CDY Initiative, April 2022

Blazars as gamma-ray emitters

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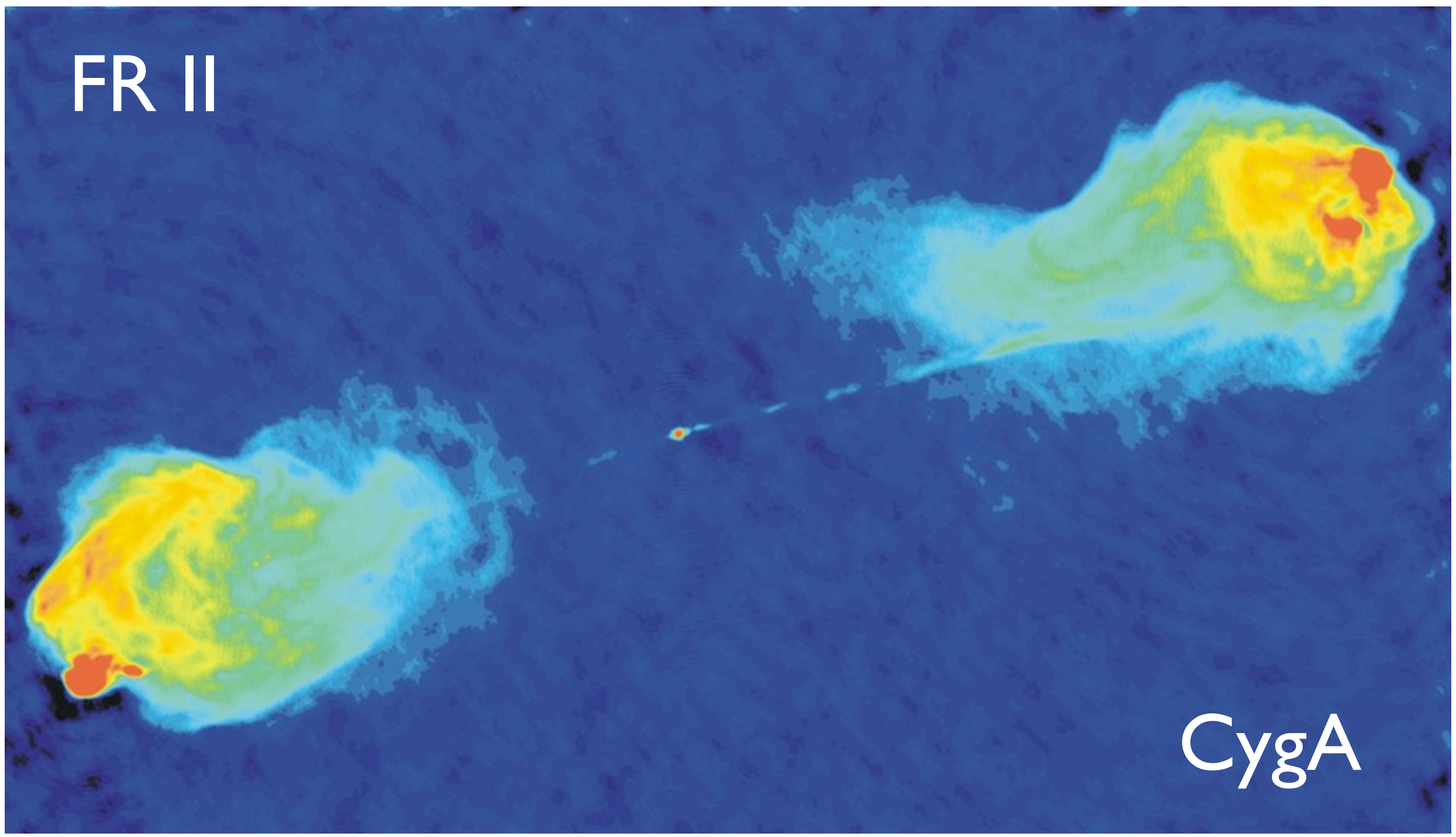
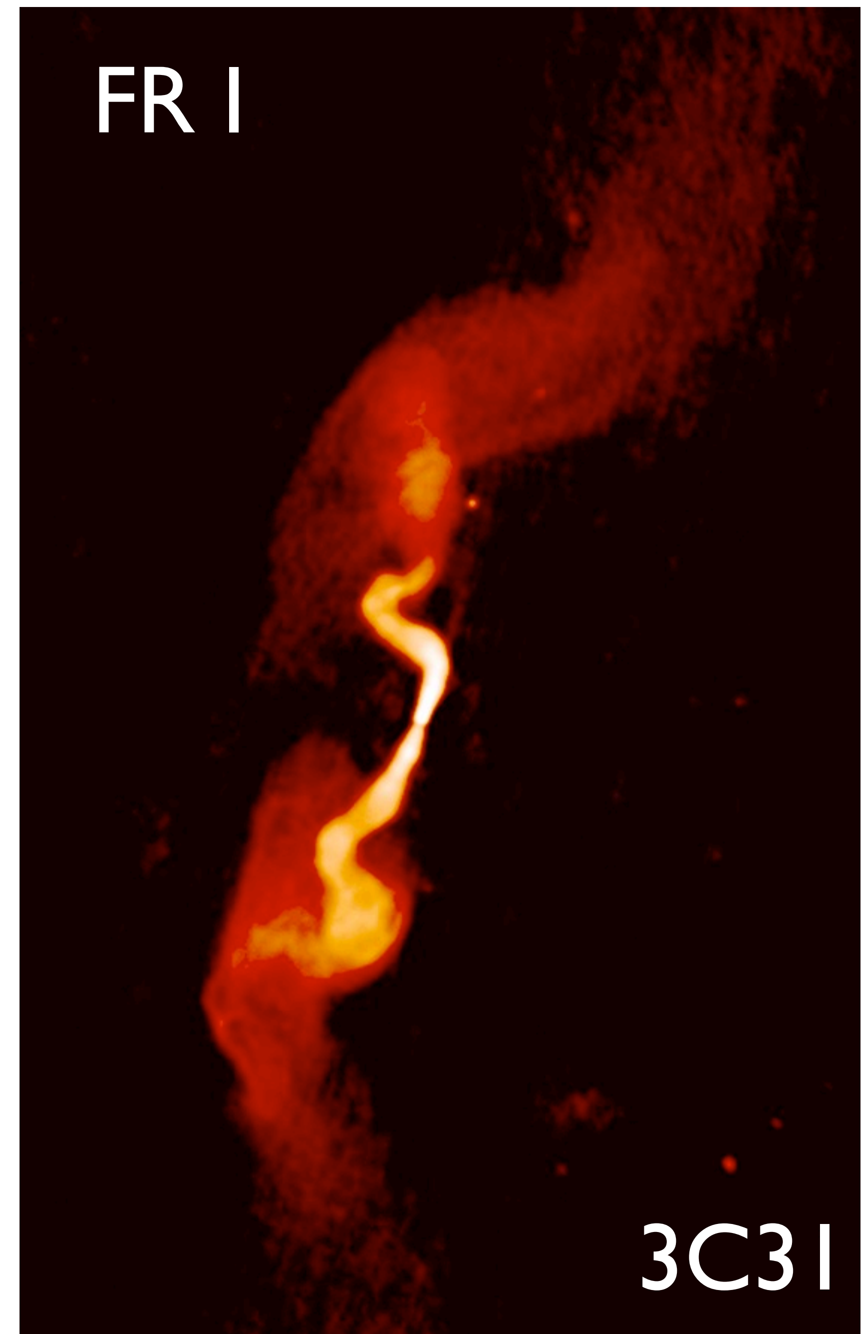
Thanks to all my long-time collaborators and mentors:
F. Aharonian & group, G. Ghisellini & group, IACTs & LAT collaborators, P. Padovani, G. Tosti et al.

Galaxies: ~1% Active Nucleus (AGN)

~0.1% relativistic jets

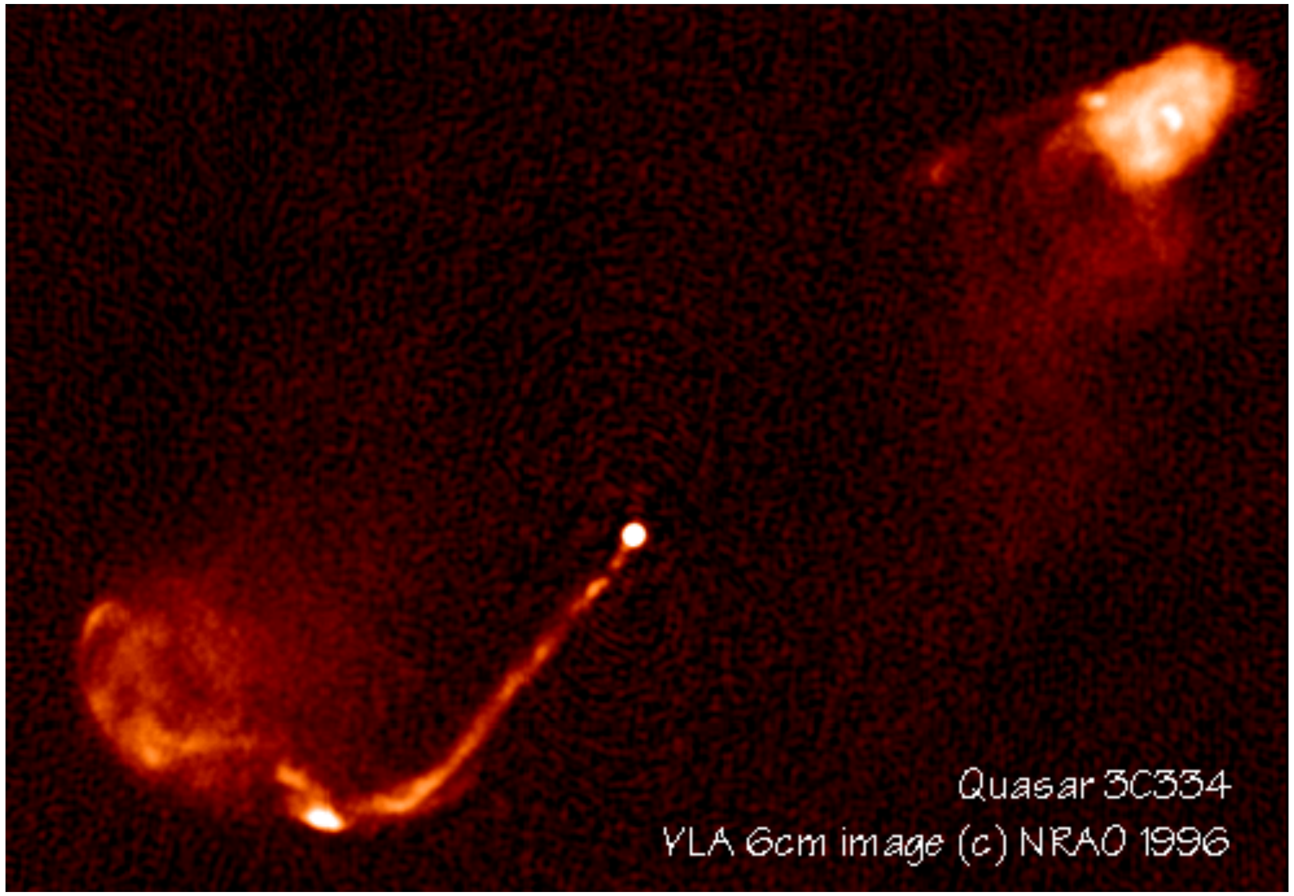


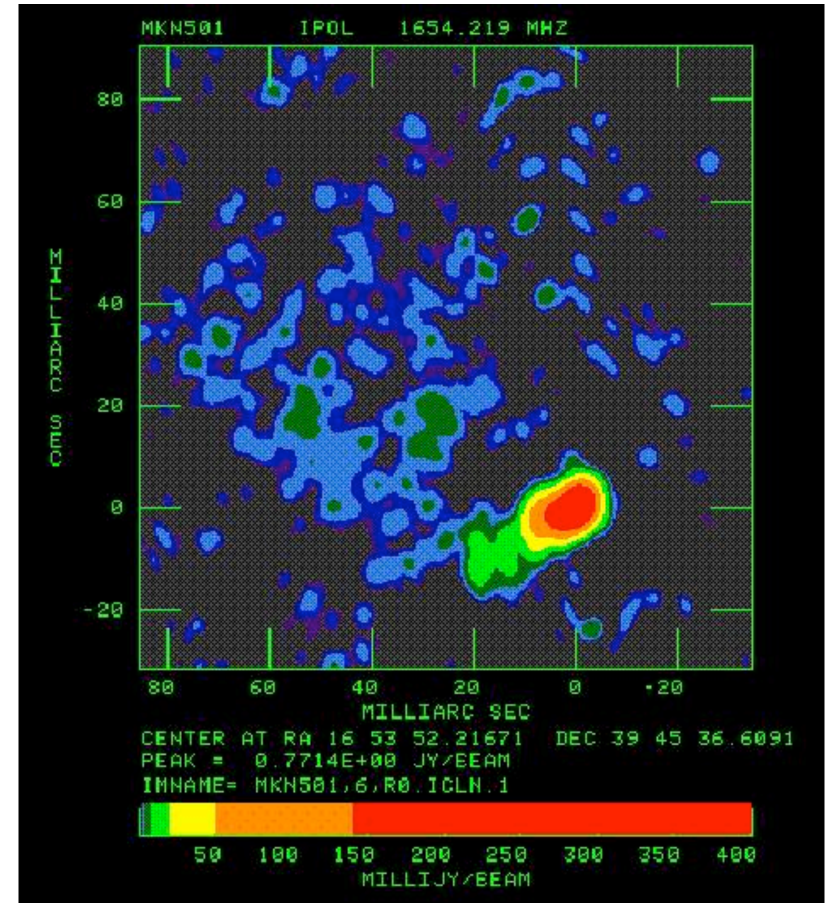


Radio Loud AGN

$F_{5Ghz} / F_{Opt(B)} > 10$

Jet closer and closer to the line of sight…



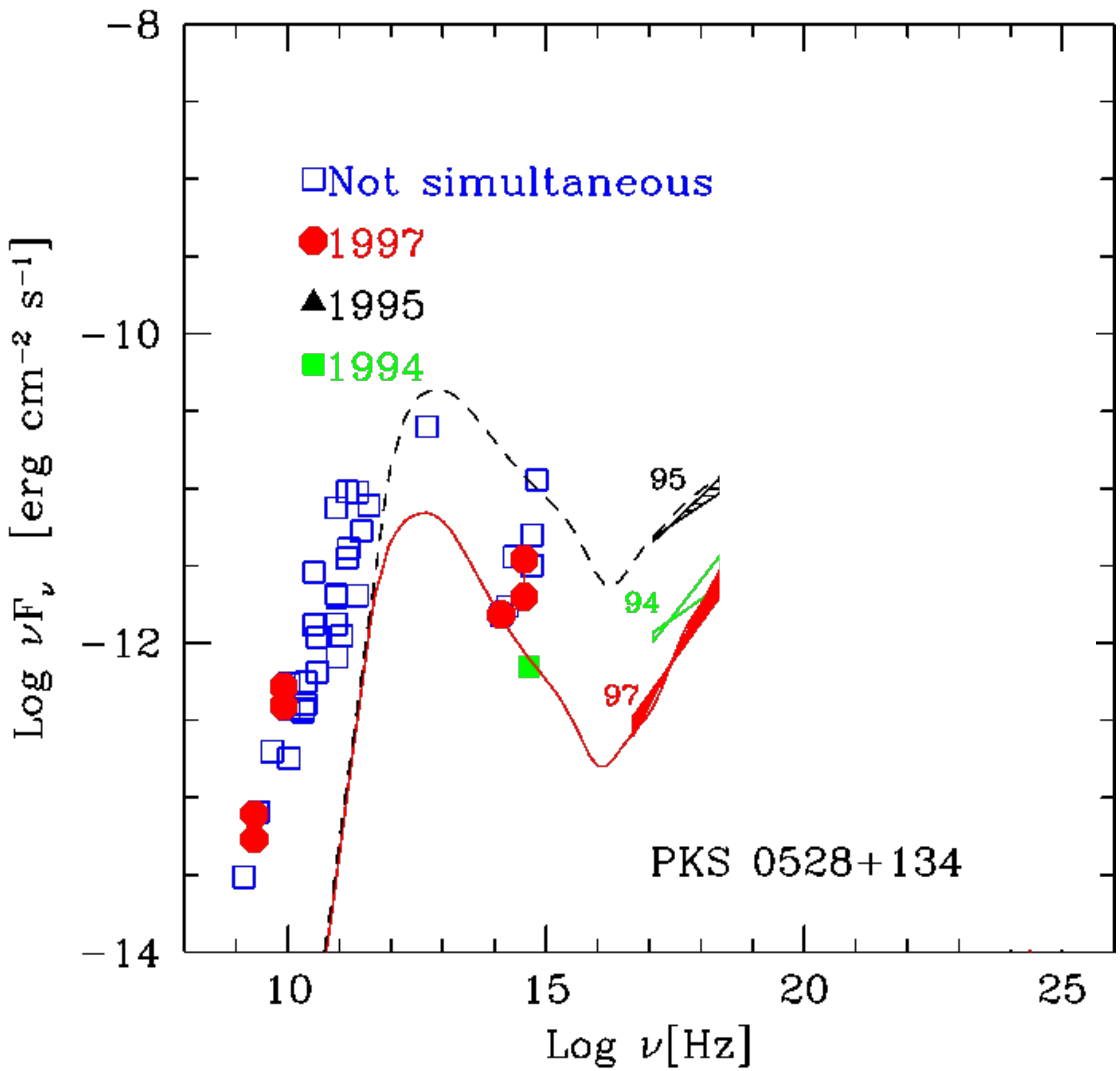


Blandford & Rees (1978):

We would therefore like to propose the hypothesis that Lacertids (and perhaps also optically violent variable quasars) are active galactic nuclei where the continuum emission is enhanced by being beamed toward us.

BLAZAR: term invented in 1978 by E. Spiegel to denote objects with properties of both BL Lacertae and OVV quasars

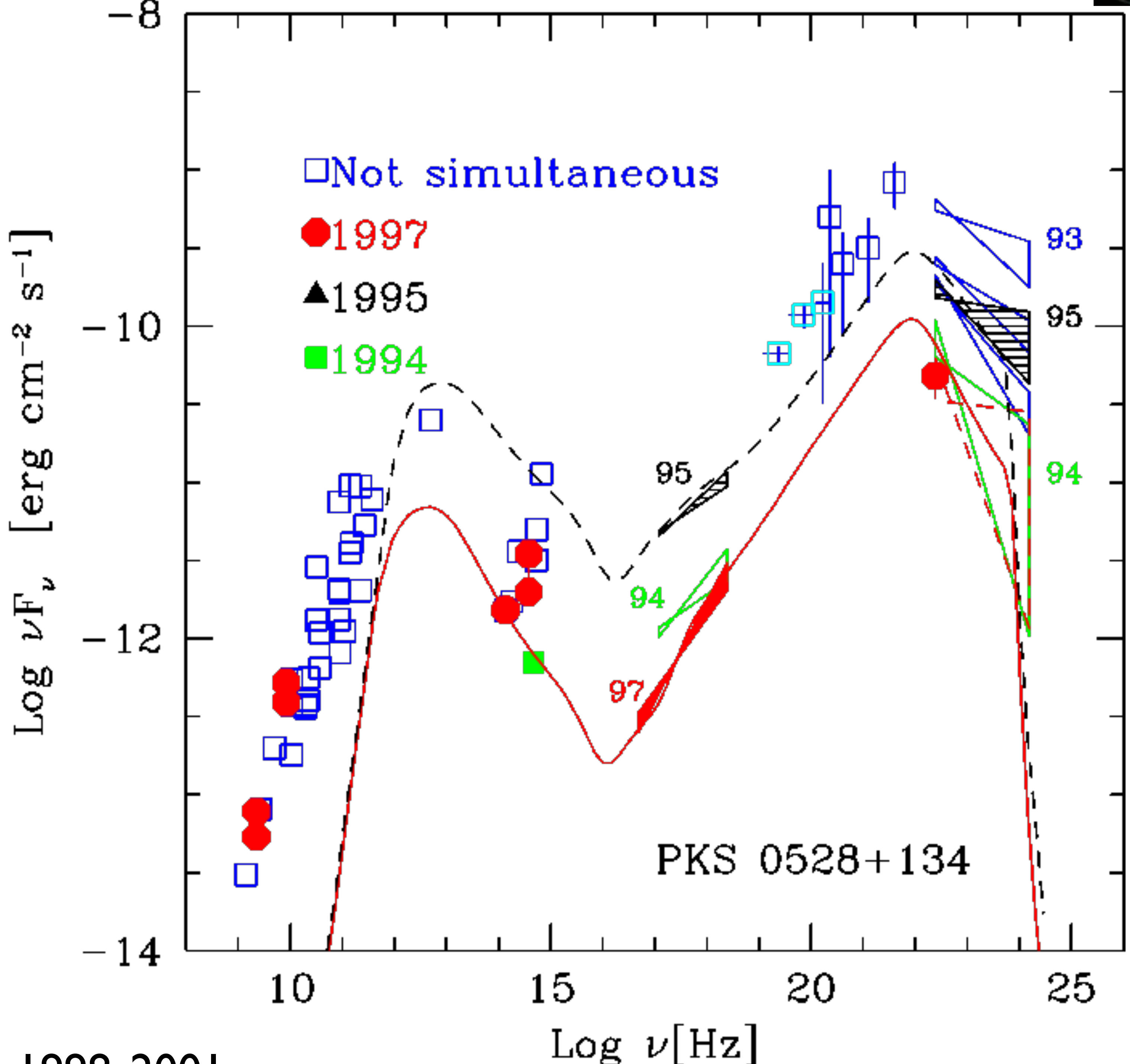
Spectral Energy Distribution (SED)



pre-1991
pre-CGRO

COS-B: 3C273
only extragalactic
γ-ray source

EGRET on-board CGRO
~67 blazars detected (1991-2000)

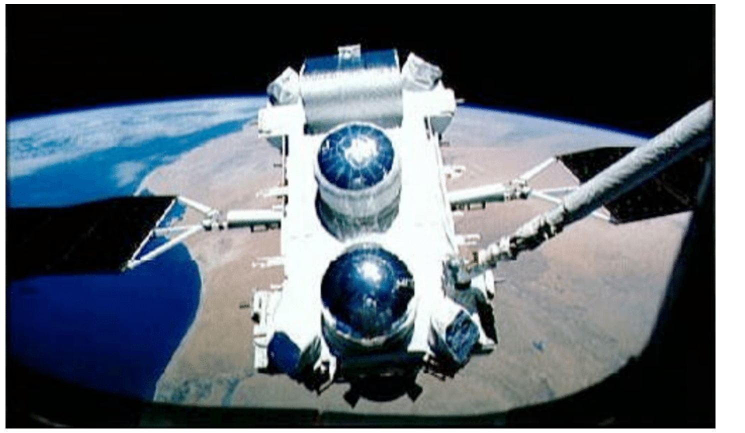


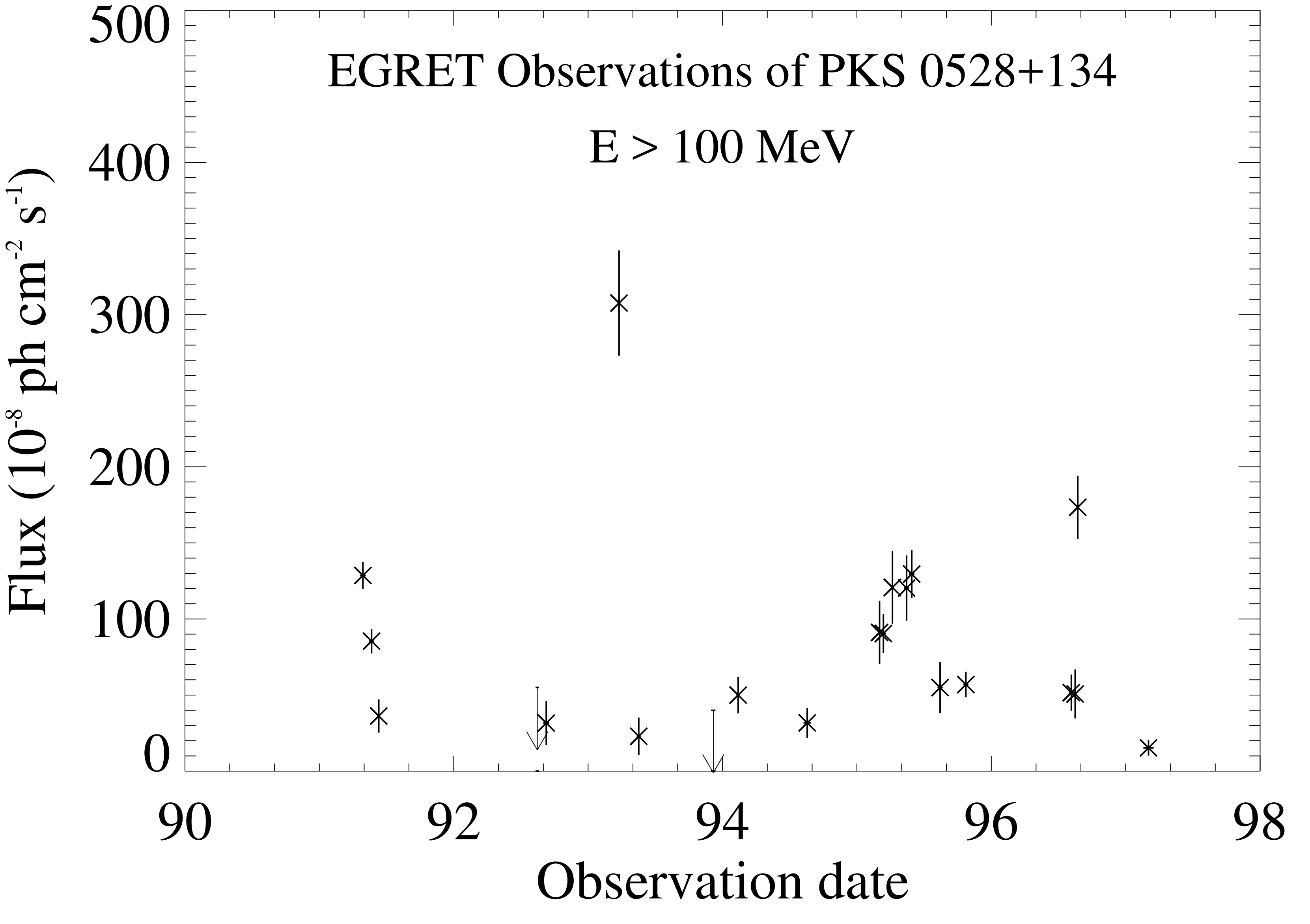
1) revealed gamma-ray peak

2) can dominate bolometric output

Mukherjee et al. 1998, 2001
Ghisellini et al. 1998

EGRET on-board CGRO
~67 blazars detected (1991-2000)



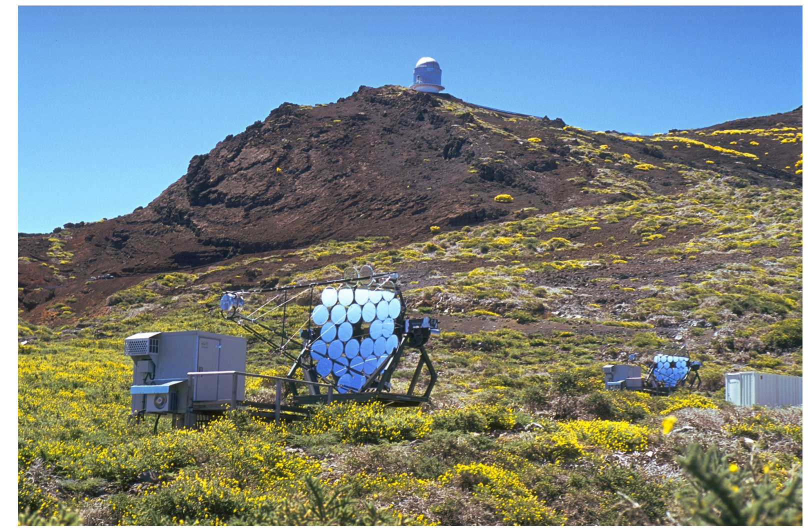


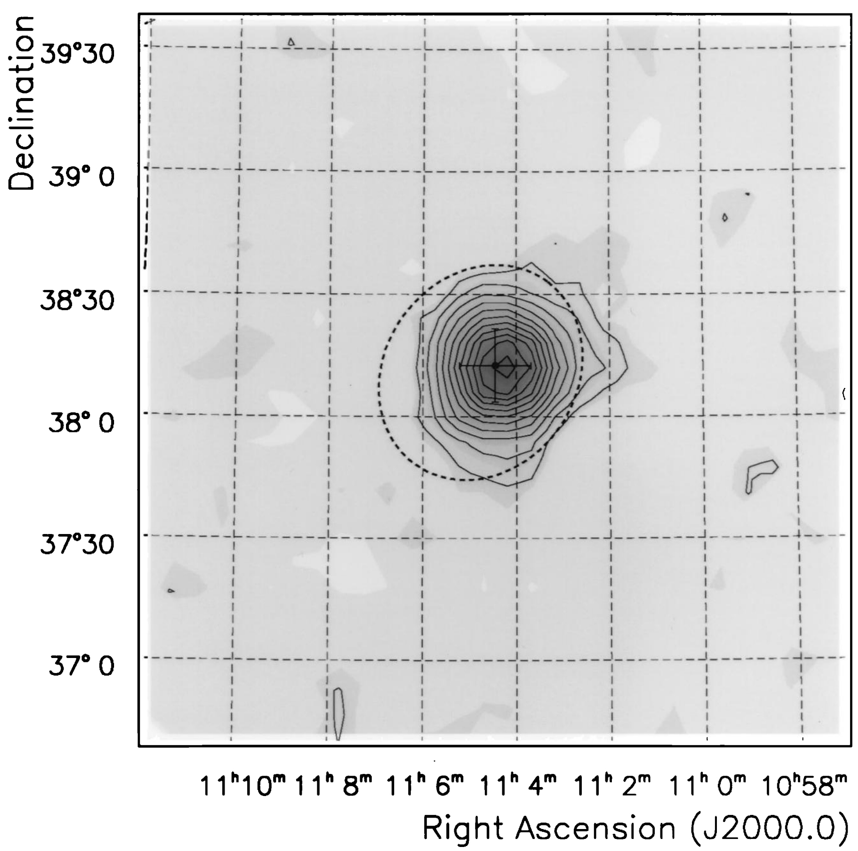
1) revealed gamma-ray peak
2) can dominate bolometric output
3) highly variable (also intraday)

Mukherjee et al. 1998, 2001
Ghisellini et al. 1998

Atmospheric Cherenkov Telescopes: opened TeV-domain (6 BL Lacs)

Whipple, CAT HEGRA (stereo 4-tel)





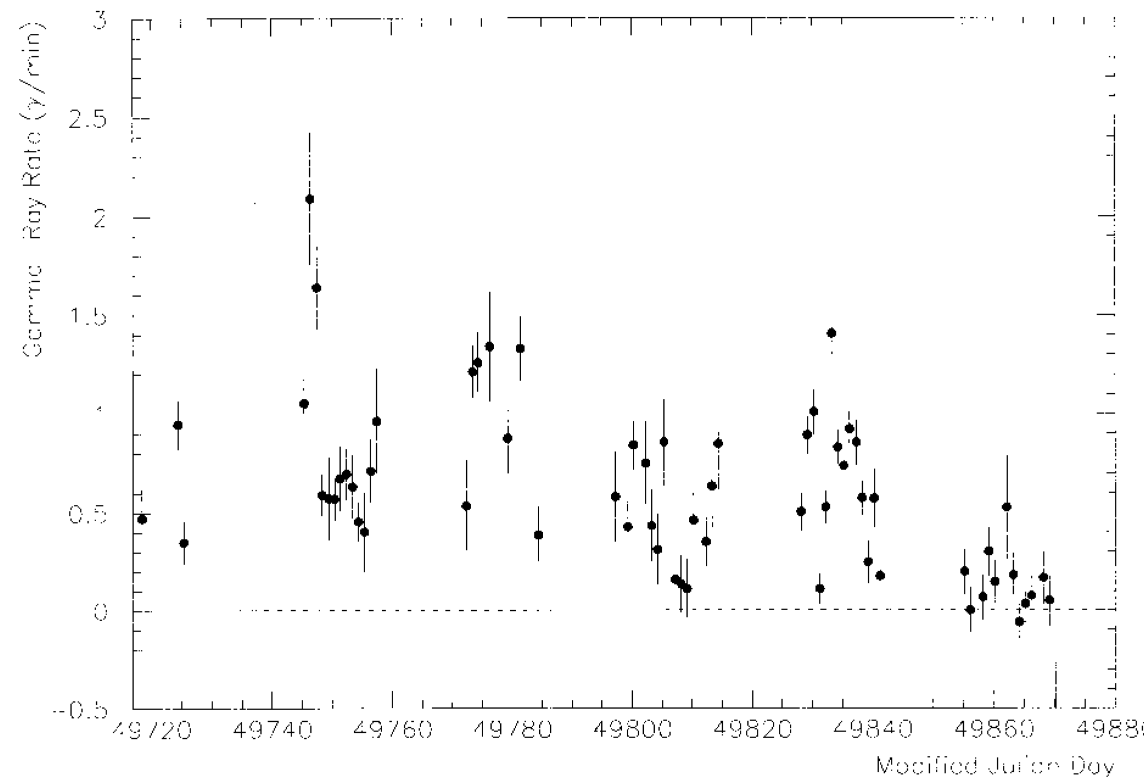


FIG. 2.—Daily γ-ray rates at $E > 300$ GeV for Mrk 421 during the 1995 season.

Mkn 421: Punch et al. 1992, Buckley et al. 1996

Blazars differ by two main properties:

1) Thermal Properties

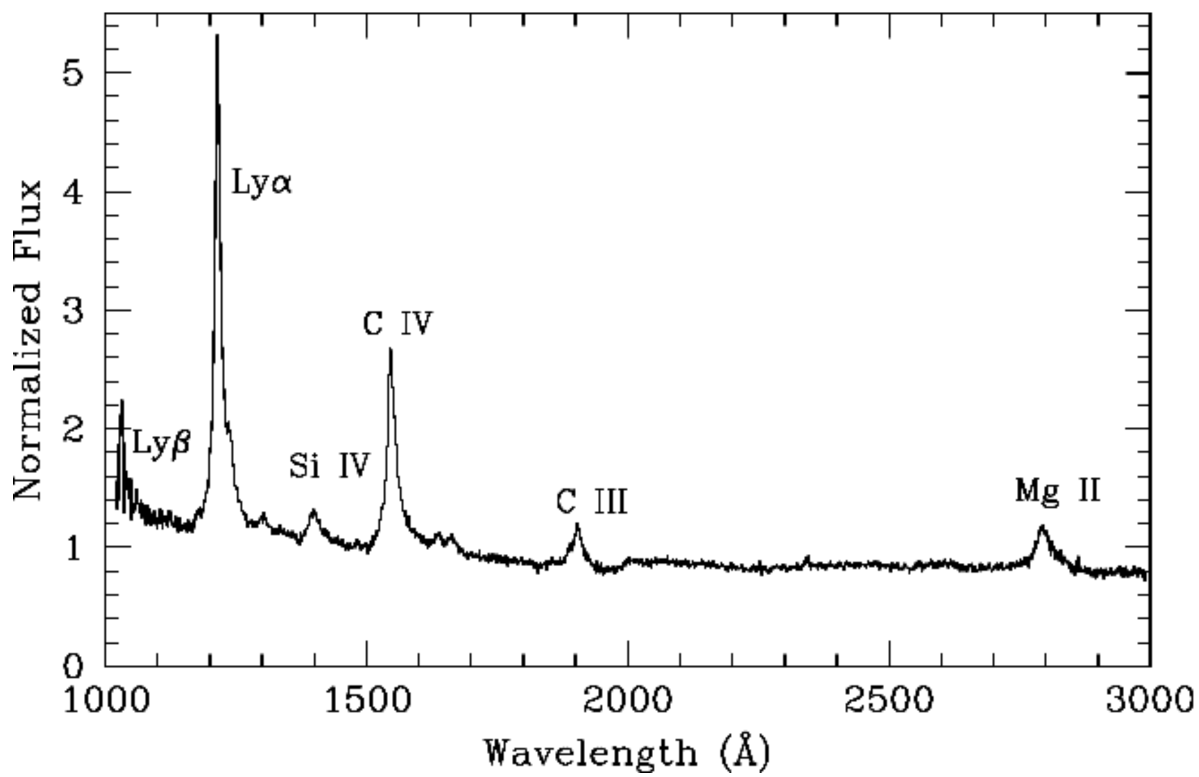
FSRQ (FR II) **BL Lacs (FR I)**

Broad Emission Lines:

EW>5 Å **EW<5 Å**

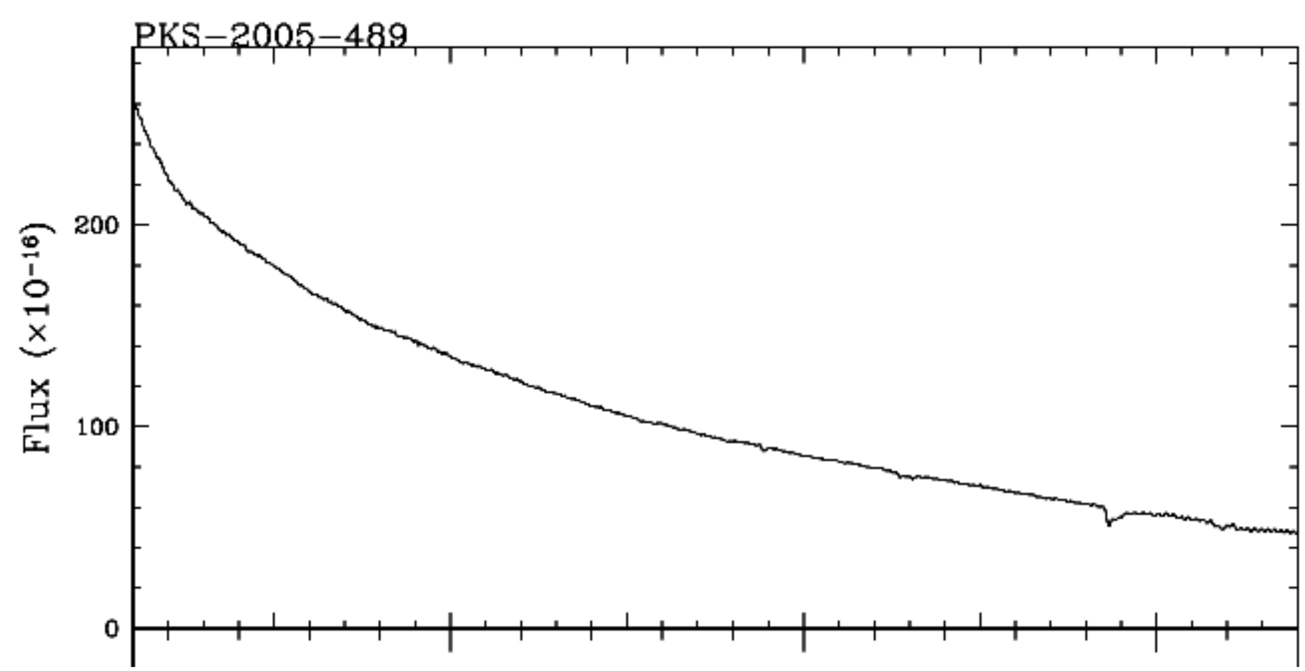
$L_{lines} \sim 10^{46}$ erg/s -------------------▶ $<10^{40}$ erg/s

Strong Disk (UV) & Torus (IR) emission



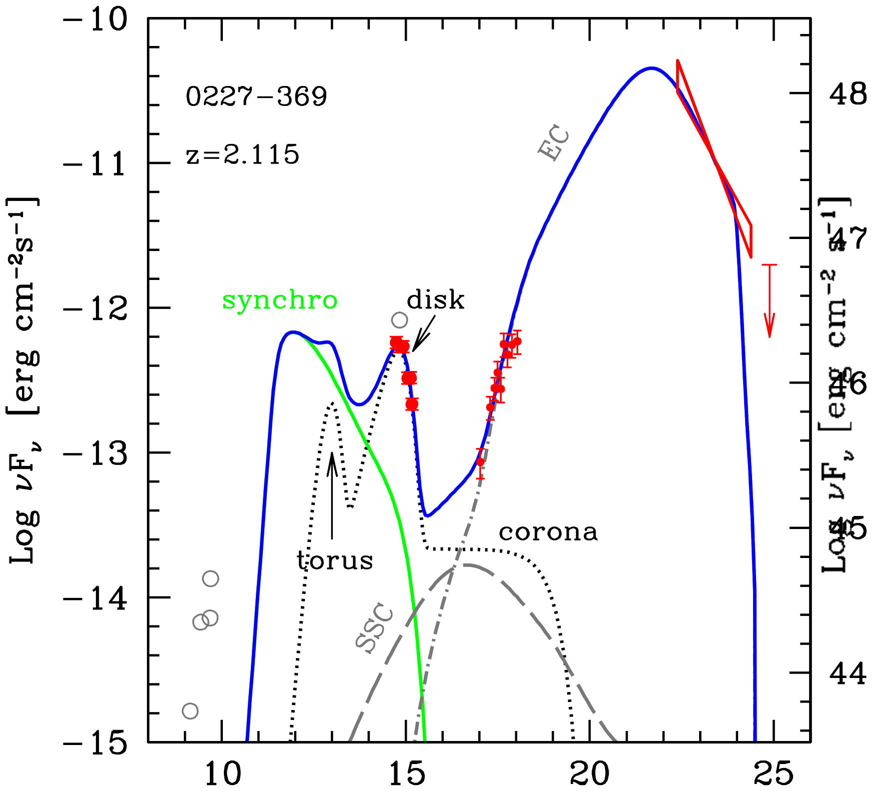
Pian et al. 2005

Weak/absent Disk (UV) & Torus (IR) emission



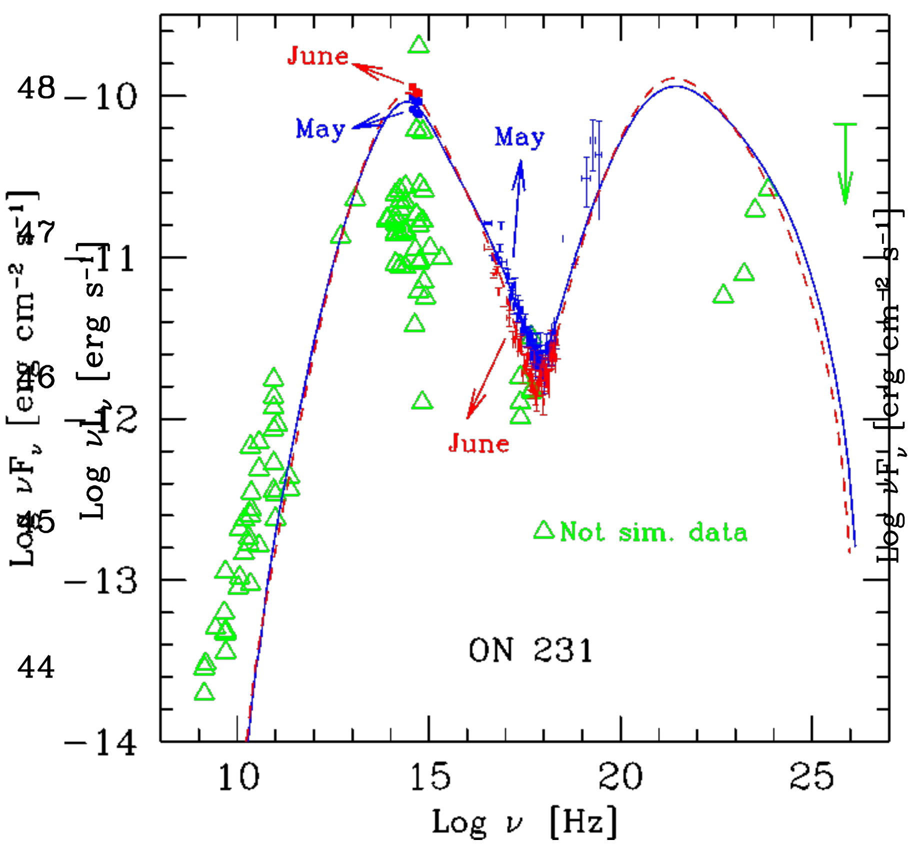
2) Blazars' SED Sequence

$\alpha_{\mathbf{x}} < \mathbf{1}$



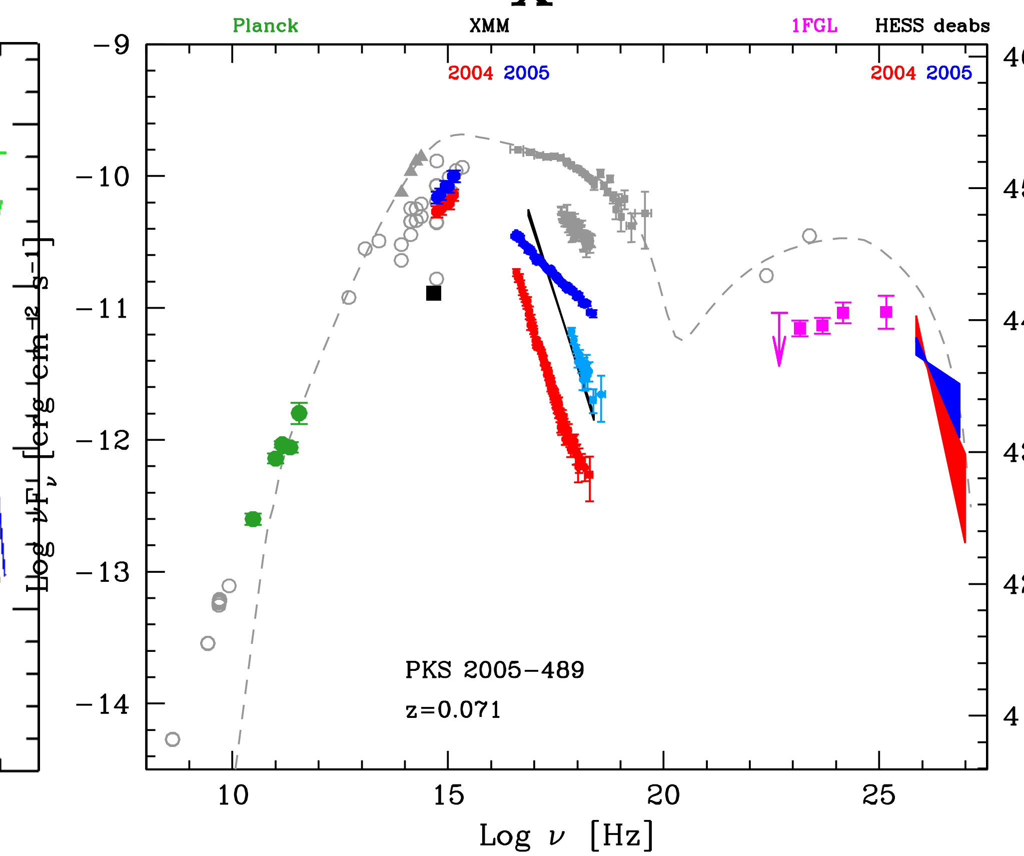
FSRQ / LBL

$\alpha_{\mathbf{X}} \simeq 1$ V-shape



IBL

$\alpha_{\mathbf{x}} > \mathbf{1}$

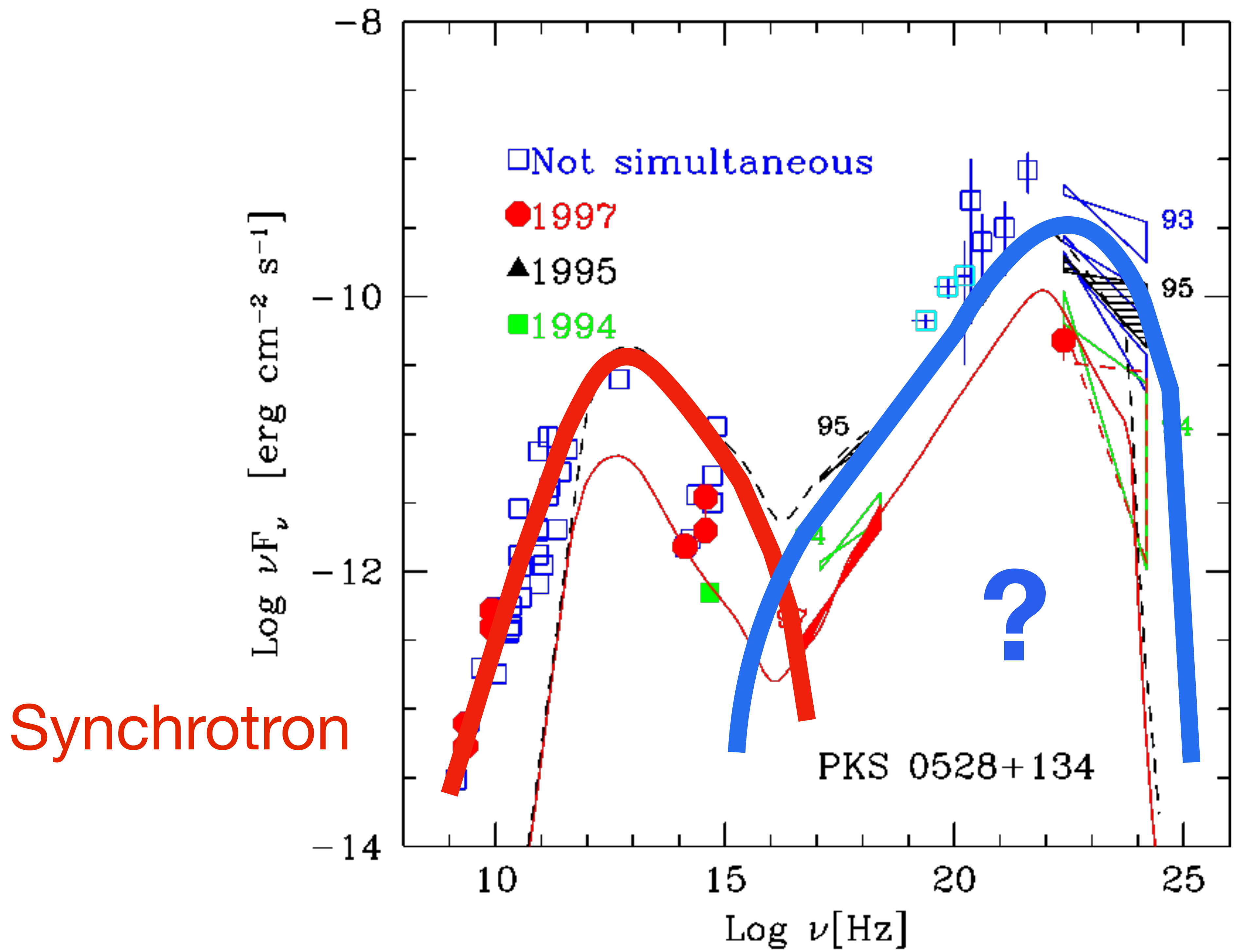


HBL

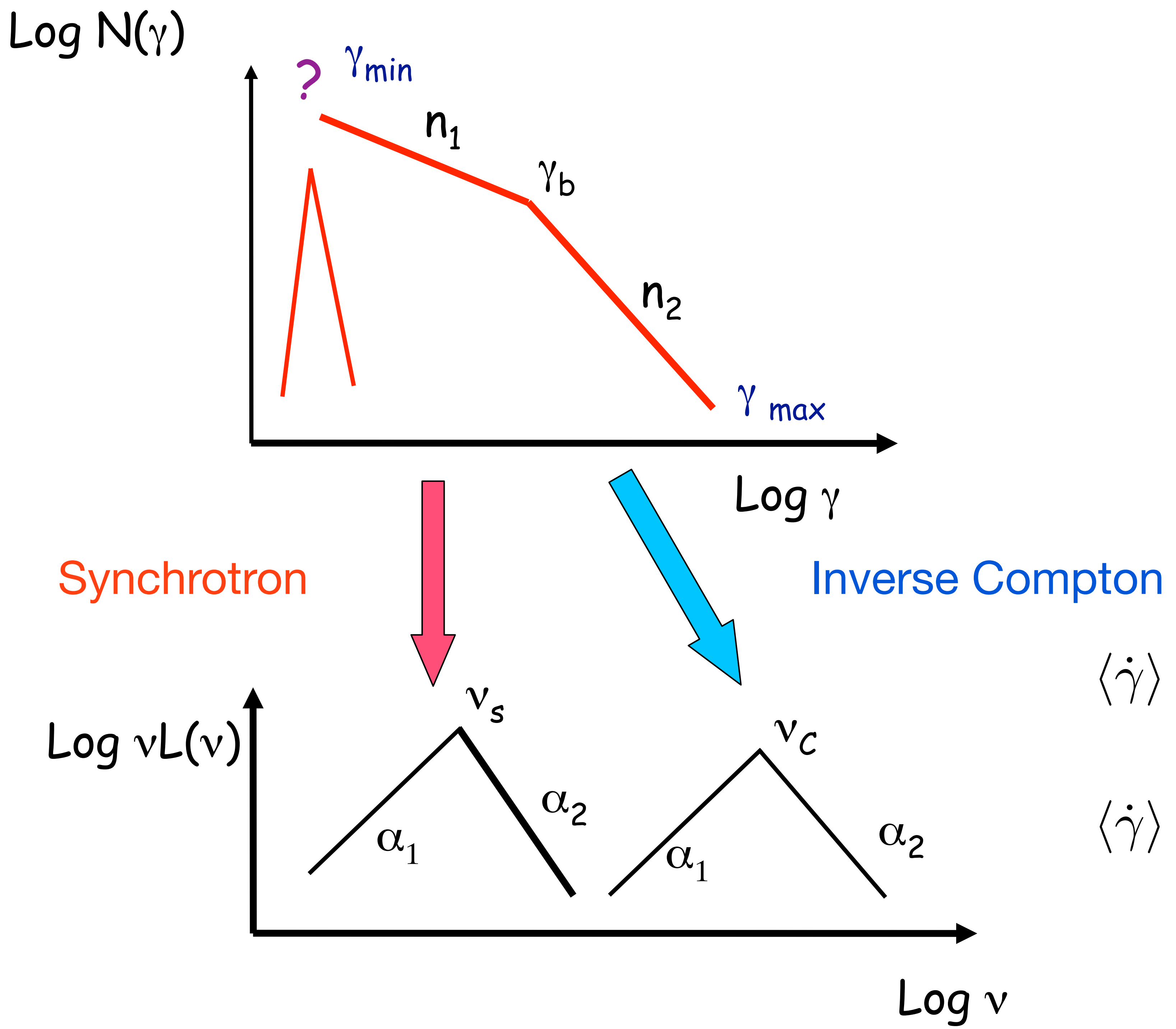
From Low to High-energy peaked Blazars

Giommi & Padovani 1994,1995

Double-humped SED:
which mechanism & location for the γ-ray emission ?



Leptonic Scenario: population of relativistic electrons

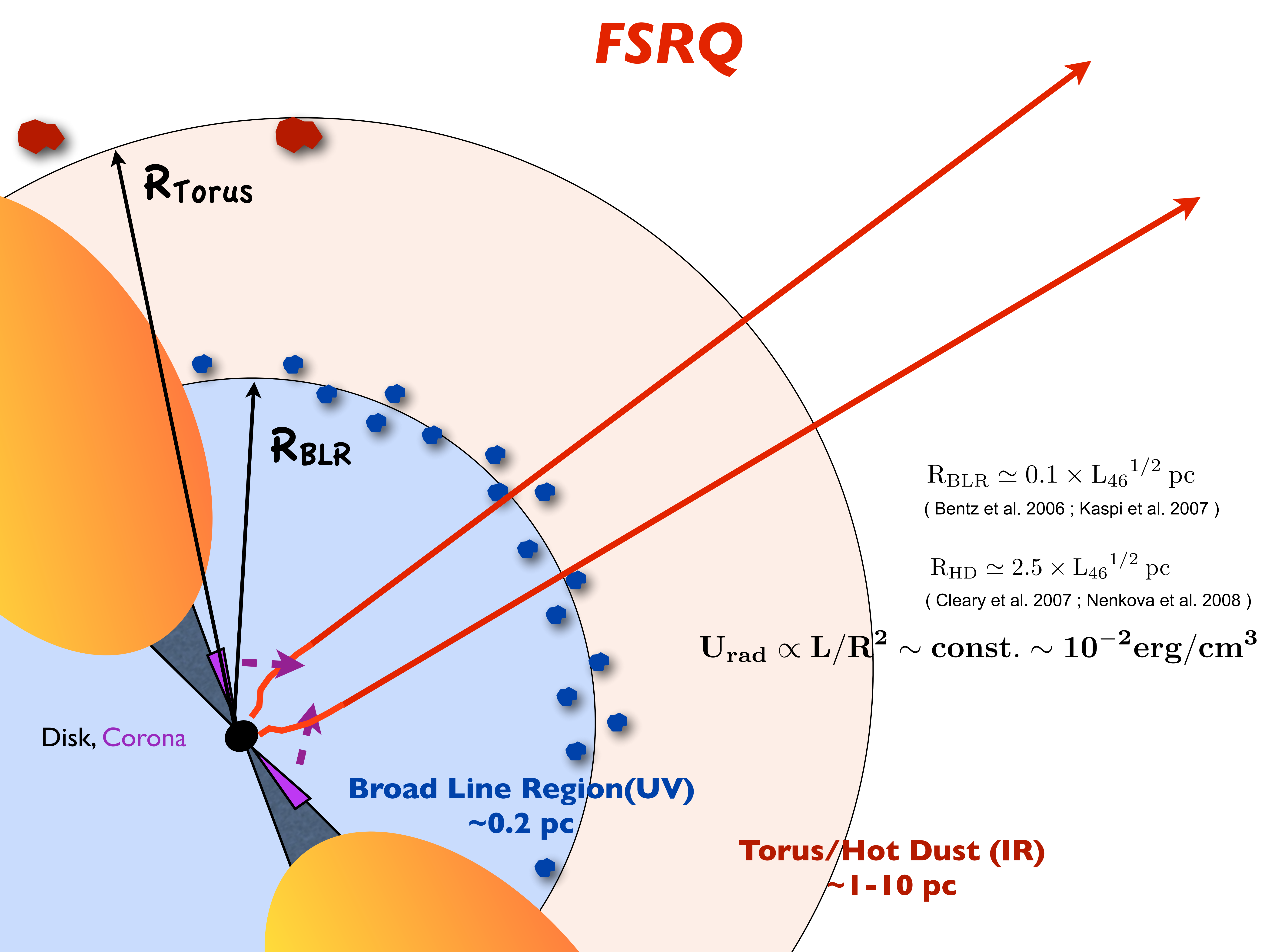


U'_{synch} (SSC)
U'_{BLR} (EC)
U'_{disk} (UV)
U'_{dust} (IR)

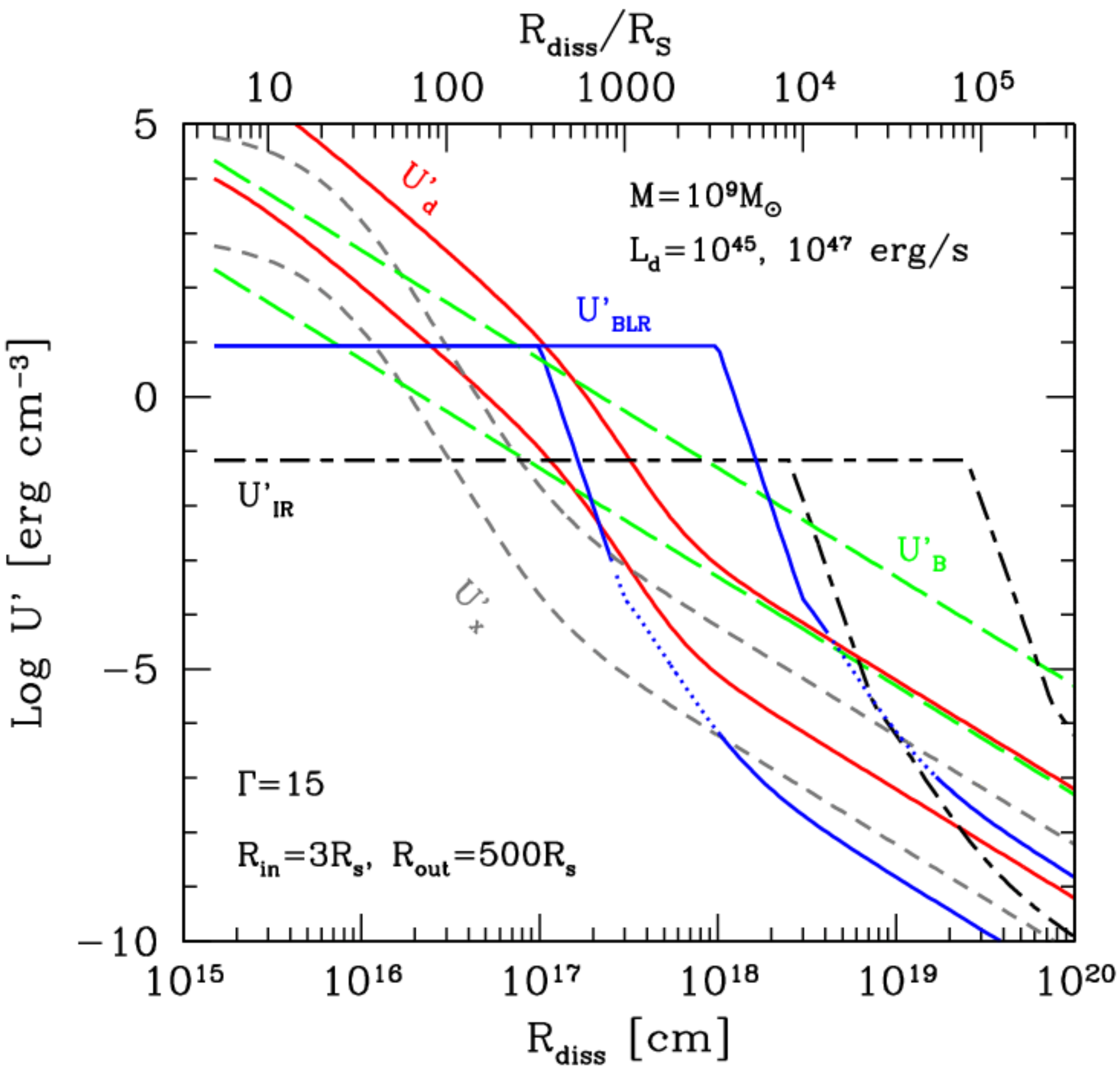
$$\langle \dot{\gamma} \rangle = \frac{4}{3} \sigma_{\rm T} c \, U'_{rad} \, \gamma^2 \beta^2$$

$$\langle \dot{\gamma} \rangle = \frac{4}{3} \sigma_{\rm T} c \, U'_{B} \, \gamma^2 \beta^2$$

Main cooling channel ? Highest energy density U' in co-moving frame


FSRQ
R_{Torus}
R_{BLR}
$R_{BLR} \simeq 0.1 \times L_{46}{}^{1/2}$ pc
(Bentz et al. 2006 ; Kaspi et al. 2007)
$R_{HD} \simeq 2.5 \times L_{46}{}^{1/2}$ pc
(Cleary et al. 2007 ; Nenkova et al. 2008)
$U_{rad} \propto L/R^2 \sim \text{const.} \sim 10^{-2} \text{erg/cm}^3$
Disk, Corona
Broad Line Region(UV)
~0.2 pc
Torus/Hot Dust (IR)
~1-10 pc

Energy density U along the jet:



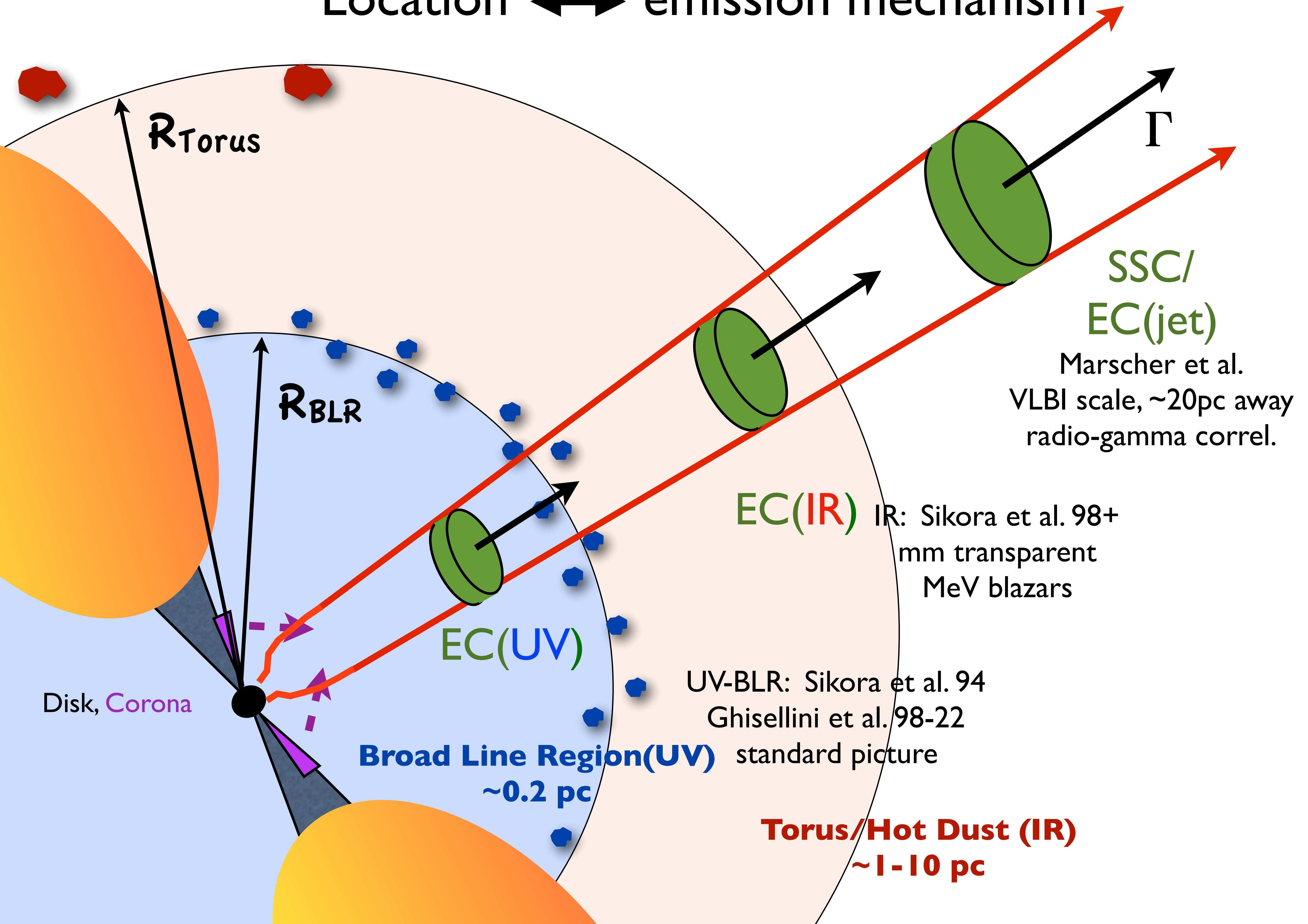
U' in jet frame

$$\dot{\gamma} \propto U'_{rad}\,\gamma^2$$

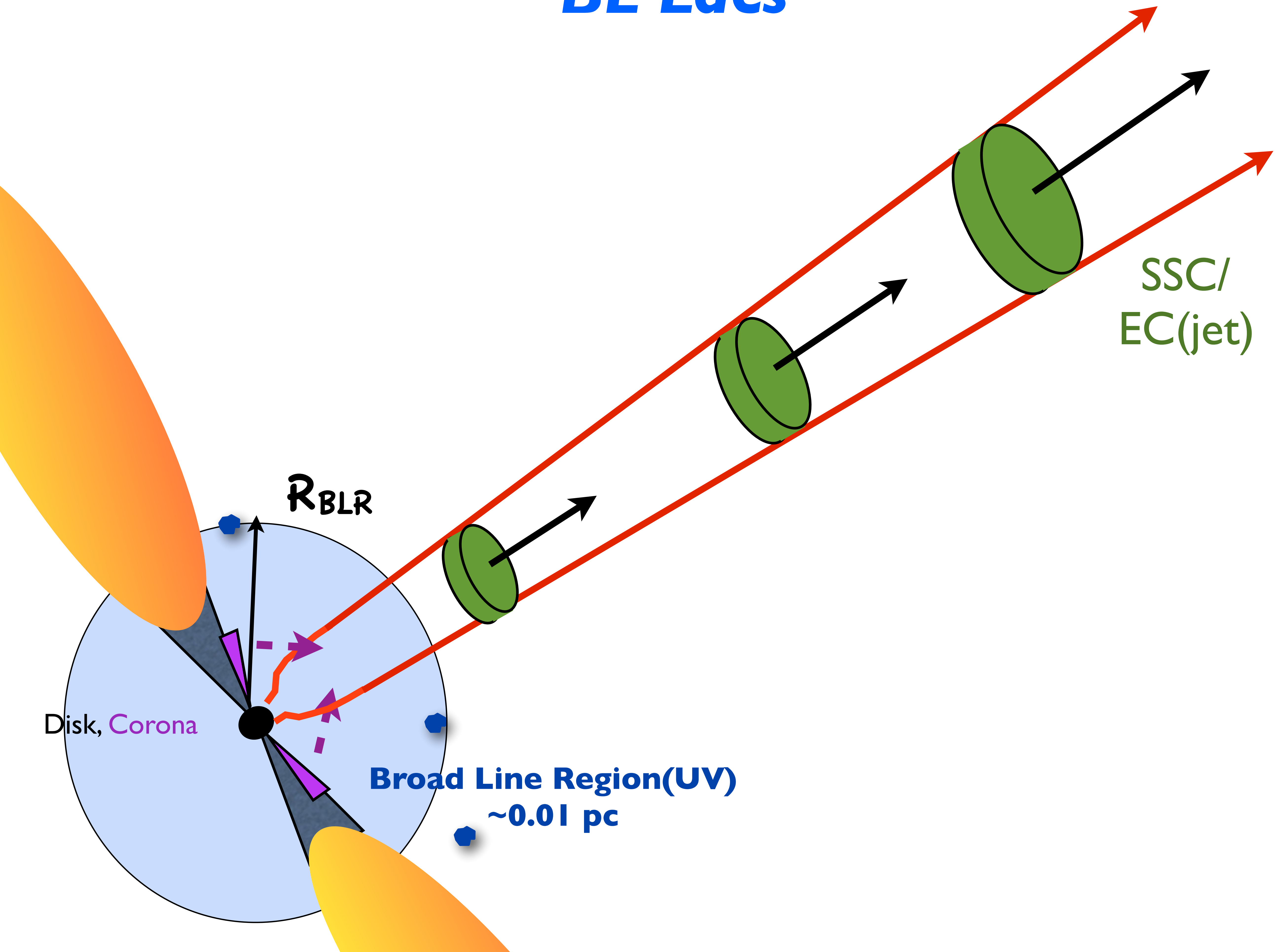
Ghisellini et al. 2009
Sikora et al. 2009

gamma-rays: Inv.Compton on highest-U' seed photons

Location ⟷ emission mechanism



BL Lacs



Proton scenarios:

p-p : not efficient, $L \sim 10^{45}$ erg/s needs target 10^6 cm^{-3}
slow, $t_{pp} \sim 10^{15}/n_p$ s

For typical blazar variability (few hrs):

p-γ : $E_p > 10^{19}$ eV, needs large densities of target photons
problem of gamma-ray transparency
generates neutrinos !

p-B : $E_p > 10^{19}$ eV, needs large magnetic fields (>100 G)

See e.g. Muecke & Protheroe 2000, Aharonian 2000
Petropoulou et al. 2014-18, Boettcher et al. 2012,
Cerruti et al. 2015, 2018

Since the beginning:
TeV fast variability, few hours - 20 min.

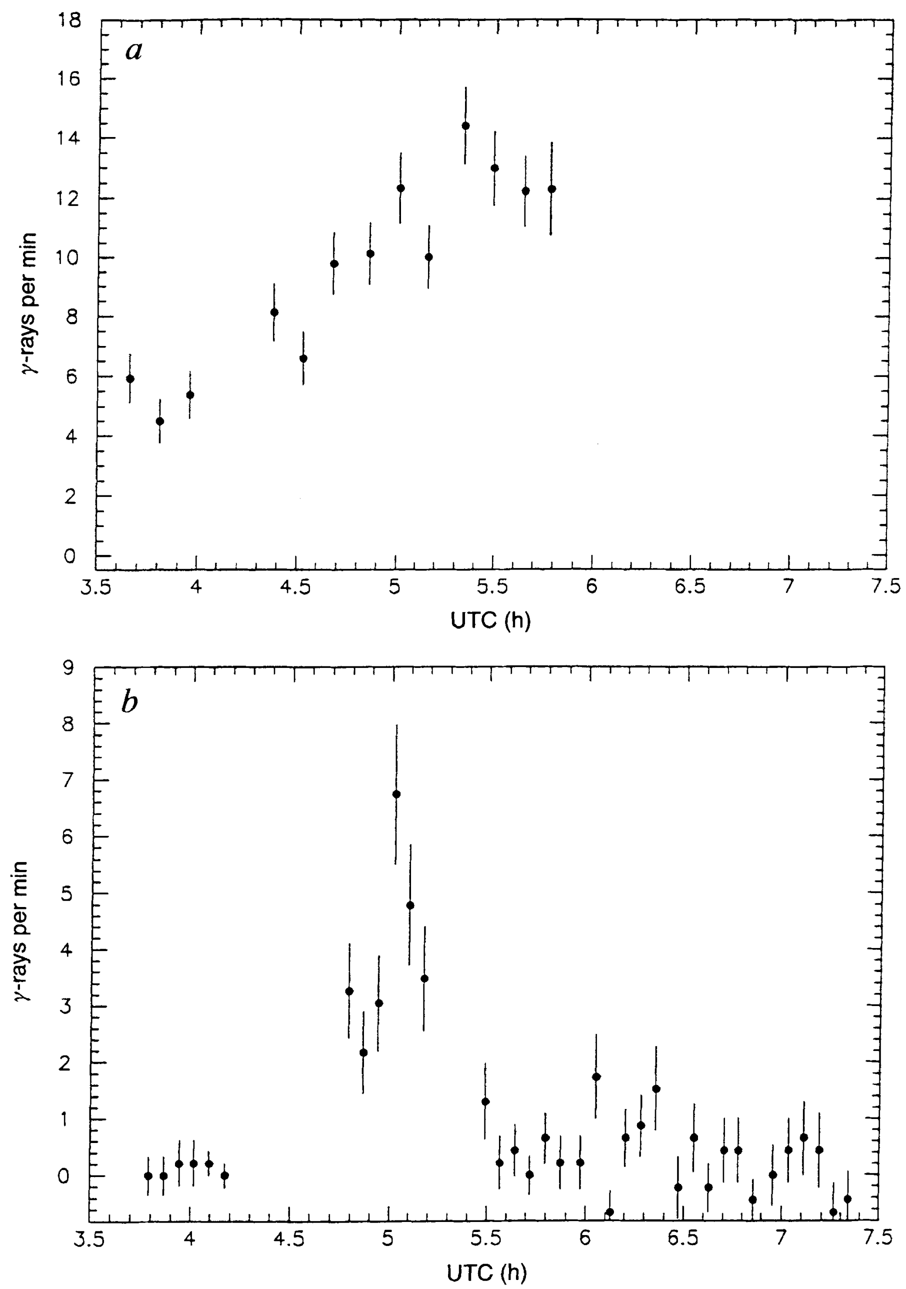
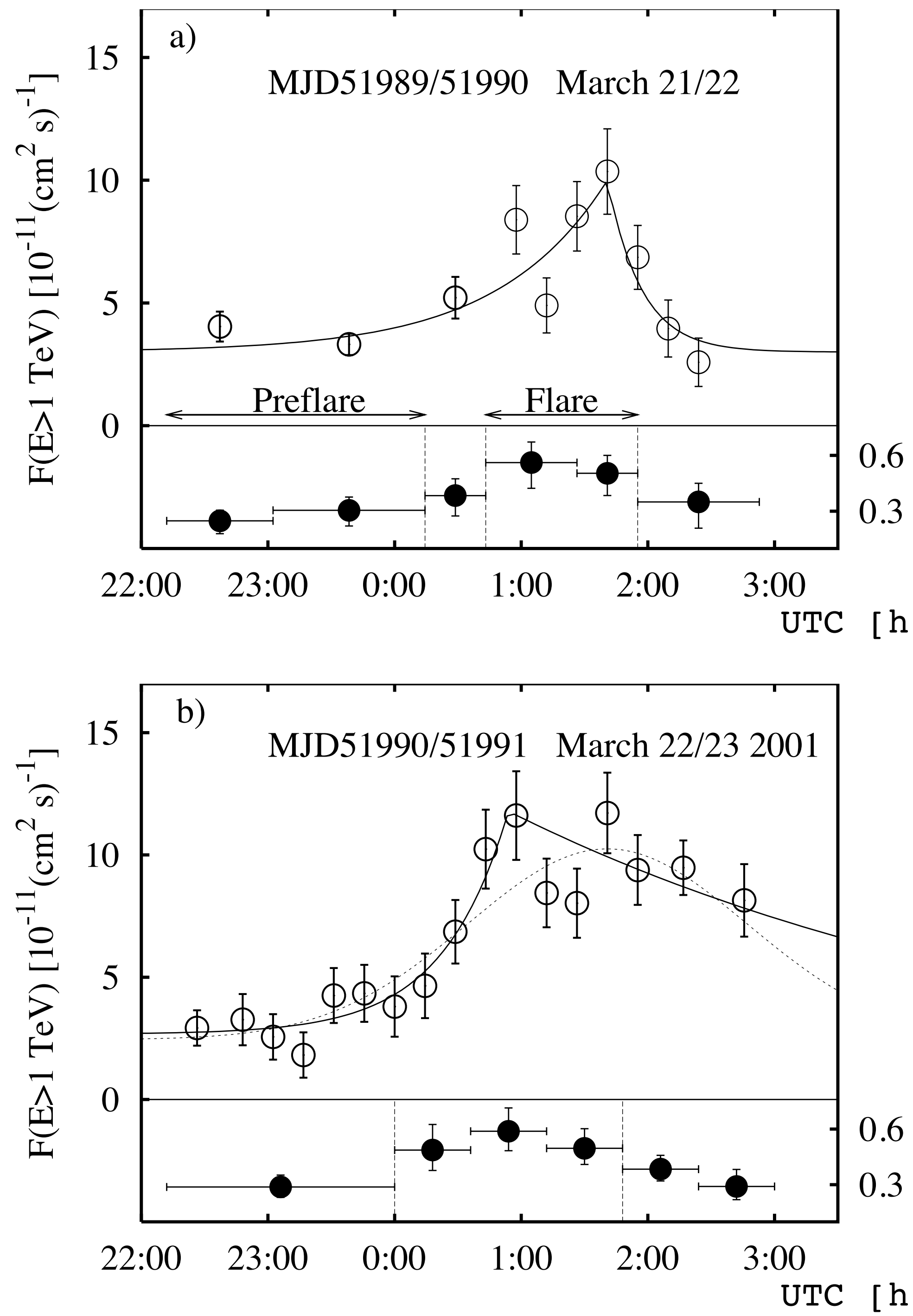


FIG. 2 Temporal histories of the two flare events. Rates are determined from the excess events after background subtractions in the interval $\alpha < 15°$. The time axes are coordinated universal time (UTC) in hours. For the 7 May flare (*a*), each point is a 9-min integration; for the 15 May flare (*b*), the integration time is 4.5 min. The error bars are statistical standard deviations.

Gaidos et al. (Whipple), Nature1996

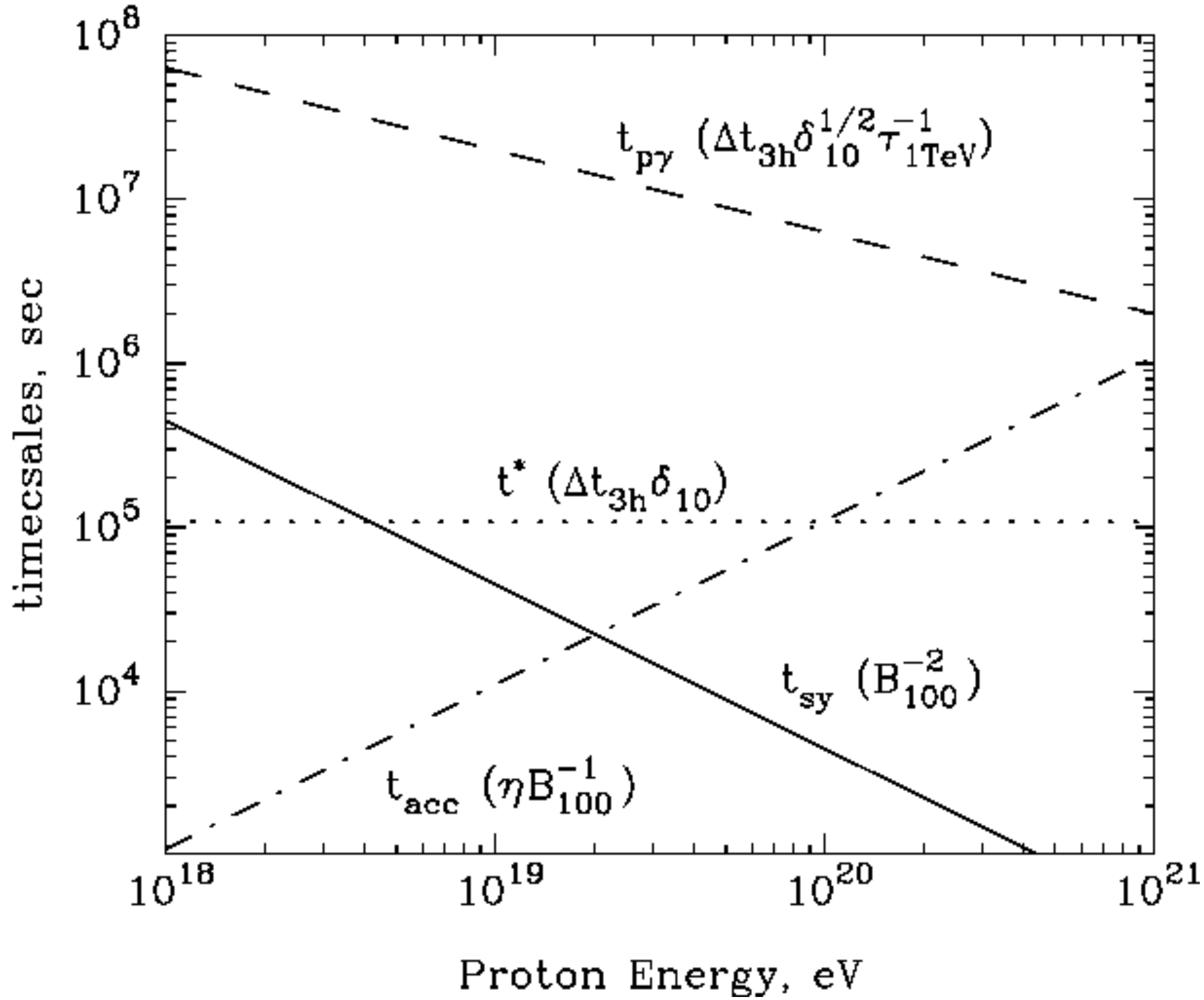
Mkn 421



Aharonian et al. (HEGRA Coll) 2002

Hadronic scenarios: cooling times

Problem: fast variability + gamma transparency + p accel.



$p\gamma$ with TeV transparency

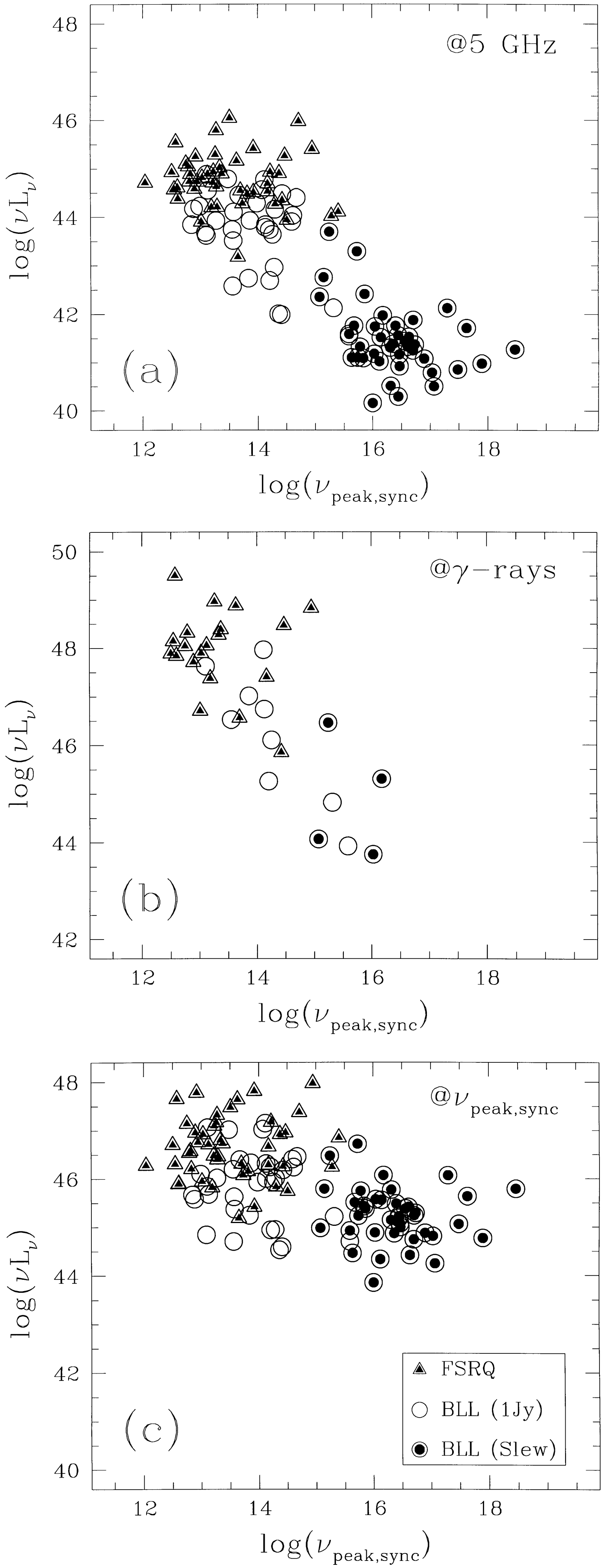
Aharonian F., 2000

in conditions for $p\gamma$ to work =>

protons cool by synchrotron much faster

Study of general trends

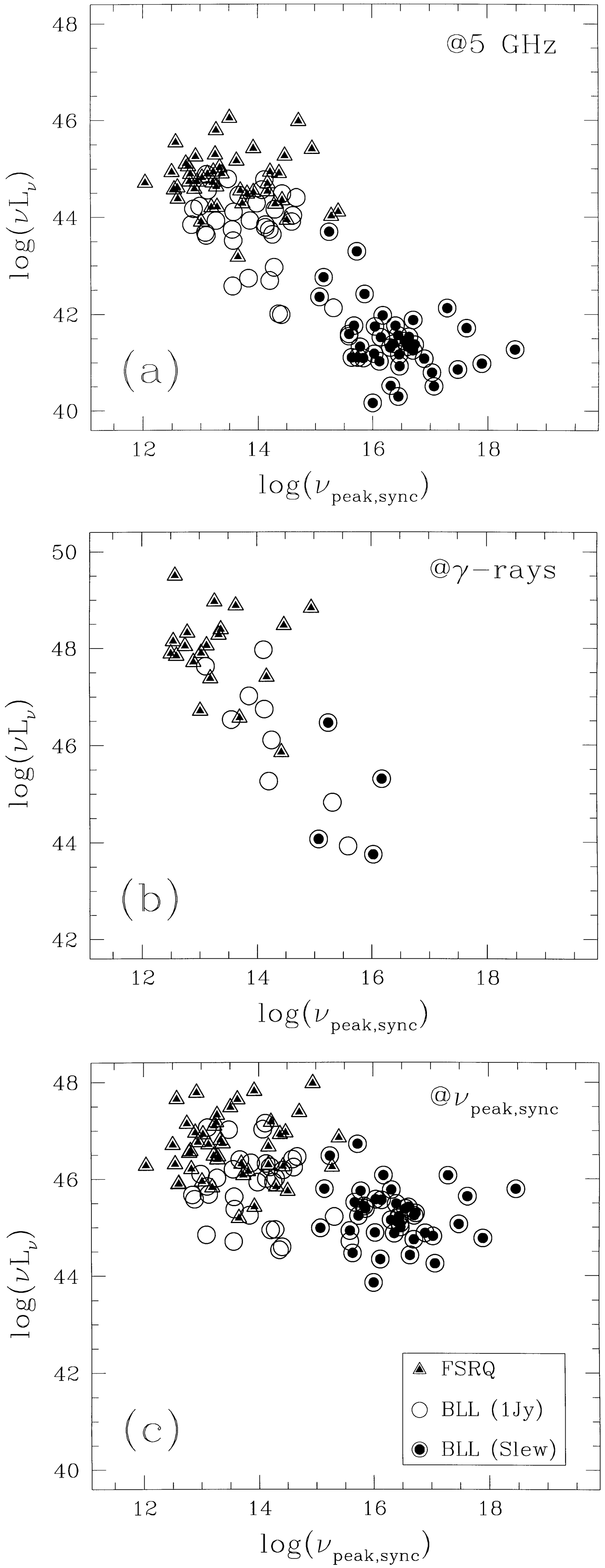
126 blazars, 33 gamma-ray detected

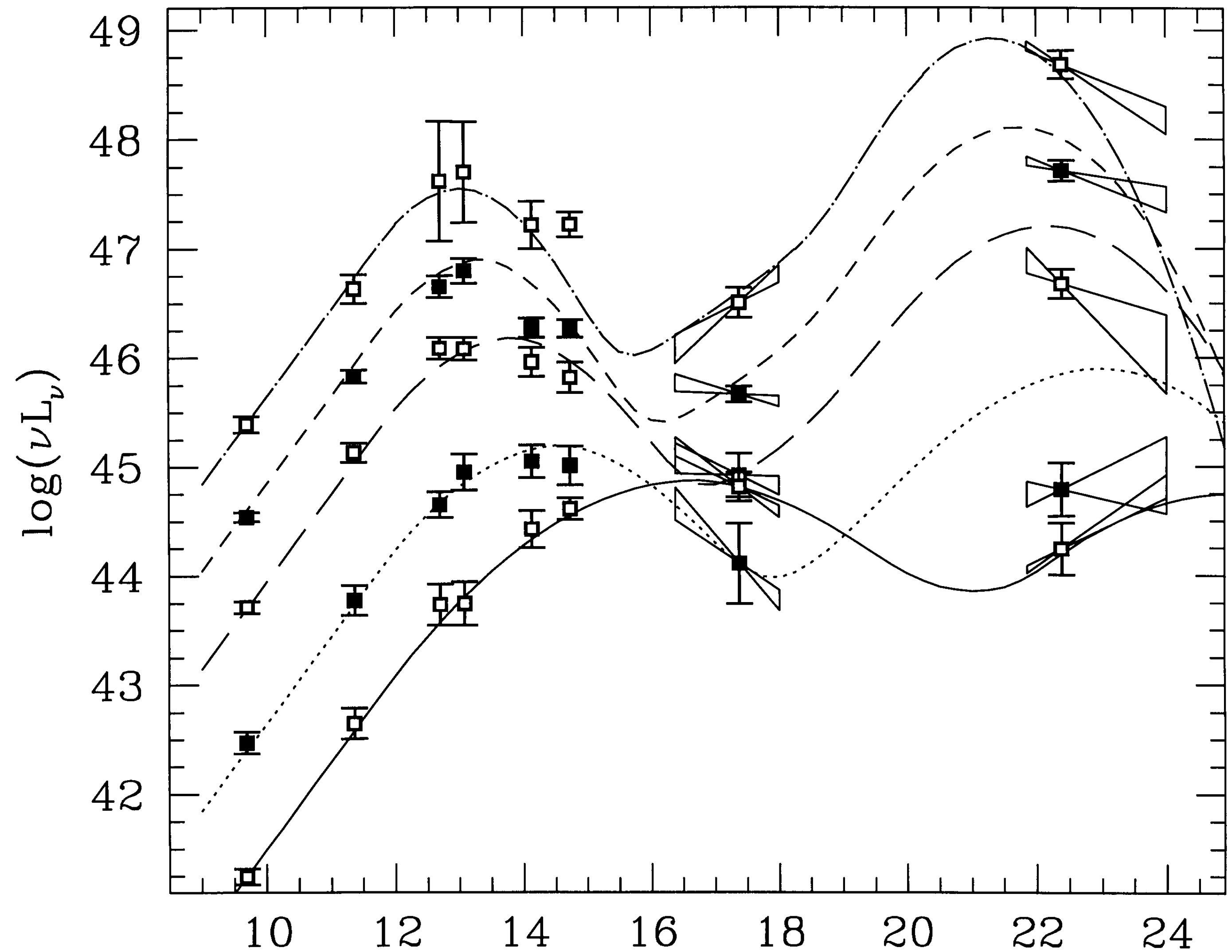


Fossati et al. 1998
Ghisellini et al. 1998

Blazar Sequence 1.0

126 blazars, 33 gamma-ray detected





Radio Luminosity bins log(ν)

Fossati et al. 1998
Ghisellini et al. 1998

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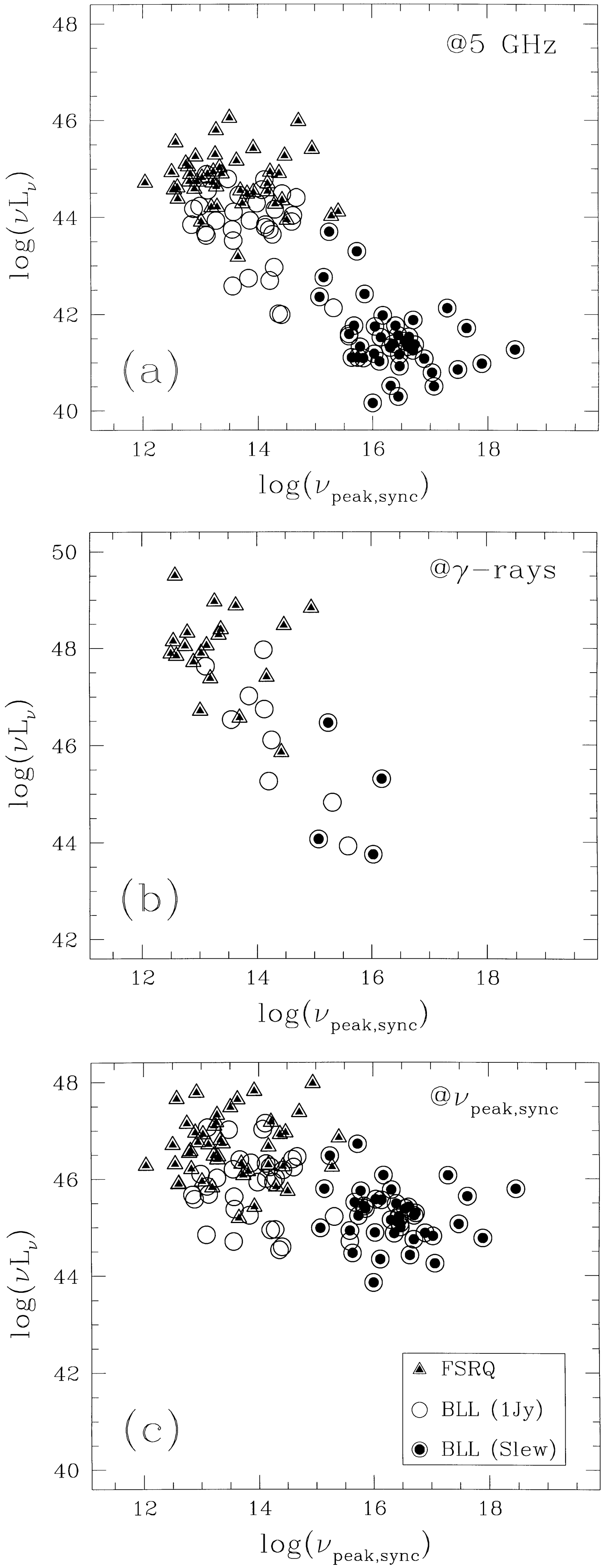

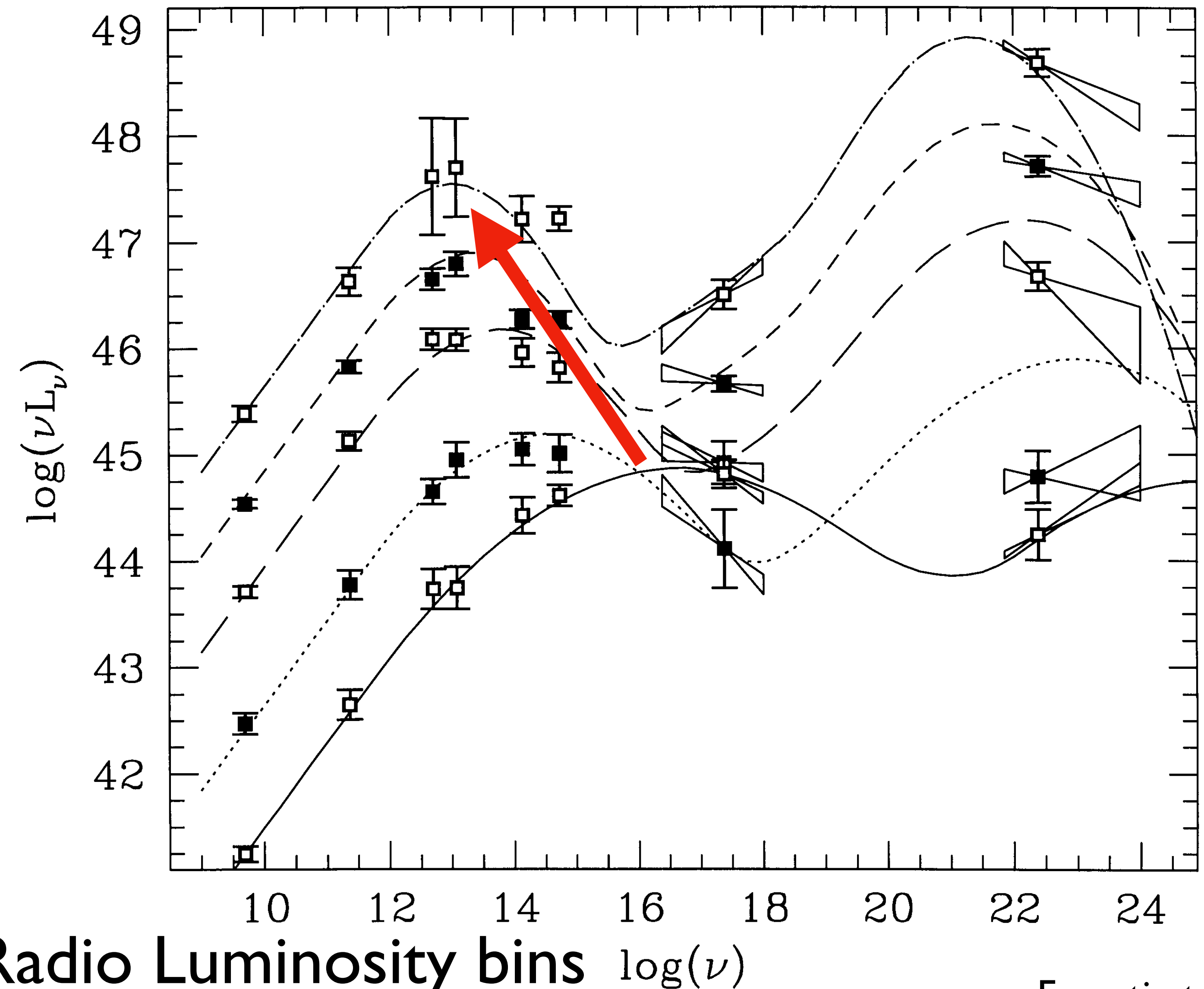

Radio Luminosity bins

Fossati et al. 1998
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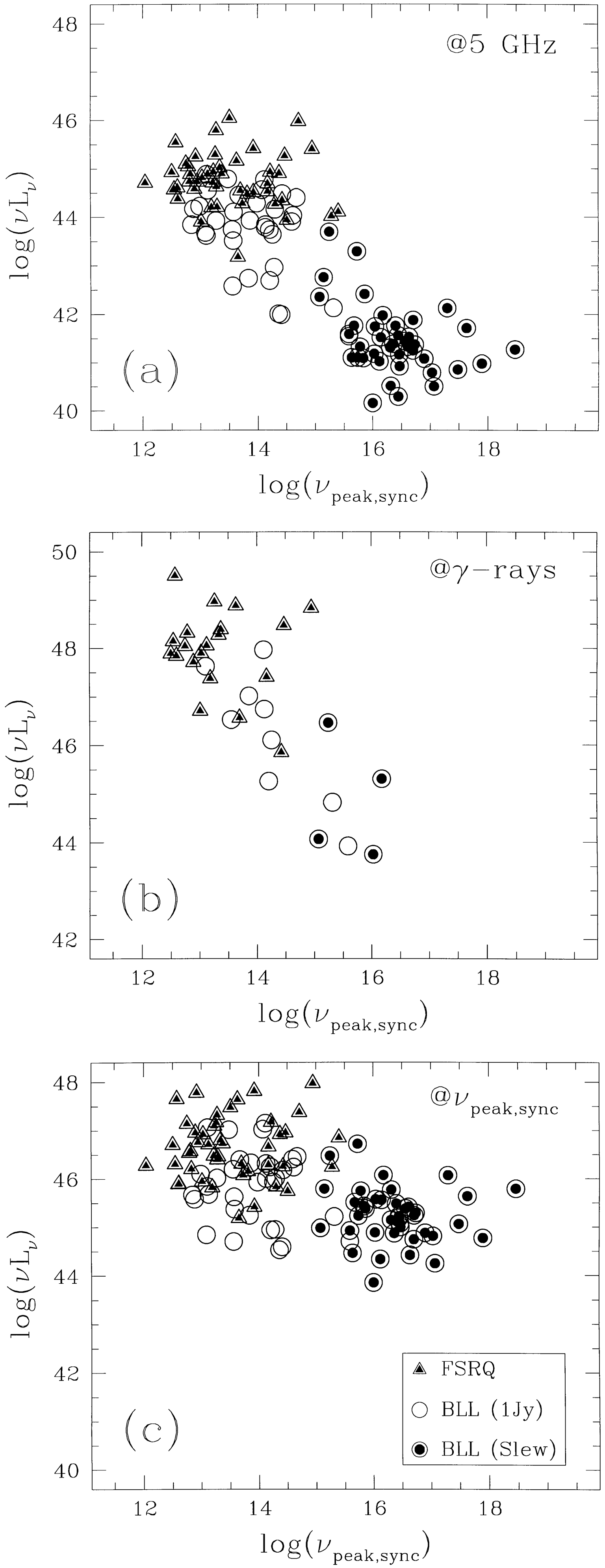
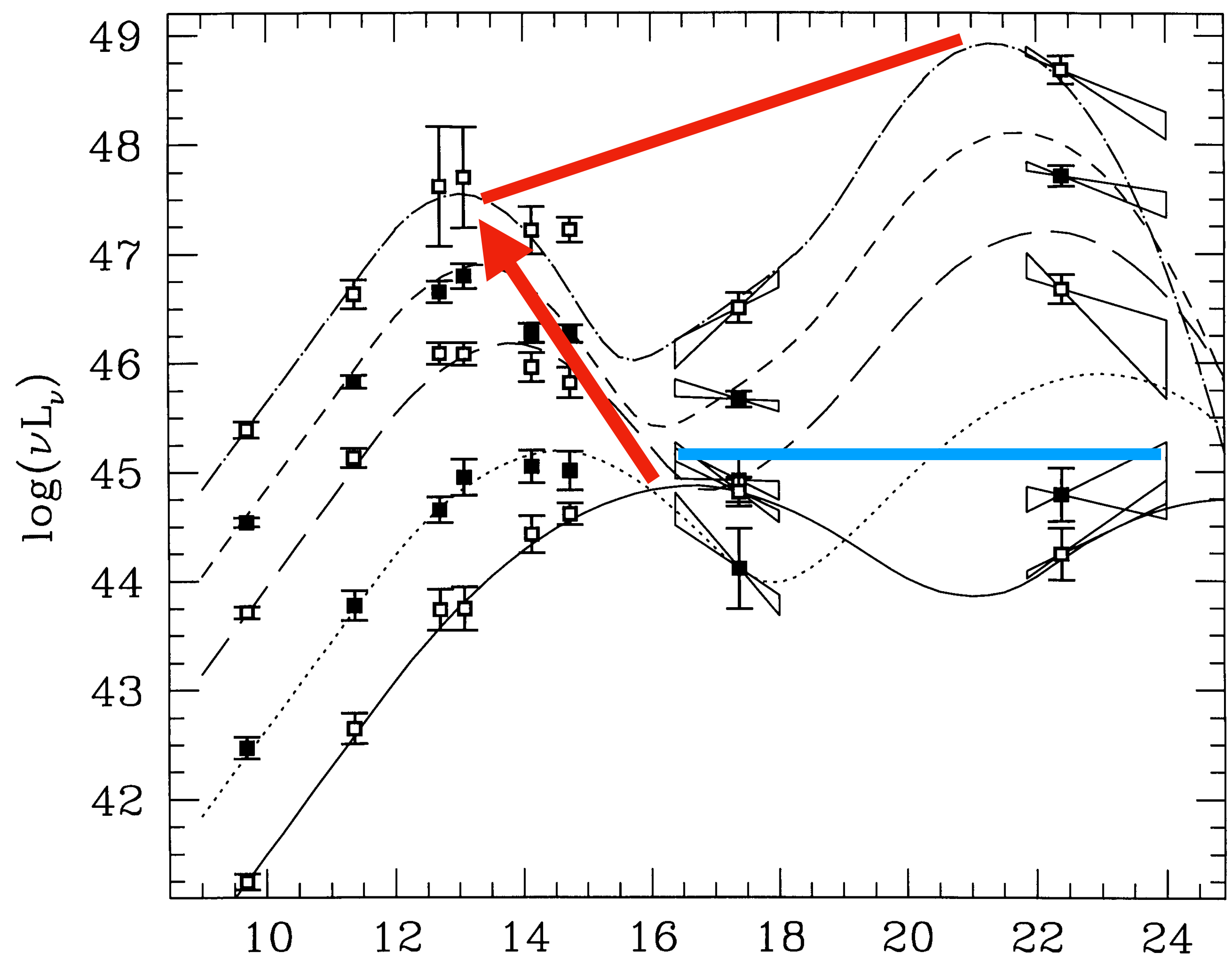


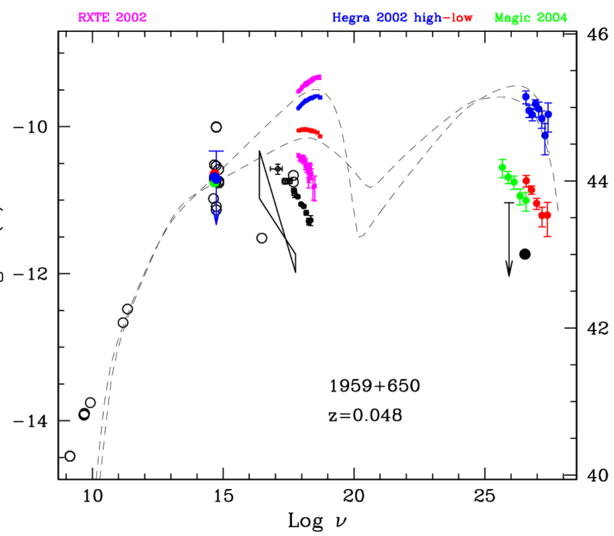


Radio Luminosity bins $\log(\nu)$

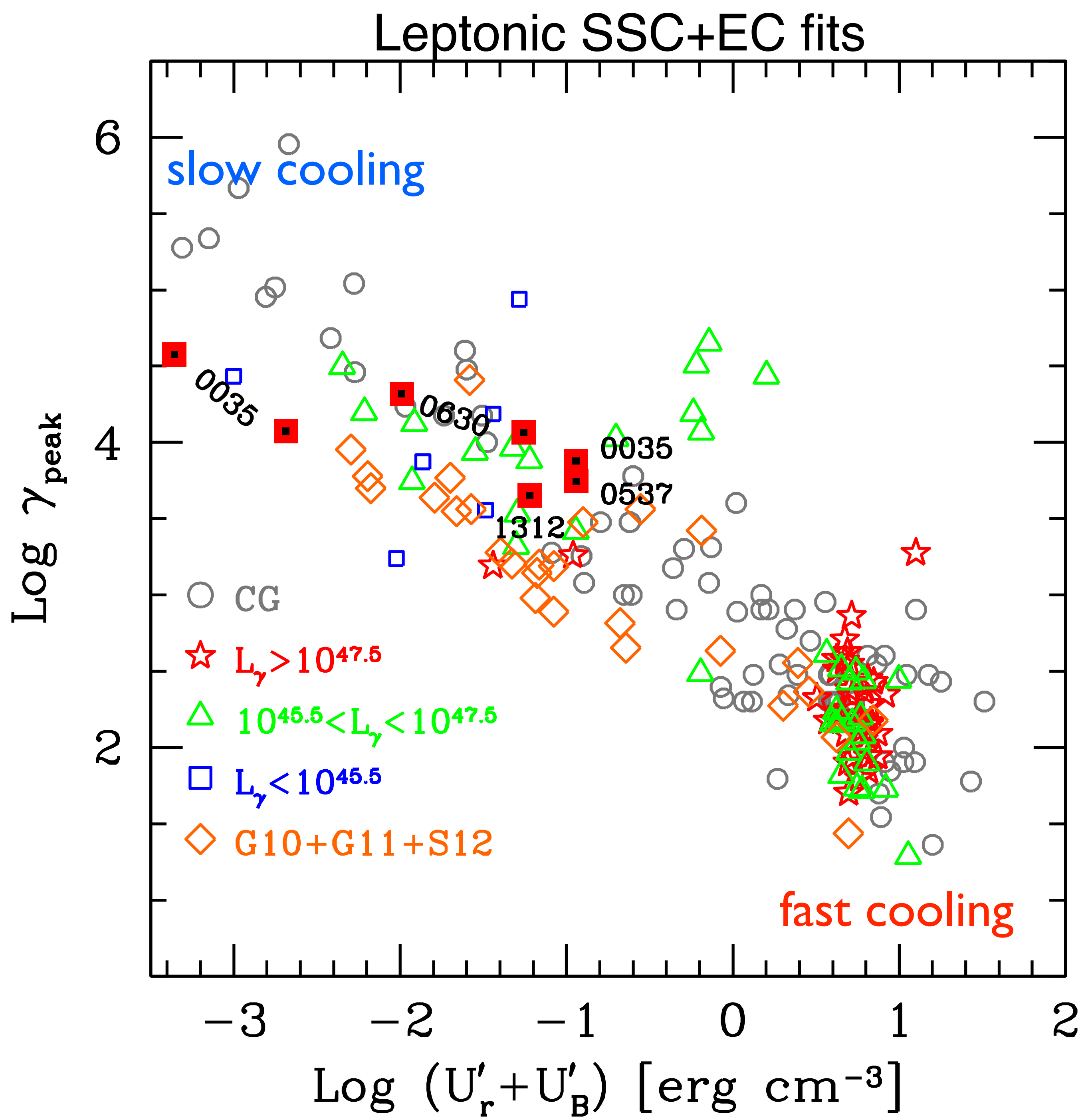
Fossati et al. 1998
Ghisellini et al. 1998

NB: ok Ltot & Lgamma (NOT Lpeak) vs ν-peak

Interpretation: balance acceleration/cooling

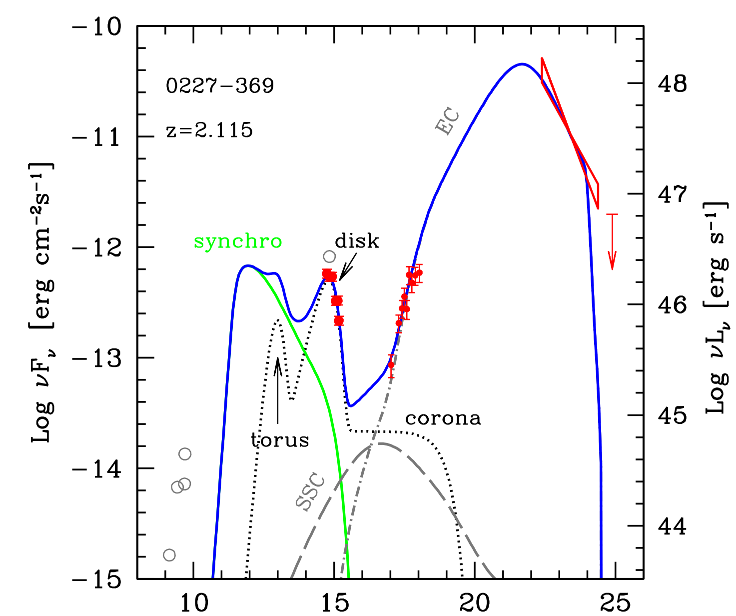


BLLacs: SSC



FSRQ

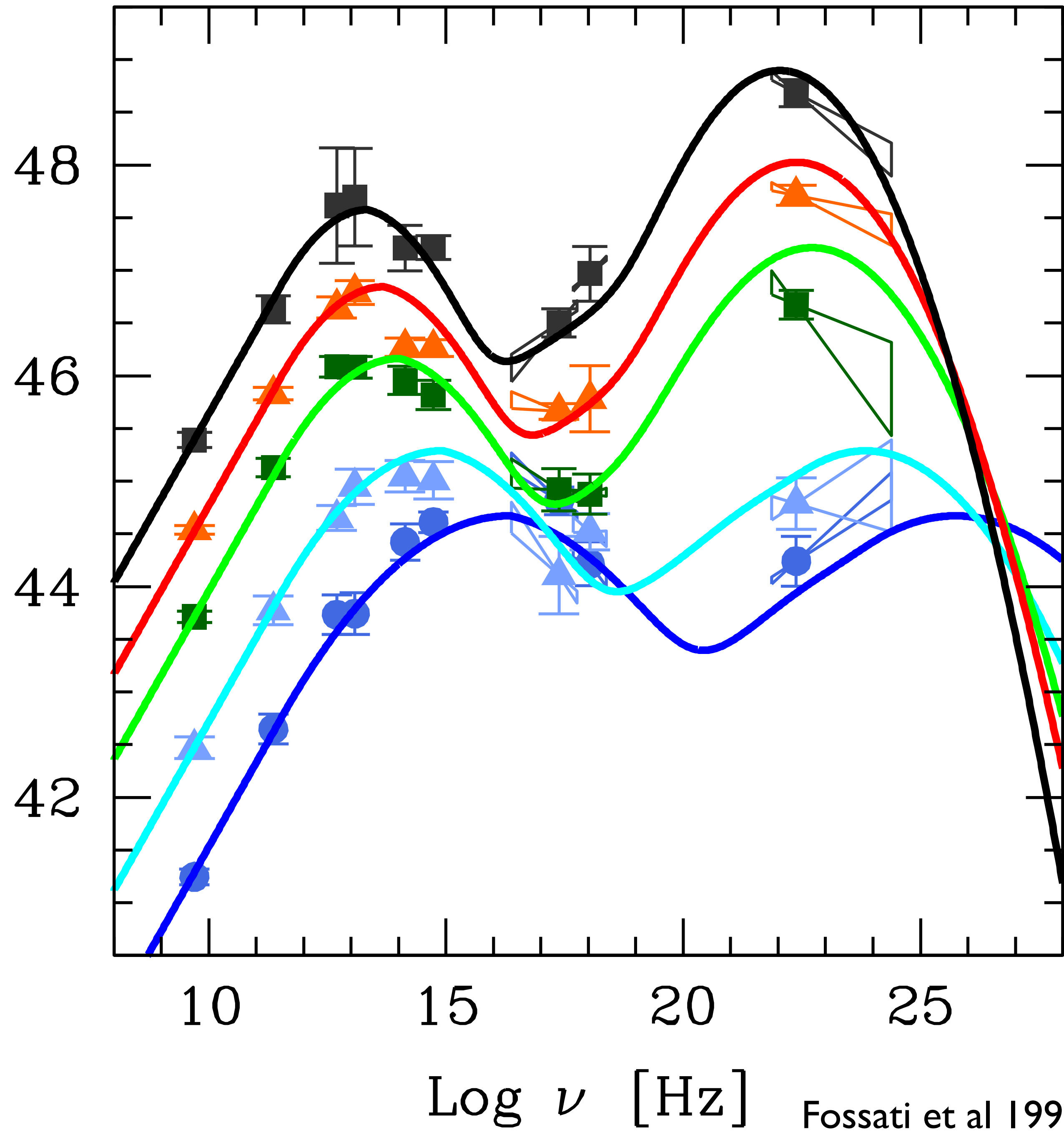
EC(BLR)



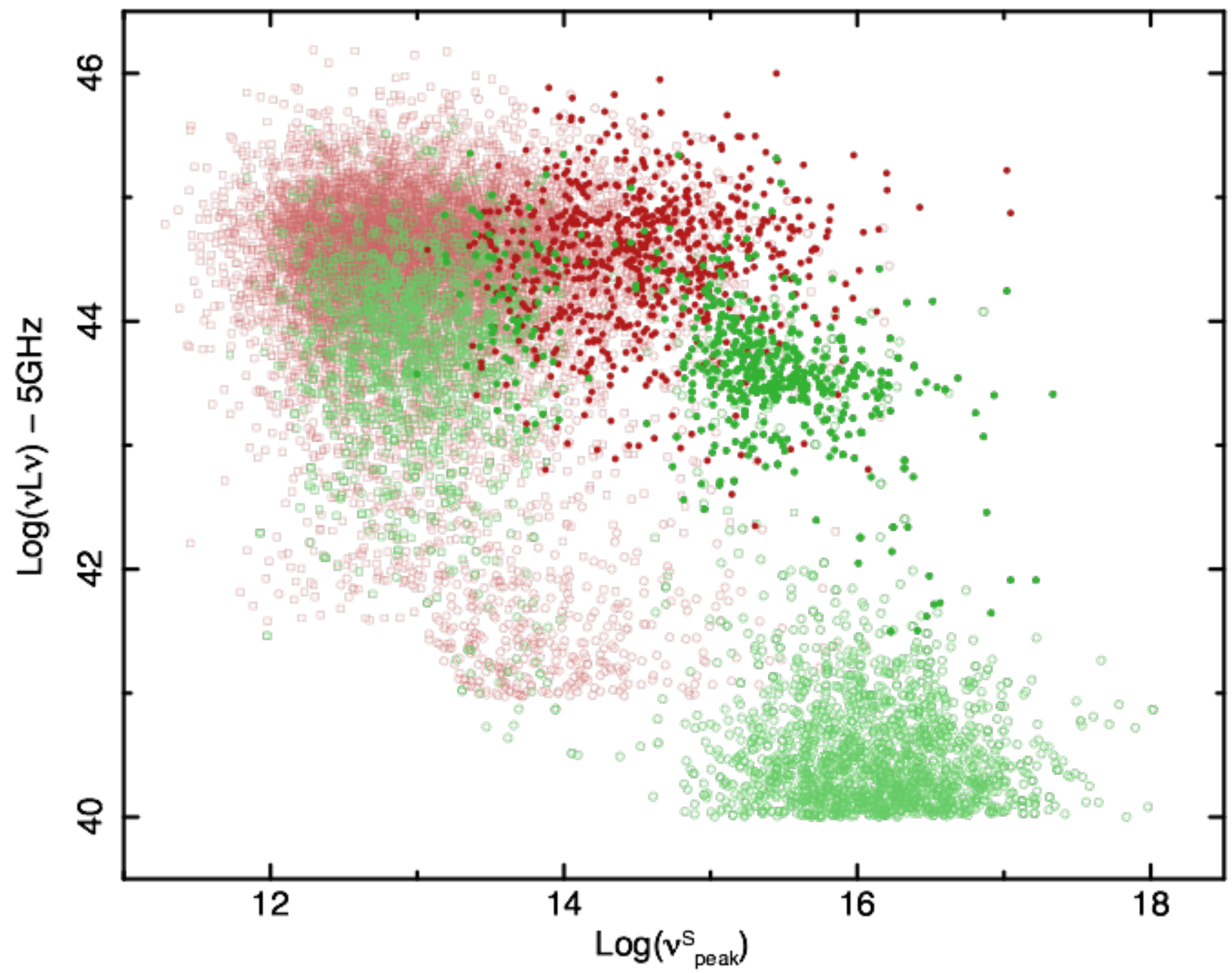
Ghisellini et al 1998-2013,
Sikora et al 1994-2013

Main criticism:

Real or Selection bias ?



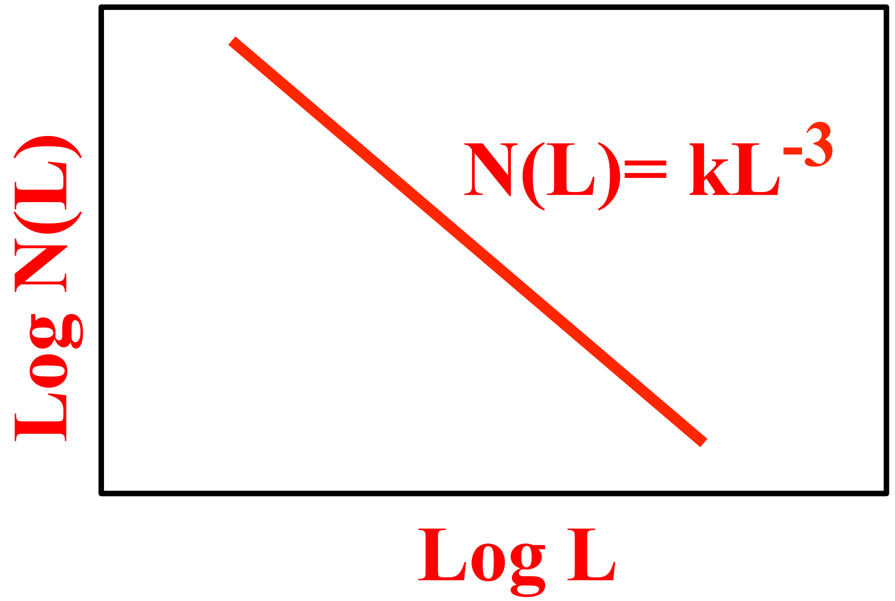
Fossati et al 1998
Donato et al 2002



Simulations of observational biases

Giommi, Padovani et al. 2012

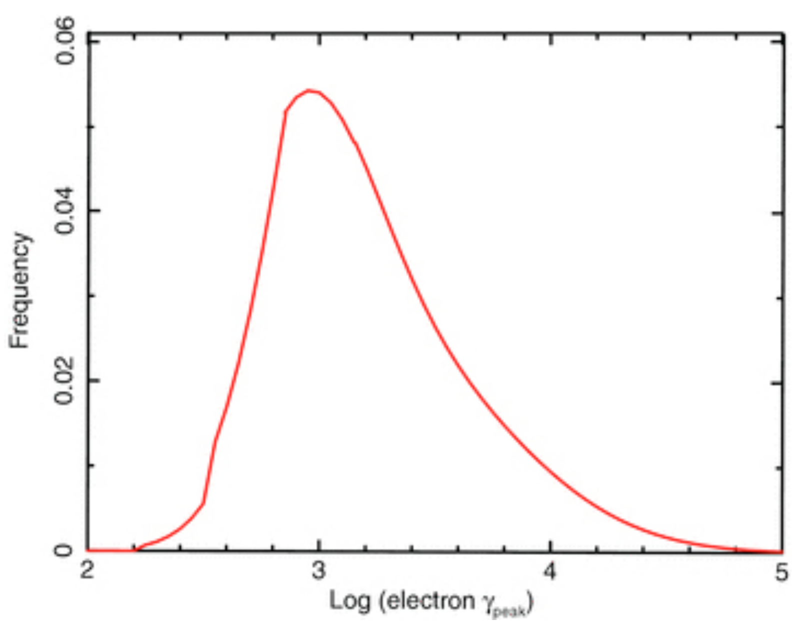
Alternative "Simplified" blazar scenario



Radio Luminosity function @ 41 GHz

B=0.15 Gauss

δ = <15>

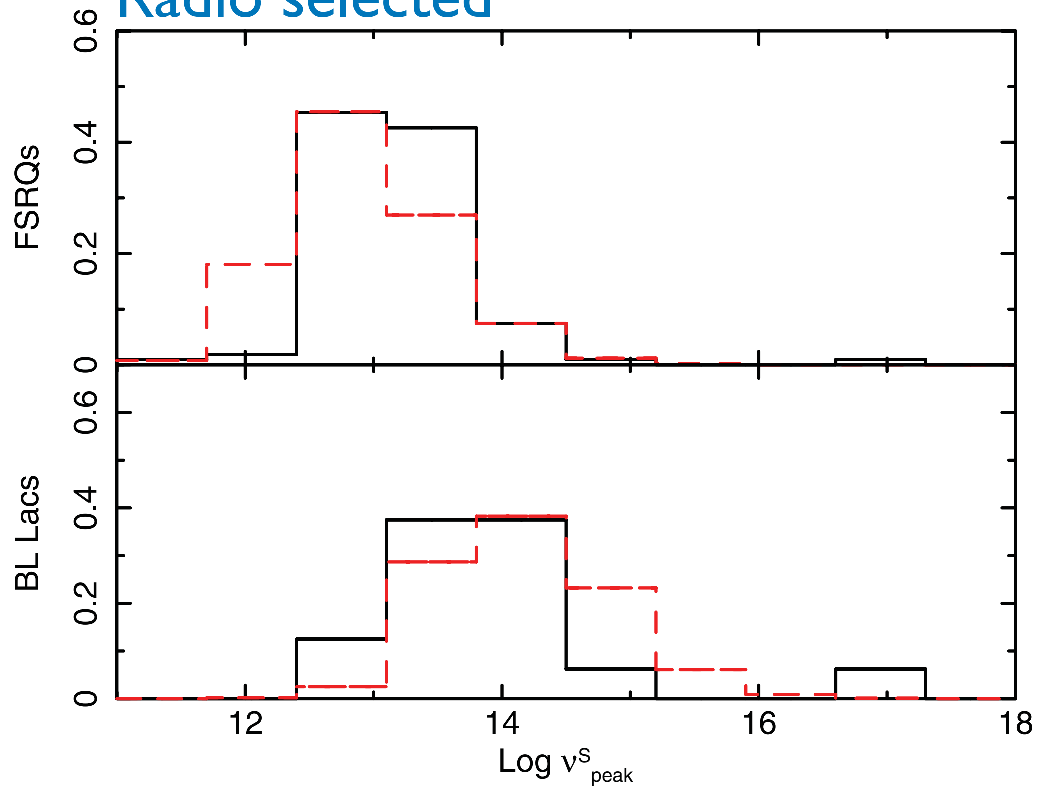


Distribution of γ_{peak} around 10^3

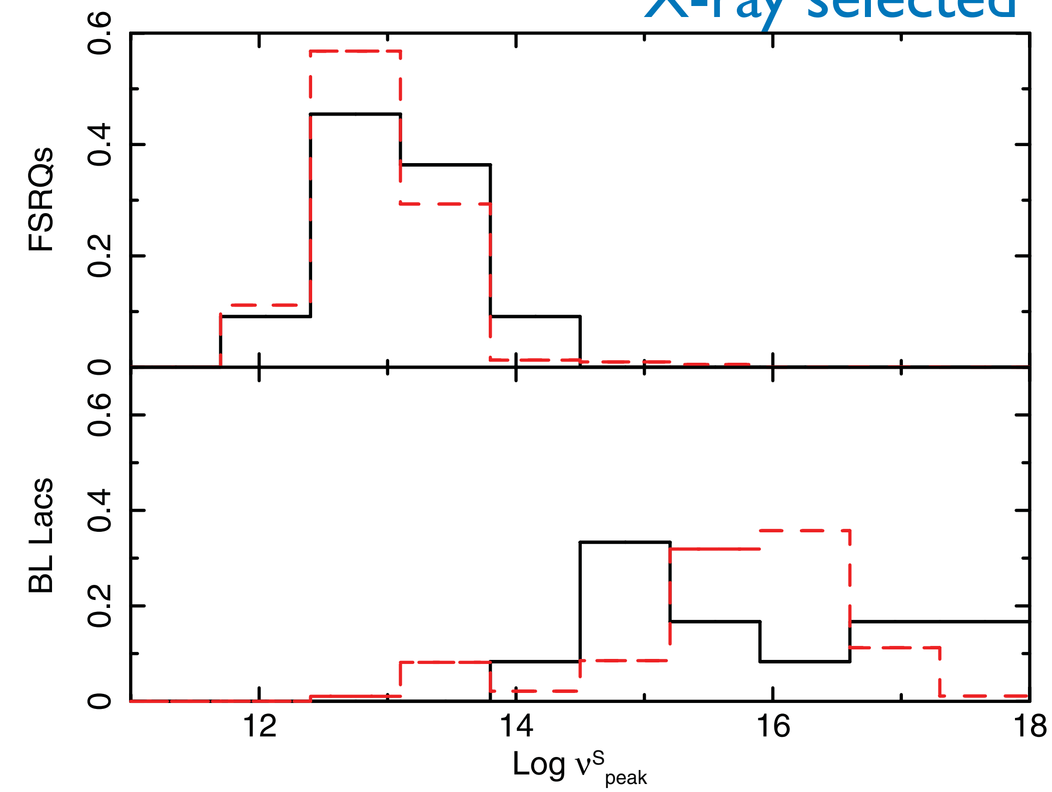
Giommi, Padovani+ 2012

Real Simulated

Radio selected



X-ray selected



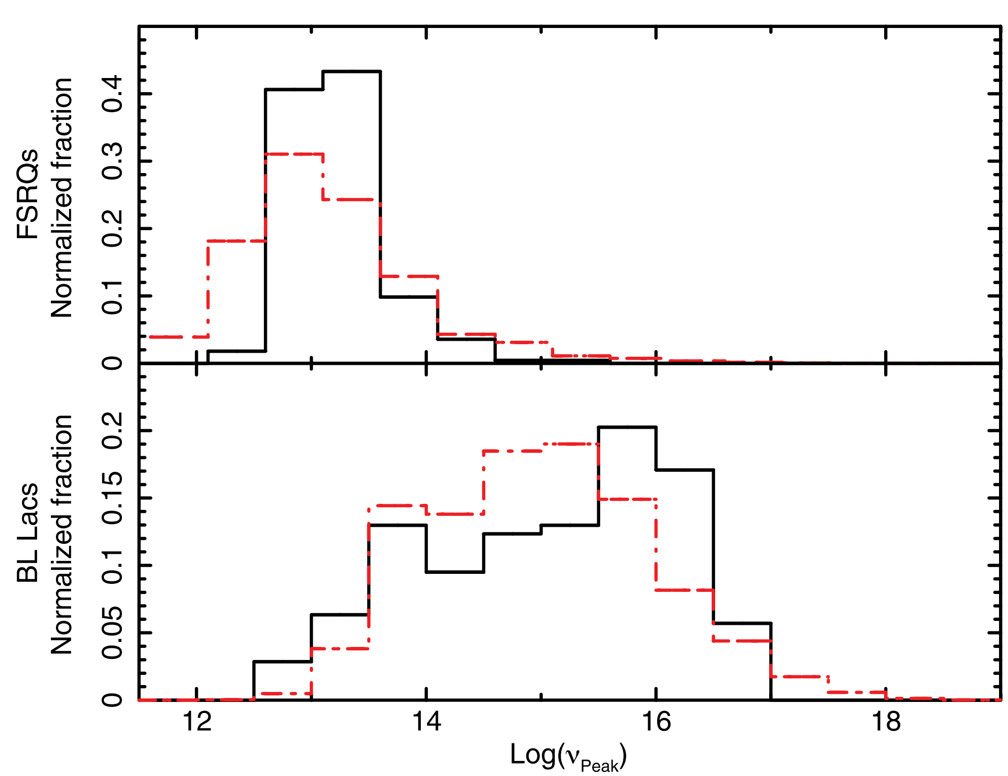


Figure 4. The distribution of synchrotron peak energies for blazars in the 2LAC catalogue (black solid histogram) and that of our simulations (red dot–dashed histogram) for FSRQs (top panel) and BL Lacs (bottom panel).

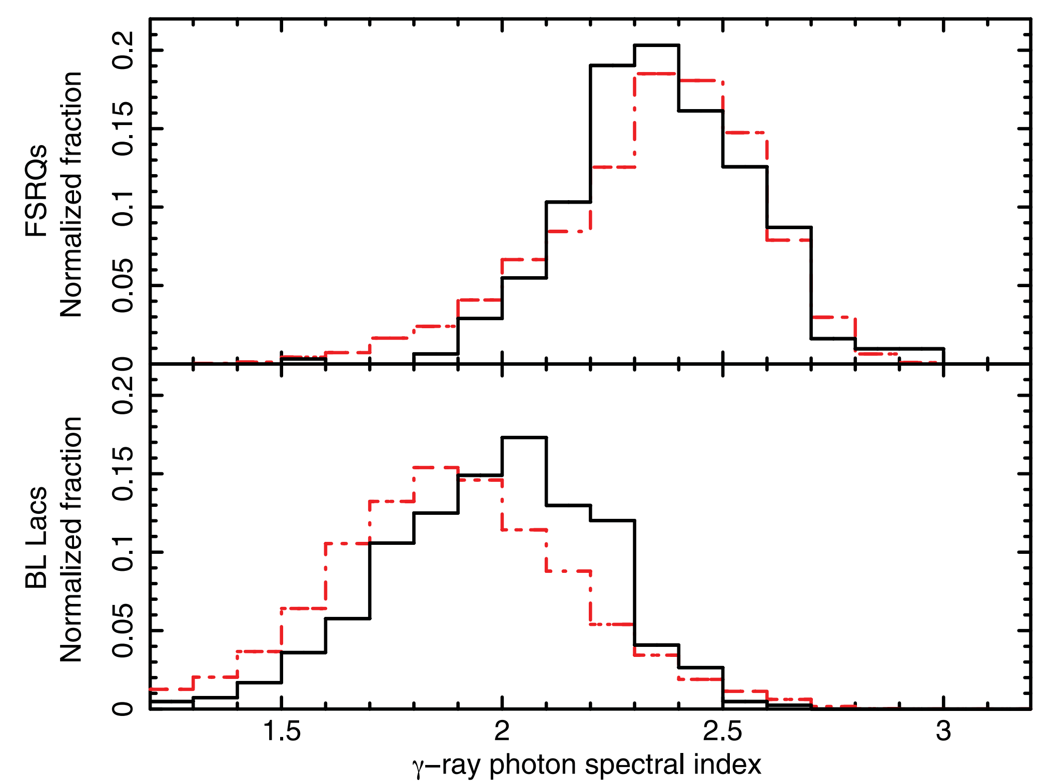
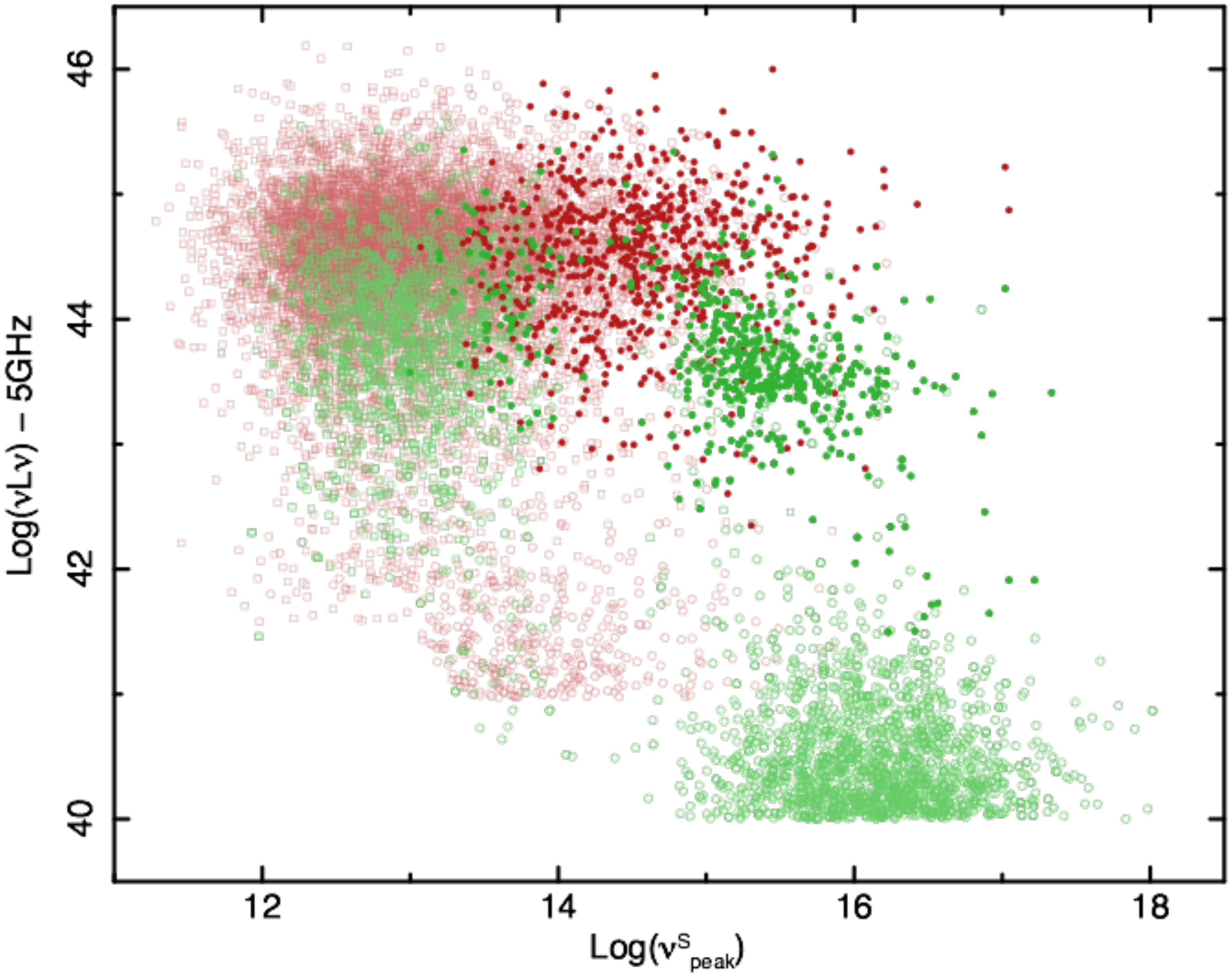


Figure 5. The γ-ray spectral (photon) index distribution of FSRQs (top panel) and BL Lacs (bottom panel). Black solid and red dot–dashed histograms represent 2LAC and simulated blazars, respectively.

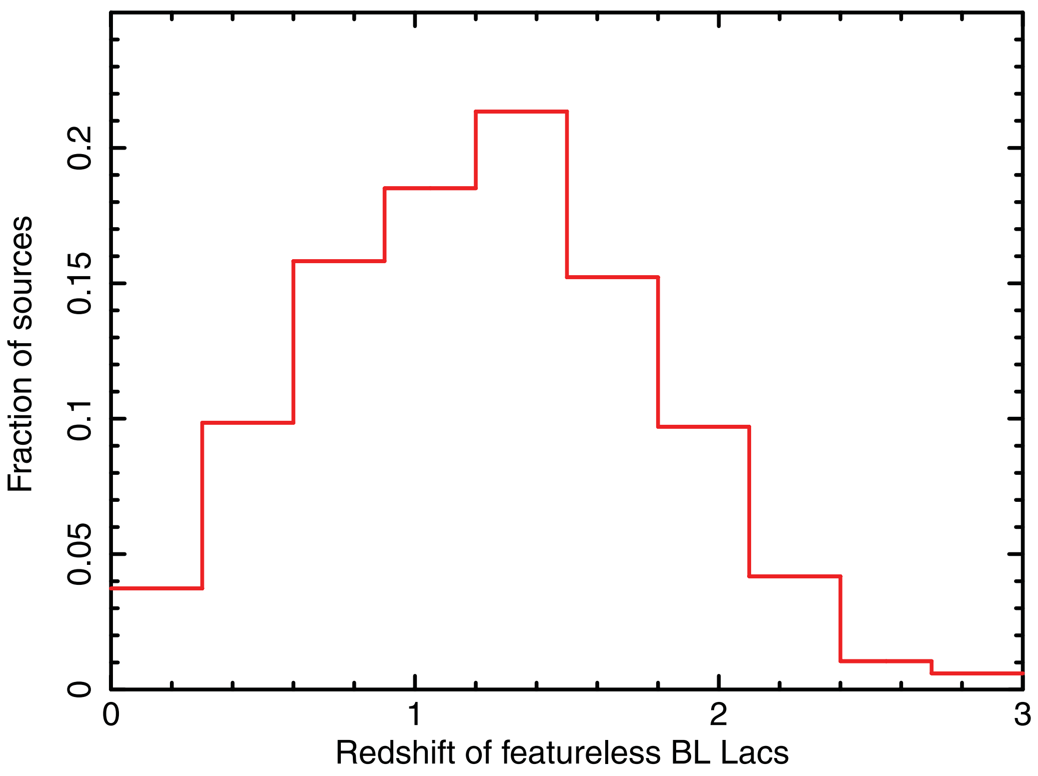
2LAC

Blazar sequence: selection bias ?

Simulations of observational biases



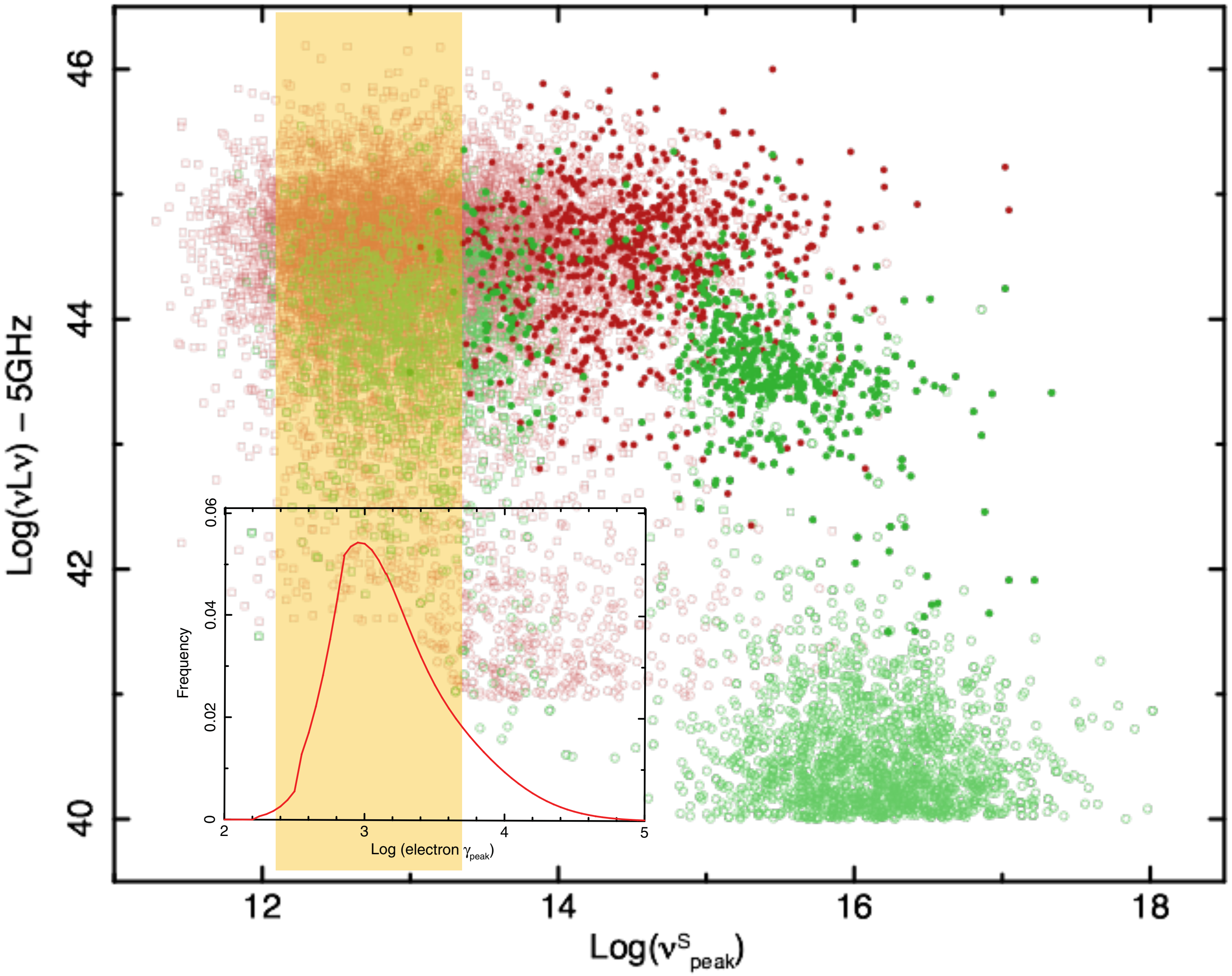
1) BL Lacs with no z



Giommi, Padovani et al. 2012, 2013

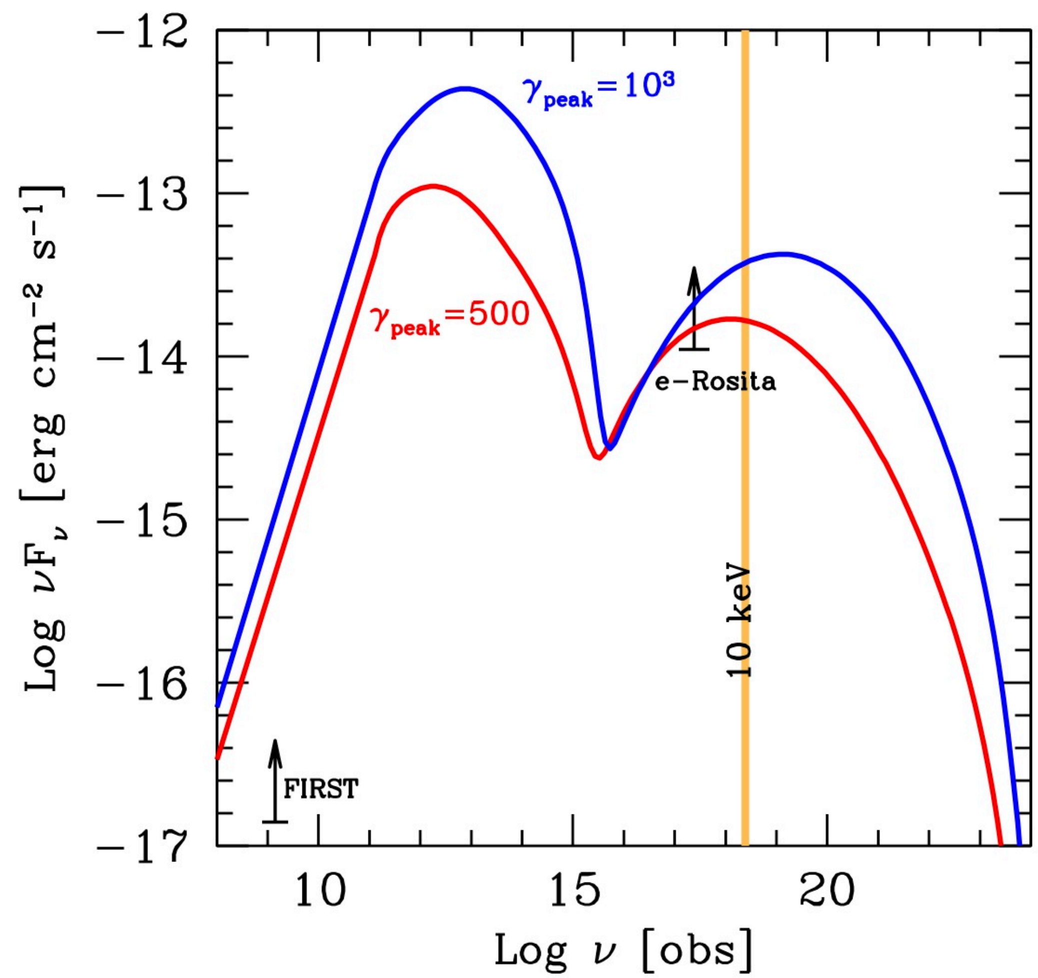
Blazar sequence: selection bias ?

Simulations of observational biases



Giommi, Padovani et al. 2012

2) There should be lots of low-peak, gamma-quiet BL Lacs



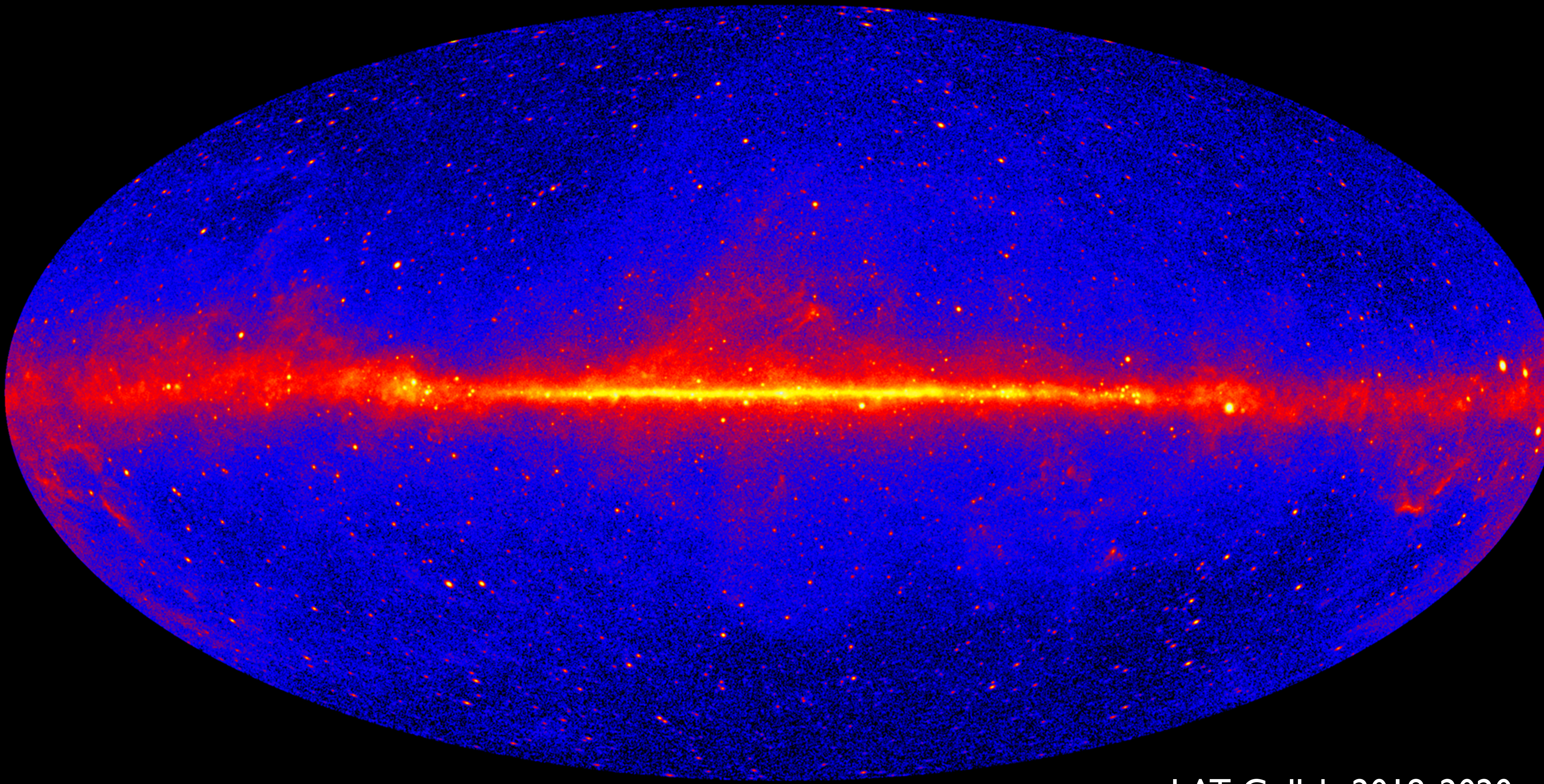
Fast-forward 20 years…

Fermi-LAT 10yr: ~ 3500 γ-ray blazars

~ 0.09 blazars / deg2

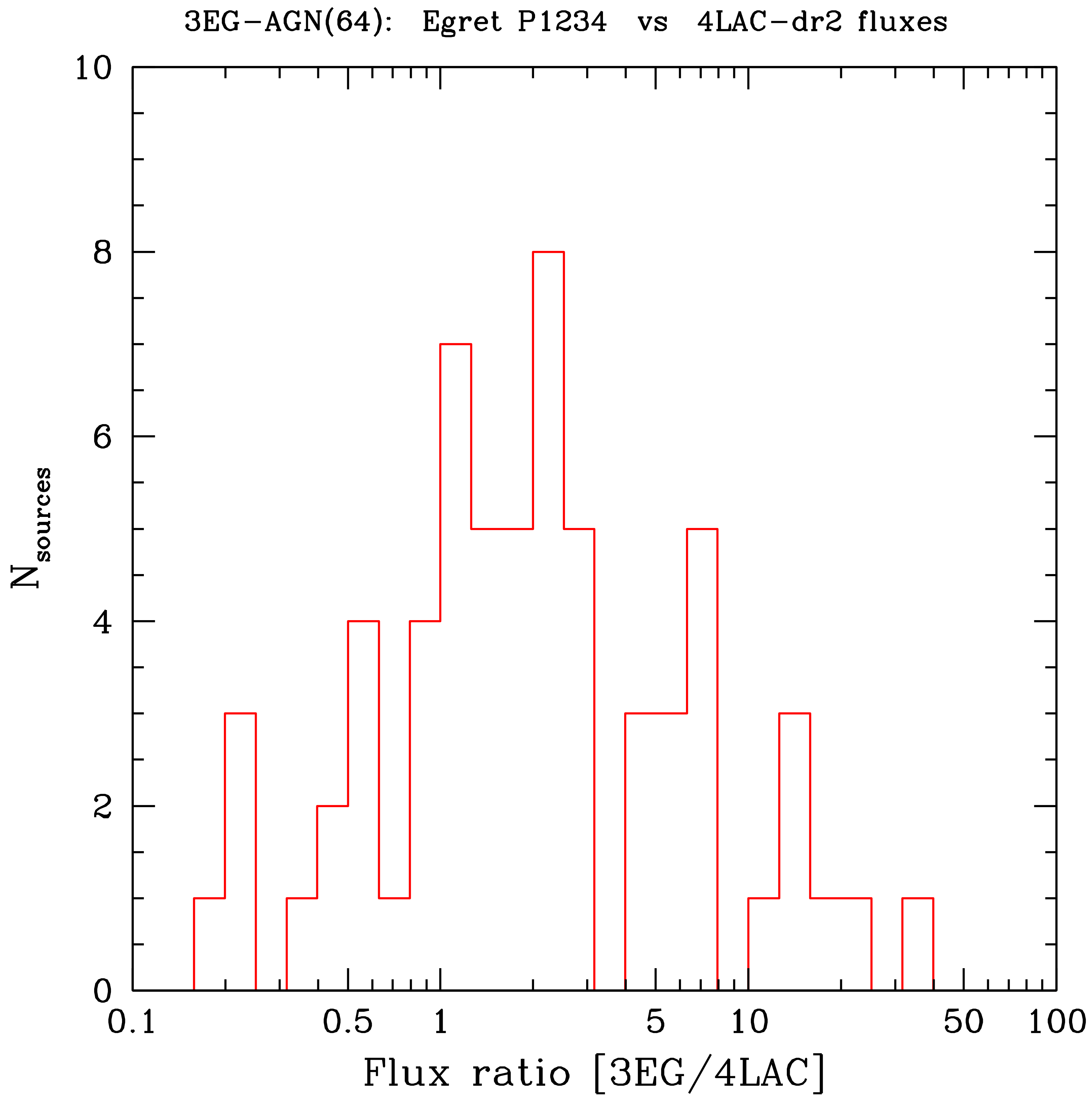
HESS, MAGIC, VERITAS:

83 blazars



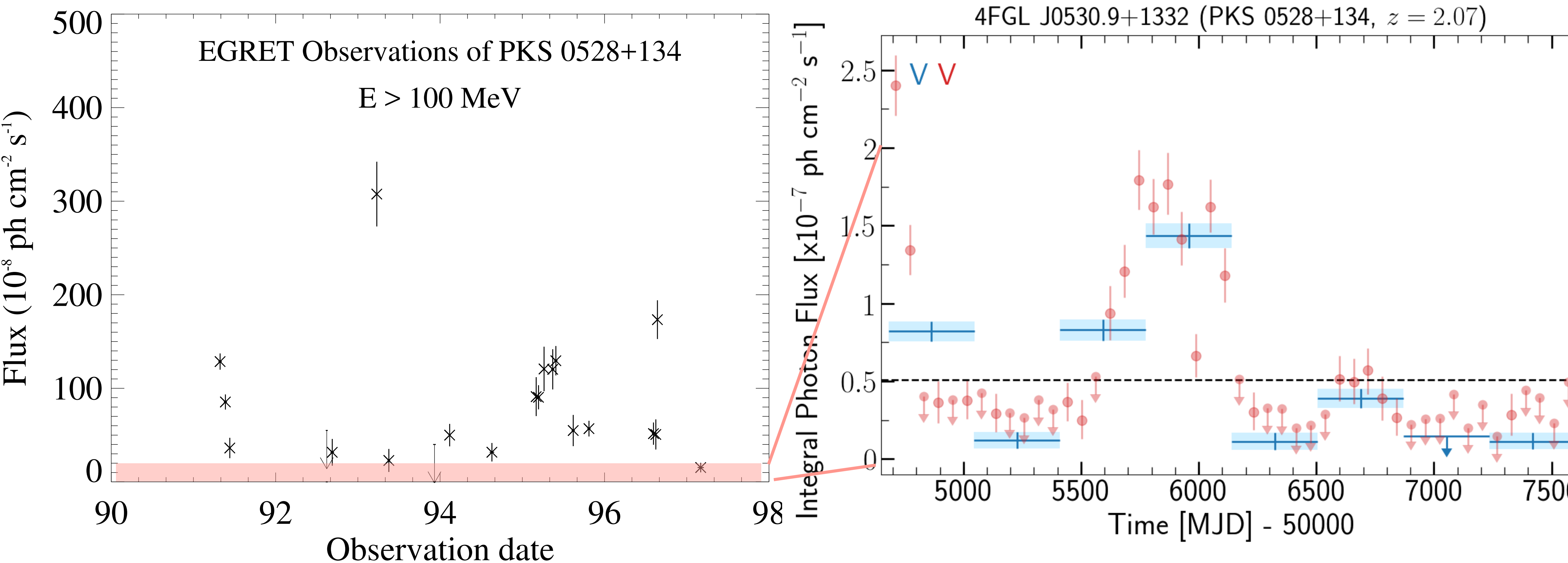
LAT Collab. 2018, 2020

EGRET - Fermi-LAT :   not the same sky



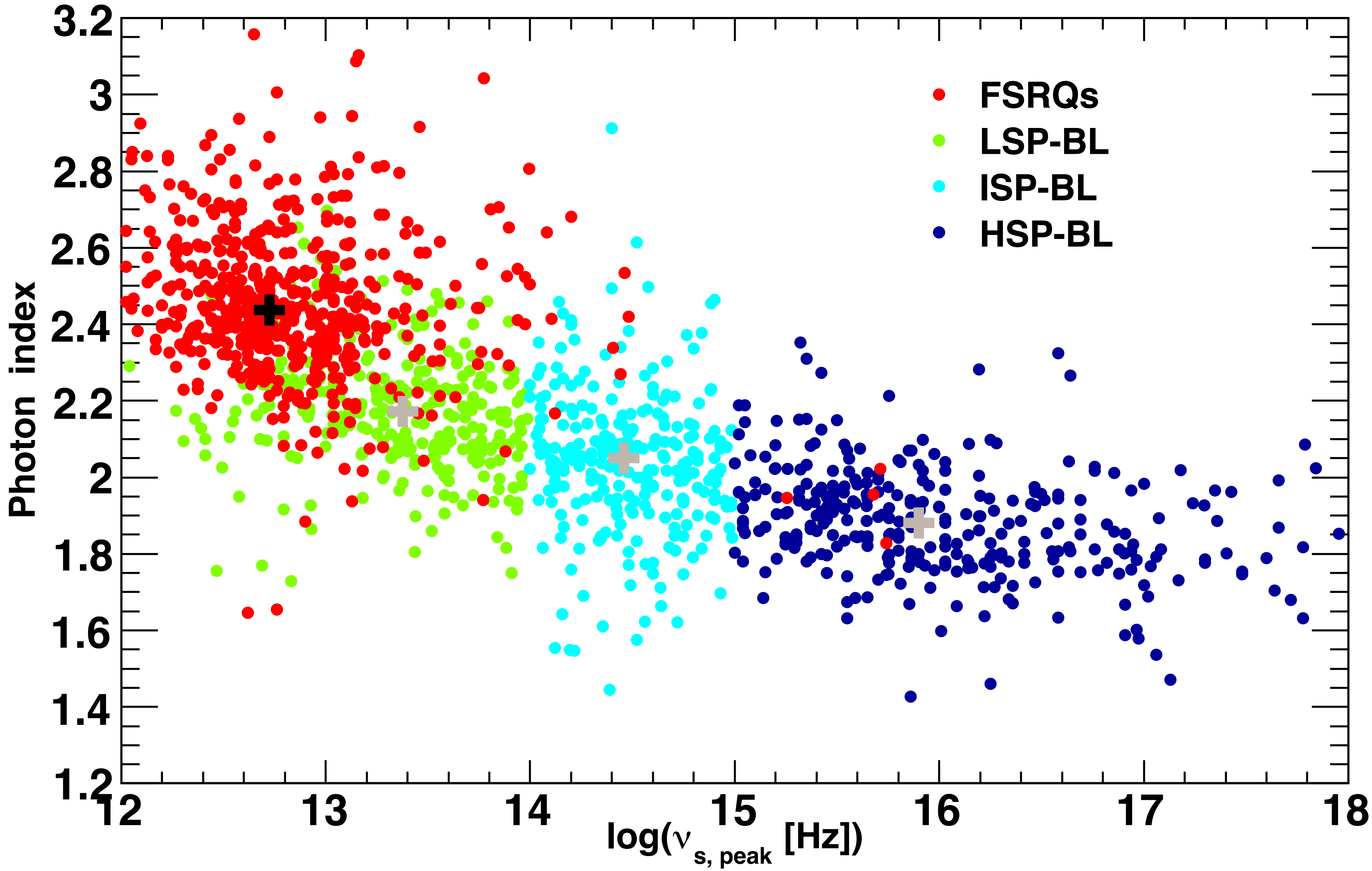
4LAC-dr2: first 8 brightest blazars

	Source_Name	Signif_Avg	Flux1000 ph / (cm2 s)	Energy_Flux100 erg / (cm2 s)	CLASS	ASSOC1	
	4FGL J2253.9+1609	465.154	8.69e-08	1.11e-09	FSRQ	3C 454.3	
	4FGL J2232.6+1143	349.938	4.84e-08	2.20e-10	FSRQ	CTA 102	
	4FGL J1104.4+3812	325.523	3.56e-08	4.49e-10	BLL	Mkn 421	
	4FGL J0721.9+7120	298.165	2.27e-08	2.17e-10	BLL	S5 0716+71	
	4FGL J1427.9-4206	293.386	3.93e-08	3.53e-10	FSRQ	PKS 1424-41	
	4FGL J1256.1-0547	291.633	4.19e-08	2.79e-10	FSRQ	3C 279	
	4FGL J0428.6-3756	249.909	2.36e-08	2.13e-10	BLL	PKS 0426-380	
	4FGL J1512.8-0906	238.707	3.46e-08	4.58e-10	FSRQ	PKS 1510-089	
	…						
brightest in EGRET	4FGL J1626.0-2950	47.1212	2.83e-09	4.23e-11	FSRQ	PKS B1622-297	(220 position in 4LAC)
	4FGL J0449.1+1121	43.8837	2.39e-09	3.31e-11	FSRQ	PKS 0446+11	(240)
	4FGL J0530.9+1332	26.4661	1.81e-09	2.58e-11	FSRQ	PKS 0528+134	(450) (…Egret 1st)

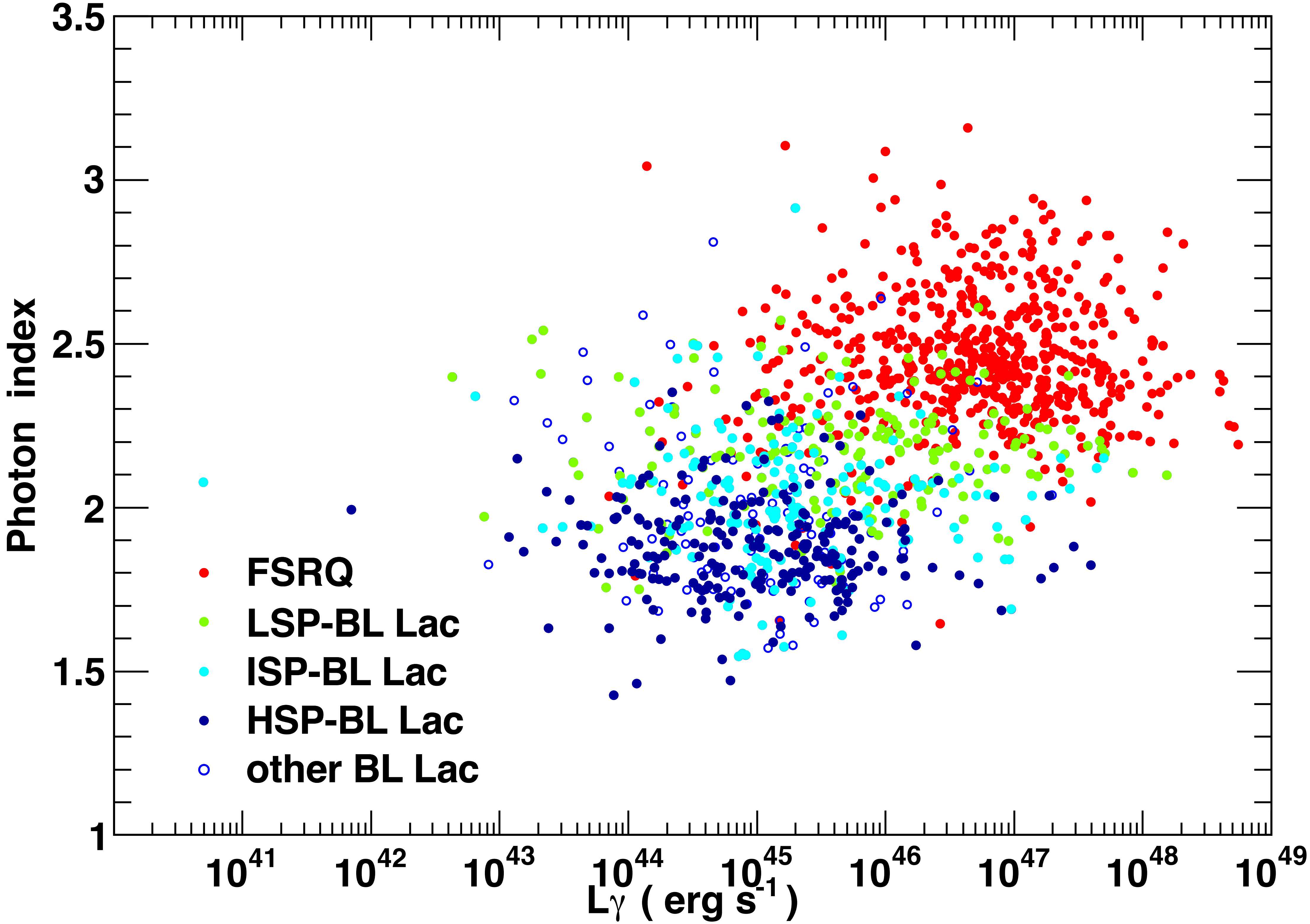


=> Blazars vary also on very long timescales (decades).

Fermi gamma-ray SED sequence



LAT Coll., 4LAC paper 2020

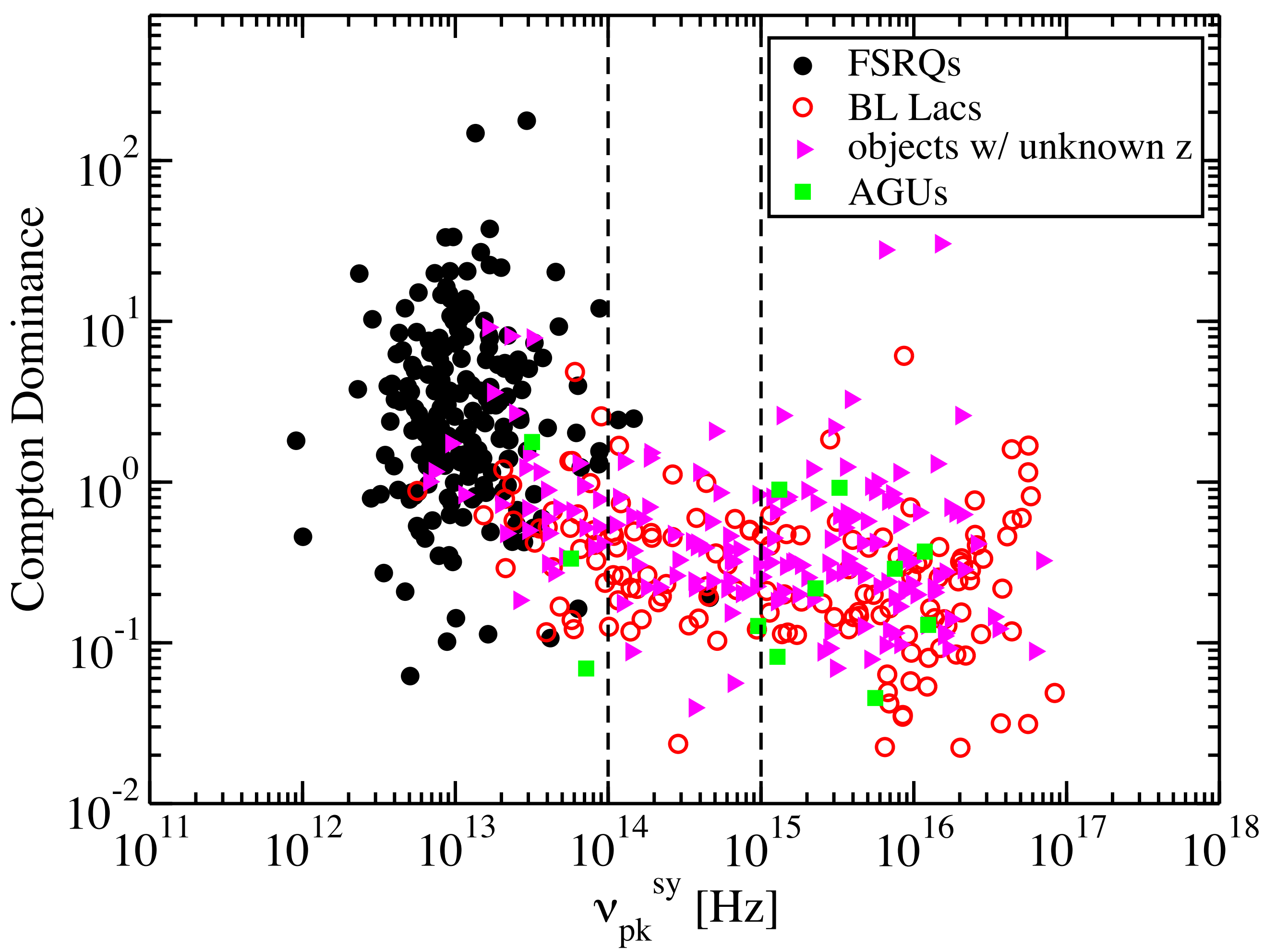


LAT Coll., 4LAC paper 2020

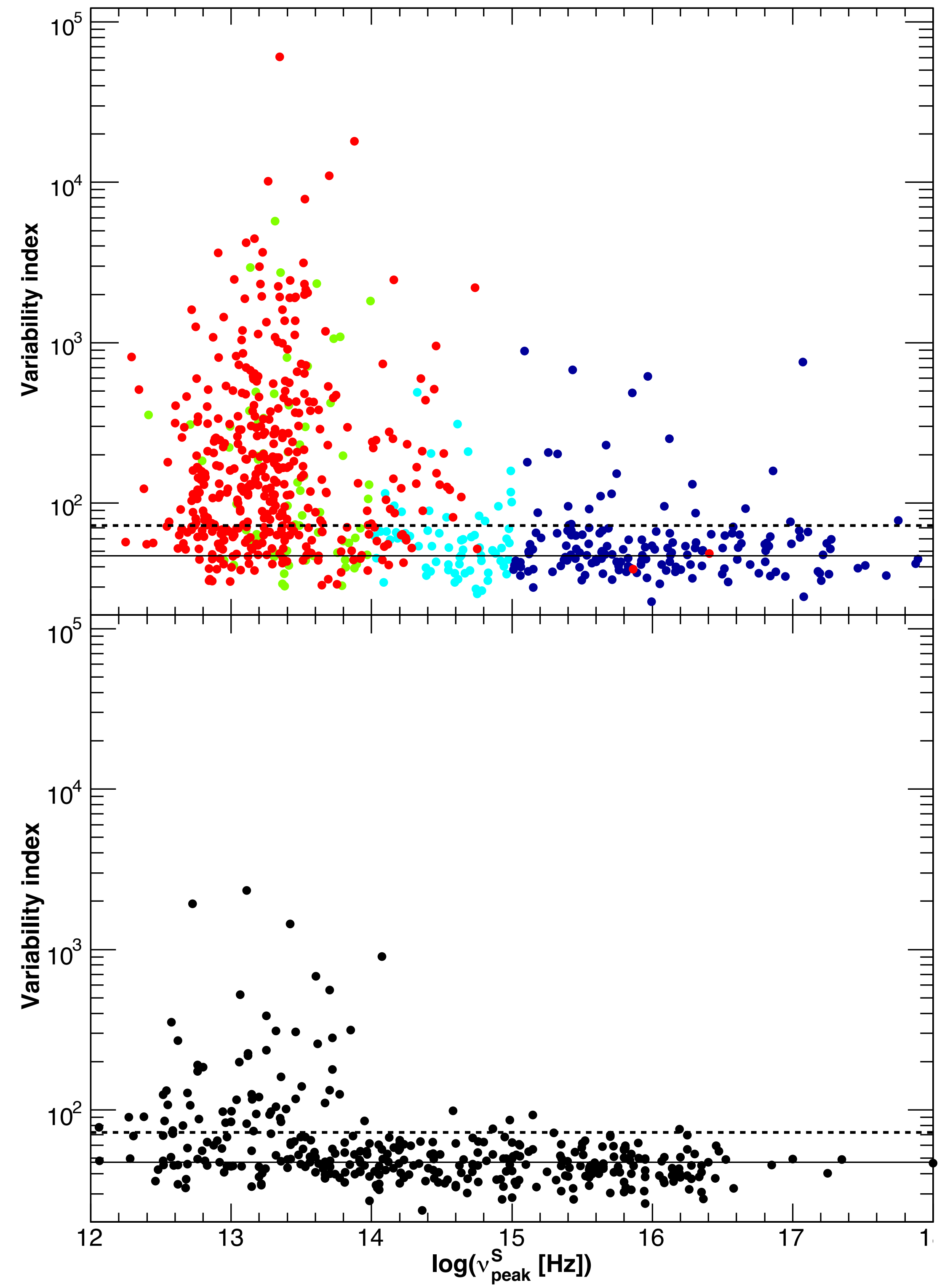
Gamma-ray dominance

GeV variability

2LAC clean sample



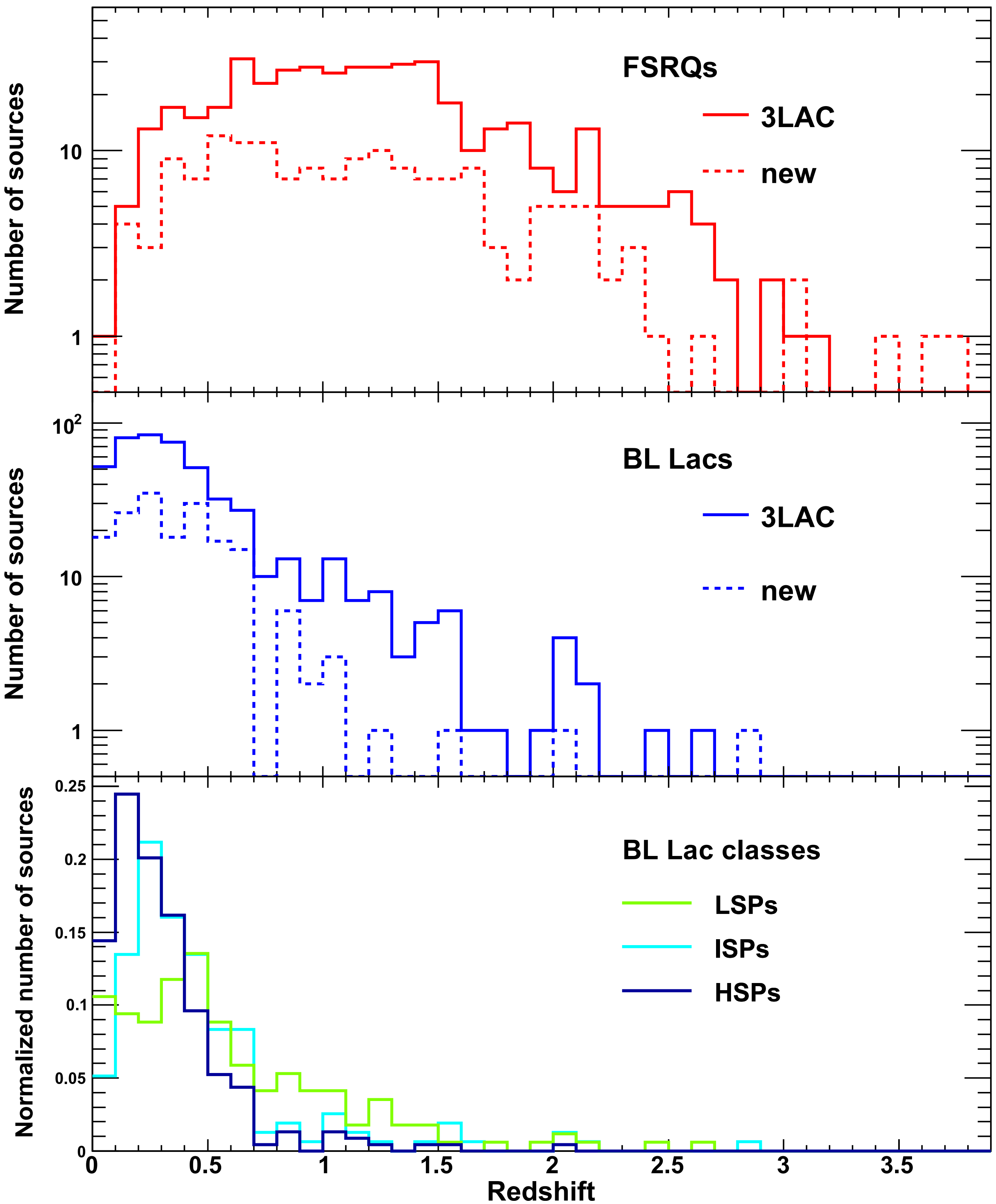
Finke 2013



LAT Coll., 3LAC paper 2015

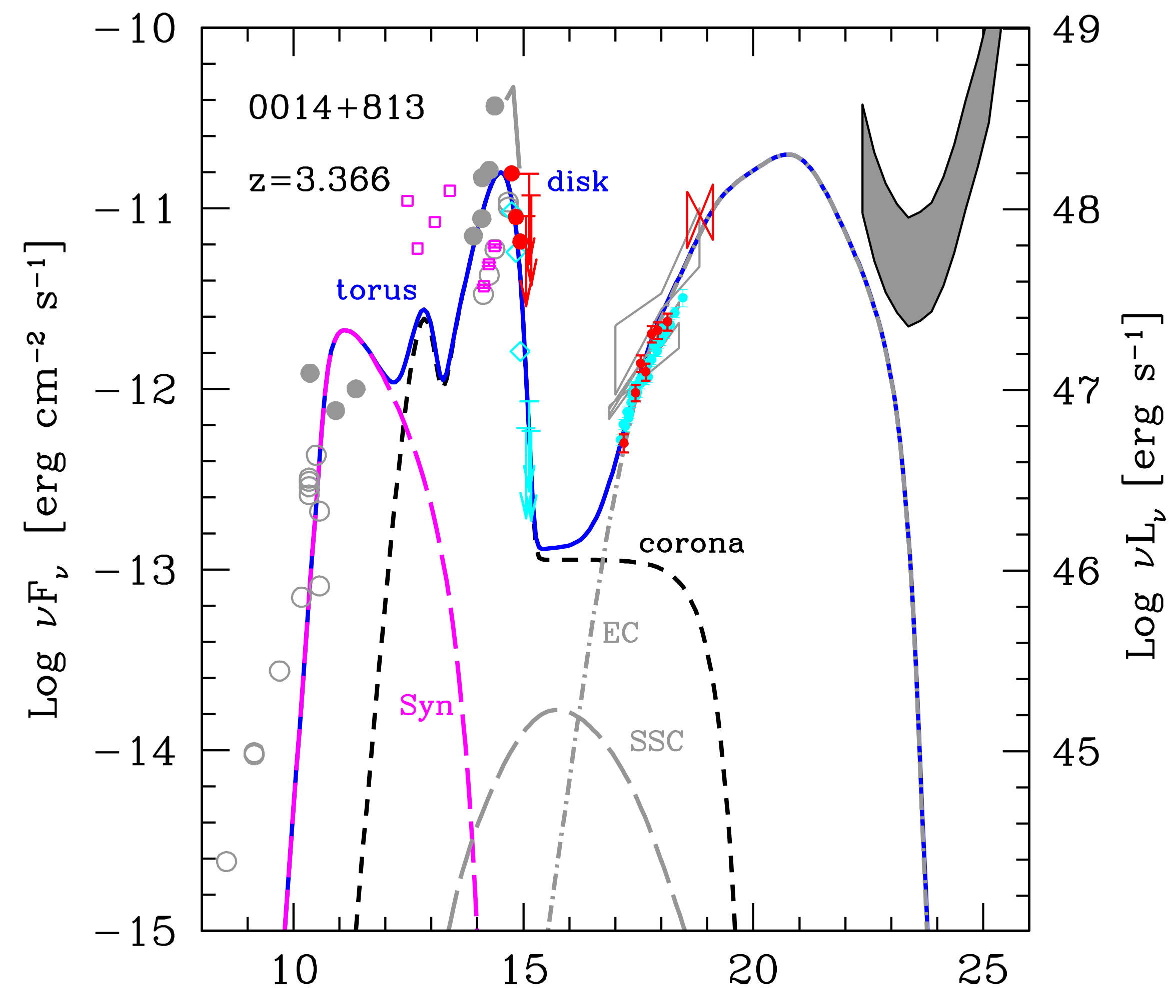
Redshift distribution

z>3: BZCAT = 80 Fermi = 10



LAT Coll., 4LAC paper 2020

Fermi misses high-z Blazars



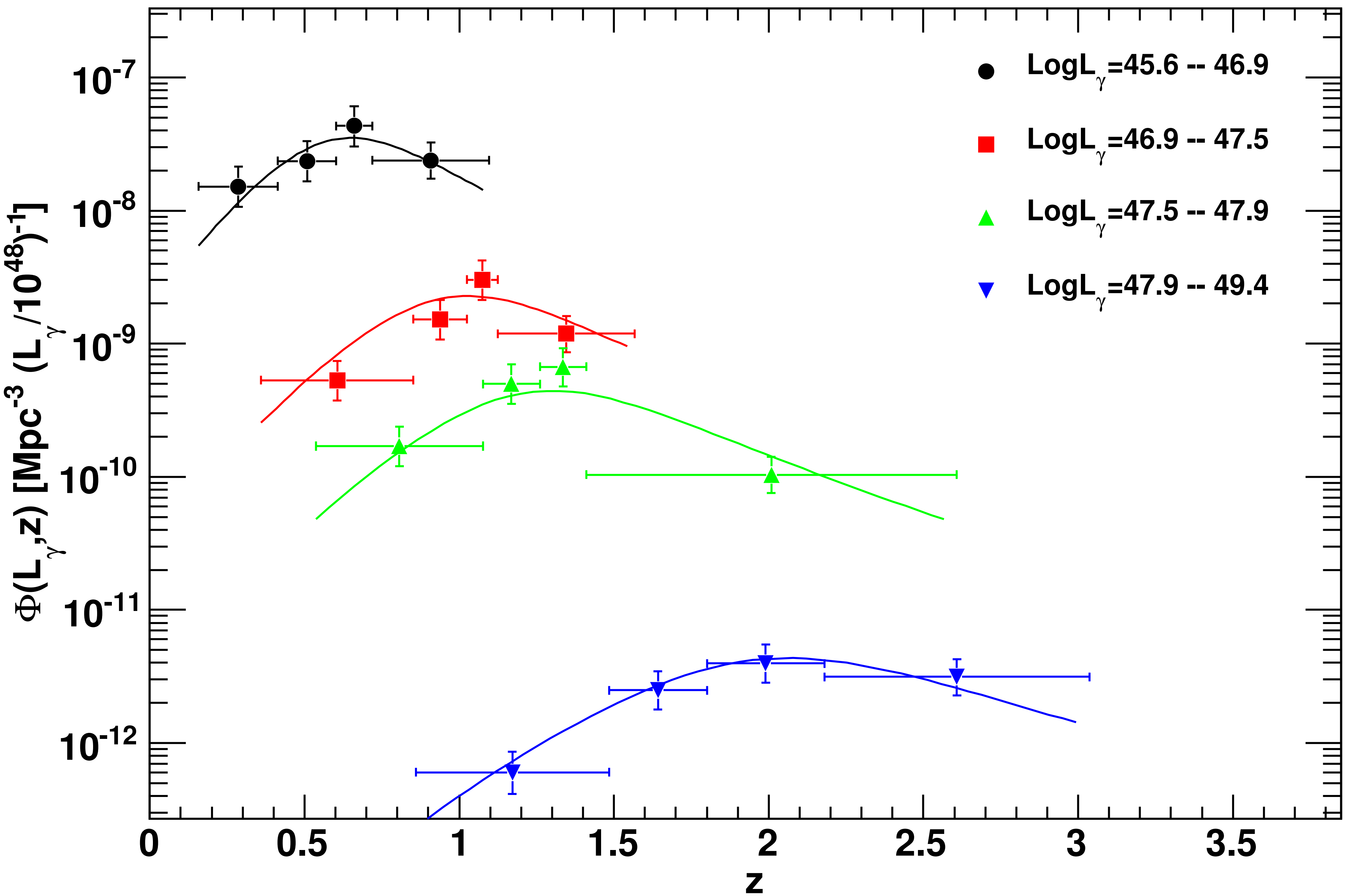
MeV-peaked (high-z)

eRosita survey ?

Sbarrato et al. 2015

Blazars Cosmological Evolution

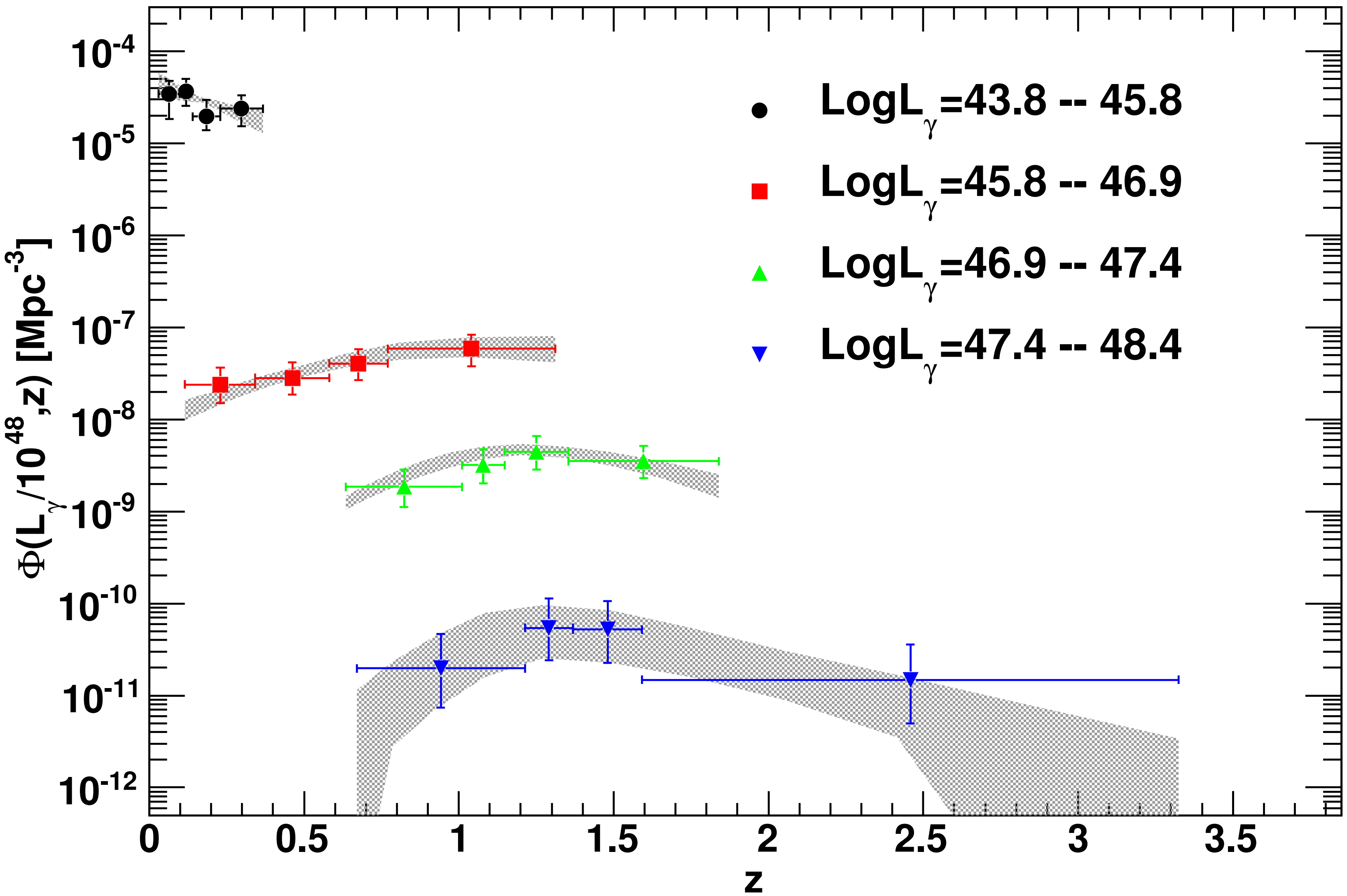
FSRQ evolve positively (V/V_{max} ~0.64-0.76)



Ajello et al. 2011

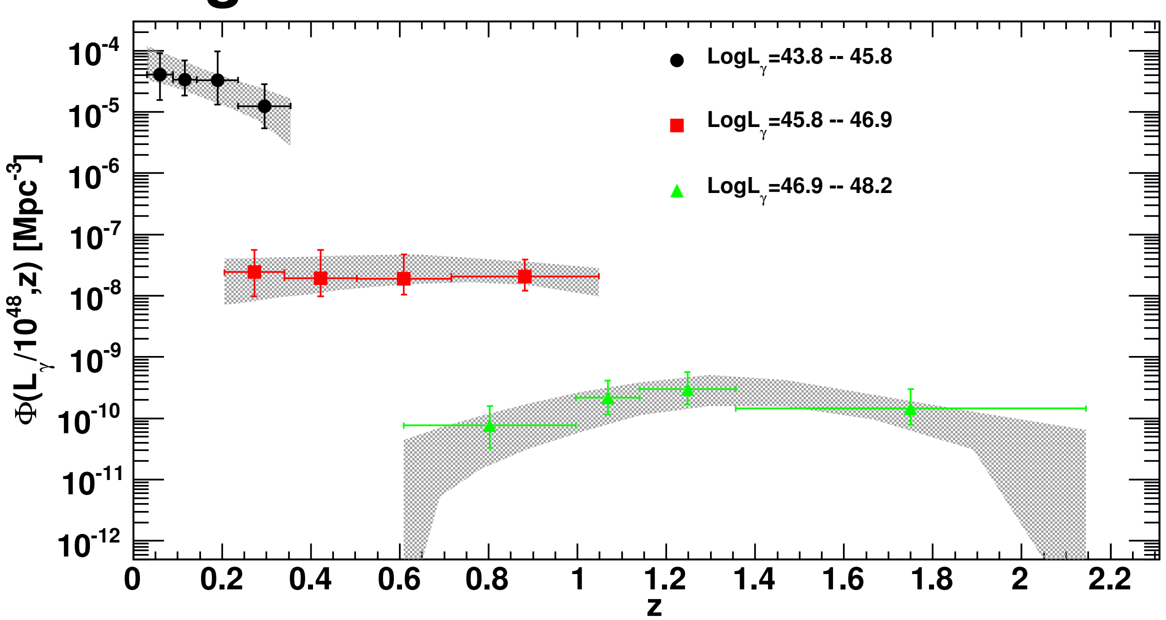
BL Lacs are a mix

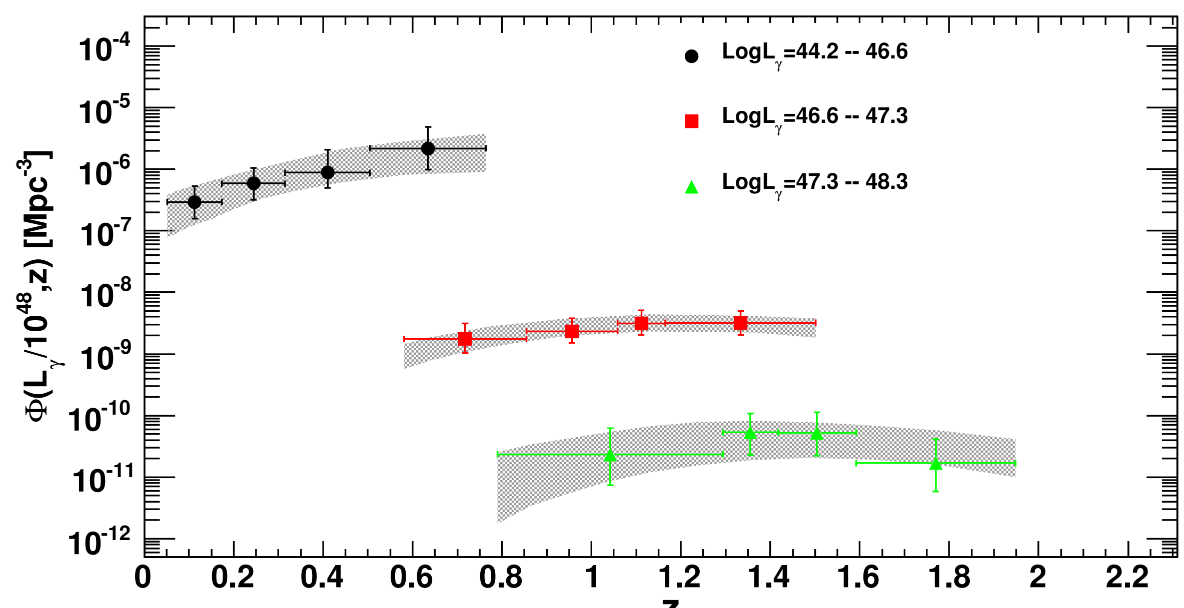
Ajello et al. 2013



Negative

Positive





HBL

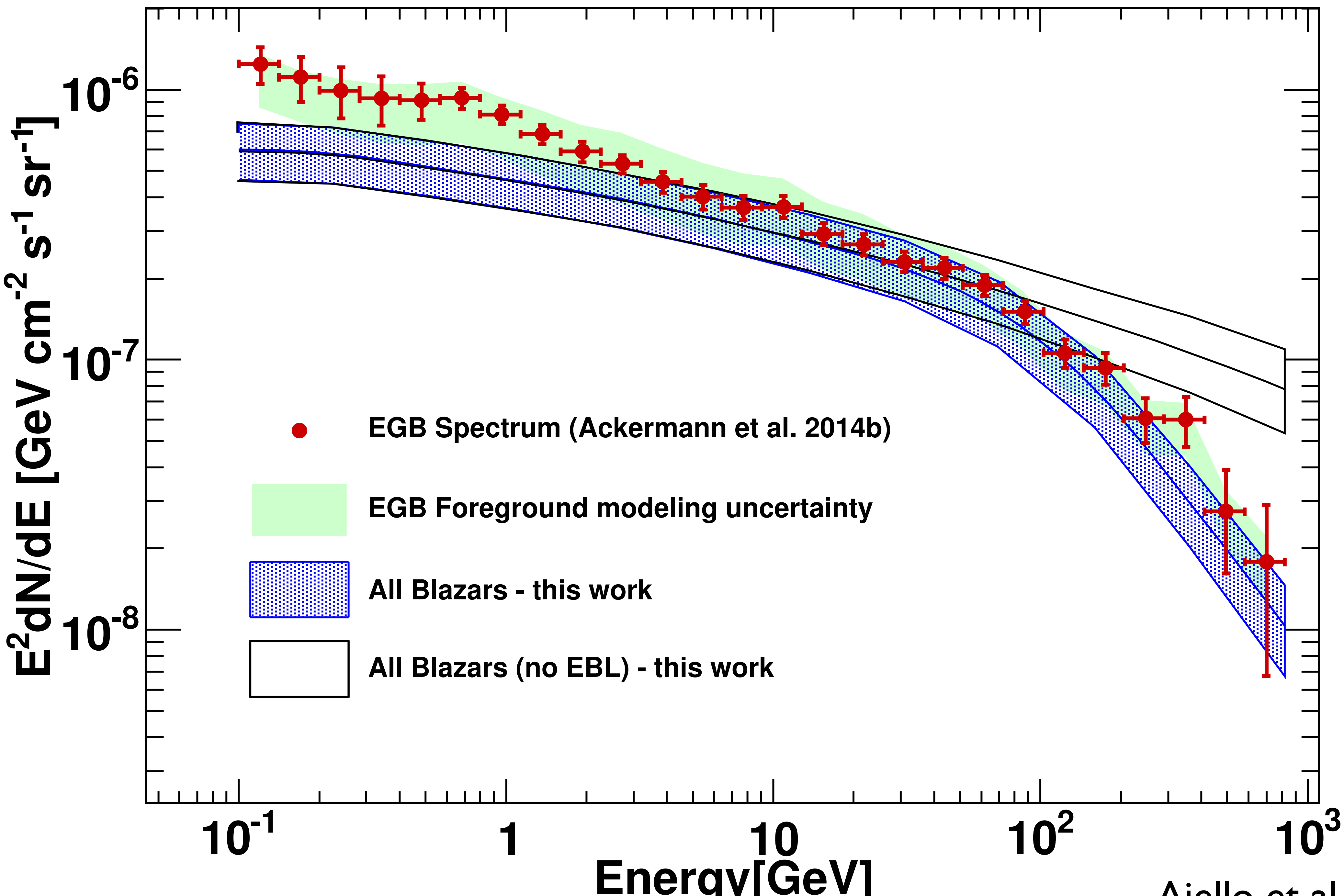
Confirming Giommi et al. 1999

IBL-LBL

Extragalactic Gamma-ray Background

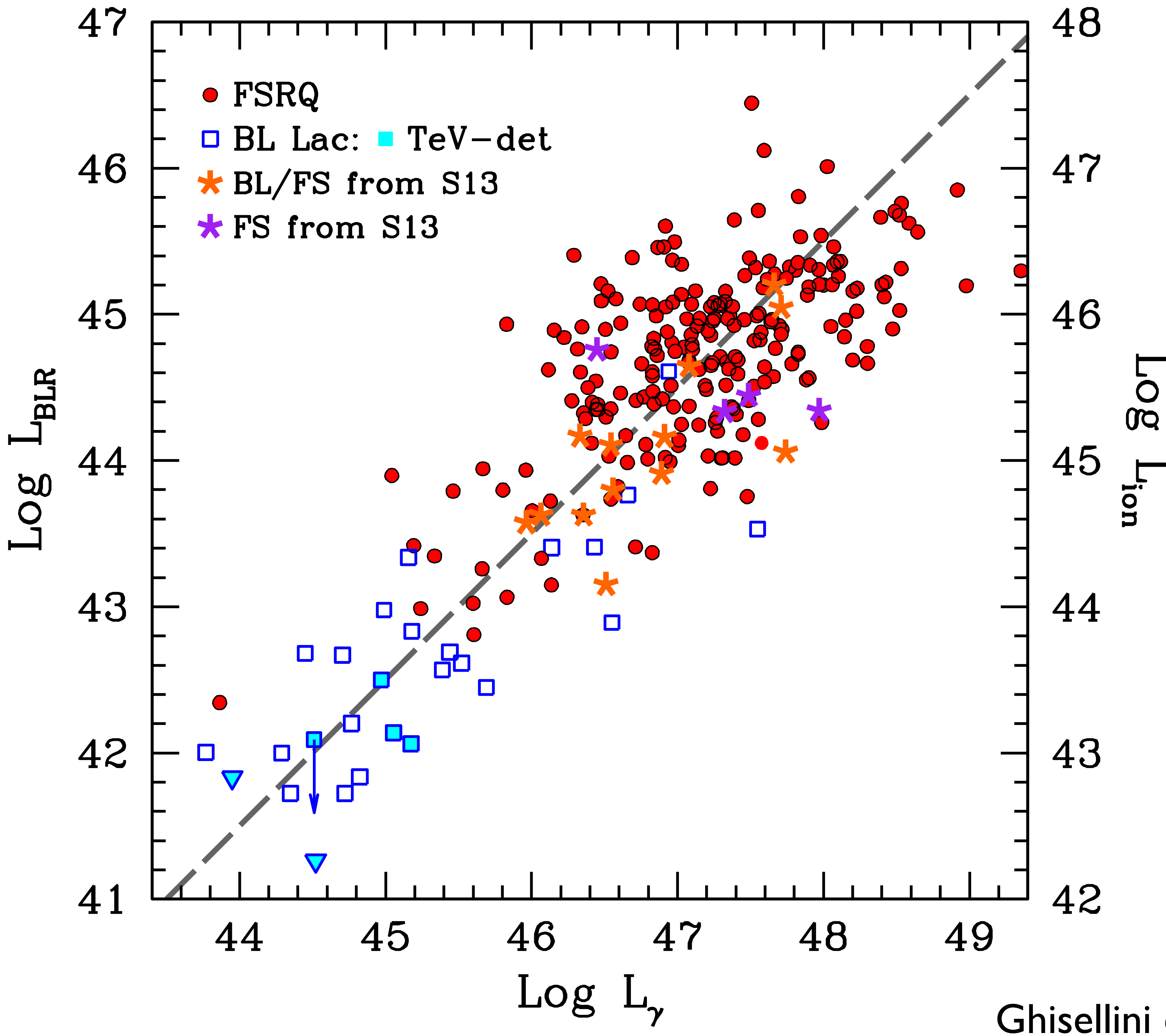
Blazars: ~100% EGB >20 GeV

~50% EGB 100 MeV - 1GeV



Ajello et al. 2015

Disk - Jet Relation



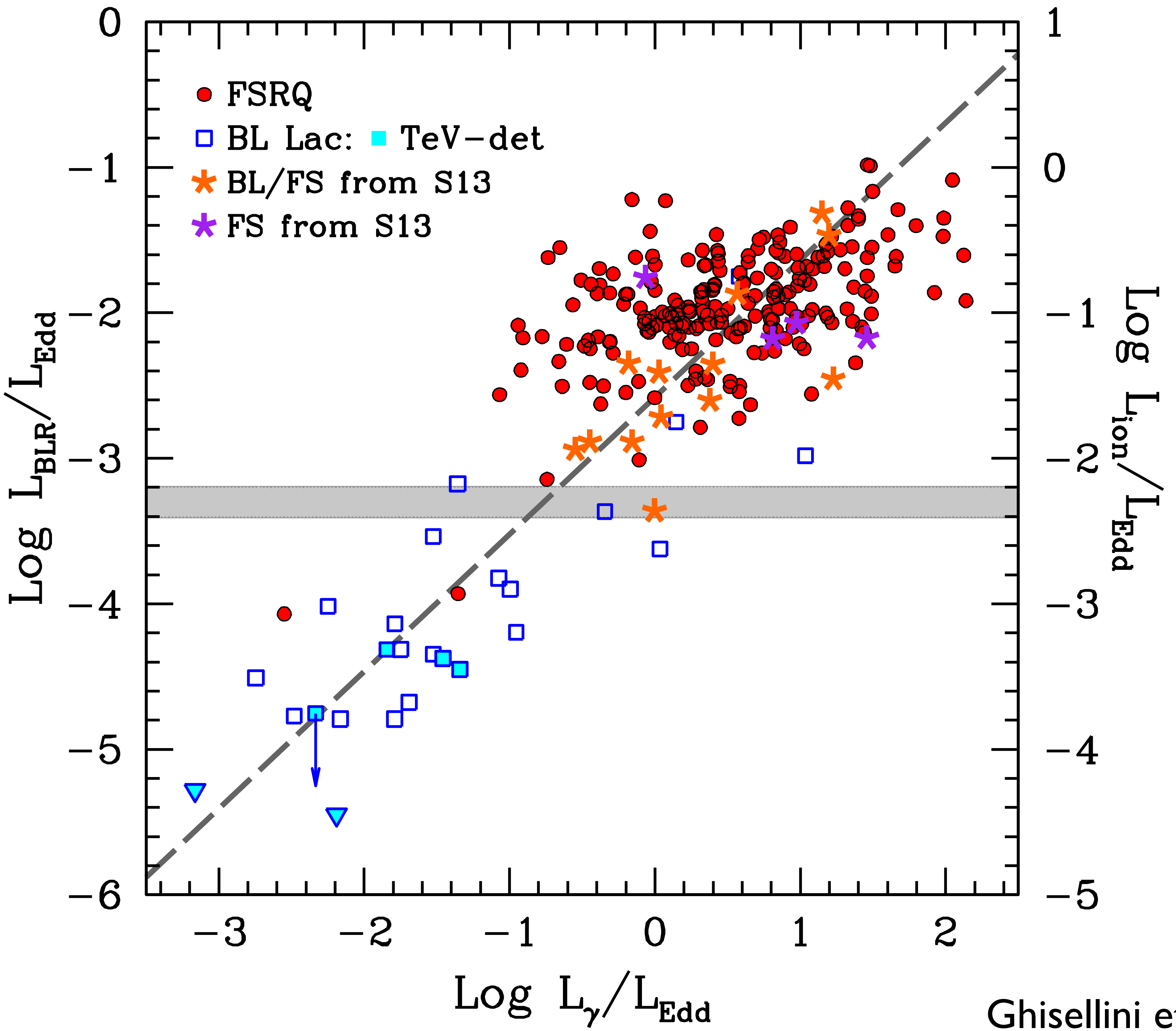
Ghisellini et al 2013
Sbarrato et al 2011, 2014

Introducing BH mass

(Virial or M_{BH} - M_R relation)

real FSRQ

real BLLacs



radiatively efficient

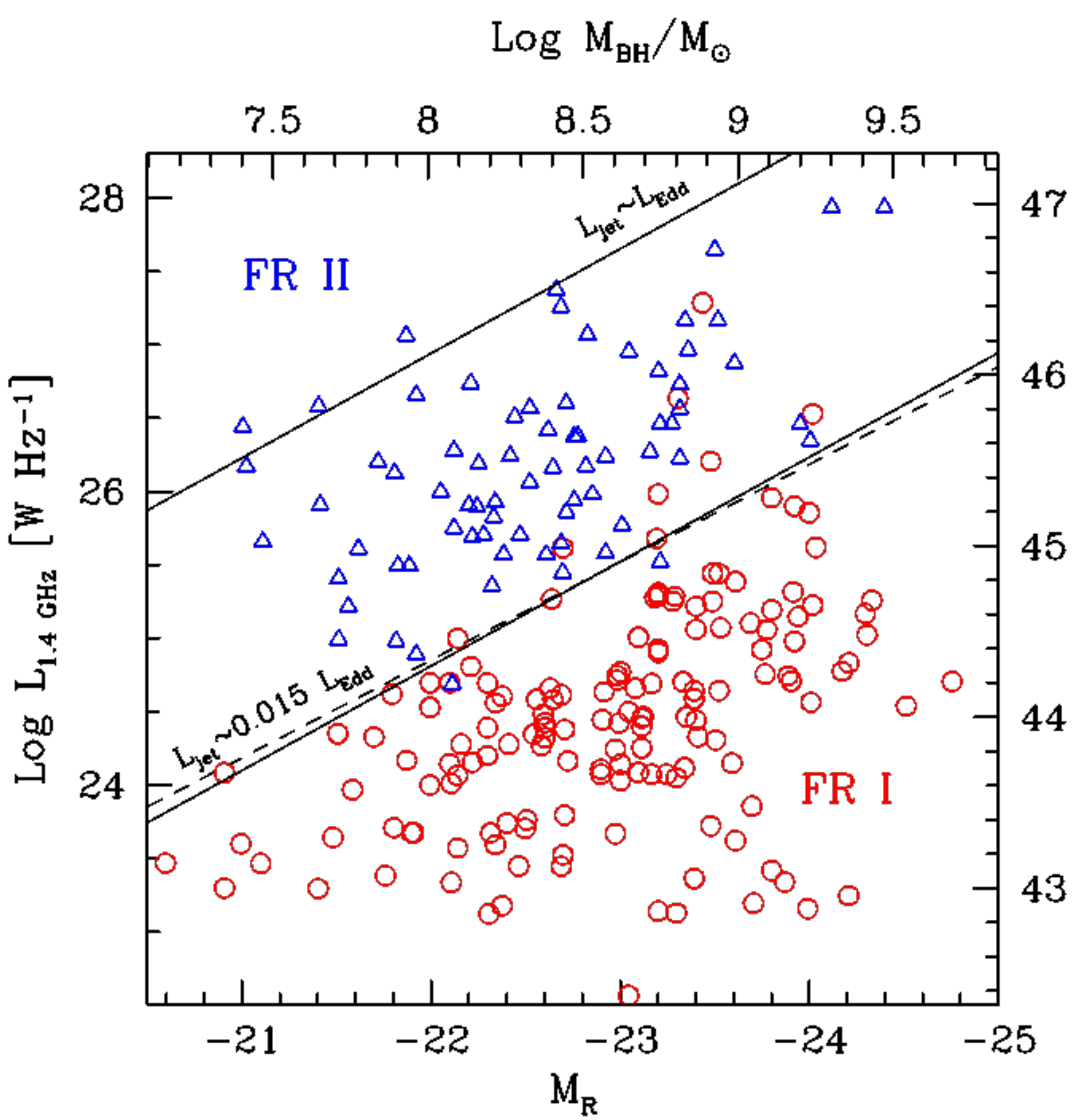
radiatively inefficient

Ghisellini et al 2013

Sbarrato et al 2011, 2014

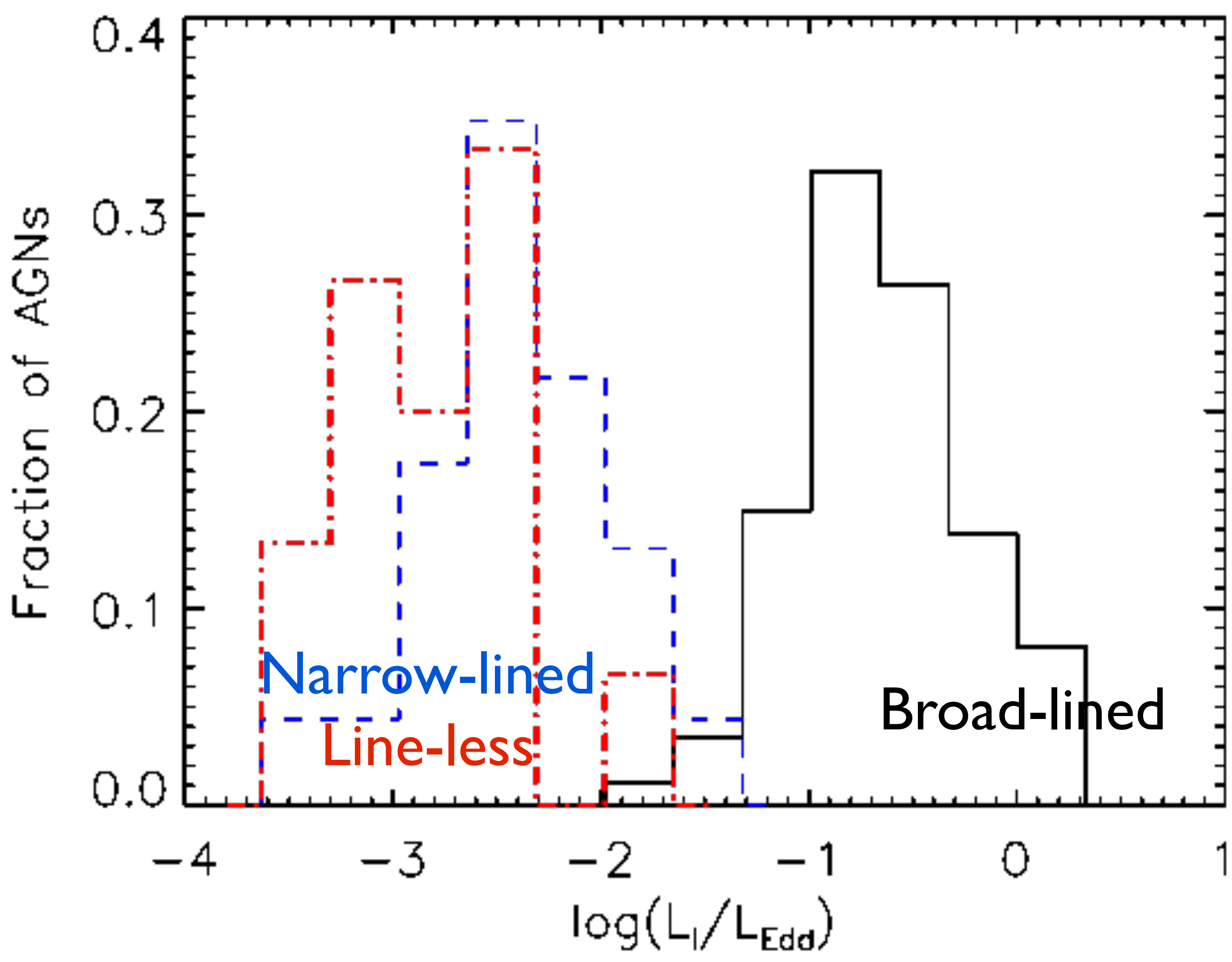
Something is happening at L ~0.01 L_{Edd}

ADAF - Shakura/Sunyaev ?



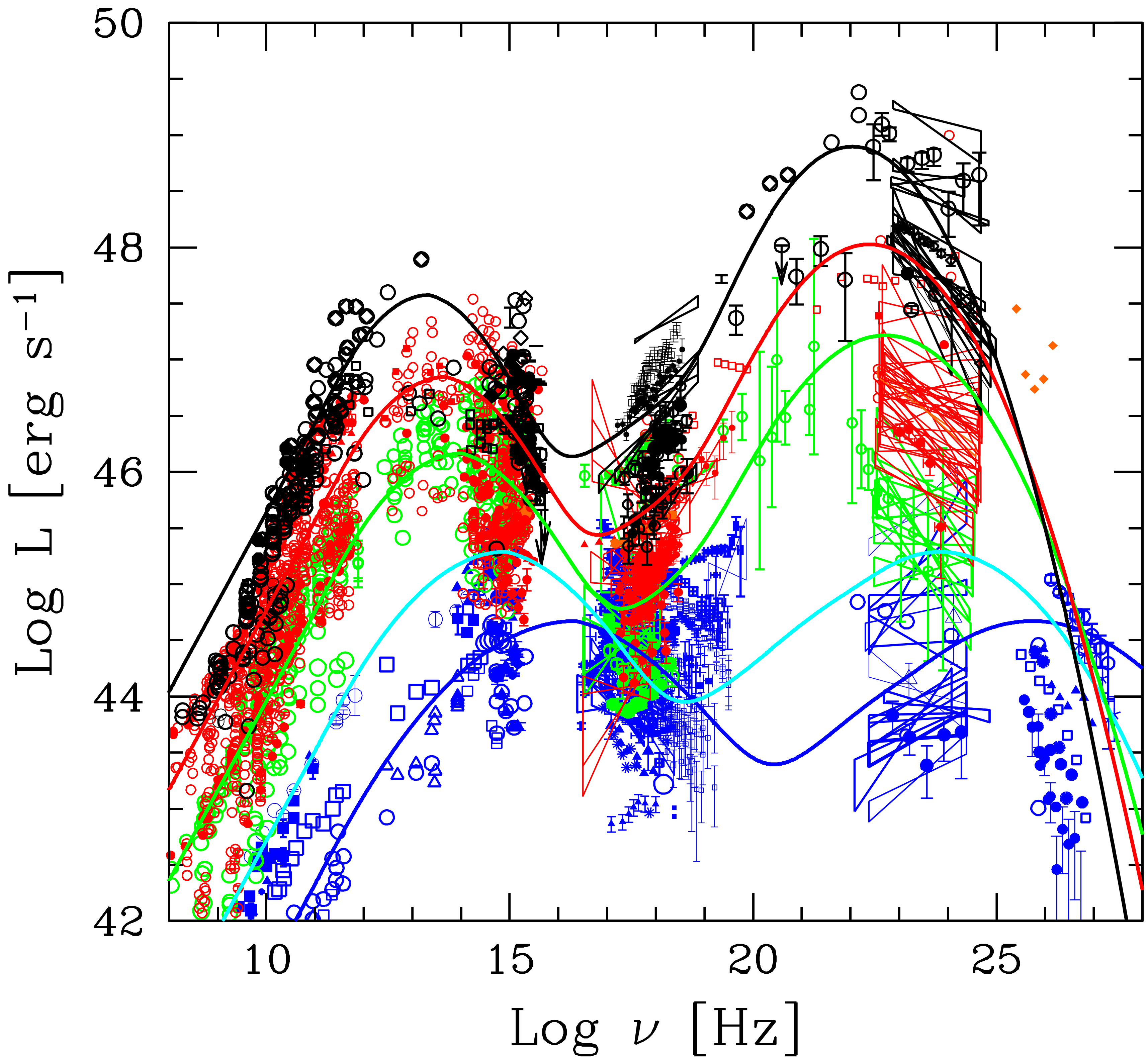
Ledlow & Owen 1996
Ghisellini & Celotti 2002

Sample 82 unobscured AGNs

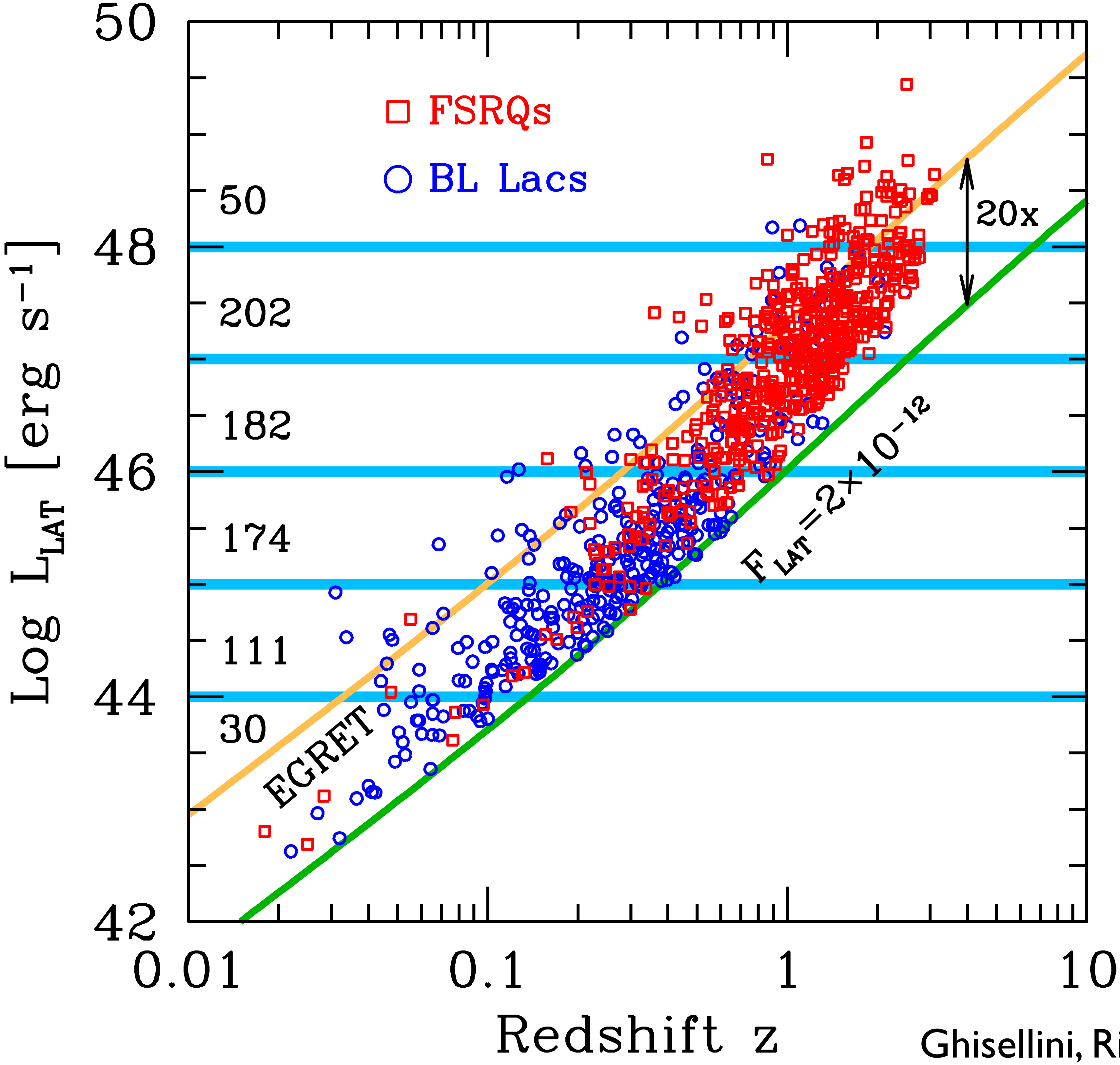


Trump et al. 2011

What about the Blazar Sequence ?



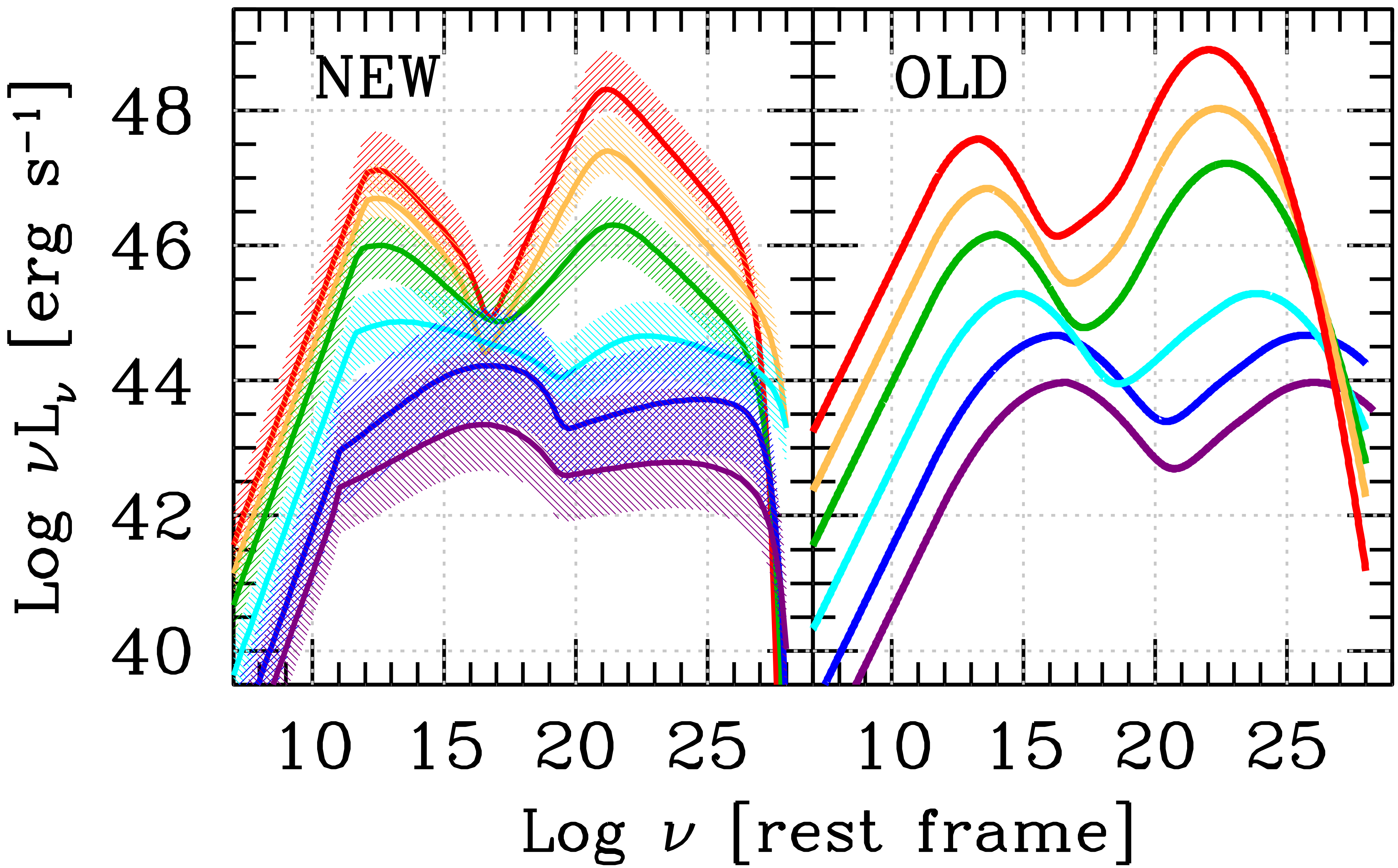
From EGRET to Fermi-LAT



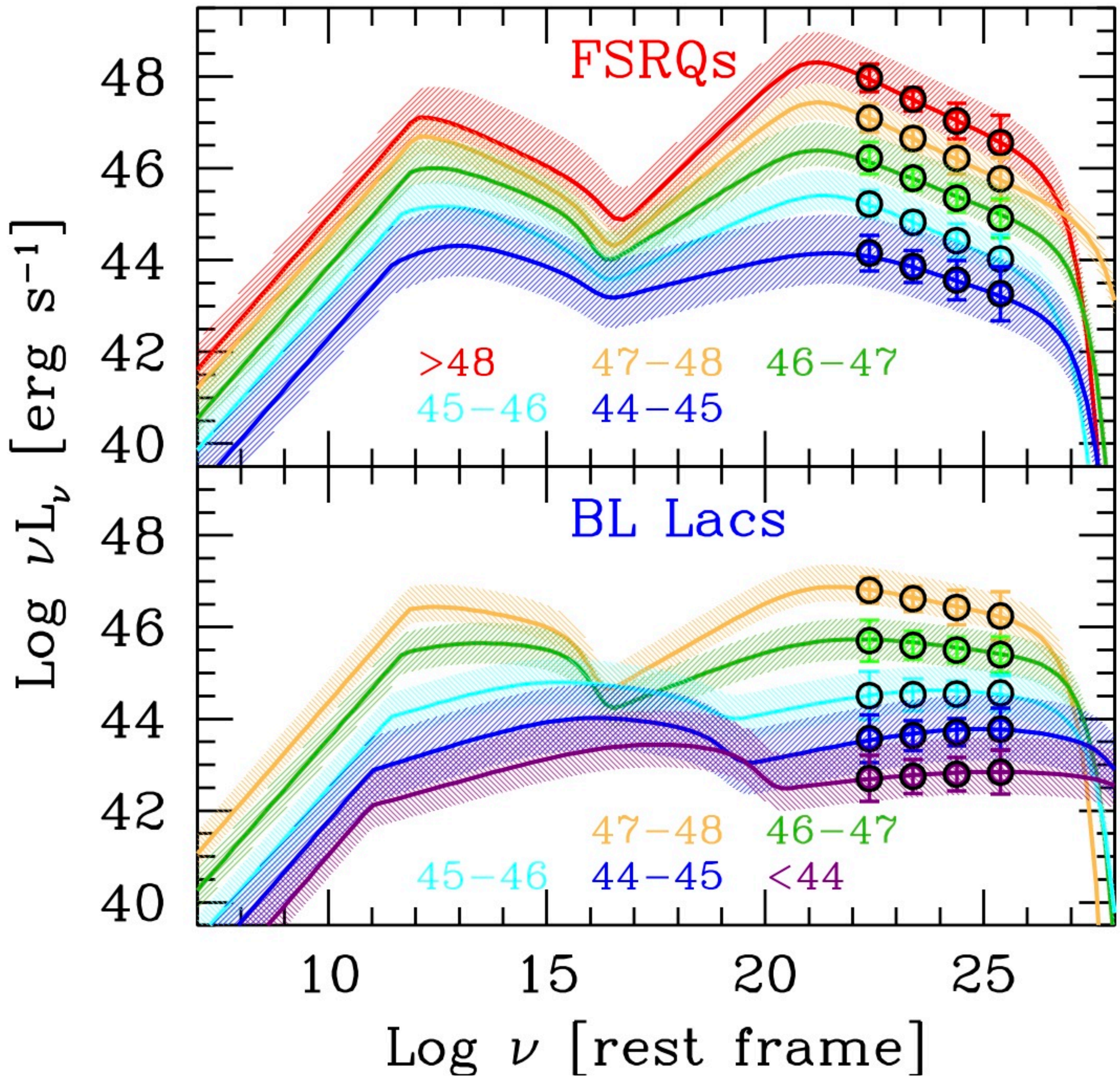
Ghisellini, Righi, LC et al. 2017

Blazar Sequence 2.0

the gamma-ray view



Ghisellini, Righi, LC et al. 2017



Ghisellini, Righi, LC et al. 2017

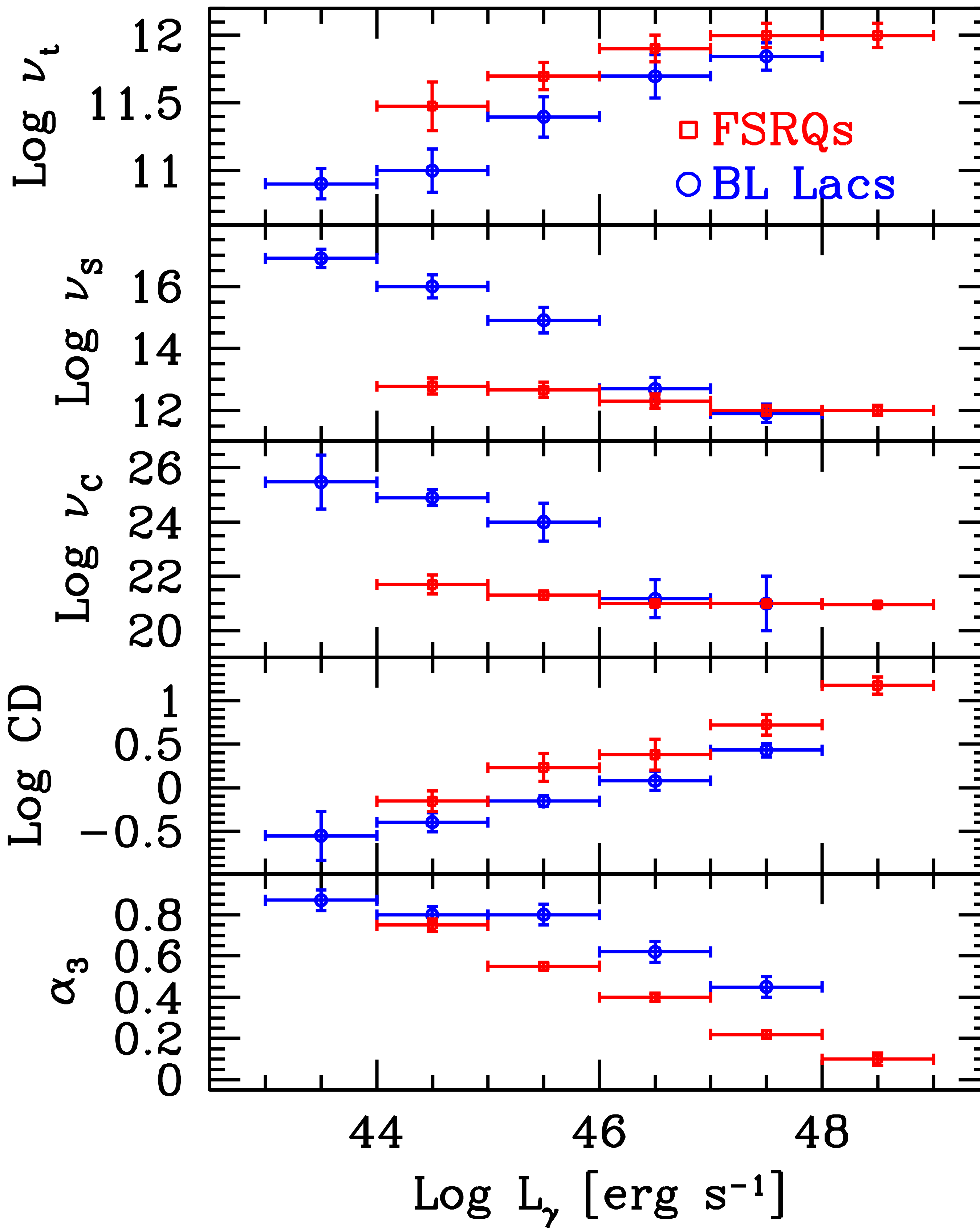
New aspects:

Self-absorbing

Synch. peak

Compton peak

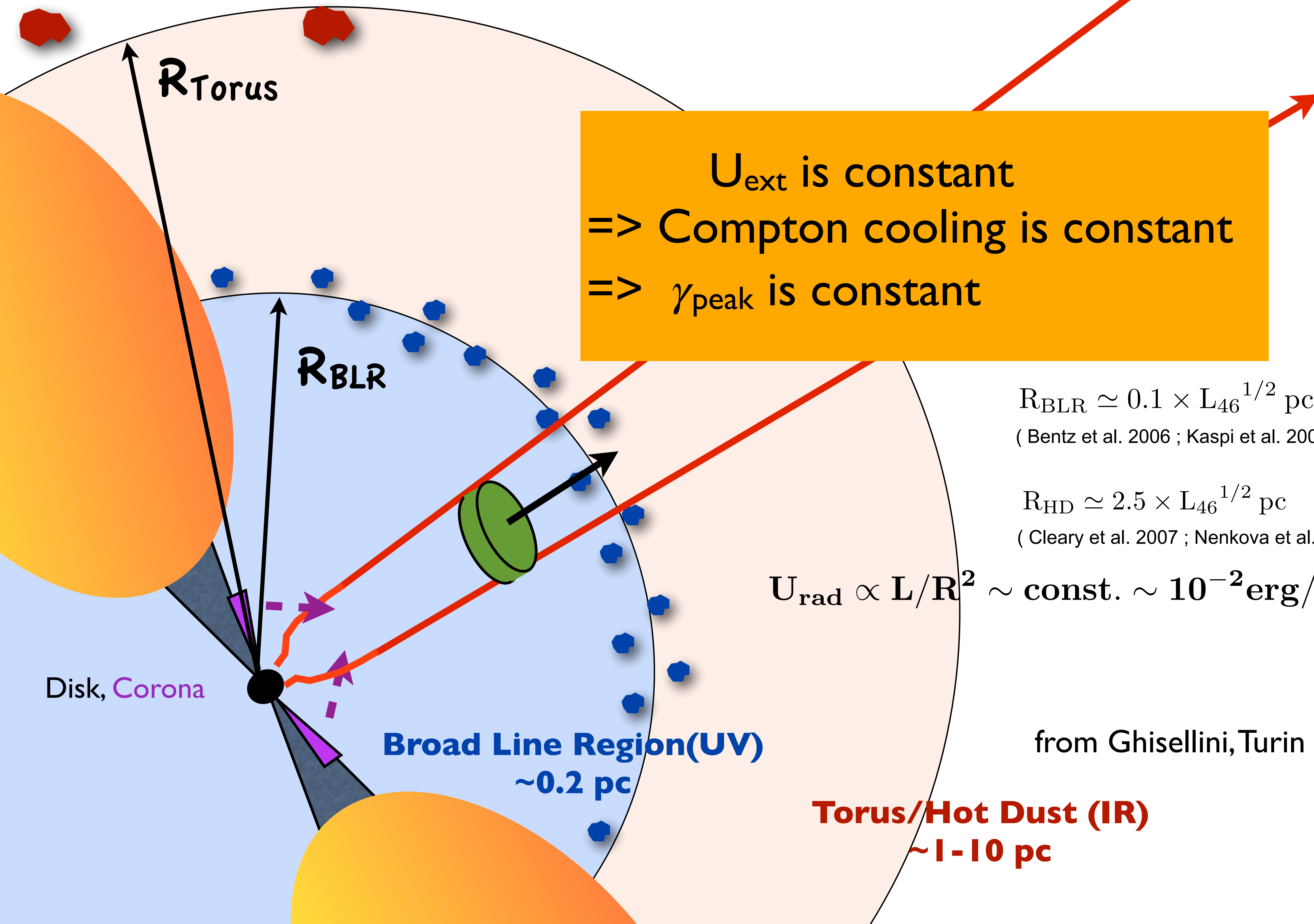
L_C/L_{synch}



Ghisellini et al. 2017

FSRQ

U_{ext} is constant
=> Compton cooling is constant
=> γ_{peak} is constant



$R_{BLR} \simeq 0.1 \times L_{46}{}^{1/2}$ pc
(Bentz et al. 2006 ; Kaspi et al. 2007)

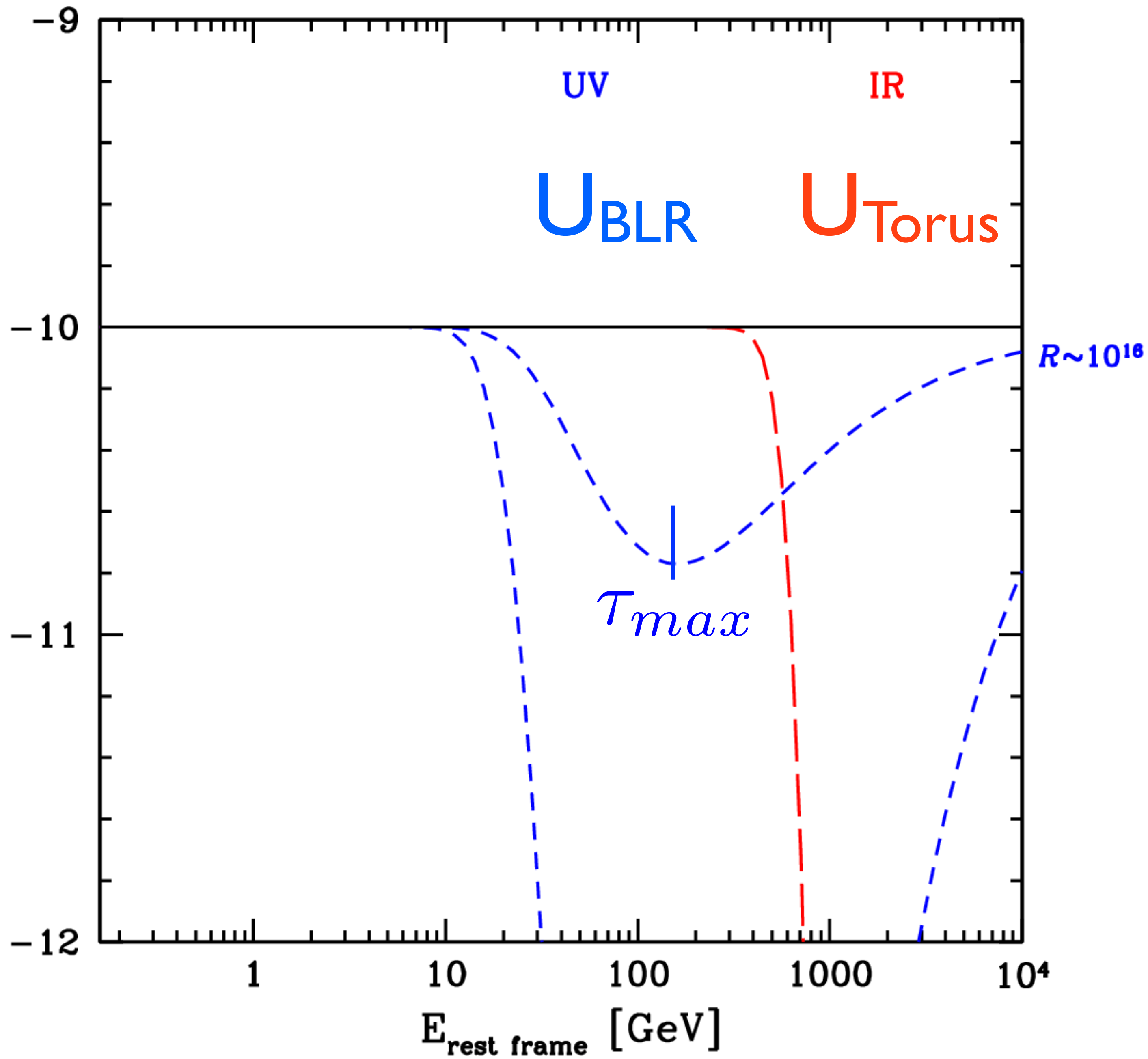
$R_{HD} \simeq 2.5 \times L_{46}{}^{1/2}$ pc
(Cleary et al. 2007 ; Nenkova et al. 2008)

$$\mathbf{U_{rad} \propto L/R^2 \sim const. \sim 10^{-2} erg/cm^3}$$

from Ghisellini, Turin 2018

TEST: BLR opacity, optical depths >>1

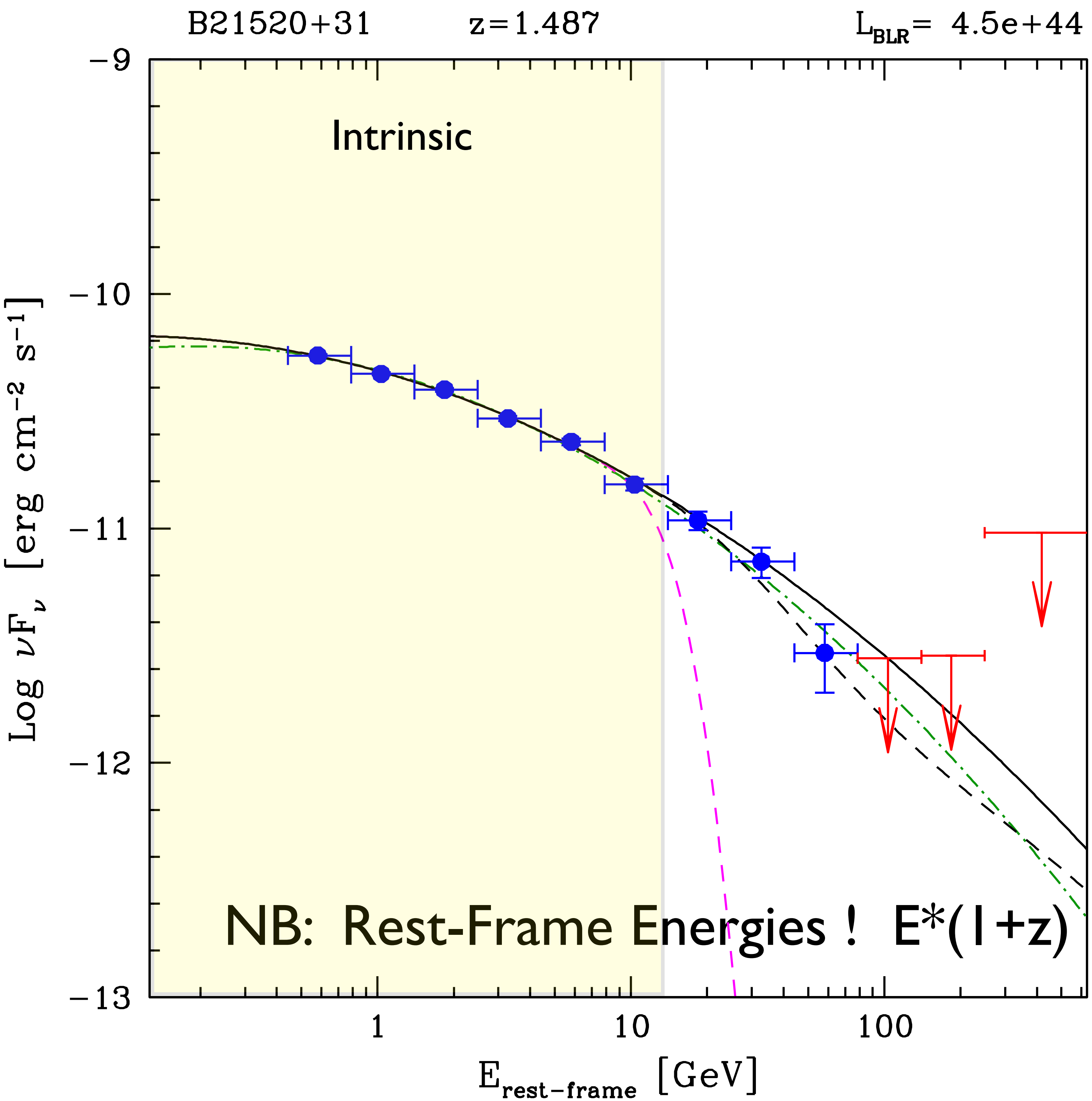
$$\gamma\gamma \rightarrow e^+e^- \qquad x_1 x_2 \geq \frac{2}{1-\cos\theta} \qquad x \equiv h\nu/m_e c^2$$



e.g. on BlackBody target field (good approximation to BLR attenuation)

Expected in FSRQ: no VHE detections, cutoff ~10-20 GeV

Methodology



Intrinsic band model:
Power-law or Log-parabolic

— Intrinsic extrapolated

--- Fitted free tau_BLR

--- Expected tau_BLR (deep in BLR, ~R_{BLR}/2)

-.- Log-parabolic Full band (no BLR)

Upper limit if:

TS <4 or
Npred <3 or
Err >50%

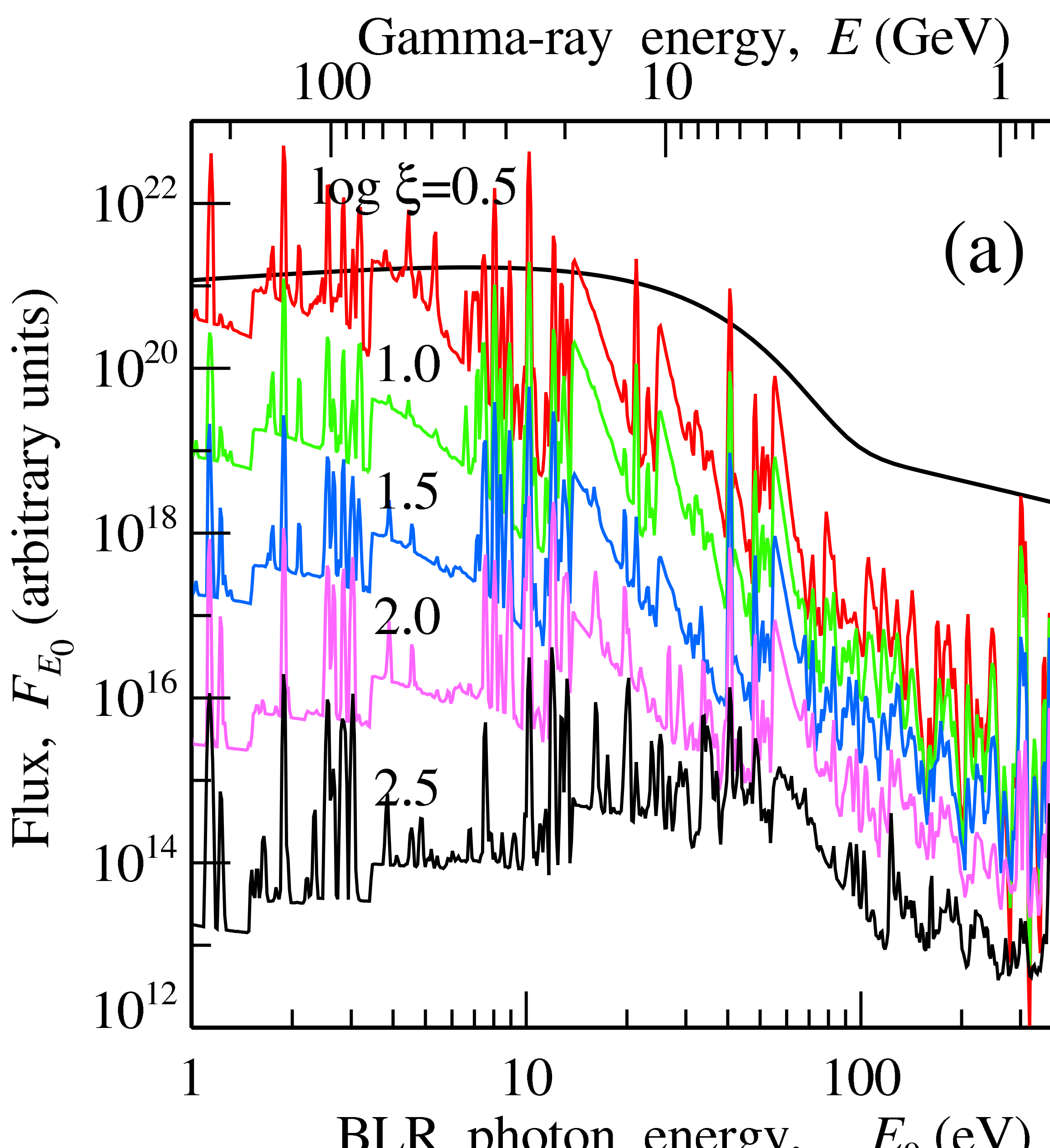
LC et al. 2018

Test on 100 brightest FSRQs in the 3LAC + 6 large-BLR cases

BLR spectrum

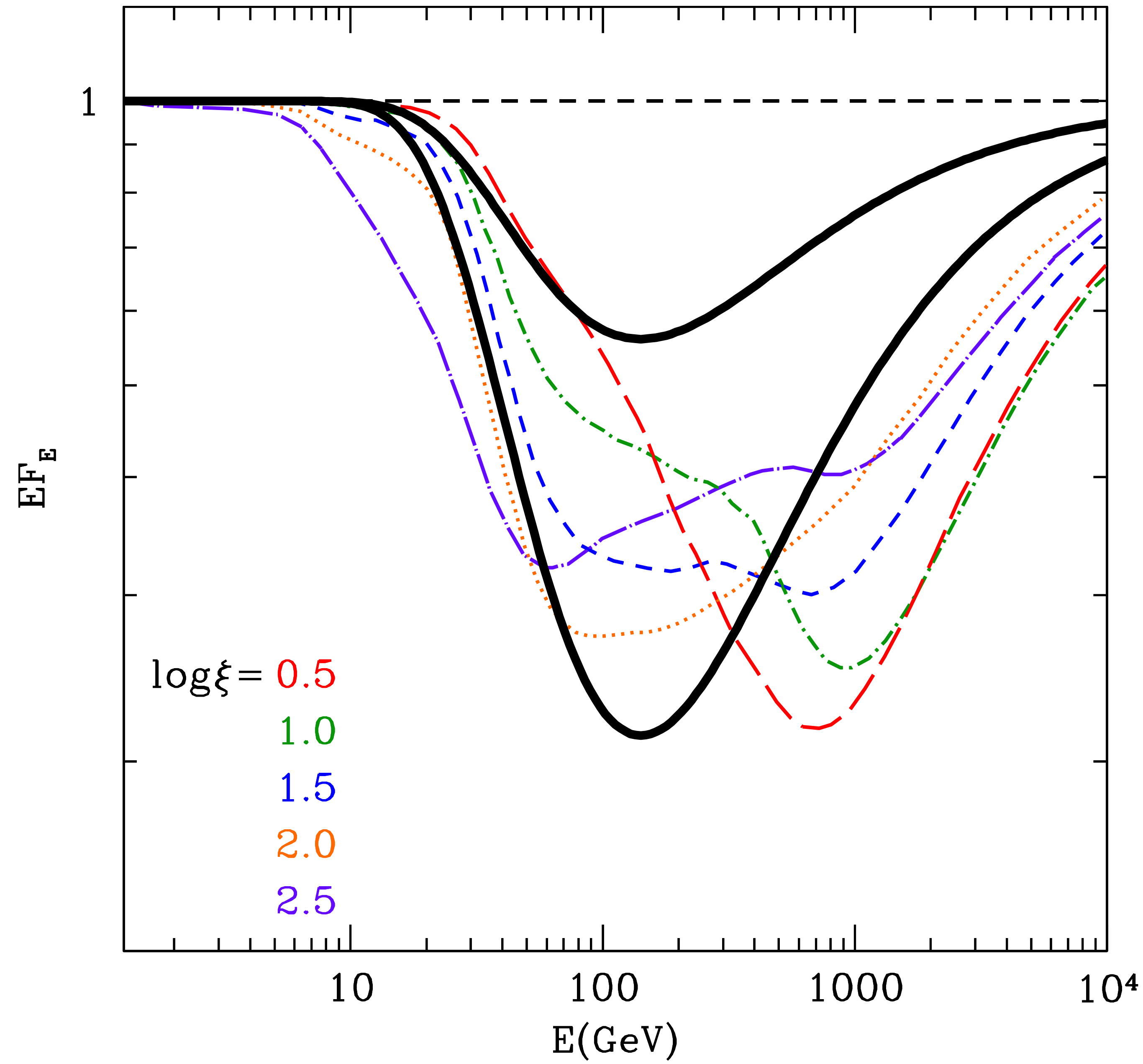
BBody (same as for EC) is a good approximation for attenuation shoulder

BLR at different ionization parameter



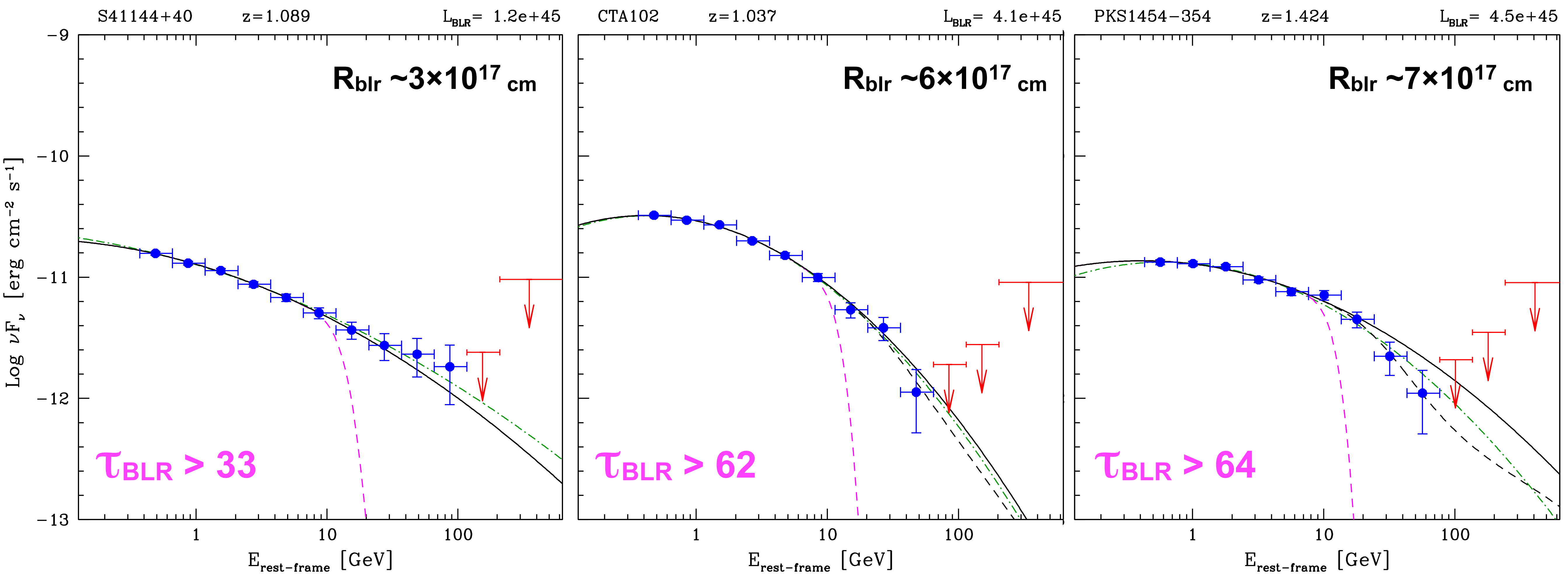
Stern & Poutanen 2014

BLR absorption feature



7.3 years of data, PASS 8 analysis

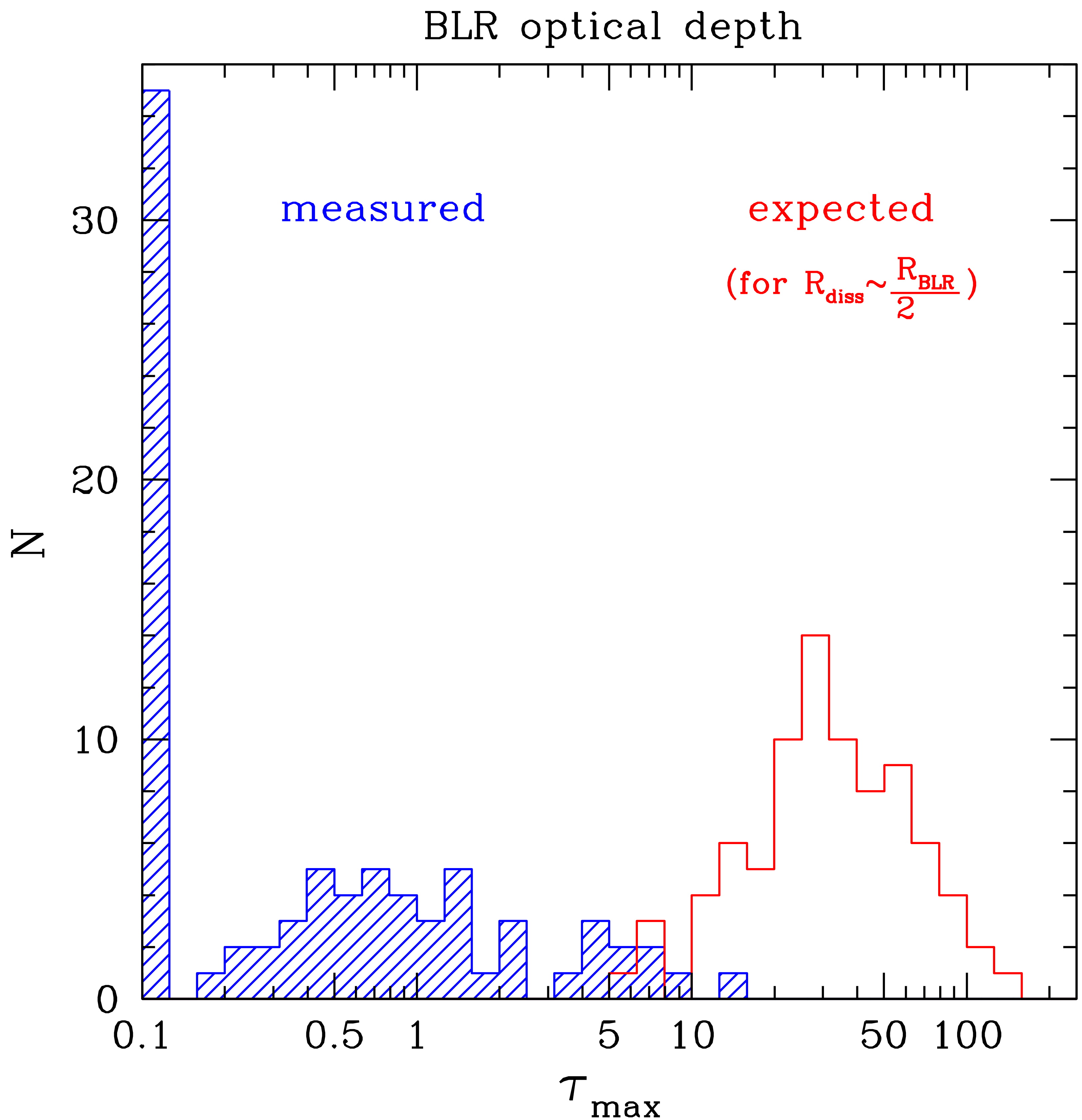
NO evidence of BLR cut-offs !



2/3 of the sample: $\tau_{max} < 1$

9/10 objects: $\tau_{max} < 3$

Only 1 out of 10 FSRQ compatible with significant BLR absorption

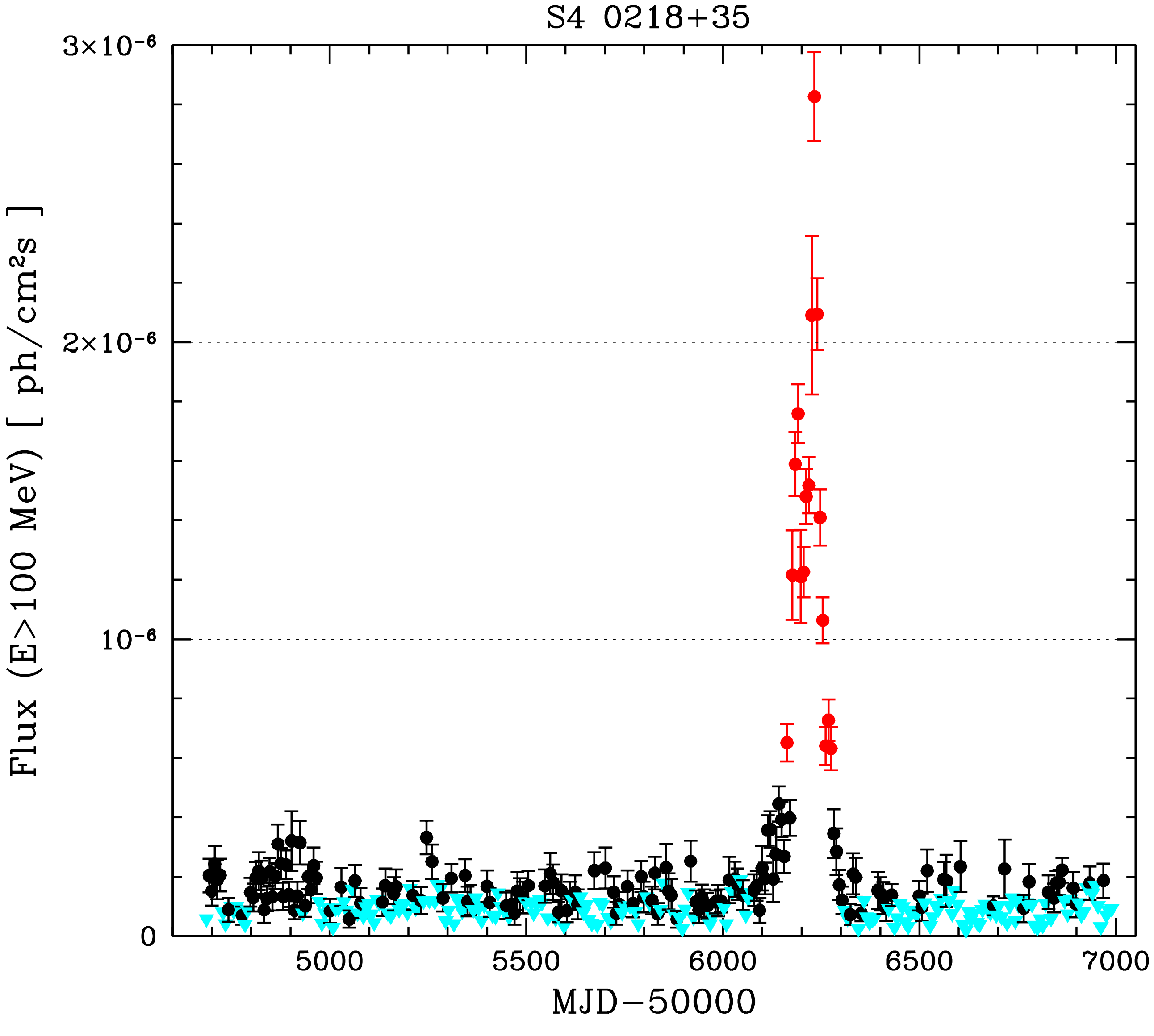


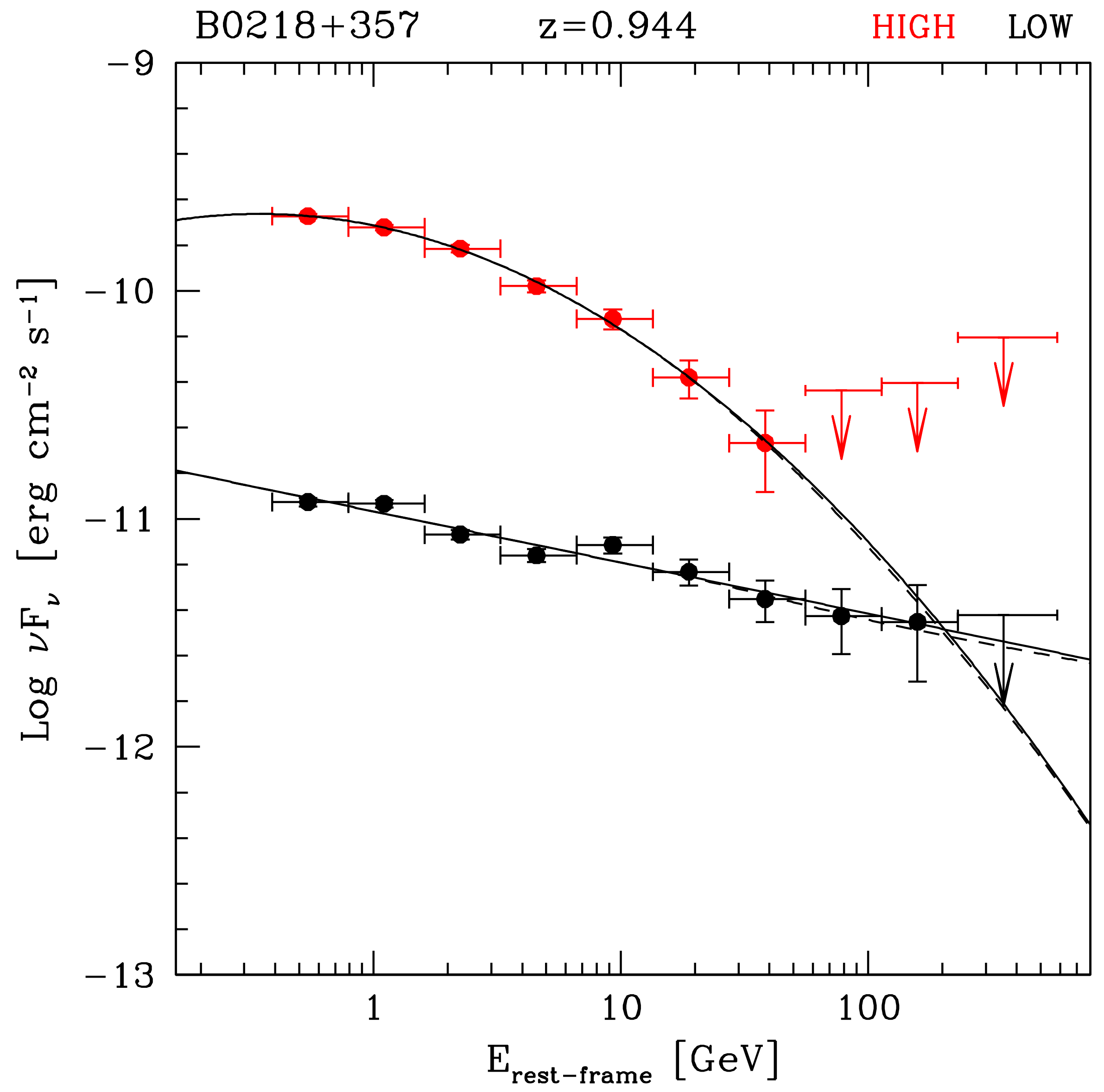
for EC(BLR)

LC et al. 2018

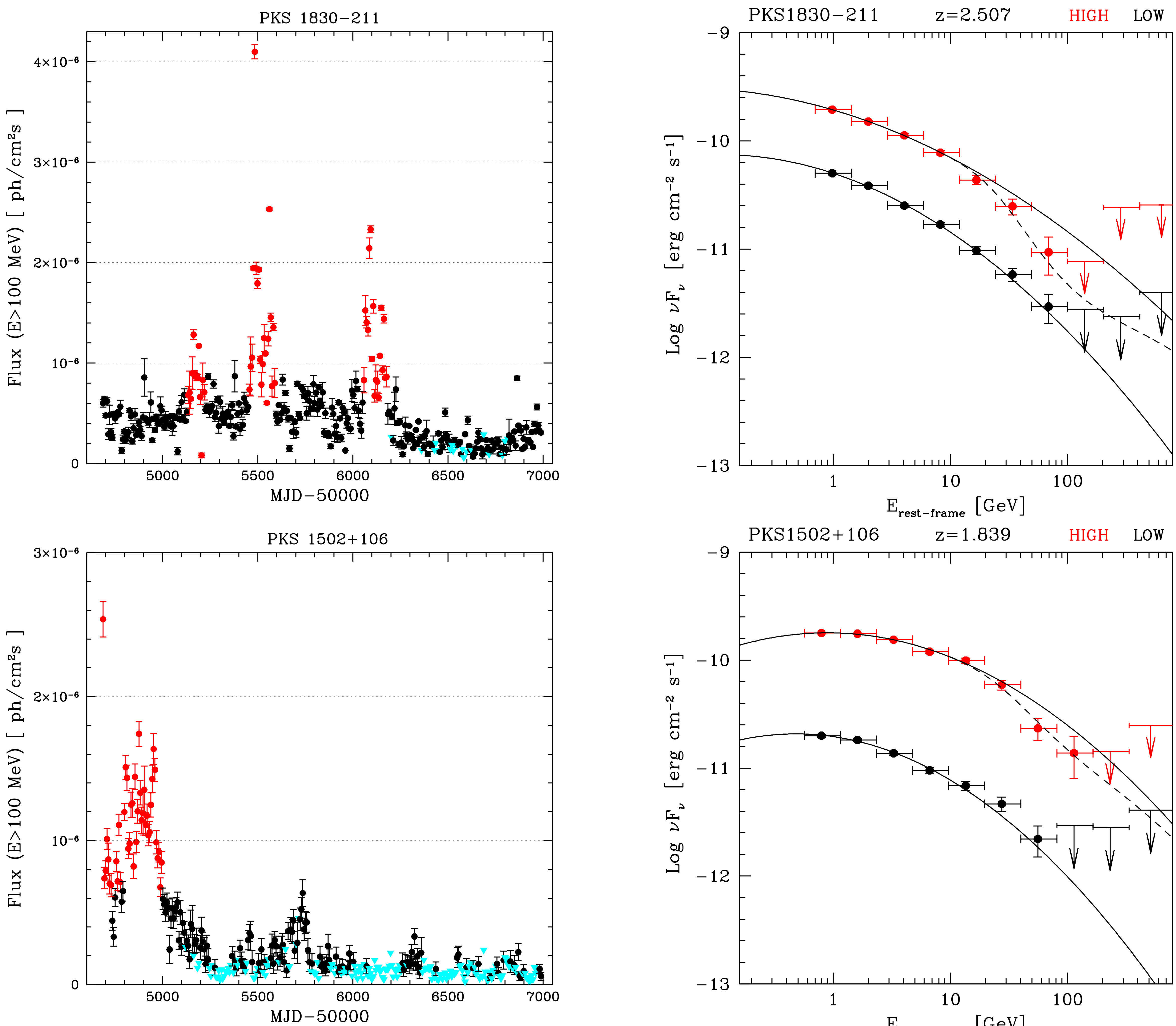
Sample 83 brightest objects with L_{BLR} estimate

For the brightest 20: difference High/Low state ?



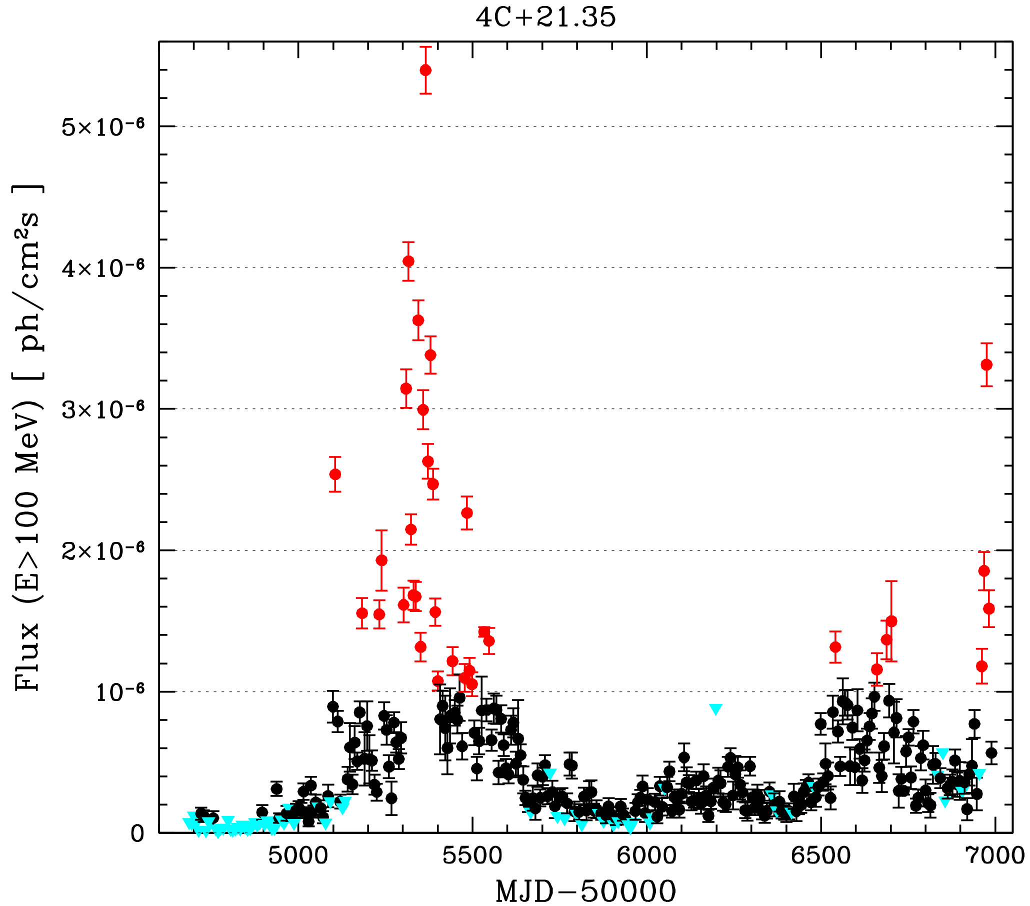


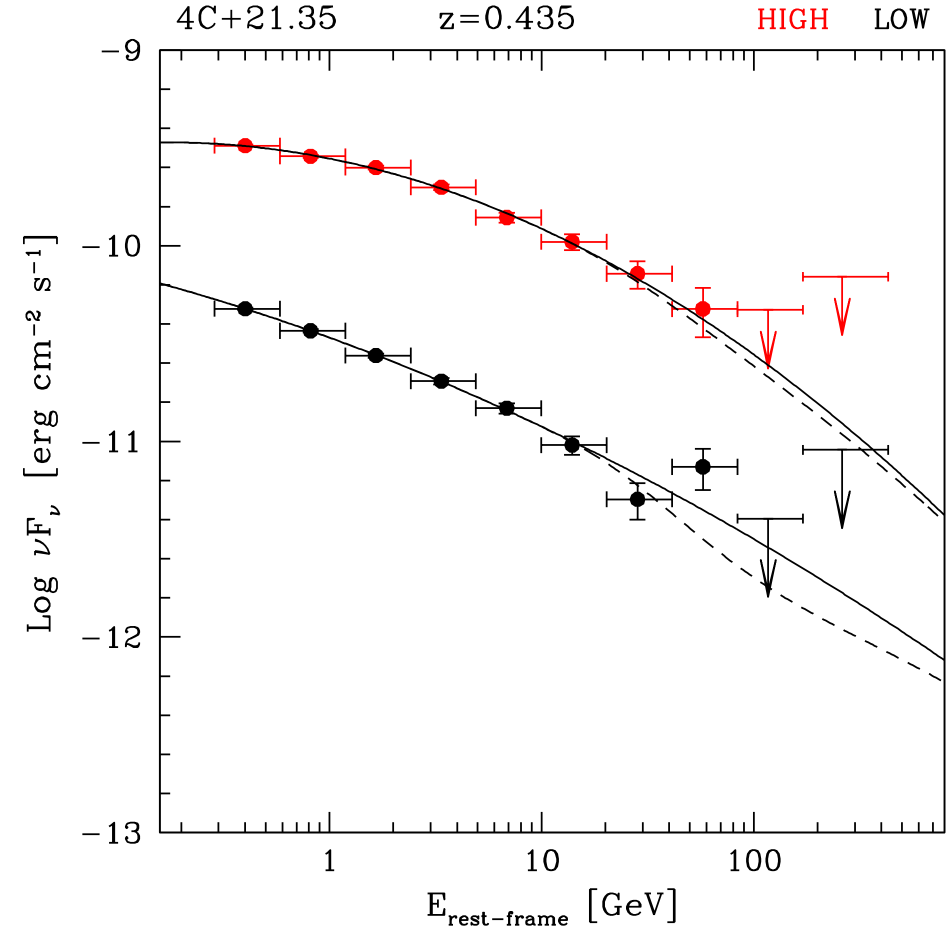
No evidence of strong interaction with BLR photons

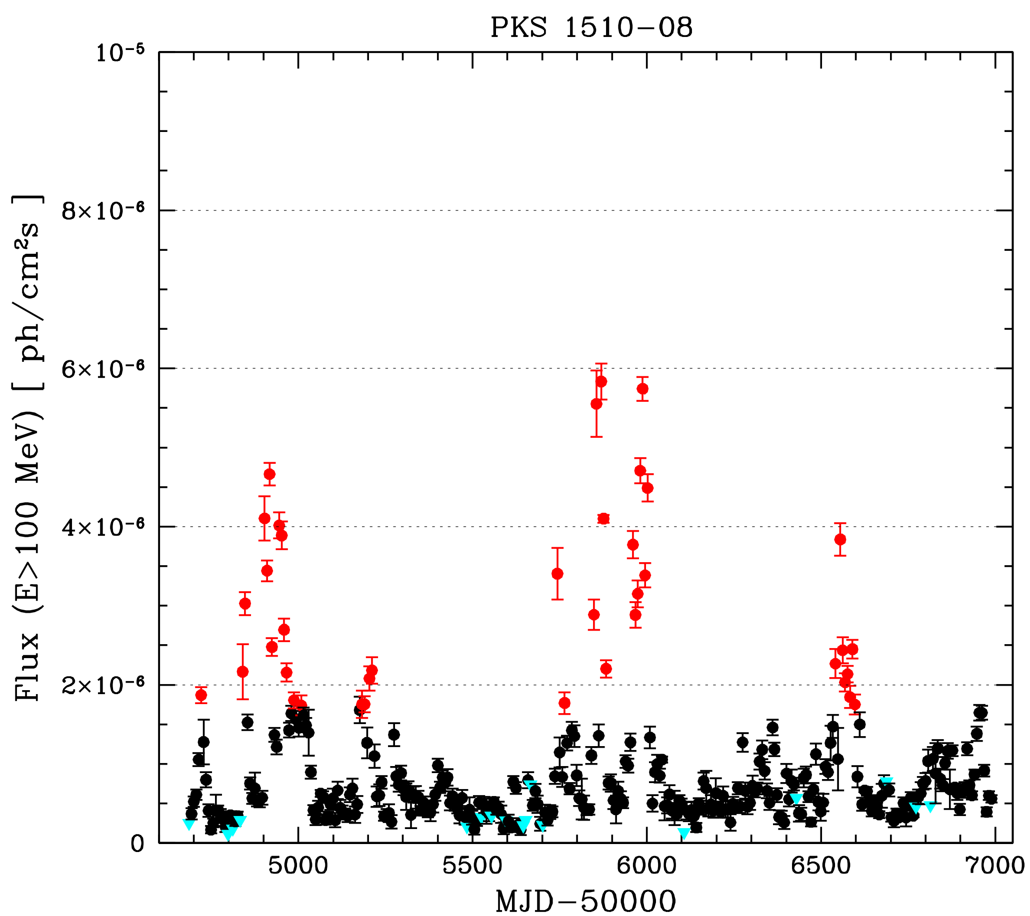


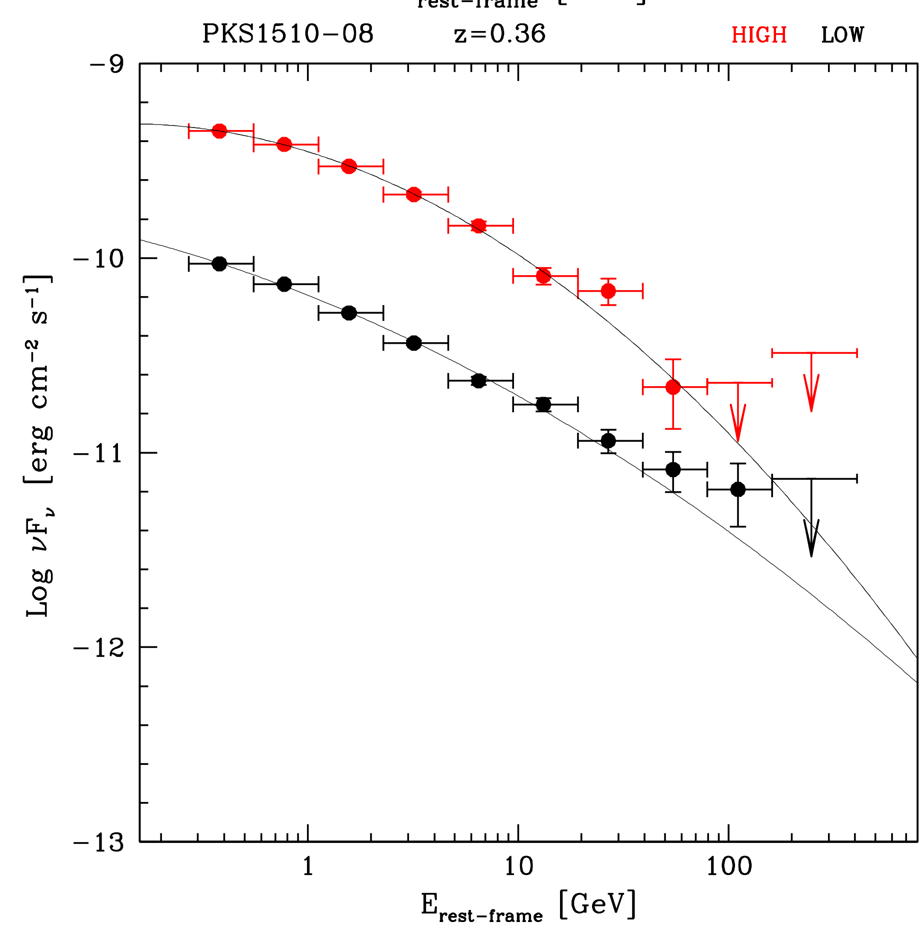
PKS 1830−211
Flux (E>100 MeV) [ph/cm²s]
4×10⁻⁶
3×10⁻⁶
2×10⁻⁶
10⁻⁶
0
5000
5500
6000
6500
7000
MJD−50000
PKS1830−211
z=2.507
HIGH
LOW
Log νFν [erg cm⁻² s⁻¹]
−9
−10
−11
−12
−13
1
10
100
E_rest-frame [GeV]
PKS 1502+106
Flux (E>100 MeV) [ph/cm²s]
3×10⁻⁶
2×10⁻⁶
10⁻⁶
0
5000
5500
6000
6500
7000
MJD−50000
PKS1502+106
z=1.839
HIGH
LOW
Log νFν [erg cm⁻² s⁻¹]
−9
−10
−11
−12
−13
1
10
100

VHE-detected FSRQs: no absorption also in Low state









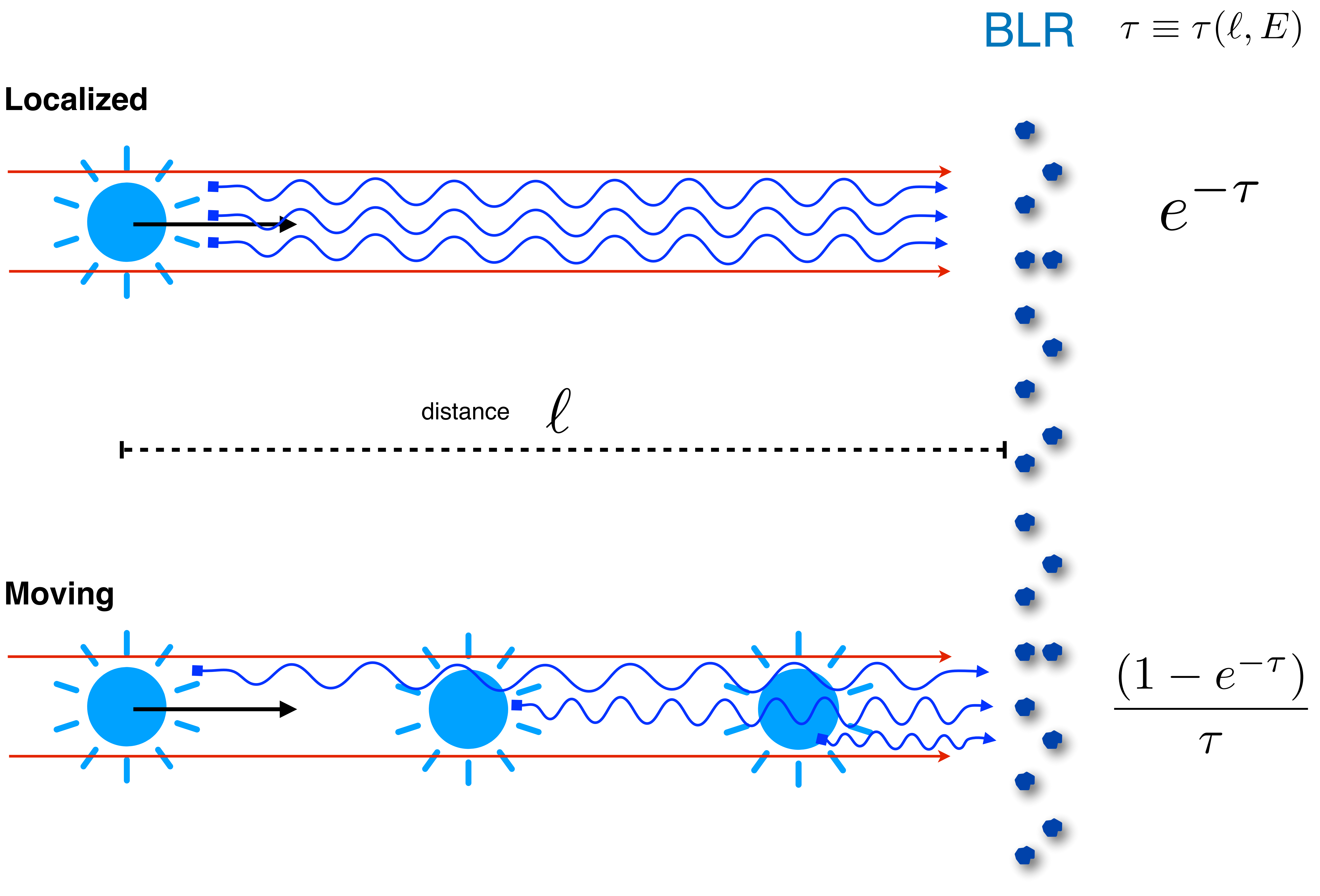
Two Caveats:

1) Long integration time (years)

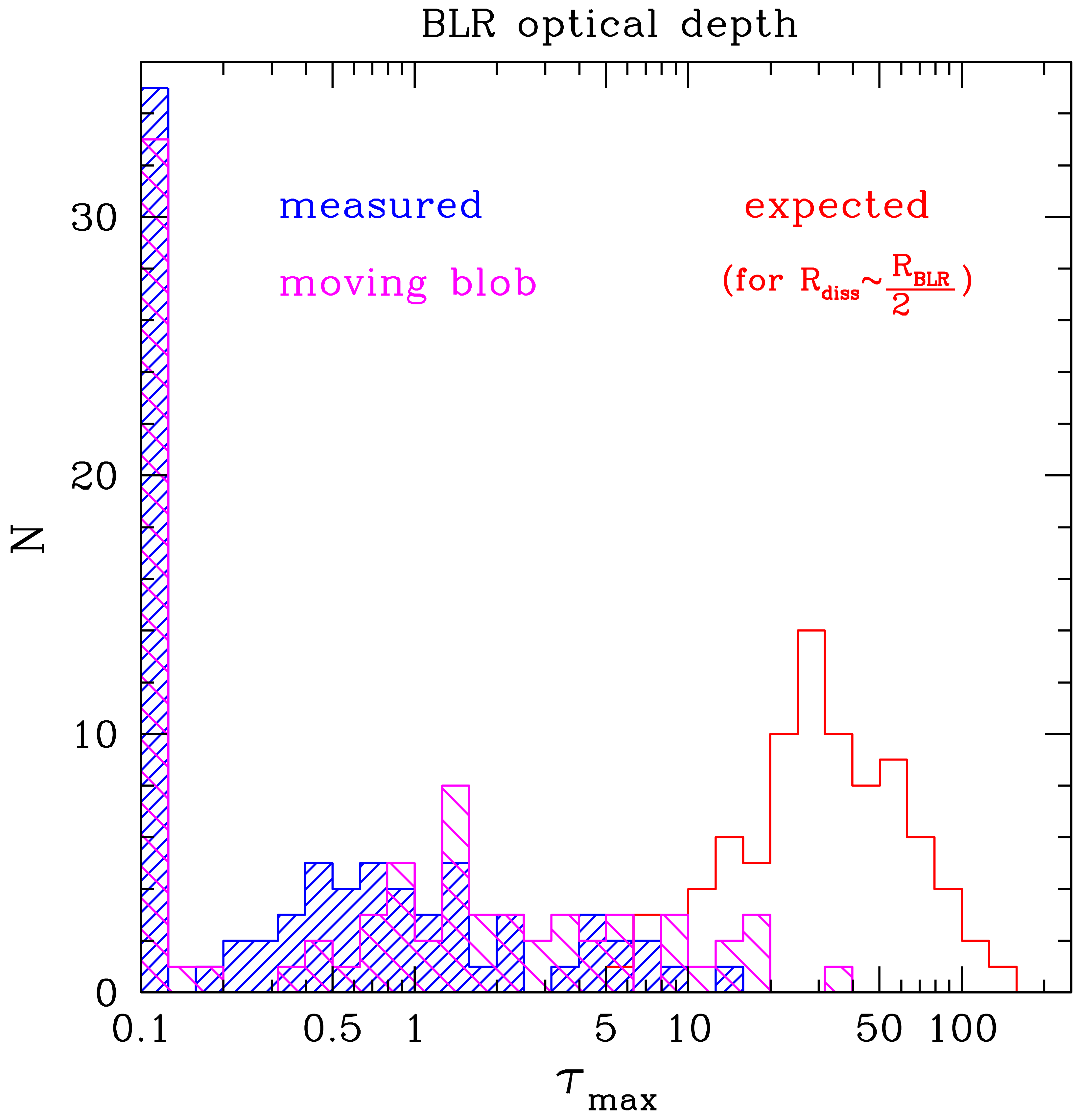
2) Kinematics of the emission
(localized dissipation vs moving blob)

Doppler effect: $\Delta R \simeq \Delta t_{obs} * \beta * \Gamma^2$

$$\Gamma = 10$$
$$\Delta t_{obs} \geq 10^5 s \quad \Longrightarrow \quad \Delta R \geq 10^{17} cm$$



BLR
$\tau \equiv \tau(\ell, E)$
Localized
$e^{-\tau}$
distance ℓ
Moving
$\frac{(1-e^{-\tau})}{\tau}$



It does **NOT** *change the main result*

Bottom line:

1. EC(BLR) is the exception, not the normality of the gamma-ray emission in Fermi Blazars

2. Gamma-ray Emission seems to originate mostly outside the BLR => EC (IR) ?

New phenomenology emerged in gamma-rays

A) Ultra-fast Variability

B) X-ray —TeV correlations

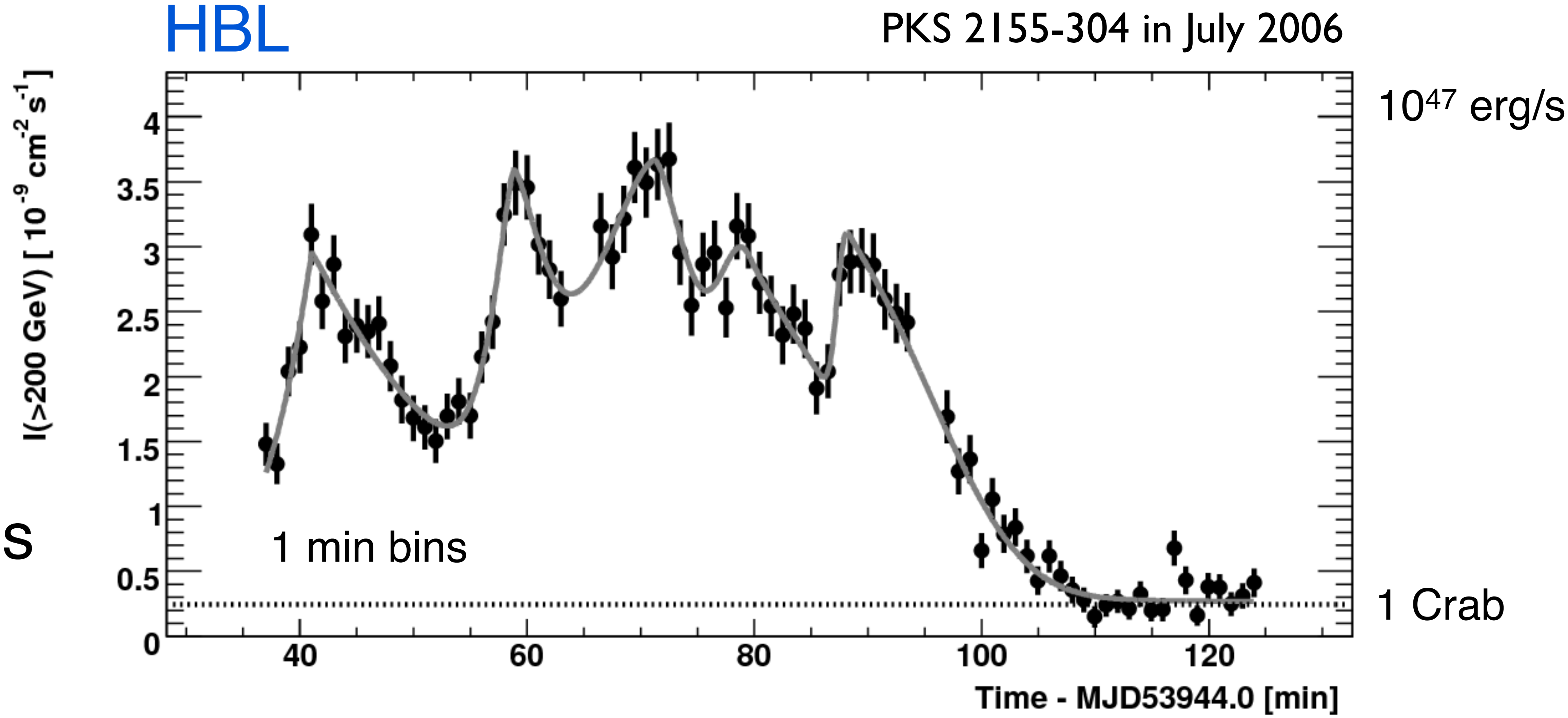
C) HBL-like flares in FSRQ/LBL

D) Extreme TeV BL Lacs

E) Periodicity

A) Ultra-fast Variability $(t \lesssim \tau_0 = R_S/c)$

HBL



t≈200s

Aharonian et al. (HESS coll) 2007

$R \sim 5\times10^{12}\,\delta$ cm $\approx 0.01\,\delta\, R_S$

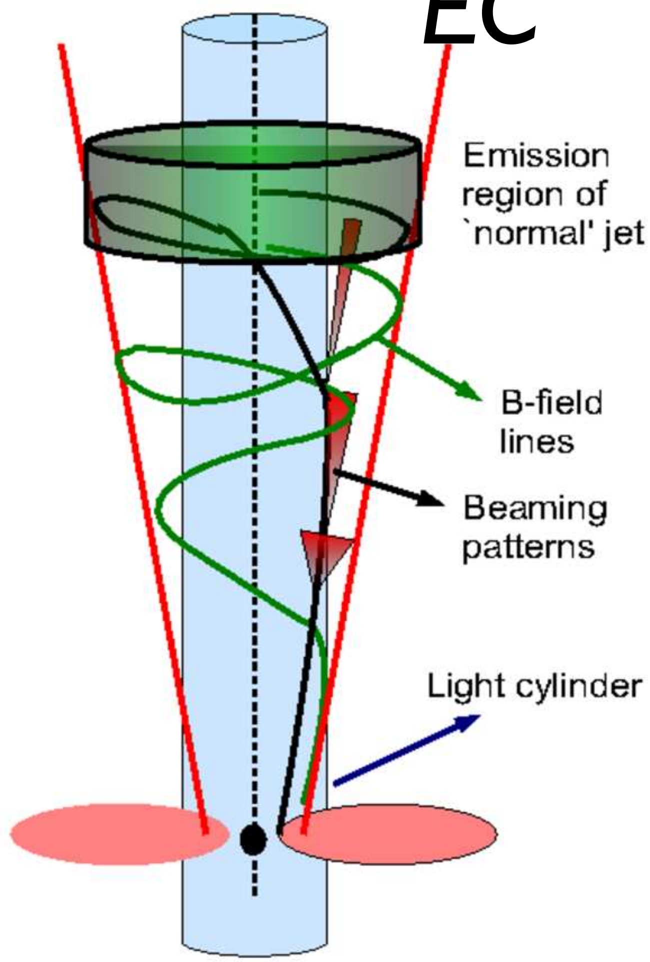
$\Gamma \geq 50\text{-}100$ for $R \sim R_S$

But… if perturbations propagate from BH, stationary in LAB frame…

=> emitter size either $R \ll r_g$ (external) or relativistic in jet frame

Possible explanations ?

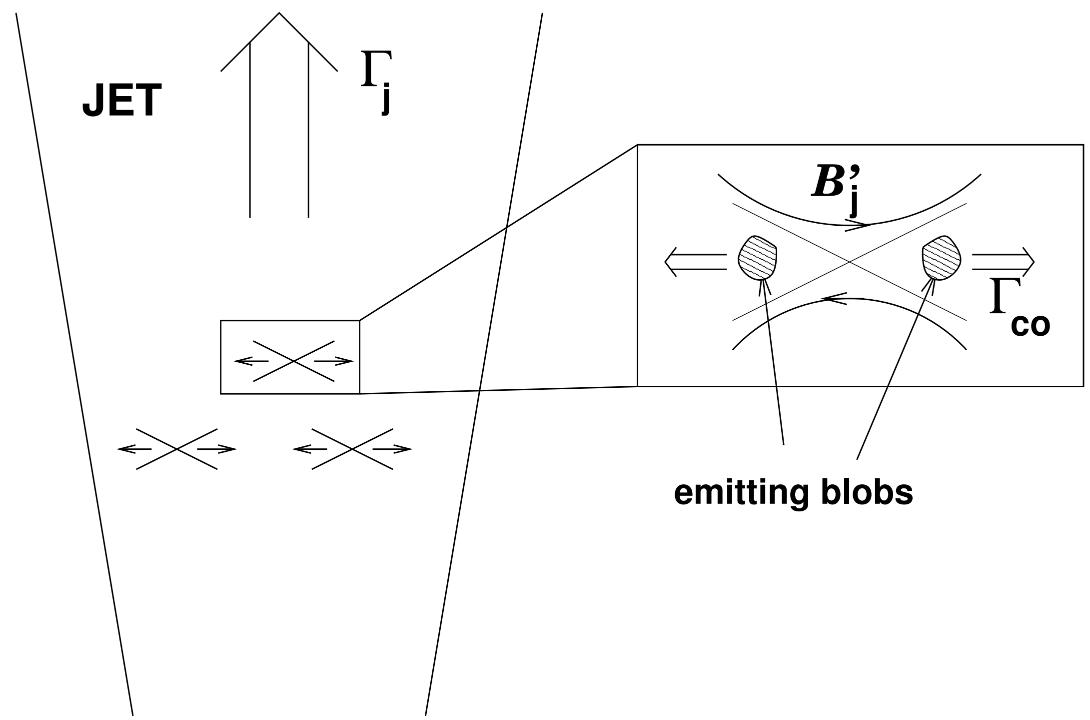
EC



Magneto-centrifugal accel ?

(Ghisellini & Tavecchio 2008; Ghisellini 2009)

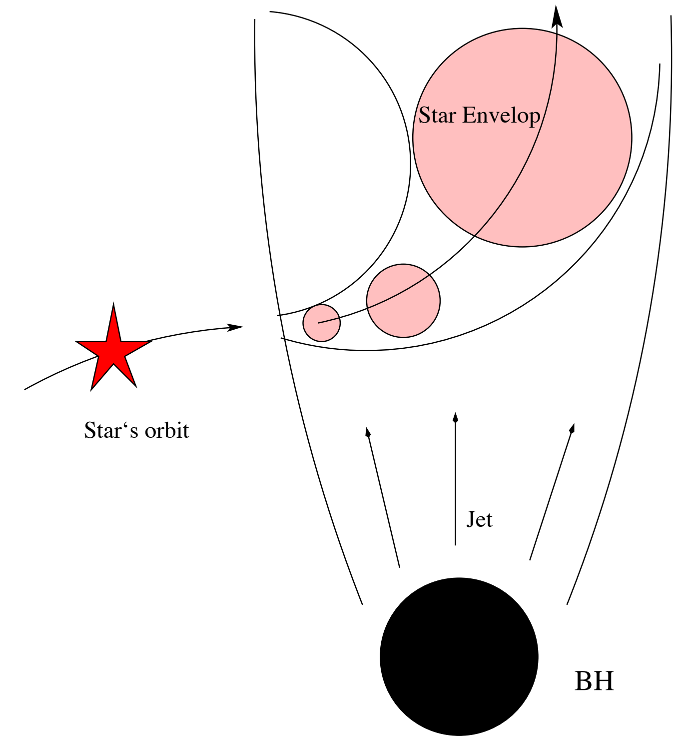
SSC



Jets-in-Jet ?

(Giannios et al 2009)

p-γ
EC



Jet-Star interaction ?

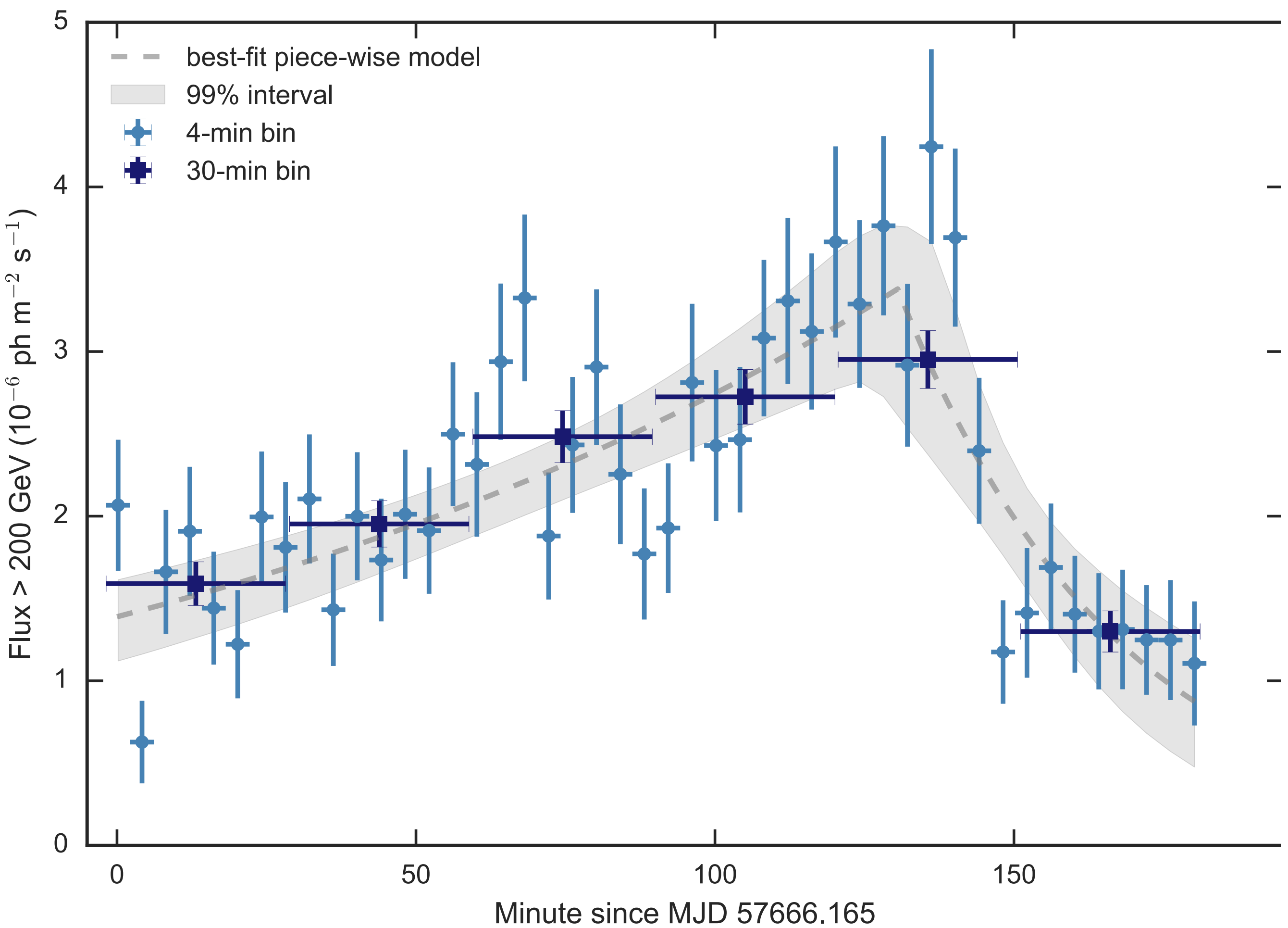
(Barkov et al. 2010, 2011)

See e.g. discussion in Aharonian et al. 2017

Ubiquitous ...and so far only in gamma-rays...

LBL

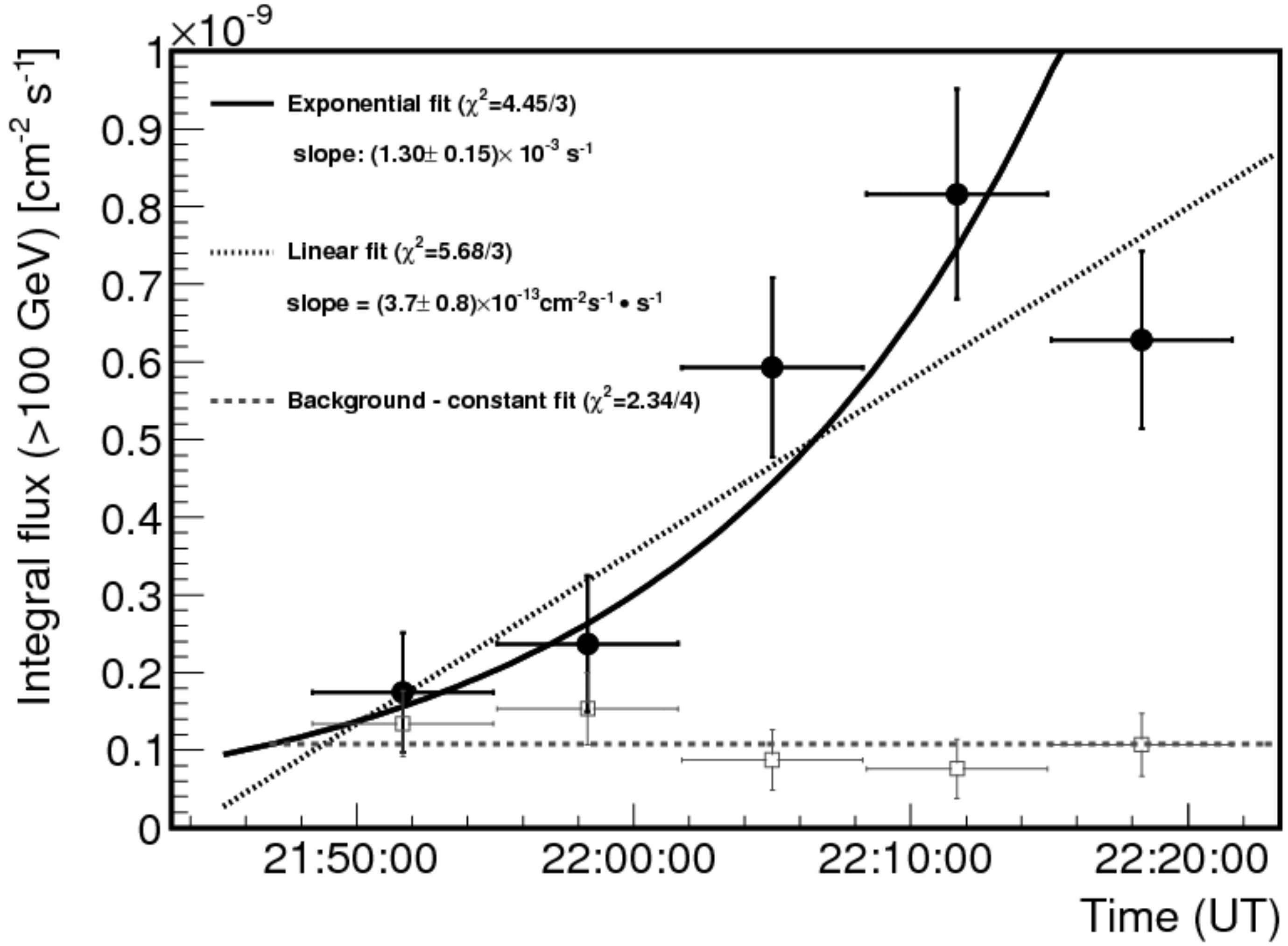
BL Lac



Veritas Collab. 2018

FSRQ

4C +21.35

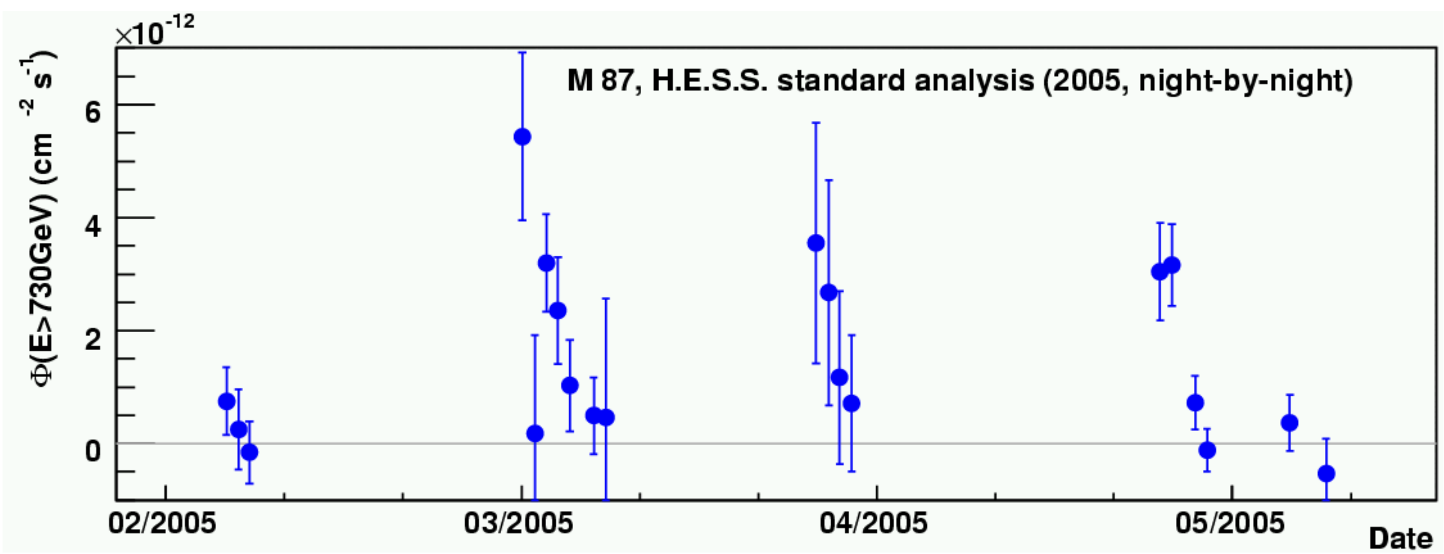


Aleksic et al. (MAGIC collab.) 2011

Radio Galaxies

$$\tau_0 = r_g/c \approx 5 \times 10^2 M_8 \text{ s.}$$

M87



Aharonian et al. (HESS coll) 2007

$$t_{var} \sim 2 - 4\ \tau_0$$

IC 310

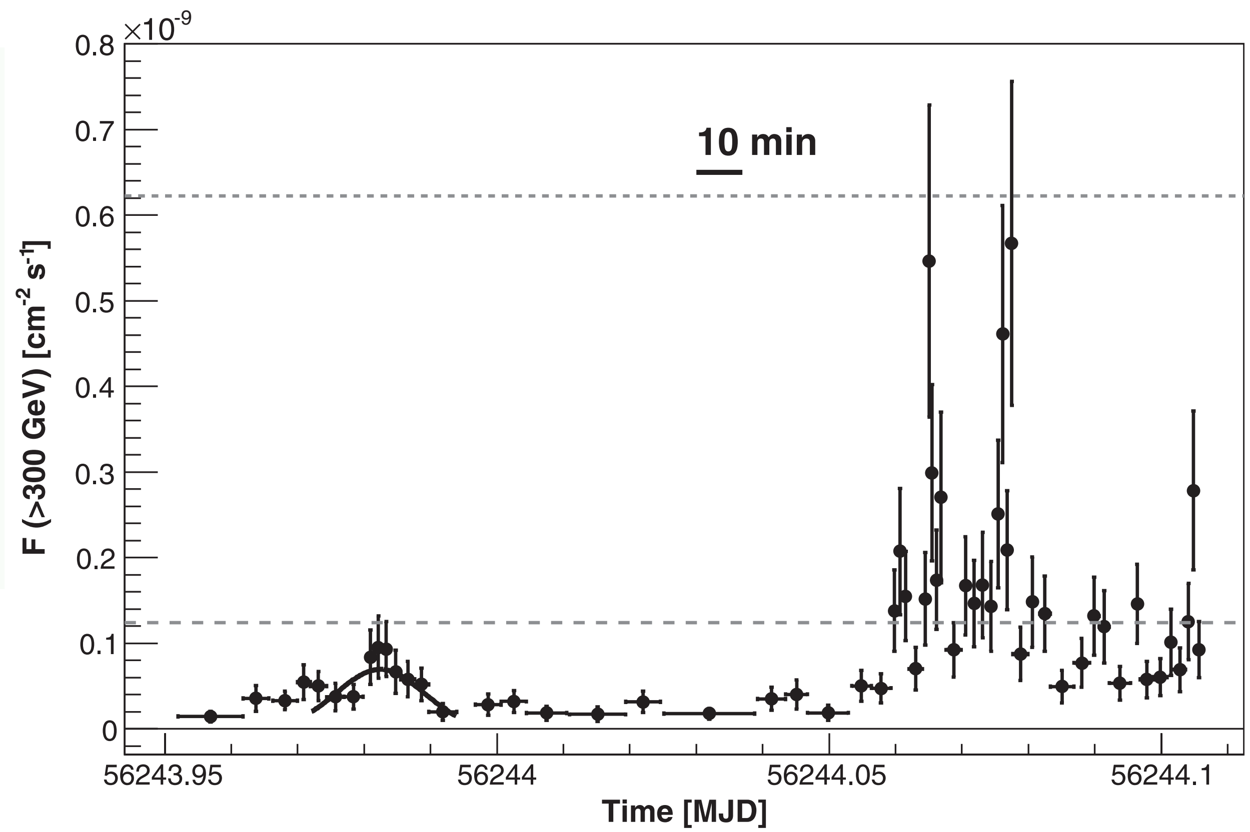
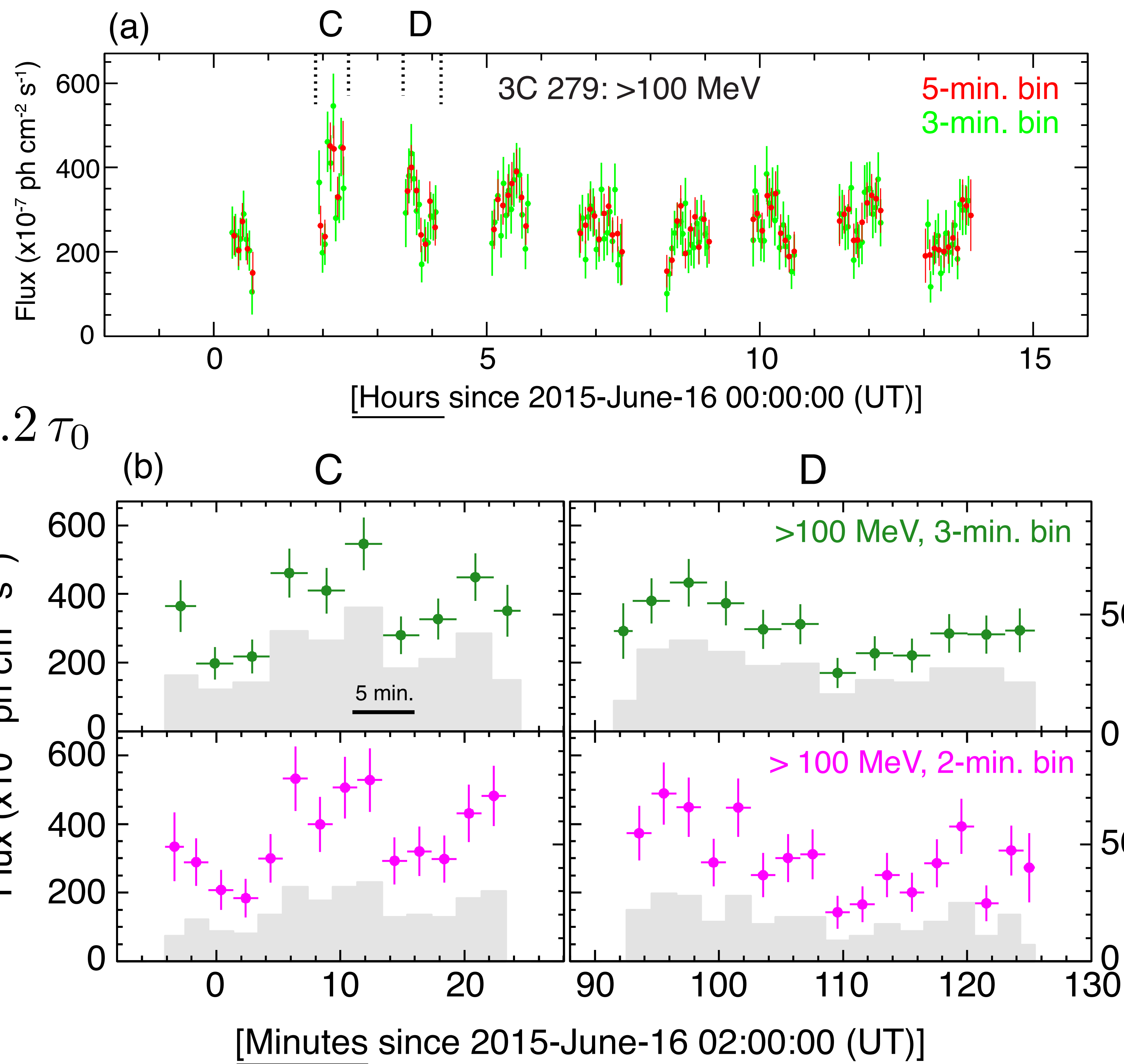


Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes on the night of 12/13 November 2012, above 300 GeV. As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972-56243.994) has been fitted with a Gaussian distribution. Vertical error bars show 1 SD statistical uncertainty. Horizontal error bars show the bin widths.

Aleksic et al. (MAGIC coll) 2014

$$t_{var} \sim 0.2 - 0.5\ \tau_0$$

…even at GeV: 3C 279 huge flare in 2015

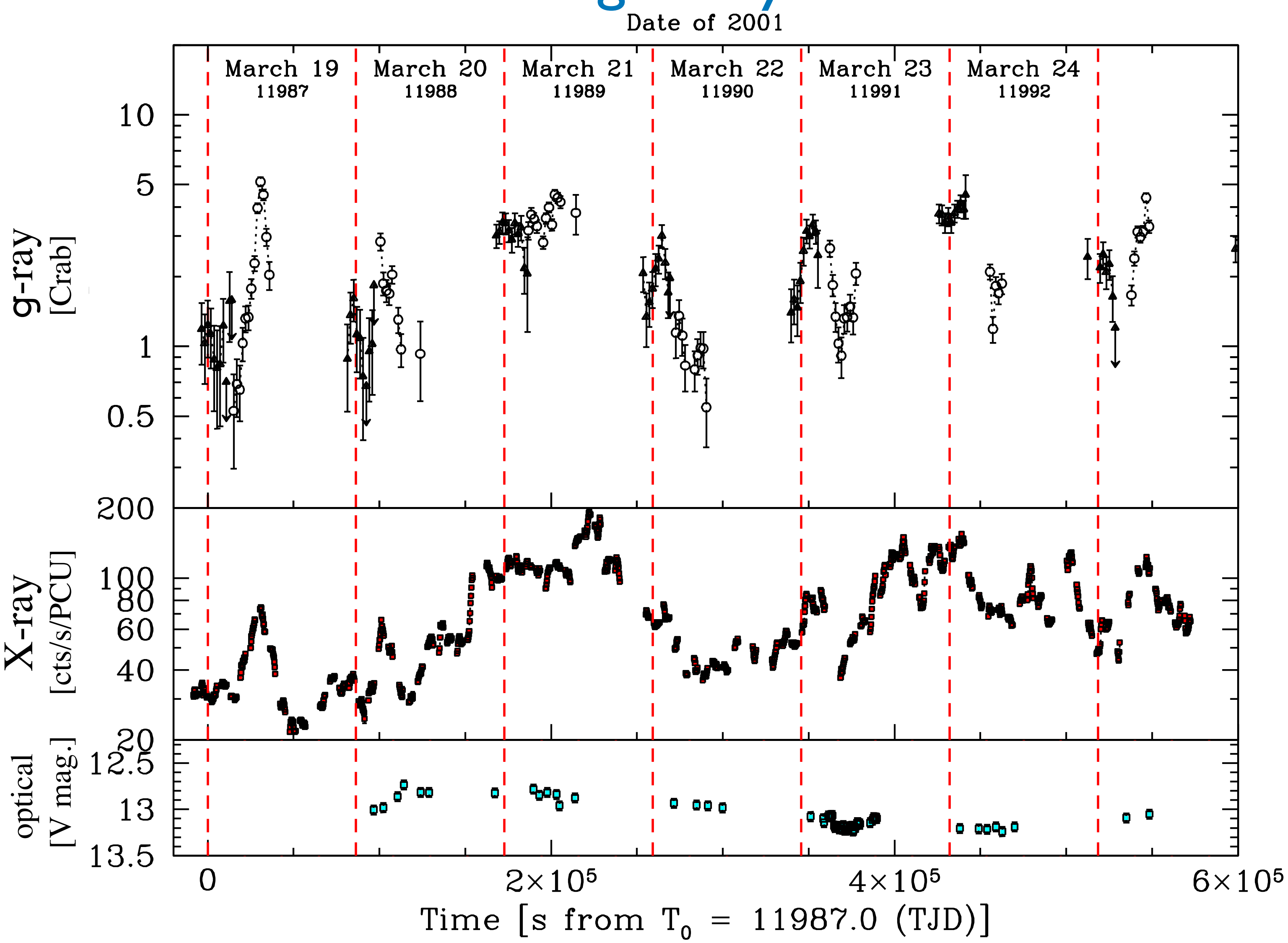


$$t_{var} \sim 0.1 - 0.2\,\tau_0$$

LAT Coll. 2016

B) X-ray - TeV correlation(s)

Mkn 421: strong X-ray-TeV correlation



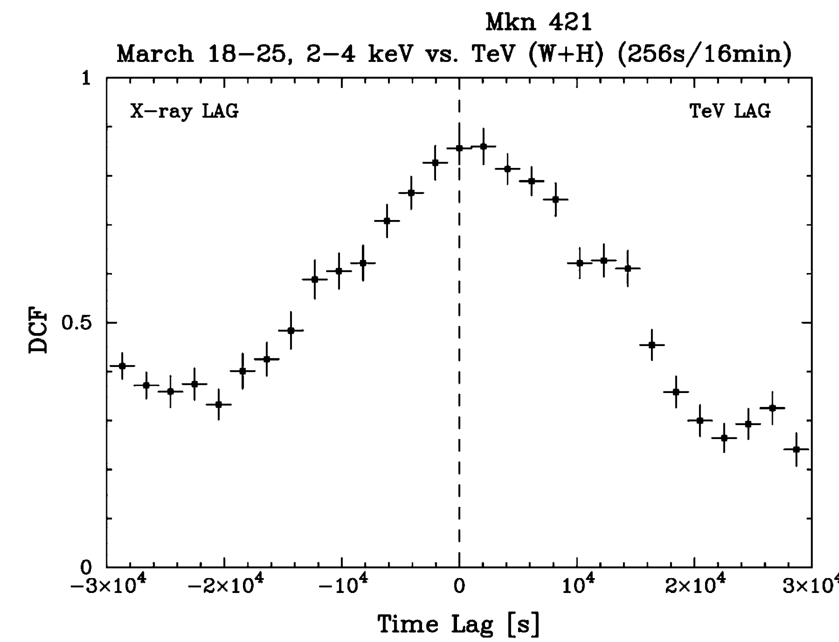
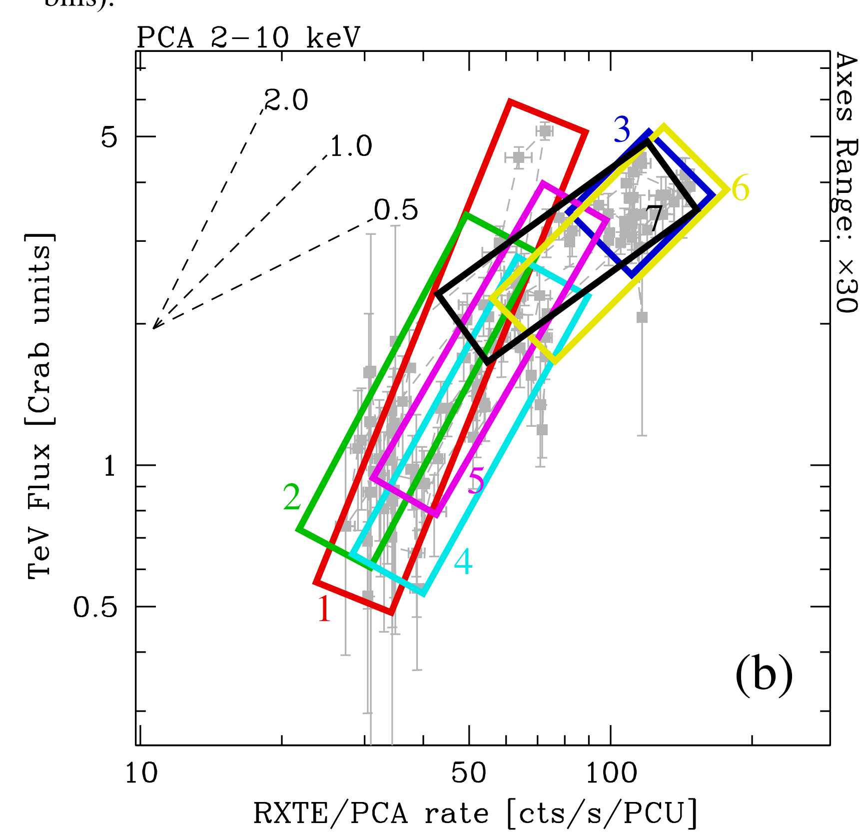


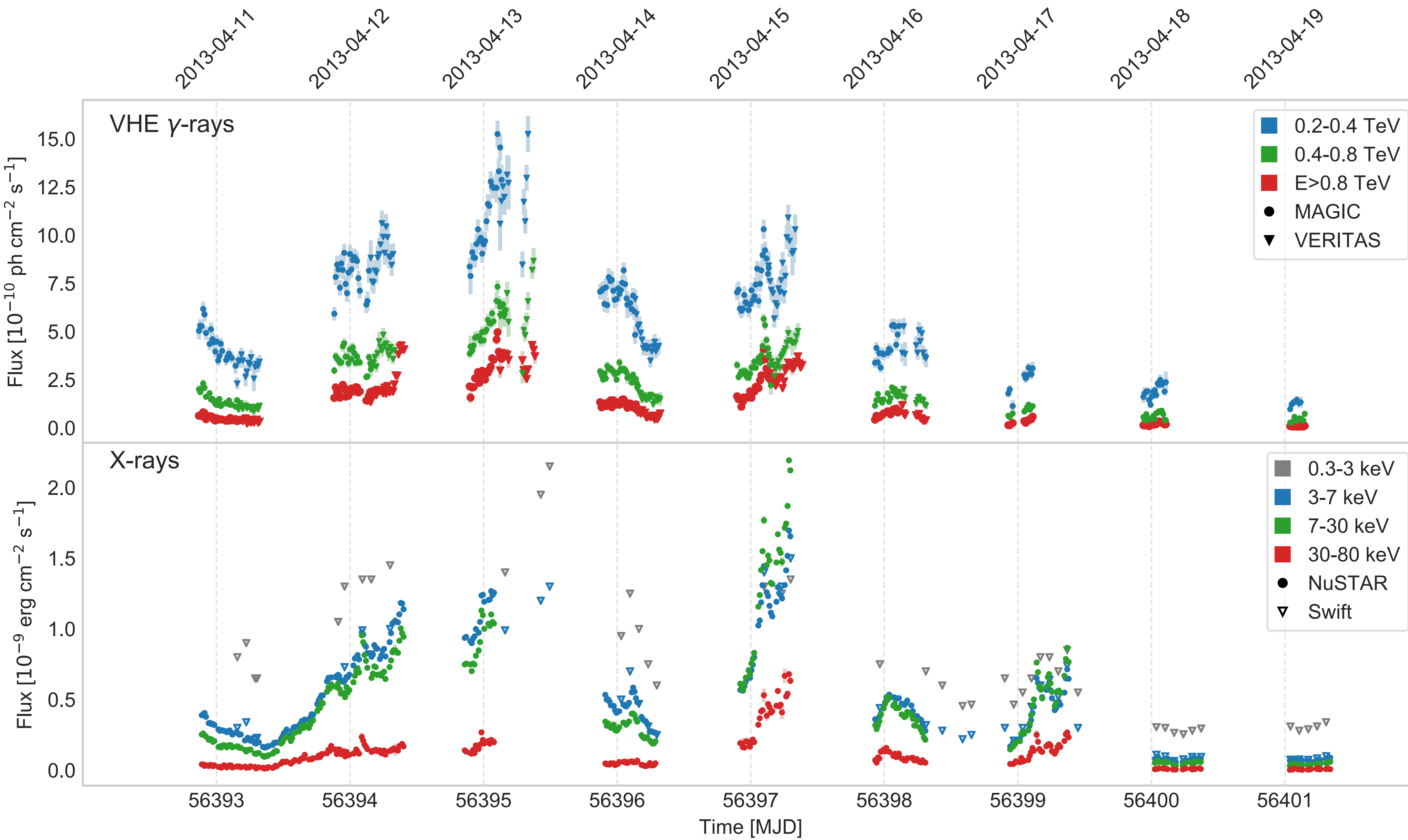
Fig. 2. Cross correlation between the X-ray (2–4 keV) and the TeV light curves for the whole campaign (computed over 2048 s bins, from X-ray data on 256 s bins, and TeV data on ~750 s bins).



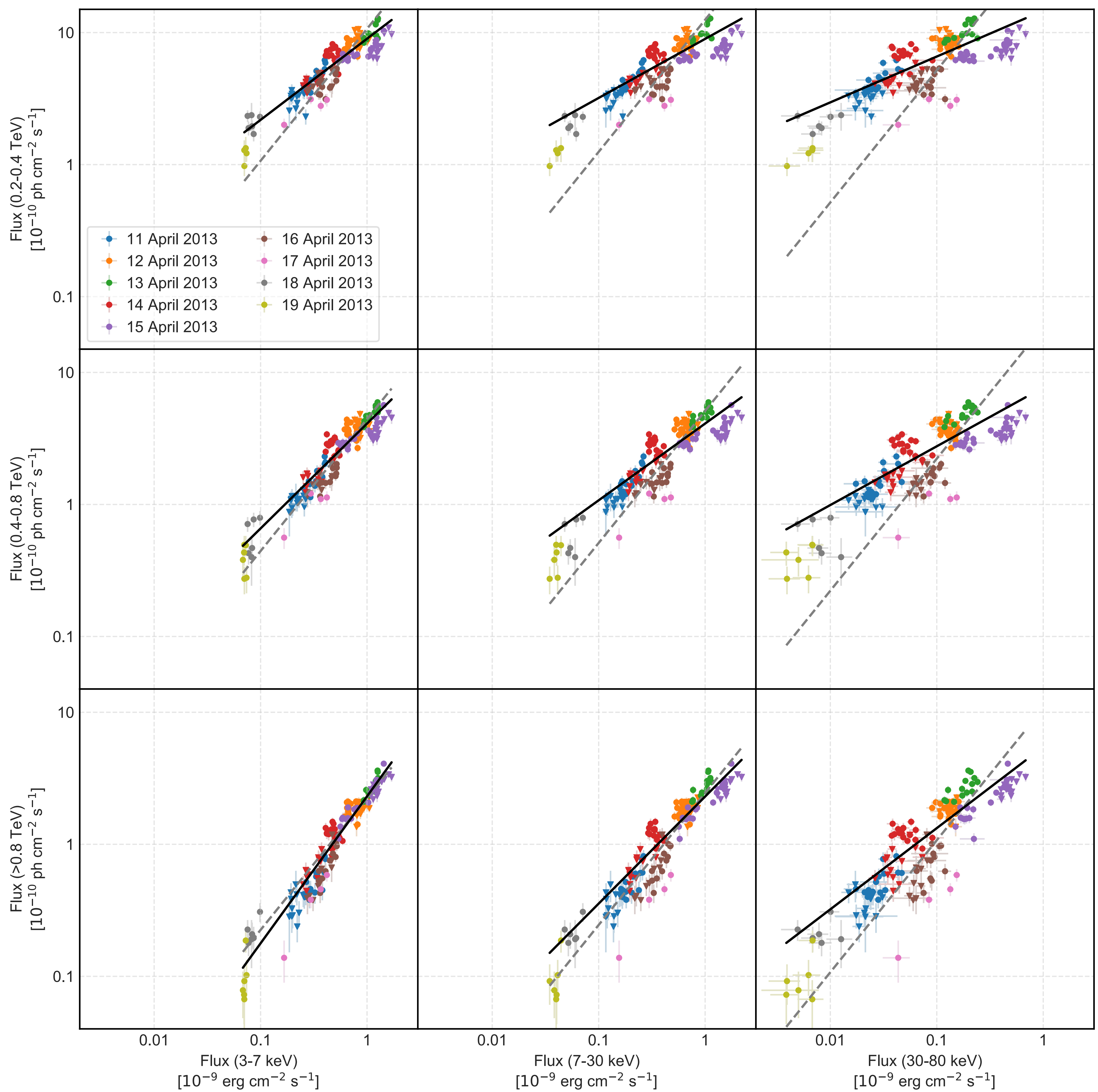
Fossati et al. 2000

=> same population of electrons

Mkn 421 more recently

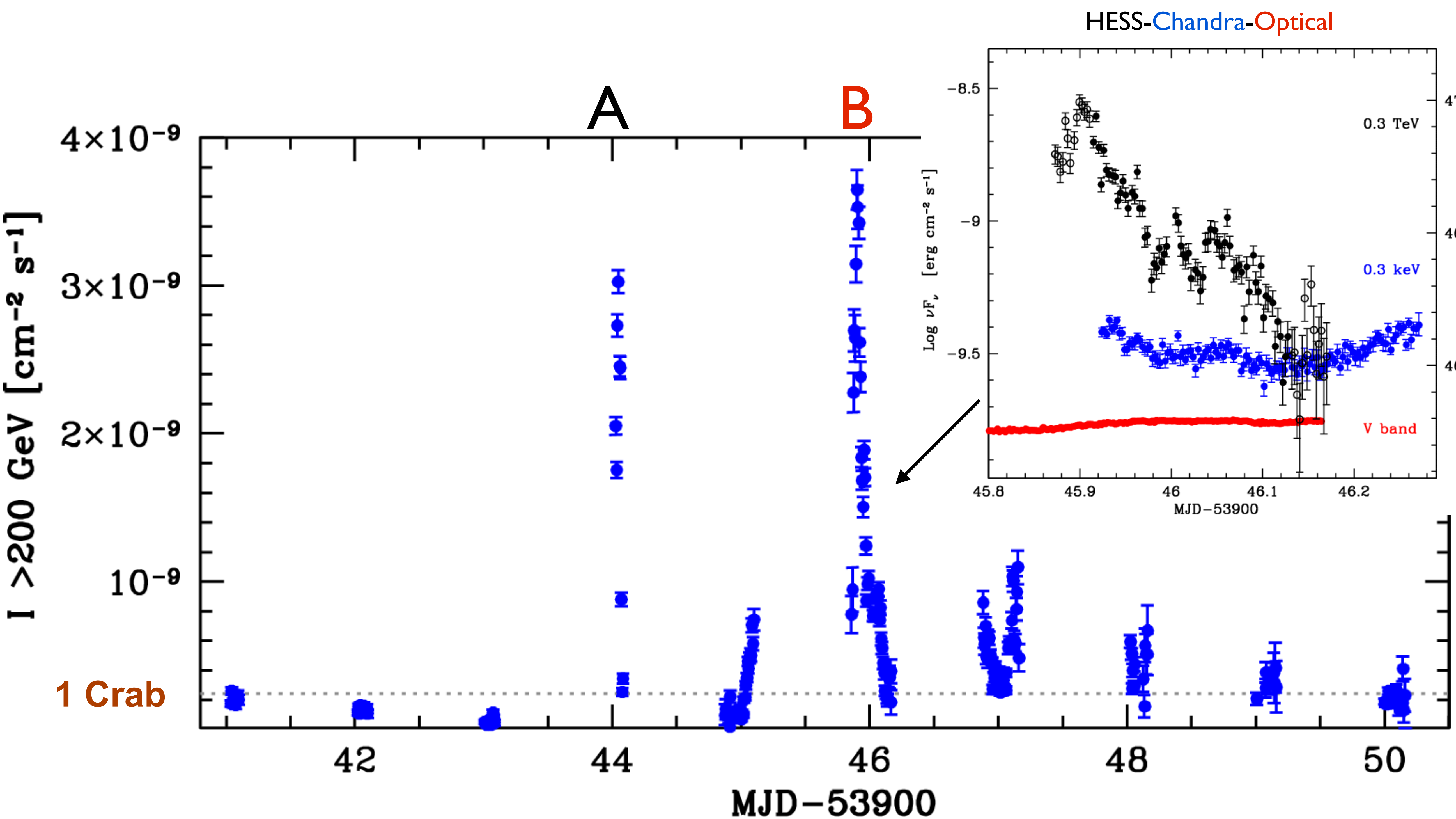


Acciari et al. 2020



Acciari et al. 2020

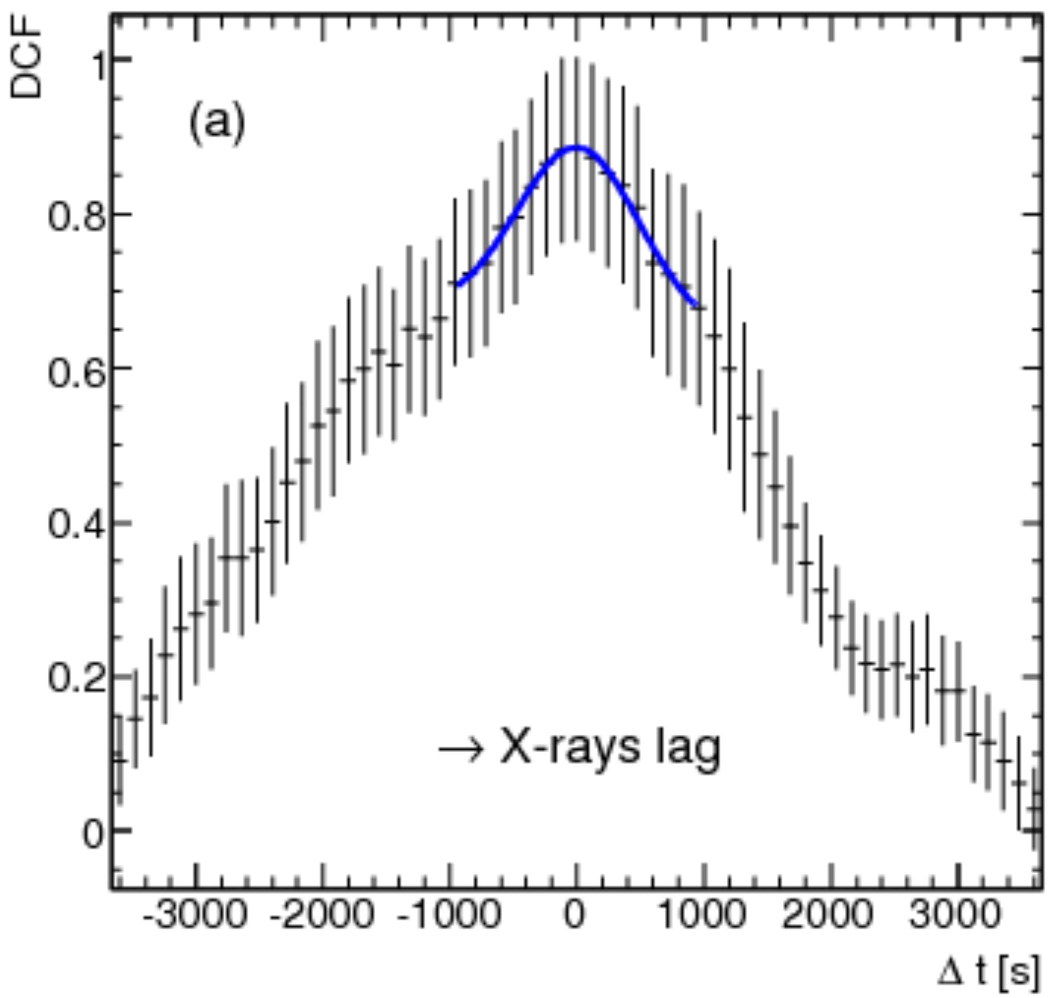
Different: PKS 2155-304 in July 2006



Aharonian et al. (HESS coll.) 2009

Strong and strict correlation in time & spectrum

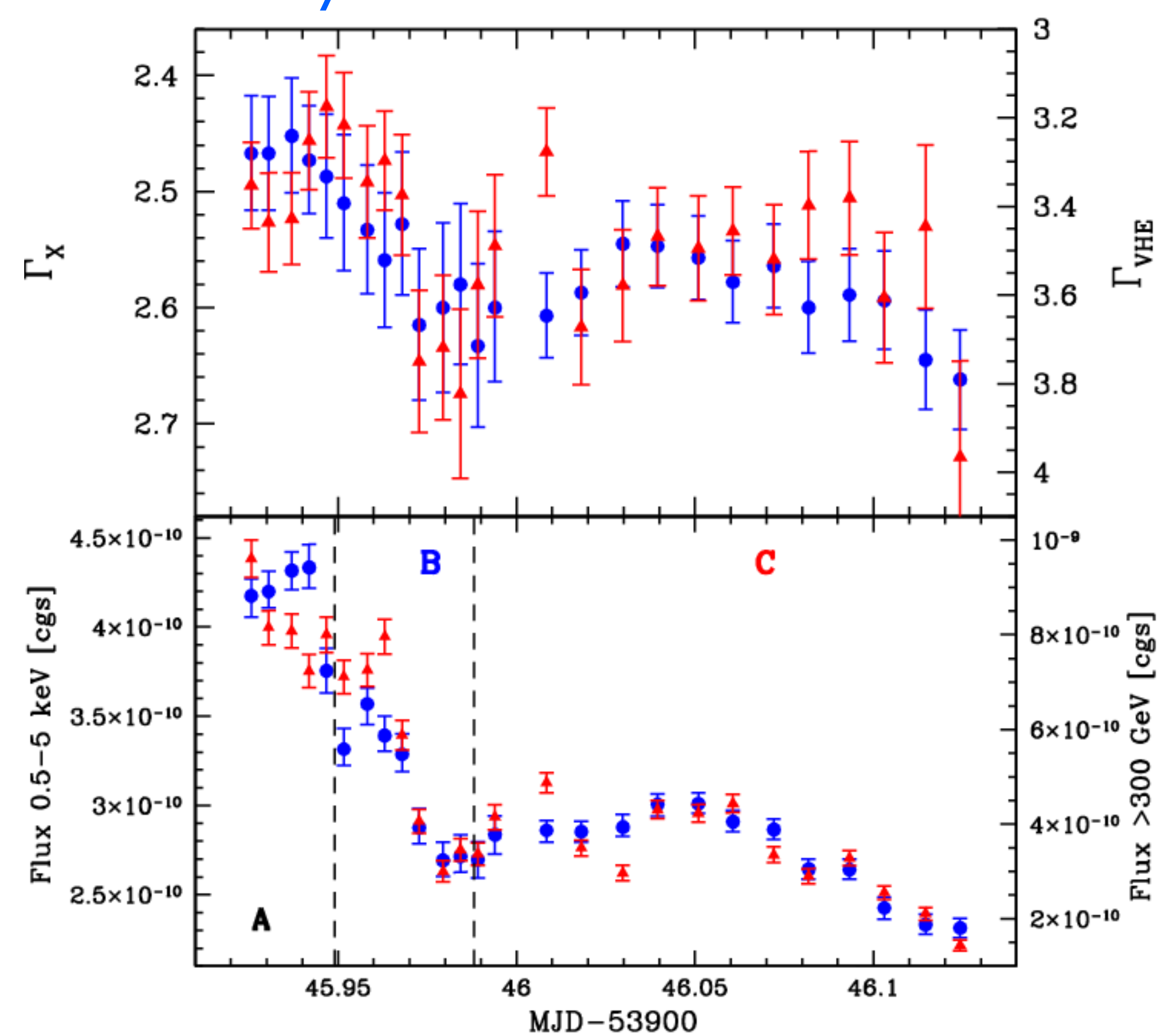
DCF X-TeV



95% upper limit on lags: ~ 200s

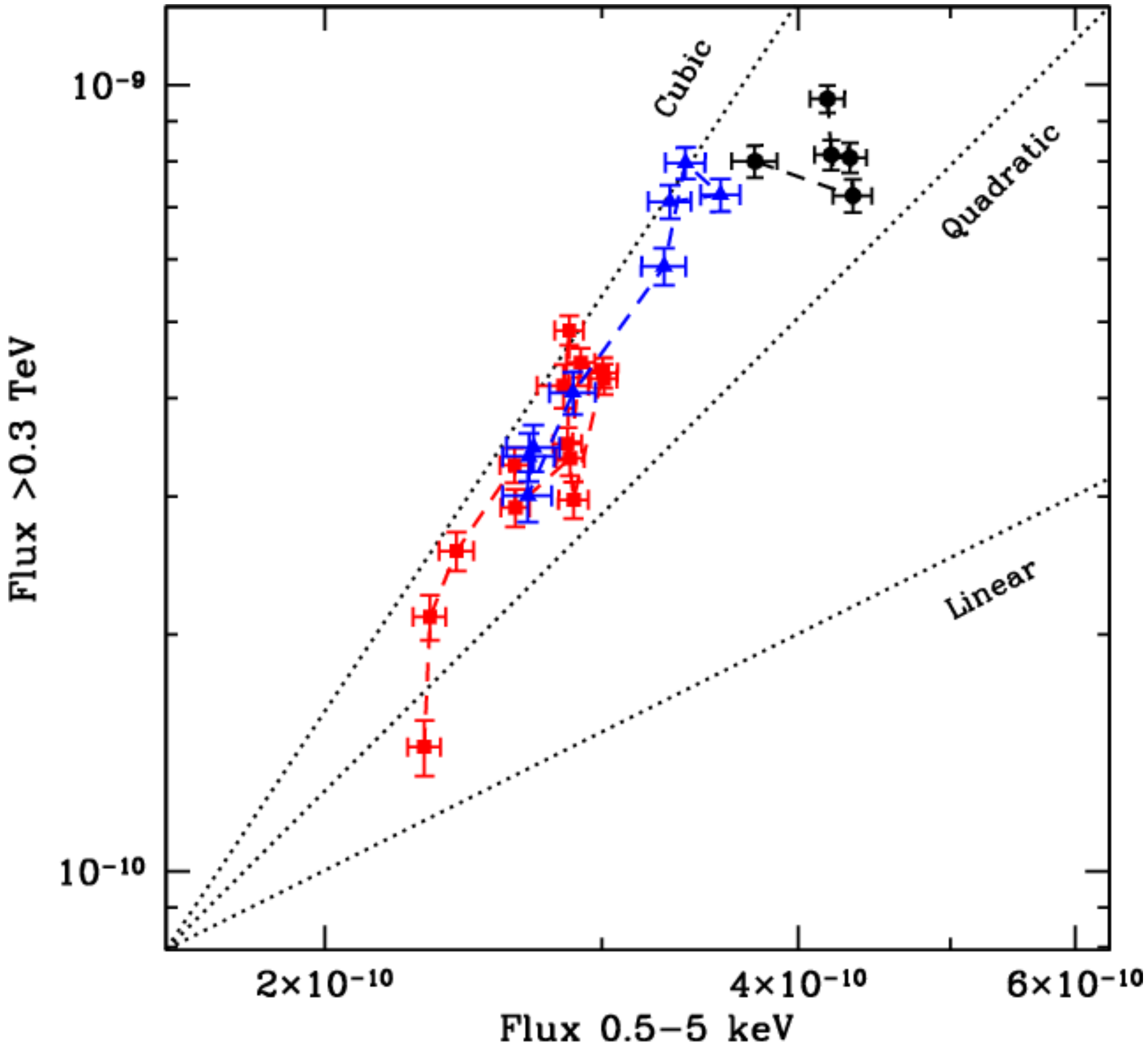
Time-resolved spectroscopy, 7-14 min bins

X-ray VHE



Aharonian et al. (HESS coll.) 2009

But Cubic relation X-ray / TeV flux

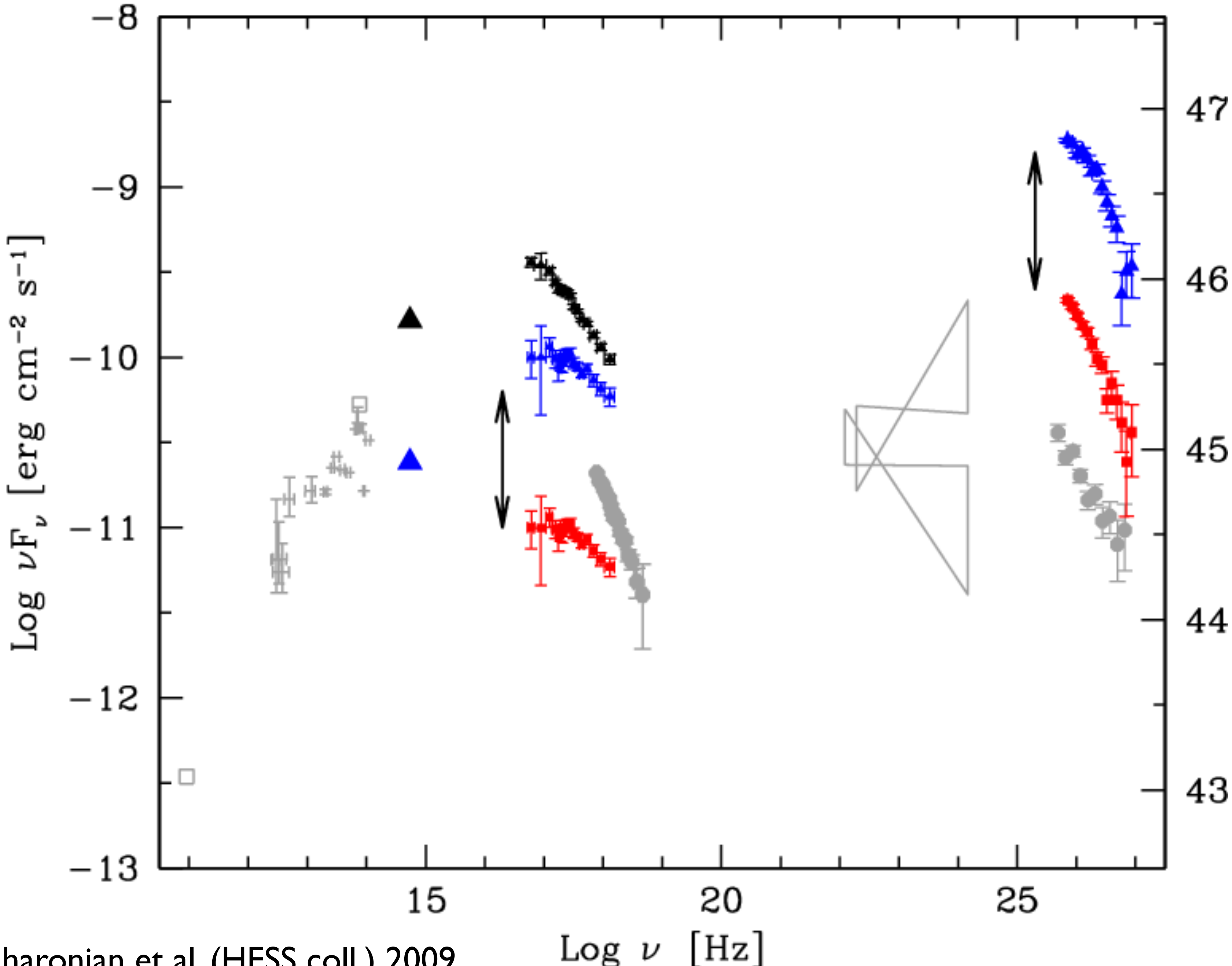


slope β of the correlation $F_\gamma \propto F_x^\beta$.

Datasets	4-min bins	7-14min bins
all	2.21 ± 0.05	2.25 ± 0.05
A	no corr.	no corr
B	2.72 ± 0.17	3.18 ± 0.18
C	2.83 ± 0.17	3.14 ± 0.18
B+C	3.13 ± 0.11	3.35 ± 0.11

Aharonian et al. (HESS coll.) 2009

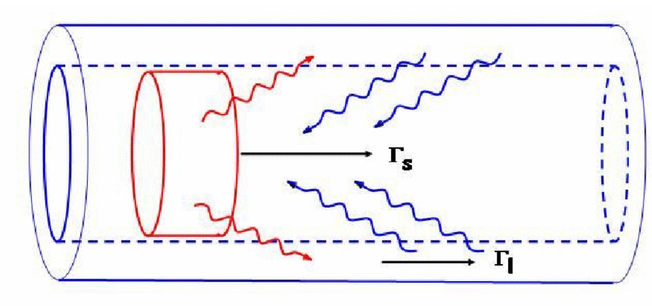
Main explanation: Superposition of 2 SEDs
2 different components/zones, 1 persistent + 1 flaring



Aharonian et al. (HESS coll.) 2009

a) If $F_\gamma \propto F_x^2$
SSC ok with B ~1G
R ~3-5 x10^{14} cm

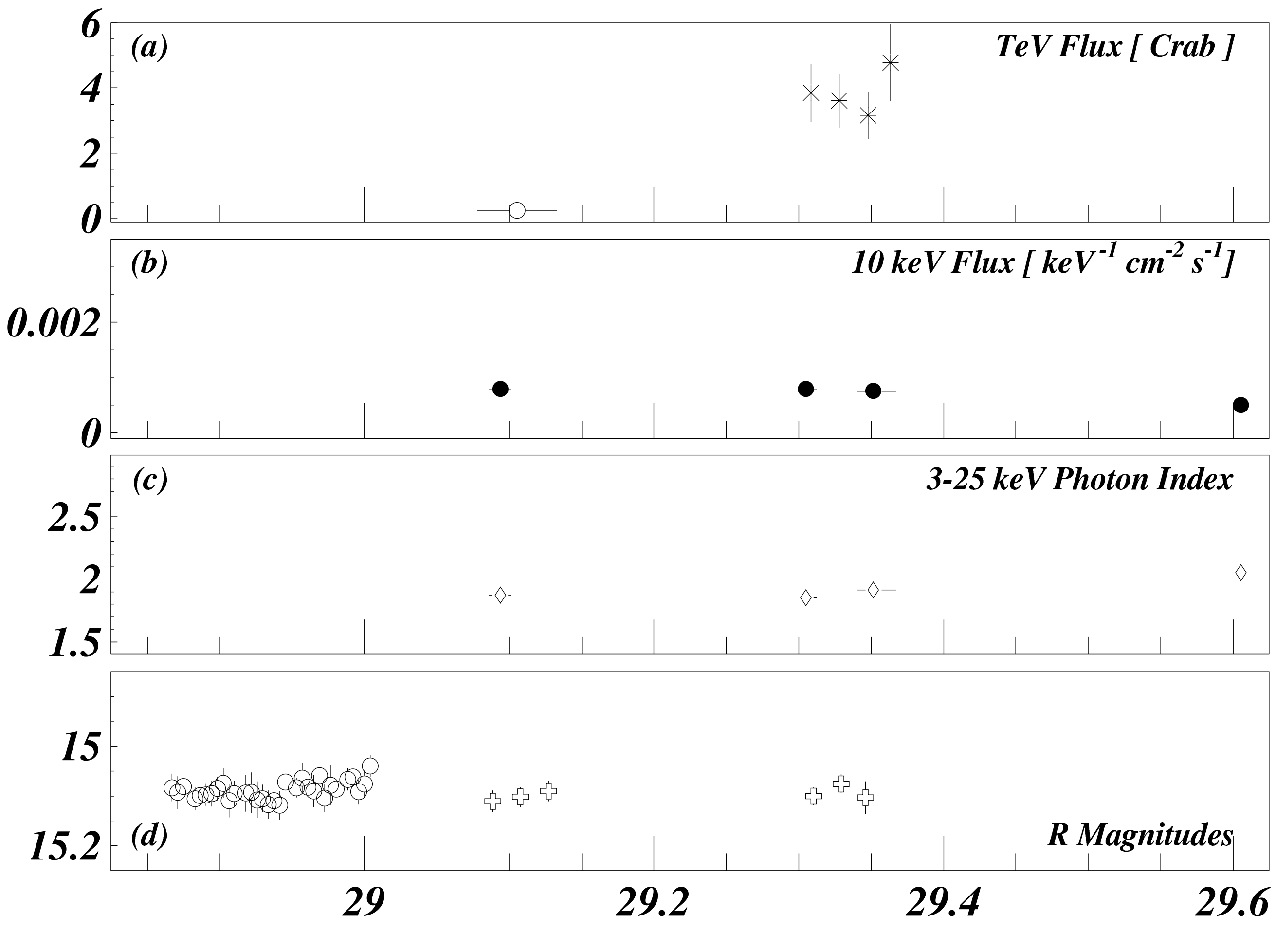
b) If $F_\gamma \propto F_x$
Constantly high
Compton Dominance !
External Compton
on structured jet ?

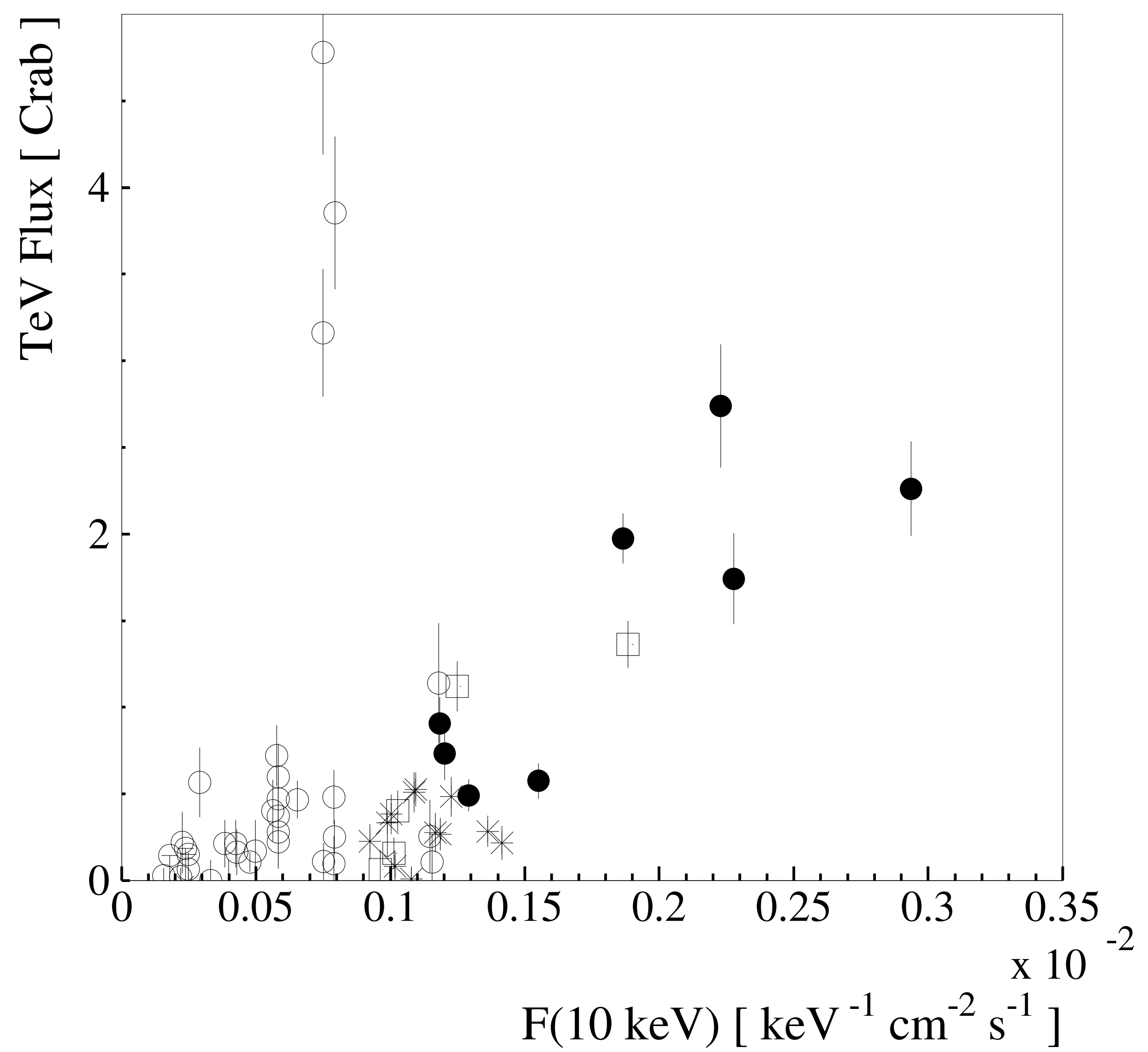


Ghisellini & Tavecchio 2008
Georganopulous & Kazanas 2004

“Orphan flare” 1ES 1959+650 in 2002

XTE - Whipple - HEGRA





Krawczynski et al. 2004

“Orphan flare” 1ES 1959+650 in 2002

in retrospect…

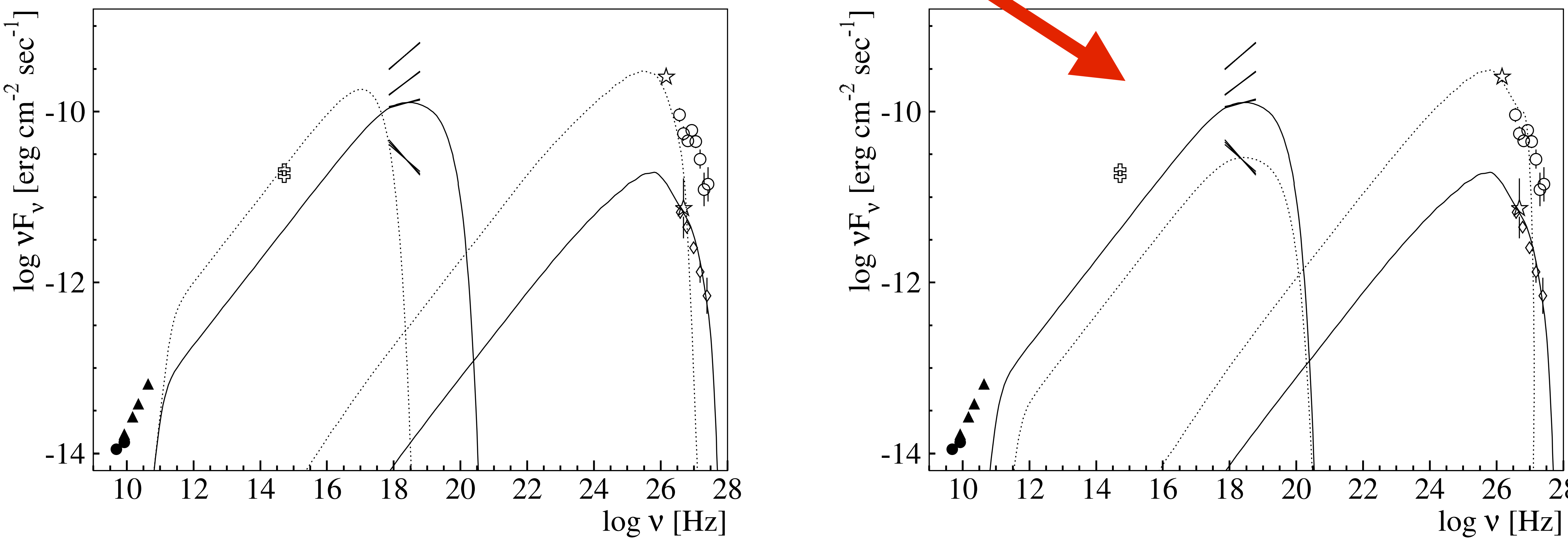
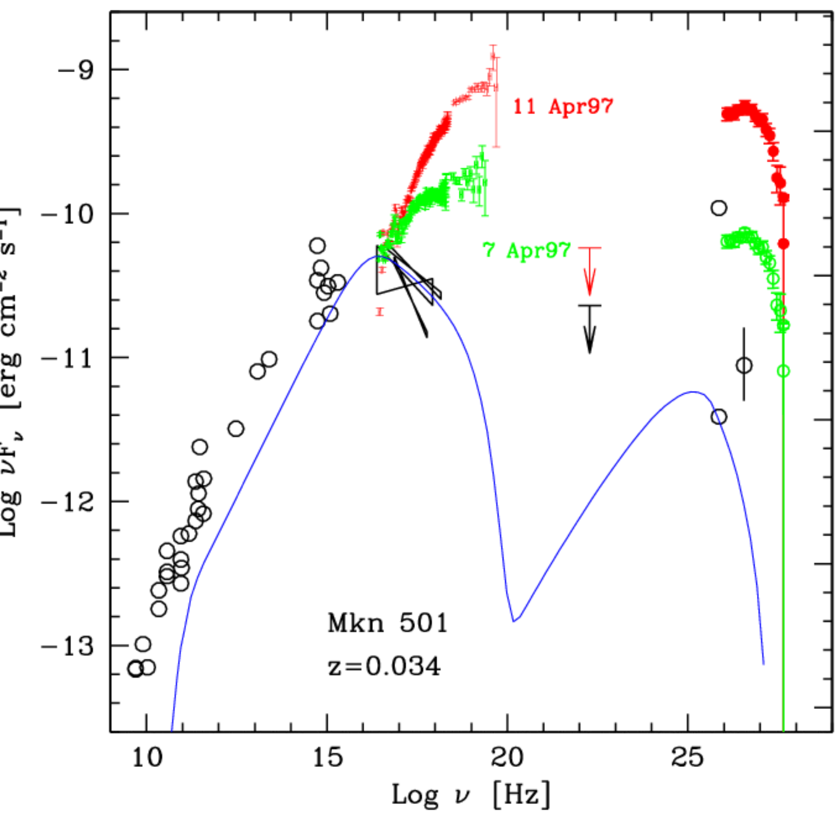


FIG. 12.—Same data as in Fig. 11. In both panels, the solid lines show the SSC model that explains the preflare X-ray and γ-ray emission, and the dotted lines show additional emission during the γ-ray flare. All models include the effect of extragalactic absorption. In the left-hand panel, the γ-ray flare is produced by an electron population with a rather low high-energy cutoff, $\log(E_{\max}/\mathrm{eV}) = 11.15$ instead of $\log(E_{\max}/\mathrm{eV}) = 12.2$. In the right-hand panel, a dense electron population confined to a small emission region produces the orphan flare. The model parameters for the flare component are as follows. *Left*: $\delta_j = 20$, $B = 0.04$ G, $R = 1.4 \times 10^{16}$ cm, single electron power law with $\log(E_{\min}/\mathrm{eV}) = 3.5$, $\log(E_b/\mathrm{eV}) = \log(E_{\max}/\mathrm{eV}) = 11.15$, $p_1 = 2$, and electron energy density of 0.07 ergs cm^{-3}. *Right*: $\delta_j = 20$, $B = 0.04$ G, $R = 8 \times 10^{14}$ cm, $\log(E_{\min}/\mathrm{eV}) = 3.5$, $\log(E_{\max}/\mathrm{eV}) = 12.2$, $\log(E_b/\mathrm{eV}) = 11.45$, $p_1 = 2$, $p_2 = 3$, and electron energy density of 17 ergs cm^{-3}. The parameters for the quiescent emission are the same as in Fig. 11.

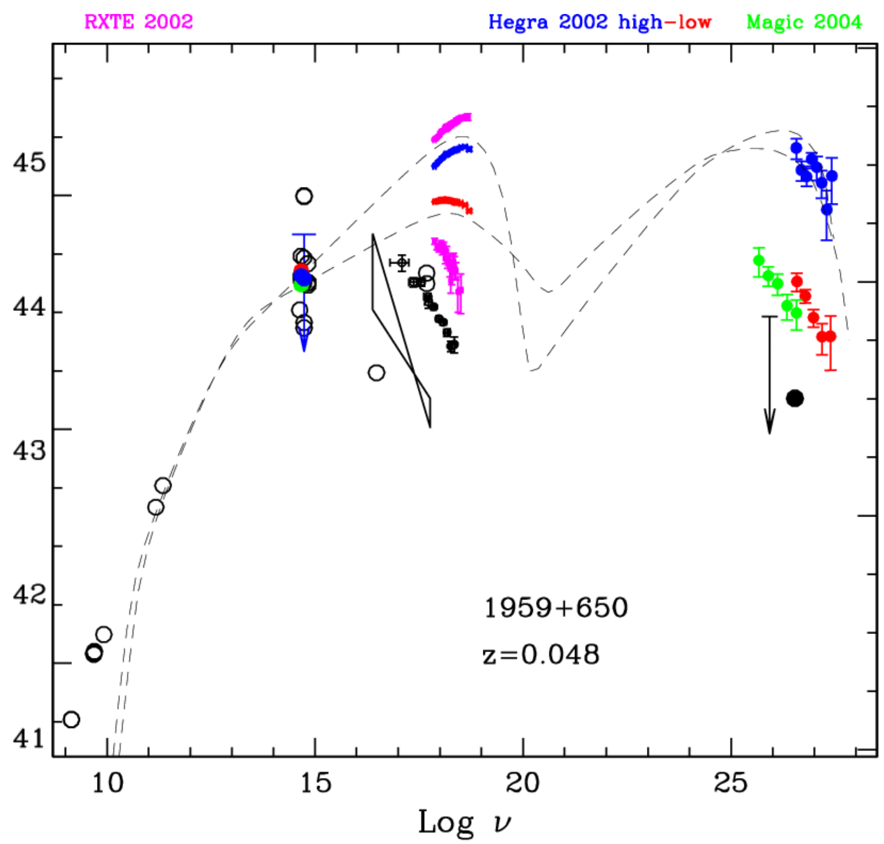
Krawczynski et al. 2004

It is a new mode of flaring in BL Lacs

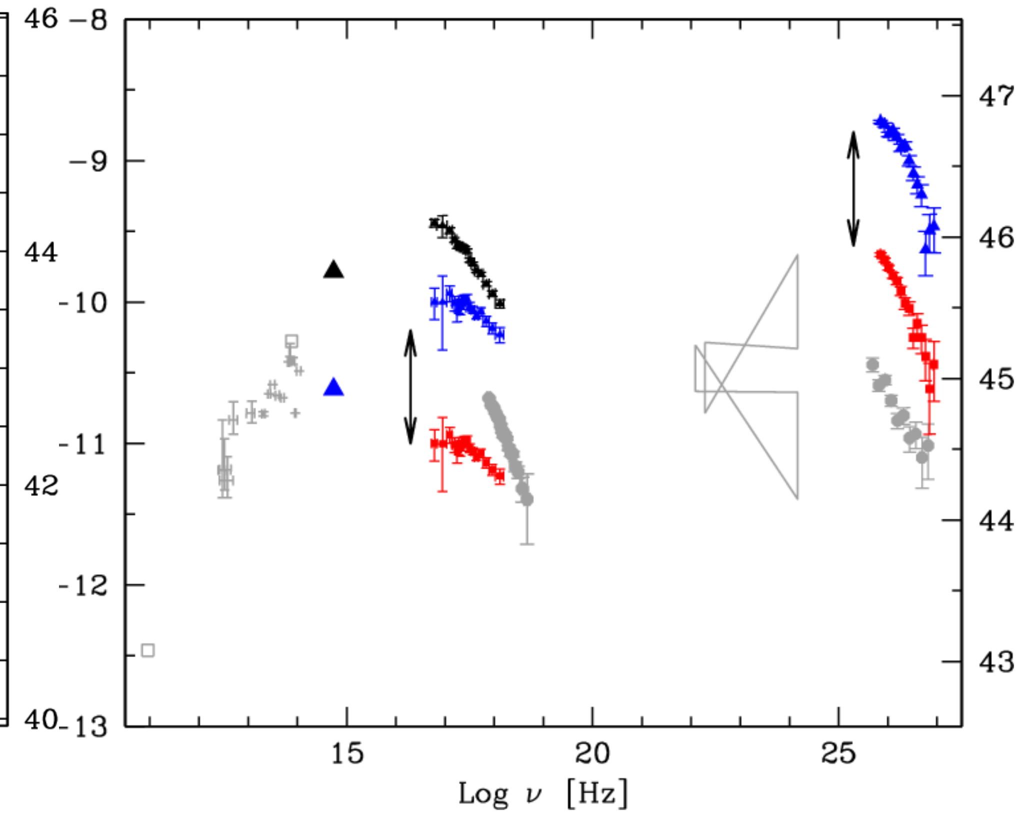
Mkn 501



1ES 1959+650



PKS 2155-304
+ 1959 orphan

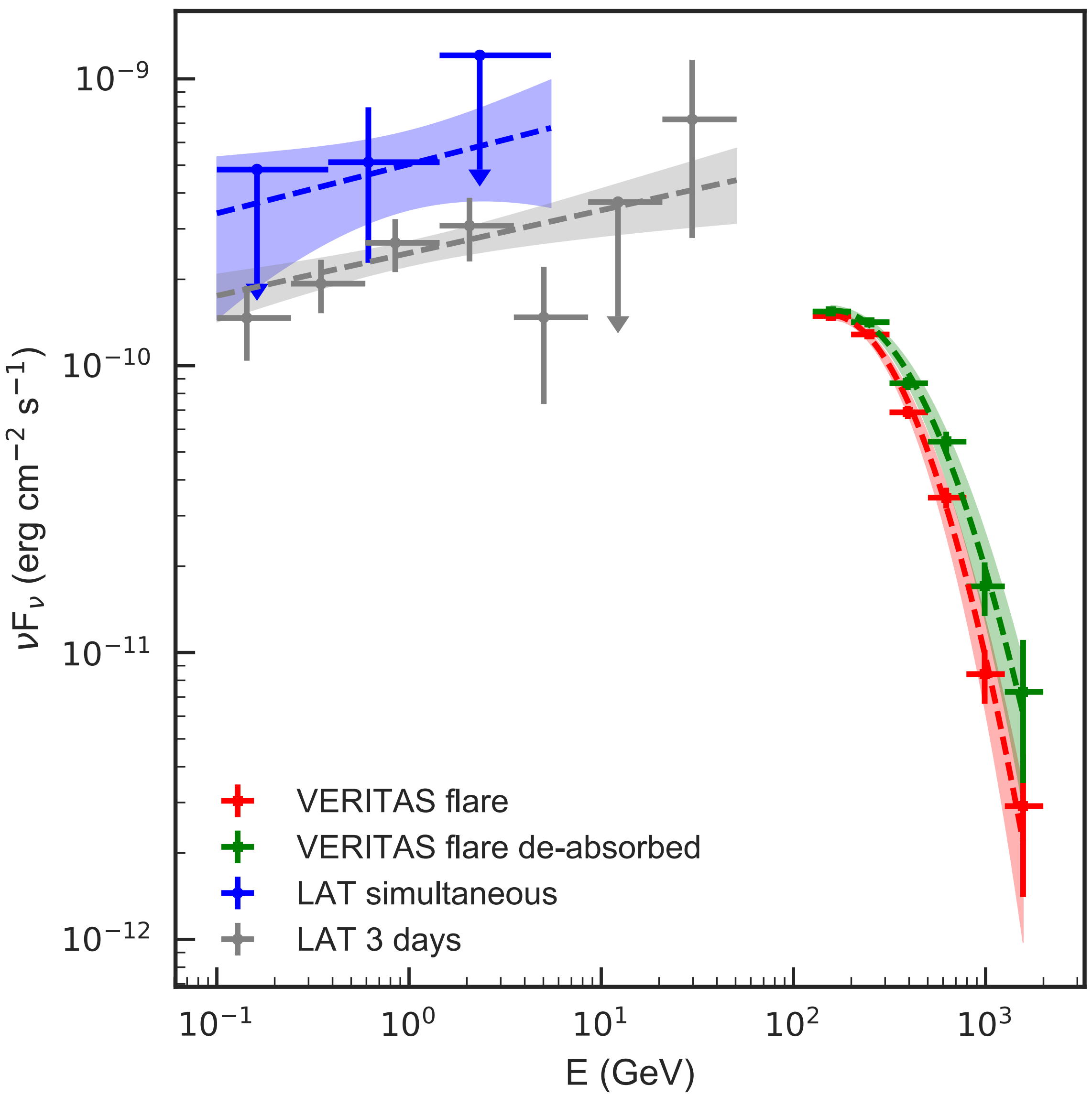


Synchrotron-dominated flares

Compton-dominated

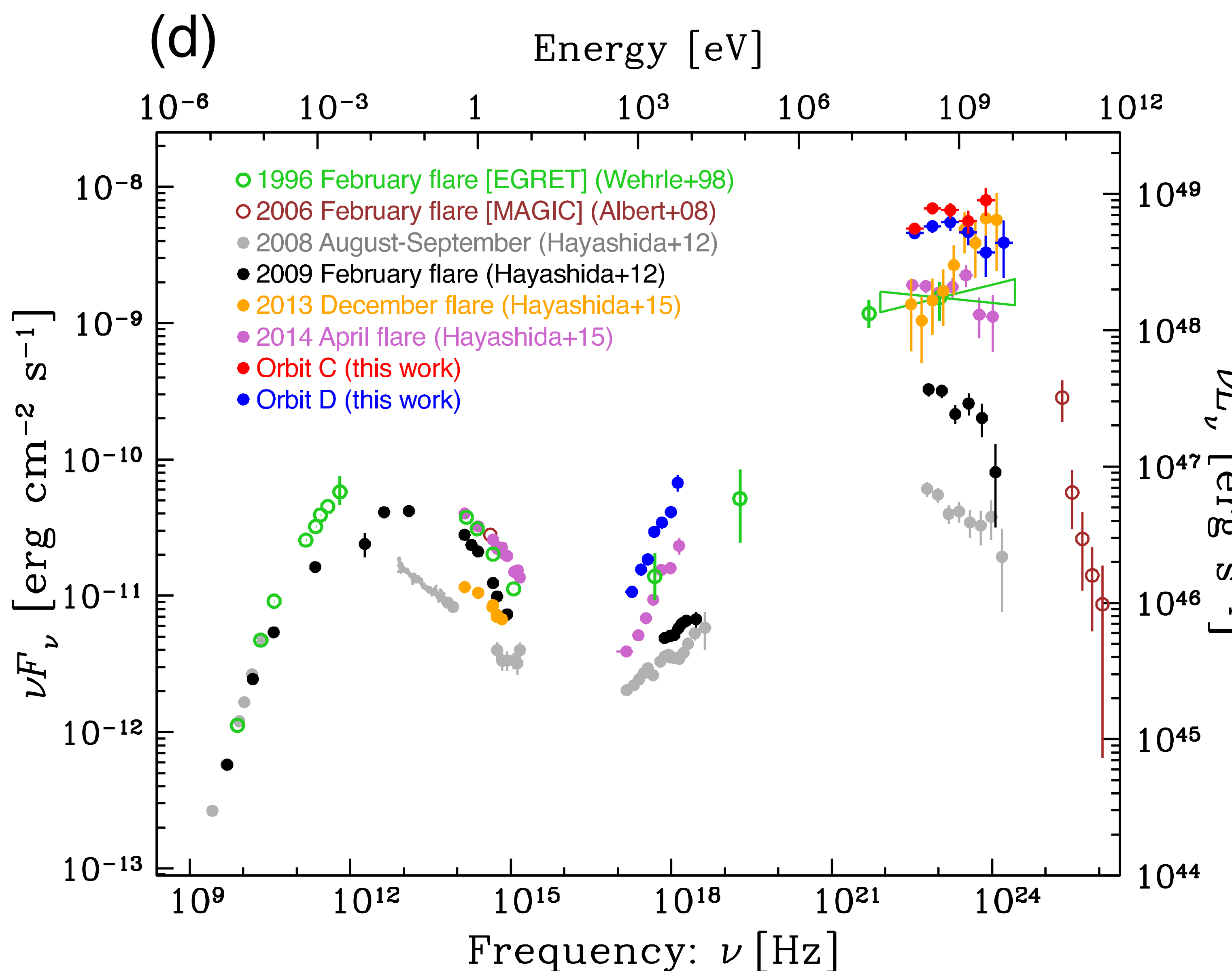
C) - All type of blazars emit at VHE (also FSRQ: 9)
- HBL-like gamma-ray spectra in LBL/FSRQ

BL Lac



Veritas Collab. 2018

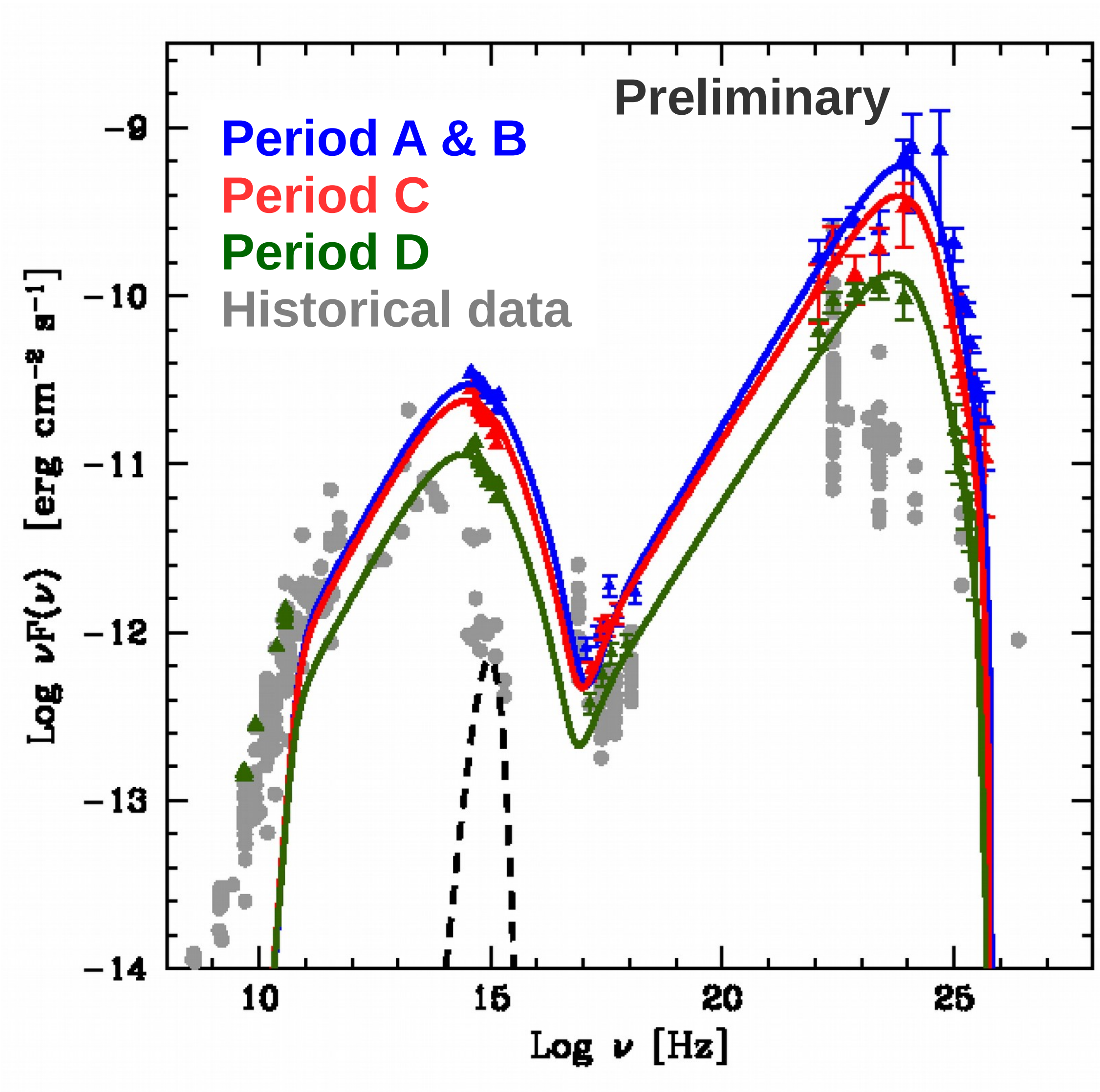
3C 279



LAT Collab. 2016

C) - All type of blazars emit at VHE (also FSRQ: 9)
- HBL-like gamma-ray spectra in LBL/FSRQ

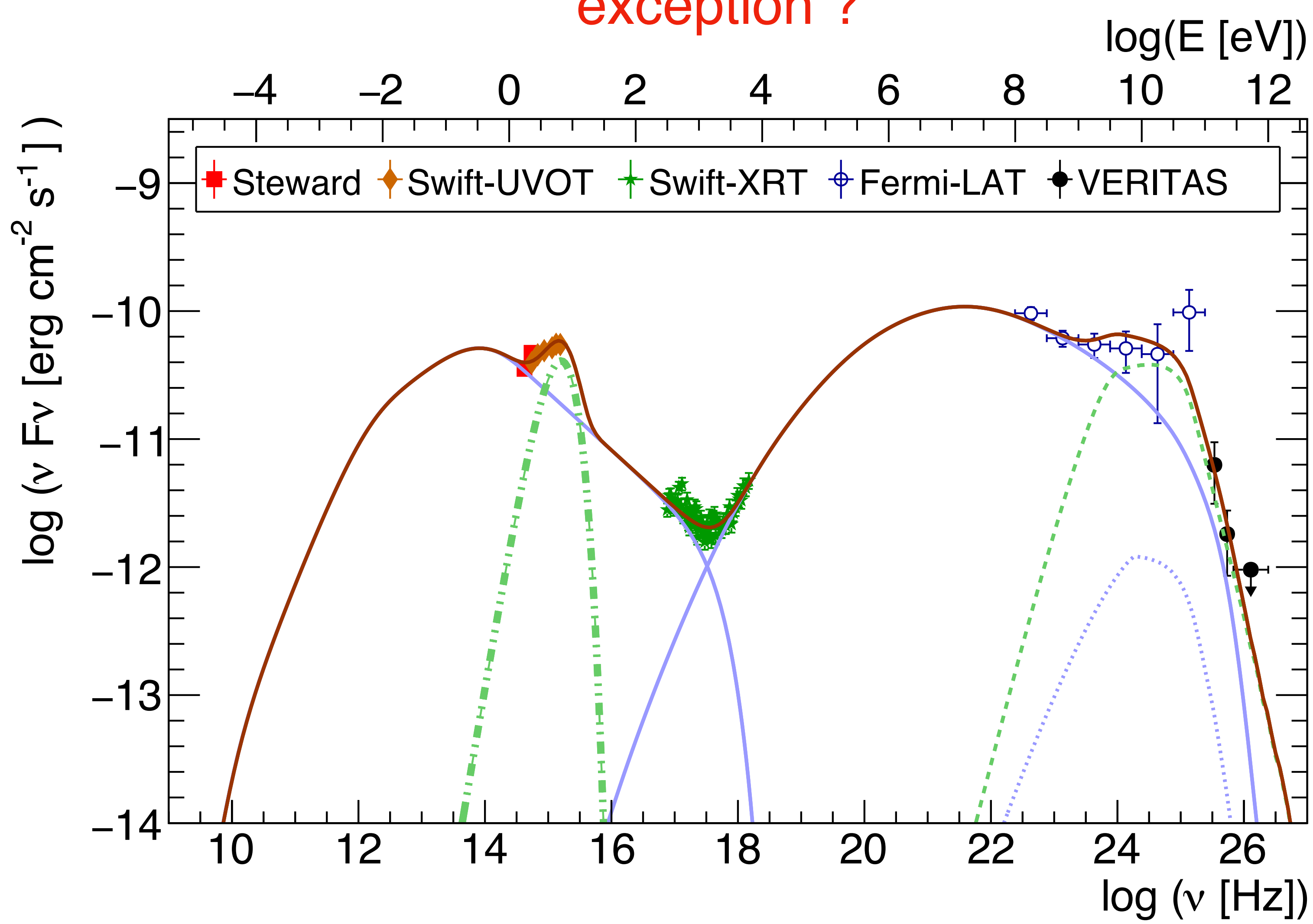
Ton599



Terzic et al. (MAGIC coll.), TeVPA 2018

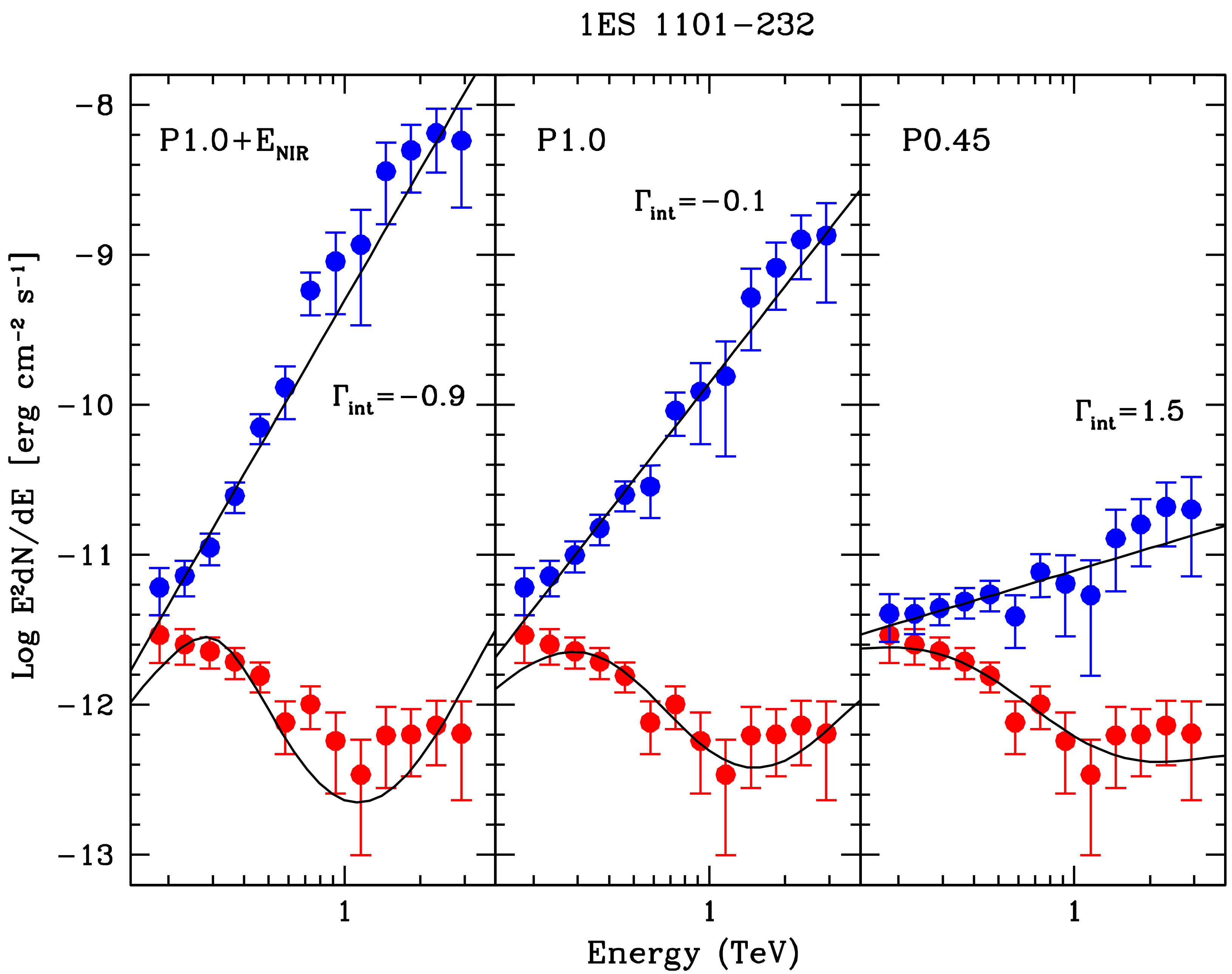
4C +21.35

exception ?



Adams et al. (VERITAS coll.), 2022

D) Discovery of Extreme TeV BL Lacs

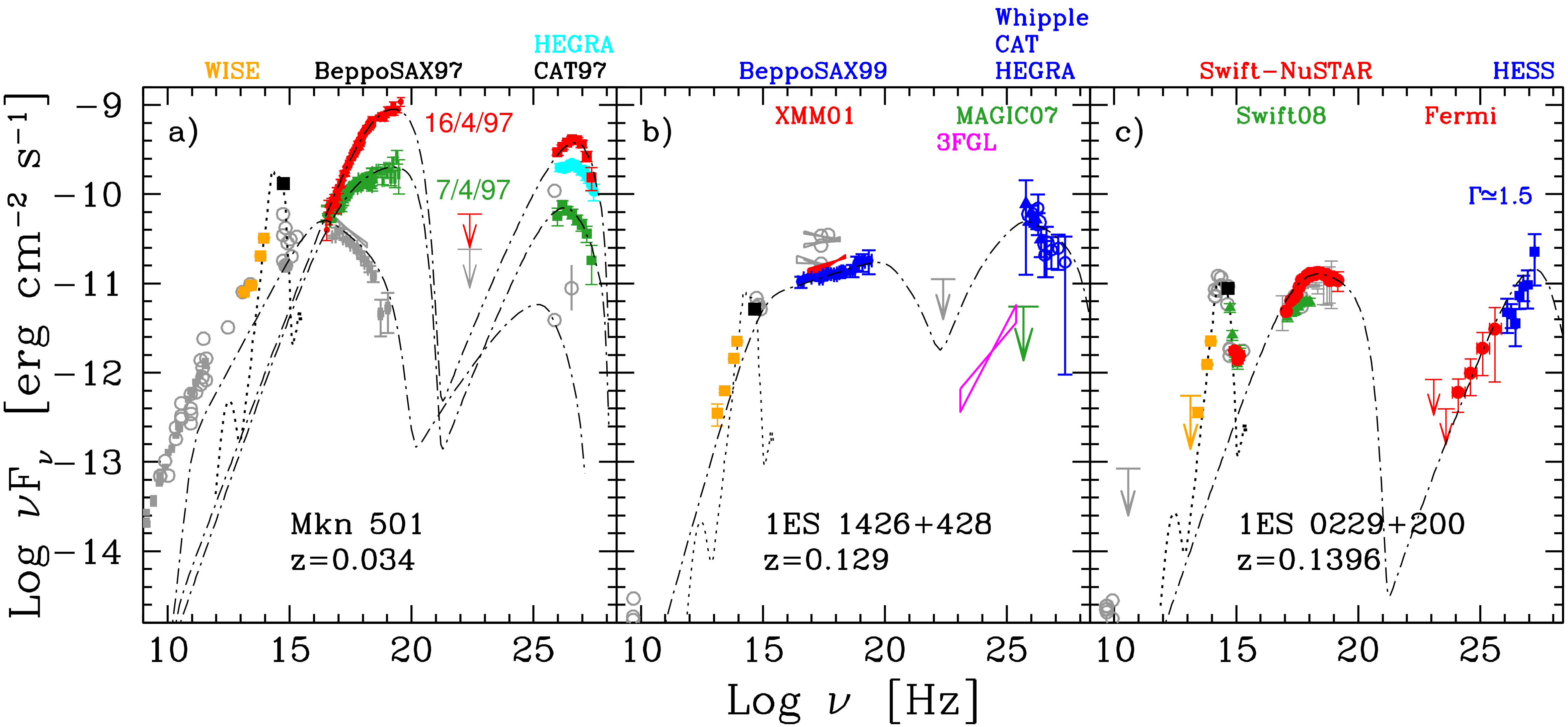


Aharonian et al.
(HESS collab.)
Nature 2006

Intrinsic Γ_{VHE} < 2 (typically 1.5-1.7), with any EBL intensity (even lowest one).

⇒ Compton peak ≥ 3-10 TeV

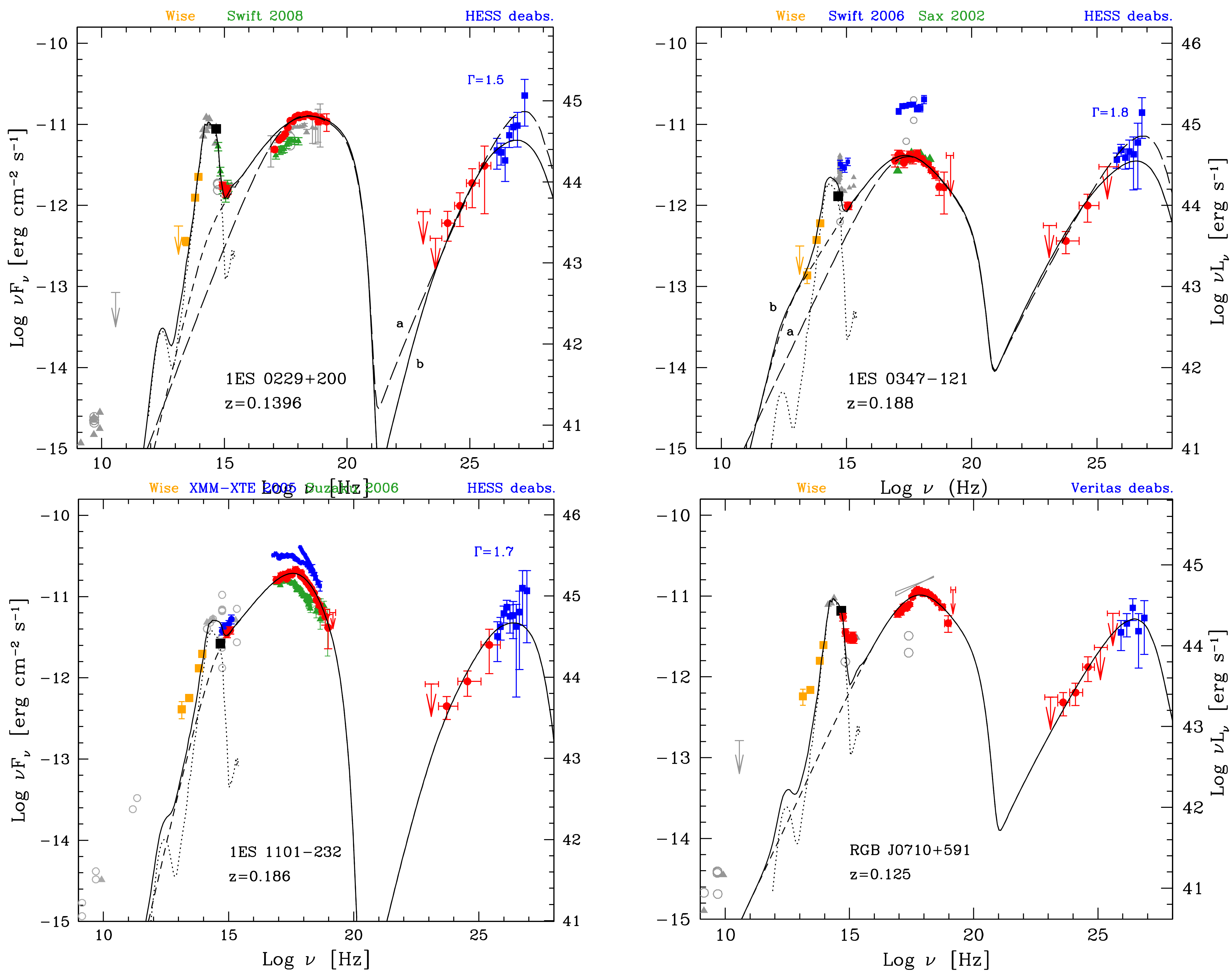
BL Lacs: 3 ways of being Extreme



If Extreme-TeV = Gamma-ray peak >1 TeV

Numbers are ~1/4 of all VHE-detected HBL
(14/55, 3 only temporarily)

See review Biteau, Prandini et al., Nature Astr. 2020


Wise
Swift 2008
HESS deabs.
Γ=1.5
a
b
1ES 0229+200
z=0.1396
Log νF_ν [erg cm⁻² s⁻¹]
Log ν [Hz]
Wise
Swift 2006
Sax 2002
HESS deabs.
Γ=1.8
a
b
1ES 0347−121
z=0.188
Log ν (Hz)
Log νL_ν [erg s⁻¹]
Wise
XMM−XTE 2005
Suzaku 2006
HESS deabs.
Γ=1.7
1ES 1101−232
z=0.186
Log νF_ν [erg cm⁻² s⁻¹]
Log ν [Hz]
Wise
Veritas deabs.
RGB J0710+591
z=0.125
Log νL_ν [erg s⁻¹]
Log ν [Hz]

LC et al. 2018

leptonic modeling:

Source [1]	γ_0 [2]	n_0 [3]	γ_1 [4]	γ_b [5]	γ_2 [6]	n_1 [7]	n_2 [8]	B [9]	K [10]	R [11]	δ [12]	U_e/U_B [13]
1ES 0229+200 a	-	-	100	1.1×10^6	2×10^7	1.4	3.35	0.002	6	0.8	50	1.7×10^5
1ES 0229+200 b	-	-	2×10^4	1.5×10^6	2×10^7	2.0	3.4	0.002	10^3	2.1	50	2.0×10^4
1ES 0347-121 a	-	-	100	7.5×10^5	1.8×10^7	1.7	3.8	0.0015	1.2×10^2	1.2	60	1.5×10^5
1ES 0347-121 b	-	-	3×10^3	7.5×10^5	1.8×10^7	2.0	3.8	0.0015	8×10^2	2.5	60	3.4×10^4
1ES 0414+009 a	10	1.7	1×10^4	10^5	10^6	3.0	4.6	0.3	8×10^6	2.1	20	0.5
1ES 0414+009 b	-	-	3×10^4	5×10^5	3×10^6	2.0	4.3	0.0025	1.6×10^2	6.5	60	9.3×10^2
RGB J0710+591	-	-	100	6×10^5	10^7	1.7	3.8	0.011	1.2×10^2	0.92	30	2.7×10^3
1ES 1101-232 a	-	-	3.5×10^4	1.1×10^6	6×10^6	2.2	4.75	0.0035	7.0×10^3	2.5	60	2.4×10^3
1ES 1101-232 b	-	-	1.5×10^4	9.5×10^5	4×10^6	2.2	4.75	0.005	2.4×10^3	3.8	50	6.0×10^2
1ES 1218+304	100	1.3	3×10^4	10^6	4×10^6	2.85	4.2	0.0035	1.2×10^7	3.5	50	4.5×10^3

SSC can work but:
1) dropping one zone (fit no data below UV)
2) strongly out of equipartition (E-3 to E-6)
3) extremely low radiative efficiency

LC et al. 2018

Note: blazars are not extreme accelerators

Maximum (theoretically possible) acceleration rate:
= minimum acceleration time $t_{min} = \eta \, R_L / c$

$\eta \geq 1$; low η (1-10) $\Rightarrow$ extreme accelerators

From $t_{acc} = t_{cool}$ $\Rightarrow$ max synchrotron frequency for electrons

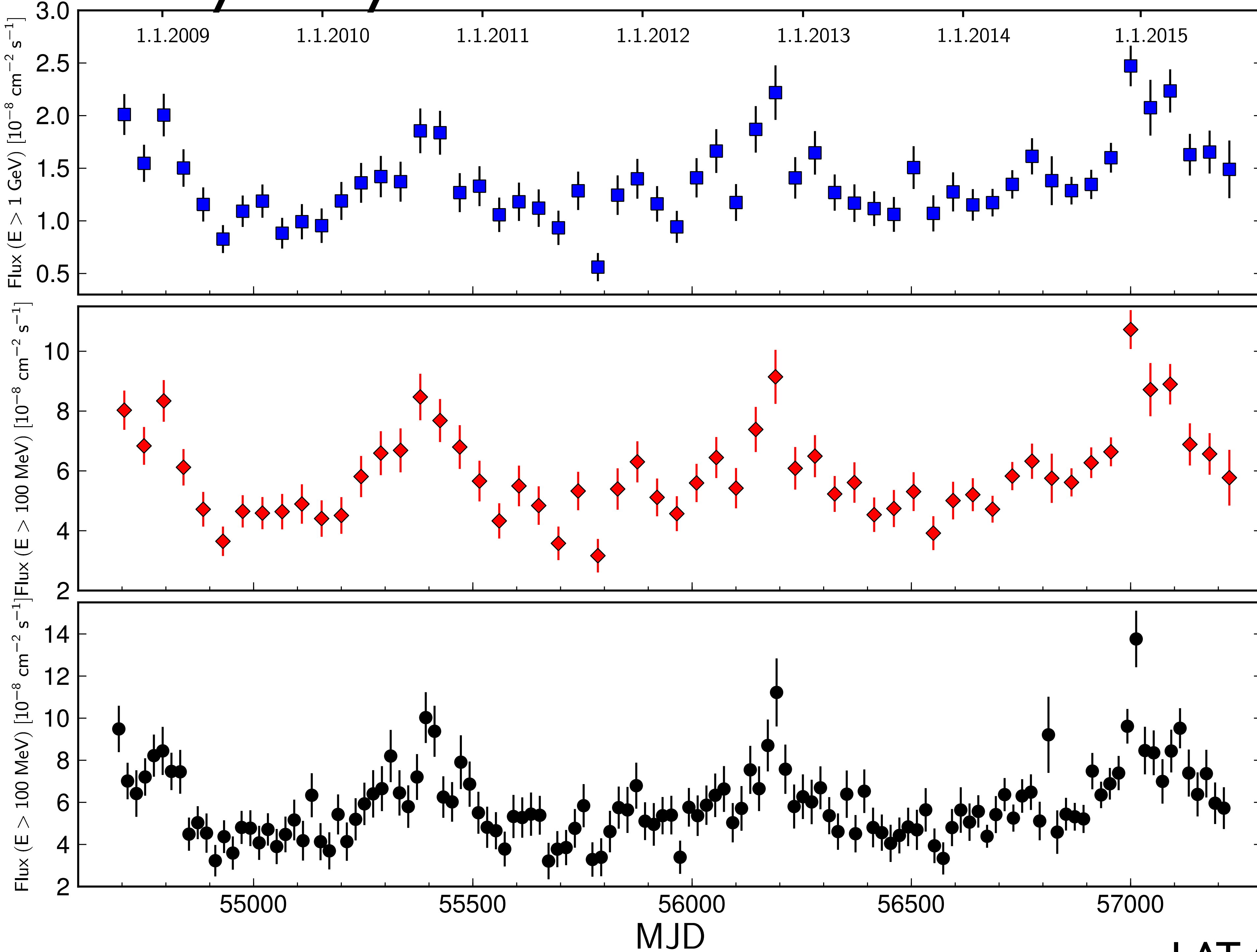
$h\nu_{cutoff} = (9/4)\, \alpha_f^{-1}\, mc^2 \approx 150\, \eta^{-1}$ MeV

Blazars (even Extreme BLLacs): $h\nu = 100 / \delta$ keV

1-10 keV $\leftrightarrow$ 150 η^{-1} MeV $\Rightarrow$ $\eta > 10^4$ NOT extreme accelerators !

E) Periodic Modulation in PG 1553+113

2.18 year cycle



LAT Coll. 2015
Covino et al. 2020

Conclusions

- Blazar Sequence concept is well and alive
(but might still be caused by observational bias)

- EC(BLR) disfavoured as main gamma-ray mechanism

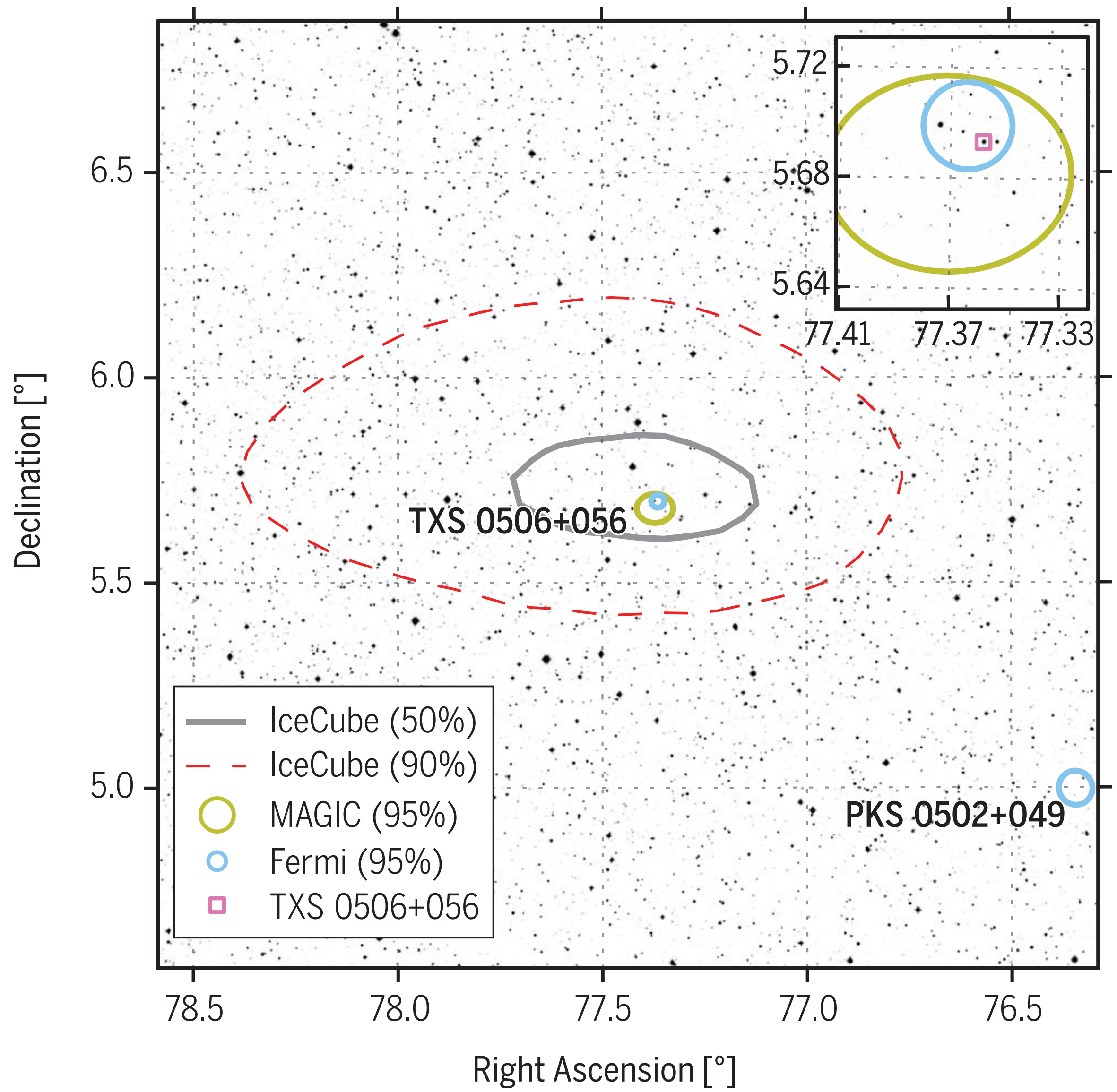
- Ultra-fast variability still a mistery, but seems everywhere

- Extreme TeV BL Lacs: which mechanisms in action ?

- Much better picture of blazar phenomenon, but we still don't know for sure the origin of gamma-rays…

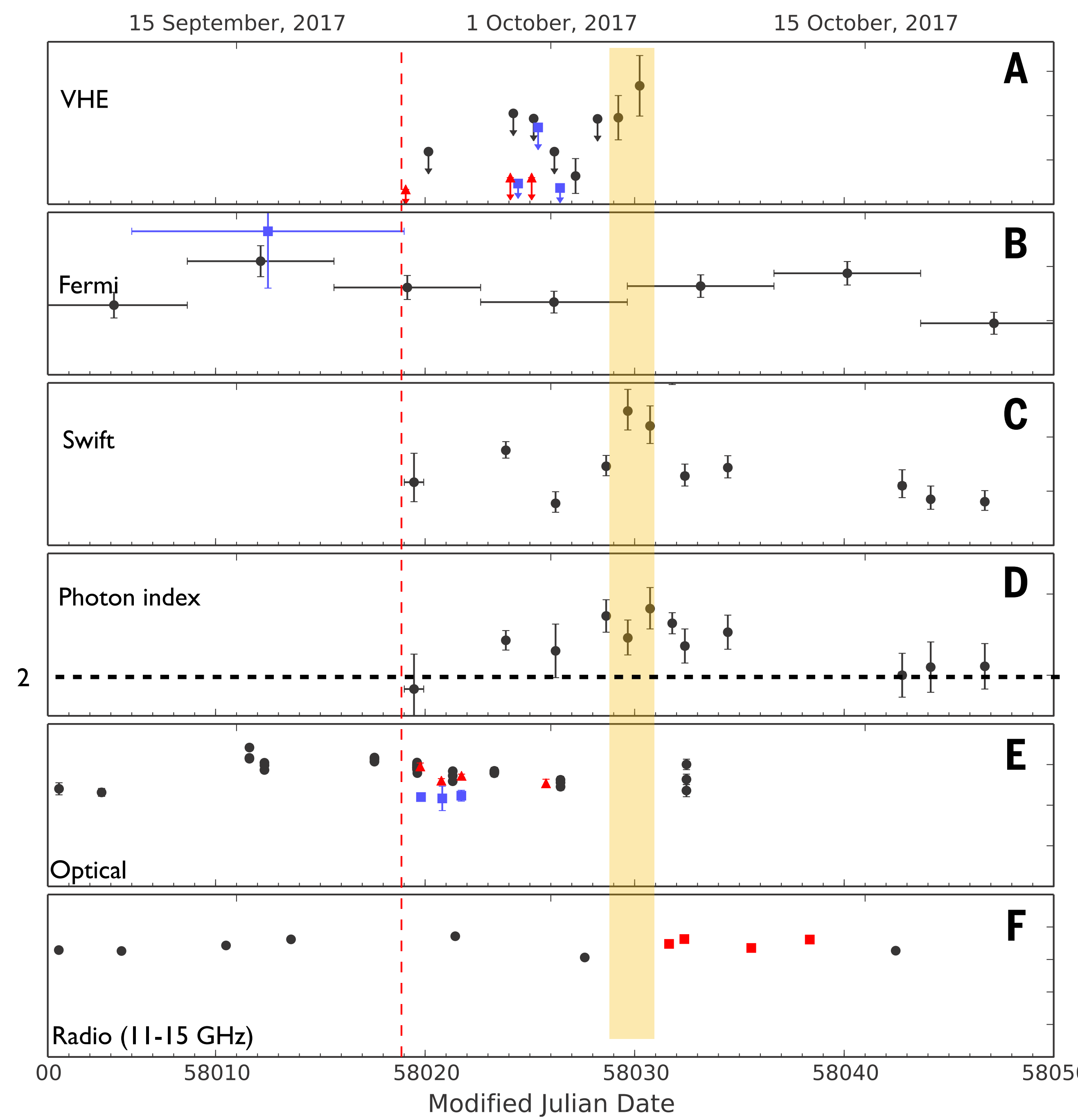
3 Hints of new aspects:

Neutrino(s) ?   so far 1



IceCube collab. et al. 2018

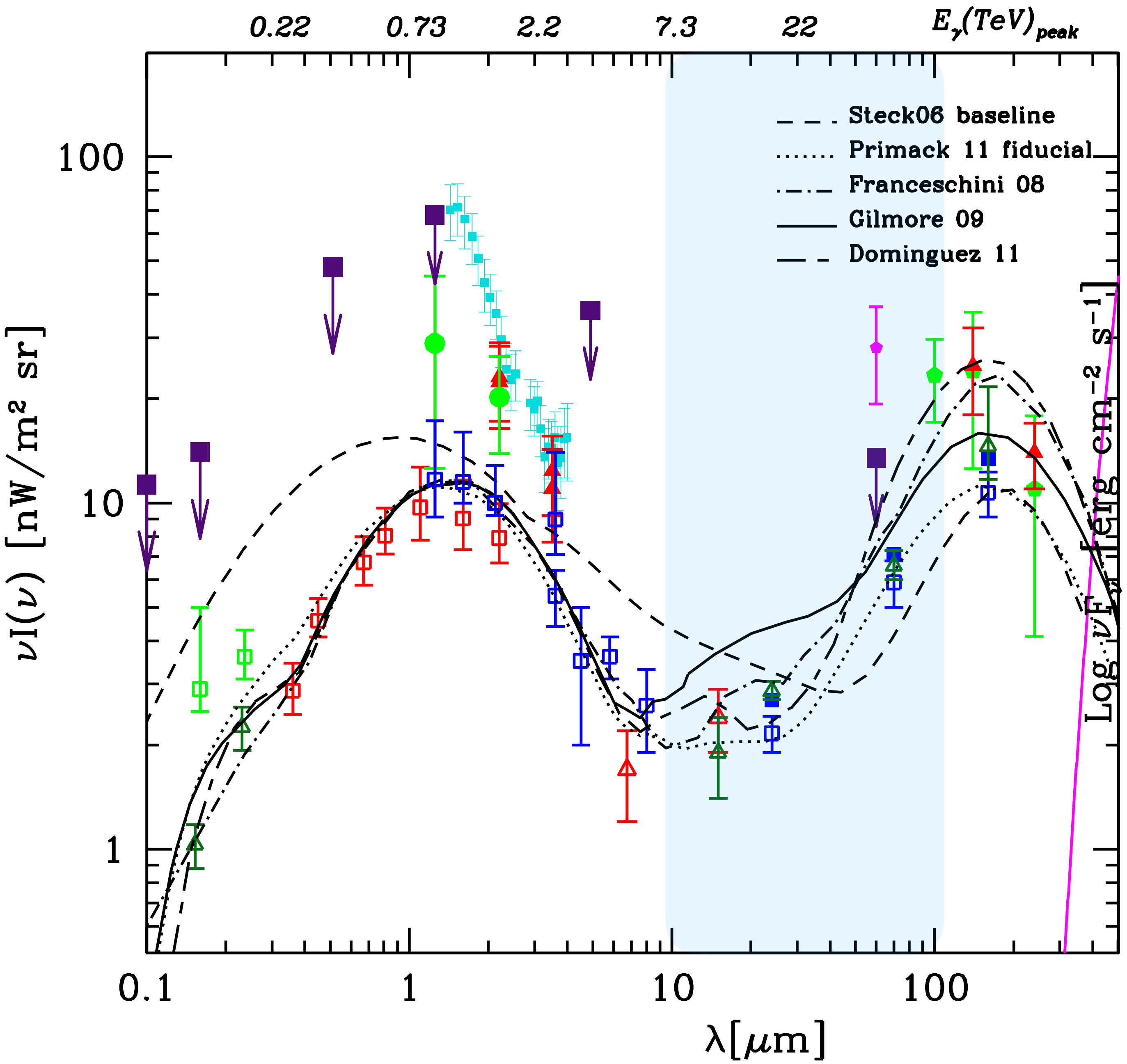
IceCube-170922A

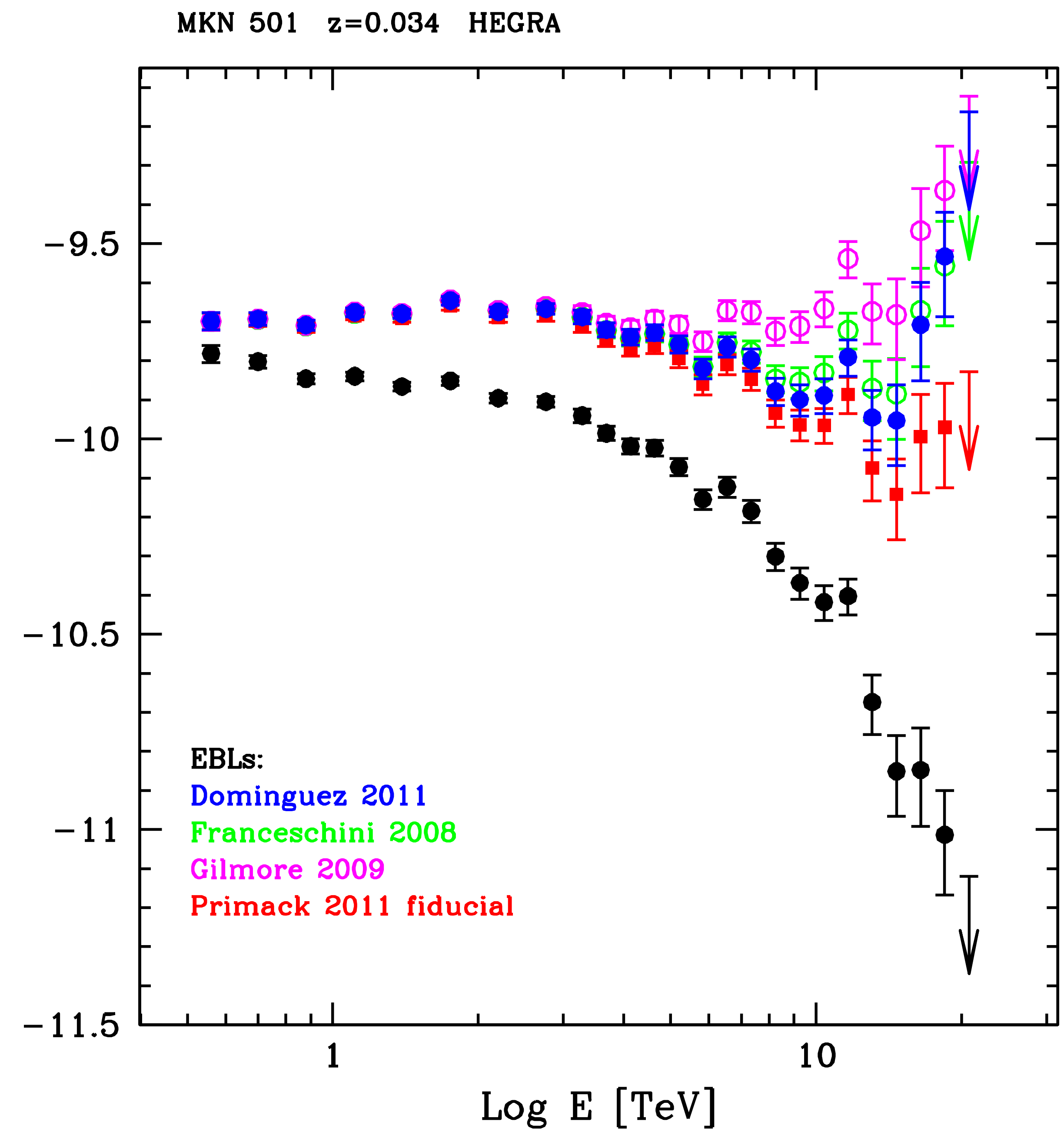


Beware of unlikely connections with gamma-ray flares

EBL above 10 μm

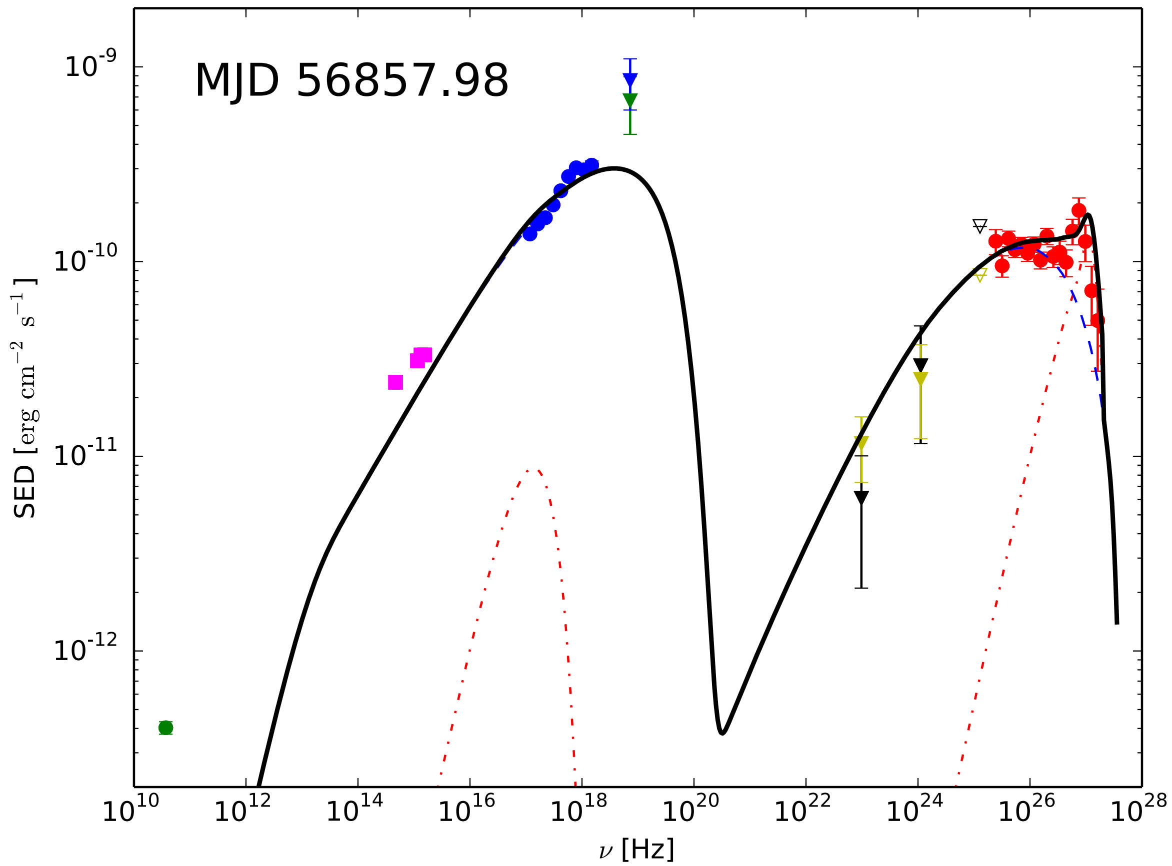
Spectra > 10 TeV,   possible problems ?

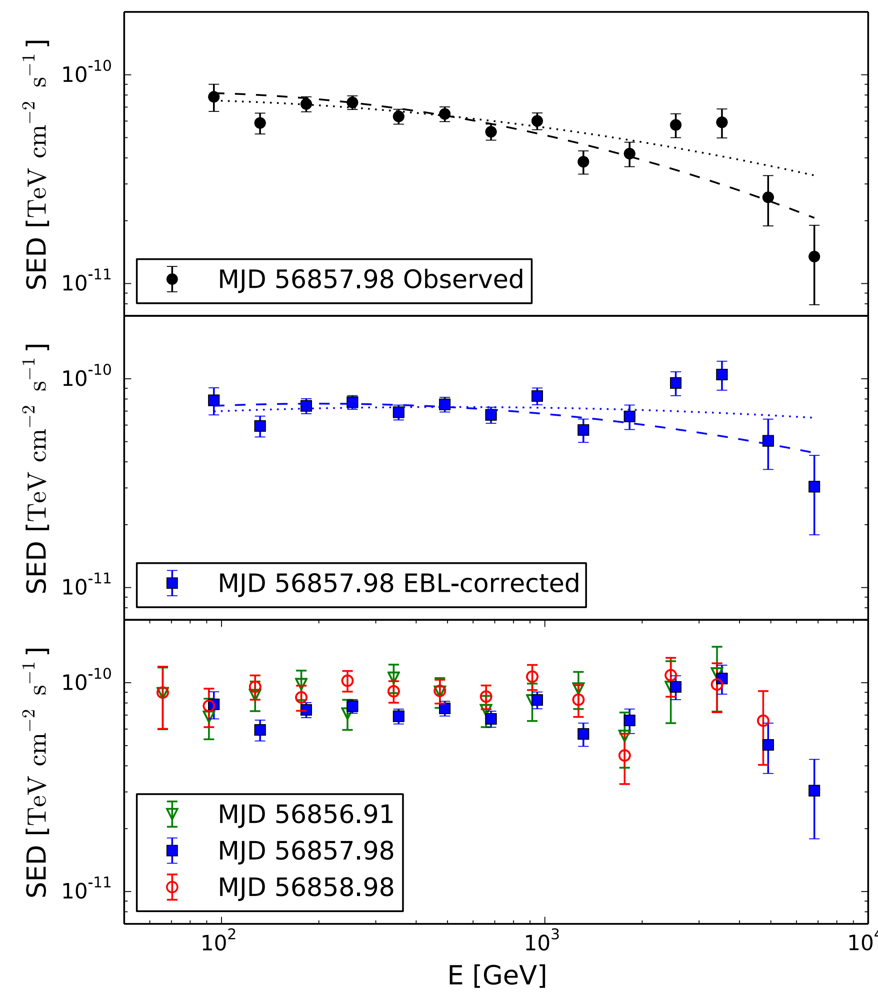




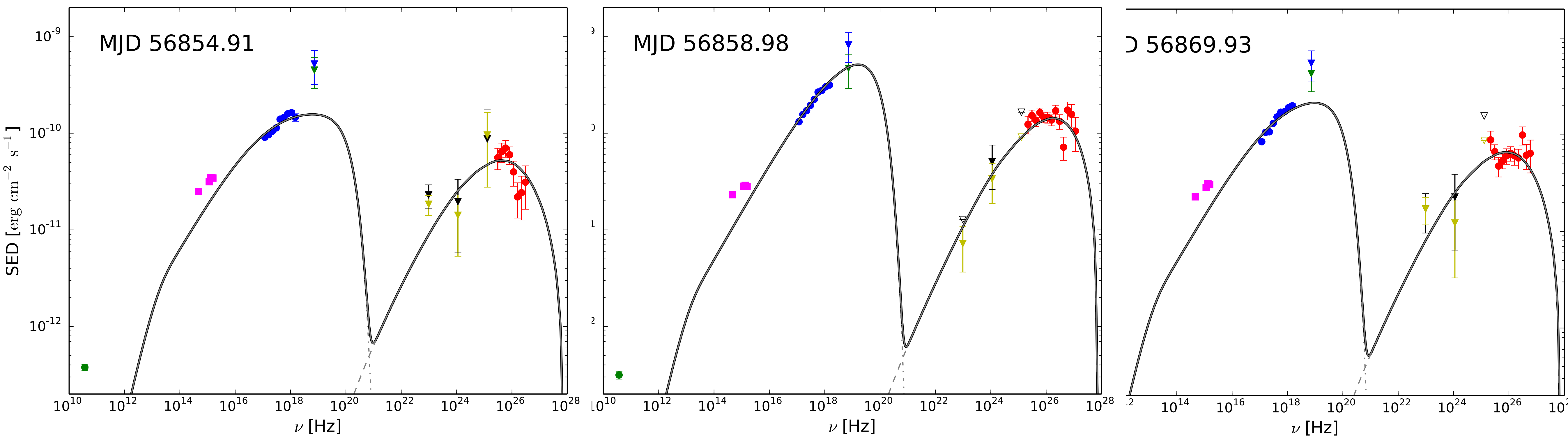
e.g. Costamante 2013

Mkn 501 in July 2014





Acciari et al (MAGIC Coll) 2021



But VHE data points seem to have large scatter day to day, so maybe instrumental ?

back-up slides

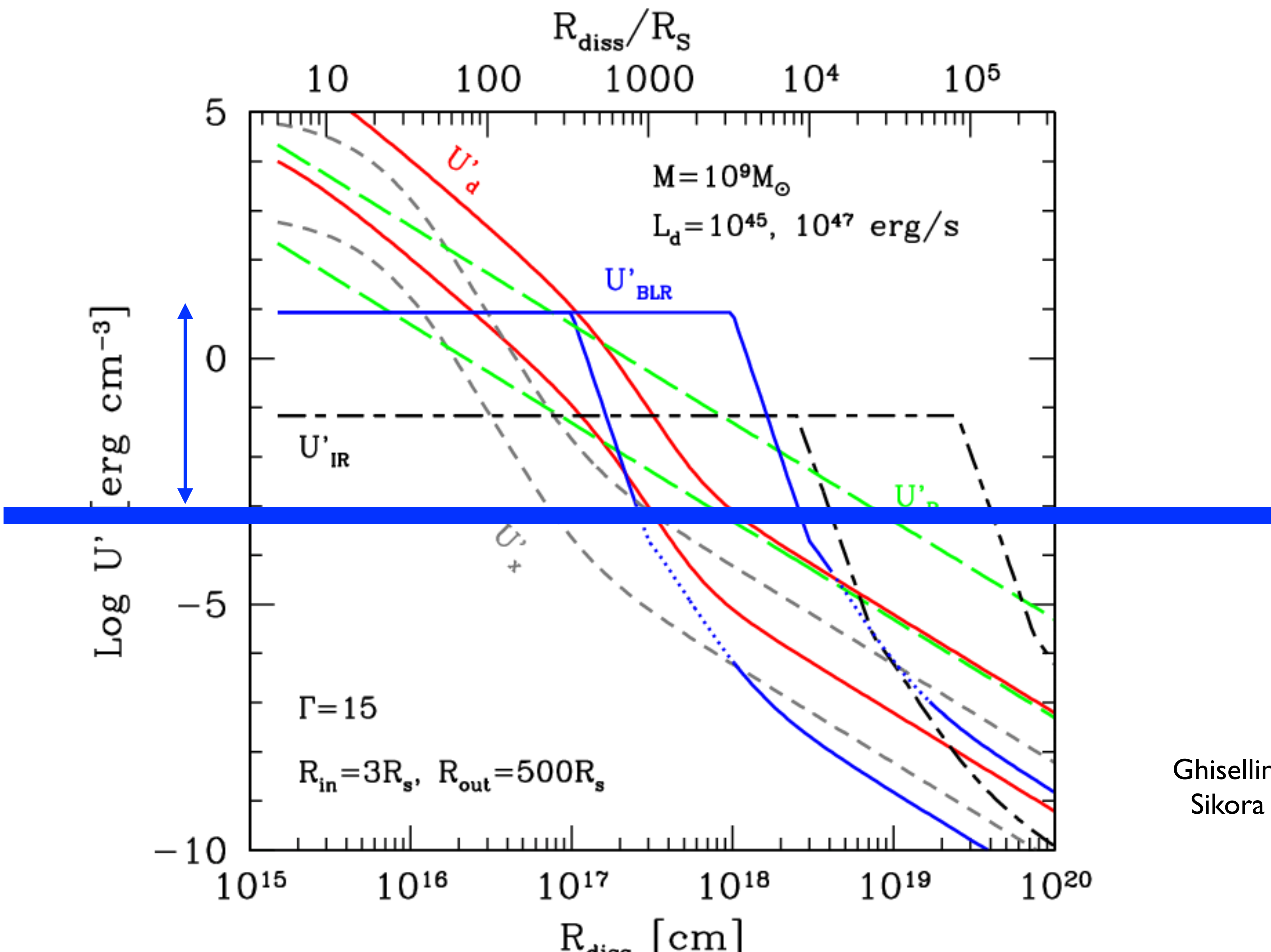
Alternatives?

to reduce absorption but staying within the BLR ?

1. *Much larger BLR (~100x)* $\tau \propto 1/R_{\rm BLR}$

2. *Shift* $\gamma\gamma$ *threshold by selecting angles ("Flattened BLR")*

1. Energy density U_{BLR} goes down 10^{-4}

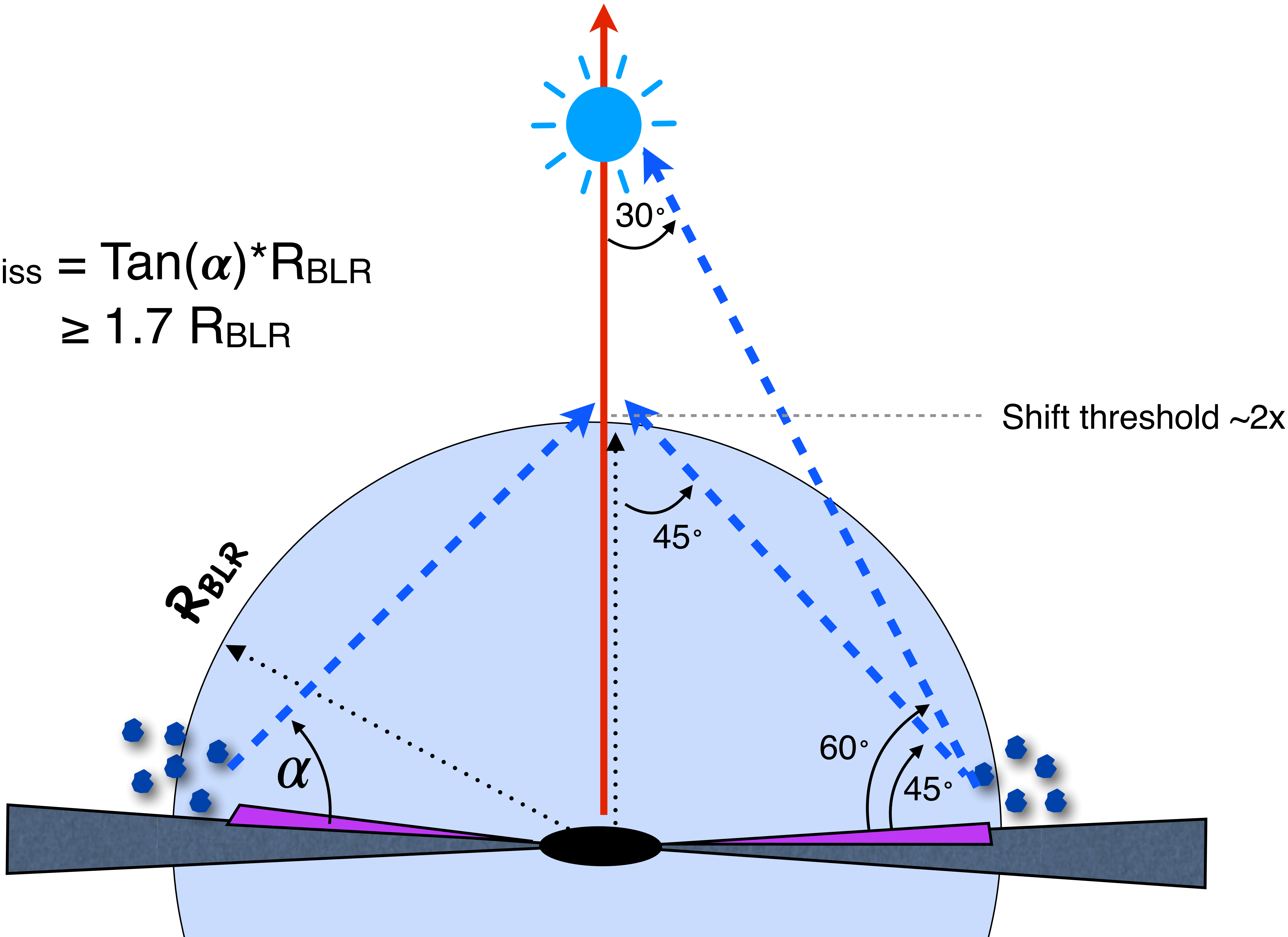


Ghisellini et al. 2009
Sikora et al. 2009

U_{BLR} becomes lower than any other radiation field —> EC(BLR) disfavoured

2. Shift threshold 5x (to ~100 GeV) —> $\vartheta \leq$ 30 deg

$R_{diss} = \mathrm{Tan}(\alpha) * R_{BLR}$
$\geq 1.7\ R_{BLR}$



Alternatives?

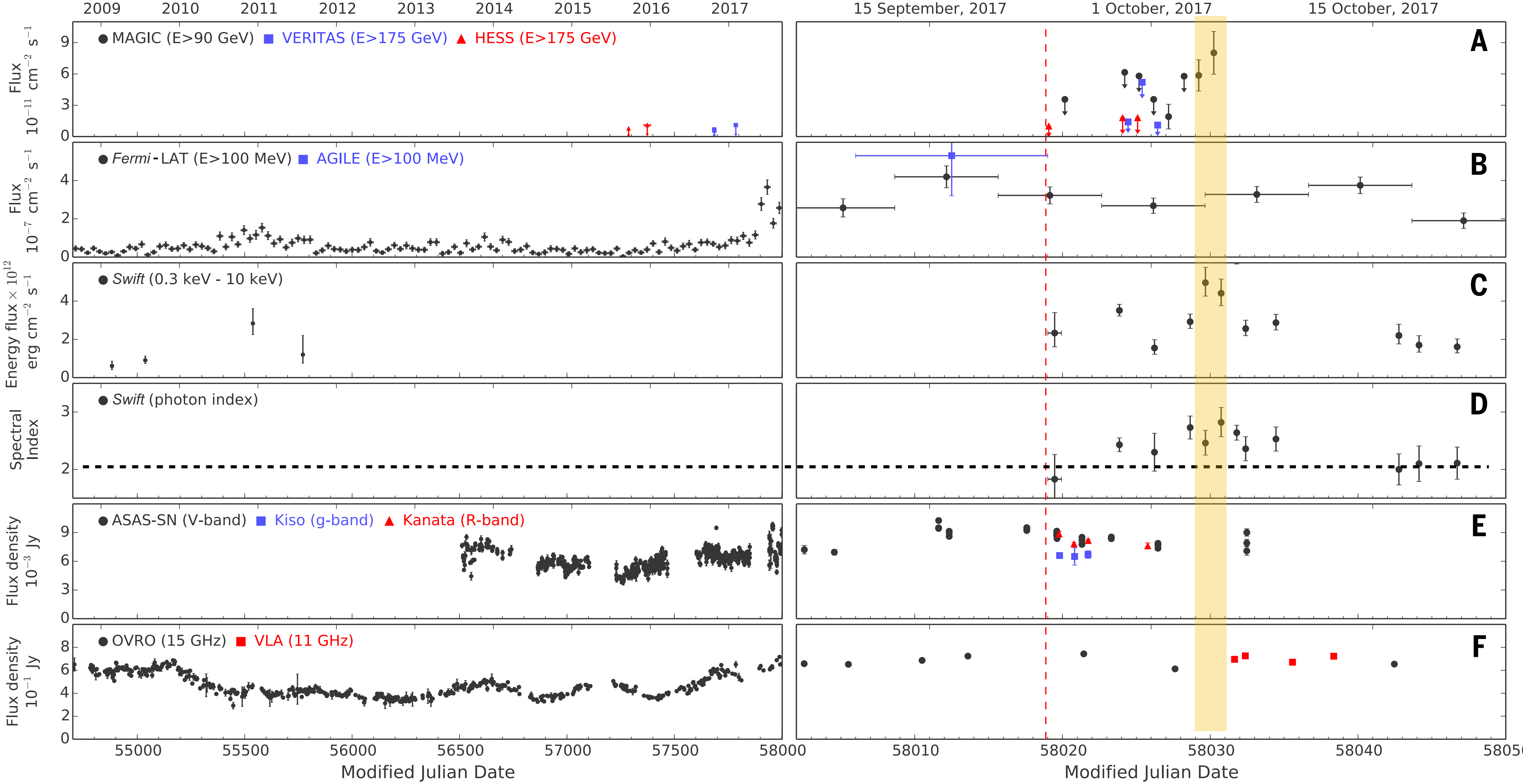
to reduce absorption but staying within the BLR ?

1. *Much larger BLR (~100x)* $\tau \propto 1/R_{\mathrm{BLR}}$

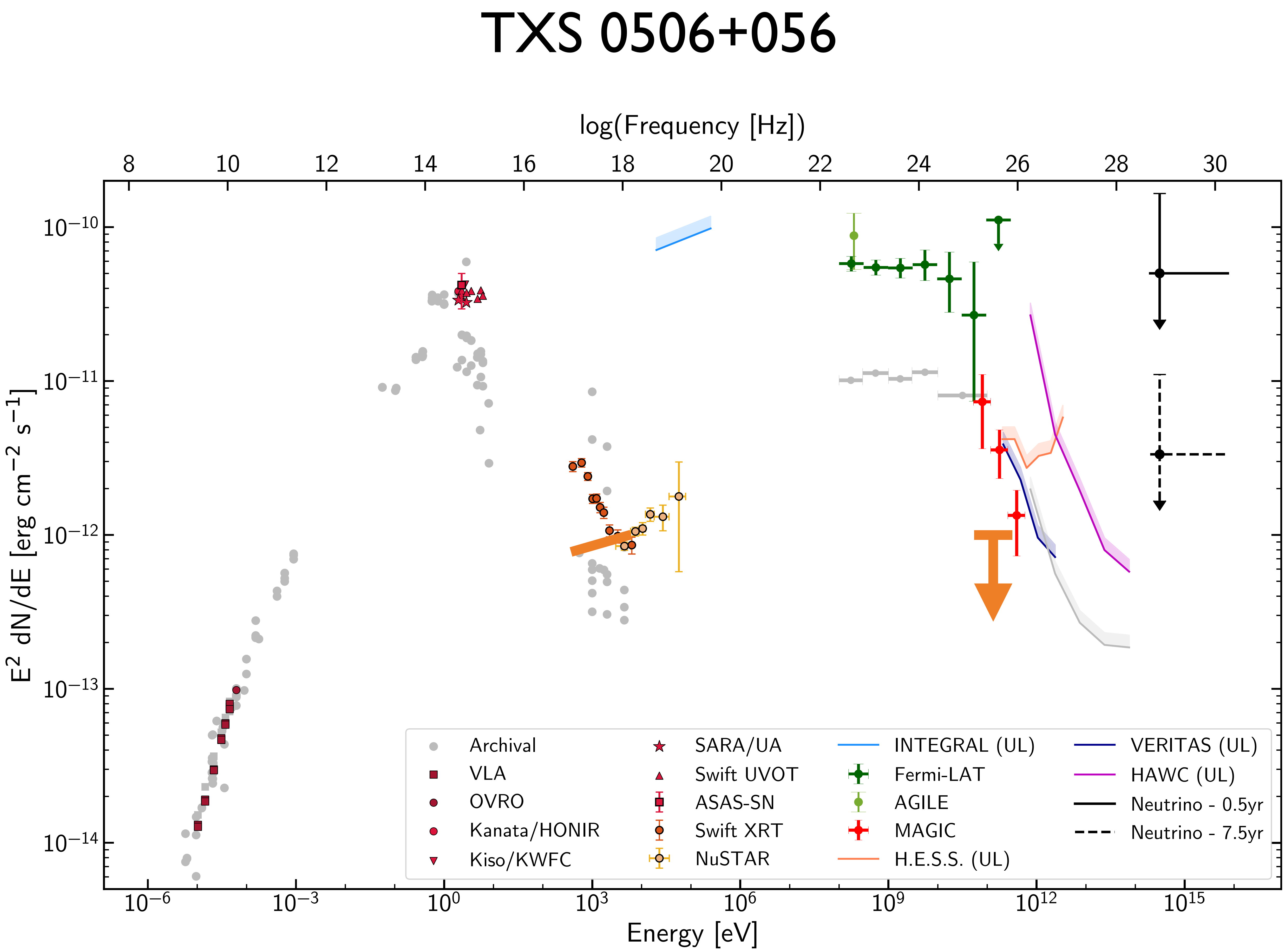
2. *Shift $\gamma\gamma$ threshold by selecting angles ("Flattened BLR")*

Both do NOT keep EC(BLR) viable

IceCube-170922A



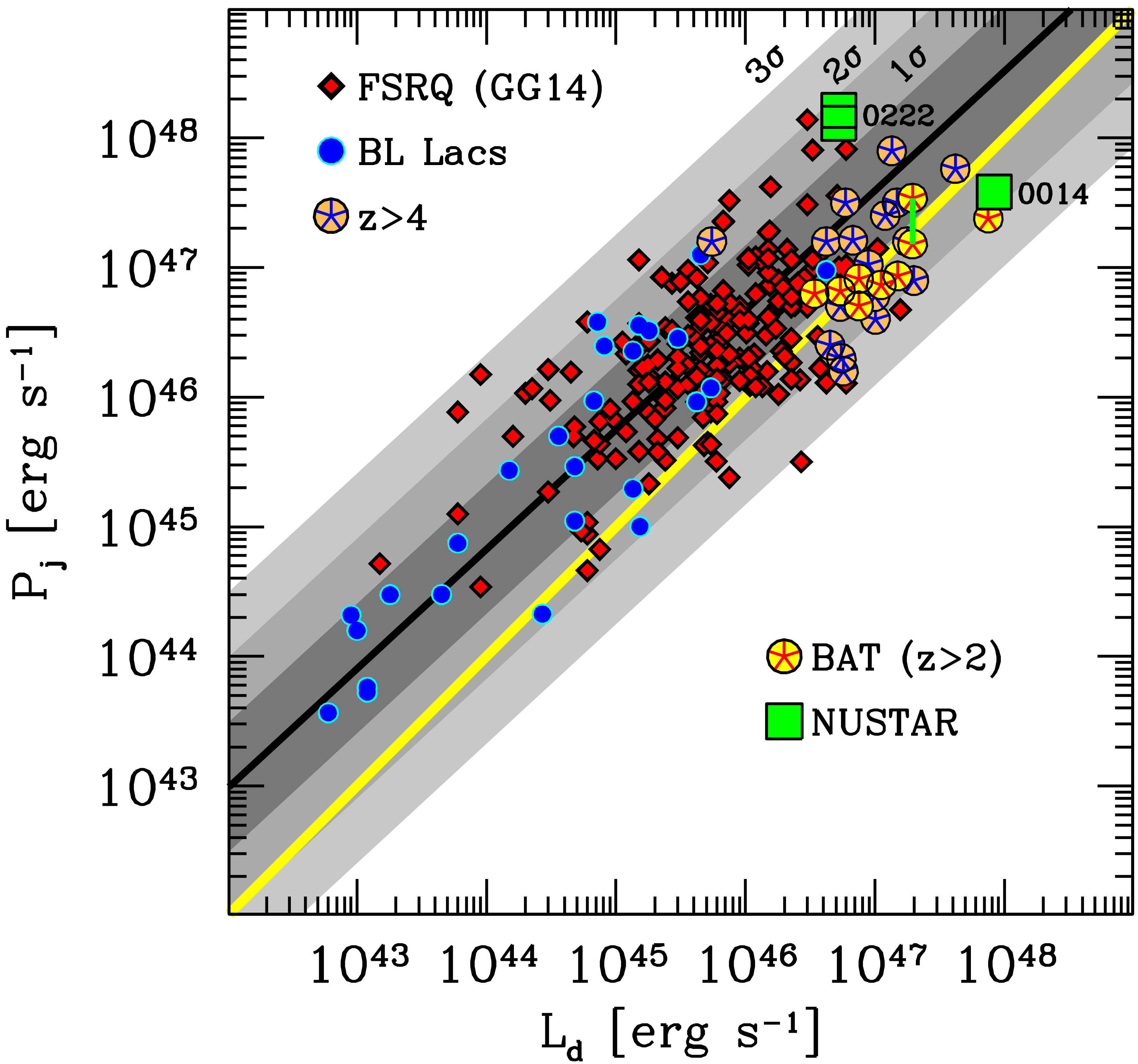
All Collaborations , Science 2018



TXS 0506+056
log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

Jet Power > Disk Luminosity

One-zone Leptonic model

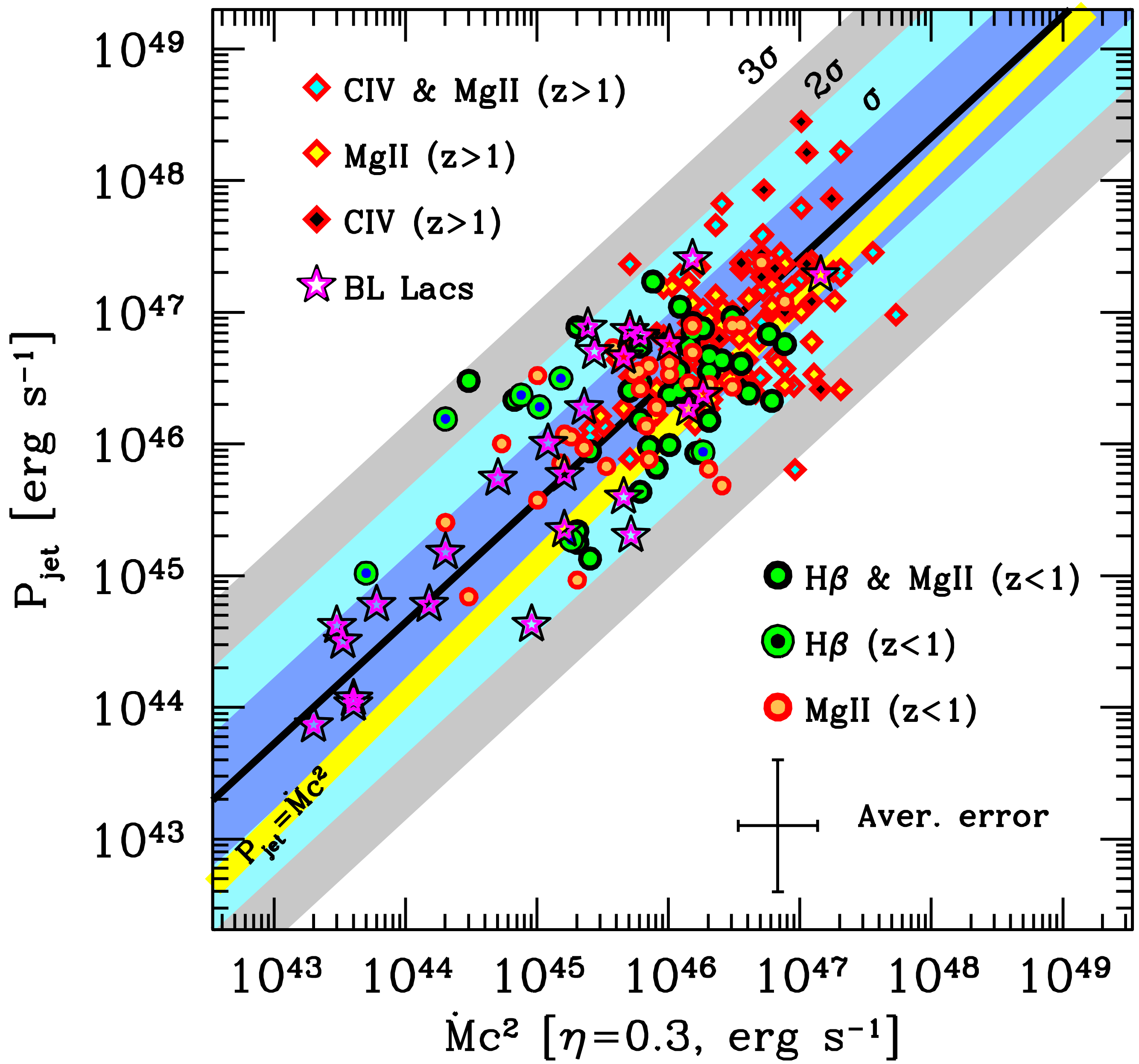


Sbarrato et al. 2014

BLR Luminosity from Opt-UV lines

$P_{jet} > P_{accretion}$

Blazars Jets are powered by BH rotational energy via B



$$\dot{M}\, c^2 = L_{disk}/\eta$$

Ghisellini et al. Nature 2015