Are blazar jets matter or poynting-flux dominated?

+ short introduction of this Session
“Particle Acceleration Mechanisms in Astrophysical Sources“

CTA-Japan workshop
at ICRR on 14 January 2016

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

Outline

1. A Short introduction of this session
   "Particle Acceleration Mechanisms in Astrophysical Sources"
2. Acceleration mechanism in blazar jets
   – Observational results (Fermi-LAT) from blazar 3C279

     Two huge outbursts

     a. Flare on 20th December 2013 (Hayashida+15, ApJ)
        – hard γ-ray index
        – high Compton dominance: $L_{IC}/L_{syn} \sim 1000$
     b. Flare on 16th June 2015 (Fermi-LAT Coll. 16)
        – Very fast variability

Particle accelerations in astronomical sources

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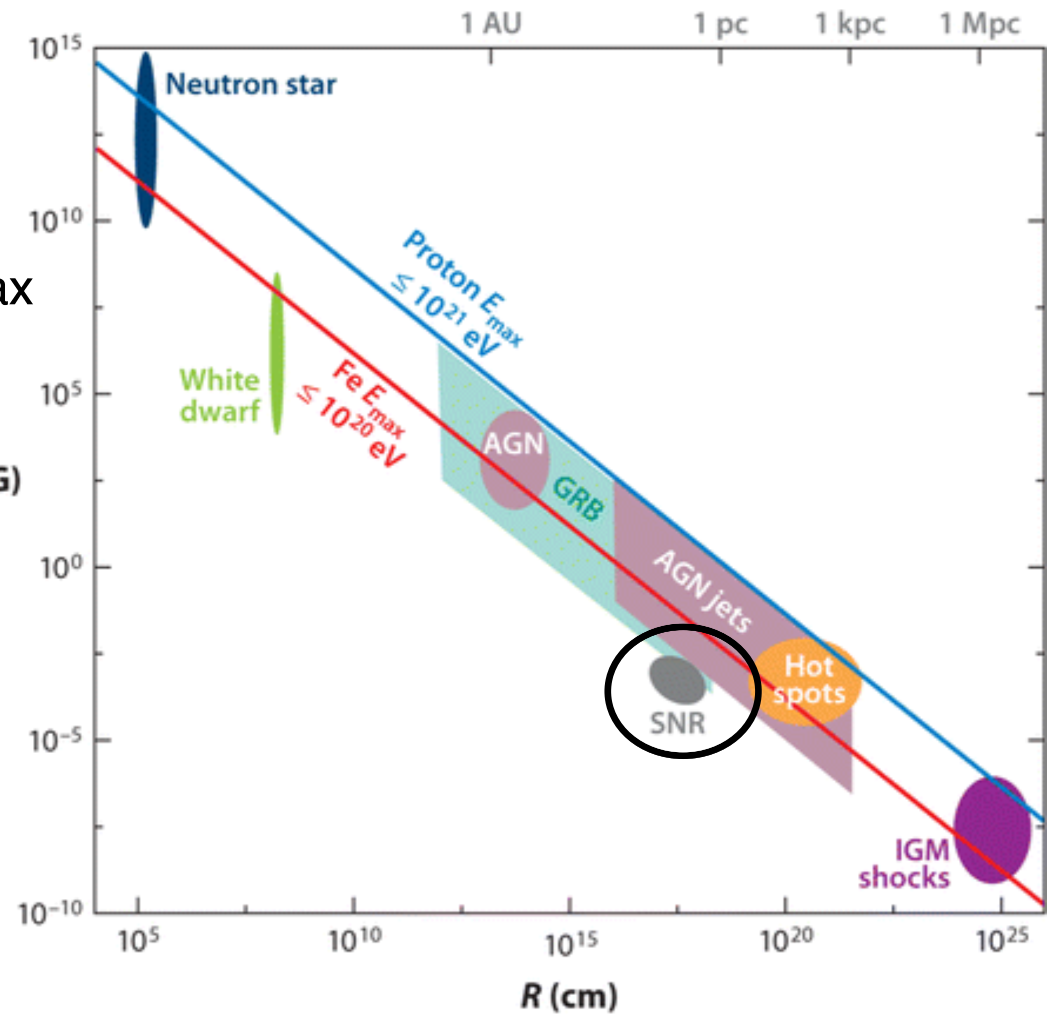
Hillas diagram

maximum energy: E_{max}

Larmor radius ($r_L = E_{max}/ZeB$) is smaller than source size, R

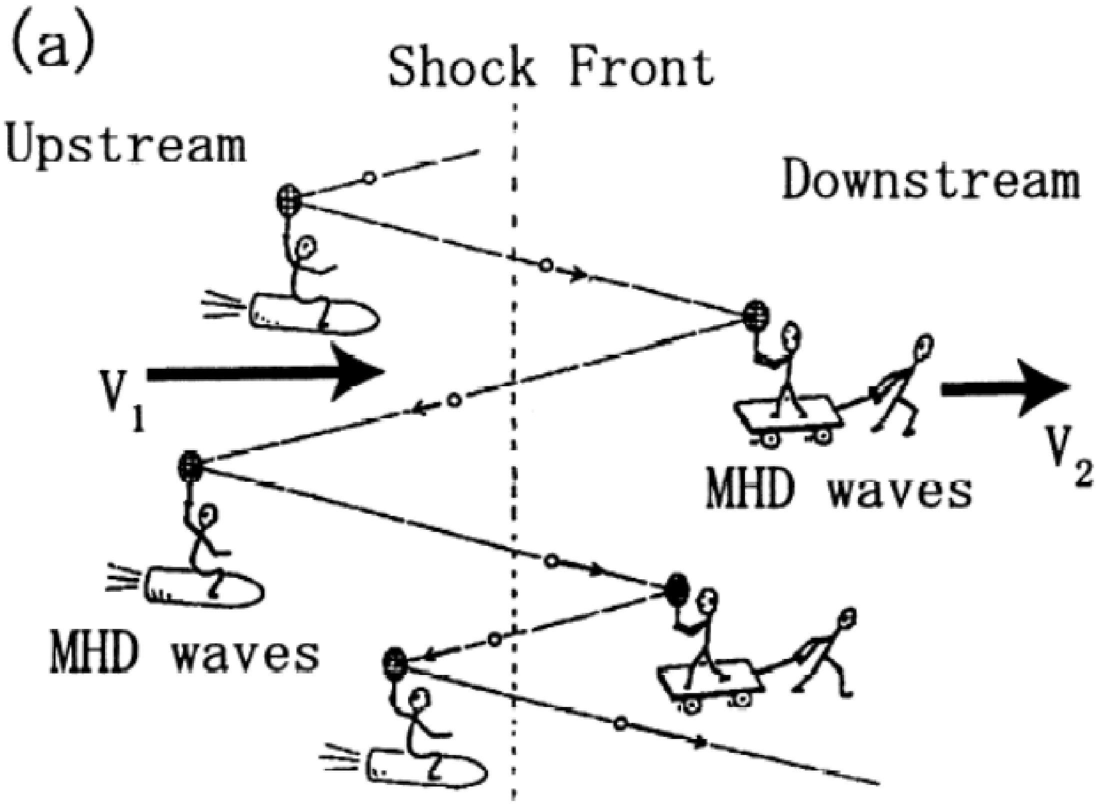
$r_L = R \rightarrow$



Kotera K, Olinto AV. 2011. Annu. Rev. Astron. Astrophys. 49:119–53

1st-order Fermi acceleration

Diffusive Shock Acceleration (DSA)



by Scholer

$dN/dE \propto E^{-p}$: $p = \dfrac{V_1/V_2 + 2}{V_1/V_2 - 1} > 2$

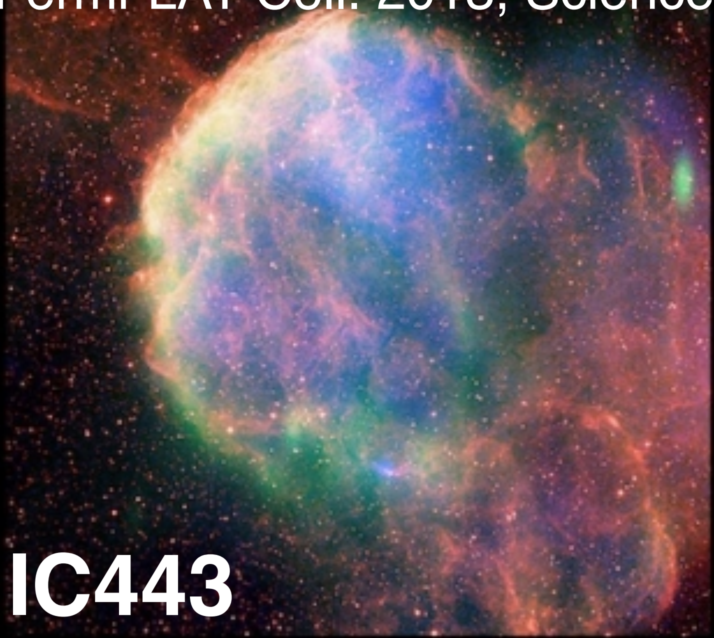
V1/V2=4 at M>>1
(M: mach number)

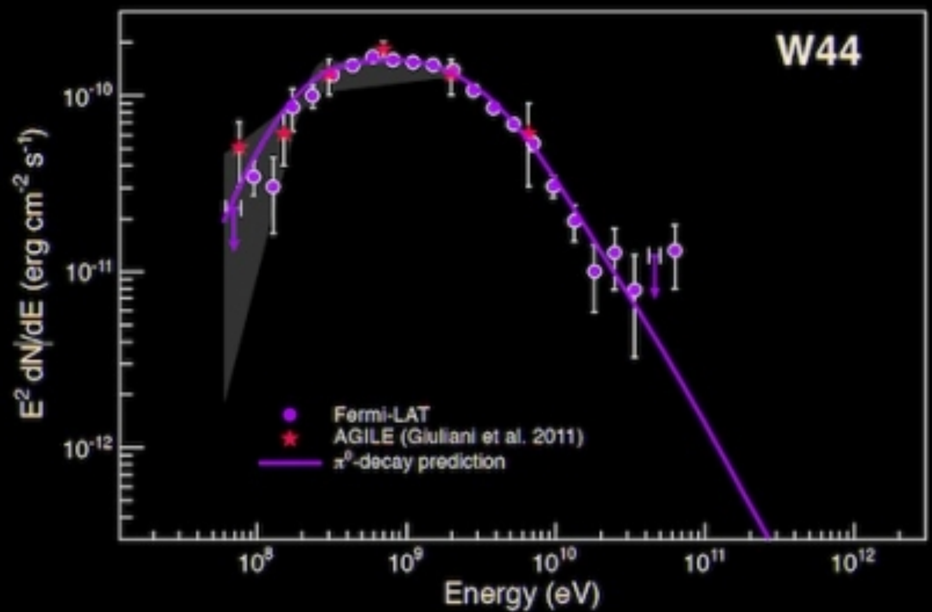
Supernova remnant as Cosmic-ray origins

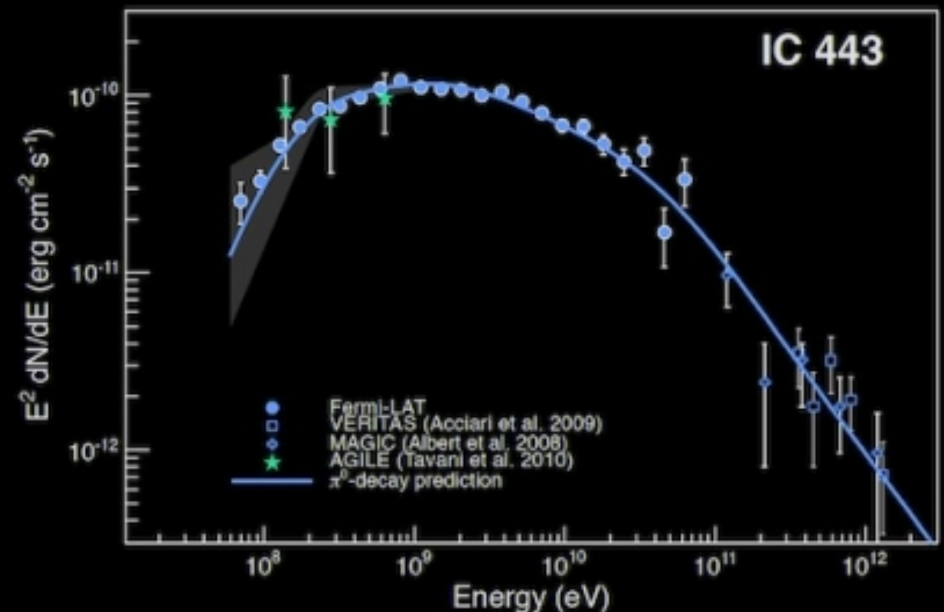
(Fermi-LAT Coll. 2013, Science)

Image data from ESA Herschel and XMM-Newton

Image data Chandra X-ray, DSS Optical and VLA radio

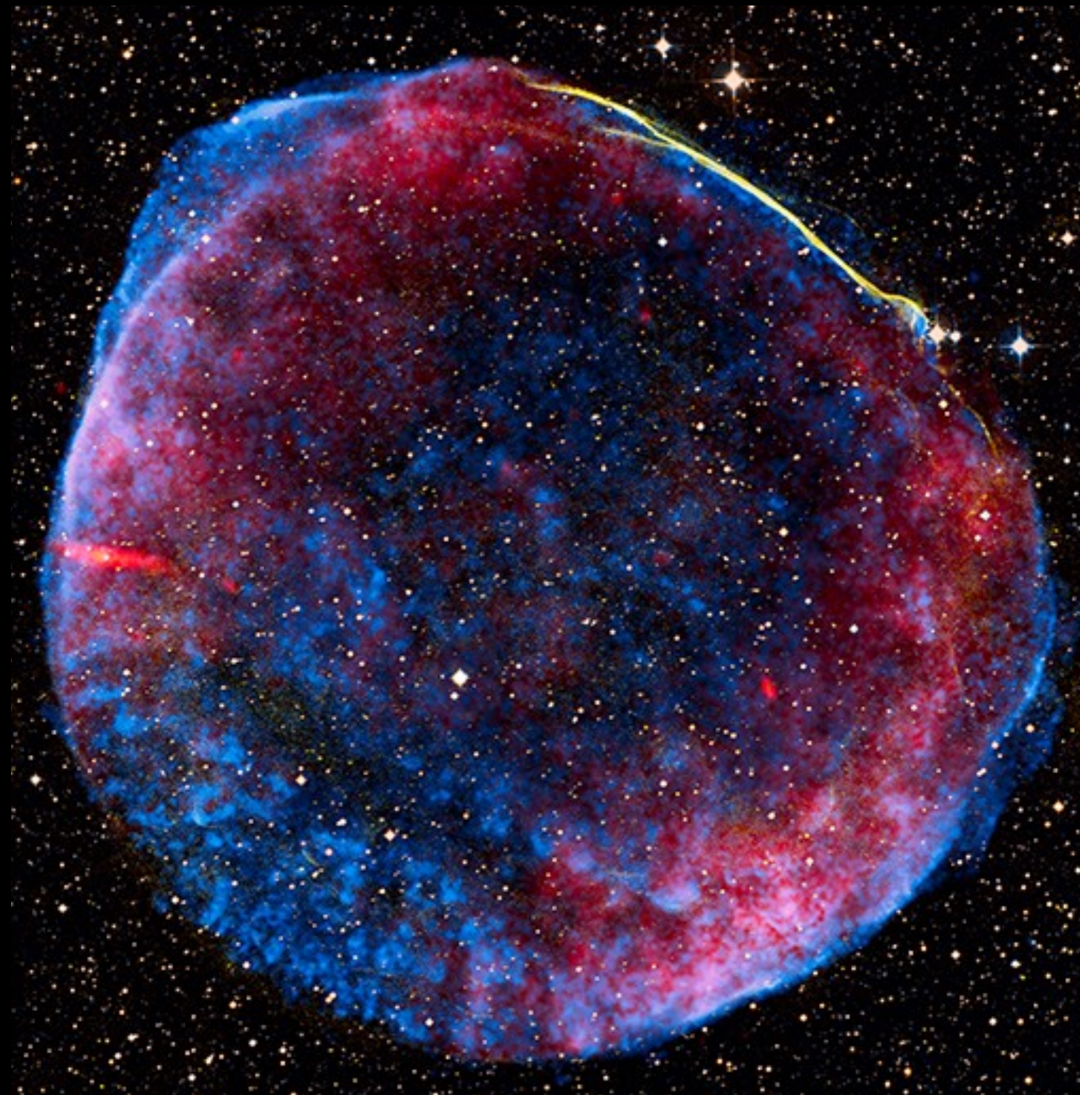






Diffusive shock acceleration (DSA) in SNR

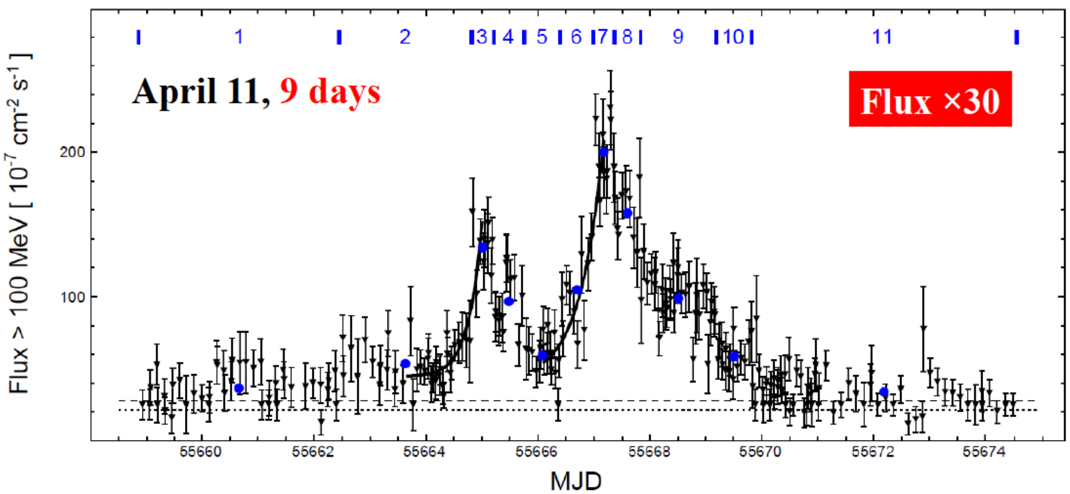
SN 1006

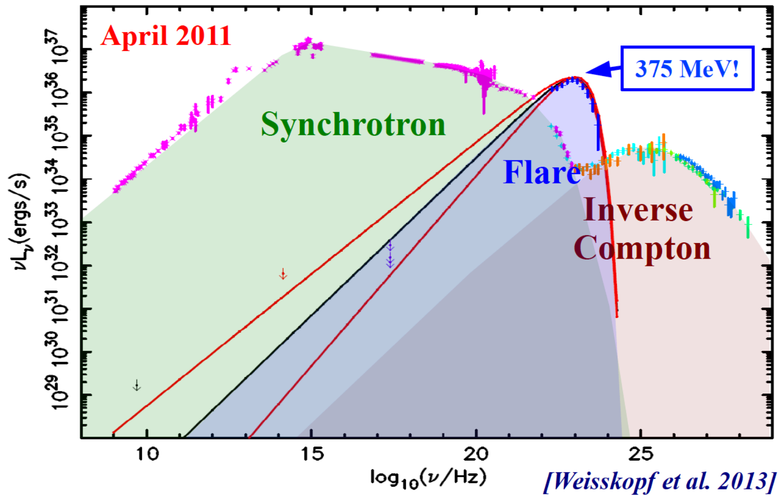


(Credit:X-ray: NASA/CXC/ Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/ AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/ F.Winkler, NOAO/AURA/NSF/ CTIO Schmidt & DSS)

(more in Amano-san's talk)

Crab flare: reconnection?

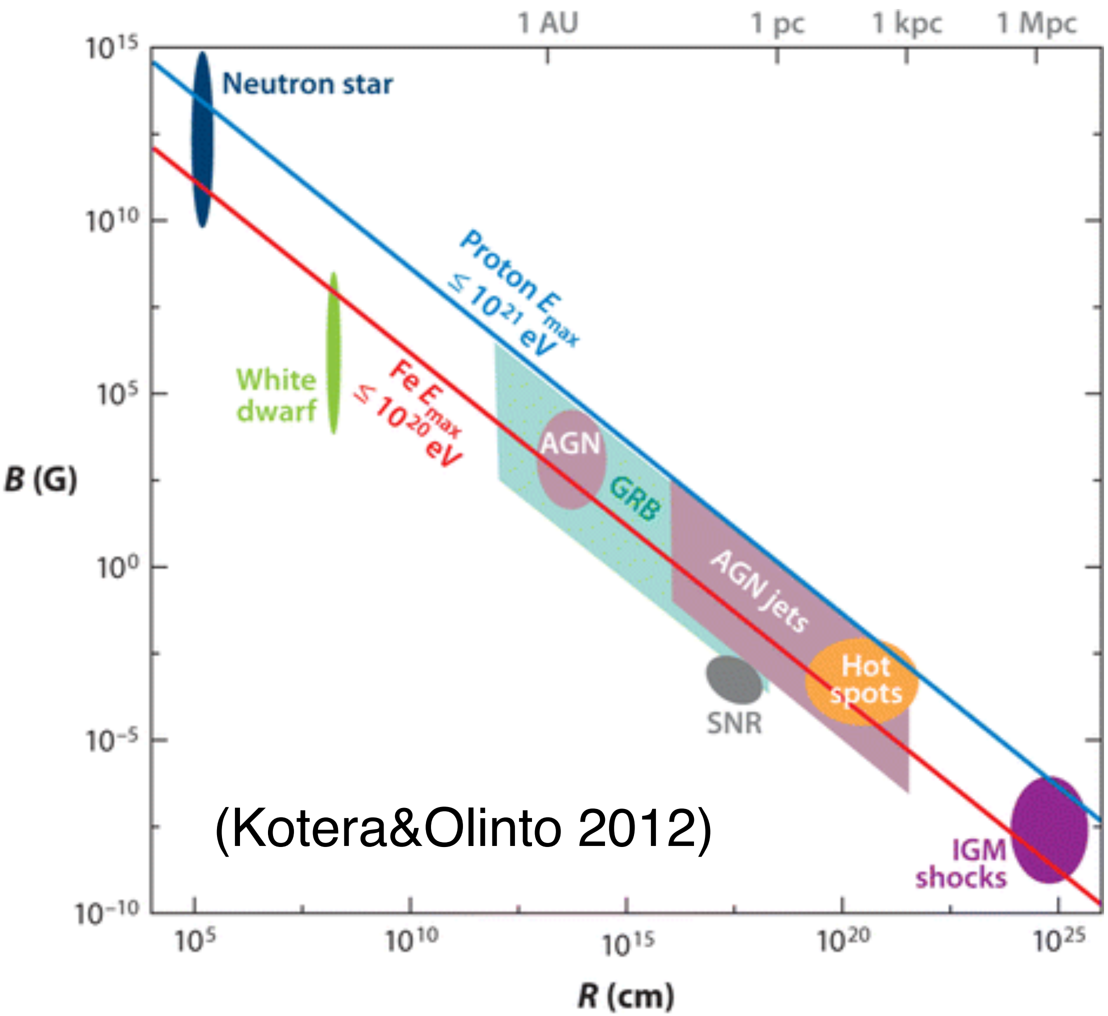




- Compactness: t_{var}~4-8 hrs → Emission region 3x10^{-4} pc
- Hard spectrum: Γ~1.3, inconsistent with shock acceleration
- Synchrotron 375 MeV > 160 MeV (radiation reaction limit)
  → challenge classical acceleration models

1. Doppler beaming? (but not seen in the Crab)
2. Reconnection!? → ***Zenitani-san's talk***

extra-galactic: relativistic jet



AGN jet:

- the most dominant gamma-ray source
- origin of Ultra-high-energy (~10^{20} eV) cosmic rays?

Blazar Jets

- ***where is the gamma-ray emission site?***
  (~ where is the jet dissipation region?)
- ***what is the acceleration mechanism?***
  (DSA (Fermi-I), Stochastic (Fermi-II), reconnection?)
- ***what is the dominant component in the jets?***
  (matter or Poynting flux dominated
  at the gamma-ray emission region?)

→ ***relativistic Jet formation***

Relativistic Jet Formation

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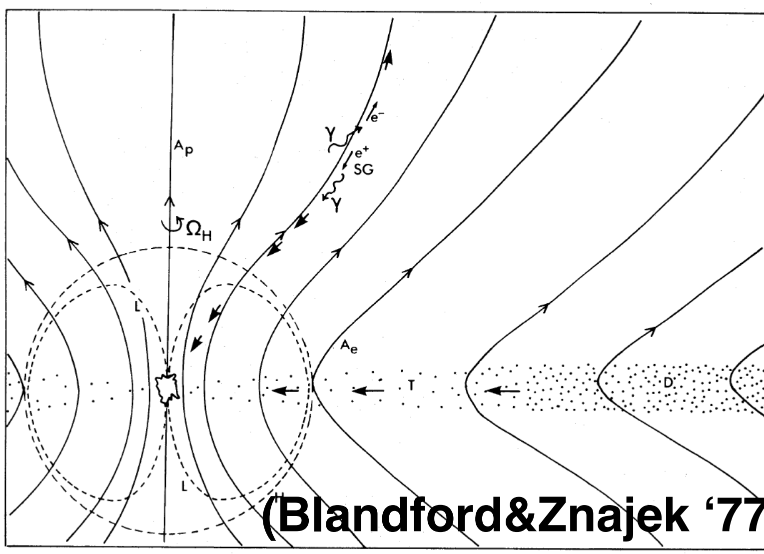
(these days) commonly considered: **MHD mechanism**

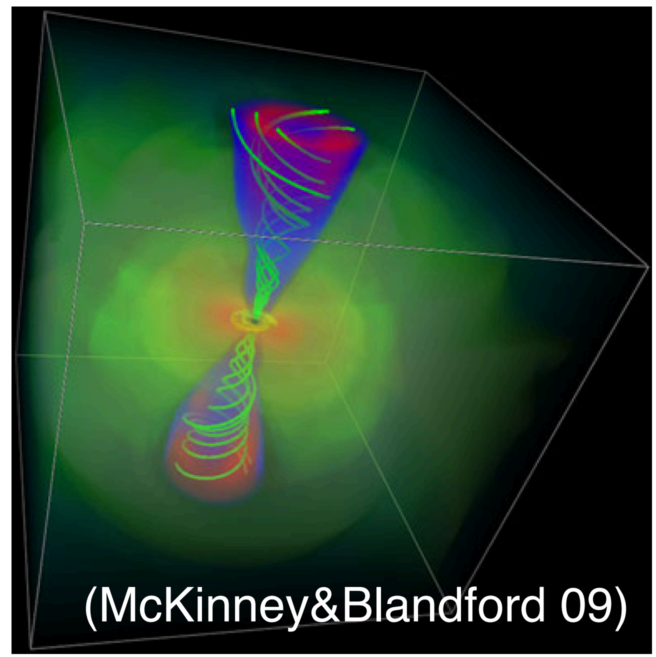
Blandford-Znajek process:
(from rotating BHs)



(Blandford&Znajek '77)

(c.f, Blandford&Payne 82,
from magnetized accretion disk)

3DMHD simulation (BZ effect)



(McKinney&Blandford 09)

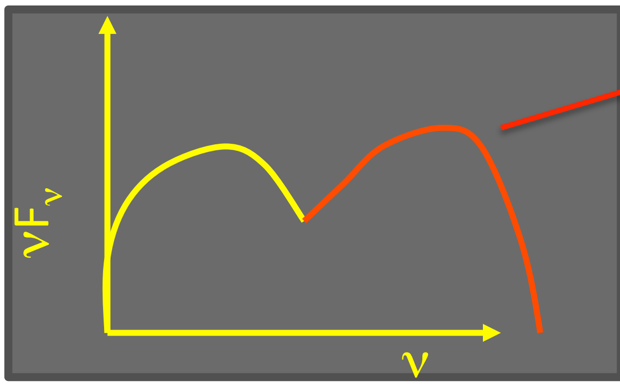
are the jets strongly magnetized?

talks by
Kojima-san
Mizuta-san

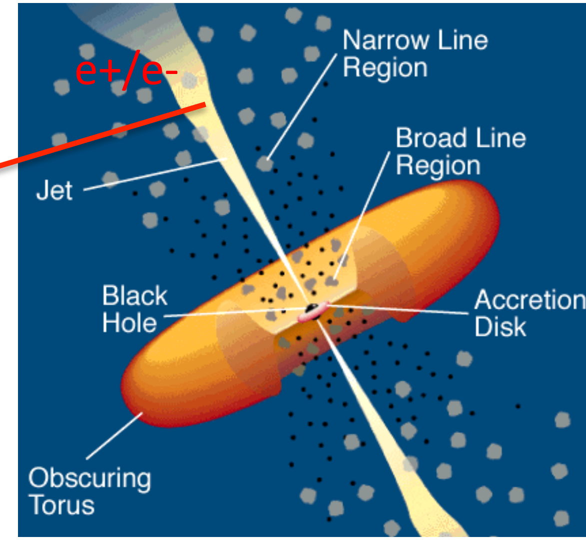
Gamma-ray emission from AGNs

AGNs with relativistic jet

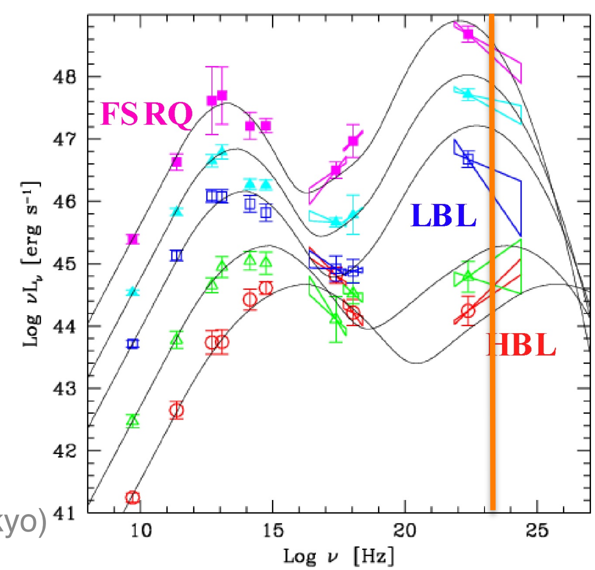
Inverse-Compton scattering
by electrons in the jets



seed photon:
synchrotron: SSC
external: EIC



	Blazar	Radio Galaxies
• low power	BL Lac	FR I
• high power	FSRQ	FR II
	small viewing angle -> relativistic beaming	mis-aligned blazar ?



Emission from Jets (FSRQ)

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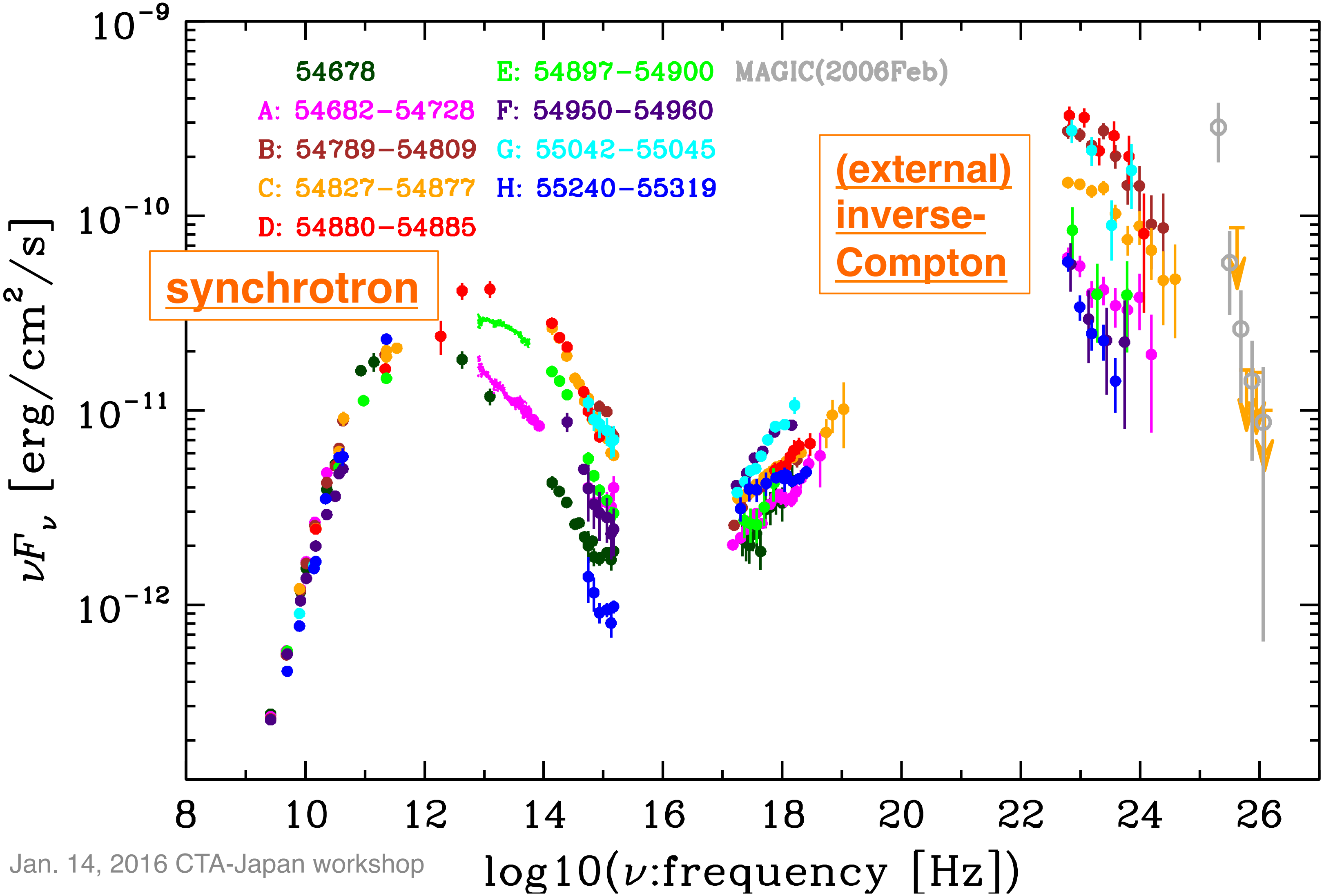
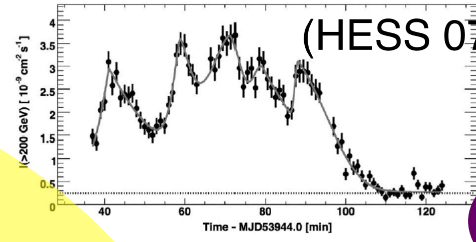
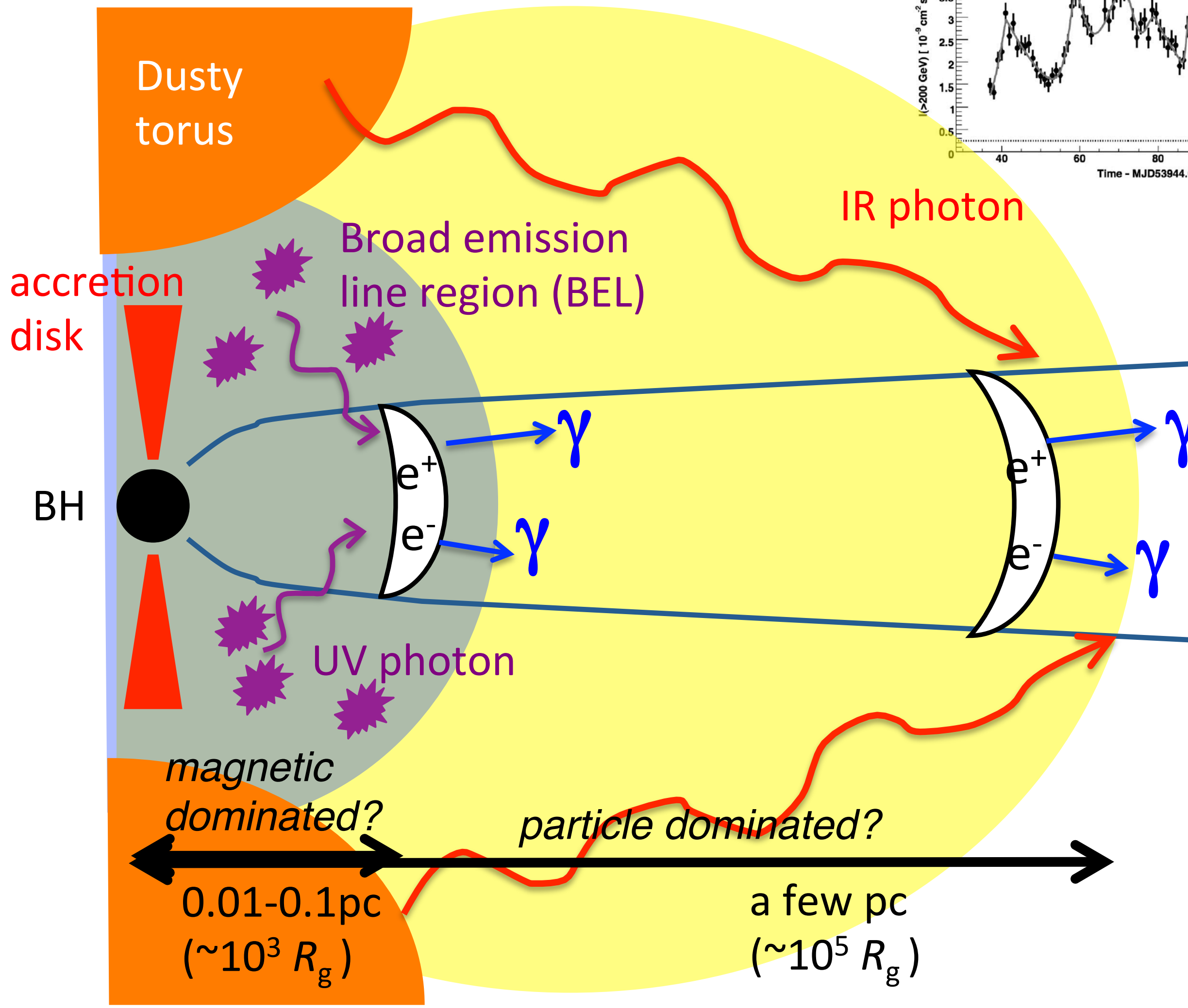
3C 279 (Hayashida+12, *ApJ*, 754, 114)



“where is the gamma-ray emission site?”



(fast variability in BL Lacs)



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

or

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

(TeV detection from FSRQs)

to avoid
$\gamma_{VHE} + \gamma_{UV} \rightarrow e^+ e^-$

3C 279 γ-ray activity for 7 years

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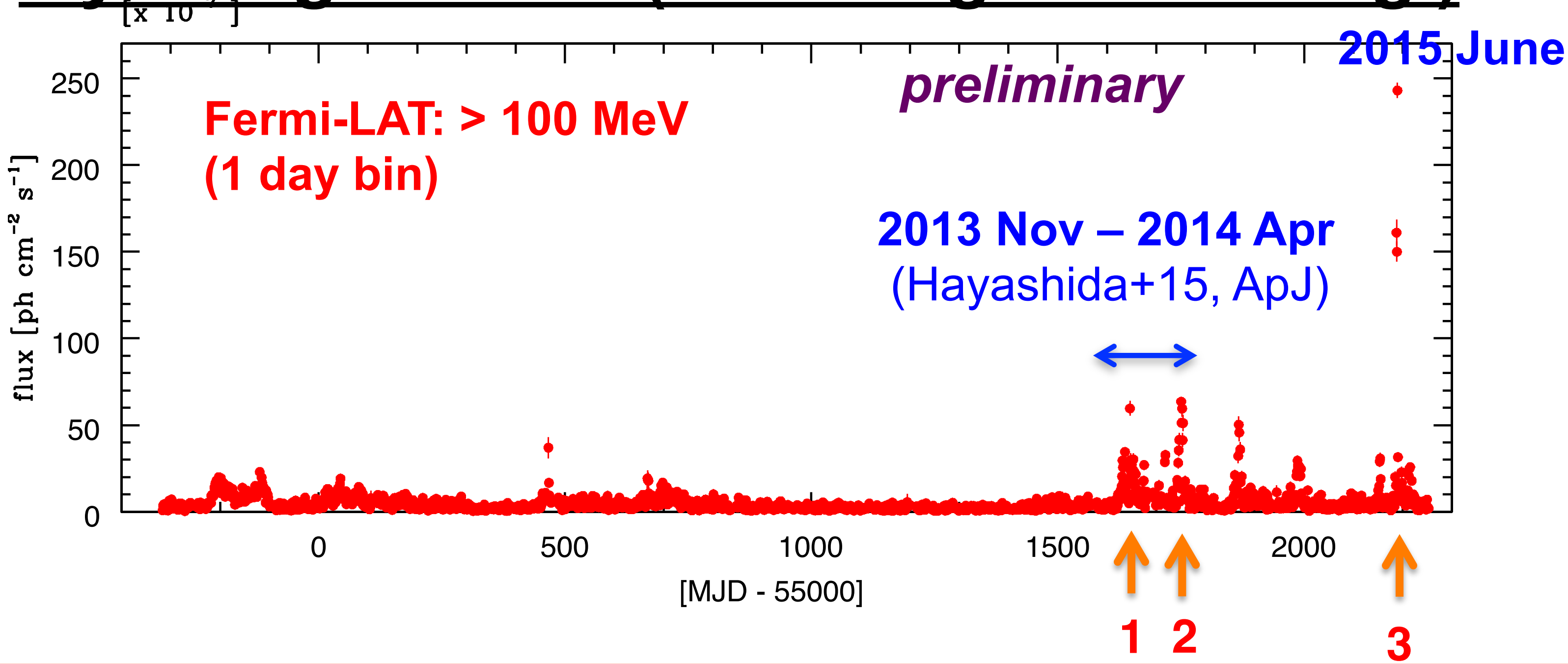
7 year light curve (2008 Aug. – 2015 Aug.)

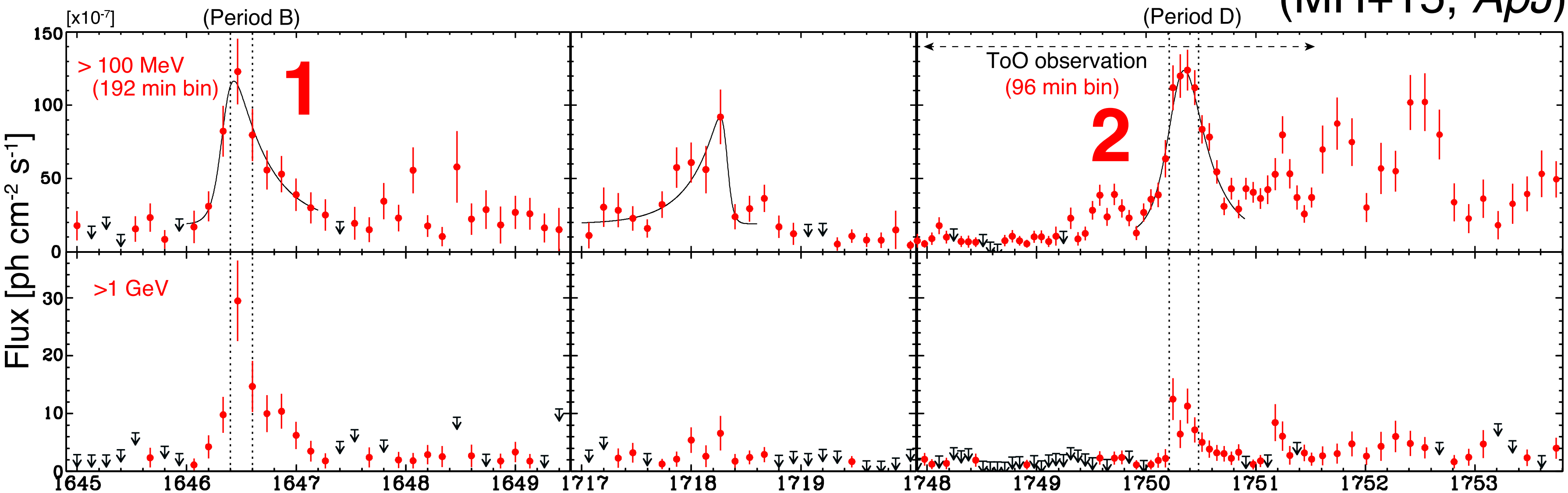


Three large outbursts with flux (>100 MeV) (1 day average)

1. 2013 December 20 : 6.0×10^{-6} ph cm^{-2} s^{-1}
2. 2014 April 03 : 6.4×10^{-6} ph cm^{-2} s^{-1}
3. 2015 June 16 : 24.3×10^{-6} ph cm^{-2} s^{-1}

Flare profile

(MH+15, *ApJ*)



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

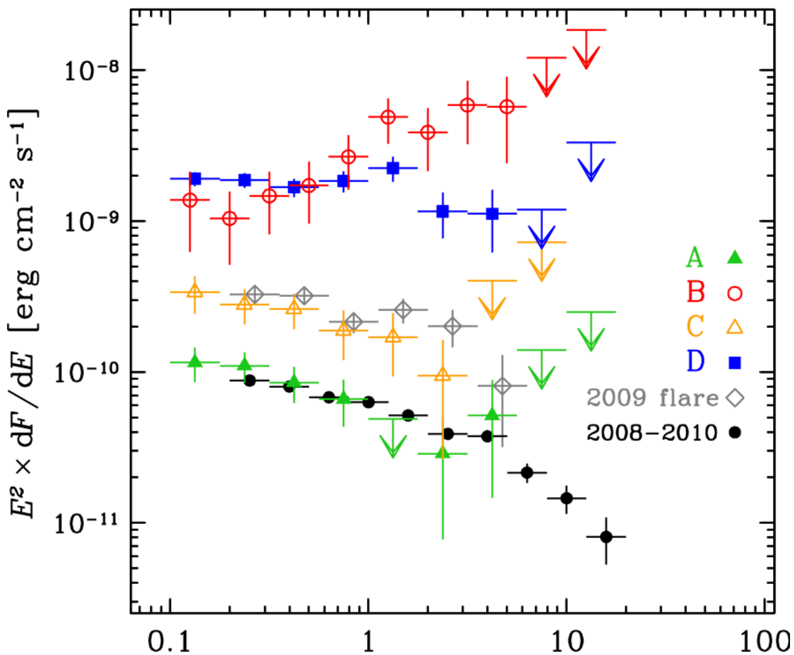
rise fall

Flare number	$\tau_{\rm rise}$ [hrs]	$\tau_{\rm fall}$ [hrs]	b ($\times10^{-7}$) photons cm^{-2} s^{-1}	F_0 ($\times10^{-7}$) photons cm^{-2} s^{-1}
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
2 Flare 3 (ToO)	2.6 ± 0.6	5.0 ± 0.8	216 ± 19	10.5 ± 6.6

- asymmetric profile
- hourly scale variability at 100 MeV:
  - very efficient cooling → need dense external photon → **inside BLR**

LAT Spectrum

(MH+15, *ApJ*)



Red (Flare 1, Period B)

- **Very hard index (1.71±0.10)**

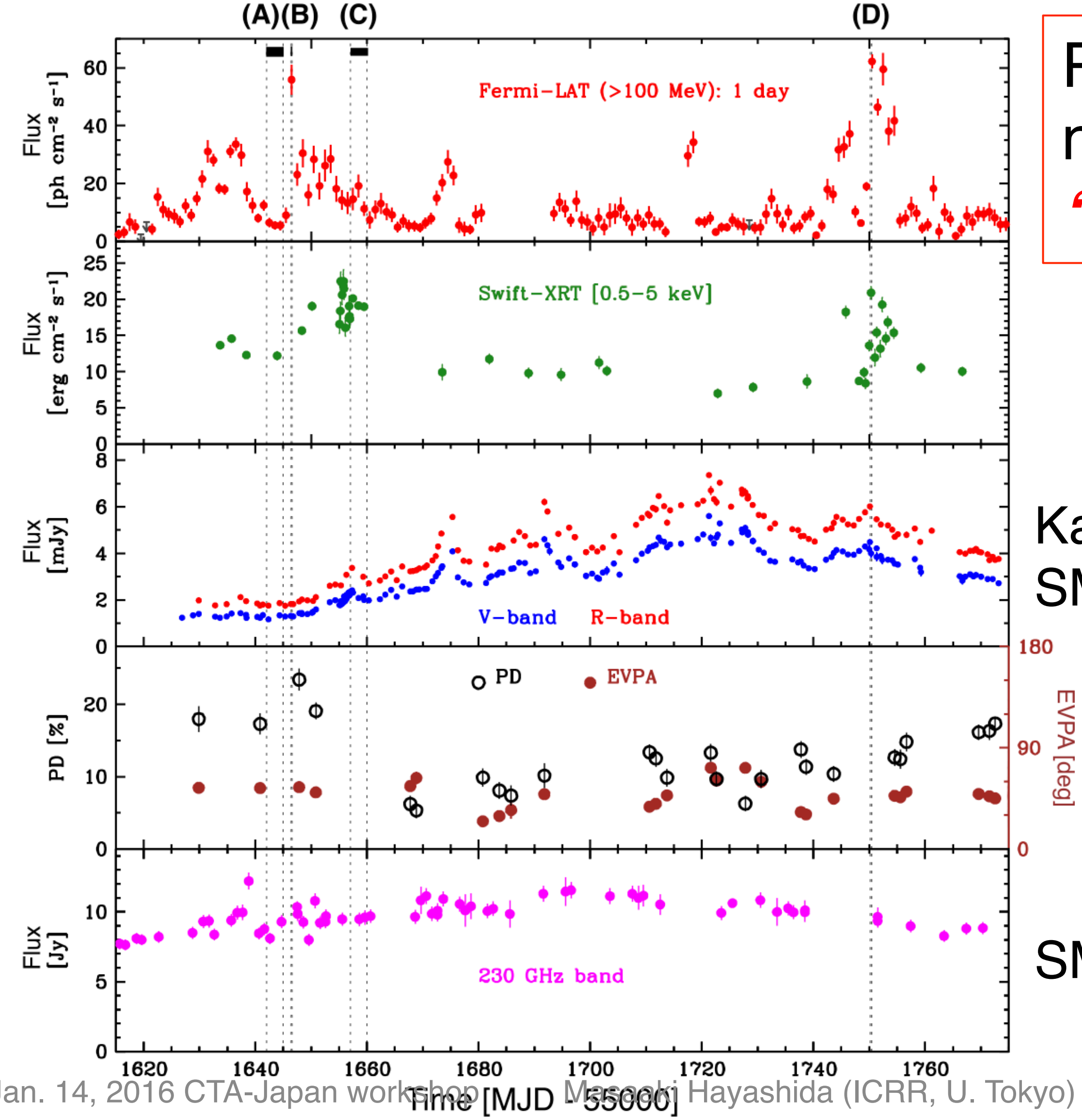
⬌ typ. FSRQ: ~2.4

- **peaked at a few GeV**

⬌ typ. FSRQ: < 100 MeV

Period (MJD - 56000)	fitting model[a]	$\Gamma/\alpha/\Gamma_1$	β/Γ_2	E_{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	

Multi-band light curve



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

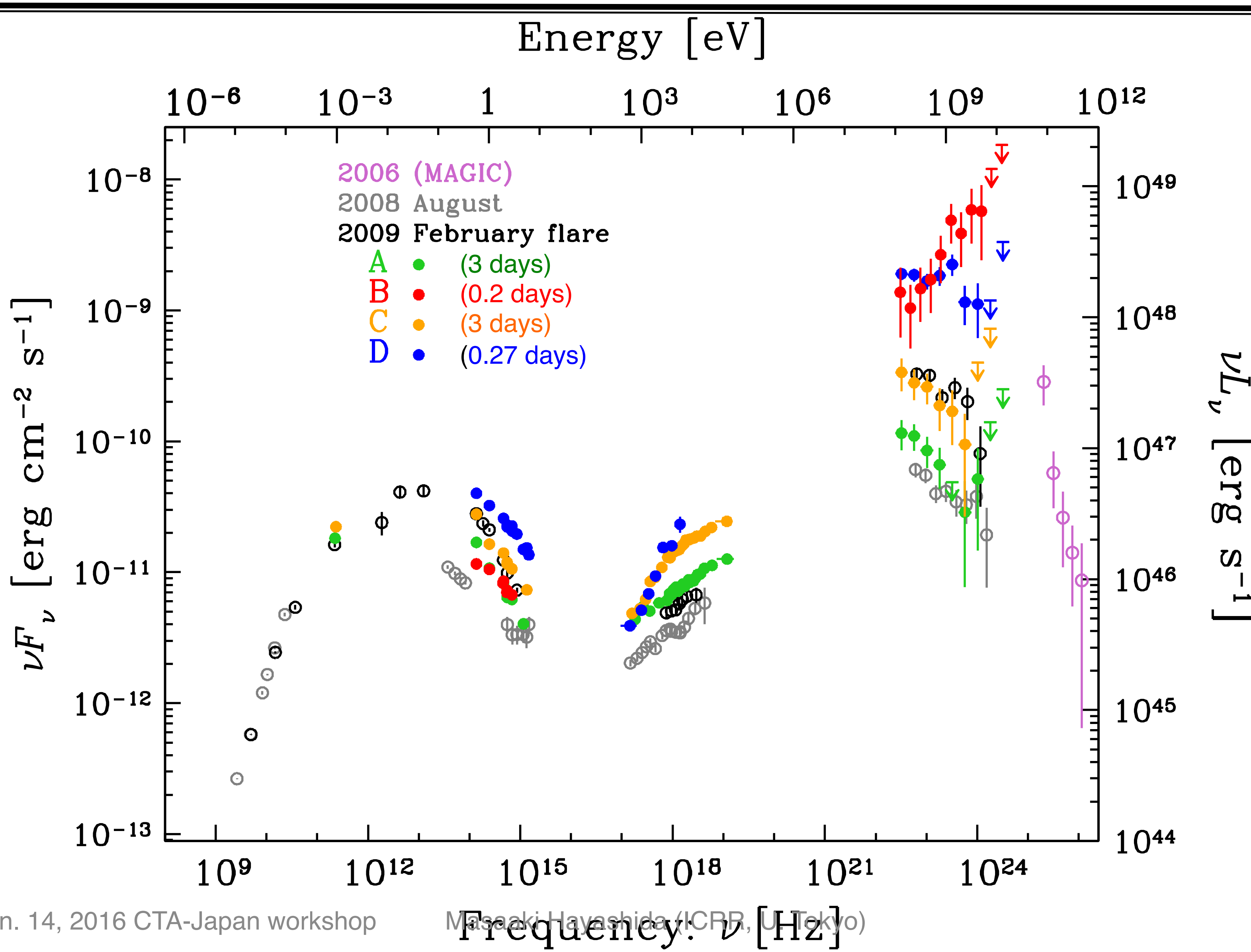
Kanata, SMART

Kanata

SMA

(MH+15, *ApJ*)

Broad band SED



emission model for Period B

(MH+15, *ApJ*)

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

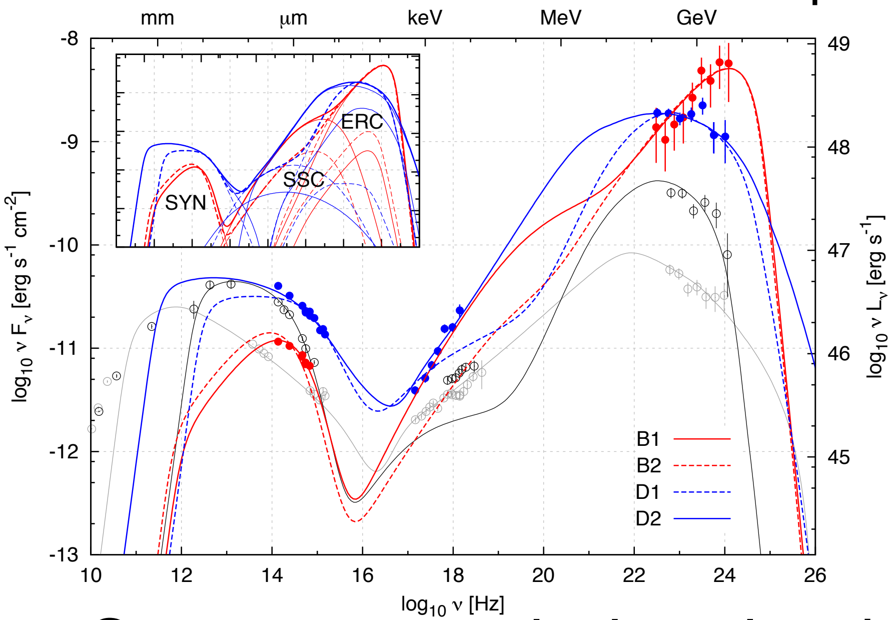


TABLE 5
PARAMETERS OF THE SED MODELS PRESENTED IN FIG. 9.

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

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(MH+15, *ApJ*)

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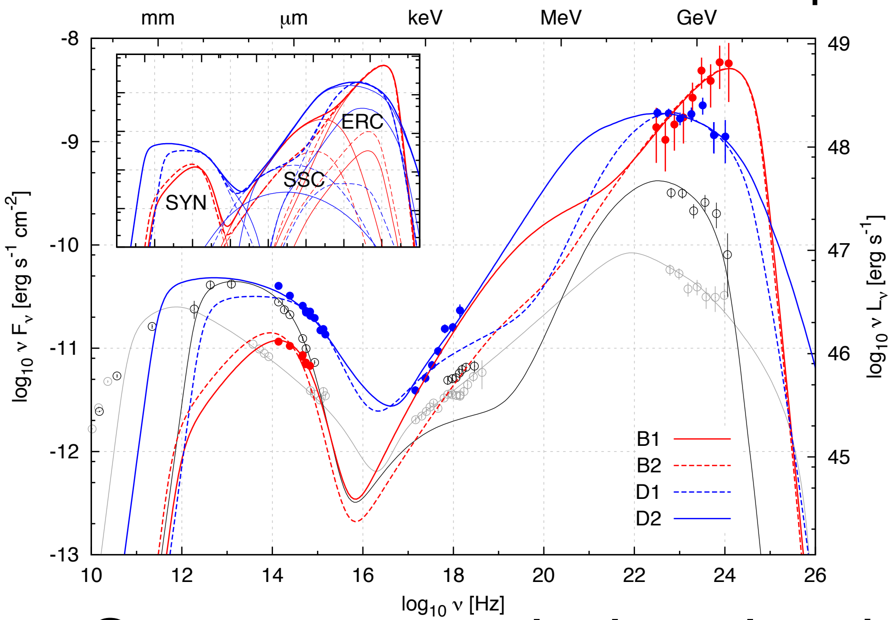

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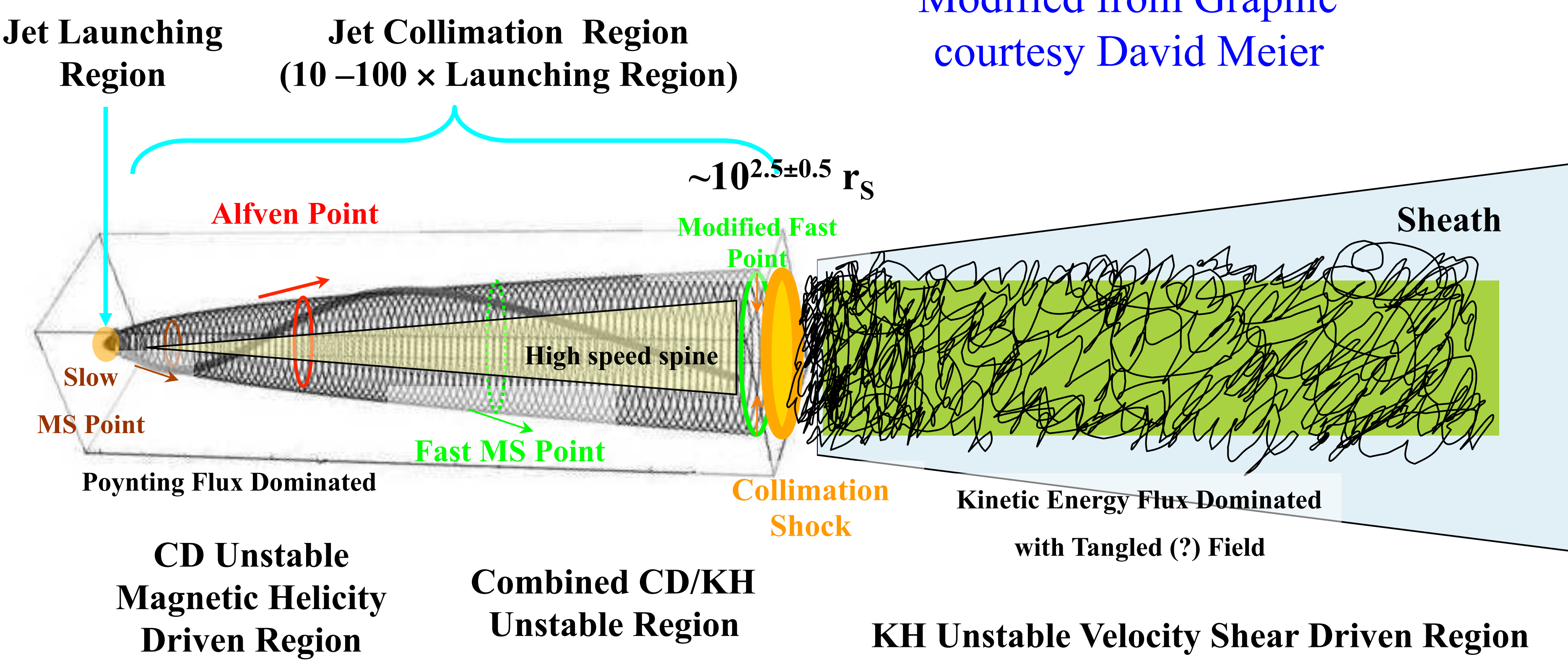
Regions of AGN Jet Propagation

Modified from Graphic courtesy David Meier



slide from Yosuke 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^{50} erg/s
  (e.g.,Zdziarski & Boettcher 15)

$U_{e(\pm)}/U_B$ at the jet base of M87

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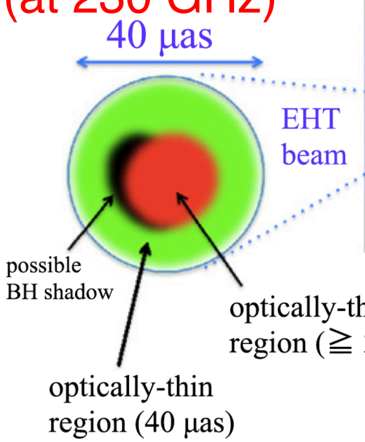
(Kino+14, *ApJ*, 786,5, Kino+15, *ApJ*, 803,30)

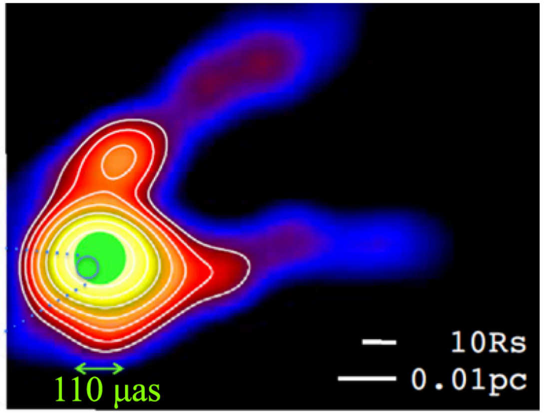
based on Synchrotron-self absorption

$$\frac{U_\pm}{U_B} = \frac{16\pi}{3b^2\left(p\right)} \frac{k\left(p\right)\epsilon_{\pm,\min}^{-p+2}}{(p-2)} \left(\frac{D_\mathrm{A}}{1\ \mathrm{Gpc}}\right)^{-1} \left(\frac{\nu_{\mathrm{ssa,obs}}}{1\ \mathrm{GHz}}\right)^{-2p-13} \times \left(\frac{\theta_{\mathrm{obs}}}{1\ \mathrm{mas}}\right)^{-2p-13} \left(\frac{S_{\nu_{\mathrm{ssa,obs}}}}{1\ \mathrm{Jy}}\right)^{p+6} \left(\frac{\delta}{1+z}\right)^{-p-5}$$

(for $p > 2$).

core detection:
θ_{thick}<40μas
(at 230 GHz)

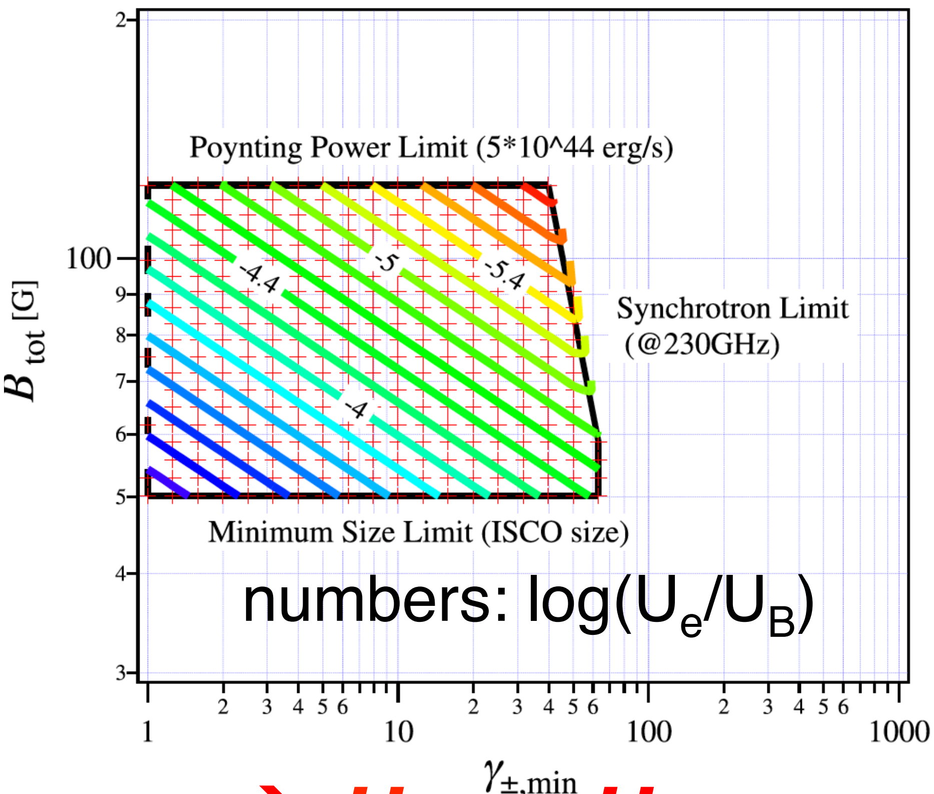




jet base of M87
(VLBA at 43GHz)

Allowed B, γ_{min} region

(L_j=5x10^{44} erg/s, p=3)



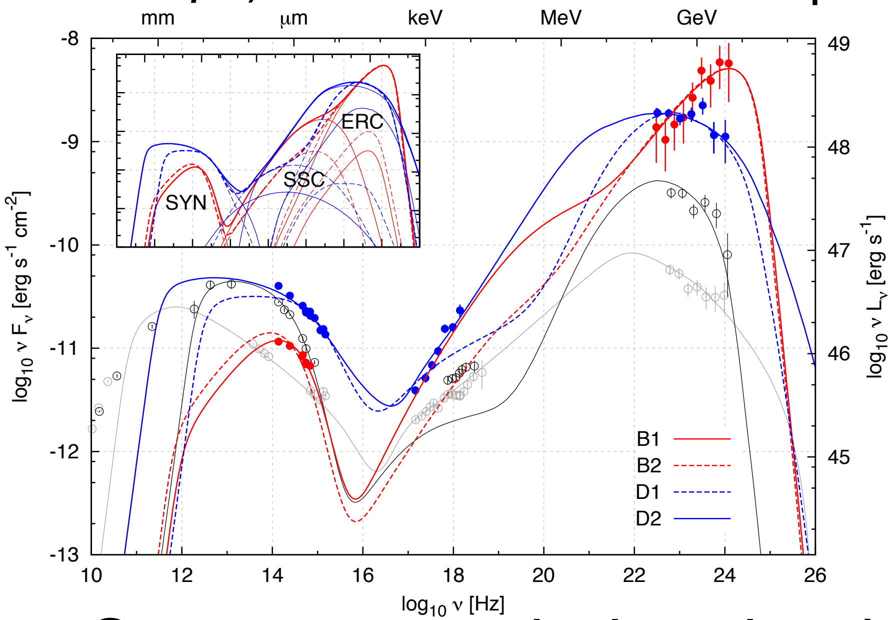
numbers: $\log(U_e/U_B)$

→ $U_B \gg U_{e(\pm)}$

(See also Nalewajko+14, *ApJL*, 796)

emission model for Period B

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



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hard (p<2) electron index

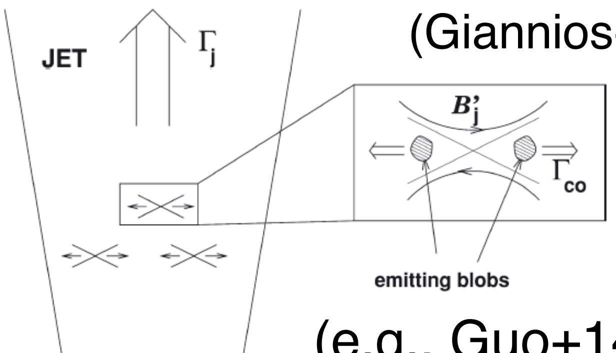
p : injected electron index

$p \geq 2$: normal standard shock (Fermi-I) acceleration

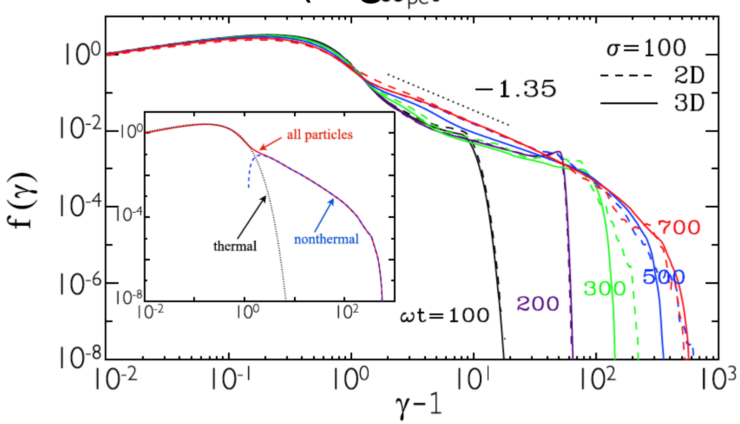
too soft!!

<u>magnetic reconnection</u>

(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?*

→ <u>Stochastic Acceleration ?</u>

<u>(2nd order Fermi acceleration)</u>

(see Asano-san's talk)

3C 279 γ-ray activity for 7 years

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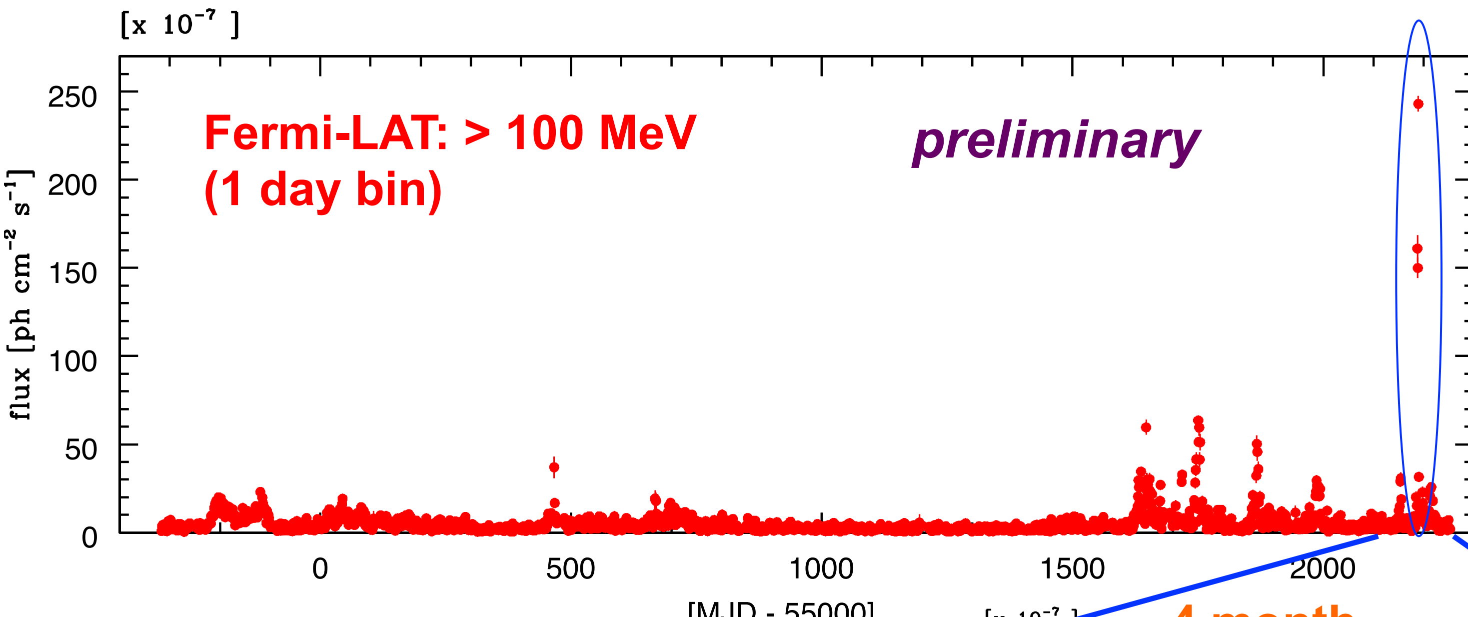
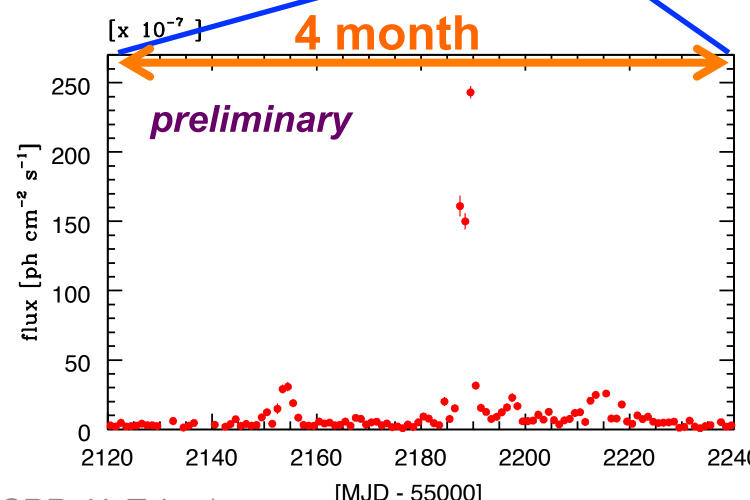


Flux ~2.5 x10^{-5} ph cm^{-2}s^{-1}

(>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.



Summary & Conclusion

- Blazar 3C 279 showed outbursts (>10^{-5} ph/cm^2/s) in last years
  - 2013 Dec.: orphan γ-ray flare, very hard index (Γ_γ~1.7)
  - 2015 Jun.: the largest flare with minute-scale variability
- where is the gamma-ray emission site?
  - *inside BRL (~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 : kinetic-flux dominated : L_B/L_{jet} ~ 10^{-4}*
  - *jet simulation: Poynting-flux dominated (< 10^3 r_g)*
  - *radio observation (SSA): Poynting-flux dominated (M87 at ~a few r_g)*
- what is the acceleration mechanism?
  - *not only shock accelerations should work (e.g., Fermi-II, reconnection)*