Slow UHECR Acceleration by Turbulence in Gamma-Ray Bursts

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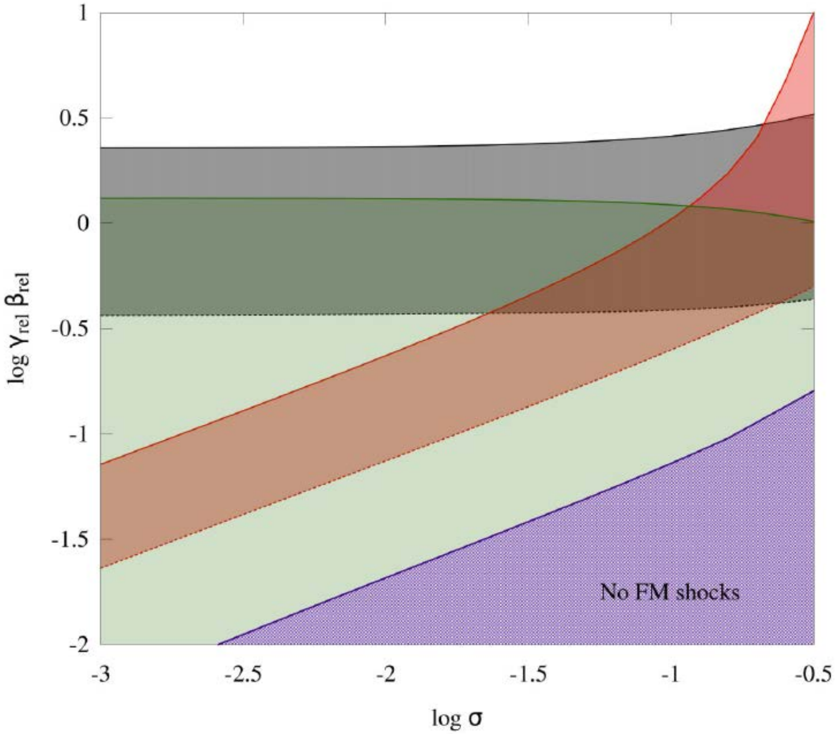
Particle Acceleration in Relativistic Jets

Shock Acceleration may be hard in highly magnetized plasma.

Kirk & Heavens 1989, Lemoine & Pelletier 2010, Sironi+ 2013 etc.

(SNR: non-rela, PWN: low sigma seem OK)

In blazar



The parameter range is very limited.

Sironi+ 2015

Acceleration via turbulence

- Park & Petrosian 1995
- Becker & Dermer 2006
- Stawarz & Petrosian 2008

In Blazars

- Bottcher+ 1999
- Schlickeiser & Dermer 2000
- Lefa+ 2011
- Kakuwa+ 2015

In GRBs

- Bykov & Meszaros 1996
- Dermer & Humi 2001
- Asano & Terasawa 2009, 2015
- Murase+ 2012

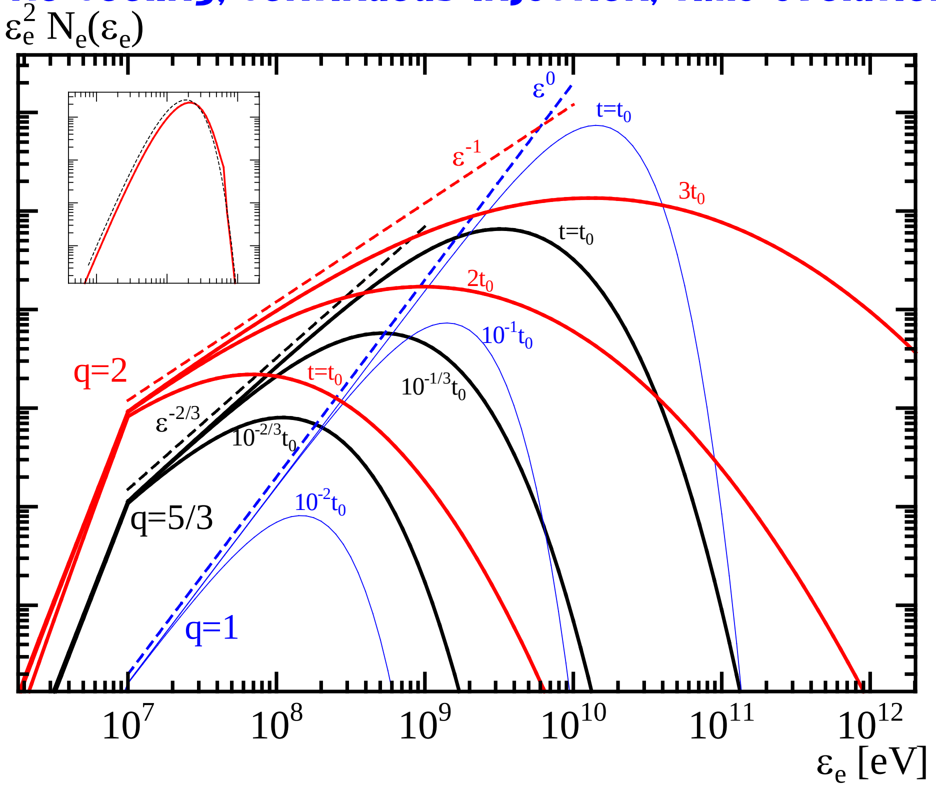
Phenomenological Treatment

$D_{EE} = K\varepsilon^q$ **Kolmogorov+Alfvenic q=5/3, Compressible q=2 (hard sphere)**

$$\frac{\partial N_\mathrm{e}(\varepsilon,t)}{\partial t} = \frac{\partial}{\partial\varepsilon}\left[D_{\varepsilon\varepsilon}\frac{\partial N_\mathrm{e}(\varepsilon,t)}{\partial\varepsilon}\right] - \frac{\partial}{\partial\varepsilon}\left[\left(\frac{2D_{\varepsilon\varepsilon}}{\varepsilon} - \langle\dot{E}_\mathrm{cool}\rangle\right)N_\mathrm{e}(\varepsilon,t)\right] + \dot{N}_\mathrm{e,inj}(\varepsilon,t)$$

Diffusion **Acceleration** **Cooling** **Injection**

No cooling, continuous injection, time evolution



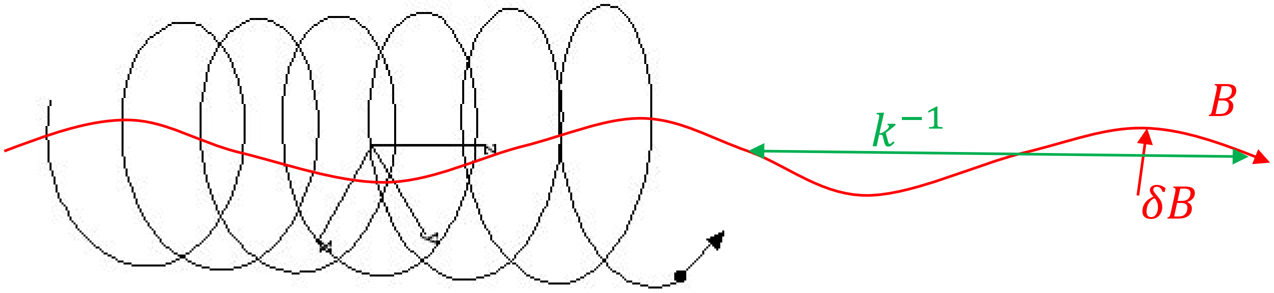
$N(\varepsilon) \propto \varepsilon^{-1}$ or harder

Stochastic Acceleration due to turbulence (2nd order Fermi acc.) leads to a hard spectrum.

harder than the shock case $N(\varepsilon) \propto \varepsilon^{-2}$

Interaction with Alfven Wave

Alfvenic Wave (transverse/incompressible)



Energy gain per scattering

$$\frac{\Delta\varepsilon}{\varepsilon} \equiv \bar{\xi} \simeq \frac{4}{3}\beta^2$$

pitch angle diffusion → mean free path $l \sim \frac{B^2}{k\delta B^2(k)} r_{\mathrm{L}},\ k \sim 1/r_{\mathrm{L}}$

resonance condition

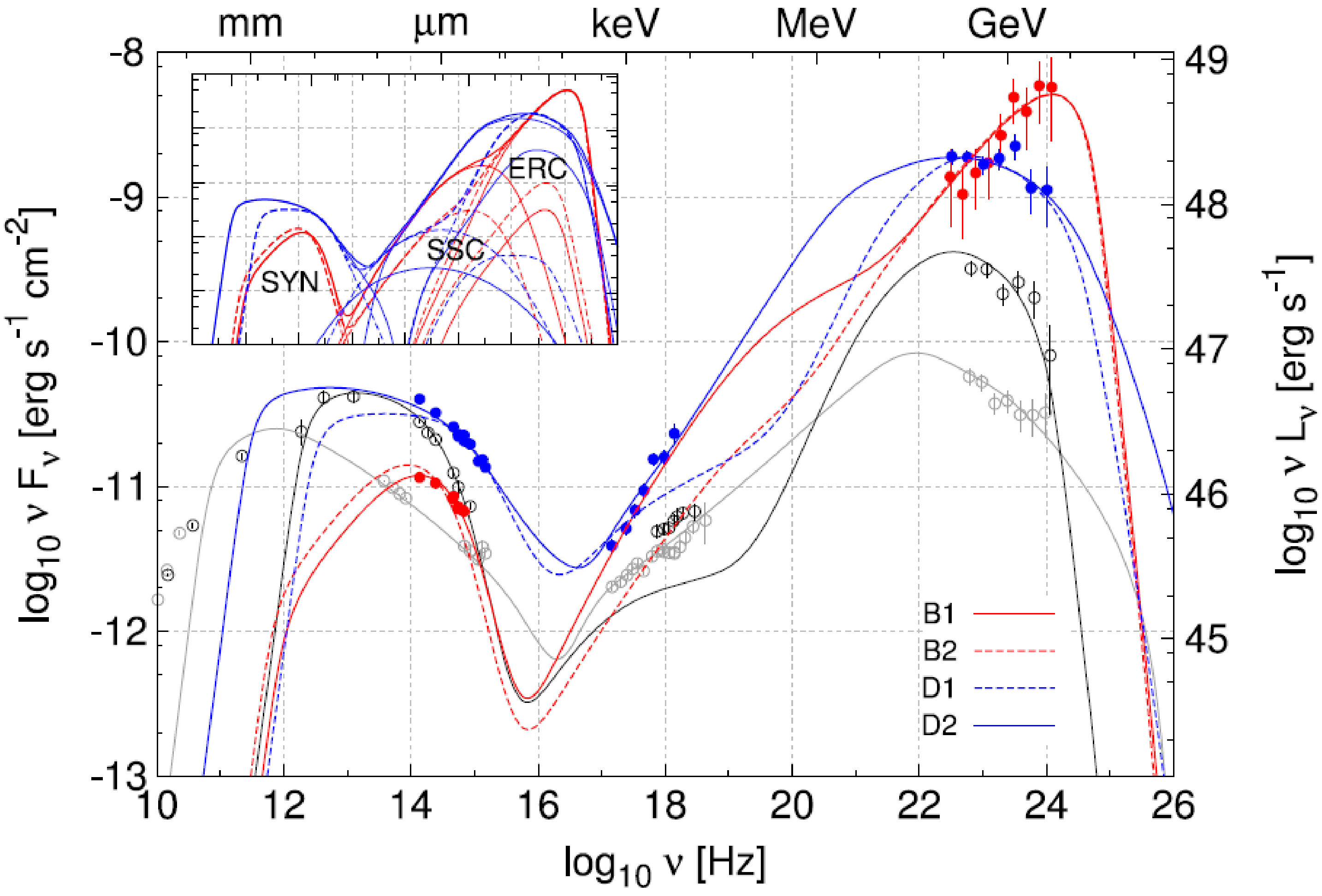
$$\delta B^2(k) \propto k^{-q} \rightarrow D_{\varepsilon\varepsilon} = \frac{< \Delta\varepsilon^2 >}{\Delta t} \sim \frac{\bar{\xi}\varepsilon^2}{l/c} \propto \varepsilon^q$$

However, the ratio $\frac{U_B}{U_e}$ is typically 0.1 in blazars.

It seems that the Alfven waves cannot be the enrgy source.

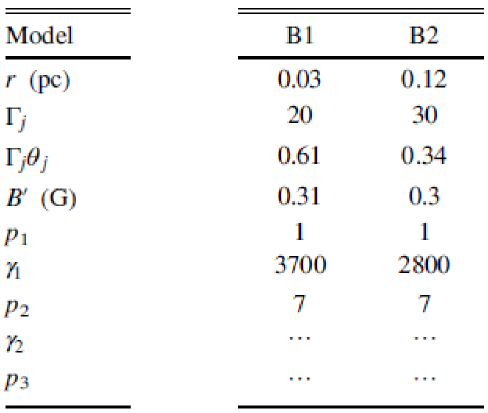
Extreme Case

3C 279 2013 Flare



Extremely hard gamma-ray flare without X-ray enhancement.

Broken power-law Model parameters



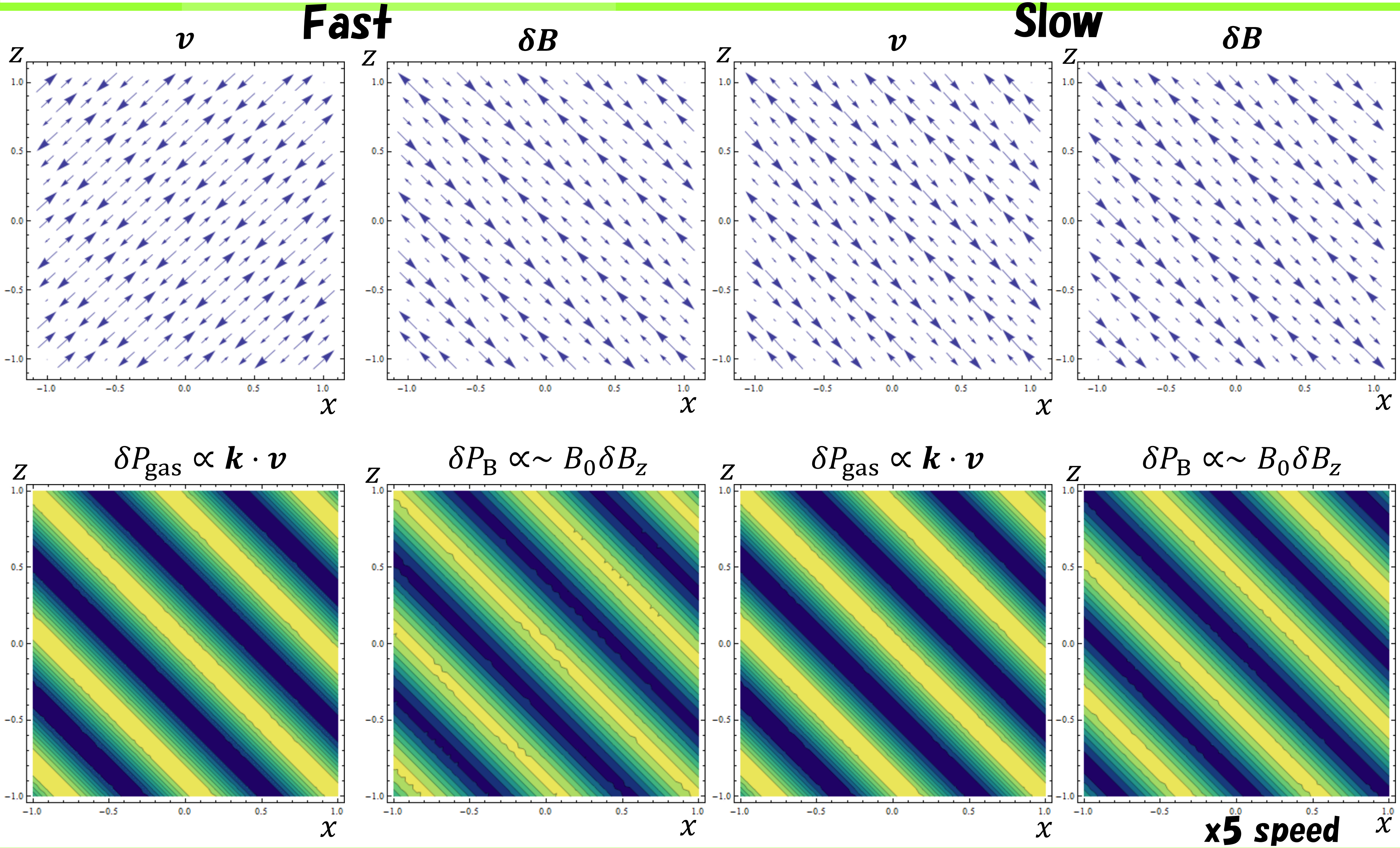
Model	B1	B2
r (pc)	0.03	0.12
Γ_j	20	30
$\Gamma_j\theta_j$	0.61	0.34
B' (G)	0.31	0.3
p_1	1	1
γ_1	3700	2800
p_2	7	7
γ_2	…	…
p_3	…	…

$$\frac{L_B}{L_{jet}} < 10^{-4}$$

Hayashida+ 2015

Alternative: Compressible Waves

$\alpha = 10, k = 10, \theta = \pi/4,$



x5 speed

Acceleration by compressible wave

Transit Time Damping (Scatter by mirror force)

Formulae of Energy Diffusion Coefficient:

Non-resonant (need spatial diffusion coeff.)

Ptuskin 1988

$$D_{\varepsilon\varepsilon} = \varepsilon^2 \frac{8\pi}{9} D_{xx} \int dk \frac{\delta V^2(k) k^2}{v_F^2 + D_{xx}^2 k^2}$$

The largest scale eddy dominates

D_{xx} **is written with the smallest eddy?**

Cho & Lazarian 2006

$$D_{\varepsilon\varepsilon} \sim \varepsilon^2 \frac{\delta V^2}{D_{xx}}$$

Resonant $(k v_F = k_\parallel v_\parallel)$

Lynn+ 2014

$$D_{\varepsilon\varepsilon} \sim \varepsilon^2 \frac{v_F^2}{cL} \frac{\delta B_F^2}{B_0^2} \int d(kL)(kL)^{1-q}$$

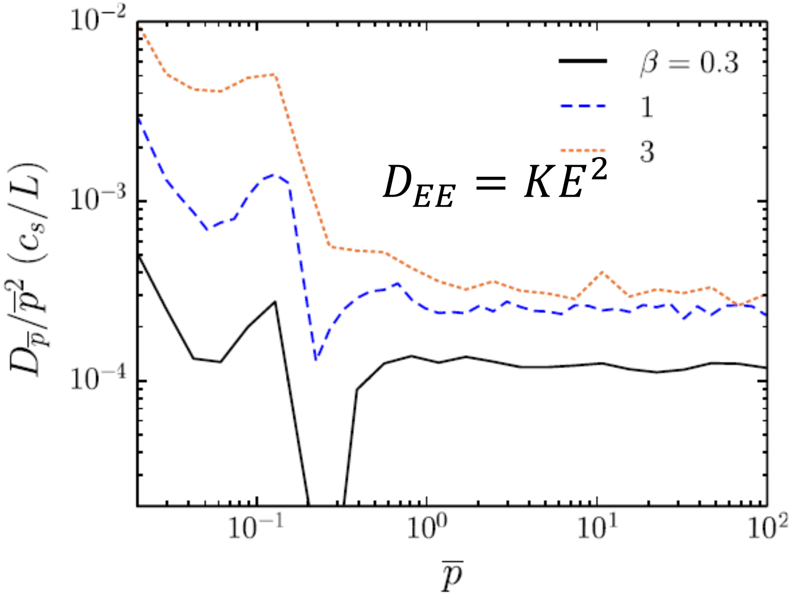
The amplitude is dominated by the smallest scale for q<2.

Test Particle Simulation

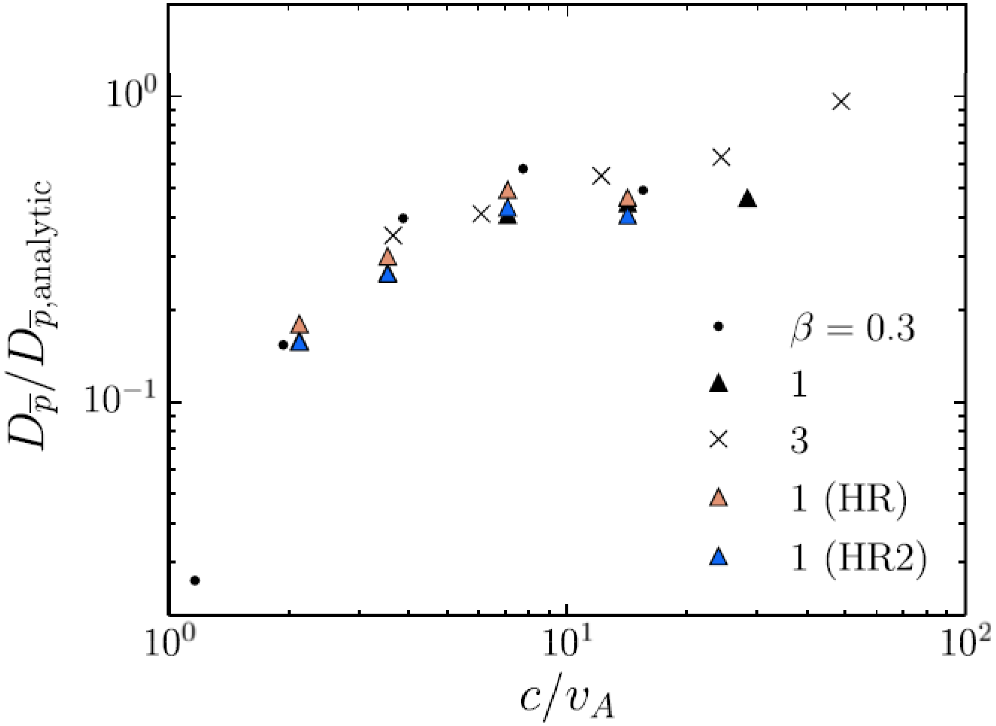
Lynn+ 2014

Particle injection in MHD simulations, where the slow-mode is dominant.

$$D_{\overline{p}} = \overline{p}^2 \frac{\pi}{24} \frac{v_A^2}{cL} \frac{\delta B_S^2}{B_0^2} \frac{(1-\alpha^2)^2}{\alpha^3} \ln(k_{\max} L),$$

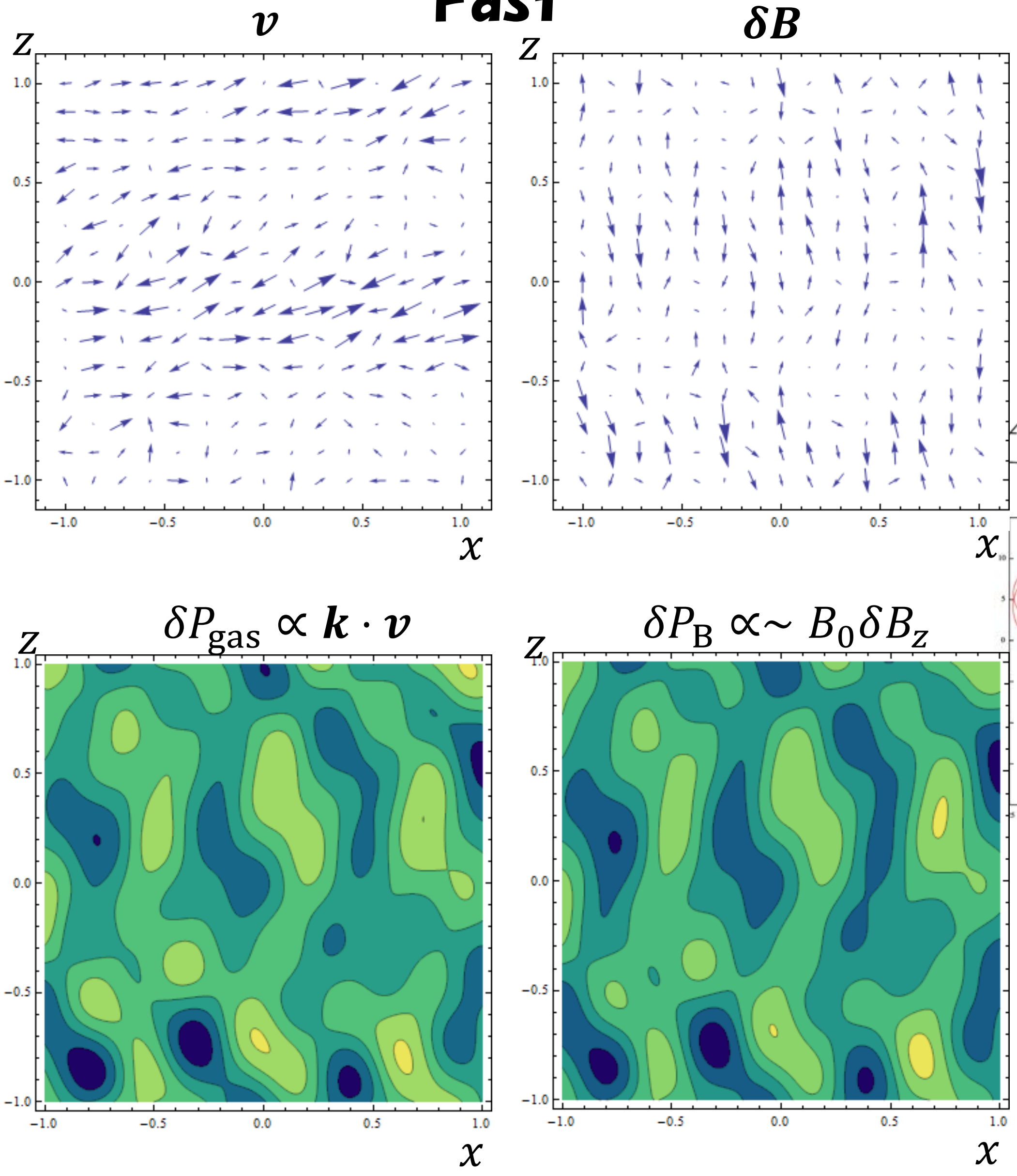


$$D_{EE} = KE^2$$

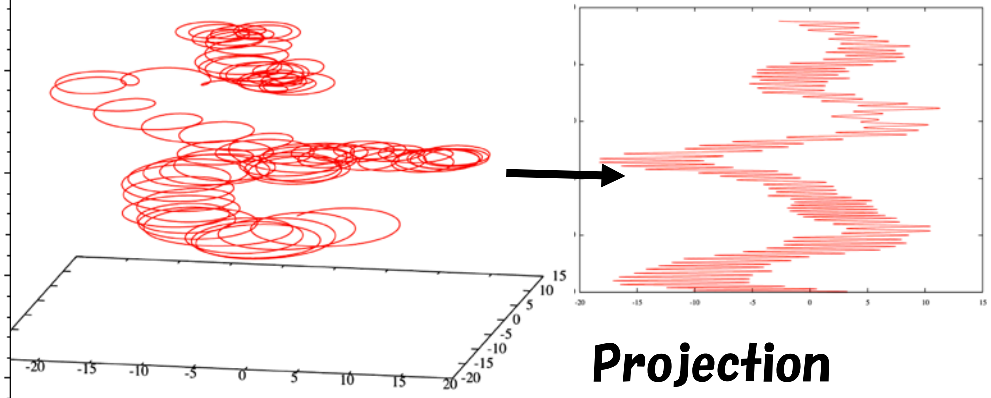


Test particle simulation in pure linear Fast Waves

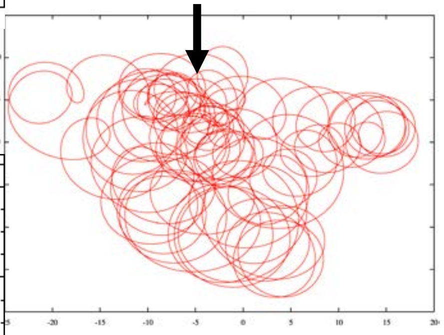
Fast

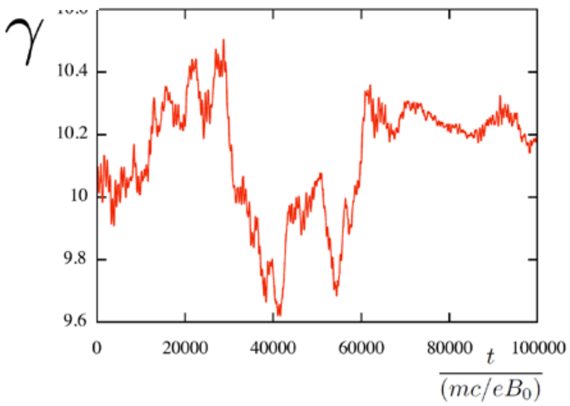


High-beta plasma



Projection

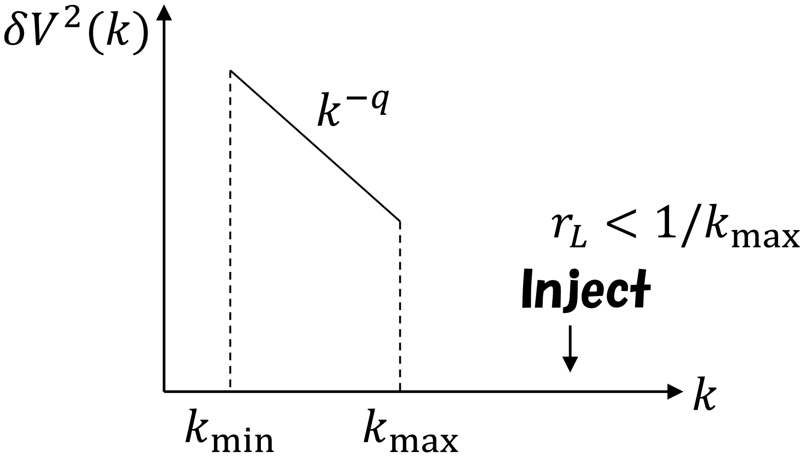




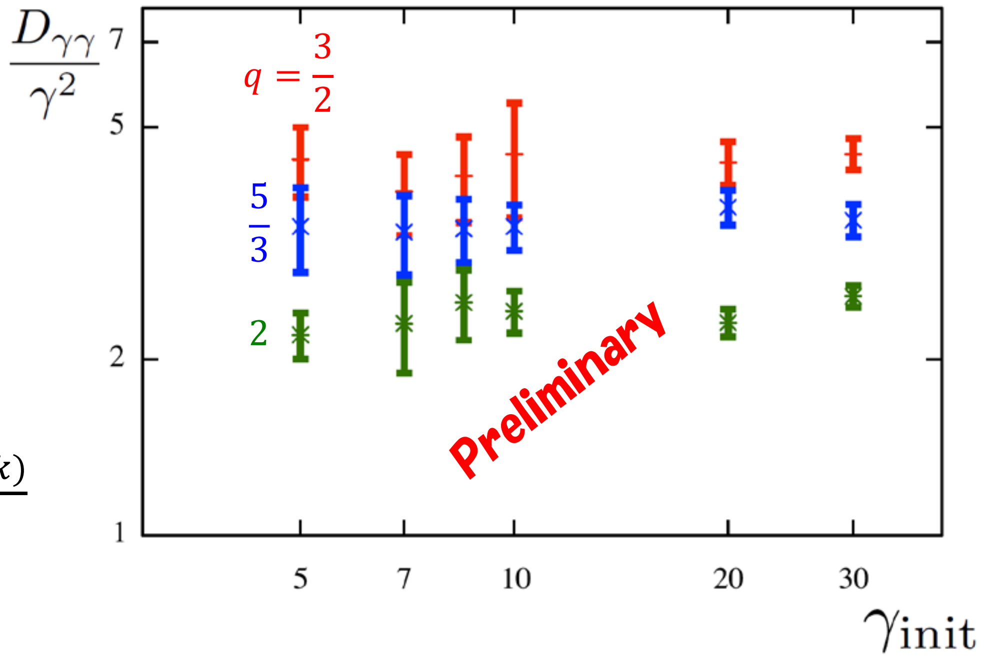
Teraki & Asano in prep.

$\alpha = 10, k = 10-20,$ **10 mode**
Kolmogorov

Results of the Test Particle Simulation



$v_F = 0.1c, \delta V = 10^{-3}$(**weak turb.**)



Mirror force: $\frac{dp}{dt} \sim \frac{p_\perp v_\perp}{2B_0} \nabla_\parallel B_\parallel \sim p v_\perp k_\parallel \frac{\delta B(k)}{B_0}$

Interaction Time scale: $\delta t \sim 1/(v_\parallel k_\parallel)$

Electric Field: $\delta E \sim \frac{v_F}{c} \delta B$

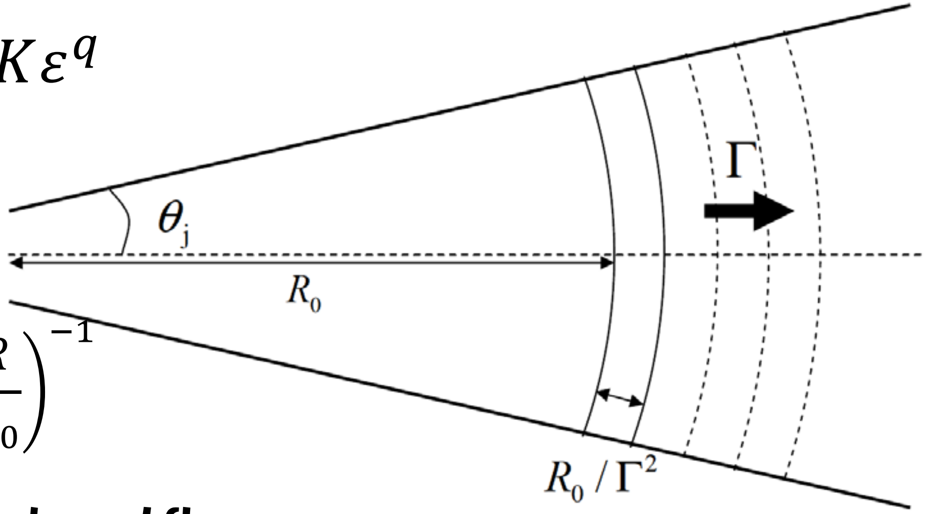
Energy Gain Rate: $\propto \delta E(k_\perp r_L)$

$$D_{\varepsilon\varepsilon} \sim \varepsilon^2 \frac{\delta V^2}{c^2} c k_{\max} (q-1) \left(\frac{k_{\max}}{k_{\min}}\right)^{1-q}$$

While only a small fraction of particles of $v_\parallel \ll c$ can be accelerated for $v_F \ll c$, almost all of relativistic particles are accelerated in $v_F >\sim 0.1c$

Blazar Modeling

$$D_{\varepsilon\varepsilon} = K\varepsilon^{q}$$



$$B = B_0\left(\frac{R}{R_0}\right)^{-1}$$

Parameters are

$\underbrace{R_0, \Gamma, B_0, \dot{N}}, \underbrace{K, q}$

Required for any model

Only two peculiar parameters

- 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
- Both injection and acceleration stop at $R=2R_0$

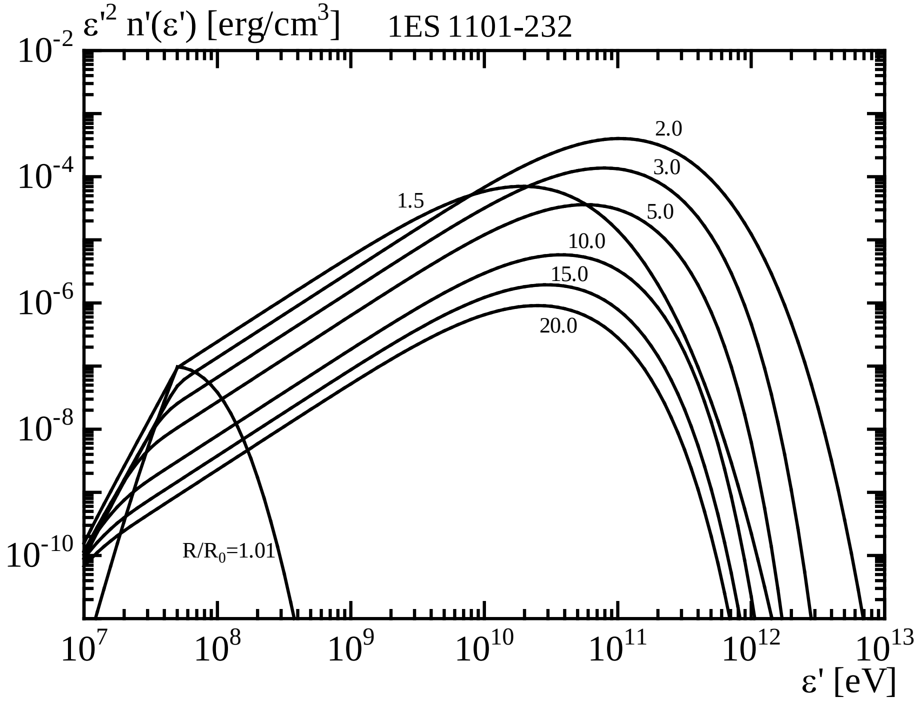
Physical Processes

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

Extreme Hard Blazar 1ES 1101-232

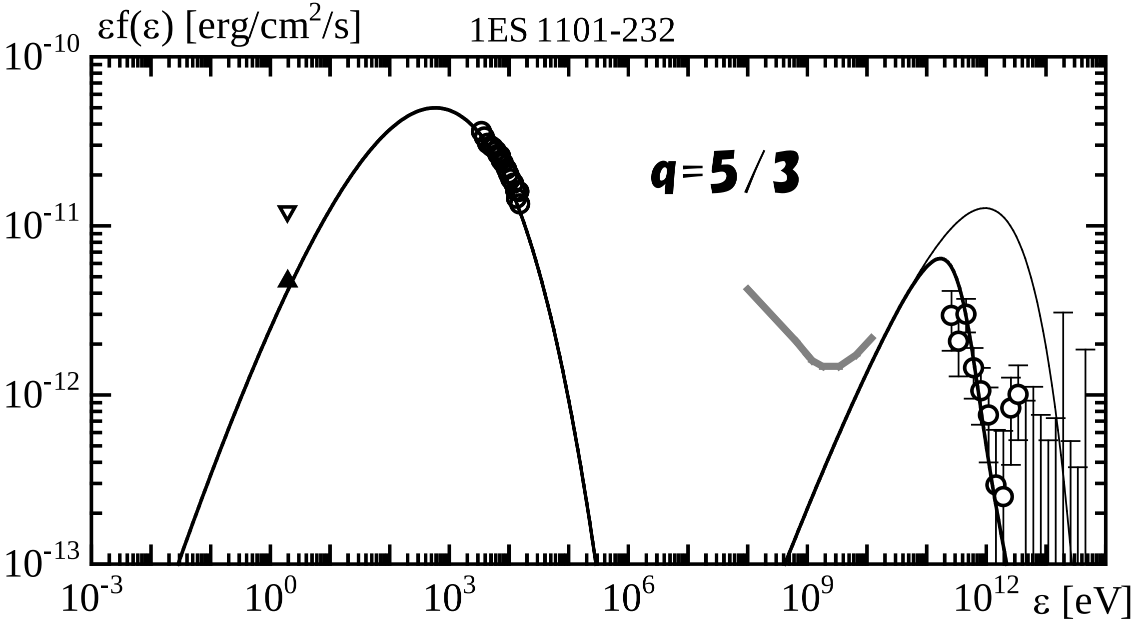
Asano+ 2014

Electron spectrum



$L_\gamma = 2.6\times10^{43}\,\mathrm{erg\,s^{-1}}$

Photon spectrum



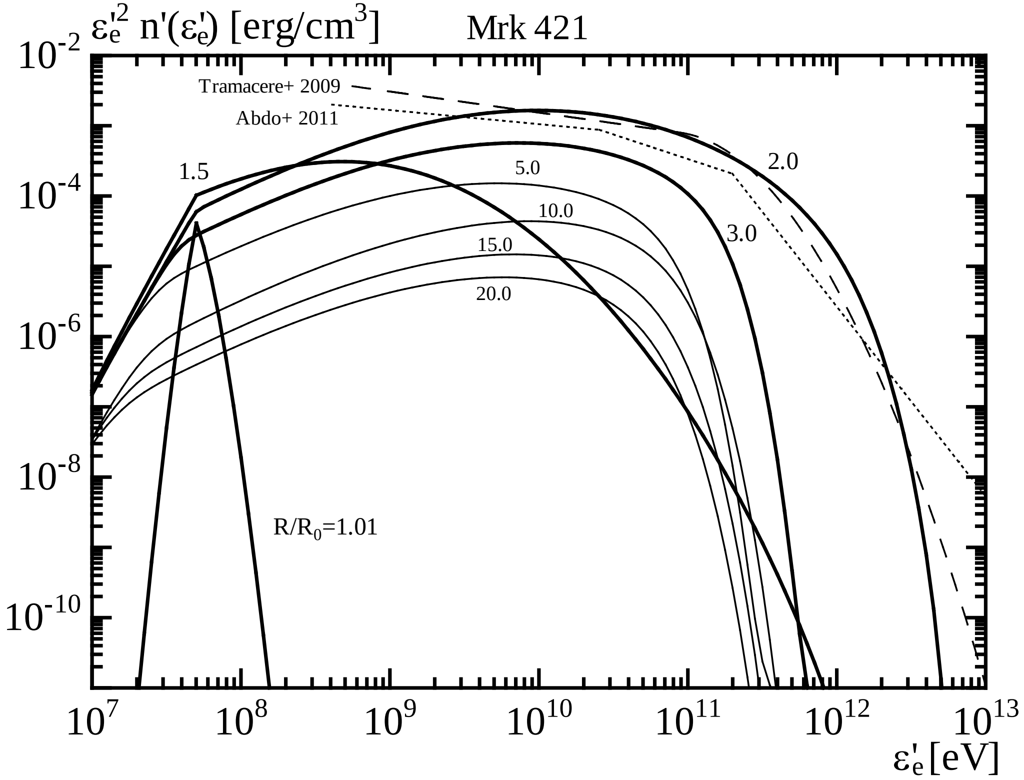
The model parameters: $\Gamma = 25$, $B_0 = 0.03$ G, $W' = R_0/\Gamma = 2.8\times10^{16}$ cm, $\Delta T'_{\rm inj} = W'/c$, $K = 4.3\times10^{-3}\ \mathrm{eV}^{1/3}\ \mathrm{s}^{-1}$, $\dot{N}_0 = 1.5\times10^{46}\ \mathrm{s}^{-1}$

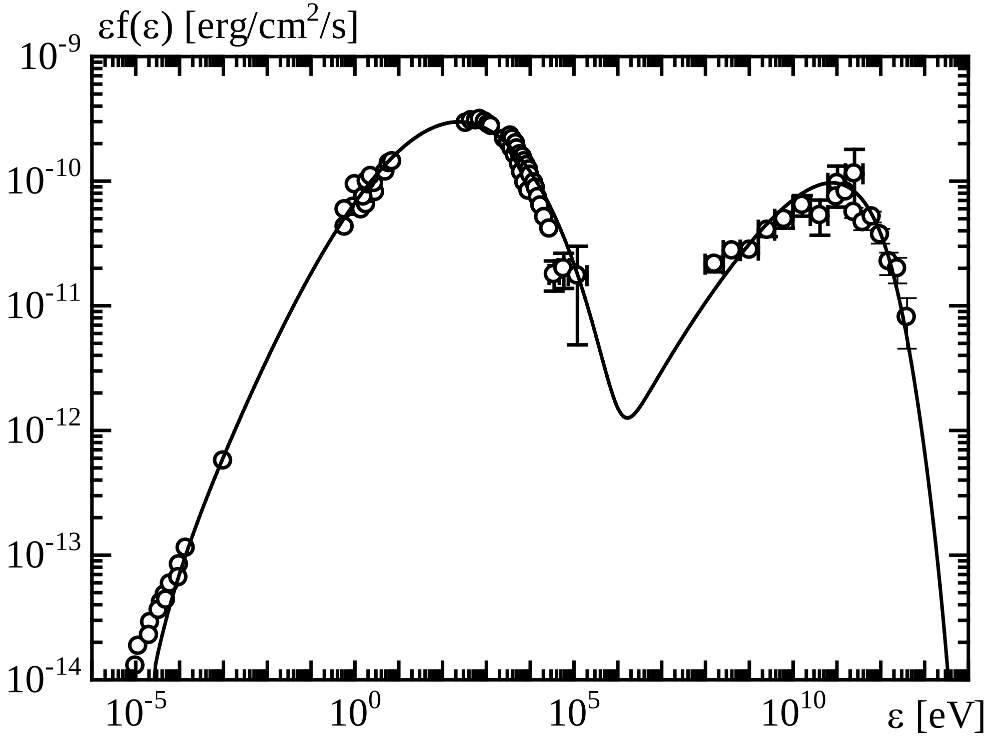
Expanding jet → No steady state → Temporal evolution is essential

Mrk421

$q = 2$

Low maximum energy and curved electron spectrum are naturally reproduced with temporal evolution effects.





$$\Gamma = 15, B_0 = 0.16\text{G}, W' = \frac{R_0}{\Gamma} = 10^{16}\text{cm}, \Delta T'_{inj} = \frac{W'}{c}, K = 3.7 \times 10^{-6}\text{s}^{-1}, \dot{N} = 9.8 \times 10^{46}\text{s}^{-1}$$

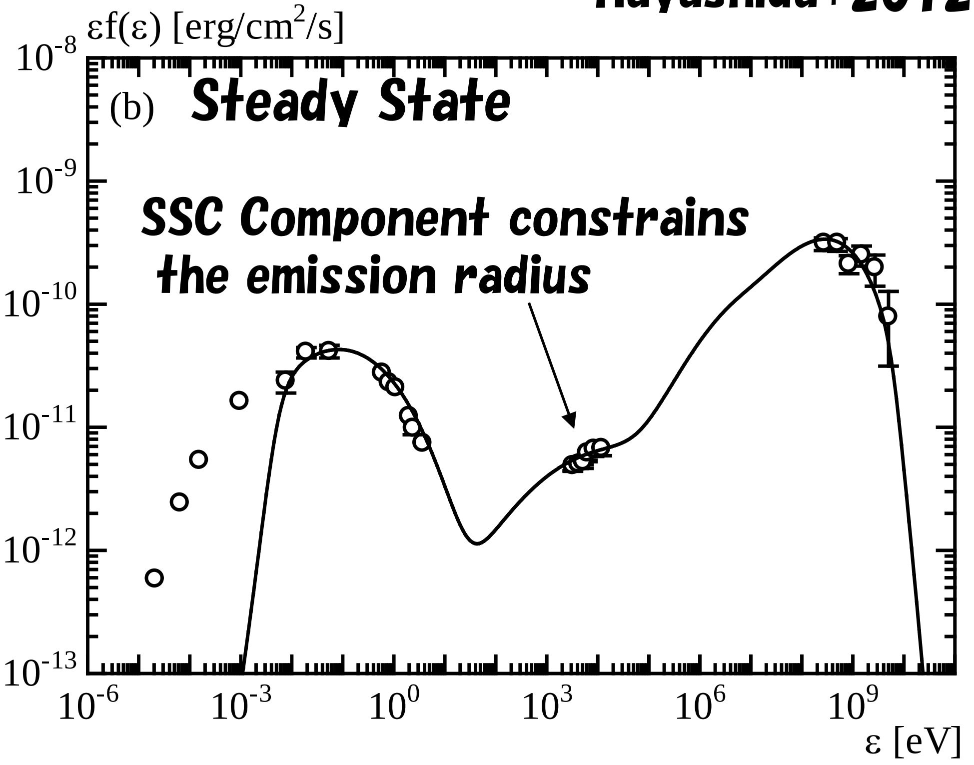
See also Kakuwa+ 2015

FSRQ 3C 279

$q = 2$

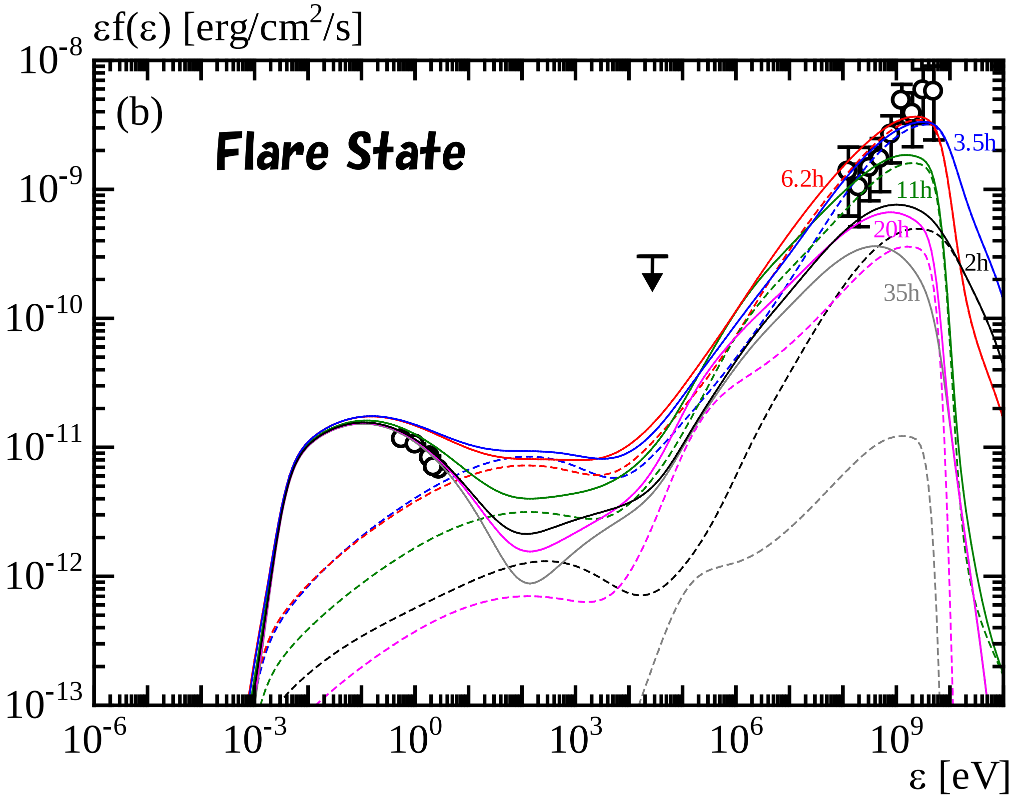
Asano & Hayashida 2015
Hayashida+2012

$$T'_{\rm UV} = 10\Gamma {\rm eV}, U'_{\rm UV} = 8\left(\frac{\Gamma}{15}\right)^2 {\rm erg\ cm^{-3}}$$



Steady State

SSC Component constrains the emission radius



Flare State

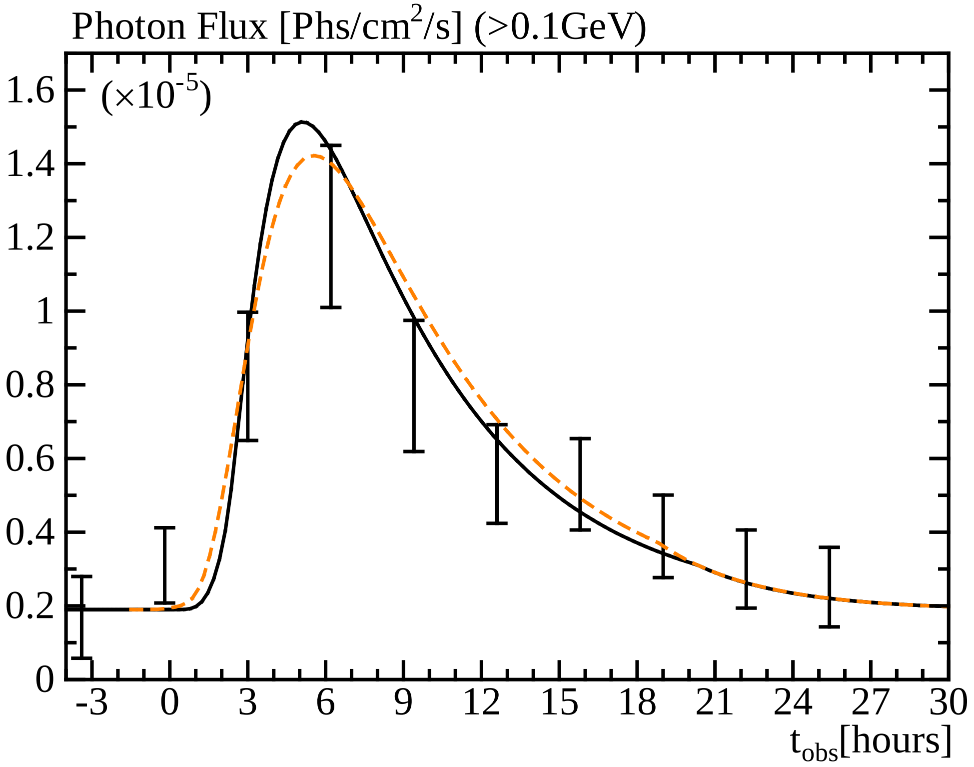
$q = 2$

parameters are $R_0 = 0.023\,{\rm pc}$, $\Gamma = 15$, $K' = 9 \times 10^{-6}\,{\rm s^{-1}}$ $(t_{\rm acc} = 1/(2\,K') = 0.35W'/c)$, $\dot{N}'_{\rm e} = 7.8 \times 10^{49}\,{\rm s^{-1}}$ $(\dot{n}'_{\rm e} = 0.26(R/R_0)^{-2}\,{\rm cm^{-3}\,s^{-1}})$, and $B_0 = 7\,{\rm G}$.

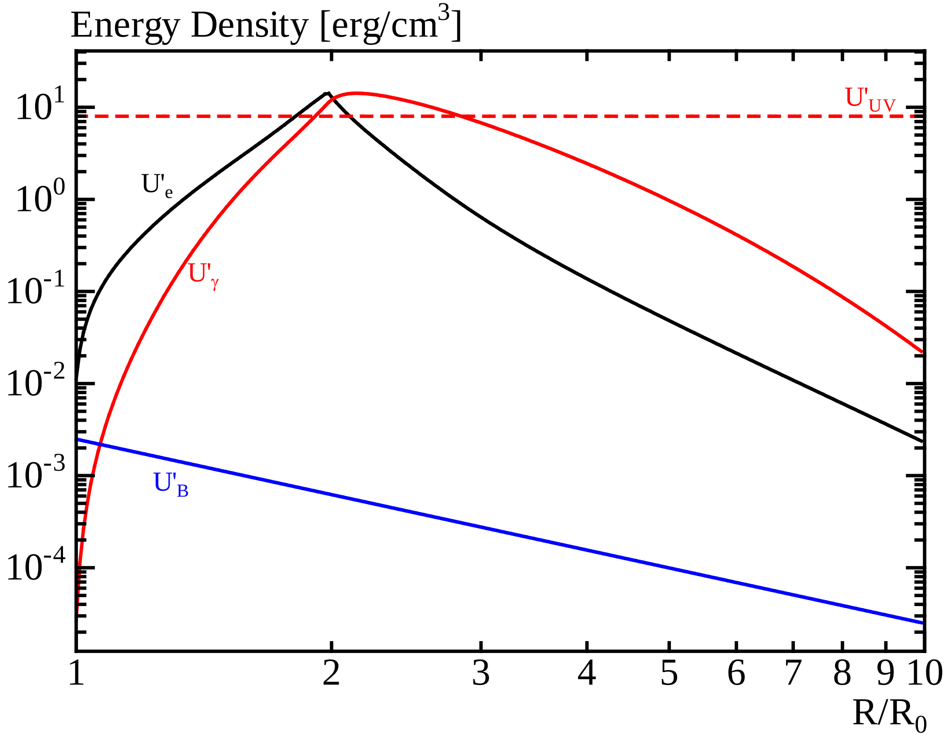
$K' = 1.3 \times 10^{-5}\,{\rm s^{-1}}$ $(t_{\rm acc} = 1/(2\,K') = 0.25W'/c)$,
$\dot{N}'_{\rm e} = 2.5 \times 10^{50}\,{\rm s^{-1}}$ $(\dot{n}'_{\rm e} = 0.85(R/R_0)^{-2}\,{\rm cm^{-3}\,s^{-1}})$,
$B_0 = 0.25\,{\rm G}$.

3C 279 Flare

Lightcurve

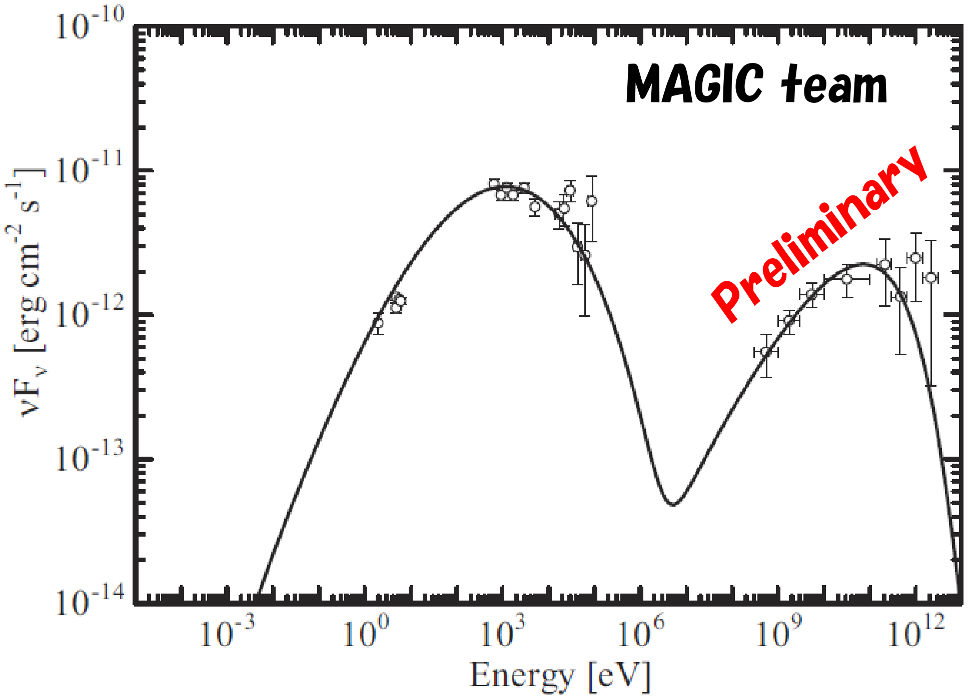


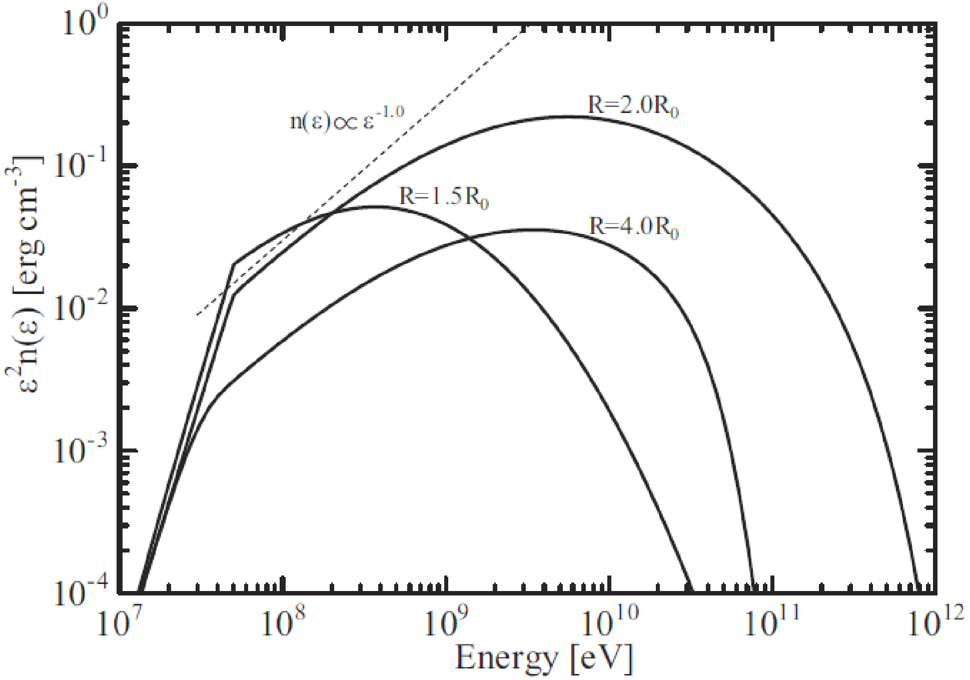
Evolution of energy density



RX J1136.5+6737

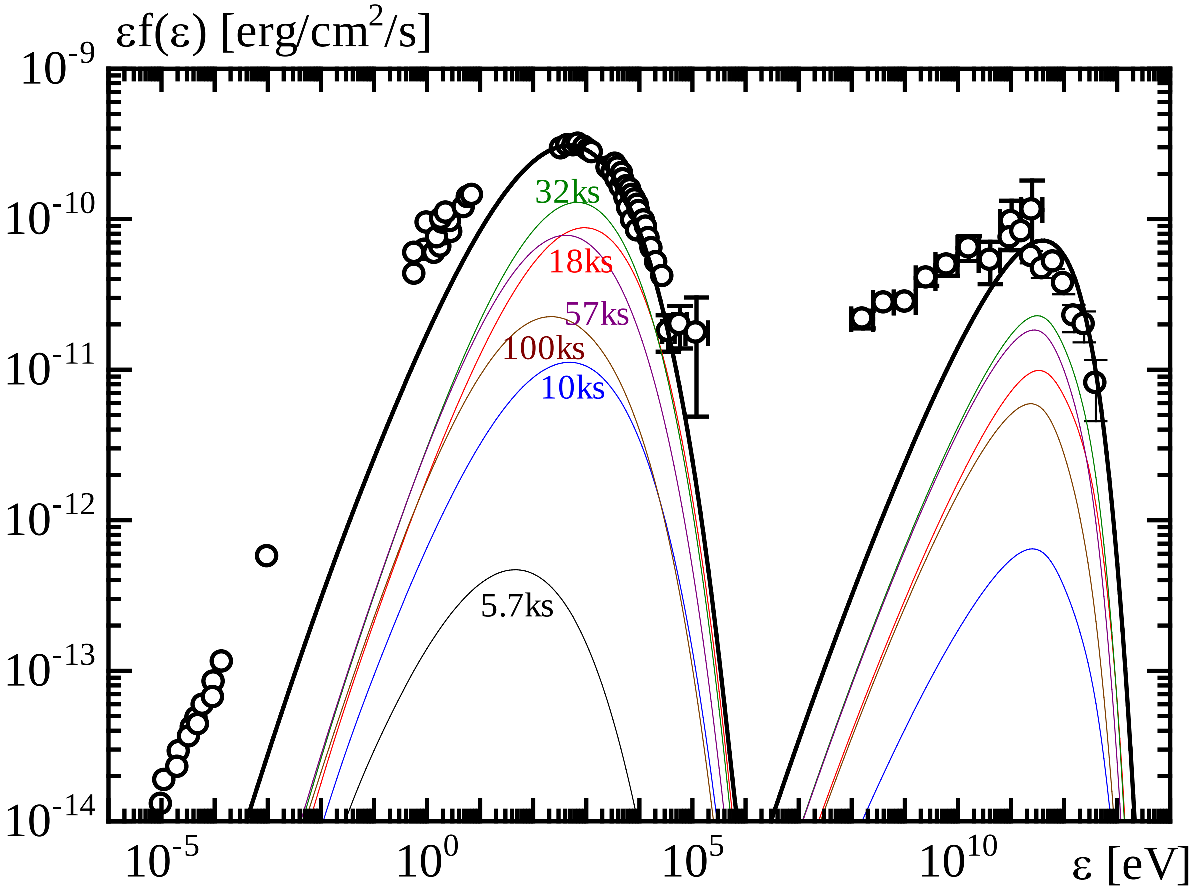
$q = 2$





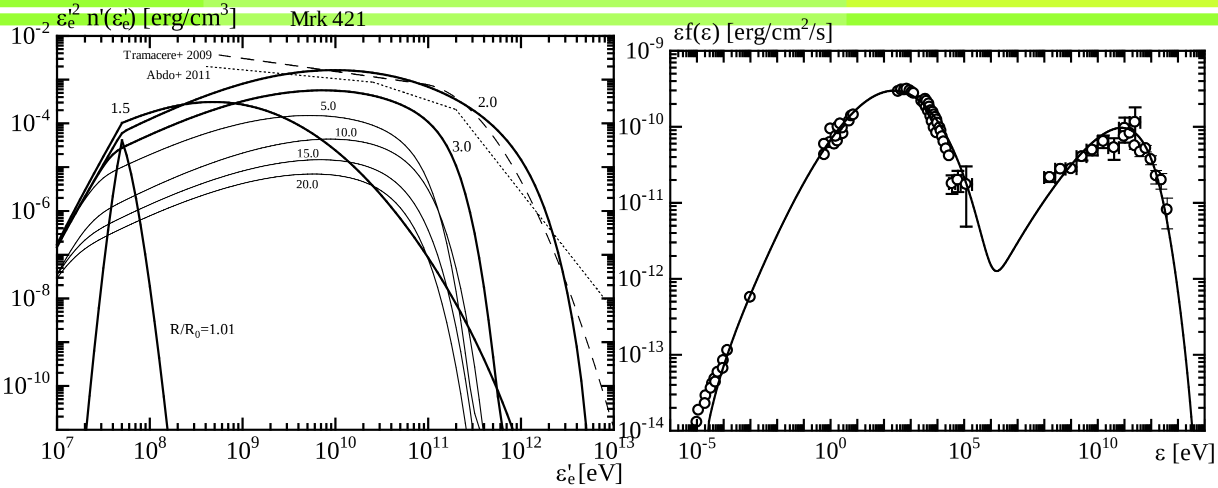
$$R_0 = 4.5 \times 10^{15}\mathrm{cm}, \Gamma = 30, K = 4.6 \times 10^{-4}\mathrm{s}^{-1}, B_0 = 2\mathrm{G}$$

q=5/3 in Mrk 421



In most cases, we need q=2 (hard sphere=energy independent acc. time scale).
This supports the non-resonant scattering with fast wave?

Diffusion coefficient in Mrk 421



$$D_{\varepsilon\varepsilon} = K\varepsilon^2$$

Not Beyond a PeV!

$$B_0 = 0.16\mathrm{G} \rightarrow r_L = 2.1 \times 10^{10}\mathrm{cm@TeV} \qquad 1/k_{\max} > r_L \sim 10^{10}\mathrm{cm}$$

$$1/k_{\min} < W' = 10^{16}\ \mathrm{cm}$$

If we assume $k_{\max} = 10^{-11}\mathrm{cm}^{-1}$ $\quad k_{\min} = 10^{-15}\mathrm{cm}^{-1}$

Adopting our formula for the index of 5/3 $\quad K = \left(\frac{\delta v}{c}\right)^2 c k_{\max} \frac{2}{3} \left(\frac{k_{\max}}{k_{\min}}\right)^{-2/3}$

Then, $\quad K = 4.3 \times 10^{-6} \left(\frac{\delta v}{0.1c}\right)^2 \mathrm{s}^{-1}$

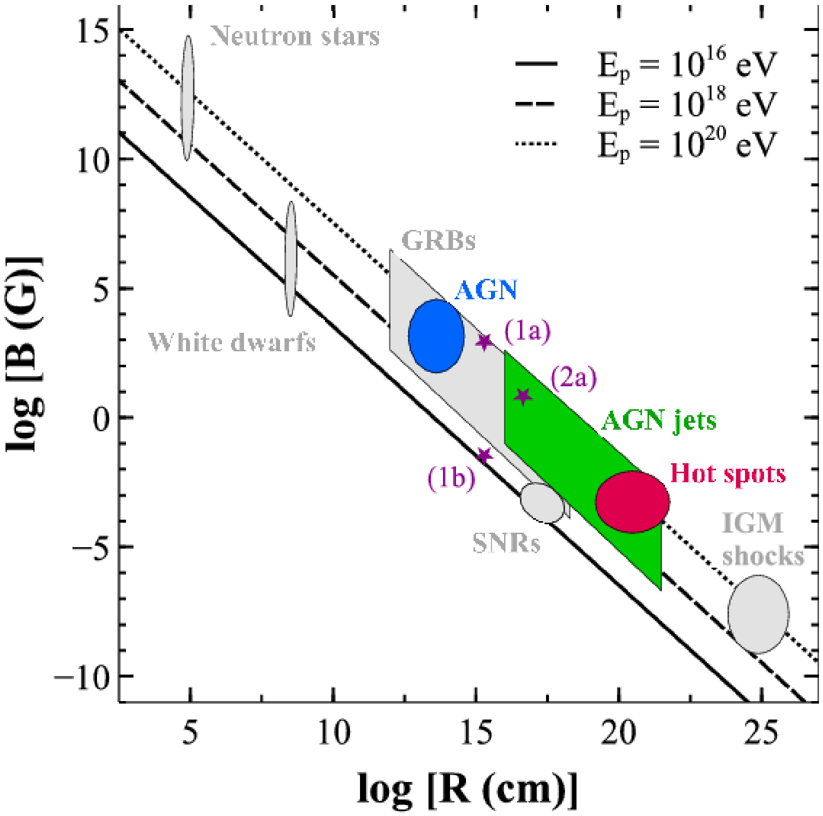
While the required value: $\quad K = 3.7 \times 10^{-6}\mathrm{s}^{-1}$

Reasonable

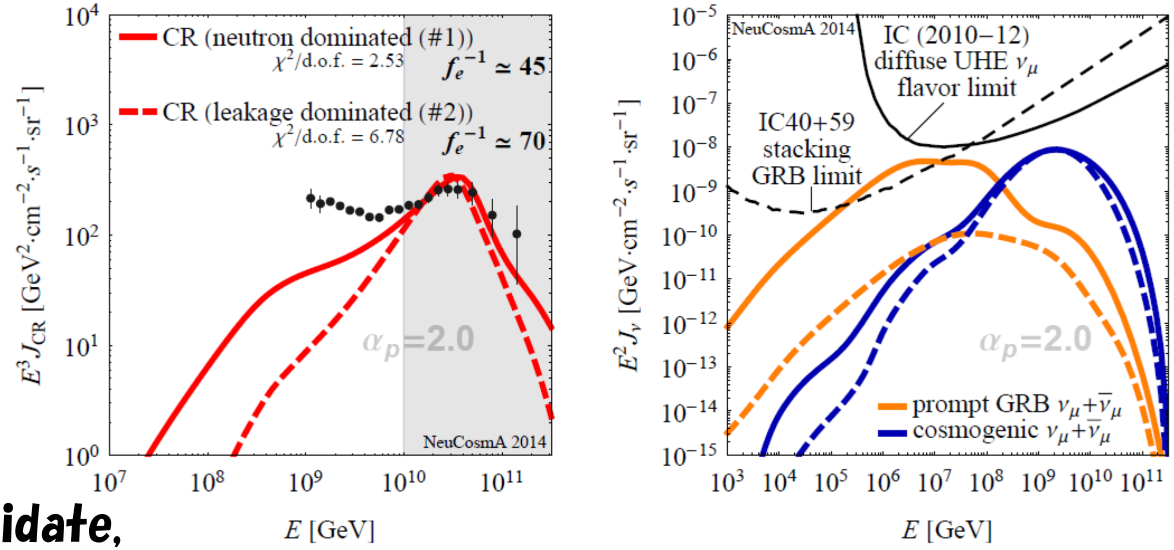
Turbulent Acceleration is applicable for GRBs as well ?

Baerwald+ 2015

$$E_{\max} = ZeBR$$



SFR model	α	f_z	$\dot{\tilde{n}}_{\mathrm{GRB}}\vert_{z=0}$ [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]
Hopkins & Beacom (2006)	1.2	25.15	0.13
	0.0	5.65	0.58
Wanderman & Piran (2010)	0.0	7.70	0.43
Madau & Porciani (2000)			
SF1	0.0	9.89	0.35
SF2	0.0	14.42	0.23
SF3	0.0	14.36	0.23

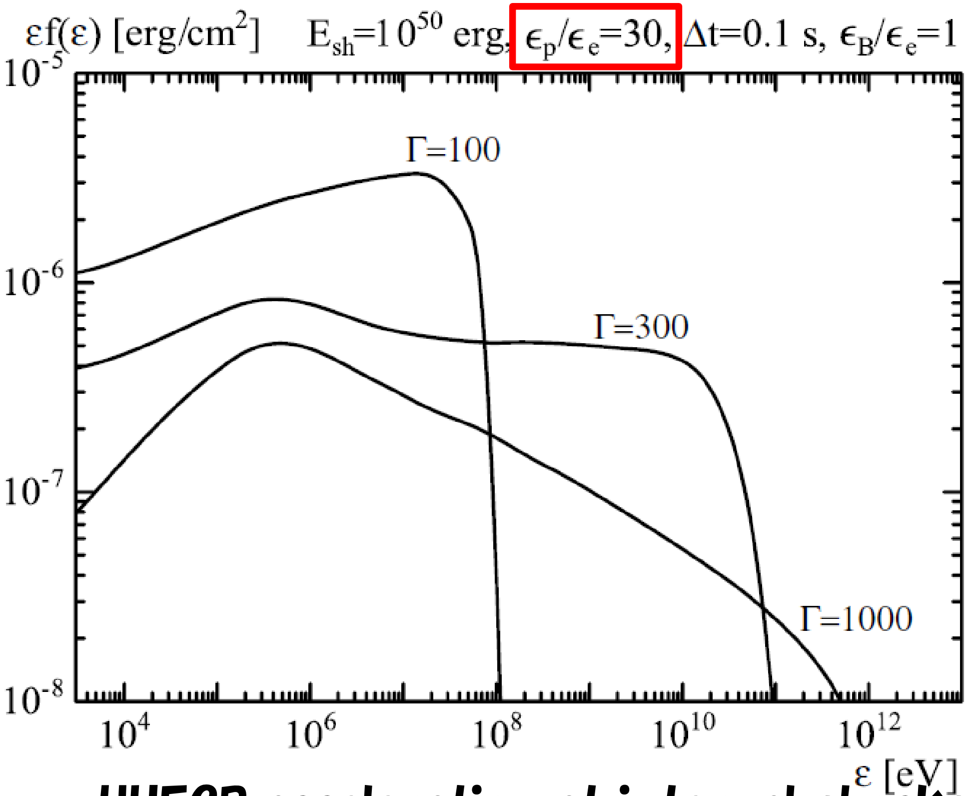


While GRBs are UHECR source candidate,
the occurrence rate is very low.

Need 50-70 times gamma-ray luminosity
for UHECRs.

Secondary gamma-ray should modify the spectrum

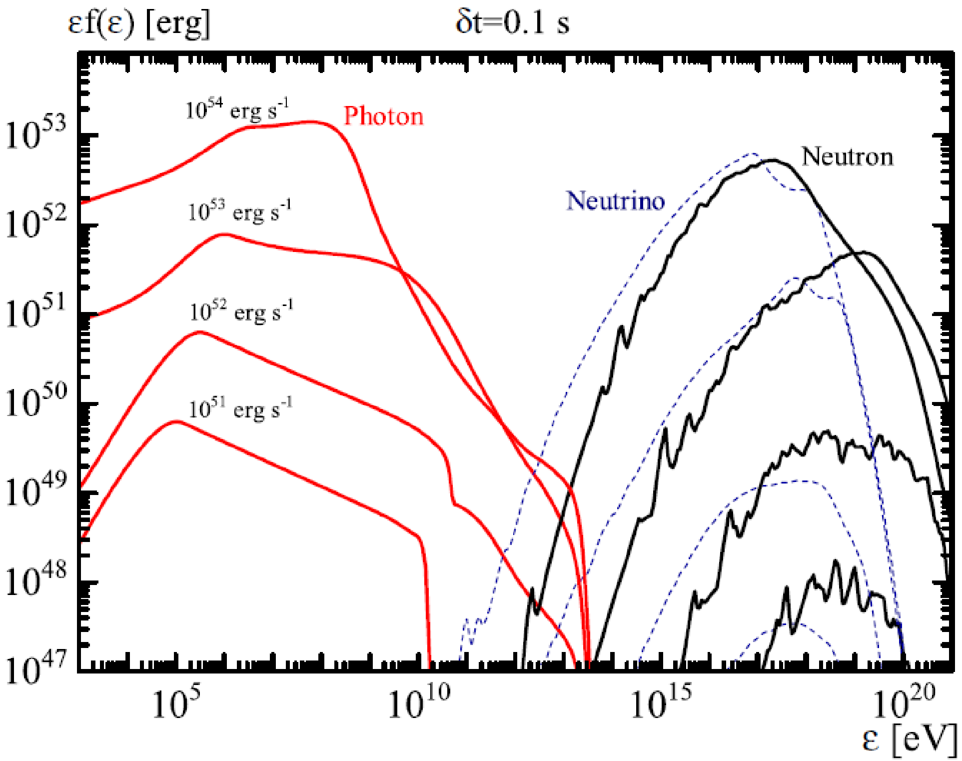
Asano, Inoue & Meszaros 2009



UHECR acceleration at internal shocks leads to the secondary gamma-rays.

$$p + \gamma \rightarrow p + \pi^0$$
$$\pi^0 \rightarrow 2\gamma$$

Asano & Meszaros 2014

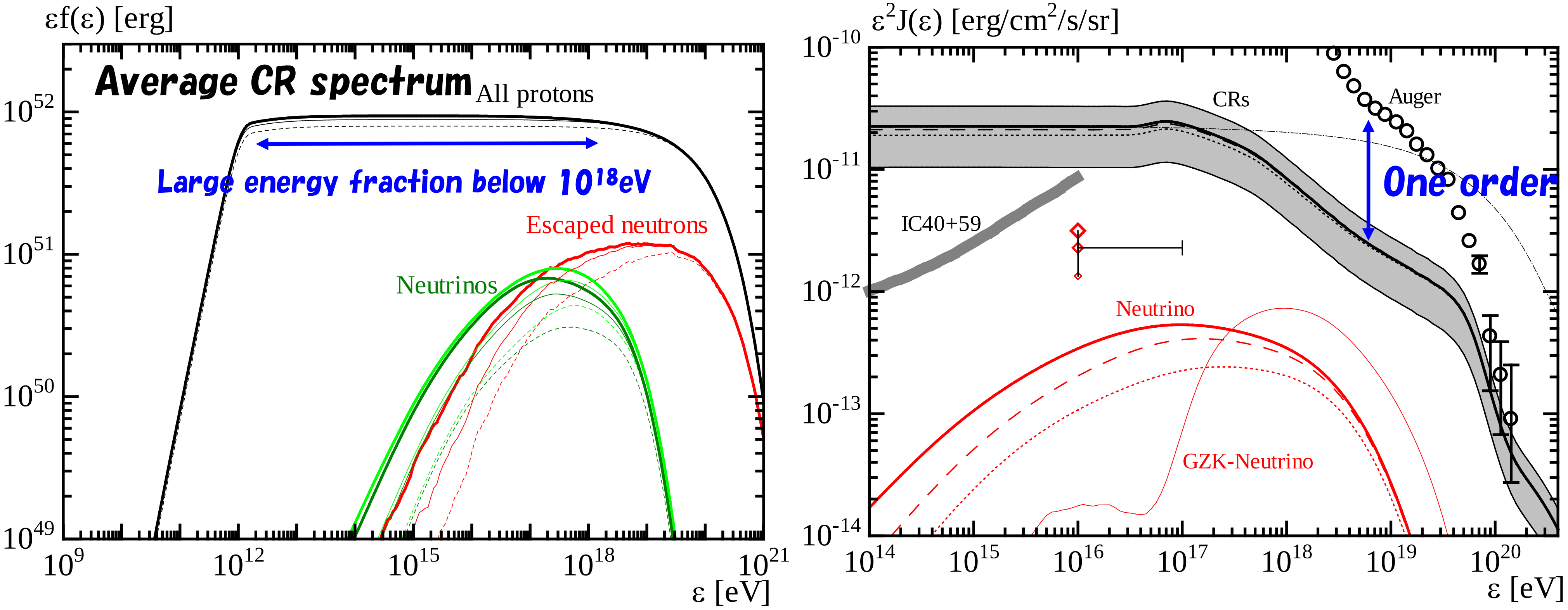


Even for $f_{\rm CR} \equiv \frac{E_{\rm CR}}{E_\gamma} = 10$

we should see the secondary above 10^{53}erg/s

When we avoid the secondary with low CR luminosity.

$f_{\mathrm{CR}} = 10$



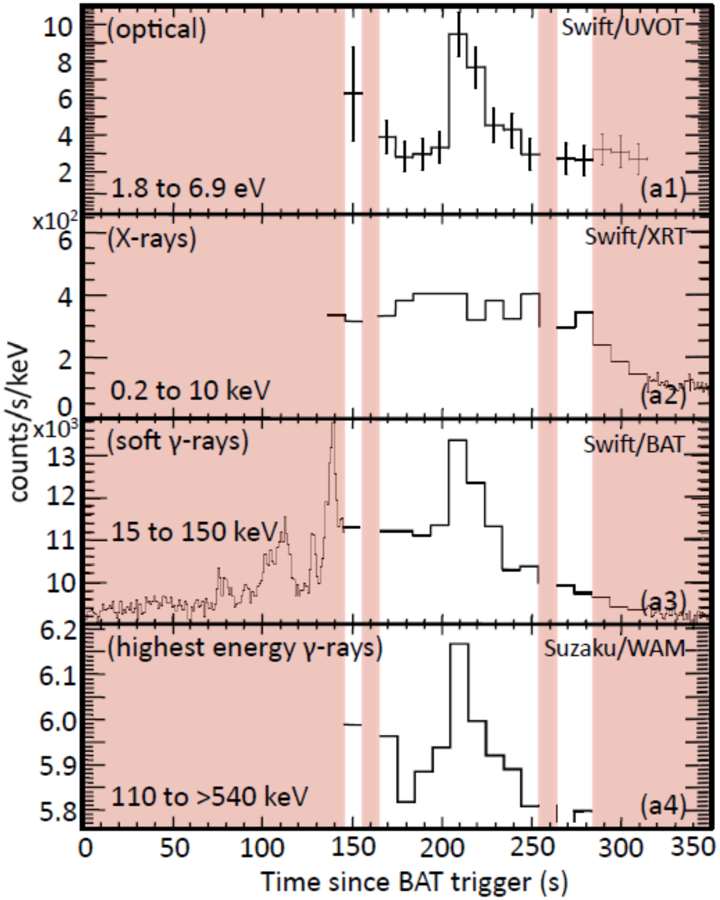
Asano & Meszaros 2014

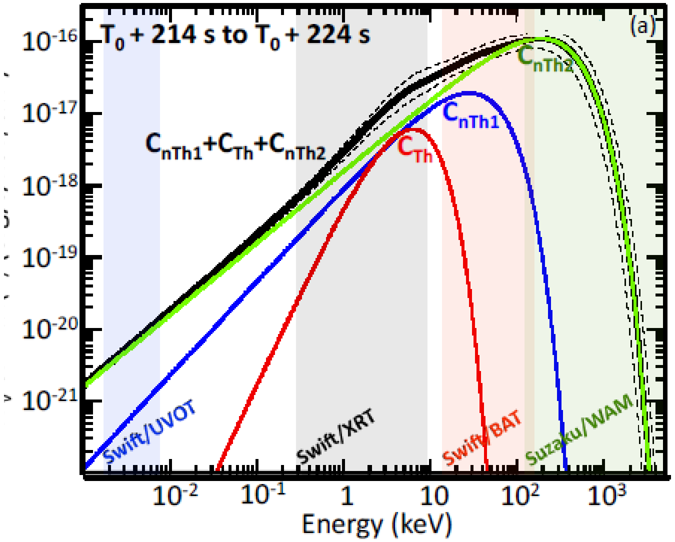
Explains the flux only above 10^{20}eV

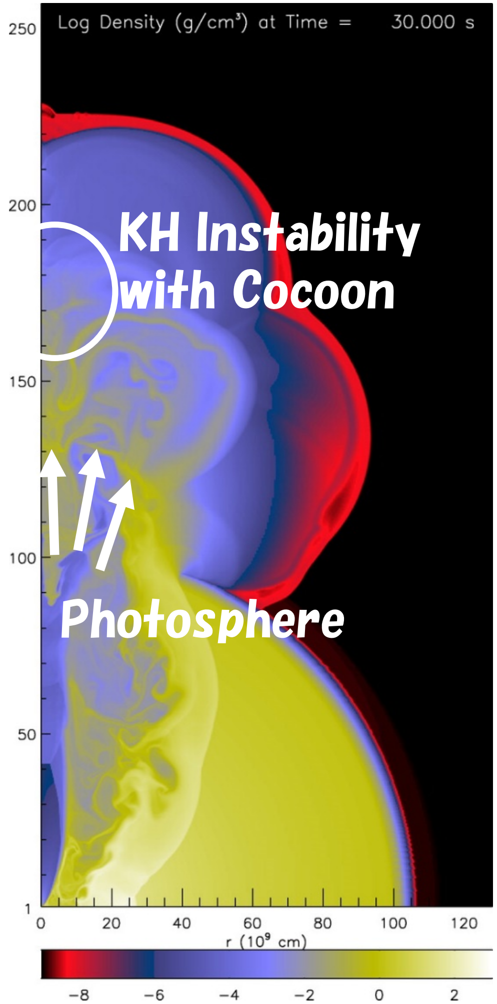
Outer acceleration site

Guiriec+ 2016

Combining the spectrum and light-curve data,
they proposed three component models.





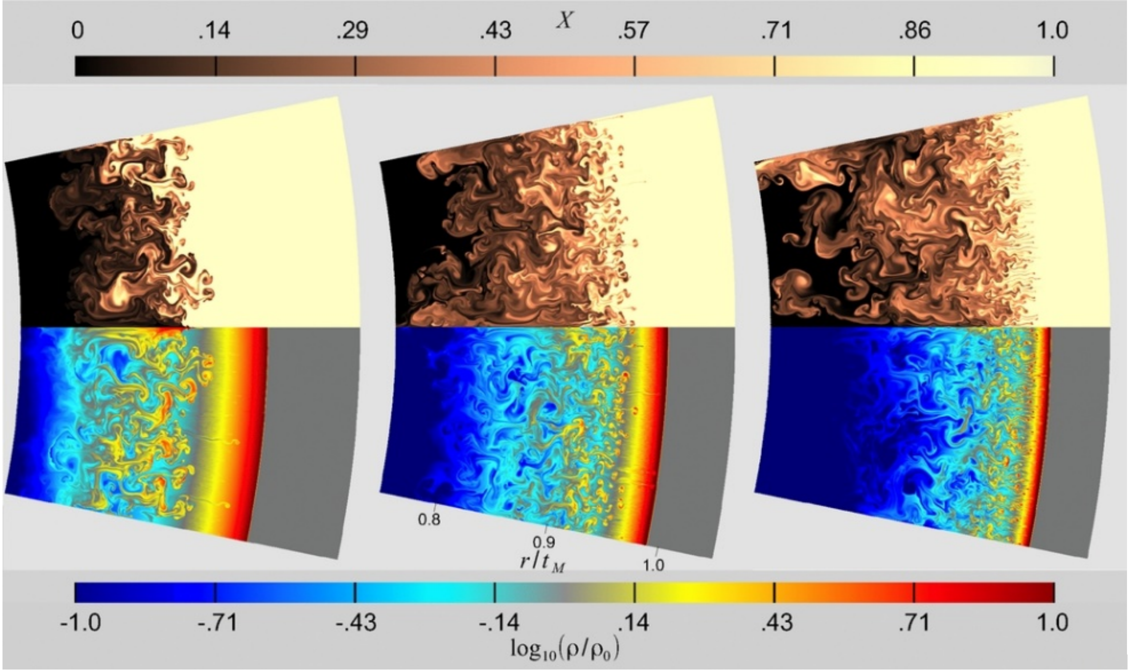


KH Instability with Cocoon

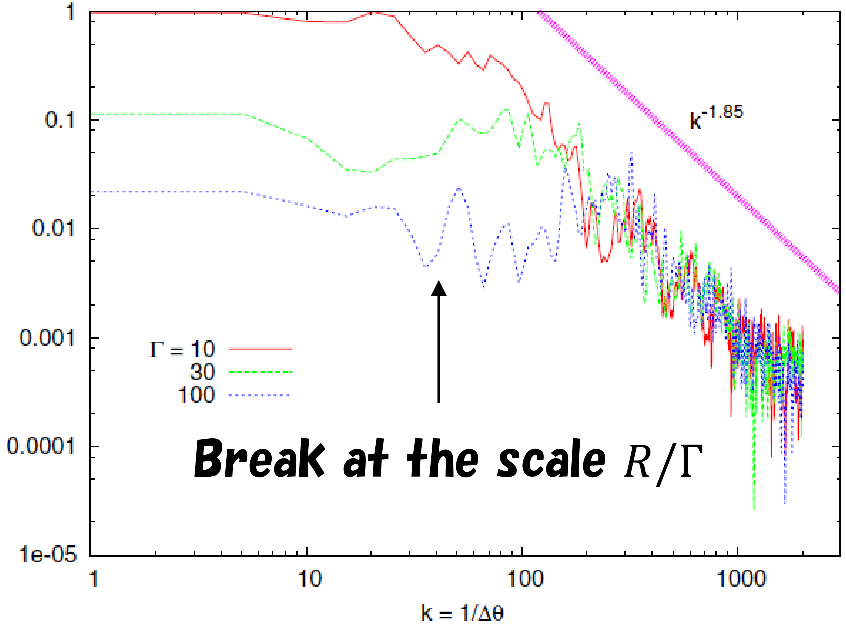
Photosphere

UHECR acceleration at outer radius may avoid the secondary gammas.

Rayleigh-Taylor Instability at the deceleration



Power spectrum



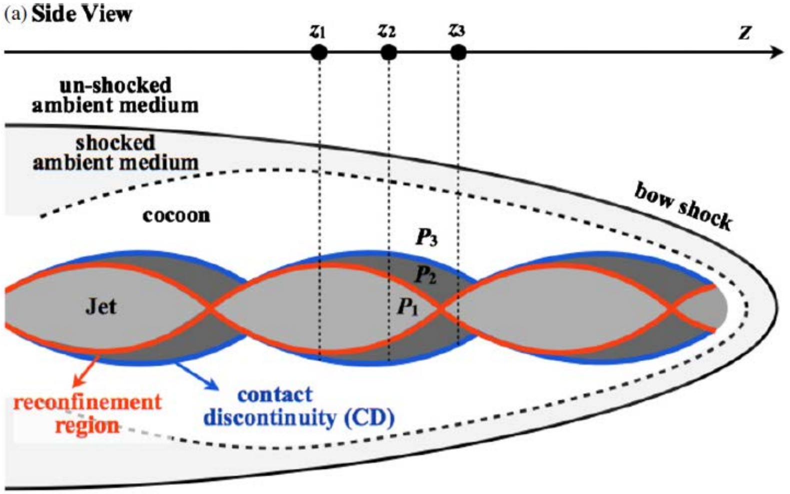
Break at the scale R/Γ

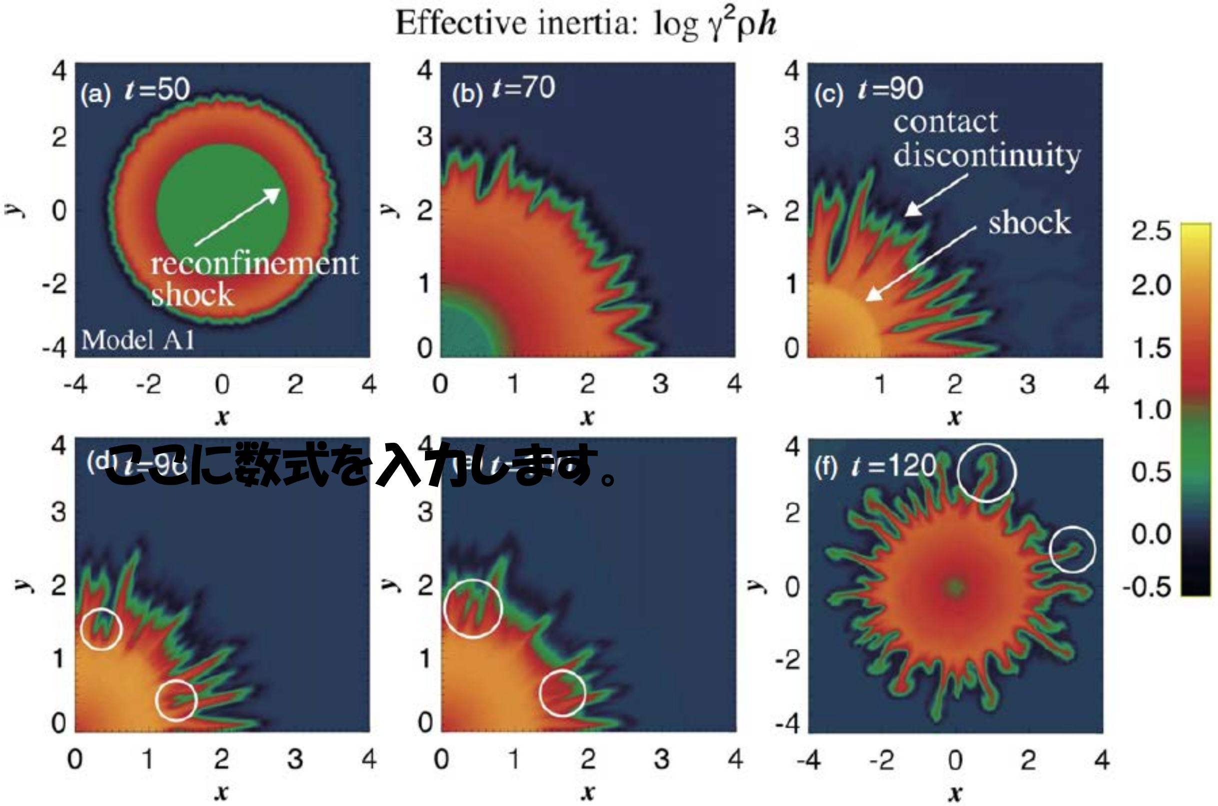
Duffell and MacFadyen 2013

May expect the turbulence acceleration at outer radius.

Radial Rayleigh-Taylor and Richtmyer-Meshkov Inst.

Matsumoto & Masada 2013





ここに数式を入力します。

Radial oscillation and turbulence

$$\eta_0 = \frac{{\gamma_{\mathrm{jet},0}}^2 \rho_{\mathrm{jet},0} h_{\mathrm{jet},0}}{\rho_{\mathrm{ext},0} h_{\mathrm{ext},0}} > 1$$

Unstable

Analytic Formula of Stochastic Acceleration

Injection energy

Injection rate

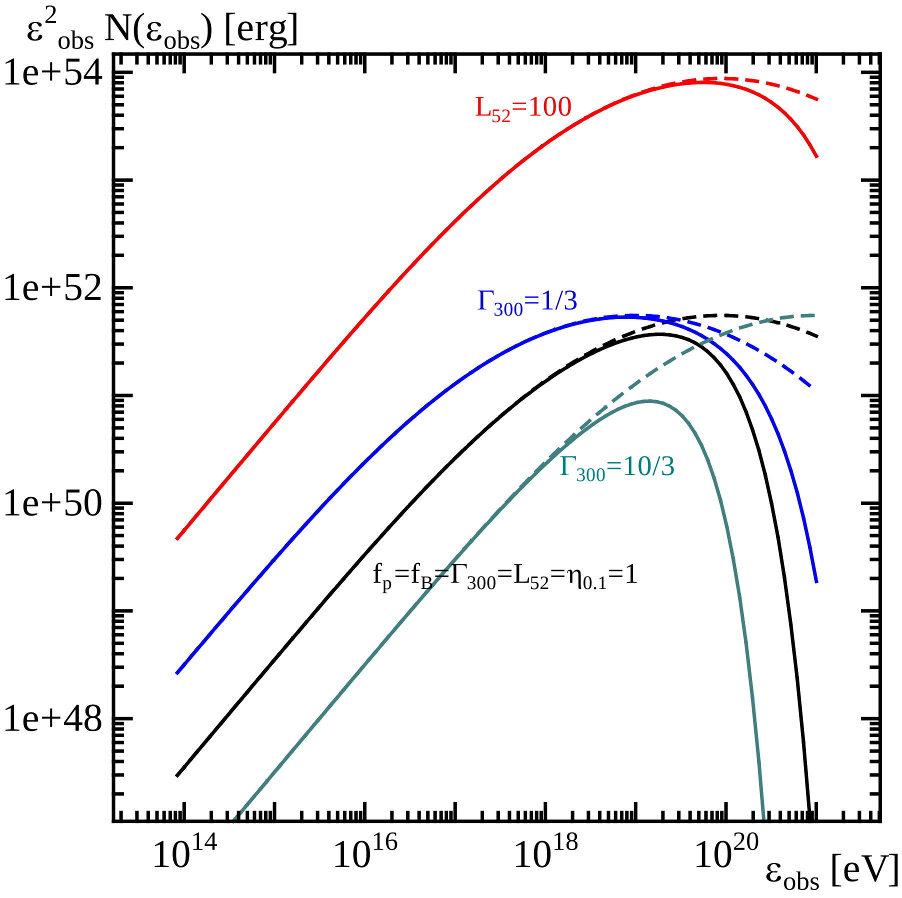
$$N_e(\varepsilon,t)=\frac{\dot{N}_{e,0}}{6K\varepsilon_0}\frac{\varepsilon_0}{\varepsilon}\left[1+\mathrm{erf}\left[\frac{3Kt-\ln\frac{\varepsilon}{\varepsilon_0}}{2\sqrt{Kt}}\right]-\left(\frac{\varepsilon}{\varepsilon_0}\right)^3\mathrm{erfc}\left[\frac{3Kt+\ln\frac{\varepsilon}{\varepsilon_0}}{2\sqrt{Kt}}\right]\right]$$

$$q=2$$

Diffusion coefficient

Elapsed time

See Becker & Dermer 2006



Single Eddy model for simplicity

$$L=\eta\frac{R}{\Gamma}=0.1\eta_{0.1}\frac{R}{\Gamma}$$

Relativistic Turbulence

$$\beta^2\sim 1/3$$

Diffusion coefficient

$$K\sim\frac{3c}{R/\Gamma}\eta_{0.1}^{-1}\quad\textbf{for}\quad\frac{\varepsilon}{eB}<L=\eta\frac{R}{\Gamma}$$

$$\varepsilon_{\rm max}=\frac{\xi e}{\Gamma}\sqrt{\frac{2f_BL_\gamma}{c}}$$

$$\simeq 8.2\times10^{19}\xi_{0.1}\Gamma_{300}^{-1}f_B^{1/2}L_{52}^{1/2}\ \mathrm{eV}$$

Slow acceleration

Acceleration timescale is comparable to the dynamical timescale

$$K t_{\mathrm{dyn}} \sim 3/\xi_{0.1}$$

Proton synchrotron is negligible.

$$\frac{t_{\mathrm{syn}}}{t_{\mathrm{dyn}}} \simeq 1600 \varepsilon_{\mathrm{obs},19}^{-1} \Gamma_{300}^{4} f_B^{-1} L_{52}^{-1} R_{16}$$

Radiative cooling prevents the electron acceleration.

$$\gamma_{\mathrm{max}} \simeq 7.5 f_B^{-1} \xi_{0.1}^{-1} R_{17} (L_* / L_\gamma)(\Gamma/127)^3$$

We cannot expect bright non-thermal emission.
⇒ Dark accelerator

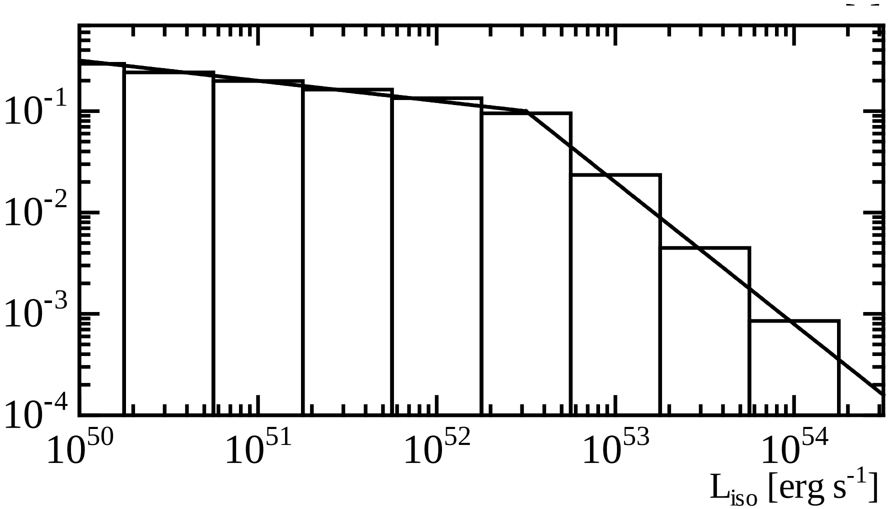
GRB Luminosity Function and Rate

Wanderman & Piran 2010

$$\phi(L_\gamma)\mathcal{R}_{\rm GRB}(z)d\log L_\gamma$$

Luminosity Function $L_{\rm iso} > 10^{50}{\rm erg\ s}^{-1}$

$$\phi(L)d\ln L \propto \begin{cases} \left(\frac{L}{L_*}\right)^{-\alpha} & L < L_* \\ \left(\frac{L}{L_*}\right)^{-\beta} & L > L_* \end{cases}$$

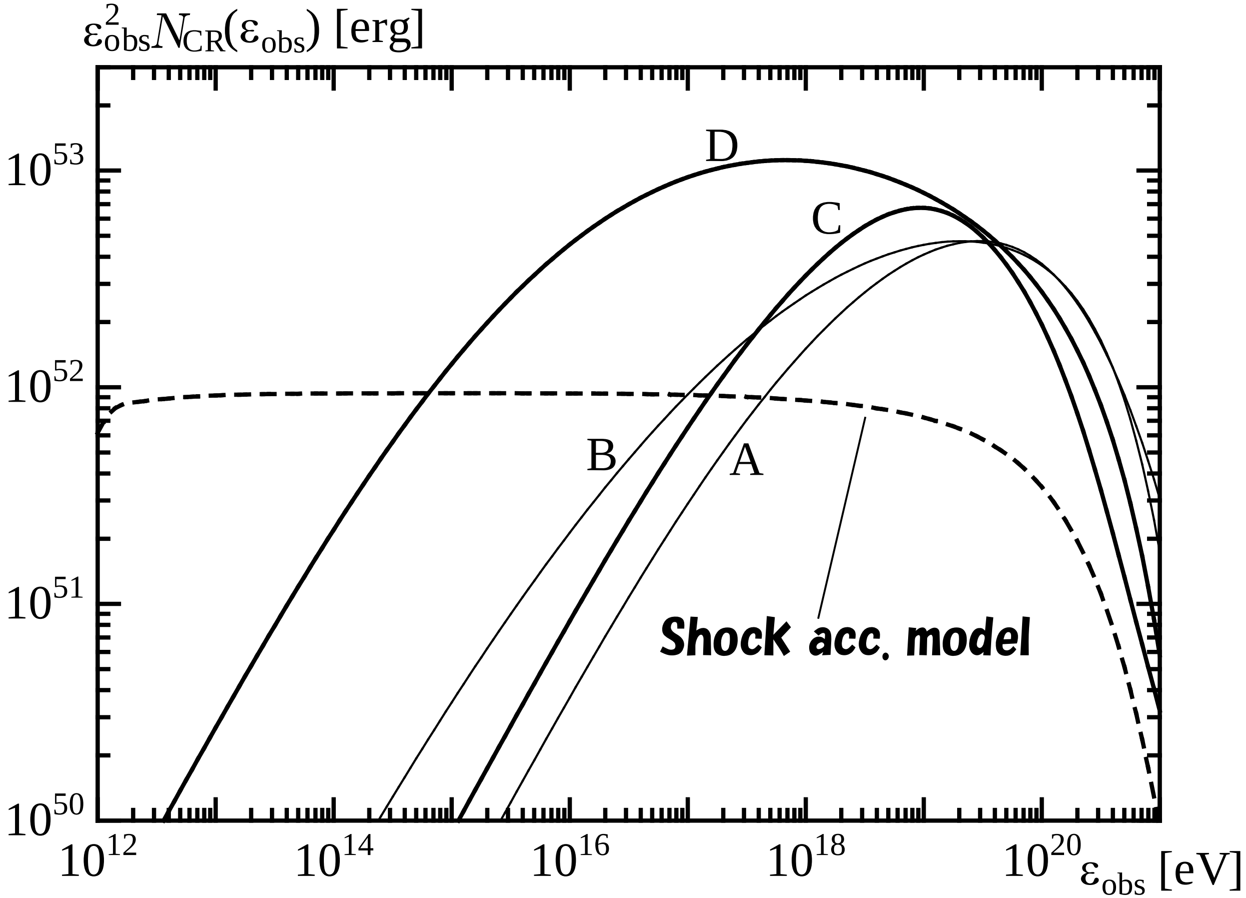


$$\alpha = 0.2^{+0.2}_{-0.1} \qquad \beta = 1.4^{+0.3}_{-0.6}$$

$$L* \simeq 10^{52.5\pm0.2}\ ({\rm erg\ s}^{-1})$$

$$\mathcal{R}_{\rm GRB} = \begin{cases} 1.3(1+z)^{2.1}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}, & {\rm for}\ z \leqq 3.0 \\ 170(1+z)^{-1.4}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}, & {\rm for}\ z > 3.0 \end{cases}$$

UHECR spectrum per GRB



Asano & Meszaros 2016

$L_{\rm CR,typ} = 10^{53.5}$ erg s^{-1}

Models A and B $f_{\rm CR} = 10$

Models C and D assume, L_p is nearly constant, irrespective of L_γ.

Models A and C, $\Gamma = 300$

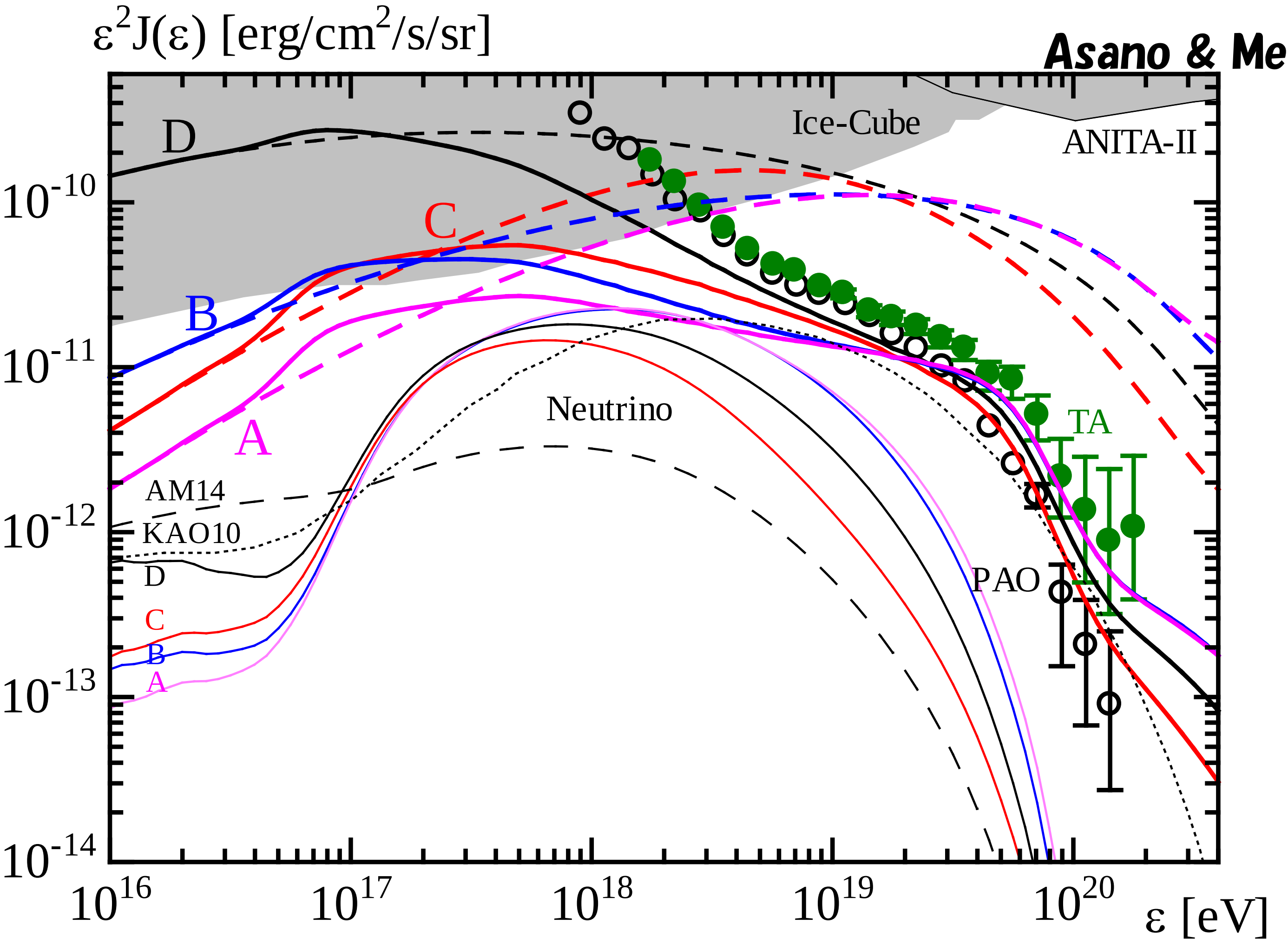
Models B and D

$$\Gamma_{G_L} = 72.1 L_{\gamma,52}^{0.49}. \qquad (24)$$

The CR energy is concentrated in the highest energy region.
Curved Spectrum.

Total UHECR Flux and cosmogenic neutrinos

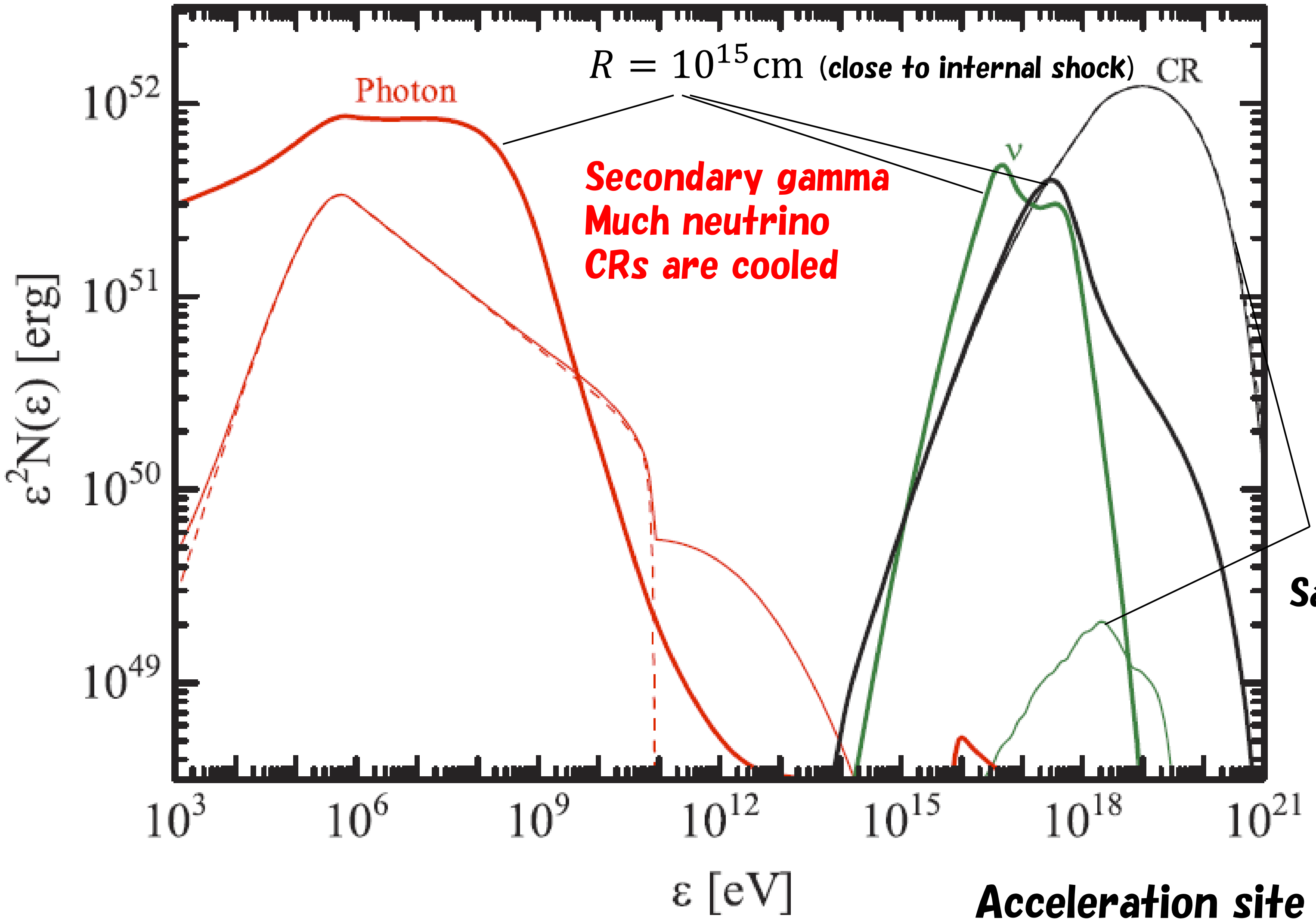
Asano & Meszaros 2016



The stochastic acceleration model agrees with the observed UHECR flux with $L_{\rm CR} \simeq 10^{53.5}$erg/s! Hard GZK neutrino spectrum.

Prompt neutrinos

Asano & Meszaros 2016



$R = 10^{15}$cm (close to internal shock)

Secondary gamma
Much neutrino
CRs are cooled

$R = 10^{16}$cm

Safe for the IceCube limit

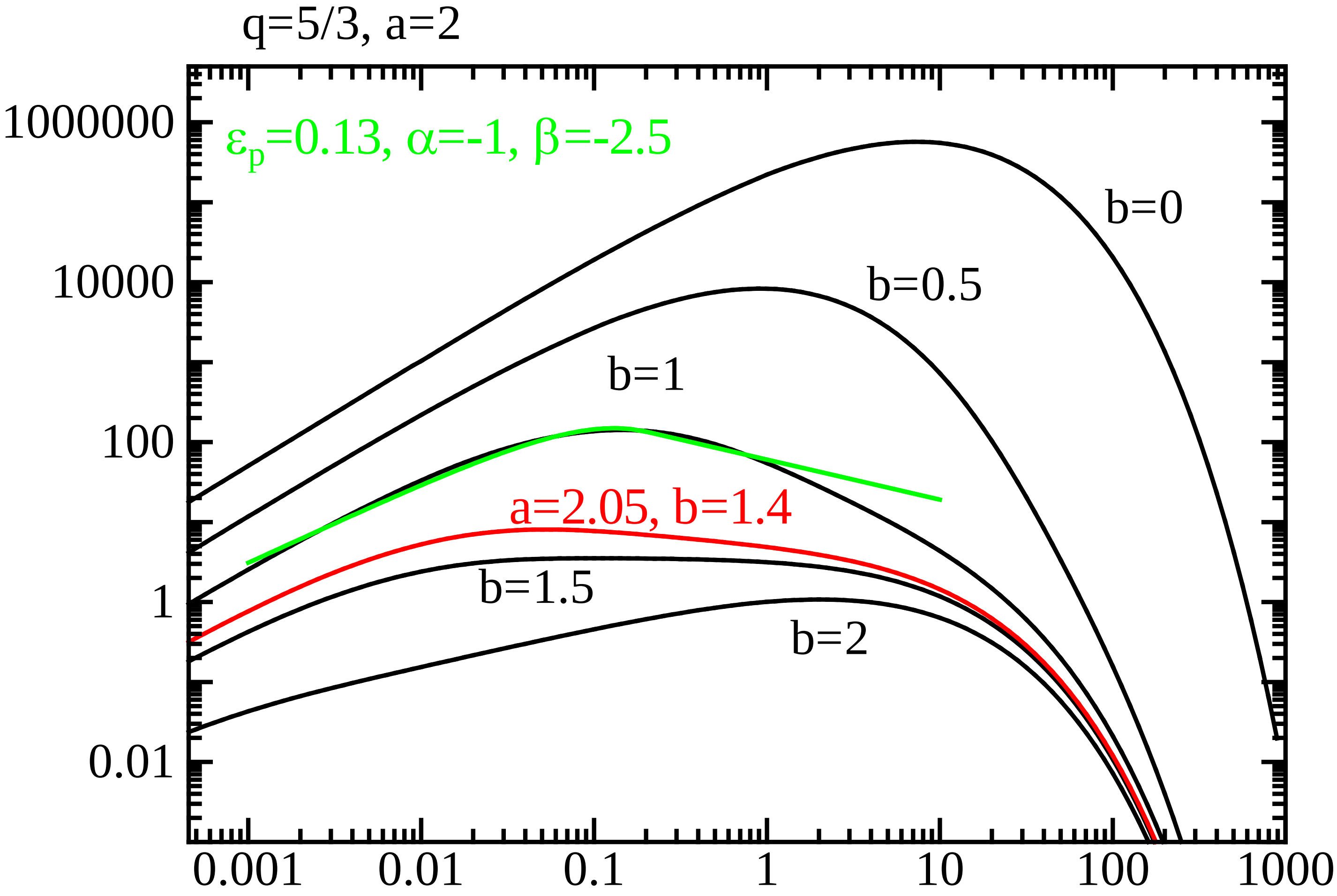
Acceleration site should be outside.

Summary

- In relativistic jets, acceleration by fast wave turbulence may be expected.
- Energy diffusion timescale becomes time-independent.
- Blazar spectra seem support the above model.
- In GRB jets, the acceleration in the outer region may produce UHECRs with a hard spectrum, which is preferable to reduce the total UHECR energy.
- Caveat: difficult to find acceleration signature.
- Hard GZK neutrino spectrum.

予備スライド

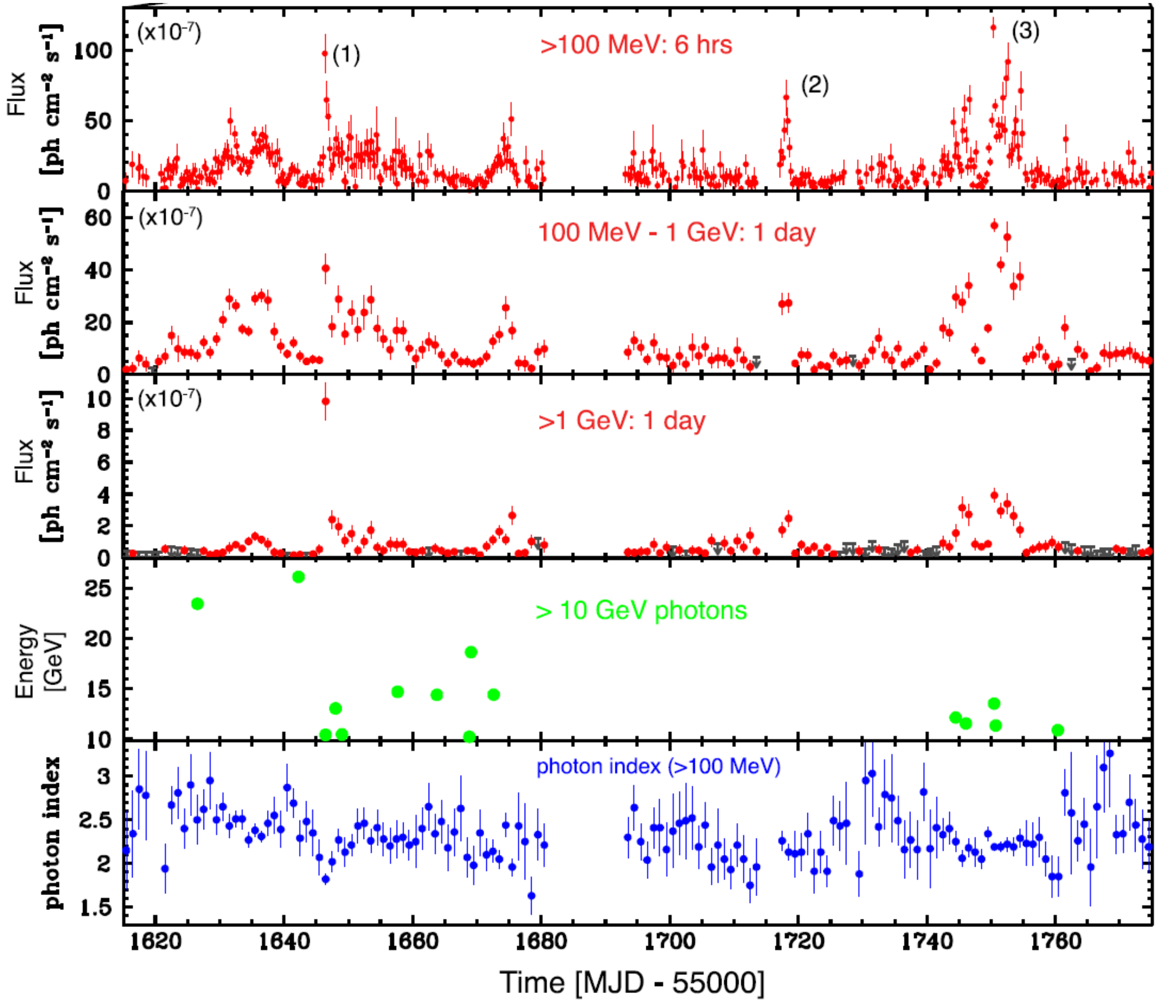
Band-like Spectra

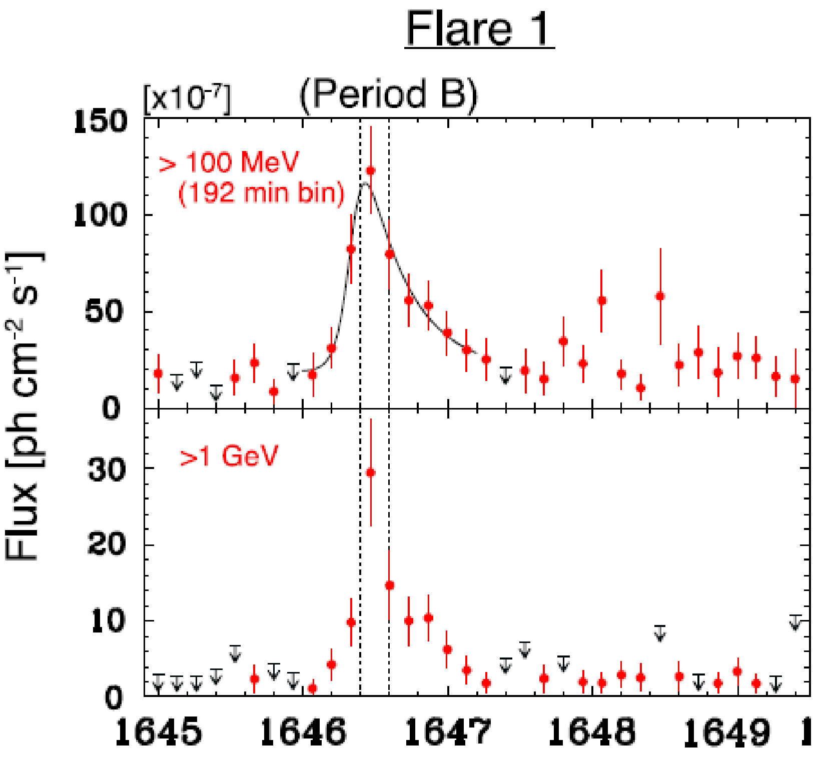


The required indices and MHD simulations seem to be reasonable.

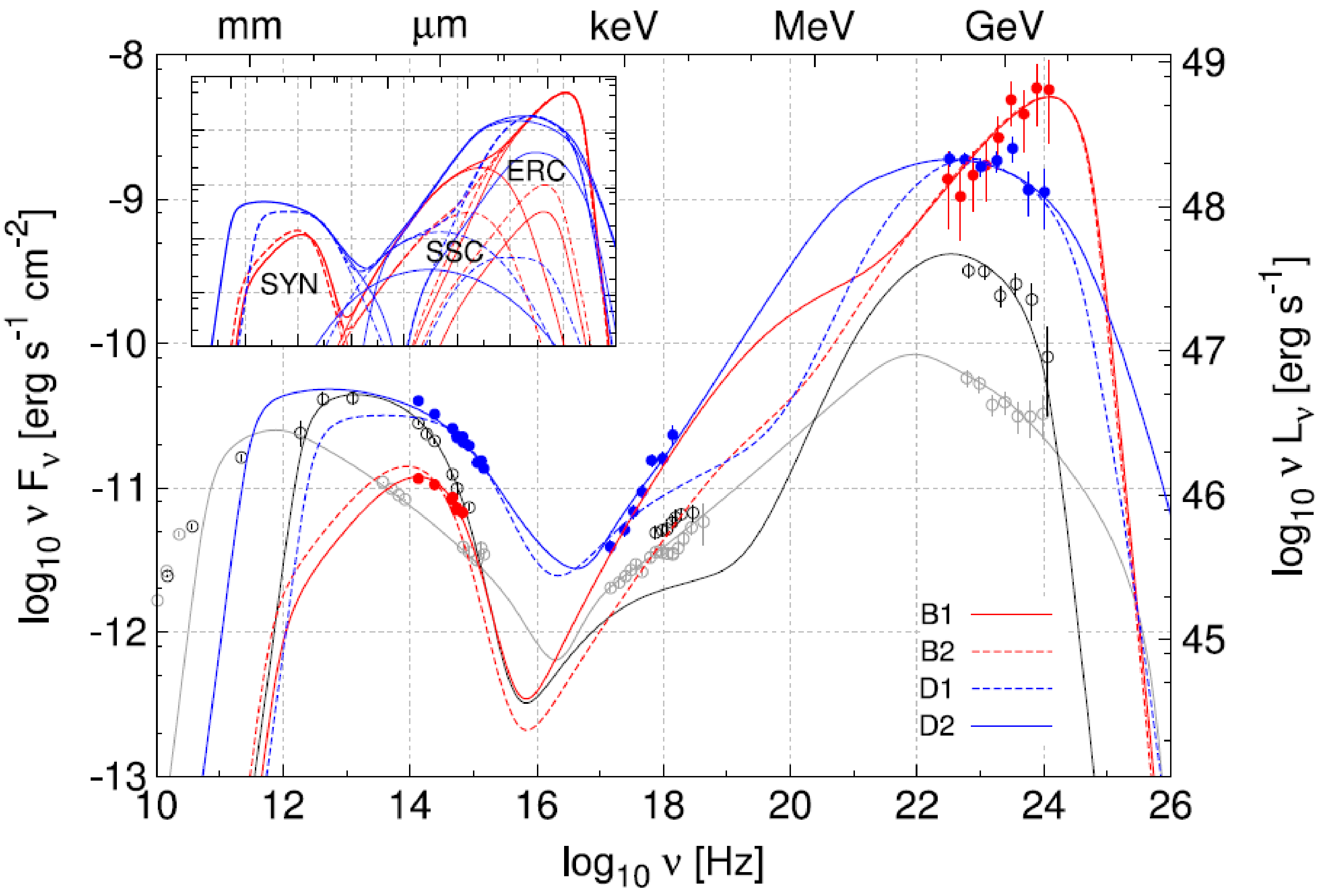
Big Flare in FSRQ 3C 279

Hayashida+ 2015





Spectrum



Extremely hard.

Stochastic Acc. seems preferable.

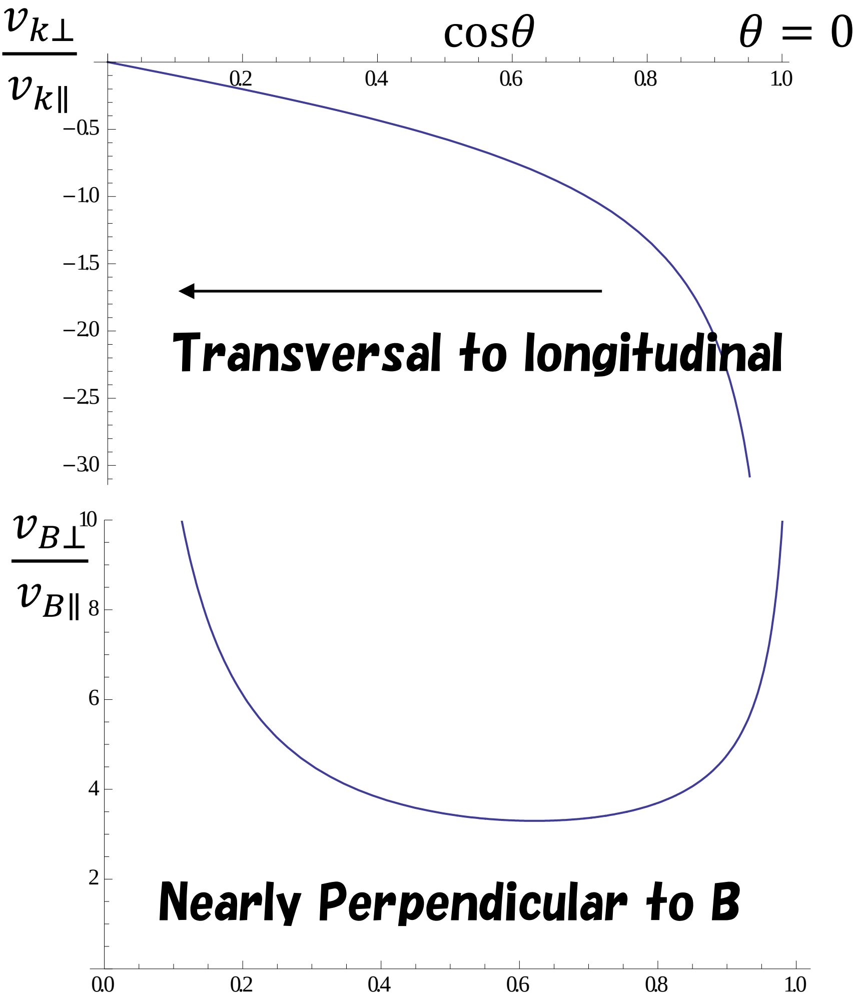
Broken power-law Model parameters

Model	B1	B2
r (pc)	0.03	0.12
Γ_j	20	30
$\Gamma_j\theta_j$	0.61	0.34
B' (G)	0.31	0.3
p_1	1	1
γ_1	3700	2800
p_2	7	7
γ_2	⋯	⋯
p_3	⋯	⋯

Magnetic Pressure Dominant Case

$$\frac{v_A}{v_c} = 10$$

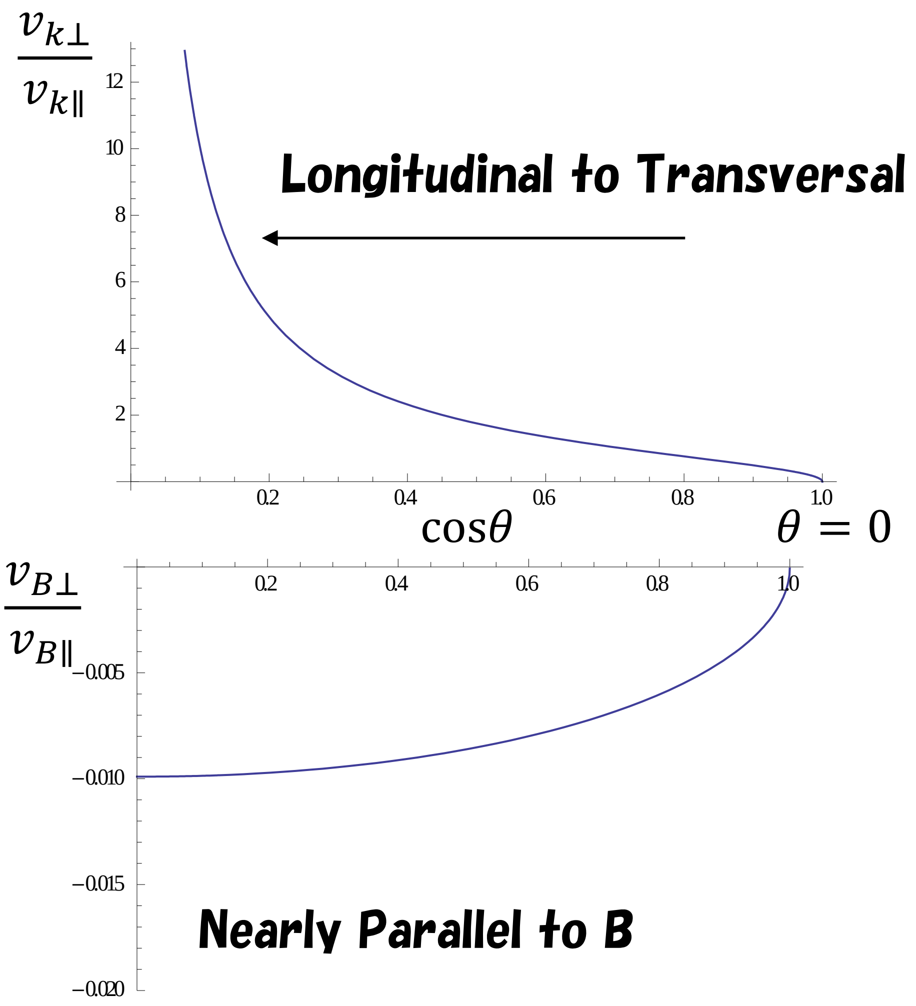
Fast Mode



Transversal to longitudinal

Nearly Perpendicular to B

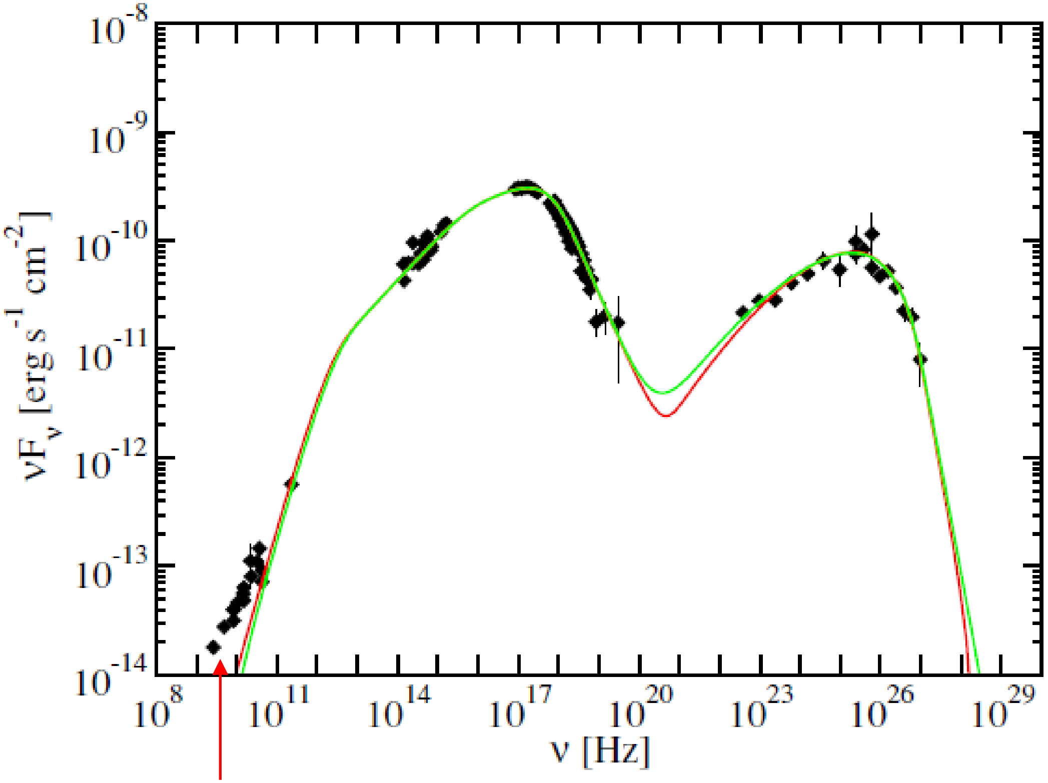
Slow Mode

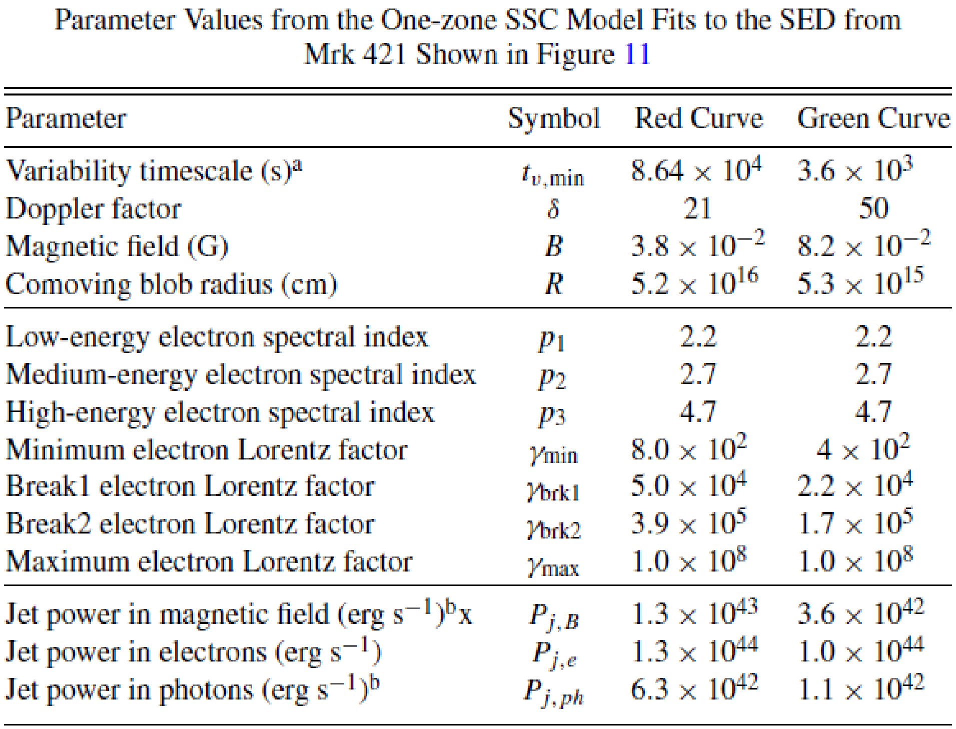


Longitudinal to Transversal

Nearly Parallel to B

Mrk421: Borken-Power-Law Model





Parameter Values from the One-zone SSC Model Fits to the SED from Mrk 421 Shown in Figure 11

Parameter	Symbol	Red Curve	Green Curve
Variability timescale (s)[a]	$t_{v,\mathrm{min}}$	8.64×10^4	3.6×10^3
Doppler factor	δ	21	50
Magnetic field (G)	B	3.8×10^{-2}	8.2×10^{-2}
Comoving blob radius (cm)	R	5.2×10^{16}	5.3×10^{15}
Low-energy electron spectral index	p_1	2.2	2.2
Medium-energy electron spectral index	p_2	2.7	2.7
High-energy electron spectral index	p_3	4.7	4.7
Minimum electron Lorentz factor	γ_{min}	8.0×10^2	4×10^2
Break1 electron Lorentz factor	γ_{brk1}	5.0×10^4	2.2×10^4
Break2 electron Lorentz factor	γ_{brk2}	3.9×10^5	1.7×10^5
Maximum electron Lorentz factor	γ_{max}	1.0×10^8	1.0×10^8
Jet power in magnetic field (erg s^{-1})[b]x	$P_{j,B}$	1.3×10^{43}	3.6×10^{42}
Jet power in electrons (erg s^{-1})	$P_{j,e}$	1.3×10^{44}	1.0×10^{44}
Jet power in photons (erg s^{-1})[b]	$P_{j,ph}$	6.3×10^{42}	1.1×10^{42}

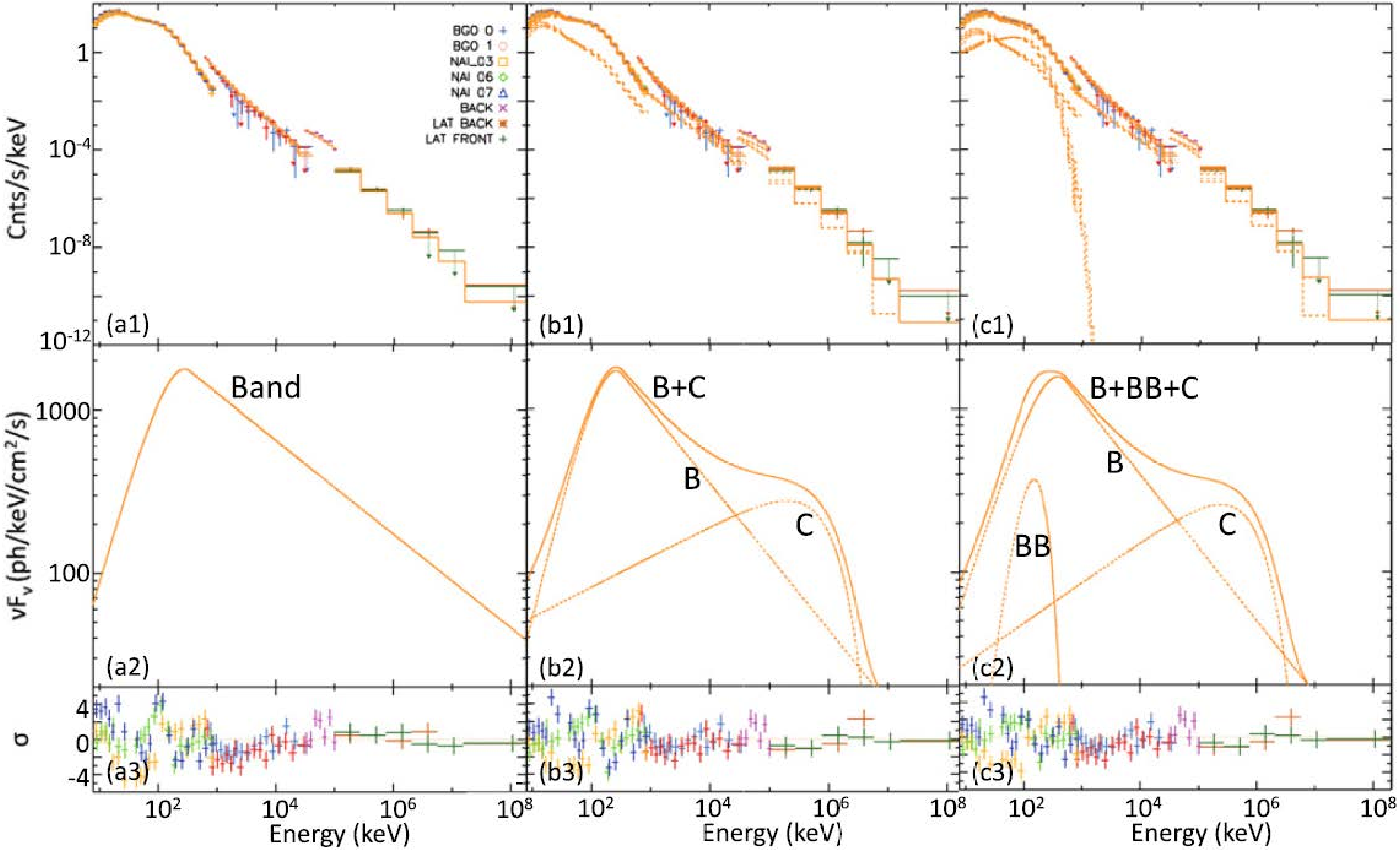
Radio should be different component in this case

Need double break and low-energy cut-off

Multiple Components?

Guiriec+ 2015

Combining the spectrum and light-curve data, they proposed three component models.



Universal tendency?

RM不安定性による磁場の増幅・乱流スペクトル