Blazar phenomenology and the first neutrino emitting CR accelerator TXS 0506+056

Animation by Science Communication Lab & DESY

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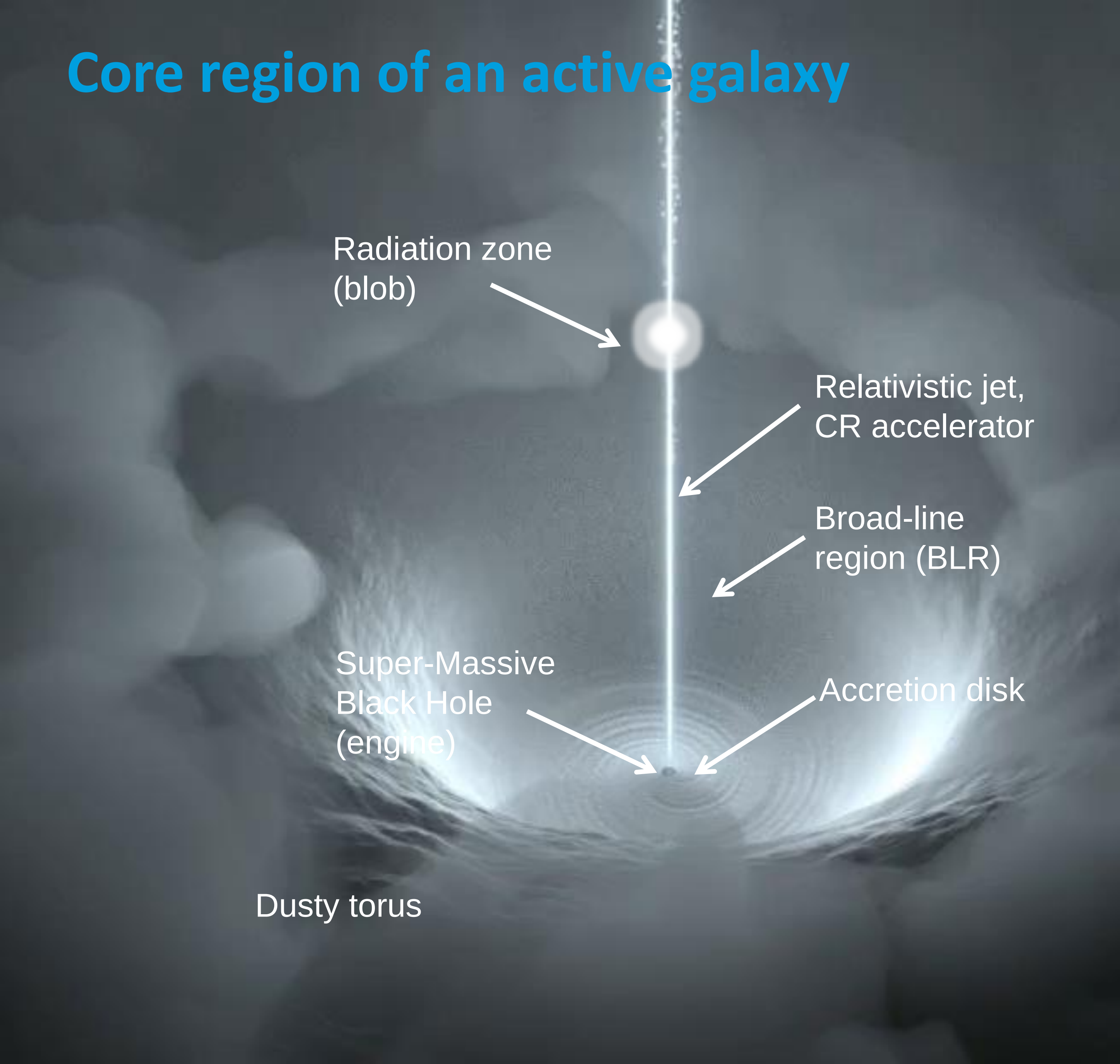
What is a blazar?

- Active core (nucleus) of a galaxy
- Energy extracted from the Super-Massive Black Hole (SMBH) drives a jet
- The jet is oriented towards the observer (us)
- Characteristic radiation pattern (SED)
- Emits bright flares every couple of years that last for weeks or months

Animations by Science Communication Lab and DESY:
check out https://multimessenger.desy.de/ for interactive version

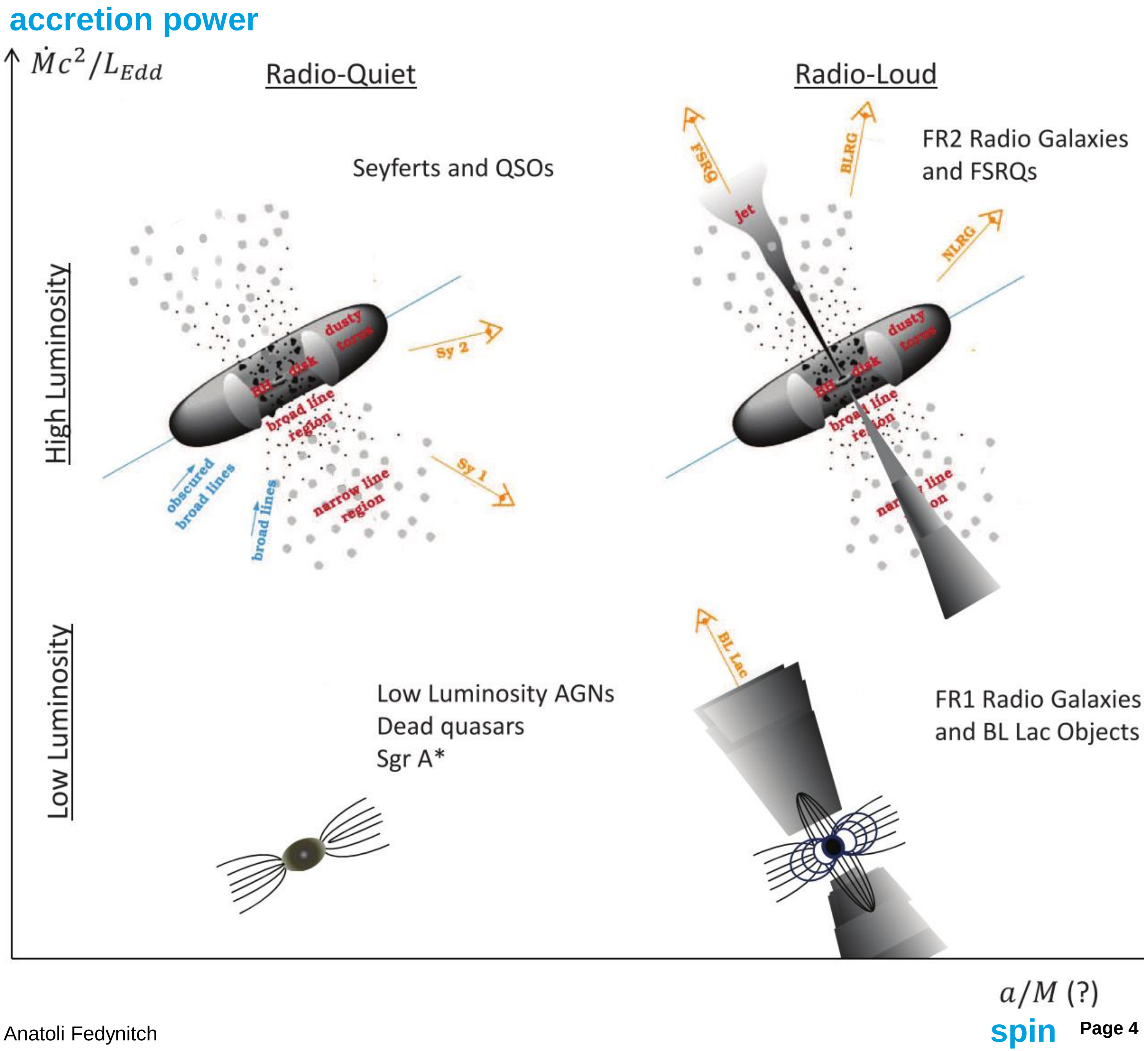
Core region of an active galaxy



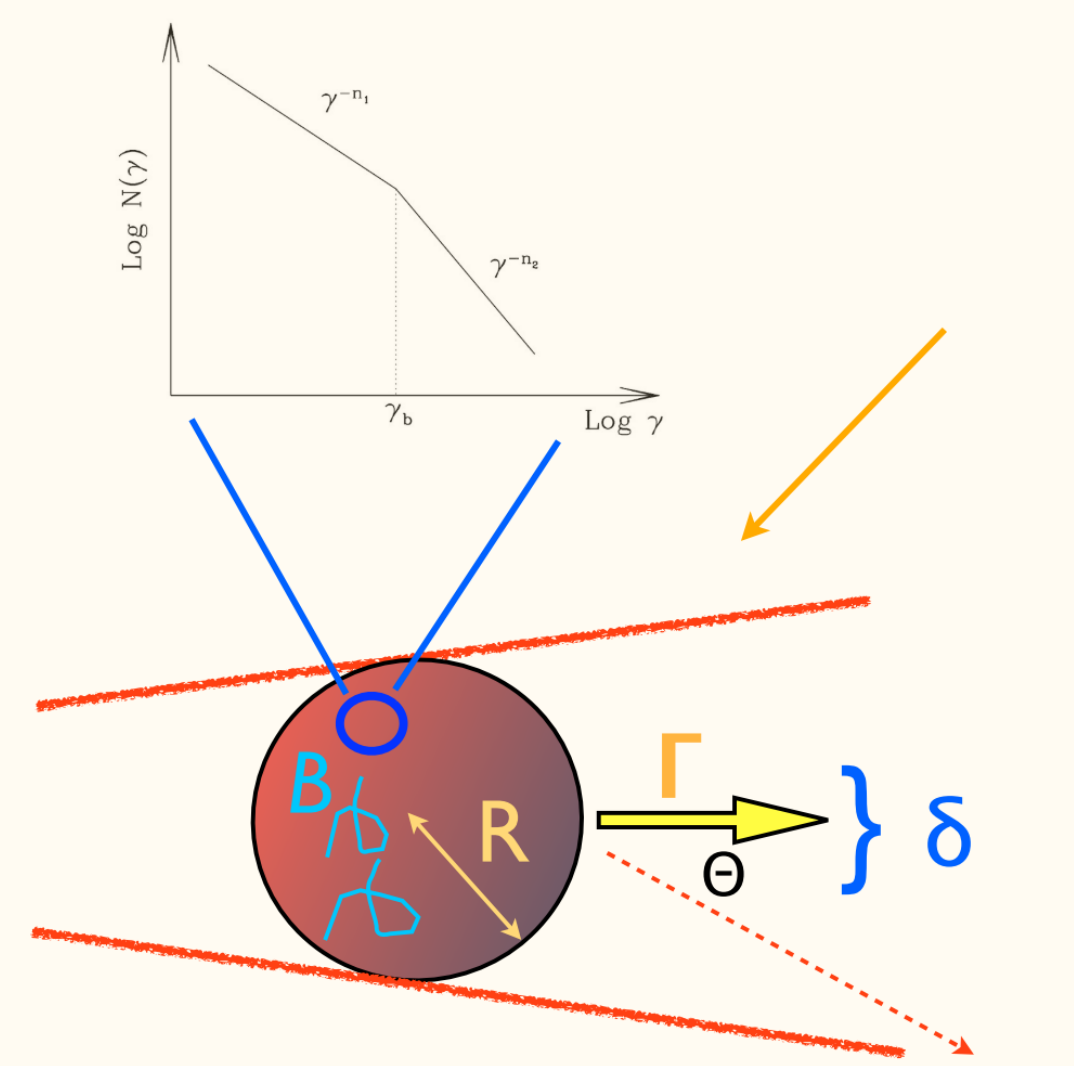
- SMBH drives accretion disk
- The radiation from the disk heats the environment; BLR and Torus
- Accretion of matter drives jet (of galactic dimension ~ kpc)
- Turbulent flow and plasma instabilities in the jet form radiation zones (blobs)
- Electrons and **protons** accelerate to ~PeV energies
- Radiation off relativistic particles produces observed spectrum

AGN/Blazar types

- In fact there **are many “blazars”**, but they are not necessarily called blazars
- **If emission** of messengers (Cosmic Rays and neutrinos) is **not beamed** then many **more dim sources** as known from gamma-ray catalogs
- Two interesting blazar types for high-energy observations are **BL Lacs & FSRQs**



Radiation from the “blob”



$\gamma + \gamma \rightarrow e^+ + e^-$
$\gamma + e \rightarrow \gamma + e$ (IC)
$e + B \rightarrow e + \gamma$ (syn.)

Leptonic cascade

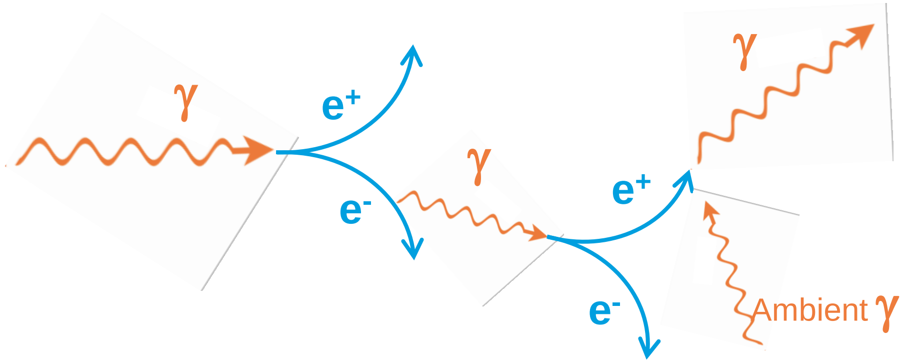
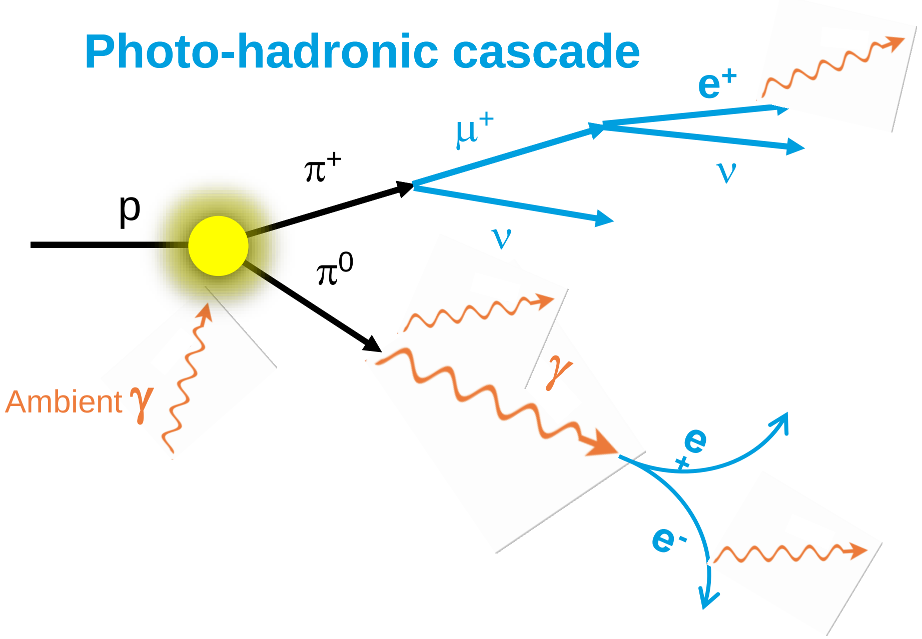
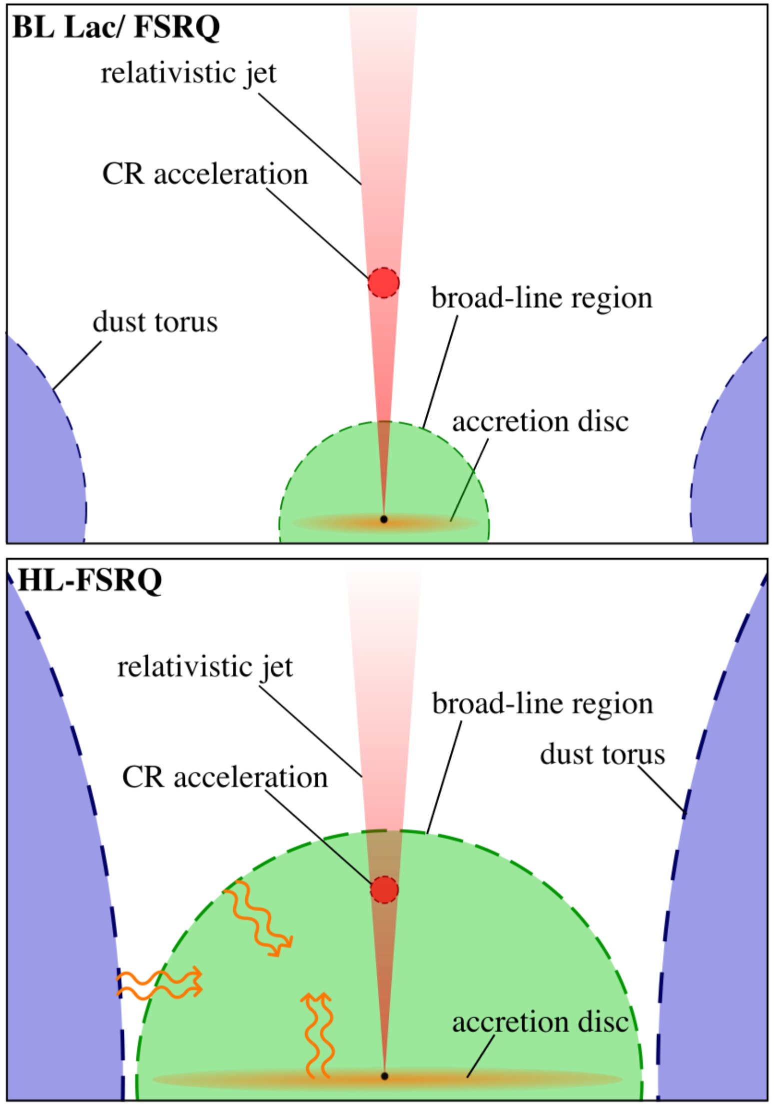


Photo-hadronic cascade



BL Lacs vs Flat Spectrum Radio Quasars (FSRQ)

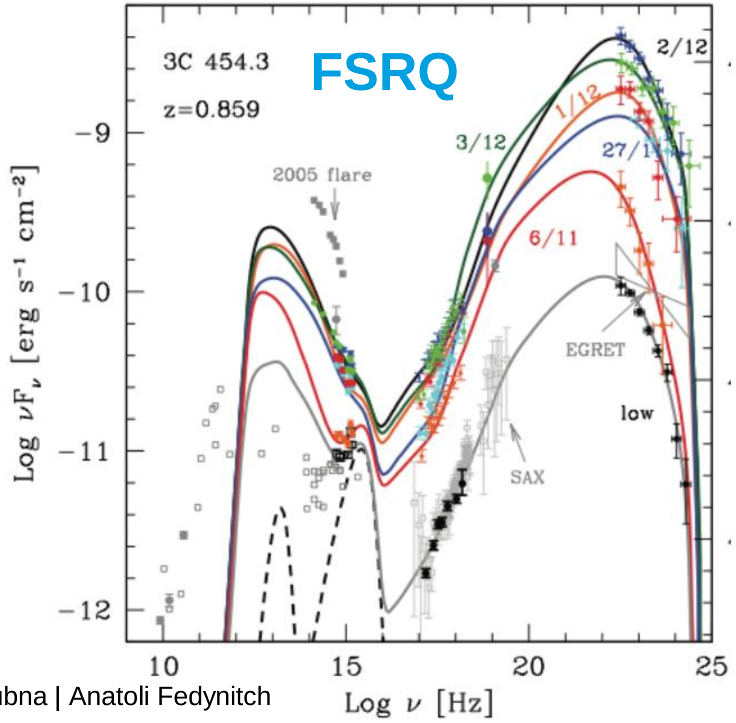
Rodrigues, AF, Gao, Boncioli, Winter, ApJ 854 (2018)



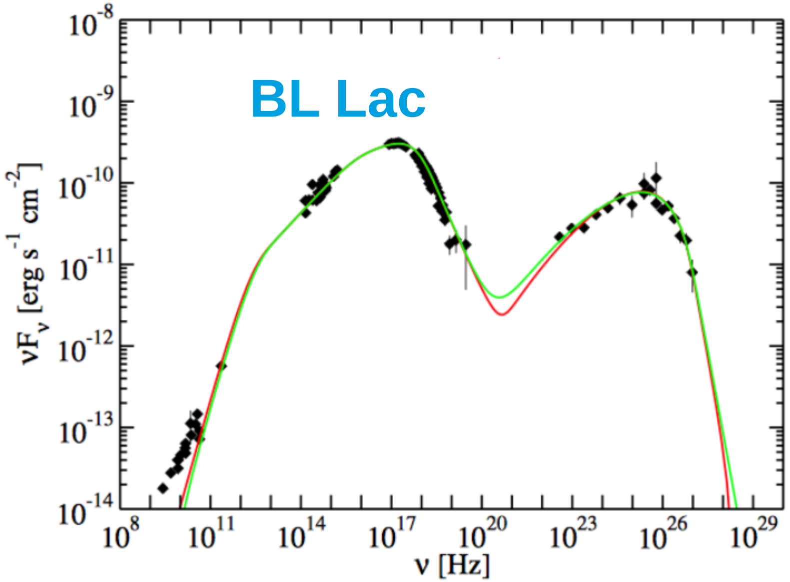
BL Lac:

1. (left) Synchrotron hump
2. (right) inverse Compton hump
3. No lines, no dust, etc.
4. Less luminous than FSRQ

Bonnoli+ 11



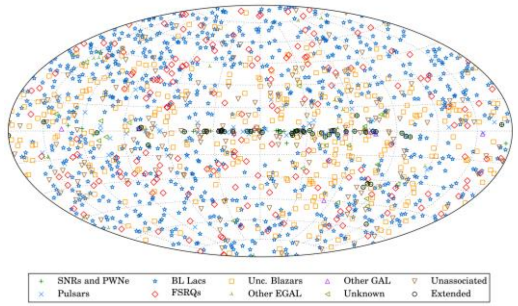
Abdo+ 11



FSRQ:

1. Line, disk and thermal emission
2. High luminousity (high second peak)
3. Low maximal photon energy

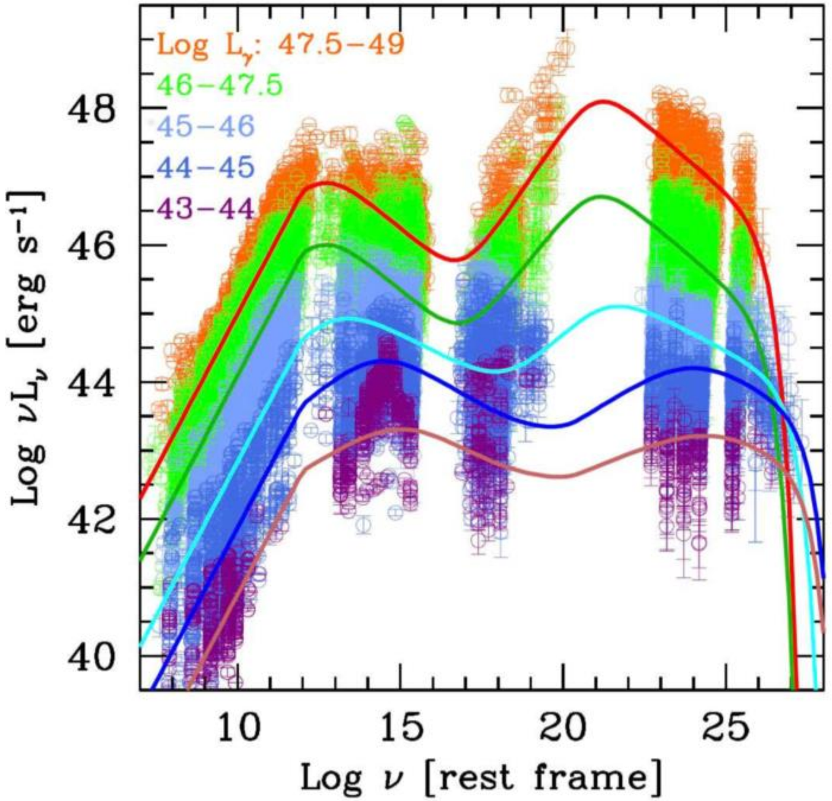
(controversial) Blazar sequence: distribution of source classes

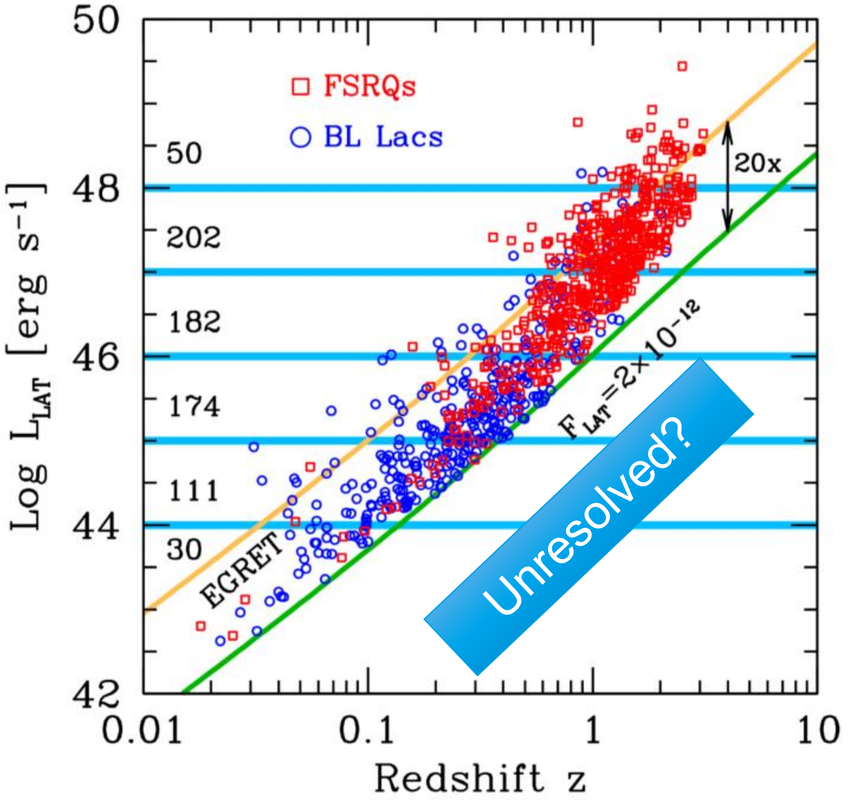


Select blazars with measured redshifts

Boost into source frame

Real relation between luminosity, type and distance? Redshift of BL Lacs harder to determine; **exp. biases**

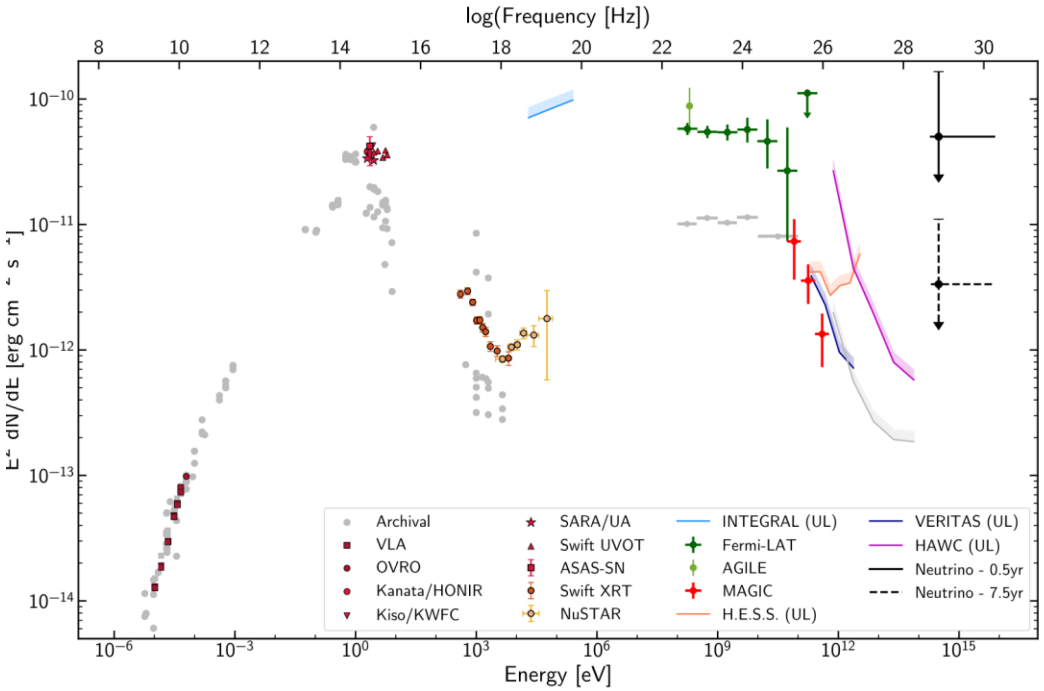




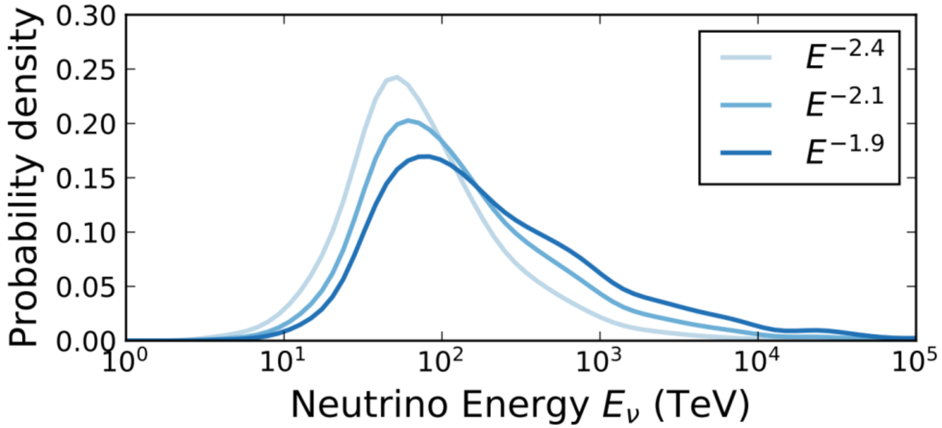
Ghisellini et al. 2017, arXiv: 1702.02571

Theoretical challenges of the TXS0506+056 MM observation

IceCube, Fermi, MAGIC,++, Science 2018

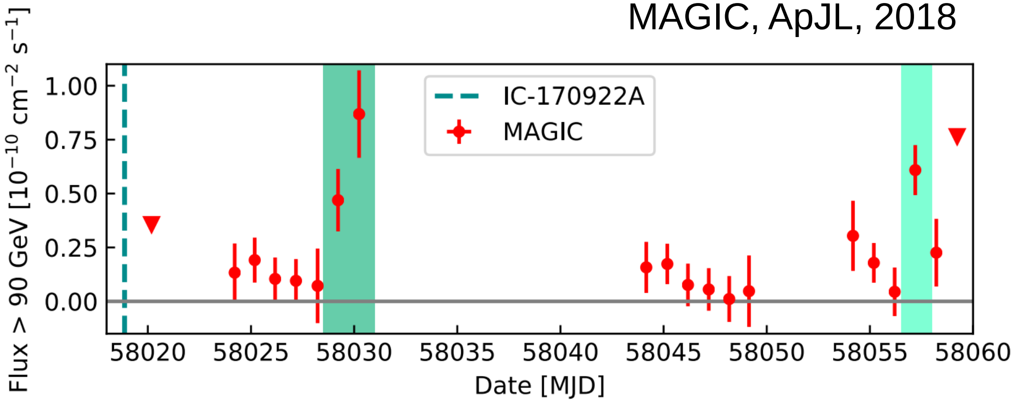


Explain the **neutrino** is detected **during flare and not during quiscence**



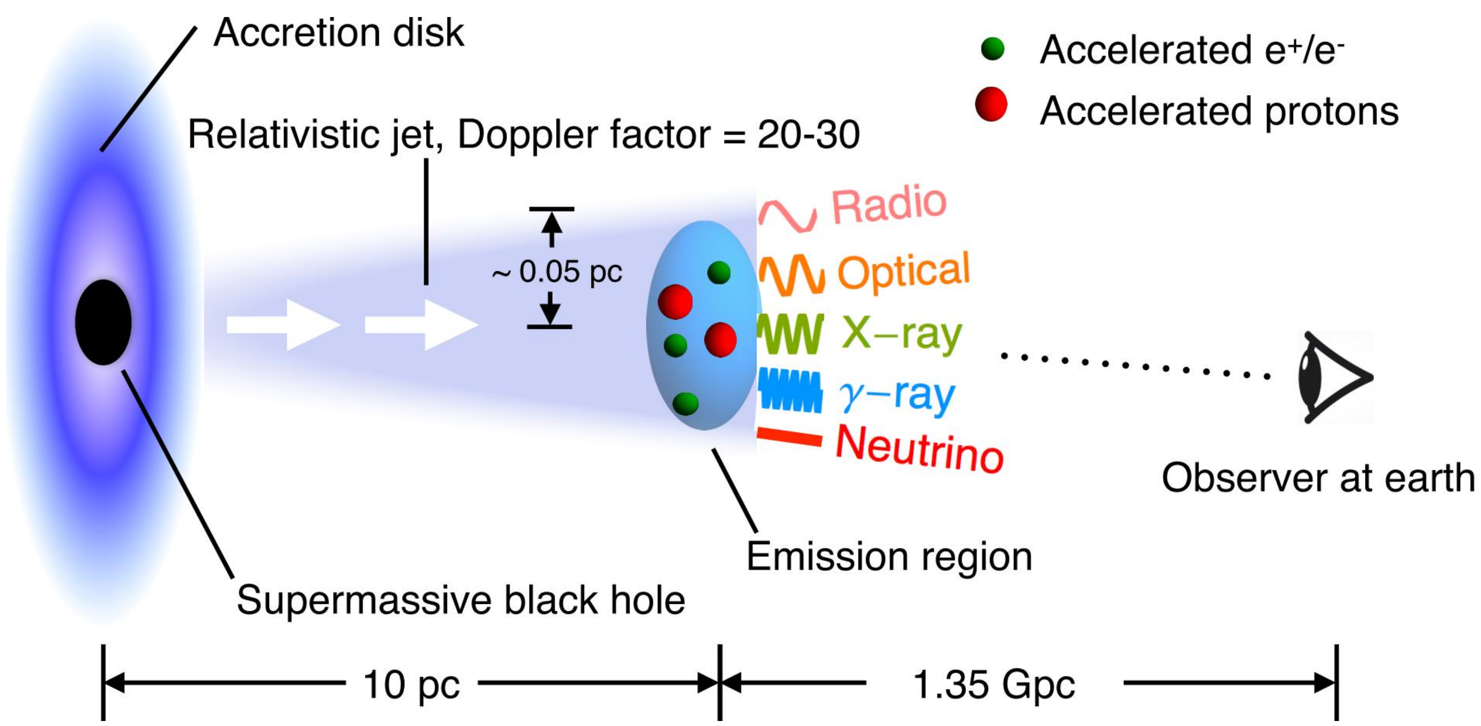
Neutrino energy around a **few hunderds TeV**

MAGIC, ApJL, 2018



Delayed or **flikering** emission of **TeV photons**

Source model



S. Gao, AF, W. Winter and M. Pohl, to appear soon in Nature Astronomy

- **One or multiple** emission regions (**blob** or plasmoid) is **spherical** in its rest frame
- Radiation and particle momenta assumed **isotropic**
- **Injection** of accelerated particles (**no** explicit **simulation**)
- Particles **escape** at **constant** rate
- Studied models with a **one** and **two zones**

Time-dependent hadro-leptonic code (AM³)*

***Astrophysical Modeling with Multiple Messengers**

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

- **Numerically** solves a set of **coupled** transport **equations** for
  - Photons
  - e^+, e^-
  - Protons and neutrons
  - pions + muons (implicit)
  - neutrinos

	injection	escape	synchrotron	inverse Compton	$\gamma\gamma \leftrightarrow e^\pm$	Bethe-Heitler	$p\gamma$
e^-	$Q_{e,inj}$	$\alpha_{e,esc}$	$\dot{\gamma}_{e,syn}$, $D_{e,syn}$	$\dot{\gamma}_{e,IC}$, $D_{e,IC}$, $\alpha_{e,IC}$, $Q_{e,IC}$	$\alpha_{e,pa}$, $Q_{e,pp}$	Q_{BH}	$Q_{e,p\gamma}$
e^+	–	$\alpha_{e,esc}$	$\dot{\gamma}_{e,syn}$, $D_{e,syn}$	$\dot{\gamma}_{e,IC}$, $D_{e,IC}$, $\alpha_{e,IC}$, $Q_{e,IC}$	$\alpha_{e,pa}$, $Q_{e,pp}$	Q_{BH}	$Q_{e,p\gamma}$
γ	–	$\alpha_{f,esc}$	$\alpha_{f,ssa}$, $Q_{f,syn}$	$\alpha_{f,IC}$, $D_{f,IC}$	$\alpha_{f,pp}$, $Q_{f,pa}$	$\alpha_{f,BH}$	$\alpha_{f,p\gamma}$, $Q_{f,p\gamma}$
p	$Q_{p,inj}$	$\alpha_{e,esc}$	$\dot{\gamma}_{p,syn}$, $D_{p,syn}$	$\dot{\gamma}_{p,IC}$ $D_{p,IC}$, $\alpha_{p,IC}$, $Q_{p,IC}$	–	$\dot{\gamma}_{p,BH}$, $D_{p,BH}$	$\alpha_{p,p\gamma}$, $Q_{p,p\gamma}$
n	–	$\alpha_{f,es}$	–	–	–	–	$\alpha_{n,p\gamma}$, $Q_{n,p\gamma}$
ν	–	$\alpha_{f,es}$	–	–	–	–	$Q_{\nu,p\gamma}$

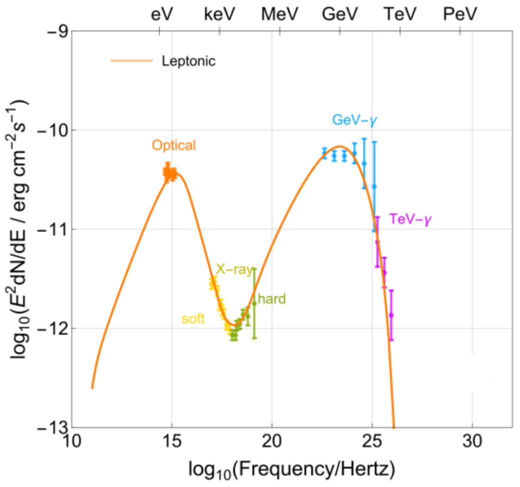
Gao,Pohl,Winter, APJ 843 (2017)

- ~500 energy bins per species
- Energy “bandwidth“ ~20 orders of magnitude (Radio-EeV)
- **Very efficient**: < 2 min to reach stationary solution of time-dependent simulation
- Photo-hadronic interactions following Hümmer et al., APJ 712, 2010

Common types of one-zone models

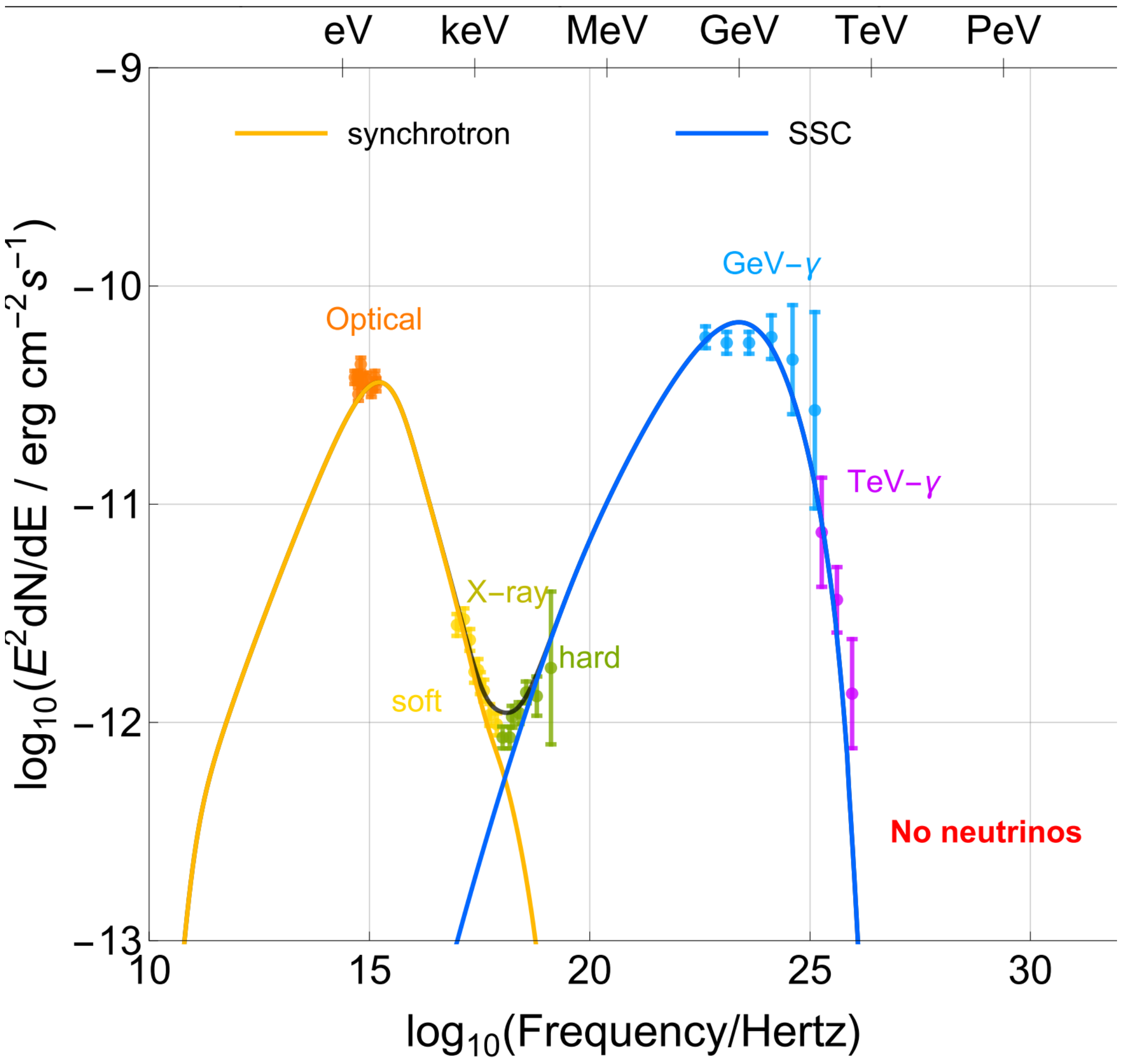
Gao,Pohl,Winter, APJ 843 (2017)

	First peak (eV-keV)	Middle range (keV-MeV)	Second peak (MeV-TeV)	Neutrinos
SSC (Pure leptonic)	**L** Primary e^- synchrotron	**L** SSC	**L** SSC	*0*
LH-SSC (Lepto-hadronic)	**L** Primary e^- synchrotron	**H** Secondary leptonic	**L** SSC by primary e^-	$L_\nu < L_\gamma$
LH-π (Lepto-hadronic)	**L** Primary e^- synchrotron	**H** Secondary leptonic	**H** Secondary leptonic or γ-rays from direct π^0 decay	$L_\nu = L_\gamma$
LH-psyn (Proton synchrotron)	**L** Primary e^- synchrotron	**H** Proton synchrotron or secondary leptonic	**H** Proton synchrotron	$L_n < L_g$, UHE E_n & E_p



We test <u>all</u> current one-zone models
for compatibility with TXS0506+056 observations

Leptonic SSC fit of the flare

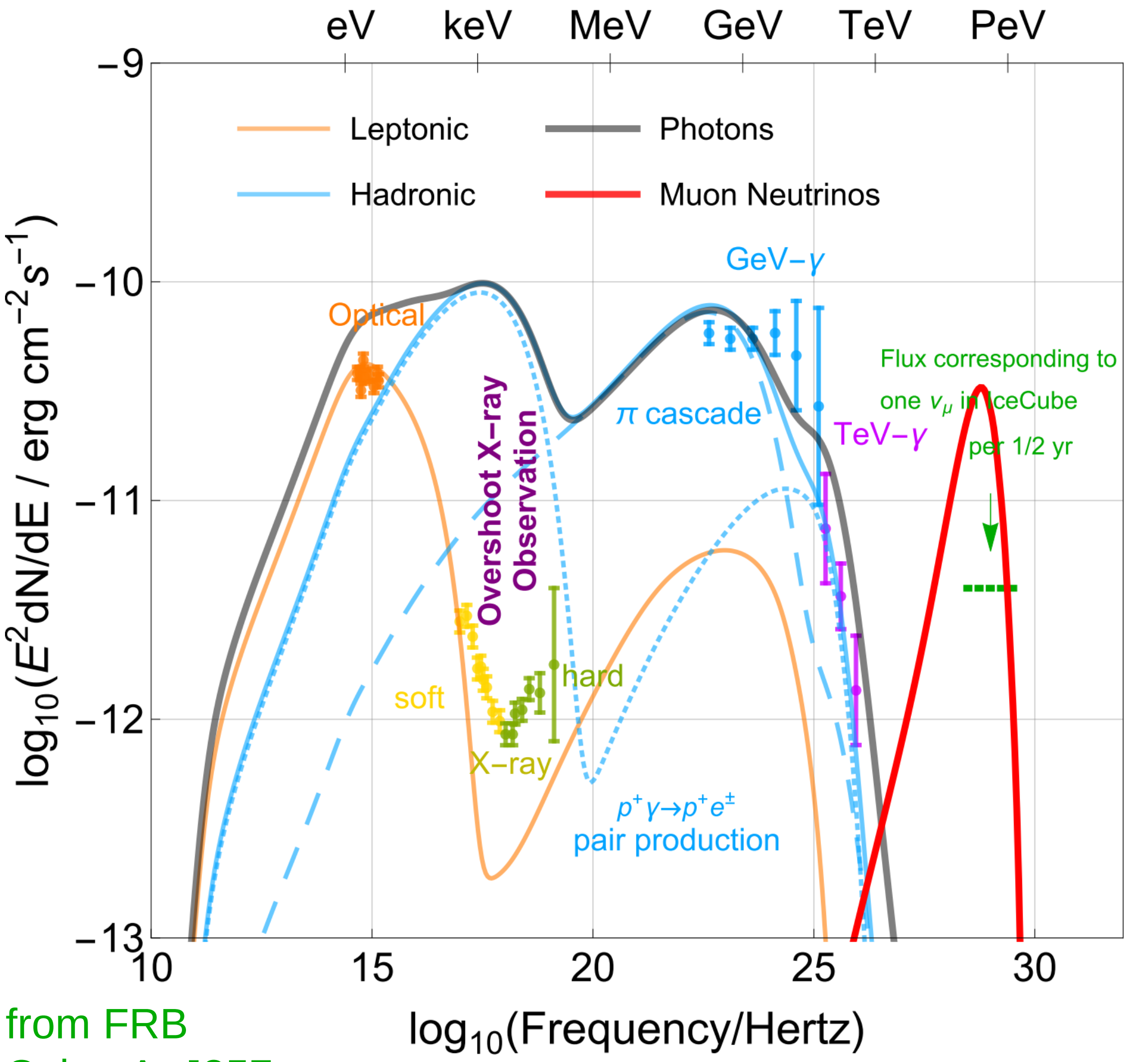


- We find a **good fit** through **extensive parameter scan**
- **Remarkably simple** assumptions r~10^{16} cm, B~0.16G and electrons with a $E^{-3.5}$ spectrum between $10^4 < \gamma < 6\text{x}10^5$
- **If neutrino** association is **real**, **leptonic model** is **excluded**

Keivani et al. 1807.04537

Hadronic model excluded ~~$p\gamma \rightarrow \pi^0 \rightarrow \gamma\gamma$~~

…from fully time-dependent hadro-leptonic calculations

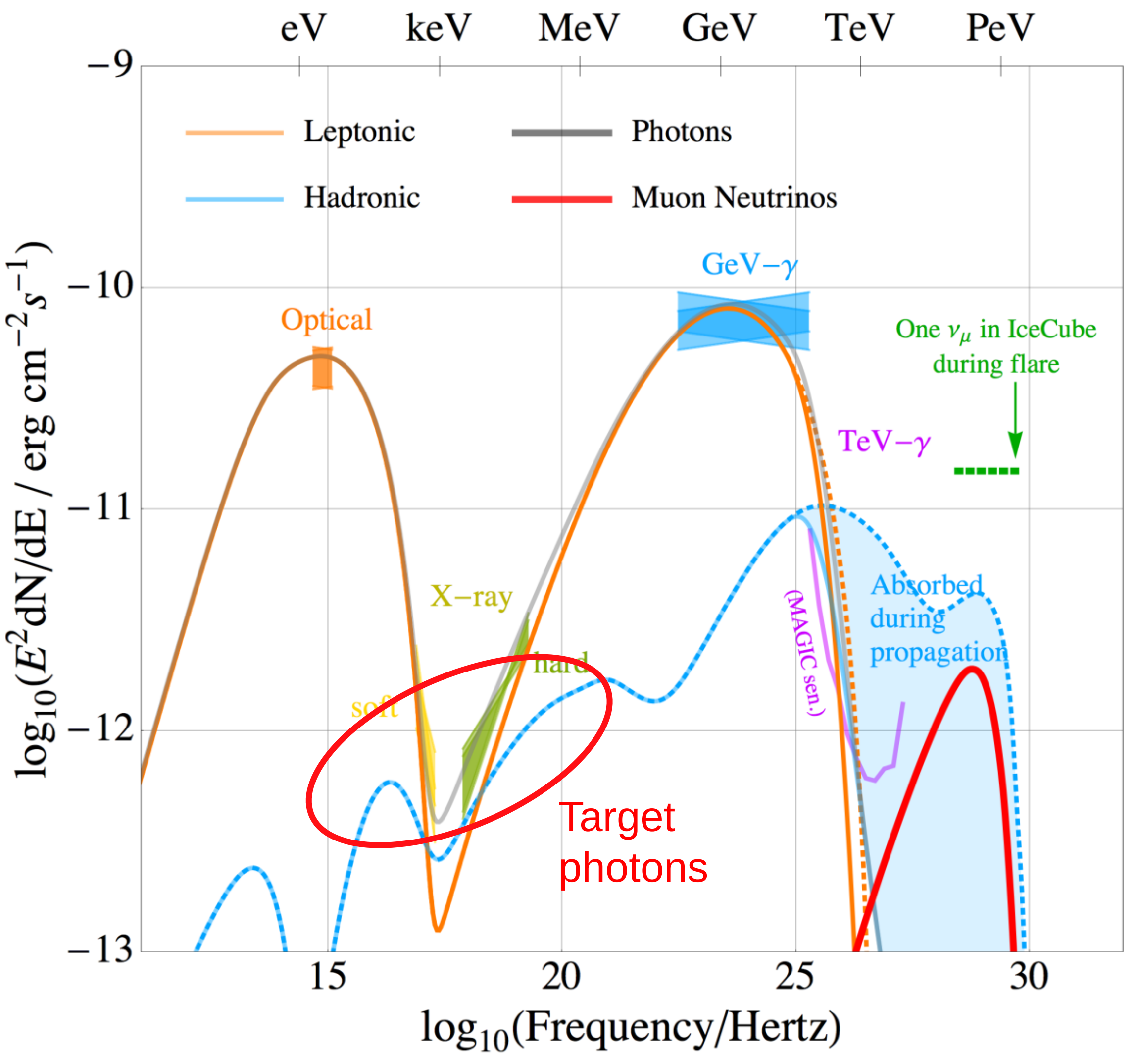


IC eff. area from FRB analysis IceCube, ApJ857

- **Various constraints** from proton-synchrotron, SSC emission, Bethe-Heiler, etc.
- Example (left) for overshooting Bethe-Heitler constrains
- No viable model in large parameter scans
- **Hadronic model excluded**

No obvious correlation between Fermi, TeV and ν lightcurves!

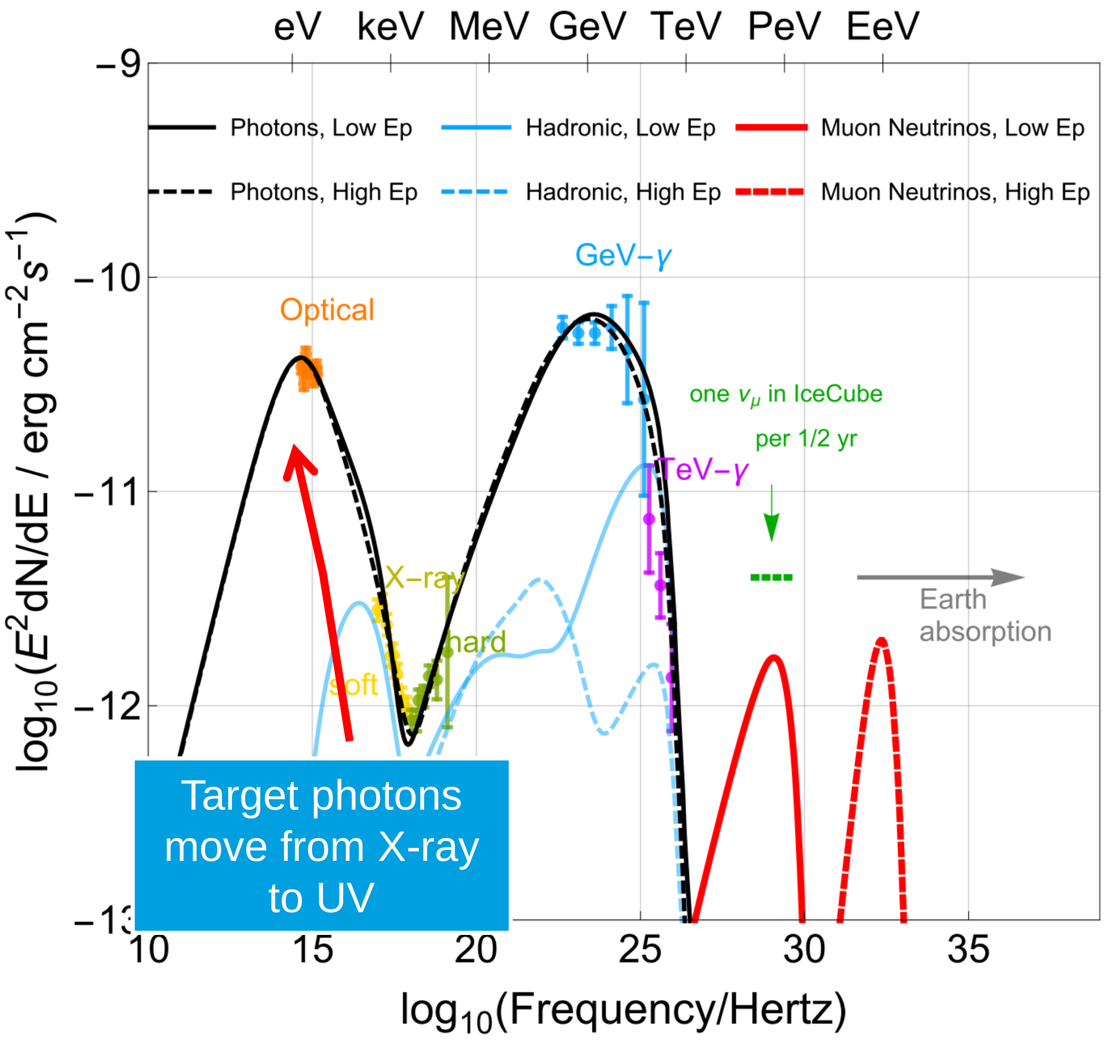
Hybrid lepto-hadronic one-zone model



- **Dominant** part of the SED originates from **leptonic SSC**
- **Sub-leading hadronic component** from proton injection with **max. energy ~4.5 PeV**
- **Reproduces neutrino energy** ~ 0.2 - few PeV
- γγ self-absorption and EBL absorption (z=0.34) cascade down PeV photons to GeV energies
- **X-Ray** variability **sensitive to hadronic** component

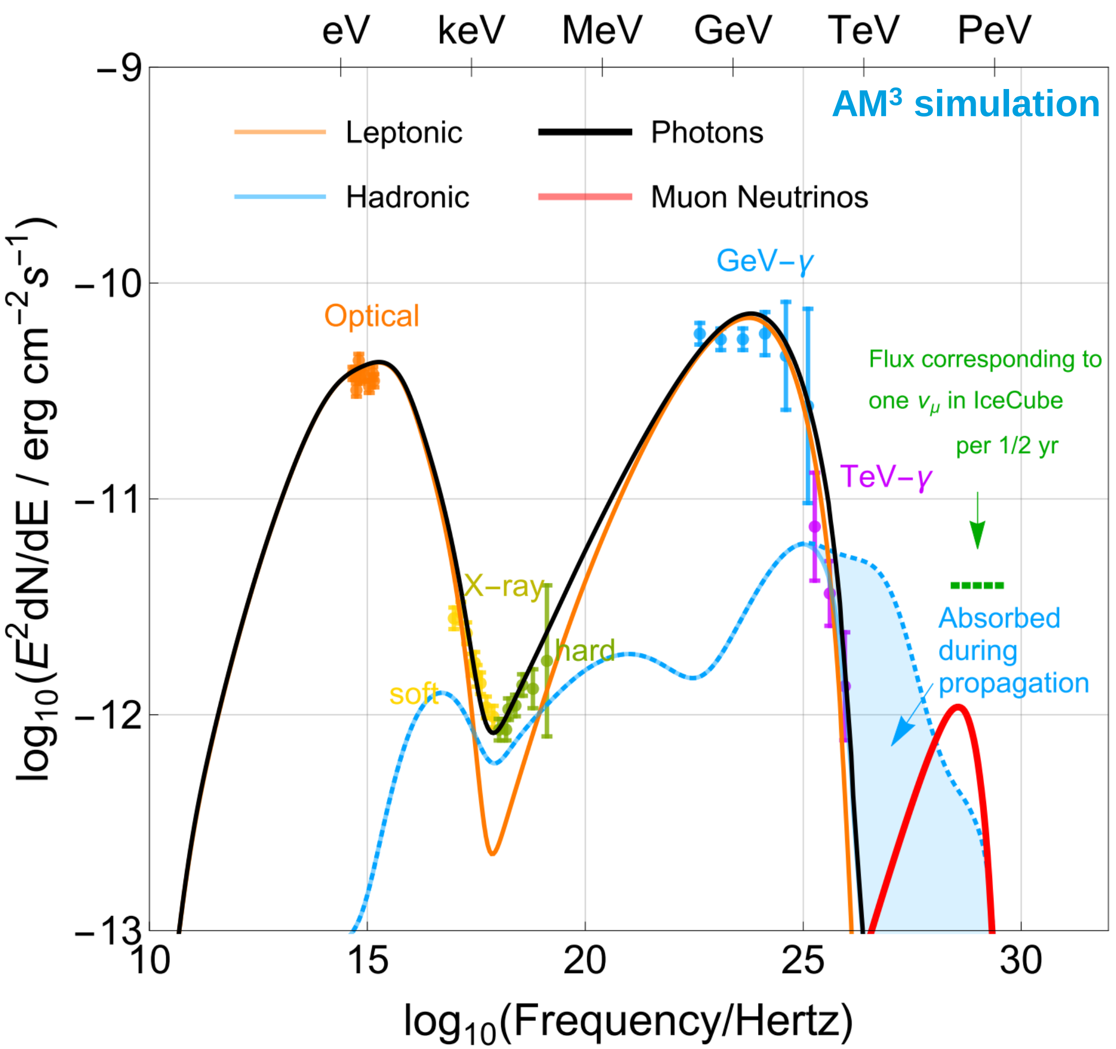
Problem with energy constraints: exceeds Eddington luminosity by 10^3

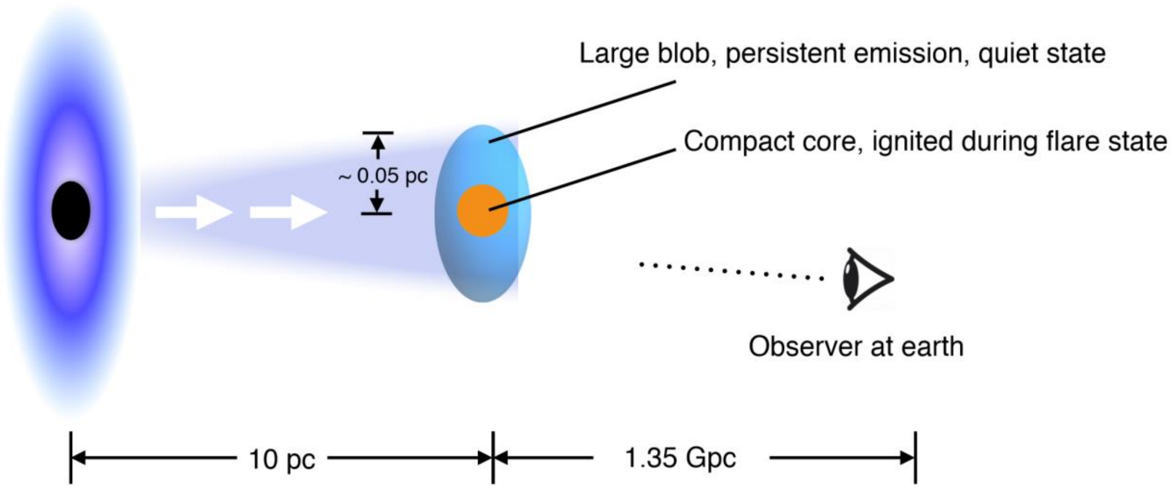
Boost ν efficiency with UHECR injection



- Instead of protons with E_{max} ~4.5 PeV we injected up to **E_{max}~17 EeV**
- **Target photon** energy **moves** down and the **density up** the synchrotron peak
- **Less power** required for the interaction rate and **almost identical SEDs** (many other models use this fact)
- However, **neutrinos** production is **at wrong energy** and a very low rate < 10^{-3}/yr expected

Two zone (core) model





- **Large zone** r~$10^{17.5}$ cm for **quiescent** state
- **Flare** generated through formation of a **compact core** r_{core}~10^{16} cm during the short period of the flare
- To power the core **7xL_{Edd} needed** to saturate X-ray flux, quiescent state is sub-Eddington
- **Neutrino rate is ~0.3/yr**, consistent with the observation of one neutrino during the flare

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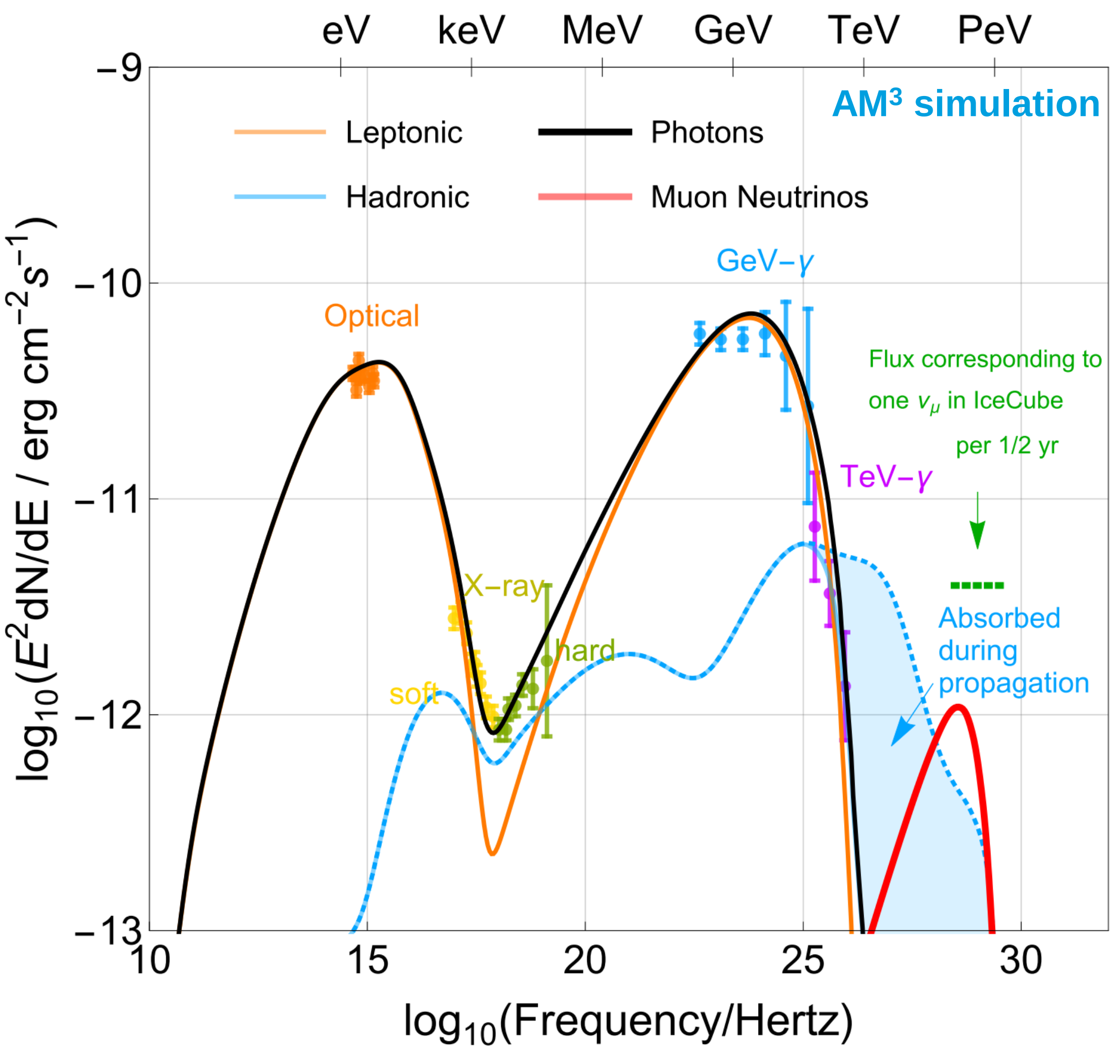

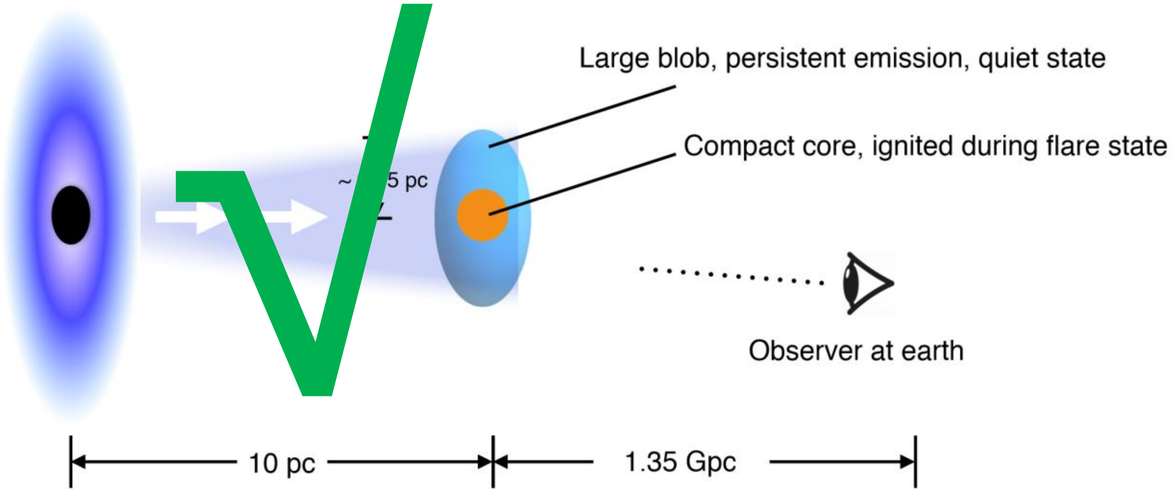

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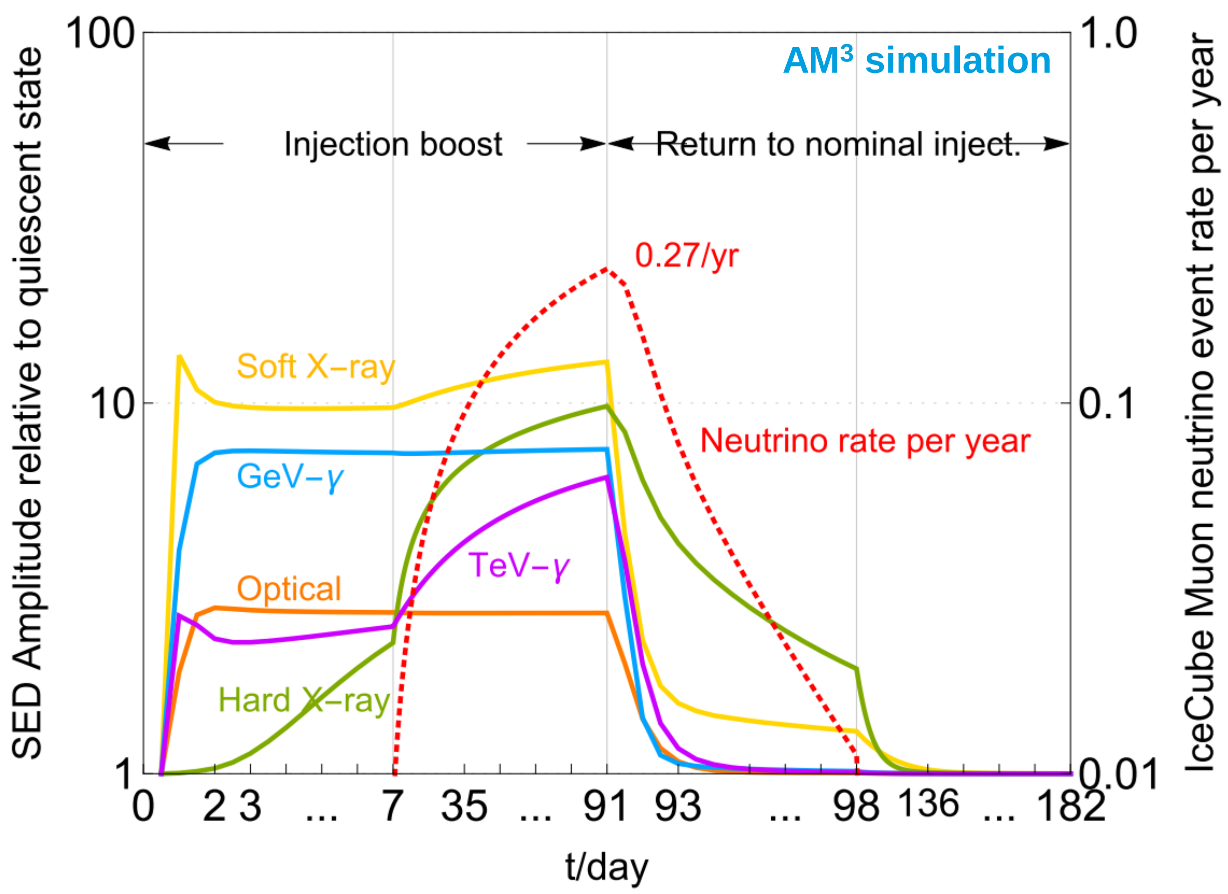
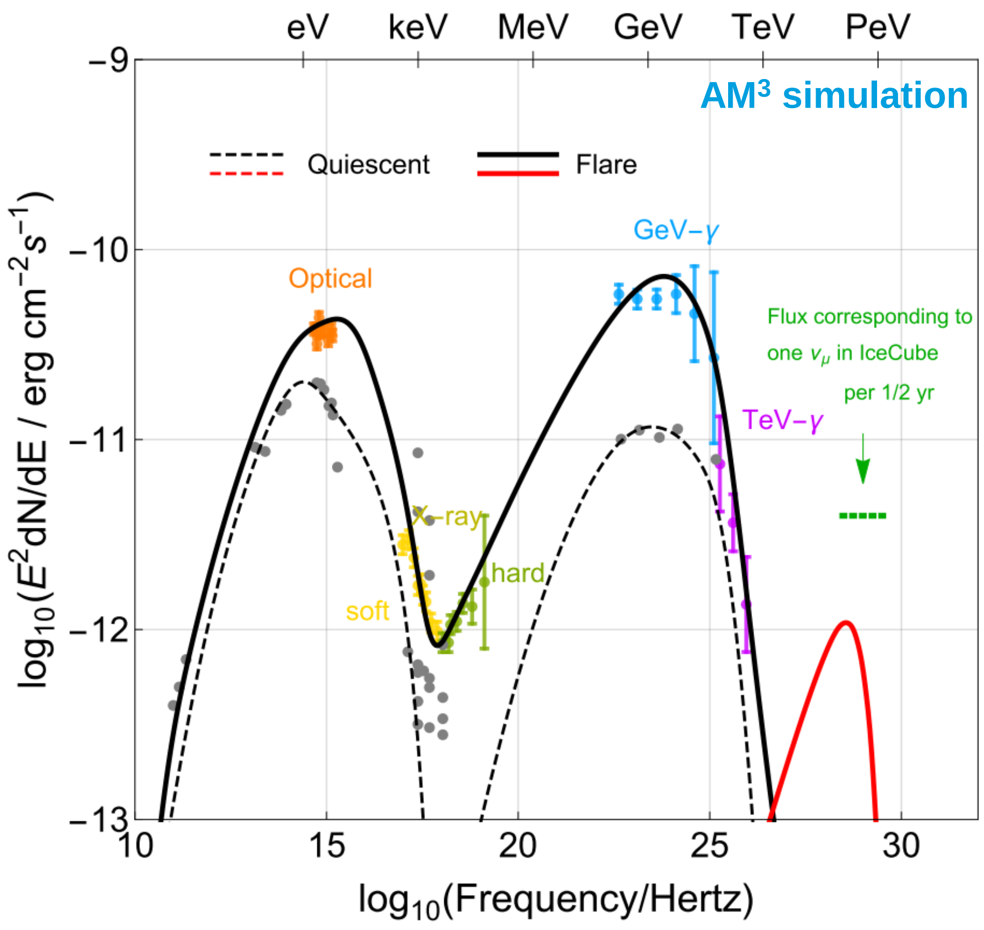
Time dependence of the core model

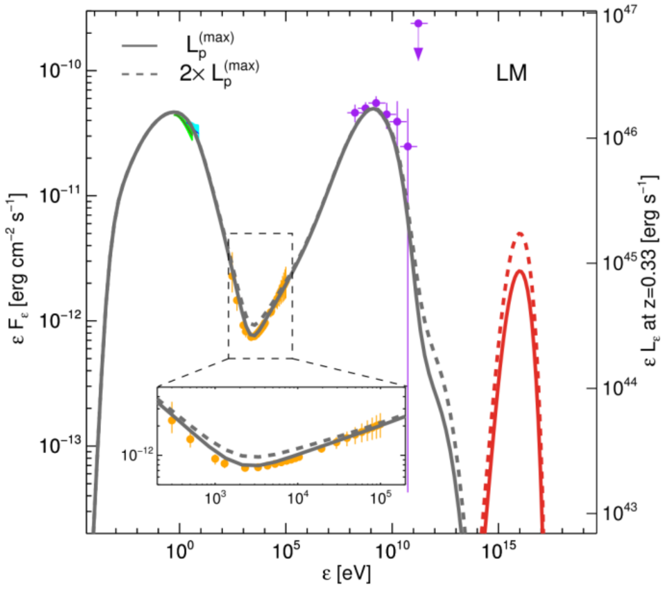


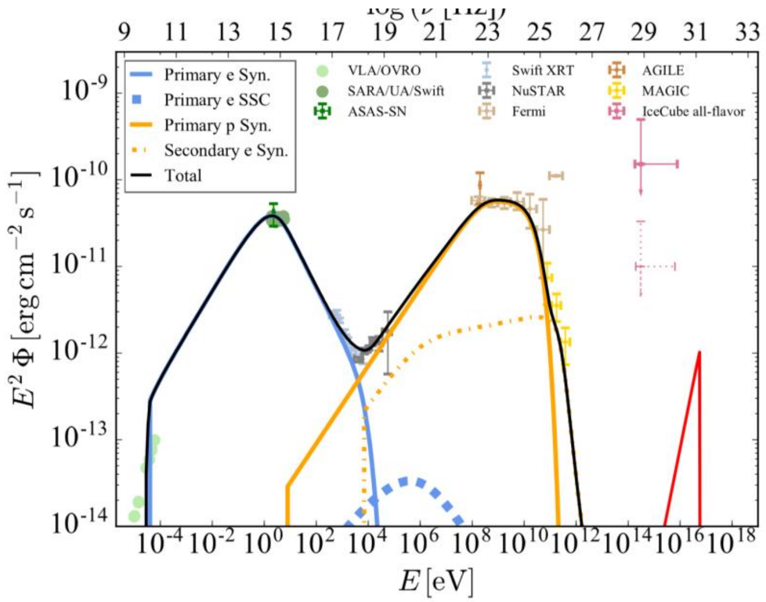


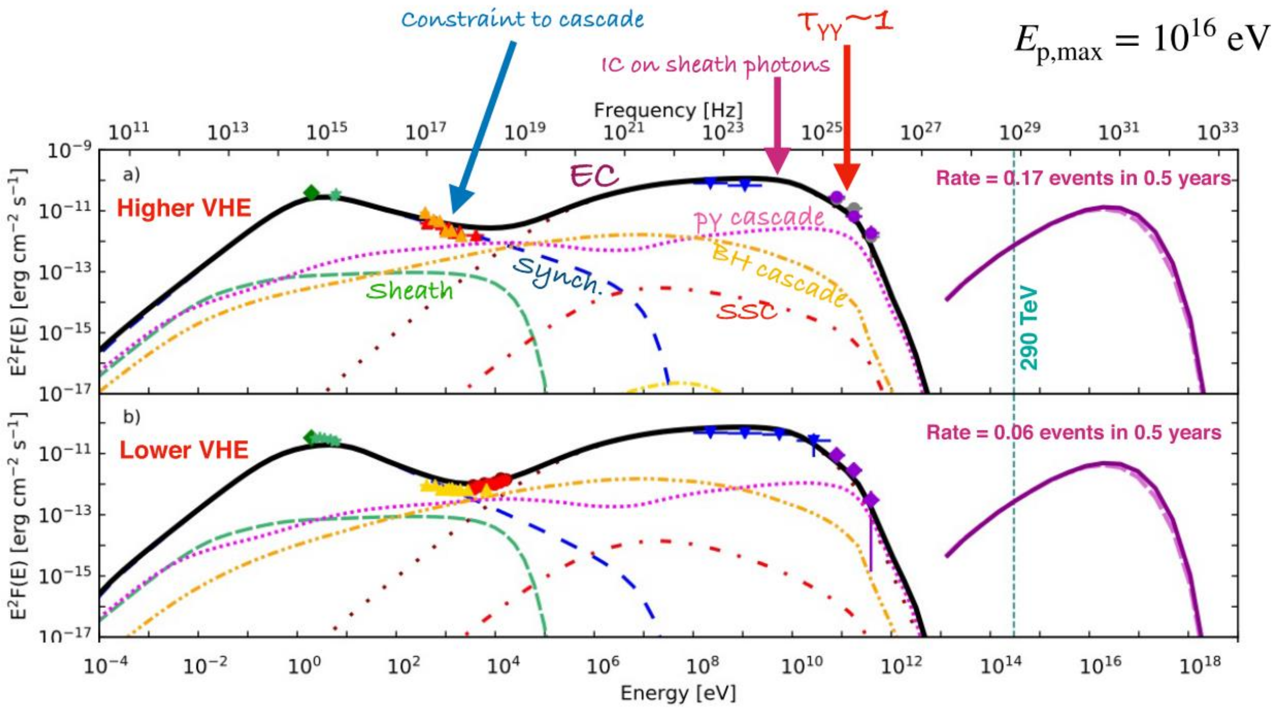
- **Leptonic** processes **react swiftly** to changes in injection
- **Neutrino** emission **needs sustained flare** activity

- **TeV** delay and **flikering** is **natural**
- **Neutrino rate limited by X-rays**

Overview of other explanations for the MM flare







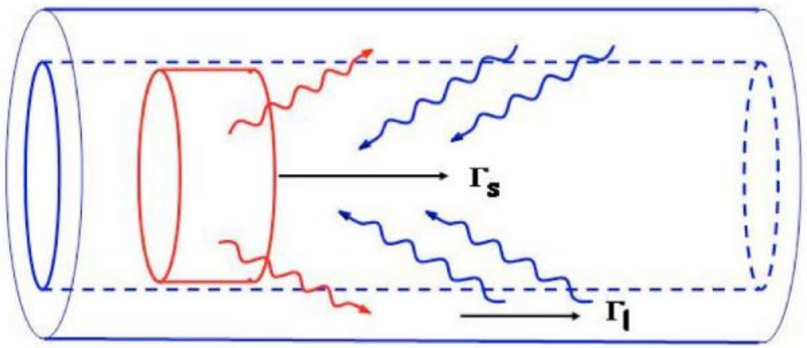
- **Ansoldi et al.** (MAGIC) (1807.04300): UHECR, spine-sheath
- Cerruti et al. (1807.04335): UHECR, proton-syn.
- **Keivani et al.** (AMON) (1807.04537): spine-sheath
- Murase et al. (1807.04748): spine-sheath
- Righi et al. 2018 (ADAF, “re-scattering with acc. disk”)
- **H. Zhang** et al. (2018), UHECR, proton synchrotron

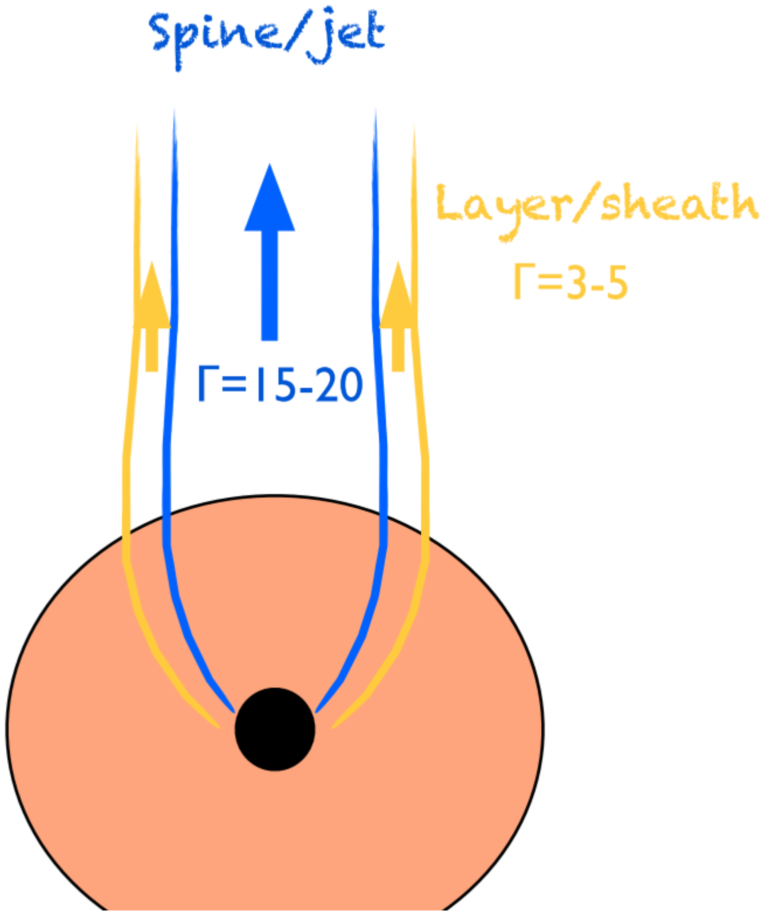
Spine-sheath models (external radiation fields)

$$\Gamma_{\rm rel} = \Gamma_{\rm s}\Gamma_{\rm l}(1-\beta_{\rm s}\beta_{\rm l})$$

$$U' \simeq U\Gamma^2_{\rm rel}$$

F. Tavecchio

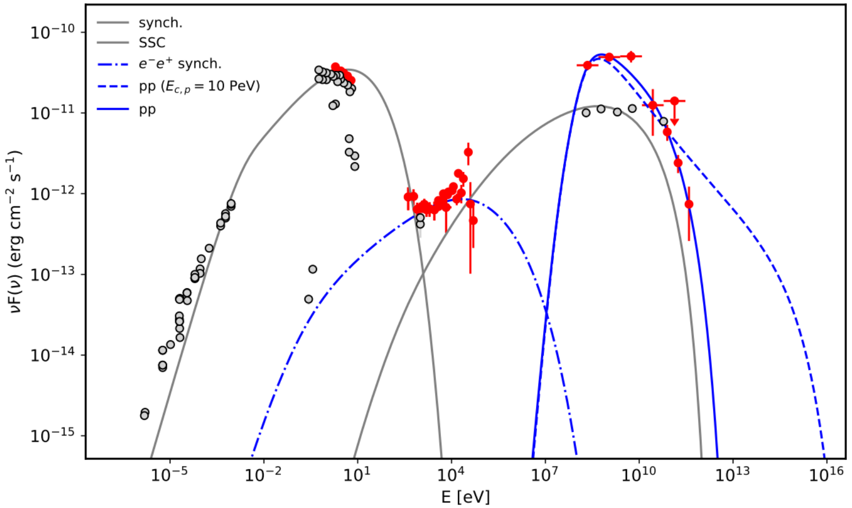


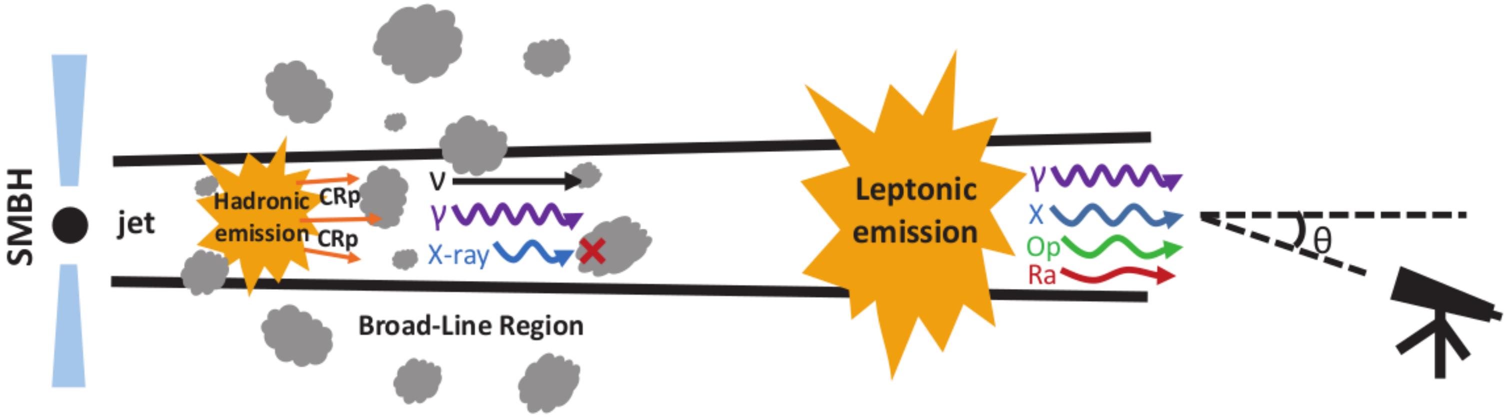


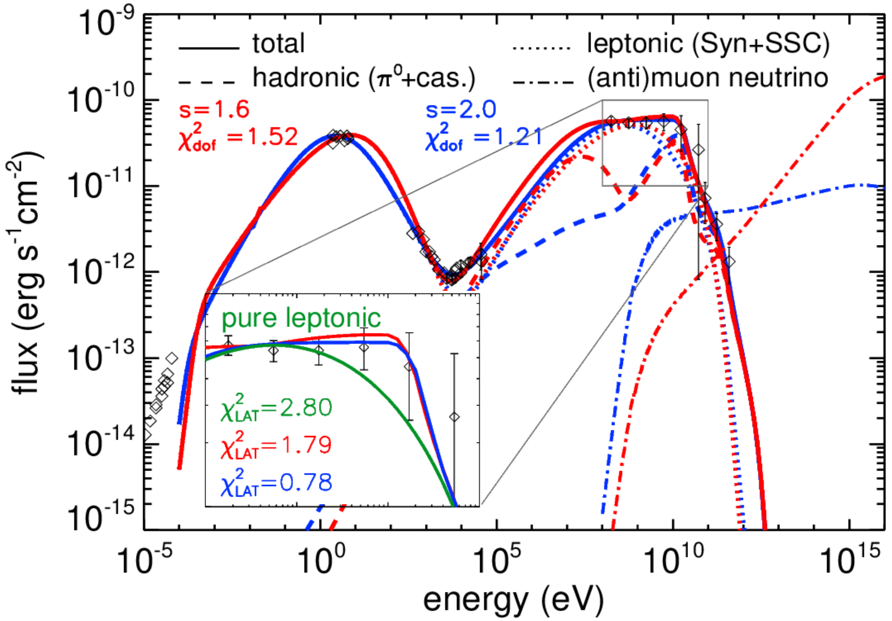
Ghisellini, FT and Chiaberge 2005
FT and Ghisellini 2008

External fields disk, dust, BLR,.. (for Spine-Sheath can be synchr.) are boosted into jet frame → **more target photons** more neutrinos

Proton-proton interactions?



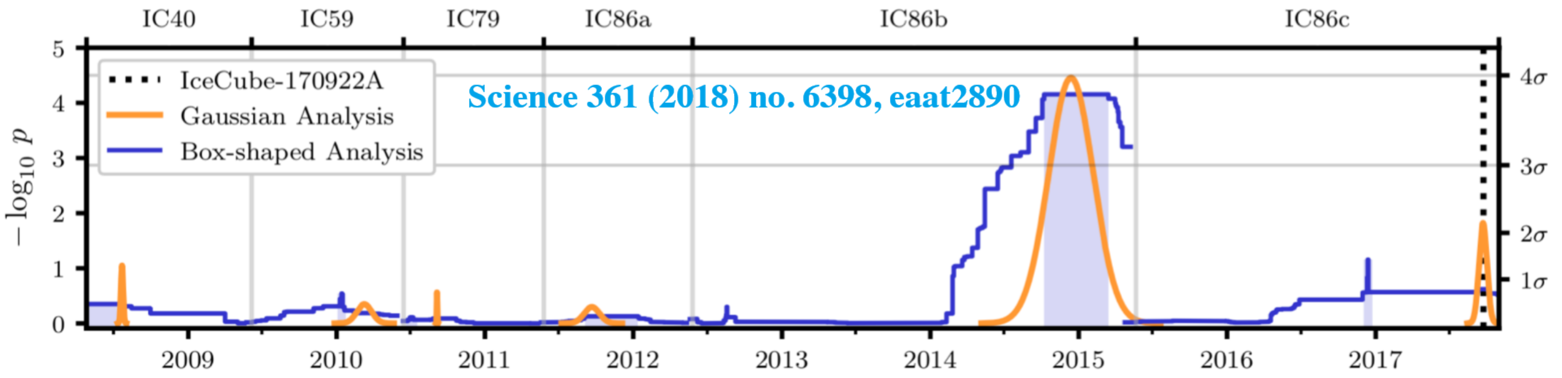


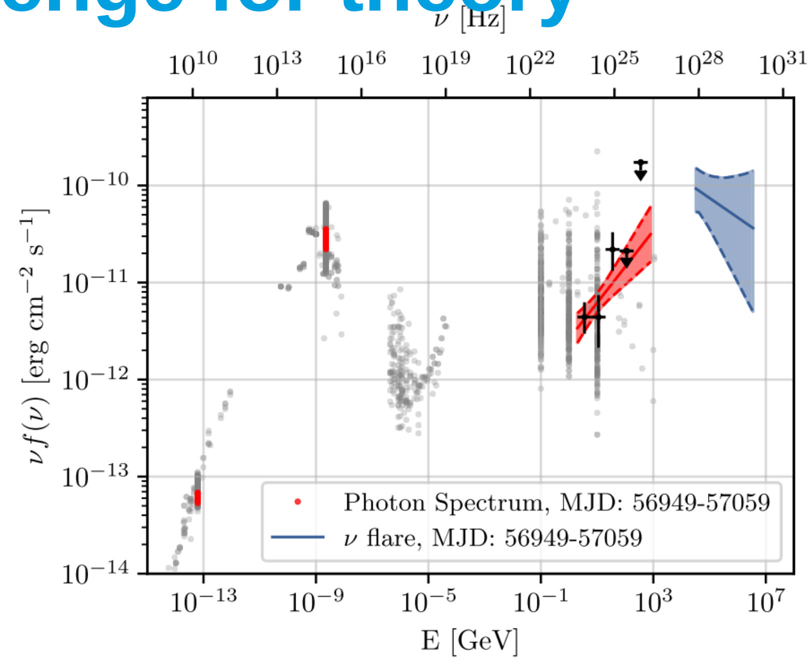


- **Liu** et al. 2018, (1807.05113)
- **Sahakyan** (1808.05651)
- + others only qualitatively

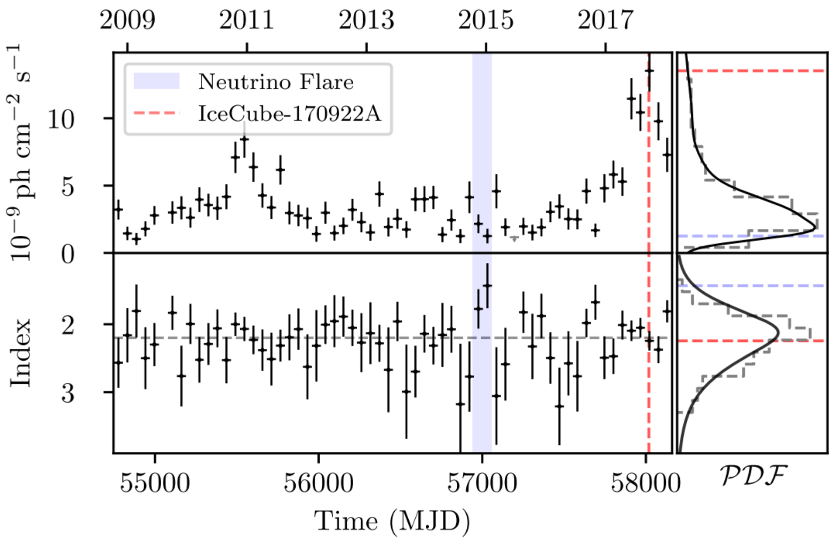
…but no obvious coincidence with flare, pp and pgamma emission can lie months or years apart

Historical emission from TXS a real challenge for theory



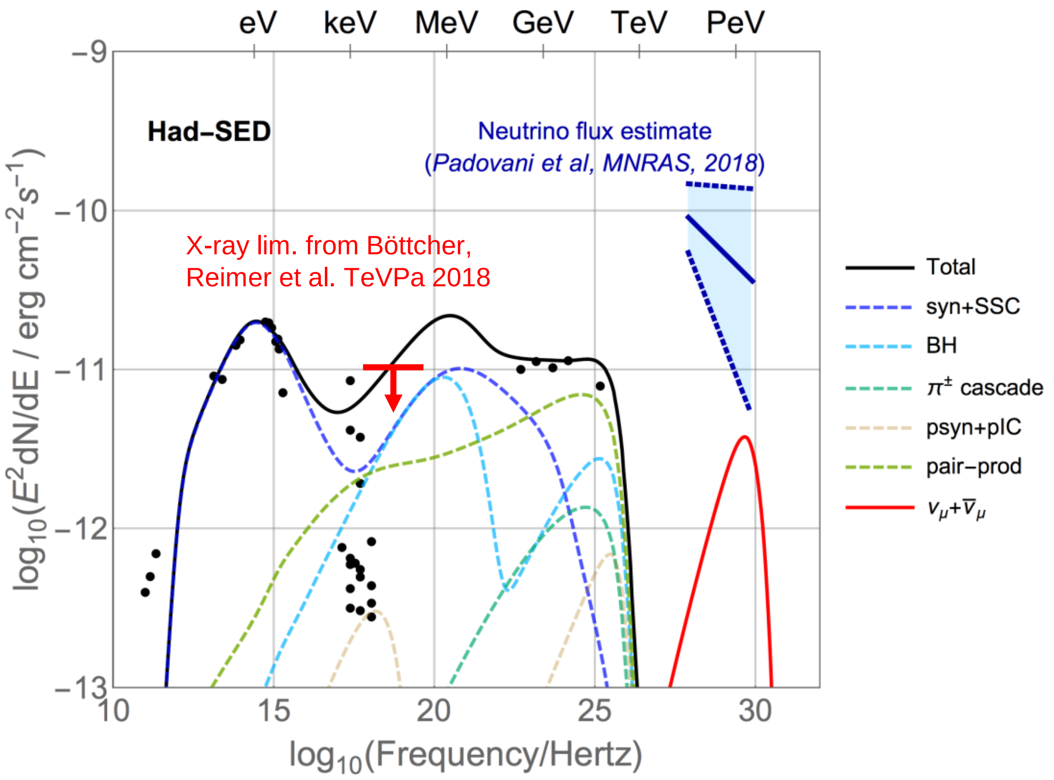


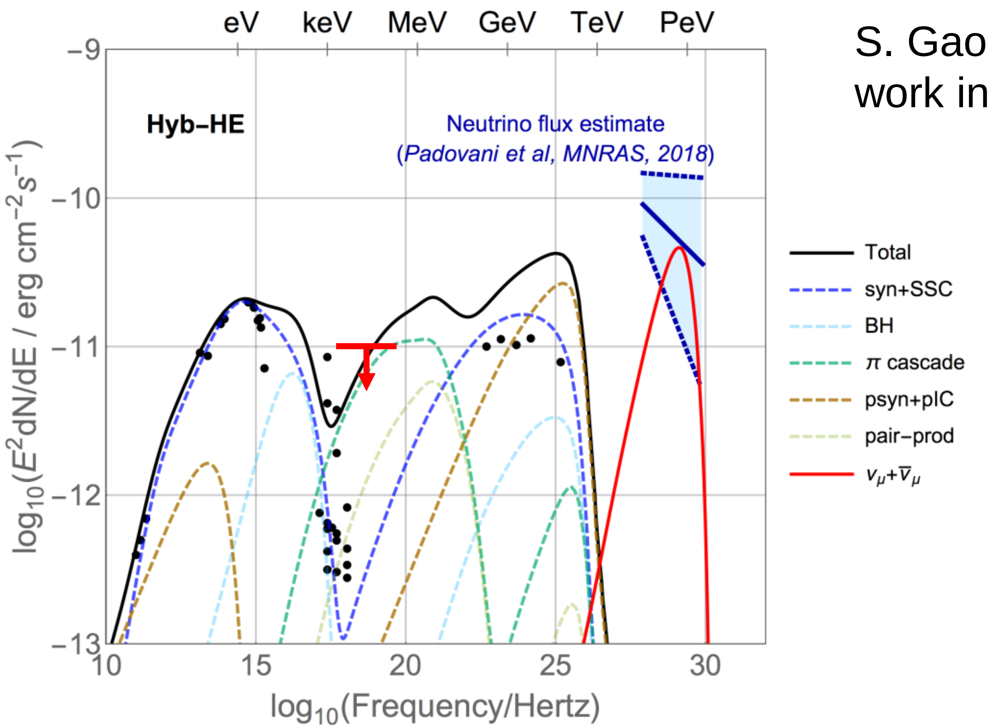
- Challenges:
  - **No enhanced gamma-ray flux** during this period
  - **Indications for spectral hardening and against it** (Garrappa, Franckowiak, Buson, TeVPA 2018)
  - **Very high flux** 13+-5 neutrinos in~6 months



Padovani, Resconi, Glauch et al. MNRAS (2018)

Lepto-hadronic models in tension with observation



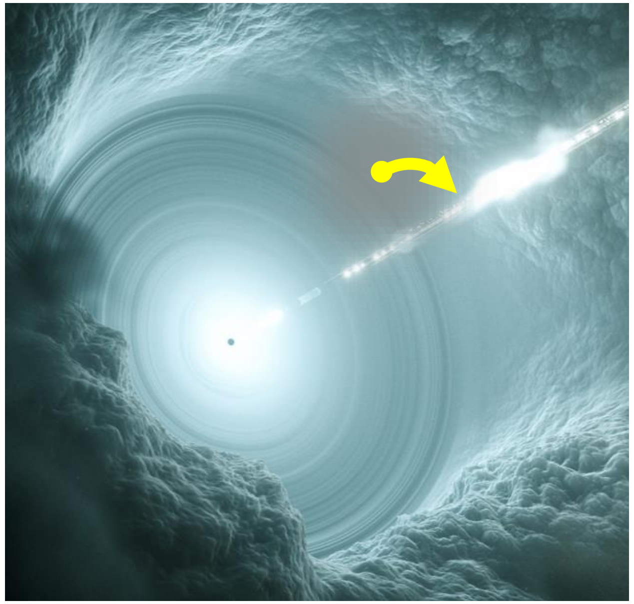


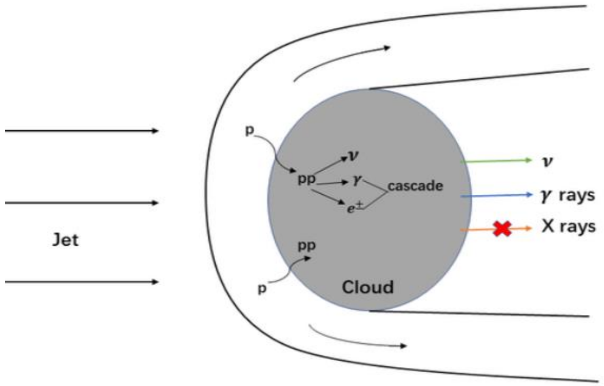
S. Gao et al.,
work in progress

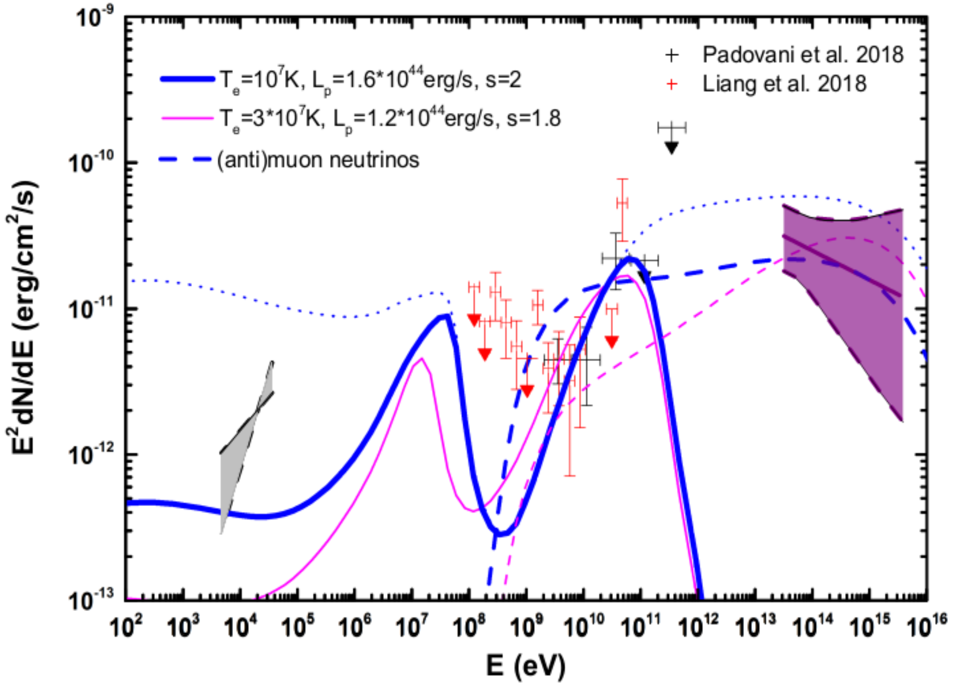
Model	Features	$R/10^{15}$cm (all one-zone)	B'/G	$\delta_{Doppler}$	v_{esc}/c ($e^{\pm}$ and p)	baryonic loading	L_{jet}/L_{Edd}	$E_{\nu,peak}/PeV$	N_ν expected during historical flare
Hyb-HE	hybrid model high $E_{\nu,peak}$ low cascade	100	0.005	70	0.1	$10^{8.0}$	$10^{4.5}$	0.81	8.8
Had-SED	hadronic model fit SED only high cascade	1	7	17	1/300	$10^{2.7}$	0.07	2.8	0.55

Jet – star/cloud interaction, a possible scenario?

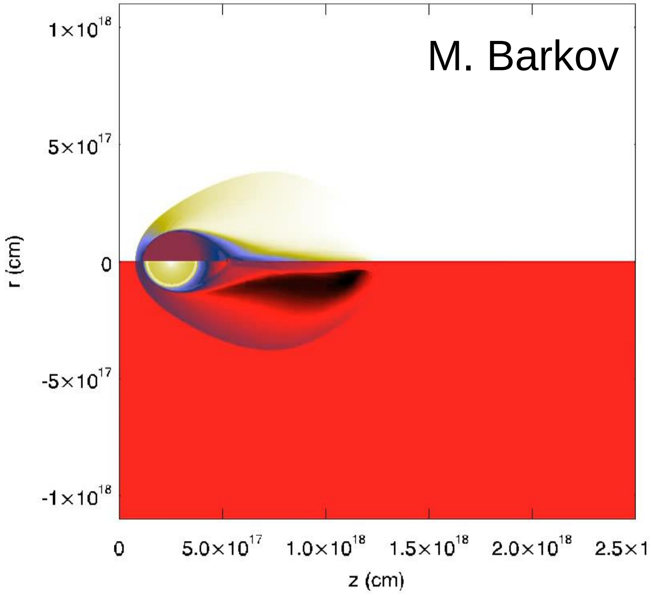
Ruoyu Liu, TeVPa 2018







M. Barkov et al. 2010, 2012; Khangulyan et al. 2013



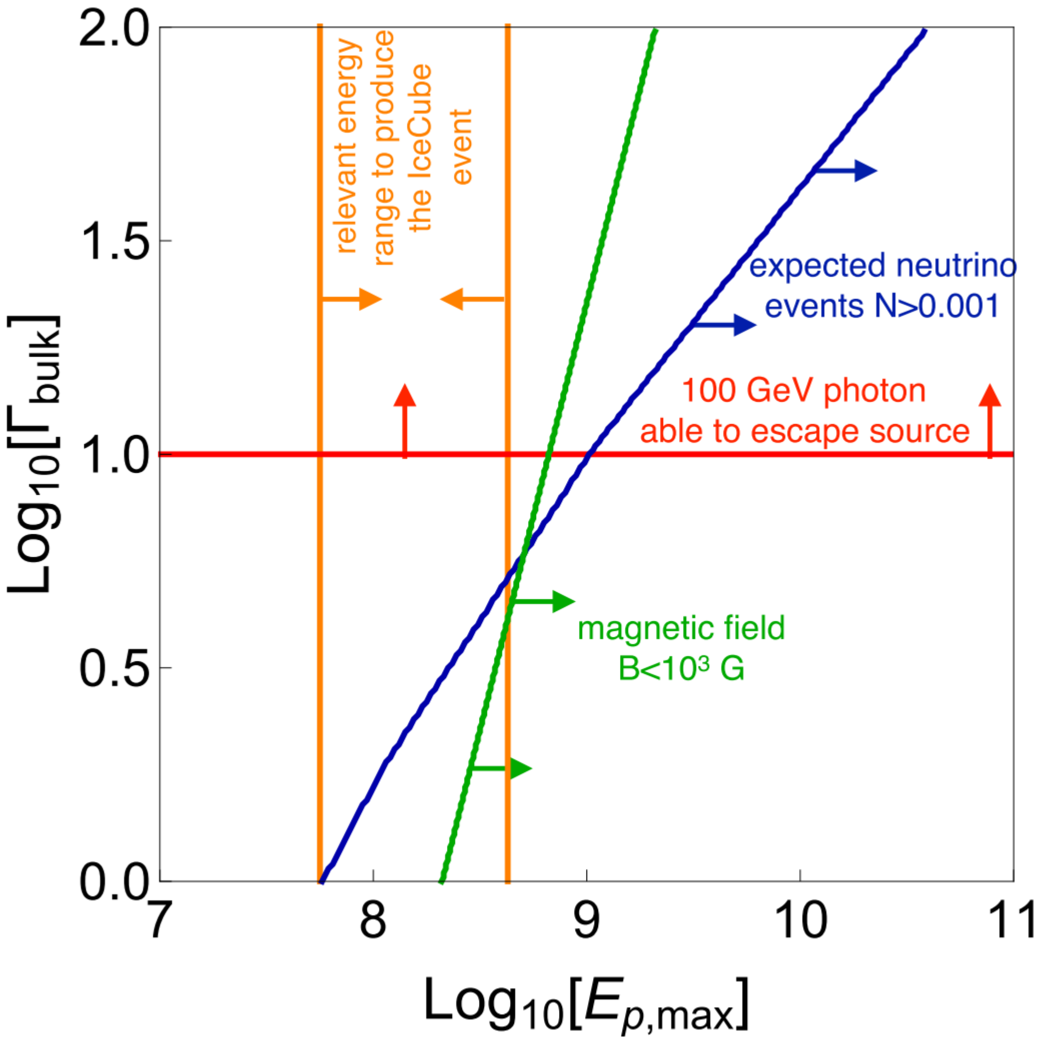
Rate not well constrained

- In Barkov's models the ablated protons still need an additional acceleration mechanism
- Comptonized radiation T~10^7 K "hides" GeV emission

What we learned from TXS 0506+056 observations

- TXS0506+056 can indeed be the **source of the one neutrino**, but detection is lucky
- The **flare** is an **extraordinary state for neutrino production**
- **Most** of the “elegant” **one zone models excluded** through observational constraints or **energetics**
- **Additional** mechanism (two zones) required to boost **pγ efficiency**, either through a compact core, or spine-sheath structures, or external fields → **more free parameters** and insufficient experimental constraints ☹
- Soft/hard **X-ray’s and TeV** (+GeV) gammas are the **strictest constraints,** all calculations/authors (e.g. Keivani et al., Cerruti et al.) agree on that
- The explanation of the **historical/orphan** 2014-2015 **flare** is still a **real challenge** due to the lack of accompanying gamma rays
- **Jet-star/cloud interaction is a first possible explanation**. Other groups working on it. Need to address the question of source confusion/background/overfluctuation
- **TXS alone** is unfortunately **not enough to understand** why this particular blazar a **neutrino source** and the others are not

Proton synchrotron scenario

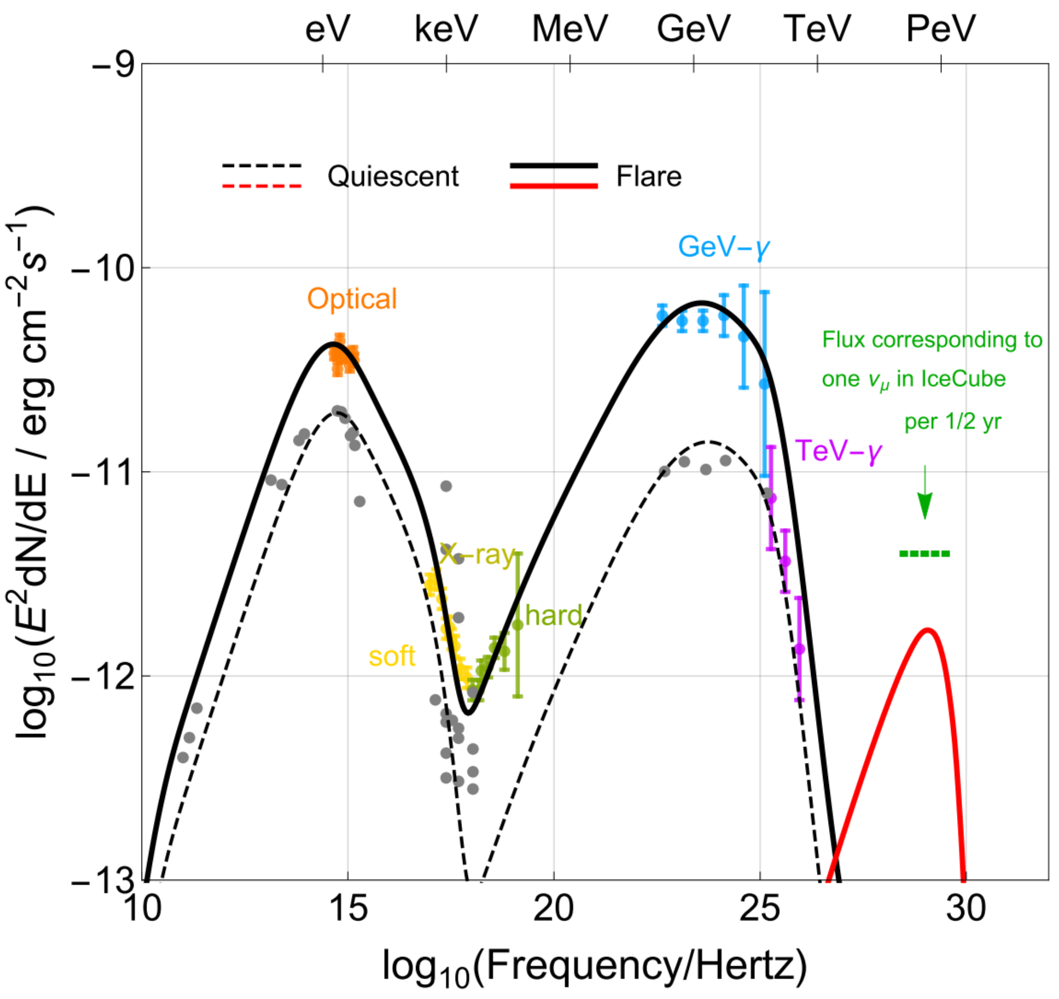


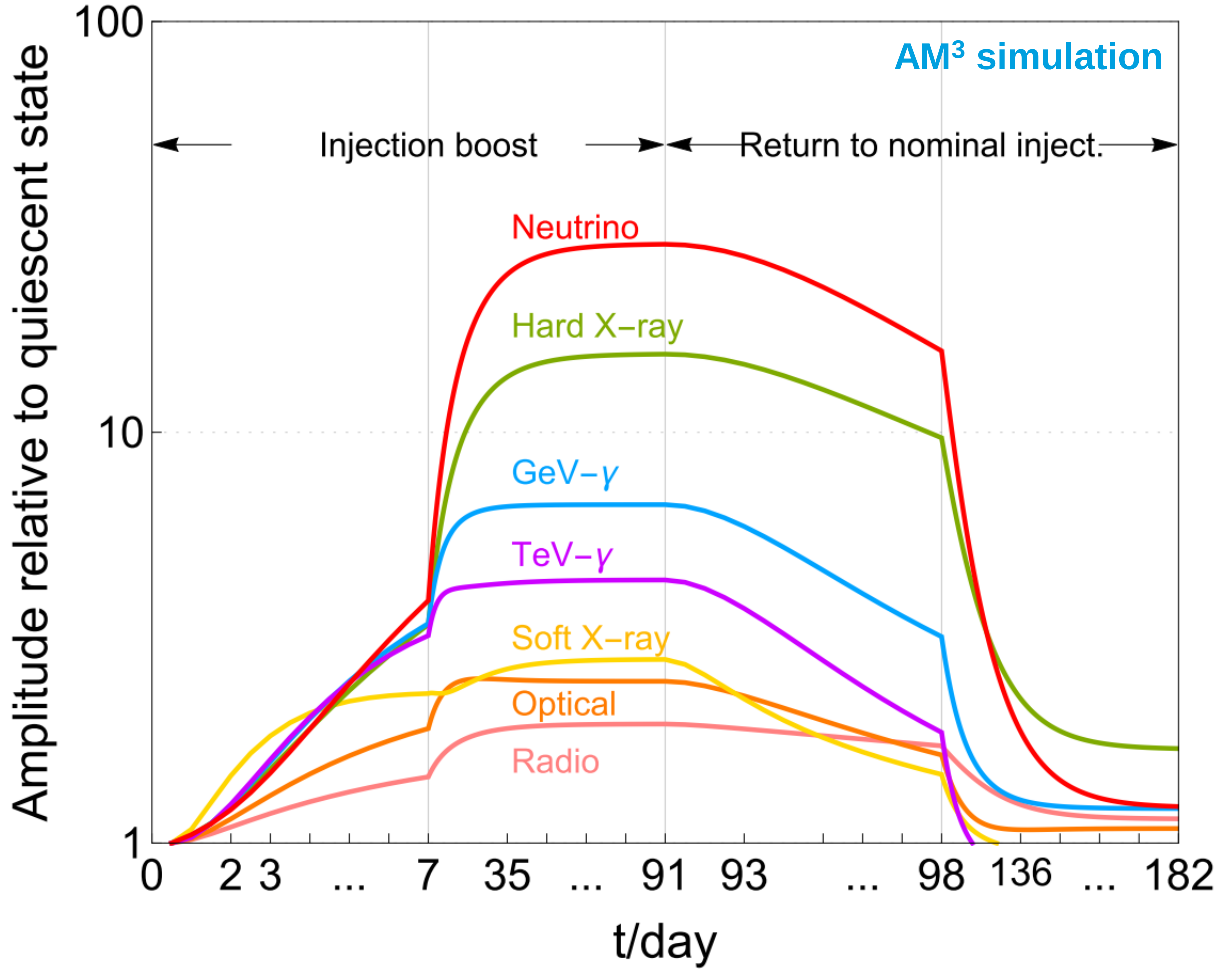
- **Requires UHECR** energies
- Qualitatively **similar** constraints as in **UHECR case**
- Results in **neutrinos at wrong energy** and thus in a negligible rate
- **MAGIC and VERITAS** observations **important** (red line)

Model parameters

Parameter	Description	Fit	Hybrid		Hadronic
			Quiescent	Flare	Flare
z	Redshift	fixed	0.34		0.34
B' (G)	Magnetic field		0.007	0.14	2.0
R'_{blob} (cm)	Blob size		$10^{17.5}$	10^{16}	10^{16}
Γ_{bulk}	Doppler factor		28.0		20.0
$L'_{e,\mathrm{inj}}$ (erg/s)	Electron injection luminosity		$10^{40.5}$	$10^{40.9}$	$10^{41.3}$
α_e	Electron spectral index		-2.5	-3.5	-2.3
$\gamma'_{e,\mathrm{min}}$	Min. electron Lorentz factor		$10^{4.2}$		$10^{3.3}$
$\gamma'_{e,\mathrm{max}}$	Max. electron Lorentz factor		$10^{5.6}$	$10^{5.1}$	$10^{4.4}$
$L'_{p,\mathrm{inj}}$ (erg/s)	Proton injection luminosity		$10^{44.5}$	$10^{45.7}$	$10^{47.0}$
$\gamma'_{p,\mathrm{min}}$	Min. proton Lorentz factor	fixed	10.0		10.0
$\gamma'_{p,\mathrm{max}}$	Max. proton Lorentz factor		$10^{5.4}$		$10^{5.6}$
α_p	Proton spectral index	fixed	-2.0		-2.0
η_{esc}	escape velocity of $e^{\pm}$ and p		$c/300$	$c/300$	$c/10$
Results					
L_{Edd} (erg/s)	Eddington luminosity *		$10^{47.8}$		$10^{47.8}$
$L_{\mathrm{jet}}/L_{\mathrm{Edd}}$	jet physical luminosity (in L_{Edd})		0.4	6.2	62.8
$E_{\nu,\mathrm{peak}}$, TeV	peak energy of neutrino spectrum		250		330
N_ν/yr	Expected neutrino rate in IceCube		$10^{-3.8}$	0.27	9.8

Increasing p & e$^-$ injection by factor 3 explains flare

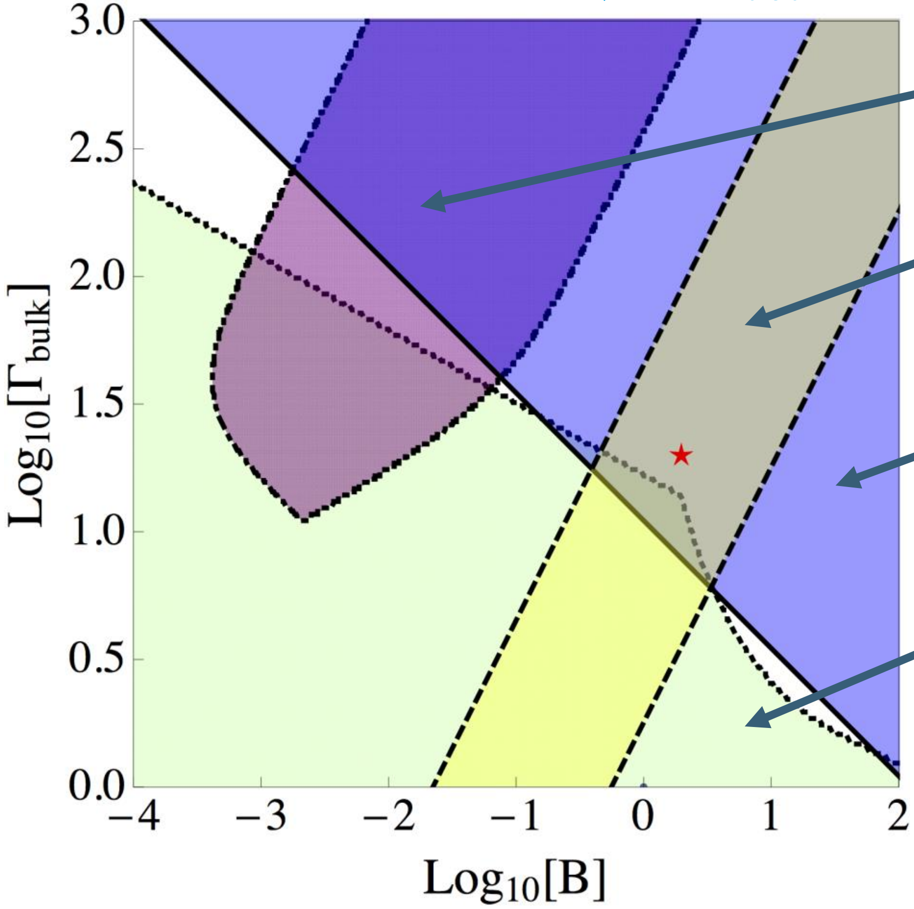




Ratio between QS and FS is x2.5 in optical and x6 in GeV supports SSC model

Scan for hadronic models with semi-analytics

Repeat procedure for all combinations of E_ν and R_{blob}



Constraints

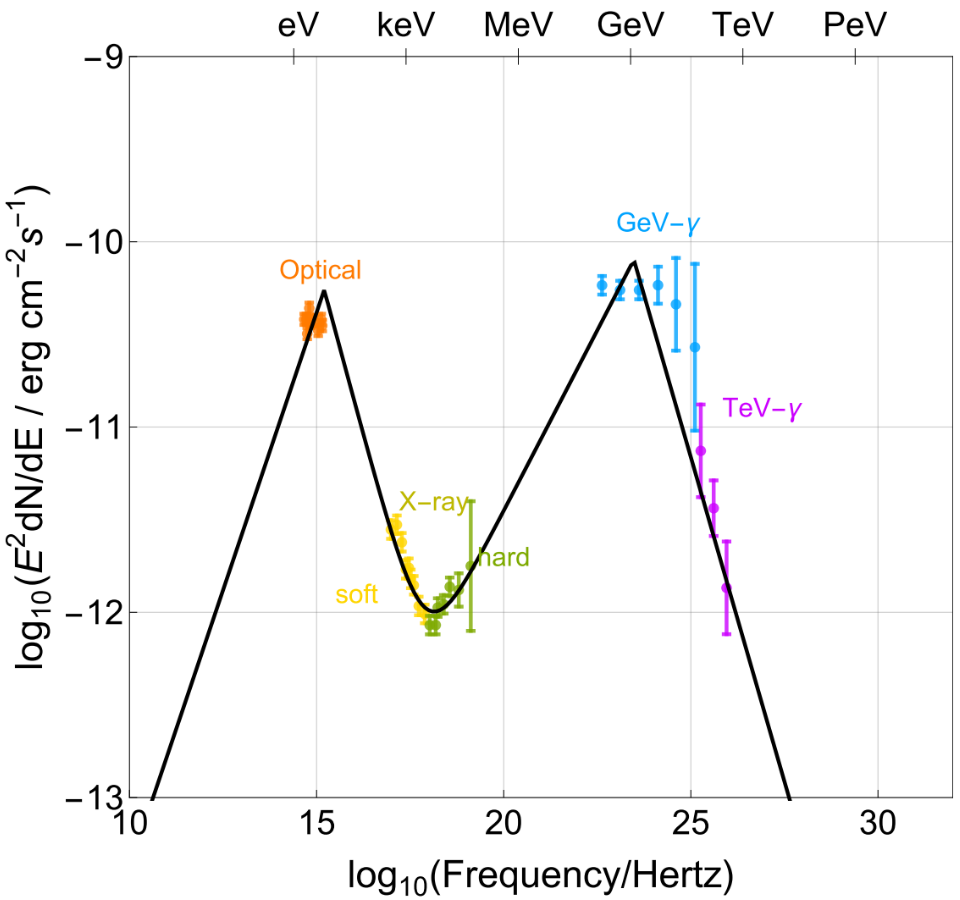
Bethe-Heitler pair production

Second peak

Inv. compton not dominant

Proton-synchrotron

4-powerlaw approximation



see Gao, Pohl, Winter, ApJ (2017) for more details on the method