AGN as neutrino sources

from IceCube to radio neutrino telescopes

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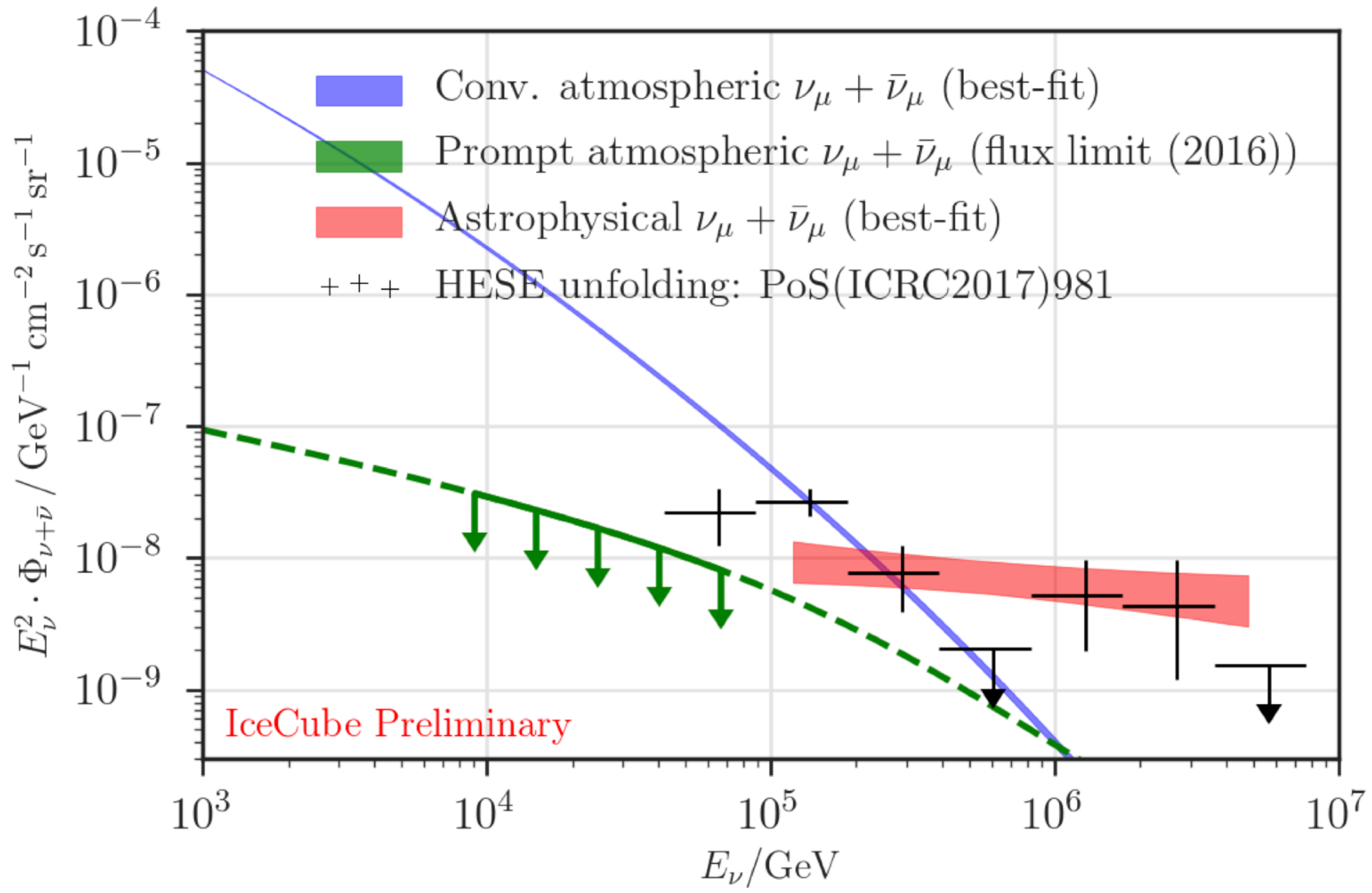
DESY Zeuthen

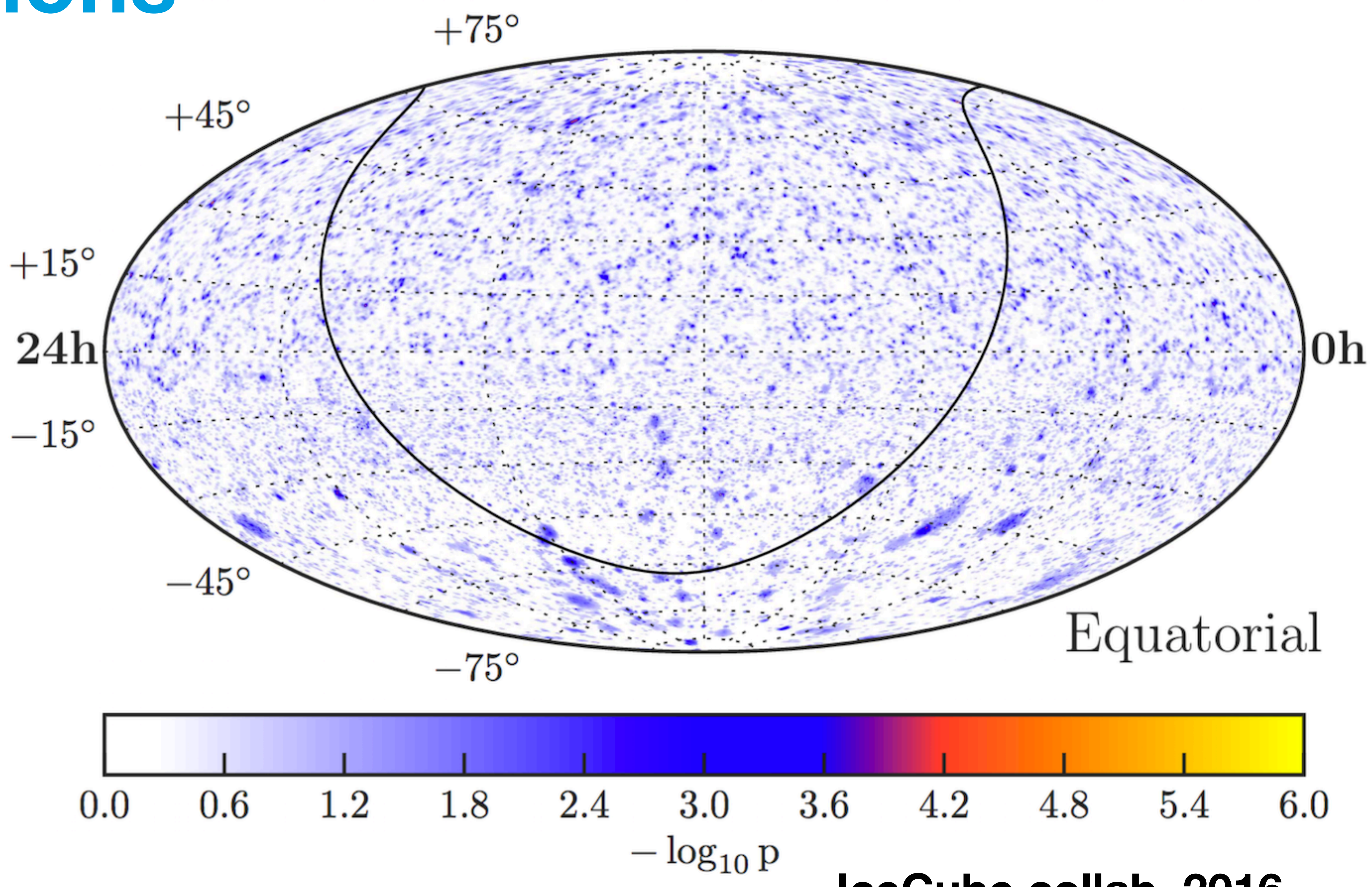
XIX International Workshop on Neutrino Telescopes
INFN/Padova University
January 23, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Astrophysical neutrino observations



Haack & Wiebusch, ICRC 2017



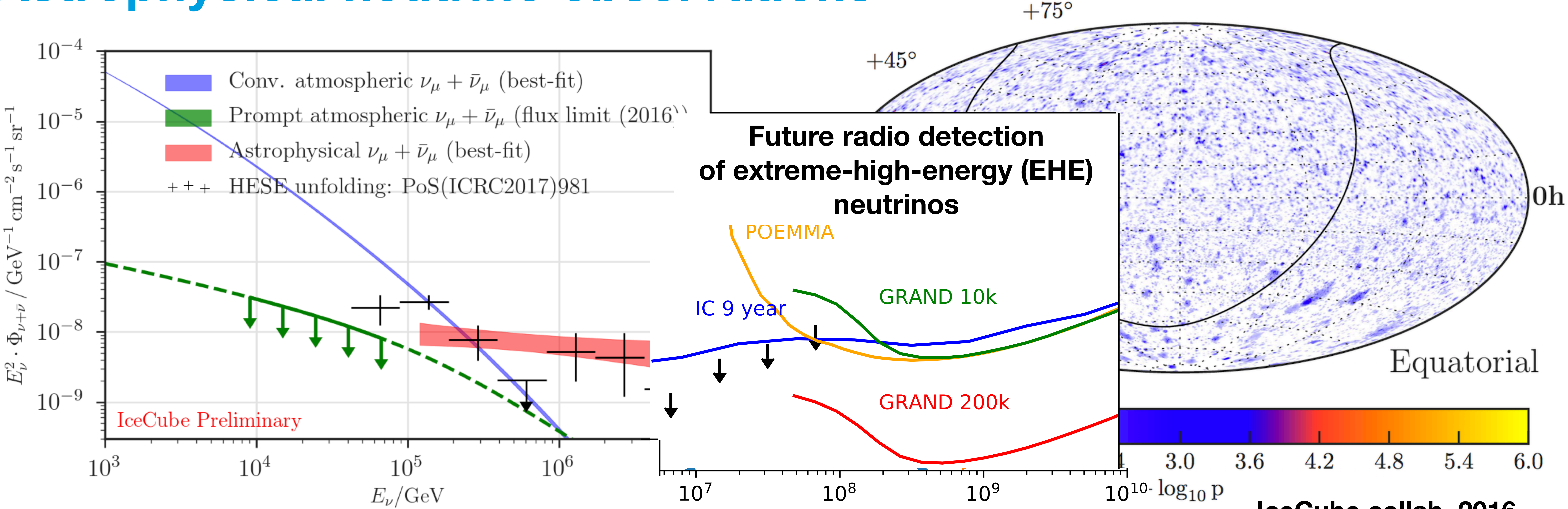
IceCube collab. 2016

- **Diffuse neutrino flux observed above atmospheric background** (first observed in 2013)
- **Astrophysical neutrinos observed with energy up to ~50 PeV**

- **No strong correlation** with **known point sources**
- **No significant clustering** observed yet
  -> **Stacking limits, multiplet constraints**

- But some hints of neutrino sources have already emerged (e.g. **TXS 0506+056**, **PKS 1502+106**)

Astrophysical neutrino observations



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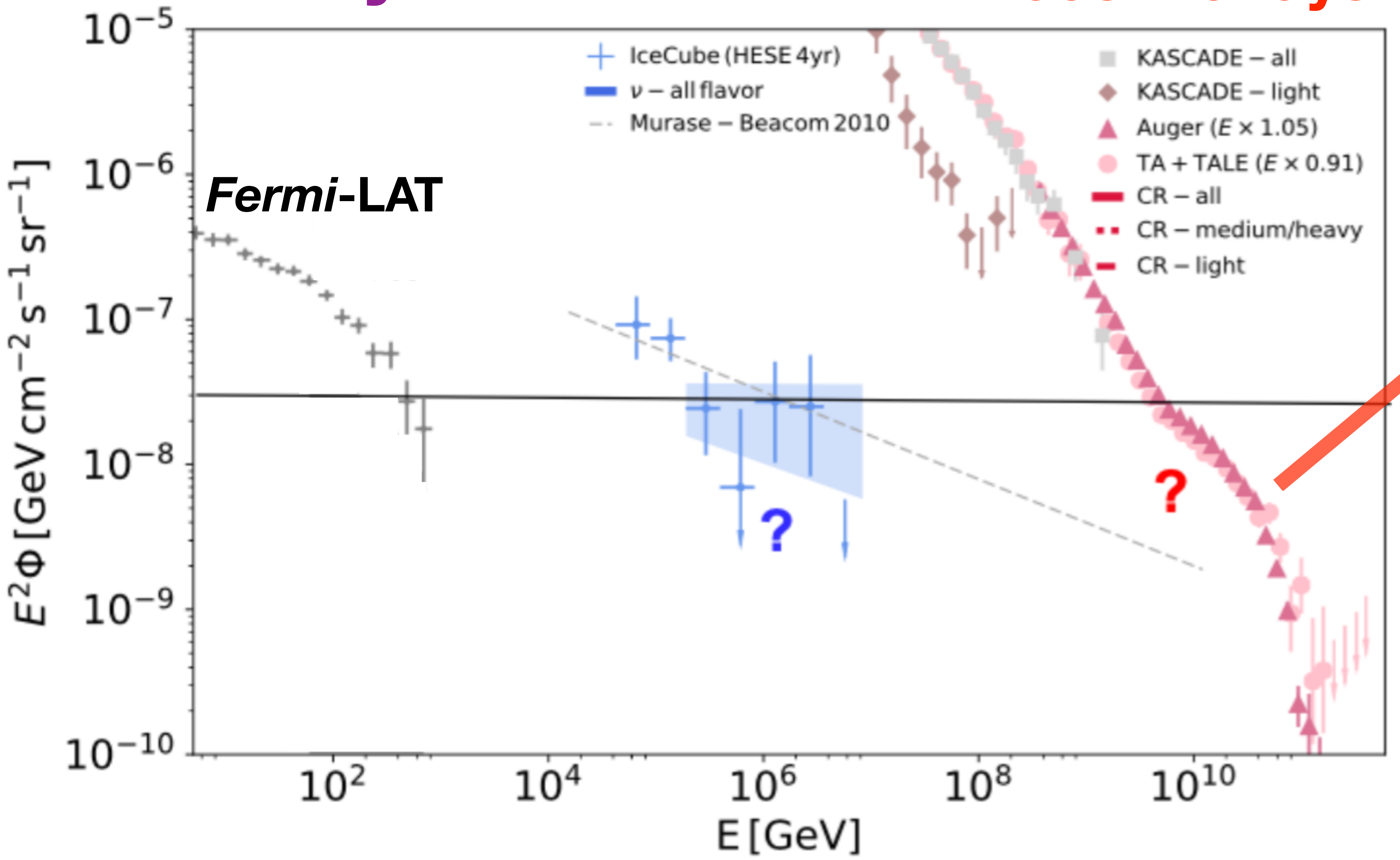
Cosmic ray interactions and the multi-messenger picture

- **Multi-messenger astrophysics:** attempting to unveil **common origin** to different cosmic radiations

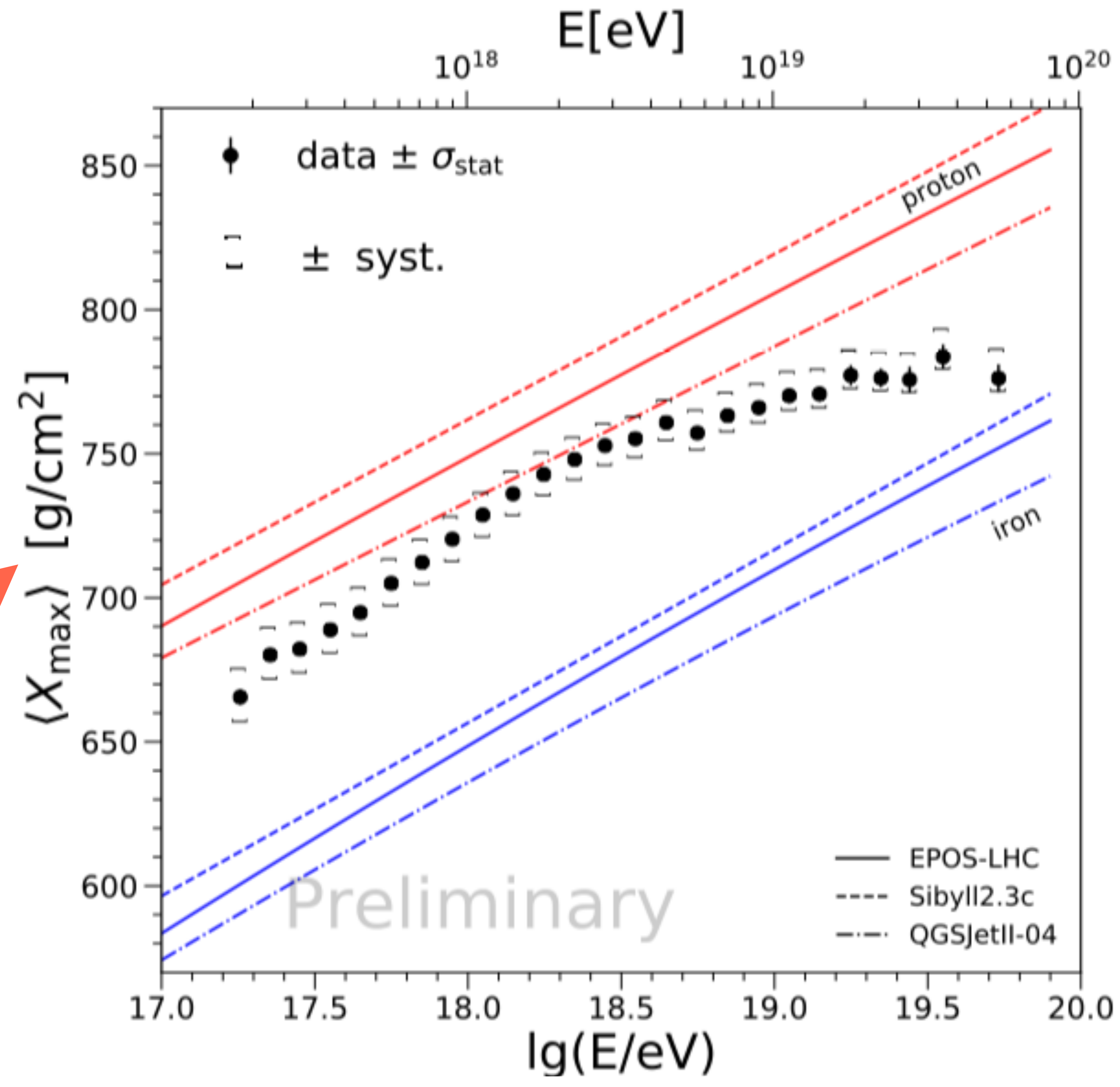
gamma rays

neutrino

ultra-high-energy cosmic rays



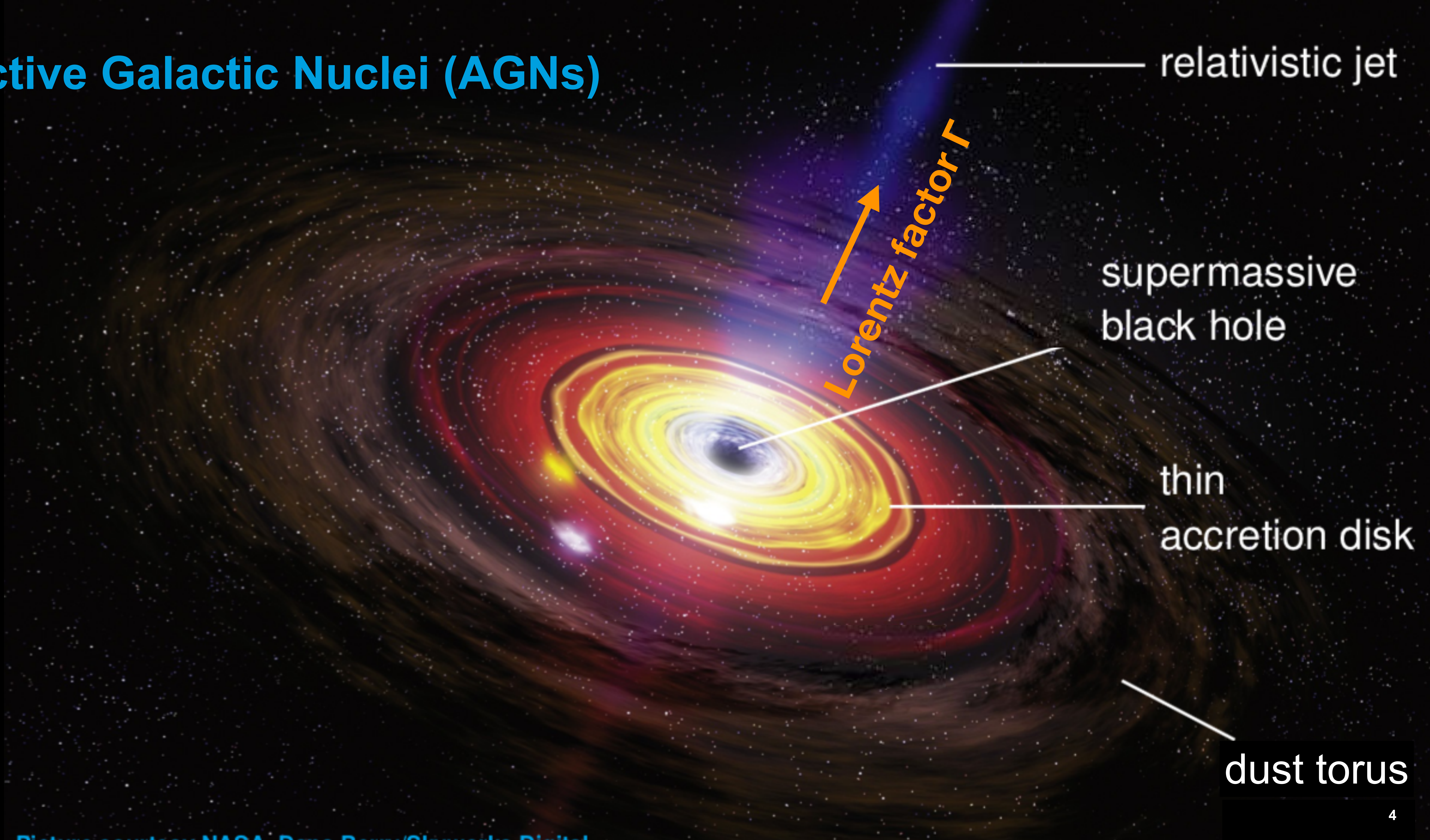
K Murase, ICRC 2019



A Yushkov, ICRC 2019

- **Evidence** of a fraction of ultra-high-energy cosmic rays **heavier than protons**

Active Galactic Nuclei (AGNs)



Picture courtesy NASA, Dana Berry/Skyworks Digital

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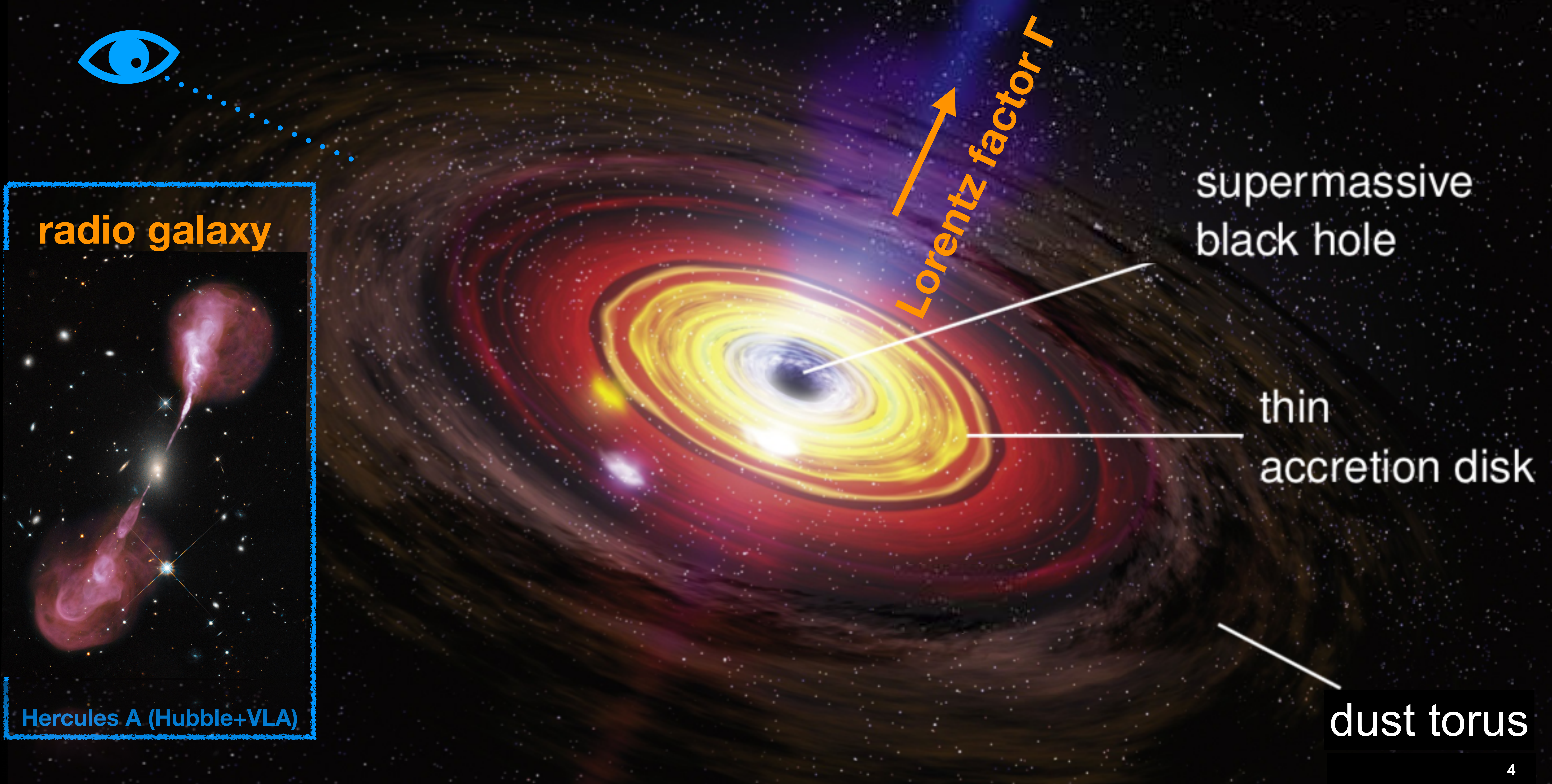

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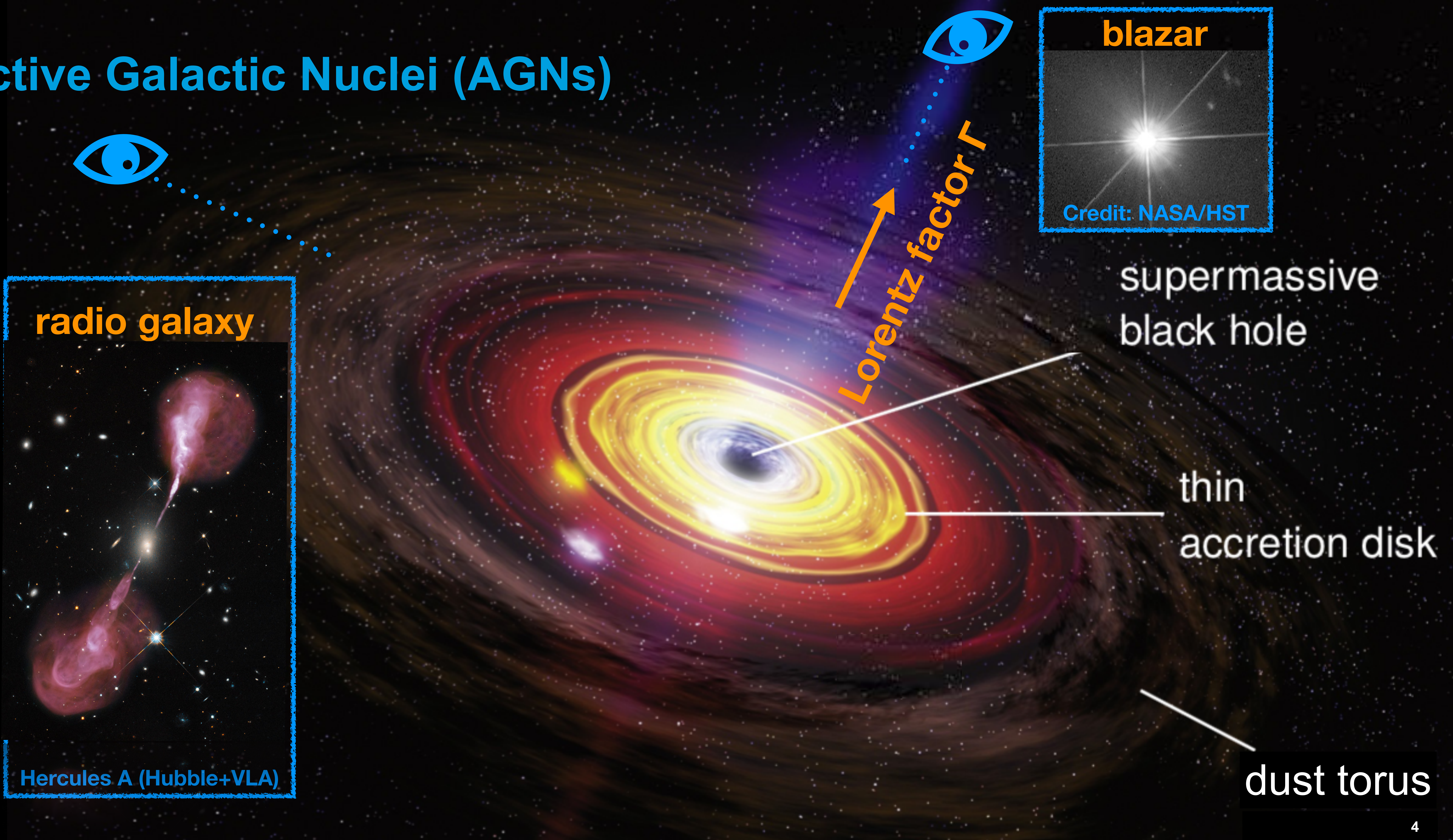

Picture courtesy NASA, Dana Berry/Skyworks Digital

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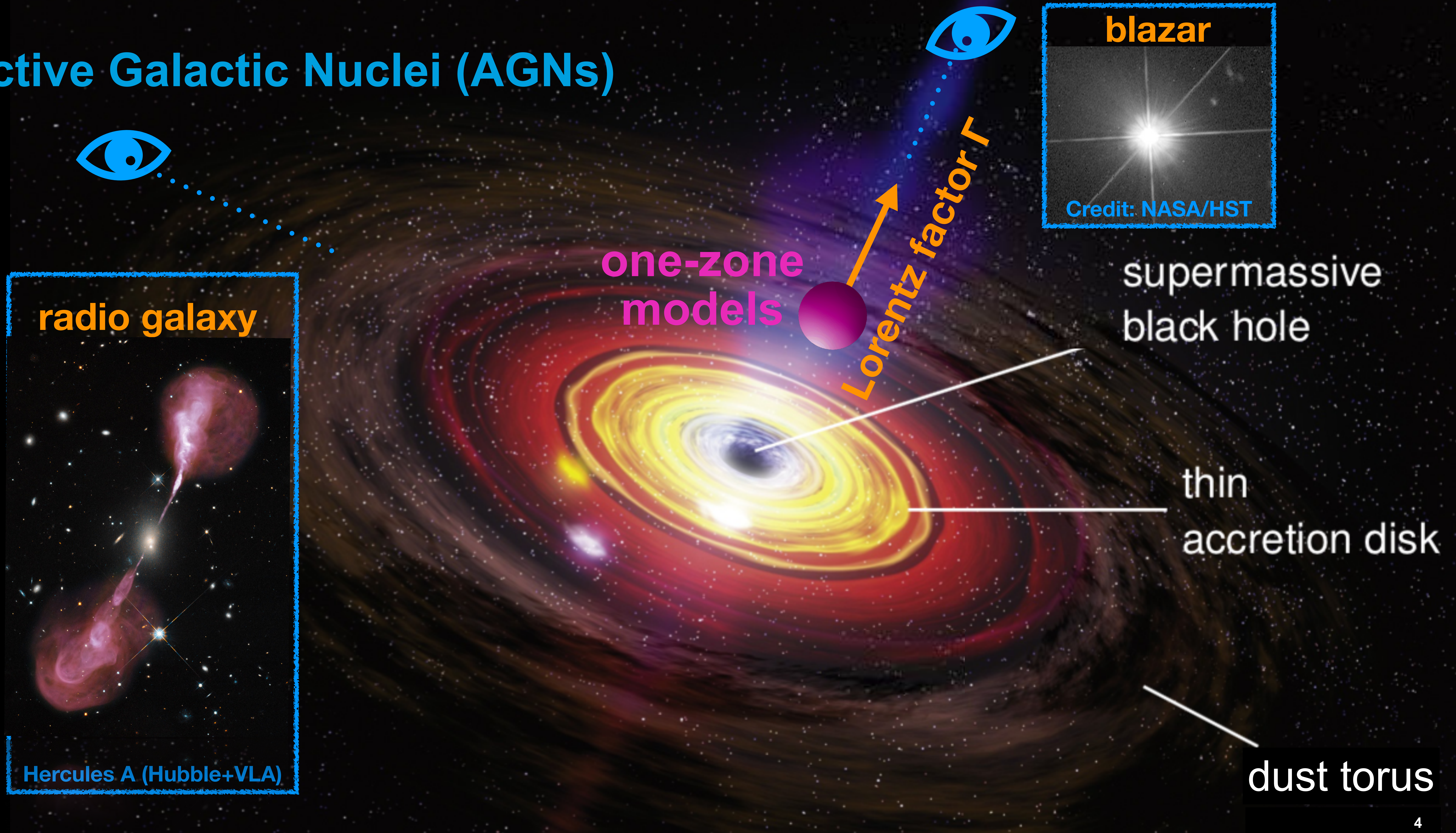
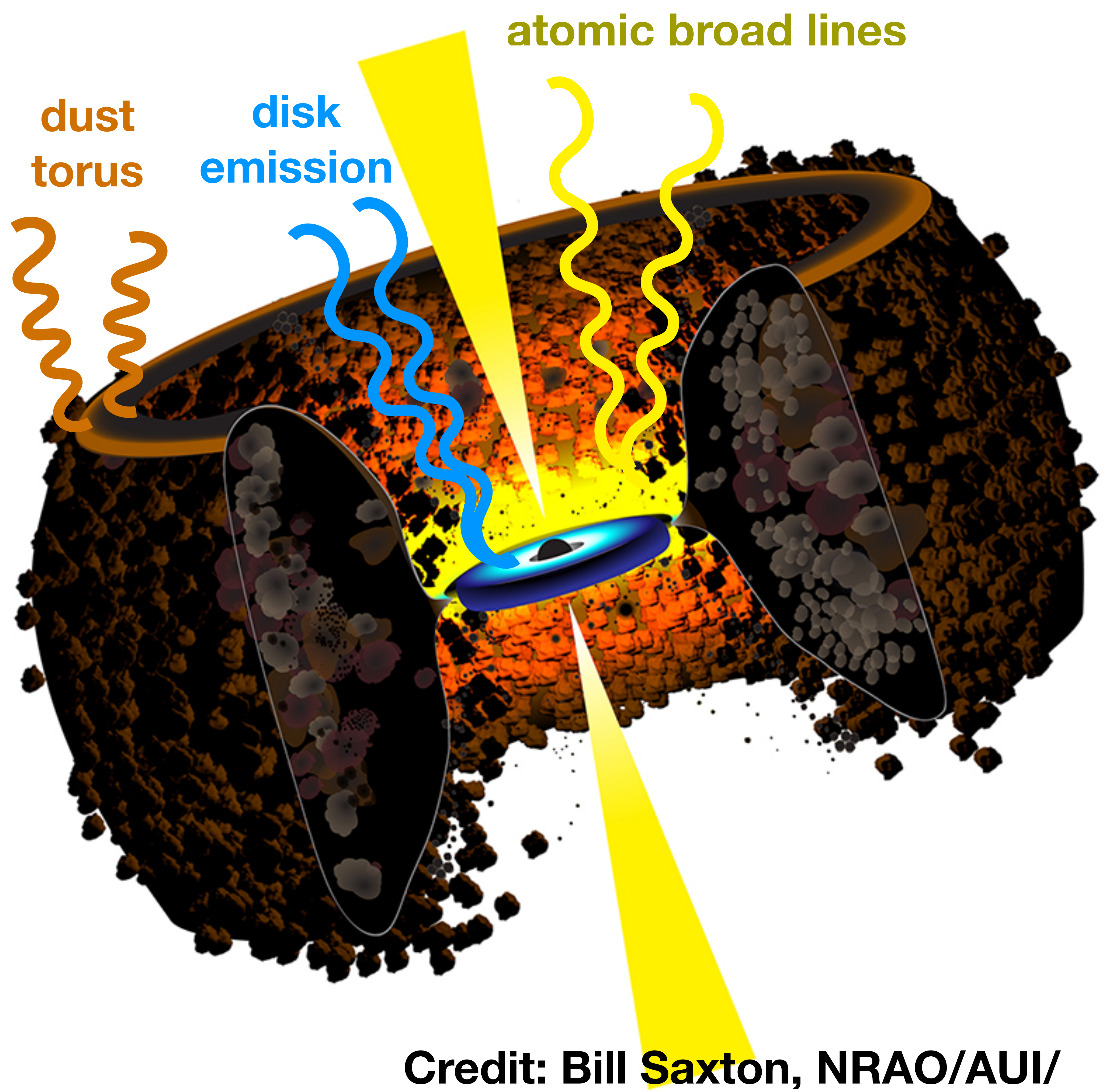


Picture courtesy NASA, Dana Berry/Skyworks Digital

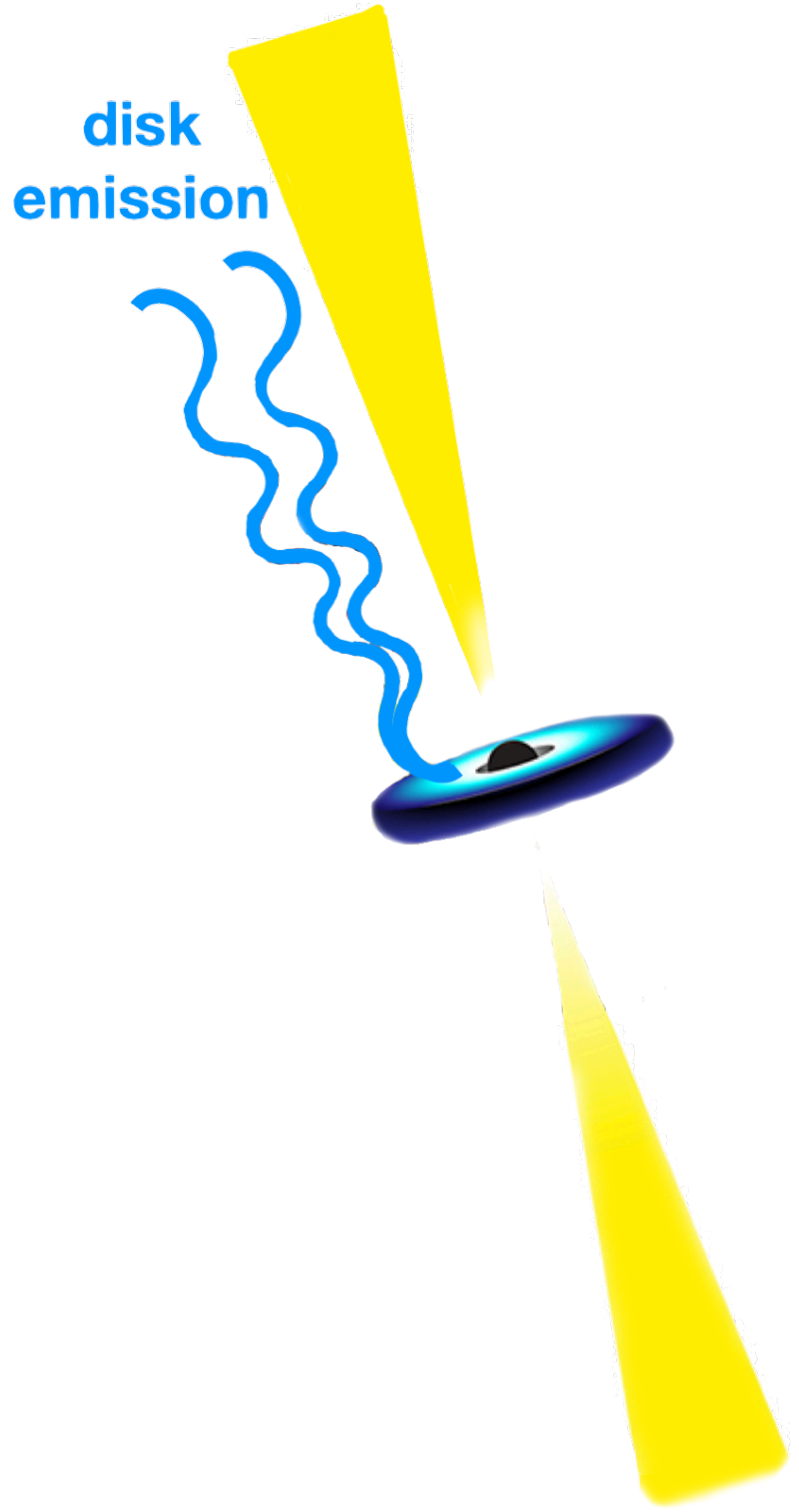
Blazar family overview

Flat-Spectrum Radio Quasars (FSRQs)



Credit: Bill Saxton, NRAO/AUI/

BL Lacs



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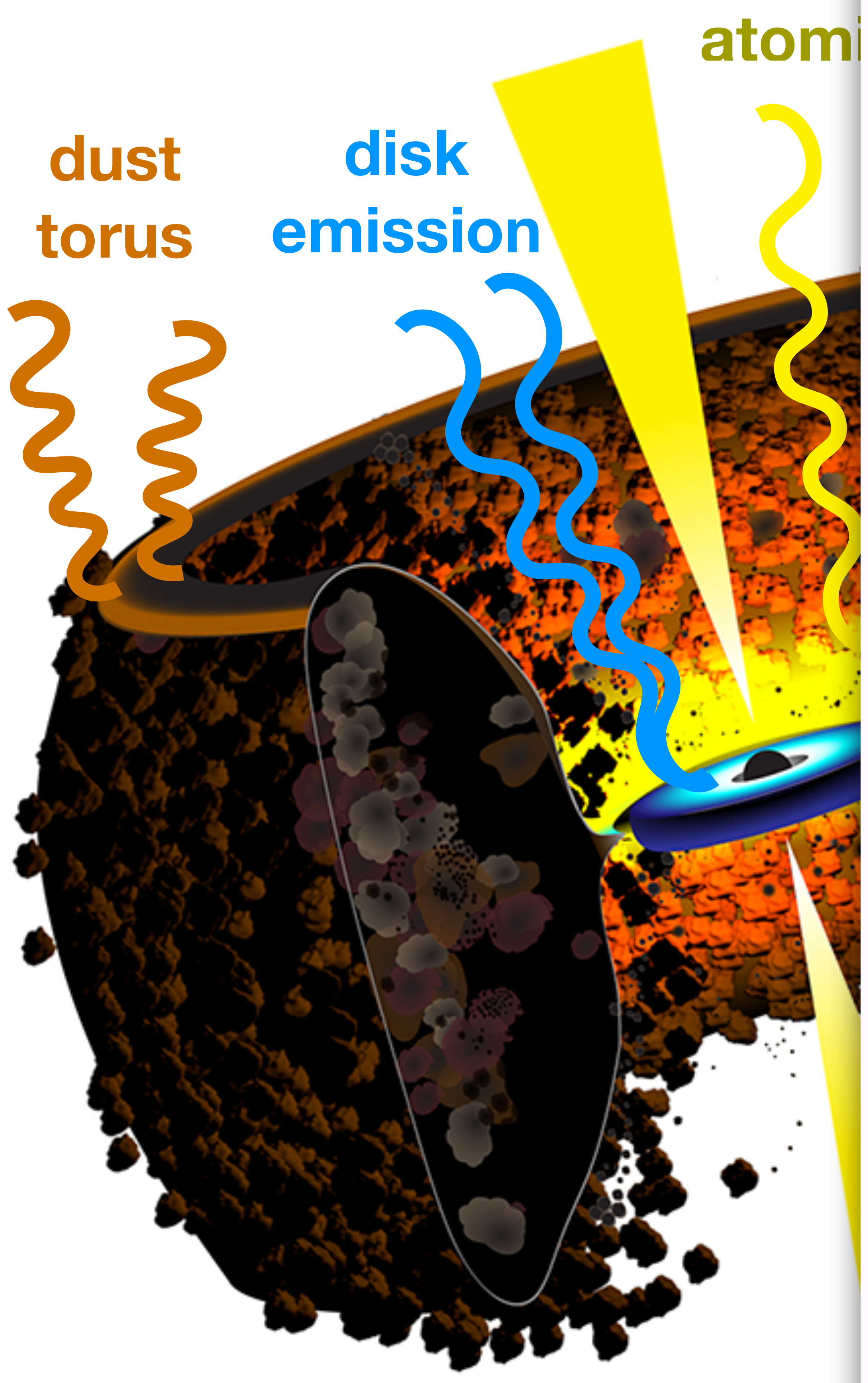
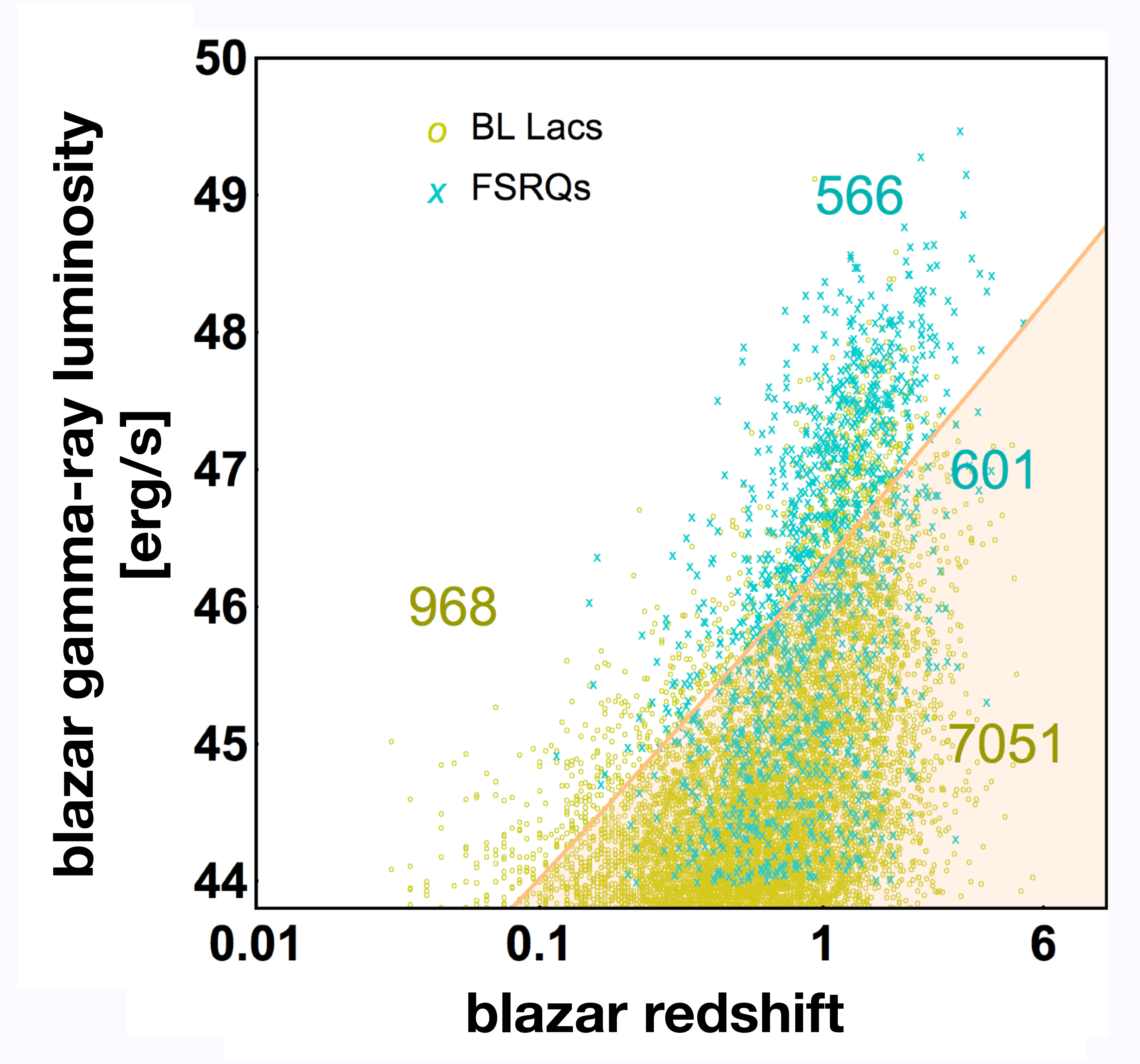
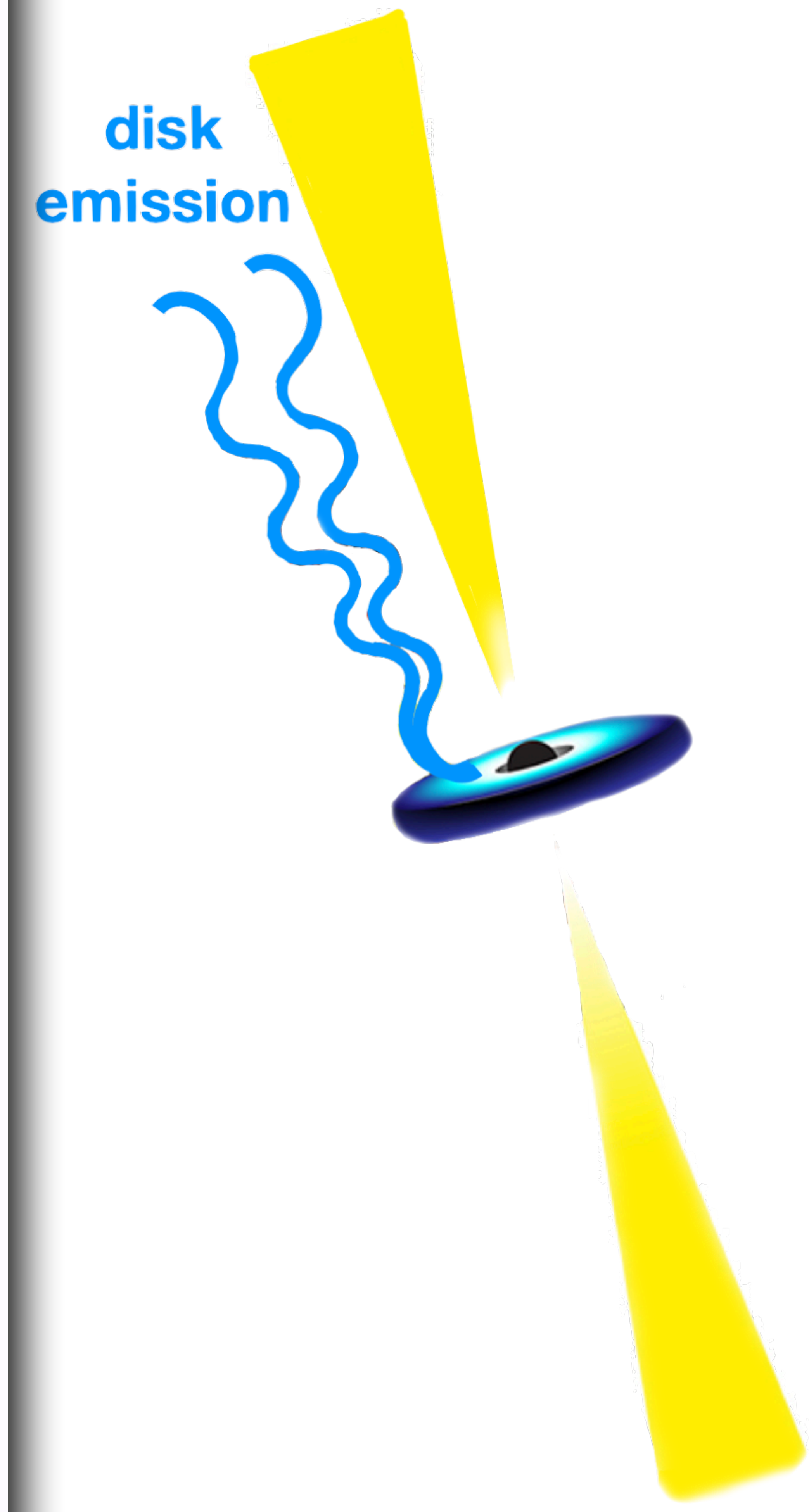


Credit: Bill



Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41



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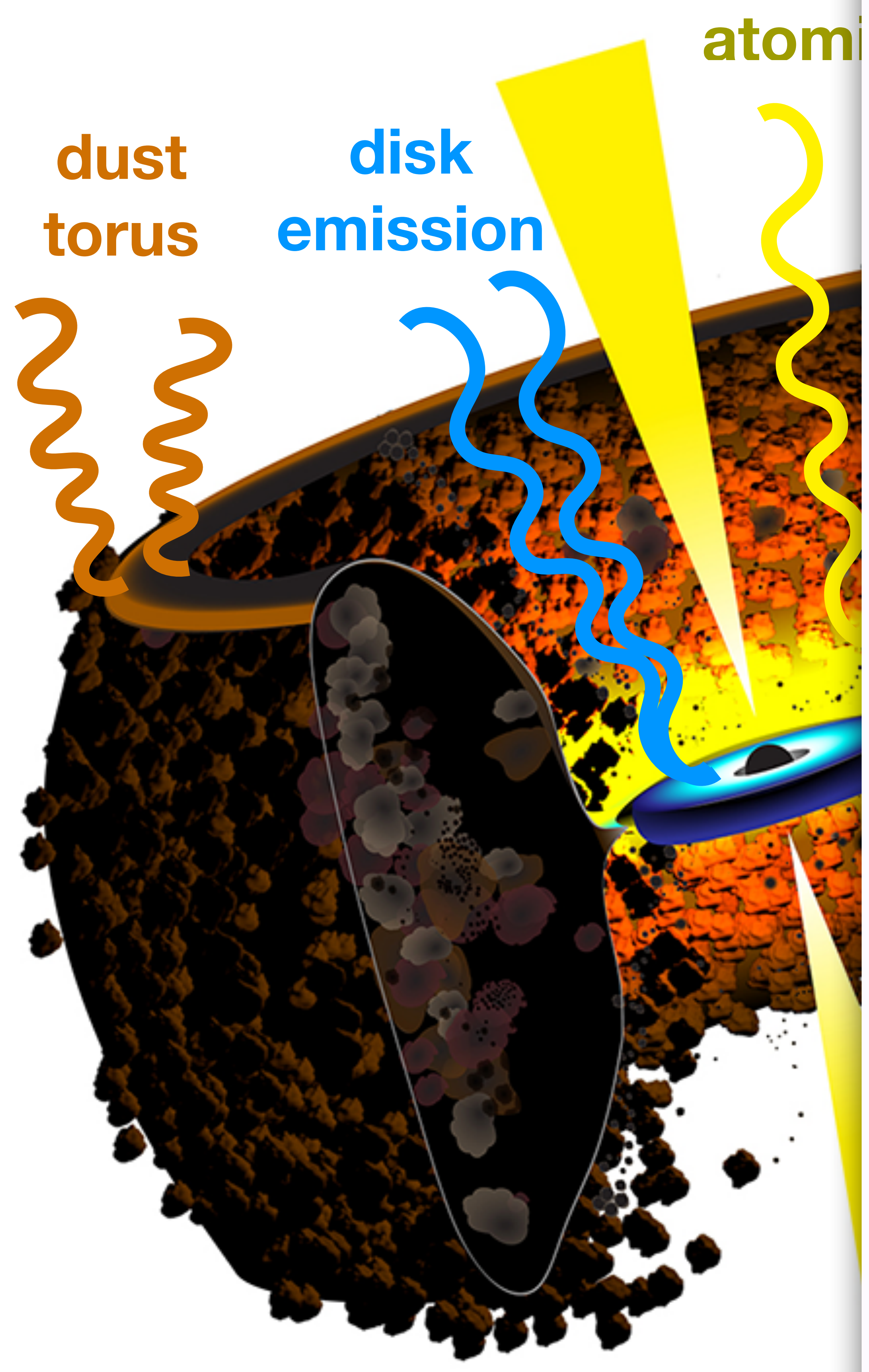

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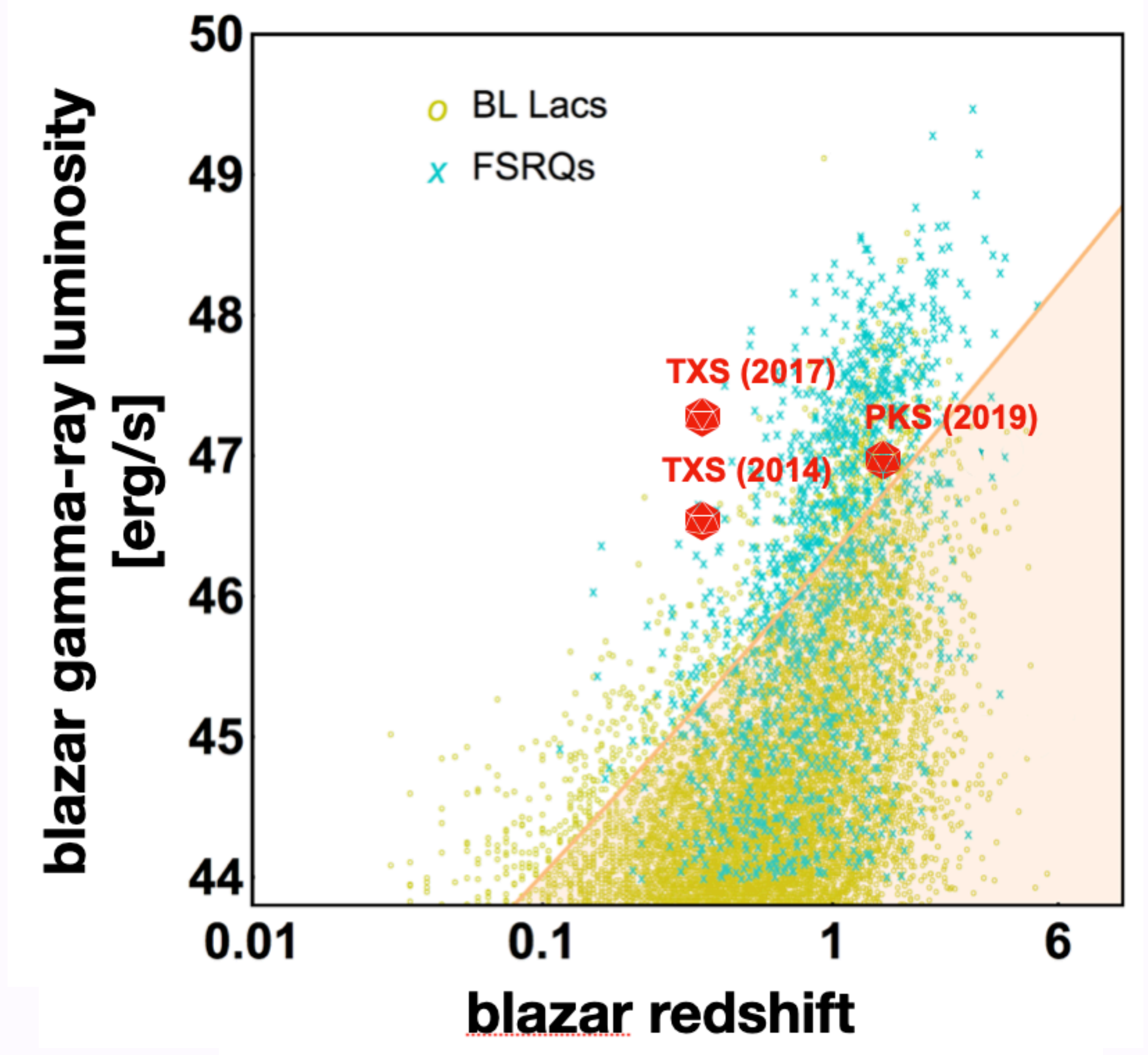
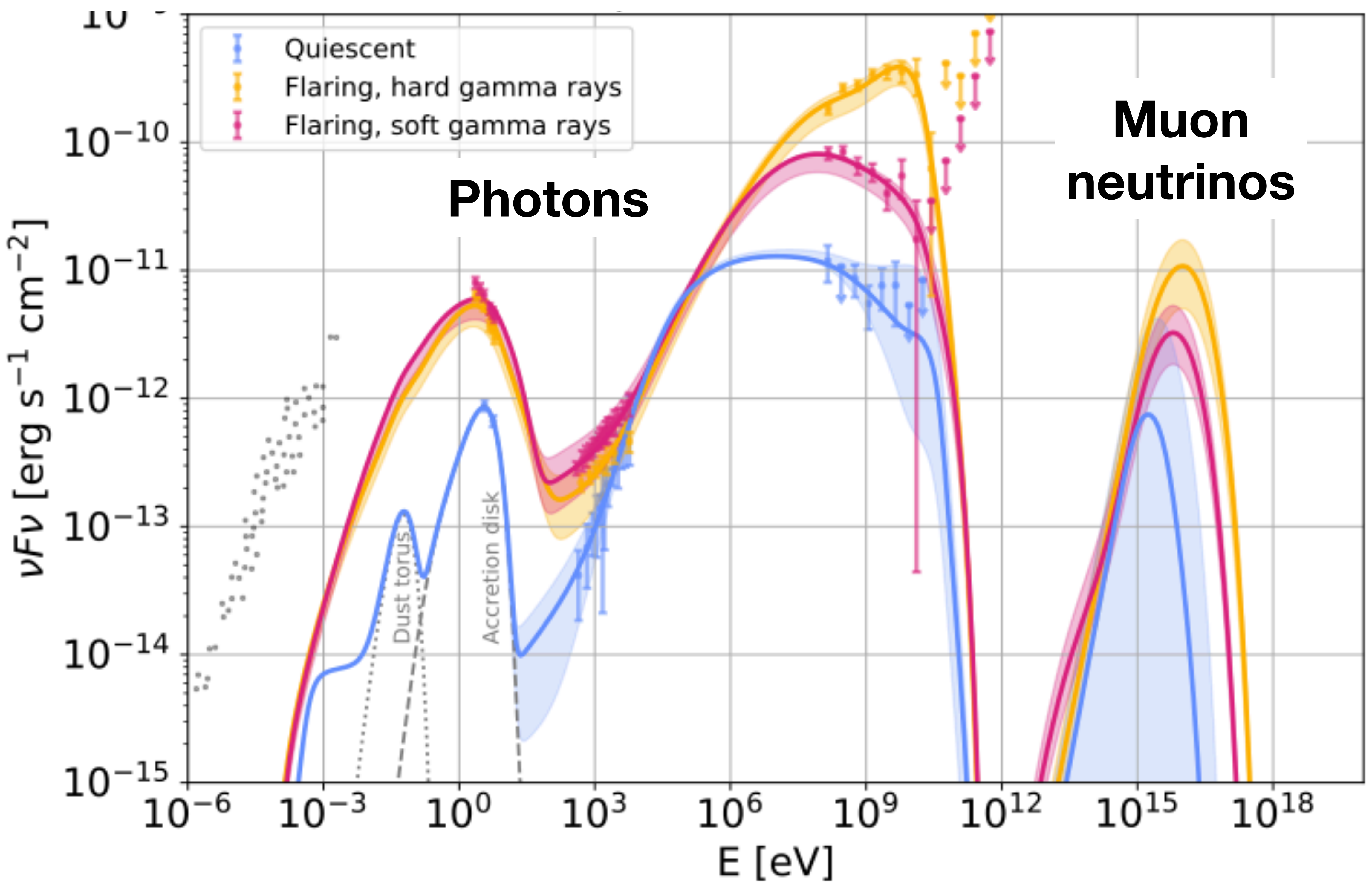


Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

PKS 1502+106: example of a leptohadronic model

Protons accelerated to ~PeV (source frame)

-> neutrinos peak at ~PeV (observer frame)



XR, Garrappa, Gao, Paliya, Franckowiak & Winter, accepted in ApJ

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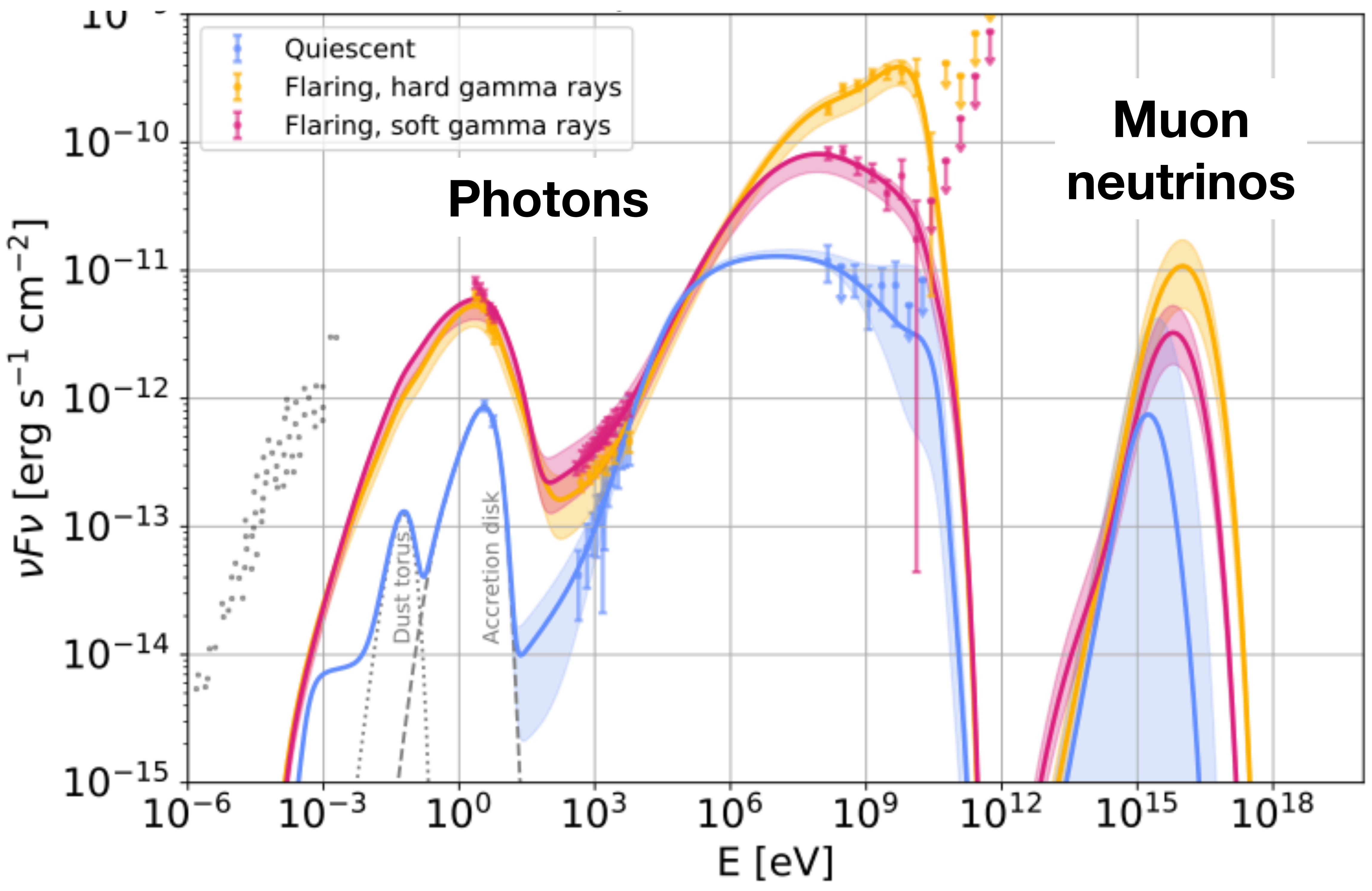

Gamma-ray - neutrino correlation

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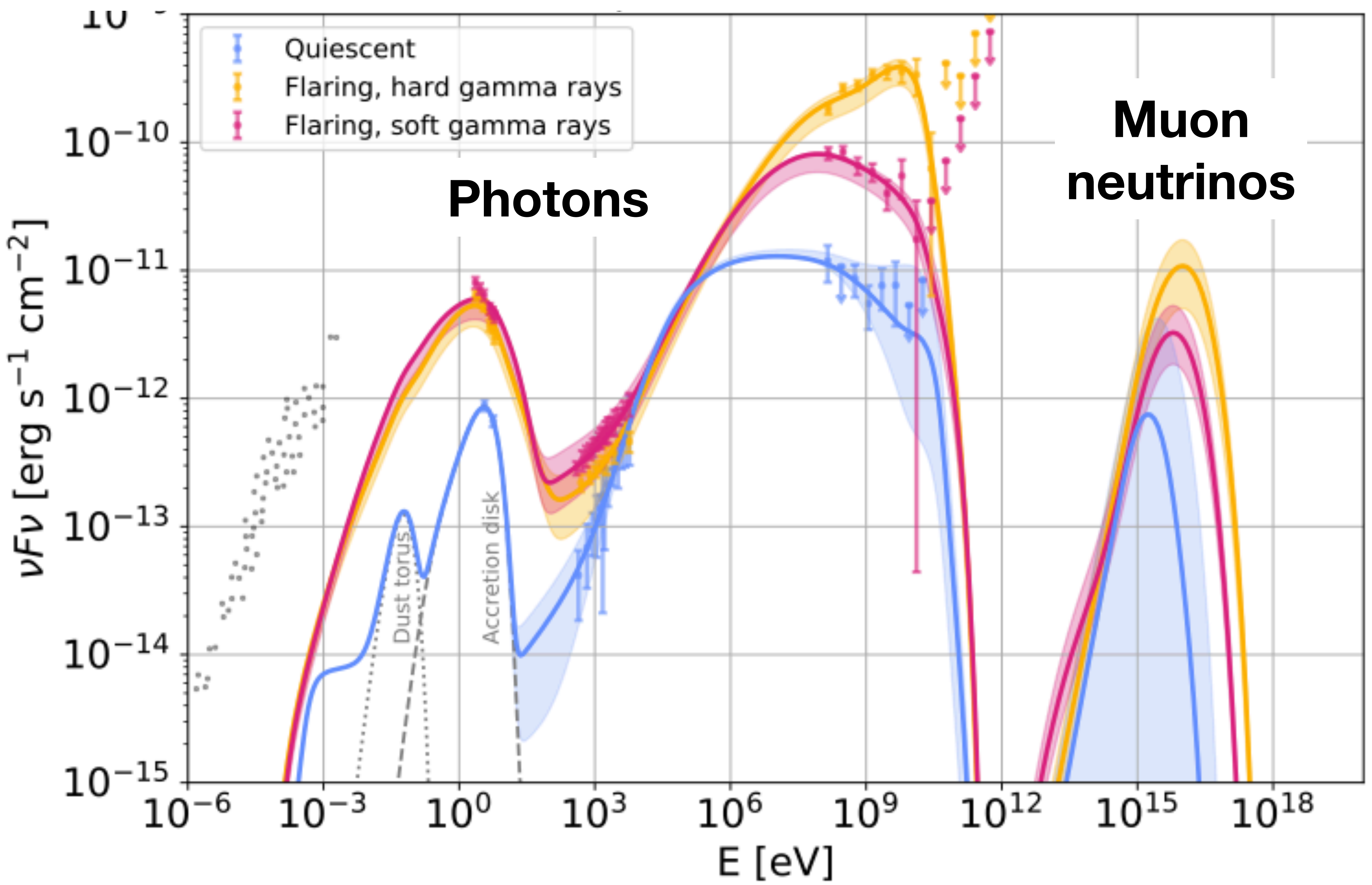

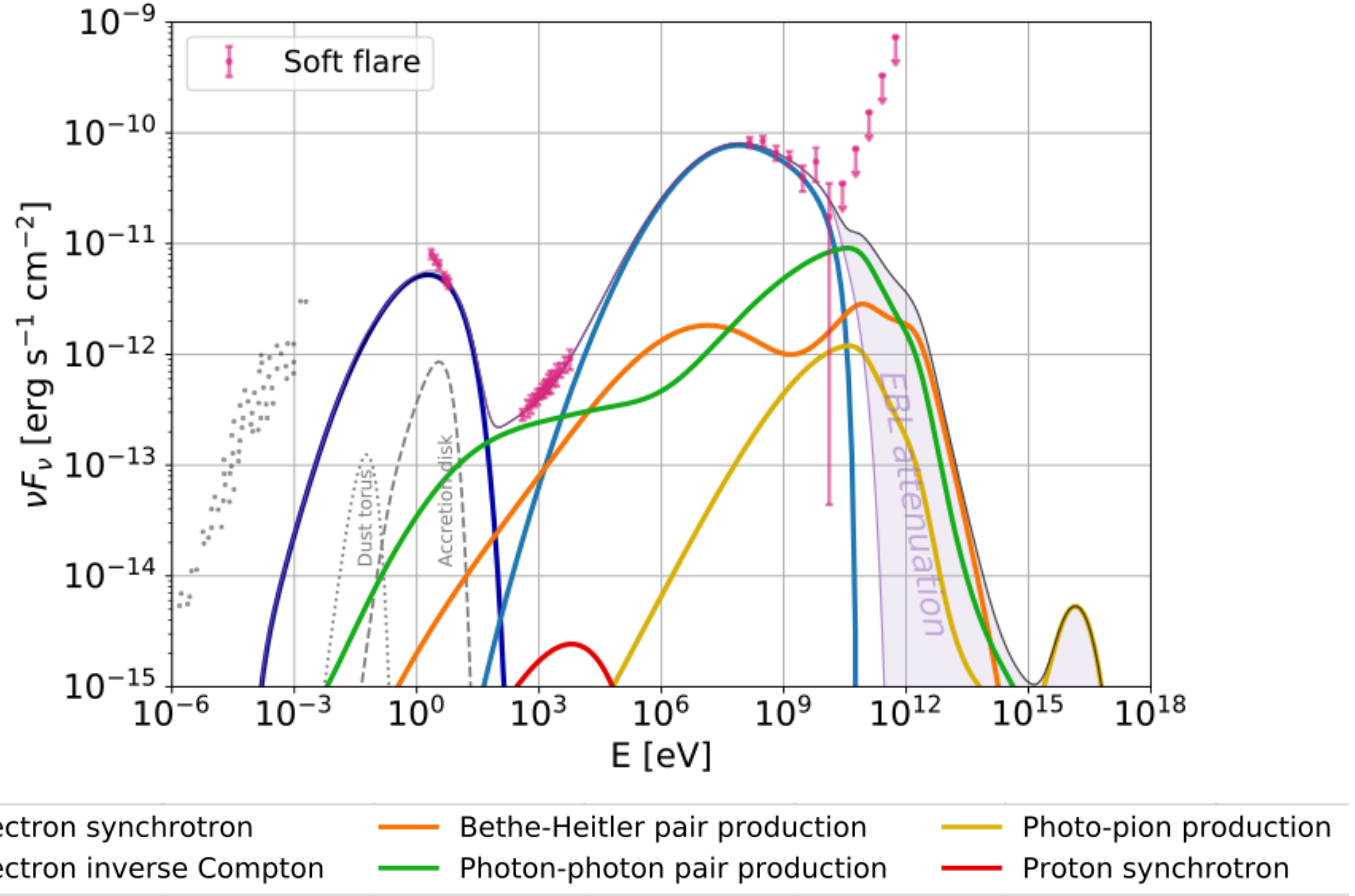

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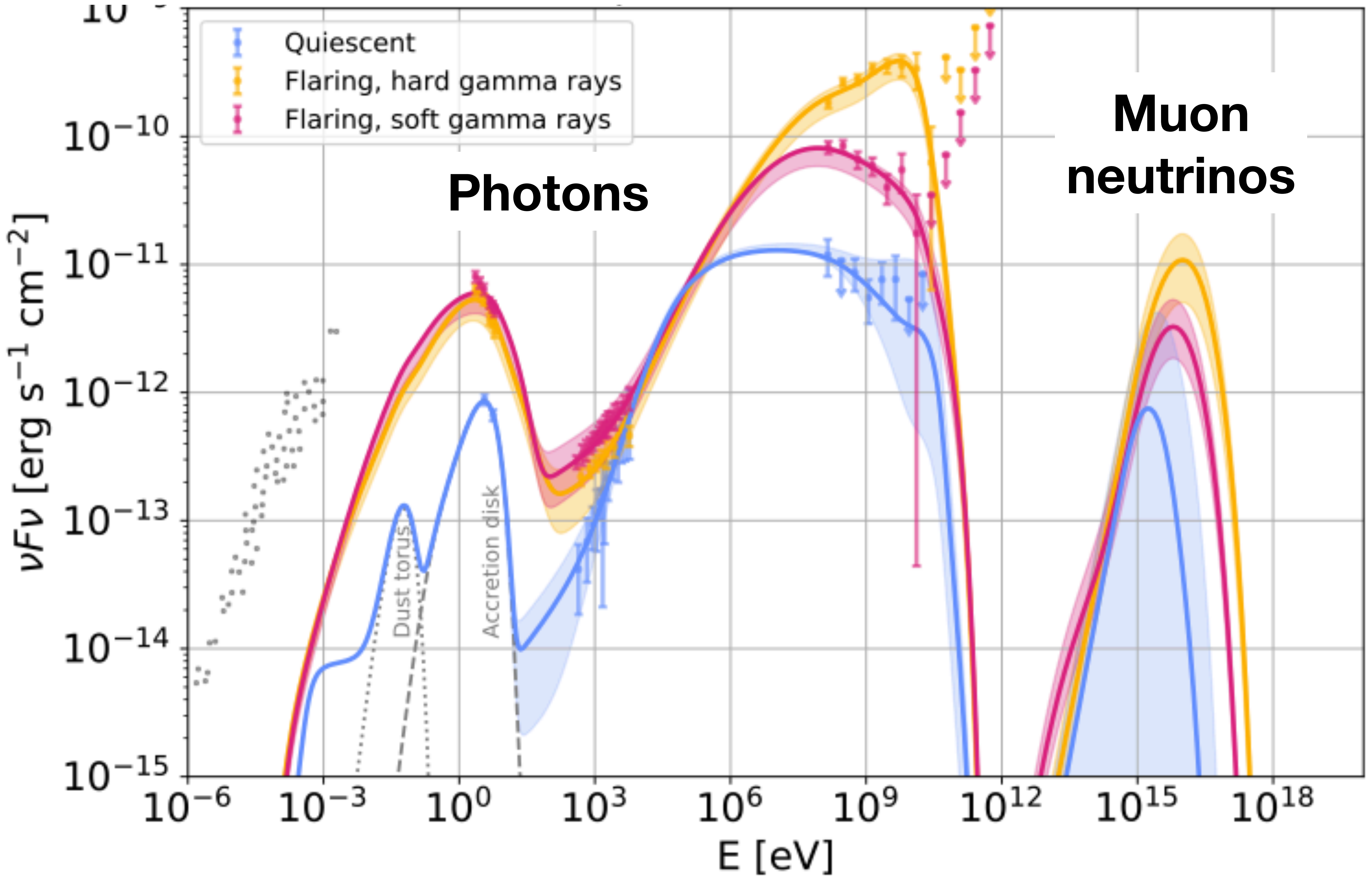

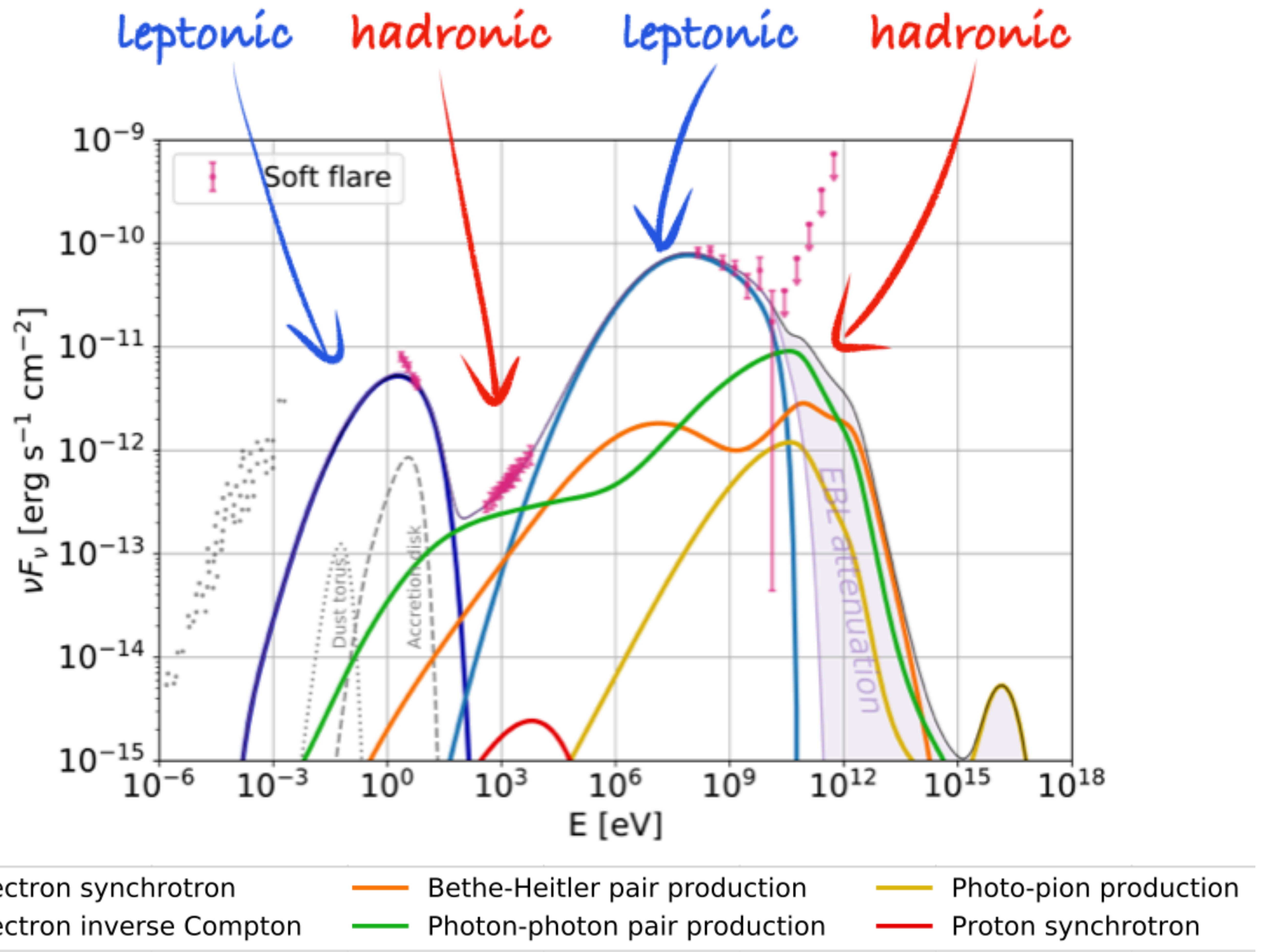

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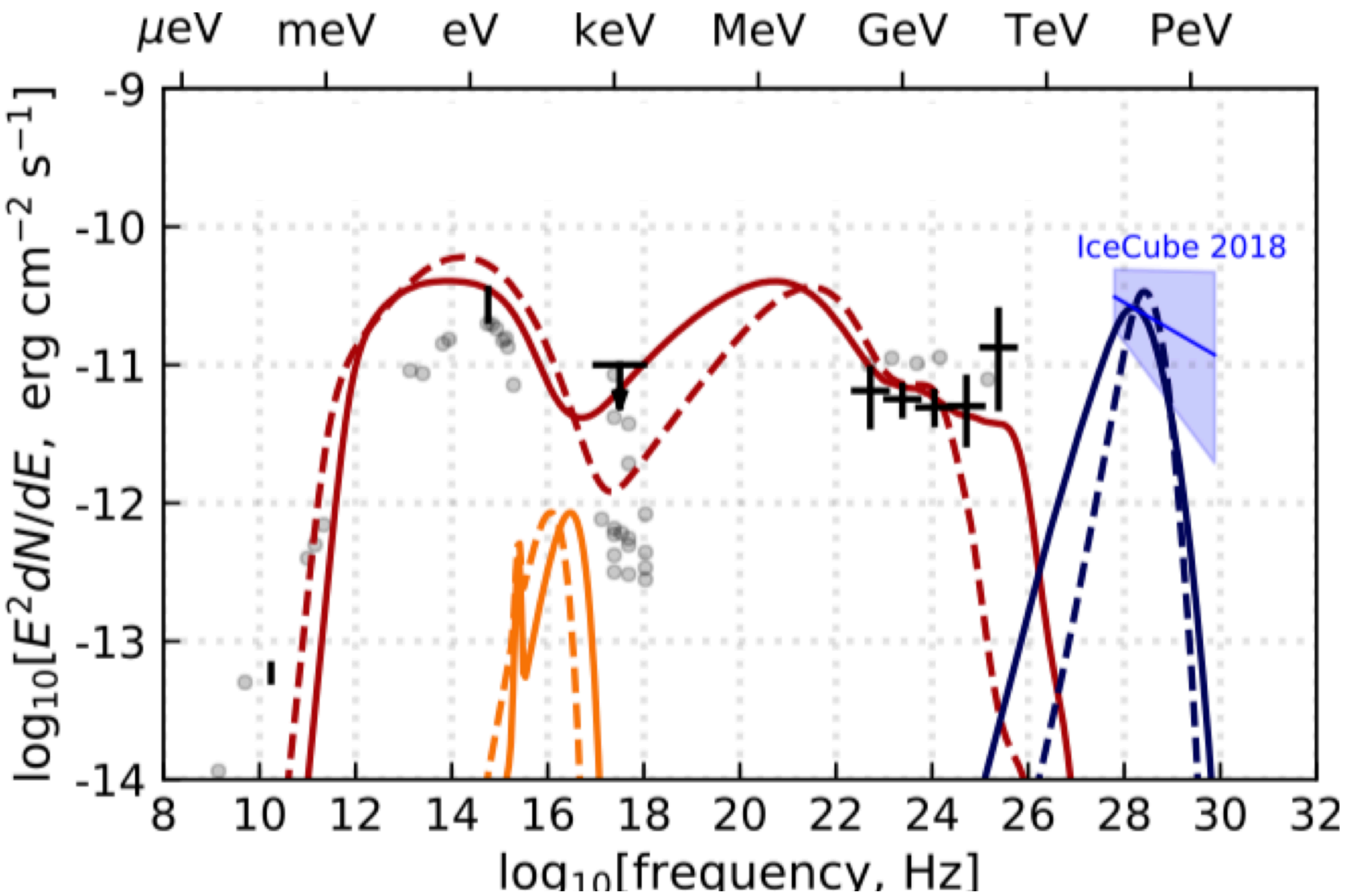
TXS 0506+056 (2014/15 IceCube signal)

Protons accelerated to 100 TeV **(source frame)**
-> neutrinos peak at 100 TeV **(observer frame)**



XR, Gao, Fedynitch, Palladino, Winter, ApJ L874 (2019)

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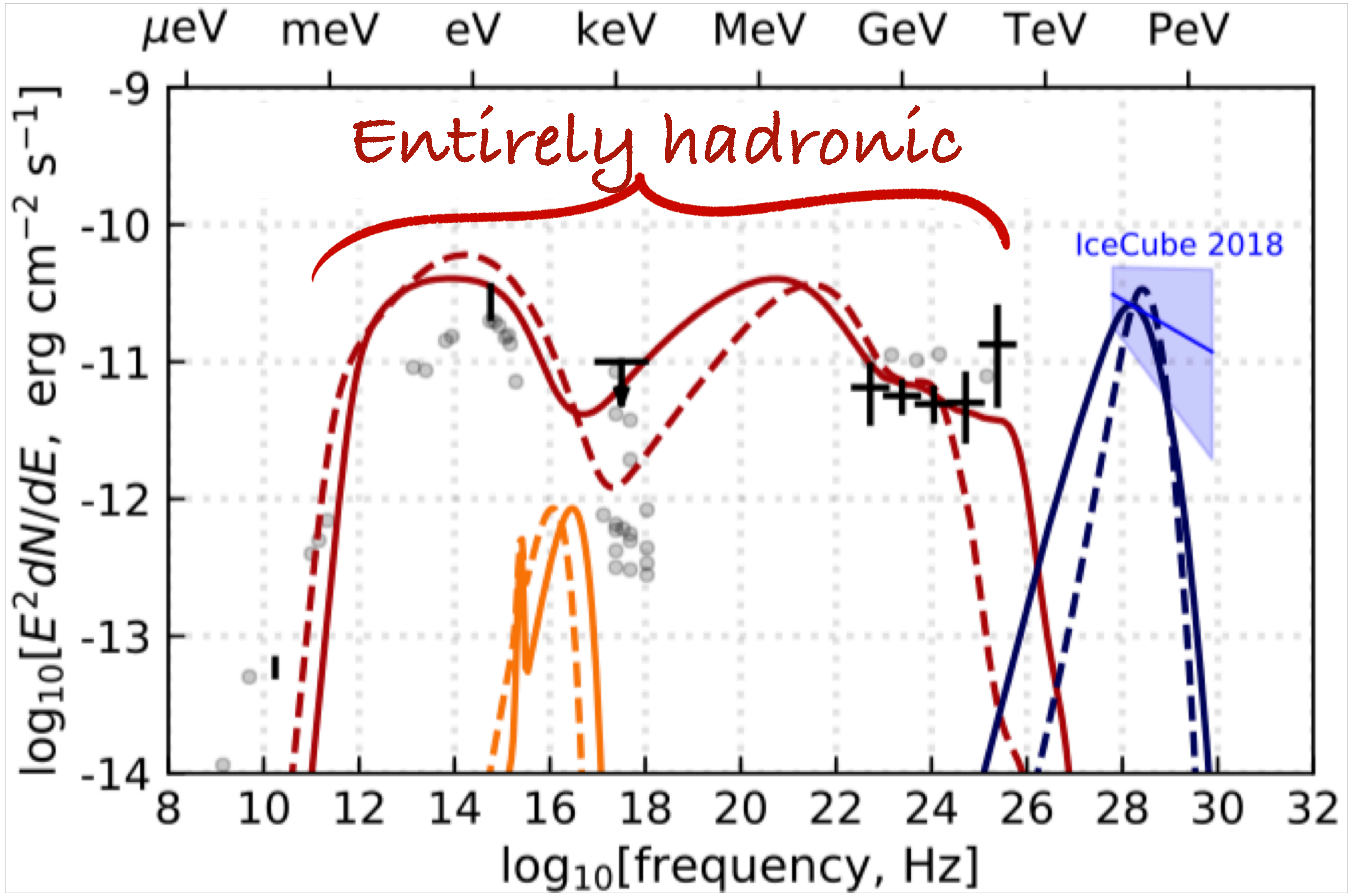

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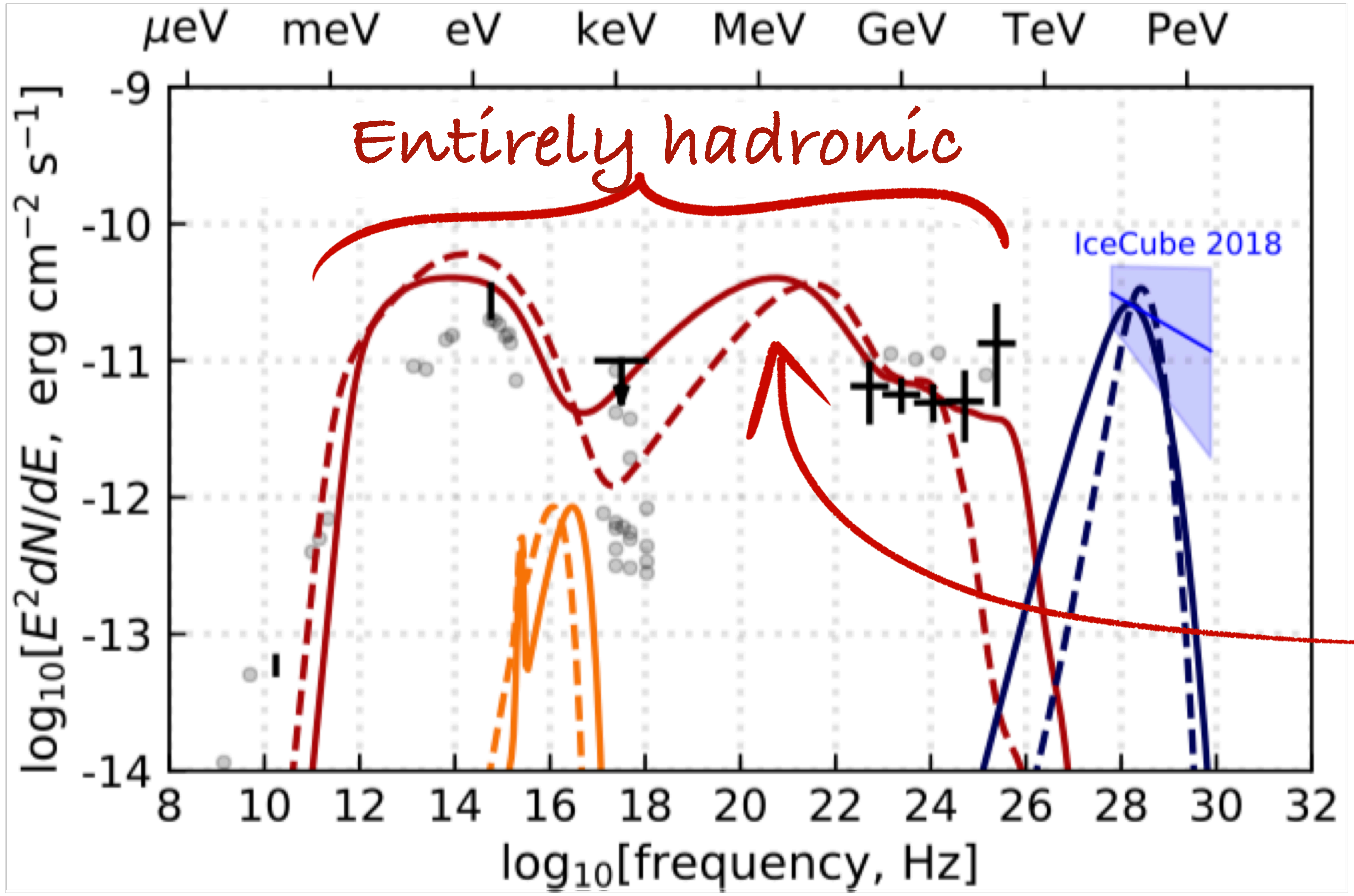
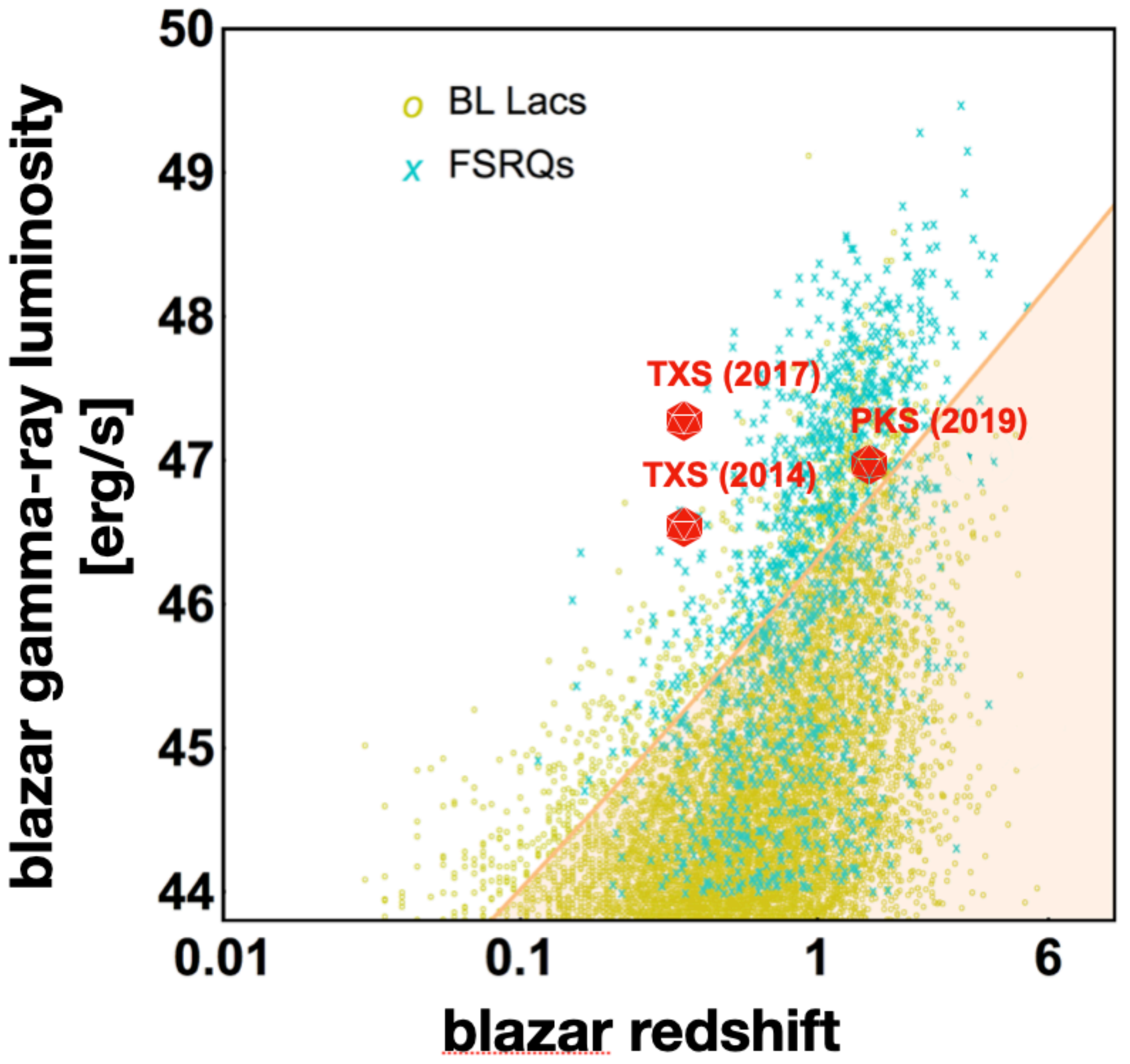


Cascades "dump" the gamma rays into the MeV range (X-ray- neutrino connection)

(cf. Reimer++ 2019 ApJ 881)

XR, Gao, Fedynitch, Palladino, Winter, ApJ L874 (2019)

CRs and neutrinos from the entire blazar population



Palladino, XR, Gao & Winter, ApJ 871 (2019)

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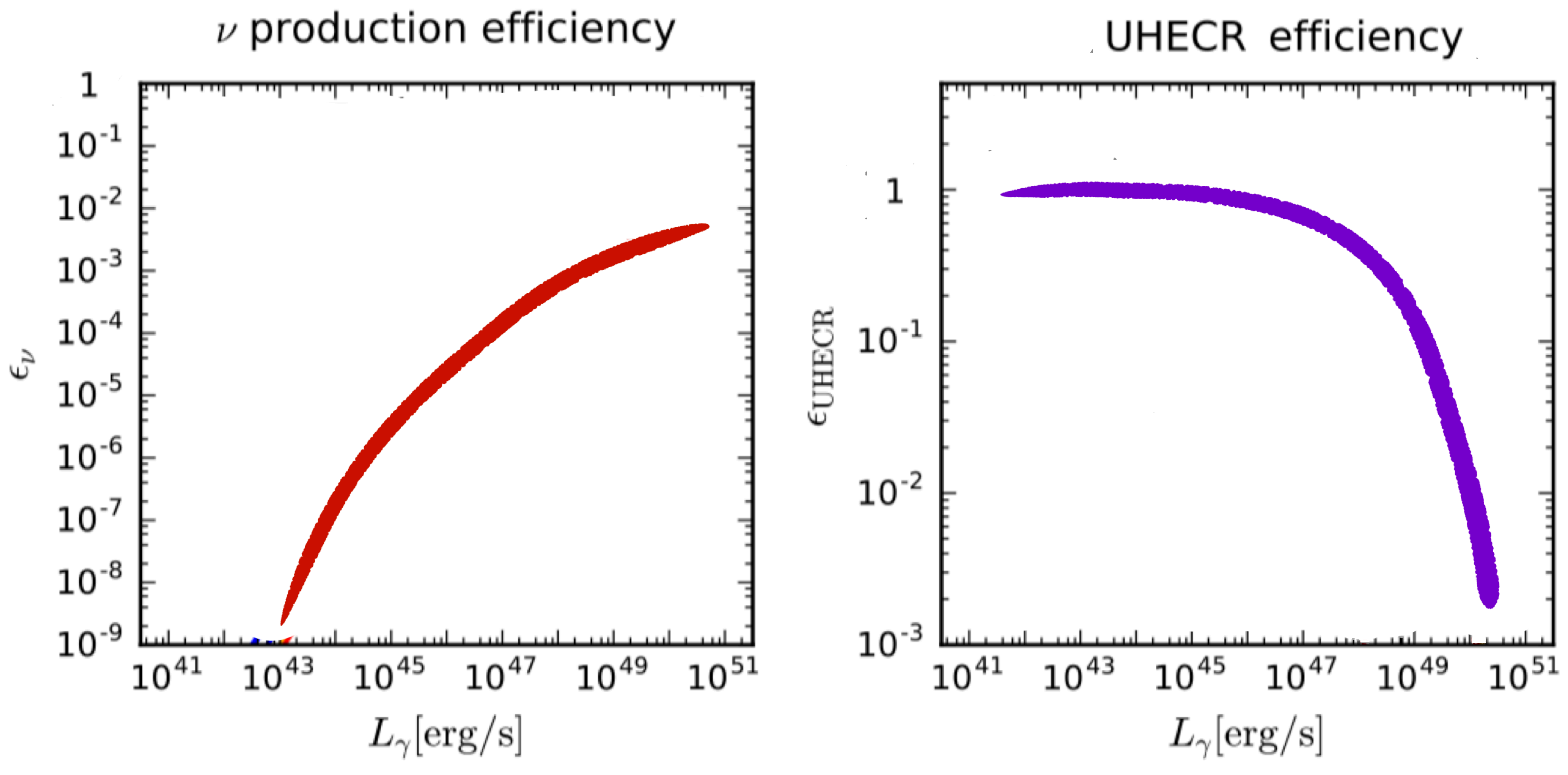
CRs and neutrinos from the entire AGN population



XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018)

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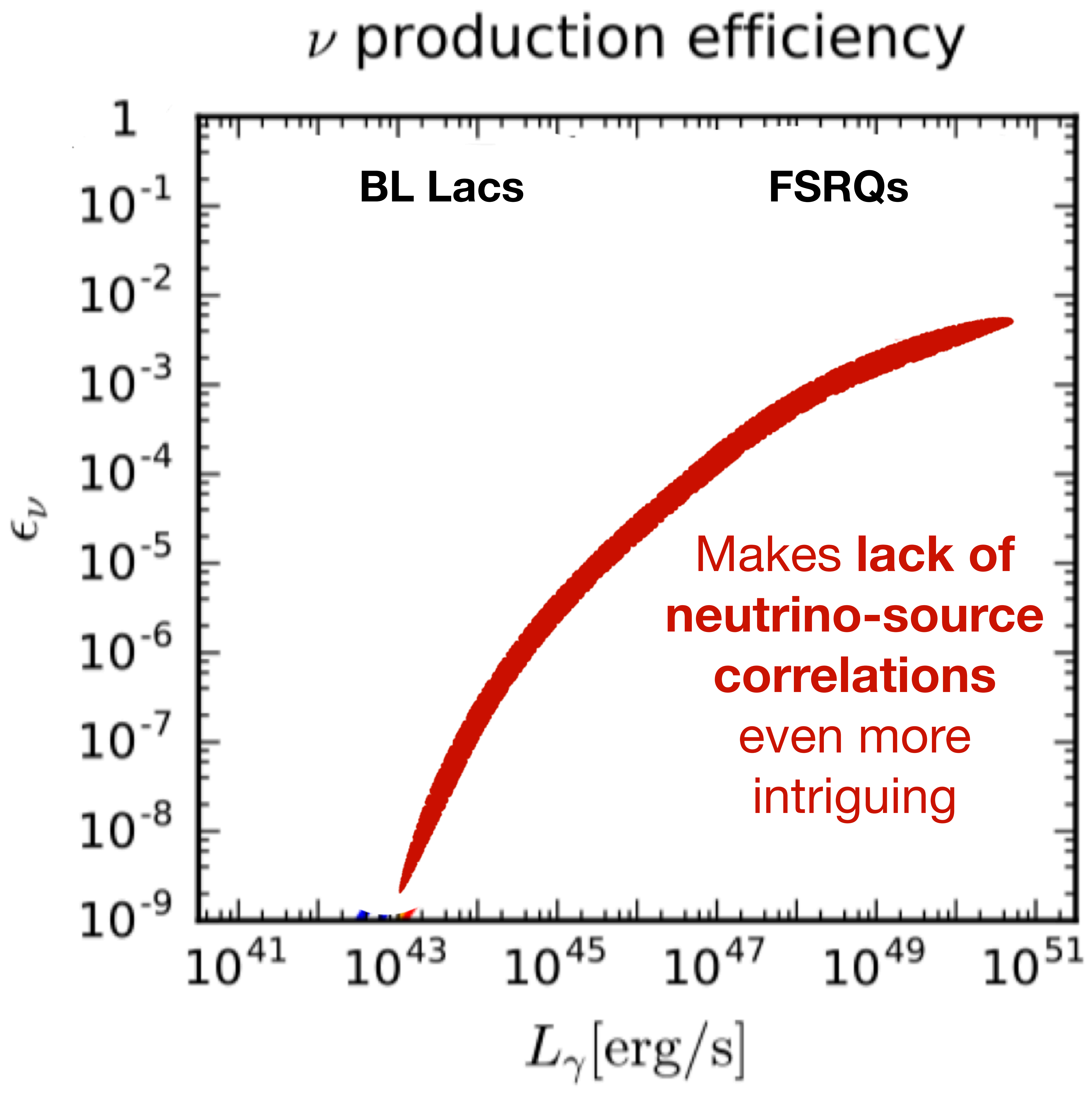

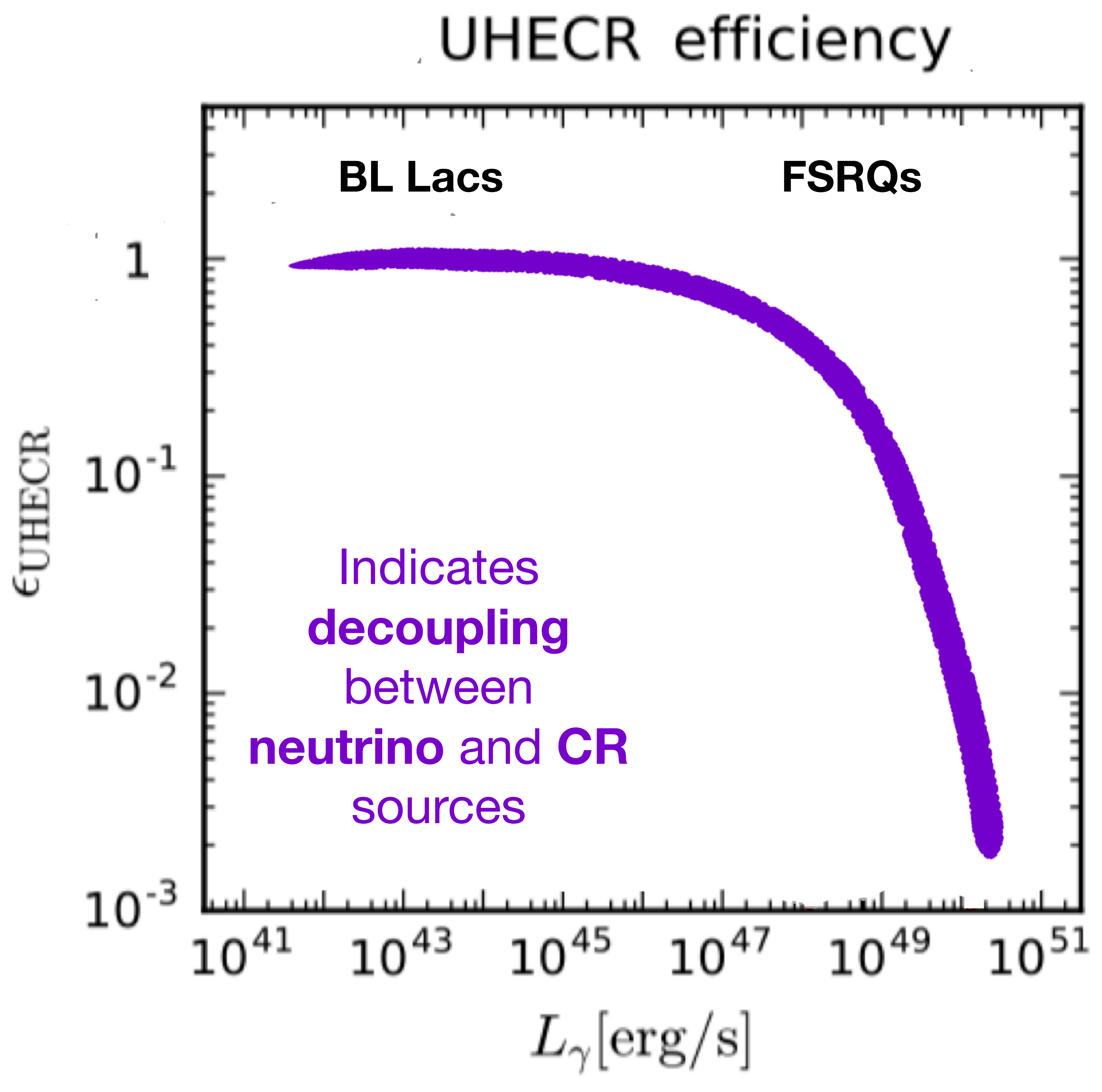

XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018)

CRs and neutrinos from the entire AGN population

Scenario 1: AGN accelerate CRs up to max 10 PeV

Scenario 2: AGN accelerate CRs up to ~EeV

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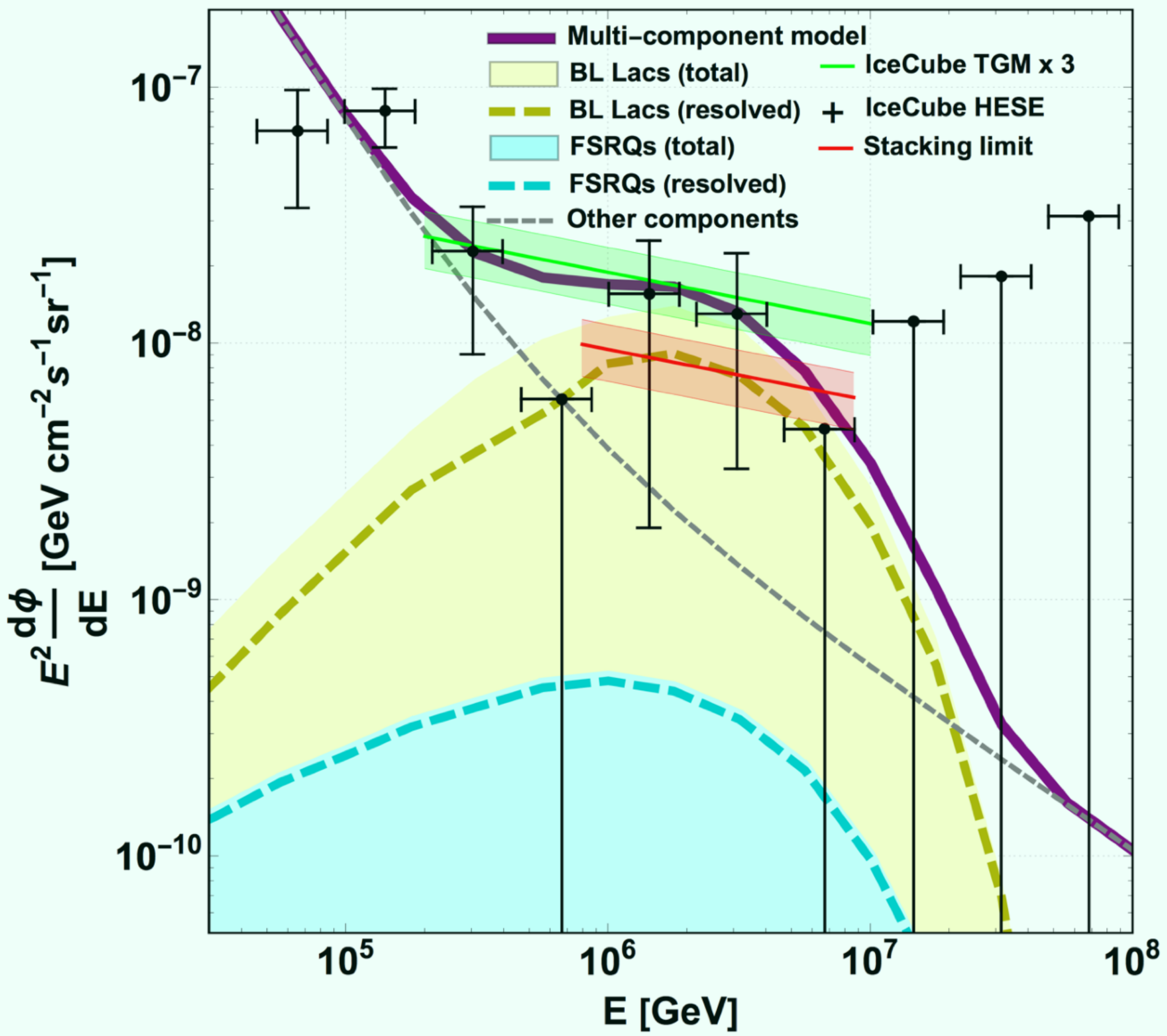

Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

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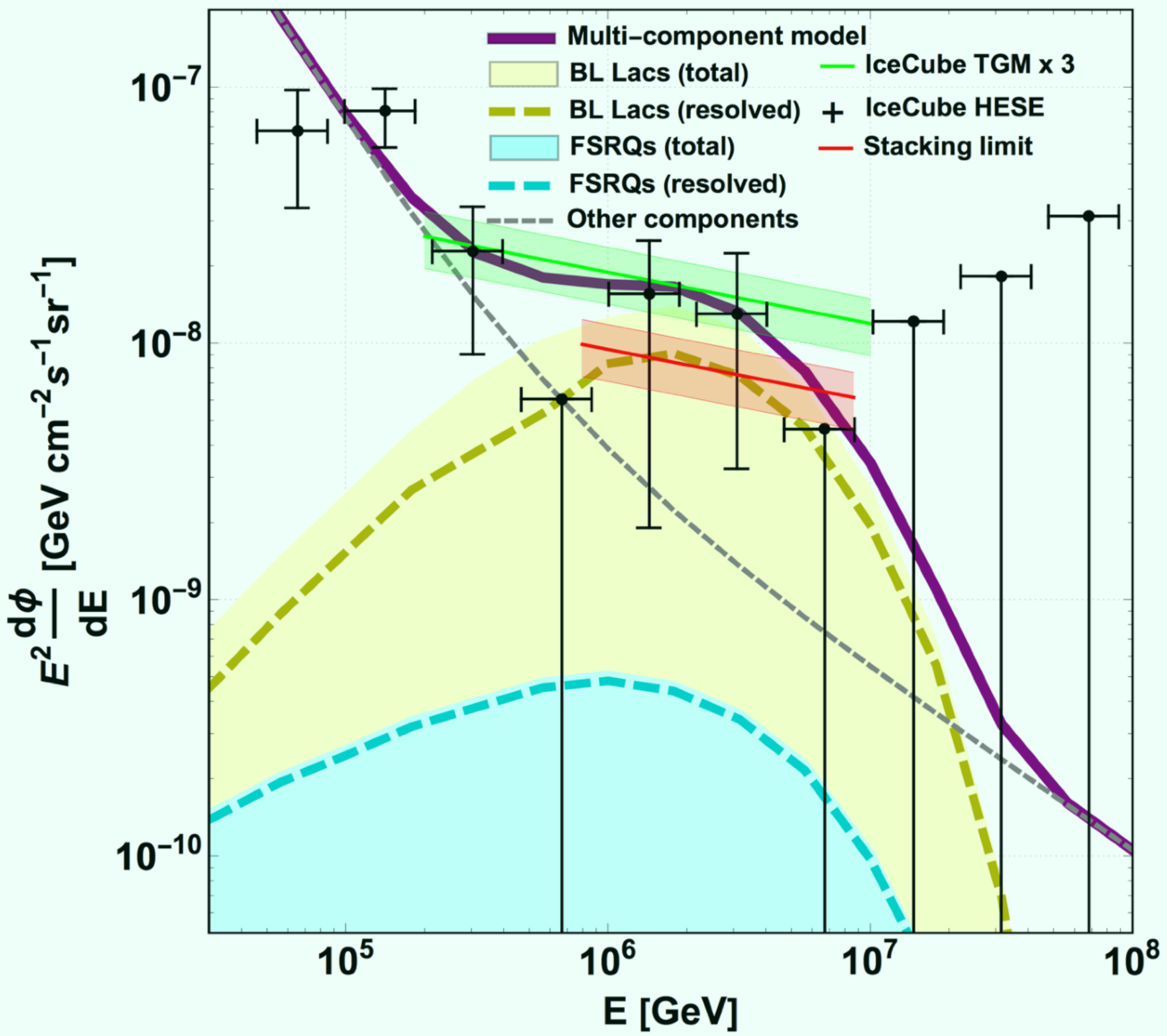

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- **Can explain IceCube sub-PeV to PeV flux**
- **UHECR** connection **lost**
- Contribution from **high-luminosity blazars** must be **suppressed** (because of lack of correlations)

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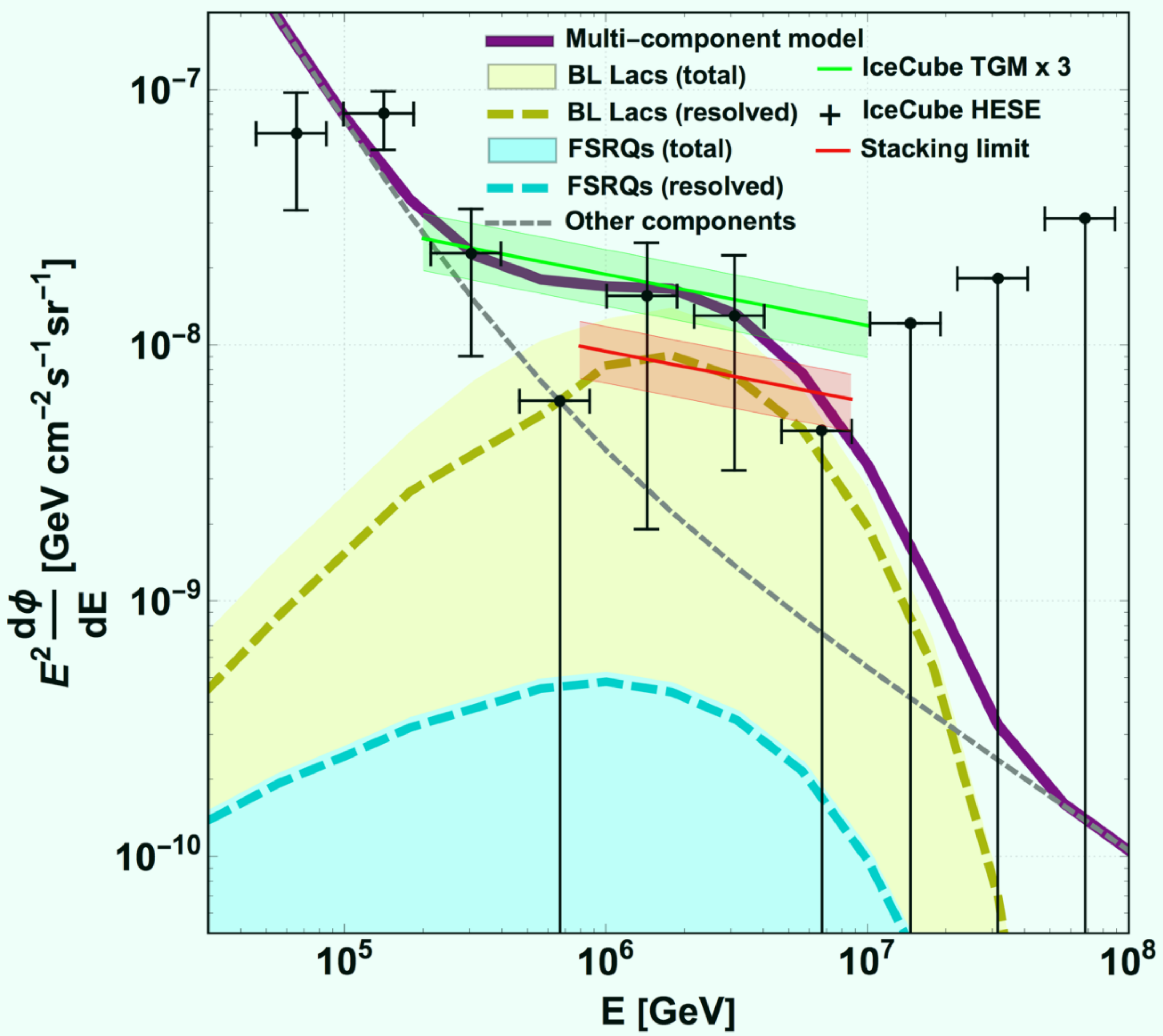

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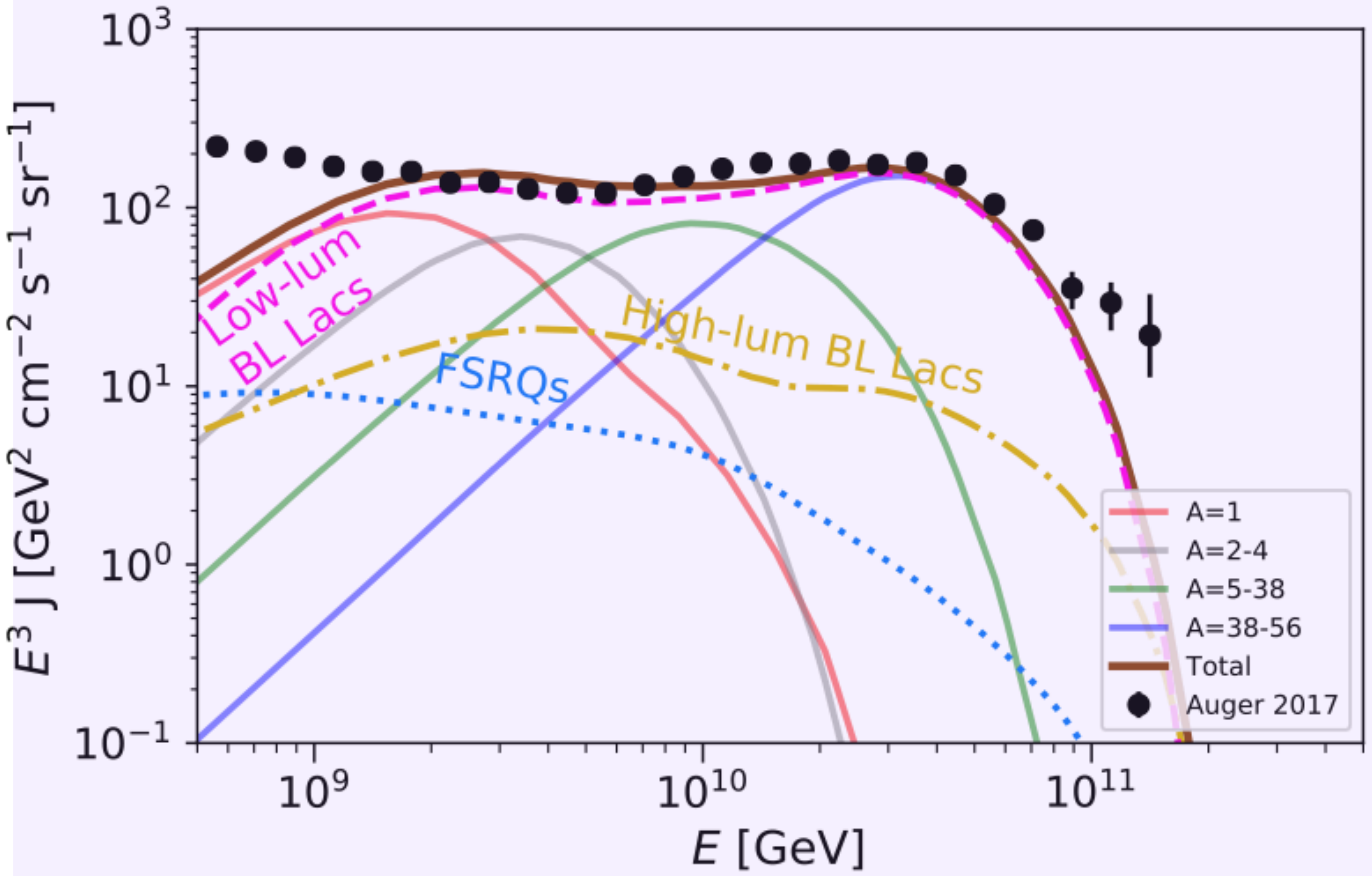

XR, Heinze, Palladino, van Vliet, Winter, submitted to PRL

- Can explain Auger spectrum

CRs and neutrinos from the entire AGN population

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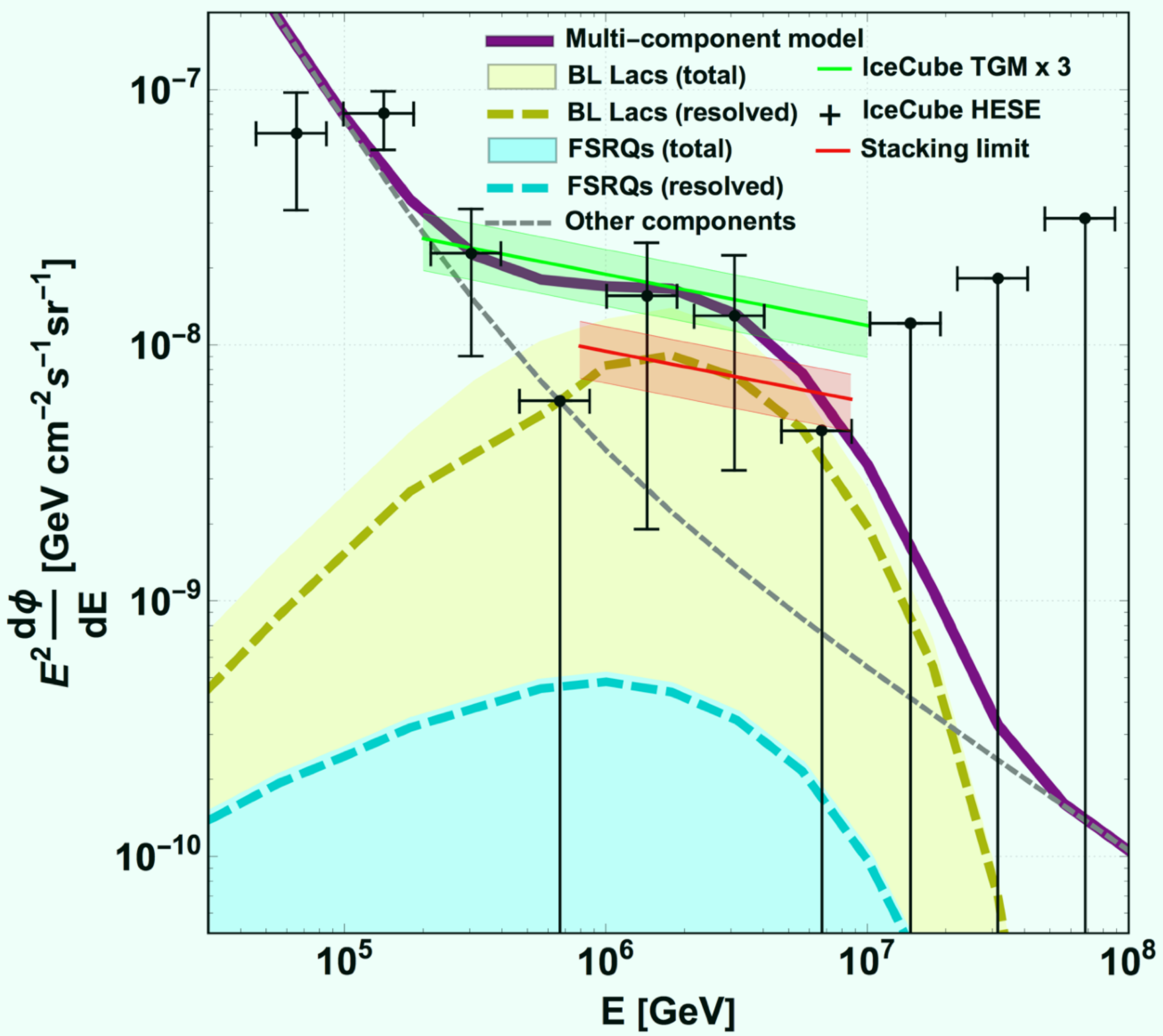

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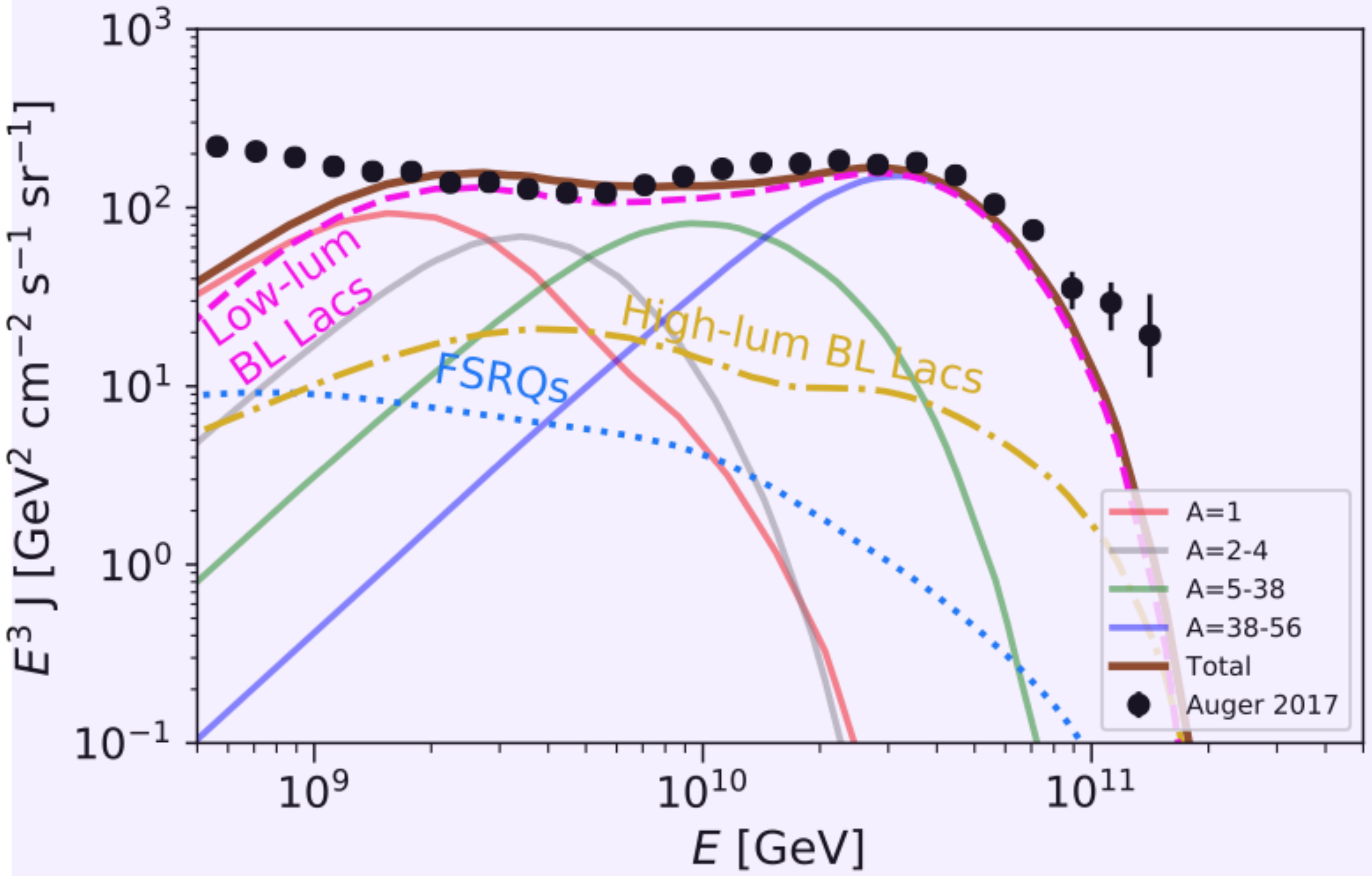

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- **Can explain Auger spectrum**
- Must obey IceCube limits at PeV and EHE
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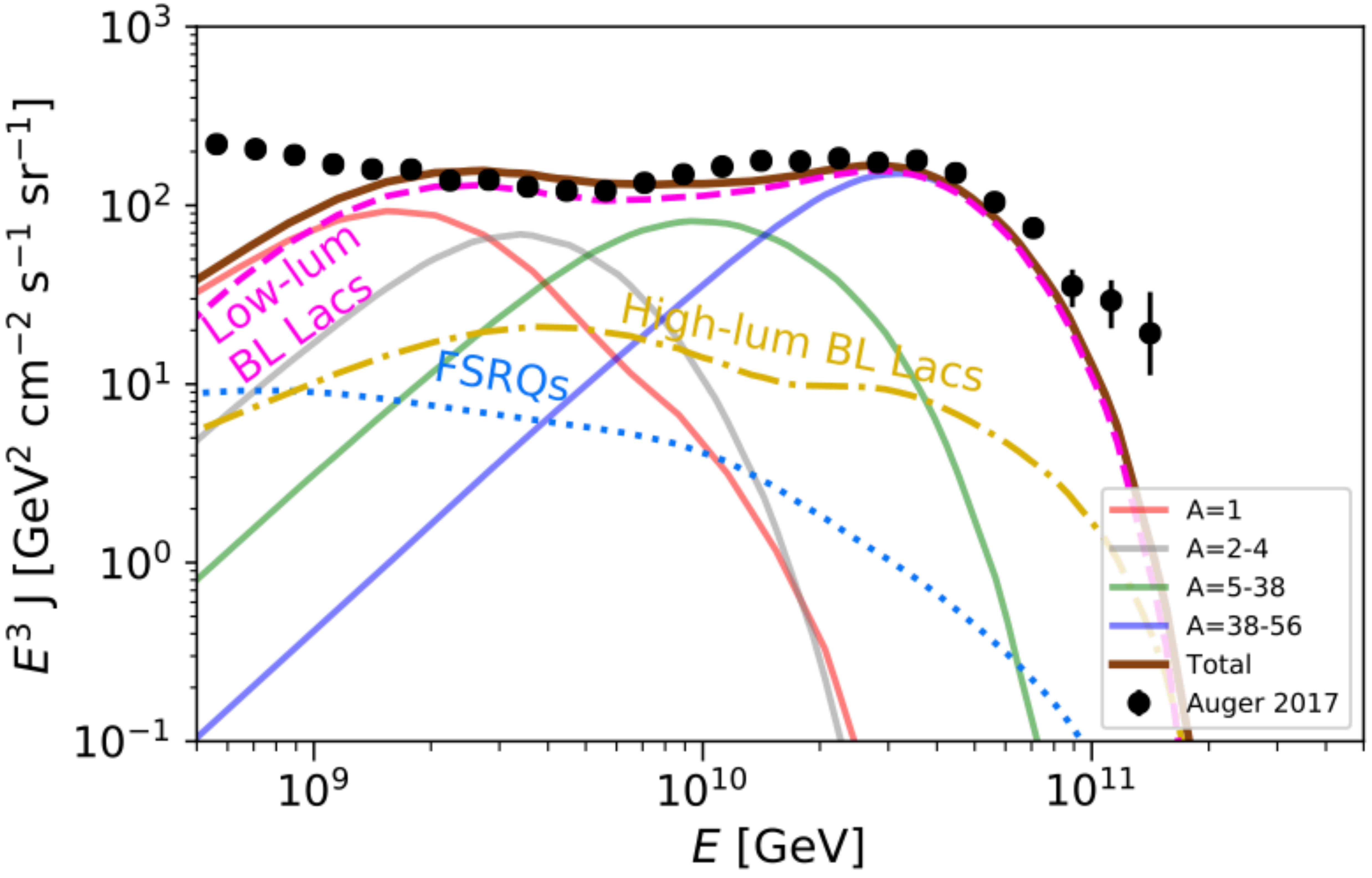
The CR-neutrino connection

Cosmic rays



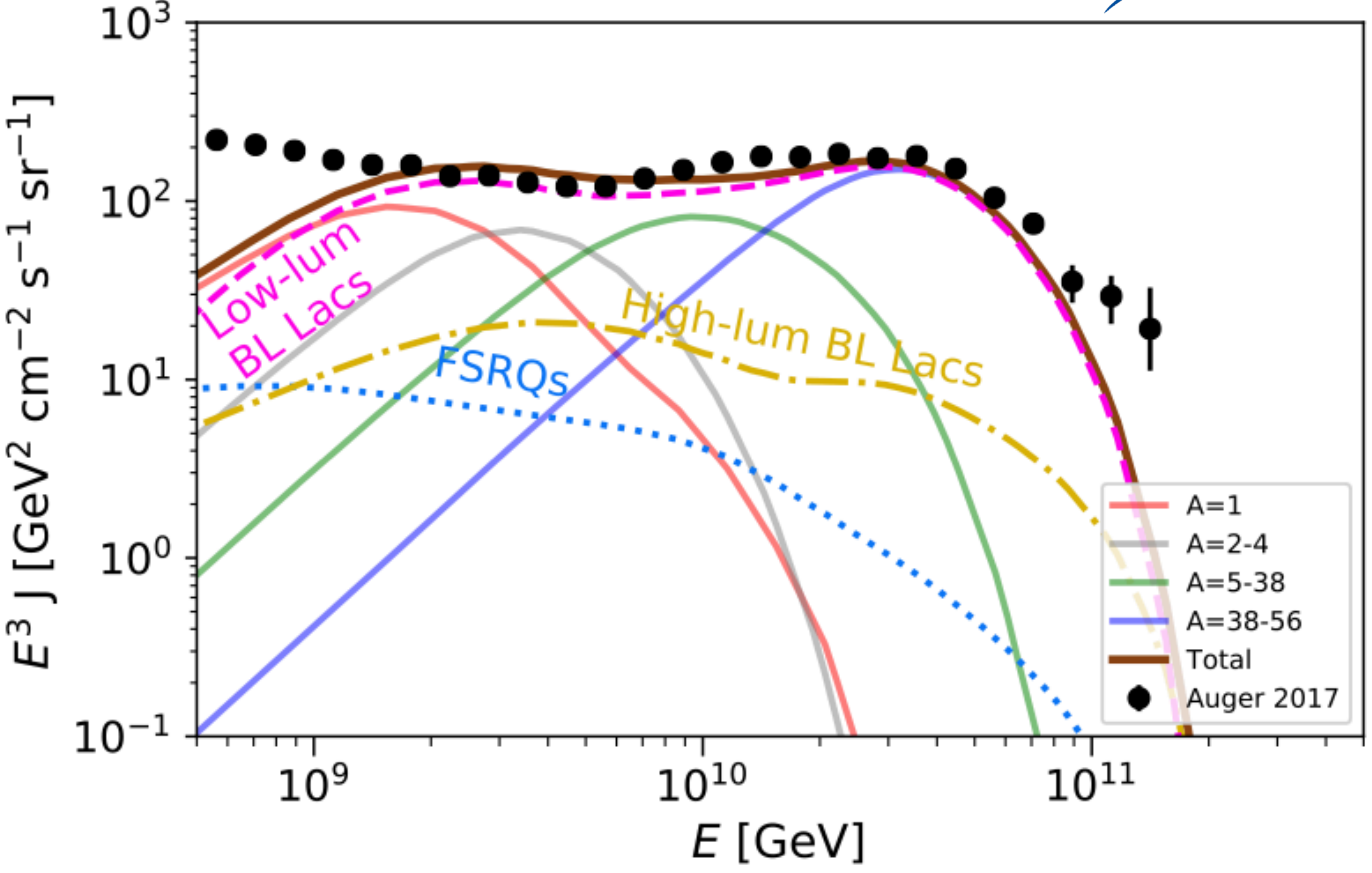
XR, Heinze, Palladino, van Vliet, Winter, submitted to PRL

The CR-neutrino connection

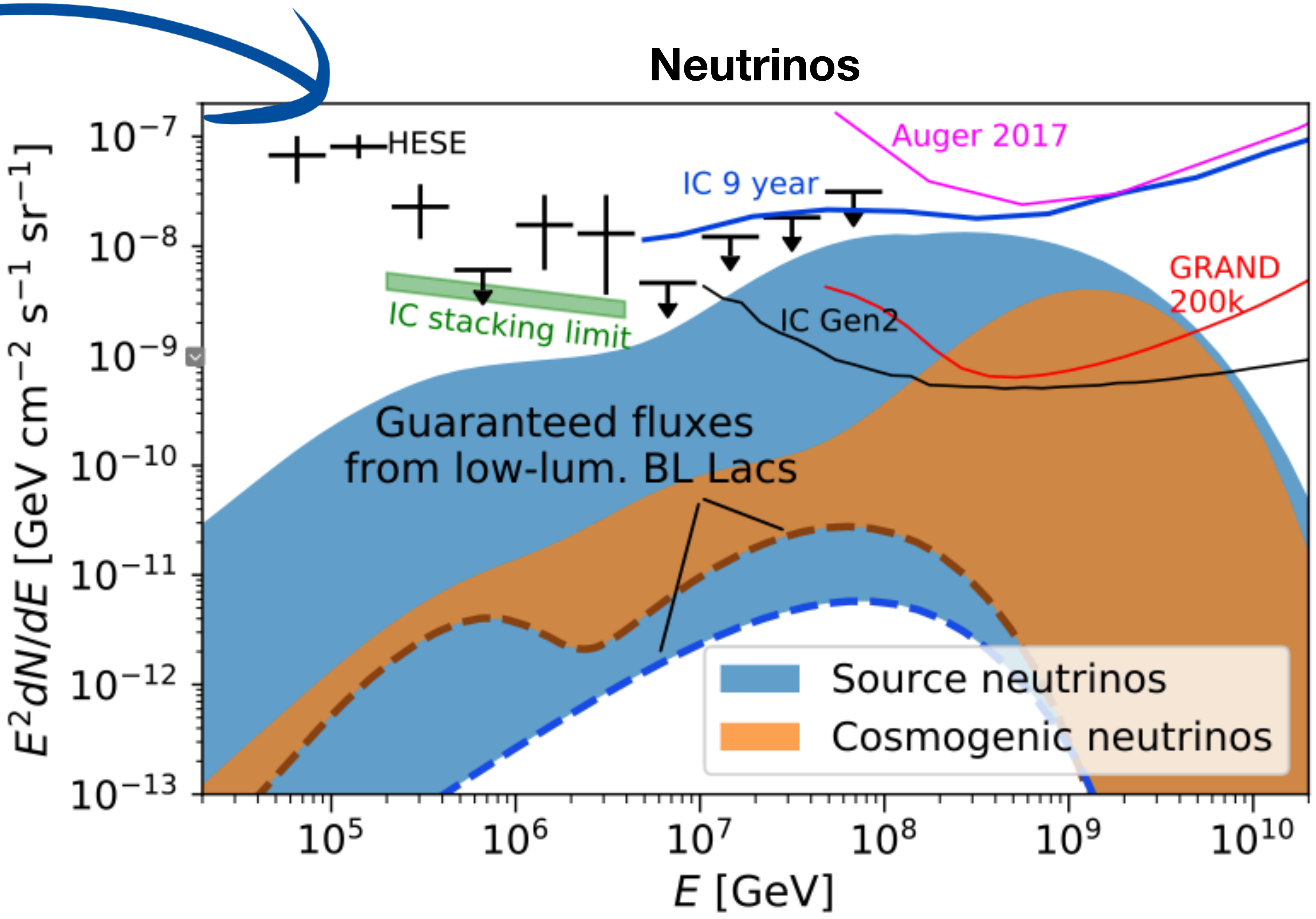
EHE neutrino flux:

- Possibly at a level detectable by IceCube Gen2, GRAND 200k
- **Source neutrinos** should **outshine cosmogenic**
- Dominated by **bright FSRQs** (only ~600 objects resolved by Fermi-LAT)

Cosmic rays



Neutrinos



XR, Heinze, Palladino, van Vliet, Winter, submitted to PRL

Conclusion

Recent IceCube from the directions of known AGN are generally **supported by multi-messenger modeling** of cosmic-ray interactions

Current challenges in the modeling point towards **more sophisticated models** -> which in turn require **more multi-wavelength coverage** and **higher neutrino statistics**

If AGN accelerate CRs to **100 TeV - 10 PeV:**

may explain the IceCube diffuse flux -> hypothesis will soon be challenged by **stacking limits** and **multiplet constraints**

If AGN accelerate **UHECRs**:

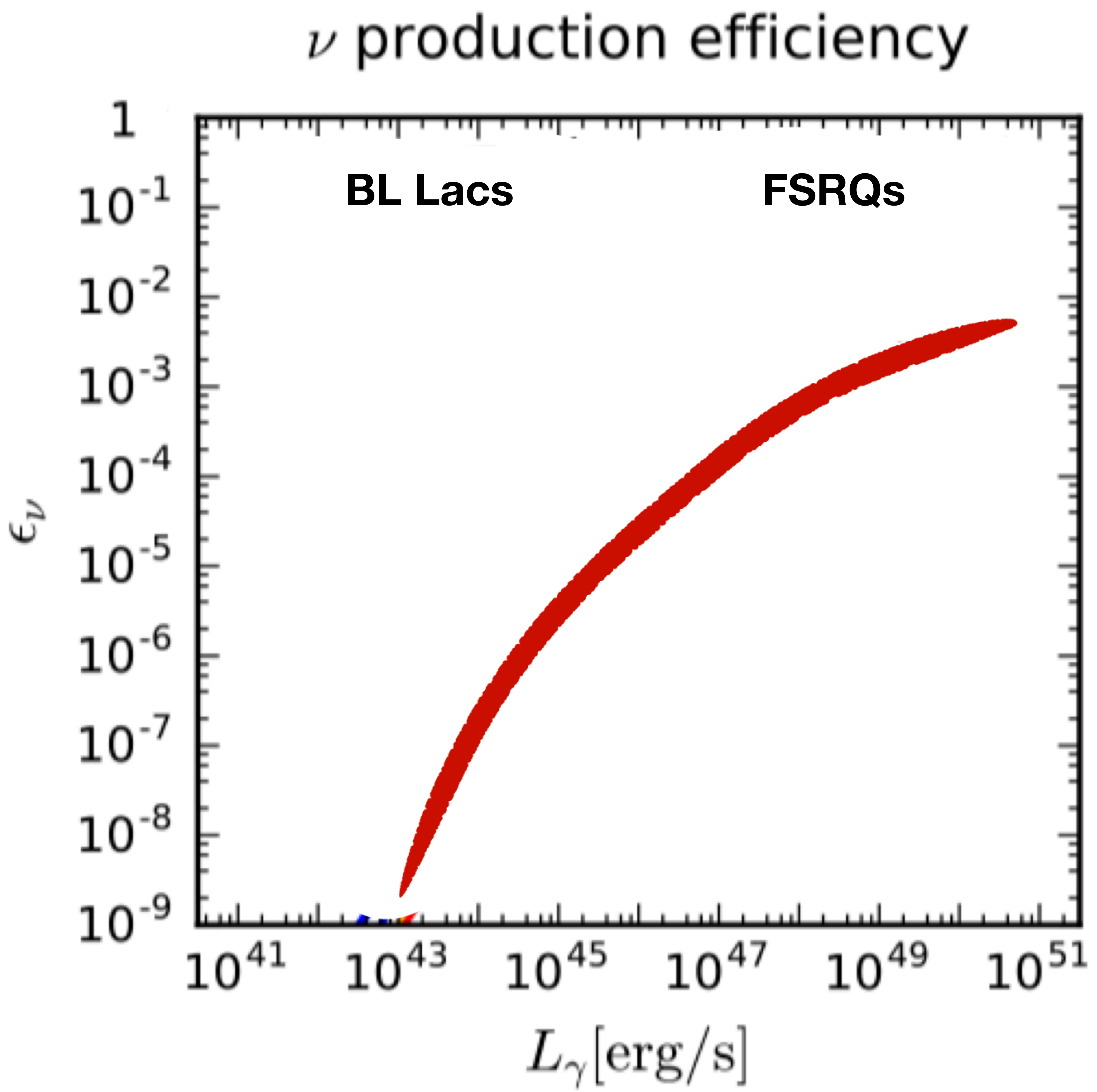
may produce UHE neutrinos at levels **detectable by future radio neutrino telescopes;**

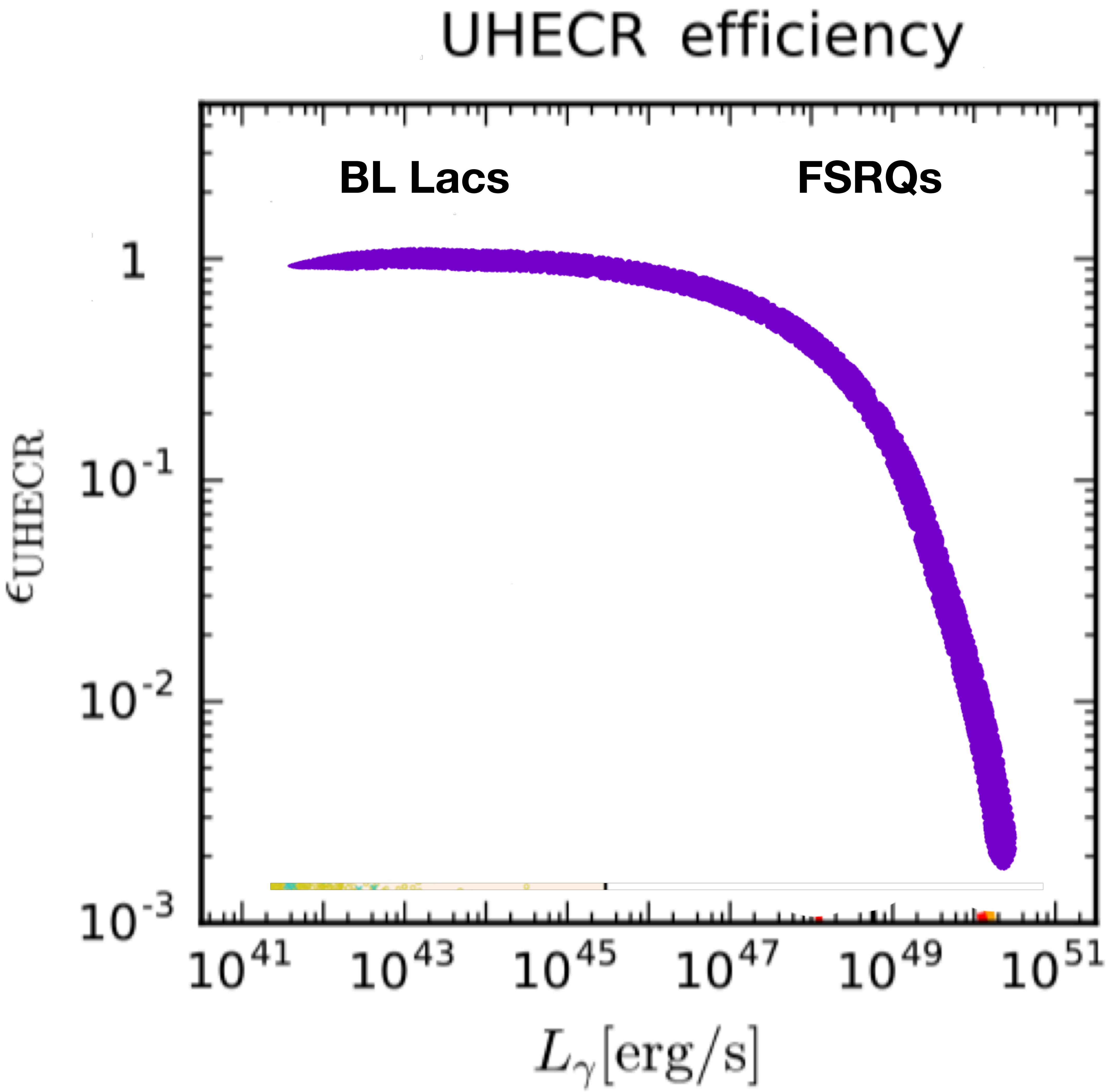
these will be **source neutrinos** from a **few powerful quasars**

-> favourable to directionality studies, time domain searches

Backup

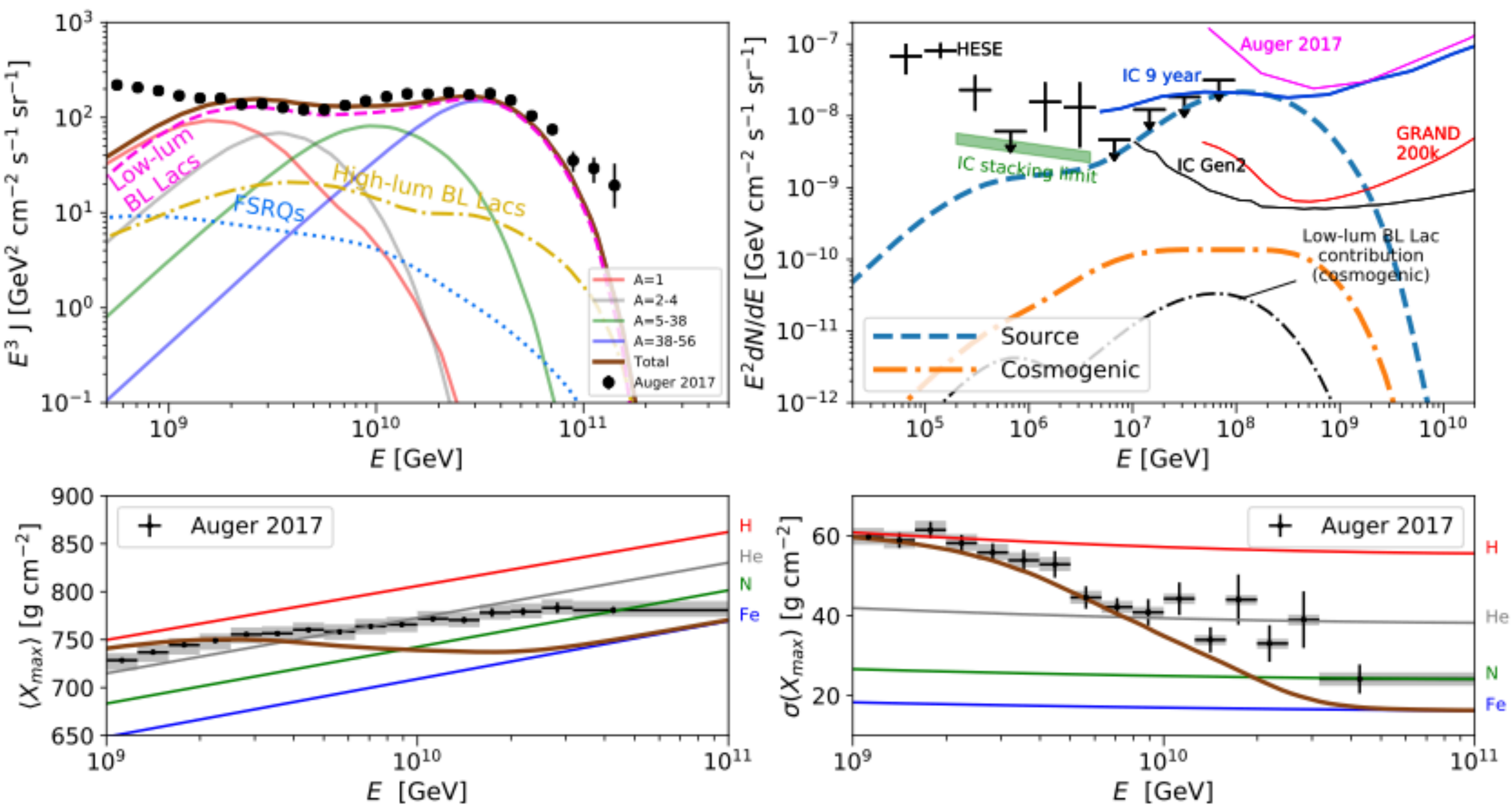
CRs and neutrinos from the entire blazar population





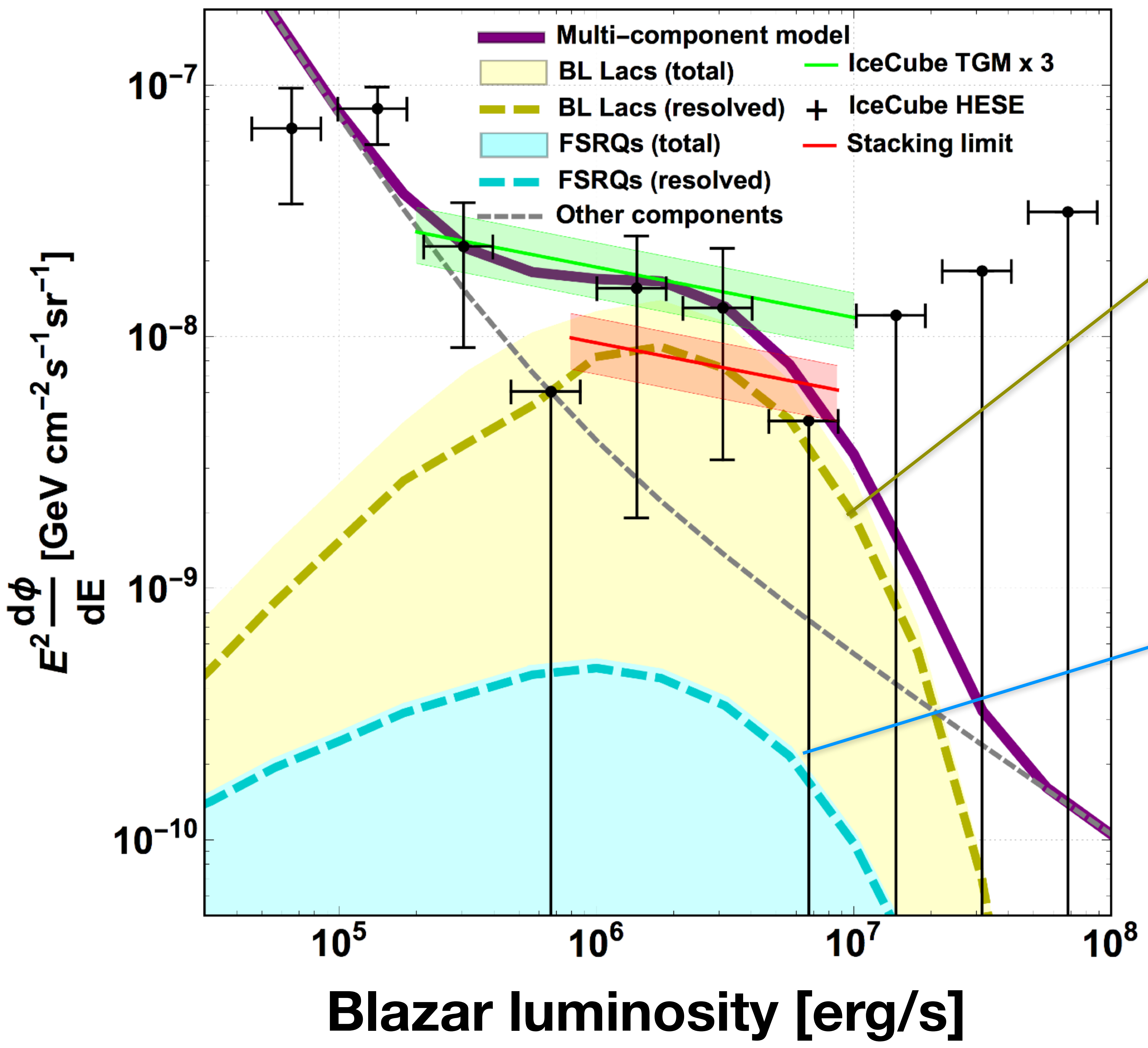
XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

CRs and neutrinos from the entire blazar population



Blazars as sources of the IceCube neutrinos?

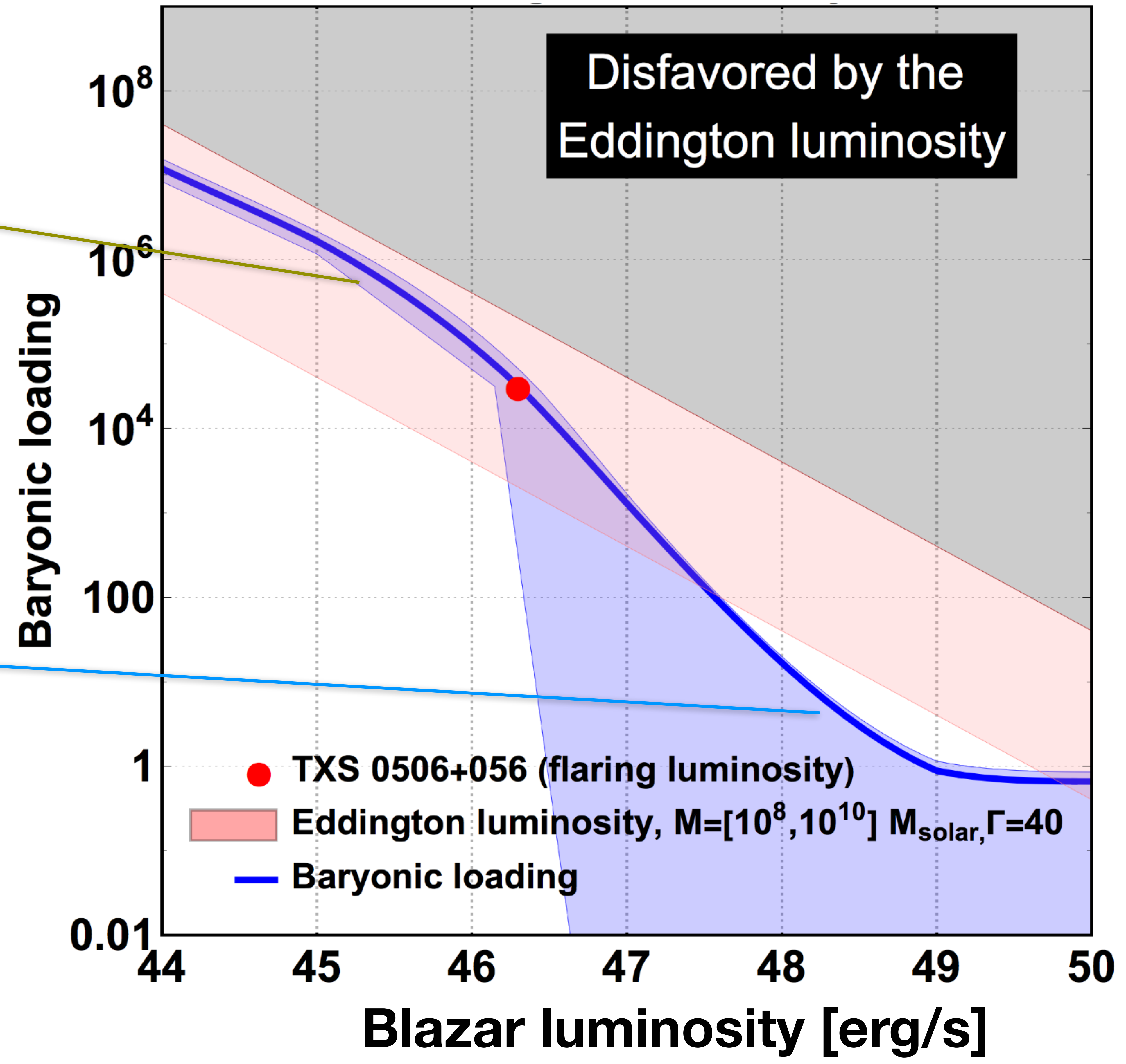
Diffuse neutrino flux



BL Lacs must have **high baryonic loadings** to power the IceCube neutrino flux

FSRQ contribution must be **highly suppressed** not to violate stacking bounds

Baryonic loading



Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

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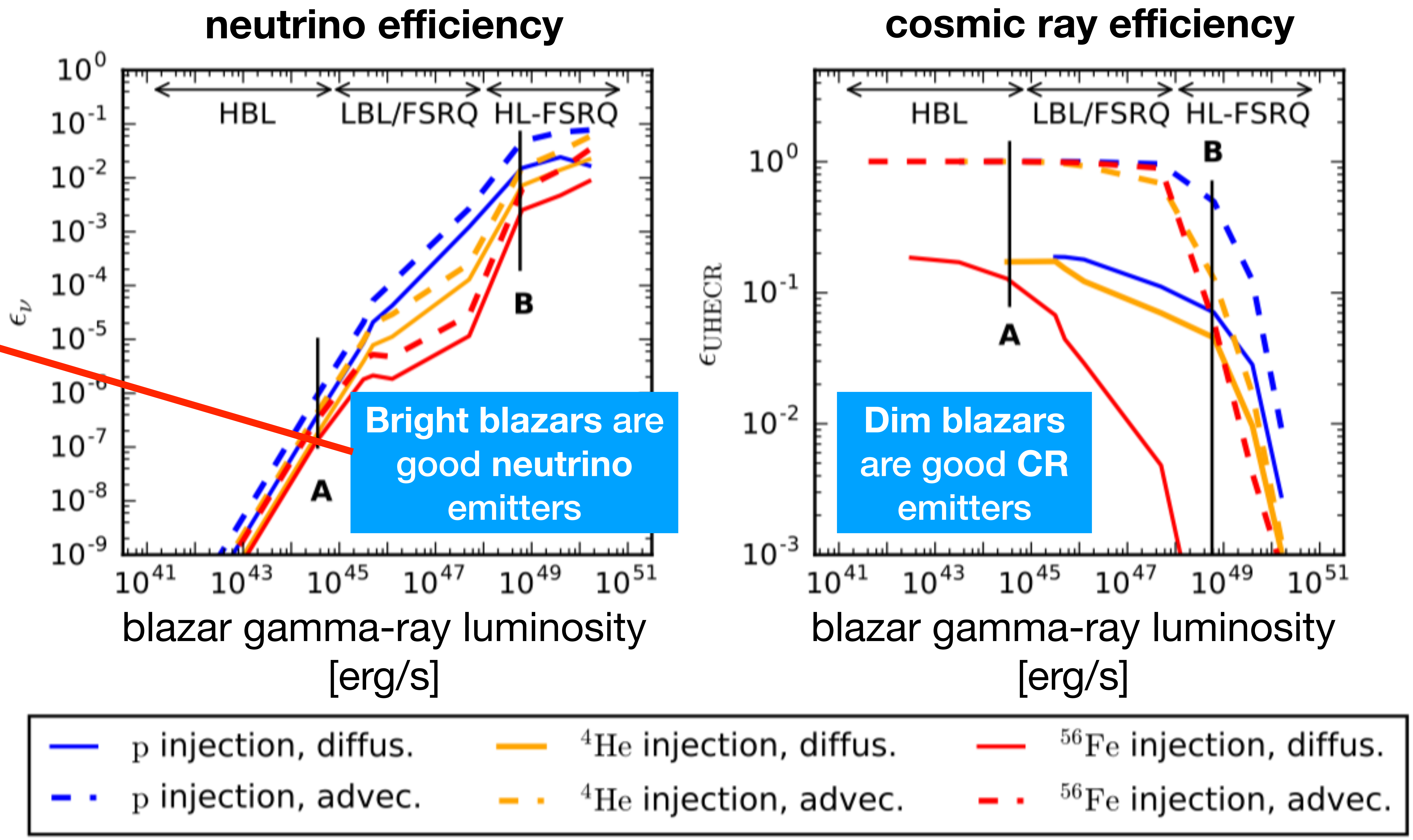
Neutrinos and CRs from the blazar family

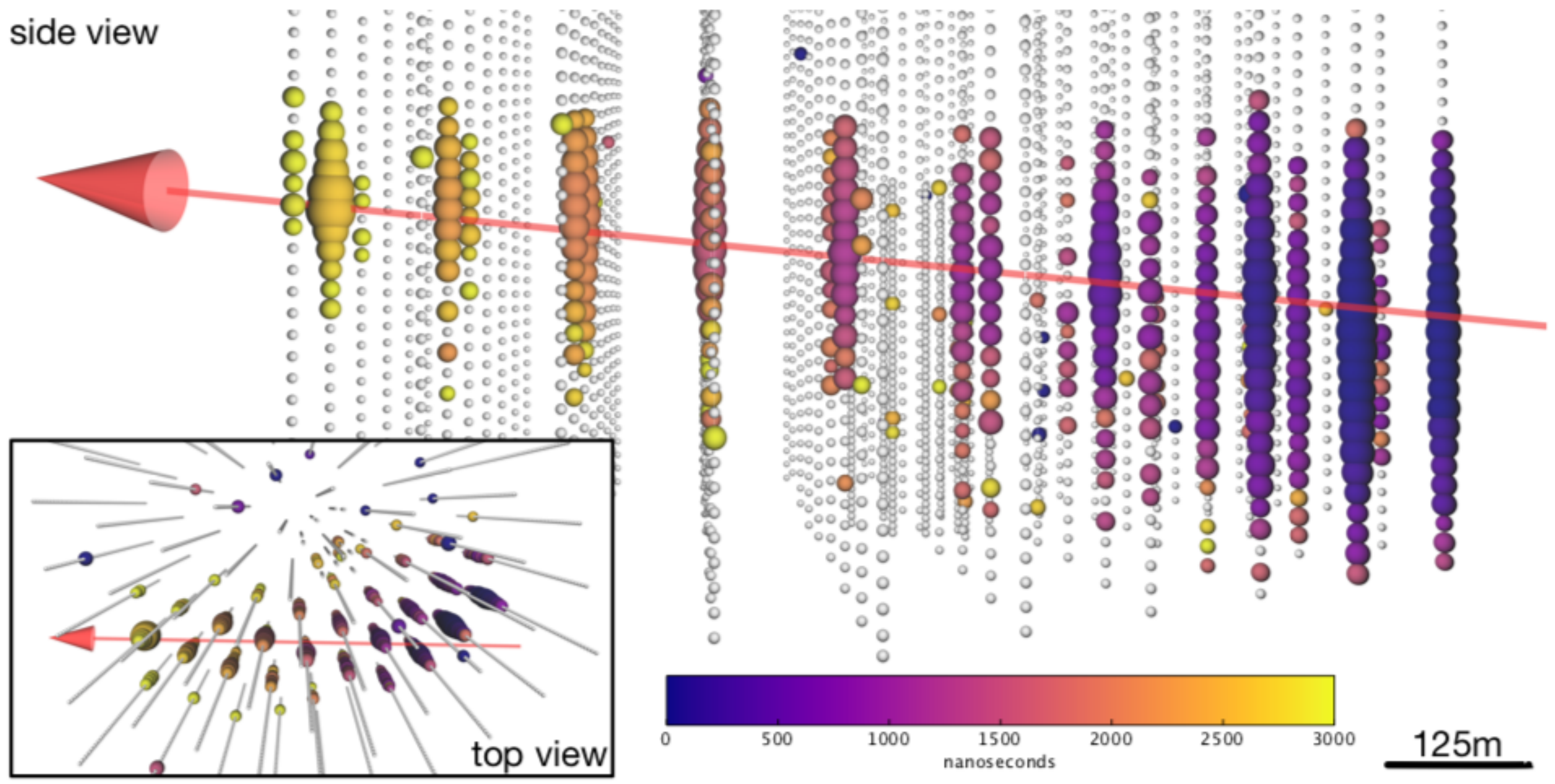
Makes **lack of neutrino-source correlations** even more **challenging**



XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

TXS 0506+056: the first neutrino blazar?

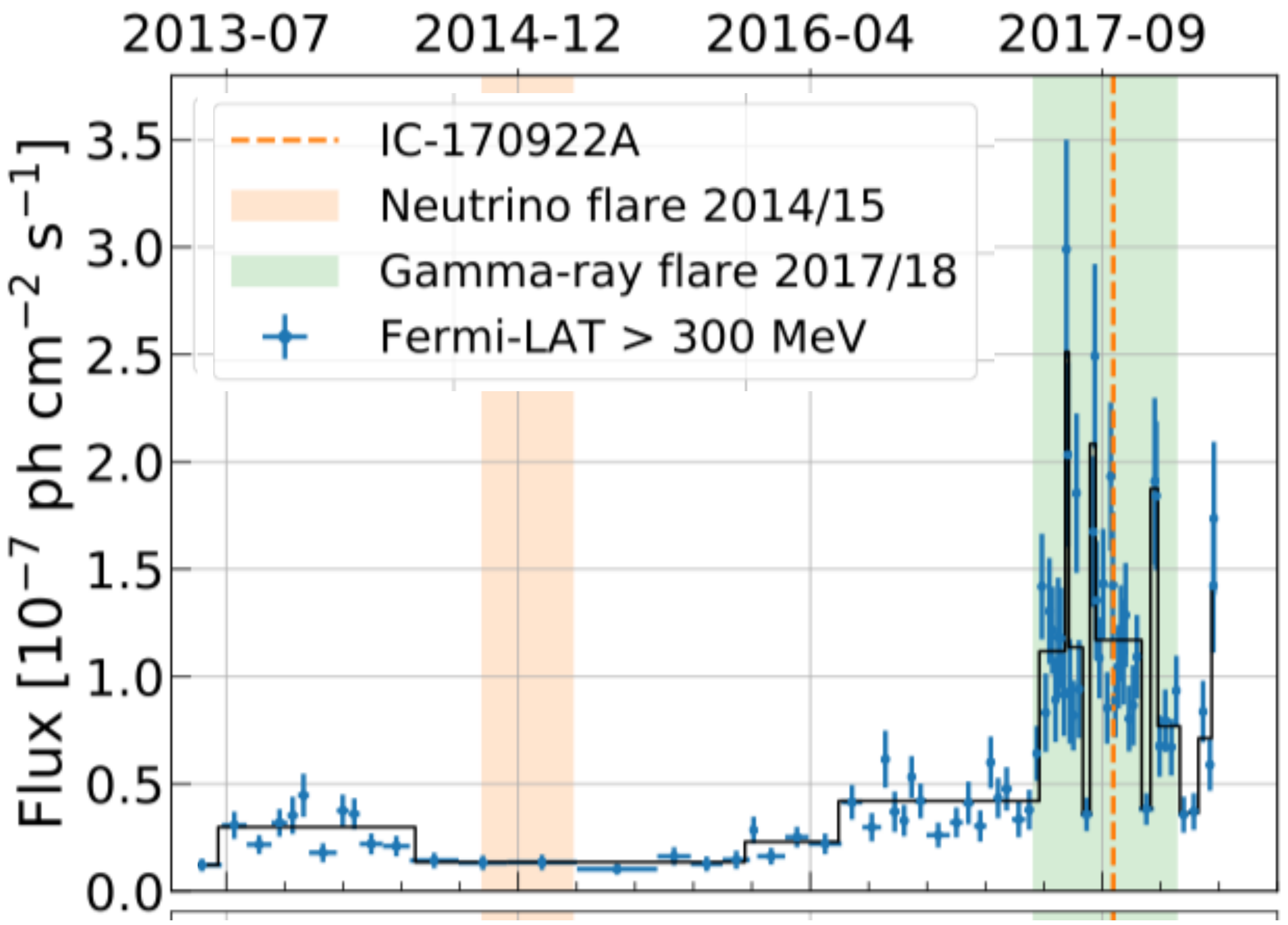
Muon track observed on Sep 22, 2017 (energy of 23.7±2.8 TeV)



Aartsen et al., 2018, Science 361, eeat1378

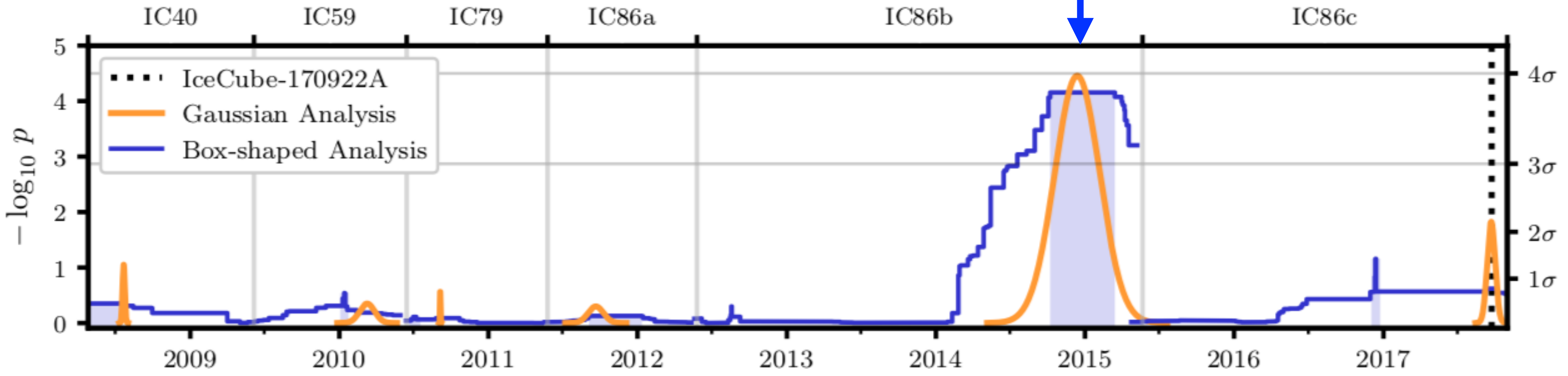
alert sent to telescopes worldwide

Simultaneous gamma-ray flare



Garrappa et al. 2019, ApJ 880 no.2.

Evidence for 13±5 neutrinos from the same source back in 2014-15



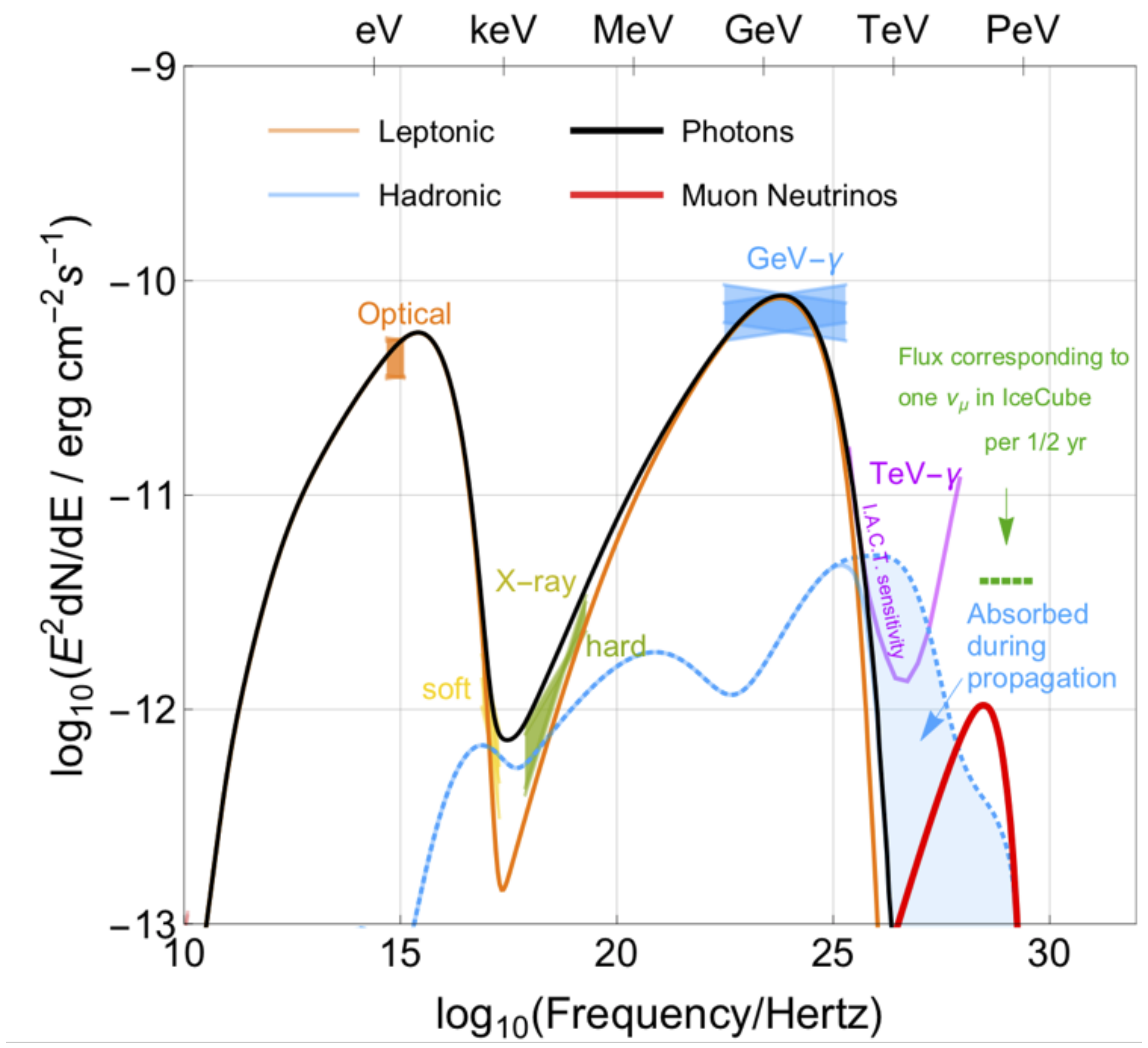
Aartsen et al. 2018, Science 361, 147

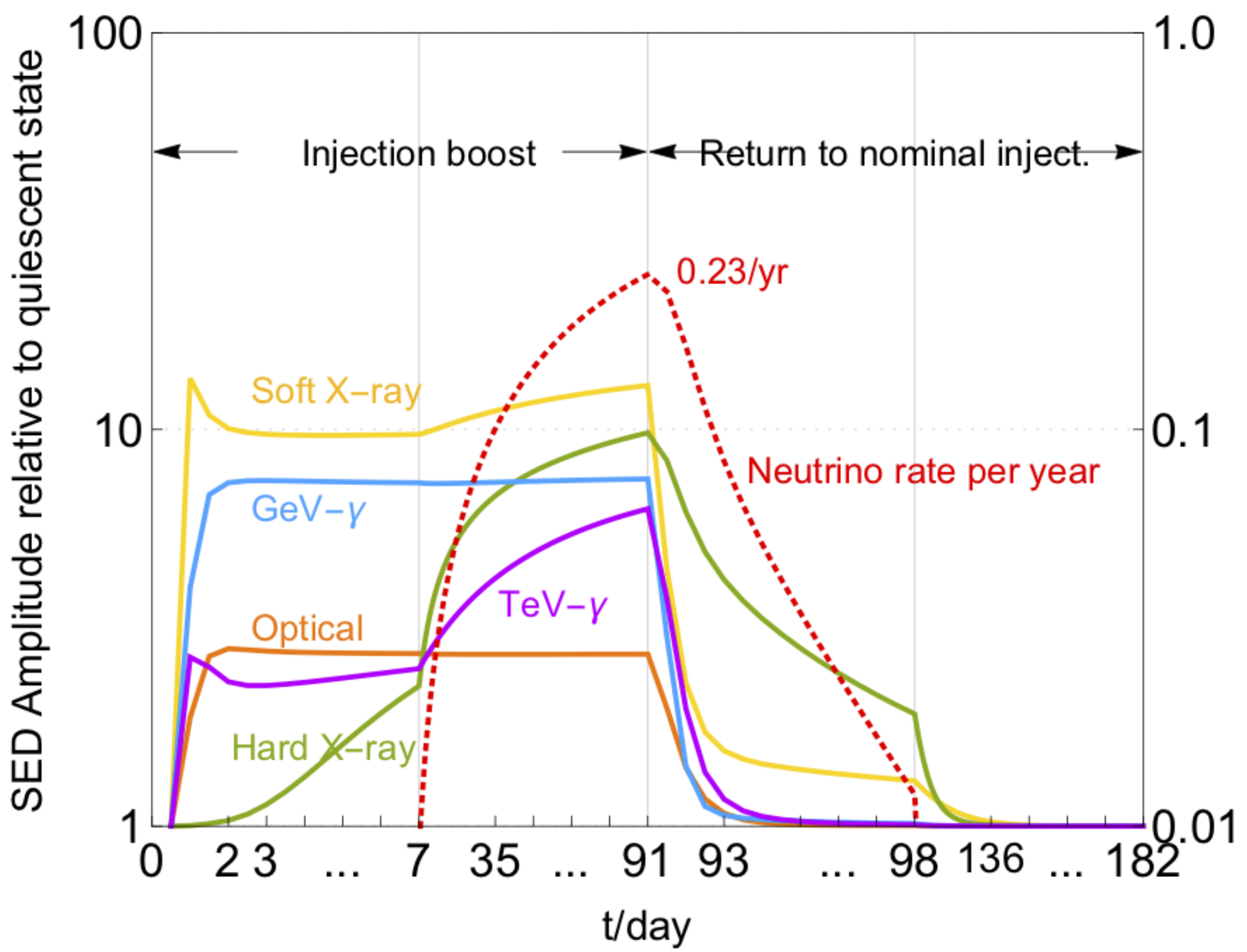
without activity in gamma rays

The 2017 neutrino event

X-rays from hadronic cascades constrain the baryonic loading of the source, but 0.2 neutrinos per year can be explained

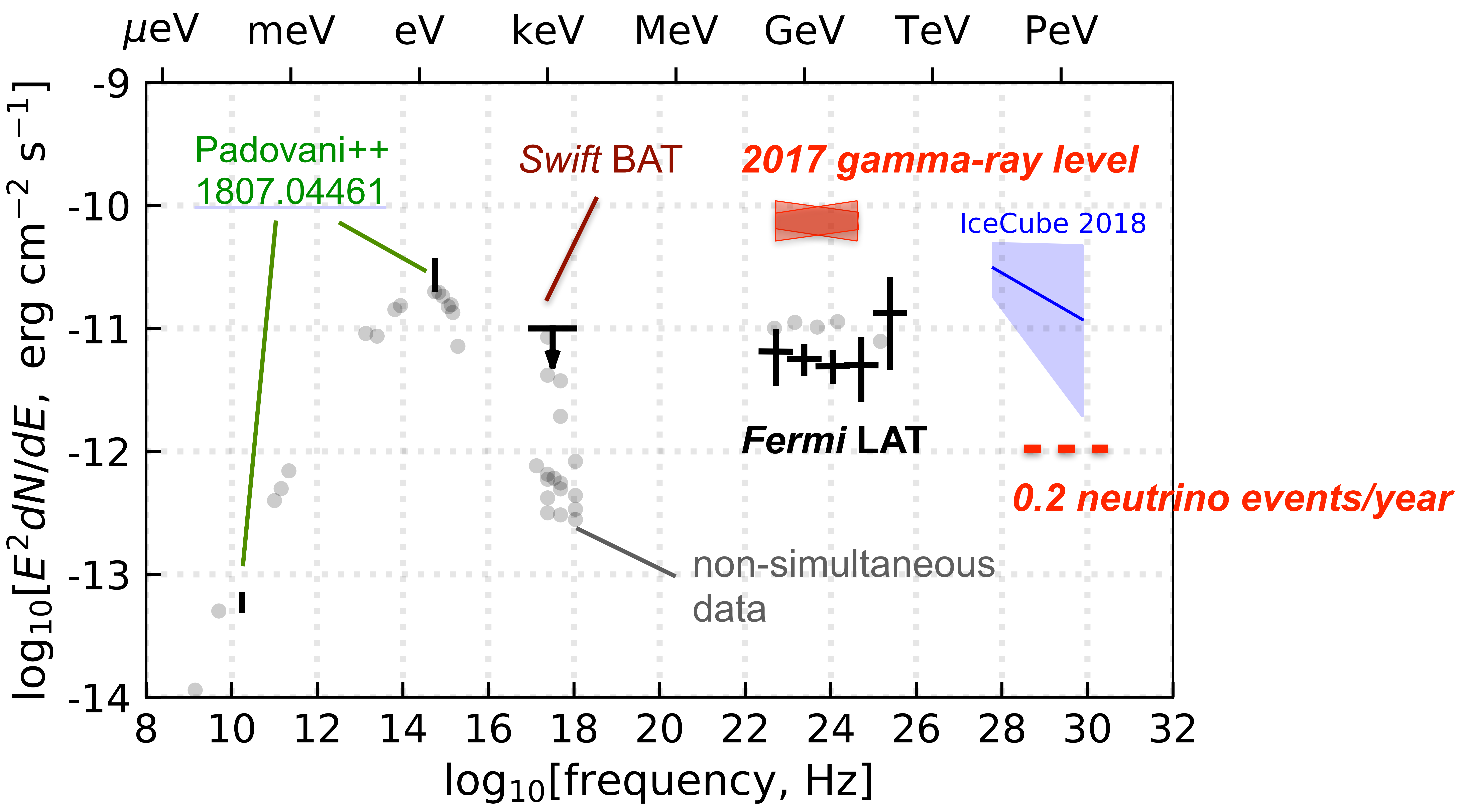
Example of lepto-hadronic model:



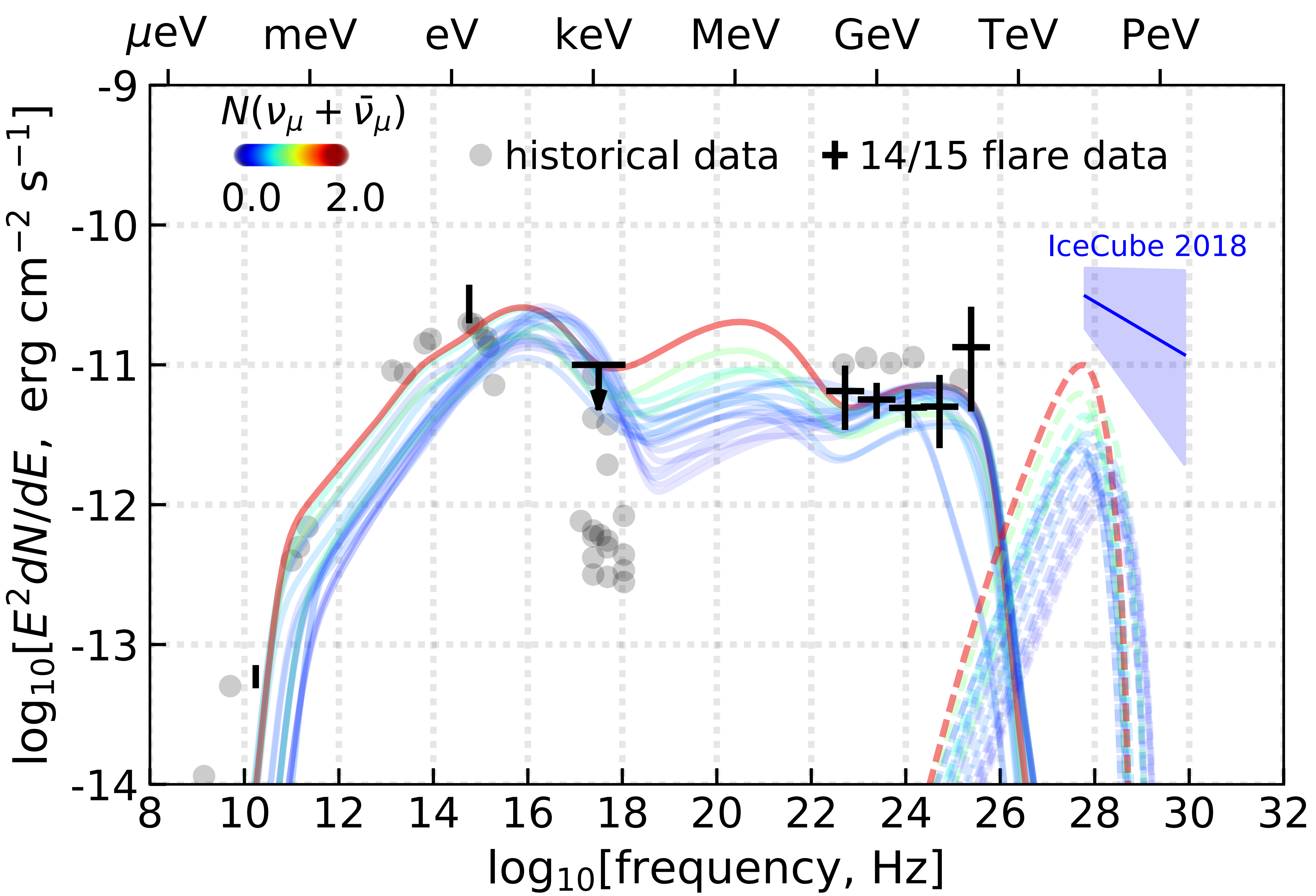


Gao et al., Nat.Astron. 3 (2019)

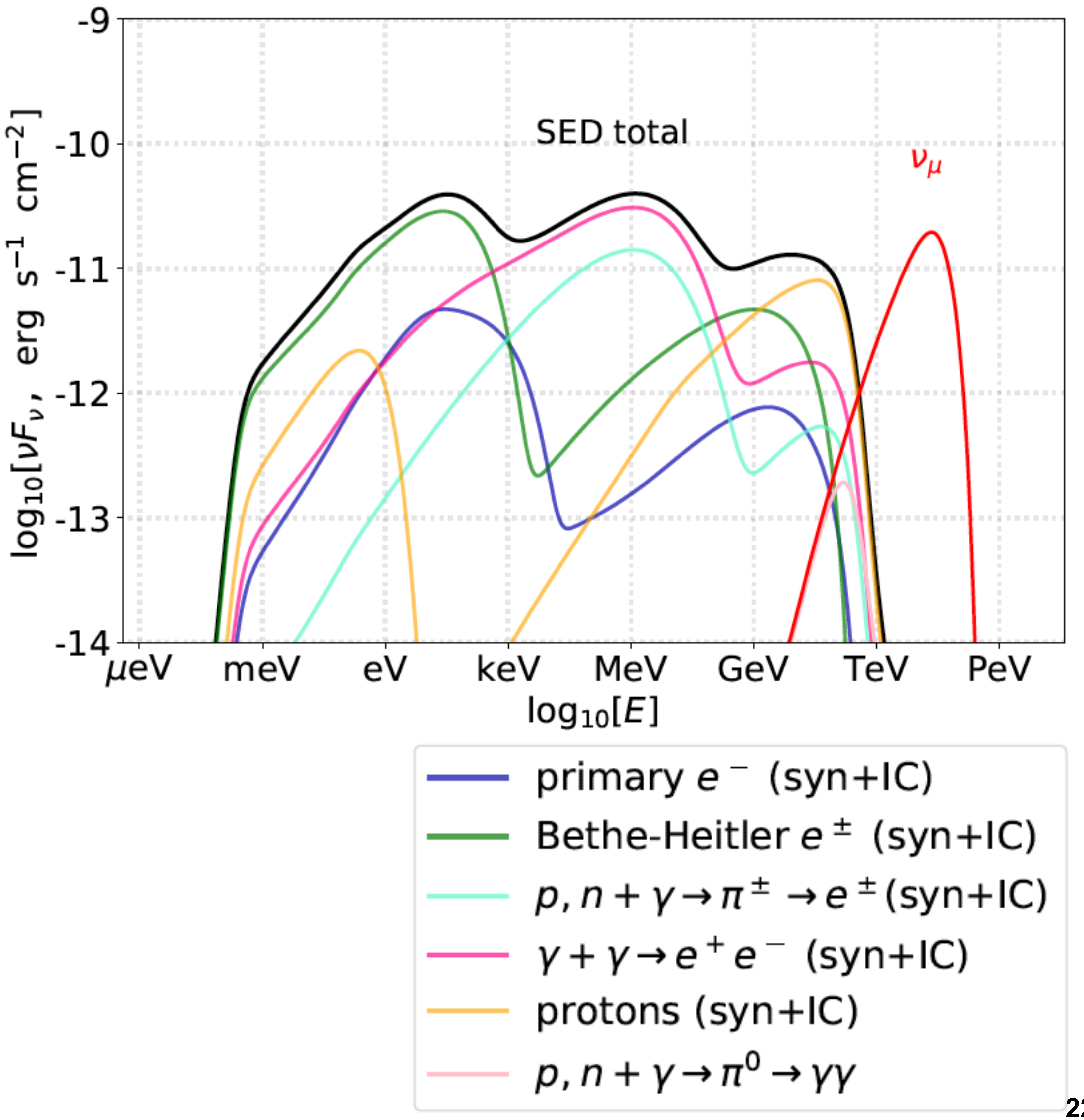
The 2014/15 neutrino flare of TXS 0506+056 — constraints



One-zone model



SED breakdown



Explain up to 2 neutrinos
without violating X- and gamma-ray fluxes

XR, Gao, Fedynitch, Palladino, Winter, ApJ L874 (2019)

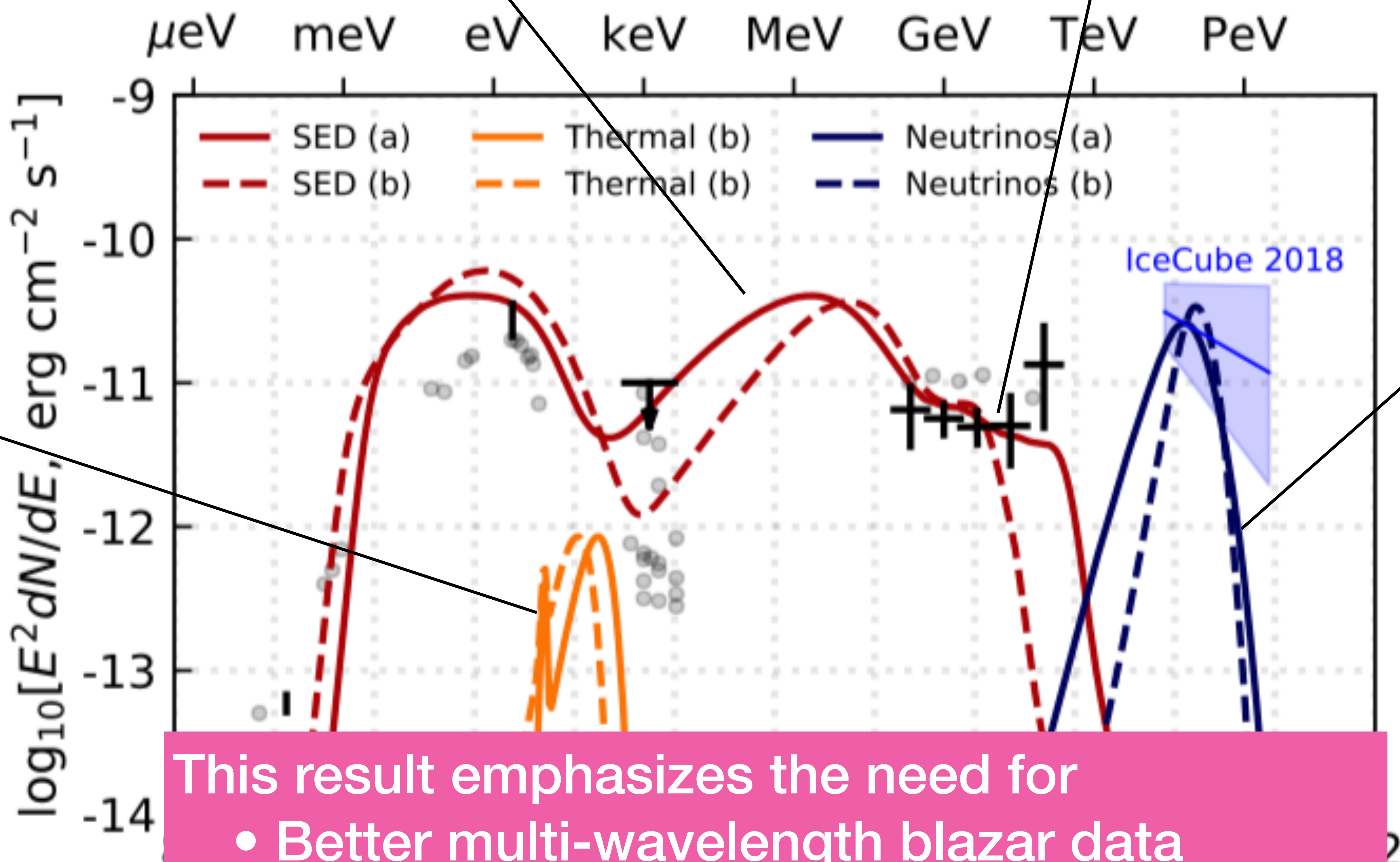
External-field (FSRQ-like) model

In-source cascades "dump" the hadronic photons into the MeV range

(cf. Reimer++ 2019 ApJ 881)

TeV spectrum too soft due to photon annihilation with the disk emission

Assume a disk luminosity consistent with observations
[Padovani et al. MNRAS 484 (2019)]



Model can explain up to 5 neutrino events
(still 2 σ discrepancy with observation)

This result emphasizes the need for
- Better multi-wavelength blazar data
- Realistic numerical modeling

XR, Gao, Fedynitch, Palladino, Winter, ApJ L874 (2019)