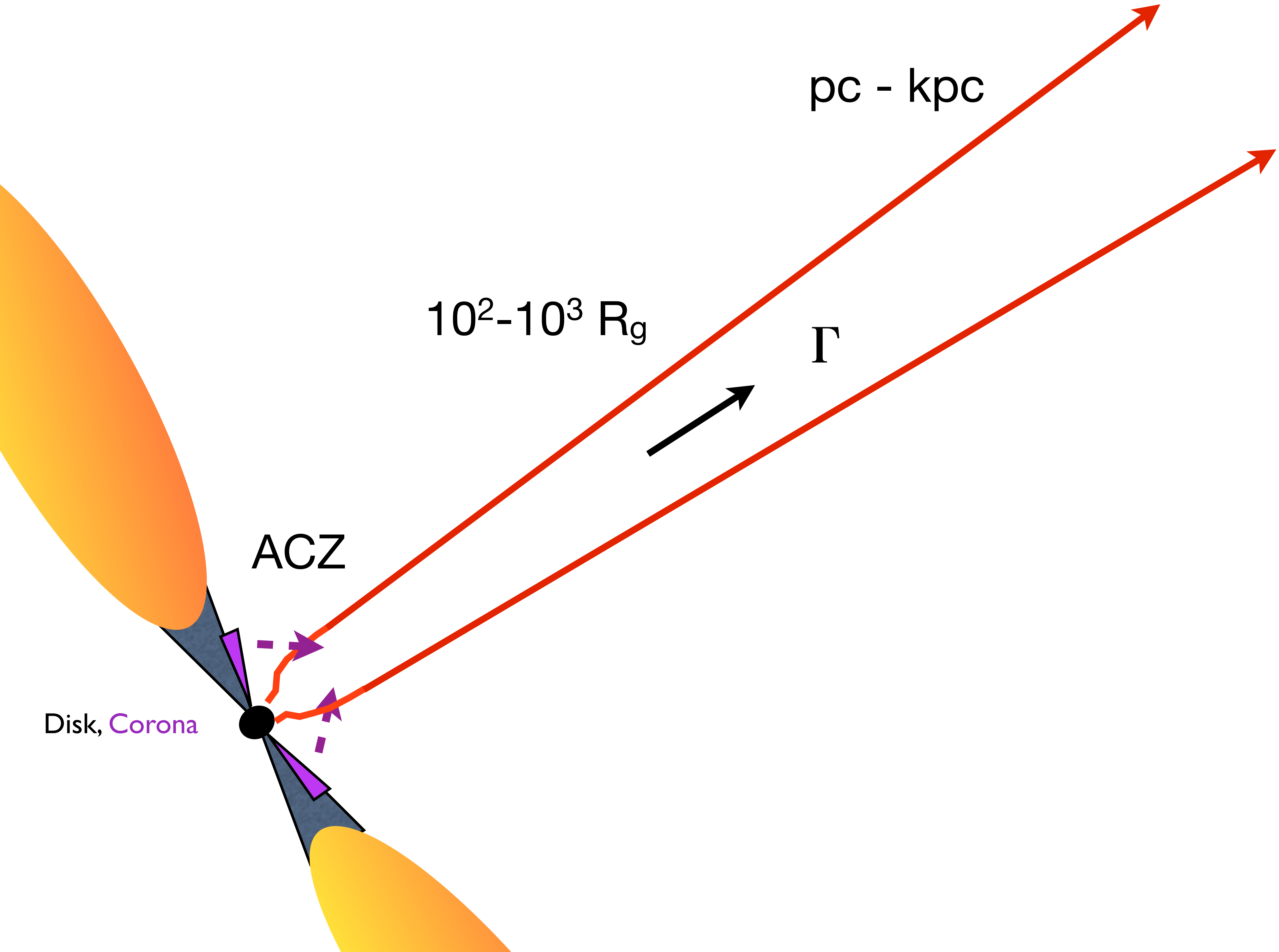
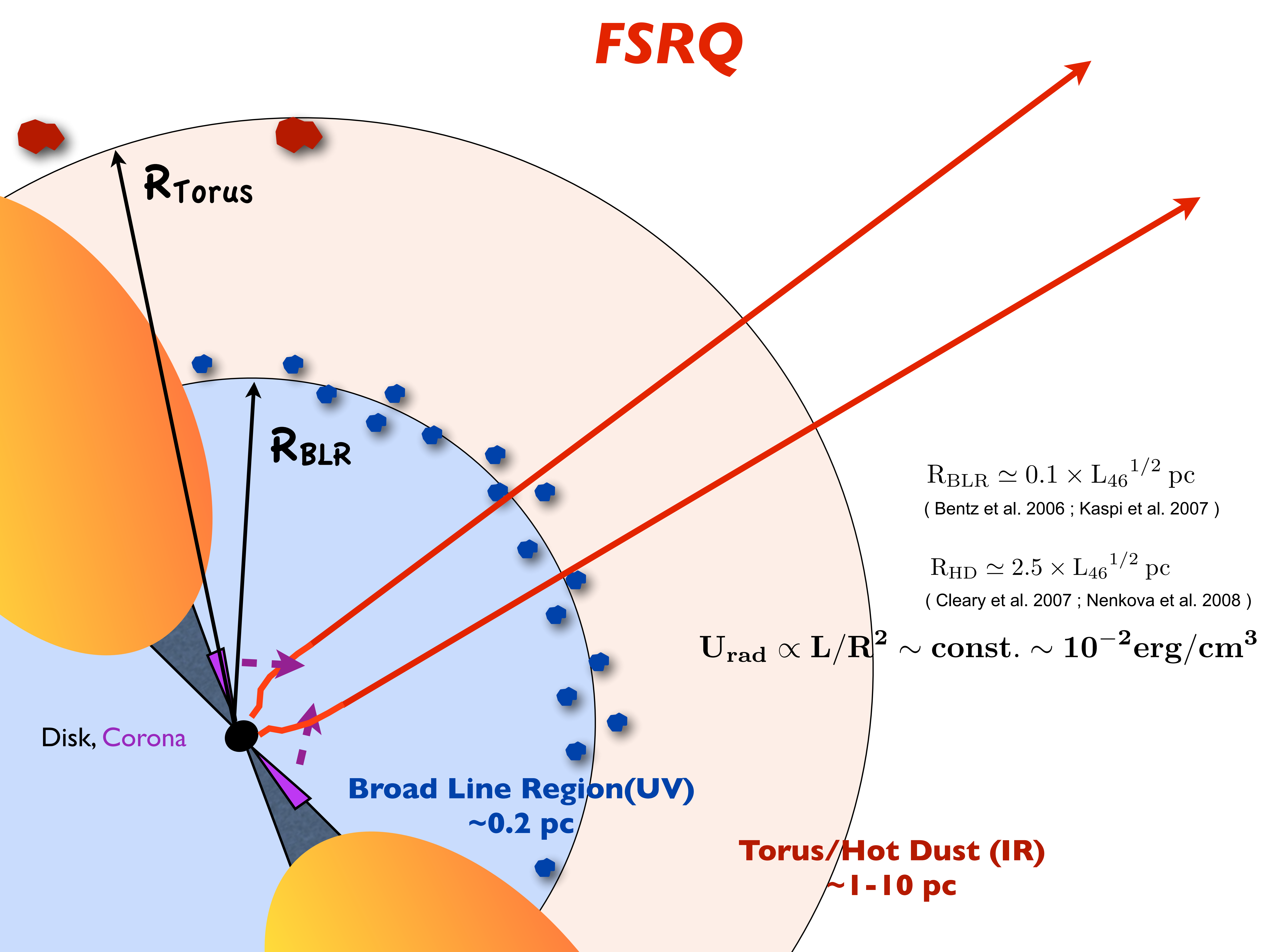
High Energy Phenomena in Relativistic Outflows VII
HEPRO VII, Barcelona, July 2019

Multi-wavelength Properties of AGN Jets: some recent highlights

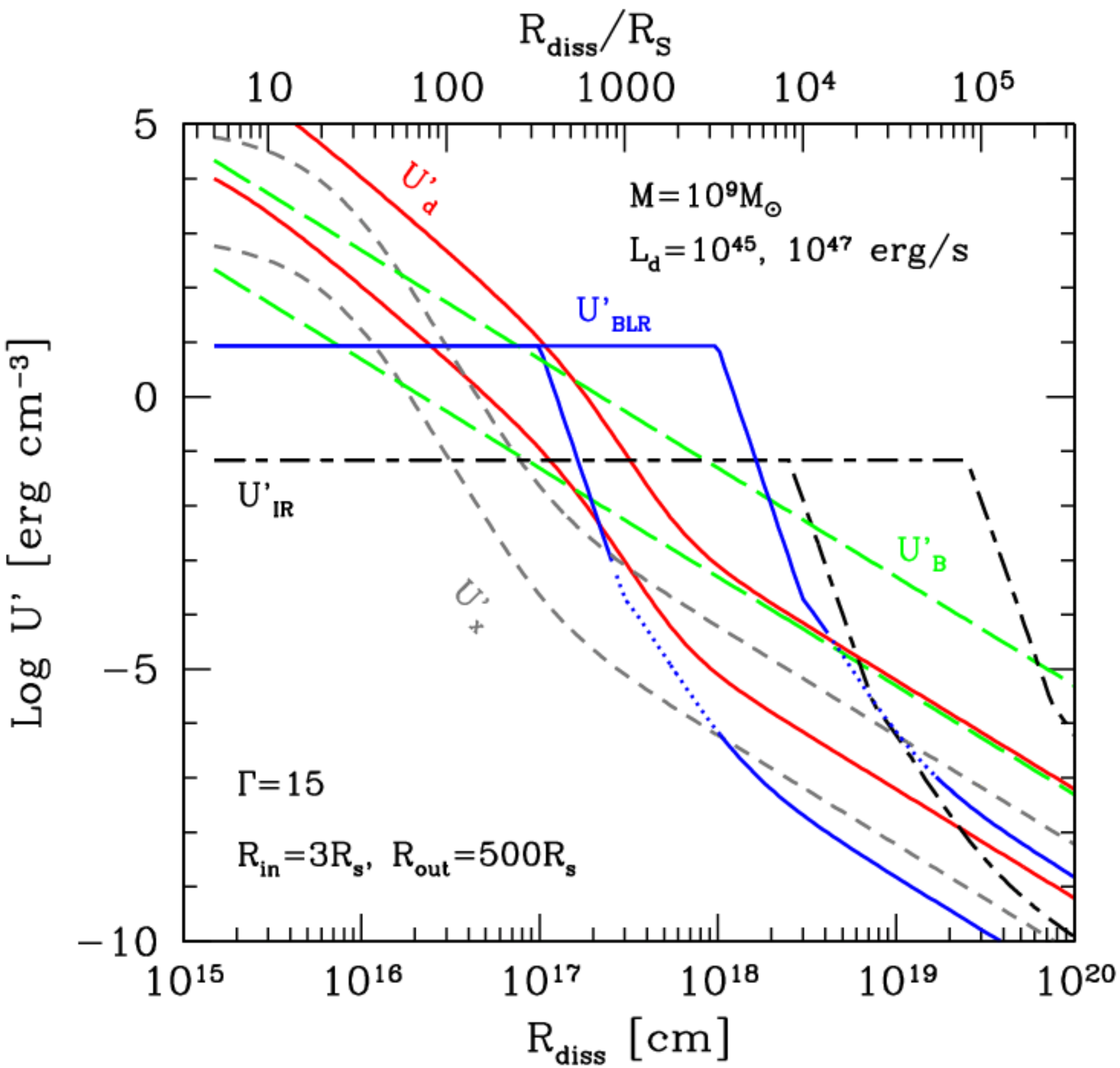
Luigi Costamante
ASI - Scientific Research Unit



pc - kpc
10^2-10^3 R_g
Γ
ACZ
Disk, Corona


FSRQ
R_Torus
R_BLR
Disk, Corona
Broad Line Region(UV)
~0.2 pc
Torus/Hot Dust (IR)
~1-10 pc
$R_{BLR} \simeq 0.1 \times L_{46}{}^{1/2}$ 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)
$\mathbf{U_{rad} \propto L/R^2 \sim const. \sim 10^{-2} erg/cm^3}$

Energy density U along the jet:



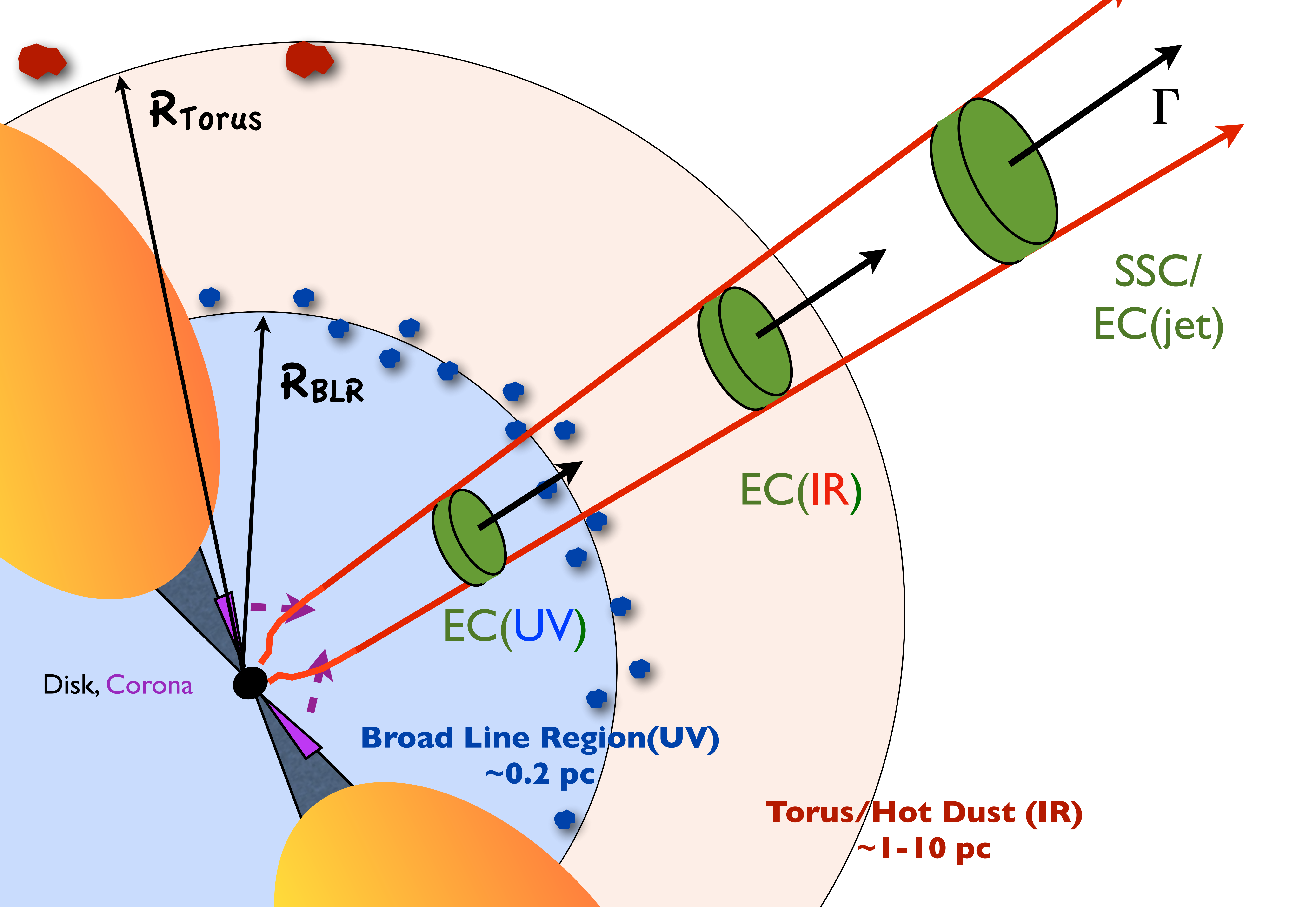
U' in jet frame

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

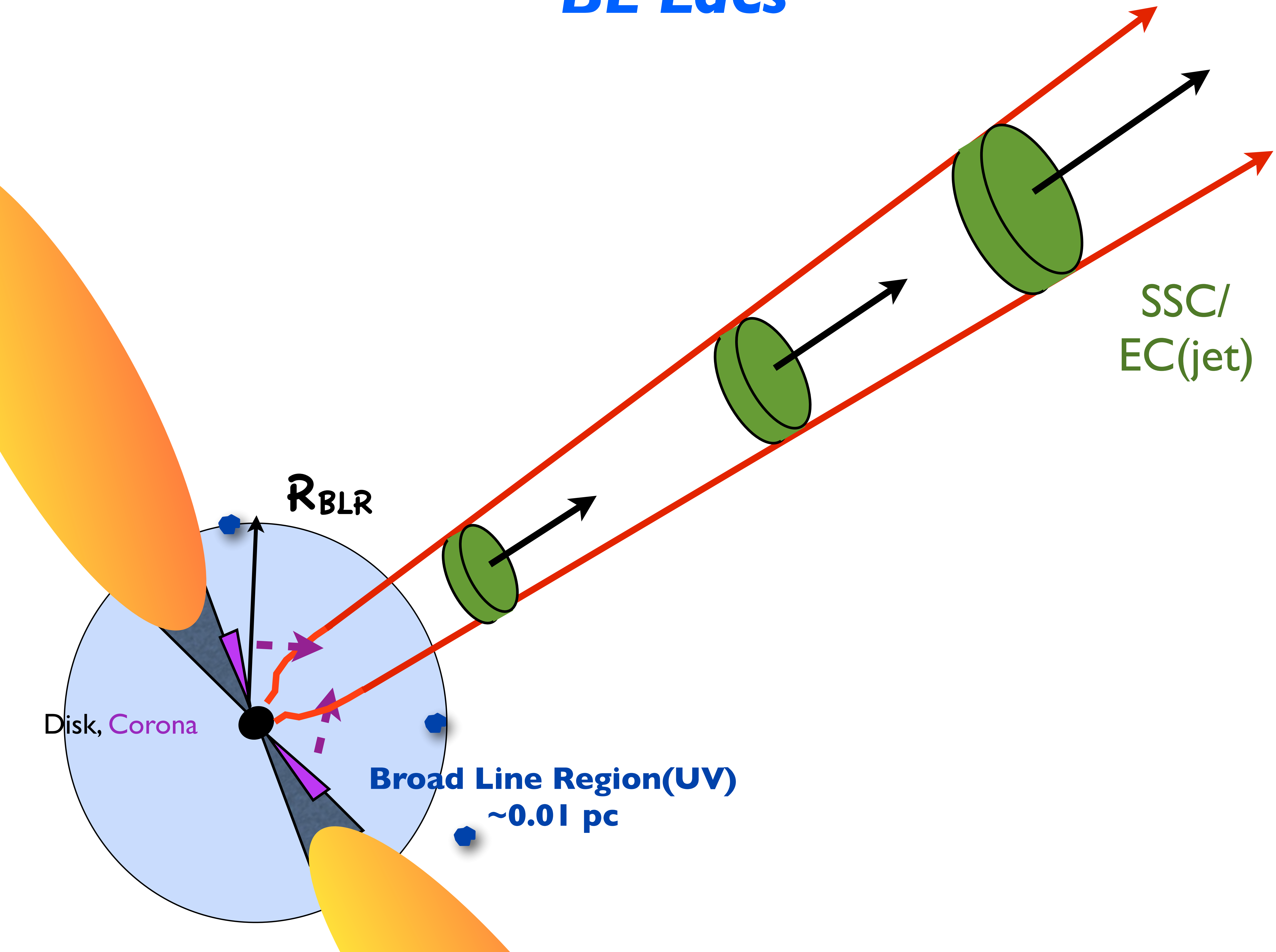
Ghisellini et al. 2009
Sikora et al. 2009

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

Location ↔ emission mechanism

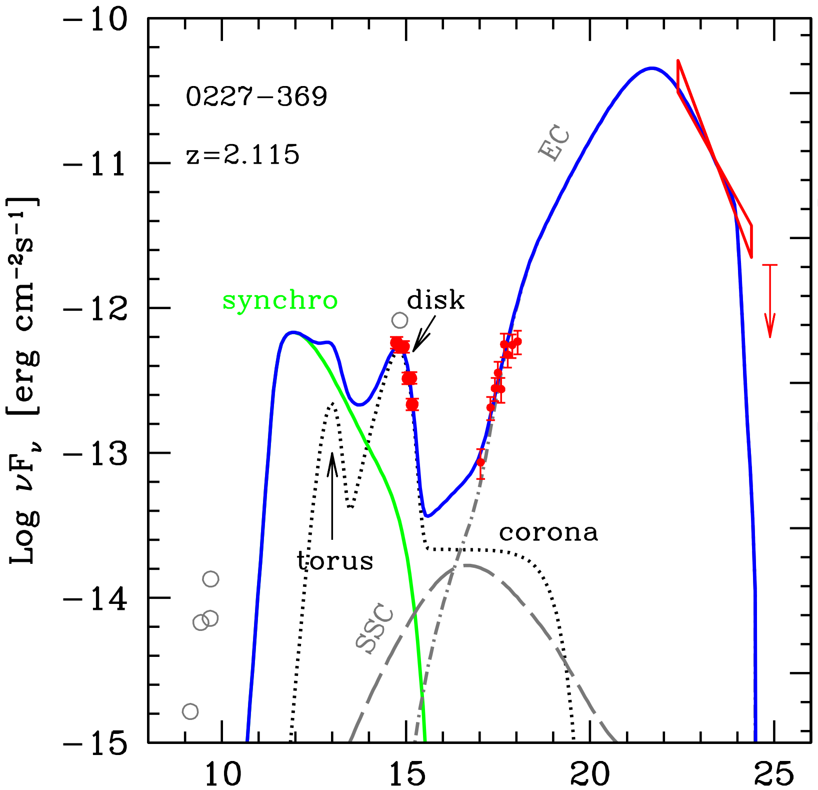


BL Lacs



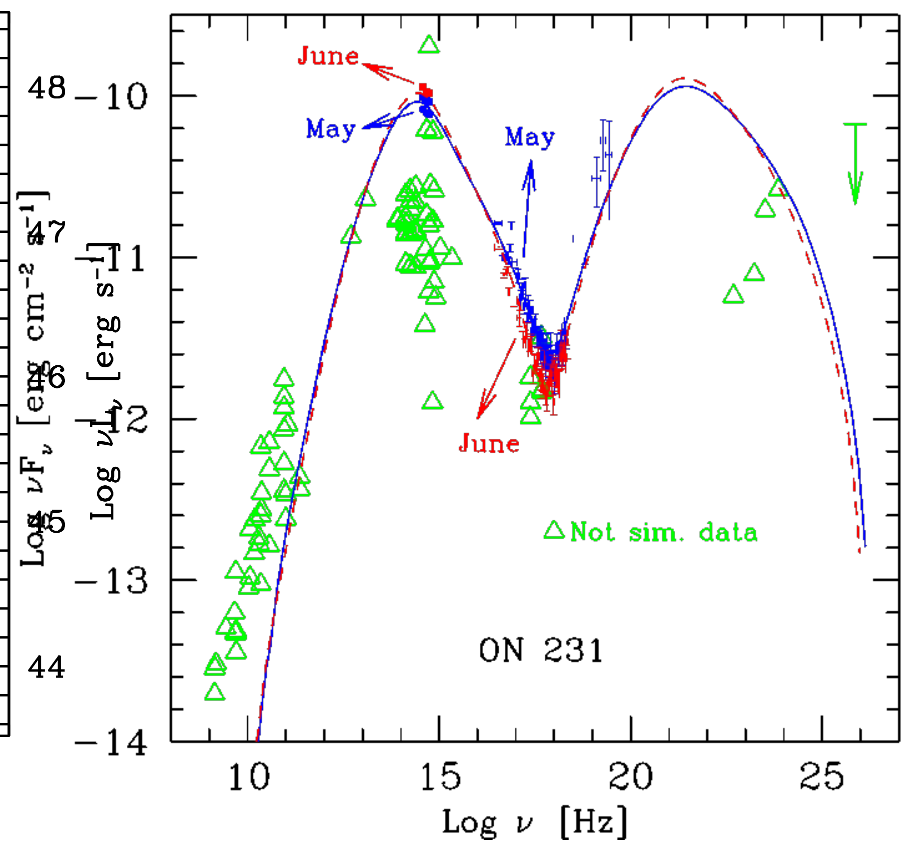
Blazars SED Sequence

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



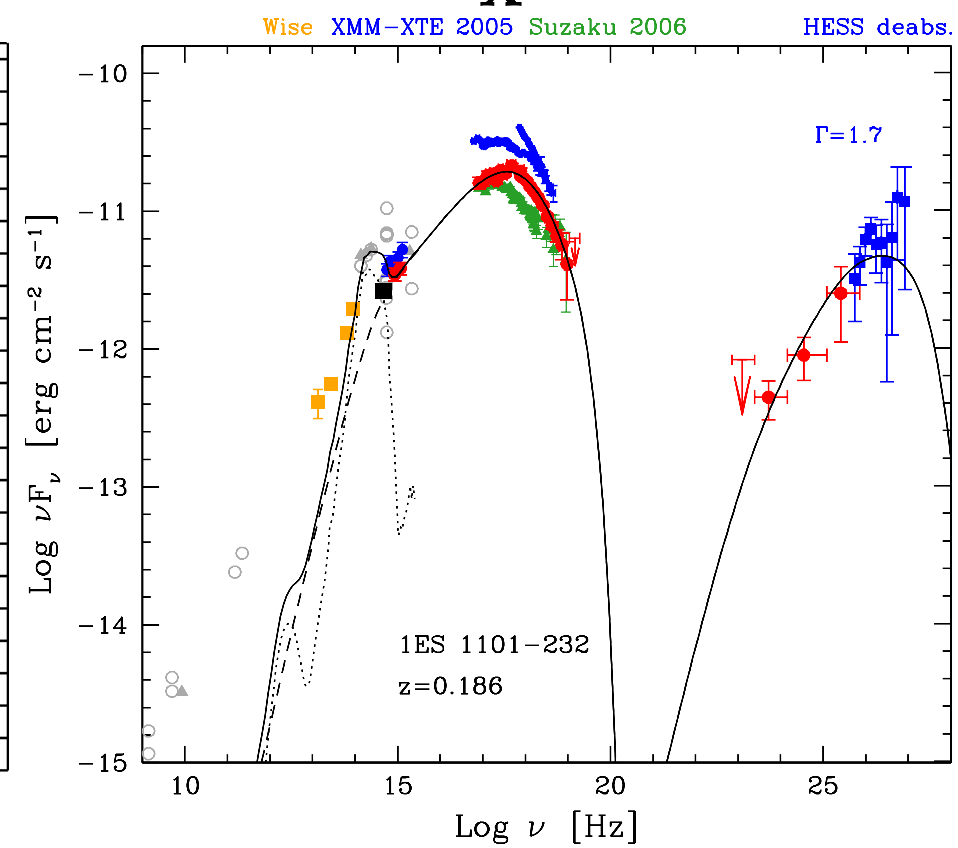
FSRQ / LBL

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



IBL

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

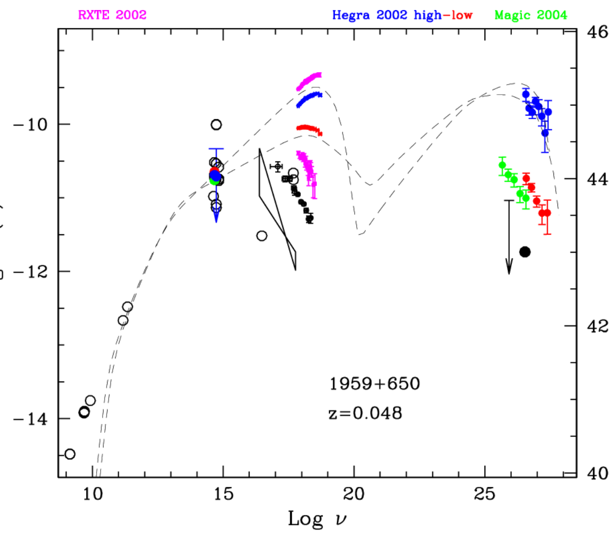


HBL

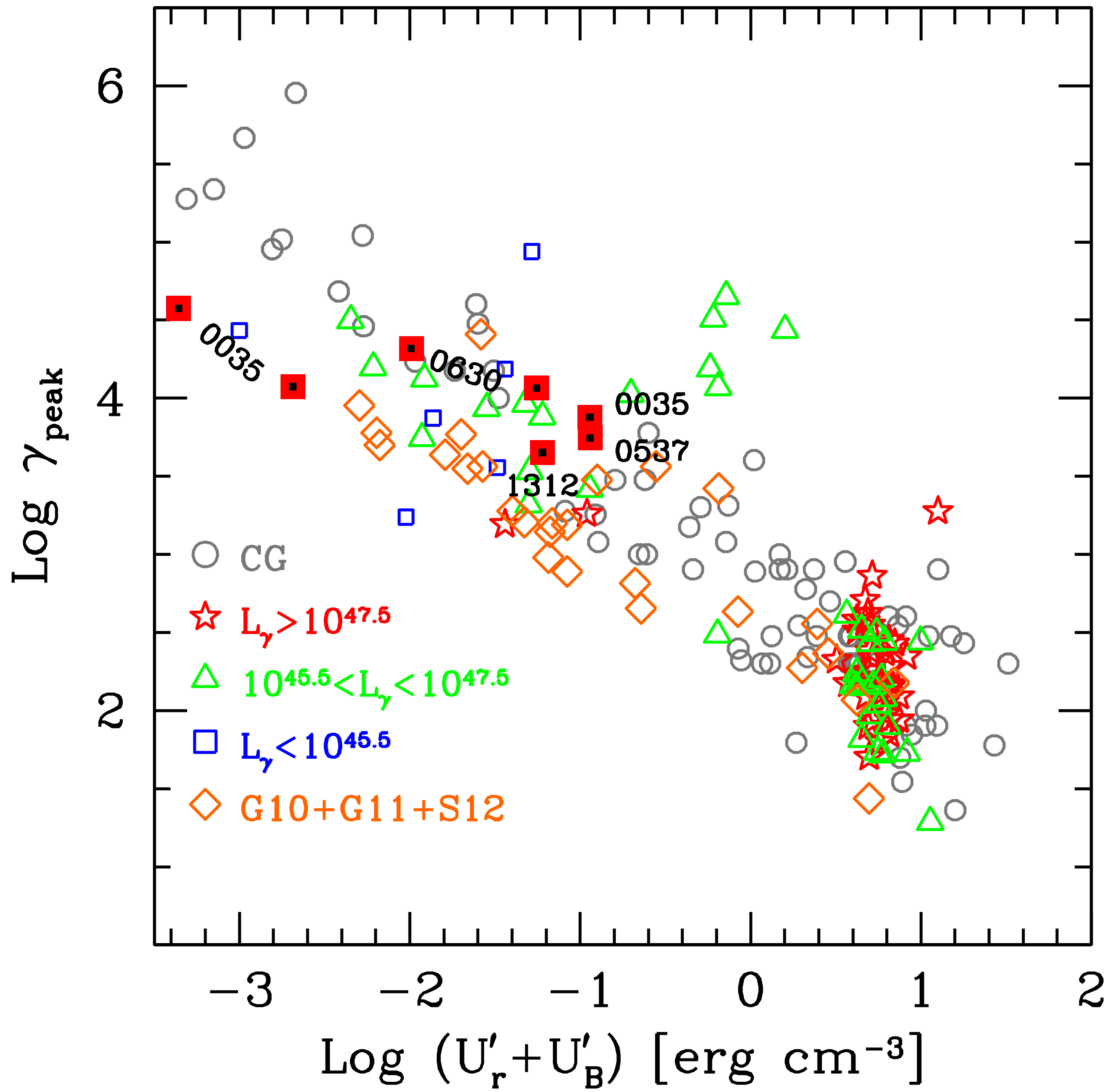
From Low to High-energy peaked Blazars

Giommi & Padovani 1994,1995

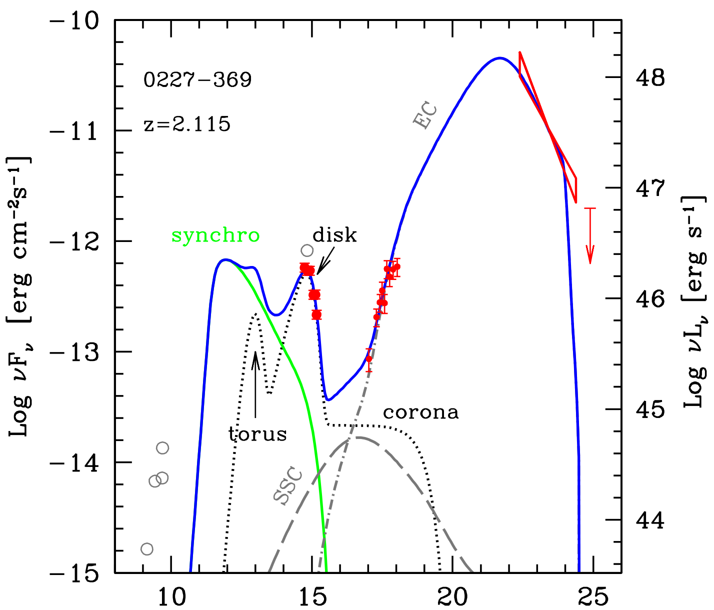
Standard picture: balance acceleration/cooling



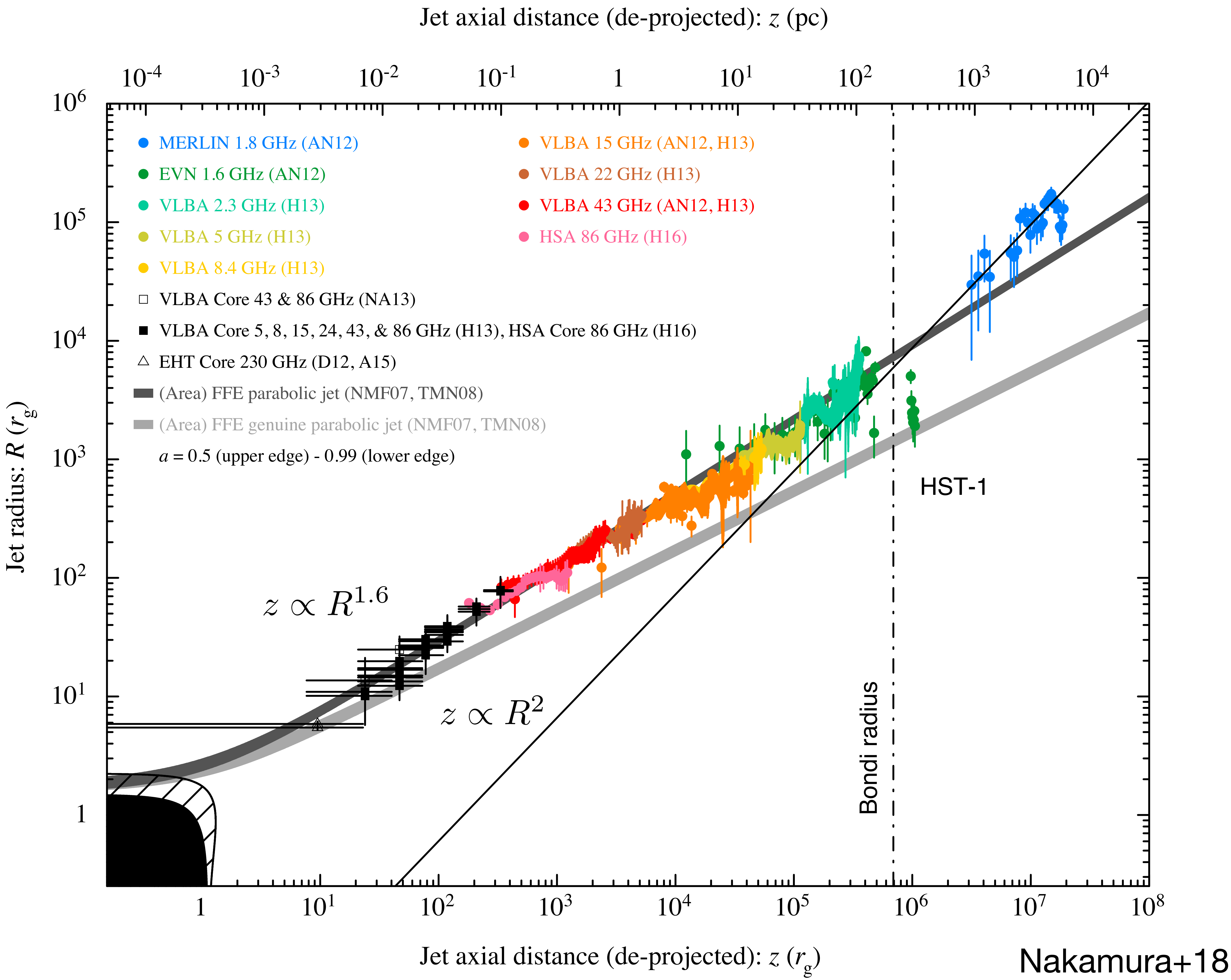
BLLacs: SSC



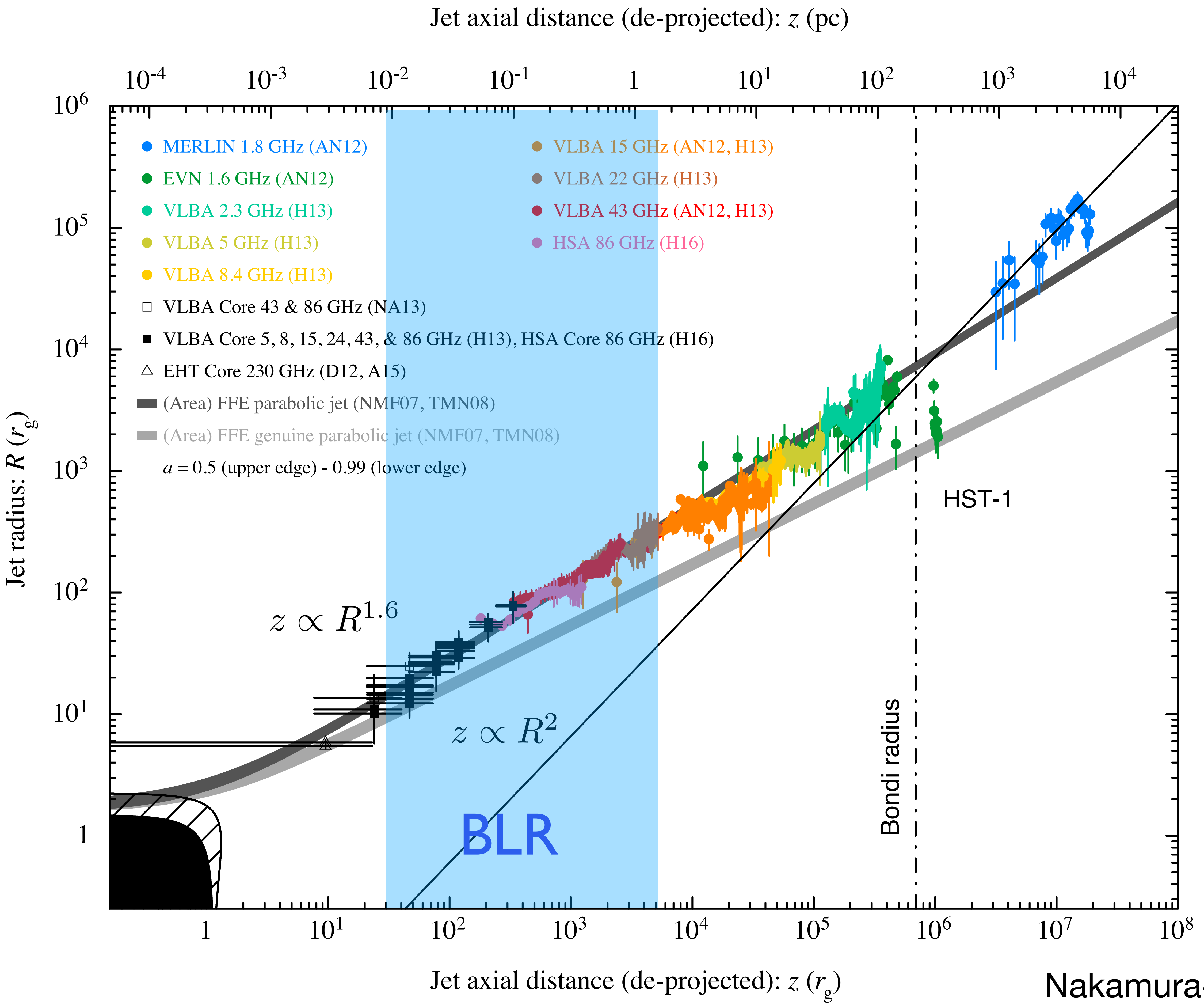
FSRQ
EC(BLR)



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



Jet axial distance (de-projected): z (pc)
10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4
MERLIN 1.8 GHz (AN12)
EVN 1.6 GHz (AN12)
VLBA 2.3 GHz (H13)
VLBA 5 GHz (H13)
VLBA 8.4 GHz (H13)
VLBA 15 GHz (AN12, H13)
VLBA 22 GHz (H13)
VLBA 43 GHz (AN12, H13)
HSA 86 GHz (H16)
VLBA Core 43 & 86 GHz (NA13)
VLBA Core 5, 8, 15, 24, 43, & 86 GHz (H13), HSA Core 86 GHz (H16)
EHT Core 230 GHz (D12, A15)
(Area) FFE parabolic jet (NMF07, TMN08)
(Area) FFE genuine parabolic jet (NMF07, TMN08)
a = 0.5 (upper edge) - 0.99 (lower edge)
Jet radius: R (r_g)
10^6 10^5 10^4 10^3 10^2 10^1 1
z ∝ R^1.6
z ∝ R^2
HST-1
Bondi radius
1 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
Jet axial distance (de-projected): z (r_g)
Nakamura+18



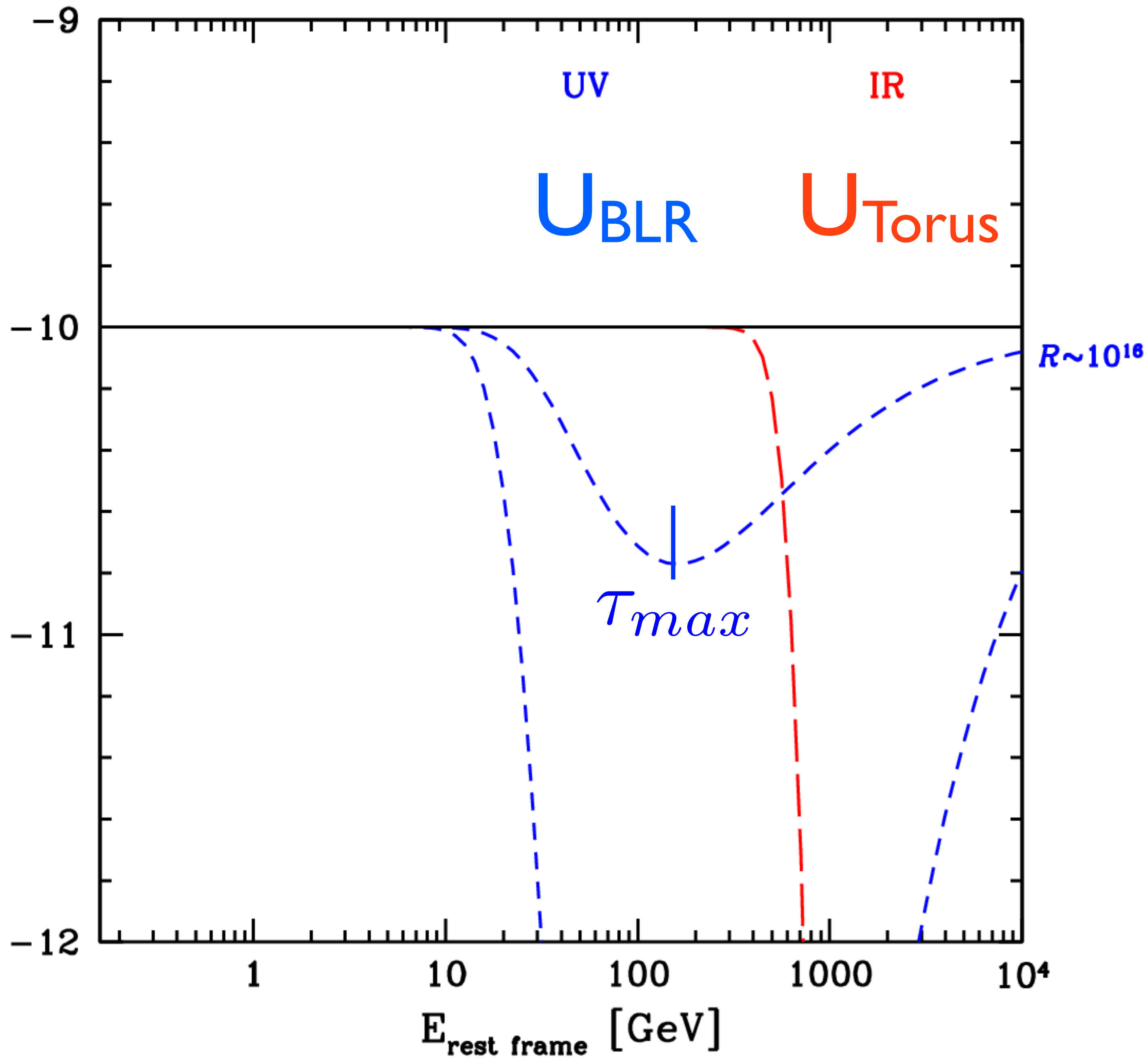
Jet axial distance (de-projected): z (pc)
10-4
10-3
10-2
10-1
1
101
102
103
104
106
105
104
103
102
101
1
Jet radius: R (rg)
MERLIN 1.8 GHz (AN12)
EVN 1.6 GHz (AN12)
VLBA 2.3 GHz (H13)
VLBA 5 GHz (H13)
VLBA 8.4 GHz (H13)
VLBA Core 43 & 86 GHz (NA13)
VLBA Core 5, 8, 15, 24, 43, & 86 GHz (H13), HSA Core 86 GHz (H16)
EHT Core 230 GHz (D12, A15)
(Area) FFE parabolic jet (NMF07, TMN08)
(Area) FFE genuine parabolic jet (NMF07, TMN08)
a = 0.5 (upper edge) - 0.99 (lower edge)
VLBA 15 GHz (AN12, H13)
VLBA 22 GHz (H13)
VLBA 43 GHz (AN12, H13)
HSA 86 GHz (H16)
HST-1
Bondi radius
z ∝ R^1.6
z ∝ R^2
BLR
1
101
102
103
104
105
106
107
108
Jet axial distance (de-projected): z (rg)

Nakamura+18

is it so ?

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

Test the EC(BLR) scenario in FSRQs

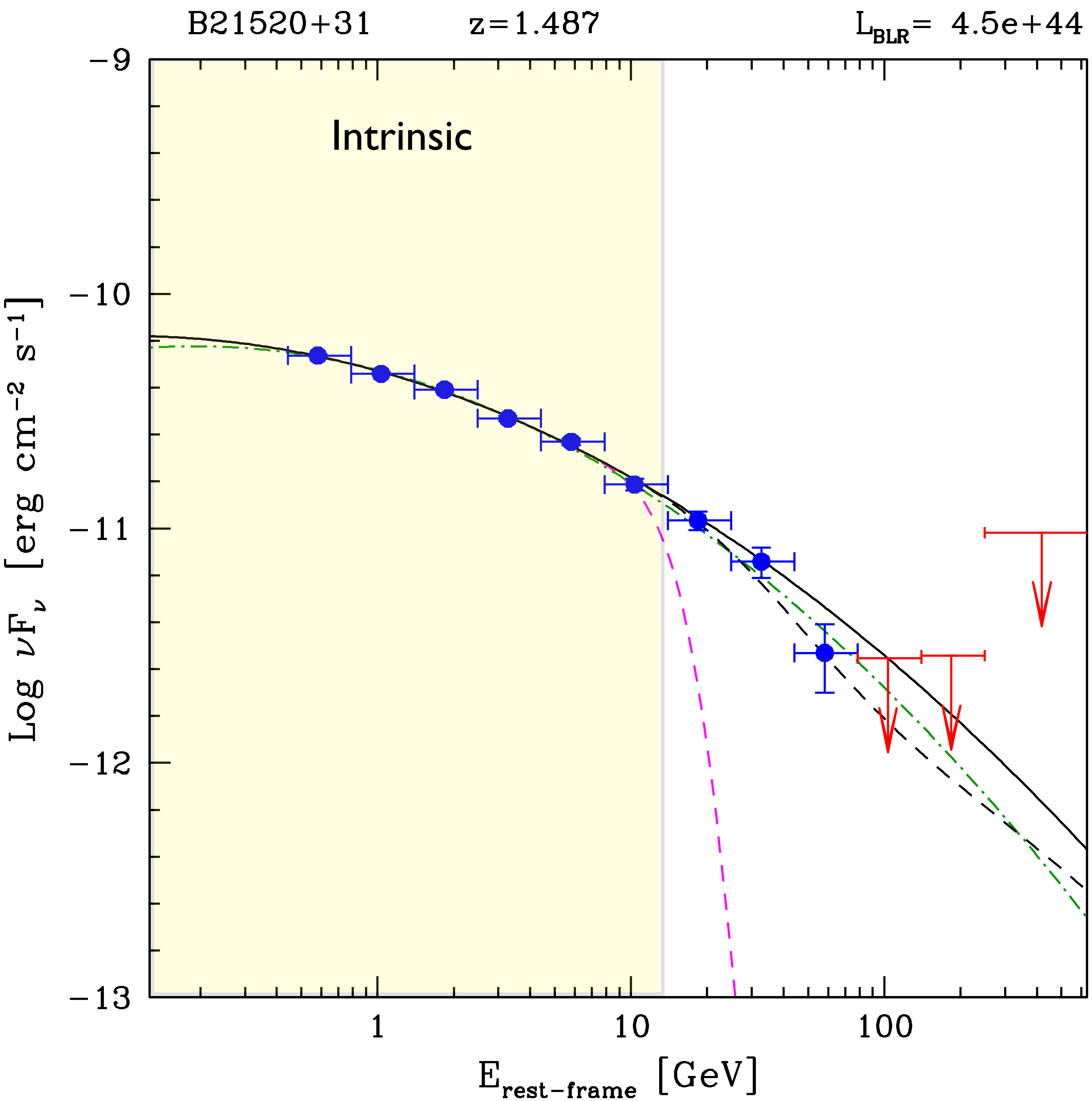
100 highest-significance Gamma-ray FSRQs in the 3LAC
+ 6 large-BLR cases

Fermi-LAT Data, PASS8, 7.3-years exposure

106 in total, 83 with L_{BLR} estimates

Costamante et al. 2018, MNRAS 477, 4749 (arXiv: 1804.06282)

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)

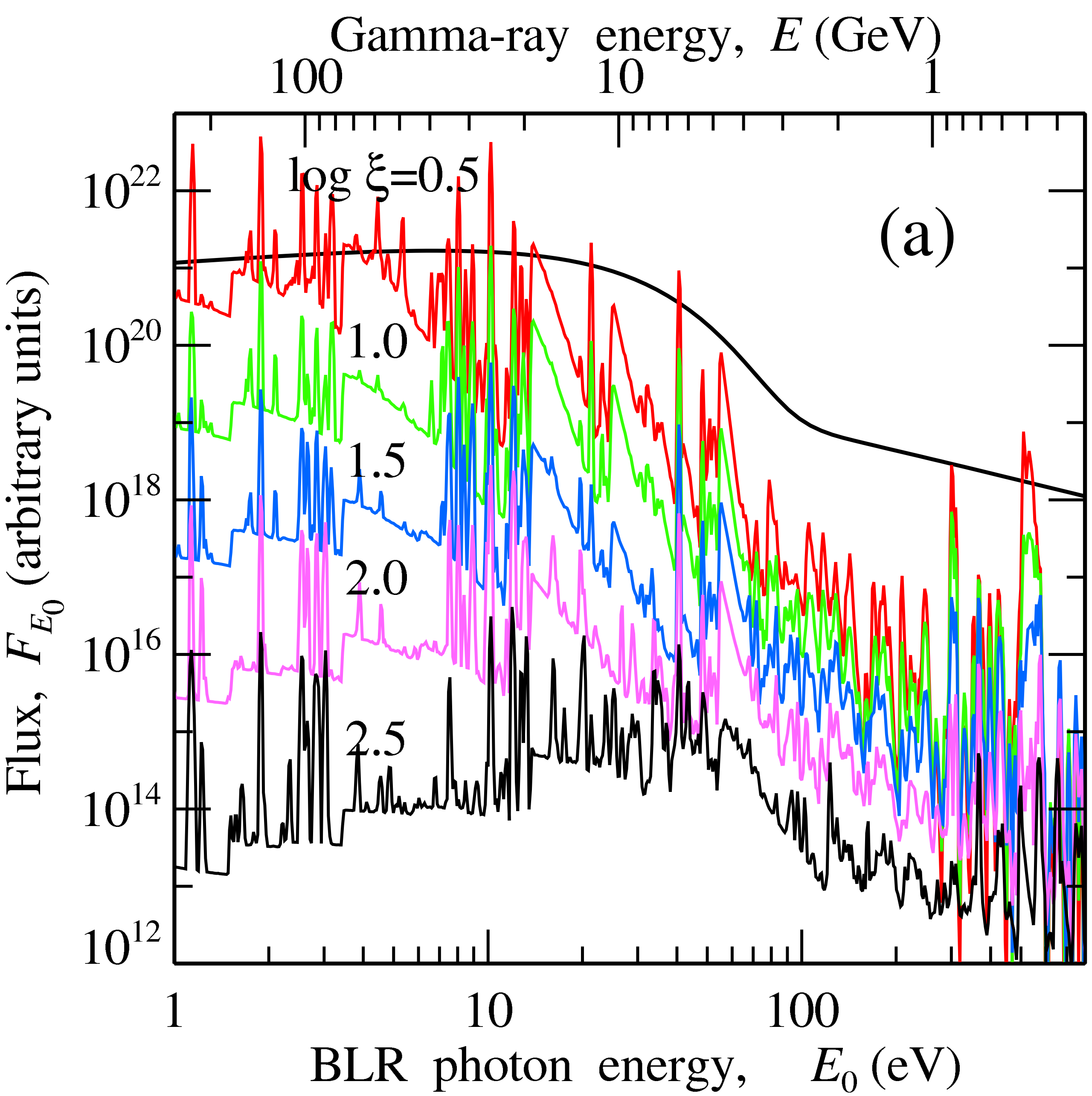
Upper limit if:
TS <4 or
Npred <3 or
Err >50%

NB: Rest-Frame Energies ! E*(1+z)

BLR spectrum

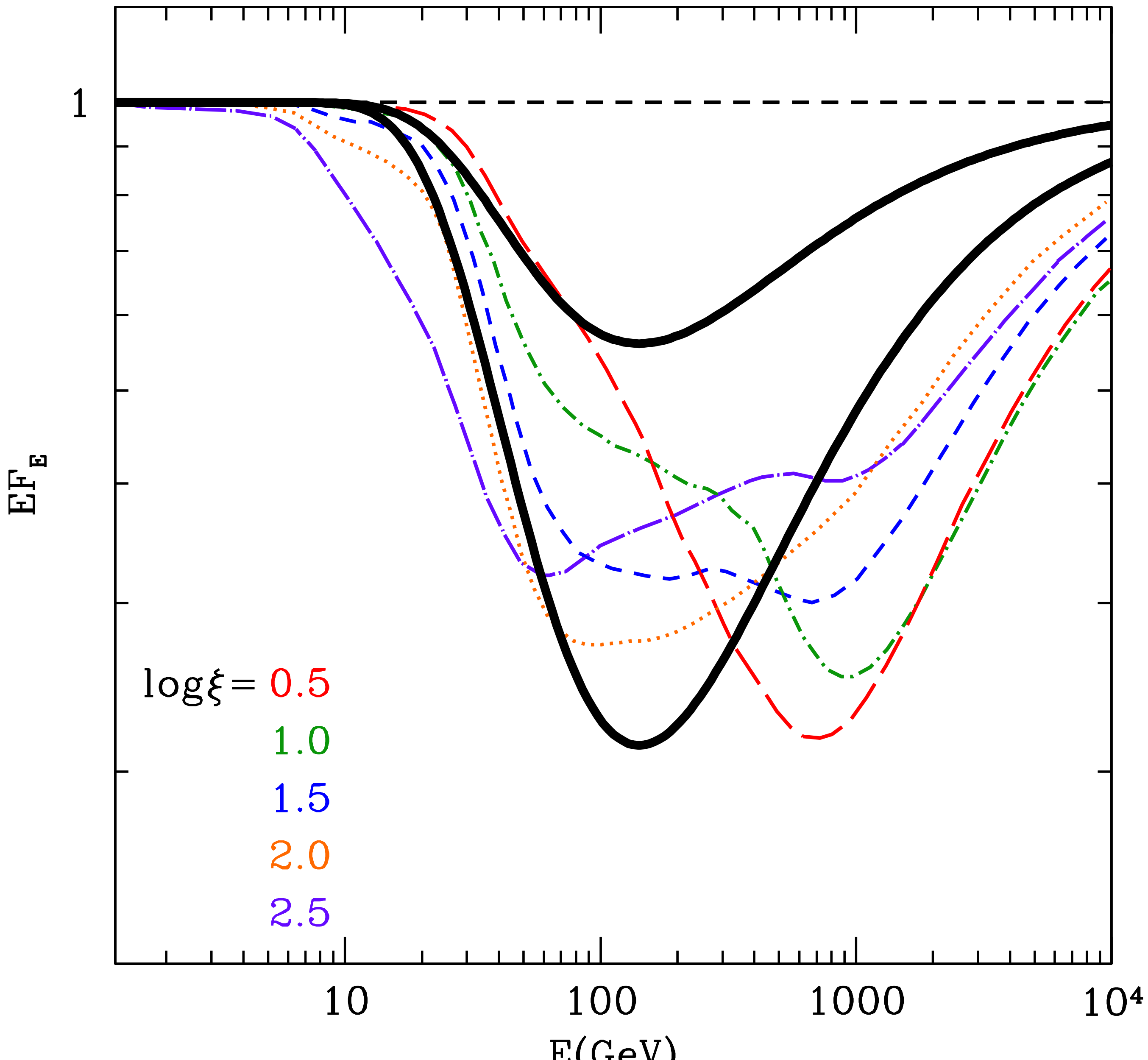
BBody (same as for EC) is a good approximation for attenuation shoulder

BLR at different ionization parameter

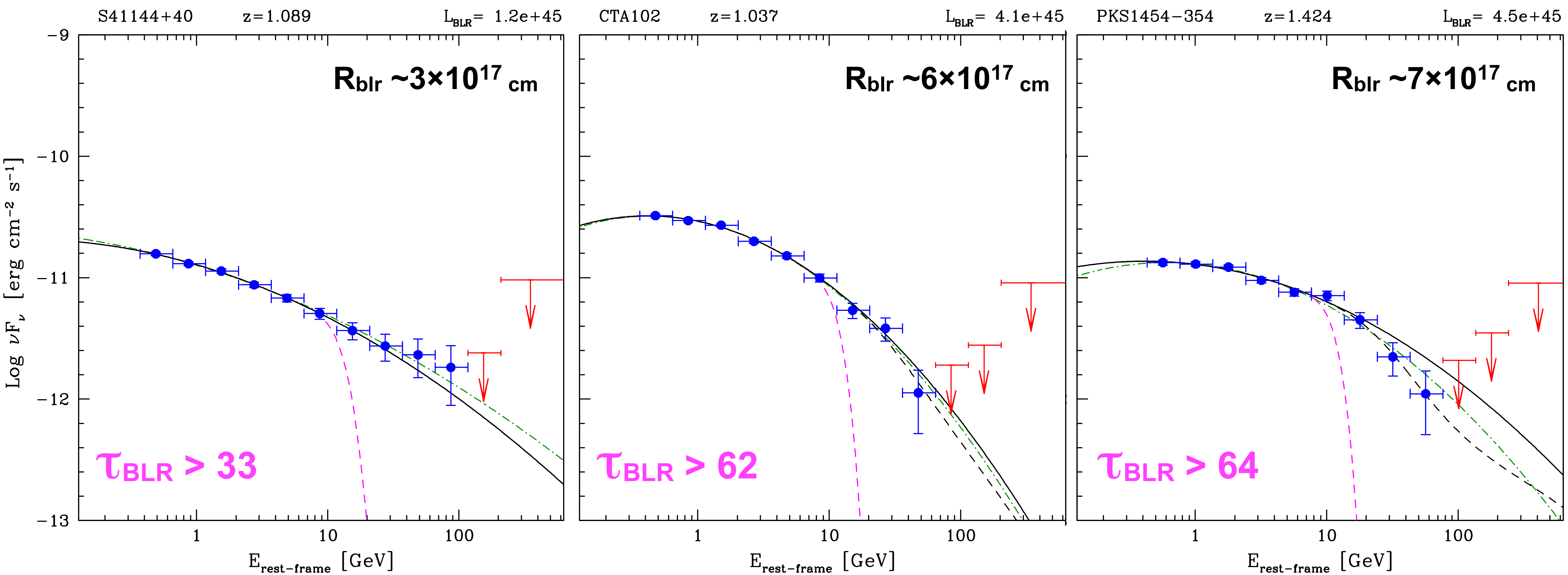


Stern & Poutanen 2014

BLR absorption feature



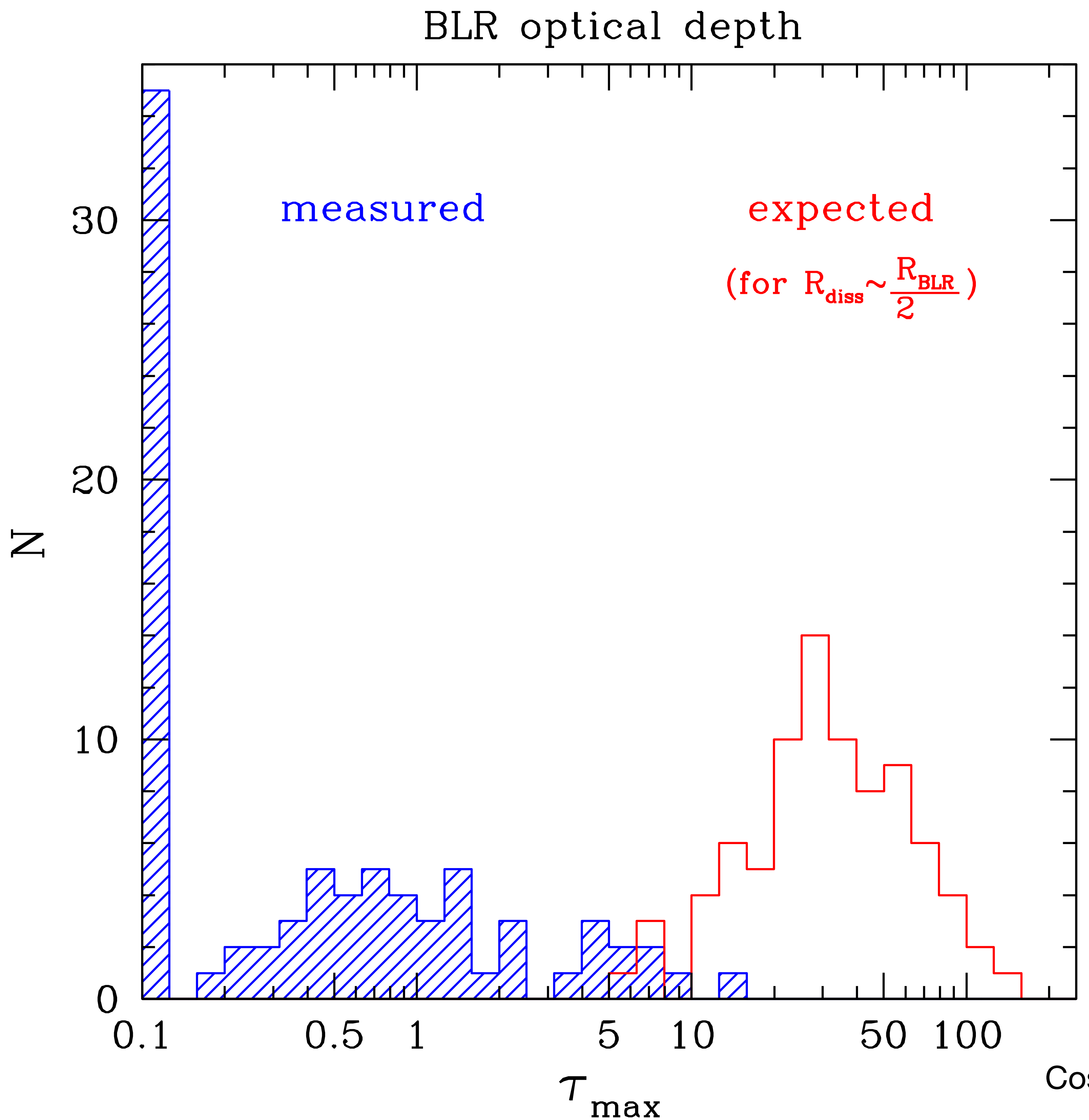
NO evidence of BLR cut-offs !



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

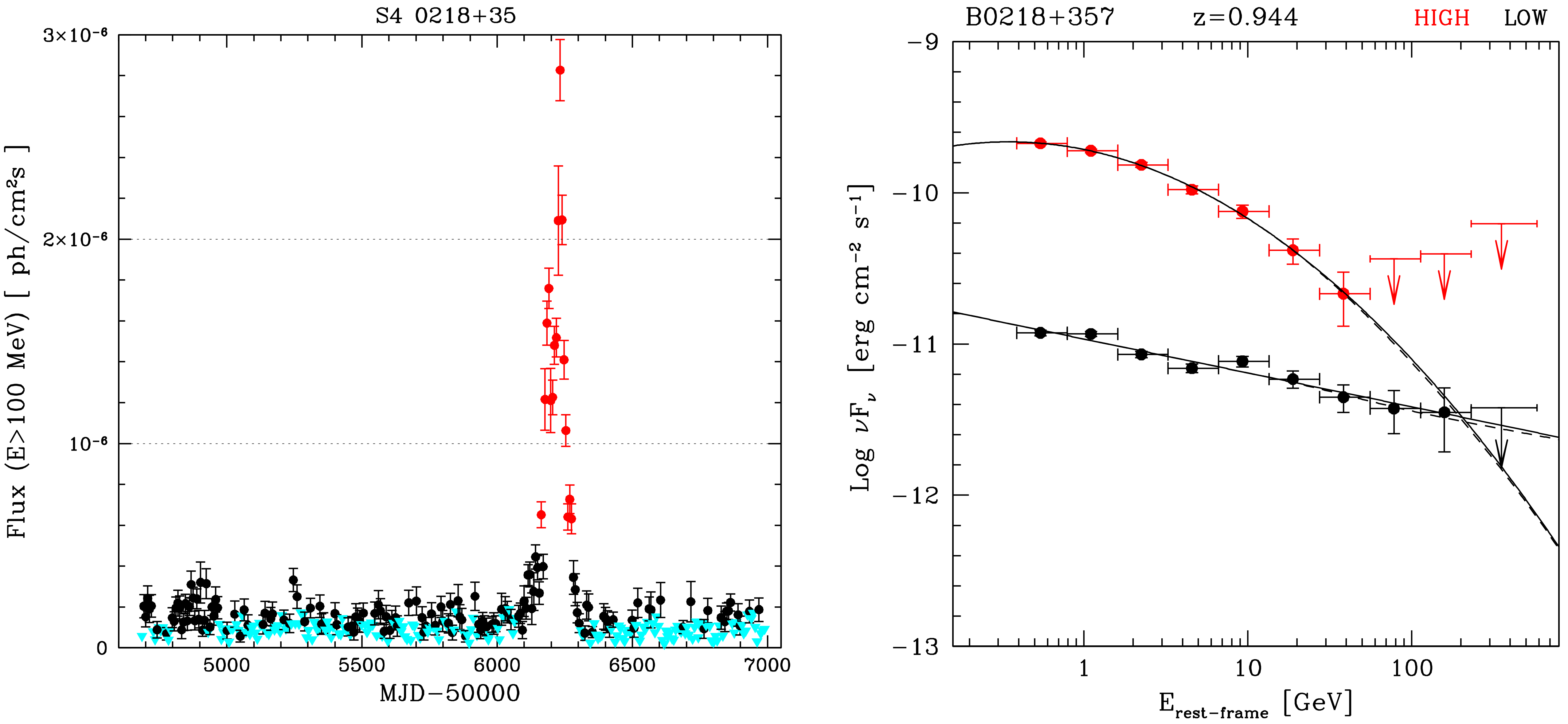


for EC(BLR)

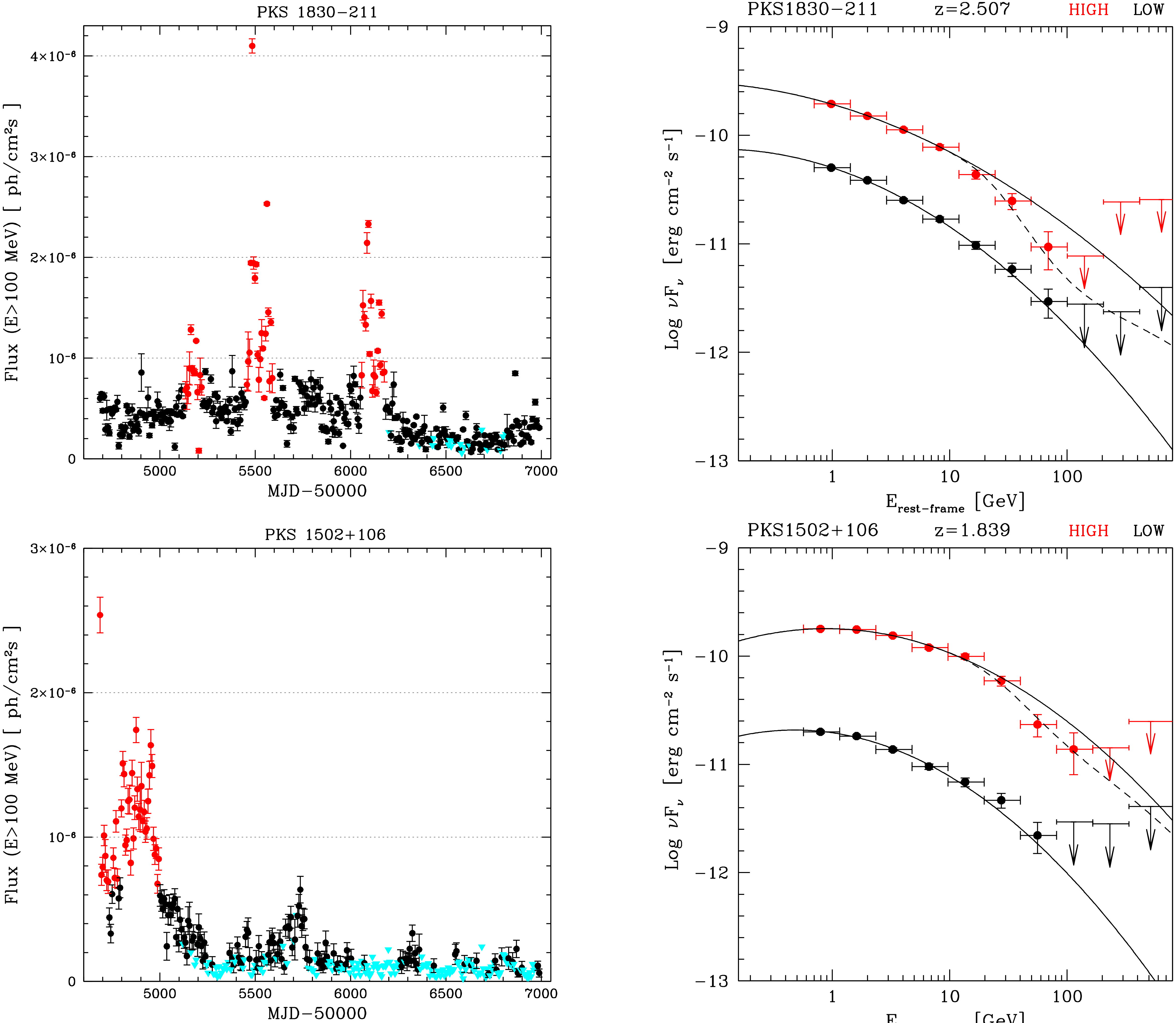
Costamante et al. 2018

Sample 83 objects with L_{BLR} estimate

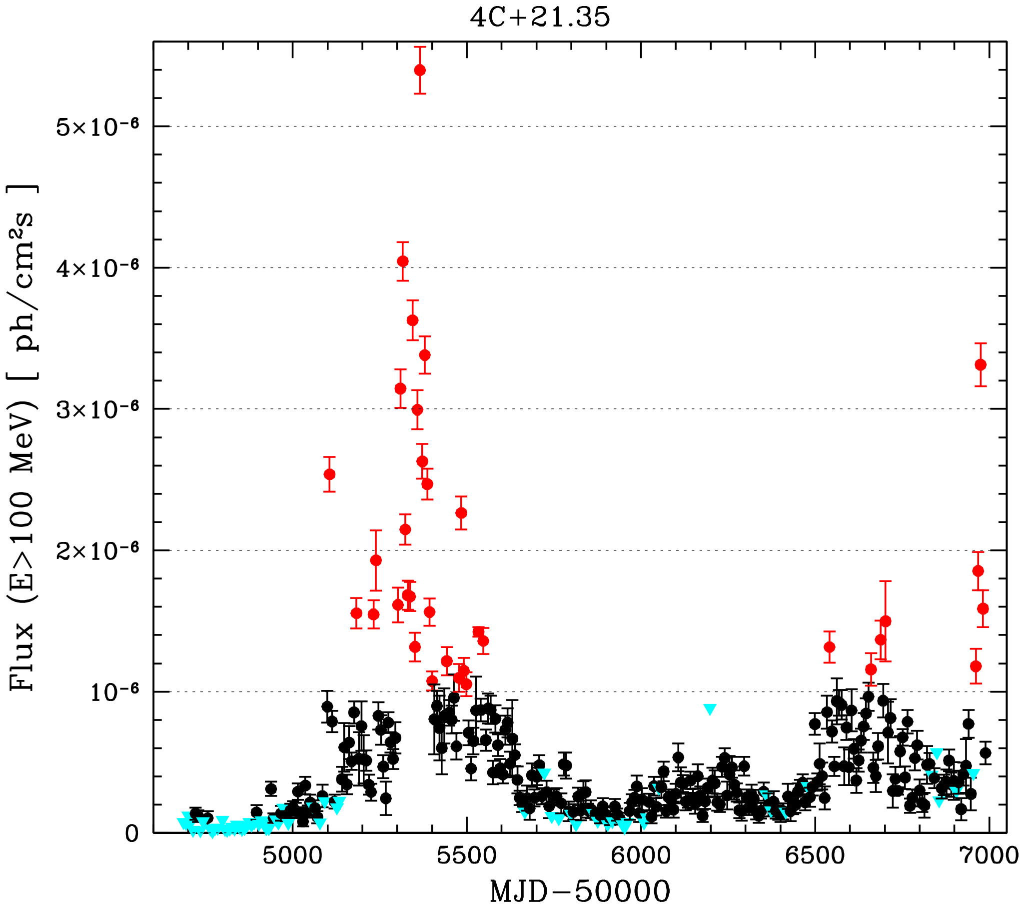
For the brightest 20:   difference High/Low state ?

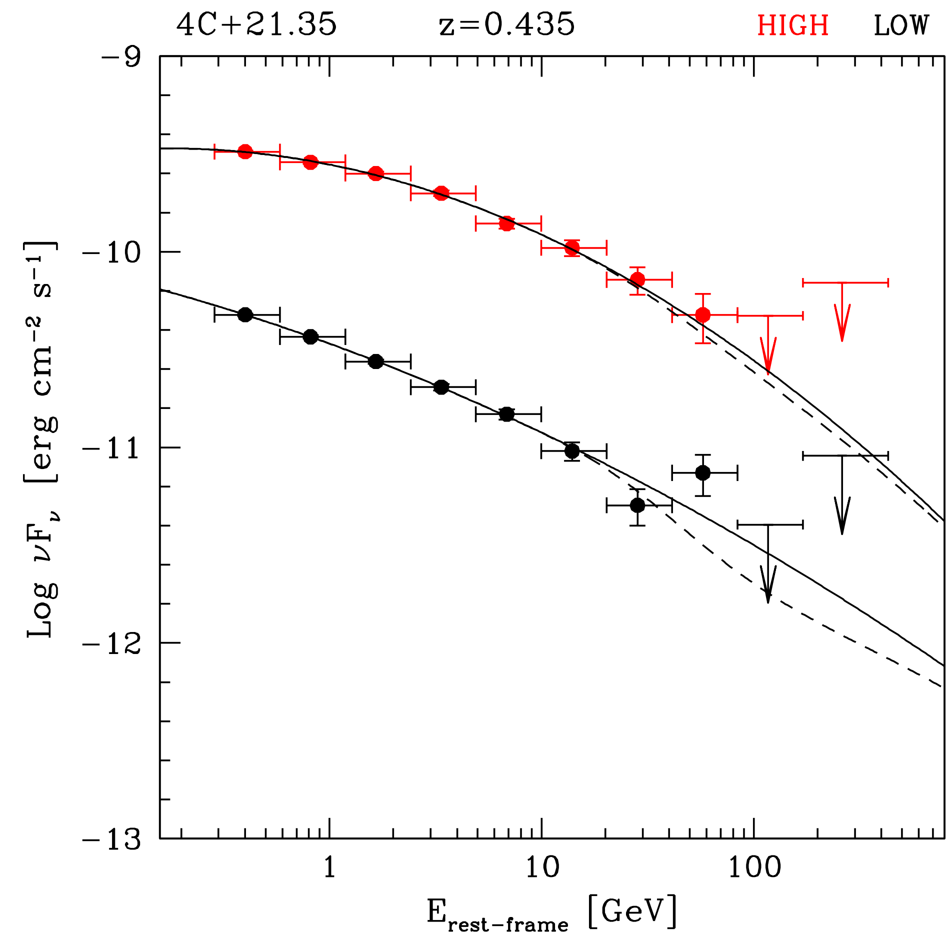


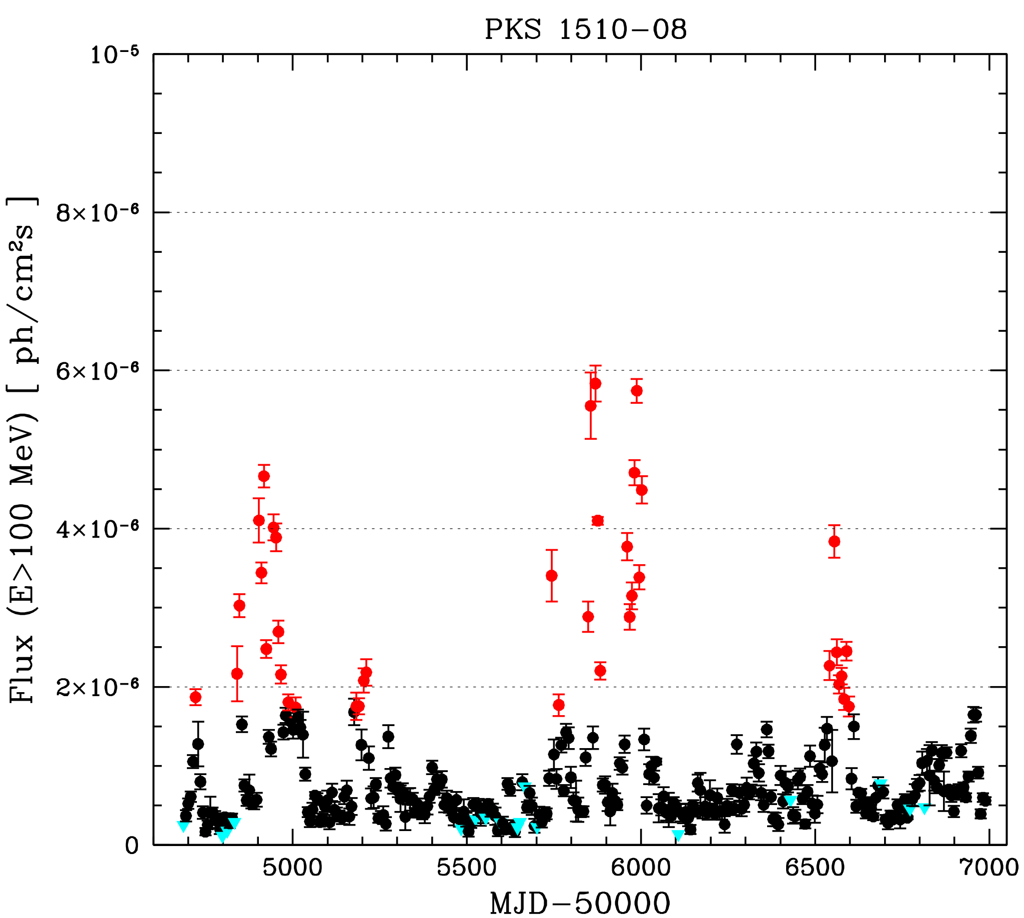
No evidence of strong interaction with BLR photons

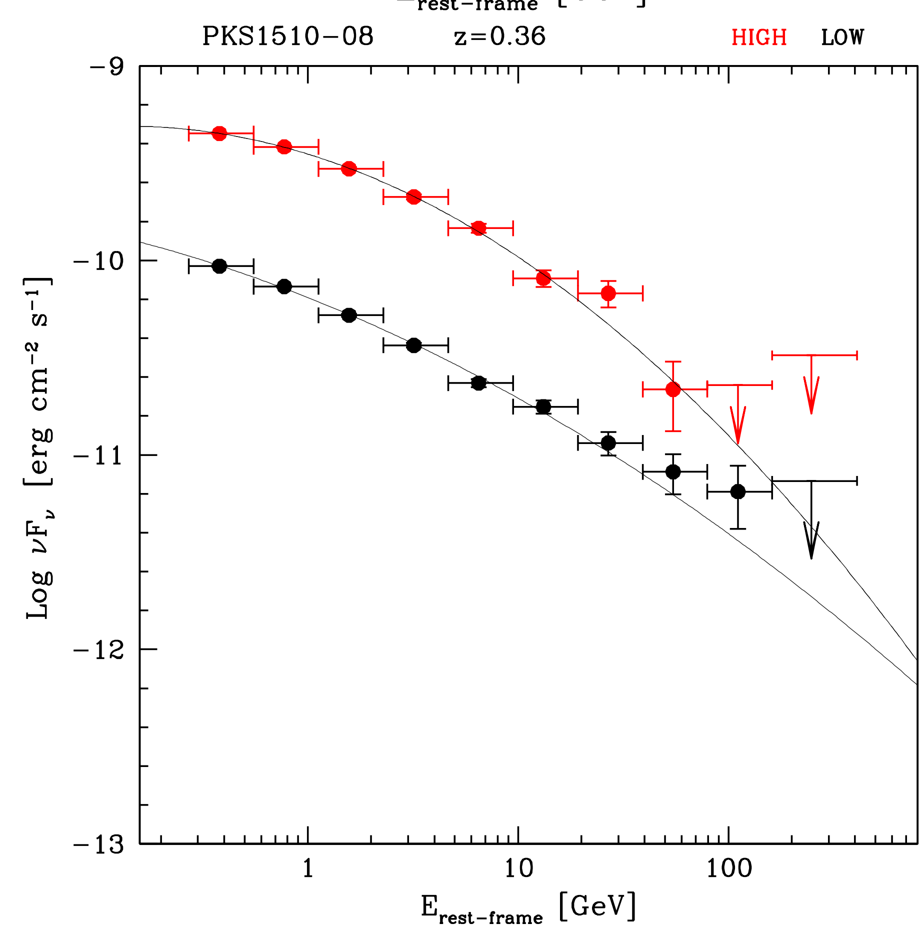

PKS 1830−211
Flux (E>100 MeV) [ph/cm²s]
MJD−50000
PKS1830−211 z=2.507 HIGH LOW
Log νF_ν [erg cm⁻² s⁻¹]
E_rest-frame [GeV]
PKS 1502+106
Flux (E>100 MeV) [ph/cm²s]
MJD−50000
PKS1502+106 z=1.839 HIGH LOW
Log νF_ν [erg cm⁻² s⁻¹]

VHE-detected FSRQs: also in Low state

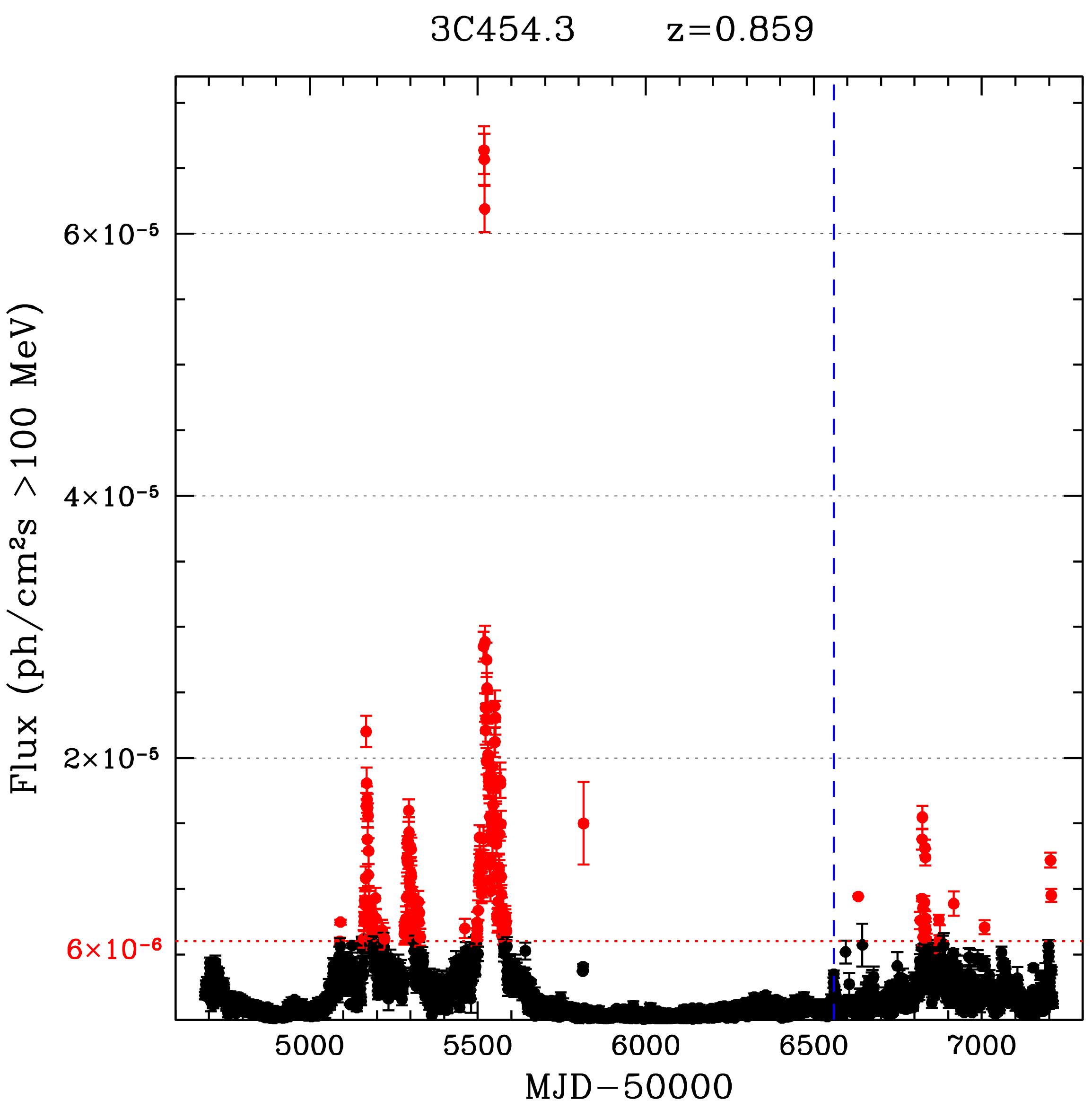




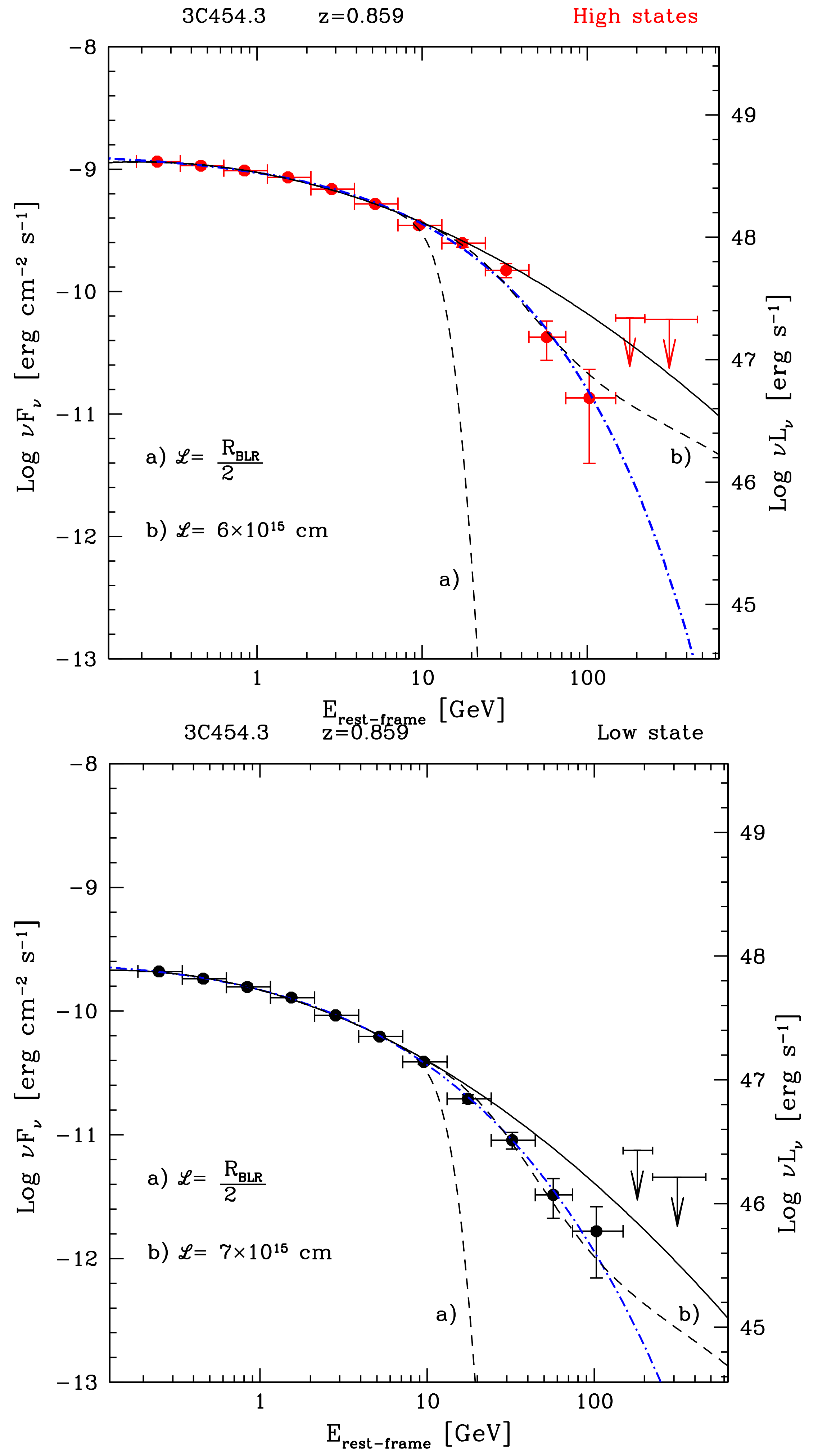




Even 3C 454.3 !



3C454.3 z=0.859
Flux (ph/cm²s >100 MeV)
6×10⁻⁵
4×10⁻⁵
2×10⁻⁵
6×10⁻⁶
5000
5500
6000
6500
7000
MJD−50000



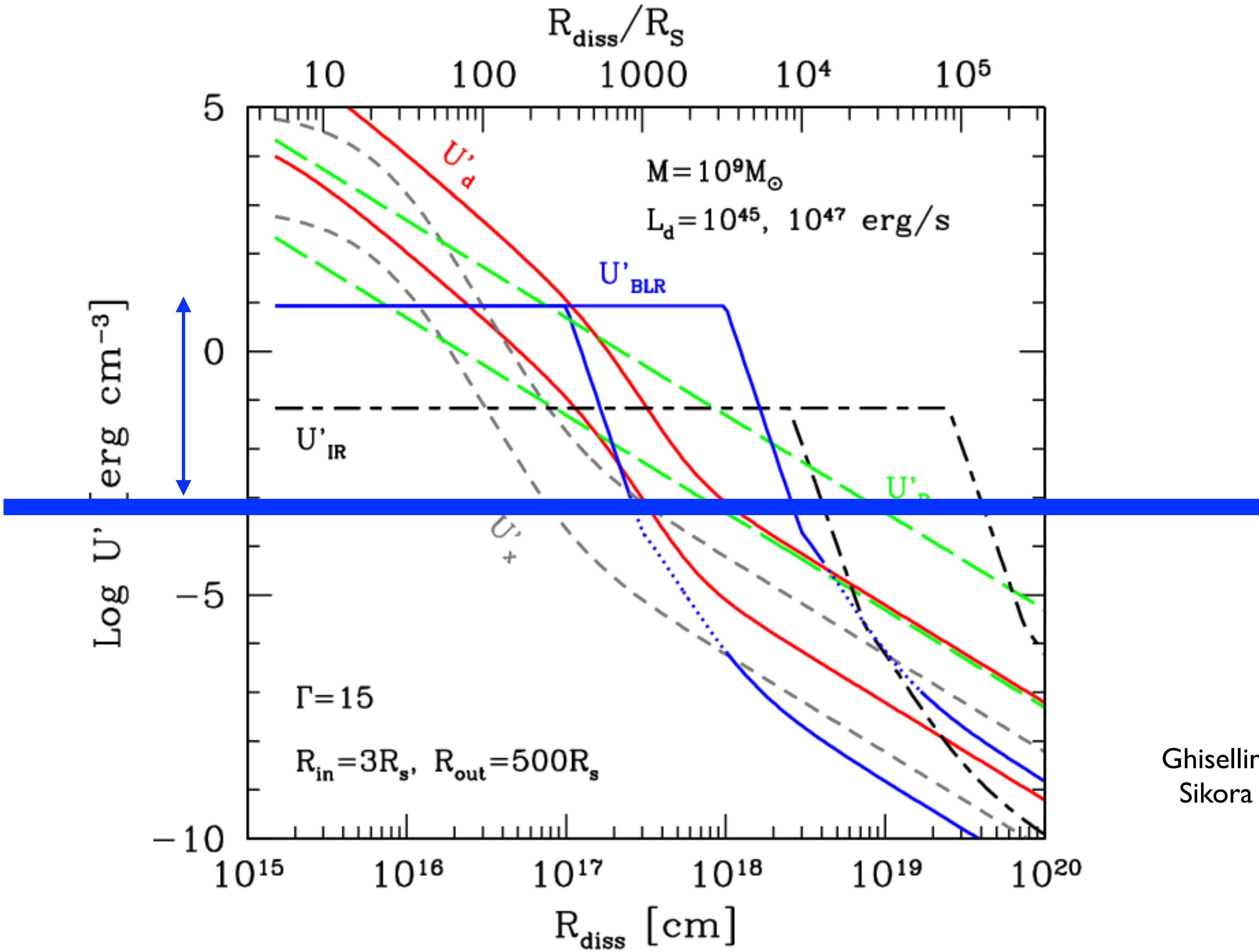
3C454.3 z=0.859 High states
Log νFν [erg cm⁻² s⁻¹]
Log νLν [erg s⁻¹]
a) ℒ= R_BLR/2
b) ℒ= 6×10¹⁵ cm
a)
b)
E_rest−frame [GeV]
3C454.3 z=0.859 Low state
Log νFν [erg cm⁻² s⁻¹]
Log νLν [erg s⁻¹]
a) ℒ= R_BLR/2
b) ℒ= 7×10¹⁵ cm
a)
b)
E_rest−frame [GeV]

Alternatives ?

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}



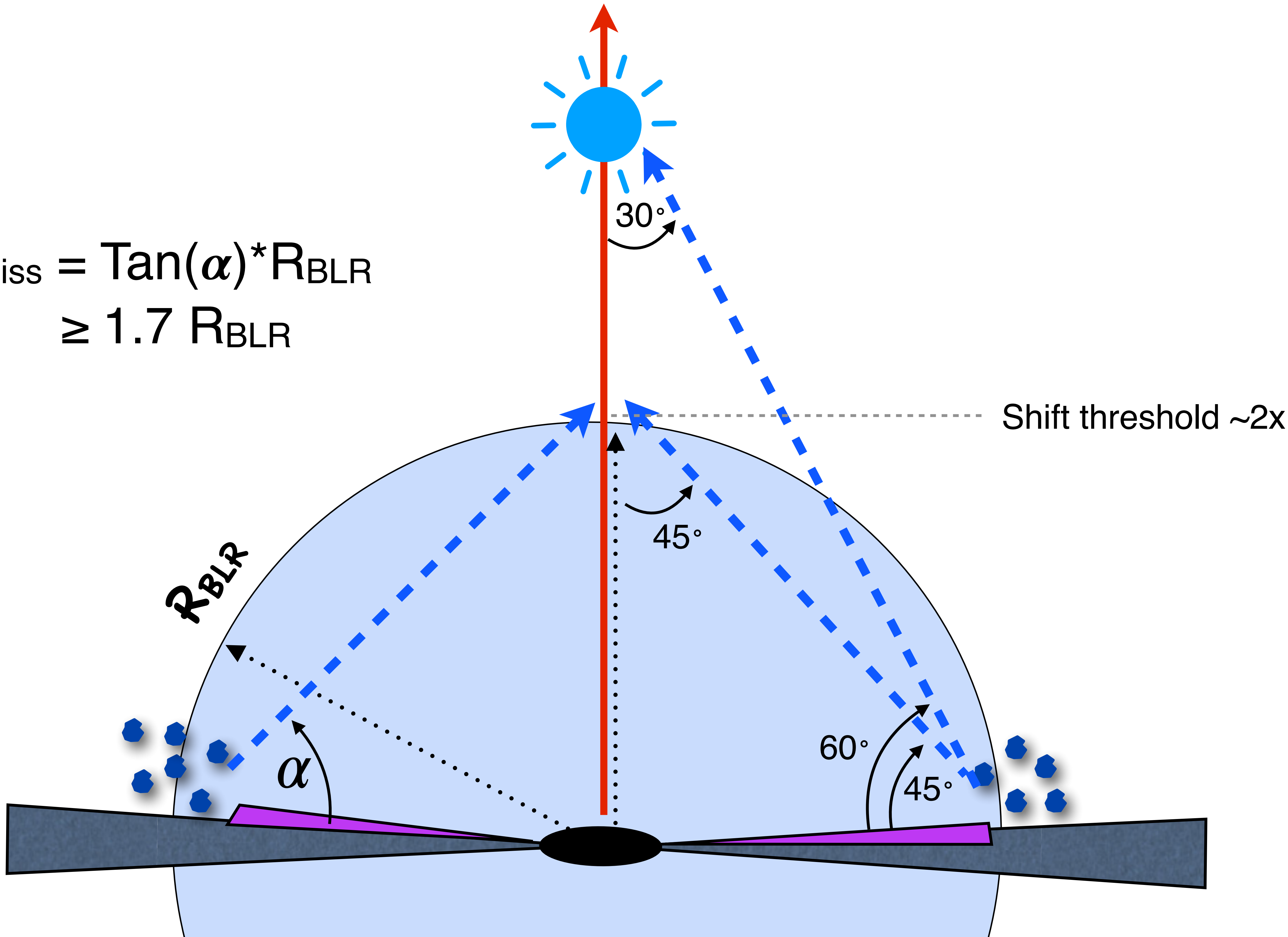
Ghisellini et al. 2009
Sikora et al. 2009

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?

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

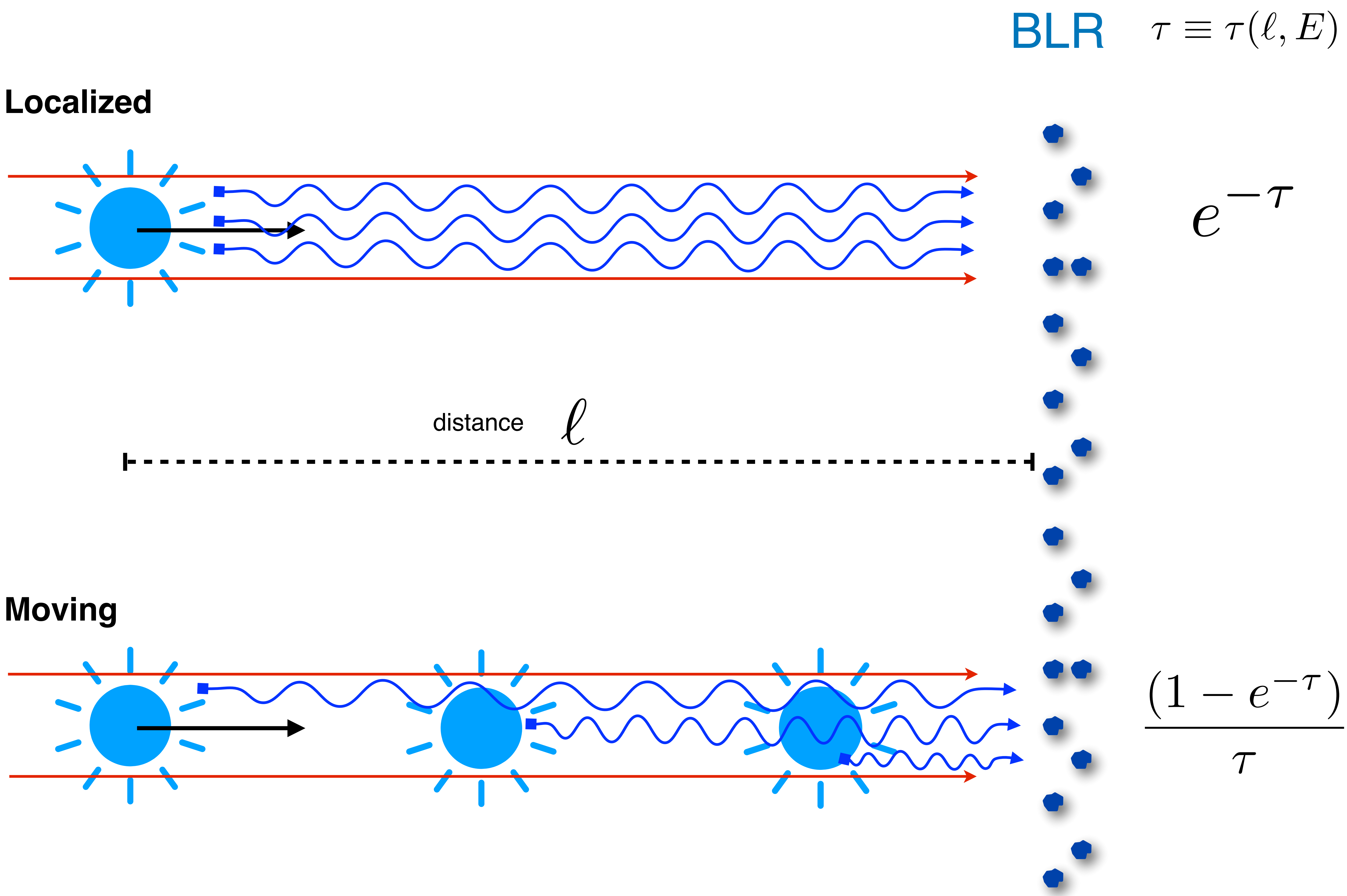
Two Caveats:

1) Long integration time (years)

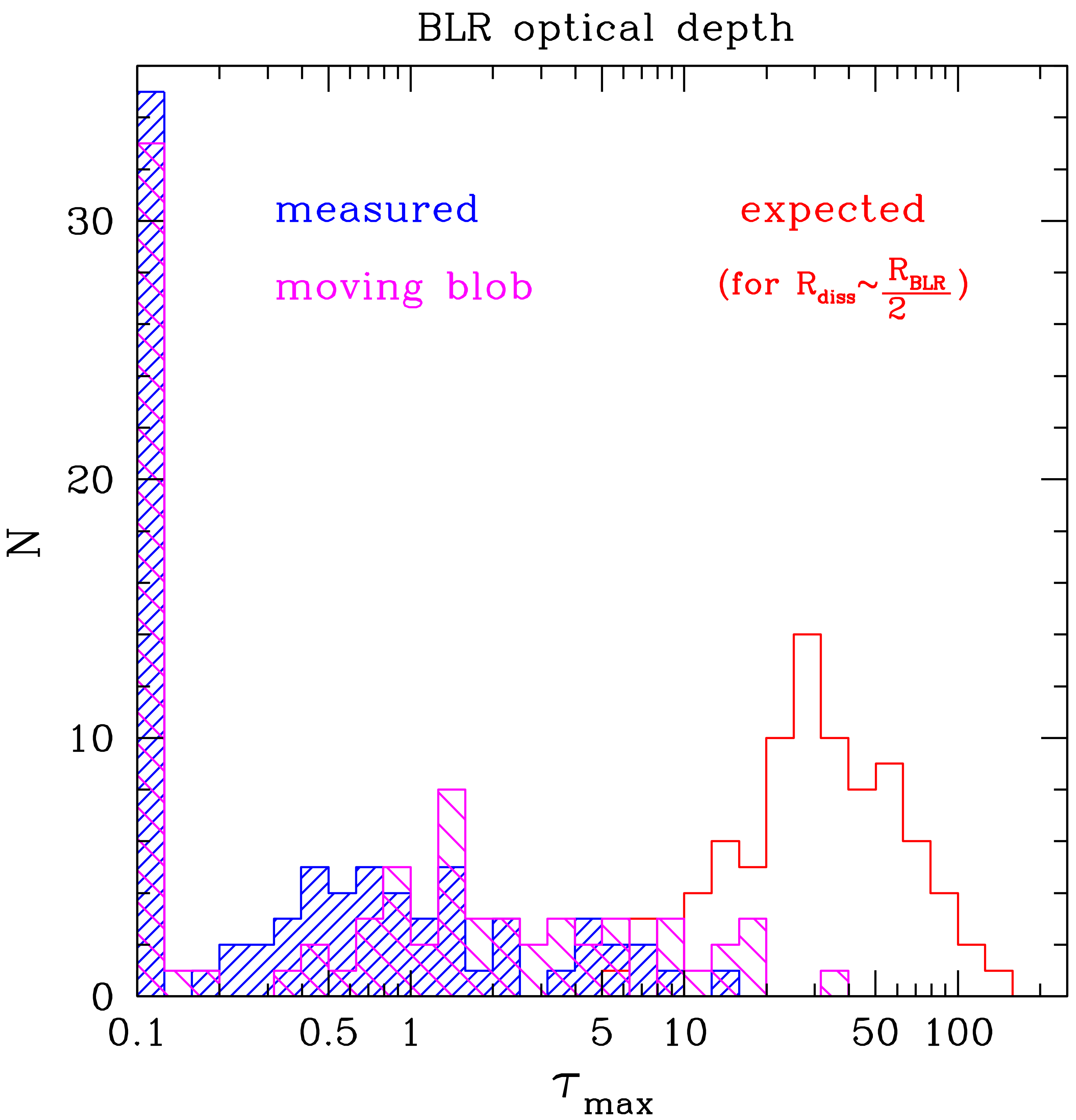
2) Kinematics of the emission
(localized dissipation vs moving blob)

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

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



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

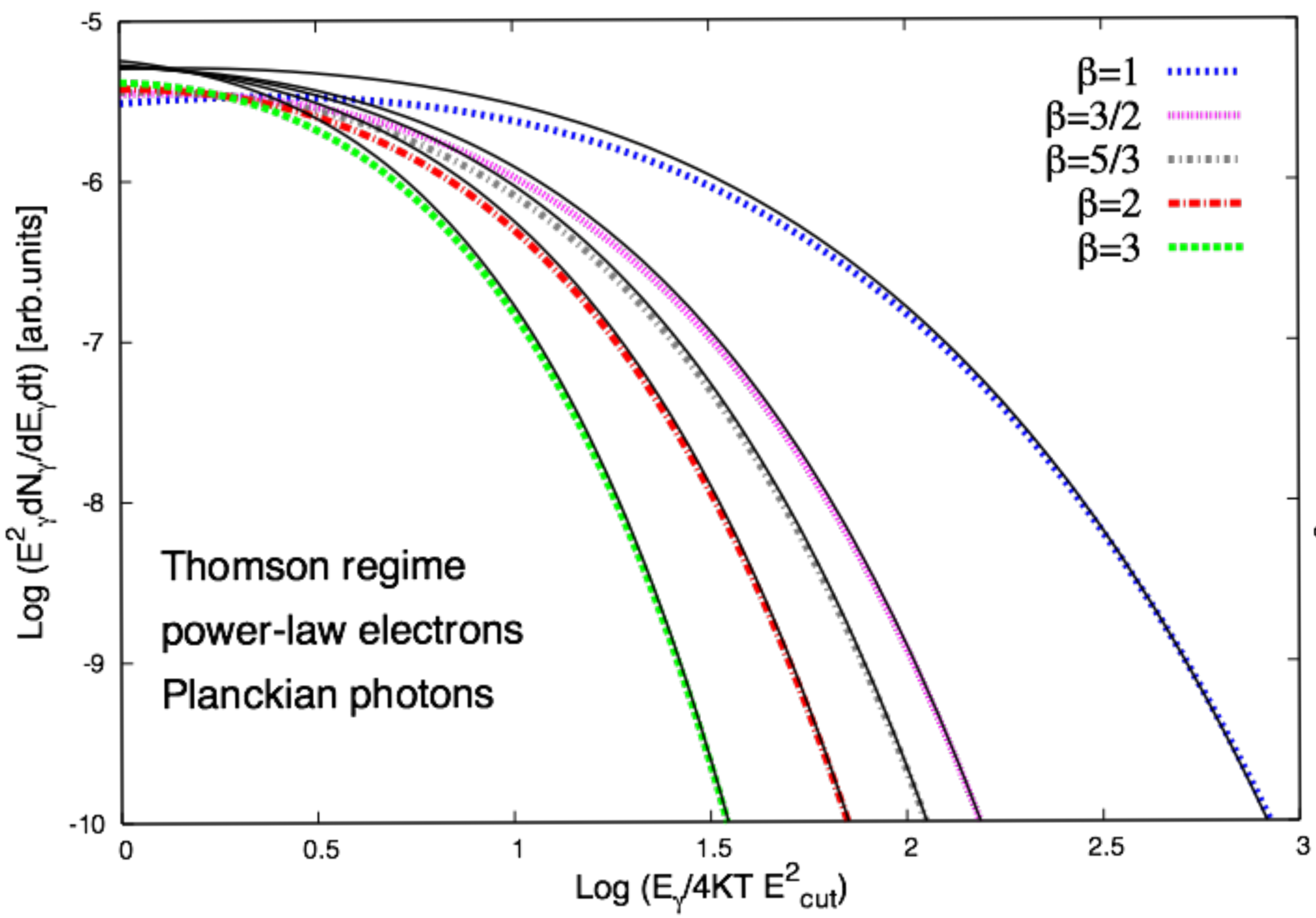


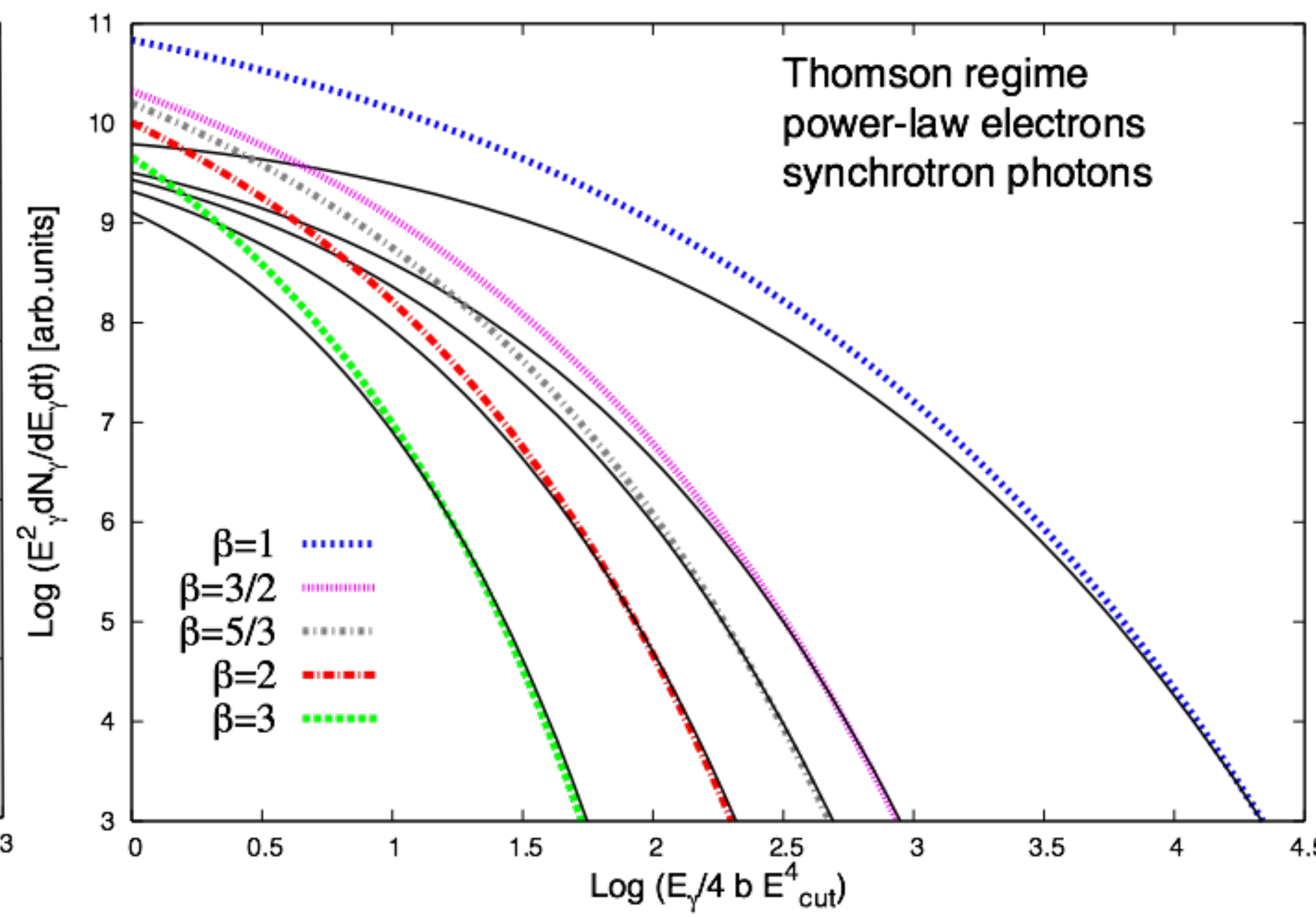
It does **NOT** *change the main result*

The Astrophysical Journal, 753:176 (14pp), 2012 July 10 doi:10.1088/0004-637X/753/2/176

ON THE SPECTRAL SHAPE OF RADIATION DUE TO INVERSE COMPTON SCATTERING CLOSE TO THE MAXIMUM CUTOFF

E. Lefa[1,3], S. R. Kelner[1], and F. A. Aharonian[1,2]
[1] Max-Planck-Institut für Kernphysik, P.O. Box 103980, 69029 Heidelberg, Germany; eva.lefa@mpi-hd.mpg.de
[2] Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
Received 2012 March 10; accepted 2012 May 11; published 2012 June 26





$$N_e \propto E^{-p} exp(-(E/E_c)^{\beta})$$

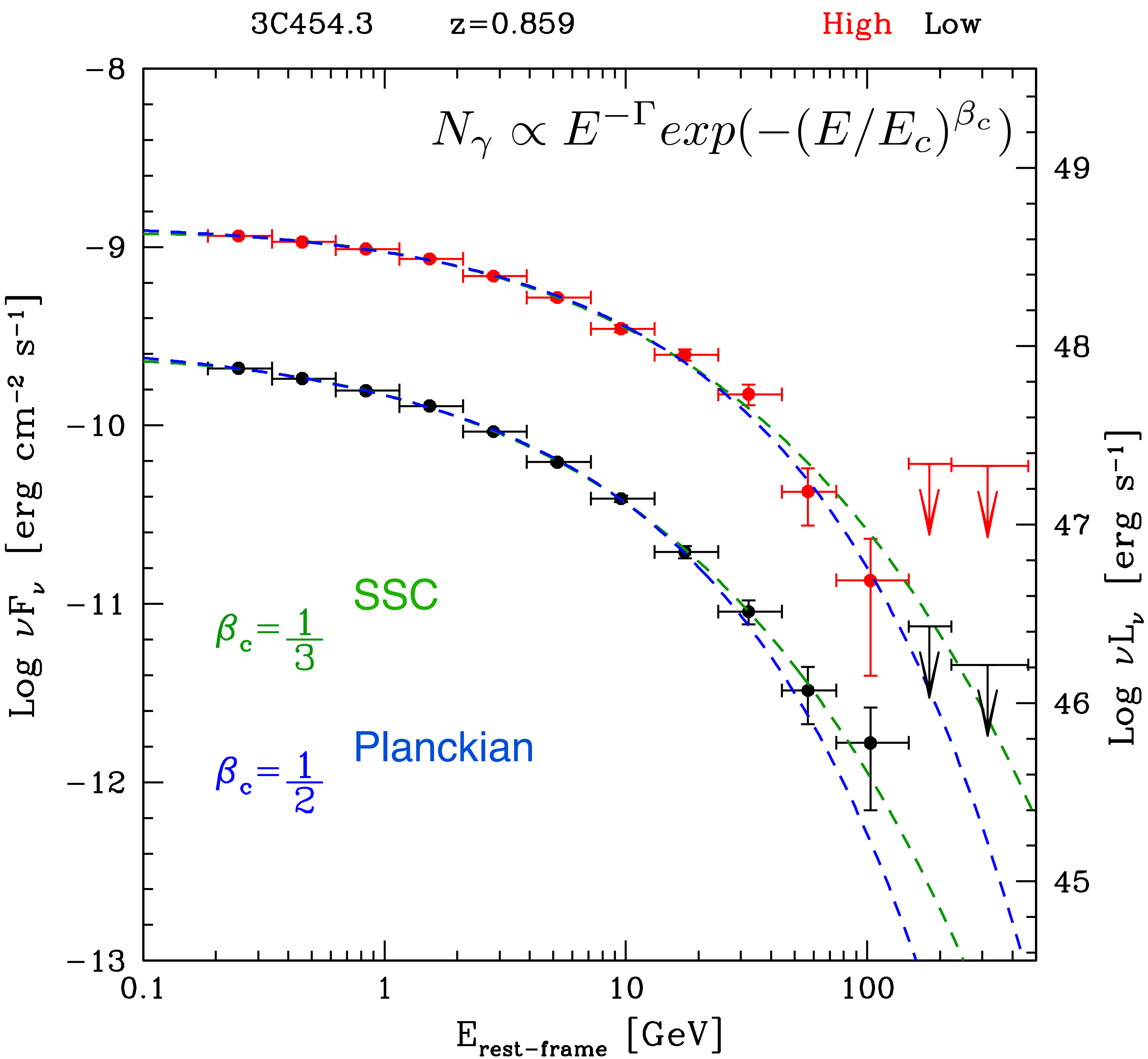
$$\beta_{synch} = \frac{\beta}{\beta+2}$$

Table 1
exponential cut-off index for Compton spectrum

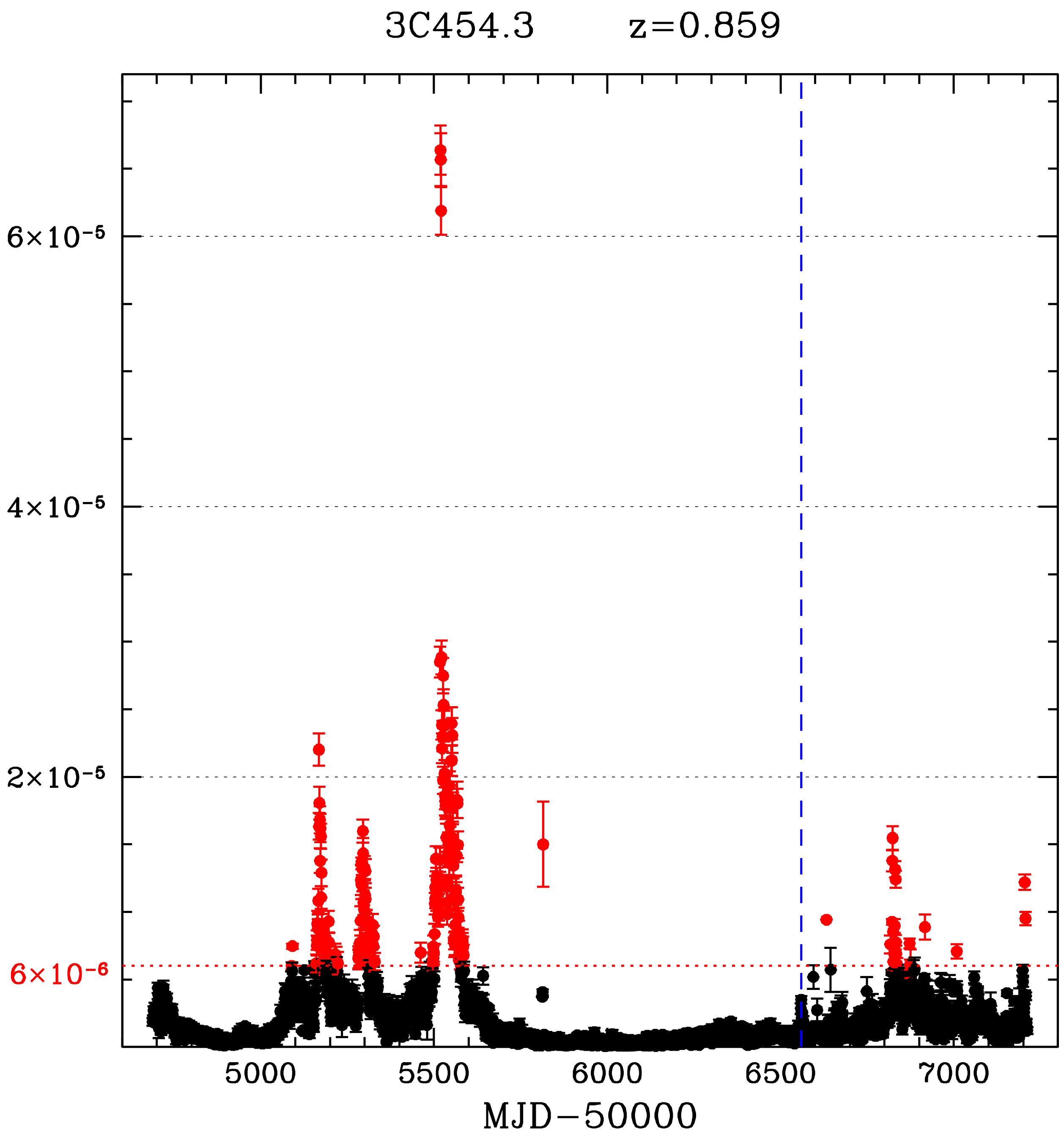
electron index	β	β	$\beta \to \infty$	$\beta \to \infty$
scattering regime	Thomson	Klein-Nishina	Thomson	Klein-Nishina
monochromatic photons	$\beta/2$	β	$\beta \to \infty$	$\beta \to \infty$
Planckian photons	$\beta/(\beta+2)$	β	1	$\beta \to \infty$
synchrotron photons	$\beta/(\beta+4)$	β	1	$\beta \to \infty$

$For\ \dot{\gamma} \propto \gamma^2 \quad \beta \simeq 2$

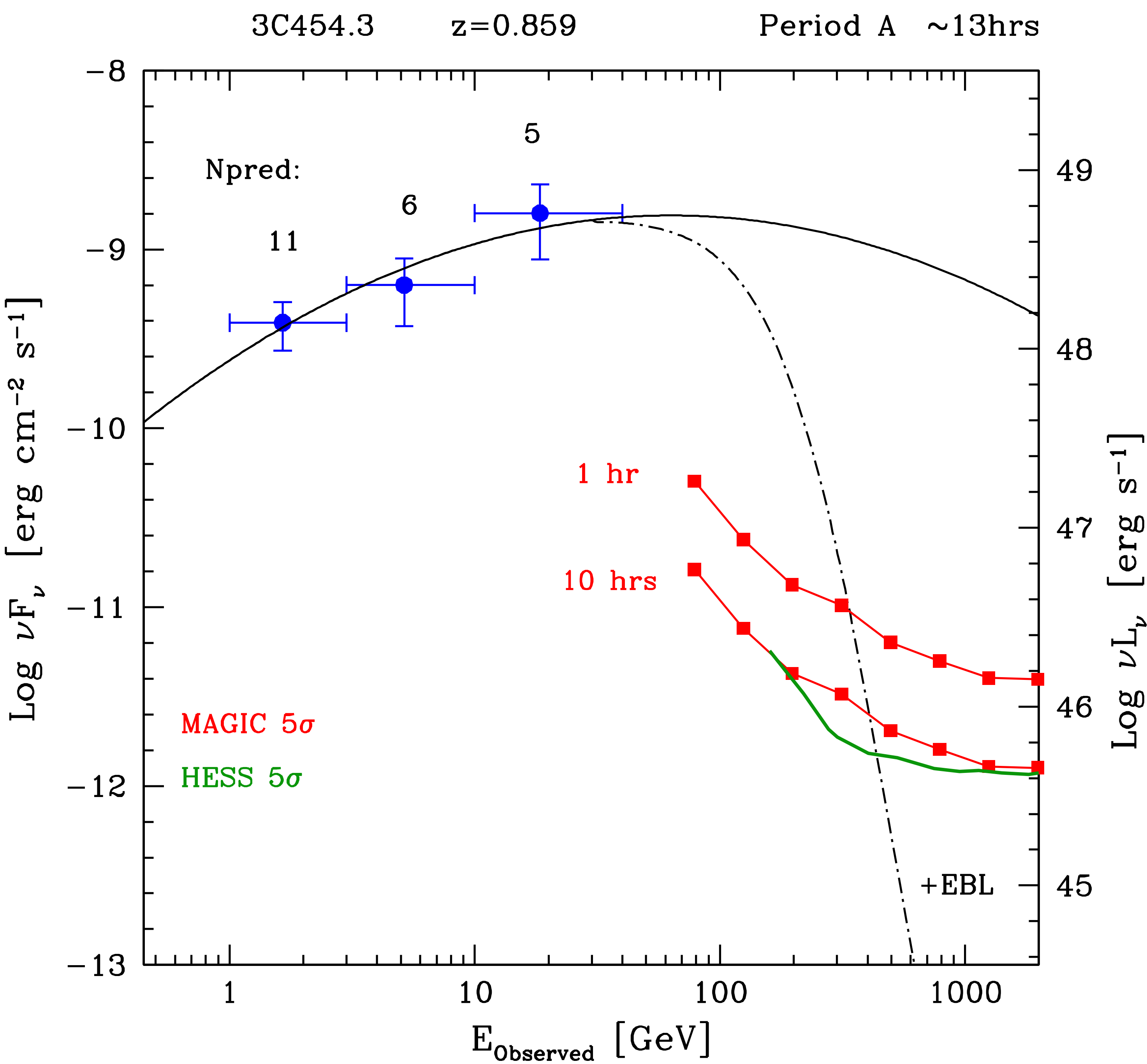
See also: Romoli et al. 2017
Zargaryan poster on 3C279



3C 454.3 can be easily detectable at VHE !

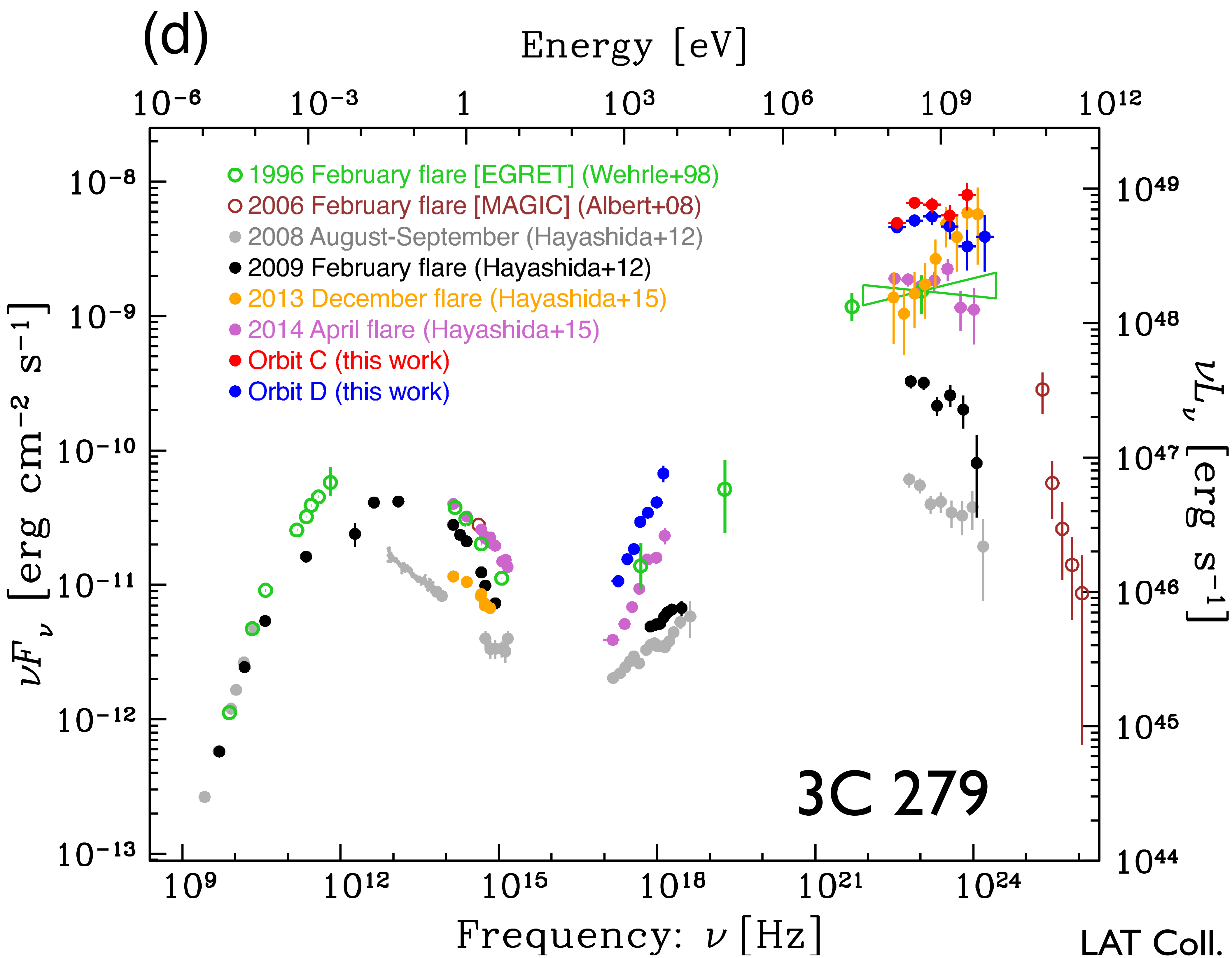


Pacciani et al. 2014 - flare



HBL-like flare !

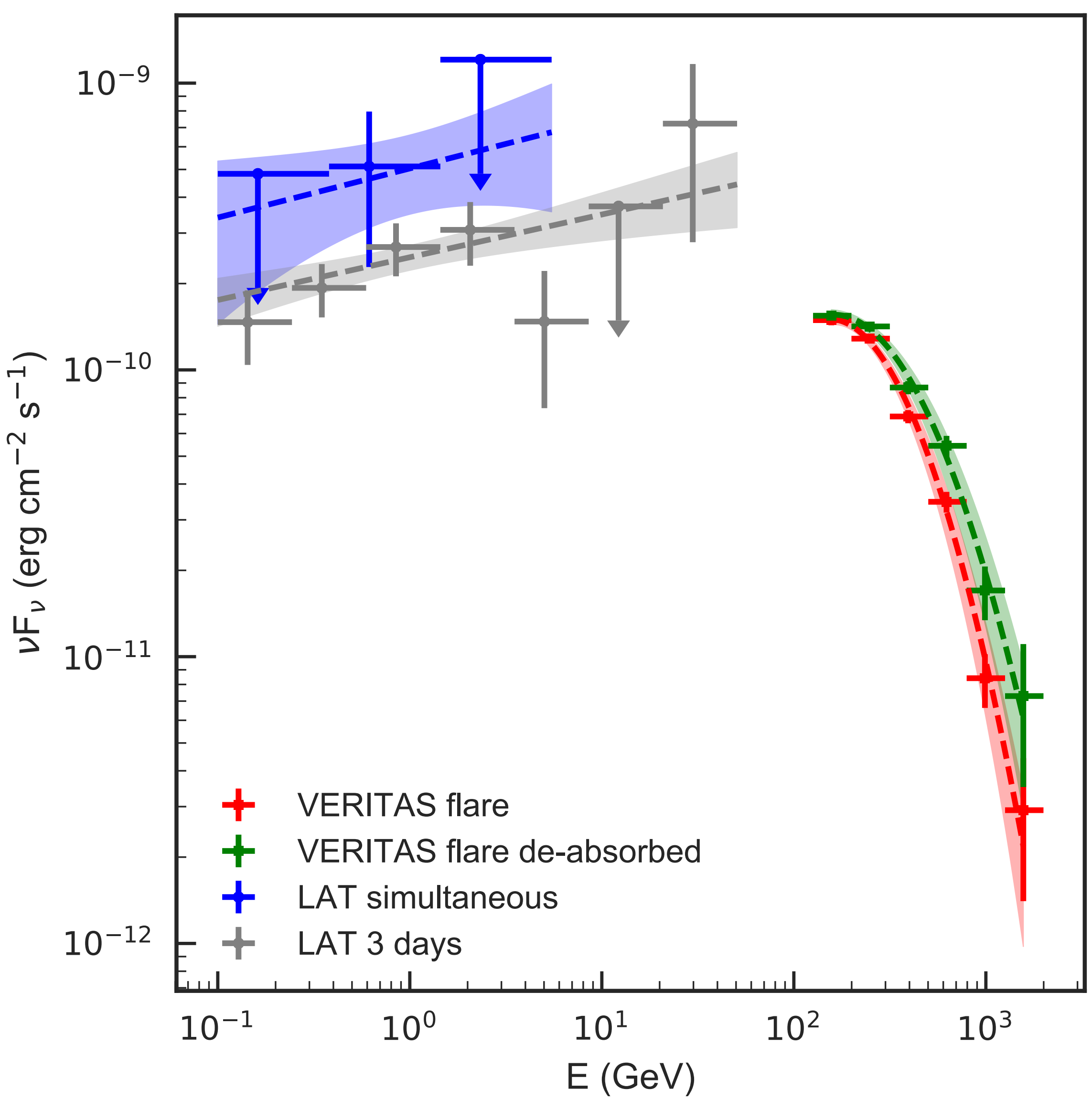
FSRQ/LBL can become HBL in gamma-rays !



LAT Coll. 2016

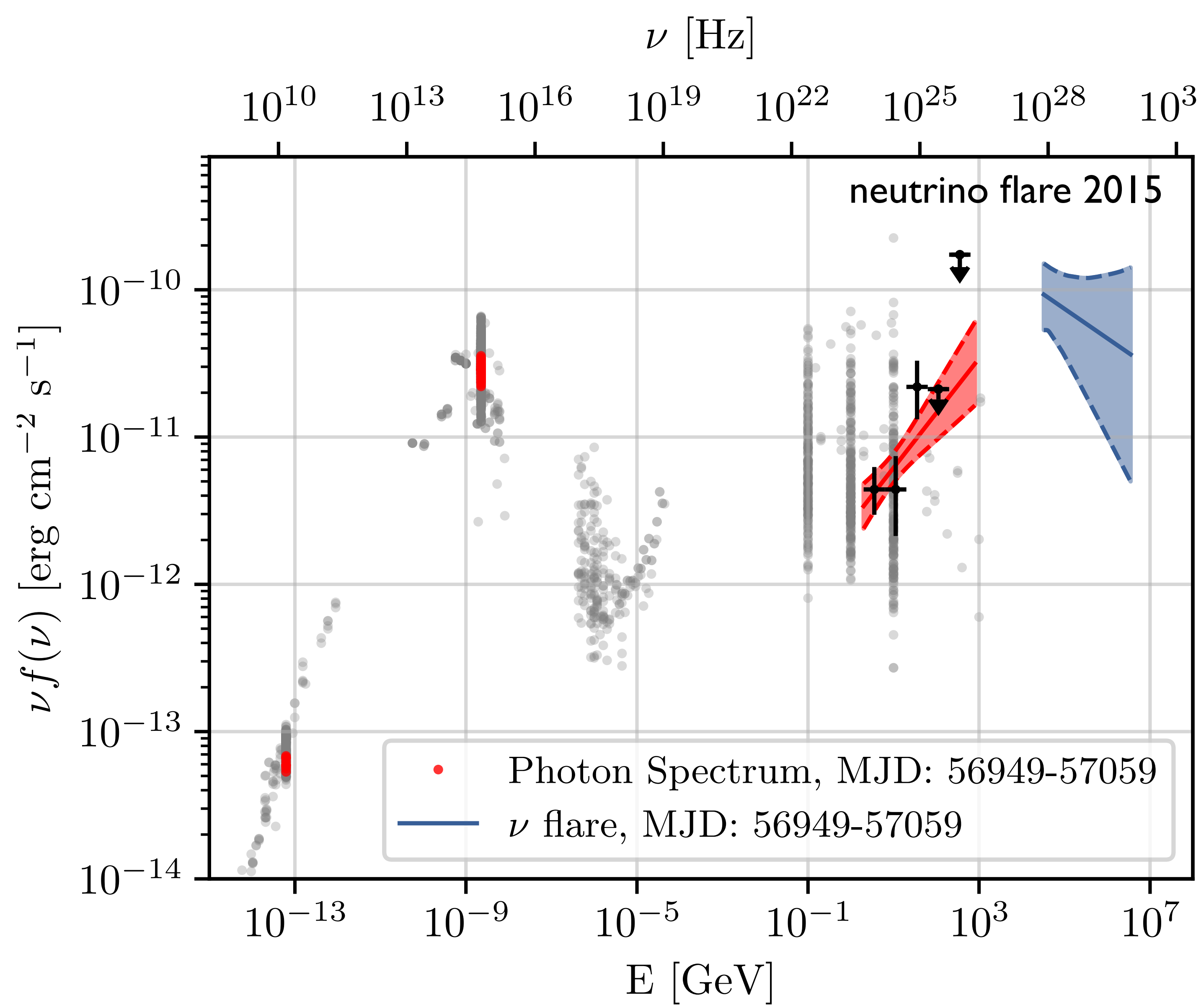
HBL-like spectra in LBL/IBL

BL Lac



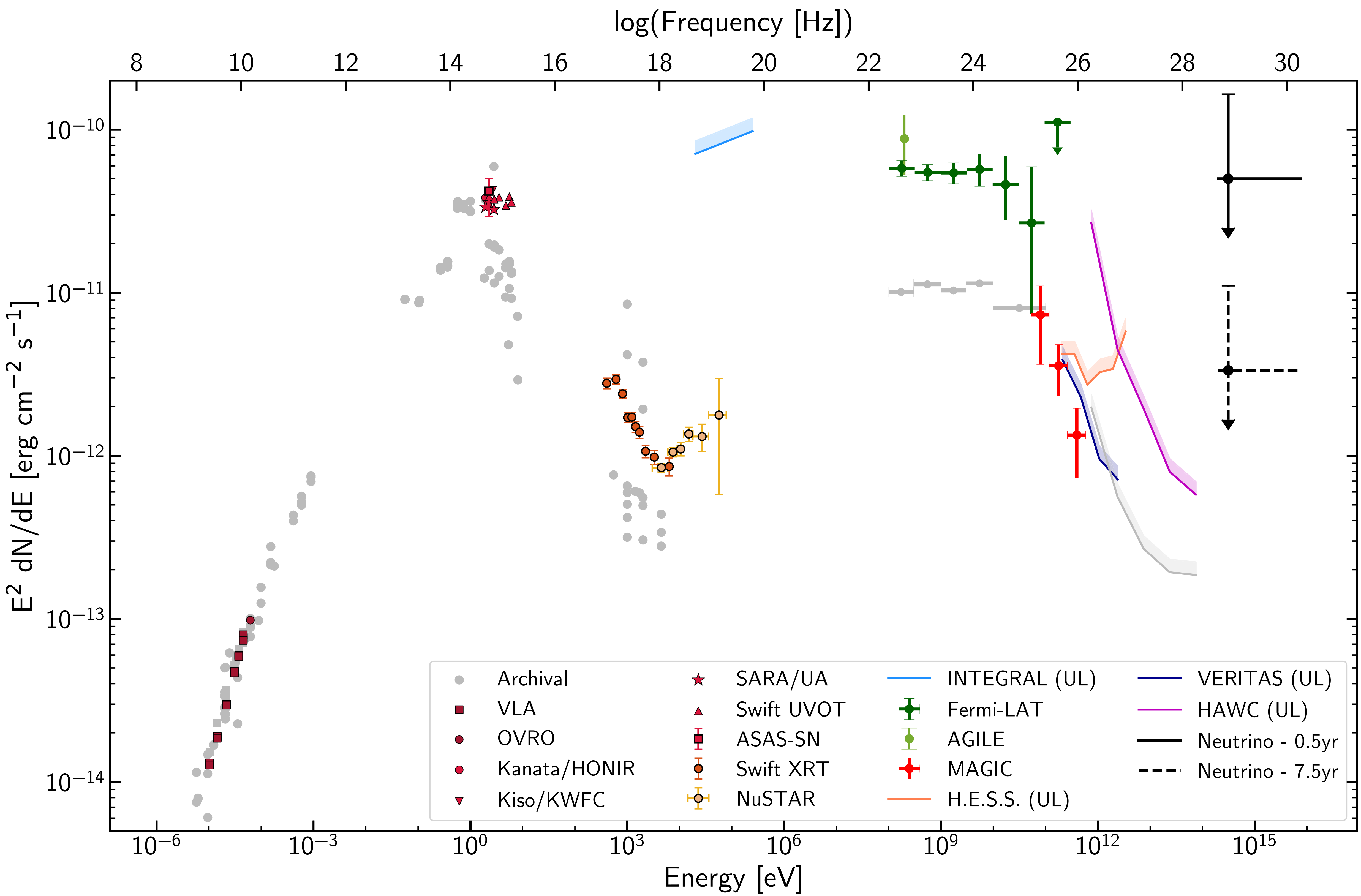
Veritas Collab. 2018

TXS 0506+056



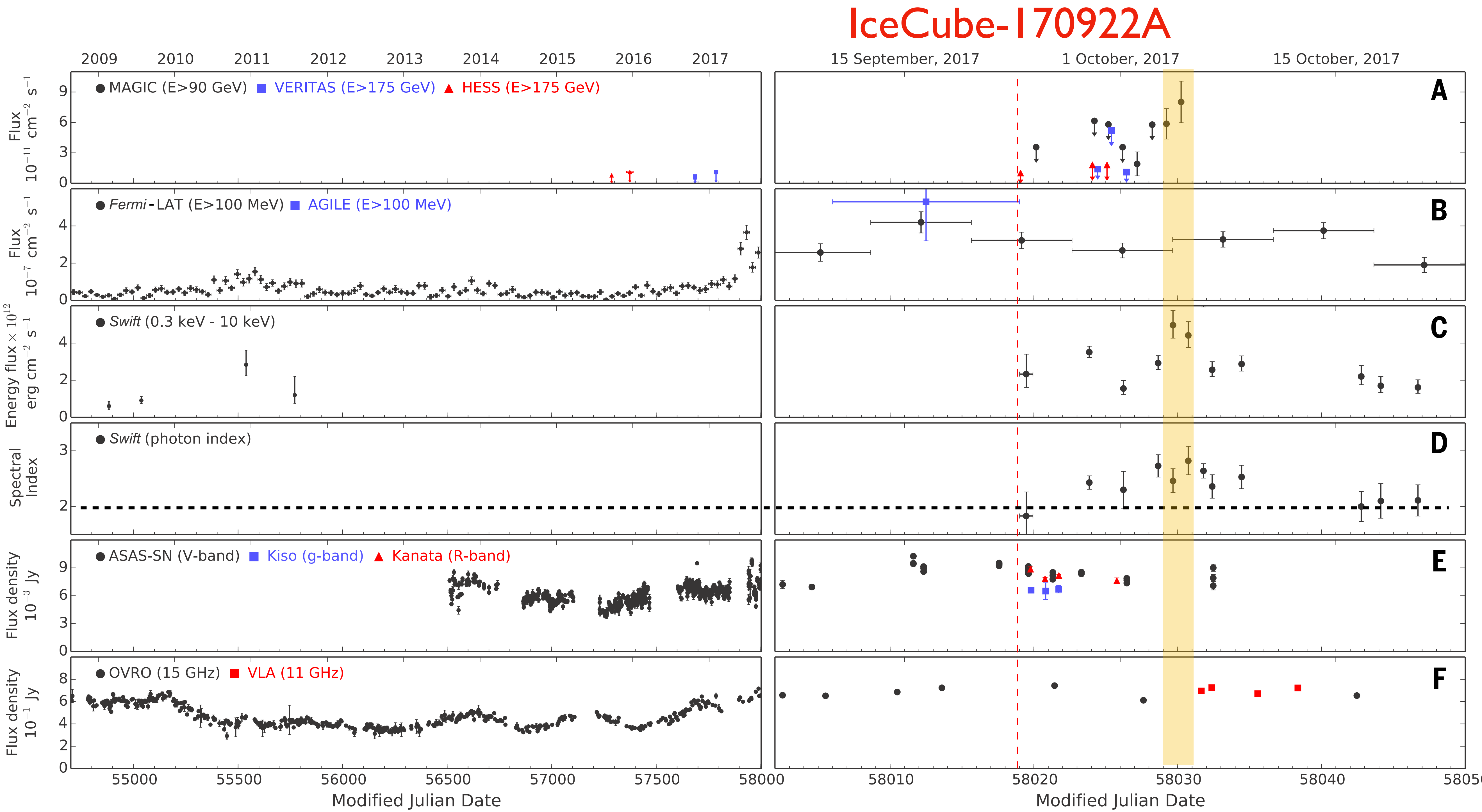
Padovani et al. 2018

TXS 0506+056

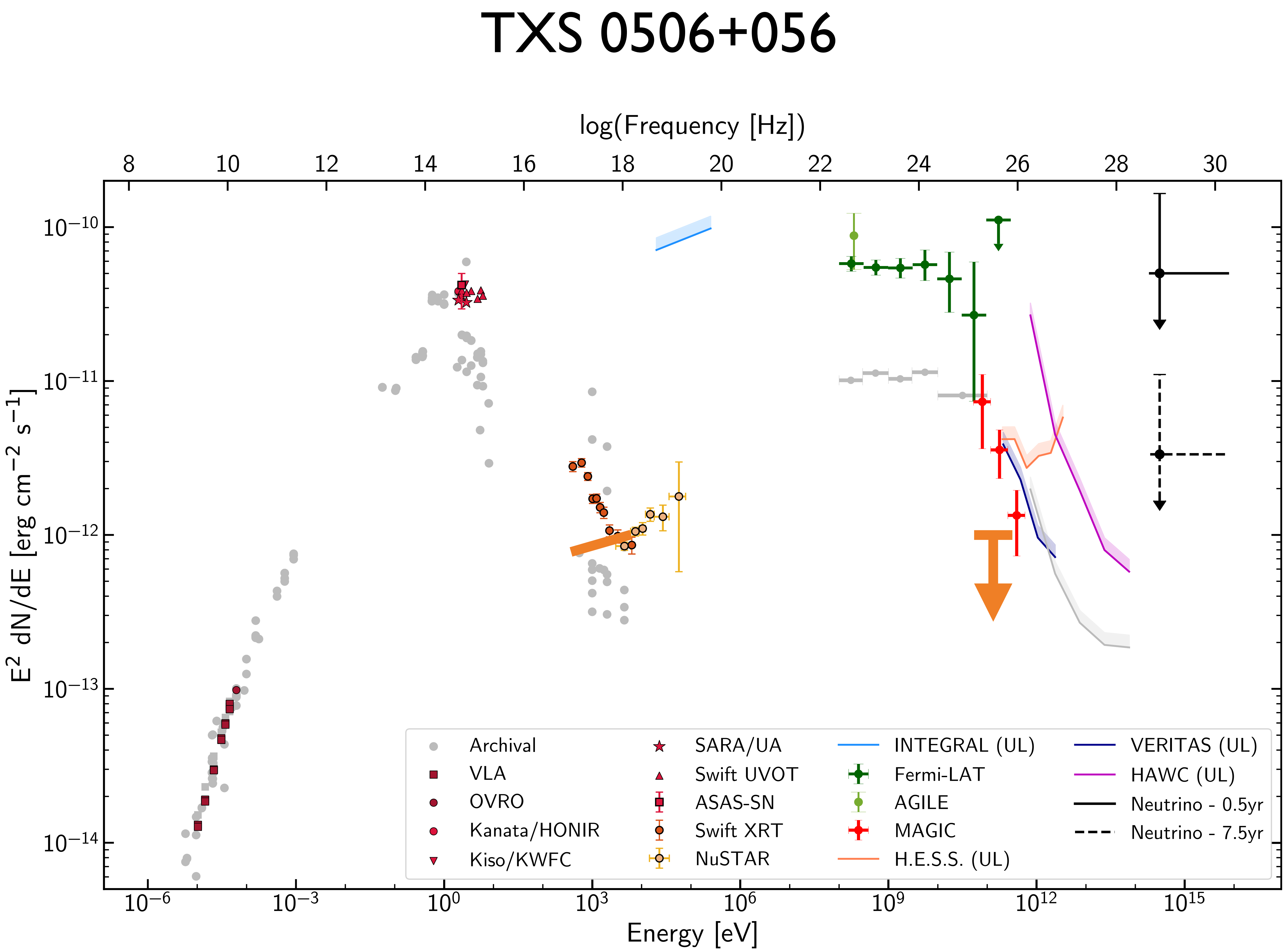


All Collaborations , Science 2018

Warning on unwarranted connections…



All Collaborations , Science 2018



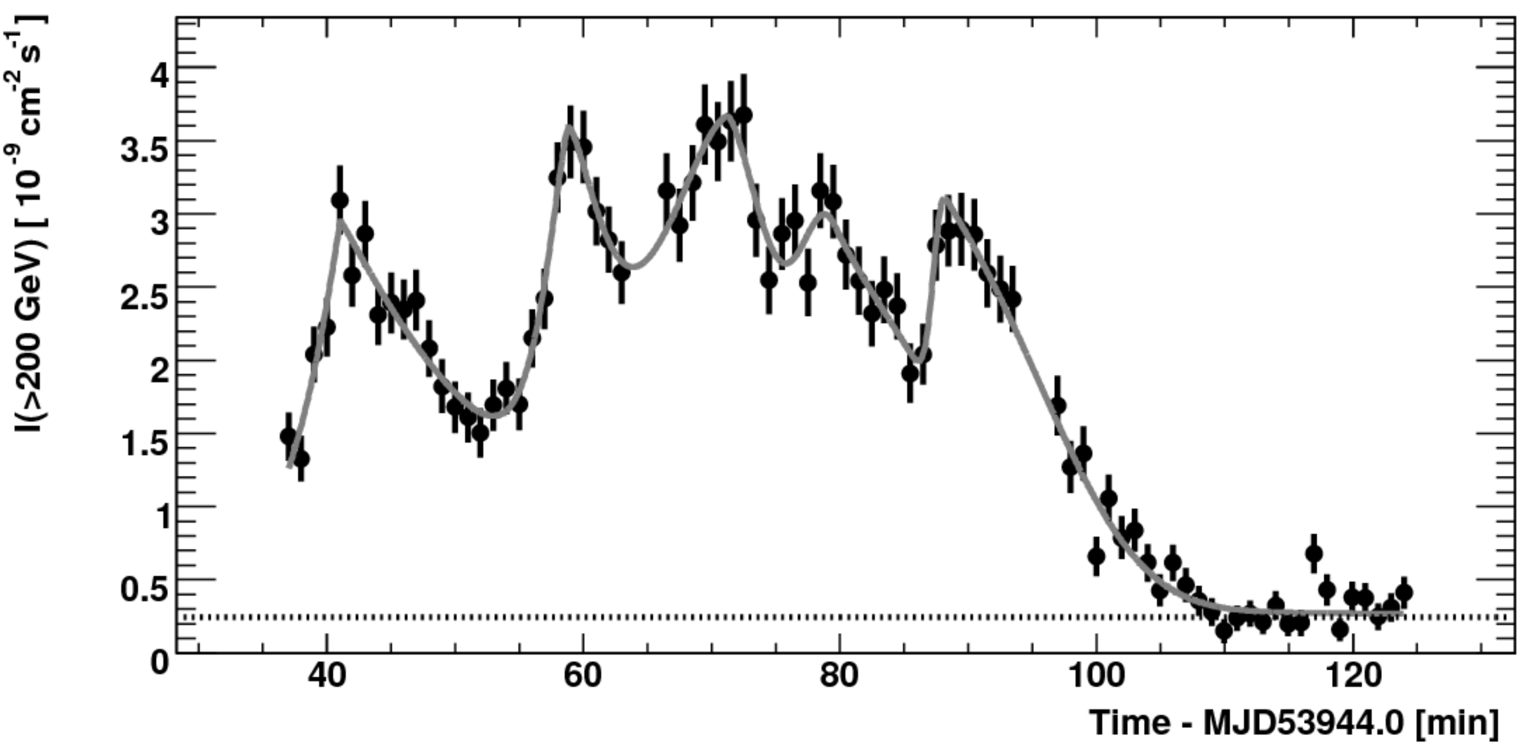
TXS 0506+056
log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR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

Ultra-fast Variability (≲ R_s/c)

see Maxim's talk !

HBL

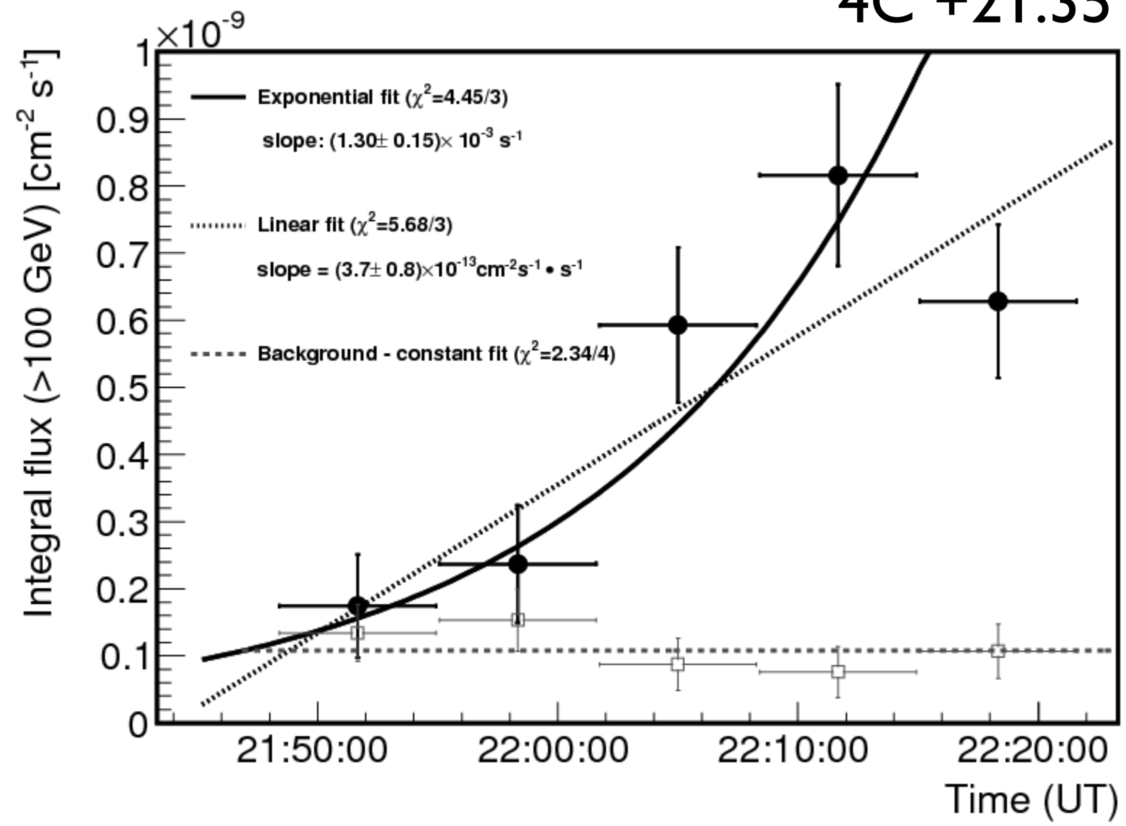
PKS 2155-304



Aharonian et al. (HESS coll) 2007

FSRQ

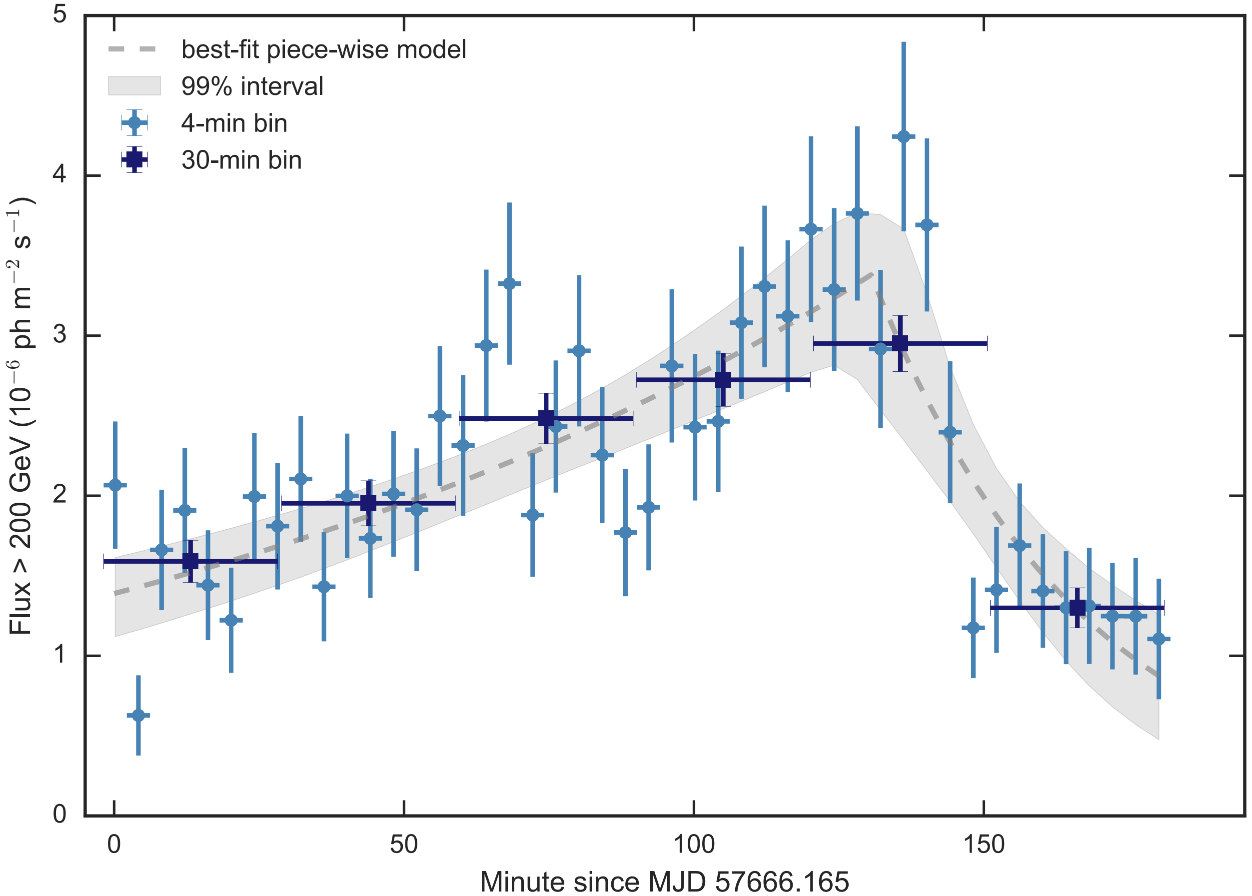
4C +21.35



Aleksic et al. 2011 (MAGIC coll)

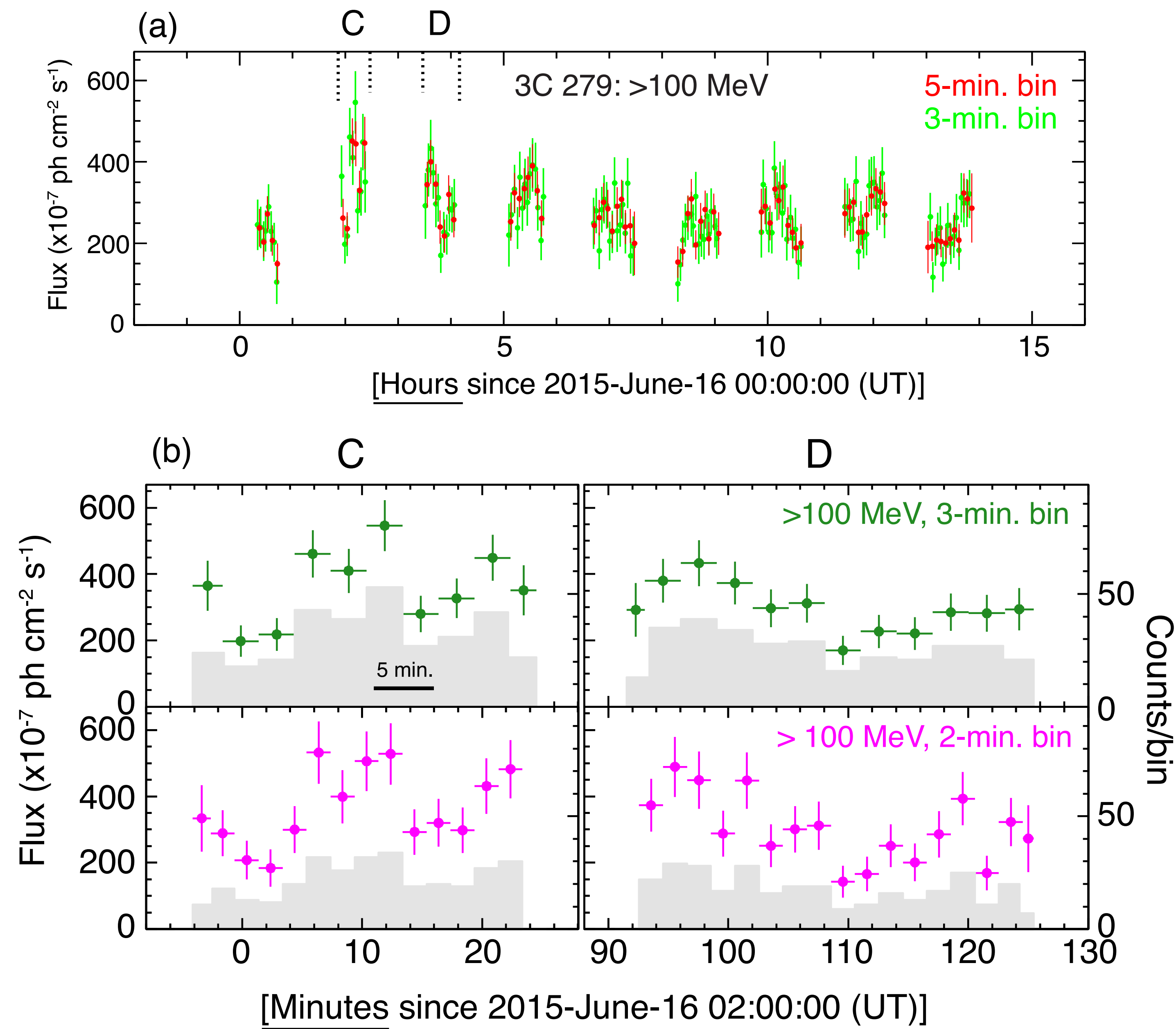
$$R/R_g \simeq 0.04$$

BL Lac (IBL/LBL)



Veritas Collab. 2018

3C 279 in 2015

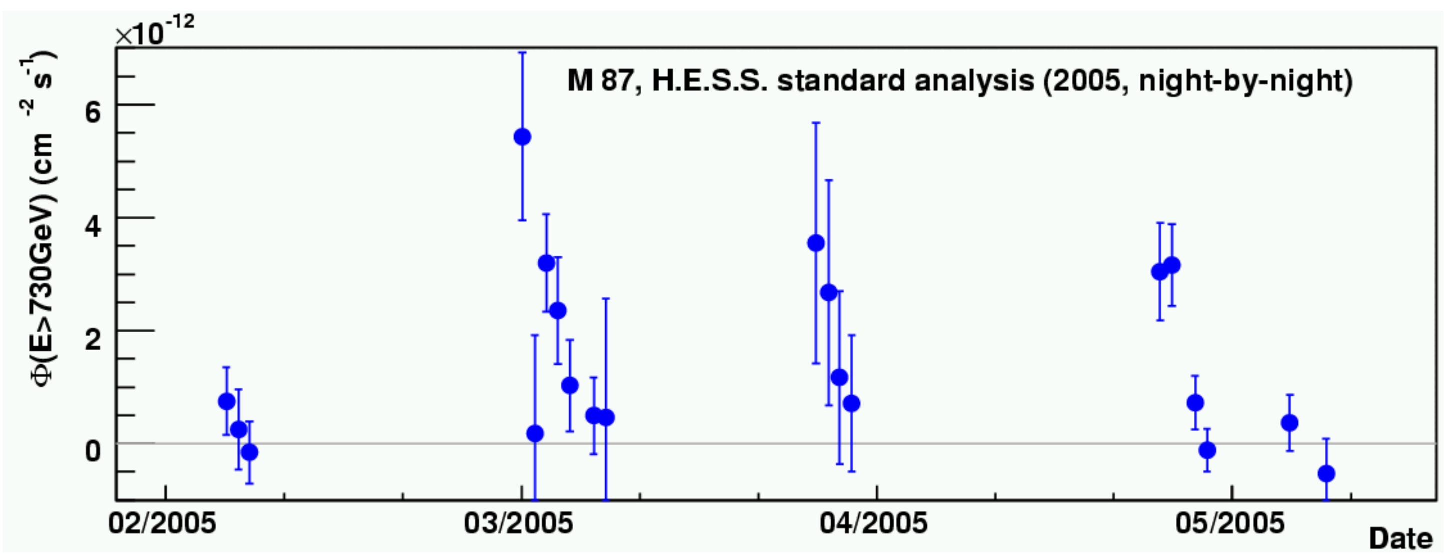


LAT Coll. 2016

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

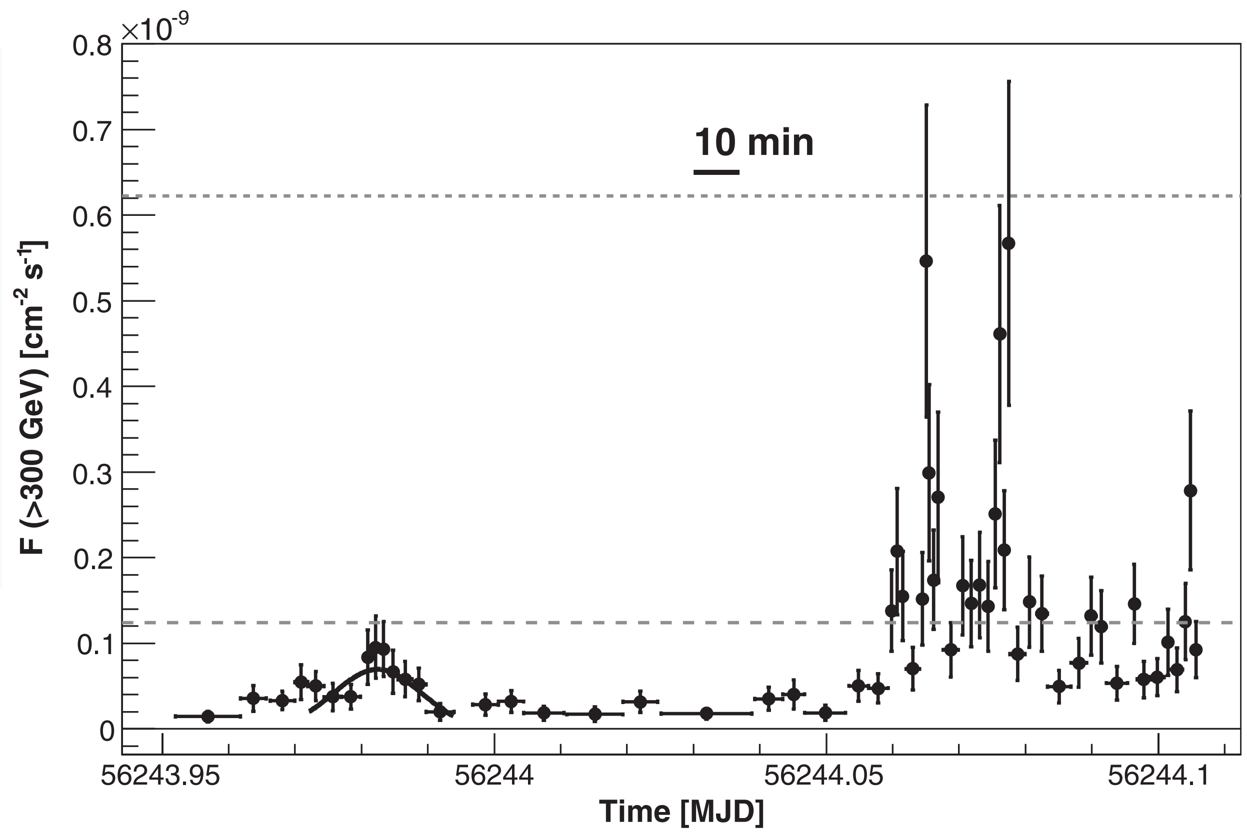
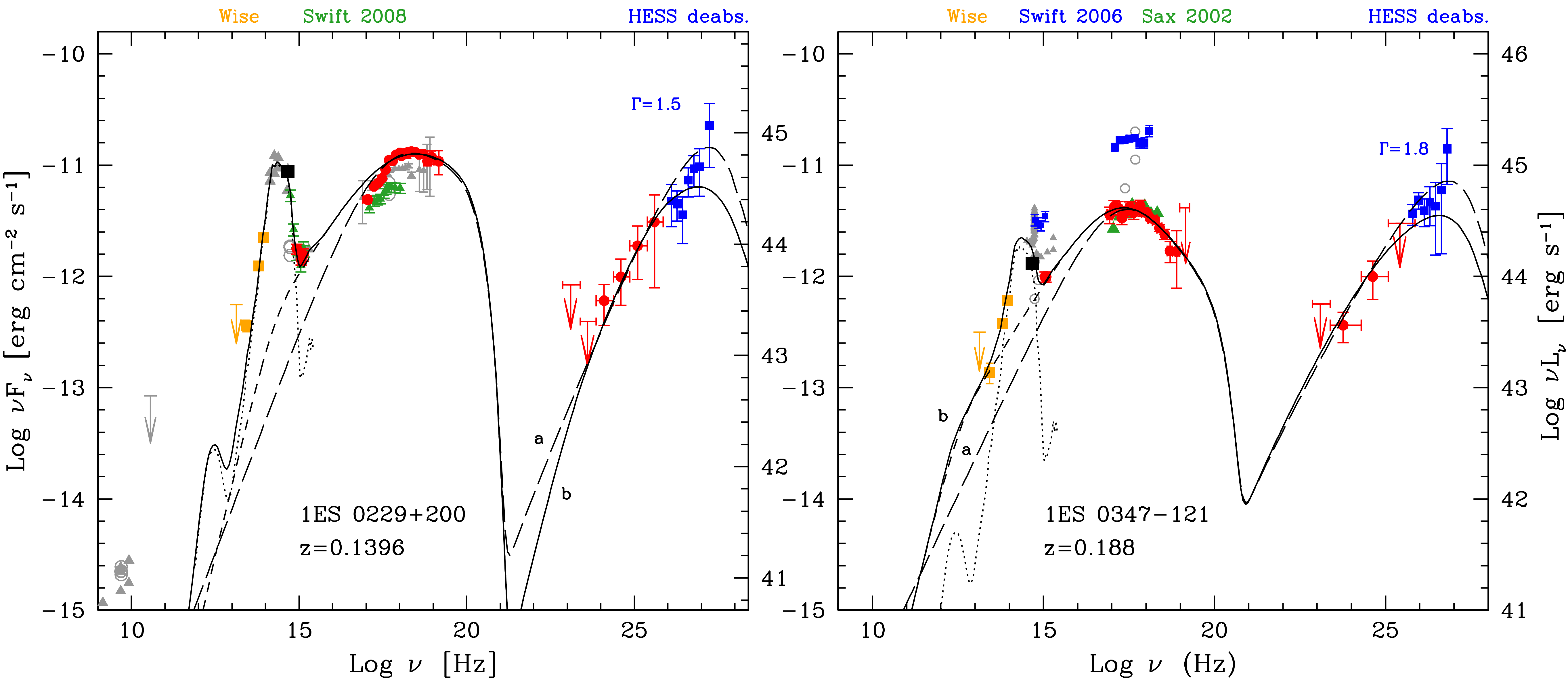


Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes on the night of 12/13 November 2012, above 300 GeV. As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972-56243.994) has been fitted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

Aleksic et al. (MAGIC coll) 2014

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

Extreme-TeV BL Lacs



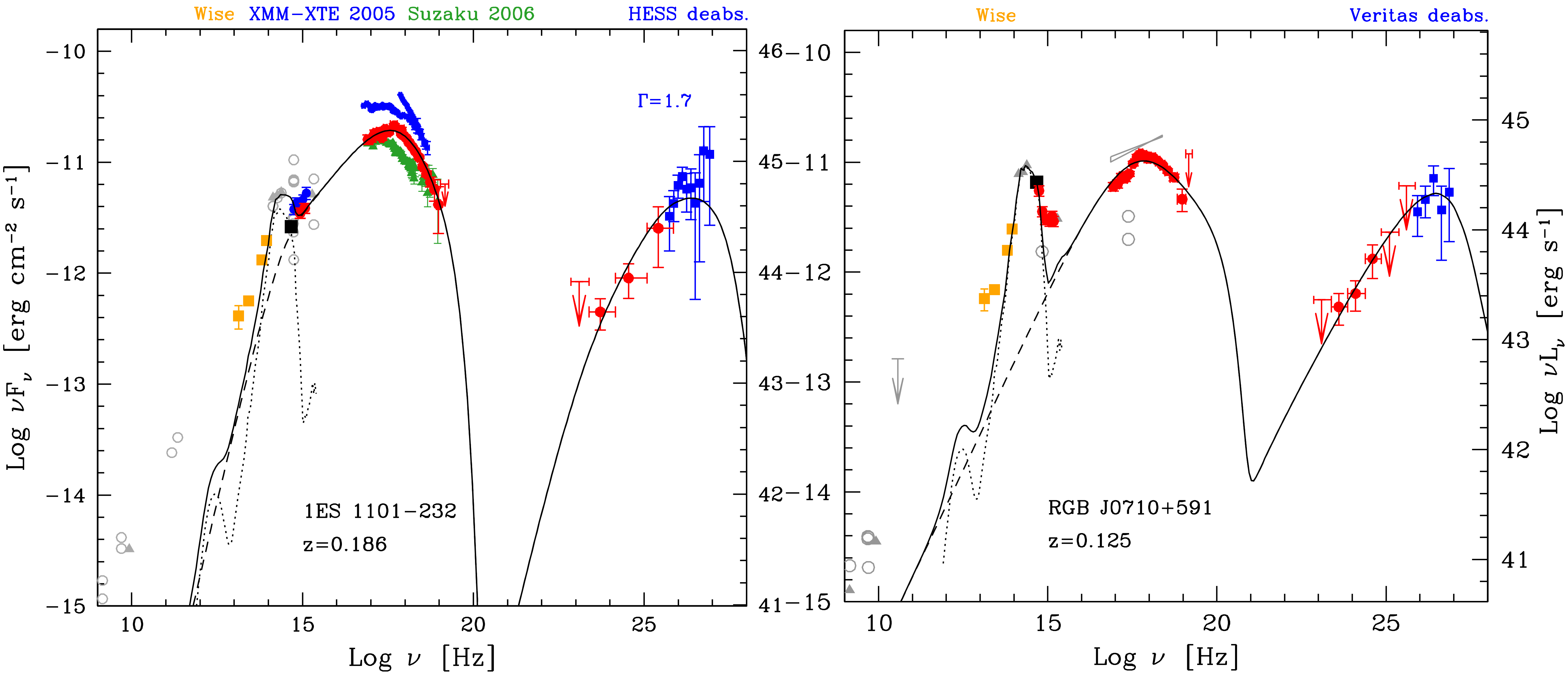
Intrinsic Γ_{VHE} < 2 (typically 1.5-1.7), with any EBL intensity (even lowest one).

⇒ "Compton" peak ≥ 3-10 TeV

Numbers are 9/34 (TeVCAT) ~ 1/4 of all HBL

Costamante et al. 2018

NuSTAR-Swift observations



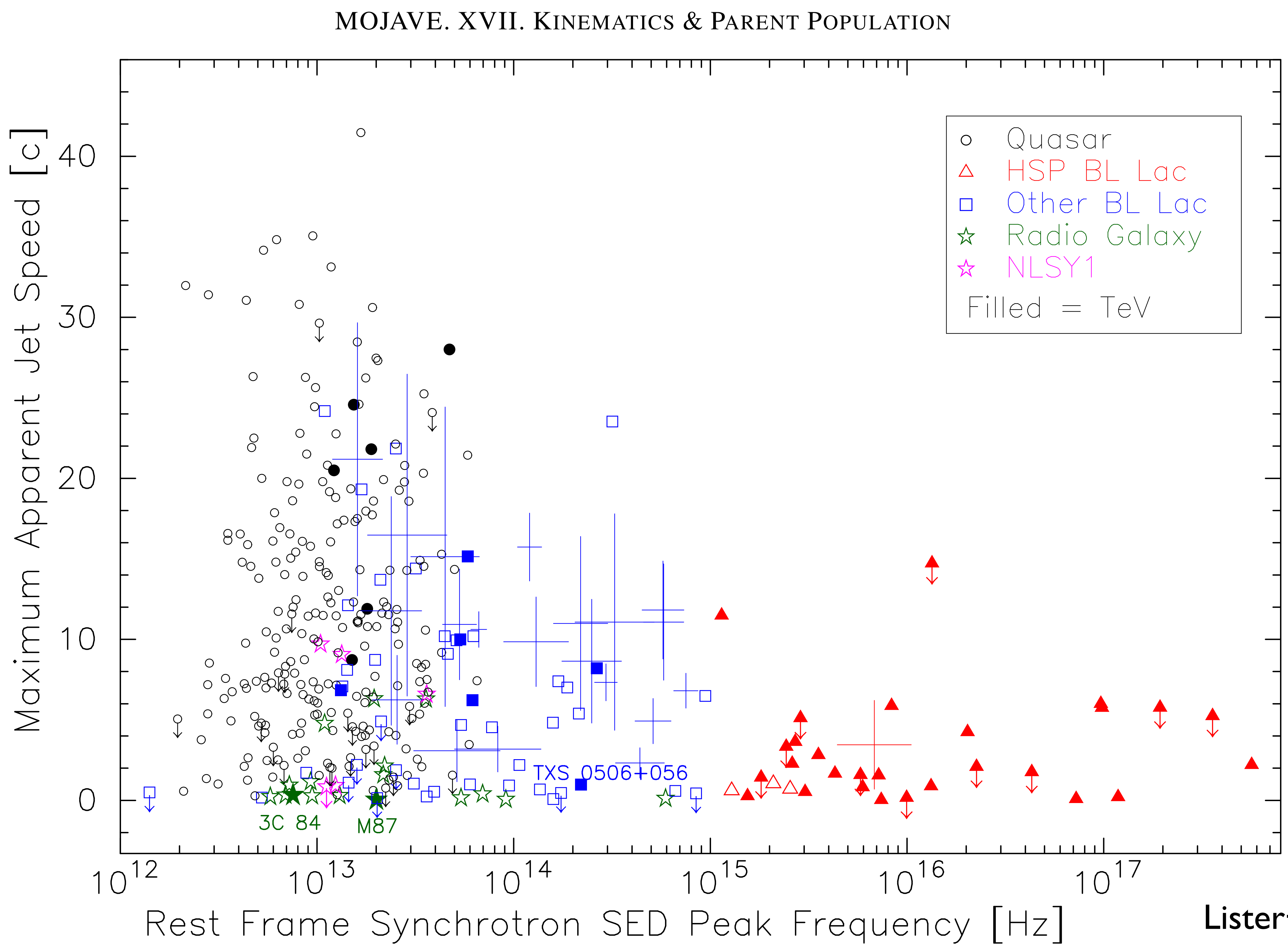
Costamante et al. 2018

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

Costamante et al. 2018, models by F. Tavecchio

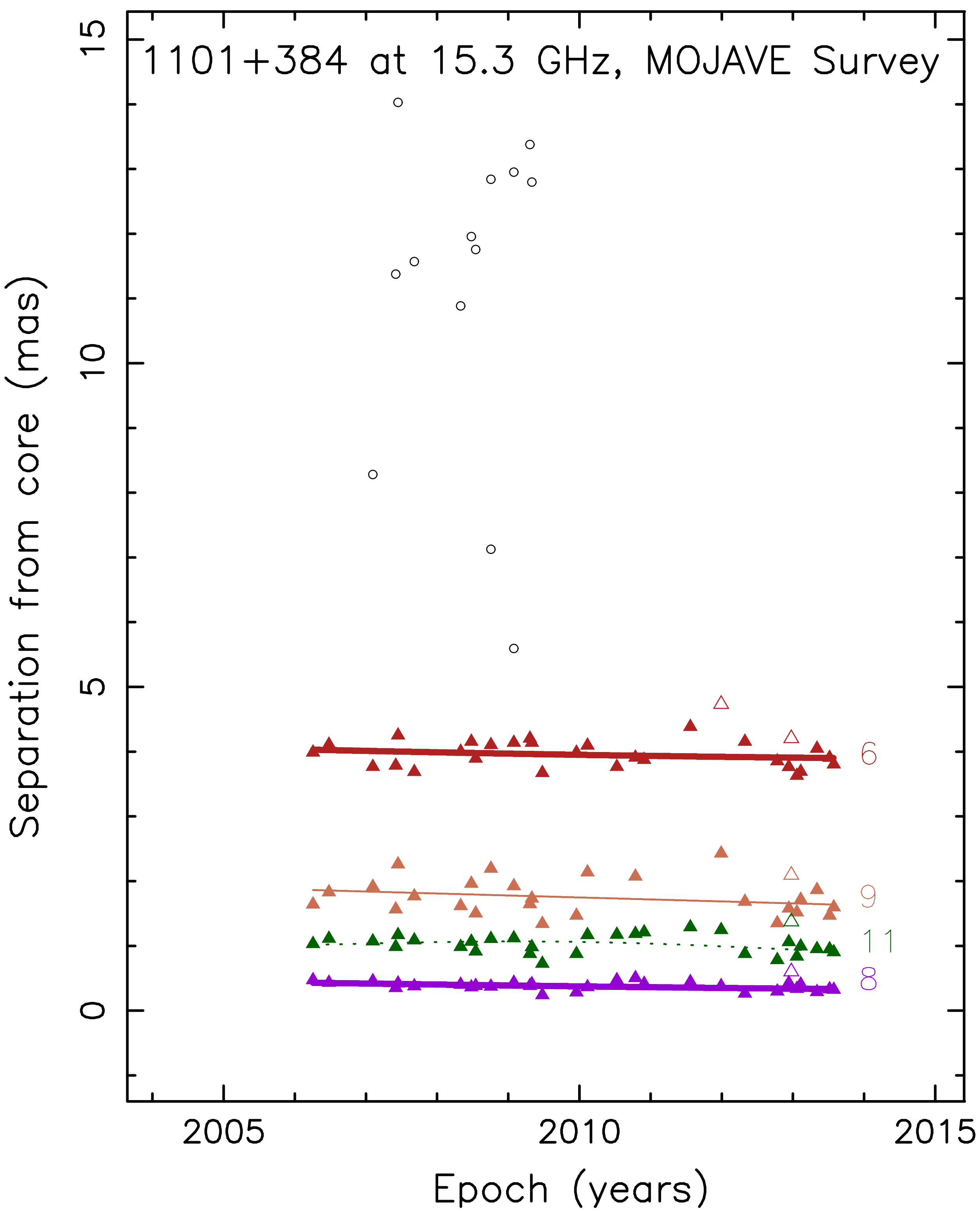
SSC can work but: 1) dropping one zone (no fit below UV)
2) strongly out of equipartition (by 10^3 to 10^6)
3) extremely low radiative efficiency

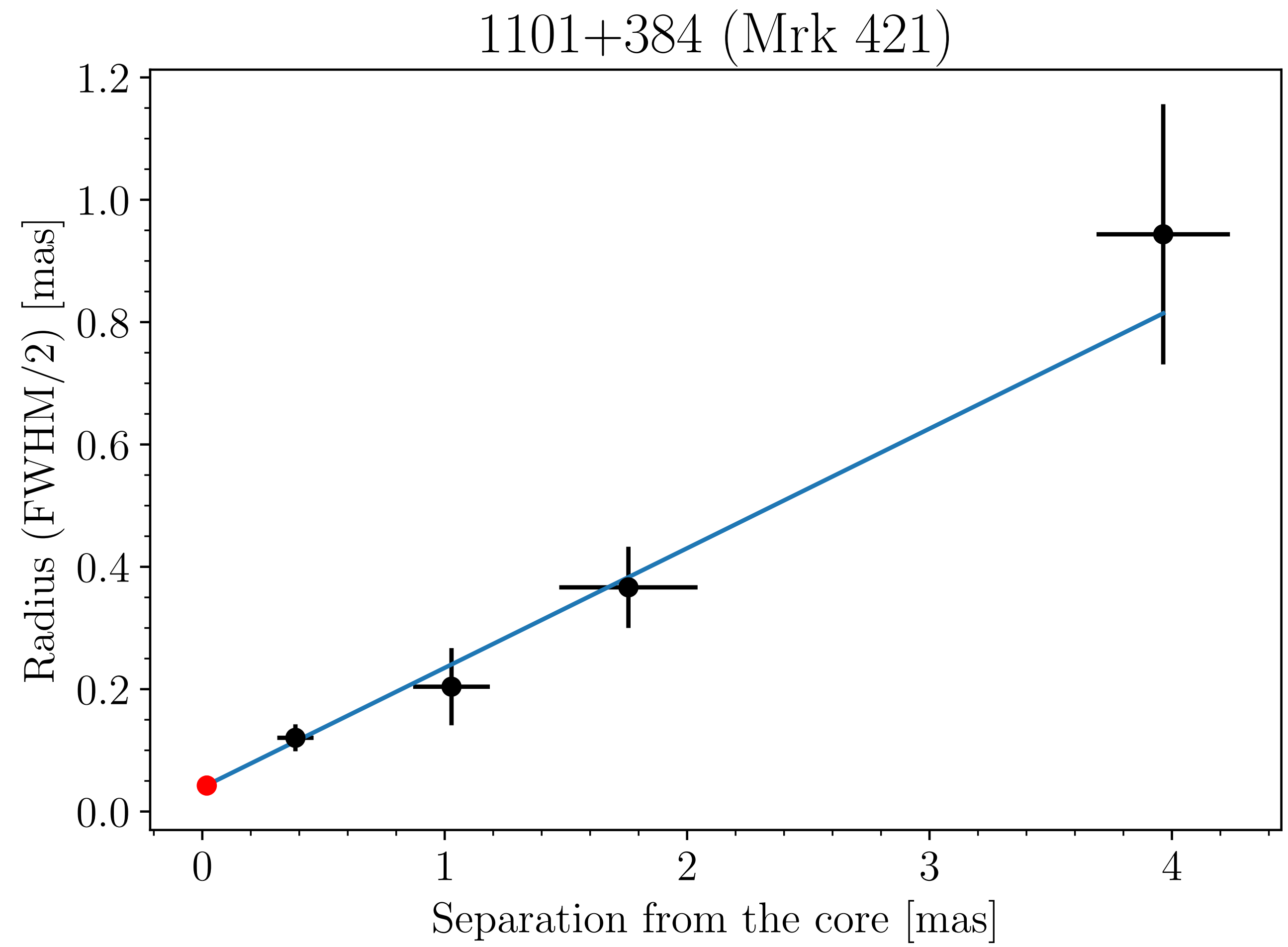
Super-Luminal Motion



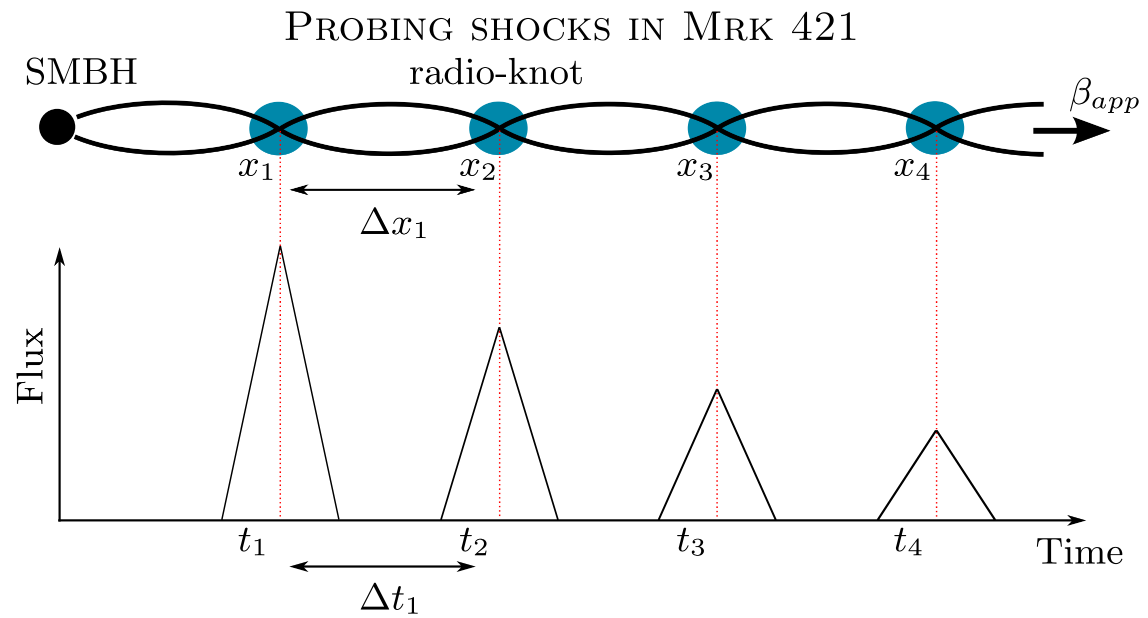
Lister+19

Mkn 421





Hervet+ 19
Lister+ 16

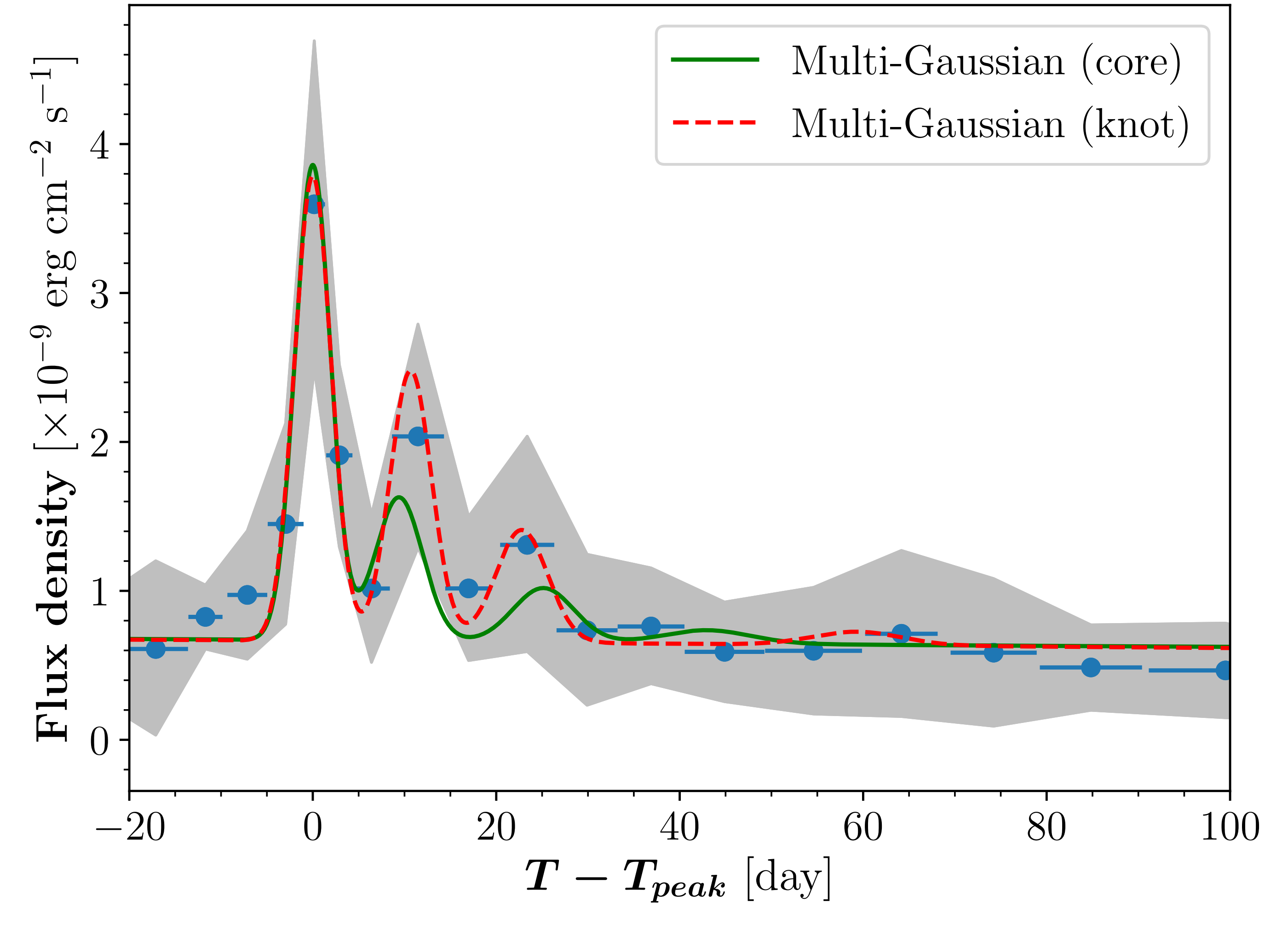

PROBING SHOCKS IN MRK 421
SMBH
radio-knot
β_{app}
x_1
x_2
x_3
x_4
Δx_1
Flux
t_1
t_2
t_3
t_4
Time
Δt_1

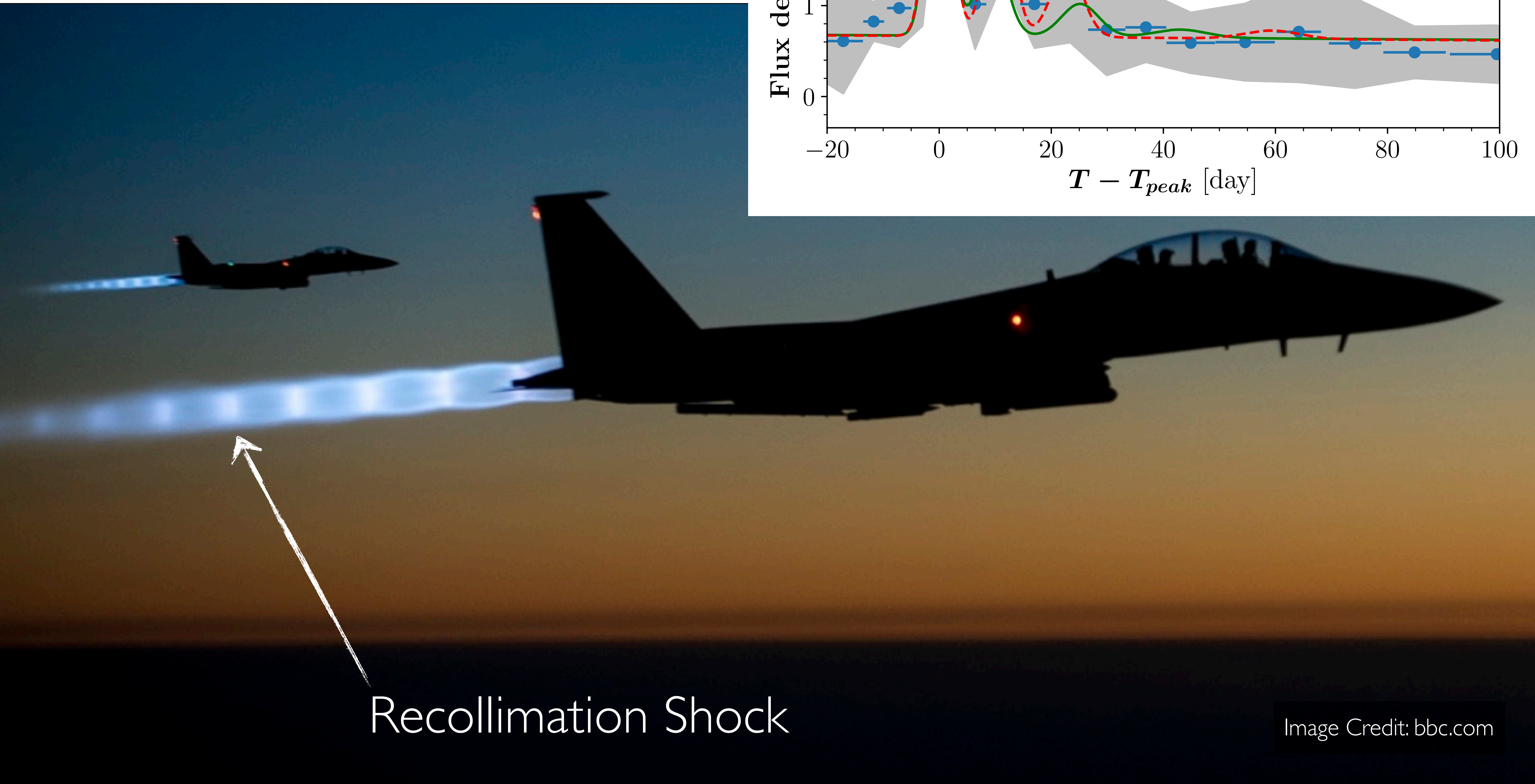

Recollimation Shock
Image Credit: bbc.com
MacDonald, CTA symposium

X-Ray SWIFT stacked lightcurves of 6 flares

$$\beta_{app} \simeq 45 \pm 4$$

Hervet+ 19





Take-home messages:

1) EC as we know it (BLR) does not work ! (IR ok)

- ⇒ FSRQ gamma-ray spectrum mostly intrinsic (particle distribution)
- ⇒ new diagnostic possibilities (e.g. Lefa et al 2014)
- ⇒ CTA sky should be much richer of FSRQ

2) SSC unrealistic for *Extreme-TeV* BL Lacs ?

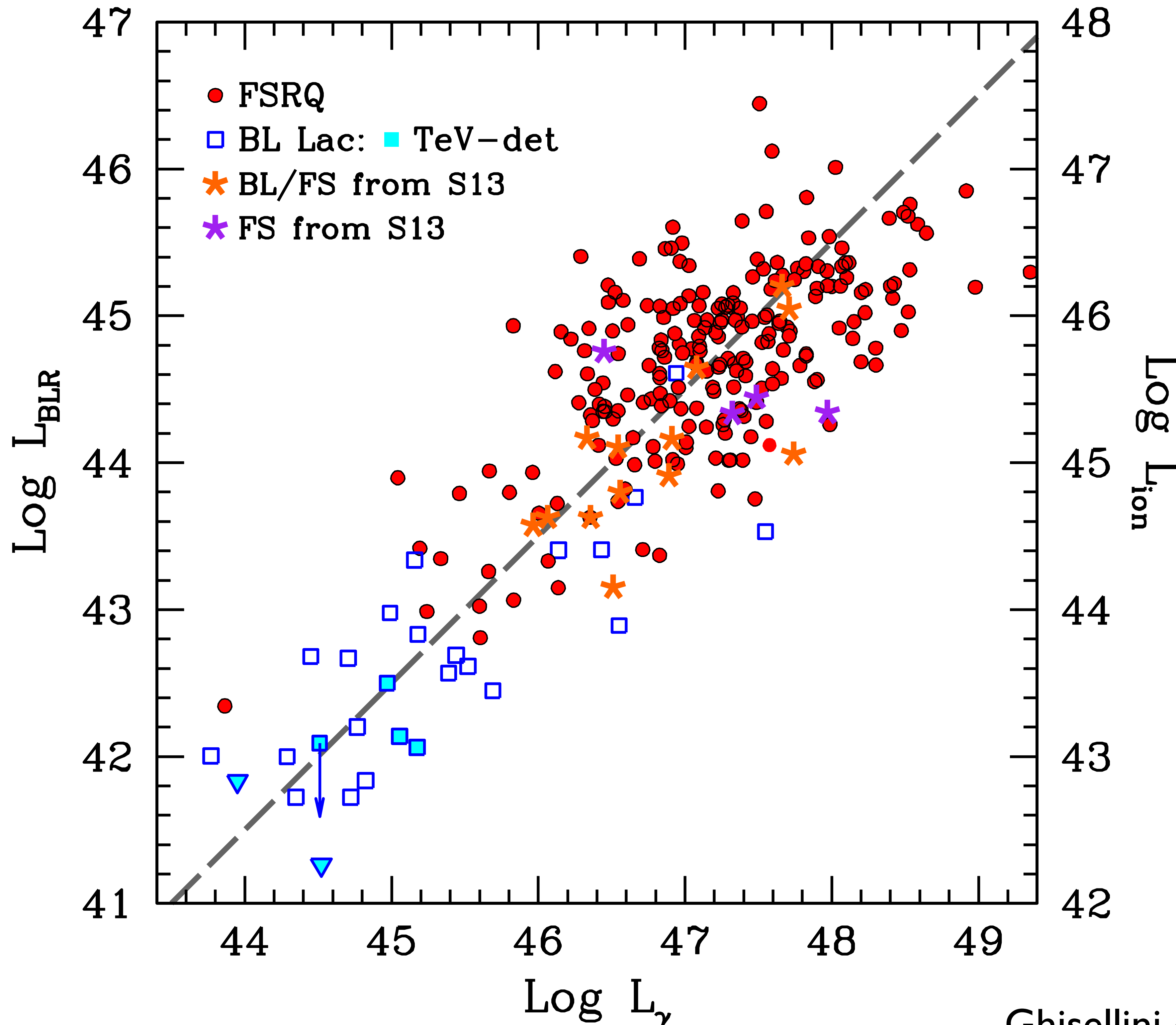
- ⇒ unrealistic parameters ? (B~mG, low eff., no equipartition, no SED)
- ⇒ still not extreme accelerators (like Crab etc), missing ?

3) Ultra-fast variability is characteristics of AGN jets (all types of RG/blazar)

4) In gamma-rays, lot of HSP-LSP interchanges

back-up slides

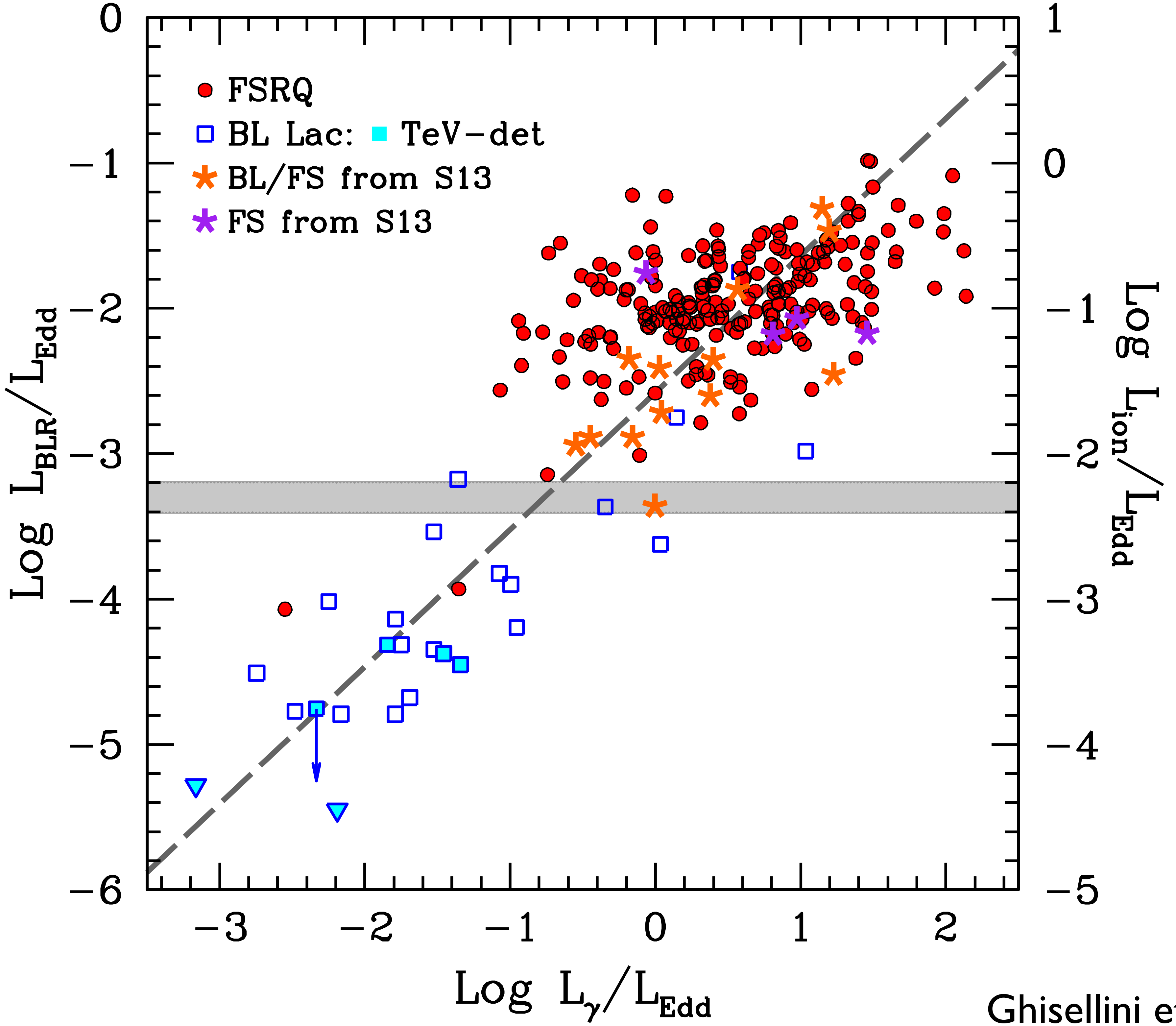
What about the Gamma-BLR connection then ?



Ghisellini et al 2013
Sbarrato et al 2011, 2014

What about the Jet-Accretion connection then ?

BLR acts as proxy of the disk, does not affect Jet radiation



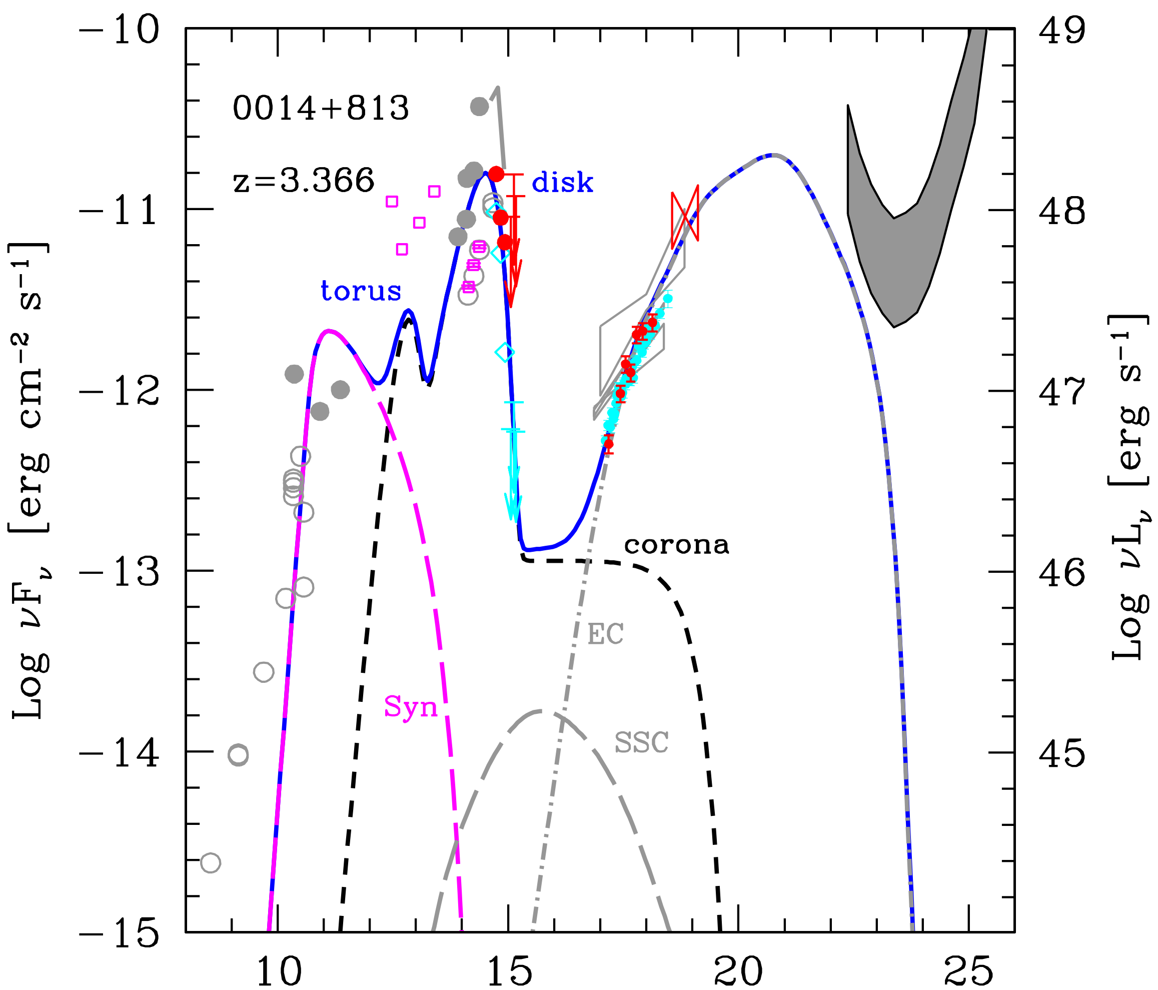
radiatively efficient

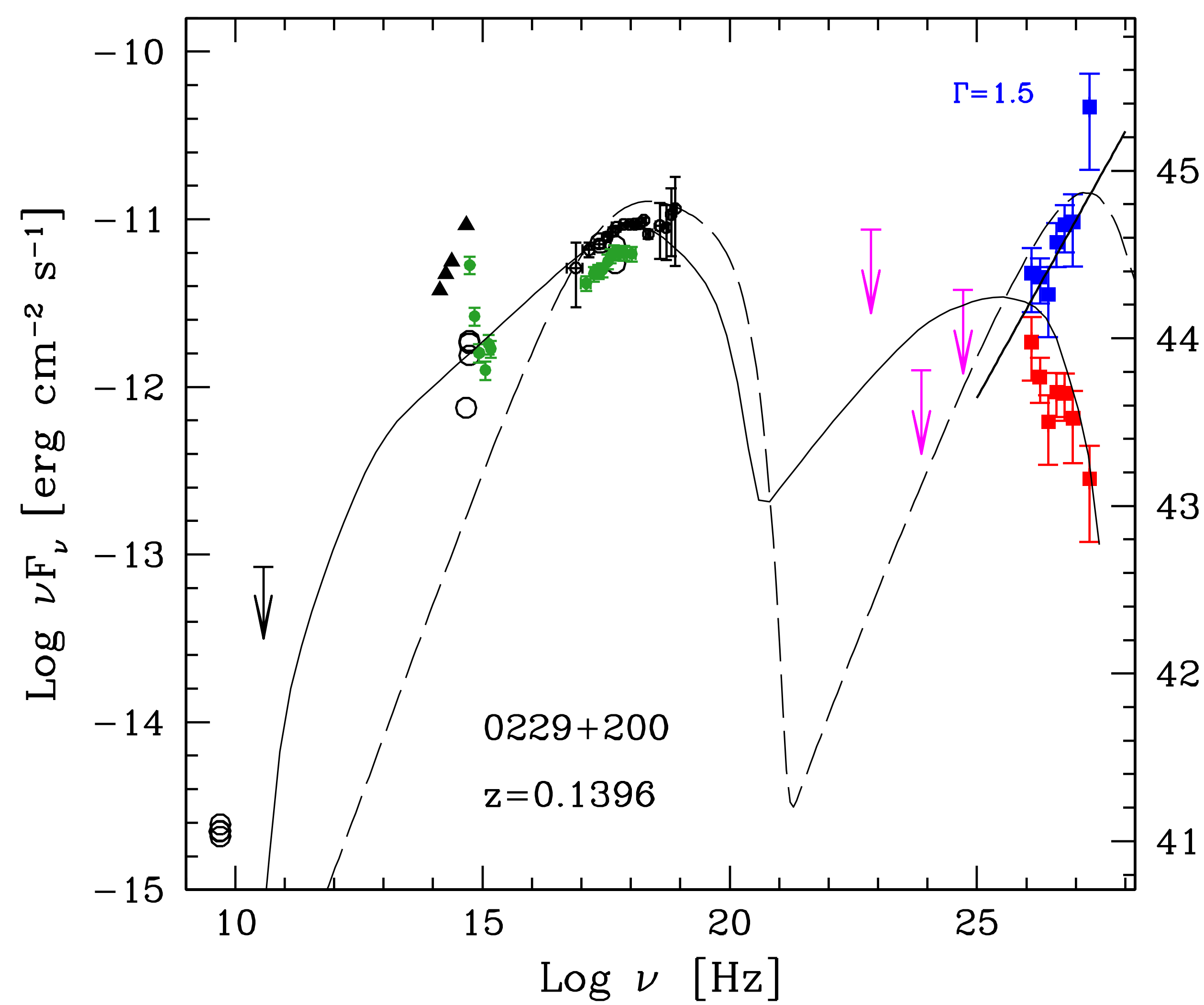
radiatively inefficient

Ghisellini et al 2013
Sbarrato et al 2011, 2014

NOTE: Fermi does ***NOT*** see all type of Blazars

misses at the two ends of SED sequence





MeV-peaked (high-z) Blazars

eRosita survey

TeV-peaked BL Lacs

CTA survey