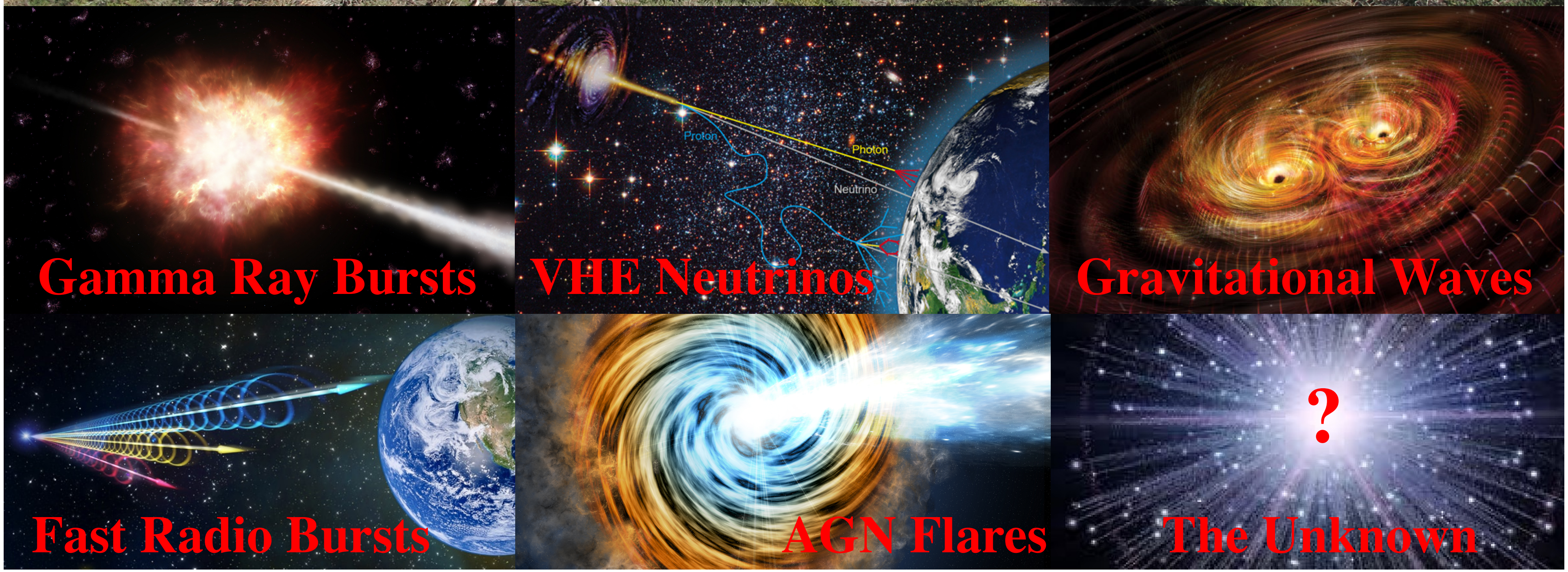
Multi-messenger Transients in the CTA Era

Susumu Inoue (RIKEN)
on behalf of many collaborators



Multi-messenger Transients Now

Susumu Inoue (RIKEN)
on behalf of many collaborators

Electroweak Transients Now

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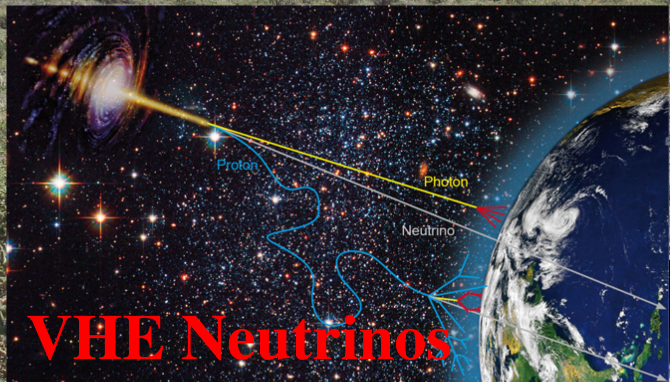
on behalf of many collaborators

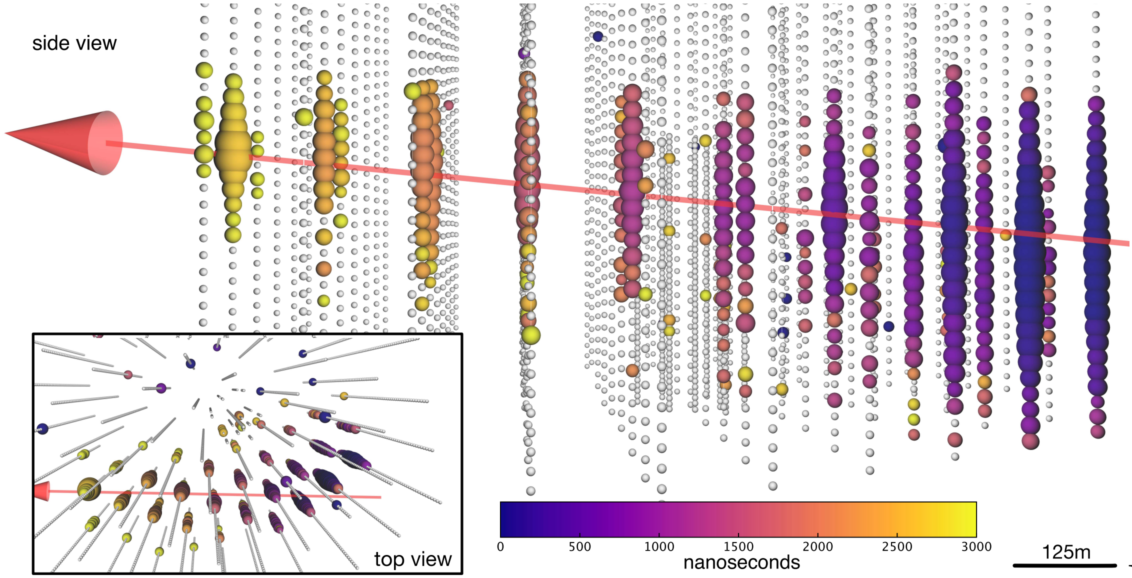


outline

1. electroweak observations of TXS 0506+056 / IC-170922A
   IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378
2. interpretation via pγ scenarios (one-zone)
   a. internal photons as targets   Cerruti, Zech, … SI+; 1807.04335
   b. "external" photons: jet-sheath (structured jet) scenario
      MAGIC Coll., ApJ 863, L10; 1807.04300
      (Bernardini, Bhattacharya, SI, Satalecka, Tavecchio)
   c. external photons: radiatively inefficient accretion flow
      Righi, Tavecchio, SI; 1807.10506
   d. brief comparison with other work   Keivani, Murase+
3. summary

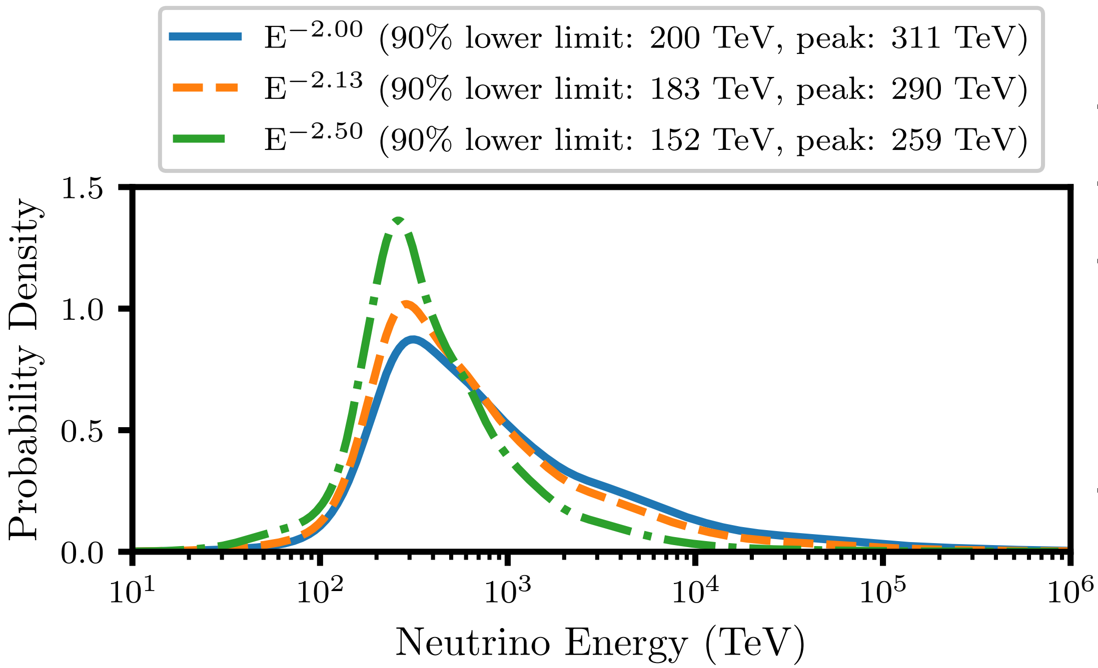
ν observation of IC-170922A

IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378

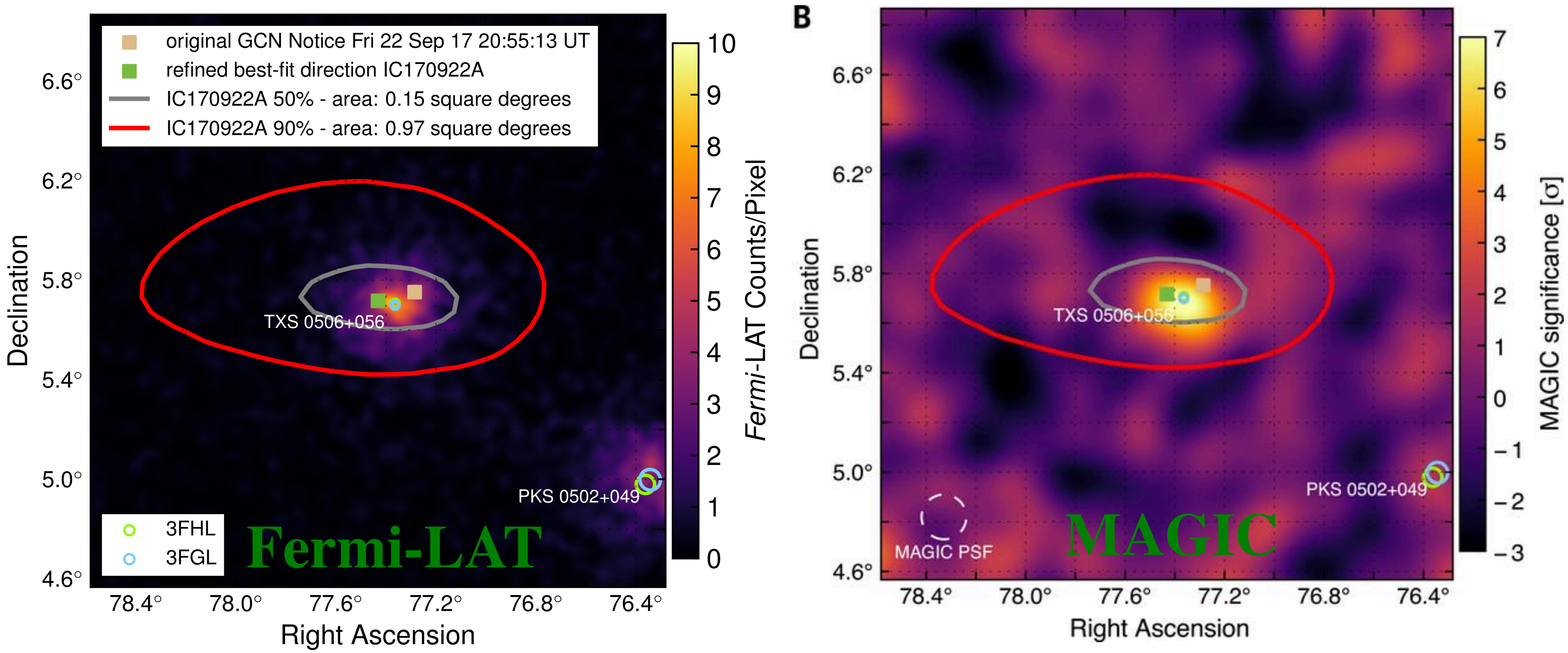


- EHE event: 56.5% probability of being astrophysical ν
- alert after 43s
- well localized, <<1 deg
- E_ν~290 TeV (183 TeV - 4.3 PeV 90% C.L.) assuming -2.13 spectrum

-> possible cosmic proton accelerator with E_p>~$20E_\nu$~several PeV



ν + EM observations of IC-170922A / TXS 0506+056



Fermi-LAT:

- coincident with blazar TXS 0506+056 in bright state (0.5 yr-long)
- significance of association ~3σ

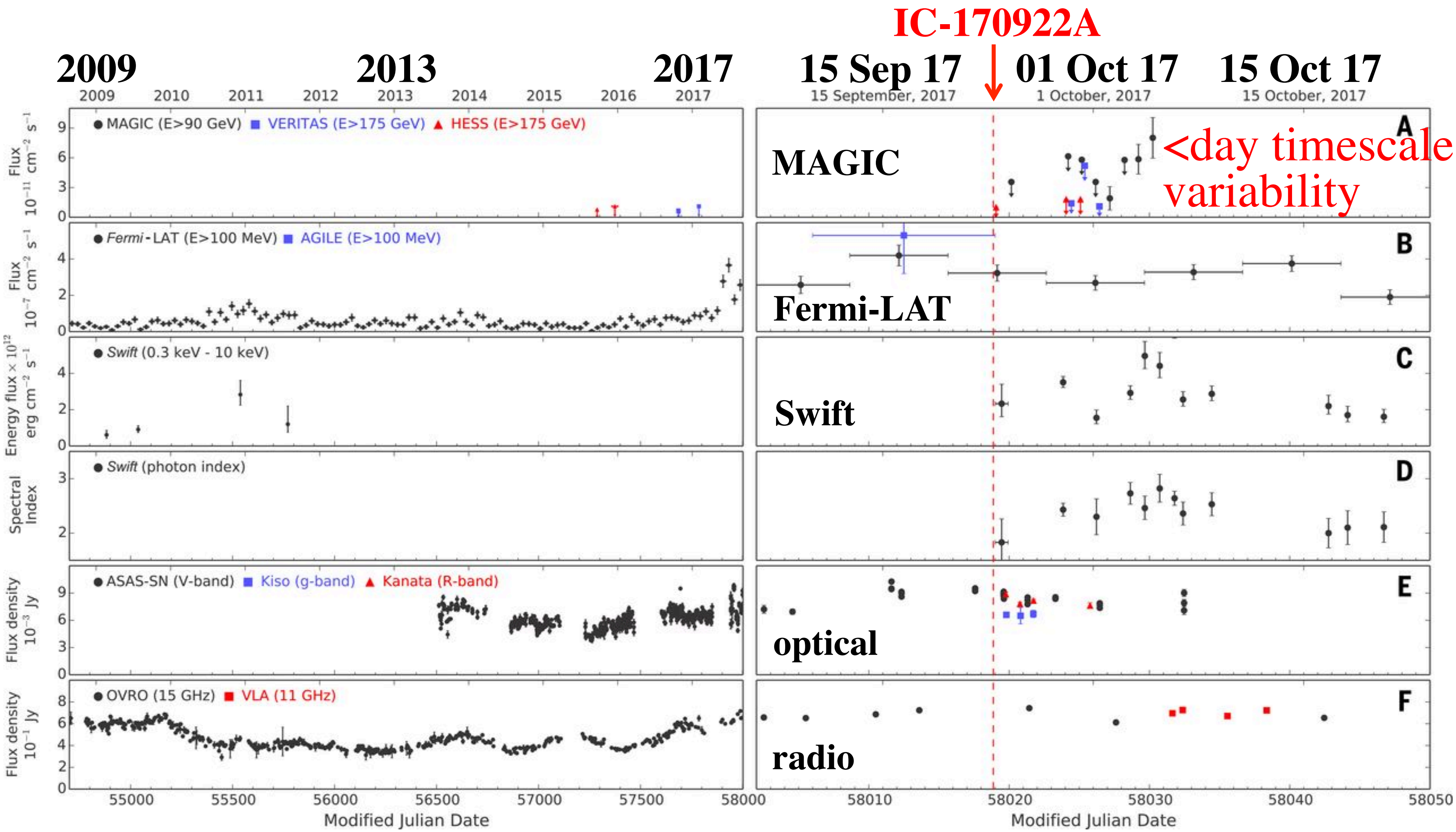
  -> possible source of possible astrophysical high-energy neutrino

MAGIC:

- ~6σ detection >~100 GeV, <day timescale flaring
- steep spectrum (Γ~-3.5 - -4.0), no significant time-dependence

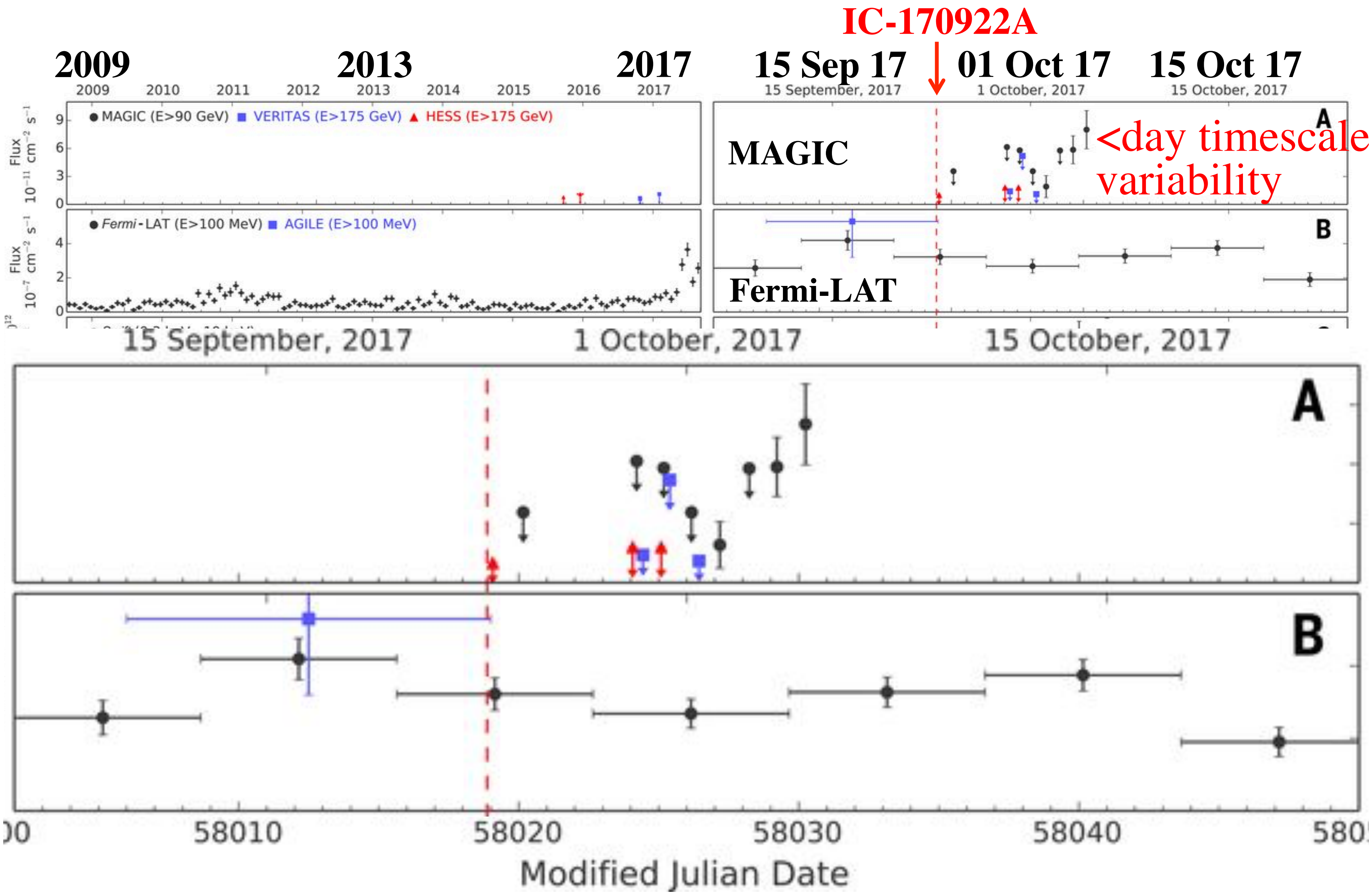
  -> crucial contraints on physical conditions of source

ν + EM observations of IC-170922A / TXS 0506+056



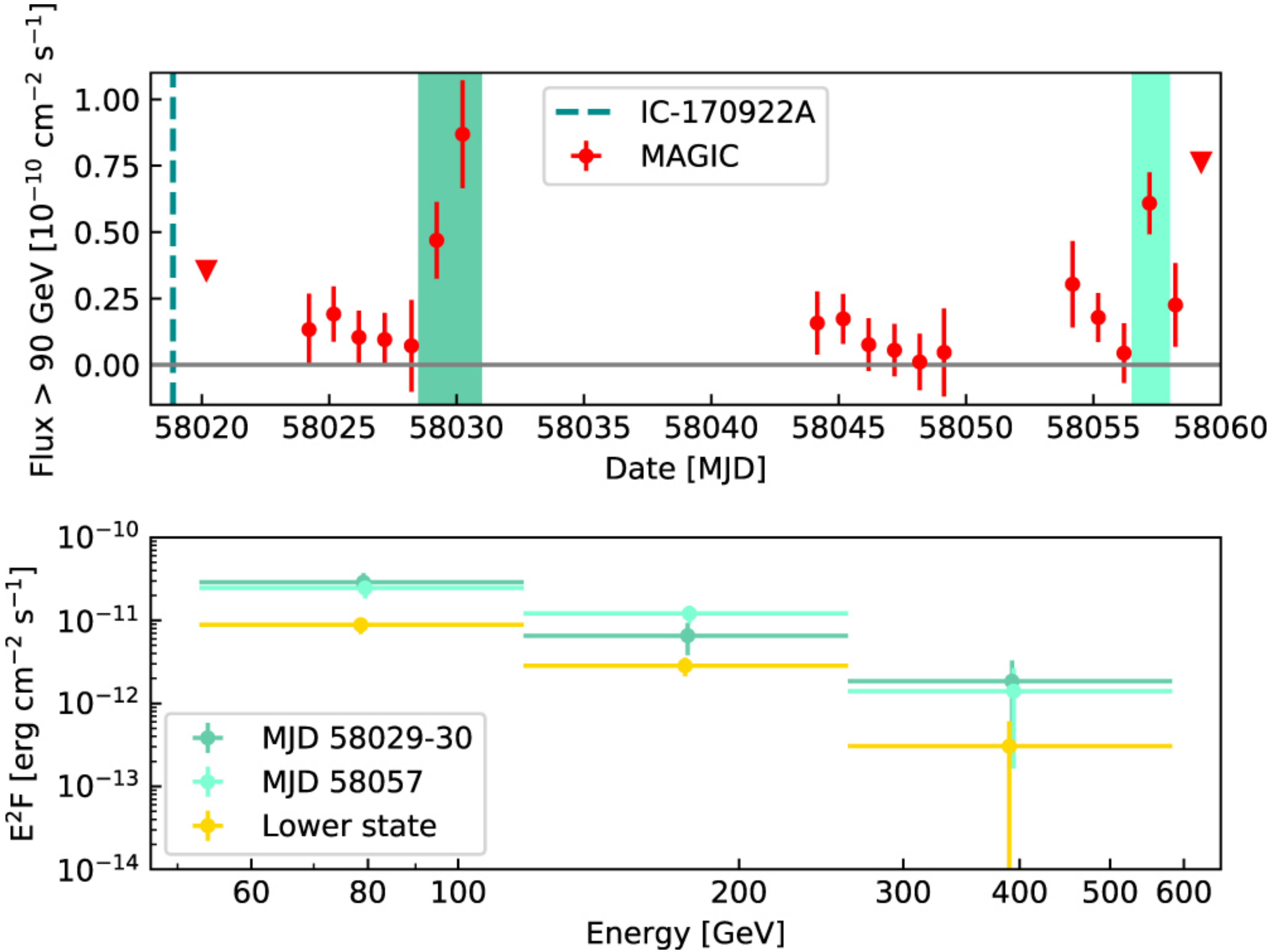
IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378

ν + EM observations of IC-170922A / TXS 0506+056



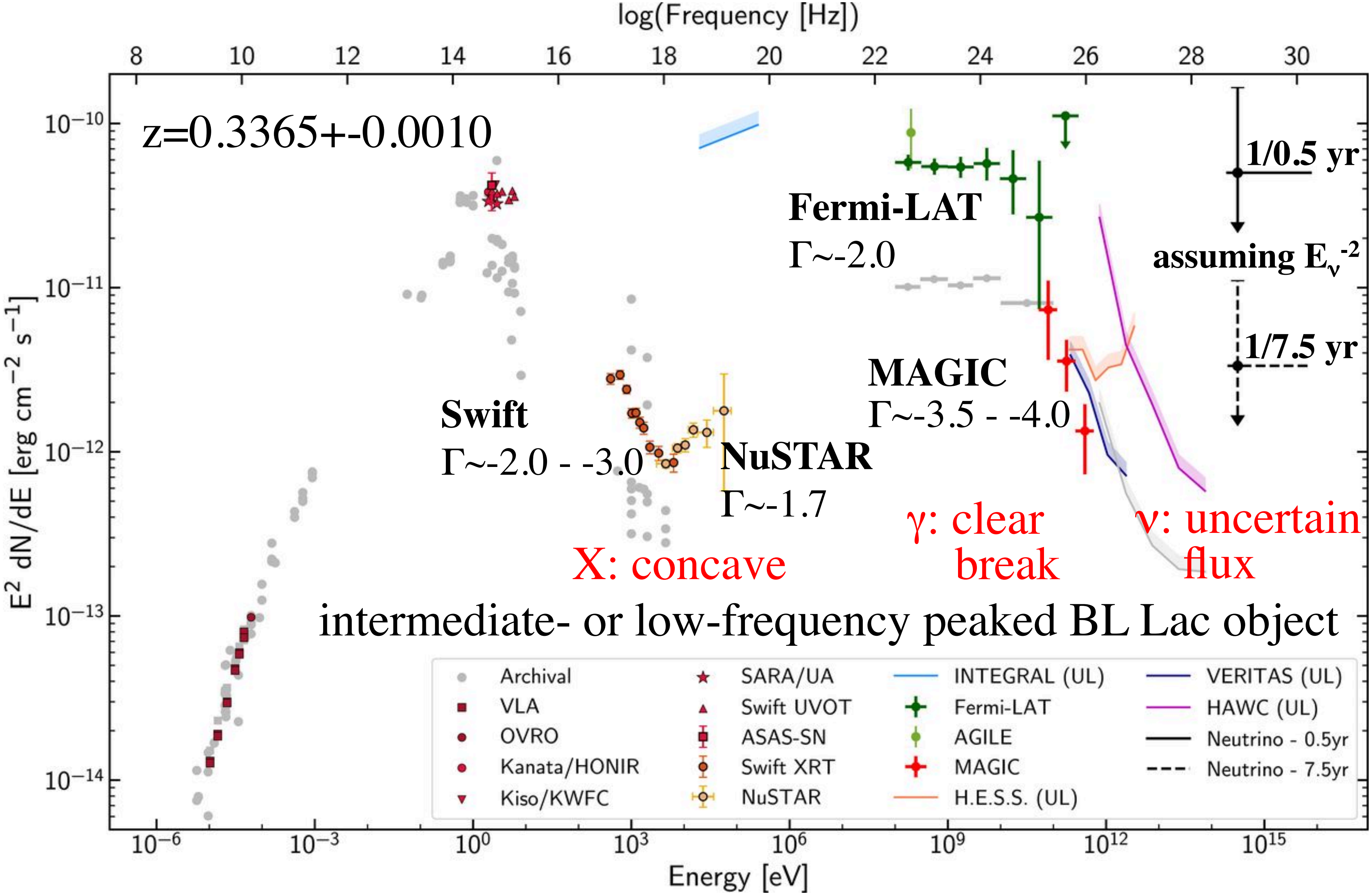
IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378

ν + EM observations of IC-170922A / TXS 0506+056



MAGIC Coll., ApJ 863, L10 (1807.04300)

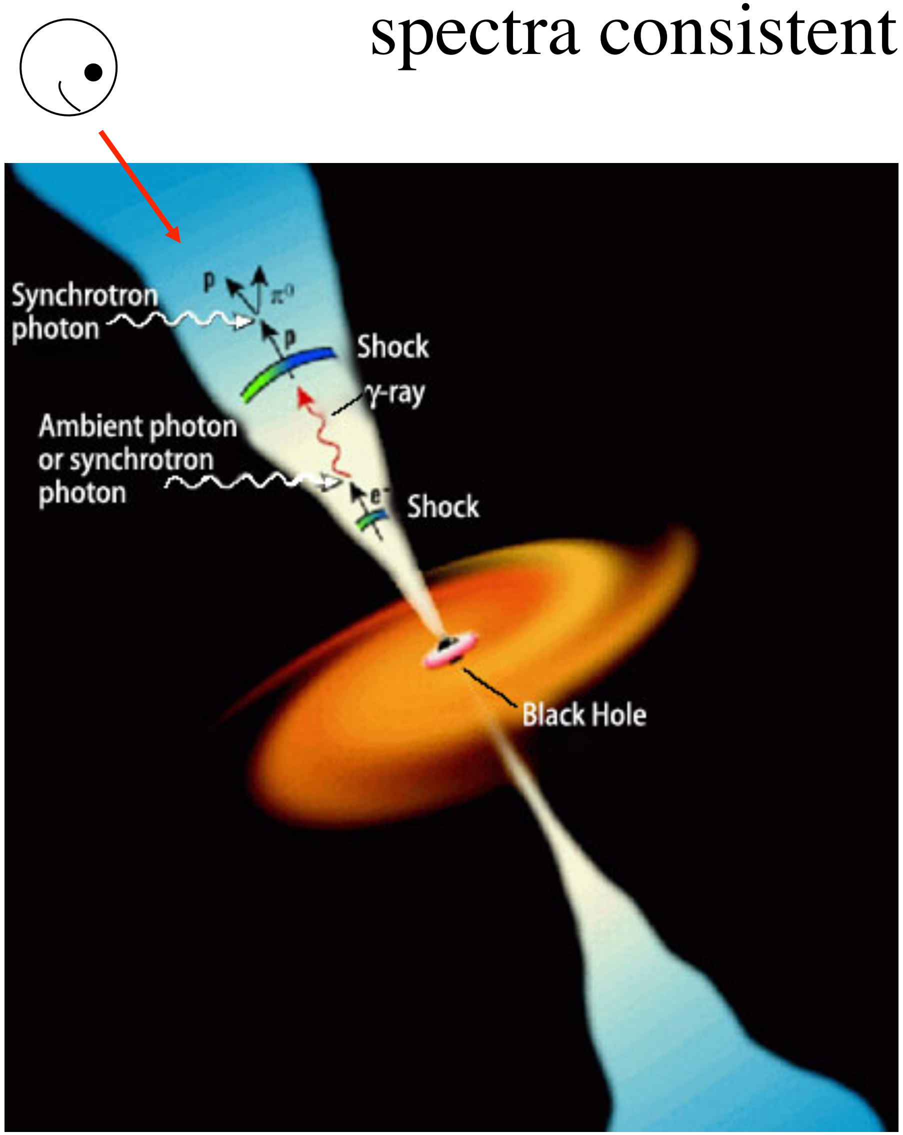
ν + EM observations of IC-170922A / TXS 0506+056

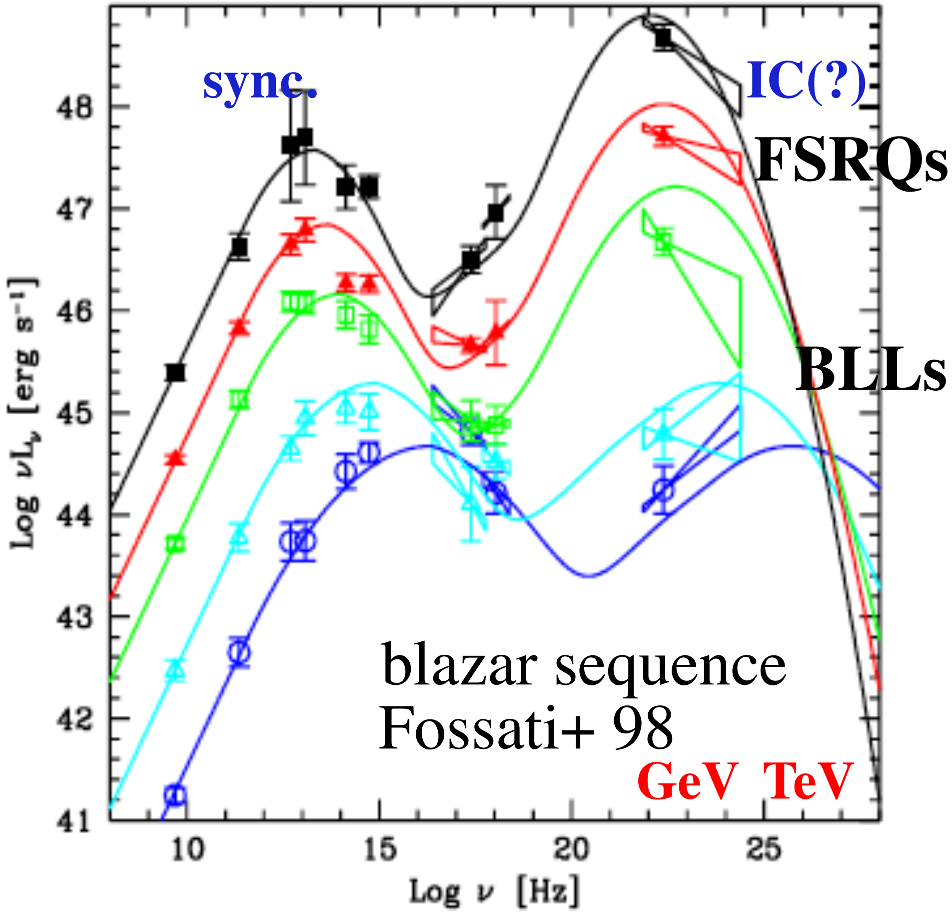


IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378

blazars

AGN with relativistic jet viewed near-axis
spectra consistent with mainly electron sync.+IC





flat spectrum radio quasars (FSRQs): high L, strong emission lines
BL Lac objects (BLLs): low L, weak emission lines

Redman's theorem

"A competent theoretician can fit any given theory to any given set of facts."

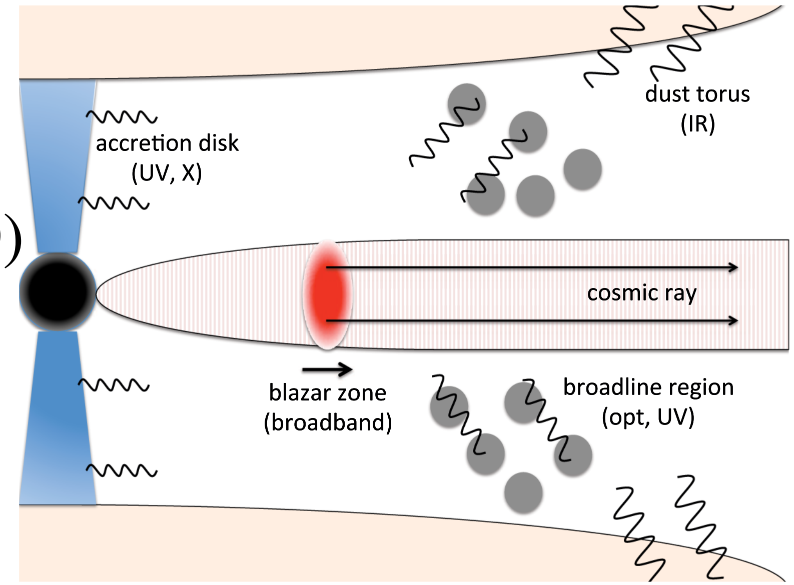
neutrino emission from blazars

- $p\gamma$ generally favored over pp in AGN jets
- target γ ε'_{γ} >~$20 m_{\pi} m_{p} c^{4}/E_{\nu} \delta^{-1}$
  ~ 0.4 keV $(E_{\nu}/300\ \mathrm{TeV})^{-1}$ $(\delta/20)$

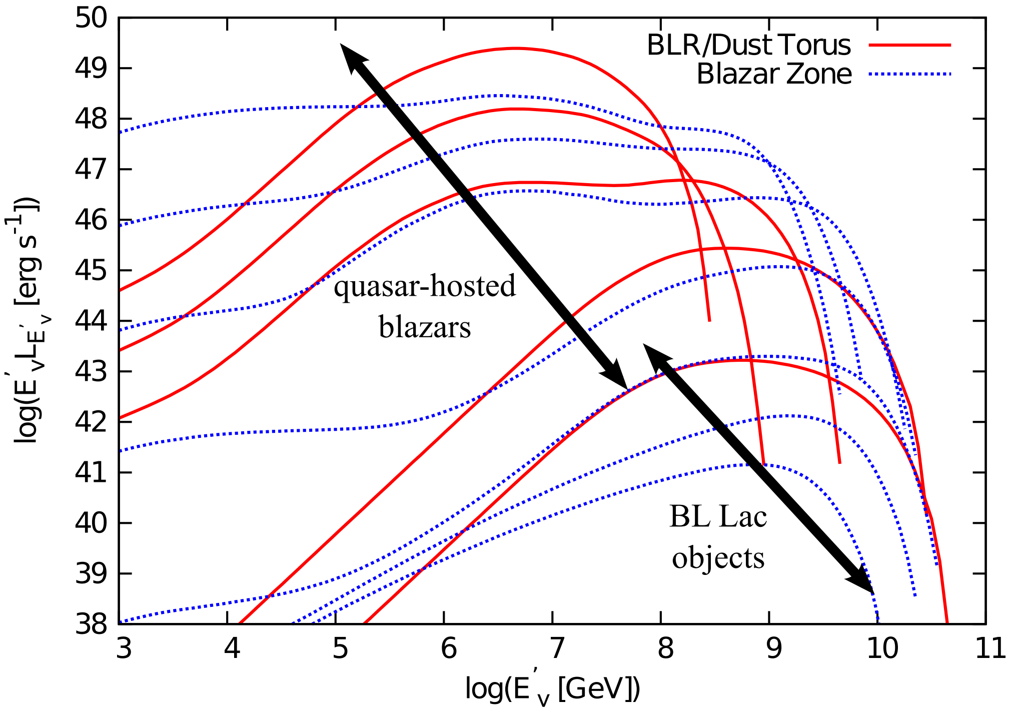
- unlike FSRQs, BL Lacs thought to:
  lack bright external γ fields,
  have low internal sync. γ fields
  -> PeV ν production inefficient?

- one-zone models (e+p co-accel.)
  with internal syn. targets only:
  very high L_p required
  Cerruti, Zech, Boisson, Emery,
  SI, Lenain, 1807.04335

  see also Gao+ 1807.04275



Murase+ 14



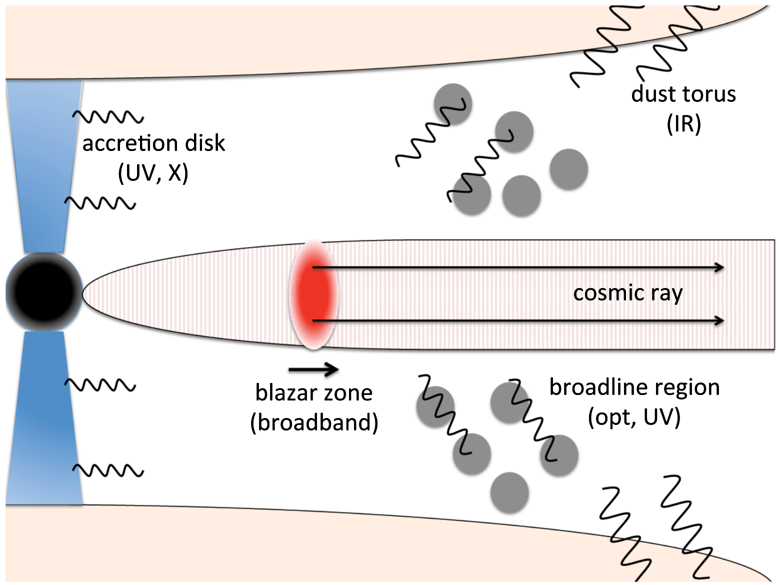
neutrino emission from blazars

- enhanced pγ efficiency via external γ fields in BL Lacs?

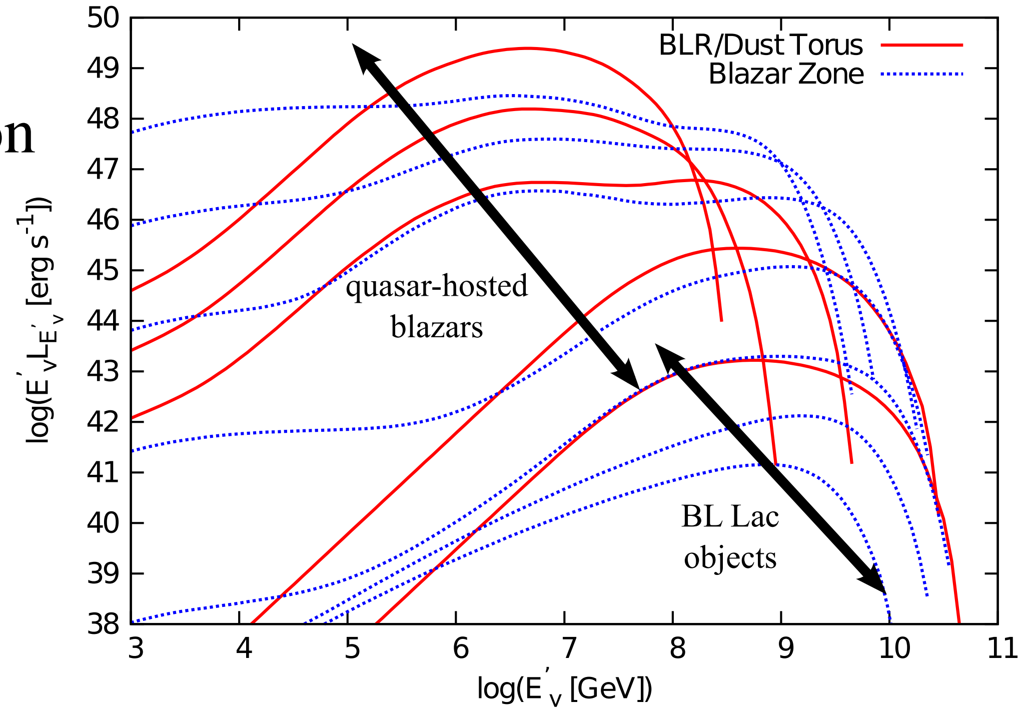
I. sync. from sheath in structured jets MAGIC Coll. 1807.04300

II. radiatively inefficient accretion flows (RIAFs) Righi+ 1807.10506

focus on one-zone models (electron+proton co-accelerated)



Murase+ 14



- questions

1. accompanying hadronic emission consistent with observed SED?
2. accompanying γγ absorption consistent with observed SED?
3. role of external Compton relative to SSC?
4. proton maximum energy (UHECR accelerator)?

3a. pγ scenarios with internal photons only model description

Cerruti, Zech, …
SI+ 1807.04335

leptonic part

- emission region: spherical with radius R, magnetic field B, Doppler factor δ
- electron distribution: broken power-law $\gamma_{e,min}$, $\gamma_{e,max}$, α_{e1},α_{e2}
- leptonic emission: synchrotron, SSC

hadronic part   follow Cerruti+ 15, Zech+ 17

- proton distribution: power-law $\gamma_{p,min}=1$, $\gamma_{p,max}$ (or η), $\alpha_{p1}=\alpha_{e1}$
- hadronic emission

$p+\gamma_{LE}\rightarrow N+\pi^0, \pi^{+-}$ photo-meson   SOPHIA: Mücke+ 02,03

$\pi^{+-}\rightarrow\mu^{+-}+\nu\rightarrow e^{+-}+3\nu$ $\pi^0\rightarrow 2\gamma$

$\mu^{+-}+B\rightarrow\mu^{+-}+\gamma$ muon synchrotron

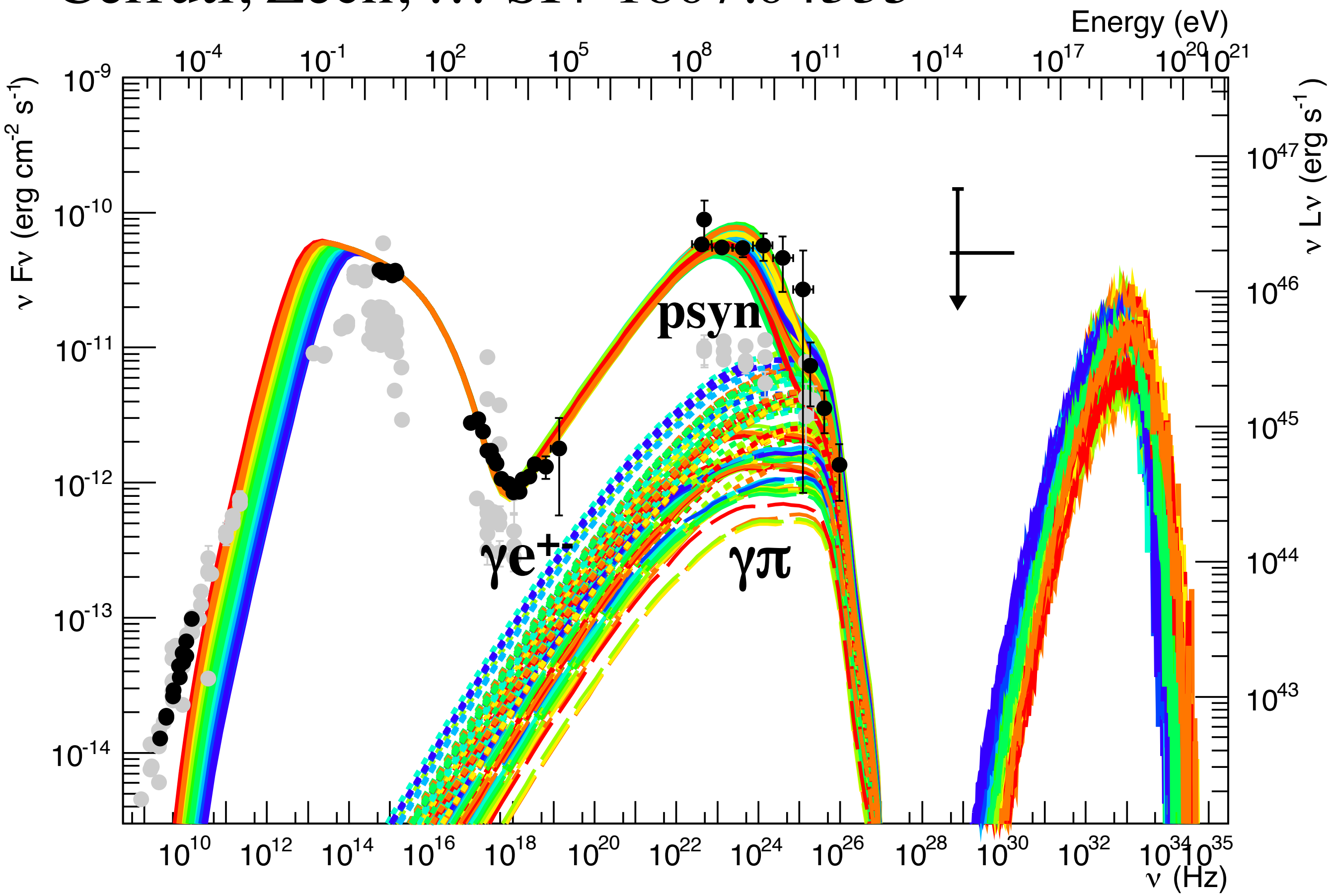
$p+\gamma_{LE}\rightarrow p+e^+e^-$ photo-pair (Bethe-Heitler)   Kelner & Aharonian 08

$\gamma+\gamma_{LE}\rightarrow e^+e^-$
$e^+e^-+B\rightarrow e^+e^-+\gamma$ electron-positron sync. cascade

$p+B\rightarrow p+\gamma$ proton synchrotron

proton sync.-dominant case (+pγ cascade)

Cerruti, Zech, … SI+ 1807.04335

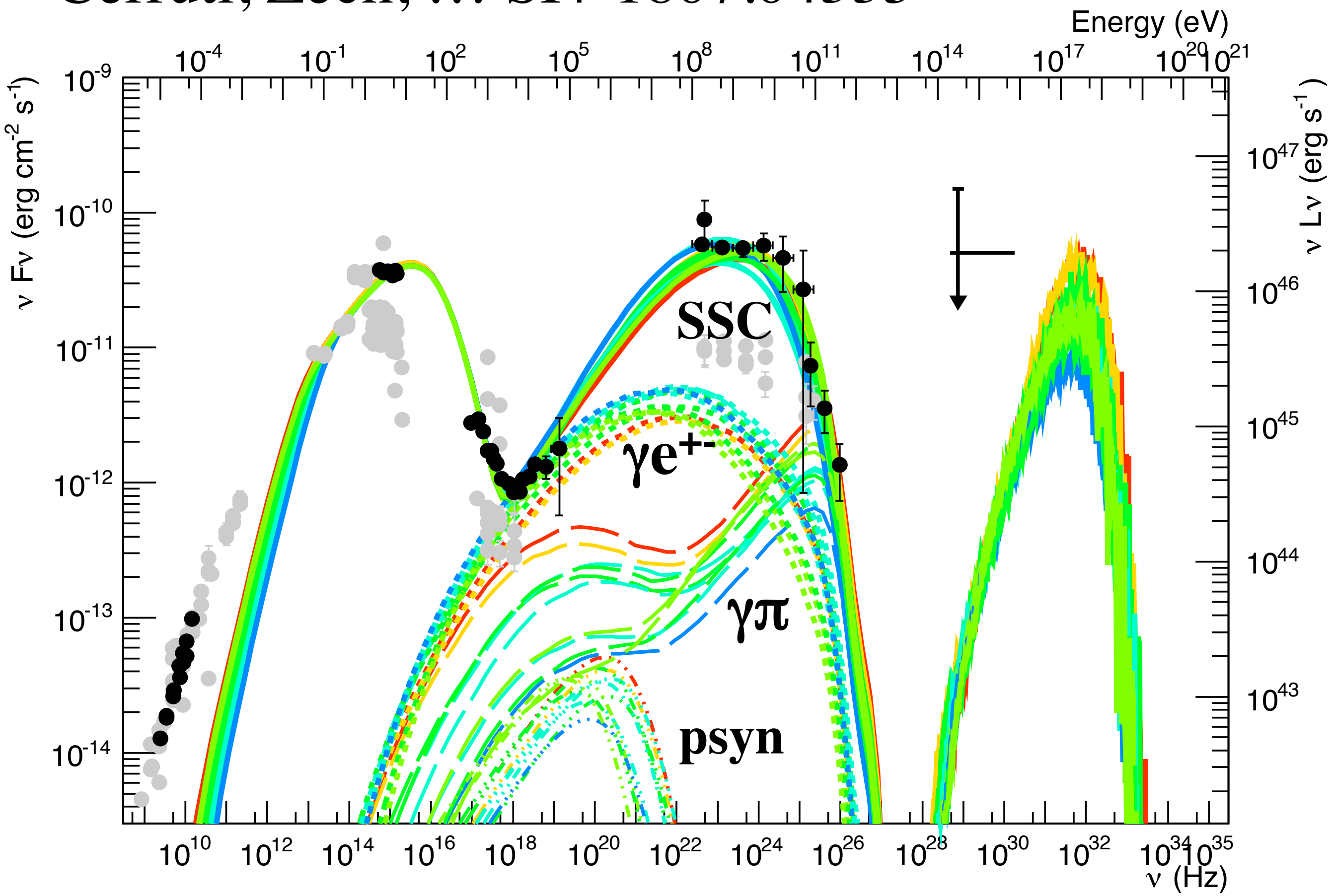


	Proton-synchrotron
z	0.337
δ	35 – 50
R [10^{16} cm]	0.1 – 9.7
$^\star\tau_{\rm obs}$ [days]	0.01 – 1.0
B	0.8 – 32
$^\star u_B$ [erg cm^{-3}]	0.02 – 0.16
$\gamma_{e,\rm min}$	500
$\gamma_{e,\rm break}$	$=\gamma_{e,\rm min}$
$\gamma_{e,\rm max}$ [10^4]	0.6 – 1.0
$\alpha_{e,1}=\alpha_{p,1}$	2.0
$\alpha_{e,2}=\alpha_{p,2}$	3.0
K_e [cm^{-3}]	6.3 – 9.1 $\times 10^3$
$^\star u_e$ [10^{-5} erg cm^{-3}]	0.4 – 15.1
$\gamma_{p,\rm min}$	1
$\gamma_{p,\rm break}$[10^9]	$=\gamma_{p,\rm max}$
$\gamma_{p,\rm max}$[10^9]	0.4 – 2.5
η	20 – 50
K_p [cm^{-3}]	10.4 – 2.0 $\times 10^4$
$^\star u_p$ [erg cm^{-3}]	0.7 – 45
$^\star u_p/u_B$	1.0 – 89
$^\star L$ [10^{46} erg s^{-1}]	0.8 – 170
$^\star\nu$ [year^{-1}]	5.7×10^{-3} – 0.2
$^\star\nu_{183-4300\,\rm TeV}$ [year^{-1}]	2.4×10^{-5} – 1.7×10^{-3}

- EM SED reproduceable with proton synchrotron dominating γ rays, pγ cascade non-negligible at VHE
- BUT neutrino flux too low to be viable
  -> detection of single ν provides crucial discriminant

SSC-dominant case (+pγ cascade)

Cerruti, Zech, … SI+ 1807.04335



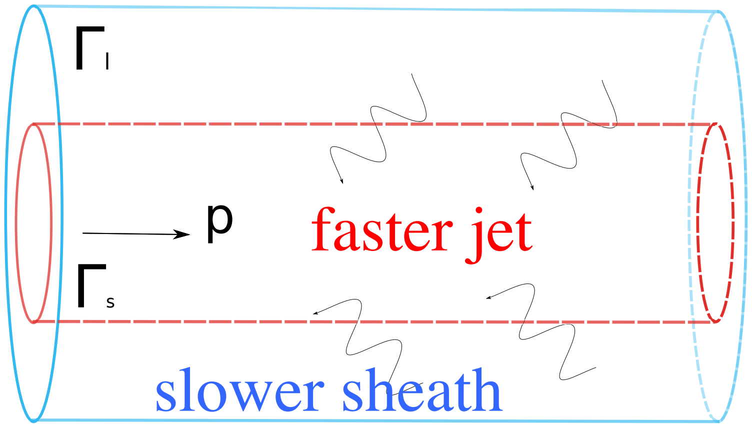
	Lepto-hadronic
z	0.337
δ	30 – 50
R [10^{16} cm]	0.2 – 1.5
$^\star\tau_{\rm obs}$ [days]	0.02 – 0.3
B	0.13 – 0.65
$^\star u_B$ [erg cm^{-3}]	6.5×10^{-4} – 0.017
$\gamma_{e,\rm min}$	500
$\gamma_{e,\rm break}$	$= \gamma_{e,\rm max}$
$\gamma_{e,\rm max}$ [10^4]	0.8 – 1.7
$\alpha_{e,1} = \alpha_{p,1}$	2.0
$\alpha_{e,2} = \alpha_{p,2}$	3.0
K_e [cm^{-3}]	$9.5 \times 10^3 - 2.6 \times 10^5$
$^\star u_e$ [10^{-5} erg cm^{-3}]	$2.2 \times 10^3 - 43 \times 10^3$
$\gamma_{p,\rm min}$	1
$\gamma_{p,\rm break}$[10^9]	$= \gamma_{p,\rm max}$
$\gamma_{p,\rm max}$[10^9]	0.06 – 0.2
η	10
K_p [cm^{-3}]	$3.5 \times 10^3 - 6.6 \times 10^4$
$^\star u_p$ [erg cm^{-3}]	100 – 1400
$^\star u_p/u_B$	$3.9 \times 10^4 - 79 \times 10^4$
$^\star L$ [10^{46} erg s^{-1}]	35 – 350
$^\star\nu$ [year^{-1}]	0.11 – 3.0
$^\star\nu_{183-4300\,\rm TeV}$ [year^{-1}]	0.008 – 0.11

- EM SED reproduceable with SSC dominating γ rays, non-neglible: pγ cascade at VHE, BH at X-ray
- BUT requires rather extreme parameters, e.g. $L_p \sim 10^{48}$ erg/s, $\gamma_{e,min} \sim 500$
- hard ν spectra also constrained by IC point source search
  -> scenarios with external photons likely more favorable

3b. pγ scenarios with “external” photons from jet sheath

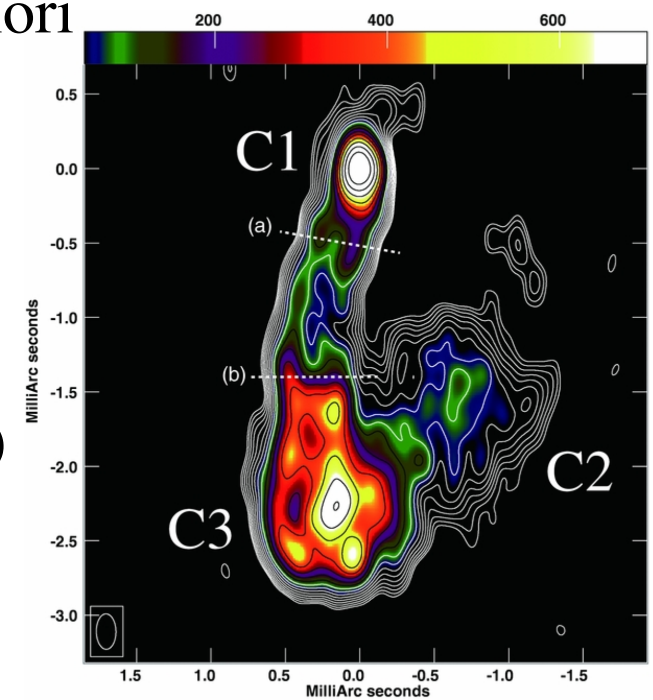
- jet structure with slower sheath (layer) surrounding faster jet (spine)
  -> supported by observations, numerical simulations
- synchrotron photons from sheath seen Doppler boosted in jet frame
  -> enhanced target for pγ ν production, EC
- caveat: spectrum of sheath radiation not well defined a-priori

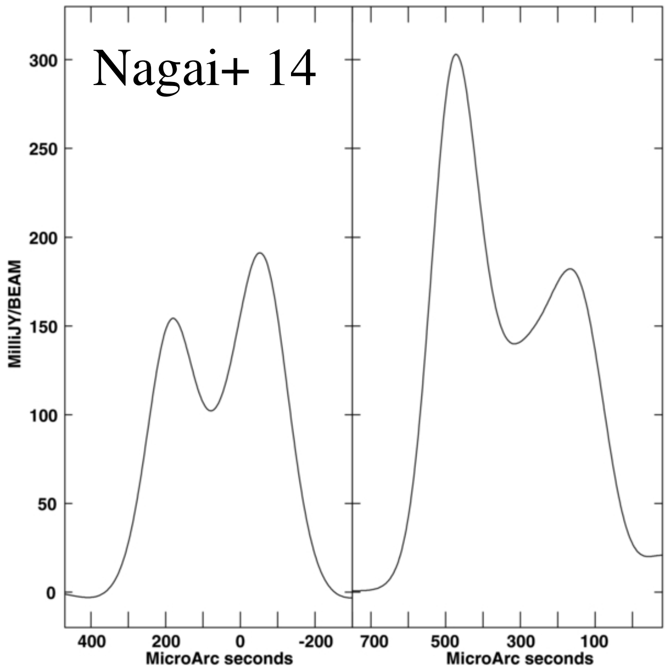
MAGIC Coll. 1807.04300



c.f. Tavecchio+ 14, 15
Righi & Tavecchio 17

limb-brightened structure in radio galaxies
e.g. 3C84 (NGC 1275)





jet-sheath model description

MAGIC Coll. 1807.04300

leptonic part   follow Tavecchio+ 14, 15

- emission region: cylindrical with radius R, length dR=R,
  magnetic field B, Lorentz factor Γ_j, viewing angle θ_v
- electron distribution: broken power-law $E_{e,min}$, $E_{e,br}$, $E_{e,max}$, s_1,s_2
- photons from sheath with Lorentz factor Γ_s, broken power-law spectrum
- leptonic emission: synchrotron, SSC, EC

hadronic part   follow Böttcher+ 13, Cerruti+ 15

- proton distribution: power-law E_p^{-2} with exp. cutoff E_{pmax}
- hadronic emission

$p+\gamma_{LE}\rightarrow N+\pi^0, \pi^{+-}$ photo-meson

$\pi^{+-}\rightarrow\mu^{+-}+\nu\rightarrow e^{+-}+3\nu$ $\pi^0\rightarrow 2\gamma$

$\mu^{+-}+B\rightarrow\mu^{+-}+\gamma$ muon synchrotron

Kelner & Aharonian 08

$p+\gamma_{LE}\rightarrow p+e^+e^-$ photo-pair (Bethe-Heitler)

$\gamma+\gamma_{LE}\rightarrow e^+e^-$

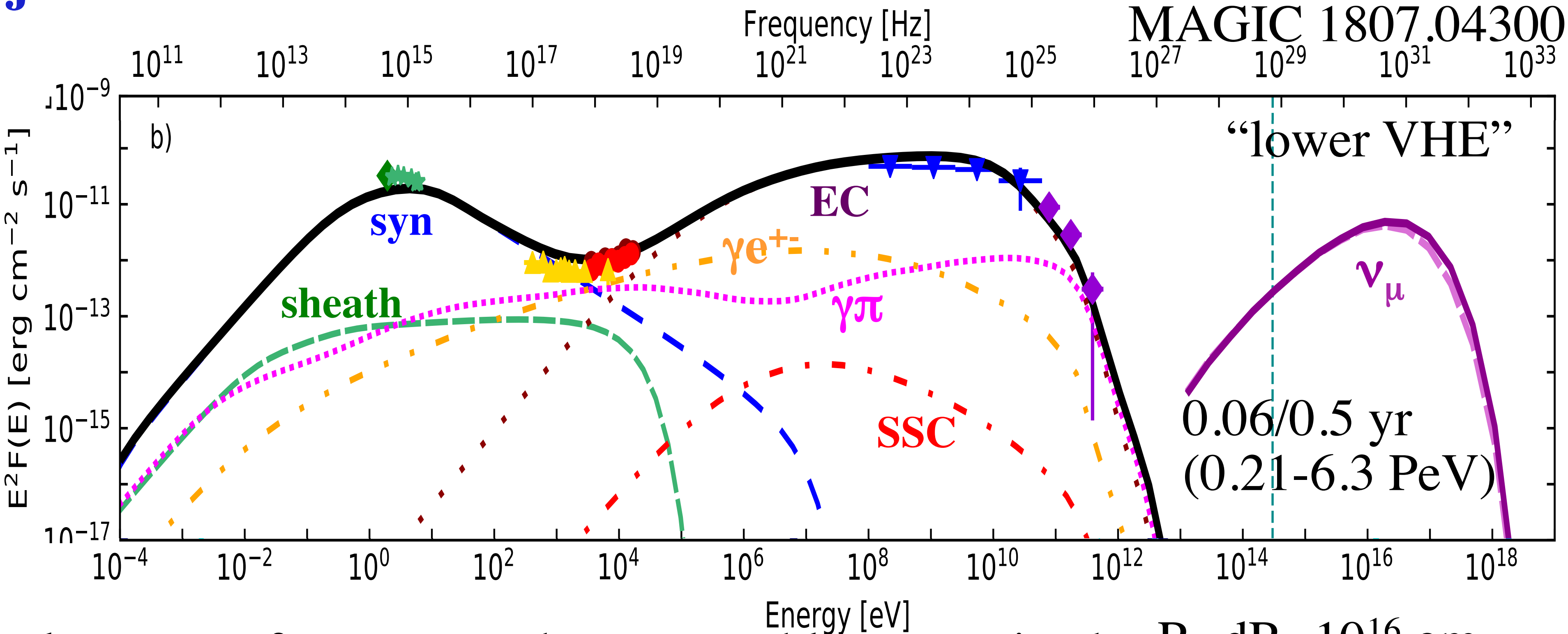
$e^+e^-+B\rightarrow e^+e^-+\gamma$

electron-positron sync. cascade

$p+B\rightarrow p+\gamma$ proton synchrotron

jet-sheath model for electroweak emission

MAGIC 1807.04300

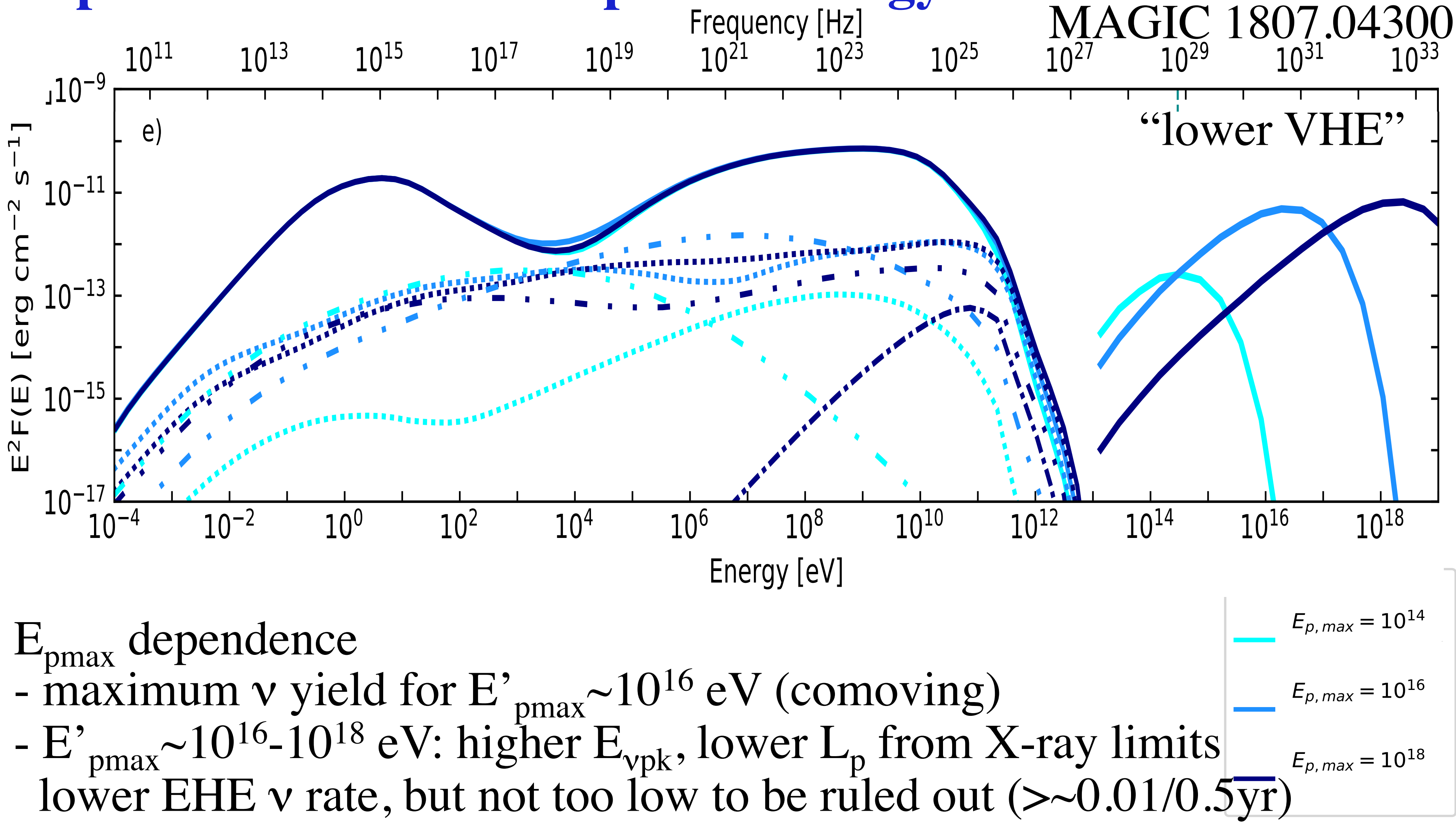


- large no. of parameters but reasonably constrained
- SED predominantly leptonic, γ-rays EC (not SSC)
- photopion+photopair cascade subdominant but non-negligible in X (+VHE)
  -> crucial constraint on proton population
- photopion efficiency $f_{p\gamma}(E_p \sim 6\ \text{PeV}) \sim 10^{-4}$
  -> $\tau_{\gamma\gamma}(E_\gamma \sim 12\ \text{GeV}) \sim 0.1$ -> $\tau_{\gamma\gamma}(E_\gamma \sim 100\ \text{GeV}) \sim 1$
  consistent with observed GeV-TeV break

$R = dR = 10^{16}$ cm
$B = 2.6$ G
$\Gamma_j = 22$, $\Gamma_s = 2.2$
$\theta_v = 0.8°(\delta_j = 40)$
$E'_{pmax} = 10^{16}$ eV
$L_e = 1.6 \times 10^{42}$ erg/s
$L_p = 3 \times 10^{45}$ erg/s(?)
($L_B = 1.2 \times 10^{45}$ erg/s)

implications: maximum proton energy

MAGIC 1807.04300



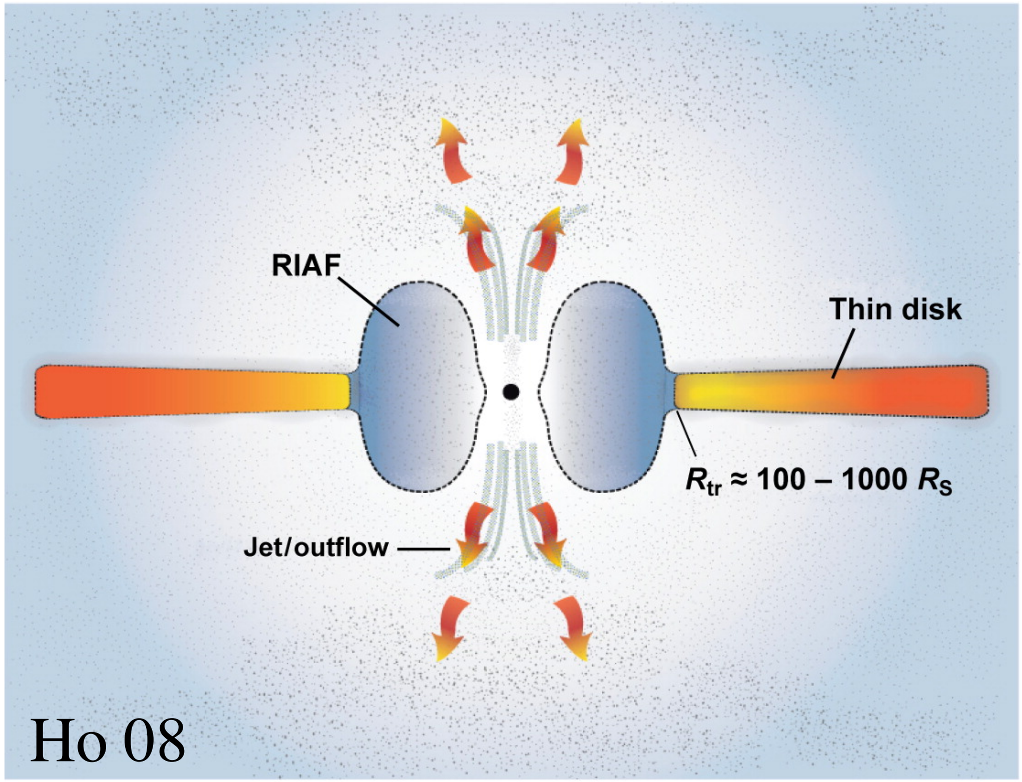
E_{pmax} dependence

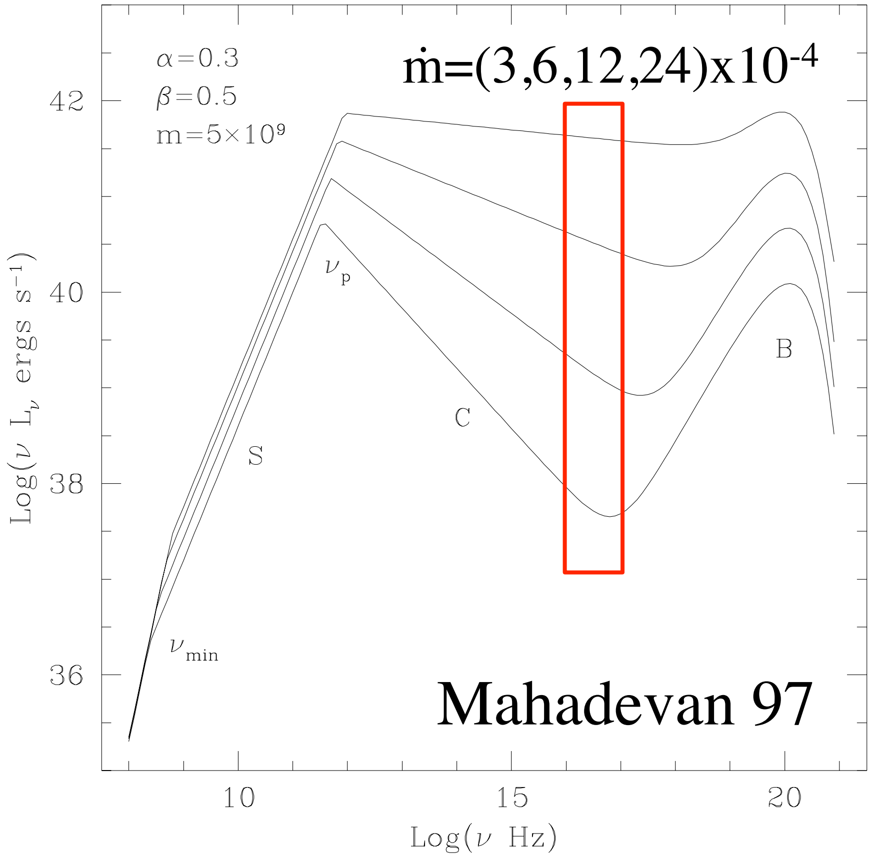
- maximum ν yield for E'_{pmax}~10^{16} eV (comoving)
- E'_{pmax}~10^{16}-10^{18} eV: higher $E_{\nu pk}$, lower L_p from X-ray limits
  lower EHE ν rate, but not too low to be ruled out (>~0.01/0.5yr)
  (simultaneously PS ν not too high, ~<0.05/0.5yr)
  -> unclear whether UHECR accelerator or not

3c. pγ scenarios with external photons from RIAFs

radiatively inefficient accretion flows

- expected at low accretion rates ($\dot{m}=\dot{M}/\dot{M}_{Edd}$~<0.01), inferred for SMBHs hosting BL Lacs
- radiatively inefficient -> hot, geometrically thick, optically thin <-> standard accretion disk for high $\dot{m}$
- broadband spectrum from radio to X-rays
- strong dependence of UV-soft X intensity on $\dot{m}$

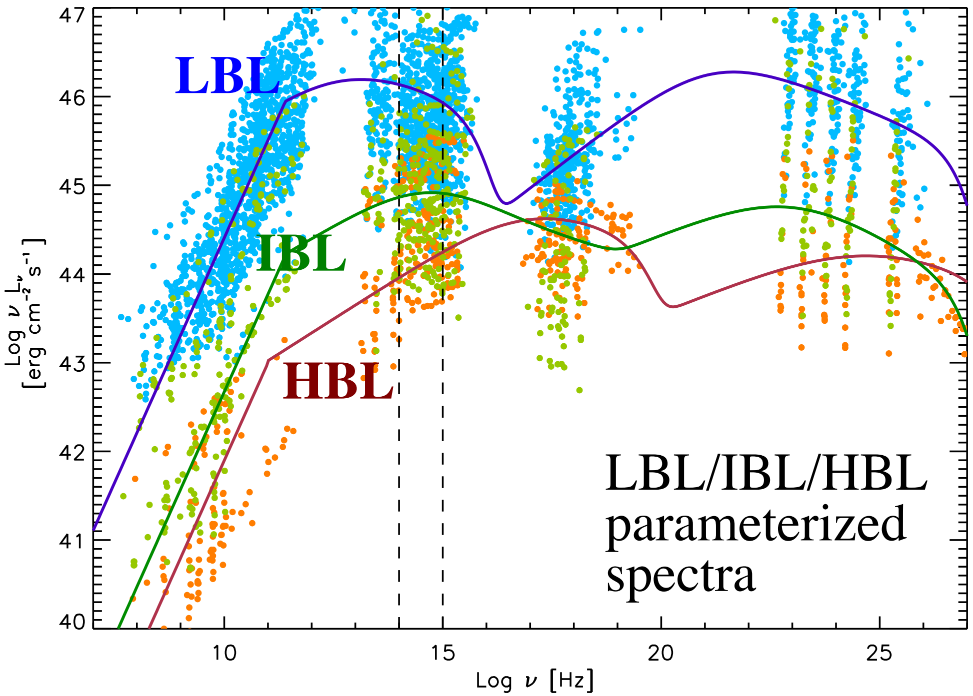


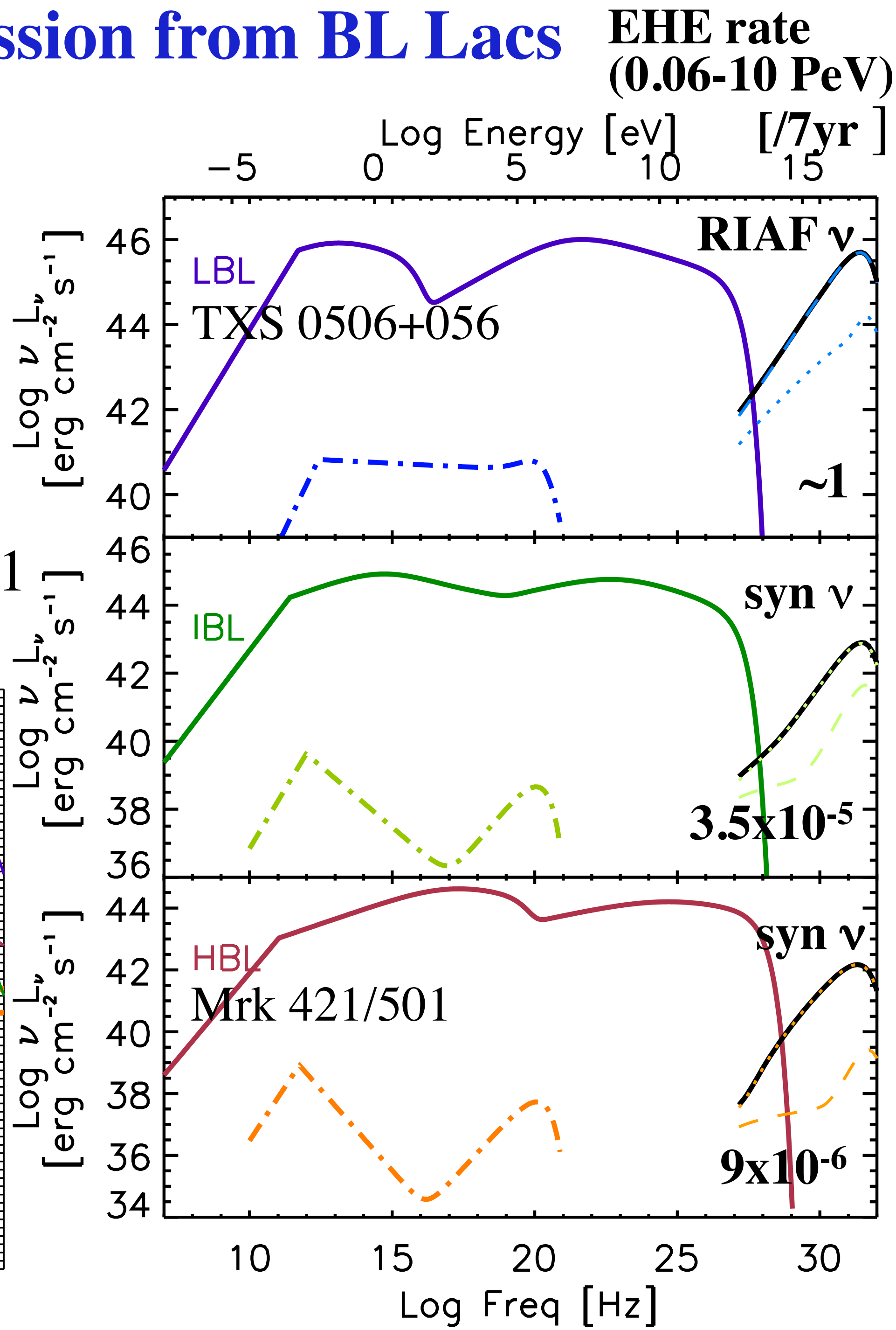


RIAF model for neutrino emission from BL Lacs

Righi, Tavecchio, SI 1807.10506

- plausible relation between P_{jet} and $\dot{m}$ of central SMBH among LBL/IBL/HBL subclasses
- RIAF model spectra well-defined
- effective pγ target only for LBLs
  -> potential explanation for why TXS 0506+056, not Mrk 421/501
- hadronic γ modeling to be done

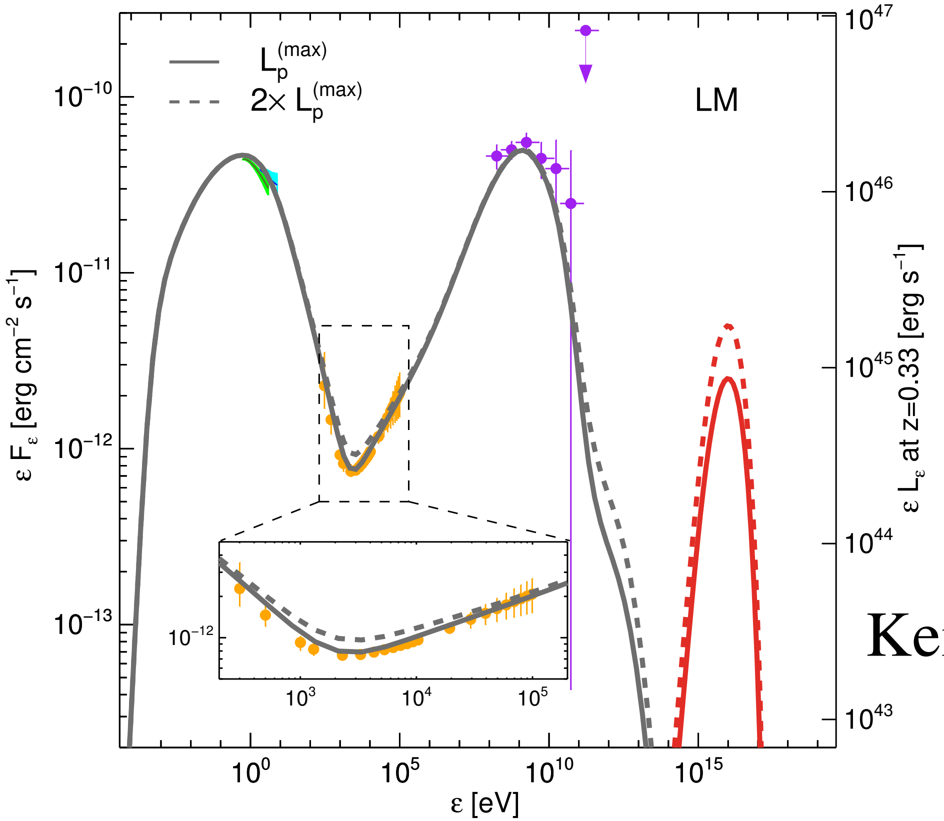


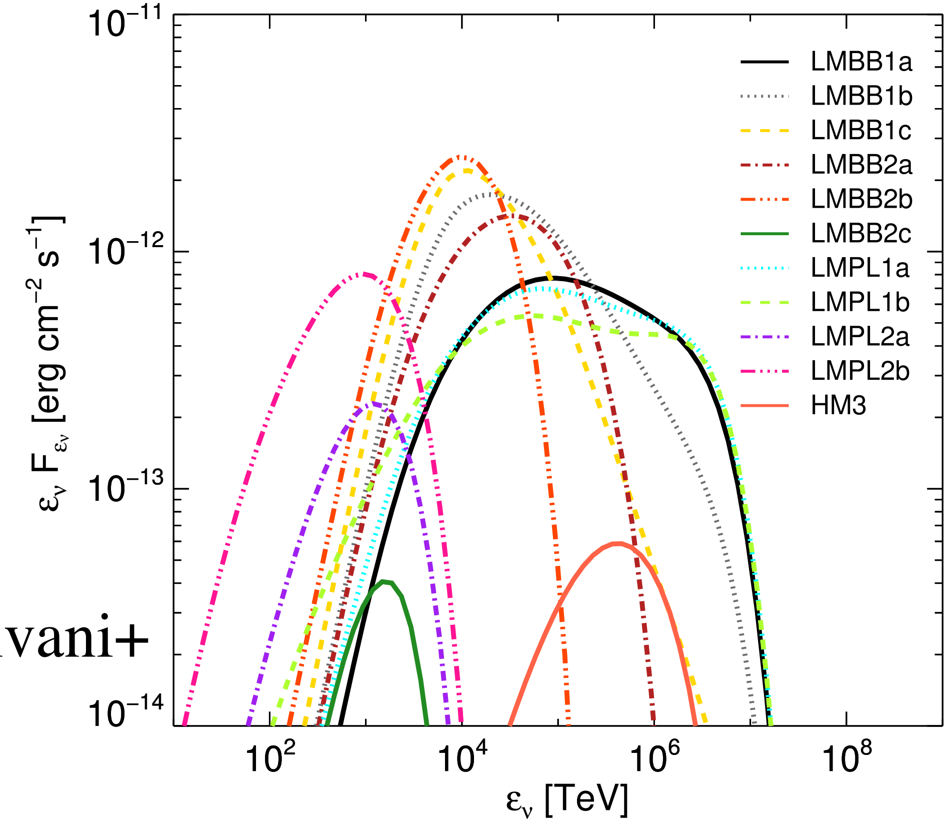


3d. brief comparison with other work

Keivani, Murase, Petropoulou+ 1807.04537

- generic internal/external photon scenarios
- hadronic-dominant scenarios difficult, likely leptonic-dominant
- X-ray cascade constraints, γ-ray absorption constraints crucial
- EHE rate <0.01/yr -> 1-zone models severely constrained if not ruled out



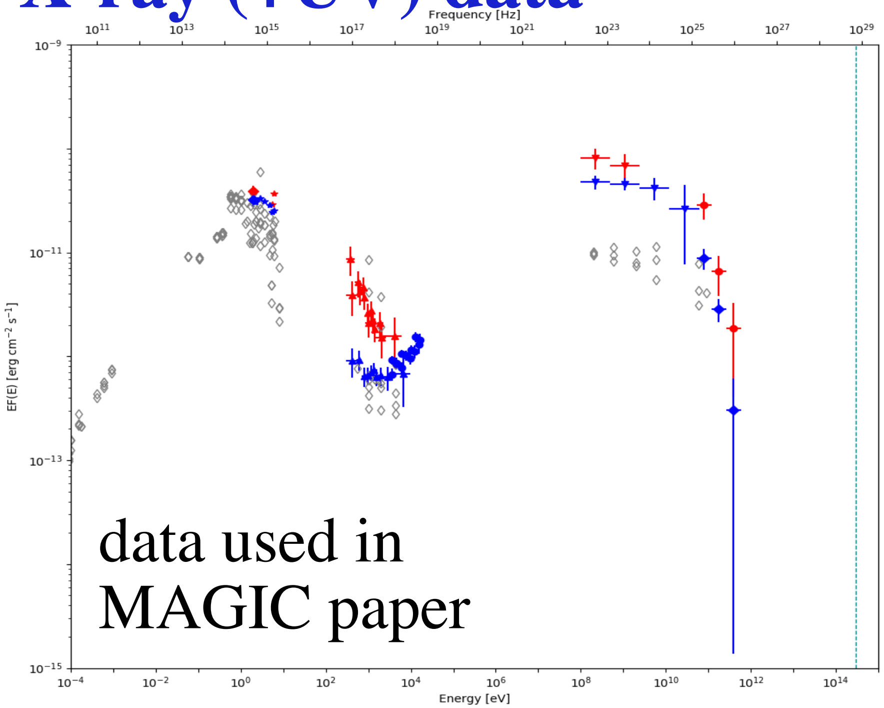


Keivani+

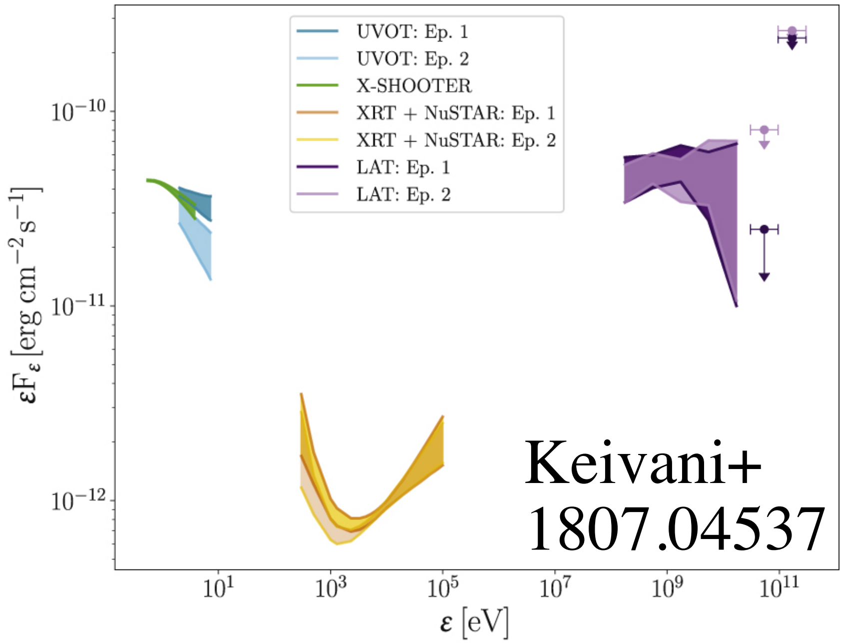
<u>notable differences</u>

- choice of data set: different X-ray + UV, no VHE
- degree of optimism (~personal preference)

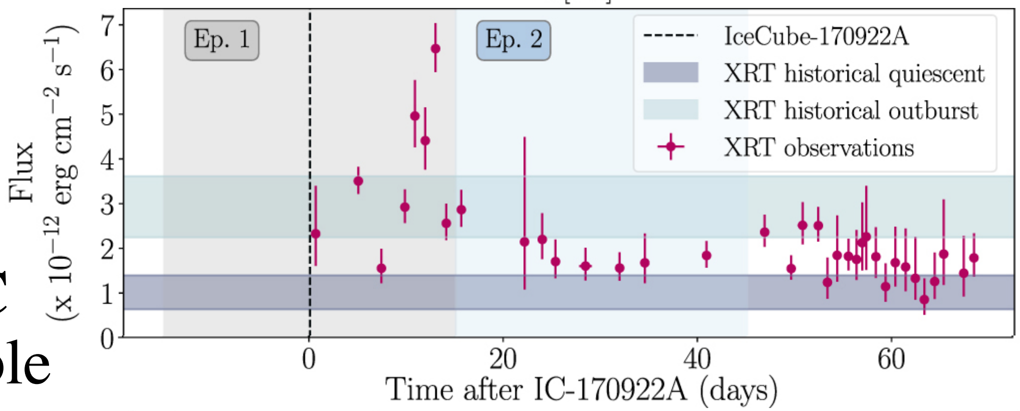
X-ray (+UV) data

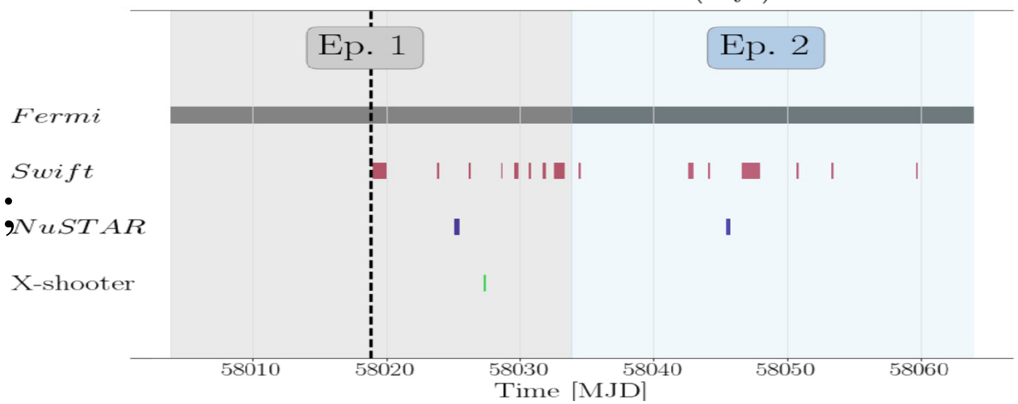


data used in MAGIC paper



Keivani+ 1807.04537





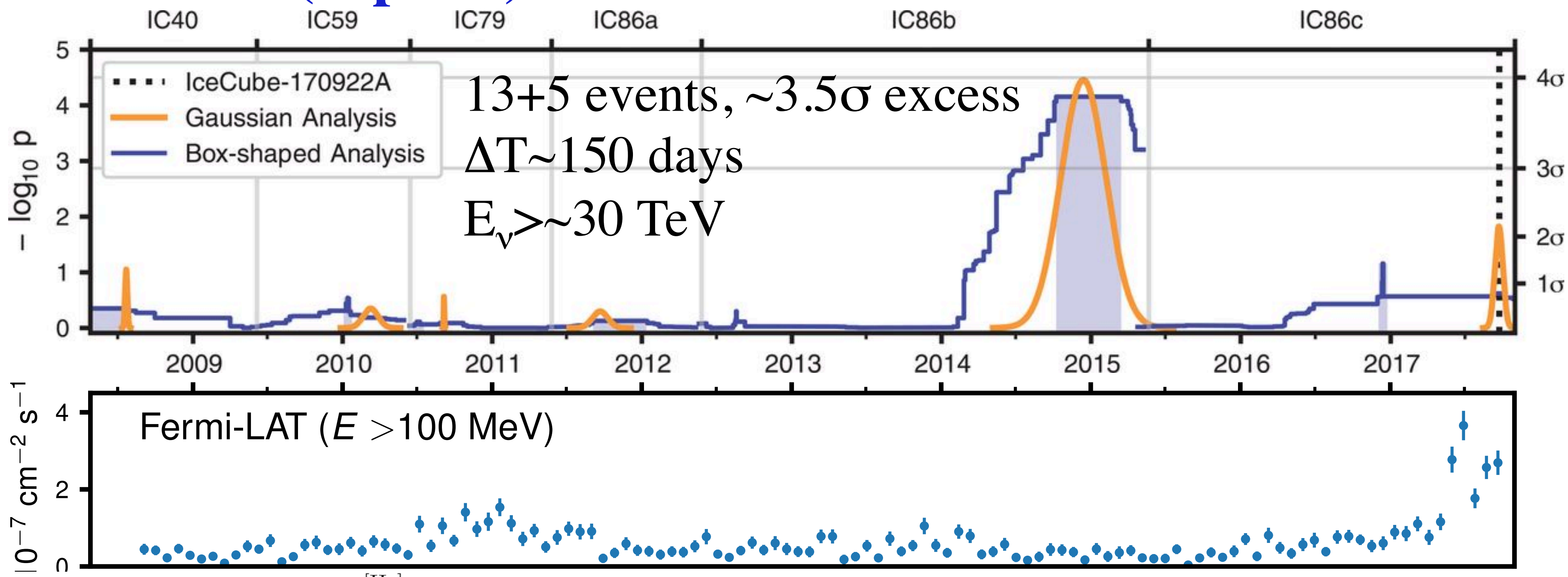
MAGIC Coll.: select only X data quasi-simultaneous with MAGIC

Keivani+: average over all available X data

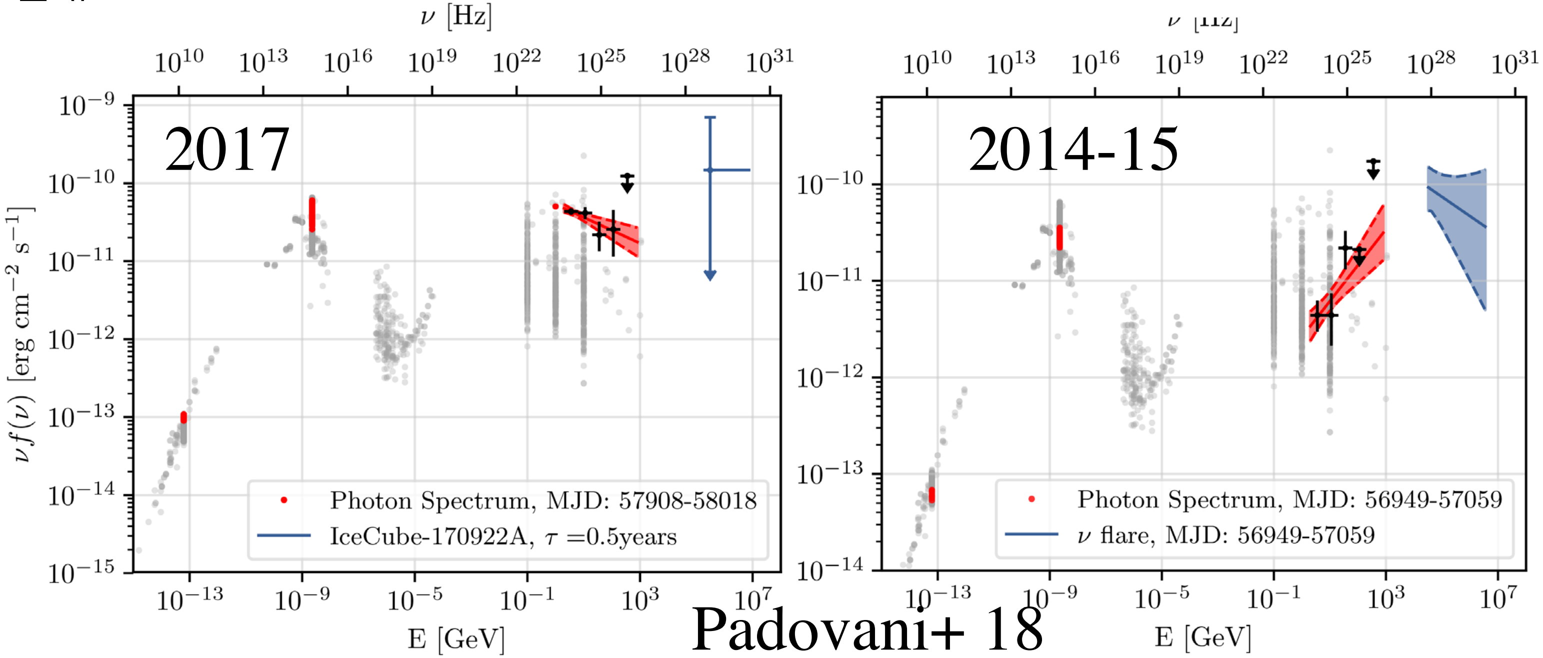
time coverage sparse, no strong reason to prefer one over the other; choice of data set subjective (~personal preference)

2014-2015 (orphan) neutrino flare

IceCube, 2018, Sci. 361, 147



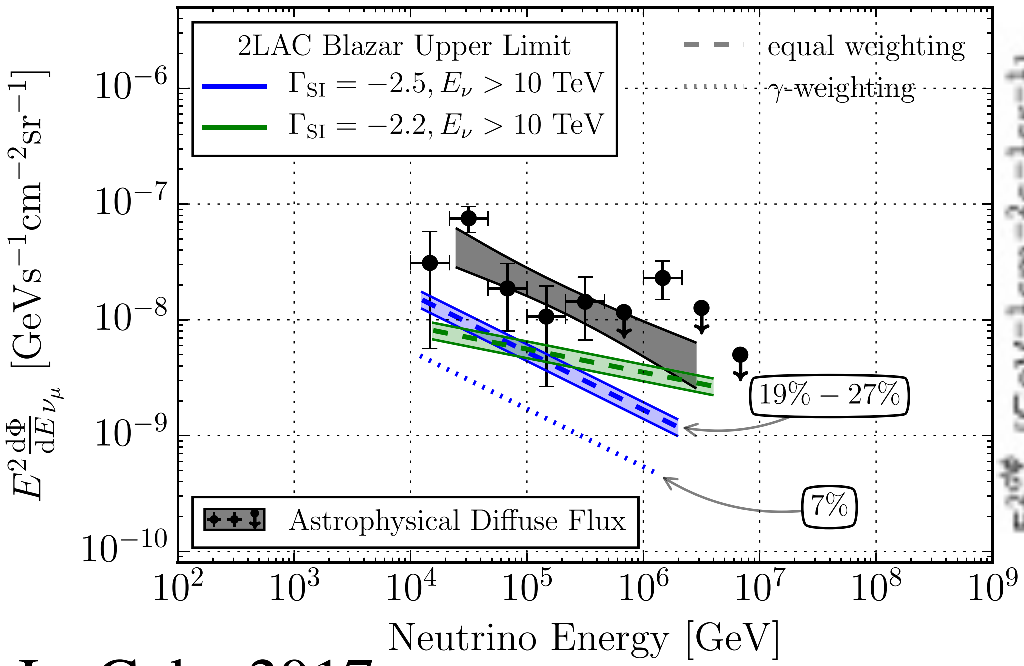
13+5 events, ~3.5σ excess
ΔT~150 days
E_ν>~30 TeV



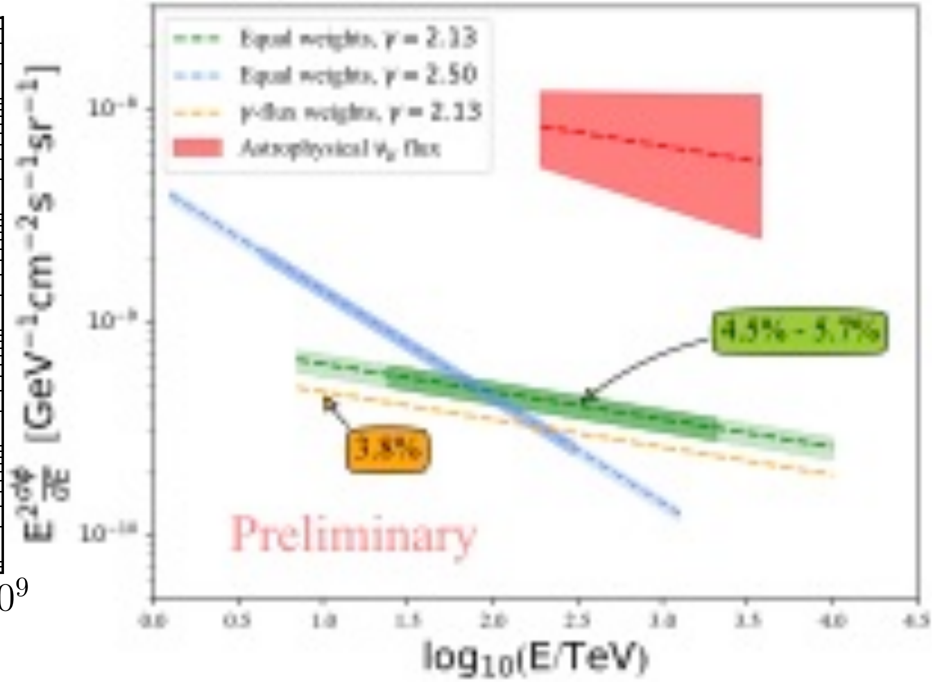
Padovani+ 18

viable interpretation via pp? modeling ongoing, stay tuned

diffuse high-energy neutrinos: constraints on blazar contribution



IceCube 2017



IceCube, ICRC 2017

2LAC: blazar contribution <7-27% of diffuse ν flux
2FHL: blazar contribution <4-6% of diffuse ν flux

blazars strongly constrained as main sources of diffuse HE ν

see however Palladino+ 1806.04769

summary electroweak observations/interpretation of TXS 0506+056

observations

- IceCube: detection of ~300 TeV neutrino, high signalness, well localized
- Fermi-LAT: bright BL Lac TXS 0506+056 associated at 3σ CL
- MAGIC: <1 day variability, steep spectrum above ~100 GeV

interpretation via pγ scenarios, one zone (e+p co-accelerated)

- internal target photons only: challenged by required high proton power
- "external" photons from jet sheath: plausible & consistent
  - observed SED predominantly leptonic (sync.+external Compton)
  - hadronic subdominant, critically constrained by X-ray (+VHE)
  - GeV-TeV break consistent with γγ absorption entailed by pγ production of ~300 TeV neutrino
  - proton max energy ~<10^{18} eV (comoving) possible in principle but not well constrained -> may or may not be UHECR accelerator
- external photons from RIAFs: also promising but only for LBLs -> potential explanation for why TXS 0506+056 and not HBLs
- addition of single neutrino to MWL SED provides crucial new insight

dawn(?) of electroweak astronomy

summary electroweak observations/interpretation of TXS 0506+056

questions

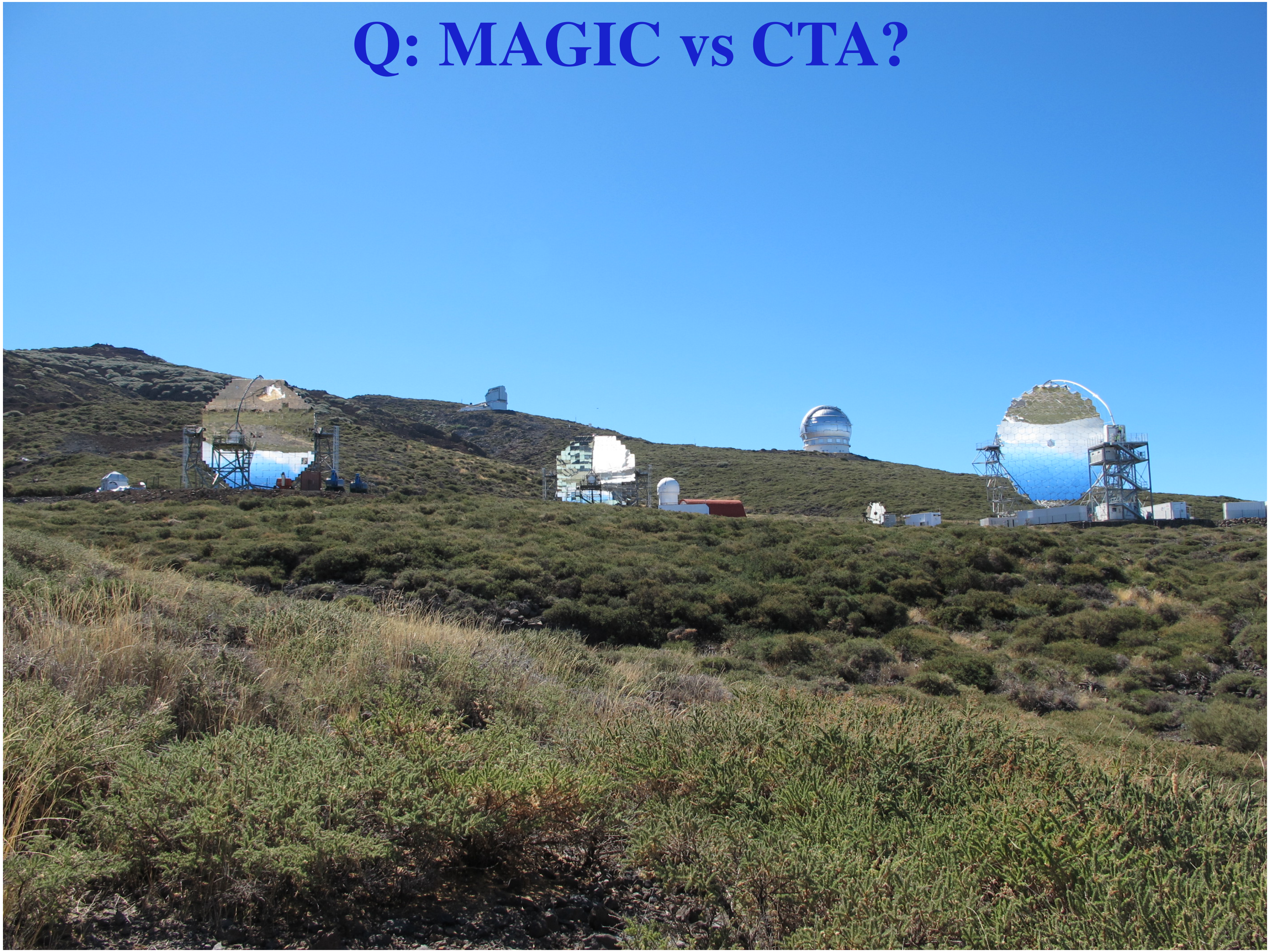
- relation to other blazars: why TXS 0506+056 and not HBLs, FSRQs?
- origin of 2014-2015 neutrino flare during low gamma-ray state (if real)
- contribution to diffuse flux, origin of dominant source(s)

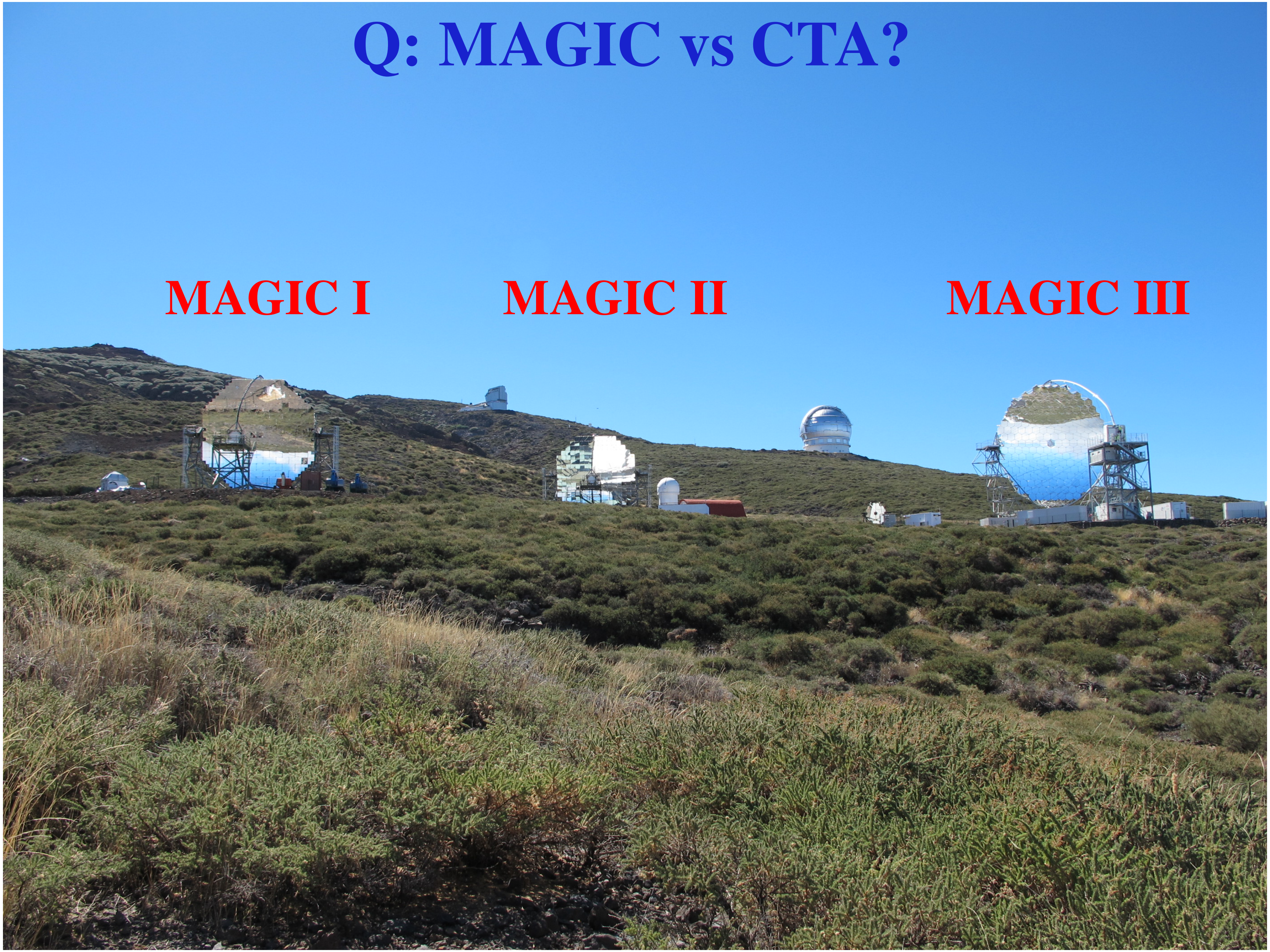
…

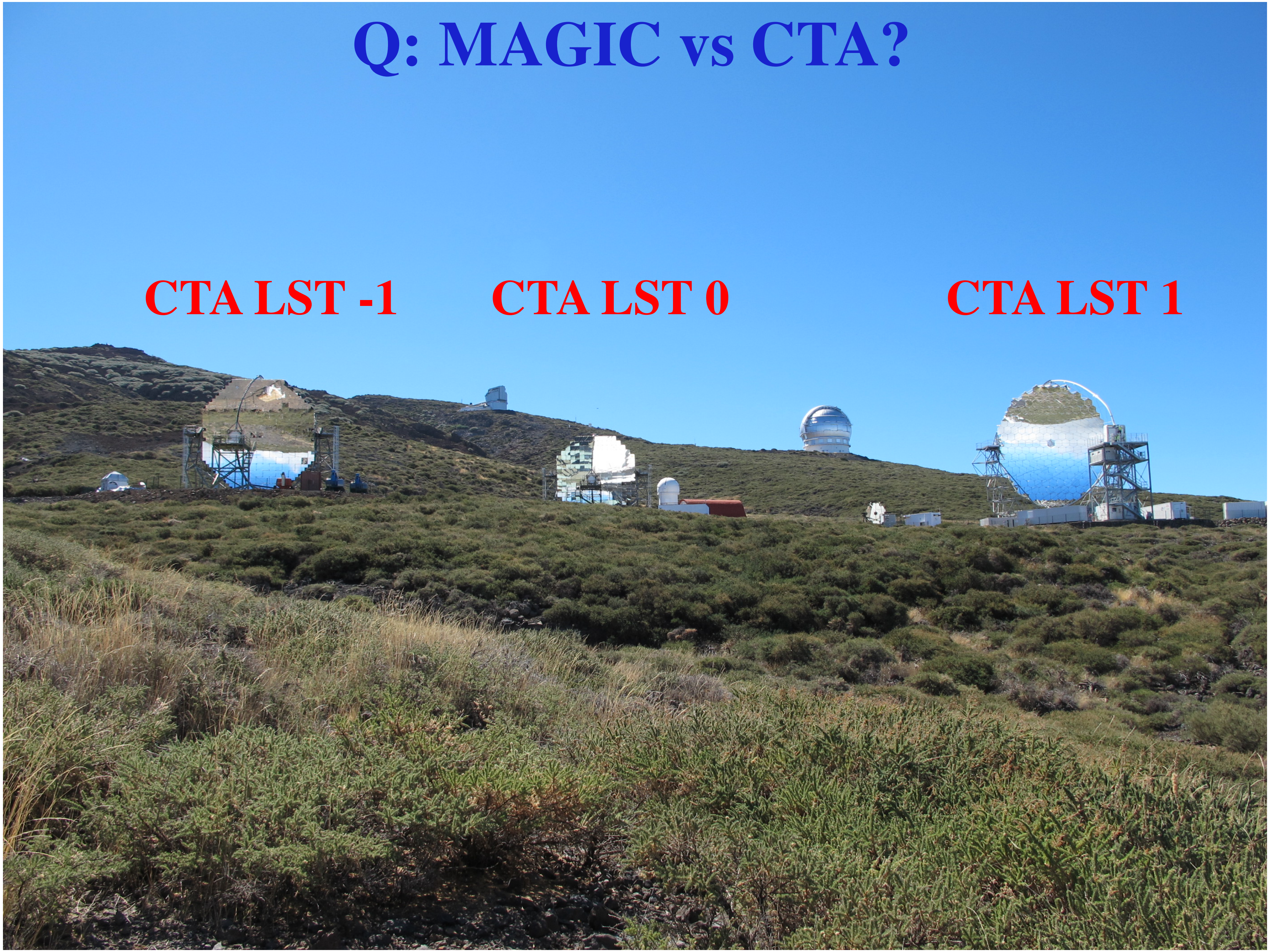
future

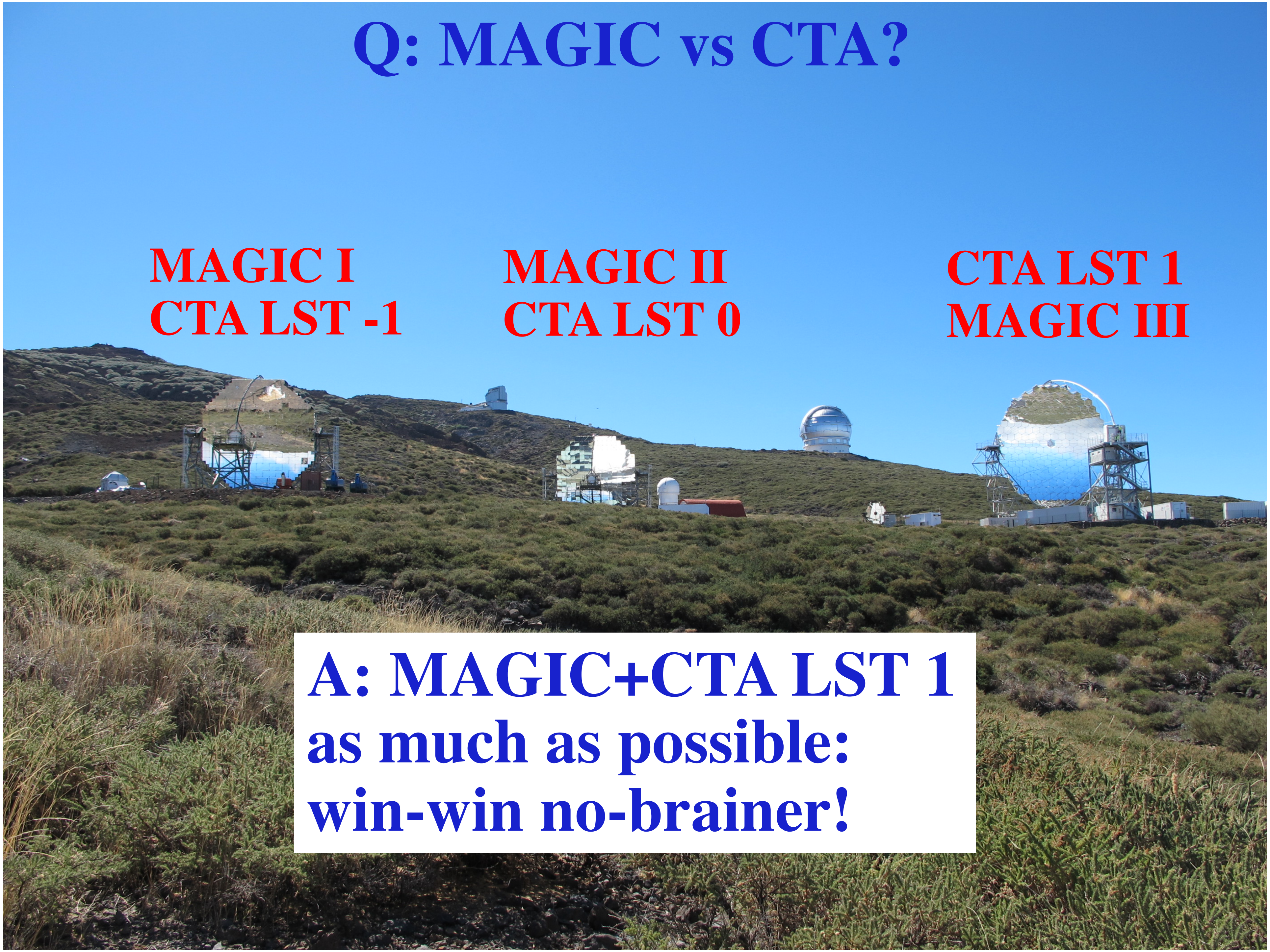
- more neutrino+EM observations necessary, especially:
  - X-rays for constraining cascade emission
  - VHE for constraining pγ target density via γγ absorption -> CTA
- more comprehensive modeling
- the game has just begun, further exciting times ahead!

Q: MAGIC vs CTA?




Q: MAGIC vs CTA?
MAGIC I
MAGIC II
MAGIC III


Q: MAGIC vs CTA?
CTA LST -1
CTA LST 0
CTA LST 1


Q: MAGIC vs CTA?
MAGIC I
CTA LST -1
MAGIC II
CTA LST 0
CTA LST 1
MAGIC III
A: MAGIC+CTA LST 1
as much as possible:
win-win no-brainer!