# Modeling neutrinos in coincidence with blazar TXS0506+056


Shan Gao, for MPIK
04.02.2018


Animation by DESY

Based on papers:

**SG**, A.Fedynitch, W.Winter & M.Pohl, Nature Astronomy 3,88 (2019) (1807.04275) and
X.Rodrigues, **SG**, A.Fedynitch, A.Palladino & W.Winter (1812.05939) (ApJ Lett. subm.)


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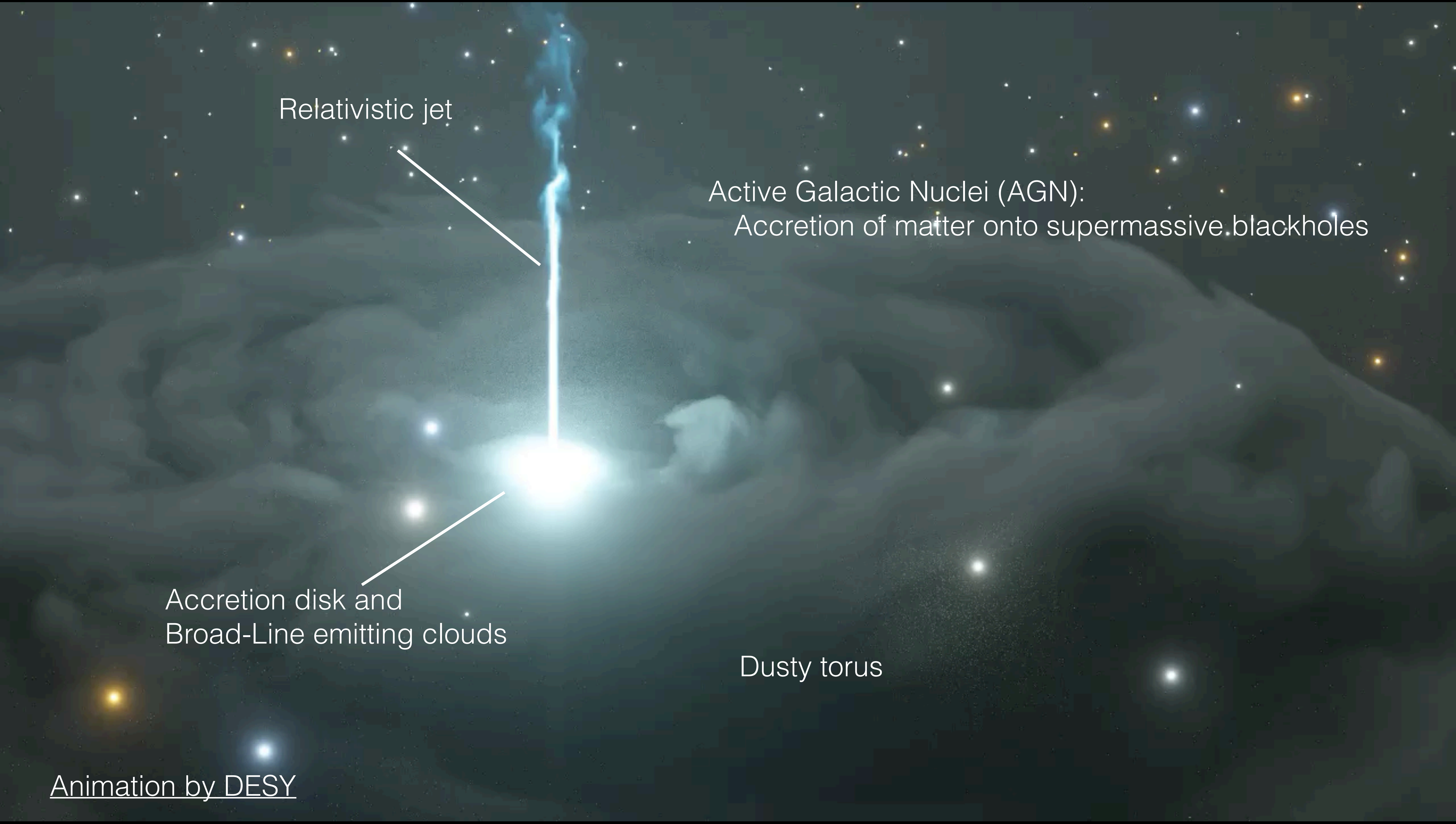
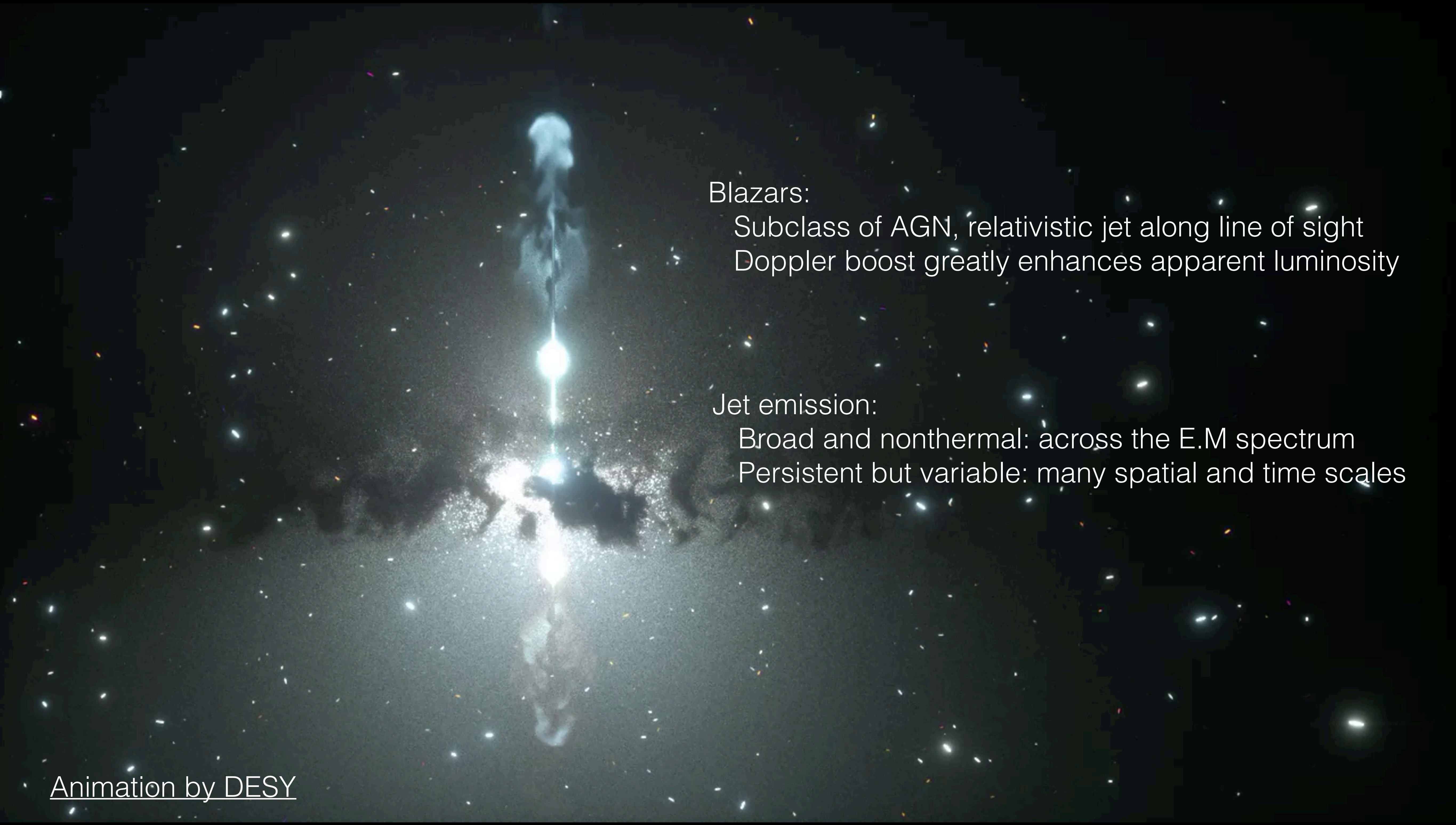
# Outline

- Introduction : AGN as cosmic accelerator
- Multi-messenger observation of TXS0506+056 (neutrino + E.M.)
- Modeling (within SM scope) of TXS:  successes and failures
  - The 2017 activity
  - The 2014-15 activity
- Summary and implications


Relativistic jet
Active Galactic Nuclei (AGN):
Accretion of matter onto supermassive blackholes
Accretion disk and
Broad-Line emitting clouds
Dusty torus
Animation by DESY



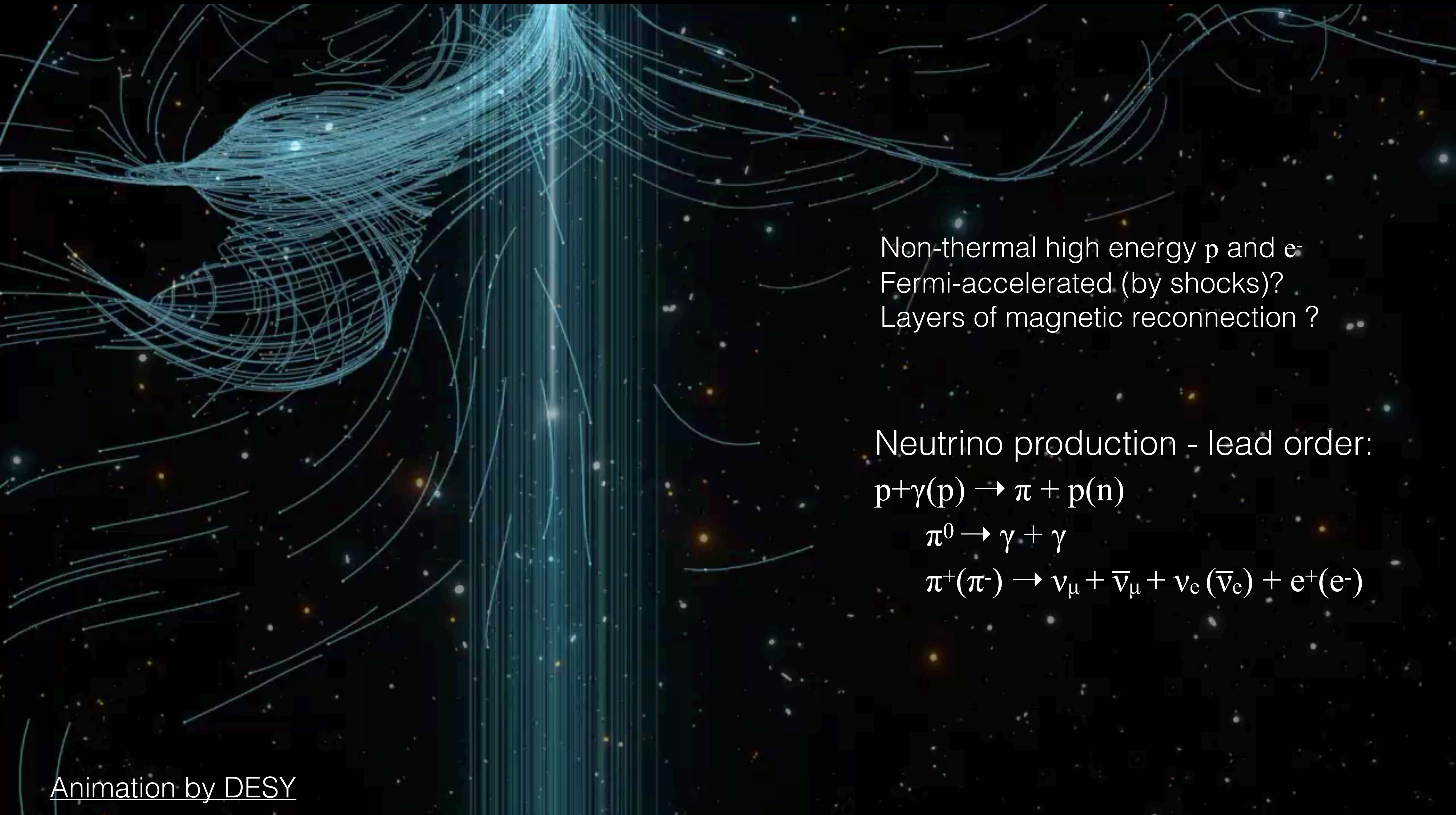
Blazars:

- Subclass of AGN, relativistic jet along line of sight
- Doppler boost greatly enhances apparent luminosity

Jet emission:

- Broad and nonthermal: across the E.M spectrum
- Persistent but variable: many spatial and time scales

Animation by DESY



Non-thermal high energy p and $e^-$
Fermi-accelerated (by shocks)?
Layers of magnetic reconnection ?

Neutrino production - lead order:

$$p+\gamma(p) \rightarrow \pi + p(n)$$

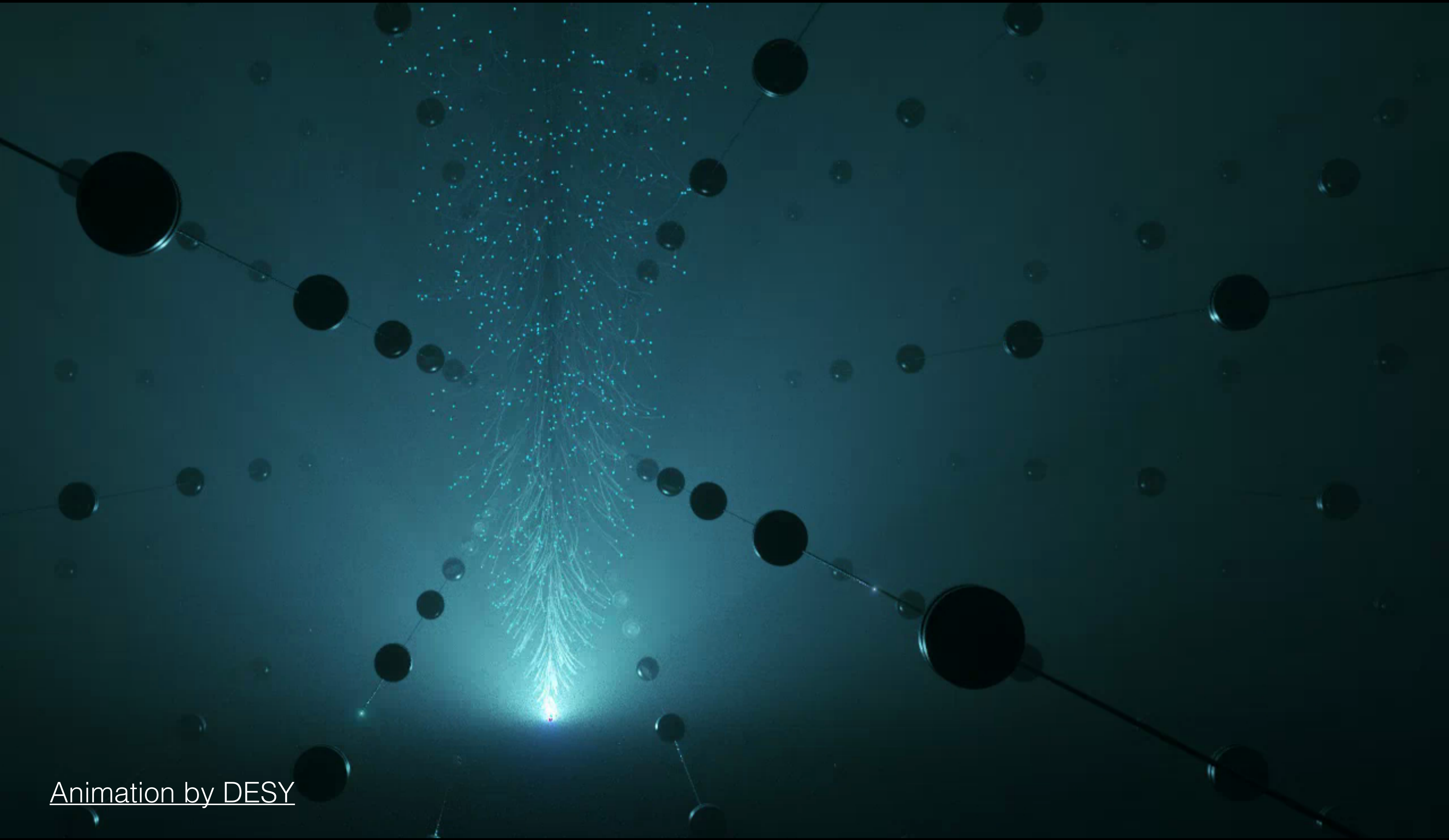
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+(\pi^-) \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e\,(\bar{\nu}_e) + e^+(e^-)$$

Animation by DESY

Photons and netrinos travel directly to earth.
Universe is opaque to TeV-PeV photons due to pair production with CMB and star-light.

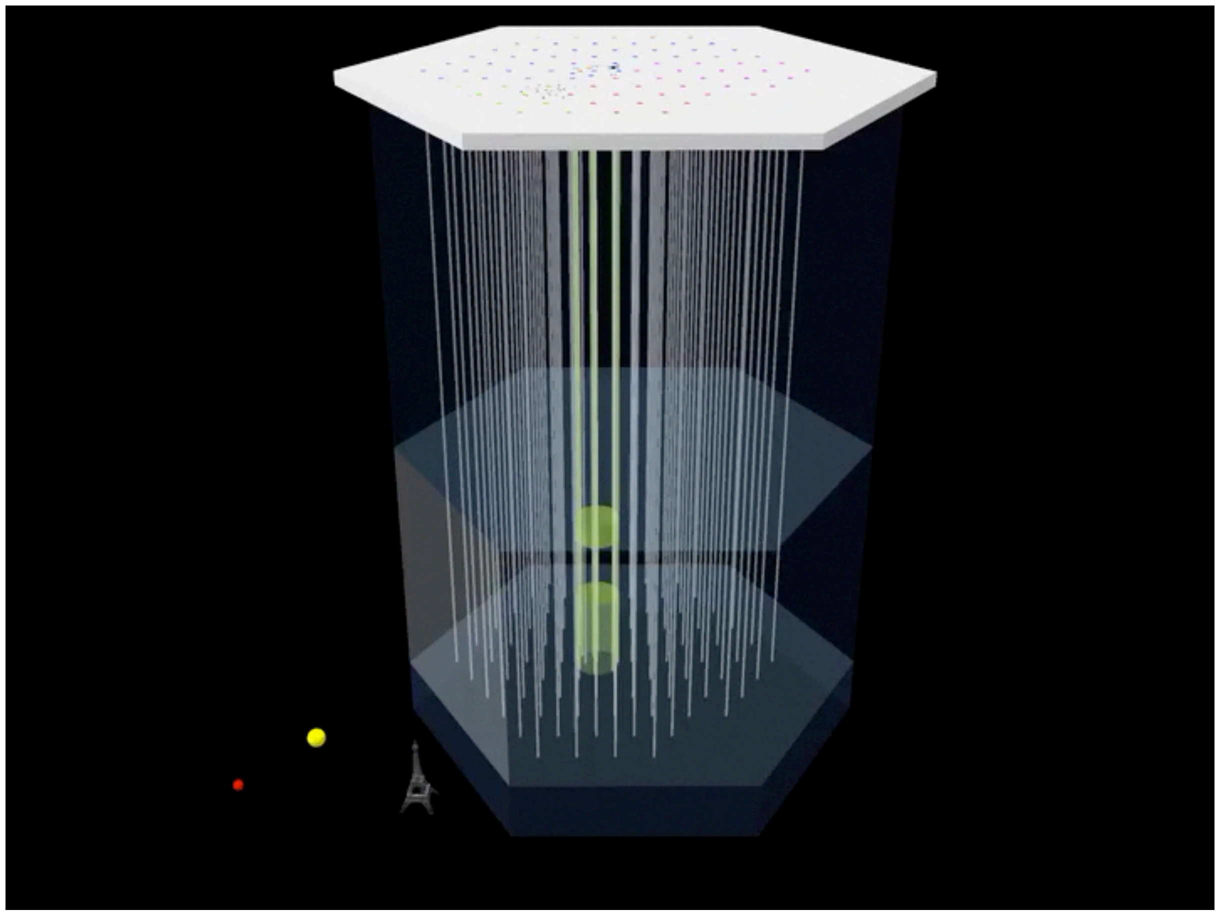
Animation by DESY



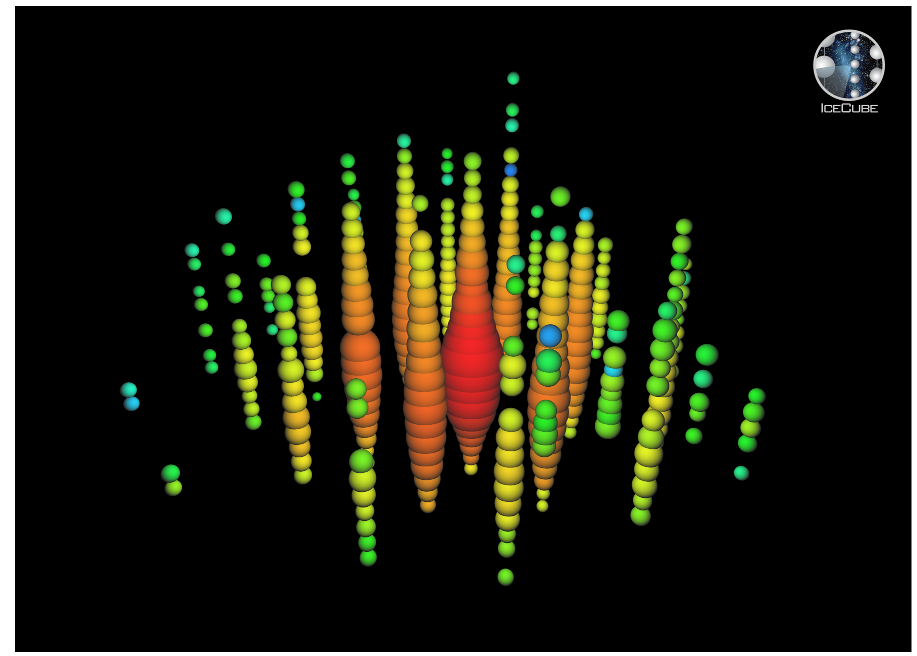
Animation by DESY


MAGIC, HESS, VERITAS
and CTA (in progress)
Animation by DESY

# Neutrino detection in IceCube



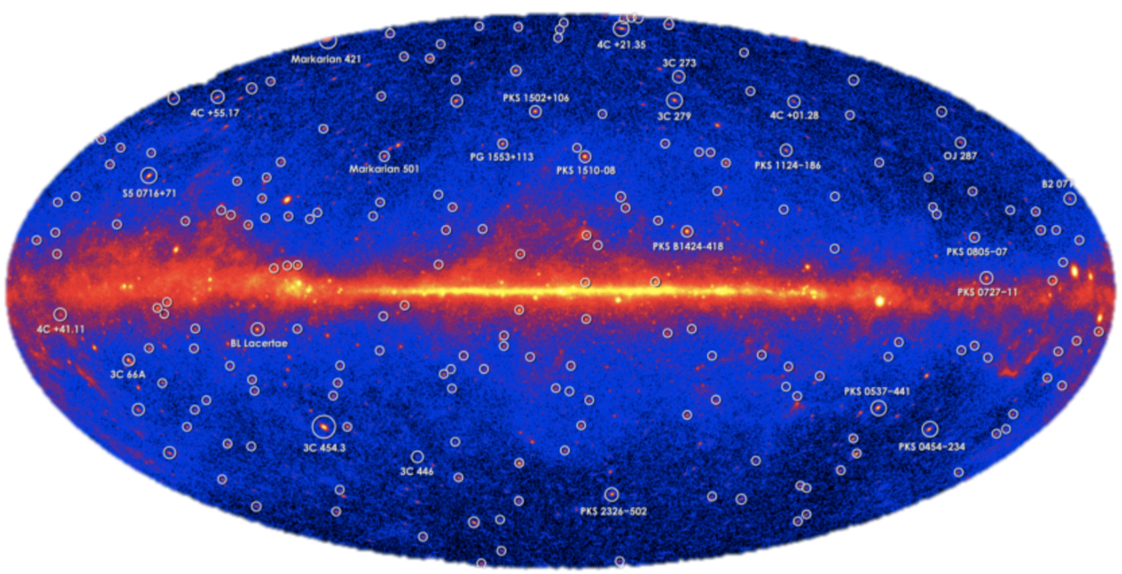
A muon-track event - good angular info. (~ 1 deg)
poor energy measurement (orders of magnitude)

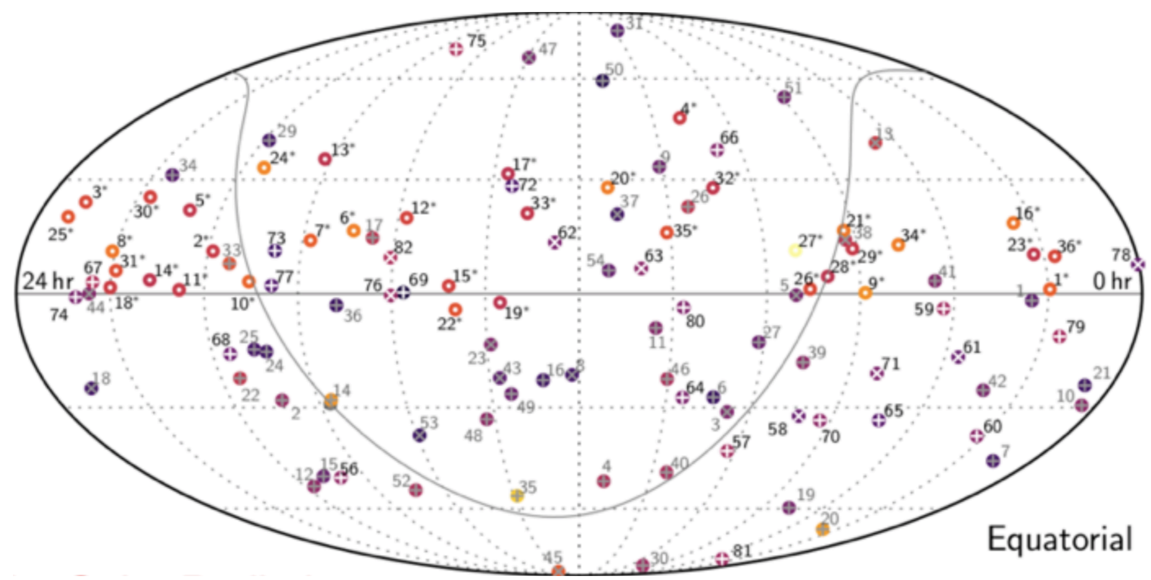



A cascade event - good energy measurement,
poor angular info. (10-15 deg uncertainty)

Animation and figure by IceCube

# Blazar population and IceCube neutrinos






Fermi Gamma-ray sky (~1500 blazars)

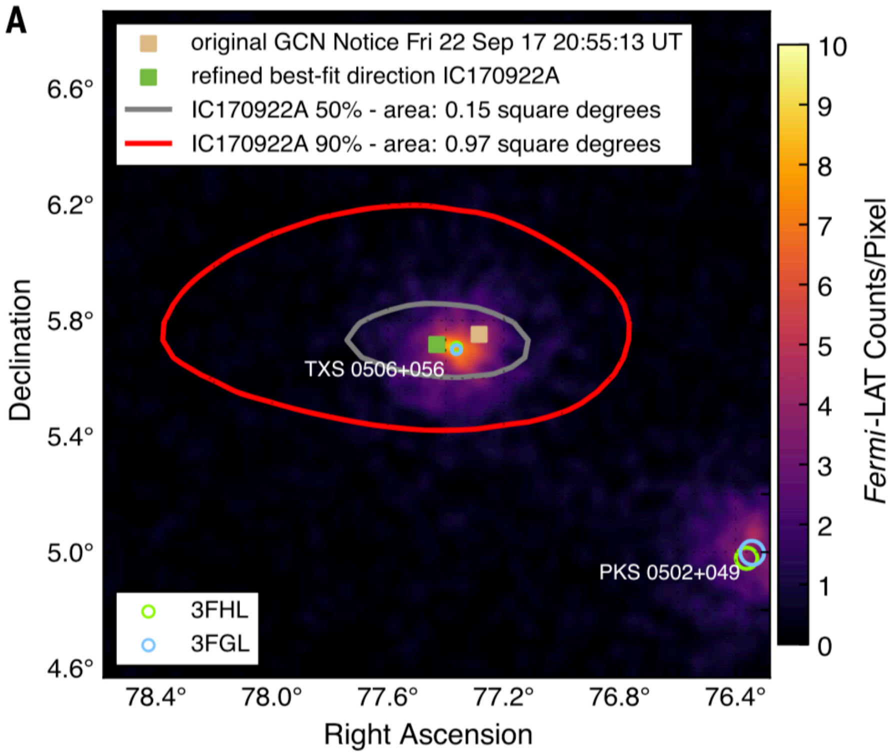
IceCube neutrinos E > 30TeV, 2010-2016

Figures from: ICRC 2017

Stacking analysis : looking for spatial correlations
**blazar contribution ≨ 20%**

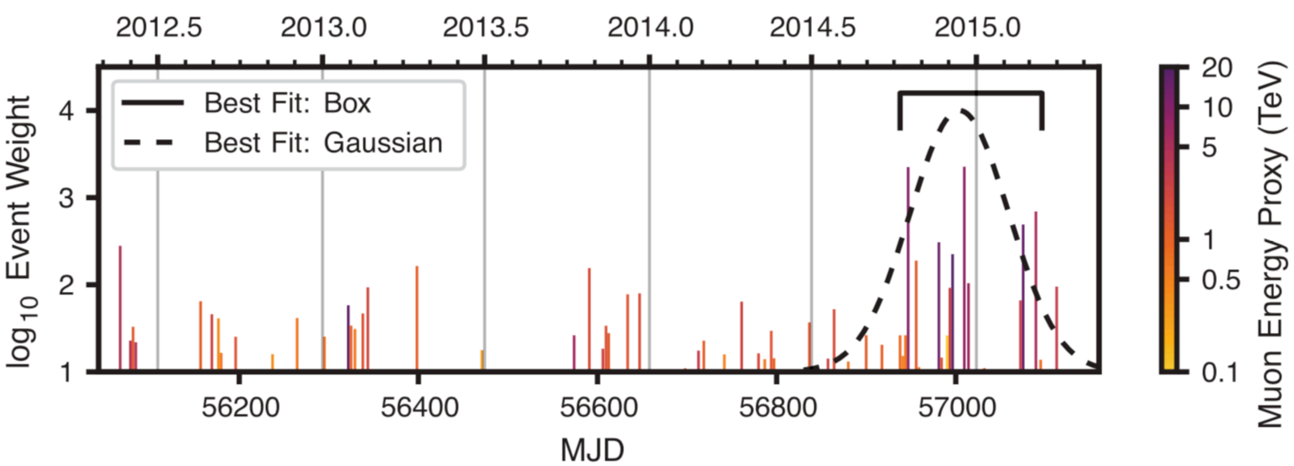
# Neutrinos coincided with TXS 0506+056

## In 2017, one 80-TeV muon track



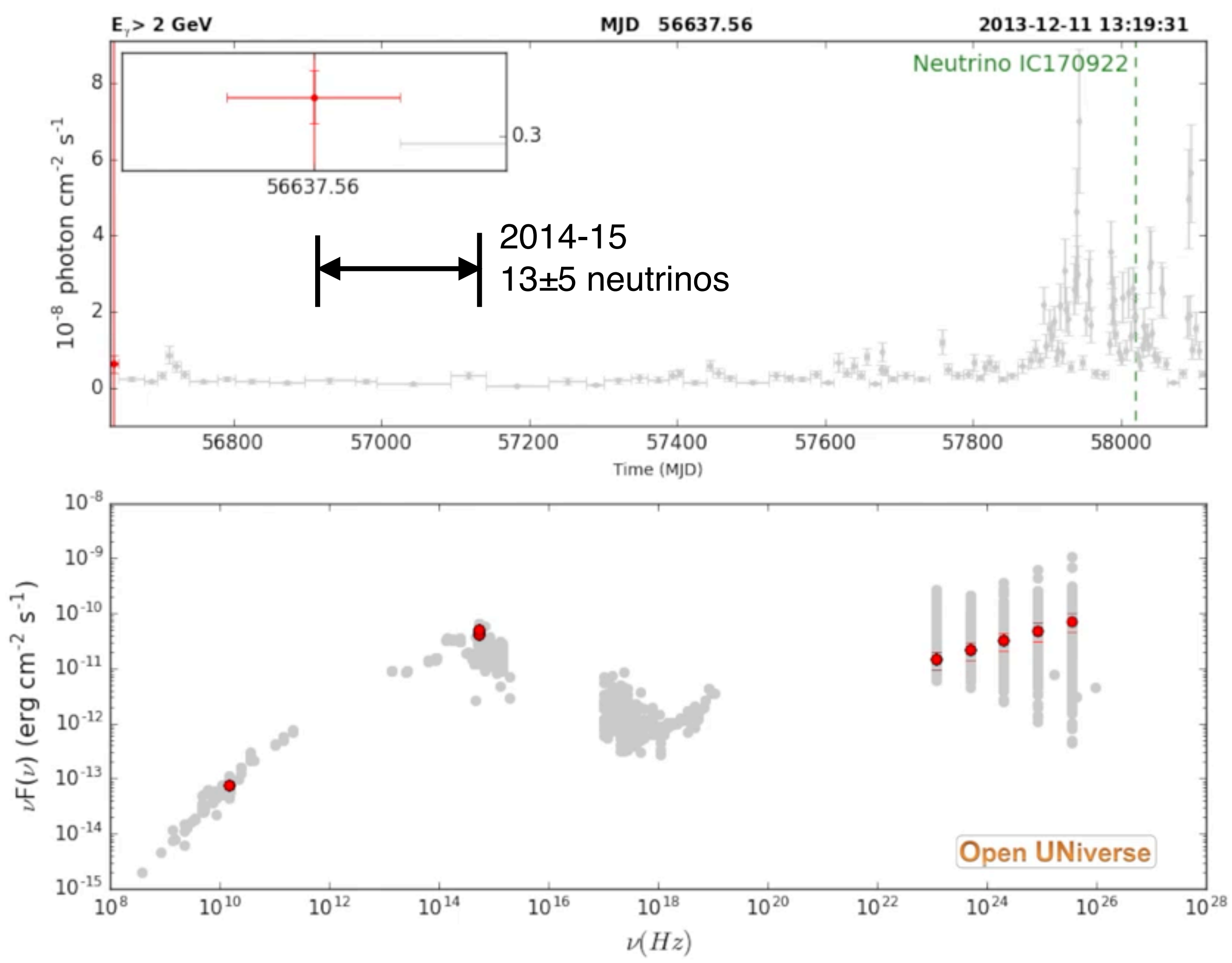

IceCube et al, Science, 361,146 (2018)

## In 2014-15, ~ 13 muon tracks (1-20TeV)



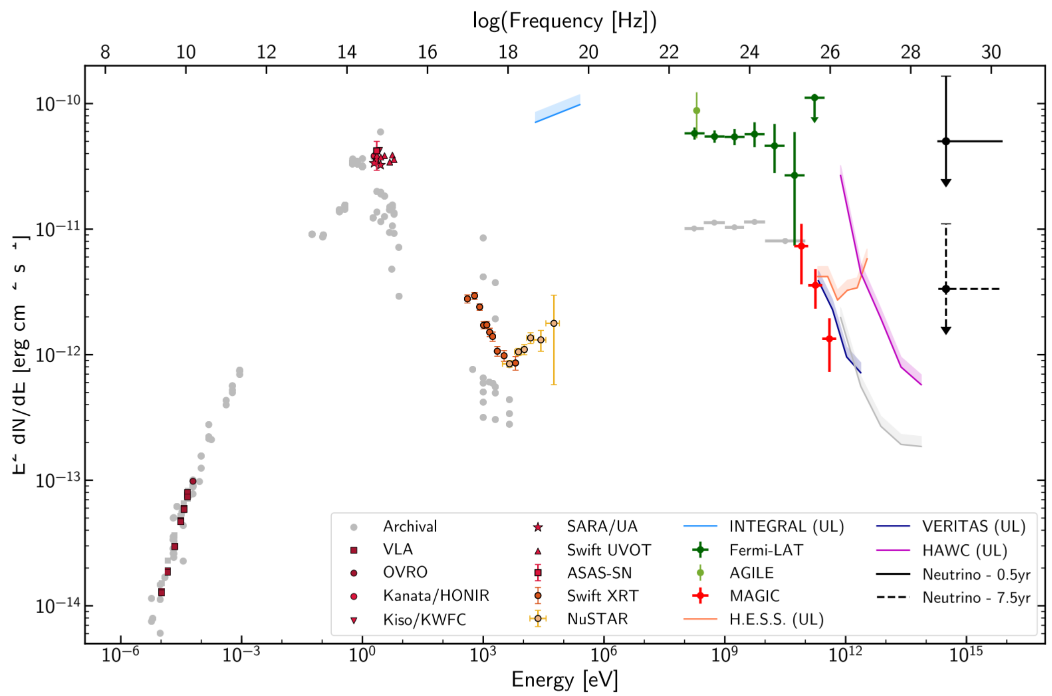

IceCube et al, Science, 361,147 (2018)

# Multi-wavelength data of TXS 0506+056



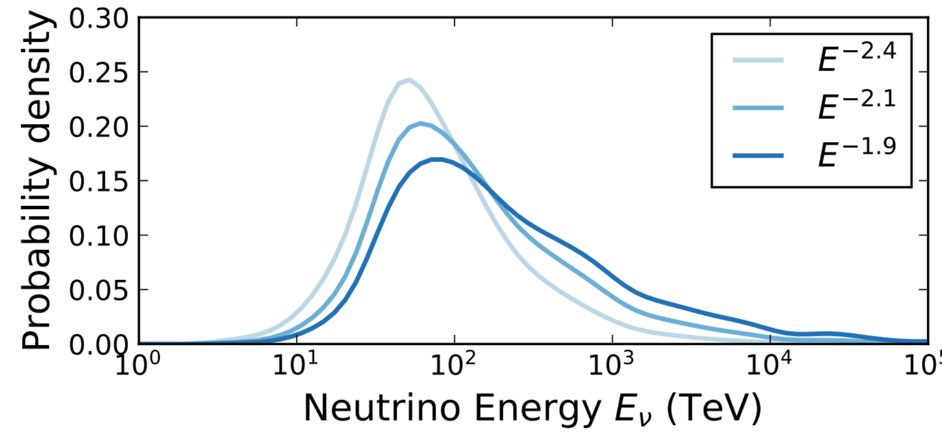

Video by Paolo Giommi et al. 2018, youtube link

# The 2017 flare



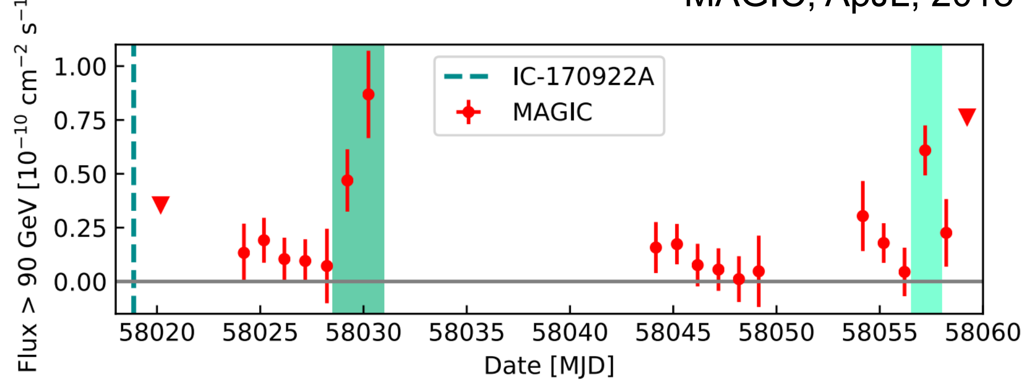

Neutrino detected during **flare, not quiet state**

Figures: IceCube et al, Science, 361,146 (2018)



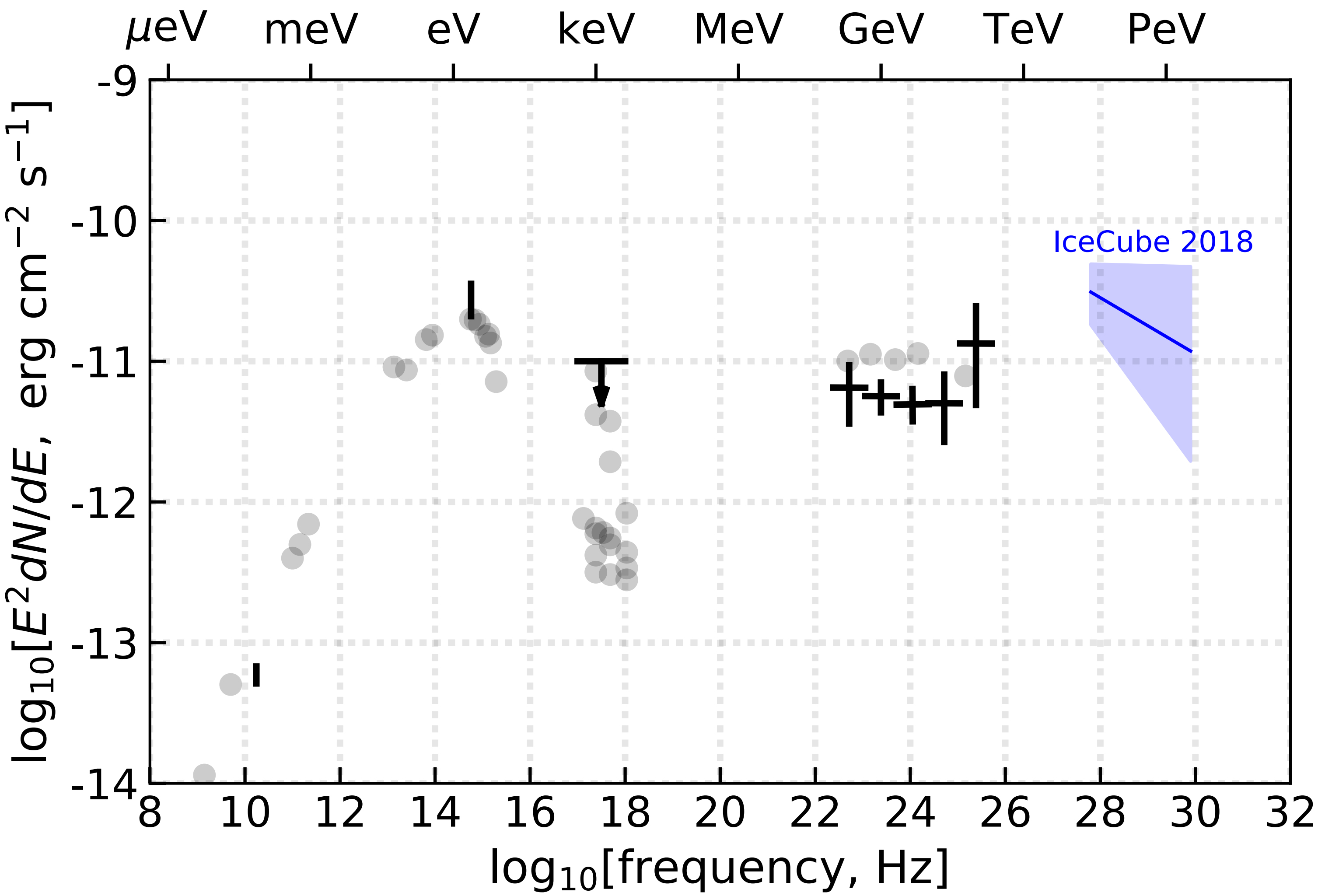

Incident neutrino energy around **a few hunderd TeV**

MAGIC, ApJL, 2018

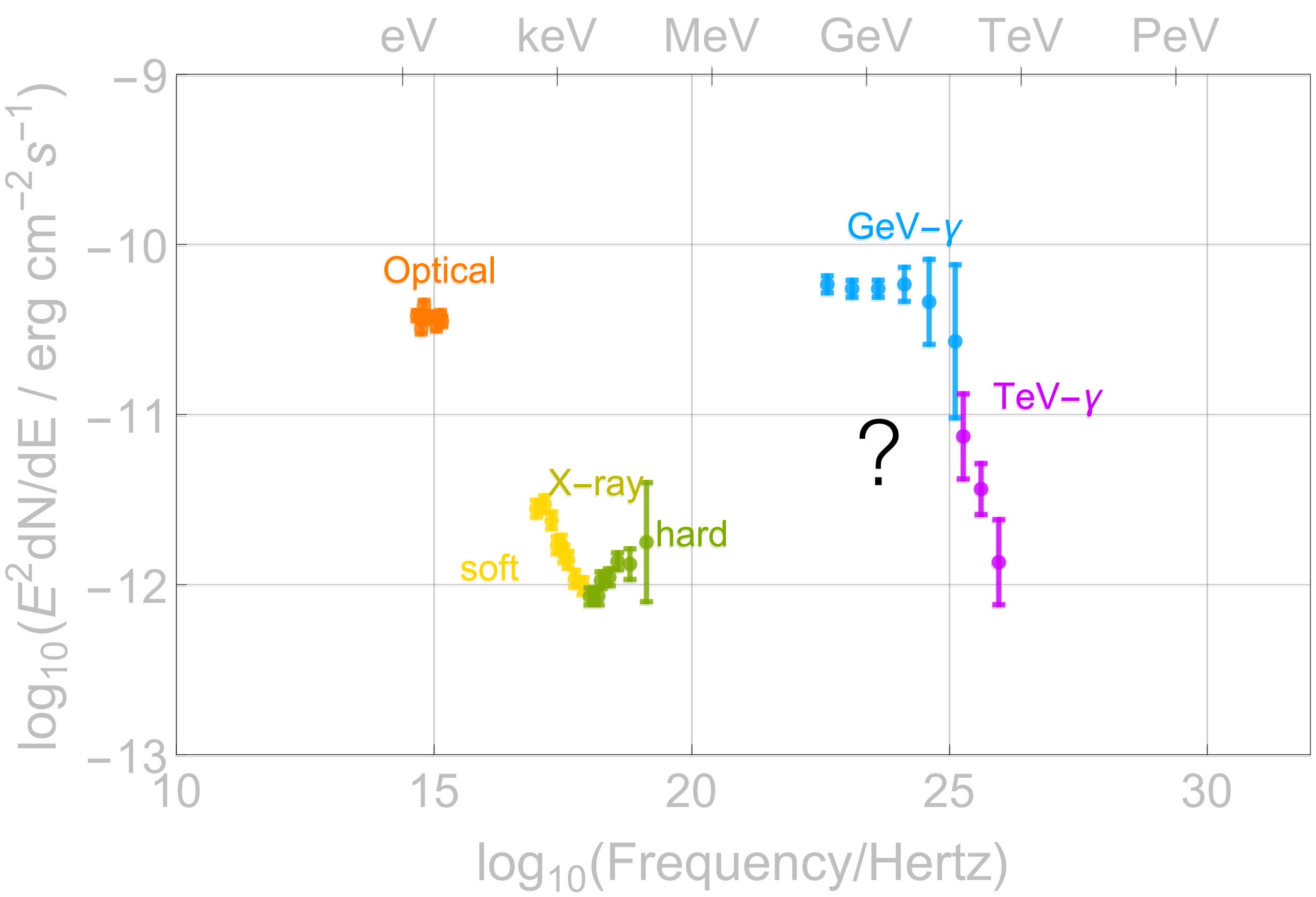



Delayed or **flikering** emission of **TeV photons**

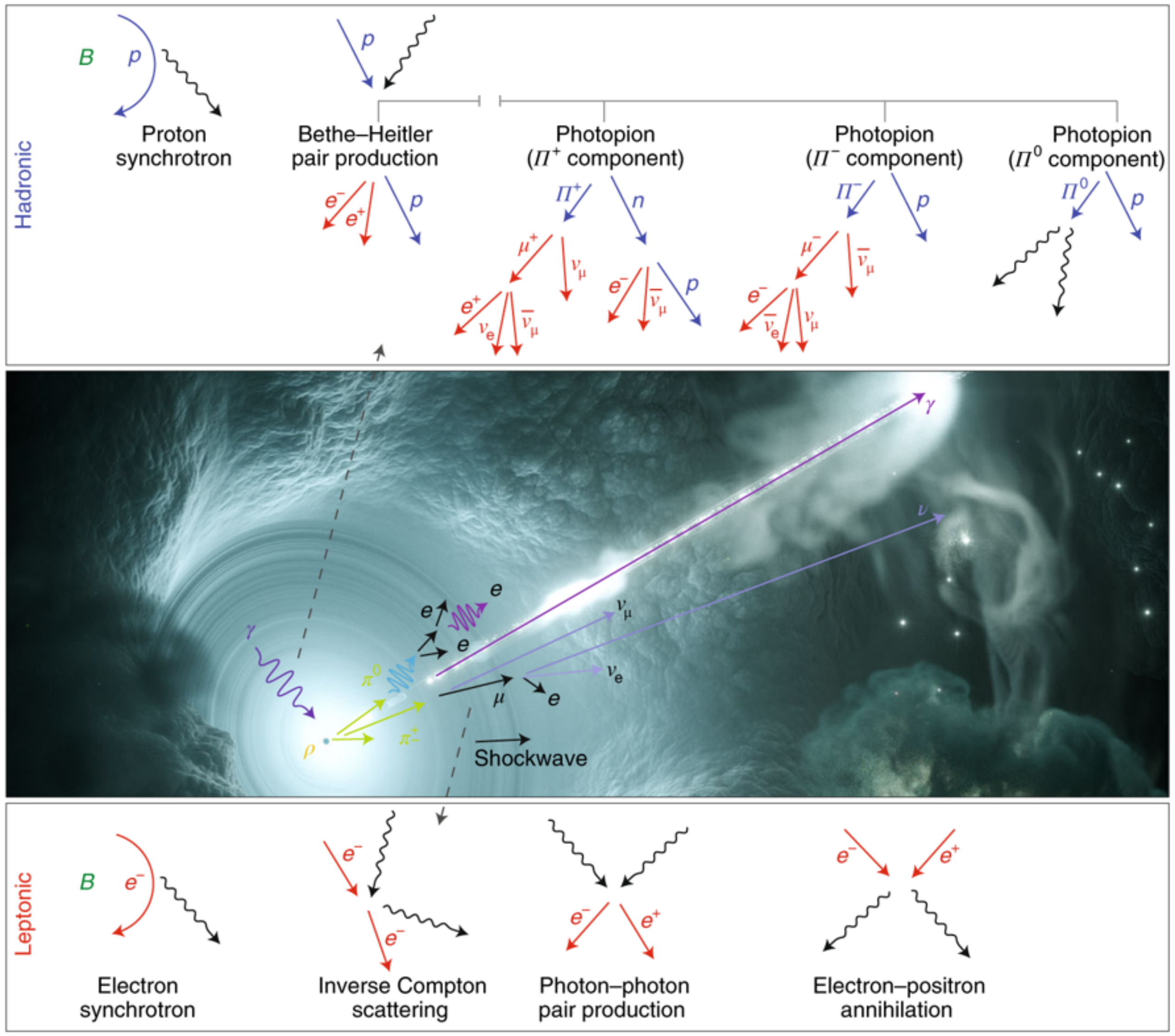
# The 2014-2015 flare



# Physics behind the Spectral Energy Distribution (SED) ?

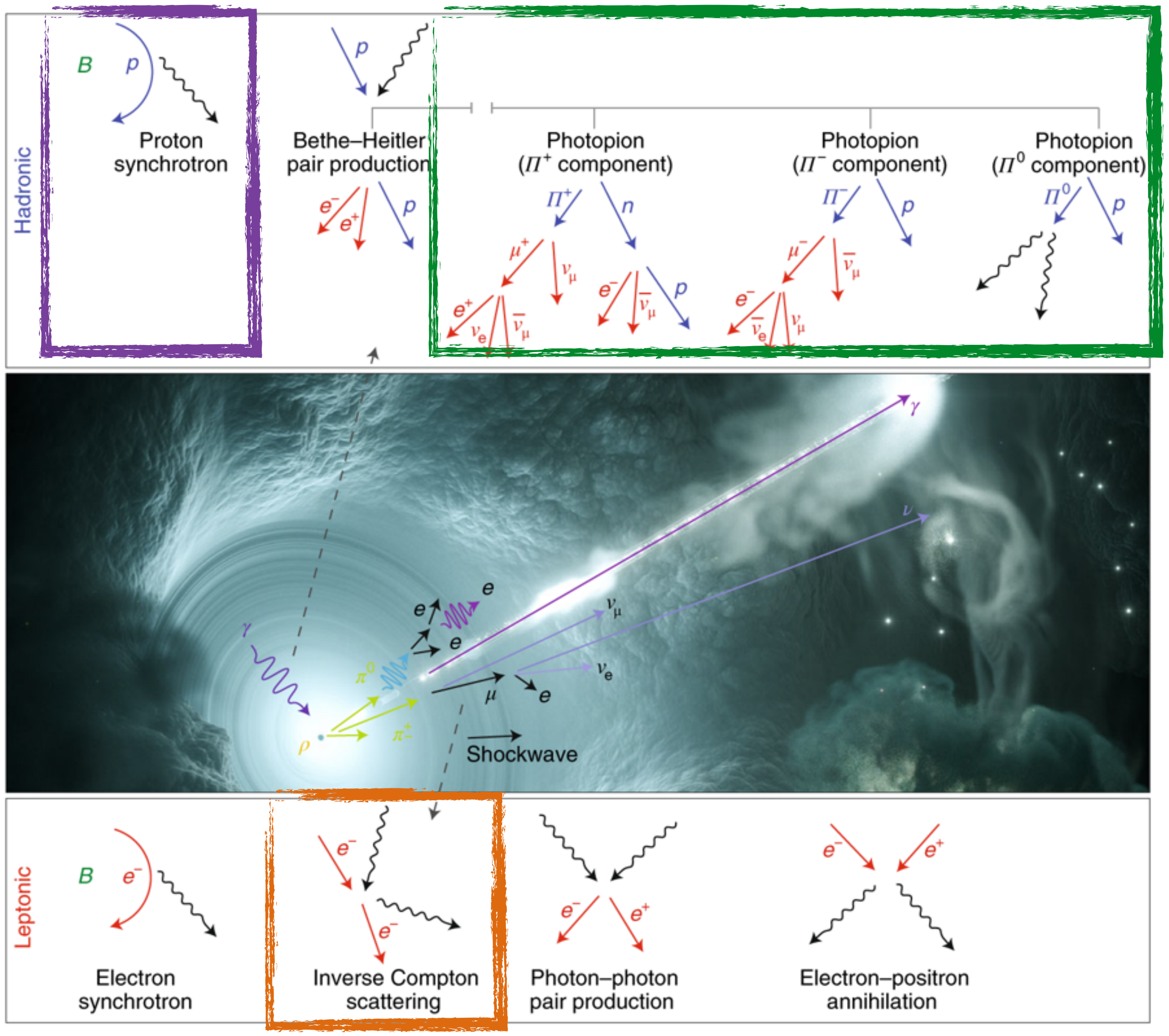


# Particle interactions (SM) and blazar emission models




Elena Pian, Nat.Astron. 2019

# Naming of models according to origin of 2nd hump




Elena Pian, Nat.Astron. 2019

Proton-synchrotron

Hadronic

Leptonic

# Time-dependent hadro-leptonic code (AM³)*

## *Astrophysical Modeling with Multiple Messengers

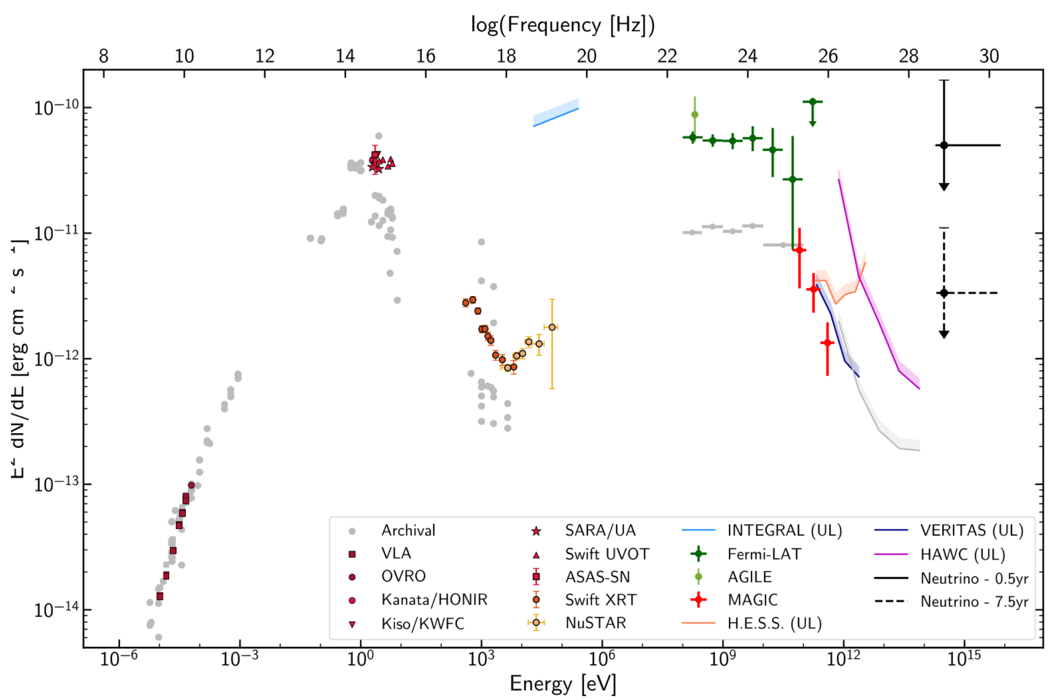
$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

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

Gao,Pohl,Winter, APJ 843 (2017)

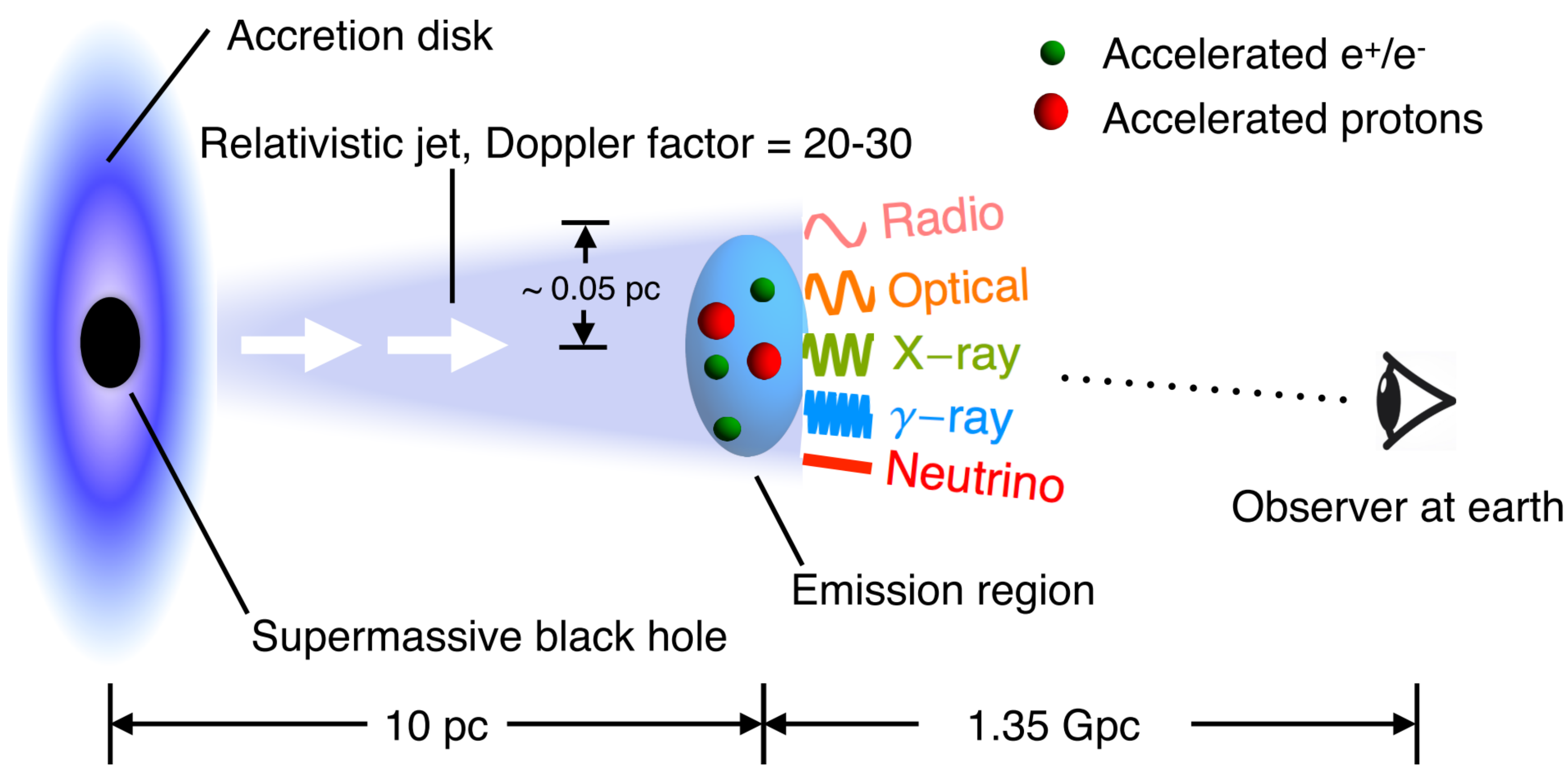
- **Numerically** solves a set of **coupled** transport **equations** for all relevant particles.
- Energy “bandwidth“ ~20 orders of magnitude (Radio-EeV)
- **Very efficient**: < 2 min per time-dependent simulation; necessary due to large number of parameters.

# Modeling the 2017 flare

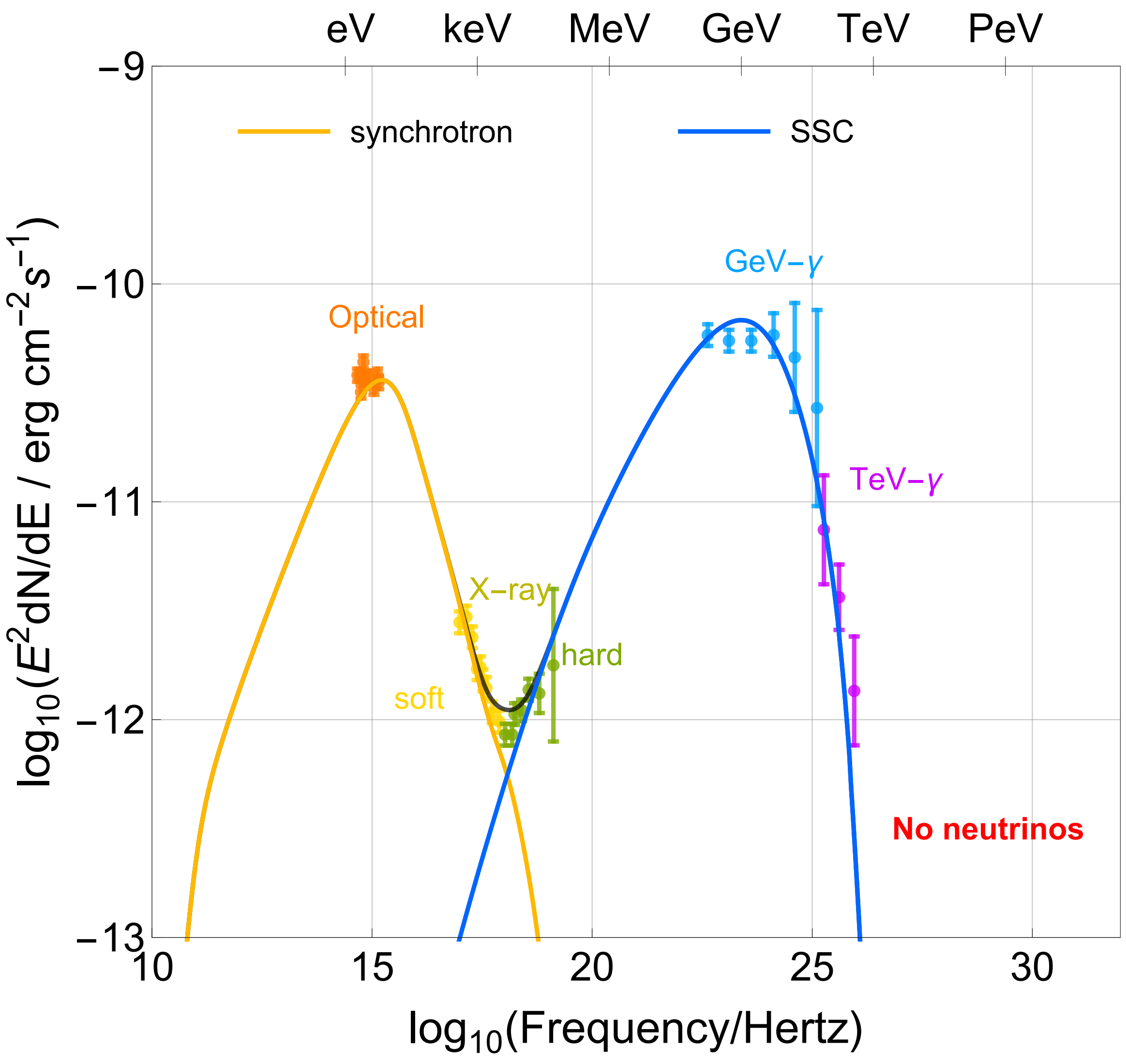



Figures: IceCube et al, Science, 361,146 (2018)

# Geometry (1-zone, spherical cow)



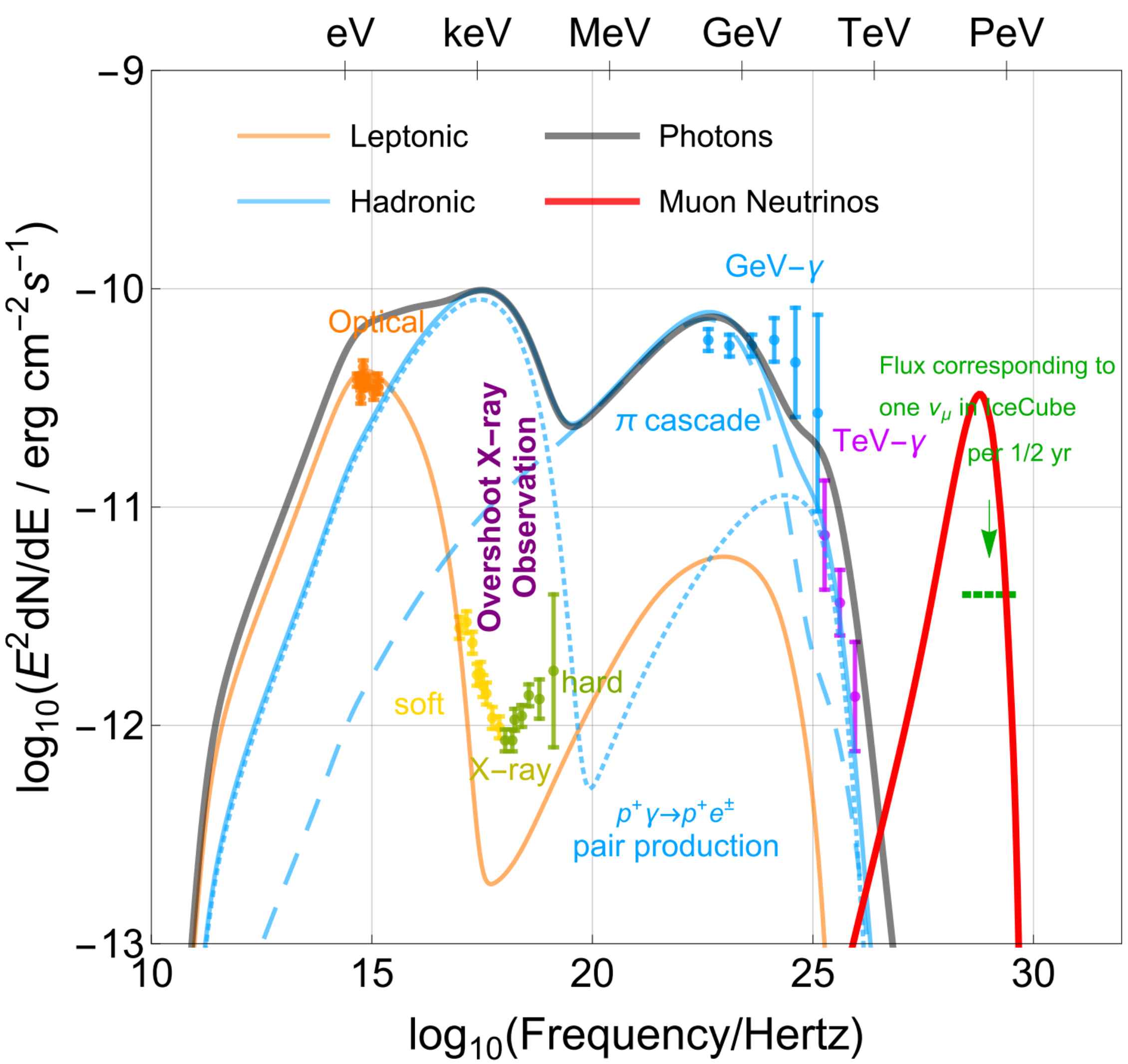
# Leptonic model (1-zone)




**Remarkably simple assumptions:**

R~$10^{16}$ cm, B~0.16G and electrons with a $E^{-3.5}$ injection pectrum between $10^4 < \gamma < 6\times10^5$

# Hadronic model (1-zone)

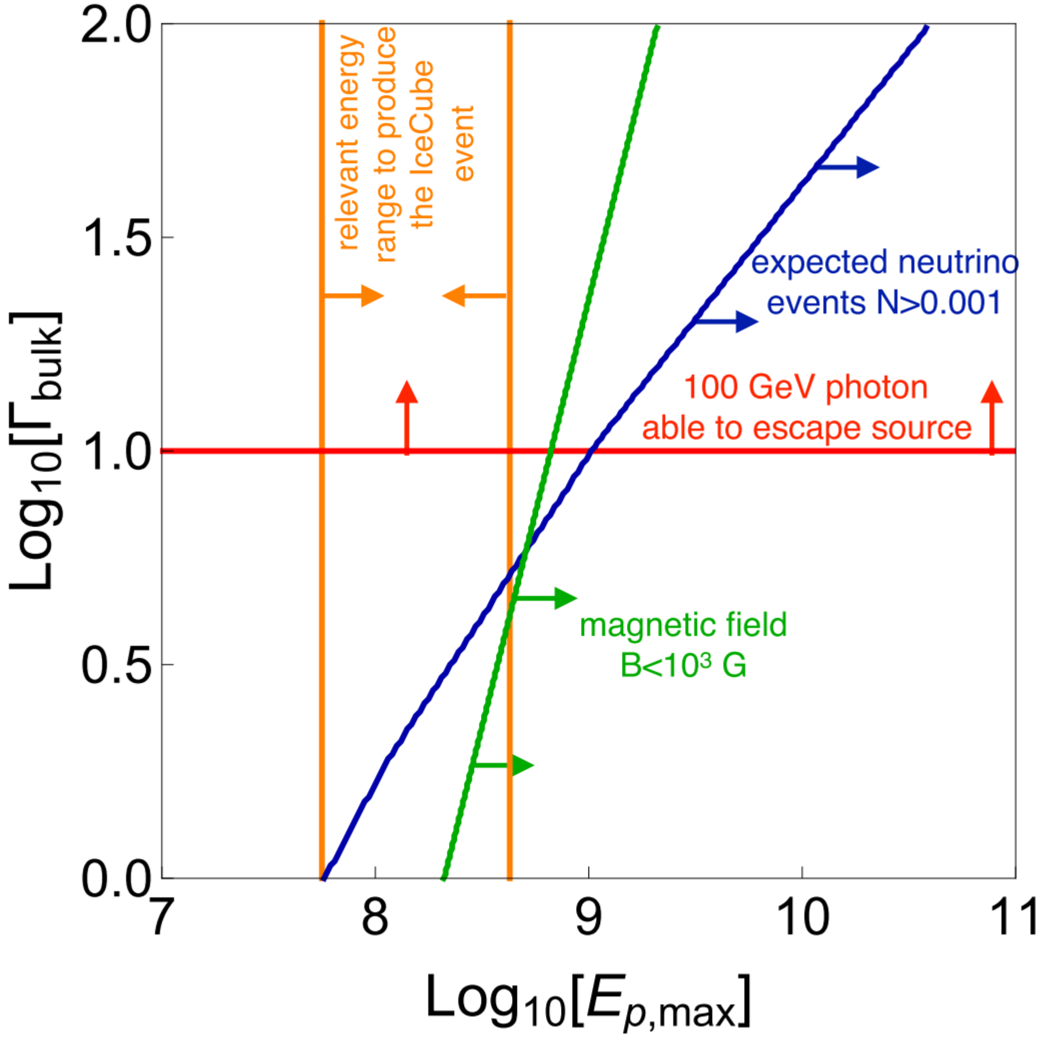



SG,Fedynitch,Winter & Pohl, Nat.Astron 2019

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

## Ruled out

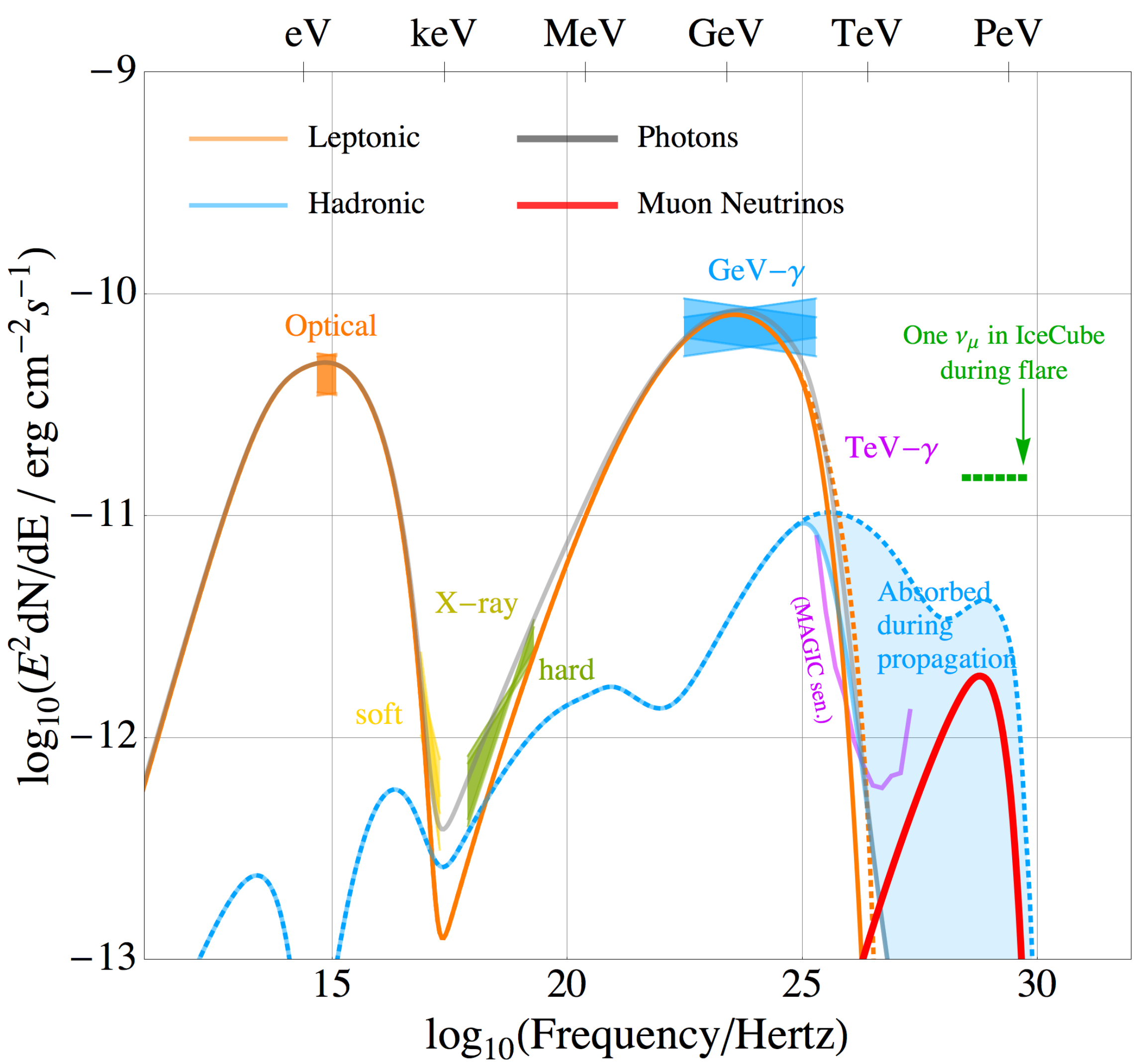
# Proton synchrotron (1-zone)




- Needs high magnetic field and proton energy, $B>10^2$G and $E_p>10^{10}$GeV protons
- Can explain spectrum, but not neutrino
- Extensive parameter scan : no solution to fit both SED and neutrino

## Also excluded

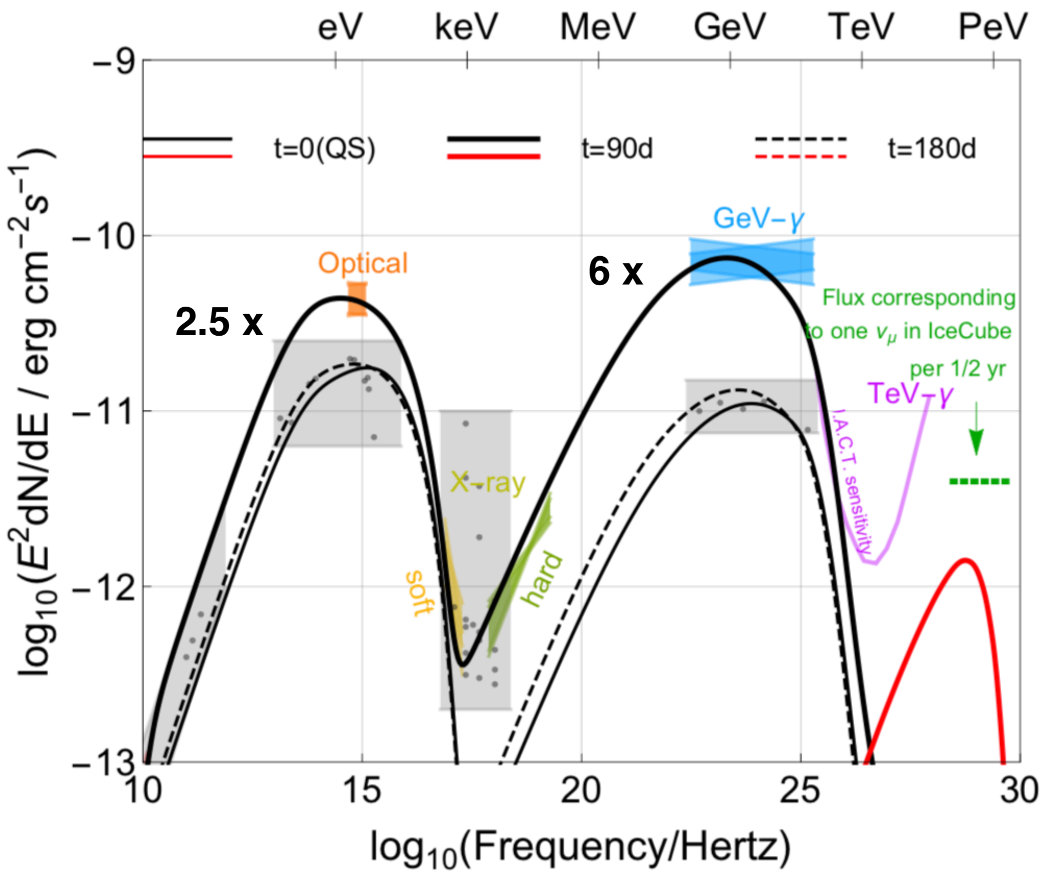
# Hybrid (1-zone)

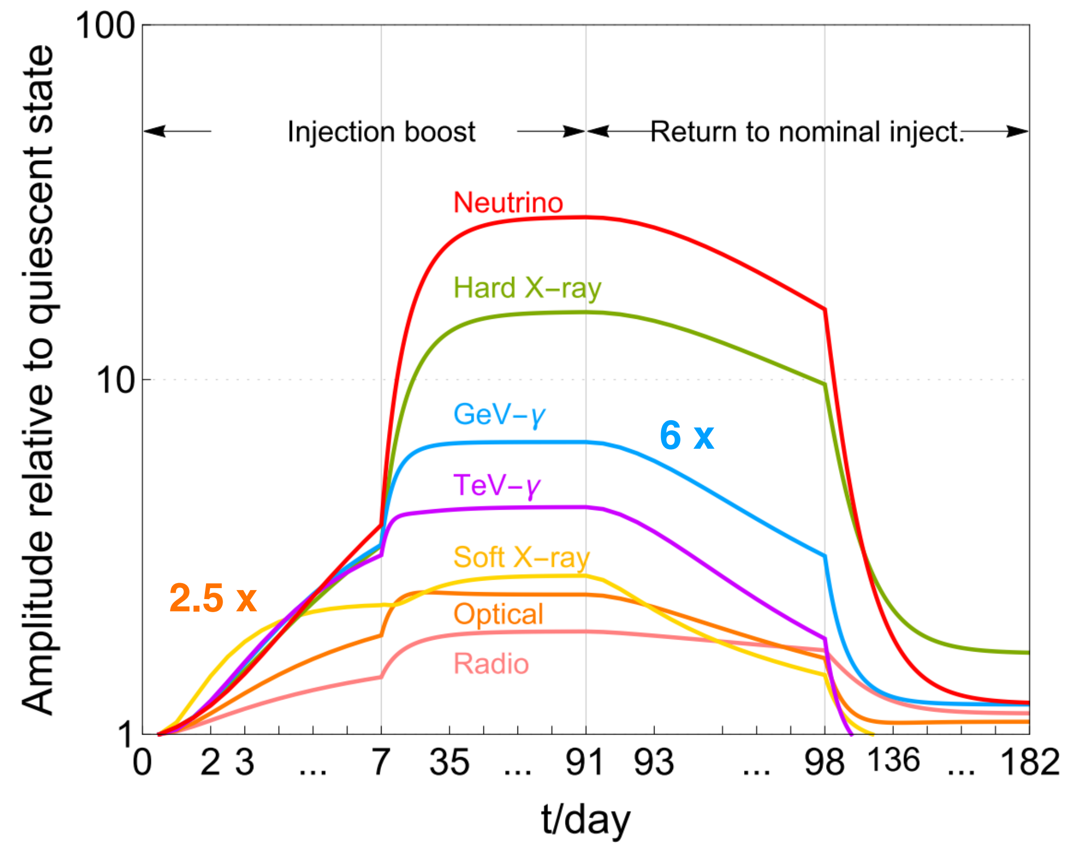



SG,Fedynitch,Winter & Pohl, Nat.Astron. 2019

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

# Hybrid (1-zone), time-dependent behavior



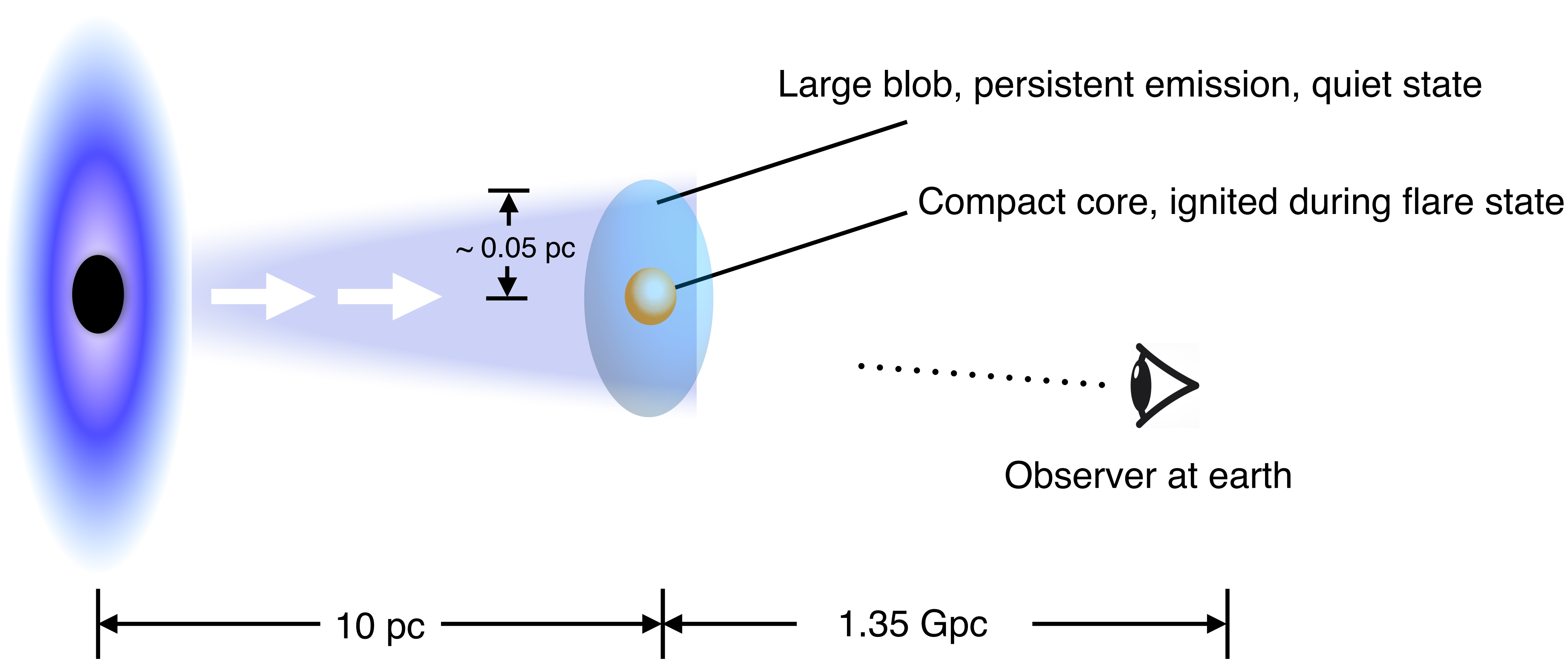

**Remarkably simple:** increasing p & e- injection rate by factor 3 explains flare

**Problem :** proton power = 500 $L_{Edd}$ (maximum output during steady accretion of AGN)

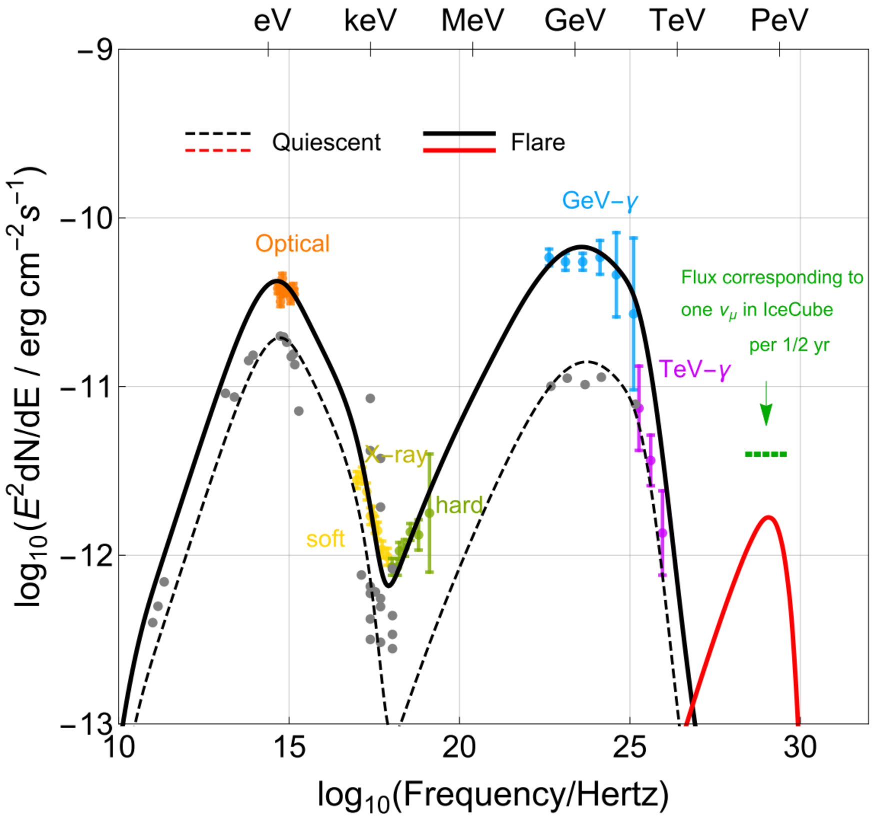
**Solution ?** Quiet state + radio => large emission region

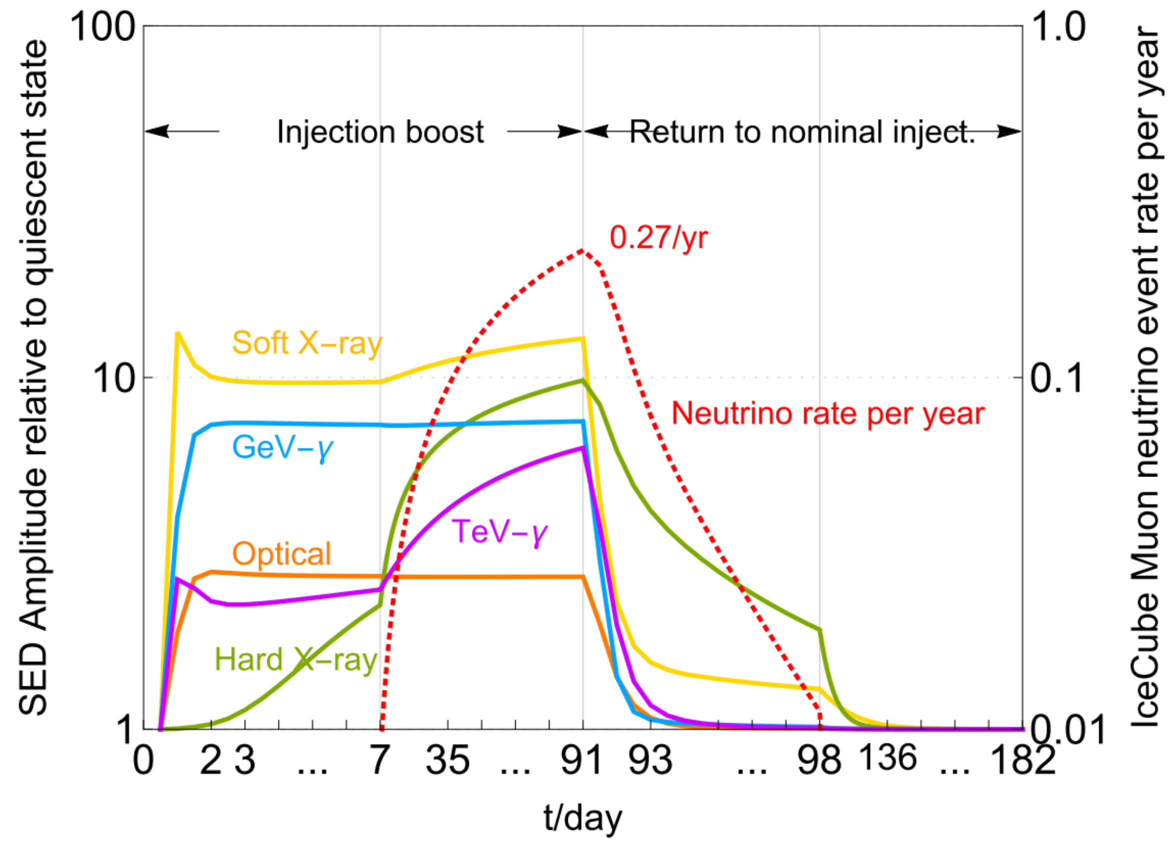
Jet power limit => small region, increase particle interaction rate

# Geometry : 2-zone model



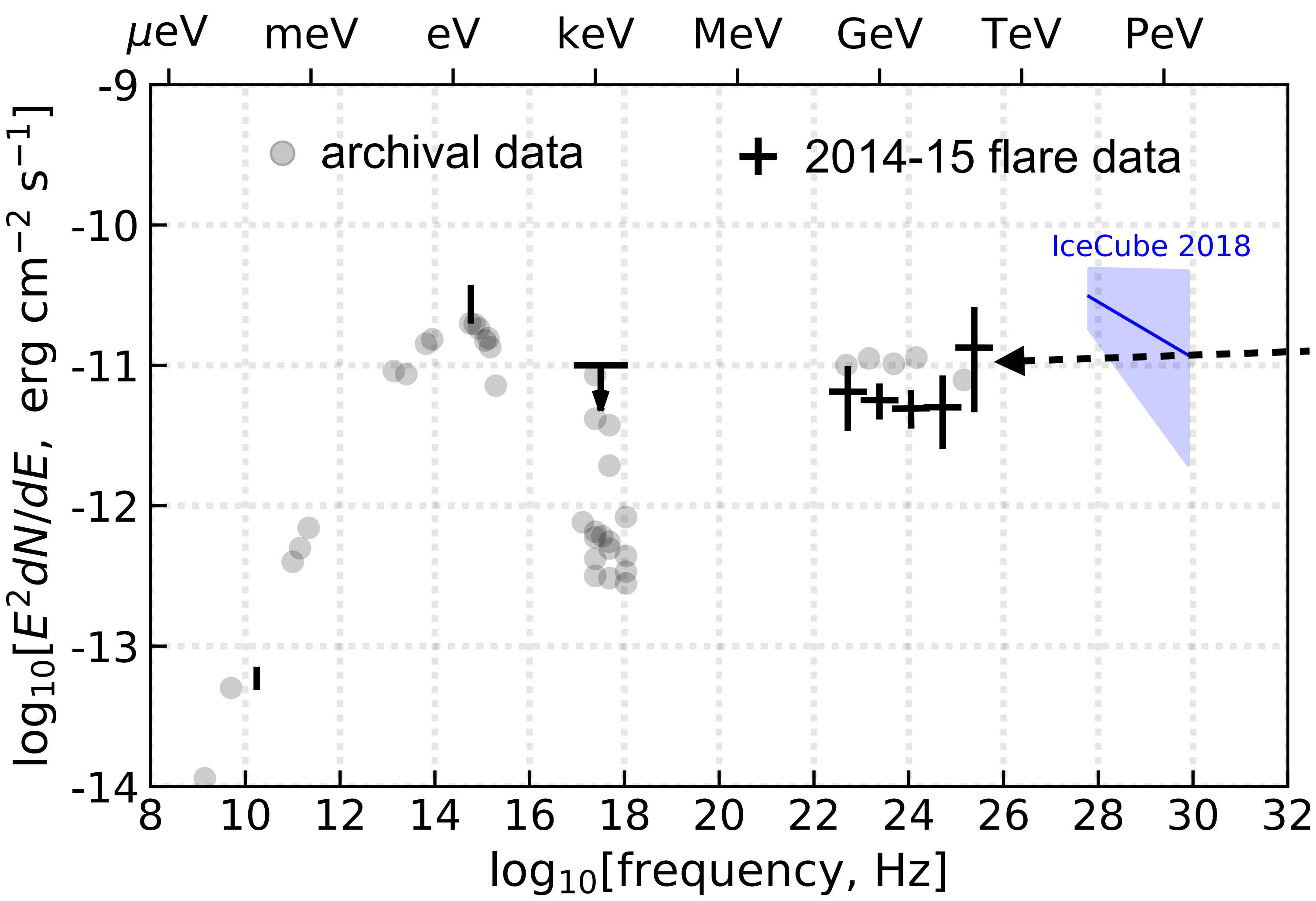
# Hybrid model (2-zone)




- **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**

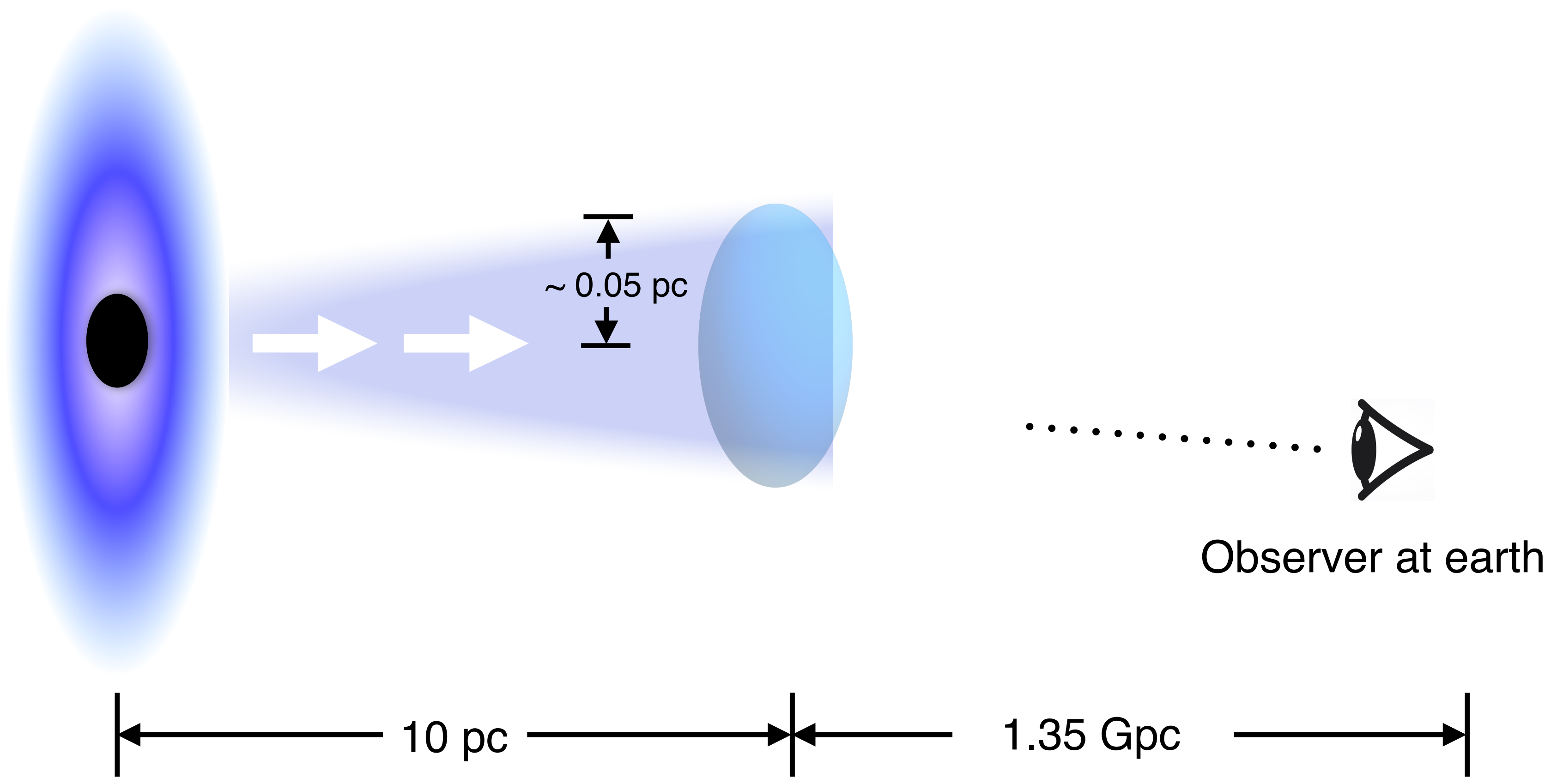
# Modeling the 2014-15 flare (“historical flare”)



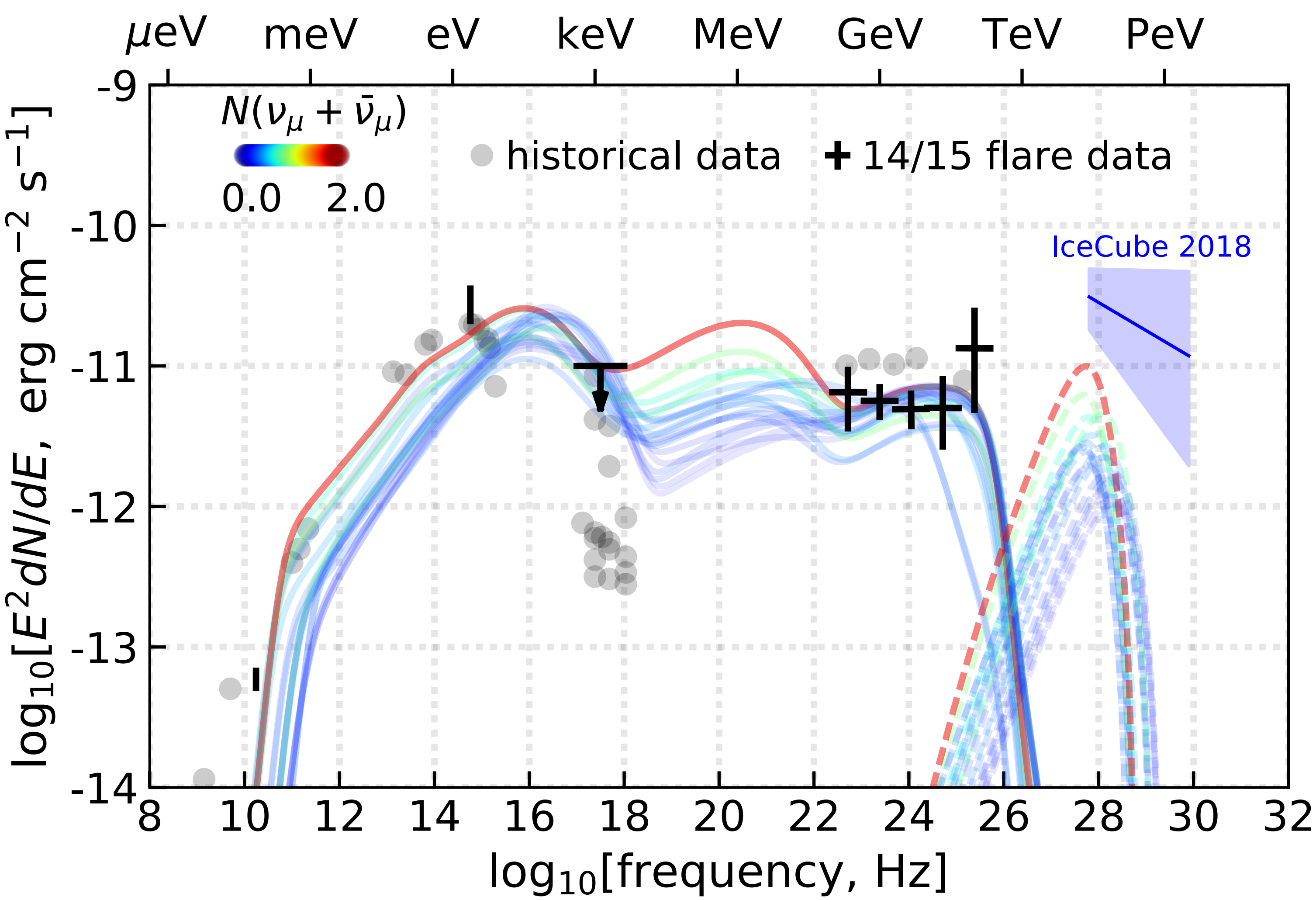

Data are sparse.

Only 2 photons detected in this bin.

# Geometry: one-zone model



# Hadronic model (1-zone)

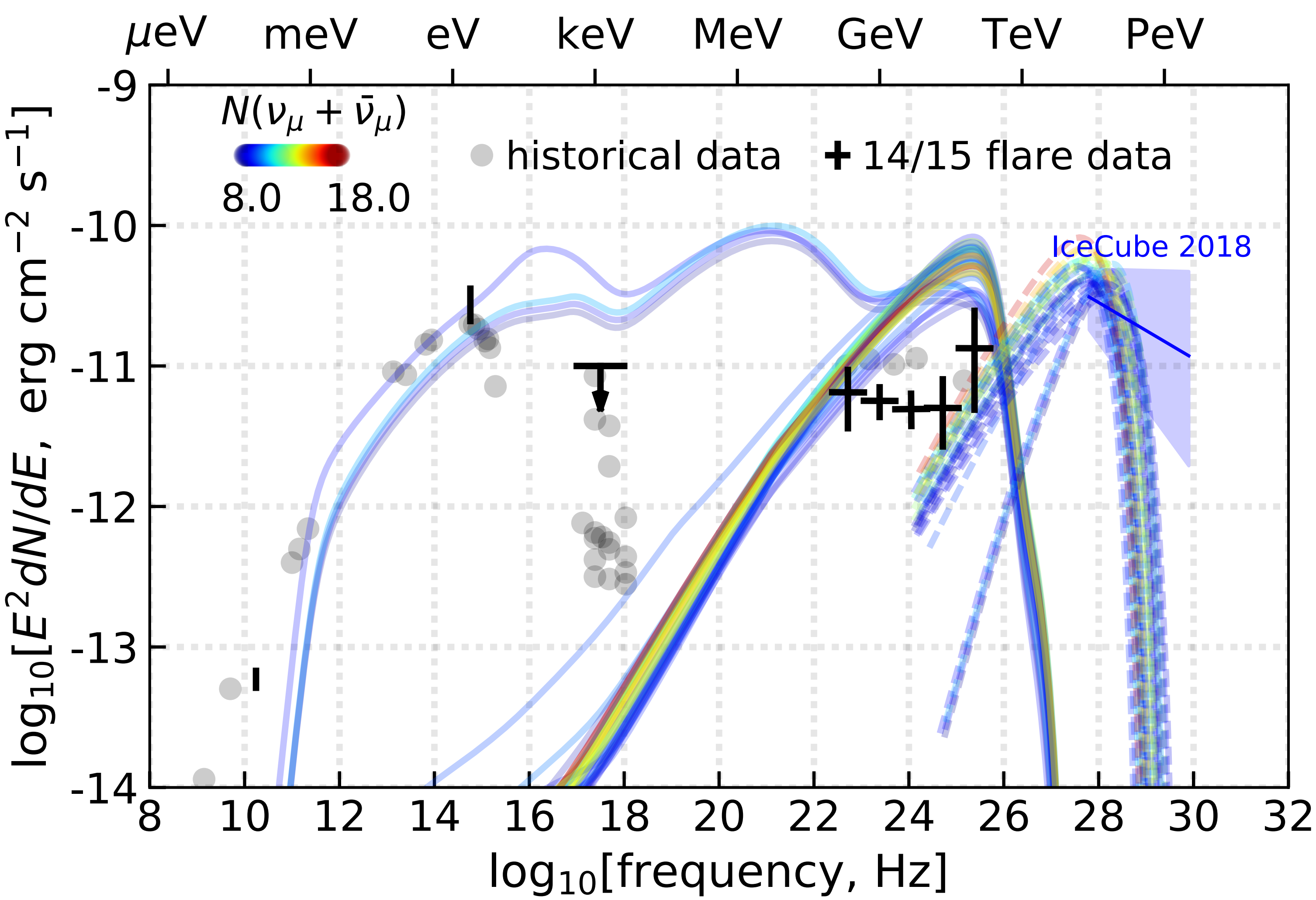



X.Rodrigues, SG, A.Fedynitch, A.Palladino & W.Winter (1812.05939)

Undershoot neutrino flux

Energy budget problem
(large dilute blob)

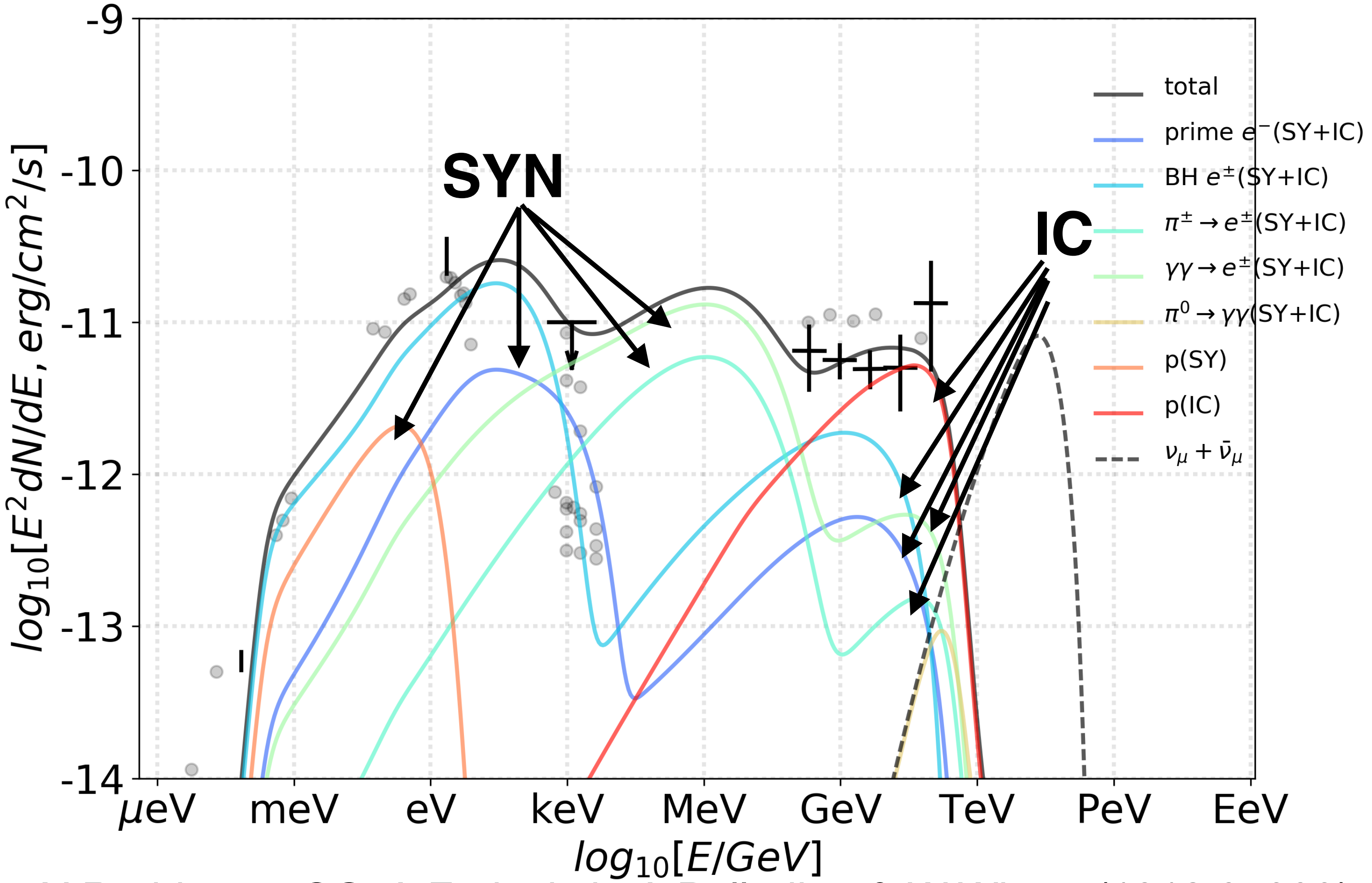
# Hadronic model (1-zone)




All overshoot observation

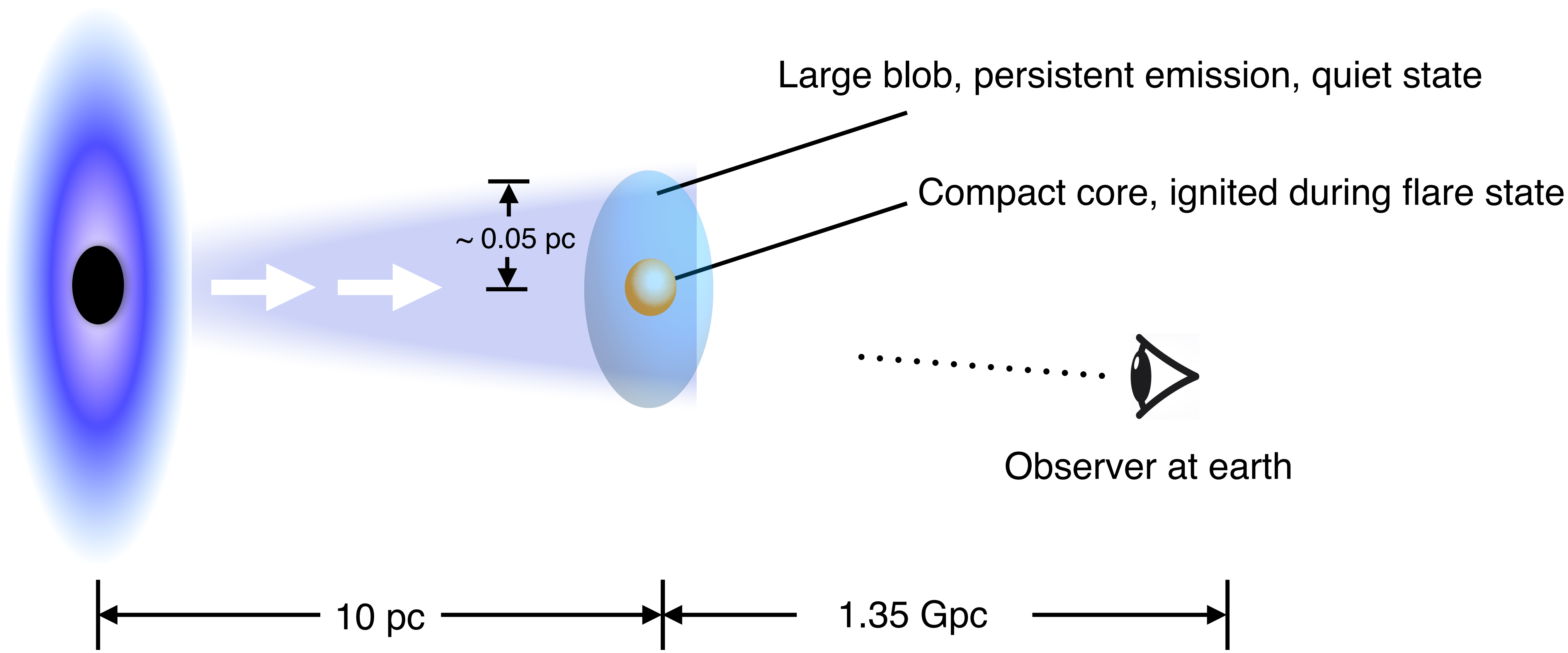
X.Rodrigues, SG, A.Fedynitch, A.Palladino & W.Winter (1812.05939)

# Hadronic model (1-zone) - anatomy of the spectrum

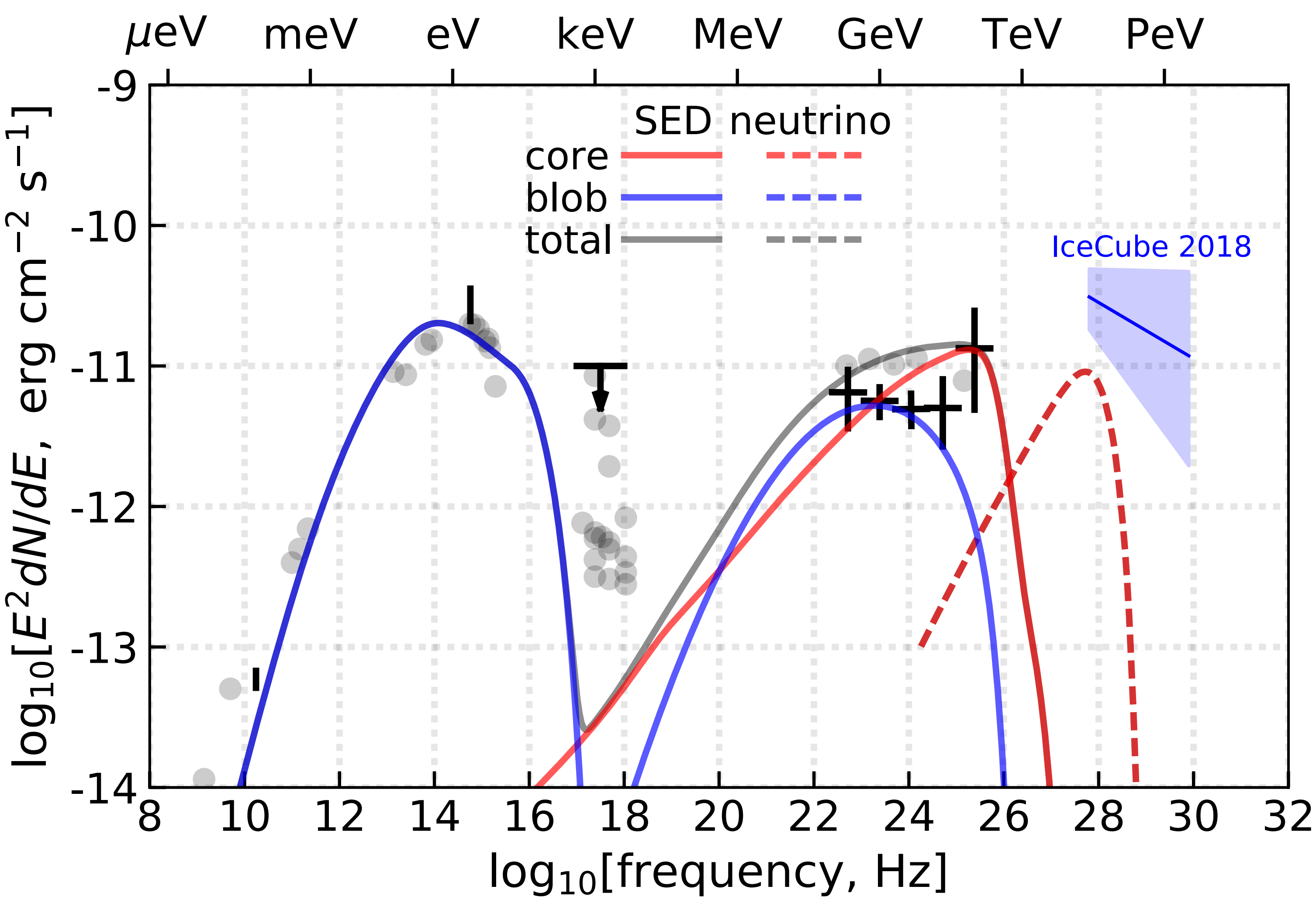



X.Rodrigues, SG, A.Fedynitch, A.Palladino & W.Winter (1812.05939)

# IC-dominated Compact core model (2-zone)



# IC-dominated Compact core model (2-zone, 2014-15 flare)



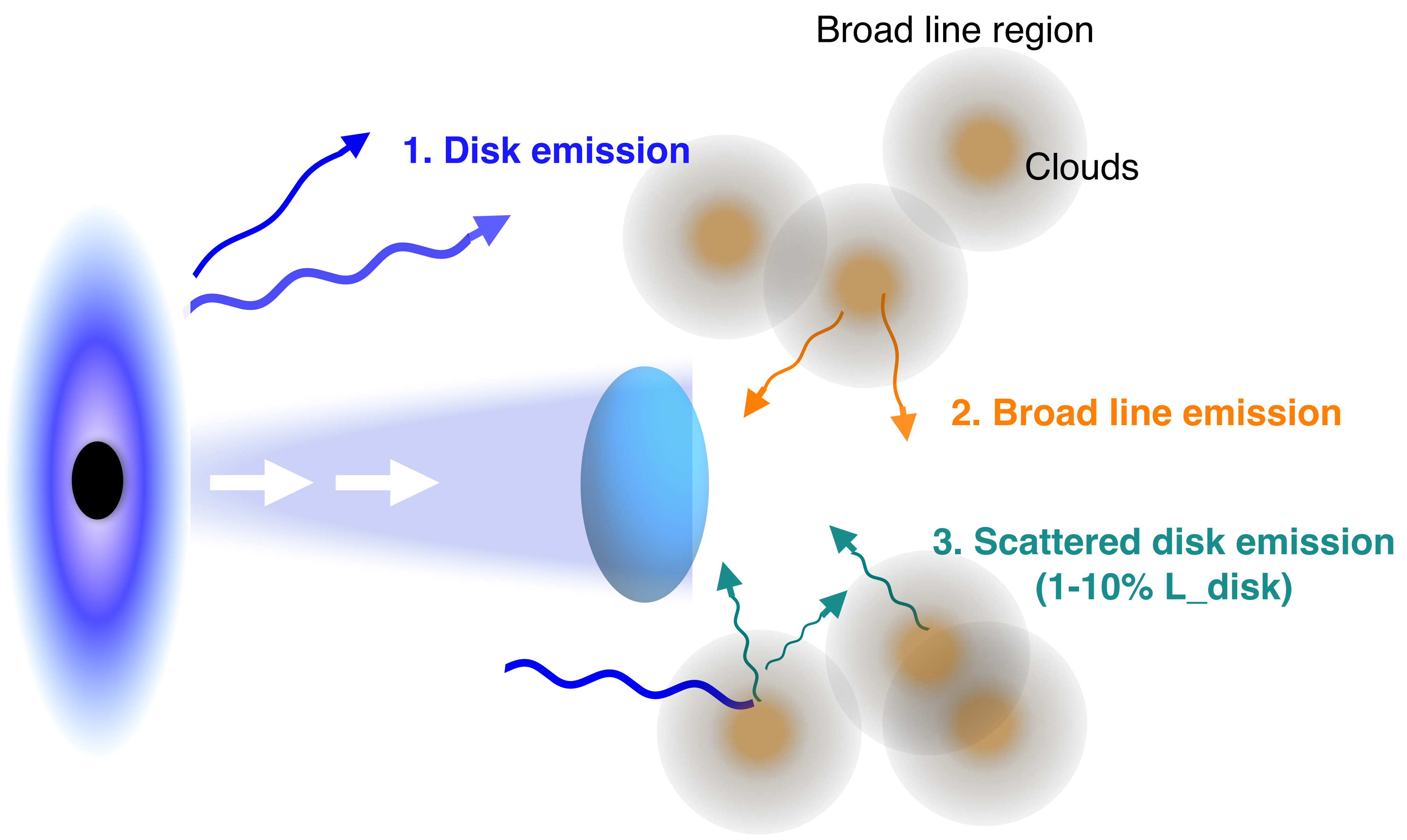

X.Rodrigues, SG, A.Fedynitch, A.Palladino & W.Winter (1812.05939)

Nν=1.8 during flare

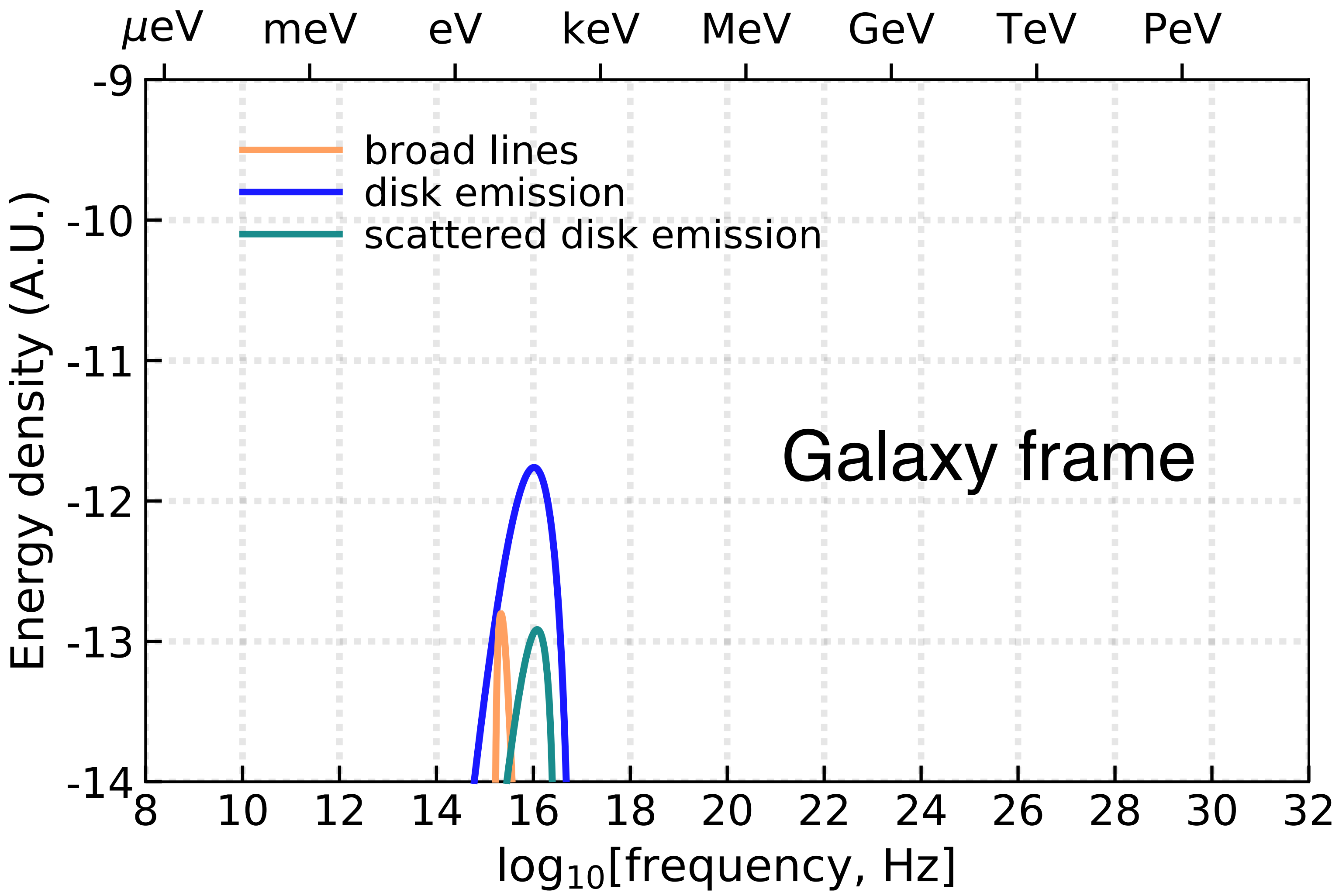
Spectral hardening?

No energy budget problem

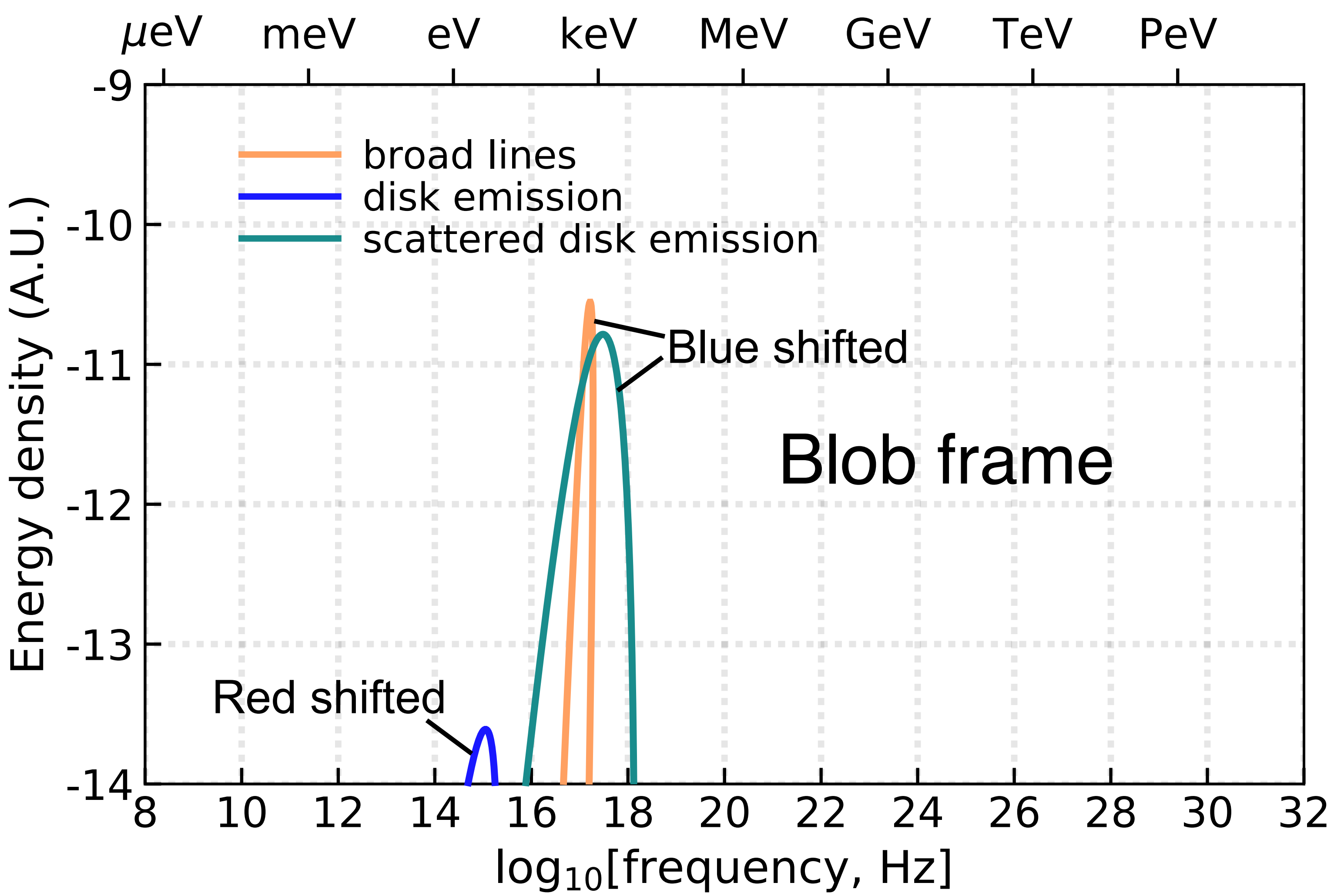
# External emission model (2-zone, 2014-15 flare)



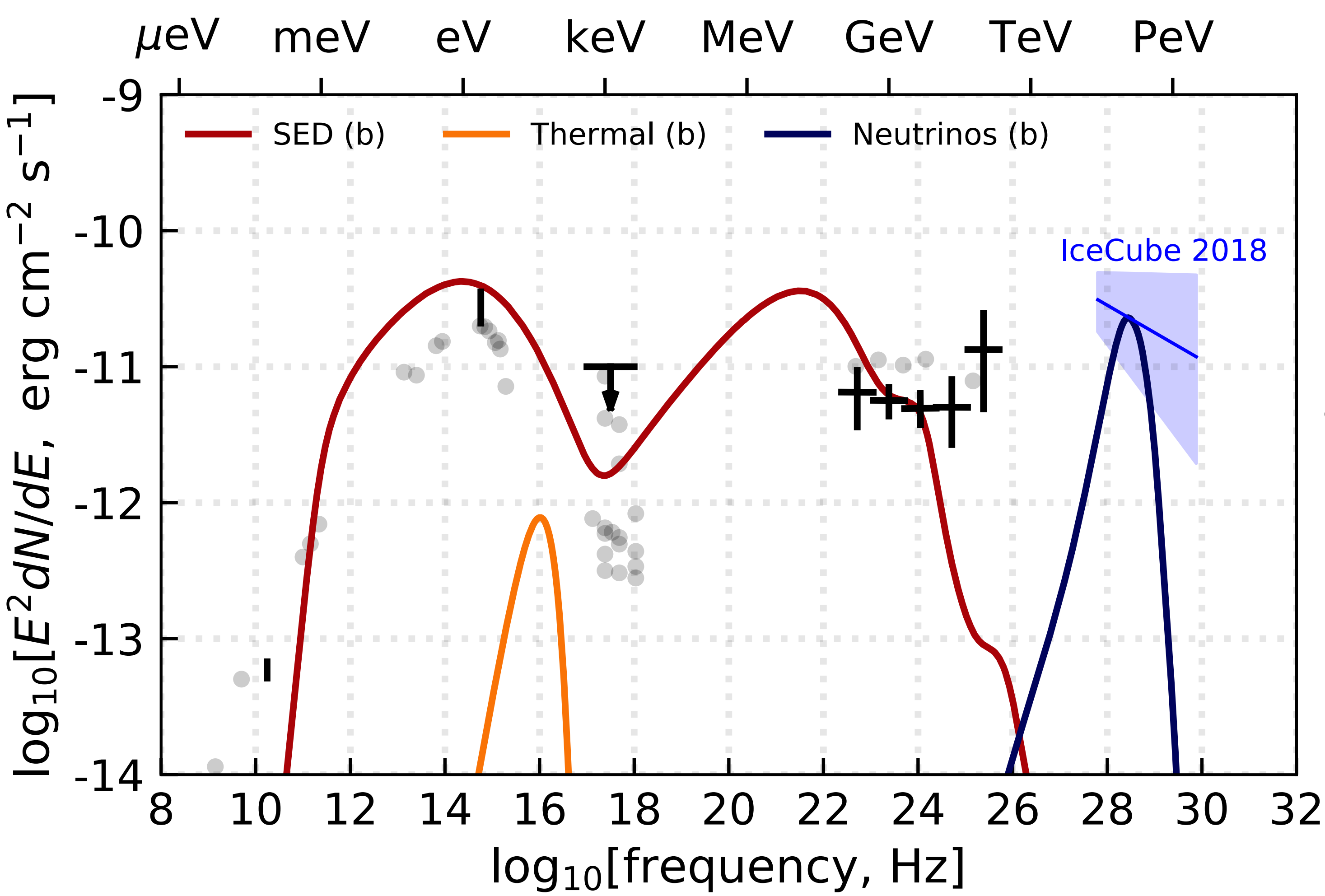
# External emission model (2014-15 flare)



# External emission model (2014-15 flare)

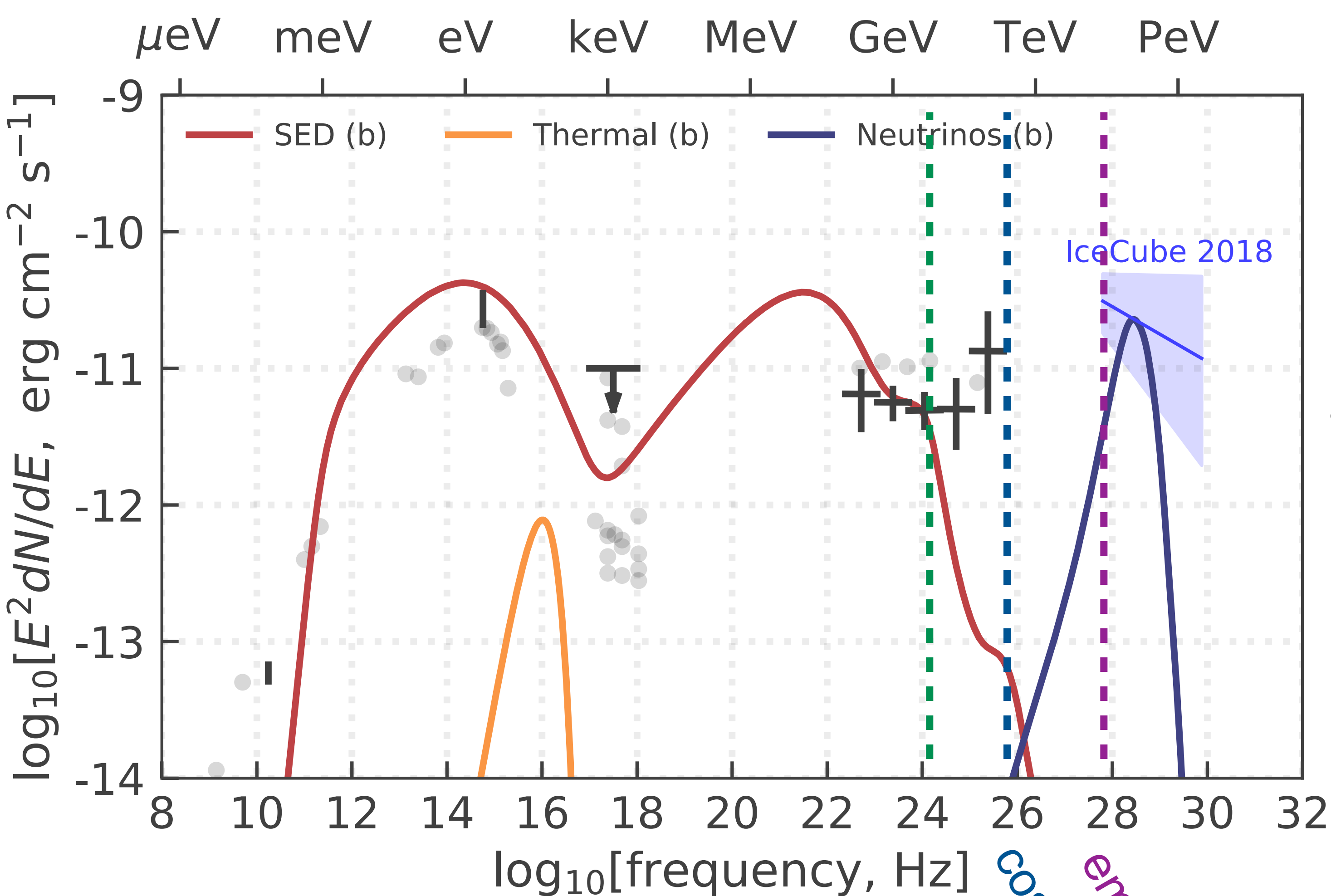


# External emission model




Nν ≈ 2, different disk temperature and resultant neutrino energy

# External emission model




Attenuation by :

clouds (AGN)

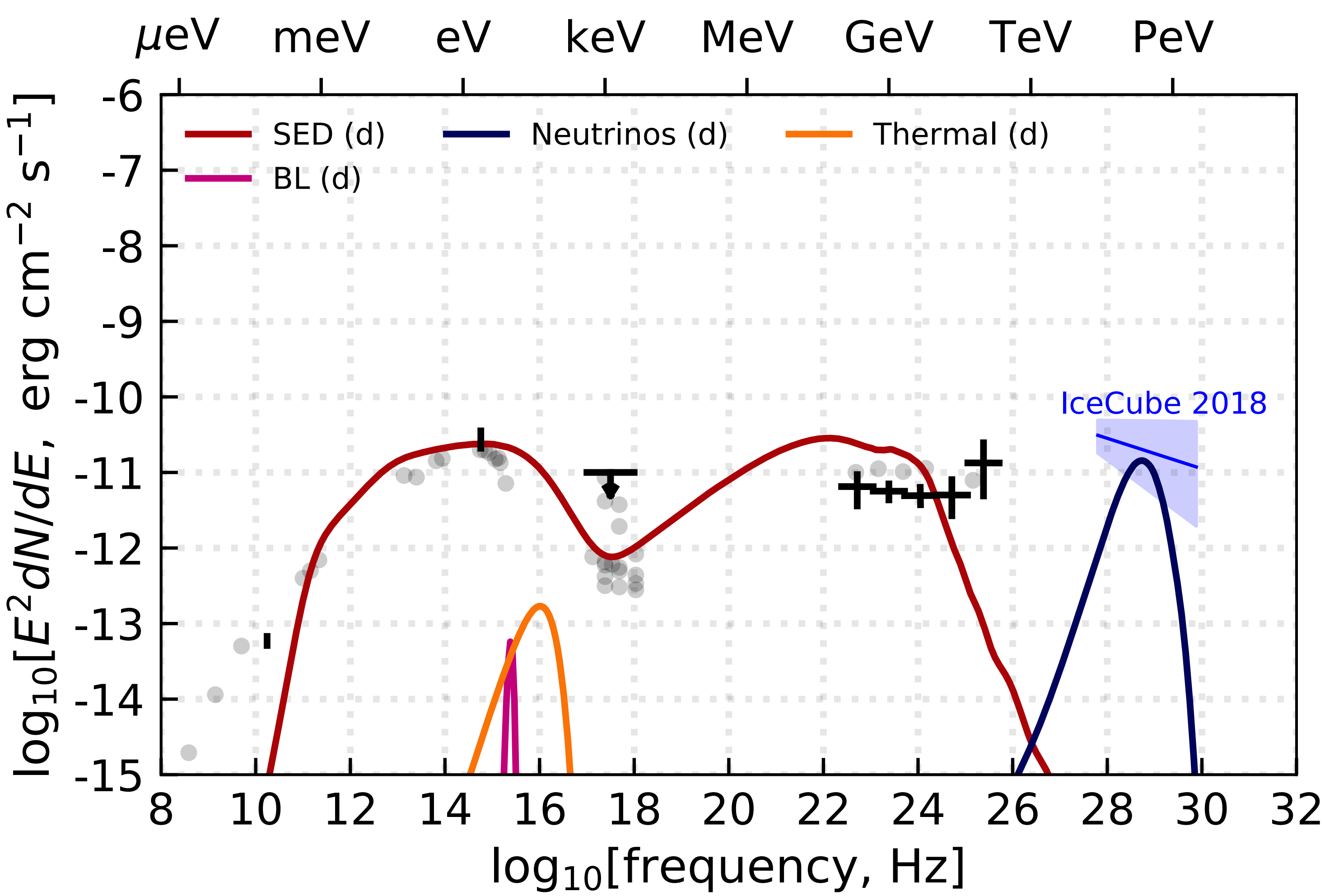
cosmic propagation

emitting blob (itself)

Nν ≈ 2, different disk temperature

and resultant neutrino energy

# External emission model (2014-15 flare)

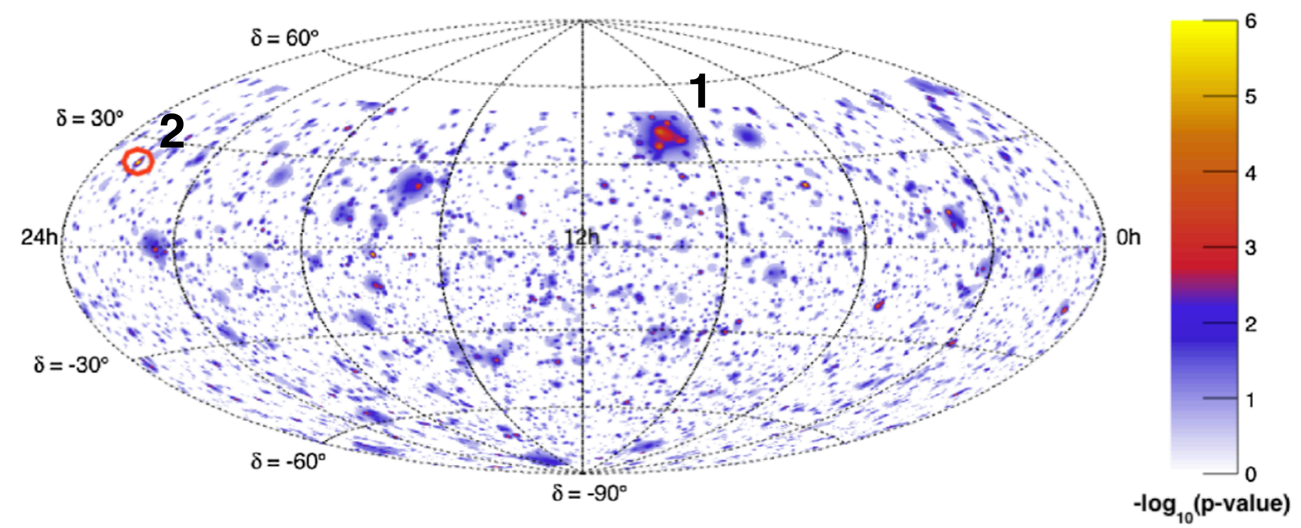



Nν ≈1.8 during flare

Figure: X.Rodrigues, SG, A.Fedynitch, A.Palladino & W.Winter (1812.05939)

# Comments on observations

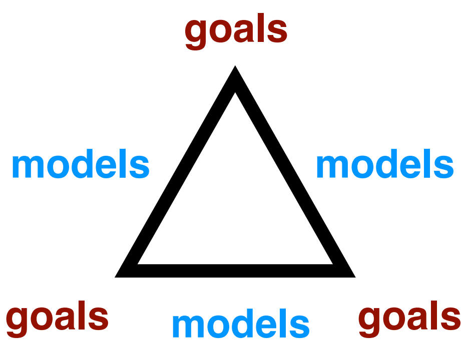
- In 2017, ~ 200 TeV muon neutrino observed
- TXS0506+056 in gamma-ray flaring state
- Assuming correlation of $\nu \sim \gamma$ ==> TXS0506+056 neutrino emitter ($>3\sigma$)
- In 2014-15, an excess of ~ 13 muon tracks excess observed
- Assuming TXS0506+056 a neutrino source ==> neutrino flare ($>3\sigma$)
- However, no correlated $\gamma$ activity ?

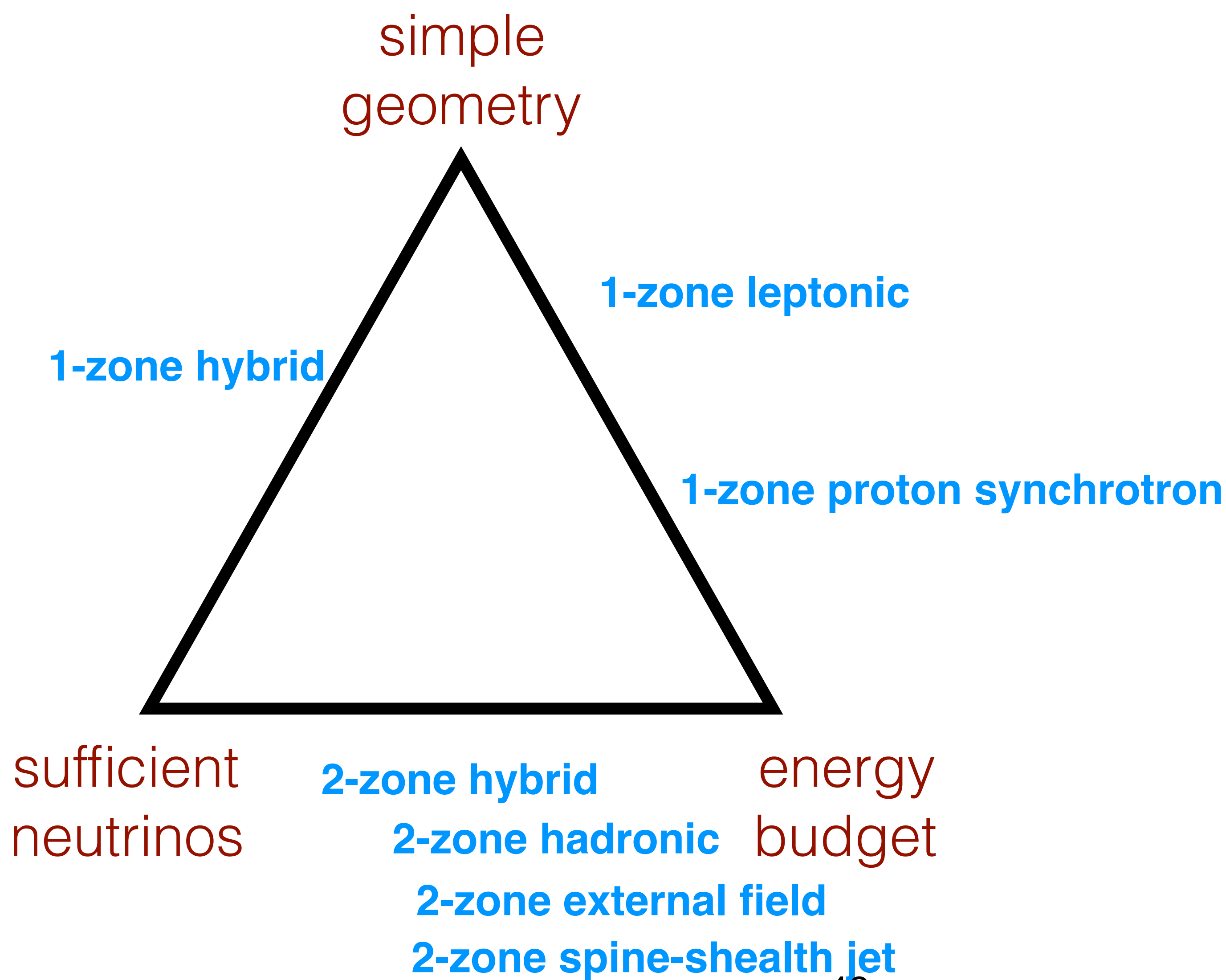



Distribution of muon tracks, Darren Grant TeVPa 2018

1: hottest spot (cluster of muon tracks), no source behind
2: second hottest (coincides with TXS 0506+056)

# Trilemma on modeling : only one side may be chosen



# Summary of modeling

| | | 2017 Flare | | | | 2014-15 Flare | | | |
|---|---|---|---|---|---|---|---|---|---|
| Zones | Model | X-ray | Neutrino | Q→F transition | $E_{budget}$ | $\gamma$-ray | Neutrino | Q→F transition | $E_{budget}$ |
| 1 | Leptonic | | | | | | | | |
| 1 | Hadronic | | | | | | | | |
| 1 | Proton-synch. | | | | | | | | |
| 1 | Hybrid | | | | | | | | |
| 2 | Hadronic | | | | | | | | |
| 2 | Hybrid | | | | | | | | |
| 2 | External-field | Keivani 18 | Keivani 18 | Keivani 18 | Keivani 18 | | | | |

consistent    partially explaining    inconsistent

Q→F : transition from quiet state to flare state    $L_{Edd}$ : Eddington limit assuming a SMBH $6\times10^9 M_\odot$

# Additional literature on modeling TXS0506-056

- A. Keivani et al. 2018 and Murase et al. 2018 (1 zone & extern. field model; 2017 flare)
- M.Cerruti et al. 2018 (1-zone & proton synch. model)
- MAGIC collaboration 2018 (Tavecchio spine-shealth jet model, 2017 flare)
- R. Liu et al. 2018 (star-jet, pp, 2017 flare)
- K. Wang et al 2018 (star-jet, pp; 2014-15 flare)
- A. Reimer et al 2018 (lepto-hadronic model, 2014-15 flare, similar results)
- …

# Open questions

- Source (TXS0506) intriguing as neutrino source, but evidence not solid, unrefutable yet.
- 2017 and 2014-15 $\nu$ are totally different. No single astro model can explain both.
- How unique is TXS0506 ?
- Modeling 2014-15 $\nu$ alone is largely unsuccessful, as one requires one of following:
  - Block $\gamma$-rays — need very high column density — unlikely in galaxy
  - Divert $e^{\pm}$ in situ — no convincing astro theory yet
  - Divert $e^{\pm}$ during propagation — source transparent — $\nu$ prod. efficiency low — proton energy budget too high for AGN
- Implications ?
  - $\gamma$-rays are not co-produced ($\nu$ not from $\pi^{\pm}$ decay)
  - TeV-PeV $\nu$ and GeV $\gamma$-rays delayed (> a few years over 4 G light years)
  - …