Ideas for modeling high-energy neutrino emission

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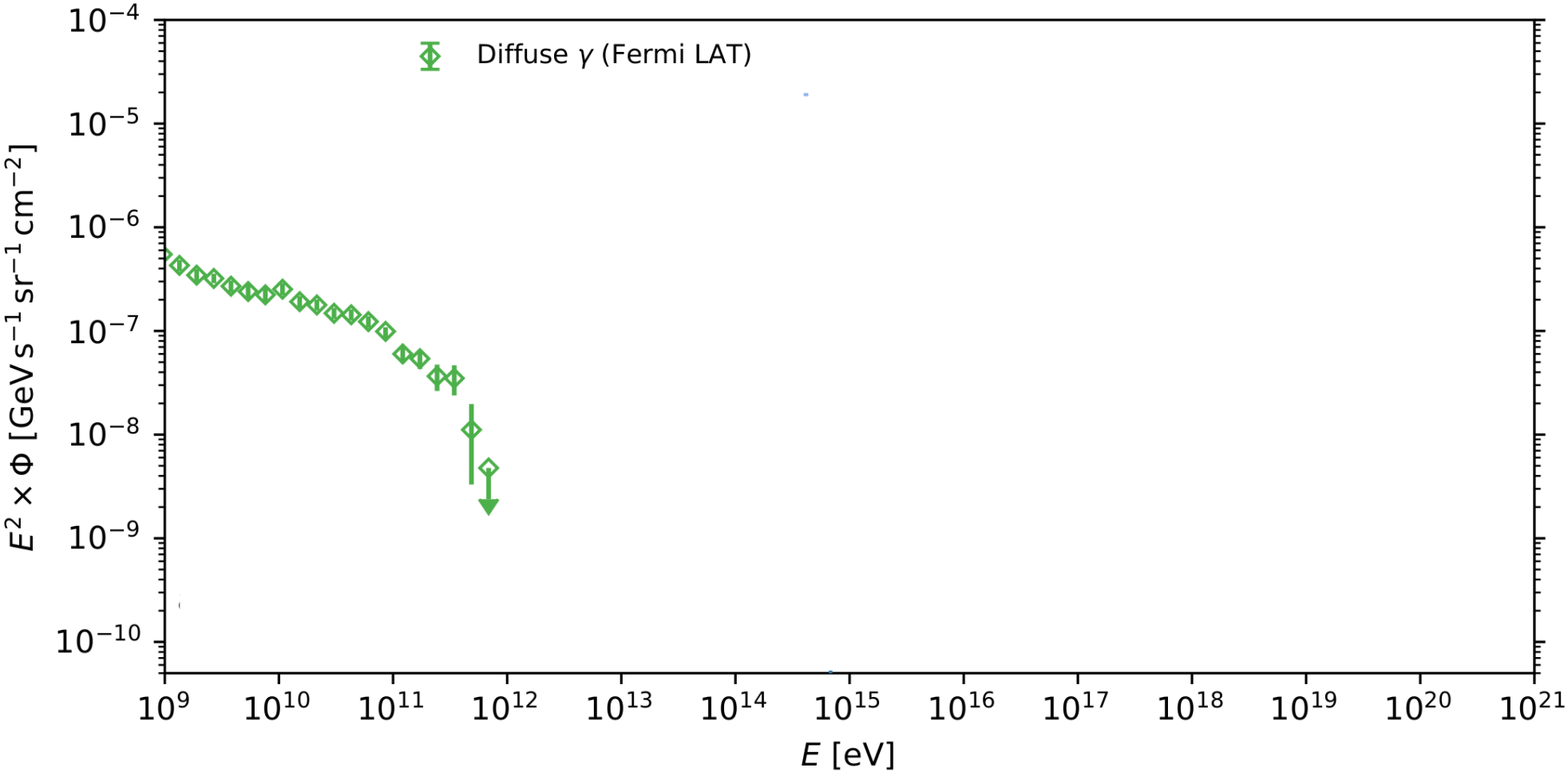
EUCAIf
December 02, 2025

The state of affairs

Gamma rays Neutrinos Cosmic rays



M. Ackermann, ***MB***, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

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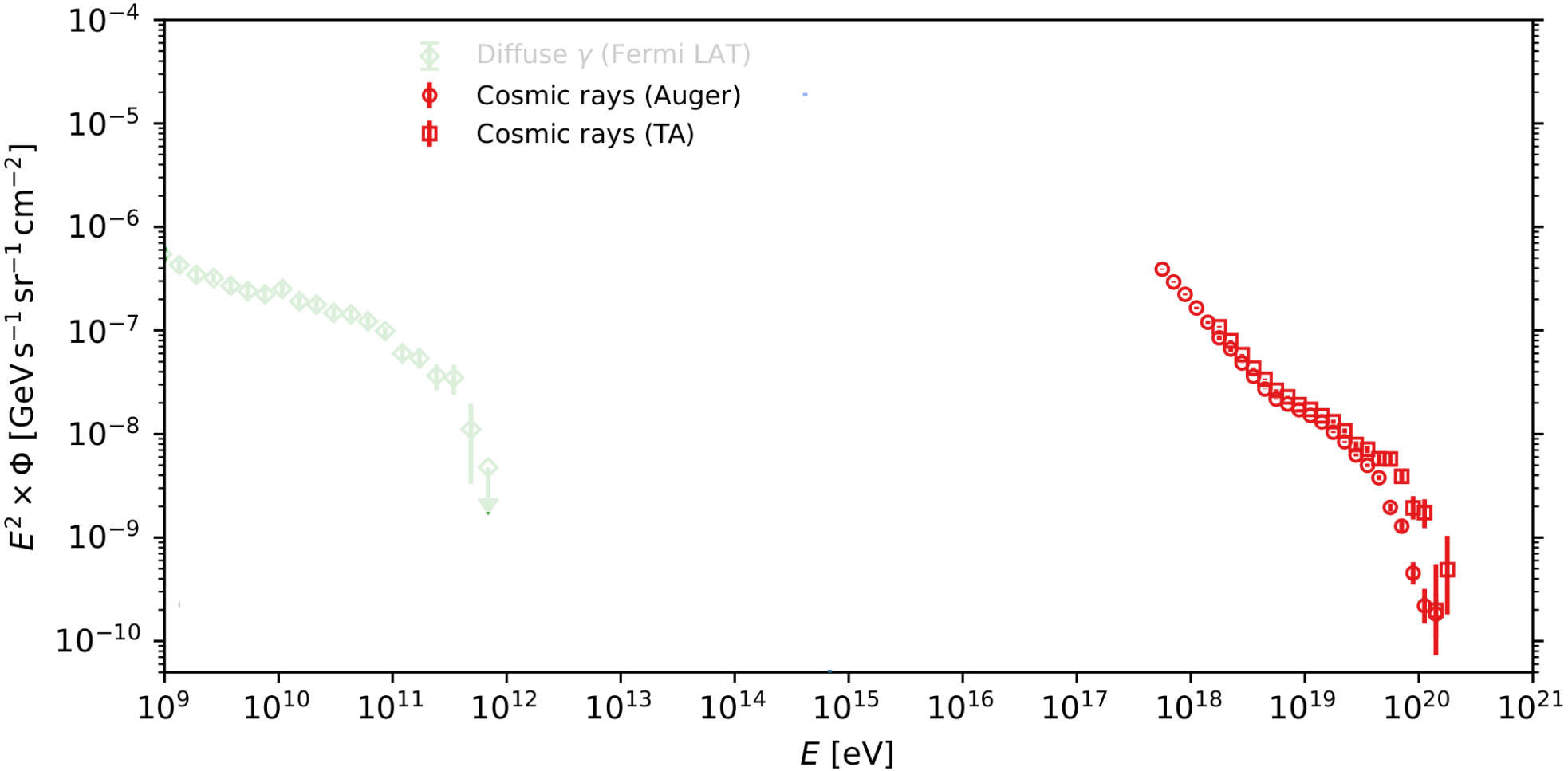

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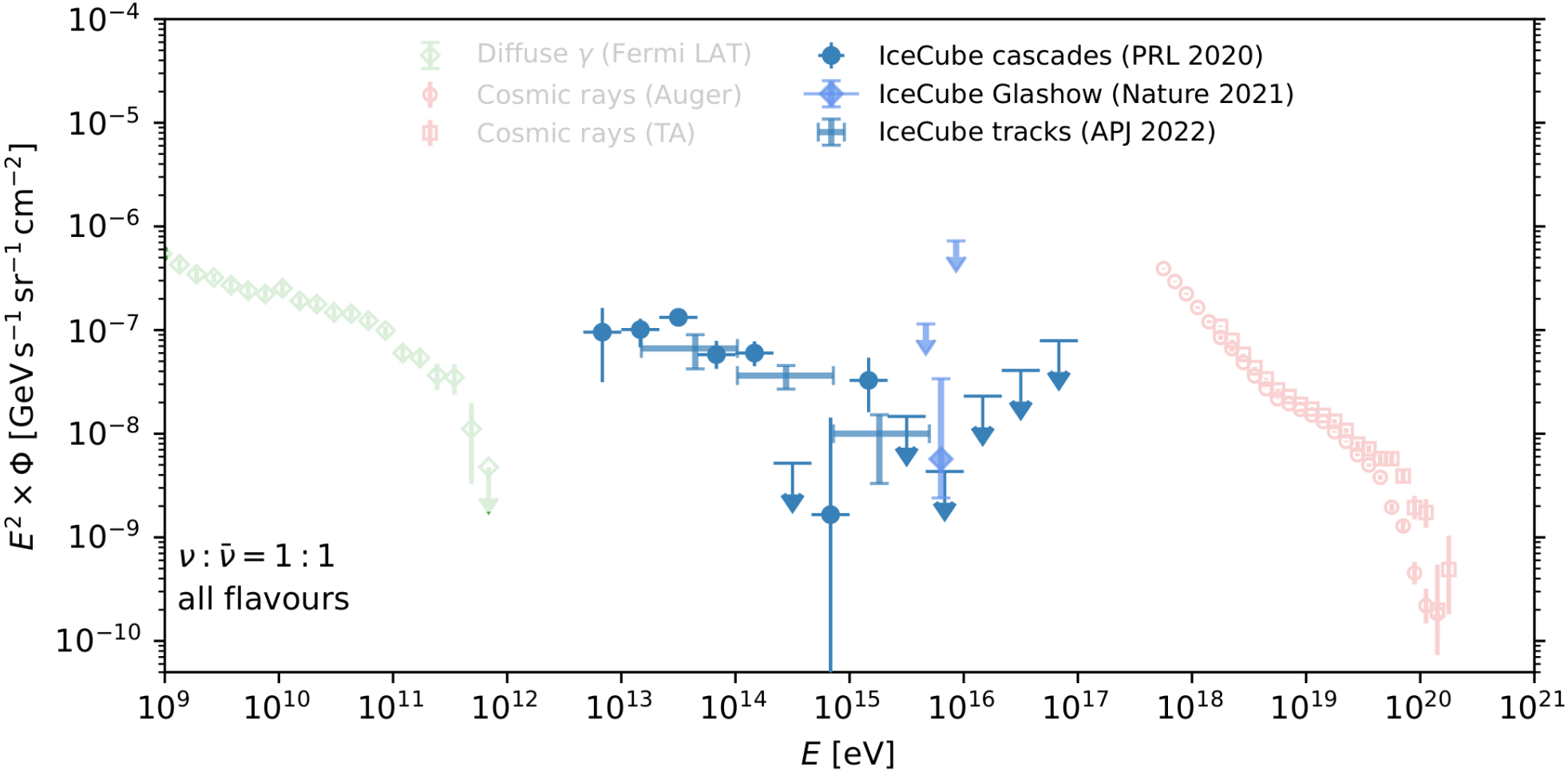
Gamma rays Neutrinos Cosmic rays



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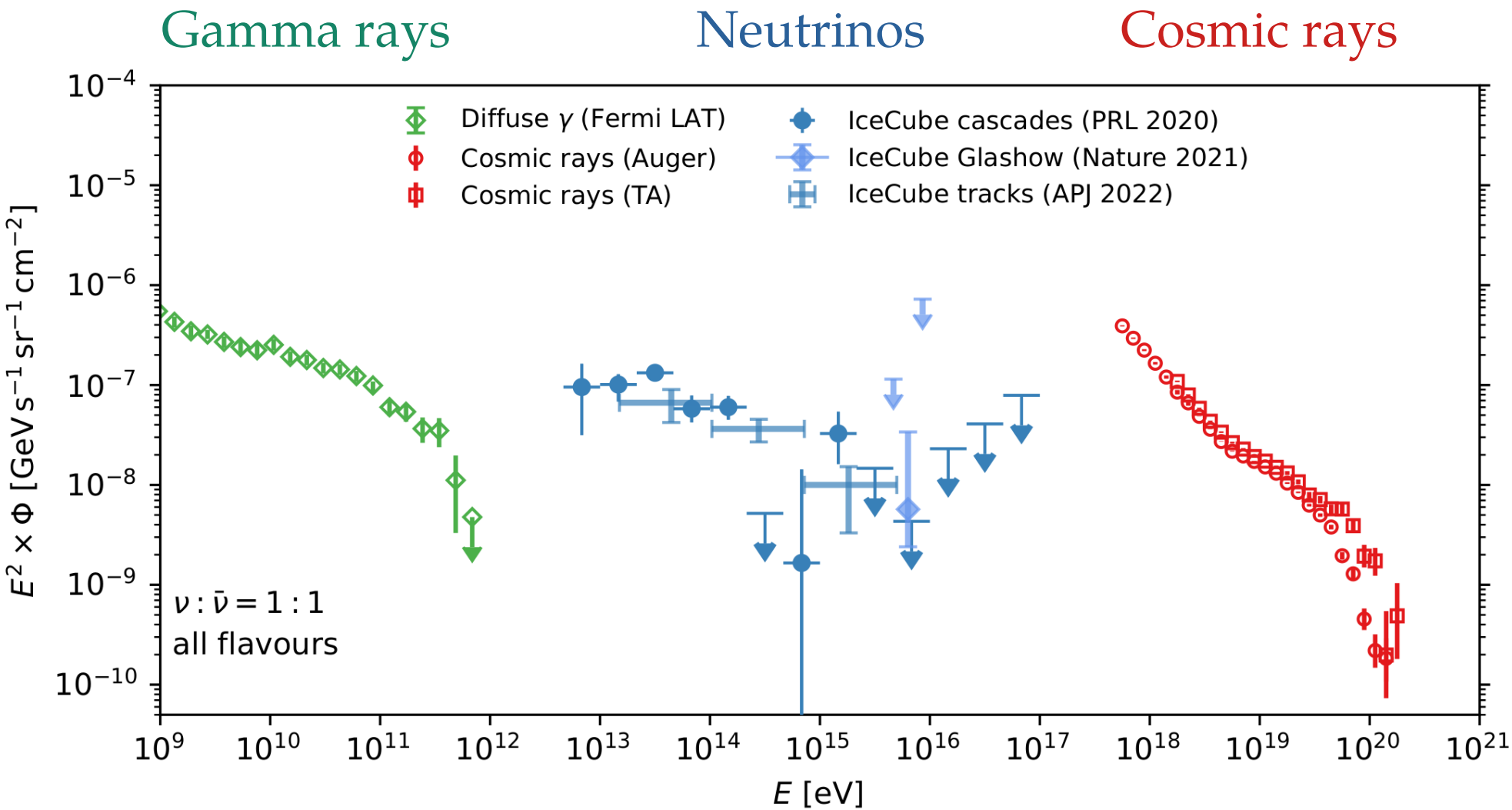

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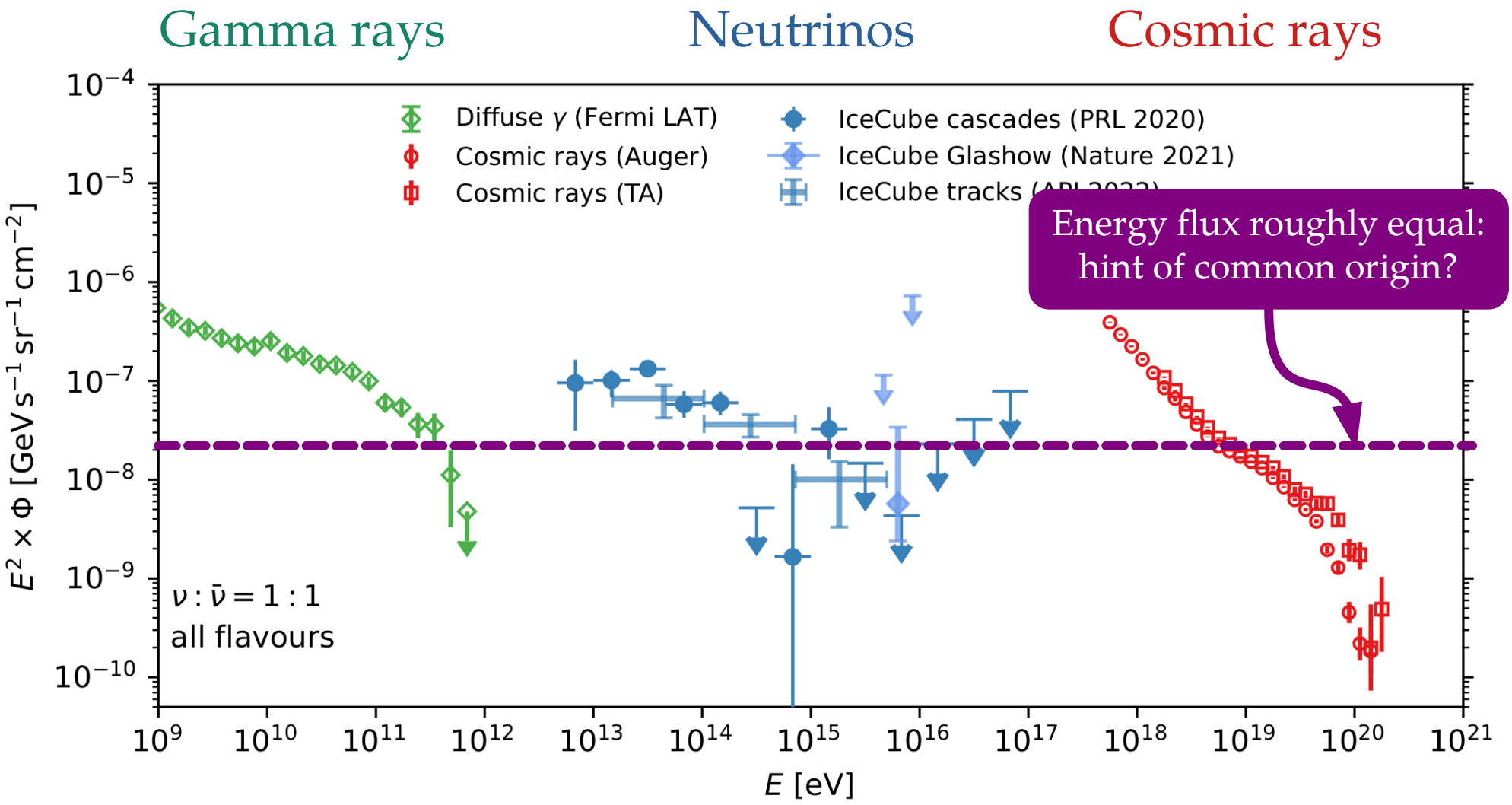

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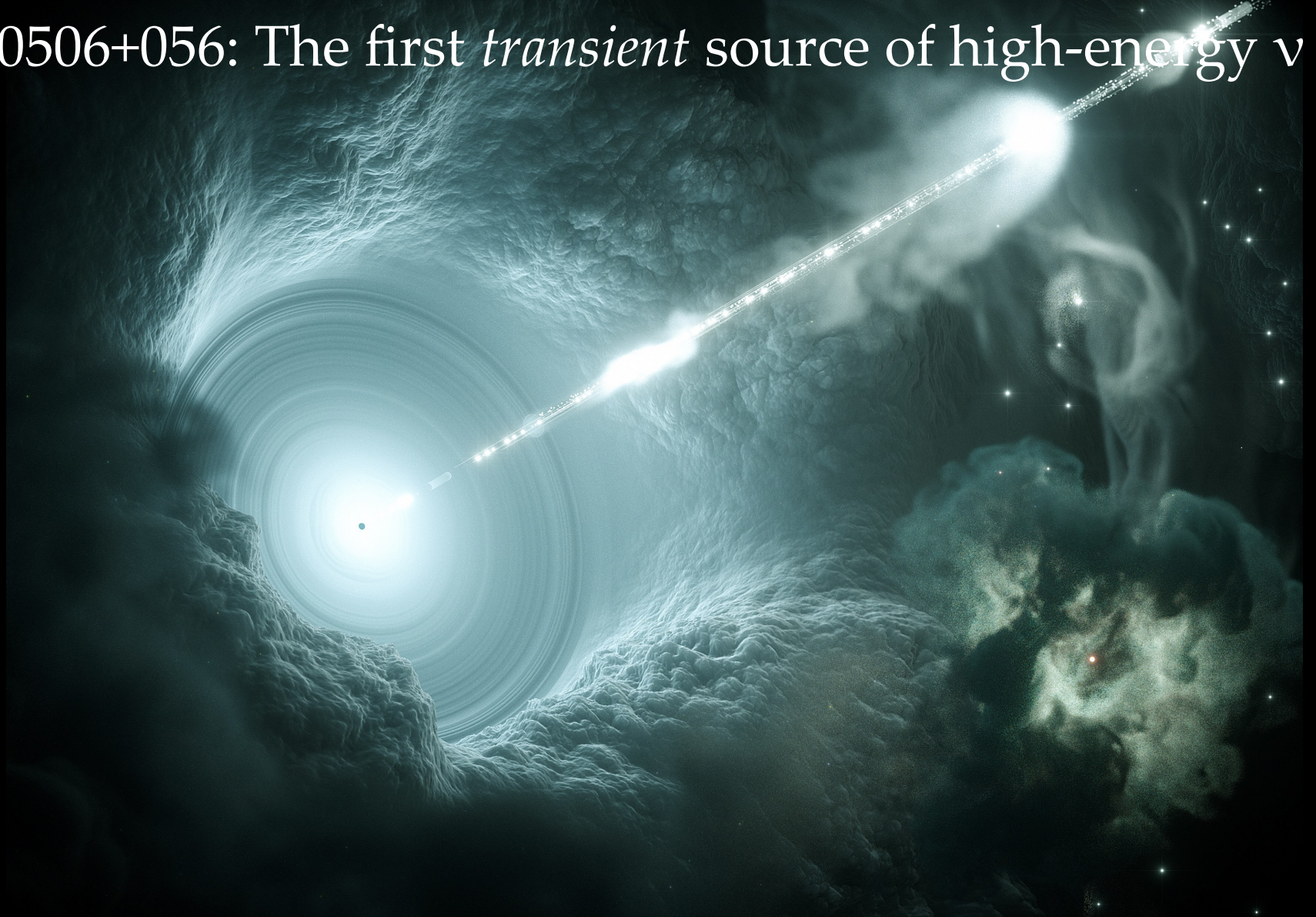
TXS 0506+056: The first *transient* source of high-energy ν

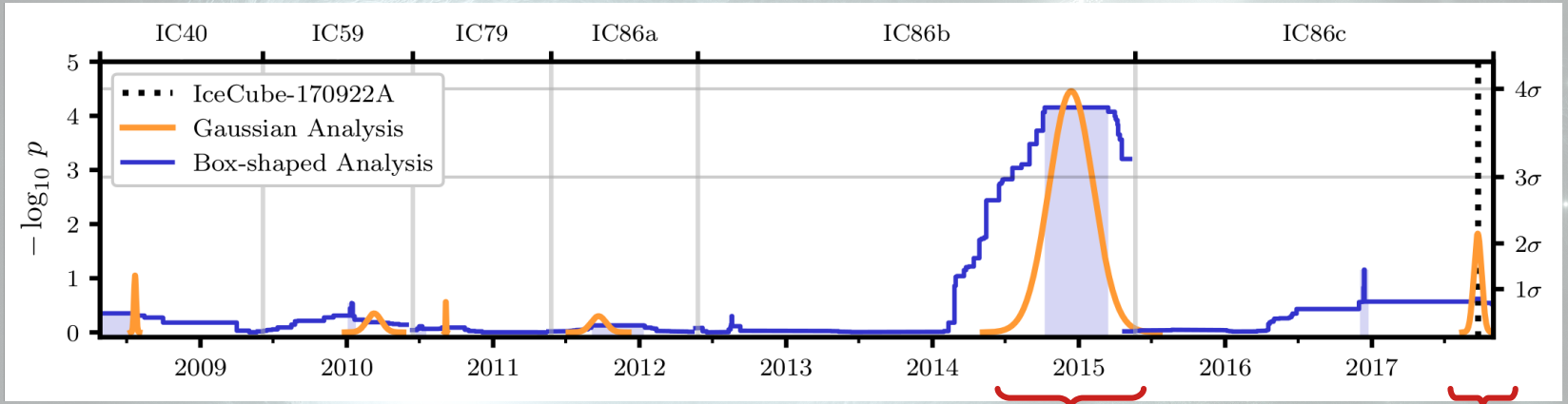


DESY

TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:

IceCube, *Science* 2018



After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

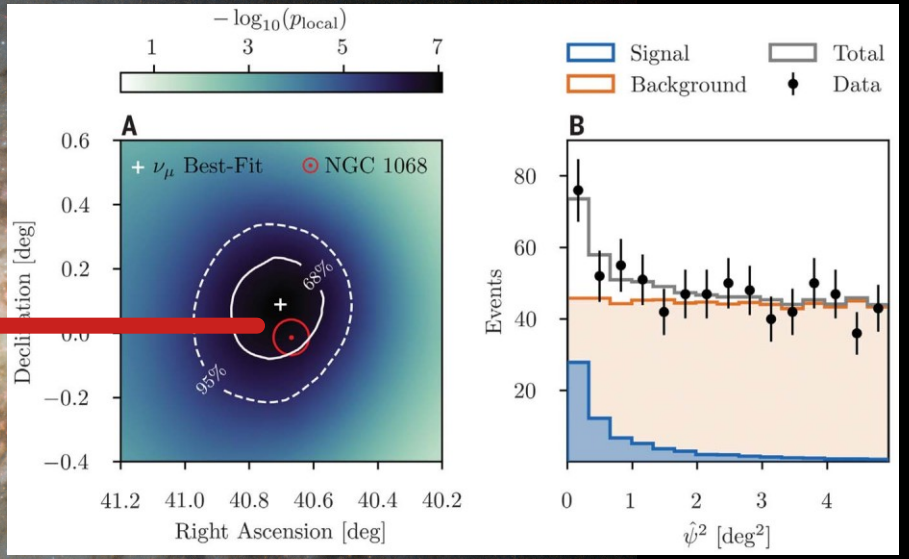
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



IceCube Collab., *Science* 378, 538 (2022)

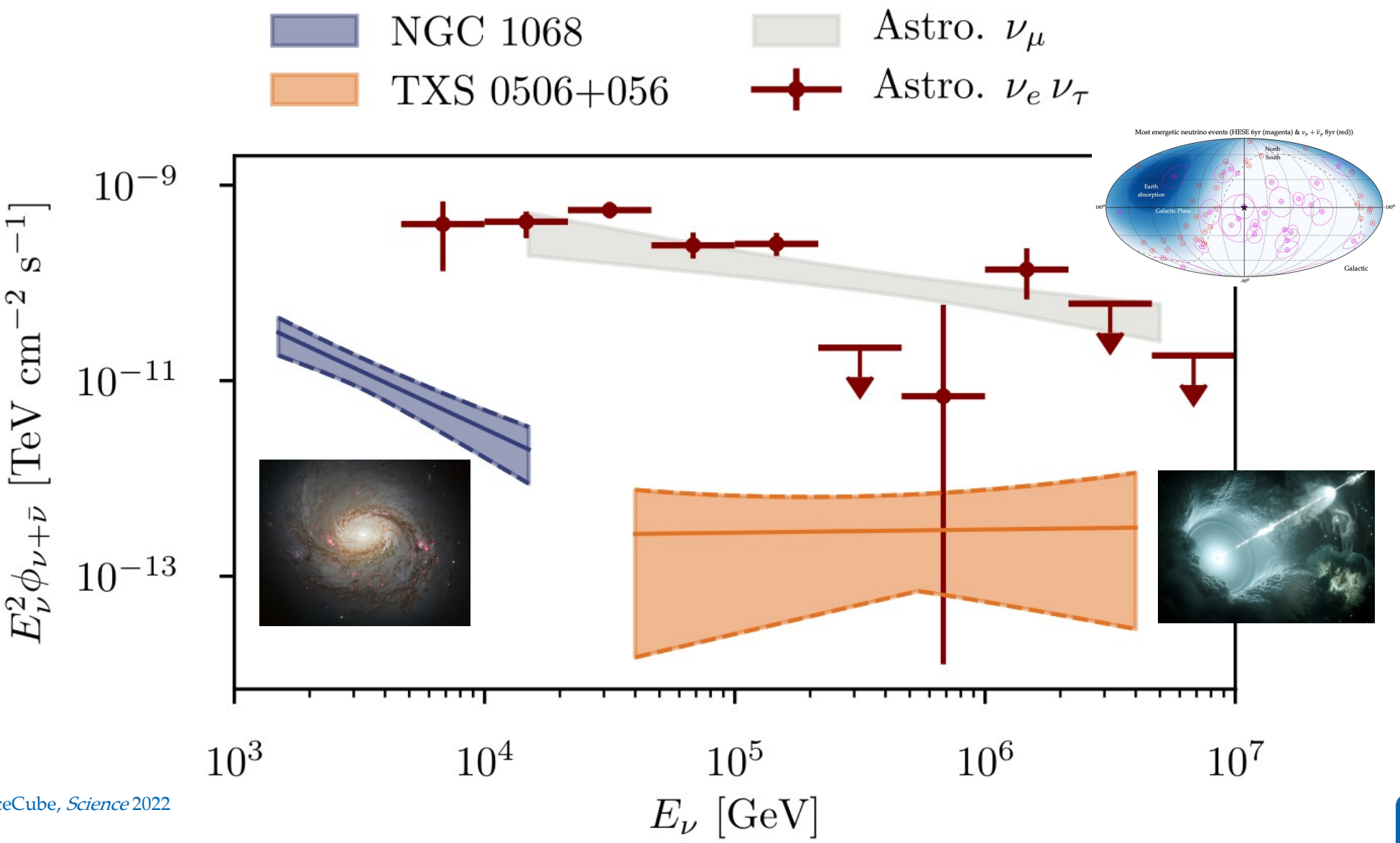
Hubble Space Telescope,
NASA, ESA & A. van der Hoeven

Tidal disruption events

Solar-mass star disrupted by SMBH (>10^5 $M_\odot$)

~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA



IceCube, *Science* 2022

What do we want

Fundamental question

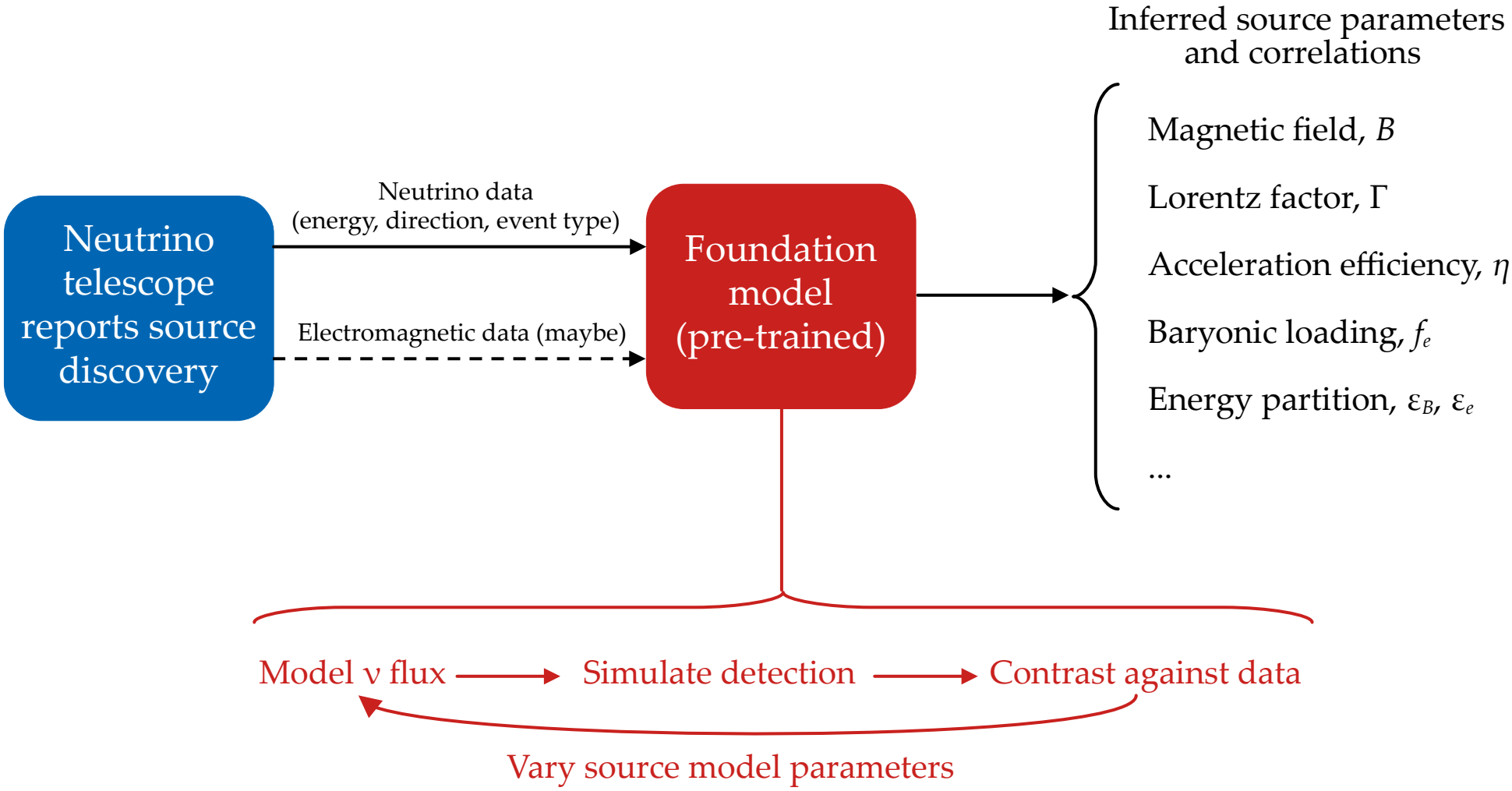
Given the observation a source of high-energy astrophysical neutrinos, (and possibly gamma rays) what can we *really* learn about it?

Fundamental problems

Theory: source models have many unknown, correlated parameters
Experiment: scant data (often, a single neutrino)

Proposed tenet

Keep the model complexity as-is (*i.e.*, don't fix parameters); let the data determine what we can learn


Inferred source parameters and correlations
Neutrino telescope reports source discovery
Neutrino data (energy, direction, event type)
Electromagnetic data (maybe)
Foundation model (pre-trained)
Magnetic field, B
Lorentz factor, Γ
Acceleration efficiency, η
Baryonic loading, f_e
Energy partition, ε_B, ε_e
...
Model ν flux
Simulate detection
Contrast against data
Vary source model parameters

Two paths to training and inference (*not* mutually exclusive):

More computationally expensive

1. **Use a simple model of neutrino emission**
   - Steady-state particle emission
   - Non-descript source and geometry
   - Generic parameters to describe neutrino production

   What do learn if we assume nothing about the identity of the source

2. **Use a sophisticated source model (*e.g.*, AM3)**
   - Time-dependent particle-transport equations
   - Tuned to geometry of specific source candidates
   - Different parameters depending on the model

   What do learn about specific source types

Essentials of neutrino production

The multi-messenger connection: a simple picture

$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0}, & \text{Br} = 2/3 \\ n + \pi^{+}, & \text{Br} = 1/3 \end{cases}$$

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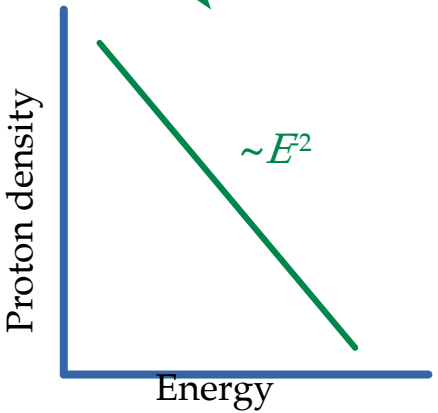

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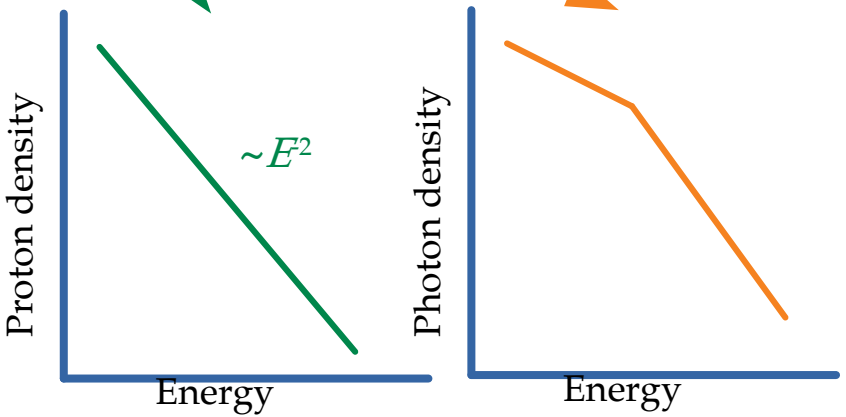

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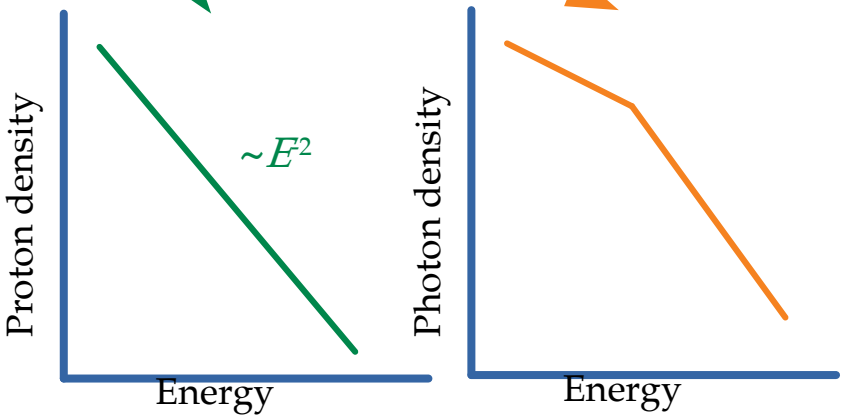
$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$n \text{ (escapes)} \rightarrow p + e^- + \bar{\nu}_e$$



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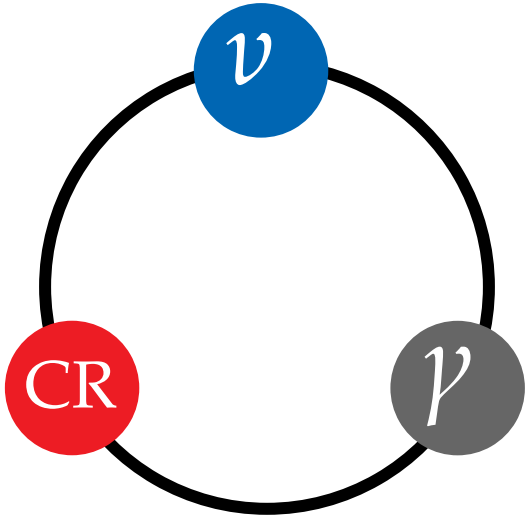

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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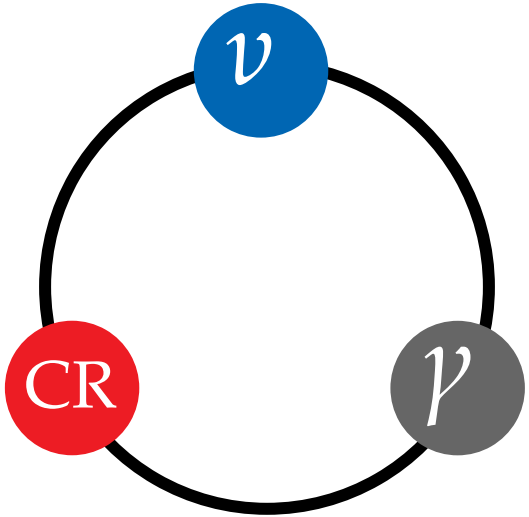

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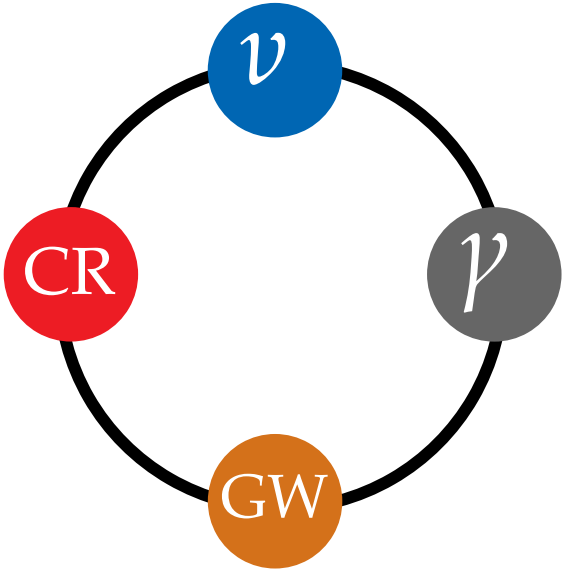

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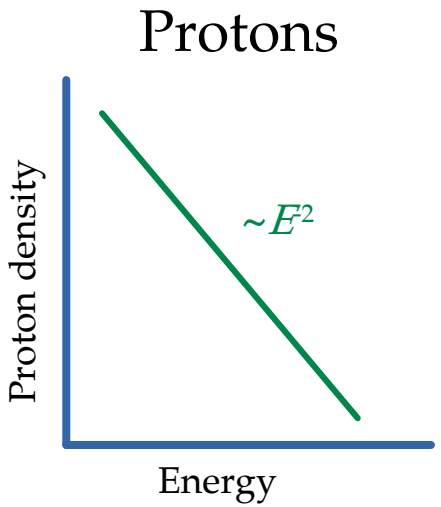
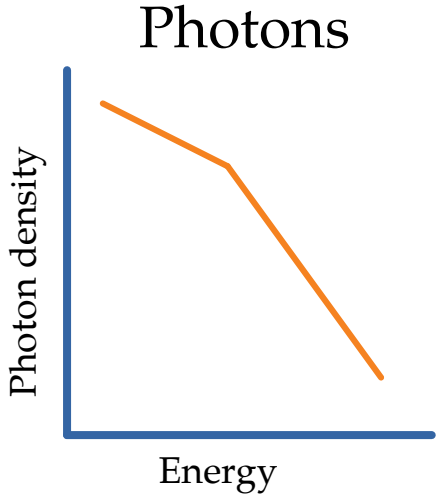
The prompt neutrino fluence from one GRB





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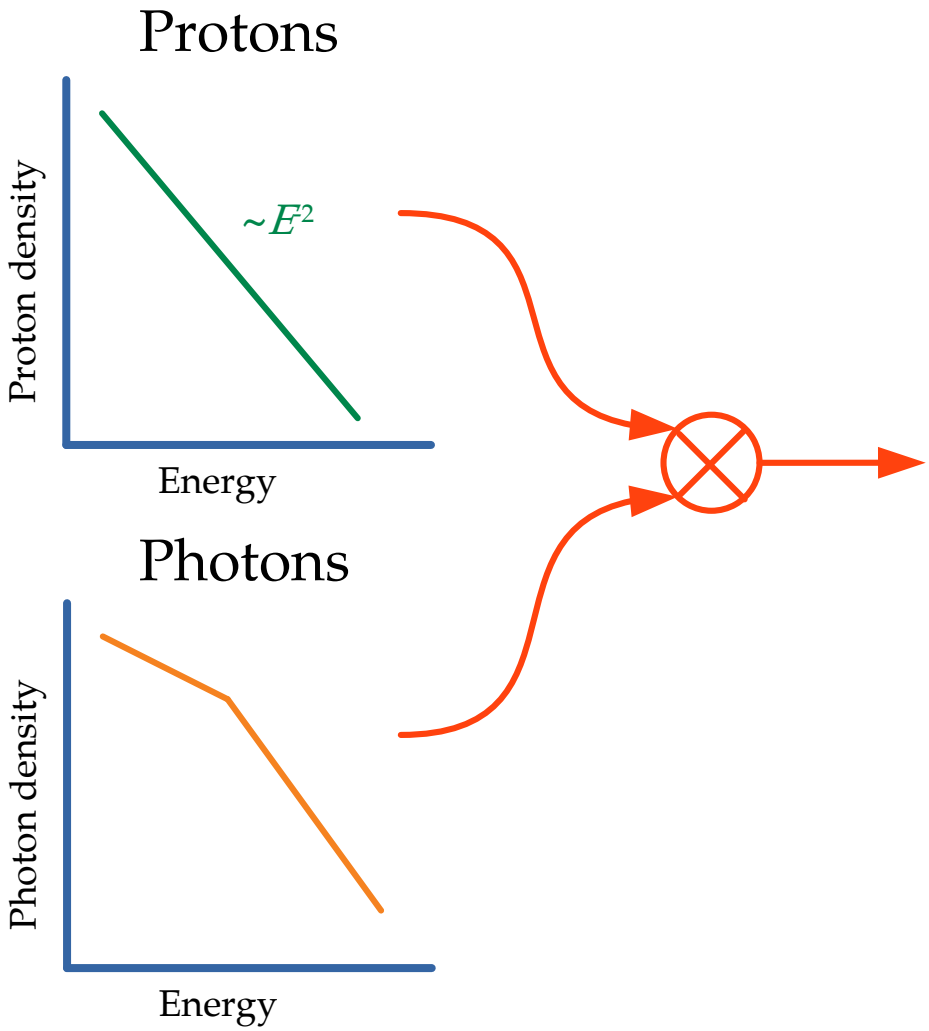

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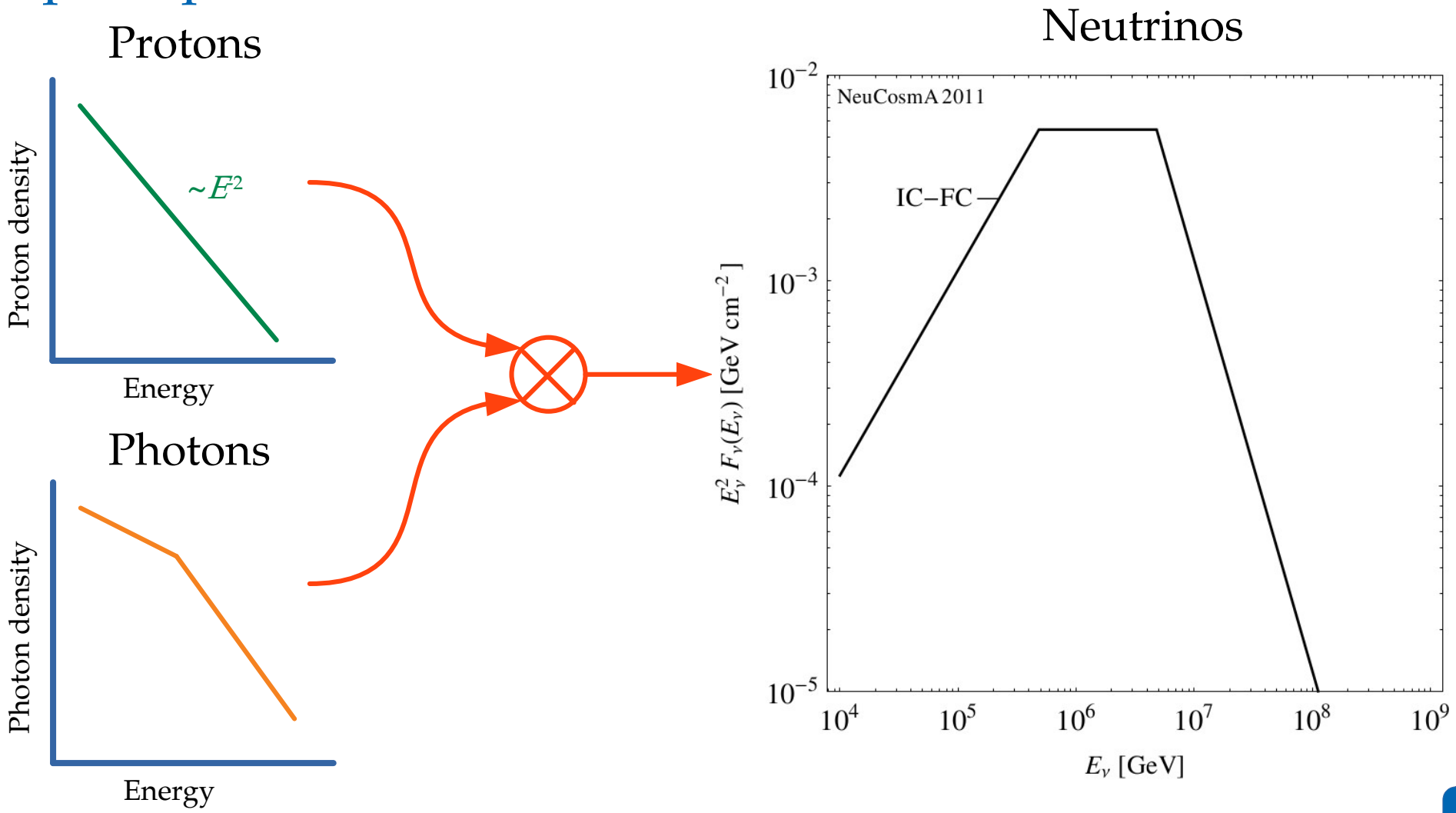

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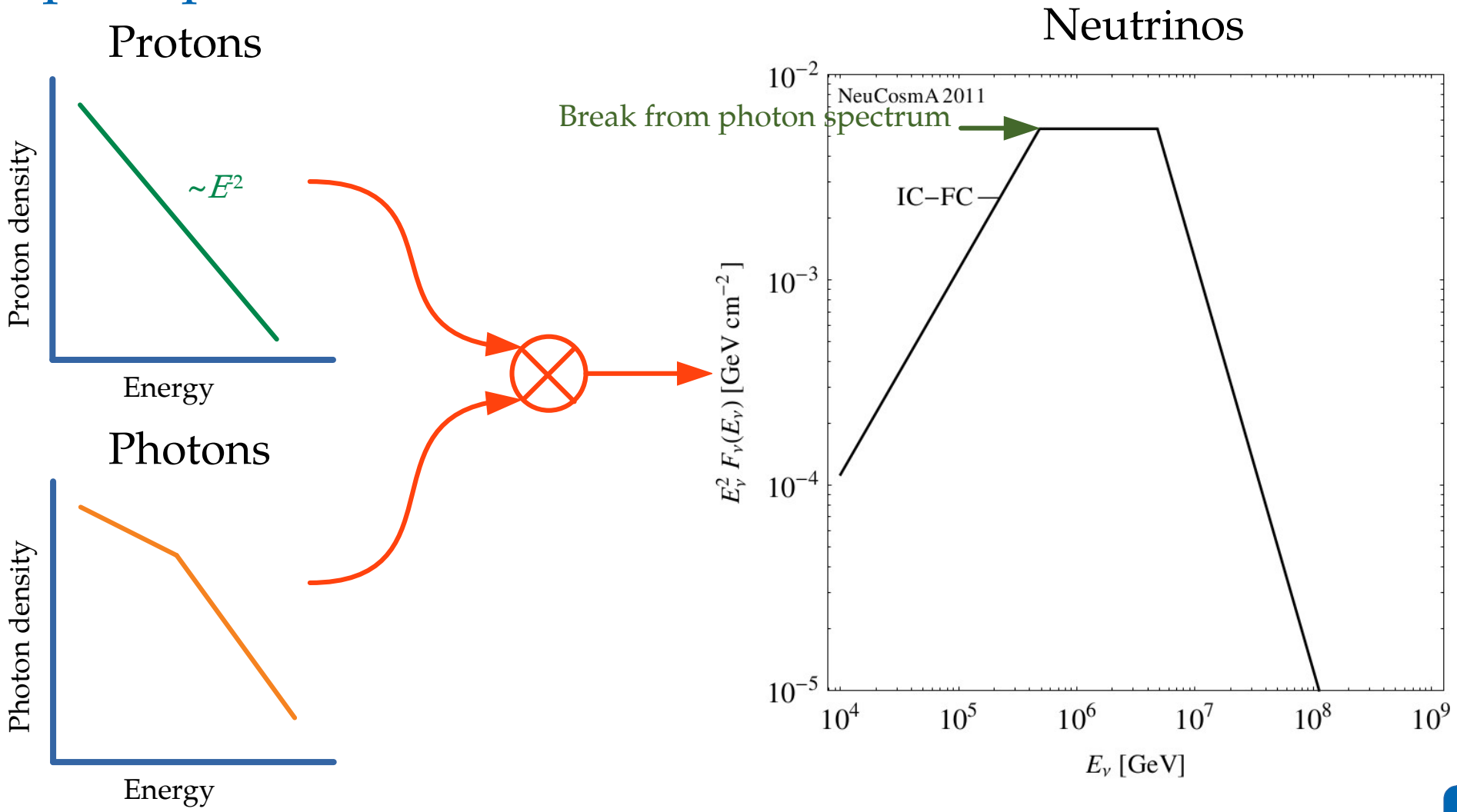

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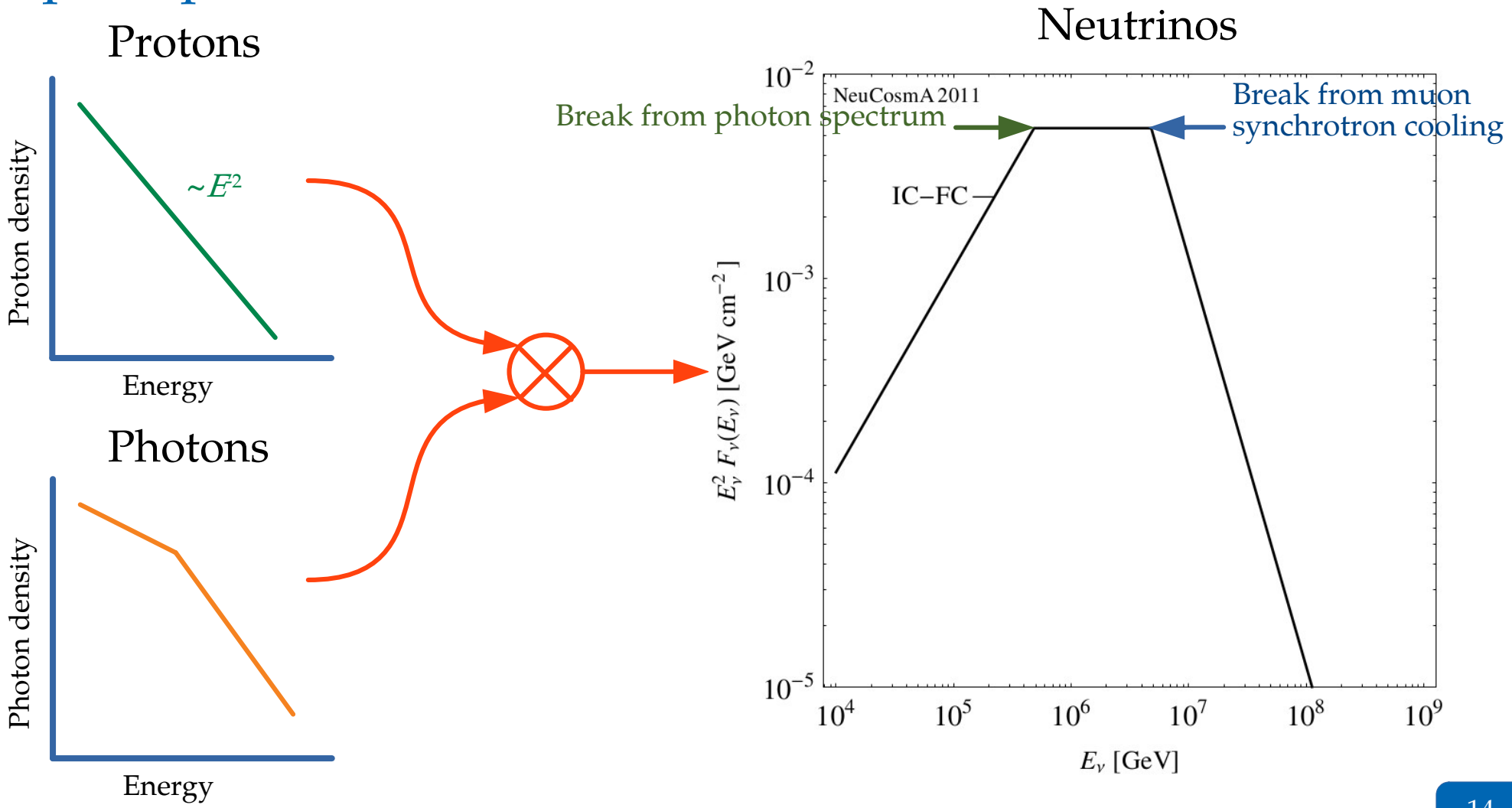
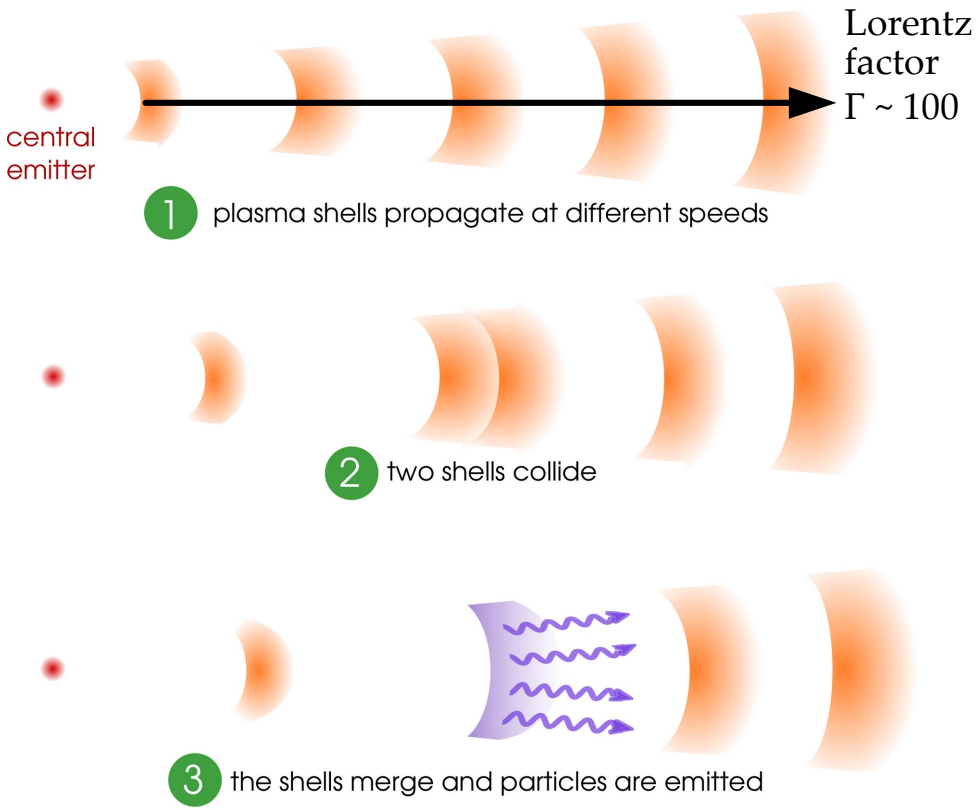
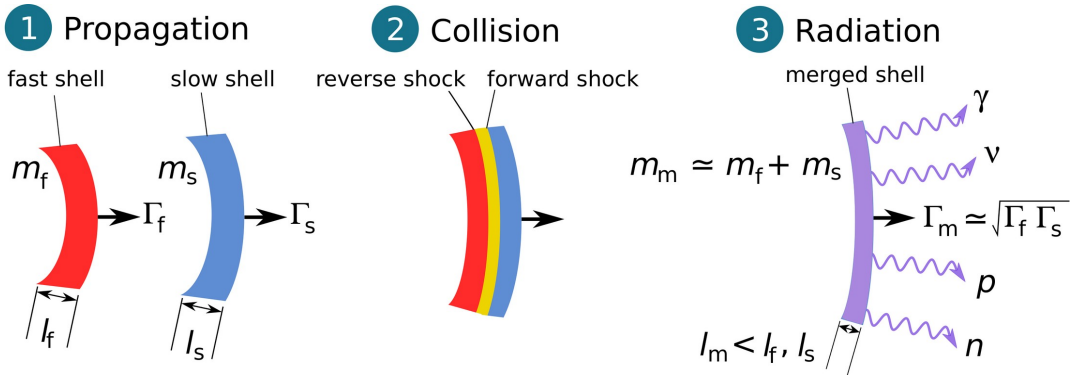


General anatomy of particle emission from a relativistic jet

Fireball model, internal collisions:





Part of the initial kinetic energy is radiated as γ, ν, and cosmic rays:

f_e : Fraction of energy in photons
f_p : Fraction of energy in protons
f_B : Fraction of energy in magnetic field

} Uncertainly known

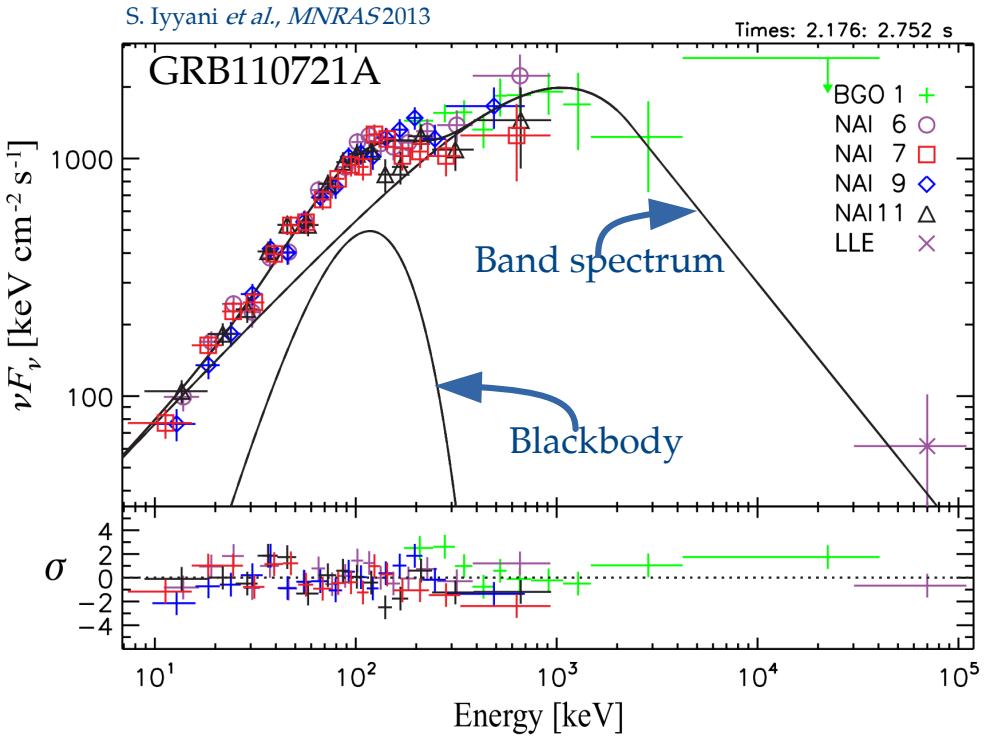
Kobayashi & Piran, *ApJ* 1997; Murase & Nagataki, *PRD* 2006; Guetta *et al.*, *ApJ* 2011
Baerwald, Hümmer, Winter, *PRD* 2011; ***MB*** *et al.*, *Nature Commun.* 2015

Gamma rays – spectrum basics

- Gamma-ray spectrum peaks at ~MeV
- Typically fitted by the Band function,

$$\nu F_\nu(E_\gamma) \propto \begin{cases} \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\alpha} \exp(-E_\gamma/E_0) & , E_\gamma < (\alpha-\beta)E_0 \\ \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\beta} & , E_\gamma \geq (\alpha-\beta)E_0 \end{cases}$$

- The spectrum evolves in time
- Some bursts are better fitted by a broken power law
- There might be multiple components



D. Band *et al.*, *ApJL* 1993

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⟨α⟩ = -1

⟨β⟩ = -2

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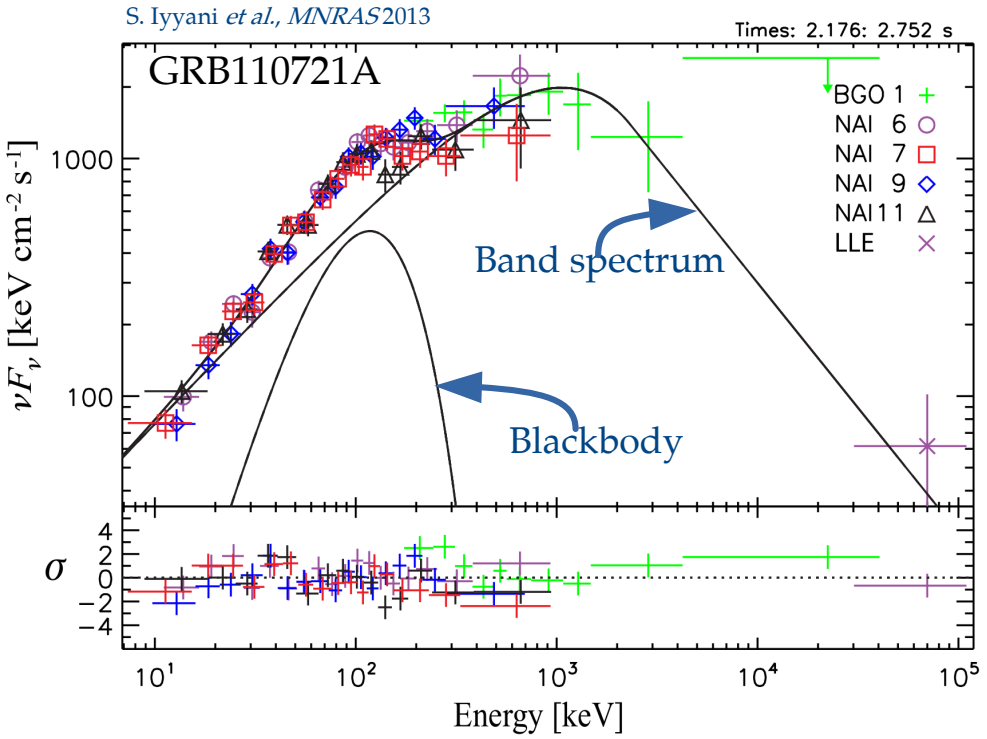

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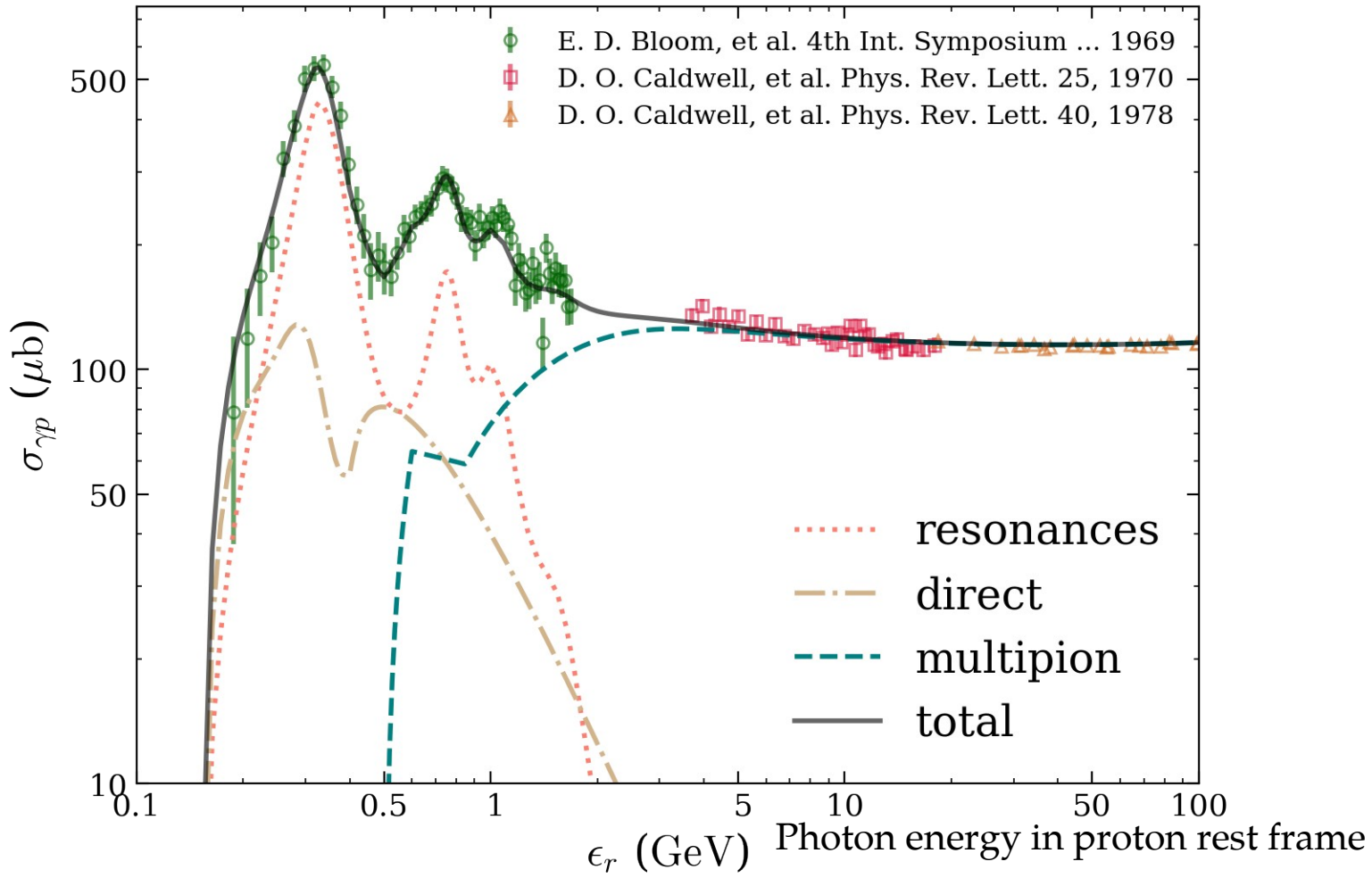
Photohadronic interactions (1/2)

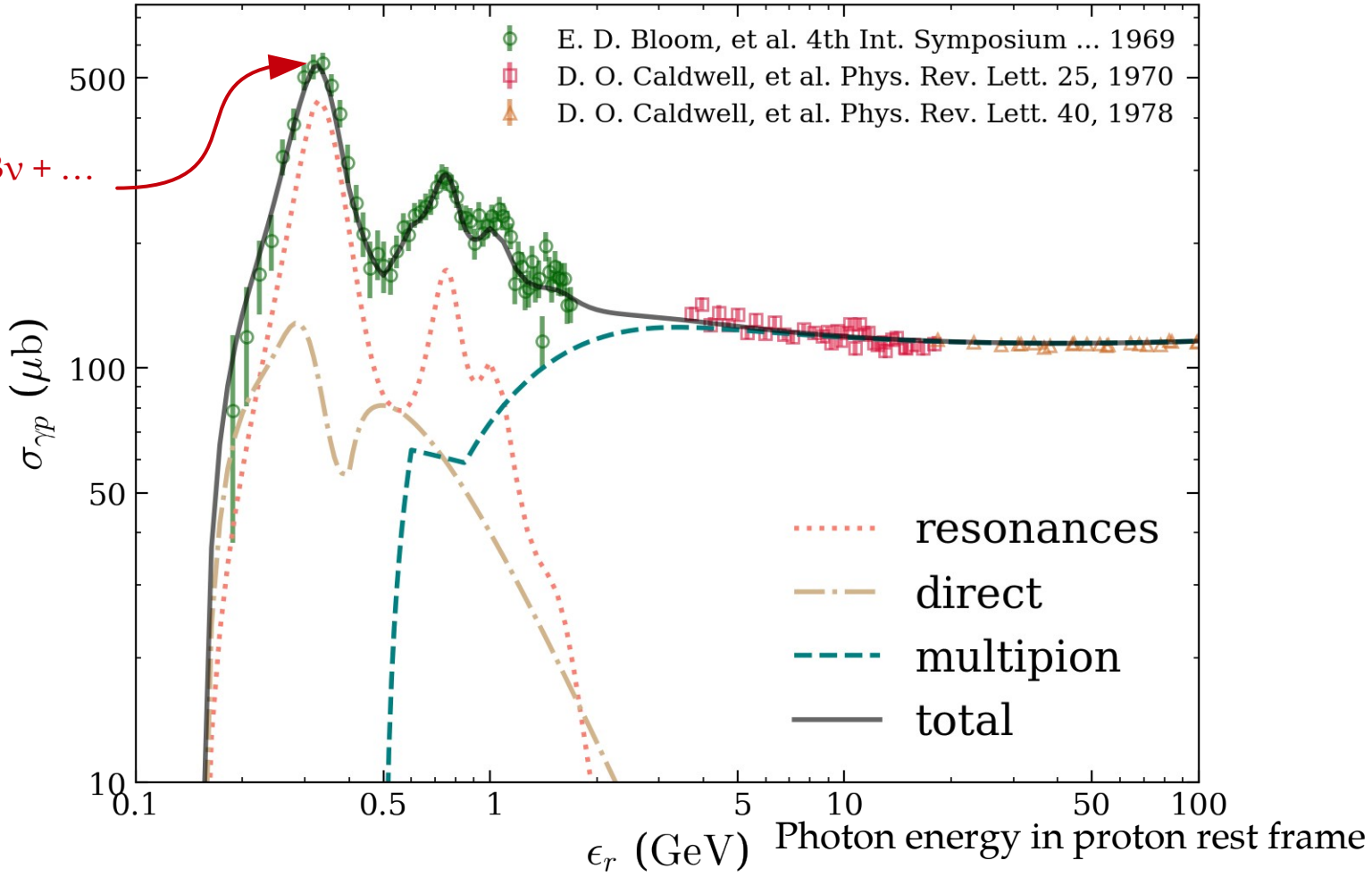


Morejón *et al.*, *JCAP* 2019

Photohadronic interactions (1/2)

Delta resonance:

$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$



Morejón *et al.*, *JCAP* 2019

Photohadronic interactions (1/2)

Delta resonance:

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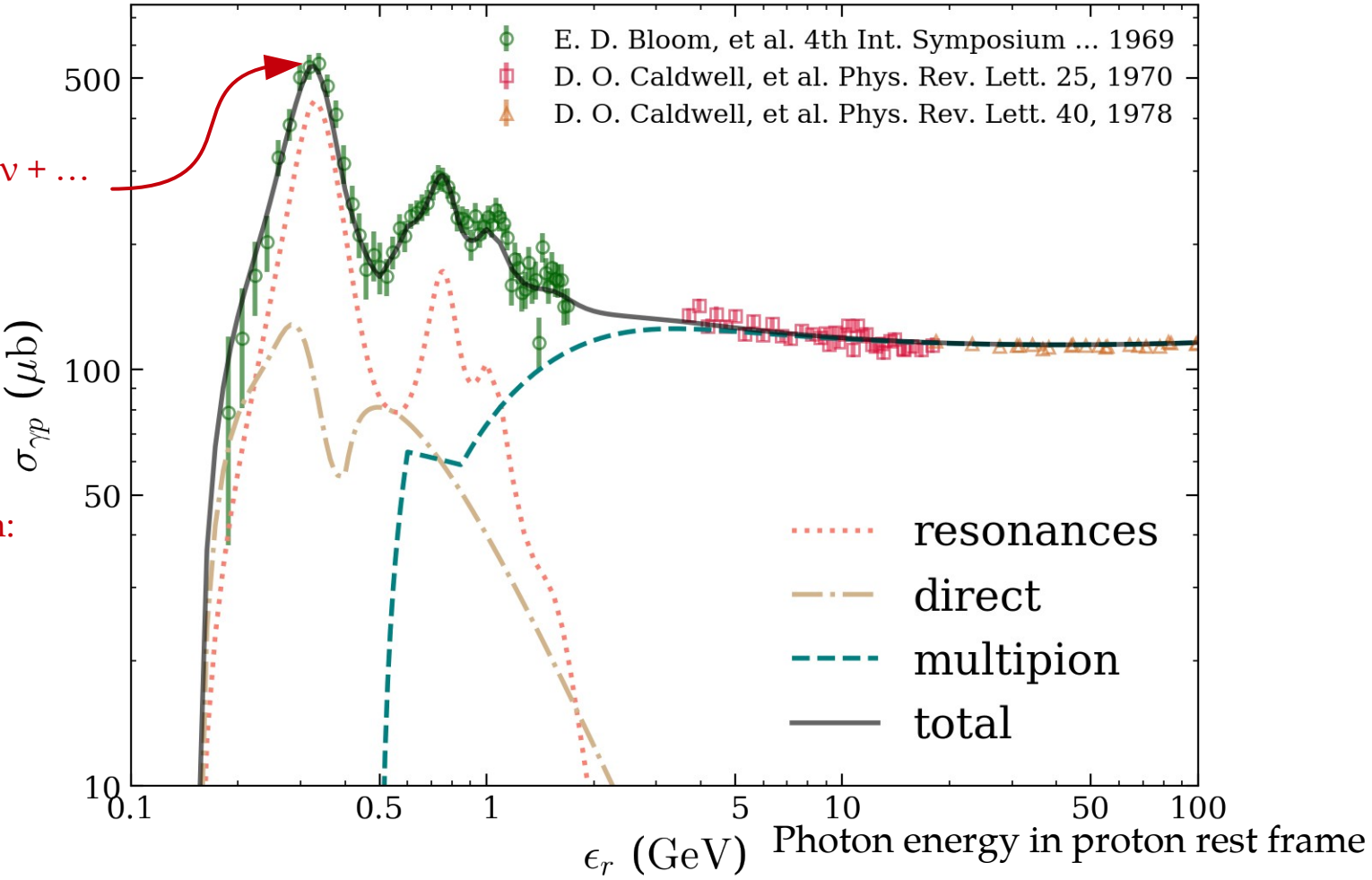
Resonance condition:

$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Morejón *et al.*, *JCAP* 2019

Photohadronic interactions (2/2)

(1) Δ-resonance region

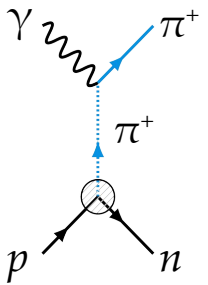
$$p + \gamma \xrightarrow{\Delta(1232)} p' + \pi$$

(2) Higher resonances

$$p + \gamma \xrightarrow{\Delta, N} \Delta' + \pi \ , \quad \Delta' \to p' + \pi$$

(3) Direct production (*t* channel)

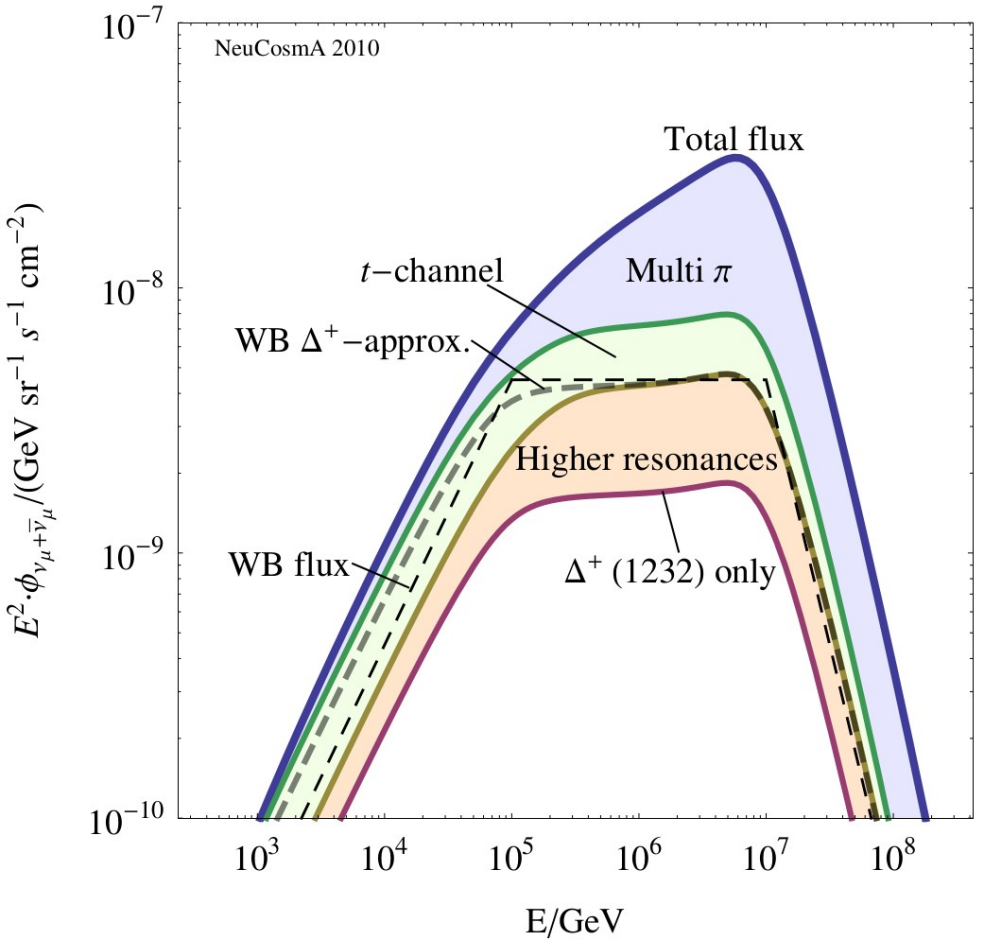
Same as (1) and (2), but in the *t* channel, *i.e.*, with a virtual pion



(4) Multi-pion production

Statistical production of two or more pions

E.g., neutrinos from a gamma-ray burst:



Mücke *et al.*, *Comput. Phys. Comm.* 2000
Hümmer *et al.*, *ApJ* 2010; Baerwald, Hümmer, Winter, *PRD* 2011

Cooking up neutrinos from a flaring gamma-ray source

Energy in neutrinos $\propto$ energy in gamma rays

All the details are in the proportionality constant

Ingredients:

▸ Gamma-ray luminosity (erg s^{-1})	Measured
▸ Variability time scale (s)	Measured
▸ Shape of photon spectrum	Measured
▸ Redshift	Measured (sometimes)
▸ Bulk Lorentz factor of jet	Estimated
▸ Energy partition into *e*, *p*, magnetic field	Estimated (if not guessed)

The fine print

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1-\left(1-\langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right]\frac{f_p}{f_e}\int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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The fine print

Energy in neutrinos ∝ energy in gamma rays

Fraction of p energy given to π in one interaction (~20%)

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Fraction of total p energy given to pions

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Fraction of total p energy given to pions

Baryonic loading

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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Fraction of p energy given to π in one interaction (~20%)

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1-\left(1-\langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right]\frac{f_p}{f_e}\int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

Fraction of total p energy given to pions

Baryonic loading

Optical depth to $p\gamma$:

$$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{ergs}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

What data do we need?

High-energy neutrinos: IceCube (plus others?) public-release data

Includes event energy, direction, type (shower *vs.* track)
Different data selections
Often accompanies a published paper

Detection alerts

Gamma rays: astronomer's telegrams, GCN circular
Neutrinos: public IceCube alerts

Gamma rays

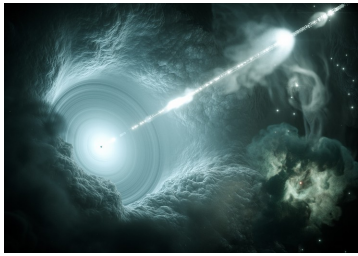
As data: repositories (*e.g.*, *Fermi* Gamma-Ray Telescope public data)
As images: directly from papers

A basic model of neutrino emission

A basic model of neutrino emission

Disclaimer:
I am not an expert
(*I learned the basics in a couple days helped by LLM*)

Leptohadronic ν + γ generator (1/2)



Particle production via Δ resonance:

$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} n + \pi^{+} \rightarrow n + \mu^{+} + \nu_{\mu} \\ p + \pi^{0} \rightarrow p + \gamma + \gamma \end{cases}$$

Production efficiency:

$$\Phi_{\nu} \propto L_p \cdot n_{\gamma} \cdot \sigma_{p\gamma}$$

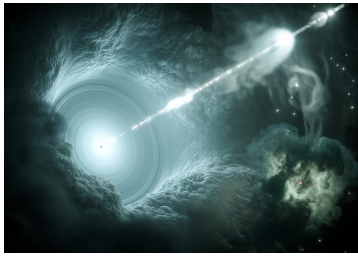
Proton luminosity

Neutrino flux

Photon density

Degeneracy warning:
A high ν flux can be cause by a powerful beam (high L_p) or a dense photon target (high n_γ). Neutrinos alone cannot distinguish these cases

Leptohadronic $\nu + \gamma$ generator (2/2)



Constraint: synchrotron cooling

Magnetic fields cool secondary pions before they decay, creating a spectral break:

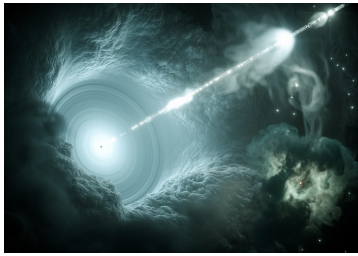
$$E_{\text{break}} \propto B^2$$

Constraint: gamma-ray opacity

Gamma rays interact with the same target photons (n_γ) that produced them:

$$\tau_{\gamma\gamma} \approx n_\gamma \cdot \sigma_{\gamma\gamma} \cdot R_{\text{src}}$$

Training the physics



We train on simulate data (for now)

Compute neutrino and gamma-ray data for the following ranges:

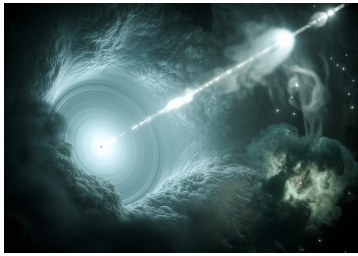
- Magnetic field: 0.1–100 G
- Photon density: 10^{8}–10^{14} cm^{-3}
- Proton index: 1.5–2.8
- Max. proton energy: 10 PeV—10 EeV

Physics loss function

Use a Log-Cosh error function because the flux spans 20 orders of magnitude

$$\mathcal{L} = \sum_{i} w_i \cdot \log\left(\cosh\left(y_{\mathrm{pred},i} - y_{\mathrm{true},i}\right)\right)$$

Physics-informed foundation model



Neural surrogate

We replace slow numerical solvers with a fast neural network using Fourier embeddings (γ):

$$\mathrm{Flux}(E) \approx \mathrm{NN}_\theta\left(\gamma(E), \gamma(B, n_\gamma, s)\right)$$

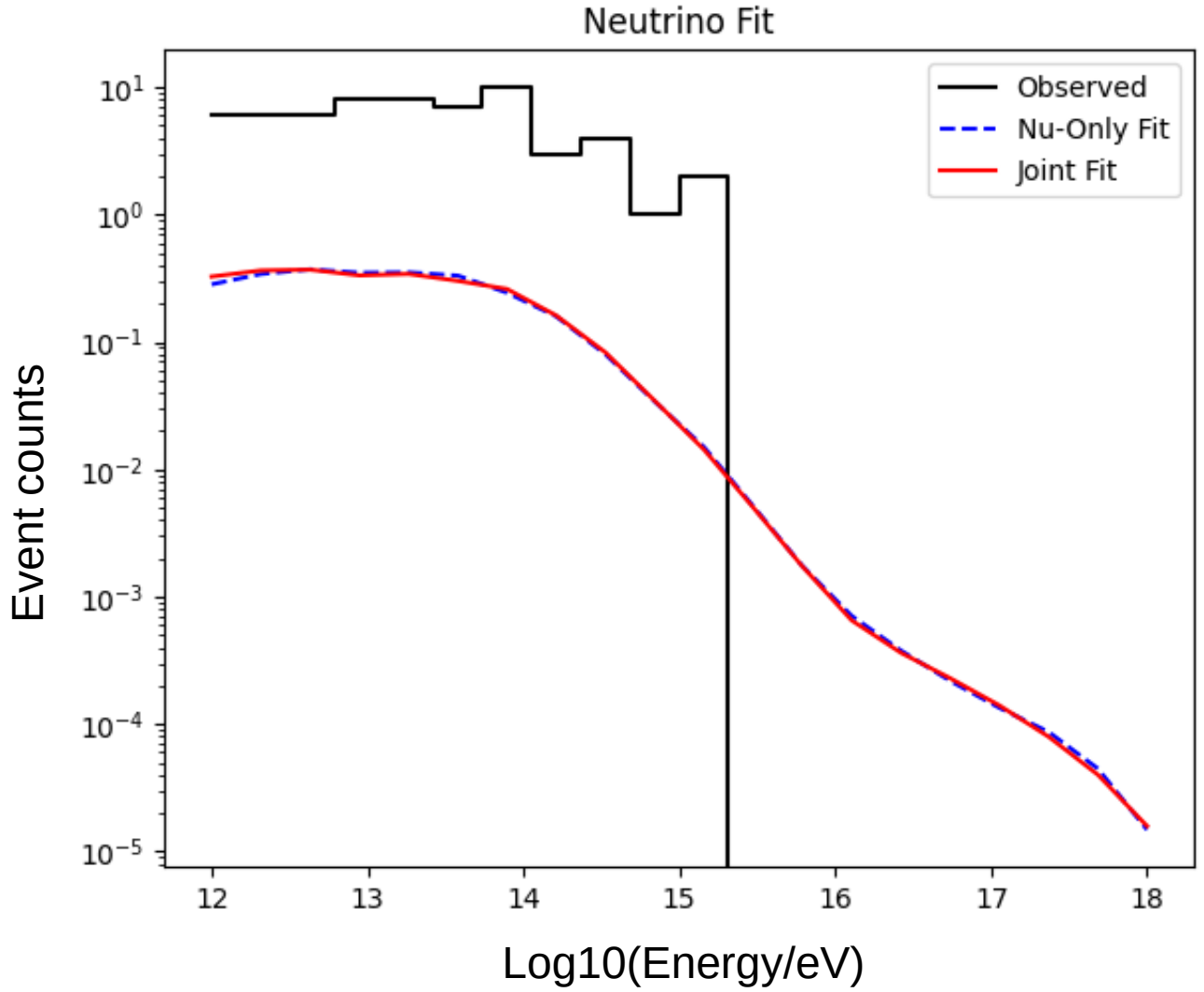
The embeddings map parameters into high-dimensional frequency space using weights ($\mathbf{W}$):

$$\gamma(x) = [\cos(2\pi \mathbf{W} x), \sin(2\pi \mathbf{W} x)]$$

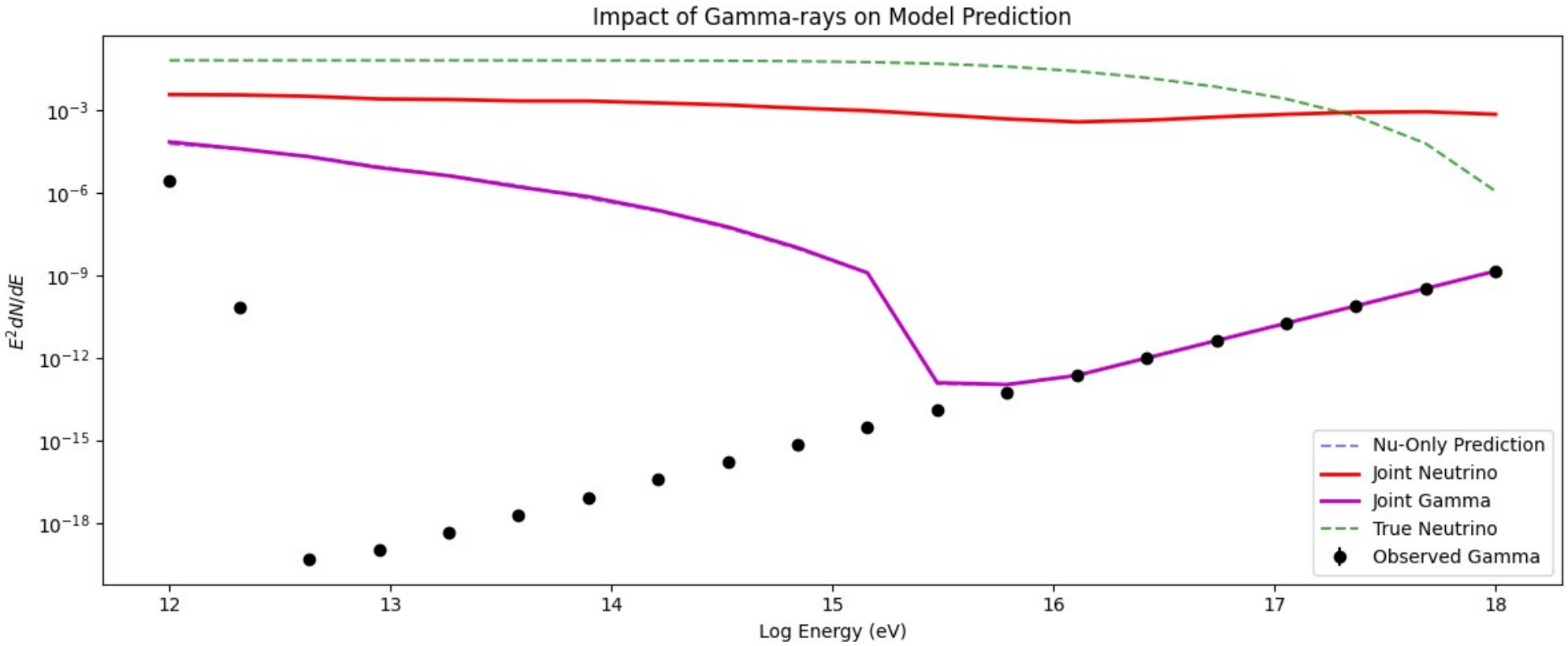
Bayesian inference (MCMC)

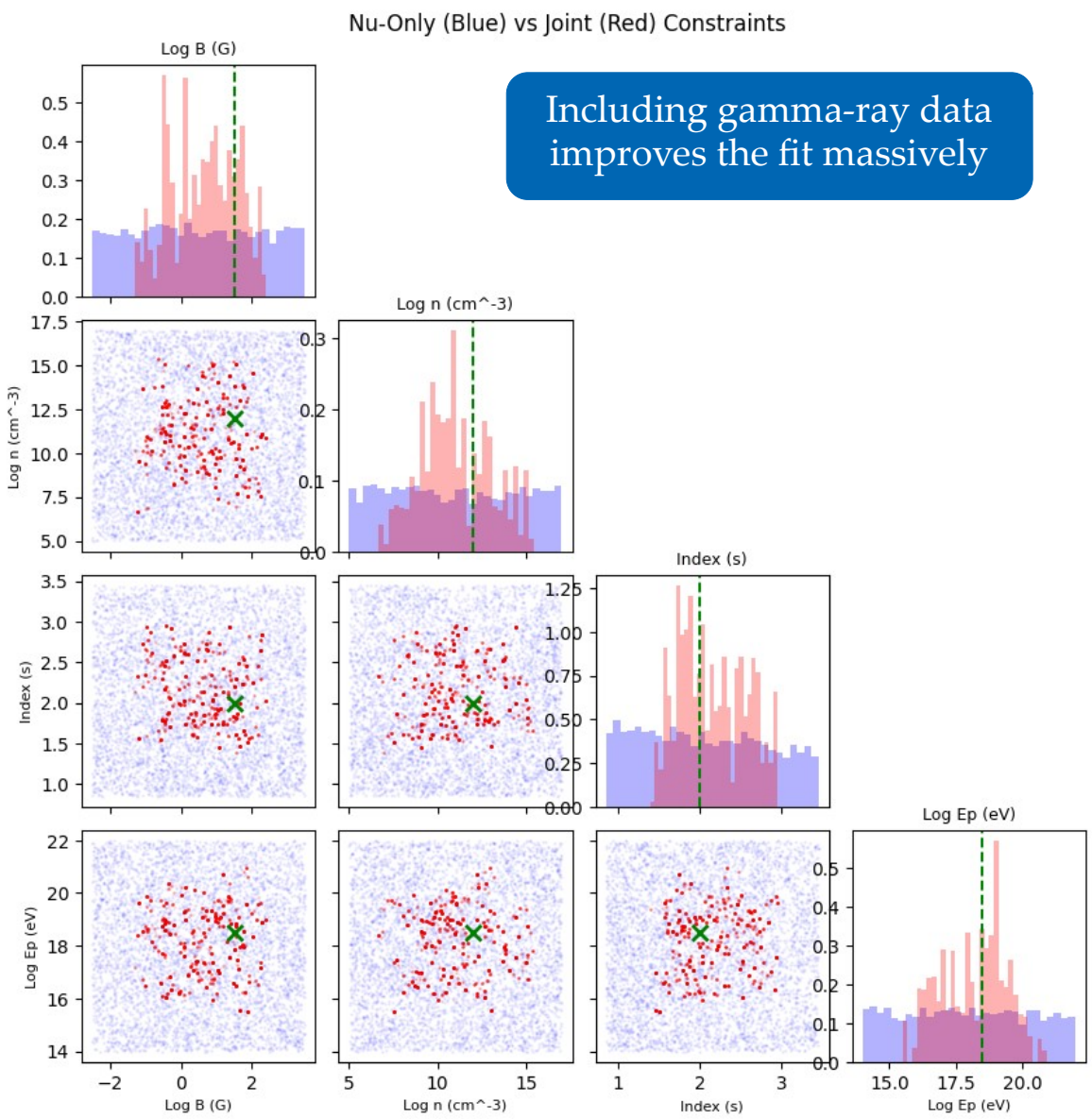
We maximize the joint neutrino and gamma-ray likelihood:

$$\ln \mathcal{L}(\theta) = \underbrace{\sum_i \left(N_{\mathrm{obs},i} \ln N_{\mathrm{exp},i}(\theta) - N_{\mathrm{exp},i}(\theta)\right)}_{\text{Neutrino (Poisson)}} - \underbrace{\frac{1}{2}\sum_j \left(\frac{\Phi_{\mathrm{obs},j} - \Phi_{\mathrm{model},j}(\theta)}{\sigma_j}\right)^2}_{\text{Gamma-ray (Gaussian)}}$$


Neutrino Fit
Observed
Nu-Only Fit
Joint Fit
Event counts
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
12
13
14
15
16
17
18
Log10(Energy/eV)

Note:
The model is not great





Including gamma-ray data improves the fit massively

Log B (G):

Nu-Only: 0.47 ± 1.73
Joint: 0.64 ± 0.93
True: 1.5

Log n (cm^-3):

Nu-Only: 10.94 ± 3.50
Joint: 11.02 ± 2.00
True: 12.0

Index (s):

Nu-Only: 2.08 ± 0.74
Joint: 2.15 ± 0.41
True: 2.0

Log Ep (eV):

Nu-Only: 17.89 ± 2.30
Joint: 18.15 ± 1.24
True: 18.5

Final thoughts

- Machine learning is underused to infer neutrino source properties
- Public data (neutrino + gamma-ray + alerts) is available

Need to define:

- What is the right machine-learning architecture to adopt?
- What kind of data we want (processed, raw)
- What models to train on (simple, sophisticated) *vs.* time cost
- Can we also learn about source *populations*?