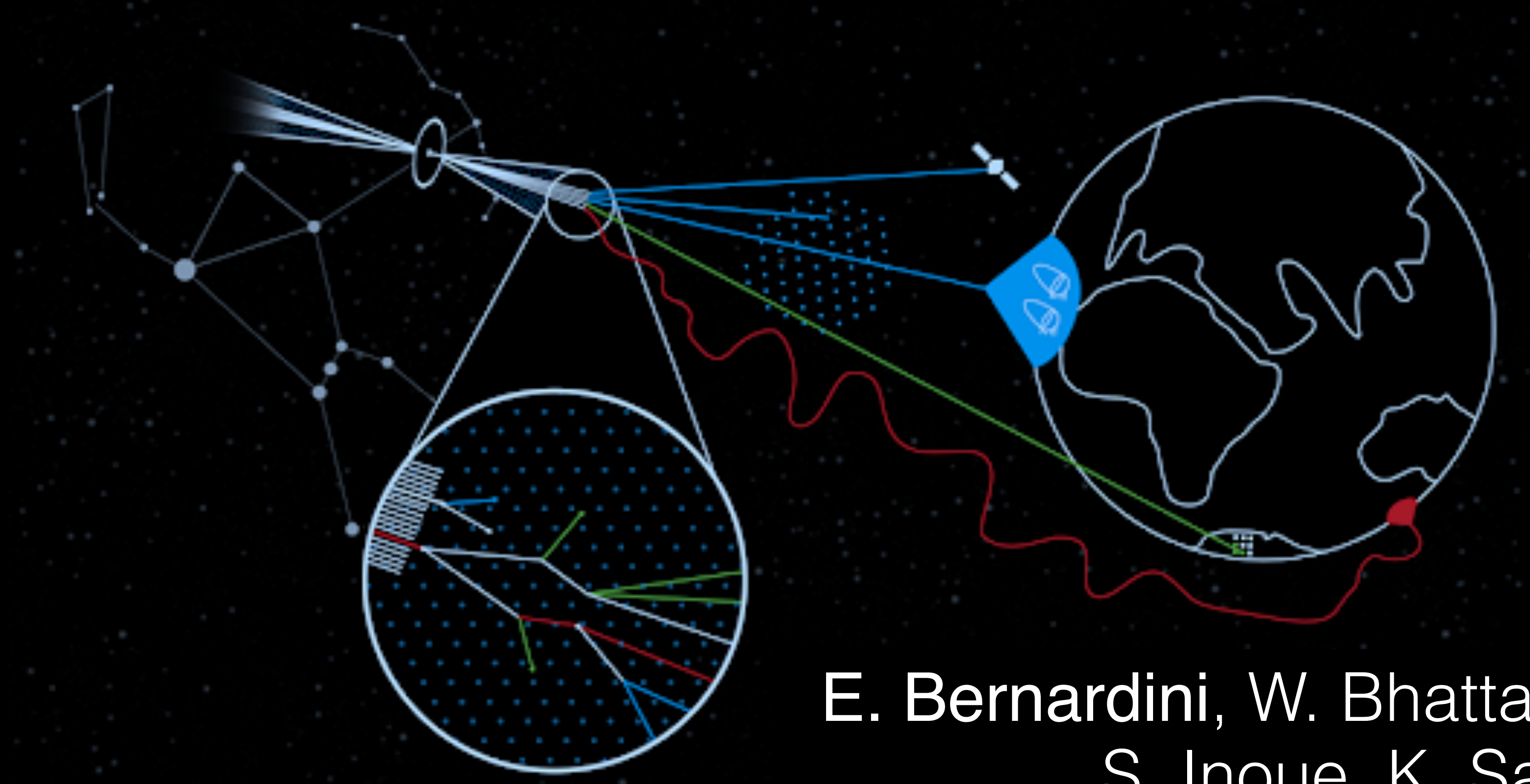
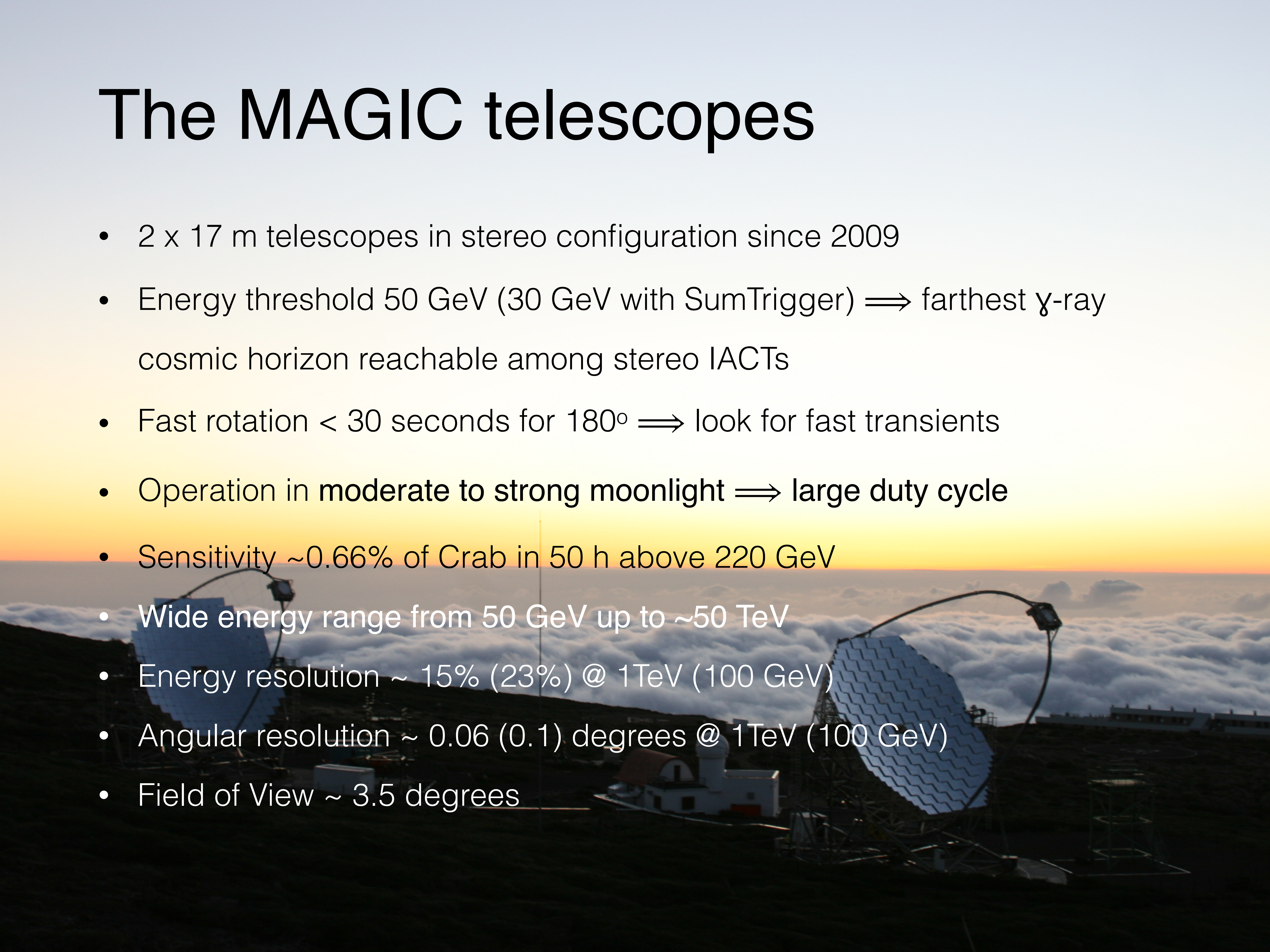
The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration



E. Bernardini, W. Bhattacharrya,
S. Inoue, K. Satalecka,
F. Tavecchio for the **MAGIC Collaboration**
& M. Cerruti

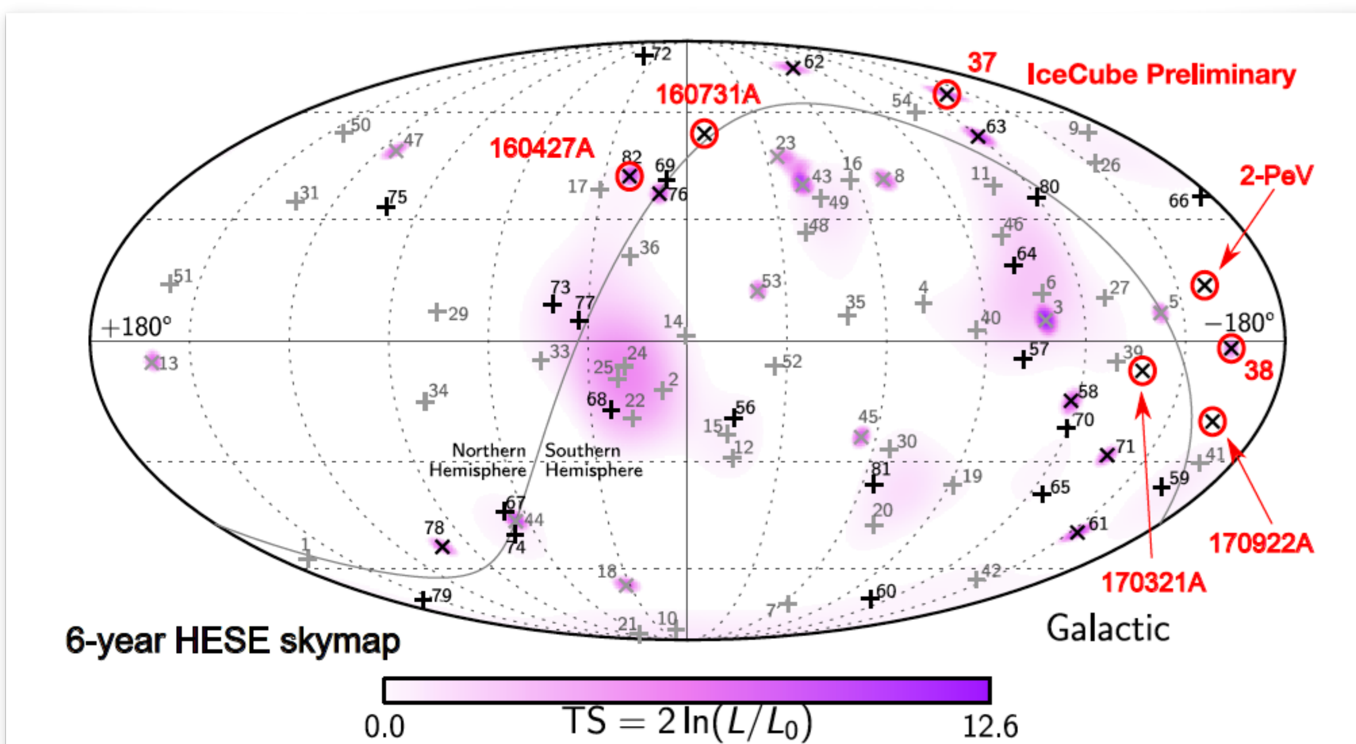
The MAGIC telescopes

- 2 x 17 m telescopes in stereo configuration since 2009
- Energy threshold 50 GeV (30 GeV with SumTrigger) $\Longrightarrow$ farthest γ-ray cosmic horizon reachable among stereo IACTs
- Fast rotation < 30 seconds for 180º $\Longrightarrow$ look for fast transients
- Operation in **moderate to strong moonlight** $\Longrightarrow$ **large duty cycle**
- Sensitivity ~0.66% of Crab in 50 h above 220 GeV
- Wide energy range from 50 GeV up to ~50 TeV
- Energy resolution ~ 15% (23%) @ 1TeV (100 GeV)
- Angular resolution ~ 0.06 (0.1) degrees @ 1TeV (100 GeV)
- Field of View ~ 3.5 degrees



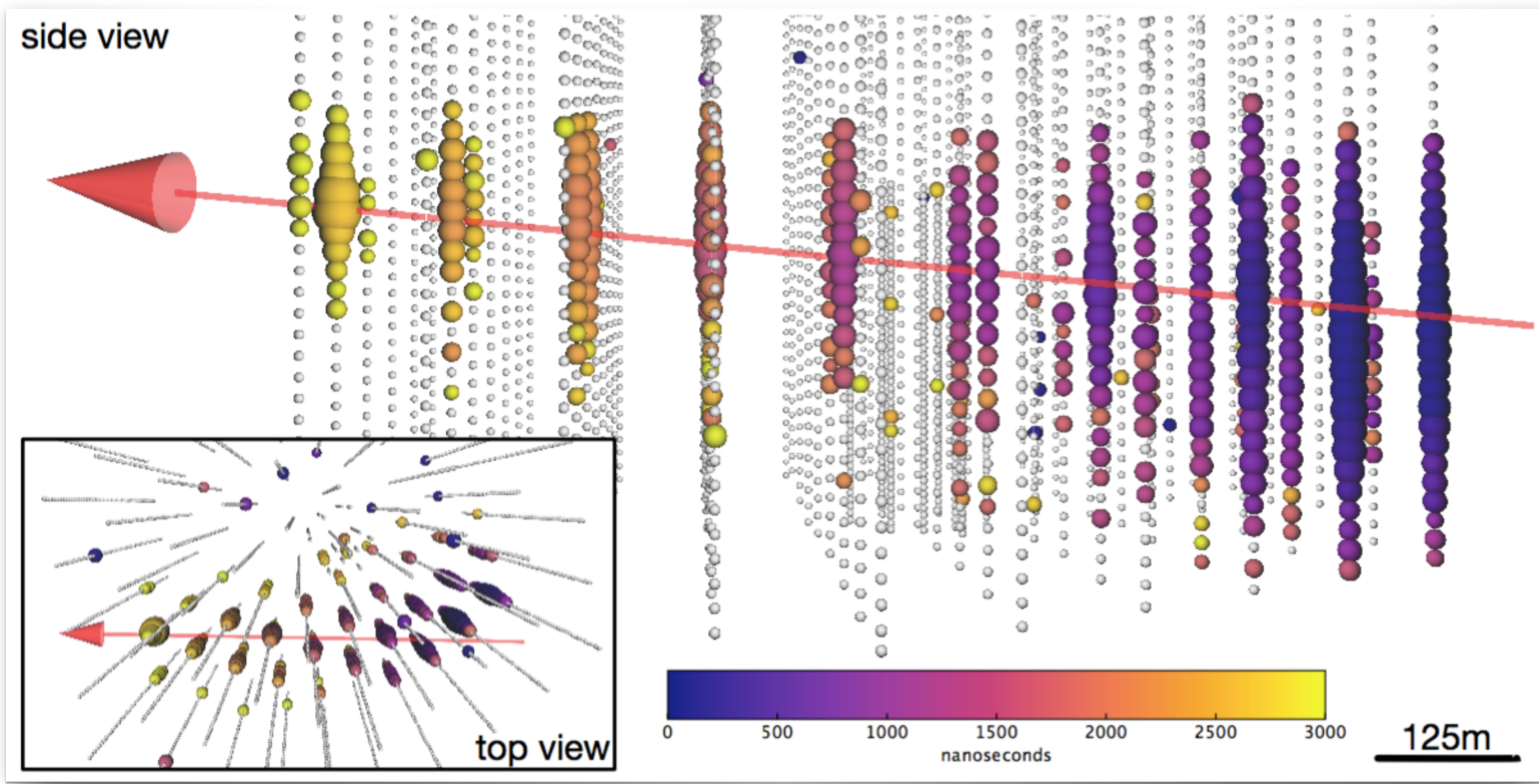
The MAGIC follow-up program

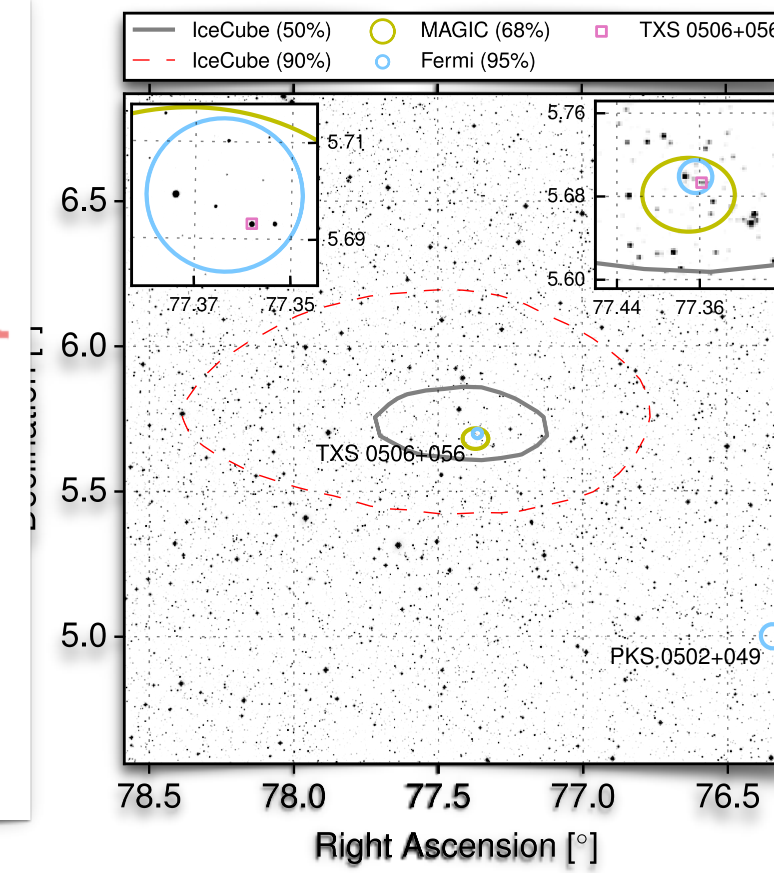
- MAGIC **pioneered the Neutrino Triggered Target of Opportunity (NToO) program** since 2007 [M. Ackermann et al. arXiv:0709.2640]
- MAGIC is part of the Gamma-Ray Follow-up program since 2012 [M.G. Aartsen et al., JINST, 11, P11009 (2016)]
- More than 30 hours invested during previous cycle (2017)
- Search for counterparts of ν_μ tracks: HESE-37, HESE-38 and a multi-PeV track (see ATel#7856)
- HESE/EHE real-time alerts: e.g. 160427A, 160731A (AMON GCN)



Also, long-term monitoring program of known TeV emitters [https://magic.mpp.mpg.de/backend/publications/articles]

IceCube 170922A (EHE)





- Probability of astrophysical origin 56.6%
- At 6 arc-minutes from the direction of TXS 0506+056
- Neutrino energy @ 90% C.L.: lower limit is 183 TeV (200 TeV), upper limit is 4.3 PeV (7.5 PeV) for a spectral index of -2.13 (-2.0)

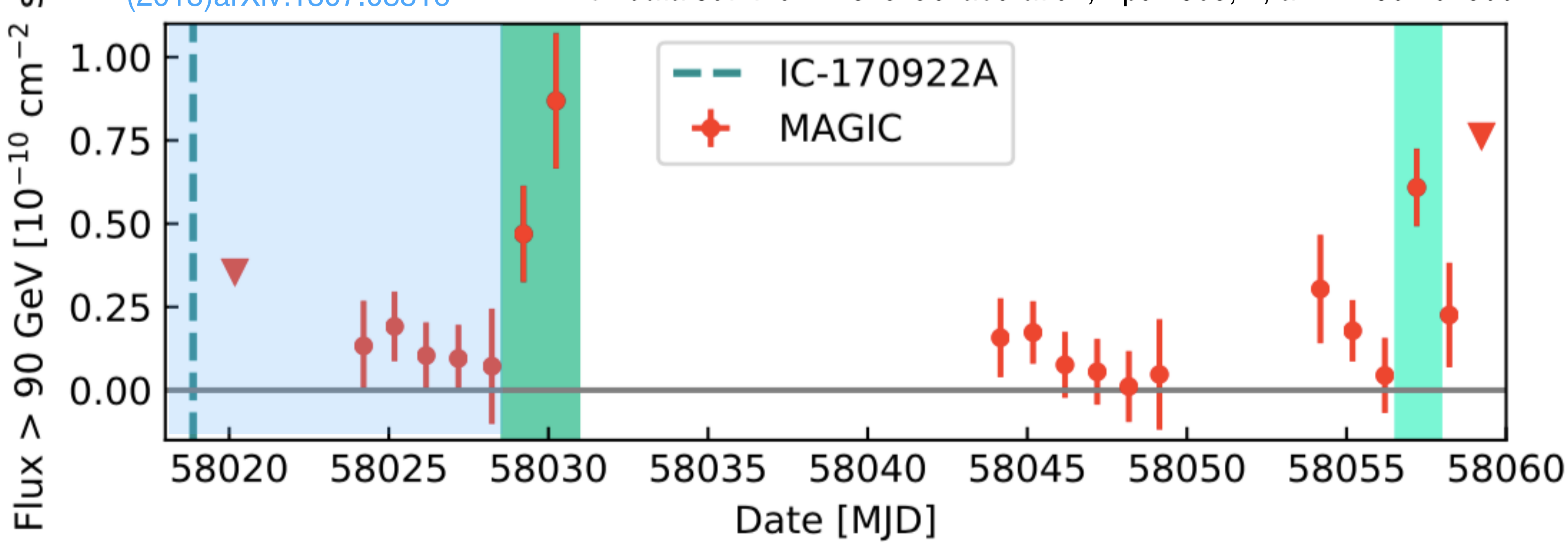
MAGIC observations

More insights on observations and results: talk by L. Foffano on August 29th 2018

- 41 hours from September 24th to November the 2nd
- ɣ-ray energy spectrum measured up to about 400 GeV, power-law spectral index ranging from (-4.0 ± 0.3) to (-3.5 ± 0.4)
- VHE flux clearly variable on daily timescales
- 2 distinctive flares observed, spectrum measured also in between (hereafter the “low state”)

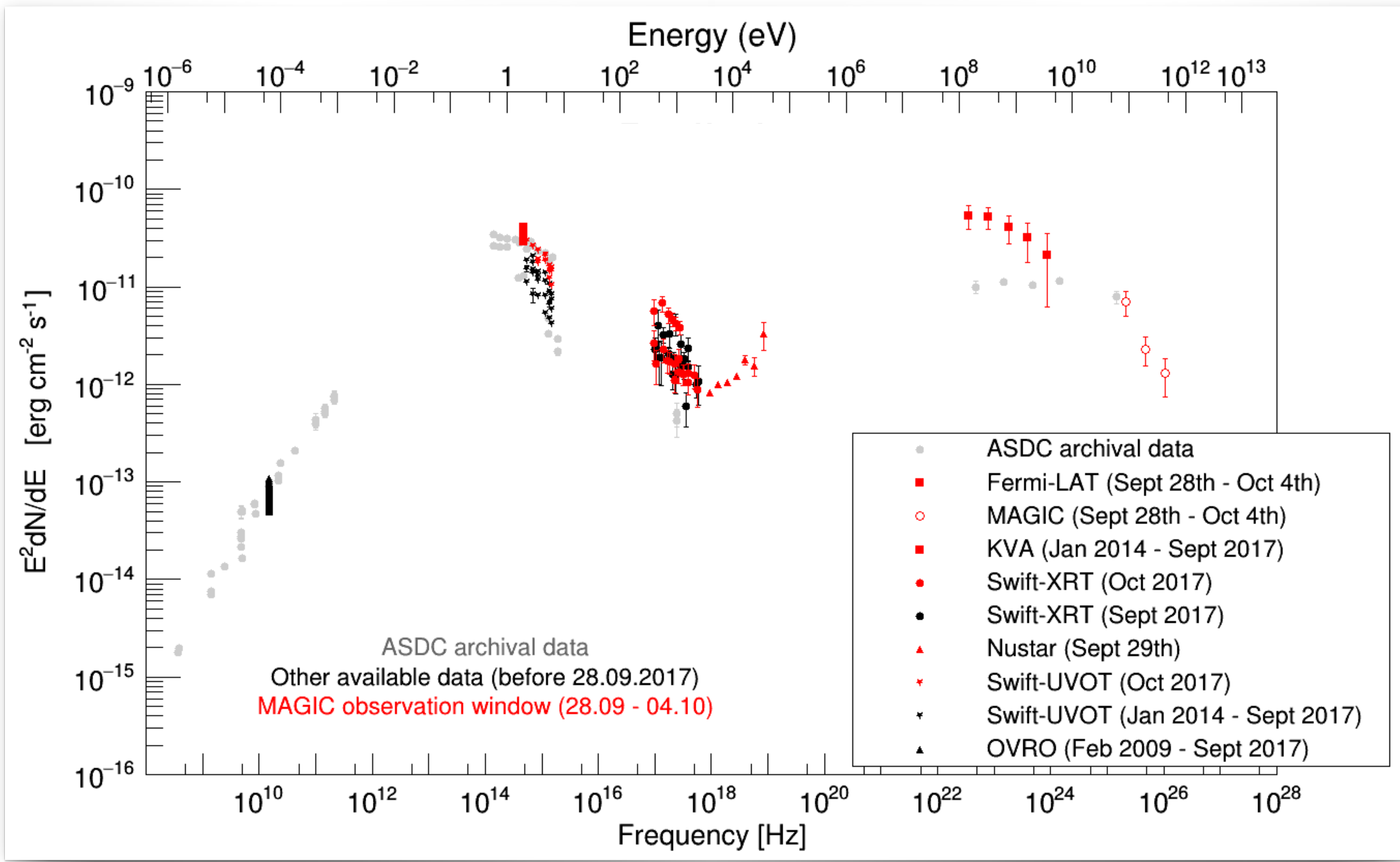
The IceCube Coll. et al., Science 361, 146 (2018)arXiv:1807.08816

Full data set: the MAGIC Collaboration, ApJL 863, 1, arXiv:1807.04300



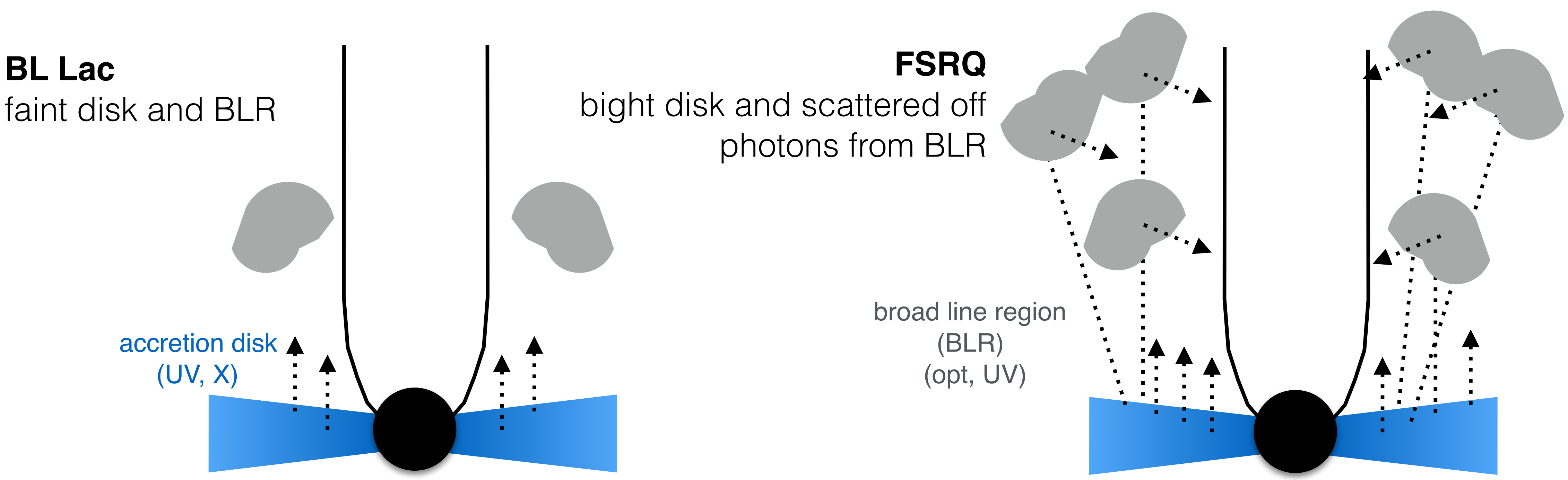
Multi-wavelength data

- Public data analyzed and combined within 24 hours from MAGIC measurements for quasi-simultaneous SED
- TXS 0506+056 classified as an intermediate synchrotron peaked (ISP) or low synchrotron peaked (LSP) Blazar, luminosity typical for a LSP [Ackermann M., et al., 2015, ApJ, 810, 14, C. Righi et al. arXiv:1807.10506]



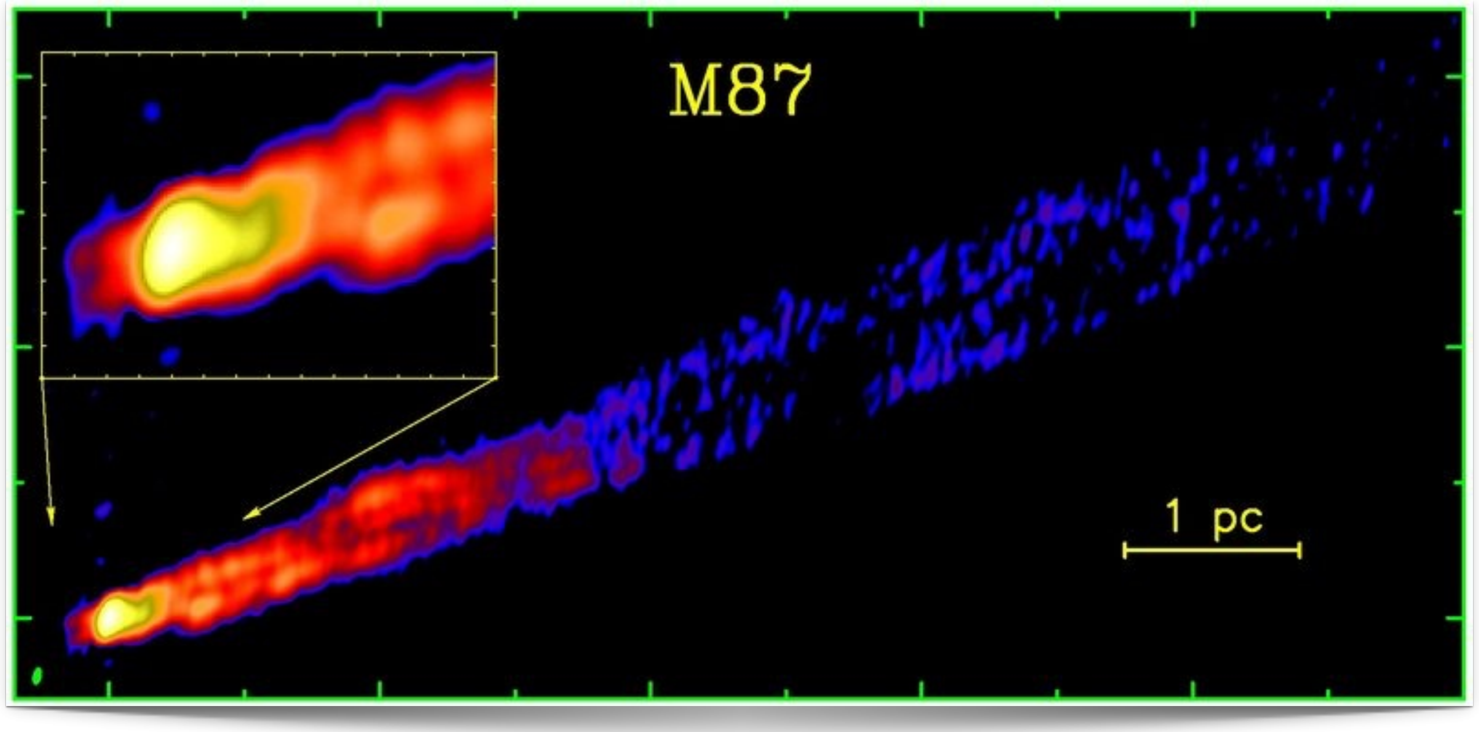
A neutrino emitter?

- High energy neutrinos can be generated through pγ interactions in the jet
- BL Lac objects generally disfavored compared to FSRQs due to low density of target photon fields [e.g. Murase et al., 2014, Phys. Rev. D, 90, 023007]
- For $E_\nu \sim 300$ TeV: protons with $E_p \geq 6$ PeV must interact with photons with energies above the photo-pion threshold, $\varepsilon \geq m_\pi m_p c^4/E_p \approx 10^2 - 10^3$ eV, in the UV to soft X-ray range



External target photon field?

- External photons can increase photo-meson rate e.g.
  - from radiative inefficient accretion flows [C. Righi et al . arXiv:1807.10506]
  - from **structured jets** [Ghisellini G., Tavecchio F., Chiaberge M., 2005, A&A, 432, 401]: synchrotron **photon density from sheath seen boosted in jet frame** $U' \simeq U\Gamma_{\rm rel}^2$ $\Gamma_{\rm rel} = \Gamma_{\rm s}\Gamma_{\rm l}(1-\beta_{\rm s}\beta_{\rm l})$



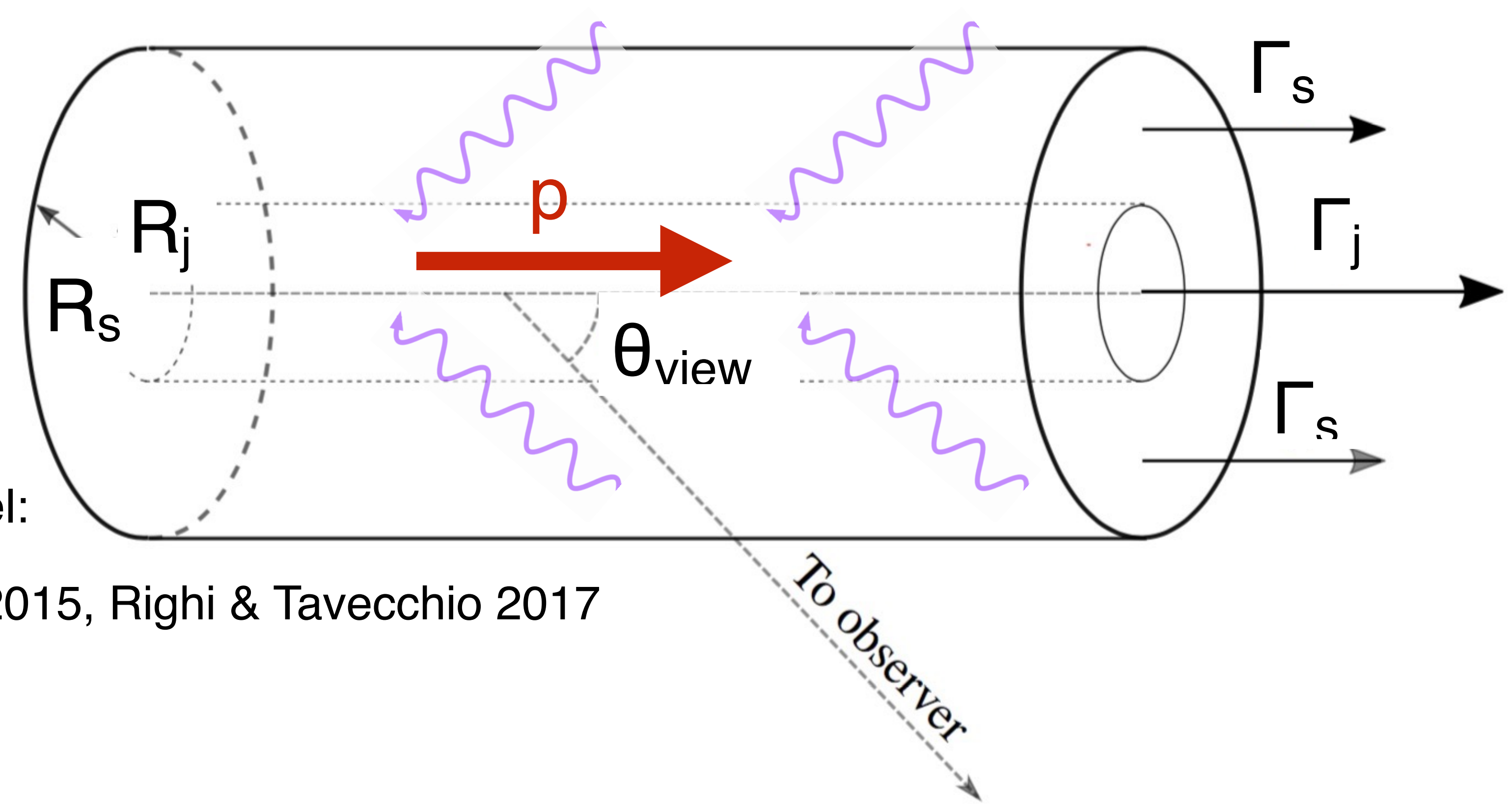
Limb brightening observed in the jet of M87 Kovalev+ 2007

More insights: talk by F. Tavecchio on August 29th 2018

The model

MAGIC Coll., ApJ 863, L10, arXiv:1803.04300

- Cylinder with spine radius $R_j=10^6$cm (t_{var} ~ 1 day), length $H_j=R_j$. For the outer layer $R_s=H_s=1.5*R_j$
- Leptonic emission: synchrotron, SSC, **EC**
- Hadronic emission: **photo-meson cascade**, BH cascade, synchrotron radiation from protons and muons
- SED of TXS 0506+056 motivates small viewing angle (θ_{view} = 0.8°)

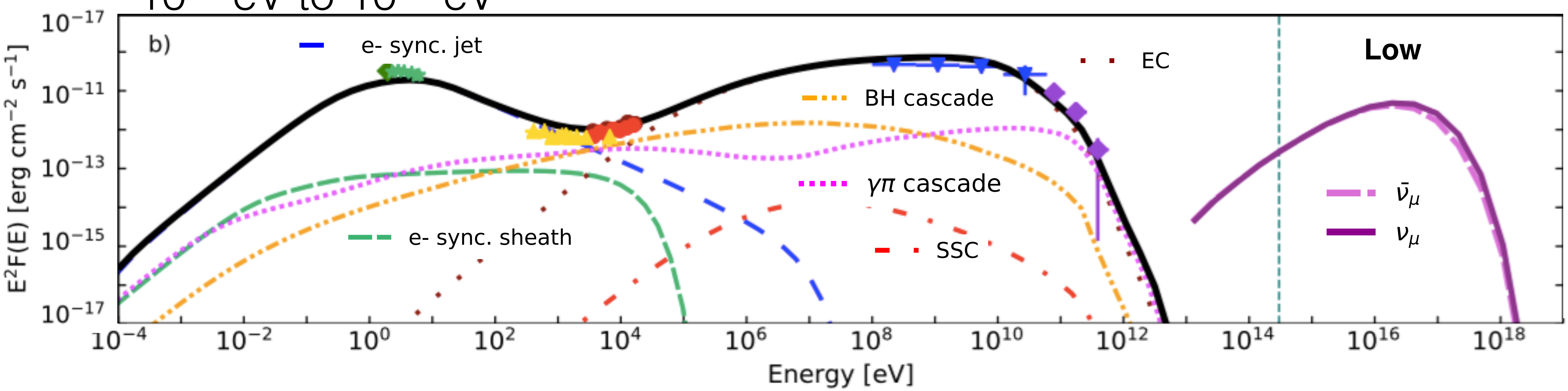


Spine-sheath model:

Tavecchio+ 2014, 2015, Righi & Tavecchio 2017

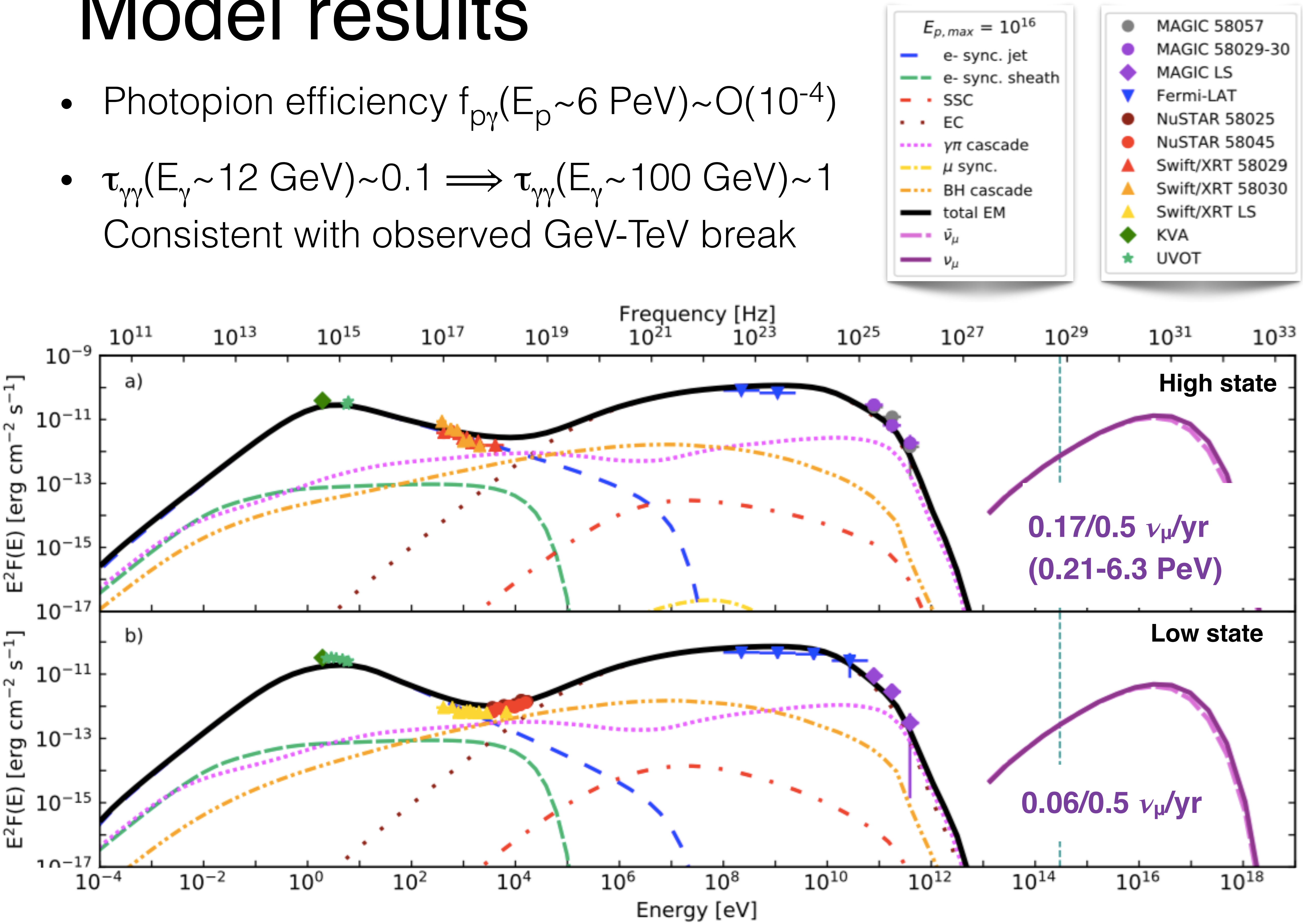
Model parameters

- Bulk Lorentz factor spine $\Gamma_j = 22$, sheath $\Gamma_s = 2.2$ ($\delta_j \simeq 40$ and $\delta_s \simeq 3.7$)
- Parameters tuned to reproduce ɣ-ray data and neutrino event rate without overproducing X-rays:
  - Magnetic field
  - Electron spectrum: broken power-law $E_{e,min}$, $E_{e,br}$, $E_{e,max}$, n_1,n_2
  - Proton spectrum: power-law E_p^{-2} with exp. cutoff E_{pmax} in the range 10^{14} eV to 10^{18} eV



Model results

- Photopion efficiency $f_{p\gamma}(E_p\sim6\text{ PeV})\sim O(10^{-4})$
- $\tau_{\gamma\gamma}(E_\gamma\sim12\text{ GeV})\sim0.1 \Longrightarrow \tau_{\gamma\gamma}(E_\gamma\sim100\text{ GeV})\sim1$
  Consistent with observed GeV-TeV break



Model results

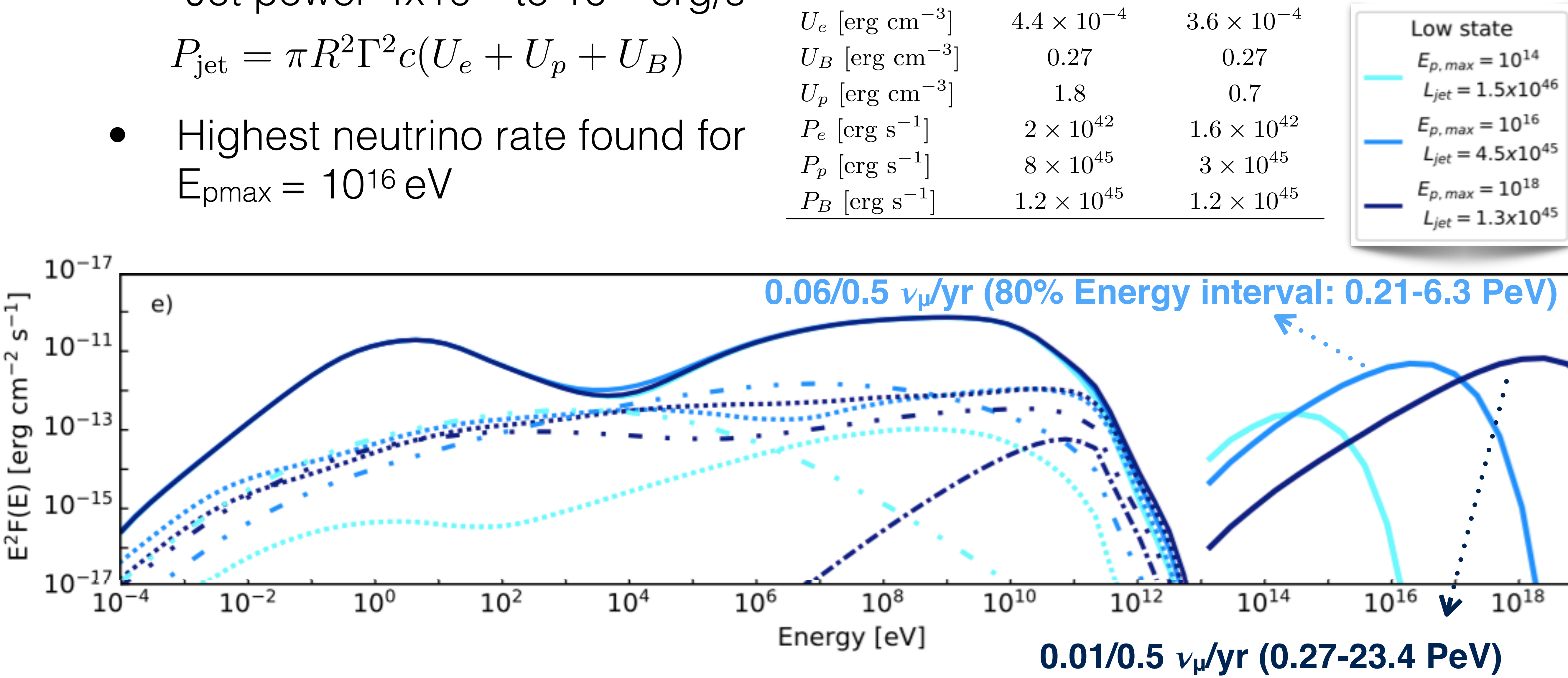
- Results similar to purely leptonic models without protons
- Jet power 4x10^{45} to 10^{46} erg/s

$$P_{\rm jet} = \pi R^2 \Gamma^2 c (U_e + U_p + U_B)$$

- Highest neutrino rate found for E_{pmax} = 10^{16} eV

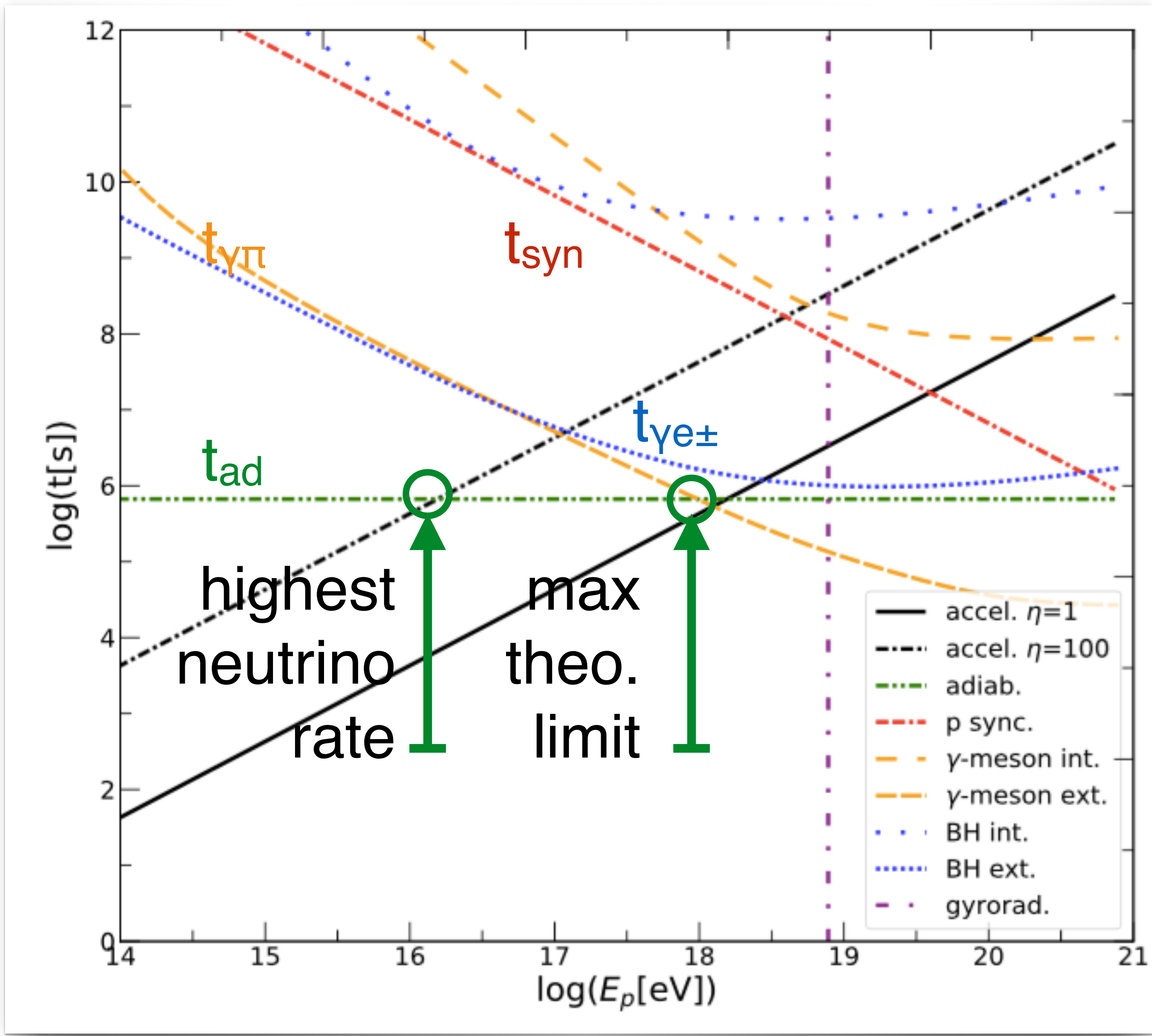
Model parameters in the jet coming frame

State	MJD 58029-30	Lower VHE
B [G]	2.6	2.6
$E_{\rm min}$ [eV]	3.2×10^8	2.0×10^8
$E_{\rm br}$ [eV]	7.0×10^8	9.0×10^8
$E_{\rm max}$ [eV]	8×10^{11}	8×10^{11}
n_1	2	2
n_2	3.9	4.4
U_e [erg cm^{-3}]	4.4×10^{-4}	3.6×10^{-4}
U_B [erg cm^{-3}]	0.27	0.27
U_p [erg cm^{-3}]	1.8	0.7
P_e [erg s^{-1}]	2×10^{42}	1.6×10^{42}
P_p [erg s^{-1}]	8×10^{45}	3×10^{45}
P_B [erg s^{-1}]	1.2×10^{45}	1.2×10^{45}

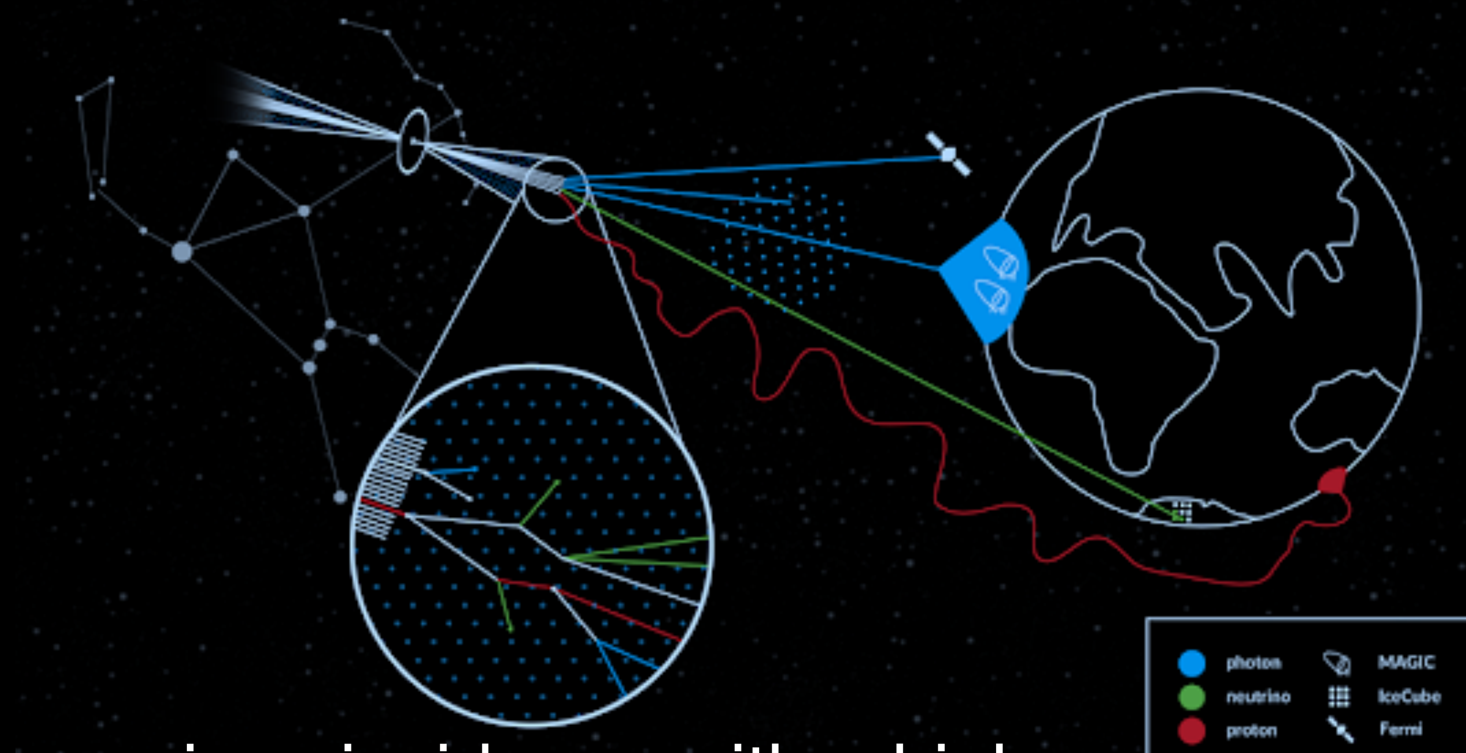


Timescales

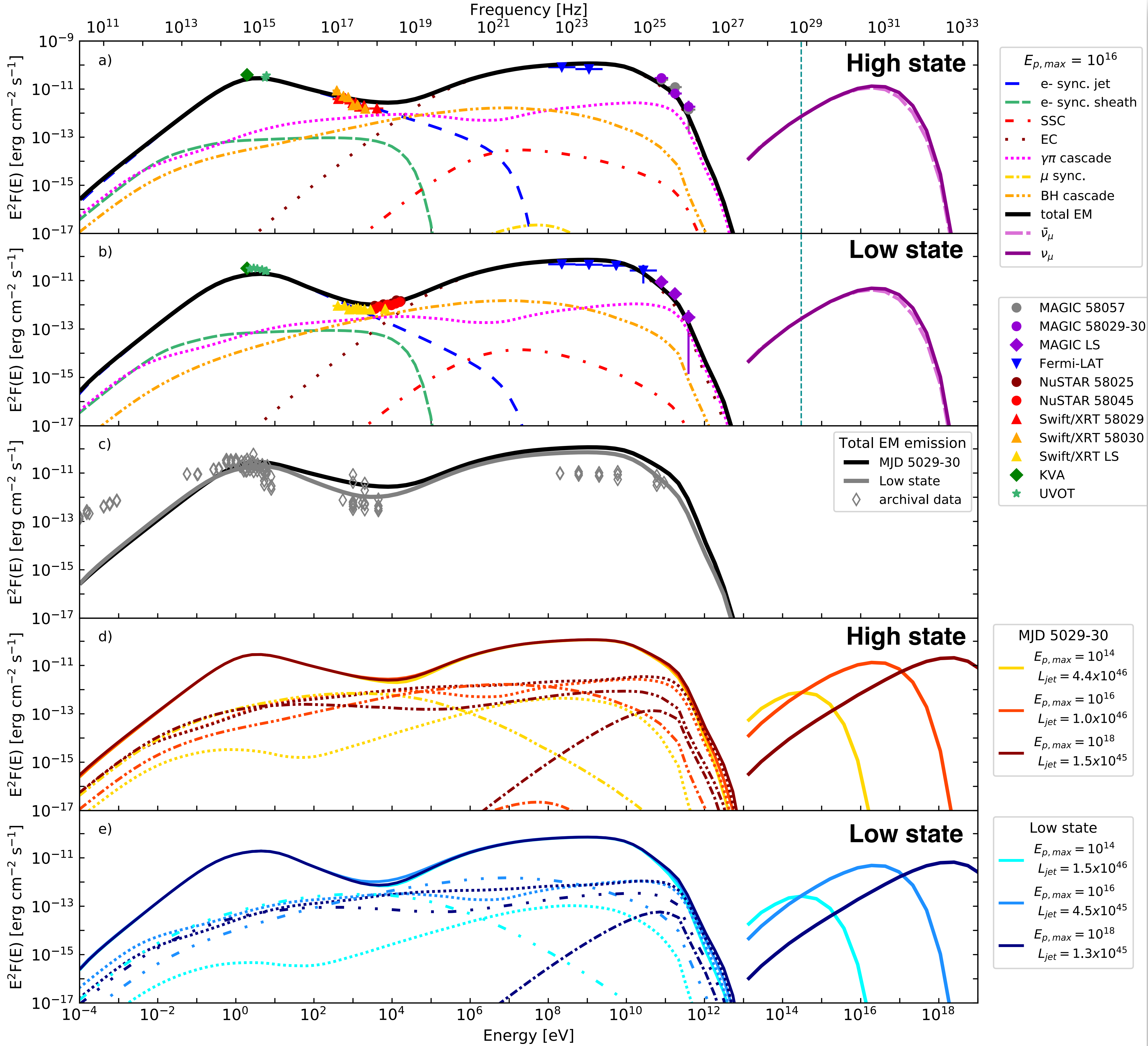
- The maximum proton energy $E_{p,max}$ can be estimated by balancing t_{acc} (E) and the shortest loss timescale $t_{loss} = \min[t_{ad}, t_{syn}, t_{\gamma\pi}, t_{\gamma e\pm}]$
- $E_{p,max}$ (in the jet co-moving frame) can be in the range ~ 10^{14} to 10^{18} eV



Conclusions



- **First time observation of VHE ɣ-rays in coincidence with a high energy neutrinos yielded by the MAGIC telescopes**
- Monitoring of TXS 0506+056 for 41 hours with the MAGIC telescopes yielded:
  - variability timescale at VHE energies < 1 day
  - 2 distinctive VHE ɣ-ray flares and a low state with similar spectrum
- **The neutrino and MWL data can be interpreted with a one-zone model and external photons from structured jets**
- The inferred proton luminosity is in the range ≈ 10^{45} – $4\text{x}10^{46}$ erg/s and **maximum CR energies in the comoving frame of 10^{14} to 10^{18} eV**



Frequency [Hz]
Energy [eV]
E²F(E) [erg cm⁻² s⁻¹]
a)
High state
b)
Low state
c)
d)
High state
e)
Low state
$E_{p,max}$ = 10^16
e- sync. jet
e- sync. sheath
SSC
EC
γπ cascade
μ sync.
BH cascade
total EM
$\bar{\nu}_\mu$
ν_μ
MAGIC 58057
MAGIC 58029-30
MAGIC LS
Fermi-LAT
NuSTAR 58025
NuSTAR 58045
Swift/XRT 58029
Swift/XRT 58030
Swift/XRT LS
KVA
UVOT
Total EM emission
MJD 5029-30
Low state
archival data
MJD 5029-30
$E_{p,max} = 10^{14}$ $L_{jet} = 4.4x10^{46}$
$E_{p,max} = 10^{16}$ $L_{jet} = 1.0x10^{46}$
$E_{p,max} = 10^{18}$ $L_{jet} = 1.5x10^{45}$
Low state
$E_{p,max} = 10^{14}$ $L_{jet} = 1.5x10^{46}$
$E_{p,max} = 10^{16}$ $L_{jet} = 4.5x10^{45}$
$E_{p,max} = 10^{18}$ $L_{jet} = 1.3x10^{45}$