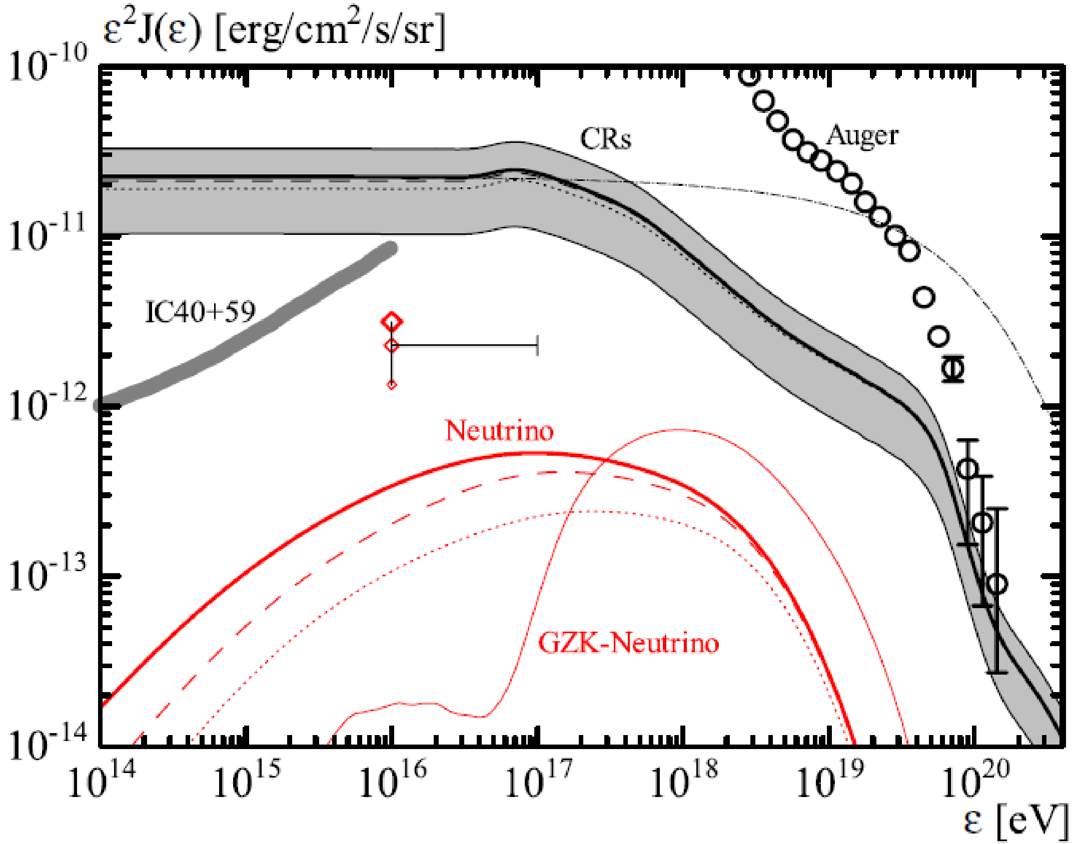
Ultra high-energy cosmic ray production at the deceleration onset of the GRB outflow

Katsuaki Asano
(ICRR, U. Tokyo)

Ultra High-Energy Cosmic-Rays

Power-law injection of protons $(p = 2)$

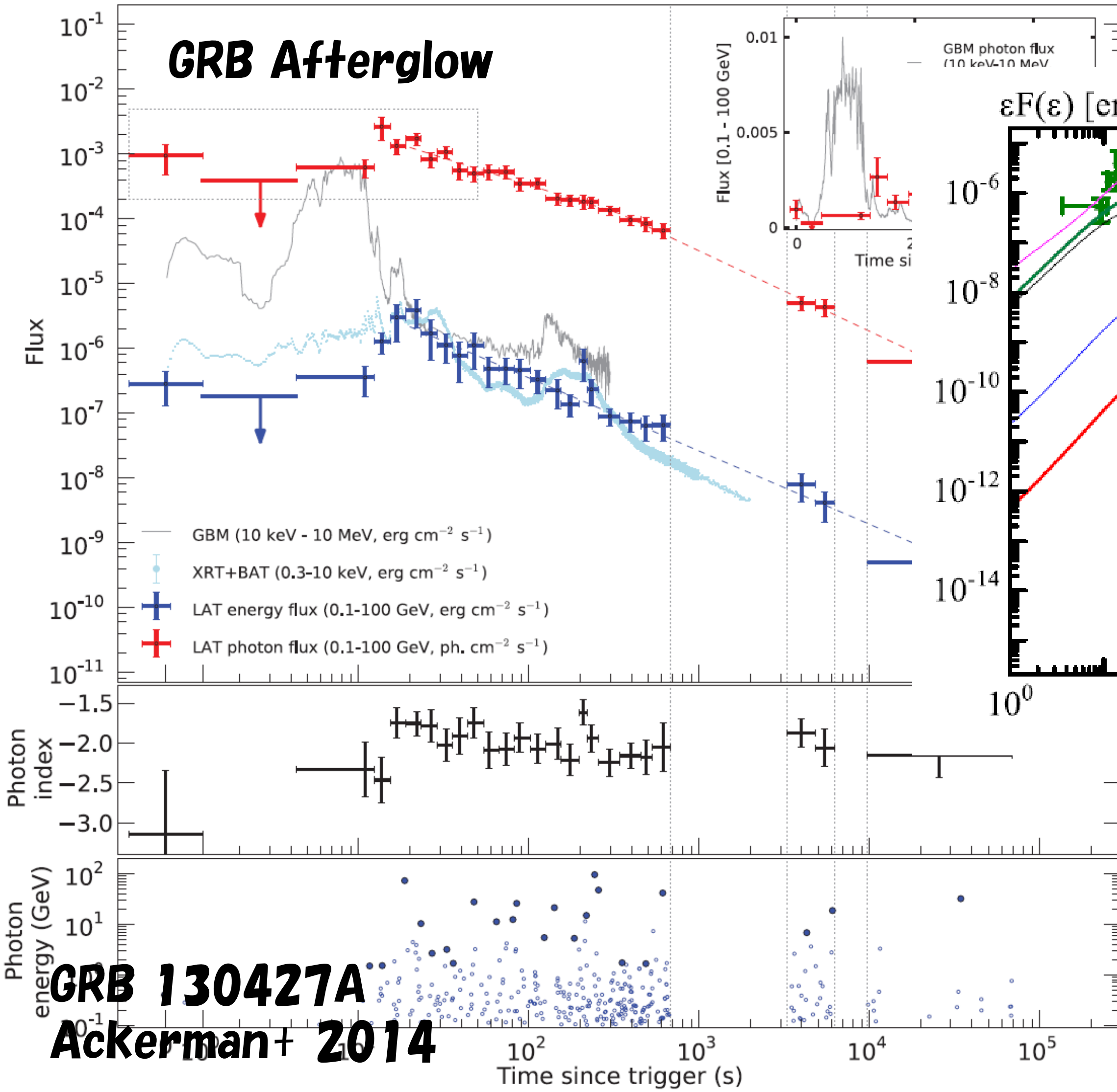
Even with $f_{\rm CR} \equiv \frac{L_{\rm CR}}{L_\gamma} = 10$



Only above $\sim 10^{20}$ eV

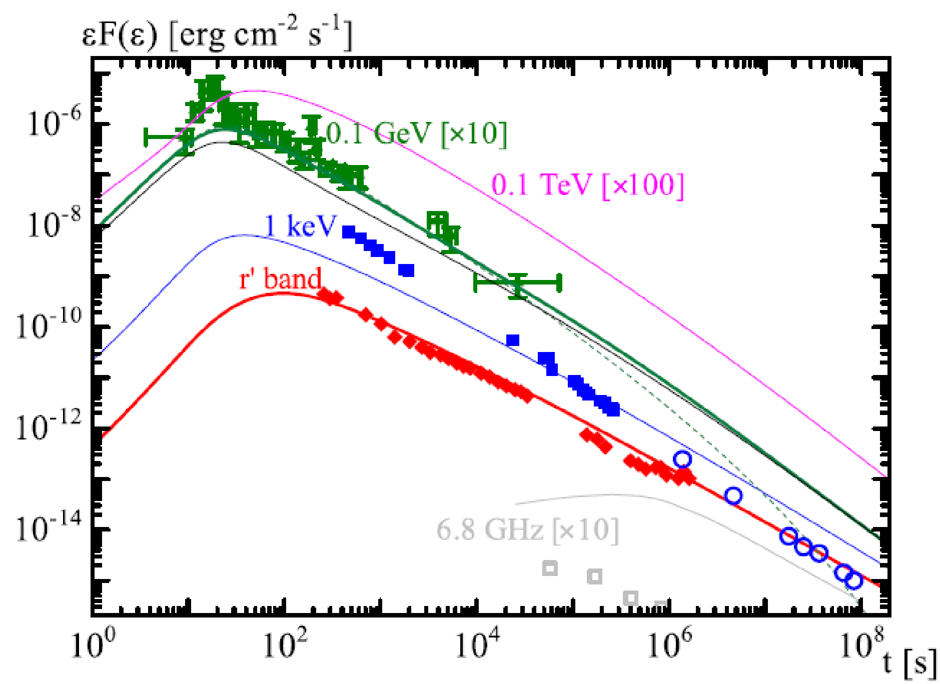
Asano & Meszaros 2014

Afterglow as calorimeter



GRB 130427A
Ackerman+ 2014

SSC emission @ TeV

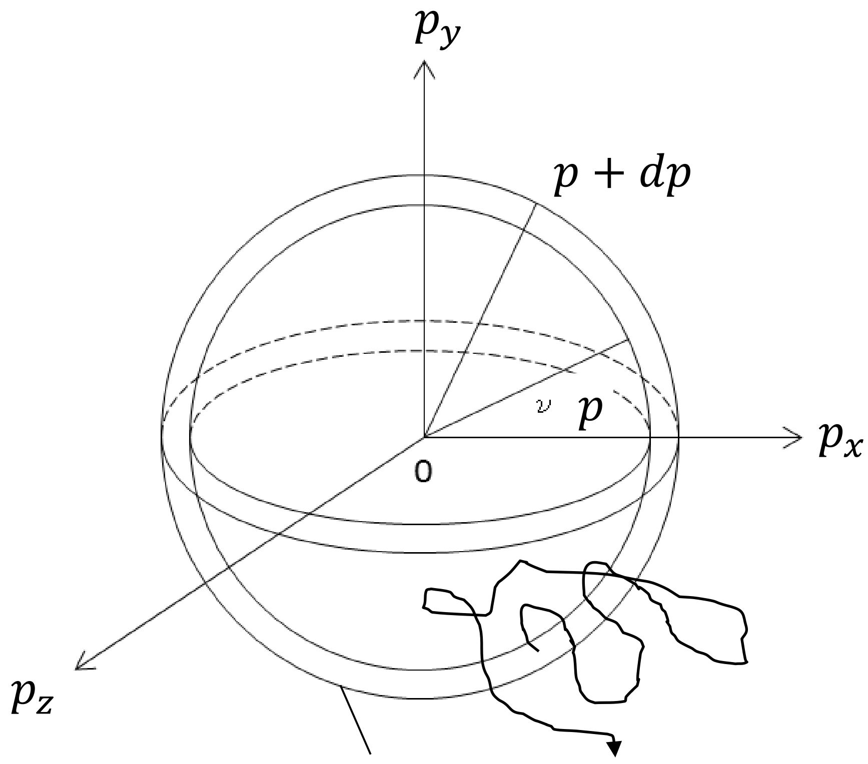


Fukushima+ 2017

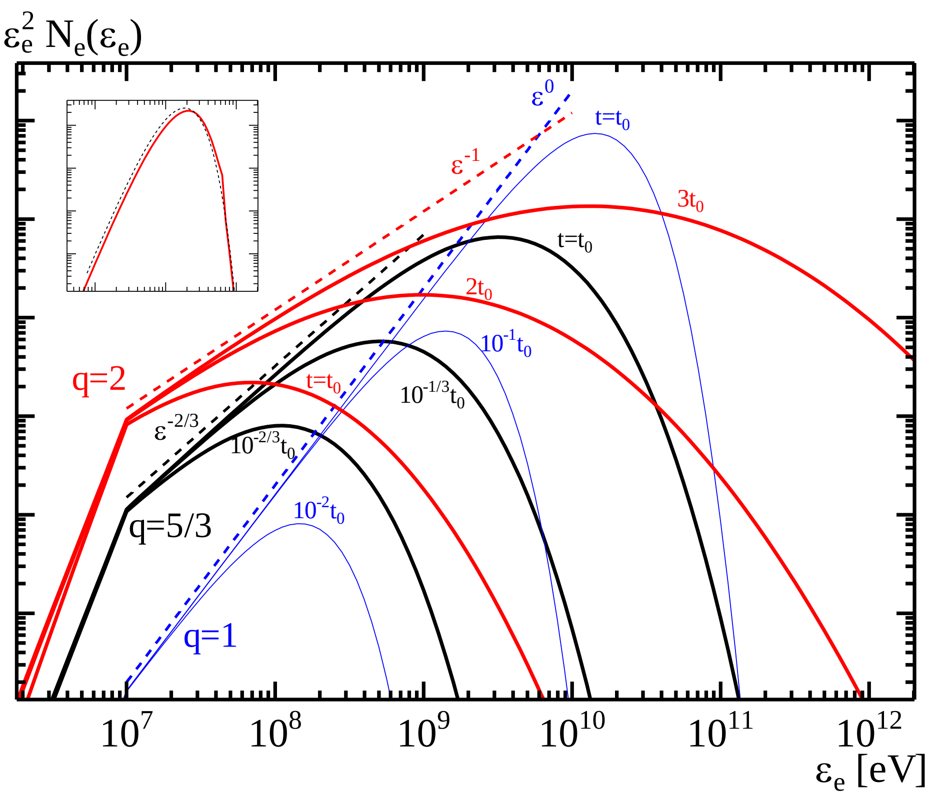
Consistent with SSC by accelerated electrons at a relativistic shock!

All non-thermal phenomena are due to shocks?

Stochastic acceleration by turbulece



Energy=const.

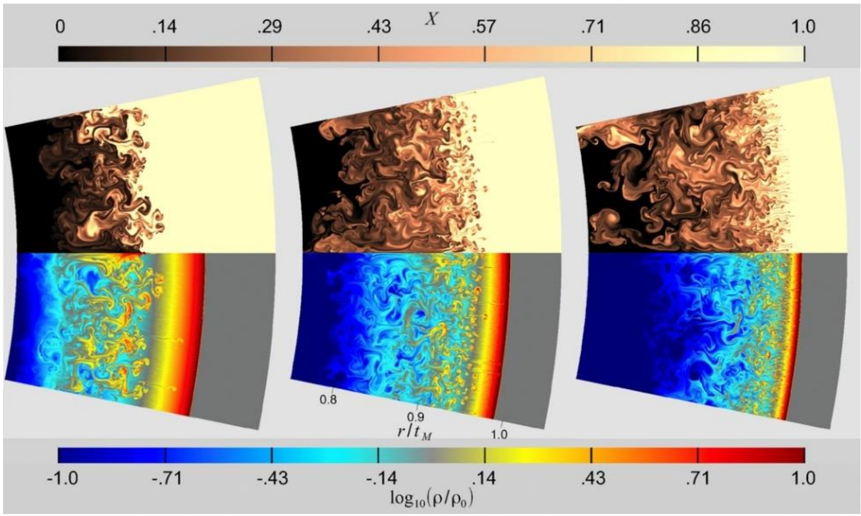


Outer: larger volume → Higher acceleration

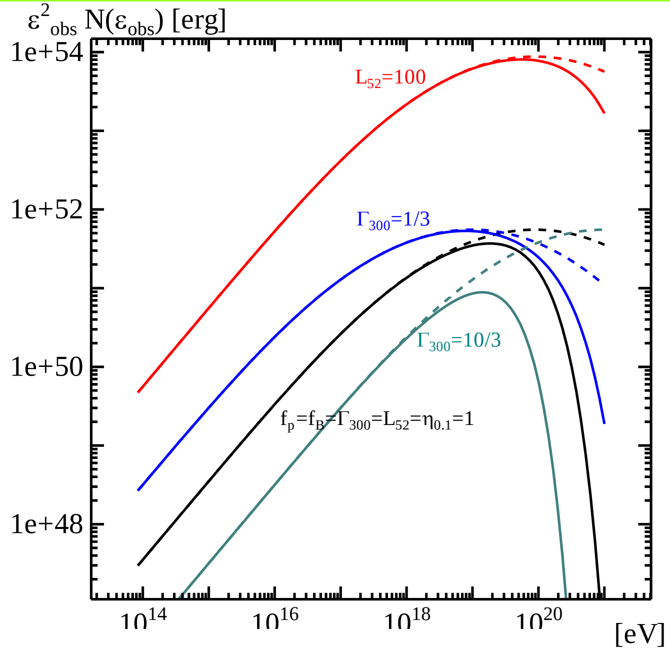
$$\frac{\partial N_e(\varepsilon,t)}{\partial t} = \frac{\partial}{\partial E}\left[D_{EE}\frac{\partial N_e(E,t)}{\partial E}\right] - \frac{\partial}{\partial E}\left[\left(\frac{2D_{EE}}{E} - \langle \dot{E}_{cool}\rangle\right)N_e(E,t)\right] + \dot{N}_{e,inj}(E,t)$$

Diffusion Acceleration Cooling Injection

UHECR production at the onset of GRB afterglow



Duffell and MacFadyen 2013



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

$$\simeq 8.2 \times 10^{19} \xi_{0.1} \Gamma_{300}^{-1} f_B^{1/2} L_{52}^{1/2}\ {\rm eV},$$

$$D_{EE} \propto E^2$$

Injection energy

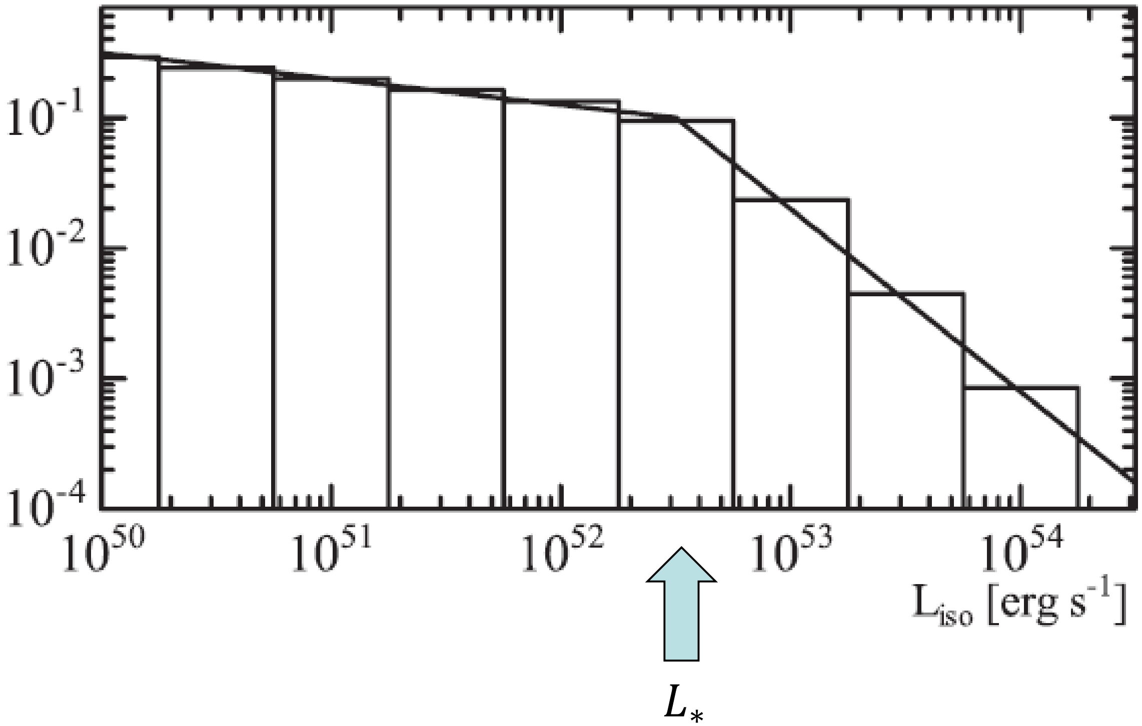
Injection rate

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

Diffusion coefficient

Elapsed time

GRB Luminosity function



Progenitors (Ibc SN) seem common for low-luminosity GRBs and Fermi-LAT GRBs.

$$L_{\rm tot} = L_\gamma + L_B + L_{\rm CR}$$

is common?

With a constraint

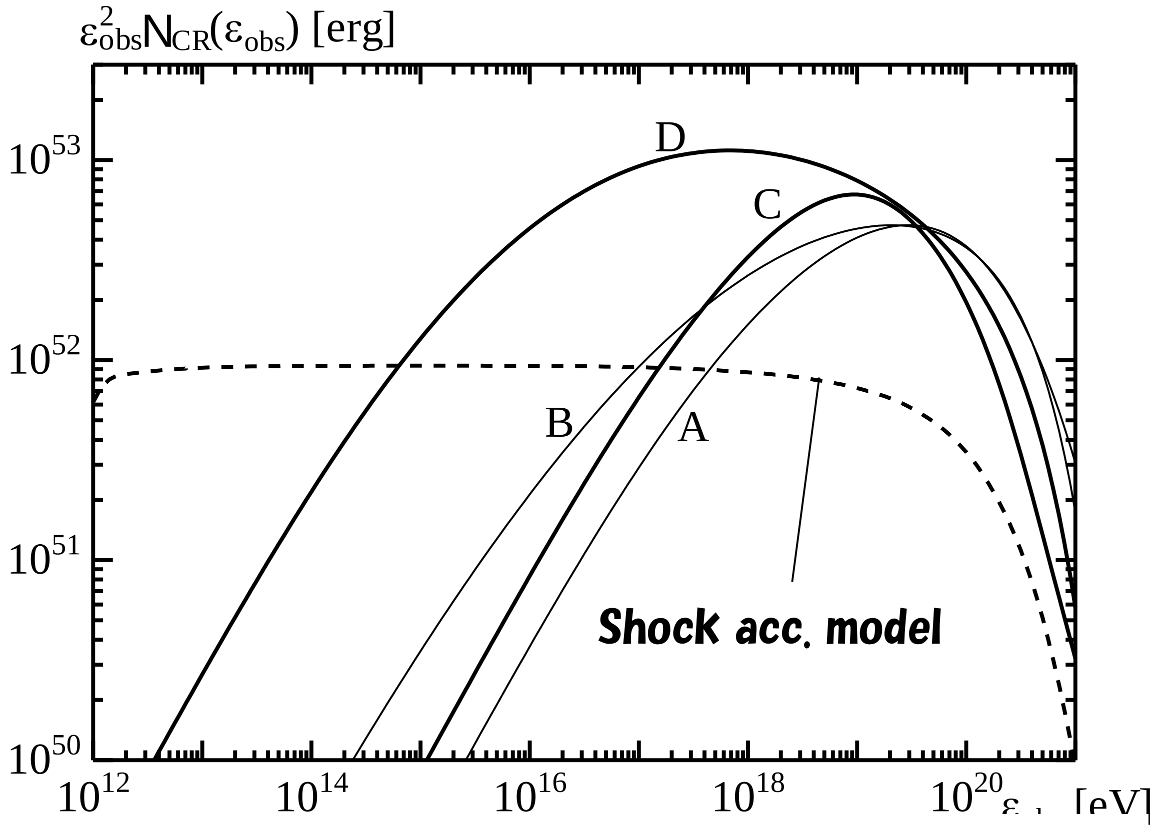
$L_{\rm tot} \leq 10 L_*$

we adopt optimistic value of $f_{\rm CR}$ for dim GRBs.

Model	A	B	C	D
$f_{\rm CR}$	10	10	U.M.[a]	U.M.
Γ	300	$72.1 L_{52}^{0.49}$	300	$72.1 L_{52}^{0.49}$
LLC[b]	30.0%	45.8%	92.3%	100%

Average UHECR spectrum for a GRB

$L_{p,\mathrm{typ}} = 10^{53.5}\ \mathrm{erg\ s^{-1}}$

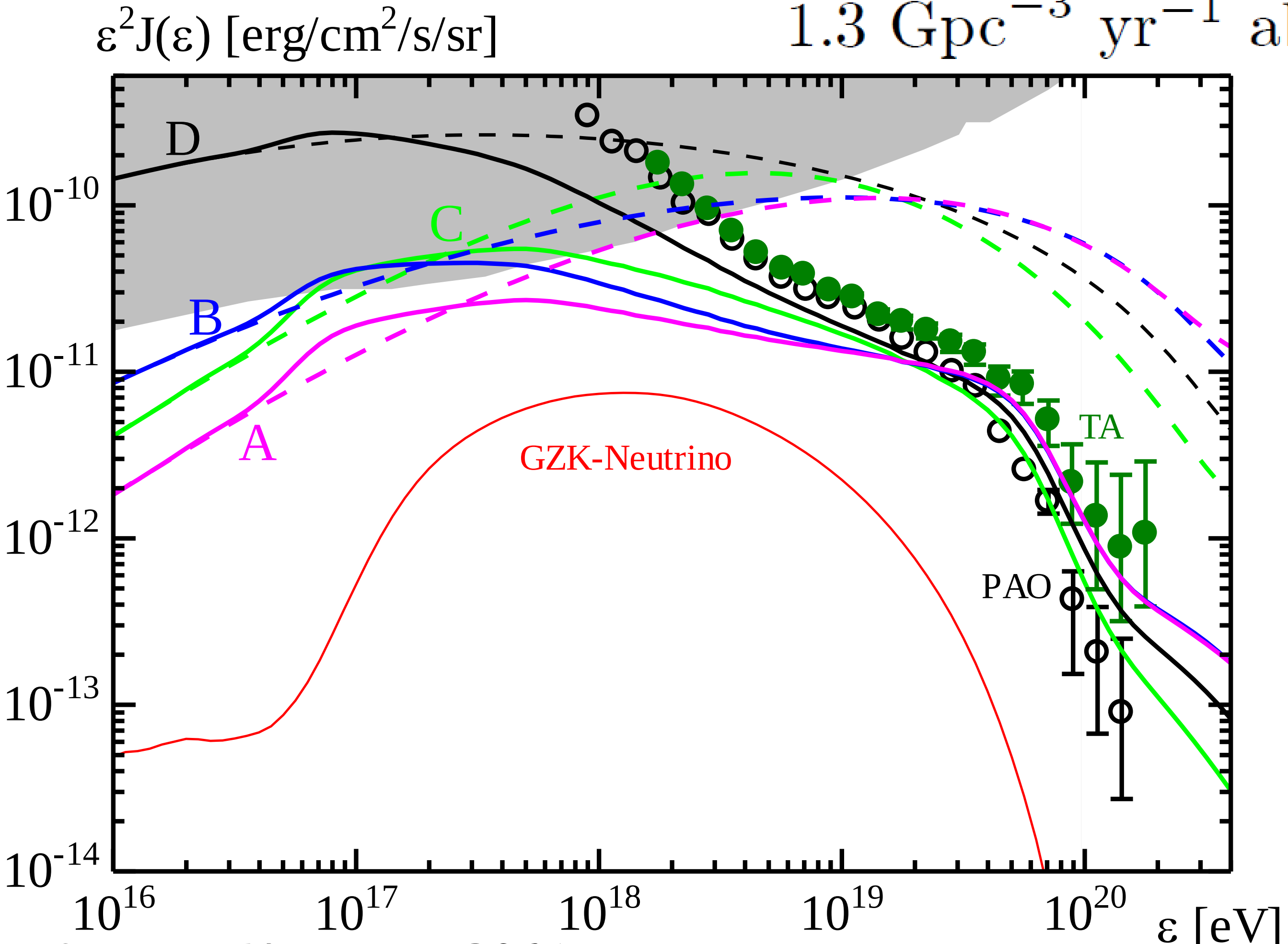


Stochastic Acc. Model can concentrate UHECRs around the highest energy region.

Total UHECR Flux

Calculating the propagation of UHECRs

$1.3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ above 10^{50} erg s^{-1}



$$p + \gamma \to p + \pi^0$$
$$\to n + \pi^+$$
$$\to p + e^+ + e^-$$

Asano & Meszaros 2016

Seems possible as UHECR sources

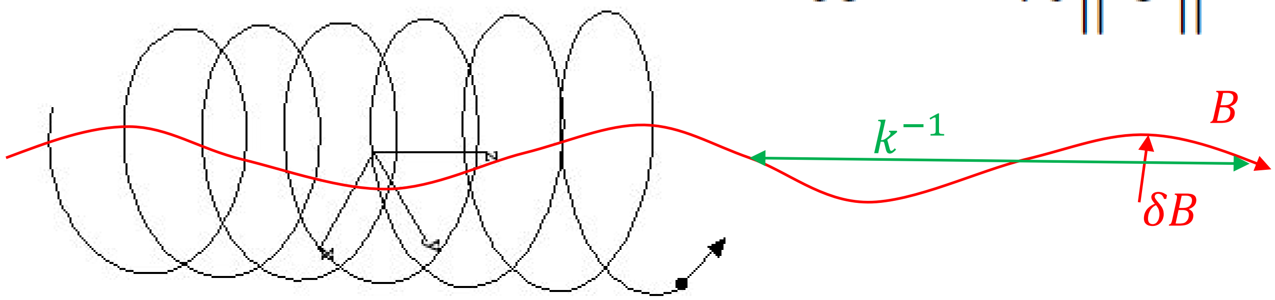
Wave-Particle Interaction

High-energy particles interact with macroscopic E-M waves.

Hereafter, we consider waves in MHD approximation.

The gyroresonance with Alfven waves has been discussed.

$$\omega - k_{\|} v_{\|} = n\Omega$$



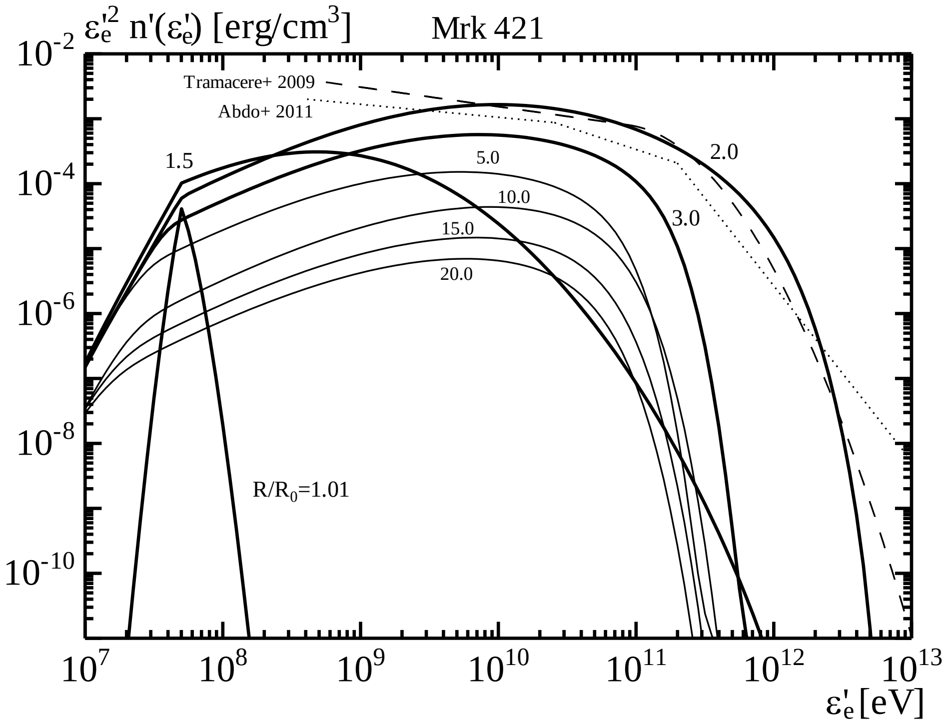
The kinetic energy and magnetic energy in perturbation are comparable.
But, the magnetic energy would be subdominant component.

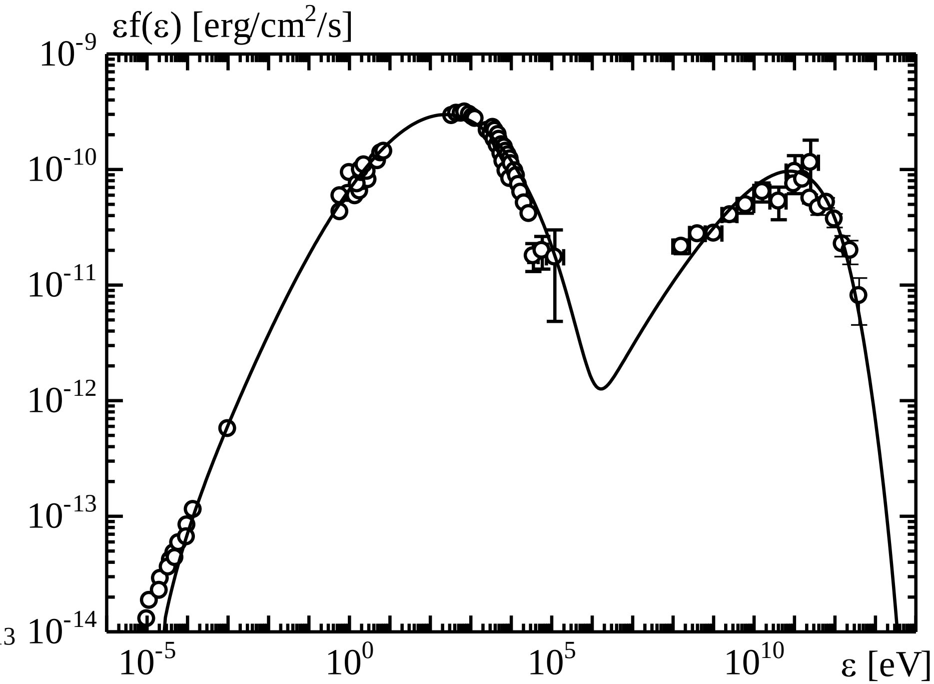
Wave energy density $\delta B^2(k) \propto k^{-q} \rightarrow D_{EE} \propto E^q$

$q = 5/3$ **Kolmogorov case is standard.**

Blazars suggest hard-sphere acceleration

Asano & Hayashida 2018





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

$$t_{\mathrm{coll}} \propto E^0,\ \ D_{EE} = KE^2$$

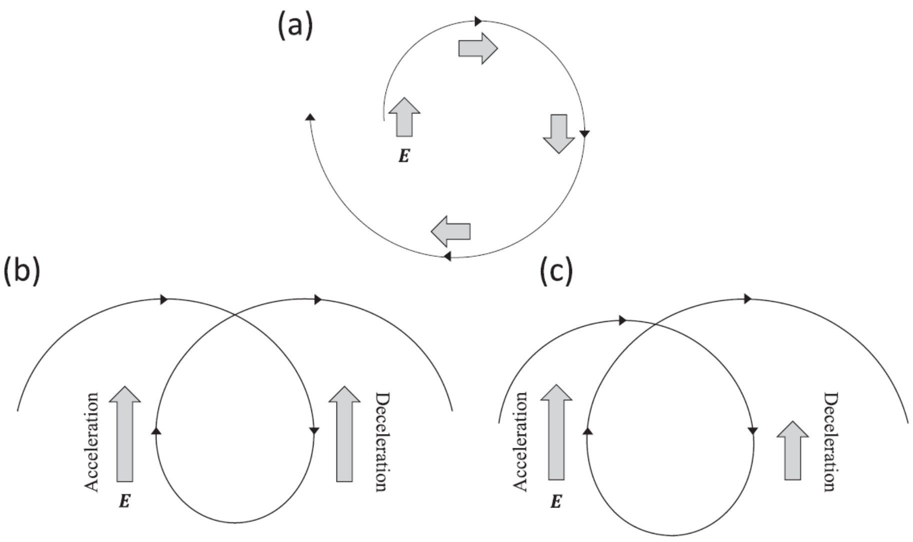
$U_B \ll U_e$ **The energy source would be not Alfven waves.**

Transit Time Damping

$$\omega - k_{\|} v_{\|} = n\Omega$$

Compressible MHD waves. Resonance with $n = 0$.
The parallel phase velocity is the same as the parallel particle velocity.

Essence: The electric field difference in one Gyro cycle.



Incompressible wave=Alfven wave has no $\nabla \times E \propto \delta \dot{B}$ along B.
No acceleration.

$k_{\perp}$ in compressible wave induces the change in E

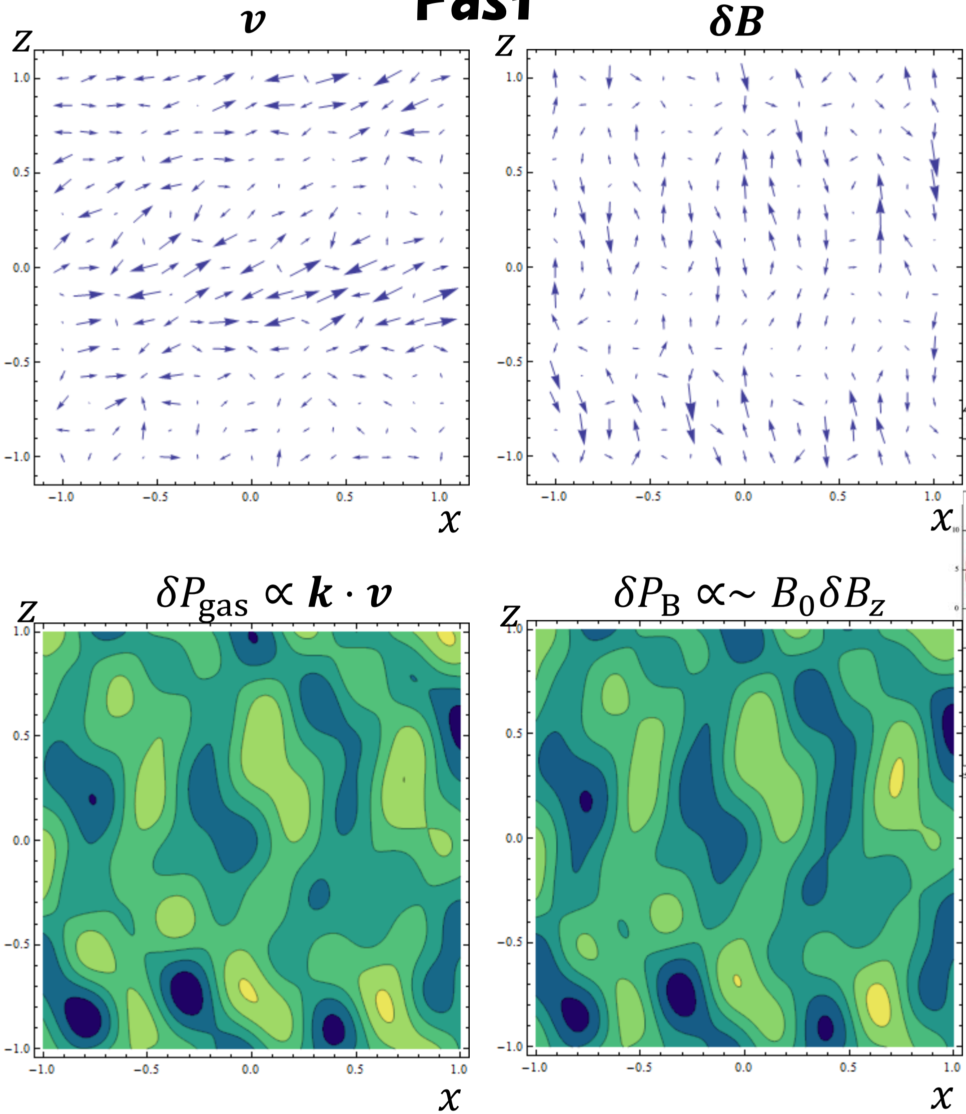
When $r_L < k_{\max}^{-1}, \rightarrow D_{EE} \propto E^2$

Problem: The number fraction of accelerated particles is small?

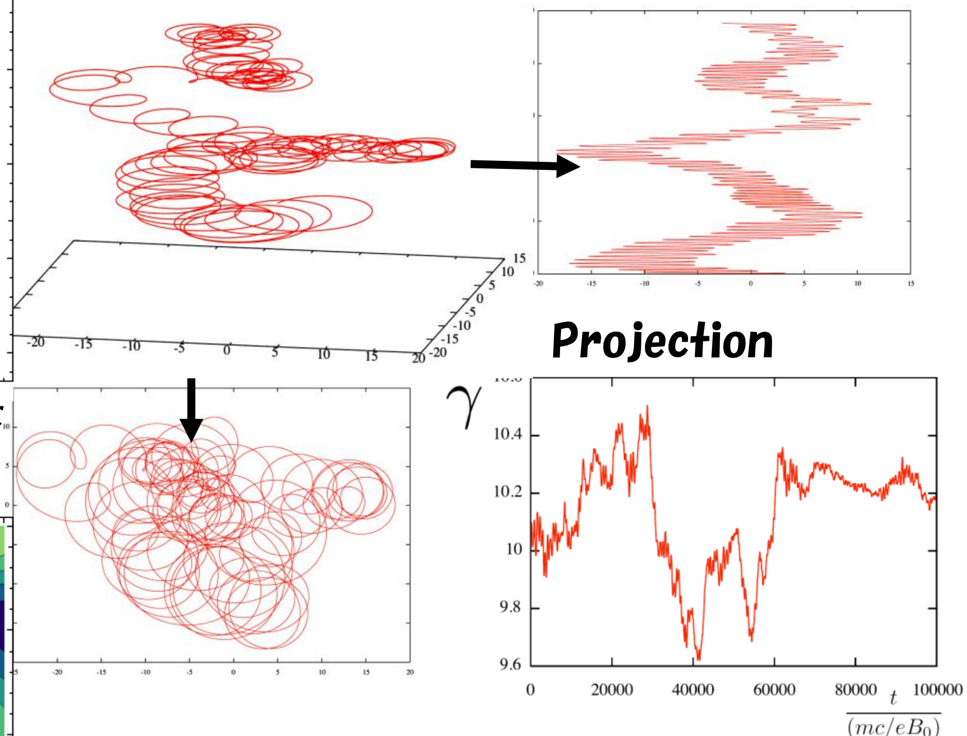
Pitch angle $\cos\theta \sim \frac{v_{\|}}{c} \ll 1$

Test particle simulation in pure linear Waves

Fast

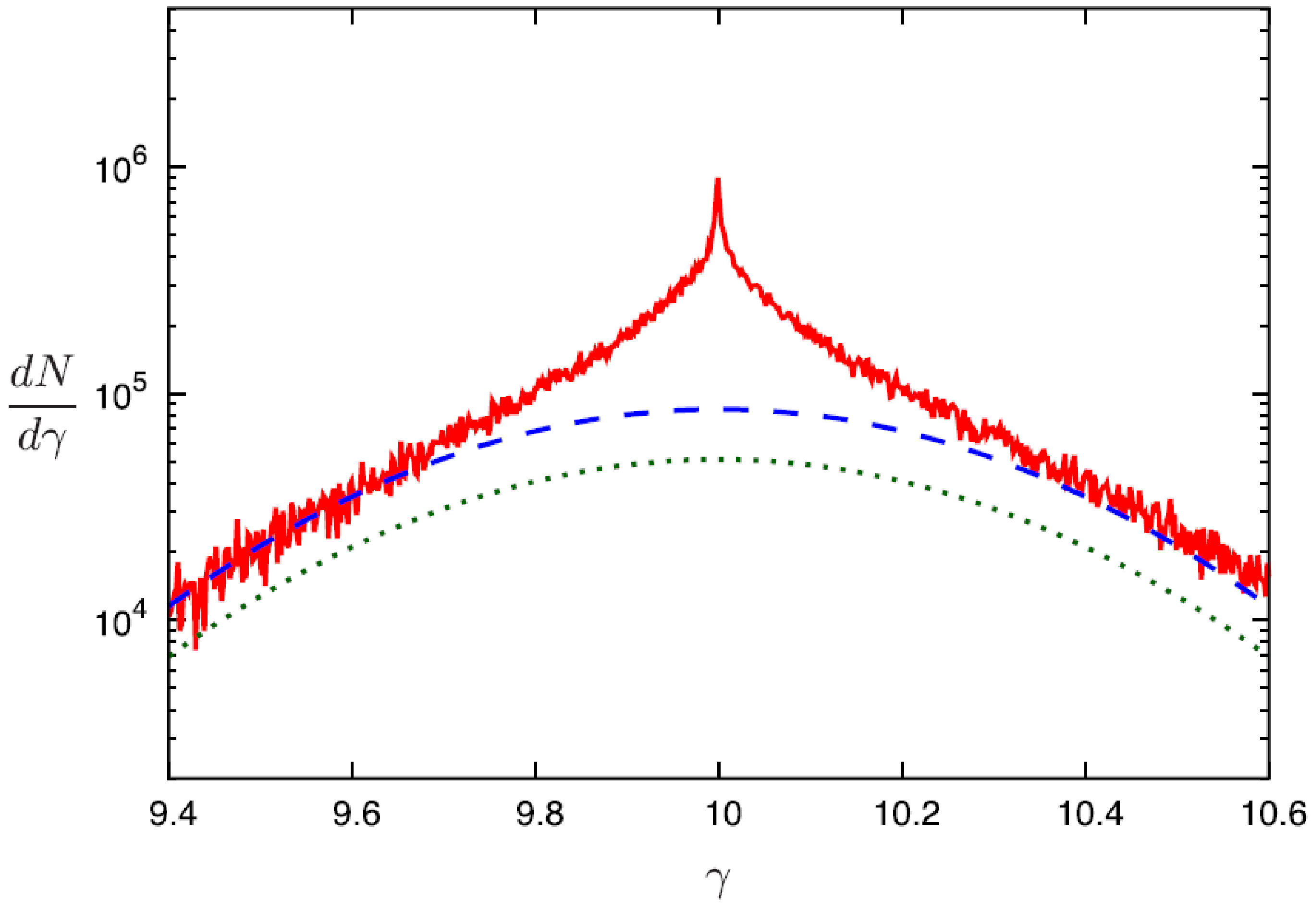


High-beta plasma



Teraki & Asano 2019

Energy Diffusion



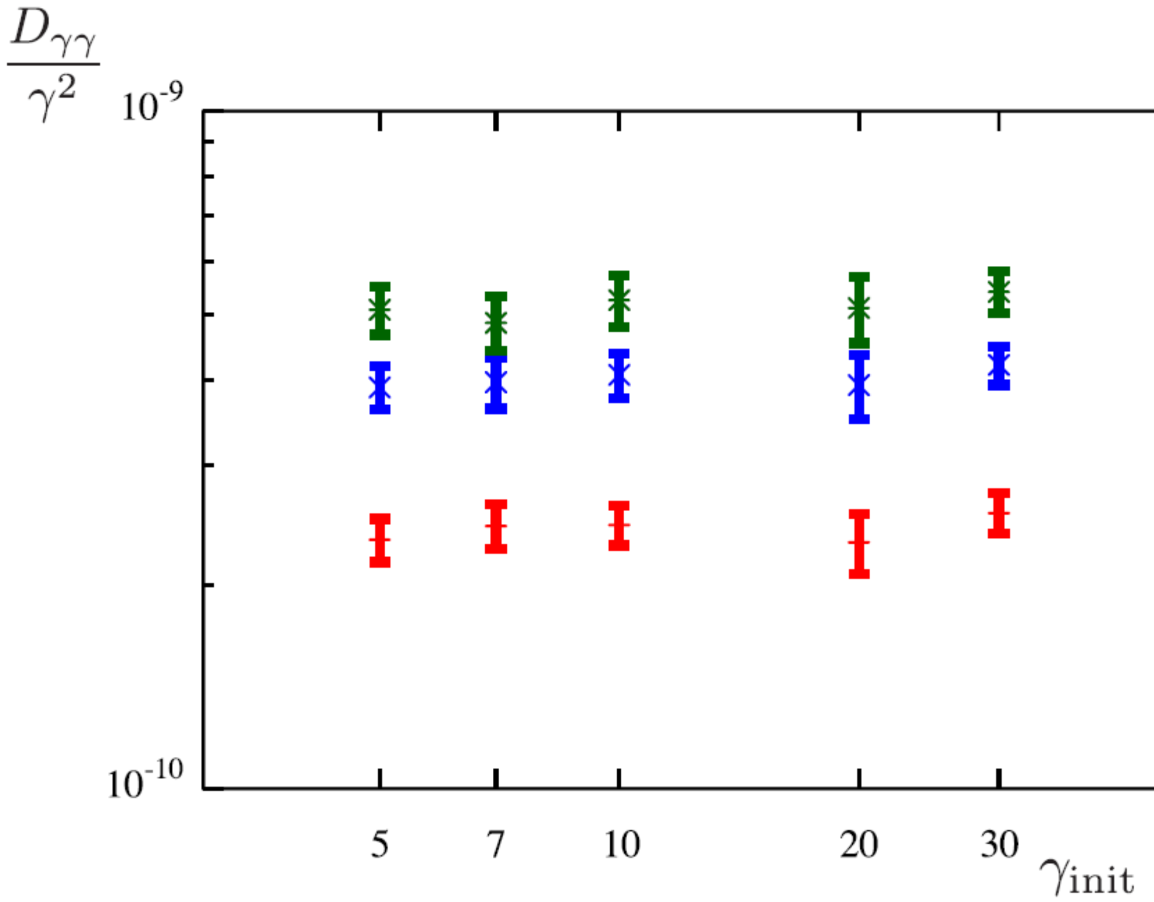
Significant fraction of particles diffuses in the energy space.

Hard Sphere-like diffusion

When $r_L < k_{\max}^{-1}$

$$D_{\gamma\gamma,\mathrm{fast}} \sim \gamma^2 \left(\frac{V}{c}\right)^2 c k_{\max}(\nu - 1)\left(\frac{k_{\max}}{k_{\min}}\right)^{1-\nu} \epsilon_{\mathrm{res,fast}}$$

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



Required Diffusion Coefficient

Size of the acceleration region: R
Diffusion Coefficient: $D_{EE} = KE^2$

In our GRB-UHECR model, we consider the particle acceleration by eddy turbulence with a scale of $\sim 0.1\,R$.
This corresponds to $\frac{K}{c} \sim \frac{3}{R}$

With the turbulence velocity of $c/\sqrt{3}$,
if the fast-wave TTD is responsible, our simulation (Teraki & Asano 2019) shows

$$\frac{K}{c} \sim 5.6\,\frac{\pi}{18}\frac{1}{R}\left(\frac{R}{\lambda_{\min}}\right)^{2/3}$$

$\lambda_{\min} \sim 0.1R$ is consistent with the above value.

Summary

- A significant fraction of particles can resonate with fast waves via TTD.
- When the cut-off scale is larger than the Larmor radius, the hard-sphere acceleration realizes.
- UHECRs can be accelerated by turbulence at the onset of GRB afterglow.
- Since the acceleration timescale is long, electrons cool before accelerating.
- The required diffusion coefficient for UHECR production is not extreme one compared to our test particle simulation.