Interpretation on the coincident observation of VHE neutrino event and a bright flare of TXS0506+056

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based on 1807.04275 For VHEPU18, Qui Nhon, Viet Nam, Aug 16, 2018

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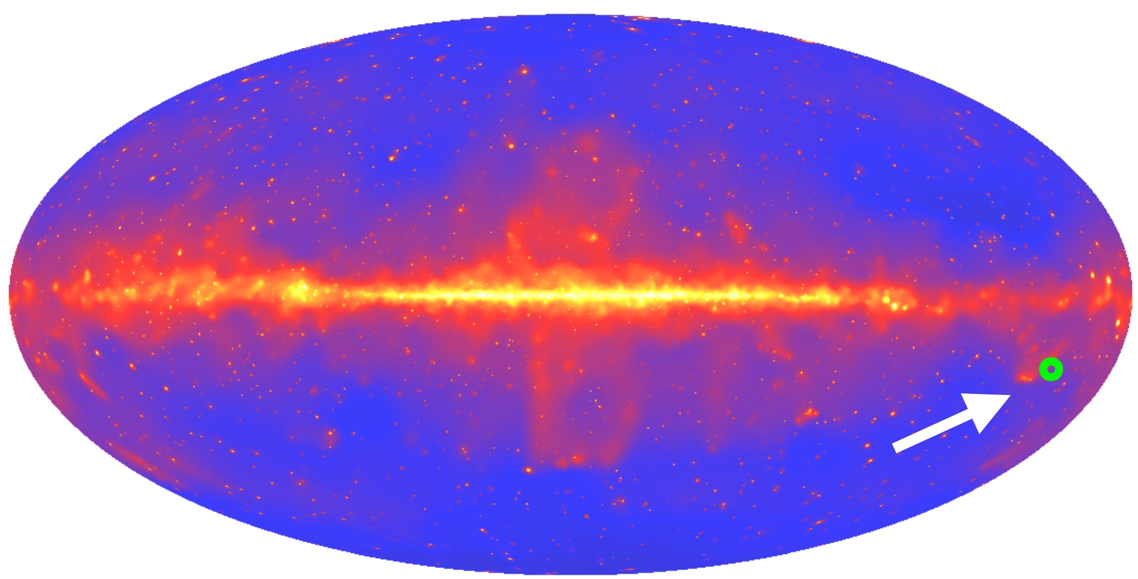
The first smoking-gun neutrino (ex-gal.) source ?

IceCube 170922A and blazar TXS0506+056



Figures reconstructed from Fermi-LAT, ApJS, 2017; IceCube, Science, 2013, GCN alert 21916 by IceCube

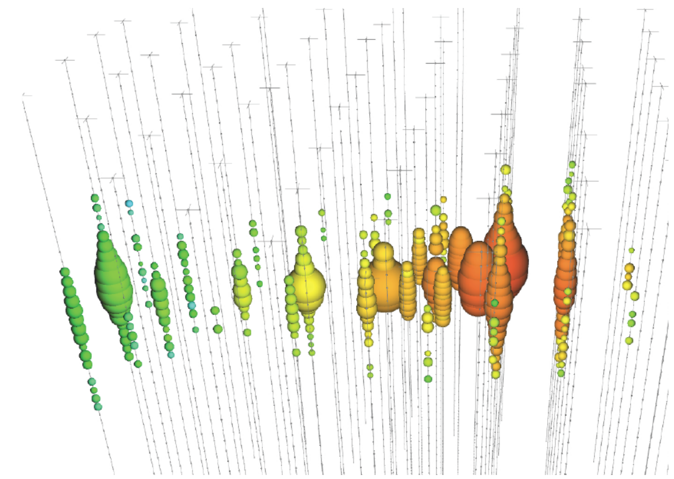
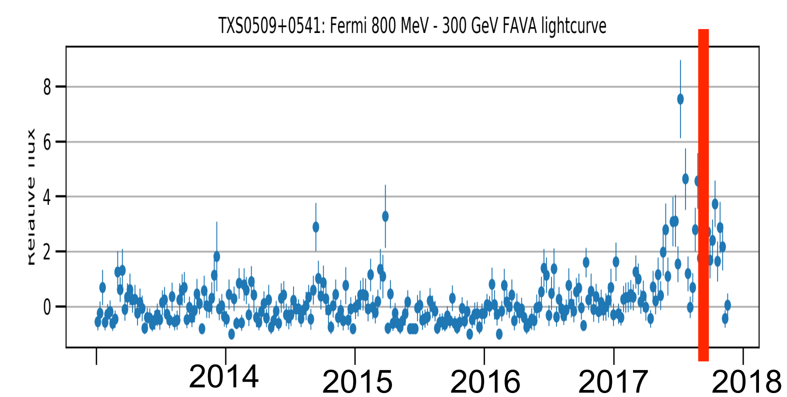


Illustration of an IceCube neutrino
track event. IceCube Collaboration



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27

Multi-messenger observation paper:

IceCube et al, Science 361 (2018)

List of follow up papers:

https://icecube.wisc.edu/pubs/neutrino_blazar

Theoretical modeling : **this talk, 1807.04275**

Observational Chronology

Date	Source	By	Content
17/09/23	GCN alert 21916	IceCube	Neutrino track 170922A, RA: 77.43 Dec: 5.72, EHE event selection (~100’s TeV), <1 degree angular resolution
17/09/26	GCN alert 21930	Swift	observations started on 09/23, few hours after neutrino, reported 12 sources within 2.1 sqd
17/09/27	ATel #10787	H.E.S.S.	observations lasted for 1h each, on 09/23 (+4h after neutrino) and 09/24. Non-detection.
17/09/28	ATel #10791	Fermi	3FGL source within error circle, 6-fold flux increase during 09/17-27, FAVA shows high-state at 800 MeV shows flaring state [since ~few months]
17/09/28	ATel #10792	Swift	additional monitoring started on 09/27, index -2.5, shows softening and “spectral evolution”
17/09/28	ATel #10794	ASAS-SN	V-band +0.5 mag in few months. Made sure light curve is available. No data during past summer, due to the Sun
17/10/04	ATel #10817	MAGIC	12h between 09/28 – 10/03. 5-sigma detection above 100 GeV
17/10/09	ATel #10833	VERITAS	non-detection: observed location on 09/23 and 09/28-30 for 5h total. Set upper limit.
17/10/12	ATel #10845	Swift + NuSTAR	Joint Swift XRT (09/27++) & NuSTAR (09/29): single power-law model disfavored, double power-law model: soft idx: -3.27, hard idx: -1.51, flux not much higher than previous obs.
17/10/17	Atel #10861	VLA	observations on 10/05,06,09,12 in 6 bands between 2.5 and 11 GHz, spectrum shows variability O(few days)

They are not exactly simultaneous

Theorist’s Chronology

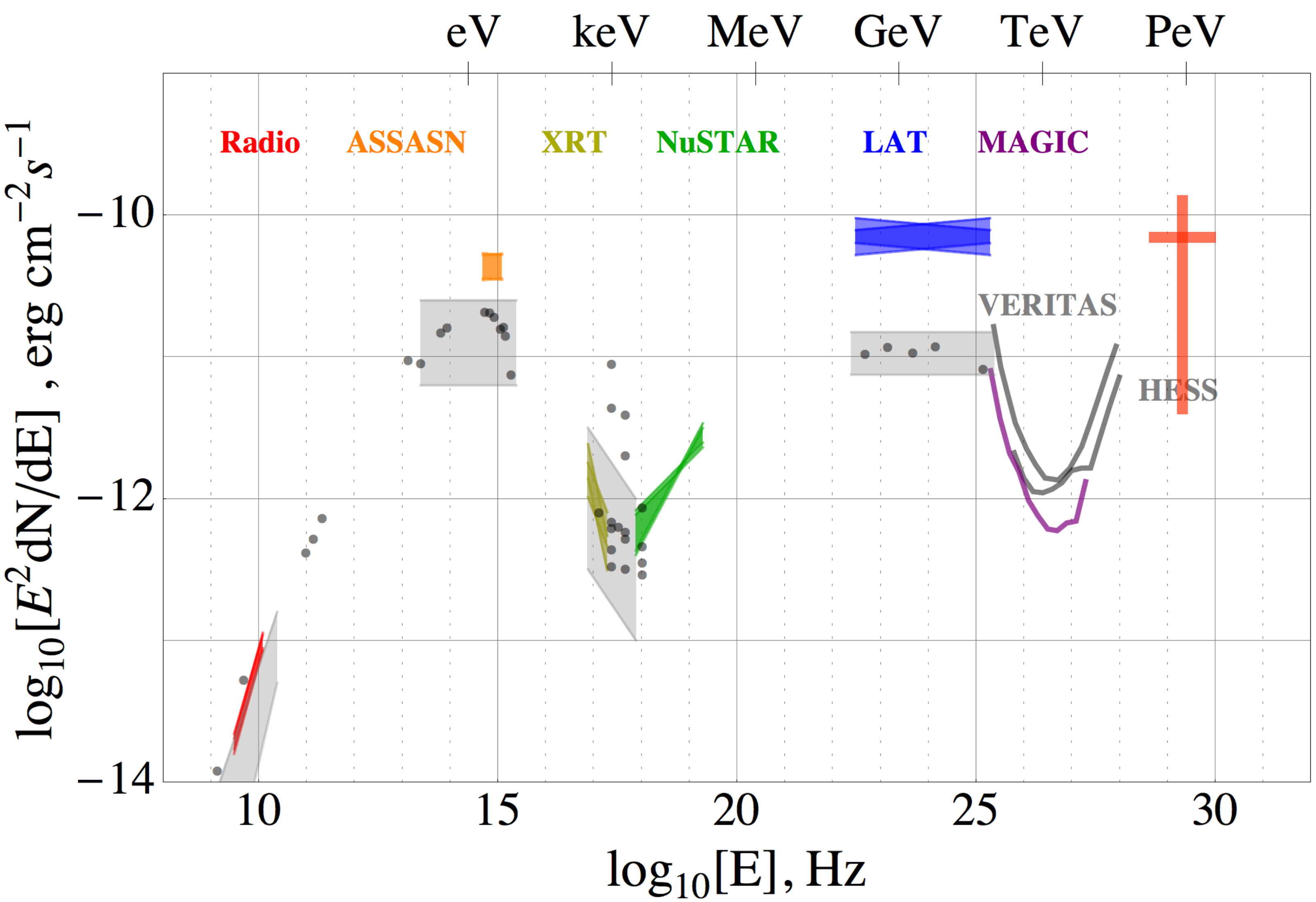
Date	Activity
Oct 2017	Analyzing publicly available data, from ATels and online tools.
Nov 2017	Analytical analysis - baseline models
Dec 2017	Numerical simulations, fit parameters Work presented in DESY
Mar 2018	Add model complexities. Work presented in MIAPP workshop. paper submitted to journal.
Jul 2018	Work with published data. paper posted on arxiv and new version resubmitted

Importance of “open data”

“Theoretical” follow-ups also don’t like delays.

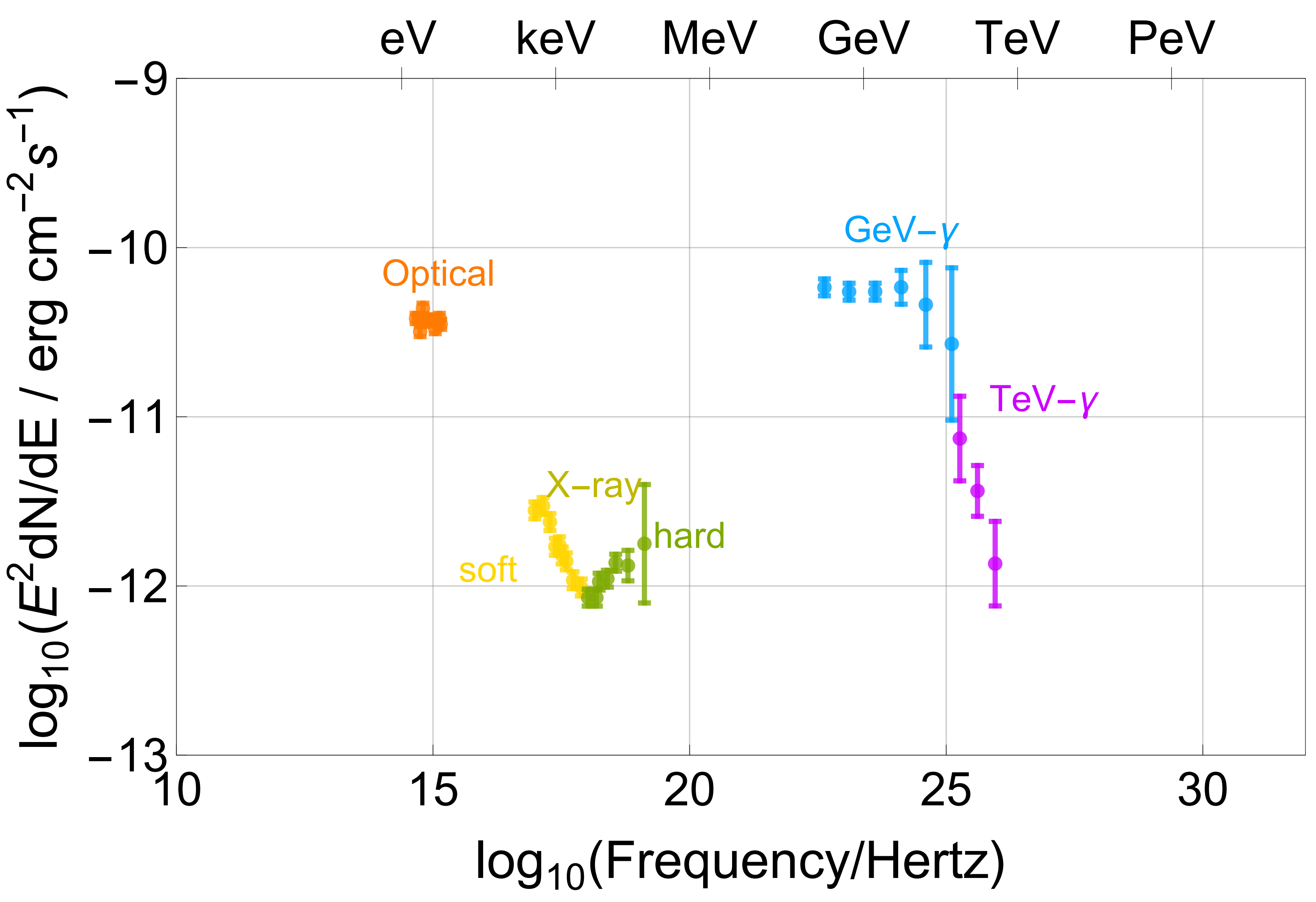
See how each “piece” of SED determines or constrains different types of models

Spectral Energy Distribution from public available data



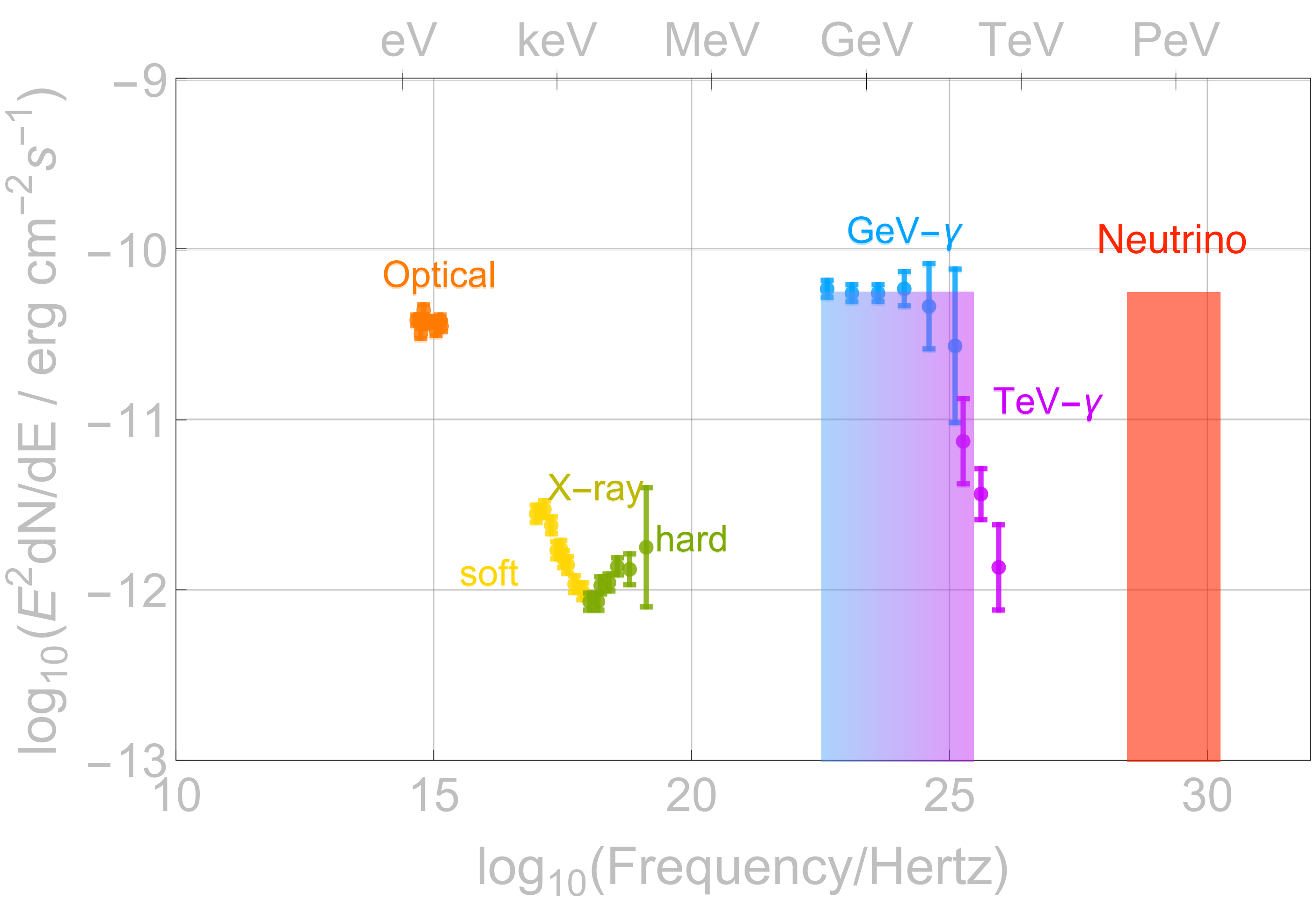
Our initial data analysis from those ATELs and online tools

Multi-wavelength Observation



Data reconstructed from IceCube et al, Science 361 (2018)

Zeroth order estimate (easy to understand; most widely used)



$$p+\gamma \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e\,(\bar{\nu}_e) + e^\pm \end{cases}$$

↓

$L\nu \sim L\gamma$, comparable energy

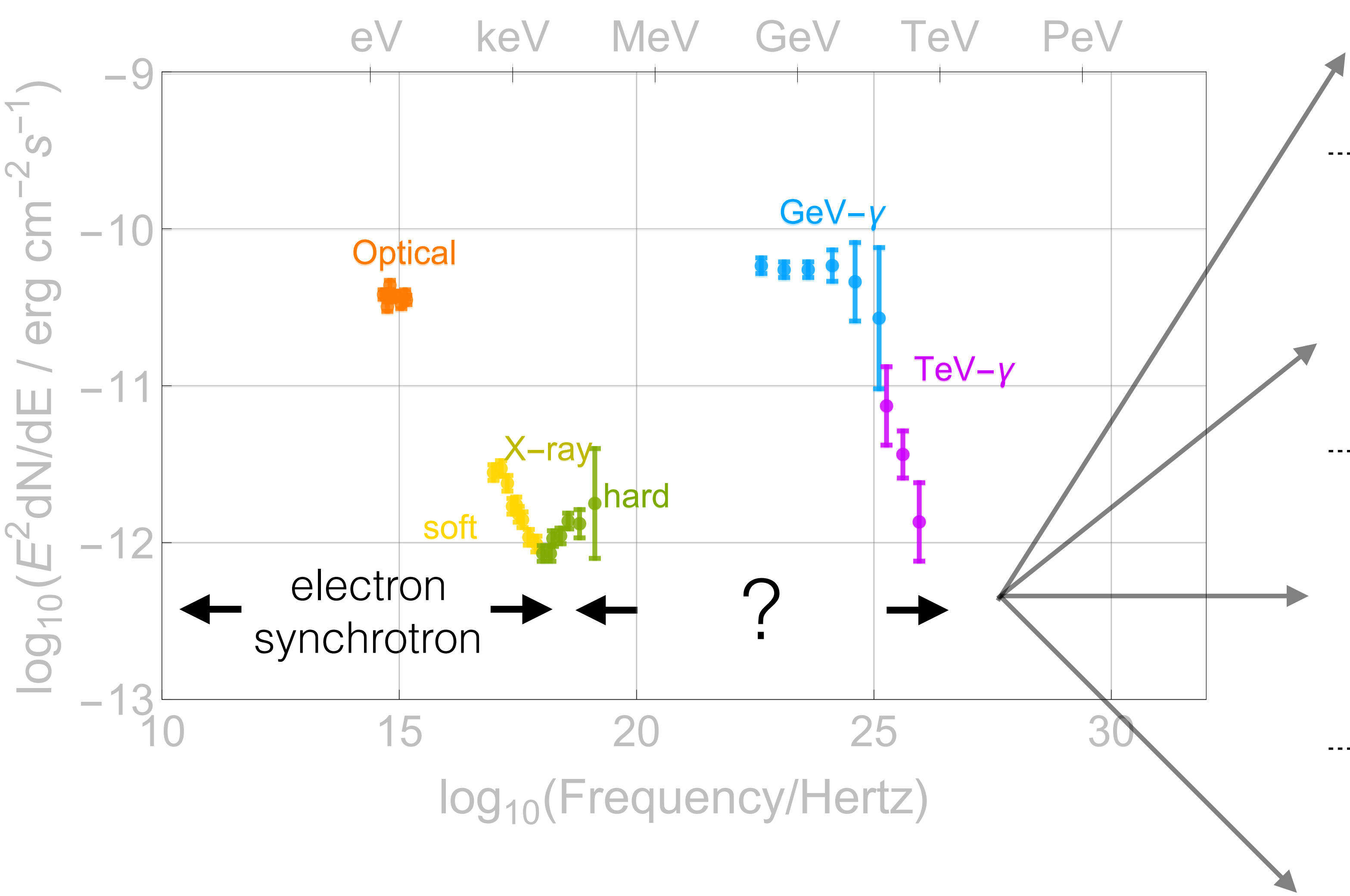
↓

Explains!

↓

Why is this wrong for TXS0506 ?

Physical explanations of SED



Leptonic ?

(inverse Compton, SSC)

no neutrino

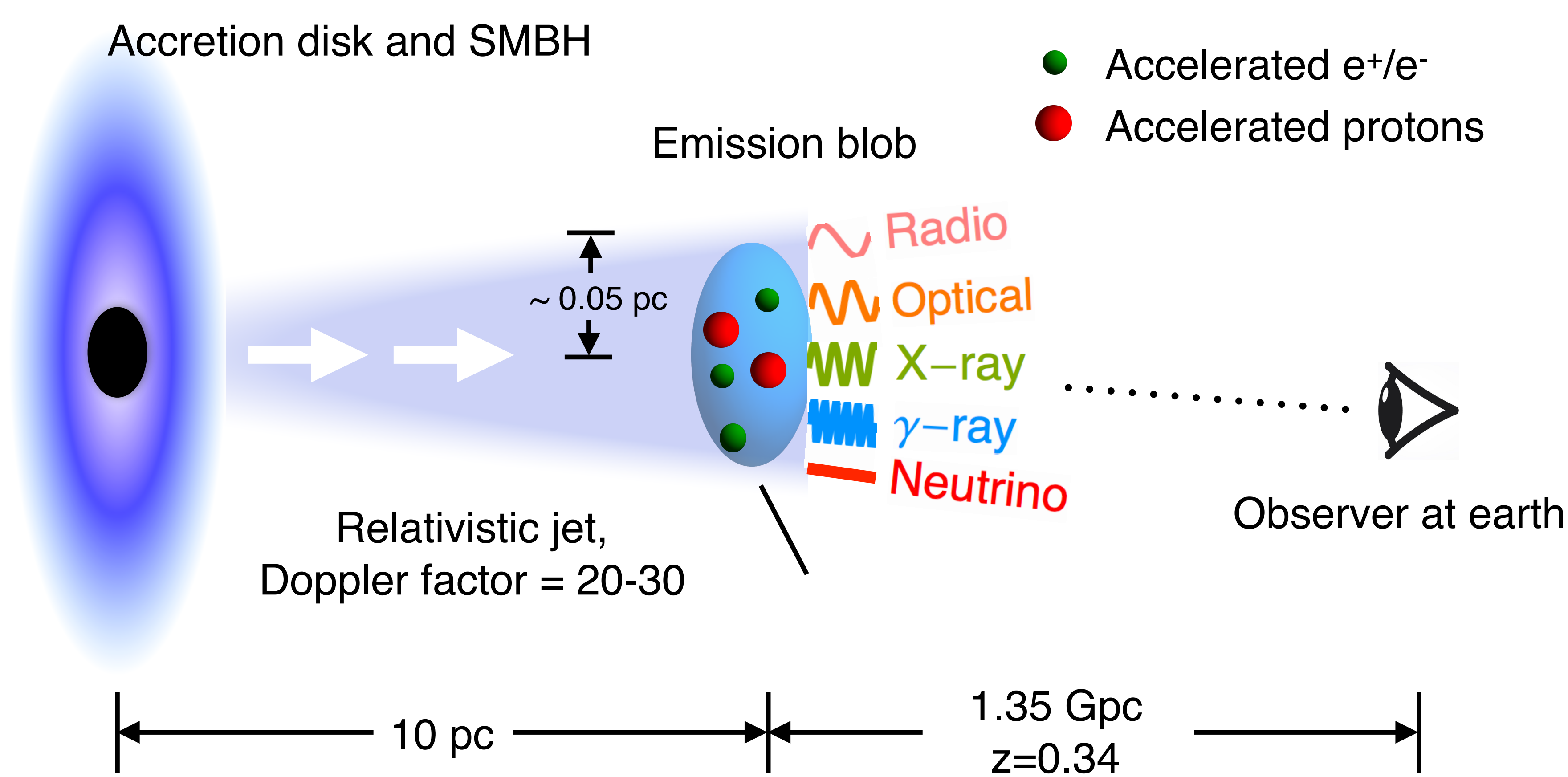
Hadronic ?

max neutrino

Proton Synchrotron ?

Others ?

Model geometry illustration



SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

The simplest to model the SED, with the least number of parameters

T-dependent numerical code for radiations (AM3)*

*Astrophysical Modeling with Multiple Messengers

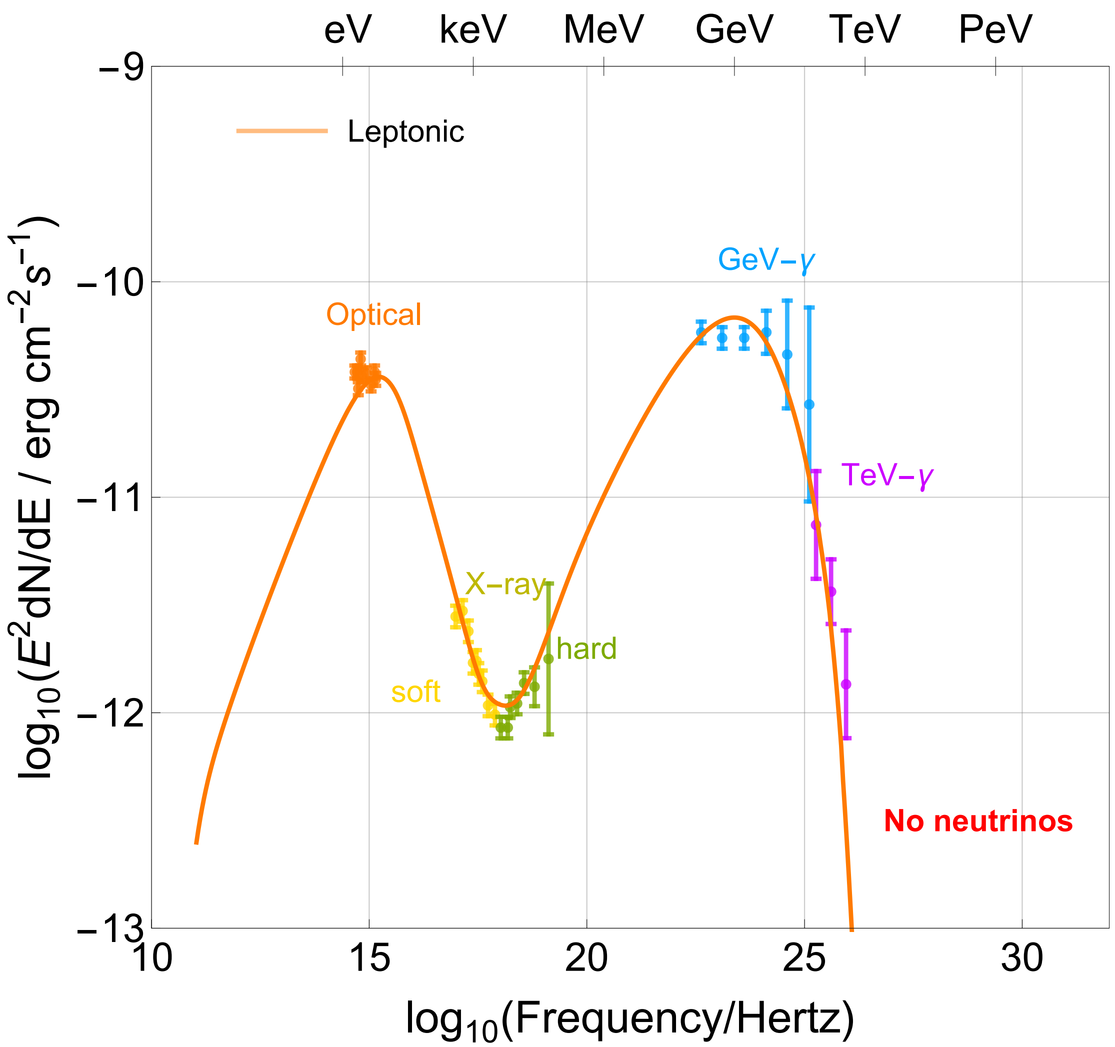
$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot\gamma(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

	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	–	$\alpha_{f,es}$	–	–	–	–	$Q_{\nu,p\gamma}$

- Numerically solve coupled equations for above particles and interactions
- Energy "bandwidth" : Radio — UHECR
- Efficient: 0.5 min per leptonic simulation, 2 min hadronic
- Photo-hadronic interactions following Hümmer et al., ApJ 712, 2010

Description of physics and the code, see SG, Martin Pohl and Walter Winter, ApJ, 2017

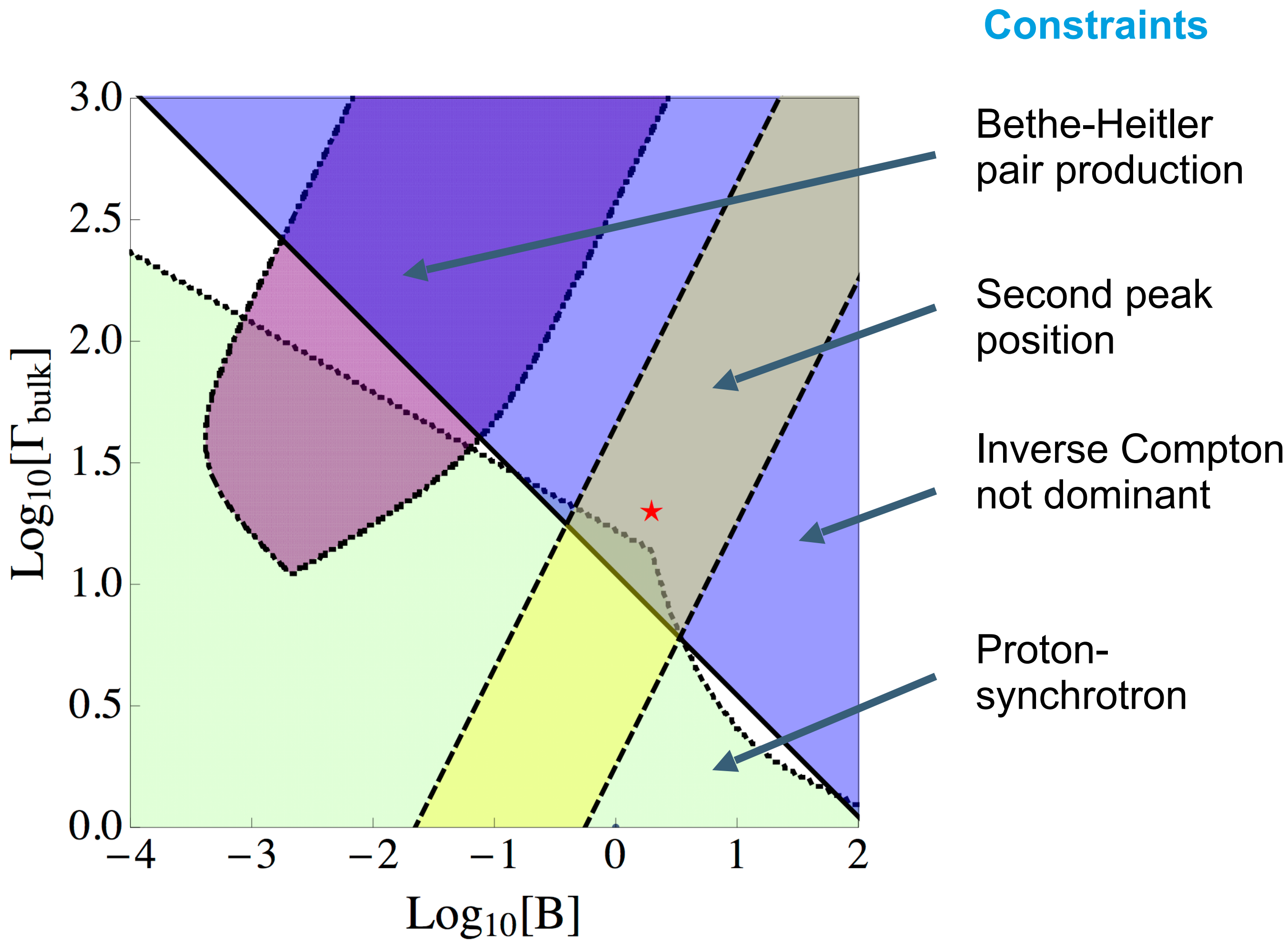
Leptonic model

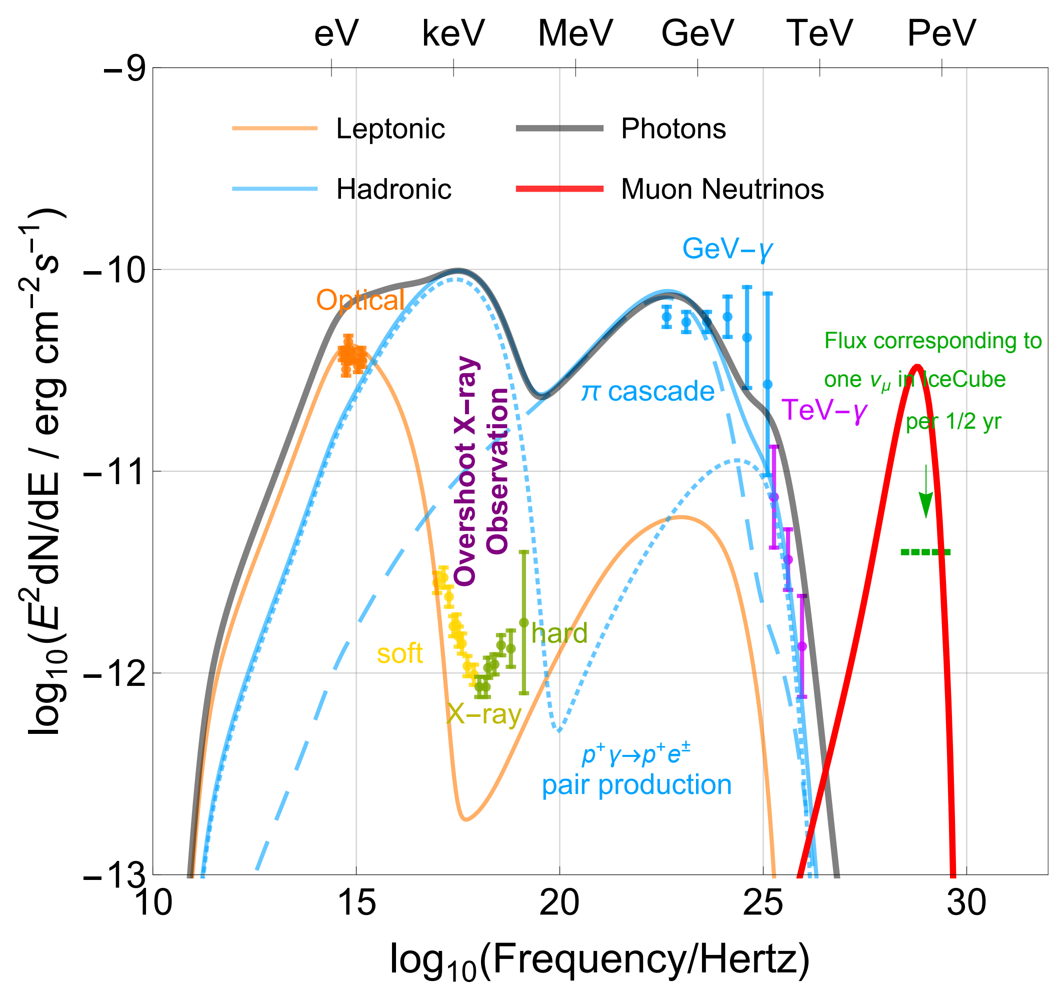


Fits SED, but no neutrinos

SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

Hadronic model, a parameter scan



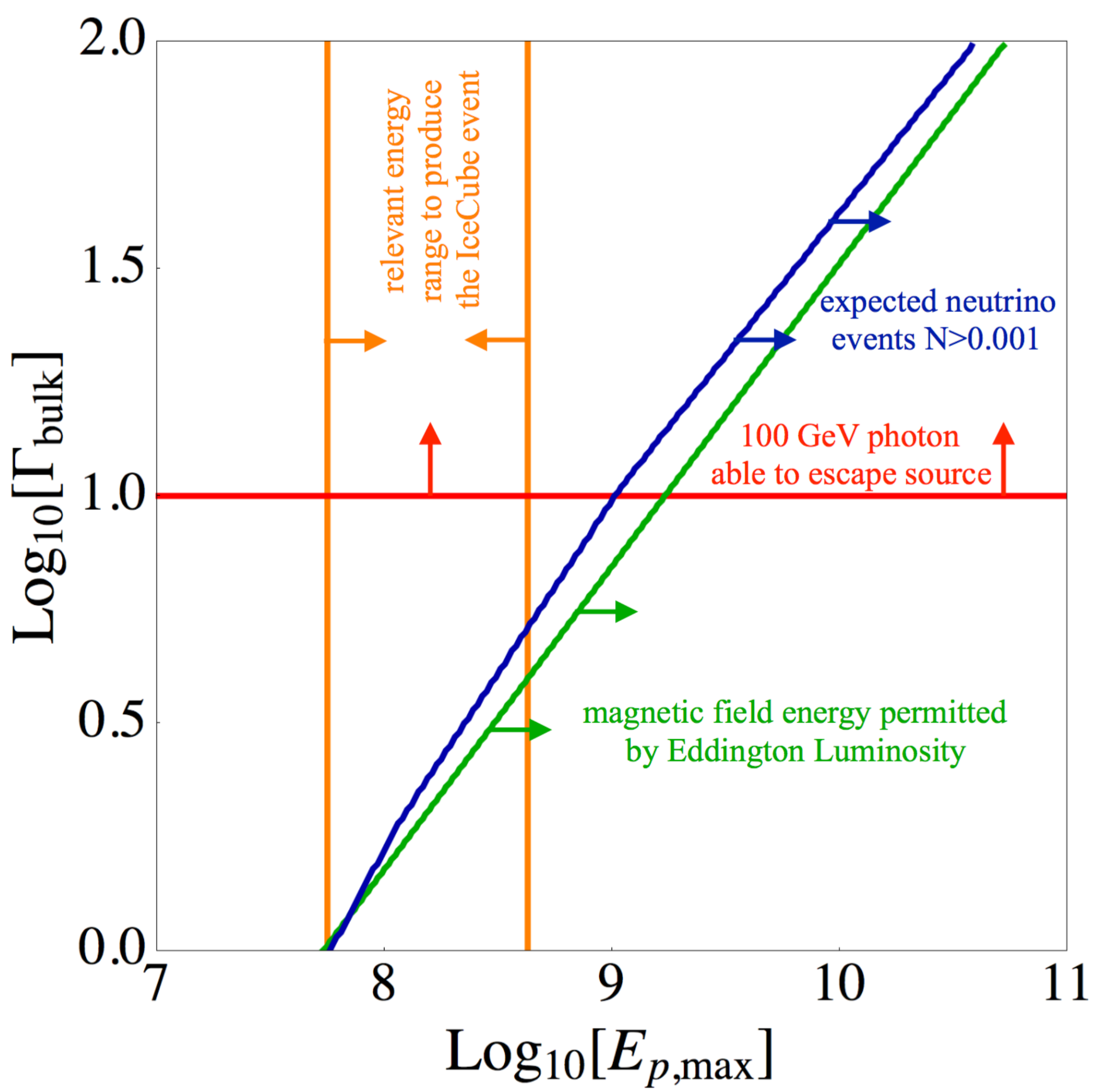


SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

We have scanned the physically reasonable choices of the blob radius 10^14 < R < 10^18 cm and found none of the above diagrams has an overlapping region of the four colors.

Ruled out

Proton synchrotron model, a similar parameter scan



SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

proton E must be within the orange stripe

↓

magnetic B must be high to produce GeV proton synchrotron flare

↓

total magnetic energy cannot be too high — overall jet E

↓

blob must be compact & a low Doppler factor

↓

blob cannot be too compact, 100 GeV photon needs to escape

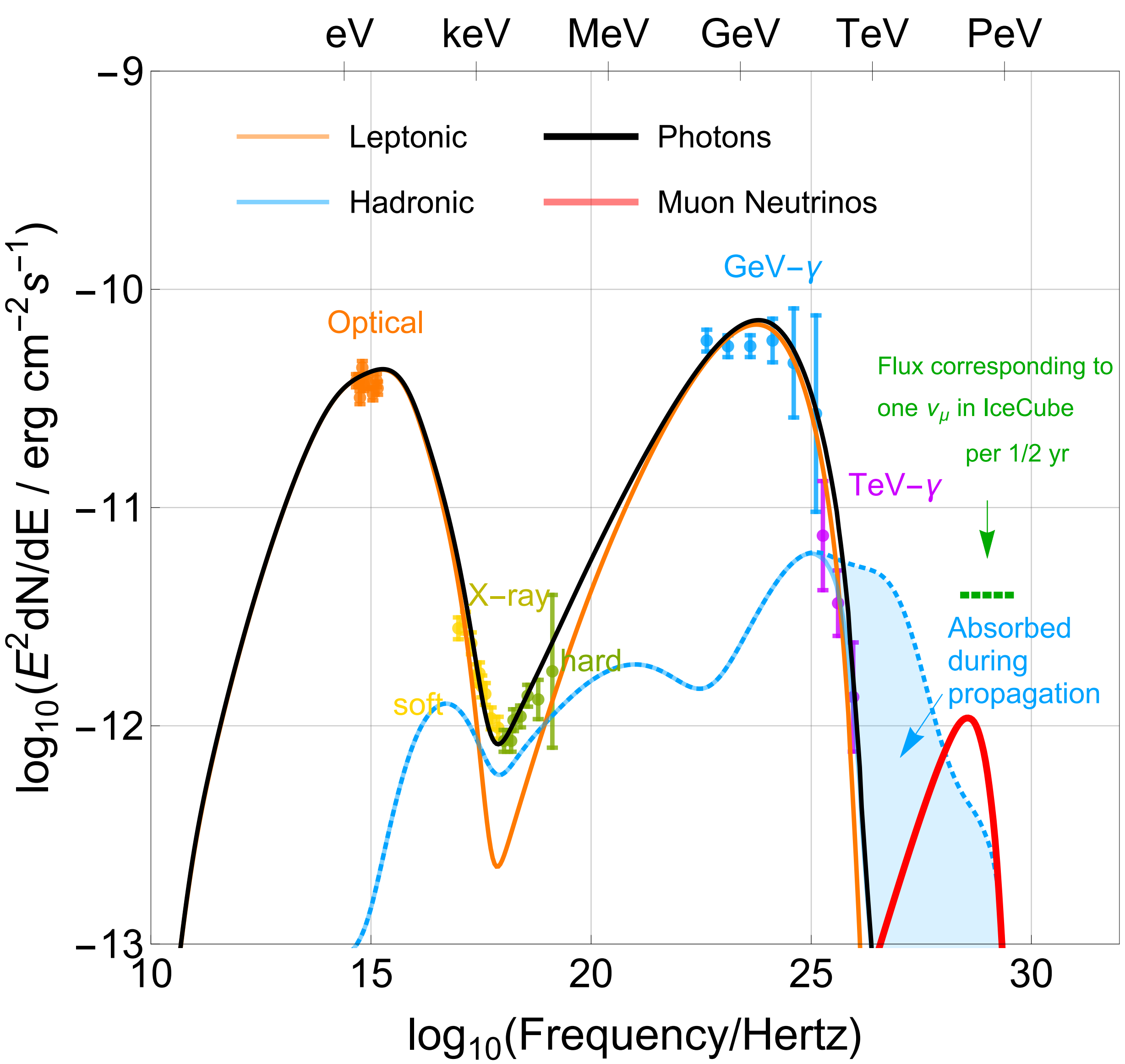
↓

p-gamma efficiency too low, N<<0.001 neutrino

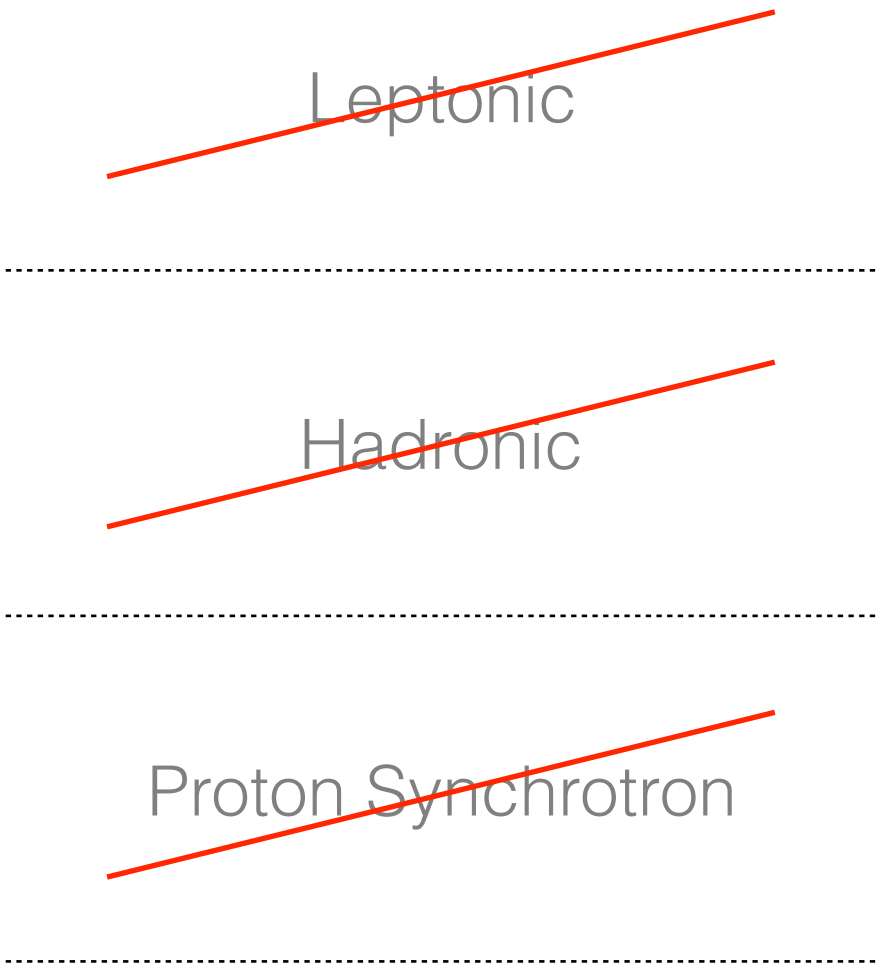
↓

Highly unlikely

The 4th possibility - hybrid model



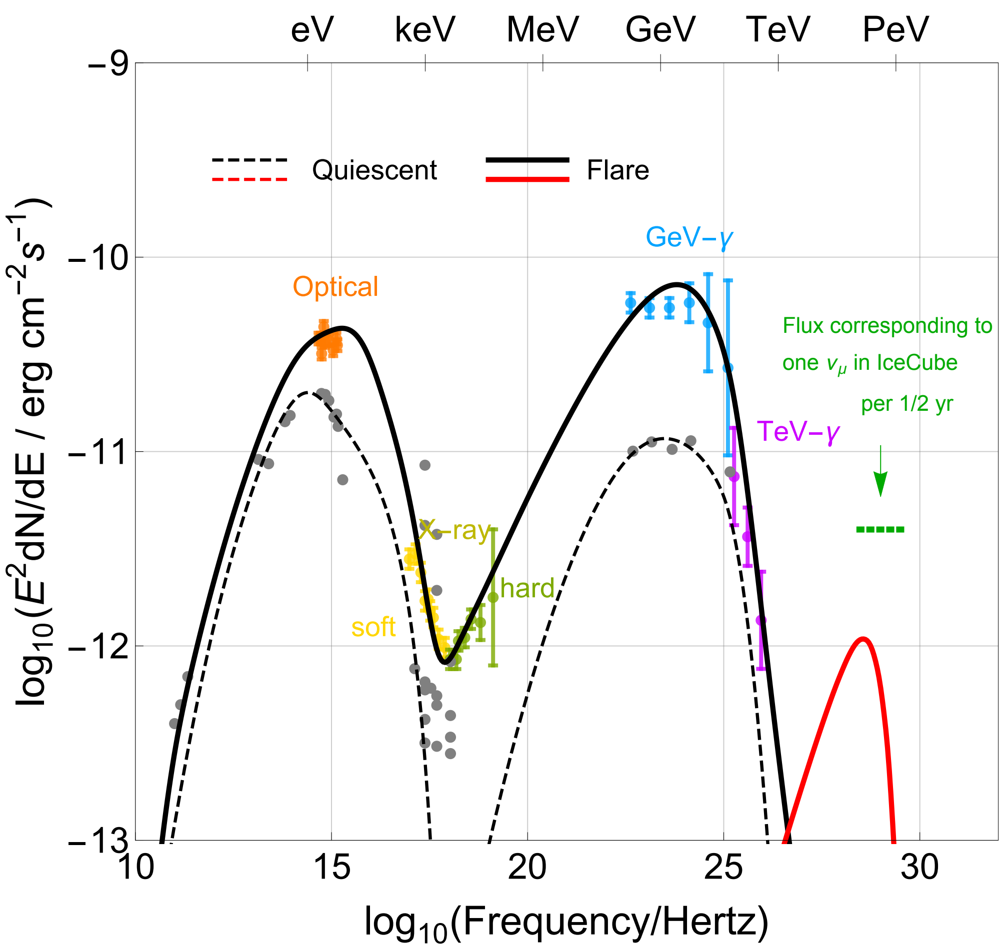
SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275



Hybrid ?

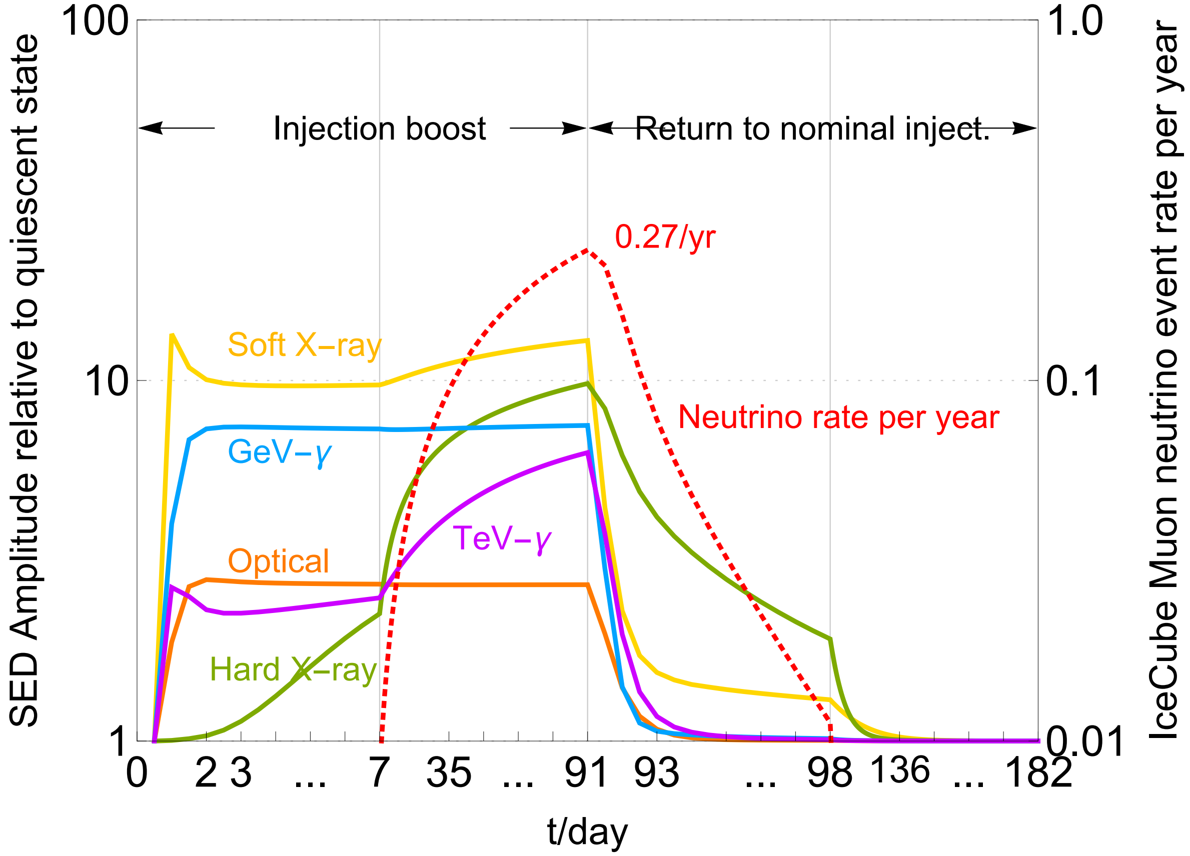
Go time-dependent : flare and quiescent state

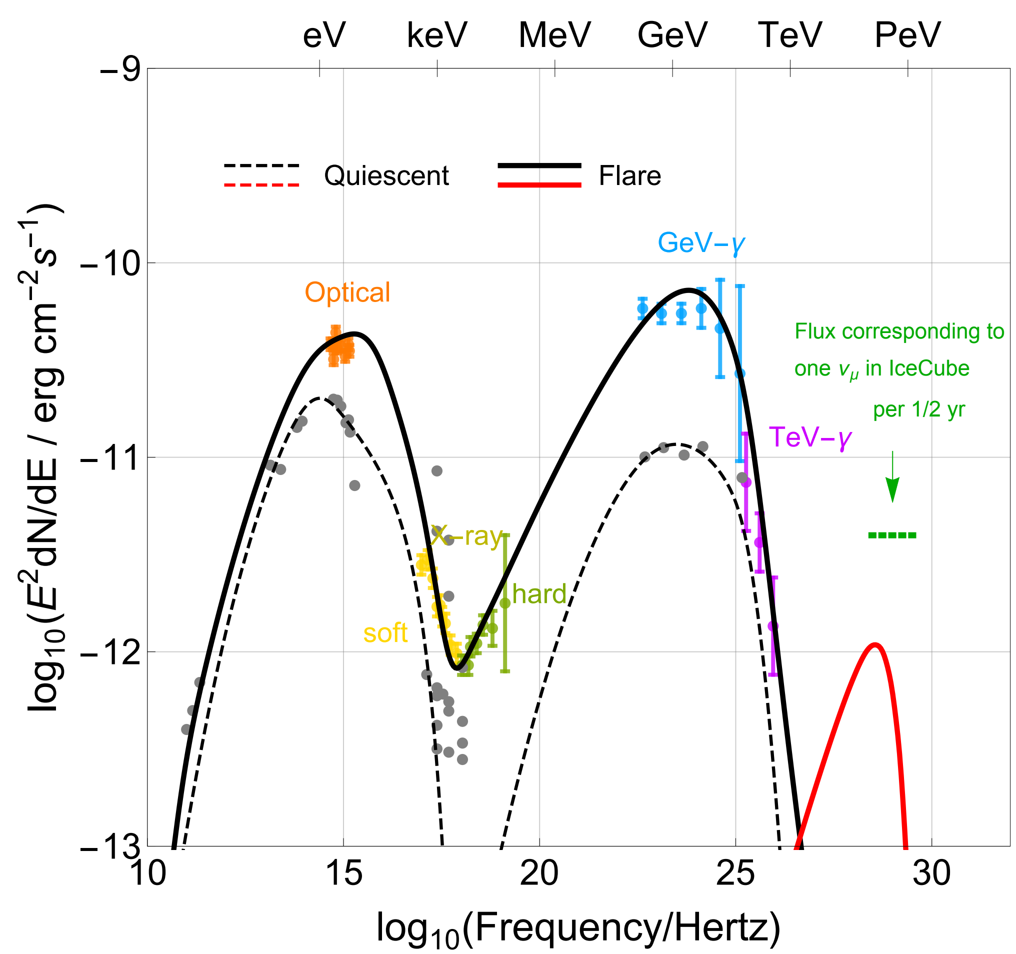
- Quiescent state produce by a persistent steady-state from a large blob R=10^17 cm
- Flare produced by boosted acceleration, dissipation of an inner core R=10^16 cm
- Quiescent state : almost no neutrinos; Flare state : 0.27 /yr — 2σ compatibility with observation.
- Atmospheric ν background low, 0.001/yr
- S/N ratio significance ~ 2.9σ



SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

The light curve





SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

Lessons learned from modeling this source

- Consider the two constraints: x-ray luminosity **L_x** and physical jet luminosity **L_jet**

L_x	L_jet
fixed by observation; neutrino yield described by **L_nu = k L_x** where k is related to fullness of cascade	unknown; but cannot exceed too much of **L_Eddington** of SMBH of high mass end
proton interaction rate cannot be too high, otherwise too much cascade decreases k and L_nu	proton interaction rate cannot be too low, otherwise needs a big load of L_p>>L_jet to produce neutrinos
favors a compact dense source ⟷	favors a large dilute source

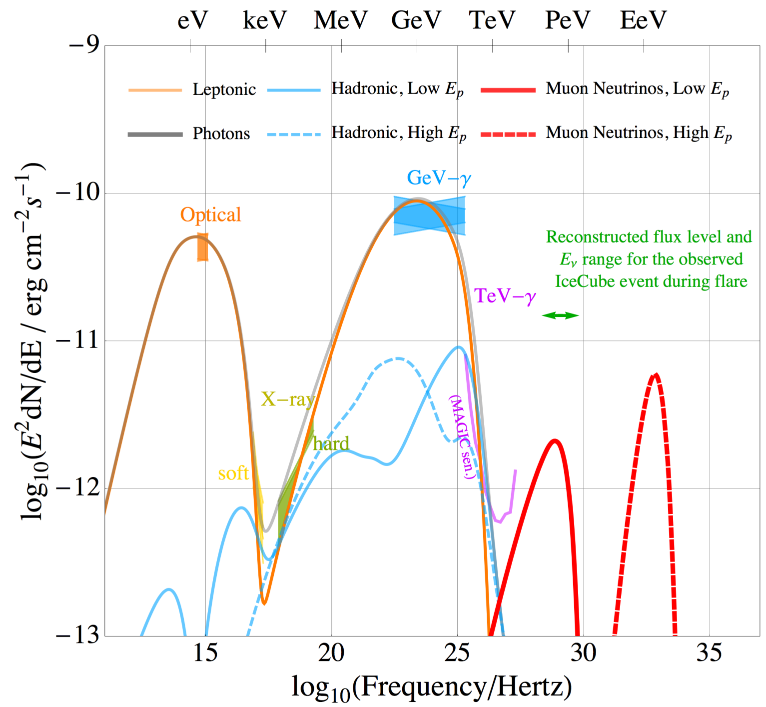
- **The sweet spot (our baseline model) yields 0.27/yr**
- **There is no such model with a simple geometry to yield 1 neutrino / flare and to observe both L_x and L_jet constraints.**

Alternative attempts

Try a higher Ep,max

+ Fits SED, neutrino rate and be consistent with L_jet
- Not compatible with observed neutrino E (too high)

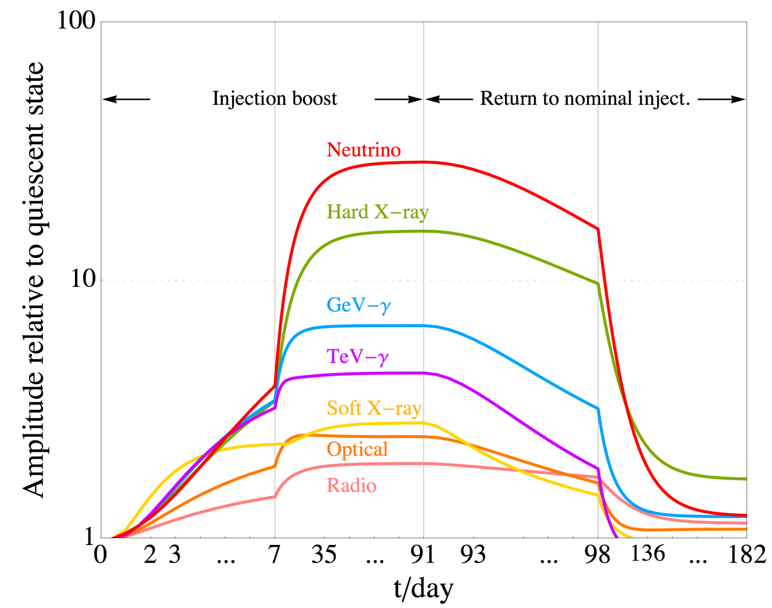
See also Cerruti et al. 1807.04335



SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

Try a larger blob R=10^17 cm

+ Simple geometry, one-zone model
+ Remarkably simple assumption to describe both quiet and flare state: flare = L_injection x 3 of quiet
- L_flare exceeds L_jet by hundreds



SG, A. Fedynitch, M. Pohl, W. Winter, arxiv: 1807.04275

Alternative attempts

Try a more complicated geometry

The MAGIC collaboration, 1807.04300

+ Structured jet model (spine + sheath). Protons and target photons from different zones, see each other with relativistic boost to enhance the reaction rate.

– These structures needs to be stably extended to ~100 pc to maintain the flare.

Liu et al, 1807.05113

+ Independent two-zone model. Clouds in the broad line region to block X-ray and γ-rays. Fits SED and predicts a neutrino flux compatible with observation.

– Leptonic emission from outside the torus. Neutrino emission and γ-ray flare not correlated.

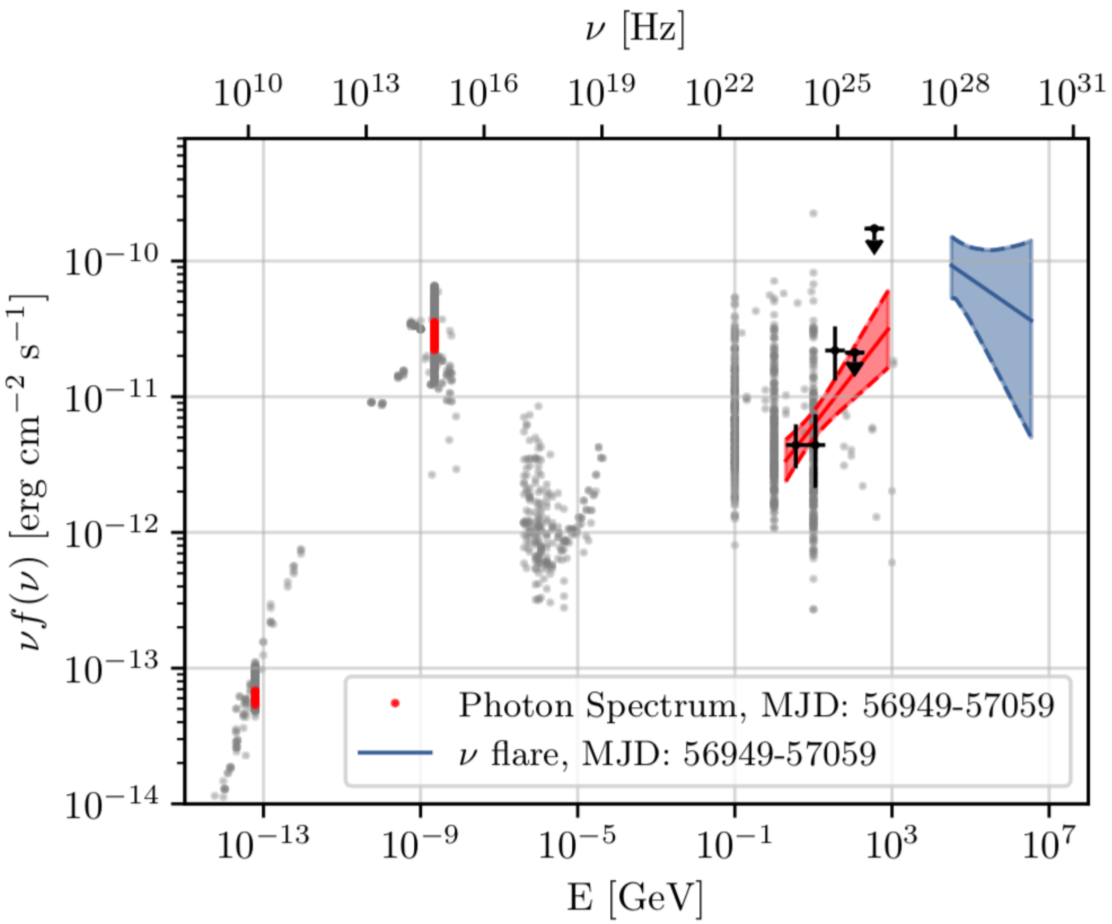
– Needs extreme column density of clouds; needs fine tuned geometry and specific viewing angle (to see photons from certain bands and block them from certain bands, etc.)

Conclusions

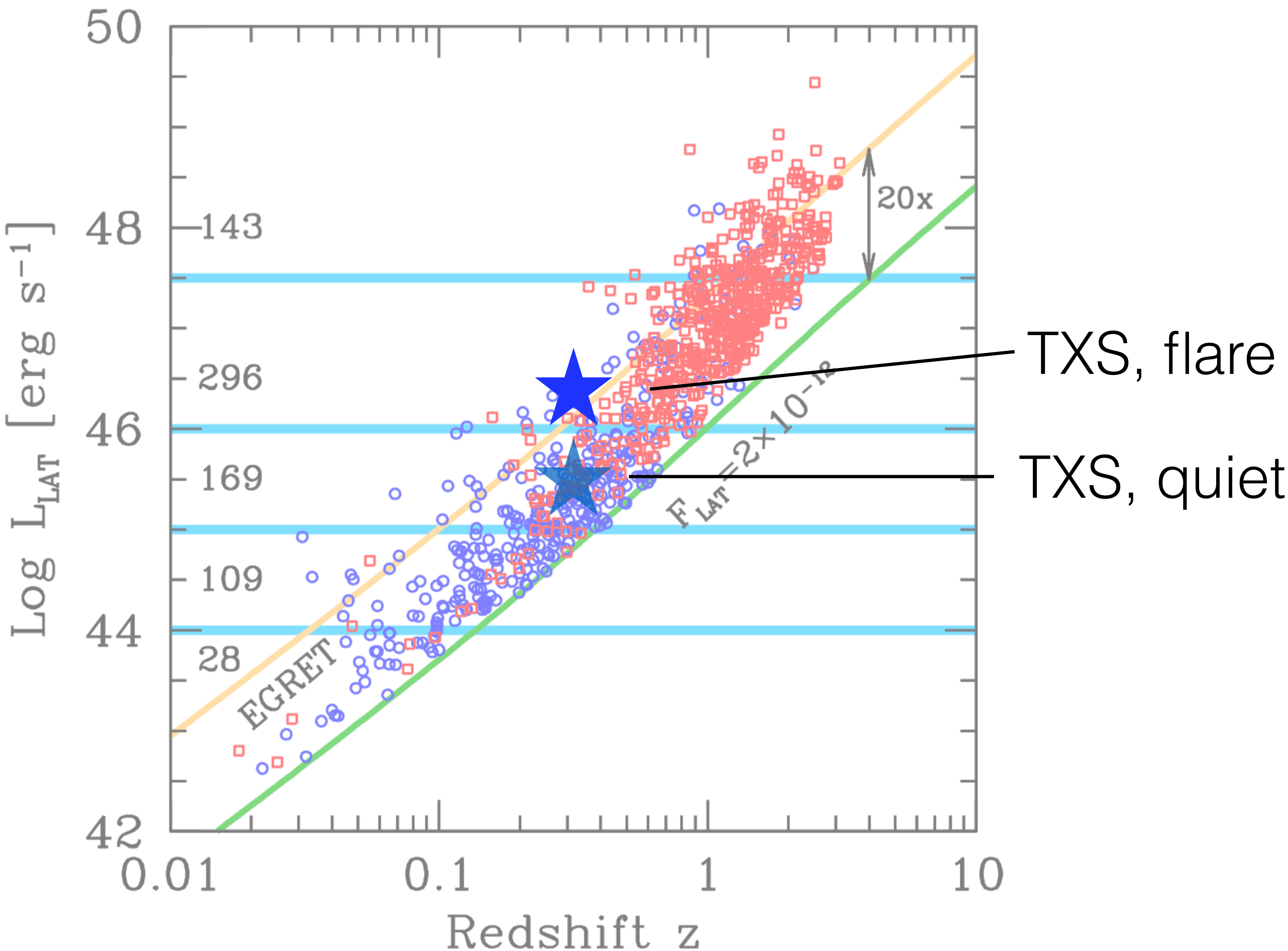
- No simple one-zone model works. Pure hadronic interpretation of γ-rays excluded.
- Pure leptonic SSC fits SED.
- A hybrid model predicts 0.3/yr flare state (2σ compatibility) , ~ 0/yr quiet state, S/N significance ~ 2.9σ
- The hybrid model explains well the trend of observation. X-ray ~ TeV ~ Neutrino correlation.
- While neutrino astronomy just about to take off, this event demonstrates :

  Multi-wavelength & neutrino observations + "open data" + sophisticated theoretical models = ground-breaking multi-messenger astronomy

BACKUP SLIDES

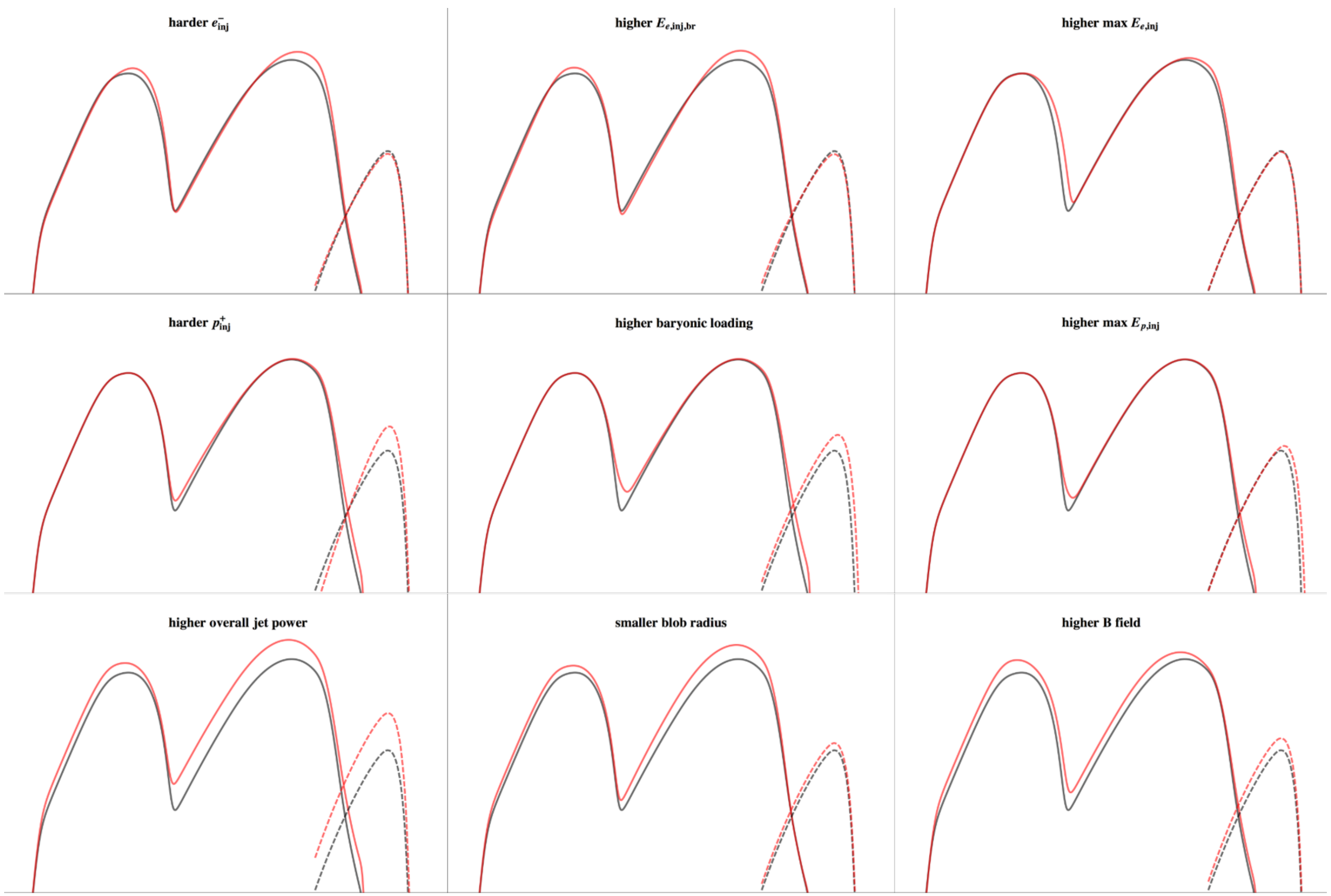


Padovani et al, 2018, MNRAS



Background figure taken from Fig.2, Ghisellini et al, MNRAS 2017

Parameter	Description	Fit	Hybrid		Hadronic
			Quiescent	Flare	Flare
z	Redshift	fixed	0.34		0.34
B' (G)	Magnetic field		0.008	0.17	2.0
$R'_{\rm blob}$ (cm)	Blob size		$10^{17.5}$	10^{16}	10^{16}
$\Gamma_{\rm bulk}$	Doppler factor		28.5		20.0
$L'_{e,\rm inj}$ (erg/s)	Electron injection luminosity		$10^{40.5}$	$10^{41.0}$	$10^{41.3}$
$\alpha_{e,1}$	Electron lower spectral index		-1.3	-1.2	–
$\alpha_{e,2}$	Electron upper spectral index		-1.7	-1.7	-2.3
$\gamma'_{e,\rm min}$	Min. electron Lorentz factor		$10^{3.3}$	$10^{4.1}$	$10^{3.3}$
$\gamma'_{e,\rm br}$	Electron break Lorentz factor		$10^{4.3}$	$10^{4.3}$	–
$\gamma'_{e,\rm max}$	Max. electron Lorentz factor		$10^{5.2}$	$10^{4.7}$	$10^{4.4}$
$L'_{p,\rm inj}$ (erg/s)	Proton injection luminosity		$10^{44.6}$	$10^{45.6}$	$10^{47.0}$
$\gamma'_{p,\rm min}$	Min. proton Lorentz factor	fixed	10.0		10.0
$\gamma'_{p,\rm max}$	Max. proton Lorentz factor		$10^{5.3}$		$10^{5.6}$
α_p	Proton spectral index	fixed	-2.0		-2.0
$\eta_{\rm esc}$	escape velocity of $e^{\pm}$ and p		$c/300$	$c/300$	$c/10$
Results					
$L_{\rm Edd}$ (erg/s)	Eddington luminosity *		$10^{47.8}$		$10^{47.8}$
$L_{\rm jet}/L_{\rm Edd}$	jet physical luminosity (in $L_{\rm Edd}$)		0.5	5.0	62.8
$E_{\nu,\rm peak}$, TeV	peak energy of neutrino spectrum		220	220	330
N_ν/yr	Expected neutrino rate in IceCube		$10^{-3.8}$	0.23	9.8


harder $e^-_{\rm inj}$
higher $E_{e,\rm inj,br}$
higher max $E_{e,\rm inj}$
harder $p^+_{\rm inj}$
higher baryonic loading
higher max $E_{p,\rm inj}$
higher overall jet power
smaller blob radius
higher B field