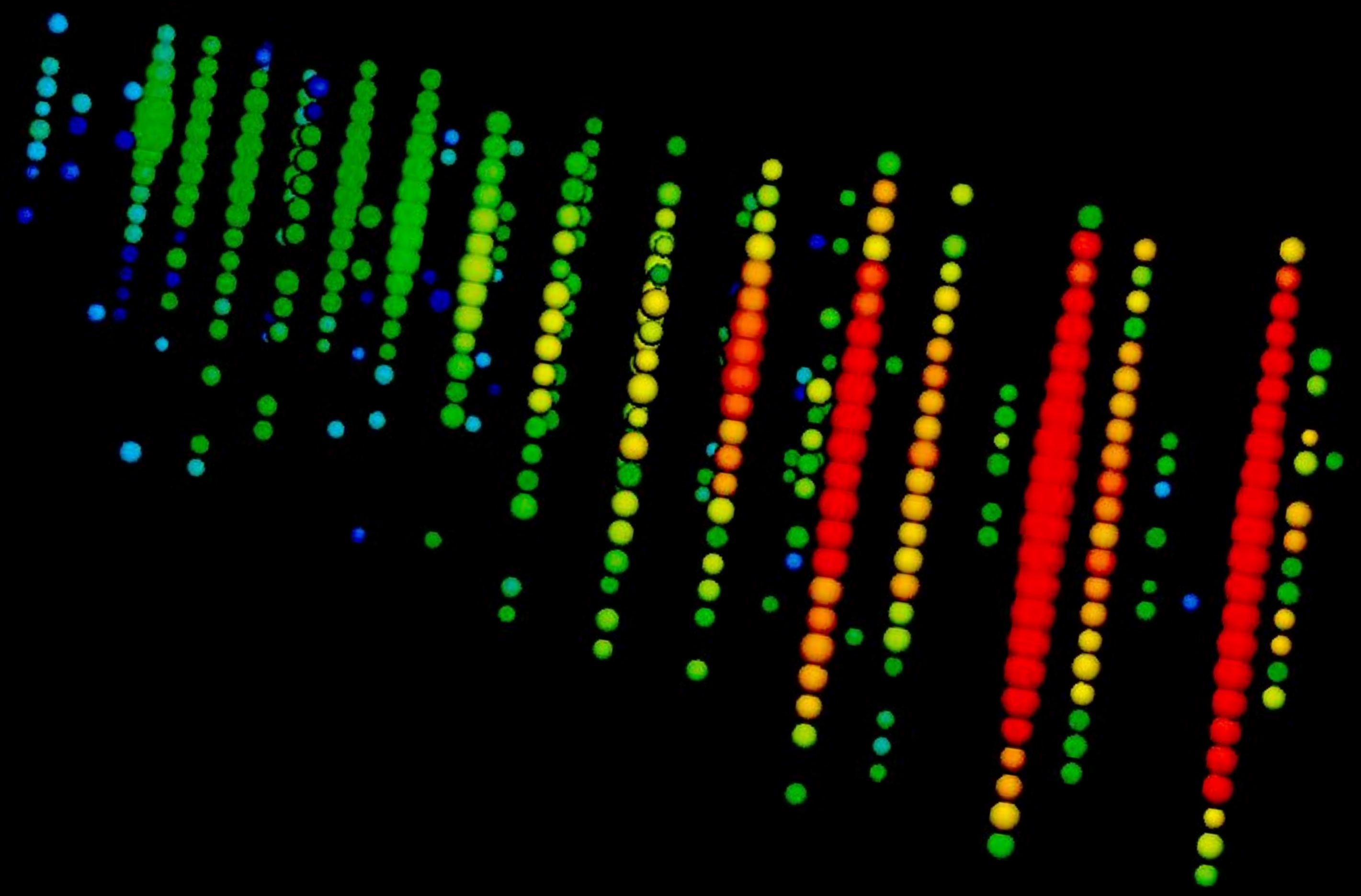


Neutrino Astronomy & Astrophysics

PhD summer school on neutrinos

Here, there & Everywhere

NBI, Copenhagen

Foteini Oikonomou

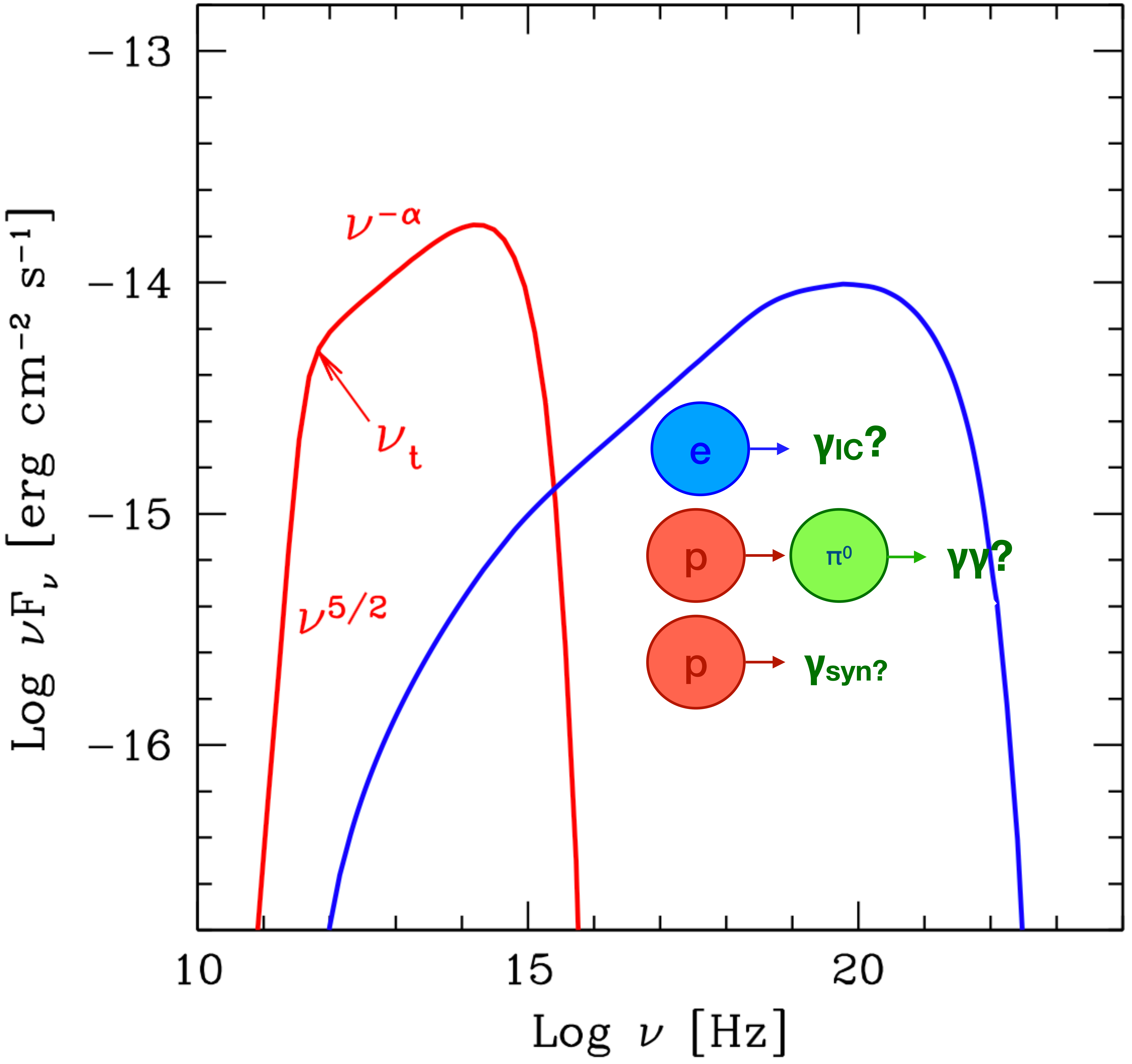
July 5th-9th

NTNU
Norwegian University of Science and Technology

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

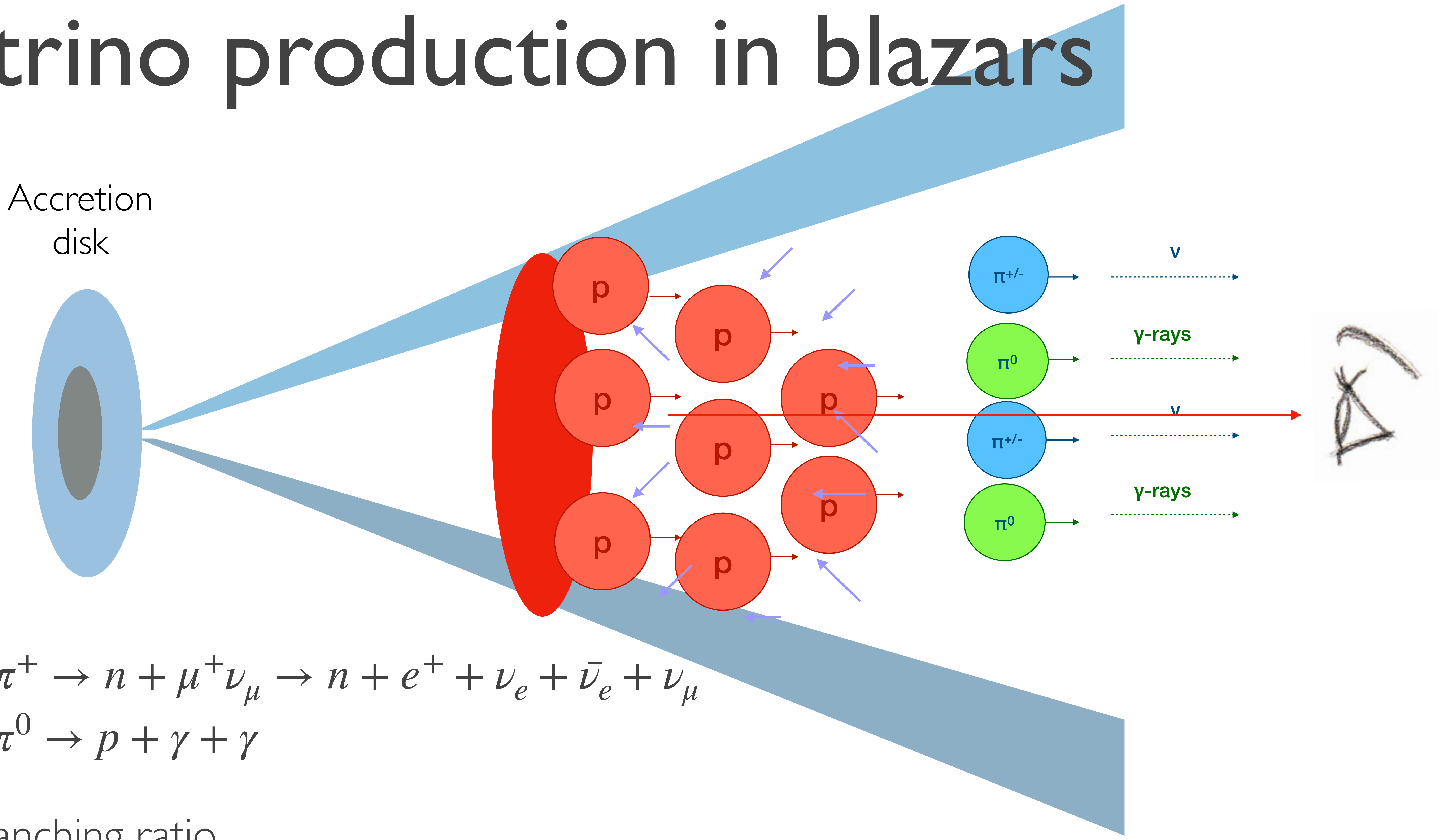
Enter the protons



For characteristic values of B, R, and delta , we end up with E_{max} in the UHECR ball park,

$$E_{\rm CR,max} \sim \left(\frac{Z}{1}\right)\left(\frac{\eta}{1}\right)\left(\frac{B}{0.35\ \rm G}\right)\left(\frac{R'}{10^{16}\ \rm cm}\right)\left(\frac{\Gamma}{25}\right) \sim Z\cdot 5\times10^{19}\ \rm eV$$

Neutrino production in blazars



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

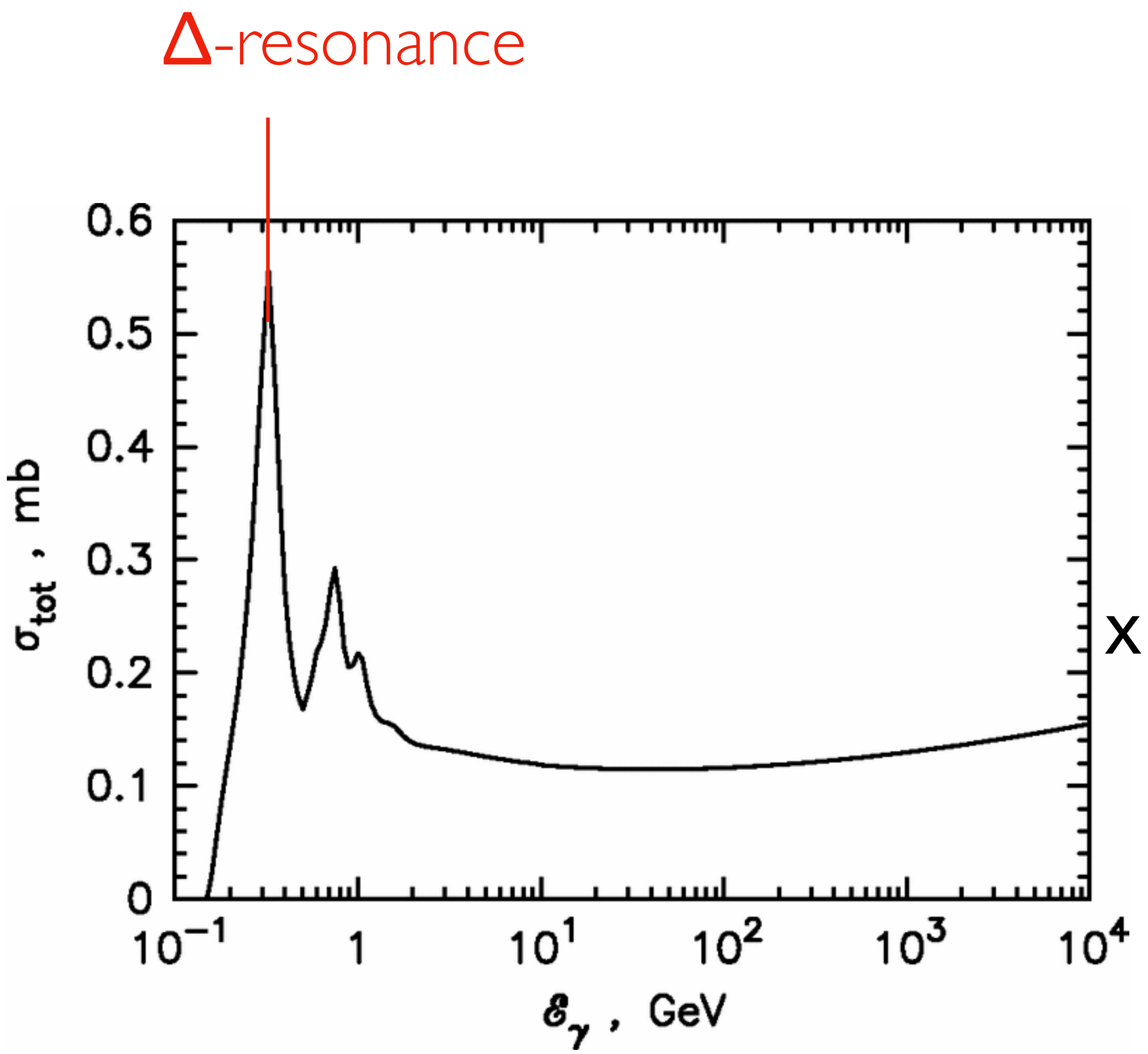
Averaged branching ratio,

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

$$E_\nu^2 \frac{\mathrm{d}N}{\mathrm{d}E_\nu} = \frac{3}{2}\frac{1}{2} E_\gamma^2 \frac{\mathrm{d}N}{\mathrm{d}E_\gamma} |_{E_\gamma = 2E_\nu}$$ $\longrightarrow$ Upper limit to the neutrino flux

Neutrino production in blazars

Neutrino production efficiency ~ cross-section x target number density



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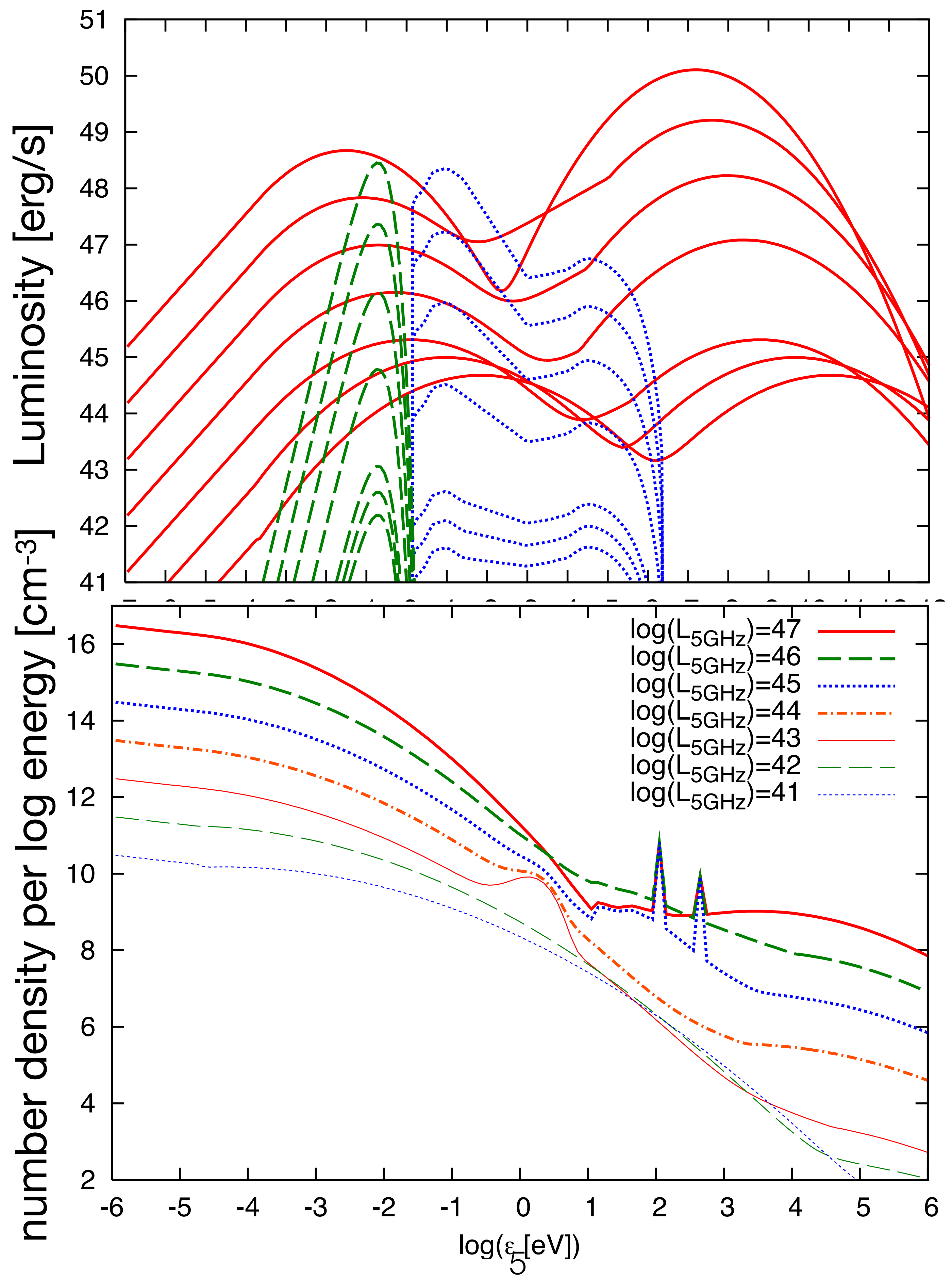

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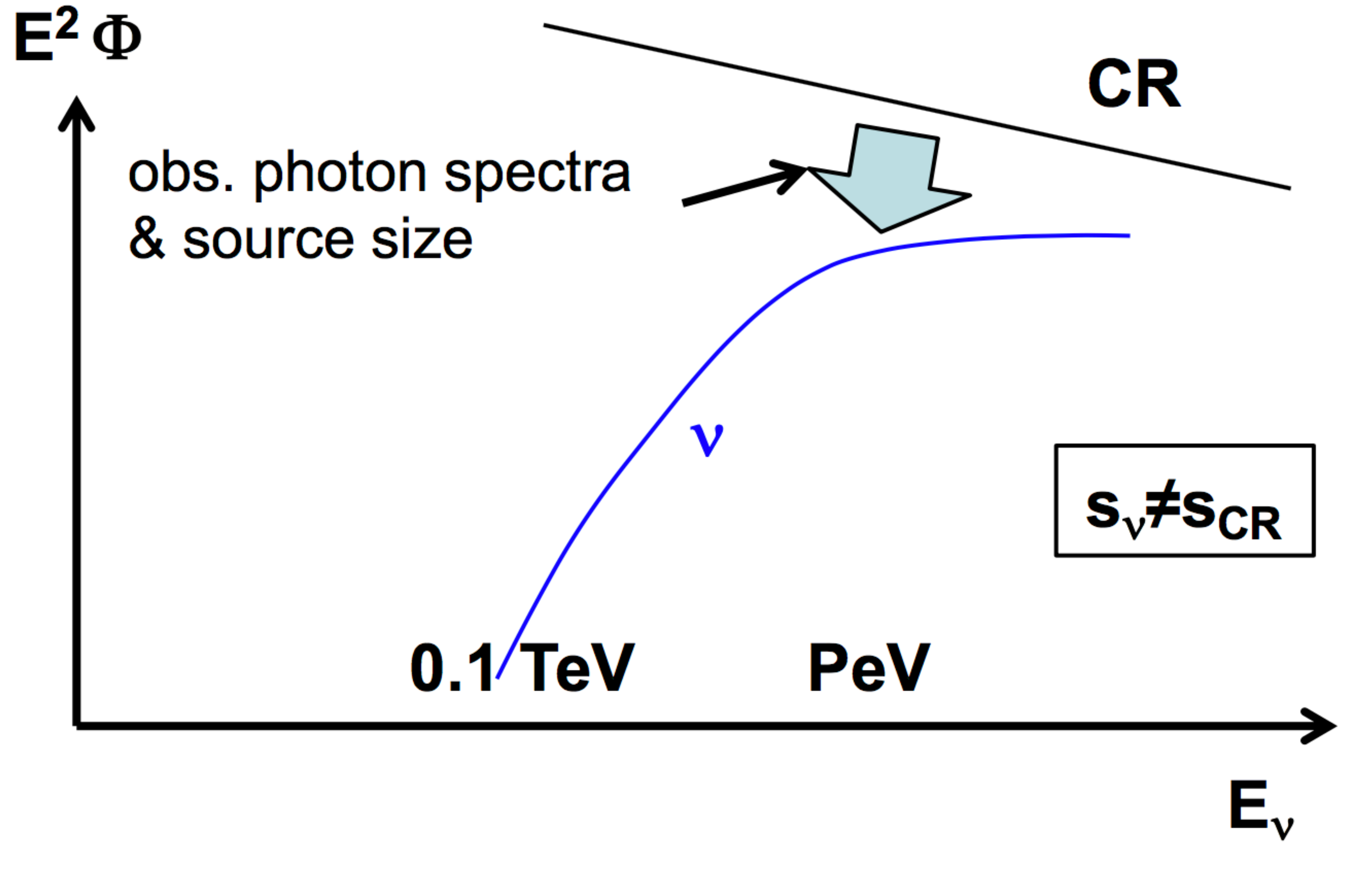
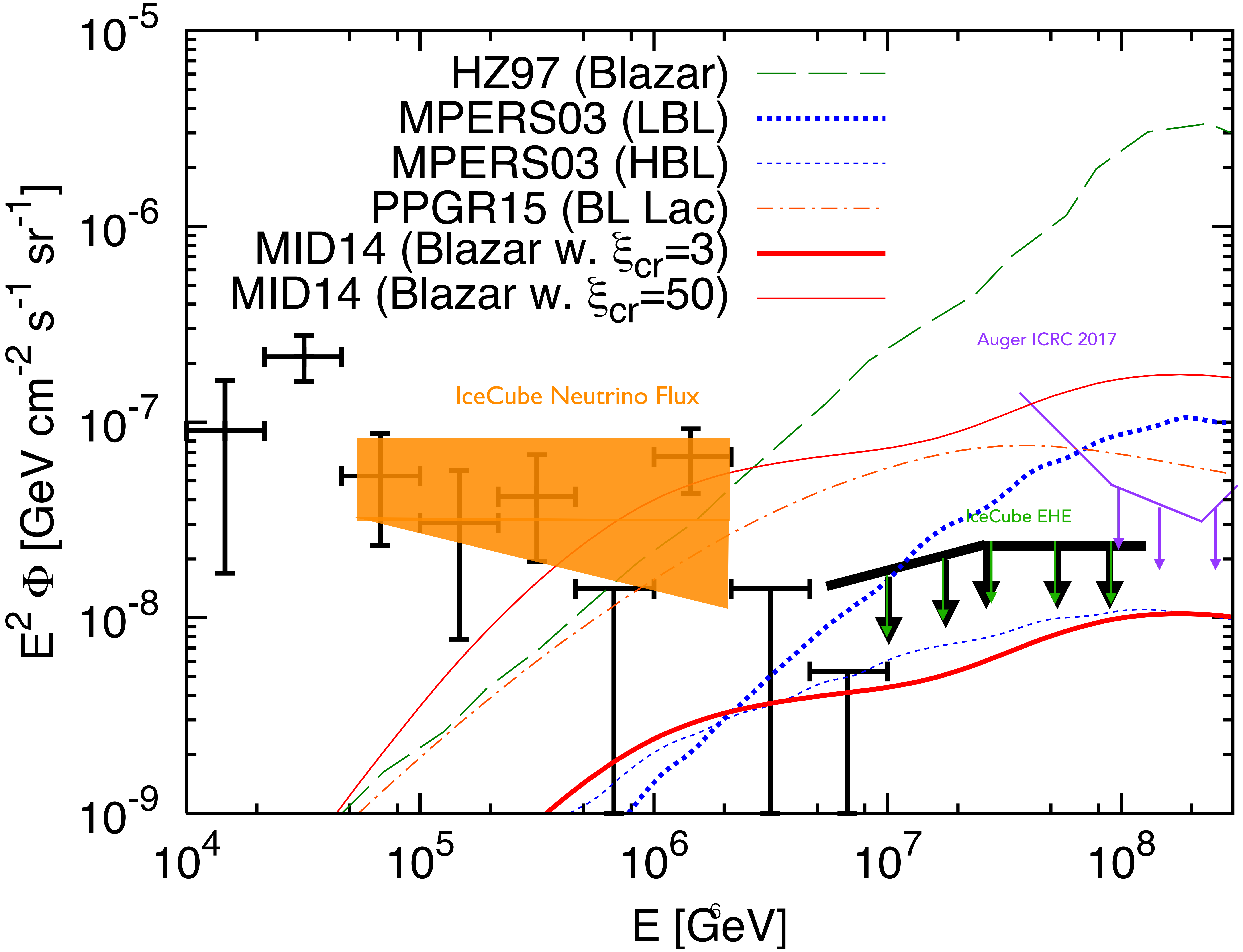
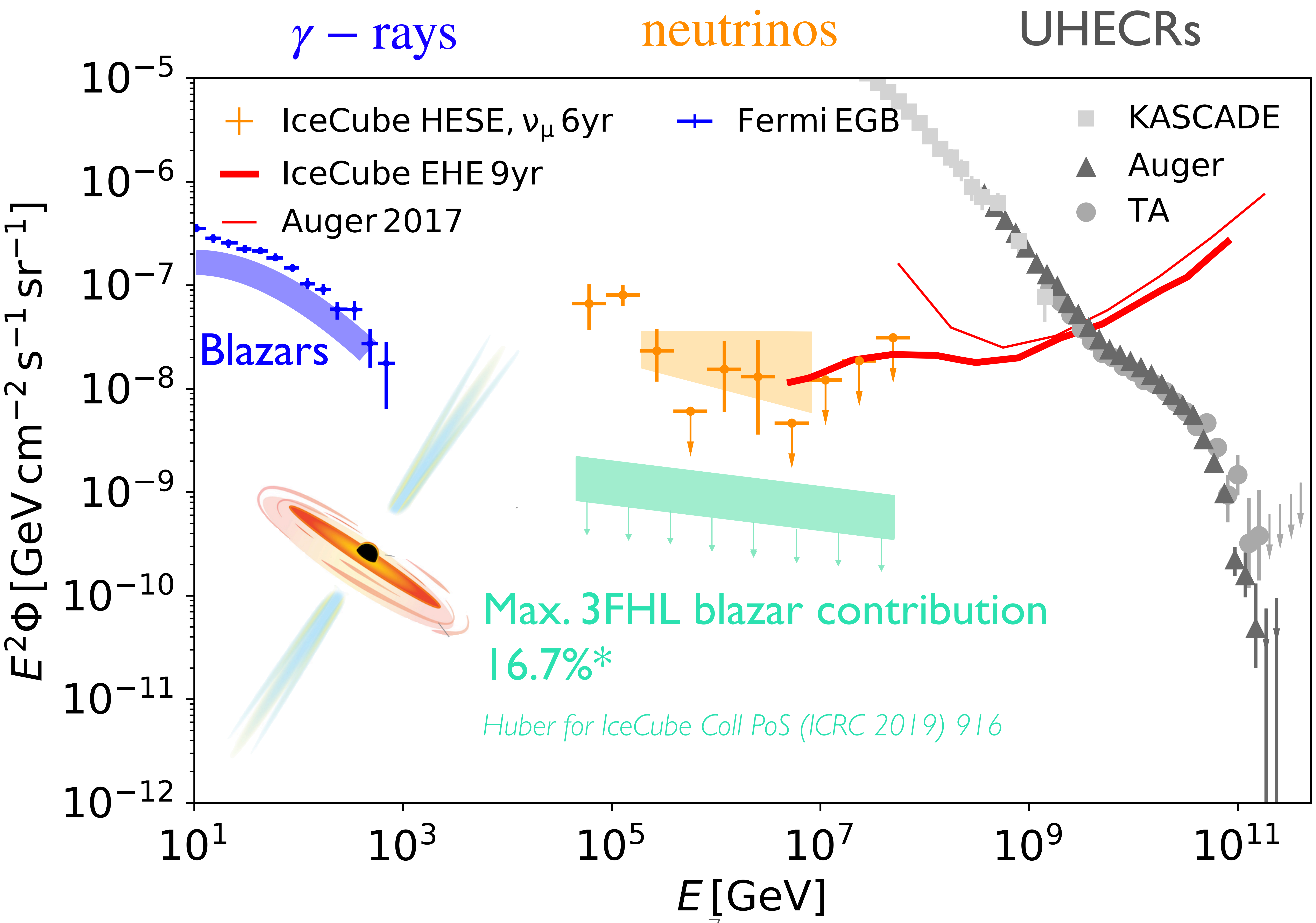


Possible contribution of blazars to the diffuse neutrino flux

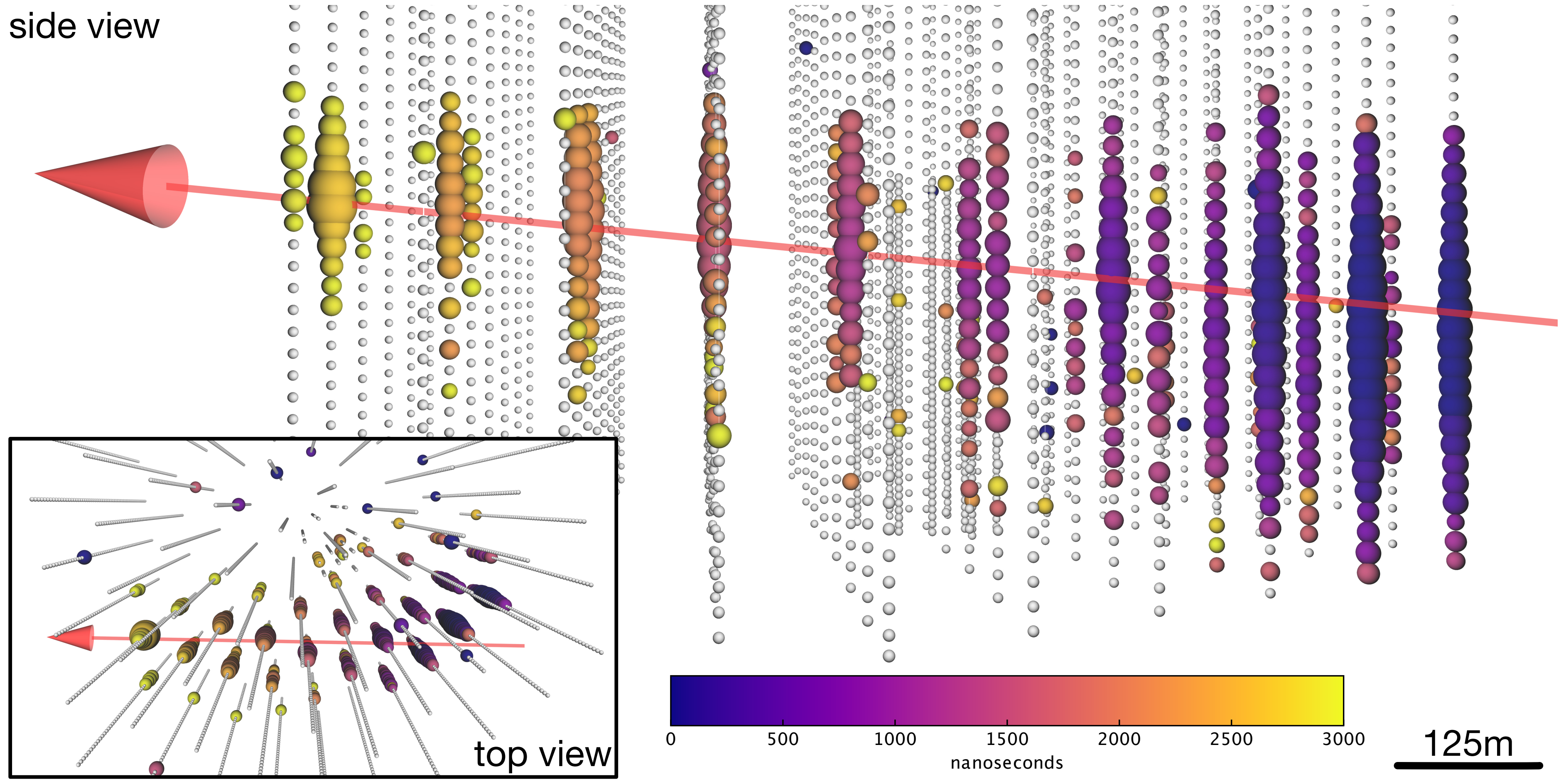


Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking

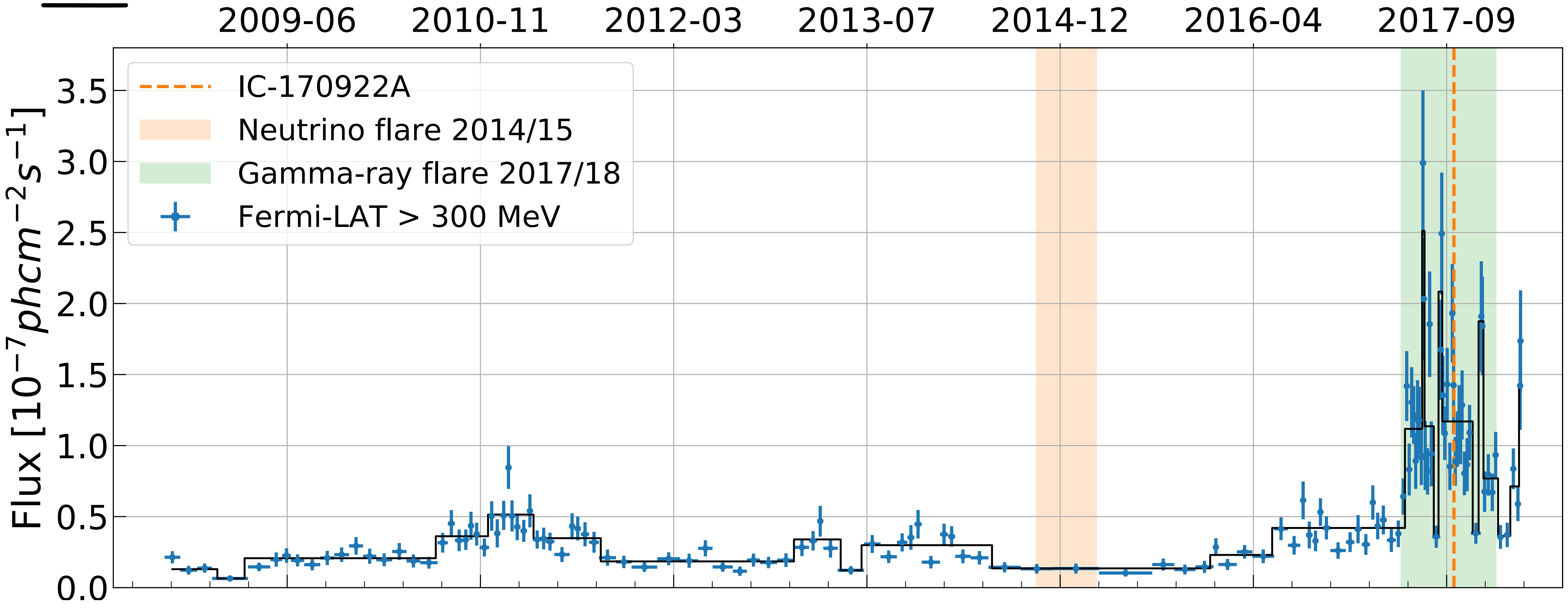


TXS 0506+056-IC 170922A

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



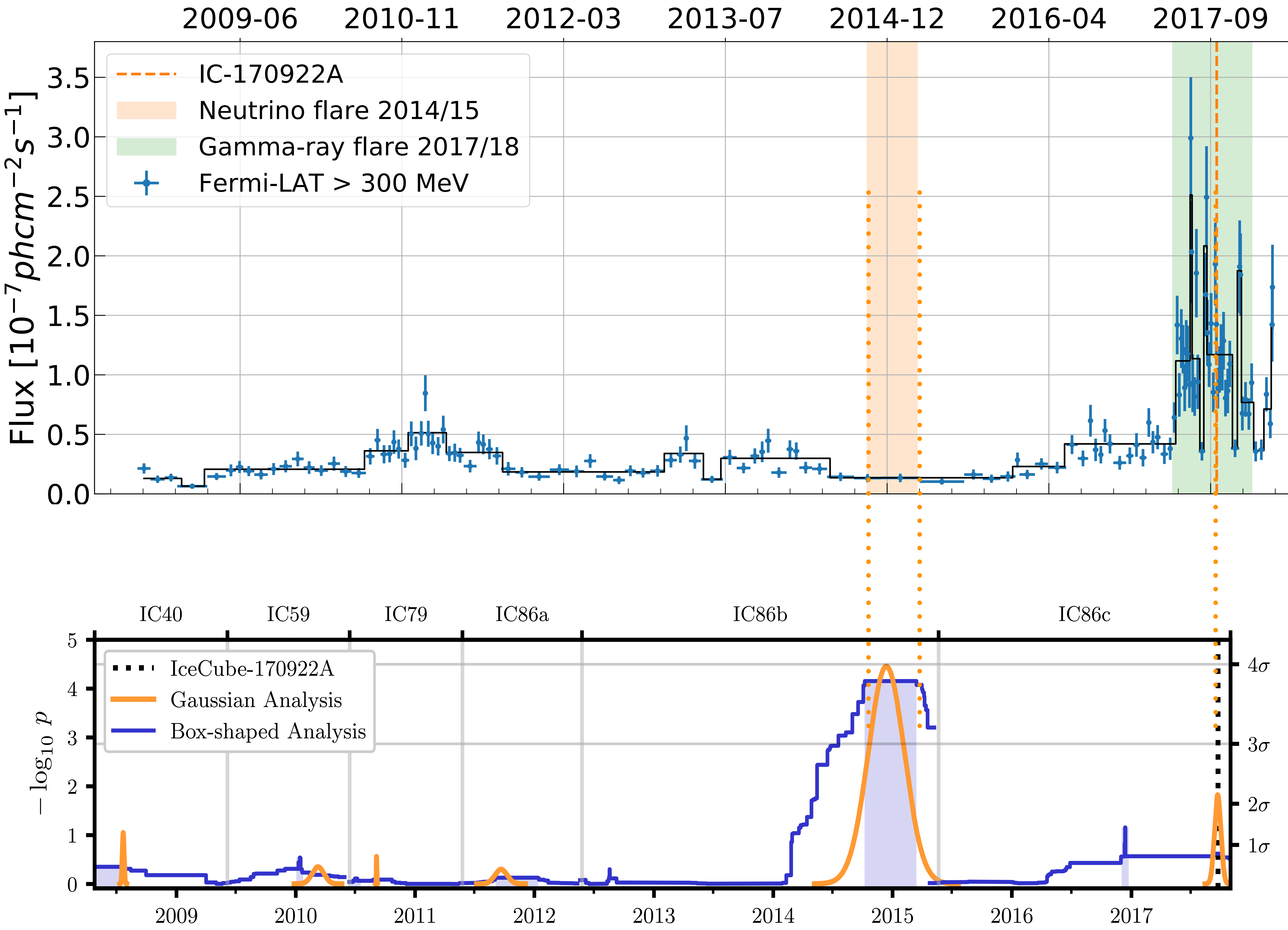
Background fluctuation? Chance probability ~0.3%



IceCube archival search 13±5 more neutrinos!

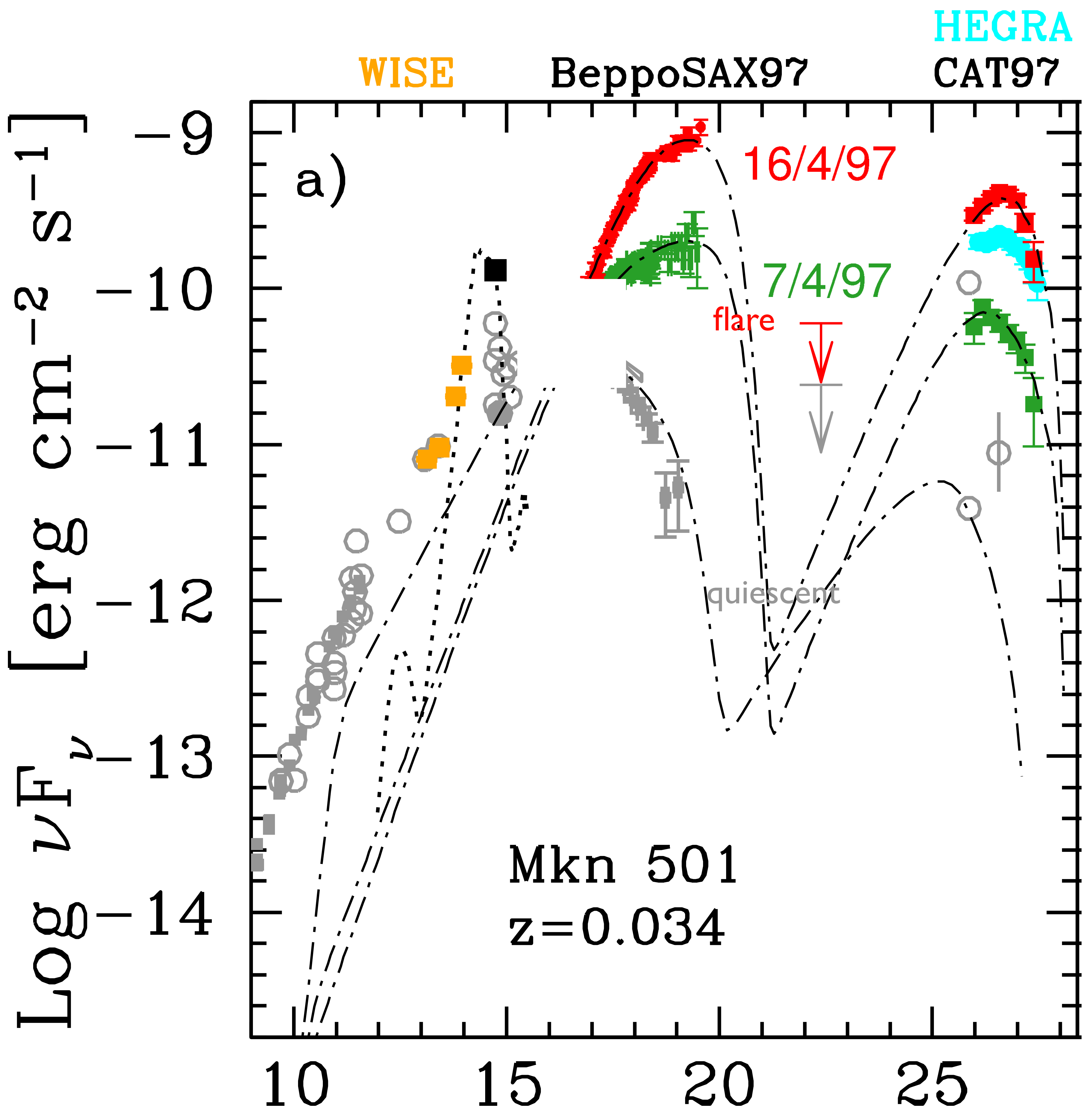
γ-rays

neutrinos



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

Blazar flares: Interesting as neutrino point sources



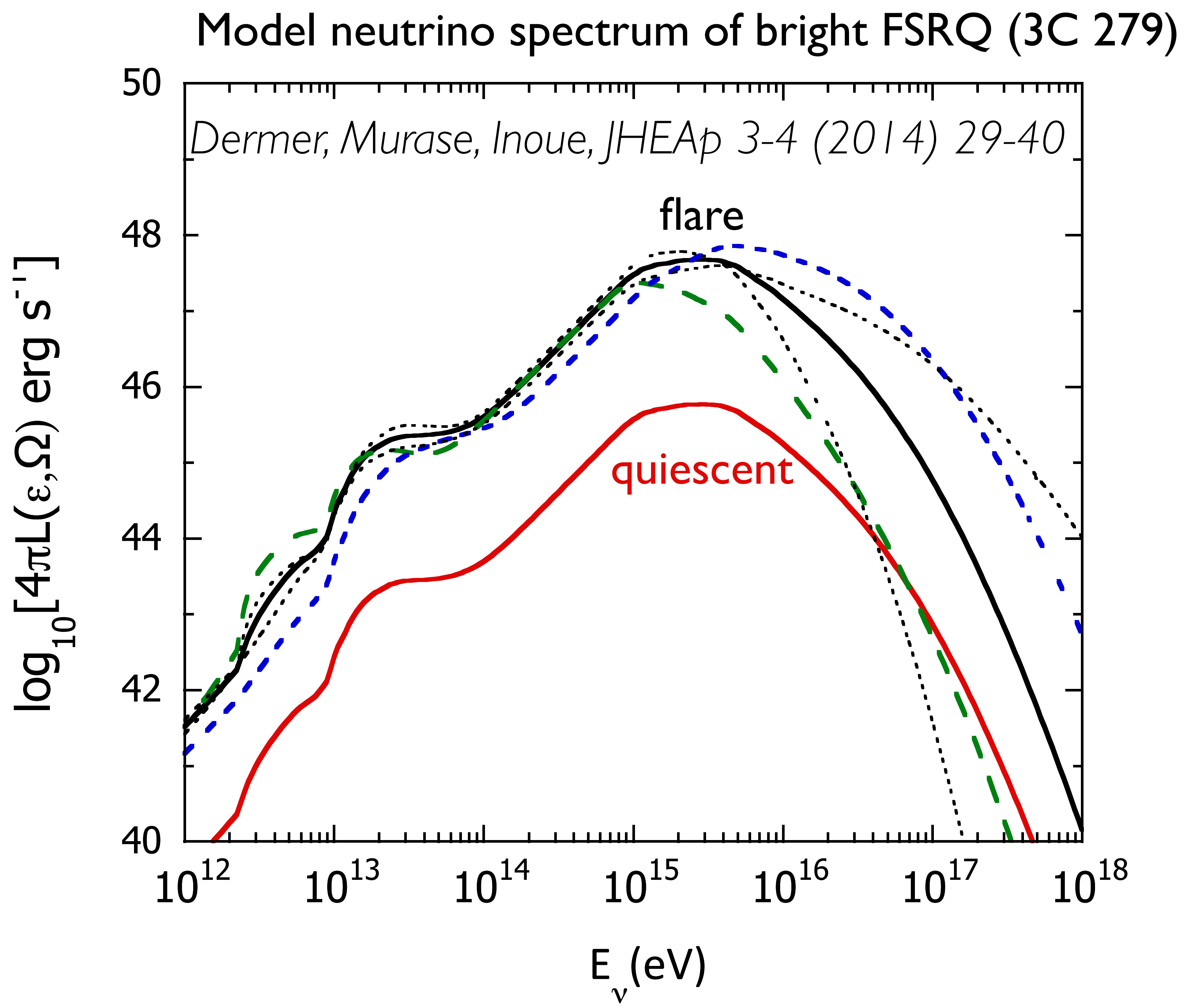
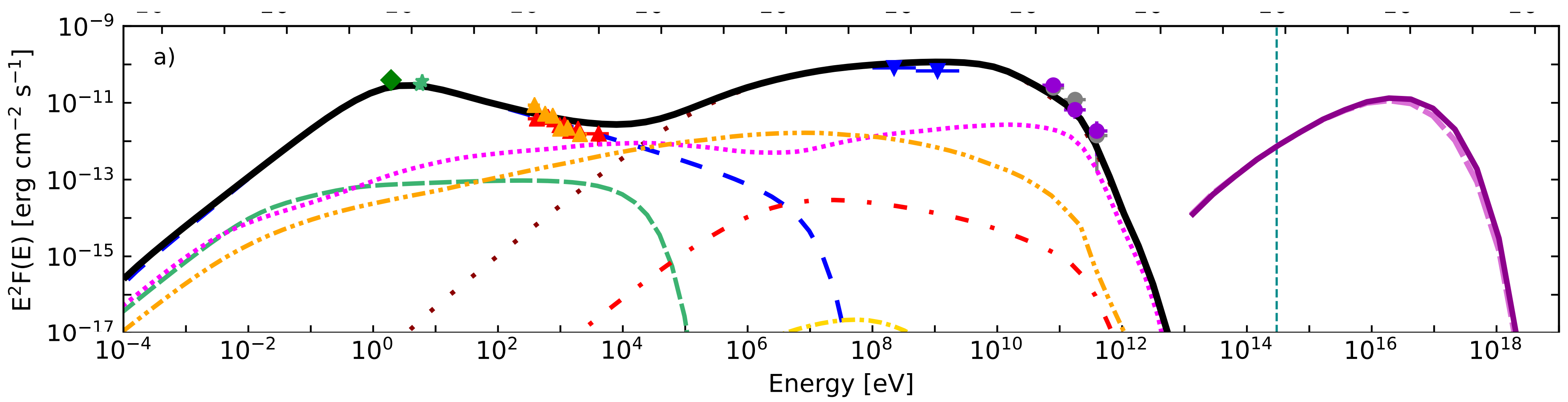


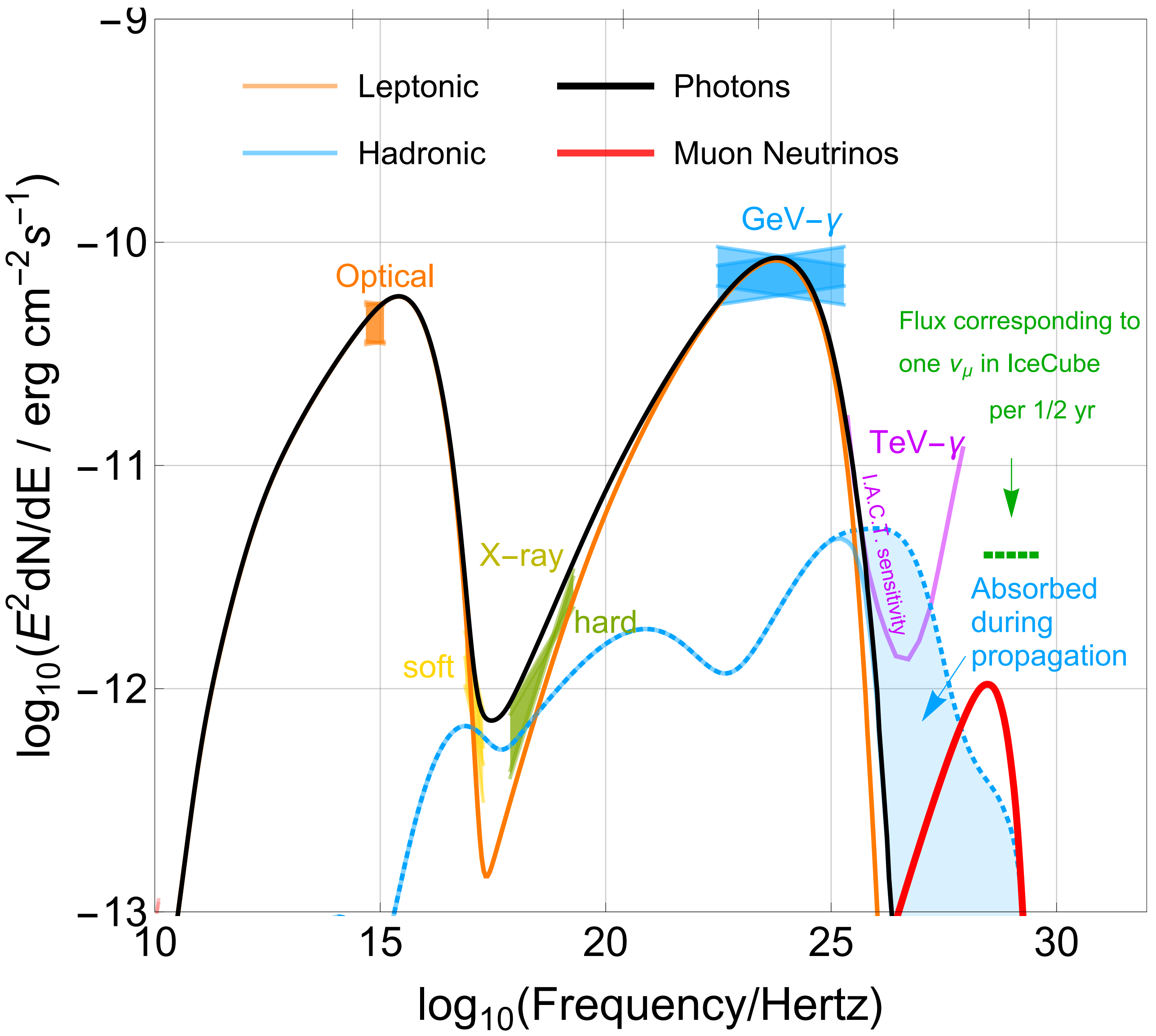
Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131(2020)

Neutrino production in TXS 0506+056 in 2017

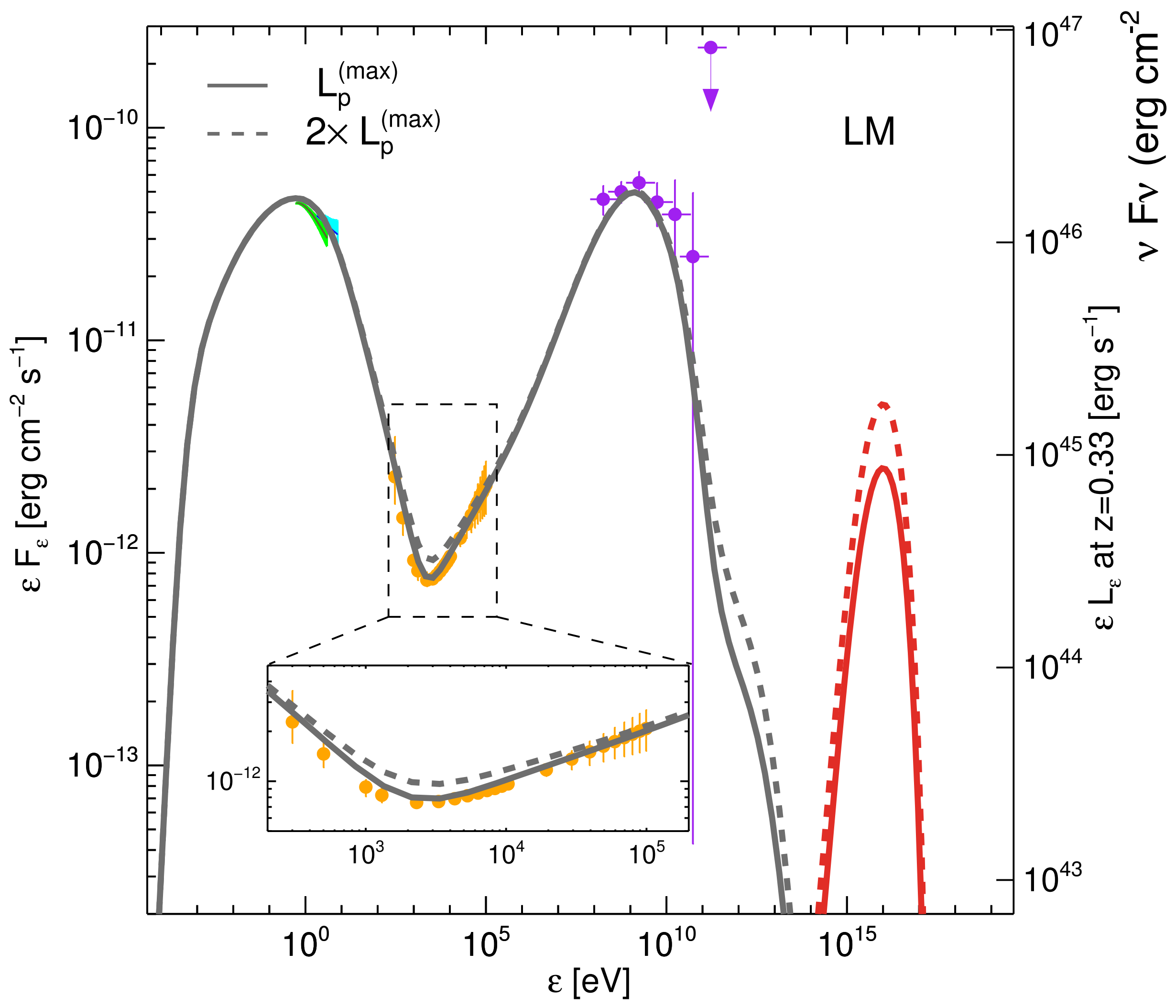
MAGIC Coll 2018, ApJ, 863, L10

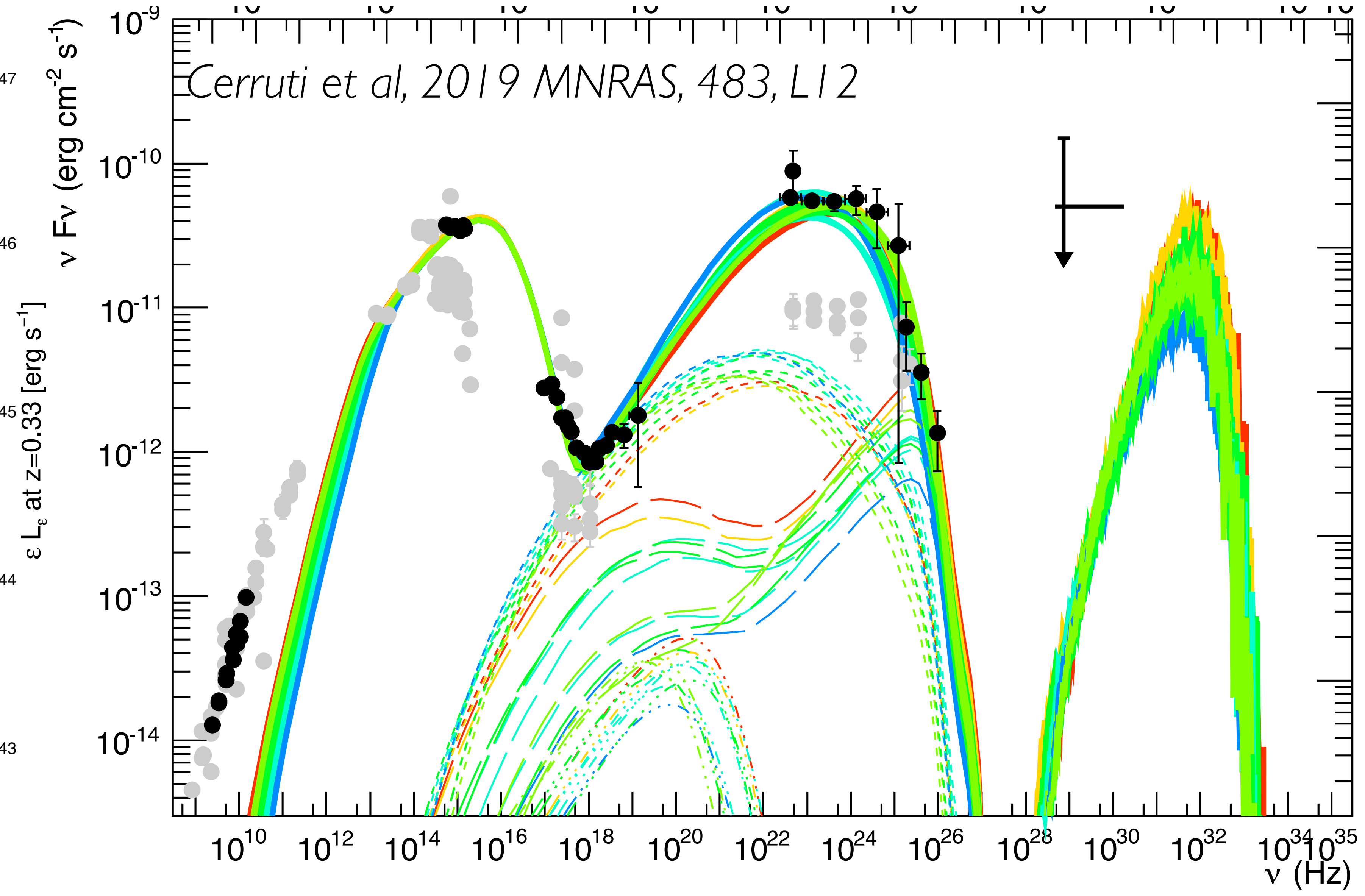


Gao et al, 2019, Nat. Astron., 3, 88



Keivani et al. 2018, ApJ, 864, 84





Cerruti et al, 2019 MNRAS, 483, L12

$$N_{\nu_\mu} \lesssim 0.01/6 \text{ months}^\star$$

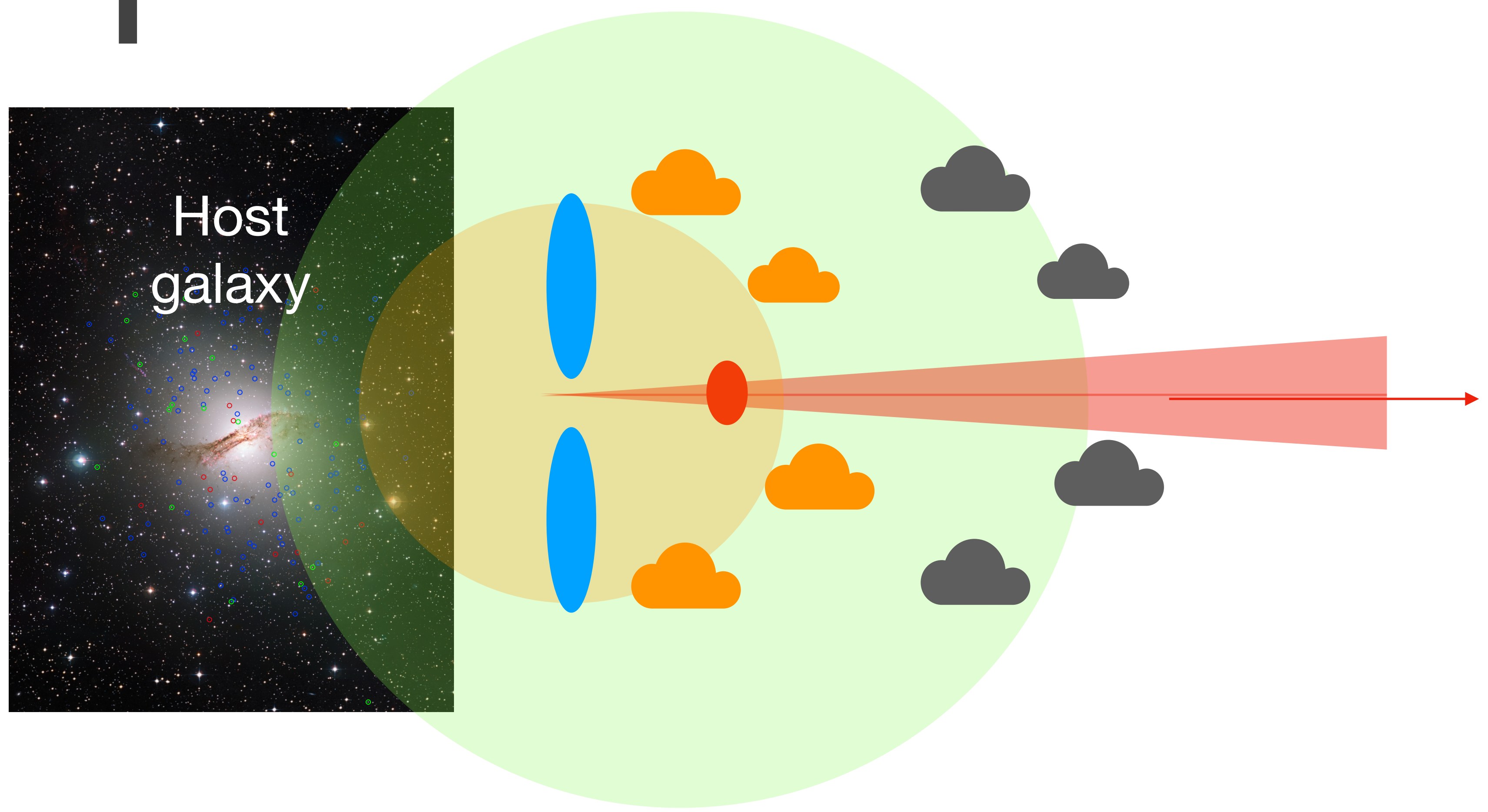
-Ok due to population bias!

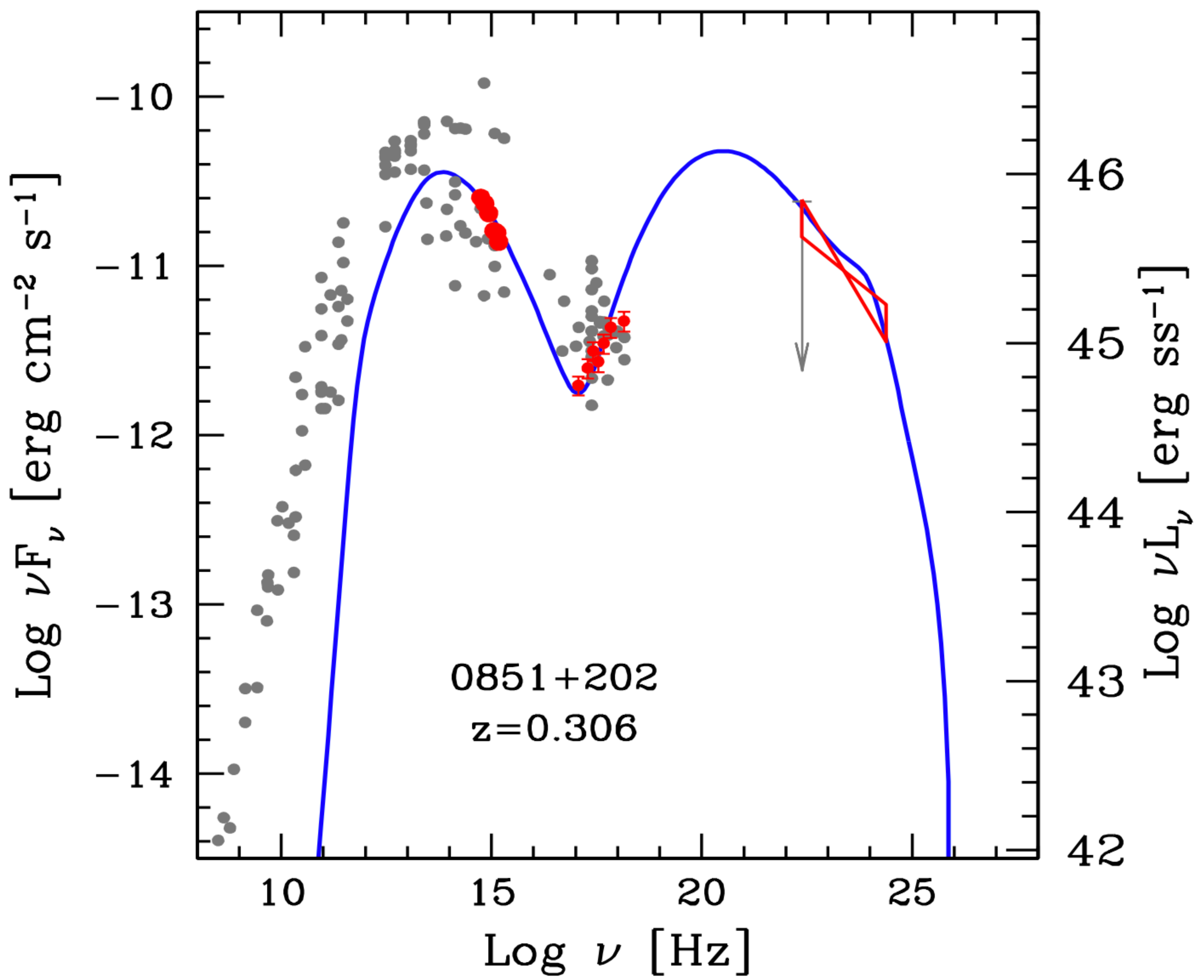
(1% chance to see one neutrino from each blazar flare)

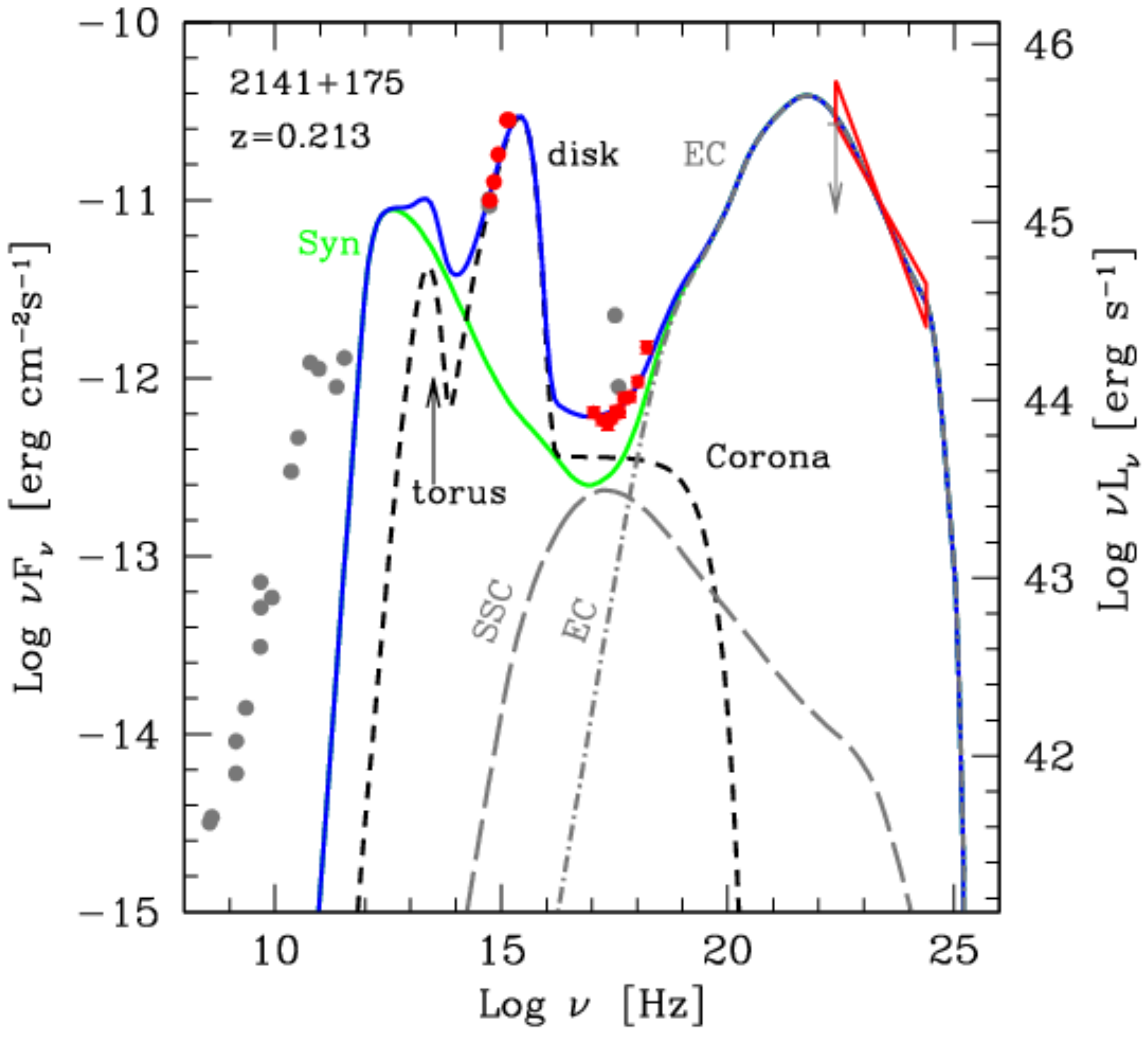
-But: What does it take to produce 0.01 neutrinos/6months in this blazar?

The jet often "hides" other photon fields from us

A semi-free parameter for models…







Neutrino production in TXS 0506+056 2017

Optical depth to pγ interactions

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

At the same time γγ,

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

Ratio of optical depths is then,

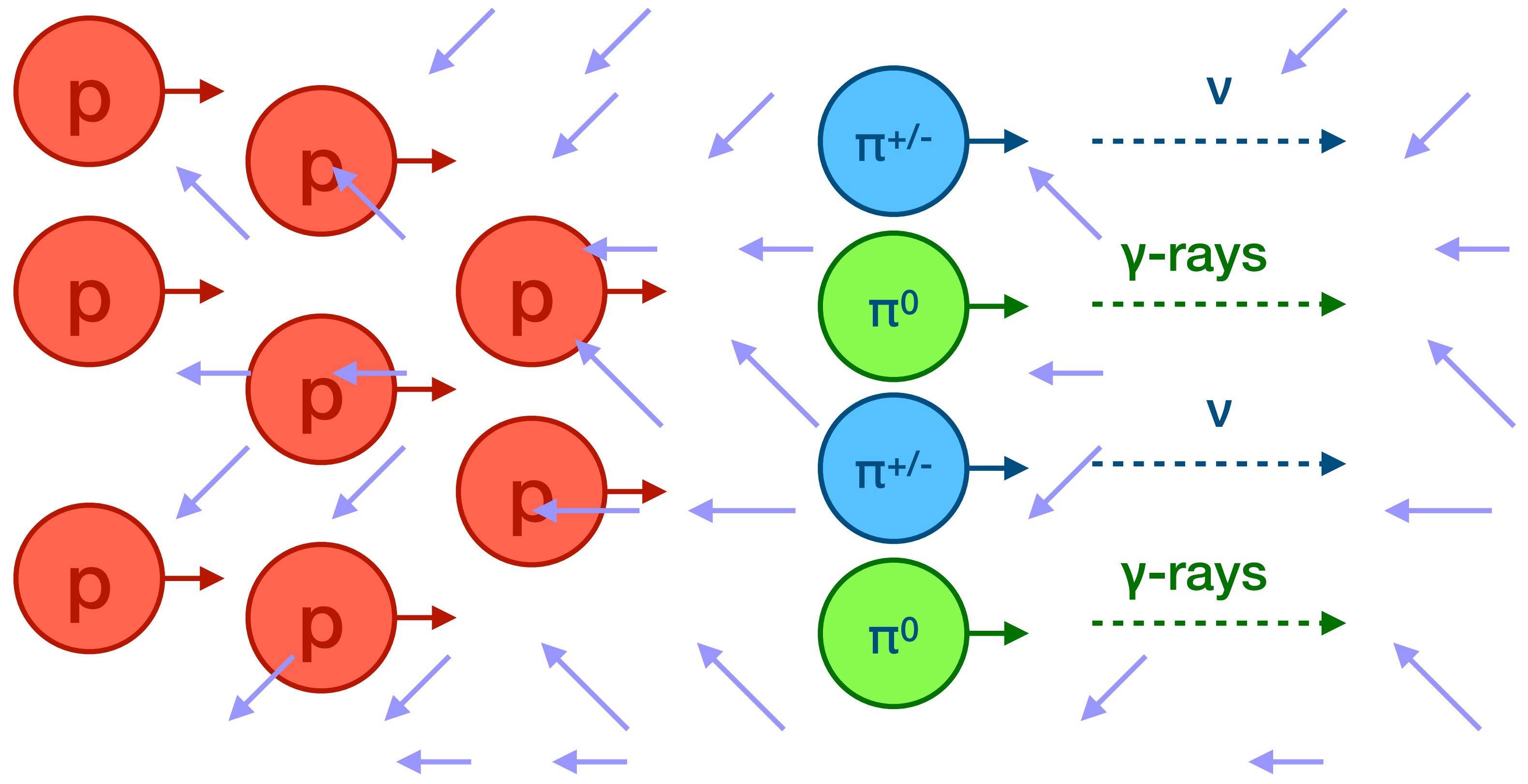
$$\tau_{p\gamma}(E'_p) \approx \frac{\eta_{p\gamma}(\alpha)}{\eta_{\gamma\gamma}(\alpha)}\frac{\sigma_{\gamma p}}{\sigma_{\gamma\gamma}}\tau_{\gamma\gamma}(E'_\gamma) \approx \frac{10^{-28}\ \mathrm{cm}^2}{10^{-25}\ \mathrm{cm}^2}\tau_{\gamma\gamma}(E'_\gamma) \approx 10^{-3}\tau_{\gamma\gamma}(E'_\gamma)$$

At energy,

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

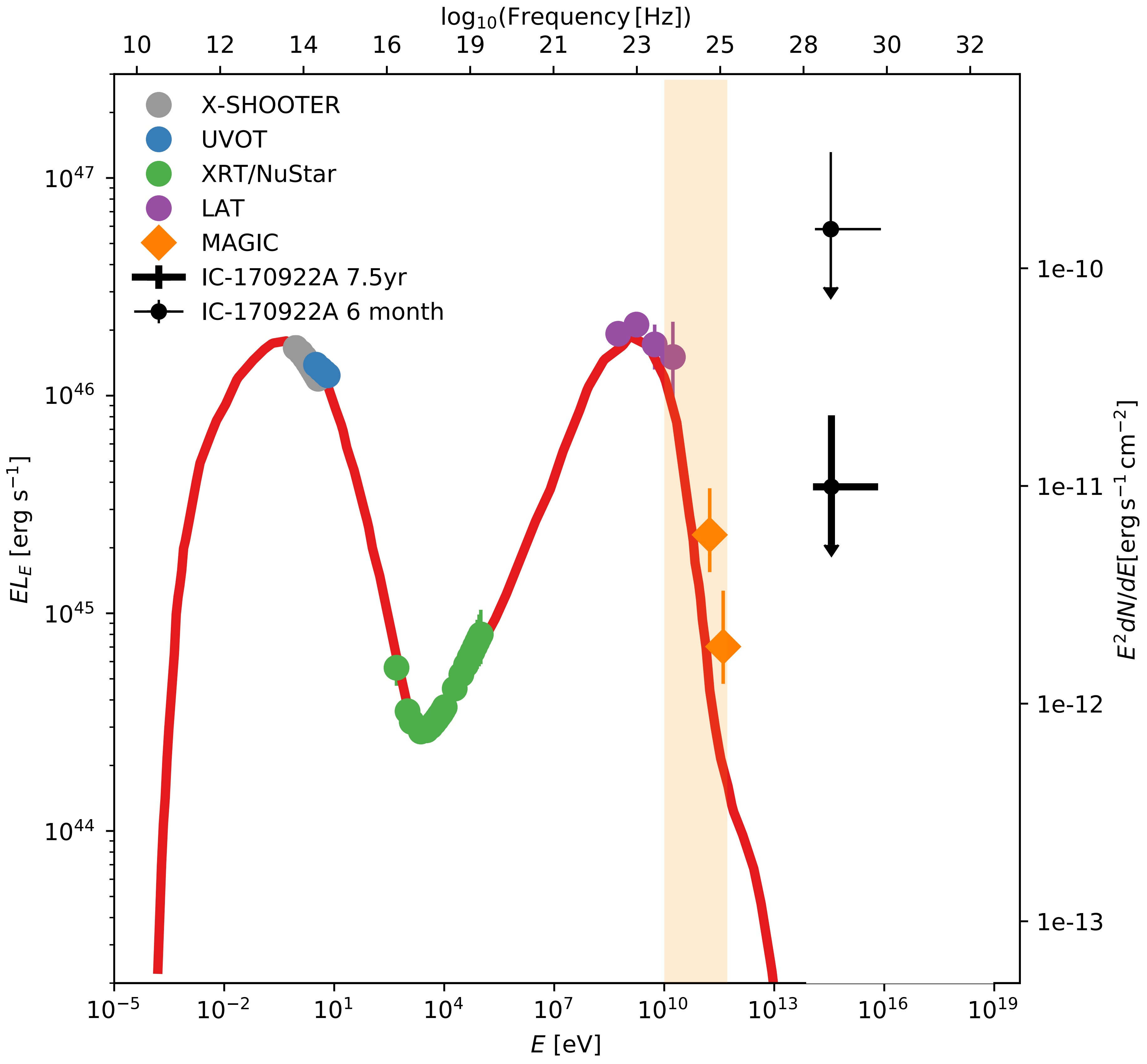
This implies that sources optically thin to gamma-rays have inefficient TeV neutrino production

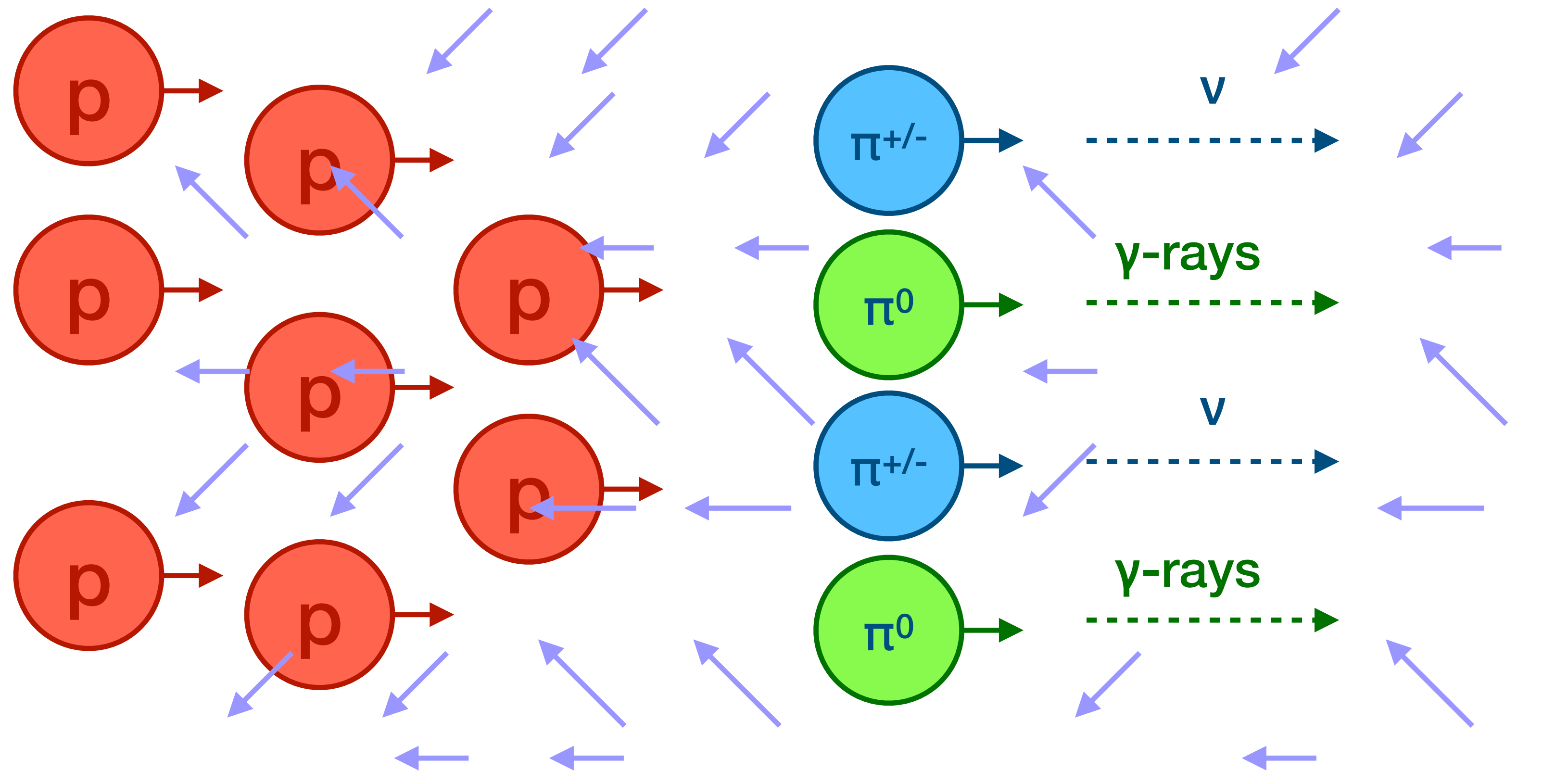
$$p + \gamma \rightarrow \pi + X$$
$$\gamma + \gamma \rightarrow e^+ + e^-$$



Neutrino production in TXS 0506+056 2017

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





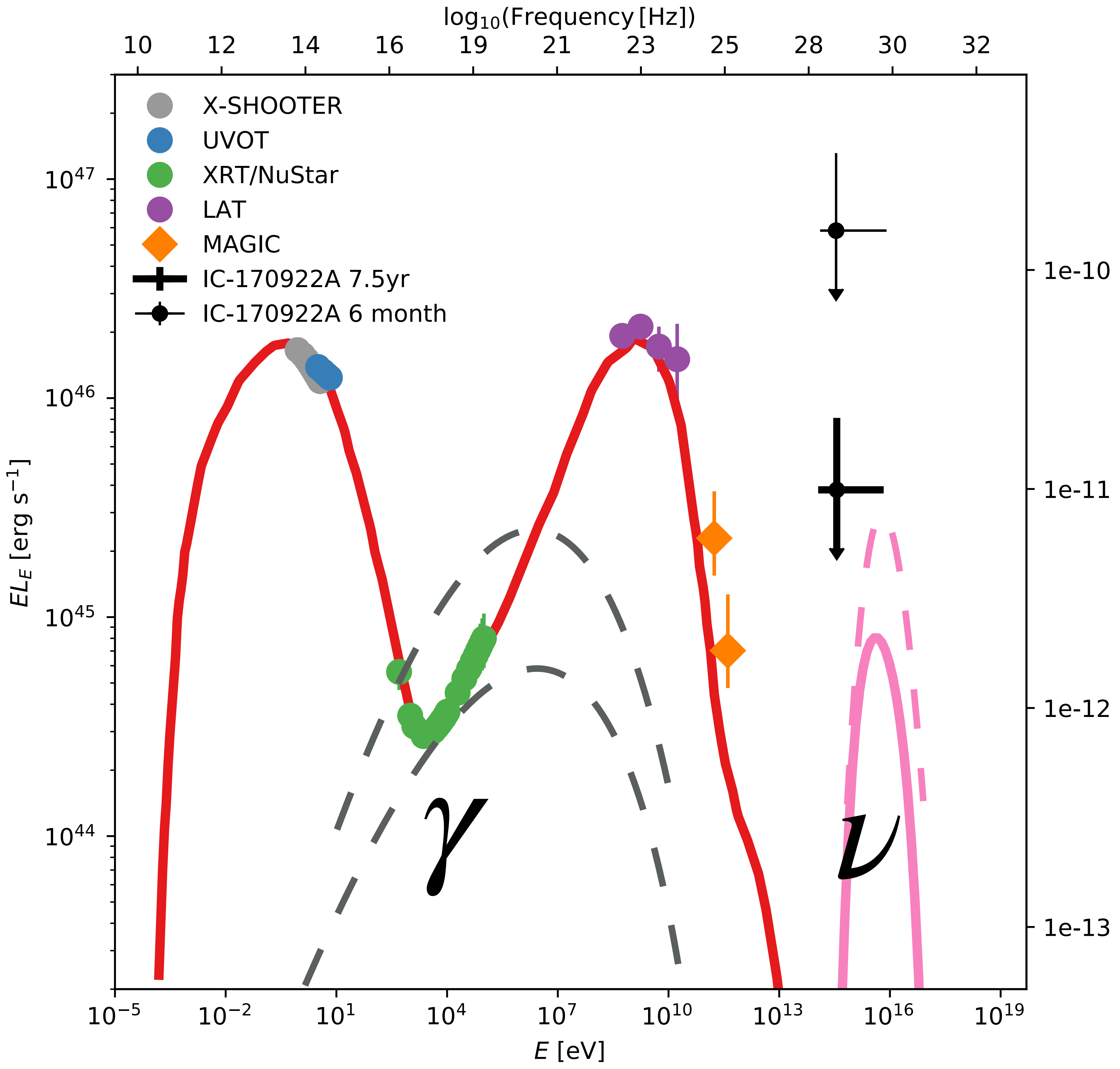
At energy,

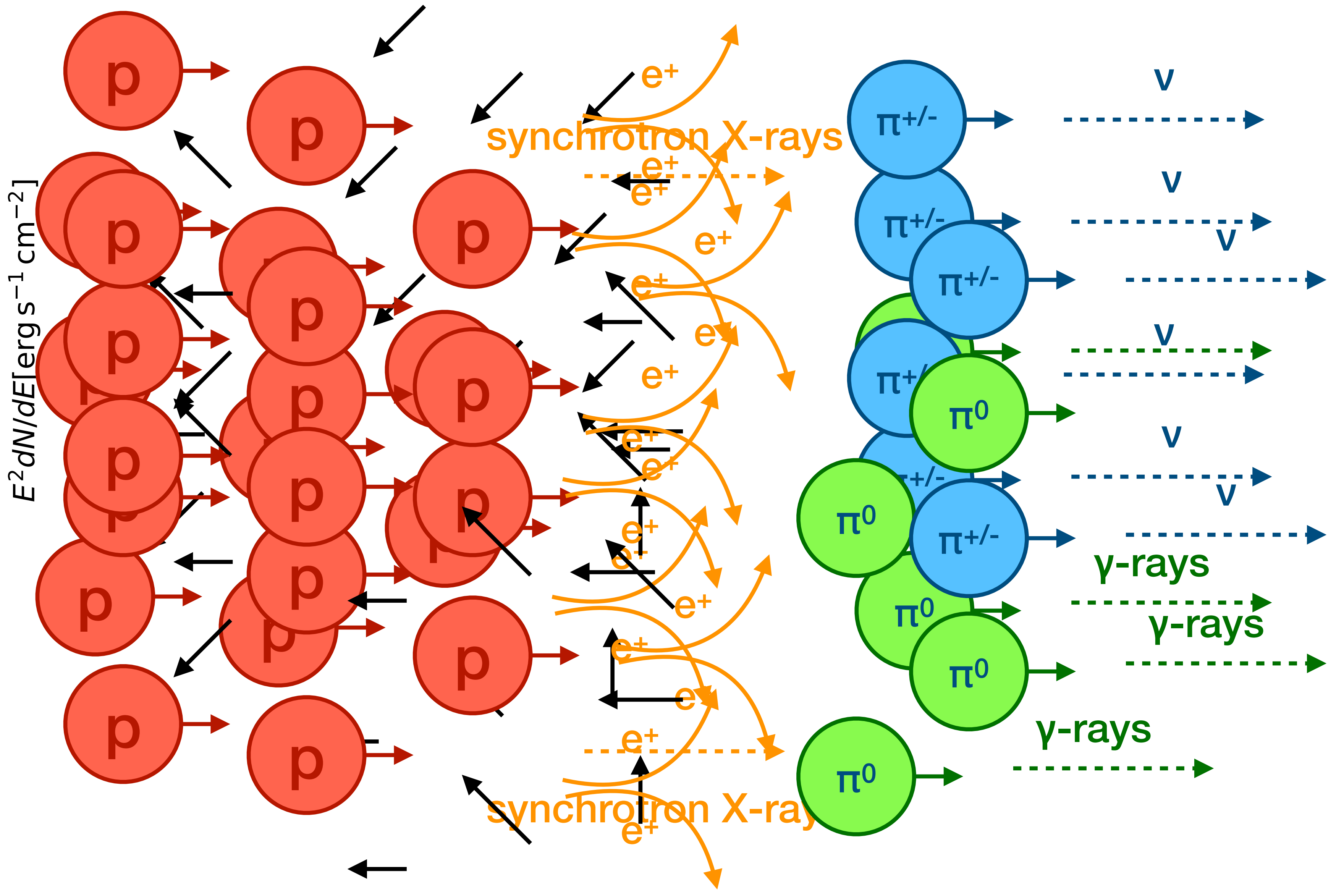
$$E'_\gamma \sim 15 \text{ GeV} \left(\frac{E'_p}{6 \text{ PeV}}\right) \sim 15 \text{ GeV} \left(\frac{E'_\nu}{300 \text{ TeV}}\right)$$

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

Neutrino production in TXS 0506+056 2017

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

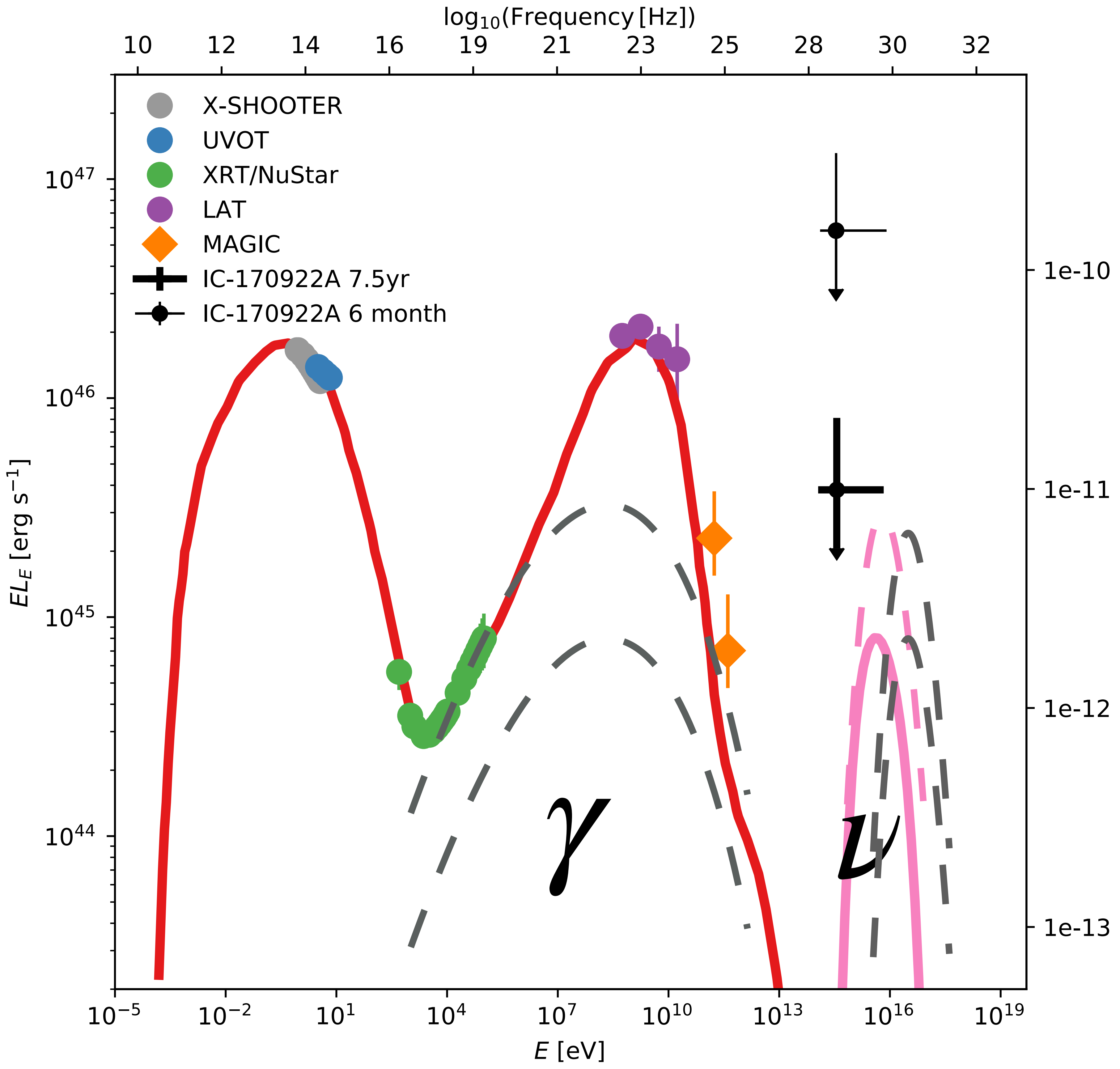


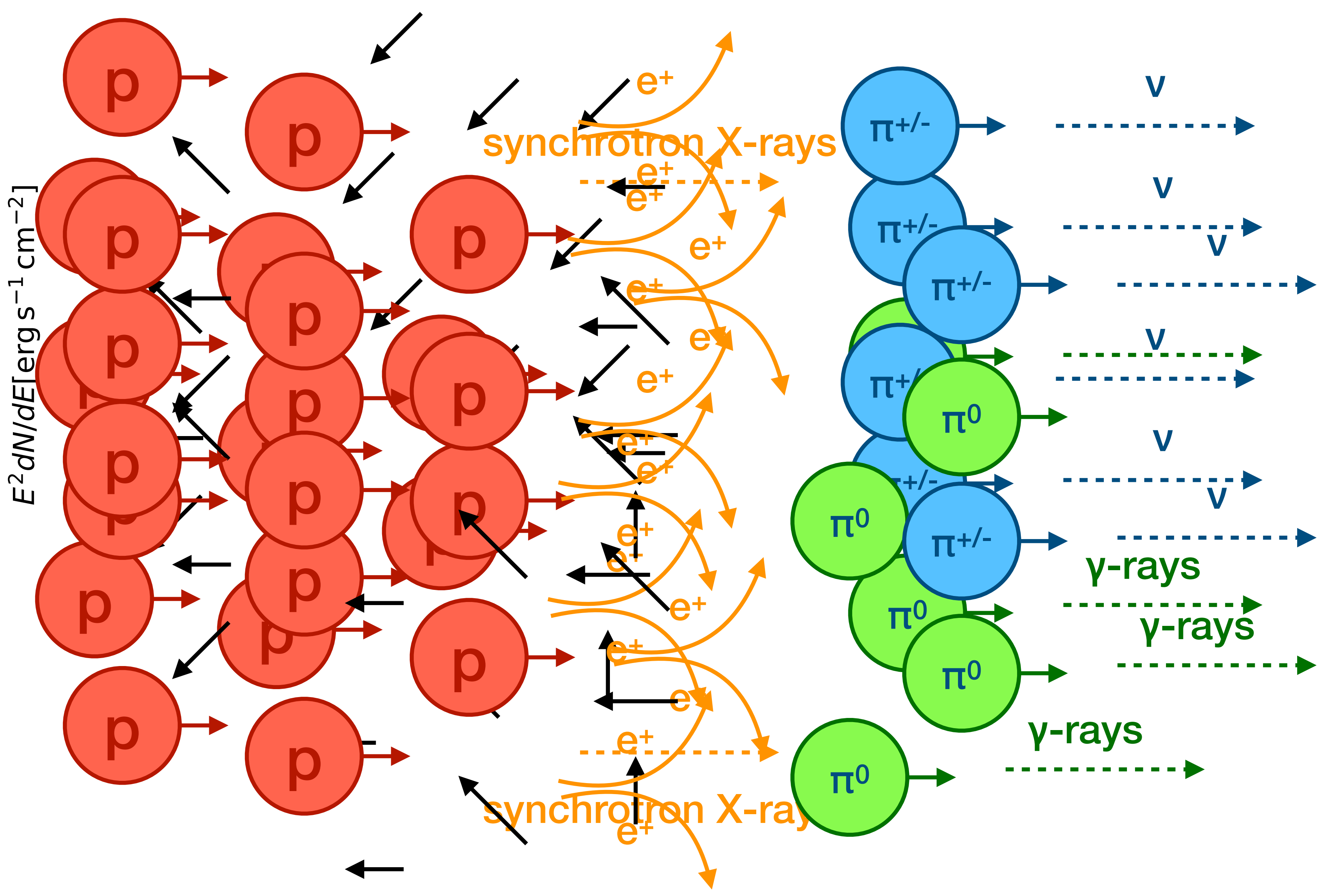


3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

Neutrino production in TXS 0506+056 2017

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





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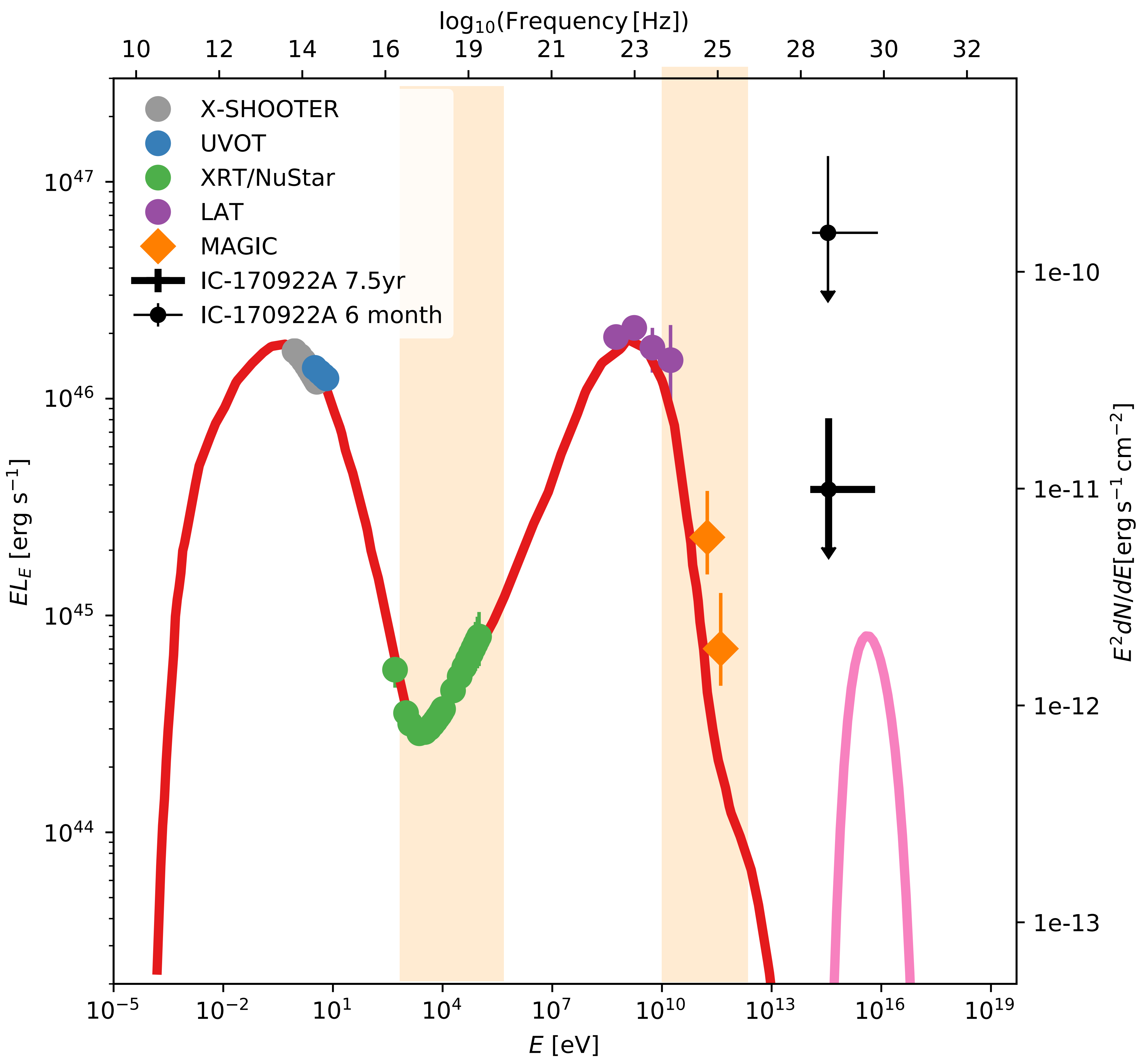
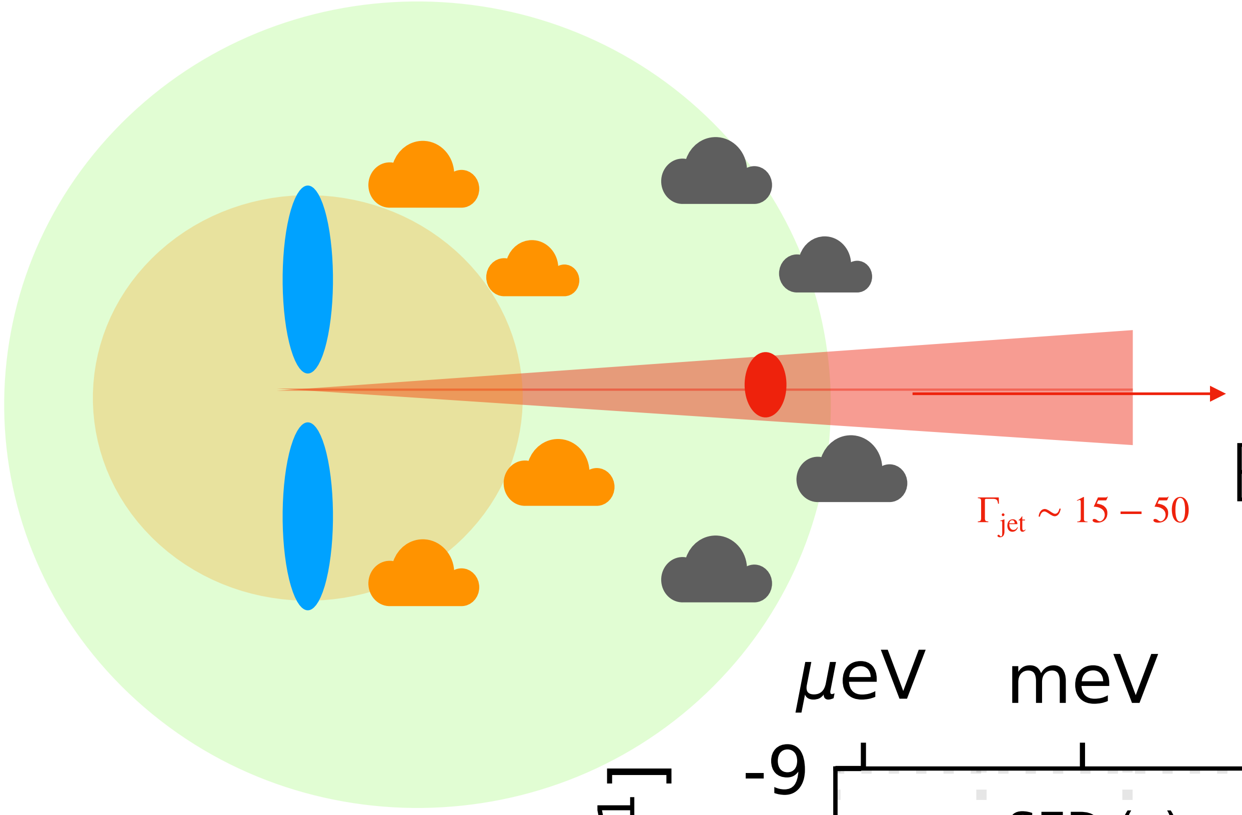
Neutrino production in TXS 0506+056 2017

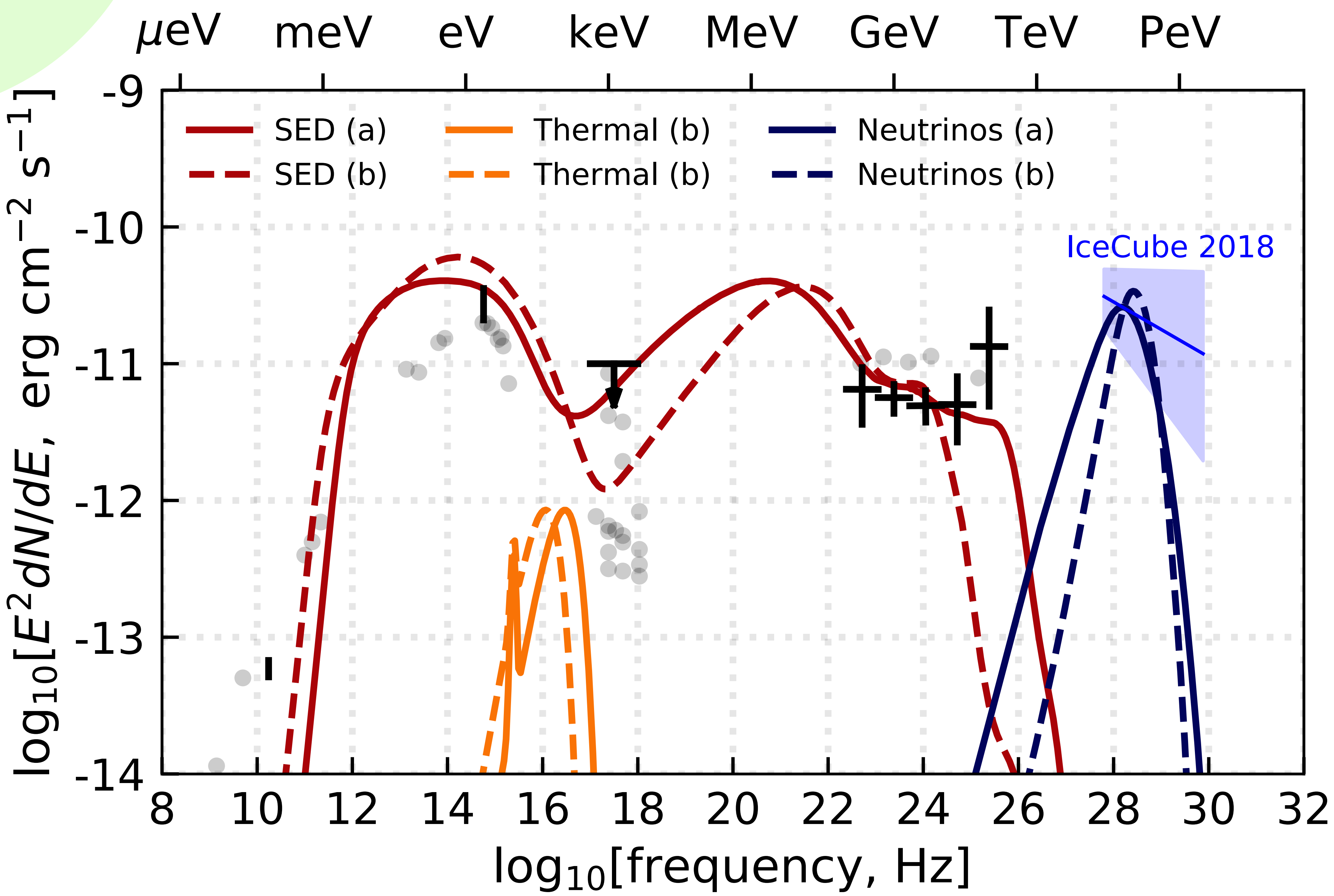


$N_{\nu_\mu} \lesssim 0.01/6$ months

Neutrino production in TXS 0506+056 2014-15

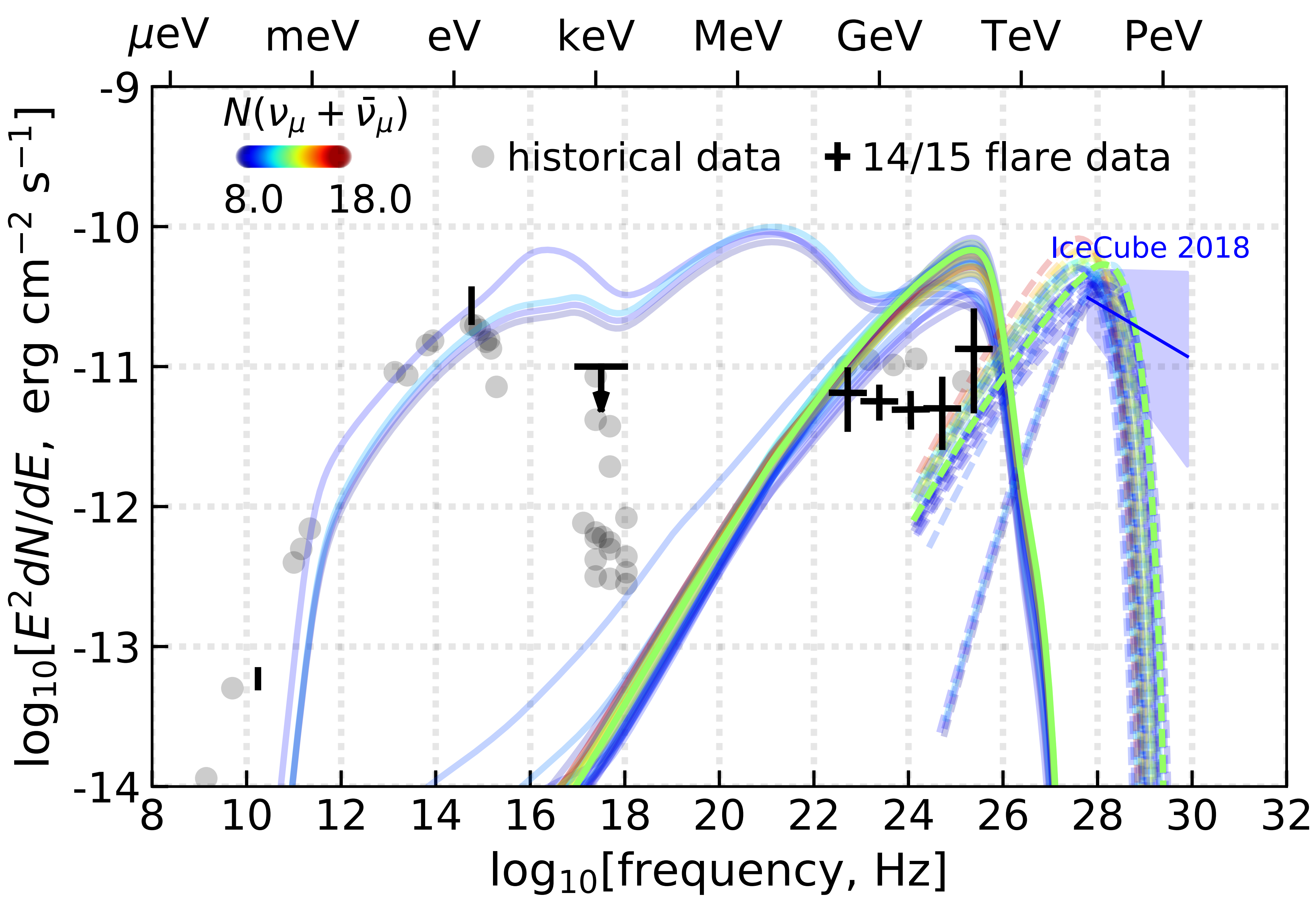


Broad-line region model



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

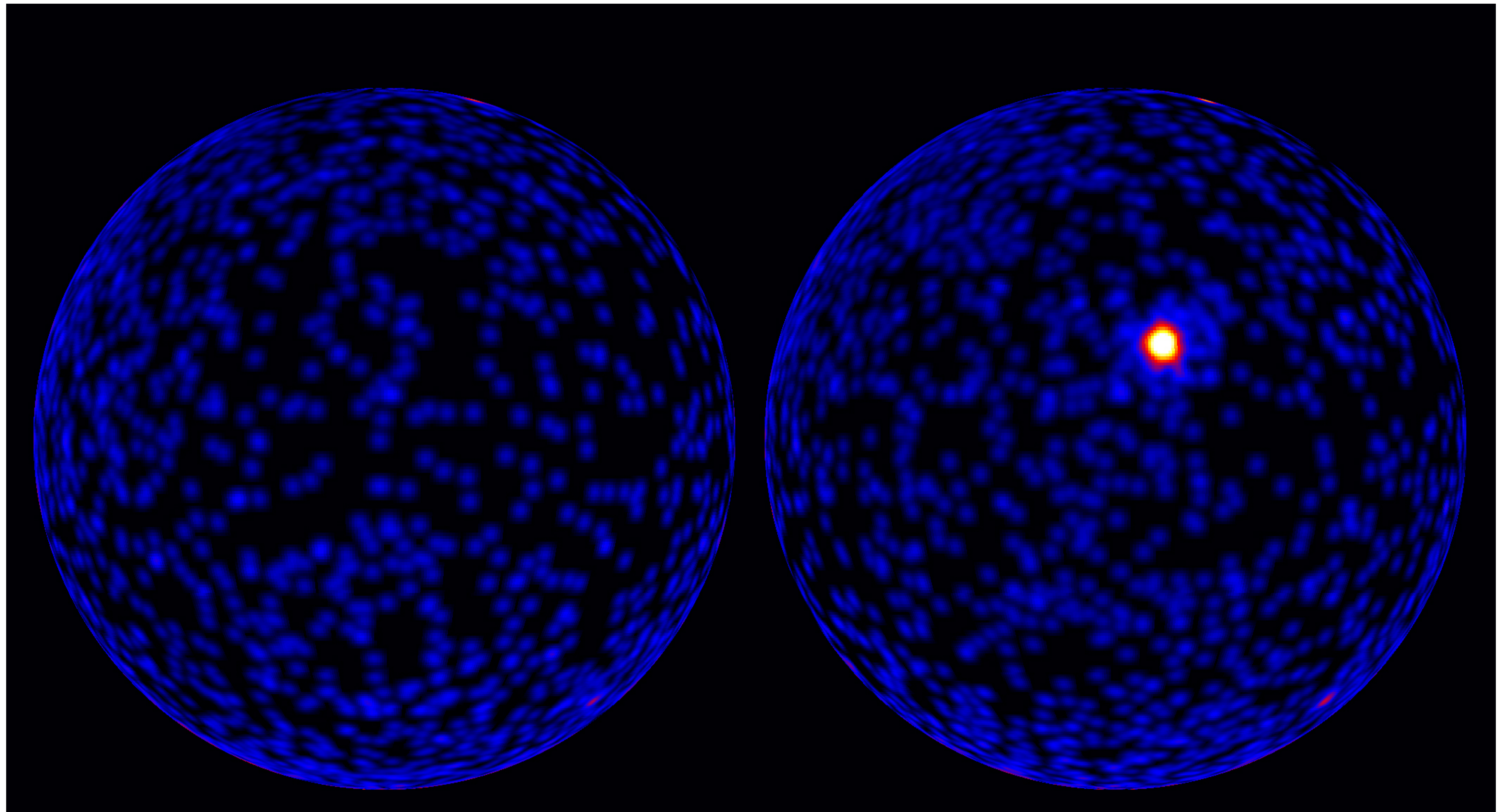
Overshoots spectrum



$N_{\nu_\mu} = 13.2$

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 ~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



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

Gamma-ray bursts, basic facts

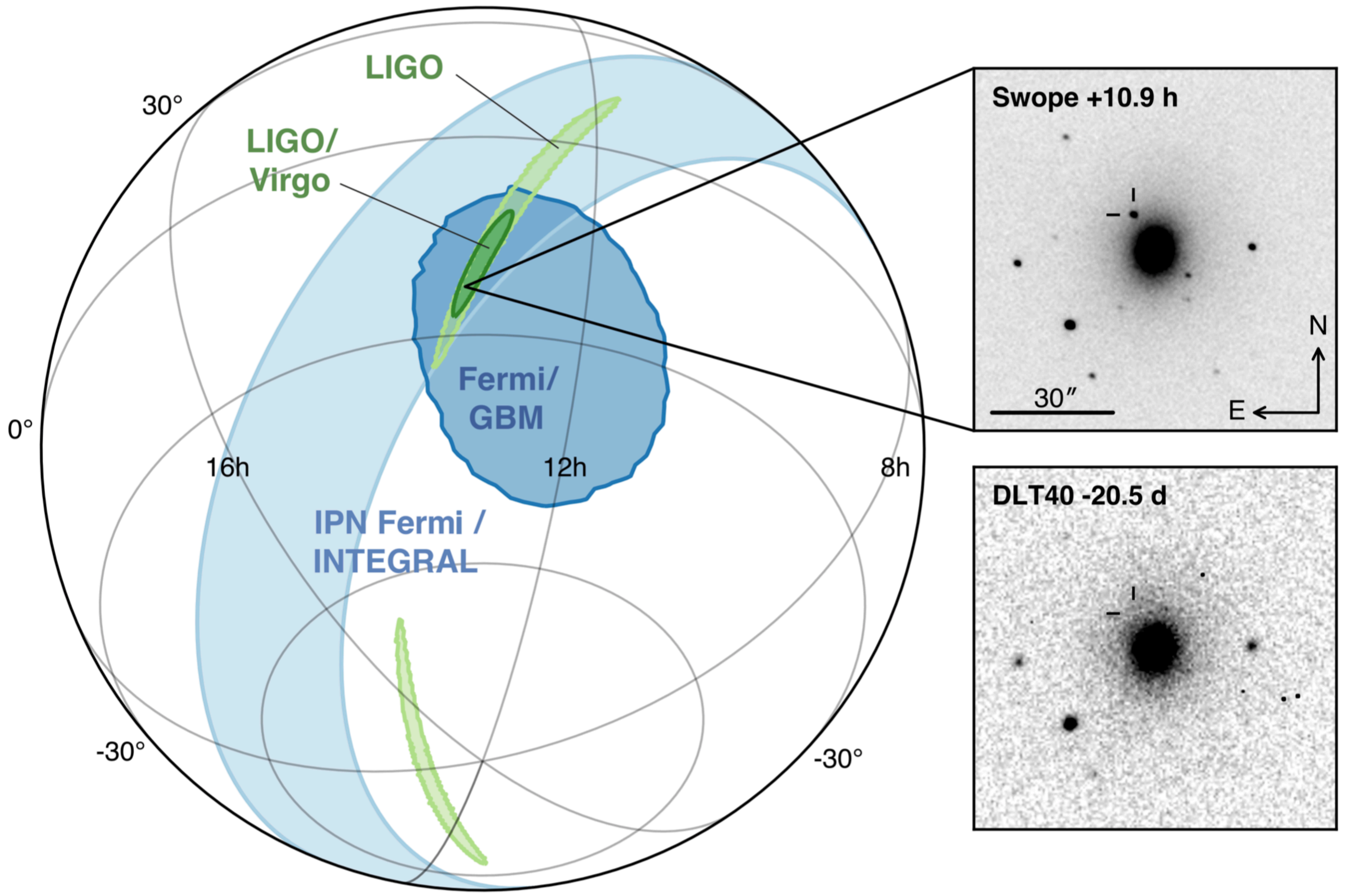
On August 17th, 2017 LIGO and Virgo reported the detection of GWs from the coalescence of a binary neutron star system

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} $\sim 10^{-8}$)

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 ~ $e^{-\tau_{\gamma\gamma}}$)

$\gamma\gamma \to e^+e^-$, 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

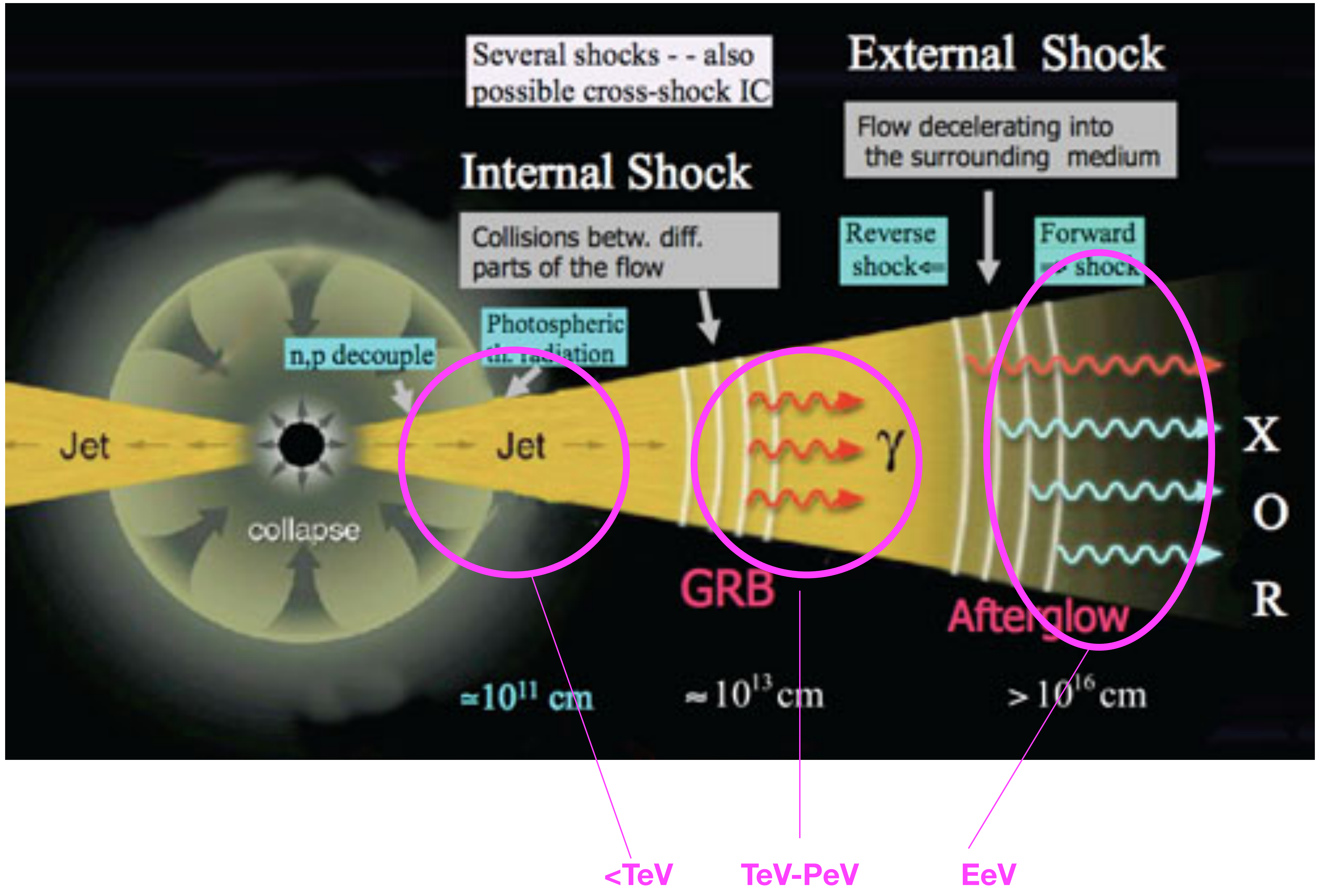
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n/p + \pi^{+}/\pi^{0}$$

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

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

e.g. prompt emission,

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



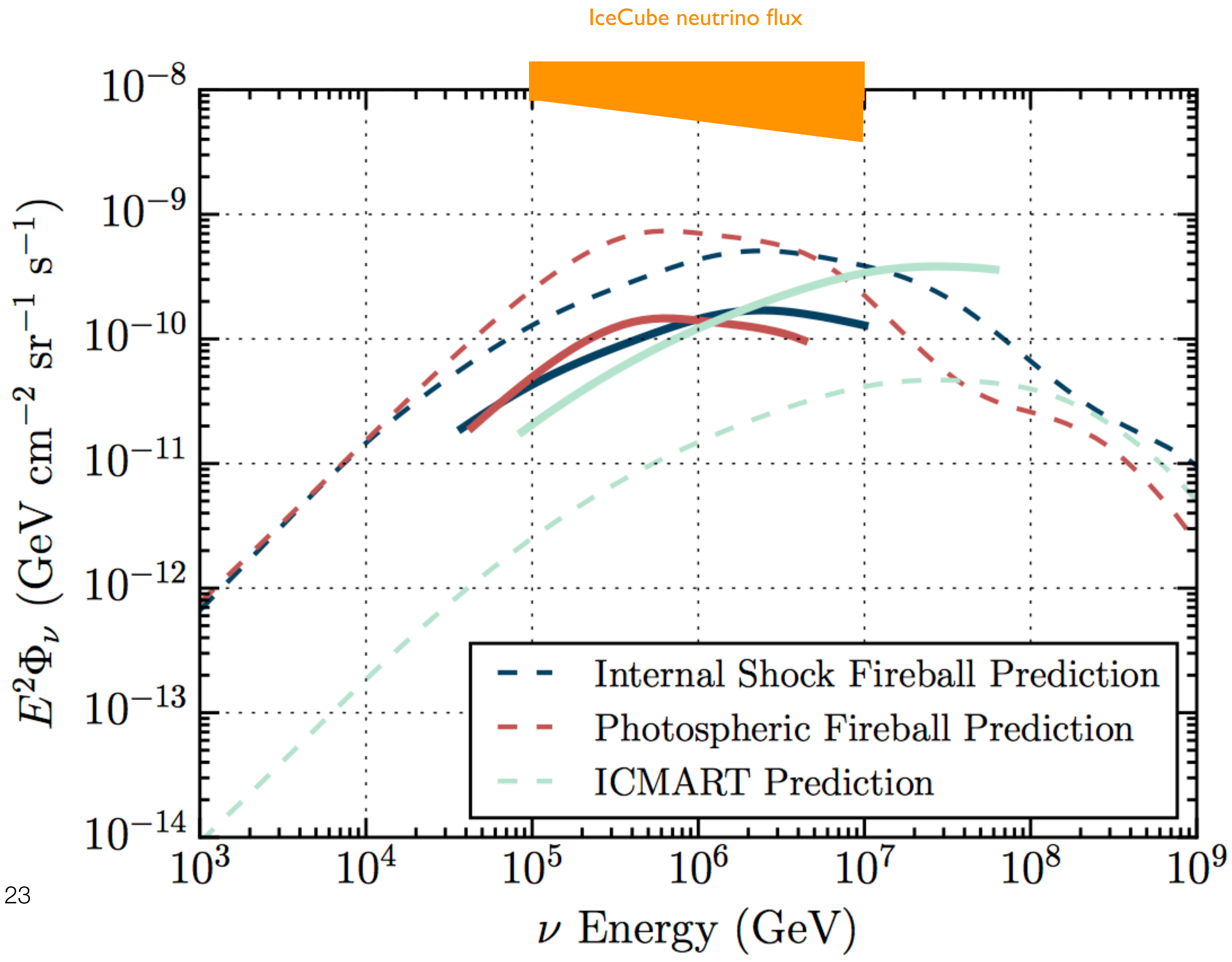
possible neutrino production sites

Neutrino production in GRBs

A stacked search for neutrinos coincident with prompt GRB emission by IceCube (now a total of 1172 GRBs) has led to limits on the neutrino production in GRBs

Standard, high-luminosity GRBs can account, at most for 1% of the diffuse IceCube flux.

Standard GRB models constrained



IceCube Coll 843 (2017) 112

Tidal disruption events

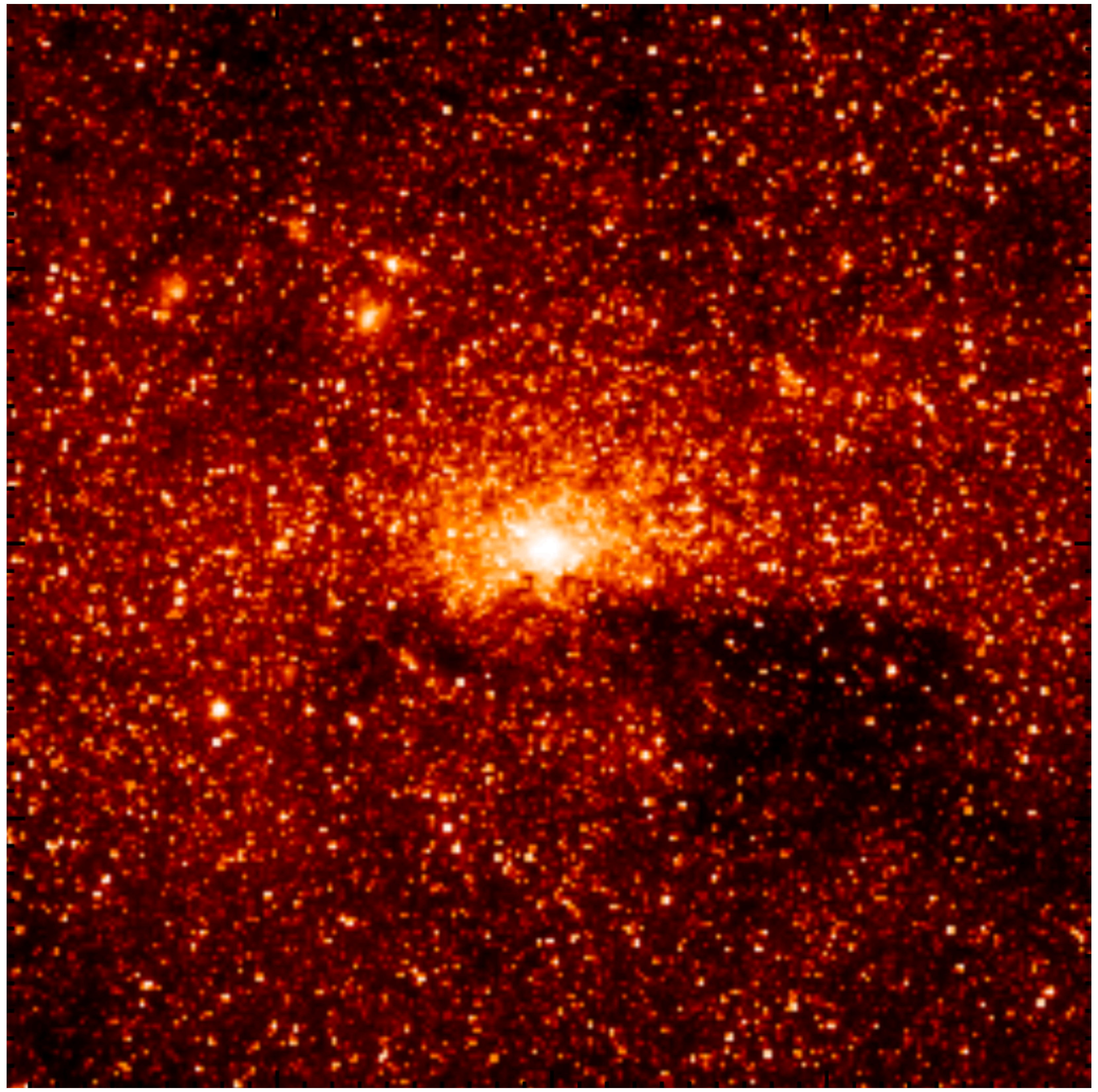
Super Massive Black Holes are orbited by star clusters

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

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

Tidal disruption events

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

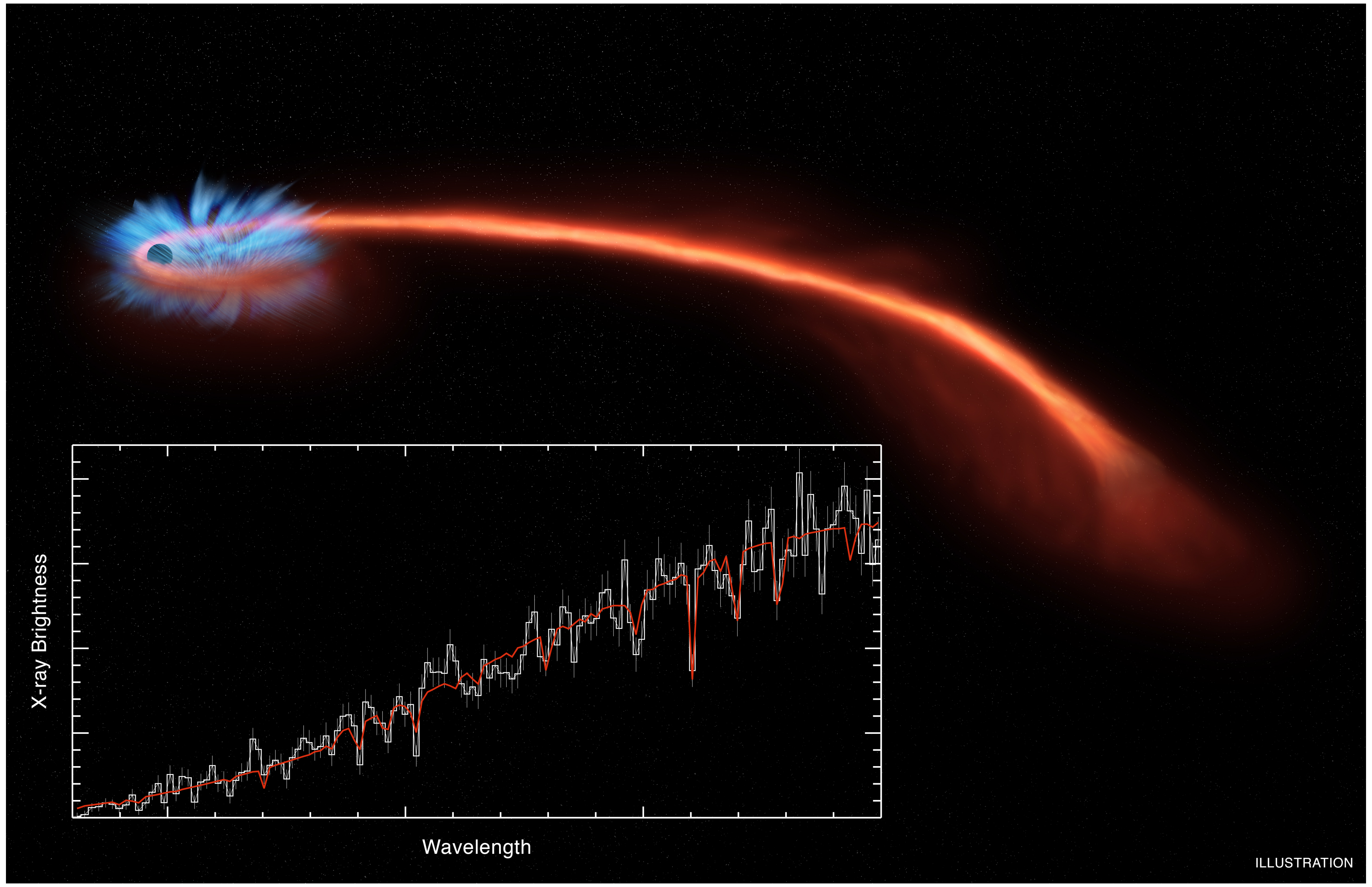
Located in the core of an otherwise quiescent, inactive galaxy

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

$\lesssim$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

$$E_{\rm max} \sim 10^{20}\ {\rm eV}\, Z \frac{BR}{3\times10^{17}\ {\rm G\ cm}} \frac{\Gamma}{10}$$

Neutrinos from TDEs?

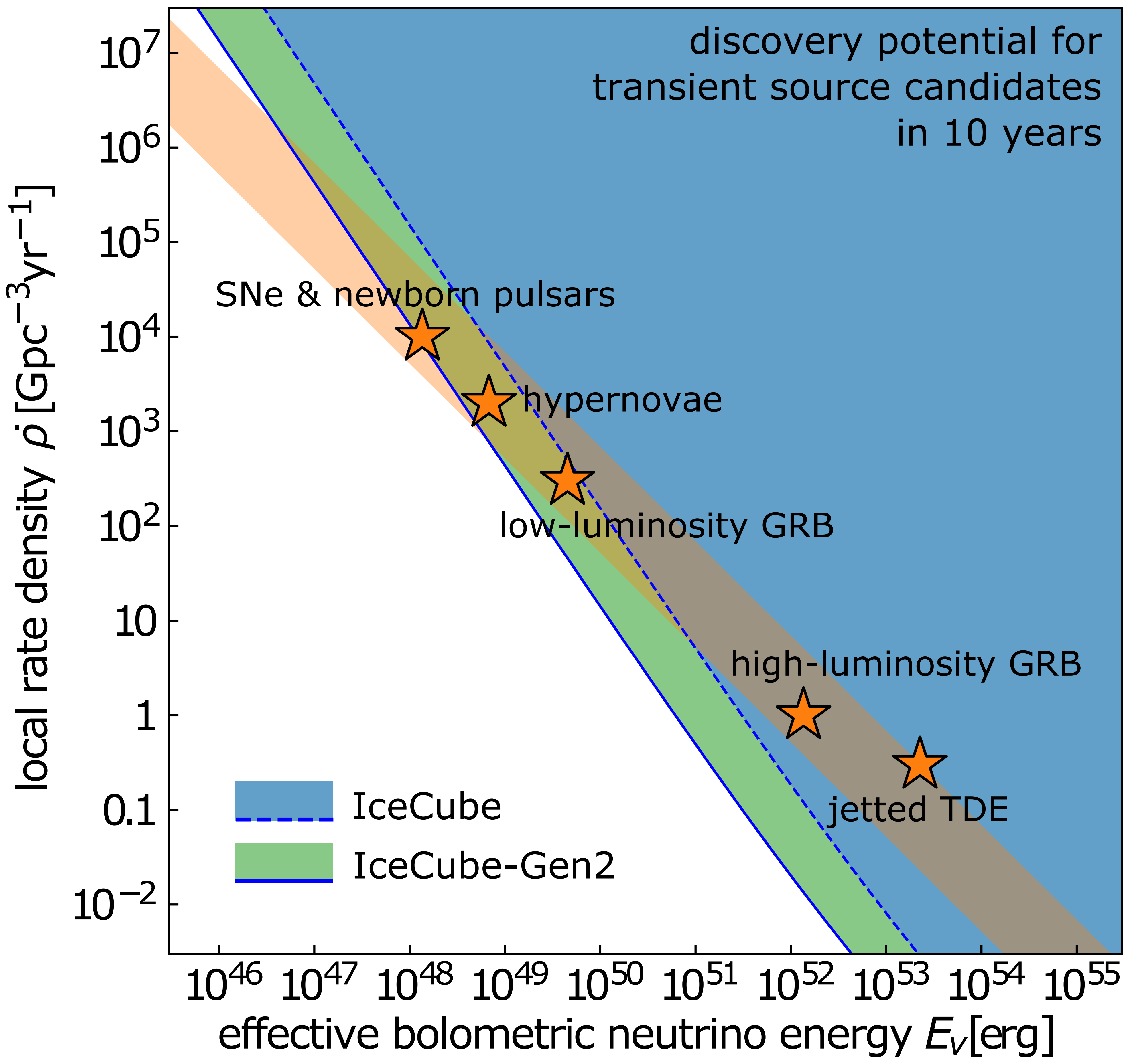
Photopion interactions in the jet (conditions similar to AGN/GRB)

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

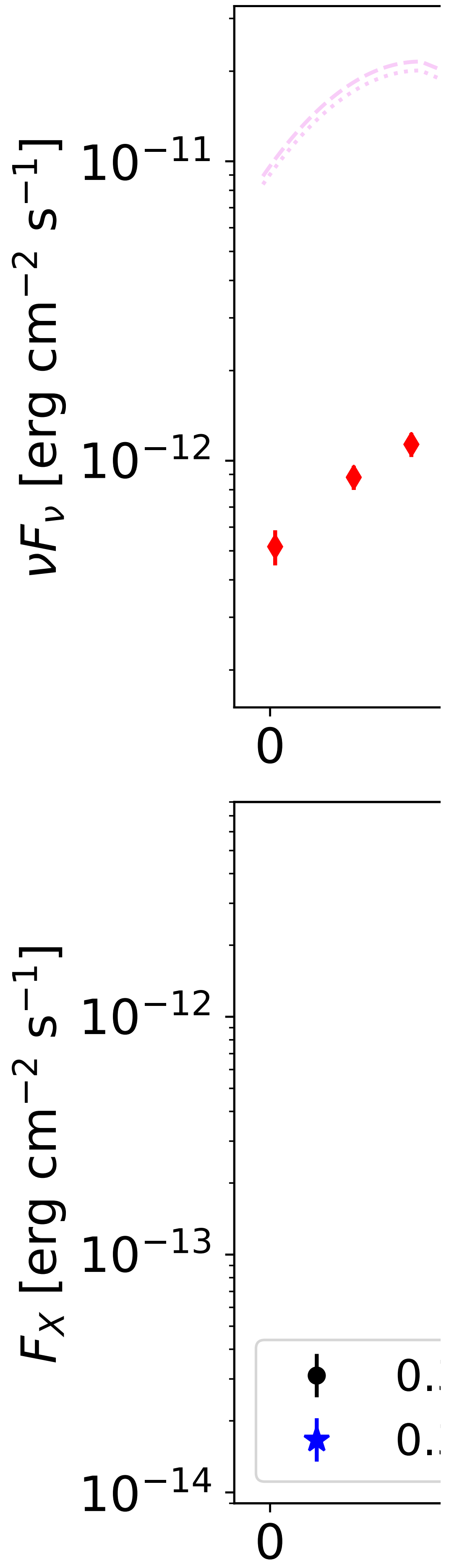
Stacking limits from IceCube (jetted TDEs < 1%, non-jetted < 26%)

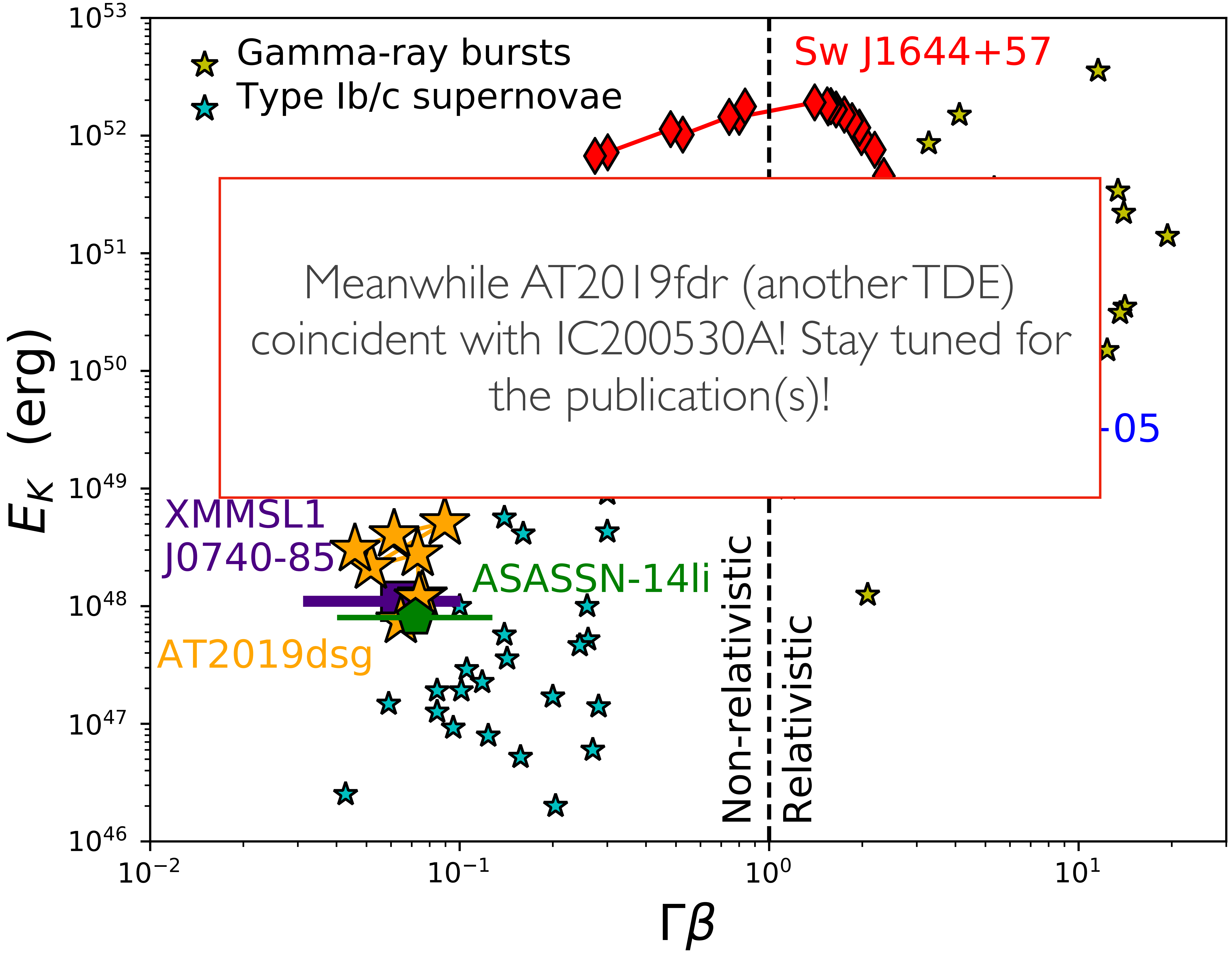


AT 2019dsg + IC191001A

UV optical flux

X-ray flux





Meanwhile AT2019fdr (another TDE) coincident with IC200530A! Stay tuned for the publication(s)!

)0 TeV muon neutrino

-e (radio emitting) TDE

19dsg association by

Starburst galaxies

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

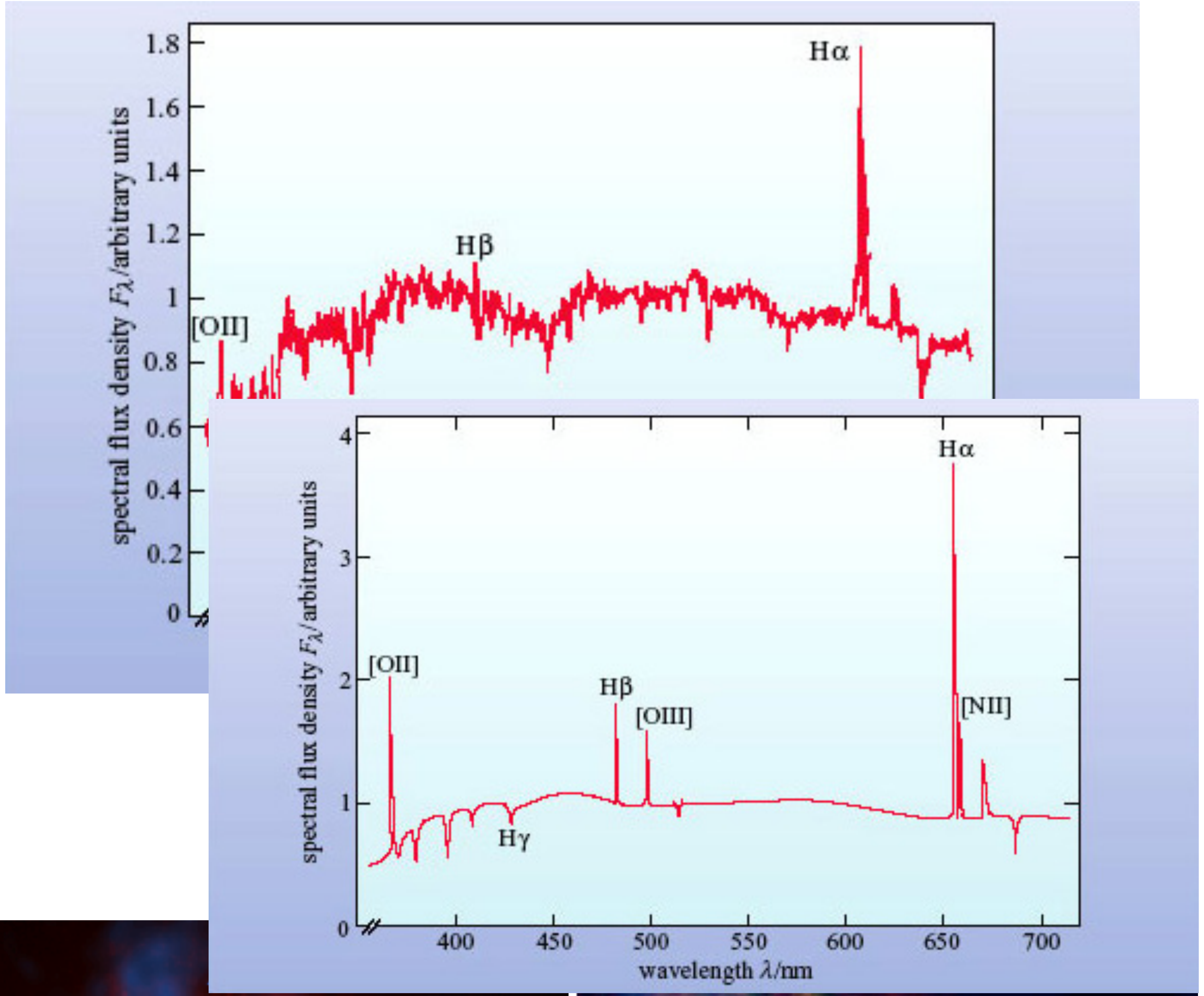
Starburst episodes are short-lived (<10^8 yrs)

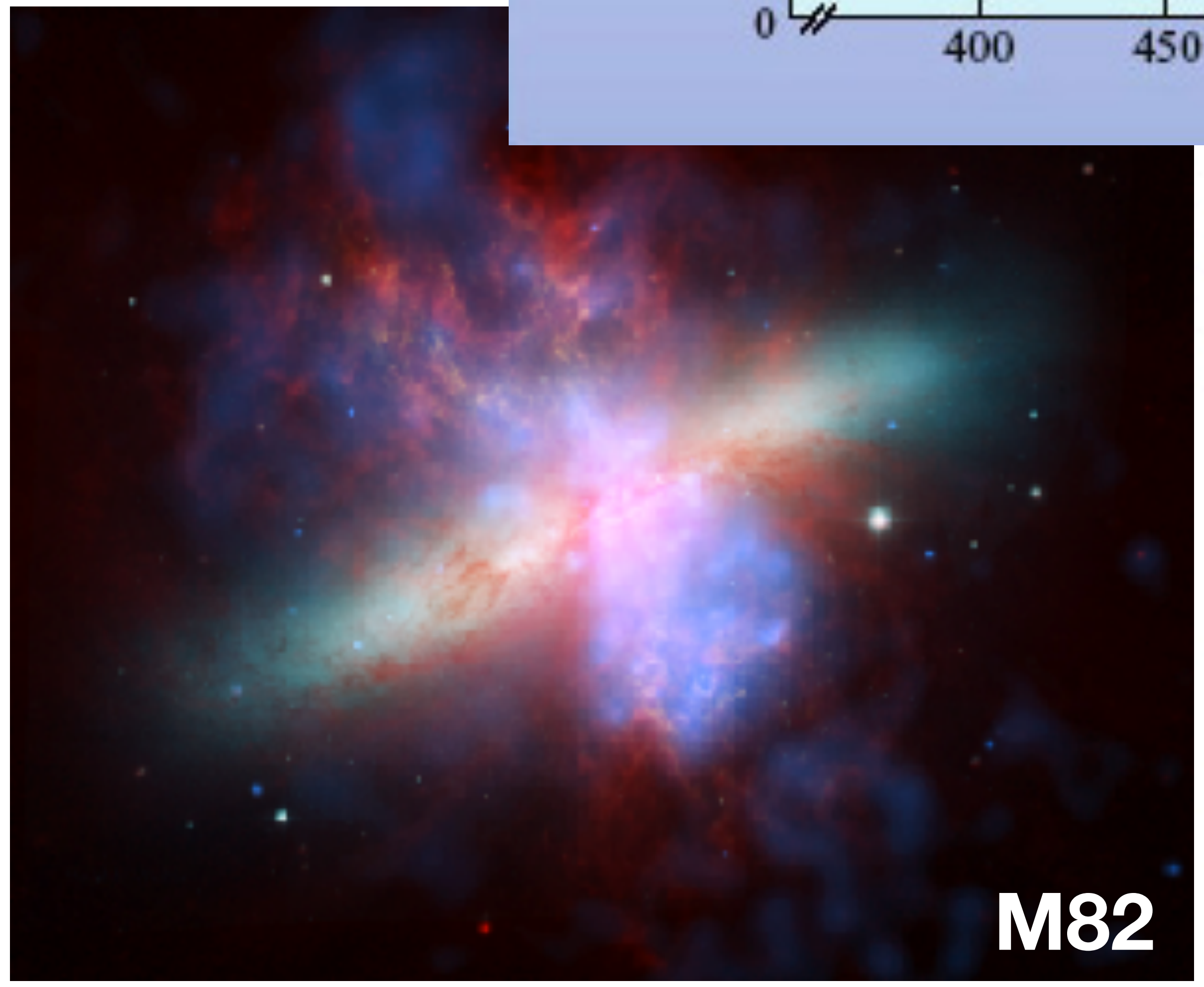
Centrally driven strong outflows (``superwinds'')

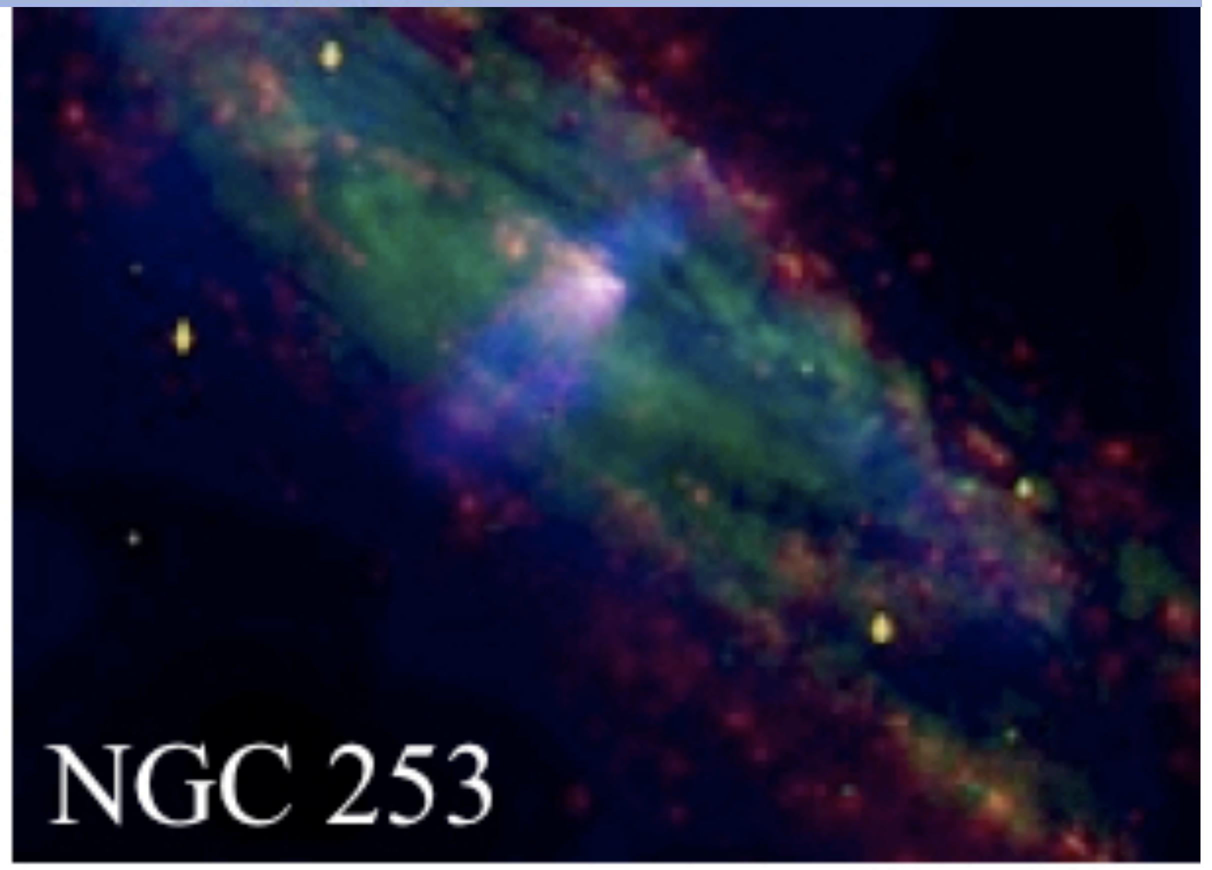
Column densities $\Sigma_g > 0.1 g/cm^2$ and magnetic fields B ~ 1 mG ($B \propto \Sigma_g$), which are much larger than those of ``normal'' spiral galaxies ($\Sigma_g \approx 0.003 g/cm^2$, B ~ 5$\mu$G in the Milky way)

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)





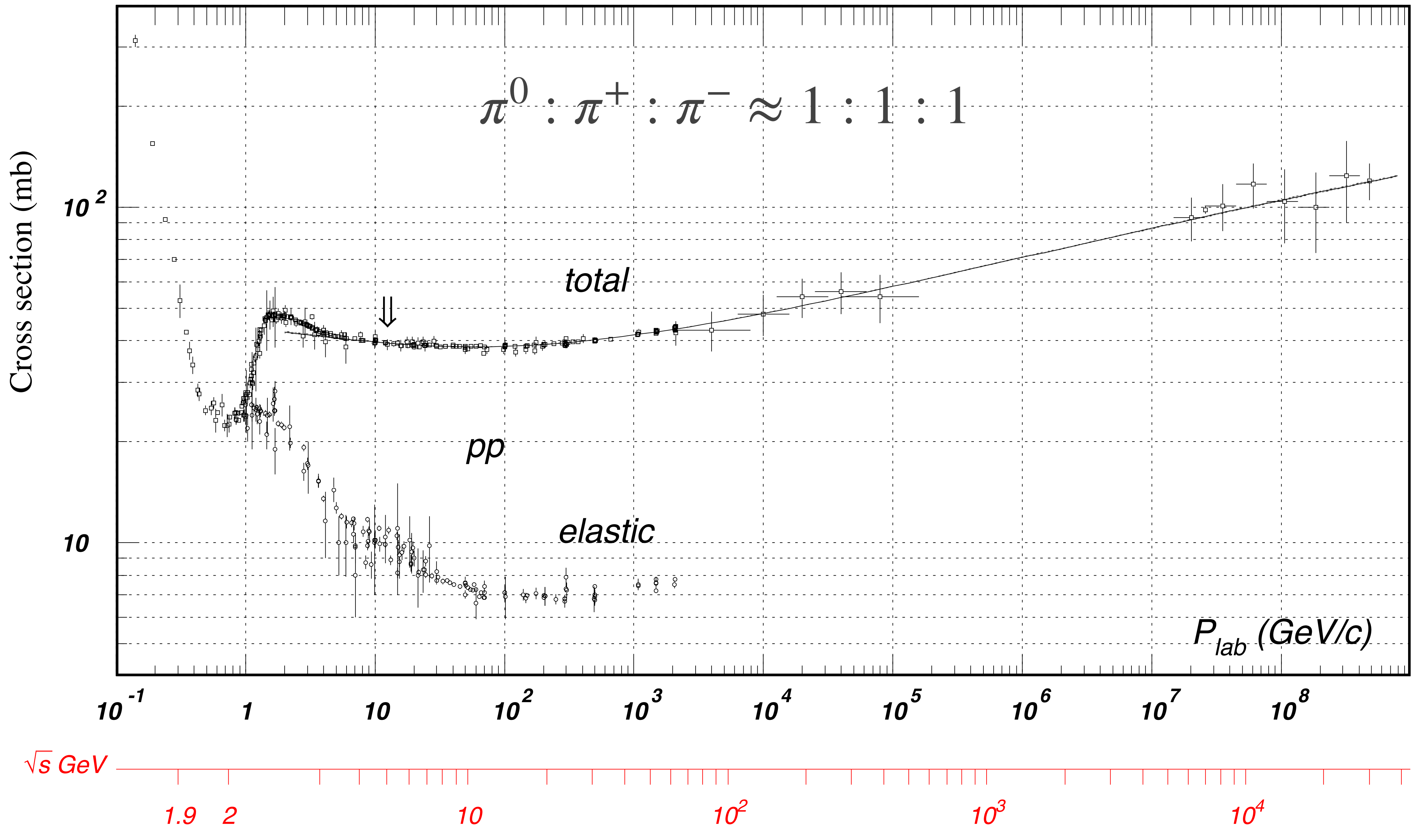


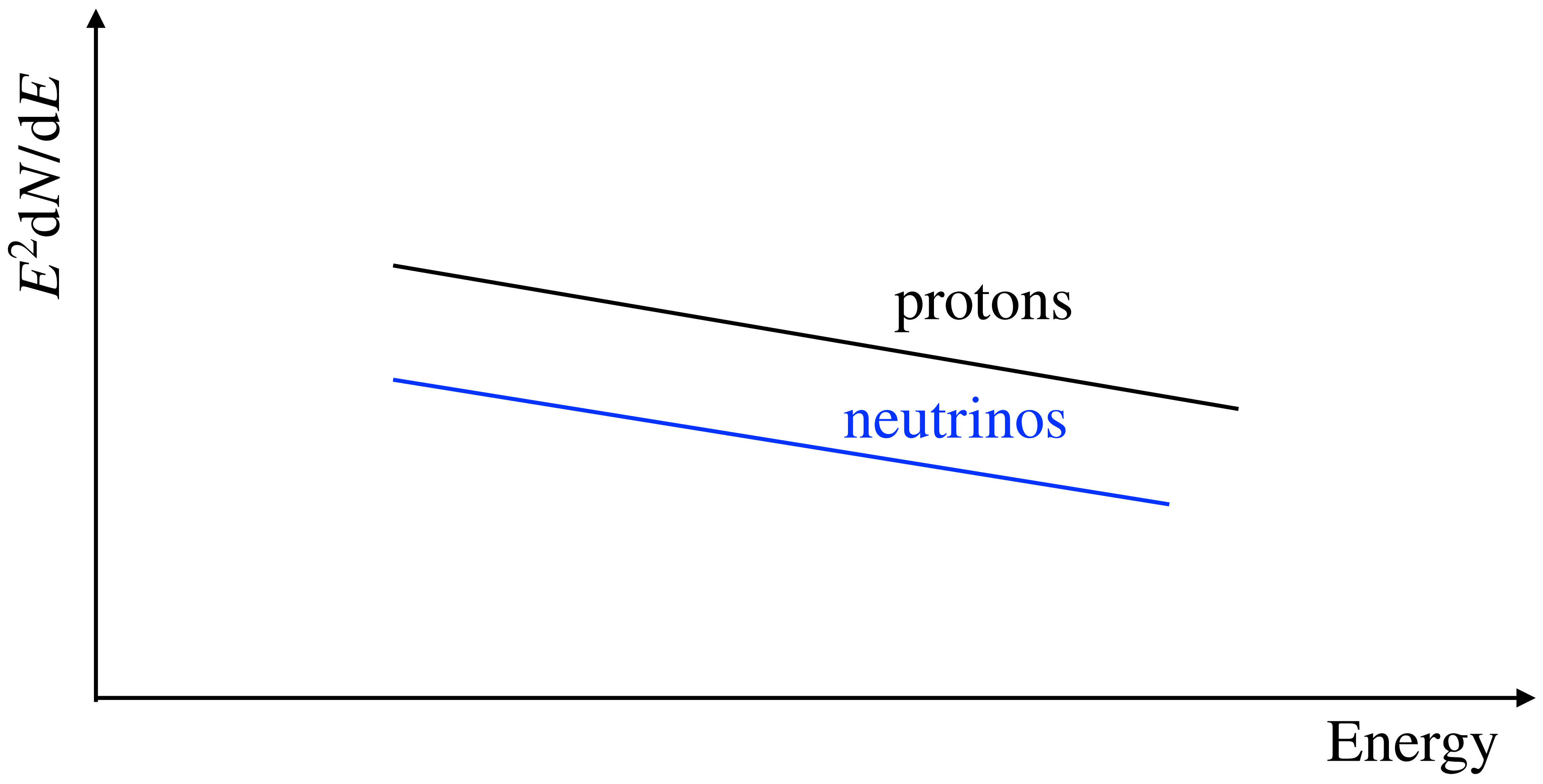
Proton-proton interactions

Gas reservoirs (Starburst galaxies, Galaxy Clusters…)

$$p + p \rightarrow N\pi + X$$

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





Starburst galaxies: Calorimetric environments?

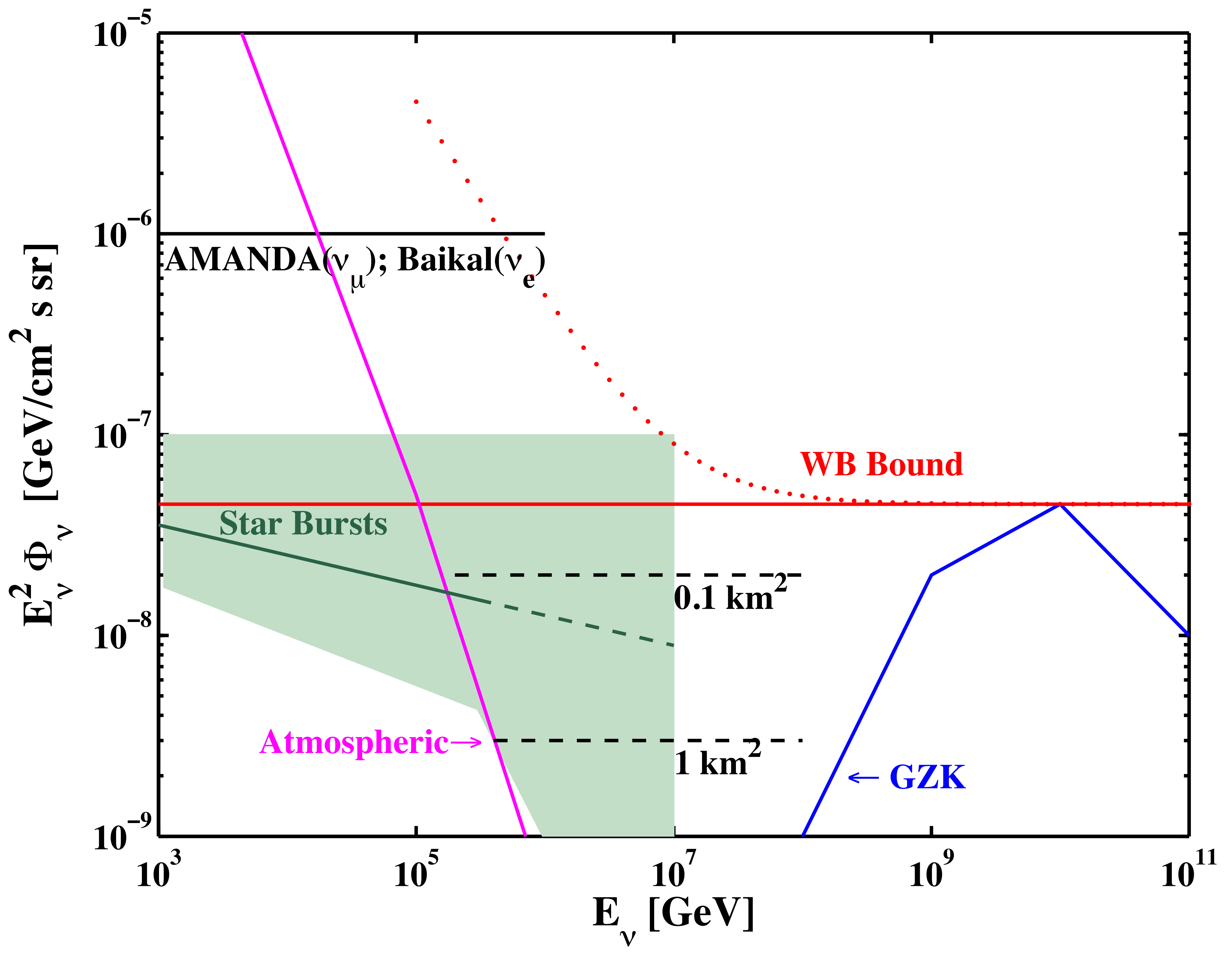
Large disc density implies pp interaction time much faster than in normal galaxies

Enhanced magnetic field ⟶
Enhanced confinement time of protons

Starbursts may be calorimetric for protons if

$$t_{\text{loss,pp}} < t_{\text{confinement}}$$

$$t_{\text{loss,pp}} < t_{\text{starburst}}$$



Reservoir model

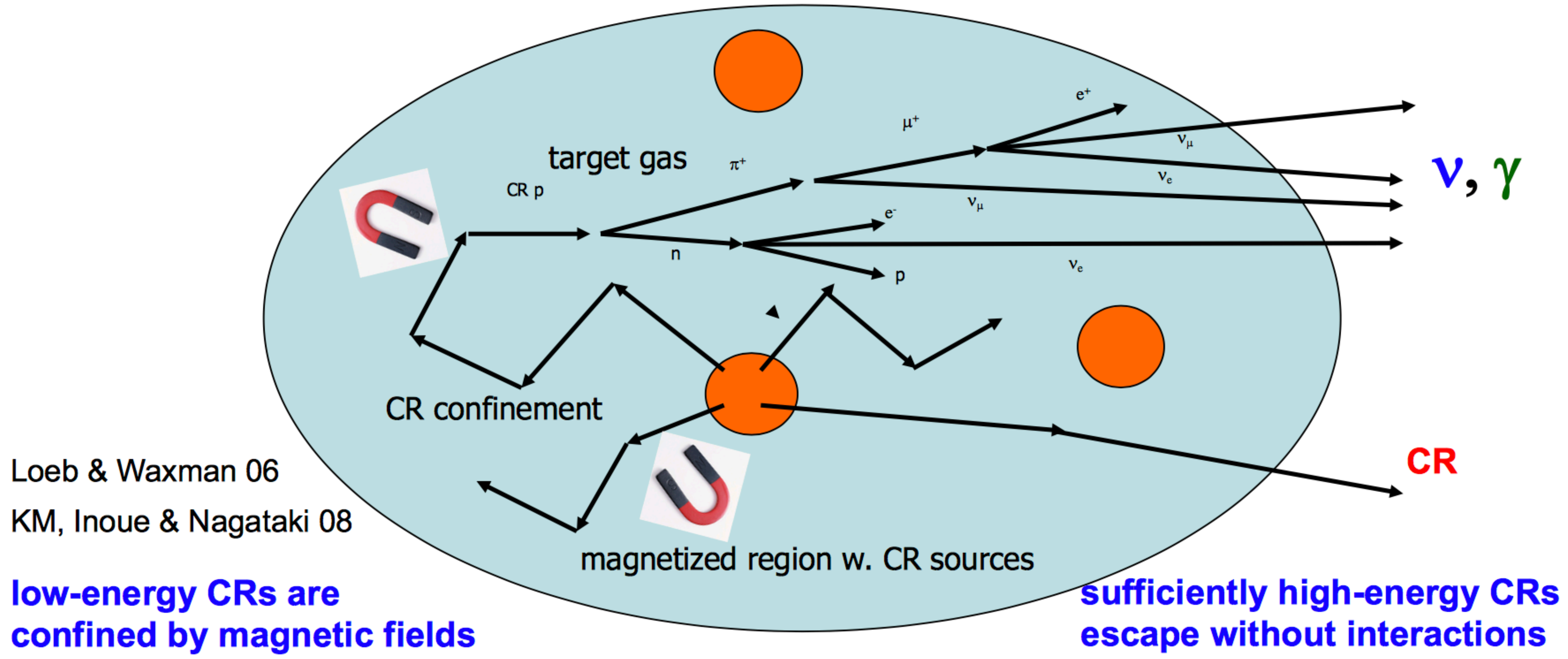
Cosmic rays in a calorimetric environment (e.g. ``starburst'')

The highest energy cosmic rays escape (observed)

Lower energy cosmic rays are confined

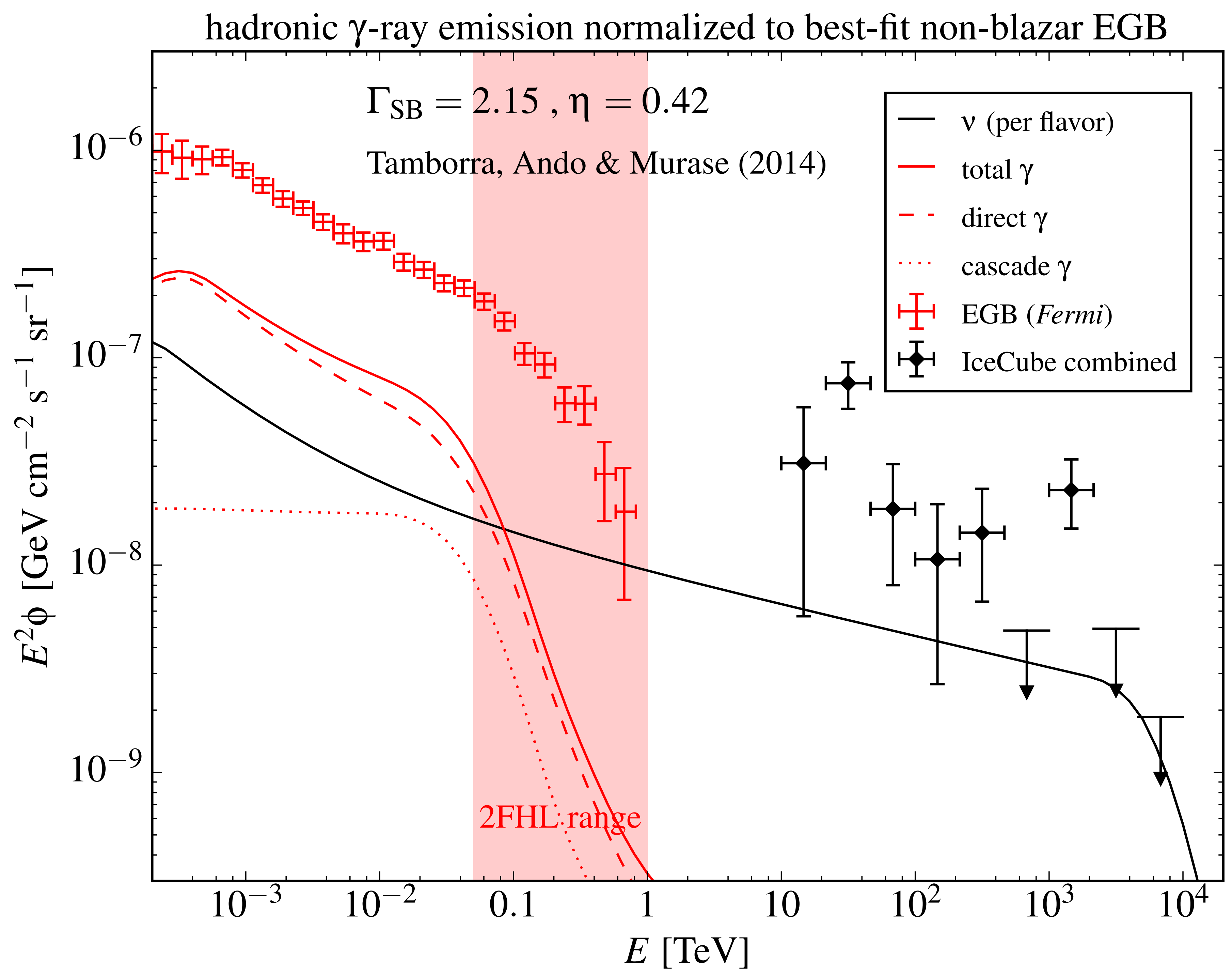
CRs lose all their energy in interactions with ambient gas

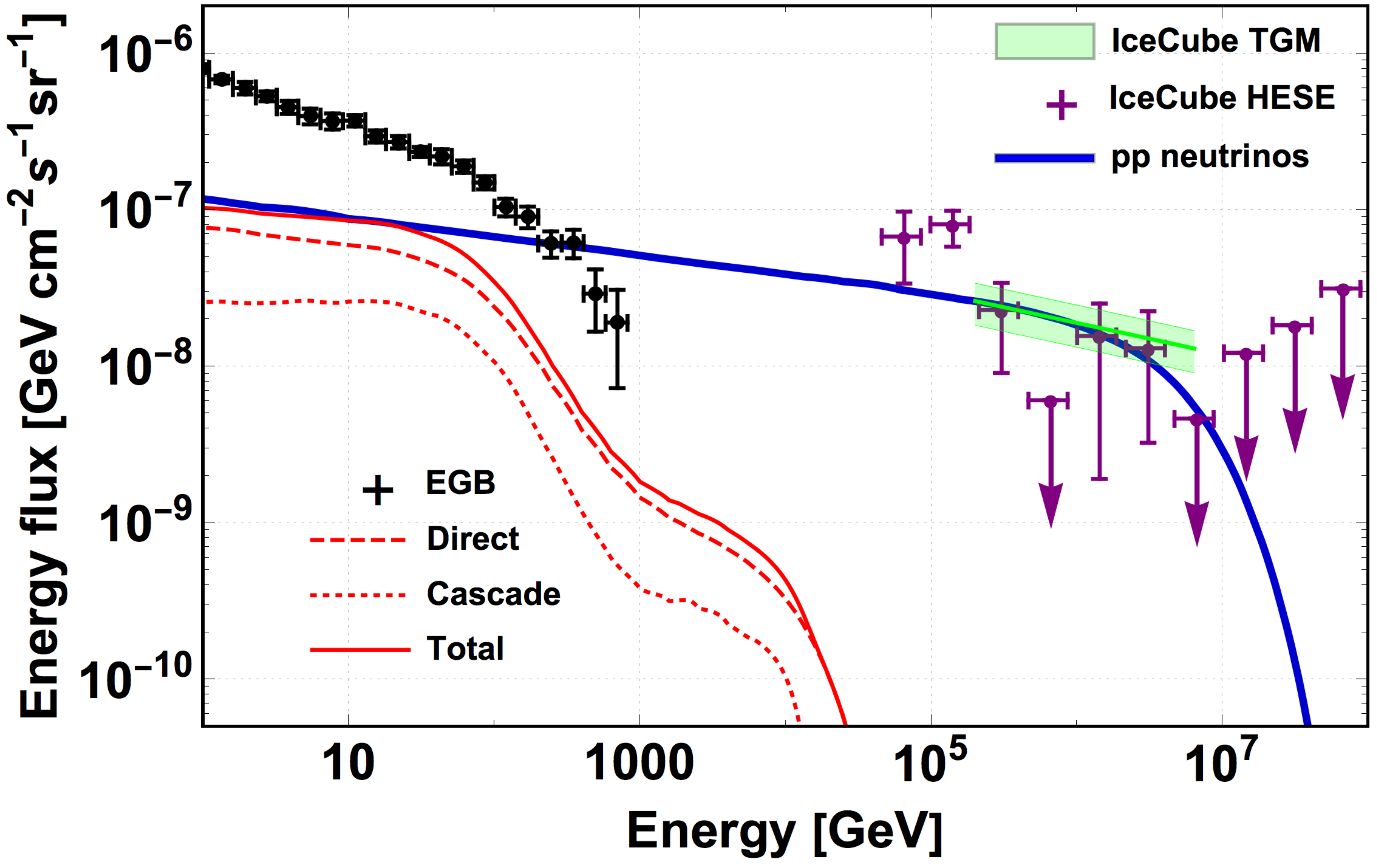
Neutrinos appear correlated with parent calorimeters



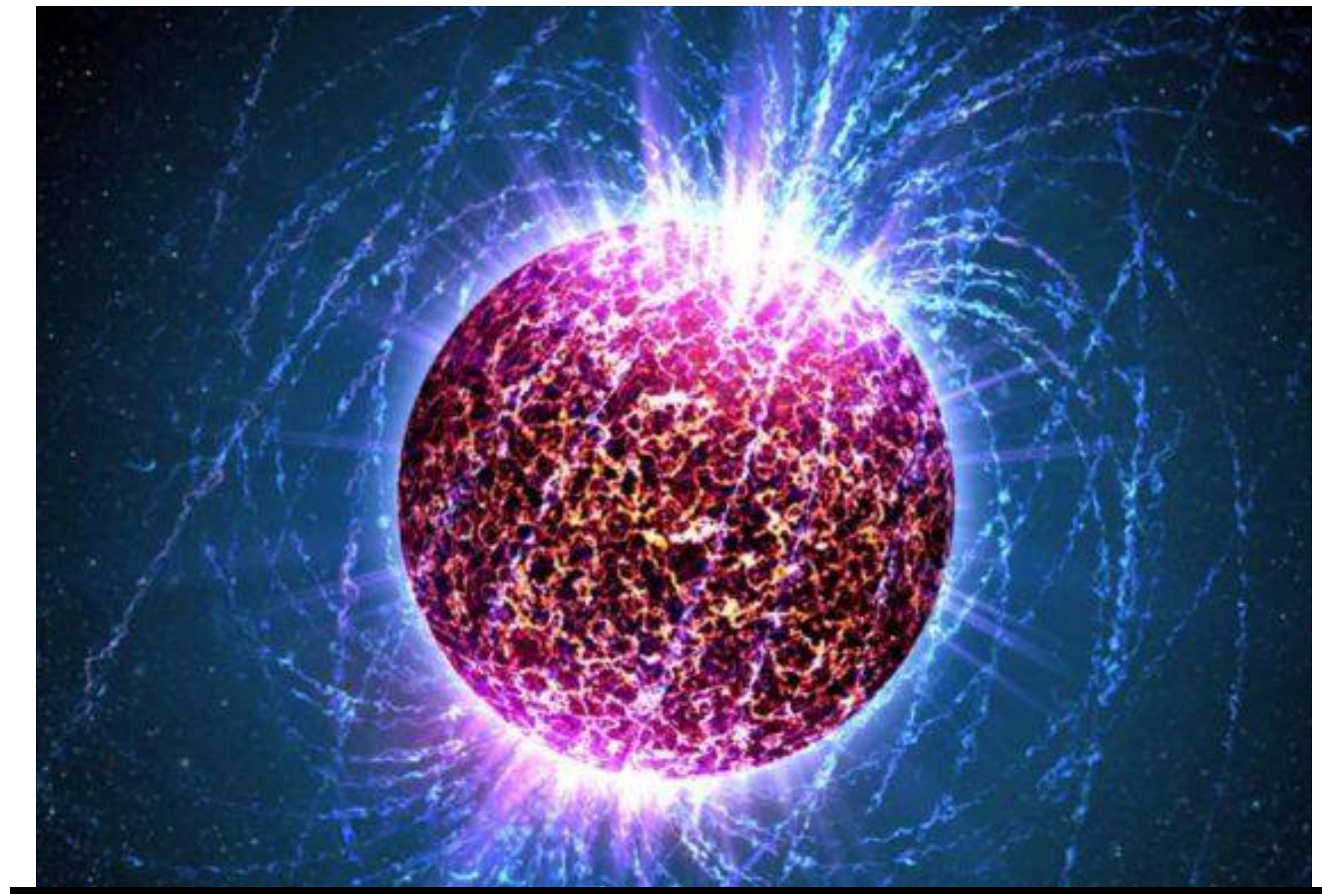
Neutrinos from starburst galaxies

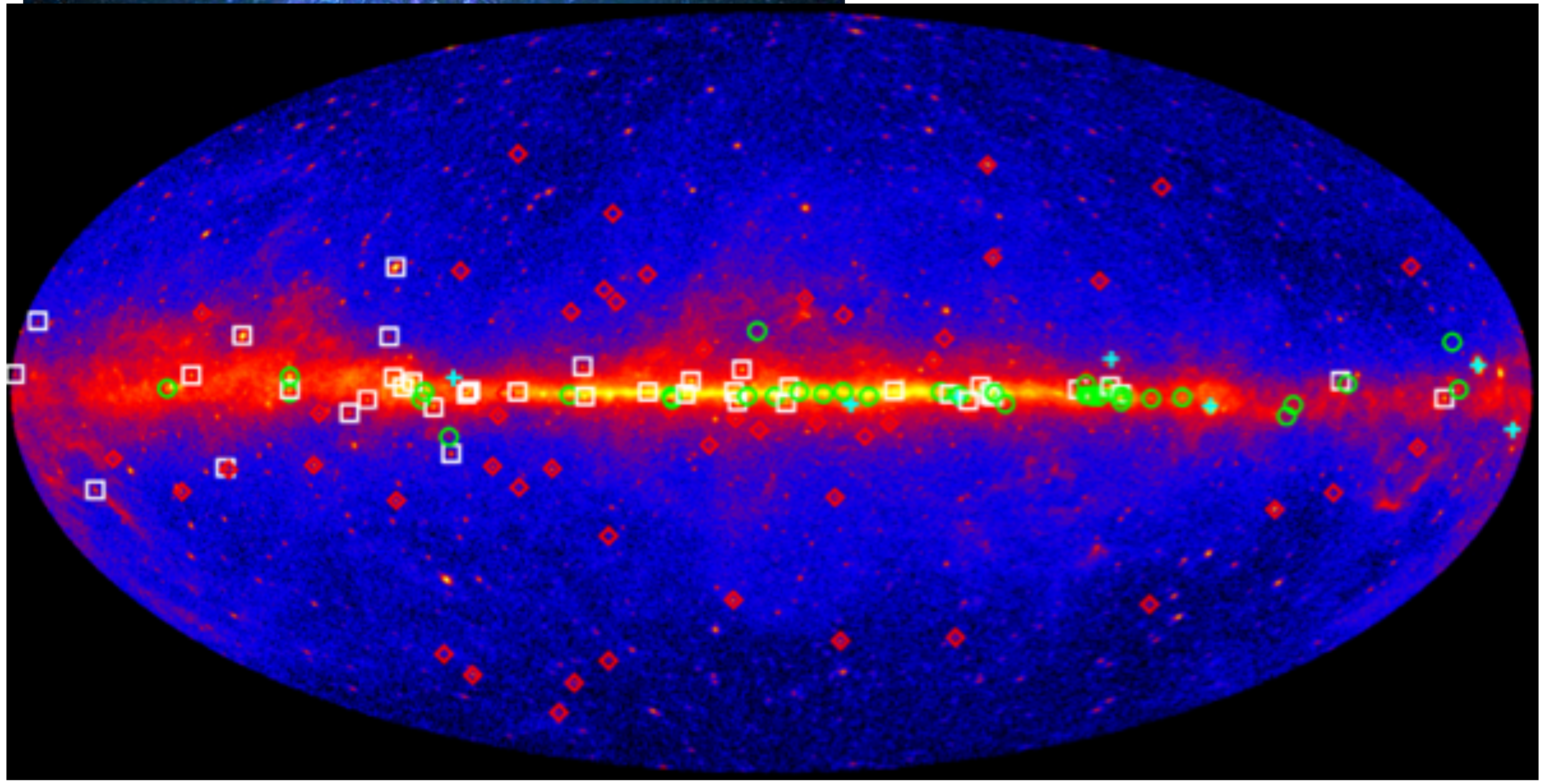
Cannot produce the IceCube flux unless we focus on >100 TeV data only due to diffuse gamma-ray constraints





Pulsars





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"

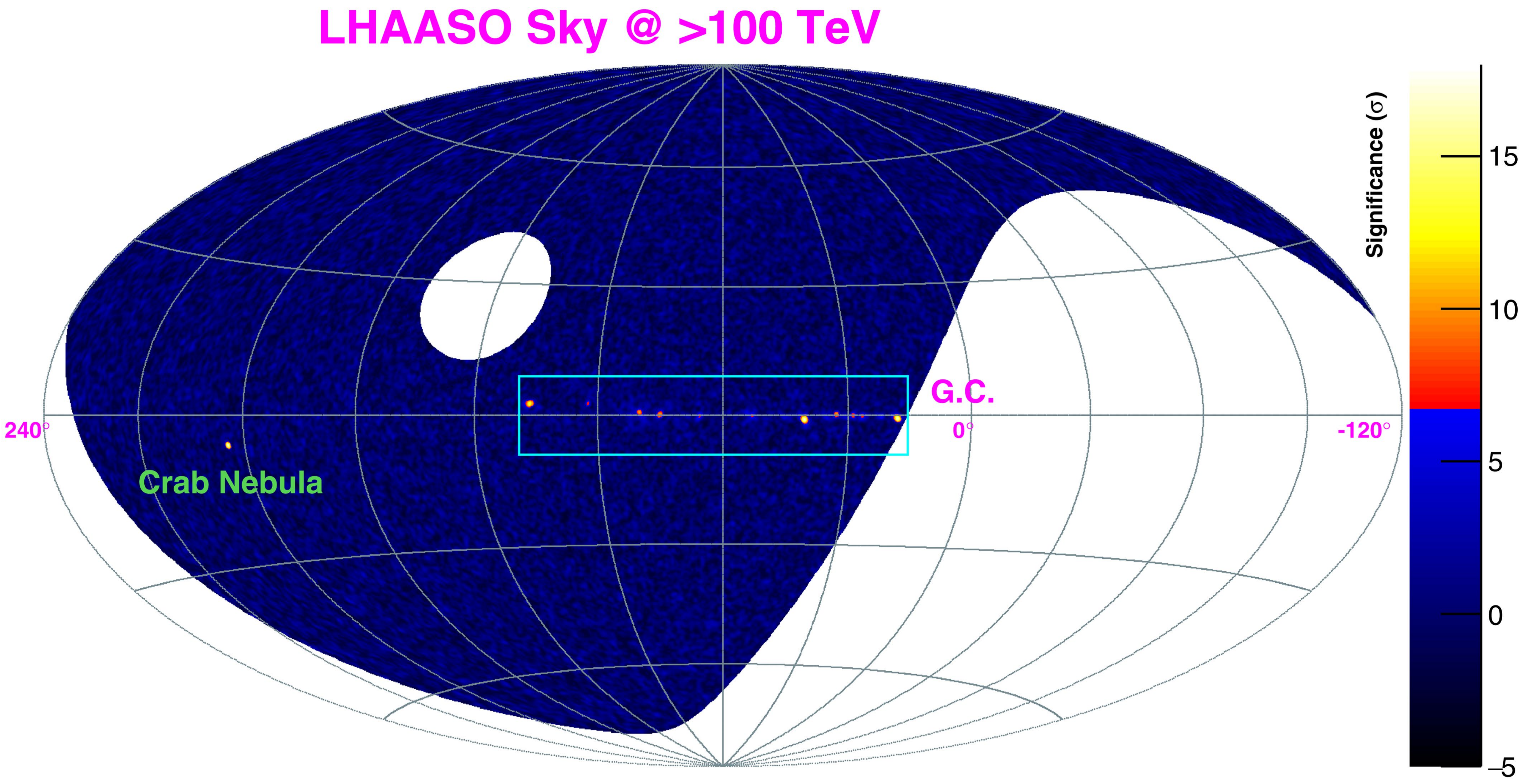
The core of the star was originally $R_{star} \sim 10^{3-4}$ km

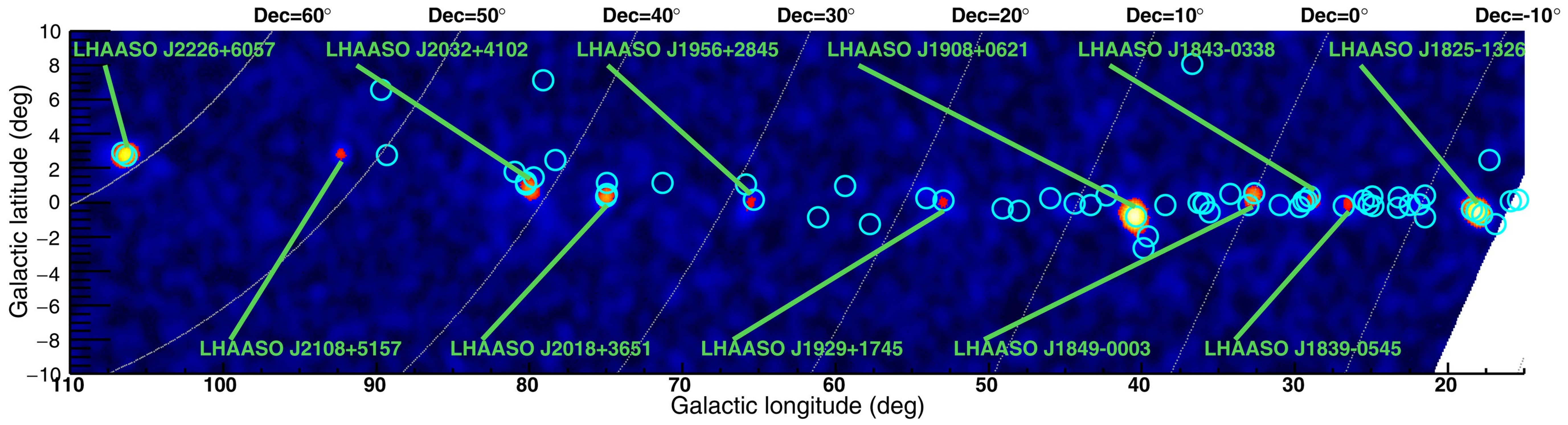
whereas the neutron star radius is $R_{NS} \sim 10$ km

Conservation of angular momentum leads to spin periods ~second

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

Interesting recent results from LHAASO/Tibet AS-γ/HAWC





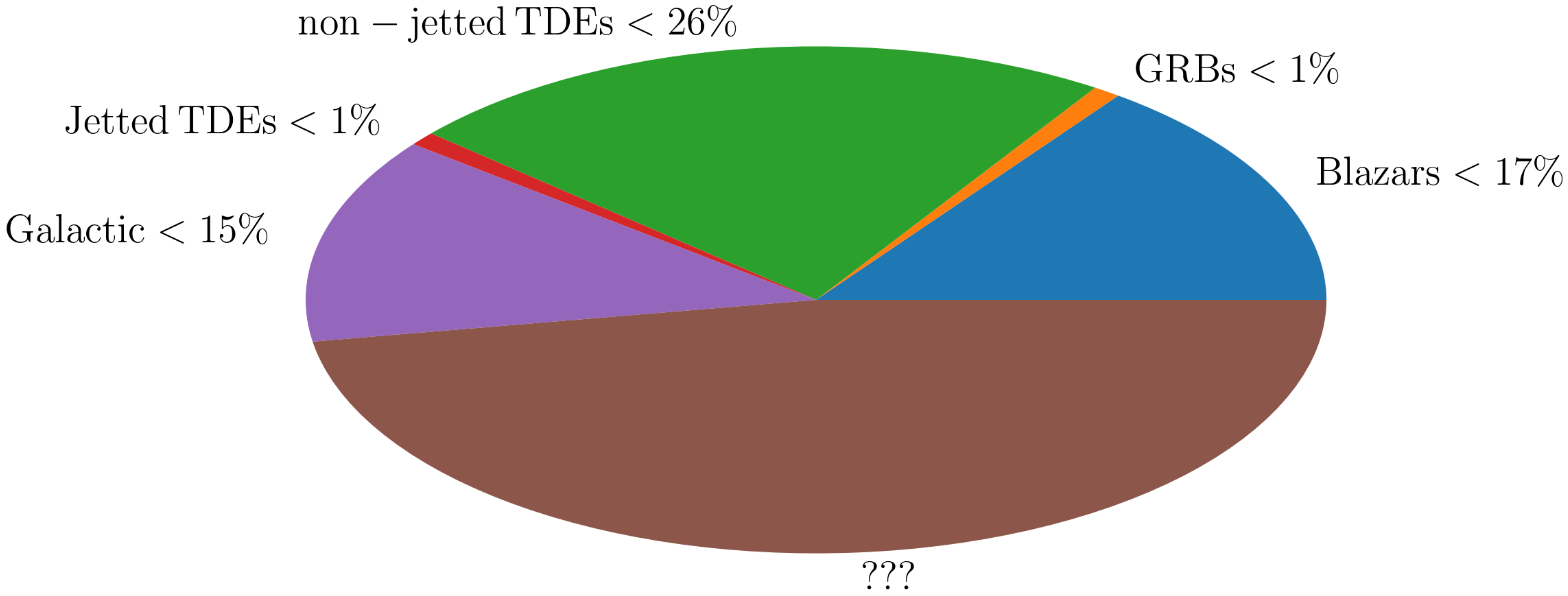
LHAASO has reported the detection of 530 photons with energy up to 1.4 PeV from 12 Galactic sources

Most directions consistent with known Galactic pulsars

Among sources Crab pulsar (confirmed) - journal in Science yesterday! Cygnus Cocoon starforming region (very likely)

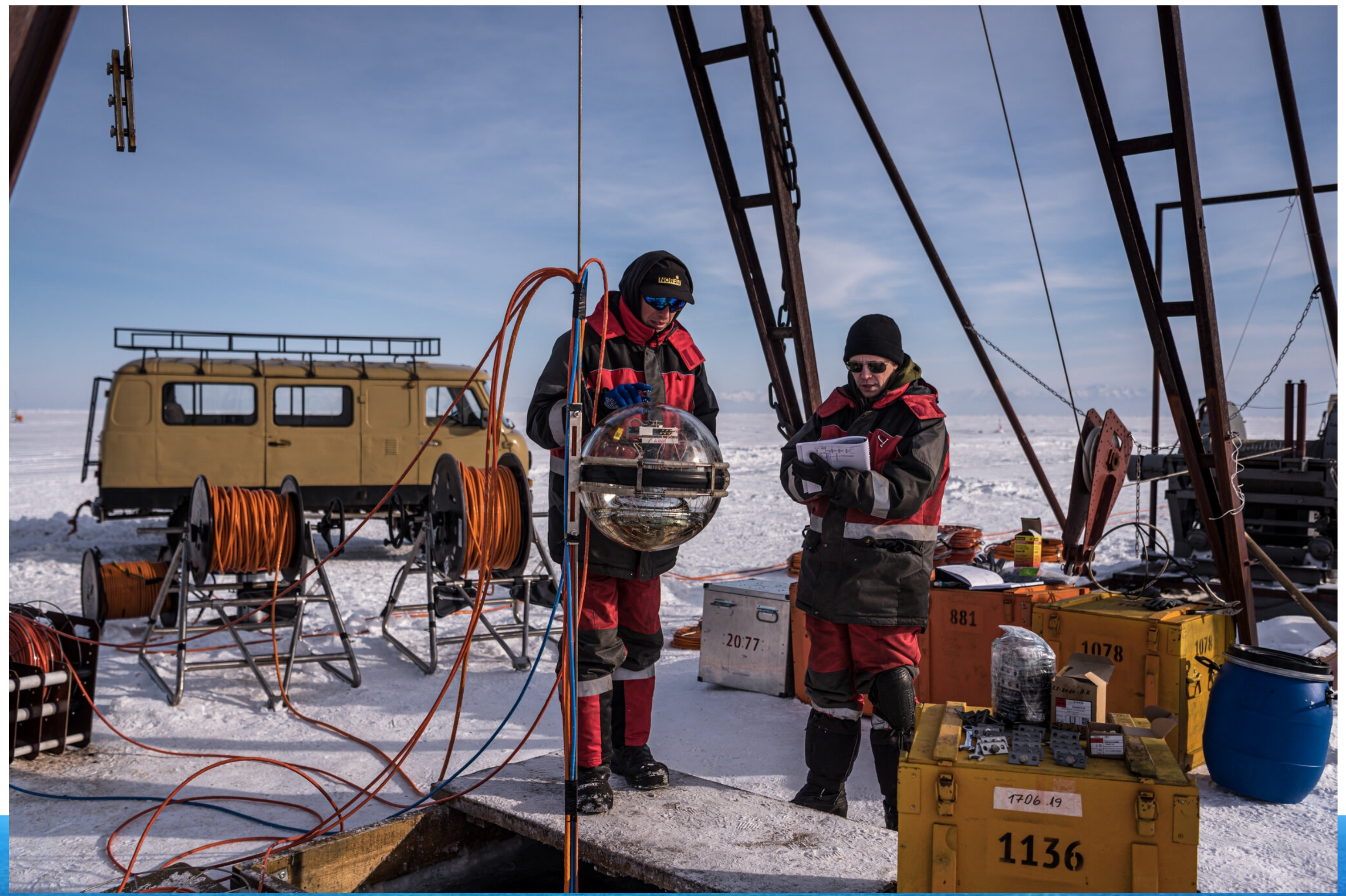
LHAASO has the potential to distinguish between leptonic and hadronic origin of the Cygnus signal in ~2 years

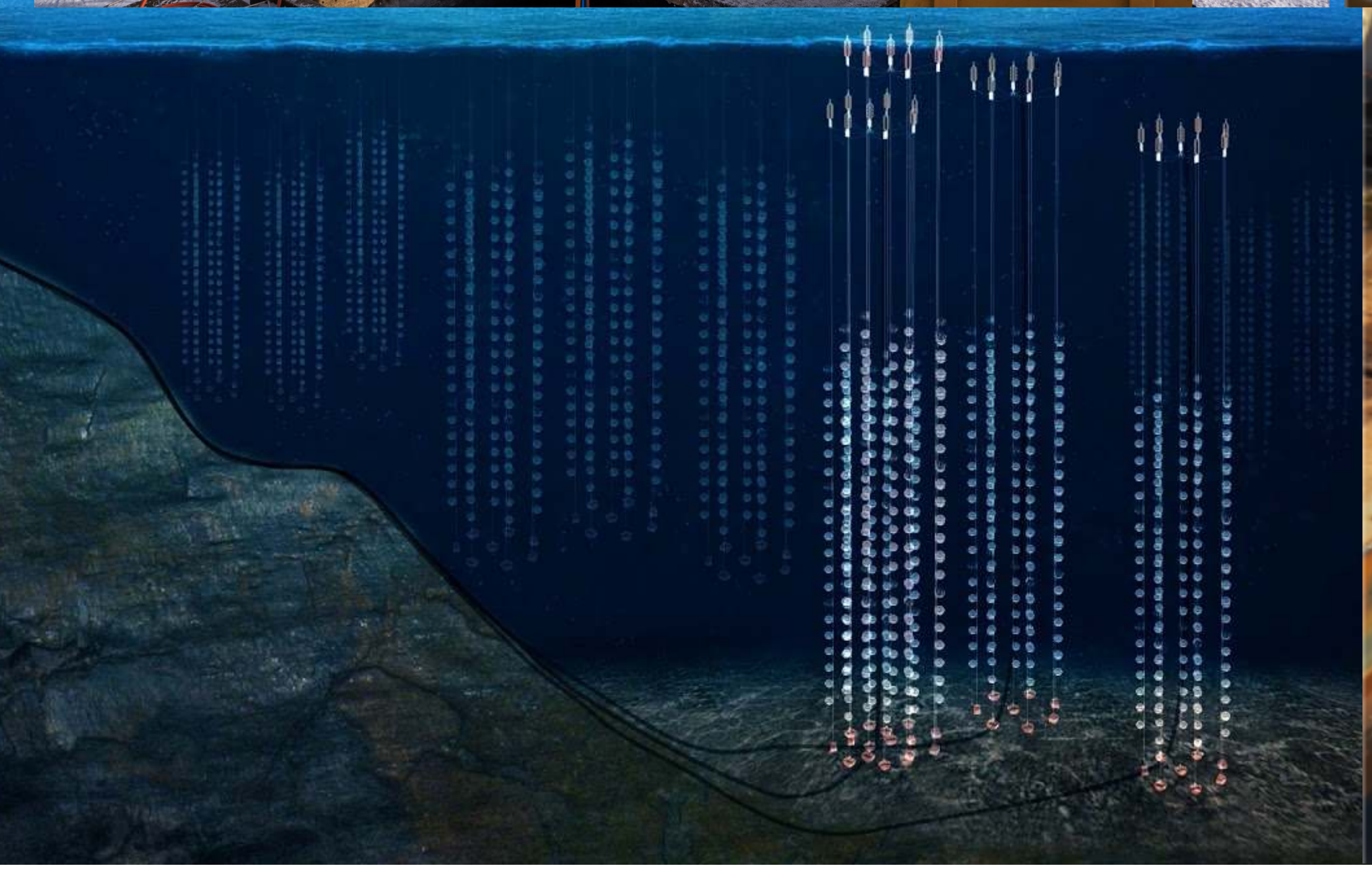
Putting everything together…



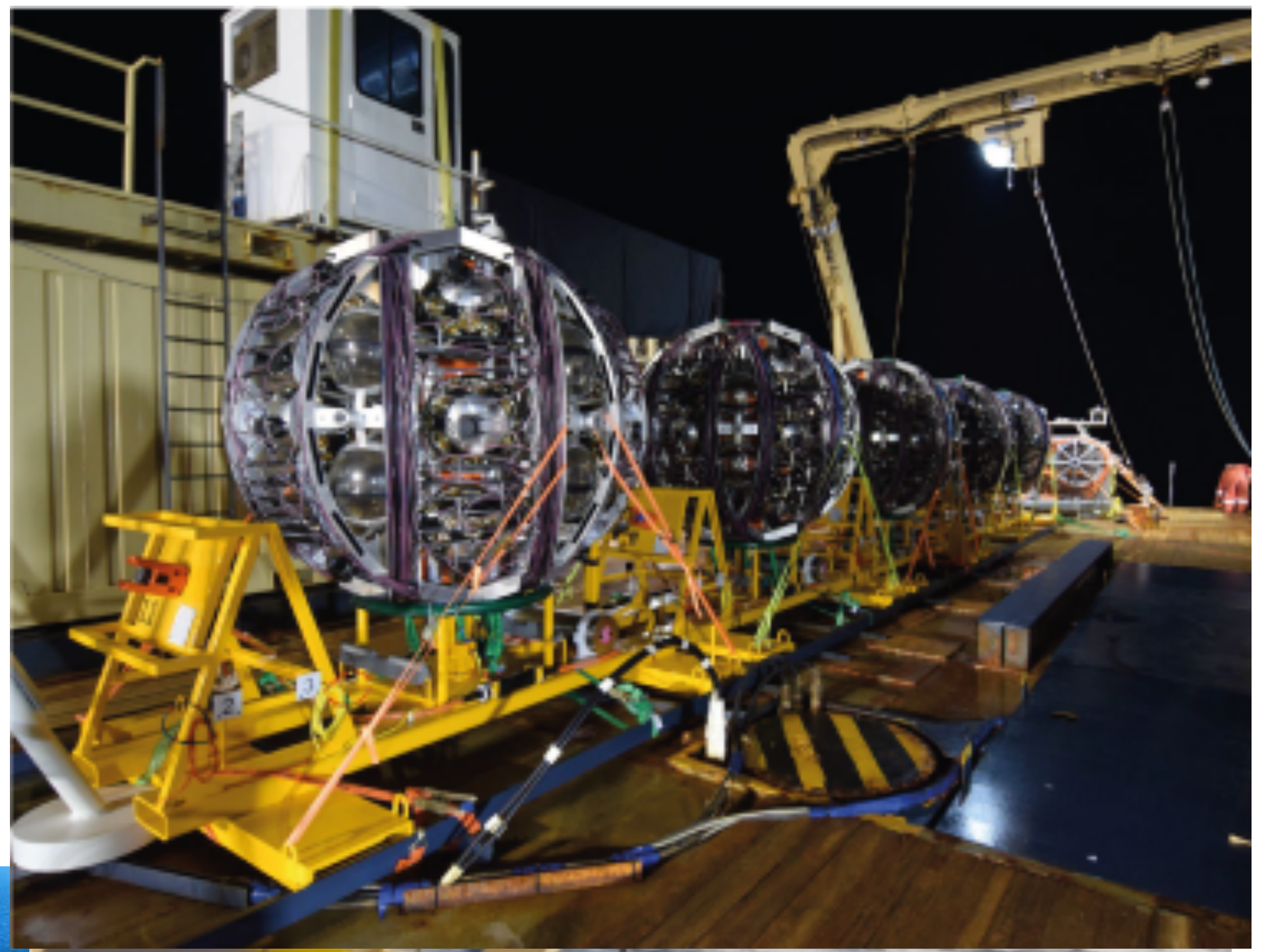
The future

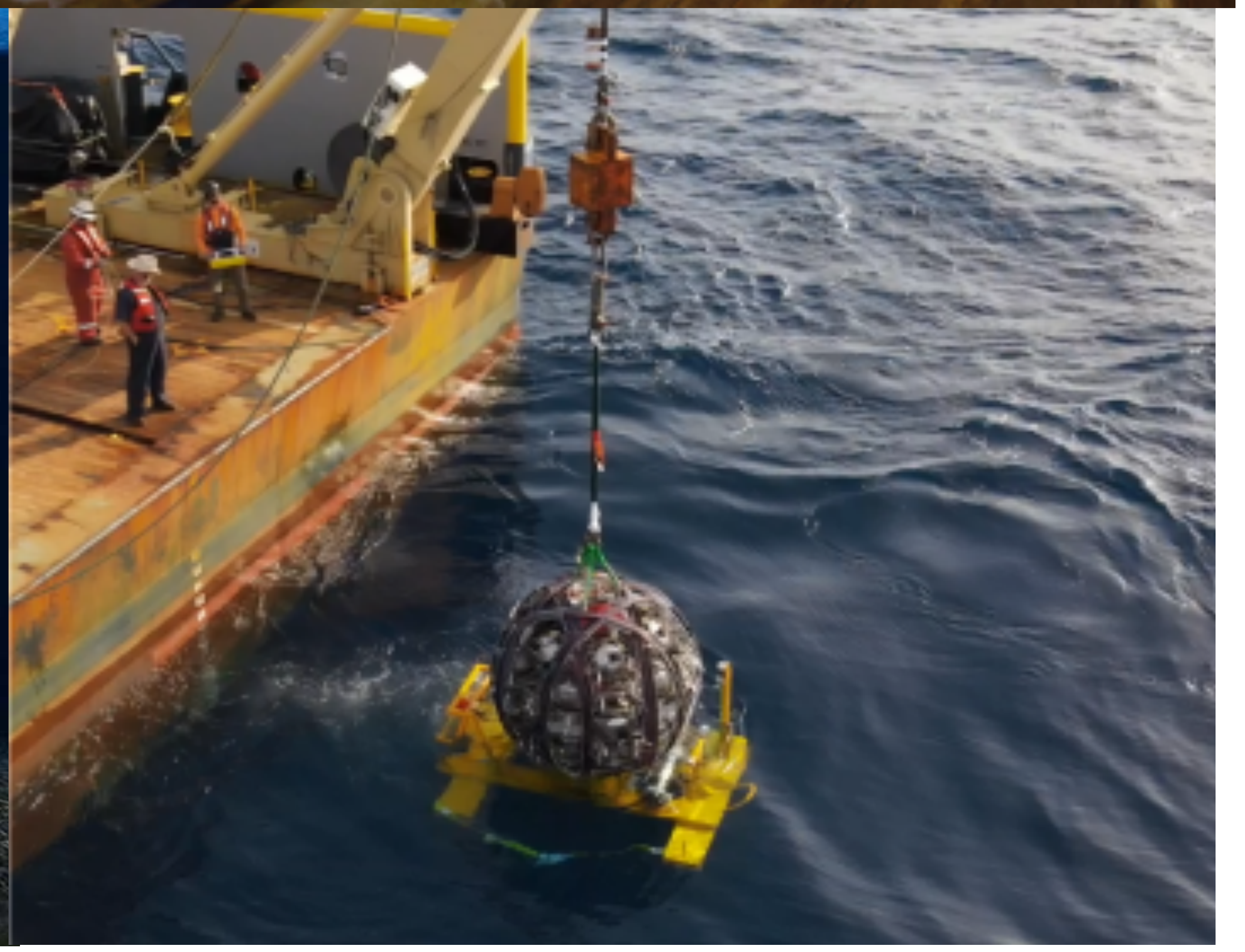
GVD - Lake Baikal



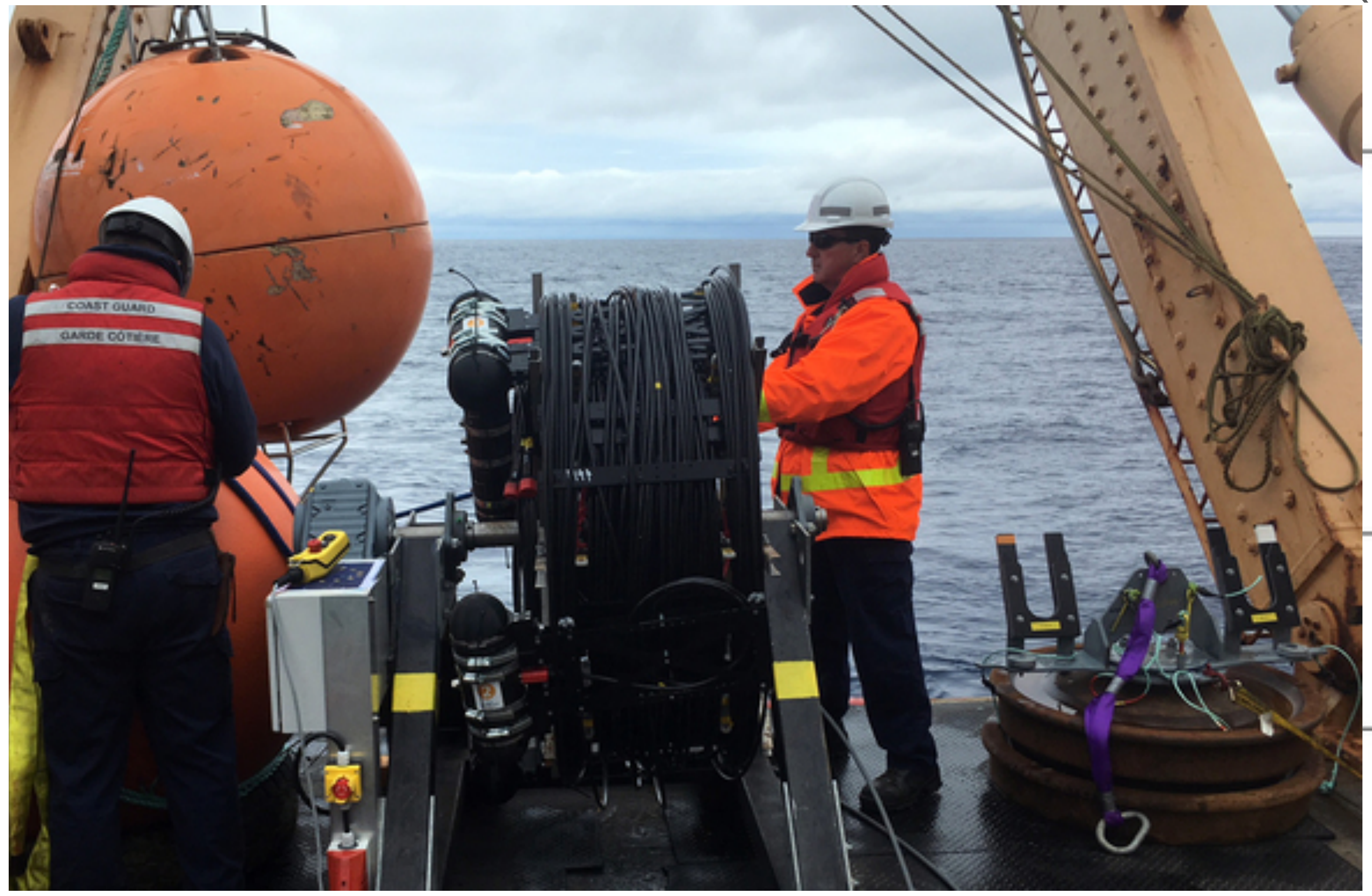


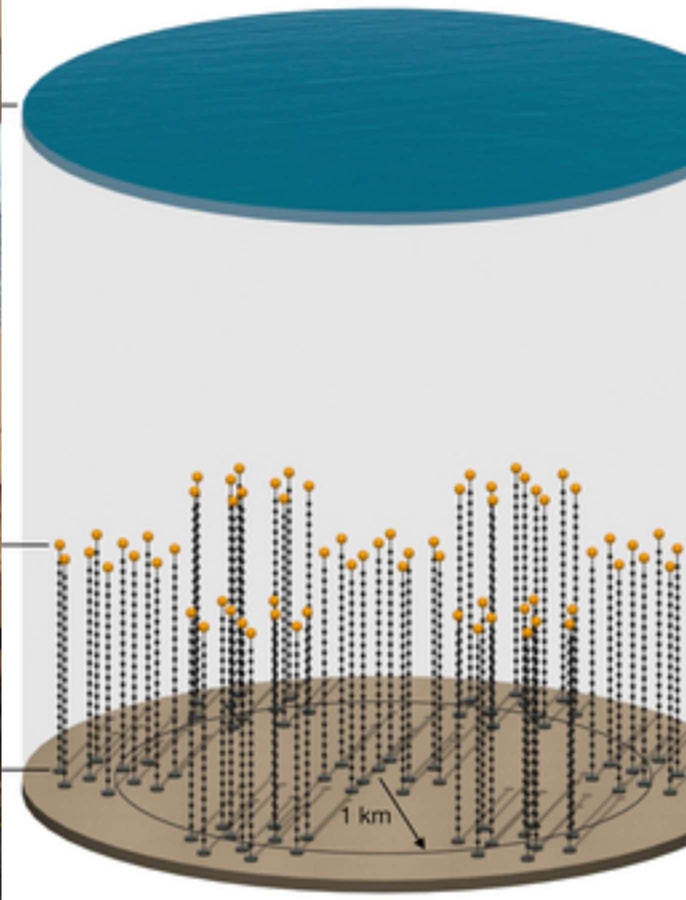
KM3NeT - France/Italy



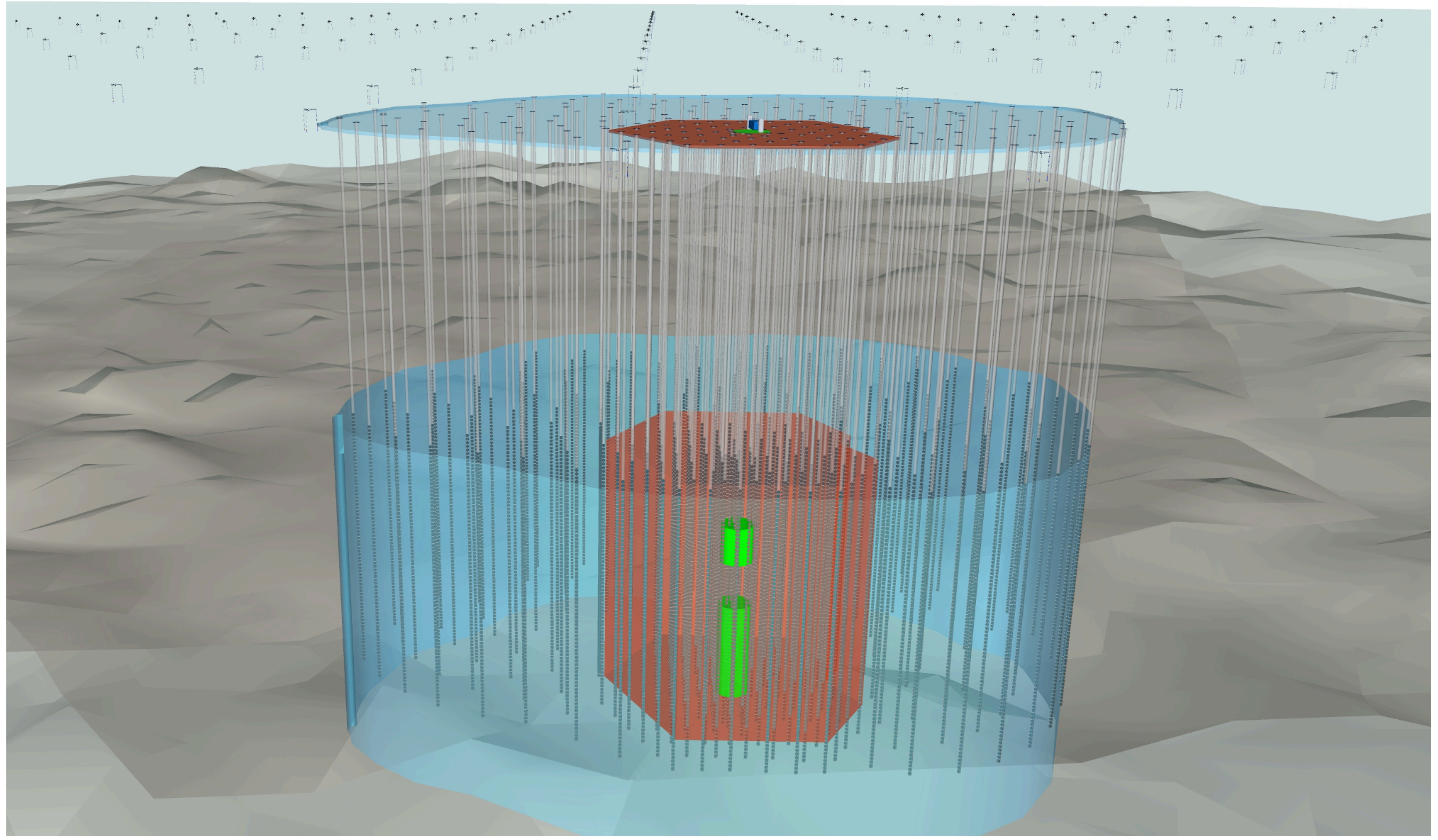


P-ONE - Canada (Pacific)



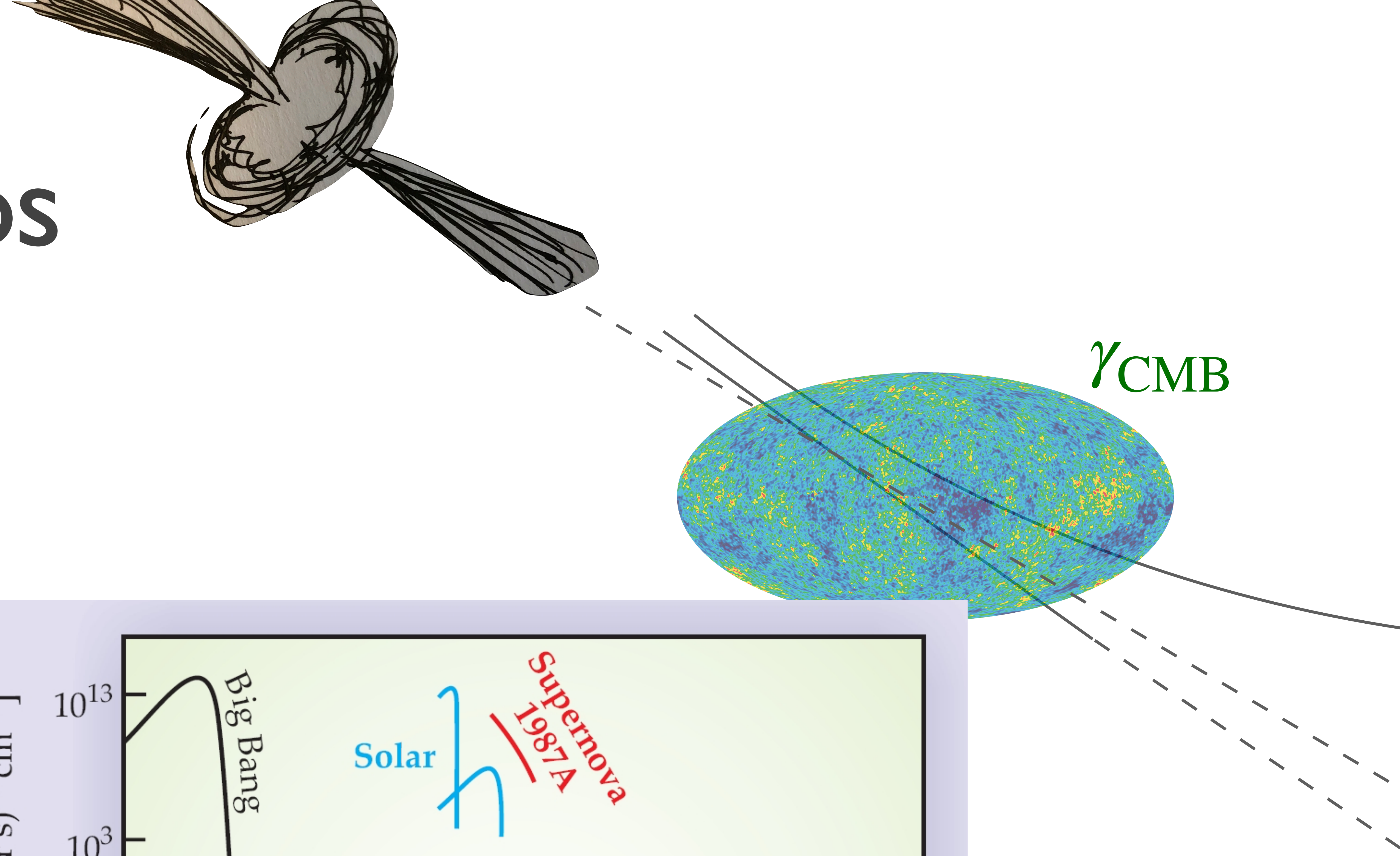


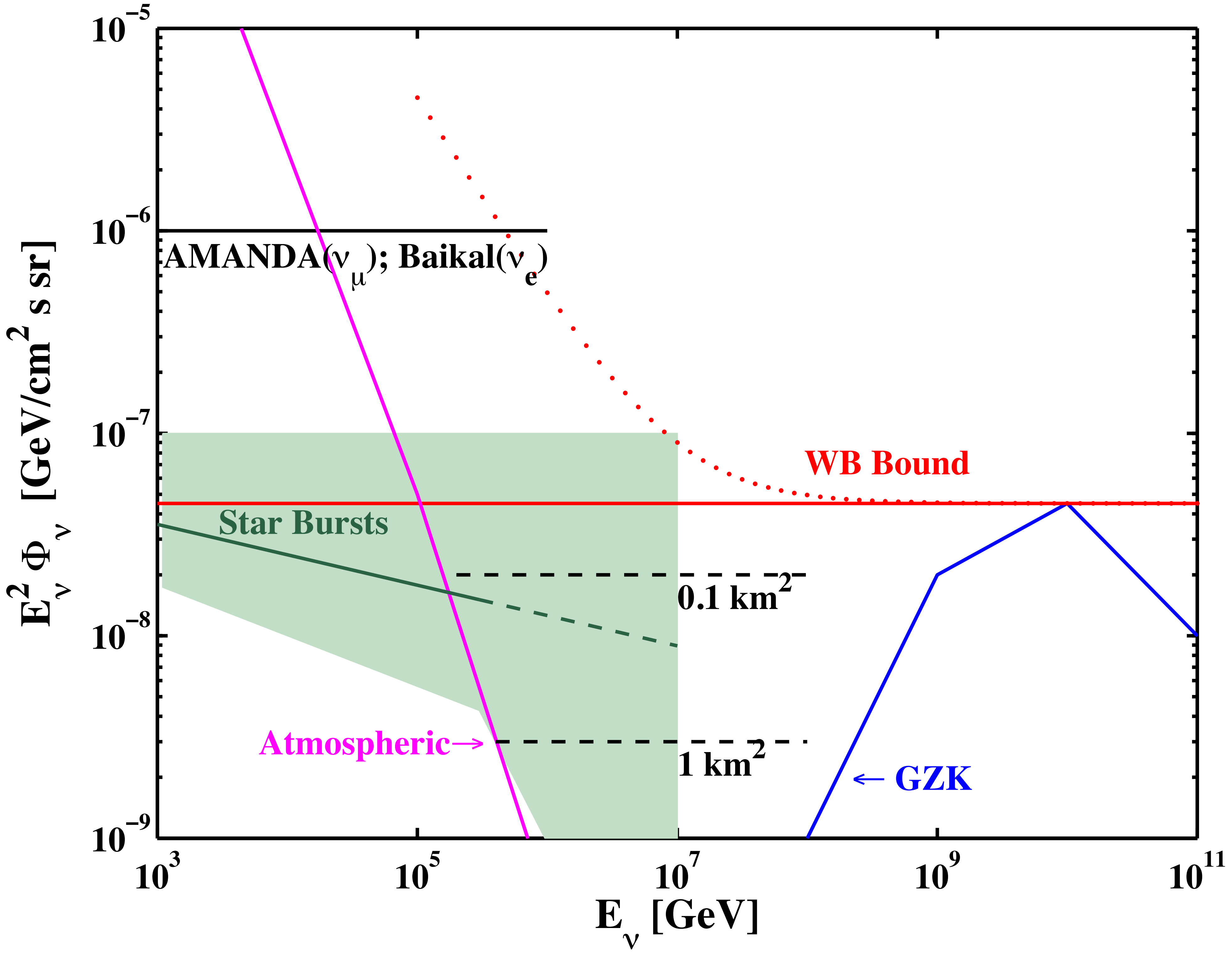
IceCube GenII

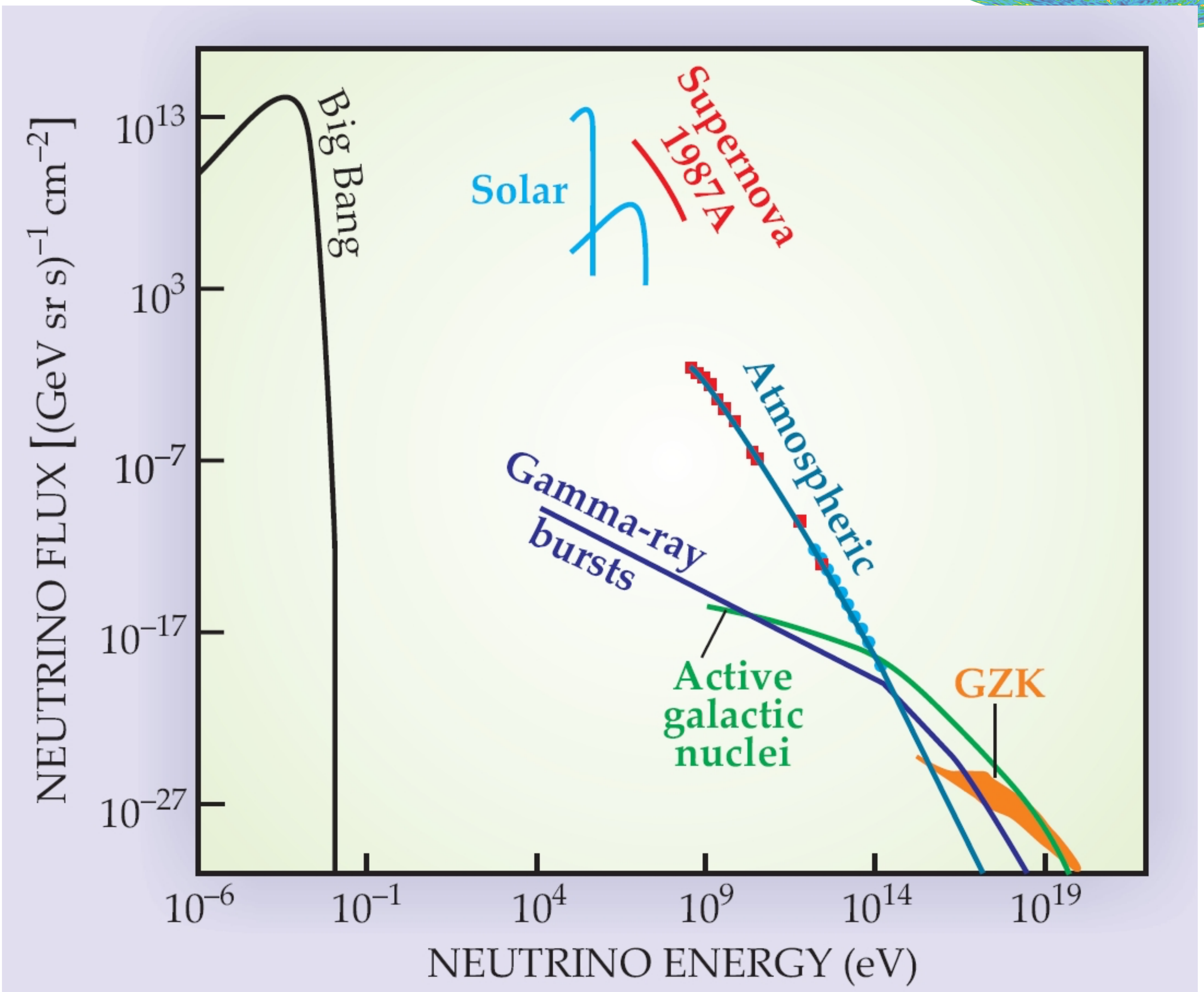


Ultra-high energy neutrinos

How to detect them?

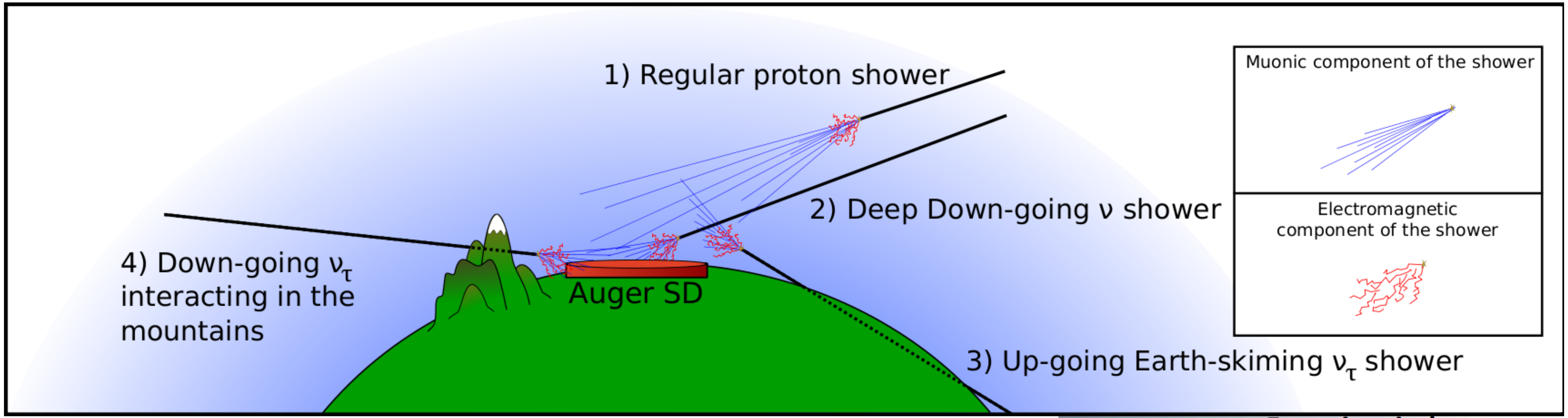






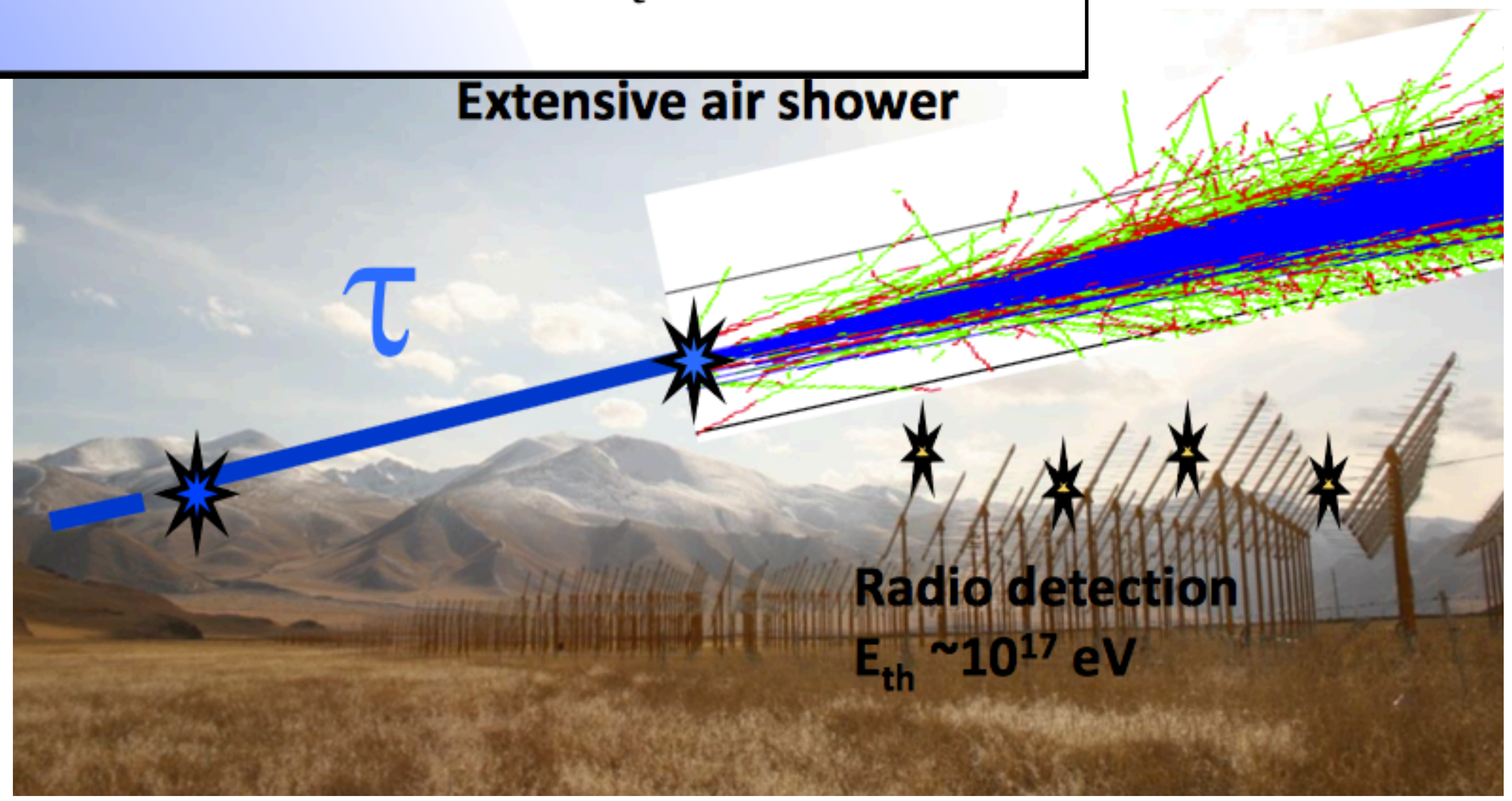
Ultra-high energy neutrinos

How to detect them? Extensive-air showers



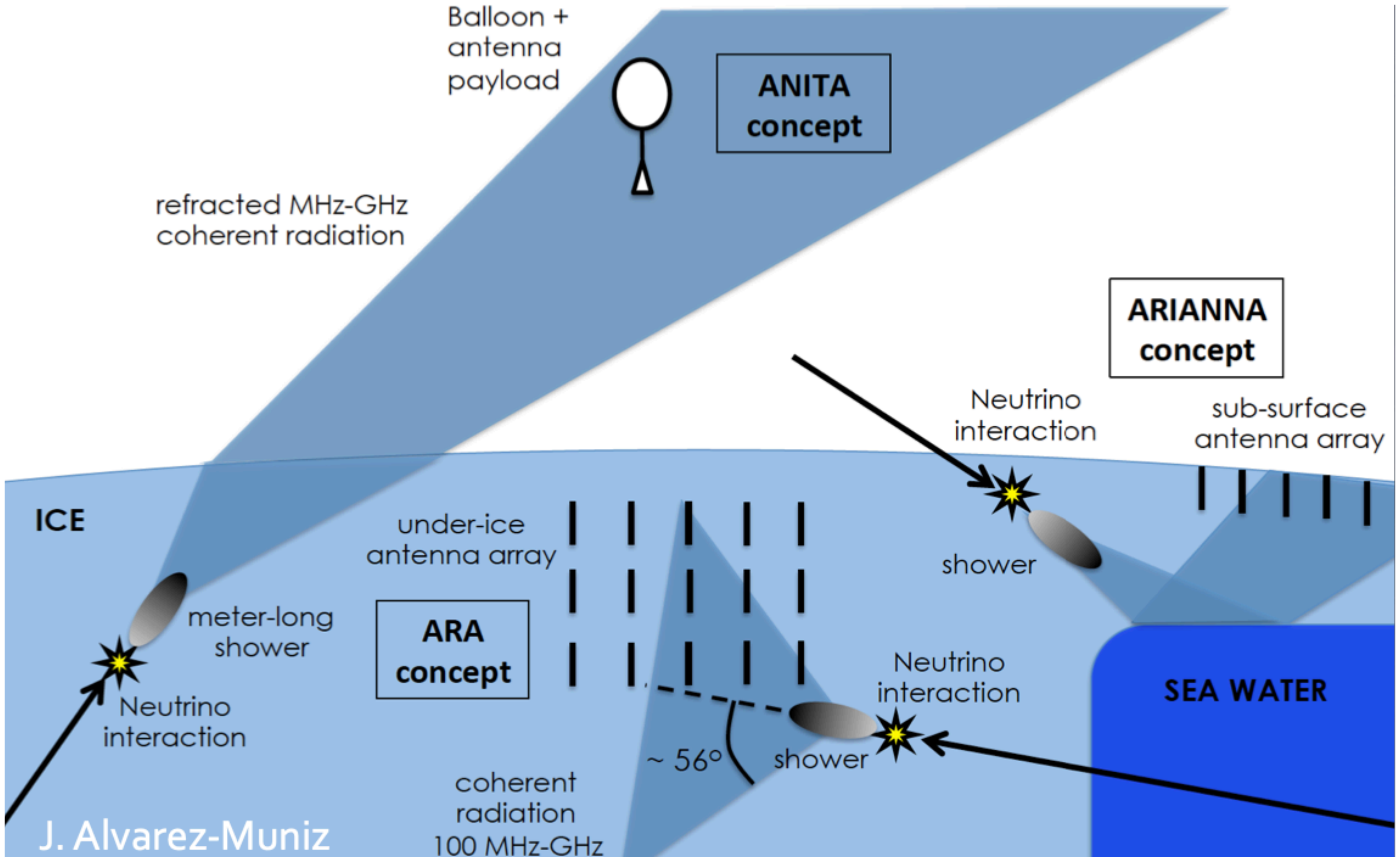
Pierre Auger Observatory ~ 3000 km^2

Planned detectors with up to 200,000 km^2 effective area (GRAND, GCOS…)



Ultra-high energy neutrinos

How to detect them? Askaryan radiation



many more ongoing efforts (Greenland Neutrino Observatory, IceCube Gen-II radio, PUEO…)

Thank you for your attention!