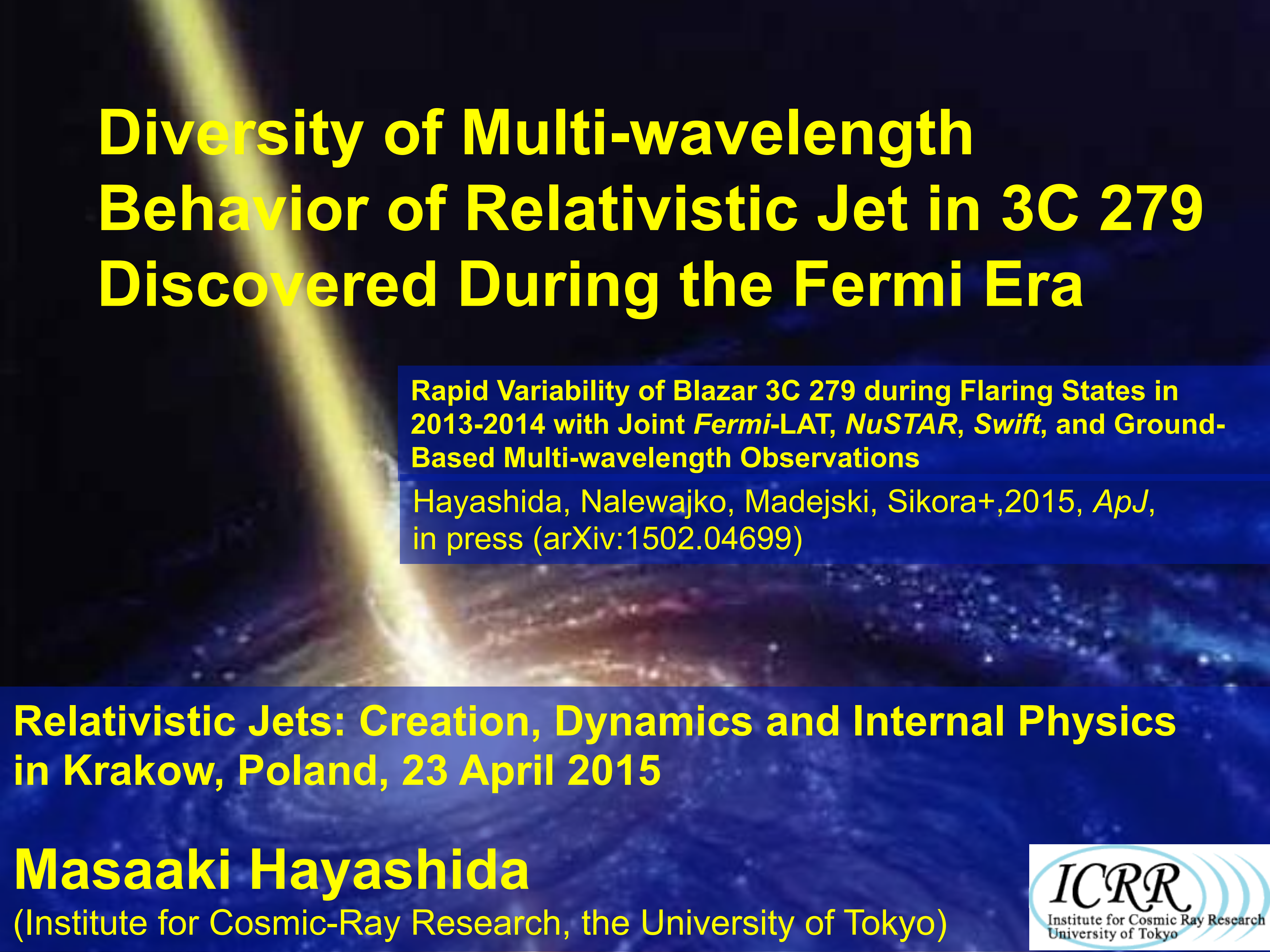


Diversity of Multi-wavelength Behavior of Relativistic Jet in 3C 279 Discovered During the Fermi Era

Rapid Variability of Blazar 3C 279 during Flaring States in 2013-2014 with Joint *Fermi*-LAT, *NuSTAR*, *Swift*, and Ground-Based Multi-wavelength Observations

Hayashida, Nalewajko, Madejski, Sikora+,2015, *ApJ*,
in press (arXiv:1502.04699)

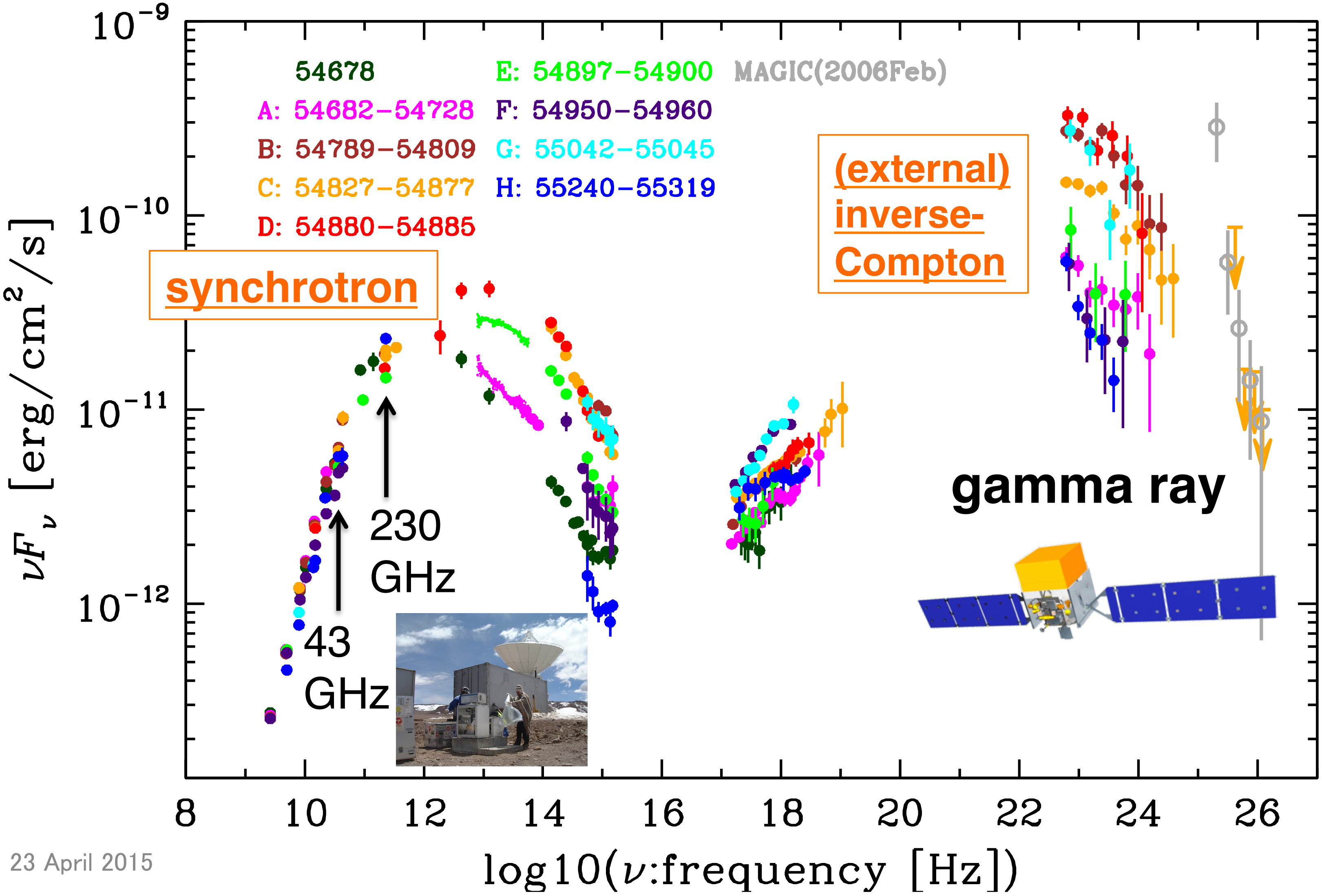
Relativistic Jets: Creation, Dynamics and Internal Physics in Krakow, Poland, 23 April 2015

Masaaki Hayashida
(Institute for Cosmic-Ray Research, the University of Tokyo)

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Emission from Jets (FSRQ)

3C 279 (MH, Madejski, Nalewajko, Sikora+12, *ApJ*, 754, 114)



Outline

- MWL observations in 2013-2014 for 3C 279 during the flaring states
  - Fermi-LAT, NuSTAR, Swift and optical, radio

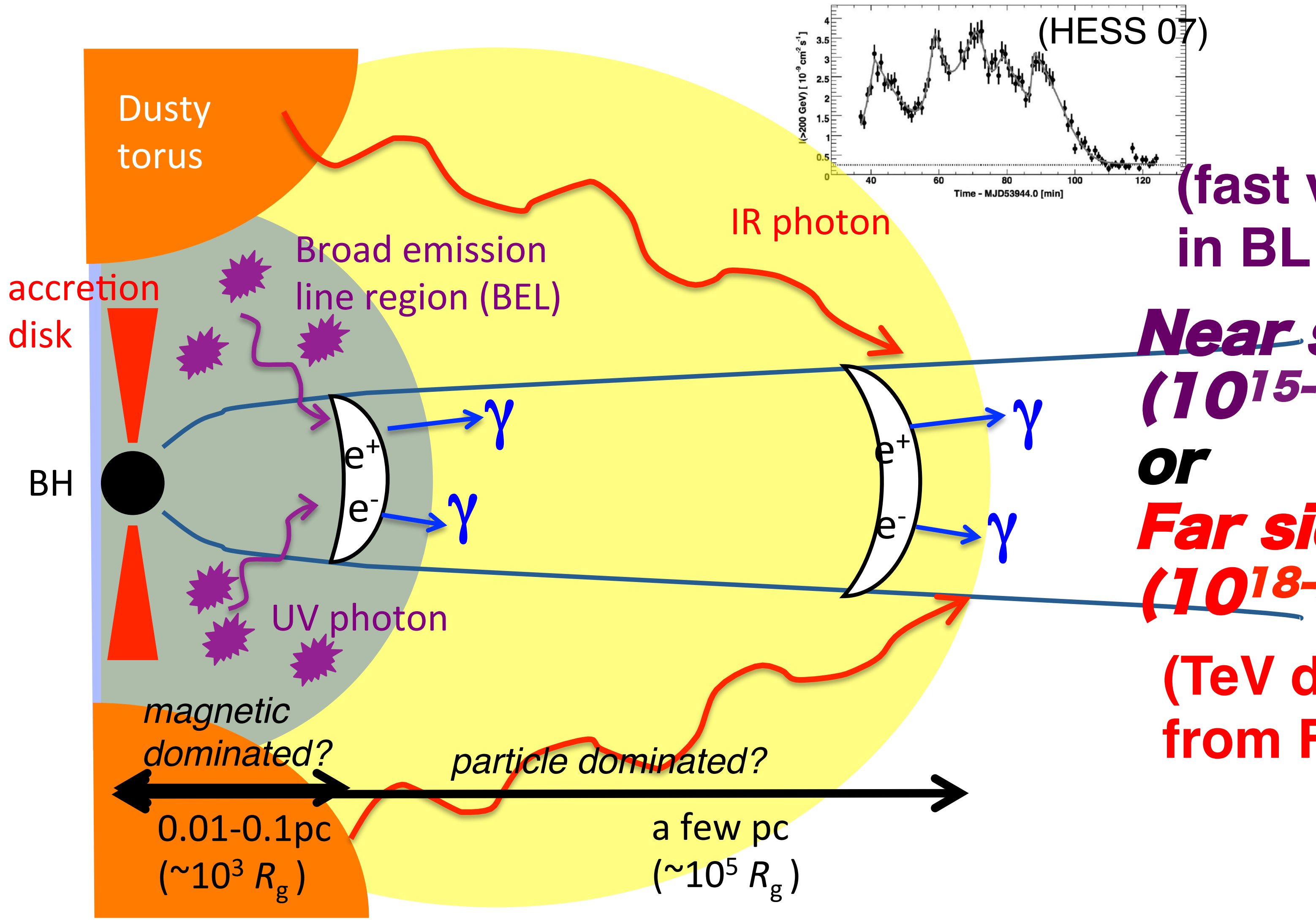
The First NuSTAR observations for the source

- origin of the X-ray emission

"orphan" γ-ray flare in 2013 December.

- *where is the gamma-ray emission site?*
- *what is the dominant component in jet?*
- *what is the acceleration mechanism?*

“where is gamma-ray emission site?”



(fast variability in BL Lacs)

Near side? (10^{15-17} cm)

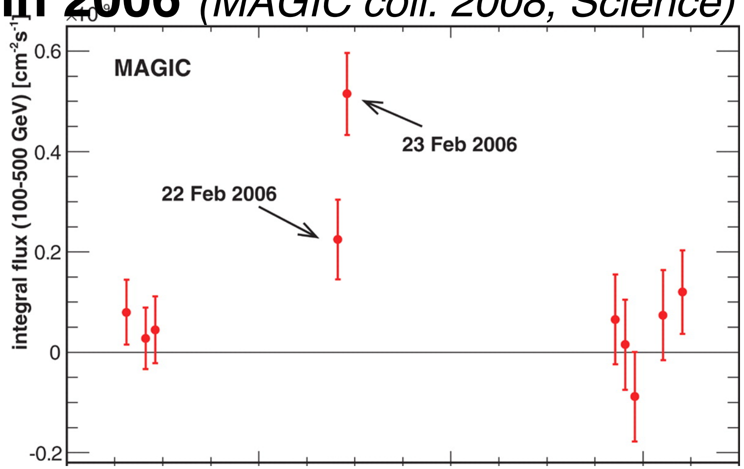
or

Far side? (10^{18-20} cm)

(TeV detection from FSRQs)

FSRQ 3C 279 (z=0.536)

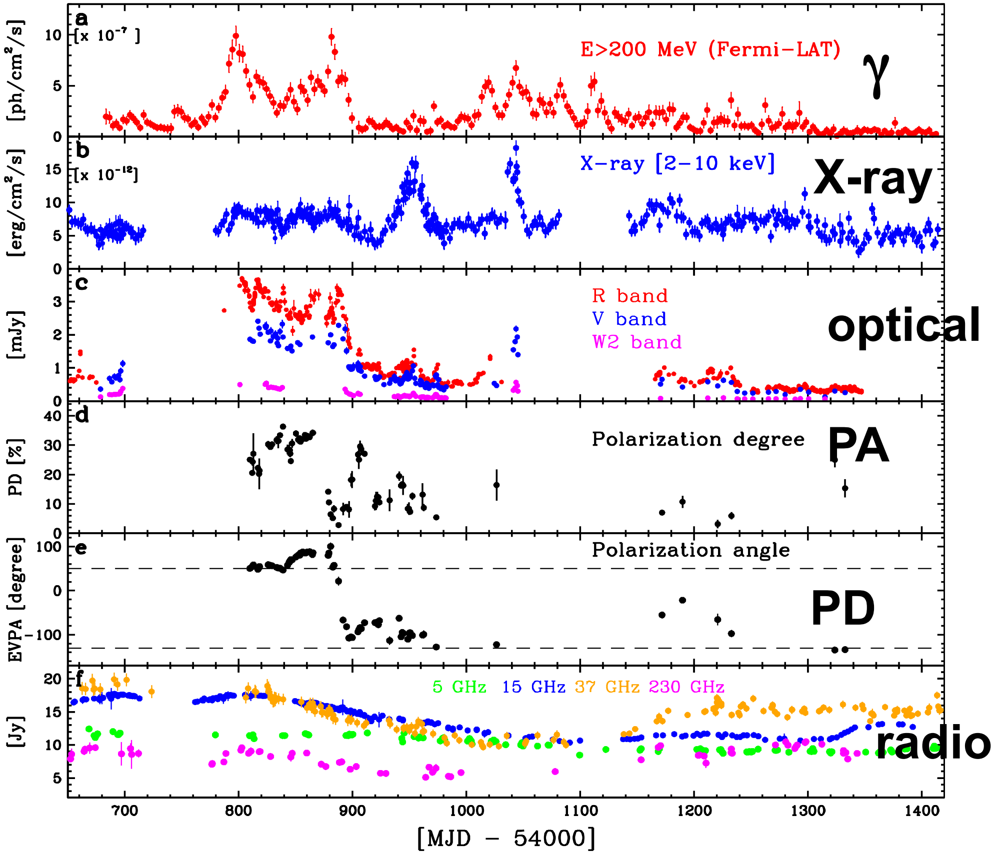
MAGIC detection (>100 GeV) **in 2006** *(MAGIC coll. 2008, Science)*



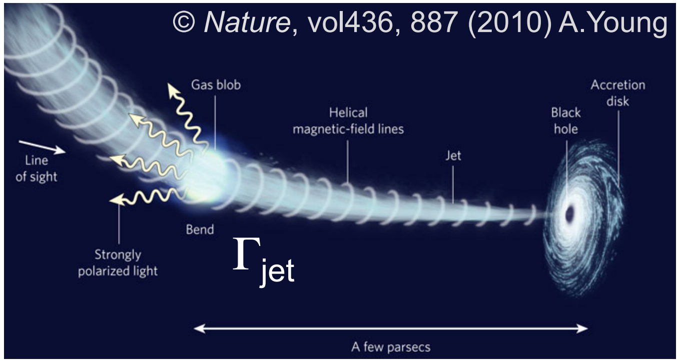
short time (~day) flare

Fermi+MWL in 2008-2010

(Abdo+ 2010, Nature; Hayashida+ 2012, ApJ)



<bent jet model: **(pc scale)**>

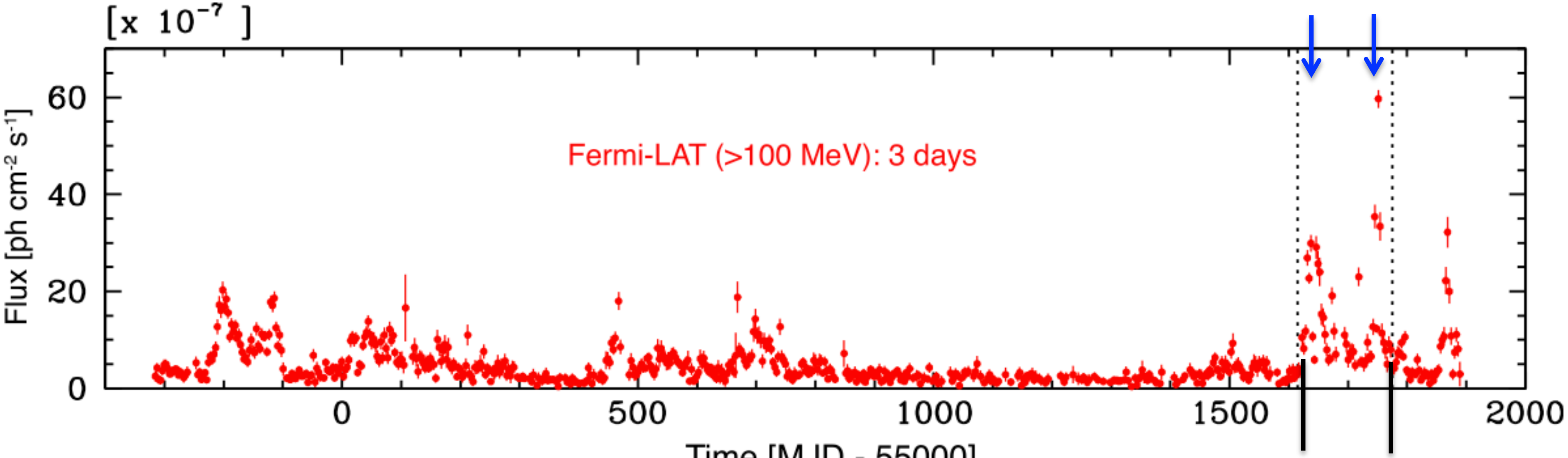


© *Nature*, vol436, 887 (2010) A.Young

no simultaneous
HE (LAT) + VHE (IACT) spectra, yet

3C 279 activity for 6 years

- 2008 August – 2014 August measured by Fermi-LAT

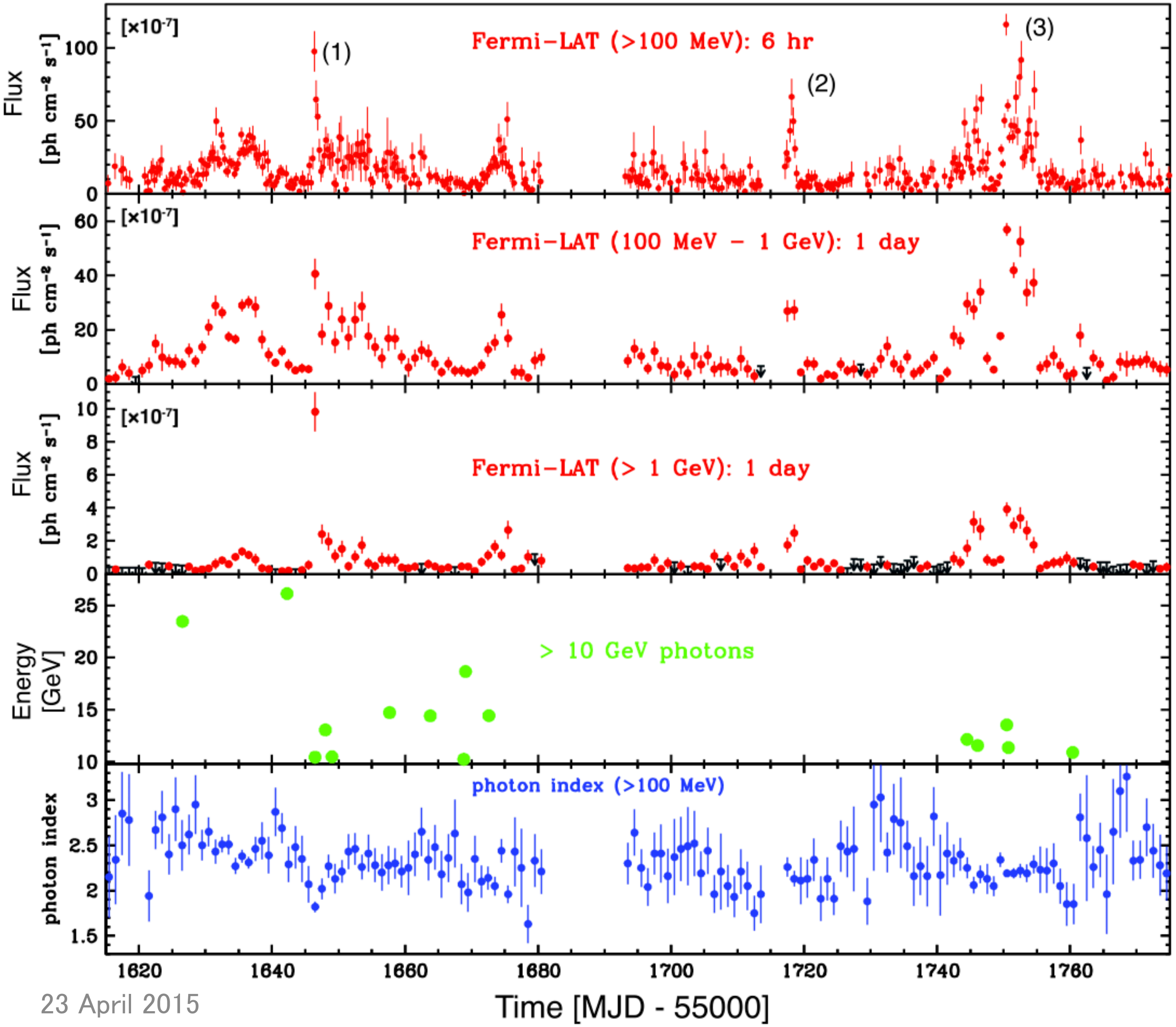


2013/11/19 – 2014/04/28
(MJD 56615 – 56775)

Gamma-ray flare activity reported in Atel

- 2013/12/21: #5680 Fermi LAT detection of a GeV flare from the FSRQ 3C 279
- 2014/04/01: #6036 Fermi LAT detection of renewed GeV activity from blazar 3C 279

Fermi-LAT light curve

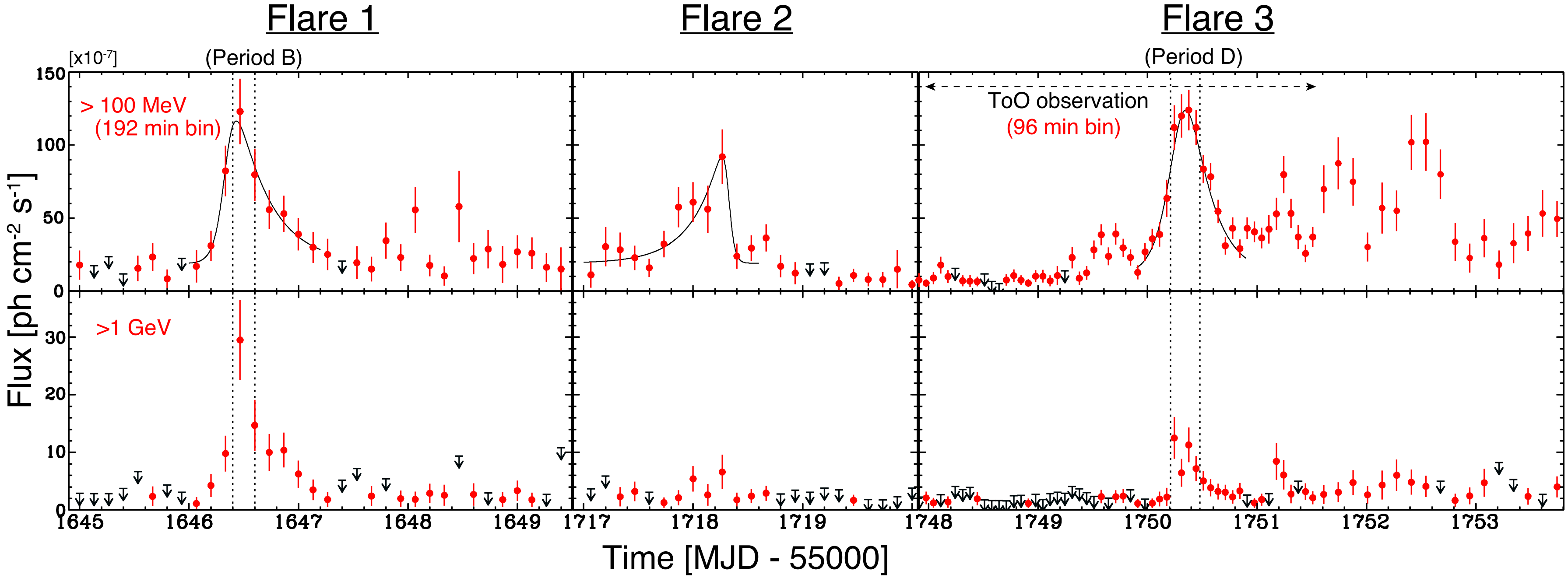


reached 10^{-5} ph/cm^2/s level in flux (> 100 MeV)

only a several FSRQs show such a high flux

c.f.
Crab: 2.5×10^{-6} ph/cm^2/s

Flare profile



$$F(t) = F_0 + \frac{b}{e^{-(t-t_0)/\tau_{\rm rise}} + e^{(t-t_0)/\tau_{\rm fall}}}$$

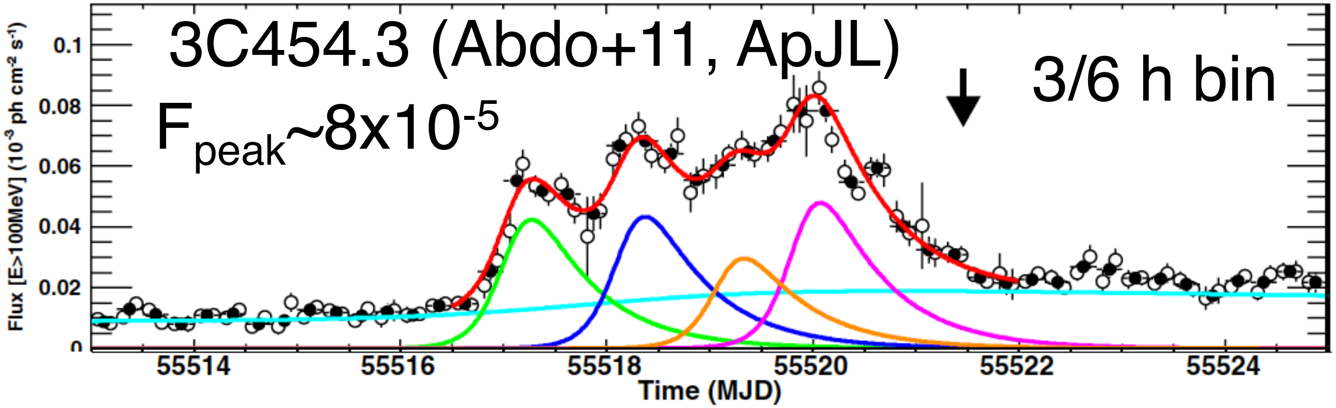
Flare number	$\tau_{\rm rise}$ [hrs]	$\tau_{\rm fall}$ [hrs]	b ($\times 10^{-7}$) photons cm^{-2} s^{-1}	F_0 ($\times 10^{-7}$) photons cm^{-2} s^{-1}
Flare 1	1.4 ± 0.8	7.4 ± 3.2	150 ± 36	19 ± 12
Flare 2	6.4 ± 2.4	0.68 ± 0.59	100 ± 26	19 ± 5
Flare 3 (ToO)	2.6 ± 0.6	5.0 ± 0.8	216 ± 19	10.5 ± 6.6

- asymmetric profile
- hourly scale variability:

(2hr → *R* [emission region size] < ~ $4\text{x}10^{15}(\Gamma/20)$ cm)

short time variability in FSRQs

Fermi-LAT
(>100 MeV)

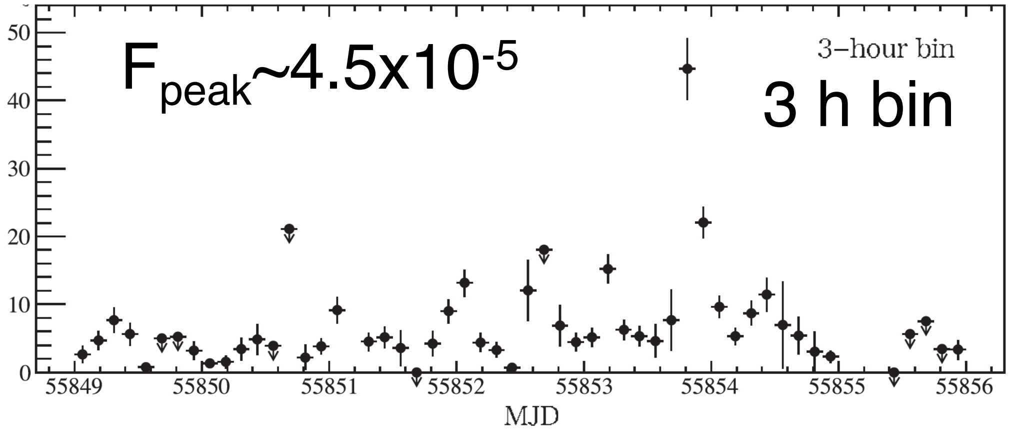


3C454.3 (Abdo+11, ApJL)

F_{peak}~8x10^{-5}

3/6 h bin

PKS1510-089 (Saito+13 ApJL)

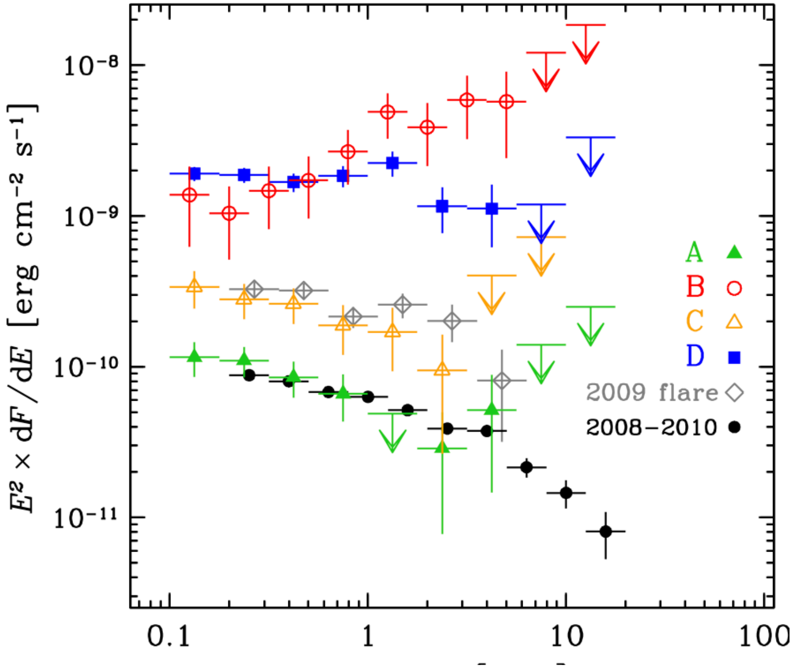


F_{peak}~4.5x10^{-5}

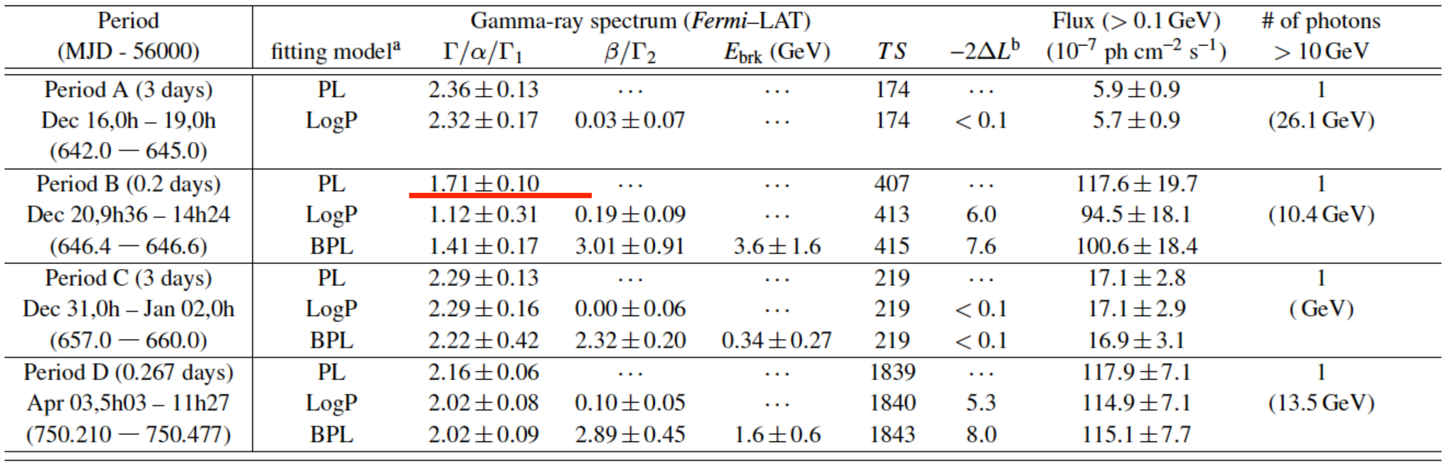
3 h bin

(see more
in Saito's talk tomorrow)

LAT Spectrum



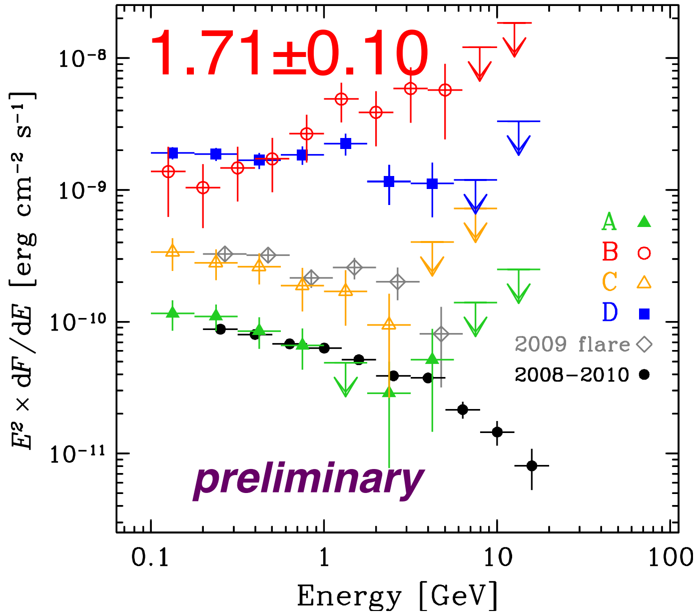
- **Very hard index (1.71±0.10)**
- **peaked at a few GeV**



Period (MJD - 56000)	fitting model[a]	$\Gamma/\alpha/\Gamma_1$	β/Γ_2	$E_{\rm brk}$ (GeV)	TS	$-2\Delta L$[b]	Flux (> 0.1 GeV) (10^{-7} ph cm^{-2} s^{-1})	# of photons > 10 GeV
Period A (3 days)	PL	2.36 ± 0.13	···	···	174	···	5.9 ± 0.9	1
Dec 16,0h – 19,0h	LogP	2.32 ± 0.17	0.03 ± 0.07	···	174	< 0.1	5.7 ± 0.9	(26.1 GeV)
(642.0 — 645.0)								
Period B (0.2 days)	PL	1.71 ± 0.10	···	···	407	···	117.6 ± 19.7	1
Dec 20,9h36 – 14h24	LogP	1.12 ± 0.31	0.19 ± 0.09	···	413	6.0	94.5 ± 18.1	(10.4 GeV)
(646.4 — 646.6)	BPL	1.41 ± 0.17	3.01 ± 0.91	3.6 ± 1.6	415	7.6	100.6 ± 18.4	
Period C (3 days)	PL	2.29 ± 0.13	···	···	219	···	17.1 ± 2.8	1
Dec 31,0h – Jan 02,0h	LogP	2.29 ± 0.16	0.00 ± 0.06	···	219	< 0.1	17.1 ± 2.9	(GeV)
(657.0 — 660.0)	BPL	2.22 ± 0.42	2.32 ± 0.20	0.34 ± 0.27	219	< 0.1	16.9 ± 3.1	
Period D (0.267 days)	PL	2.16 ± 0.06	···	···	1839	···	117.9 ± 7.1	1
Apr 03,5h03 – 11h27	LogP	2.02 ± 0.08	0.10 ± 0.05	···	1840	5.3	114.9 ± 7.1	(13.5 GeV)
(750.210 — 750.477)	BPL	2.02 ± 0.09	2.89 ± 0.45	1.6 ± 0.6	1843	8.0	115.1 ± 7.7	

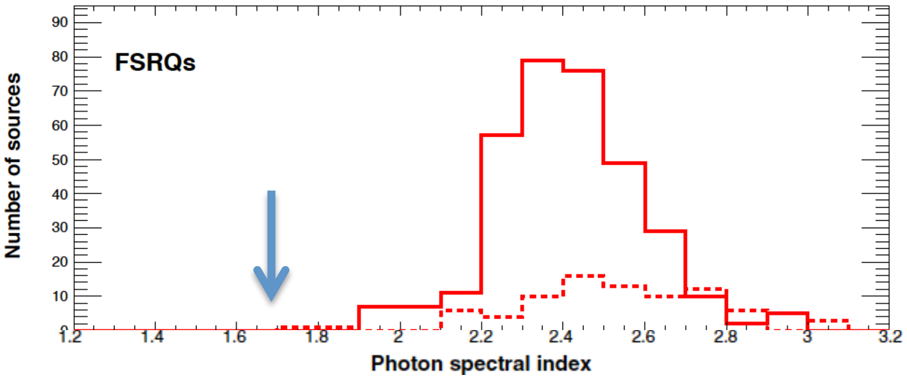
Hard spectra in FSRQs

3C 279 (this work)



Fermi 3rd AGN catalog (3LAC)

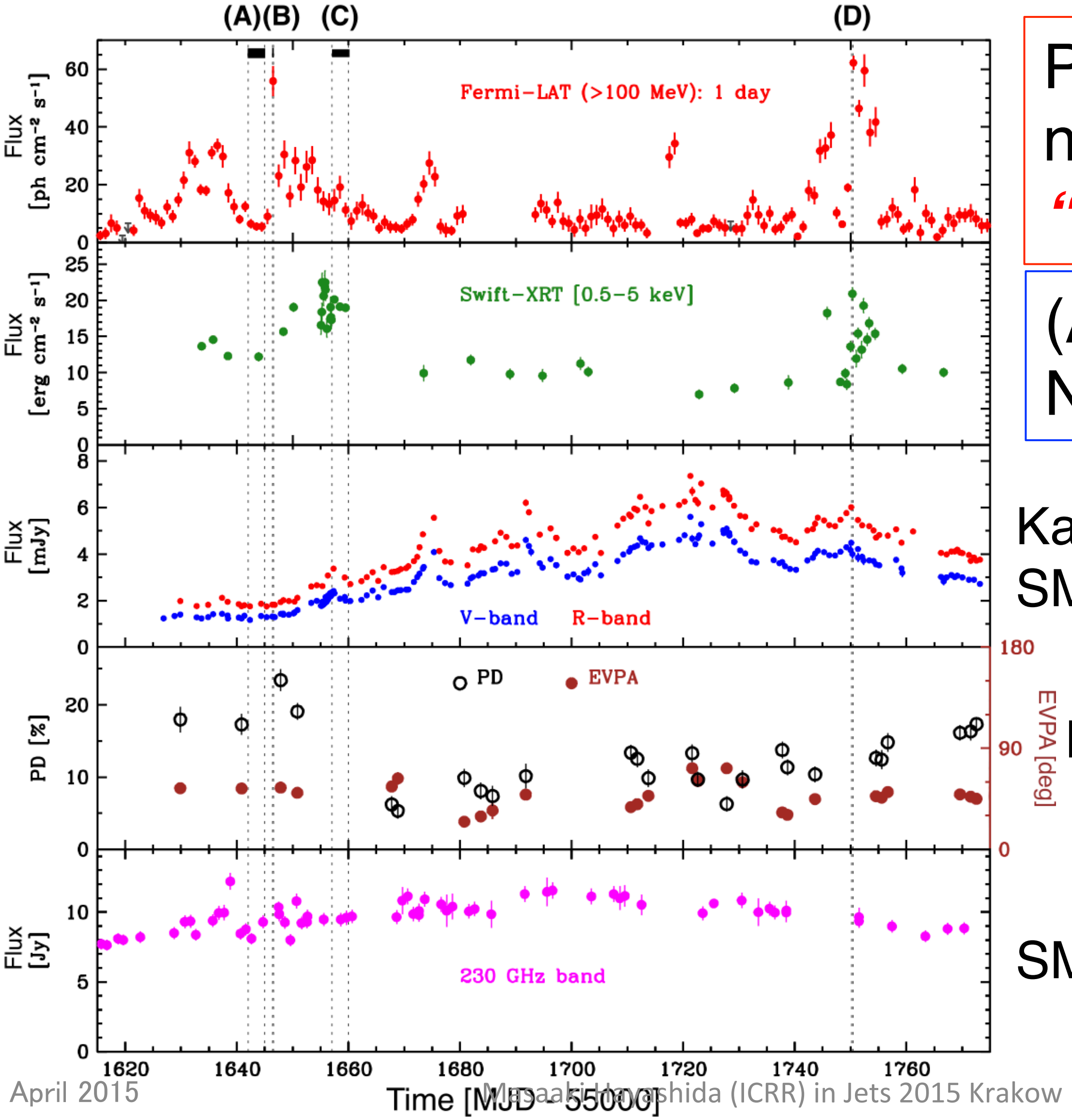
(= average state)



(Pacciani+14, ApJ, flaring FSRQs)

Source	Period A	Δ_t (days)	No. of HE Photons	Chance Prob. (%)****	$\Gamma_{\rm ph}$ (0.2–10 GeV)	Δ_t (days) for Period B	C	D	Prob shape$_A$ = shape$_B$ (%)
PKS 1502+106	2009 May 6 05:20–2009 May 6 13:11	0.326 (0.38)*	2	0.27/32.3	1.99 ± 0.31	4	8		<3.4
CTA 102	2012 Sep 22 18:12–2012 Sep 22 21:55	0.155	4	0.16/2.3****	1.73 ± 0.14	3	4***	4	0.36
3C 454.3	2013 Sep 24 15:00–2013 Sep 25 04:12	0.55	5	4.1/15.3	1.77 ± 0.17 (1.84 ± 0.08)**	3	3	3	<0.053
PKS 0805−07	2009 May 15 00:21–2009 May 15 08:26	0.337 (0.38)*	4	0.028/0.82	1.51 ± 0.34 (1.77 ± 0.10)**	8	8		0.97
4C +38.41	2011 Jul 3 15:39–2011 Jul 3 18:56	0.136 (0.30)*	2	0.038/4.1	1.85 ± 0.23	4	8		<1.4

Multi-band light curve



Period (B):
no flare in other bands
"orphan" γ-ray flare

(A), (C)
NuSTAR observations

Kanata,
SMART

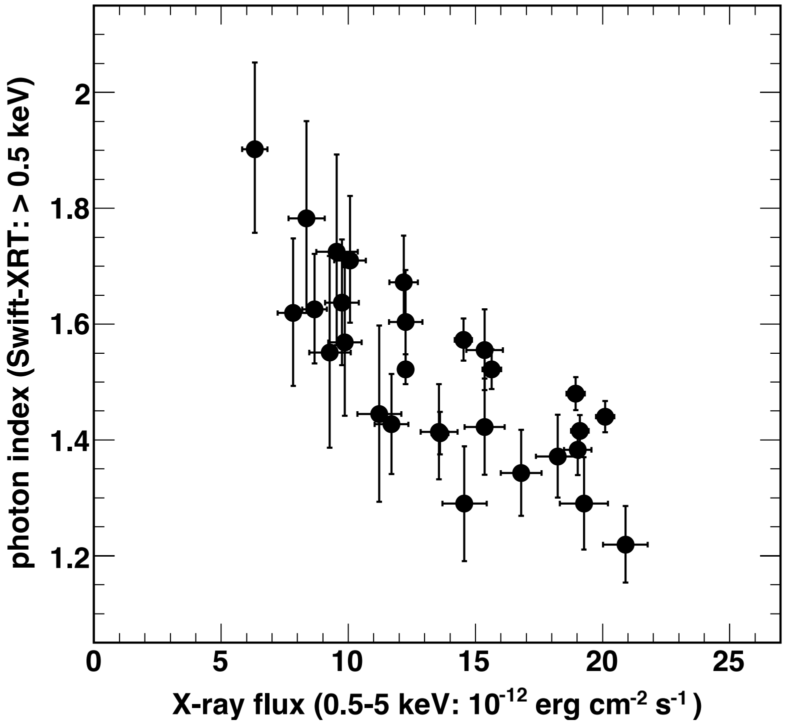
Kanata

SMA

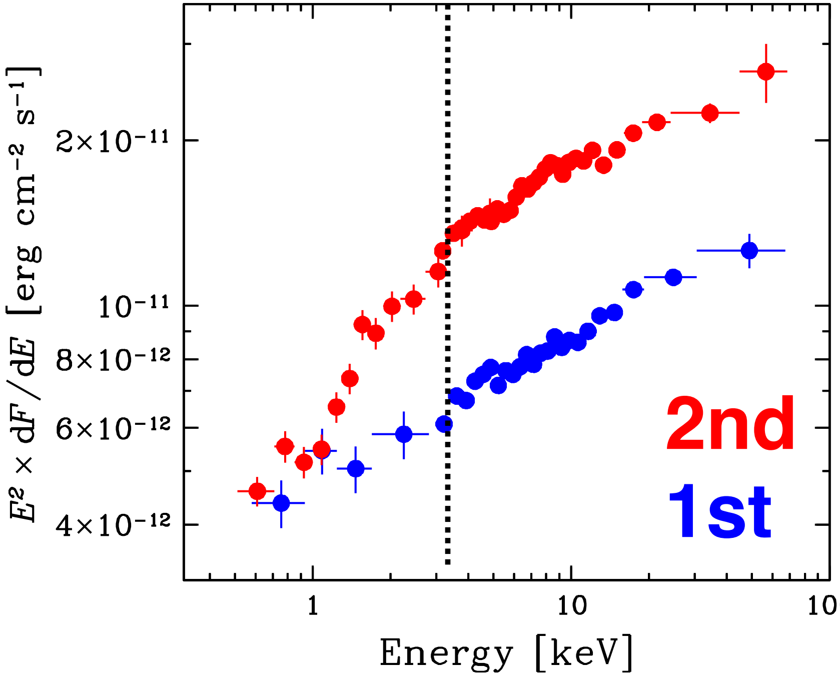
X-ray bands (Swift+NuSTAR)

Two NuSTAR observations (1: Dec.18 2013, 2: Jan.1 2014)
: ~ 40 ks exposure for each

Swift-XRT



Swift(XRT)+NuSTAR



1st: simple power law: 1.74±0.01

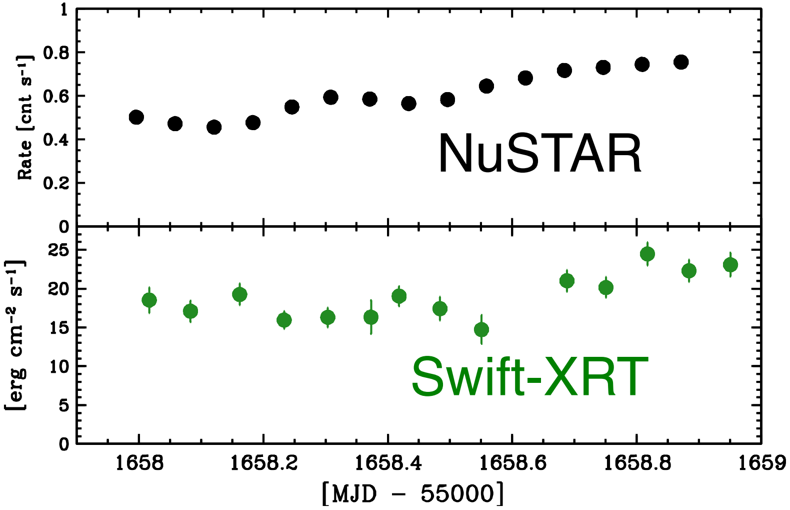
2nd : double broken power law:

1.37±0.3, 1.72±0.02, 1.81±0.02

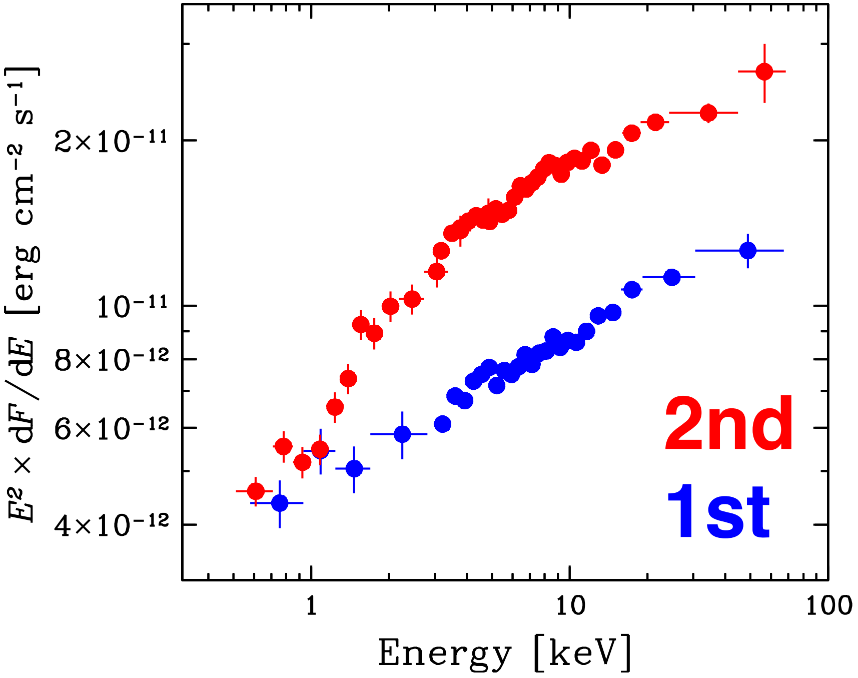
X-ray bands (Swift+NuSTAR)

Two NuSTAR observations (1: Dec.18 2013, 2: Jan.1 2014)
: ~ 40 ks exposure for each

<Light curve in the 2nd obs.>

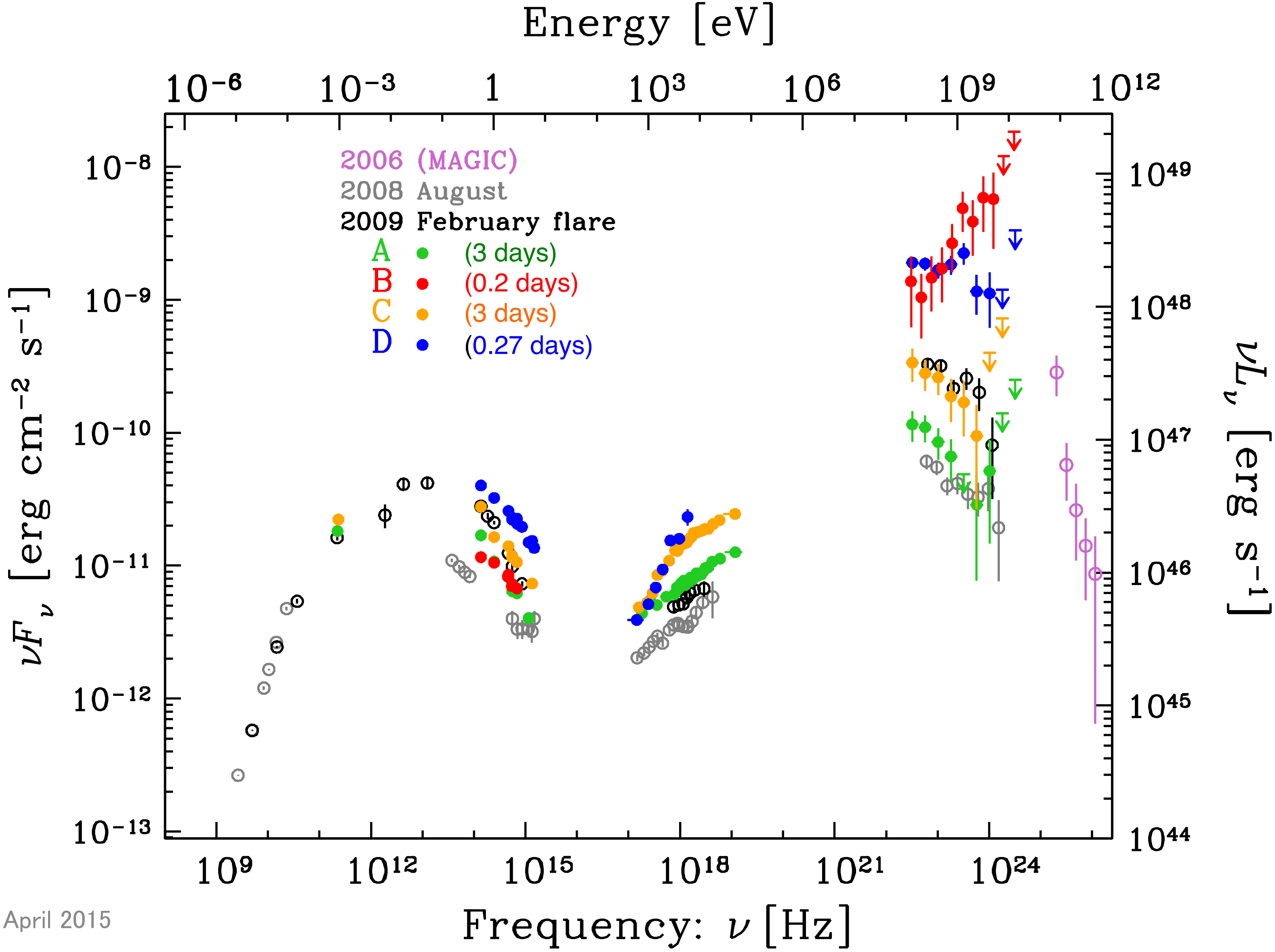


Swift(XRT)+NuSTAR



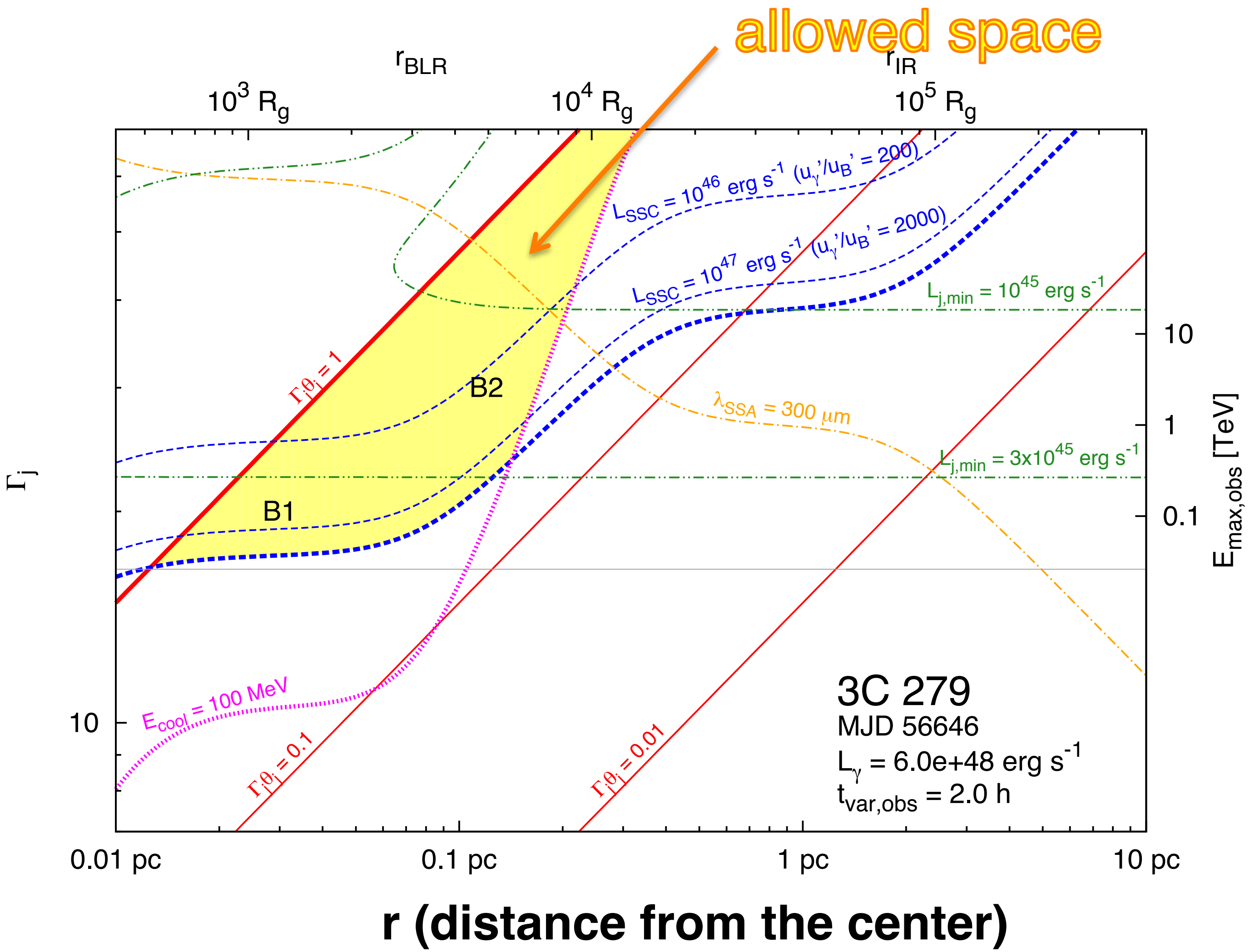
- EIC by low energy electrons? (should *not* be variable in a day)
- SSC? (too hard of Γ_x=1.37 in the Swift-XRT band)
- another region? (slower (sheath) part?)

Broad band SED



constraints of emission model parameter

(see details in Nalewajko's talk tomorrow)



collimation

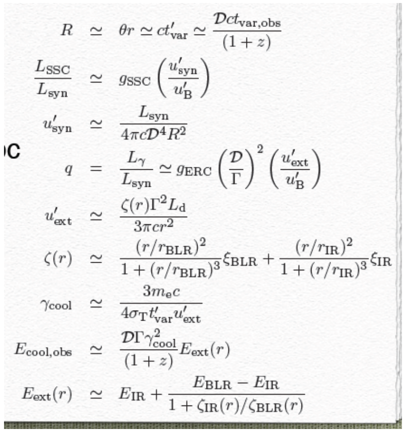
SSC

cooling

SSA

jet power

opacity



$$R \simeq \theta r \simeq c t'_{\rm var} \simeq \frac{\mathcal{D} c t_{\rm var,obs}}{(1+z)}$$

$$\frac{L_{\rm SSC}}{L_{\rm syn}} \simeq g_{\rm SSC}\left(\frac{u'_{\rm syn}}{u'_{\rm B}}\right)$$

$$u'_{\rm syn} \simeq \frac{L_{\rm syn}}{4\pi c \mathcal{D}^4 R^2}$$

$$q = \frac{L_\gamma}{L_{\rm syn}} \simeq g_{\rm ERC}\left(\frac{\mathcal{D}}{\Gamma}\right)^2\left(\frac{u'_{\rm ext}}{u'_{\rm B}}\right)$$

$$u'_{\rm ext} \simeq \frac{\zeta(r)\Gamma^2 L_{\rm d}}{3\pi c r^2}$$

$$\zeta(r) \simeq \frac{(r/r_{\rm BLR})^2}{1+(r/r_{\rm BLR})^3}\xi_{\rm BLR} + \frac{(r/r_{\rm IR})^2}{1+(r/r_{\rm IR})^3}\xi_{\rm IR}$$

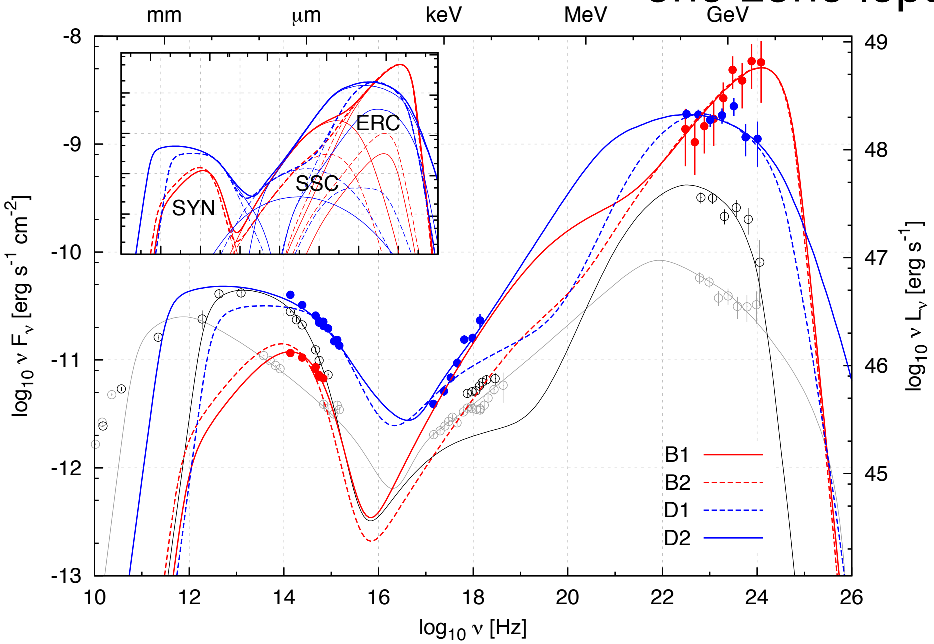
$$\gamma_{\rm cool} \simeq \frac{3 m_e c}{4\sigma_{\rm T} t'_{\rm var} u'_{\rm ext}}$$

$$E_{\rm cool,obs} \simeq \frac{\mathcal{D}\Gamma\gamma_{\rm cool}^2}{(1+z)} E_{\rm ext}(r)$$

$$E_{\rm ext}(r) \simeq E_{\rm IR} + \frac{E_{\rm BLR} - E_{\rm IR}}{1+\zeta_{\rm IR}(r)/\zeta_{\rm BLR}(r)}$$

emission model for Period B

one-zone leptonic model: BLAZAR (Moderski+2003)



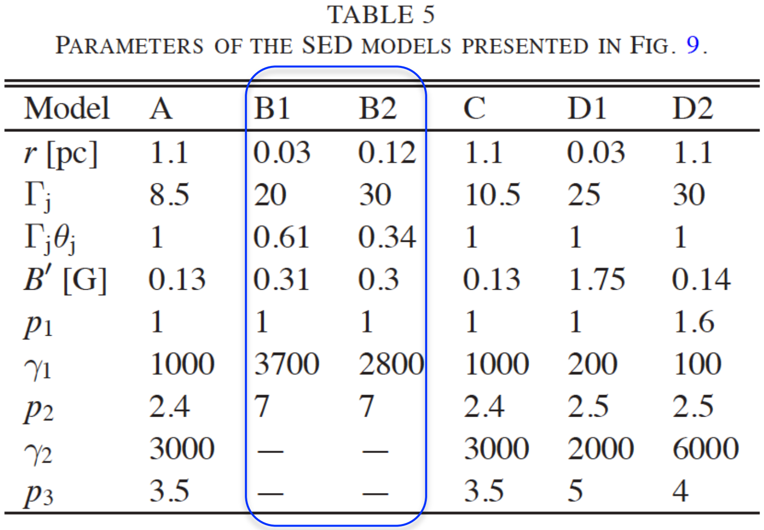


TABLE 5

PARAMETERS OF THE SED MODELS PRESENTED IN FIG. 9.

Model	A	B1	B2	C	D1	D2
r [pc]	1.1	0.03	0.12	1.1	0.03	1.1
Γ_j	8.5	20	30	10.5	25	30
$\Gamma_j\theta_j$	1	0.61	0.34	1	1	1
B' [G]	0.13	0.31	0.3	0.13	1.75	0.14
p_1	1	1	1	1	1	1.6
γ_1	1000	3700	2800	1000	200	100
p_2	2.4	7	7	2.4	2.5	2.5
γ_2	3000	—	—	3000	2000	6000
p_3	3.5	—	—	3.5	5	4

1. Gamma-ray emission site should be inside BLR (< 0.1 pc)
2. very matter dominated jet: ***$L_B/L_{jet} \sim 10^{-4}$***
3. hard index (γ-ray band) in the fast cooling regime
   - required very hard index for electron injection spectrum: ***p=1***

emission model for Period B

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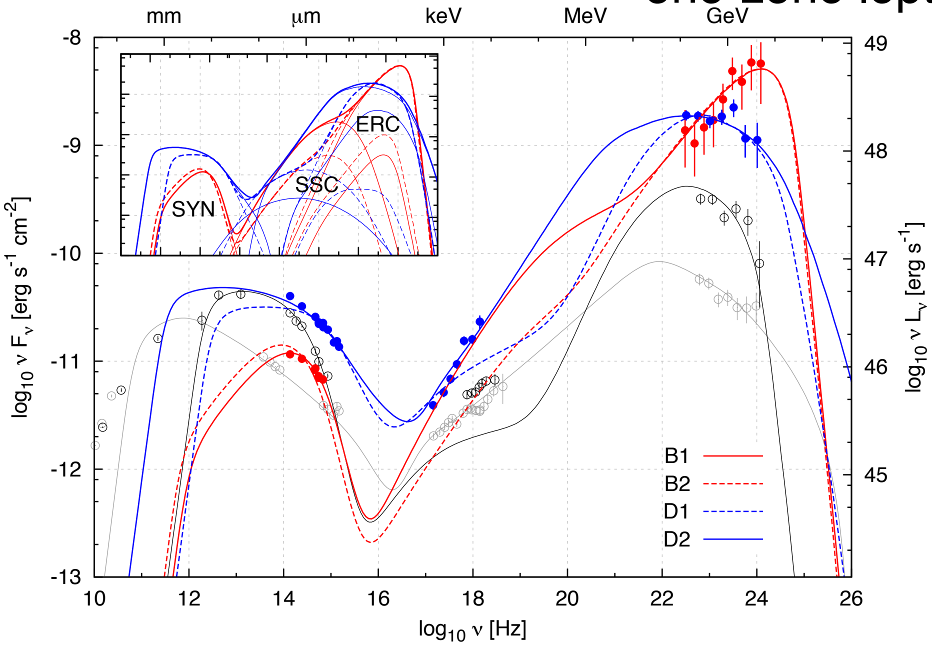

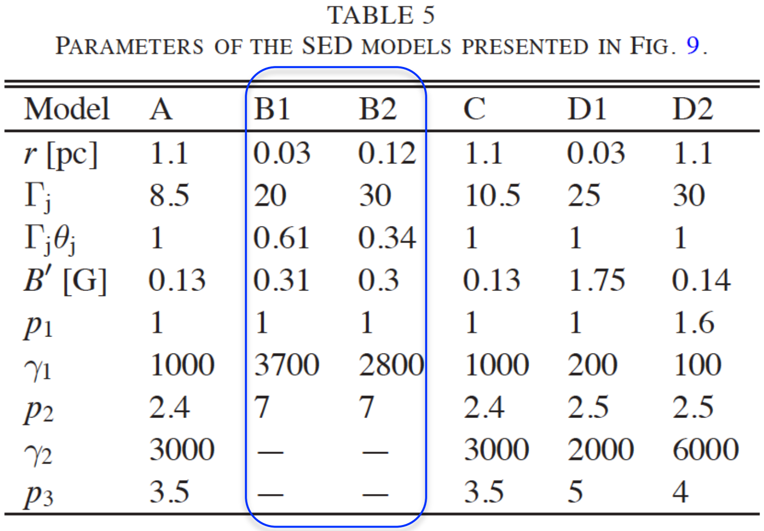

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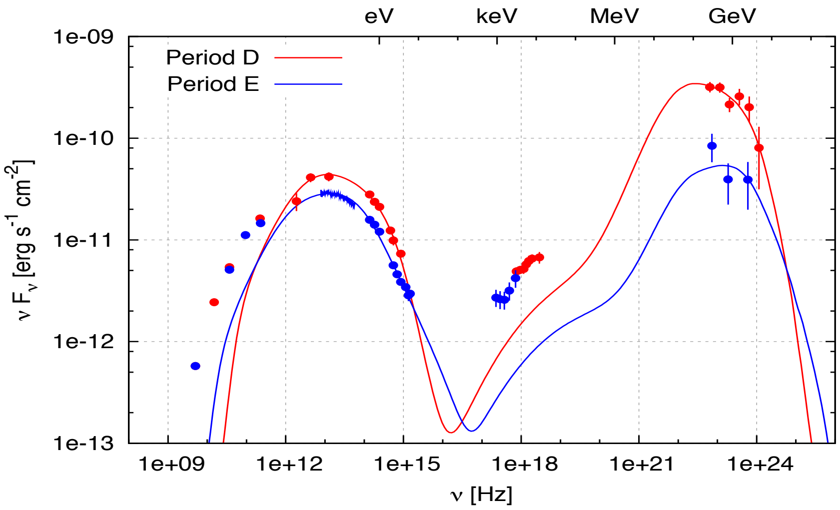
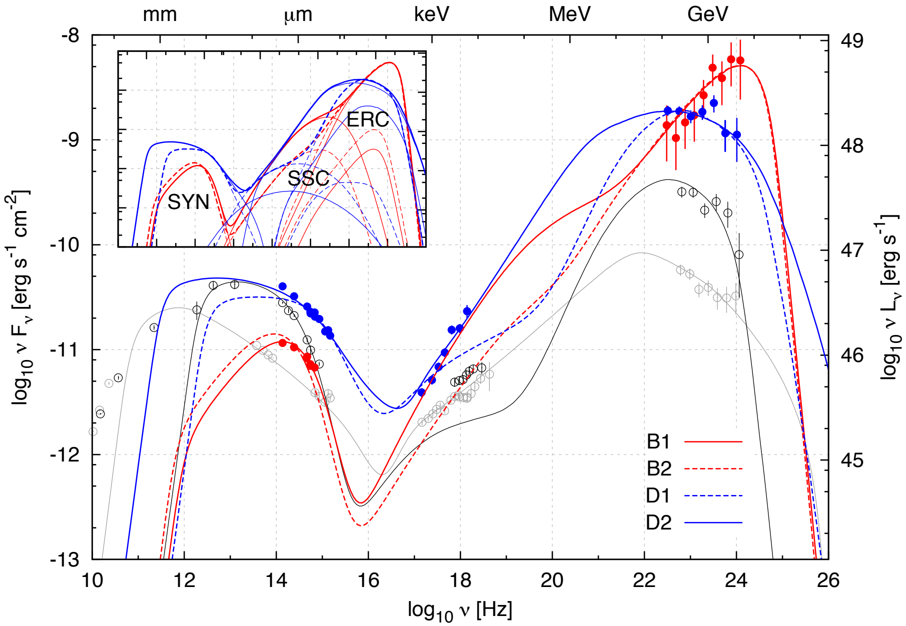
where is the emission region?

2009 (Hayashida+12)



a few pc (outside BLR)

2013-14 (this work)



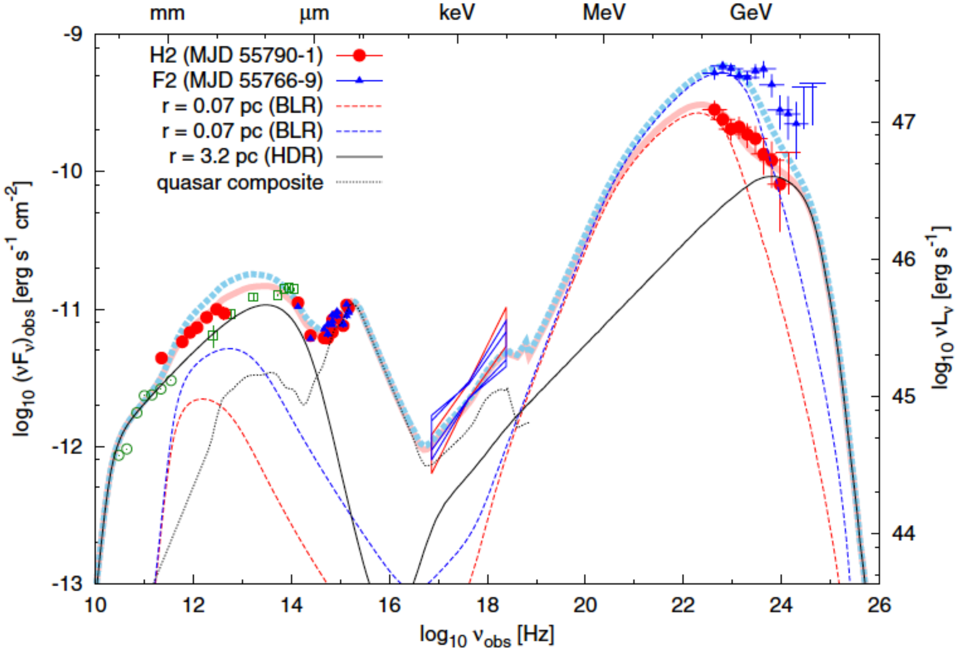
0.03 pc (inside BLR)

emission site is not unique!

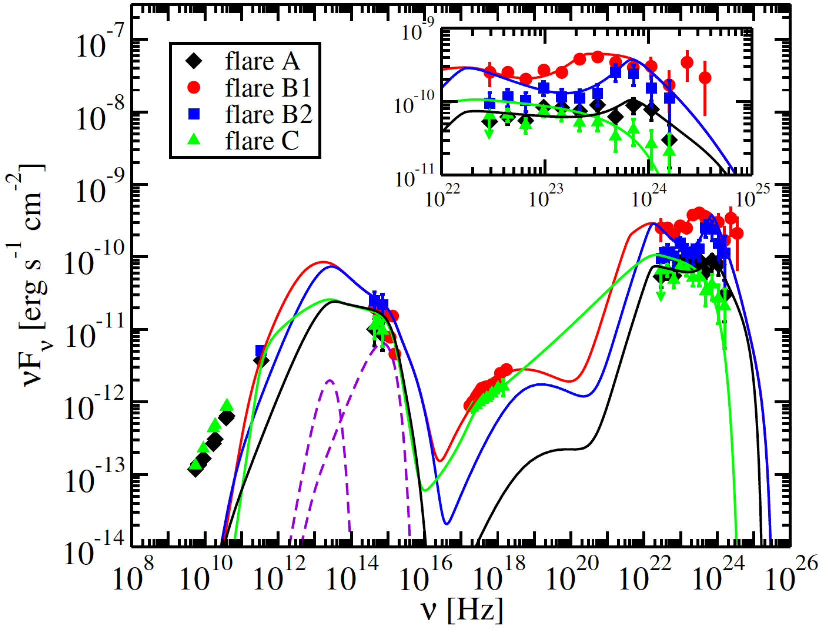
Multi-components for gamma-ray emission

Just examples

PKS1510-089 (z=0.31)
2011 (Nalewajko+12)



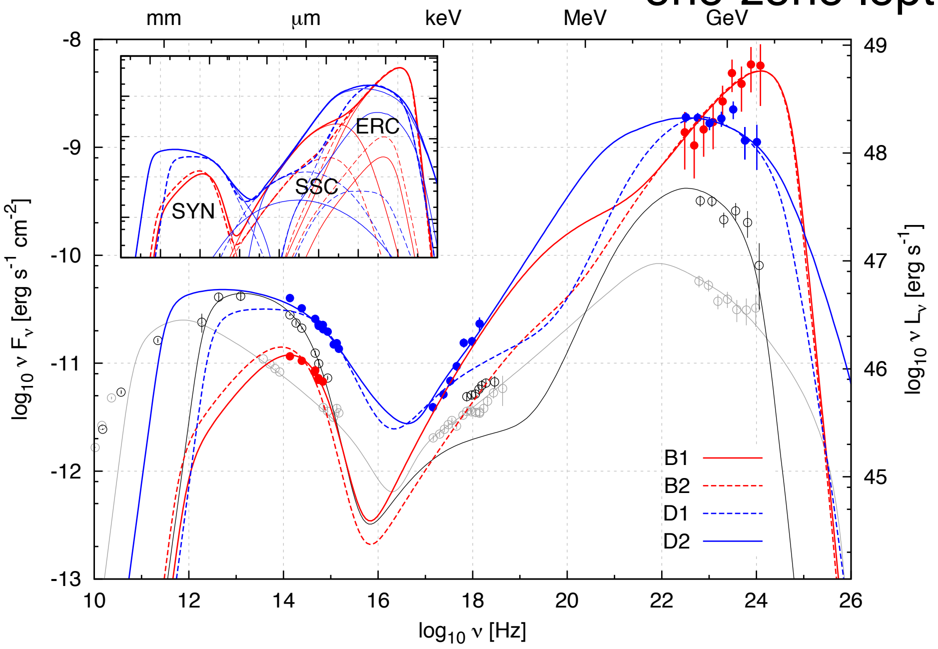
PKS1424-418 (z=1.522)
2008-2011 (Buson+14)

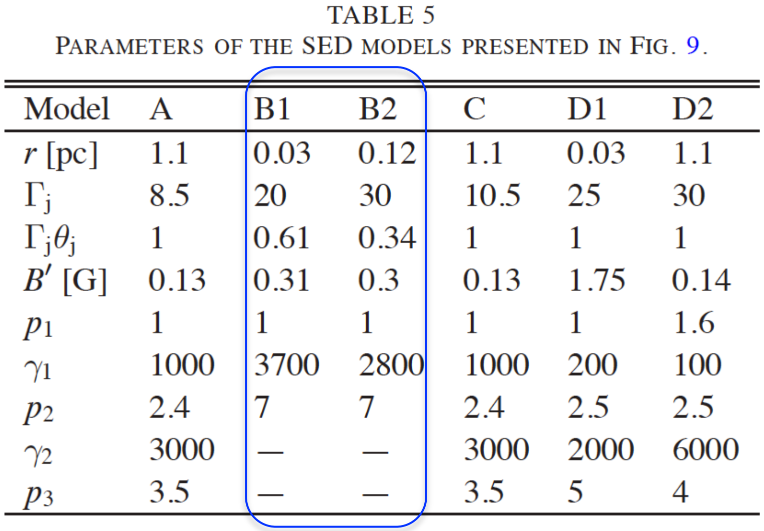


See also Fink&Demer+10 for 3C454.3
and many other works

emission model for Period B

one-zone leptonic model: BLAZAR (Moderski+2003)





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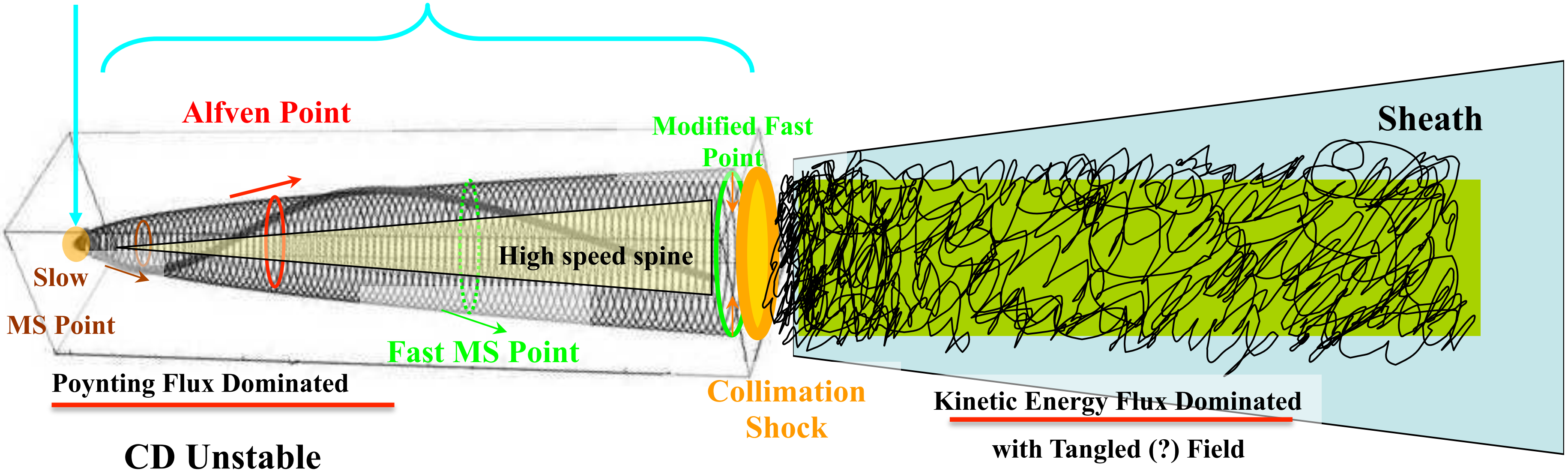
Regions of AGN Jet Propagation

Jet Launching Region

Jet Collimation Region (10 –100 × Launching Region)

Modified from Graphic courtesy David Meier



Alfven Point

Modified Fast Point

Sheath

High speed spine

Slow MS Point

Fast MS Point

Poynting Flux Dominated

Collimation Shock

Kinetic Energy Flux Dominated with Tangled (?) Field

CD Unstable Magnetic Helicity Driven Region

Combined CD/KH Unstable Region

KH Unstable Velocity Shear Driven Region

slide by Y.Mizuno

Poynting flux dominated?
Kinetic energy flux dominated?

- if jet is derived by the magnetic field
  (e.g., Blandford-Znajek process) ,,,,

  → jet should be Poynting-flux dominated jet < 10^3 r_g (= inside BRL)
- Leptonic models can explain well the broad band SED inside BLR (0.03 pc < 10^3 r_g for 5×10^8 M_{solar})
  - the emission model results suggest kinetic energy dominated jets (some models with equipartition
    see e.g., Dermer+14, *ApJ, 782* for 3C 279)
- Hadronic models require stronger magnetic fields (10-100 G) than the Leptonic models (0.01-1 G), but also requires very high power of relativistic protons, 10^{49} erg/s
  (e.g.,Zdziarski & Boettcher 15)

emission model for Period B

one-zone leptonic model: BLAZAR (Moderski+2003)

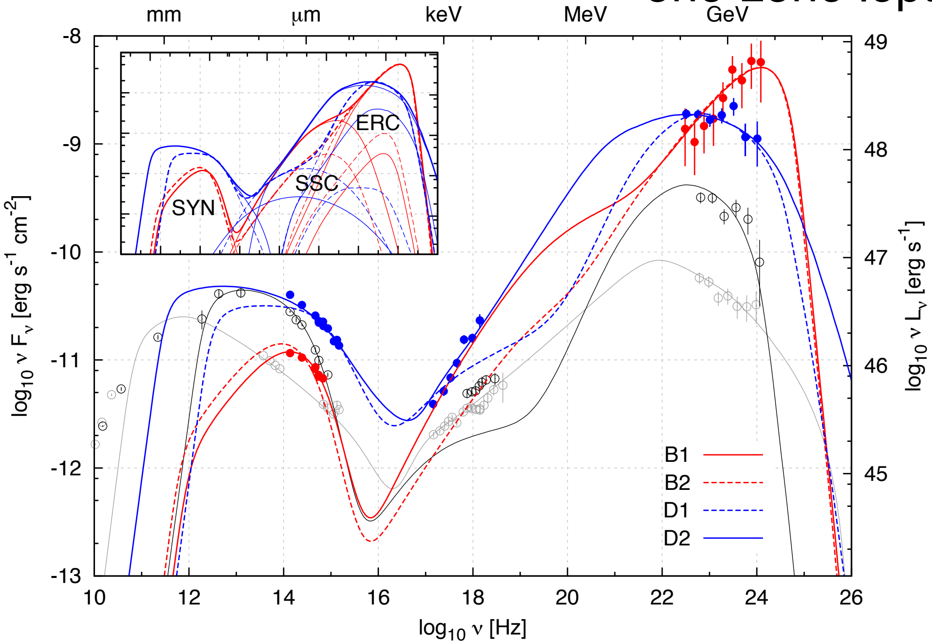


TABLE 5

PARAMETERS OF THE SED MODELS PRESENTED IN FIG. 9.

Model	A	B1	B2	C	D1	D2
r [pc]	1.1	0.03	0.12	1.1	0.03	1.1
Γ_j	8.5	20	30	10.5	25	30
$\Gamma_j \theta_j$	1	0.61	0.34	1	1	1
B' [G]	0.13	0.31	0.3	0.13	1.75	0.14
p_1	1	1	1	1	1	1.6
γ_1	1000	3700	2800	1000	200	100
p_2	2.4	7	7	2.4	2.5	2.5
γ_2	3000	—	—	3000	2000	6000
p_3	3.5	—	—	3.5	5	4

1. Gamma-ray emission site should be inside BLR (< 0.1 pc)
2. very matter dominated jet: ***L_B/L_{jet} ~ 10^{-4}***
3. hard index (γ-ray band) in the fast cooling regime
   - required very hard index for electron injection spectrum: ***p*=1**

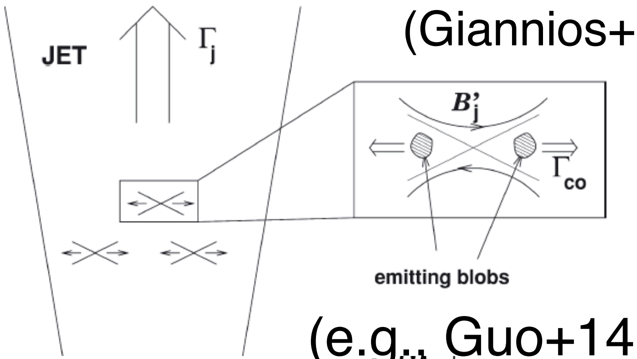
hard (p<2) electron index

p : injected electron index

p ≥ 2: normal standard shock (Fermi-I) acceleration

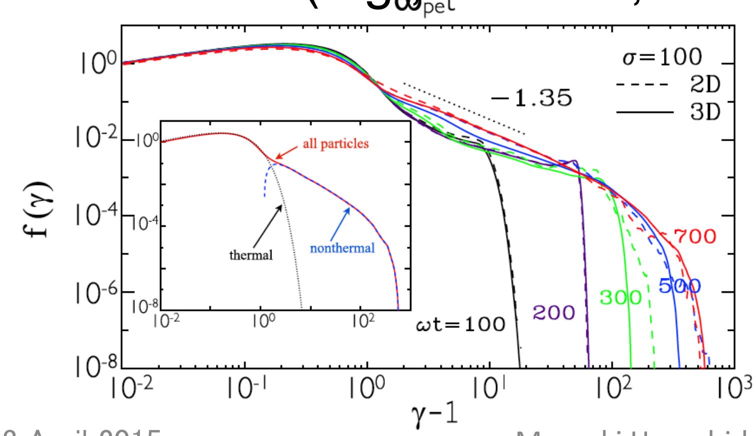
too soft!!

magnetic reconnection



(Giannios+09)

(e.g., Guo+14, PRL)



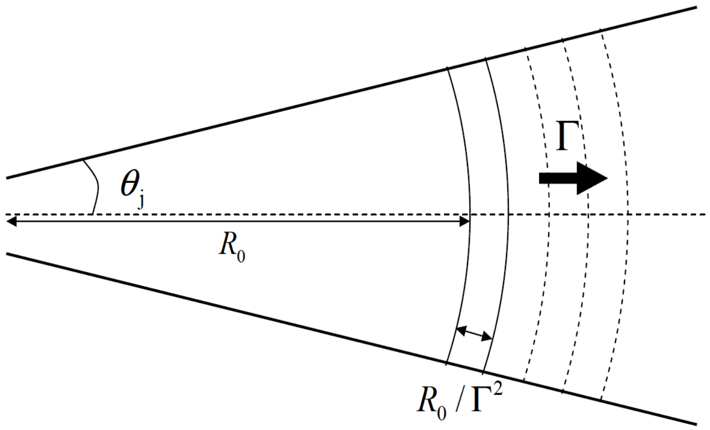
<u>Our result:</u>

jet magnetization: $\sigma < 10^{-3}$

- *the reconnection will efficiently work in this condition?*
- *very localized acceleration sites?*
    - *can generate 10^{48} erg/s emission?*

Stochastic acceleration (Fermi-II)

(Model: Asano+2014, *ApJ* 784, 64)



- Steady outflow
- Continuous shell ejection with a width of R_0/Γ in commoving frame
- Electron injection from $R=R_0$ to $2R_0$ with stochastic acceleration
- Turbulence Index: q=2 (hard-sphere scattering)
- Both injection and acceleration stop at $R=2R_0$

Physical Processes

- Electron injection
- Stochastic acceleration
- Synchrotron emission and cooling
- Inverse Compton emission and cooling
- Adiabatic cooling ($V \propto R^2$)
- Photon escape
- *No electron escape!*

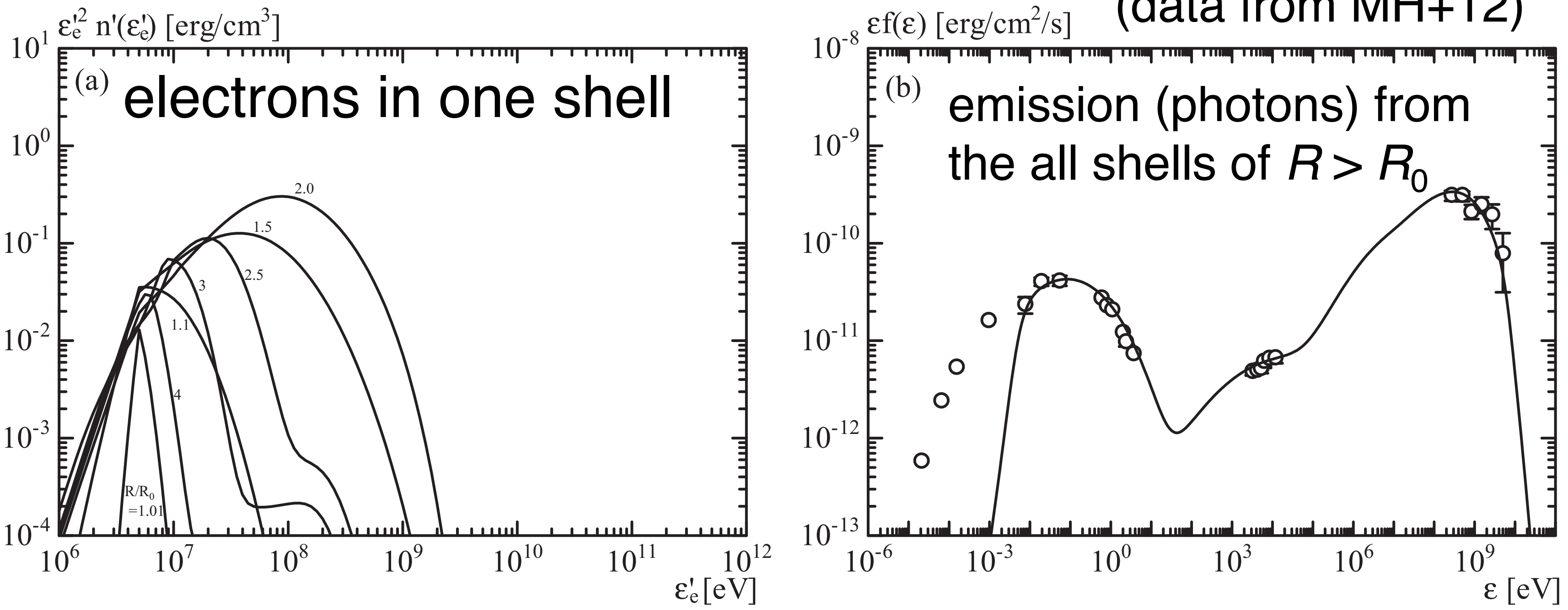
$$D(\varepsilon_{\rm e}) = \frac{\bar{\xi}\pi e c \varepsilon_{\rm e} k |\delta B^2|_k}{8B} \equiv K\varepsilon_{\rm e}^q$$

Hereafter, $q = 2$, $\theta_{\rm j} = 1/\Gamma$, $\gamma_{\rm inj} = 10$

$$B' = B_0(R/R_0)^{-1}$$

Steady (base line) model

A high state in 2009 as reference (Asano & Hayashida, in prep)



(data from MH+12)

electrons in one shell

emission (photons) from the all shells of $R > R_0$

R_0 = 0.023 pc, Γ = 15, B_0= 7 G

K (energy diffusion coefficient) = 9×10^{-6} s^{-1}

N_e (electron injection rate) = 7.8×10^{49} s^{-1}

application for the 2013 flare

(Asano & Hayashida, in prep)

emission from a single shell

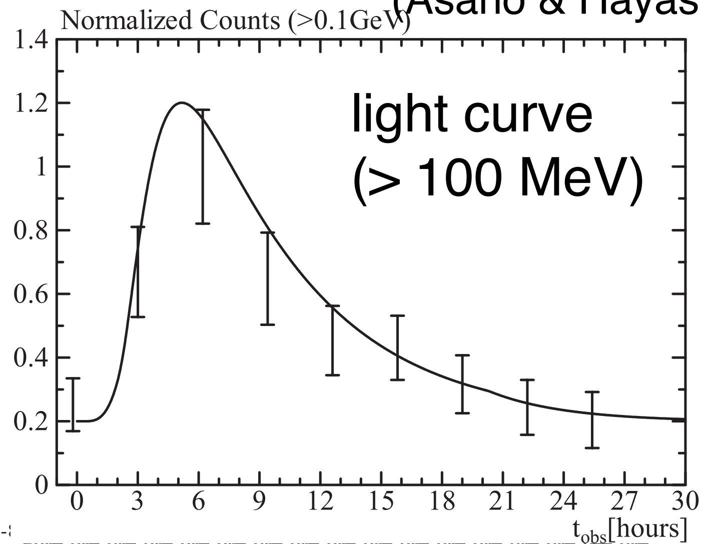
R_0 = 0.023 pc, Γ = 15,

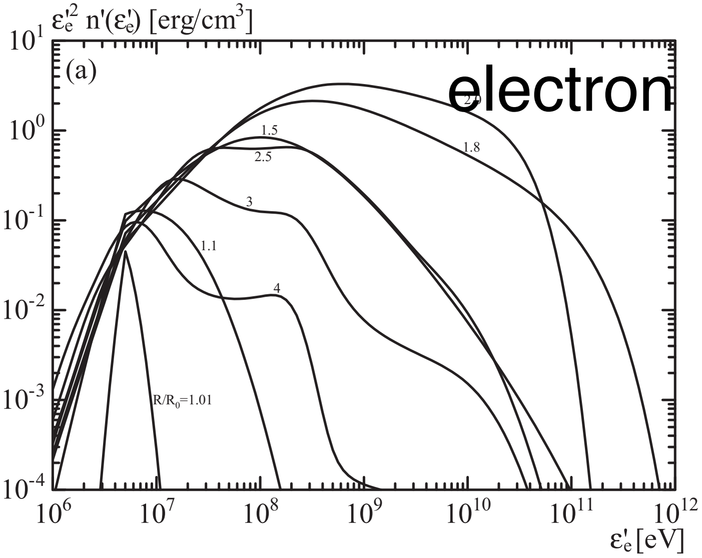
B_0: 7 G → 0.25 G

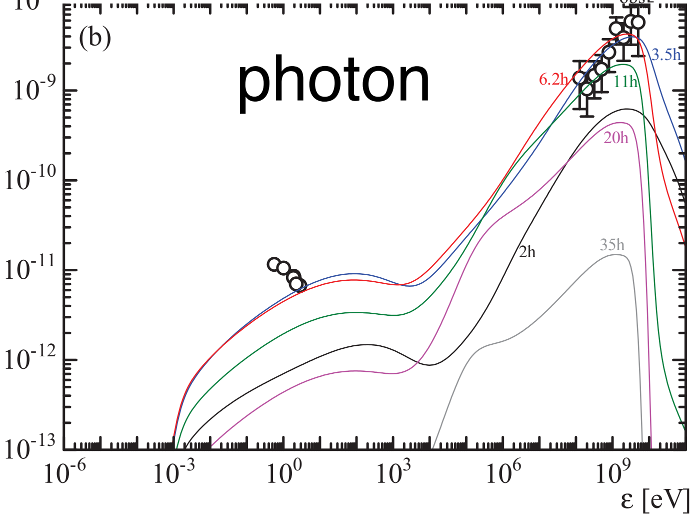
K: 9×10^{-6} s^{-1} → 1.3×10^{-5} s^{-1}

N_e :7.8×10^{49} s^{-1} → 3.2×10^{50} s^{-1}

low B in the dflare ??







the turbulence is generated by the hydrodynamical instability?

Summary & Conclusion

- 3C 279 showed the highest γ-ray flux level in 2013-2014.
  - **“orphan γ-ray flare was detected”**
- where is the gamma-ray emission site?
  - *inside BRL (~0.03 pc < 10^3 r_g) for hourly scale variability at 100 MeV*

    (both inside and outside BLR ($10^{2\text{-}3}$ to $10^{5\text{-}6}$ r_g) event by event)
- what is the dominant component in jet?
  - *emission model : kinetic energy dominated : $L_B/L_{jet} \sim 10^{-4}$*
  - *jet simulation: Poynting-flux dominated (< 10^3 r_g)*

    Any ideas for this issue?
- what is the acceleration mechanism?
  - *not only shock accelerations*
    - *stochastic acceleration (Fermi-II) can also work for rapid γ-ray flares*

back up

energetics

- $L_\gamma \simeq 6\times10^{48}$ erg s^{-1}
- $L_j \simeq L_\gamma/(\eta\Gamma^2)$ $(\eta=0.1)$
- $L_j \simeq 1.5\times10^{47}$ erg s^{-1}
- $L_B \simeq 1.1\times10^{42}$ erg s^{-1},
- $L_{disk} \simeq 6\times10^{45}$ erg s^{-1}
- $L_{Edd} \simeq 8\times10^{46}$ erg s^{-1}
- $M_{BH} \simeq 5\times10^{8}\,M_\odot$,

- $L_j/L_{disk} \simeq 25$
- $L_B/L_j \simeq 10^{-5}$
- $L_j > L_{Edd}$