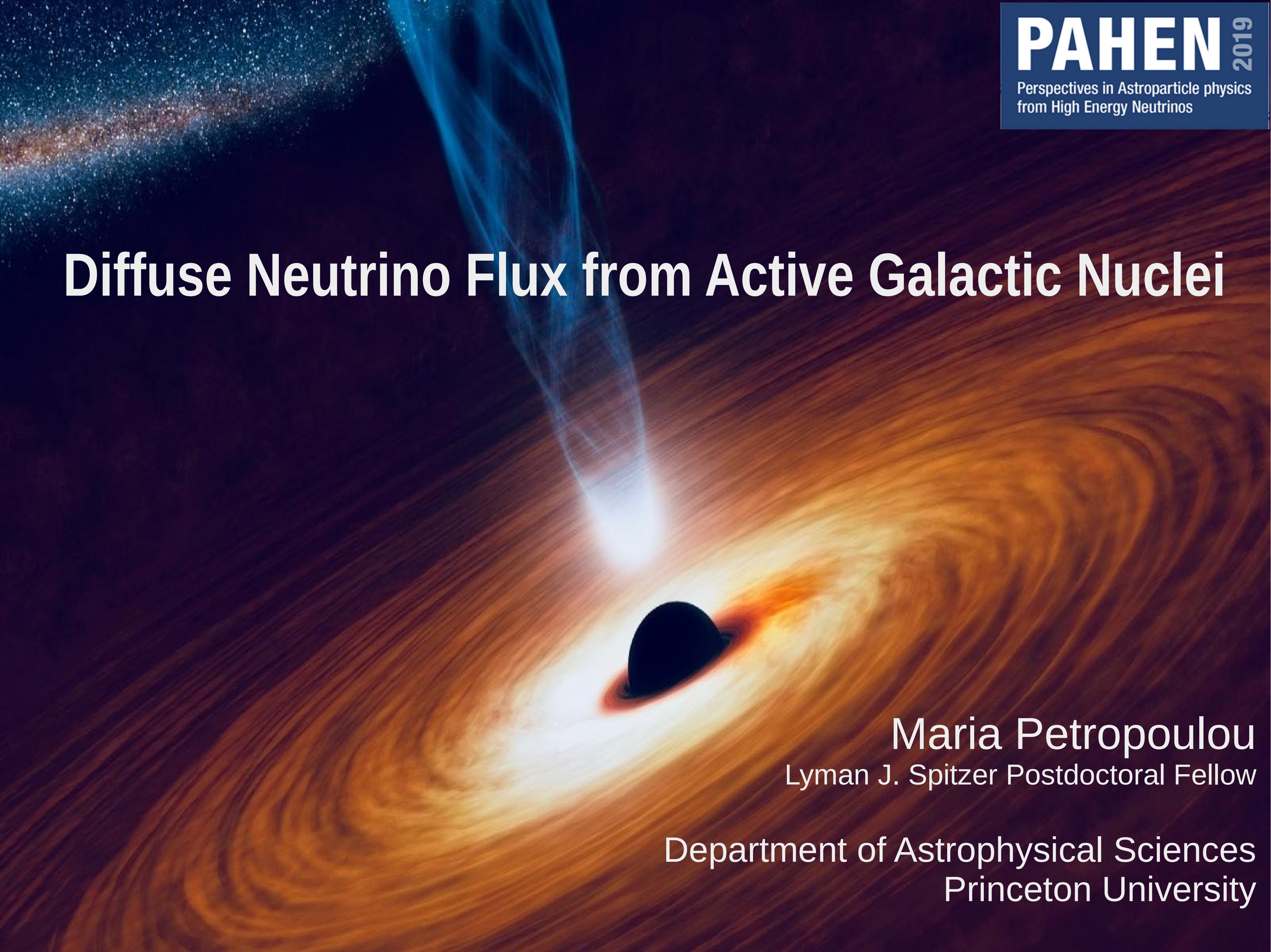


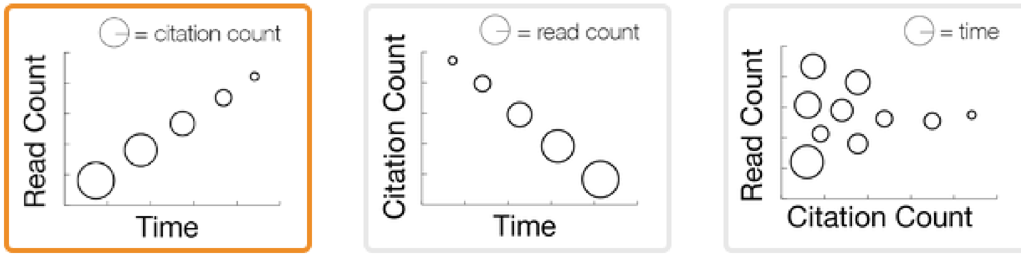
PAHEN 2019
Perspectives in Astroparticle physics from High Energy Neutrinos

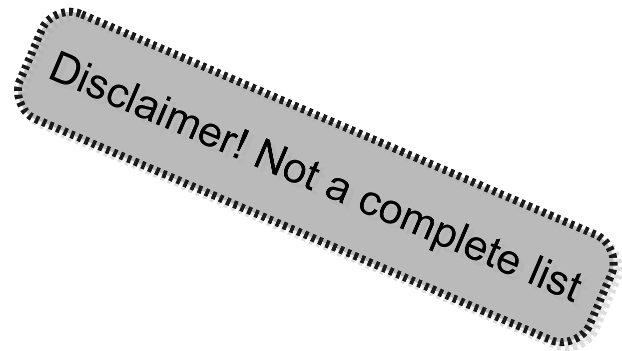
Diffuse Neutrino Flux from Active Galactic Nuclei

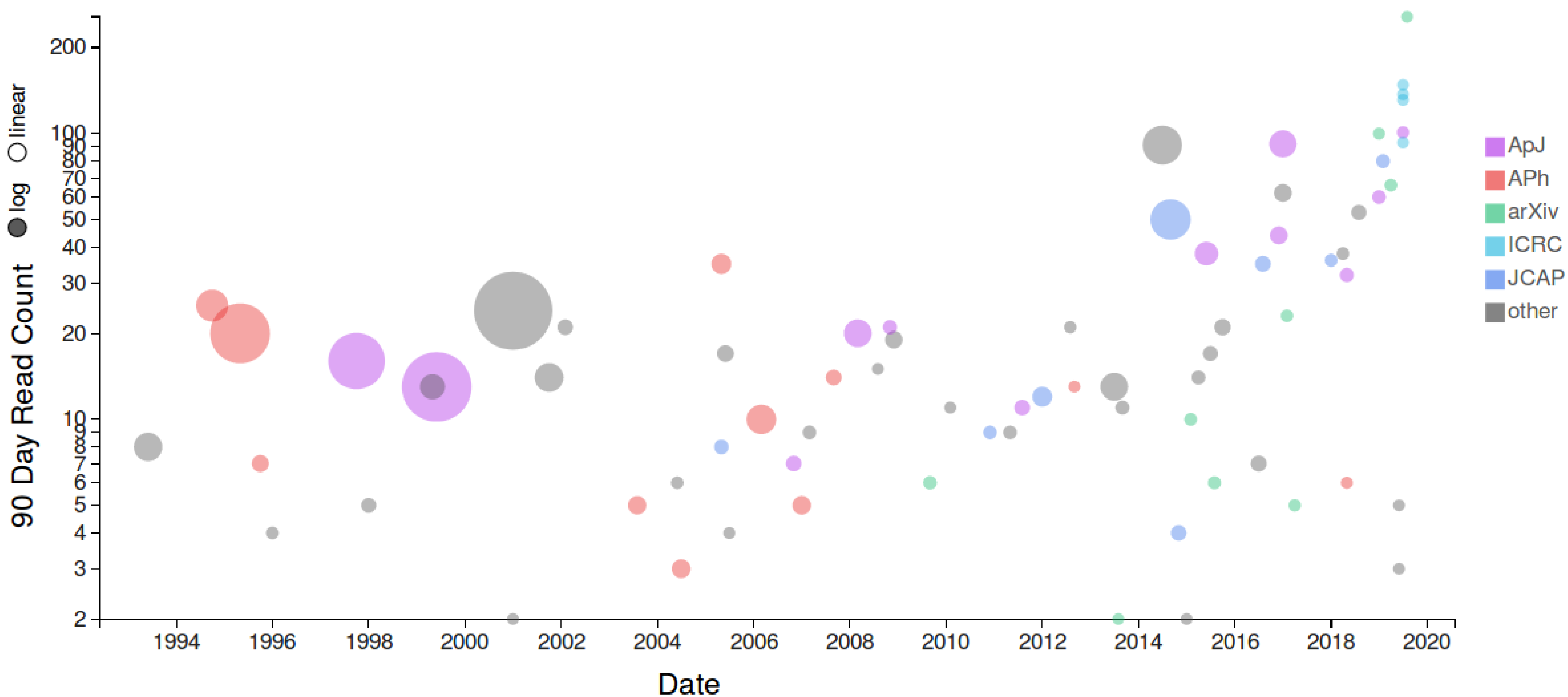
Maria Petropoulou
Lyman J. Spitzer Postdoctoral Fellow

Department of Astrophysical Sciences
Princeton University

A long history of models







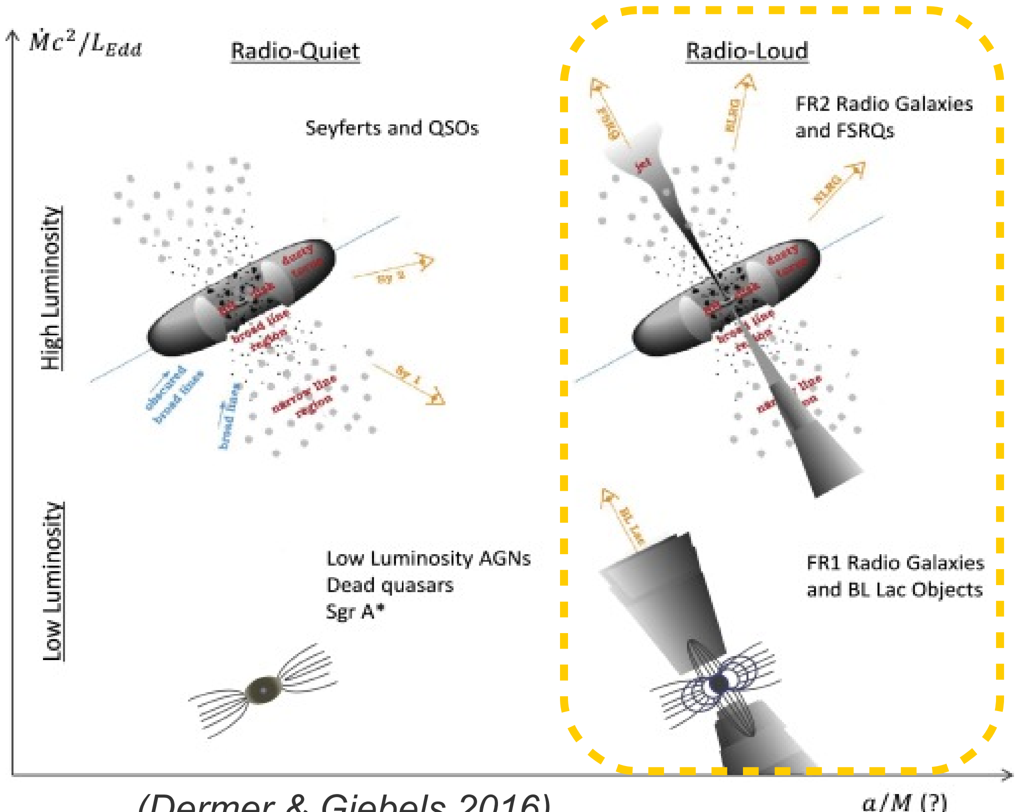
(Graphic from NASA ADS)

A variety of AGN neutrino models

Core/Disk models

- **Target photons/gas:** accretion flow
- **Relativistic protons:** accelerated in the accretion flow (?) or in the X-ray corona (?)

(e.g., Nellen et al. 1993, Bednarek & Protheroe, Stecker 2005, Stecker 2013, Murase et al. 2019, Inoue et al. 2019...)



(Dermer & Giebels 2016)

Jet/Lobe models

- **Target photons:** jet core/sheath or BLR or accretion disk
- **Relativistic protons:** accelerated in the jet (?)

(e.g., Mannheim 1995, Dermer & Atoyan 2001, Atoyan & Dermer 2004, Becker Tjus et al. 2014, Murase et al. 2014, Petropoulou et al. 2015, Padovani et al. 2015, Gao et al. 2017, Righi et al. 2018, Palladino et al. 2019 ...)

Main ingredients & assumptions

Diffuse neutrino intensity:

$$\Phi_\nu = \frac{c}{4\pi H_0}\int^{z_{\mathrm{max}}} dz \, \frac{1}{\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}} \int dL_\nu \, \boxed{\frac{dn_s}{dL_\nu}(z)} \, \frac{\boxed{L_{E'_\nu}}}{E'_\nu}$$

Neutrino luminosity function (LF)

$$\frac{dn_s}{dL_{ph}}(z)$$

Source neutrino luminosity

$$L_\nu = K\, L_{ph}^{\gamma}$$

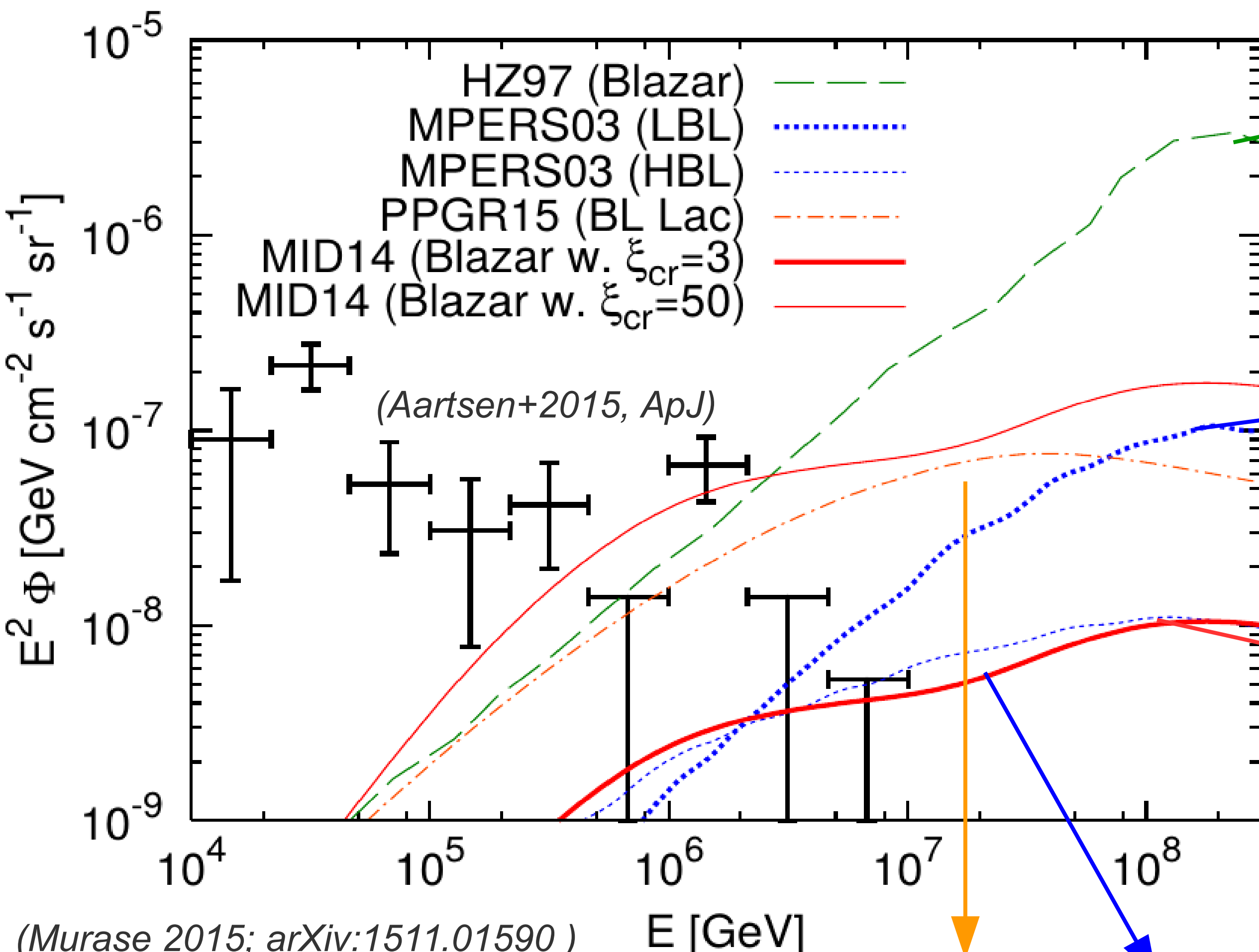
K, γ depend on source model

<u>Assumptions:</u>

I. The neutrino-photon luminosity scaling relation is universal.

II. The neutrino & photon luminosities are the average ones.

Diffuse neutrino flux from blazars



(Murase 2015; arXiv:1511.01590)

- γ-rays → pγ interactions
- L_ν=(3/13) L_γ
- EGRET γ-ray LF

- γ-rays → pγ interactions
- L_ν → L_{5GHz} → L_{syn}
- 5GHz LF *(Urry et al.)*

- γ-rays → ICS
- $L_\nu \sim L_x^{1/2} L_{CR} \sim \xi\, L_x^{3/2}$
- X-ray LF *(Ueda et al.)*

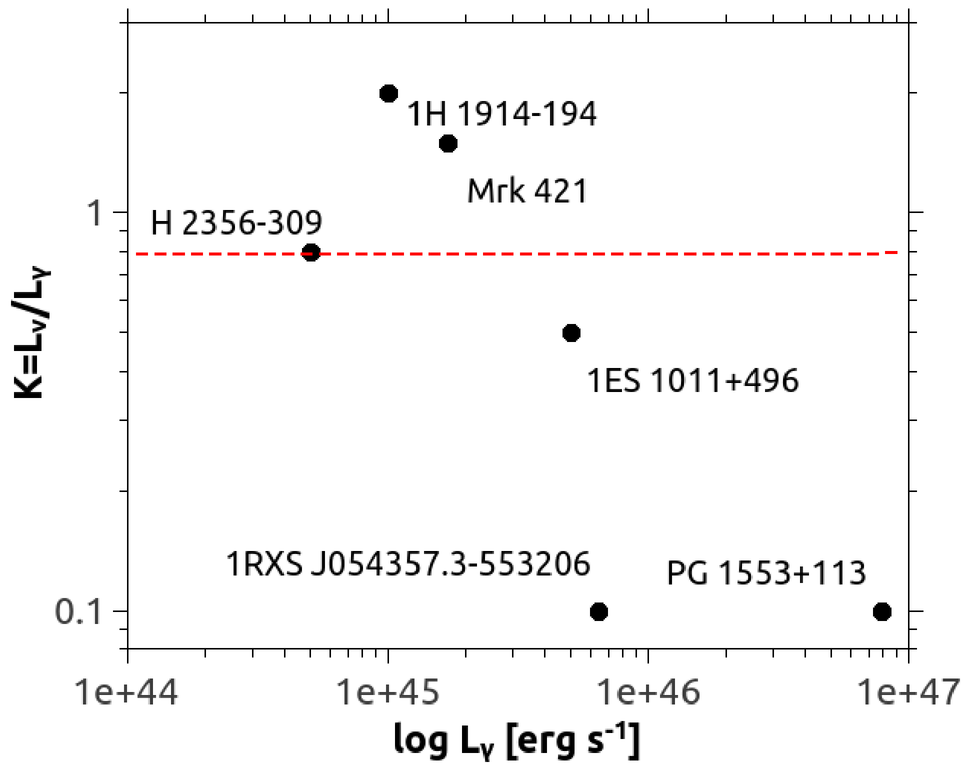
- γ-rays → pγ interactions
- L_ν=0.8 L_γ
- Monte-Carlo simulation *(Padovani+2015)*

- γ-rays → proton synchrotron
- L_ν → L_{syn}
- No redshift evolution (10% LBL)

A simplified view of blazars

$$E_\nu F_\nu(E_\nu) = \frac{Y_{\nu\gamma} F_\gamma(>10\ \mathrm{GeV})}{\int_{x_{\min}}^{\infty} dx\ x^{-s} e^{-x}} \left(\frac{E_\nu}{E_{\nu,p}}\right)^{-s+1} \exp\left(-\frac{E_\nu}{E_{\nu,p}}\right)$$

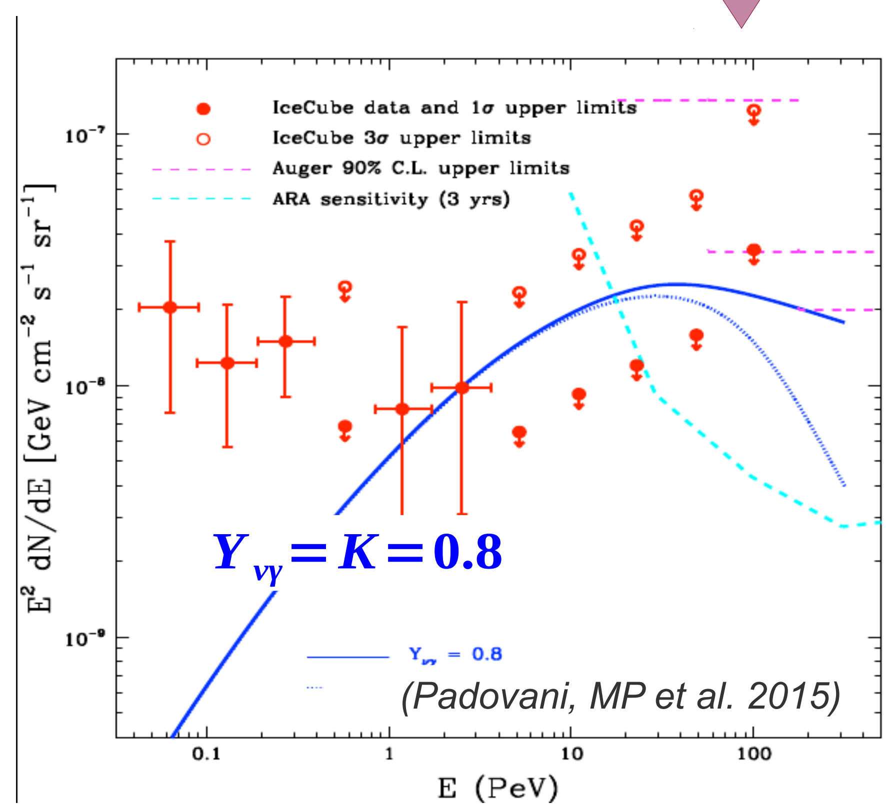
$$E_{\nu,p}(\delta, z, \nu^S_{\rm peak}) \simeq \frac{17.5\ \mathrm{PeV}}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \left(\frac{\nu^S_{\rm peak}}{10^{16}\ \mathrm{Hz}}\right)^{-1}$$



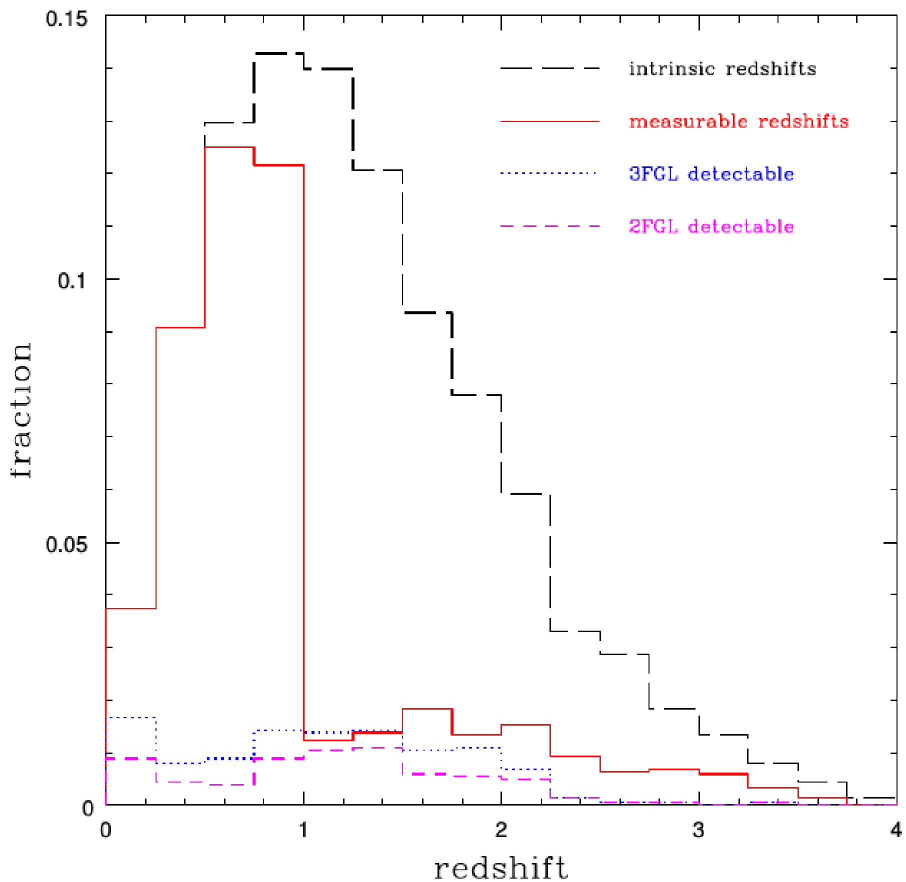
(Petropoulou et al. 2015)

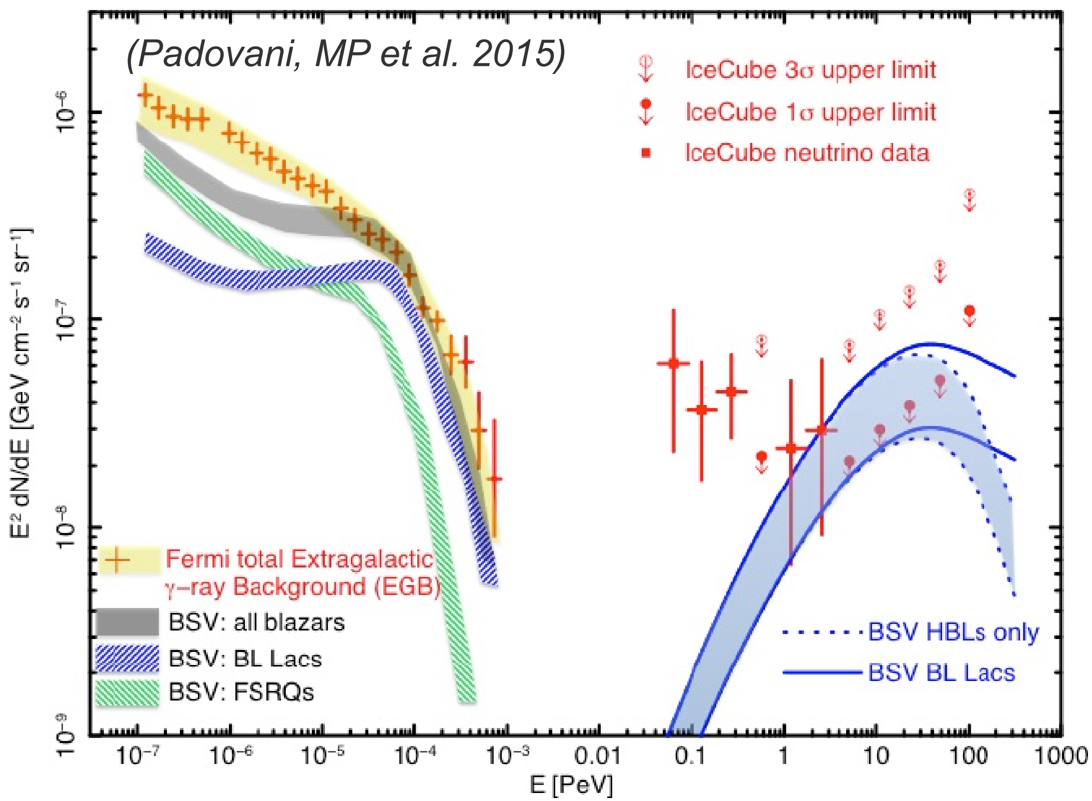
Monte-Carlo simulation for blazar population:
(*Giommi & Padovani 2012,2013, 2015*)

- Radio LF
- Distribution of syn. peak frequency
- Distribution of Doppler factor
- Redshift
- γ-ray constraints



BL Lac contribution to the neutrino background (NBG)



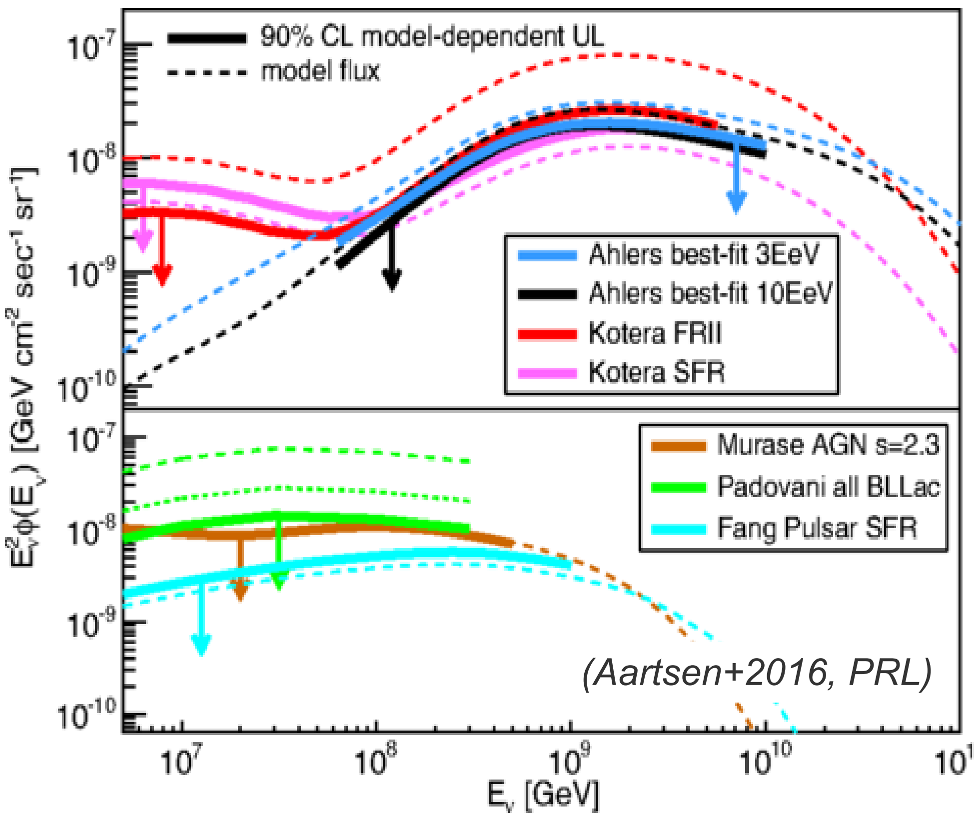


- ~0.5% of all BL Lacs make ~95% of NBG at 1 PeV.
- 50% of this sub-sample have measurable redshifts.
- 3FGL (2FGL) detectable sources make ~15% (~12%) of total NBG.

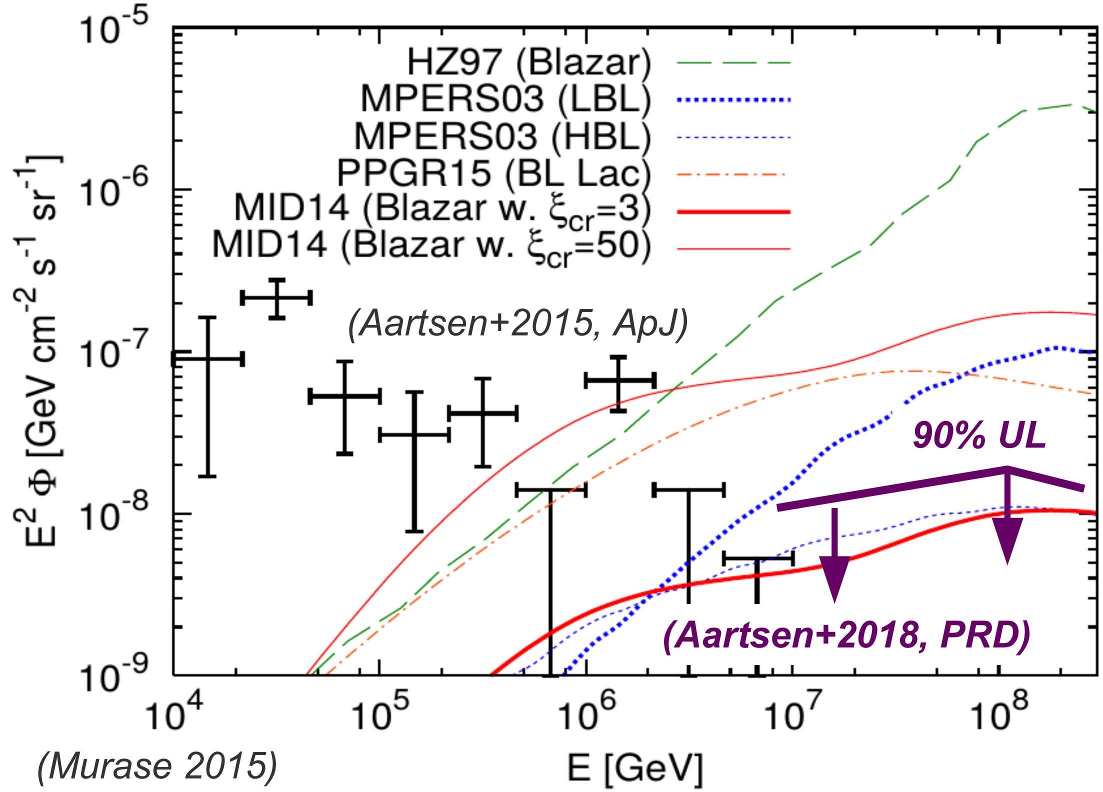
- EGB includes contributions from resolved & unresolved sources.
- HBL dominate the NBG (up to ~30 PeV), but *Fermi*-detectable are a small fraction.
- **Masquerading** BL Lacs are ~ 2% of all BL Lacs, but their contribution to NBG is ~60% of all BL Lacs.

Model constraints: EHE IceCube flux

7yr IceCube data (EHE flux)



9yr IceCube data (EHE flux)

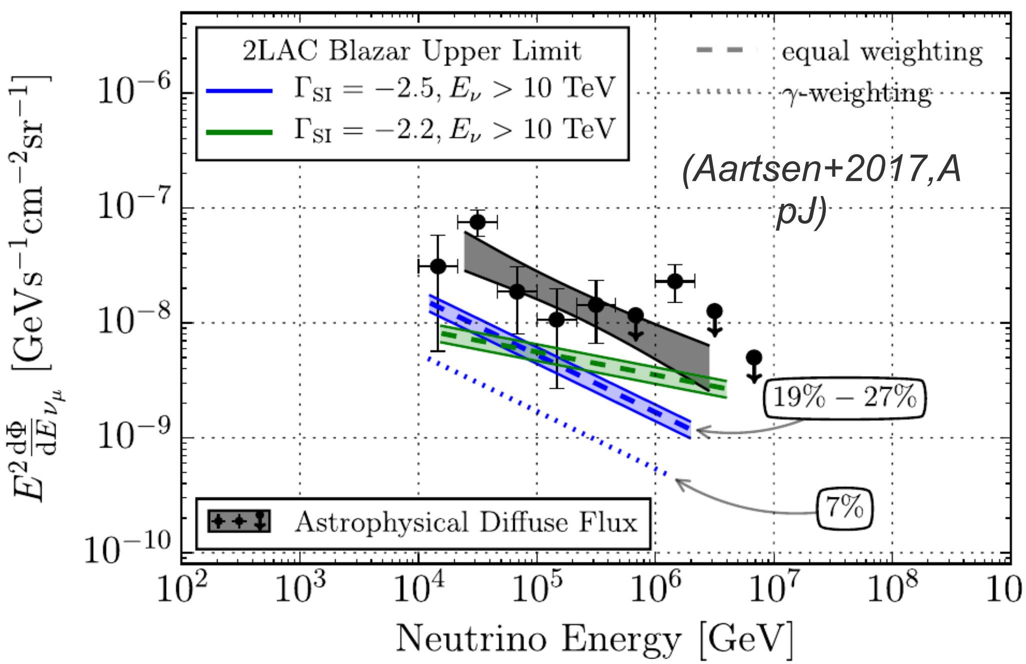


$$Y_{\nu\gamma} = K \leq 0.15\,(90\,\%CL)$$

$$Y_{\nu\gamma} = K < 0.1\,(90\,\%CL)$$

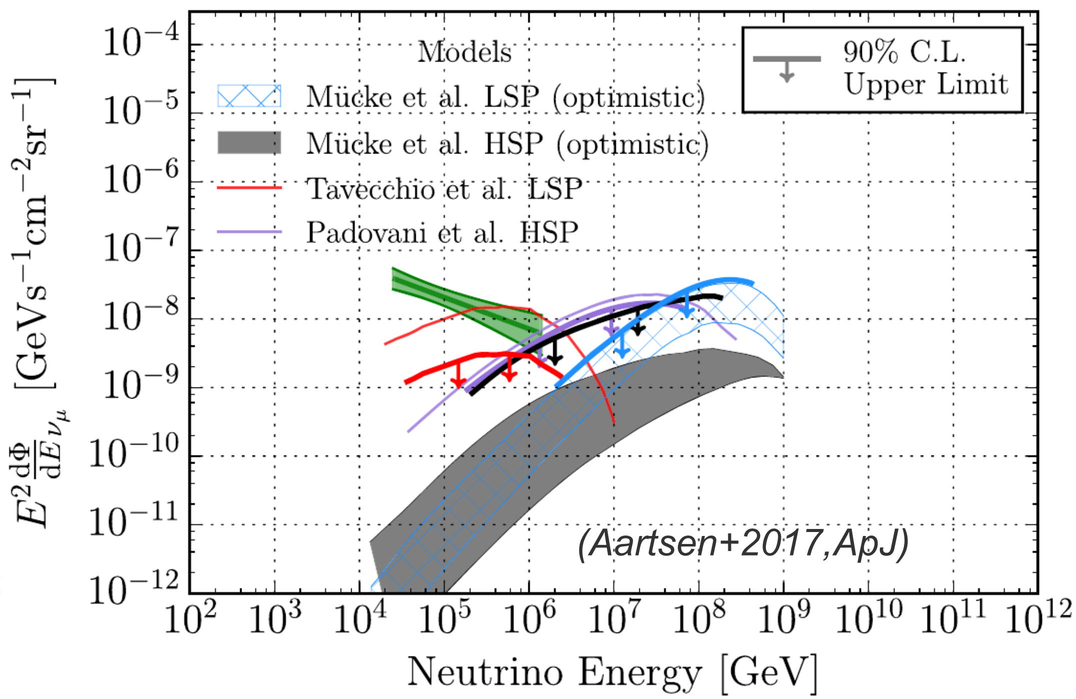
Model constraints: stacking limits from *Fermi*-LAT AGN

Generic constraints



- UL obtained for the 10 TeV – 2 PeV energy range.
- $L_\nu = L_\gamma$ (γ-ray weighting scheme) & soft neutrino spectra place the strongest constraints.

Model-specific constraints



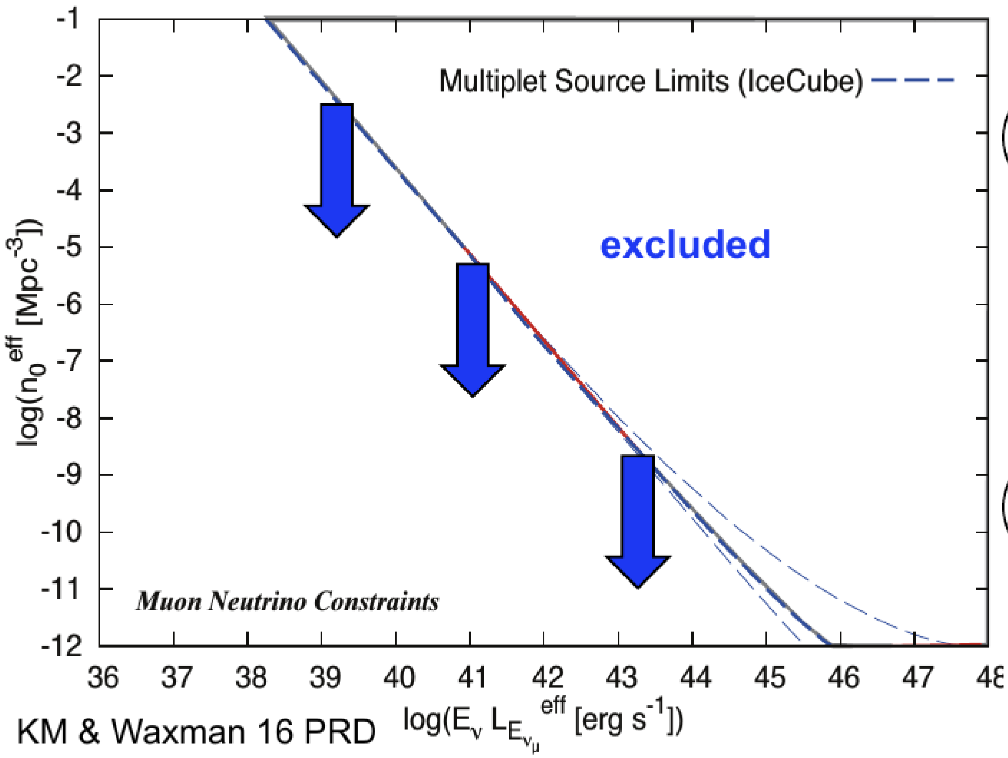
(b) BL Lacs

- Weaker constraints on specific models predicting hard neutrino spectra peaking beyond PeV energies.

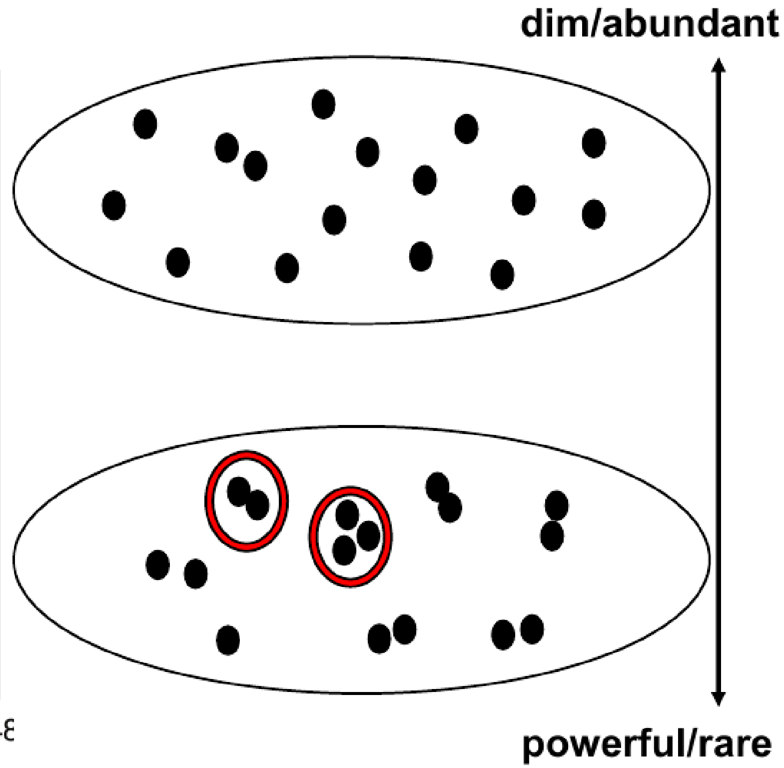
$$Y_{\nu\gamma} = K < 0.6\,(90\%CL)$$

Model constraints: neutrino multiplet limits

Non-detection of neutrino clustering constrains the source population



KM & Waxman 16 PRD



Limit on effective number density from the lack of **doublets:**

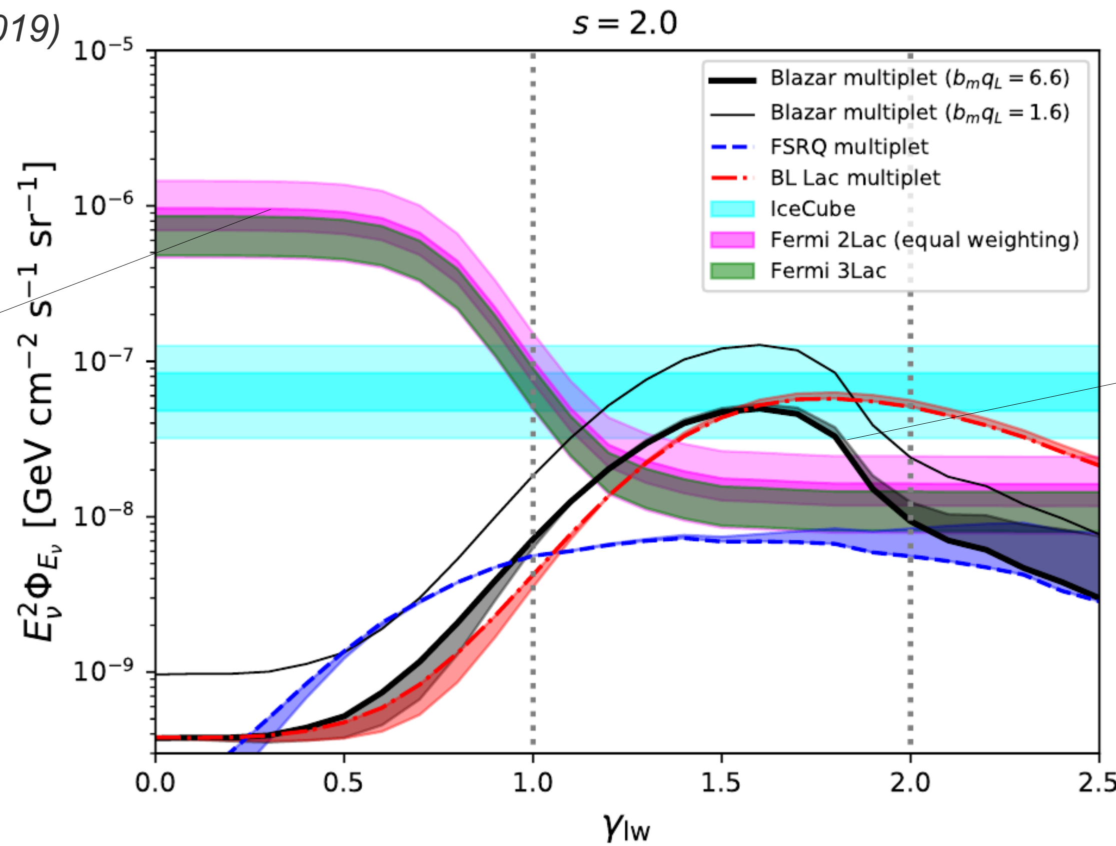
$$n_0^{\rm eff} \lesssim 1.9 \times 10^{-10}\ {\rm Mpc}^{-3} \left(\frac{\varepsilon_\nu L_{\varepsilon_\nu}^{\rm ave}}{10^{44}\ {\rm erg\ s}^{-1}}\right)^{-3/2} \left(\frac{b_m q_L}{6.6}\right)^{-1}$$
$$\times \left(\frac{F_{\rm lim}}{10^{-9.2}\ {\rm GeV\ cm}^{-2}\ {\rm s}^{-1}}\right)^{3/2} \left(\frac{2\pi}{\Delta\Omega}\right),$$

Constraints from combined stacking & multiplet limits

(Yuan, Murase & Meszaros 2019)

$$L_\nu = K\, L_\gamma^{\gamma_{lw}}$$

Constraints from stacking analysis



Constraints from lack of doublets

Main conclusions:

- Stacking limits are stronger than multiplet limits for γ~1.2 – 1.8
- Multiplet limits are stronger than stacking limits for γ < 1.2 & γ > 1.8

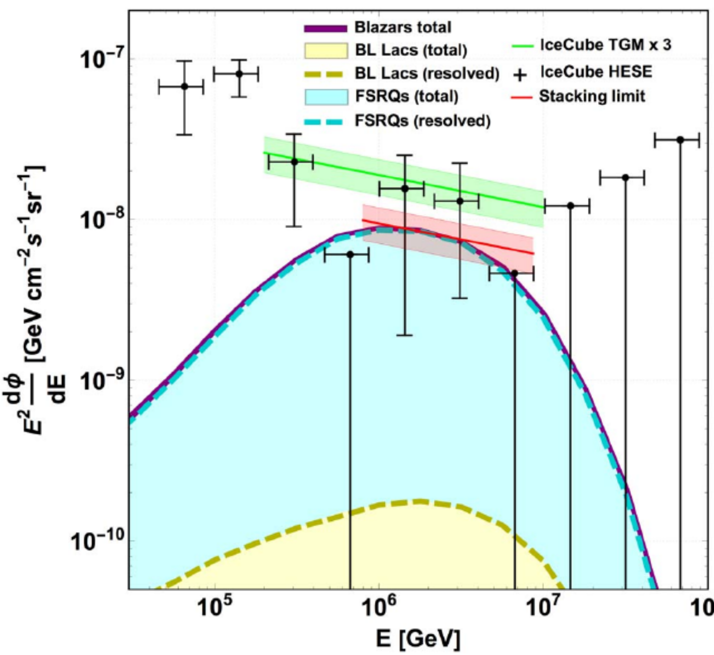
Things to remember!

- Stacking limits used were obtained for the 10 TeV – 2 PeV energy range *(Aartsen+2017, ApJ)*.
- Multiplet limits become weaker at energies > 1 PeV.

Diffuse neutrino flux from the revised blazar sequence

Constant baryon loading

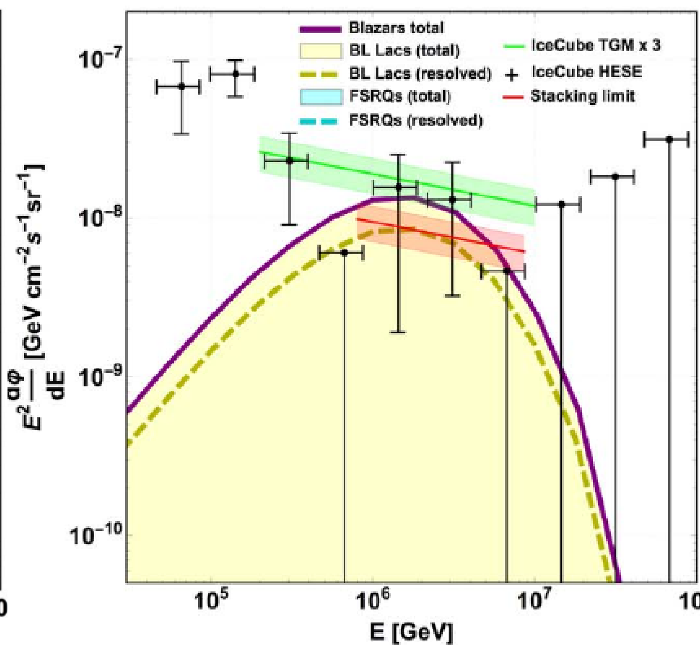
$$L_\nu = f_{p\gamma}\,\xi\,L_\gamma \propto \xi\,L_\gamma^2$$



- The NBG is powered by **resolved** sources.
- Not consistent with *Fermi* stacking limits.

Constant ratio L_ν/L_γ

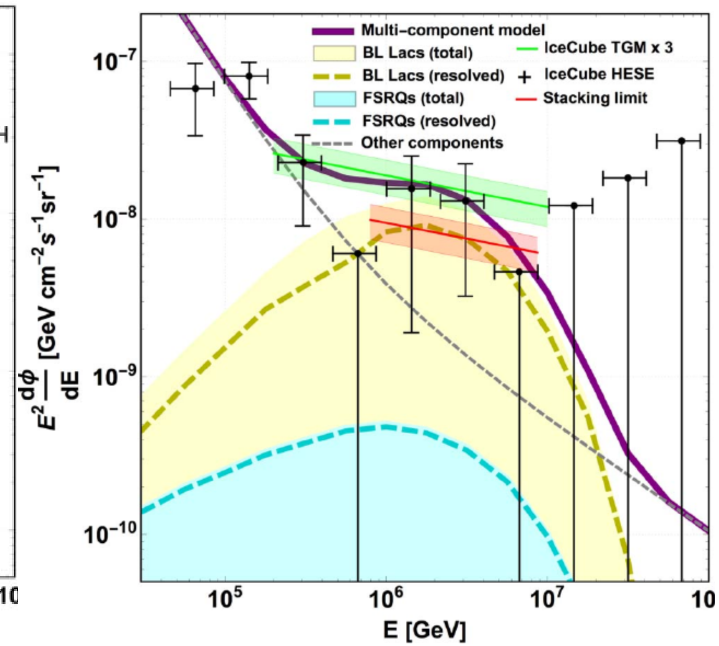
$$L_\nu = K\,L_\gamma \propto L_\gamma$$



- The NBG is powered solely by BL Lacs (**K_{FSRQs}=0**), mostly low-luminosity sources.
- Consistent with Fermi stacking limits.

L_γ – dependent baryon loading

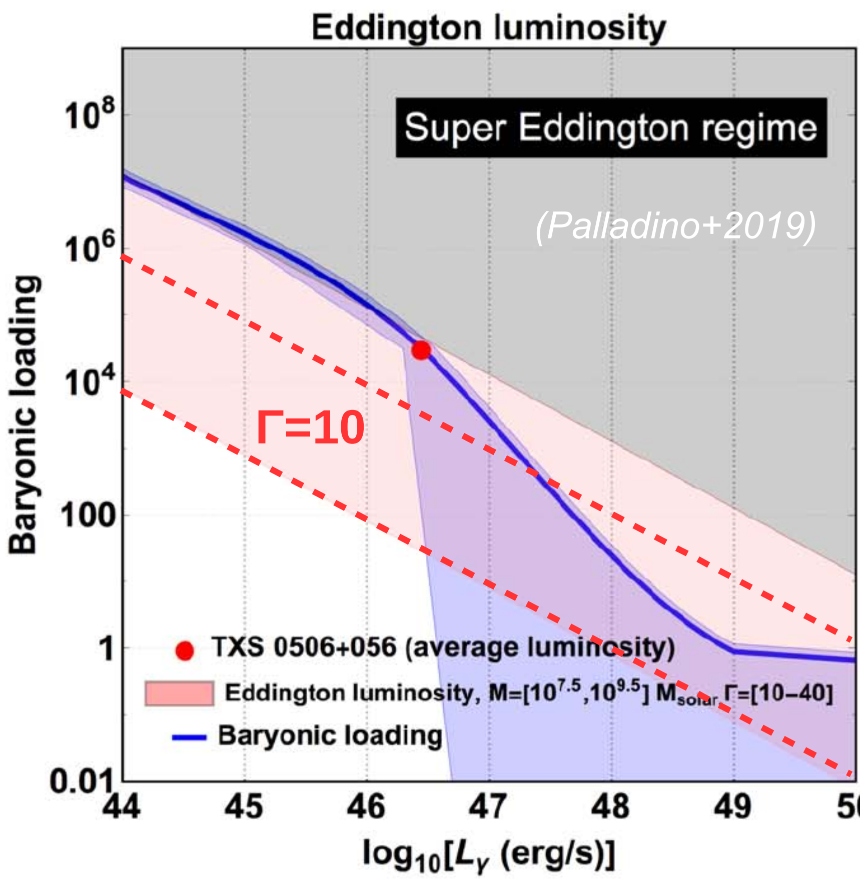
$$L_\nu = f_{p\gamma}\,\xi(L_\gamma)\,L_\gamma \propto \xi(L_\gamma)\,L_\gamma^2$$

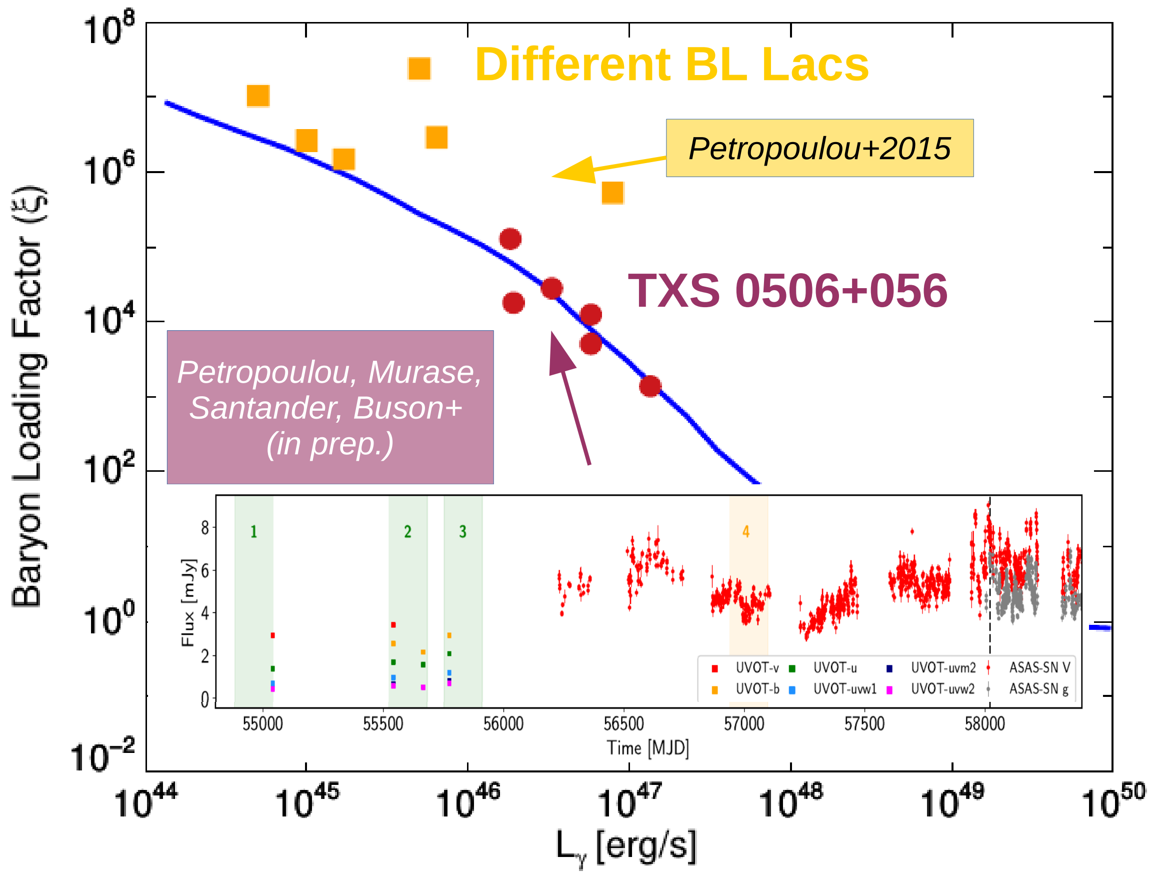


- The NBG is powered mostly by **low-luminosity** BL Lacs, with **$\xi > 10^6$**.
- Consistent with Fermi stacking limits.

(Palladino+2019)

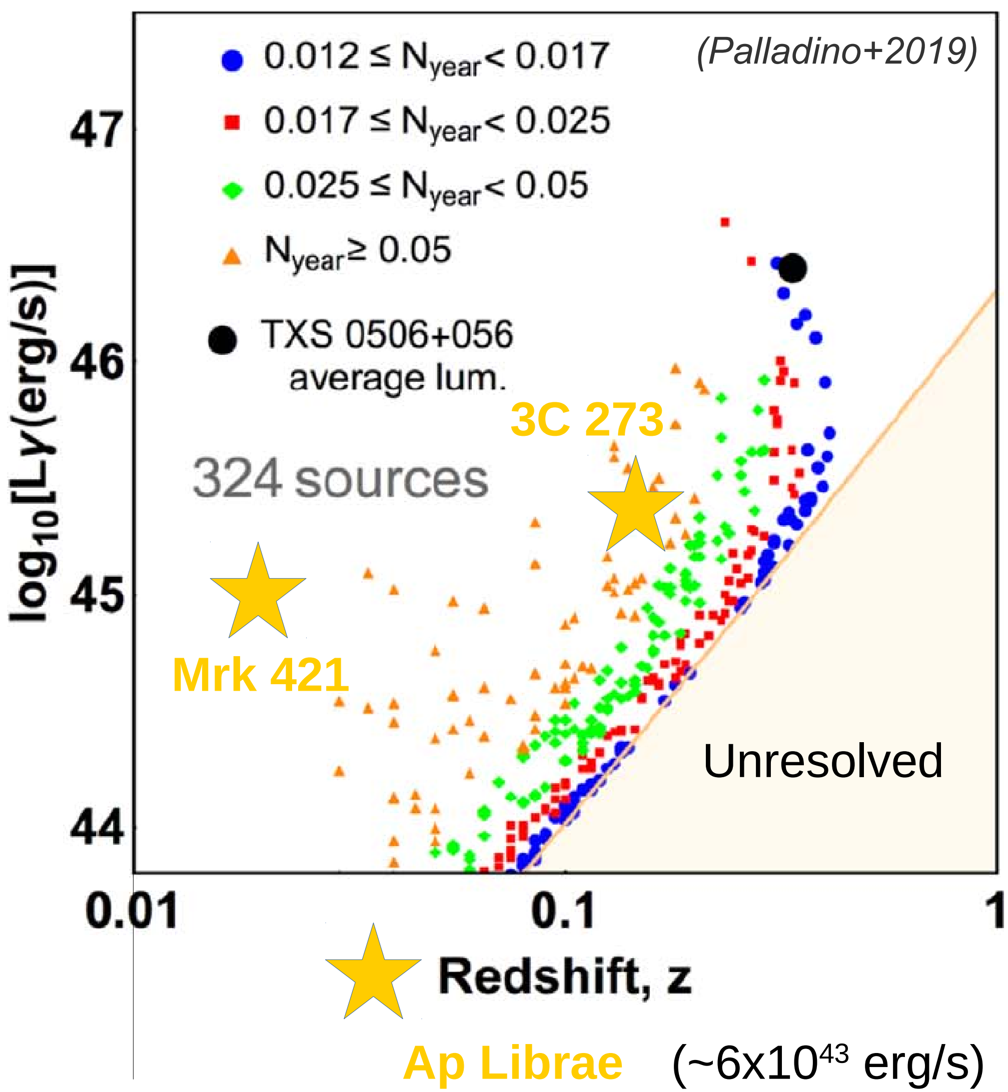
Implications for individual sources – 1

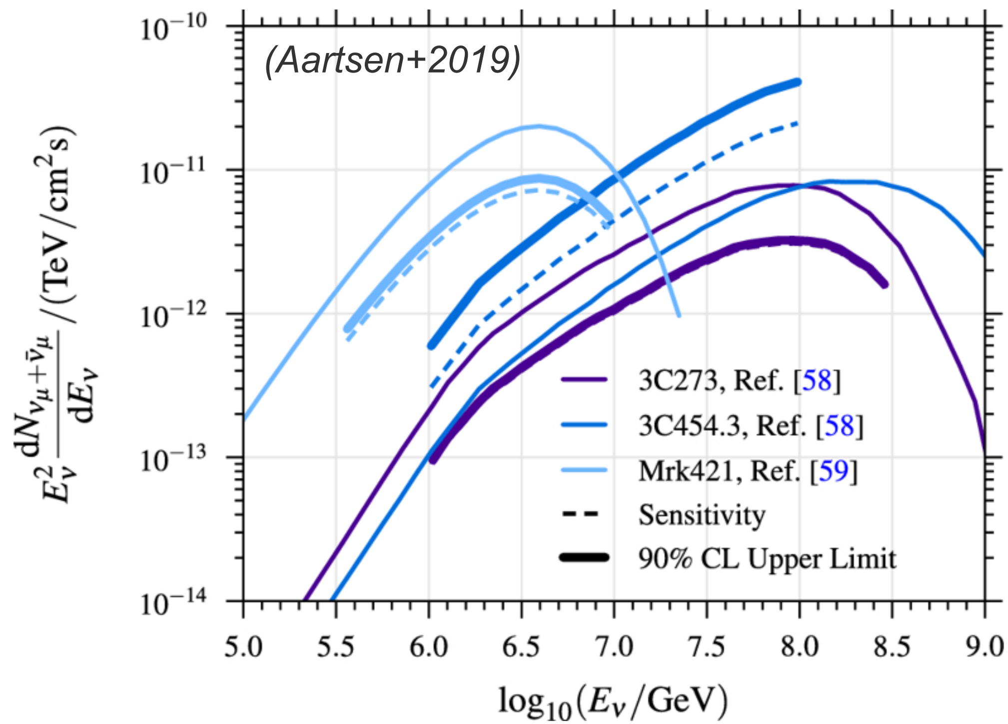




- Highly super-Eddington jet power for low-luminosity BL Lacs. **Is this physical?**
- High baryon loading factors suggest large contribution of hadronic EM emissions. **Are blazar SEDs consistent with observed ones?**
- Baryon loading for blazars with similar γ-ray luminosity as TXS 0506+056 is consistent with leptonic multi-epoch modeling. **Lucky coincidence?**

Implications for individual sources – 2





- Are nearby low-luminosity BL Lacs (e.g. Mrk 421, Ap Librae) good candidate neutrino point sources?
- What about current IceCube limits on specific sources?

Contribution of γ-ray flares to diffuse neutrino flux

Diffuse neutrino flux from flares in accordance with multiplet limits:

$$E_\nu^2\Phi_\nu \lesssim 3.8\times10^{-10}\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}\left(\frac{\xi_z}{0.7}\right)\left(\frac{0.05}{f_{fl}}\right)^{1/2}\left(\frac{b_{fl}^\nu}{1.0}\right)^{1/2}\left(\frac{10^{46}\mathrm{erg\,s^{-1}}}{\epsilon_\nu L^{fl}_{\epsilon_{\nu_\mu}}}\right)^{1/2}$$

γ-ray flare duty factor

Neutrino flare energy fraction

Neutrino flare luminosity

Derived from the FAVA Analysis (Abdollahi et al. 2017)

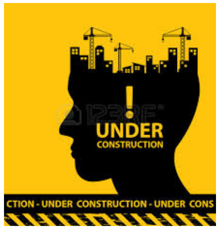
Name	L_γ	$f_{\rm fl}^{\rm LE}$	$f_{\rm fl}^{\rm HE}$	$b_{\rm fl}^{\rm LE}$	$b_{\rm fl}^{\rm HE}$	α
TXS 0506+056	$10^{46.3}$	0.1	0.03	0.1	0.1	3.0
OJ 287	$10^{46.1}$	0.02	0.01	0.04	0.1	2.9
PKS 0426–380	10^{48}	0.1	0.1	0.2	0.2	1.7
PKS 0301–243	10^{46}	0.04	0.05	0.1	0.3	2.5
S5 0716+071	$10^{46.7}$	0.07	0.08	0.1	0.2	1.7
S4 0954+065	$10^{45.5}$	0.04	0.03	0.07	0.3	2.5

See Oikonomou's poster for leptonic models of individual flares

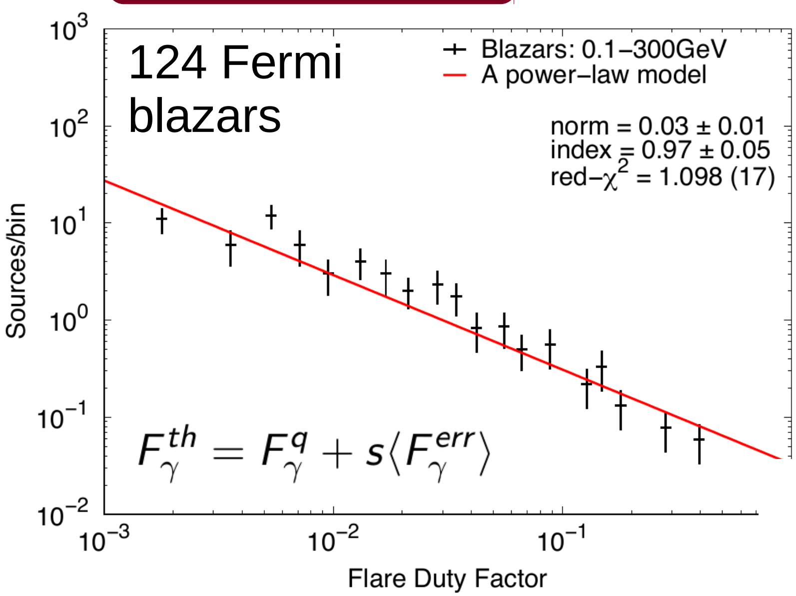
(Murase, Oikonomou, MP 2018)

Main ingredients

- Daily binned decay-long Fermi-LAT light curves of 124 blazars (public products)
- X-ray light curves based on the 14 years of Swift/XRT data (Open Universe for Blazars; *Giommi et al. 2019*)

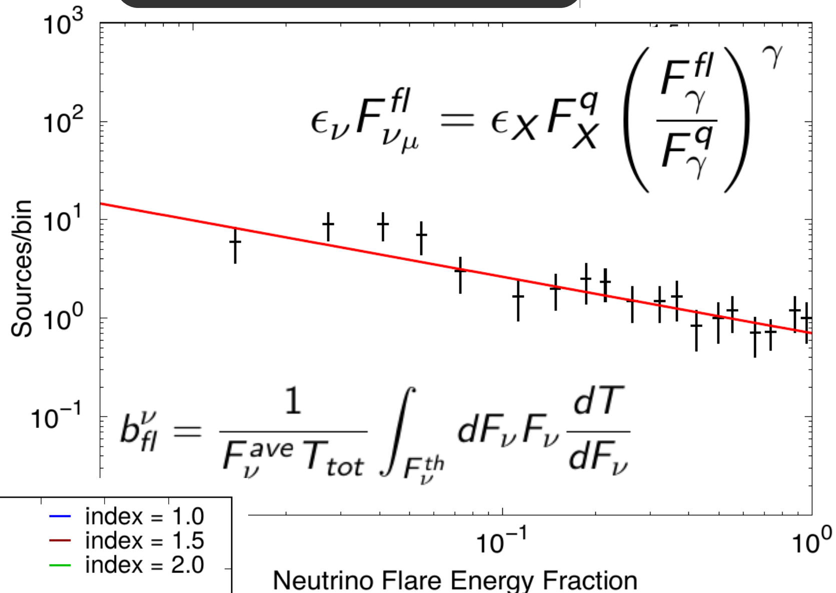


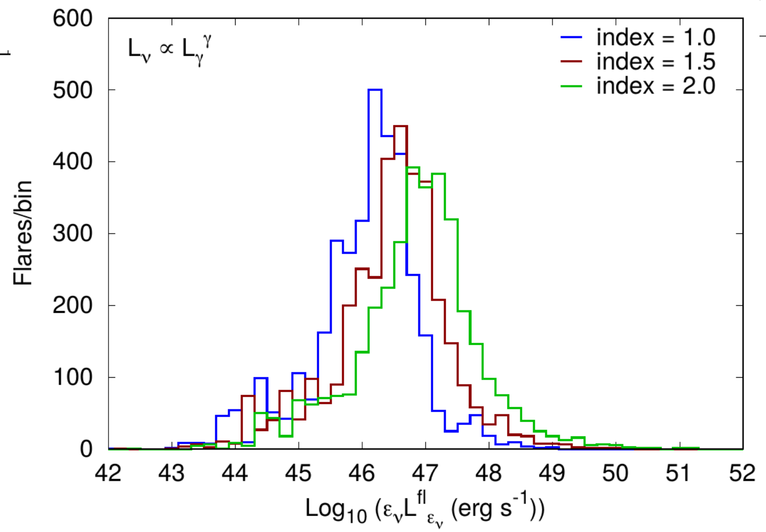
γ-flare duty factor



(Yoshida, MP, Murase+ in prep.)

Neutrino flare energy fraction

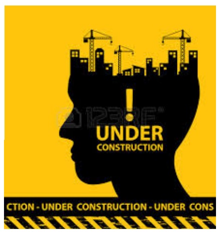


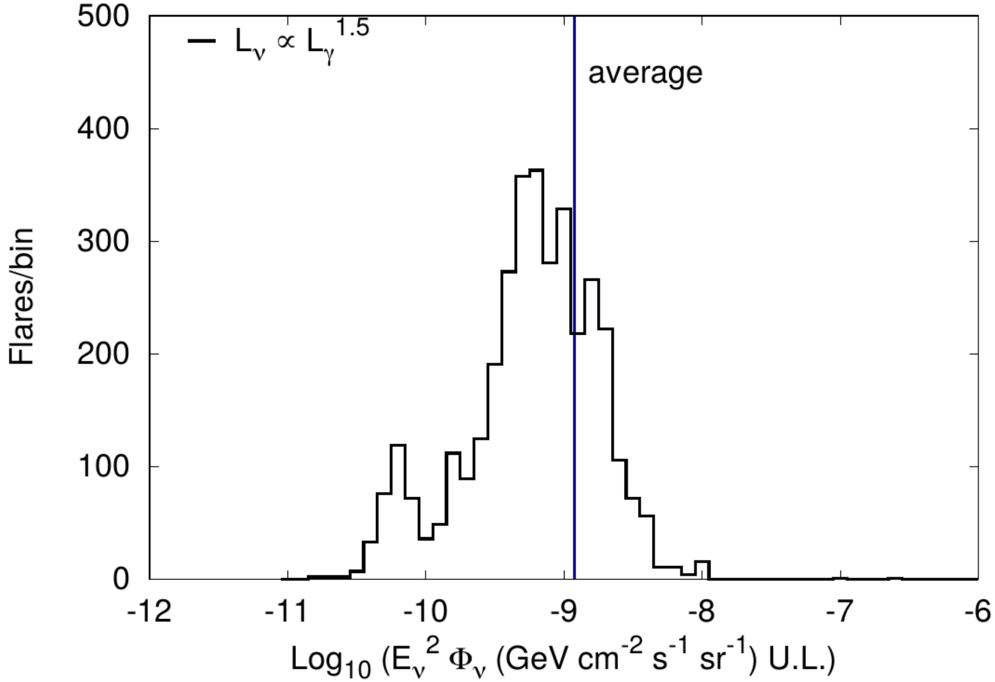


Neutrino flare luminosity

Maximal flare contribution to the NBG

$$E_\nu^2\Phi_\nu \lesssim 3.8\times10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\left(\frac{\xi_z}{0.7}\right)\left(\frac{0.05}{f_{fl}}\right)^{1/2}\left(\frac{b^\nu_{fl}}{1.0}\right)^{1/2}\left(\frac{10^{46}\,\mathrm{erg\,s^{-1}}}{\epsilon_\nu L^{fl}_{\epsilon_{\nu_\mu}}}\right)^{1/2}$$

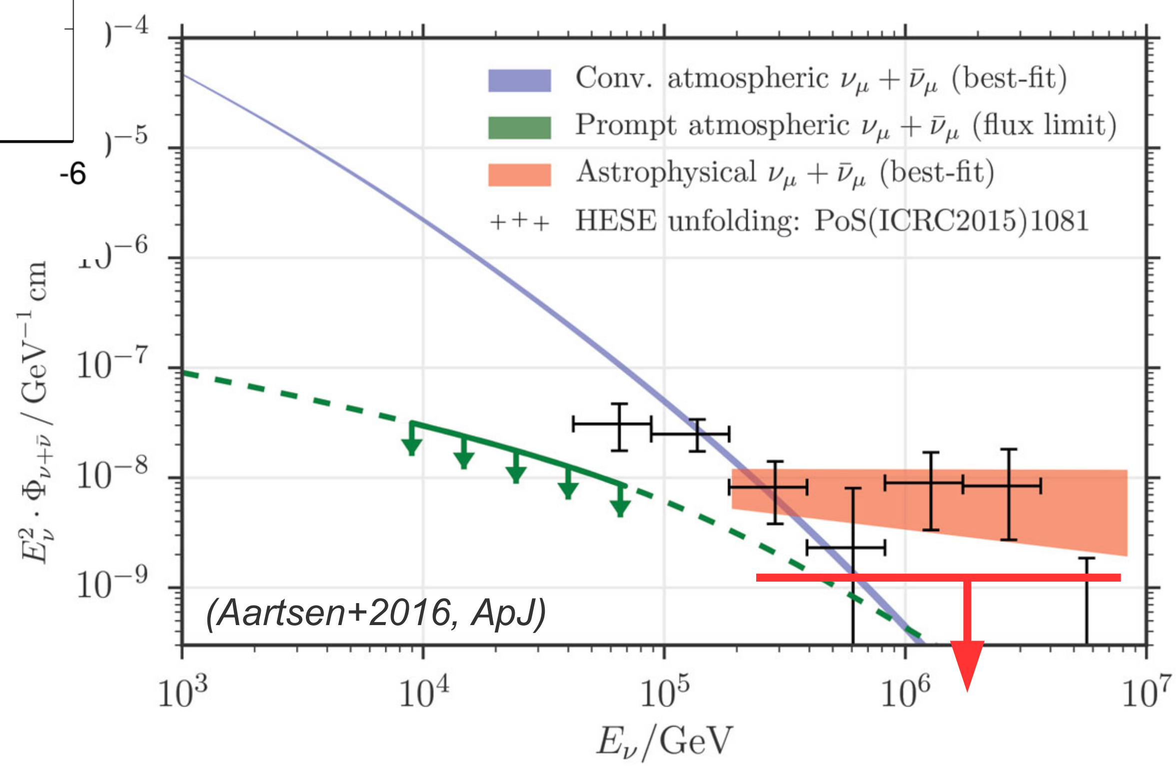




(Yoshida, MP, Murase+ in prep.)

$< E_\nu^2\Phi_\nu \mathrm{U.L.} >$ (GeV cm^{-2} s^{-1} sr^{-1})

$(0.96\pm0.08)\times10^{-9}$ for $\gamma = 2.0$
$(1.20\pm0.08)\times10^{-9}$ for $\gamma = 1.5$
$(1.43\pm0.08)\times10^{-9}$ for $\gamma = 1.0$



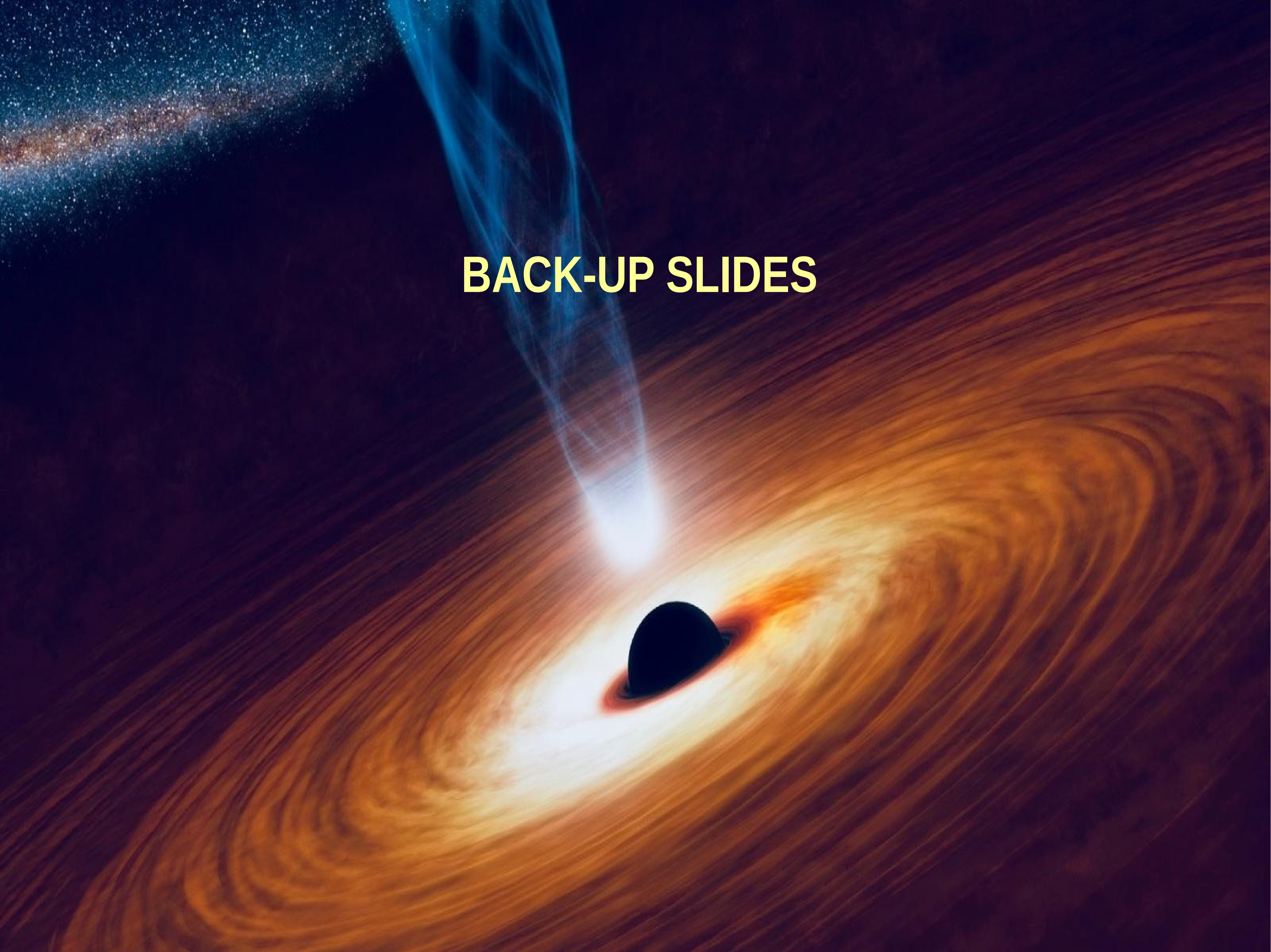
- Bright γ-ray flares can contribute up to ~10 – 14% to the diffuse neutrino flux.
- Larger contribution from less luminous γ-ray flares?

Summary

- Diffuse neutrino models from jetted AGN predict hard neutrino spectra typically peaking in the range of 1 – 10 PeV.
- Models can now be constrained by: EHE IceCube upper limits, stacking limits from Fermi-LAT detected AGN, and multiplet limits.
- Jetted AGN cannot explain the total diffuse neutrino flux measured by IceCube, but they can have a non-negligible contribution at E >1 PeV.
- Typically adopted baryon loading factors imply very high jet powers which is difficult to theoretically explain.
- To better constrain the contribution of flares to the neutrino output from blazars we need sensitive X-ray monitoring.

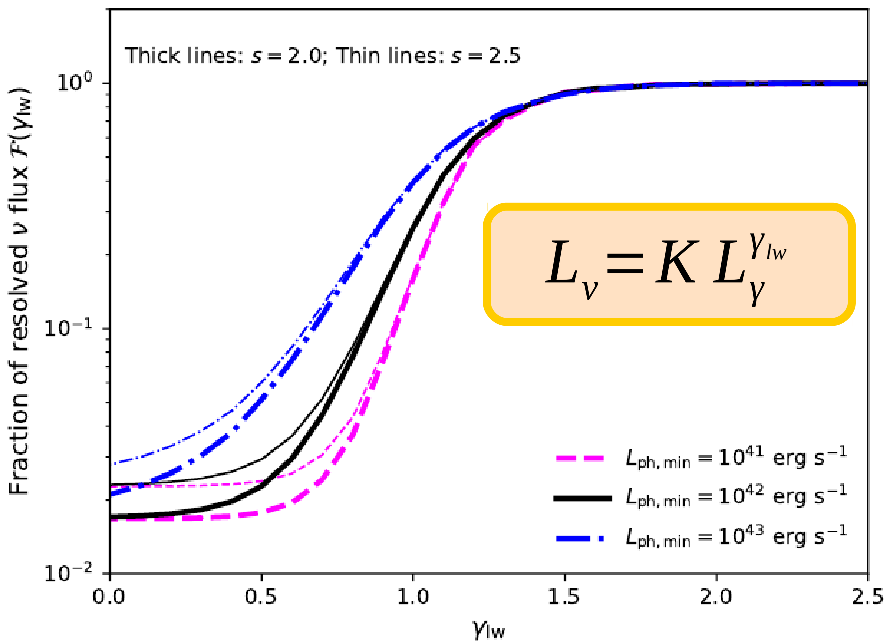
Thank you!

BACK-UP SLIDES

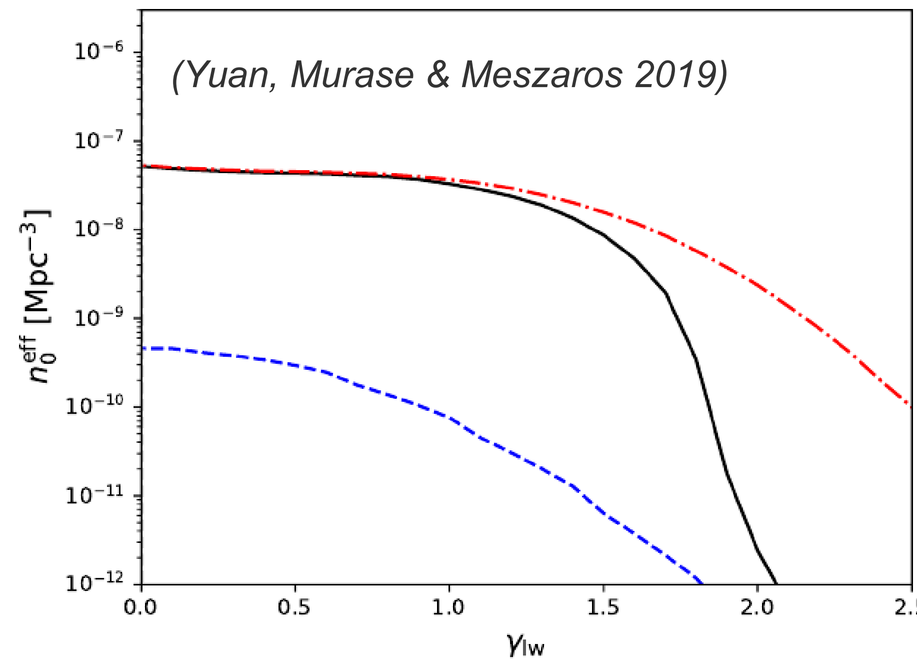


Constraints from combined stacking & multiplet limits

Fraction of resolved blazars to neutrino flux



Effective number density of sources



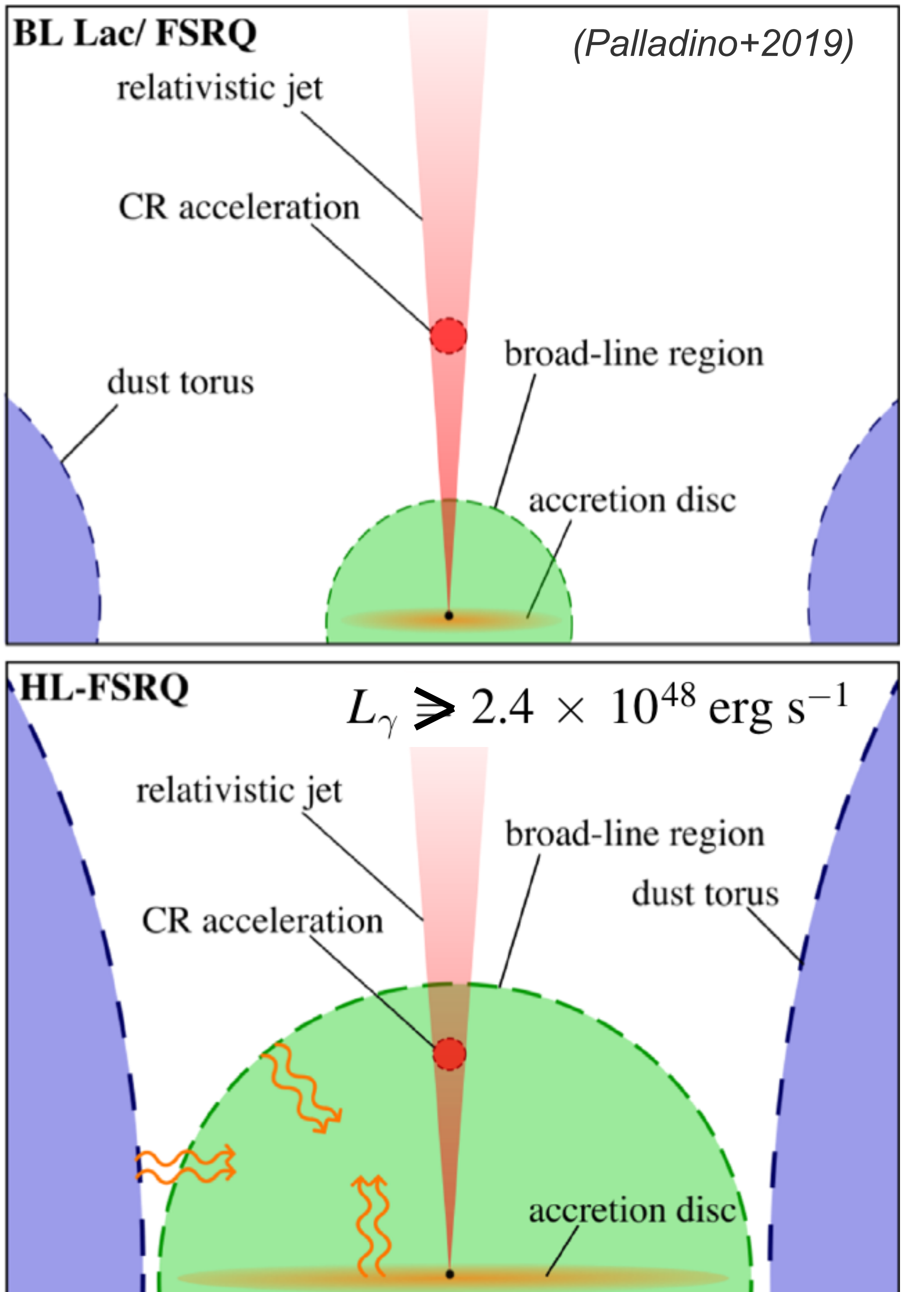
Constraint I:

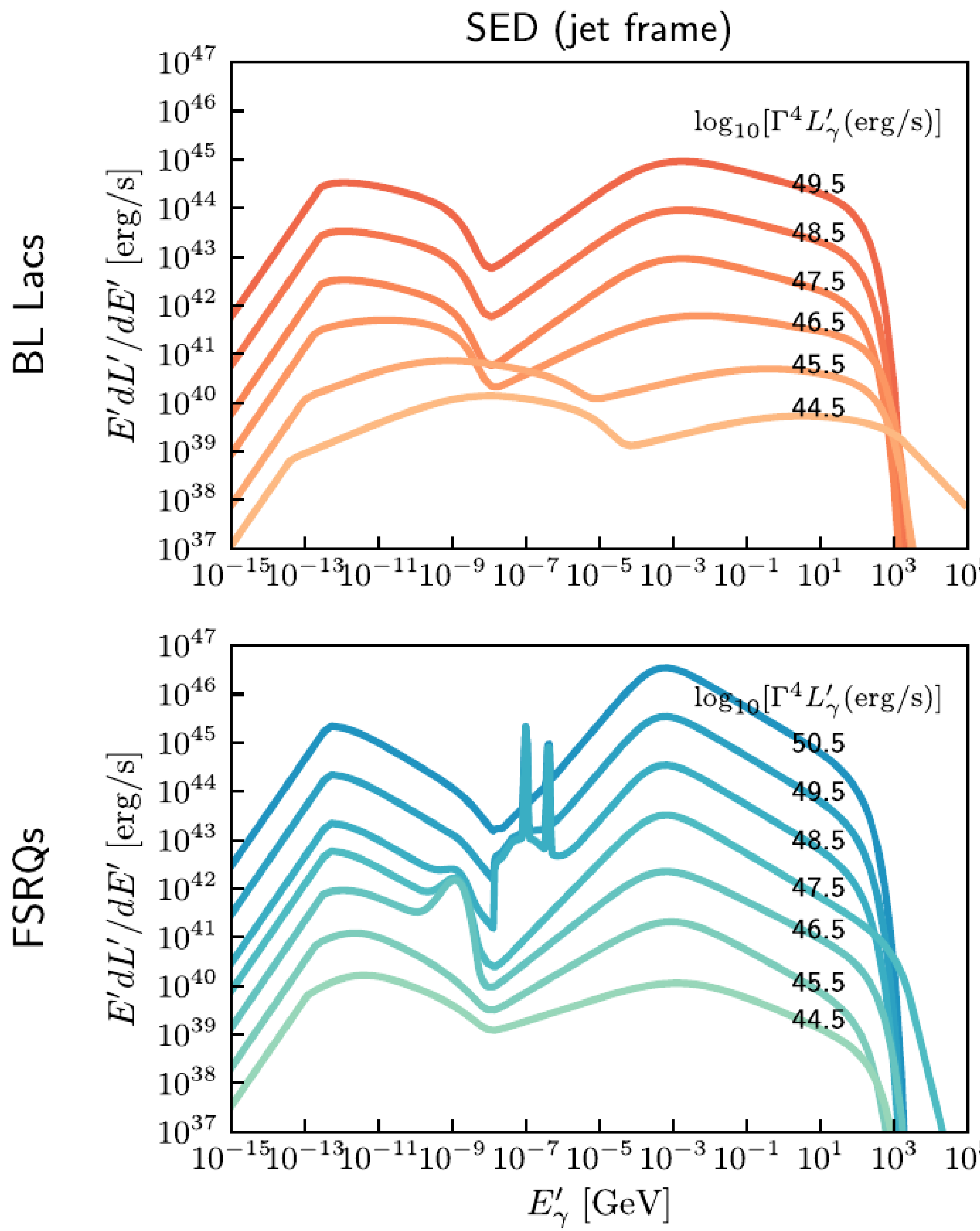
$$E_\nu^2 \Phi_{E_\nu}^{(\rm 2LAC/3LAC)} = \frac{E_\nu^2 \Phi_{E_\nu}^{(\rm 2LAC/3LAC, stacking)}}{\mathcal{F}(\gamma_{\rm lw})}$$

Constraint II:

$$E_\nu^2 \Phi_{E_\nu}^{(\rm m)} \approx \frac{3\xi_z c t_H}{4\pi} n_0^{\rm eff}(\varepsilon_\nu L_{\varepsilon_\nu}^{\rm ave})$$
$$\lesssim 6.9 \times 10^{-9} \left(\frac{\Delta\Omega}{2\pi}\right)^{2/3} \left(\frac{\xi_z}{0.7}\right) \left(\frac{b_m q_L}{6.6}\right)^{-2/3}$$
$$\times \left(\frac{n_0^{\rm eff}}{10^{-7}\ {\rm Mpc^{-3}}}\right)^{1/3} \left(\frac{F_{\rm lim}}{10^{-9.2}\ {\rm GeV\ cm^{-2}\ s^{-1}}}\right)$$

Diffuse neutrino flux from the revised blazar sequence





Multiplet constraint

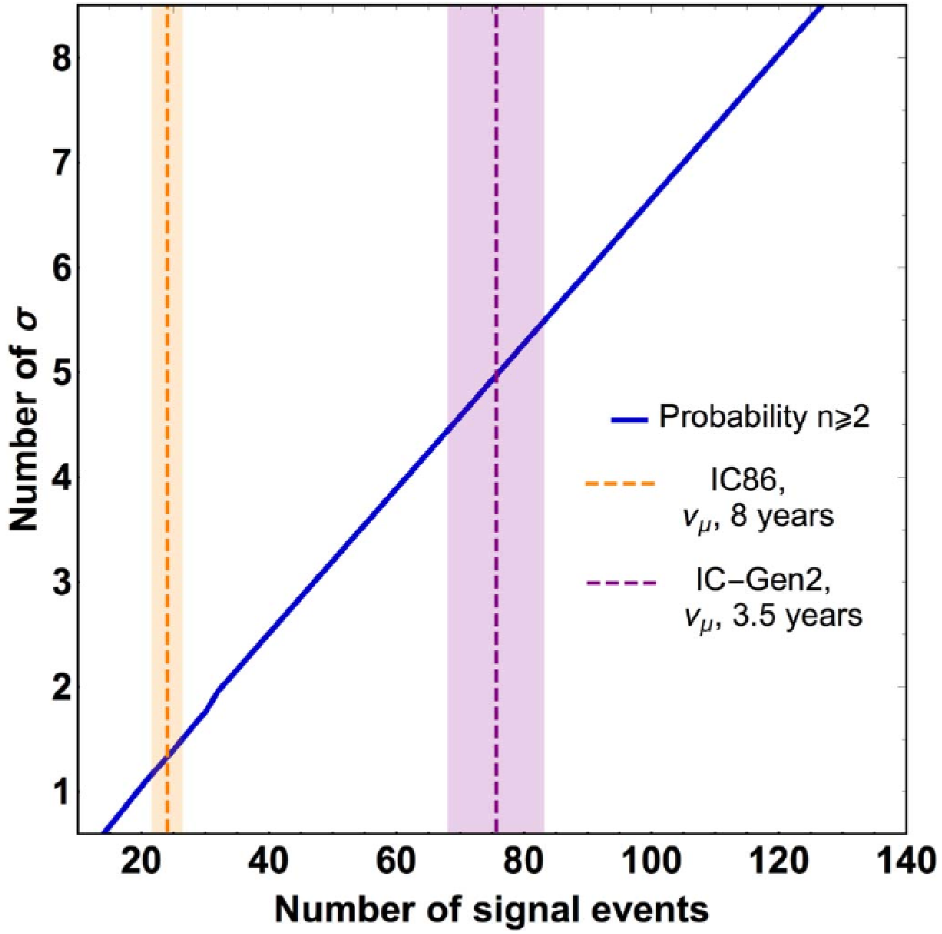


Figure 9. Multiplet limit (number of standard deviations σ of exclusion of the model due to the nonobservation of multiplets) as a function of the observed number of signal events in the throughgoing muon data set. In this analysis we use our baseline model (scenario 3) and consider all 9186 blazars contained in the distribution by Ajello et al. We show as an orange band the present number of signals detected using throughgoing muons (Aartsen et al. 2016). The purple band represents the number of years required for IceCube-Gen2 to reach the 5σ level (Aartsen et al. 2014). The band is due to the uncertainty on the contribution of the atmospheric background (mainly prompt neutrinos) to the throughgoing muons, which is about 10% (see Equation (12) of Palladino & Vissani 2017).