Can the neutrinos from TXS 0506+056 have a coronal origin?

Damiano F. G. Fiorillo

DESY, Zeuthen

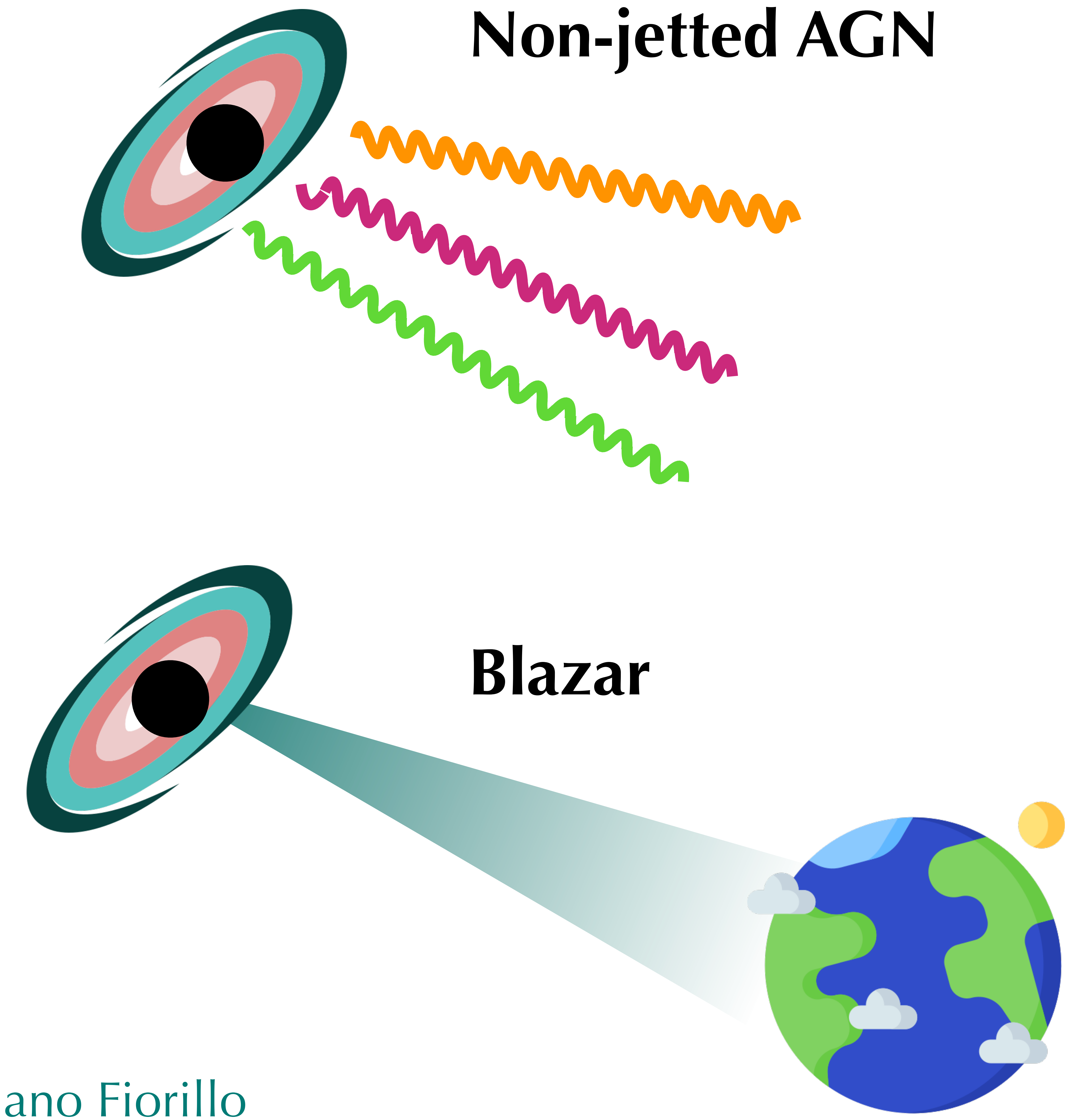
Based on **DF**, Testagrossa, Petropoulou, Winter, ApJ, arXiv:2502.01738

Alexander von HUMBOLDT STIFTUNG

TeV Particle Astrophysics TeVPA Valencia 2025

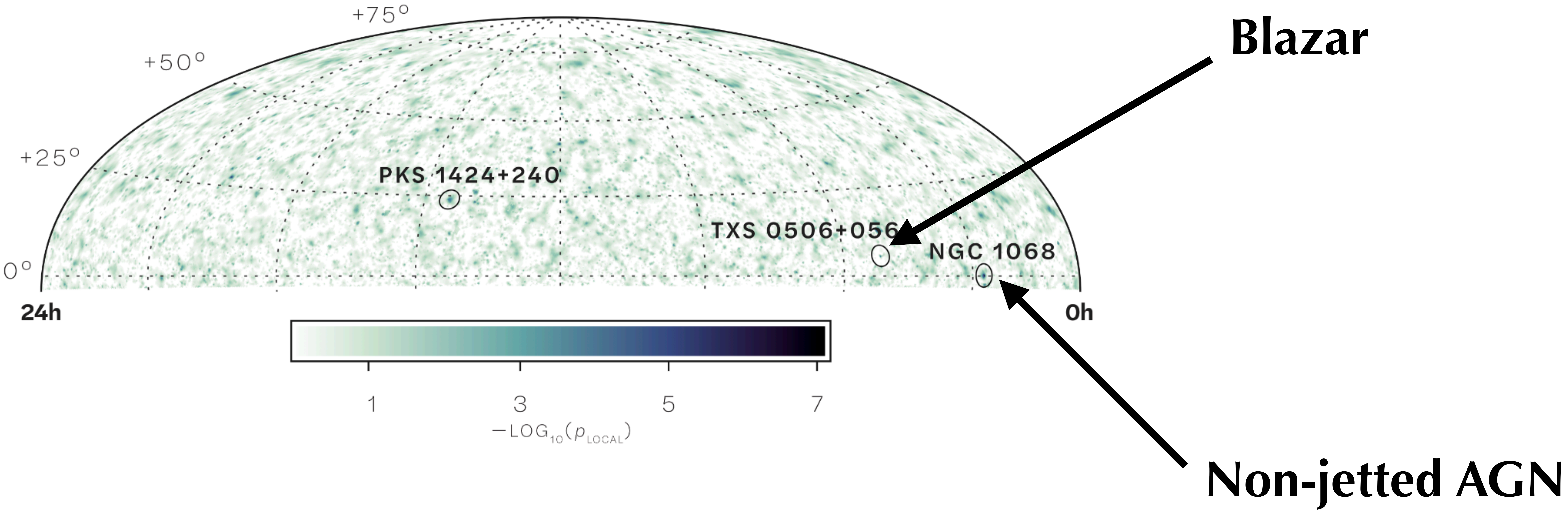
DESY.

The AGN-neutrino connection



- AGN and blazars contain non-thermal particles
- If they also contain non-thermal hadrons, then $\pi^{\pm}$ production is possible, hence **neutrinos!**
- Long-standing theoretical connections (Berezinsky, Zatsepin, Stecker, Mannheim, …)

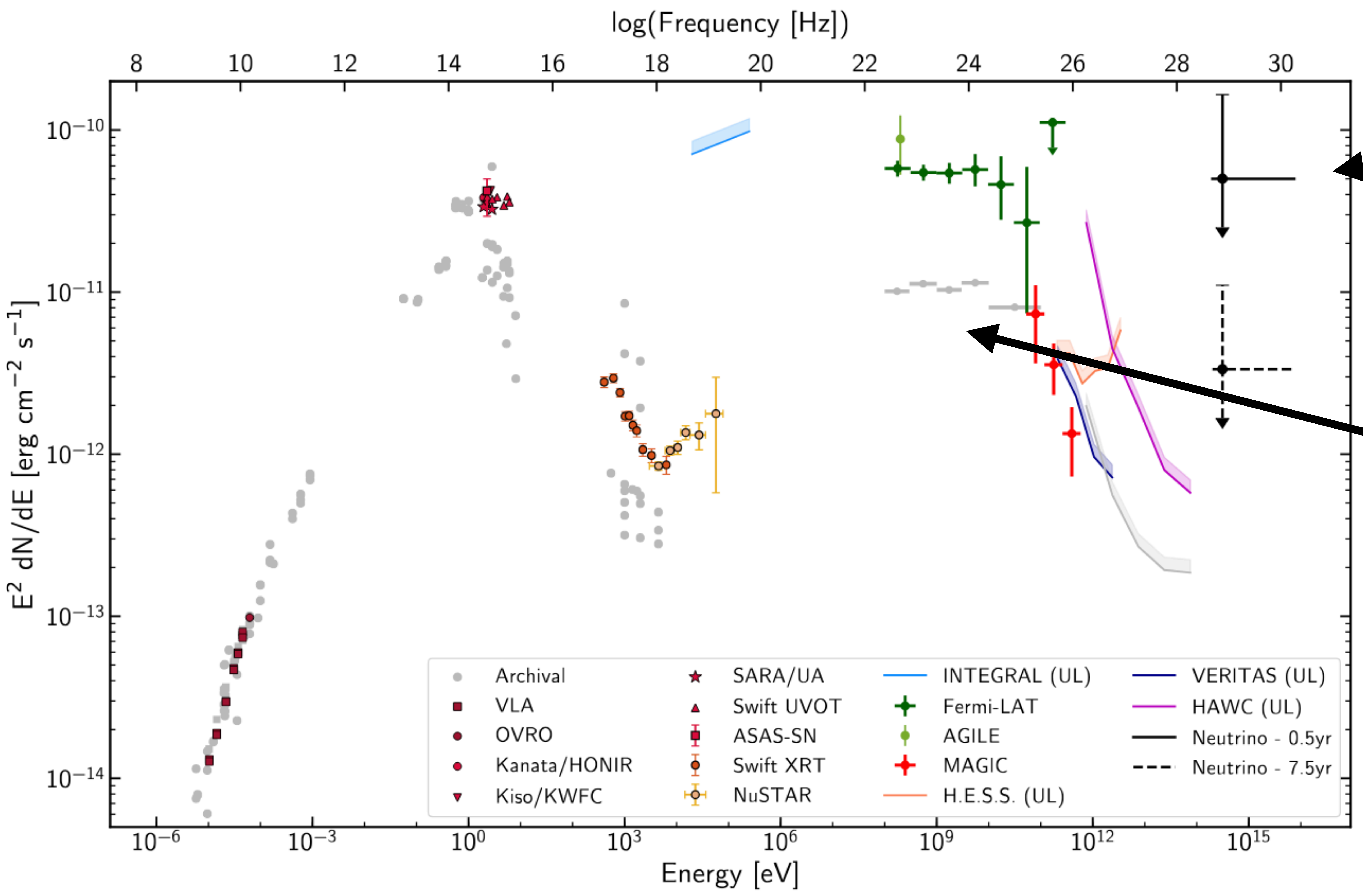
AGN as neutrino sources



Could they come from the same underlying mechanism?

IceCube, 2022

TXS 0506+056 in 2017

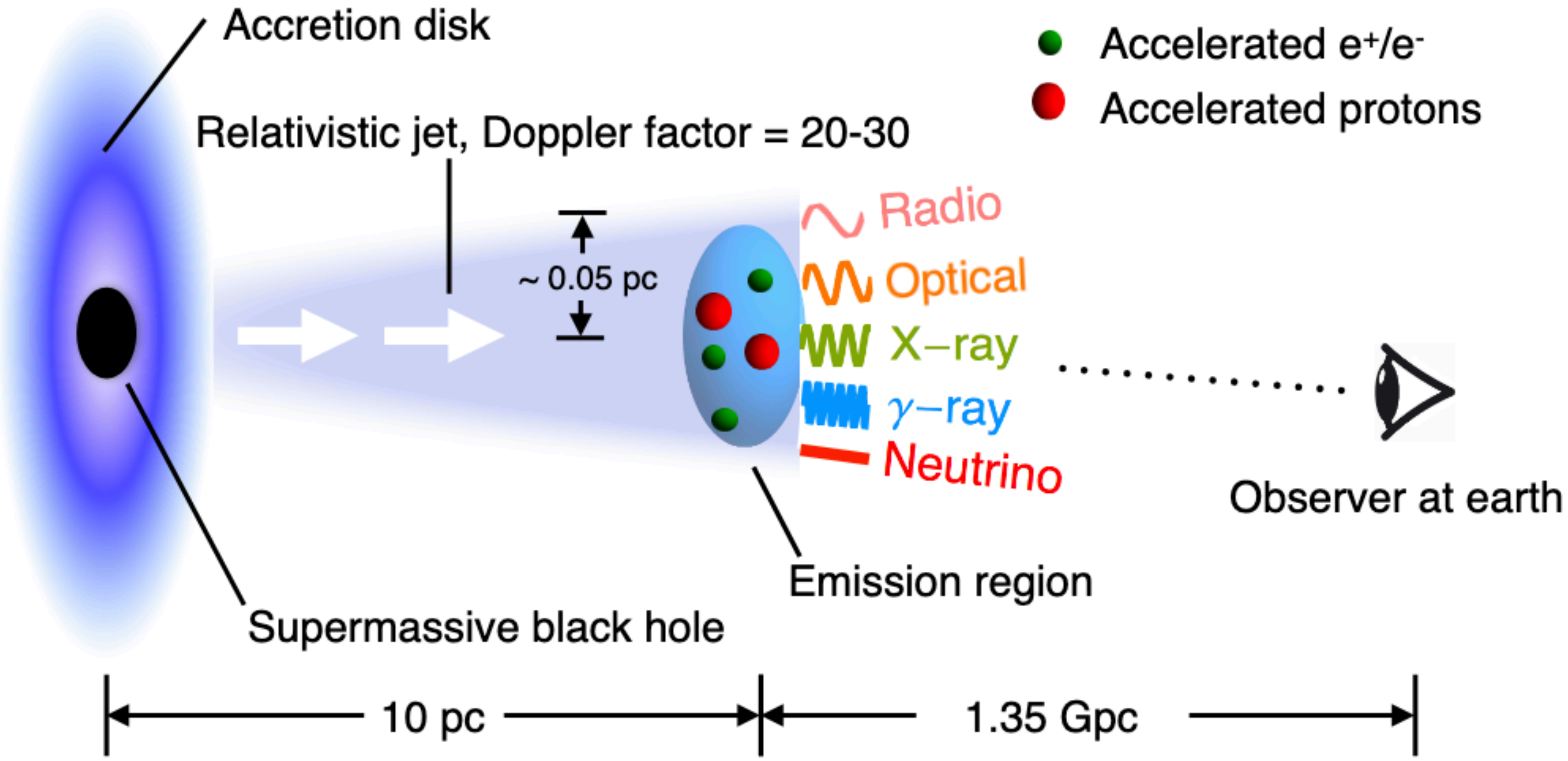


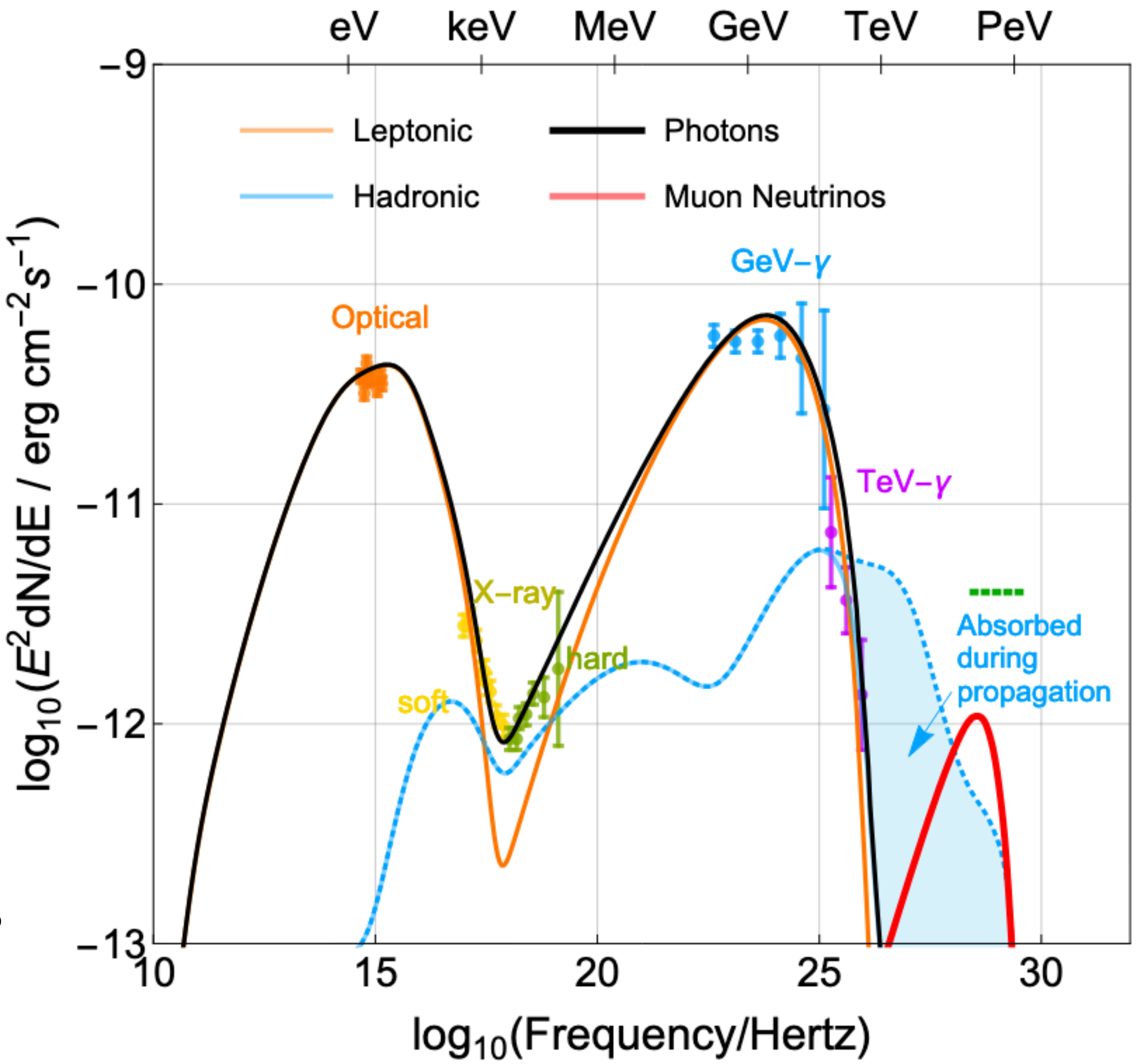
$L_\nu \sim 10^{46}$ erg/s

Gamma-ray flare

IceCube, 2019

TXS 0506+056 in 2017

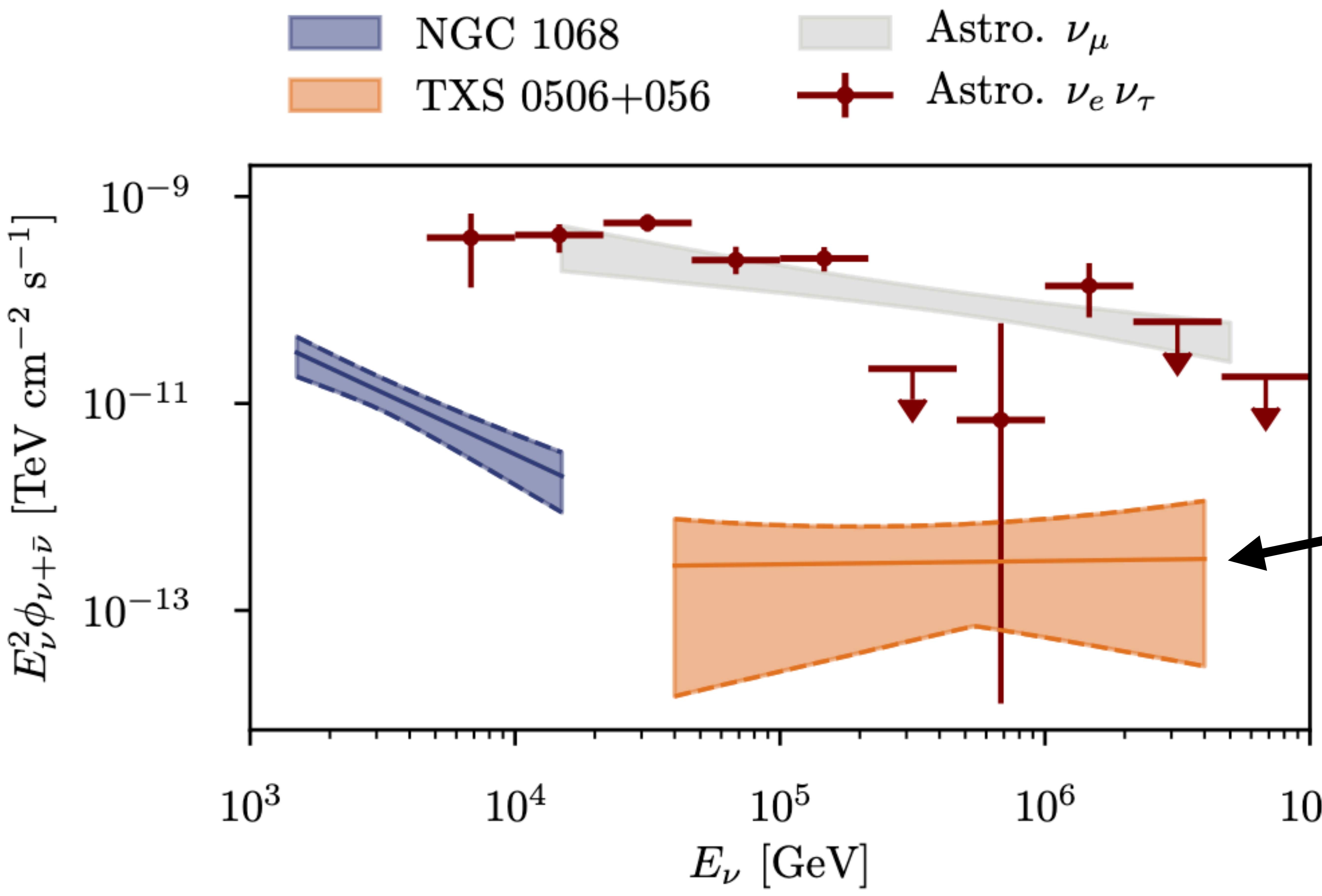




Leptohadronic models due to strong X-ray constraints

Gao et al., 2019 (see also Cerutti et al., 2018; Sahakyan, 2018; Gokus et al., 2018; Keivani et al., 2018, …)

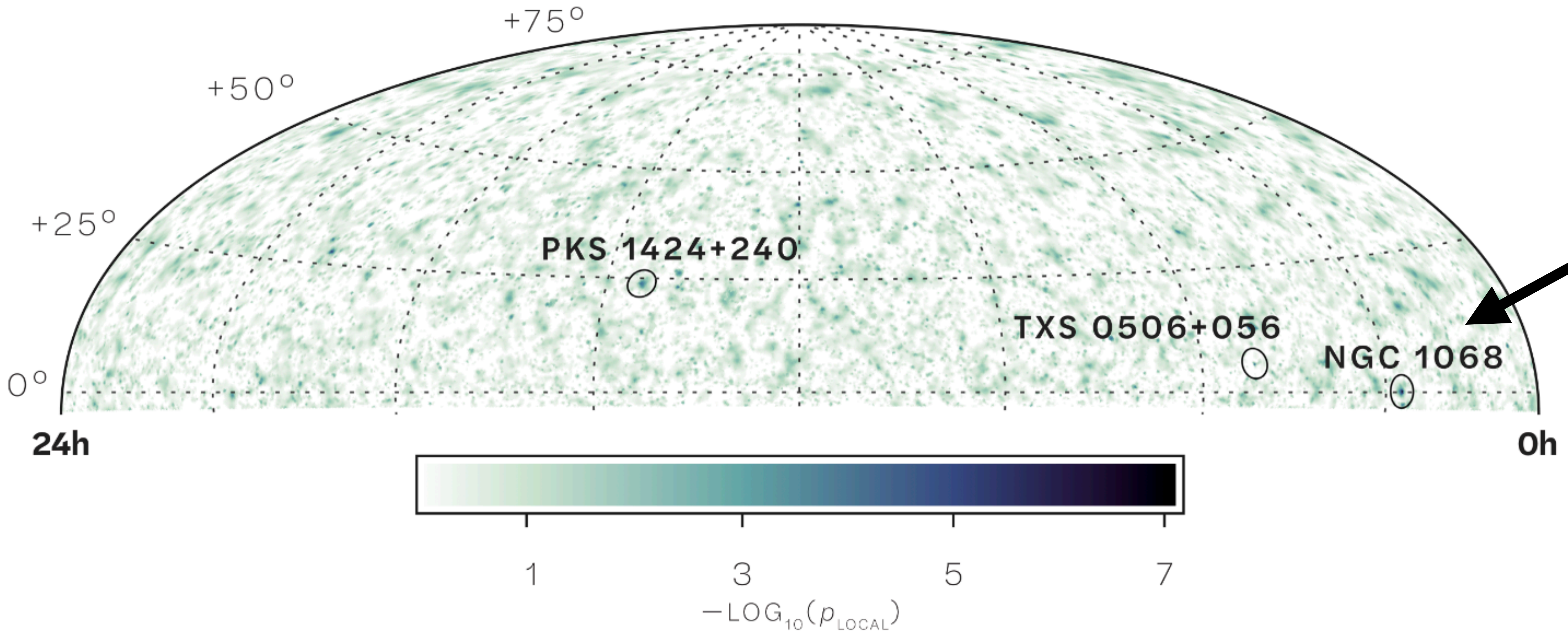
TXS 0506+056 in 10-years data



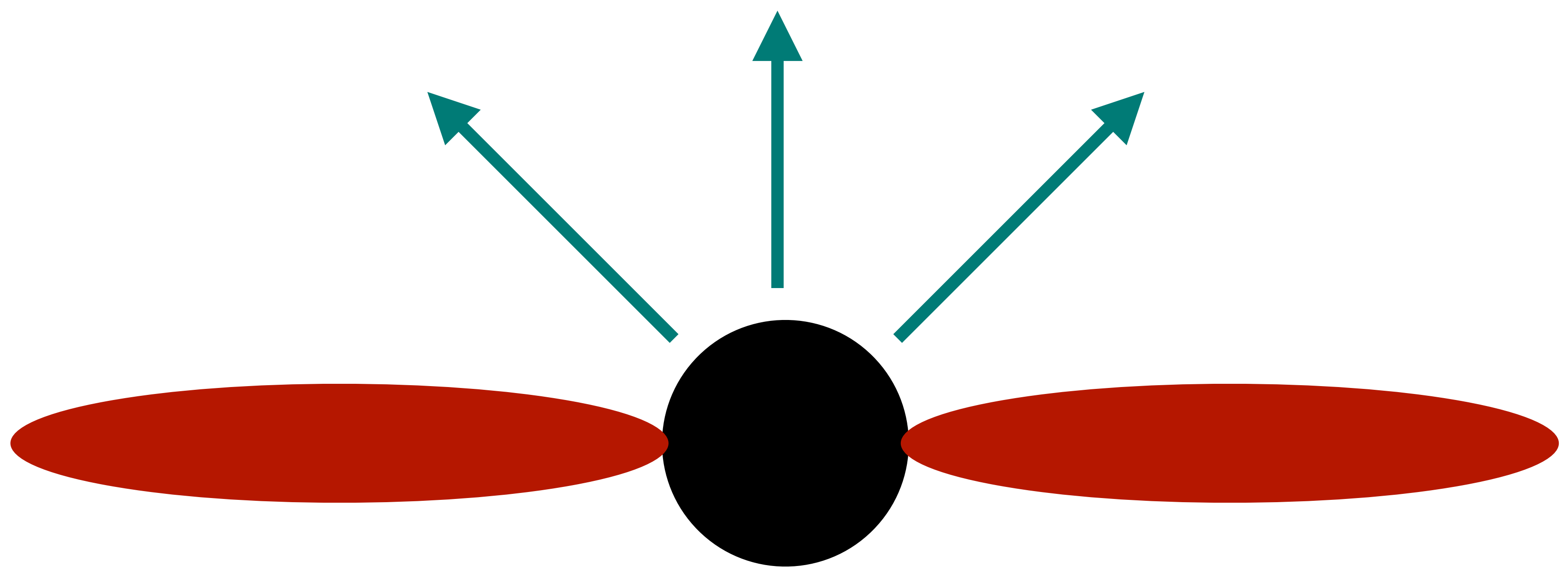
$L_\nu \sim 10^{44-45}$ erg/s

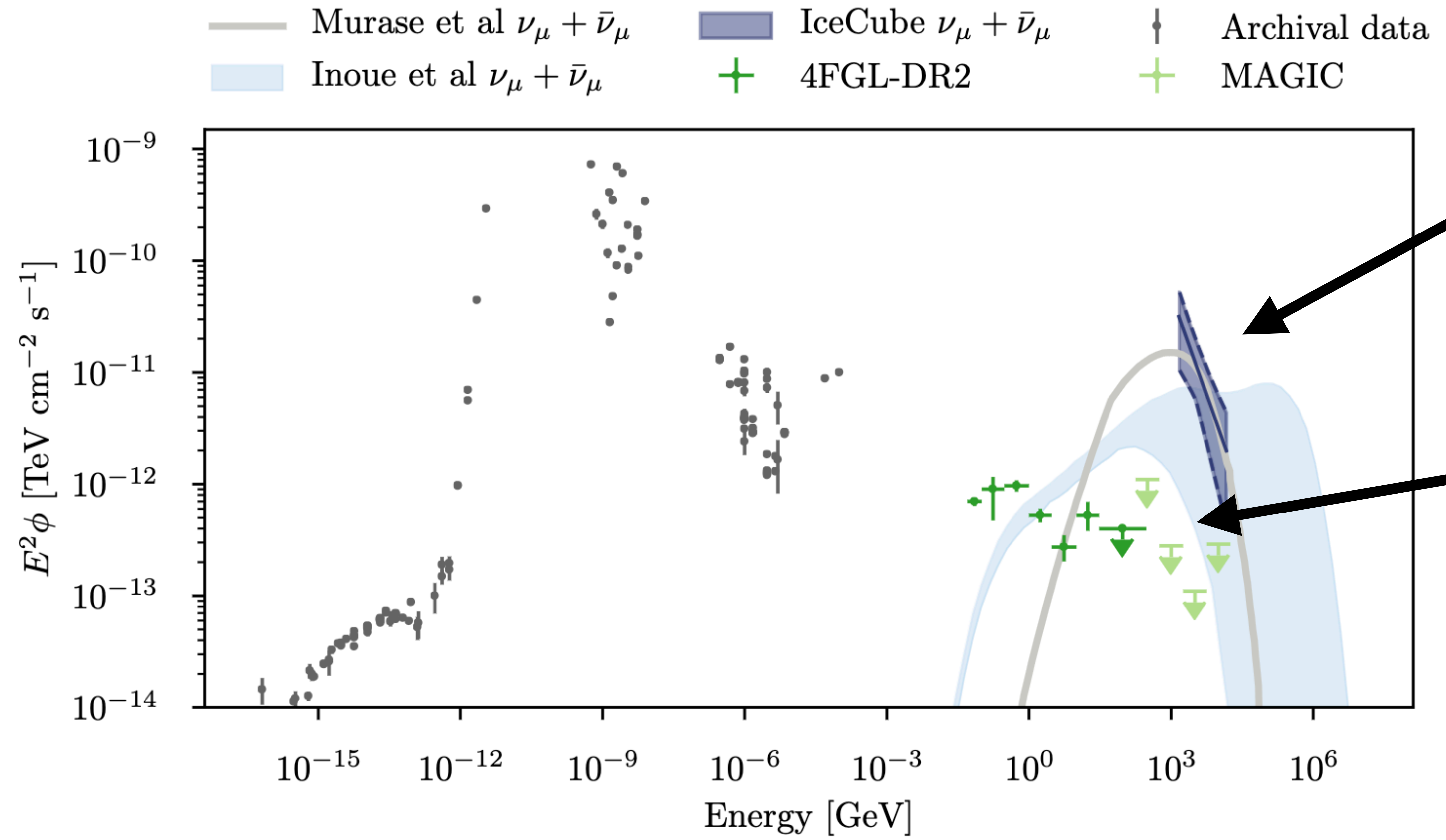
IceCube, 2022

Searches for point sources



Active Galactic Nucleus (AGN)



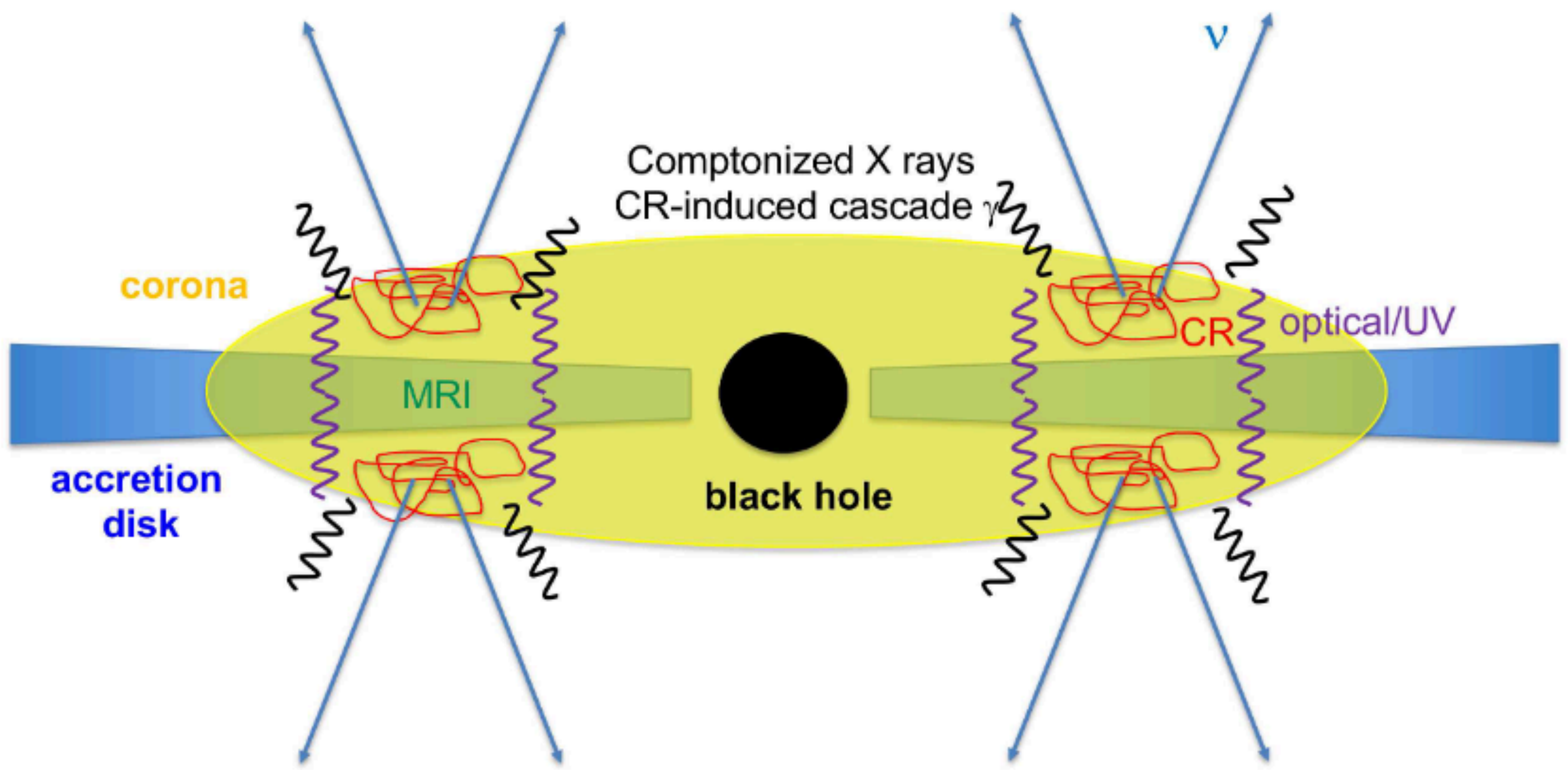


Soft ν production ($\propto E_\nu^{-3}$?)

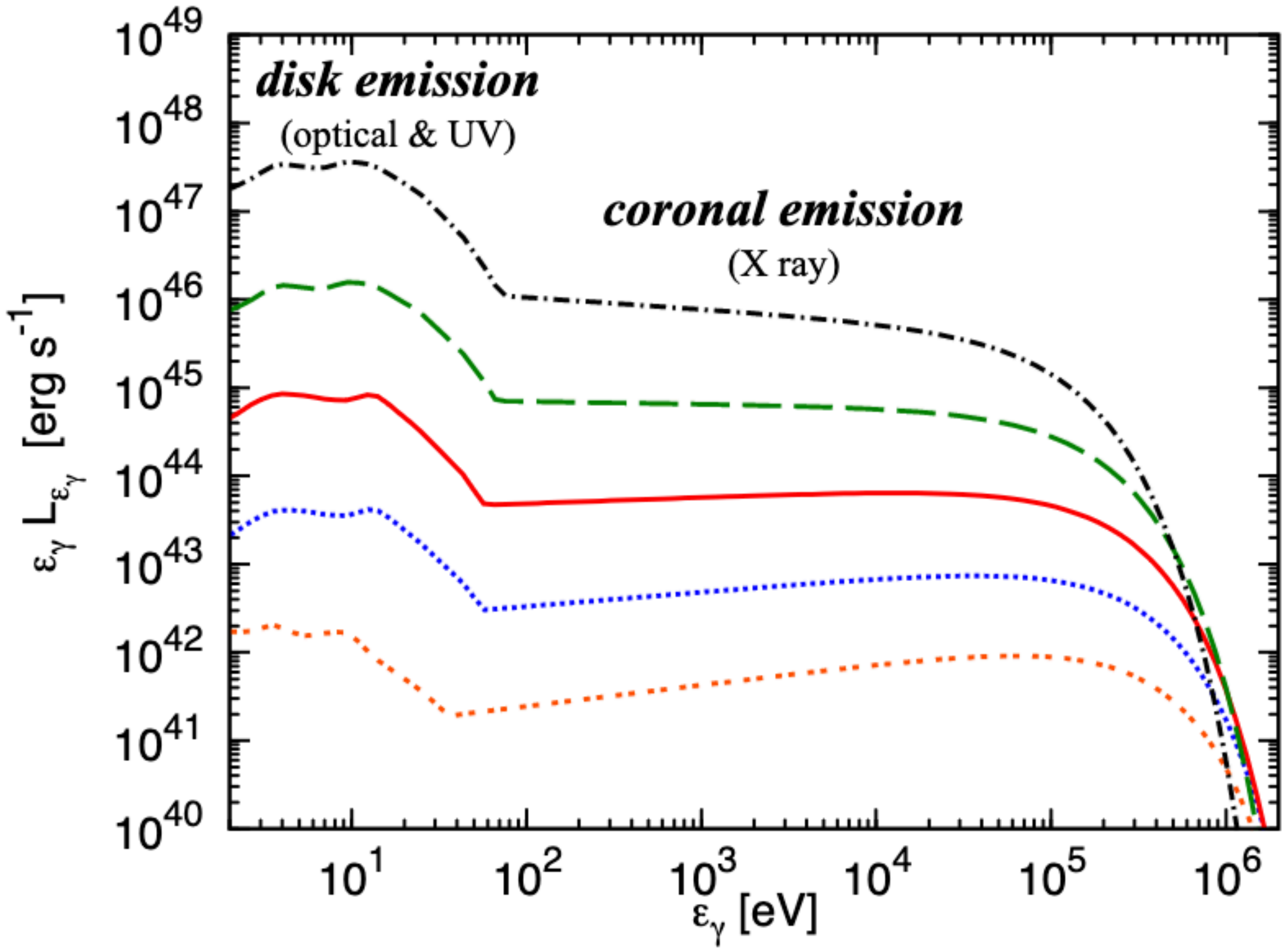
No associated γ

IceCube, 2022

Coronae in AGN

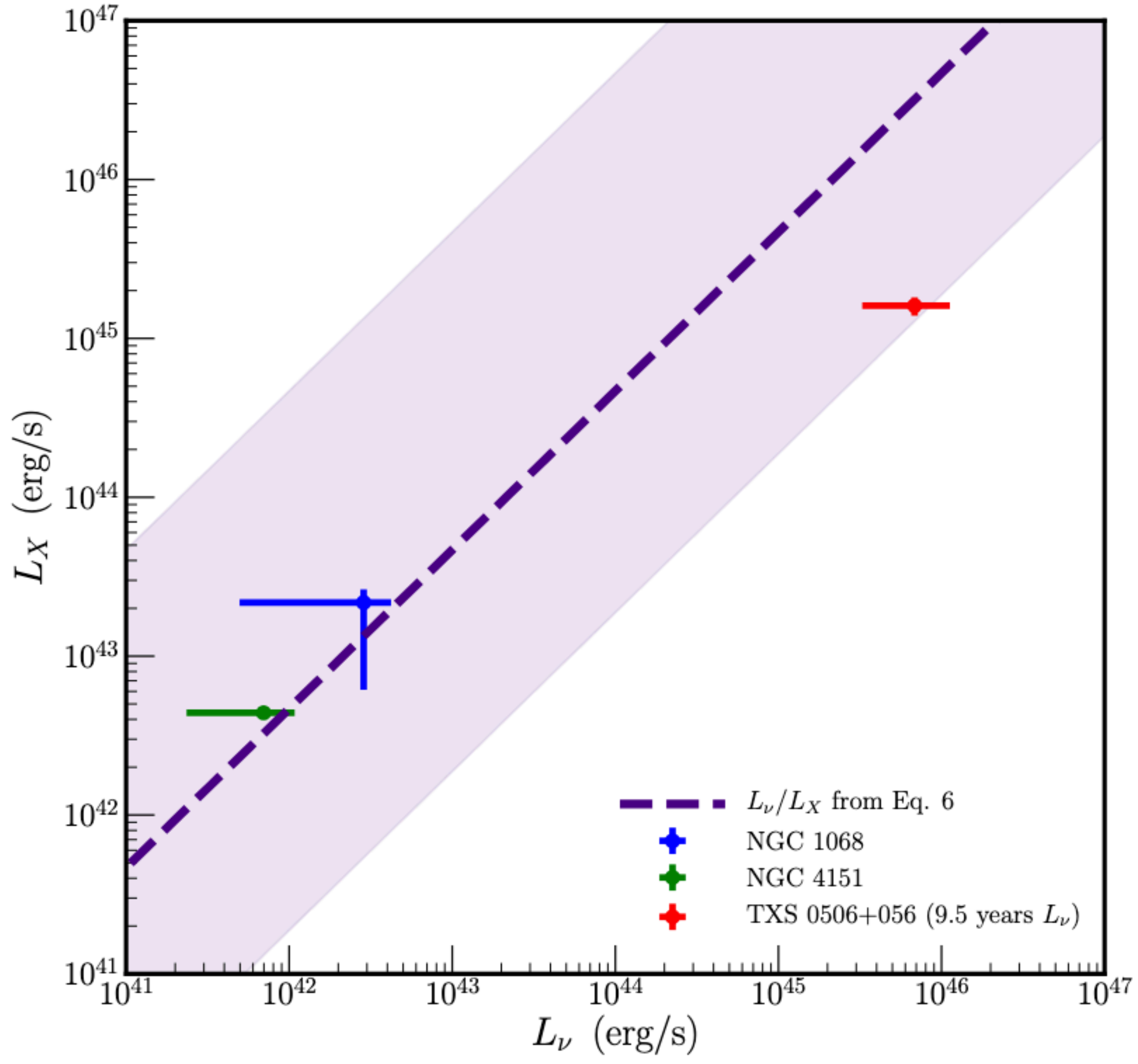


Inoue et al., 2019; Murase et al., 2019

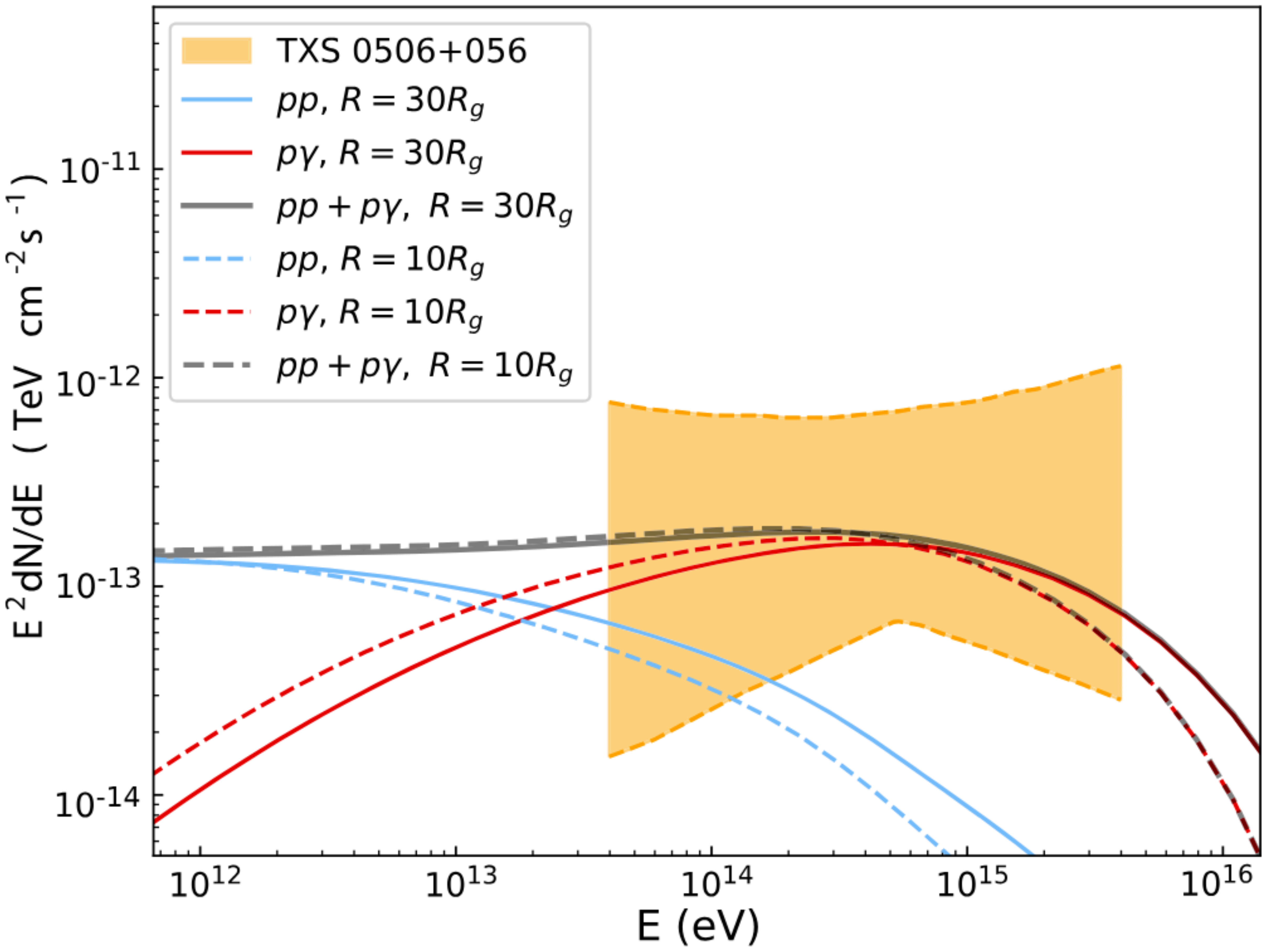


Figs. from Murase et al., 2019

Non-jetted origin of TXS neutrinos?



Khatee Zathul et al., 2024



Yang et al., 2024

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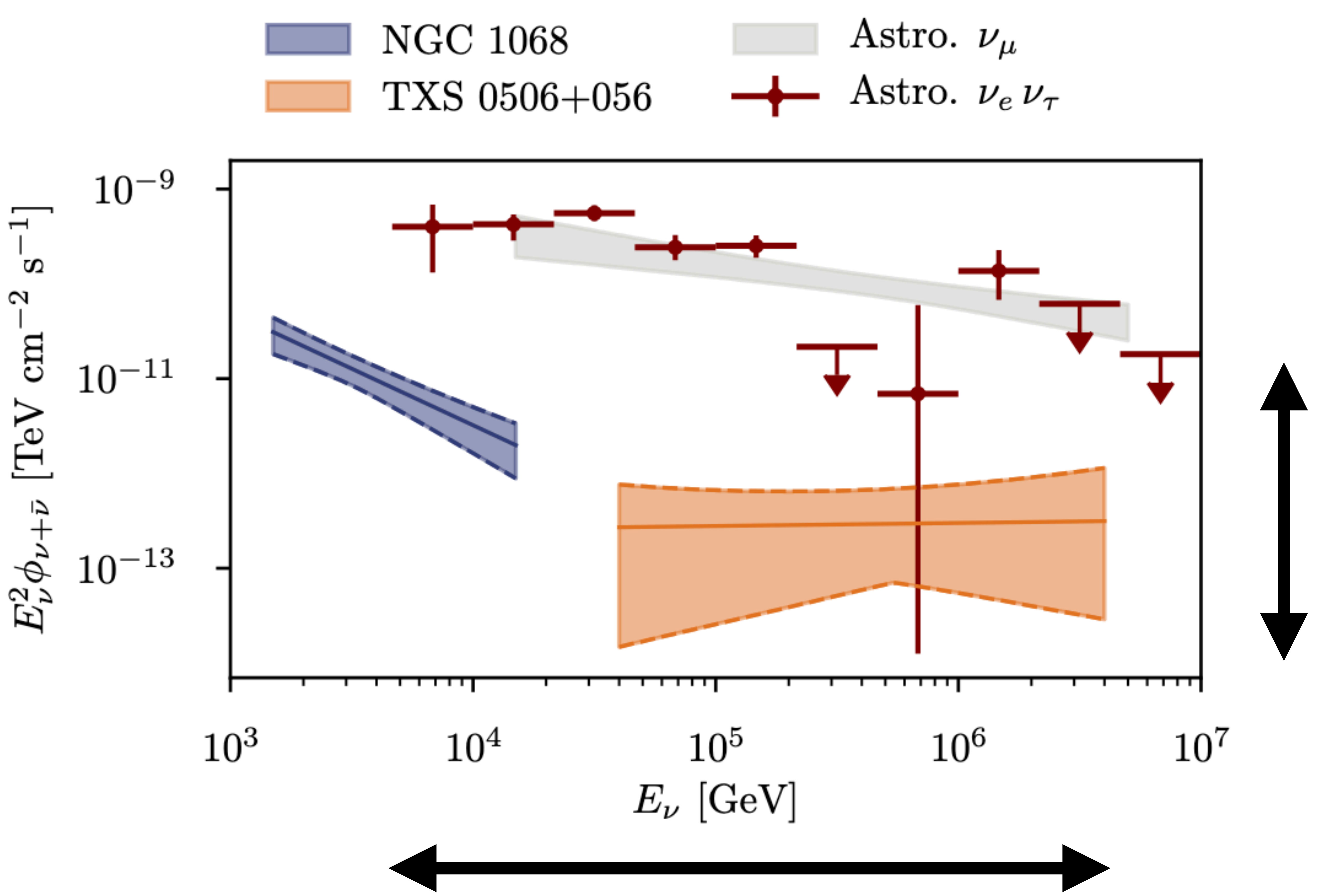
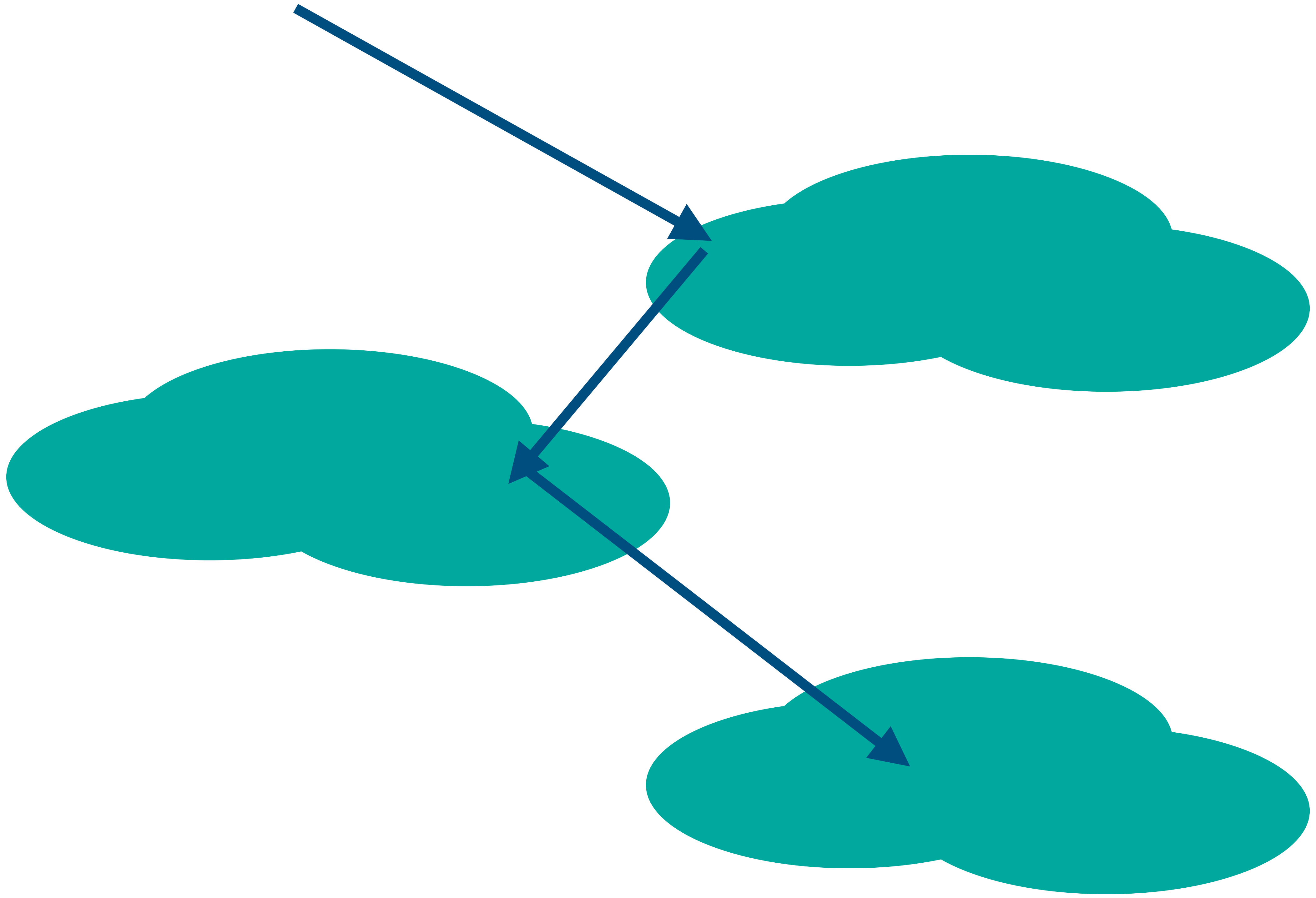
Main requirements: acceleration



Normalization: how much **energy budget** do we have?

Peak energy: how **rapid** is acceleration?

Acceleration in turbulence



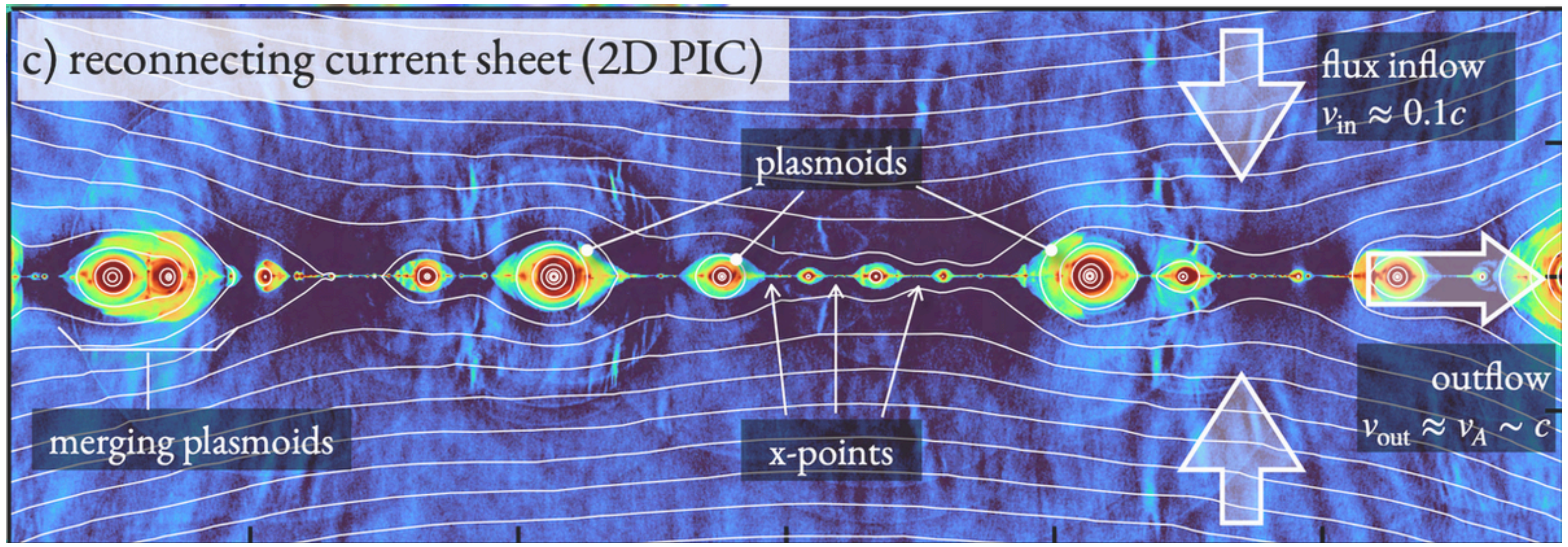
Slow acceleration mechanism

Maximum neutrino energies $\sim 1 - 10\,\mathrm{TeV}$

Too **slow** for TXS signal!

Magnetized turbulence (Murase et al., 2019; **DF**, Comisso, Peretti, Petropoulou, Sironi, 2024)

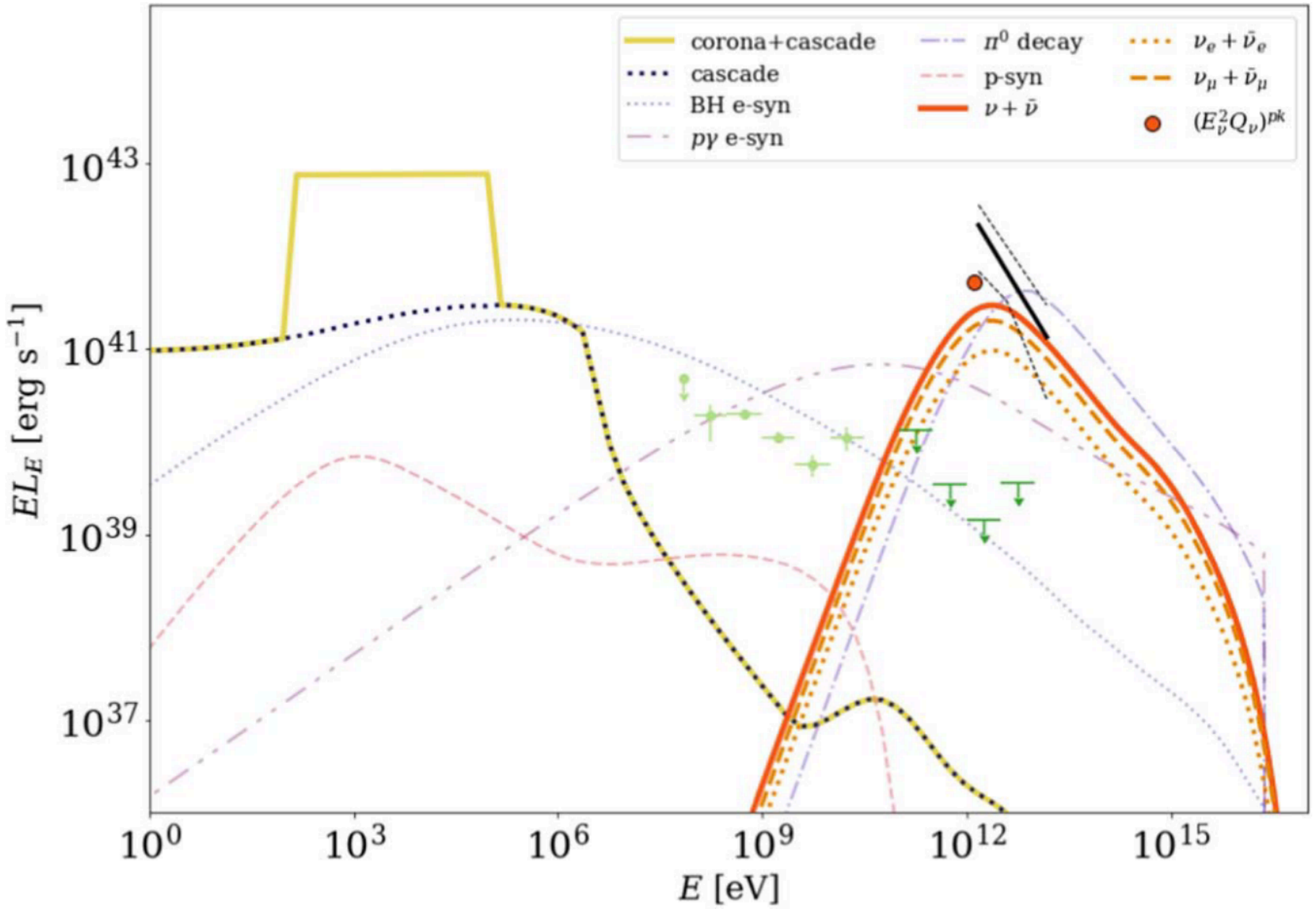
Acceleration in reconnection



Lee et al., 2020

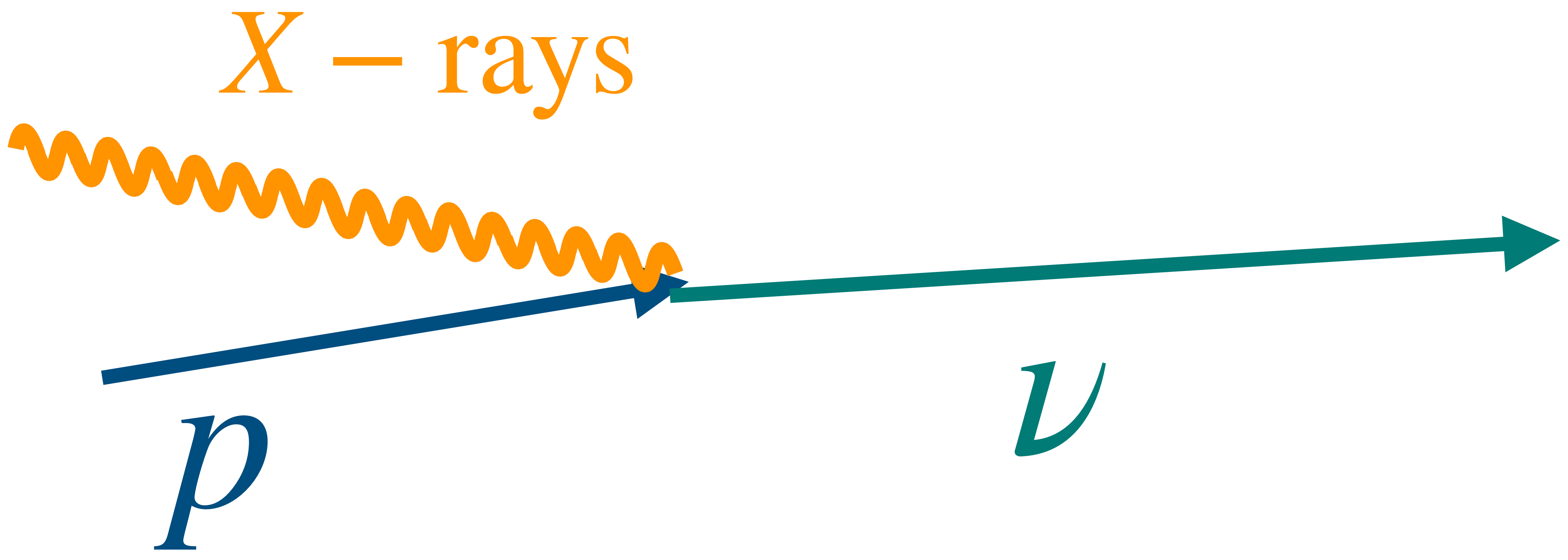
Fast acceleration

Peak neutrino energies can range from 1 TeV to 10 PeV



Magnetic reconnection (**DF**, Petropoulou, Comisso, Peretti, Sironi, 2023)

Reconnection: energy budget



$$L_\nu \propto L_X \, L_p$$

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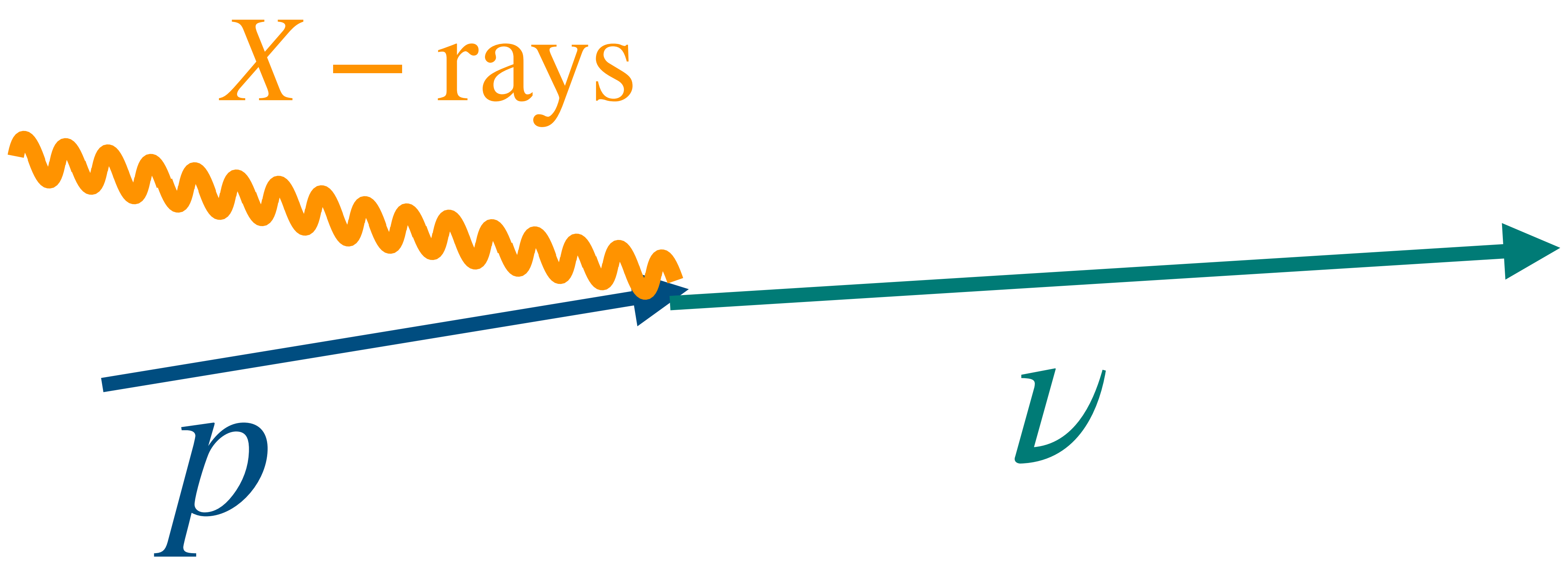

$$L_\nu \propto L_X \, L_p$$

- L_X cannot be directly observed
- We infer it from luminosity of O II and O III lines
- $L_X \simeq 4 \times 10^{43-44}$ erg/s between 0.1-100 keV

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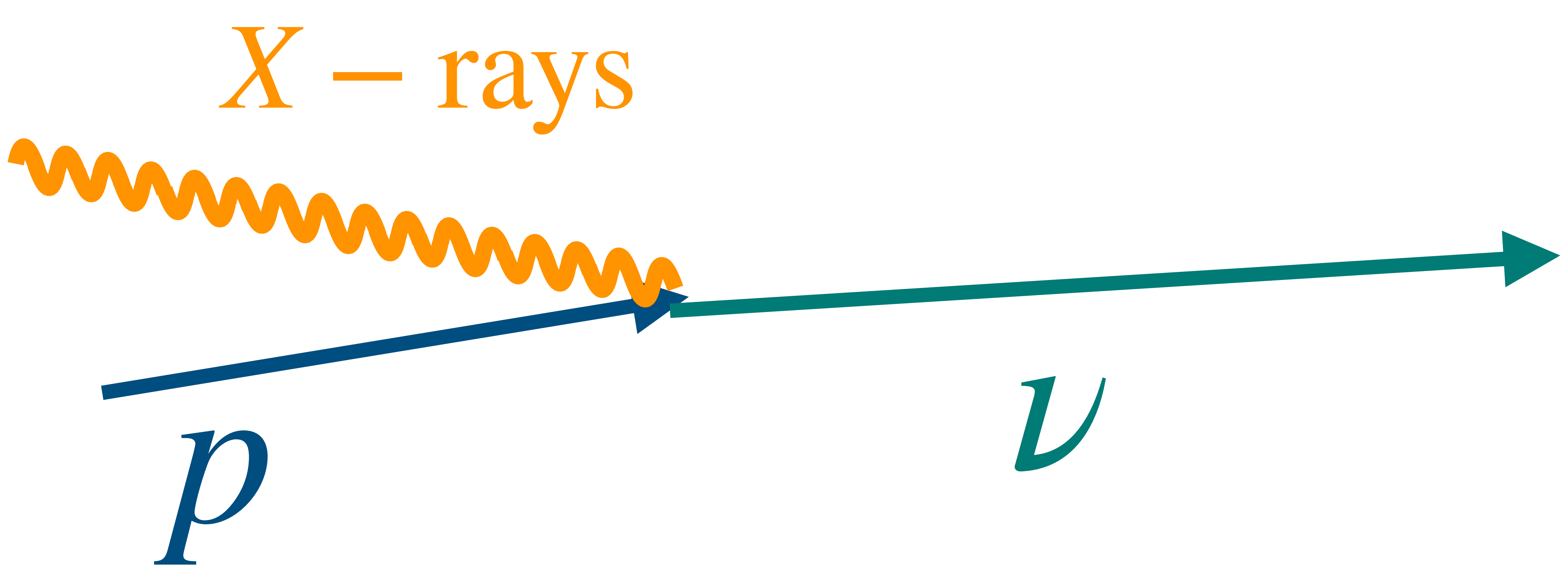

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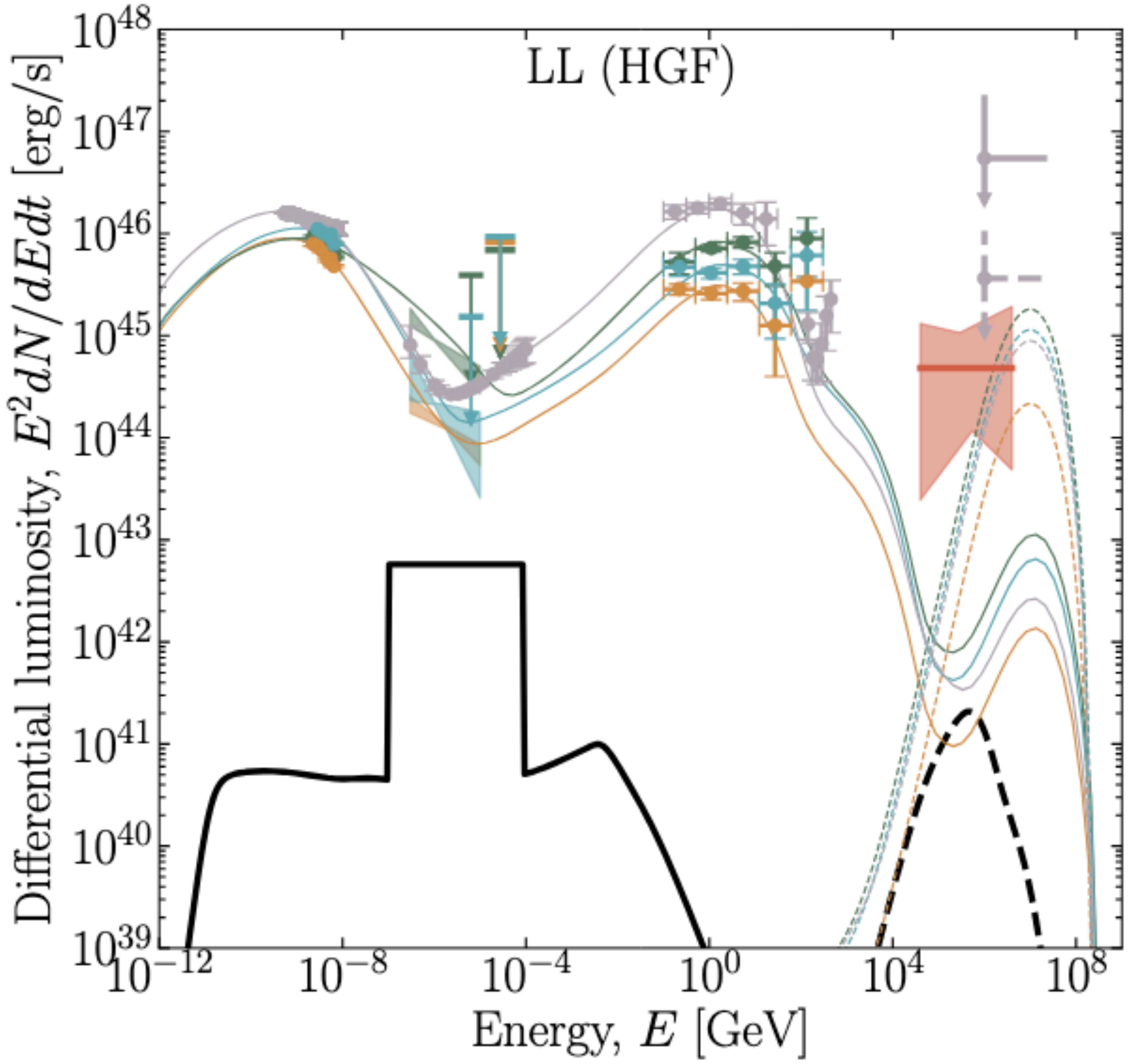
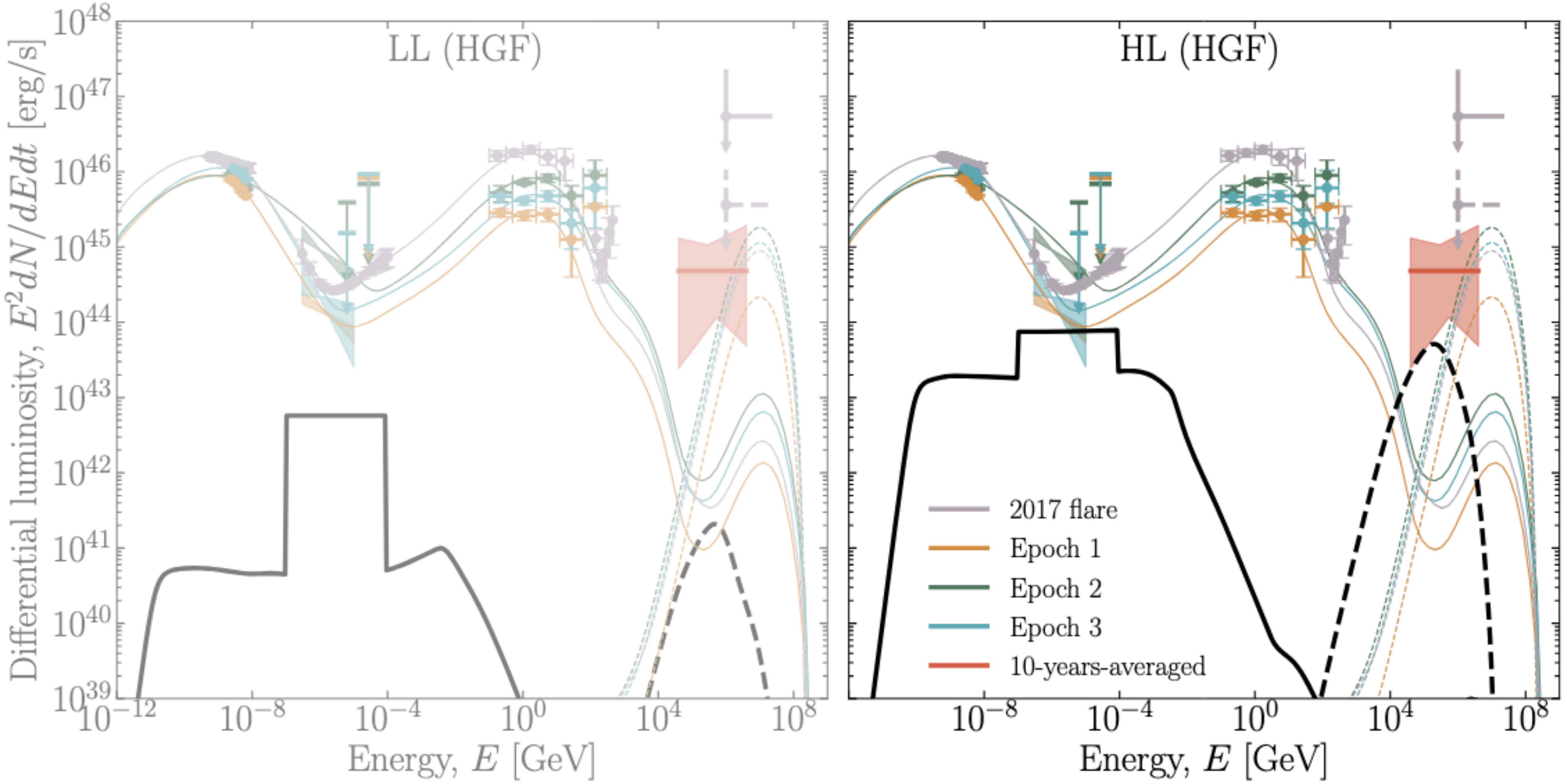
- In magnetic reconnection layer, $L_p \sim 0.2 L_X$
- We take as extreme case $L_p \sim 2 L_X$

Spectral emission from TXS corona



Simulations using AM3 (Klinger et al., 2023)

Spectral emission from TXS corona



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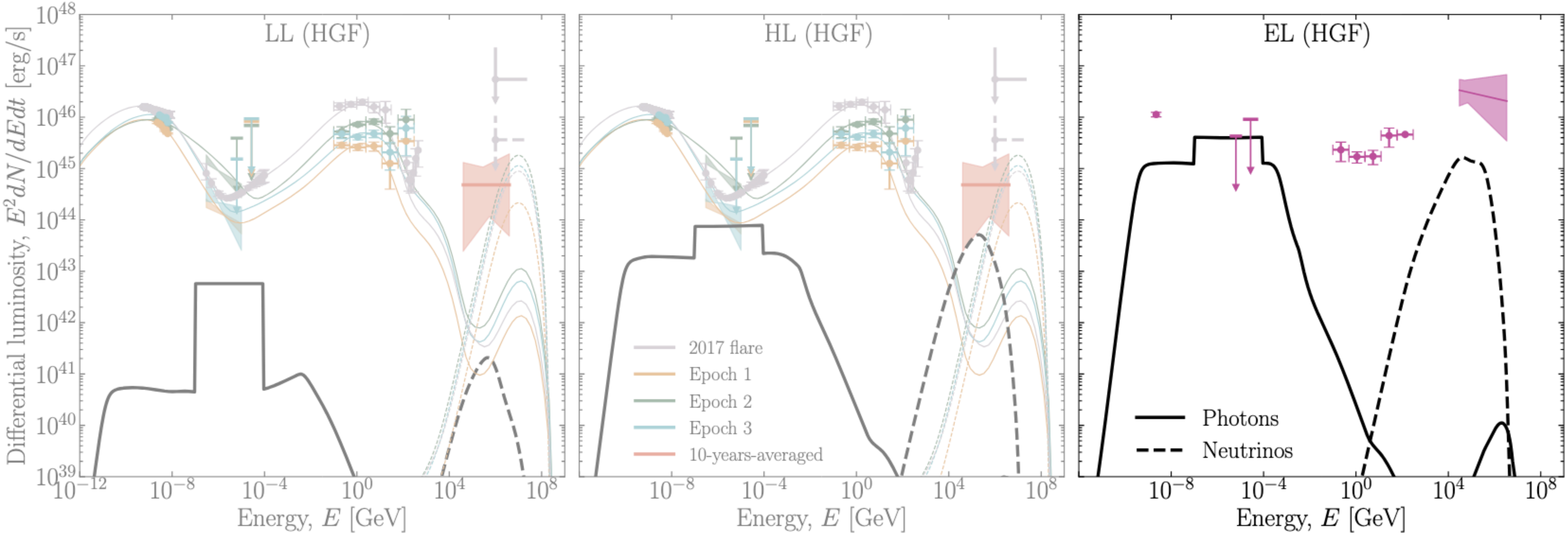

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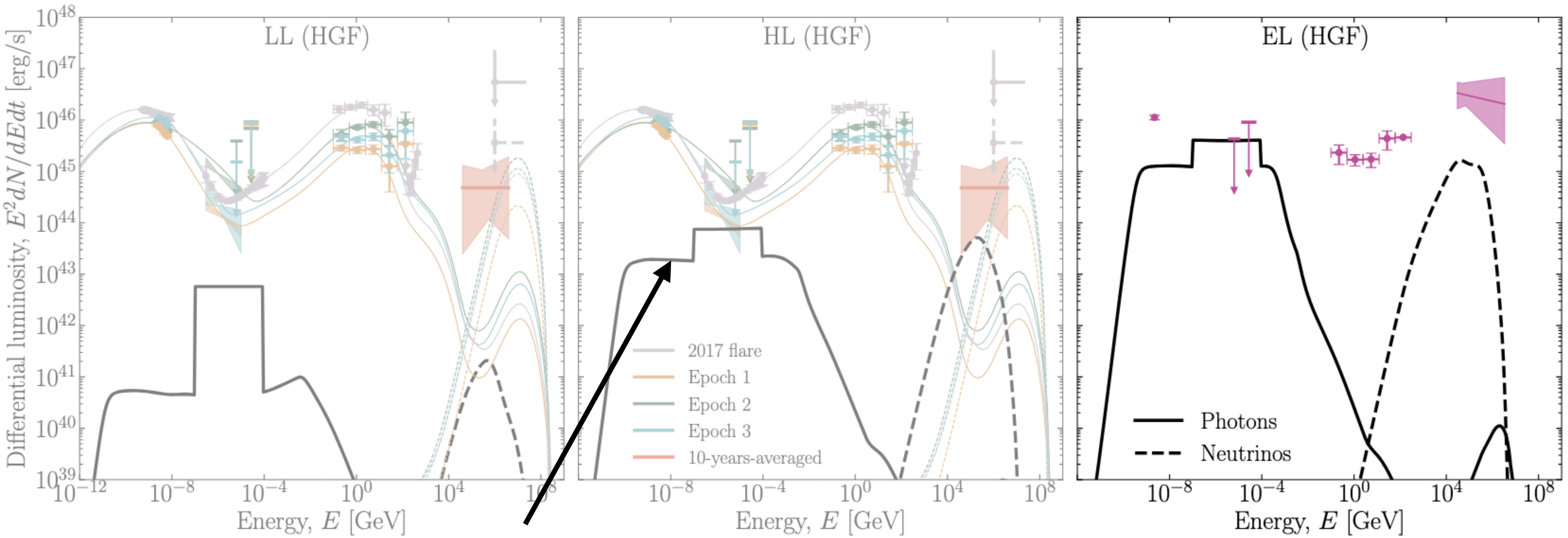


Cascade crucial multi-messenger target (see Testagrossa)

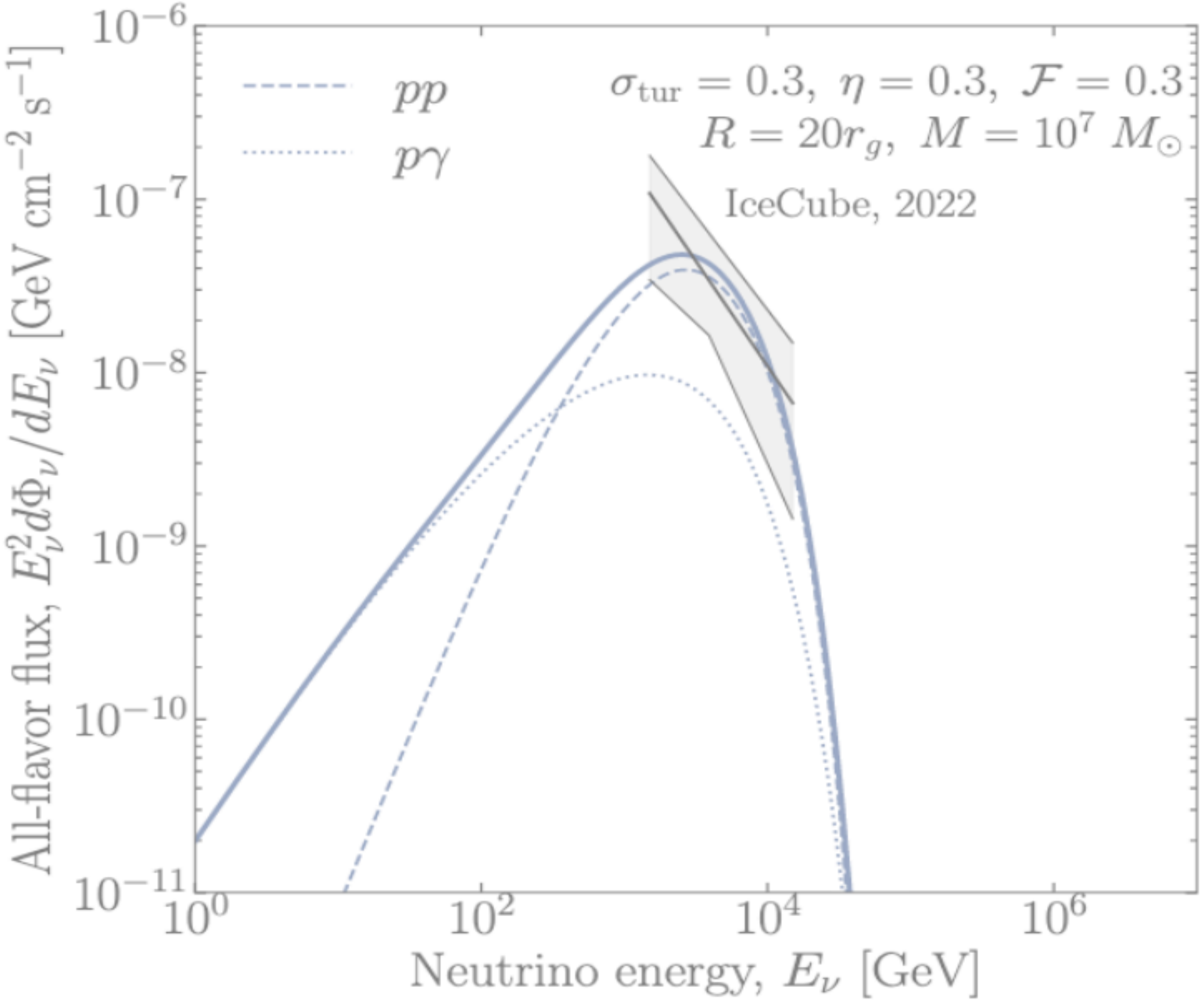
Simulations using AM3 (Klinger et al., 2023)

Conclusions

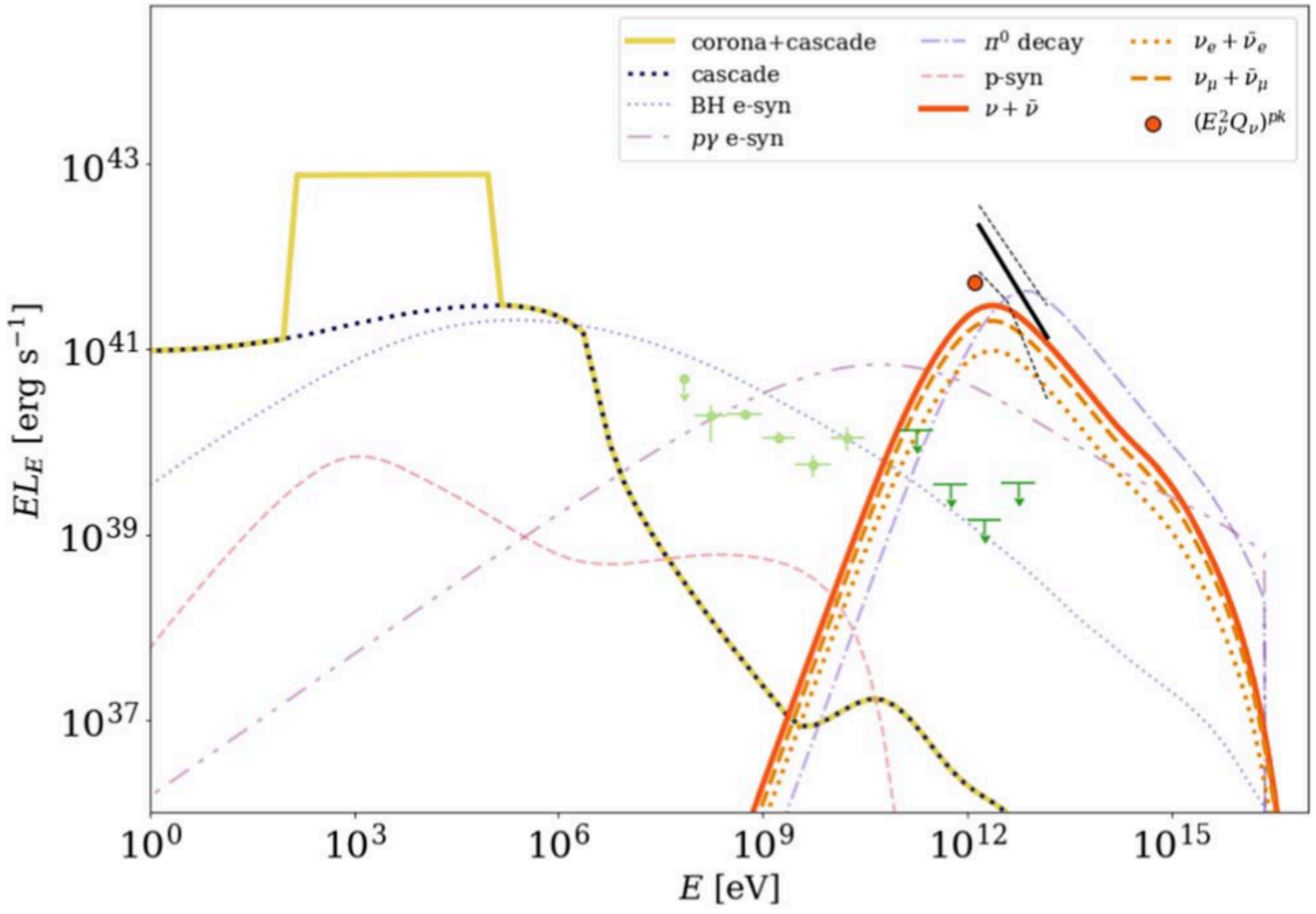
- If neutrinos are coronal, or from inner regions, we need
  - Reconnection (or rapid acceleration)
  - L_X comparable with jet luminosities (disfavored by AGN correlations)
  - $L_p \gg L_X$ (disfavored by PIC simulations)
- Time variability, population studies, as complementary observables

Backup slides

Coronal emission



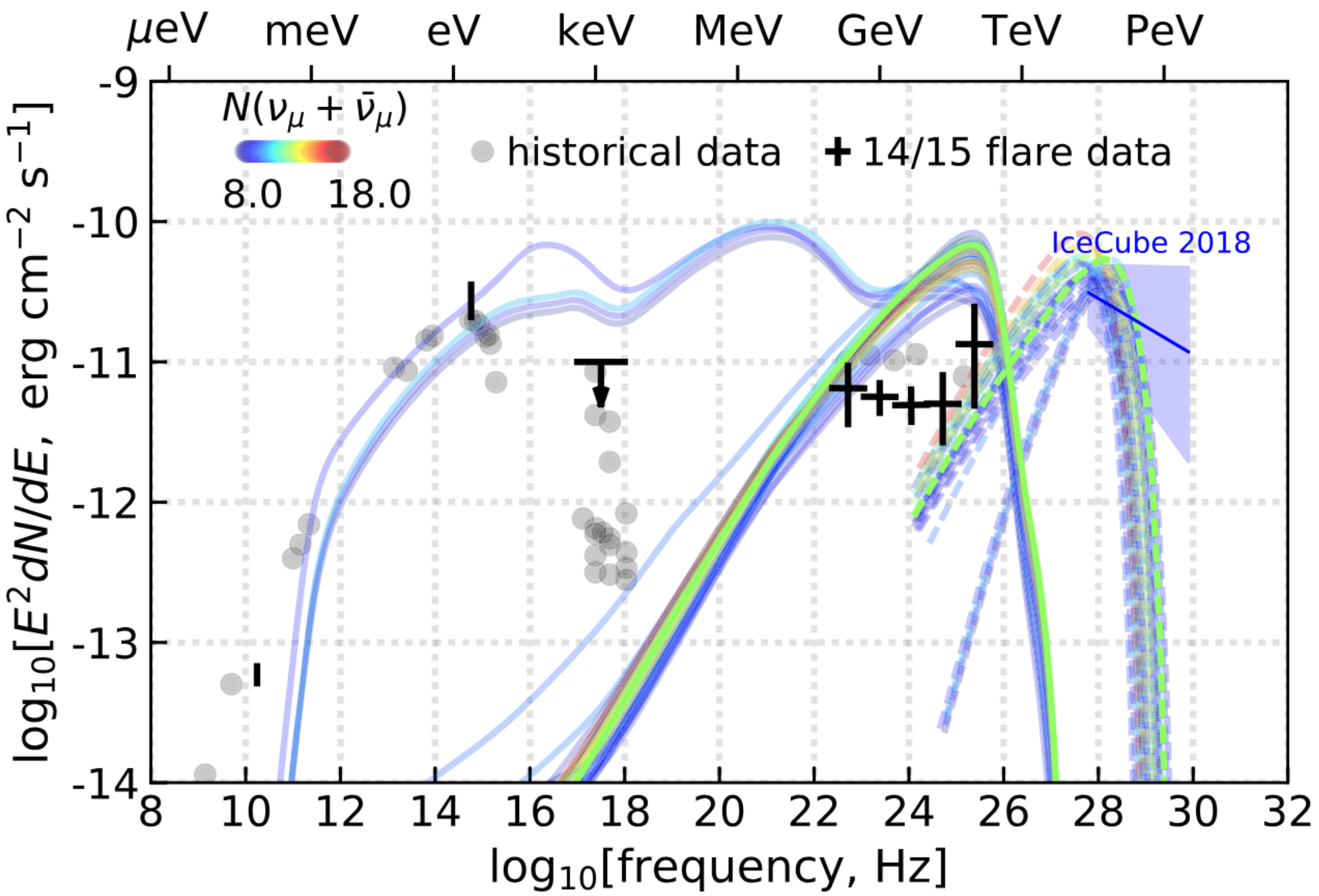
Magnetized turbulence (Murase et al., 2019; **DF**, Comisso, Peretti, Petropoulou, Sironi, 2024)



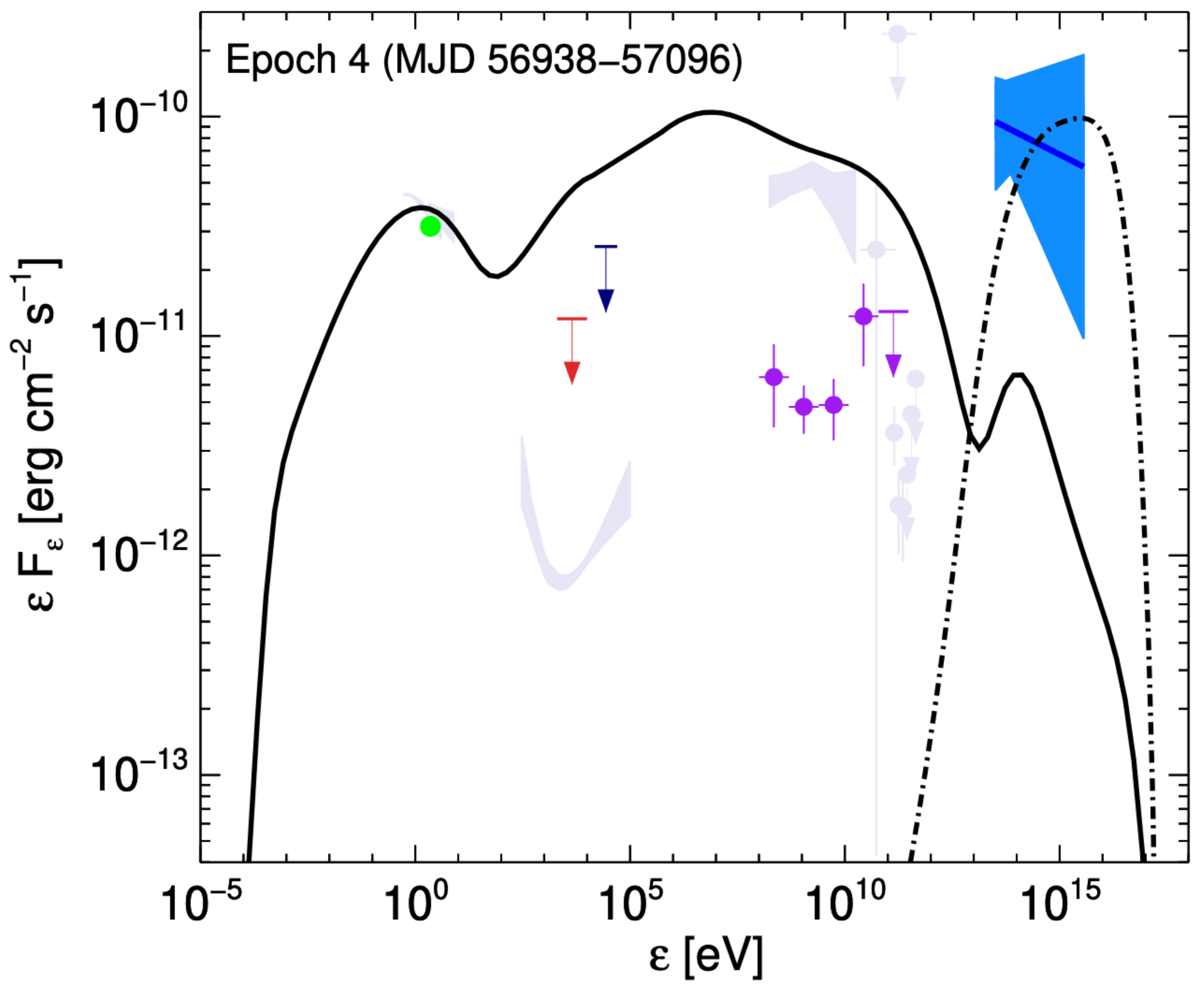
Magnetic reconnection (**DF**, Petropoulou, Comisso, Peretti, Sironi, 2023)

TXS 0506+056 in 2014/15

Neutrino flux much larger than gamma-rays!

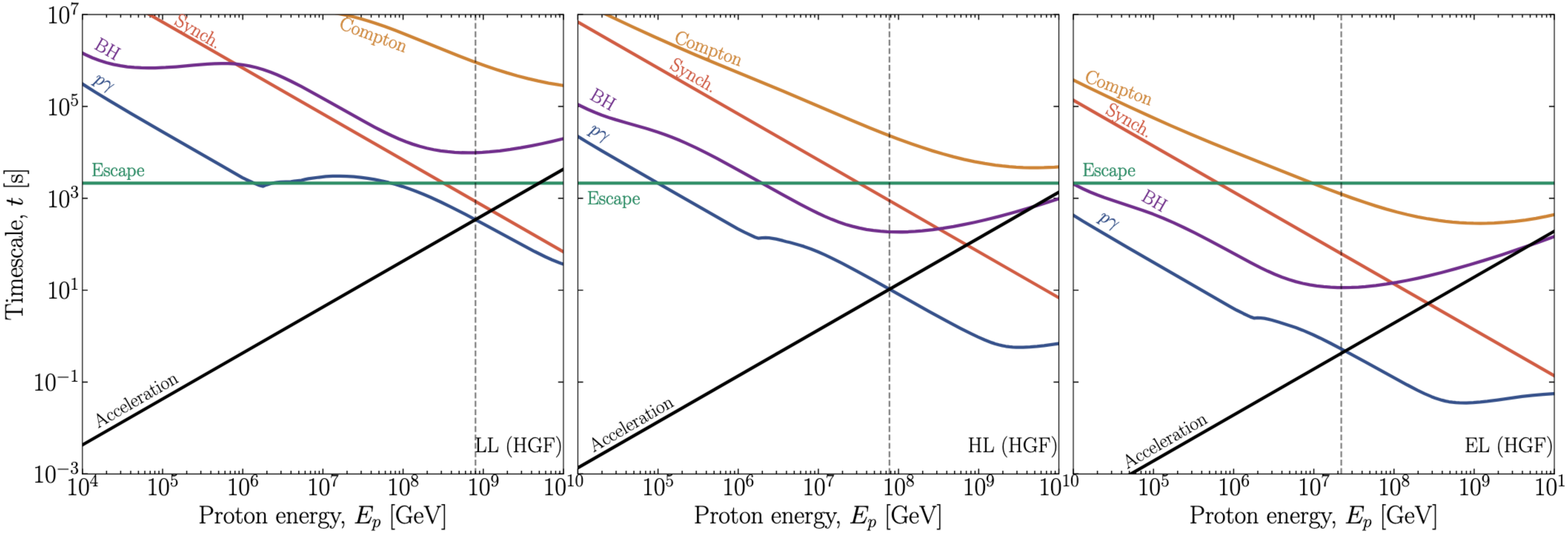


Rodrigues et al., 2019

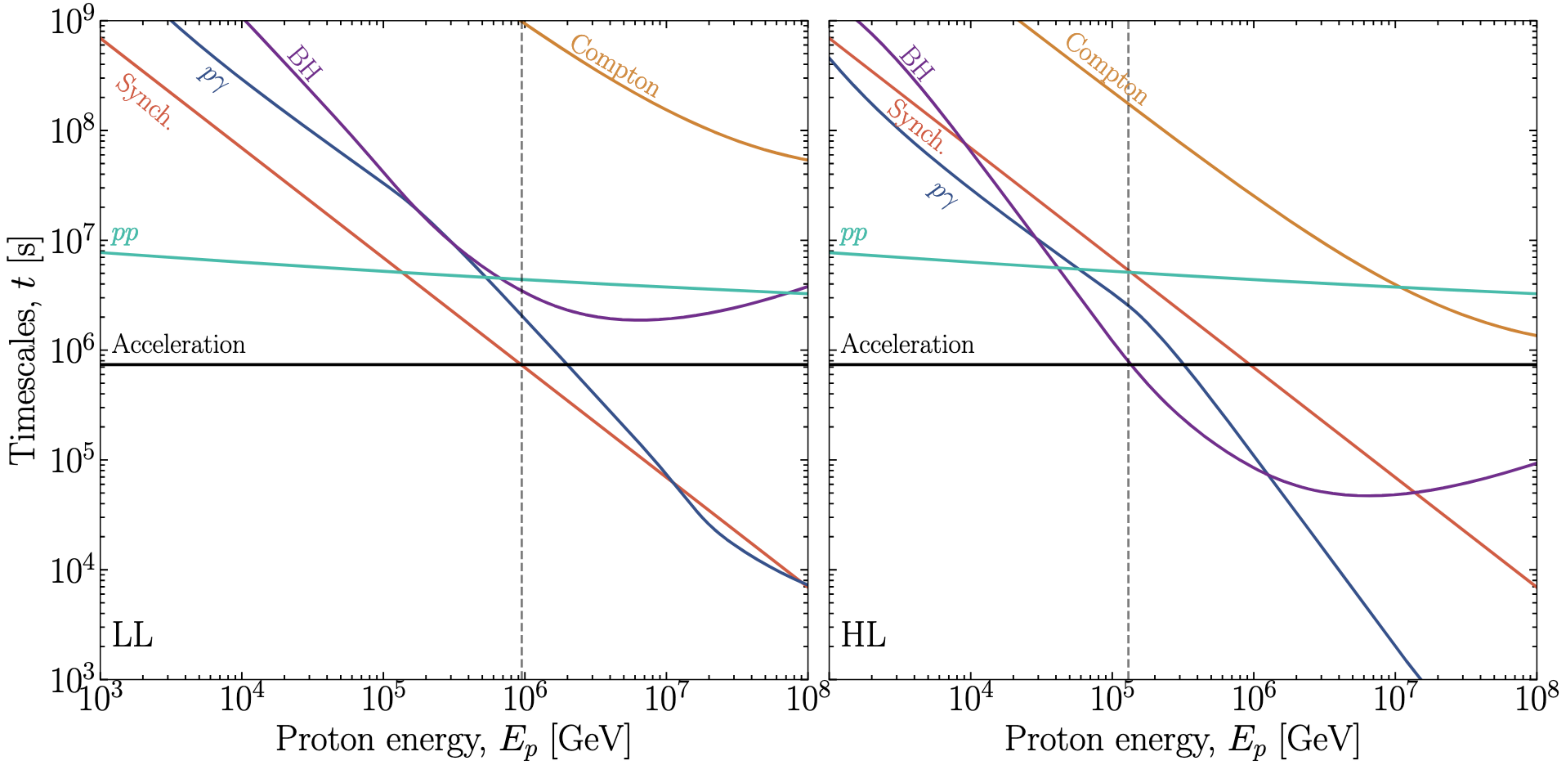


Petropoulou et al., 2019

Timescales for magnetic reconnection



Timescales for magnetic turbulence



Estimated coronal properties

Magnetic dissipation rate comparable with X-ray luminosity

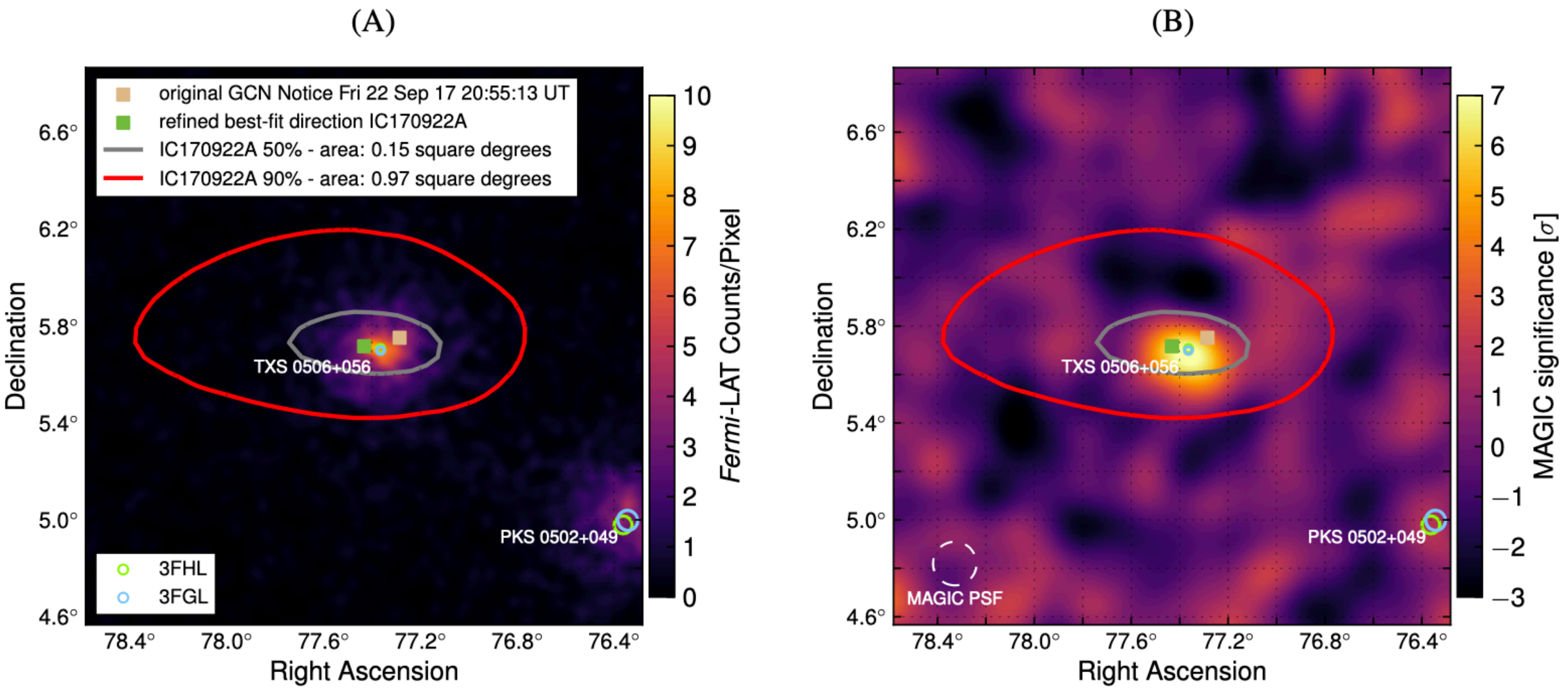
$$B = \left(\frac{L_X}{\eta_X c \beta_{\rm rec} R^2}\right)^{1/2} \simeq 1.3\, L_{X,43}^{1/2} \eta_{X,-0.3}^{-1/2} \beta_{\rm rec,-1}^{-1/2} R_{13.8}^{-1}\ {\rm kG}. \quad (1)$$

$$n_p \sim 10^{1-3}\ \mathrm{cm}^3$$

$$\sigma \sim 10 - 100,\ \sigma_p \sim 10^{5-7}$$

Parameter	TXS (LL)	TXS (HL)	TXS (EL)
L_X [10^{43} erg/s]	4	40	2×10^3
L_p [10^{43} erg/s]	0.8	80	4×10^3
B [kG]	2.6	8.1	57.3
η_p	0.1	1	1

TXS 0506+056 in 2017



Astrophysical neutrino production

$\mathbf{pp} \to \pi^+\pi^-\pi^0$

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$$\mathbf{pp} \rightarrow \pi^+\pi^-\pi^0$$

$$\mathbf{p}\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n\pi^+, & \text{1/3 of all cases} \\ p\pi^0, & \text{2/3 of all cases} \end{cases}$$

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Pion decay

$$\pi^+ \rightarrow \mu^+\nu_\mu$$

$$\hookrightarrow e^+\nu_e\bar{\nu}_\mu$$

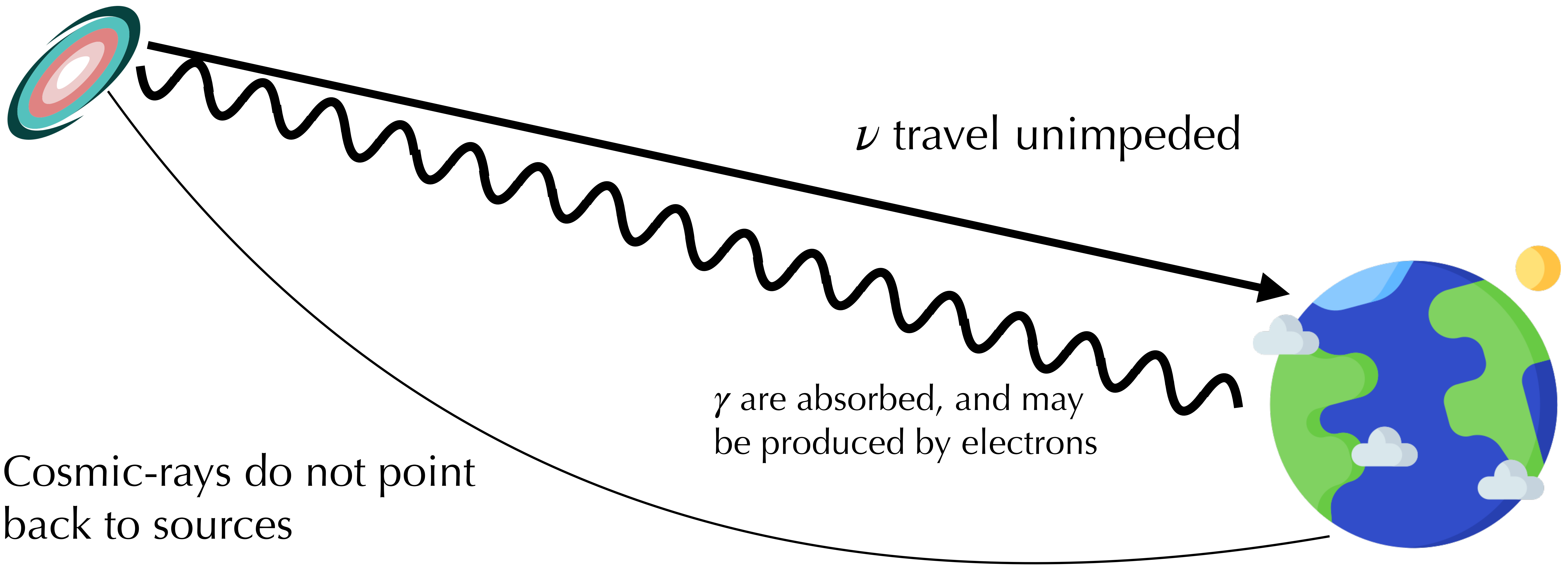
$$\pi^0 \rightarrow \gamma\gamma$$

Multi-messenger connection

$$E_\nu \simeq E_p/20!$$

Neutrino astrophysics

- What is the origin of cosmic-rays?
  - How can we test the presence of cosmic-rays in a given source?



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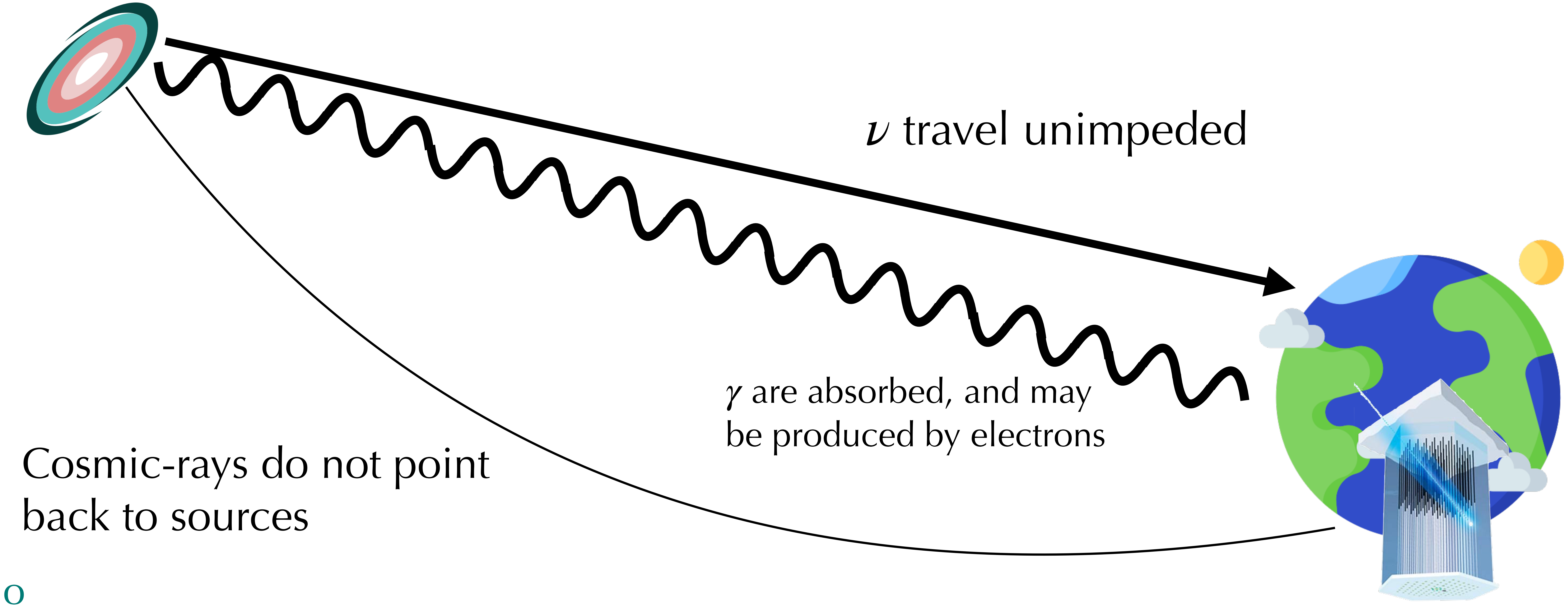
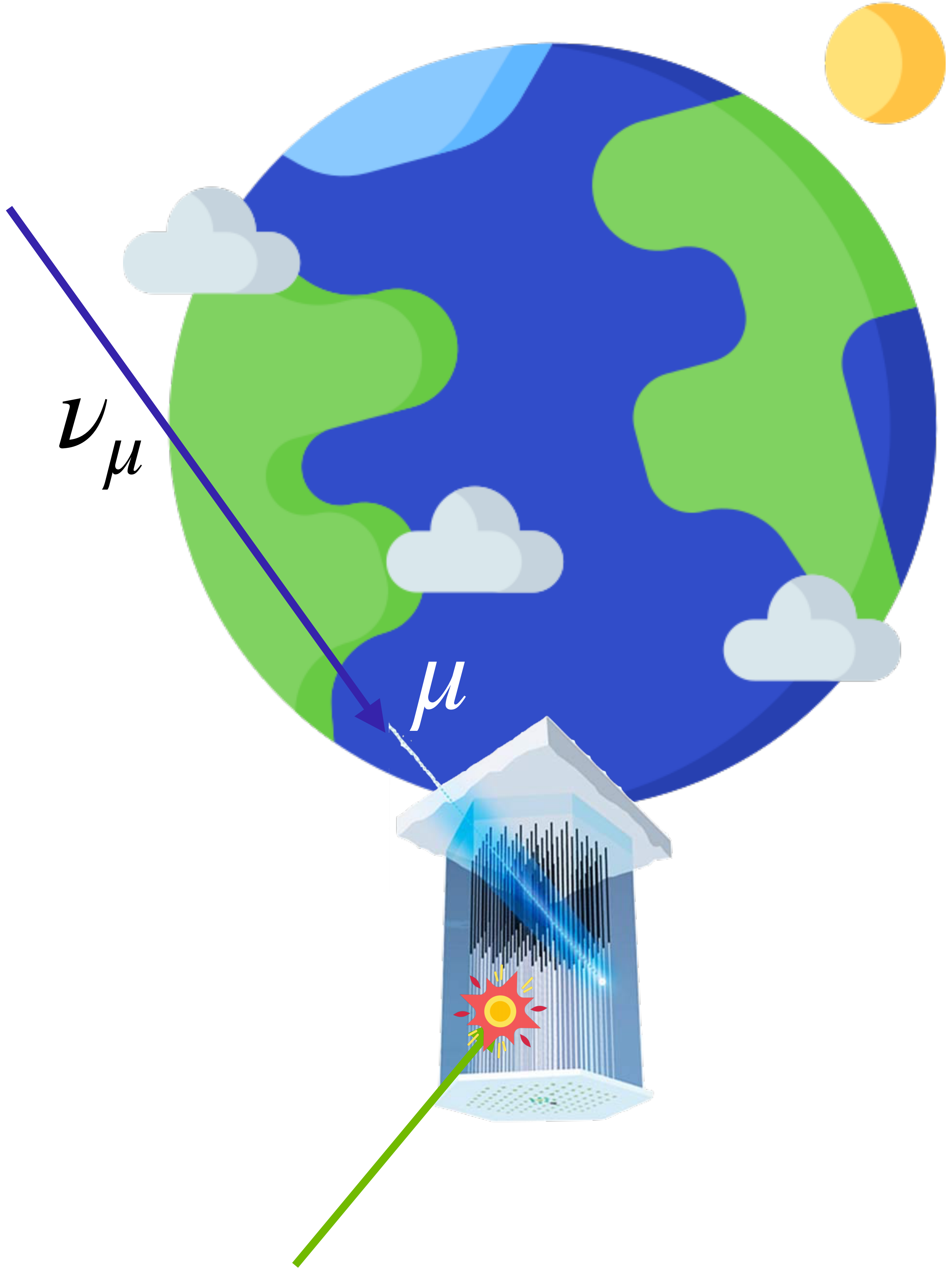
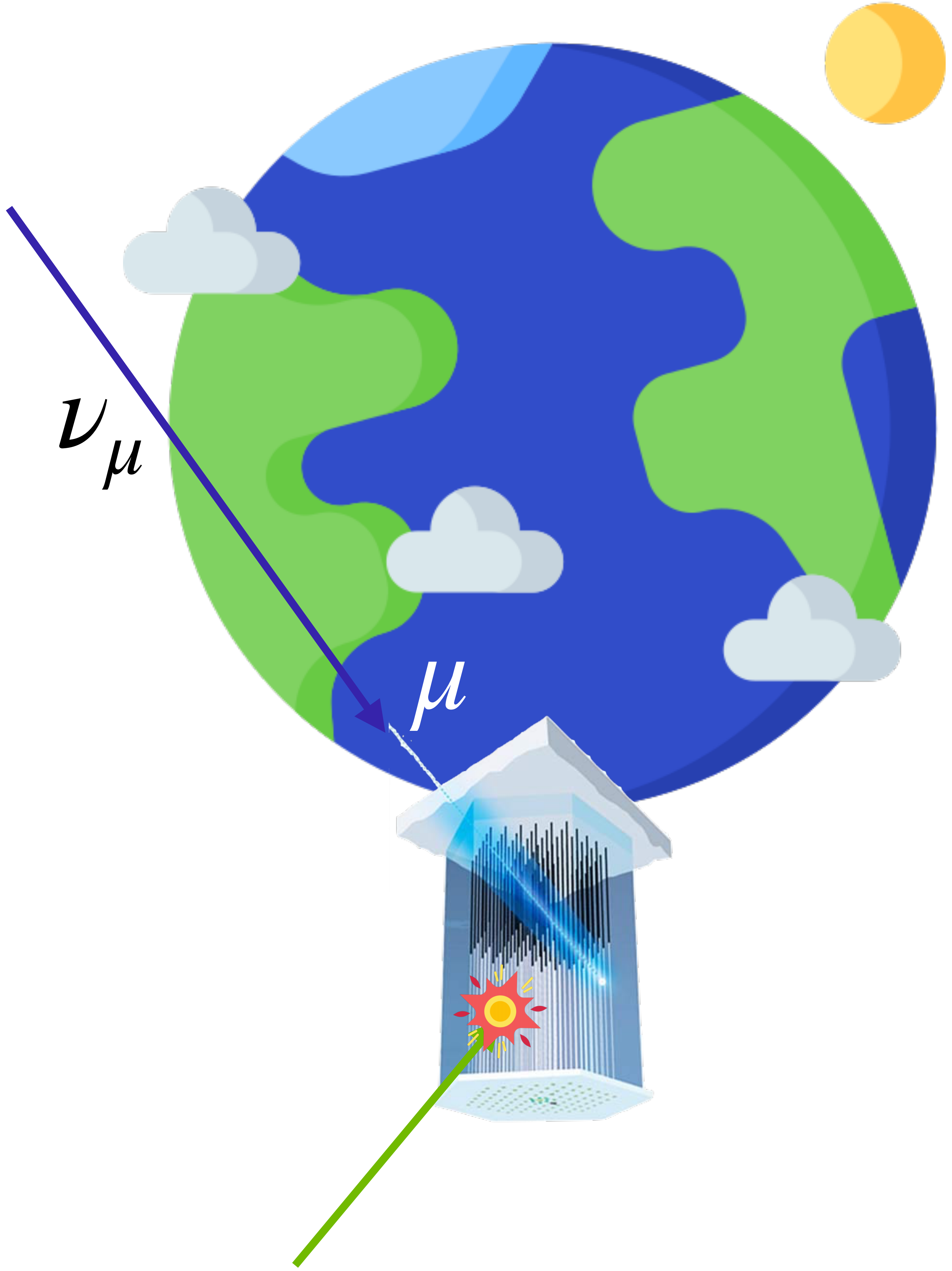


IceCube



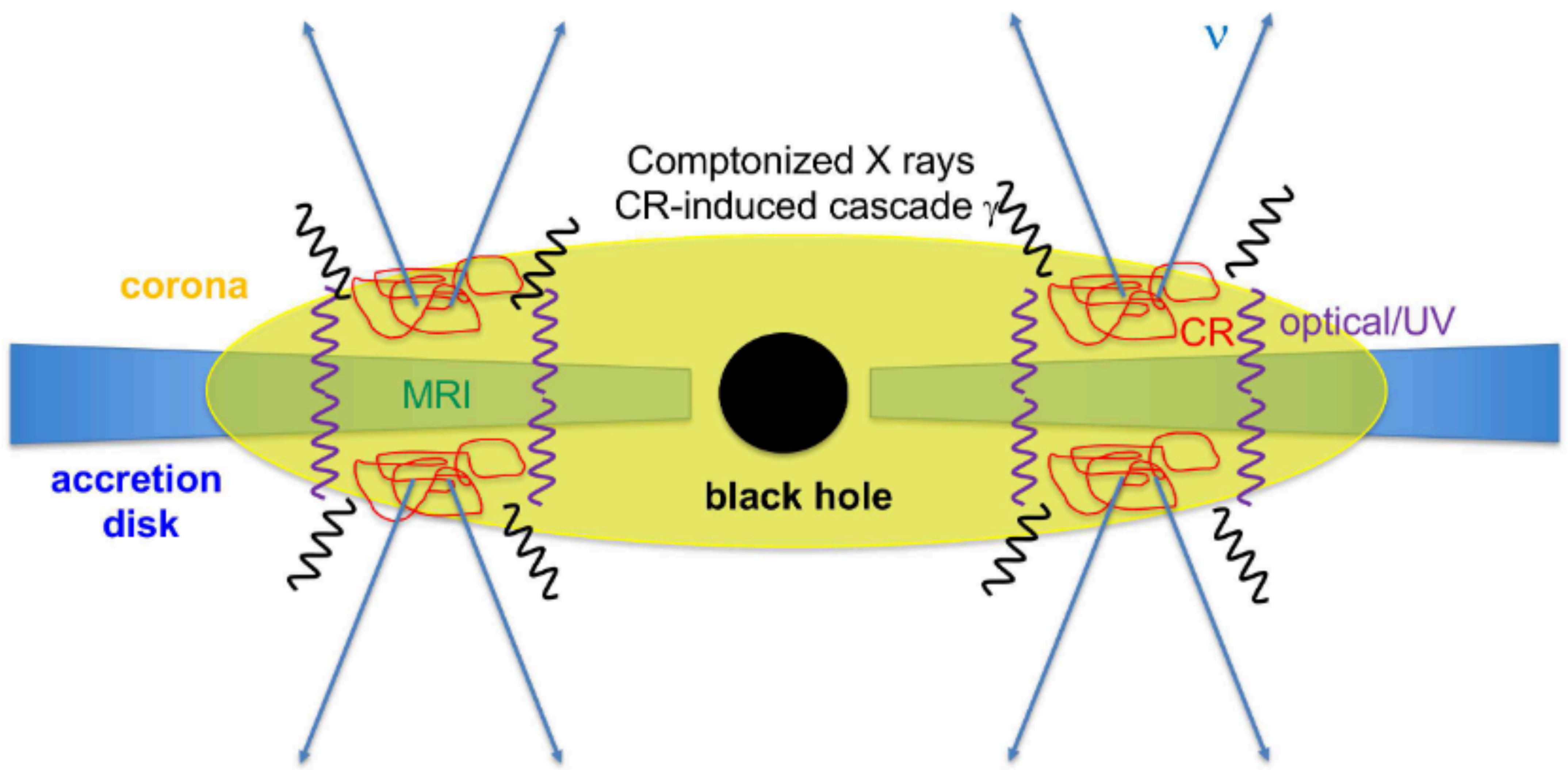
- **Cascades** allow precise energy reconstruction
  - Mainly ν_e and ν_τ
  - Detection of a diffuse astrophysical neutrino spectrum

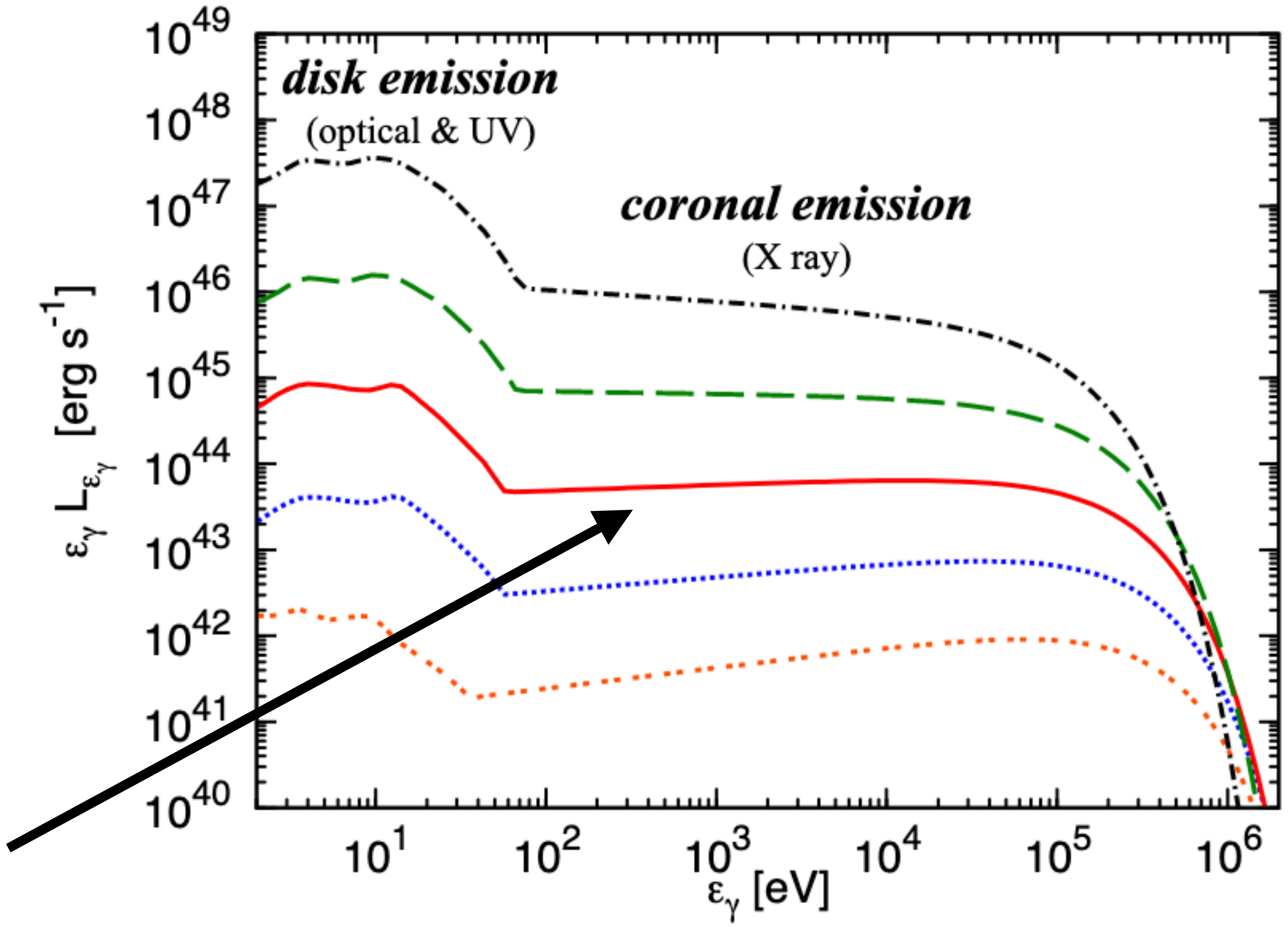
IceCube



- **Cascades** allow precise energy reconstruction
  - Mainly ν_e and ν_τ
  - Detection of a diffuse astrophysical neutrino spectrum
- **Tracks** allow precise angular reconstruction
  - Mainly ν_μ
  - Only few point sources detected as yet!

Coronae in AGN





$n_e \sim 10^{12}\ \mathrm{cm}^{-3}$

Figures from Murase et al., 2019

Neutrinos in AGN coronae

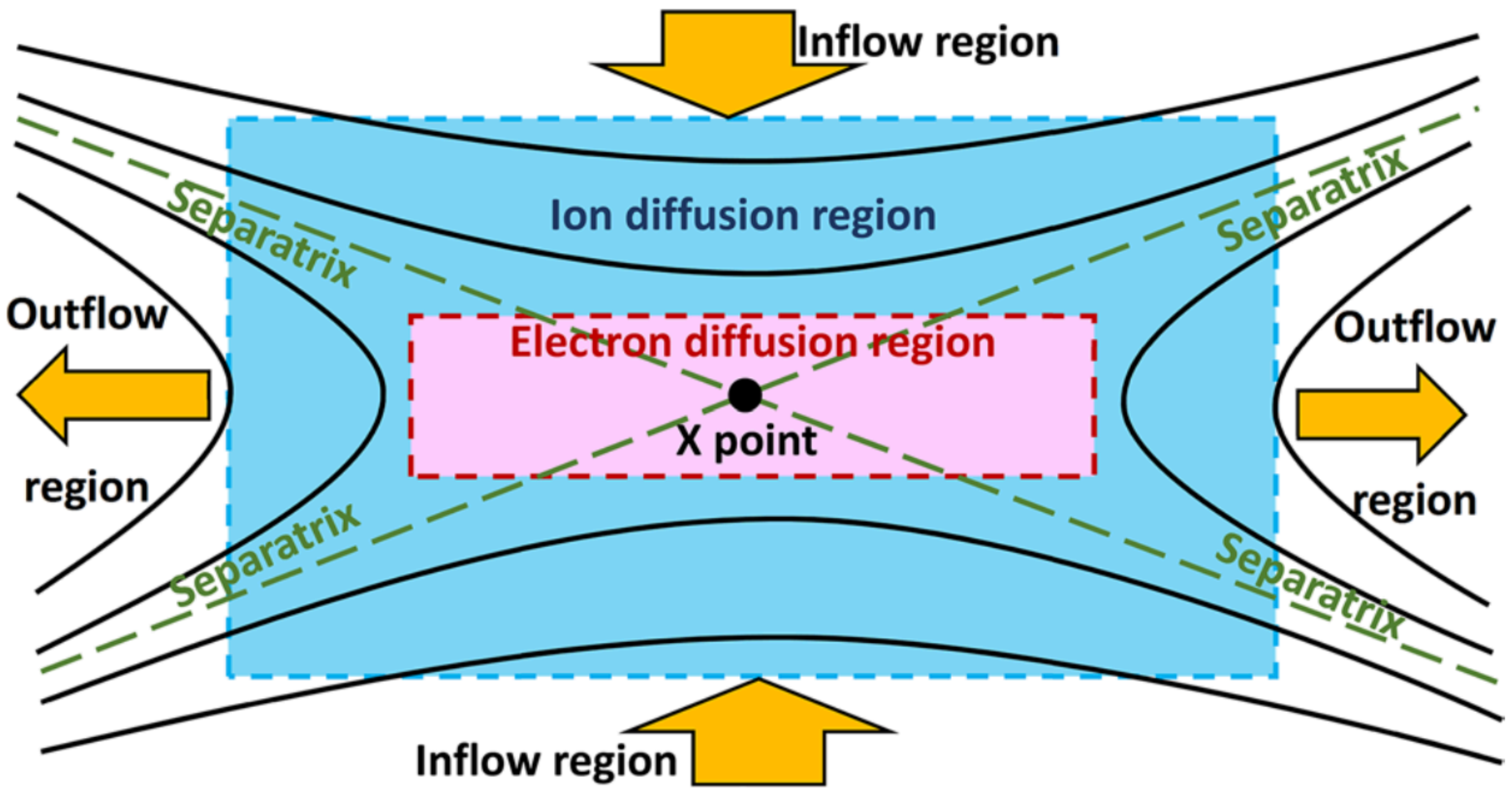
- Dense X-rays means **optically thick**
- Dense X-rays are also a **target for** $p\gamma$ **neutrino production**
- Strong magnetic fields are connected with **promising particle accelerators**

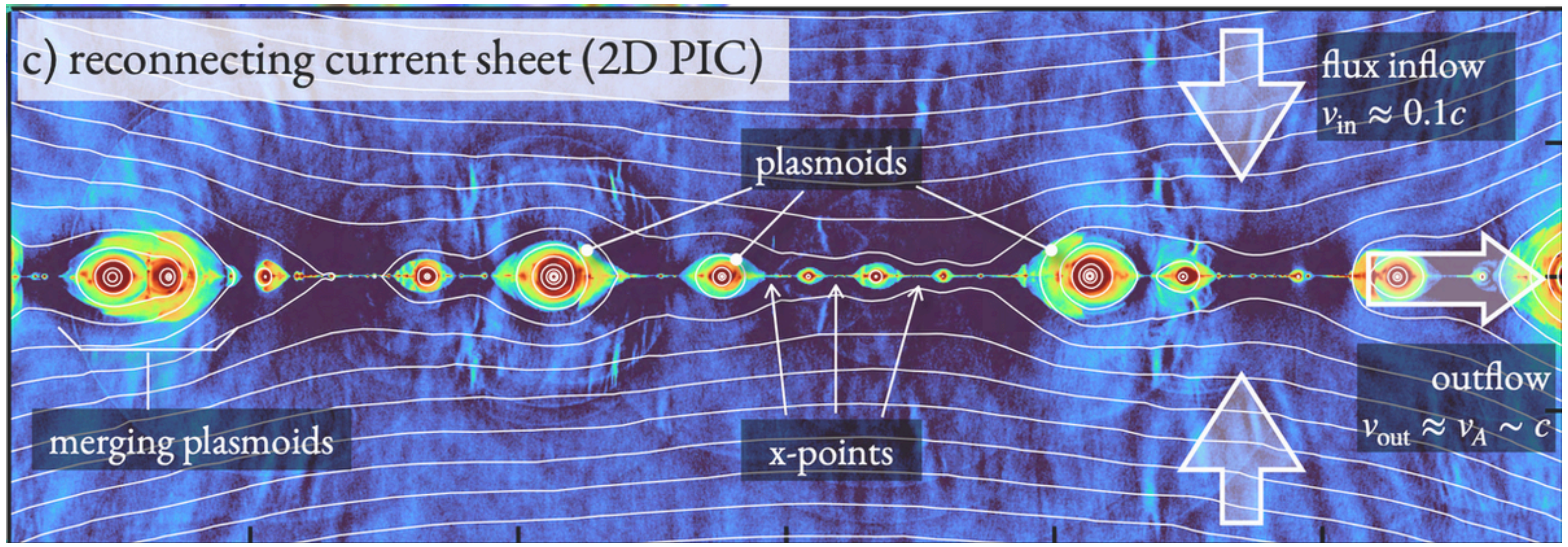
- **What is the acceleration process?**

Reconnection-based scenario

Based on Fiorillo, Petropoulou, Comisso, Peretti, Sironi,
ApJ Lett. 961 (2024) 1, L14

Magnetic reconnection

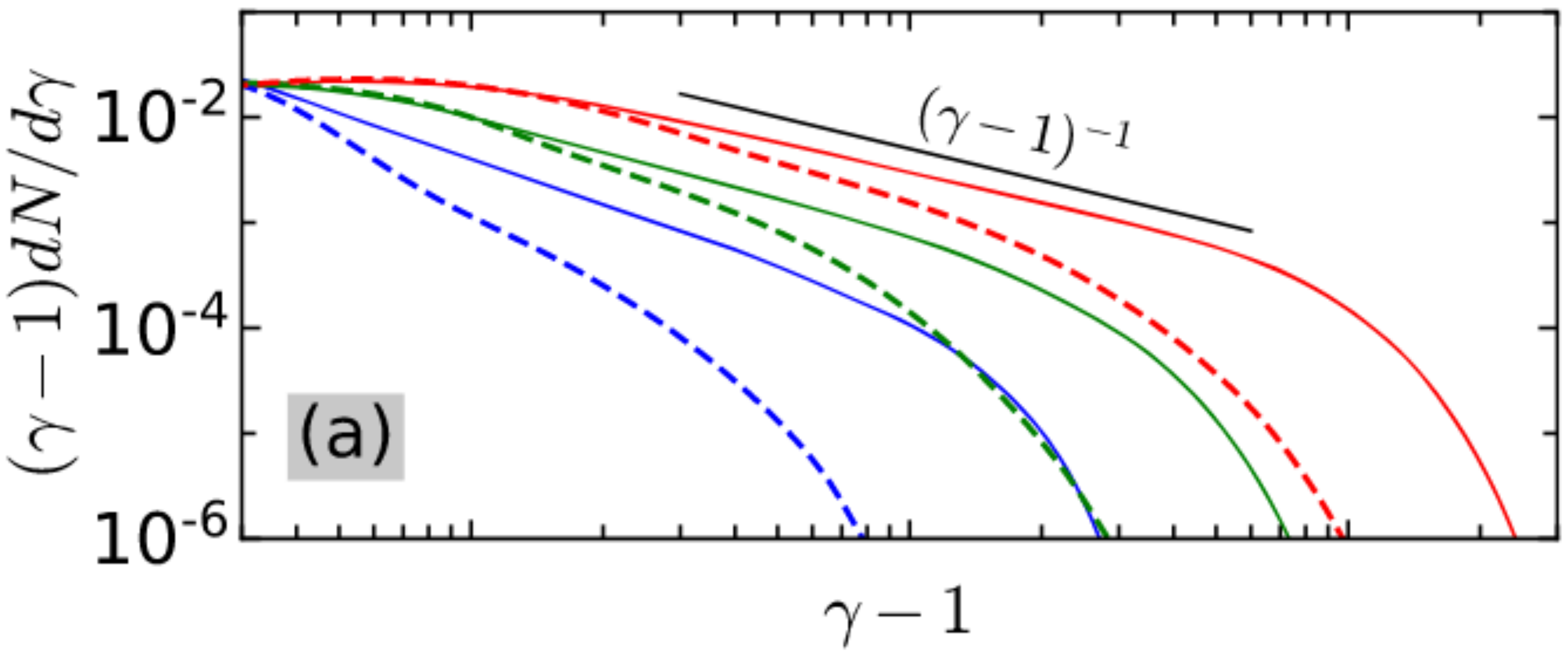




Lee et al., 2020

Ion acceleration in reconnection layers

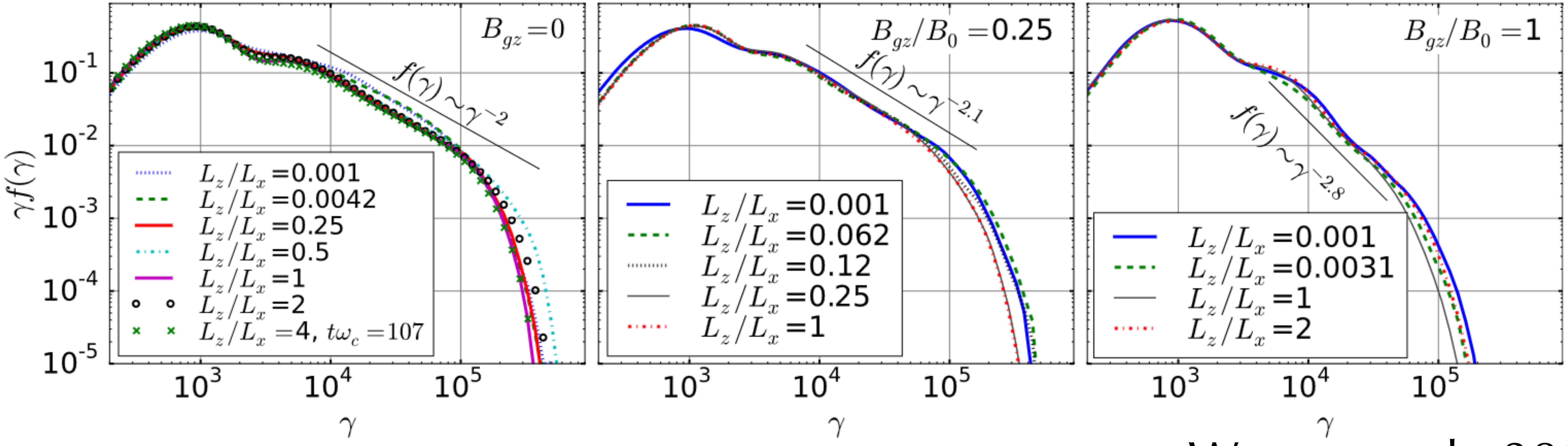
$$\sigma_p = \frac{B^2}{4\pi n_p m_p c^2}$$



Zhang et al., 2023

- Hard spectrum $dN/d\gamma \propto \gamma^{-1}$ up to $\gamma \sim 3\sigma$
- Soft spectrum $dN/d\gamma \propto \gamma^{-2}$ at higher energies
- Rapid acceleration over timescales $t_{\rm acc} \sim E/\beta_{\rm rec}eBc$

Ion acceleration in reconnection layers



Werner et al., 2017

For large guide field, high-energy spectrum is softer ($dN/d\gamma \propto \gamma^{-3}$)

Most energy concentrated at $\gamma \sim \sigma_p$, so rough equipartition!

NGC 1068 and reconnection

- If neutrinos peak at 1 TeV, protons peak at 20 TeV

NGC 1068 and reconnection

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- Reconnection would imply $\sigma_p \simeq 20\ \mathrm{TeV}/m_p c^2 \sim 10^4$

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NGC 1068 and reconnection

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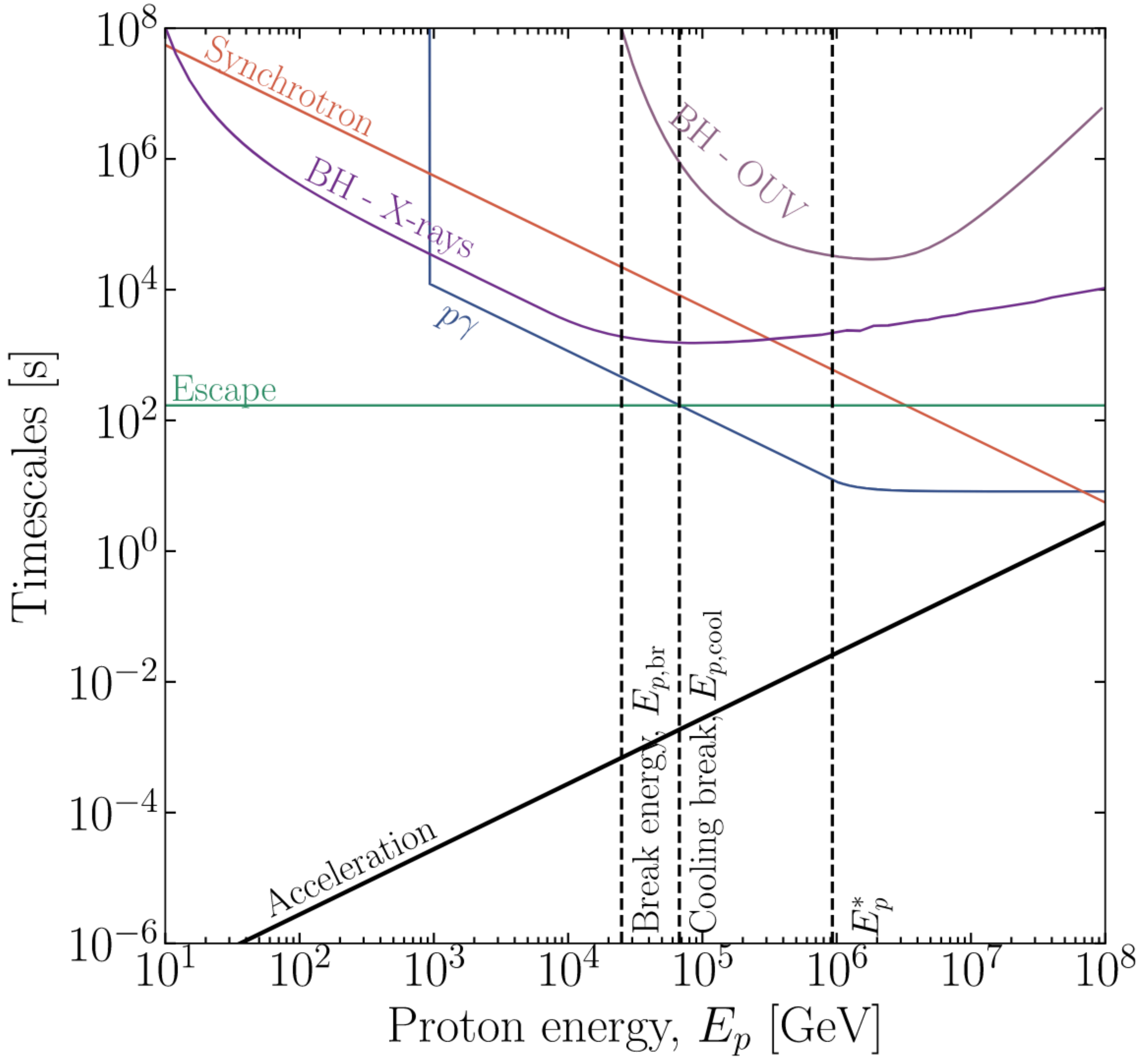
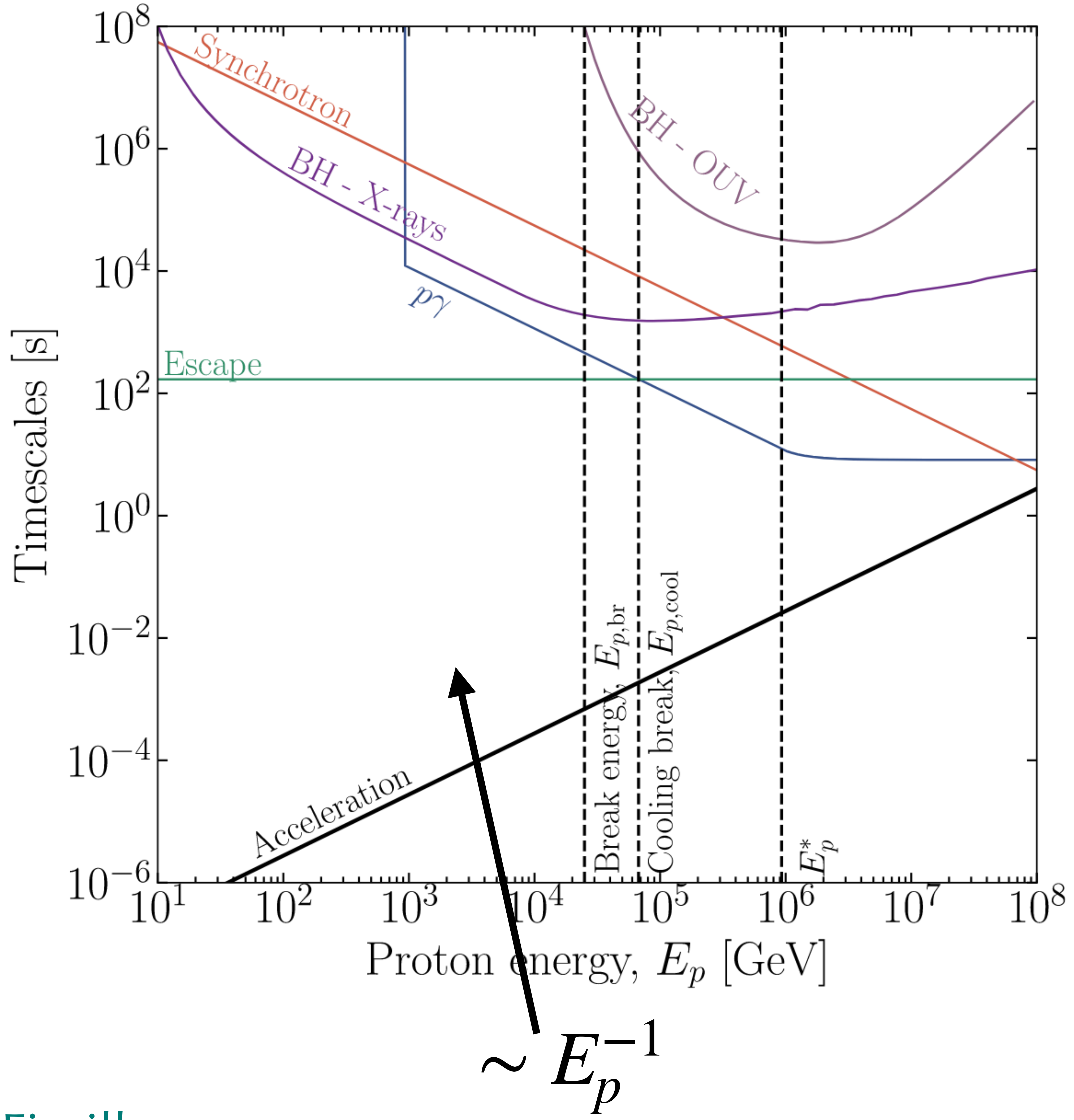
- Magnetic field in rough equipartition with X-rays (**magnetically powered corona**) implies $B \sim 10^4$ G
- Proton density must be $n_p \simeq 10^5 \text{ cm}^{-3}$ (**pair-dominated corona**)

Acceleration and cooling



- Acceleration very fast - protons could be accelerated to 10^8 GeV
- Global, not local, properties constrain proton energy

Acceleration and cooling



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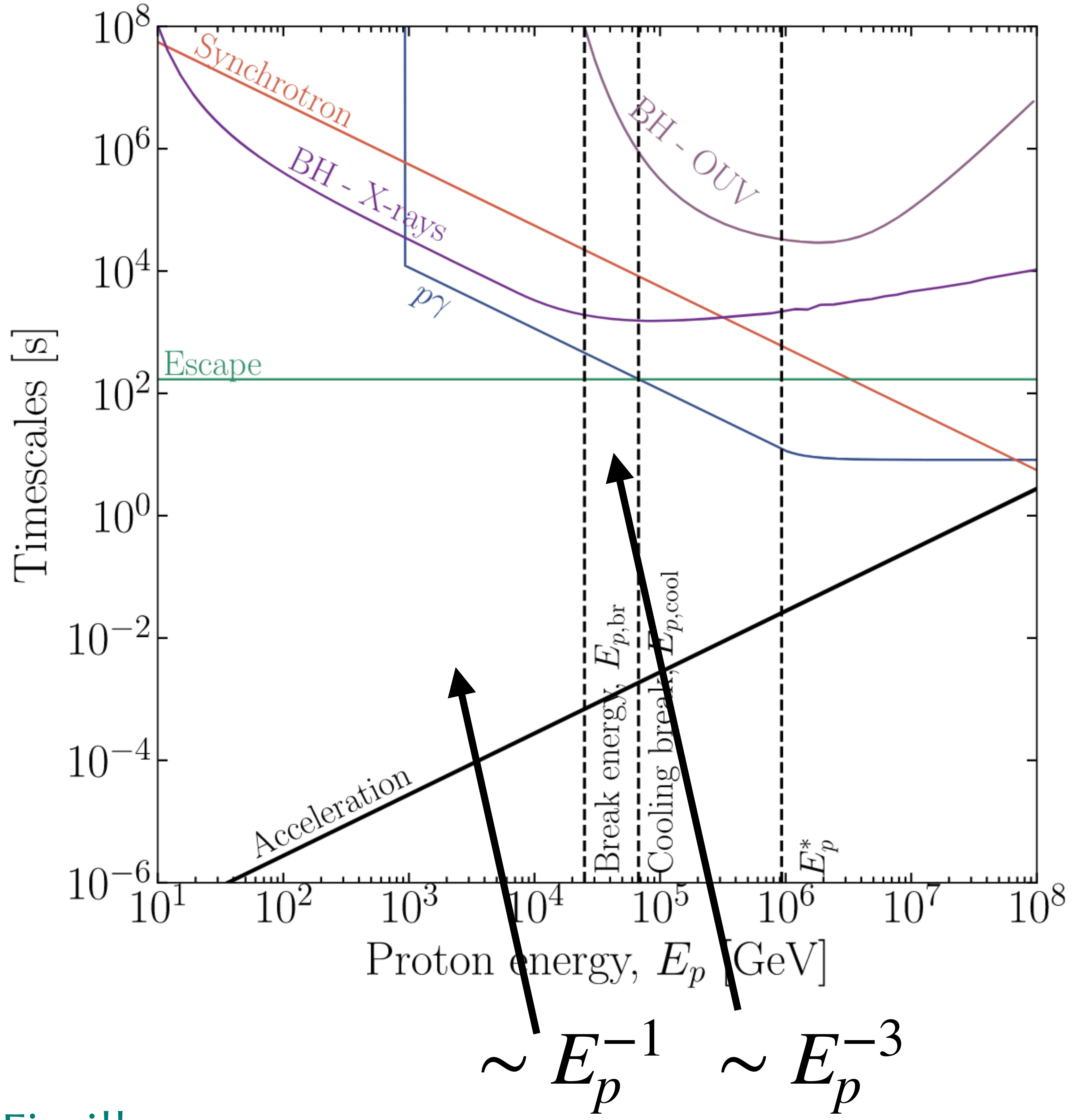

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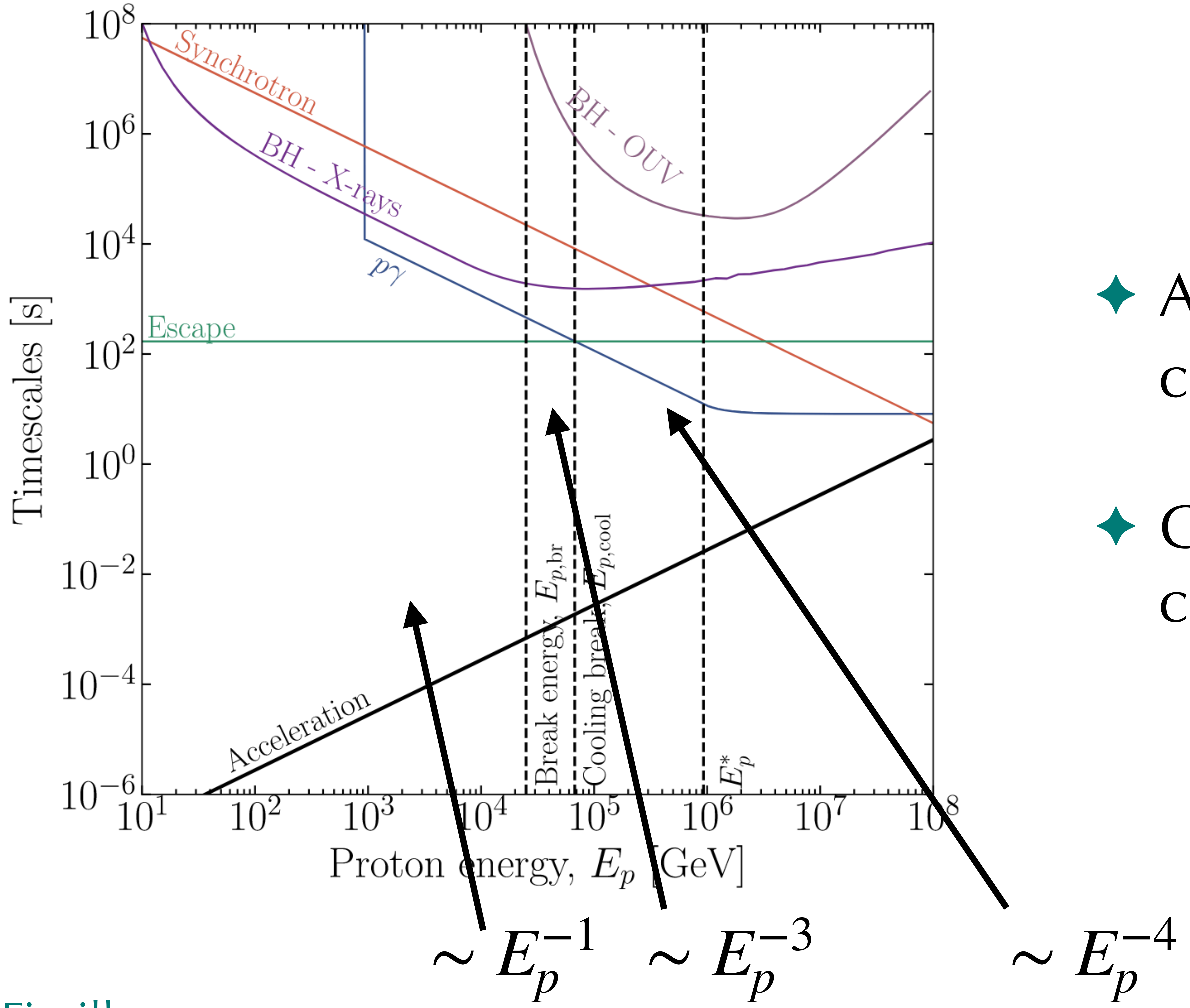

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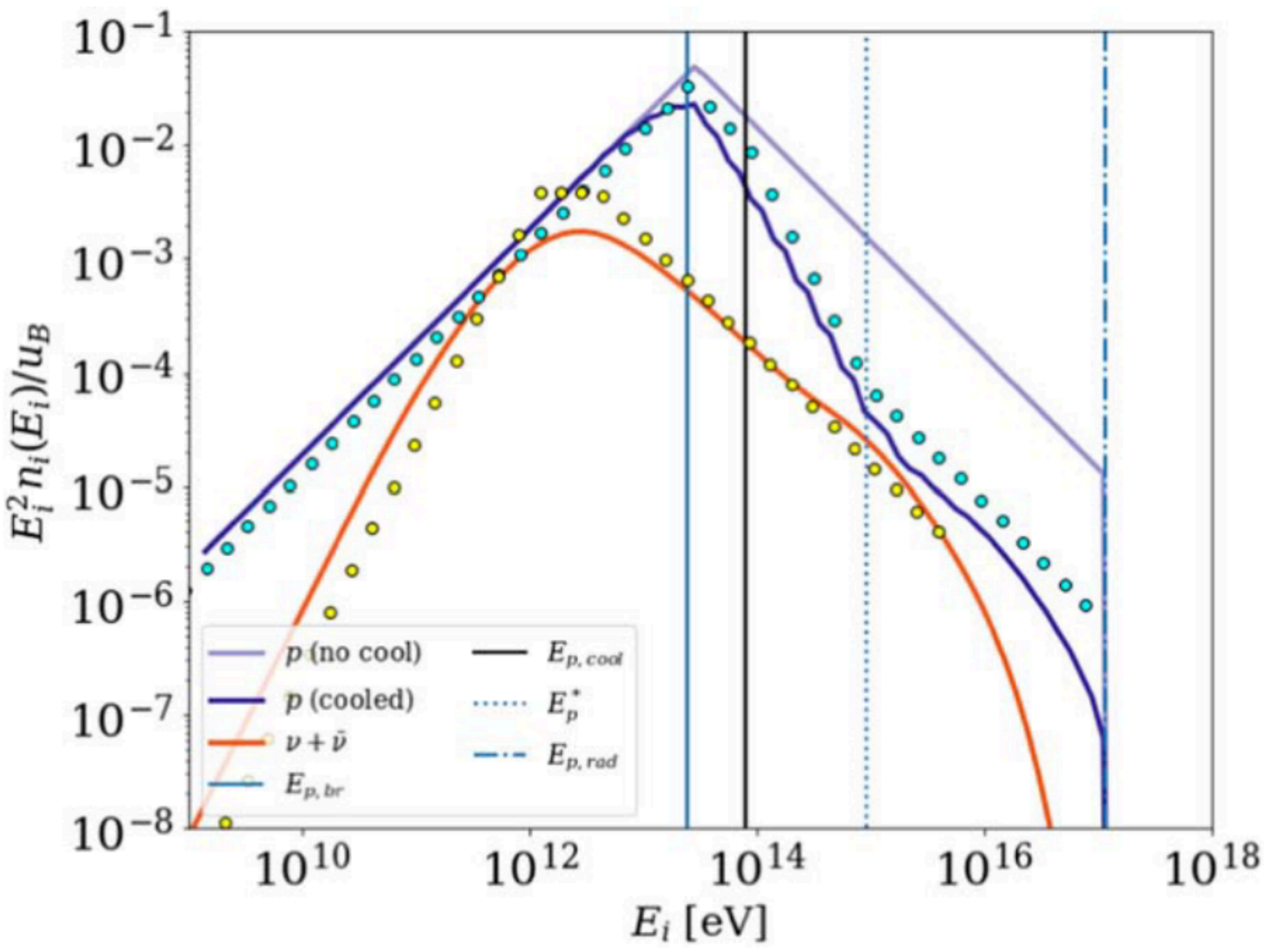
Multimessenger emission



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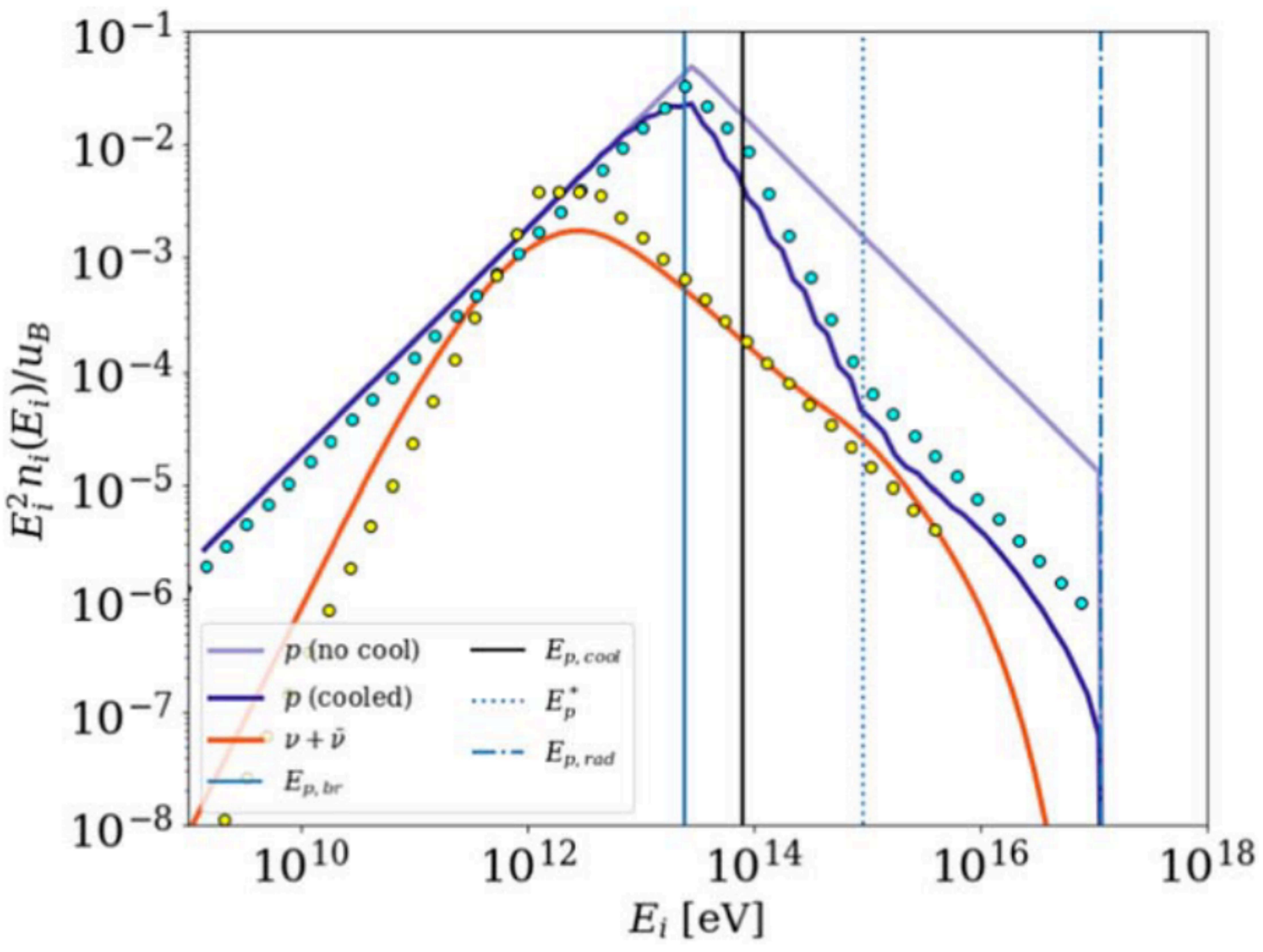
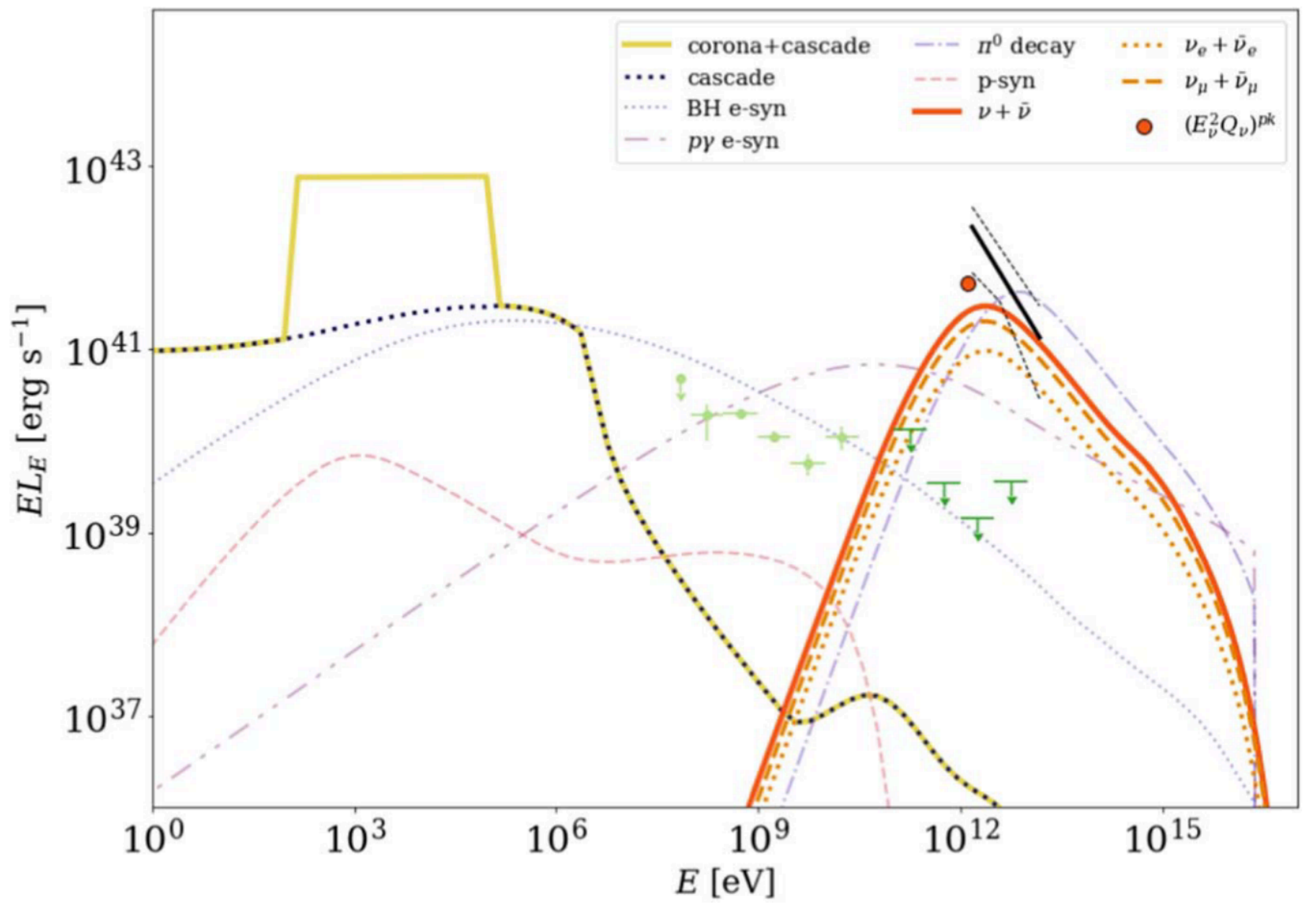


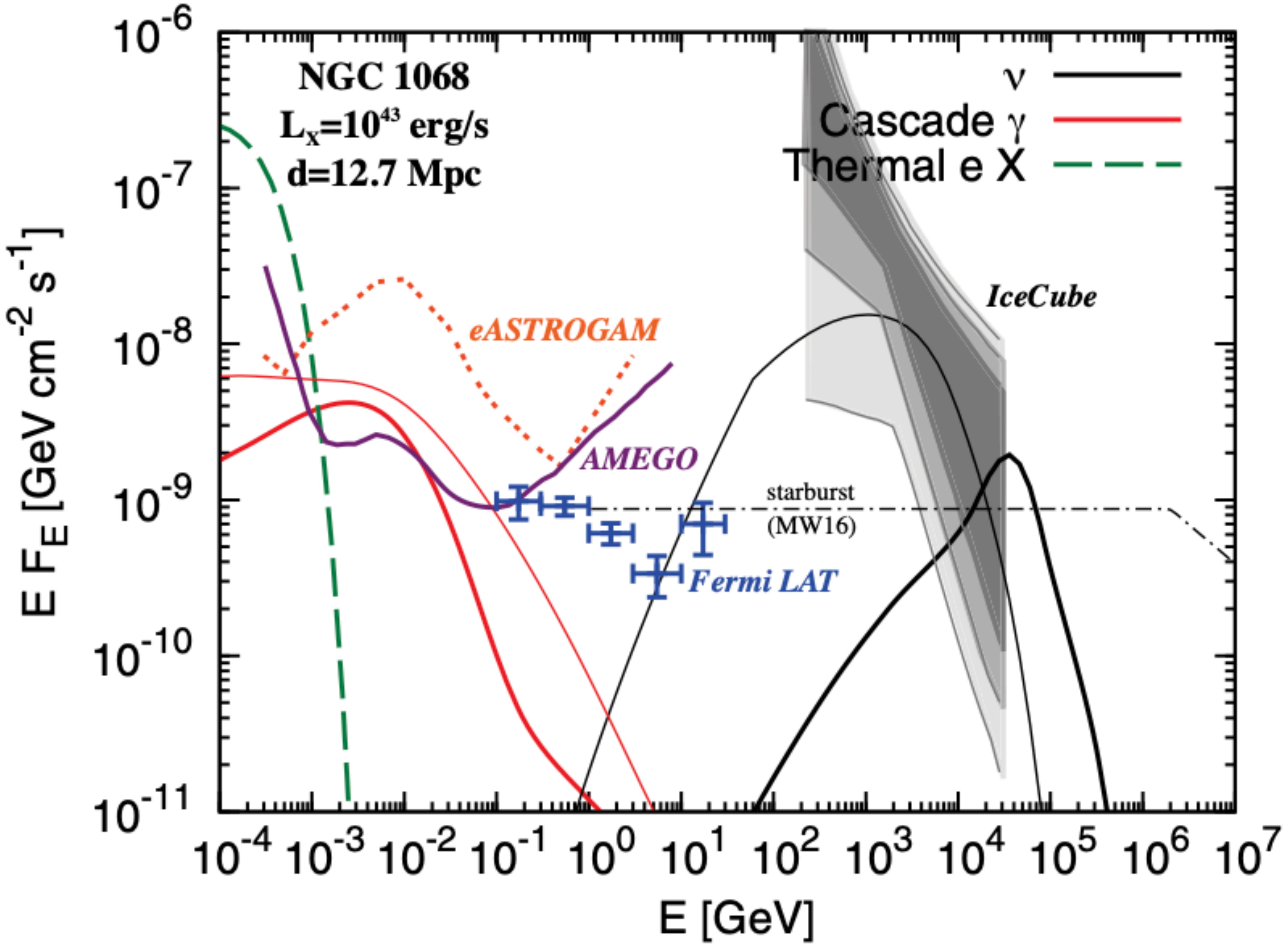


Damiano Fiorillo

Turbulence-based scenario

Based on Fiorillo, Comisso, Peretti, Petropoulou, Sironi,
in preparation

Stochastic acceleration



- Turbulence has time-varying magnetic fields
- Historical picture: ensemble of waves (**gyroresonance**)
- Murase et al., 2019, propose weak turbulence ($\sigma_{\rm tur} \sim 10^{-4}$) in NGC 1068

Stochastic acceleration

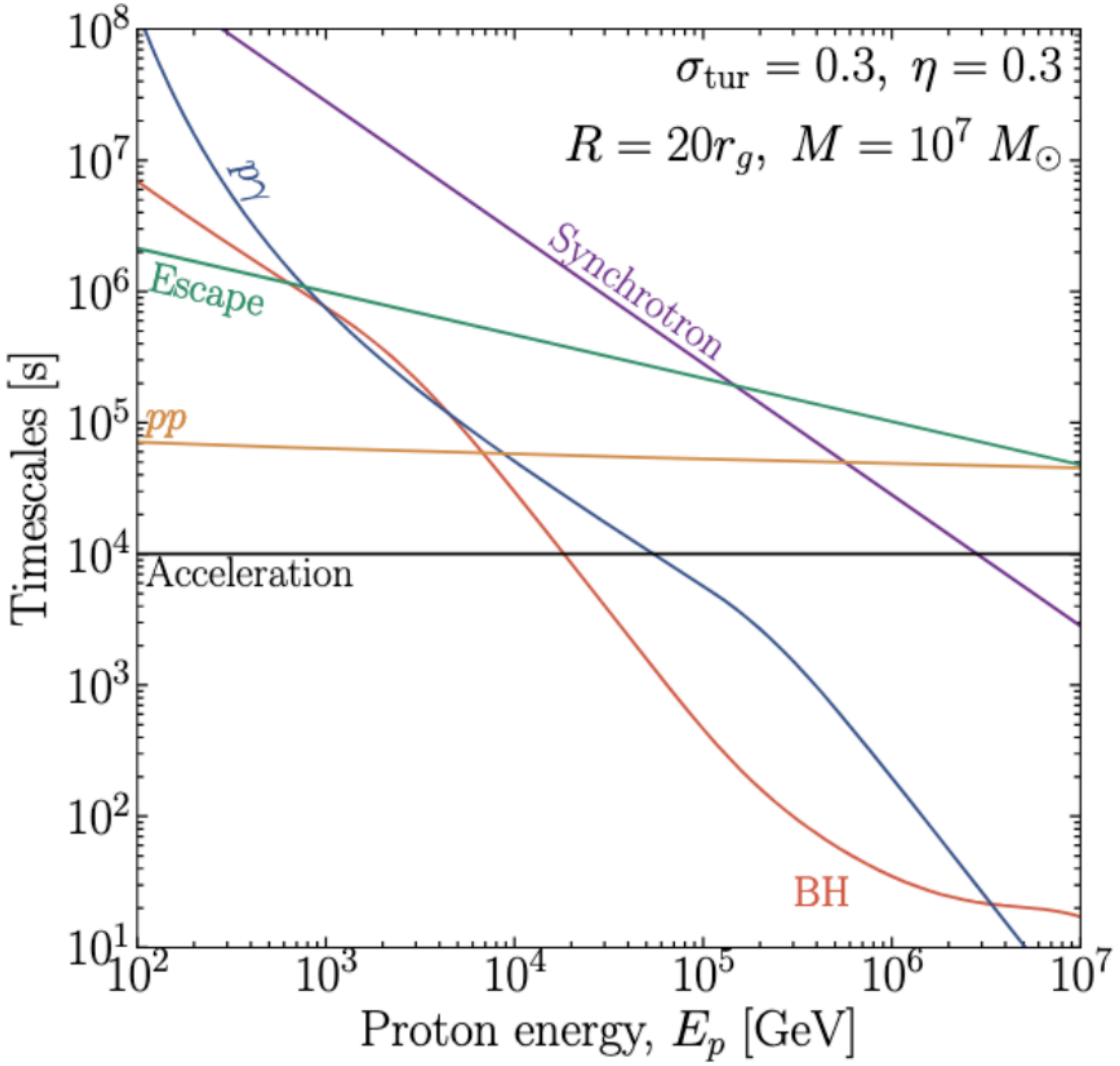
- In MHD turbulence, broadened resonance means gyroresonance is inapplicable

- **Non-resonant** acceleration: all protons dominated by largest structures ($t_{\rm acc} \sim \ell / \sigma_{\rm tur} c$)

Stochastic acceleration

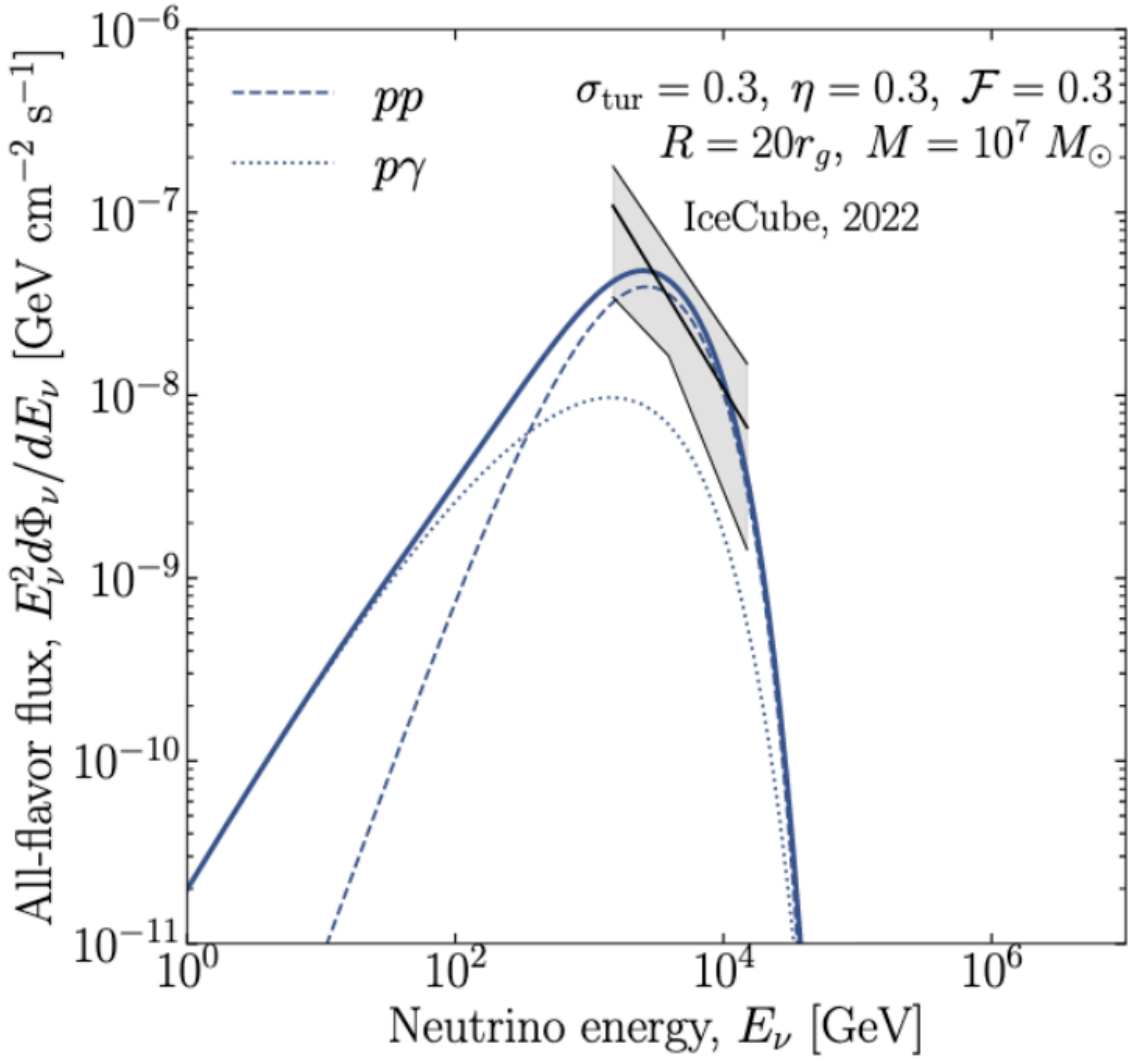
- In MHD turbulence, broadened resonance means gyroresonance is inapplicable
- **Non-resonant** acceleration: all protons dominated by largest structures ($t_{\rm acc} \sim \ell / \sigma_{\rm tur} c$)
- Dissipation rate must be large enough to explain IceCube neutrino normalization!
- $L_B \simeq 2.1 \times 10^{44}\ \mathrm{erg/s}\ \dfrac{\sigma_{\rm tur}^{3/2}}{\eta}\ \dfrac{RM_7}{20 r_g}$ erg/s is the available energy, so $\sigma_{\rm tur} \sim 10^{-2} - 1$

Acceleration and cooling



- Acceleration rate is energy-independent
- Bethe-Heitler cooling limits proton energy to 20 TeV — sufficiently compact corona!
- Not all protons are accelerated by turbulence — no need to invoke pair-dominated corona!

Acceleration and cooling

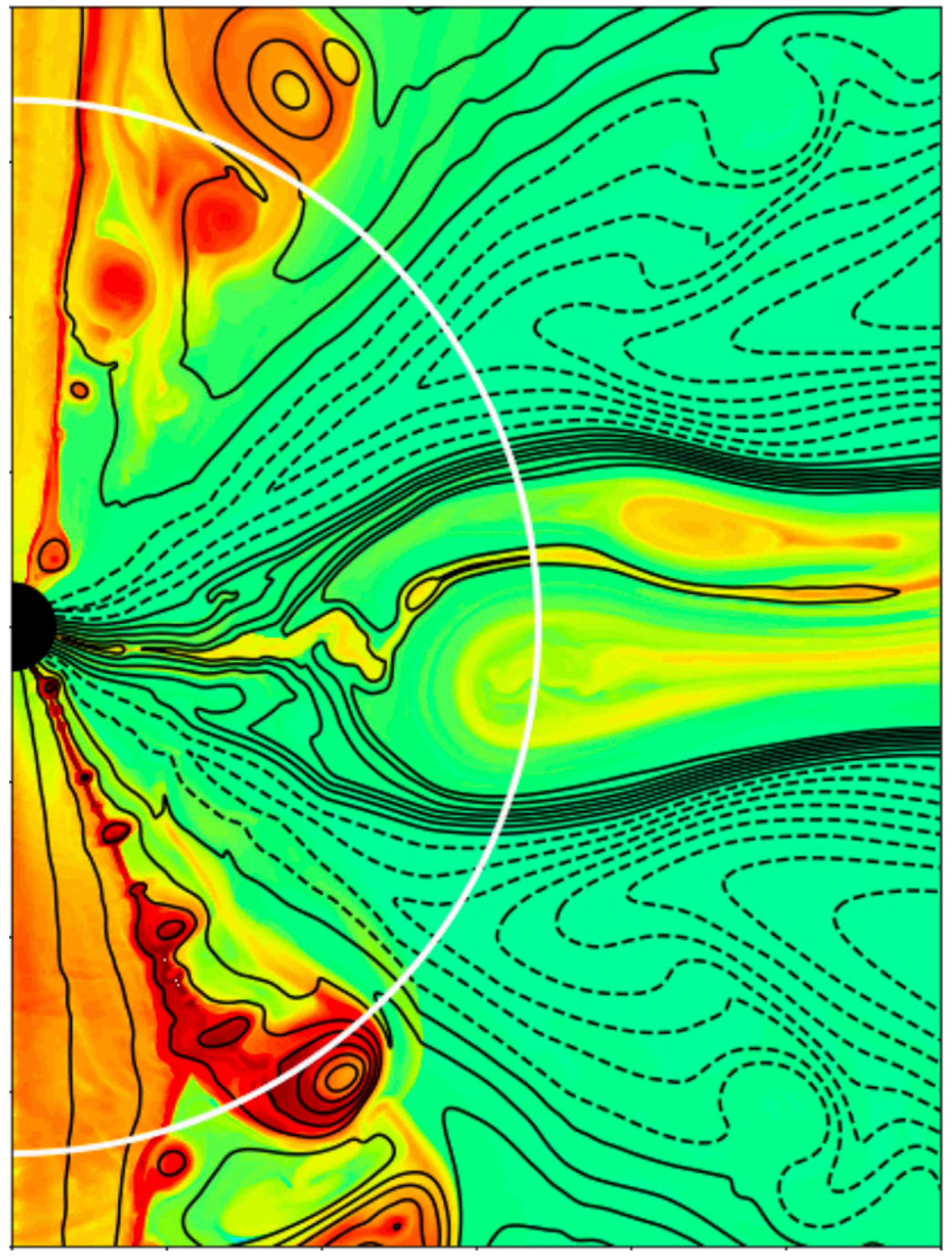


- pp and $p\gamma$ production compete
- Exponential cutoff rather than power-law suppression
- Spectral index below the peak is $\propto E_\nu^{-1}$ independently of turbulence properties

Conclusions

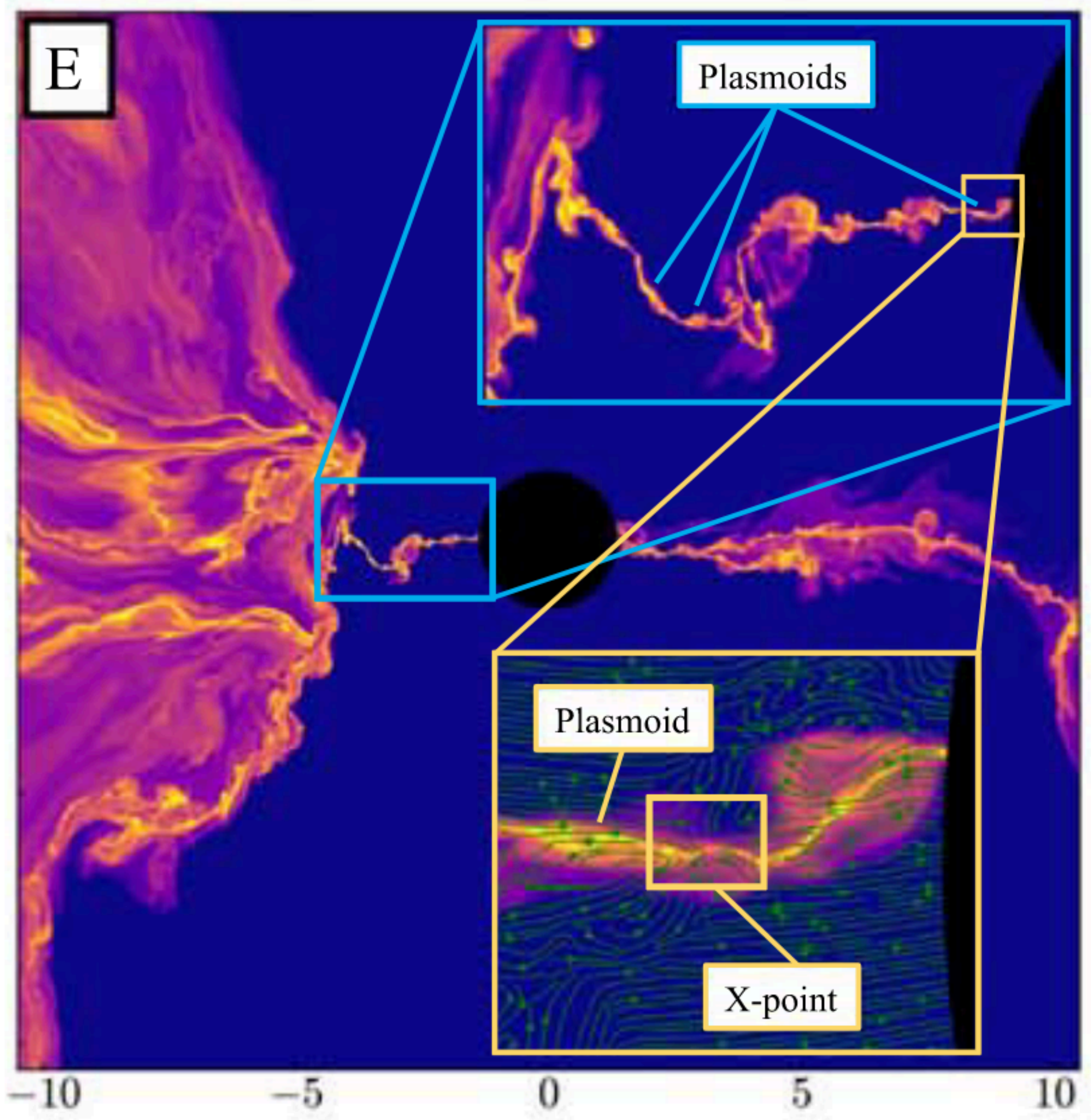
- **Reconnection-based scenario**
  - Global equipartition limits maximum proton energy
  - Reconnection layer with strong guide field, pair-dominated corona
  - Likely short-scale time-dependent features
- **Turbulence-based scenario**
  - Acceleration competes with Bethe-Heitler
  - Strong magnetic turbulence, non-resonant acceleration

Reconnection layers in AGN coronae



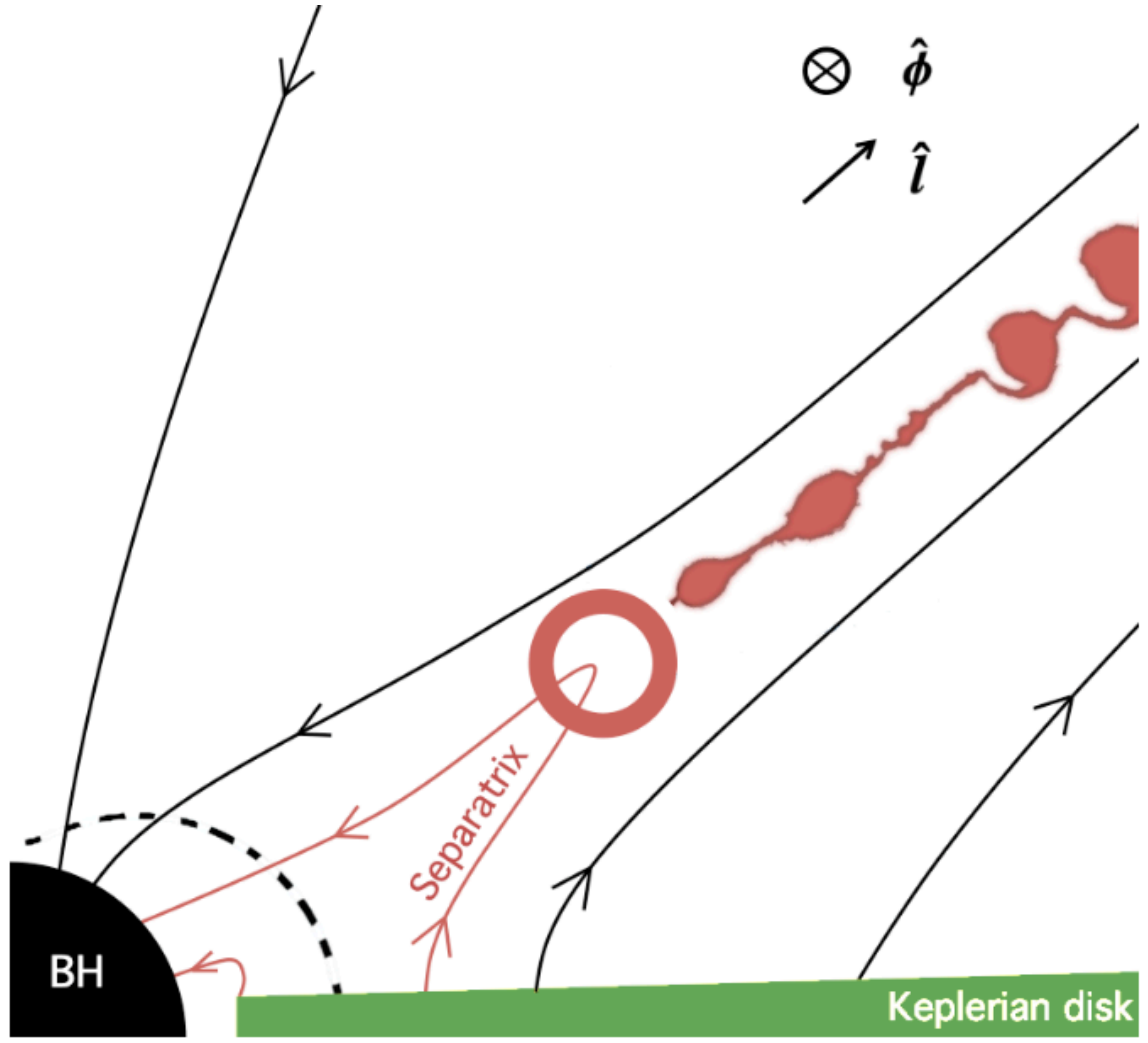
Jet boundary current sheet

Chashkina et al., 2021



Equatorial current sheet

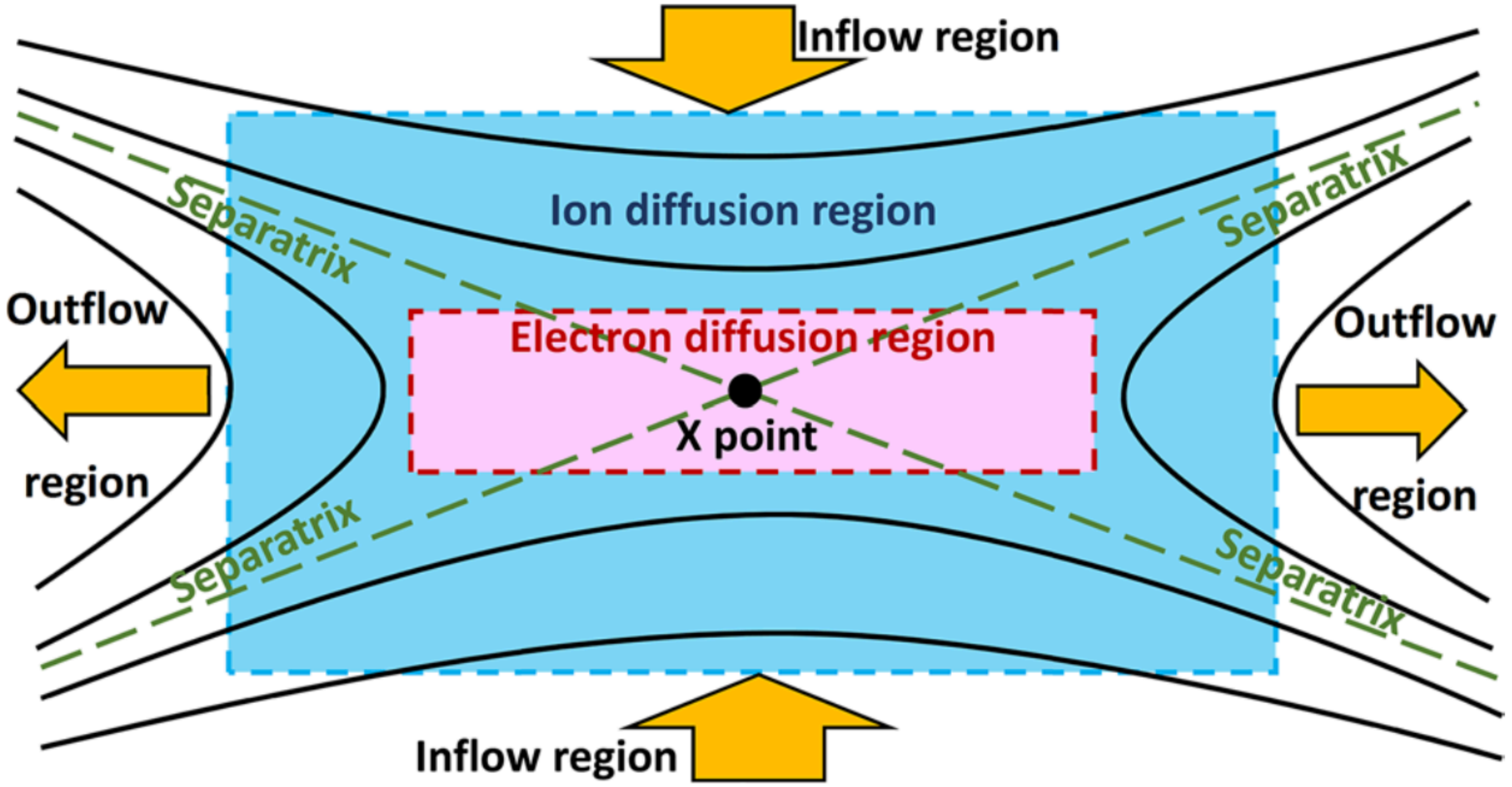
Ripperda et al., 2022



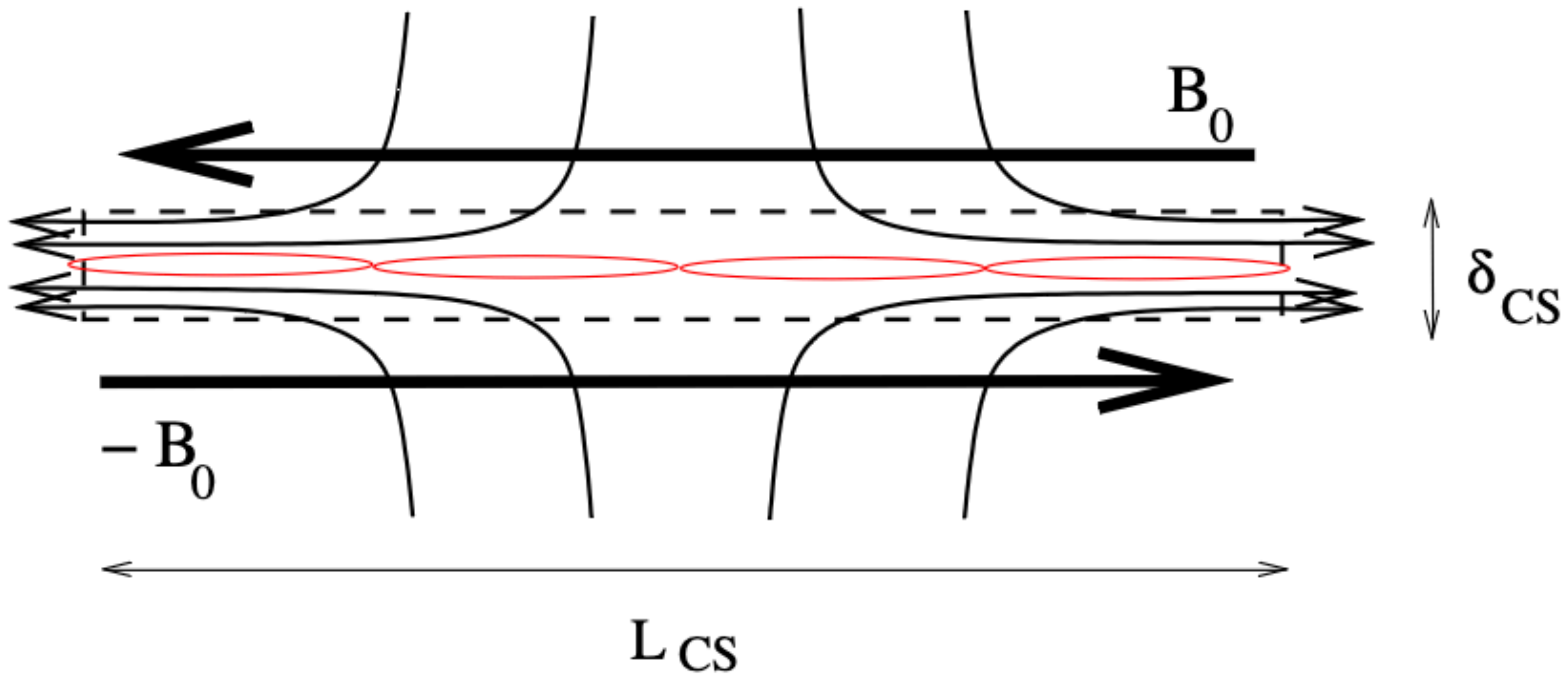
Y-point current sheet

El Mellah et al., 2023

Magnetic reconnection



Lee et al., 2020



Loureiro et al., 2005