Interpretation of the coincident observation of a high energy neutrino and a bright flare

Shan Gao for “Monitoring the non-thermal universe” 2018, Cochem

Animation by DESY

Based on paper submitted to *Nature Astronomy* by SG, A.Fedynitch, W. Winter and M. Pohl, preliminary **arXiv version 1807.04275**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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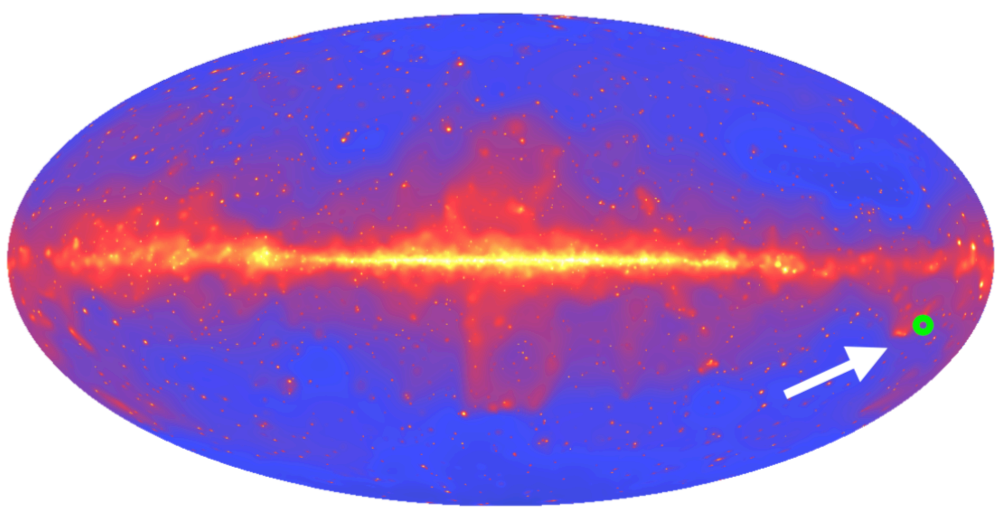
The first smoking-gun signature of a VHE neutrino source?

IceCube 170922A and blazar TXS0506+056



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

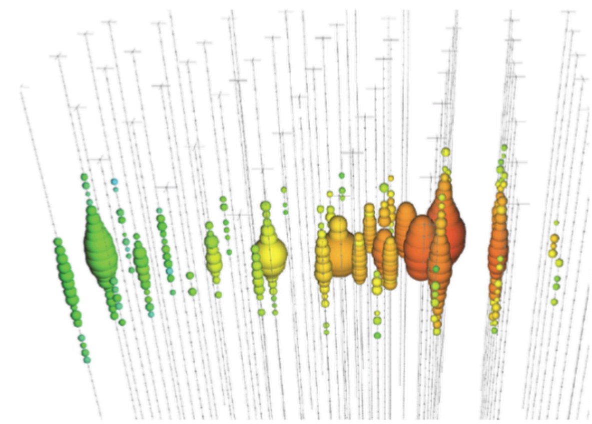
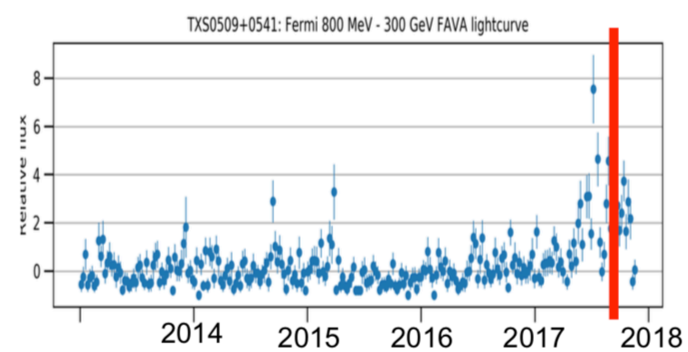


Illustration of an IceCube neutrino track event. IceCube Collaboration



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)

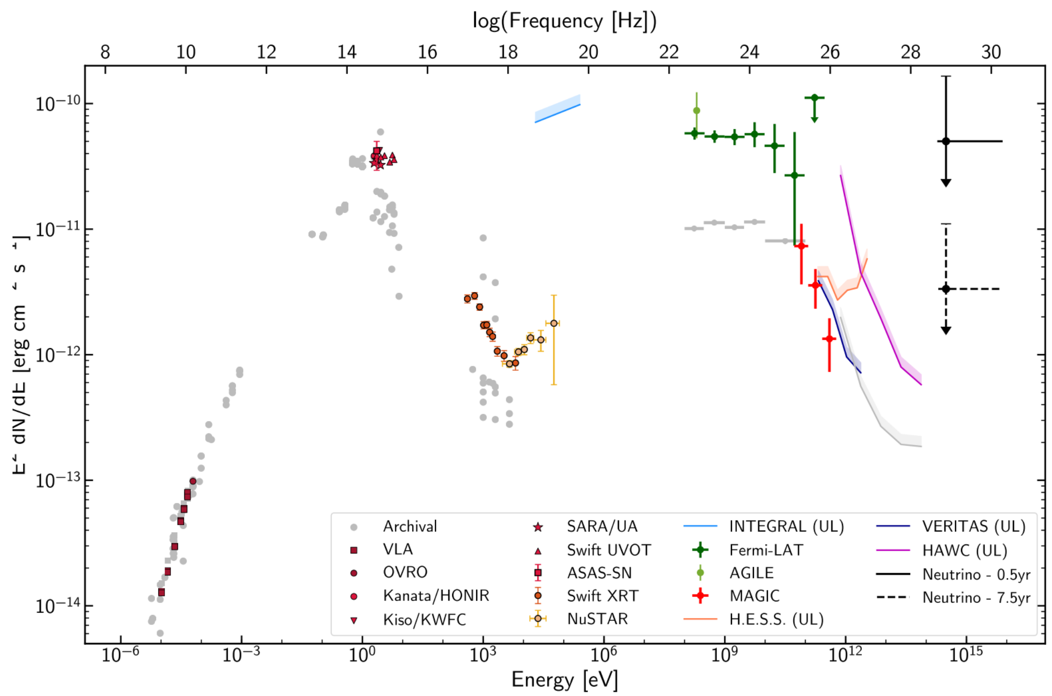
List of follow up papers:

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

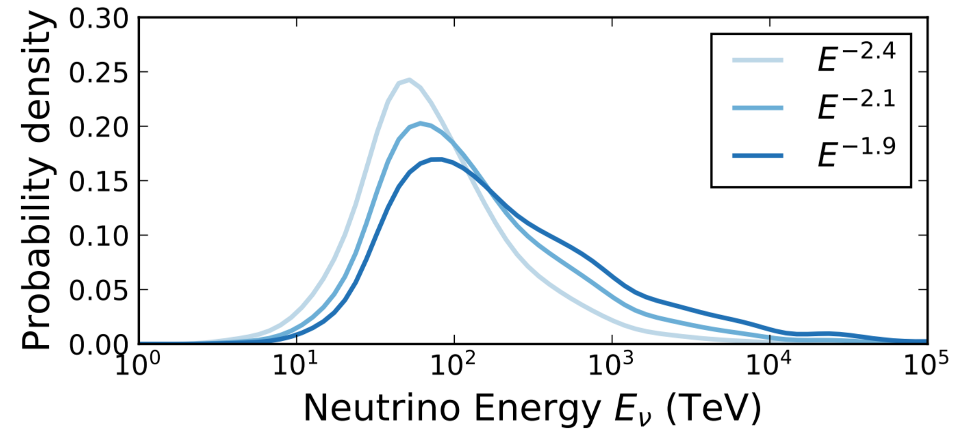
Theoretical modeling : **this talk, 1807.04275**

Theoretical challenges

IceCube, Fermi, MAGIC,++, Science 2018

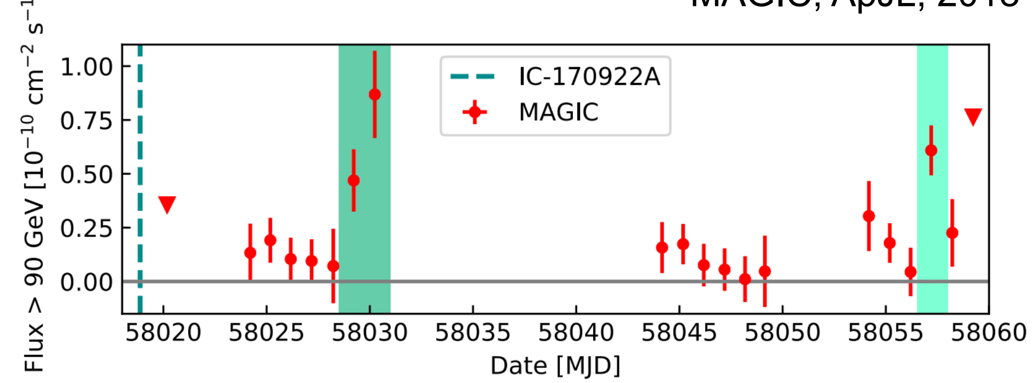


Neutrino detected during **flare, not quiet state**



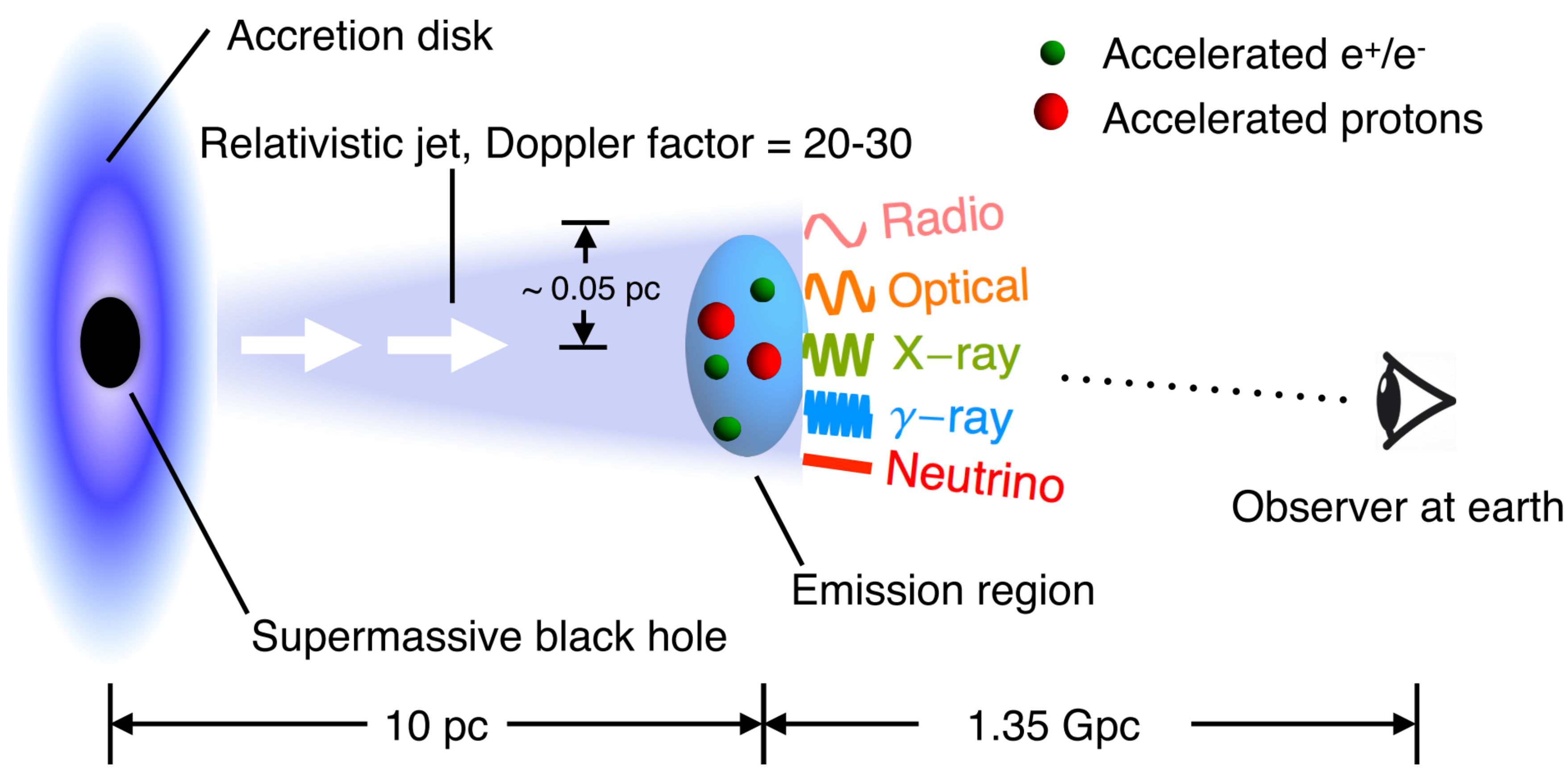
Incident neutrino energy around **a few hunderd TeV**

MAGIC, ApJL, 2018



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

Geometry


Accretion disk
Accelerated e+/e-
Accelerated protons
Relativistic jet, Doppler factor = 20-30
~ 0.05 pc
Radio
Optical
X–ray
γ–ray
Neutrino
Observer at earth
Emission region
Supermassive black hole
10 pc
1.35 Gpc

Time-dependent hadro-leptonic code (AM³)*

*Astrophysical Modeling with Multiple Messengers

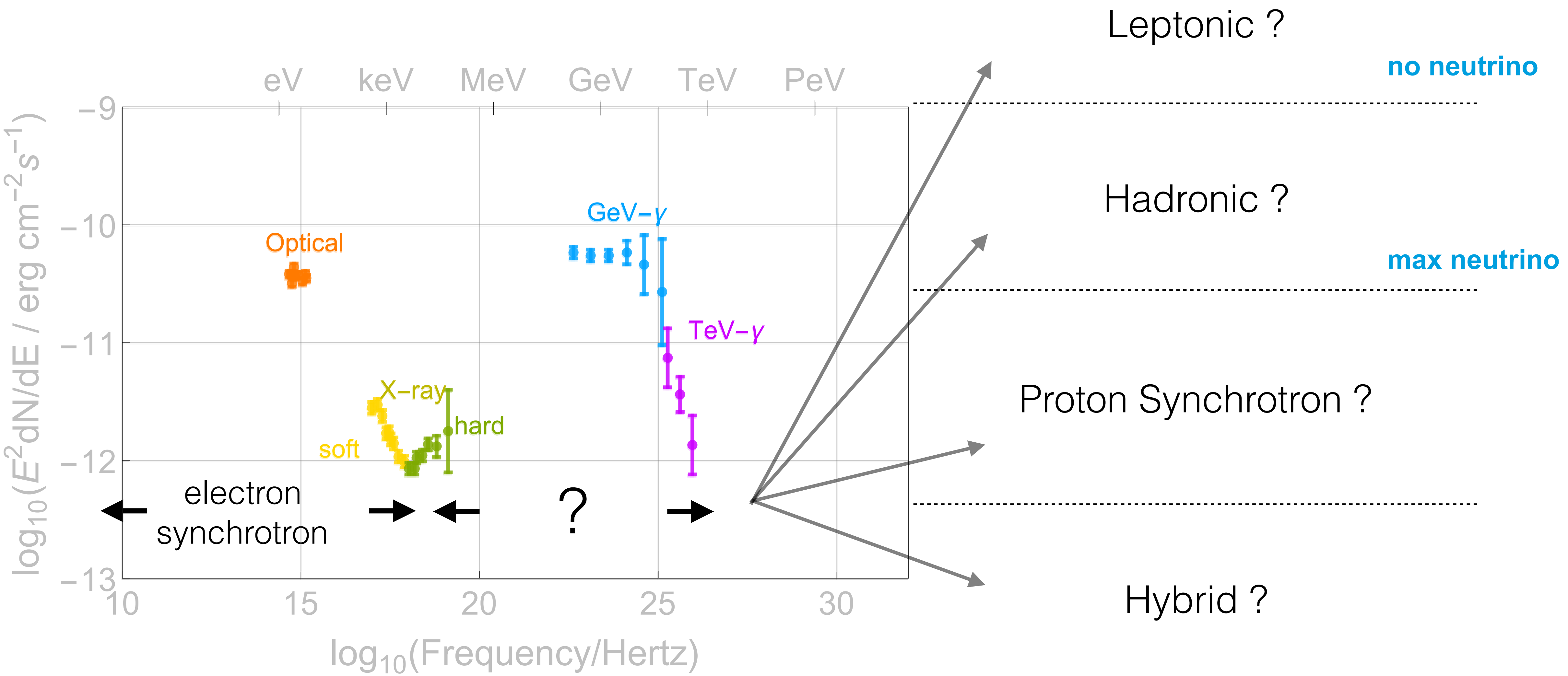
$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

	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)

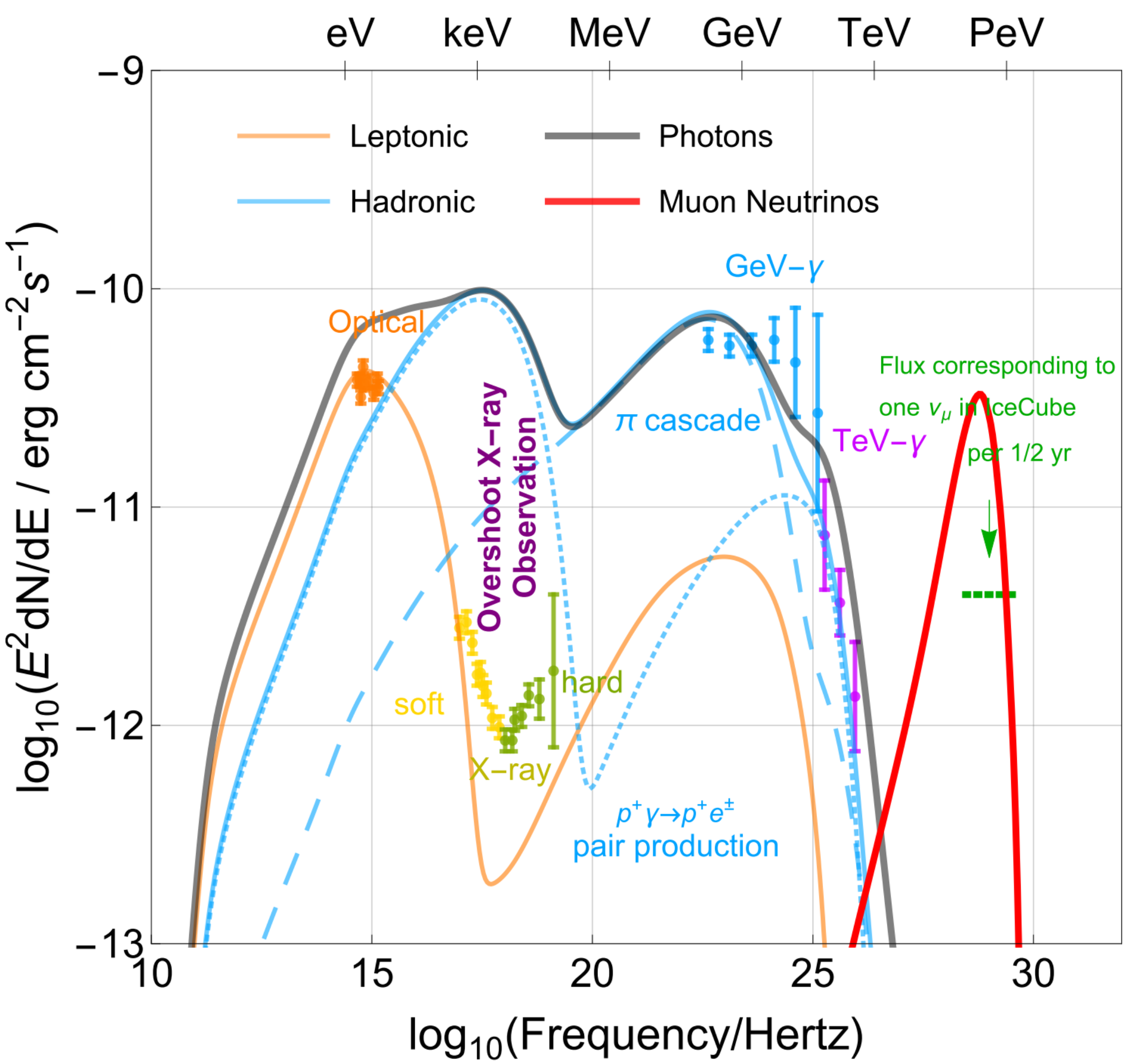
- **Numerically** solves a set of **coupled** transport **equations** for all relevant particles.
- Energy “bandwidth“ ~20 orders of magnitude (Radio-EeV)
- **Very efficient**: < 2 min per time-dependent simulation
- Photo-hadronic interactions following Hümmer et al., APJ 712, 2010

Physical origin of the SED ?



We scan each type of model for compatibility with observations

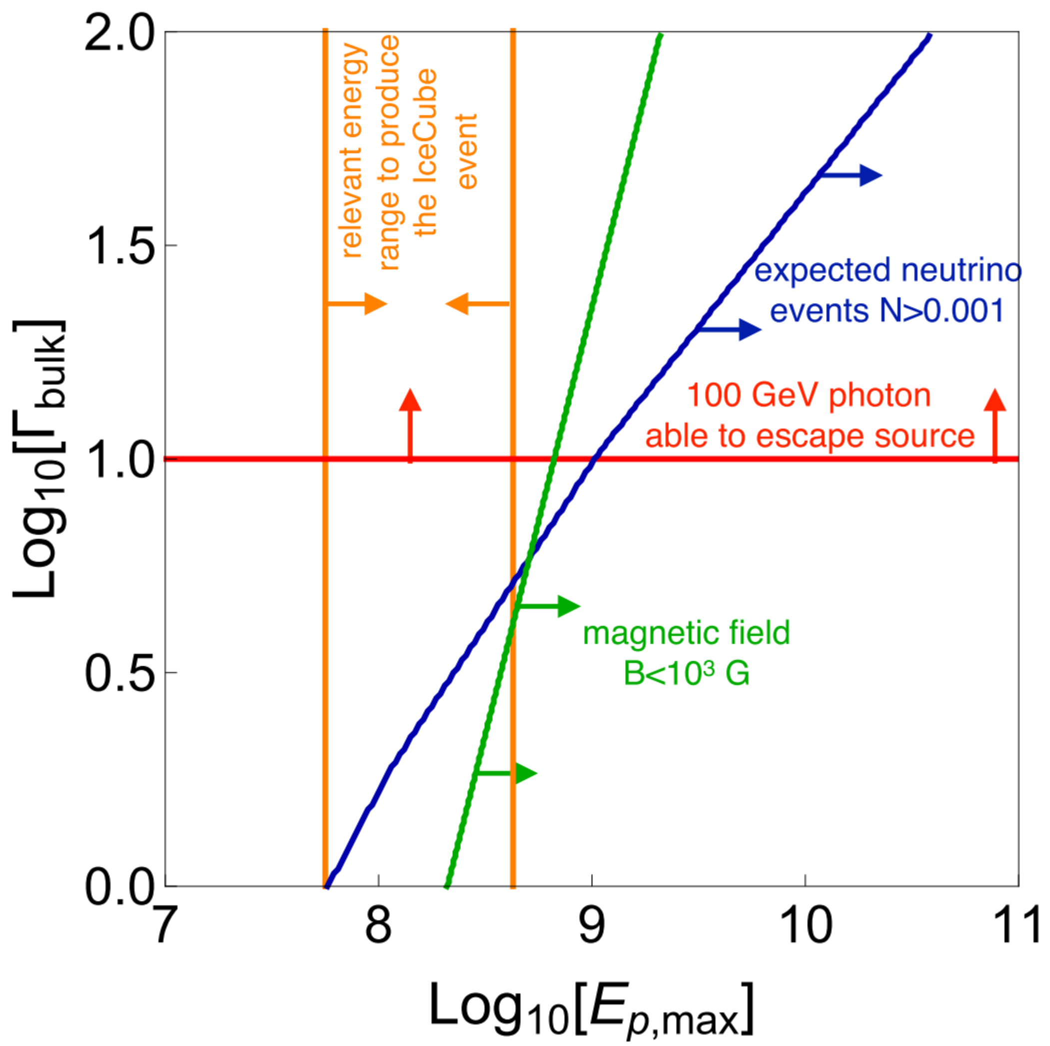
[Model-1/4] Hadronic γ-rays



- Constraints: proton-synchrotron, Bethe-Heitler, SSC emission, etc.
- Example (left): Bethe-Heitler overshoots X-ray
- Extensive parameter scan : no solution

Ruled out

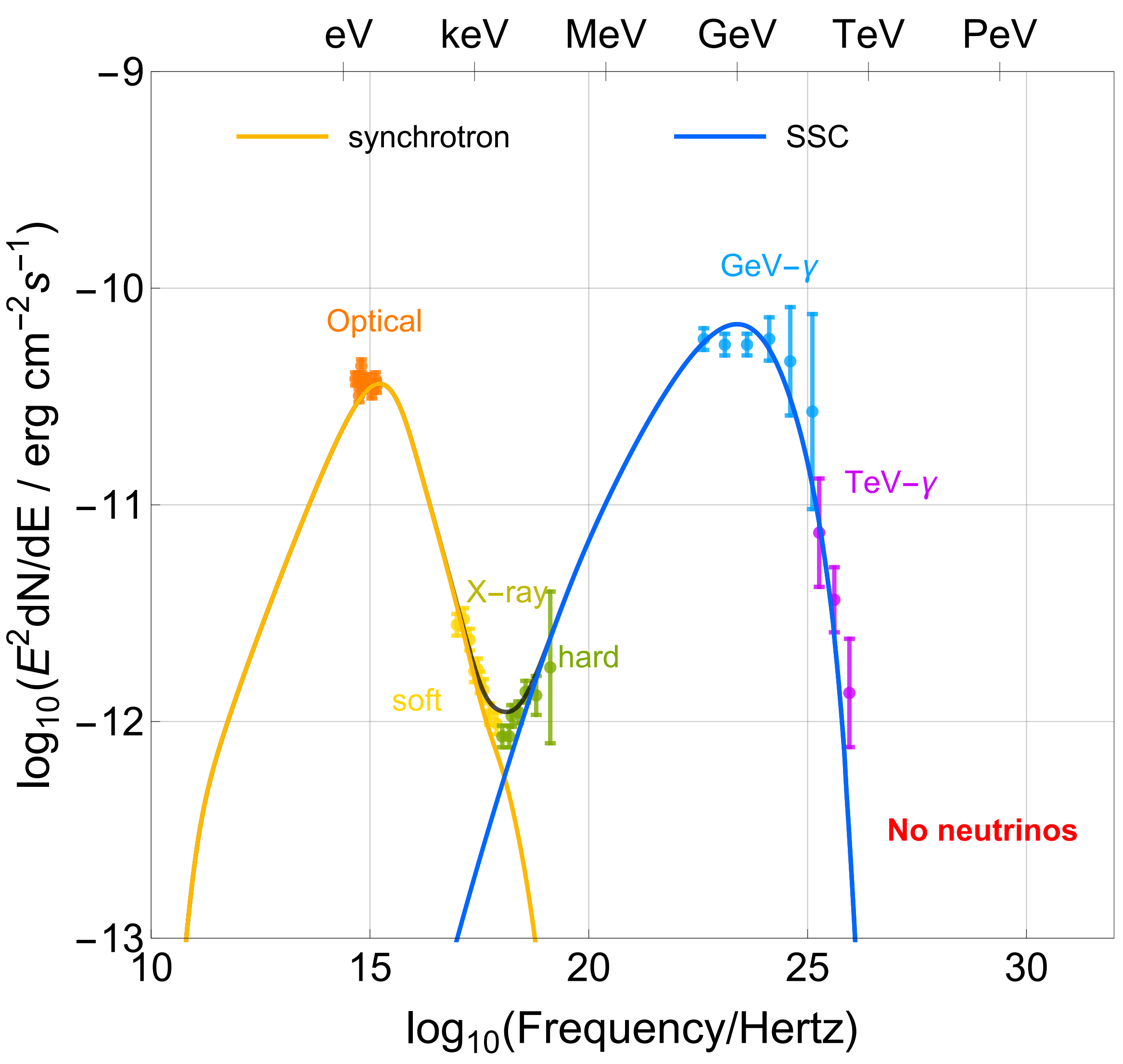
[Model-2/4] Proton synchrotron as γ-rays



- Multiple constraints
- Can explain SED, but not SED + observed neutrino
- Extensive parameter scan : no solution

Also excluded

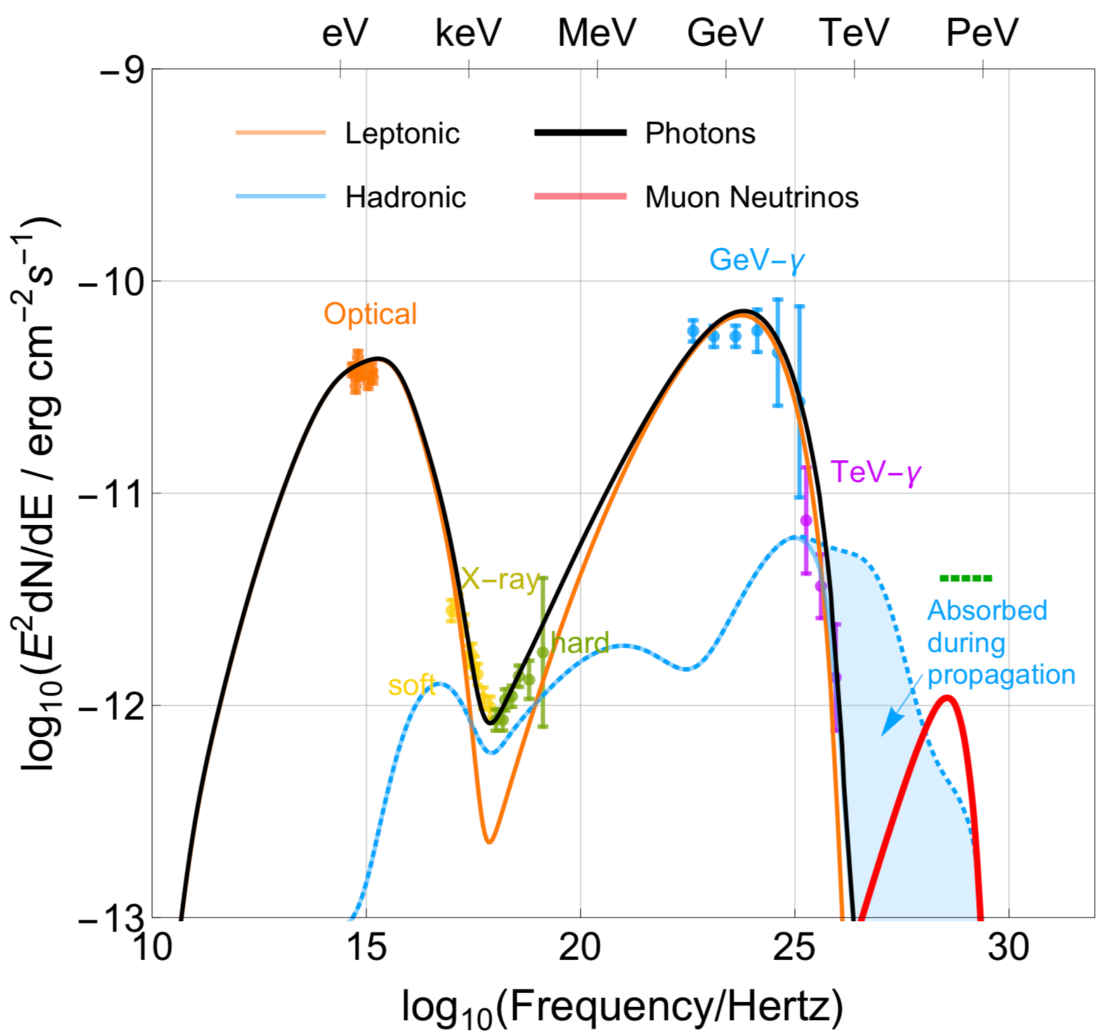
[Model-3/4] Pure leptonic SED (SSC model)



Remarkably simple assumptions:

R~10^{16} cm, B~0.16G and electrons with a $E^{-3.5}$ injection pectrum between $10^4 < \gamma < 6x10^5$

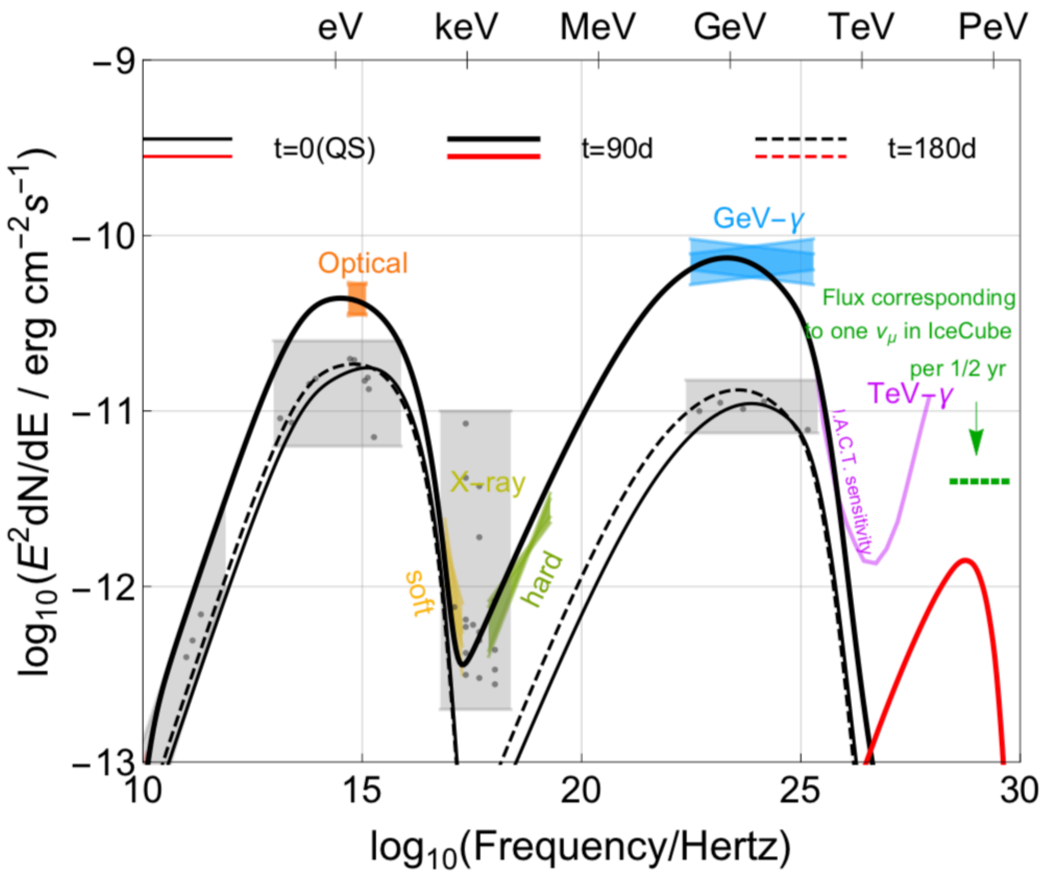
[Model-4/4] Hybrid SED

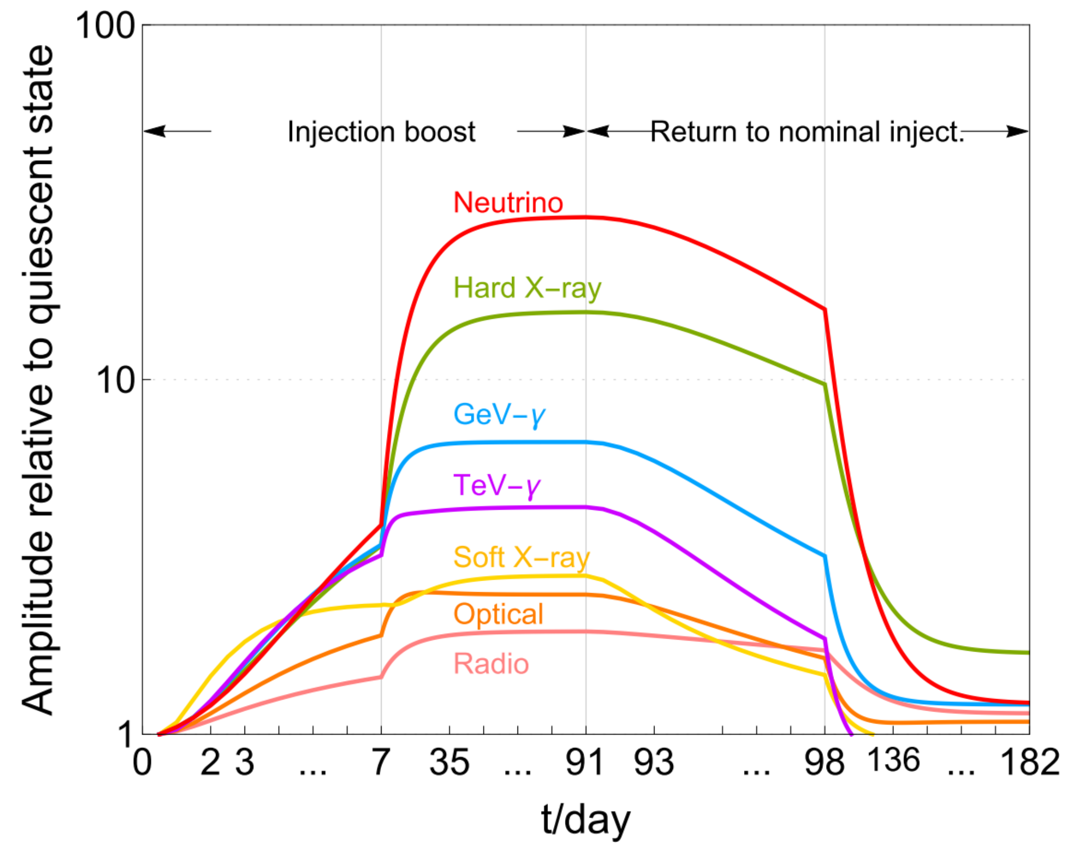


- γ-rays via leptonic SSC
- Subdominant hadronic emission in X-ray
- Reproduces neutrino energy 100TeV~PeV
- γγ pair production by EBL (z=0.34) absorbs

  E >100 GeV photons

[Model-4/4] Hybrid : time-dependent





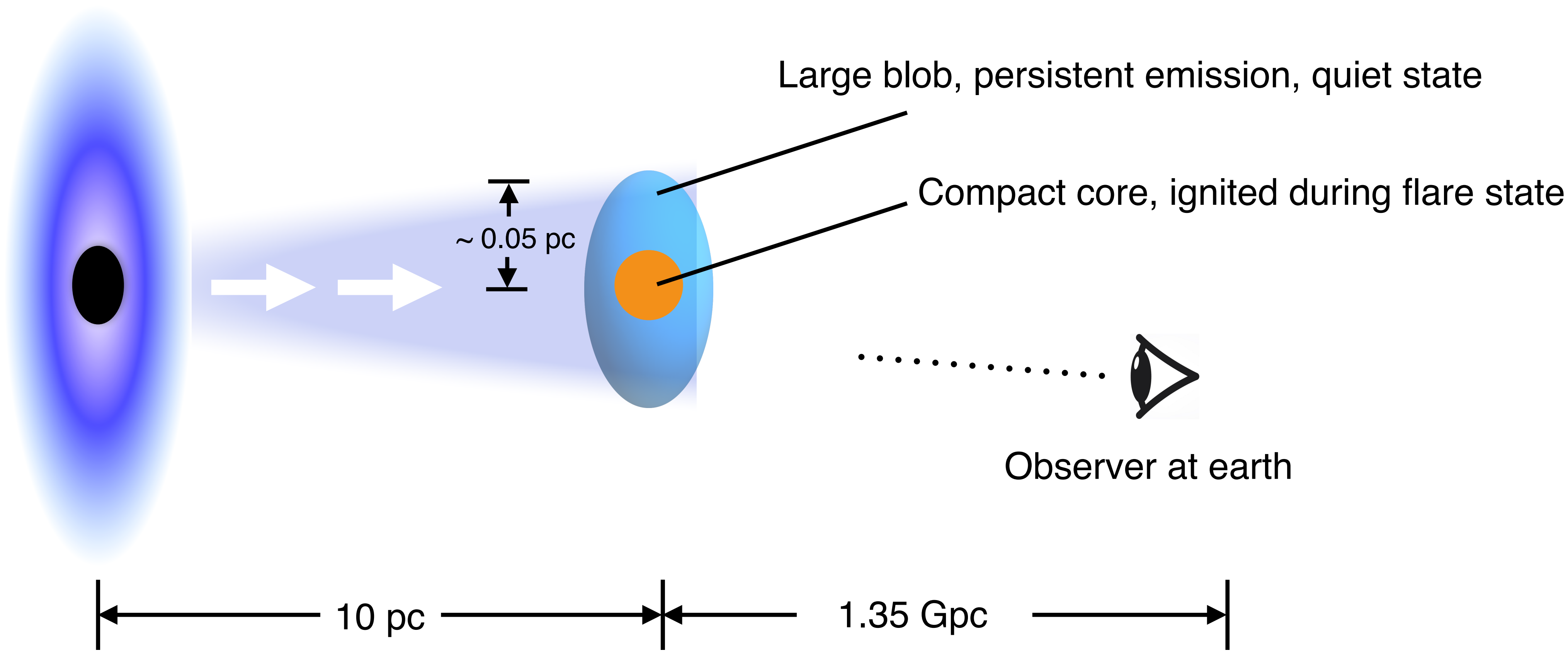
Remarkable: increasing p & e- injection by factor 3 explains flare

Problem : proton power = 500 L_{Edd}

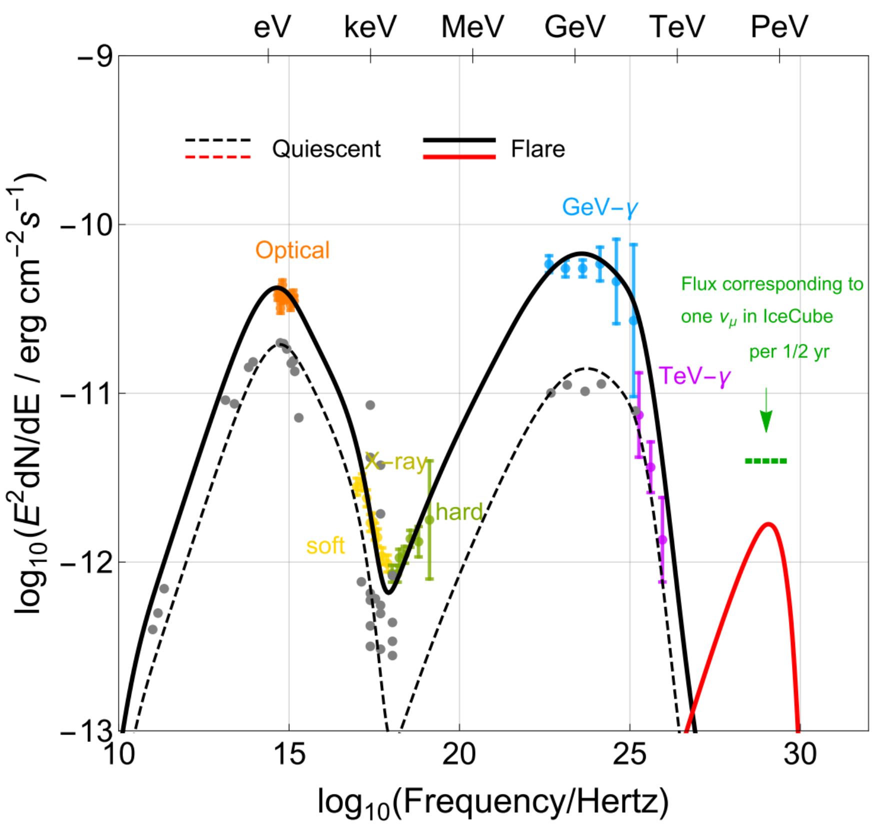
Solution ? Quiet state + radio => large emission region

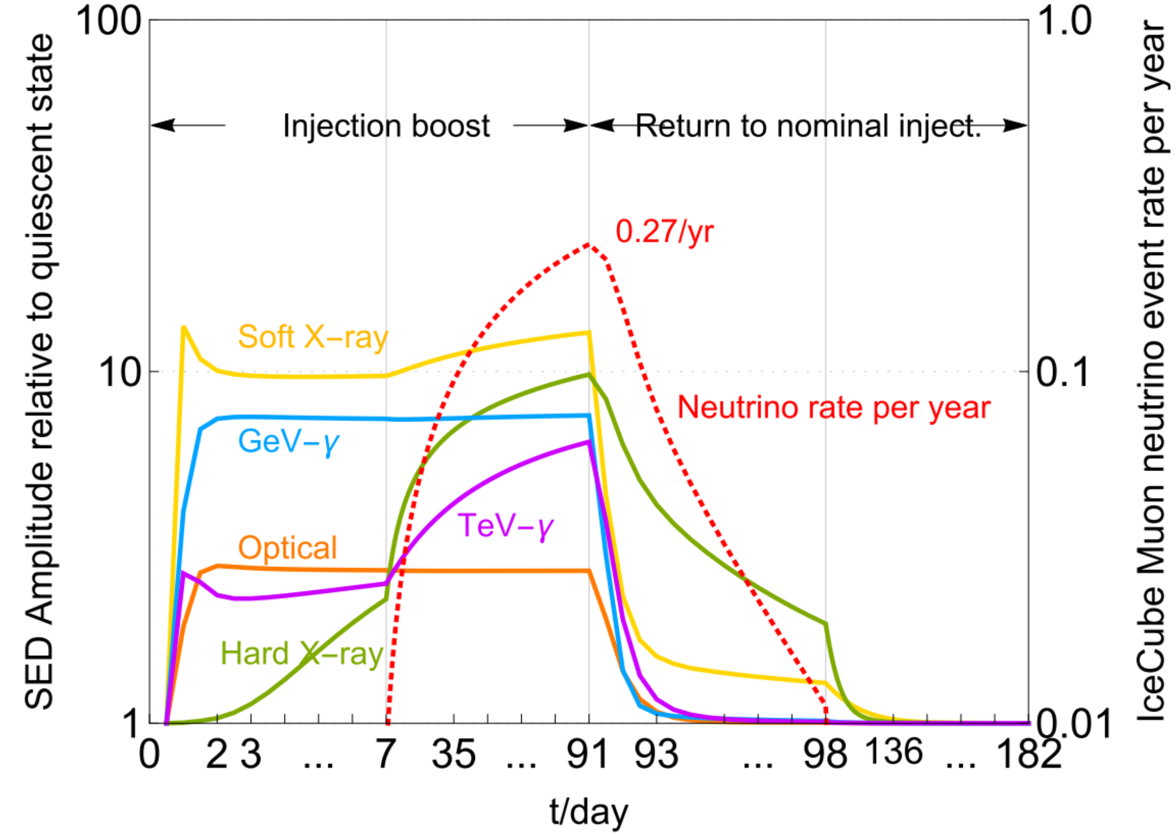
Jet power limit => compact emission region, confine particle (low leak rate)

Two-zone model



Two-zone model





- **Proton power = 5 L_Edd (flare), 0.5 L_Edd (quiet)**
- **0.27 neutrinos / yr (flare), 0 (quiet)**
- **Optical ~ Soft X ~ GeV-γ : leptonic**
- **Hard X ~ TeV-γ ~ Neutrino: hadronic**

General remark: how dense should the source be ?

Dilute

- \+ Less in-source cascade, higher ν to X-ray ratio
- \+ Simple geometry
- − Super-Eddington proton power

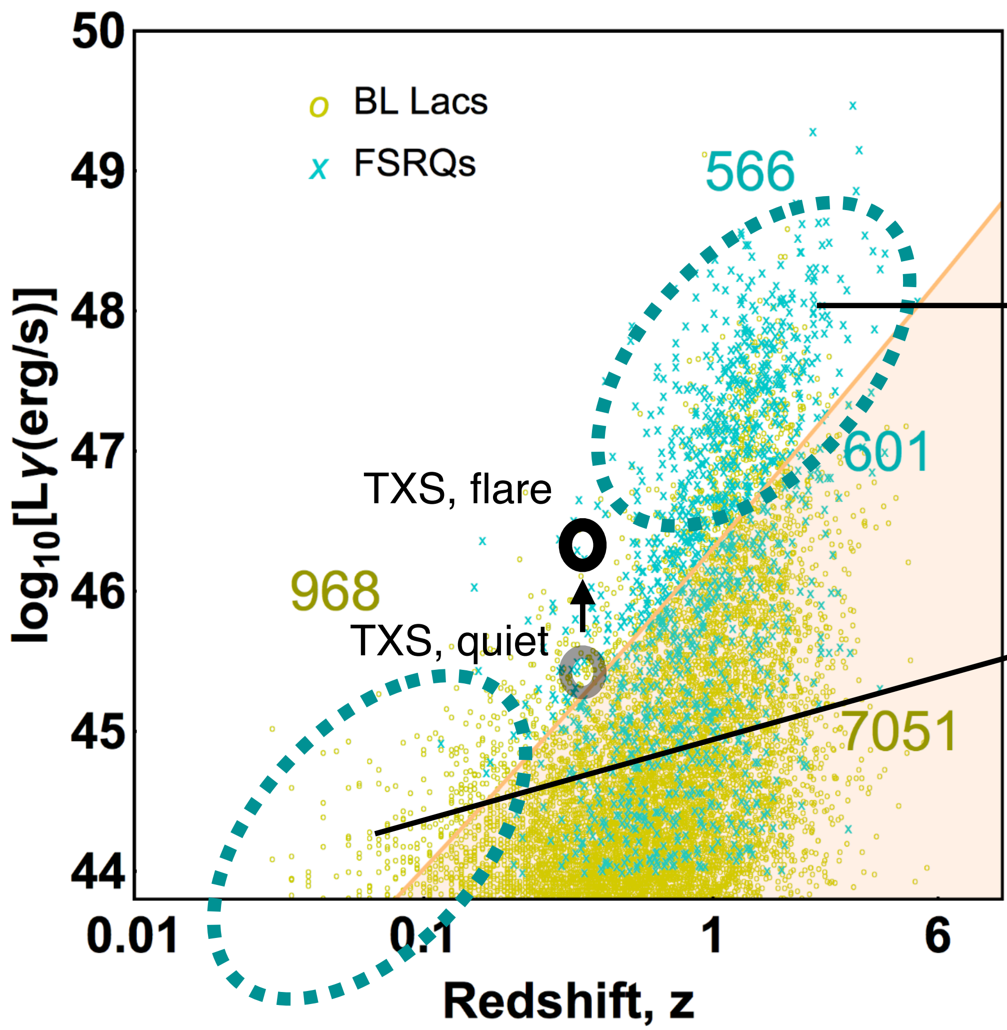
Dense

- \+ Realistic proton power
- − Less in-source cascade — lower ν to X-ray ratio

Super dense

- \+ Block/absorb E.M. cascade, allow more neutrinos
- − Complicated geometry and fine-tuning (ad hoc)
- − No correlation between γ and ν

How unique is TXS ?



Input: assumption on how much the jet is loaded with protons

Stongly limited by IceCube "stacking analysis"

Too inefficient neutrino emitters

0.4 γ-ν alert per year from all blazars

Palladino, Rodrigues, SG, Winter, 1806.04769

Summary : lessons learned from modeling TXS

- TXS0506+056 can be the source of the **one neutrino**

- The **flare** is an **extraordinary state for neutrino production** while the quiet state produces negligible neutrinos

- Most of the “elegant” **one zone models** faces severe constraints: (1) sub-PeV neutrino energy => low efficiency => jet power problem; (2) X-ray constraints => favors less cascade; findings in line with e.g. Keivani et al., Cerruti et al. Böettcher et al. etc.

- **TXS requires** a more complex model with **multiple zones**, to avoid the above contraints (see also Tavecchio et al, Liu et al)

- **Lepto-hadronic signatures** could be observable **for nearby blazars in TeV** as a break and hardening of the spectrum, coordinated with X-ray activity.

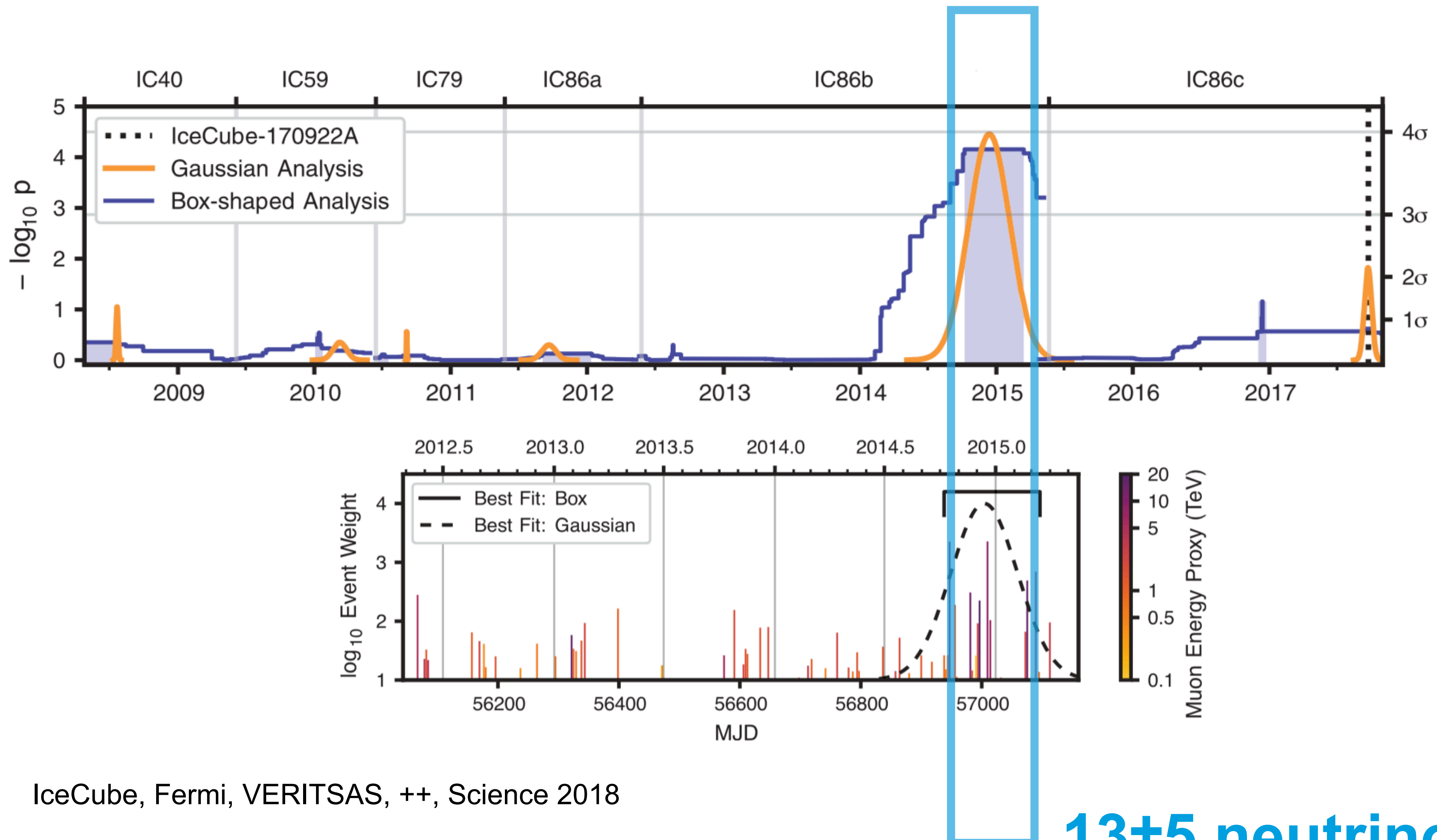
- **TXS alone** is unfortunately **not** enough to understand why this blazar is a particular neutrino source

Backup - parameters

Parameter table

Param.	Description	Fit	Hybrid		Hadronic	Leptonic
			Quiescent	Flare	Flare	Flare
z	Redshift	fixed	0.34		0.34	0.34
B'	Magnetic field (G)		0.007	0.14	2.0	0.16
$R'_{\rm blob}$	Blob radius (cm)		$10^{17.5}$	10^{16}	10^{16}	10^{16}
$\Gamma_{\rm bulk}$	Doppler factor		28.0		20.0	28.0
$L'_{e,\rm inj}$	e^- injection luminosity (erg/s)		$10^{40.5}$	$10^{40.9}$	$10^{41.3}$	$10^{41.0}$
α_e	e^- spectral index		-2.5	-3.5	-2.3	-3.5
$\gamma'_{e,\rm min}$	Min. e^- Lorentz factor		$10^{4.2}$		$10^{3.3}$	$10^{4.1}$
$\gamma'_{e,\rm max}$	Max. e^- Lorentz factor		$10^{5.6}$	$10^{5.1}$	$10^{4.4}$	$10^{5.9}$
$L'_{p,\rm inj}$	p injection luminosity (erg/s)		$10^{44.5}$	$10^{45.7}$	$10^{47.0}$	–
$\gamma'_{p,\rm min}$	Min. p Lorentz factor	fixed	10.0		10.0	–
$\gamma'_{p,\rm max}$	Max. p Lorentz factor		$10^{5.4}$		$10^{5.6}$	–
α_p	p spectral index	fixed	-2.0		-2.0	–
$\eta_{\rm esc}$	escape velocity of $e^{\pm}$ and p	fixed	$c/300$	$c/300$	$c/10$	$c/10$
Results						
$L_{\rm Edd}$	Eddington luminosity * (erg/s)		$10^{47.8}$		$10^{47.8}$	$10^{47.8}$
$L_{\rm jet}$	jet physical luminosity (in $L_{\rm Edd}$)		0.4	6.2	62.8	10^{-4}
$E_{\nu,\rm peak}$	peak energy of ν spectrum (TeV)		250		330	–
N_ν/yr	Expected IceCube ν events		$10^{-3.8}$	0.27	9.8	0

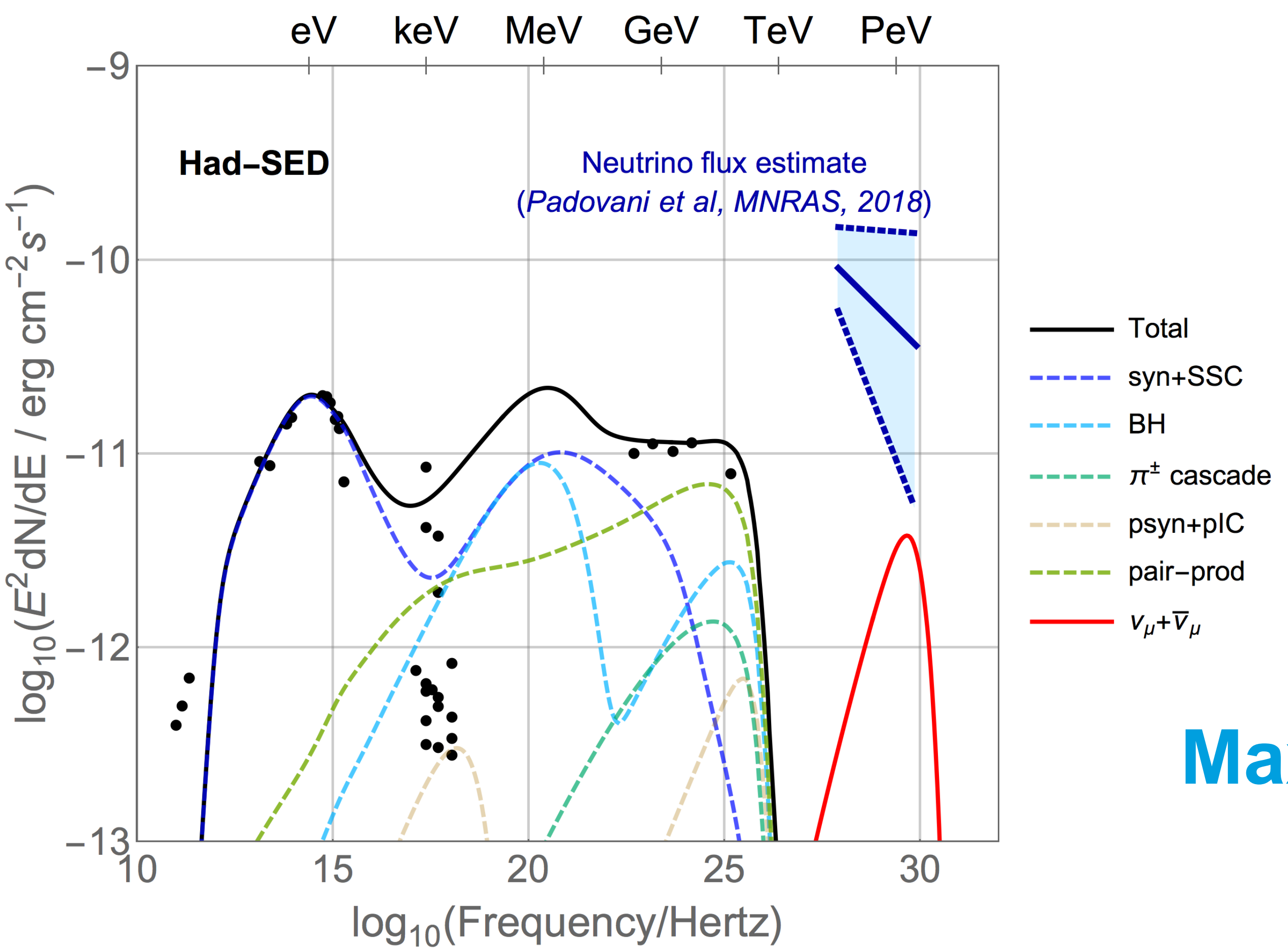
Backup - neutrino flare 2014-2015?



IceCube, Fermi, VERITSAS, ++, Science 2018

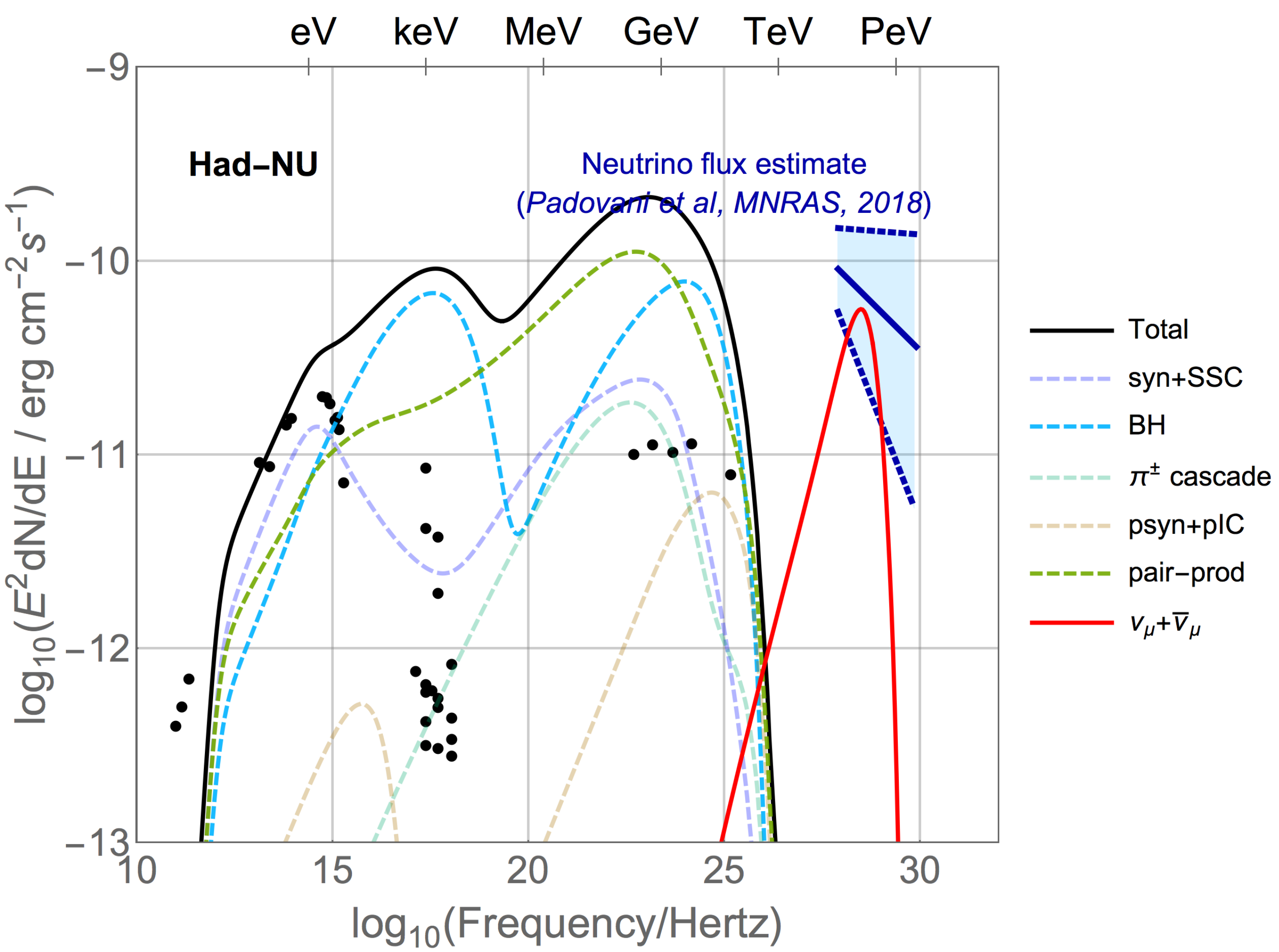
13±5 neutrinos ?

Backup - neutrino flare 2014-2015?



Maximum neutrino flux?

Backup - neutrino flare 2014-2015?



Sufficient neutrino flux but overshoots SED