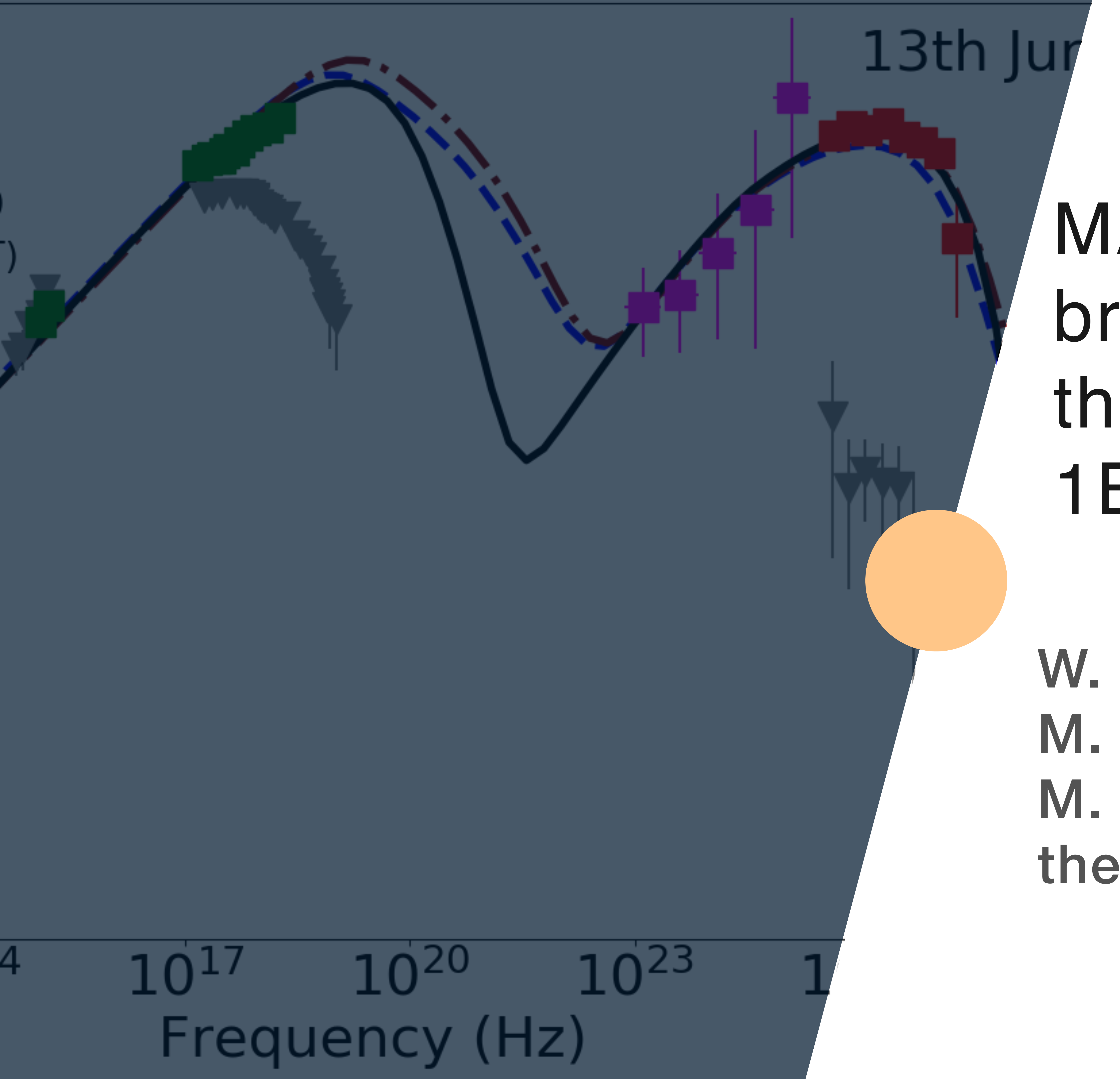


MAGIC observation and broadband characterization of the remarkably bright flares of 1ES 1959+650 in 2016

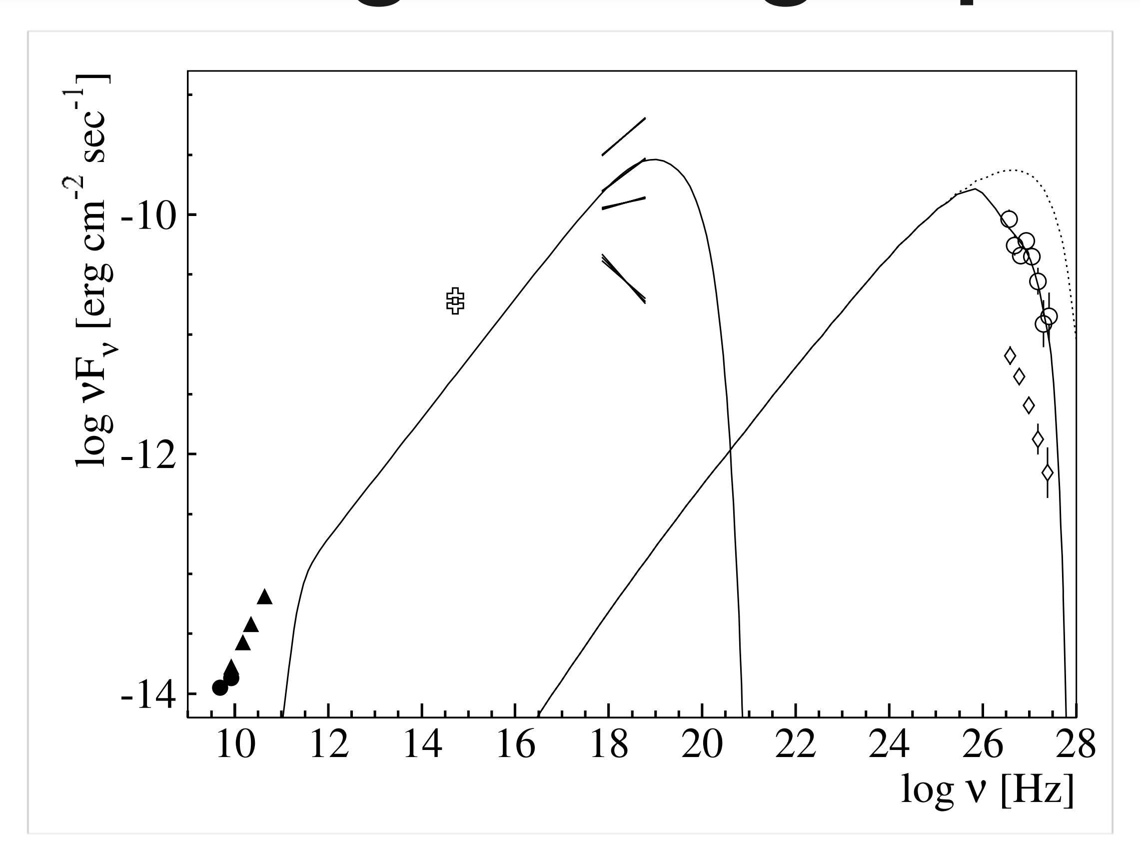
W. Bhattacharyya (DESY),
M. Takahashi* (ICRR) and
M. Hayashida (Rikkyo U.) on behalf of
the MAGIC and Fermi-LAT collaboration

TeV BLAZAR 1ES 1959+650

- ✦ Well-known TeV blazar
- ✦ High-frequency-peaked BL Lac object (HBL)
- ✦ Redshift z=0.048
- ✦ Features challenging for simple one-zone SSC* scenario
  - “orphan” flares
    - γ-ray flare without X-ray counterpart
  - hint of high-energy neutrino emission with AMANDA [Halzen & Hooper 05]
    - although not significant

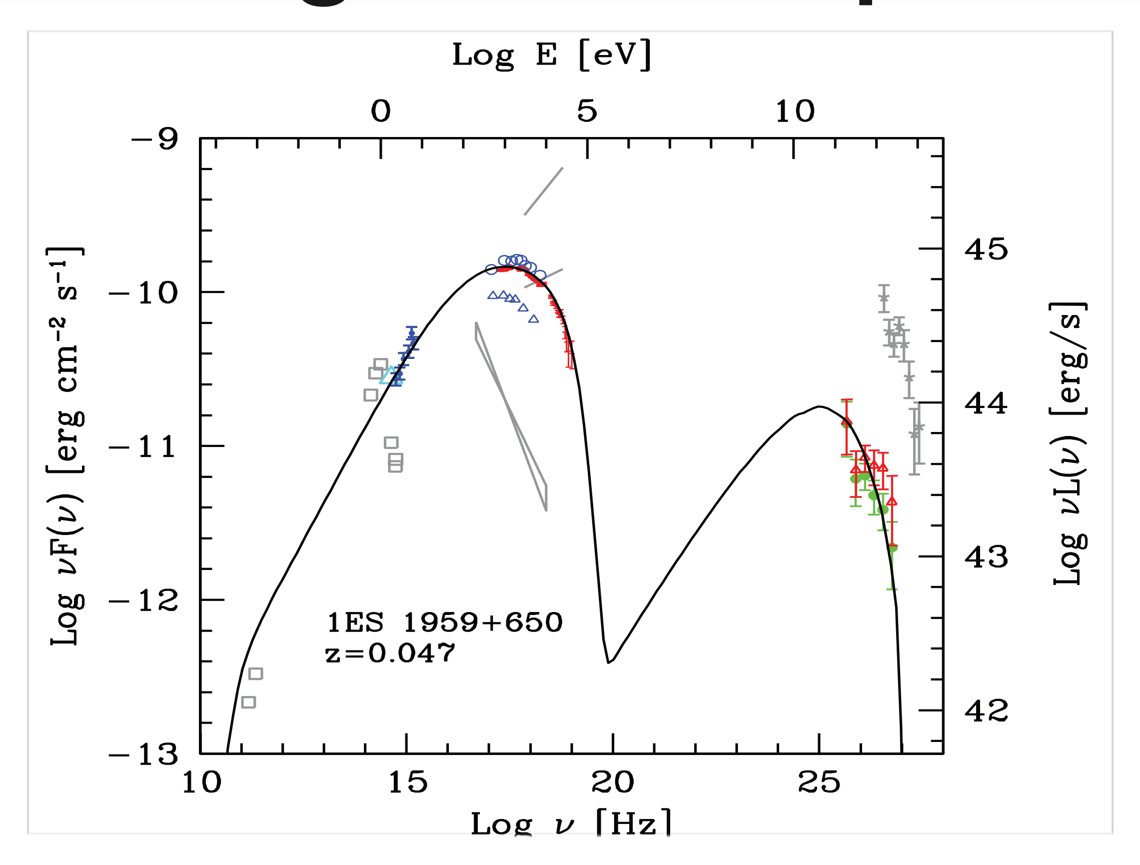
* SSC: synchrotron self-Compton

● high-X/high-γ



[Krawczynski+ 04]

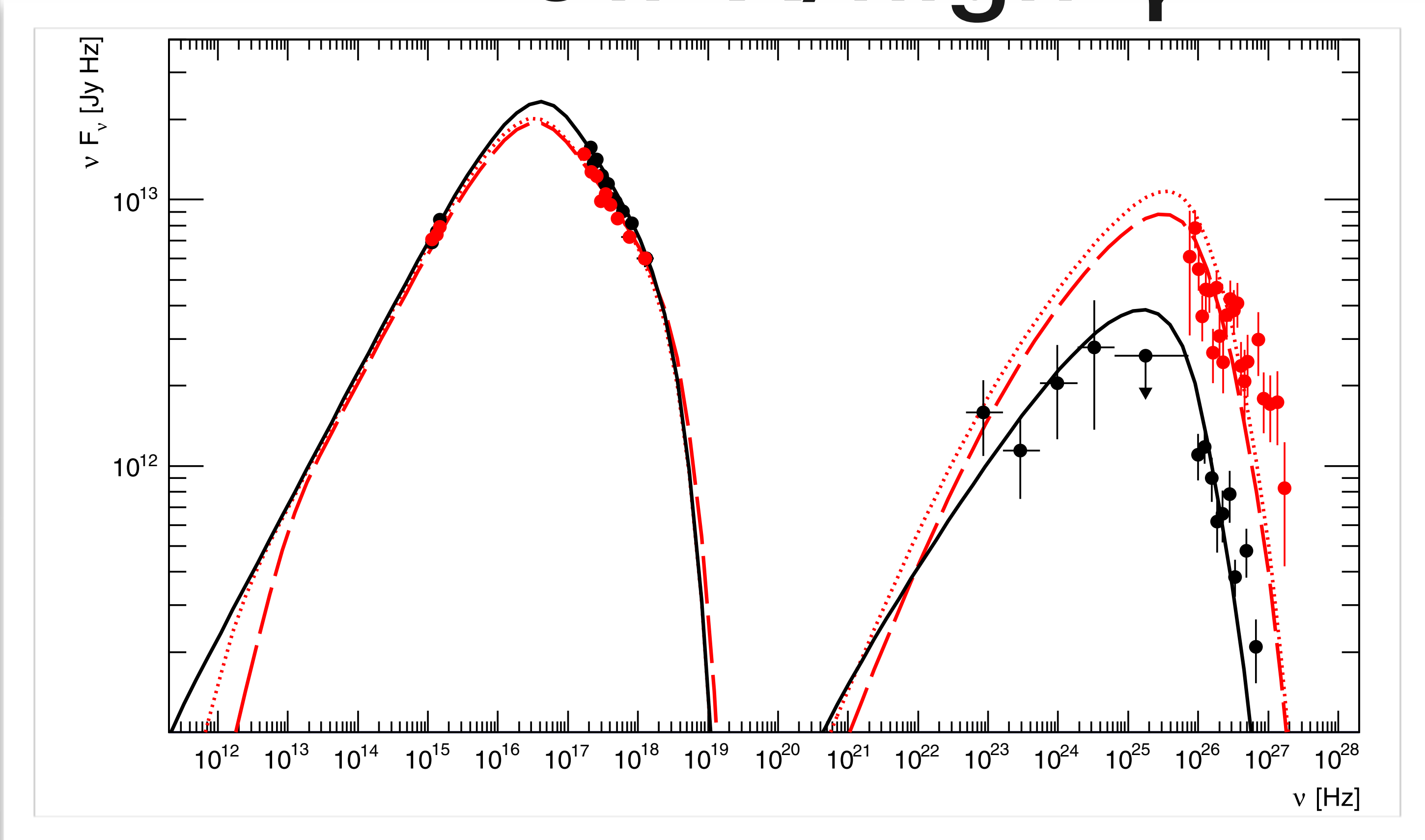
● high-X/low-γ



[Tagliaferri+ 08]

Variety of flaring activities

● low-X/high-γ



[Aliu+ 04]

INSTRUMENTS

MAGIC

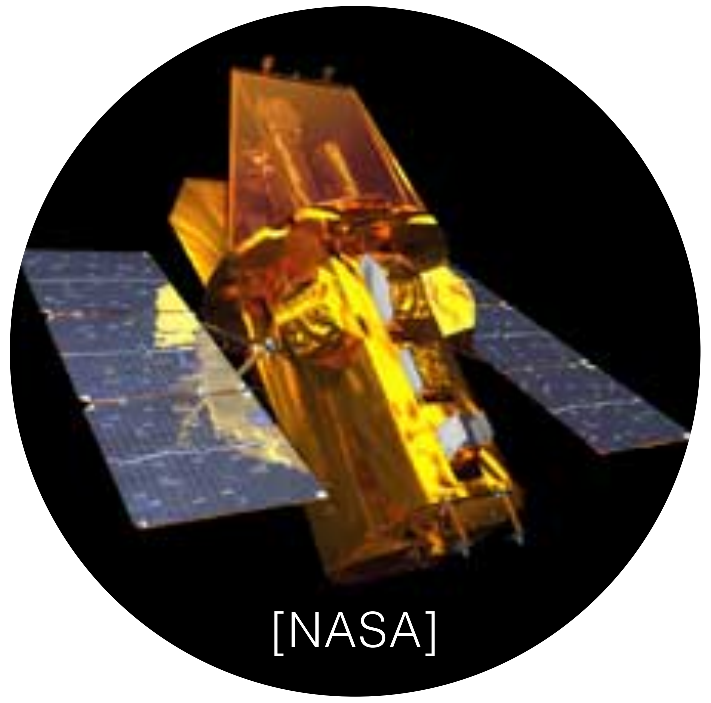
- System of two Imaging Atmospheric Cherenkov Telescopes
- Located at La Palma, Spain
  - 28°.7N, 2,200 m a.s.l.
- Mirror dish: D17 m
- Energy range: ≳50 GeV for low zenith angle

Fermi-LAT

- Onboard *Fermi* Gamma-ray Space Telescope
- Covering whole sky every 3 hr in standard survey mode
- Energy range: Tens of MeV—≳300 GeV

Swift

- Publicly available data of two instruments onboard *Neil Gehrels Swift* Observatory were used



XRT

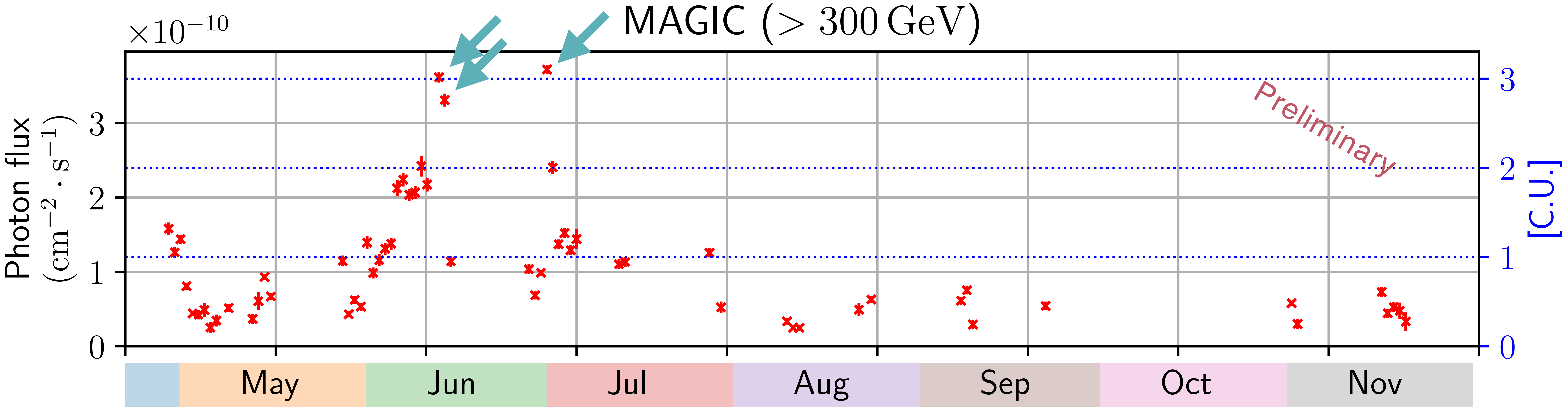
- Energy range: 0.2—10 keV

UVOT

- Waveband range: 170—600 nm

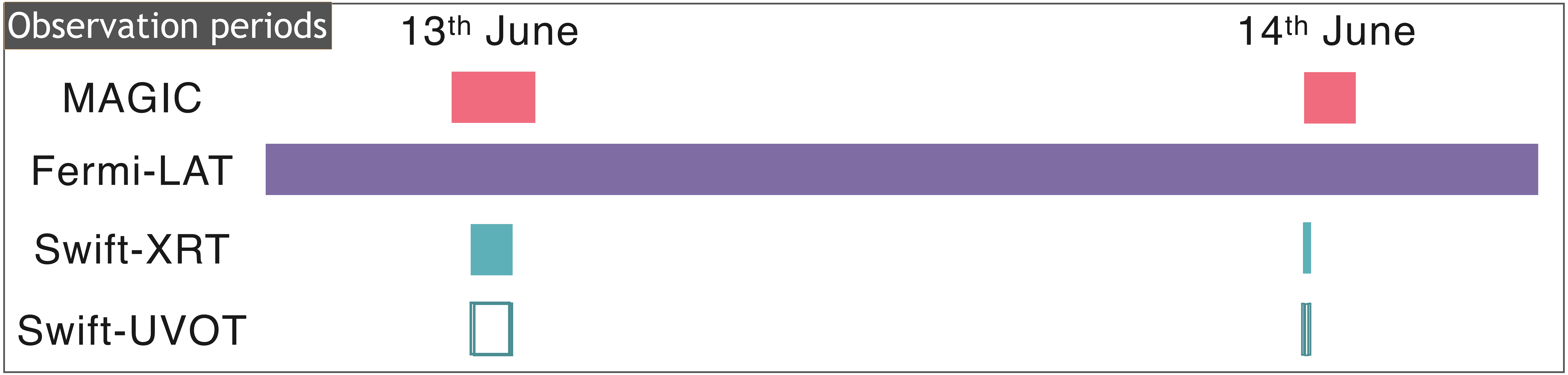
FLARES in 2016

- Remarkably bright flares in VHE* γ rays were observed on 13th, 14th June and 1st July 2016
  - flux reached ~3 Crab Unit (C.U.)
- We focus on flares on 13th, 14th June
  - quasi-simultaneous data of MAGIC, *Fermi*-LAT and *Swift*-XRT/UVOT



* VHE: very high energy; >100 GeV

OBSERVATIONS and DATA ANALYSIS



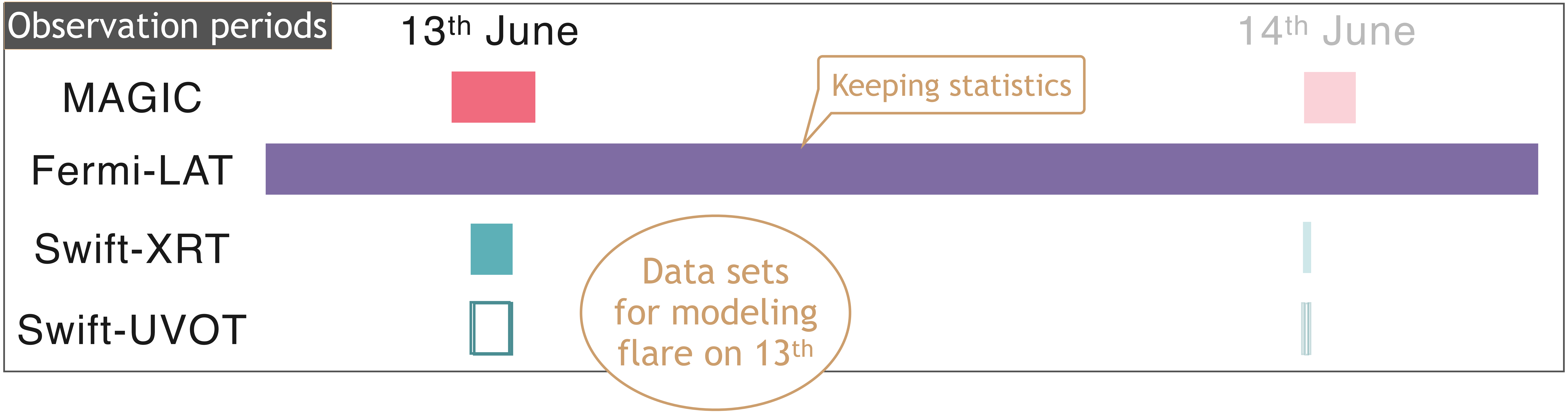
MAGIC
- Energy threshold: ~100 GeV
  - Spectra above ~100 GeV on both nights
  - Light curve with 10-min binning

Fermi-LAT
- Survey mode
  - Spectral fit with power-law for 0.3—300 GeV

XRT
- Spectral fit with power-law and log-parabola for >0.5 KeV

UVOT
- Waveband filters
  - 13th June: W1 and W2
  - 14th June: W1, M1 and W2
- Flux for each filter

OBSERVATIONS and DATA ANALYSIS



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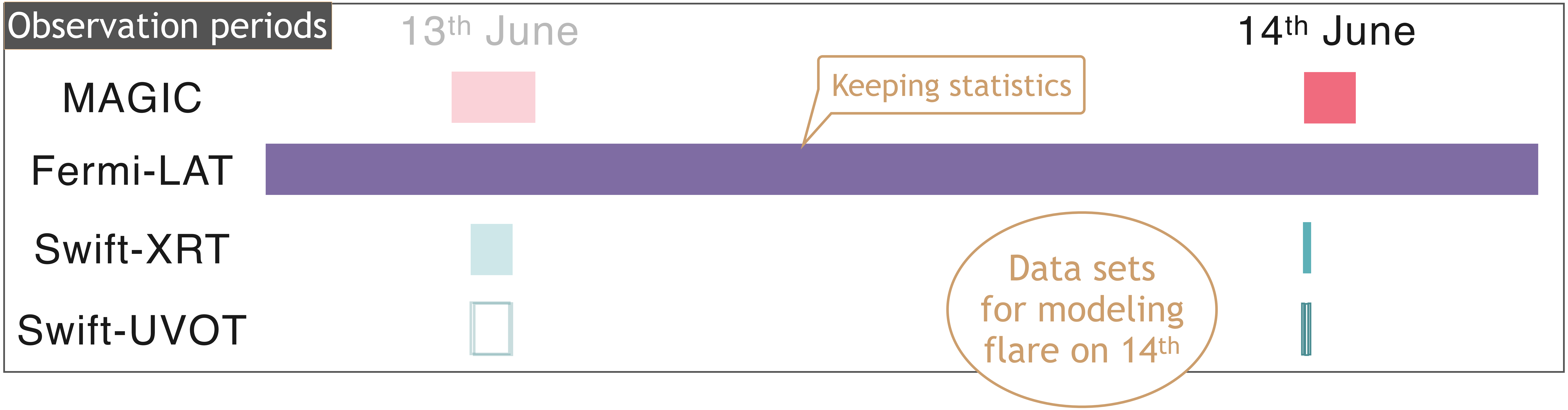

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UVOT

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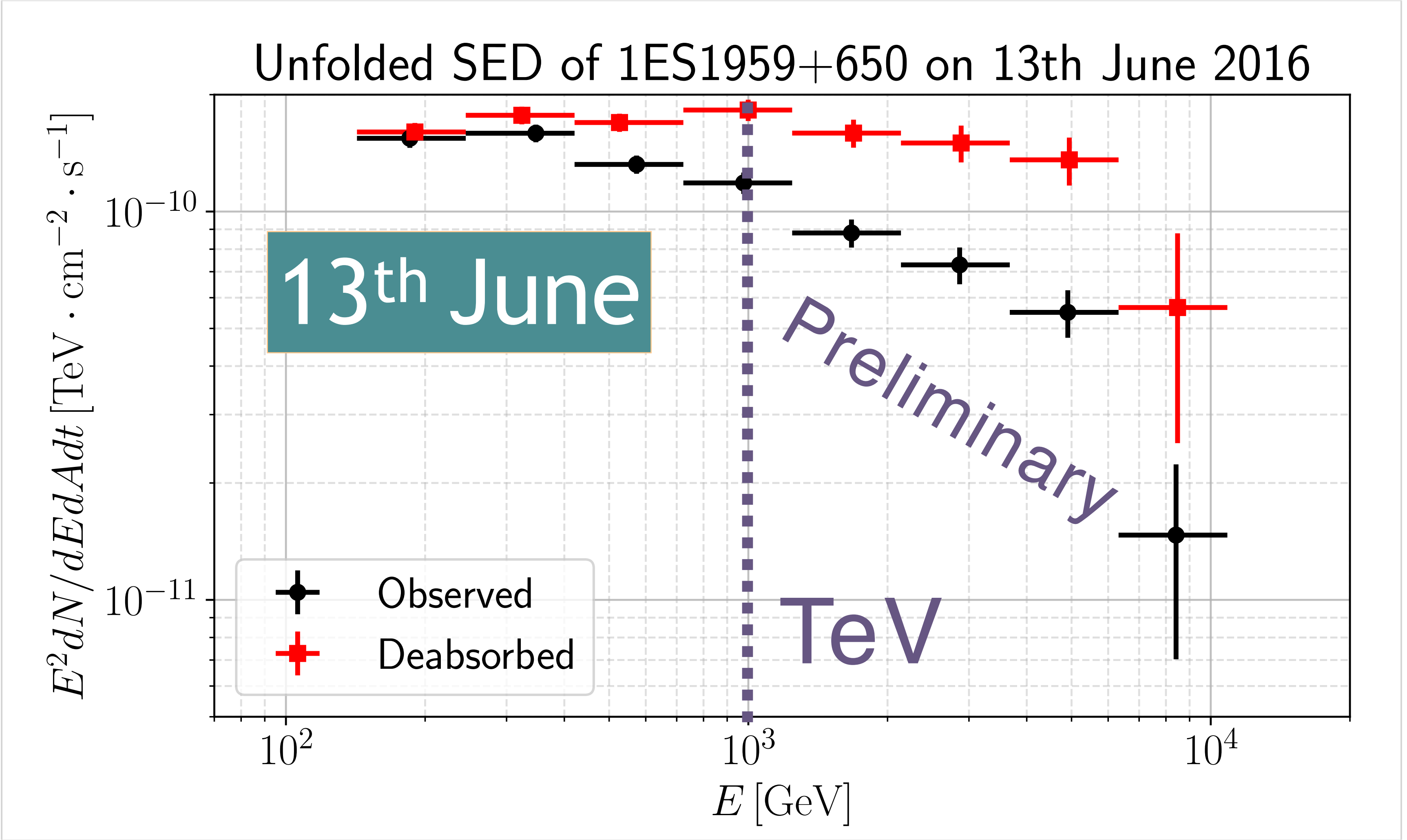
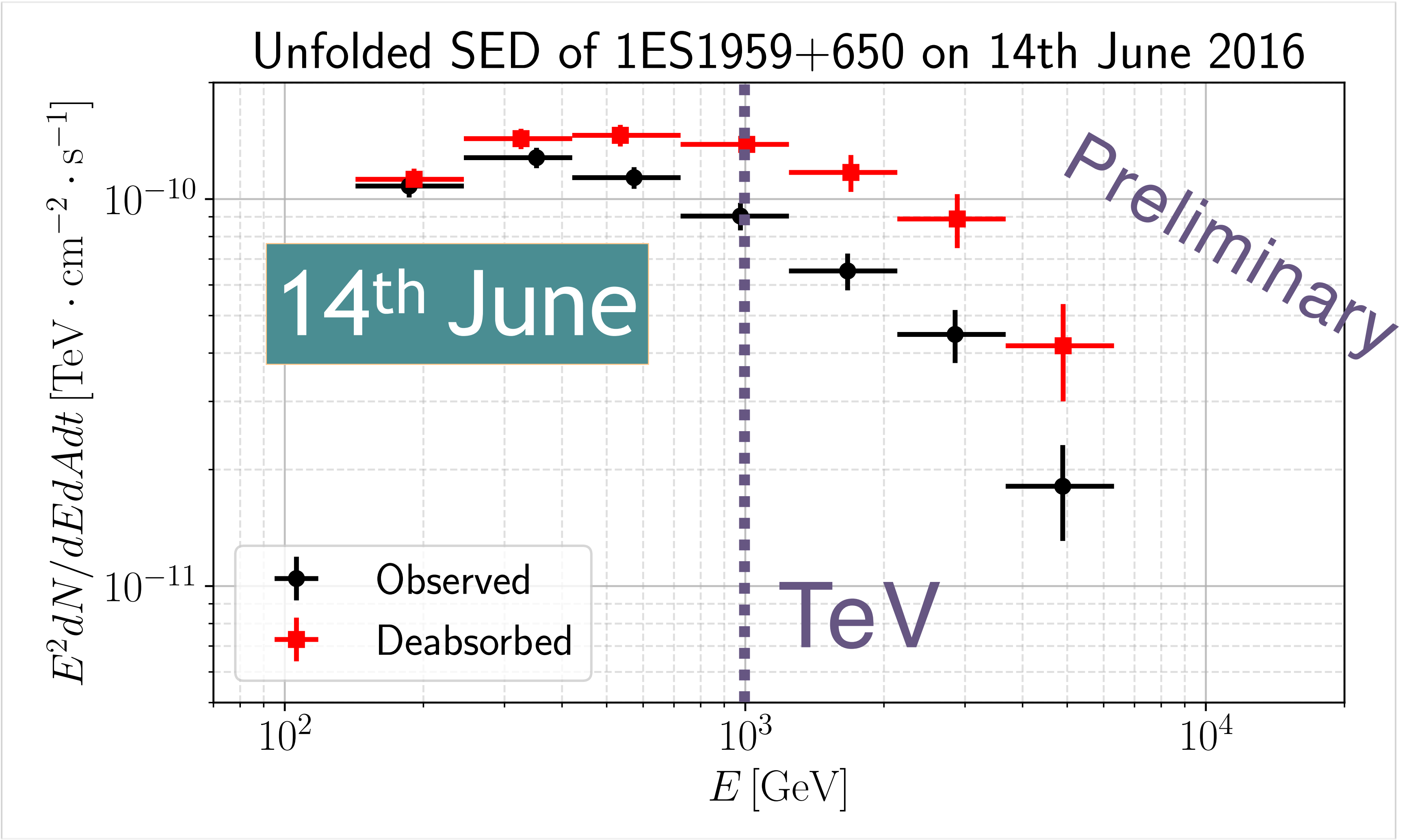
  - 13th June: W1 and W2
  - 14th June: W1, M1 and W2
- Flux for each filter

VHE γ-RAY SPECTRUM

- Deabsorbed† SEDs* are very flat and extend up to a few TeV
- SEDs peak at 0.4—0.7 TeV
- No decisive preference among fits by
  - log-parabola
  - power-law with exponential cutoff
  - log-parabola with exponential cutoff
- Local power-law index <2 around 300 GeV
- Spectrum is harder on 13th than on 14th





† Extragalactic-background-light absorption was corrected with [Franceschini+ 08]

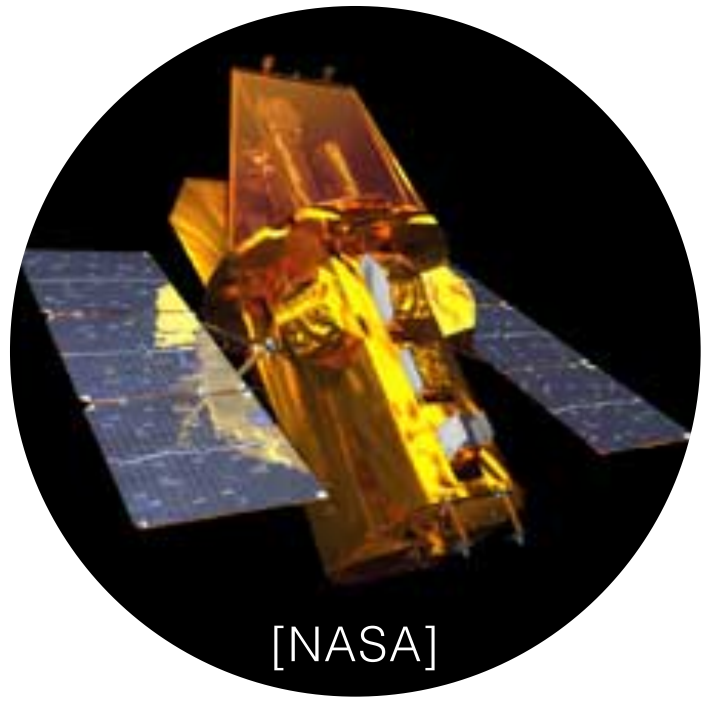
* SED: spectral energy distribution

HIGH-ENERGY γ-RAY and X-RAY SPECTRUM

Fermi-LAT

- ✦ Power-law fit yielded index of 1.56±0.20
  - for 0.3–300 GeV and single 1.5-day bin
  - *cf*. 1.82±0.01 (for 50 MeV—1 TeV; 4FGL catalog)

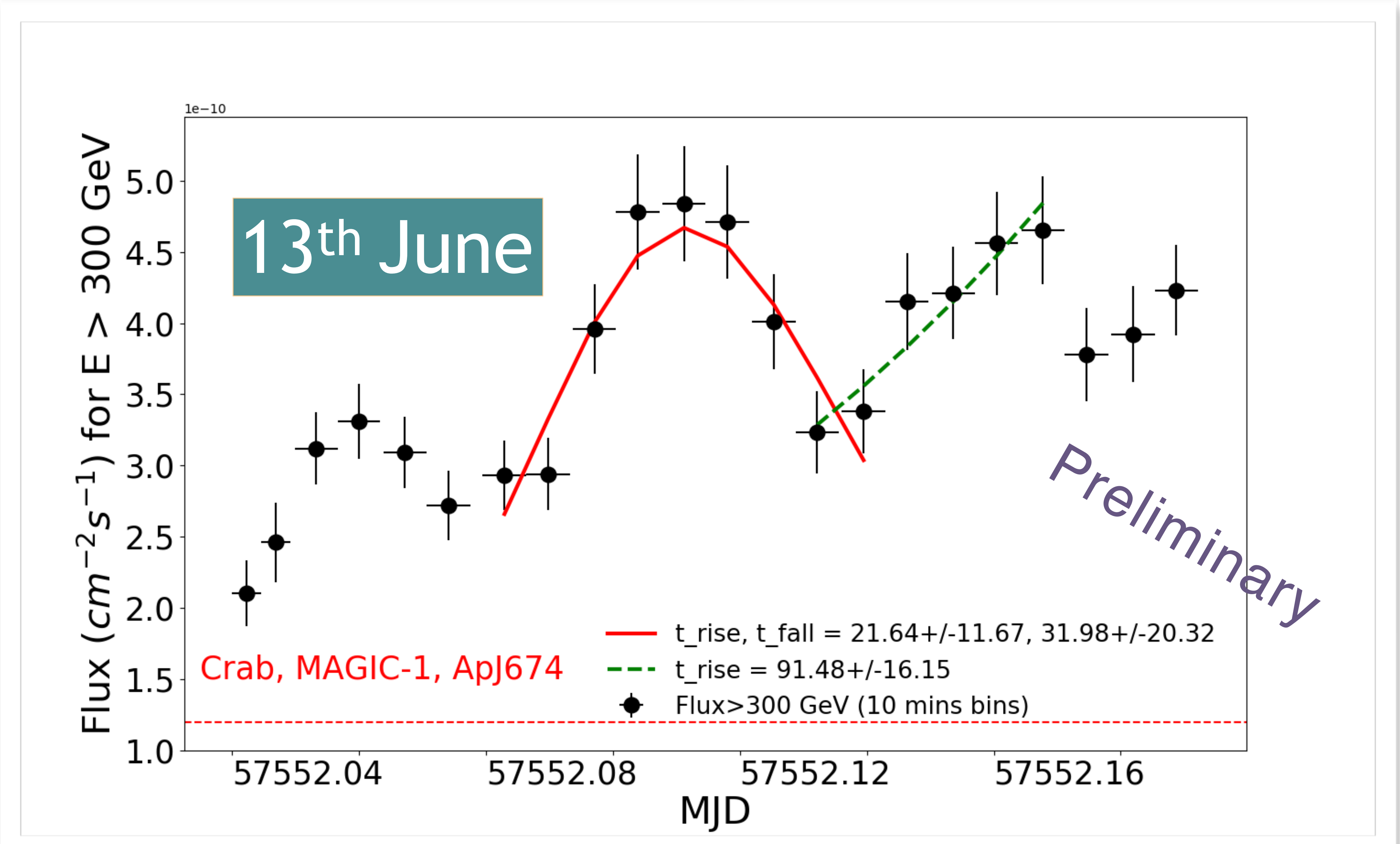
Swift



- ✦ Log-parabola does not improve goodness of fit compared to power-law
- ✦ power-law index
  - 13th June: 1.81±0.01
  - 14th June: 1.82±0.01

FAST VARIABILITY in VHE γ RAYS

- ✦ VHE flux exhibited fast variability on 13th June 2016
- ✦ Doubling time scale: 36 ± 14 min
  - based on steepest step in the VHE flux between two consecutive light curve bins [Zhang+ 99]
  - fitting substructure in light curves leads to similar results
    - during middle part
    - with exponential-like functions
- ✦ Emission region size ≲ 10^{15} cm for Doppler factor δ=20



$$F(t) = A_0/(e^{\frac{t_0-t}{t_r}} + e^{\frac{t-t_0}{t_f}})$$

$t_{rise} = t_r \ln 2 = 22 \pm 12$ min

$t_{fall} = t_f \ln 2 = 32 \pm 20$ min

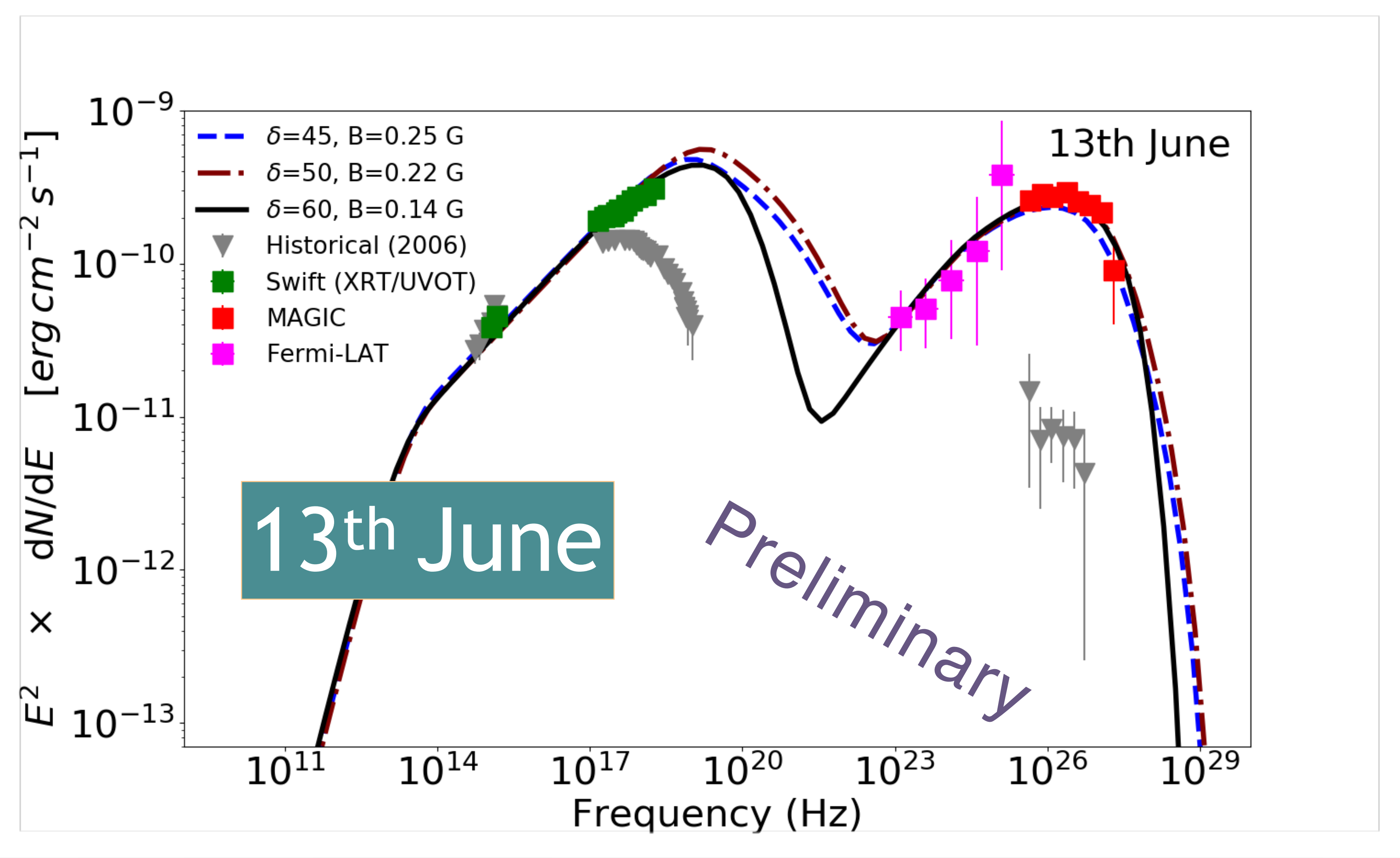
$$F(t) = A_0 e^{-|t-t_0|/t_r}$$

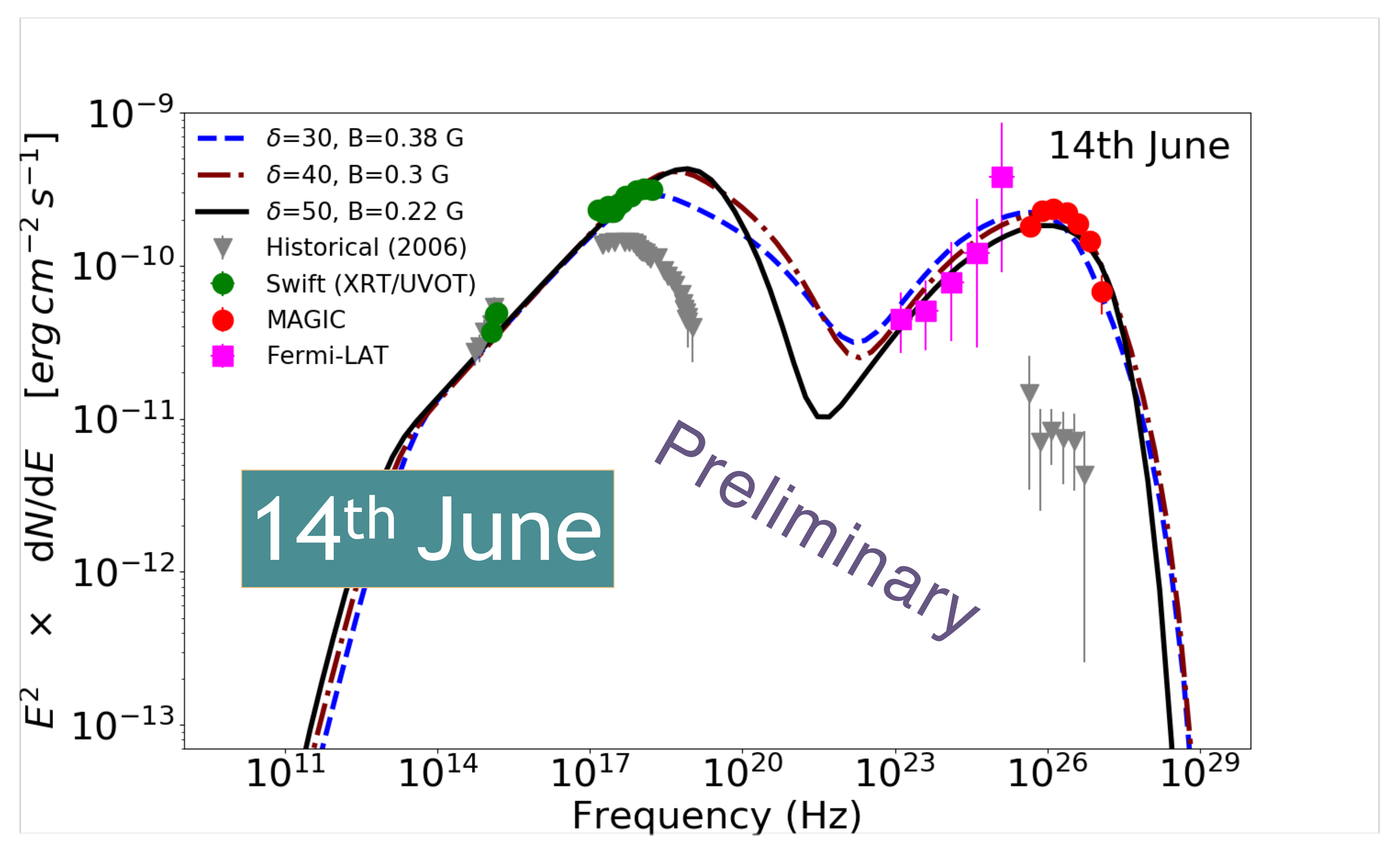
$t_{rise} = t_r \ln 2 = 91 \pm 16$ min

LEPTONIC MODEL

- One-zone SSC model
  - Electron spectrum: broken power-law
  - difference between indices below/above break is fixed at 1
- Large Doppler factor (>40 for 13th) is required by hard and flat VHE SED
- Extreme γ-ray state is interpreted to be caused by:
  - high Compton dominance related to small emission region
  - strong relativistic boost because of large Doppler factor

Parameters	13th June	14th June
Doppler factor δ	40—60	30—50
Emission region size R [cm]	7×10^{14}—10^{15}	8×10^{14}—10^{15}
Magnetic field strength B [G]	0.10—0.25	0.2—1.4
Electron break Lorentz factor $\gamma_{e,brk}$	4×10^{5}—10^{6}	10^{5}—5×10^{5}
Low-energy electron index n_1	2.2—3.2	2.2—3.2
Jet luminosity [erg/s]	$(1$—$5)\times10^{43}$	$(1$—$3)\times10^{43}$

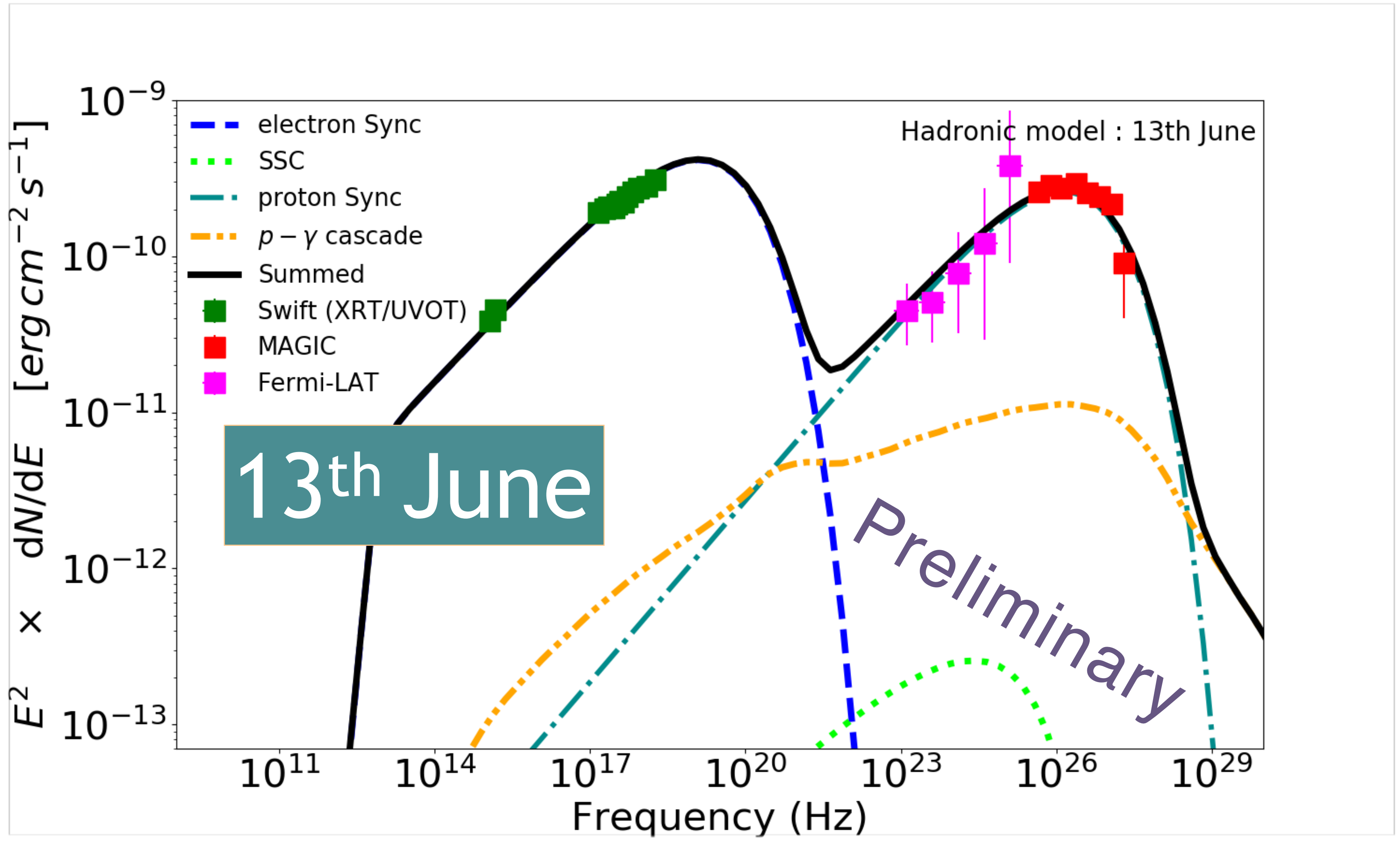


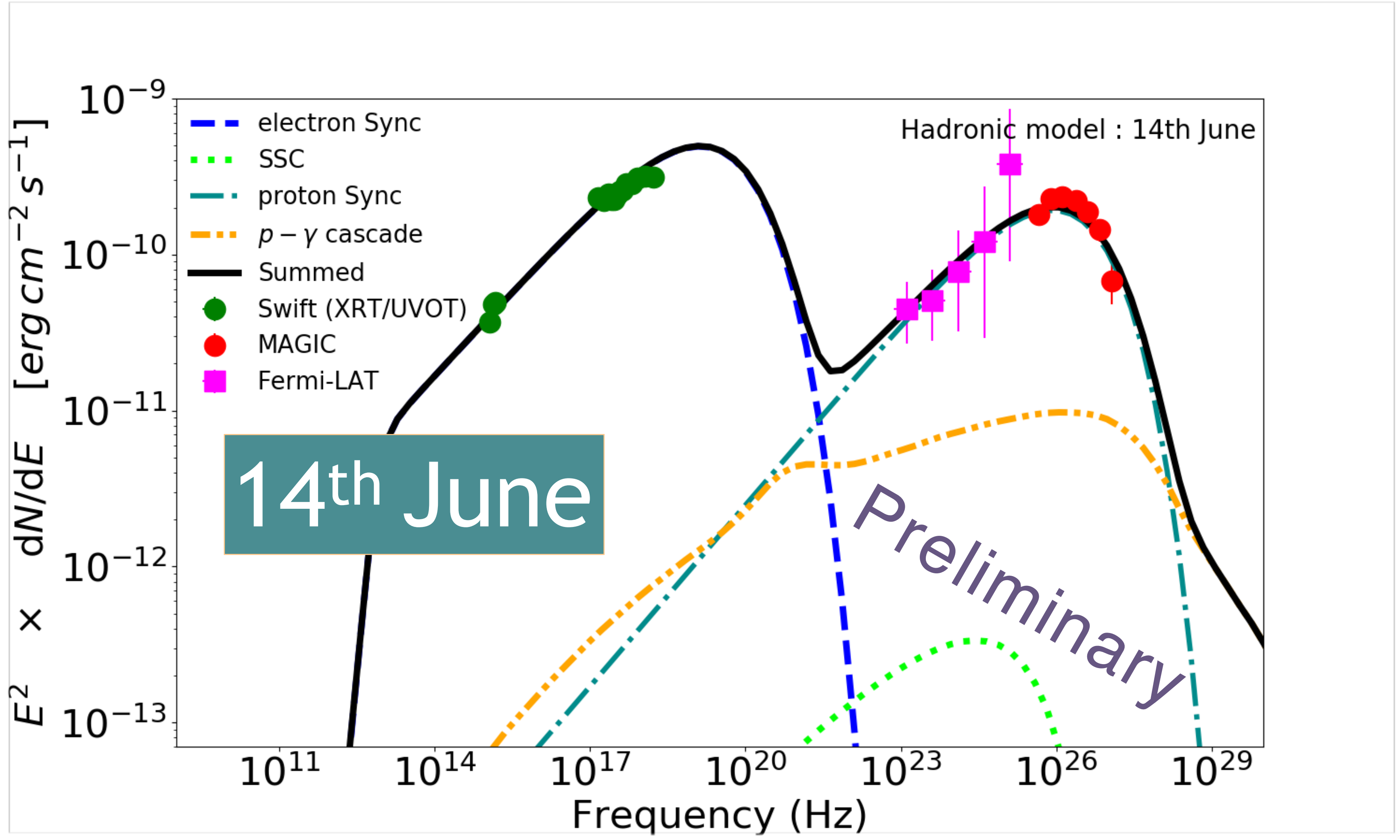


HADRONIC MODEL

- ✦ One-zone proton-synchrotron model
  - Proton spectrum: power-law with exponential cutoff
  - low-energy peak is attributed to electron synchrotron
- ✦ Doppler factor is mild (δ~25)
- ✦ Max proton energy: ≳EeV
- ✦ Very strong magnetic field B≳150 G is required by fast variability in flux
  - electrons are in fast-cooling regime

Parameters	13th June	14th June
Doppler factor δ	25	25
Emission region size R [cm]	2.1×10^{14}	2.1×10^{14}
Magnetic field strength B [G]	150	150
Proton max Lorentz factor $\gamma_{p,max}$	7×10^{9}	5×10^{9}
Proton index n_p	2.23	2.23
Jet luminosity [erg/s]	1.5×10^{46}	10^{46}

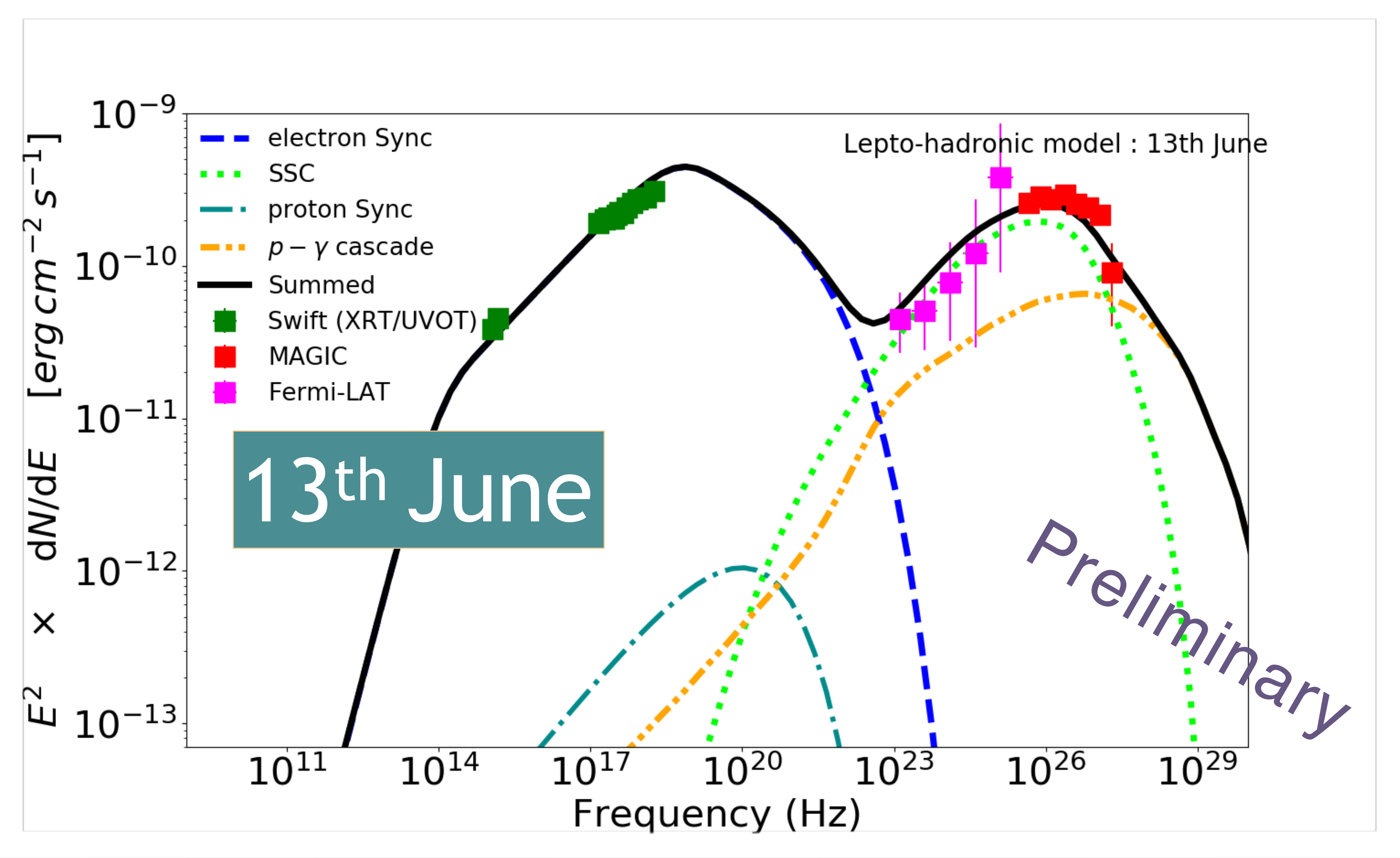


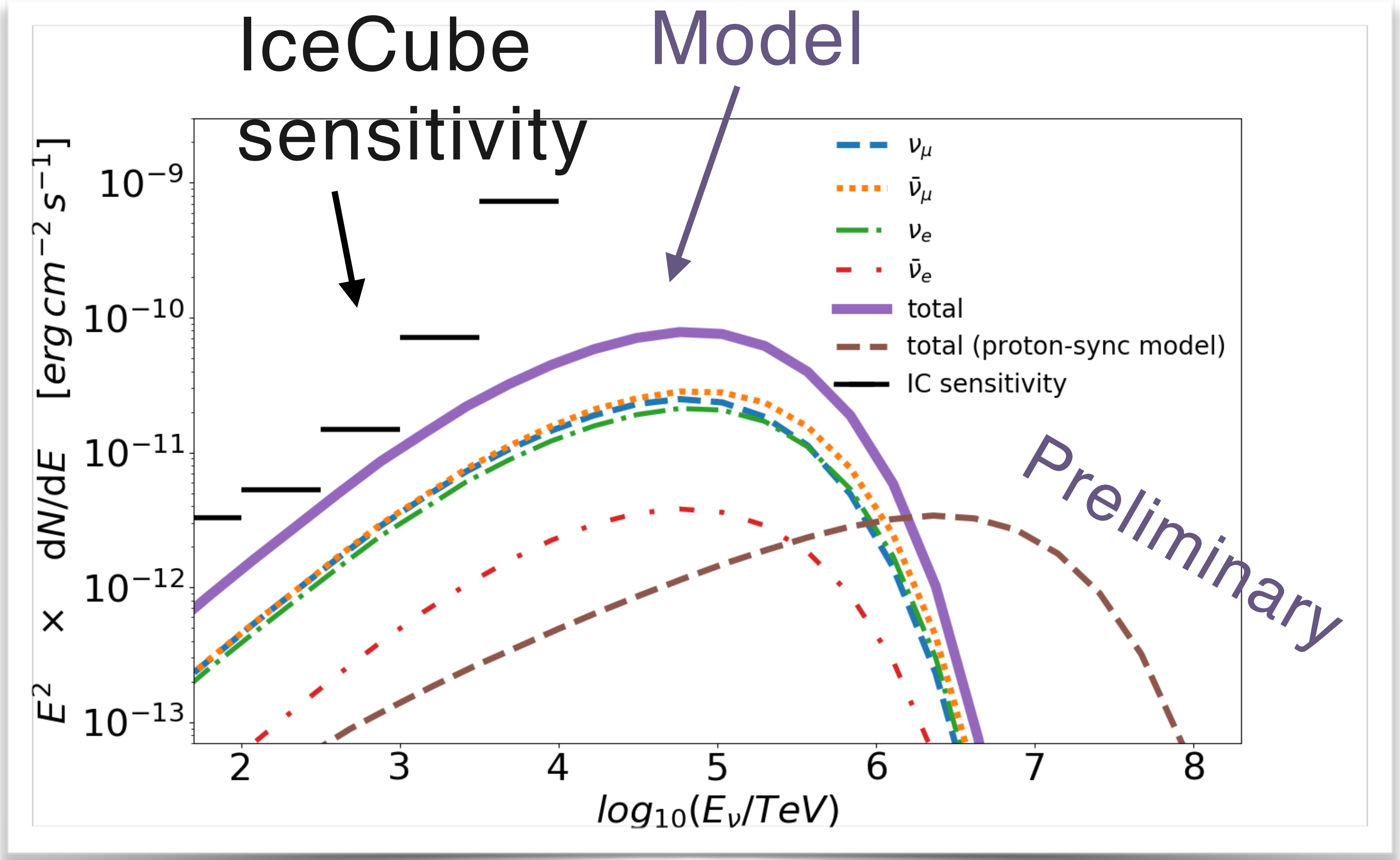


LEPTO-HADRONIC MODEL

- ✦ p-γ cascade component in addition to SSC for high-energy peak
- ✦ Extremely large jet power $L_j \gtrsim 10^{48}$ erg/s is required
  - more than two orders of magnitude larger than Eddington luminosity
- ✦ Predicted neutrino flux is comparable with IceCube upper limit for 8-year data [IceCube Collaboration+ 18]
  - consistent with null detection

Parameters	13th June
Doppler factor δ	45
Emission region size R [cm]	4×10^{14}
Magnetic field strength B [G]	0.6
Proton max Lorentz factor $\gamma_{p,max}$	6×10^{7}
Proton index n_p	2.2
Jet luminosity [erg/s]	8×10^{48}





SUMMARY

- HBL 1ES 1959+650 showed historically bright VHE flares (~3 C.U.) in 2016
- High flux and hard spectrum were observed in both γ-ray and X-ray during those flares
- VHE SEDs are very flat and extends up to multi-TeV
- Fast variability in VHE flux with time scale of ~40 min was observed

- Spectra and fast variability can be reproduced by either leptonic, hadronic or lepto-hadronic model
- Leptonic (one-zone SSC) model requires large Doppler factor $\delta \gtrsim 40$
- Hadronic (p-synchrotron) model requires extreme magnetic field $B \gtrsim 150$ G
- Lepto-hadronic (SSC + p-γ) model implies producing detectable neutrino emission during similar flares is difficult

BACK UP

OBSERVATIONS AND DATA ANALYSIS

MAGIC

- Observation time
  - 13th June: 137 min
  - 14th June: 81 min
- Energy threshold: ~100 GeV
- Spectral fit with some functions for 100 GeV—9 TeV on both nights
- Light curve with 10-min binning

XRT

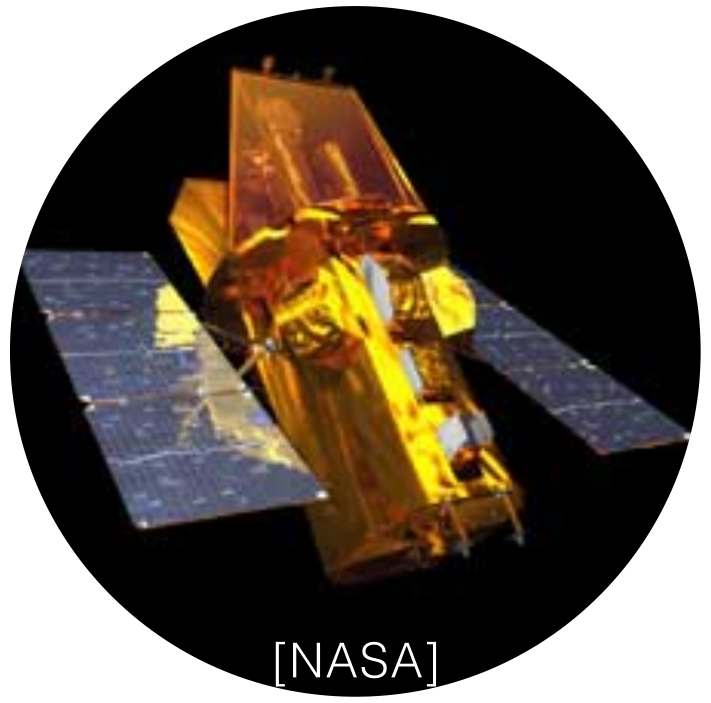
- Observation time
  - 13th June: 70 min
  - 14th June: 15 min
- Spectral fit with power-law and log-parabola for >0.5 KeV

Contained in MAGIC observation periods

Fermi-LAT

- Survey mode
- Data of 1.5 days are combined
  - for statistics
  - Covering both MAGIC observation periods
- Spectral fit with power-law for 0.3—300 GeV

UVOT



- Observation time
  - 13th June: 314 min
  - 14th June: 138—275 min
- Waveband filters
  - 13th June: W1 and W2
  - 14th June: W1, M1 and W2
- Flux for each filter

FITTING PARAMETERS of VHE SPECTRA on 13th and 14th June 2016

✦ Fit range: 0.1 — 9 TeV

Preliminary

Time	Flux[a] (10^{-10} cm^{-2} · s^{-1})	Fit model	F_0 (10^{-9} TeV^{-1} · cm^{-2} · s^{-1})	Γ or α	E_{cut} (TeV)	β	E_{peak}[b] (TeV)	$\chi^2/d.o.f$
13th June 02:15–04:37 (MJD 57552.094 –57552.192)	4.06 ± 0.13	(1) PL	$1.81^{+0.05}_{-0.05}$	$2.00^{+0.02}_{-0.02}$	···	···	···	34.0/10
		(2) PL w/ cutoff	$1.93^{+0.06}_{-0.06}$	$1.81^{+0.05}_{-0.05}$	$5.4^{+1.7}_{-1.1}$	···	···	14.1/9
		(3) LogP	$1.89^{+0.05}_{-0.05}$	$1.83^{+0.04}_{-0.04}$	···	$0.24^{+0.05}_{-0.05}$	$0.67^{+0.09}_{-0.07}$	11.4/9
		(4) LogP w/ cutoff	$1.89^{+0.05}_{-0.05}$	$1.83^{+0.04}_{-0.04}$	$+\infty^{c}$	$0.24^{+0.05}_{-0.05}$	$0.67^{+0.002}_{-0.002}$	11.4/8
14th June 02:07–03:35 (MJD 57553.088 –57553.149)	3.28 ± 0.13	(1) PL	$1.46^{+0.05}_{-0.04}$	$2.07^{+0.03}_{-0.03}$	···	···	···	35.3/10
		(2) PL w/ cutoff	$1.67^{+0.07}_{-0.07}$	$1.77^{+0.07}_{-0.07}$	$2.9^{+0.8}_{-0.5}$	···	···	5.9/9
		(3) LogP	$1.58^{+0.05}_{-0.05}$	$1.86^{+0.05}_{-0.05}$	···	$0.36^{+0.07}_{-0.07}$	$0.47^{+0.05}_{-0.05}$	6.0/9
		(4) LogP w/ cutoff	$1.63^{+0.09}_{-0.08}$	$1.81^{+0.07}_{-0.07}$	$5.7^{+6.2}_{-6.2}$	$0.18^{+0.21}_{-0.20}$	$1.0^{+1.8}_{-1.8}$	5.3/8

PL: $$\frac{dF}{dE} = F_0\left(\frac{E}{E_0}\right)^{-\Gamma}$$

LogP: $$\frac{dF}{dE} = F_0\left(\frac{E}{E_0}\right)^{-\alpha-\beta[\log_{10}(E/E_0)]}$$

PL w/ cutoff: $$\frac{dF}{dE} = F_0\left(\frac{E}{E_0}\right)^{-\Gamma}\exp\left(-\frac{E}{E_{cut}}\right)$$

LogP w/ cutoff: $$\frac{dF}{dE} = F_0\left(\frac{E}{E_0}\right)^{-\alpha-\beta[\log_{10}(E/E_0)]}\exp\left(-\frac{E}{E_{cut}}\right)$$

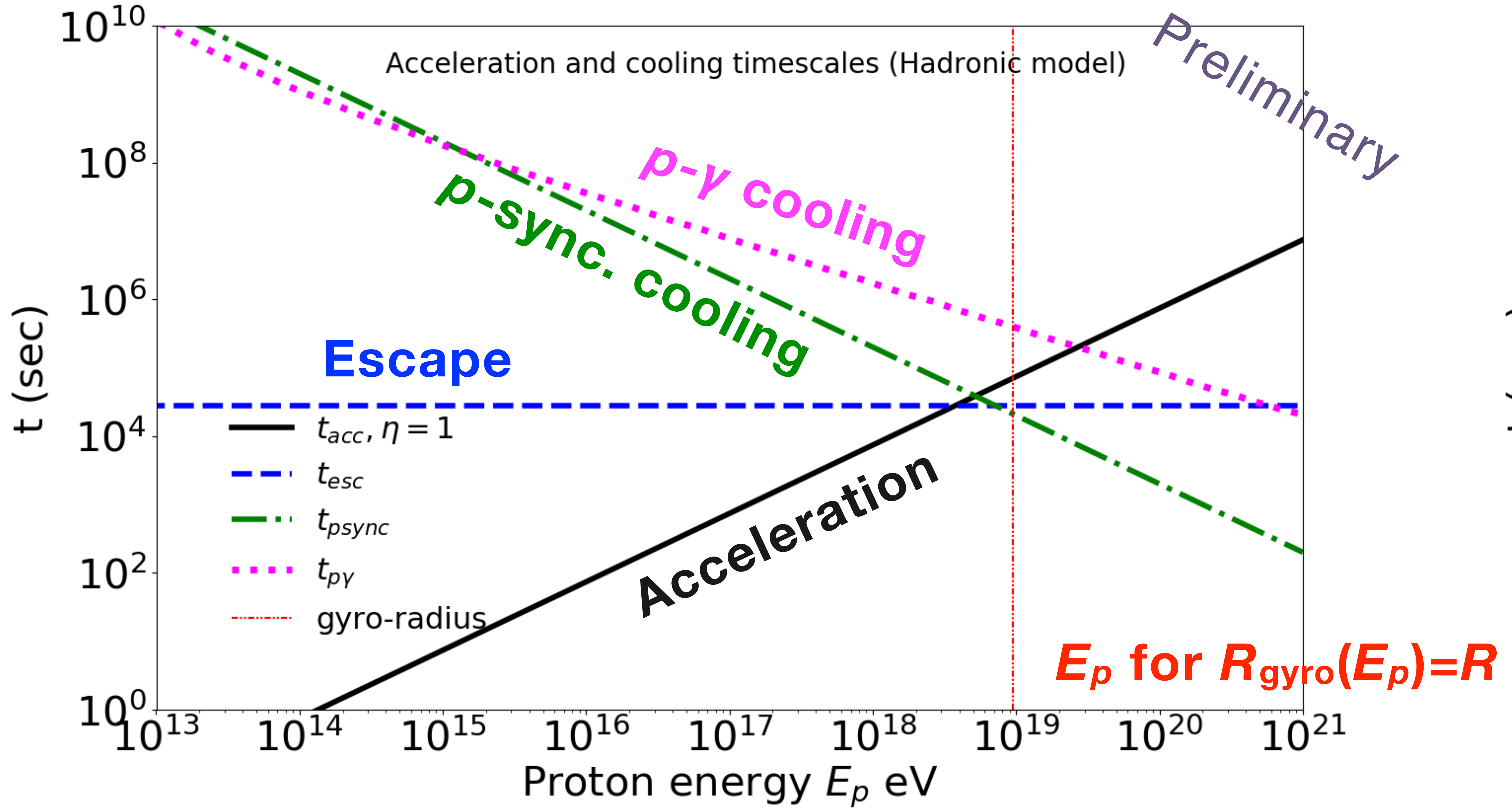
PARAMETERS for MODELING

Preliminary

	13th June			14th June	
Parameters	SSC	Hadronic	Lepto-hadronic	SSC	Hadronic
δ	40–60	25	45	30–50	25
B (G)	0.1–0.25	150	0.6	0.2–0.4	150
R (cm)	7×10^{14}–10^{15}	2.1×10^{14}	4×10^{14}	8×10^{14}– 10^{15}	2.1×10^{14}
n_1	2.2–2.3	2.3	2.3	2.2–2.3	2.28
n_2	3.2–3.3	...	3.3	3.2–3.3	...
$\gamma_{e,\mathrm{min}}$	7×10^2	5	8×10^2	3–7×10^2	5
$\gamma_{e,\mathrm{max}}$	10^6–7×10^6	5×10^4	7×10^6	10^6–7×10^6	5×10^4
$\gamma_{e,\mathrm{brk}}$	4×10^5–10^6	...	2×10^5	10^5–5×10^5	...
n_p	...	2.23	2.2	...	2.23
$\gamma_{p,\mathrm{min}}$	...	1	1	...	1
$\gamma_{p,\mathrm{max}}$	...	7×10^9	6×10^7	...	5×10^9
L_j (erg/s)	10^{43}–5×10^{43}	1.5×10^{46}	8×10^{48}	10^{43}–3×10^{43}	10^{46}

ACCELERATION/COOLING TIME SCALES

Hadronic model (13th June)



Lepto-hadronic model (13th June)