Very fast gamma-ray variability and multi-wavelength view of 3C 279 during outbursts in 2013-2015

1. Hayashida, M., et al. 2015, ApJ, 807, 79
2. Asano, K., & Hayashida, M. 2015, ApJL, 808, L18
3. Ackermann, M., et al. (Fermi-LAT Collaboration) 2016, ApJL, in press arXiv:1605.05324 (CA: Hayashida, Madejski, Nalewajko)

Blazars through Sharp Multi-Wavelength Eyes. Malaga.
31 May 2016

Masaaki Hayashida

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Main collaborators:

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Krzysztof Nalewajko, and Marek Sikora

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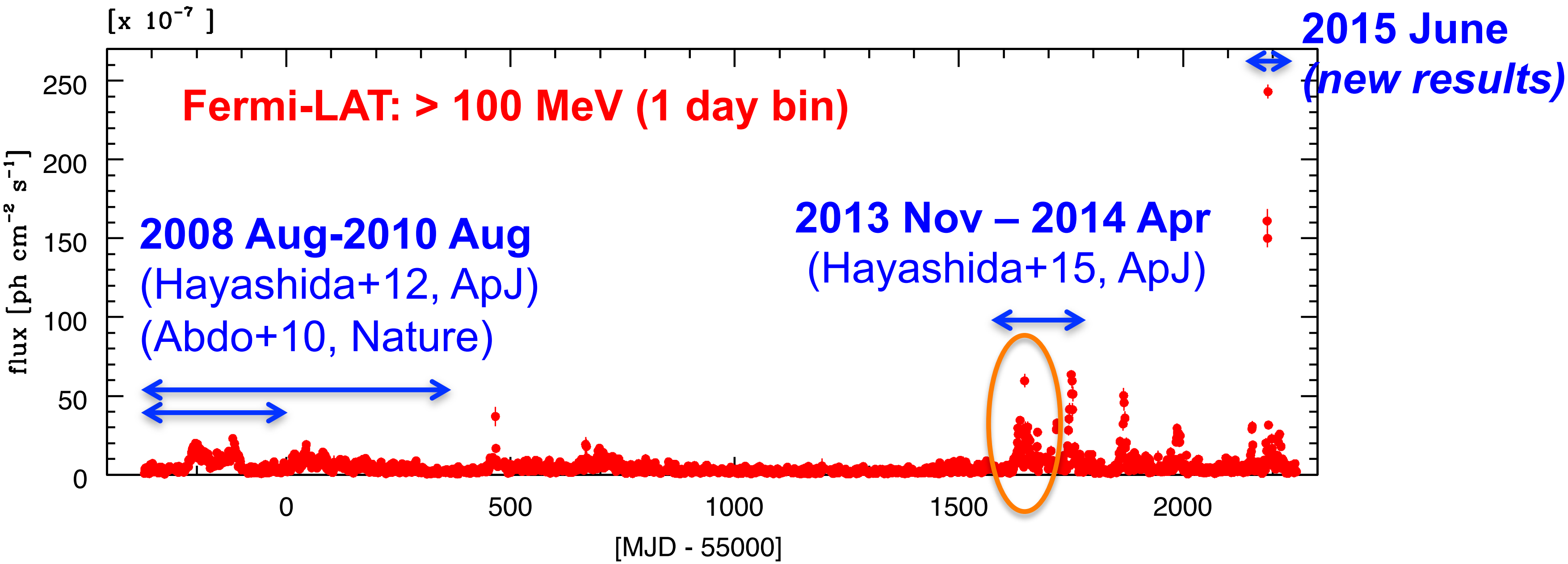
Outline

1. Gamma-ray and multi-and observations of 3C 279
   1. 2013-2014 (briefly)
      - Flare in December 2013, 2nd order Fermi acceleration model
   2. 2015 June flare (main part)
      - first minute-scale variability observed by Fermi-LAT
2. Discussions
   - constraint of jet parameter at γ-ray emission region
     1. *where is the γ-ray emission region in jet?*
     2. *what is the dominated energy component?*
     3. *what is the origin of the γ-ray radiation?*

     (what is the acceleration mechanism?)

3C 279 (FSRQ: z=0.536)

Fermi-LAT 7 year light curve (2008 Aug. – 2015 Aug.)



- Mass ~ (3-8) x $10^8 M_{solar}$
- L_d ~ 6×10^{45} erg/s
- bright γ-ray source (both EGERT and *Fermi*-LAT)
- the first TeV FSRQ (among 4 TeV FSRQ)

Intensive γ-ray flare in 2013 Dec.

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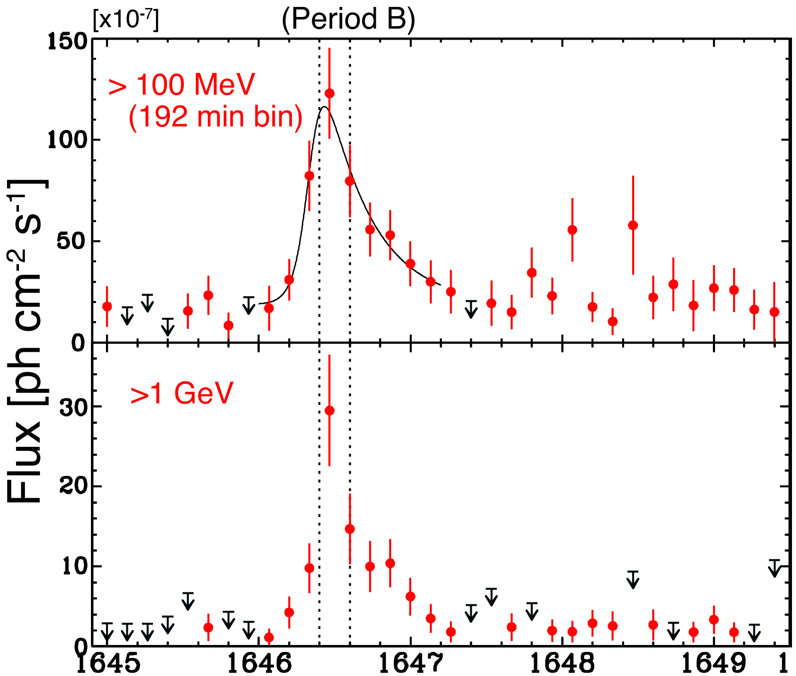
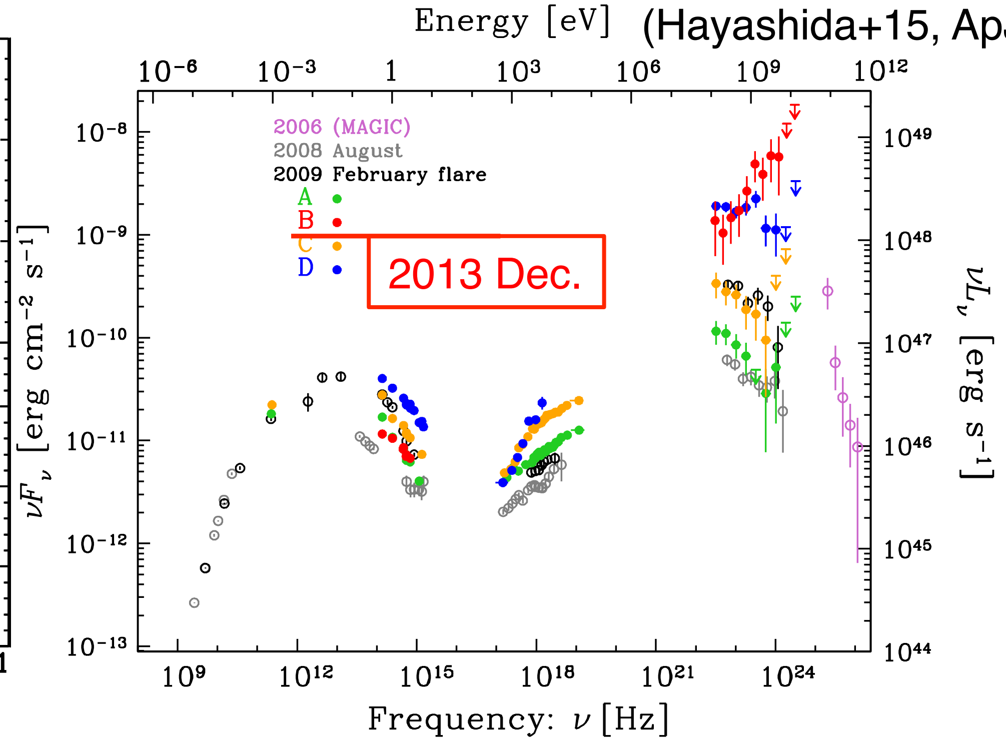




(Hayashida+15, ApJ)

- **a few hours variability**
  (t_{rise} ~ 2h, t_{fall} ~ 6h)
- asymmetric profile

- **Very hard γ-ray index (Γ~1.7)**
  (need hard electron p<2)
- no concurrent flare in other bands
  → **'orphan' γ-ray flare**
- $L_{IC}/L_{sync} > 100$
  → **very matter dominated**

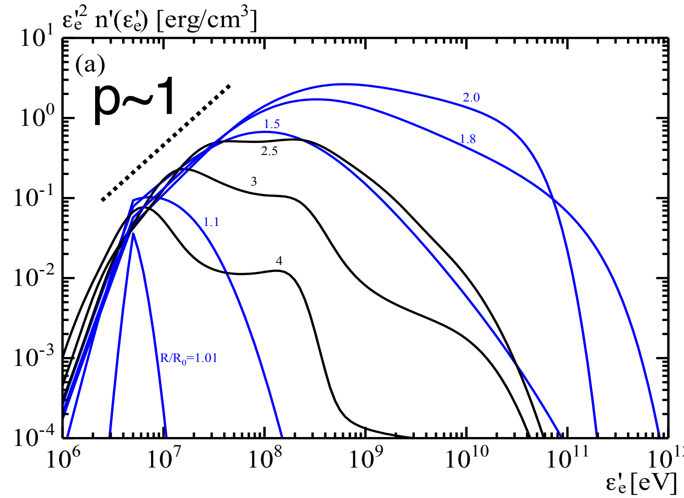
Fermi-II acceleration for hard γ-ray spectrum

(Asano & Hayashida 15, *ApJ*, 808 L18)

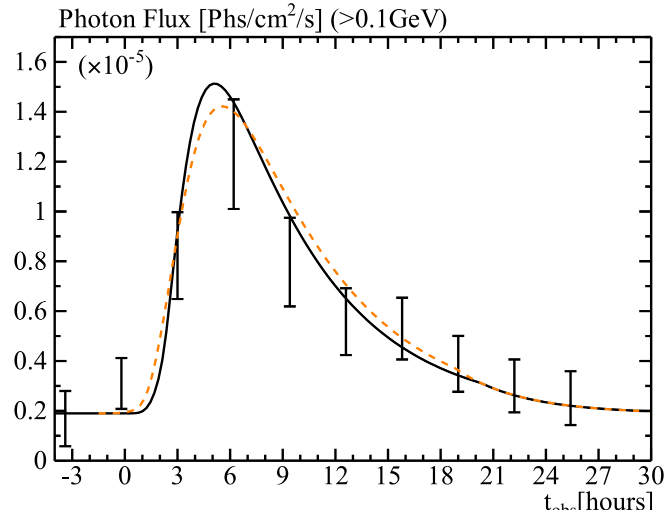
Flare on December 2013
with hard γ-ray spectrum
and hour-scale variability
could be reproduced.

R_0 = 0.023 pc, Γ = 15, B_0: 0.25 G K (energy diffusion coefficient) : 1.3×10^{-5} s^{-1} N_e (electron injection rate) : 3.2×10^{50} s^{-1}

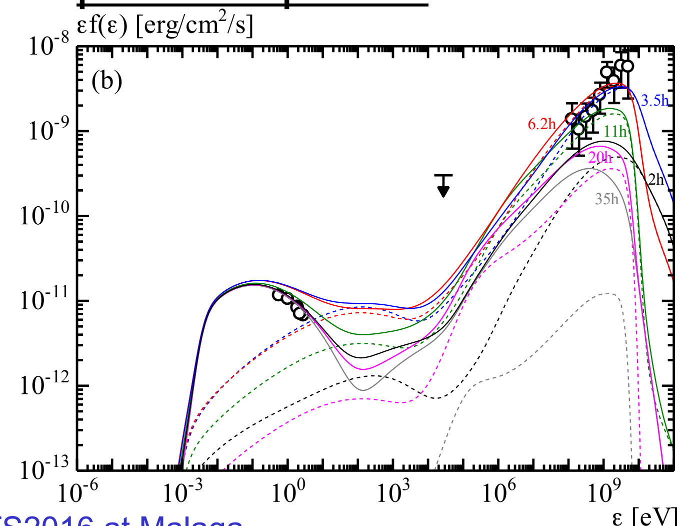
evolution of electron spectra



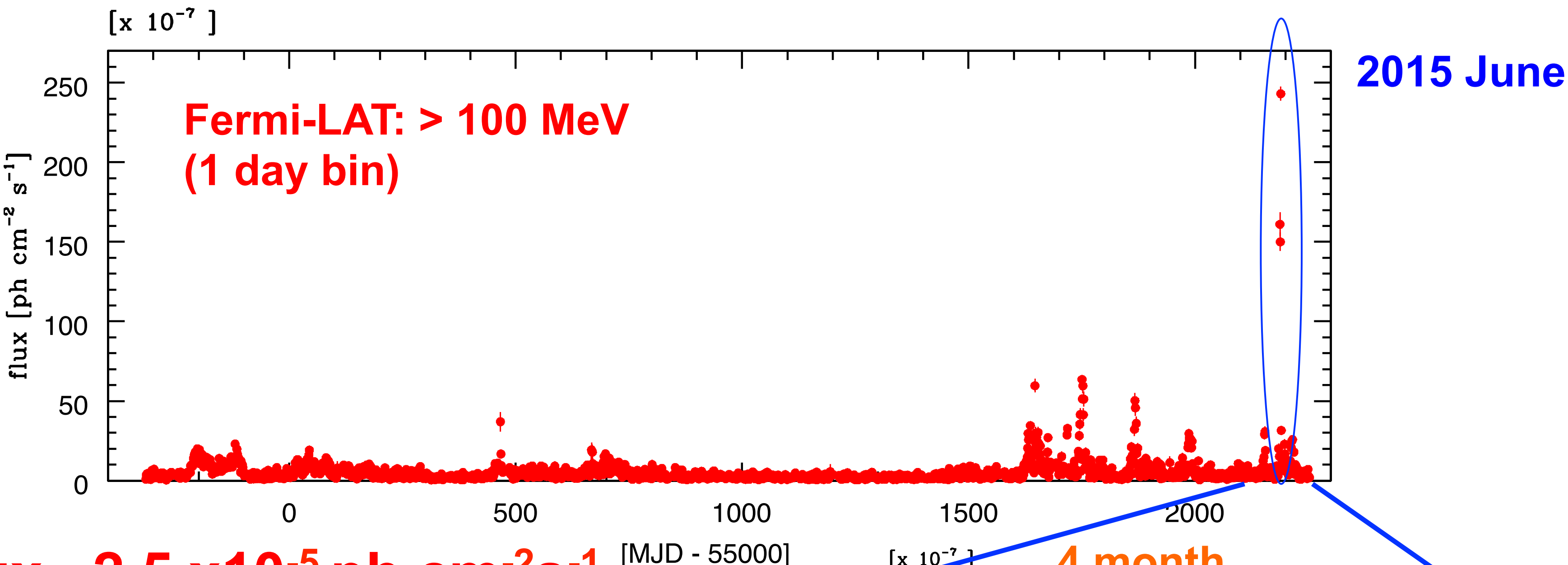
light curve (>0.1 GeV)



photon spectra

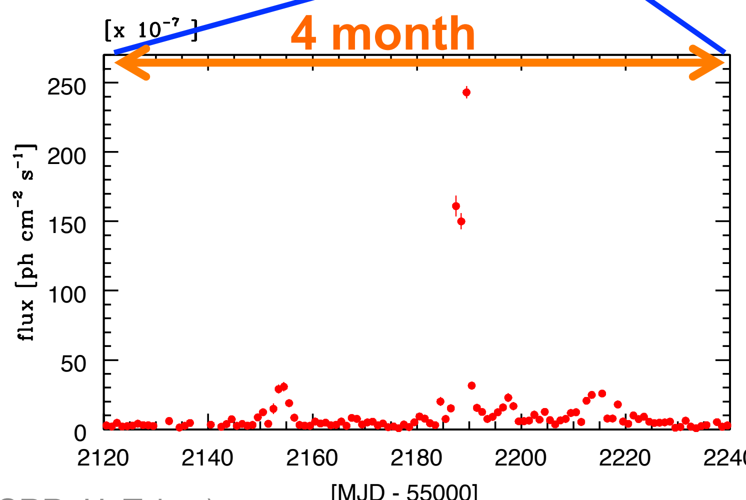


Giant outburst in 2015 June



Flux ~2.5 x10^{-5} ph cm^{-2}s^{-1}
(>100 MeV in 1 day bin)
was recorded on 2015 June 16.
ToO observations started
at 2015 June 15 17:31:00

Outburst during the ToO obs.
(~3 times more exposure than usual.)



LAT light curves (orbit bin): 4.5 days

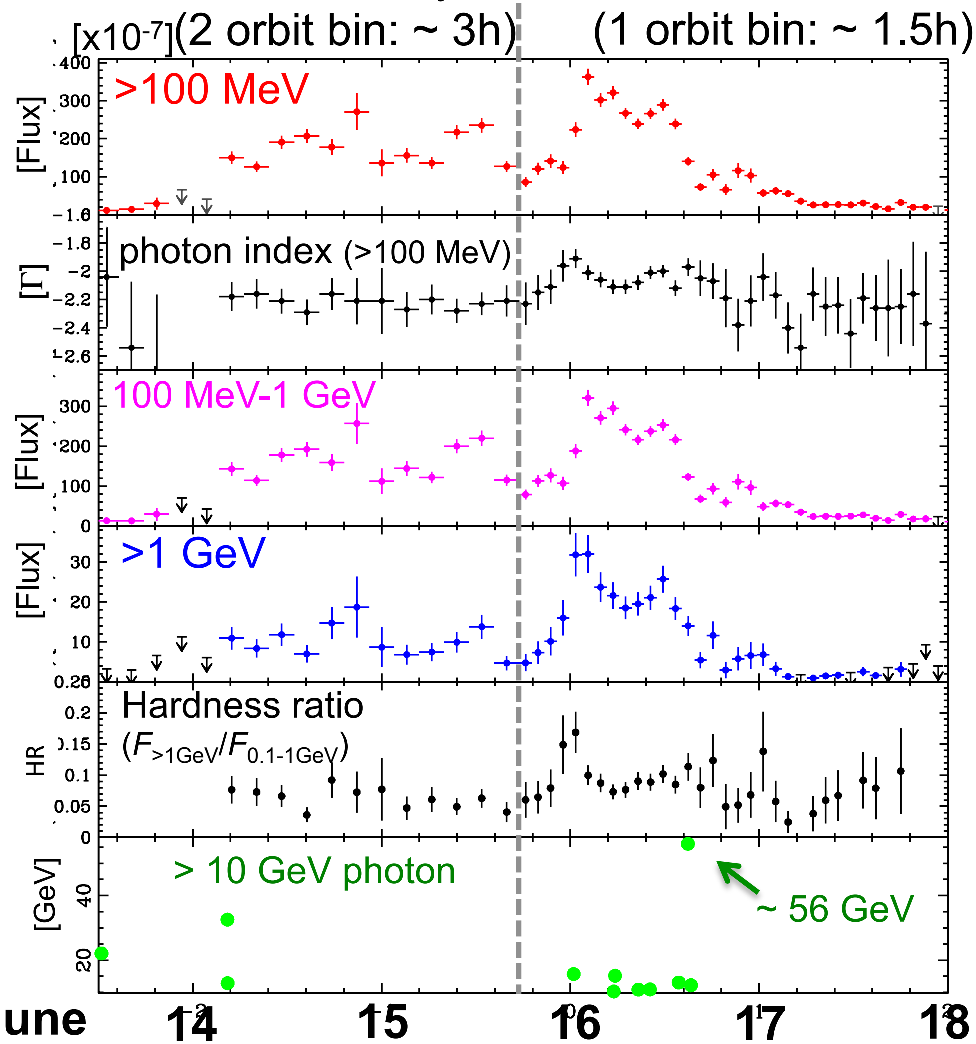
(Fermi-LAT Coll.,16, ApJL, arXiv:1605.05324)

reached F(>100 MeV): ~4x10^{-5} ph cm^{-2} s^{-1}

<past flares>
2013-2014
(Hayashida+2015, ApJ)
~1.2x10^{-5} ph cm^{-2} s^{-1}

1996 (EGRET)
~1.2x10^{-5} ph cm^{-2} s^{-1}

the current LAT spectrum (~2.0) is *not* as hard as the hardest seen in the 2013/2014 flaring activity (it was ~1.7)



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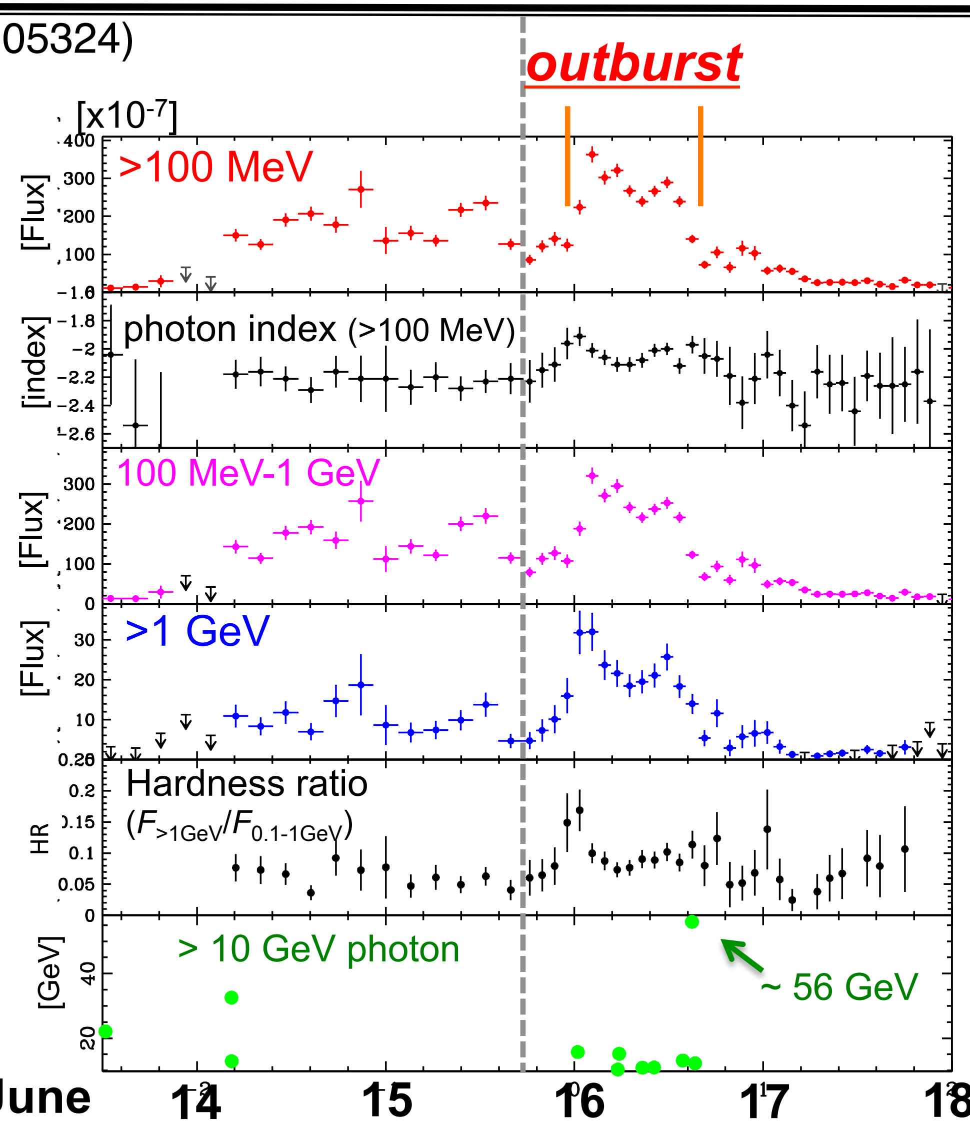
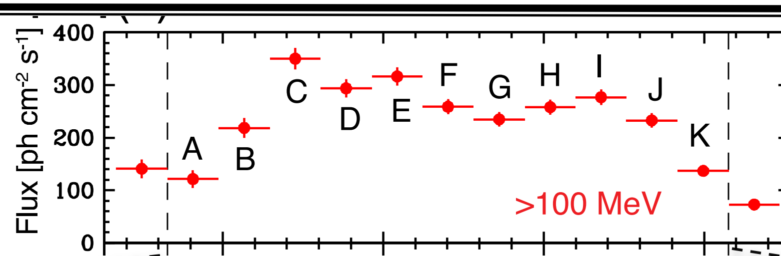


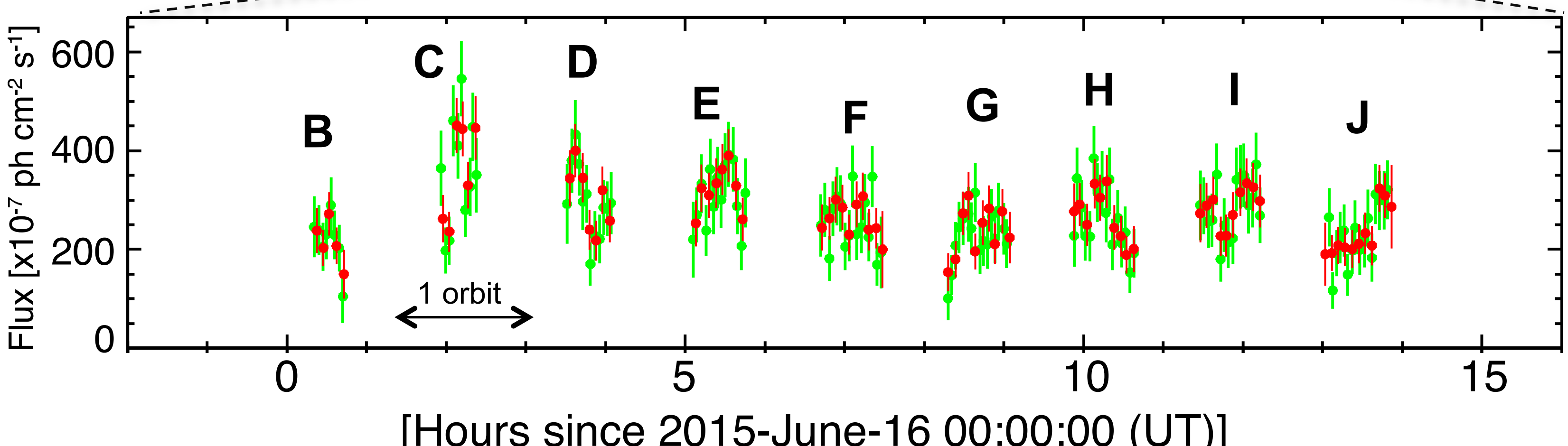
Sub-orbital time scale light curve

Red : 5 minutes bin

Green : 3 minutes bin



> 100 MeV



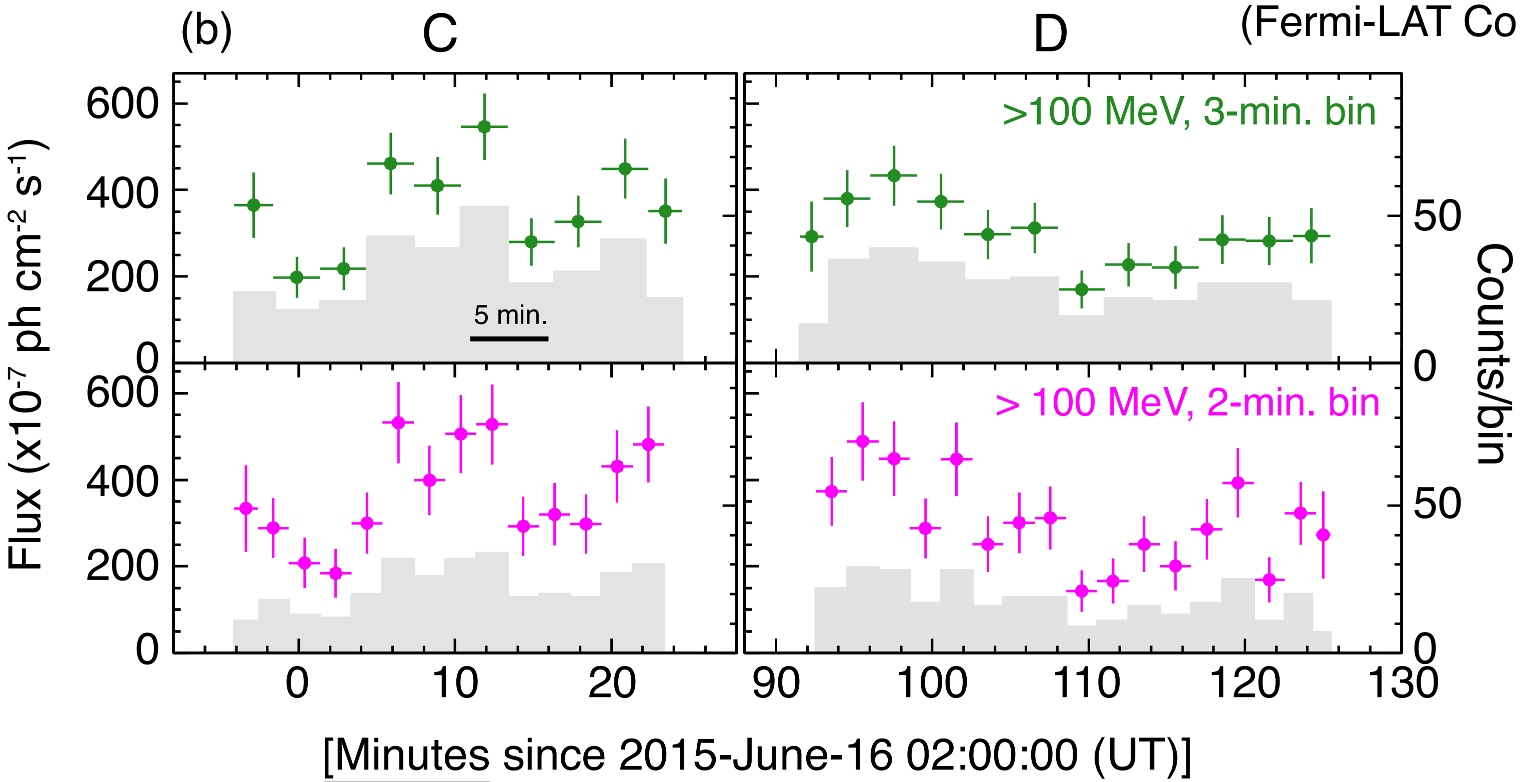
p-value from fits with a constant value for each orbit range

orbit #	B	C	D	E	F	G	H	I	J
5 min	0.43	**0.0015**	0.067	0.51	0.90	0.17	0.23	0.71	0.40
3 min	0.45	**0.00047**	0.068	0.43	0.42	0.31	0.14	0.44	0.18

significant variability in orbit C *(and a possible hint in orbit D)*

Minute-scale variability by Fermi-LAT

(Fermi-LAT Coll.,16, ApJL)



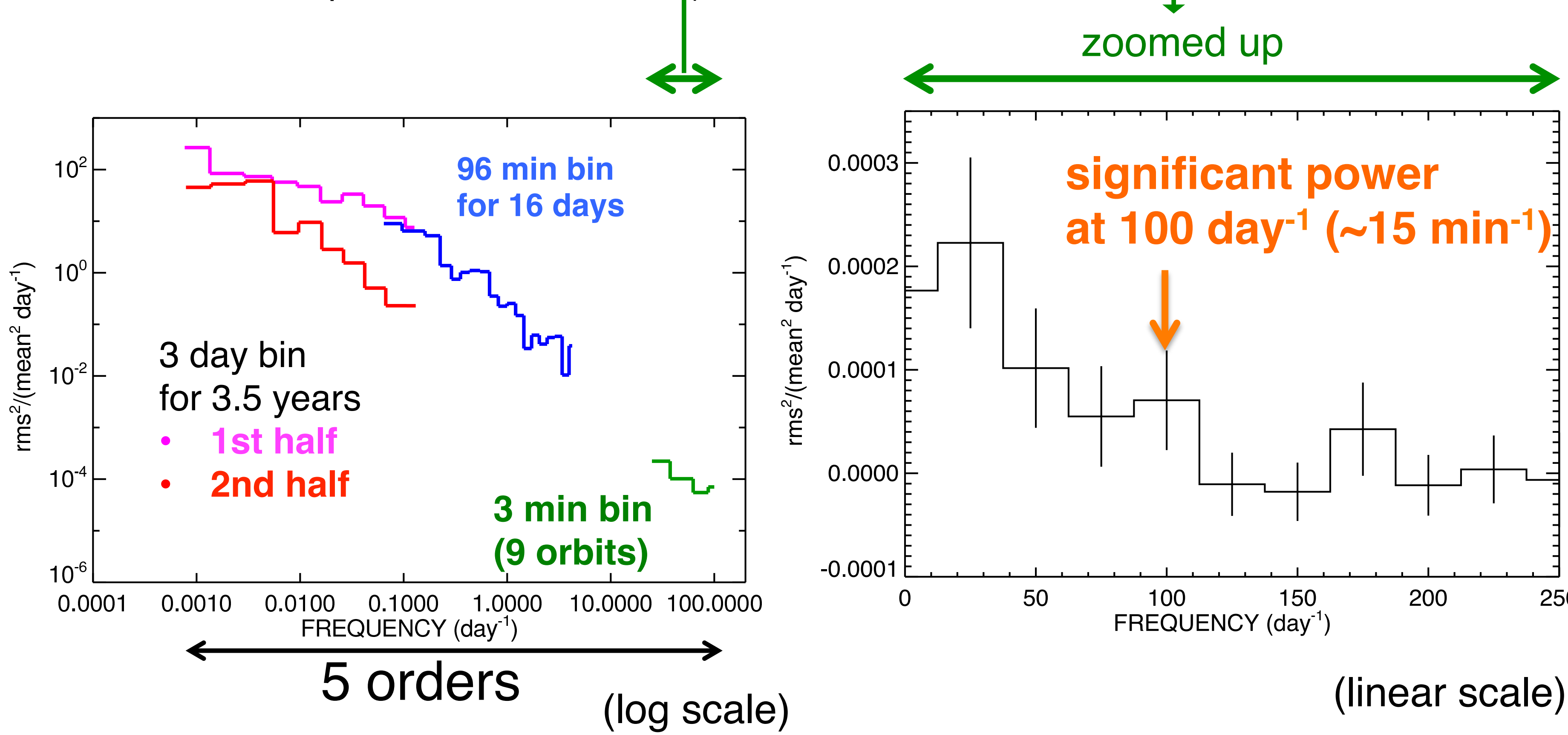
flux reached ~5×10^{-5} ph cm^{-2} s^{-1}

the > 100 MeV flux doubled in ~ 5 minutes

→***minute-scale variability***

Power density spectrum

(Fermi-LAT Coll.,16, ApJL, arXiv:1605.05324)



See more details in a talk by Stefan Larsson (tomorrow, 10:30am ~)

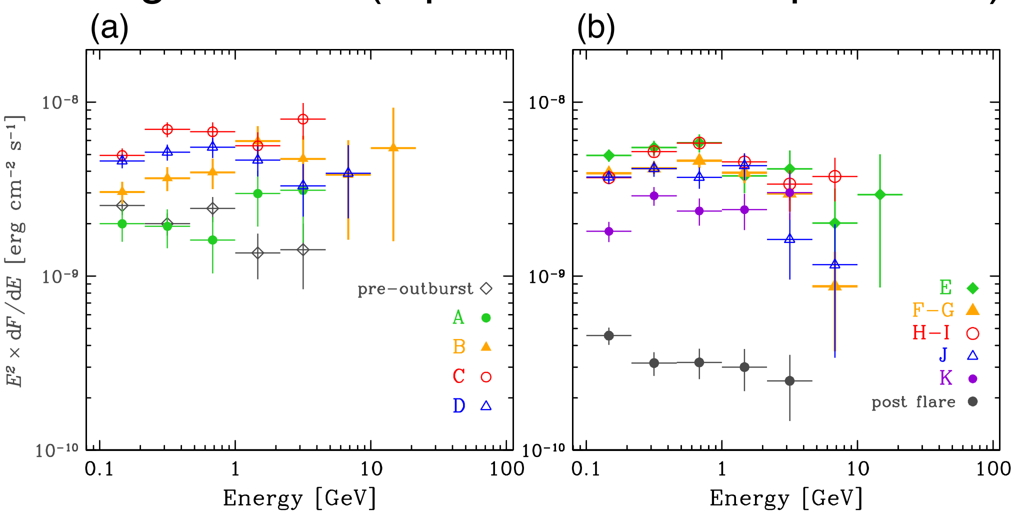
Gamma-ray spectra during the outburst

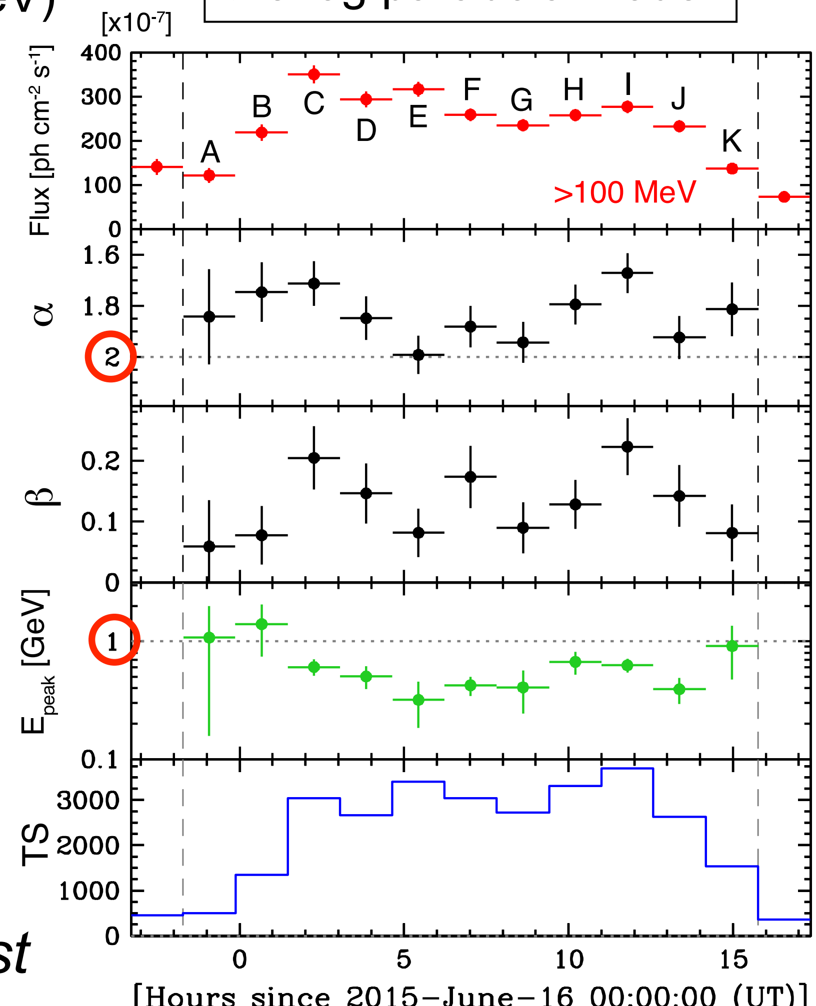
$$dN/dE' \propto (E/E_0)^{-\alpha-\beta\log(E/E_0)}$$

(E_0=300 MeV)

fitting results by
the log parabola model

spectral points for each orbit bin (A – K)
during outburst (+ pre-outburst and post flare)



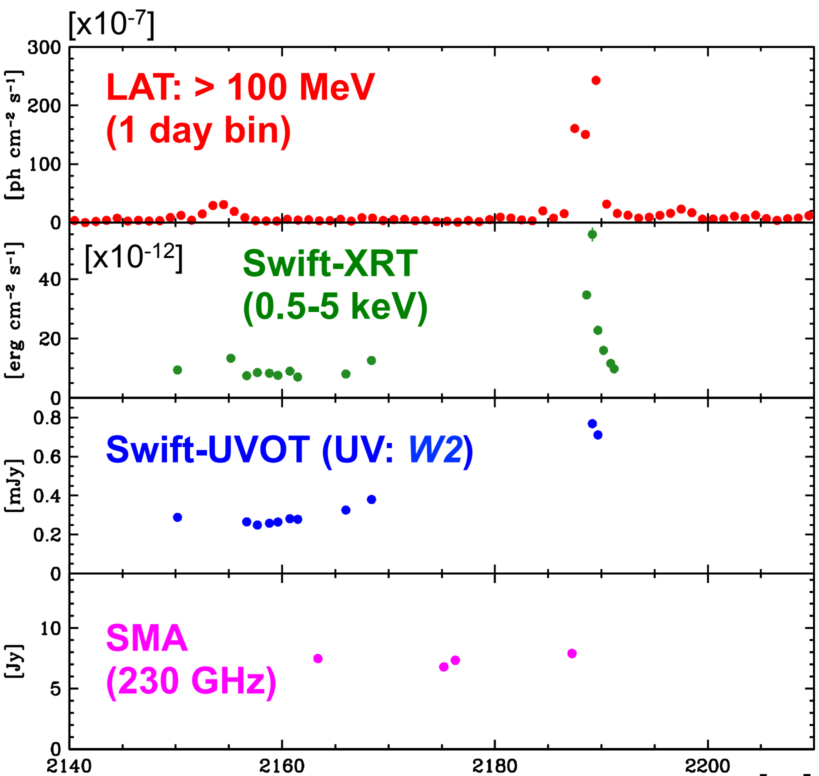


- **α < 2 in all bins**
- **Peak located at a few 100 MeV–1 GeV**

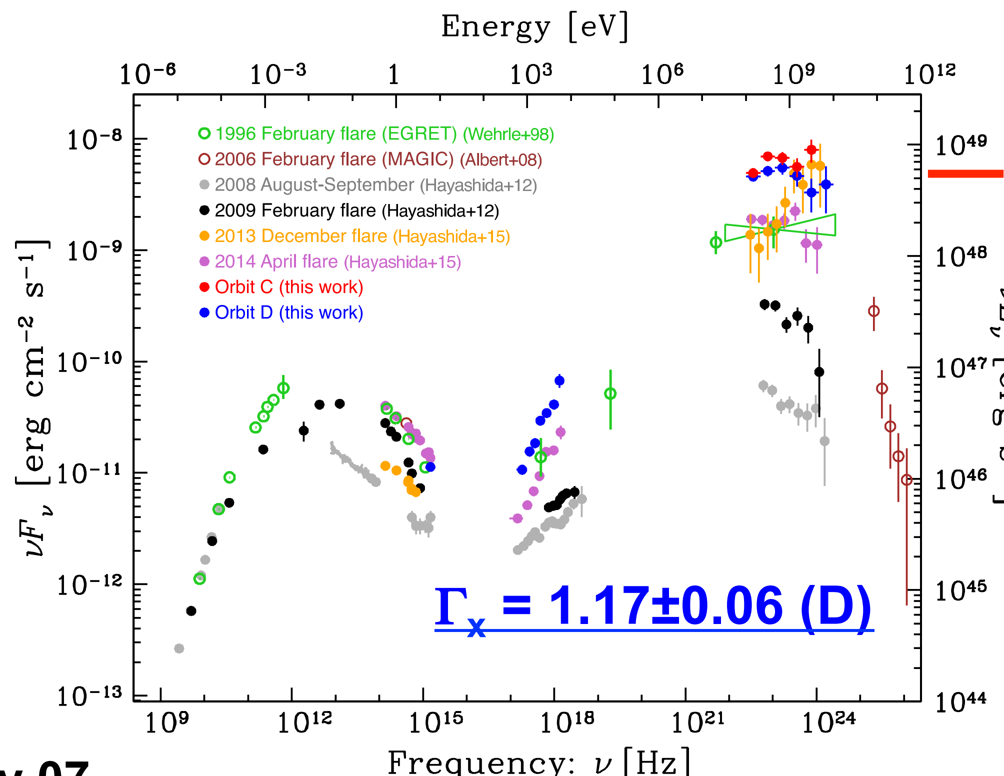
spectra seems to be slightly harder
at the beginning and end of the outburst

Multi-band observations

flares were also observed in X-ray
and optical (UV) band, but not in the radio band



May 28 **July 07**



Very fast variability in blazars

source name	*z*	src type	t_{var}	energy	Lum.[erg/s]
PKS 2155-304	0.116	BL Lac	~ 2 min	>0.2 TeV	1e47
Mkn 501	0.034	BL Lac	~ 2 min	>0.15 TeV	1e45
PKS1222+21	0.432	**FSRQ**	~ 10 min	>0.1 TeV	1e47
IC310	0.0189	radio gal.	< 4 min	>0.3 TeV	1e44
3C 279	0.536	**FSRQ**	~ 5 min	**>100 MeV**	**1e49**

variability time scale: 5 minutes ***very small region***

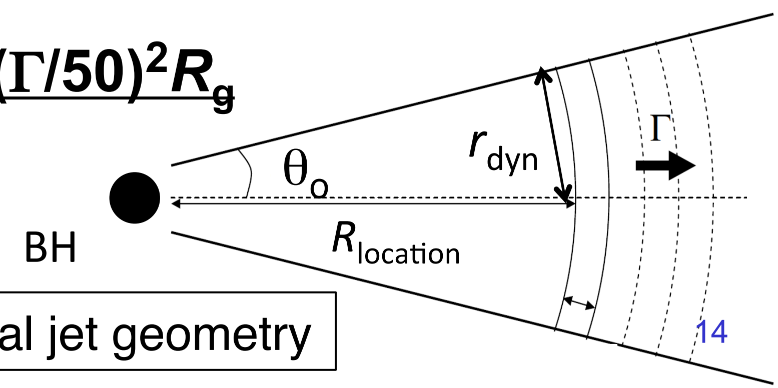
$\Gamma\theta_o = 1$
$\delta \sim \Gamma$

- r_{dyn} (emission region size) ~ 10^{-4} (δ/50) pc (~3×10^{14} cm)
- $R_{location}$ (emission location) ~$r_{dyn}/\theta_o \sim 0.005\ (\Gamma/50)^2\ (\Gamma\theta_o)^{-1}$ pc (~10^{16}cm)

  (R_{BLR} (broad line region size) ~ 0.05 pc)

→ ***very near to BH (inside BLR)*** **~ $100(\Gamma/50)^2 R_g$**

(R_g ~ 5×10^{-5} pc @ $5\times10^{8} M_{solar}$)



conical jet geometry

constraints on jet parameters

- internal (inside emission region) absorption: (E_{max}~15 GeV)
  - $L_{soft\ (x\text{-}ray)}$ ~ 10^{47} erg/s → **Γ > 25** to avoid the absorption
- SSC constraint: L_γ ~ 10^{49} erg/s, L_γ / L_{syn}~100 (Compton dominance)
  - $L_{SSC} < L_x$ ~ 10^{47} erg/s → **Γ > 46**
- jet energetics: $L_{jet} \sim L_\gamma/(\eta_j\Gamma^2) \sim 4\times10^{46}(\Gamma/50)^{-2}$ erg/s (η_j~0.1)

  (~ 7 L_{disk} ~ 0.5 L_{Edd} : L_{Edd}~8×10^{46} erg/s)
  - $L_B/L_{jet} \sim 5\times10^{-4}(\Gamma/50)^8$ → very low magnetization
    - if Γ ~ 120, then $L_B \sim L_j/2$ (equipartition)
- jets need to be accelerated to Γ~50 (low magnetization case) at 100 R_g or Γ~120 (equipartition case) at 1200 R_g

it's challenging the current jet acceleration/formation models

At jet base: which energies is dominated? magnetic or kinematic?

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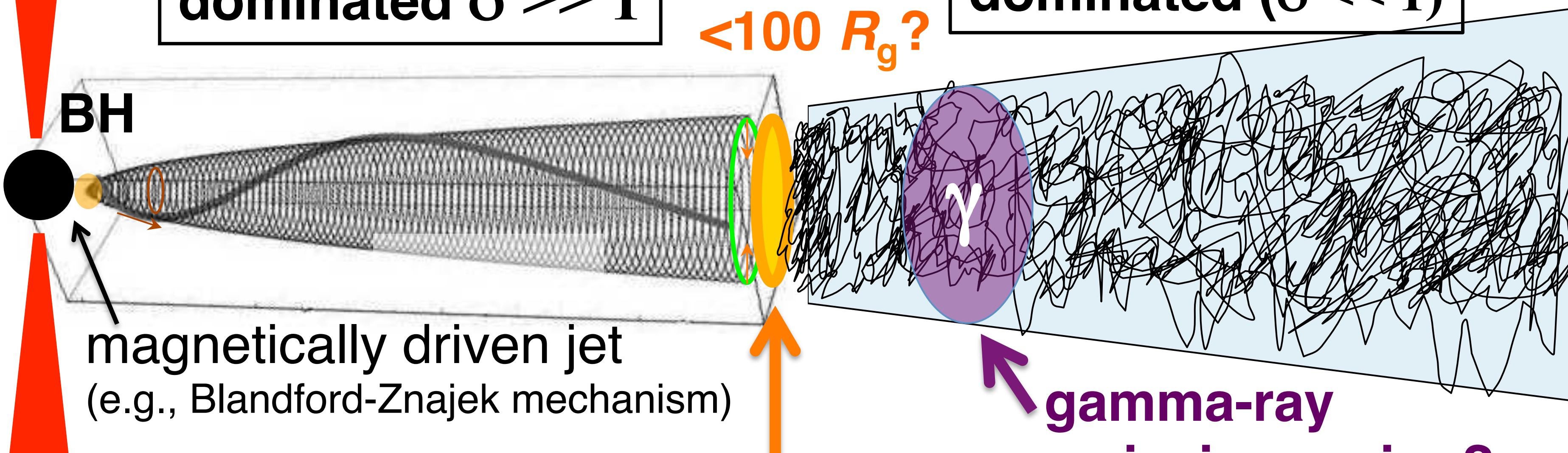
(thanks to D.Meier, Y.Mizuno for Graphic)

magnetic energy dominated $\sigma >> 1$

Γ>50? at <100 R_g?

kinematic energy dominated ($\sigma << 1$)



magnetically driven jet
(e.g., Blandford-Znajek mechanism)

gamma-ray emission region? (~100 R_g)

At shorter than 100 R_g:
can jets be accelerated to Γ>50 and can the magnetic energy be converted to the kinetic energy?

(or, is Γ>120 at 1000 R_g possible for equipartion?)

'Standard' jet model could be too simple?

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<u>$R_{location}$ ~ r_{dyn}/θ_o ~ 0.005 $(\Gamma/50)^2$ $(\Gamma\theta_o)^{-1}$ pc (0.005 pc ~ 100r_g)</u>

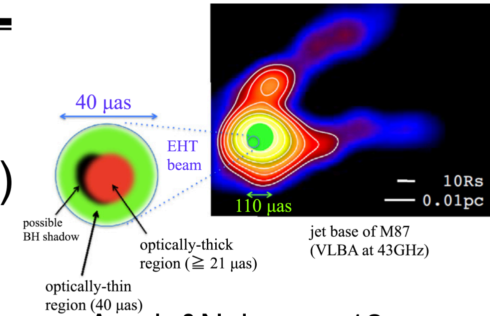
- *simple conical jet with opening angle $\Gamma\theta_o$=1 (θ_o~1.1deg)?*
  - small opening angle, $\Gamma\theta_o$=0.1 (→ θ_o~0.1deg with Γ=50)
    - $R_{location:}$ 100 R_g → 1000 R_g (0.05 pc), still inside BLR
  - parabolic? re-confinement jet? (r_{dyn} ~ 10^{-4} pc [4×10^{14}cm])
- *emission from the entire jet cross section?*
  - in a internal narrow fast component (spine sheath jet structure)?
  - γ-ray emission region (r_{dyn}) and particle accelerating region (r_{acc}) can be different ?
    - magnetic reconnection: r_{dyn}/r_{acc} ~ 0.01-0.1 (Cerutti+12, Nalewajko+12)

Note: γ-ray isotropic luminosity of flare: ~10^{49} erg/s

- *just biased on γ-ray observations?*

Radio views on blazar jets for γ-ray views

(by my non-professional views)



- radio core shift measurements
  (idea: e.g.,Marscher+83, results: M87 [~a few R_g] :Kino+15)
  - favor magnetically dominated jets
- evidence of parabolic shape of inner jet(e.g.,M87: Asada&Nakamura12 Hada+13)

Any differences in the jet energy component between FRI/BLLac (M87) and FRII/FSRQ (3C279)?

- generally good corrections between radio and γ-ray flux
- VLBI core ejections (and optical polarization) coincide with γ-ray flares → emission region in pc scales (>$10^5 R_g$)

γ-ray dissipation region is not unique in jet (10^2 –$10^{5\text{-}6}$ R_g)

Both views on γ-ray and radio bands is important to understand blazar jets

‘Standard’ jet model could be too simple?

<u>$R_{location} \sim r_{dyn}/\theta_o \sim 0.005\ (\Gamma/50)^2\ (\Gamma\theta_o)^{-1}$ pc (0.005 pc ~ $100 r_g$)</u>

- *simple conical jet with opening angle $\Gamma\theta_o=1$ ($\theta_o \sim 1.1$deg)?*
  - small opening angle, $\Gamma\theta_o=0.1$ (→ $\theta_o \sim 0.1$deg with $\Gamma=50$)
    - $R_{location:}$ 100 R_g → 1000 R_g (0.05 pc), still inside BLR
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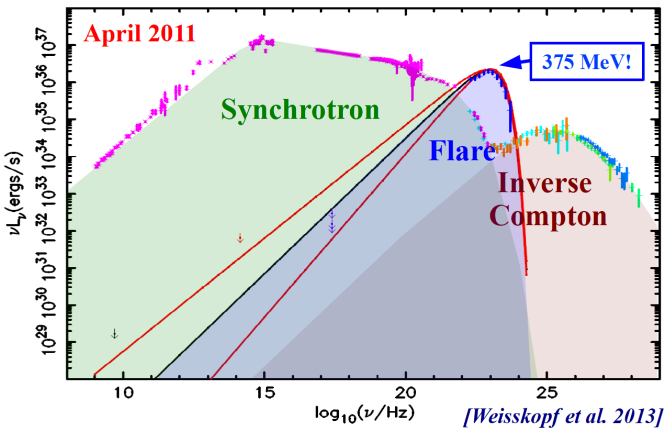
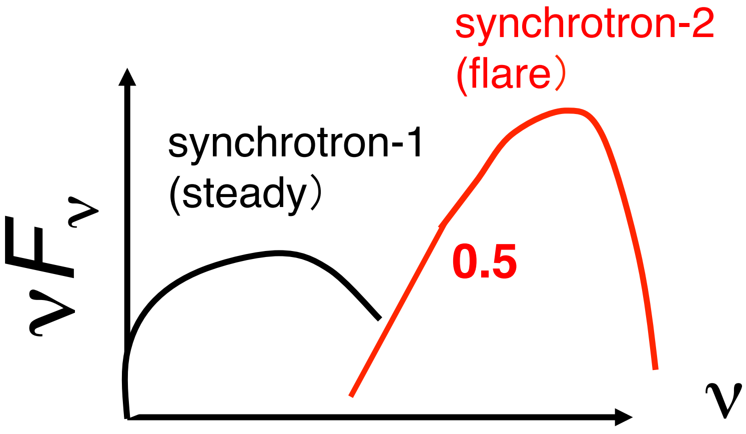
Note: γ-ray isotropic luminosity of flare: $\sim10^{49}$ erg/s

- *just biased on γ-ray observations?*
- *the γ-ray origin is inverse-Compton scattering?*

Synchrotron emission origin for γ-rays





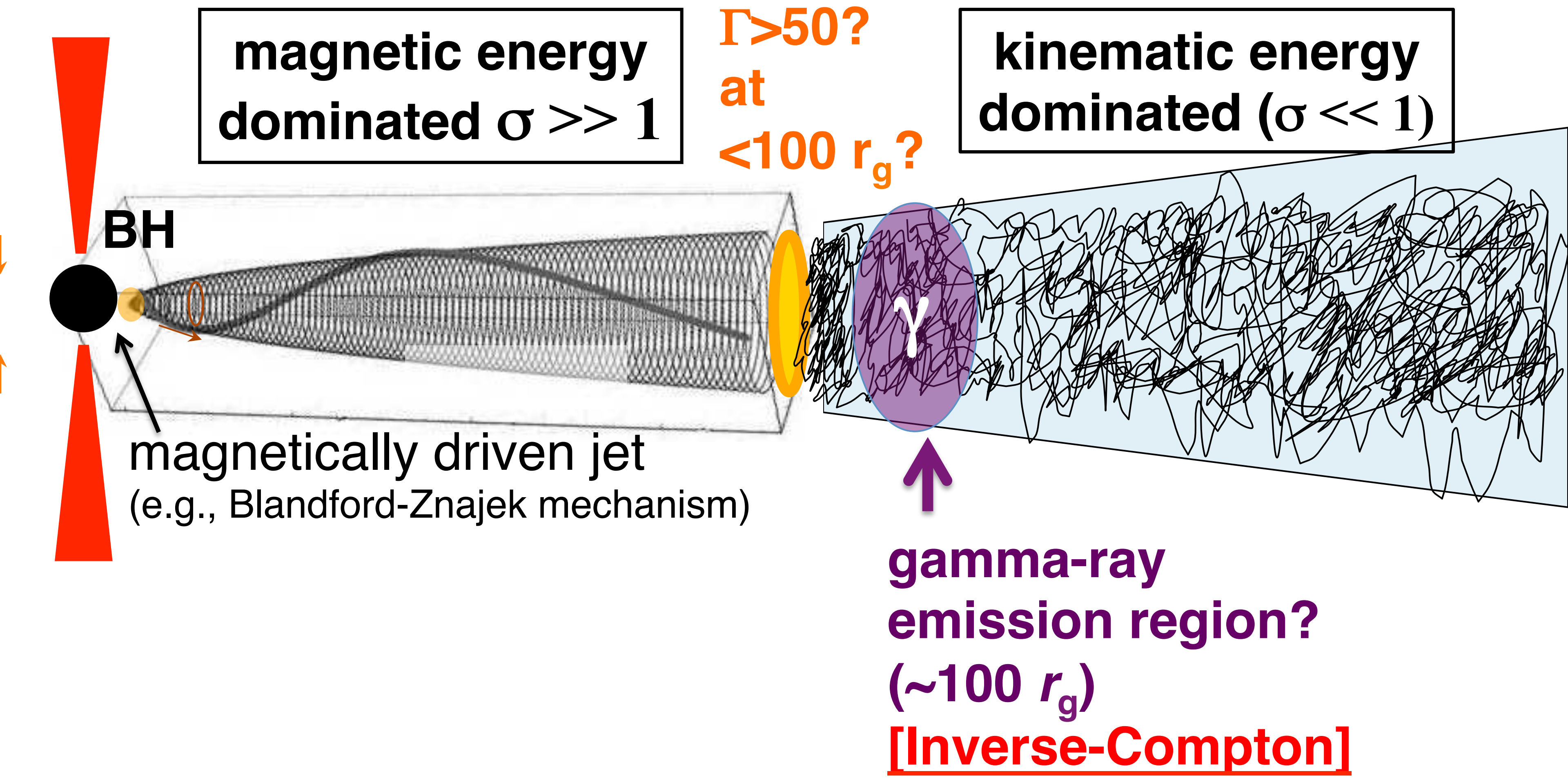
similar case to Crab flares.

- radiation reaction limit : $E_{sync,max}$ = 4(δ/25) GeV (> E_{peak}~1GeV)
  (e.g, Guilbert et al., 1983 ; de Jager et al., 1996 ; Cerutti et al., 2012)

- constraint of Γ can be reduced to **>25** because SSC constraint is no longer valid

- γ_e ~ 1.6x10^6 at *B*=1.3kG (and Γ=25)→ L_B ~ $L_{jet}/2$ (equipartition)
  - cooling time ~ 3 ms : $EF(E) \propto E^{0.5}$ (X to γ rays: a rising part of SED)
    - *but the observed X-ray spectrum was rather hard ($\propto E^{0.83\pm0.06}$)…*
  - not easy to explain (sub-)TeV energy flare

At jet base: which energies is dominated? magnetic or kinematic?



At jet base: which energies is dominated? magnetic or kinematic?

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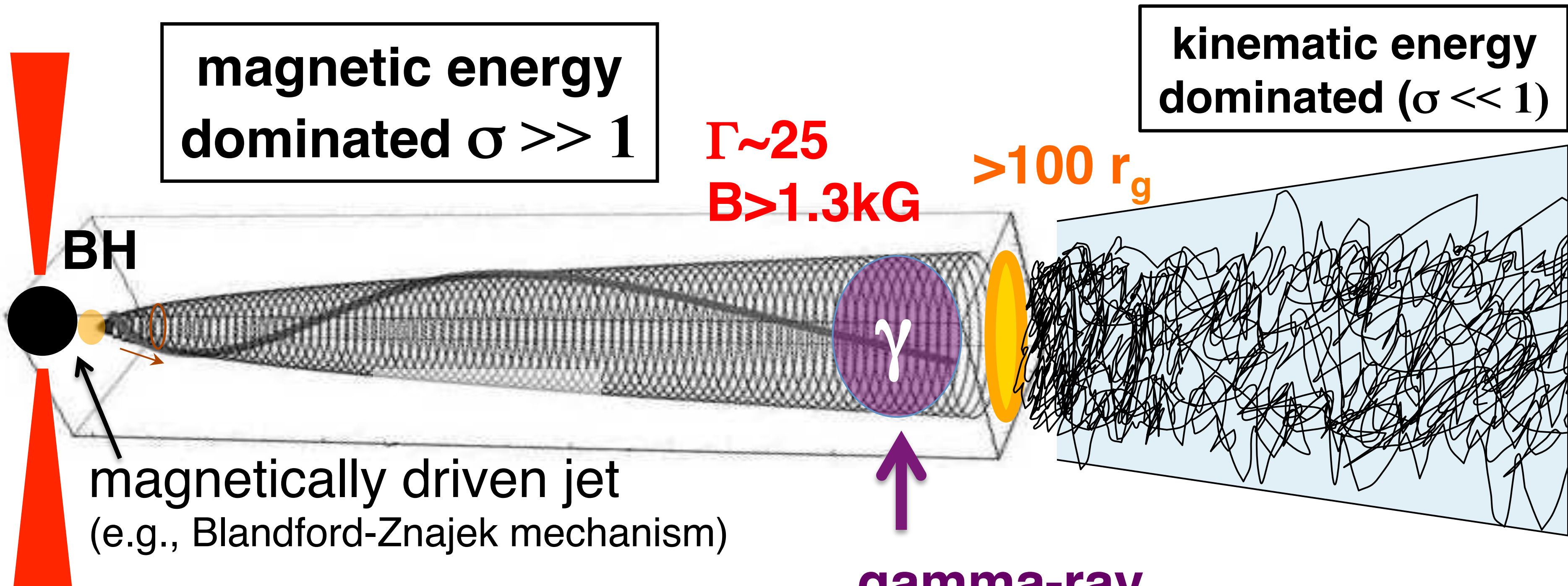

gamma-ray emission region? (~100 r_g)
[Synchrotron]

Proton synchrotron mechanism may also work at jet base
(with very strong magnetic fields, dense target radiation fields)

Summary & Conclusion

- FSRQ 3C 279 showed γ-ray outbursts (>10^{-5} ph/cm^2/s) in last years
  - 2013 Dec.: orphan γ-ray flare, very hard index (Γ_γ~1.7)
    - Fermi-II acceleration model could reproduce the results
  - 2015 Jun.: historical largest outburst in 3C 279
    - 5 min flux doubling time, F_γ~4x10^{-5} ph/cm^2/s[1] , L_γ~10^{49} erg/s
- *where is the γ-ray emission site?*
  - inside BLR (~100 R_g) for vary fast variability at 100 MeV
    - Jets should be sufficiently accelerated (Γ>50) even at 100 R_g
- *what is the dominant component in jet?*
  - emission model with γ-ray : matter dominated : $L_B/L_{jet} < 10^{-3}$ (at 100 R_g)
  - jet simulation: magnetically dominated at jet base
  - radio observation (SSA): magnetically dominated (M87 at ~a few R_g)
- *what is the origin of the γ-ray radiation?*
  - synchrotron origin scenario may work as solution for the **`σ problem'**.

back up

Stochastic acceleration (Fermi-II)

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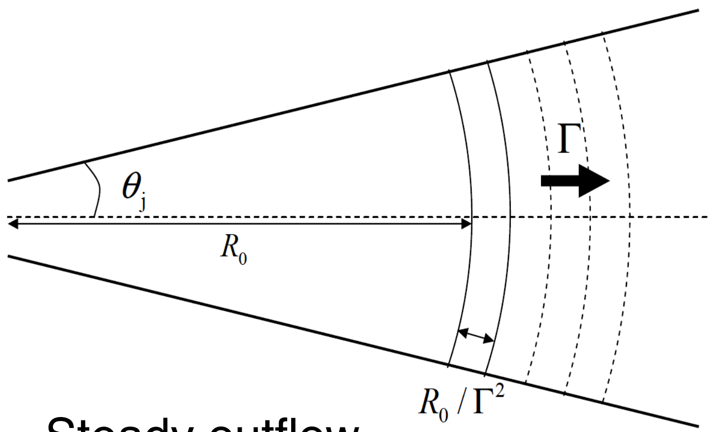

(Model: Asano+2014, *ApJ* 784, 64)

conical jet geometry

$B' = B_0(R/R_0)$

$\theta = 1/\Gamma$

- 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!*

<energy (ε) diffusion coefficient>

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

Hereafter, $q = 2$, $\theta_j = 1/\Gamma$, $\gamma_{inj} = 10$.

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

All results on the Fermi-II for the 3C279 flare

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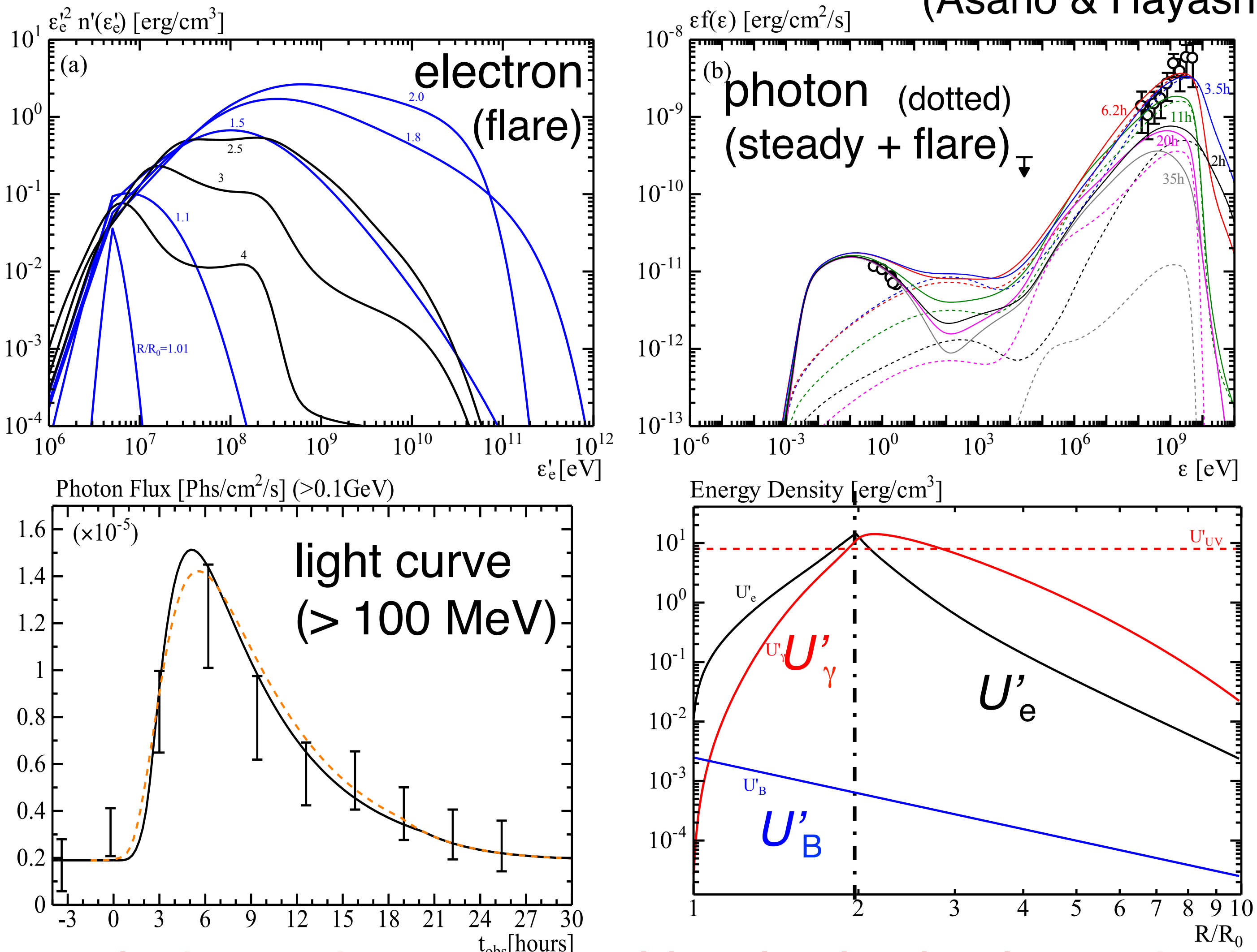
(Asano & Hayashida, *ApJL*, 2015)



very low U'_B/U'_e: 4×10^{-5} (@$R=2R_0$)

the turbulence is generated by the hydrodynamical instability?

emission model for Period B

(MH+15, *ApJ*) one-zone leptonic model: BLAZAR (Moderski+2003)

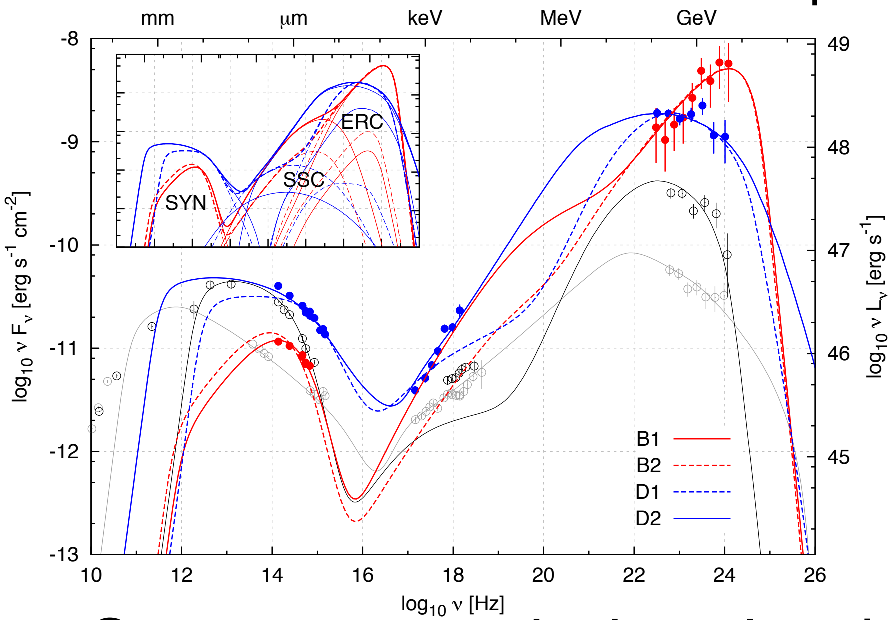


TABLE 5
PARAMETERS OF THE SED MODELS PRESENTED IN FIG. 9.

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)
   - efficient cooling at 100 MeV for 2hr variability
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