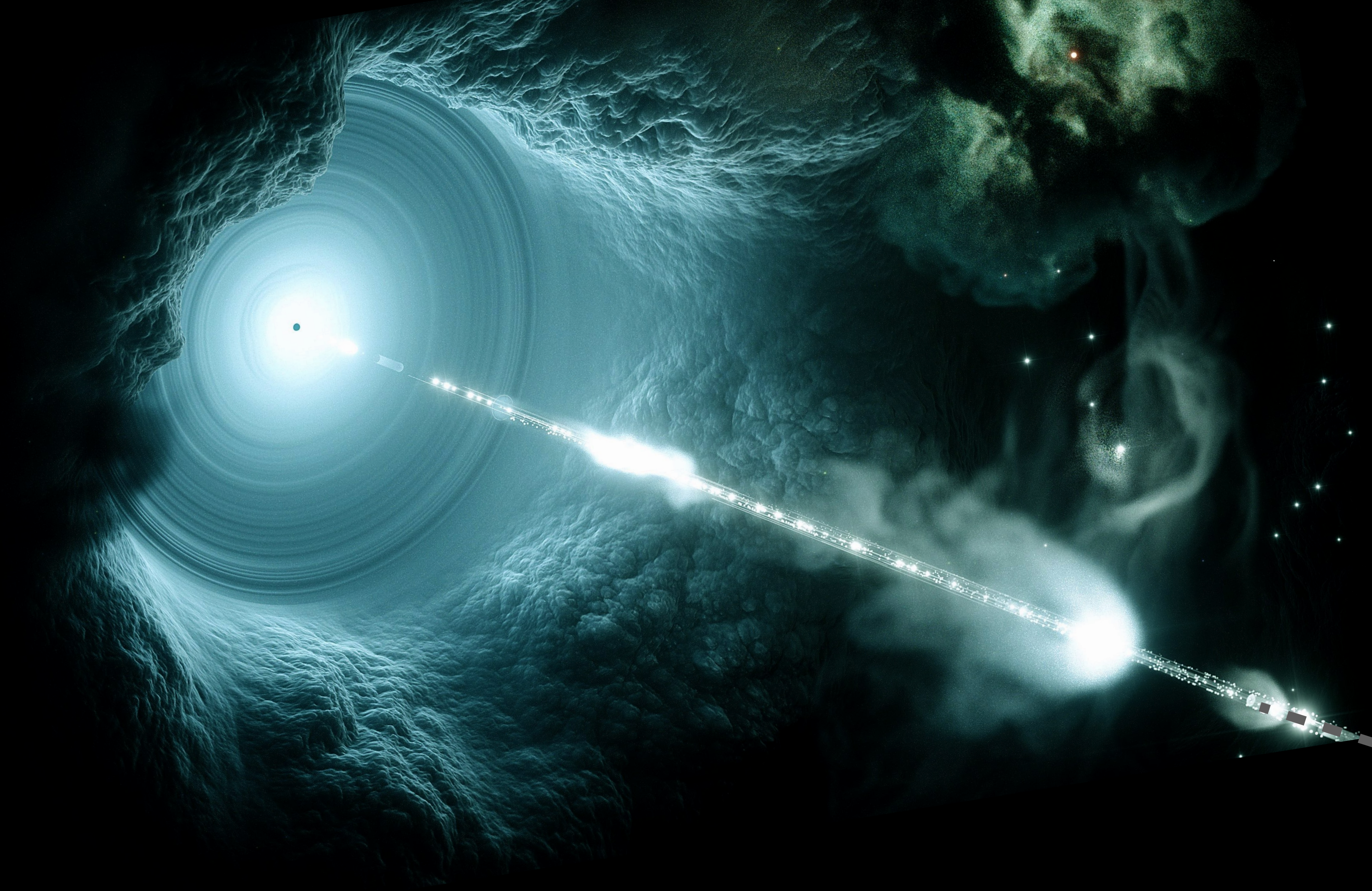
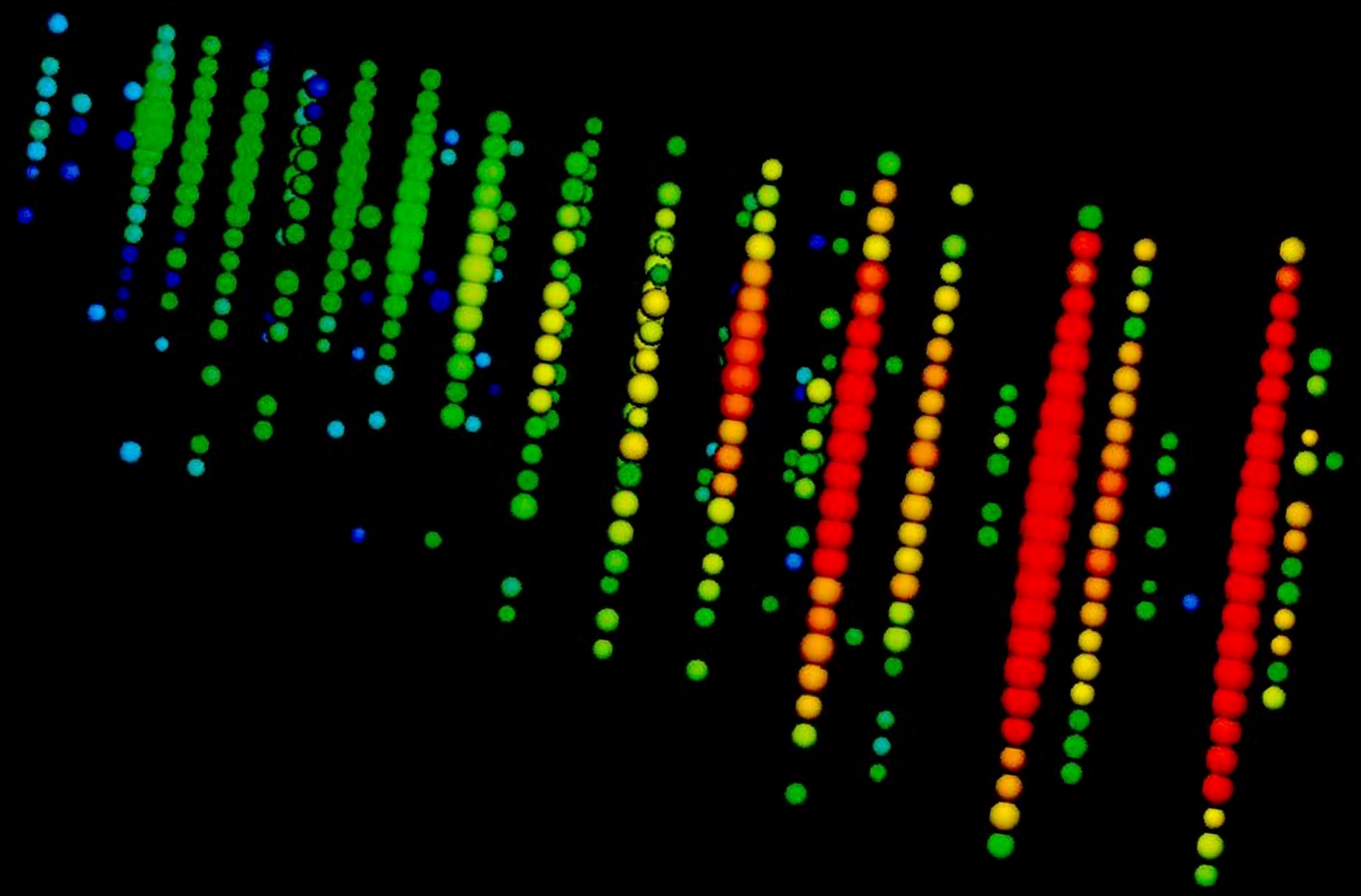




Neutrino Astronomy & Astrophysics

Summer school on neutrinos

Here, there & Everywhere

NBI, Copenhagen

Foteini Oikonomou

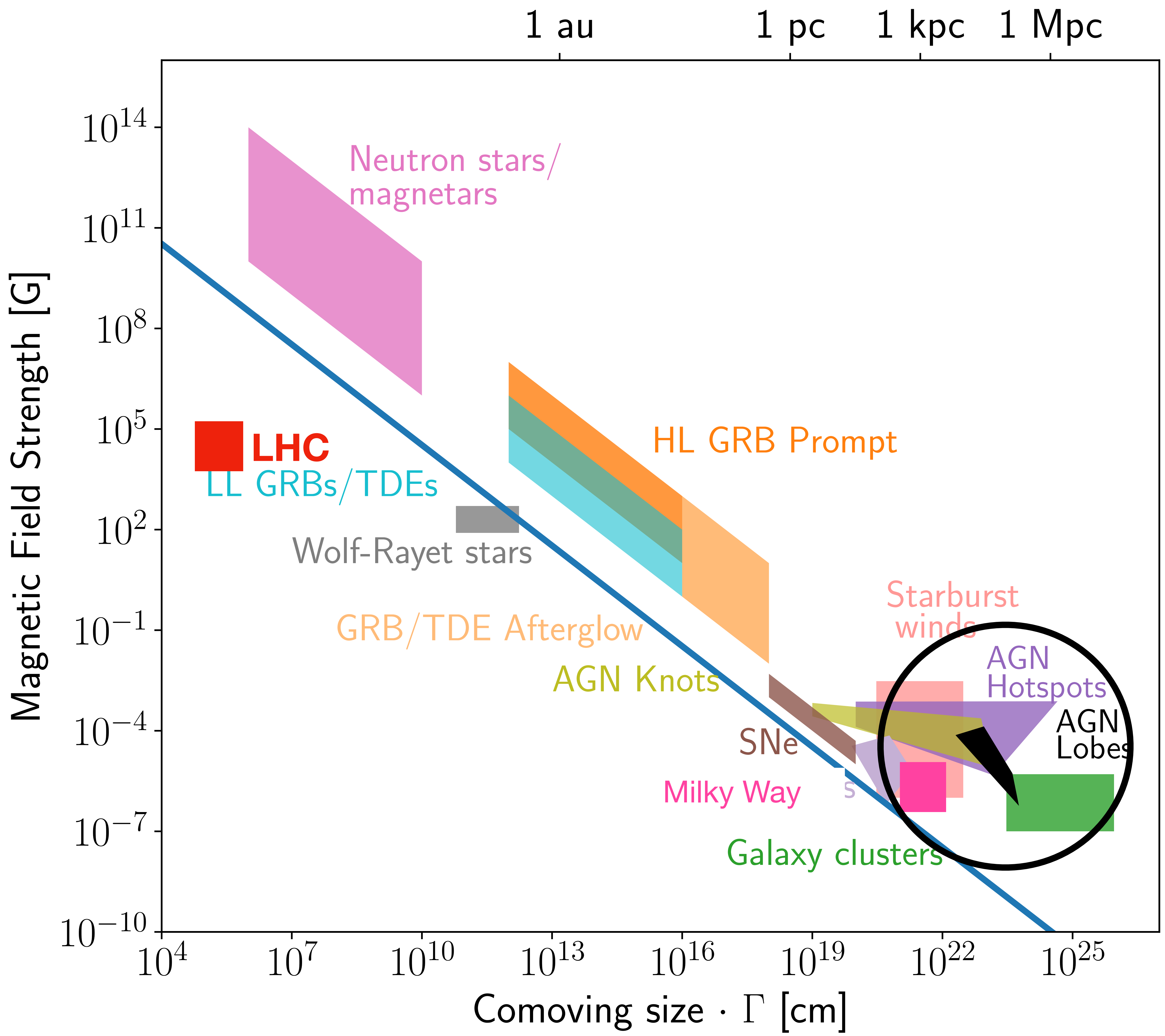
Norwegian University of Science and Technology

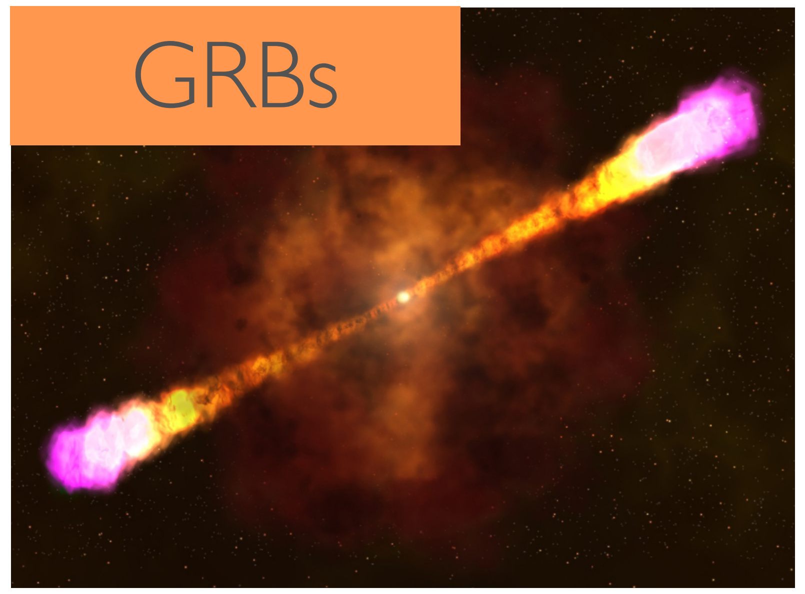
July 11th-15th

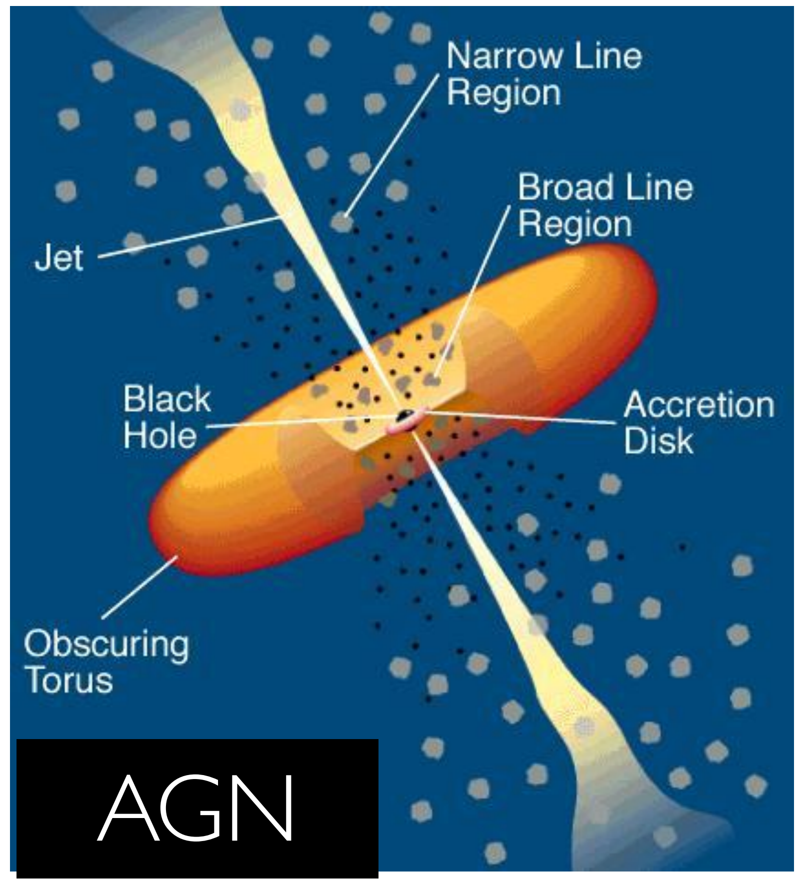
Lecture plan

- Experimental facts and basic theoretical concepts
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)
- Overview of candidate sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events) constraints and prospects

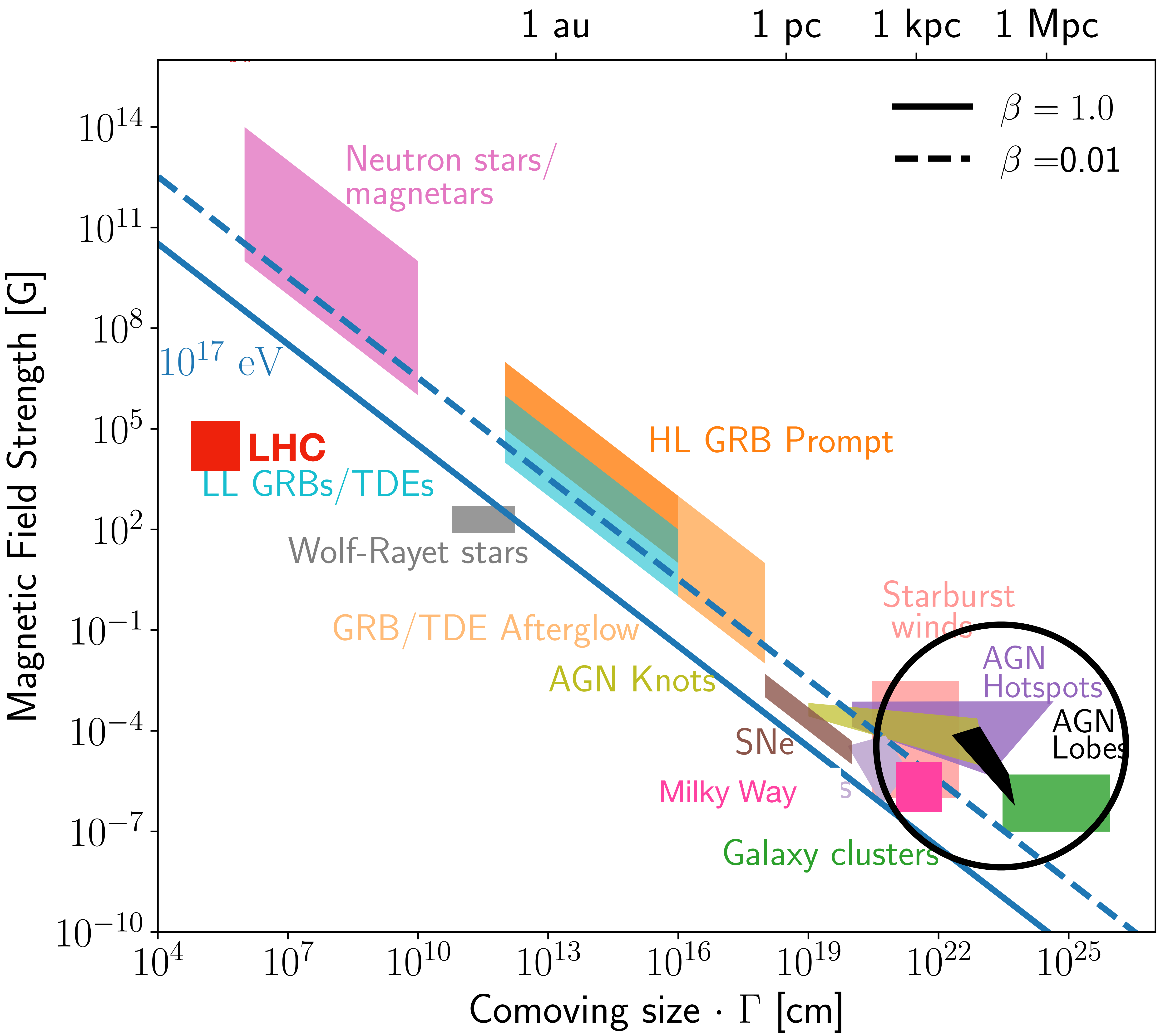
Cosmic-ray accelerators that satisfy the confinement req… ^{17} eV)

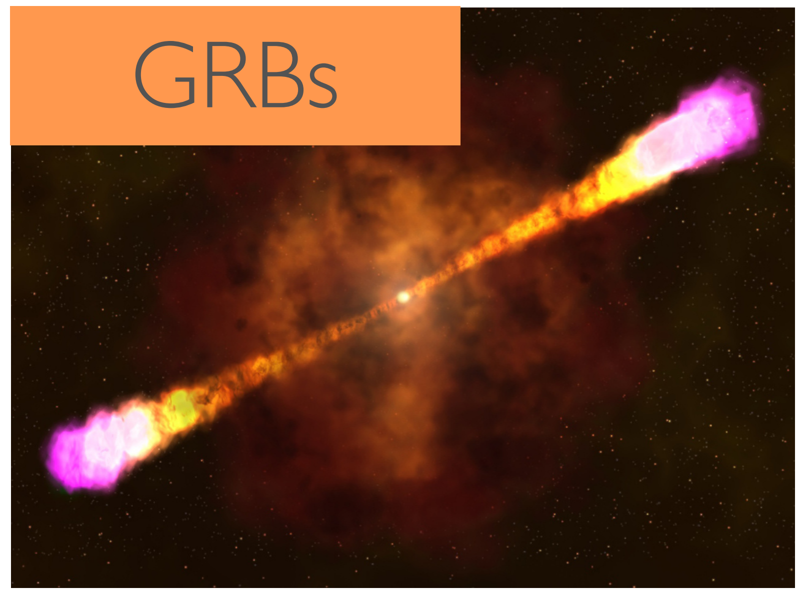


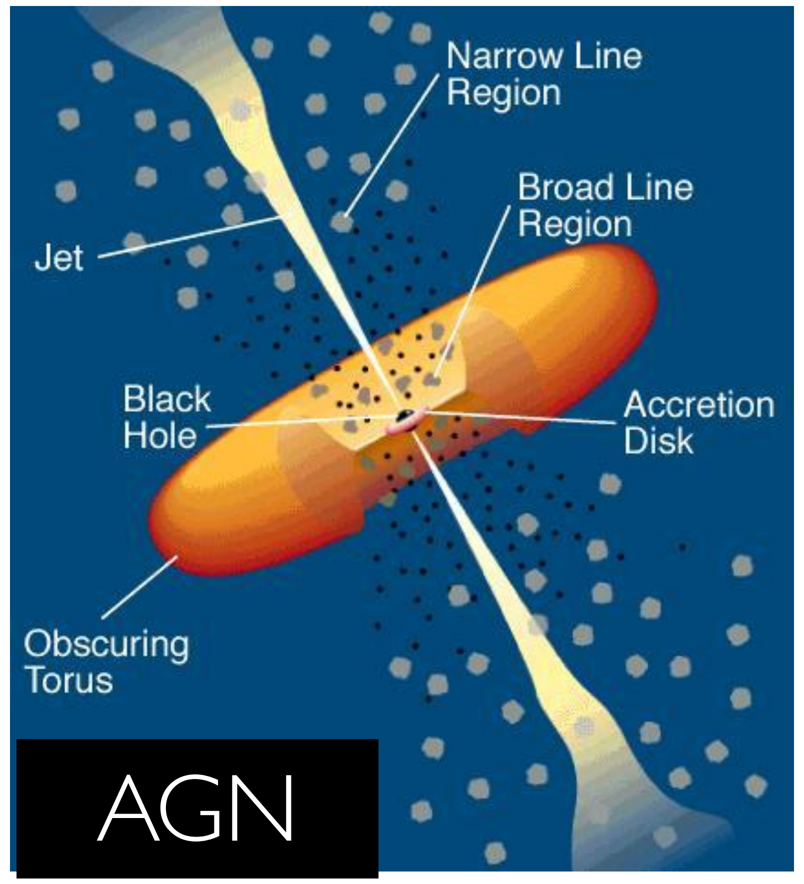




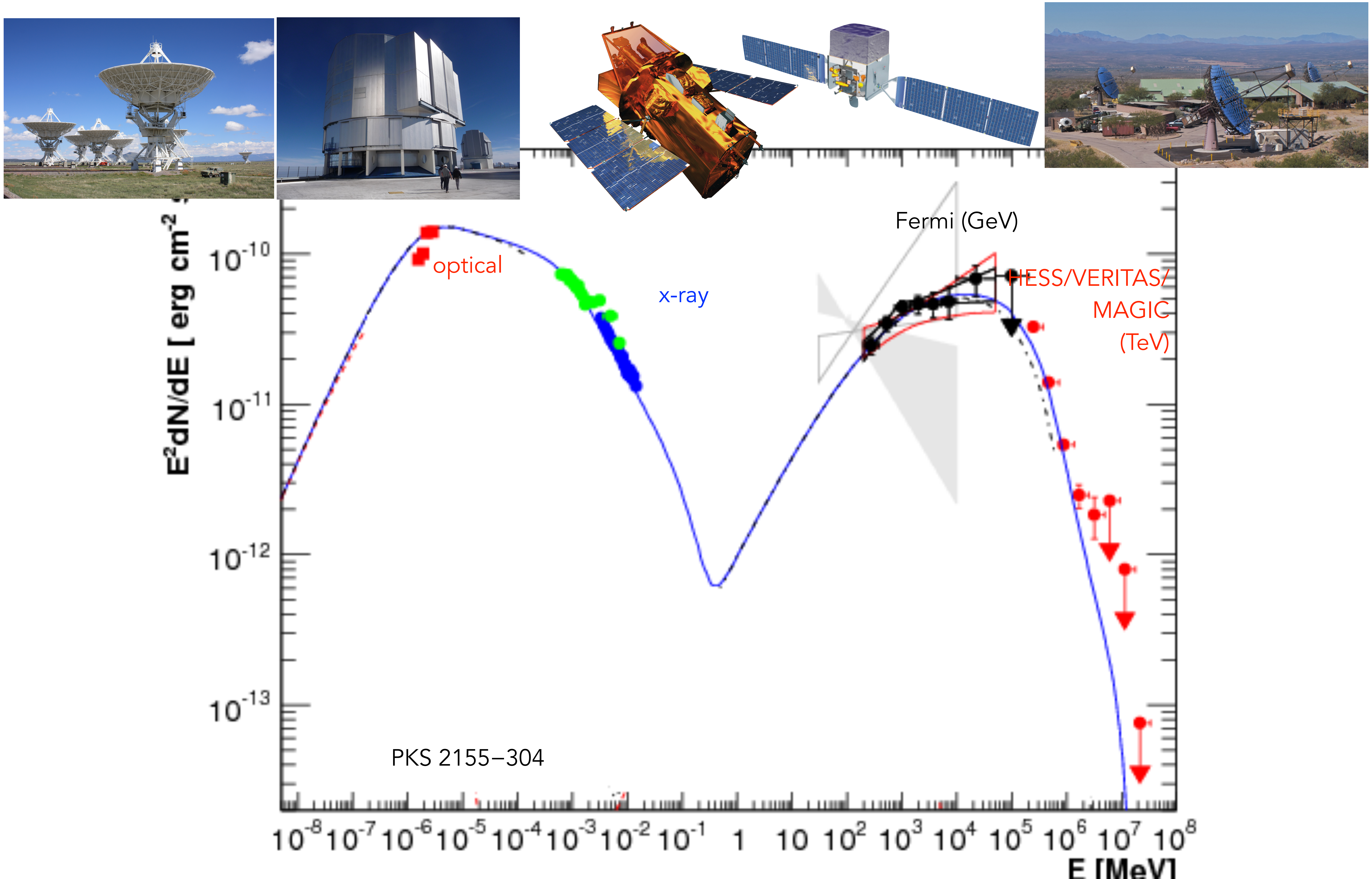
Cosmic-ray accelerators that satisfy the confinement req 17 eV)





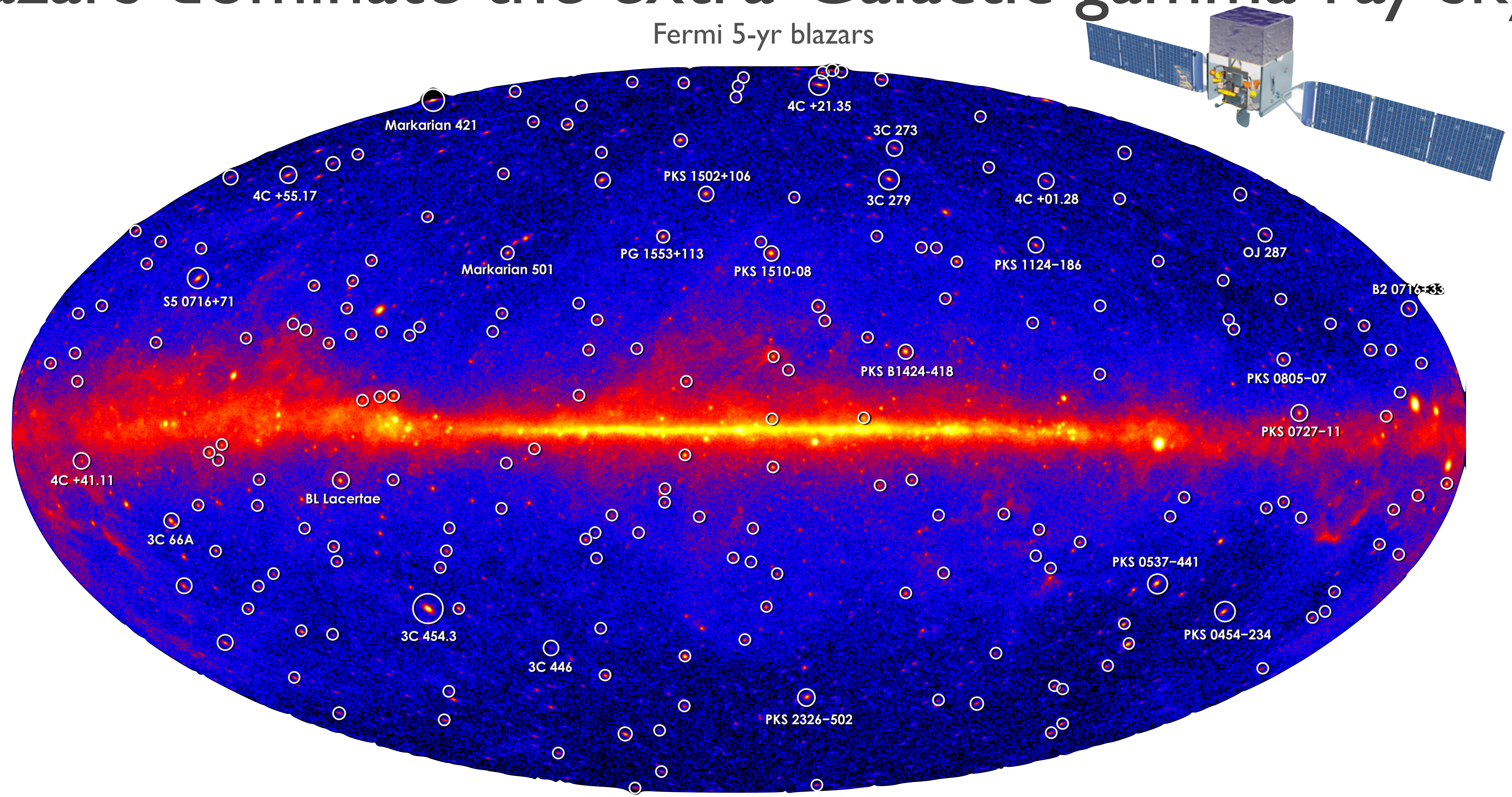


Blazar spectral energy distribution



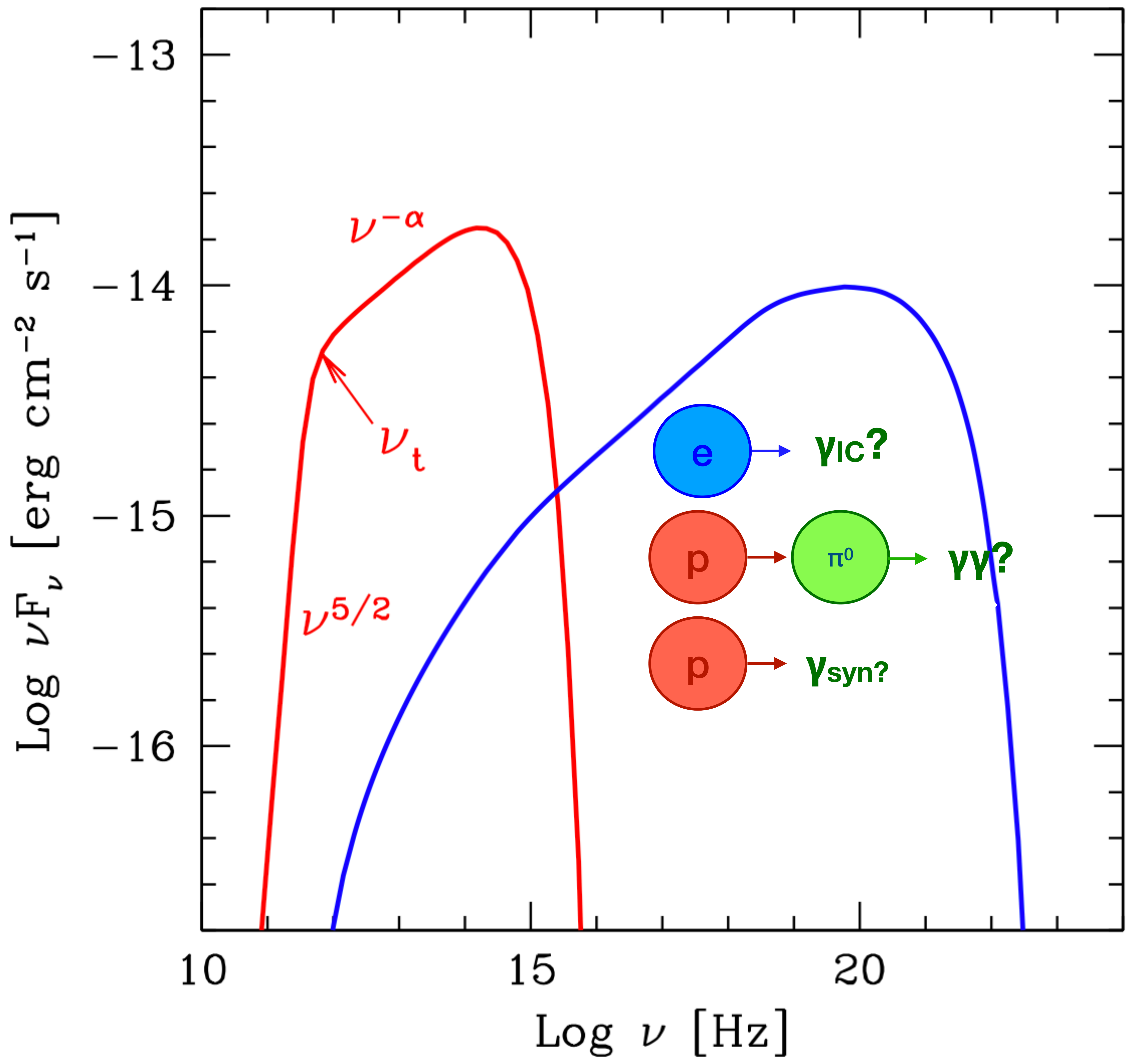
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars

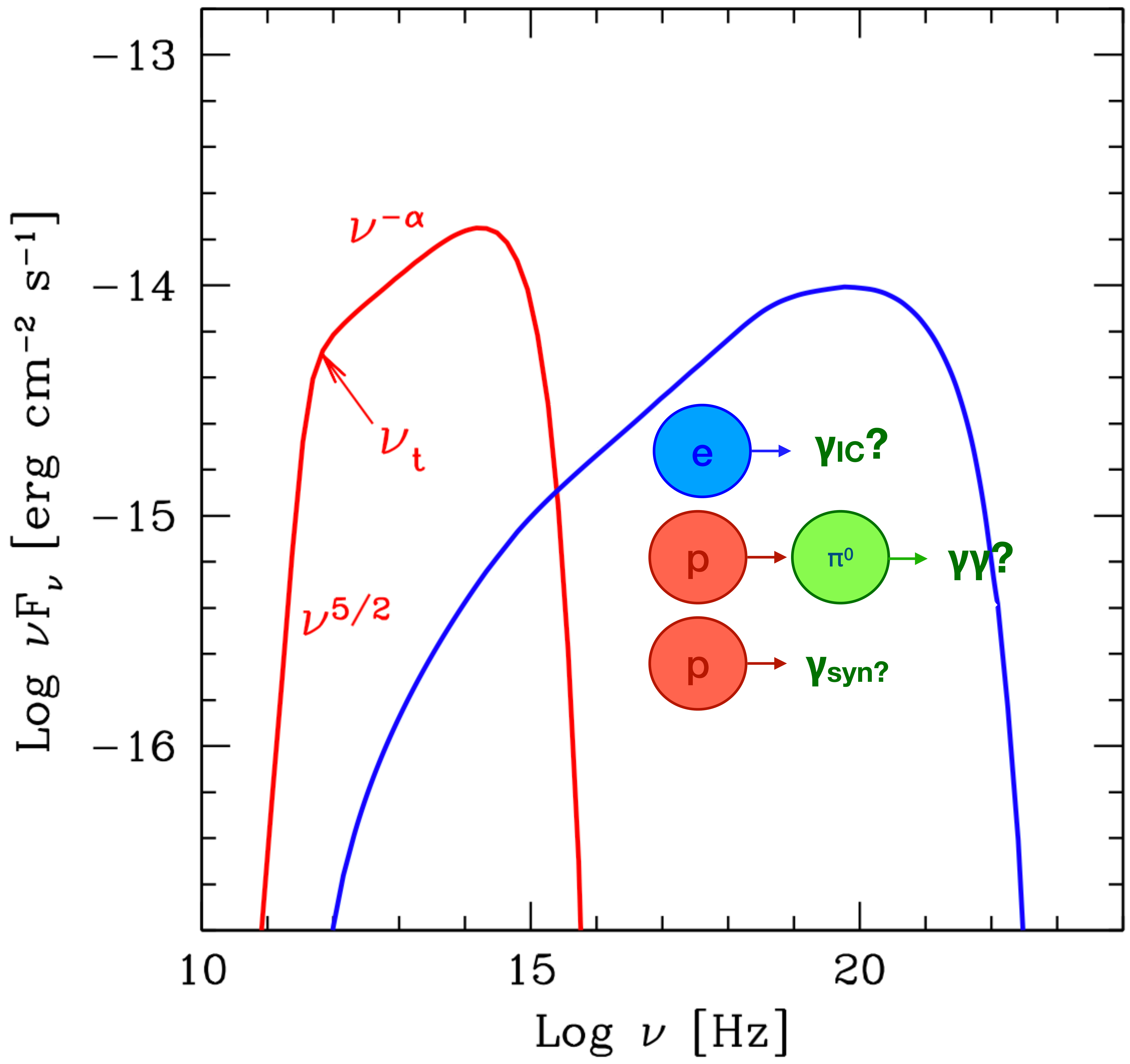


>90% of extragalactic Fermi sources (see also TeVCaT)

Neutrino production in blazars



Neutrino production in blazars



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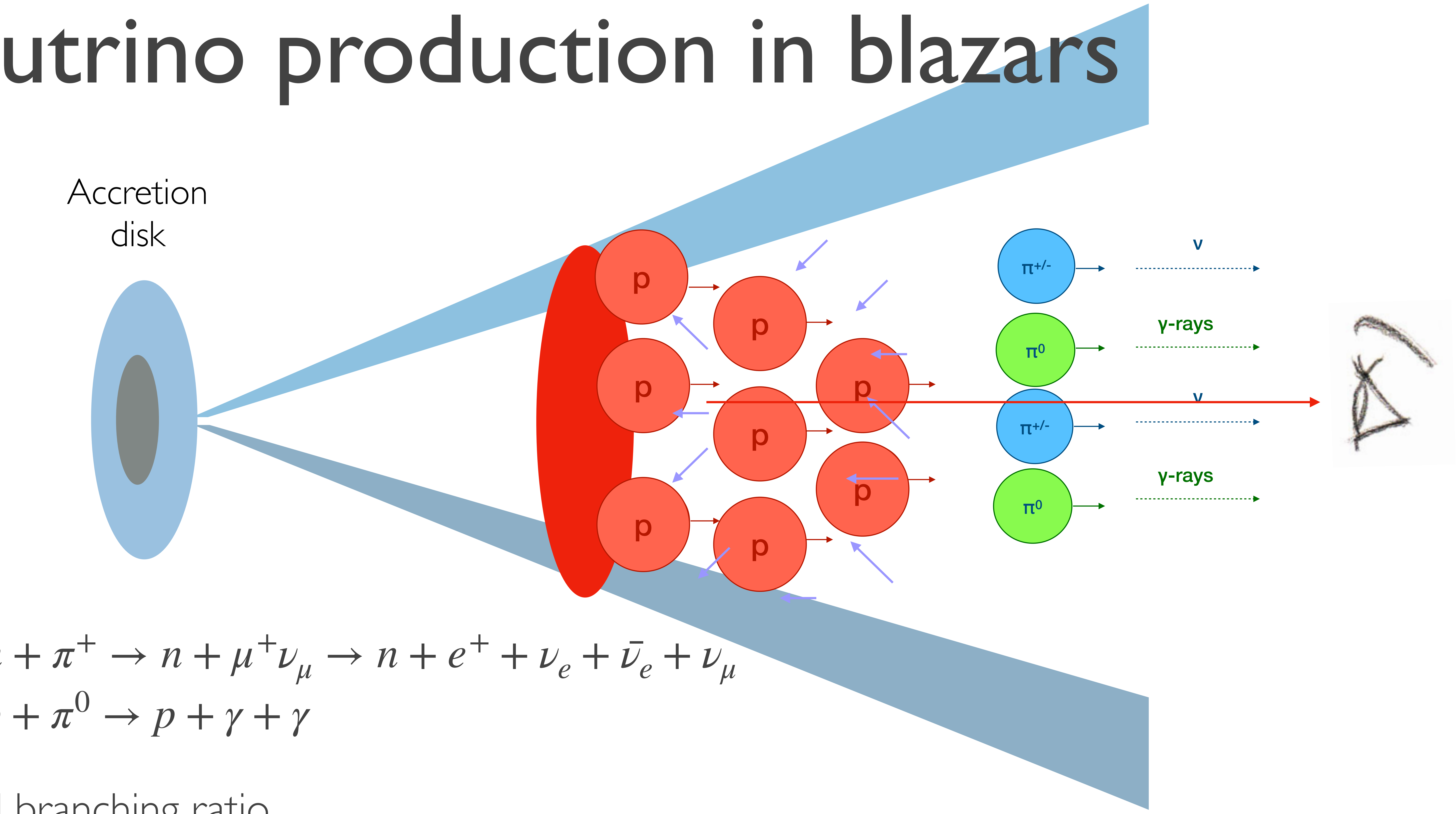


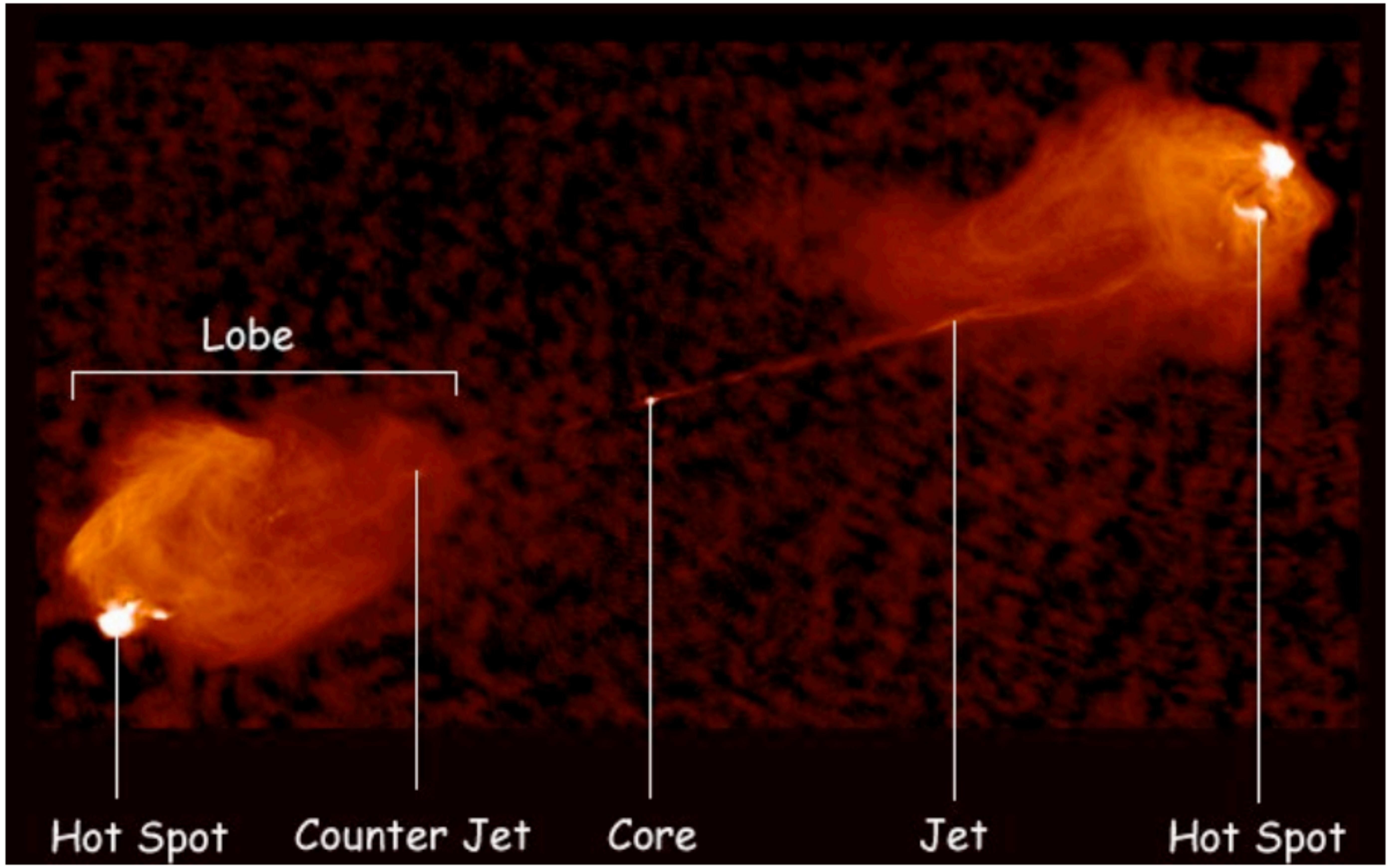
$$p + \gamma \rightarrow n + \pi^+ \rightarrow n + \mu^+ \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu_e} + \nu_\mu$$
$$p + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$

Averaged branching ratio,

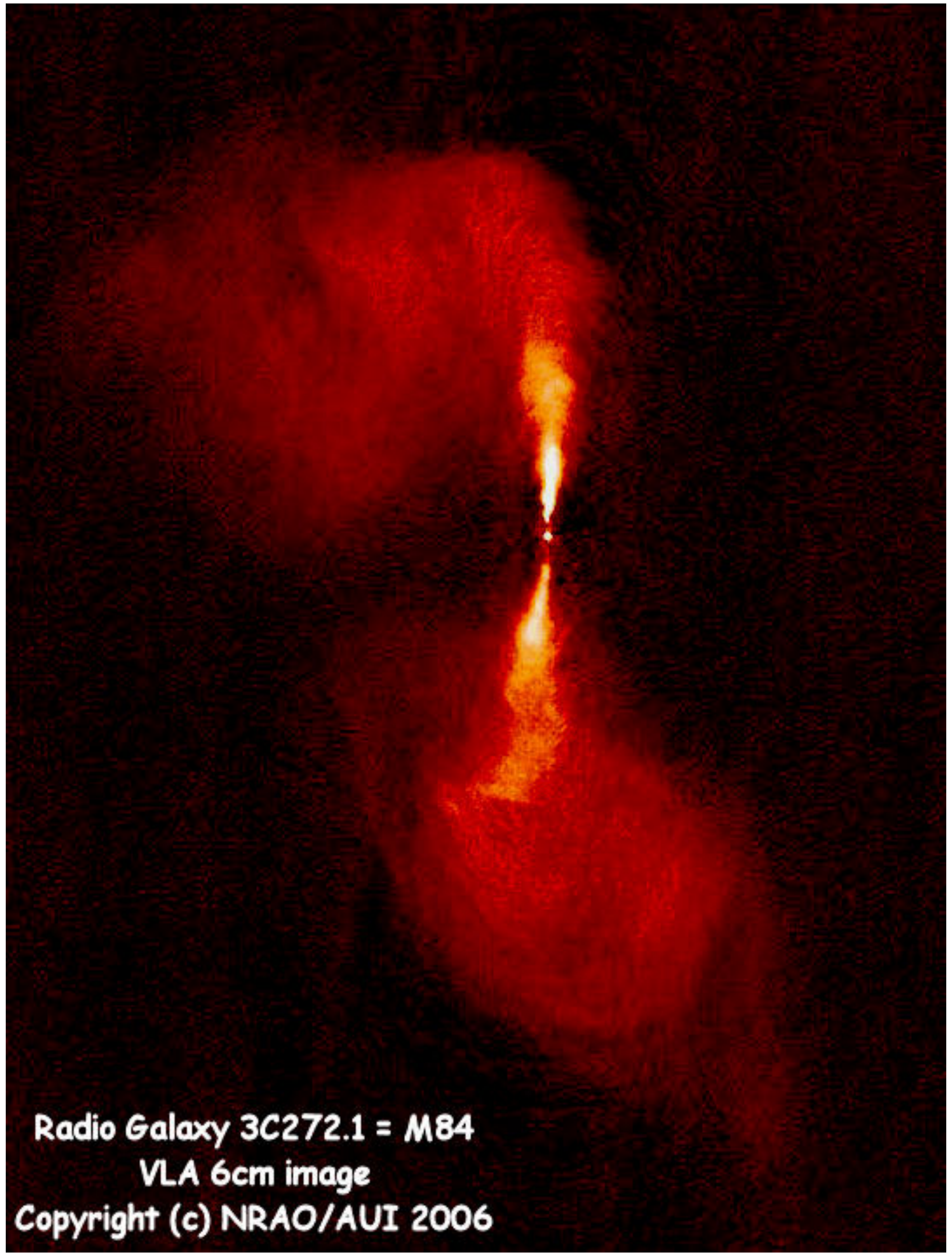
$$R_\pi = \frac{\Gamma(\rightarrow \pi^{+/-})}{\Gamma(\rightarrow \pi^0)} \sim 1$$

$$E_\nu^2 \frac{dN}{dE_\nu} = \frac{3}{2}\frac{1}{2} E_\gamma^2 \frac{dN}{dE_\gamma}\Big|_{E_\gamma = 2E_\nu} \longrightarrow$$ gamma-rays give us an upper limit to the neutrino flux

Jetted AGN subclasses

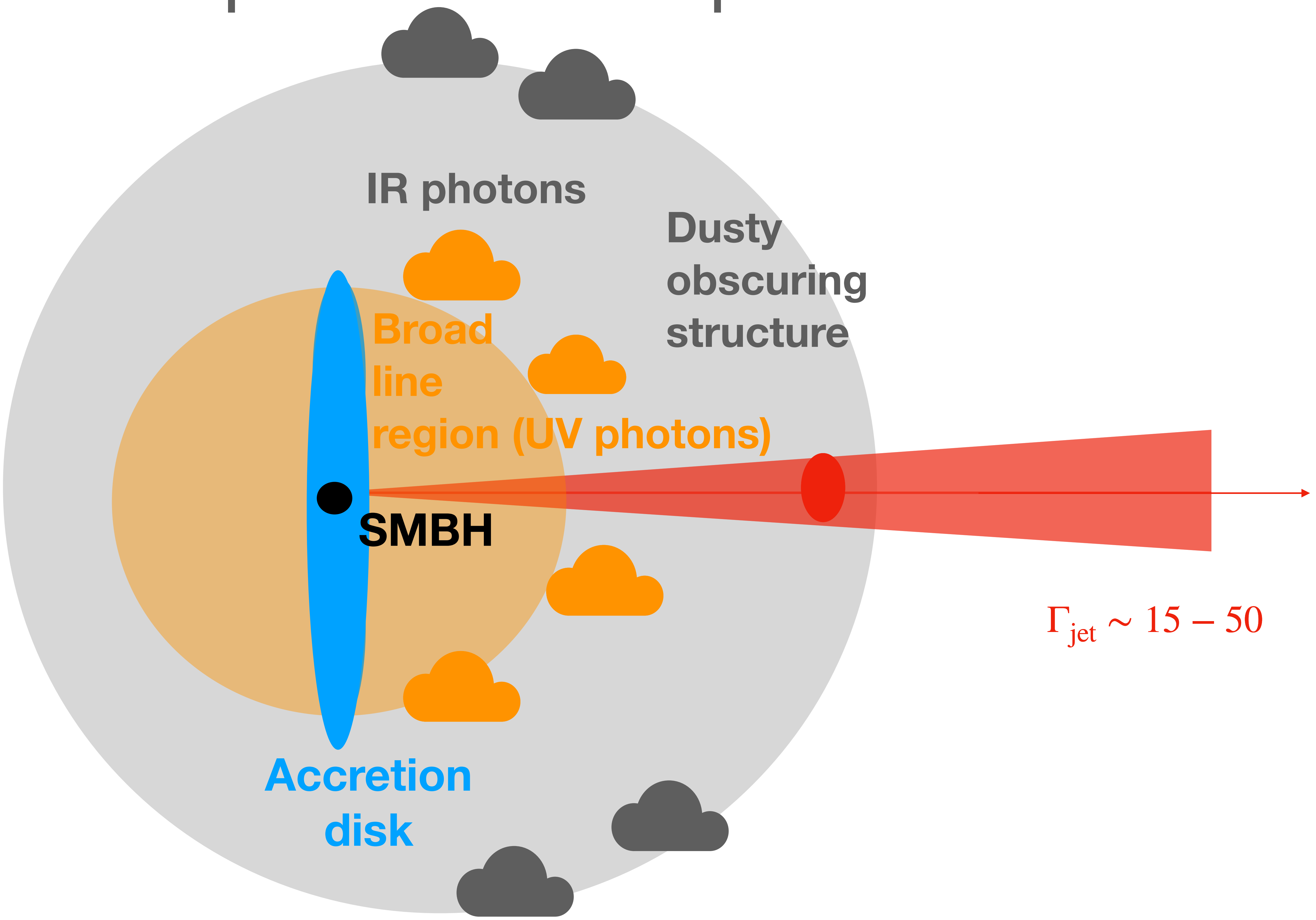


Radio galaxy Cygnus A Image credits: NRAO/AUI,A. Bridle



Blazar subclasses and photon fields

Flat spectrum radio quasars



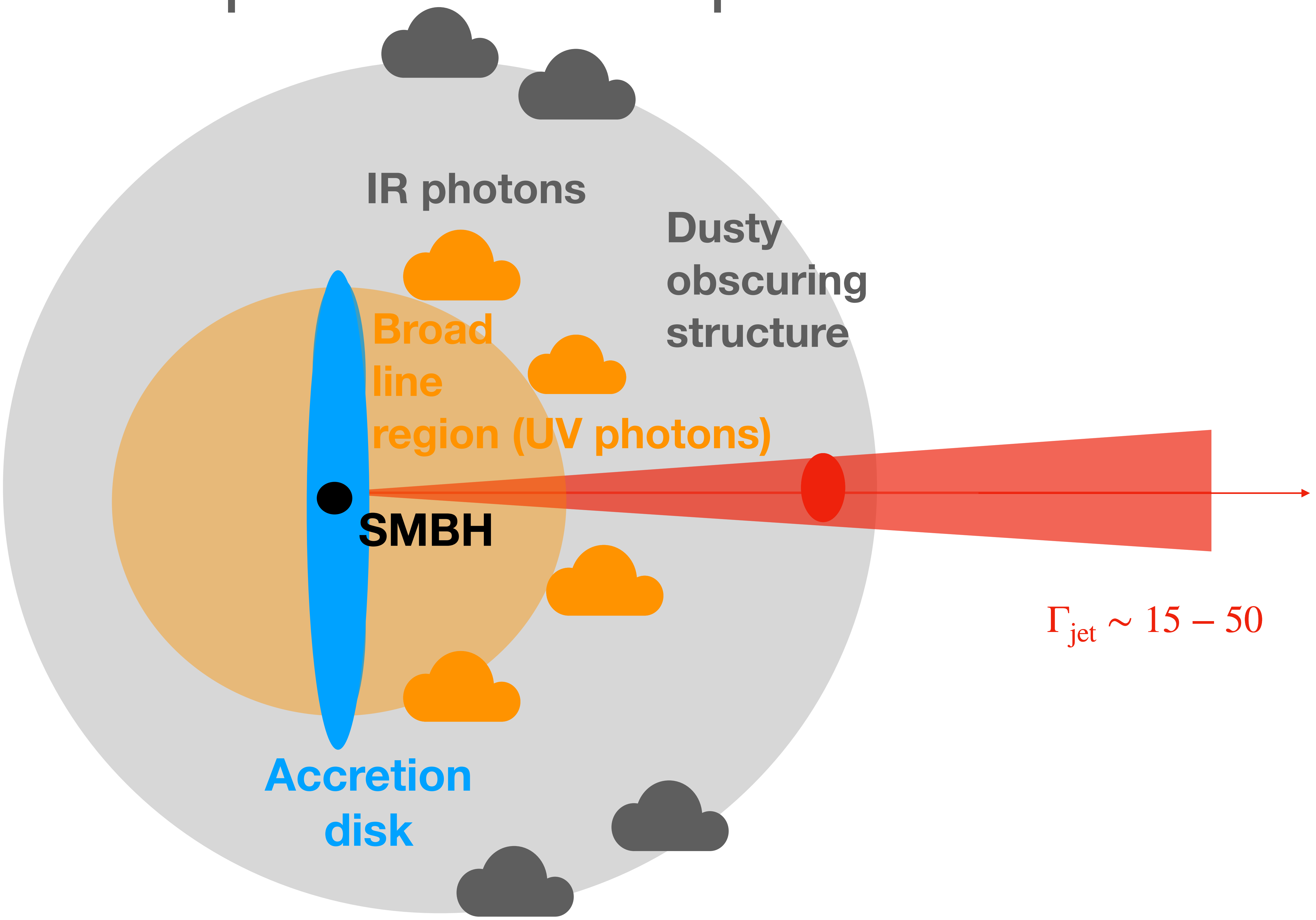
Very powerful collimated jets

Radiatively efficient accretion disk

Luminosity close to Eddington limit

Blazar subclasses and photon fields

Flat spectrum radio quasars



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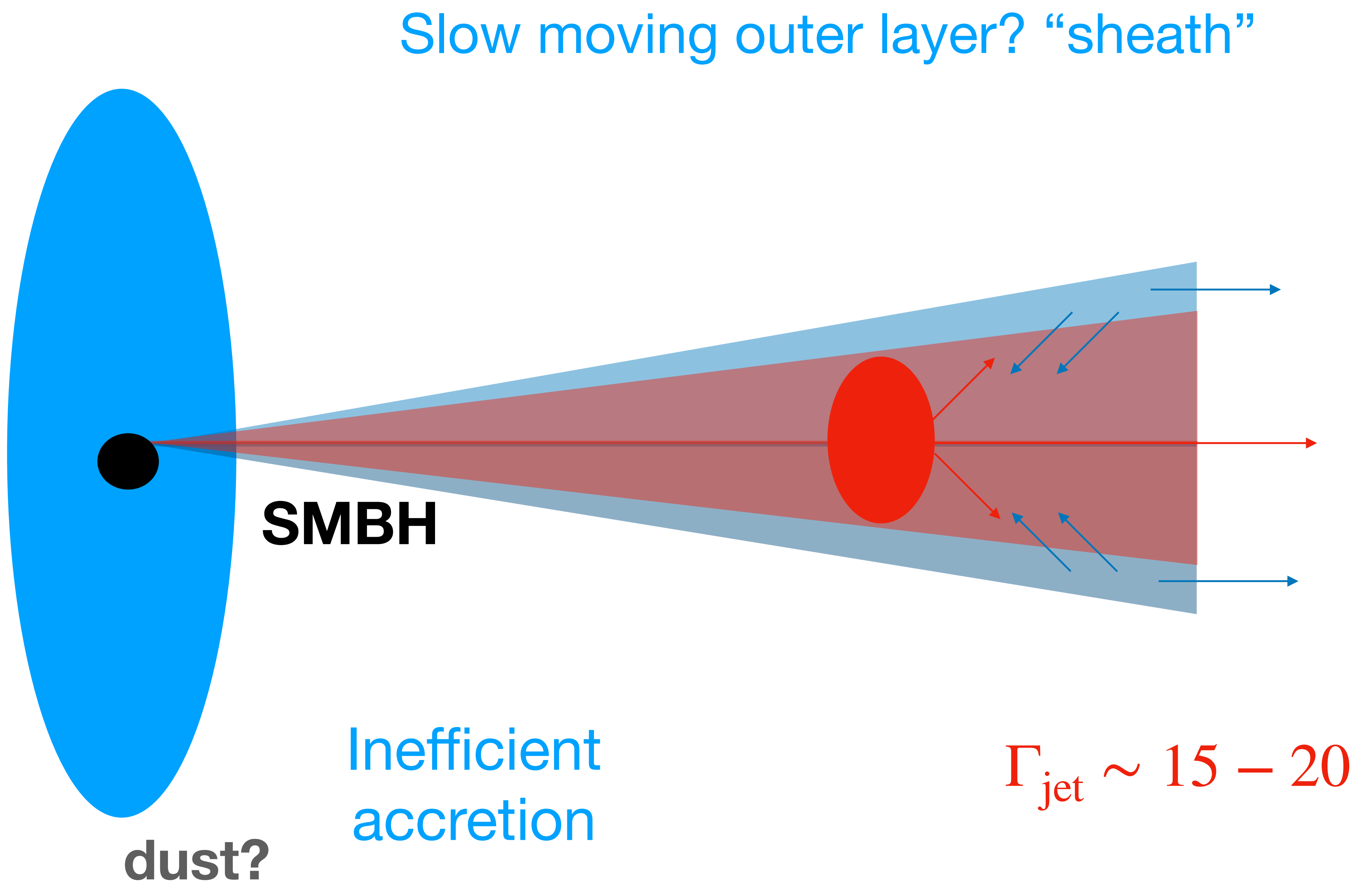
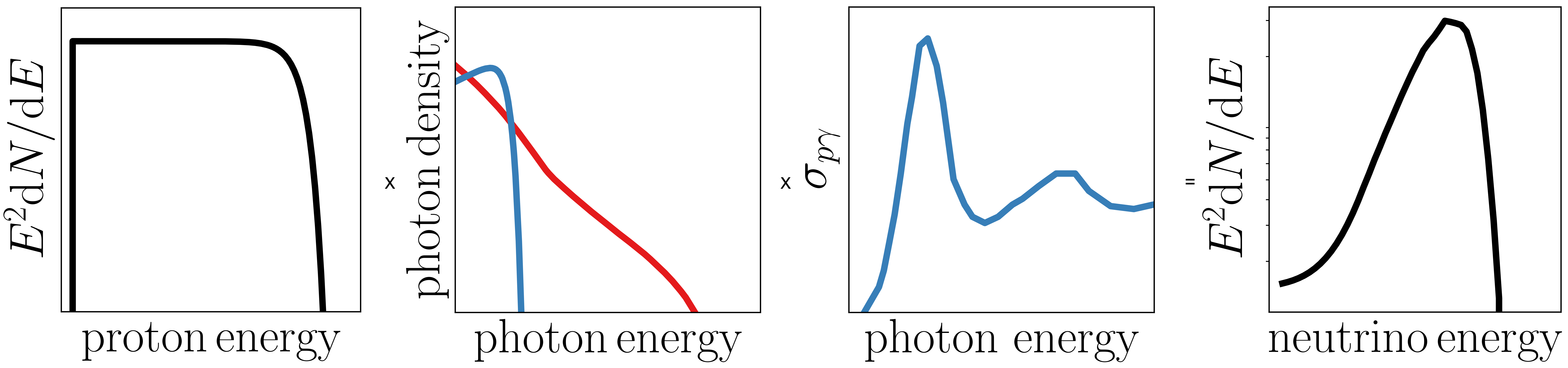
BL Lac Objects



Less collimated jets

Radiatively inefficient accretion disk

Neutrino production in blazars



$$E_{\mathrm{BLR}} = 10.2\ \mathrm{eV}$$

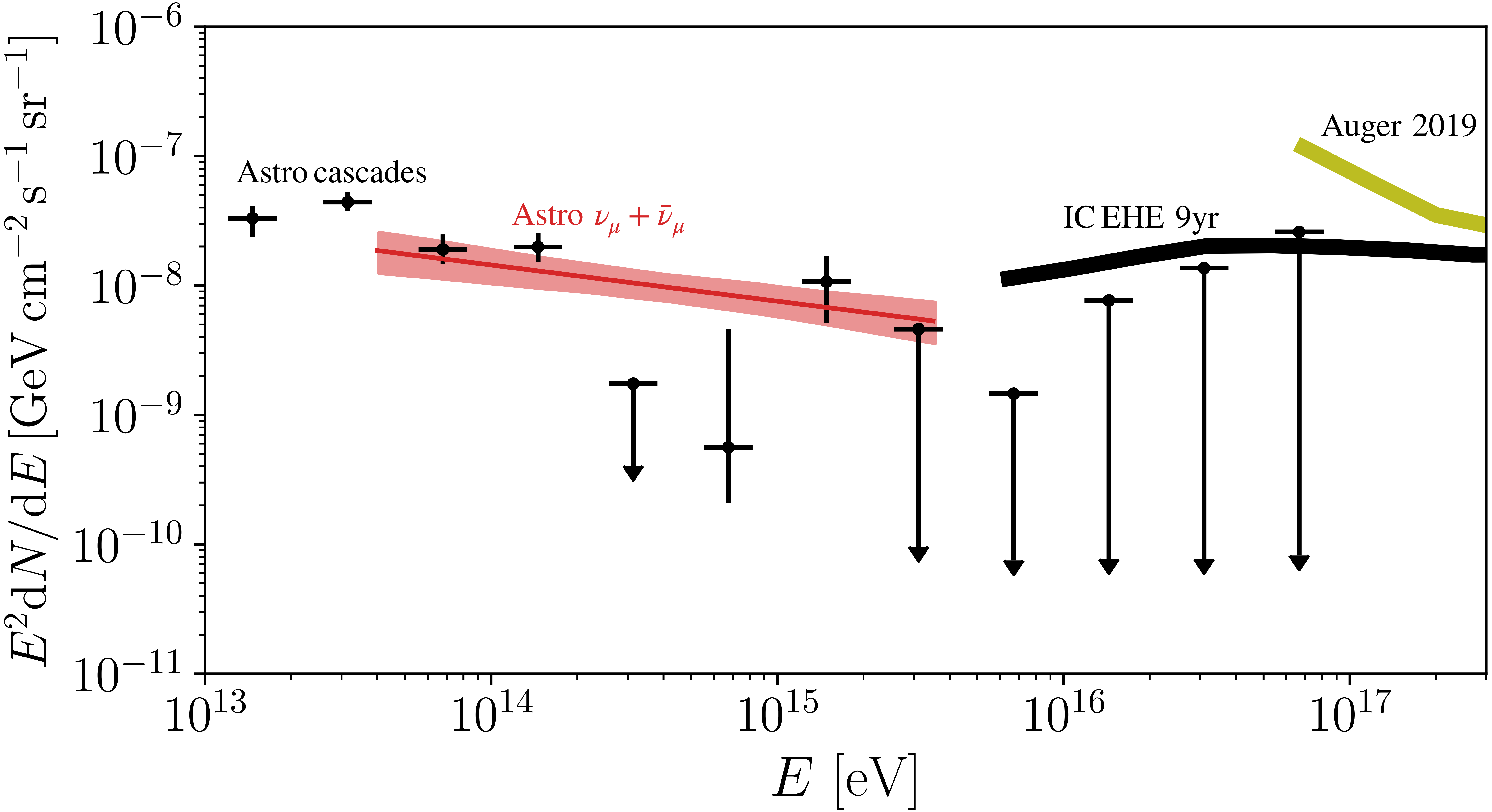
$$E_{\mathrm{dust\ torus}} = 0.1\ \mathrm{eV}$$

Neutrino typical energy:

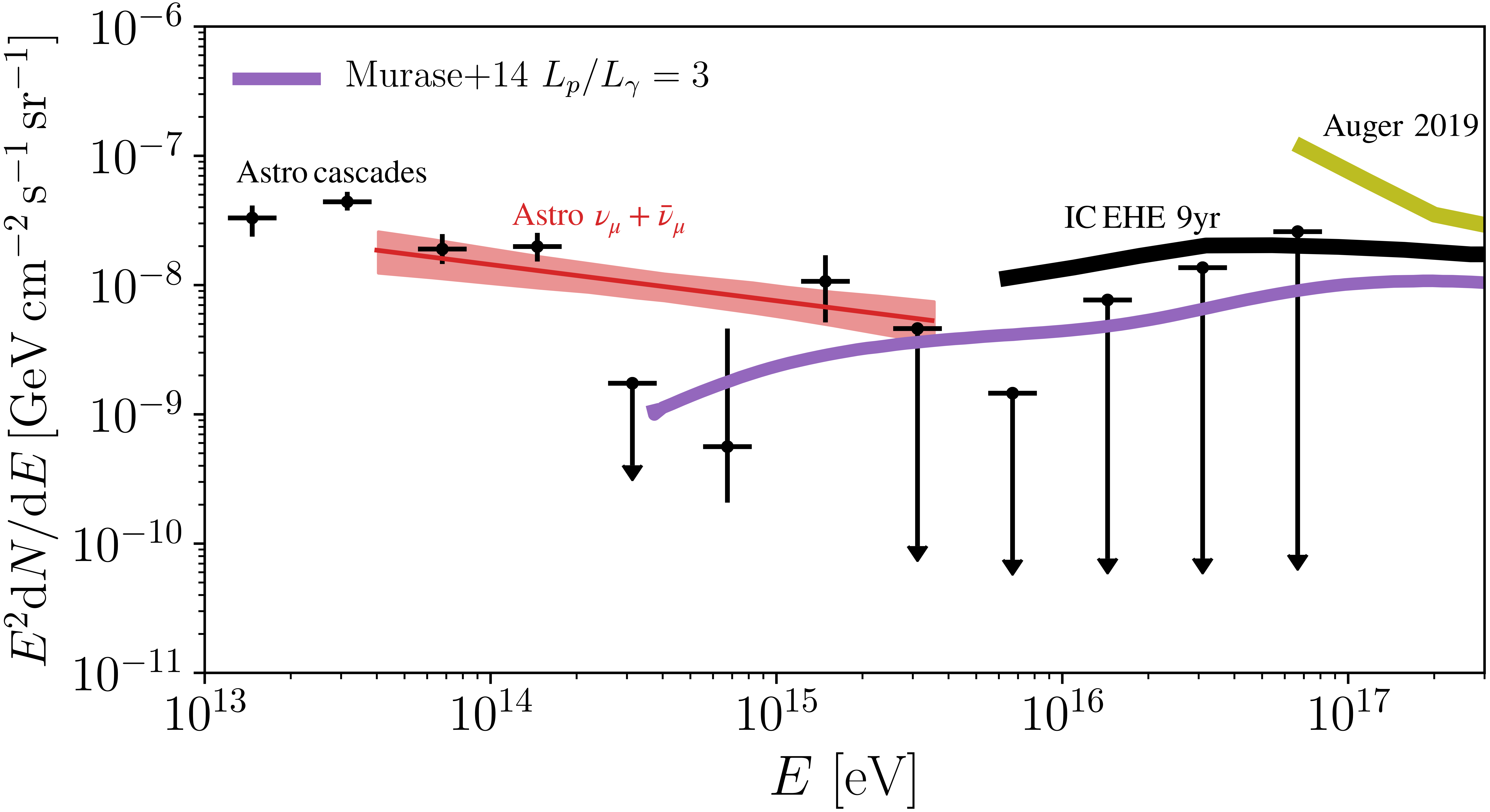
$$E_{\nu,\mathrm{BLR}} = \frac{80\ \mathrm{PeV}}{(1+z)^2}\left(\frac{\delta}{10}\right)^2 \frac{10\ \mathrm{eV}}{E_\gamma}$$

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

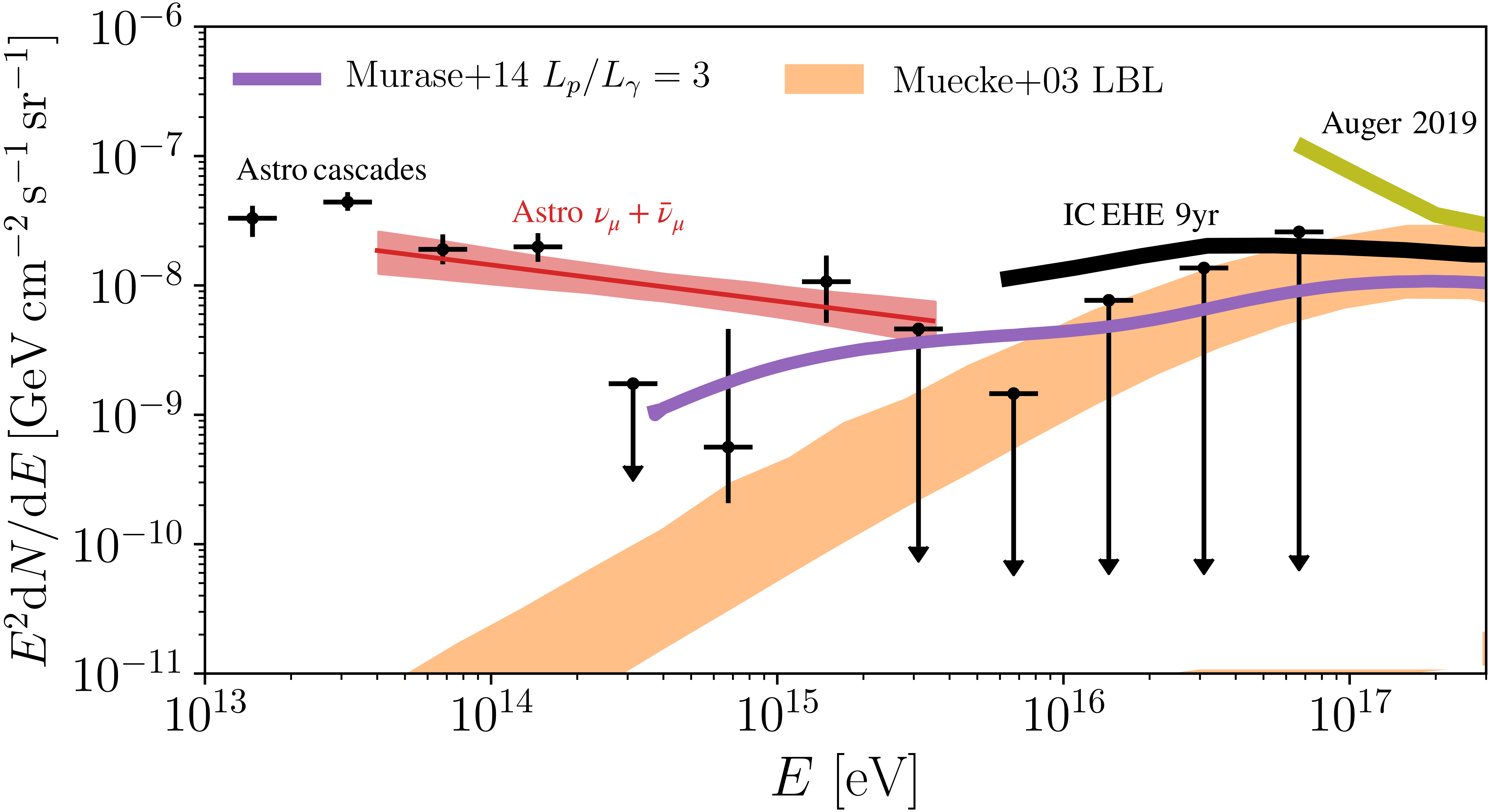
Possible contribution of blazars to the diffuse neutrino flux



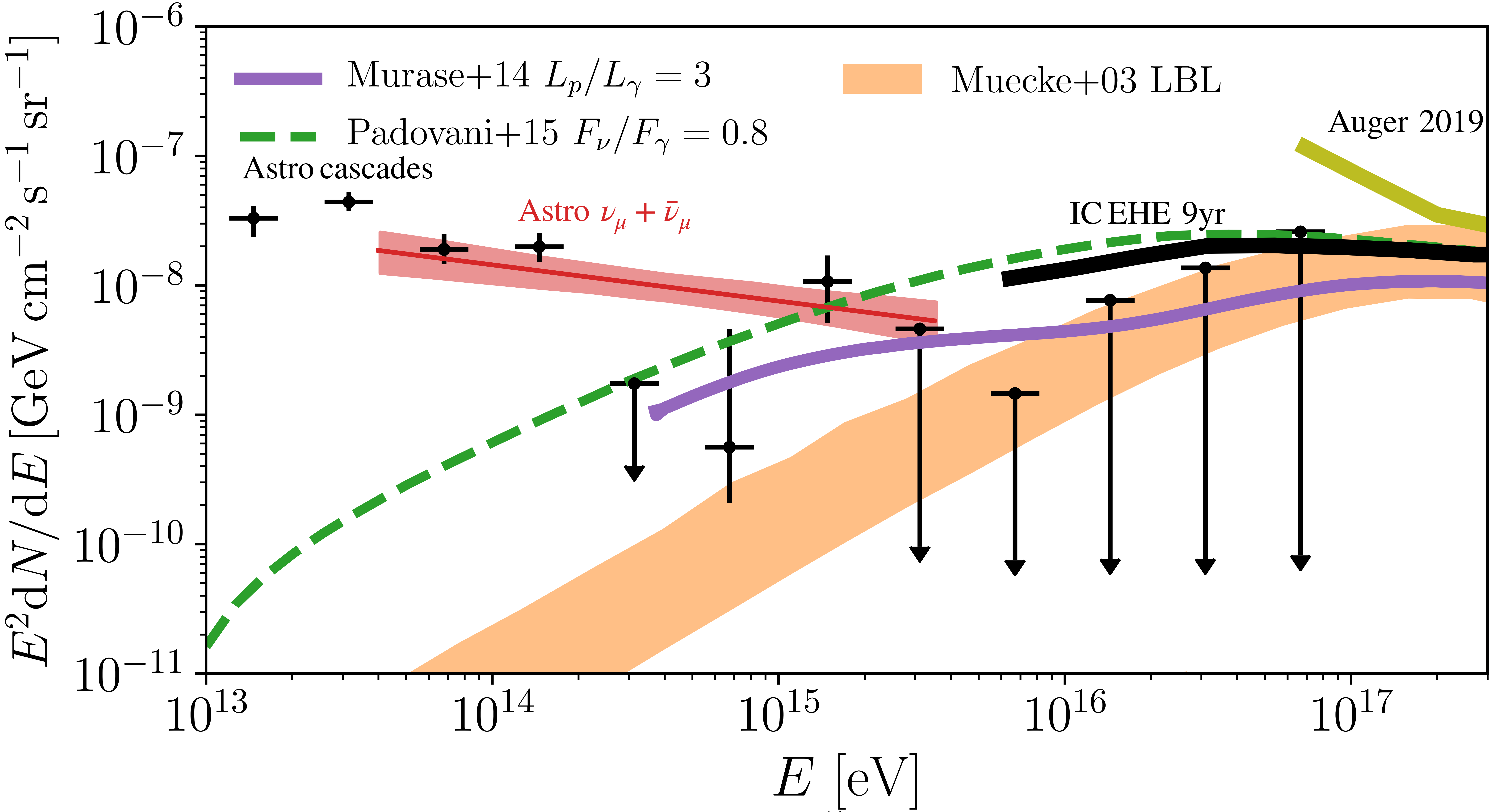
Possible contribution of blazars to the diffuse neutrino flux



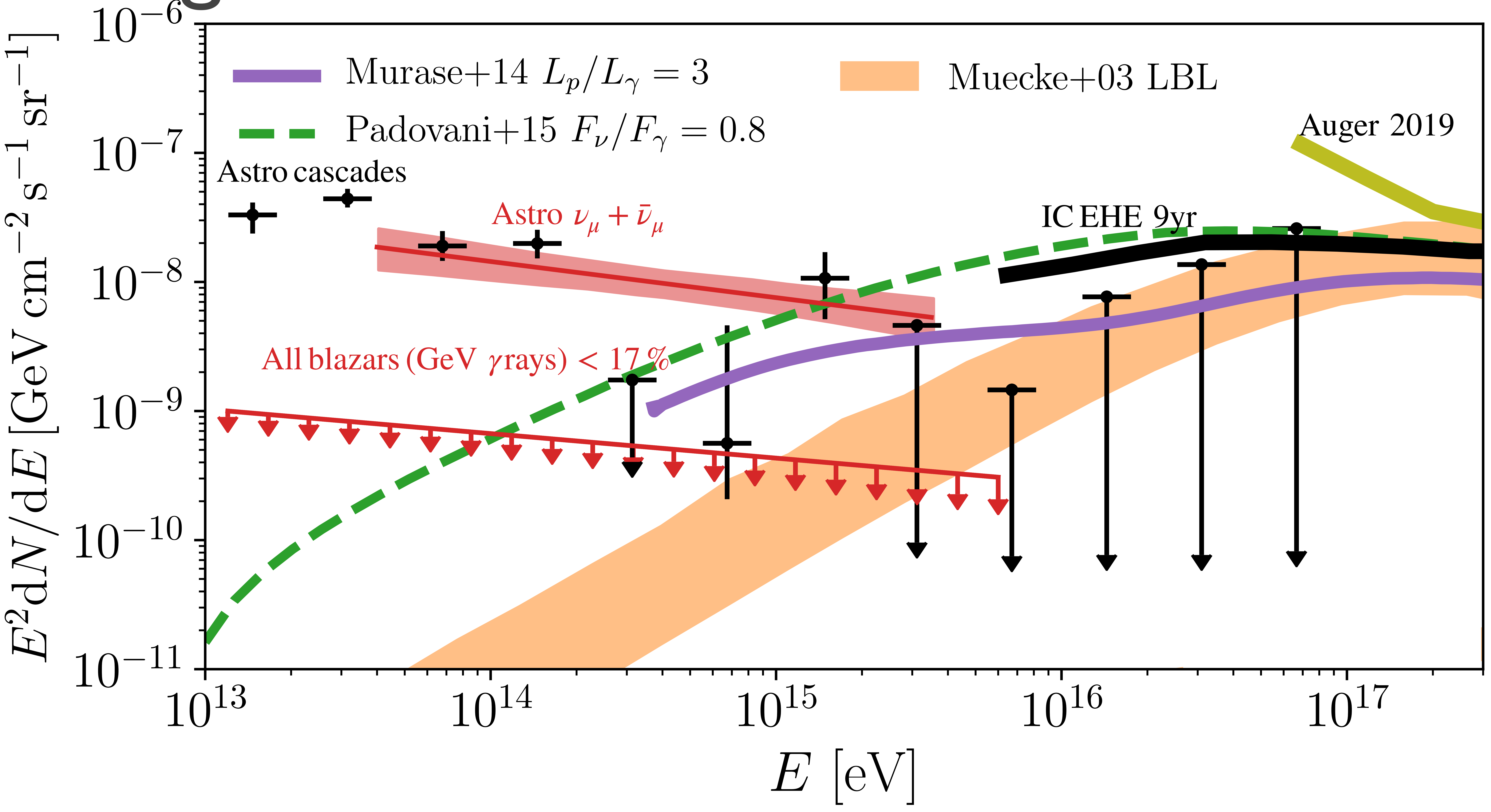
Possible contribution of blazars to the diffuse neutrino flux



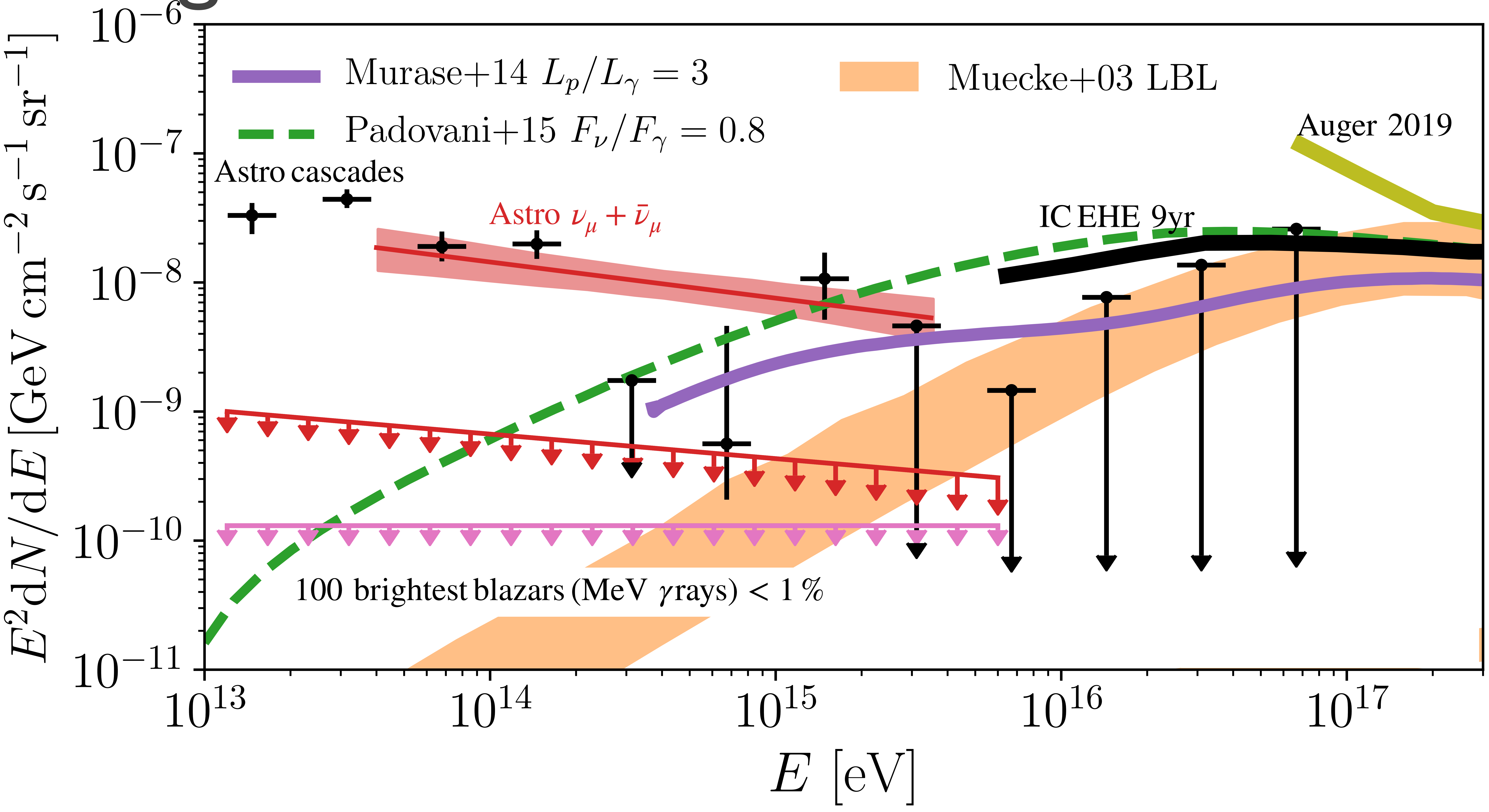
Possible contribution of blazars to the diffuse neutrino flux



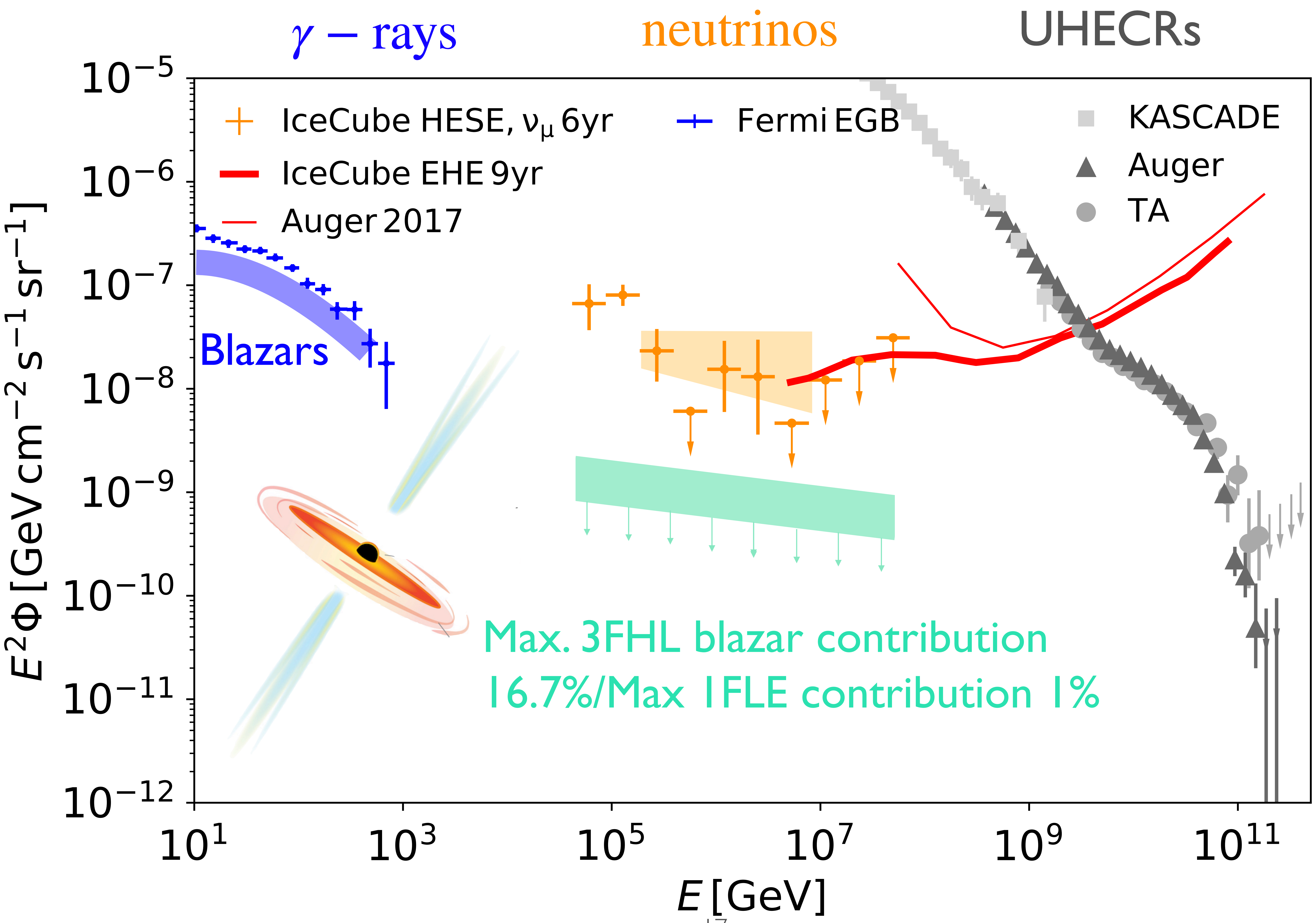
Stacking limits from IceCube



Stacking limits from IceCube

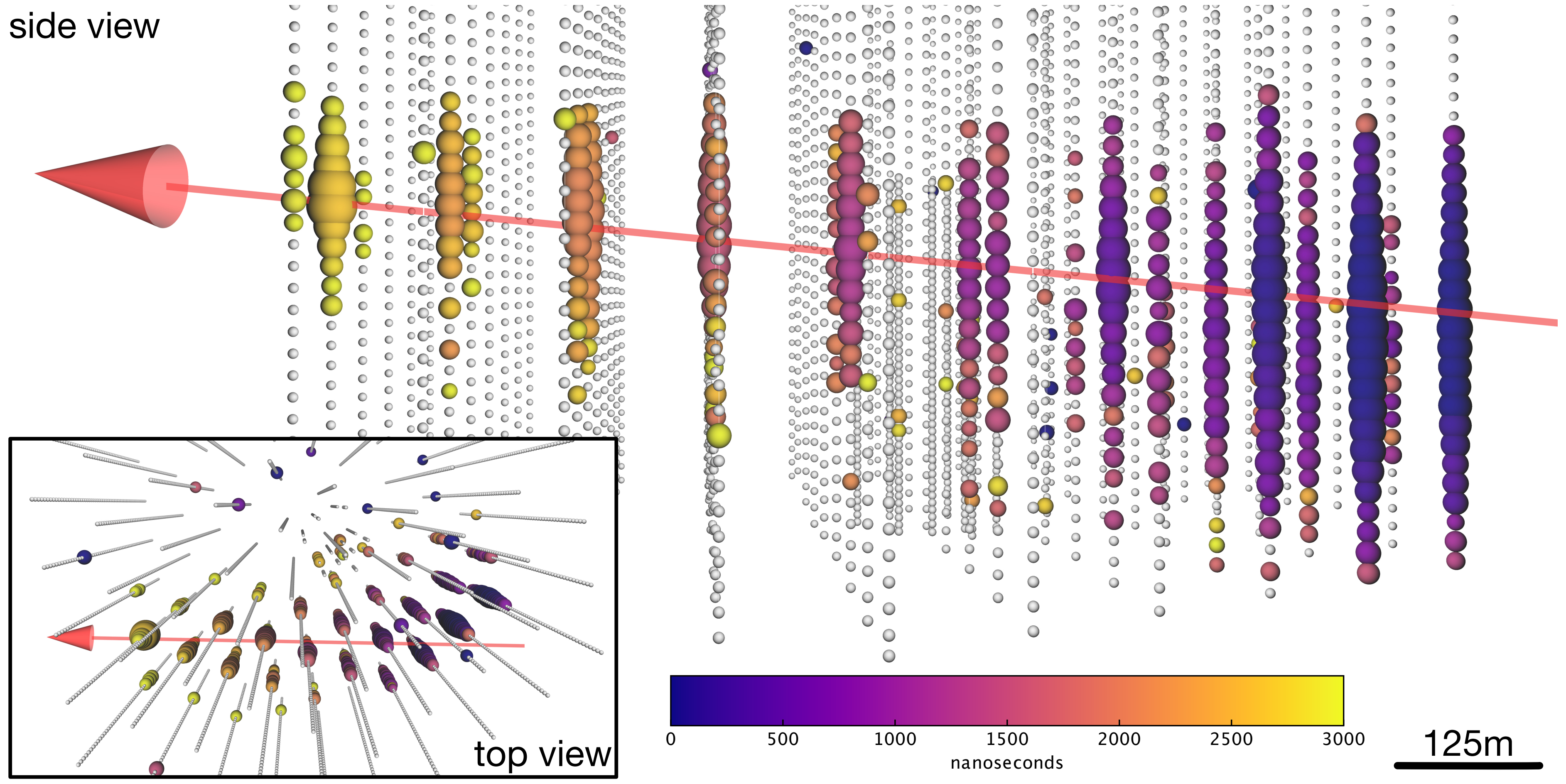


Stacking limits from IceCube

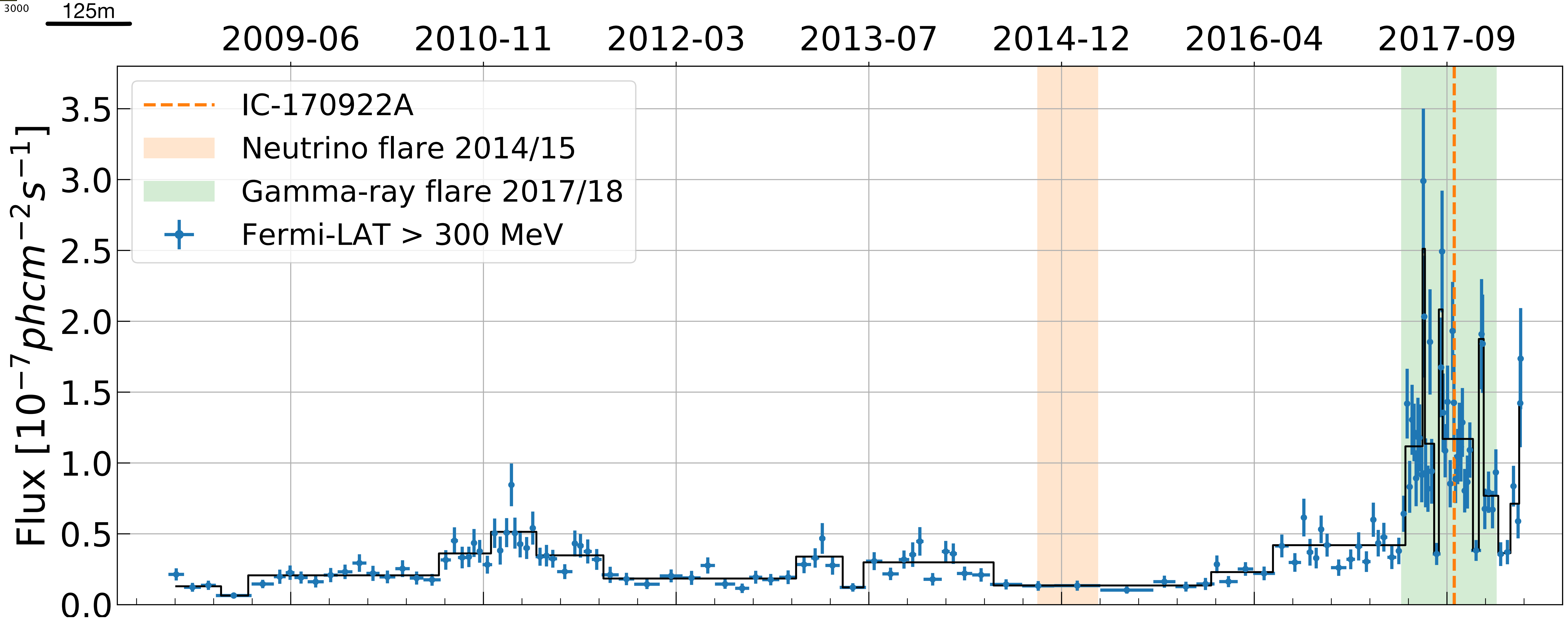


TXS 0506+056-IC 170922A

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



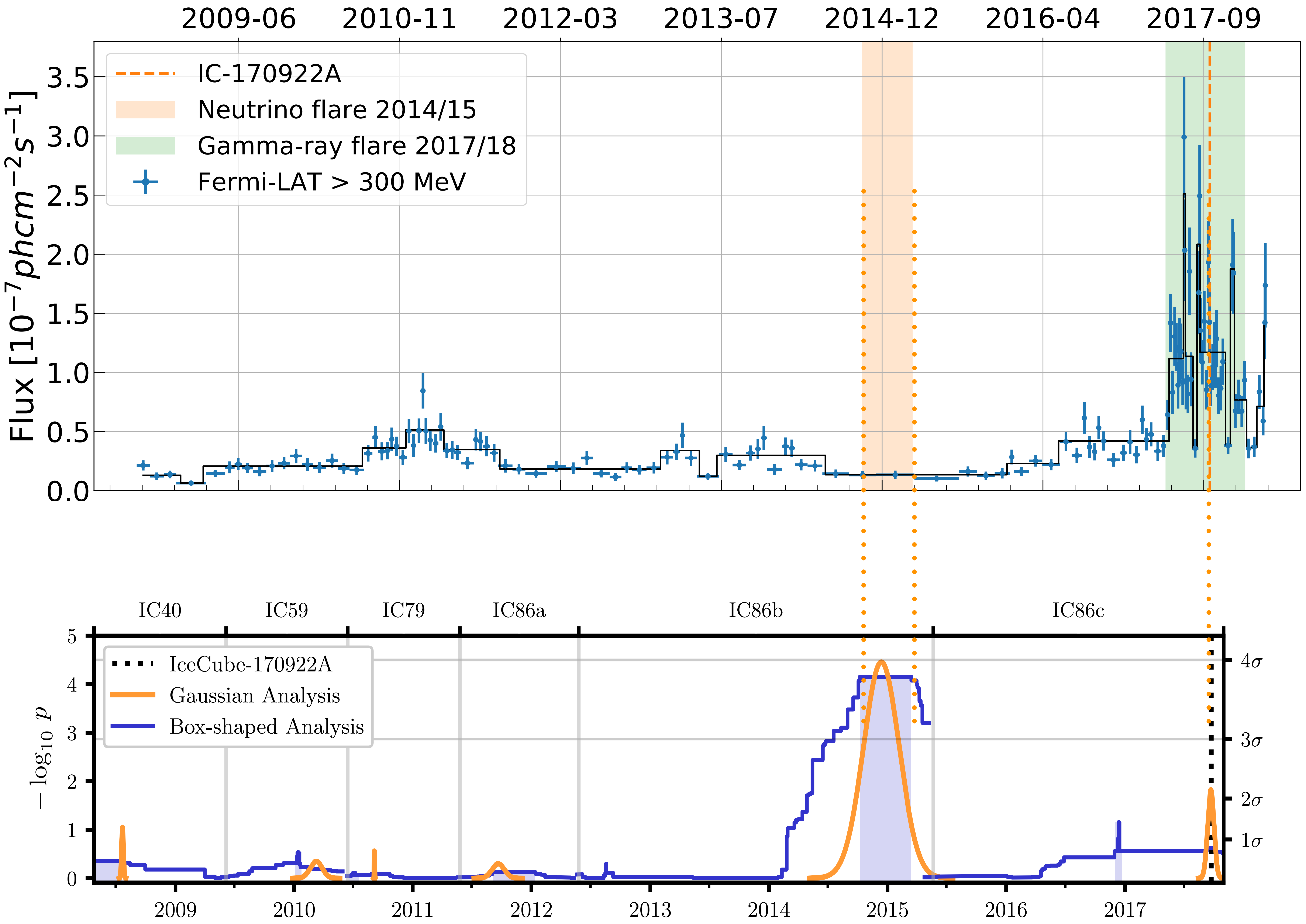
Background fluctuation? Chance probability ~0.3%



IceCube archival search 13±5 more neutrinos!

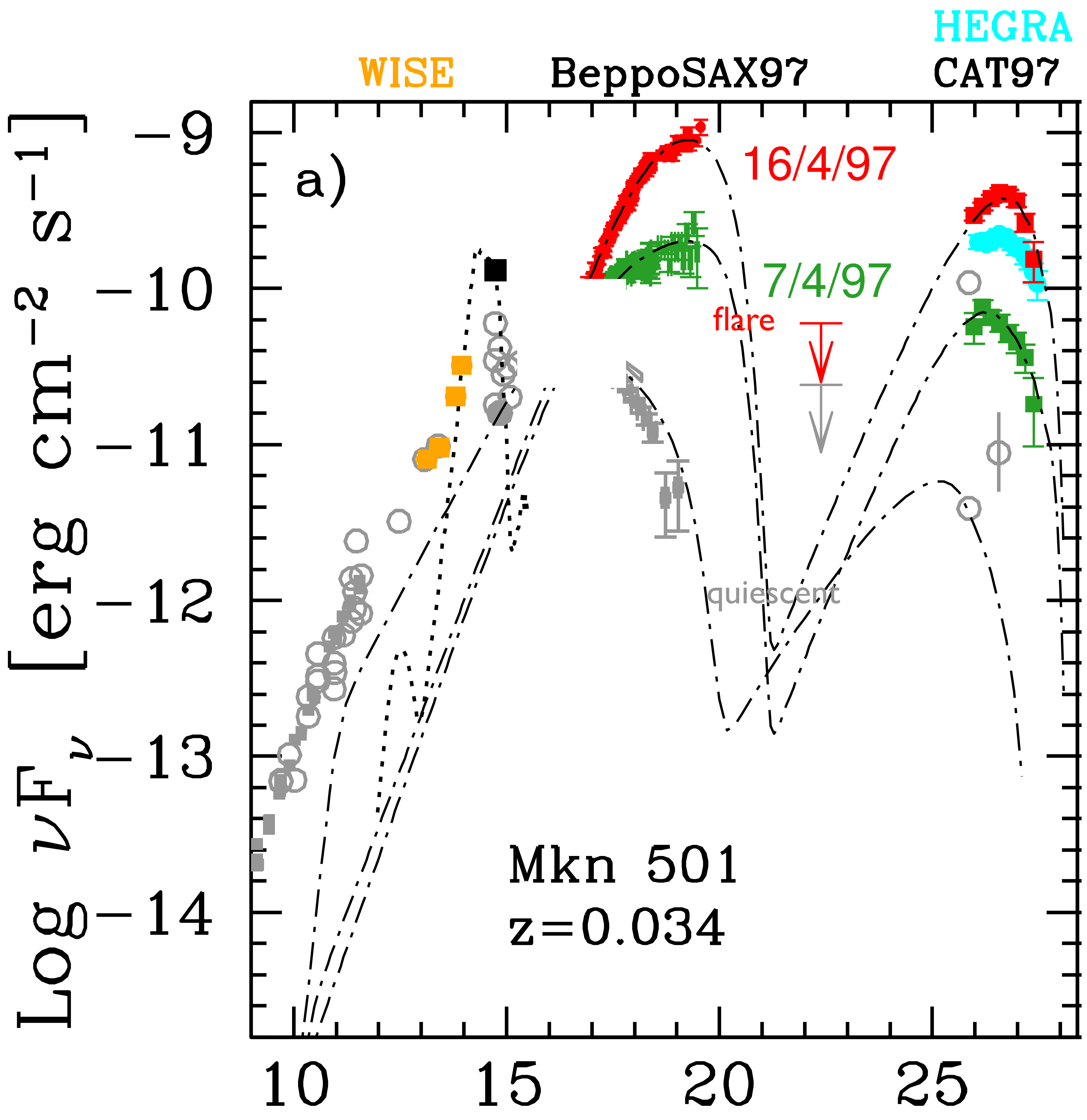
γ-rays

neutrinos



IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)

Blazar flares: Interesting as neutrino point sources



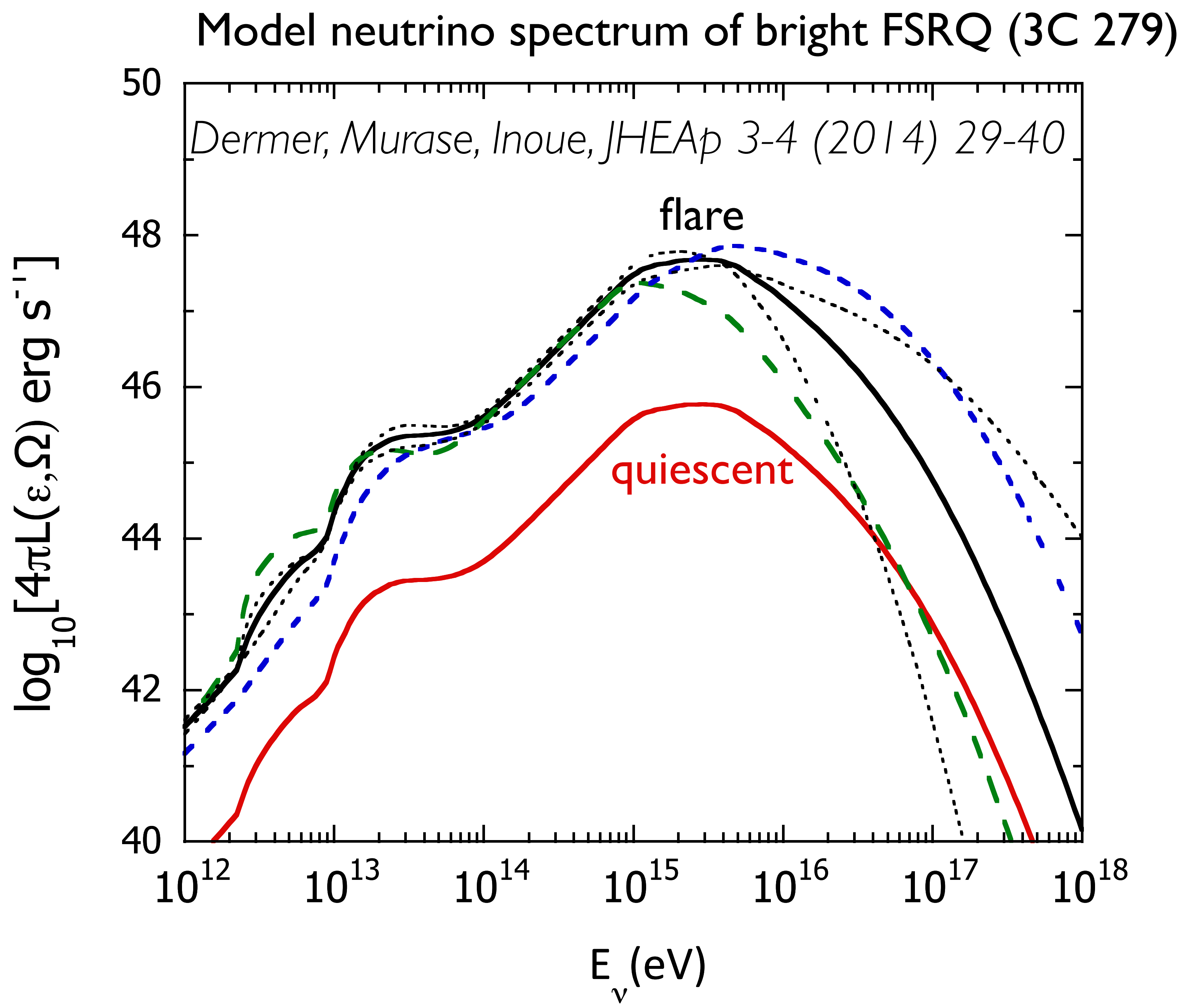
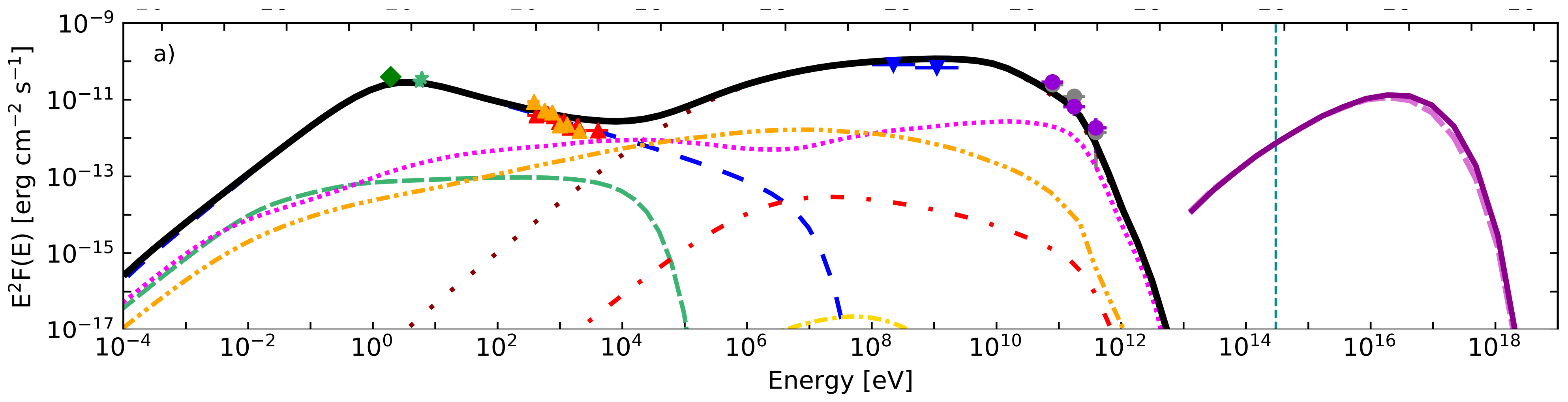


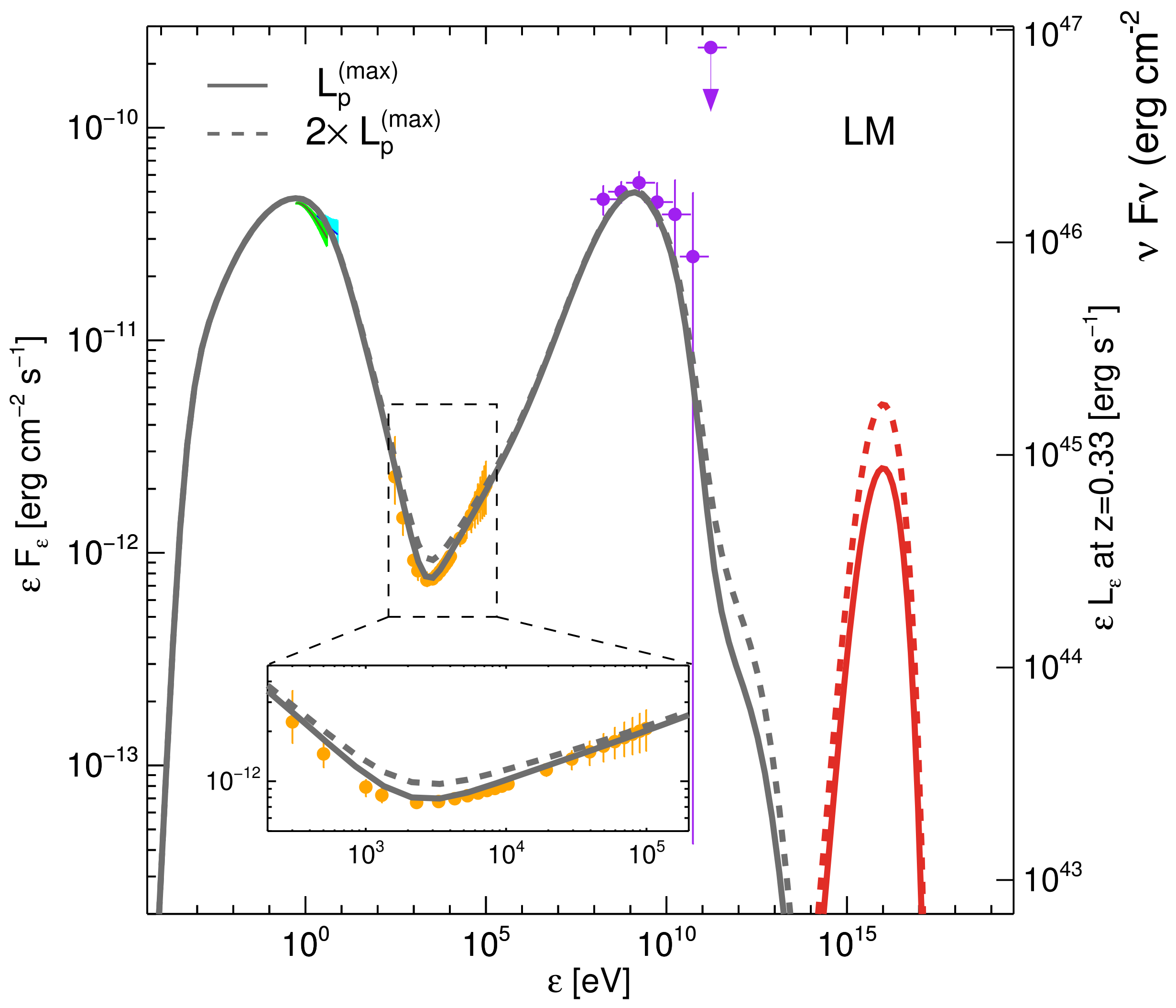
Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131 (2020)

Neutrino production in TXS 0506+056 in 2017

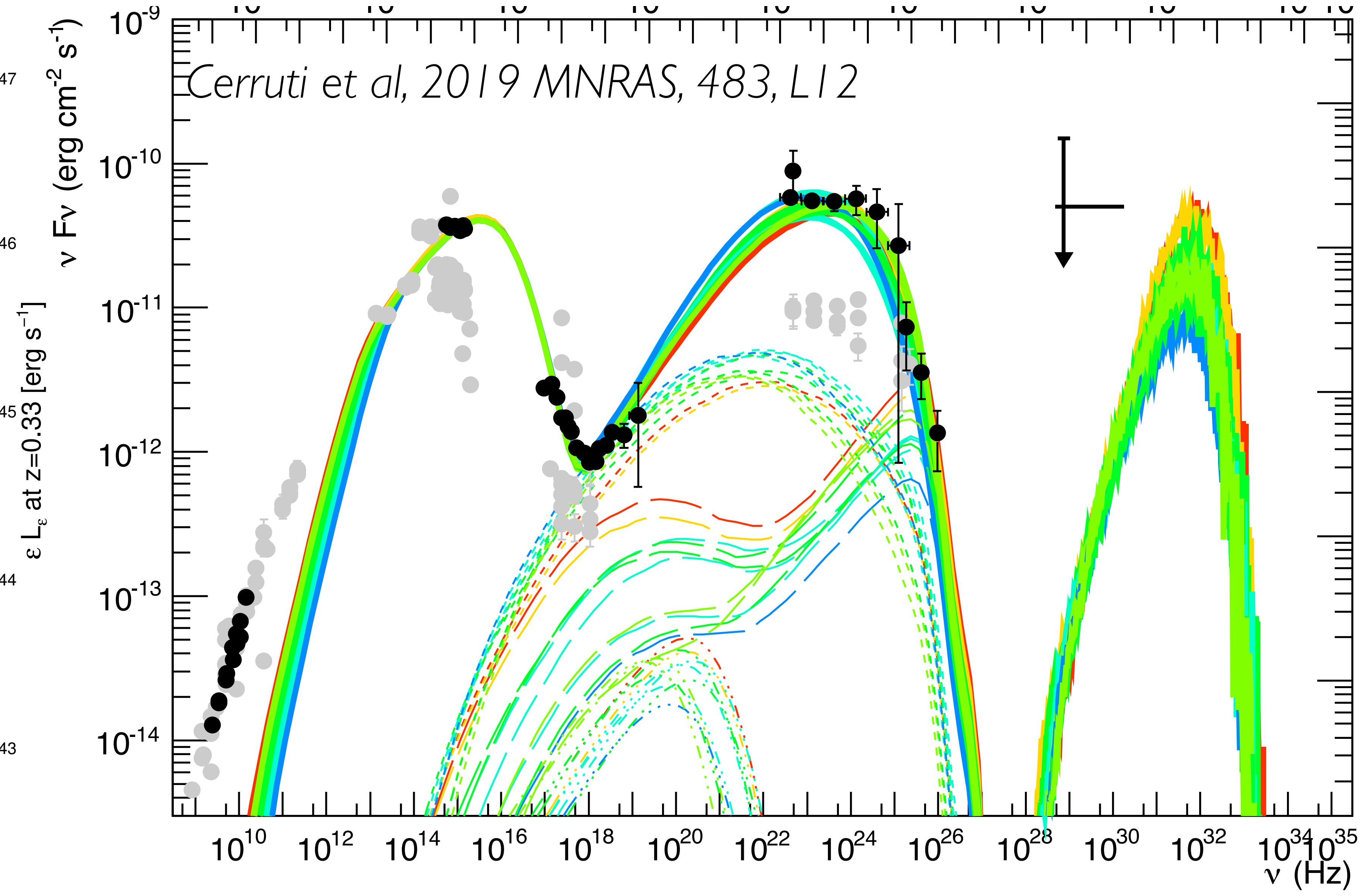
MAGIC Coll 2018, ApJ, 863, L10



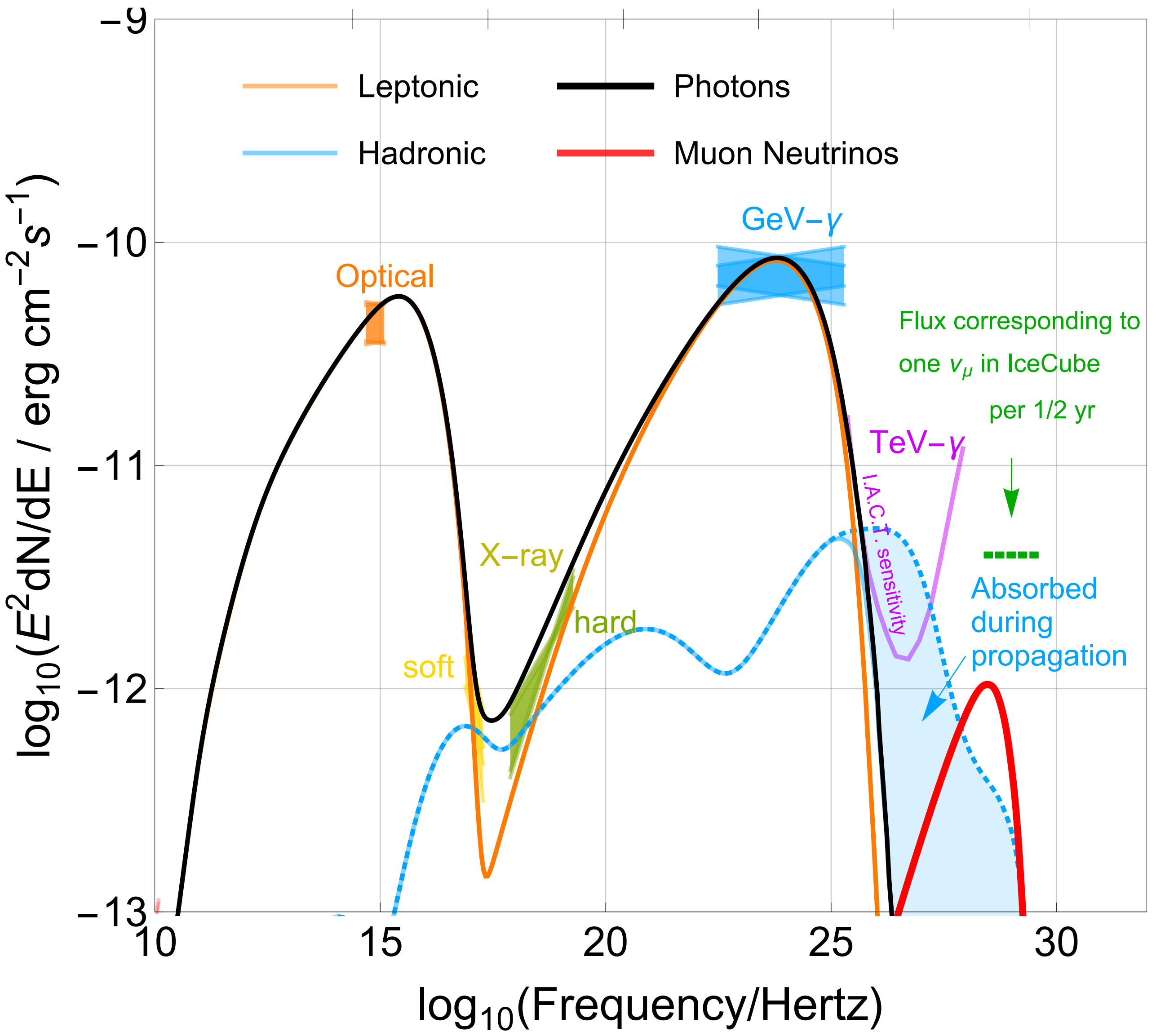
Keivani et al. 2018, ApJ, 864, 84



Cerruti et al, 2019 MNRAS, 483, L12



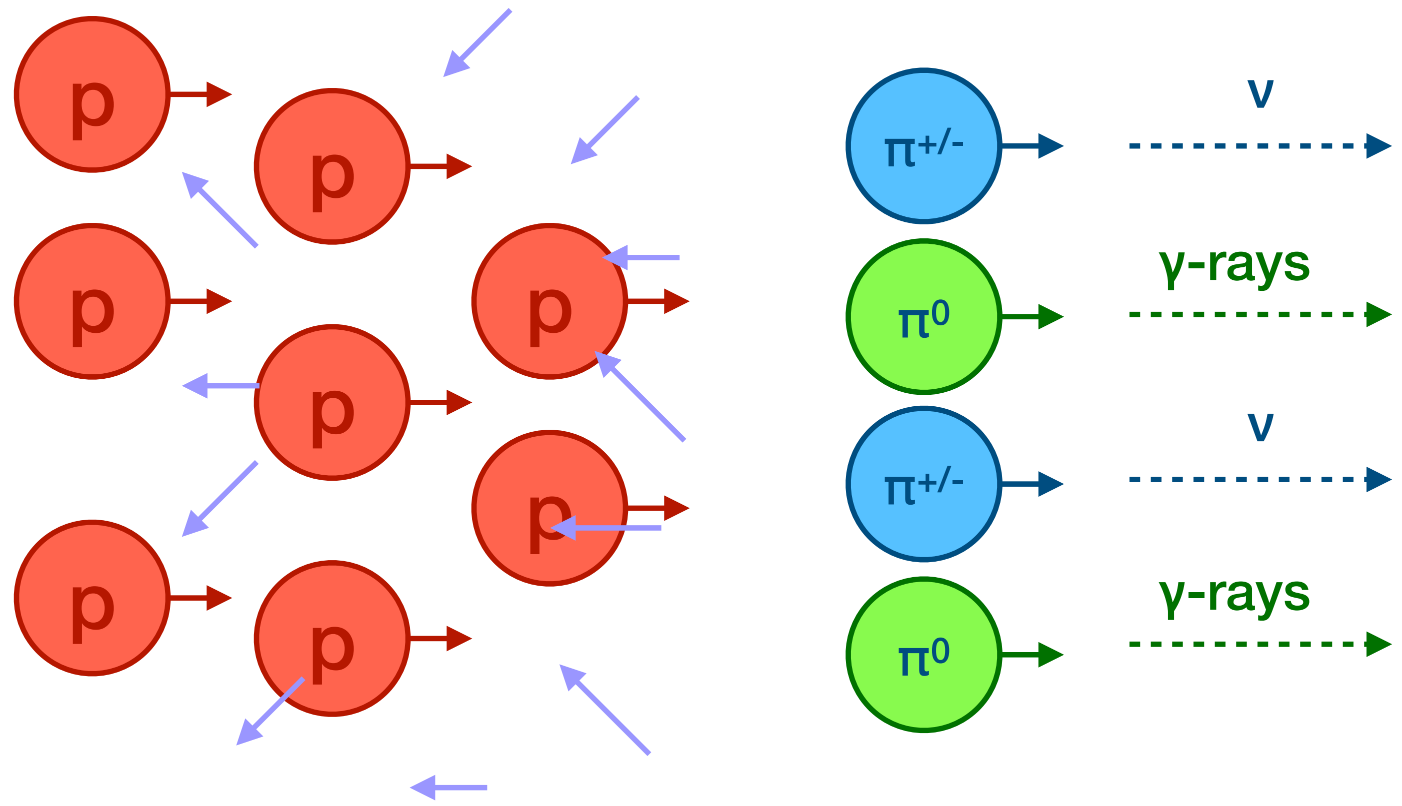
Gao et al, 2019, Nat. Astron., 3, 88



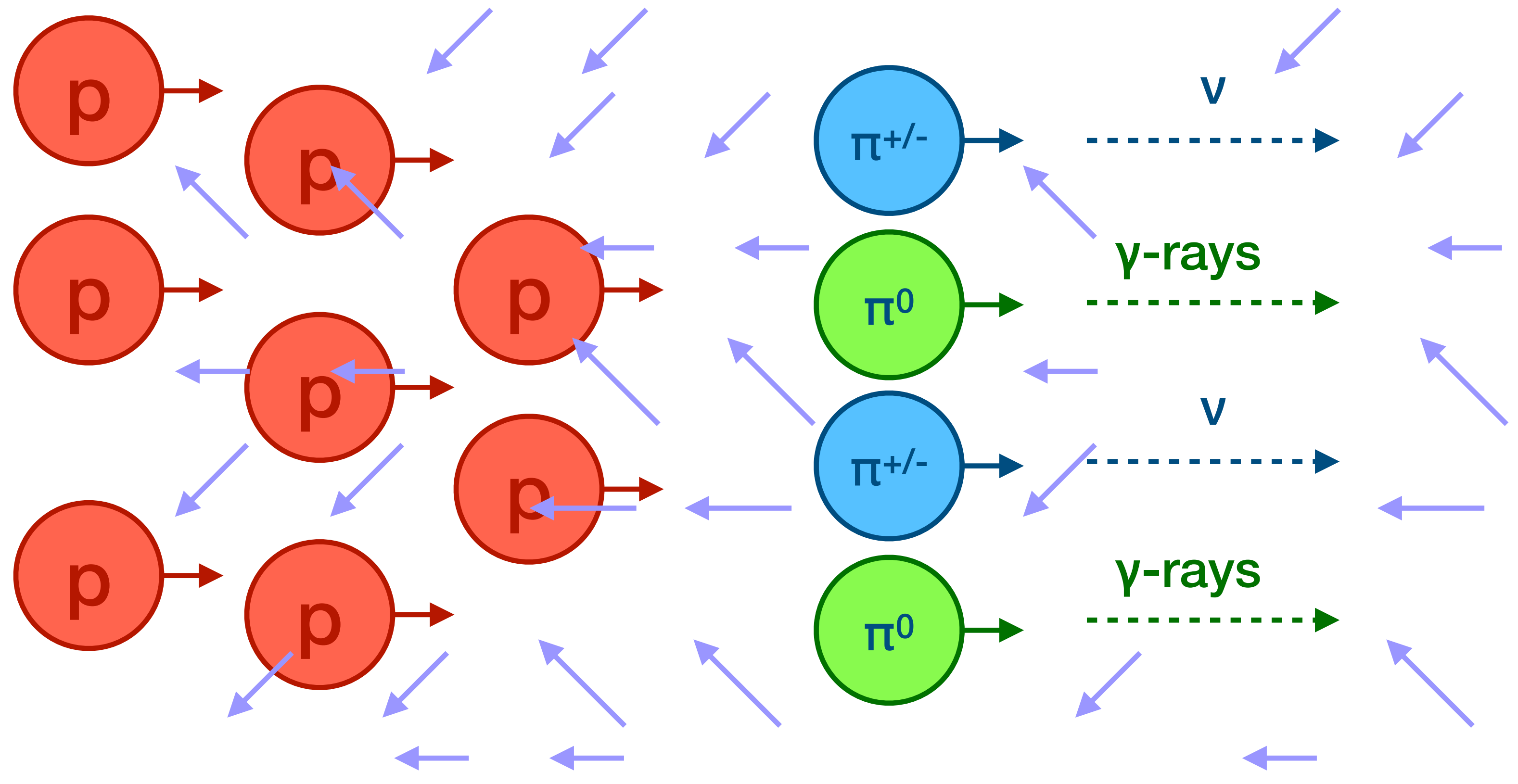
$$N_{\nu_\mu} \lesssim 0.05/6 \text{ months}^\star$$

-Ok due to population bias!
(1% chance to see one neutrino from each blazar flare)
-But: What does it take to produce 0.05 neutrinos/6months in this blazar?

What sets the neutrino flux upper limit?



What sets the neutrino flux upper limit?



$$p + \gamma \rightarrow \pi + X$$
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

What sets the neutrino flux upper limit?

Optical depth to **pγ** interactions

$$\tau_{p\gamma}(E'_p) \approx \sigma_{p\gamma} r_b n_{\epsilon'_t}\big|_{\epsilon'_t = m_\pi c^2 (m_\pi c^2 + m_p c^2)/2E'_p}$$

At the same time **γγ**,

$$\tau_{\gamma\gamma}(\varepsilon'_\gamma) \approx \sigma_{\rm T} r'_{\rm b} n_{\epsilon'_t}\big|_{\epsilon'_t = m_e^2/E'_\gamma}$$

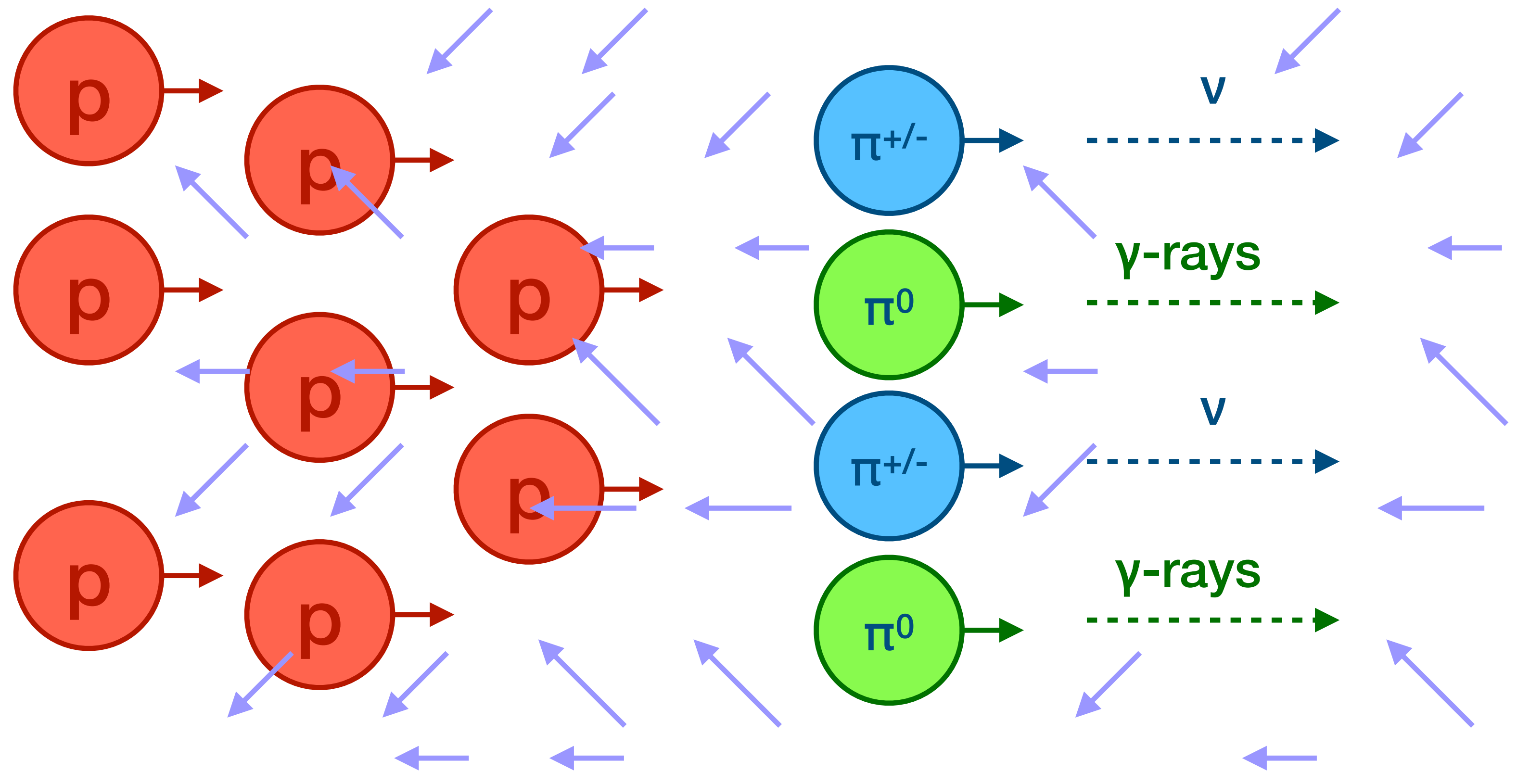
Ratio of optical depths is then,

$$\tau_{p\gamma}(E'_p) \approx \frac{\kappa_{p\gamma}}{\kappa_{\gamma\gamma}} \frac{\sigma_{\gamma p}}{\sigma_{\gamma\gamma}} \tau_{\gamma\gamma}(E'_\gamma) \approx \frac{10^{-28}\ \mathrm{cm}^2}{10^{-25}\ \mathrm{cm}^2} \tau_{\gamma\gamma}(E'_\gamma) \approx 10^{-3} \tau_{\gamma\gamma}(E'_\gamma)$$

At energy,

$$E'_\gamma \sim 15\ \mathrm{GeV} \left(\frac{E'_p}{6\ \mathrm{PeV}}\right) \sim 15\ \mathrm{GeV} \left(\frac{E'_\nu}{300\ \mathrm{TeV}}\right)$$

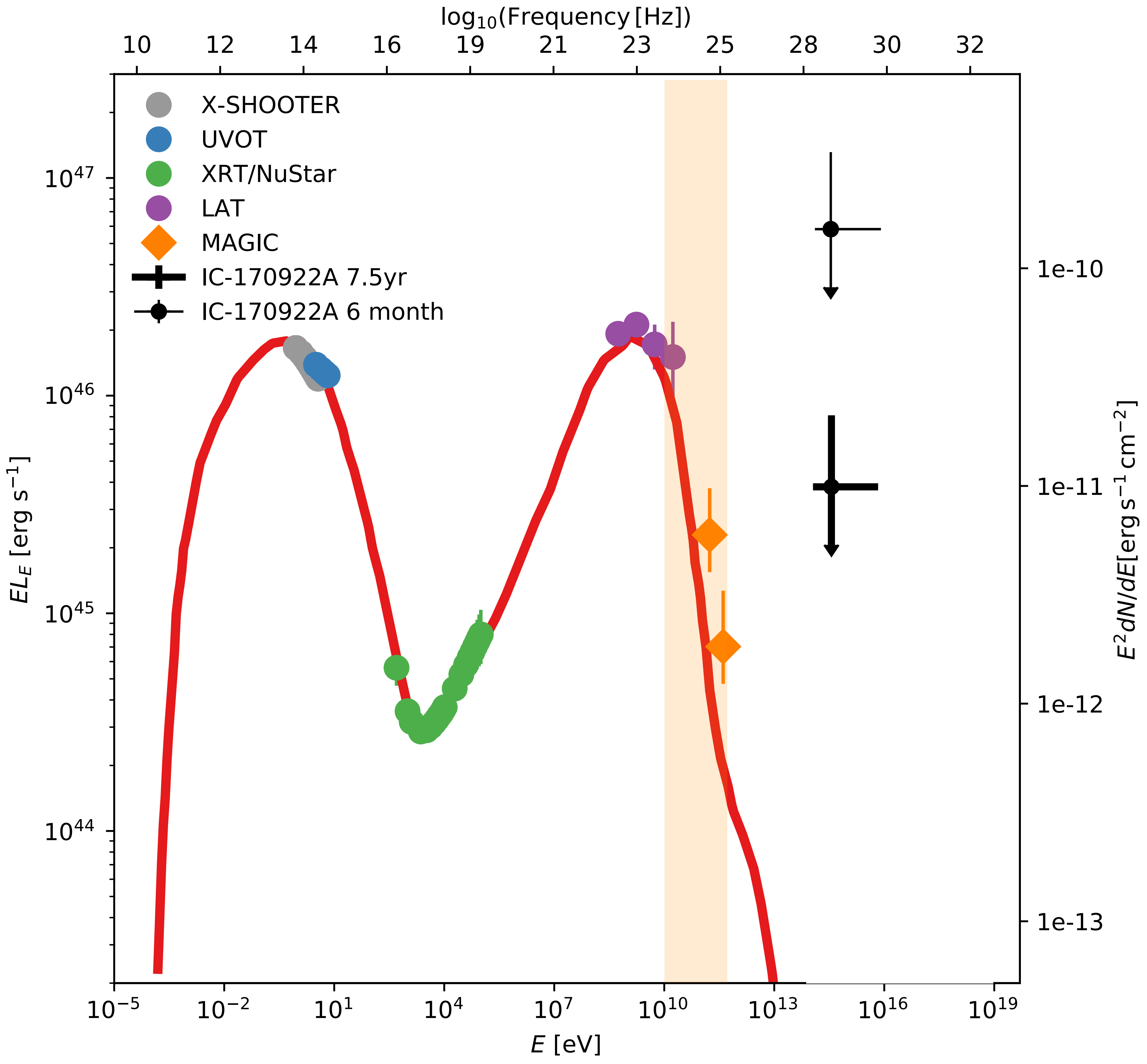
This implies that sources optically thin to gamma-rays have inefficient TeV neutrino production

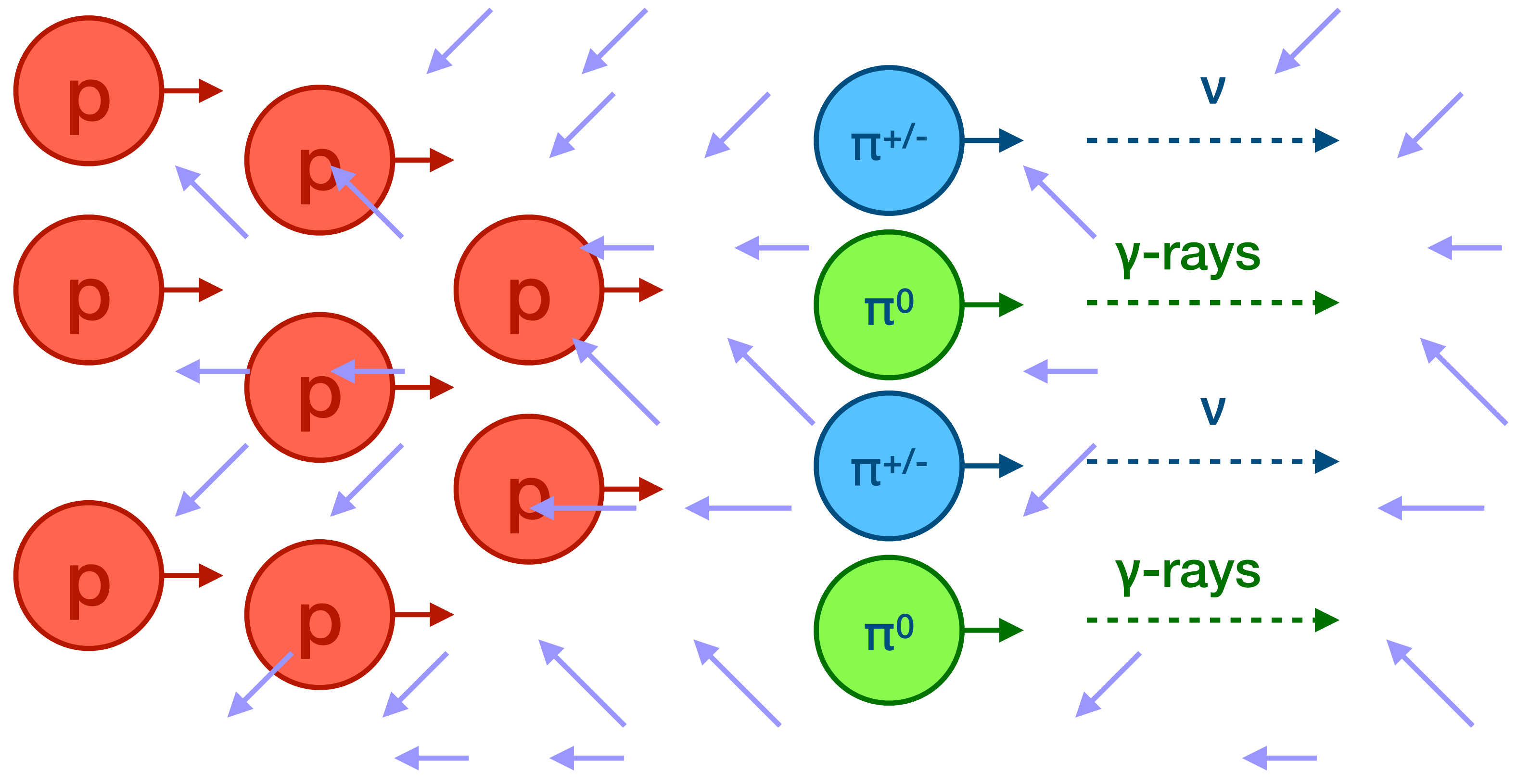


$$p + \gamma \to \pi + X$$
$$\gamma + \gamma \to e^+ + e^-$$

What sets the neutrino flux upper limit?

1. $\tau_{\gamma\gamma}(10-100\,\mathrm{GeV}) \lesssim 1$





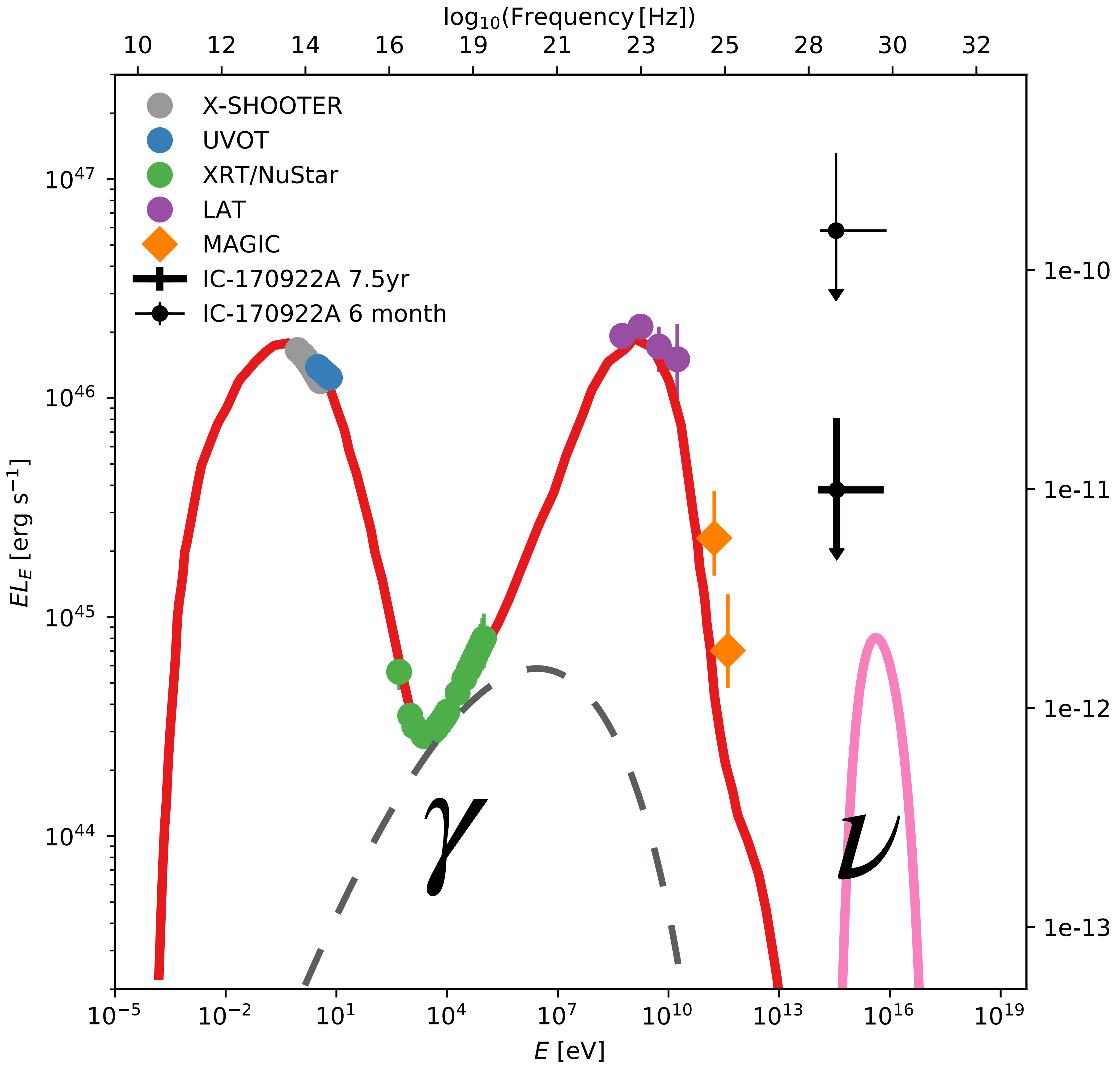
At energy,

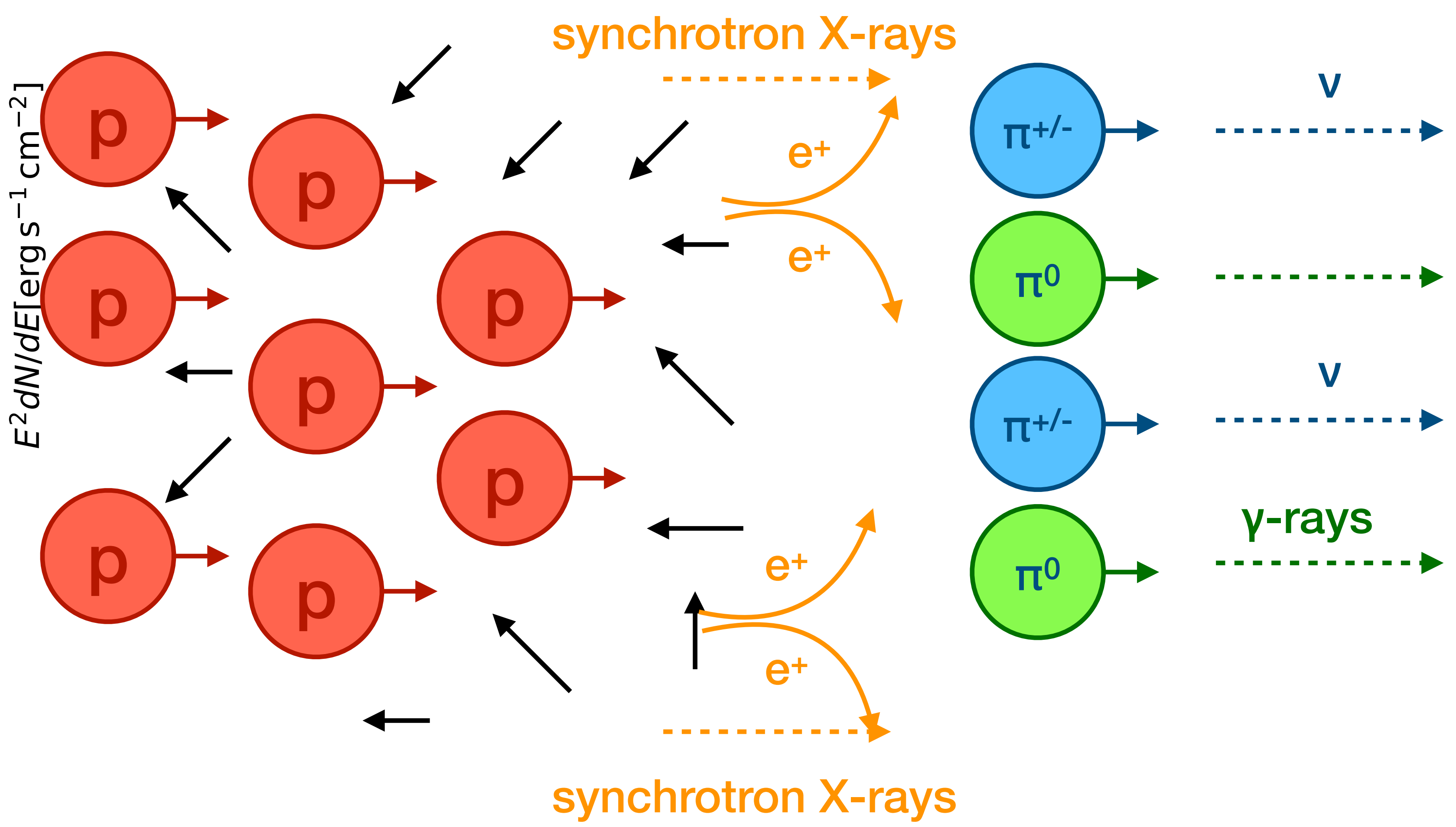
$$E'_\gamma \sim 15\ \mathrm{GeV}\left(\frac{E'_p}{6\ \mathrm{PeV}}\right) \sim 15\ \mathrm{GeV}\left(\frac{E'_\nu}{300\ \mathrm{TeV}}\right)$$

$$\tau_{\gamma\gamma}(E'_\gamma) \approx 10^3 \tau_{p\gamma}(E'_p)$$

What sets the neutrino flux upper limit?

$p_{\mathrm{PeV}} + \gamma \rightarrow p + e^{+} + e^{-} \rightarrow$ the electrons undergo synchrotron or Inv. Compton $\rightarrow$ cascade that peaks in keV band





3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

What sets the neutrino flux upper limit?

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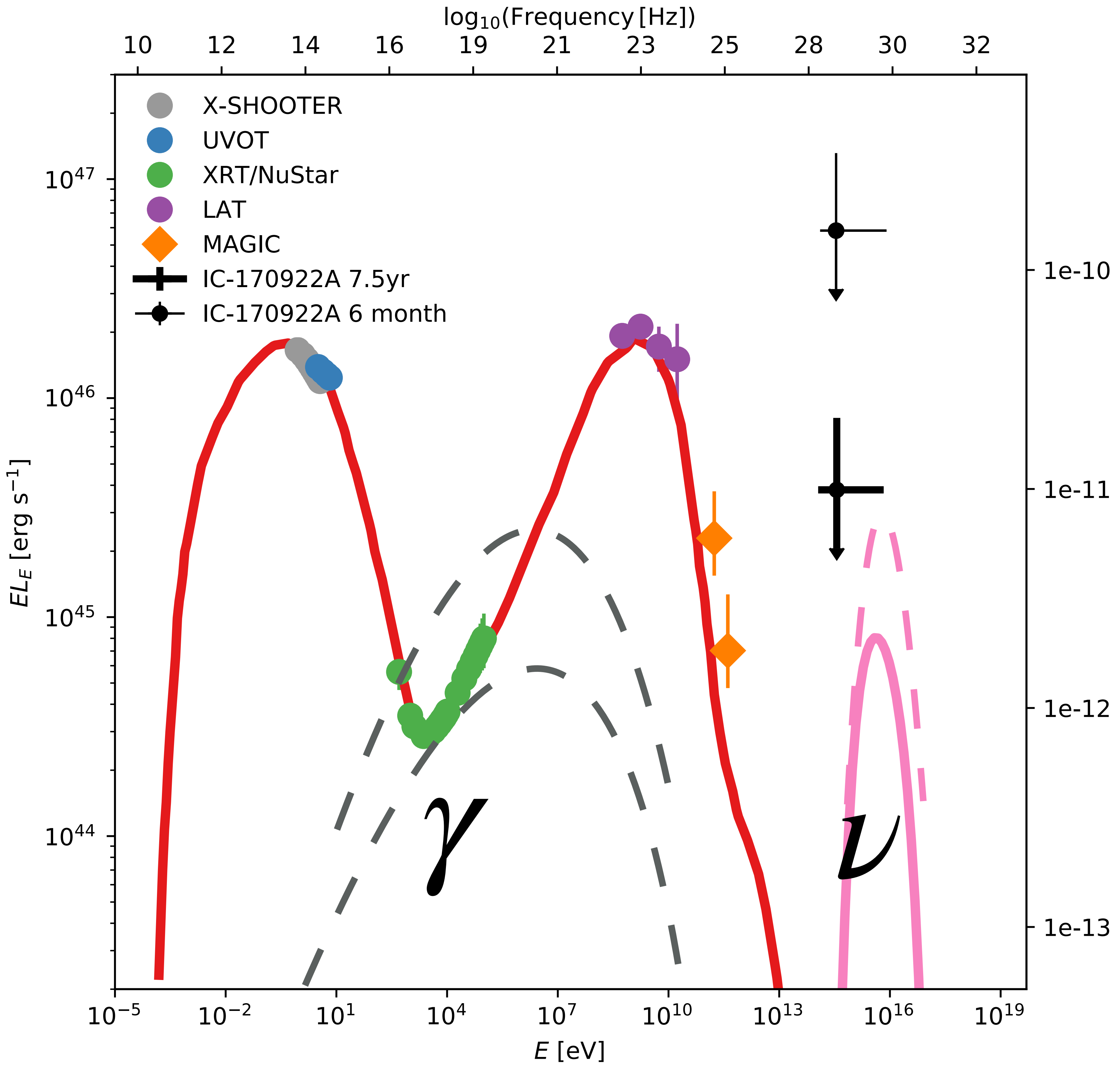

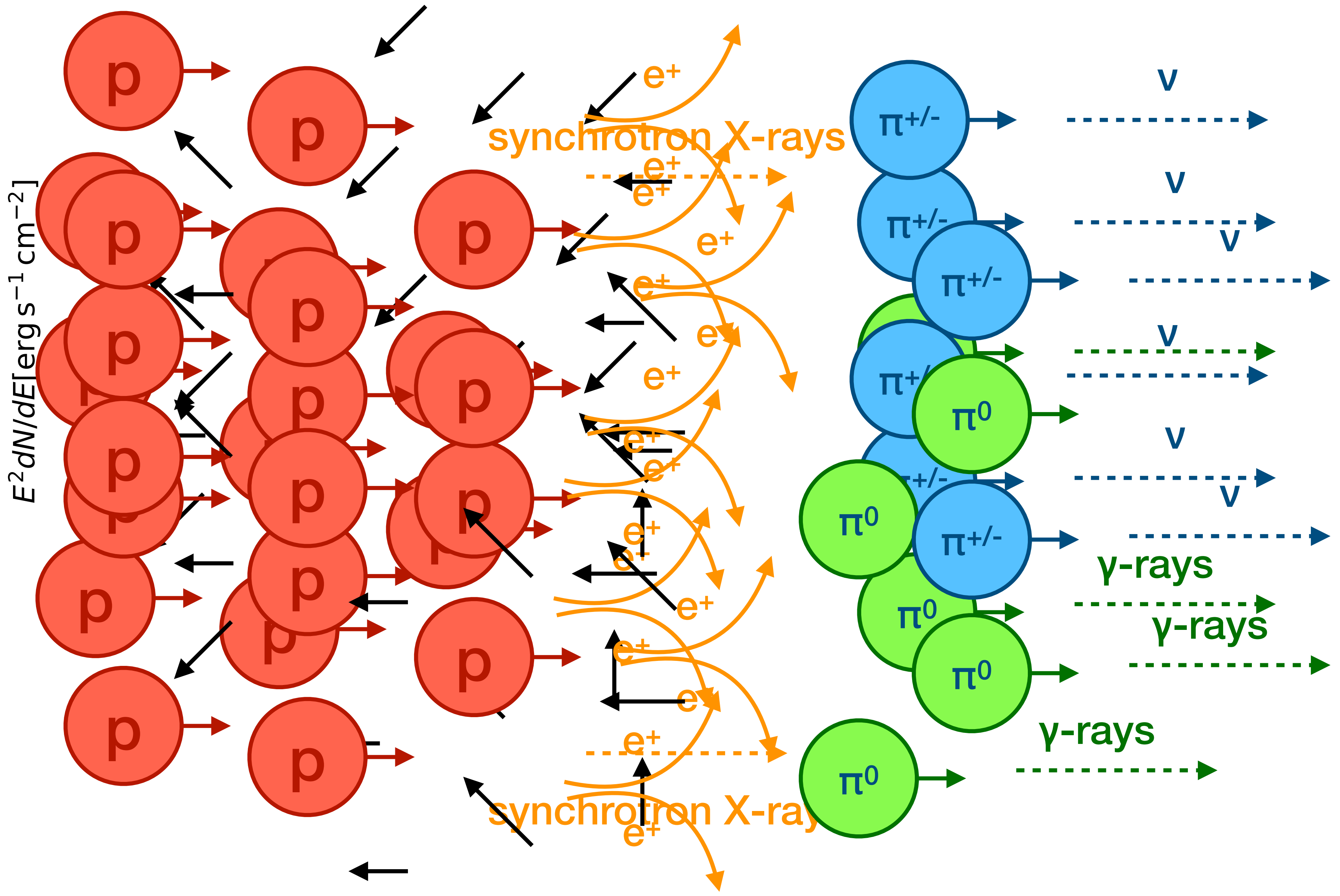

3/8ths of proton energy lost → neutrinos
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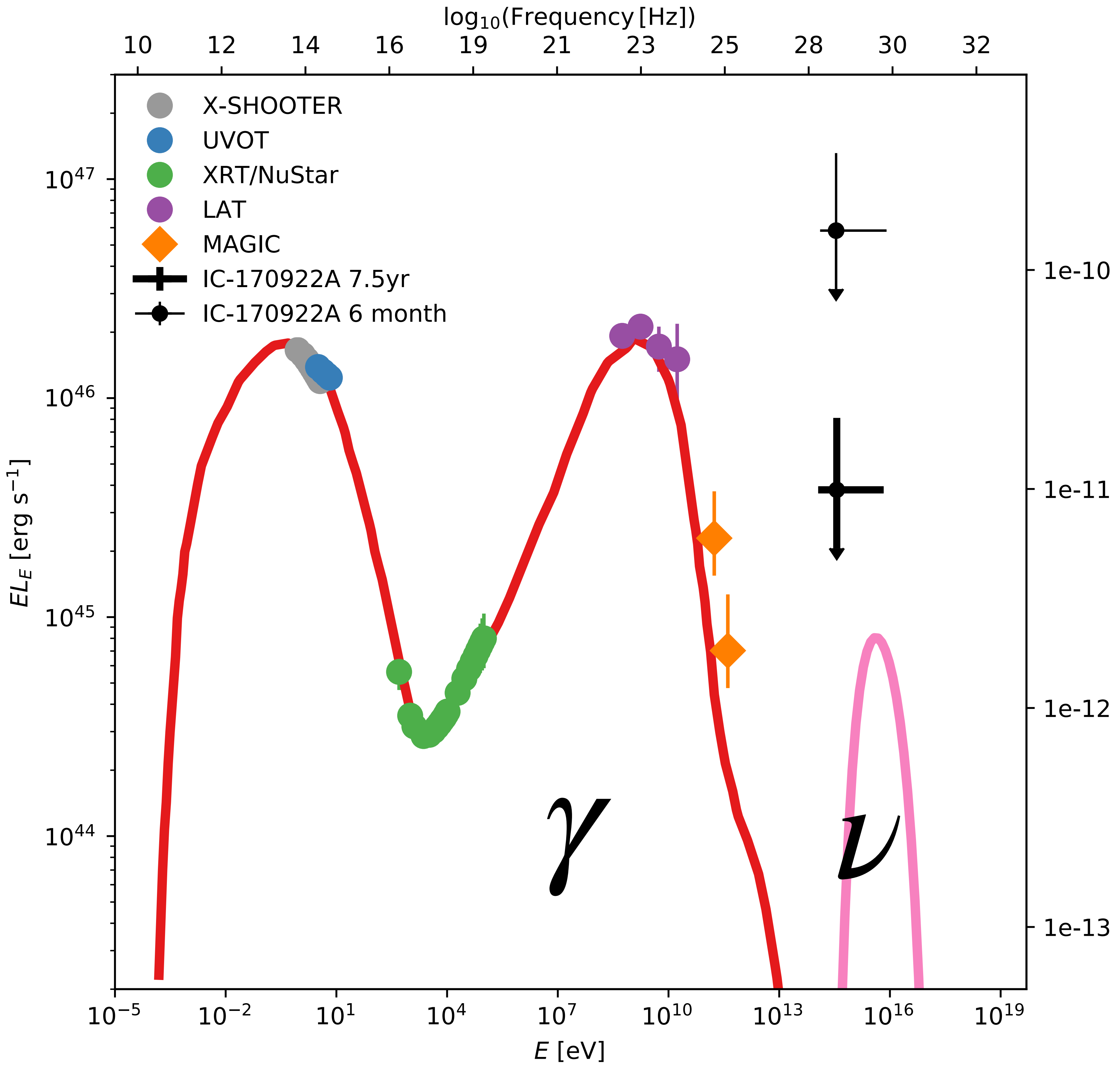
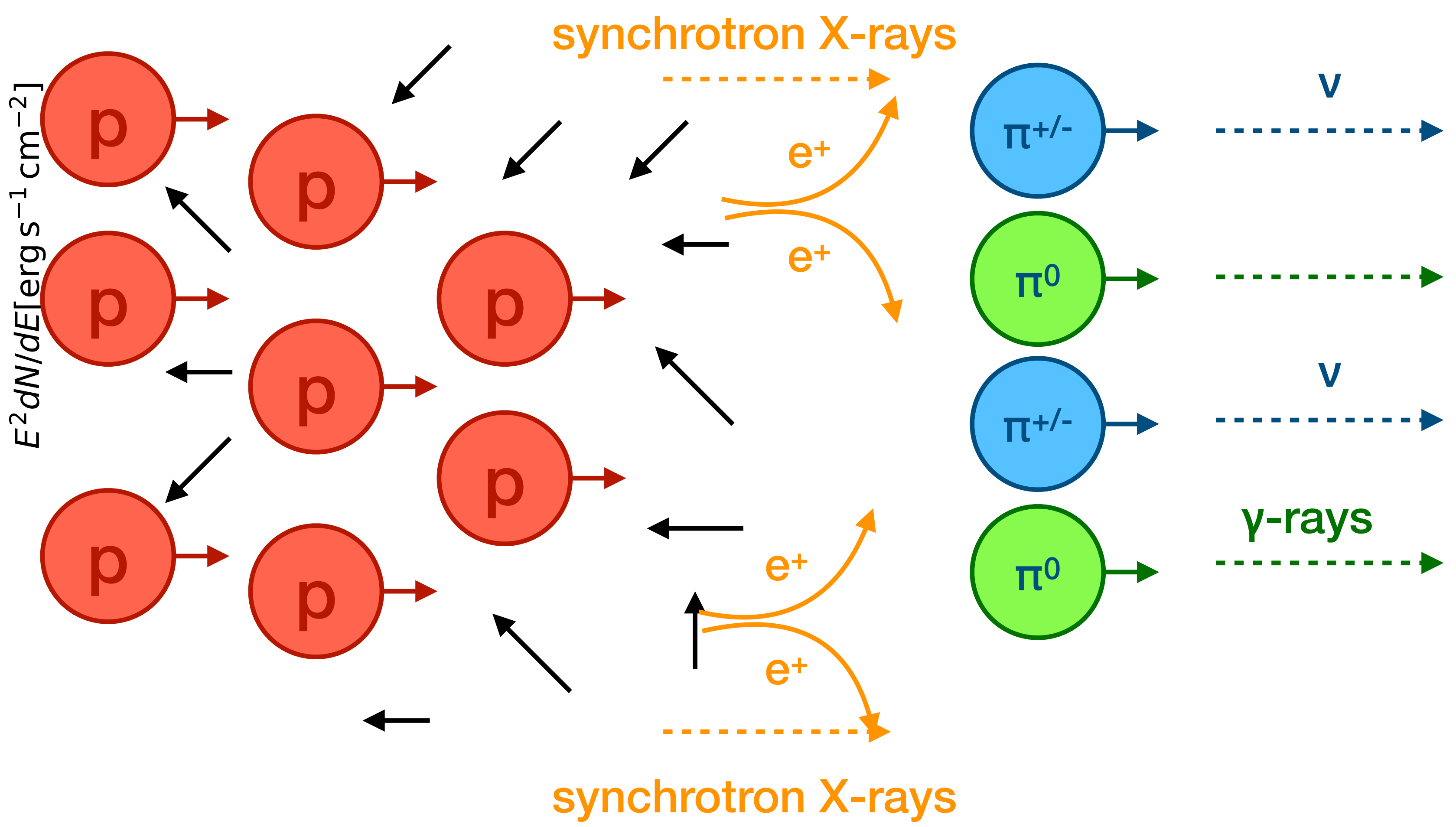
What sets the neutrino flux upper limit?

$p_{\mathrm{PeV}} + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma \qquad \gamma + \gamma_{\mathrm{jet/BLR}} \rightarrow e^+e^- \rightarrow \mathrm{synchrotron\ or\ inv.Compton}$





3/8ths of proton energy lost → neutrinos
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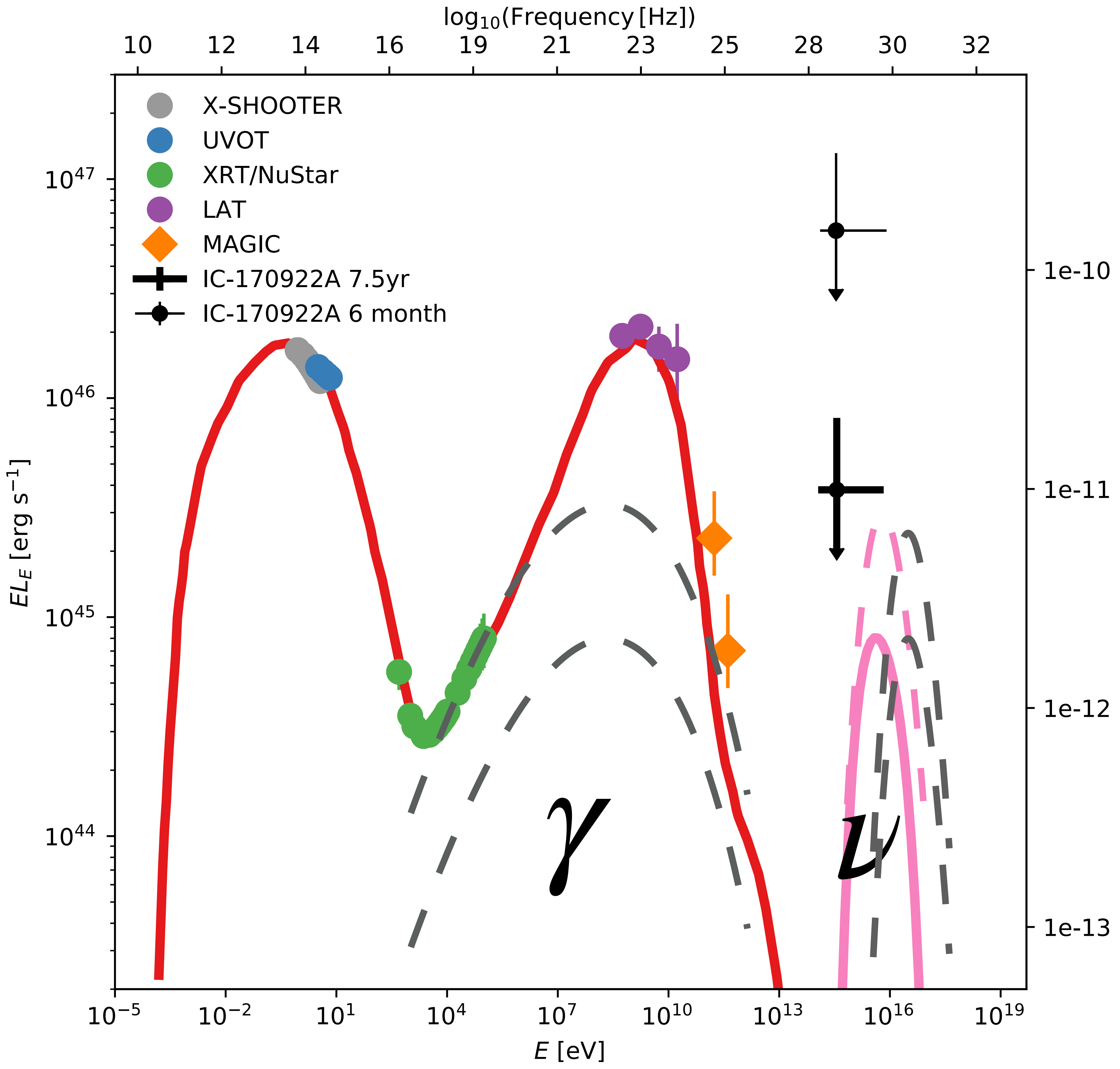
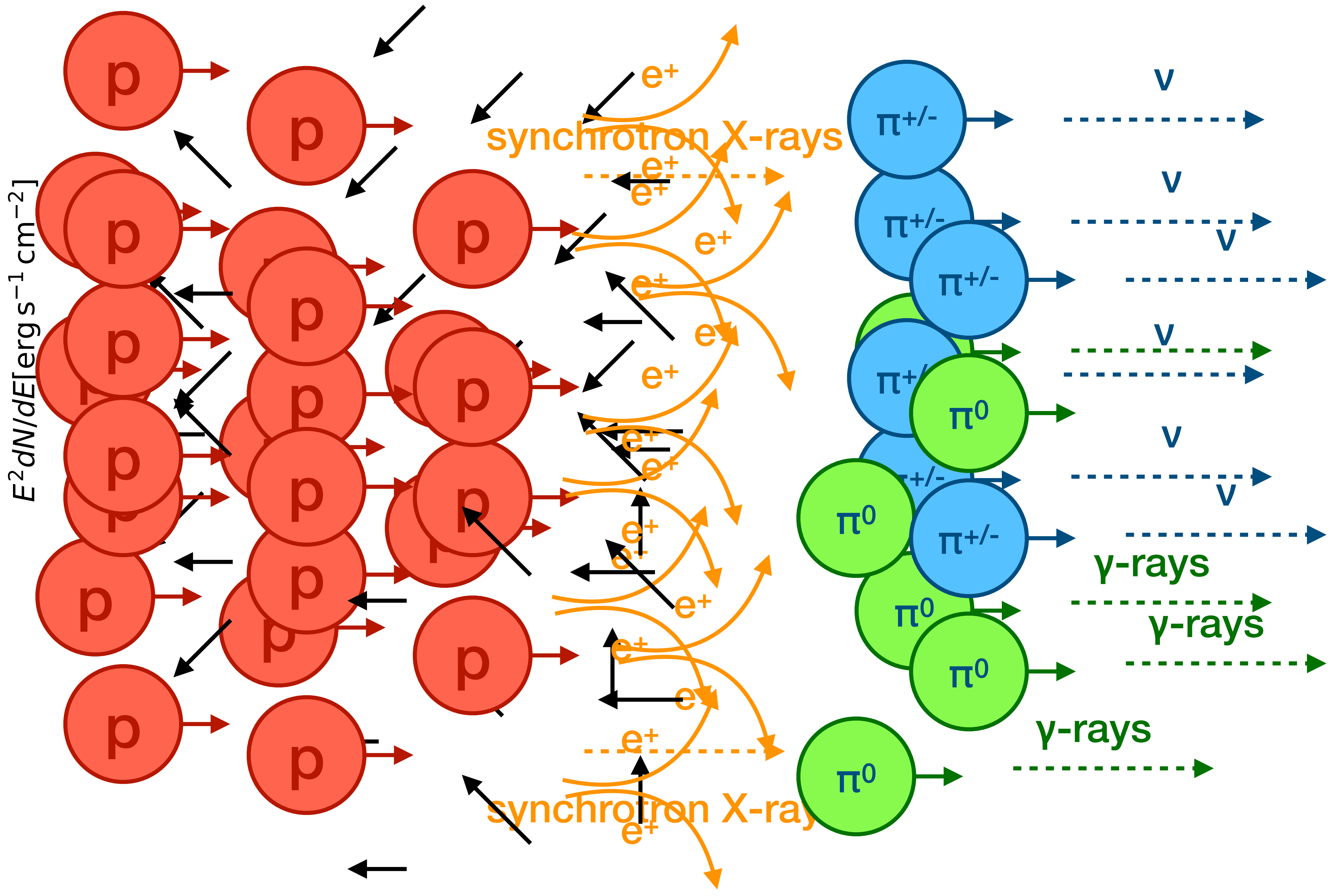
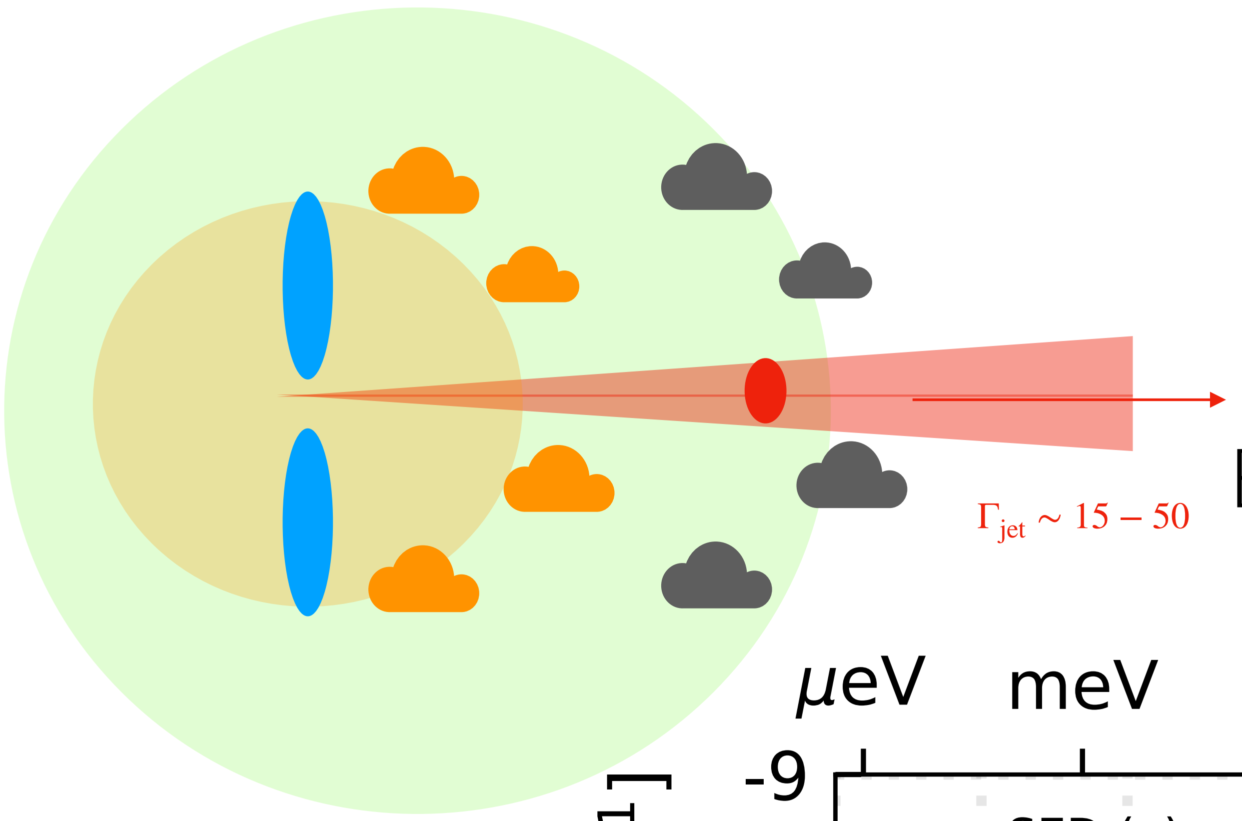
$p_{\mathrm{PeV}} + \gamma \to p + \pi^0 \to p + \gamma + \gamma$ $\gamma + \gamma_{\mathrm{jet/BLR}} \to e^+e^- \to \mathrm{synchrotron\ or\ inv.Compton}$



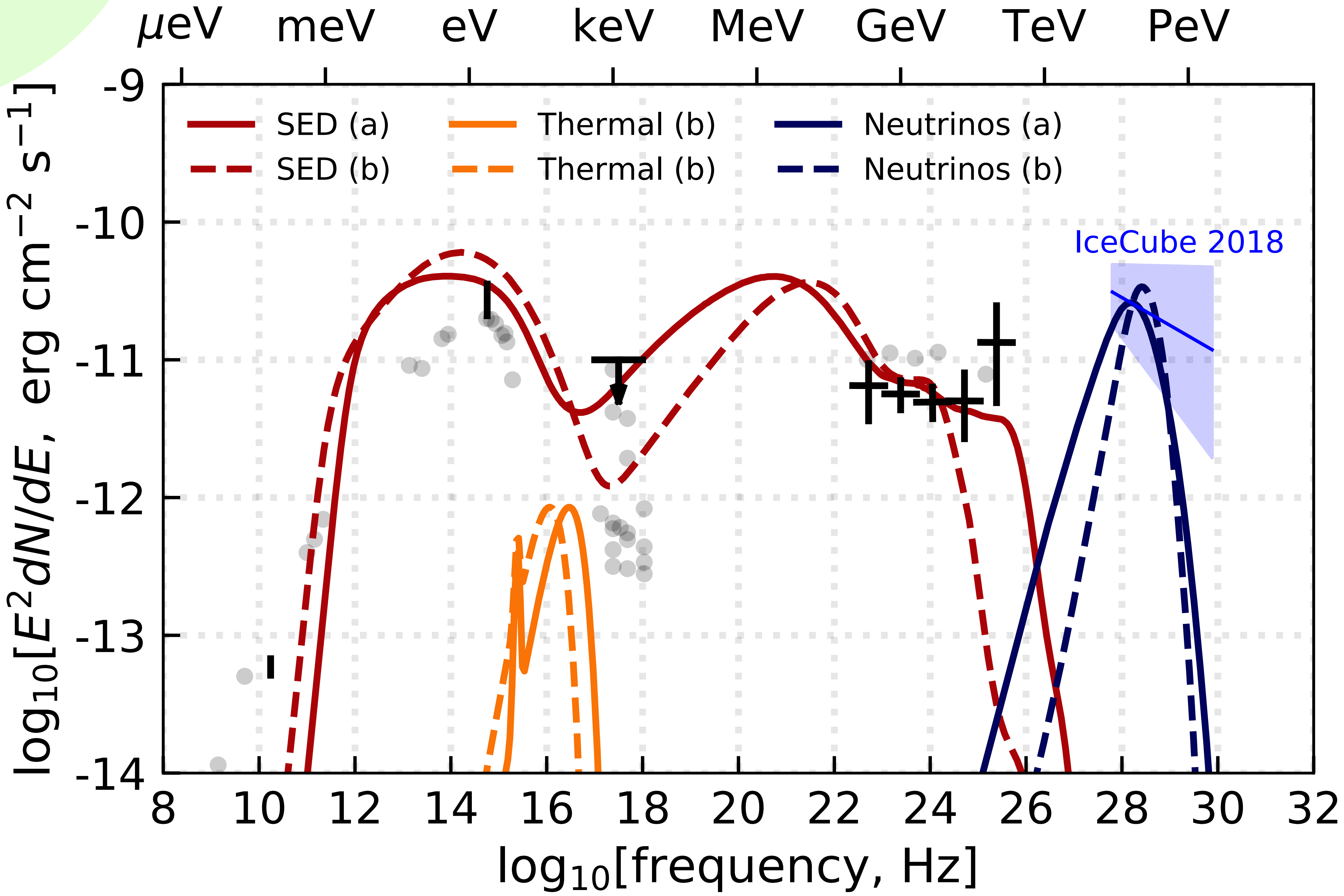


3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

Neutrino production in TXS 0506+056 2014-15

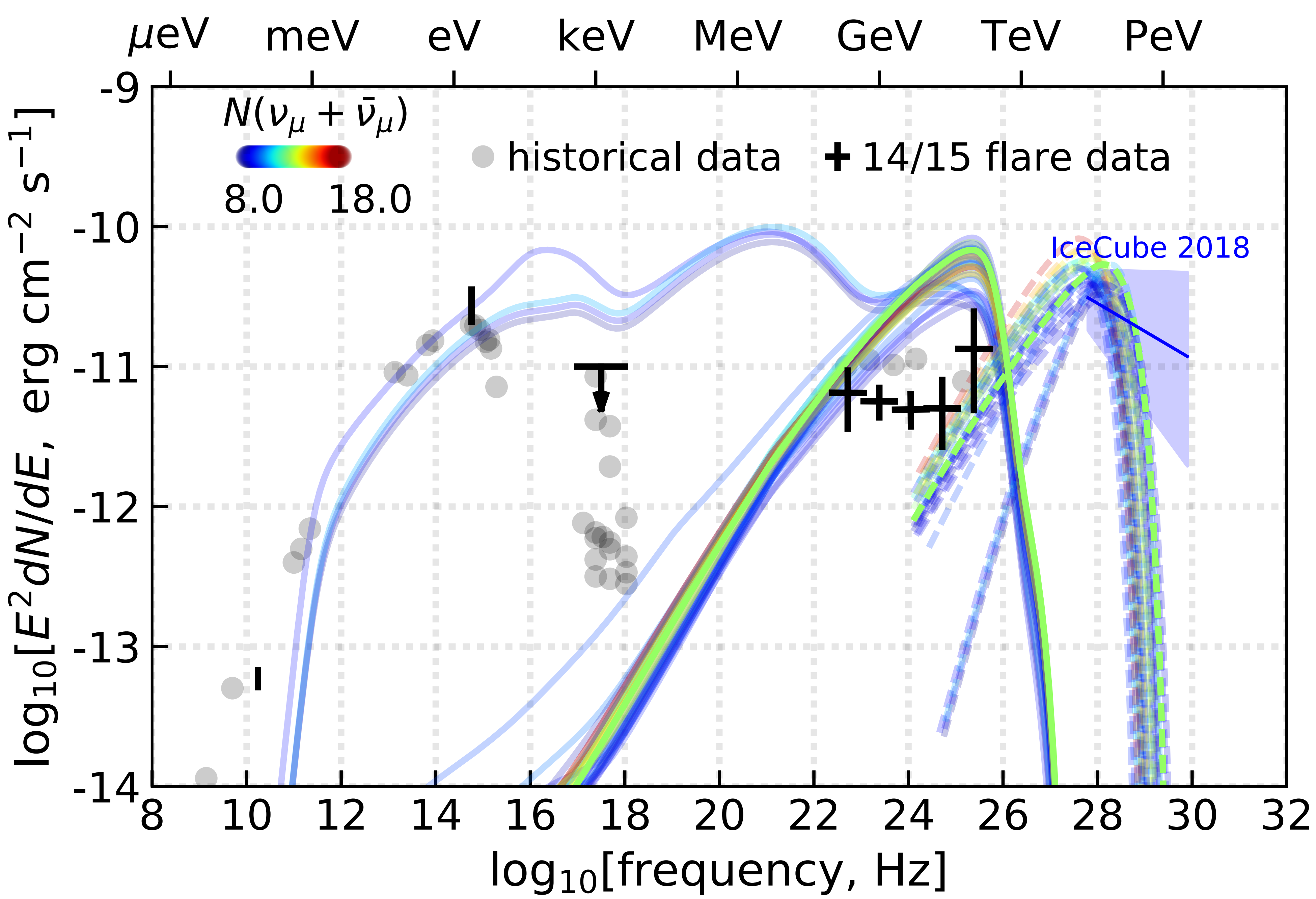


Broad-line region model



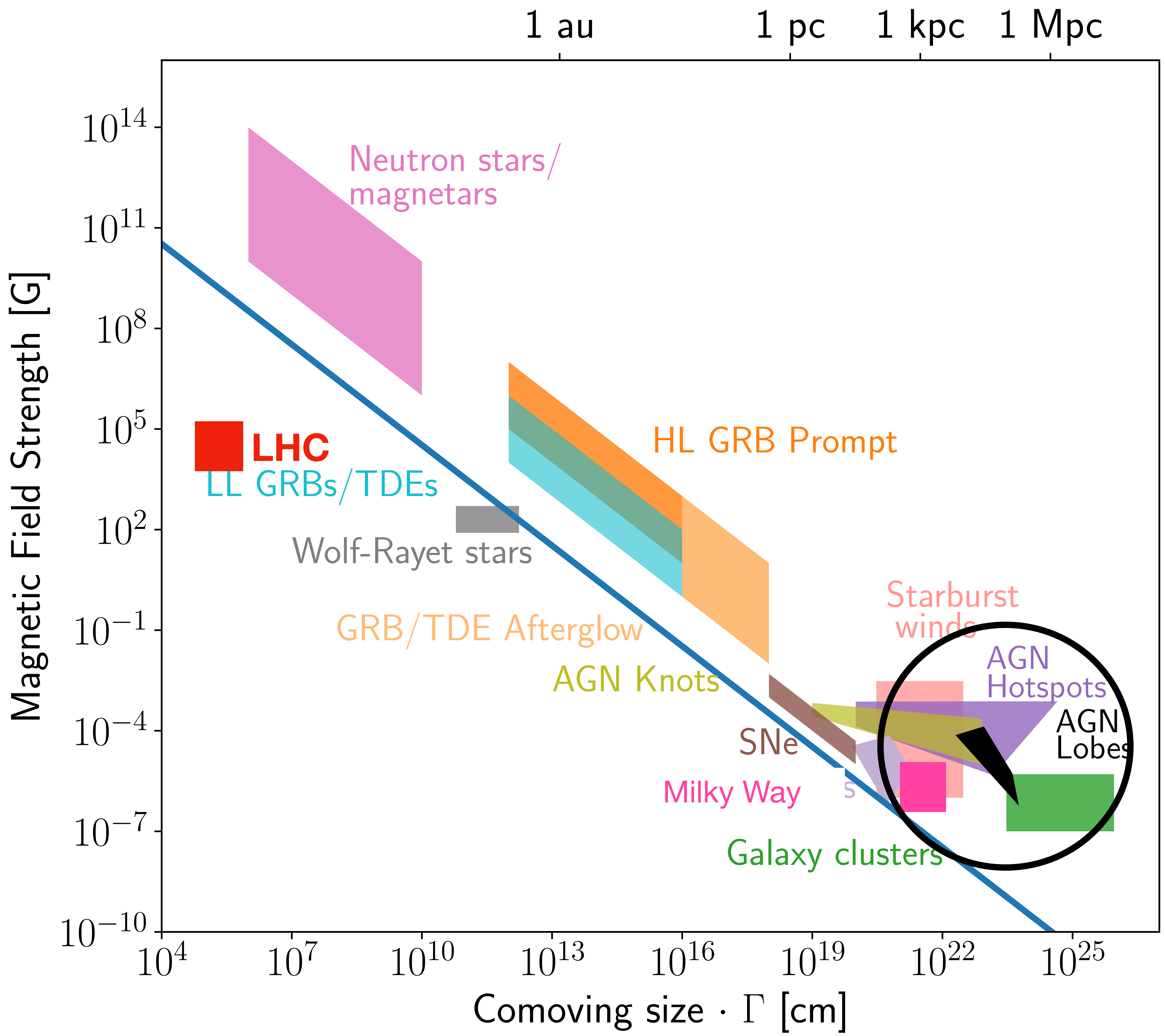
$N_{\nu_\mu} \leq 4.9$

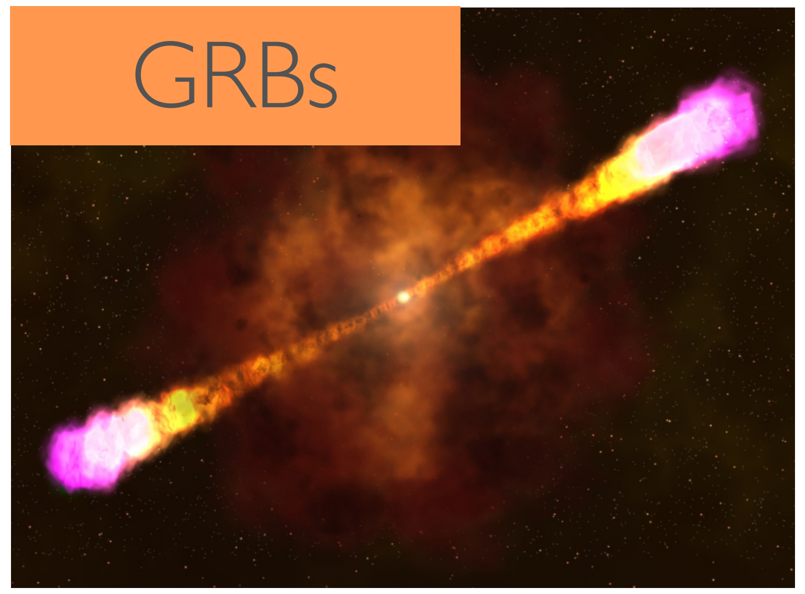
Overshoots spectrum

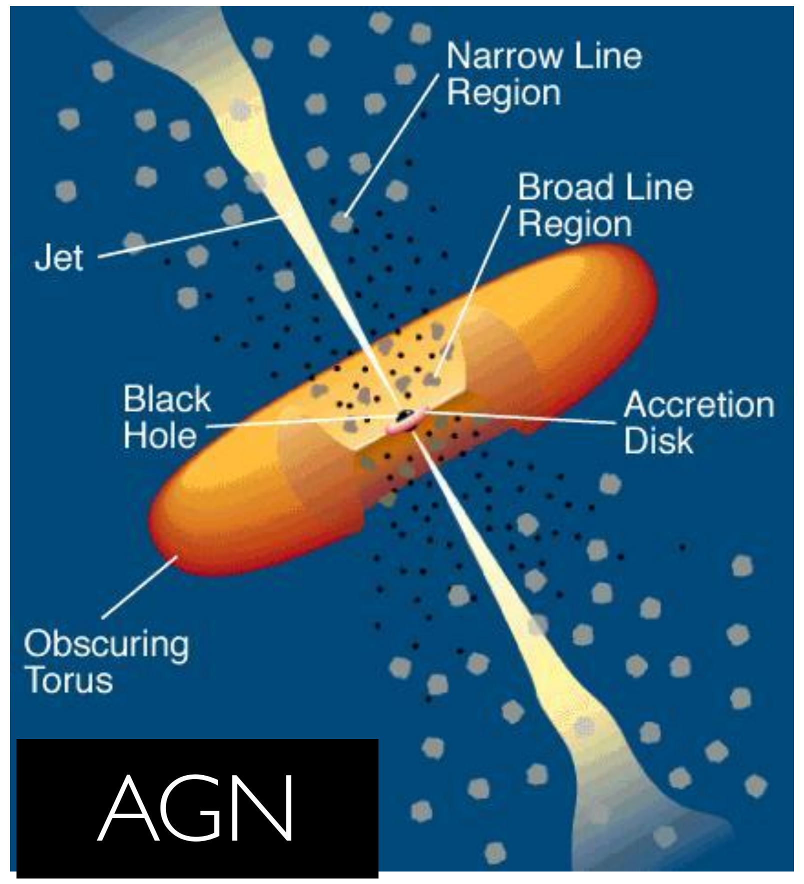


$N_{\nu_\mu} = 13.2$

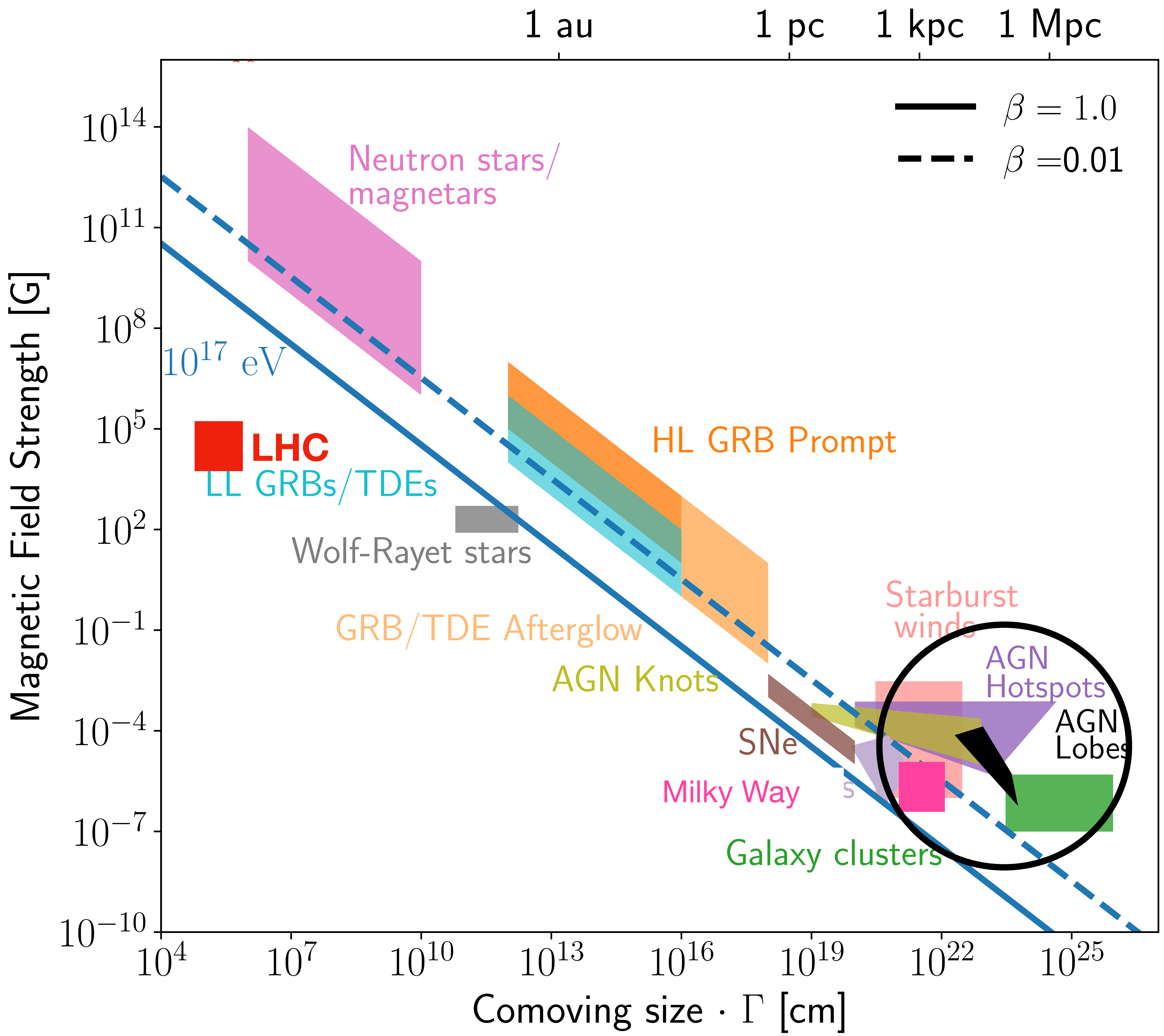
Cosmic-ray accelerators that satisfy the confinement req… ^{17} eV)

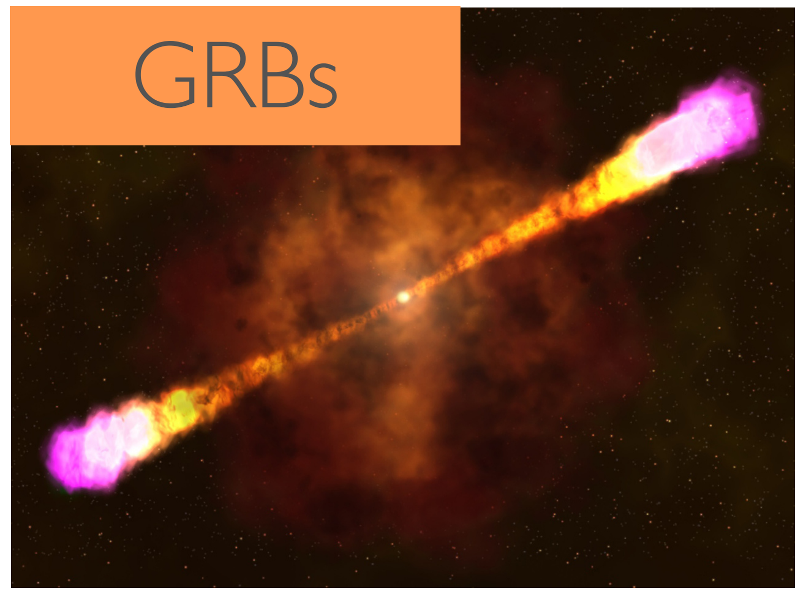


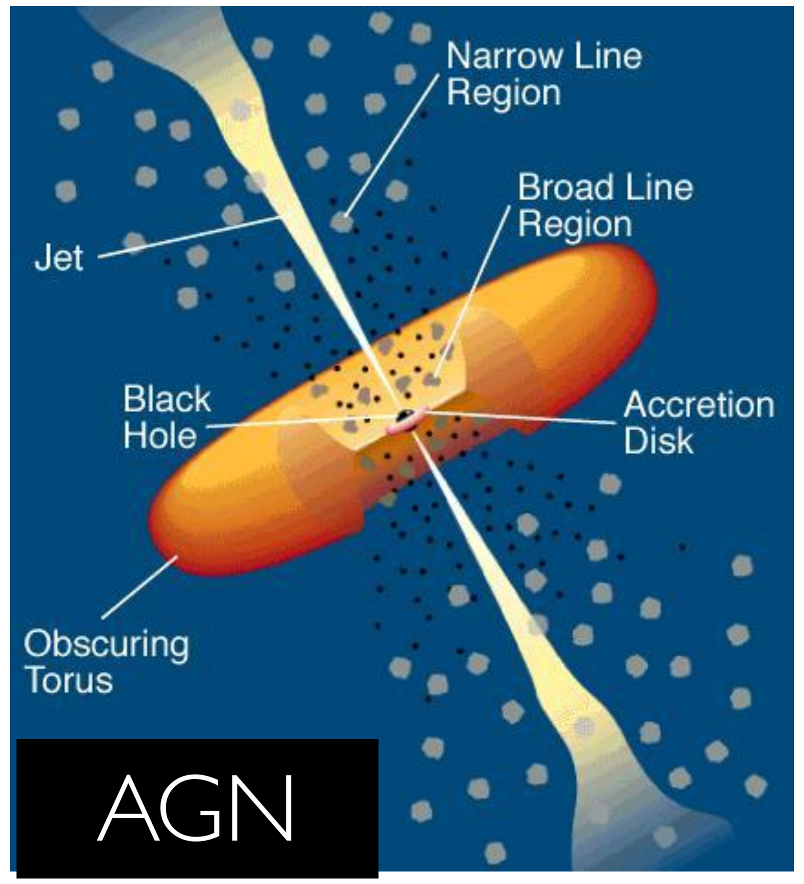




Cosmic-ray accelerators that satisfy the confinement req ^{17} eV)

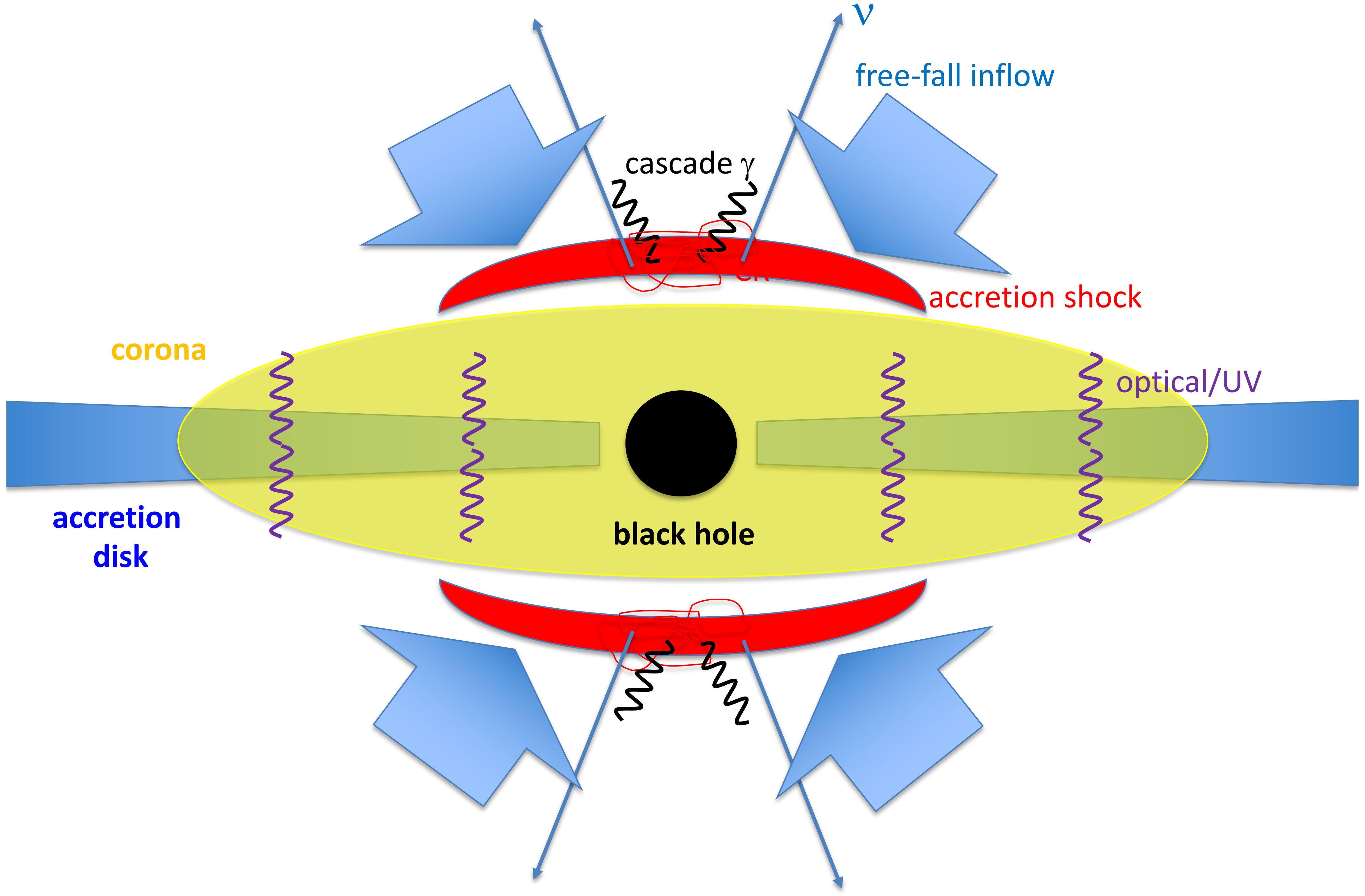


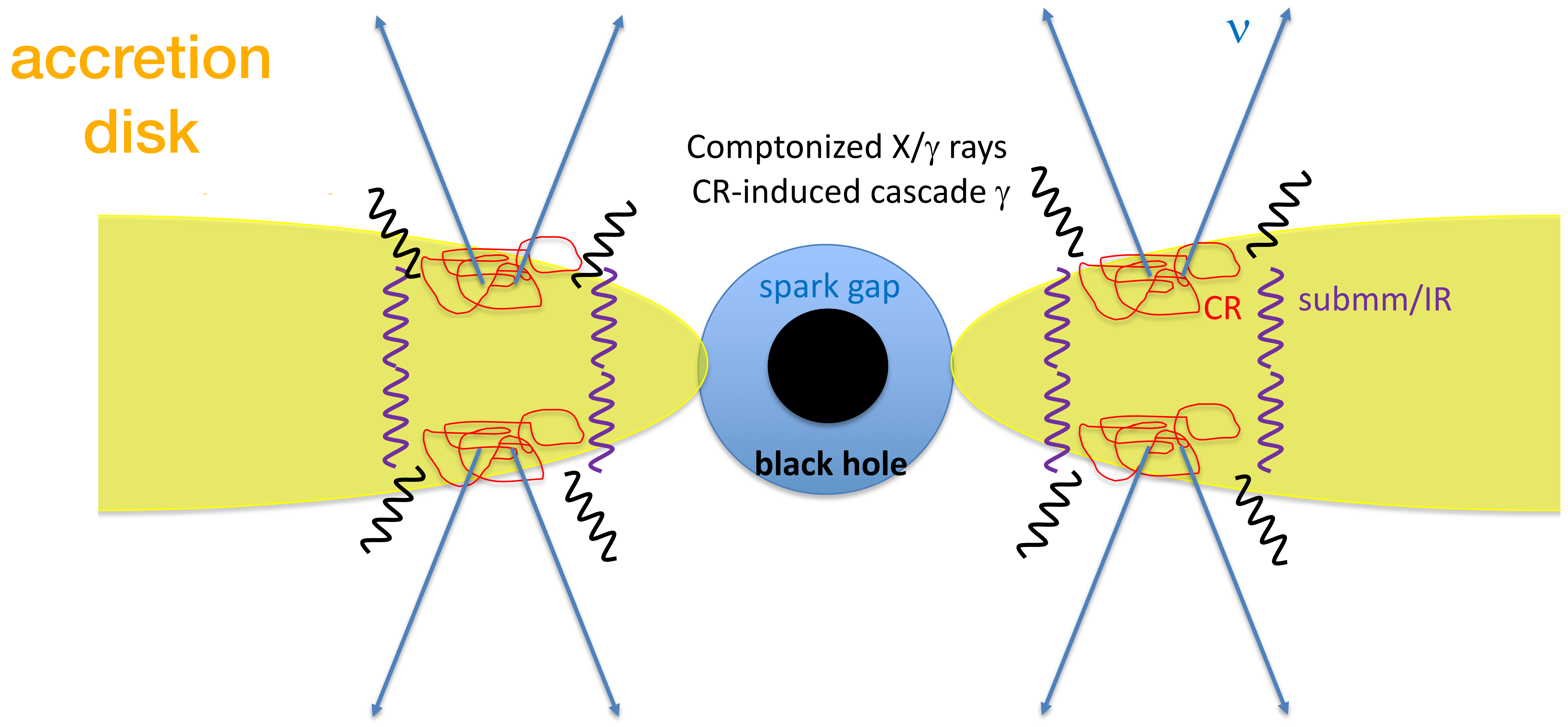




Possible sites of neutrino production in non-jetted AGN

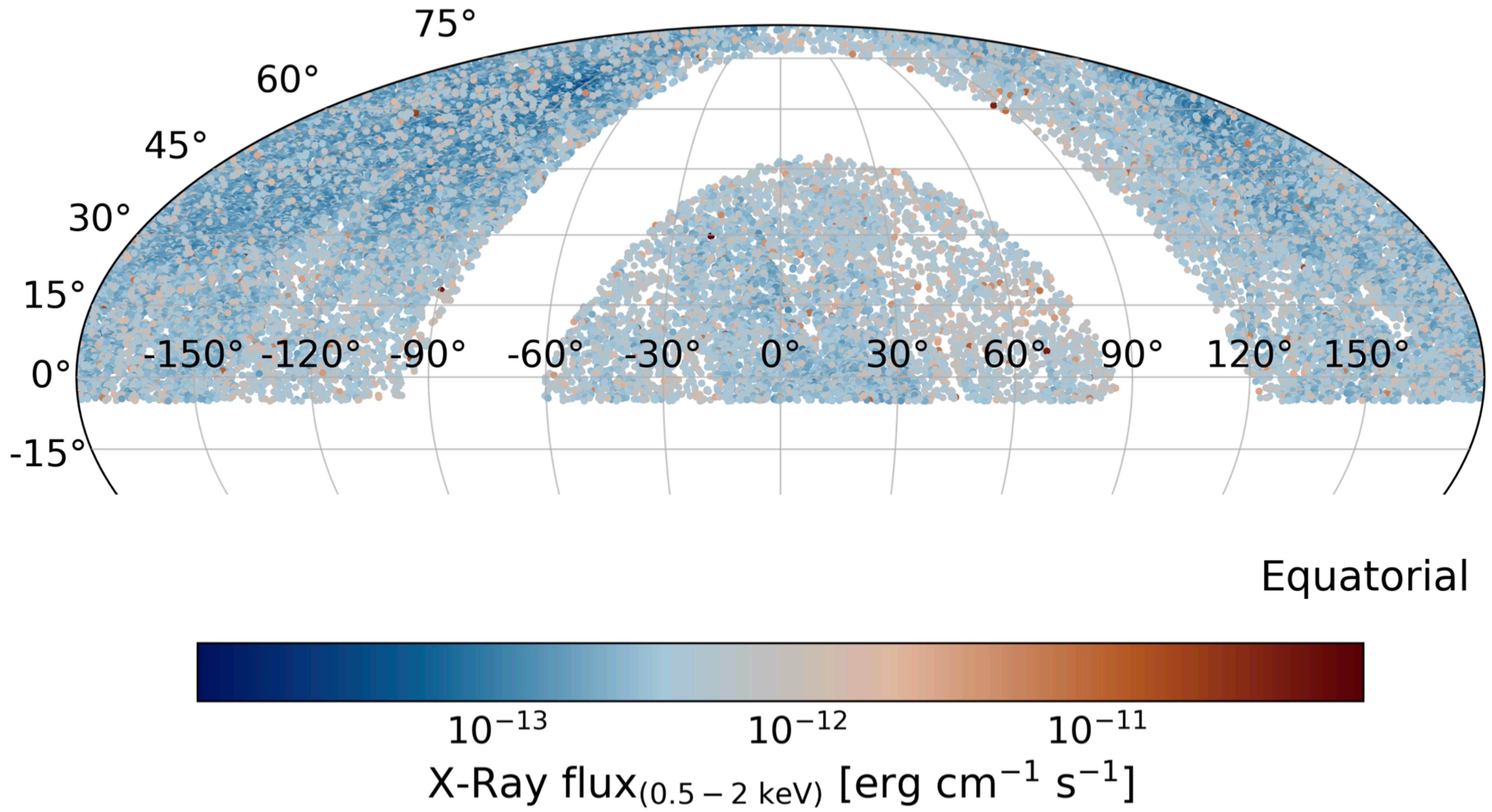
F. Stecker, Phys. Rev. Lett. 66, 2697 (1991)

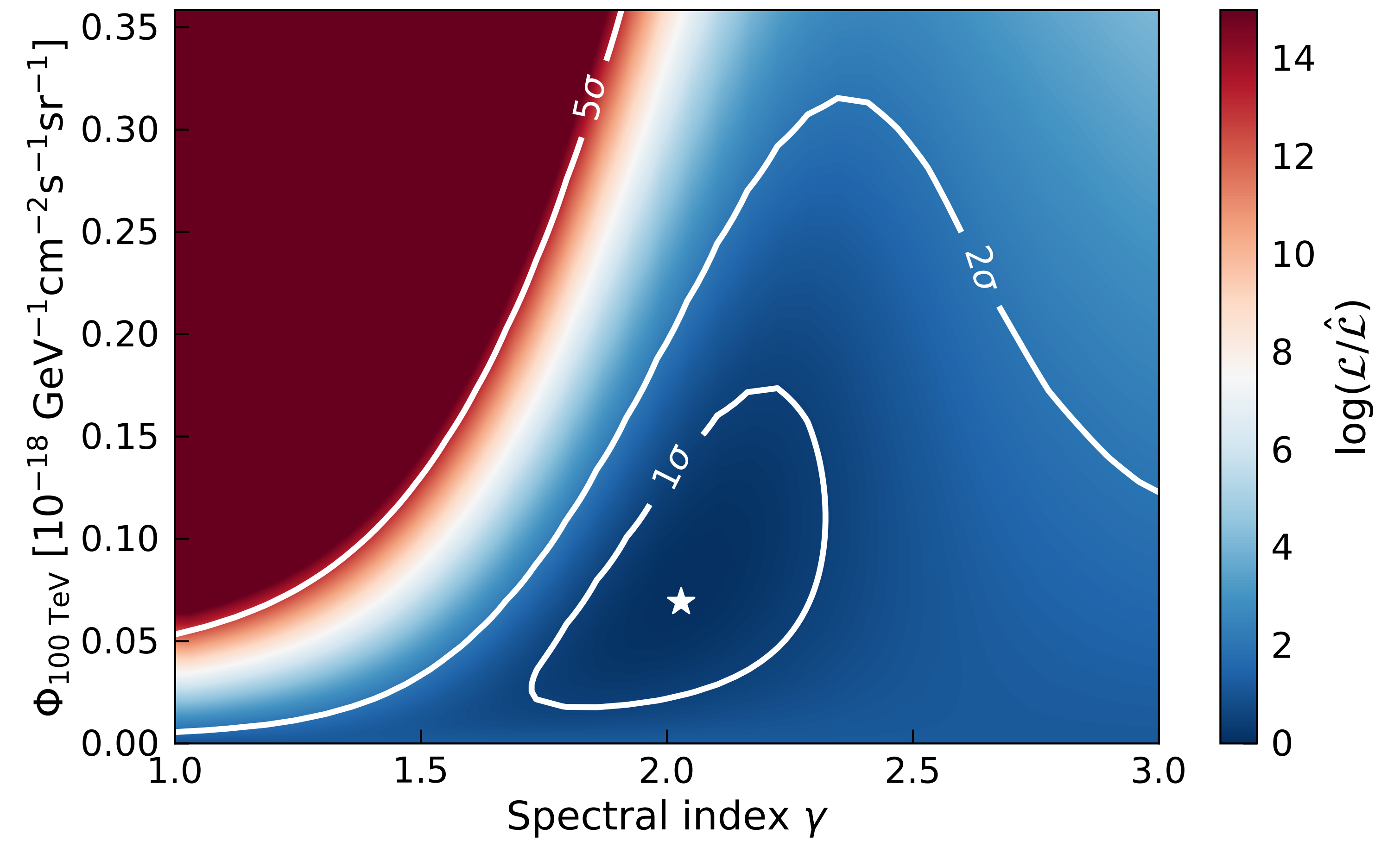


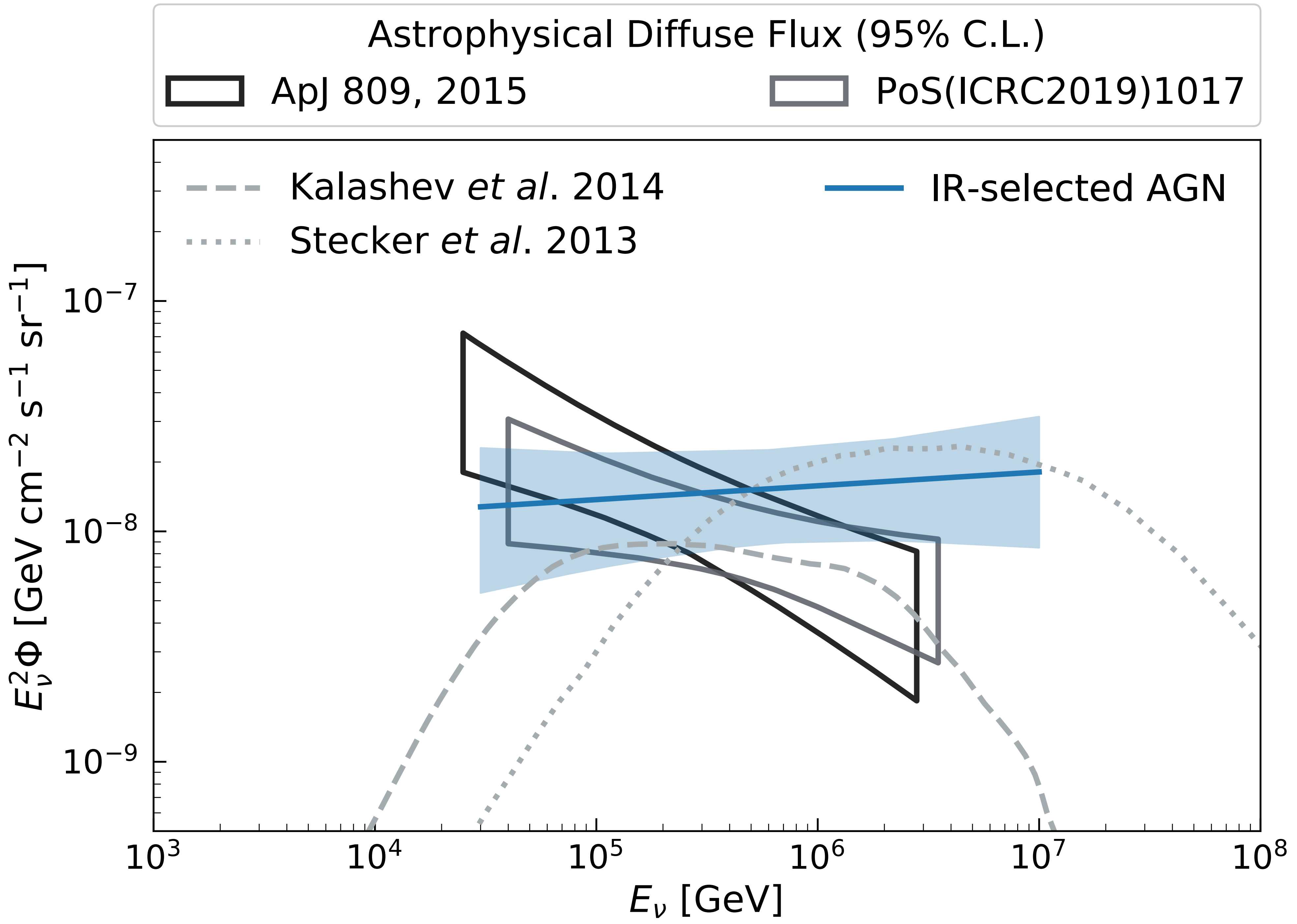


K. Murase, F. Stecker "Neutrino Physics & Astrophysics" Review 2022

Non-jetted AGN

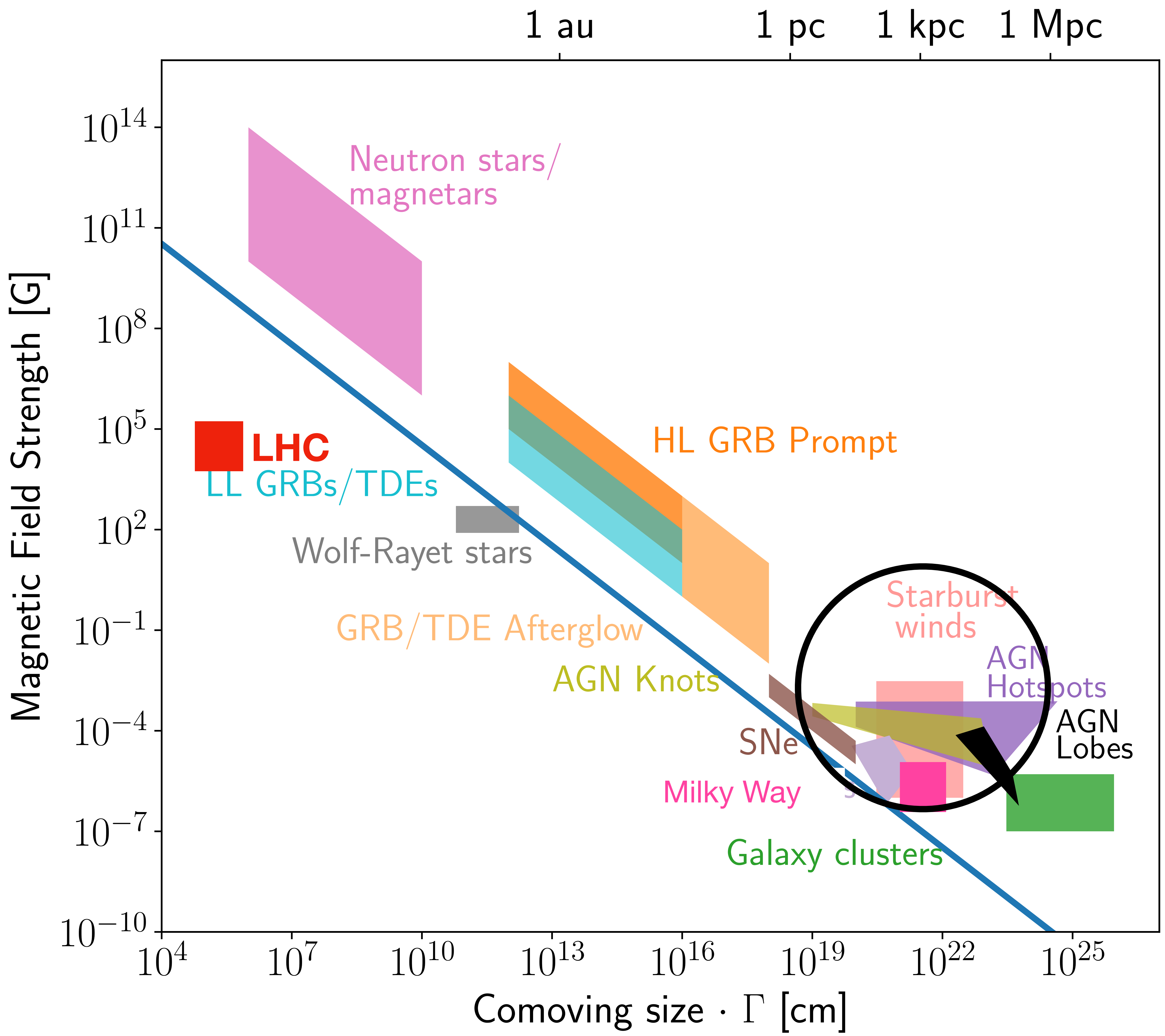


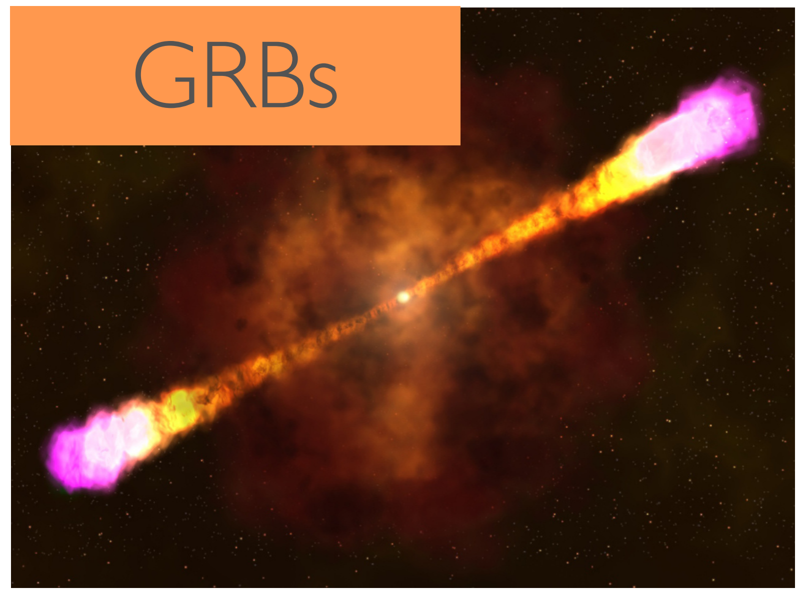


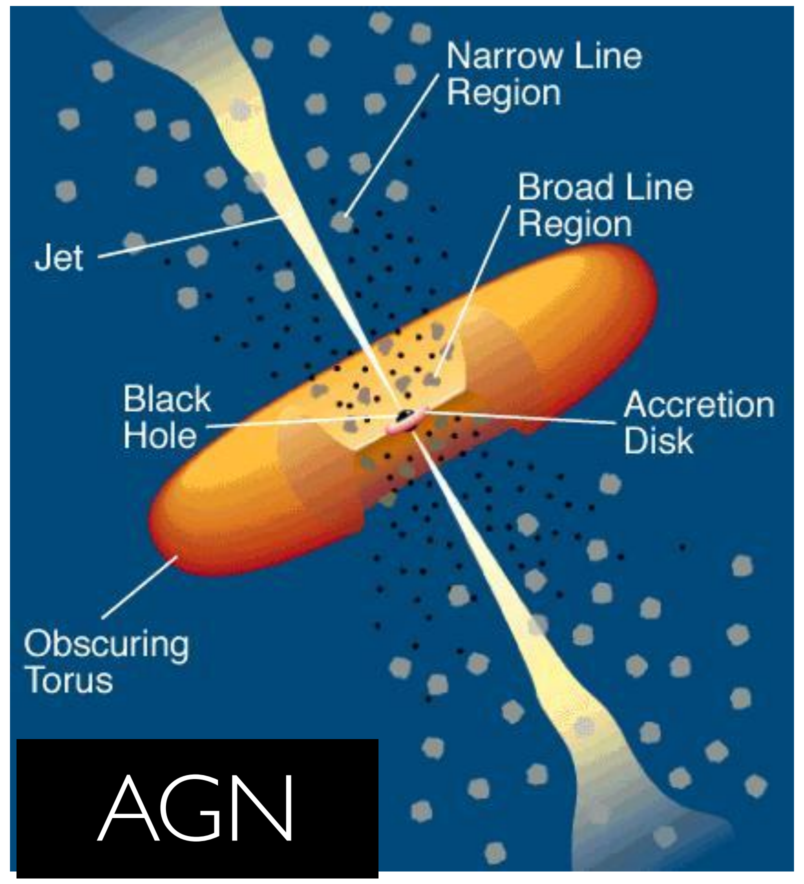


Infrared selected (ALLWISE) AGN with soft-X-ray weights
could account for 27-100 % of neutrino flux at 100 TeV (2.6σ excess w.r.t. background expectations) with ~E^{-2} spectrum.
IceCube Coll in press. arXiv: 2111.10169

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







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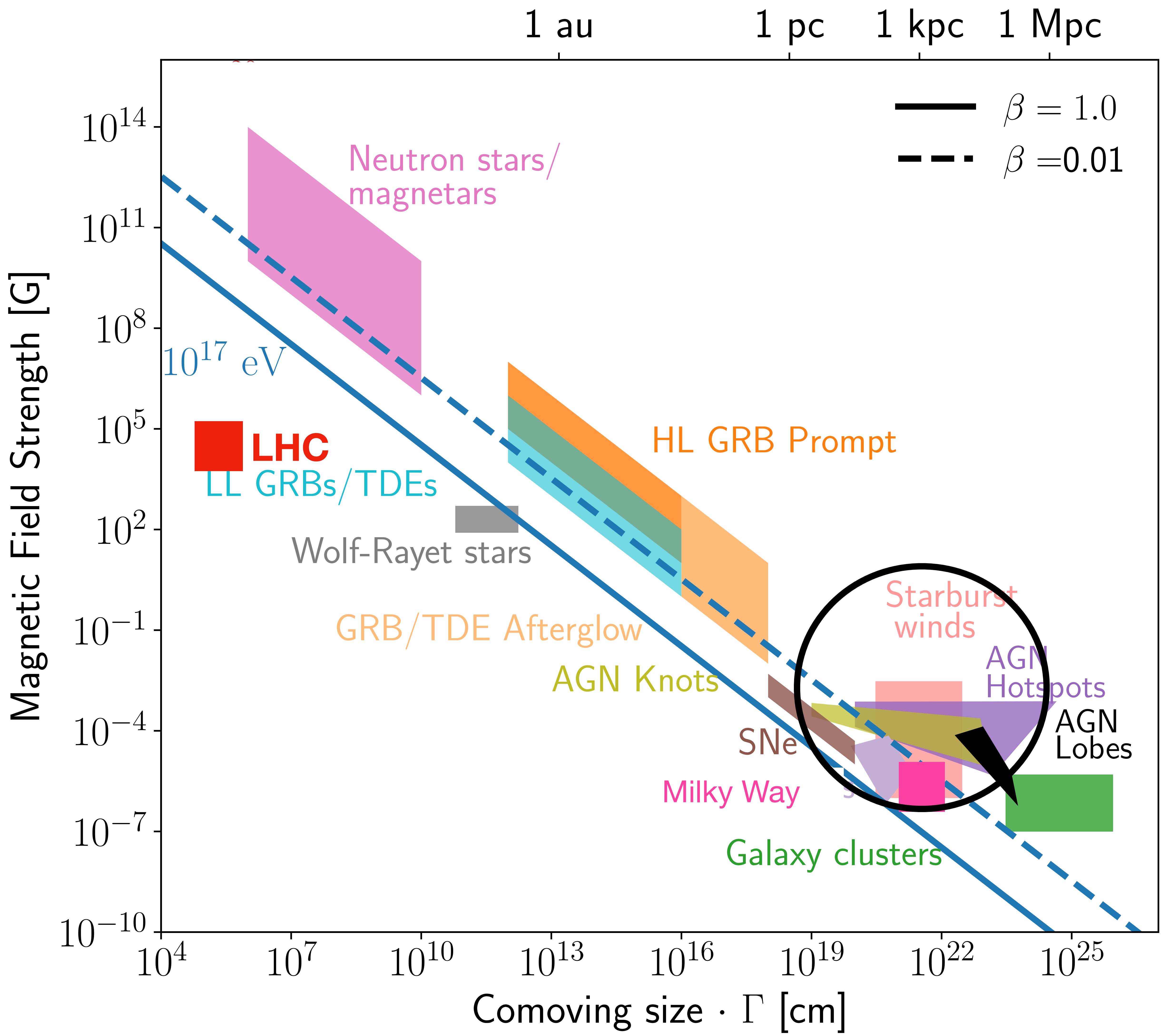
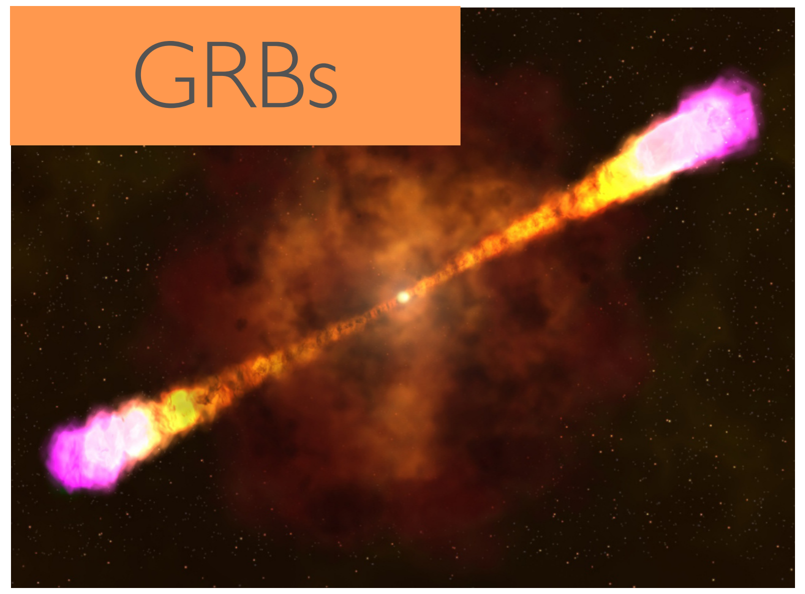
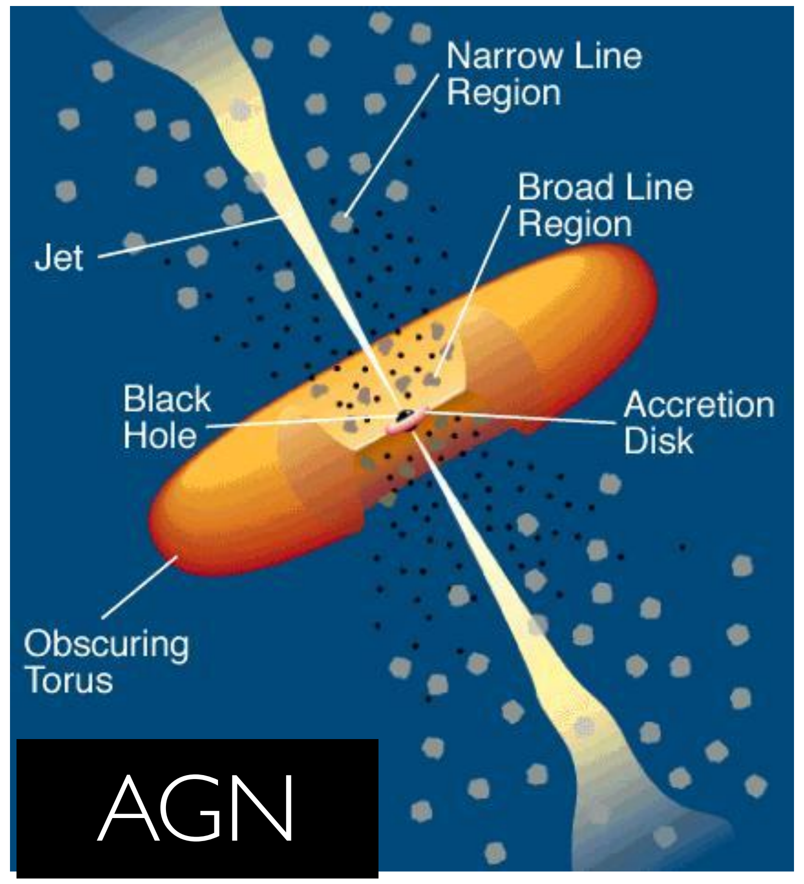






Starburst galaxies

Starburst definition: High star-formation rate per unit stellar mass compared to average galaxy at that redshift (> 100 x Milky Way)

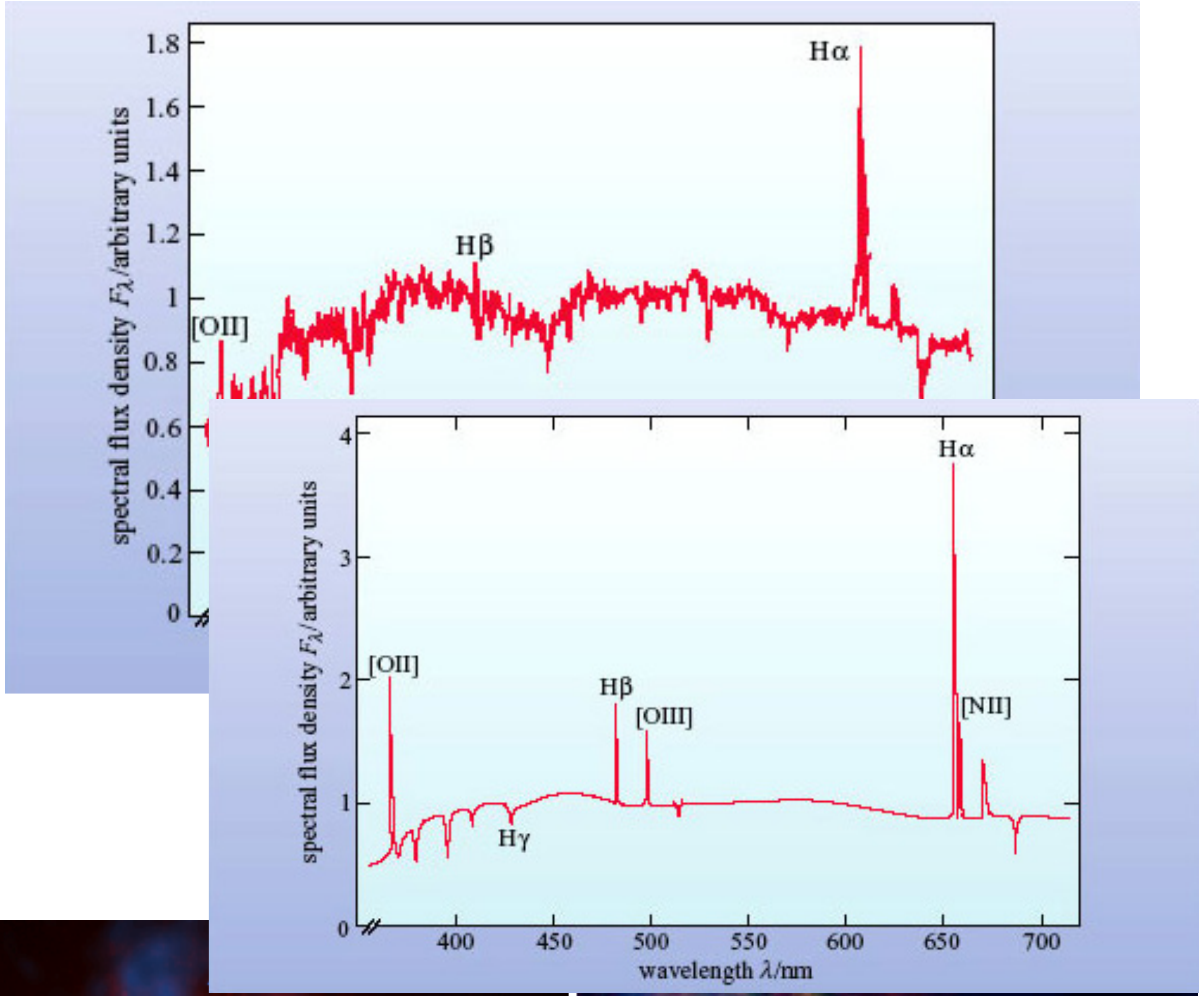
Starburst episodes are short-lived (<10^8 yrs)

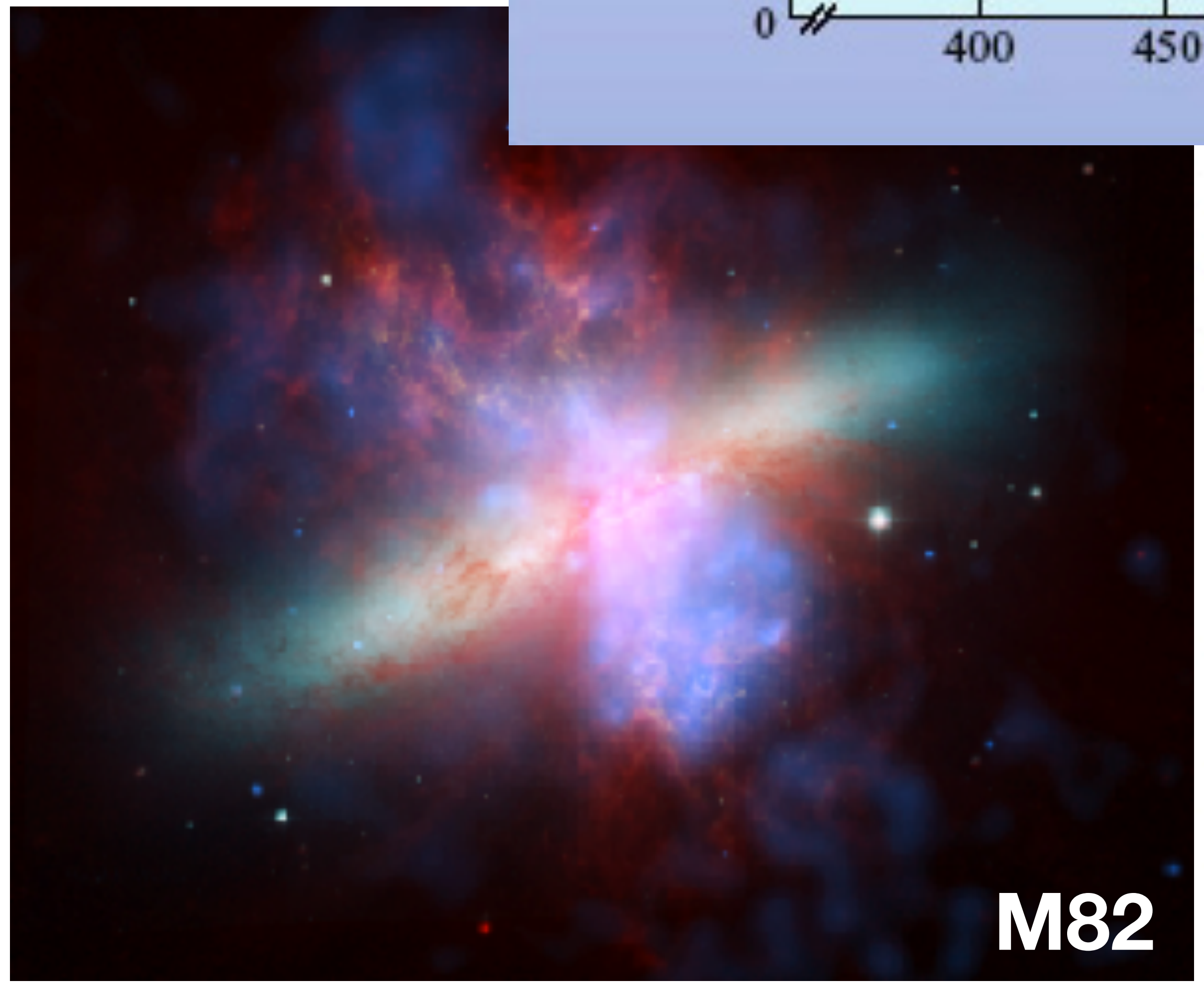
Centrally driven strong outflows (``superwinds'')

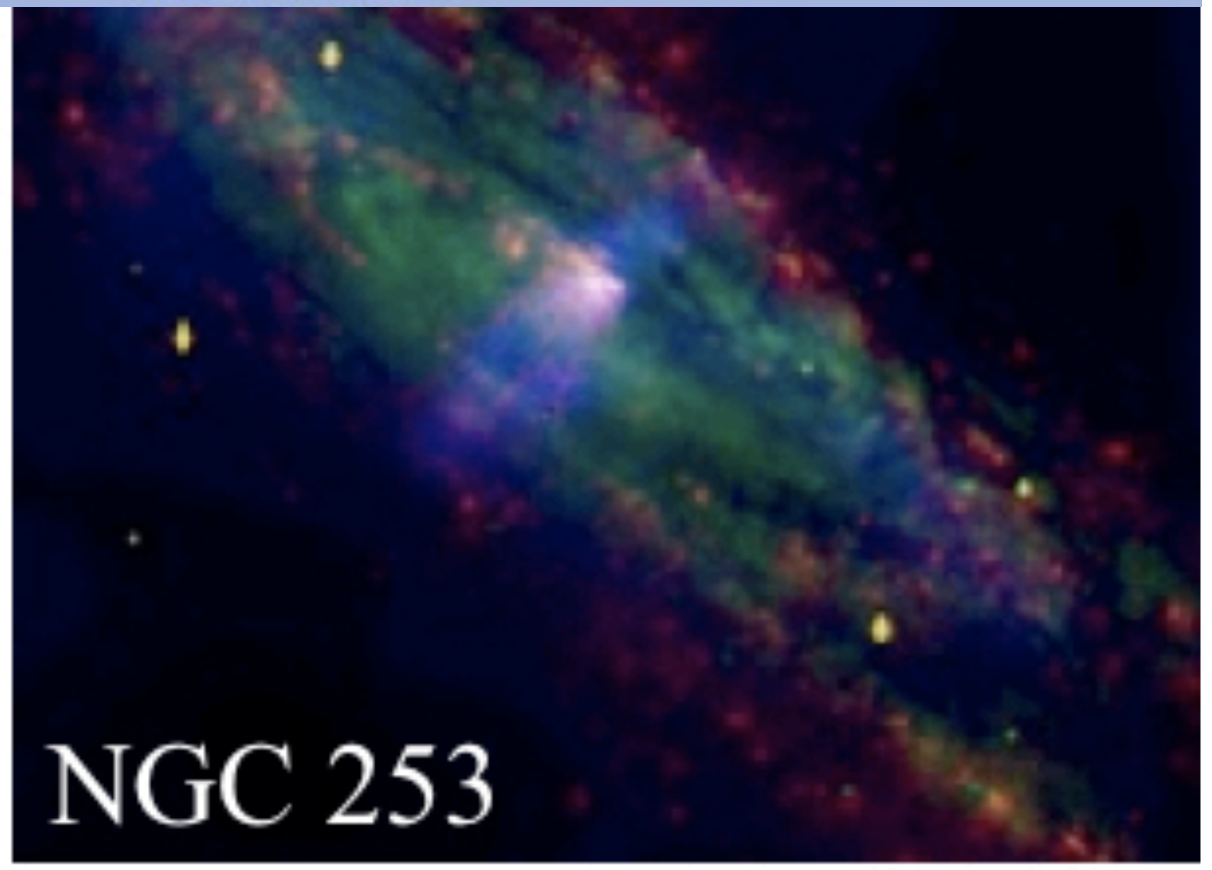
Column densities Σ_g > 0.1g/cm^2 and magnetic fields B ~ 1 mG (B ∝ Σ_g), which are much larger than those of ``normal'' spiral galaxies ($\Sigma_g \approx$ 0.003g/cm^2, B ~ 5μG in the Milky way)

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)



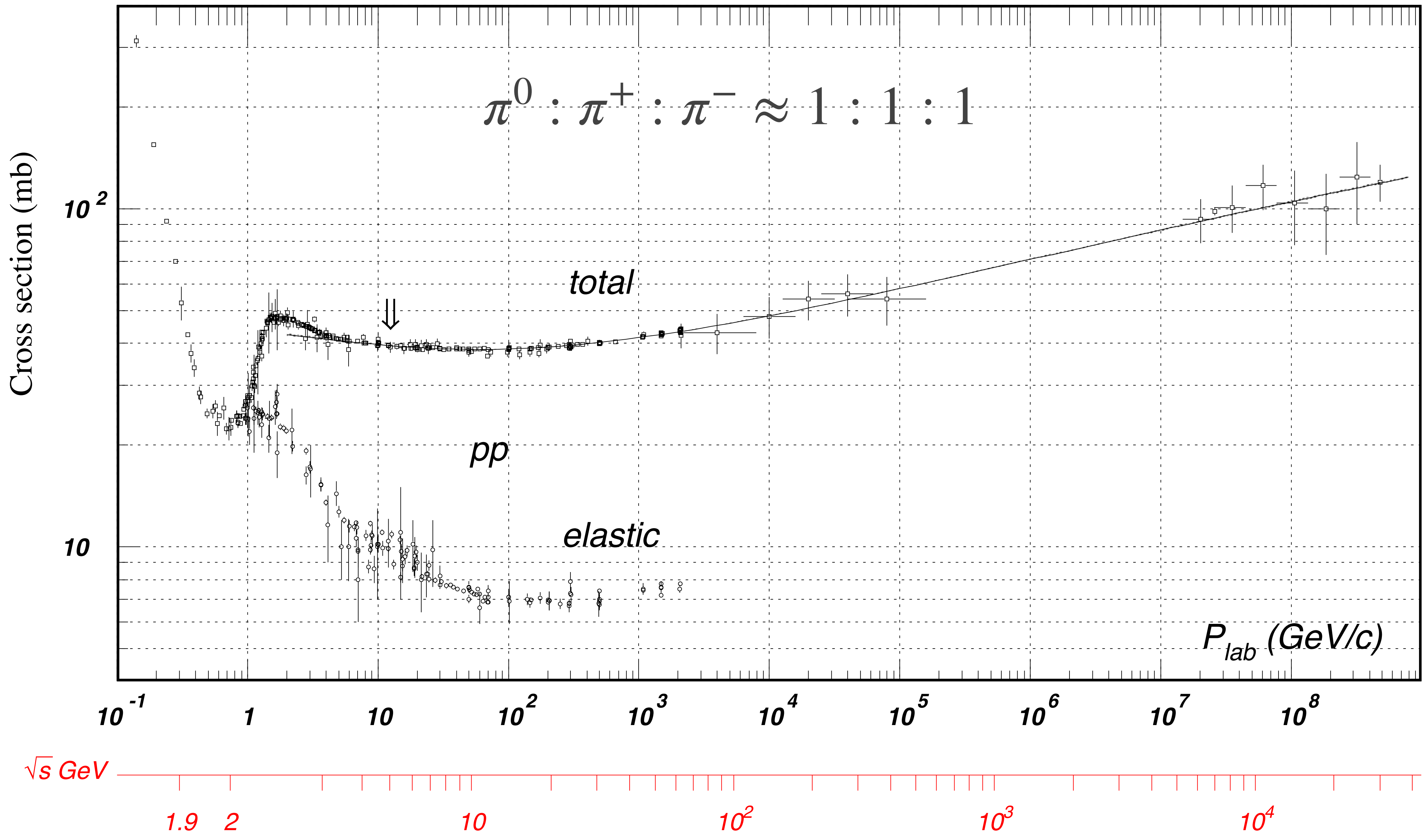


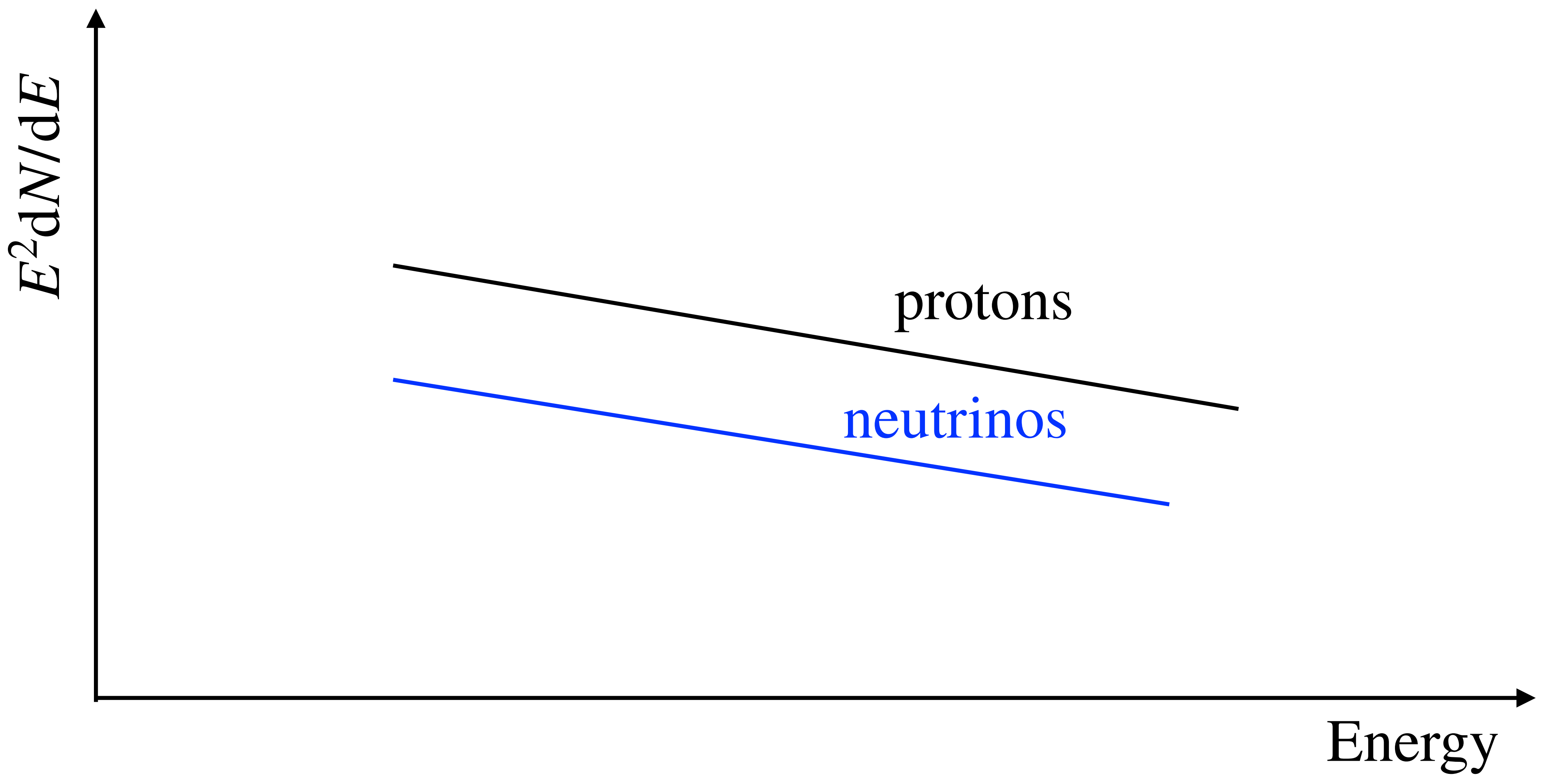


Proton-proton interactions

Gas reservoirs (Starburst galaxies, Galaxy Clusters…)

$$p + p \rightarrow N\pi + X$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e \ldots$$





Reservoir model

Cosmic rays in a calorimetric environment (e.g. ``starburst/galaxy cluster'')

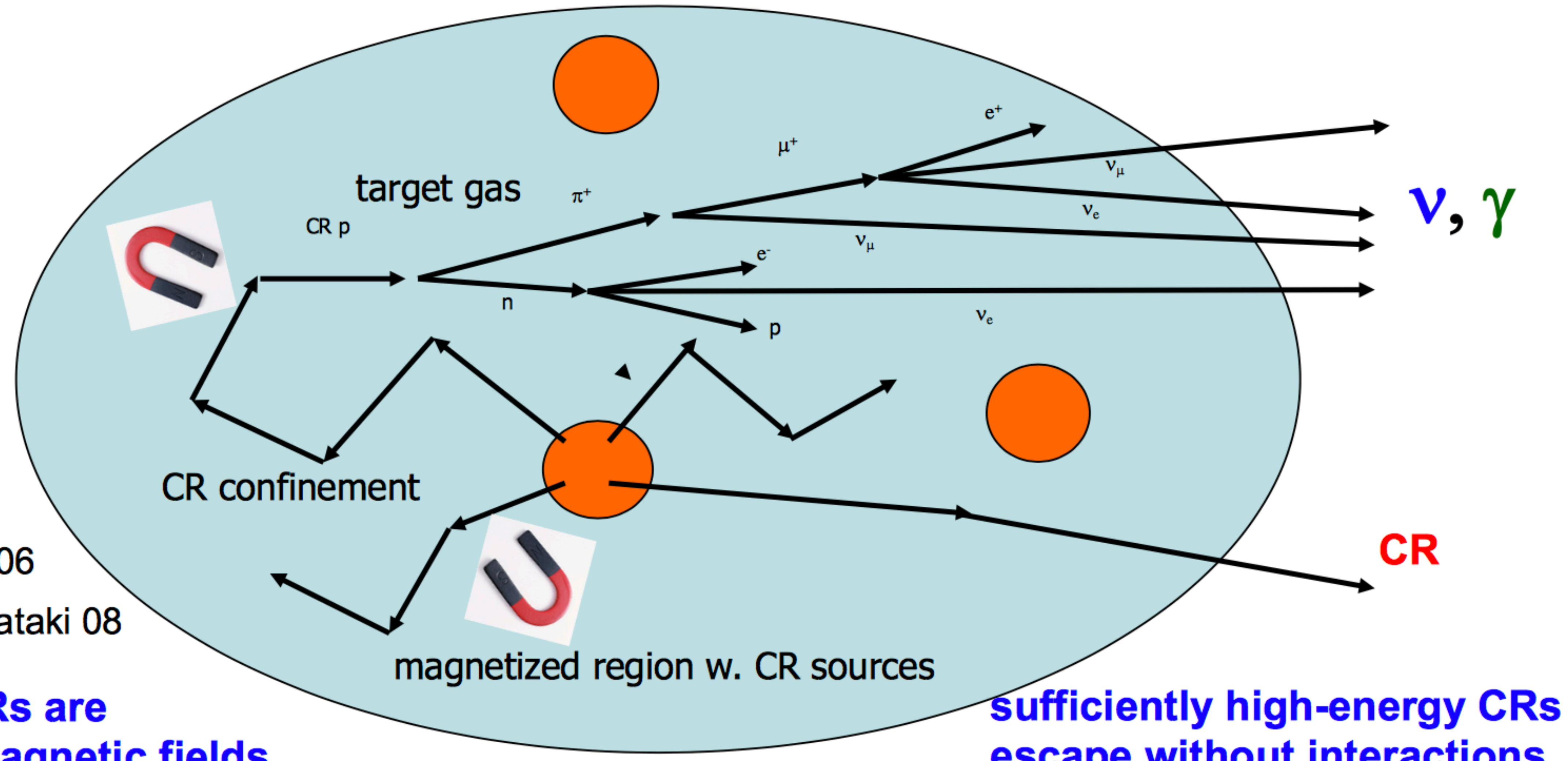
The highest energy cosmic rays escape (observed)

Lower energy cosmic rays are confined

CRs lose all their energy in interactions with ambient gas

Neutrinos appear correlated with parent calorimeters

Galaxy clusters constrained by stacking analyses to <few %



Loeb & Waxman 06

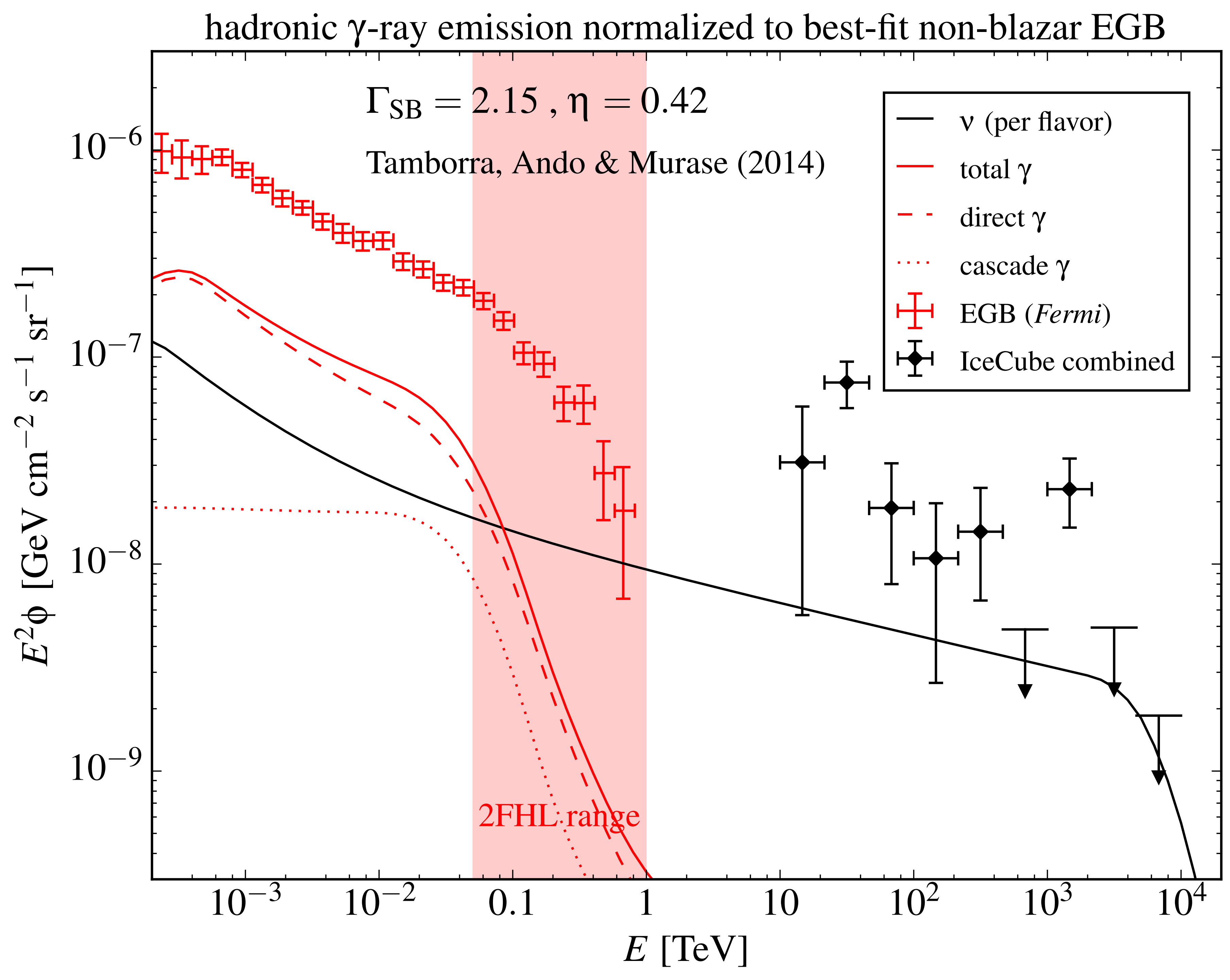
KM, Inoue & Nagataki 08

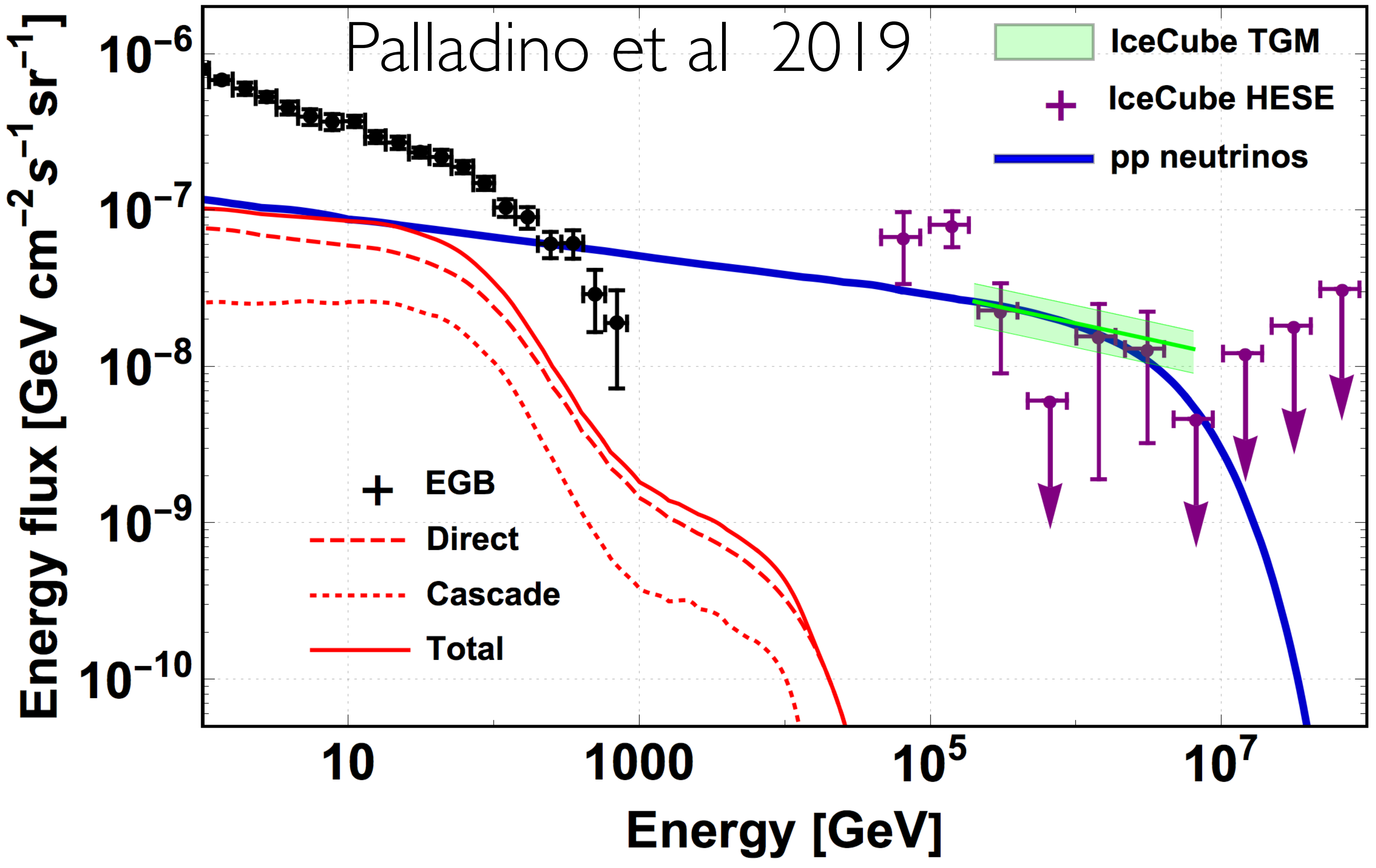
low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions

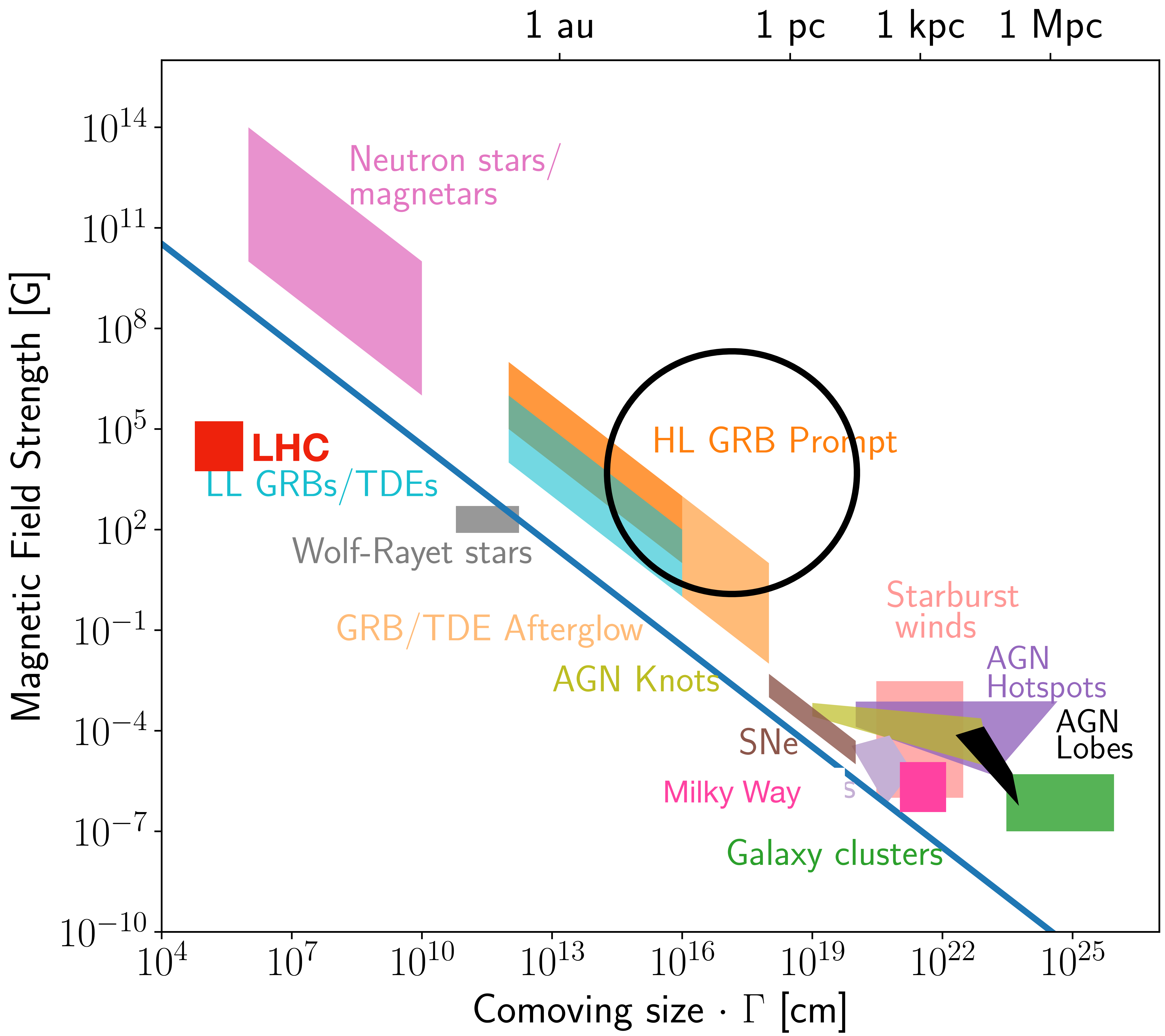
Neutrinos from starburst galaxies

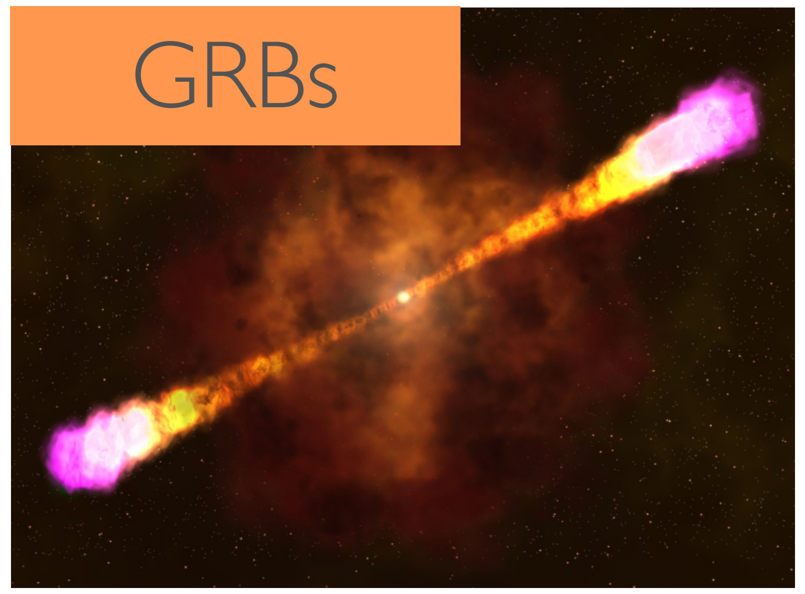
Cannot produce the IceCube flux unless we focus on >100 TeV data only due to diffuse gamma-ray constraints

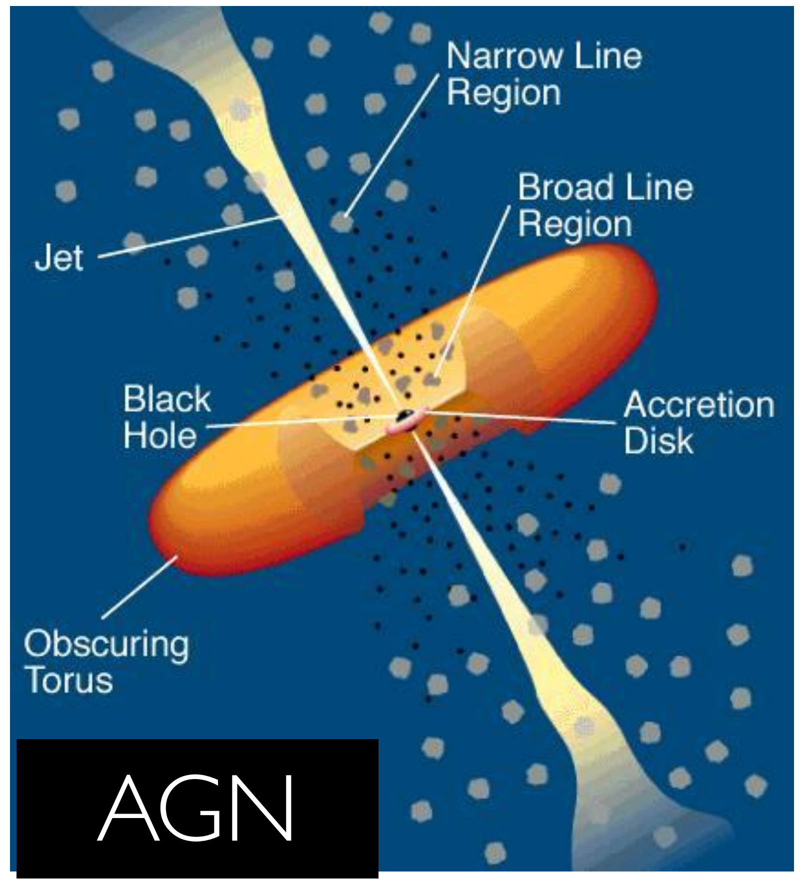




Cosmic-ray accelerators that satisfy the confinement req… ^{17} eV)







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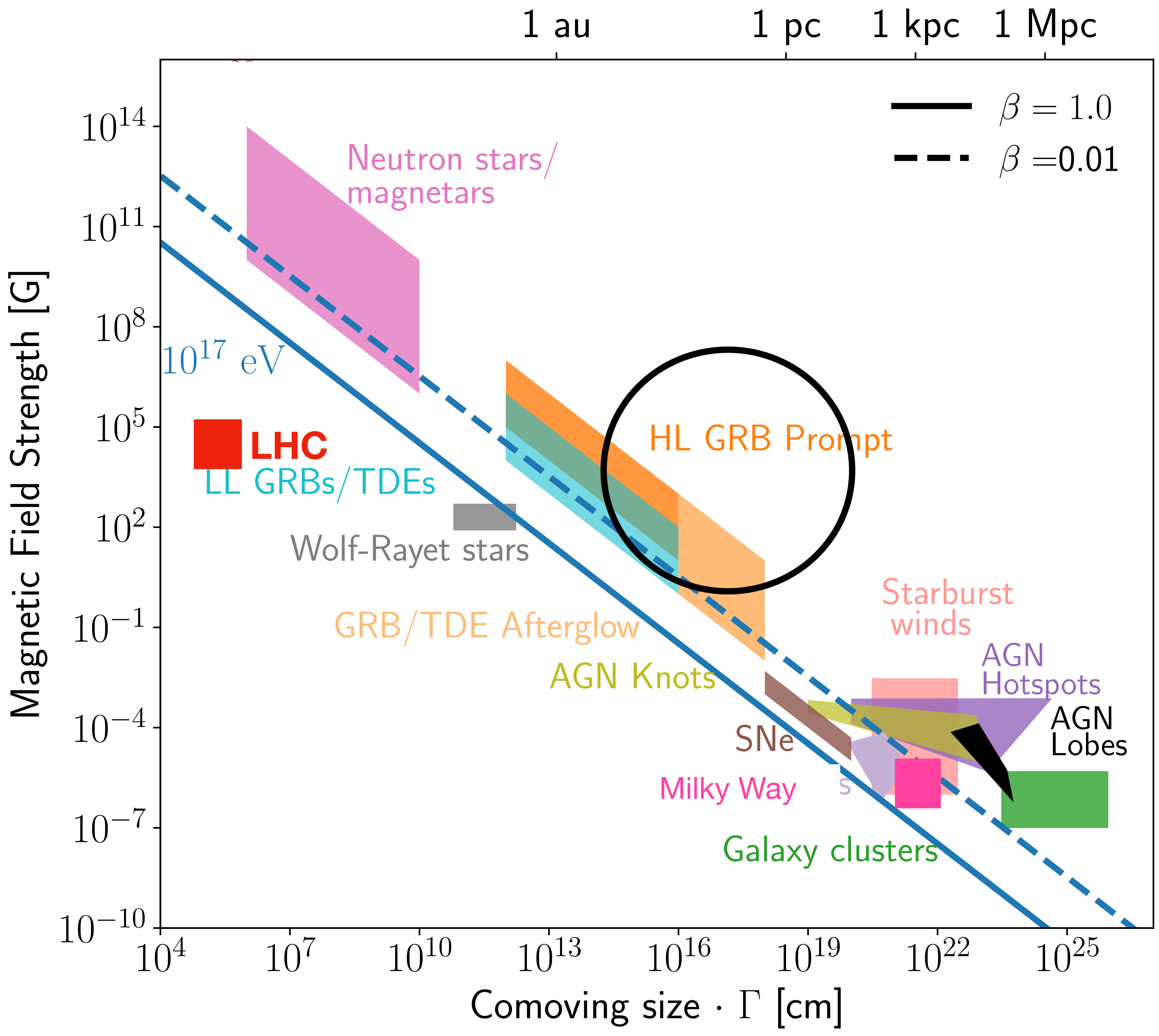
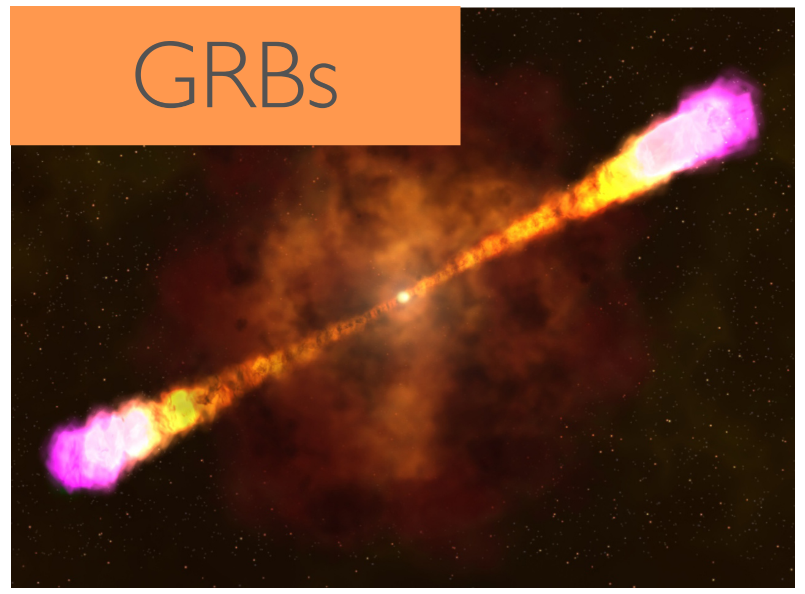
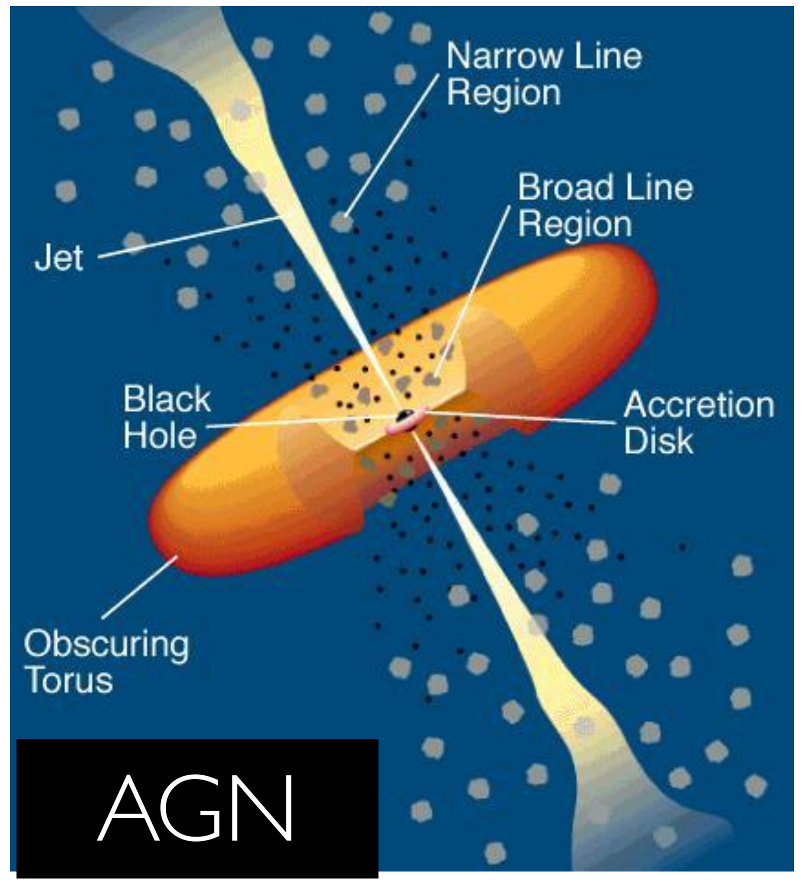
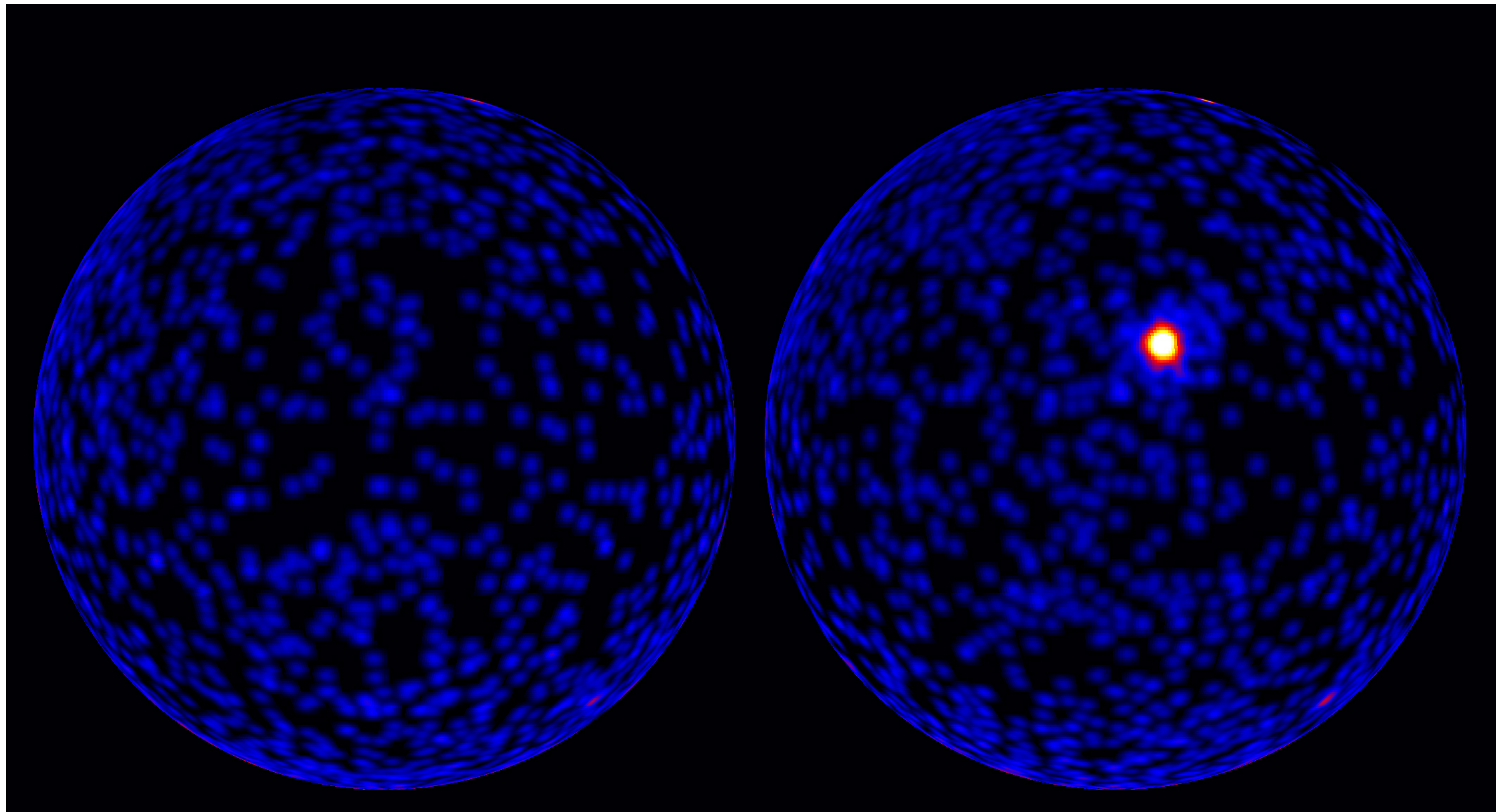






Gamma-ray bursts, basic facts

- Discovered serendipitously in 1967
- Intense short flashes of light peaking in the 10 keV -1 MeV range
- Isotropic equivalent energy release $\sim 10^{52}$-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, basic facts

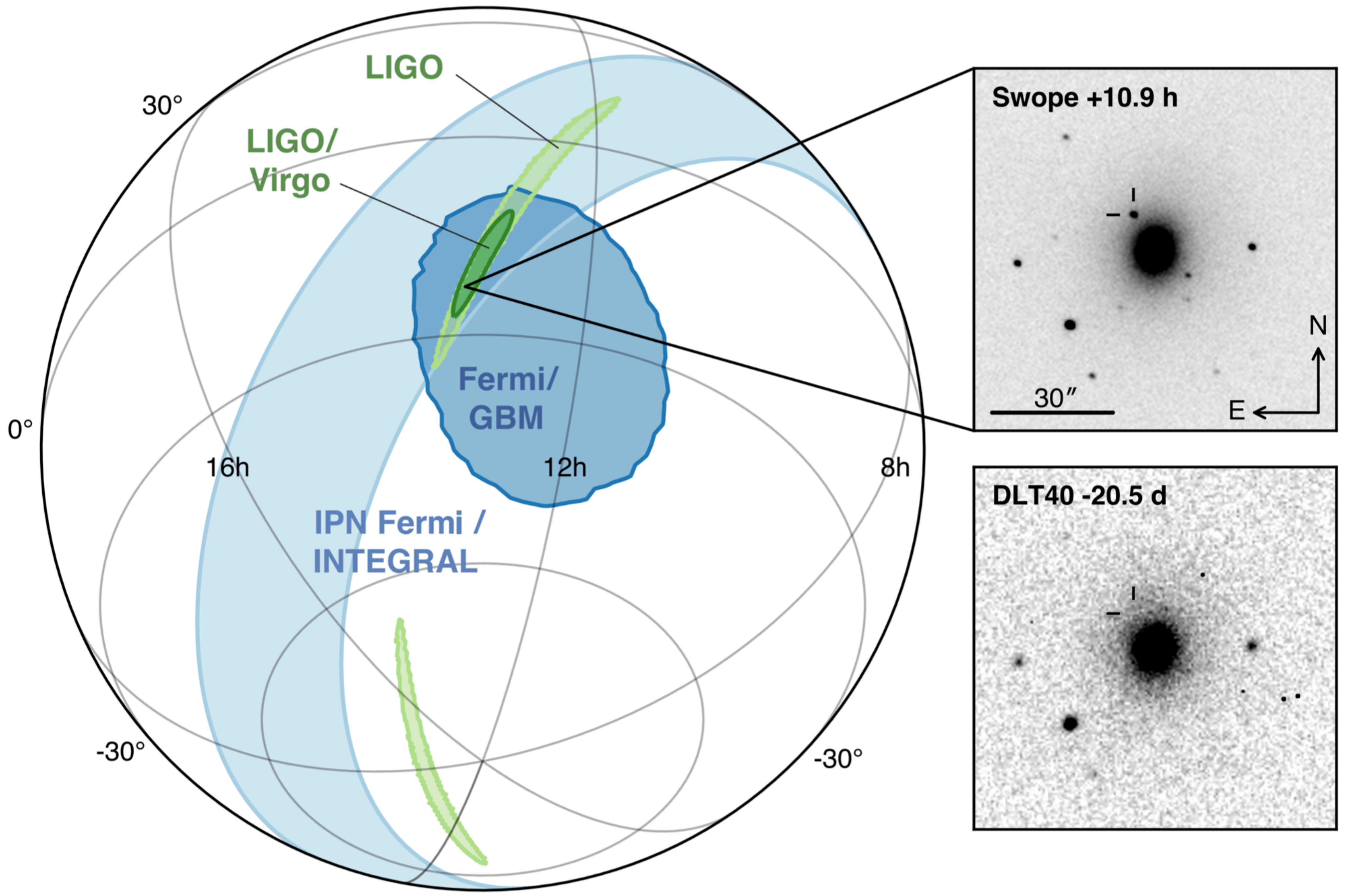
On August 17th, 2017 LIGO and Virgo reported the detection of GWs from the coalescence of a binary neutron star system

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



Gamma-ray bursts, basic facts

- ``Compactness'' problem: Photons are crowded in GRBs. The observed luminosity implies that gamma-rays shouldn't be able to escape
- But, $\tau_{\gamma\gamma}$ (10 GeV) < 1, since we observe these photons (gamma-rays that escape are ~ $e^{-\tau_{\gamma\gamma}}$)

$\gamma\gamma \rightarrow e^+e^-$, at threshold, $\varepsilon'_{\gamma,1}\varepsilon'_{\gamma,2}(1-\cos\theta) \geq 2m_e^2$. For head-on collision $\cos\theta = \pi$, $\varepsilon'_{\gamma,1} = m_e^2/\varepsilon'_{\gamma,2}$

But $\varepsilon = \varepsilon'\Gamma$, thus, $\varepsilon_{\gamma,1} = m_e^2\Gamma^2/\varepsilon_{\gamma,2}$

$$\tau_{\gamma\gamma} = \sigma_T n'_\gamma R'$$

$$\tau_{\gamma\gamma} = \sigma_T \frac{L_{\rm iso}(\varepsilon_\gamma)}{4\pi R^2 c\Gamma\varepsilon_\gamma}\ \frac{ct_{\rm v}}{\Gamma}$$

Implies $\Gamma > 10^3$ for the brightest GRBs

Neutrino production in GRBs

Ample photon fields ⟶photopion interactions

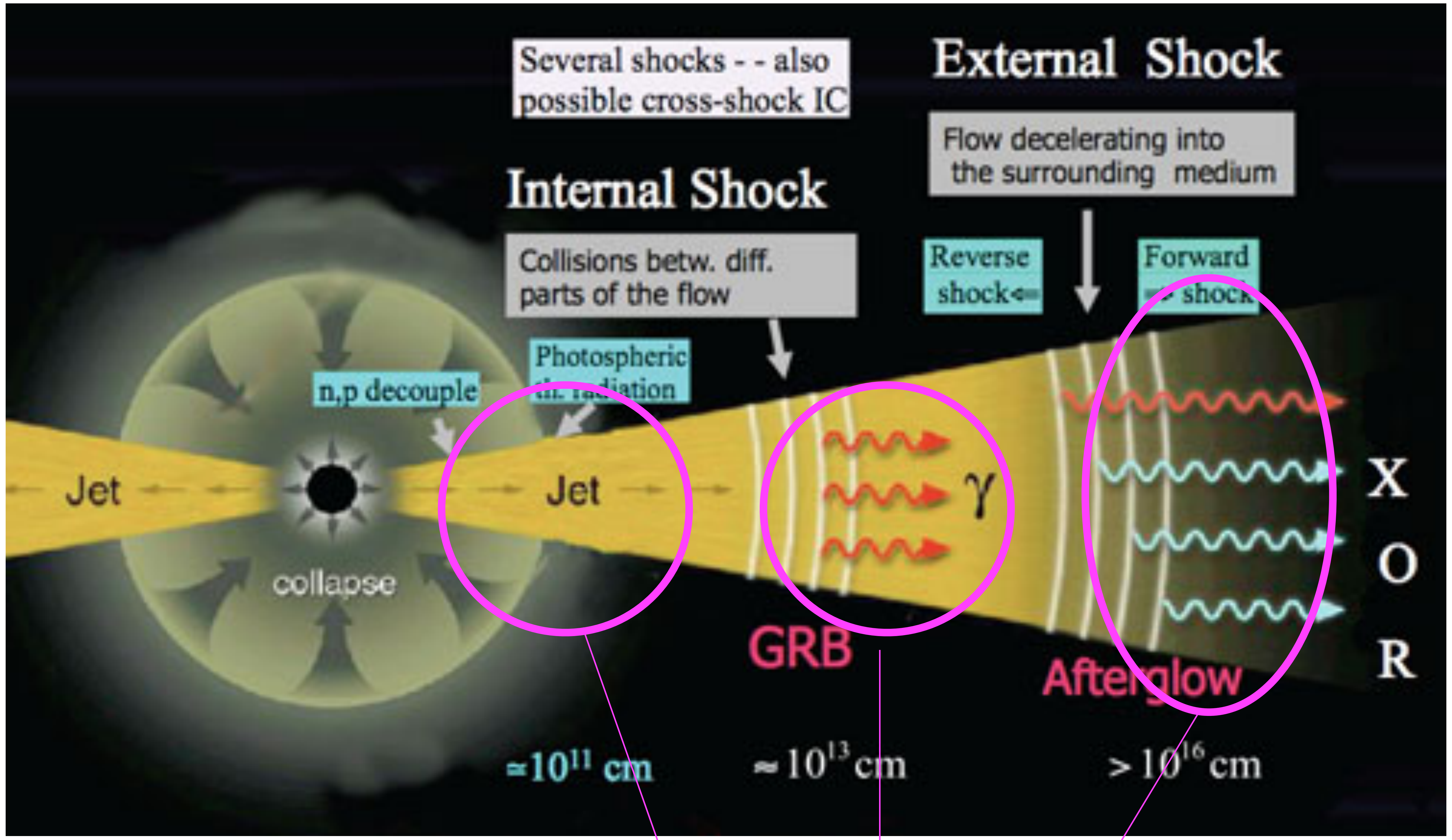
$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n/p + \pi^+/\pi^0$$

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

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

e.g. prompt emission,

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



<TeV TeV-PeV EeV

possible neutrino production sites

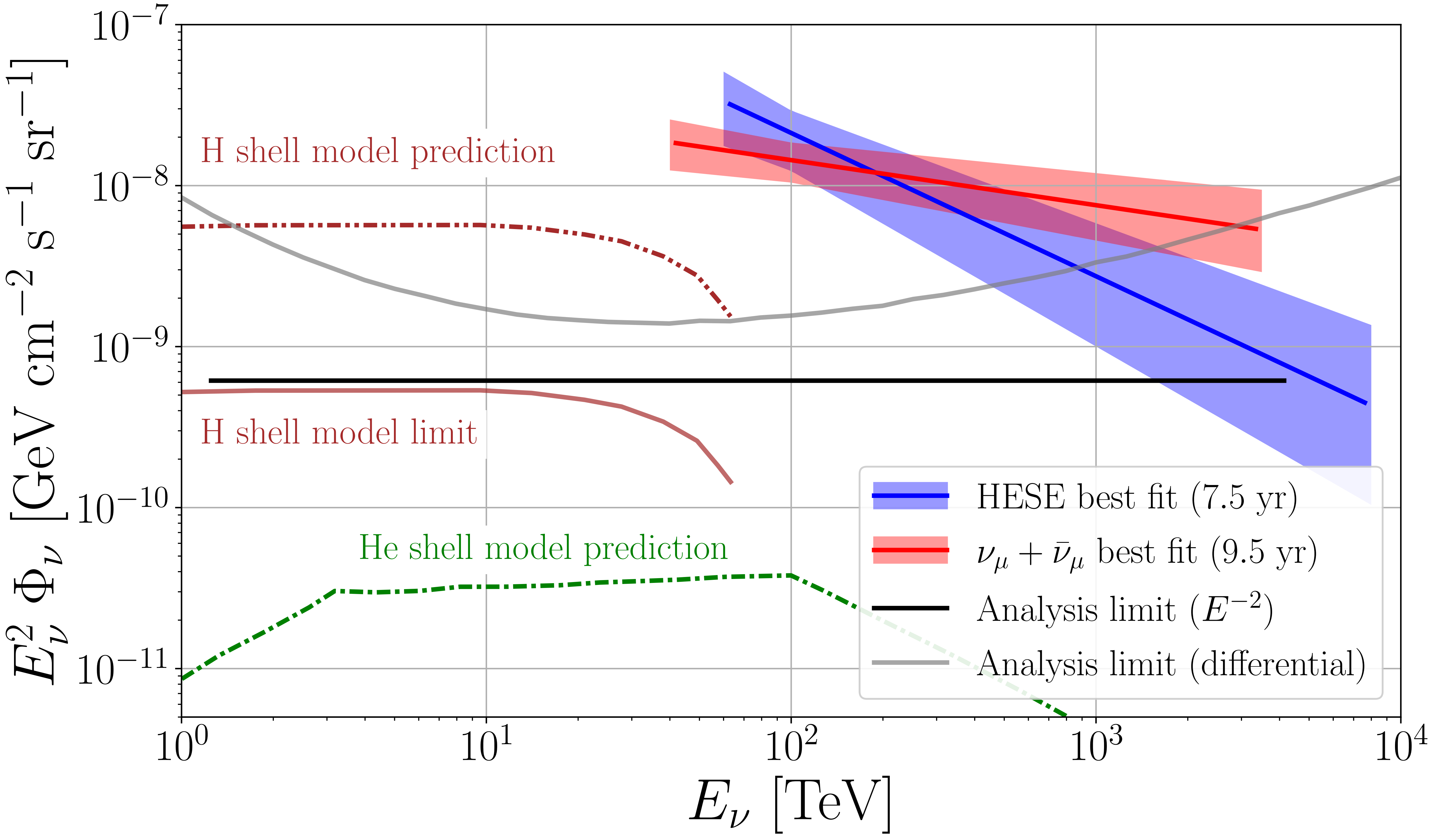
Neutrino production in GRBs

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

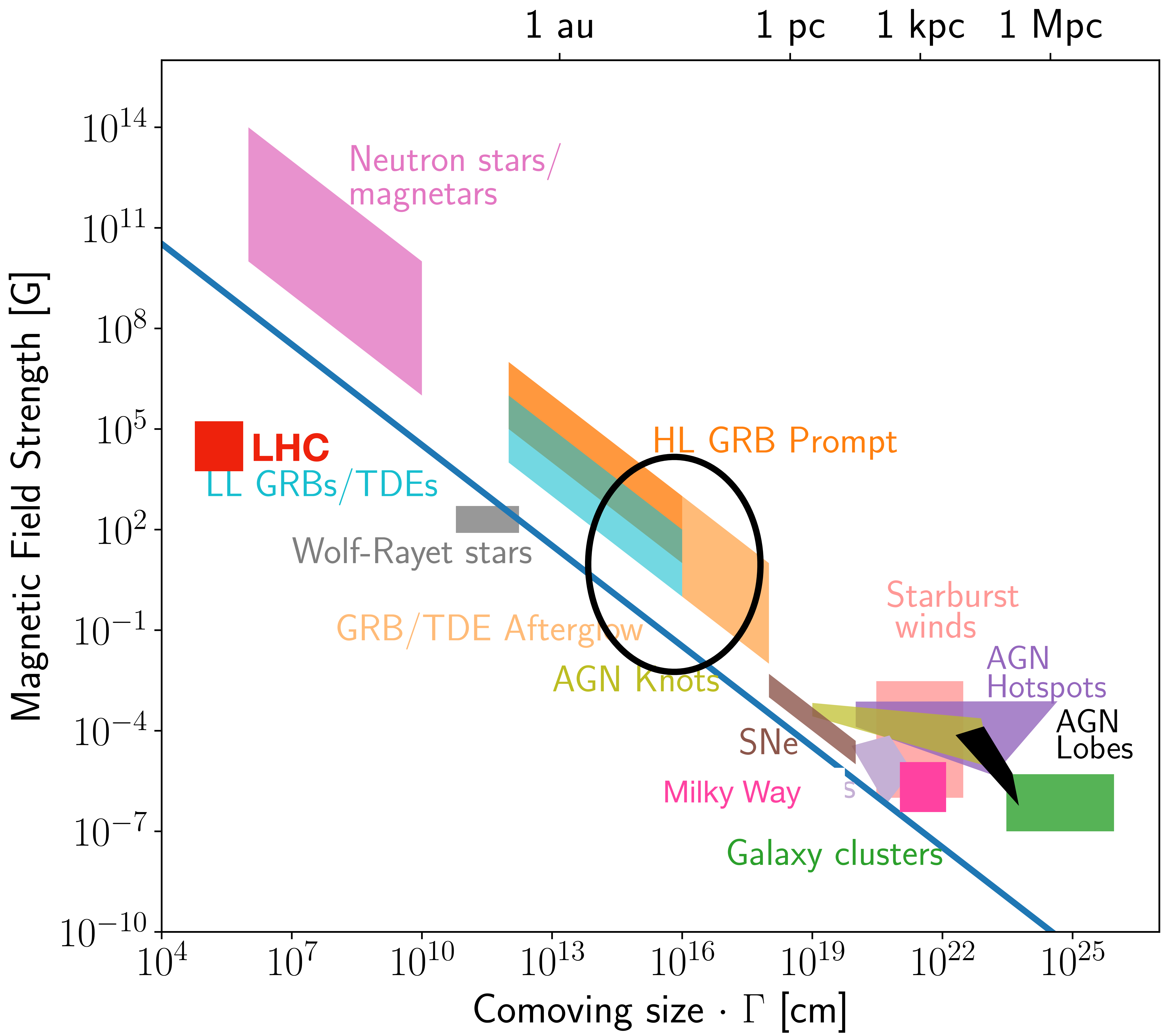
GRBs (prompt emission) can account, at most for 1% of the diffuse IceCube flux.

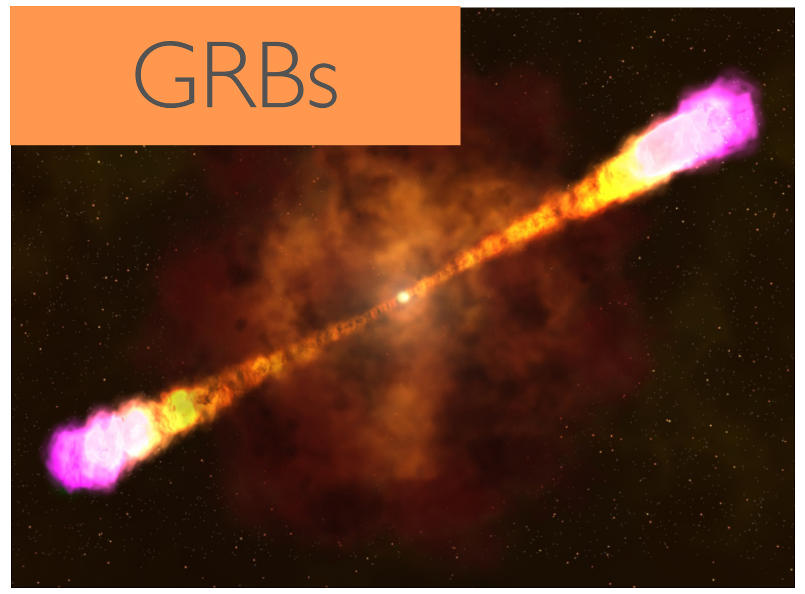
Afterglows < 24%

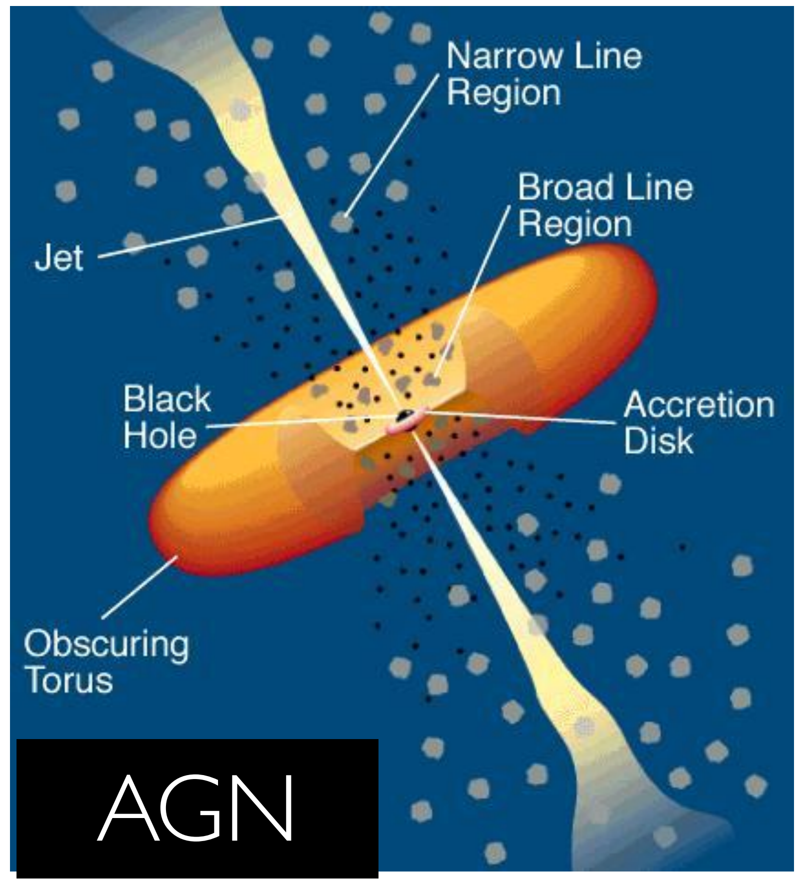
Standard GRB models constrained



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







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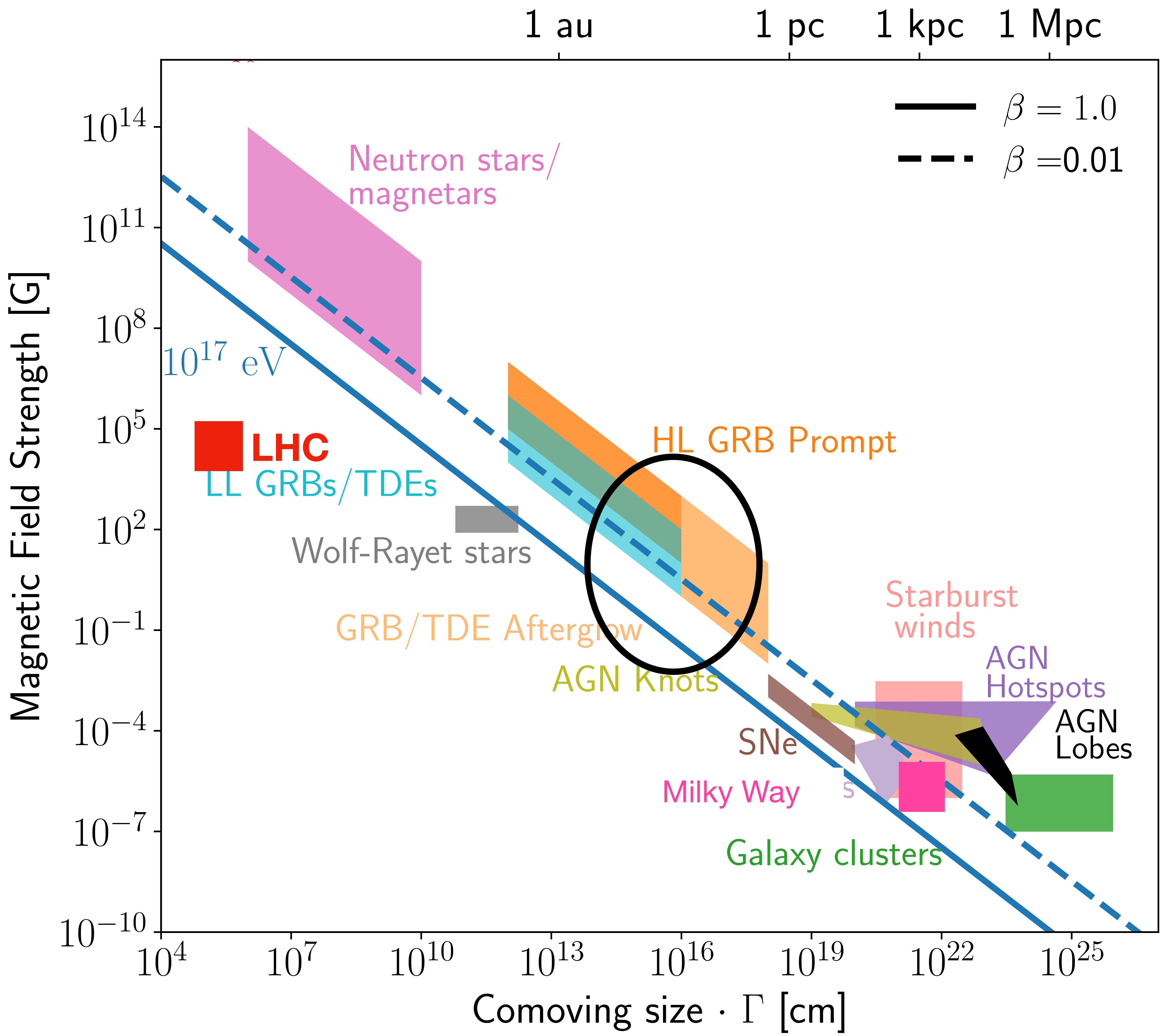
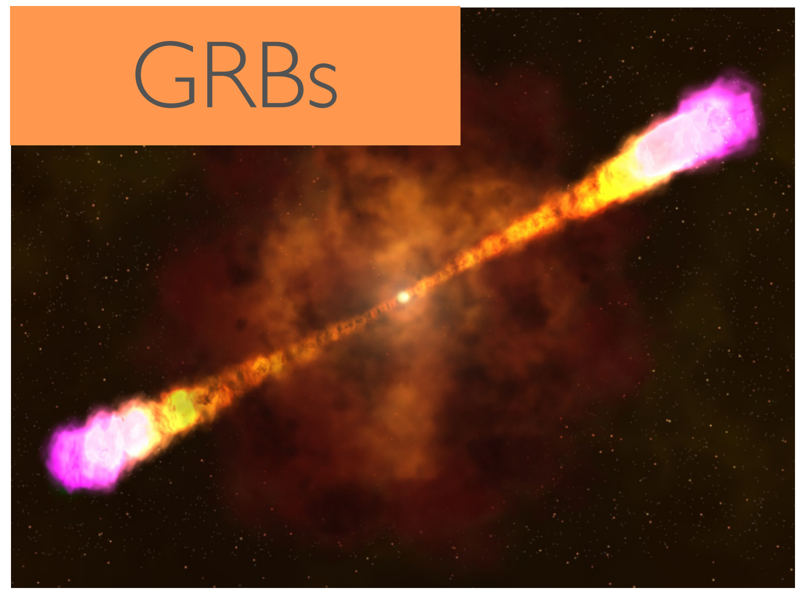
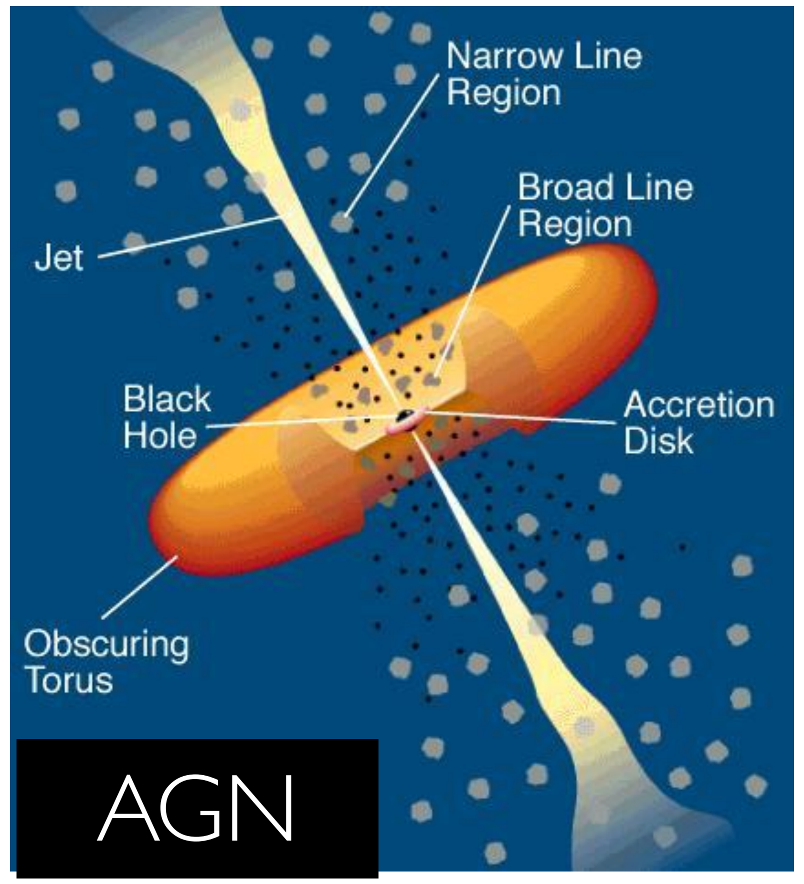






Tidal disruption events

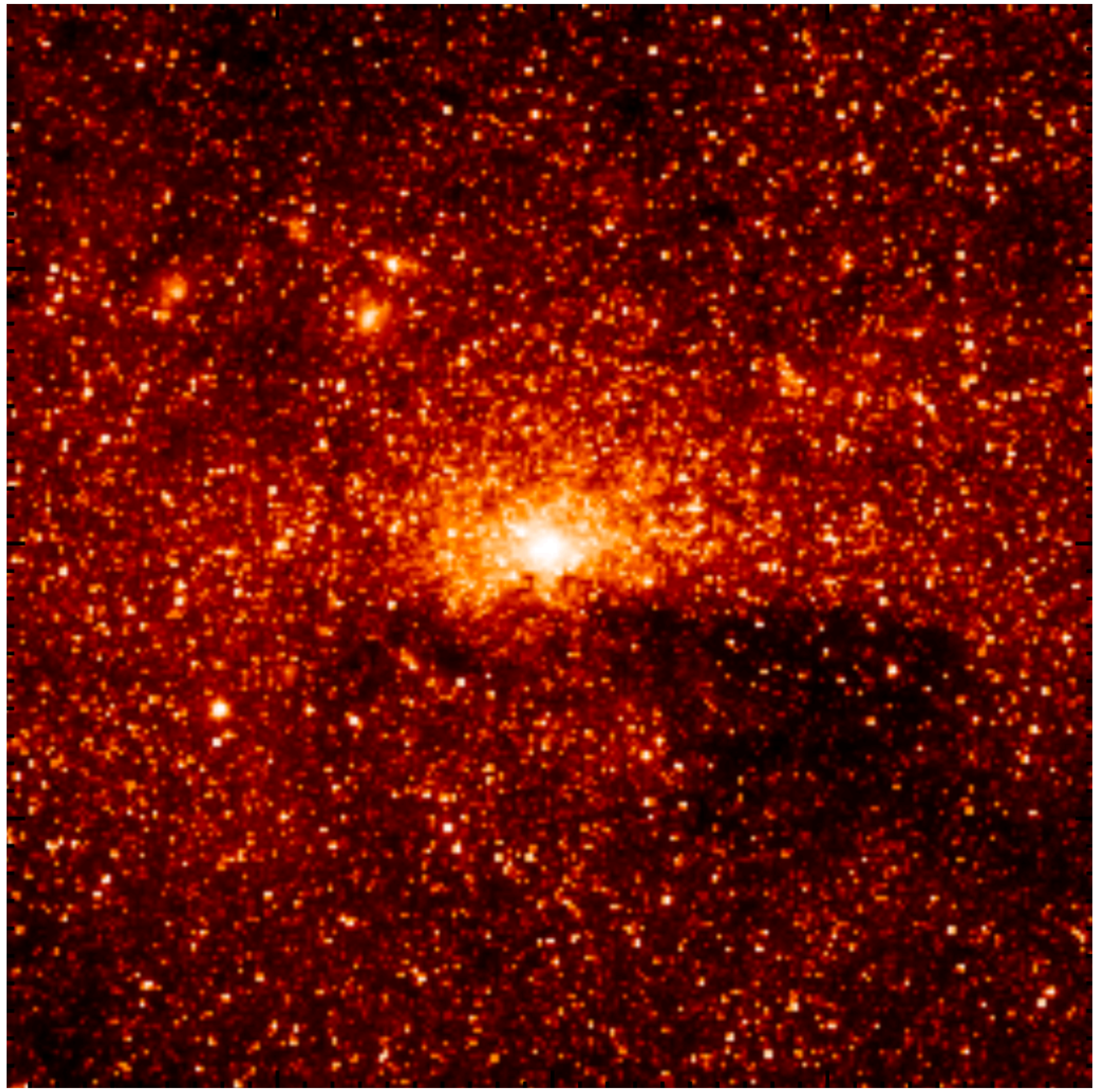
Super Massive Black Holes are orbited by star clusters

Millions or billions of stars in random orbits

Tidal forces may deform, or tear into pieces a star approaching too closely

Predicted rates of 1 TDE in 10000 to 10^9 years per super massive black hole (SMBH)

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



Tidal acceleration > Accel. due to self gravity

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

Tidal disruption events

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

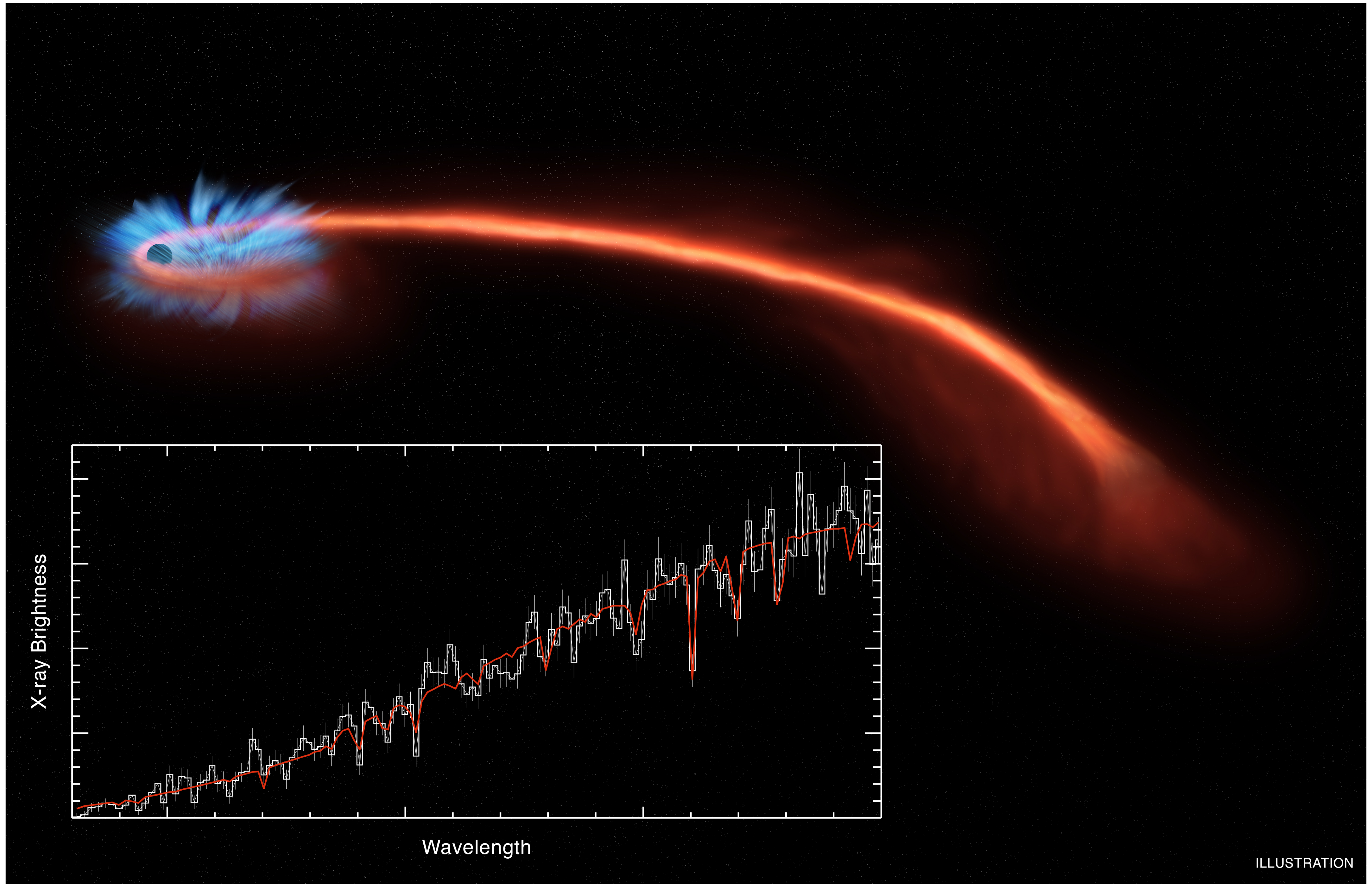
Located in the core of an otherwise quiescent, inactive galaxy

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

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

Neutrinos from TDEs?

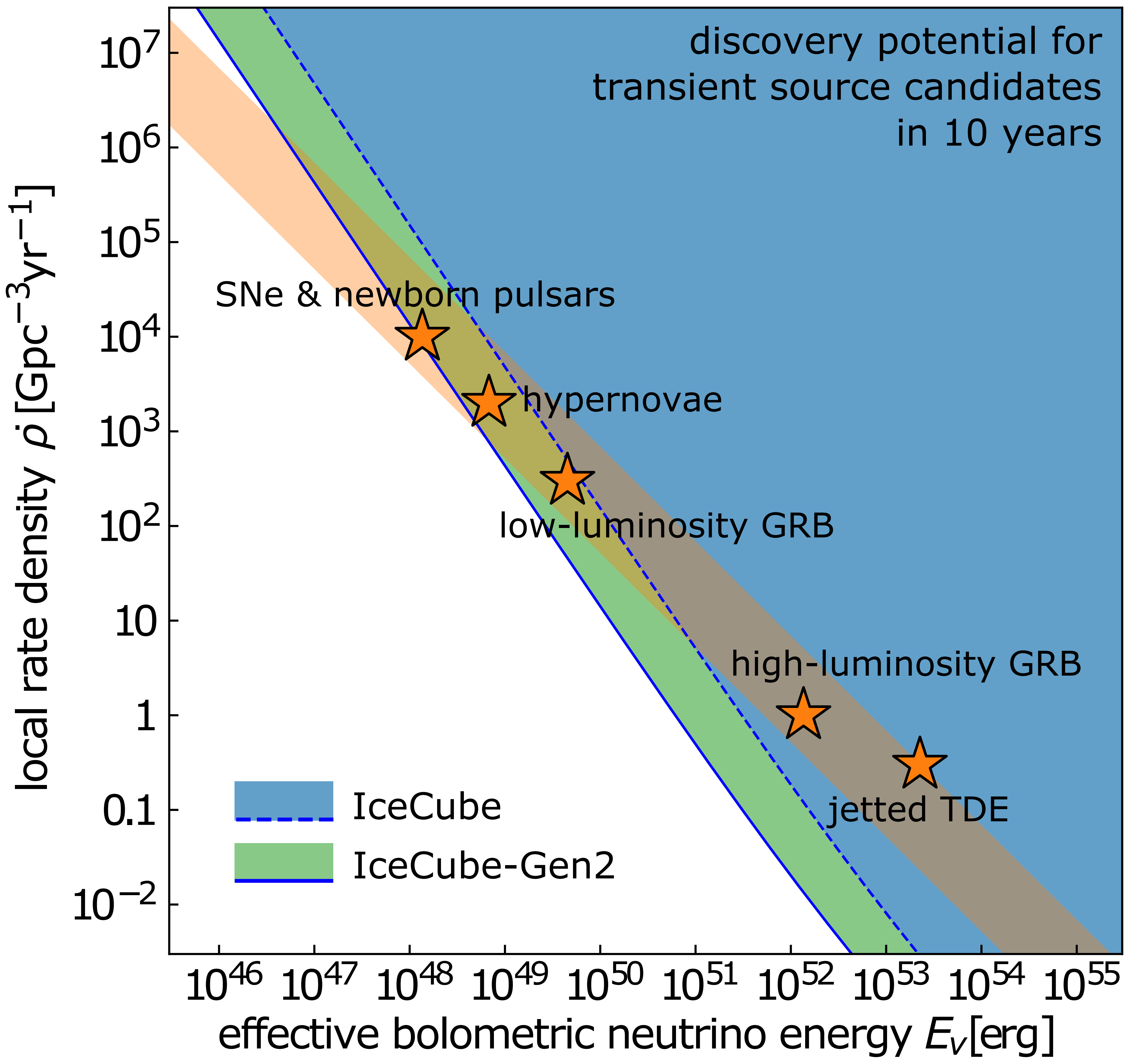
Photopion interactions in the jet (conditions similar to AGN/GRB)

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

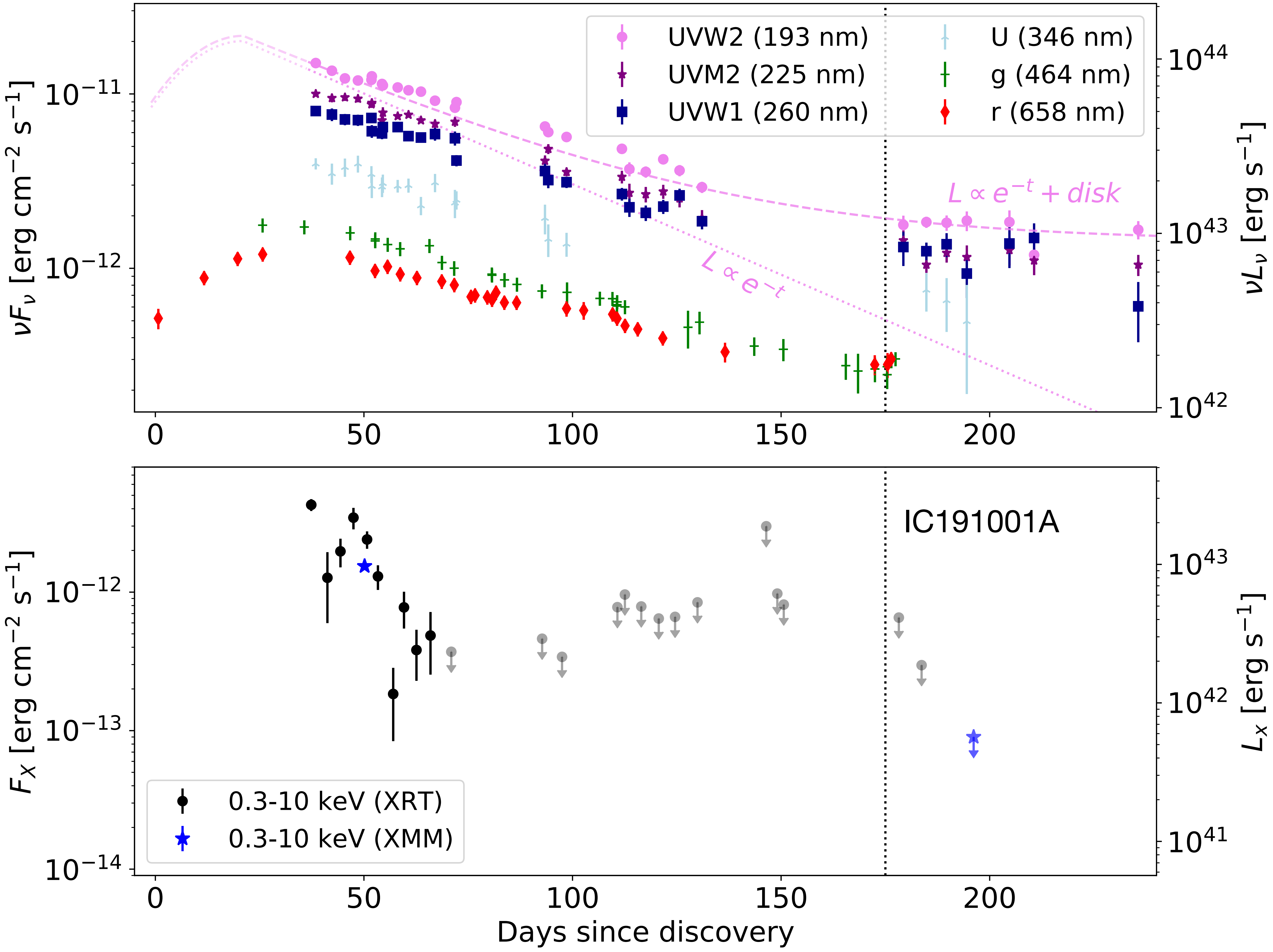
Stacking limits from IceCube (jetted TDEs < 1%, non-jetted < 26%)



AT2019dsg + IC191001A

UV optical flux

X-ray flux



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

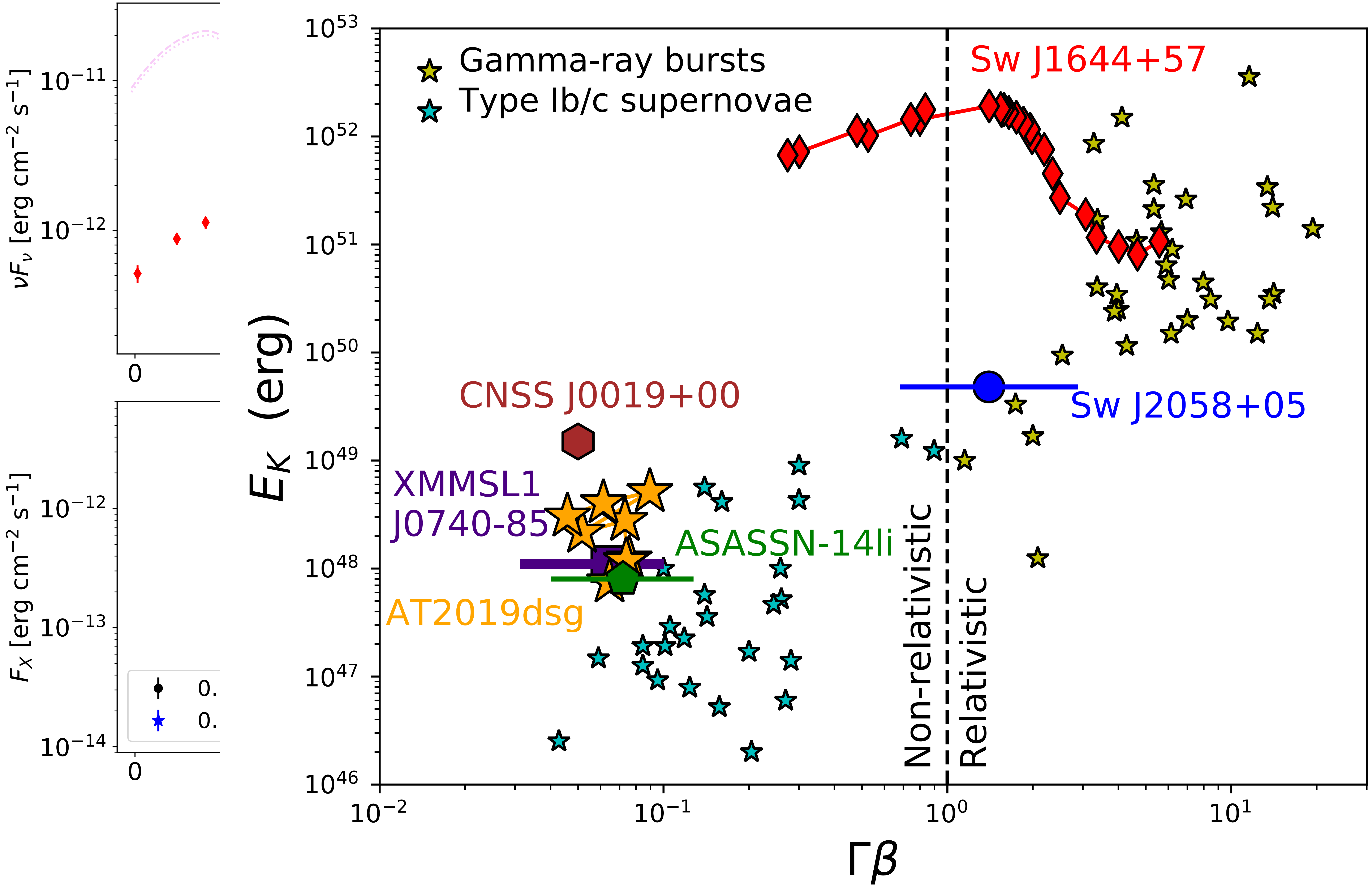
AT 2019dsg was a rare (radio emitting) TDE sign of jet?

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

AT2019dsg + IC191001A

UV optical flux

X-ray flux



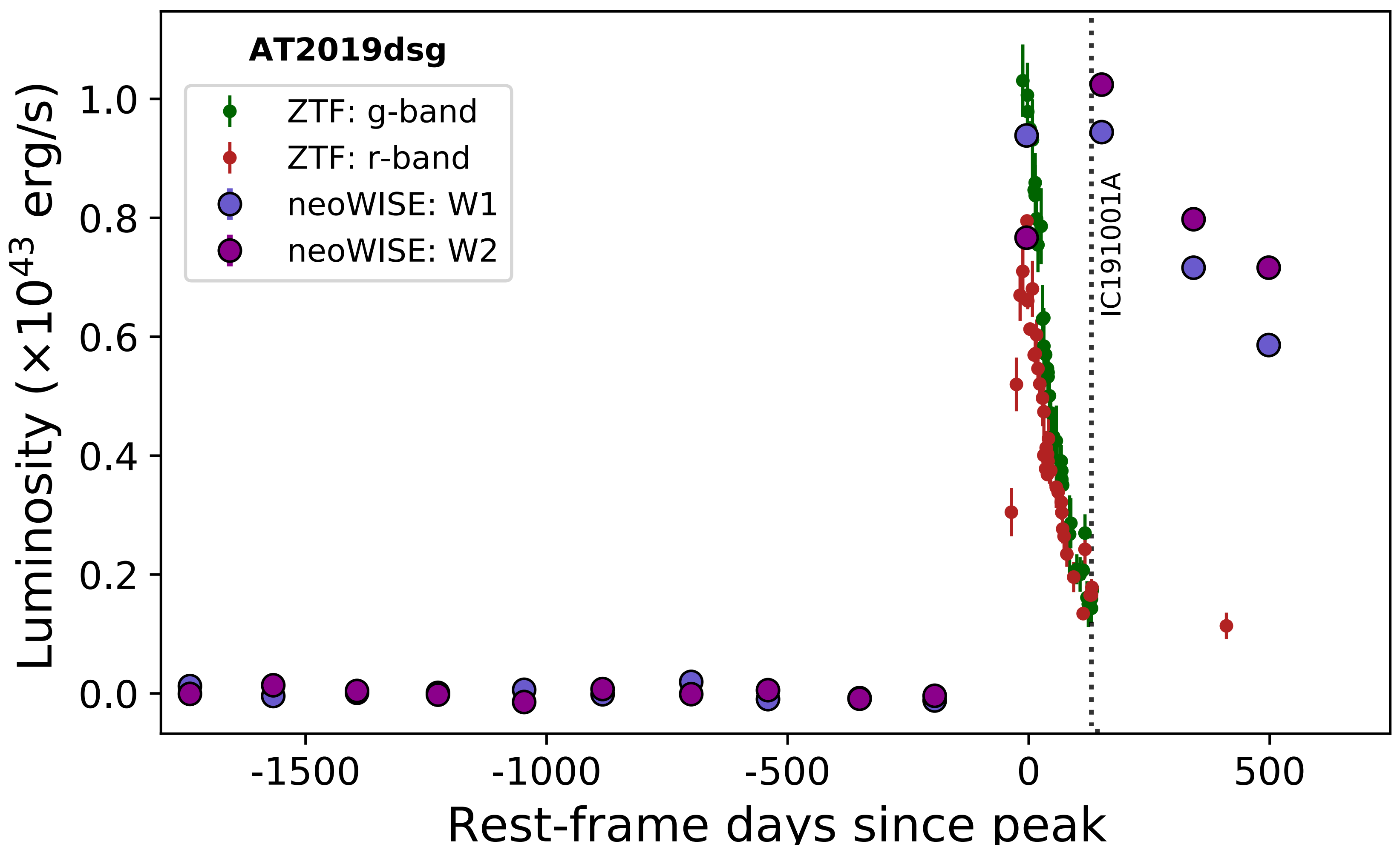
)0 TeV muon neutrino

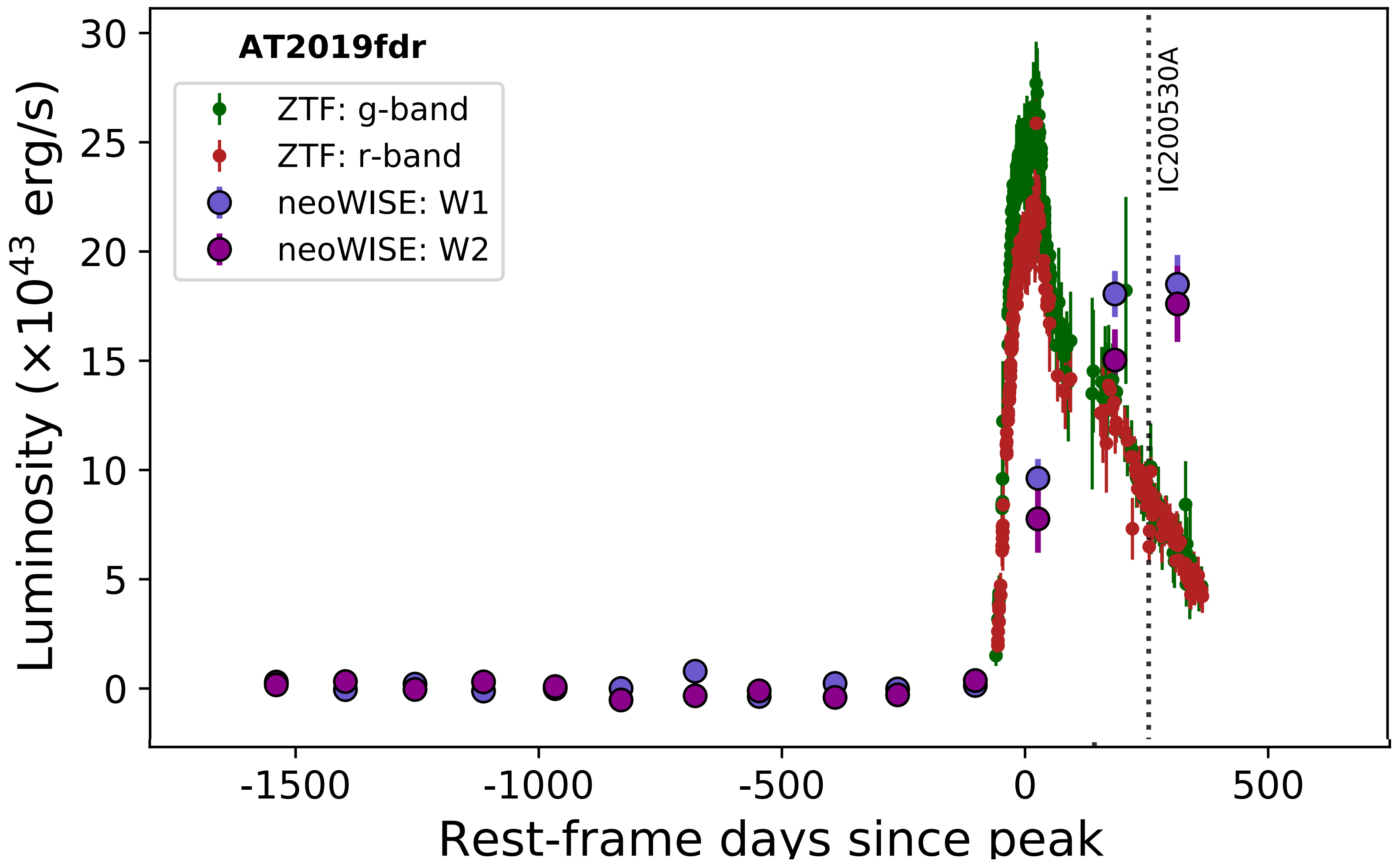
re (radio emitting) TDE

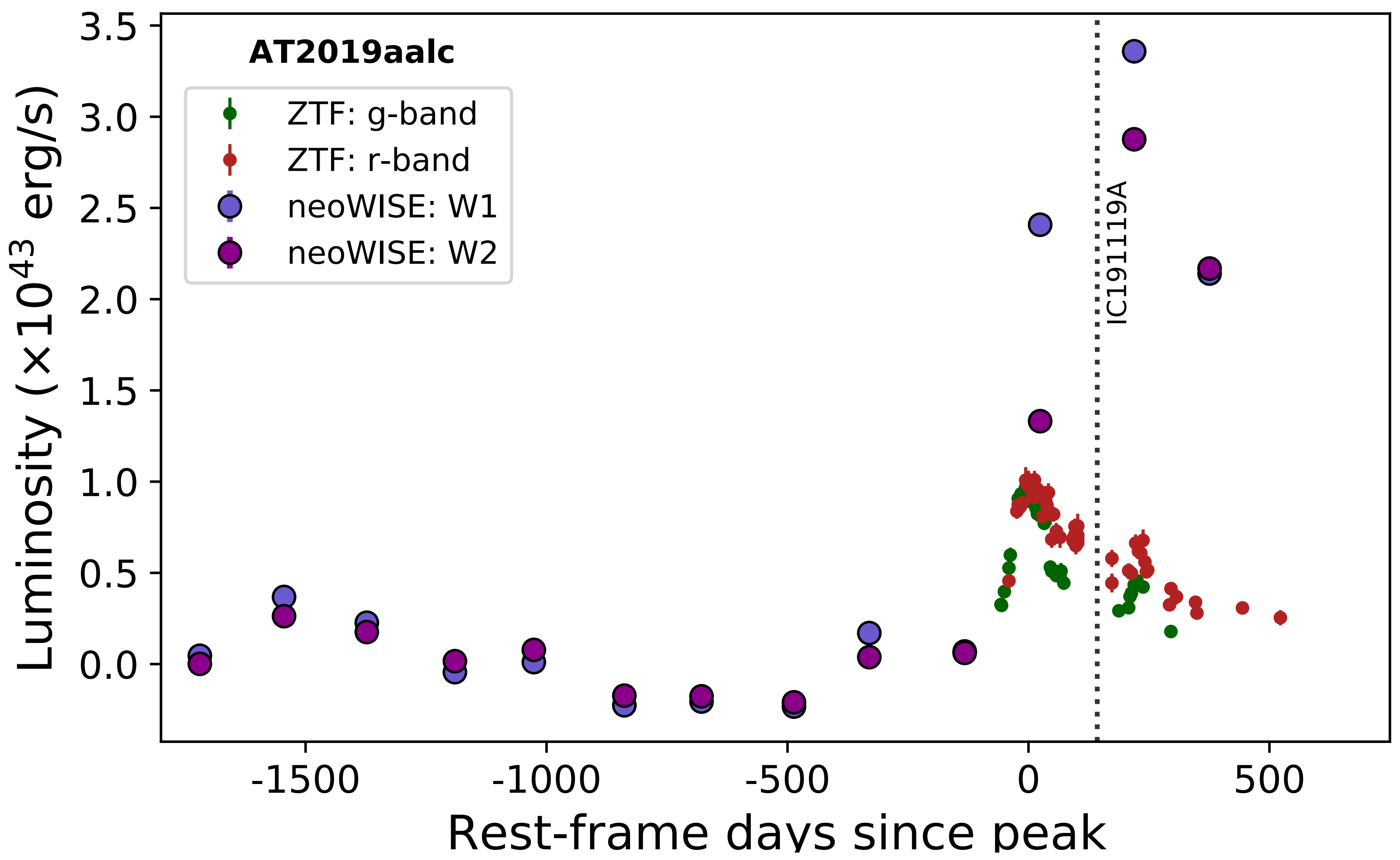
19dsg association by

AT2019fdr+IC200530A, AT2019aalc+IC191119A

Van Velzen et al 2021.09391





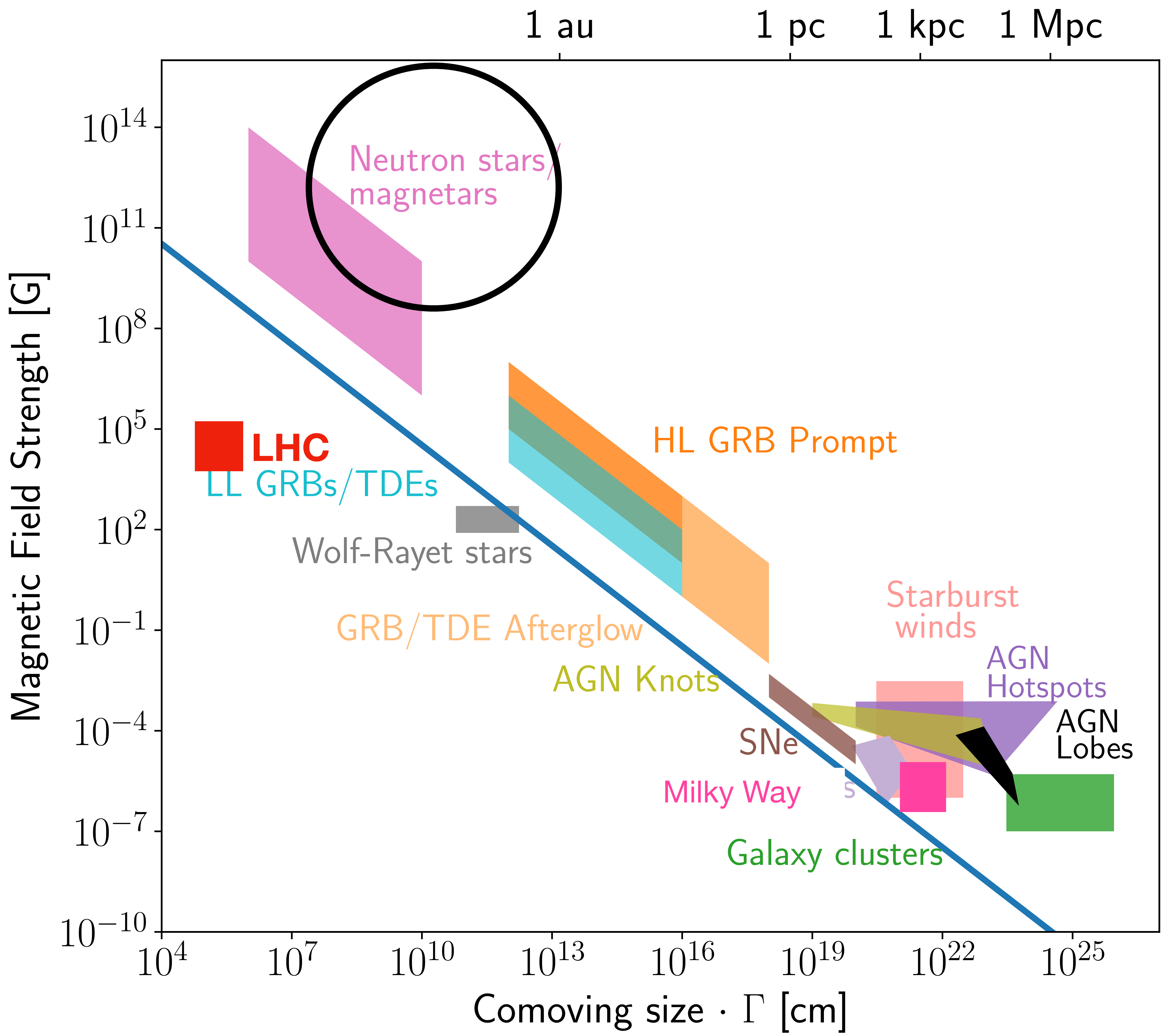


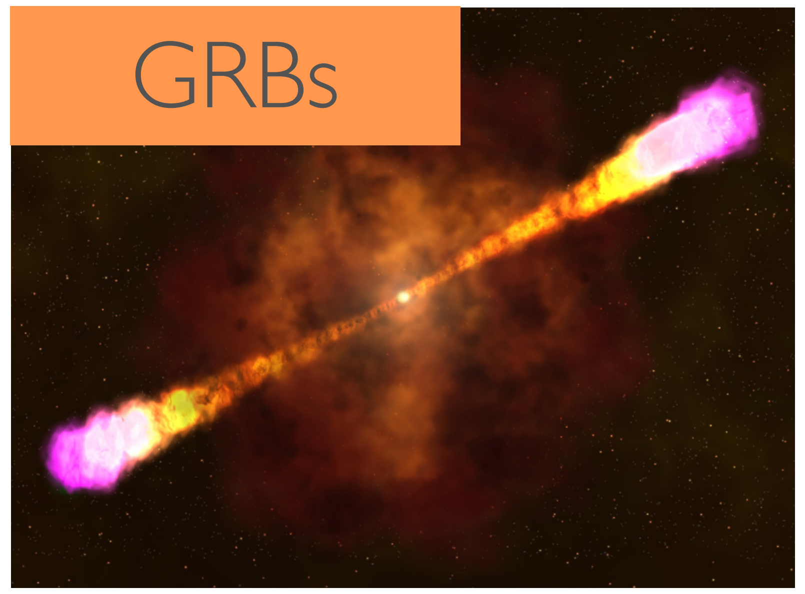
Combined significance 3.7σ

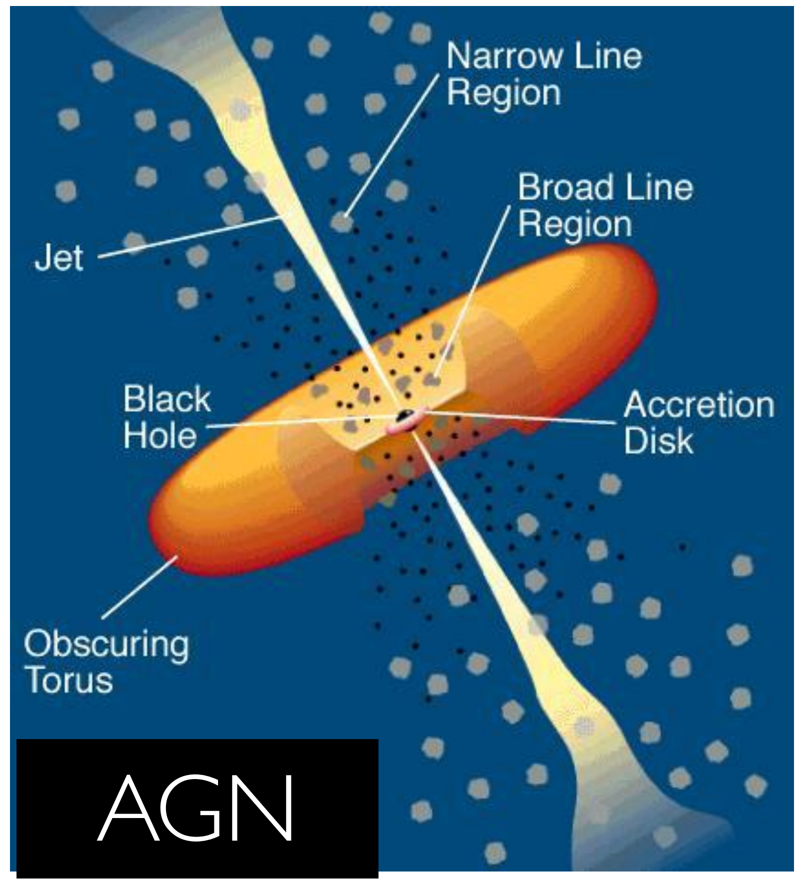
If the associations are real they point to very extreme physical conditions

“super_Eddington” accretion

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







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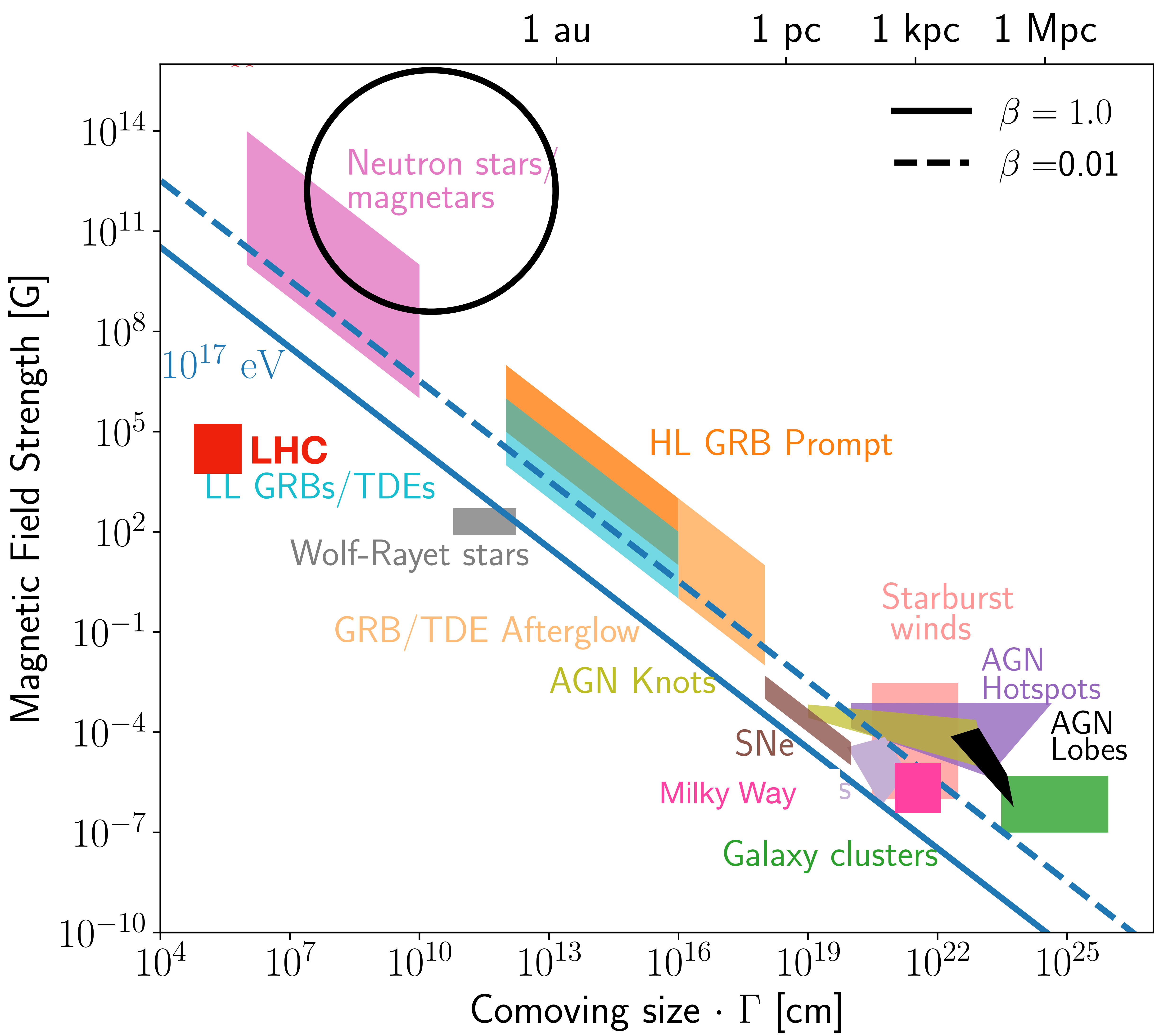
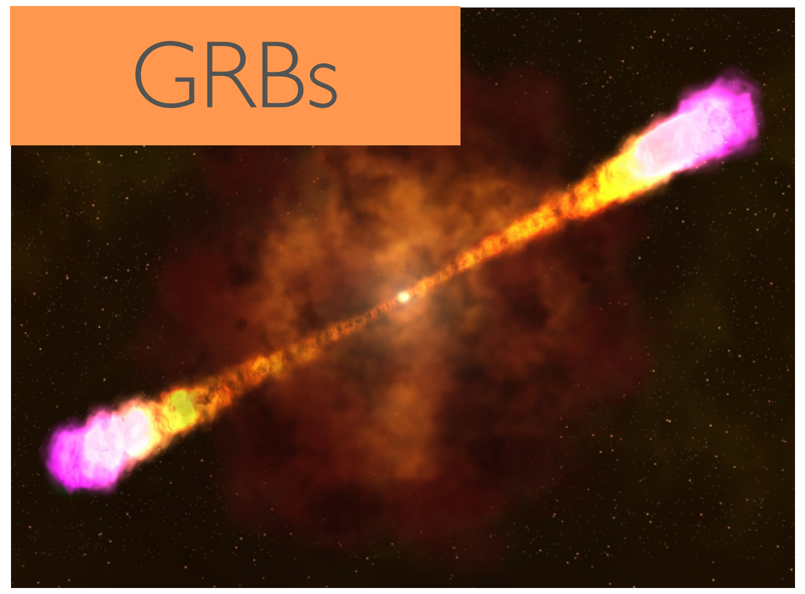
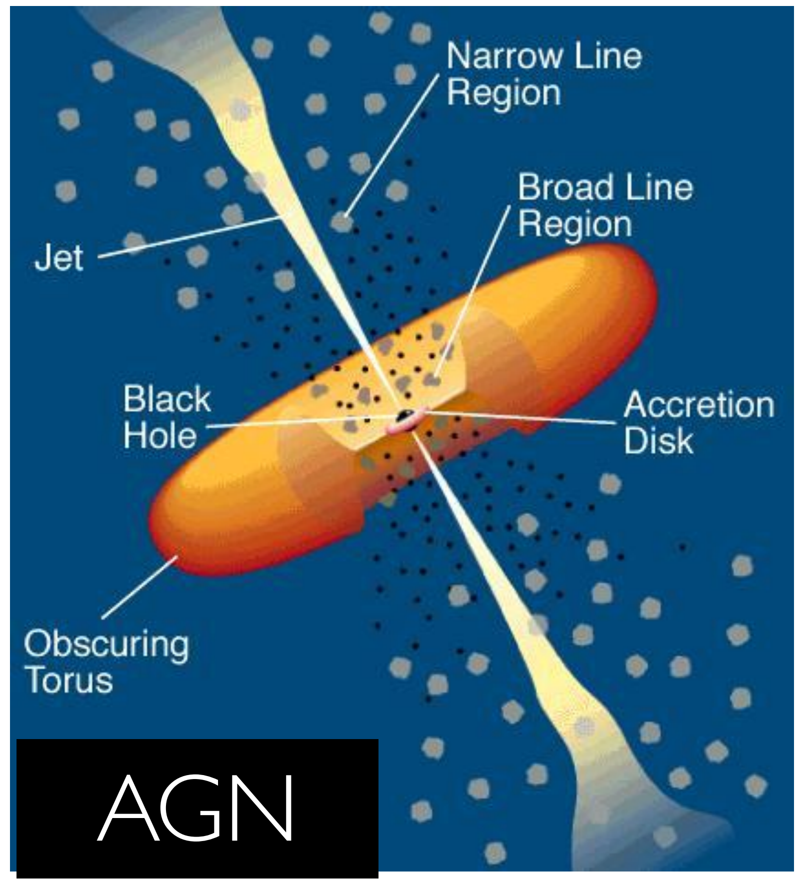
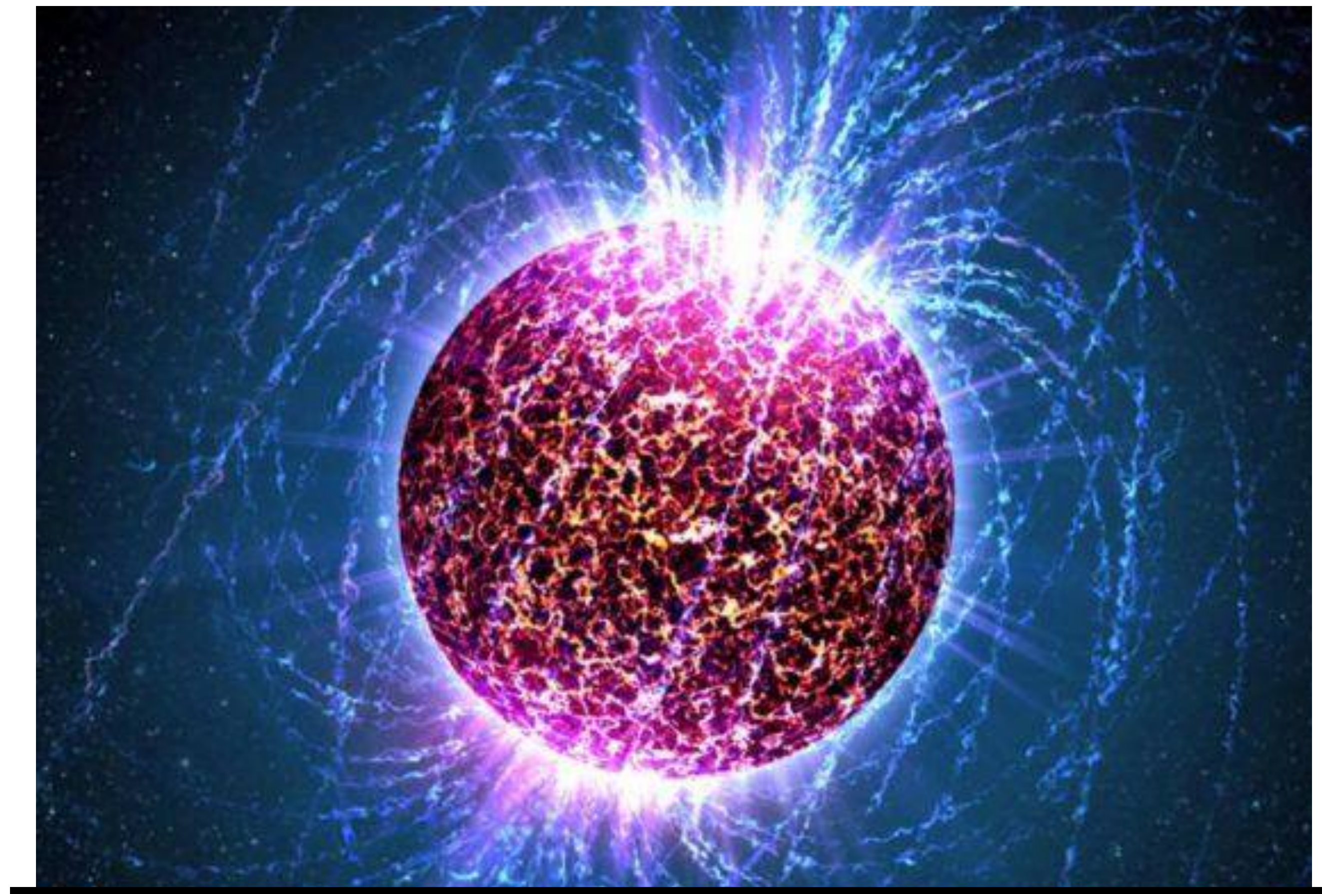
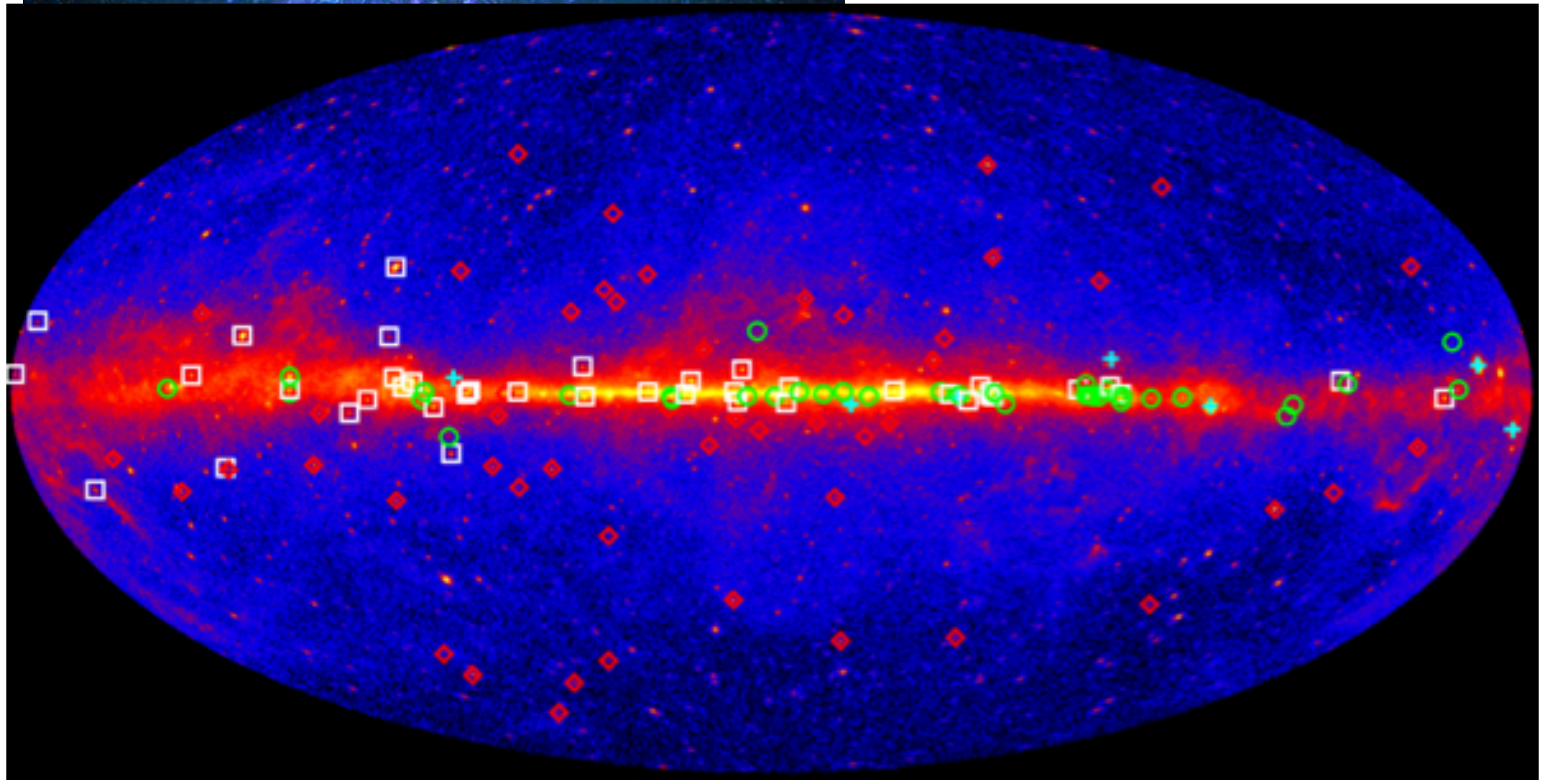






Neutron stars





Fermi has detected >200 Galactic pulsars

Collapsing stars with mass > 8 M_{Sun}

Collapse leads to heating up and density approaches nuclear densities

$$e^- + p^+ \rightarrow n + \nu_e$$

"neutronisation"

The core of the star was originally $R_{star} \sim 10^{3-4}$ km

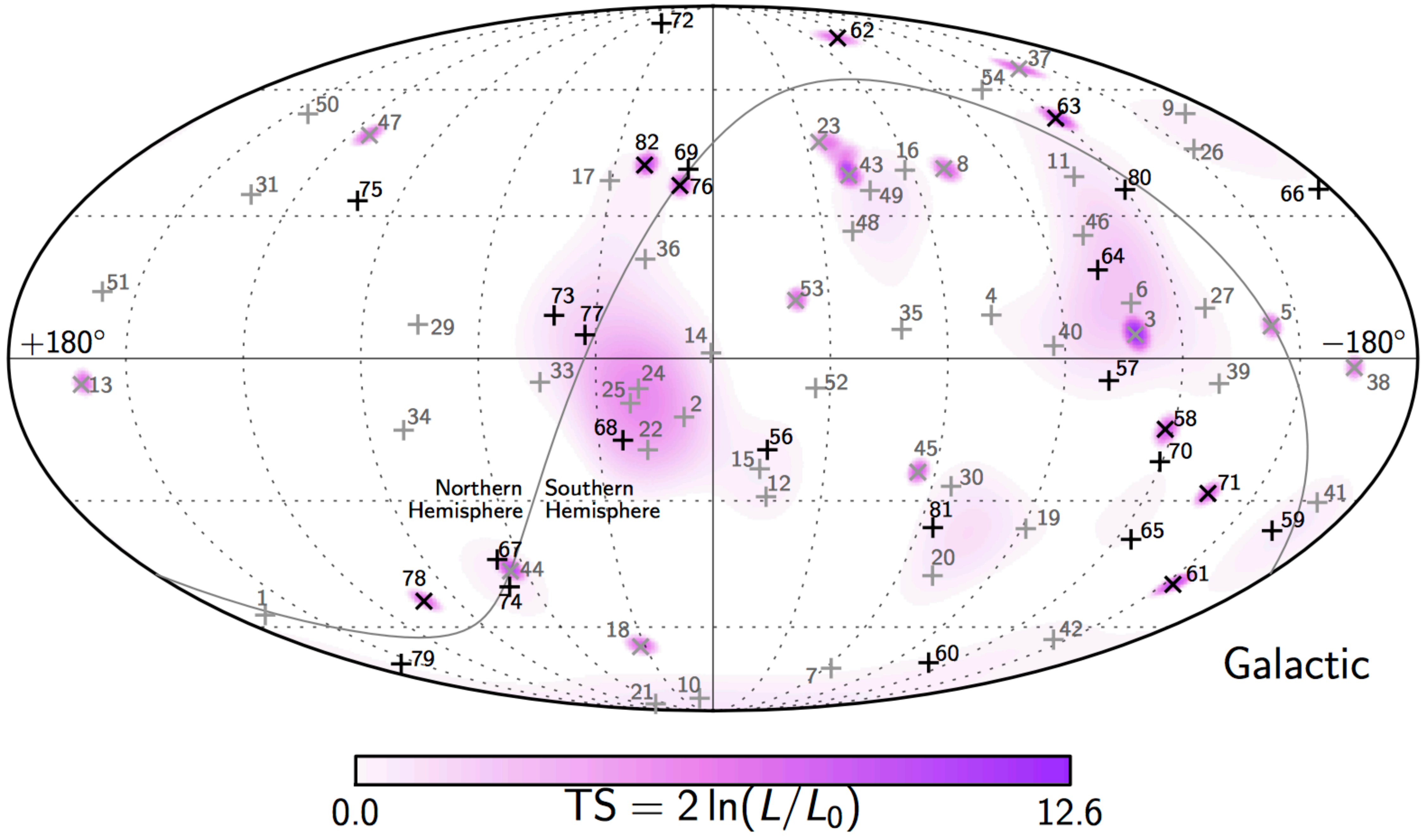
whereas the neutron star radius is $R_{NS} \sim 10$ km

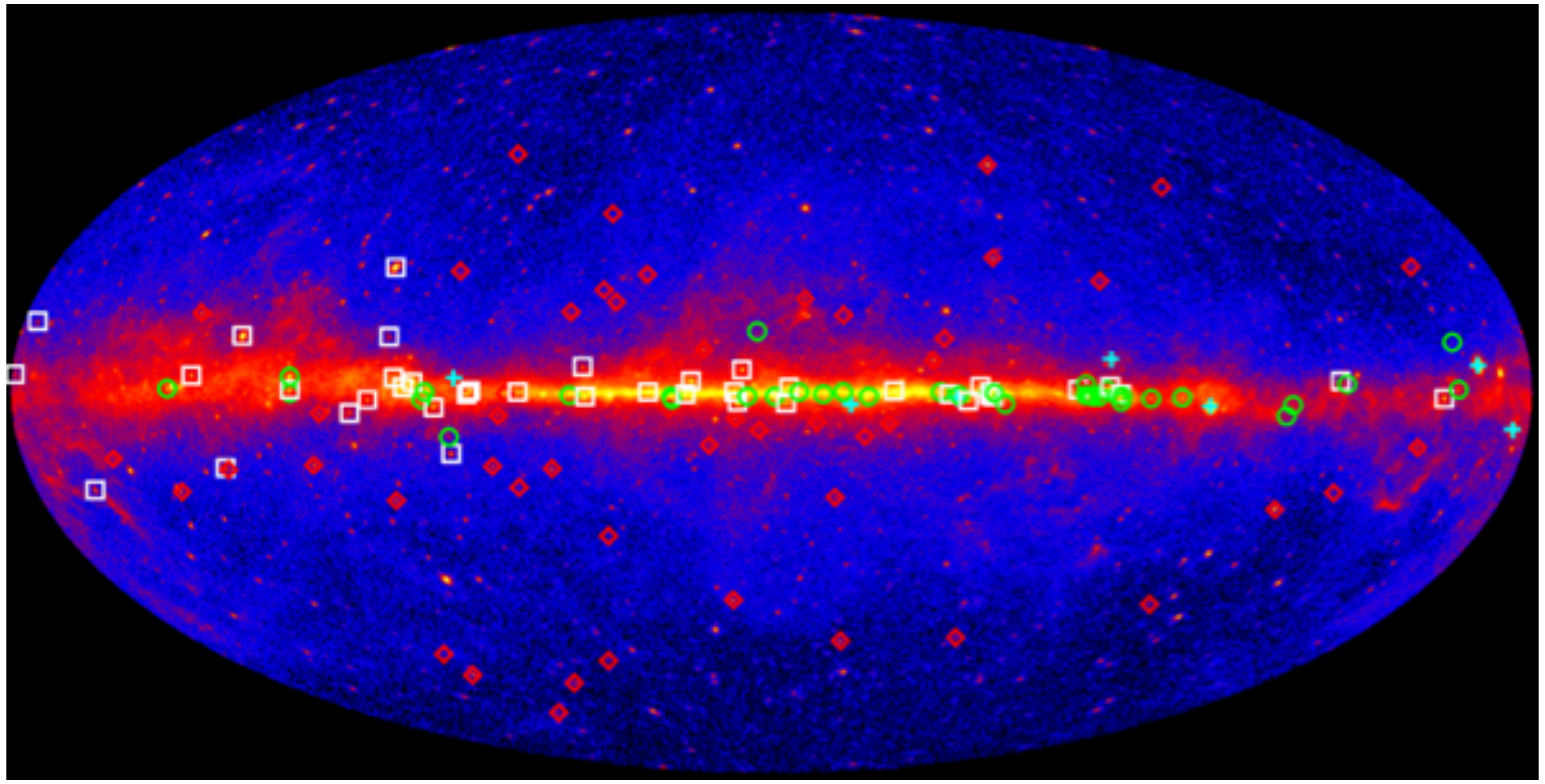
Conservation of angular momentum leads to spin periods ~second

Conservation of magnetic flux leads to B ~10^{10} G

Pulsar origin of IceCube neutrinos?

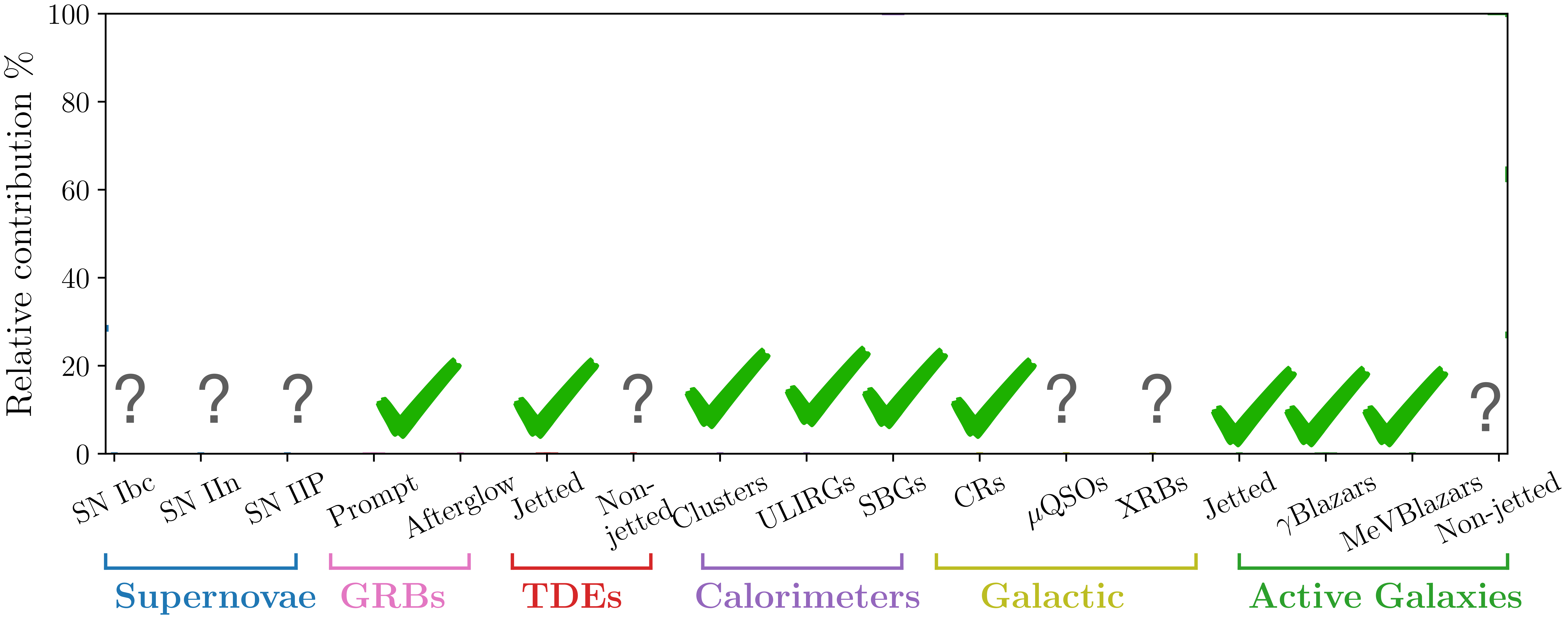
IceCube Coll. PoS(ICRC2017)981





Fermi has detected >200 Galactic pulsars

The current landscape: Maximum energy

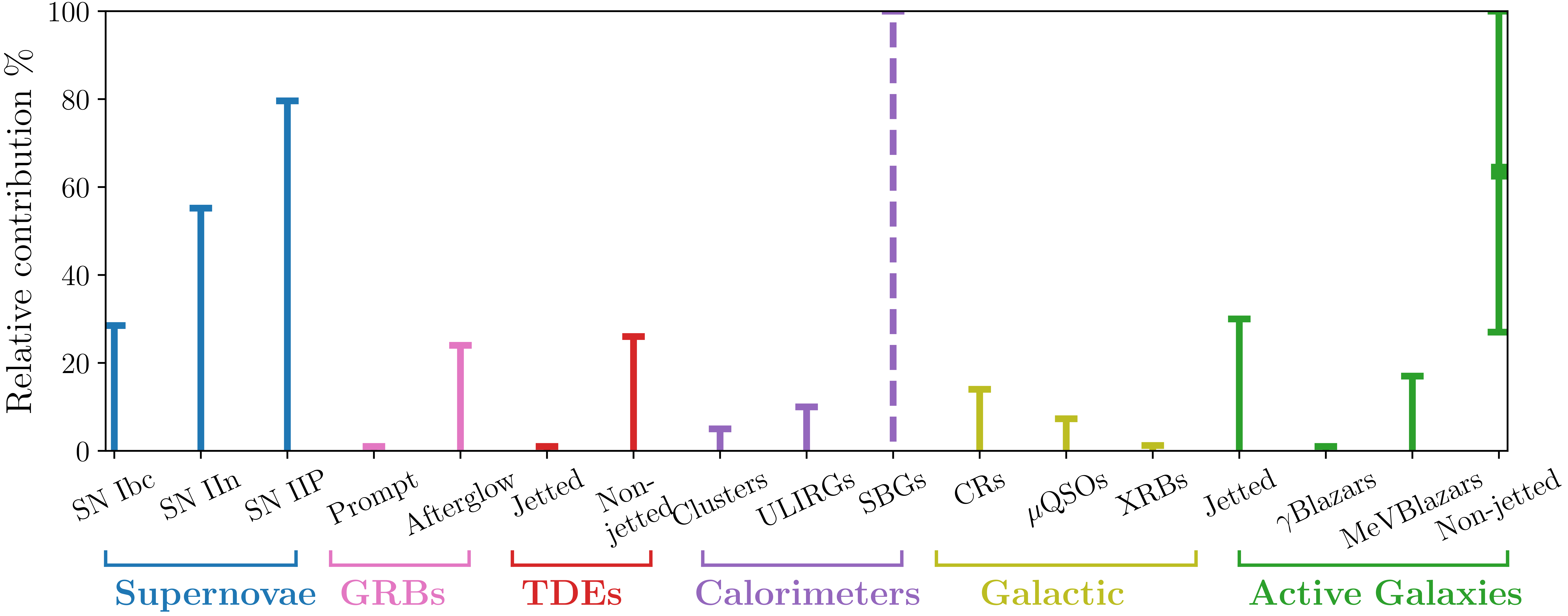


The current landscape: Point source limits

The current landscape: Connection to UHECRs

The current landscape: Stacking upper limits

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



The current landscape: Stacking upper limits

Thank you for your attention!