

VHE gamma-ray spectral hint of two-zone emitting region in Mrk 501

Josefa Becerra González

on behalf of MAGIC, Fermi-LAT collaborations and MWL collaborators

Instituto de Astrofísica de Canarias

jbecerra@iac.es

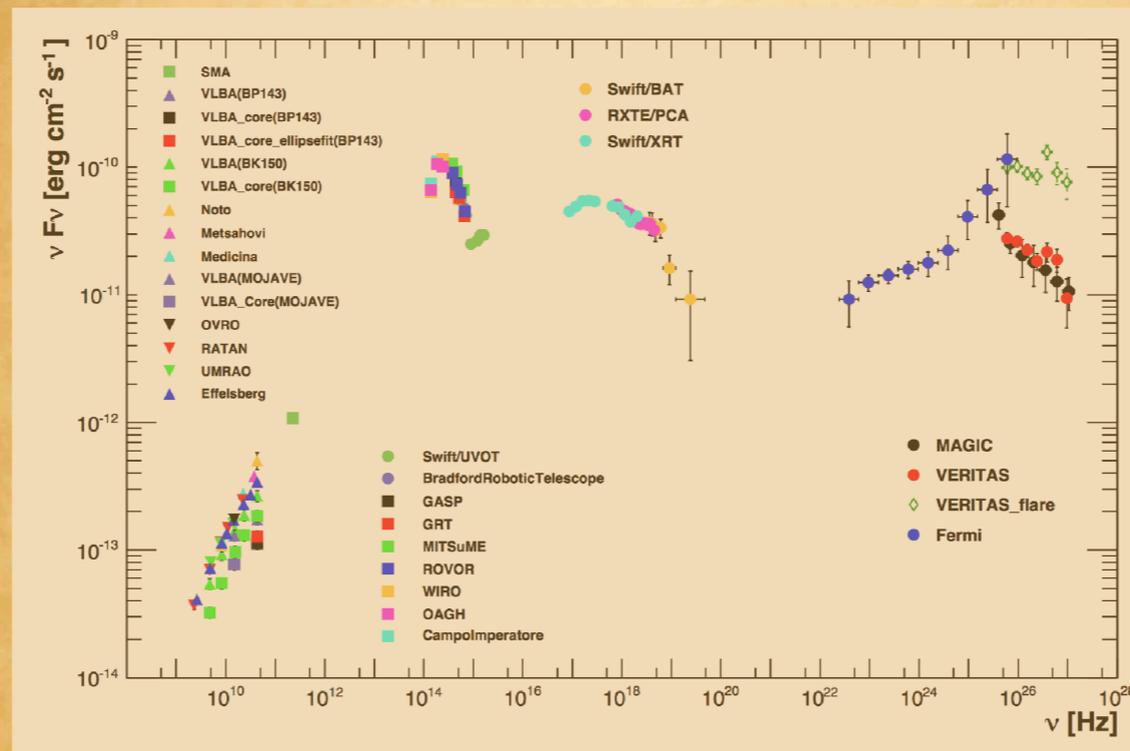
Collaborators: D. Paneque, C. Wendel, K. Noda, F. Tavecchio, K. Ishio, K. Mannheim, A. Tramacere ++

WANTED

MRK 501

FLARING OR QUIESCENT

FOR JETS AND EBL STUDIES



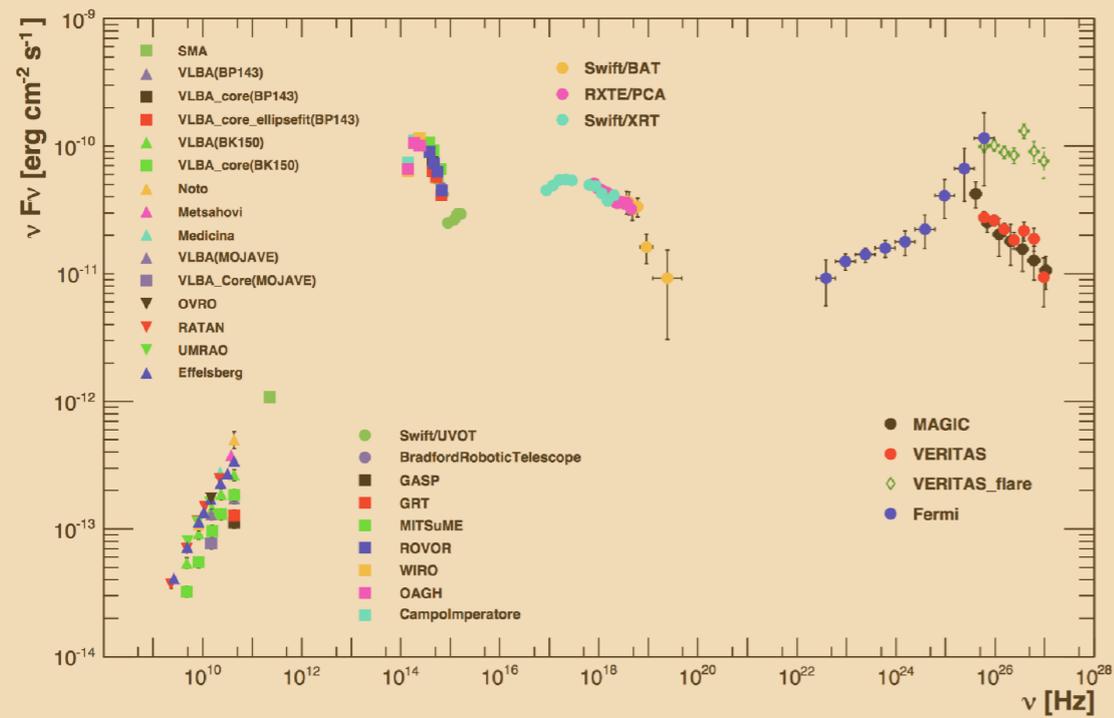
MWL STUDIES REWARDED

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Mrk 501:
high-peaked BL Lac at $z=0.03$
a famous TeV emitter

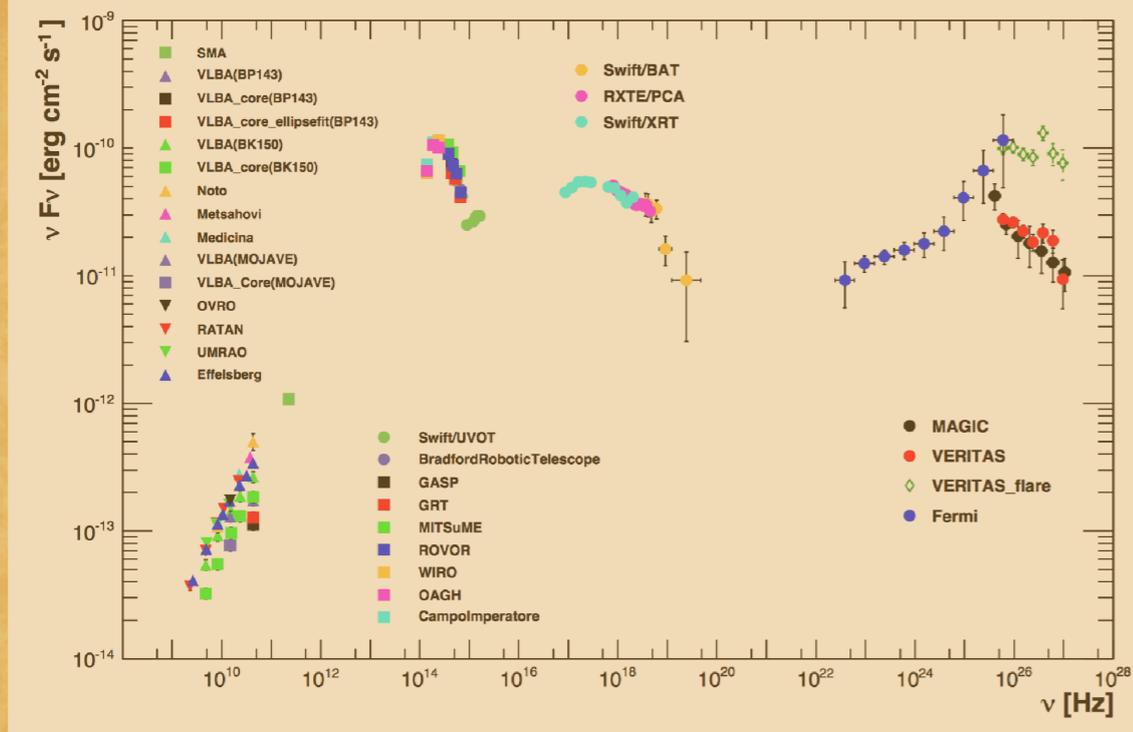


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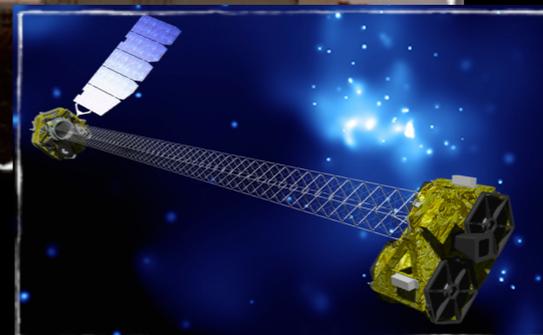
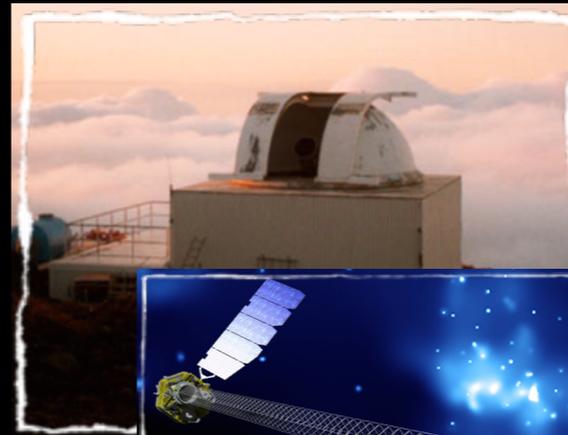
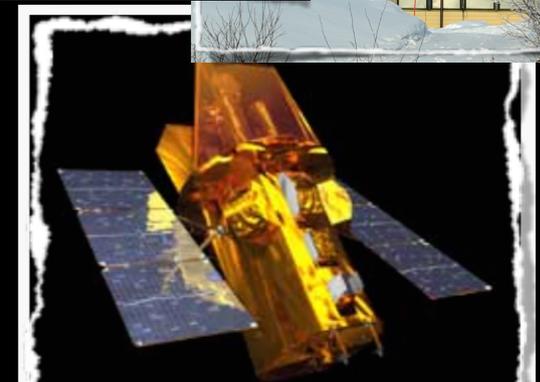


MWL STUDIES REWARDED

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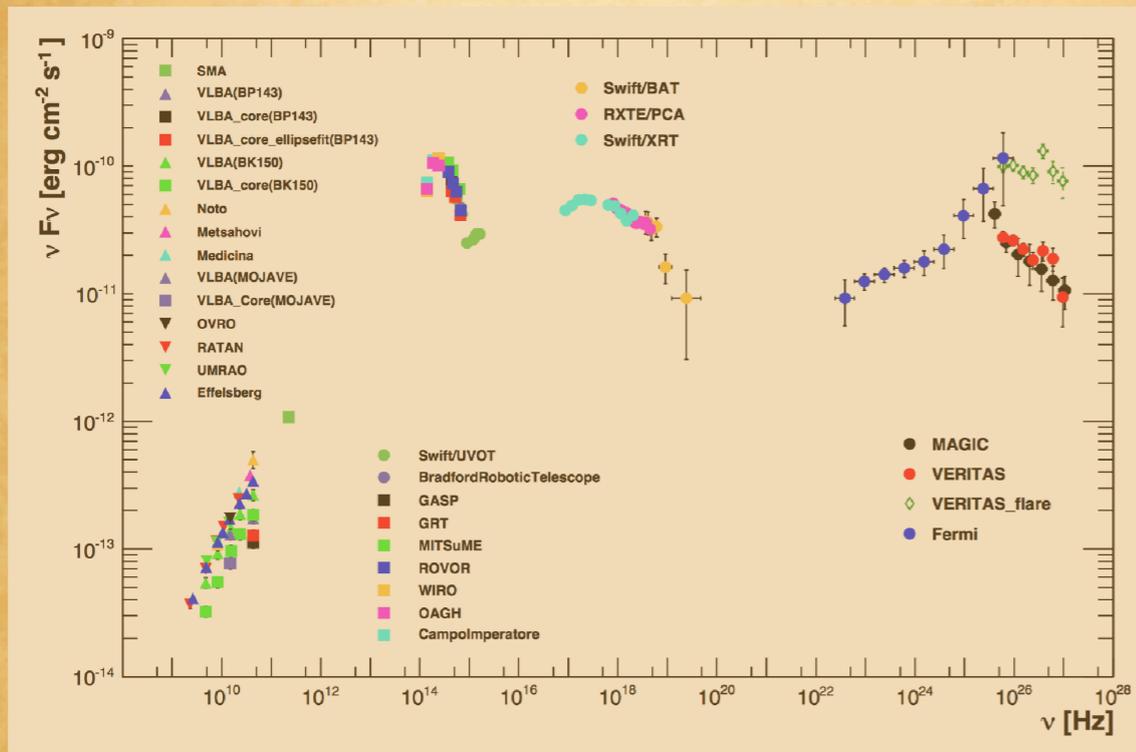
Its **persistent TeV** emission during flaring and quiescent phases makes this blazar an excellent candidate for **detailed multi-wavelength studies**



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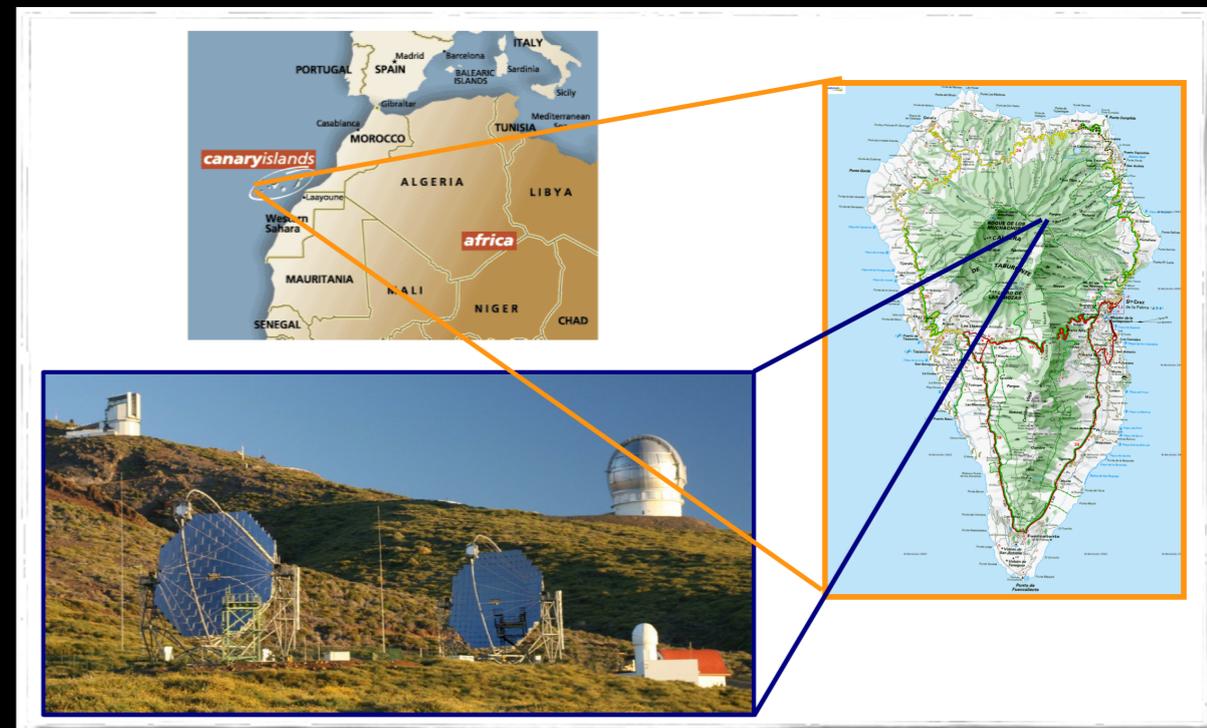
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Mrk 501:

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Its **persistent TeV** emission during flaring and quiescent phases makes this blazar an excellent candidate for **detailed multi-wavelength studies**

MAGIC telescopes

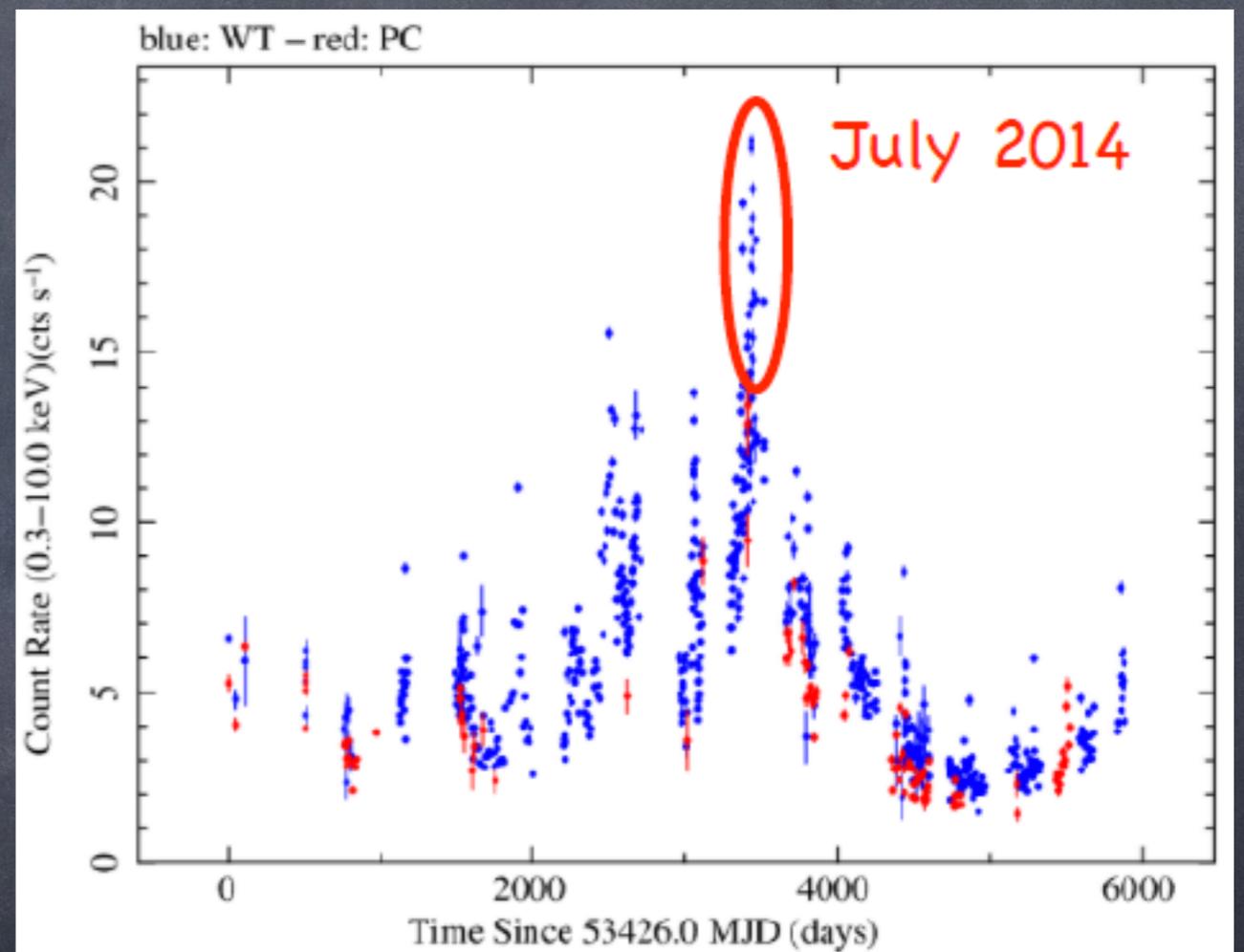


Energy threshold
 $E > 50$ GeV

Extreme X-ray flaring activity in 2014

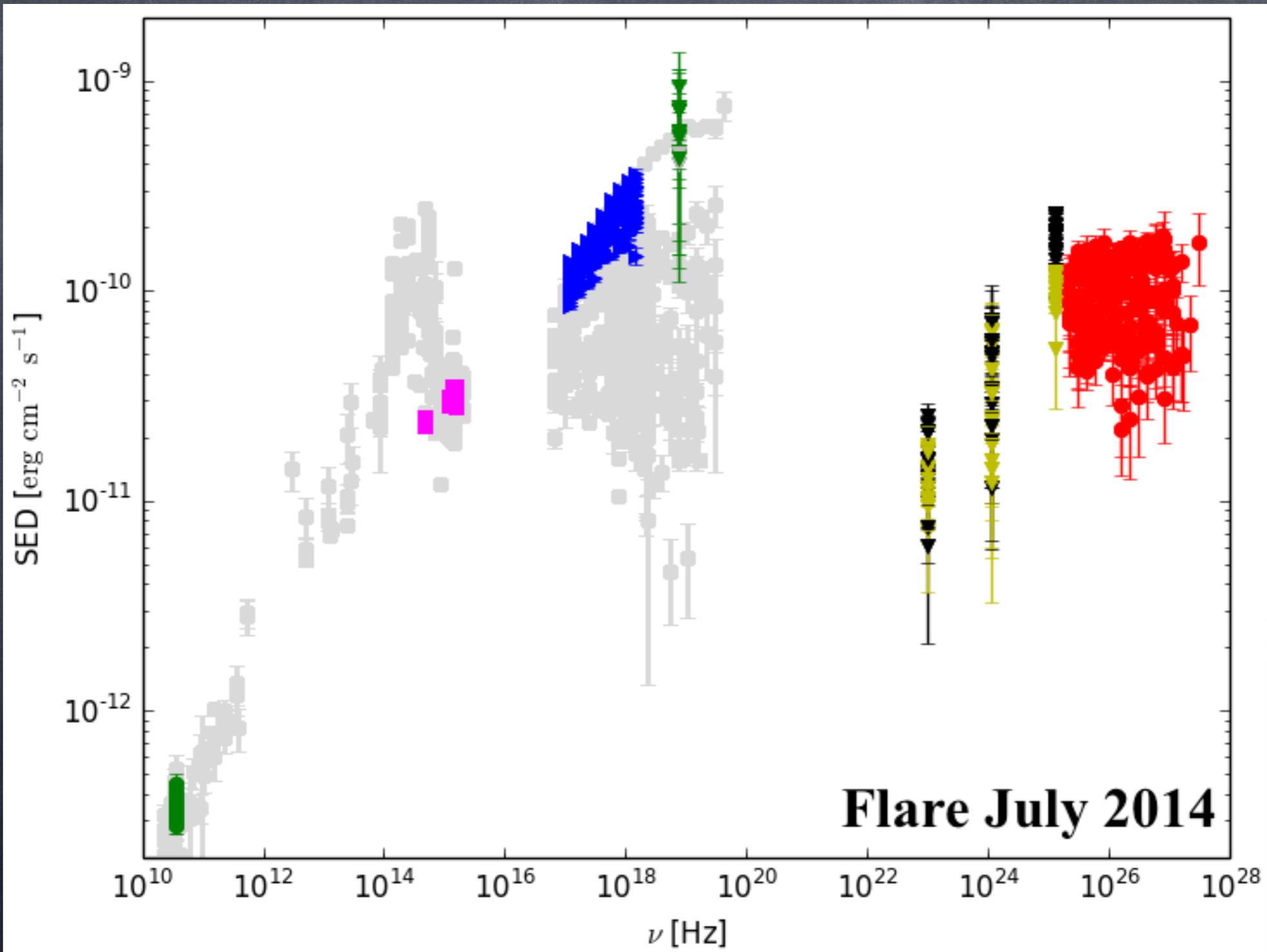
Outstanding X-ray activity during one of our MWL campaigns, in July 2014.

Largest X-ray flux detected by Swift-XRT in 16 years of operation.

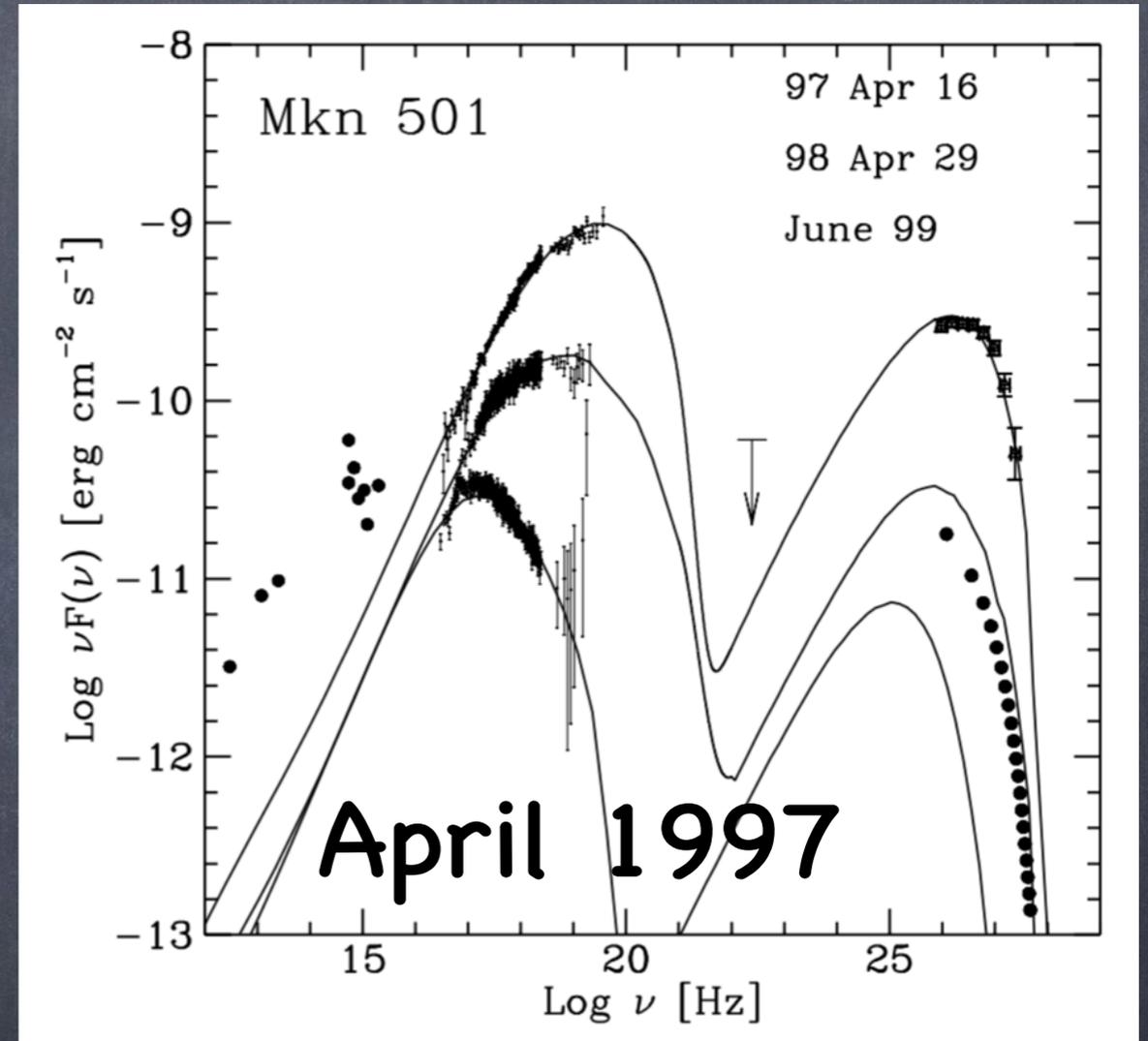
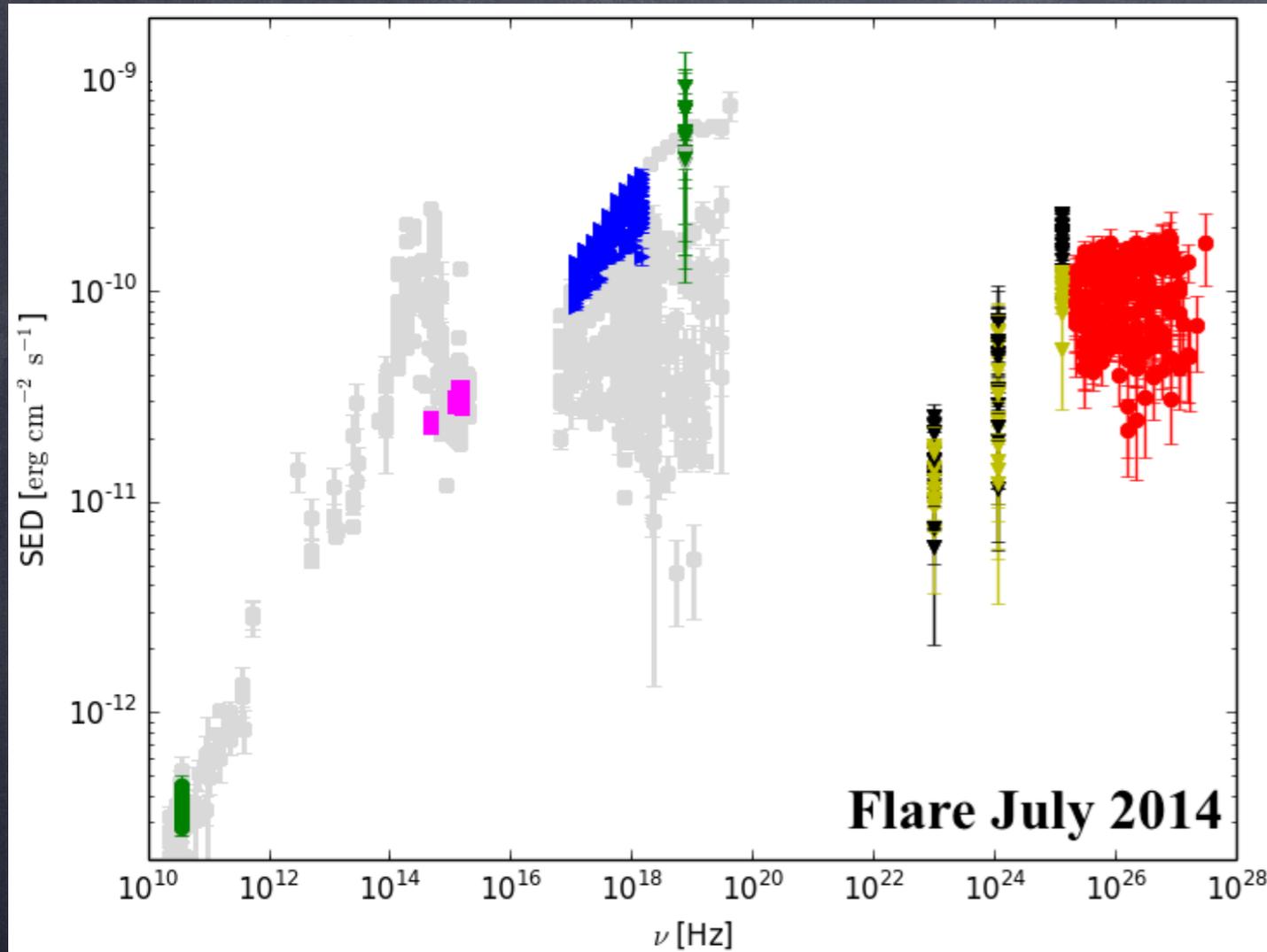


From Abe Falcone, Michael Stroh et al.
Swift blazar monitoring
(<https://www.swift.psu.edu/monitoring/>)

MWL SED overview



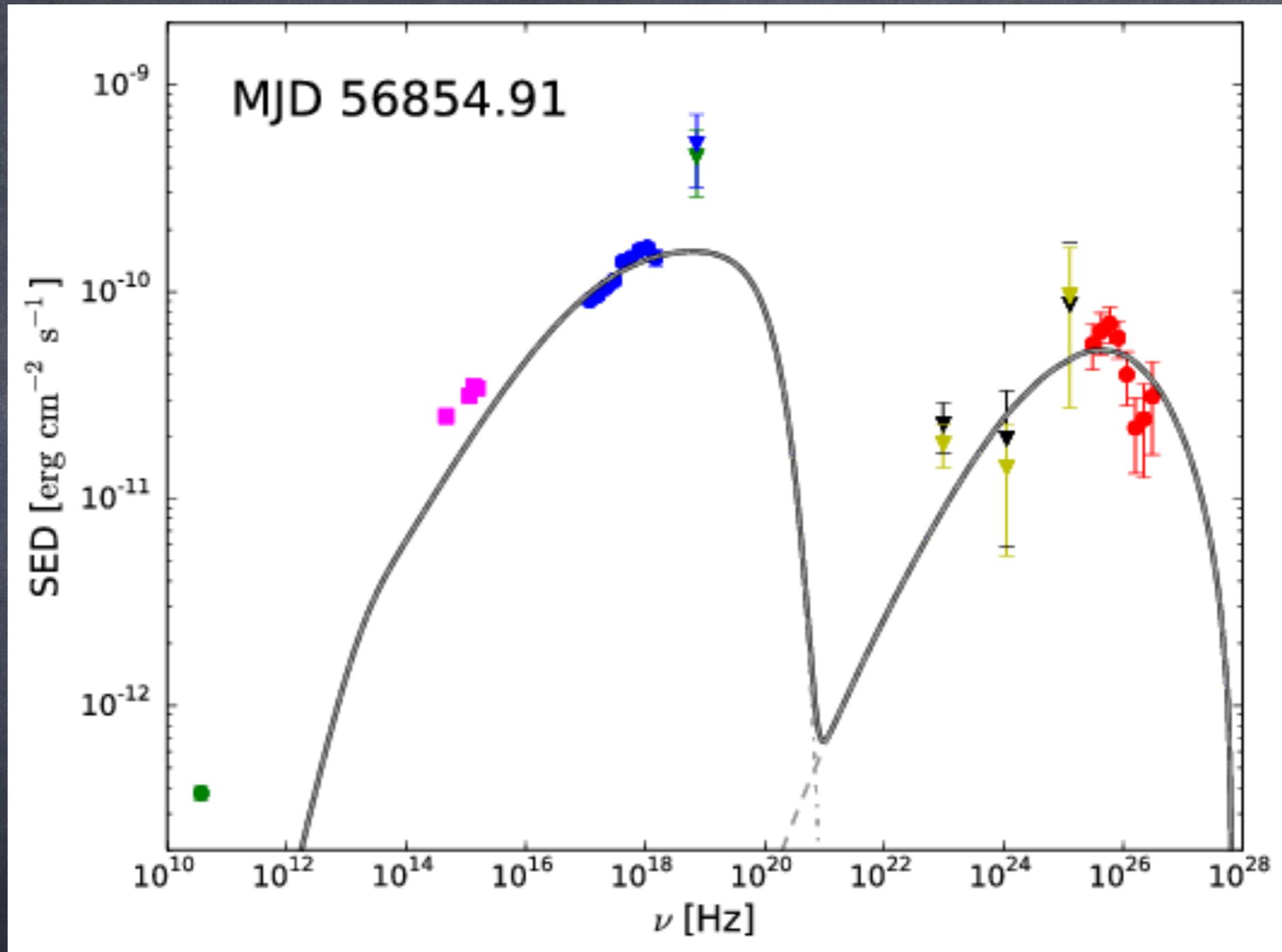
MWL SED overview



X-ray flux comparable
TeV more variable in 1997

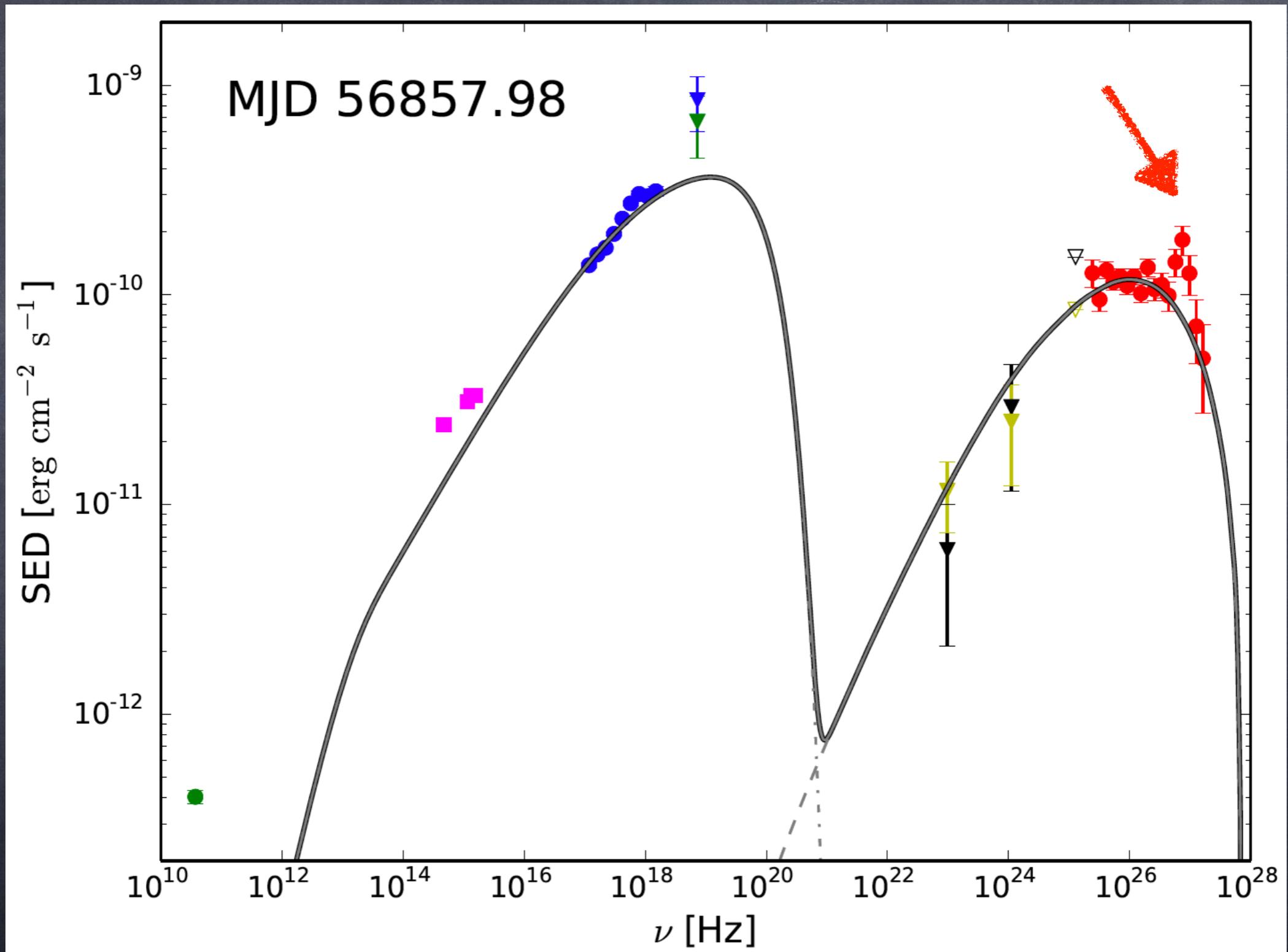
Tavecchio et al. (2001)
ApJ 554, 725

MWL SED evolution

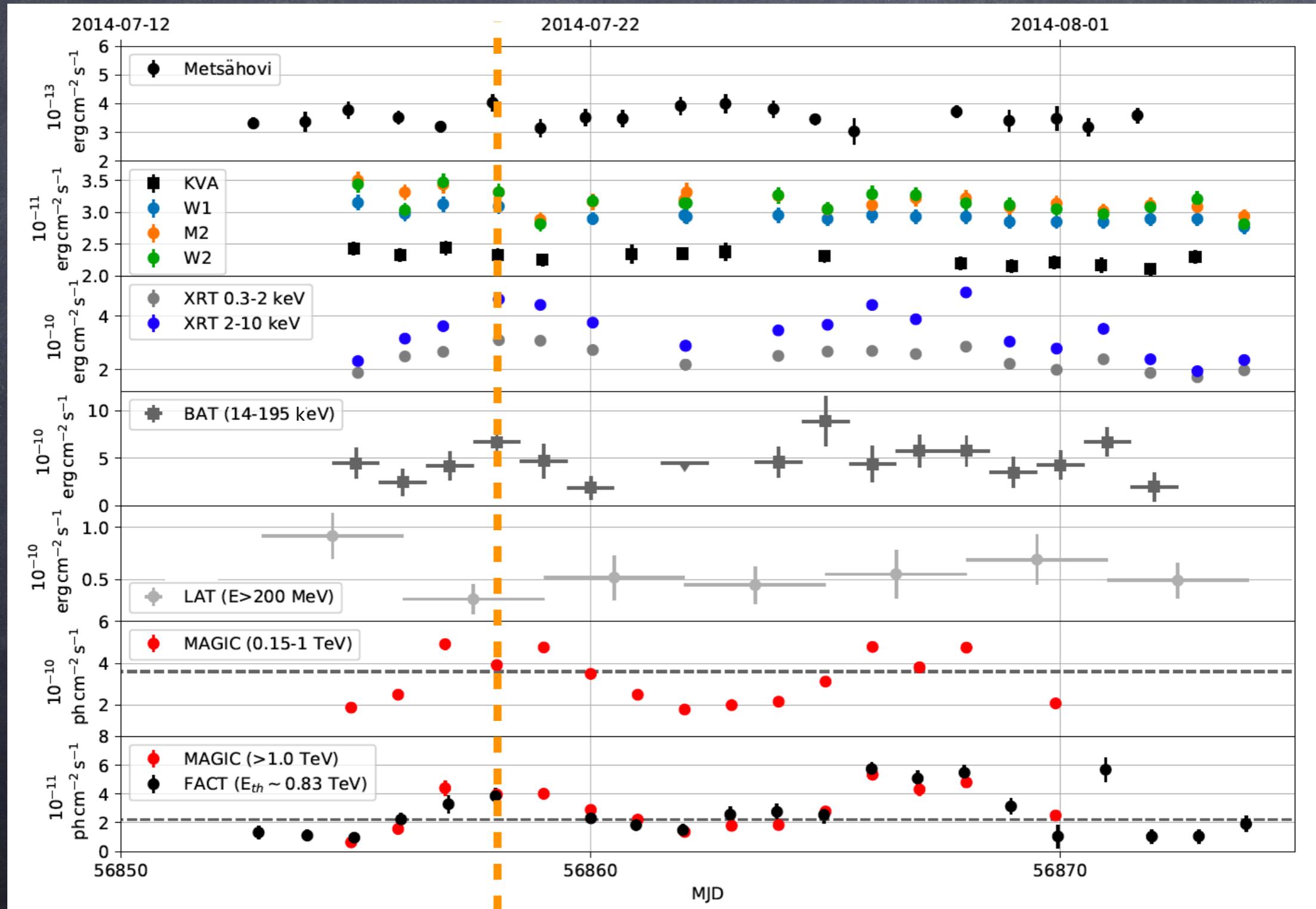


One-zone Synchrotron Self-Compton (SSC)

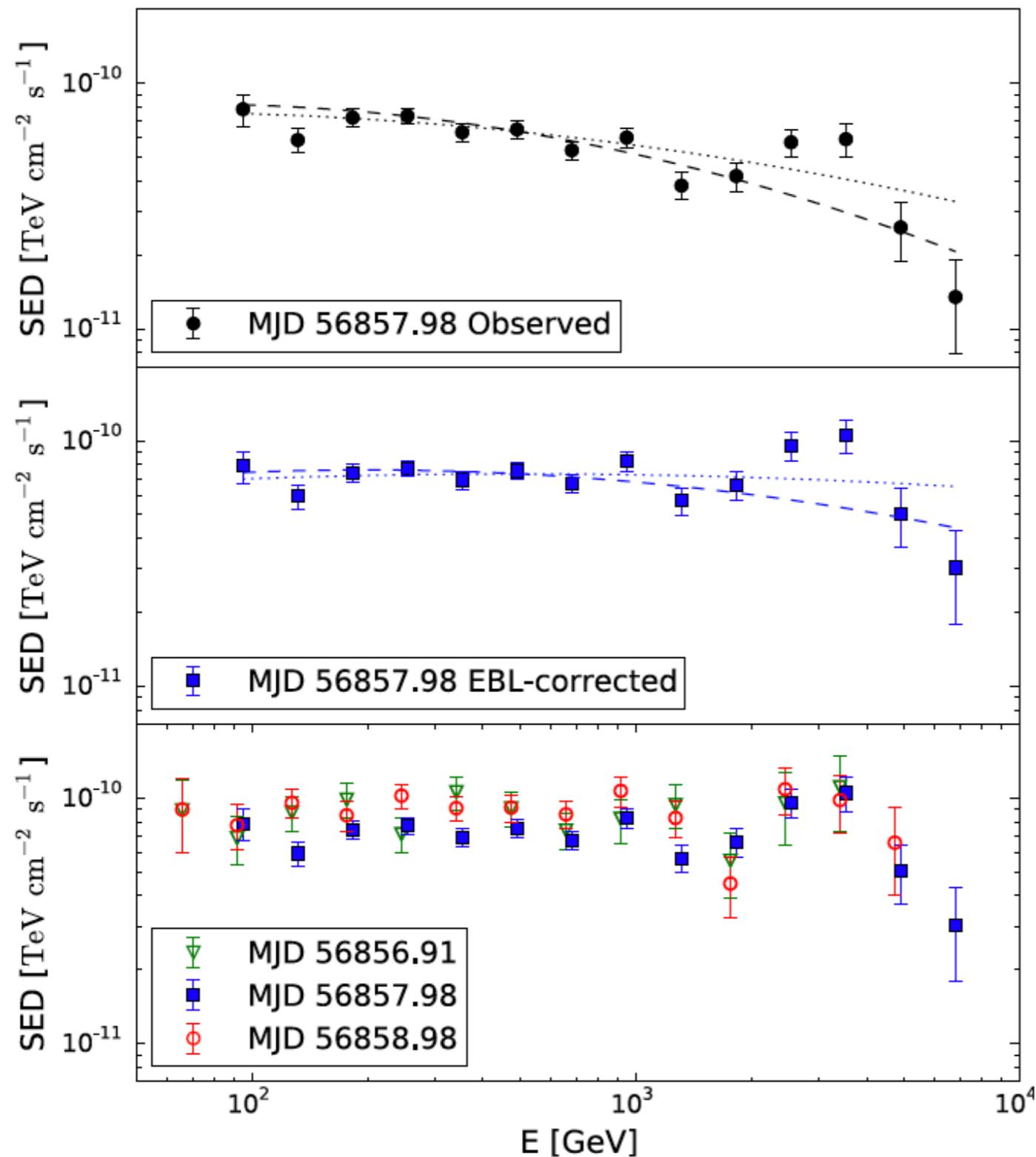
July 19-20



MWL flux evolution during the 2014 flare



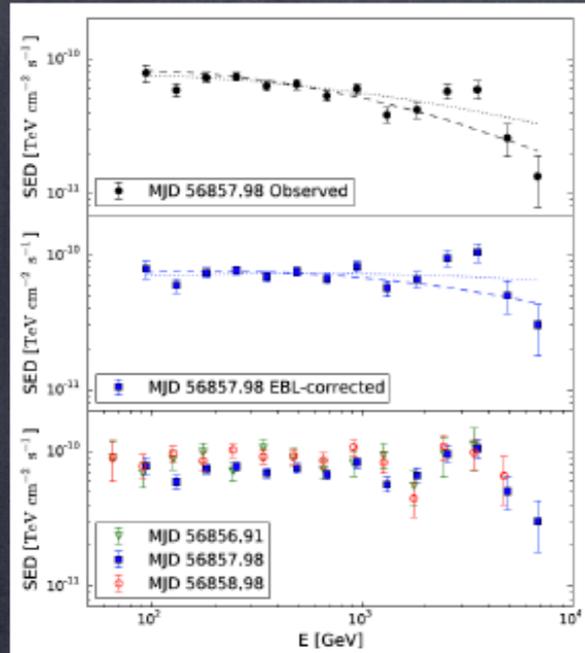
Hint of a narrow VHE spectral feature



- The spectral feature appears in both the observed and EBL-corrected SED
- It is compatible with the previous and following nights SED

July 19–20
(MJD 56857.98)

Hint of a narrow VHE spectral feature



Classical functions can be discarded at 3-4 σ C.L.

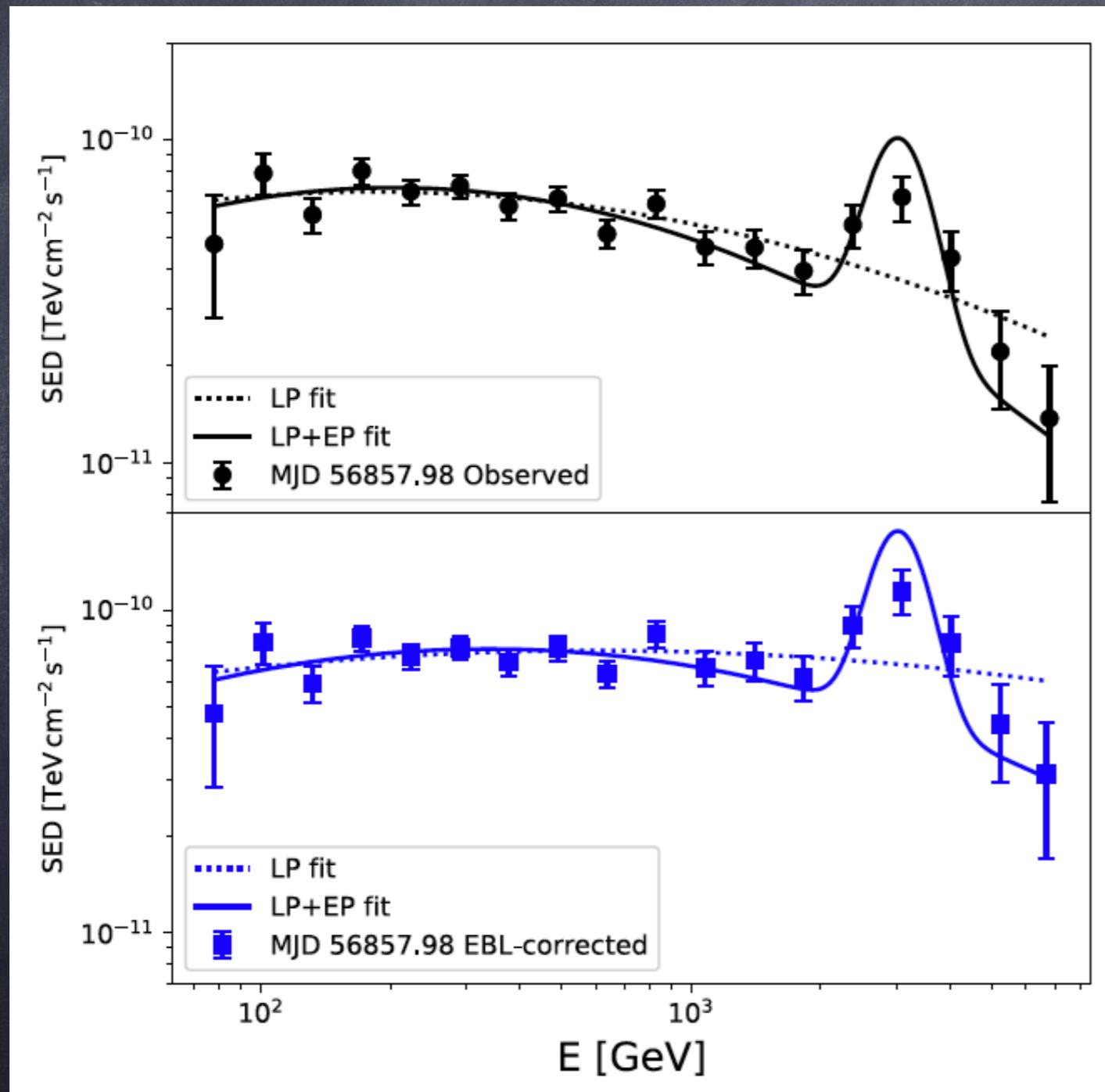
Fits to classical function

	Fit	f_0 [$10^{-10}\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$]	Γ	b	E_c [TeV]	χ^2/df	p-value
Observed	PL	2.32 ± 0.07	-2.20 ± 0.03	-	-	52.1/15	5.5×10^{-6} (4.6 σ)
EBL-corr	PL	2.81 ± 0.08	-2.02 ± 0.03	-	-	36.0/15	1.8×10^{-3} (3.1 σ)
Observed	LP	2.54 ± 0.09	-2.16 ± 0.03	0.08 ± 0.02	-	37.9/14	5.4×10^{-4} (3.5 σ)
EBL-corr	LP	2.93 ± 0.10	-2.00 ± 0.03	0.04 ± 0.02	-	33.0/14	2.9×10^{-3} (3.0 σ)
Observed	ELP	2.69 ± 0.12	-2.02 ± 0.07	-0.02 ± 0.05	5.7 ± 2.9	34.8/13	9.0×10^{-4} (3.3 σ)
EBL-corr	ELP	3.11 ± 0.15	-1.87 ± 0.08	-0.05 ± 0.05	5.8 ± 3.2	31.0/13	3.3×10^{-3} (2.9 σ)

July 19-20 (MJD 56857.98)

Hint of a narrow VHE spectral feature

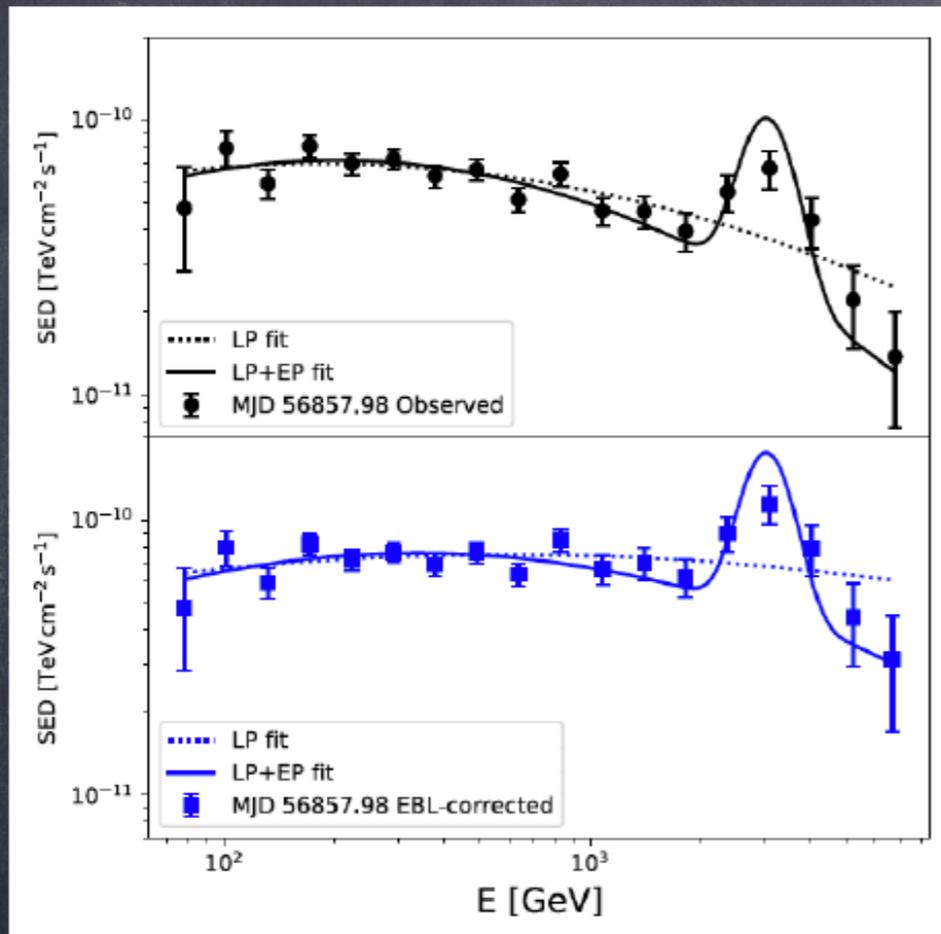
Likelihood Ratio Test



July 19-20
(MJD 56857.98)

Hint of a narrow VHE spectral feature

Likelihood Ratio Test

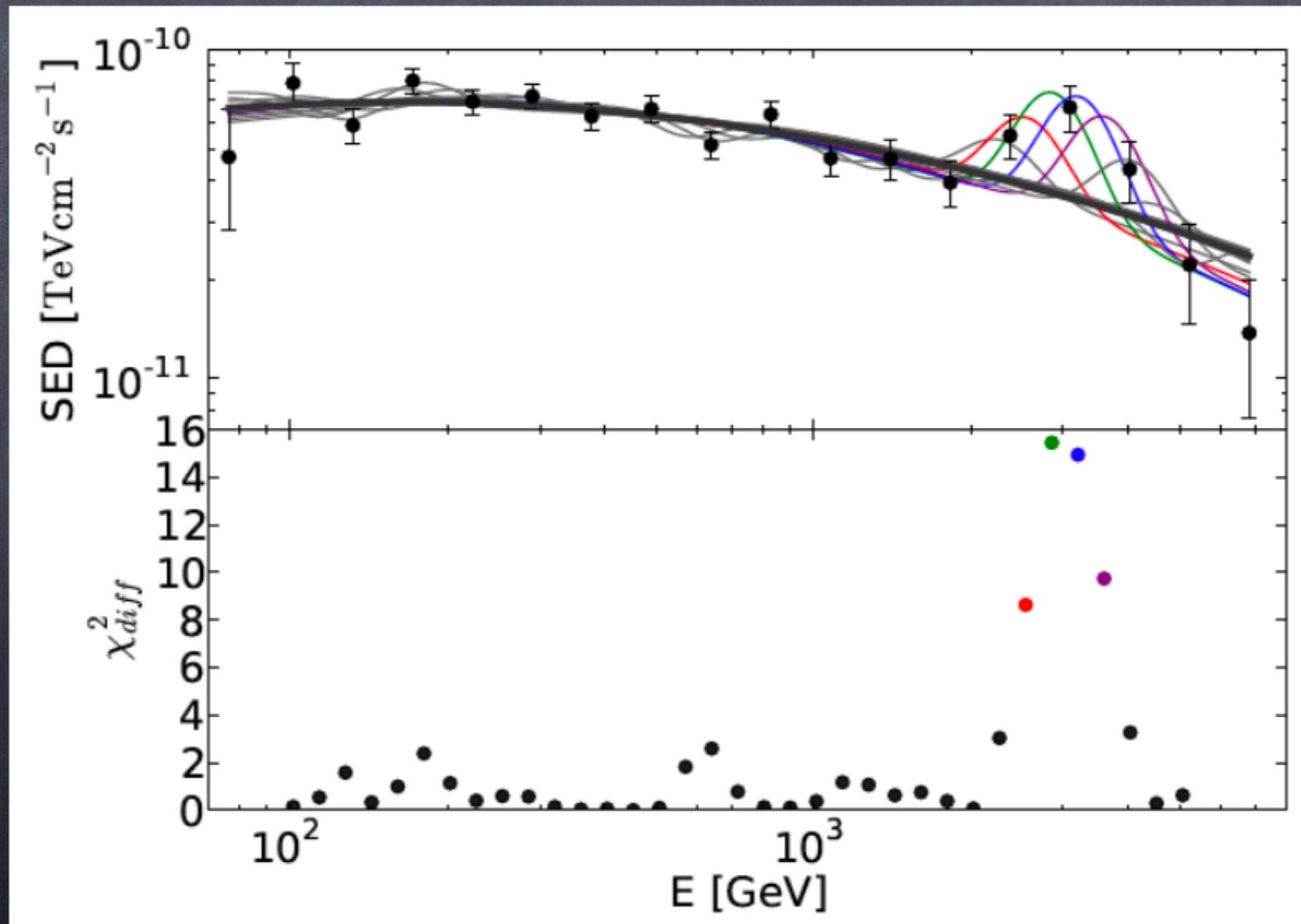


July 19-20
(MJD 56857.98)

	Fit	$f_0 \cdot 10^{10}$ [TeV ⁻¹ cm ⁻² s ⁻¹]	Γ	b	$K \cdot 10^5$ [TeV ⁻¹ cm ⁻² s ⁻¹]	β	E_p [TeV]	χ^2/df	LRT
Observed	LP	2.56 ± 0.09	-2.16 ± 0.03	0.08 ± 0.02	-	-	-	39.8/19	
Observed	LP+EP	2.54 ± 0.10	-2.26 ± 0.04	0.14 ± 0.03	7.7 ± 1.7	9.1 ± 3.2	3.04 ± 0.10	13.5/16	4.5σ
EBL-corr	LP	3.00 ± 0.11	-1.99 ± 0.03	0.04 ± 0.02	-	-	-	35.4/19	
EBL-corr	LP+EP	2.99 ± 0.11	-2.08 ± 0.04	0.10 ± 0.03	13.0 ± 3.0	10.0 ± 3.6	3.03 ± 0.10	14.6/16	3.9σ

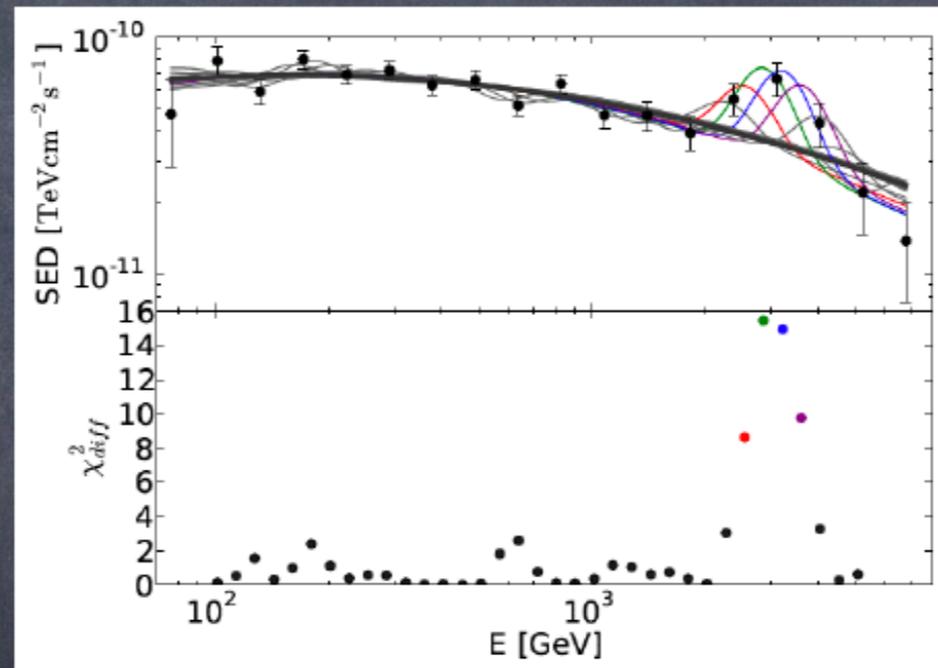
Hint of a narrow VHE spectral feature

Monte Carlo simulations (10,000 realizations): χ^2 difference between a log-parabola fit (null hypothesis) w.r.t. log-parabola+narrow component peaking at different energies



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Monte Carlo simulations (10,000 realizations): χ^2 difference between a log-parabola fit (null hypothesis) w.r.t. log-parabola+narrow component peaking at different energies

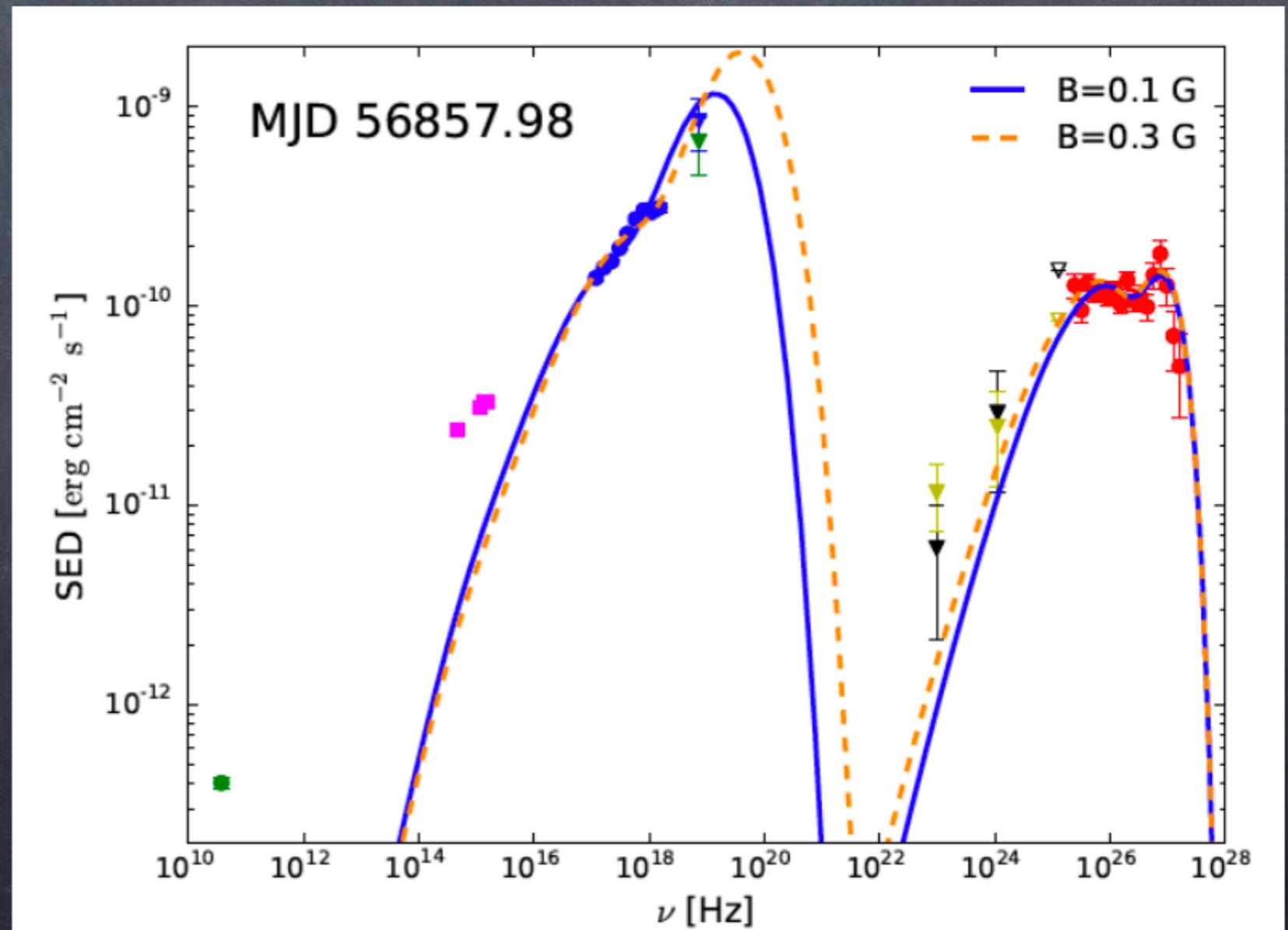


	Experimental data		MC data: 10^4 simulated spectra	
	$\chi^2_{diff-data}$	P_{value} (significance)	$N > \chi^2_{diff-data}$	P_{value} (significance)
Observed	18.1	4.2×10^{-4} (3.5σ)	3	3.0×10^{-4} (3.6σ)
EBL-corr	15.8	1.2×10^{-3} (3.2σ)	11	1.1×10^{-3} (3.3σ)

Theoretical interpretation

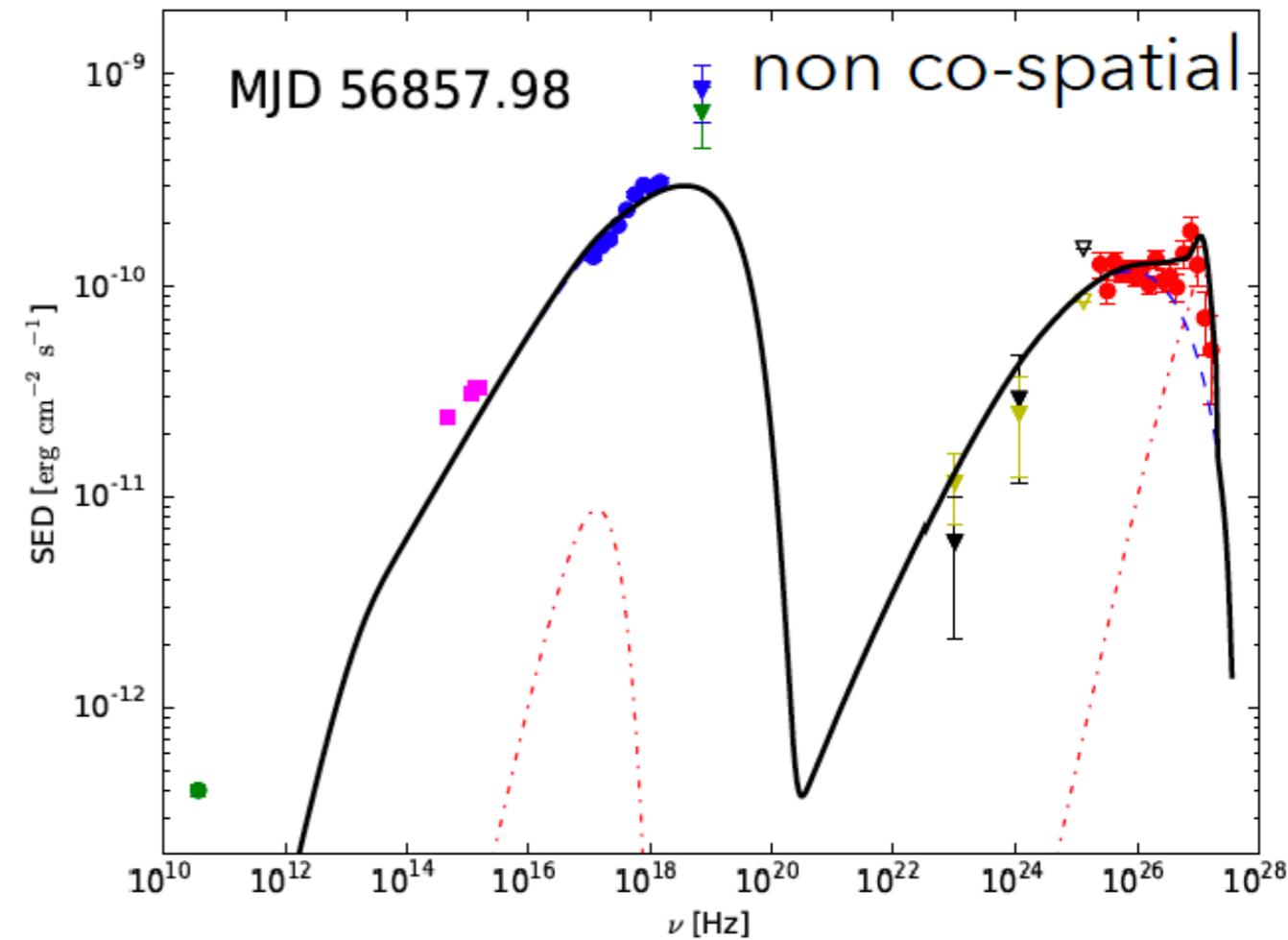
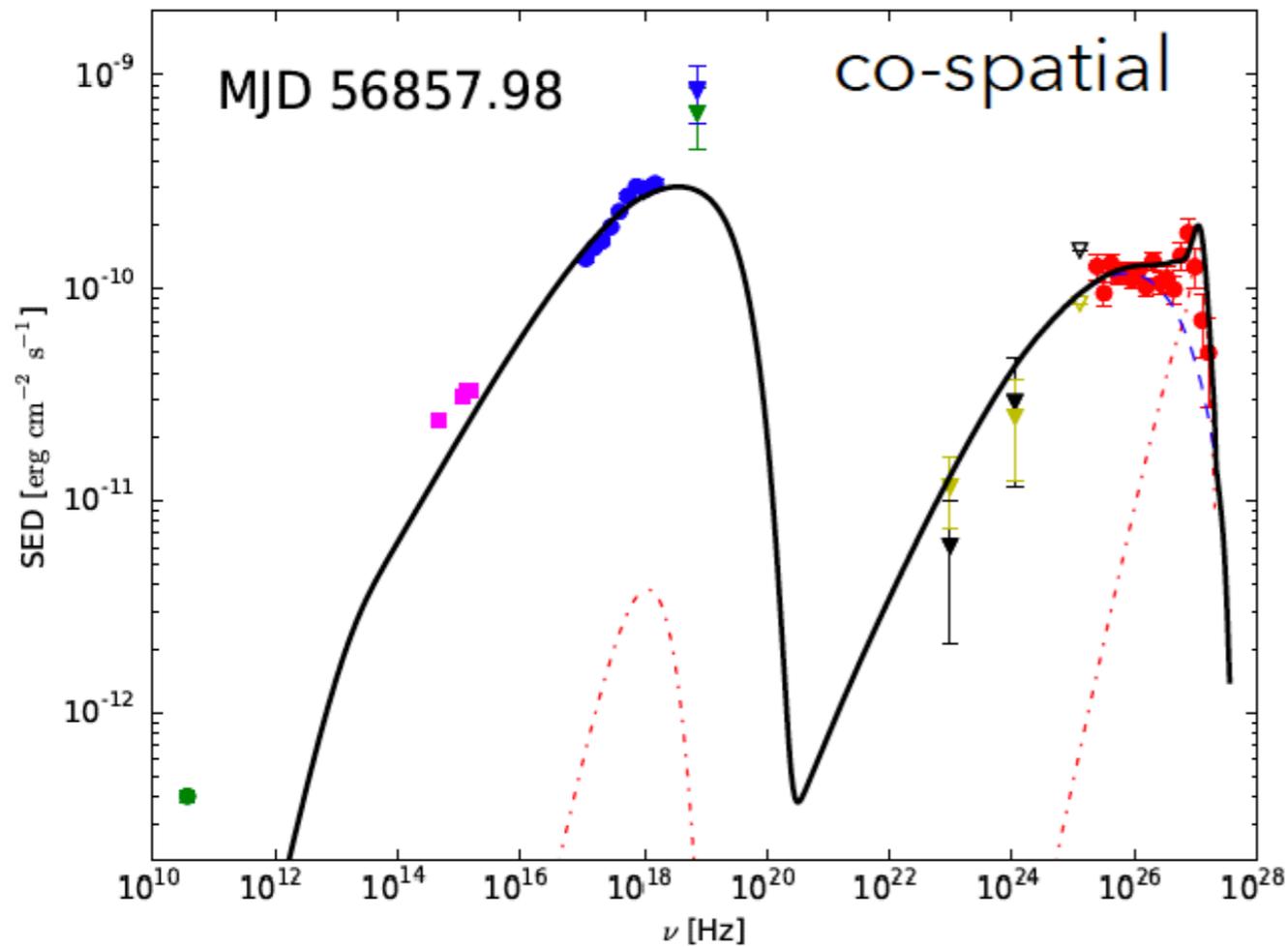
a) Pile up in the energy electron distribution due to stochastic acceleration

JetSeT open code



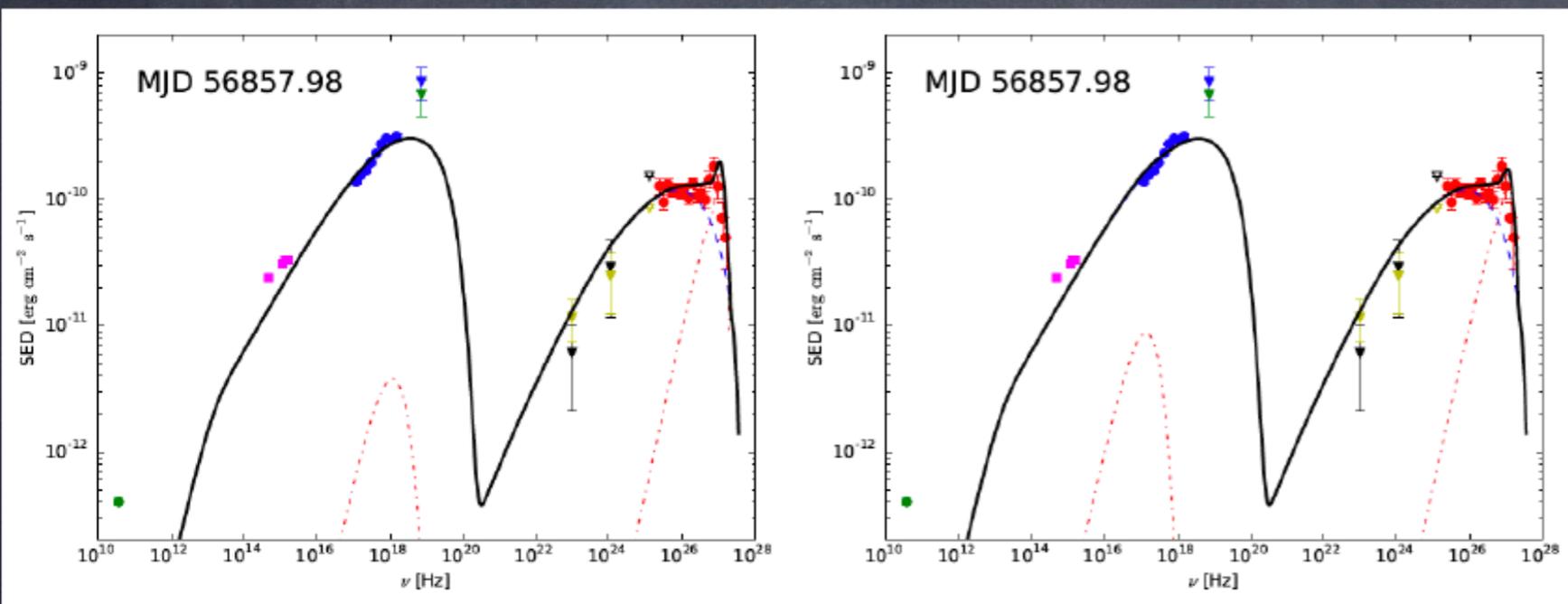
Theoretical interpretation

b) Structured jet: two-zone SSC model

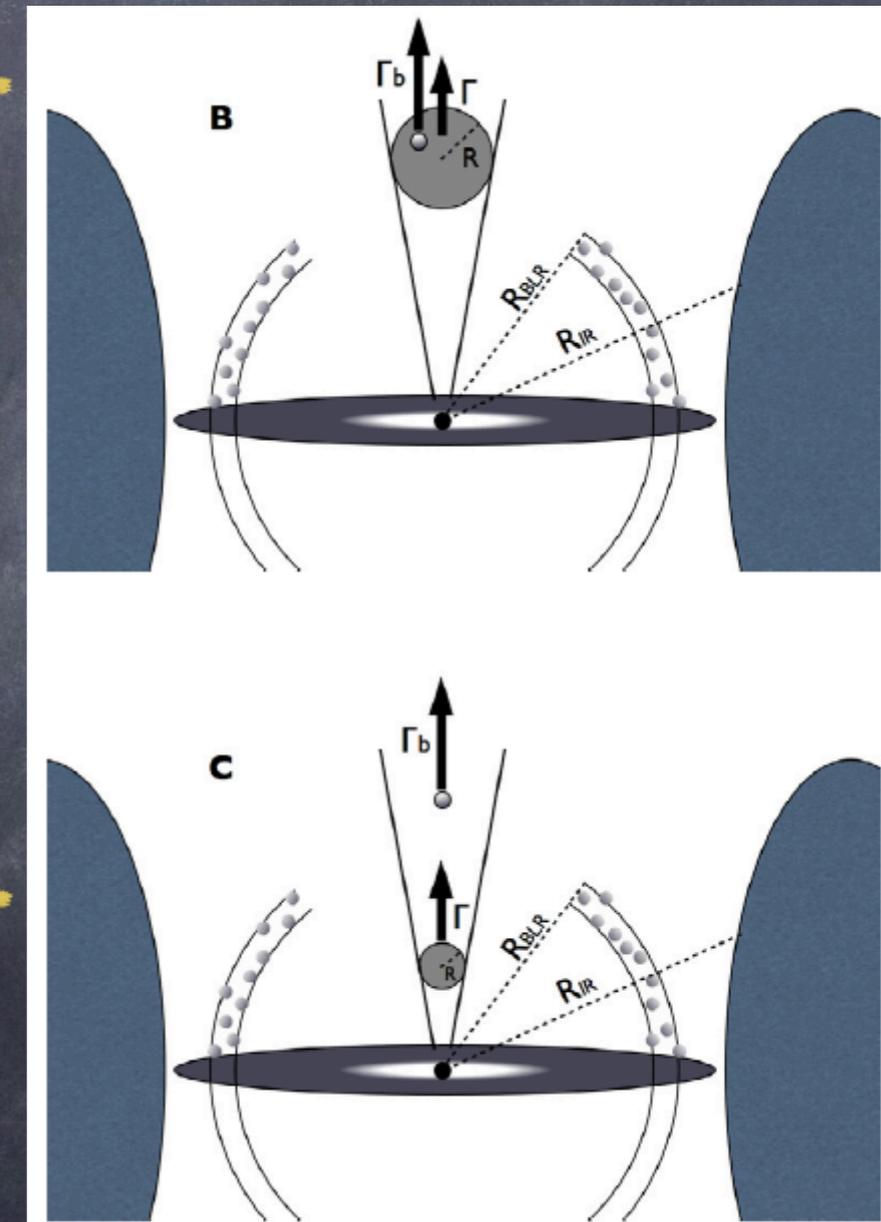


Theoretical interpretation

b) Structured jet: two-zone SSC model



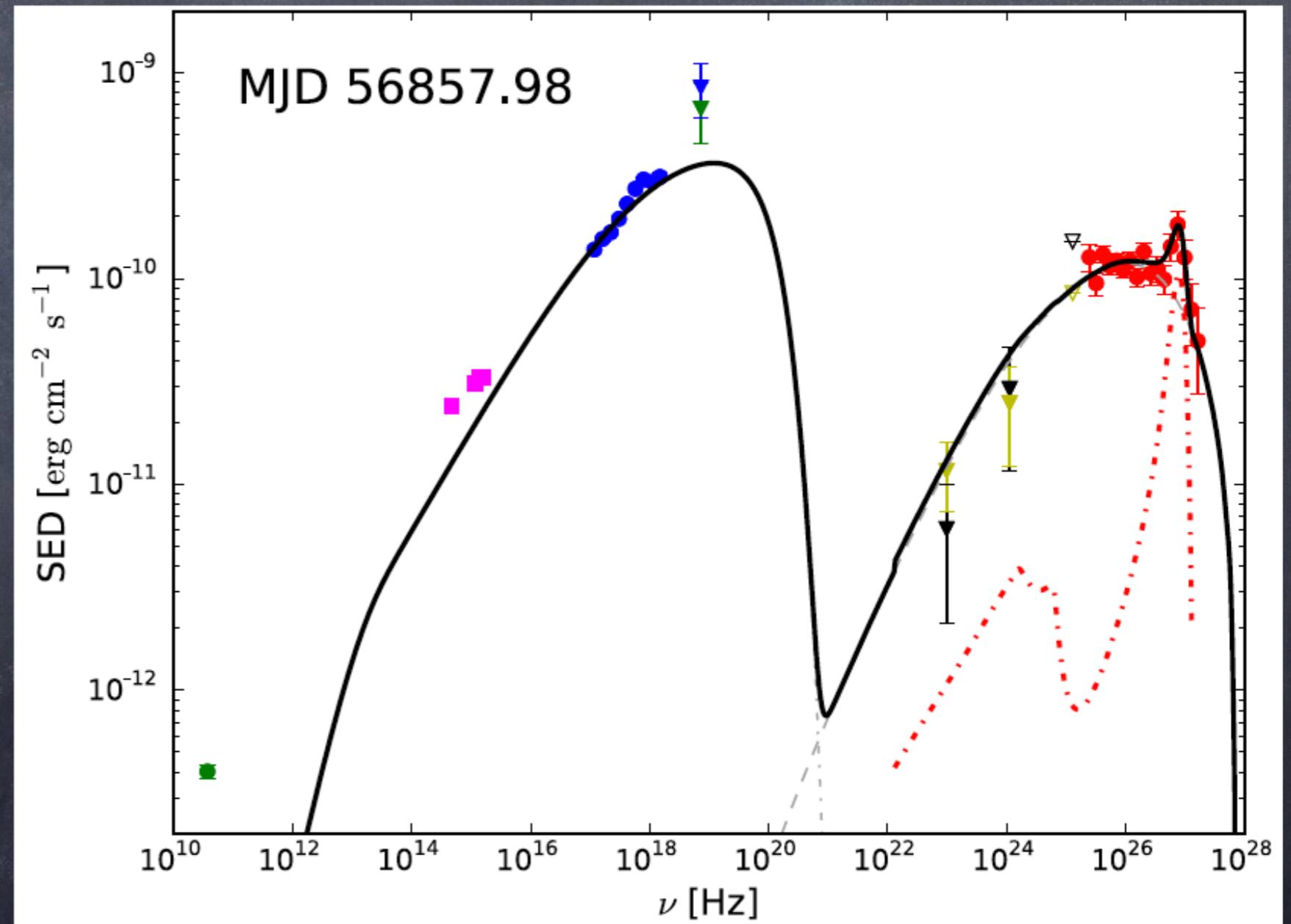
MAGIC Coll. (JBG, DP) 2020, A&A, 637, A86



Tavecchio, JBG et al., 2011, A&A, 534, A86

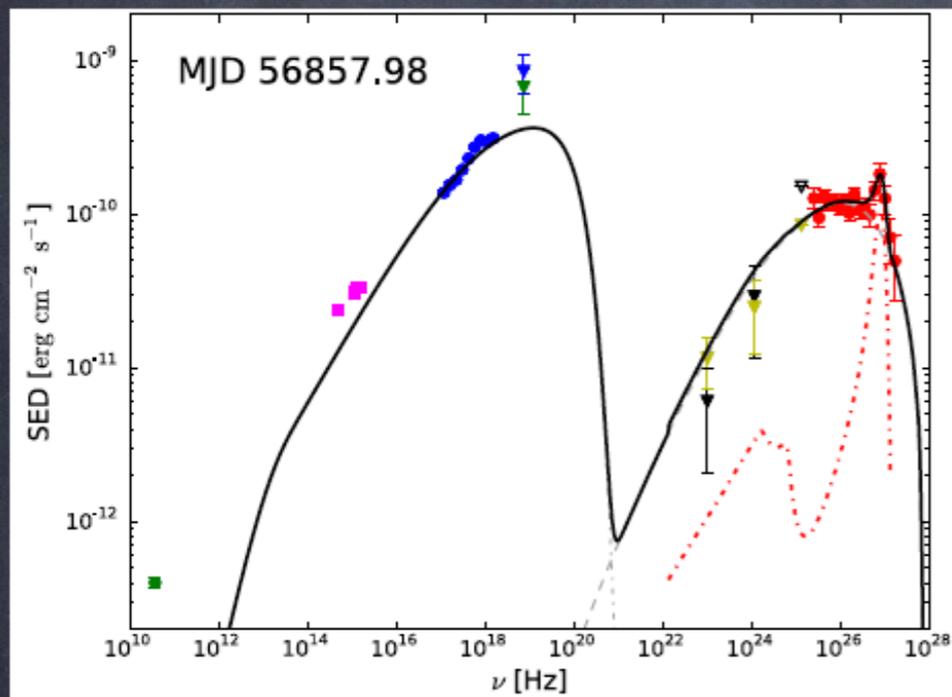
Theoretical interpretation

c) Magnetospheric vacuum gap model + one-zone SSC



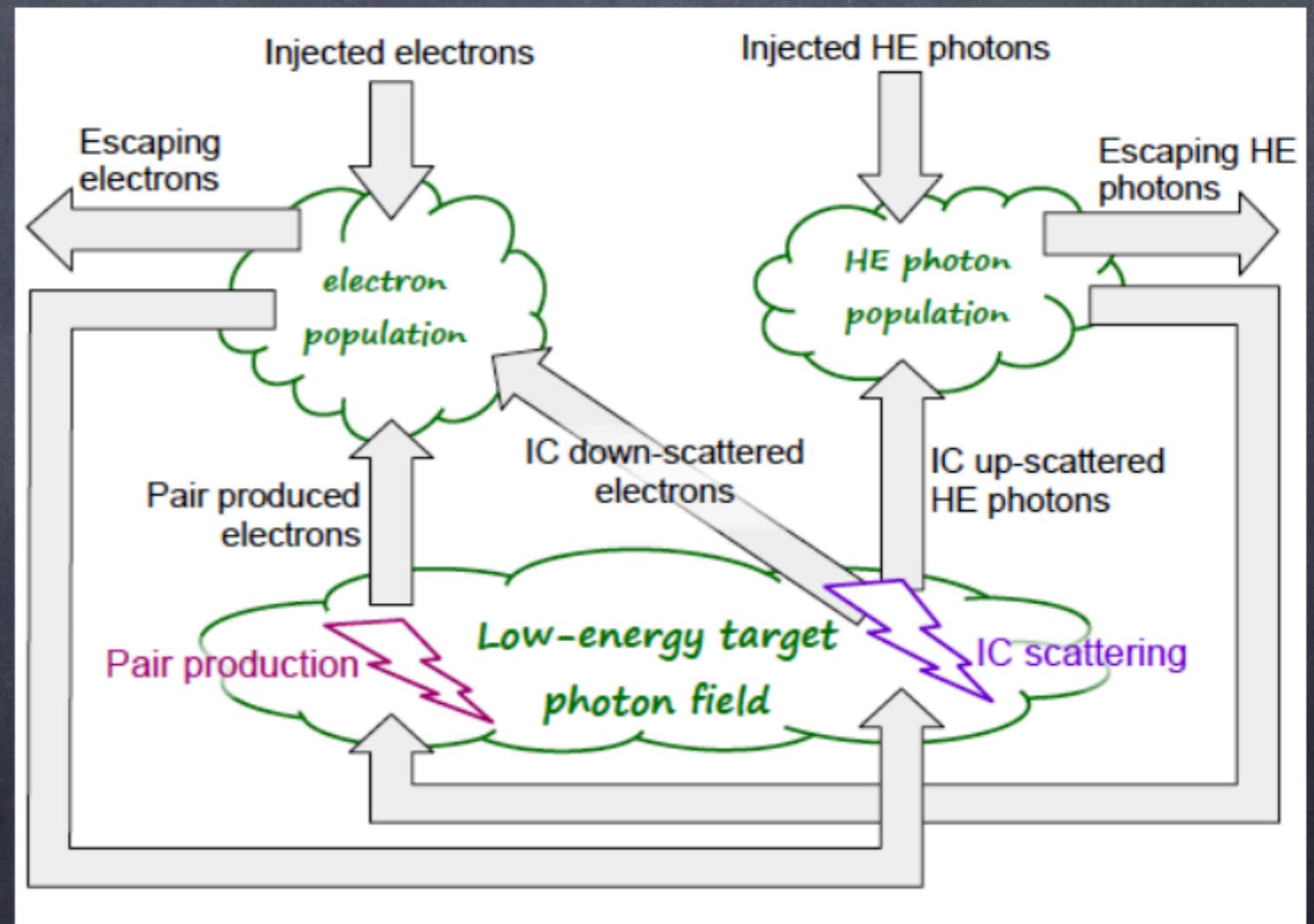
Theoretical interpretation

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MAGIC Coll. (JBG, DP) 2020, A&A, 637, A86

Wendel, JBG, et al. 2021, A&A, 646, A115



See Talk #141 by C. Wendel

Take home message

- Detection of the **historical maximum** of the X-ray emission during the 16 years Swift-XRT operation (at the level of the historical 1997 flare)
- Detected the first **evidence for a narrow VHE spectral feature**, centered at approx. 3 TeV
- This feature could be interpreted within the framework of 3 different theoretical scenarios:
 - A) Pile up in the electron energy distribution
 - B) Two-zone SSC model
 - C) Magnetospheric gap model + one-zone SSC