Stochastic Particle Acceleration via Turbulence in Various High-Energy Astrophysical Phenomena

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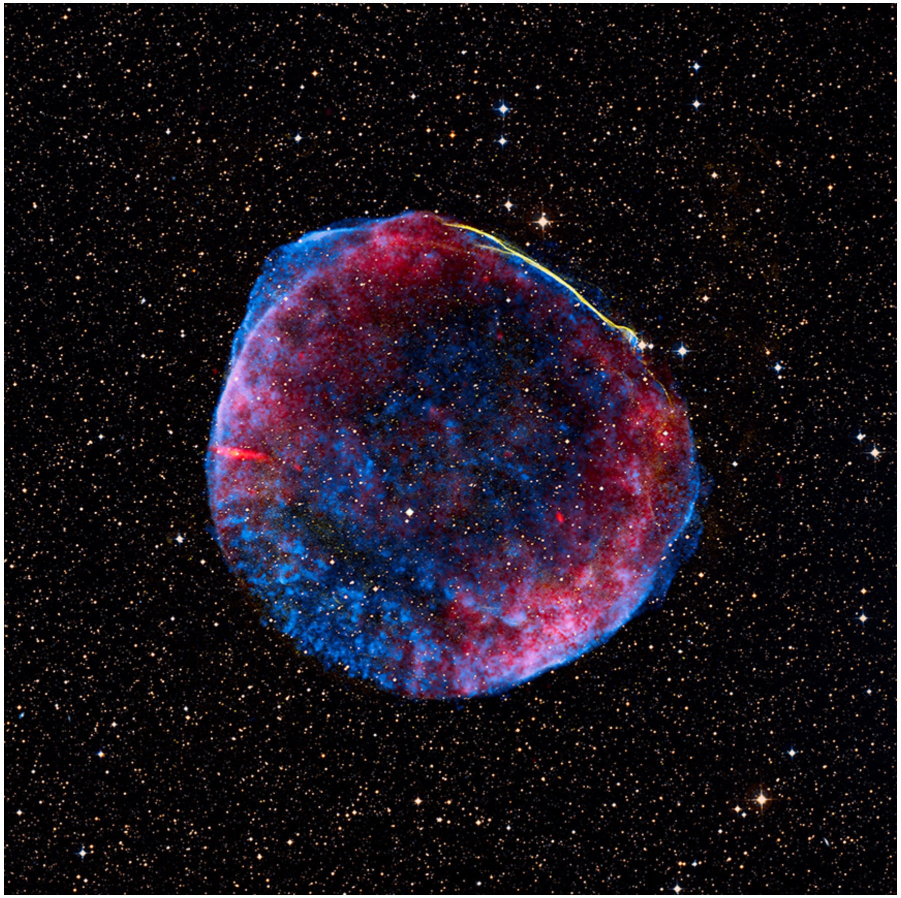
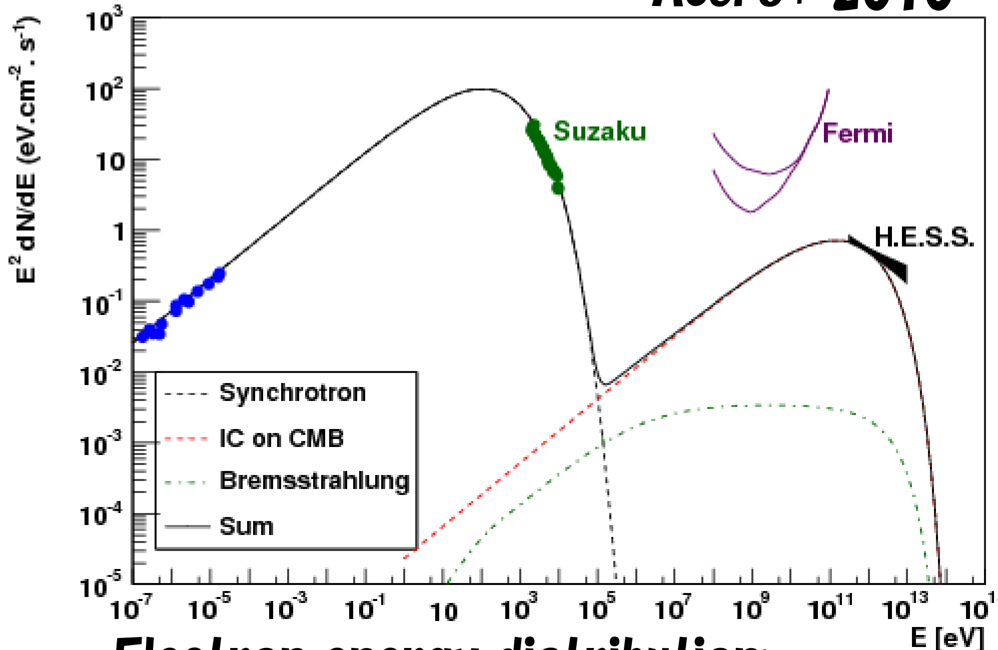
Non-thermal Emission

Supernova Remnant SN1006



Acero+ 2010



Electron energy distribution:
Single power-law with the index of 2.1, cut off at 10 TeV and B=30μG.

$$t_{\rm acc} = \frac{20\eta E}{3eBc\beta_{\rm SNR}^2} \;\&\; t_{\rm cool} = \frac{6\pi m_e^2 c^3}{\sigma_T B^2 E}$$

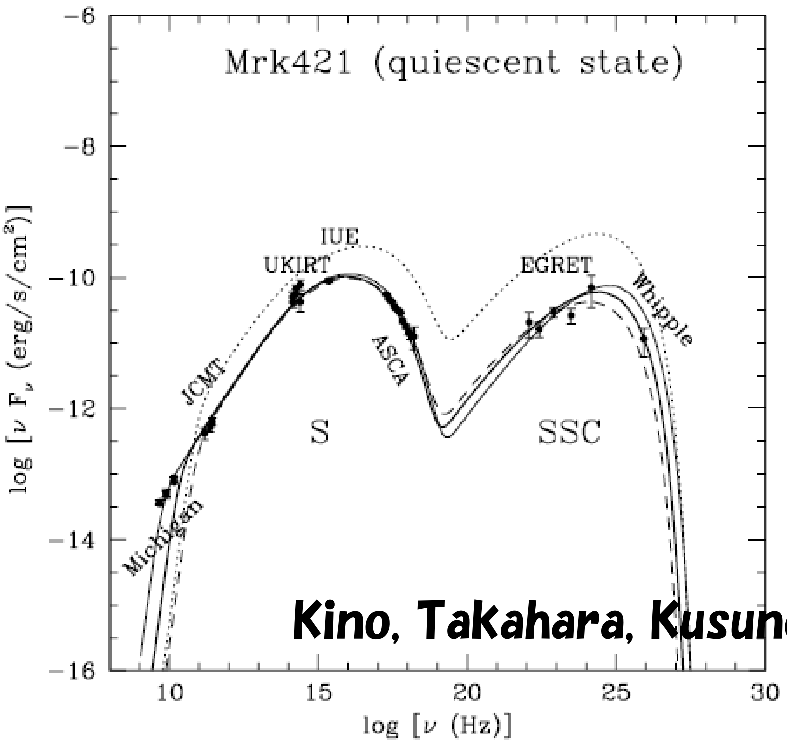
Bohm Limit $(\eta = 1)$ **&** $v_{\rm SNR} = \frac{1000{\rm km}}{\rm s} \rightarrow E_{\rm max} = 8{\rm TeV}$

Consistent with the diffusive shock acceleration (Fermi I)+Bohm Limit!

All non-thermal phenomena are due to shocks?

Troubles in Blazar Emission

1. Index harder than 2 for the electron injection spectrum.



Kino, Takahara, Kusunose 2002

FIG. 4.—One-zone SSC model spectra for the steady state emission of Mrk 421. The thick solid line shows the best-fit spectrum where the adopted parameters are $\delta = 12$, $R = 2.8 \times 10^{16}$ cm, $B = 0.12$ G, $\gamma_{\max} = 1.5 \times 10^5$, $q_e = 9.6 \times 10^{-6}$ cm^{-3} s^{-1}, $s = 1.6$, and $u_e/u_B = 5$. The dotted line shows the spectrum obtained using the analytic estimates for Mrk 421. The thin solid and dashed lines show the spectra of low and high injection models, respectively, to indicate the uncertainty range of the spectral fitting.

2. Lower maximum energy

Mrk 421:

B=38mG
If $\eta = 1$, even for $\beta_{\rm sh} = 0.1$,
$E_{\max} = 7$ TeV.
But actual Max. Energy 50 GeV

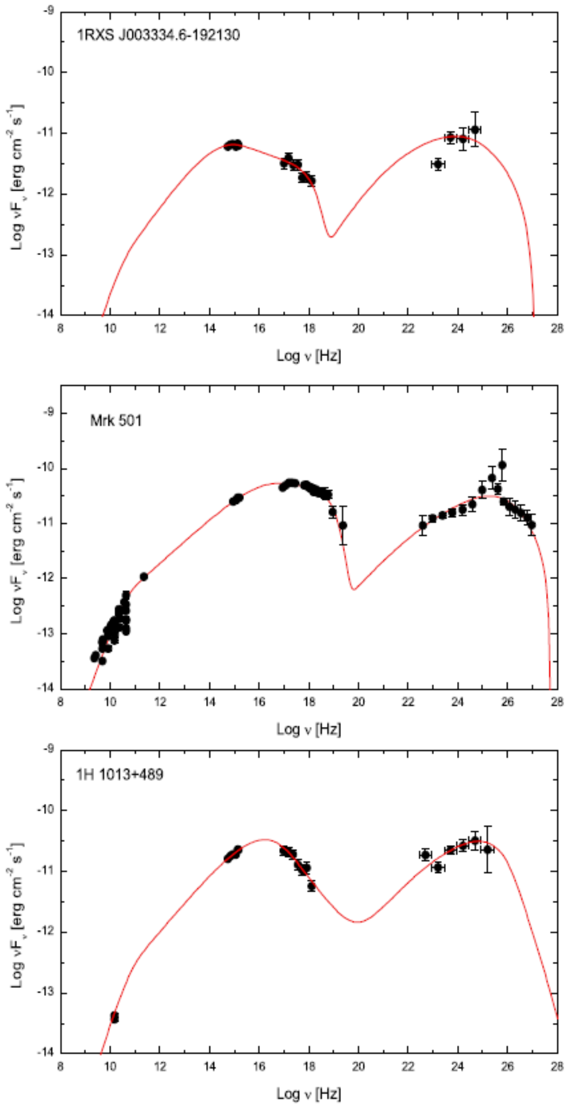
The Bohm factor should be $\sim 10^4$

Inoue & Takahara 2002

3. Too sharp break in the electron spectrum.

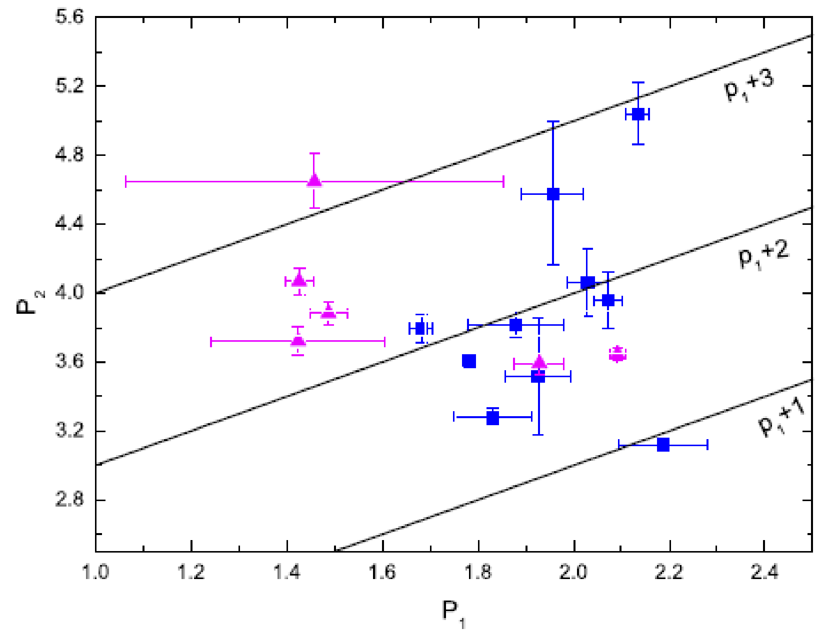
Compared to the cooling break, the difference in the indices seems large.

Electron Index in Fermi BL Lacs



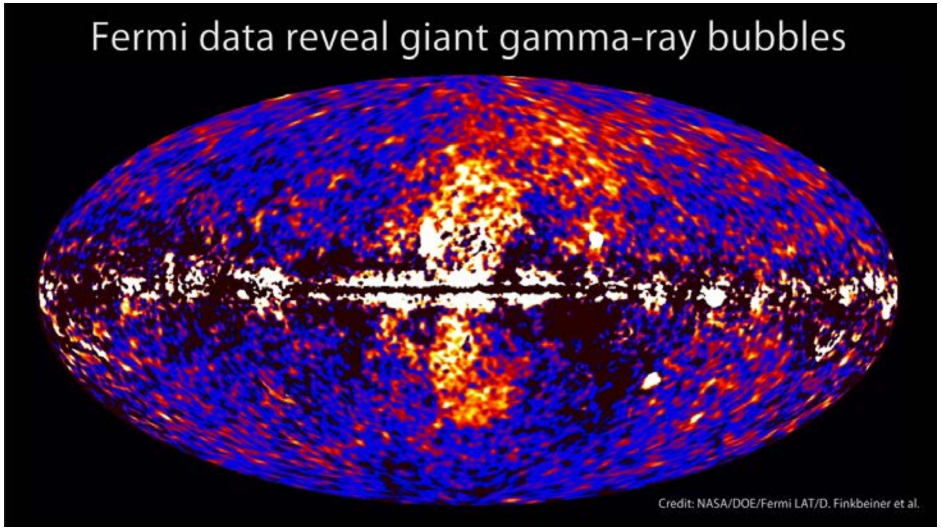
Yan+

MNRAS 439, 2933–2942 (2014)

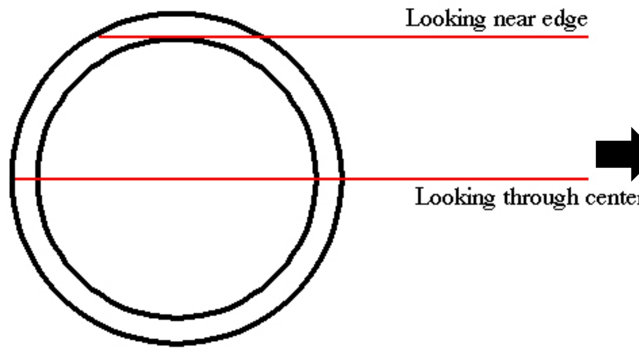


Name	B (0.01 G)	δ_D (10)	$t_{v,\,min}$ (10^5 s)	γ'_{max} (10^7)	γ'_b (10^4)	K'_e (10^{55})	p_1	p_2	χ^2_{red}
0033−1921	4.06 ± 1.24	2.43 ± 0.17	2.48 ± 1.21	0.07 ± 0.01	1.62 ± 0.20	0.12 ± 0.01	1.83 ± 0.08	3.29 ± 0.05	1.14
0414+009	1.30 ± 0.58	2.96 ± 1.36	3.54 ± 4.31	1.49 ± 2.70	12.67 ± 1.36	0.04 ± 0.02	1.88 ± 0.10	3.82 ± 0.07	3.96
0447−439	5.47 ± 1.38	3.63 ± 0.08	0.43 ± 0.11	0.052 ± 0.002	3.18 ± 0.29	0.05 ± 0.02	2.07 ± 0.03	3.96 ± 0.17	0.70
1013+489	5.72 ± 0.75	2.75 ± 0.47	0.55 ± 0.22	0.08 ± 0.04	6.82 ± 0.74	0.03 ± 0.01	2.03 ± 0.04	4.06 ± 0.19	2.11
2155−304	4.89 ± 0.66	1.97 ± 0.06	3.47 ± 0.52	0.087 ± 0.004	3.57 ± 0.20	0.011 ± 0.002	1.68 ± 0.02	3.79 ± 0.08	2.48
Mrk 421	4.23 ± 0.41	2.71 ± 0.27	0.42 ± 0.10	3.73 ± 0.81	18.43 ± 0.79	0.012 ± 0.002	2.13 ± 0.02	5.04 ± 0.18	1.39
Mrk 501	2.77 ± 0.63	2.99 ± 0.70	0.16 ± 0.11	0.16 ± 0.03	15.81 ± 3.10	0.007 ± 0.006	2.19 ± 0.09	3.12 ± 0.04	1.29
RBS 0413	5.48 ± 1.57	2.60 ± 0.55	0.23 ± 0.11	1.29 ± 0.42	9.97 ± 1.26	0.0014 ± 0.0006	1.93 ± 0.07	3.52 ± 0.34	1.91
1215+303	3.49 ± 0.17	3.58 ± 0.10	0.22 ± 0.02	0.27 ± 0.01	1.13 ± 0.04	0.0031 ± 0.0001	1.78 ± 0.01	3.61 ± 0.04	1.99
2247+381	5.45 ± 1.64	3.62 ± 0.05	0.14 ± 0.05	0.10 ± 0.06	8.87 ± 1.96	0.0004 ± 0.0002	1.96 ± 0.06	4.58 ± 0.42	0.54
0048−09	6.50 ± 5.84	2.50 ± 0.28	2.19 ± 1.74	0.10 ± 0.02	0.52 ± 0.04	0.015 ± 0.002	1.42 ± 0.18	3.72 ± 0.08	2.90
0716+714	5.90 ± 1.23	2.71 ± 0.47	3.51 ± 1.21	0.04 ± 0.01	0.92 ± 0.10	0.010 ± 0.002	1.49 ± 0.04	3.88 ± 0.07	1.98
0851+202	4.05 ± 2.41	2.40 ± 1.10	2.43 ± 3.34	0.14 ± 0.45	0.26 ± 0.10	0.13 ± 0.12	1.46 ± 0.40	4.65 ± 0.16	1.49
1058+5628	2.20 ± 1.14	2.40 ± 0.73	1.29 ± 0.72	0.06 ± 0.03	2.61 ± 0.30	0.06 ± 0.03	1.93 ± 0.05	3.59 ± 0.07	1.36
1246+586	8.82 ± 1.89	2.34 ± 0.34	3.06 ± 0.96	0.40 ± 0.02	0.89 ± 0.08	0.006 ± 0.006	1.43 ± 0.03	4.08 ± 0.08	1.52
W Comae	4.91 ± 0.12	2.70 ± 0.13	0.32 ± 0.04	0.06 ± 0.01	1.94 ± 0.09	0.046 ± 0.002	2.09 ± 0.02	3.65 ± 0.04	1.75
0426−380	1.08 ± 2.42	3.53 ± 4.01	0.93 ± 1.31	0.47 ± 0.02	1.77 ± 0.51	0.36 ± 0.78	1.78 ± 0.51	3.58 ± 0.93	2.41
0537−441	2.12 ± 1.55	3.62 ± 1.54	1.51 ± 1.38	0.38 ± 0.40	0.54 ± 0.09	0.20 ± 0.07	1.56 ± 0.13	3.96 ± 0.06	5.64
1717+177	1.79 ± 0.20	3.52 ± 0.18	0.036 ± 0.005	0.013 ± 0.003	1.79 ± 0.17	0.020 ± 0.001	2.12 ± 0.04	3.53 ± 0.19	3.97
BL Lac	1.86 ± 1.89	3.23 ± 1.70	0.95 ± 0.90	0.11 ± 0.09	0.29 ± 0.06	0.24 ± 0.04	1.84 ± 0.18	3.87 ± 0.04	4.10
OT 081	9.82 ± 9.80	2.31 ± 5.16	0.12 ± 0.55	2.00 ± 2.10	0.52 ± 0.58	0.007 ± 0.022	1.75 ± 0.66	3.76 ± 0.59	1.69
4C 01.28	10.56 ± 19.20	2.47 ± 3.42	0.66 ± 6.02	0.12 ± 0.43	0.30 ± 0.18	0.06 ± 0.13	1.69 ± 0.64	3.70 ± 0.32	0.96

Fermi Bubbles



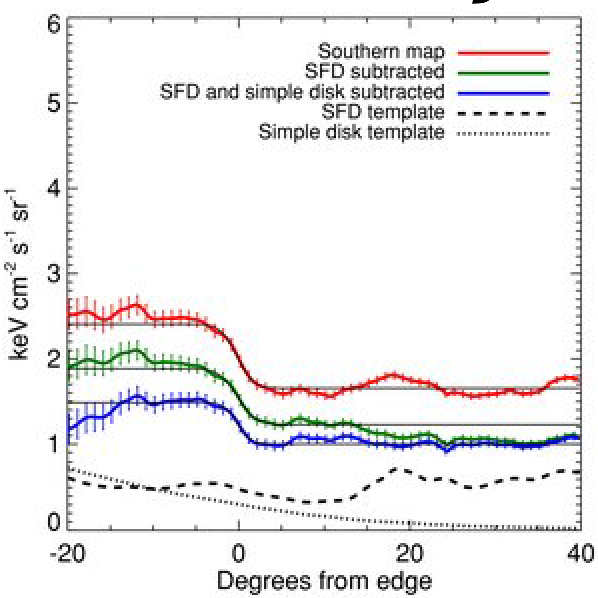
Emission from thin shell



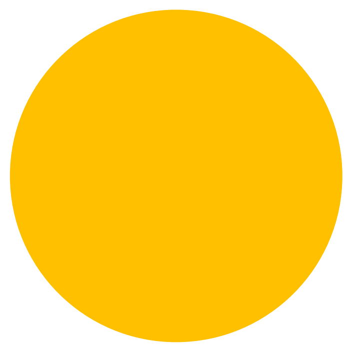
Surface brightness

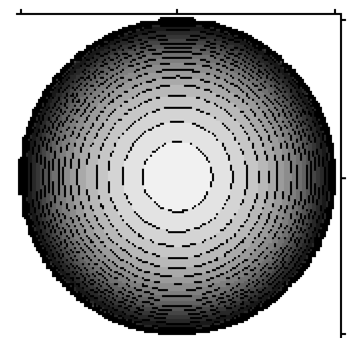
Limb Brightening

Uniform Surface brightness



Uniform Emissivity



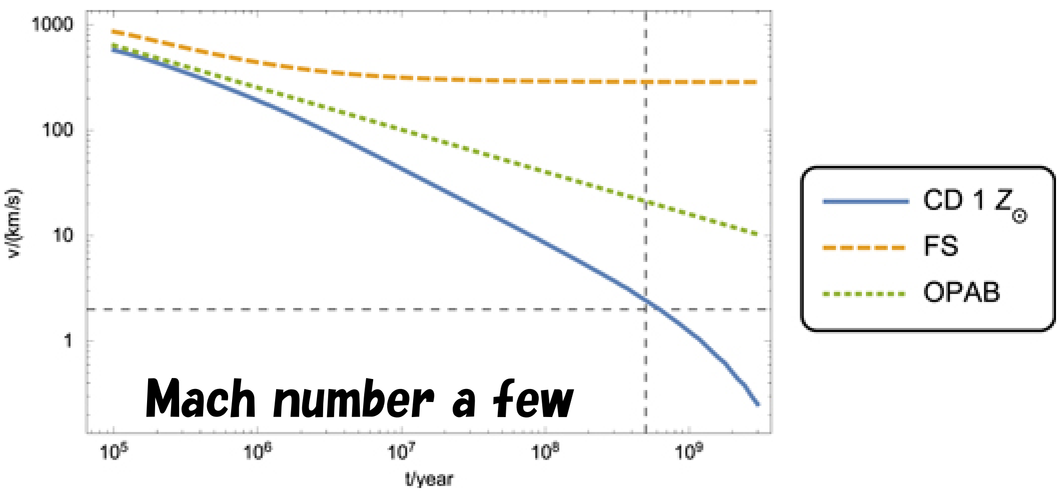


Center Brightening

indicates thick shell >> Electron cooling timescale × shock speed (90pc for TeV e)

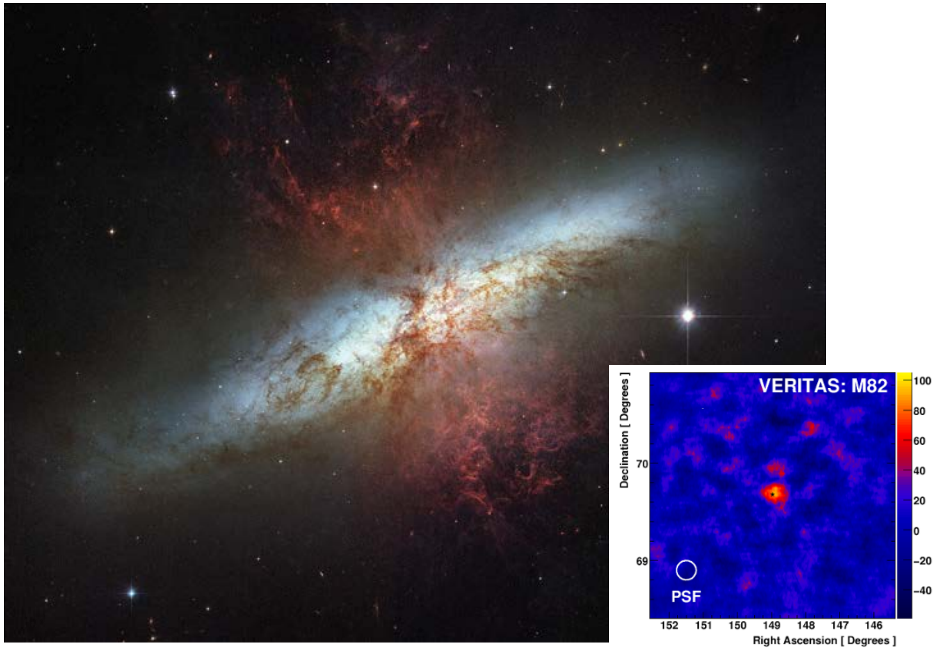
Hadronic?

Shock velocity (Crocker+ 2015)



$10^{40}\mathrm{erg\,s^{-1}} \rightarrow 3\times10^{55}\mathrm{erg}@10^{8}\mathrm{yr}$

M82 starburst galaxy ($L \sim 3\times10^{42}\mathrm{erg/s}$)

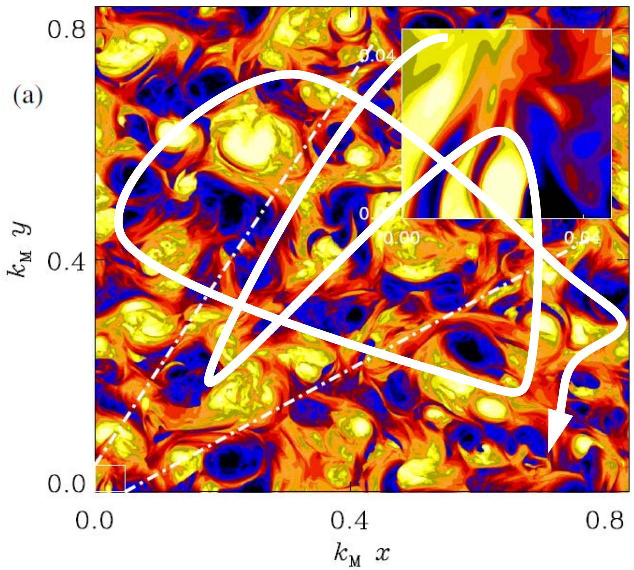


Hadronic model requires > 10^{57} erg.
(CRs in the Galactic Disk: ~6×10^{54} erg)

If the past GC activity deposited an energy > 10^{57} erg as the hadronic model implies, the structure may be more prominent as M82 shows. In a sense, the Fermi bubble is shabby or faint.

Weak shock + Thick Shell + Leptonic → continuous electron acceleration via turbulence

Alternative Model



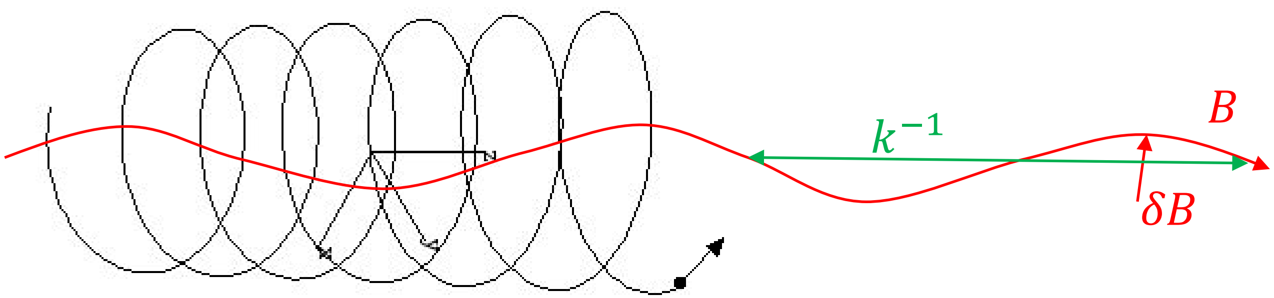
Continuous Acceleration by Scattering with Turbulence. (2nd Order Fermi Acceleration)

See e.g. Stawarz & Petrosian 2008

Energy gain per scattering

$$\frac{\Delta E}{E} \equiv \bar{\xi} \cong \frac{4}{3}\beta^2$$

Alfvenic Wave (transverse/incompressible)



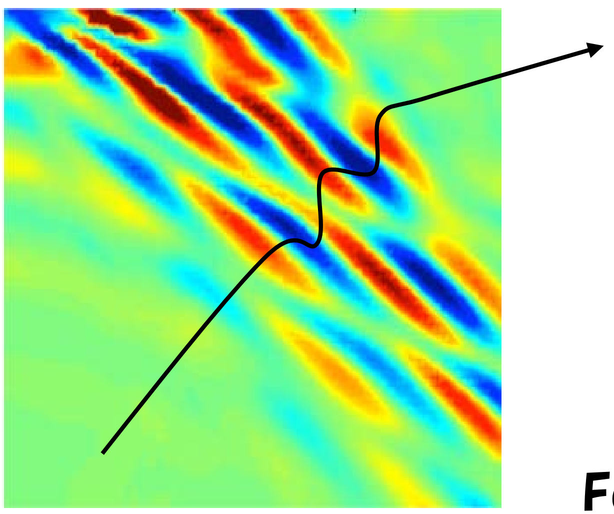
pitch angle diffusion → mean free path $l \sim \frac{B^2}{k\delta B^2(k)} r_L,\ \ k \sim 1/r_L$

resonance condition

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

Compressible wave

Acoustic Wave (longitudinal / compressible)



Mirror Force

$$\frac{\Delta p}{\Delta t} \sim \frac{p_\perp v_\perp}{2B} |\nabla B| \sim \frac{p_\perp v_\perp}{2B} k \delta B(k)$$

$$D_{EE} \sim \frac{c^2 < \Delta p^2 >}{\Delta t} \sim \frac{E^2 c^2}{8B^2} \int d^3 k k_\parallel^2 \delta B^2(k) \frac{1}{k_\parallel v_{\rm ph}}$$

For fast wave with a typical eddy size L

$$D_{EE} \sim E^2 \frac{v_{\rm ph}^2}{cL} \frac{\delta B_F^2}{B^2} \int_{k_{\rm min}}^{k_{\rm max}} d(Lk)(Lk)^{1-q} \sim E^2 \left(\frac{v_{\rm ph}}{c}\right)^2 \frac{c}{L} \propto E^2$$

$B^2 \sim \delta B_F^2$

$t_{\rm acc} \propto E^0$

(Hard sphere)

Ptuskin 1988; Cho & Lazarian 2006;
Yan & Lazarian 2008; Lynn et al. 2014

Focker-Planck Equation

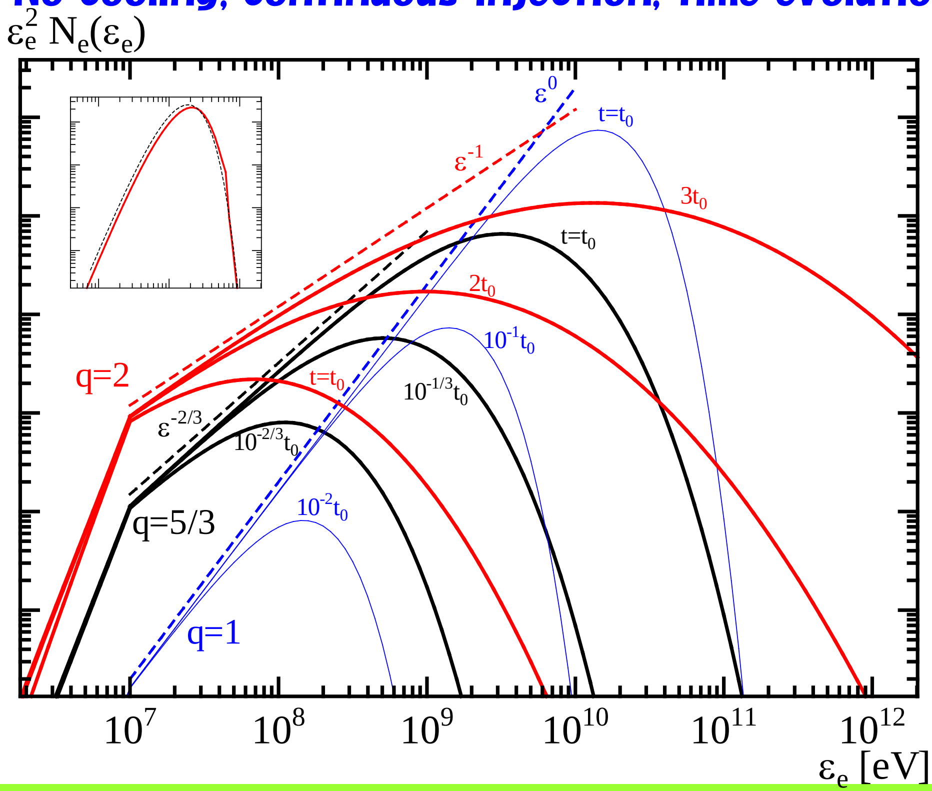
$D_{EE} = KE^q$ **Kolmogorov+Alfvenic q=5/3, Compressible q=2 (hard sphere)**

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

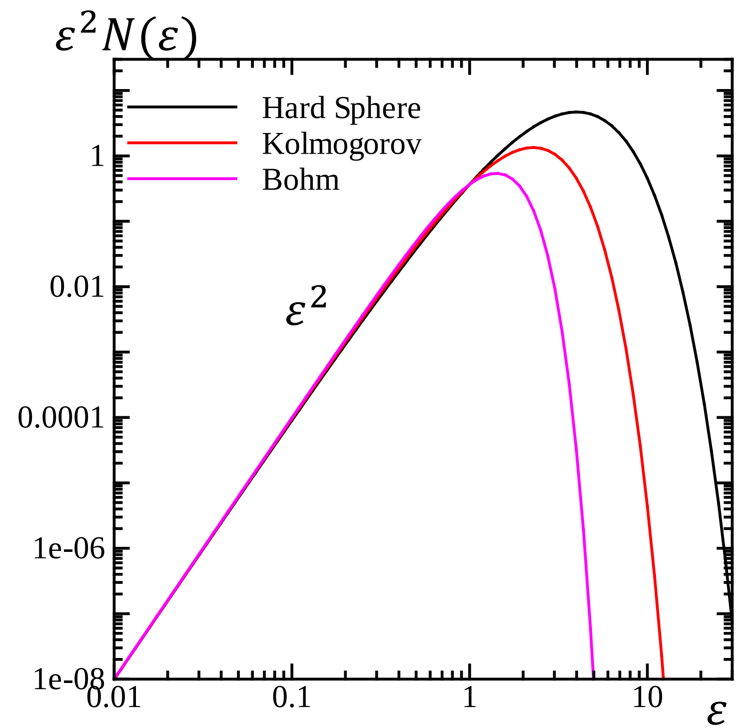
Diffusion **Acceleration** **Cooling** **Injection**

$N(\varepsilon) \propto \varepsilon^{-1 \text{ or } -\frac{2}{3} \text{ or } 2}$ **harder than the shock case** $N(\varepsilon) \propto \varepsilon^{-2}$

No cooling, continuous injection, time evolution



No injection, balance with cooling, steady

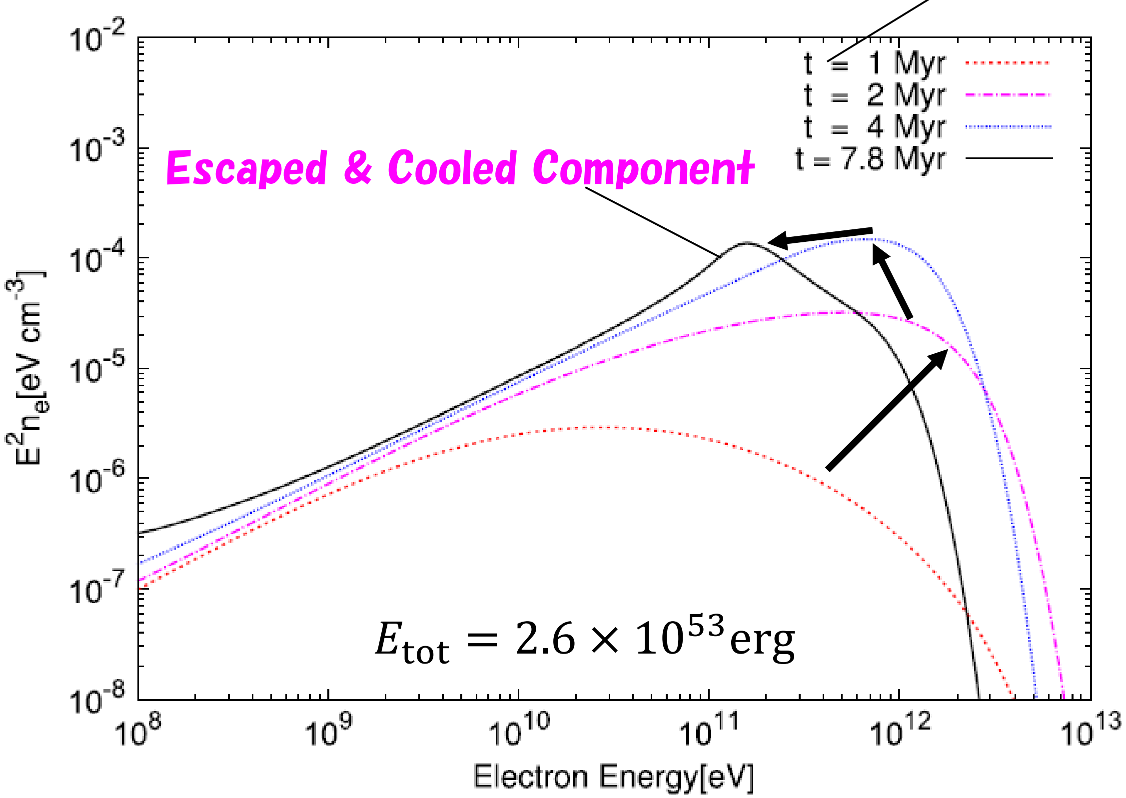


Fermi Bubble

Sasaki, Asano & Terasawa 2015

$q = 2$ **with escape effect from the disturbed region**

Evolution of Electron spectrum



Decaying turbulence

$$D(t) \equiv D_0 \left(1 + \frac{t}{t_0}\right)^{-\alpha}$$

Spatial diffusion coefficient

$$D_{xx}(t) \equiv \frac{c^2}{3D}$$

Growing escape efficiency

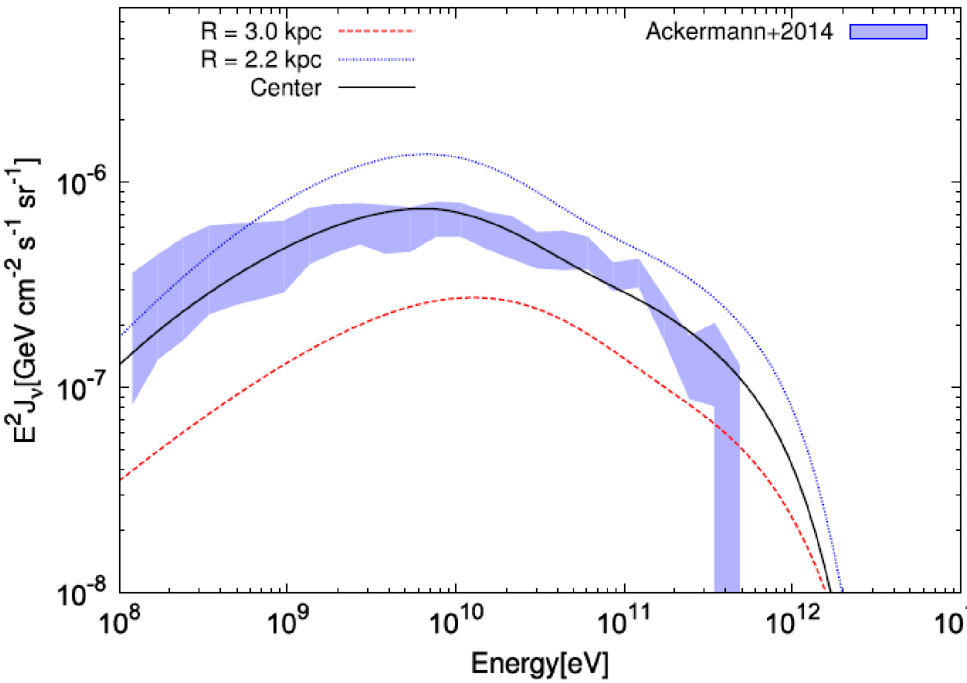
$$t_{\rm esc} \equiv L^2 / D_{xx}$$

L: Region size～180pc

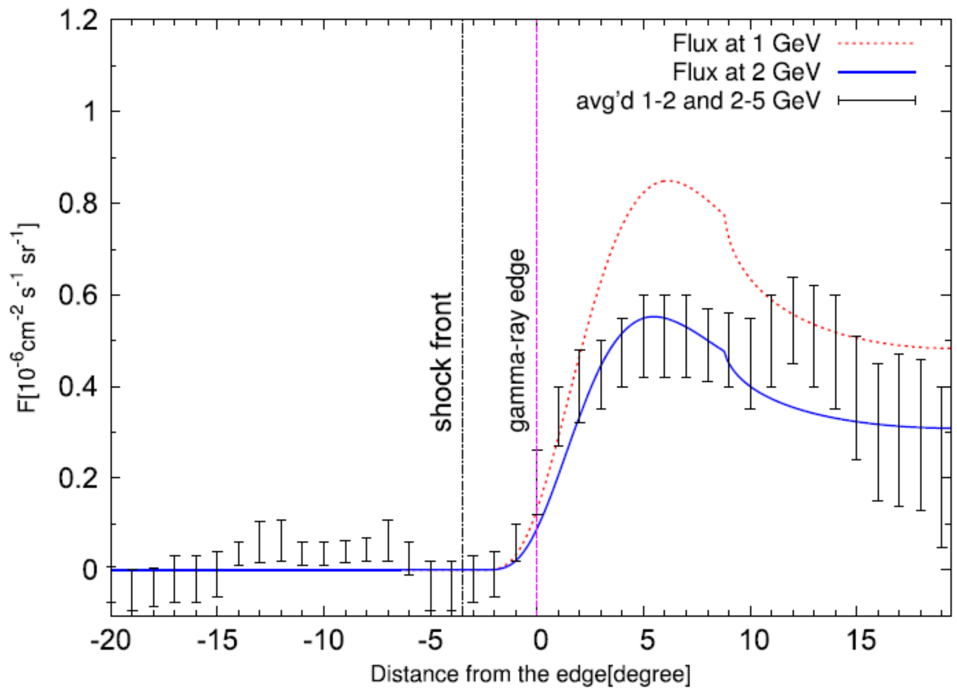
Slow process so the temporal evolution is essential.

Fermi bubble

Gamma-ray spectrum



Surface brightness

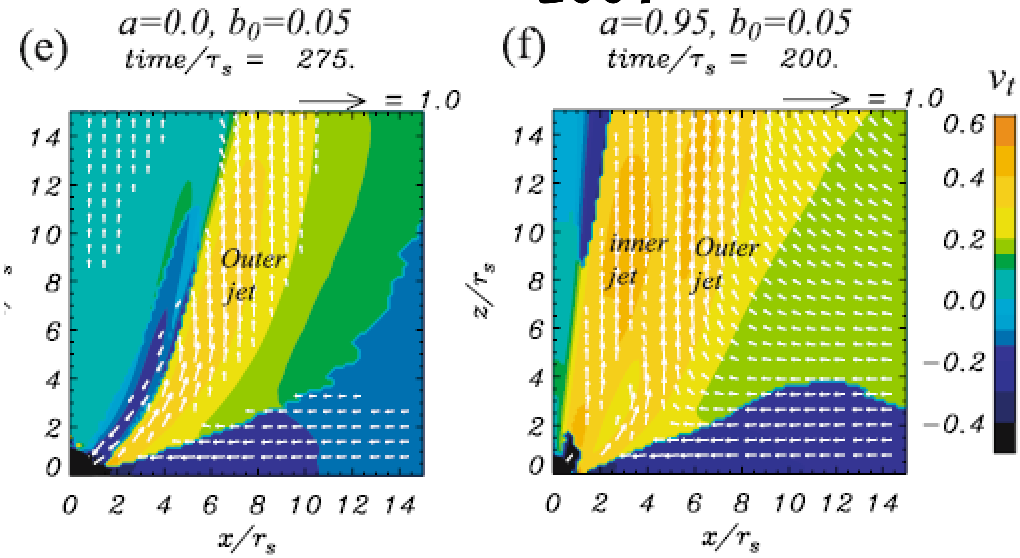


The spectrum and surface brightness are reproduced by the phenomenological stochastic acceleration model.

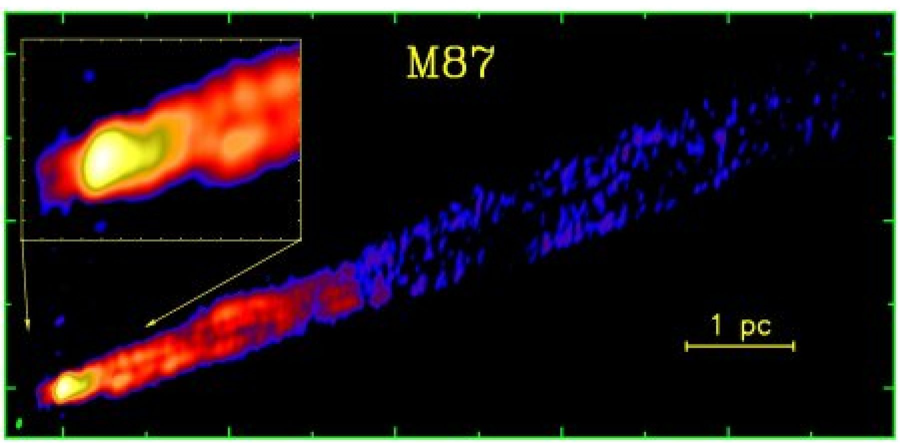
Turbulence in AGN jets

Spine-Sheath structure

Hardee+ 2007 MHD simulation

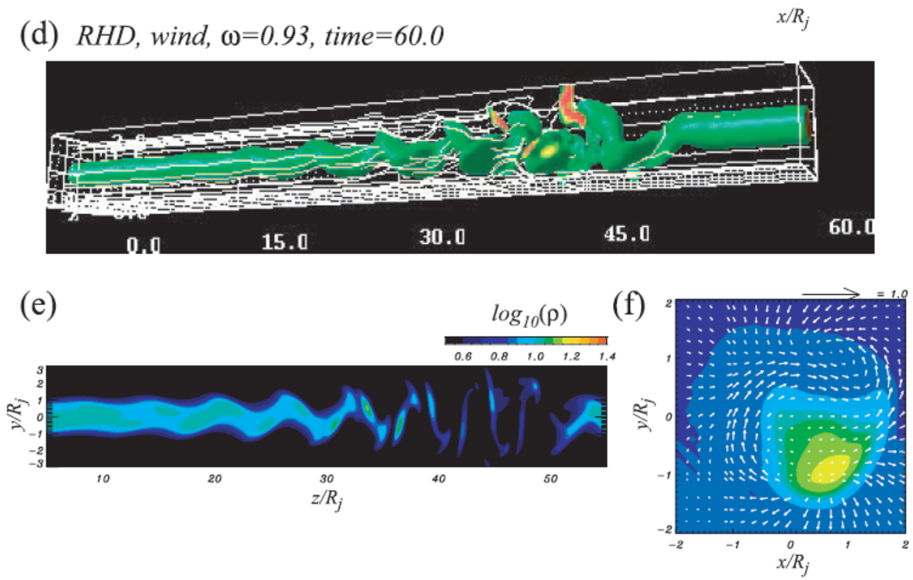


Double layer in M87 jet



Kelvin Helmholtz Instability

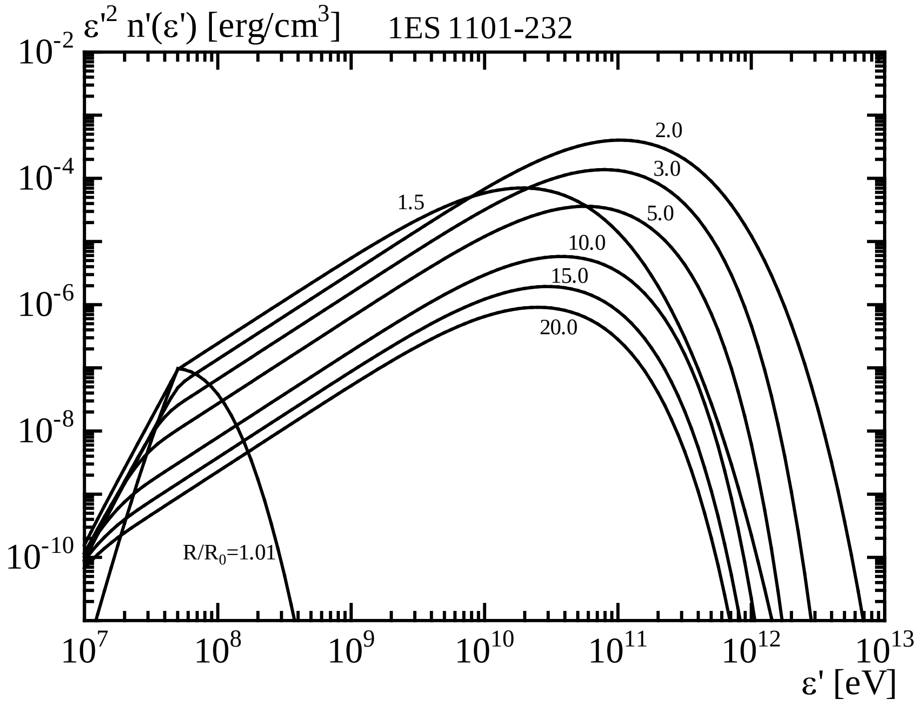
Mizuno+ 2007



Extreme Hard Blazar 1ES 1101-232

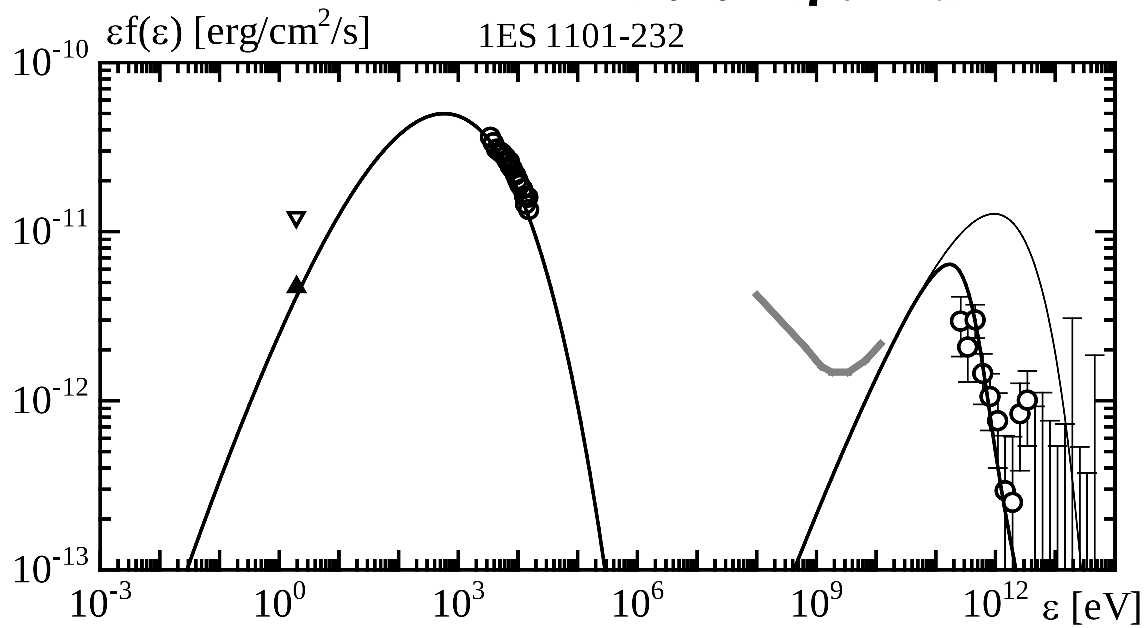
Asano+ 2014

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, $\Delta T'_{\mathrm{inj}} = W'/c$, $K = 4.3\times10^{-3}\ \mathrm{eV}^{1/3}\ \mathrm{s}^{-1}$, $\dot{N}_0 = 1.5\times10^{46}\ \mathrm{s}^{-1}$

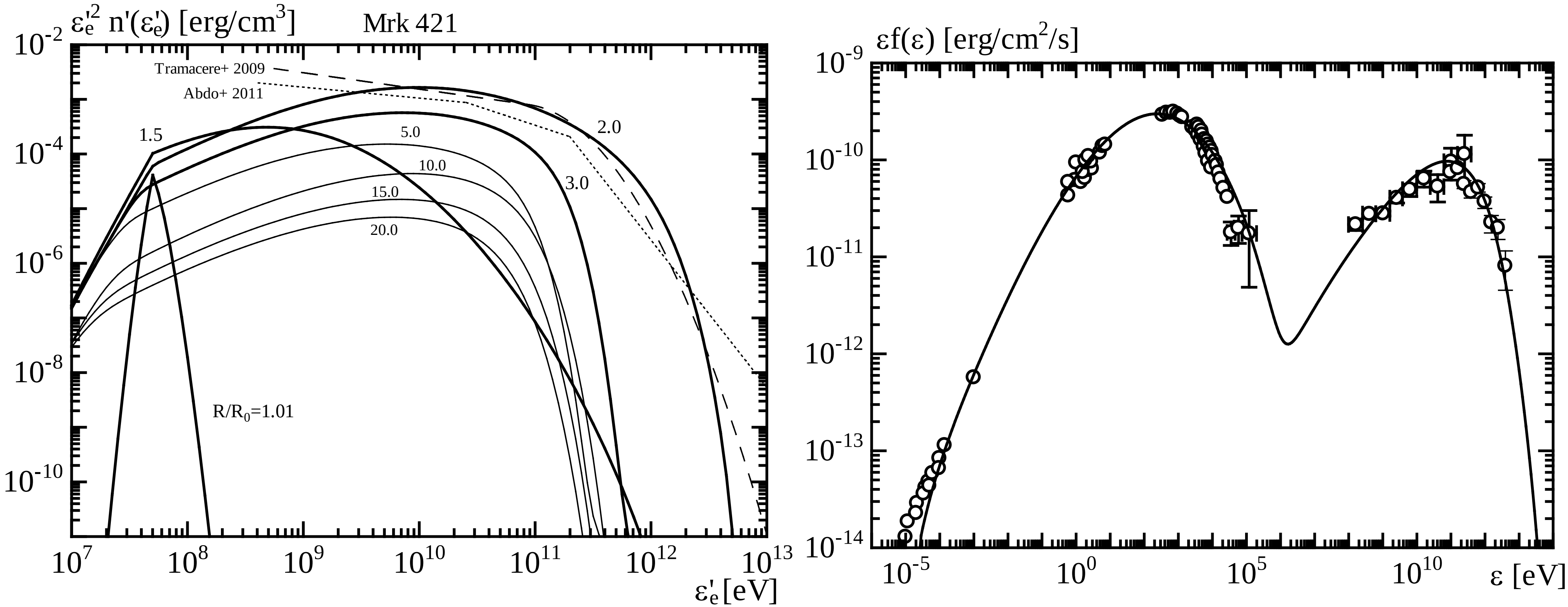
Kolmogorov value q=5/3

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.



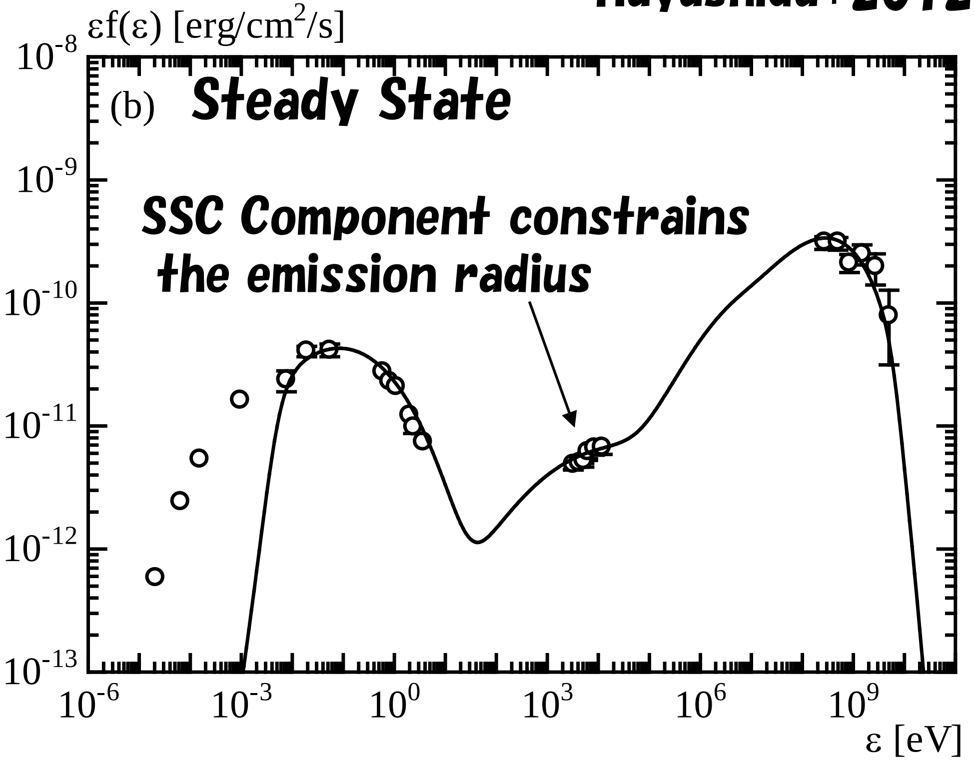
$$\Gamma = 15, B_0 = 0.16\mathrm{G}, W' = \frac{R_0}{\Gamma} = 10^{16}\mathrm{cm}, \Delta T'_{inj} = \frac{W'}{c}, K = 3.7 \times 10^{-6}\mathrm{s}^{-1}, \dot{N} = 9.8 \times 10^{46}\mathrm{s}^{-1}$$

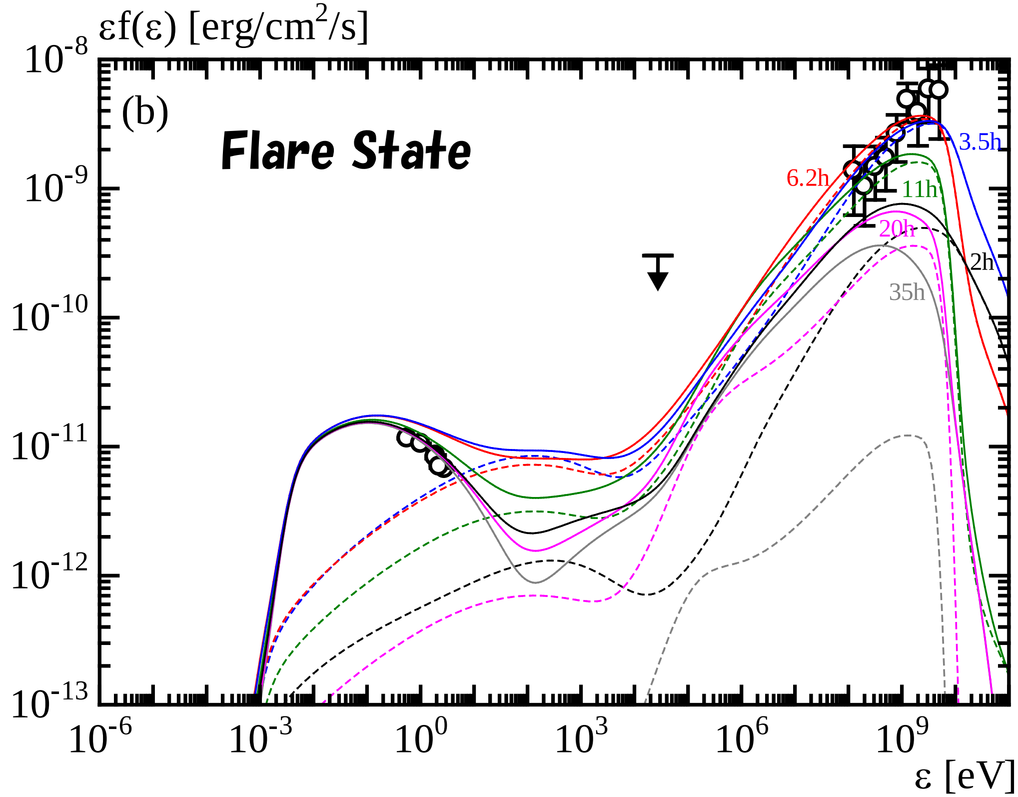
See also Kakuwa+ 2015

FSRQ 3C 279

Asano & Hayashida 2015
Hayashida+2012

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





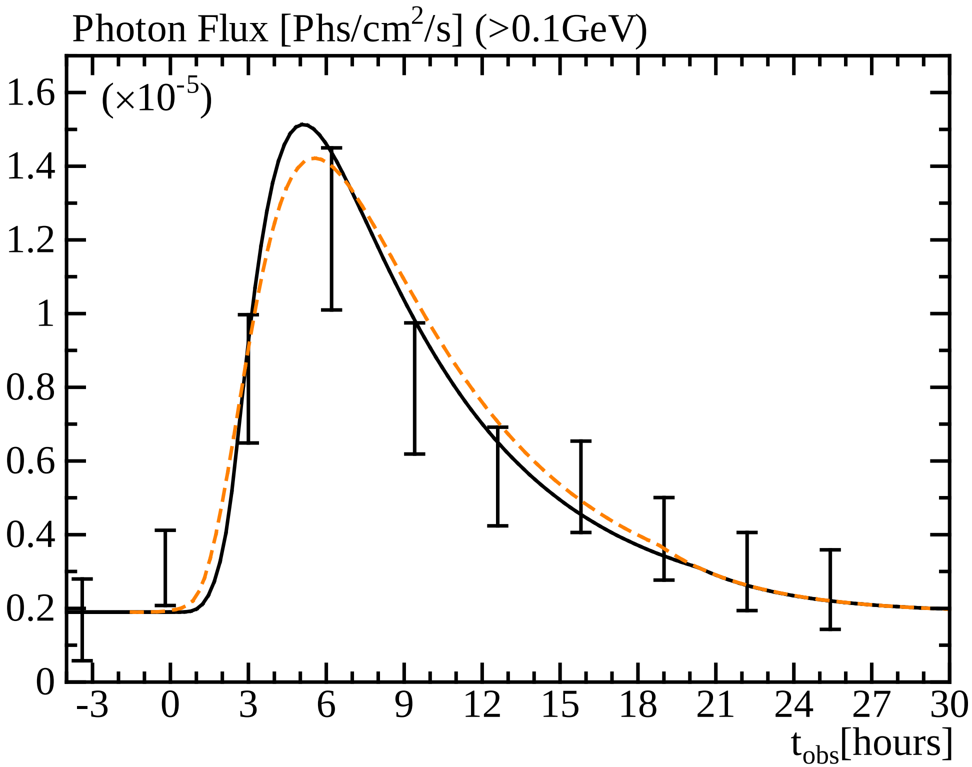
$q = 2$

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

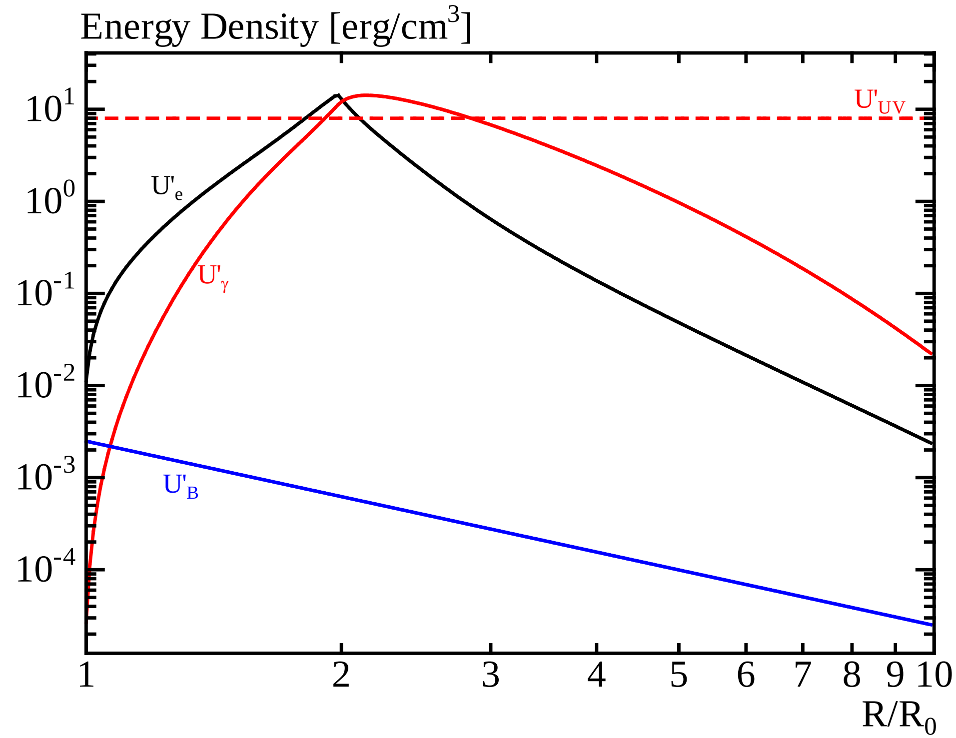
$K' = 1.3 \times 10^{-5}\ {\rm s^{-1}}$ ($t_{\rm acc} = 1/(2K') = 0.25W'/c$),
$\dot{N}'_{\rm e} = 2.5 \times 10^{50}\ {\rm s^{-1}}$ ($\dot{n}'_{\rm e} = 0.85(R/R_0)^{-2}\ {\rm cm^{-3}\ s^{-1}}$),
$B_0 = 0.25$ G.

3C 279 Flare

Lightcurve

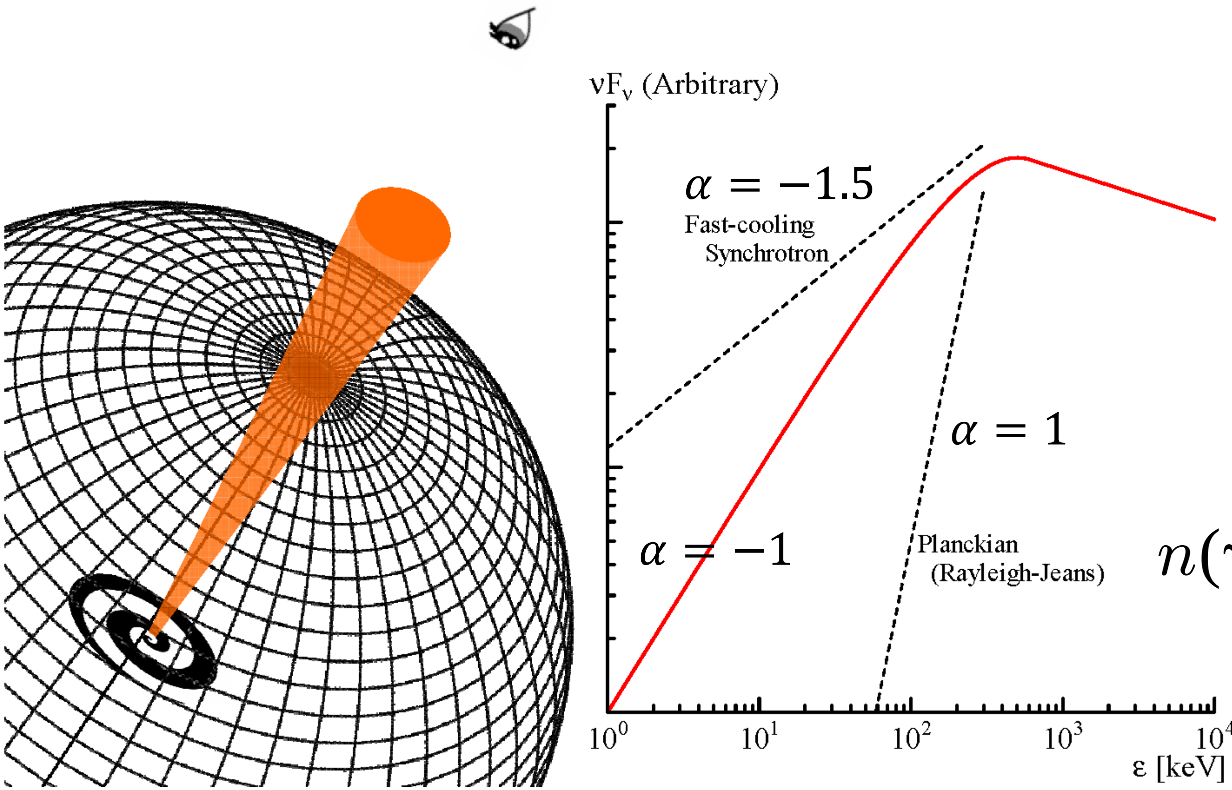


Evolution of energy density

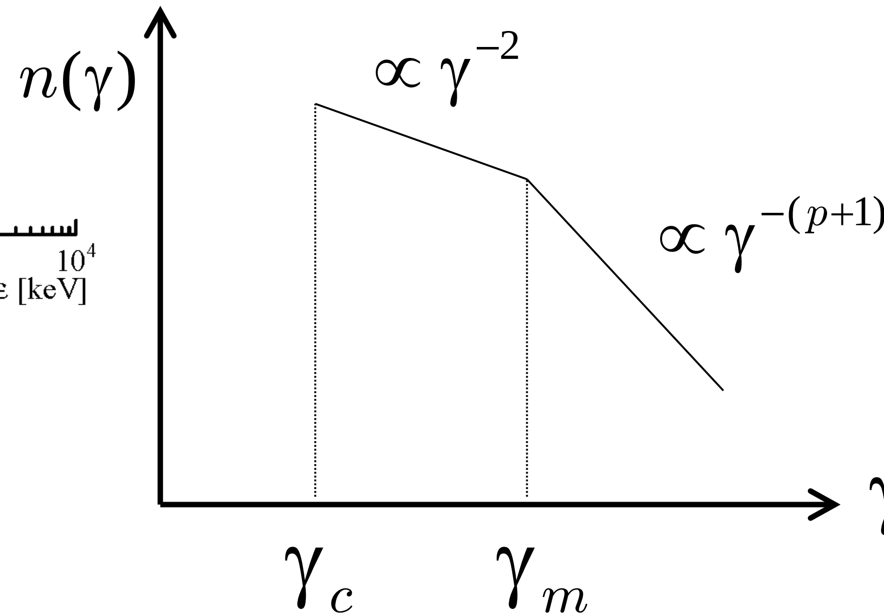


Weak magnetic field:
Acoustic waves rather than Reconnection

Gamma Ray Burst



- **Power-law injection with a minimum energy leads to an electron spectrum below.**
- **The index for cooled electrons becomes 2, then photons index should be 1.5.**



Softer than the thermal spectrum, but harder than the synchrotron spectrum.

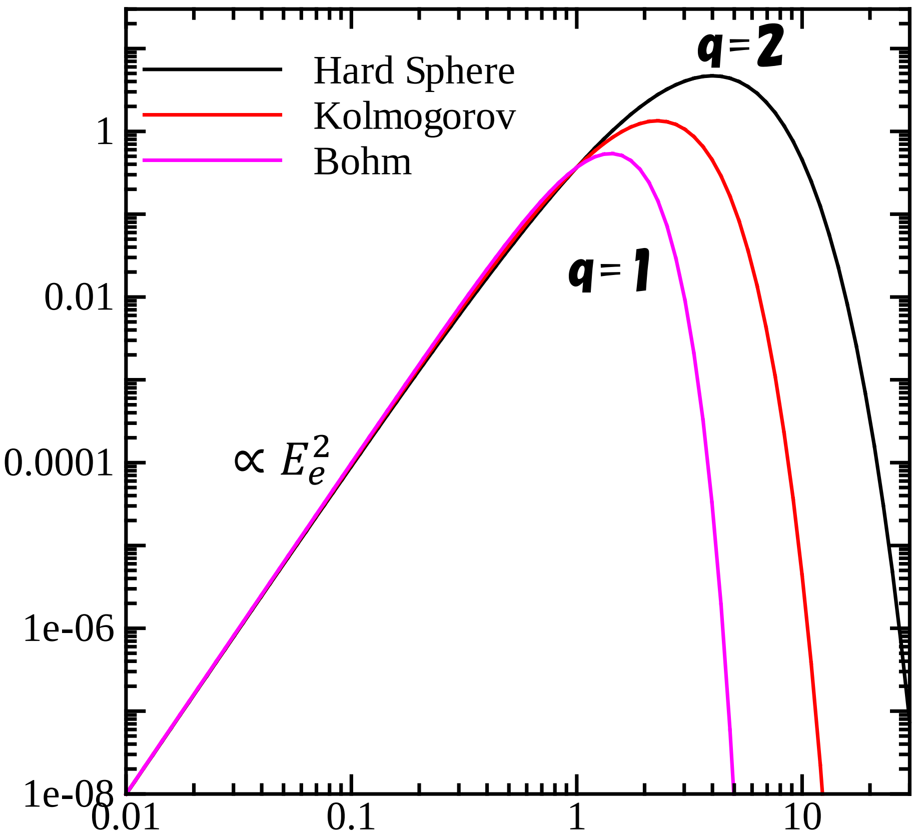
See Daigne, Bosnjak, Dubus 2011

Balance between Acceleration and Cooling

Magnetic Field is so strong that balance with acceleration.

Analytic Steady Solution for Electrons

$$D(\varepsilon) = \frac{\bar{\xi}\pi e c \varepsilon k \delta B_k^2}{8B} \equiv K\varepsilon^q.$$

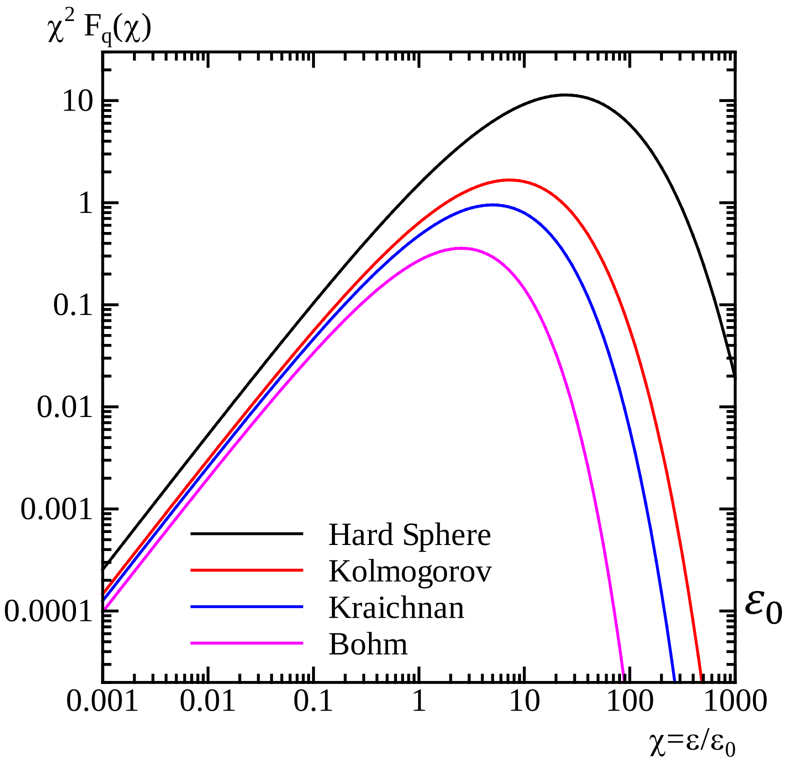


$$N(E_e) = \frac{3N_{tot}}{\Gamma\left(\frac{6-q}{3-q}\right)E_{pk}}\left(\frac{E_e}{E_{pk}}\right)^2 \exp\left[-\left(\frac{E_e}{E_{pk}}\right)^{3-q}\right],$$

$$E_{pk} = \left(\frac{6\pi(3-q)K_0 m_e^2 c^3}{\sigma_T B^2}\right)^{1/(3-q)}.$$

See Lefa+ 2011

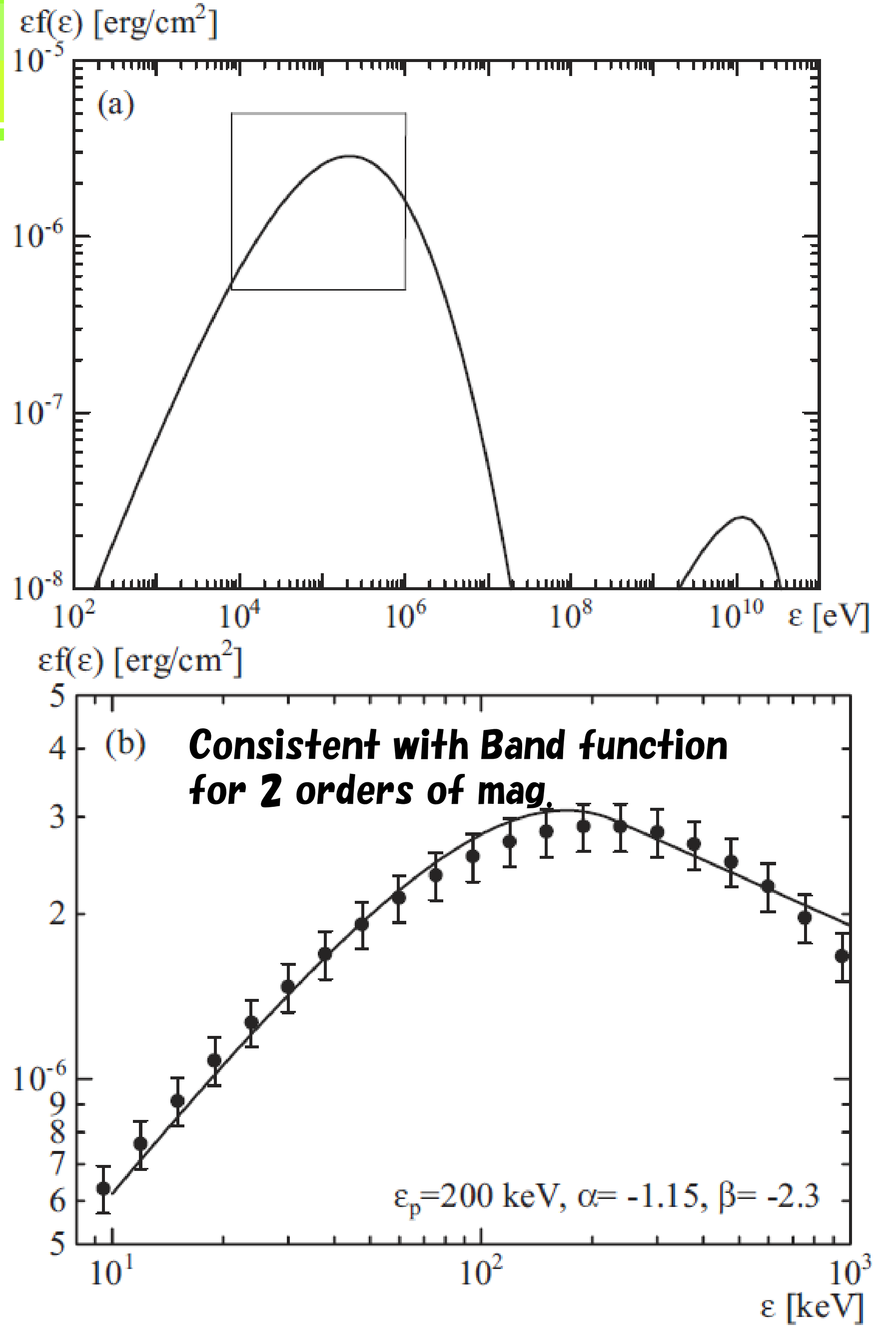
Synchrotron Photon



$$\varepsilon_0 = \frac{3\pi\hbar eB}{m_e c}\gamma_{\rm pk}^2$$

$$\varepsilon_{\rm p} = 1.0\left(\frac{\Gamma}{500}\right)\left(\frac{K_0}{10^2\ {\rm s}^{-1}}\right)^2\left(\frac{B}{10^4\ {\rm G}}\right)^{-3}\ {\rm MeV}, \quad {\rm for}\ q = 2,$$

$$l_{\rm edd} \sim ct_{\rm acc}\beta_{\rm eff}^2 \sim 3\times10^7(t_{\rm acc}/10^{-2}\ {\rm s})(\beta_{\rm eff}^2/0.1)\ {\rm cm}$$



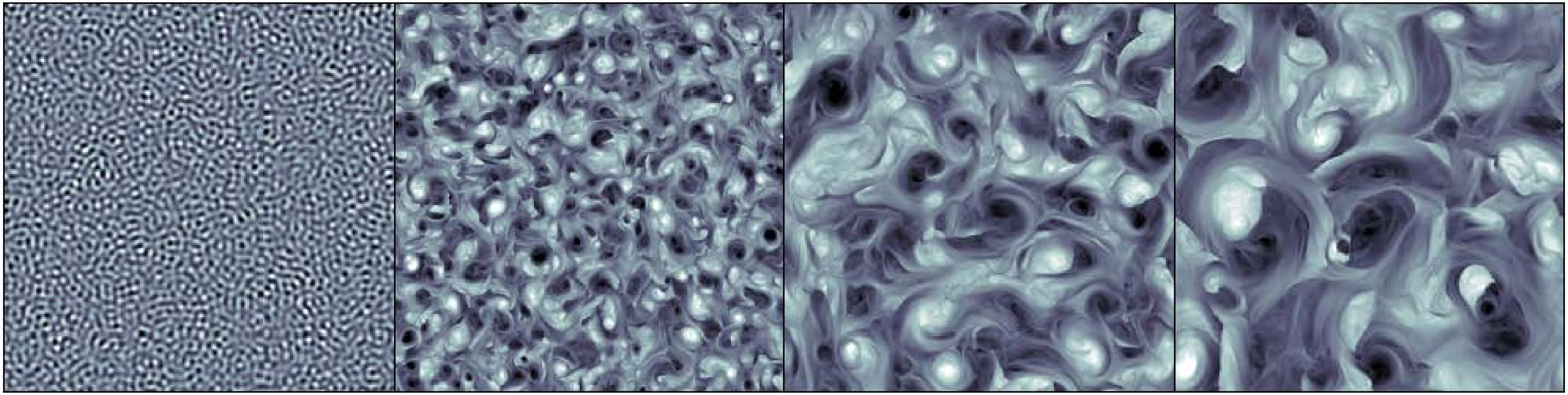
Numerical Simulation in Asano & Terasawa 2009

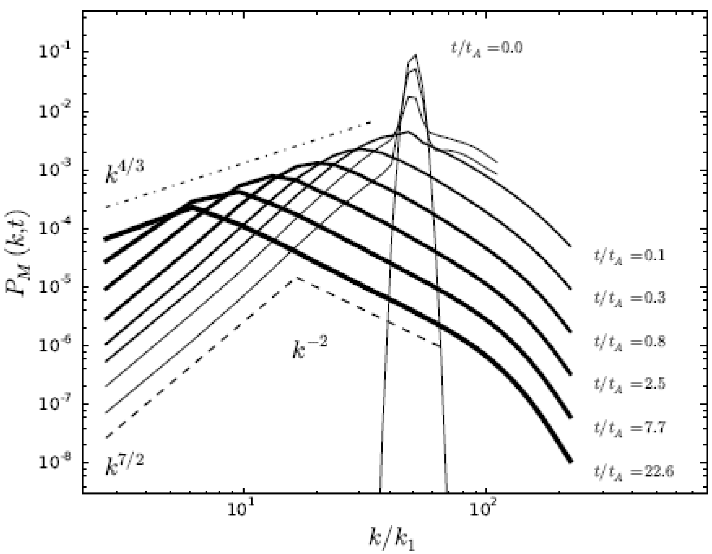
Decaying Turbulence

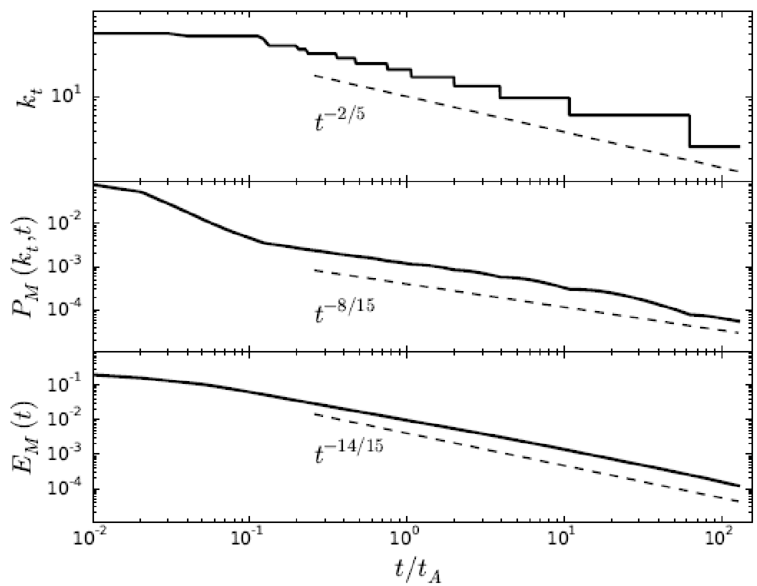
Zrake 2014

INVERSE CASCADE OF NON-HELICAL MAGNETIC TURBULENCE IN A RELATIVISTIC FLUID

JONATHAN ZRAKE







Temporal Evolution of the Spectrum

$$N_\gamma(\varepsilon') = \int dt \dot{N}_\gamma(\varepsilon')$$
$$= \frac{\sqrt{3}e^2 m_e^2 c^3}{\pi \Gamma\left(\frac{6-q}{3-q}\right)\hbar^2} \int dt \frac{N_{\rm tot}}{E_{\rm pk}^2} F_q\left(\frac{\varepsilon'}{\varepsilon'_0}\right)$$

Electron Number: Increase with injection

Electron peak energy: Decay as the efficiency of acceleration/cooling drops.

The temporal evolutions of two combinations determine the final photon spectrum

$$N_{\rm tot}/E_{\rm pk}^2 \propto (t+t_0)^a \text{ and } \varepsilon'_0 \propto B E_{\rm pk}^2 \propto (t+t_0)^{-b}$$

High-energy photon index

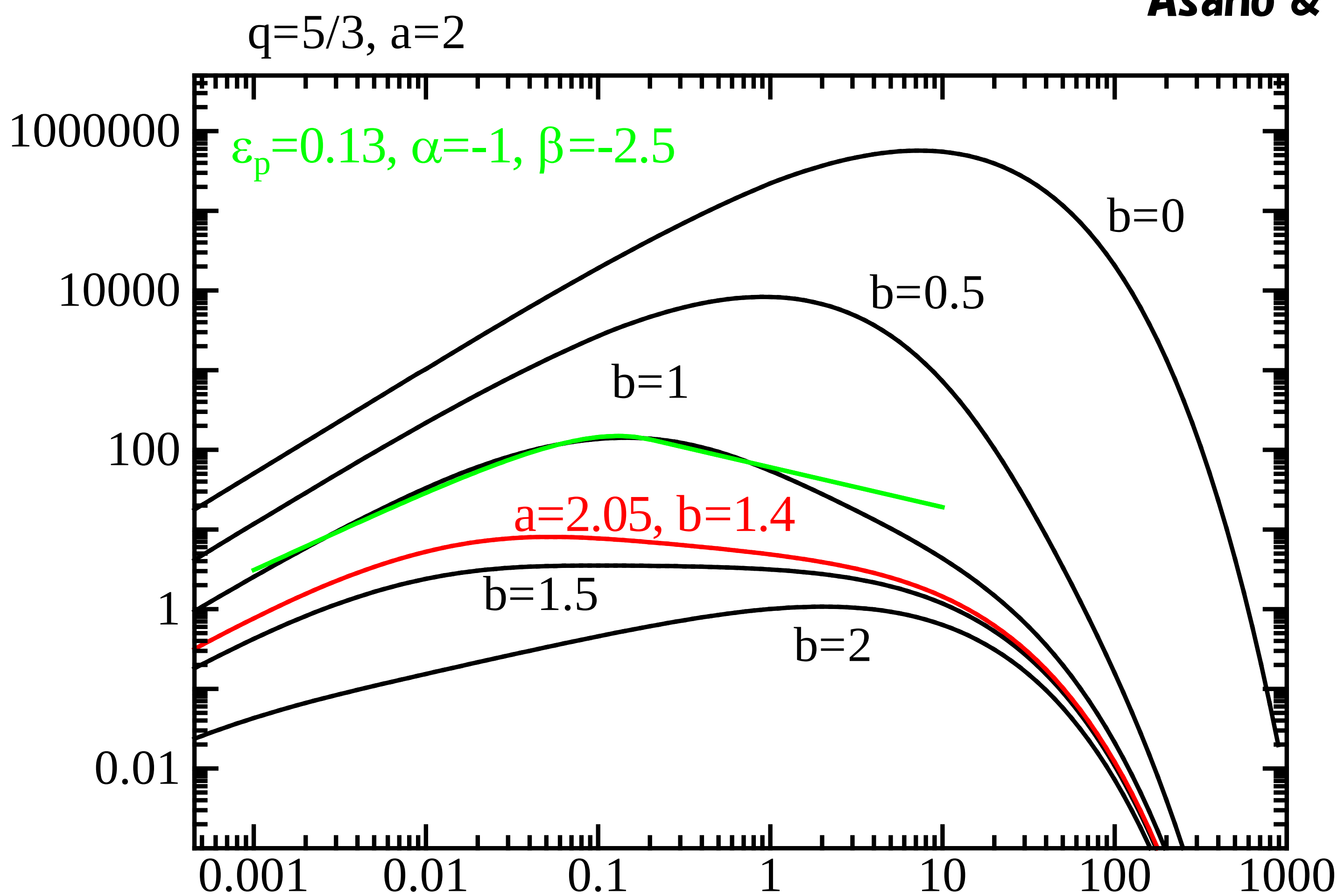
$$\beta = -(1+a)/b$$

Note

$$E_{\rm pk} = \left(\frac{6\pi(3-q)K_0 m_e^2 c^3}{\sigma_{\rm T} B^2}\right)^{1/(3-q)}.$$

Band-like Spectra

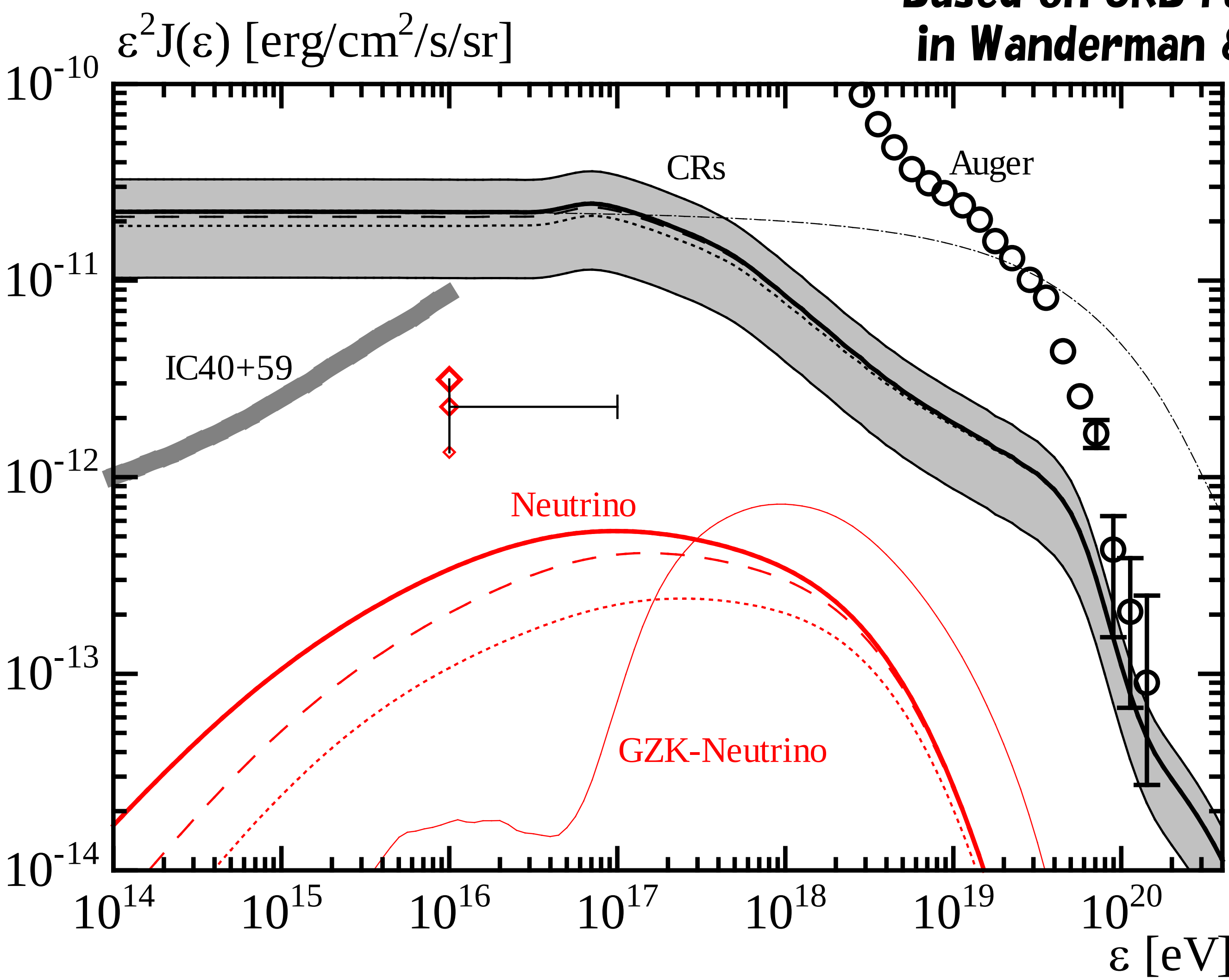
Asano & Tersawa 2015



The required indices and MHD simulations seem to be reasonable.

Ultra High-Energy Cosmic Ray from GRBs

Based on GRB rate & Luminosity function in Wanderman & Piran 2010.



Assuming E^{-2}-spectrum,

$$\frac{L_p}{L_\gamma} = 10, \frac{L_B}{L_\gamma} = 0.1$$

In this shock acceleration model, only the highest energy region is explained.

Asano & Meszaros 2014

Summary

- The stochastic acceleration is a slow process, but enough to explain the Fermi bubble.
- In relativistic jets (AGN, GRB…), the acceleration timescale can be comparable to the shock acceleration.
- The curved spectra in blazars are reproduced by the stochastic acceleration model with the temporal evolution effect.
- The problem in the GRB spectra is solved by the balance between the acceleration and cooling with decaying turbulence.
- The hard spectrum in this GRB model is favorable to agree with the UHECR flux.