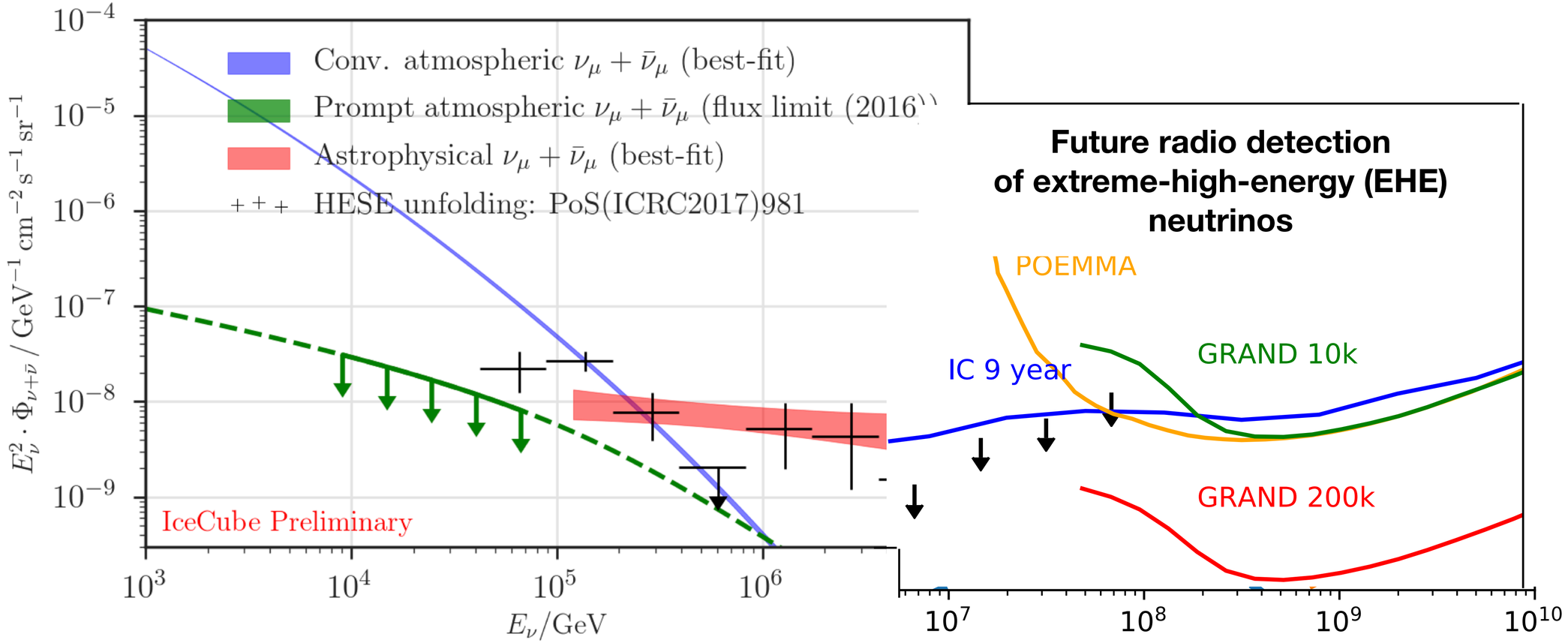
Active Galactic Nuclei as neutrino sources in the PeV and EeV regimes

Xavier Rodrigues
DESY Zeuthen

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Astrophysical neutrino observations



Haack & Wiebusch, ICRC 2017

IceCube flux detected up to ~50 PeV…

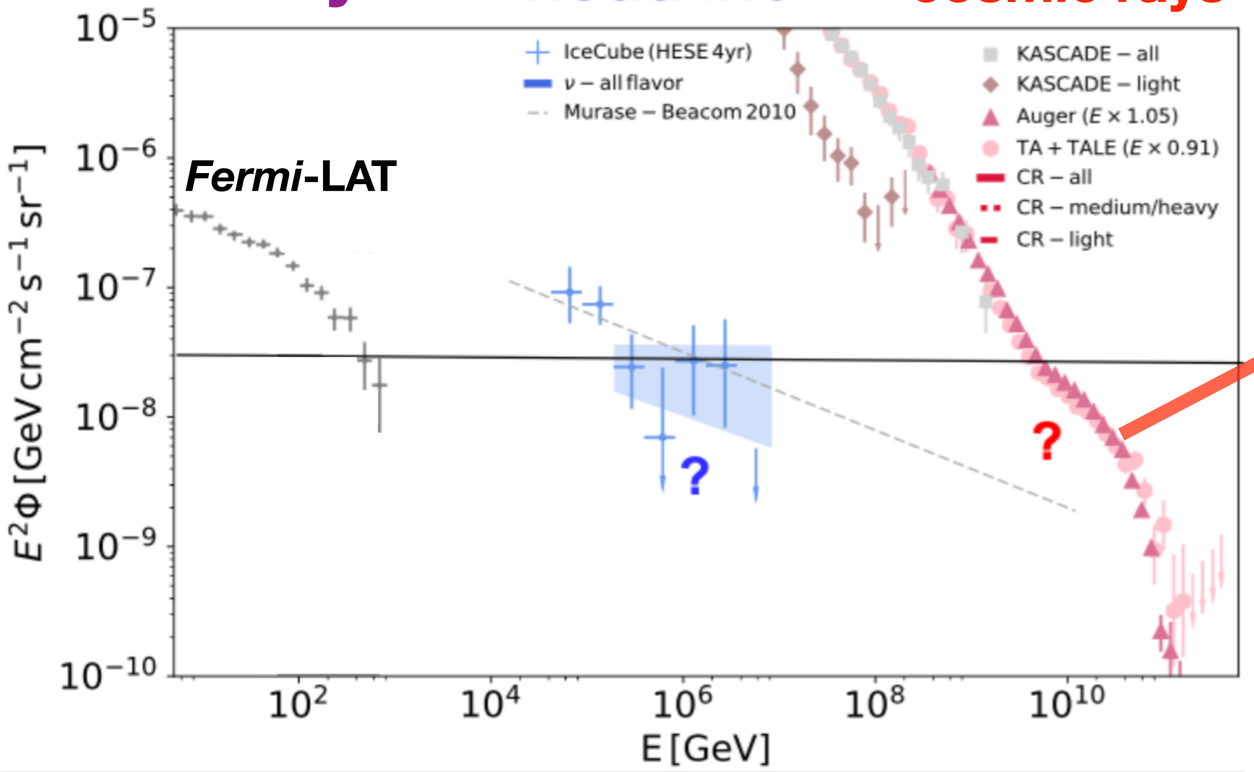
…. and future experiments will improve our sensitivity to EeV neutrinos

The multi-messenger picture

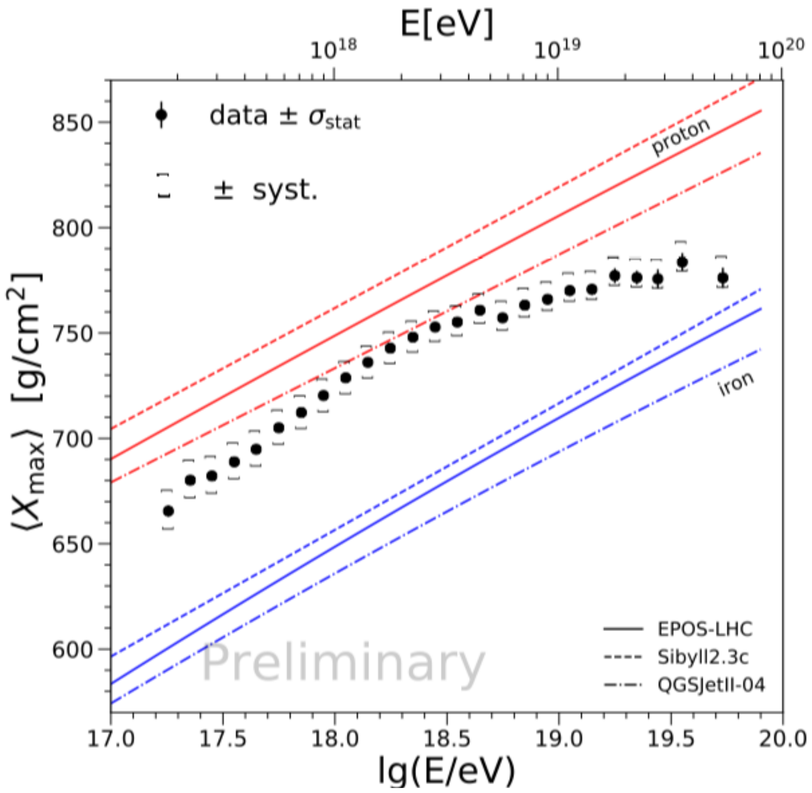
gamma rays

neutrino

ultra-high-energy cosmic rays



K Murase, ICRC 2019



A Yushkov, ICRC 2019

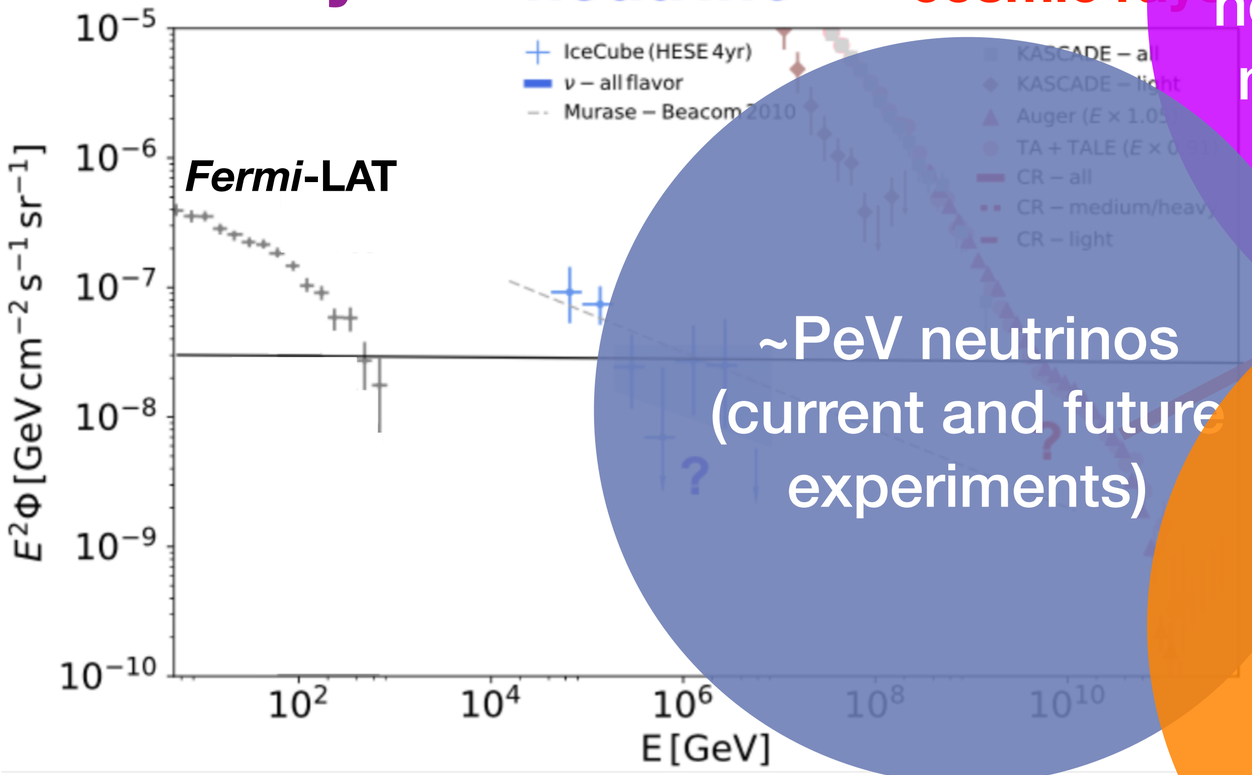
Evidence of a fraction of ultra-high-energy cosmic rays **heavier than protons**

The multi-messenger picture

gamma rays

neutrino

ultra-high-energy cosmic rays

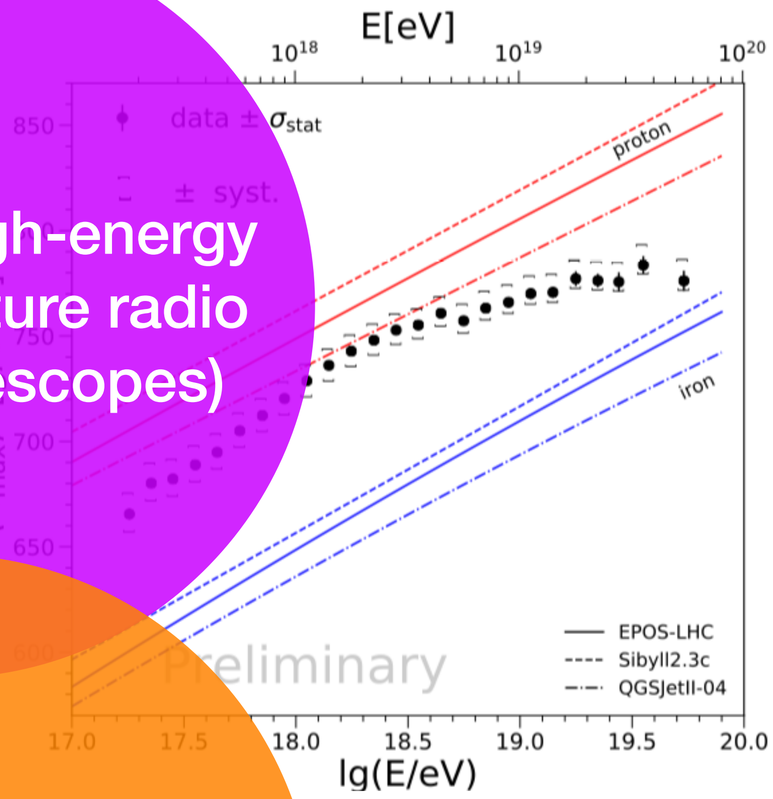


K Murase, ICRC 2019

Extremely-high-energy neutrinos (future radio neutrino telescopes)

~PeV neutrinos (current and future experiments)

Ultra-high-energy cosmic ray nuclei



A Yushkov, ICRC 2019

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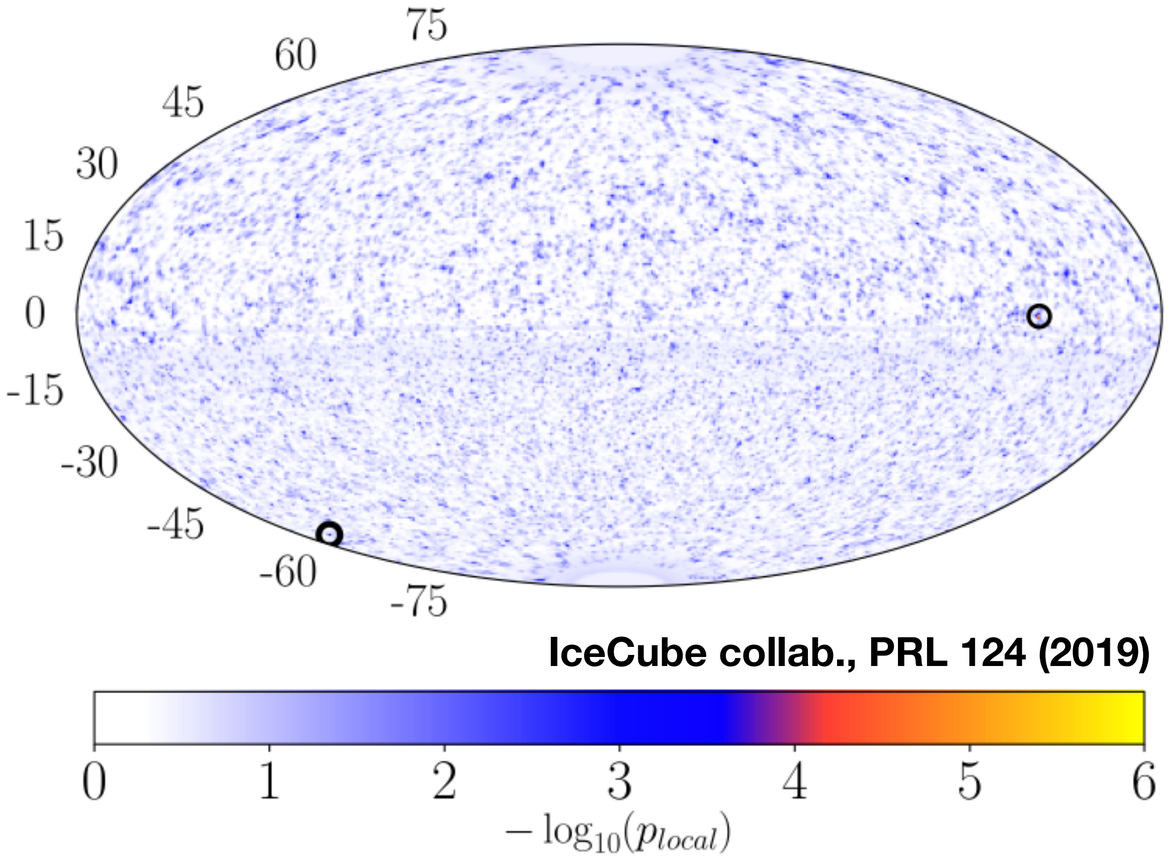
Astrophysical neutrino observations



IceCube collab., PRL 124 (2019)

- **No strong correlation** with **known point sources**

  -> Stacking limits on source populations

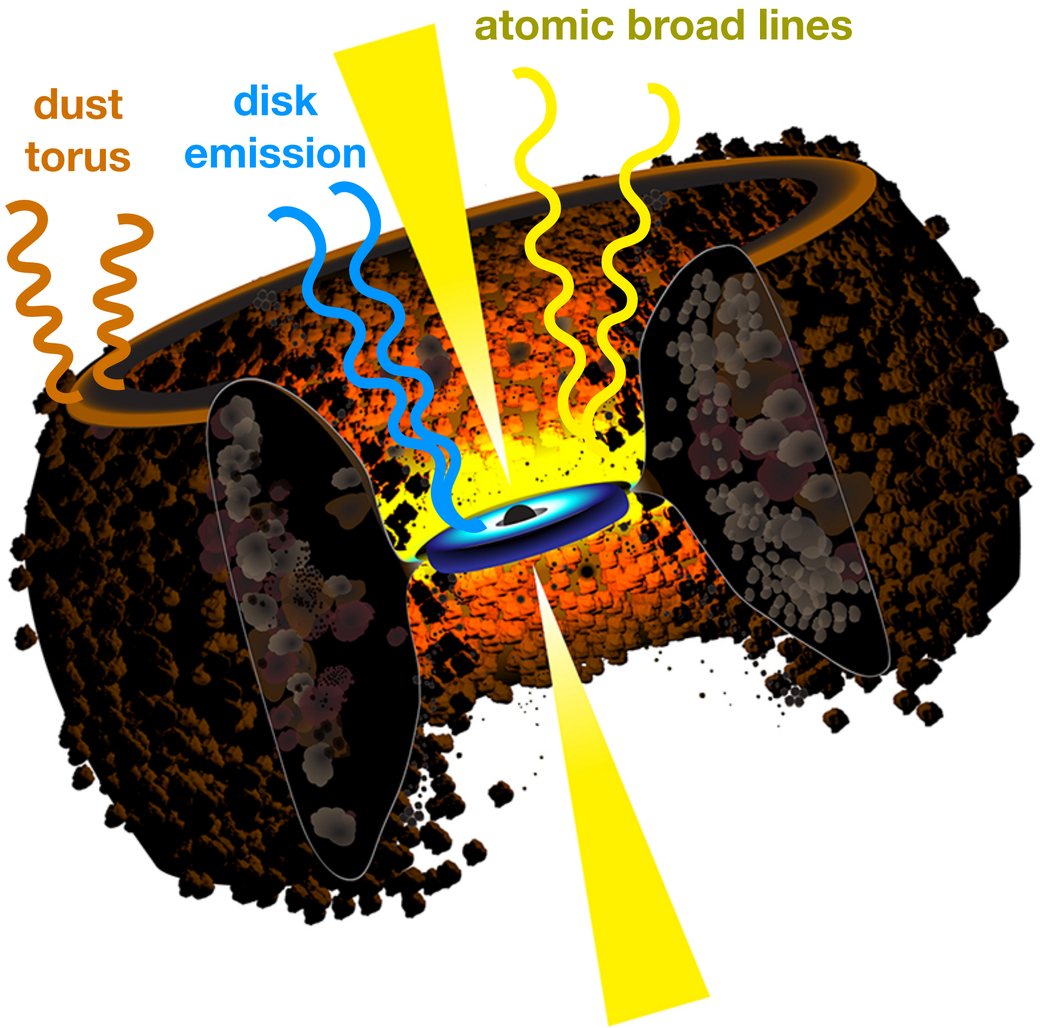
  -> **Gamma-ray AGN do not dominate the IceCube flux**

- Hints of individual neutrino sources are starting to emerge:
  - Event in 2017 spatially and temporally coincident with a gamma-ray flare from blazar **TXS 0506+056**
  - An archival search around the position of the same source showed a significant **neutrino flare** back in in 2014/15
  - Dozens of individual high-energy events spatially coincident with candidate sources, such as the quasar **PKS 1502+106**
  - Significant excesses in time-integrated search from the directions of starburst galaxy **NGC 1068** and BL Lacs **PKS 1424+240** and **GB6 J1542+6129**

Multi-messenger models of blazar AGN

BL Lacs

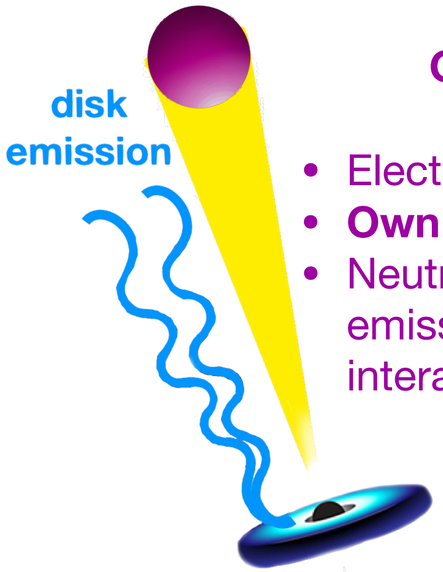
Flat-Spectrum Radio Quasars (FSRQs)



Credit: Bill Saxton, NRAO/AUI/

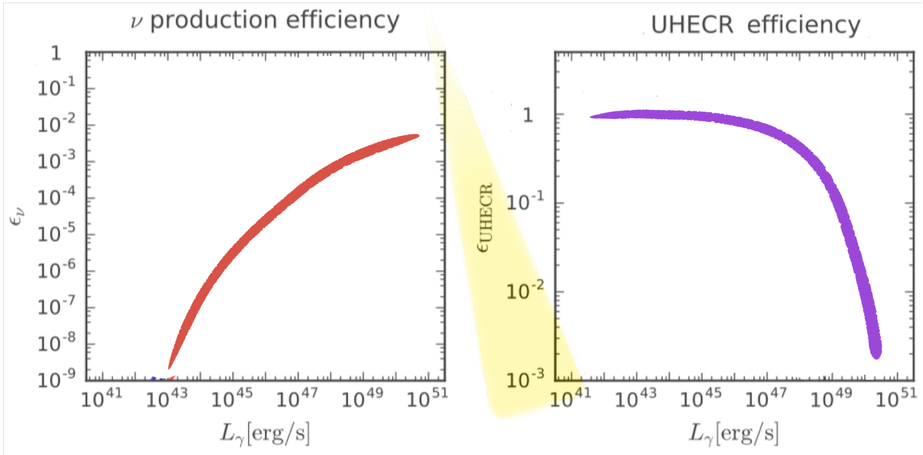
Multi-messenger models of blazar AGN

BL Lacs



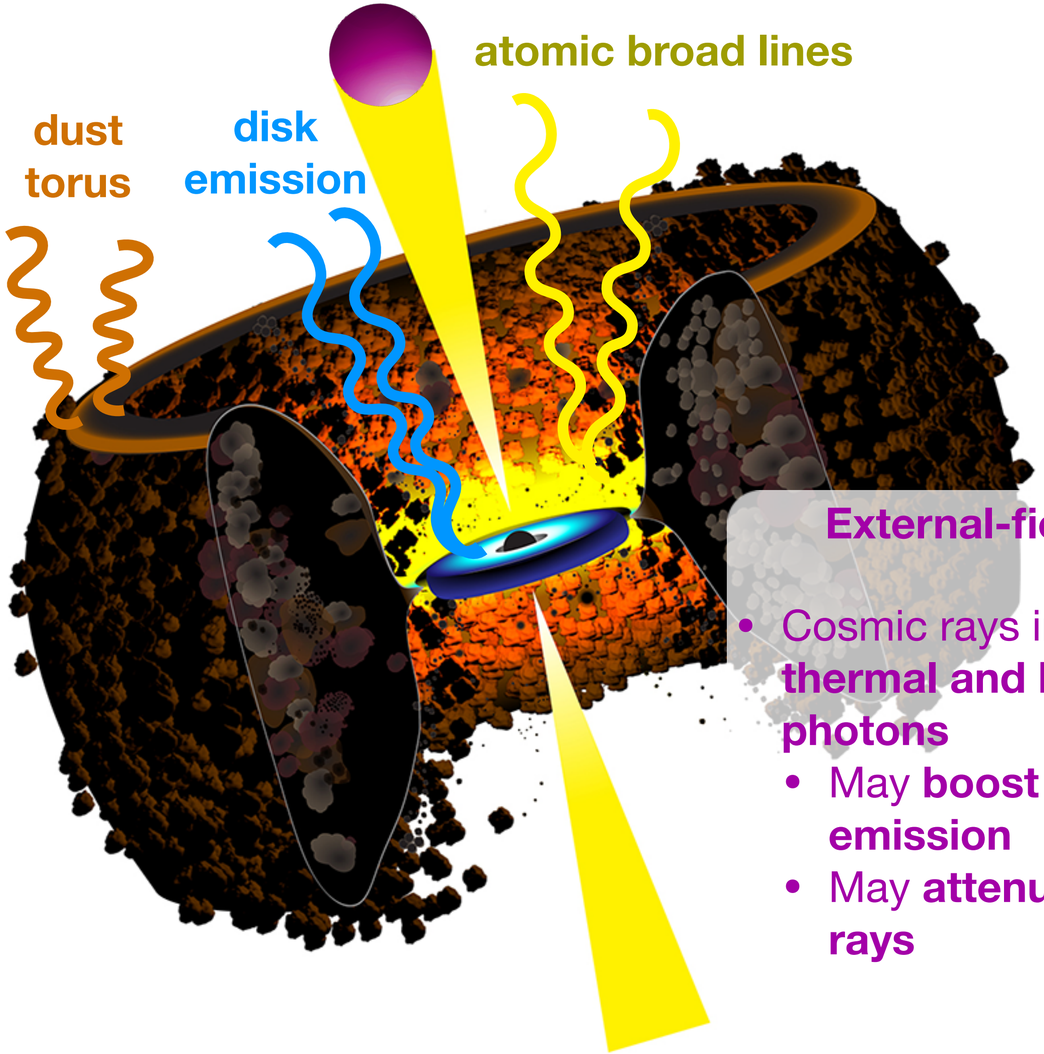
One-zone model

- Electrons + cosmic rays
- **Own non-thermal radiation**
- Neutrino and gamma-ray emission from p-gamma interactions



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

Flat-Spectrum Radio Quasars (FSRQs)

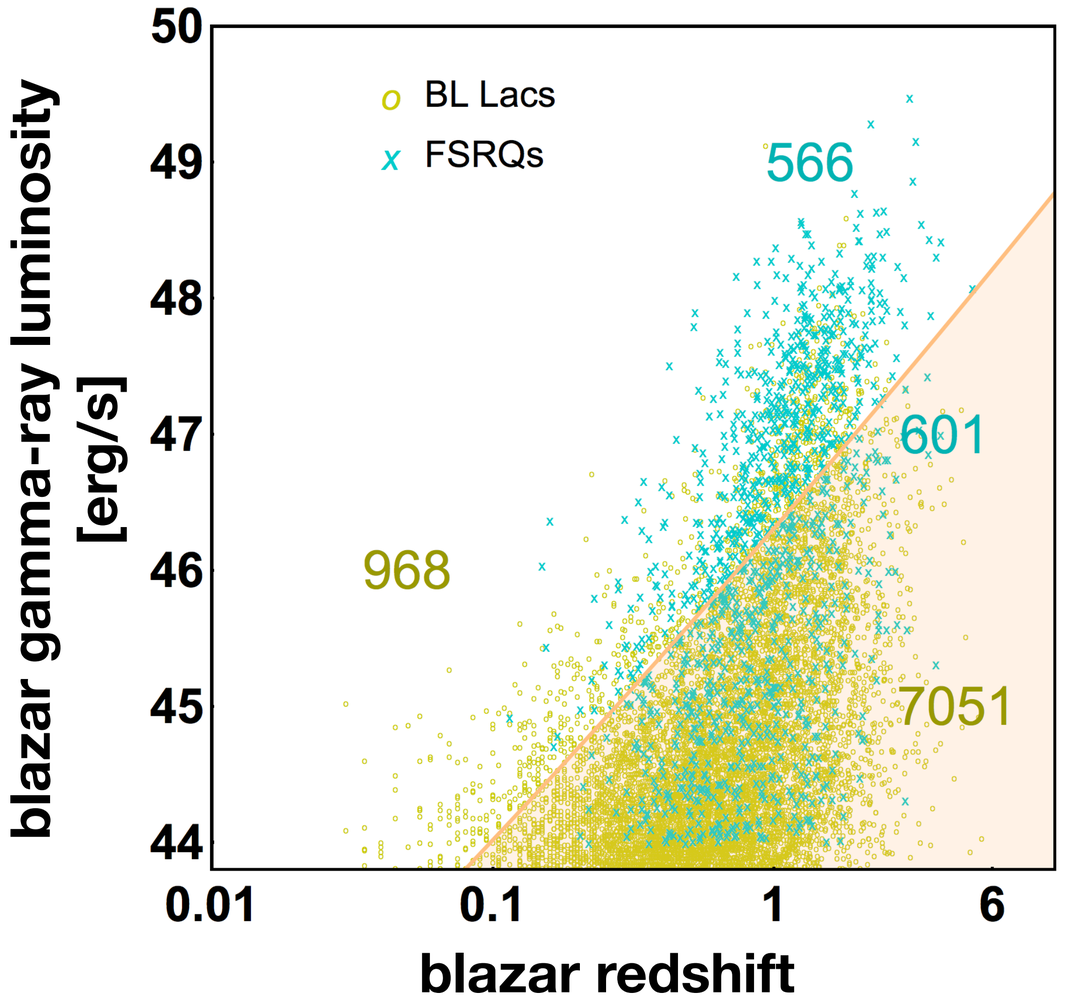


External-field model

- Cosmic rays interact with **thermal and broad line photons**
  - May **boost neutrino emission**
  - May **attenuate gamma rays**

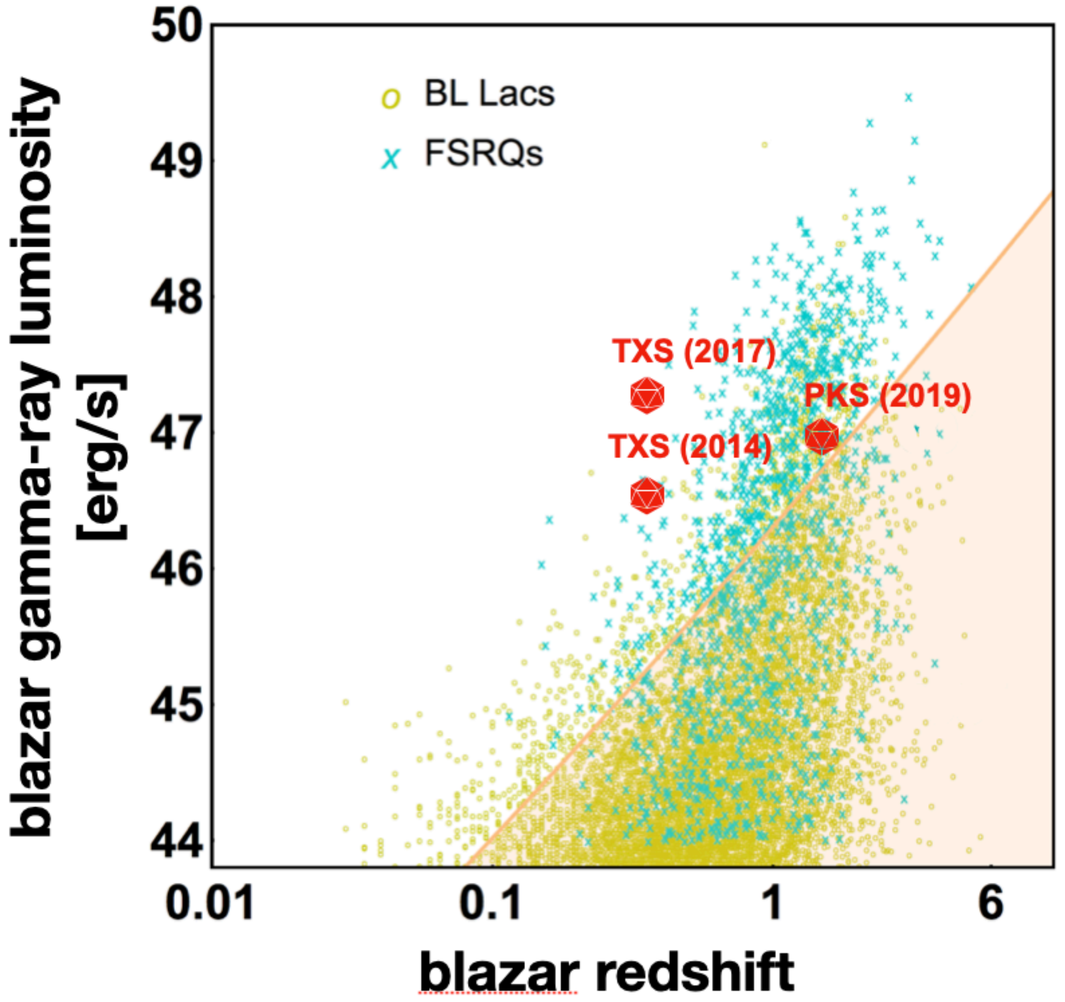
Credit: Bill Saxton, NRAO/AUI/

The cosmological distribution of blazar AGN



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

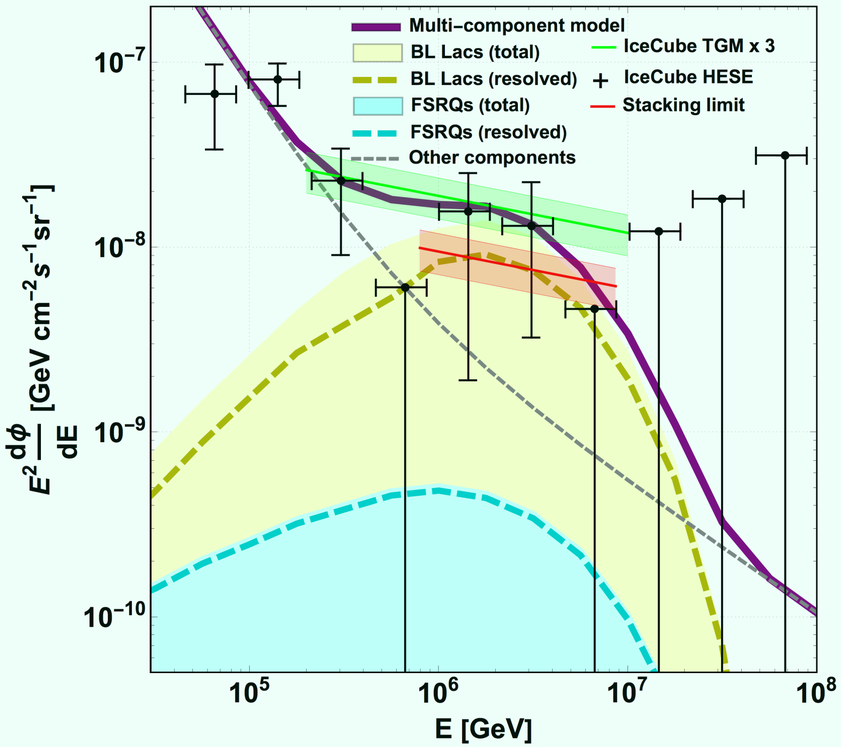
The cosmological distribution of blazar AGN



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

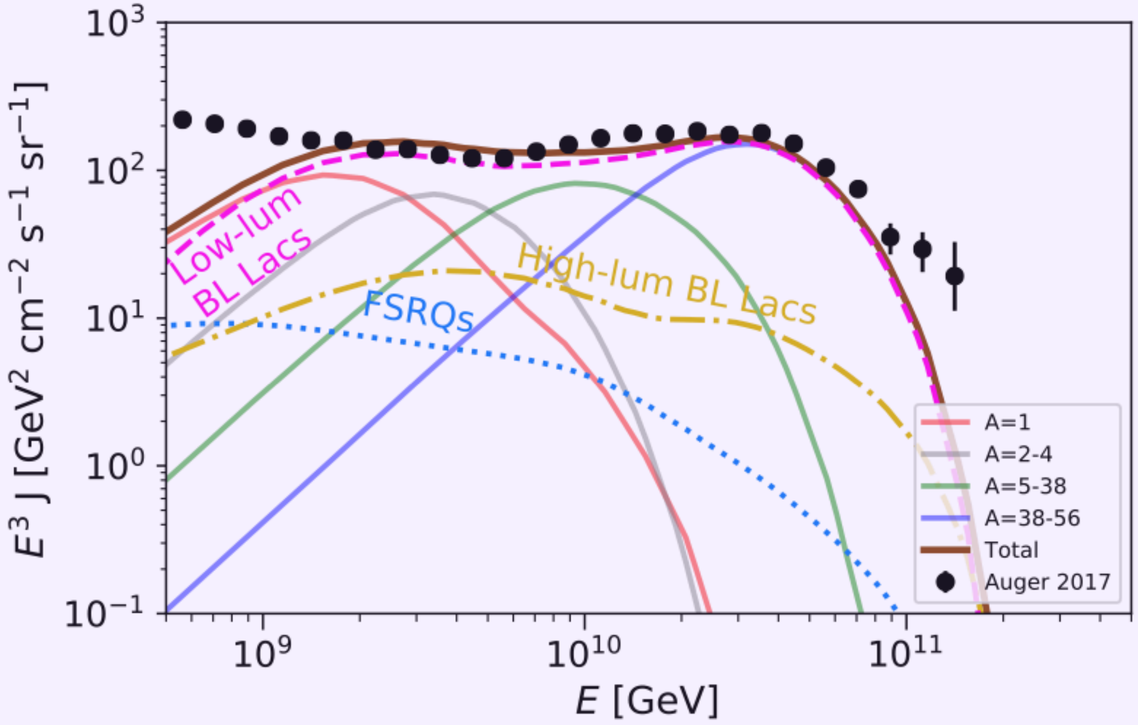
CRs and neutrinos from the entire AGN population

Scenario 1: AGN accelerate CRs up to max 10 PeV



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

Scenario 2: AGN accelerate CRs up to ~EeV



XR, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021)

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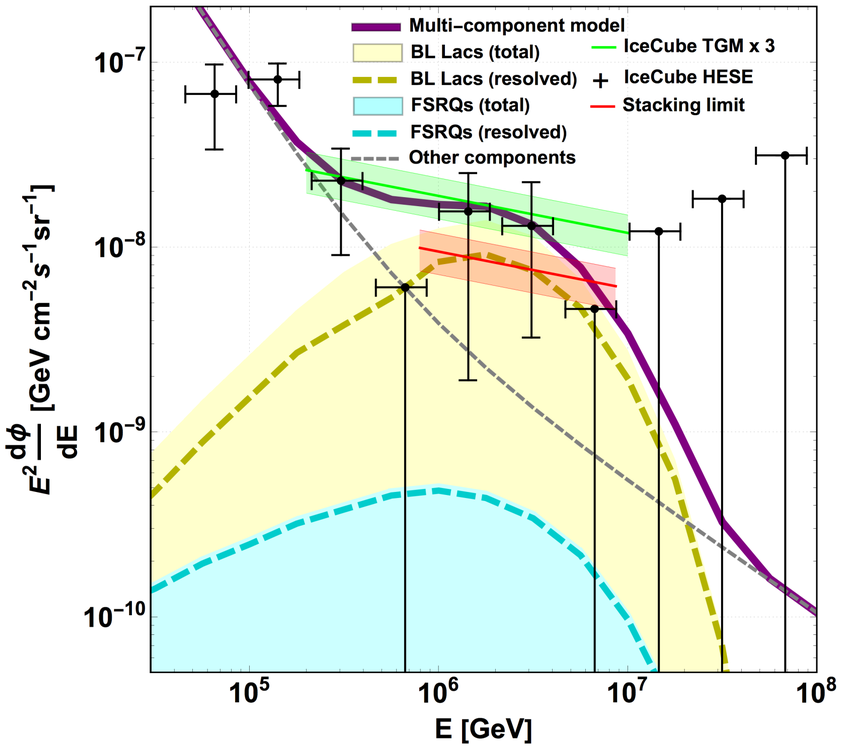

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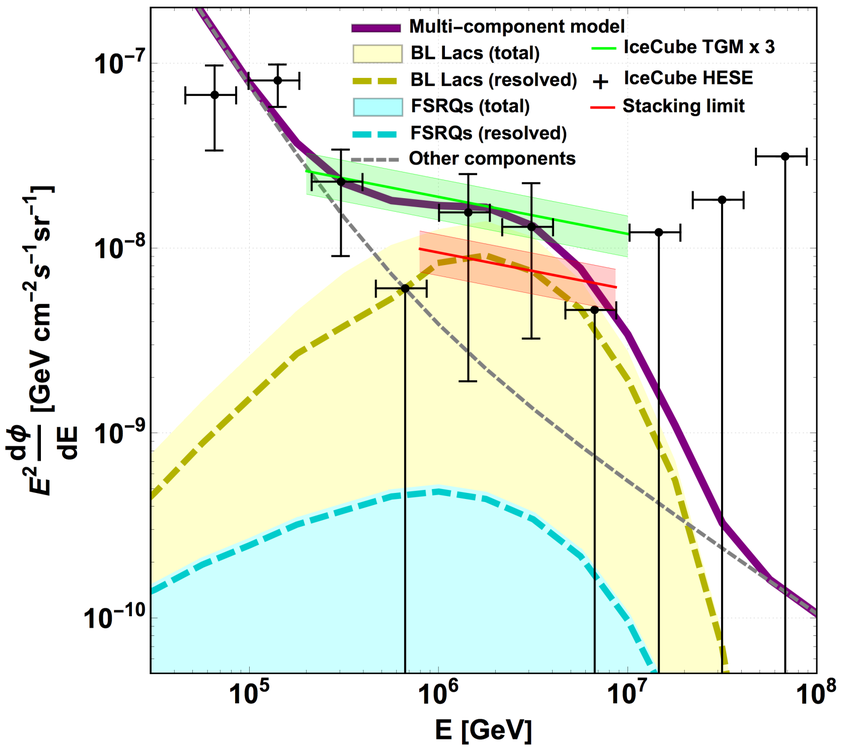
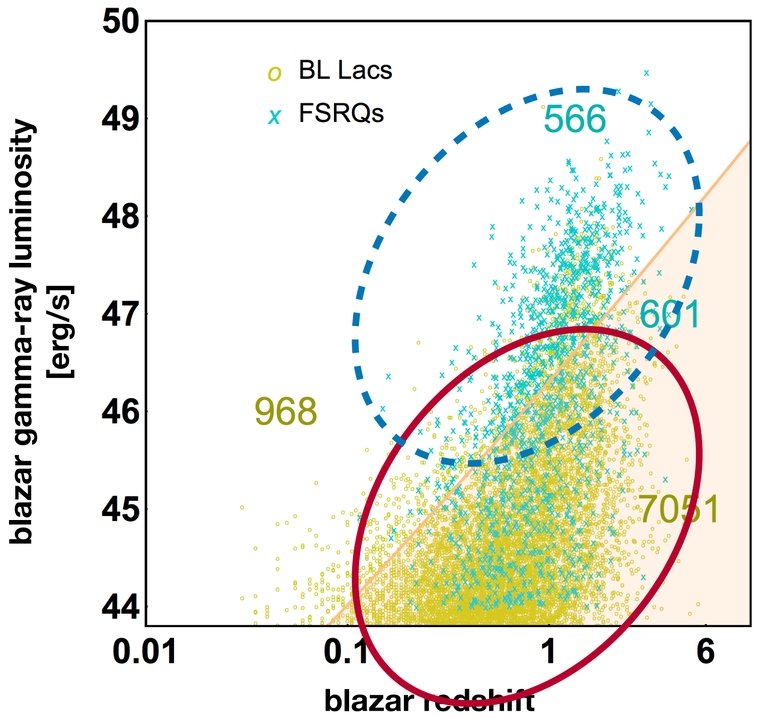
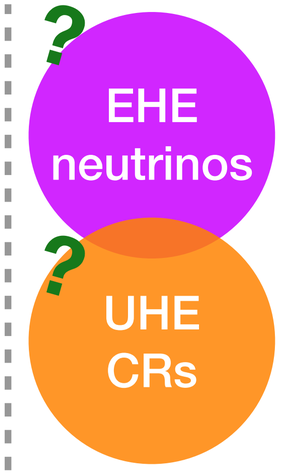


Palladino, XR, Gao & Winter, ApJ 871 (2019)



Essentially leptonic

Dominate neutrino emission



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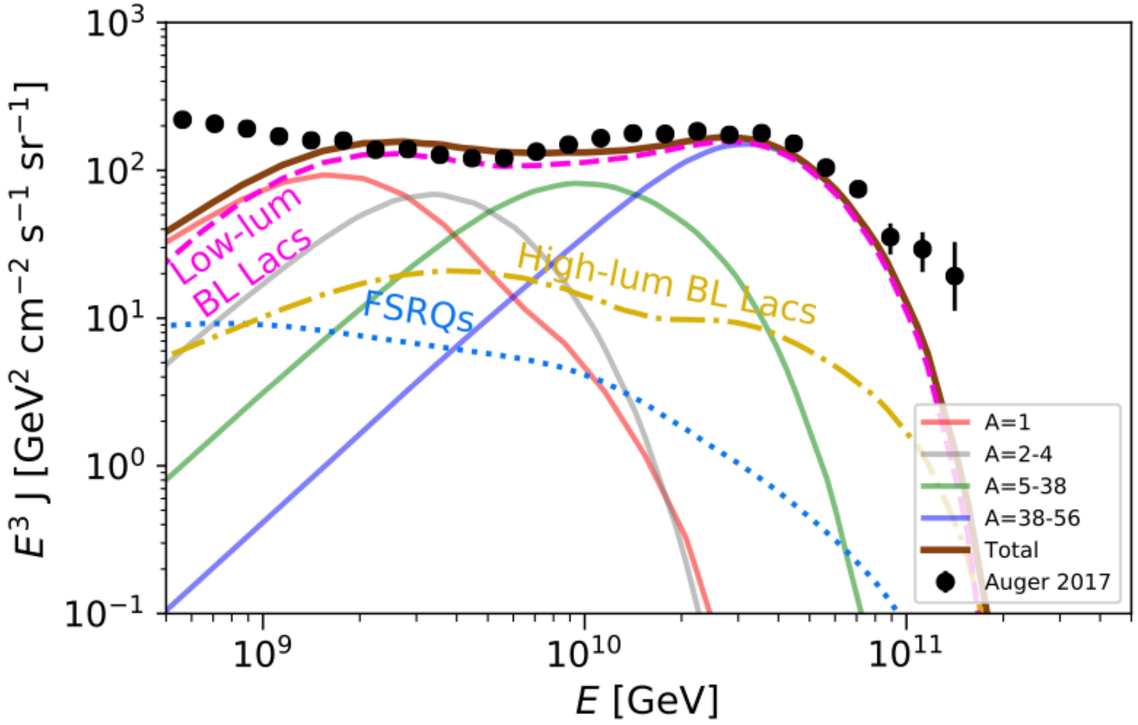

XR, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021)

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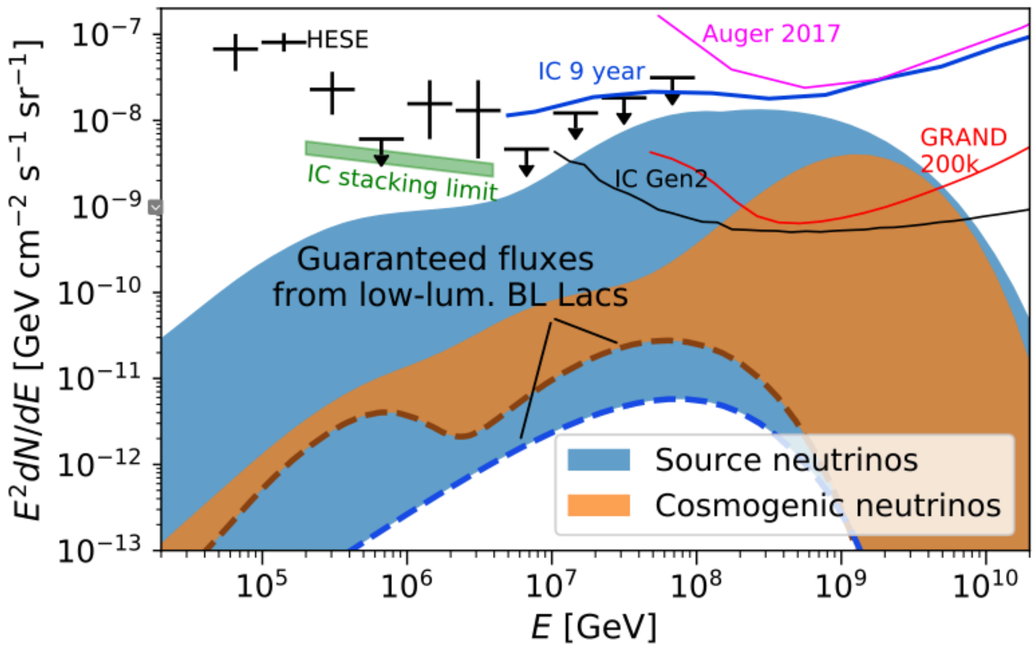
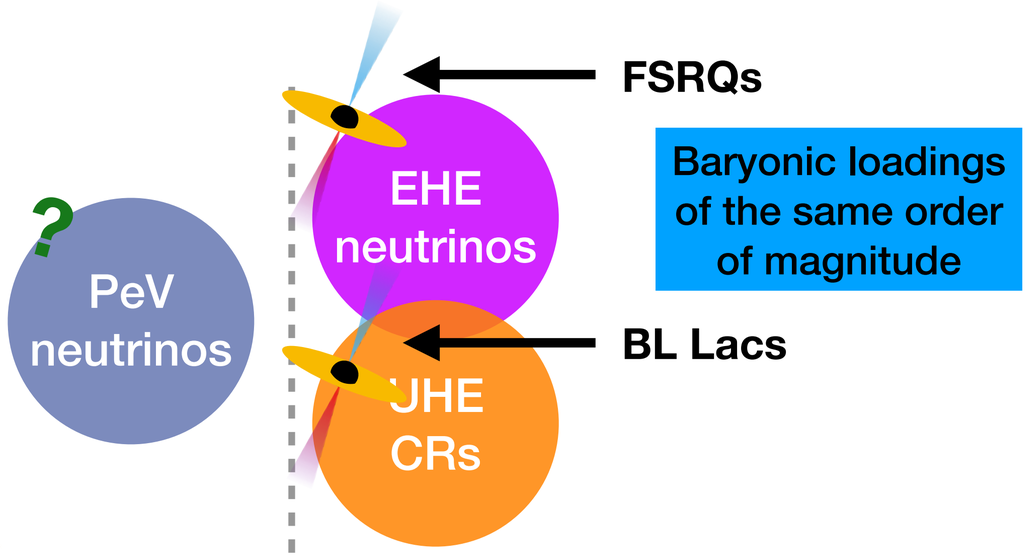
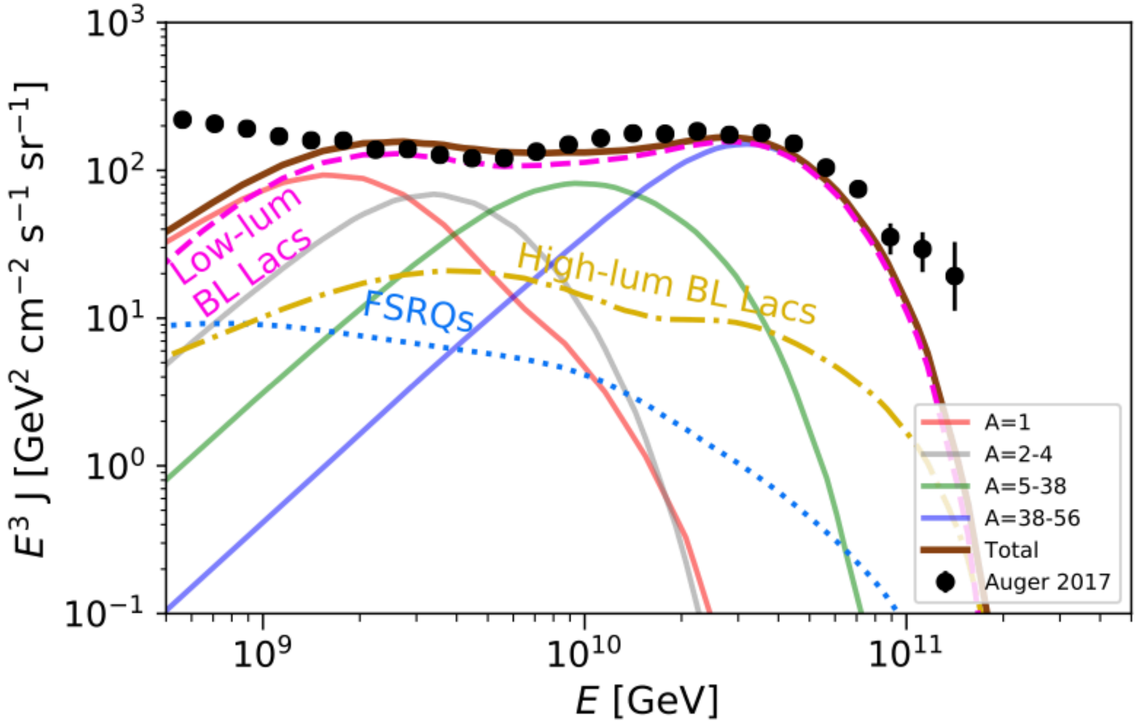




Baryonic loadings of the same order of magnitude

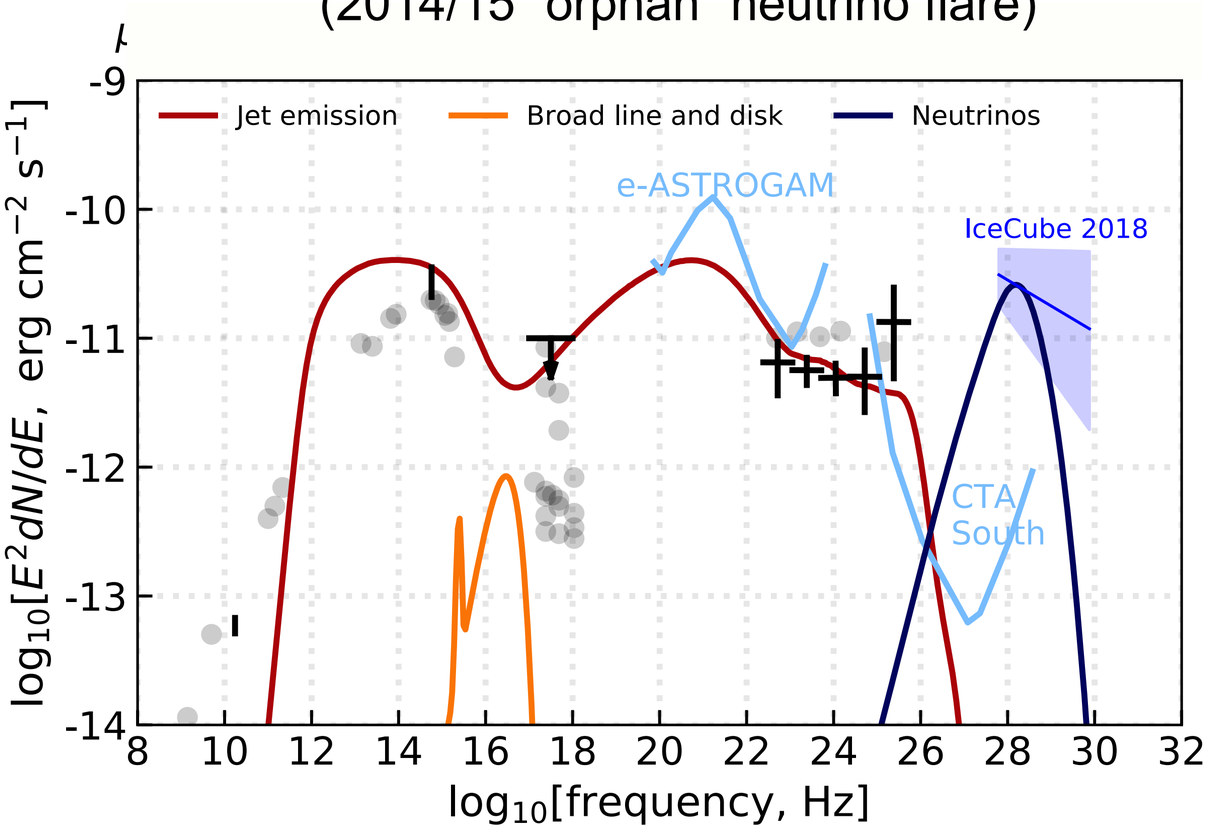
Scenario 2: AGN accelerate CRs up to ~EeV



XR, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021)

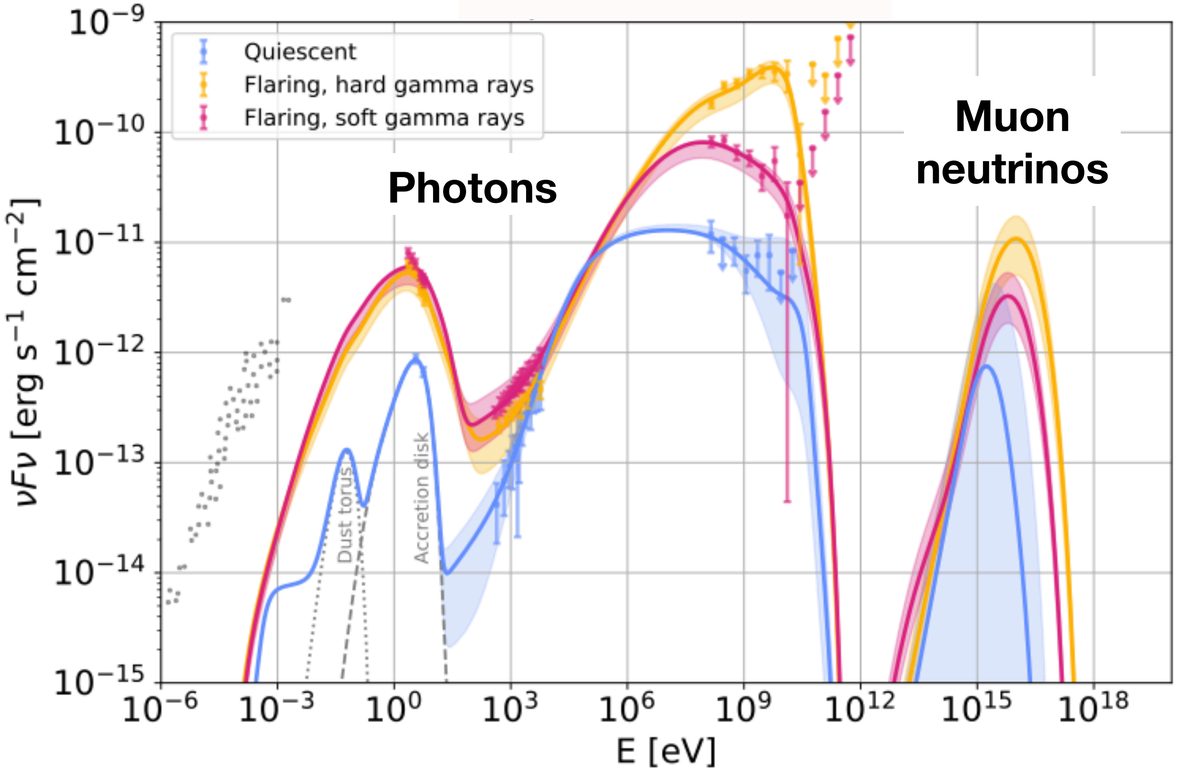
Dedicated modeling of individual candidate sources

Blazar TXS 0506+056
(2014/15 “orphan” neutrino flare)



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

Blazar PKS 1502+106
(coincident with event IC-170922)



XR, Garrappa, Gao, Paliya, Franckowiak & Winter, ApJ 912 (2021)

see also Reimer+ ApJ 881 (2018), Petropoulou+ ApJ 891 (2020), Mastichiadis+ ApJ 906 (2021), Xue+ ApJ 906 (2021)

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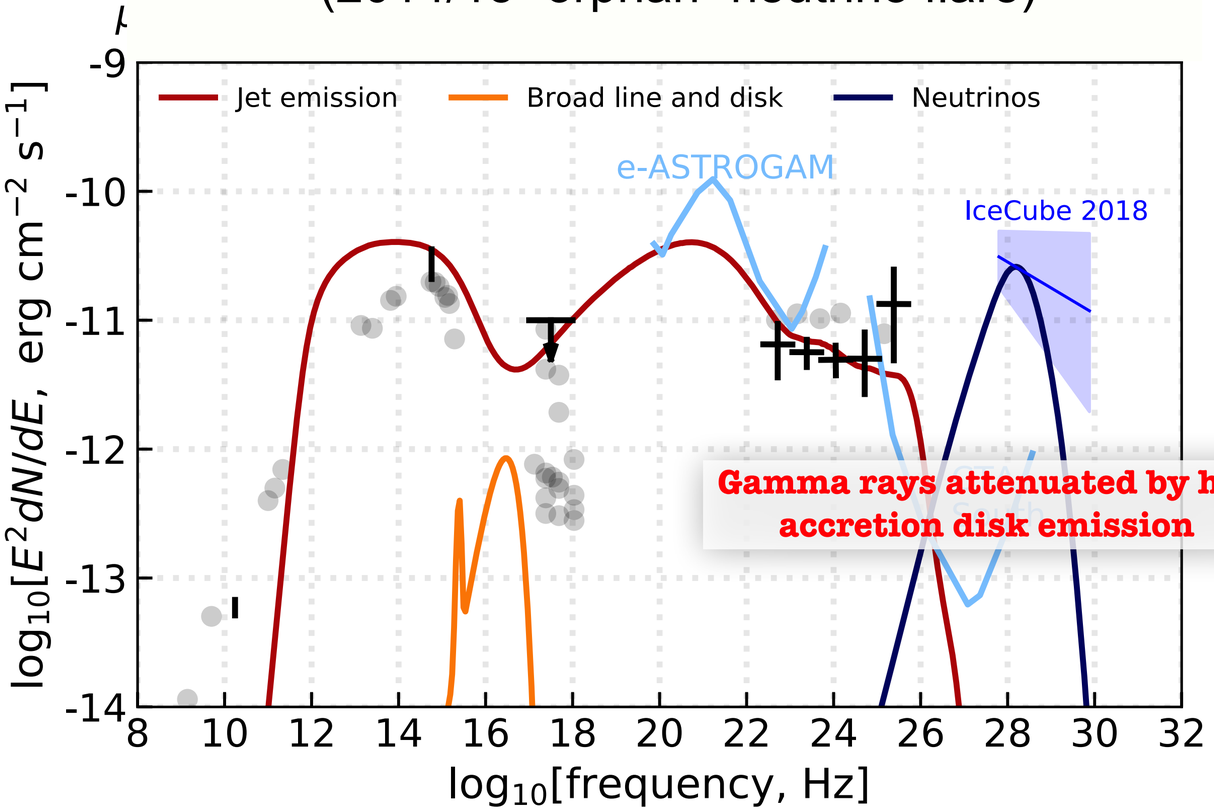

Gamma rays attenuated by hot accretion disk emission

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

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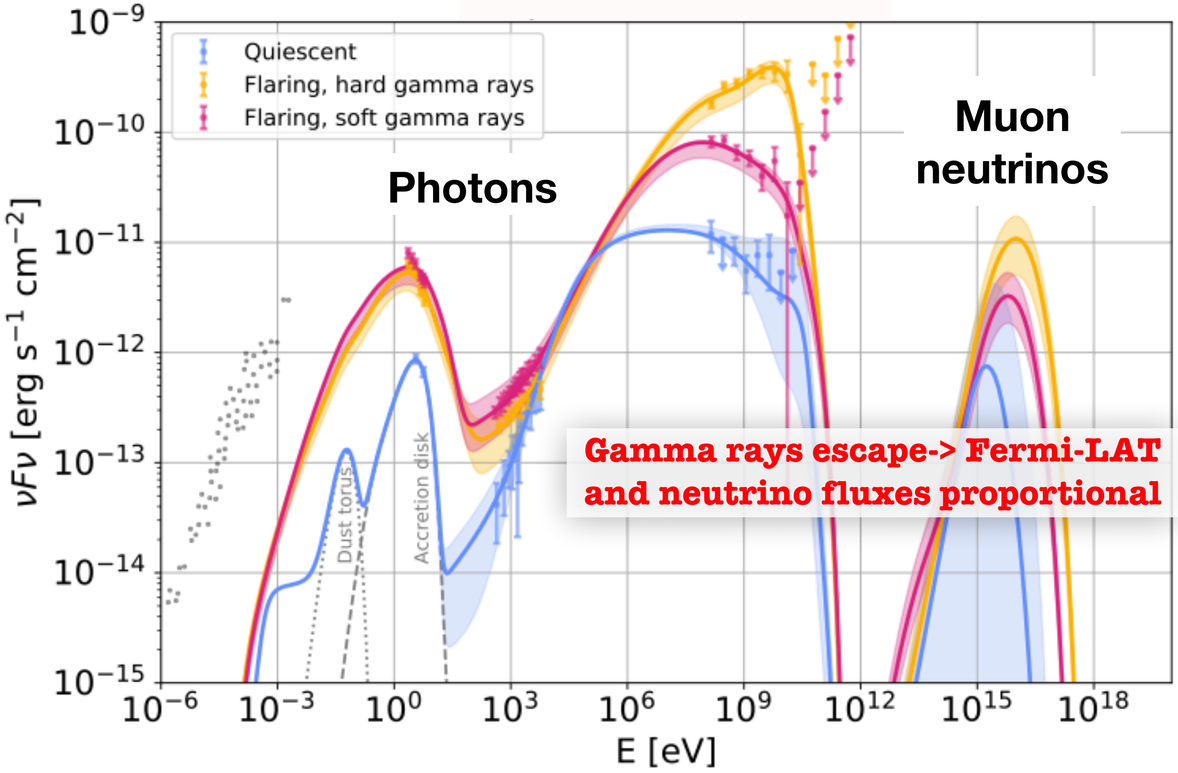

Gamma rays escape-> Fermi-LAT and neutrino fluxes proportional

XR, Garrappa, Gao, Paliya, Franckowiak & Winter, ApJ 912 (2021)

see also Reimer+ ApJ 881 (2018), Petropoulou+ ApJ 891 (2020), Mastichiadis+ ApJ 906 (2021), Xue+ ApJ 906 (2021)

Relationship between multi-messengers depends on source properties -> need for dedicated modeling

Conclusions

- The IceCube neutrino flux must be dominated by a **large amount of low-luminosity sources, or** by sources that are **optically thick to the gamma-rays** co-emitted in cosmic-ray interactions.

- A large population of **low-luminosity AGN** could explain the diffuse IceCube flux up to PeV energies, but the parameter space of the sources is already strongly constrained.

- If AGN accelerate UHECRs, they can emit a flux of **EeV neutrinos detectable** by next-generation experiments, while still obeying current IceCube constraints at PeV.

- Cosmic-ray interactions with external fields in AGN jets can provide a natural explanation of **neutrino emission** from candidate sources **during gamma-ray quiescent states**, but current models still face challenges

- **X-ray follow-ups** (**including polarization measurements)** by future missions like e-ASTROGAM and AMEGO will be essential in **constraining source models**