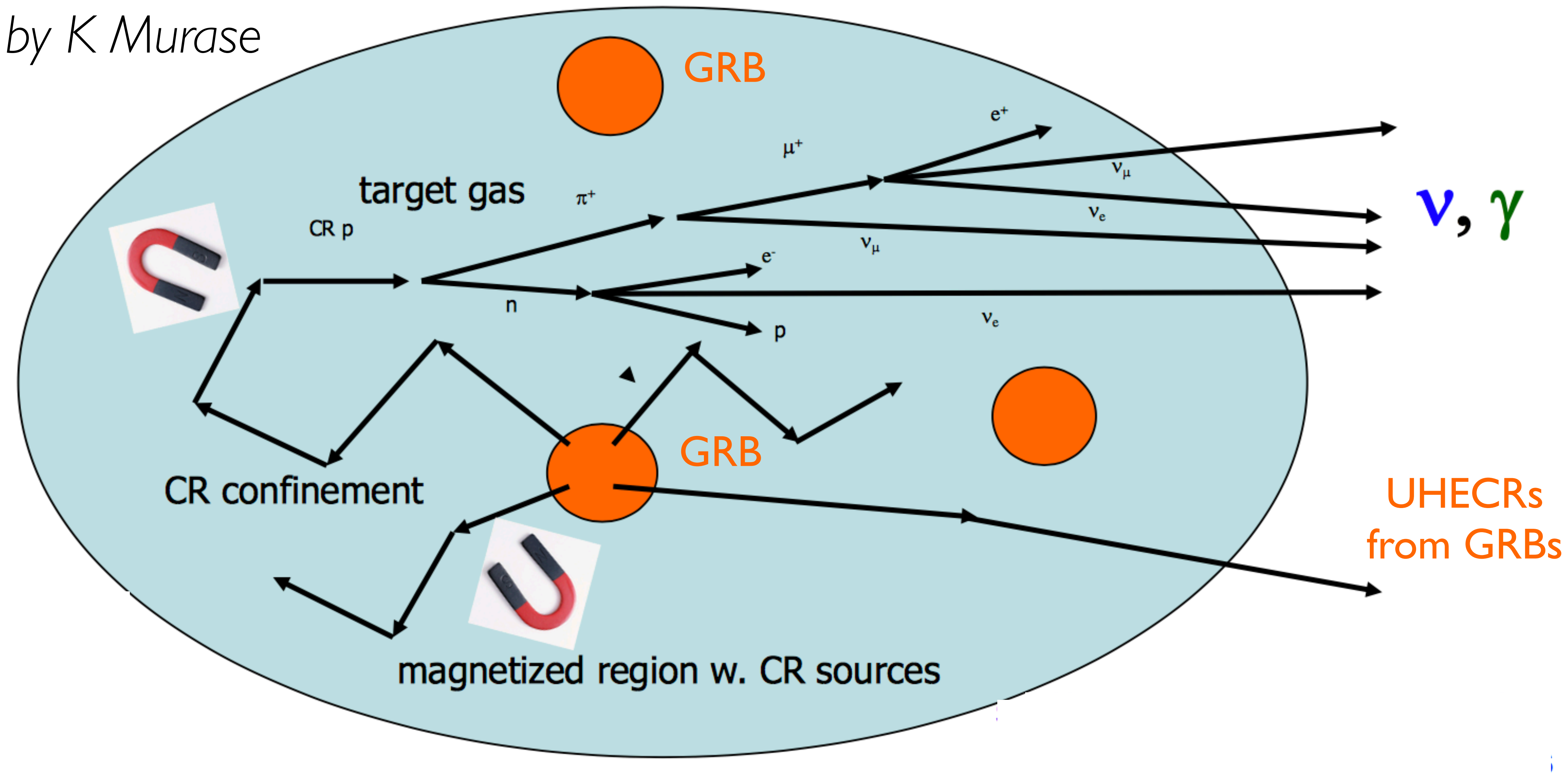
For $\mathrm{d}N/\mathrm{d}E \sim E_p^{-\gamma}$

$\mathrm{d}N/\mathrm{d}E_\nu \sim \mathrm{d}N/\mathrm{d}E_\pi \sim E_p^{-\gamma}$

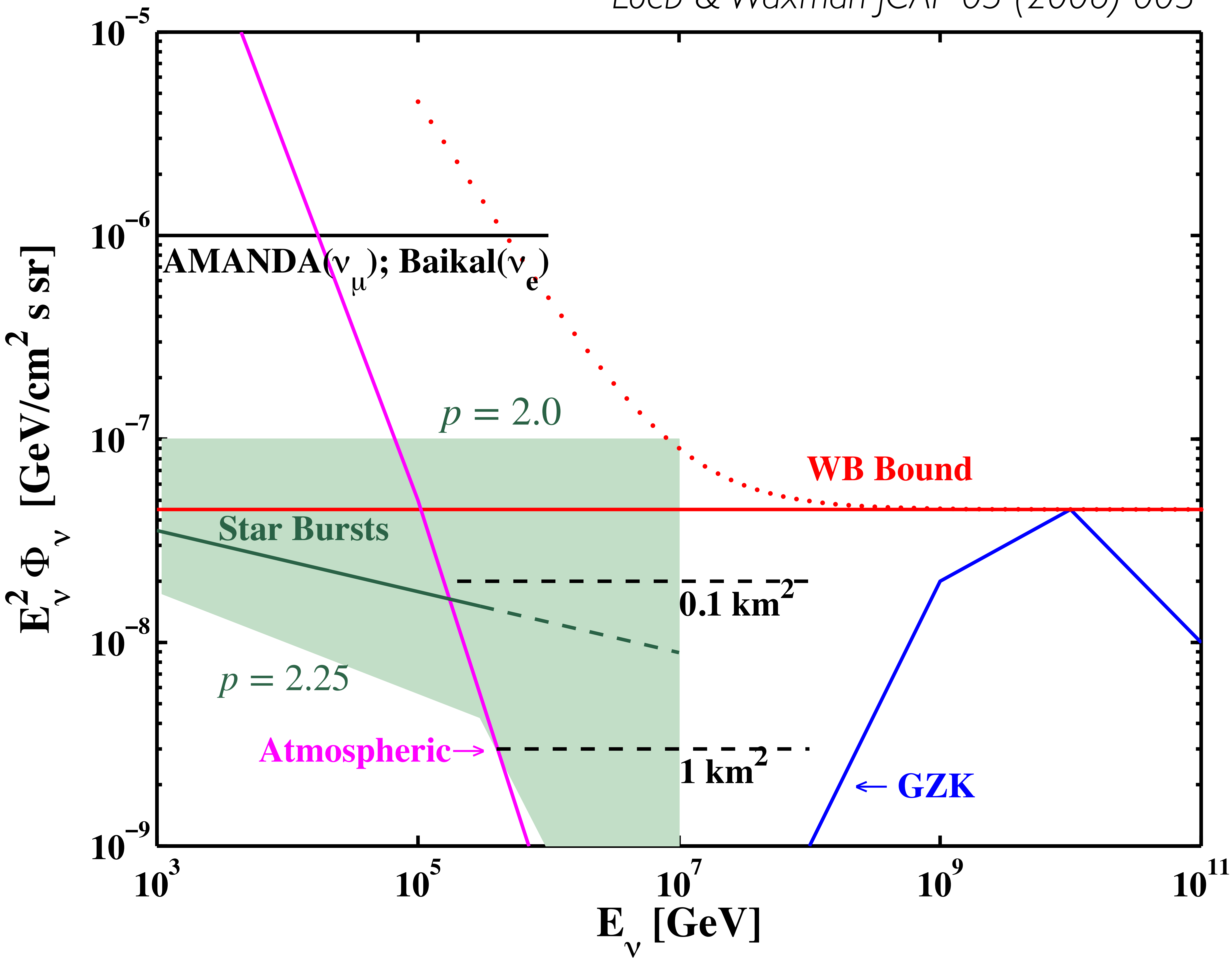


Neutrinos from starburst galaxies: Reservoir model

sketch by K Murase



Loeb & Waxman JCAP 05 (2006) 003



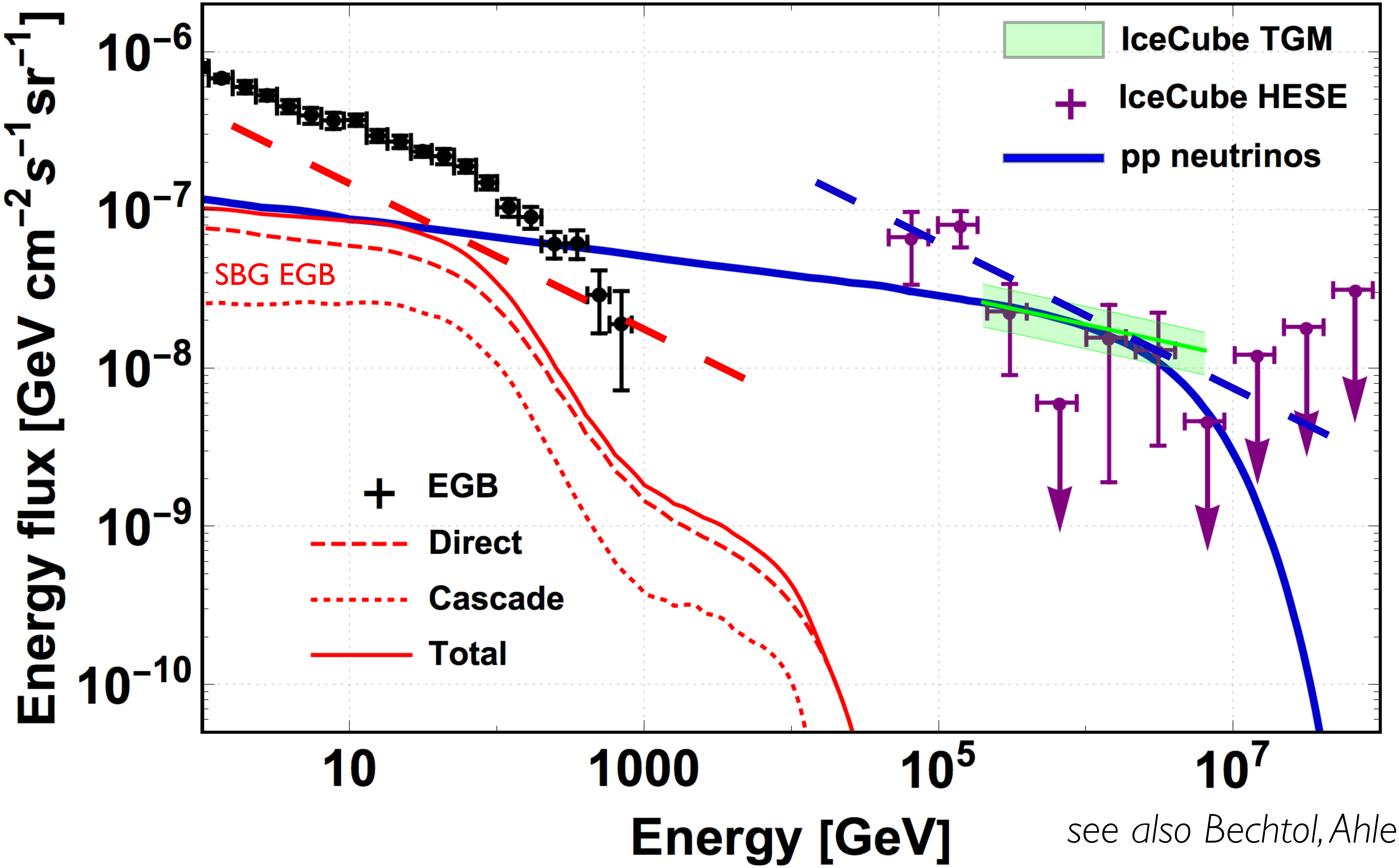
High gas density, high B environment

The highest energy cosmic rays escape (observed)

Lower energy CRs lose all their energy in pp interactions

Neutrinos from starburst galaxies

Palladino et al 2019

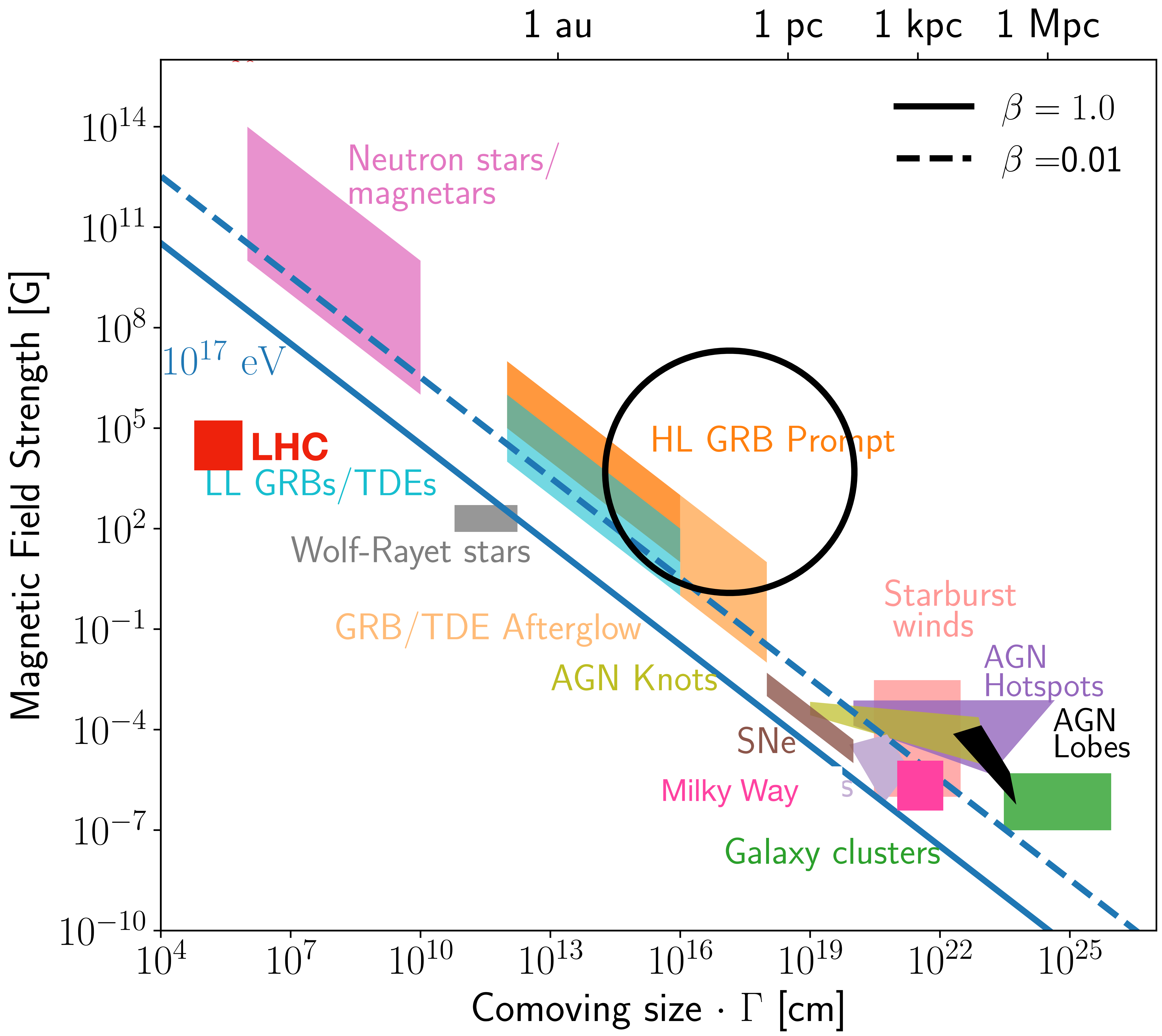


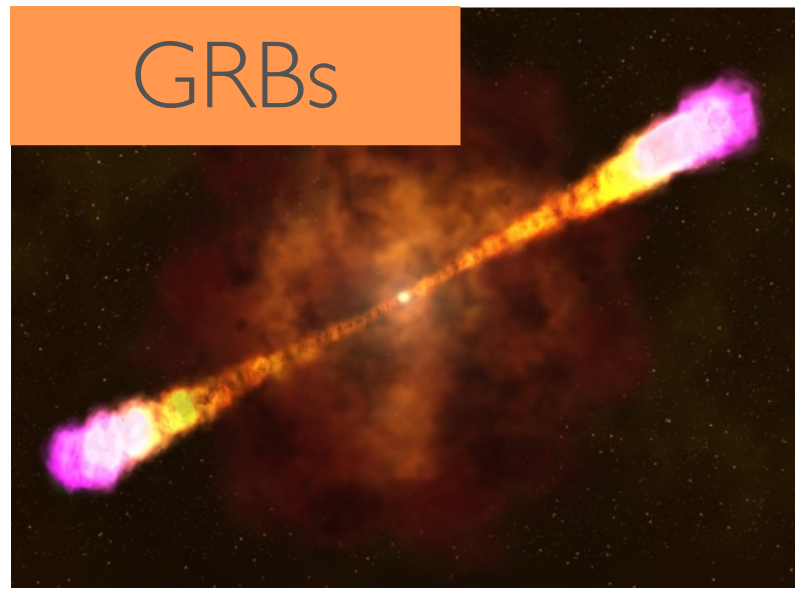
see also Bechtol, Ahlers et al 2015

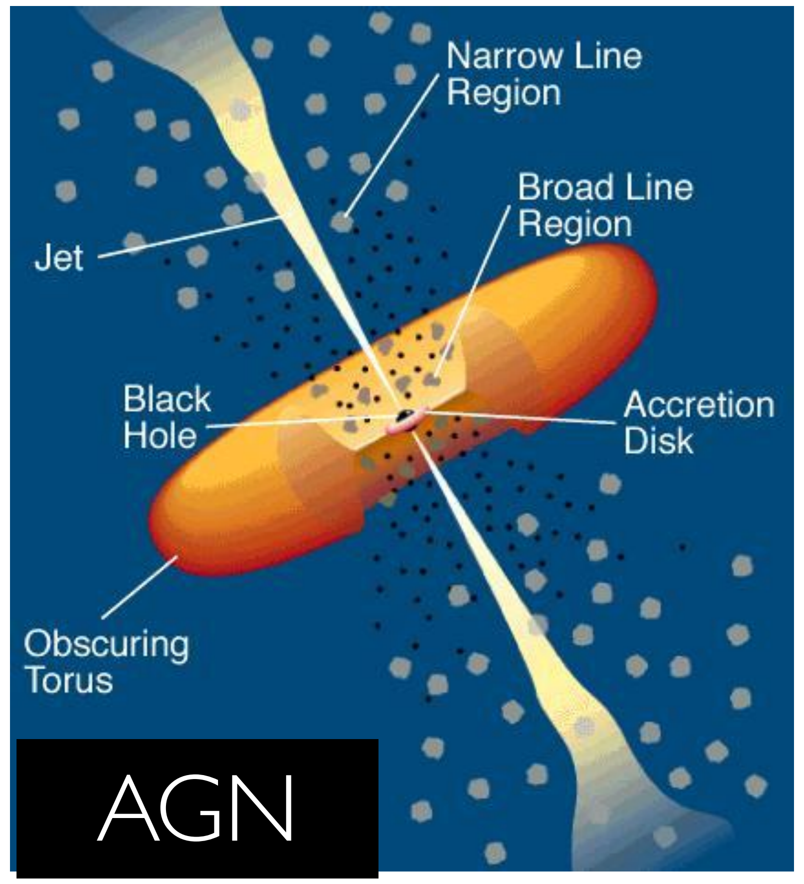
Scorecard

	$E_{\mathrm{max}}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_{ν}	**Stacking UL**	
BL Lacs	😀	😞	😀	😞	≲20%	
FSRQs	😀	😞	😀	😞	≲20%	
FR I	😀	😀	😀	😀	≲20%	
FR II	😀	😀	😀	😀	≲20%	
Non-jetted AGN	😐	😀	😀	😀	≲100%	
Starburst galaxies	😞	😀	😀	😀	≲100%	*(but problems at medium E)
HL GRBs						
LL GRBs						
Pulsars						
TDEs						

Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)







Gamma-ray bursts

Discovered serendipitously in 1967

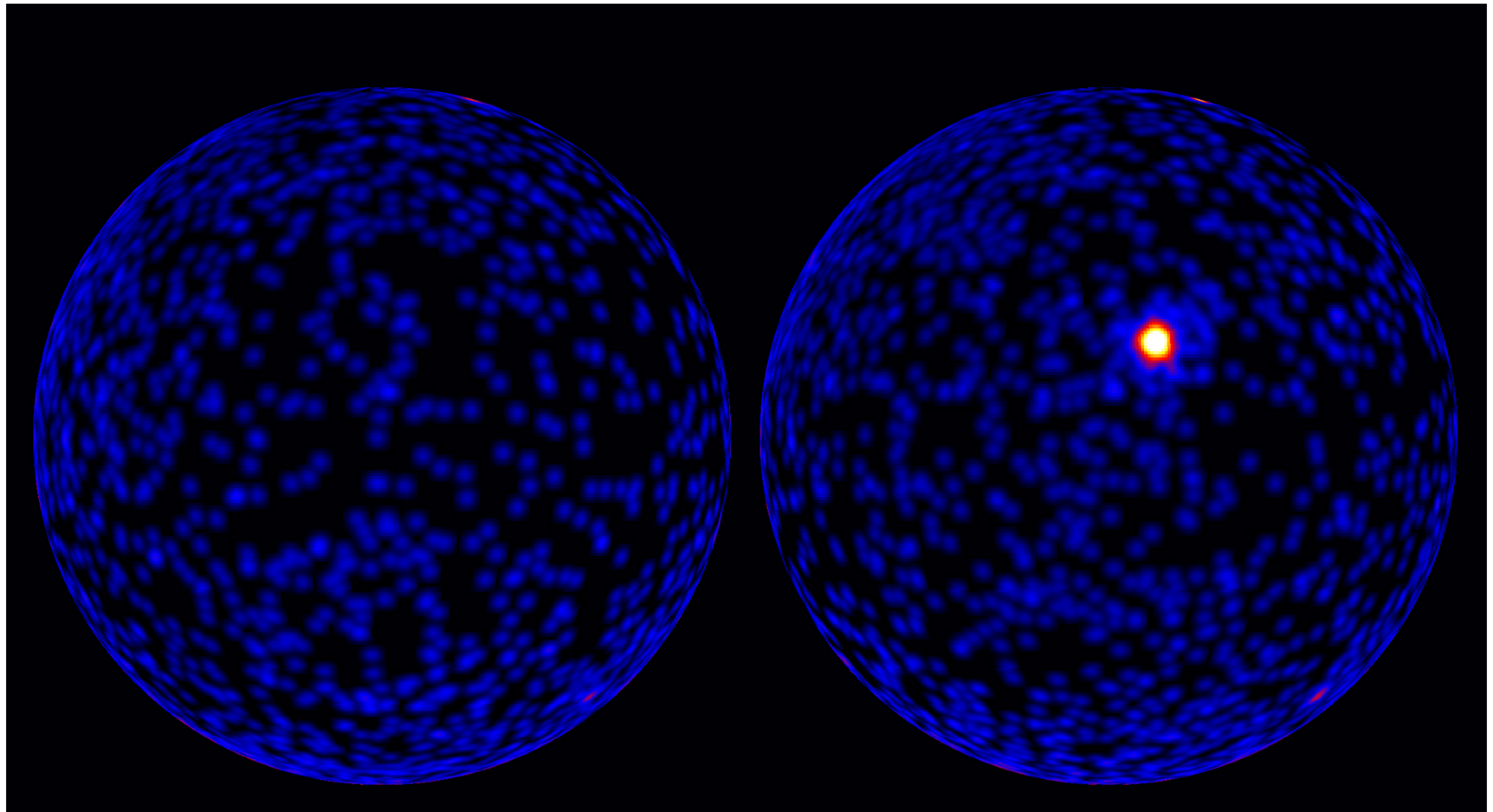
Intense short flashes of light peaking in the 10 keV -1 MeV range

Isotropic equivalent energy release ~10^{52}-10^{55} erg (cf <10^{49} erg/s in AGN)

Rate ~ 1000 year occur in the Universe

Short (0.3 second) and long (50 second) bursts - Two distinct populations

``Afterglow'' fading emission for hours to months

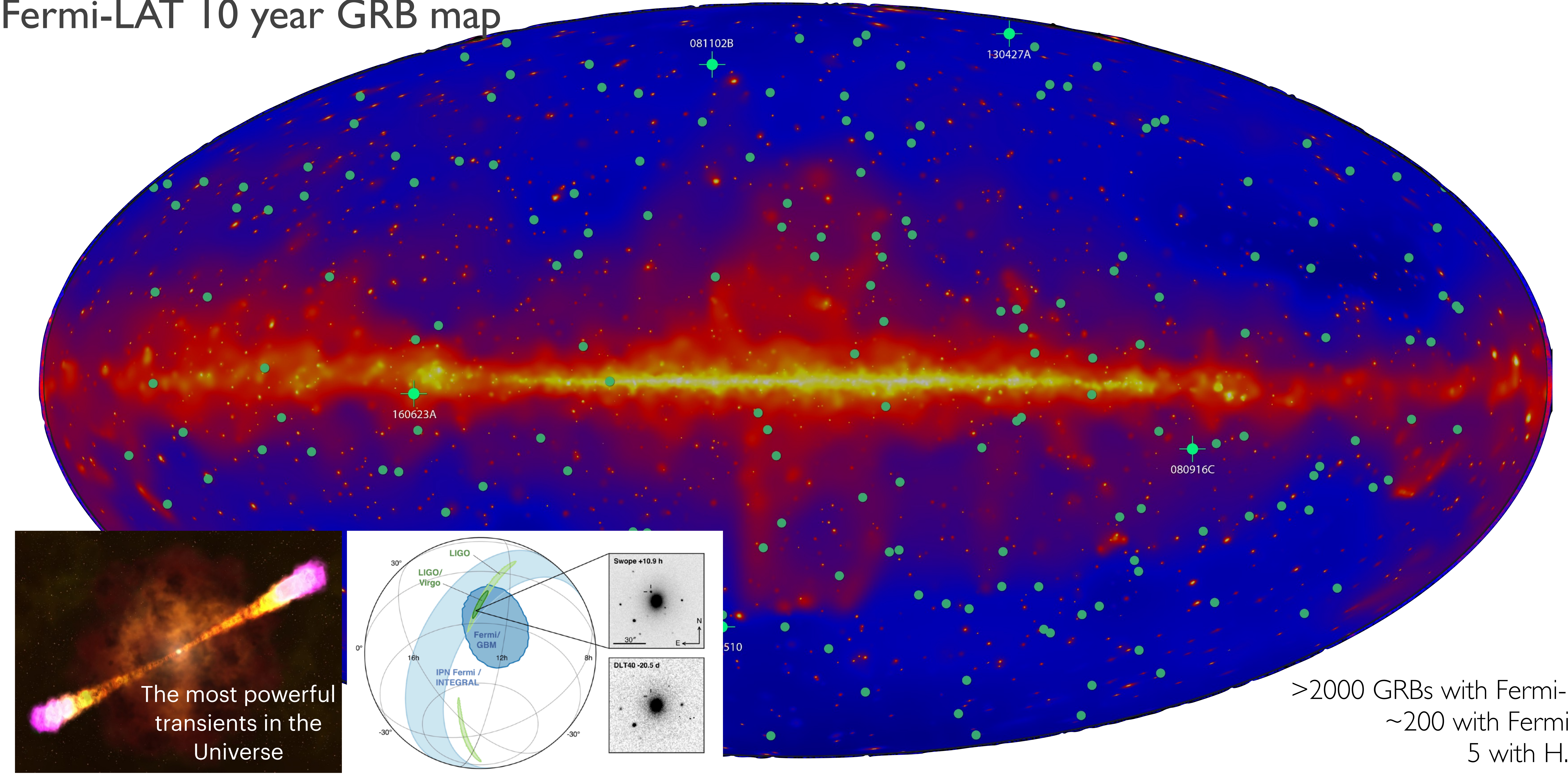


Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

Gamma-ray bursts

Fermi-LAT 10 year GRB map

Fermi-LAT 2nd GRB Catalogue,2019



The most powerful transients in the Universe

>2000 GRBs with Fermi-GBM
~200 with Fermi-LAT
5 with H.E.S.S.

Binary neutron star mergers: GW170817

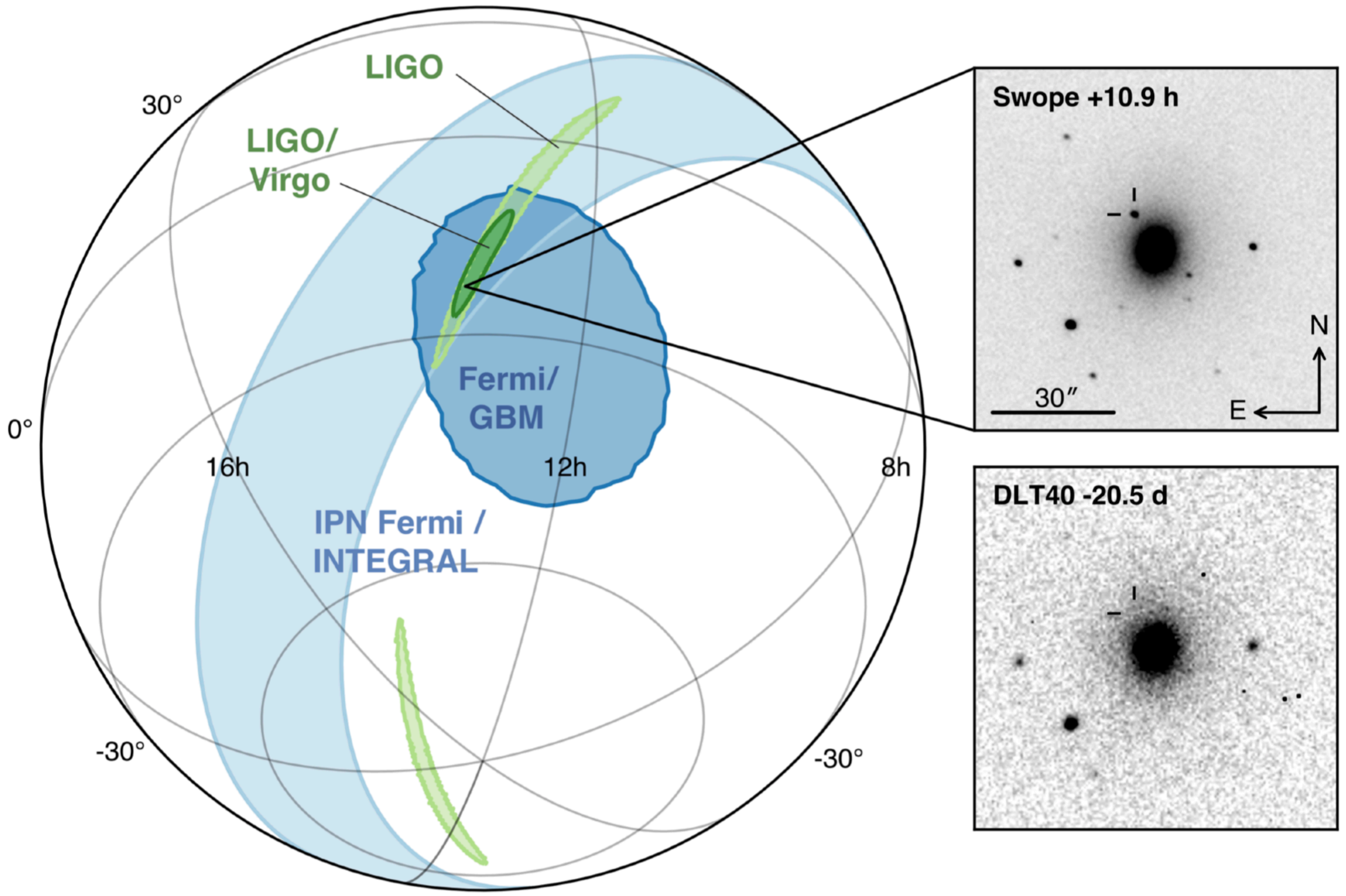
On August 17th, 2017 LIGO and Virgo reported the detection of GWs from the coalescence of a binary neutron star system

Fermi GBM independently detected the sGRB GRB170817A, 1.7s later

An extensive observational campaign localised SGRB in the early type NGC 4993, at d ~ 40 Mpc

GW170817 and GRB170817A confirm binary neutron stars as progenitors of SGRBs (p_{chance} ~10^{-8})

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



UHECR maximum energy

Very high Lorentz factors

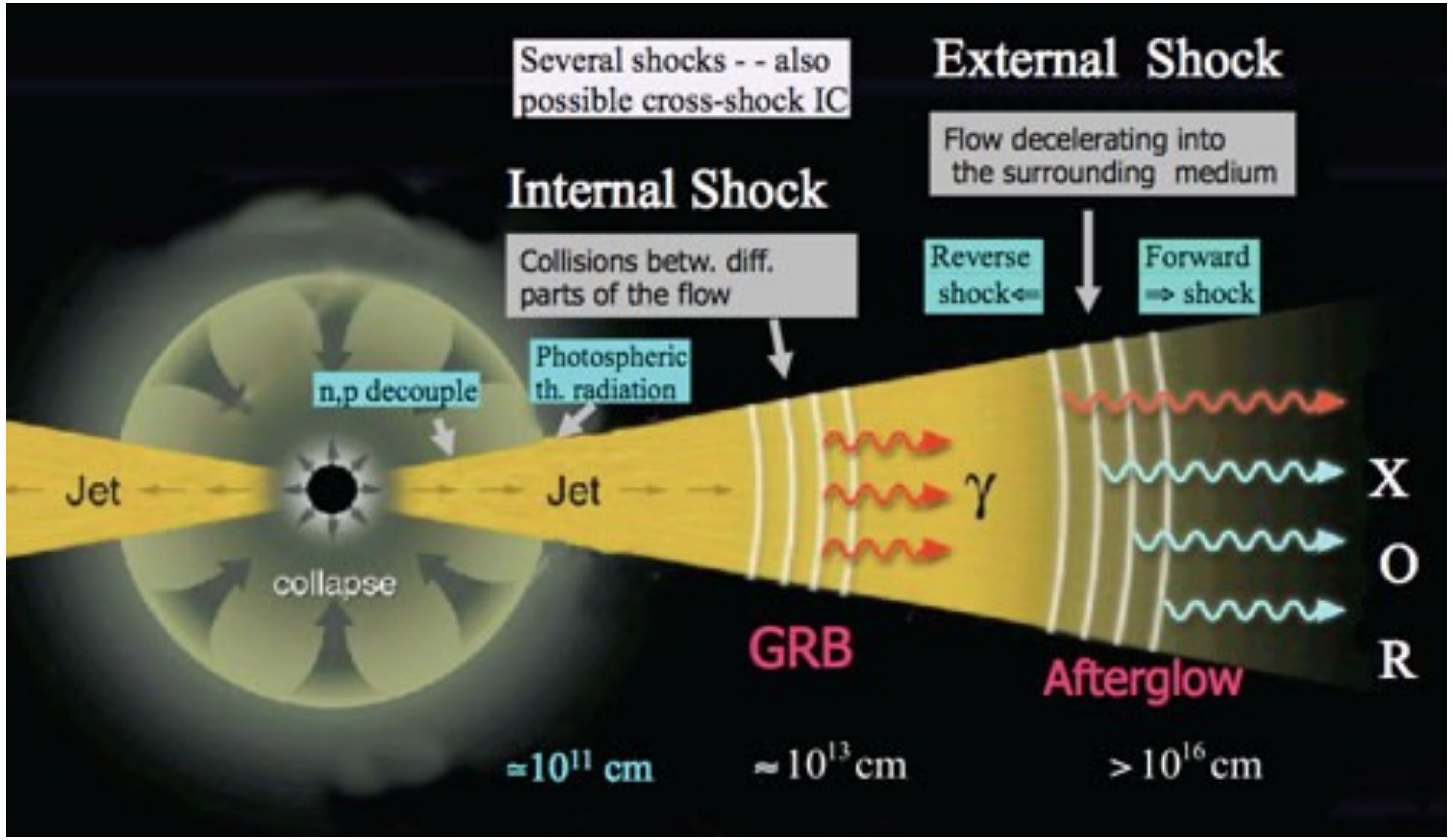
Highly magnetised expanding jet

$$E_{\max} \approx 10^{20}\ \mathrm{eV} \cdot Z \cdot \left(\frac{\dot{\varepsilon}_{\mathrm{GRB}}}{10^{51}\ \mathrm{erg}}\right)$$

Waxman 1995, Vietri 1995

Maximum energy OK for protons

Nuclei survival in GRB photon fields?



UHECRs from GRBs?

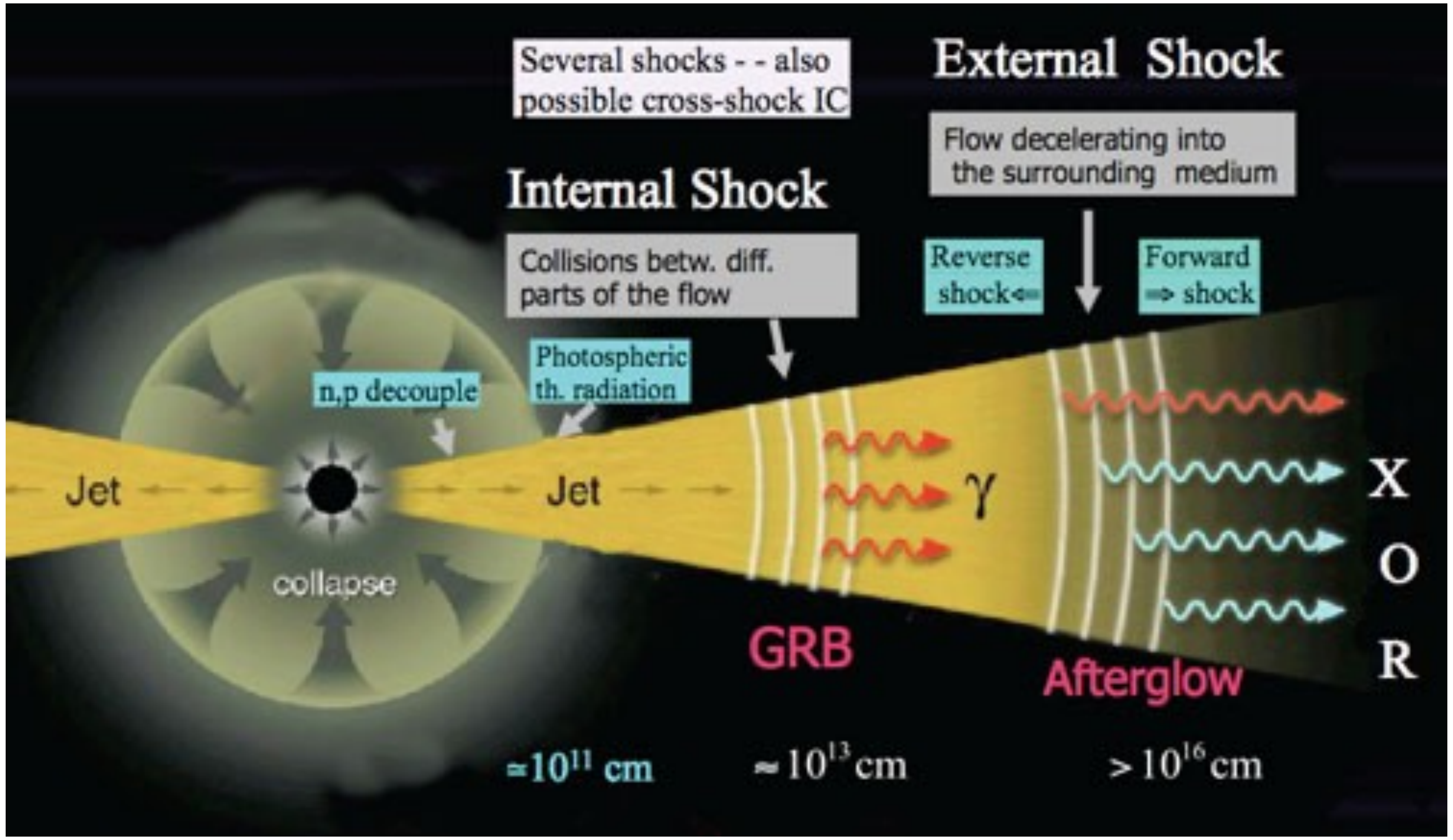
GRB rate:

$$\rho \approx 1 \times 10^{-9}\ \mathrm{Mpc}^{-3}\ \mathrm{year}^{-1}$$

The apparent number density is:

$$n_{\text{eff, jetted TDE}} \sim \delta t \cdot \rho$$

And we inferred $n_{\mathrm{UHECR}} \gtrsim 10^{-5}\ \mathrm{Mpc}^{-3}$



Thus GRBs may just about satisfy the number density constraint for $B_{\mathrm{EGMF}} \sim 0.1\ \mathrm{nG}$

$$\delta t_{\mathrm{delay}} \approx 1.5 \times 10^{3}\ \mathrm{yr} \cdot \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{2} \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2} \left(\frac{\lambda_{\mathrm{coh}}}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{0.1\,\mathrm{nG}}\right)^{2}$$

Neutrino production in GRBs

Ample photon fields

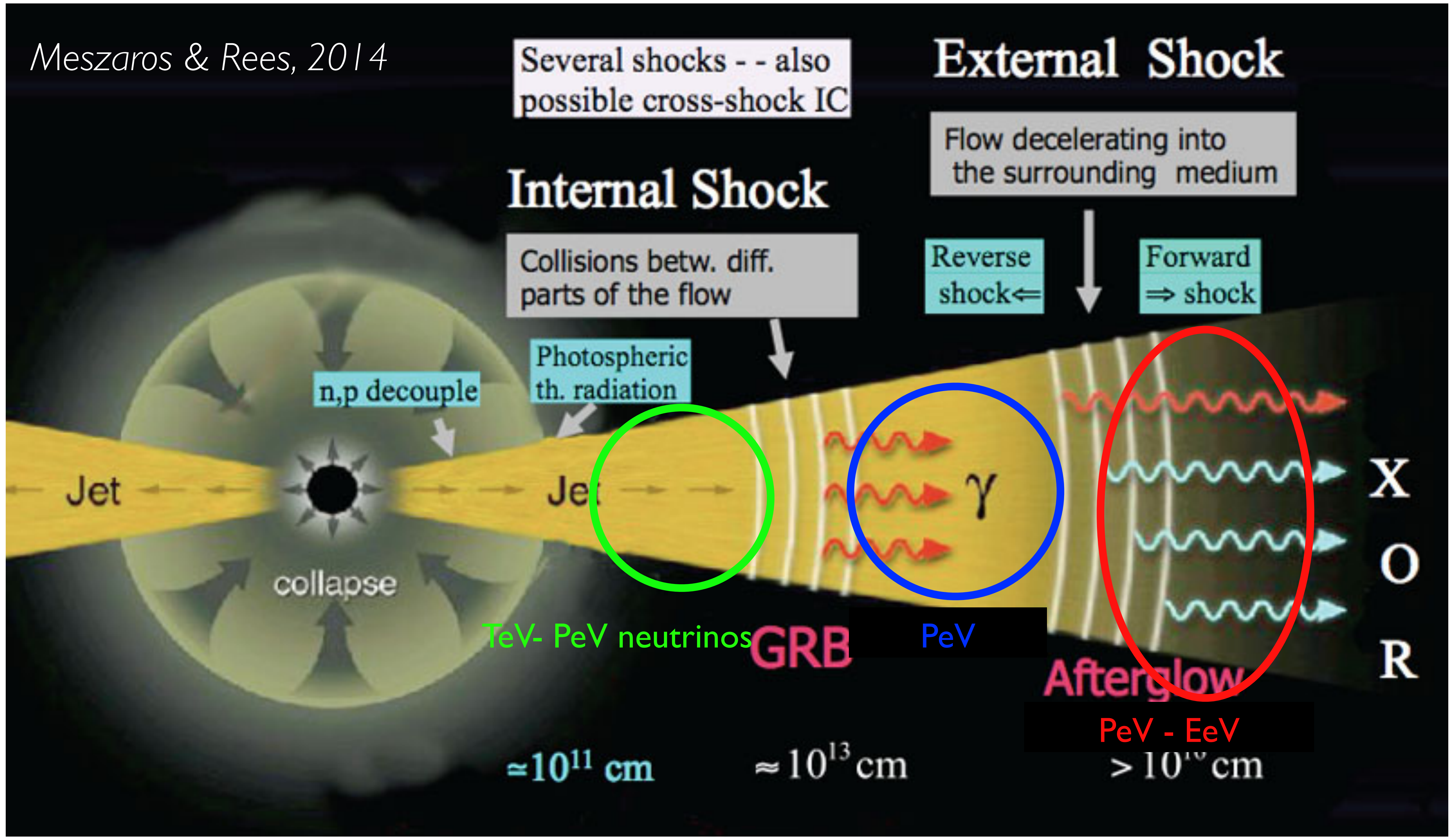
$$p + \gamma_{\text{jet}} \rightarrow n/p + \pi^+/\pi^0$$

$$E_p E_\gamma \gtrsim \frac{m_\Delta^2}{4}\left(\frac{\Gamma}{1+z}\right)^2 = 0.16\ \text{GeV}\left(\frac{\Gamma}{1+z}\right)^2$$

$$E_\nu \geq 8\ \text{GeV}\left(\frac{\Gamma}{1+z}\right)^2\left(\frac{E_\gamma}{\text{MeV}}\right)^{-1}$$

e.g. prompt emission,

$$z = 1,\ \Gamma^2 = 10^5,\ E_\gamma \sim 250\ \text{keV} \rightarrow E_\nu \sim \text{PeV}$$

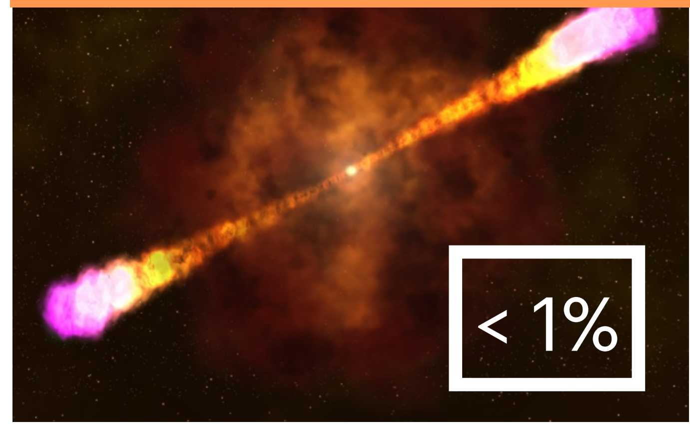


Meszaros & Rees, 2014

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

GRB contribution to the cosmic-neutrino flux

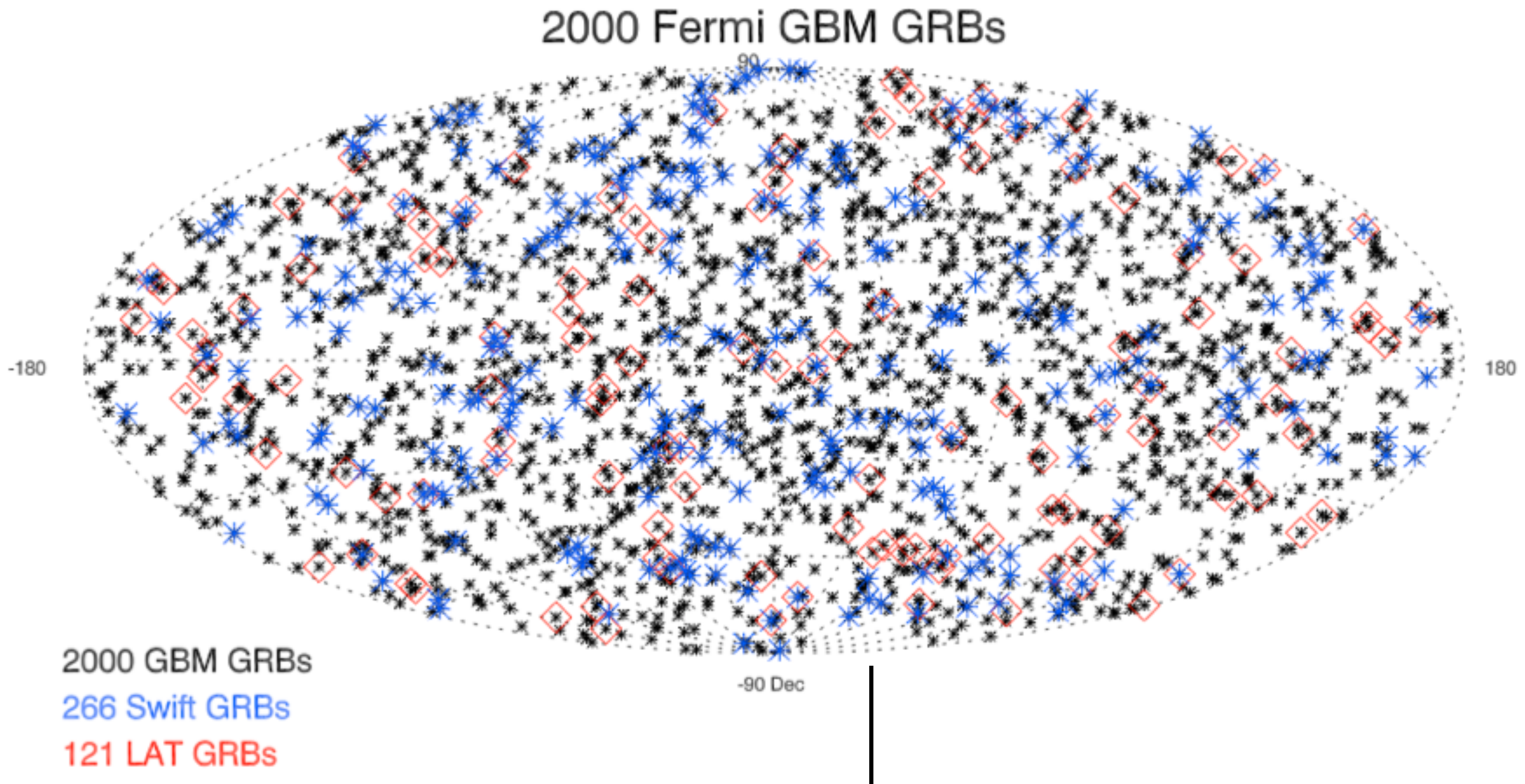
GRBs

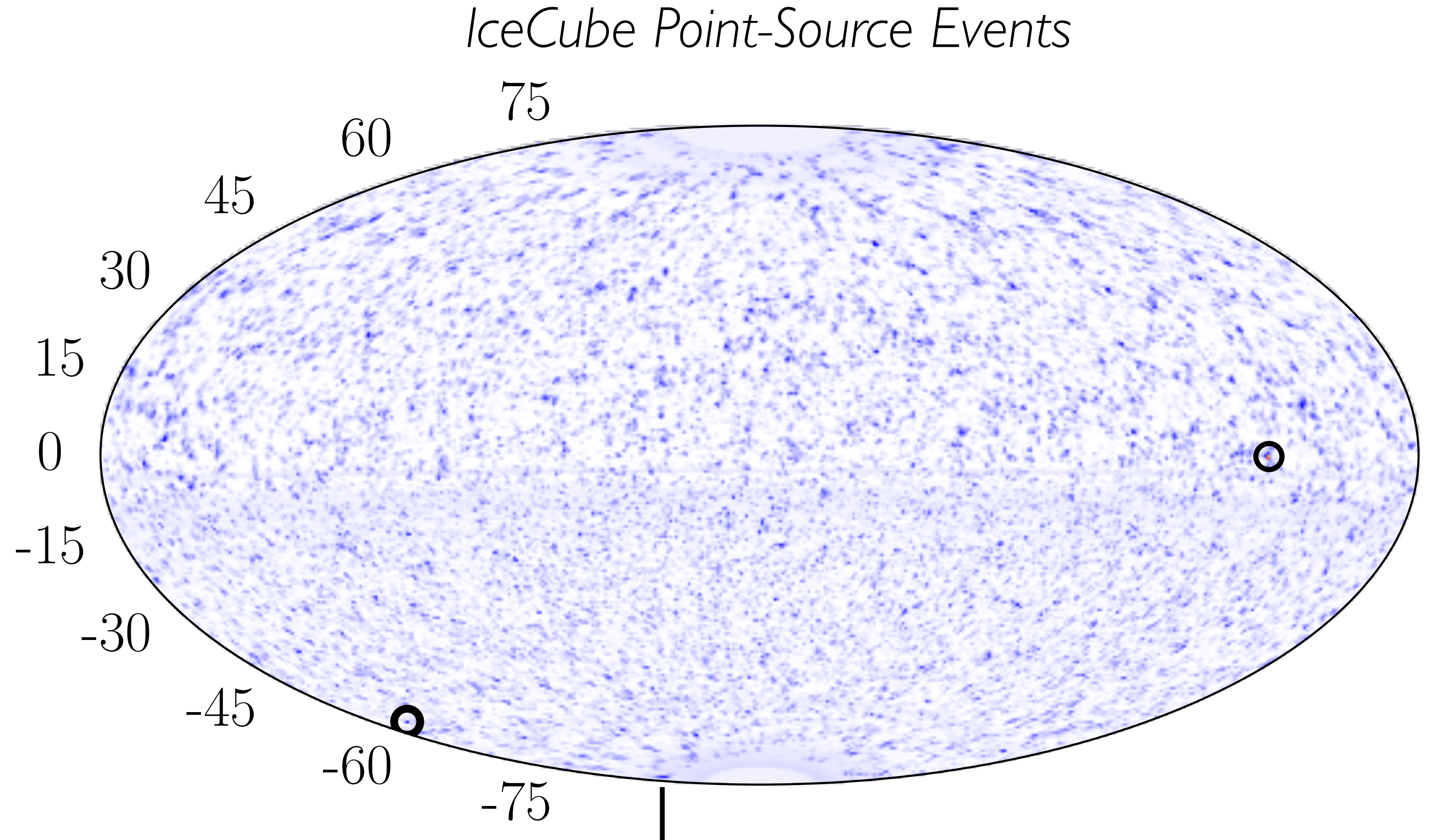


NS/NS Mergers

Stacked search for neutrinos coincident with prompt GRB emission.

2091 GRBs



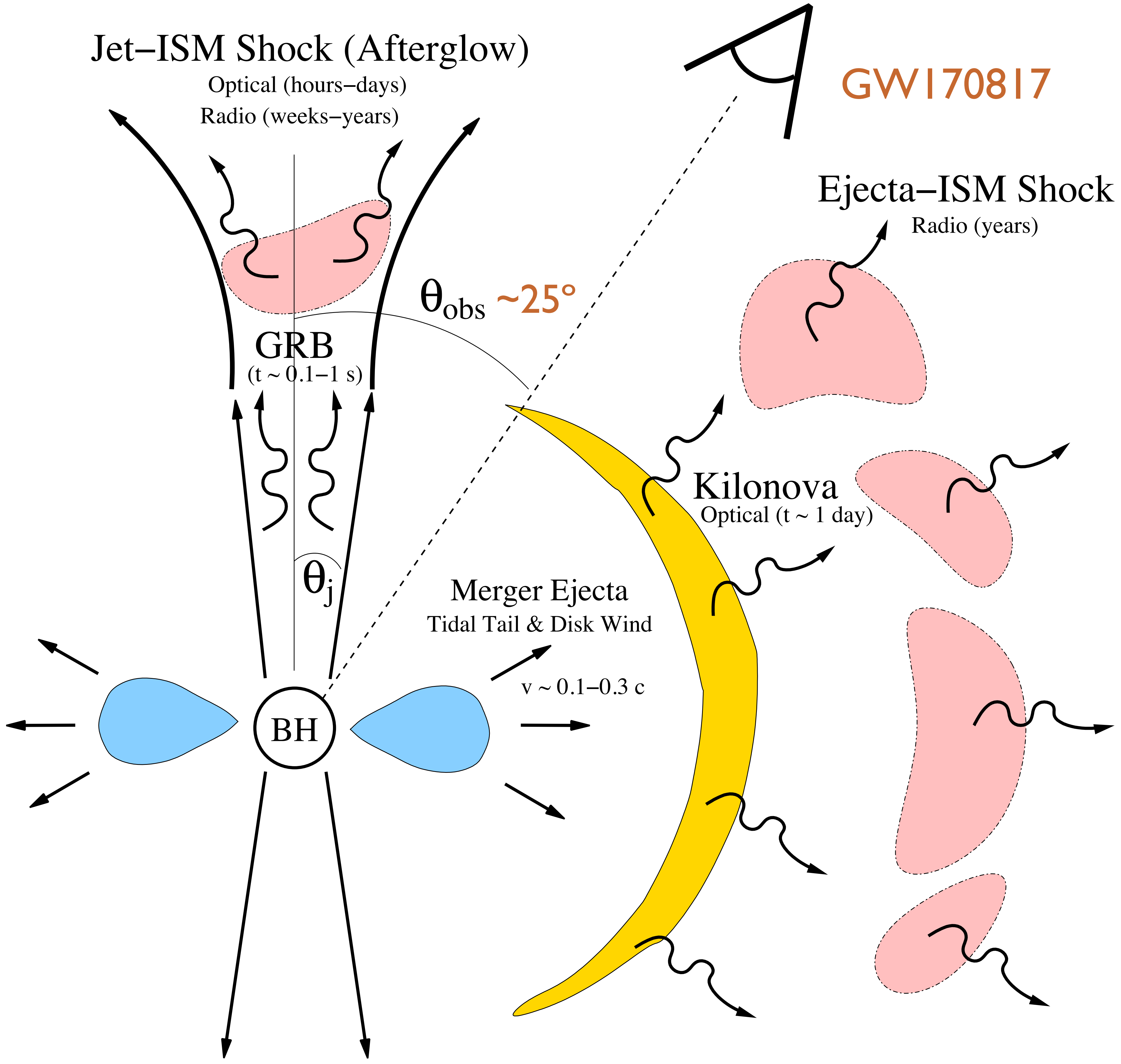


IceCube Coll, ApJ 843 (2017) 112
IceCube Coll., Fermi GBM Coll, Apj 939 (2022) 2
+strong limits from GRB221009A (the ``BOAT")
IceCube Coll ApJL 946 L26 (2023)
ANTARES Coll MNRAS 469 906 (2017)

Prompt (ΔT_{promt} ~1-100s): < 1% diffuse neutrino flux

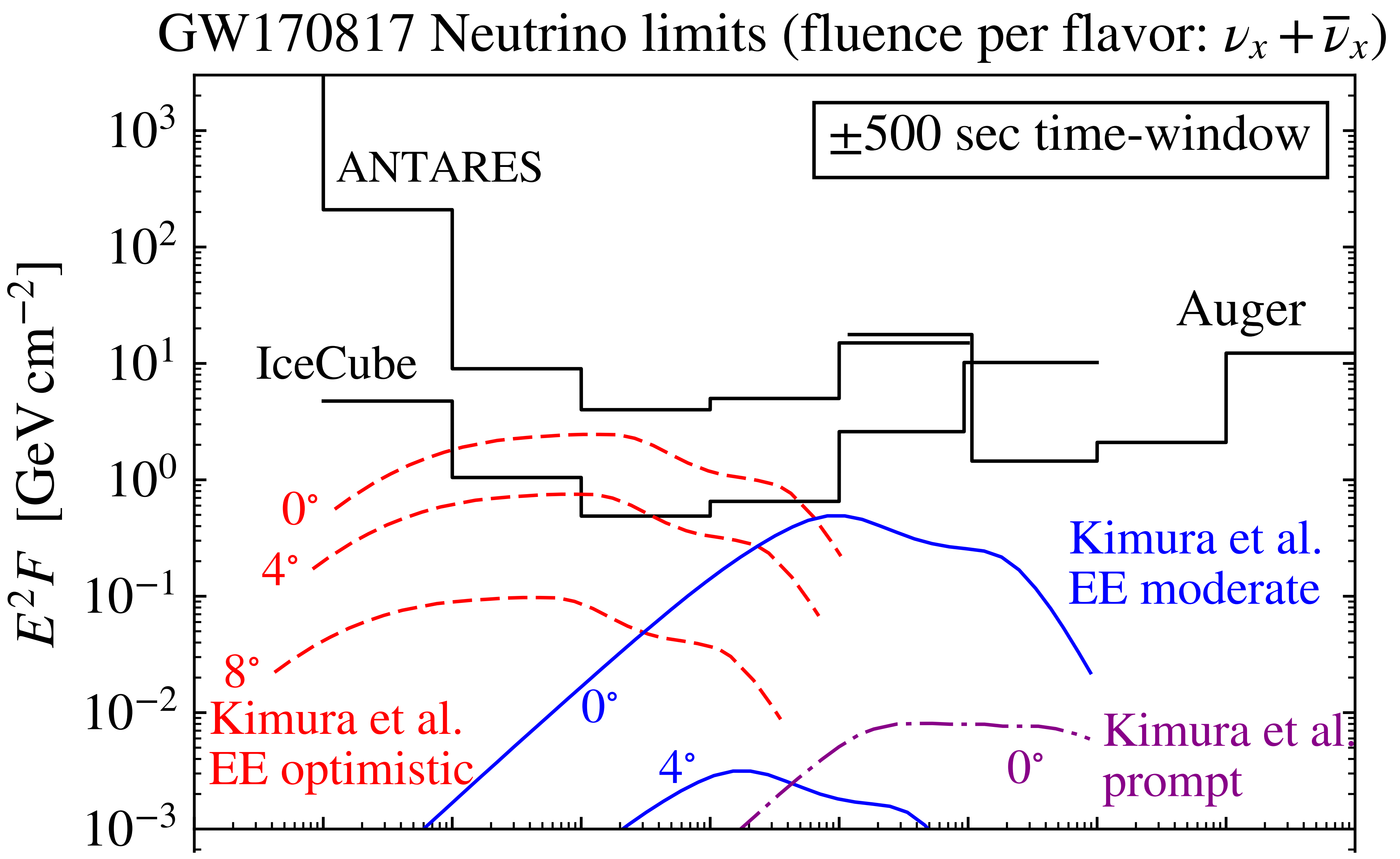
Precursor/Afterglow ($\Delta T_{afterglow}$ ± 14d): < 24% diffuse neutrino flux

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

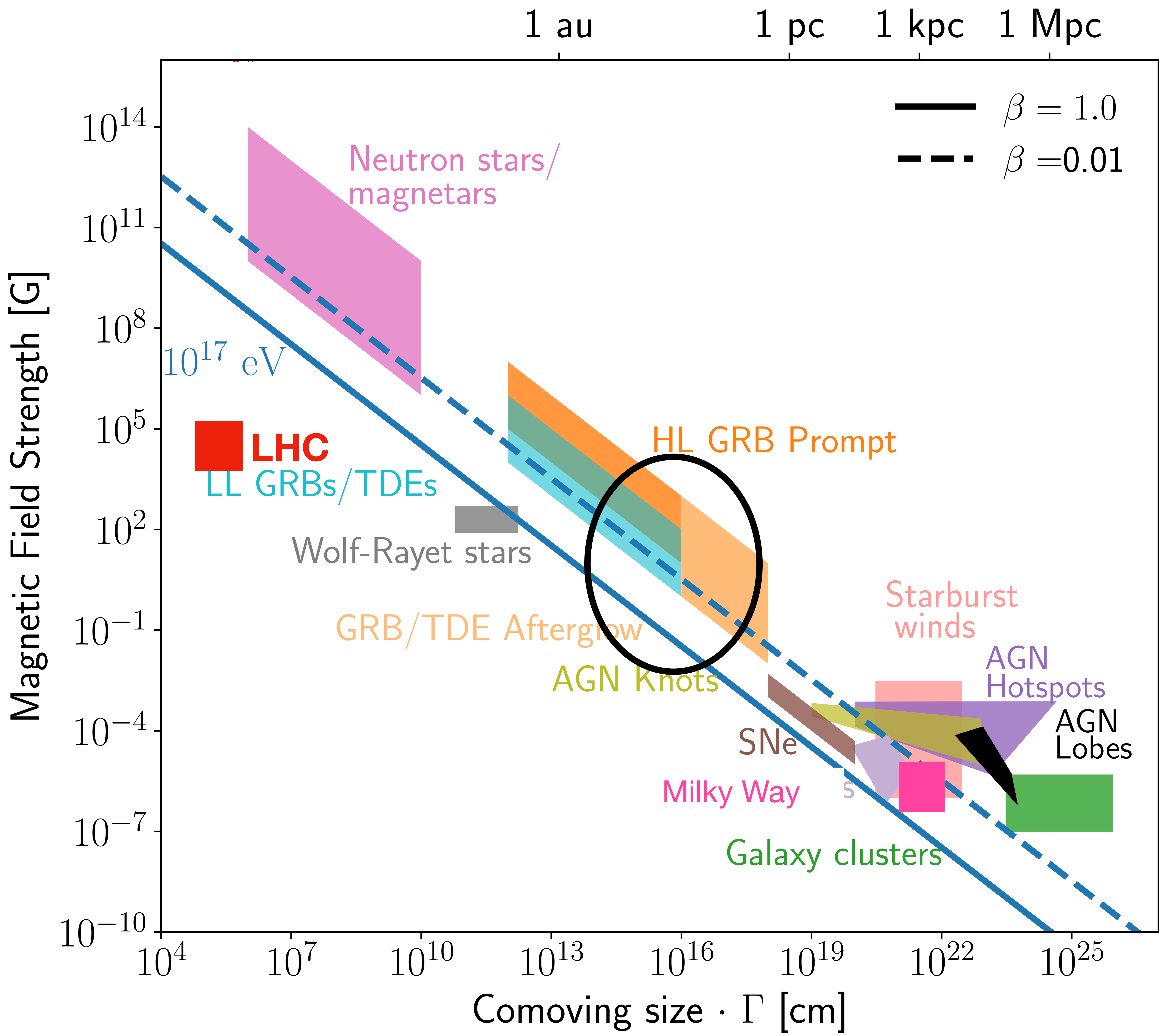
+ CR could sources of CRs up to the ankle

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

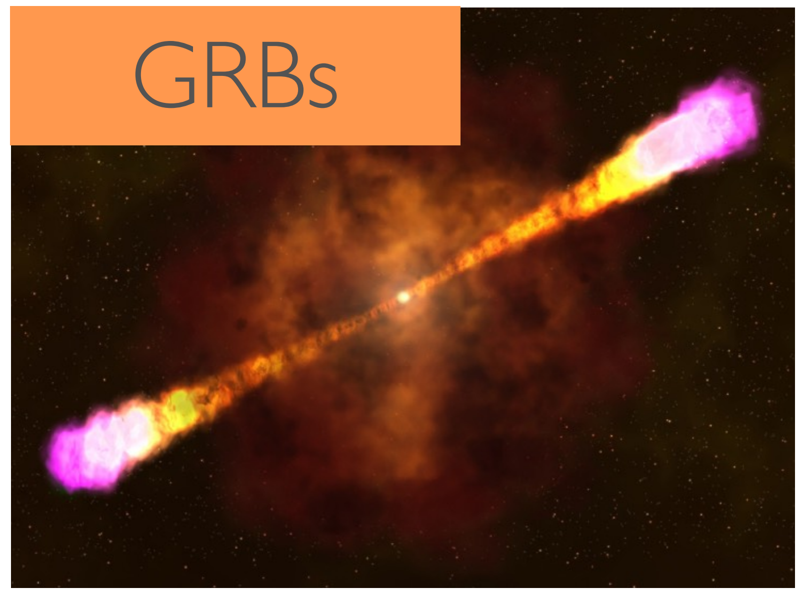
Scorecard

	$E_{\mathrm{max}}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_{ν}	Stacking UL
BL Lacs	😀	😞	😀	😞	≲20%
FSRQs	😀	😞	😀	😞	≲20%
FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN	😐	😀	😀	😀	≲100%
Starburst galaxies	😞	😀	😀	😀	≲100%
GRBs	😀	😐	😐	😐	≲1%
TDEs					

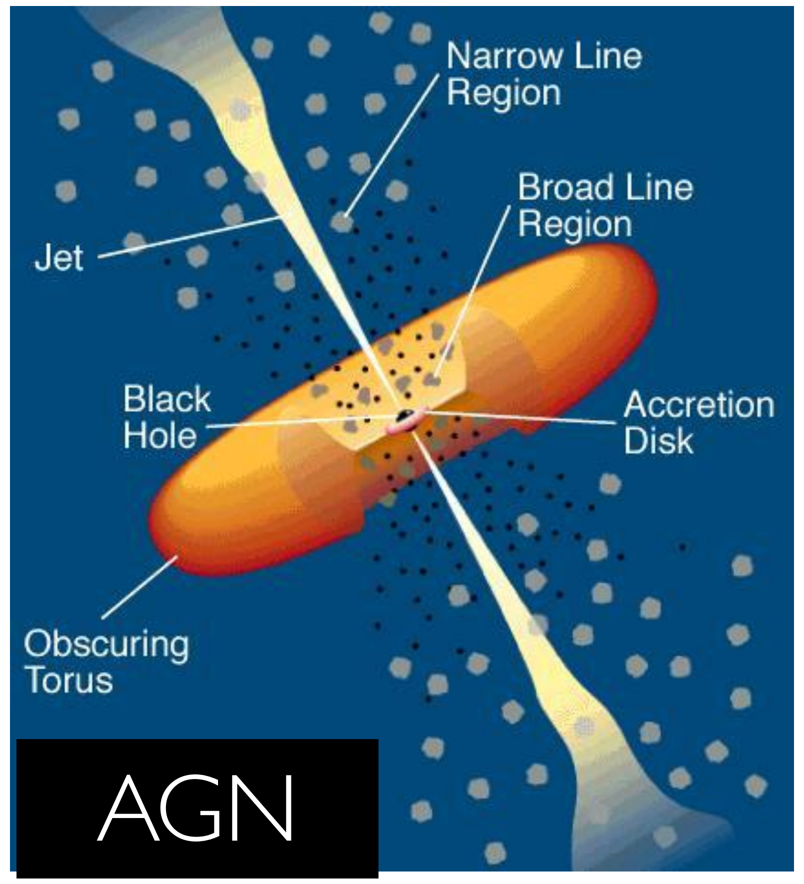
Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)




Neutron stars


GRBs


Starbursts



AGN

Tidal disruption events

SMBHs are orbited by star clusters

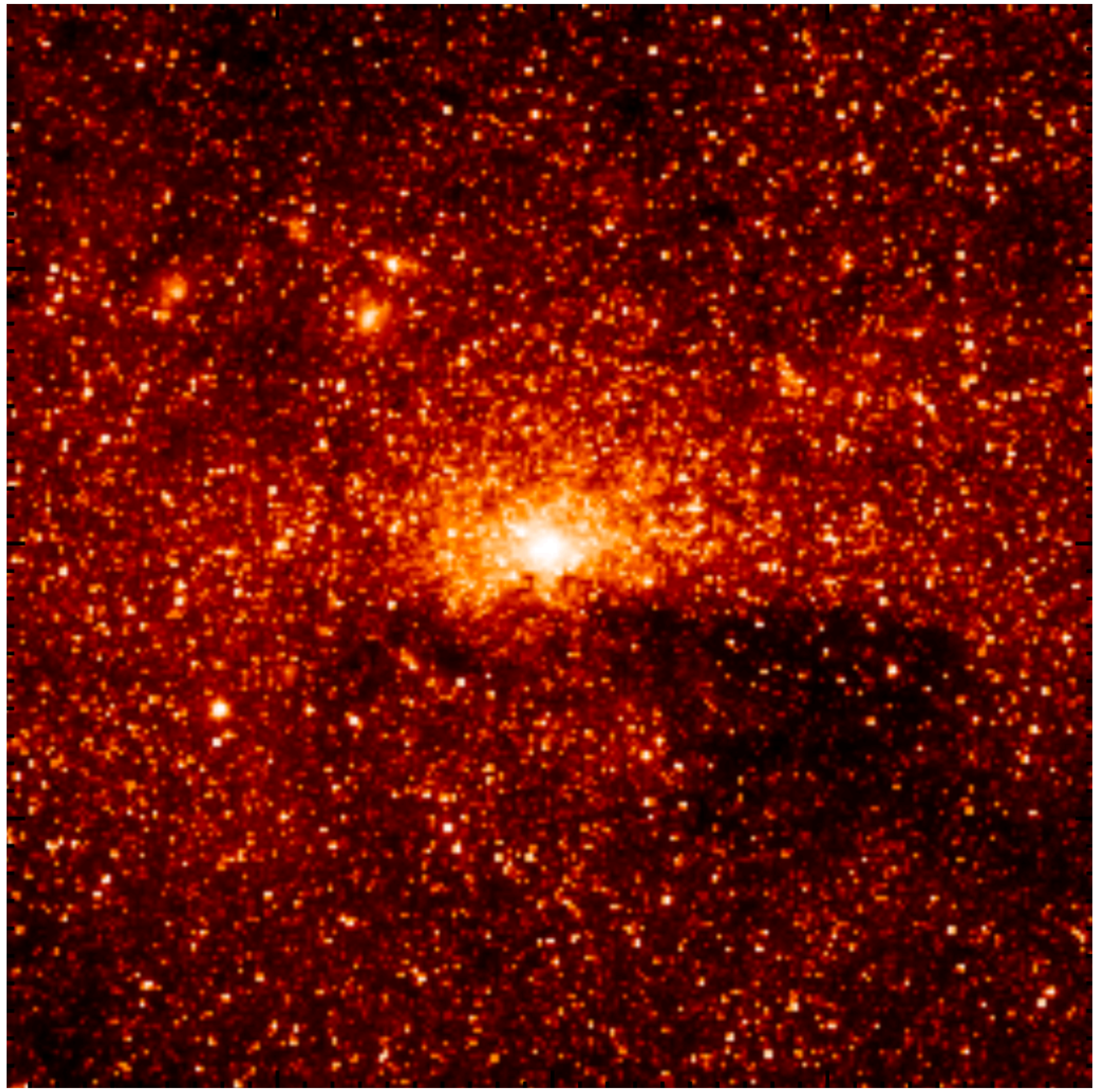
Millions of stars in random orbits

Tidal forces may deform, or tear into pieces a star

One TDE in 10^{4}-10^{9} years per SMBH

For tidal forces to be relevant they must be stronger than the star's self gravity

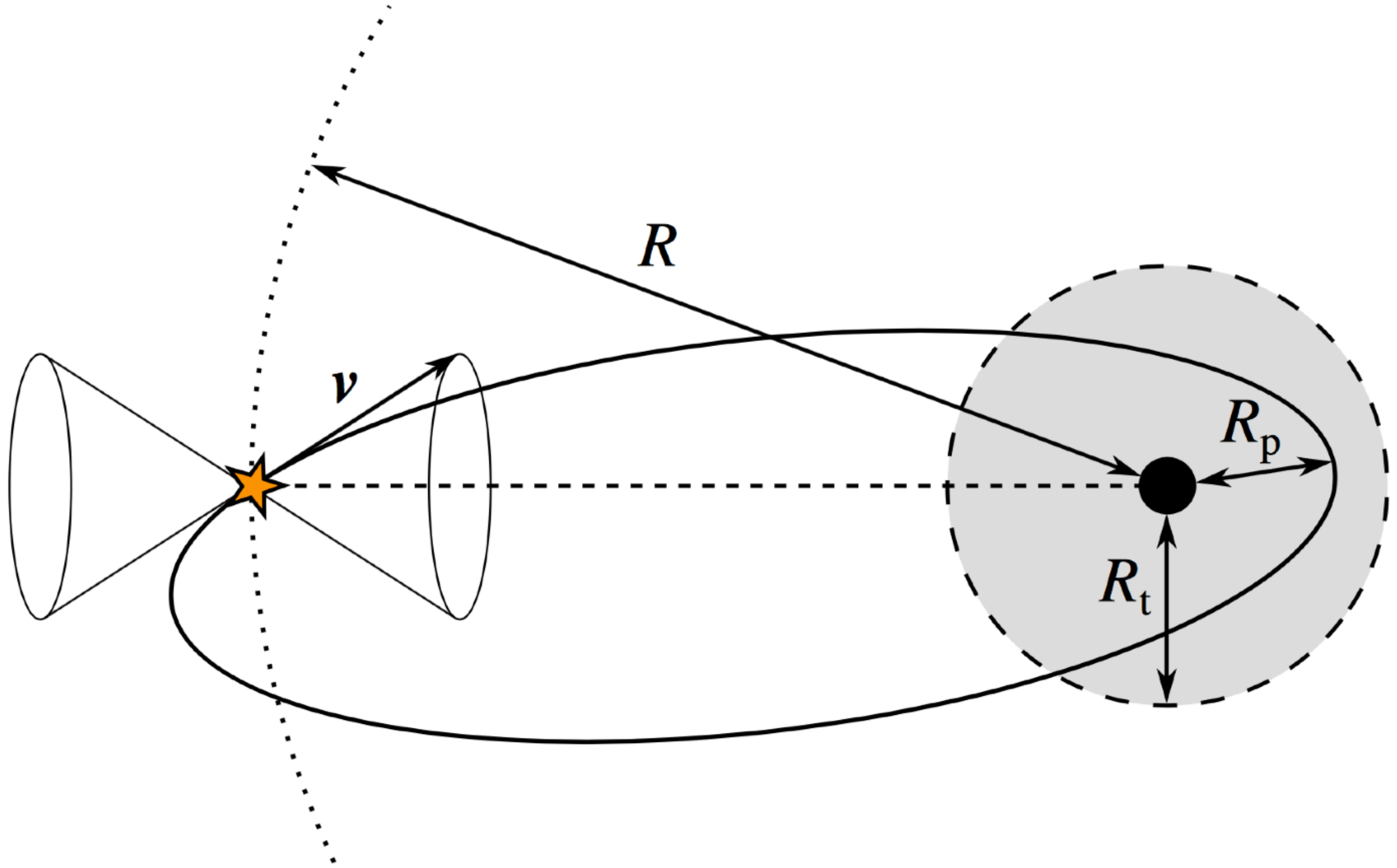
$$\frac{GM_{\mathrm{SMBH}}R_\star}{R_t^3} = \frac{GM_\star}{R_\star^2}$$



Tidal disruption events

$$\frac{GM_{\text{SMBH}}R_\star}{R_t^3} = \frac{GM_\star}{R_\star^2}$$

For tidal disruption to occur $R_p < R_t$



R_t must be outside the event horizon for visible TDE

The Schwarzschild radius is

$$M_{\text{SMBH}} \leq M_\star^{-1/2}\left(\frac{c^2R_\star}{2G}\right)^{3/2} \approx 10^8 M_\odot \left(\frac{R_\star}{R_\odot}\right)^{3/2}\left(\frac{M_\star}{M_\odot}\right)^{-1/2}$$

For $R_t > r_s$

Tidal disruption events

Flare of electromagnetic radiation at high peak luminosity (X-rays)

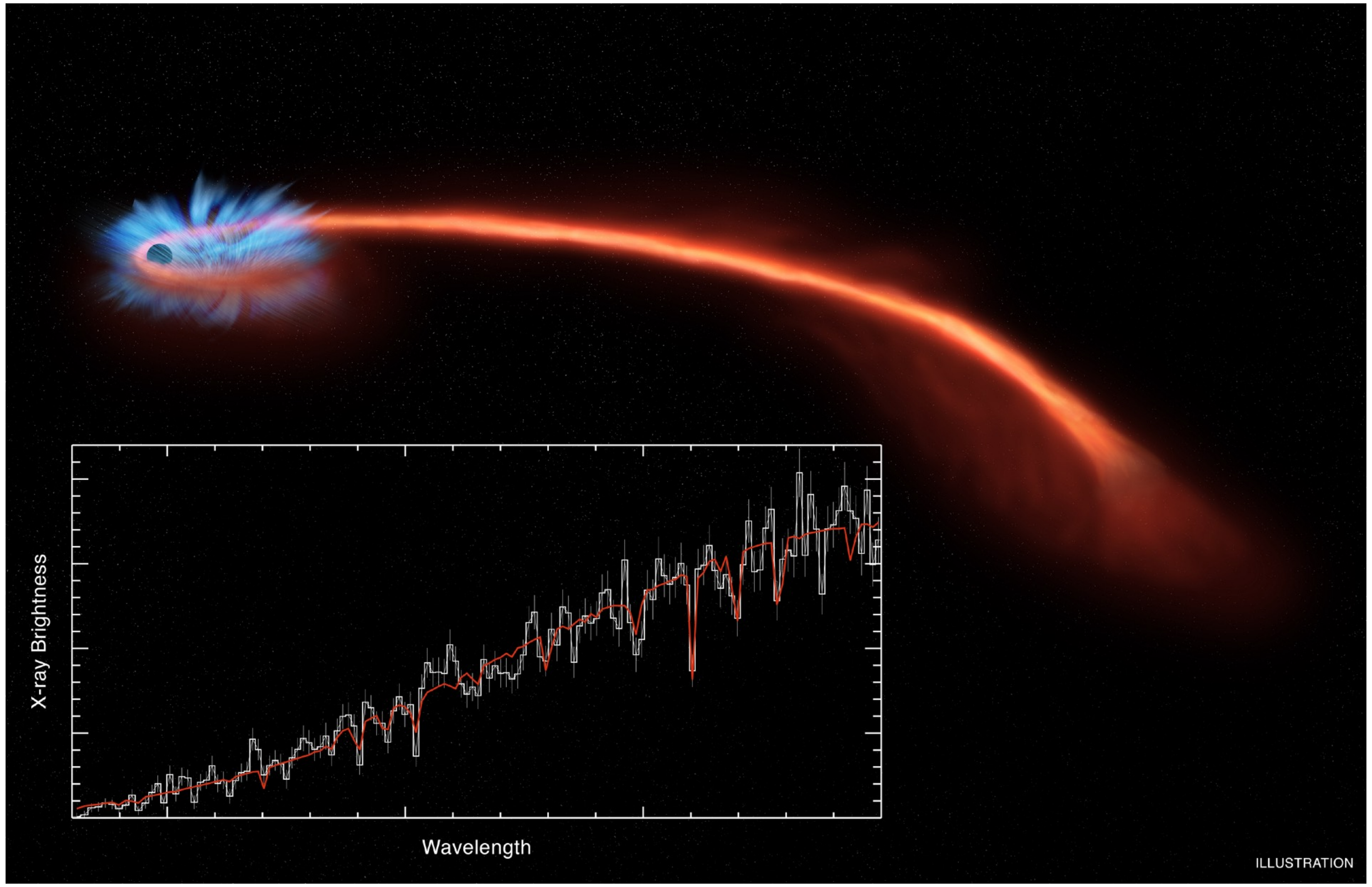
Located in the core of an otherwise quiescent, inactive galaxy

Extreme flares can host a relativistic hadronic jet

Typically 50% of the star's mass expected to stay bound to the SMBH and be ultimately accreted

~100 candidate TDEs observed so far, 3 with jets (hard X-ray spectrum)

Timescale of months to years



Swift J1644+57

Test case, Swift J1644+57, jetted TDE observed in ``blazar'' mode

Observed for ~600 days, in a small quiescent galaxy in the Draco constellation at z = 0.35

$$E_{\max} \sim 10^{20}\ \mathrm{eV}\, Z \frac{BR}{3 \times 10^{17}\ \mathrm{G\ cm}} \frac{\Gamma}{10}$$

Swift J1644+57

Test case, Swift J1644+57, jetted TDE observed in ``blazar'' mode

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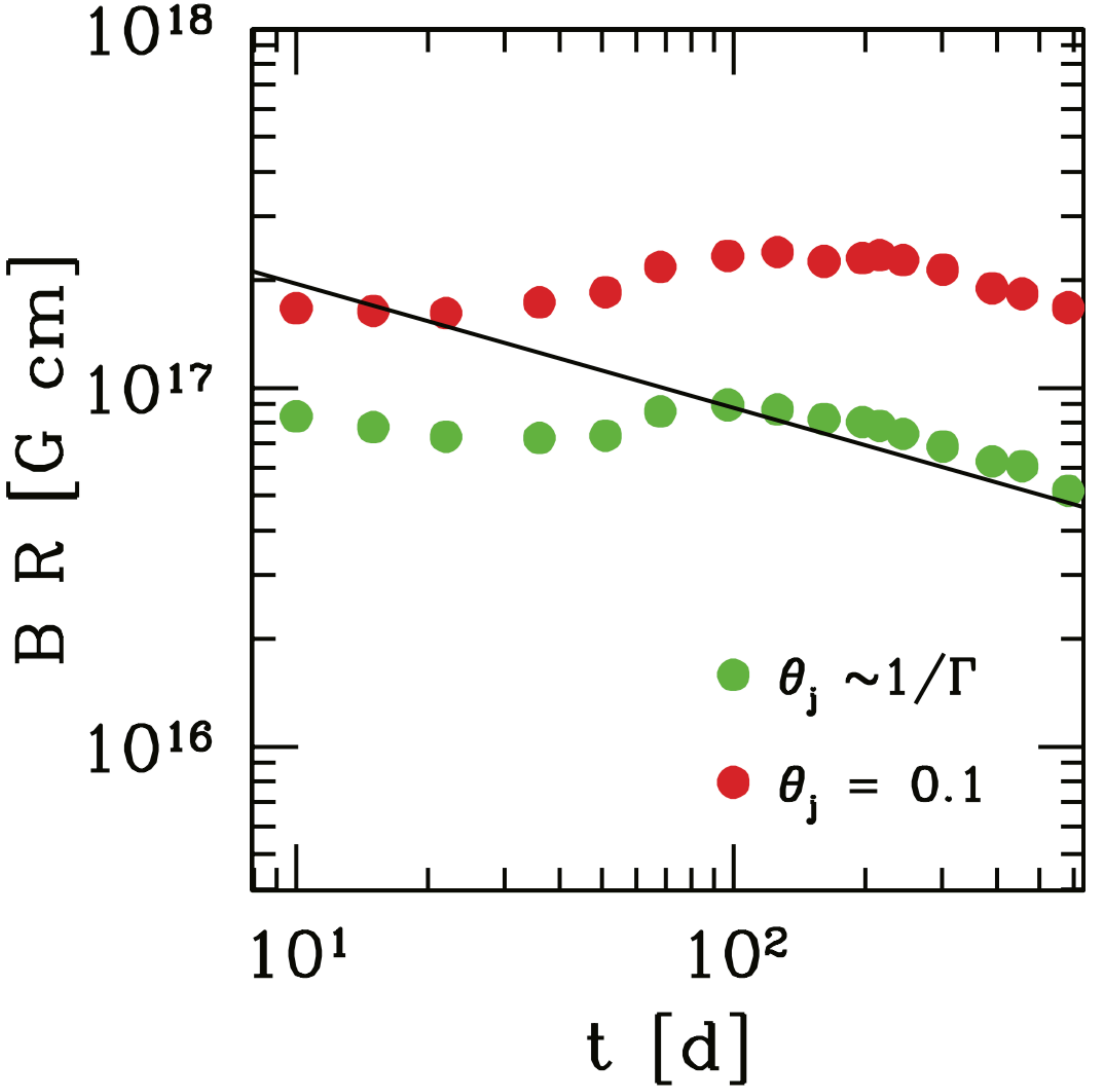
$$E_{\rm max} \sim 10^{20}\ {\rm eV}\, Z \frac{BR}{3\times 10^{17}\ {\rm G\ cm}} \frac{\Gamma}{10}$$

For Swift J1644+57 from radio observations in the outer jet (but dependent on assumed opening angle of jet)

$$BR \gtrsim 1 - 3\times 10^{17}\ {\rm G\ cm}$$

Farrar & Piran 2014



Can TDEs be the main sources of UHECRs?

The ``apparent” source number density must satisfy the observational bound, with δt the spread in arrival times

$$n_{\mathrm{eff}} \sim \delta t \cdot \rho$$

From Auger

$$n_{\mathrm{UHECR}} \gtrsim 2 \times 10^{-5}\ \mathrm{Mpc}^{-3}$$

The observed rate of jetted TDEs

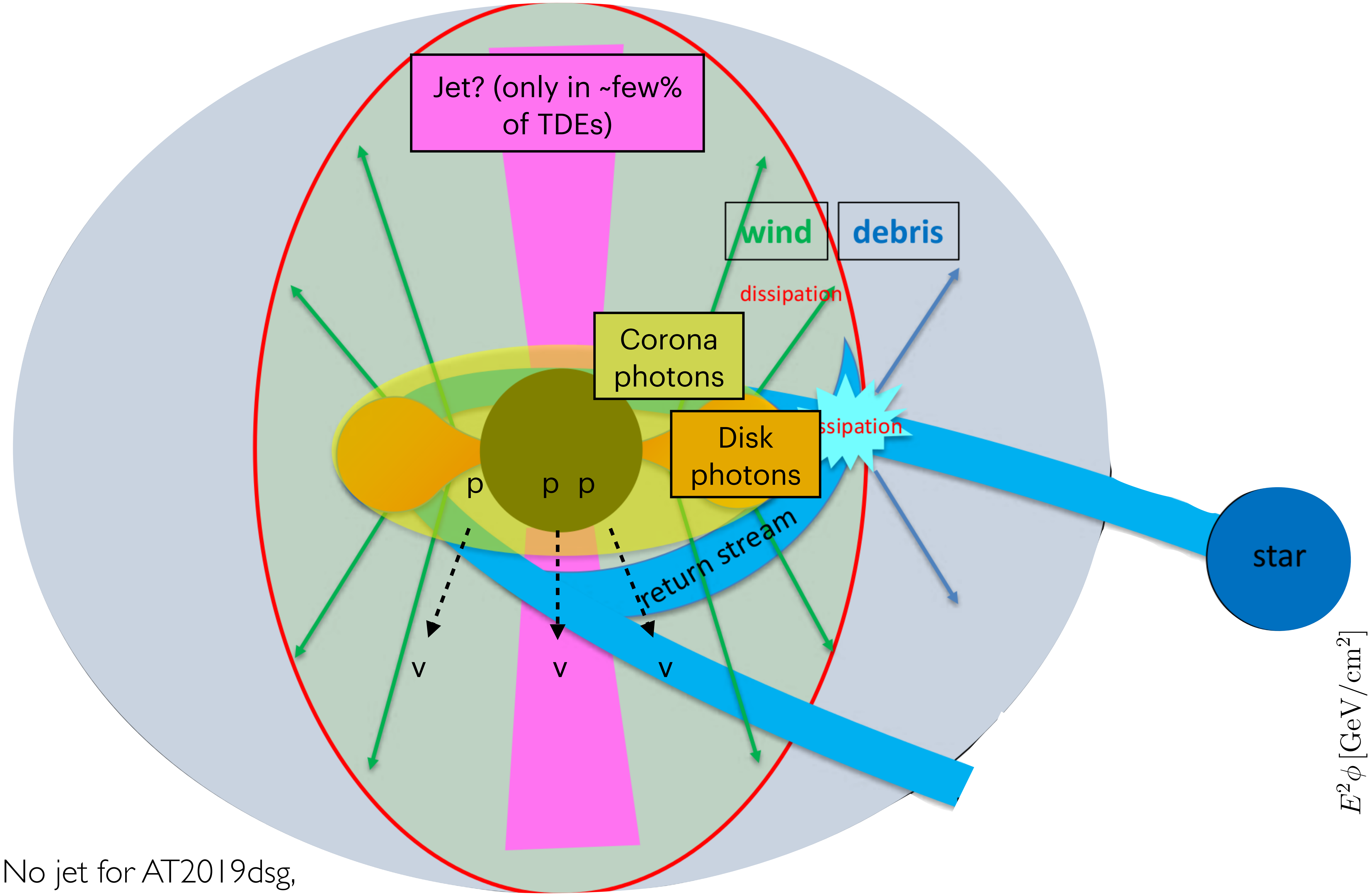
$$\rho \approx 10^{-11} - 10^{-10}\ \mathrm{Mpc}^{-3}\ \mathrm{year}^{-1}$$

TDEs can satisfy the number density requirement if

$$\delta t_{\mathrm{delay}} \approx 10^{5}\ \mathrm{yr} \cdot \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{2} \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2} \left(\frac{\lambda_{\mathrm{coh}}}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{1\,\mathrm{nG}}\right)^{2}$$

Neutrino production in TDEs

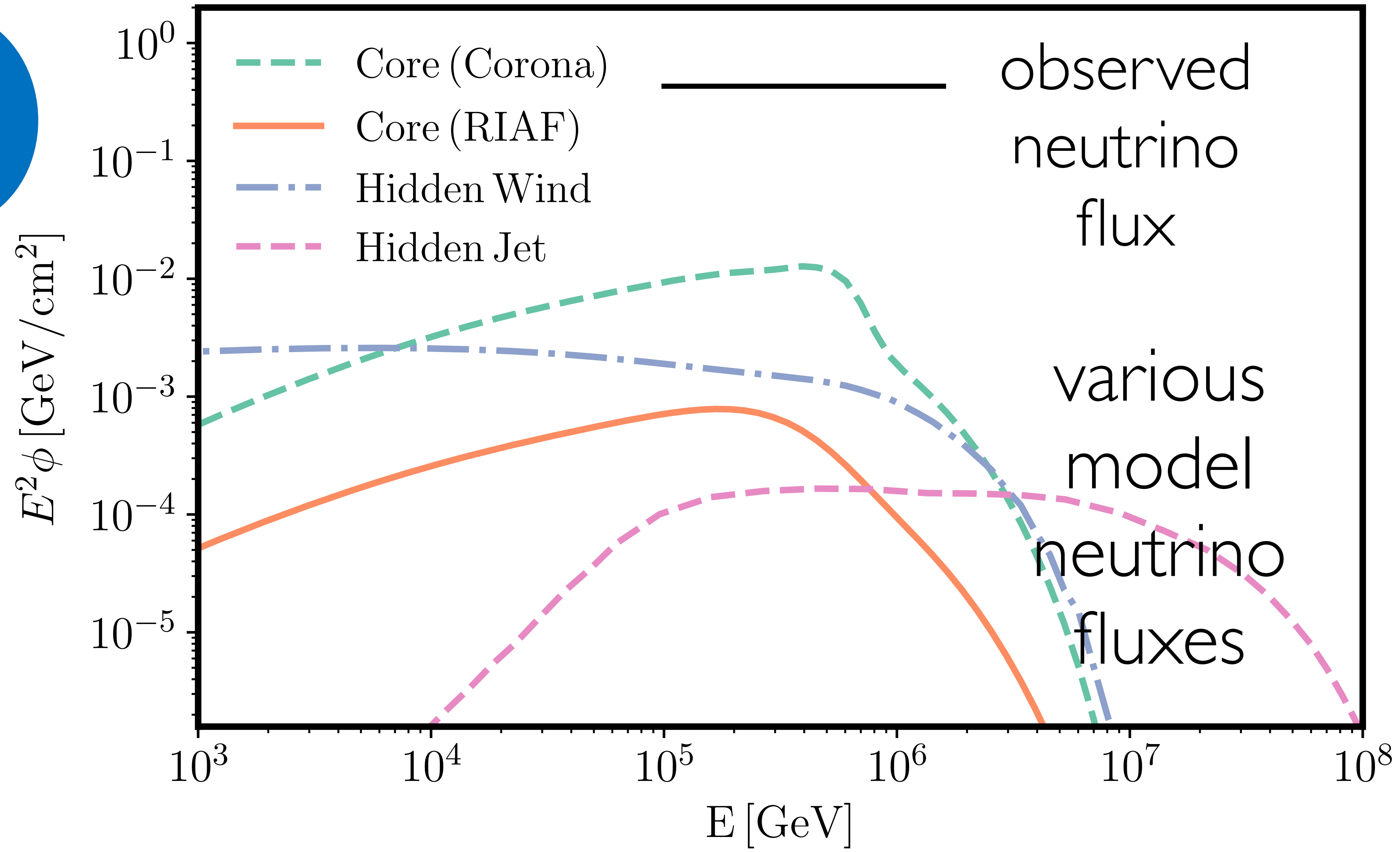
see also Hayasaki et al 2019
Winter, Lunardini 2020
Winter, Lunardini 2022
Banik & Bharda 2022



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

Example neutrino spectra (AT2019dsg)

Murase, Zhang, Kimura, FO, Petropoulou 2020



Neutrinos from TDEs?

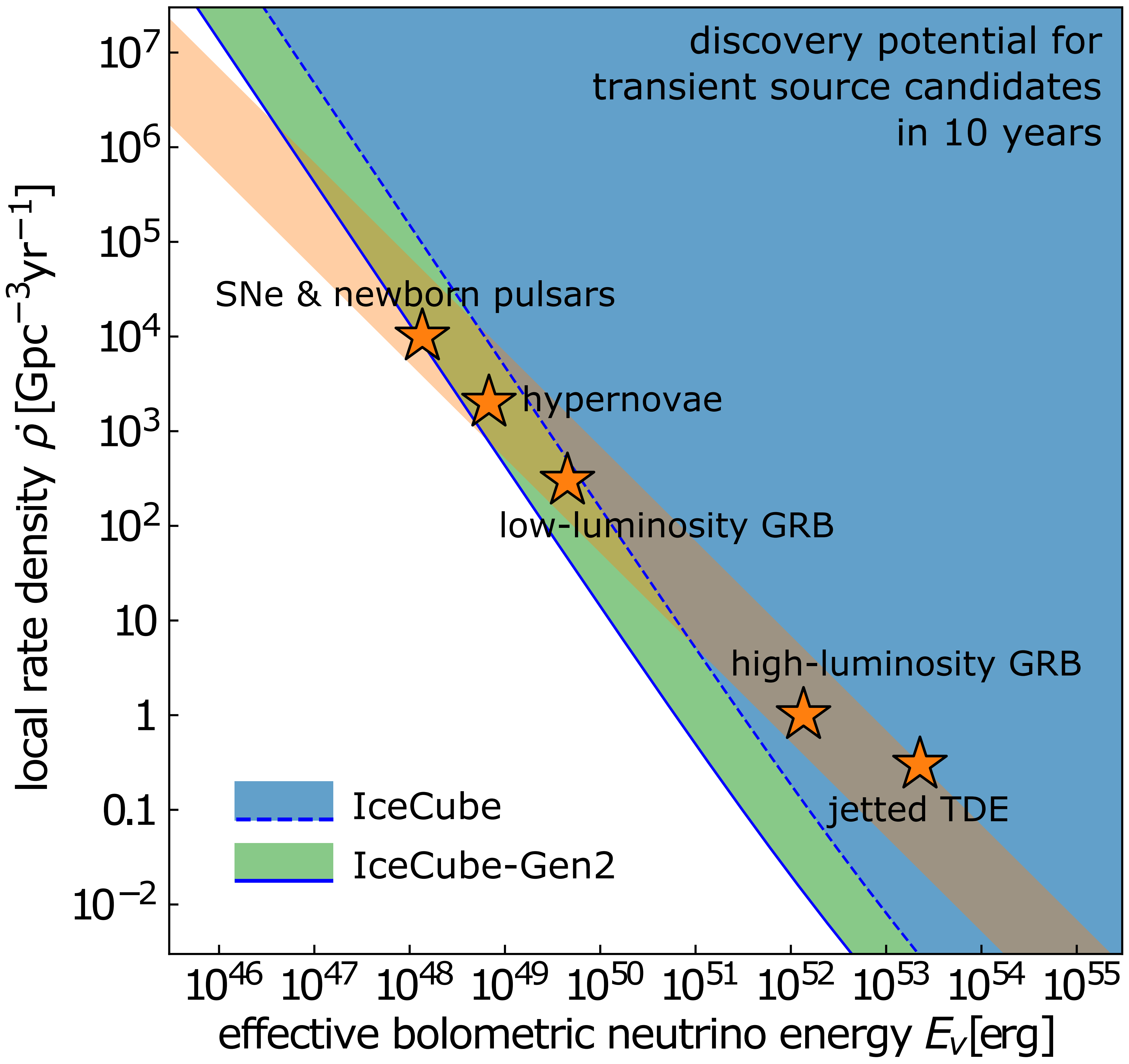
Photopion interactions in the jet (conditions similar to AGN/GRB)

One problem is that jetted TDEs are very rare

$n = 10^{-11}$ Mpc^3 cf GRBs, $n = 10^{-9}$ Mpc^3

Non-jetted TDEs 10 -100 times more numerous, but not clear if (where?) they accelerate 10^{17} eV protons

Stacking limits from IceCube (jetted TDEs < 1%, non-jetted < 26%)

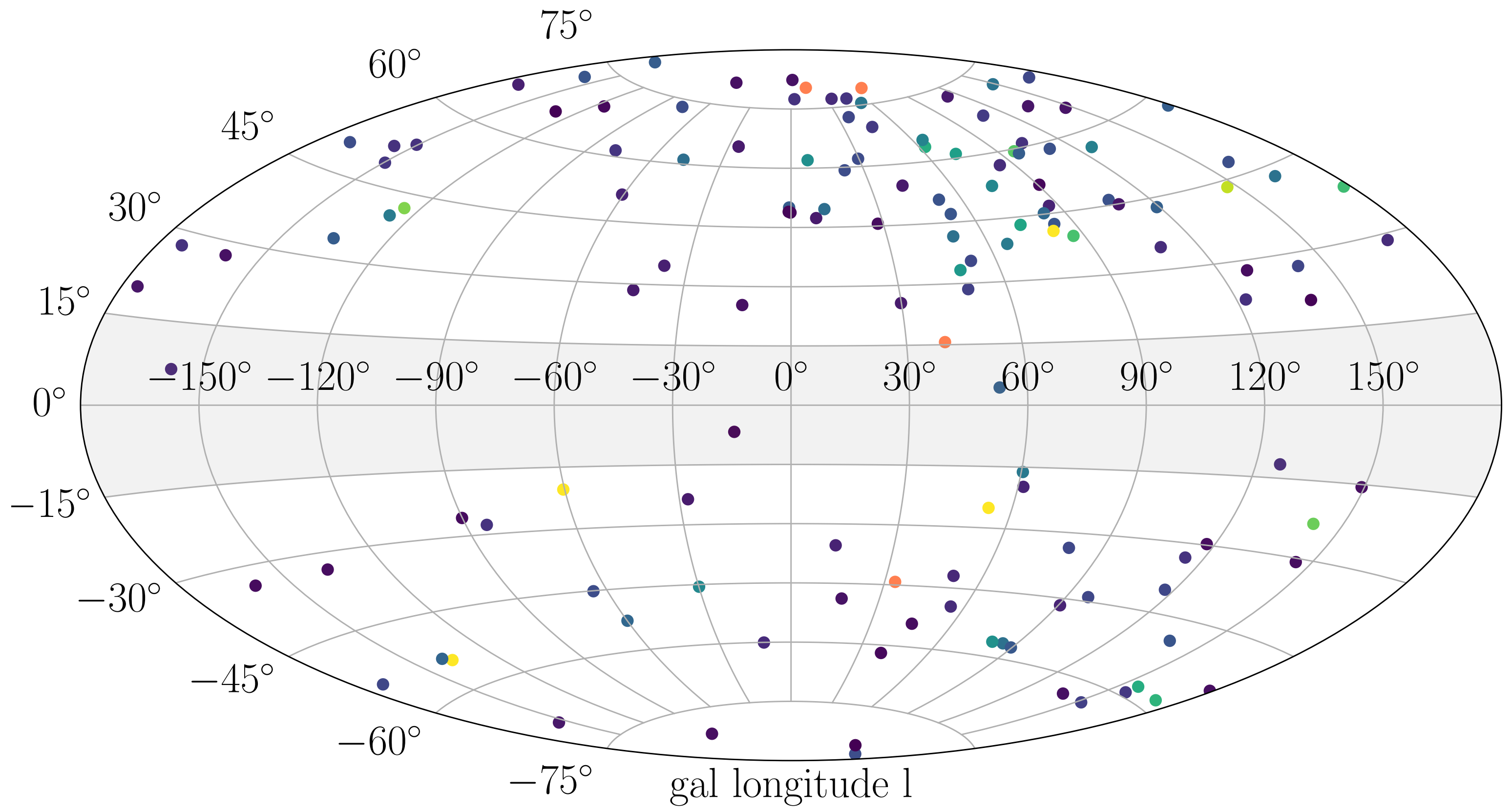


TDE contribution to the cosmic−neutrino flux

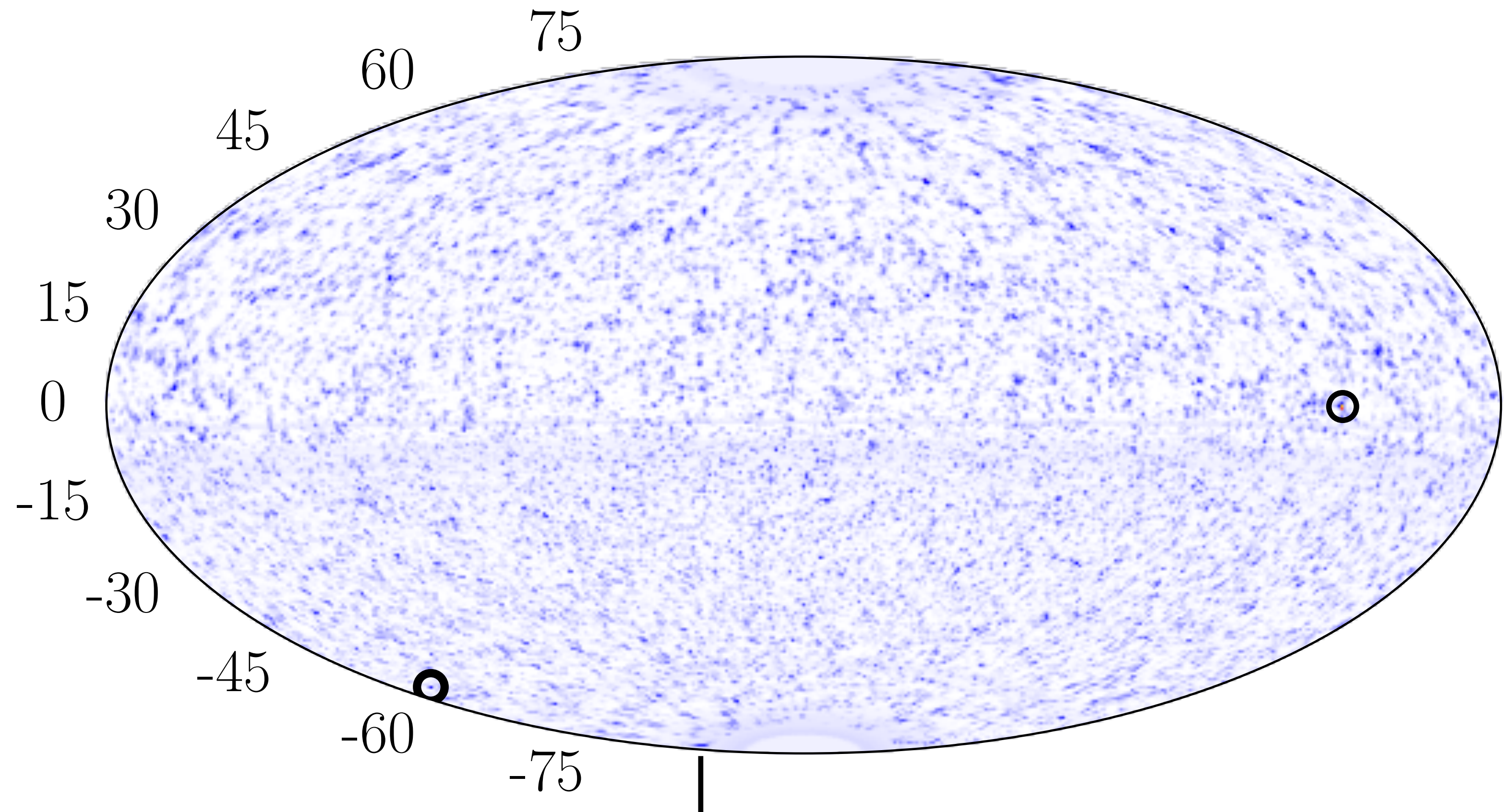
3 jetted TDEs
40 non-jetted TDEs (mixture of X-ray / UV / optical TDEs)

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%

Tidal disruption events

X-ray observed TDEs

tidally disrupted star
in the vicinity of a
Massive Black Hole

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

TDEs coincident with high−energy neutrinos

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

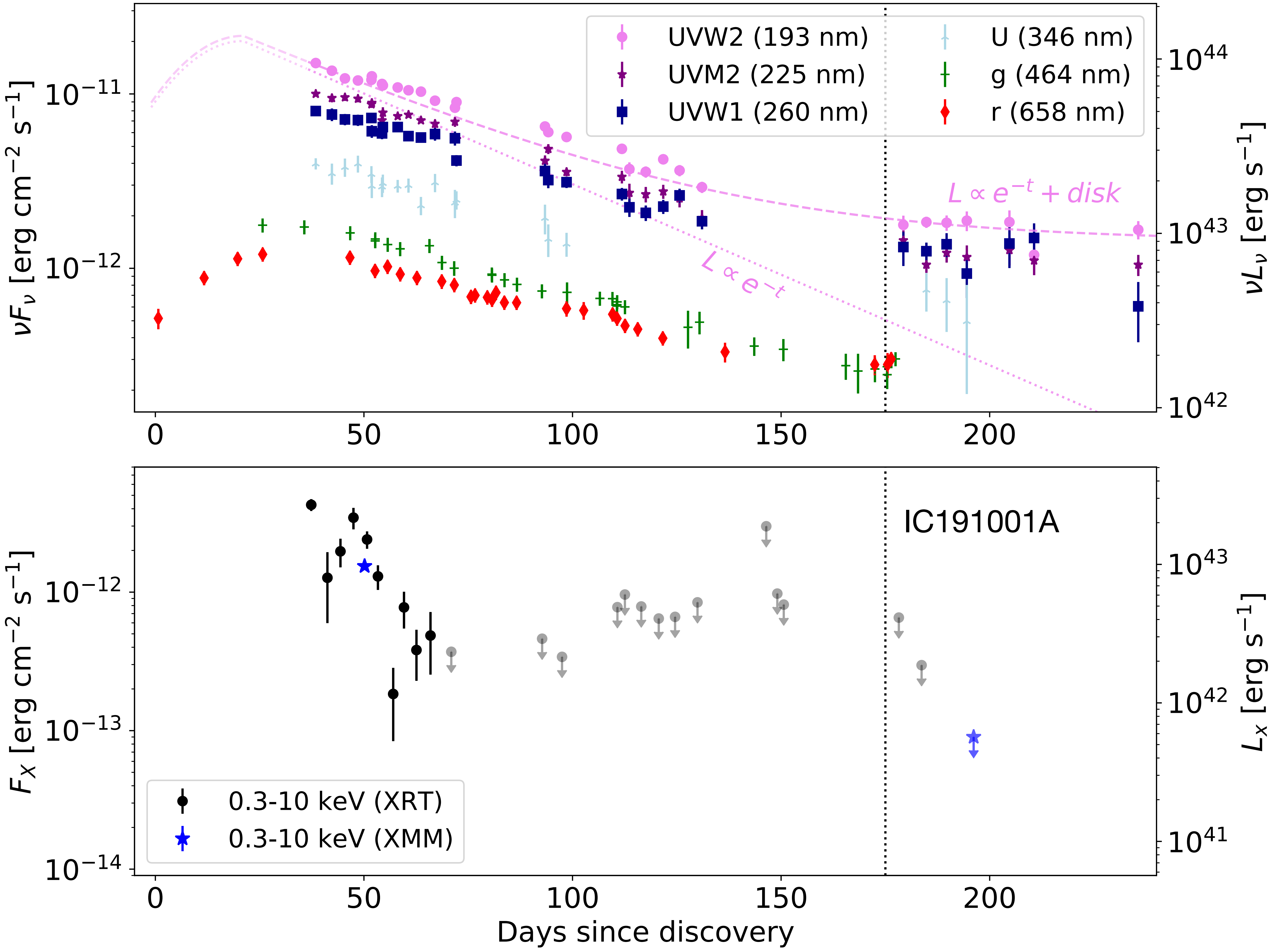
tidally disrupted star in the vicinity of a Massive Black Hole

combined significance: 3.7σ

AT2019dsg + IC191001A

UV optical flux

X-ray flux



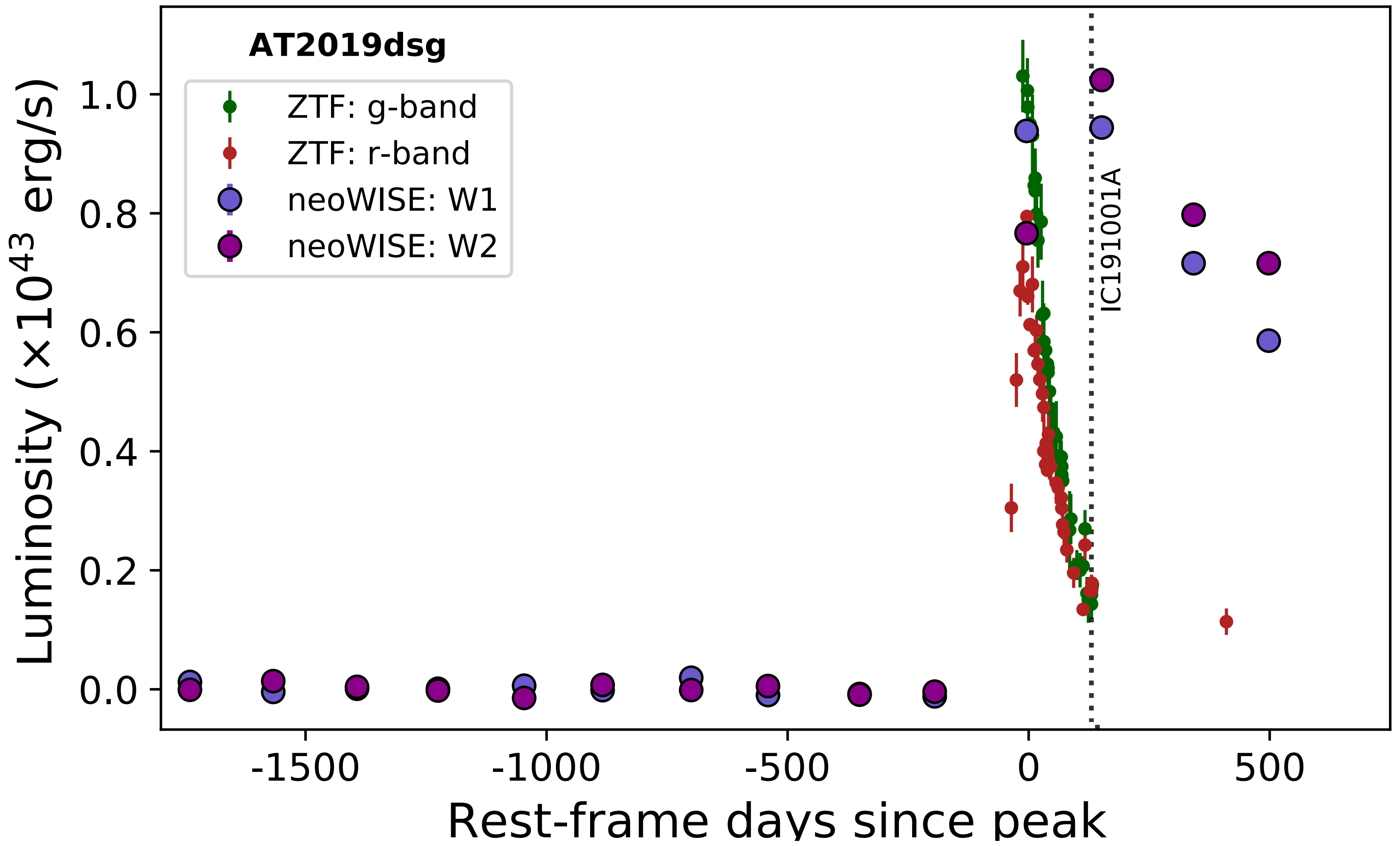
IC 191001A was a 200 TeV muon neutrino (pAstro ~ 60%)

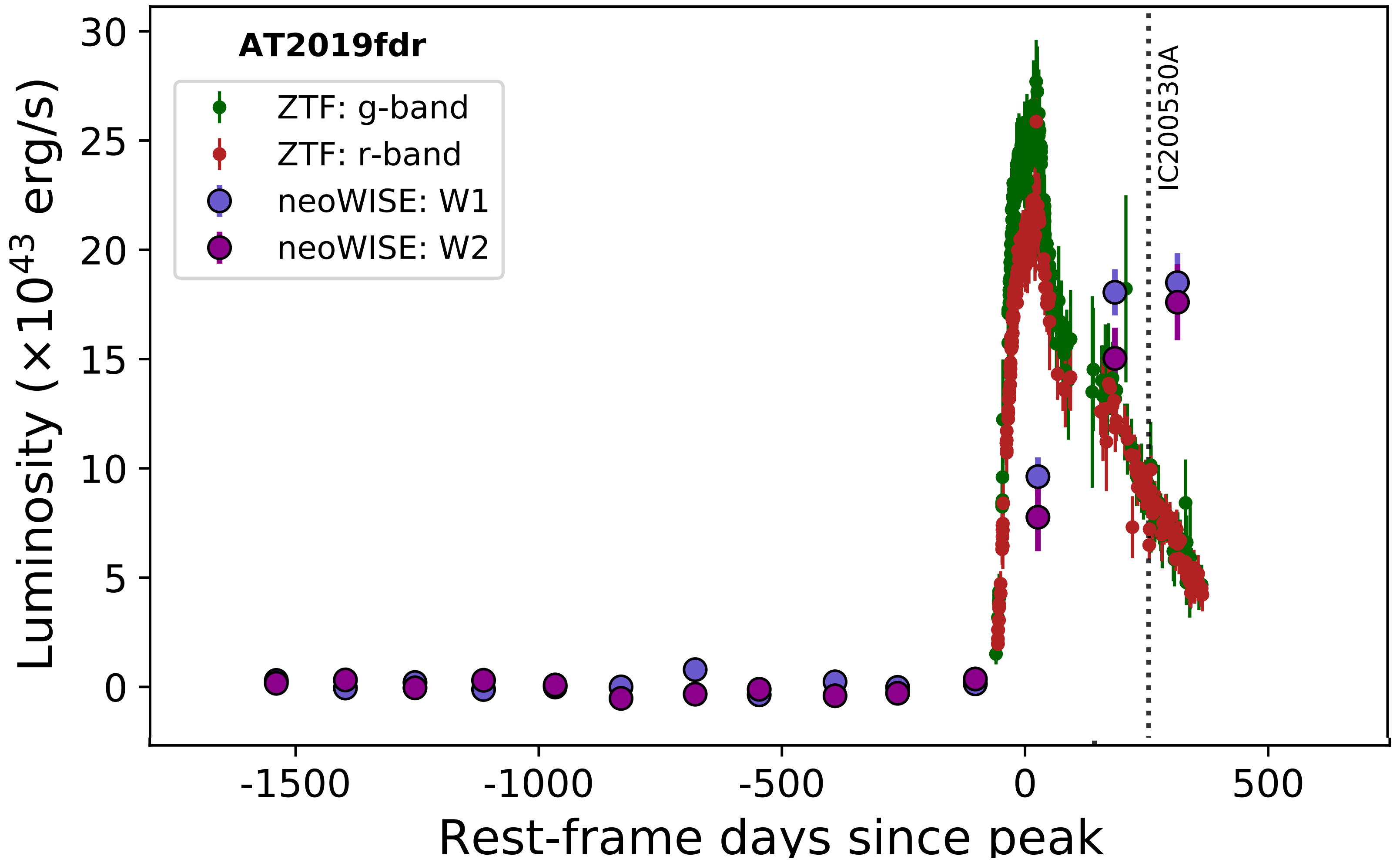
AT 2019dsg was a rare (radio emitting) TDE sign of jet?

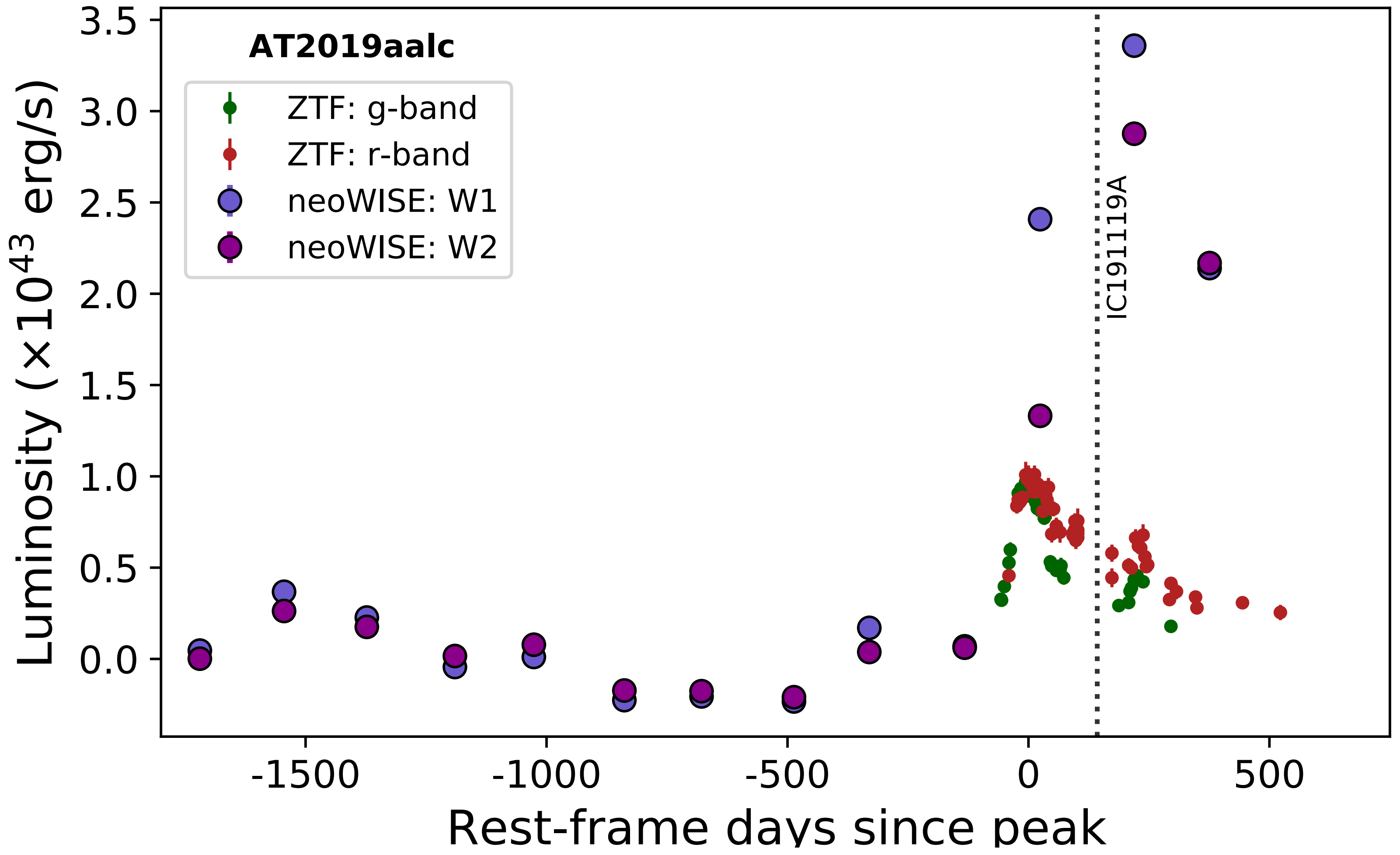
IC 191001A +AT 2019dsg association by chance? p = 0.5%

AT2019fdr+IC200530A, AT2019aalc+IC191119A

Van Velzen et al 2021.09391



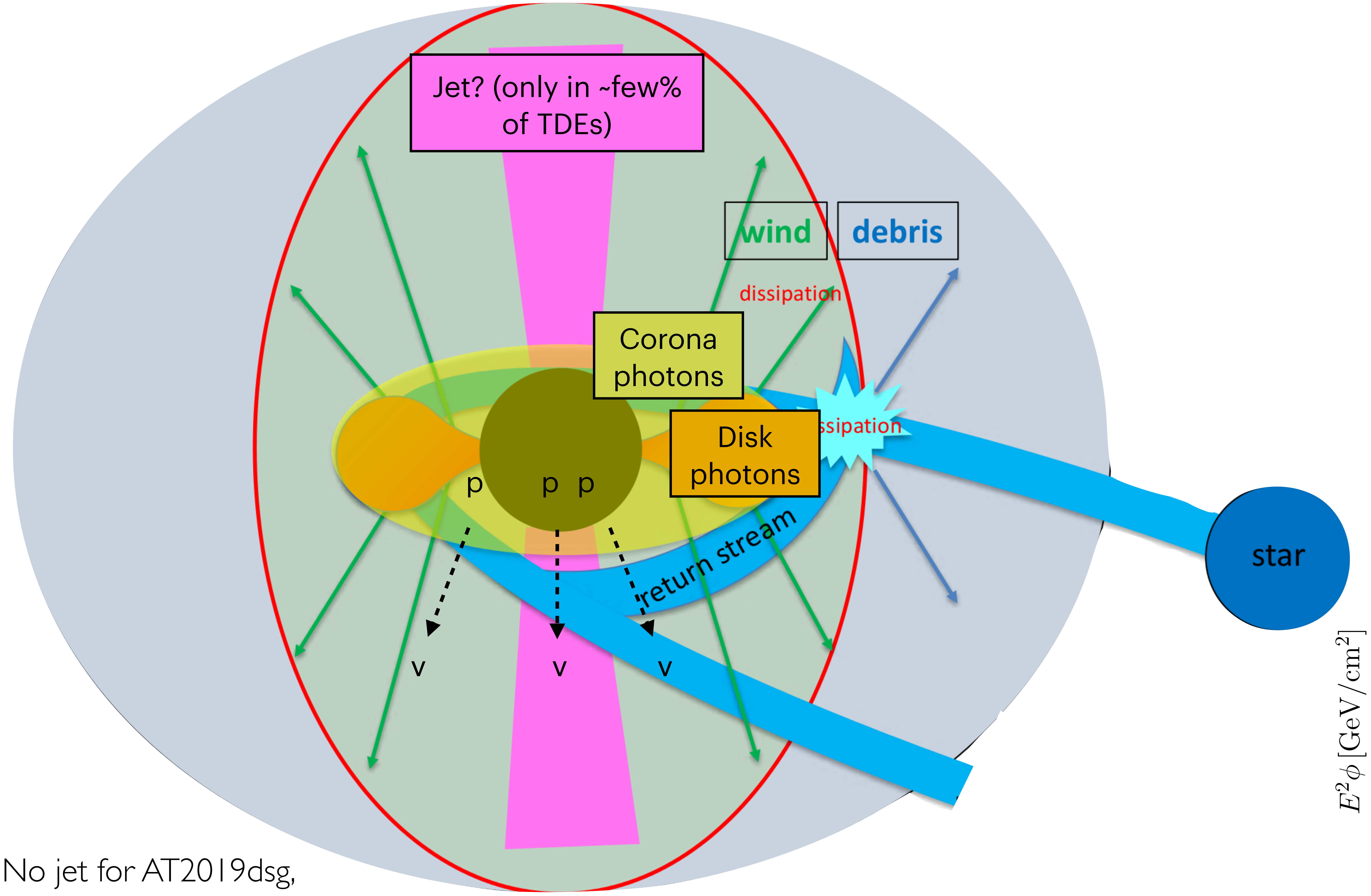




Combined significance 3.7σ

Neutrino production in AT2019dsg

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



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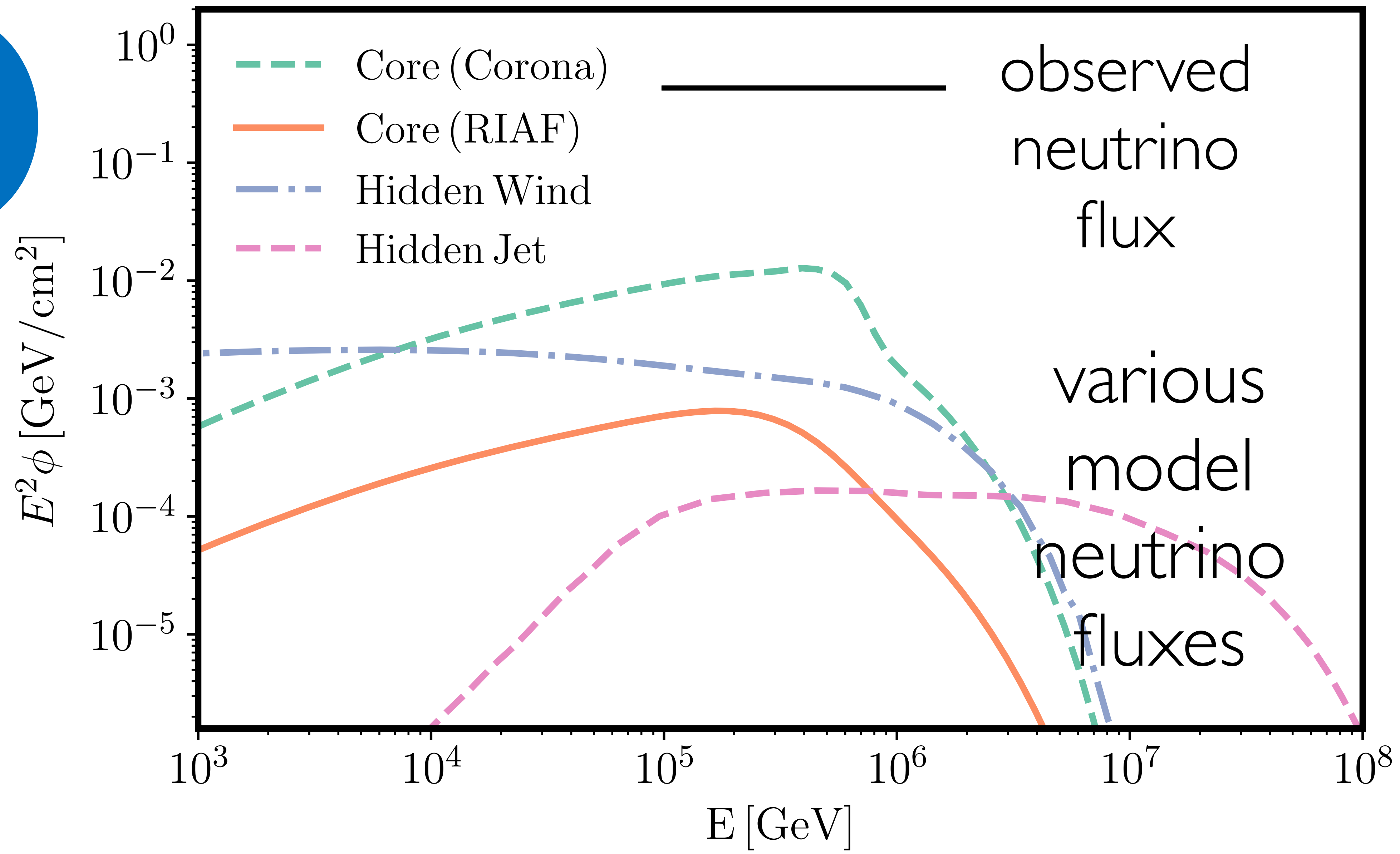

Scorecard

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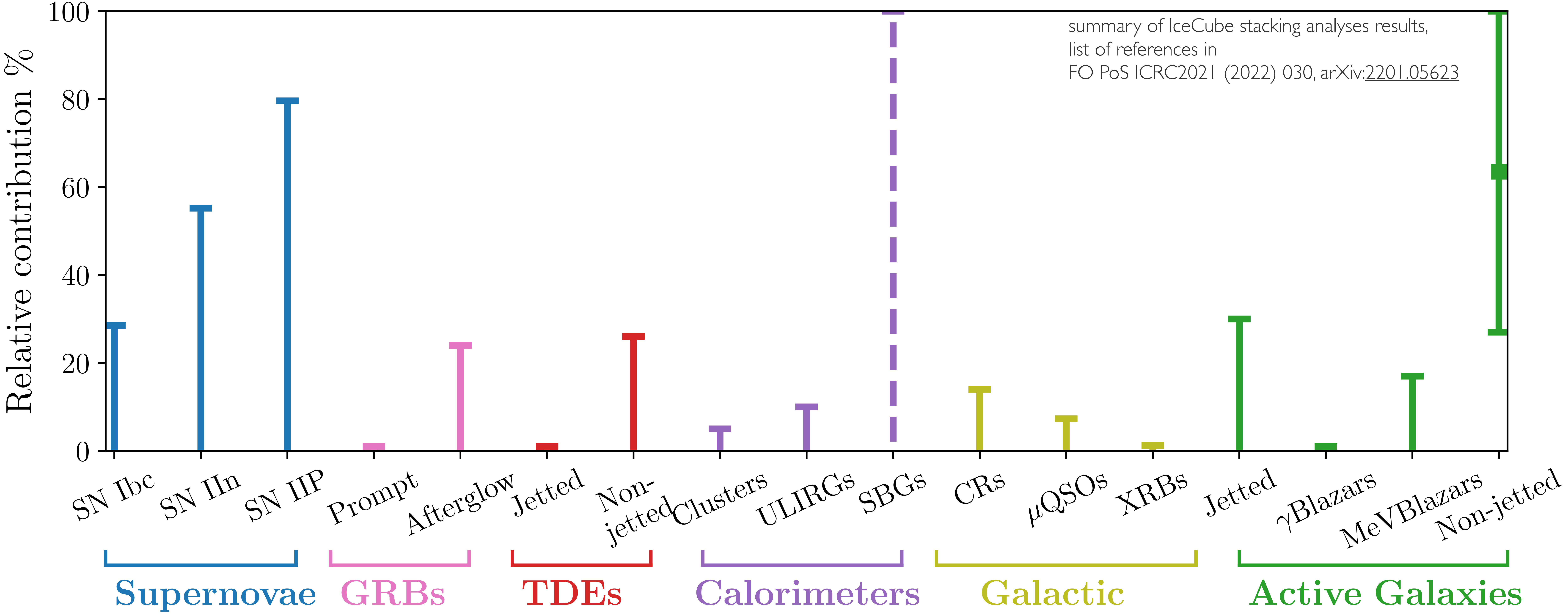
BL Lacs	😀	😞	😀	😞	$\lesssim$20%
FSRQs	😀	😞	😀	😞	$\lesssim$20%
FR I	😀	😀	😀	😀	$\lesssim$20%
FR II	😀	😀	😀	😀	$\lesssim$20%
Non-jetted AGN	😐	😀	😀	😀	$\lesssim$100%
Starburst galaxies	😞	😀	😀	😀	$\lesssim$100%
GRBs	😀	😐	😐	😞	$\lesssim$1%
Jetted TDEs	😀	😞	😞	😞	$\lesssim$3%

The current neutrino source landscape: Stacking upper limits



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

Scorecard

	$E_{\max}^{\mathrm{UHECR}}$	n_{UHECR}	$\dot{\varepsilon}_{\mathrm{UHECR}}$	n_{ν}	Stacking UL
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FR I	😀	😀	😀	😀	≲20%
FR II	😀	😀	😀	😀	≲20%
Non-jetted AGN	😐	😀	😀	😀	≲100%
Starburst galaxies	😞	😀	😀	😀	≲100%
GRBs	😀	😐	😐	😞	≲1%
Jetted TDEs	😀	😞	😞	😞	≲3%

*(but problems at medium E)

Thank you for your attention!