Neutrino predictions for 3HSP J095507.9+355101, an extreme X-ray flaring blazar

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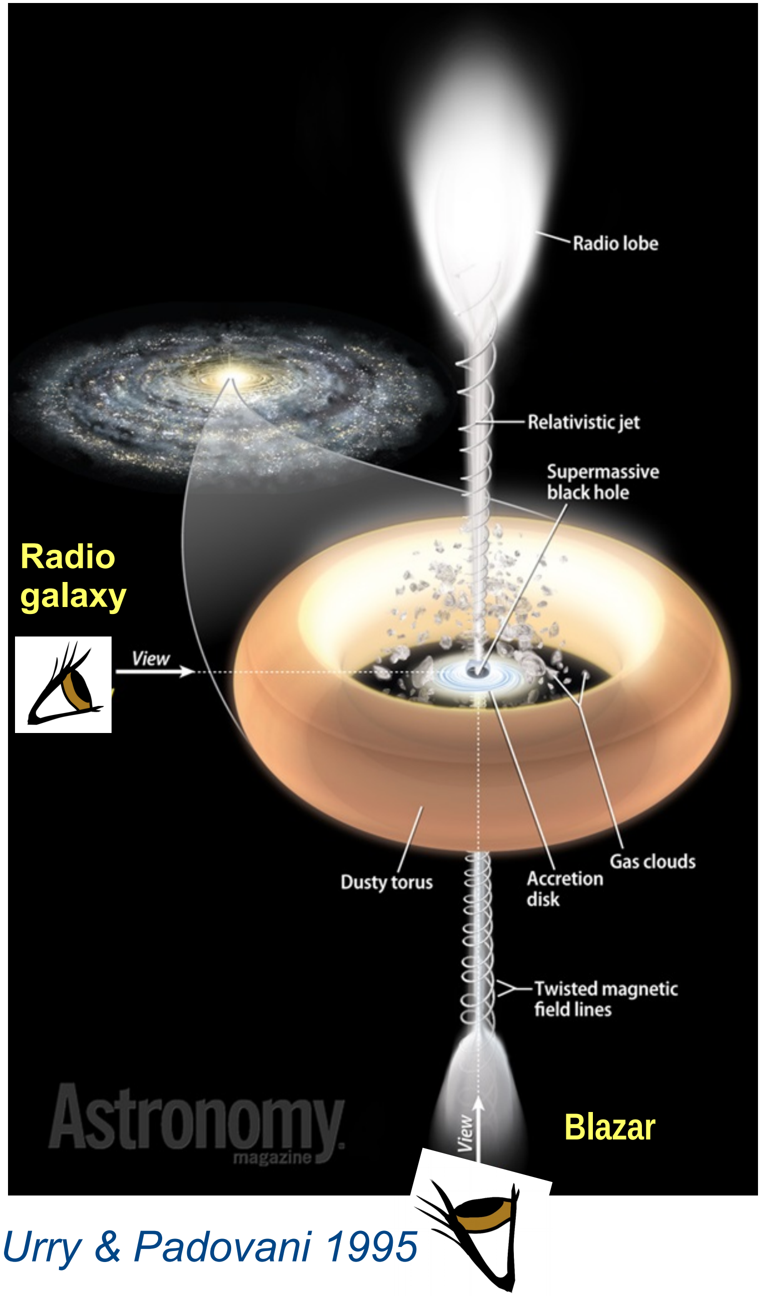
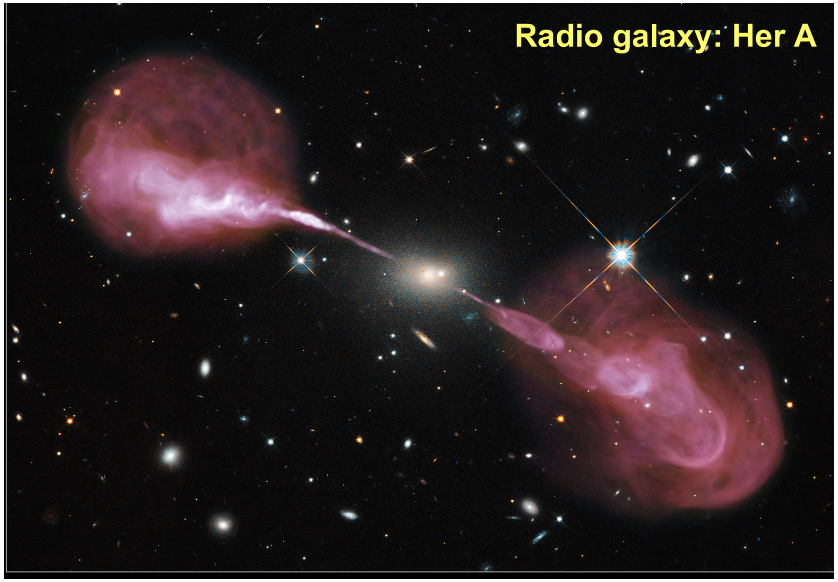
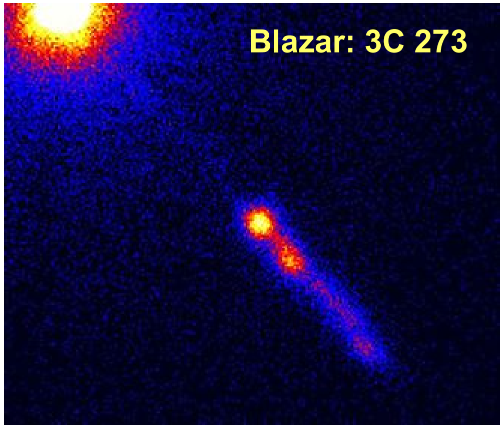
Blazars: AGN with jets viewed face-on



Urry & Padovani 1995



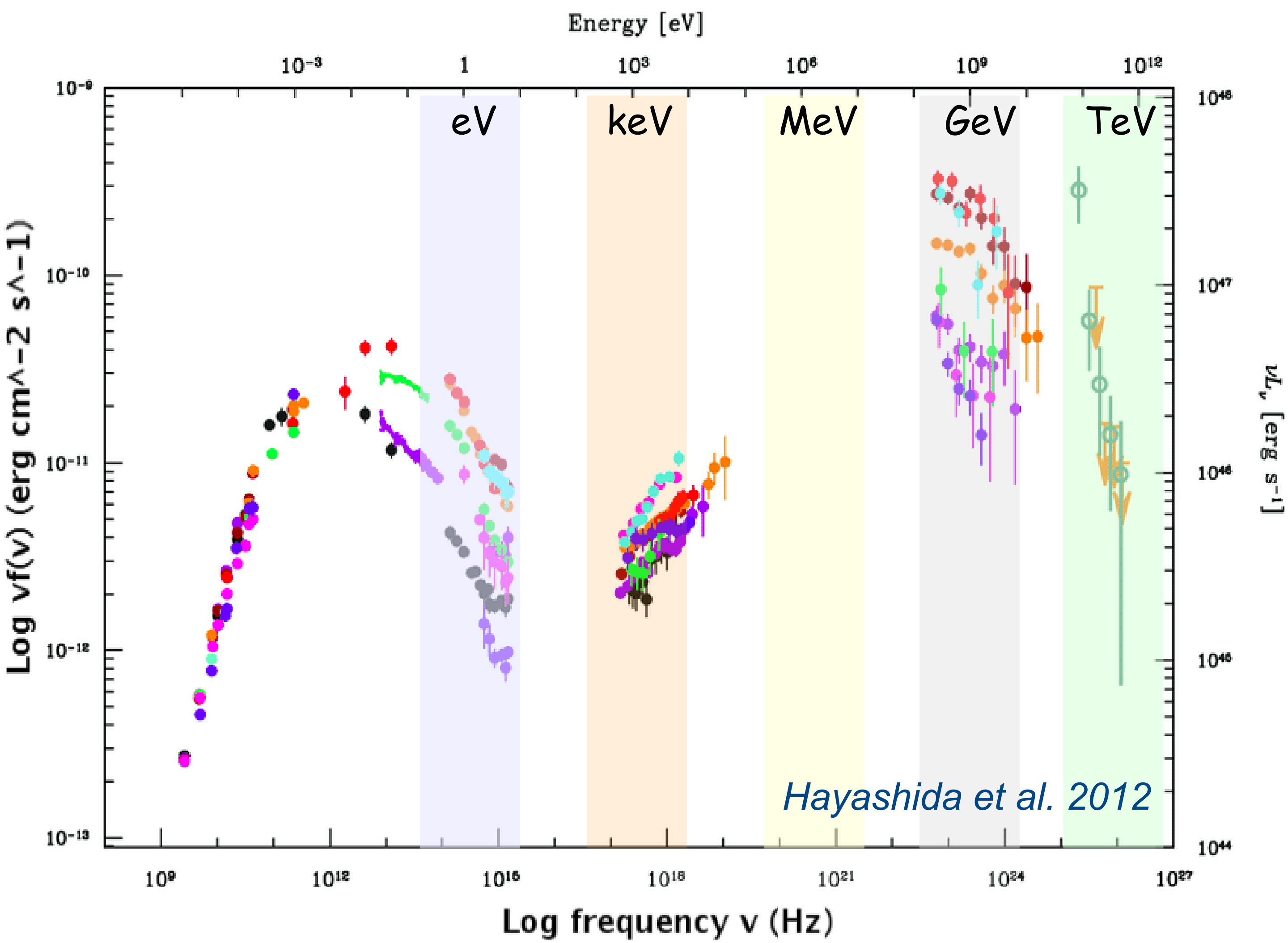
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)



Credit: Chandra X-ray observatory

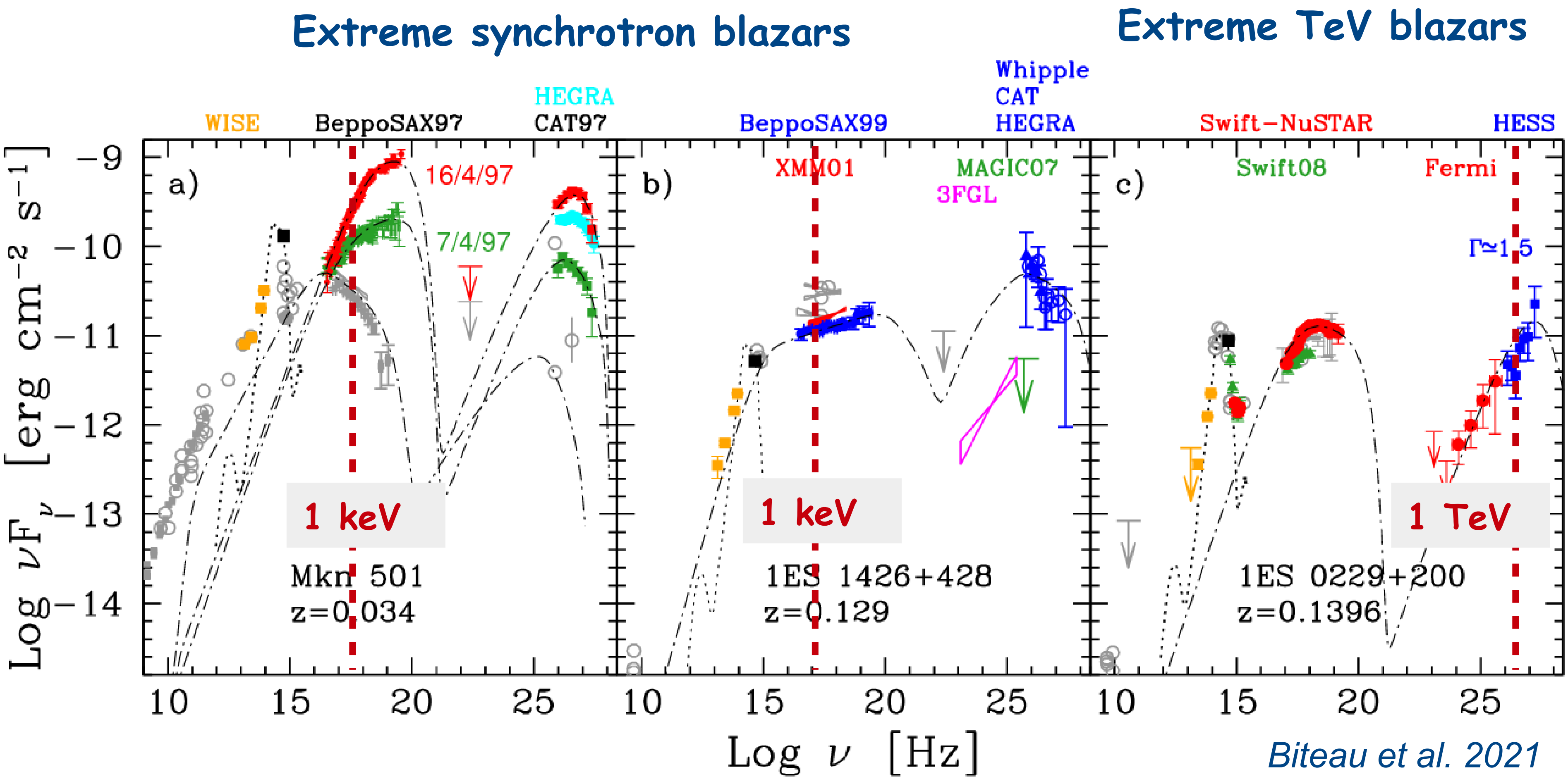
- ~10% of Active Galactic Nuclei (AGN) have relativistic jets.
- Blazars → jetted AGN viewed at small viewing angles.
- Blazar emission dominated by the jet due to Doppler beaming.

Multi-wavelength variable photon emitters



- Multi-wavelength emission.
- Double-humped photon spectra.
- Flux variability on multiple timescales (min to months).
- Flares across the EM spectrum (not always correlated)

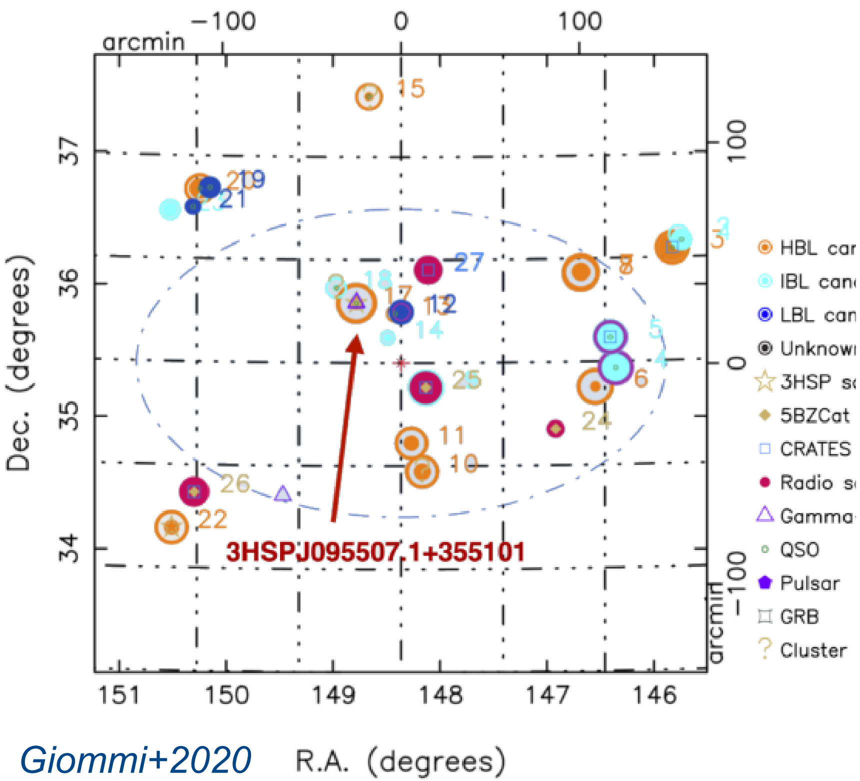
Extreme blazars



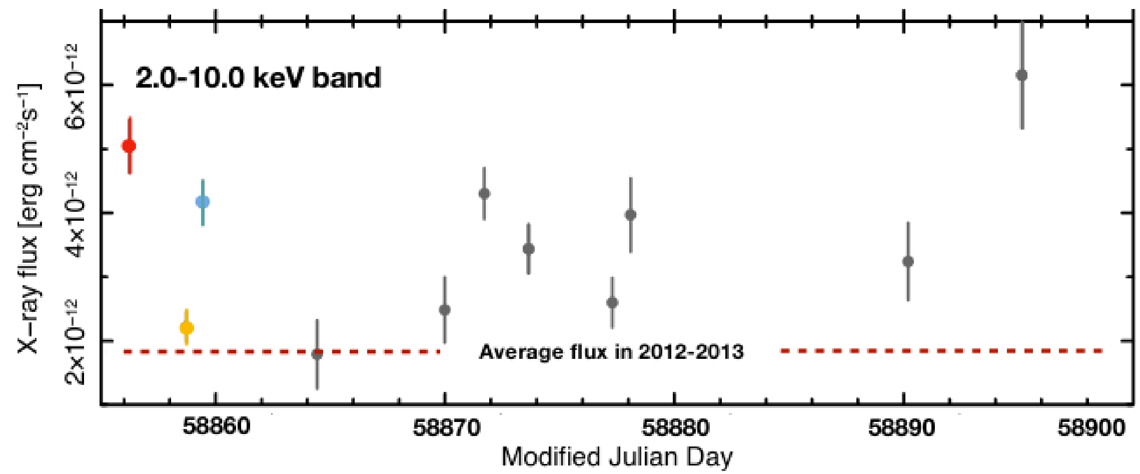
Biteau et al. 2021

- Extreme synchrotron blazars: **$h\nu_X$ > 1 keV** and **Γ_X < 2**
- Extreme TeV blazars: **$h\nu_\gamma$ > 1 TeV** and **Γ_γ < 2**
- Extreme "appearance": **transient** (flares) or **long-lasting** (quiescent)

3HSP J095507.9+35510 / IceCube-200107



Giommi+2020



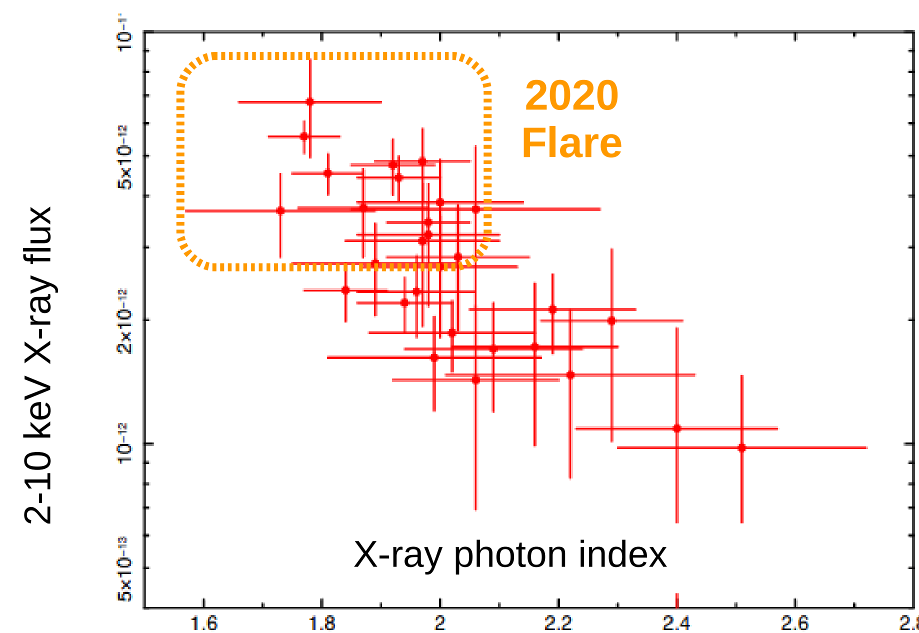
Giommi+2020

- 3HSP J095507.9+35510 is an extreme blazar at z~0.56 *(Paiano+2020, Paliya+2020)*

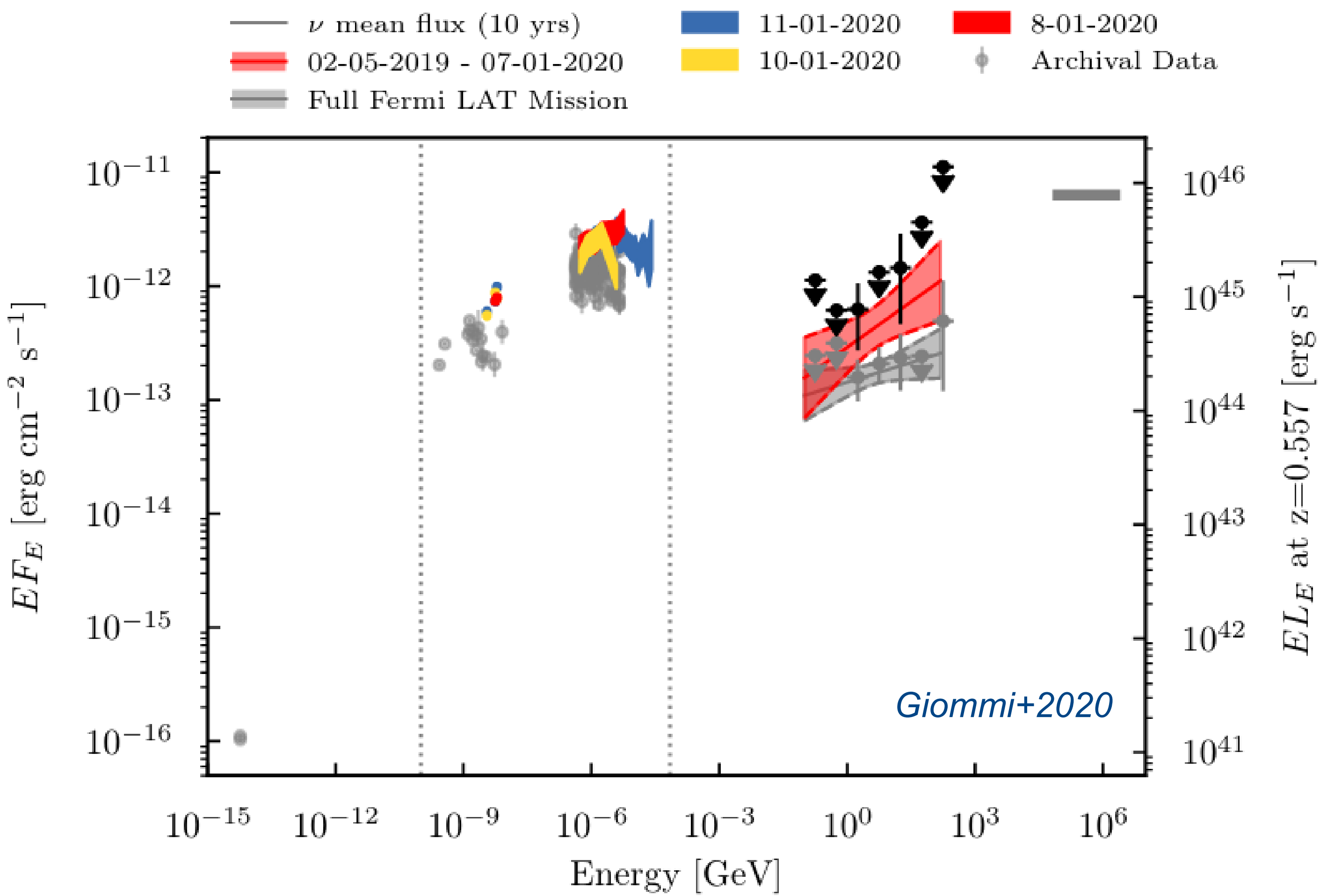
- Spatially coincident with IceCube-200107A while undergoing its brightest X-ray flare.

- X-ray flux increased by a factor of ~3 and X-ray spectrum hardened.

(Giommi+2020, Paliya+2020)

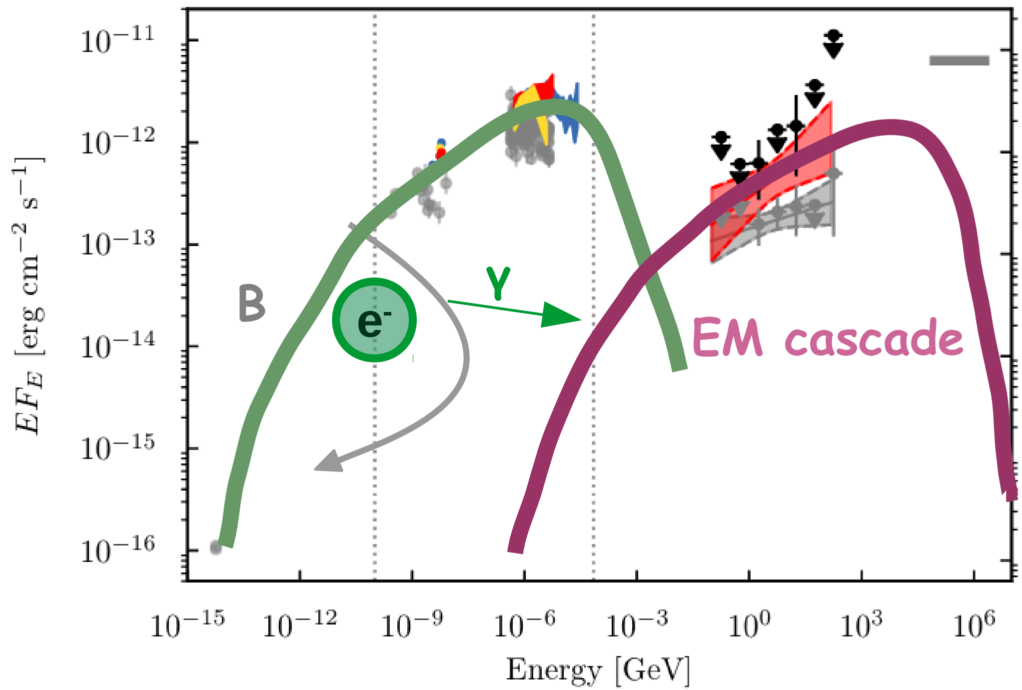


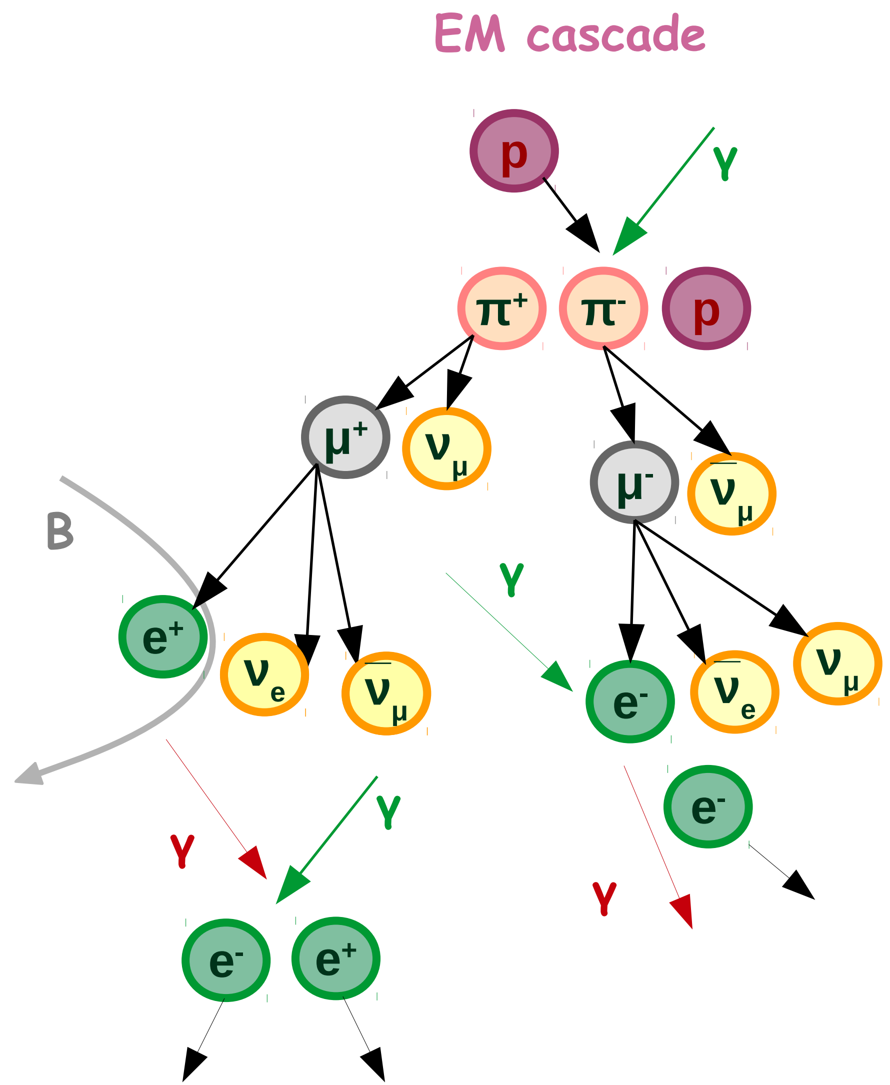
Hybrid spectral energy distribution



- **Optical/UV:** *Swift*/UVOT (3 days starting ~1 day after ν alert)
- **X-rays:** *Swift*/XRT, NuSTAR (3 days starting ~1 day after ν alert)
- **γ-rays:** *Fermi*-LAT (time-average over 250 days prior to ν alert / full mission)

Leptohadronic blazar modeling





ATHEvA code *(Dimitrakoudis+2012)*

- Synchrotron radiation
- Inverse Compton scattering
- Photon-photon pair production
- Proton-photon pair production
- Proton-photon pion production
- Neutron-photon pion production

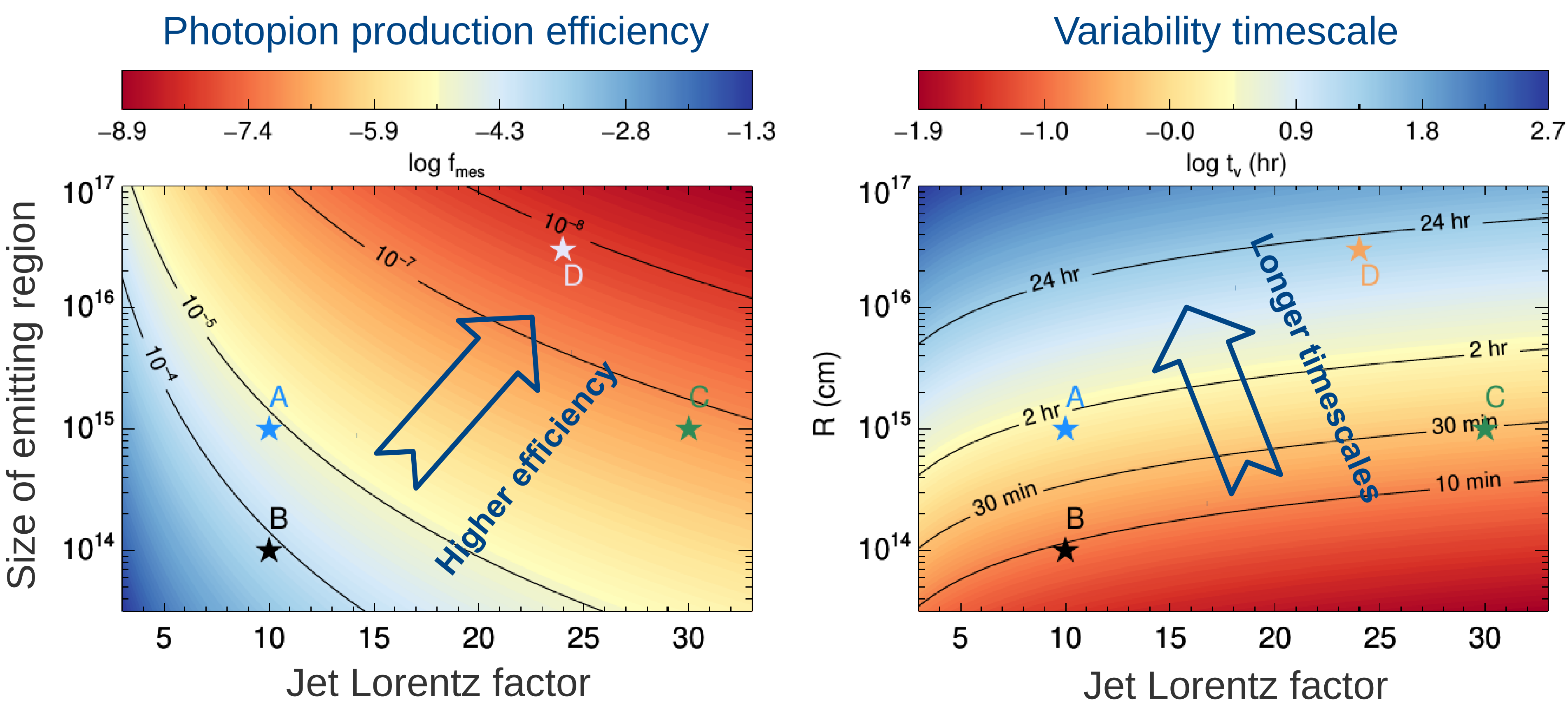
Mannheim+1991; Mannheim & Biermann 1992; Mannheim 1993; Petropoulou+2015; Cerruti+2015; Petropoulou+2016; Gao+2017 +++

Leptohadronic modeling of the X-ray flare

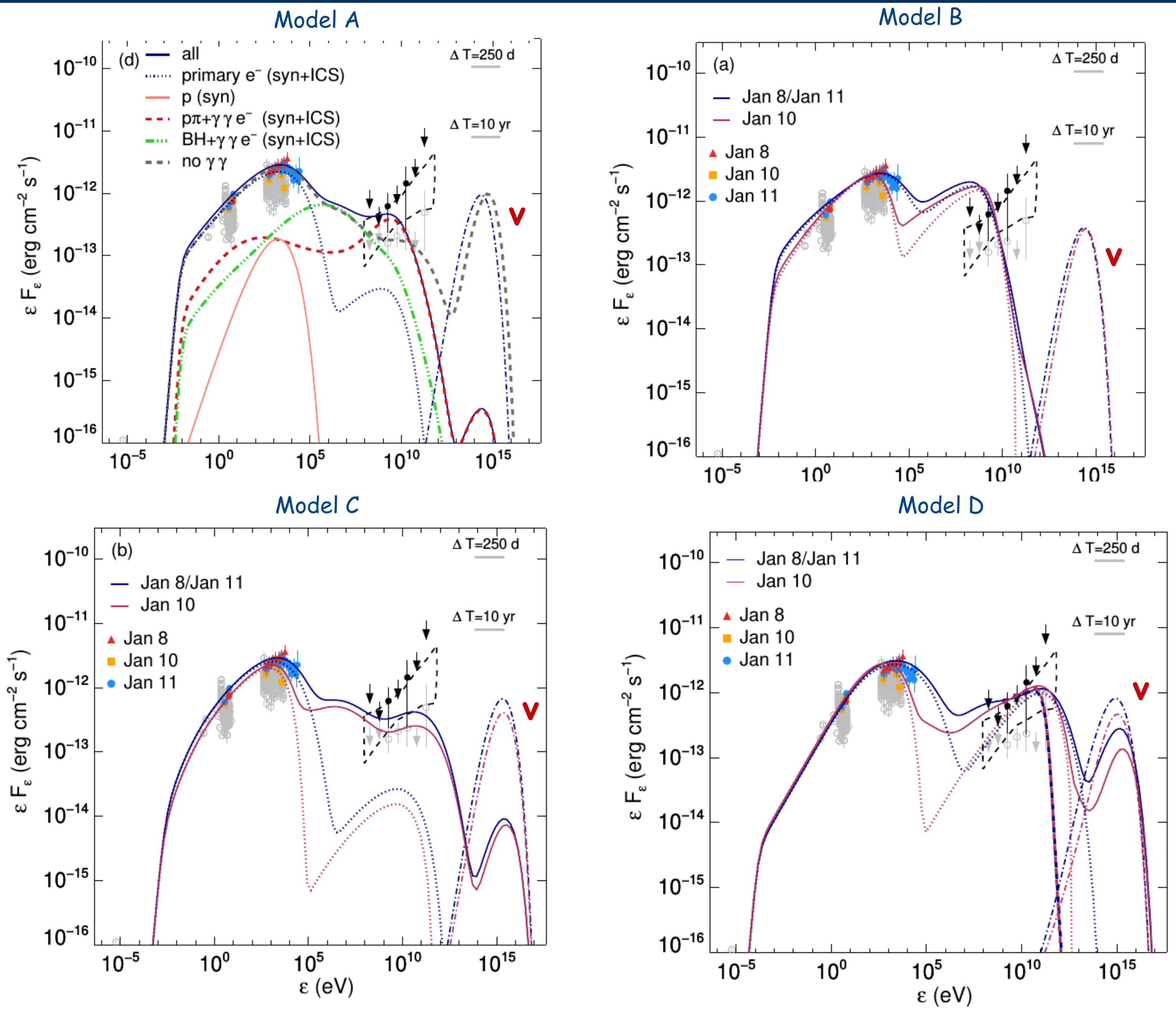
Petropoulou+2020

Photopion production efficiency: $f_{p\gamma}(E'_p) \approx \frac{t_{\rm dyn}}{t_{p\gamma}} \simeq \frac{2\kappa_\Delta \sigma_\Delta}{1+\beta} \frac{\Delta\bar{\varepsilon}_\Delta}{\bar{\varepsilon}_\Delta} \frac{3L^s_{\rm rad}}{4\pi r_b \Gamma^2 c E'_s} \left(\frac{E'_p}{E'^b_p}\right)^{\beta-1}$

Proton energy (E'_p) · **Jet photon number density** ($\frac{3L^s_{\rm rad}}{4\pi r_b \Gamma^2 c E'_s}$) · **Spectral index** ($\beta-1$)

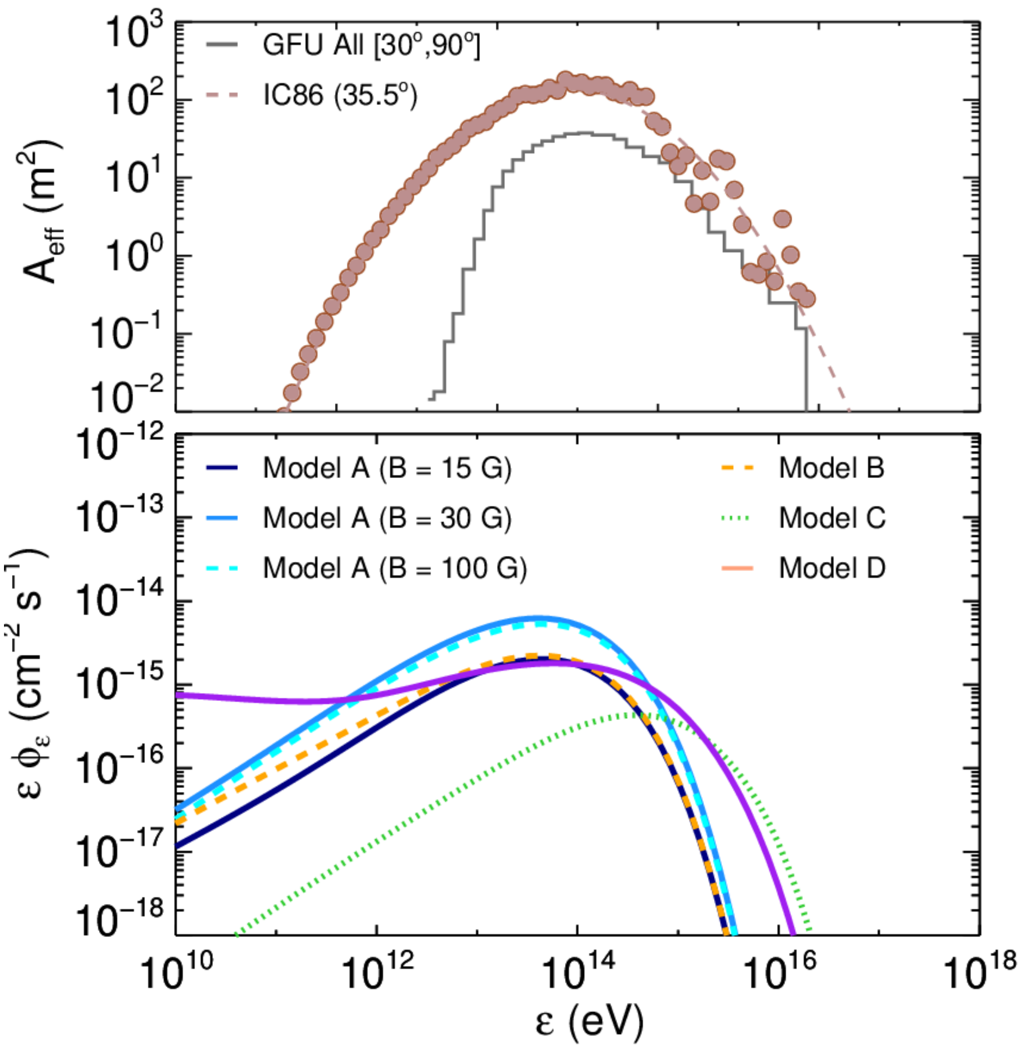


Leptohadronic modeling of the X-ray flare



Neutrino expectation in the leptohadronic model - 1

SED modeling of the X-ray flare



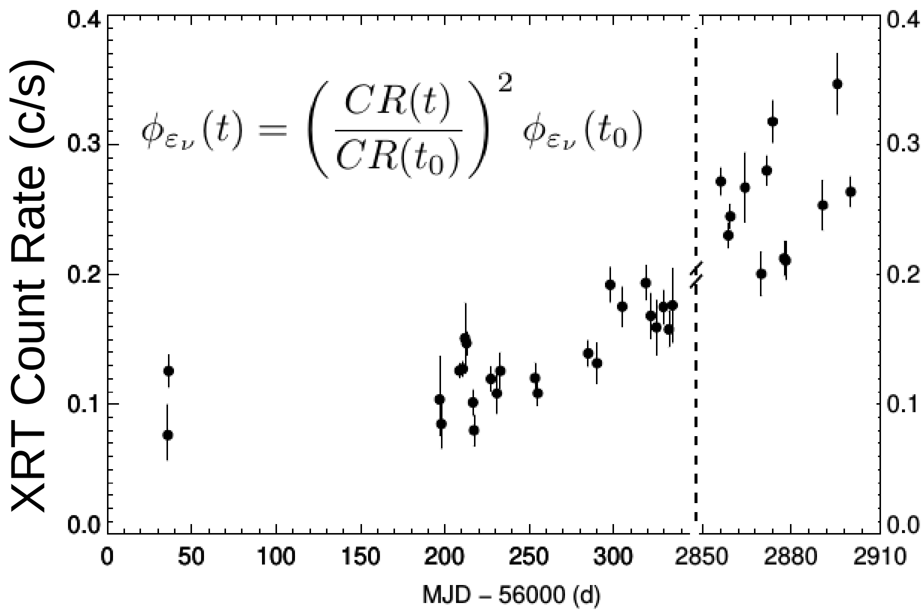
$$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu} = \frac{1}{3}\int_{\varepsilon_{\nu,\min}}^{\varepsilon_{\nu,\max}} d\varepsilon_\nu \, A_{\rm eff}(\varepsilon_\nu, \delta)\phi_{\varepsilon_\nu}.$$

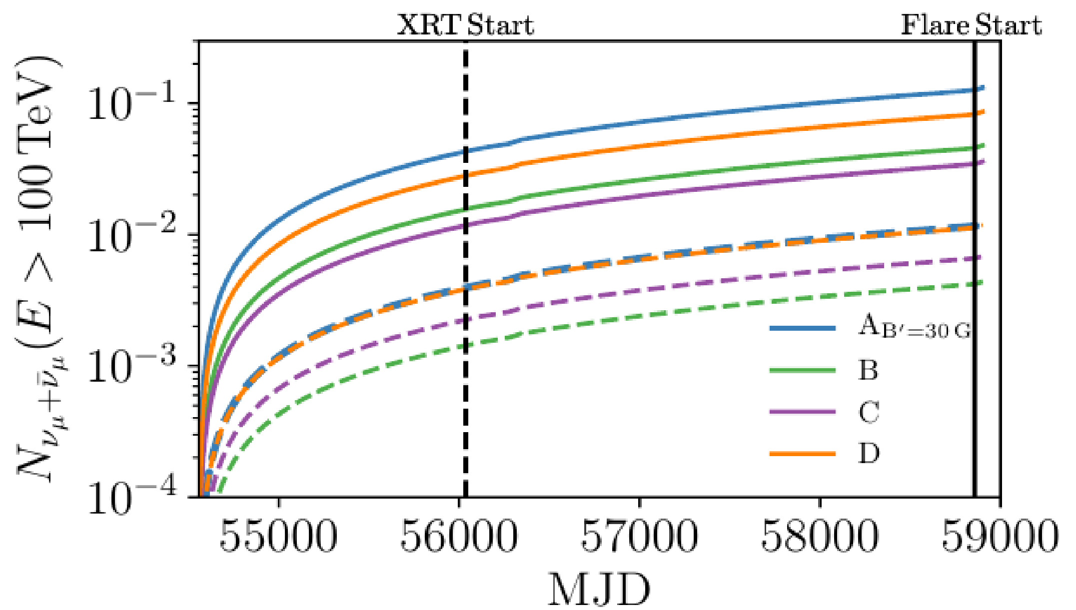
Model	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}(> 100$ TeV) ($\times 10^{-4}$ yr^{-1}) Alert (Point Source)	$\mathcal{P}\|_{1\,\nu_\mu \text{ or } \bar{\nu}_\mu}(> 100$ TeV) Alert (Point Source)
$A_{(B'=15G)}$	17 (190)	0.02 (0.2) %
$A_{(B'=30G)}$	50 (540)	0.06 (0.7) %
$A_{(B'=100G)}$	45 (490)	0.05 (0.6) %
B	18 (200)	0.02 (0.2) %
C	25 (100)	0.03 (0.1) %
D	40 (210)	0.05 (0.3) %

Probability to detect 1 ν_μ during X-ray flare (~44 d) « 1

Neutrino expectation in the leptohadronic model - 2

Full XRT light curve + ν /X-ray correlation



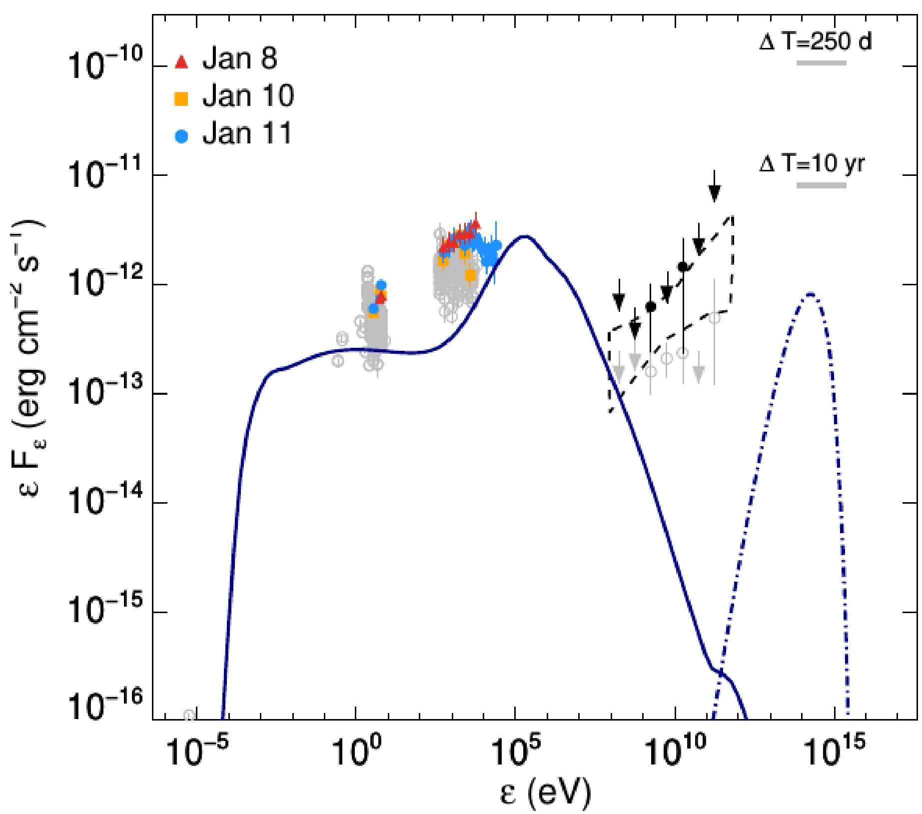


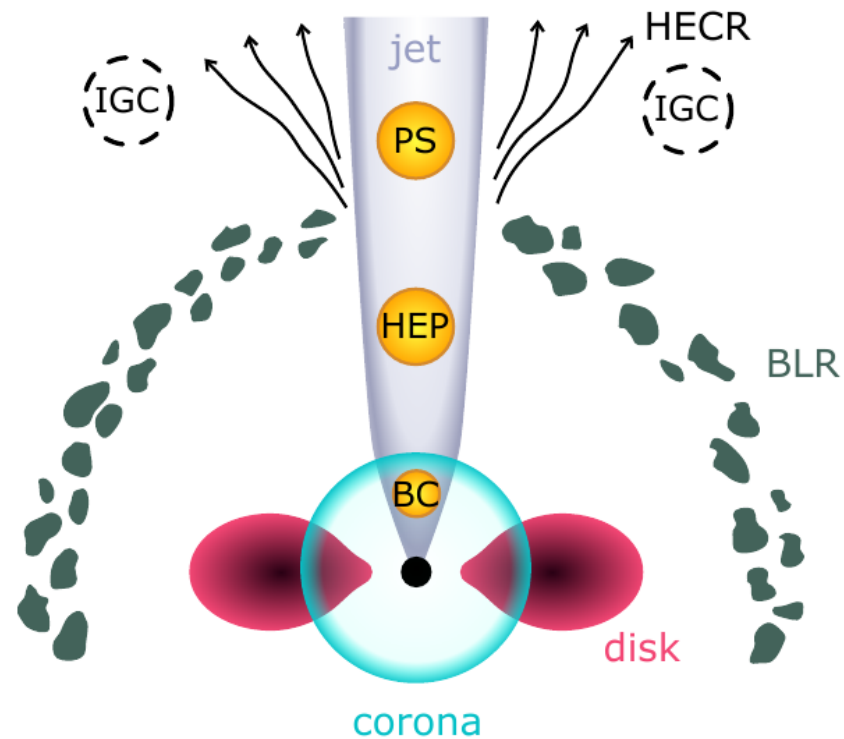
- ~ 0.02 - 0.1 ν_μ within 10 yrs (with Point Source effective area)
- Most optimistic neutrino prediction similar to TXS 0506+056 *(Petropoulou,Murase+2020)*

Alternative theoretical scenarios (BC)

Blazar Core (BC)

- X-ray coronal field
- Production from inner jet (close to black hole)
- Low jet Lorentz factor (Γ~5)
- Very strong magnetic field ($B \sim 10^4$ G)
- Size ($R \sim 10^{14}$ cm)





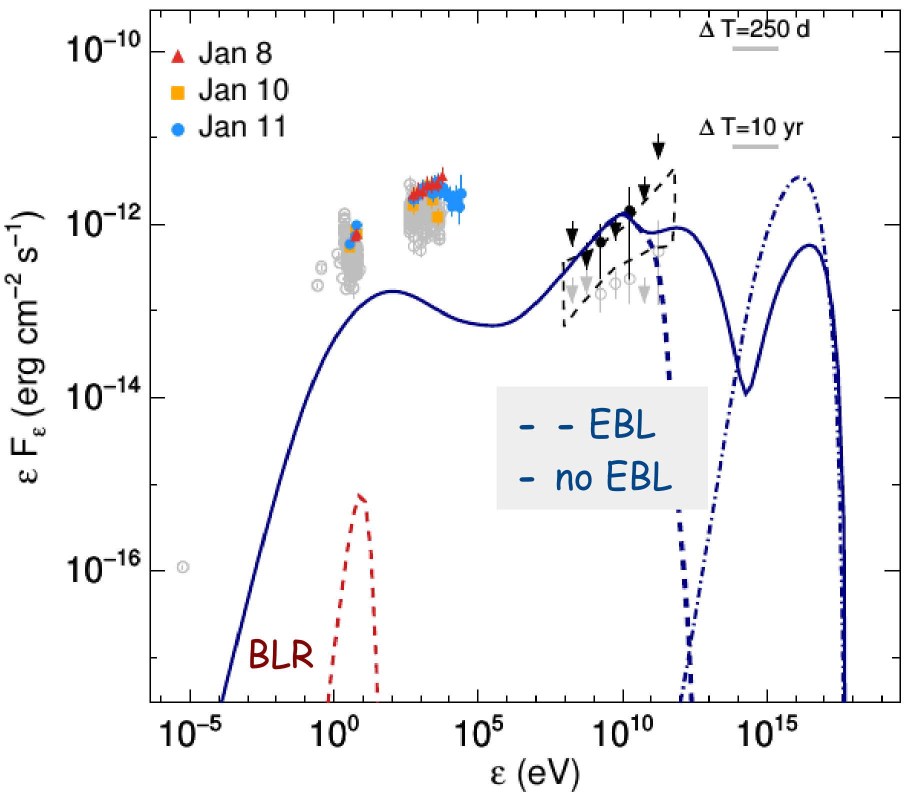
Findings:

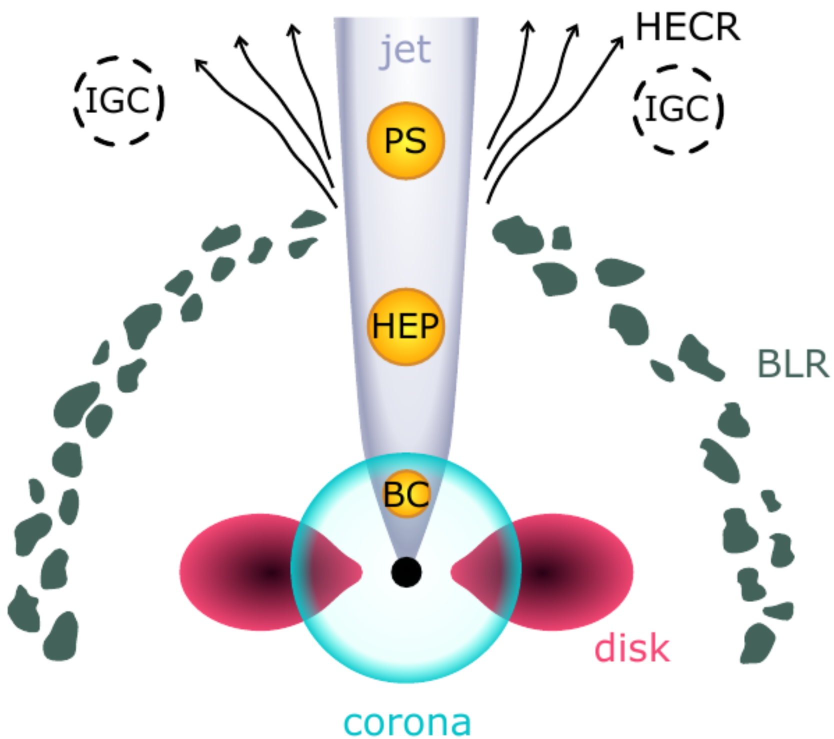
- Applies to transient & persistent emissions
- EM cascade peaks at sub-MeV energies
- Cannot explain optical/UV, X-rays and γ-ray emissions

Alternative theoretical scenarios (HEP)

Hidden External Photons (HEP)

- Weak BLR ? (L_{BLR} < 10^{43} erg/s)
- Production from sub-pc jet
- Typical jet Lorentz factor (Γ~25)
- Weak magnetic field (B~1 G)
- Size (R~2 10^{15} cm)





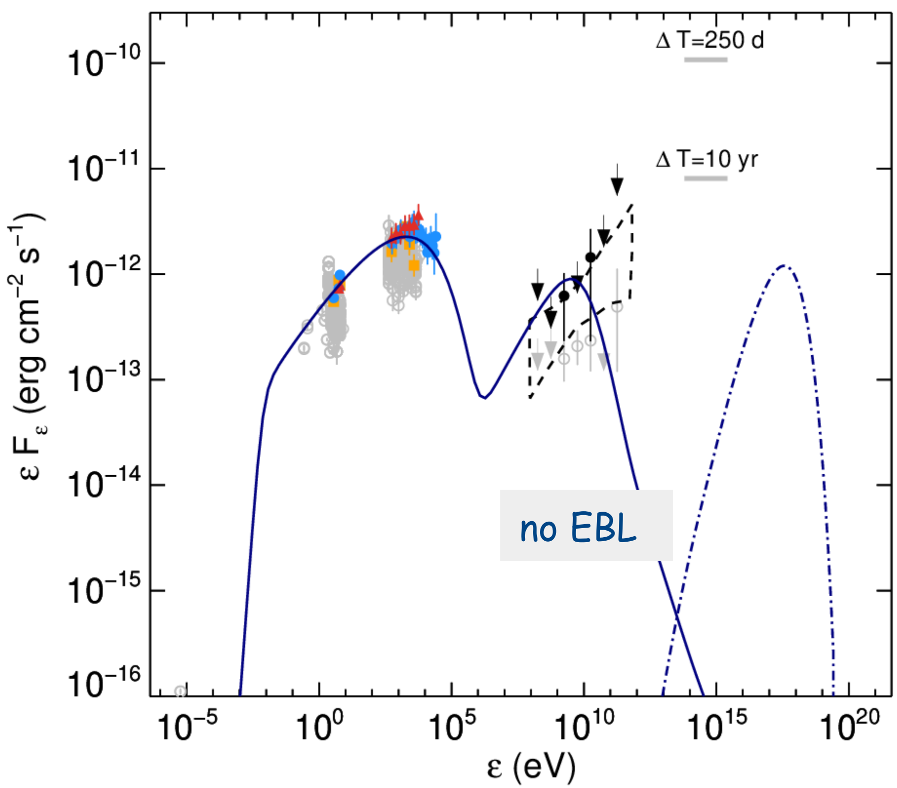
Findings:

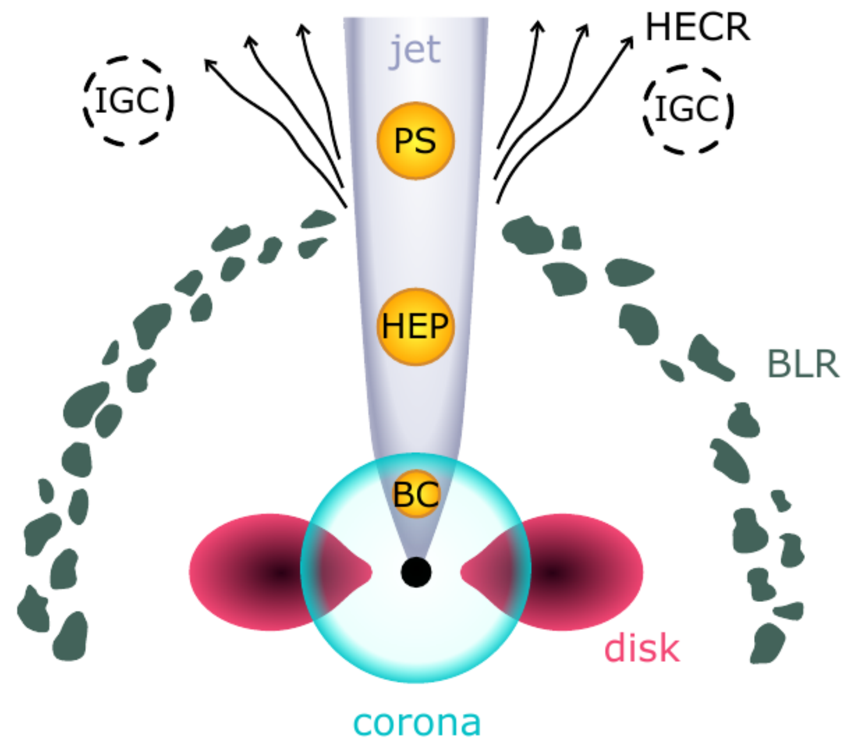
- Applies to transient & persistent emissions
- UV & soft X-rays from the same region or not
- Enhanced neutrino flux by a factor of ~3

Alternative theoretical scenarios (PS)

Proton Synchrotron (PS)

- Ultra-high energy protons in jet ($E_{p,max}$ ~ 10 EeV)
- Production from sub-pc jet
- Typical jet Lorentz factor (Γ~10)
- Strong magnetic field (B~100 G)
- Size (R~10^{15} cm)





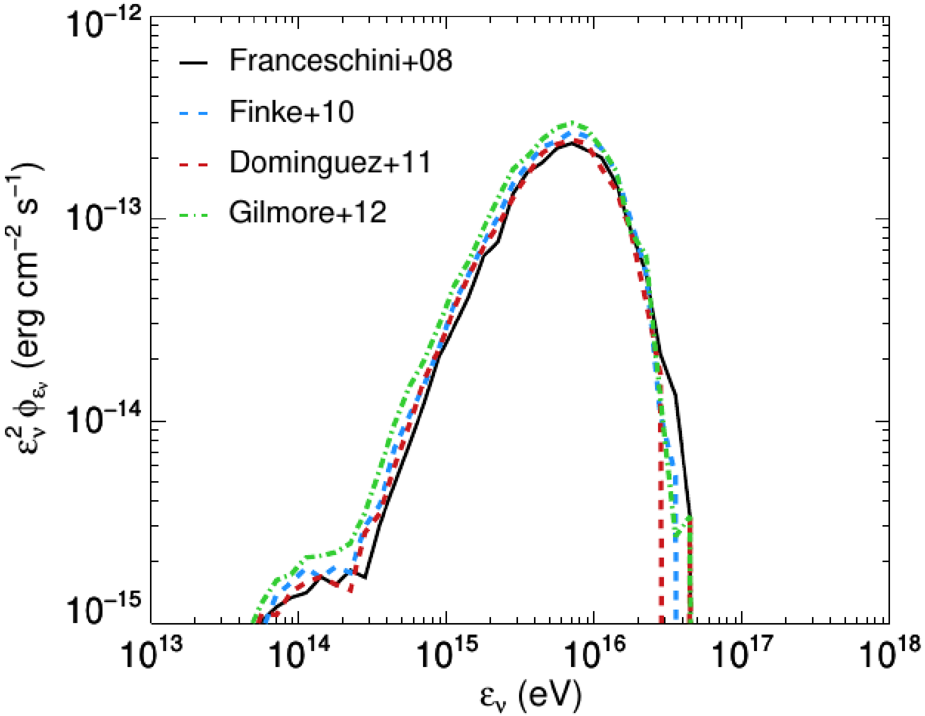
Findings:

- Can explain the transient MW emission
- Neutrino flux peaks at EeV energies
- Neutrino flux similar to leptohadronic models

Alternative theoretical scenarios (IGC)

Intergalactic cascade (IGC)

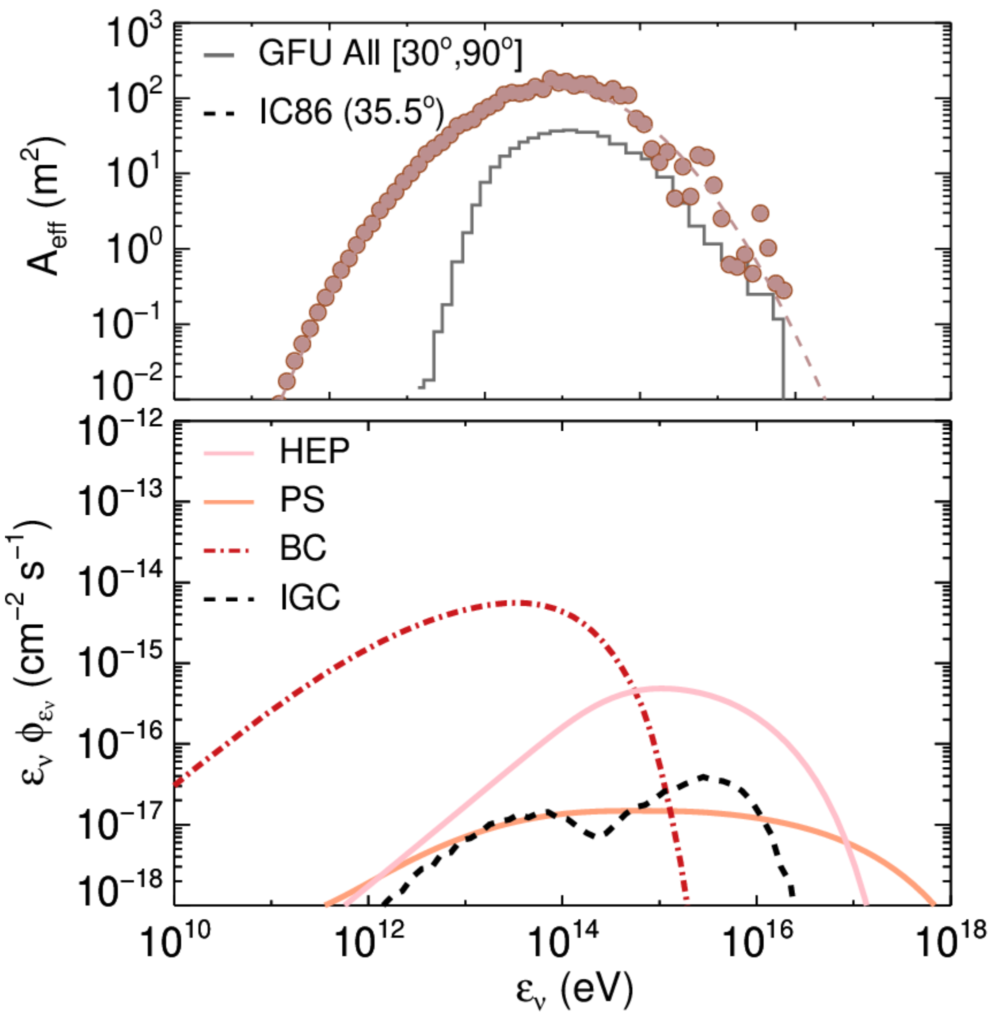
- Ultra-high energy protons escaping the jet ($E_{p,max}$ ~ 0.2 EeV, L_{CR}~L_{Edd})

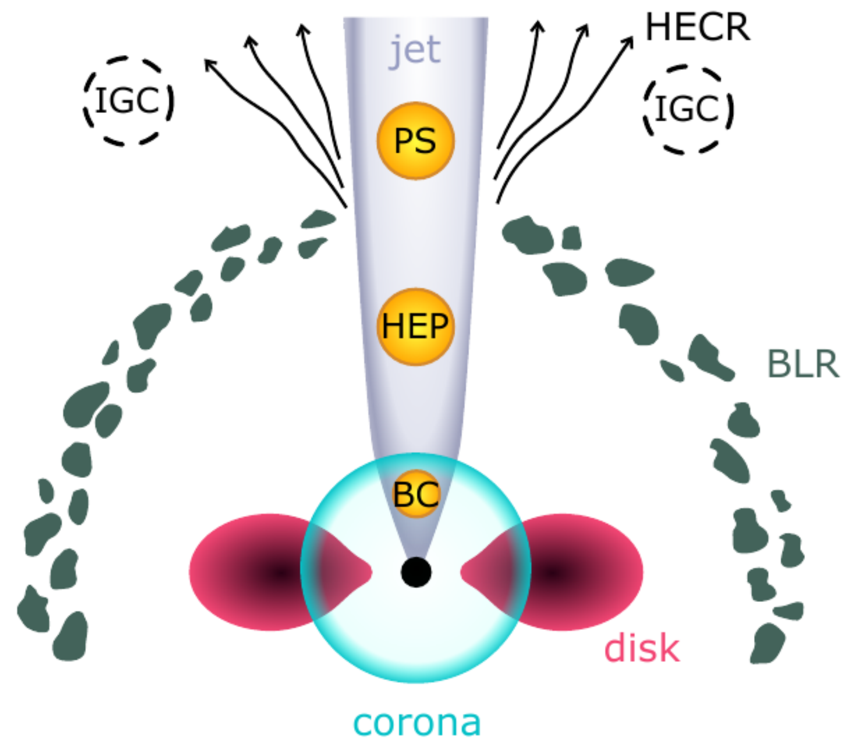


Findings:

- Applies to persistent EM emissions
- IGC γ-ray emission does not overshoot LAT data
- Lower neutrino flux than leptohadronic models

Alternative theoretical scenarios

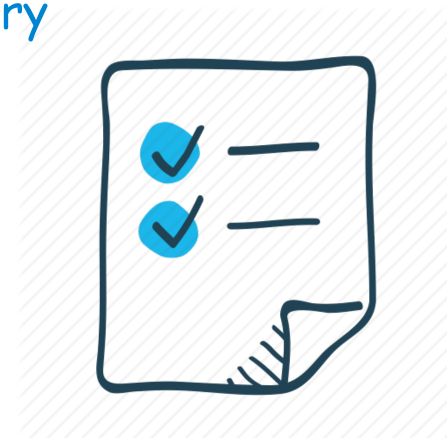




Model	State	$\dot{\mathcal{N}}_{\nu_\mu+\bar{\nu}_\mu}$(> 100 TeV) ($\times 10^{-4}$ yr^{-1}) Alert (PS)	$\mathcal{P}\|_{1\,\nu_\mu \text{ or } \bar{\nu}_\mu}$ (> 100 TeV) Alert (PS)
HEP	transient high	50 (190)	0.3 (1)%
PS	transient high	2.1 (7.3)	0.01 (0.05)%
BC	persistent average	33 (370)	3 (30)%
IGC	persistent average	3.6 (10)	0.4 (1)%

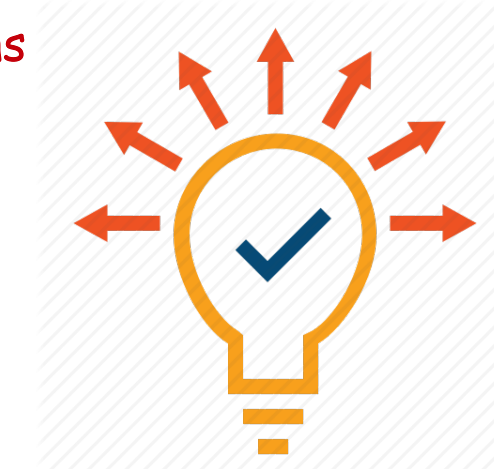
Summary & Conclusions

Summary



- 3HSP J095507.9+355101 is an extreme synchrotron blazar possibly associated with IceCube-200107A.
- Hard X-ray flare (Jan 8-11 2020) followed by ~40 d high X-ray flux state.
- Association of IceCube-200107A with hard X-ray flare is likely coincidental.
- There is ~1% (3%) probability of the neutrino coming within 10 yrs in the Leptohadronic scenario (Blazar Core model) with the real-time IceCube alert analysis.

Conclusions



- IceCube-Gen 2 could detect ~1-3 muon neutrinos in 10 yrs. If not, most promising neutrino models could be constrained.
- If an IceCube archival search finds additional neutrinos, our models have to be revisited.
- If ~ 100 blazars similar to 3HSP J095507.9+355101 emit comparable neutrino flux, the summed expectation can be ~1.
- No TeV emission predicted in most promising neutrino emission model. Are extreme TeV blazars weak PeV neutrino emitters?