Collisionless Shocks as Particle Accelerator in the Universe

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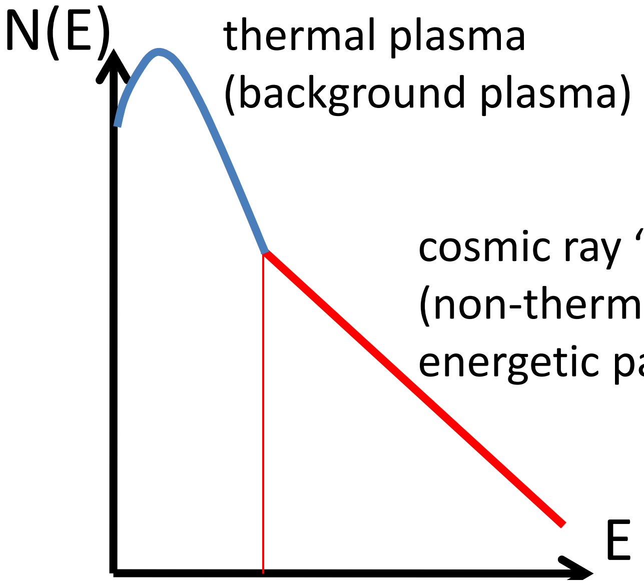
Diffusion Convection Equation



Two fluid approach:

(1) cosmic ray "fluid" : n, u, p
(2) background plasma: ρ, V, P

$$nm\left(\frac{\partial}{\partial t}\vec{u} + (\vec{u}\cdot\nabla)\vec{u}\right) = -\nabla p + \vec{F} + \frac{nm}{\tau}(\vec{V} - \vec{u}) \qquad (1)$$

F represents for electromagnetic force E, B or gravity.
τ is "friction term" due to collsion between background plasma & cosmic ray via Alfven wave.

$nm \rightarrow 0$, neglect inertia term for cosmic ray in Eq.(1)

$$-\nabla p + \frac{nm}{\tau}(\vec{V} - \vec{u}) = 0 \qquad (2)$$

$$p = \frac{1}{3} n m c^2 \qquad (3)$$

c is the "thermal velocity" for cosmic ray.

$$n\vec{u} = n\vec{V} - \kappa \nabla n \qquad (4)$$

where $\kappa \equiv \frac{\tau}{3} c^2 = \frac{\lambda c}{3}$

κ : diffusion coefficient

λ : mean free path

If $\kappa \to 0$, then $\vec{u} = \vec{V}$

(background plasma & cosmic ray are frozen-in.)

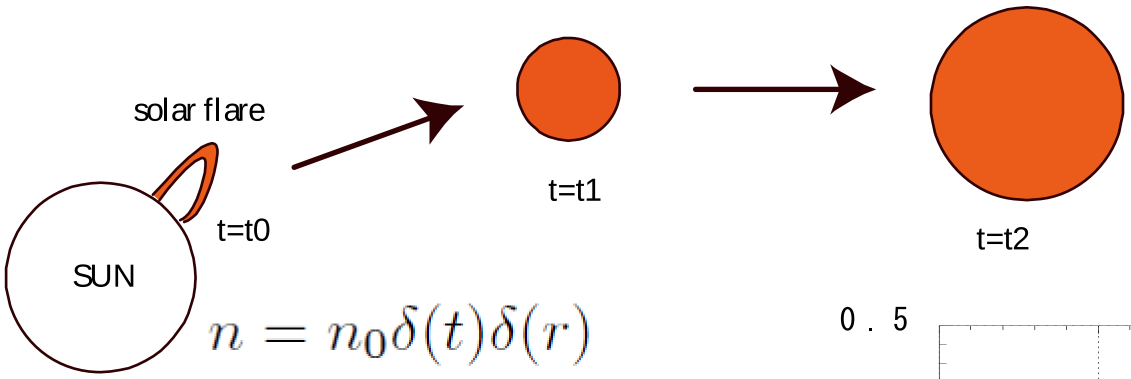
$$\frac{\partial}{\partial t} n + \nabla \cdot (n\vec{u}) = 0 \qquad (5)$$

$$\frac{\partial}{\partial t} n + \nabla \cdot (n\vec{V}) = \nabla \cdot (\kappa \nabla n) \qquad (6)$$

If BG plasma (V) is given, cosmic ray behavior (n) can be obtained.

Diffusion Convection Eq for *n* (cosmic ray)

Impulsive Release of Solar Energetic Particle (SEP)

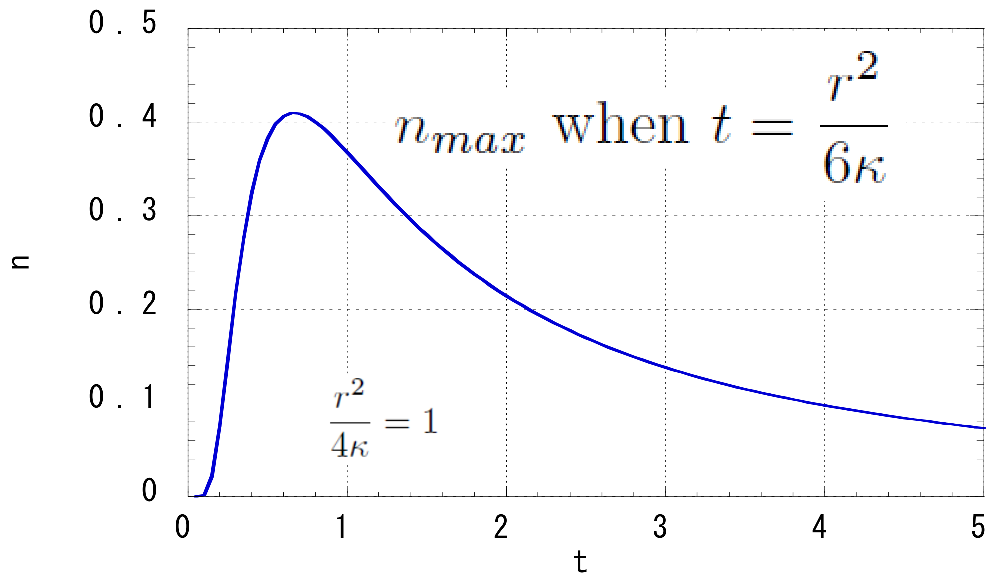


$$n = n_0 \delta(t) \delta(r)$$

$$\vec{V} \simeq 0$$

(neglect solar wind velocity)

$$\begin{aligned} \frac{\partial}{\partial t} n &= \nabla \cdot (\kappa \nabla n) \\ &= \frac{1}{r^2} \frac{\partial}{\partial r} \left(\kappa r^2 \frac{\partial}{\partial r} n \right) \end{aligned}$$



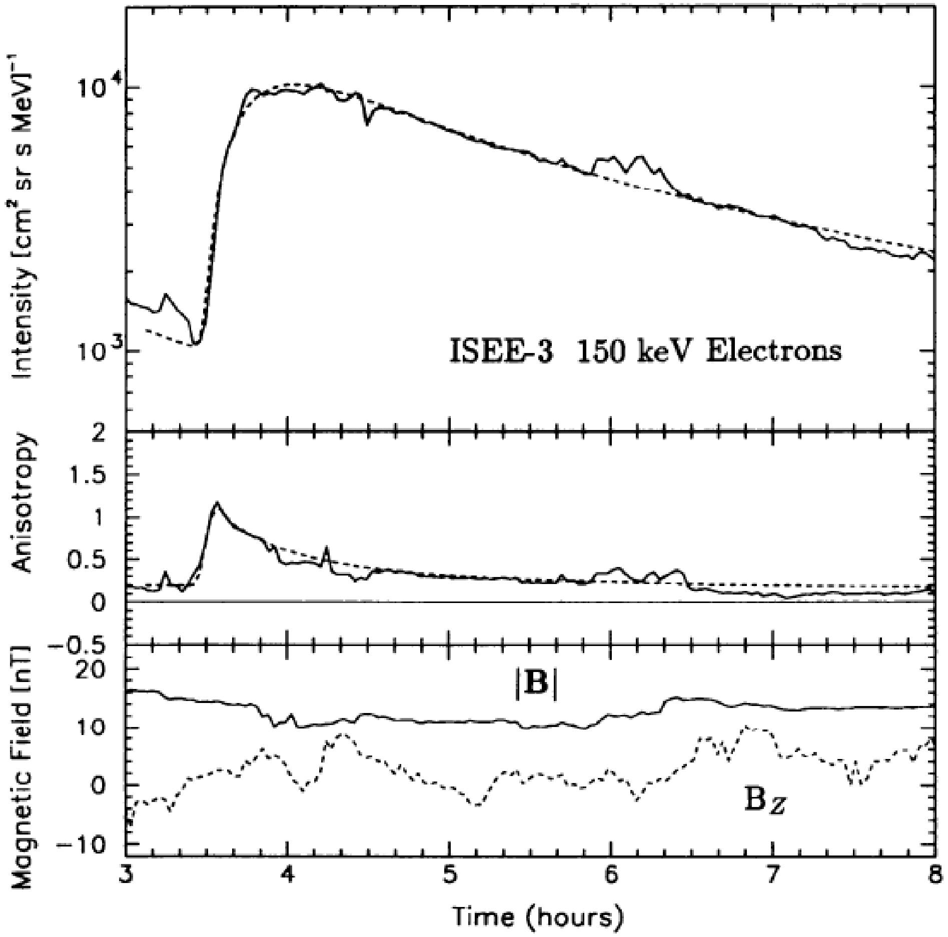
$$n = \frac{n_0}{2\pi^{1/2} t^{3/2}} \exp\left(-\frac{r^2}{4\kappa t} \right)$$

Observation of SEP at 1 AU

$t_{max} \sim 1$ hour
at $r = 1$ AU$=1.5 \times 10^{13}$ cm

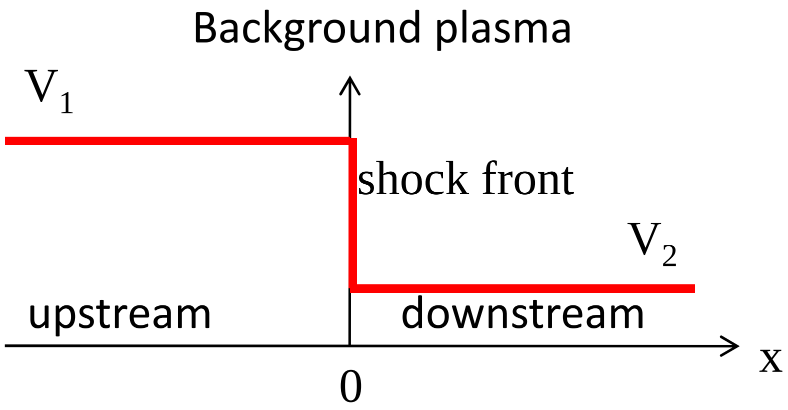
$\kappa = r^2/6t_{max} \simeq 10^{22}\text{cm}^2/\text{s}$
$\lambda = 3\kappa/c \simeq 10^{12}\text{cm}$

Anisotropy $\dfrac{u}{c} = \dfrac{r}{2tc} \propto \dfrac{1}{t},$

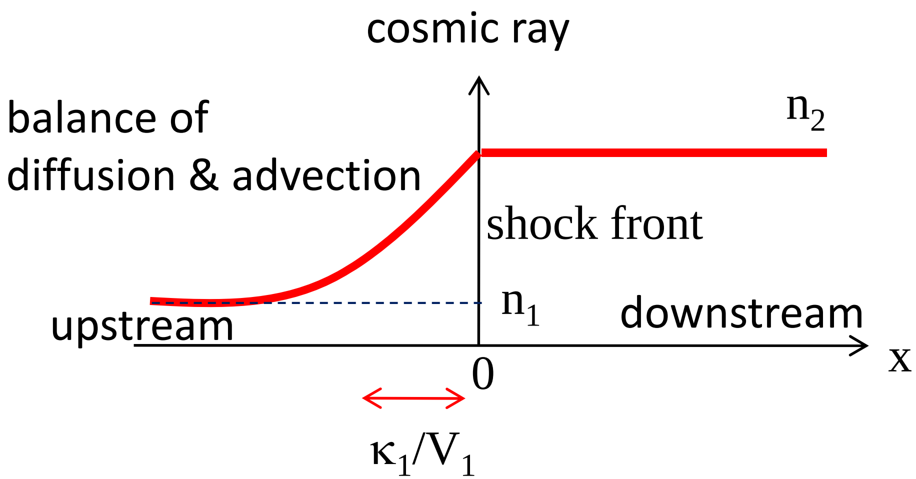


Droege, ApJ (1994)

Cosmic Ray around Shock



(shock front of BG plasma is thin)



(n, u are continuous)

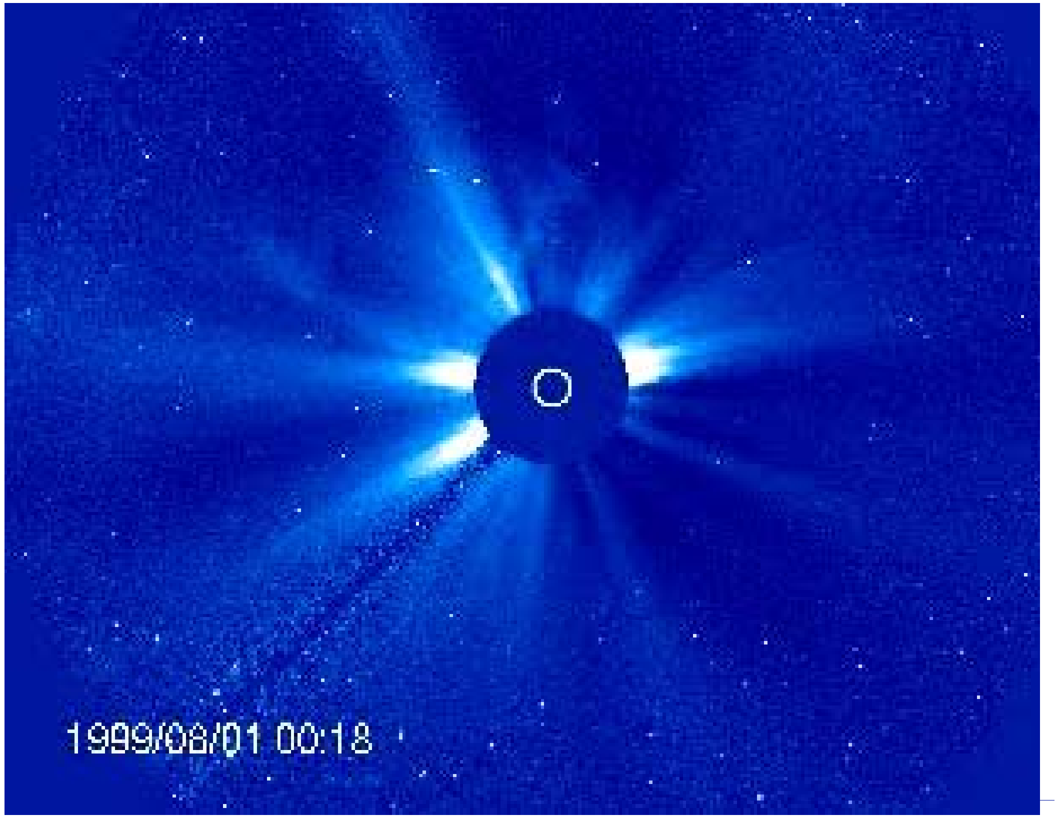
$$nV - \kappa \frac{\partial}{\partial x} n = n_1 V_1 = const.$$

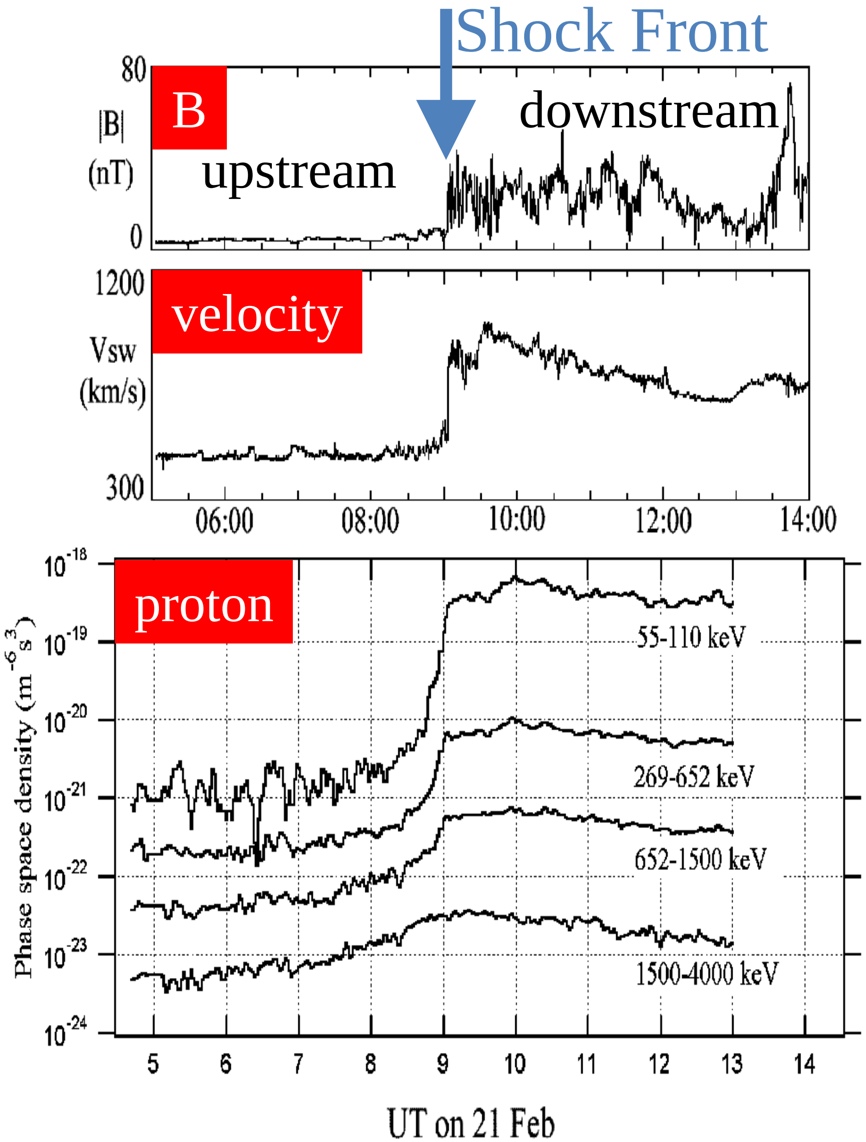
$$\begin{aligned} x &\to -\infty, \quad n = n_1, \; V = V_1 \\ x &\to \infty, \quad n = n_2, \; V = V_2 \end{aligned}$$

$$n = \begin{cases} (n_2 - n_1) \exp\left(\frac{V_1}{\kappa_1} x\right) + n_1 & x < 0 \\ n_2 & x \geq 0 \end{cases}$$

Interplanetary Shock in Heliosphere

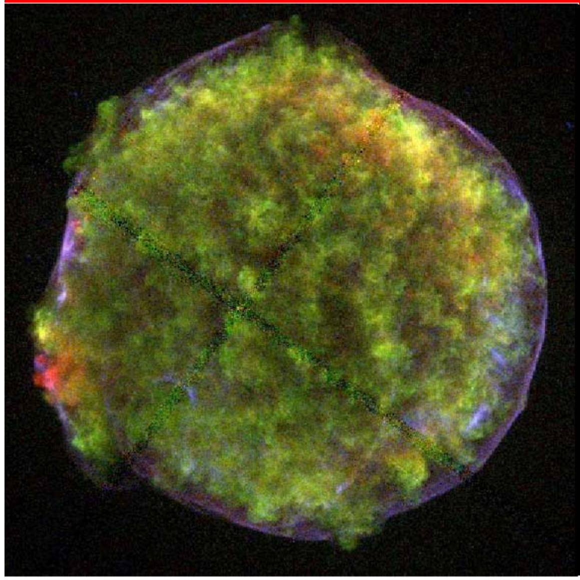
(Solar Flare-Initiated Shock)



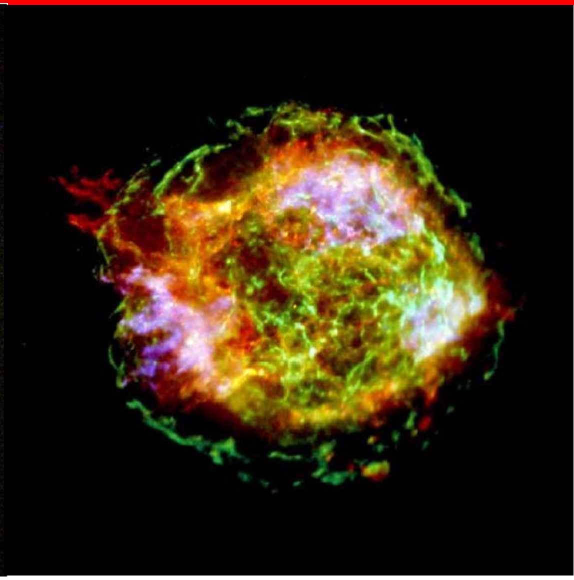


Shimada et al. ASS (1999)

Shock in Supernova Remnant (SNR)



Tycho (1752)

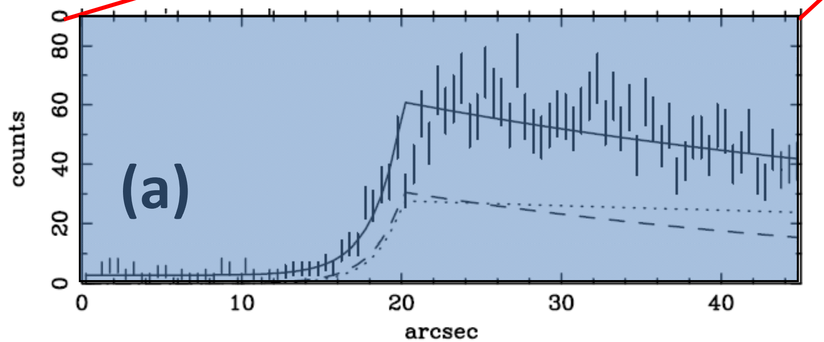


Cas A (1680)

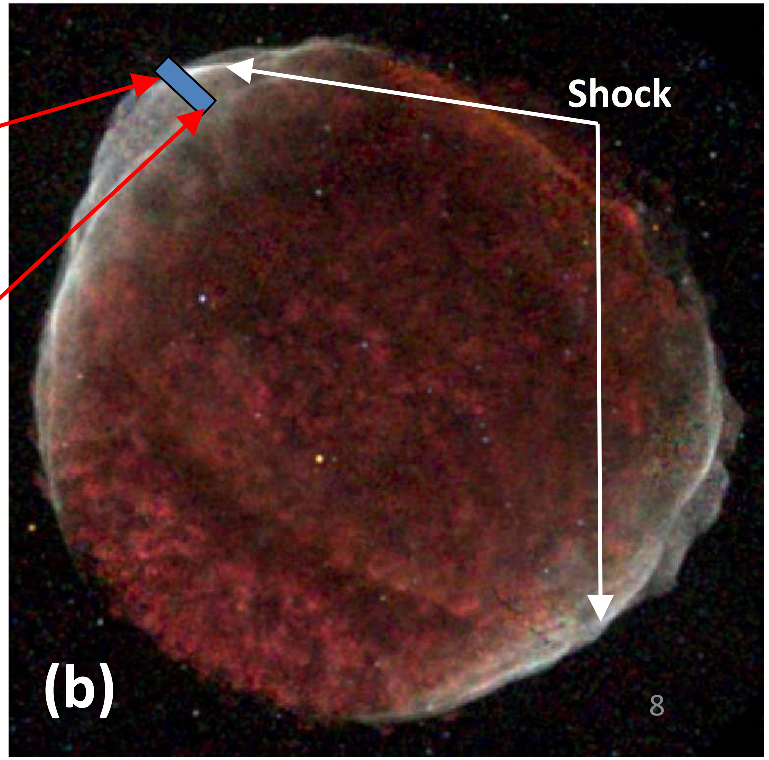
Bamba et al. (2003)

SN1006

shock width＝
electron gyro-radius of 10 TeV

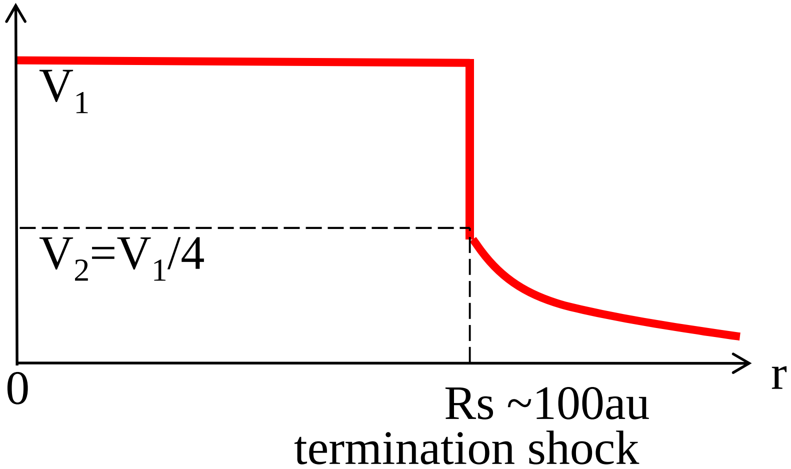


upstream downstream

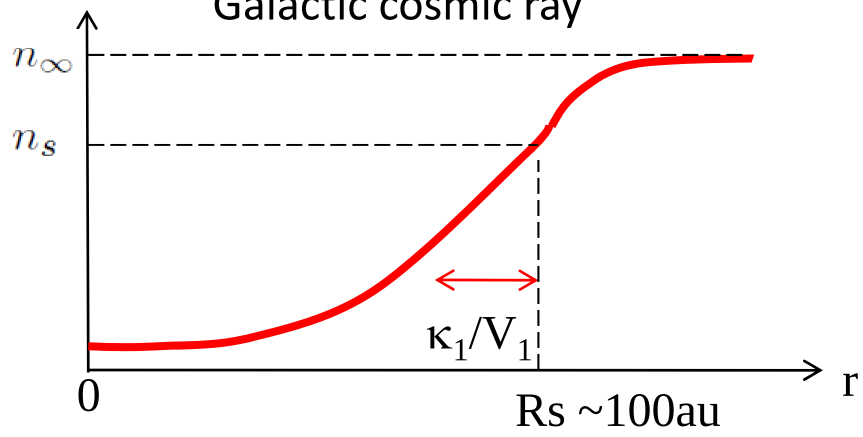


Cosmic Ray Modulation

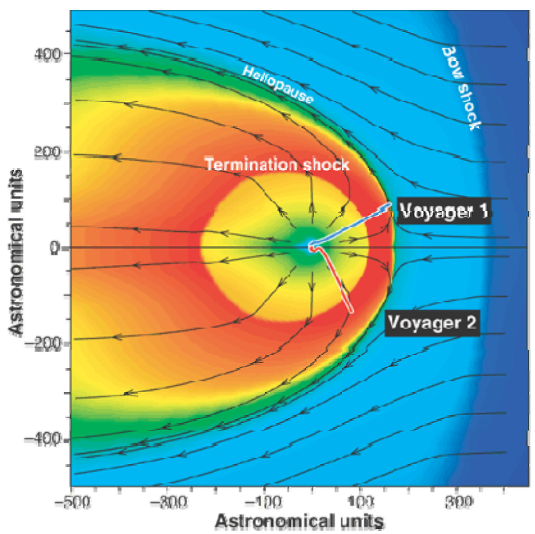
Background plasma (solar wind)



Galactic cosmic ray

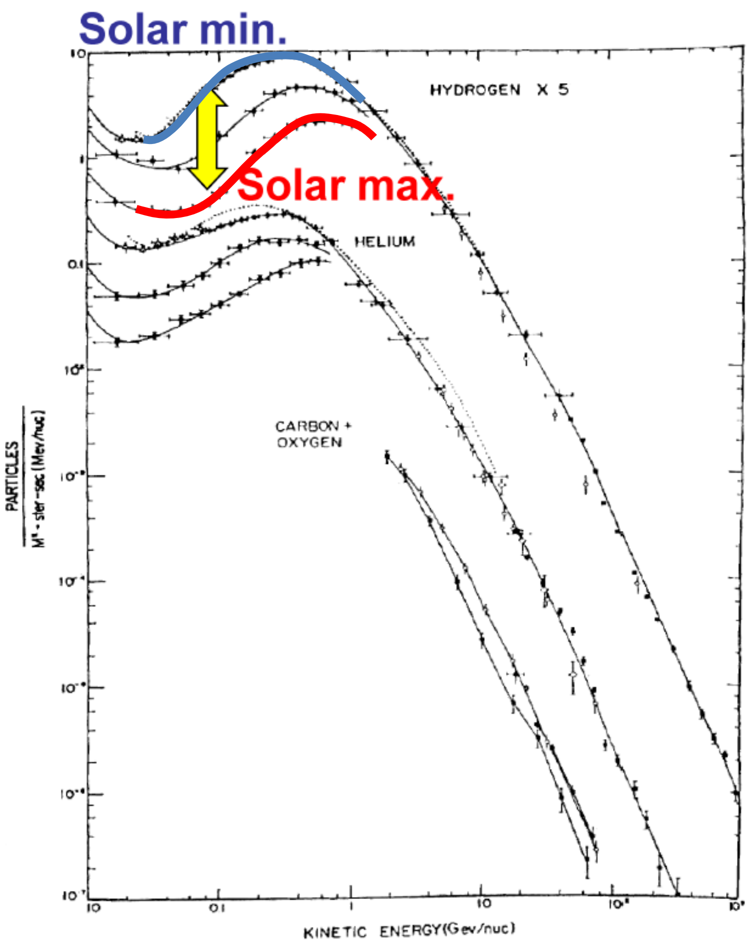


$$V = \begin{cases} V_1 & r < R_s \\ \frac{1}{4} V_1 \left(\frac{R_s^2}{r^2} \right) & r \geq R_s \end{cases}$$

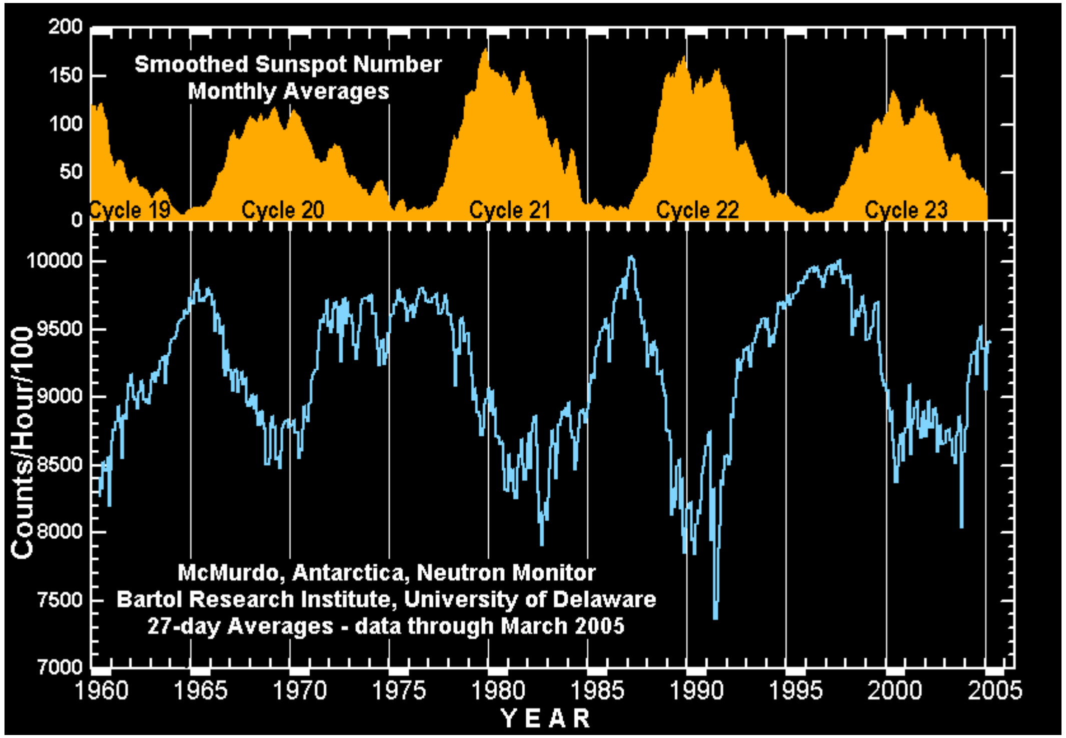


$$n = \begin{cases} n_s \exp\left(\frac{V_1}{\kappa_1} (r - R_s) \right) = & \\ n_\infty \exp\left(-\frac{V_1 R_s}{4\kappa_2} + \frac{V_1}{\kappa_1} (r - R_s) \right) & r < R_s \\ n_\infty \exp\left(-\frac{V_1 R_s^2}{4\kappa_2 r} \right) & r \geq R_s \end{cases}$$

Observation of Cosmic Ray Modulation



Sunspot Number (top) and Neutron Monitor (bottom)



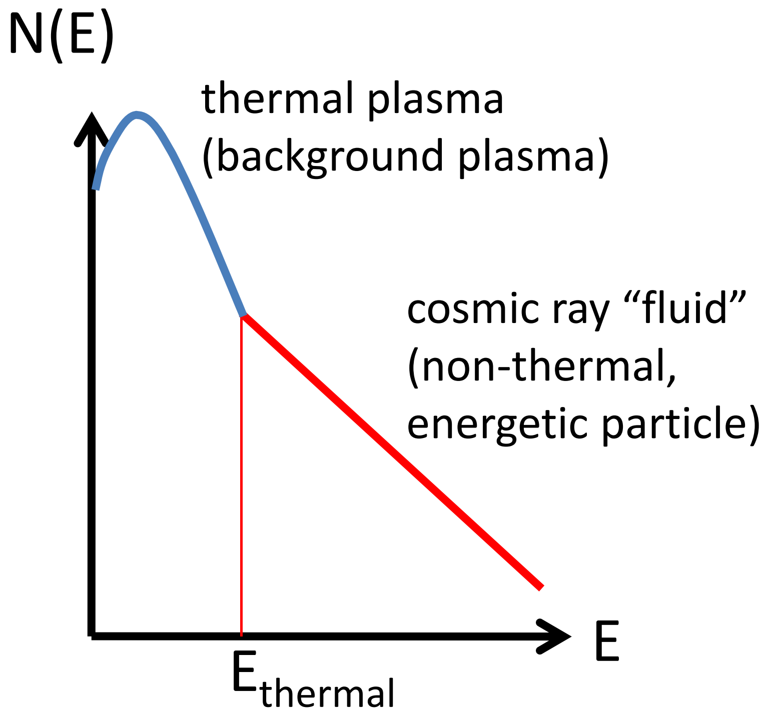
11 year cycle variation (22 year cycle)

CR flux decreases with increasing solar activity

Diffusion Convection Equation including energy change

$$n(\vec{x}) = \int_{E_{thermal}}^{\infty} N(\vec{x}, E)dE$$

$$\frac{\partial}{\partial t}n + \nabla \cdot (n\vec{V}) = \nabla \cdot (\kappa \nabla n)$$



$$\frac{\partial}{\partial t}N + \nabla \cdot (N\vec{V}) + \frac{\partial}{\partial E}(N\frac{dE}{dt}) = \nabla \cdot (\kappa \nabla N)$$

Glesson & Axford ApJ (1967)

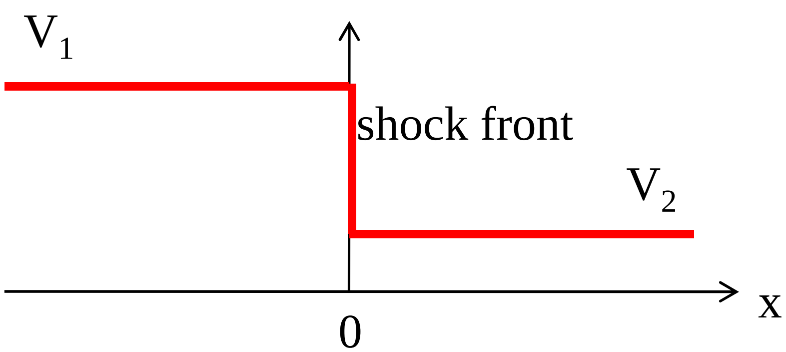
Diffusion Convection Equation in Shock Wave

(1) (3) (2)

$$\frac{\partial}{\partial t}N + \nabla \cdot (N\vec{V}) = \frac{1}{3}(\nabla \cdot \vec{V})\frac{\partial}{\partial E}(NE) + \nabla \cdot (\kappa \nabla N)$$

(1) Convection (V)
(2) Diffusion (κ)
(3) Energy Changes (E)

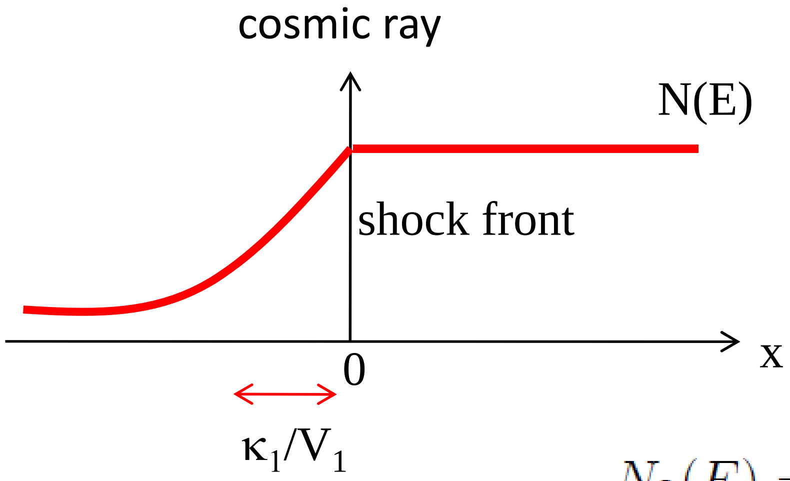
Background plasma (V)



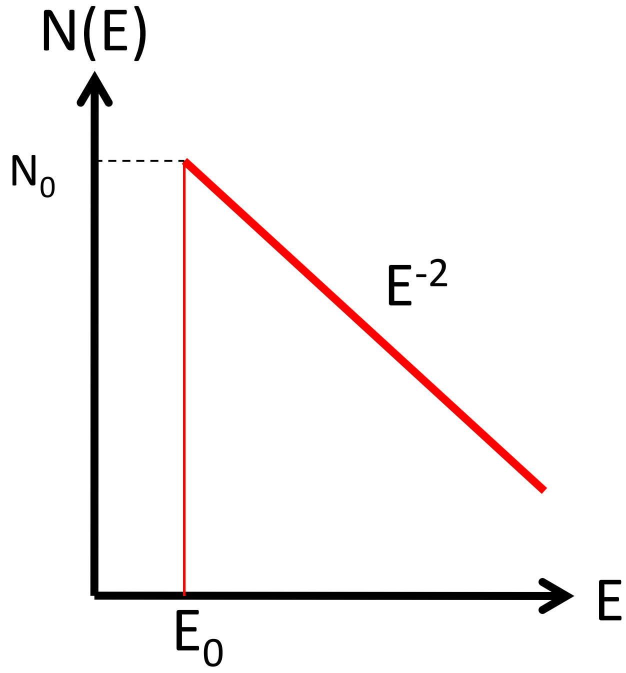
$\nabla \cdot V < 0$ plasma compression,
then energy gain & acceleration

Bell, MNRAS (1978), Blandford & Ostriker, ApJ (1980)

Energy Spectrum of DSA



$$N_2(E) = N_0 \left(\frac{E}{E_0} \right)^{-2}$$



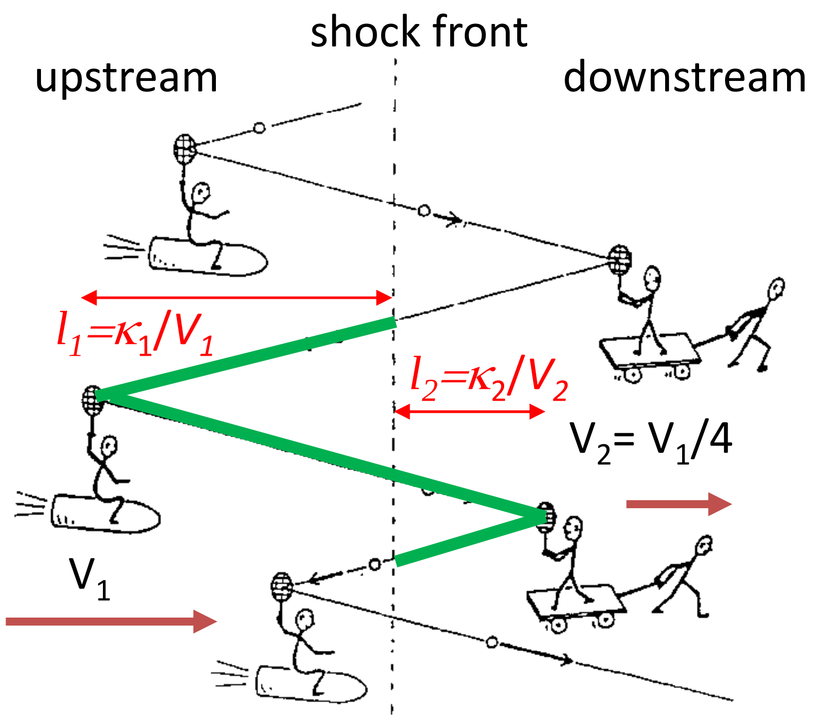
For $\gamma = 5/3$ and $M = V_1/C_s \to \infty$,

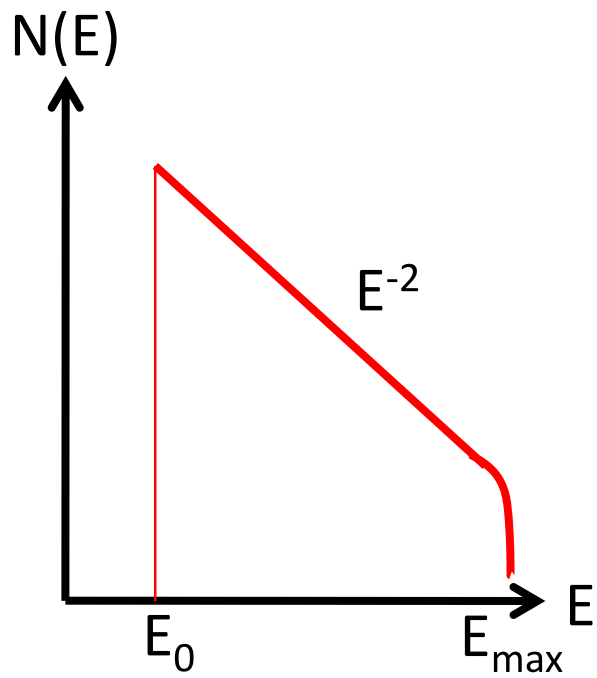
$$\frac{V_1}{V_2} \to 4, \lambda \to 1$$

Rankine-Hugoniot relation
(shock jump condition)

$$N(x,E) = \begin{cases} N_0 \left(\frac{E}{E_0} \right)^{-2} \exp\left(\frac{V_1}{\kappa} x \right) & \text{for } x < 0 \text{ (upstream)} \\ N_0 \left(\frac{E}{E_0} \right)^{-2} & \text{for } x > 0 \text{ (downstream)} \end{cases}$$

Maximum Attainable Energy of DSA





$$\frac{dE}{dt} = E\left(\frac{4(V_1 - V_2)}{3c}\right)\left(2\frac{l_1 + l_2}{c}\right)^{-1} = \frac{2}{3}E\,(V_1 - V_2)\left(\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2}\right)^{-1} \quad (1)$$

energy gain/cycle (time/cycle)$^{-1}$

$$\kappa_1 = \eta \kappa_B = \eta \frac{\rho_c c}{3} \tag{2}$$

Bohm diffusion (η=1) $\rho_c \equiv \frac{E}{ZeB}$

For simplicity $\frac{\kappa_1}{V_1} = \frac{\kappa_2}{V_2}$ (3)

$$E_{max} = \frac{3}{4\eta} Ze \left(\frac{V_1 B_1}{c} \right) L \quad \text{where } L = V_1 t \tag{4}$$

$$E_{max} = 2 \times 10^{13} \text{eV} \left(\frac{Z}{\eta} \right) \left(\frac{V_1}{3000 \text{ km/s}} \right)^2 \left(\frac{B_1}{1 \ \mu\text{G}} \right) \left(\frac{t}{10^3 \text{ year}} \right) \tag{5}$$

For Sedov solution, $L \propto t^{2/5}$, $V \propto t^{-3/5}$, then $E_{max} \propto t^{-1/5}$.

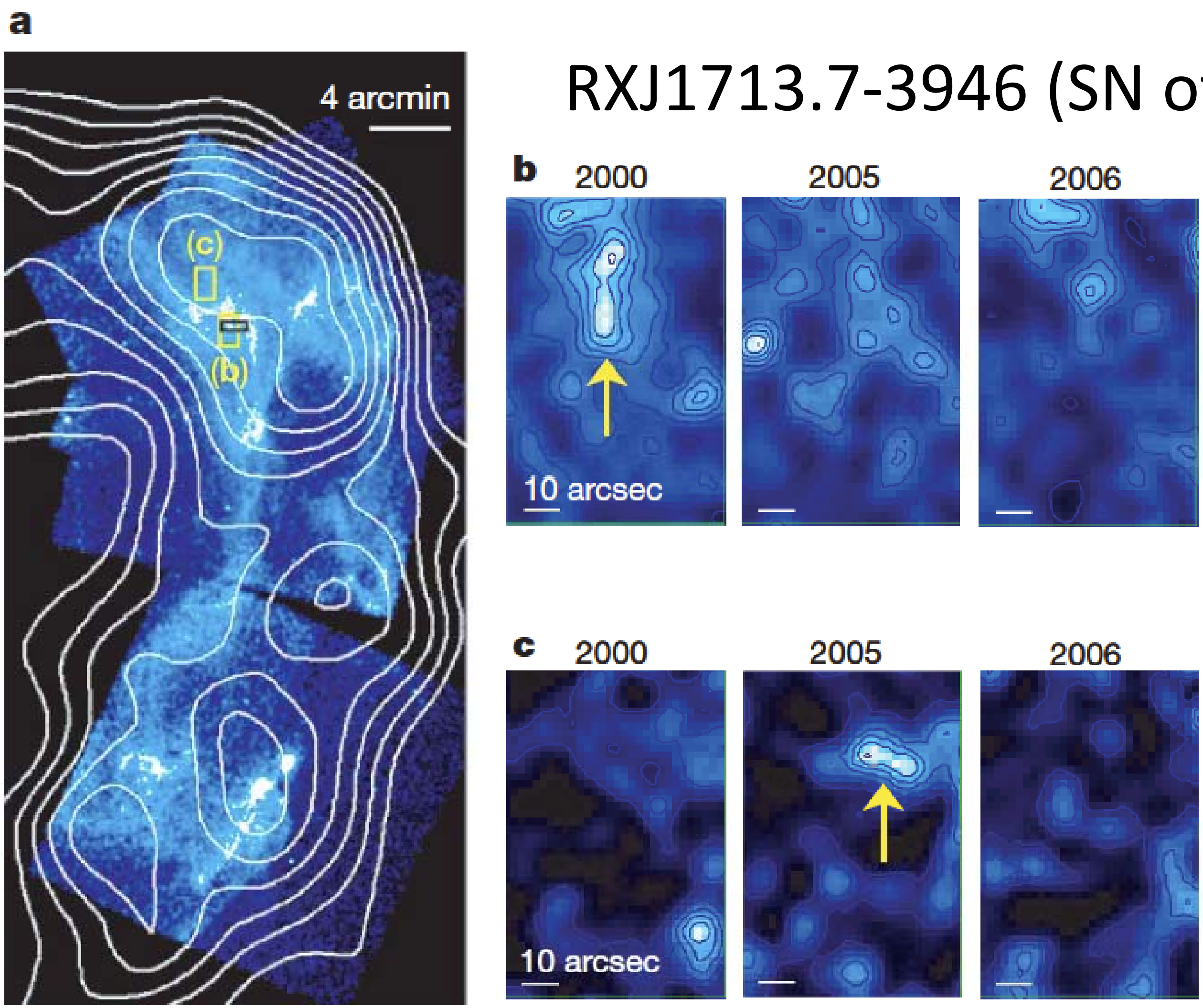
Note: probably $\eta > 1$, $E_{knee} = 10^{15.5}$eV > E_{max}

Diffusive Shock Acceleration Model

- Can predict
  - Spectrum is a power law E^{-2}
  - Energy up to $10^{13\text{-}14}$ eV for SNR,
    but not at E_{knee} of $10^{15.5}$ eV

- Open issues
  - Magnetic field amplification (*B*)
  - Behavior of scattering/Turbulence (κ)
  - Nonlinear shock structure (*p/P* is not small)
  - Injection Problem (E_0 , Q_0)

Observation of Strong B field



RXJ1713.7-3946 (SN of 393AD)

Chandra X-ray

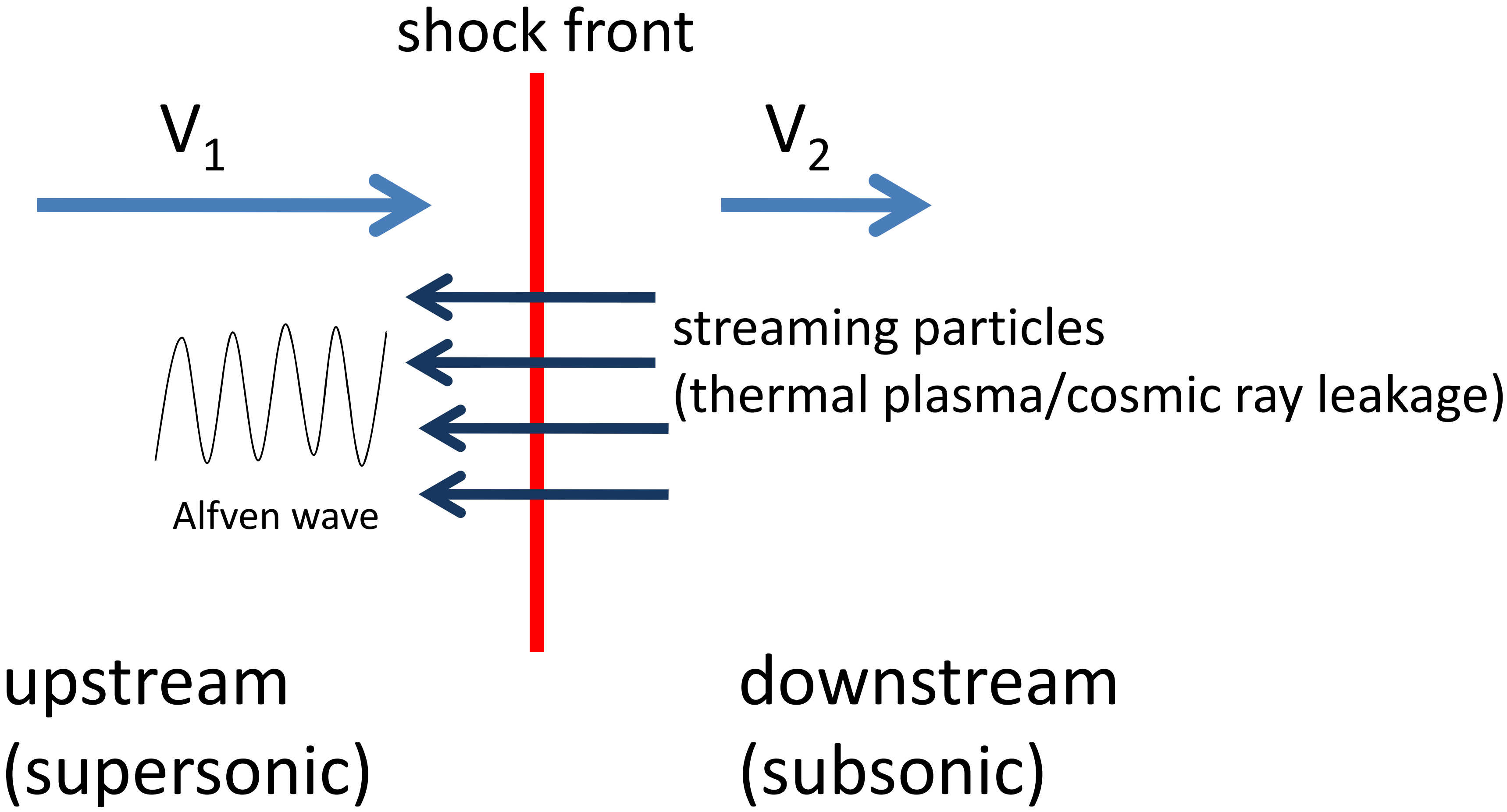
Most filaments have Rapid Time Variability

Timescale ~ 1 years

B ~ 0.1 - 1mG

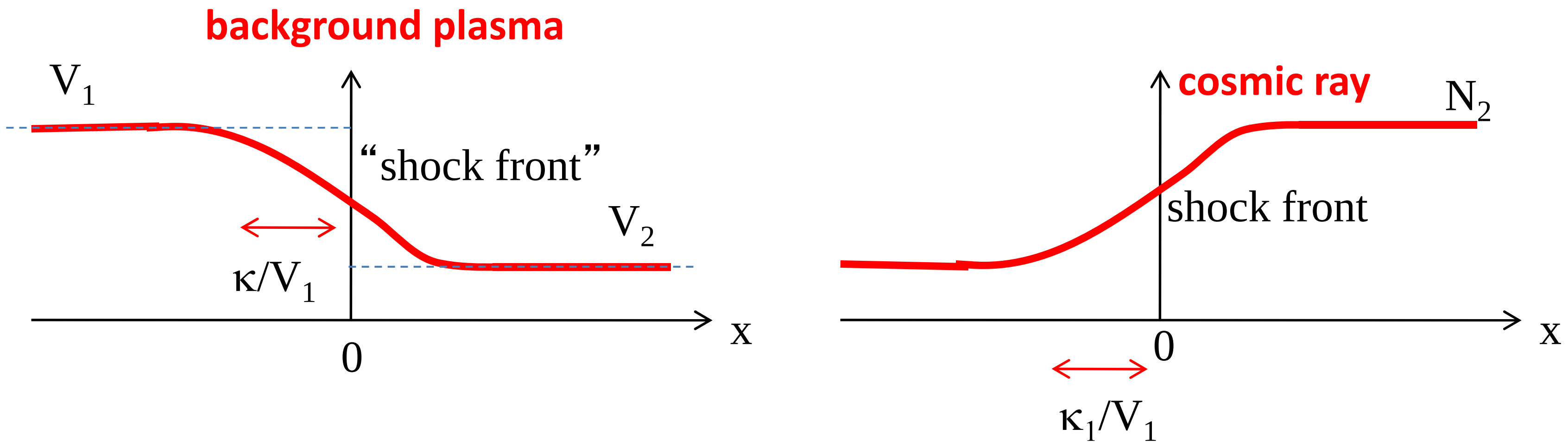
Uchiyama et al. Nature 2007

B generation by streaming particles



Bell, ’78; Achterberg, ‘83; MH & Terasawa, ‘85; Bell & Lucek, ‘01

Nonlinear Shock



$$\rho V = \text{const.}$$

$$P + p + \rho V^2 = \text{const.}$$

$$\frac{1}{2}\rho_1 V_1 V^2 + \frac{\gamma_c}{\gamma_c - 1} V p - \frac{\kappa}{\gamma_c - 1}\frac{\partial}{\partial x} p = \text{const.}$$

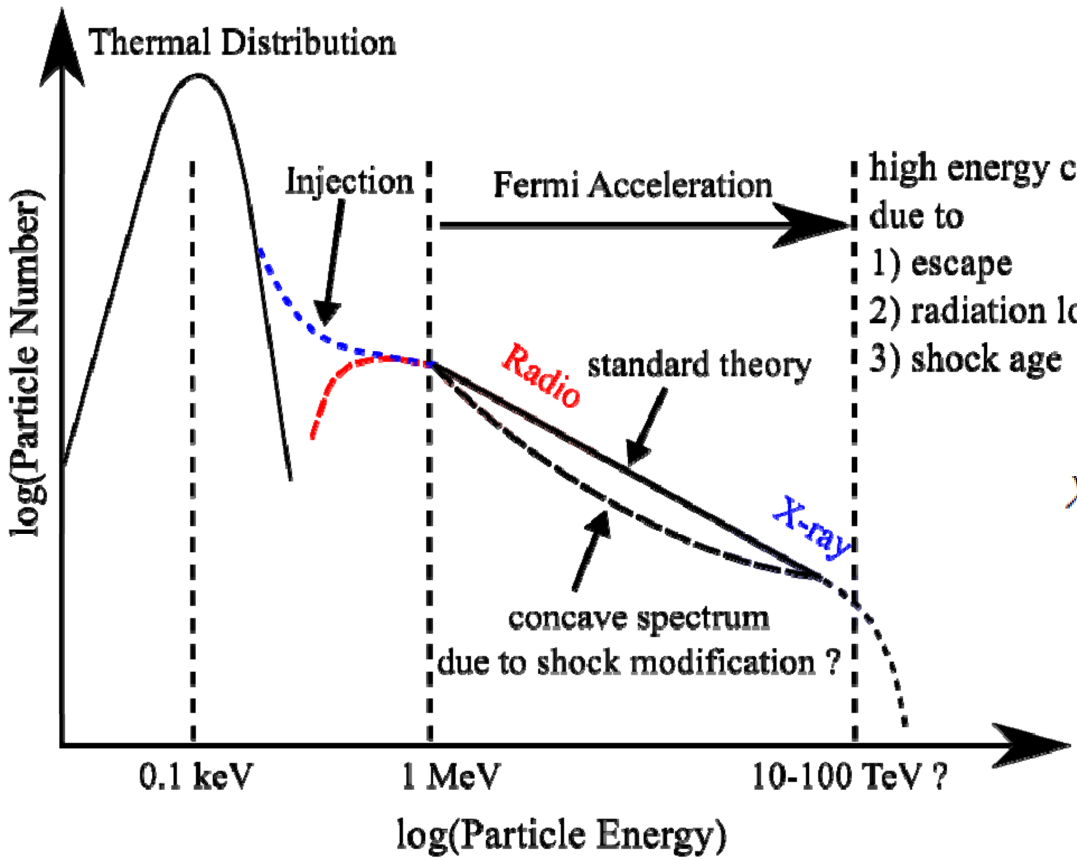
Axford+, '77; Drury & Voelk, '81; Ellison+, '00; Blasi, Malkov, Kirk, ...

If $P << p$ (cosmic ray pressure),

$$V = \frac{1}{2}(V_1 + V_2) - \frac{1}{2}(V_1 - V_2)\tanh(\frac{x}{x_0})$$

$$M_1 \rightarrow \infty$$

$$x_0 = \frac{2\kappa}{V_1}\frac{1}{1 - 1/M_1^2} \qquad M_1^2 = \frac{\rho_1 V_1^2}{\gamma_c p_1} \qquad \frac{V_2}{V_1} \rightarrow \frac{\gamma_c - 1}{\gamma_c + 1} = \frac{1}{7}$$



Critically Self-Organised Shock

$$N_2(E) \propto E^{-(\lambda_{nl}+1)}$$

$$\lambda_{nl} = \frac{3V_2}{V_1 - V_2} + \frac{2}{\gamma_c + 1}\frac{3V_1V_2}{(V_1 - V_2)^2} \rightarrow 1$$

Drury+, 1982

Non-Standard Shock Accelerations

Energy Spectra in AGN jets

– Diffusive Shock Acceleration Model can predict $N(E) \propto E^{-(p+\delta)}$, ($p=2$, $\delta>0$ by radiation loss/propagation)

– Observations with harder energy spectra of $p < 2$ (e.g. Blazar/AGN jet)

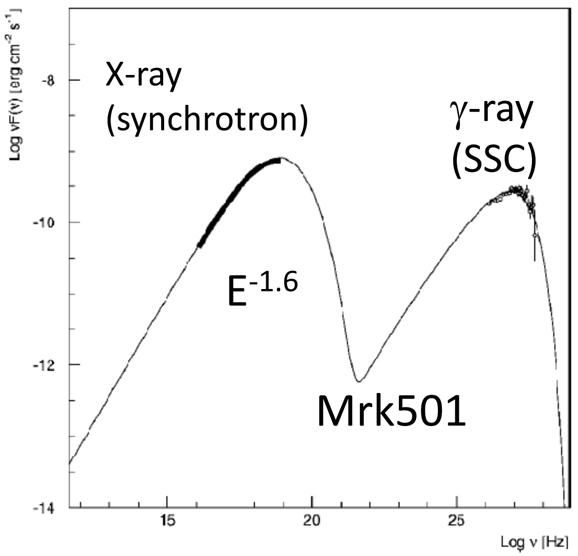
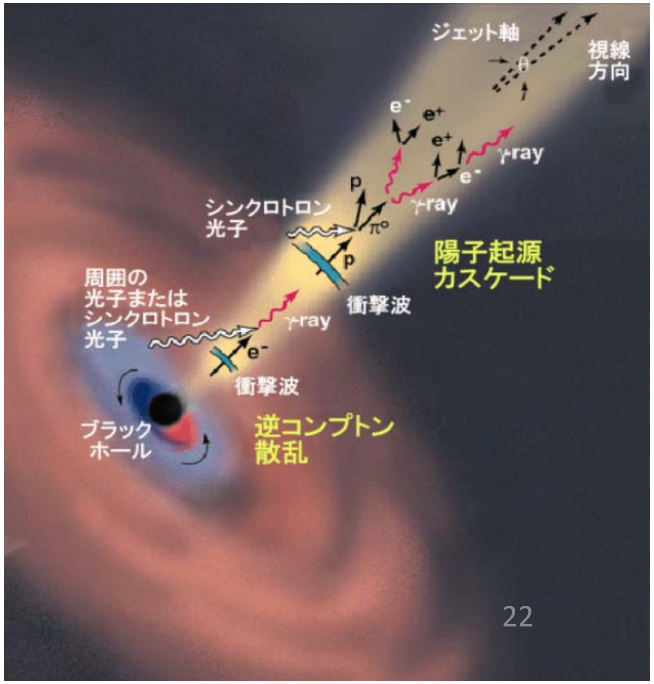


FIG. 7.—Combined X-ray/TeV γ-ray spectrum of Mrk 501 together with the best-fit SSC model.



Blazars with Hard X-ray Spectra

Low energy electron spectra p=2α+1=1.4-1.8

Table 1
Luminous Blazar Sources with the Hardest Recorded X-ray Spectra

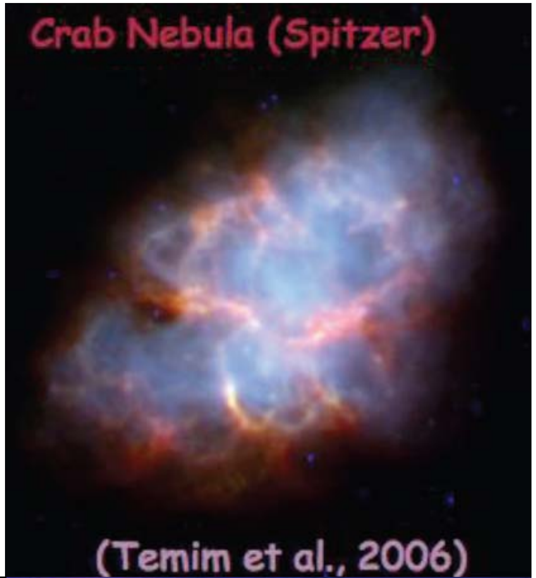
Name (1)	z (2)	α_x (3)	α_γ^E (4)	α_γ^F (5)	Reference (6)
S5 0212+73	2.367	0.32 ± 0.19	...	...	Sambruna et al. (2007)
PKS 0229+13	2.059	0.39 ± 0.09	...	...	Marshall et al. (2005)
PKS 0413-21	0.808	0.39 ± 0.12	...	...	Marshall et al. (2005)
PKS 0528+134	2.060	0.12 ± 0.26	1.46 ± 0.04	1.54 ± 0.09	Donato et al. (2005)
PKS 0537-286	3.104	0.27 ± 0.02	1.47 ± 0.60	...	Reeves et al. (2001)
PKS 0745+241	0.409	0.35 ± 0.12	...	...	Marshall et al. (2005)
SWIFT J0746.3+2548	2.979	0.17 ± 0.01	...	...	Watanabe et al. (2009)
PKS 0805-07	1.837	0.20 ± 0.20	1.34 ± 0.29(?)	...	Giommi et al. (2007)
S5 0836+710	2.172	0.34 ± 0.04	1.62 ± 0.16	...	Donato et al. (2005)
RGB J0909+039	3.200	0.26 ± 0.12	...	...	Giommi et al. (2002)
PKS 1127-145	1.184	0.20 ± 0.03	1.70 ± 0.31	1.69 ± 0.18	Siemiginowska et al. (2008)
PKS 1424-41	1.522	0.20 ± 0.30	1.13 ± 0.21	...	Giommi et al. (2007)
GB 1428+4217	4.715	0.29 ± 0.05	...	...	Fabian et al. (1998)
PKS 1510-089	0.360	0.23 ± 0.01	1.47 ± 0.21	1.48 ± 0.05	Kataoka et al. (2008)
PKS 1830-211	2.507	0.09 ± 0.05	1.59 ± 0.13	...	De Rosa et al. (2005)
PKS 2149-306	2.345	0.38 ± 0.08	...	...	Donato et al. (2005)
PKS 2223+210	1.959	0.31 ± 0.26	...	...	Donato et al. (2005)
3C 454.3	0.859	0.34 ± 0.06	1.21 ± 0.06	1.41 ± 0.02	Donato et al. (2005)

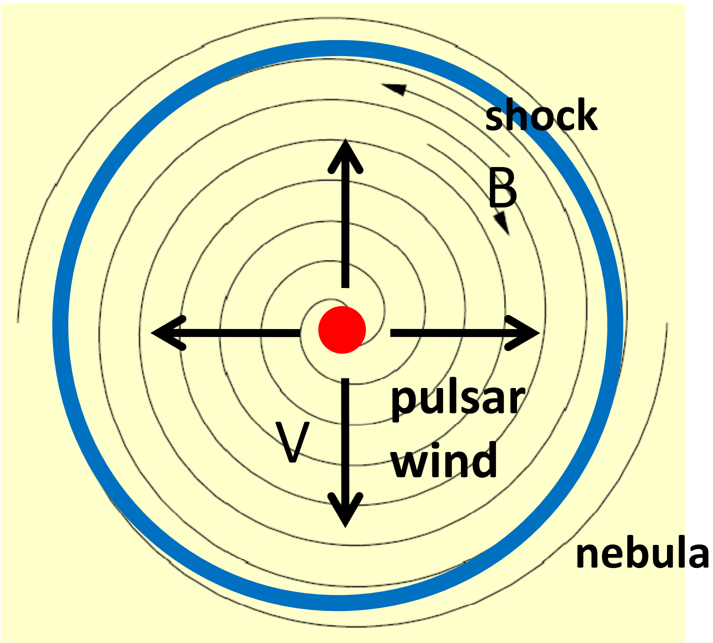
Notes. (1) Name of a source; (2) redshift of a source, z; (3) X-ray spectral index, α_x; (4) EGRET γ-ray spectral index, α_γ^E (Hartman et al. 1999); (5) *FERMI* γ-ray spectral index, α_γ^F (Abdo et al. 2009b); and (6) references.

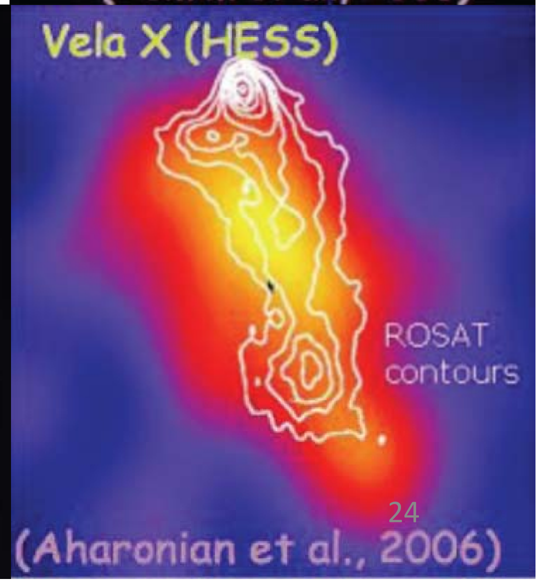
(Sikora et al, ApJ, 2009)

Luminous Sources in Perpendicular Shock

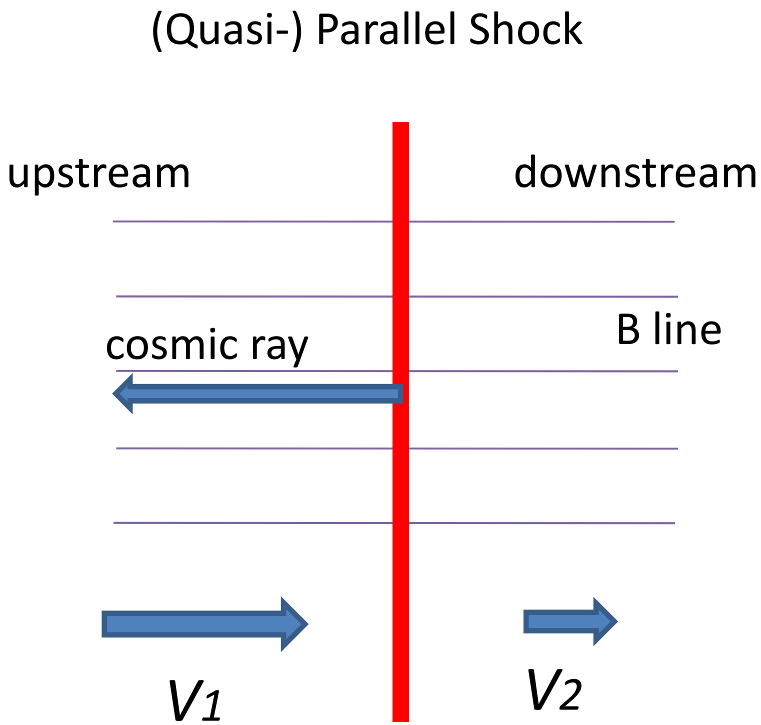
– Pulsar-wind nebulae may have a relativistic perpendicular shock
– Diffusion across B line is difficult, implying no DSA

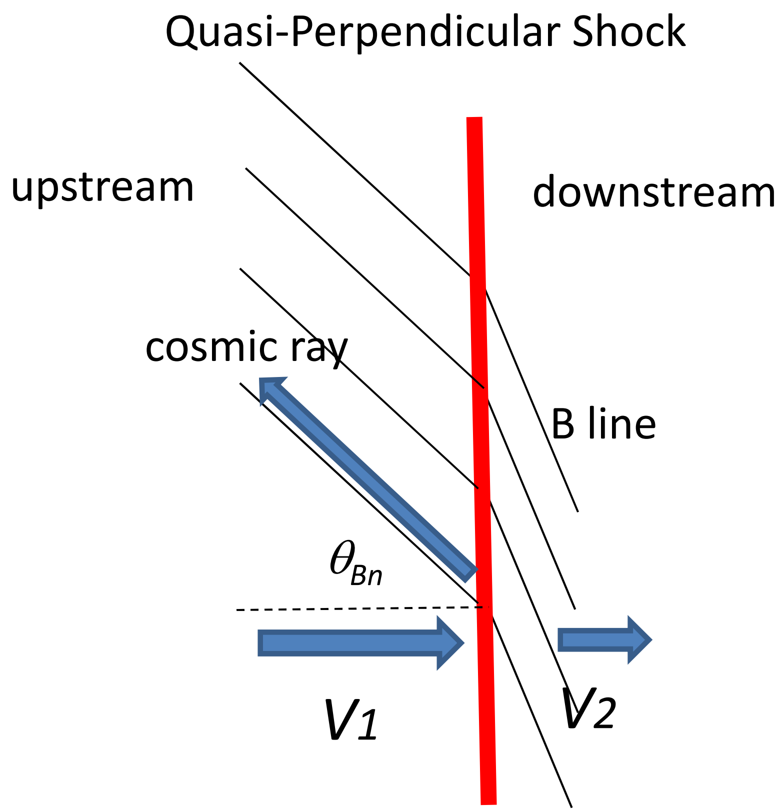






Shock Crossing (parallel /perpendicular shock)





cosmic ray can cross the shock front when

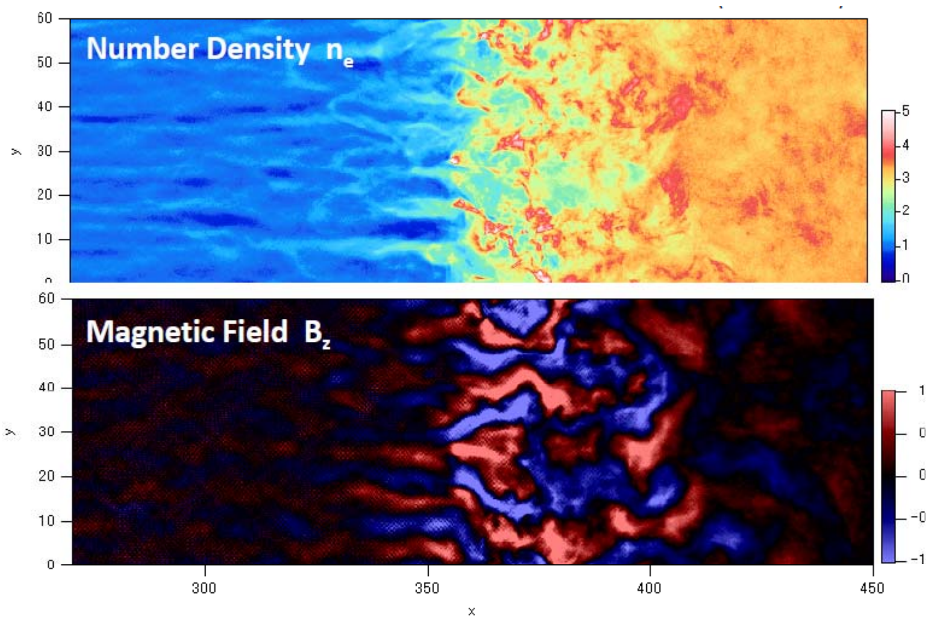
$$V_1 \tan\theta_{Bn} = V_{HT} < c$$

For relativistic shock, $\theta_{BN} < 45$

Strong Turbulence near Shock Front by Weibel Instability

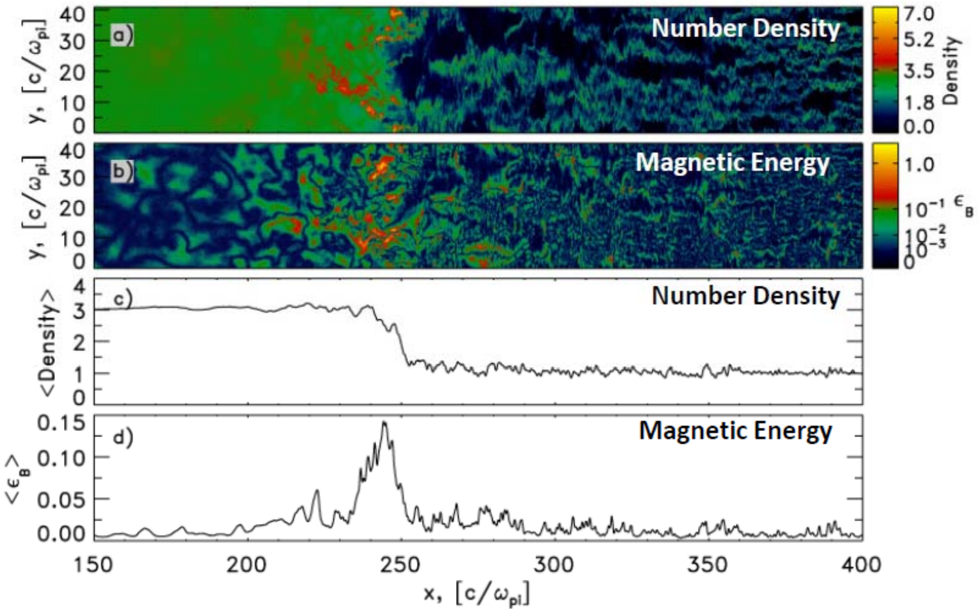
If $\sigma < 10^{-2}$-10^{-3}, strong turbulence may exist…

Electron-Positron Plasma



(Kato, ApJ, 2007)

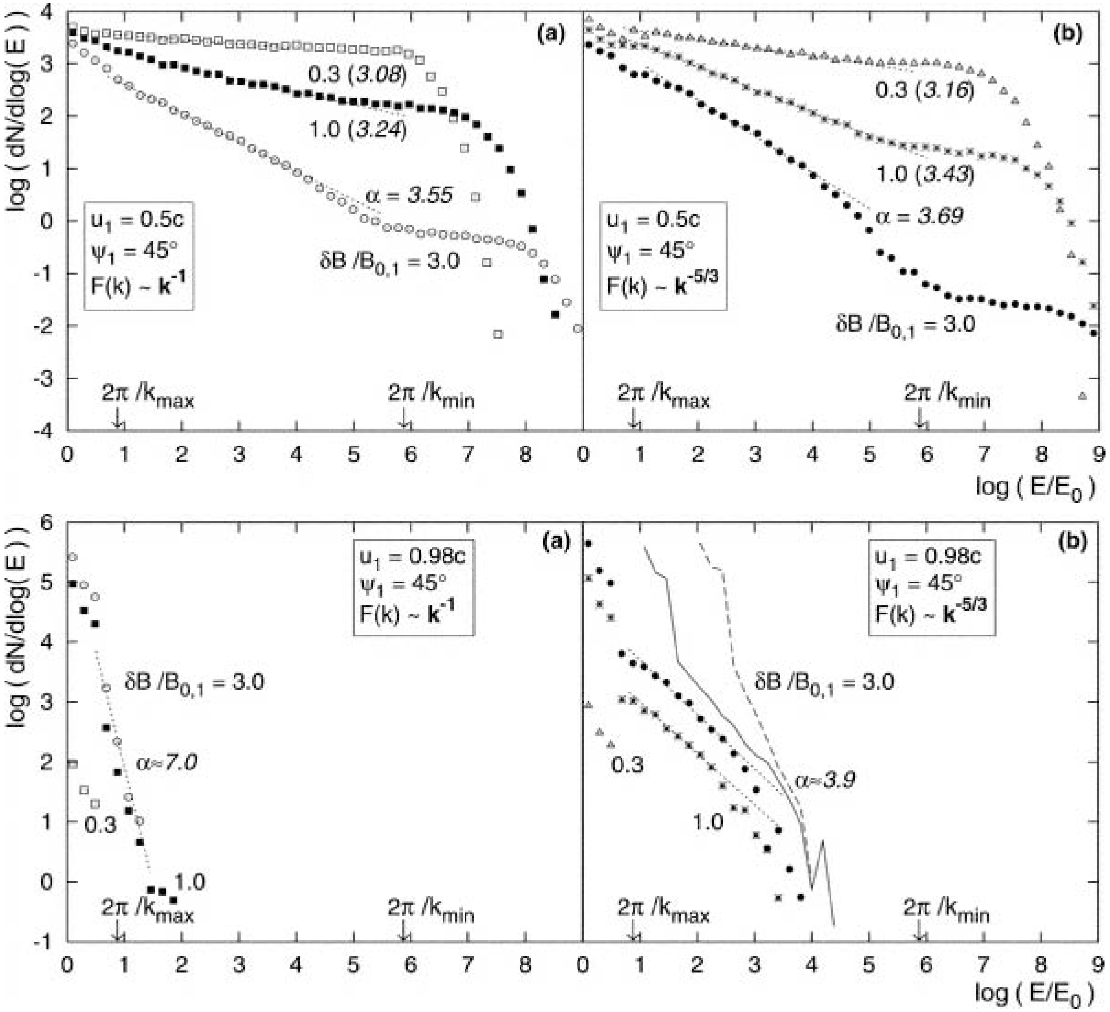
Electron-Ion Plasma



(Spitkovsky, ApJ, 2008)

But, if $\sigma > 10^{-2}$-10^{-3}, acceleration in perp-shock??

Monte-Carlo Simulation of Diffusive Shock Acceleration



Niemiec & Ostrowski, ApJ (2004)

Subluminal shock

MC simulation suggests variety of particle spectra in Fermi acceleration

Superluminal shock

Acceleration is not effective

Plasma Dynamics in Relativistic Perpendicular Shock

So far no standard model for particle acceleration in perpendicular shock....

Possible models may be

- Shock Surfing Acceleration
- Cyclotron Resonant Acceleration
- Wakefield Acceleration

  & Magnetic Field Amplification

Shock Numerical Experiment

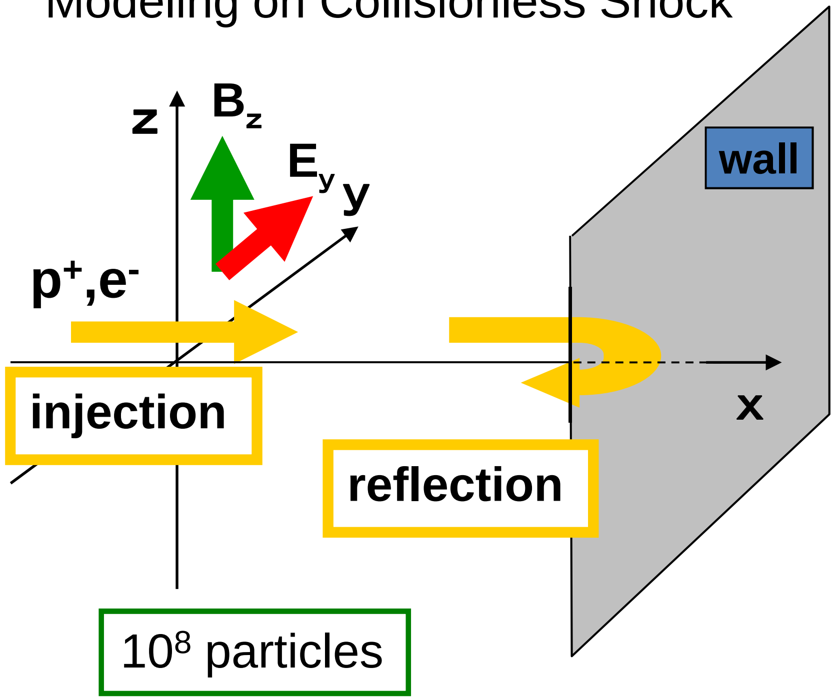
Particle-in-Cell (PIC) Simulation

$$m\frac{d(\gamma v)}{dt} = q(E + \frac{v}{c} \times B)$$

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t},$$

$$\nabla \times B = \frac{1}{c}\frac{\partial E}{\partial t} + \frac{4\pi}{c} J$$

Modeling on Collisionless Shock



$\sigma >> 1 \Rightarrow \text{high } \sigma$

$\sigma \approx 1 \Rightarrow \text{medium } \sigma$

$\sigma << 1 \Rightarrow \text{low } \sigma$

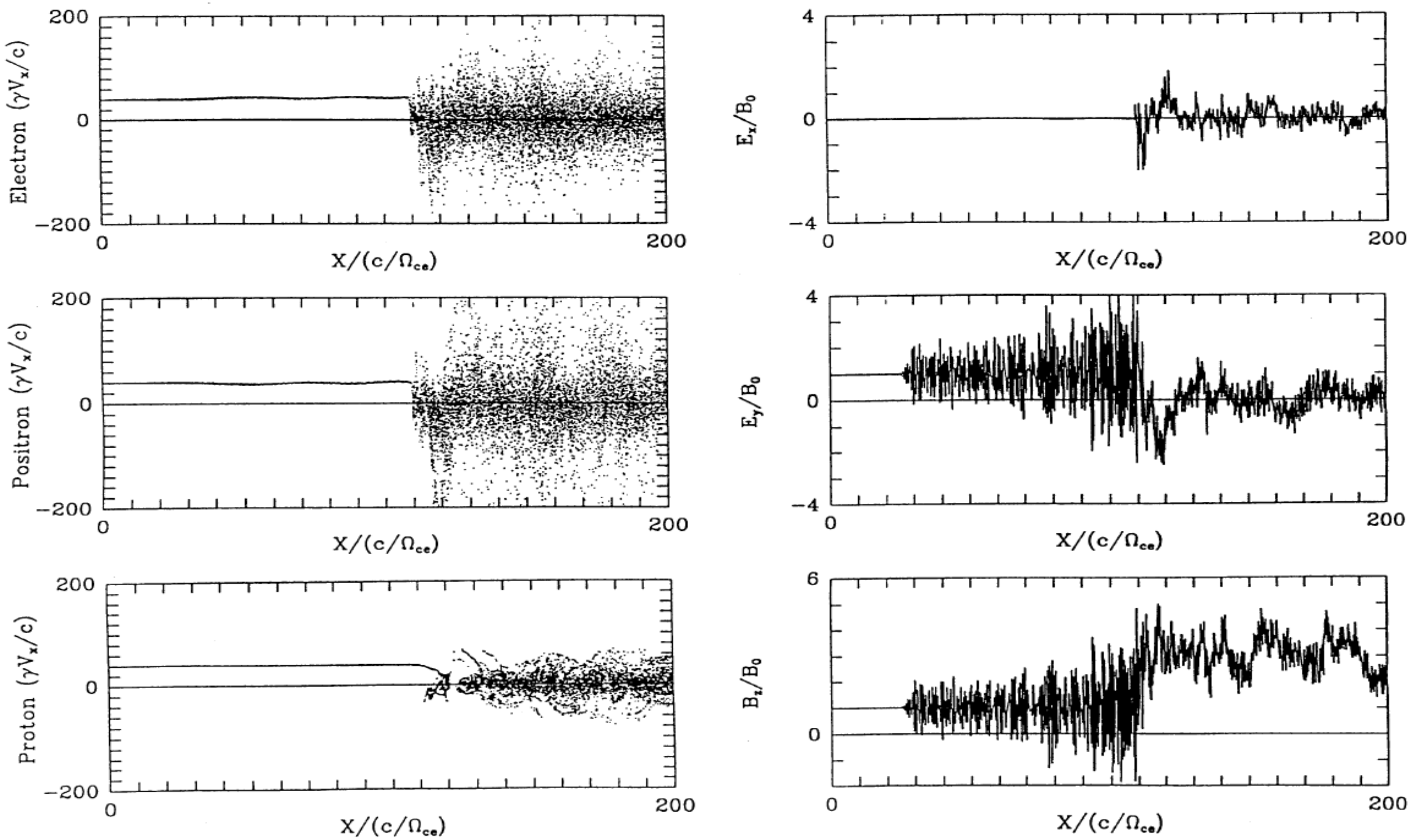
$$\sigma = \frac{\text{Poynting Flux}}{\text{Particle-born Flux}}$$

Resonant Acceleration

(Relativistic Resonant Cyclotron Absorption)

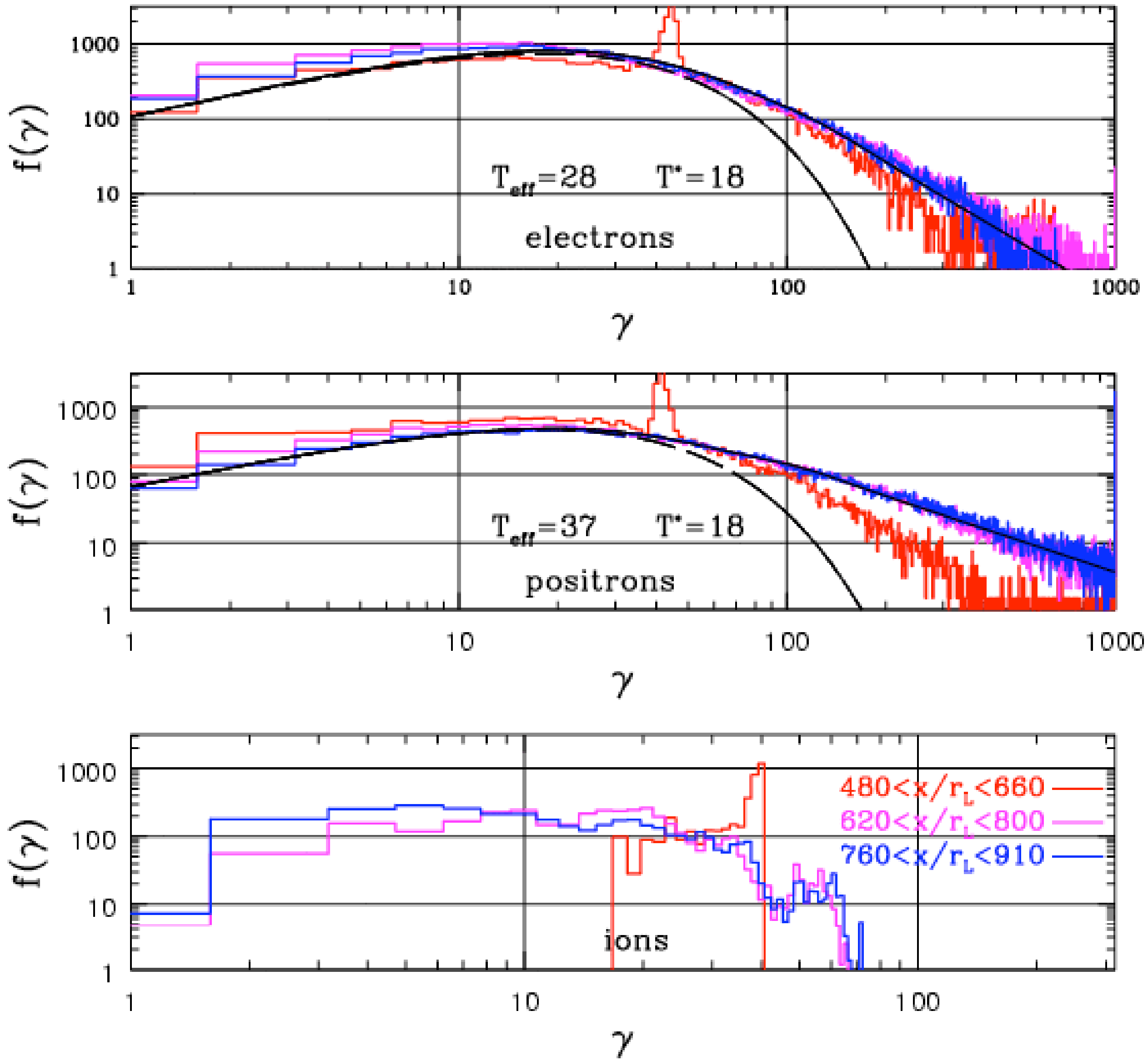
Relativistic Perpendicular Shock

3 component plasma of e-, e+, and p+. $N_{p+} << N_{e+}, N_{e-}$ but $M_{p+} N_{p+} > M_{e+} N_{e+}, M_{e-} N_{e-}$



MH et al., ApJ 1992; Amato & Arons, ApJ 2006

Energy Spectra: e+/e- acceleration



Power Law Electron

Power Law Positron

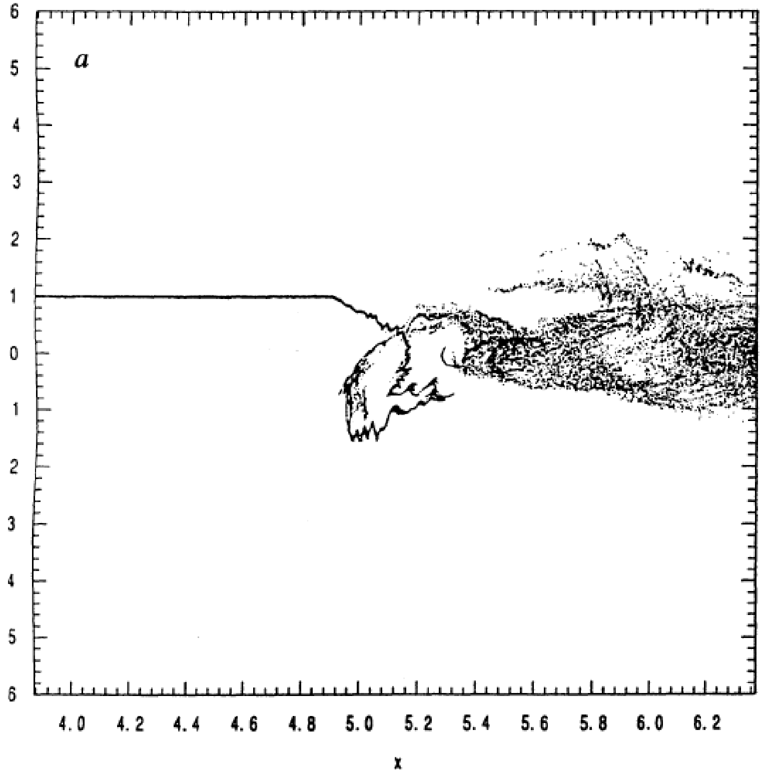
$N(E) = E^{-p}$ (1<p<2)

Maxwellian Proton (?)

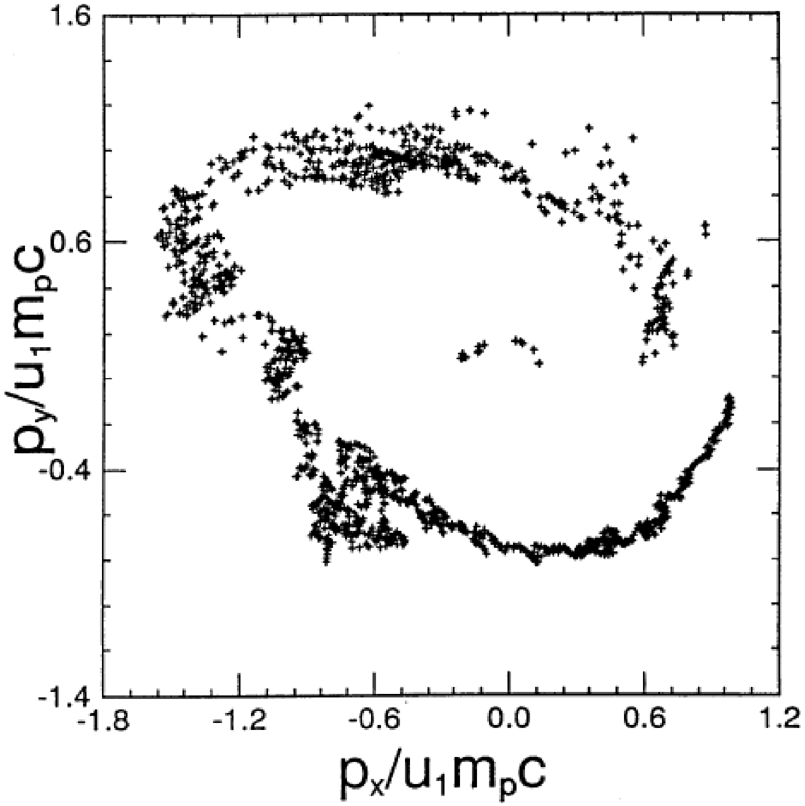
Amato & Arons, ApJ 2006

f(p) just behind the shock front

Ion phase space around shock front



velocity distribution function f(p)



Ring distribution function -> Cyclotron Instability

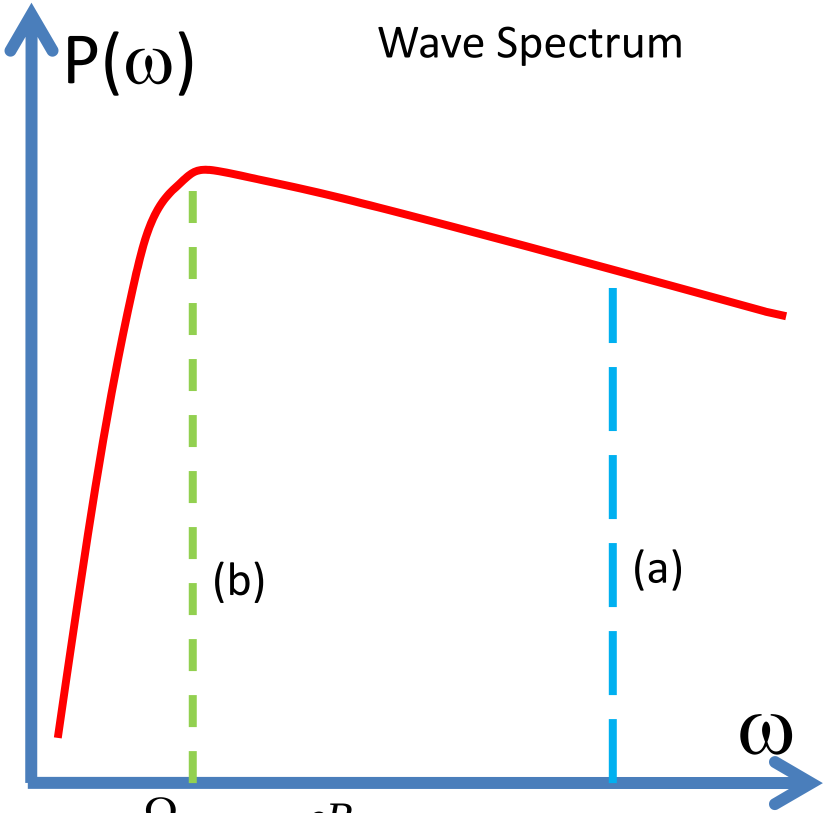
(cf. aurora kilometric radiation)

Relativistic Cyclotron Resonance

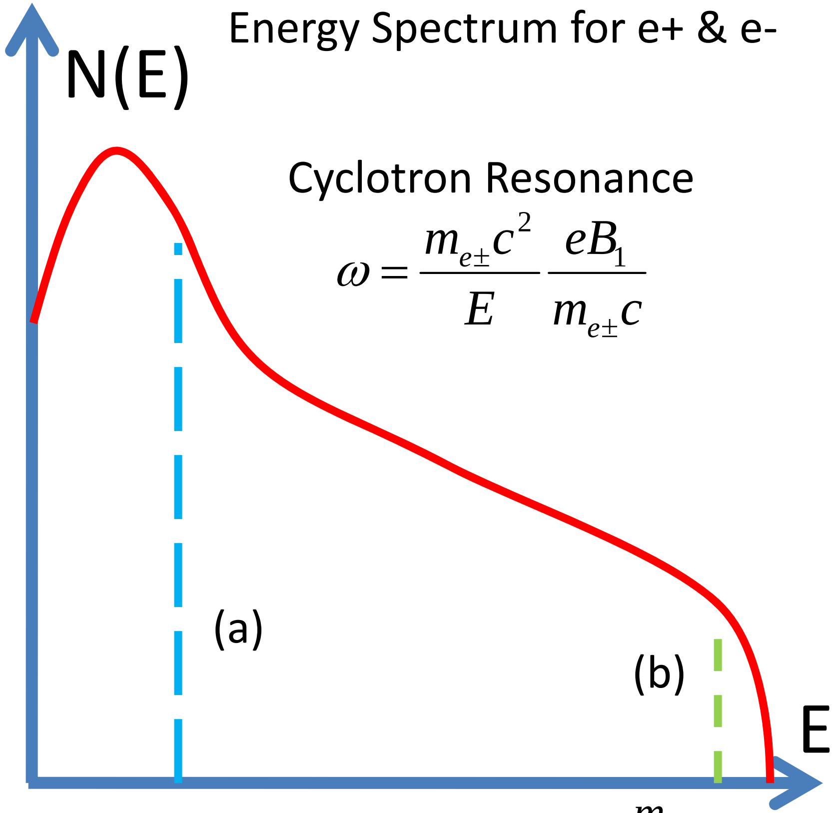
Growth rate for proton ring

MH & Arons, PoF 1991

$$\frac{\delta}{\Omega_{cp+}} \cong \left(\frac{3}{2^{14}}\right)^{1/9} \left(\frac{\Gamma(2/3)}{\pi}\right)^{2/3} \left(\frac{1+i\sqrt{3}}{\sigma_{p+}^{1/3}}\right) \left(\frac{\Omega_{cp+}}{\omega}\right)^{1/9}$$



$$\omega_{\min} = \frac{\Omega_{cp+}}{\gamma_1} = \frac{eB_1}{\gamma_1 m_{p+} c} \qquad \frac{\Omega_{ce\pm}}{\gamma_0}$$

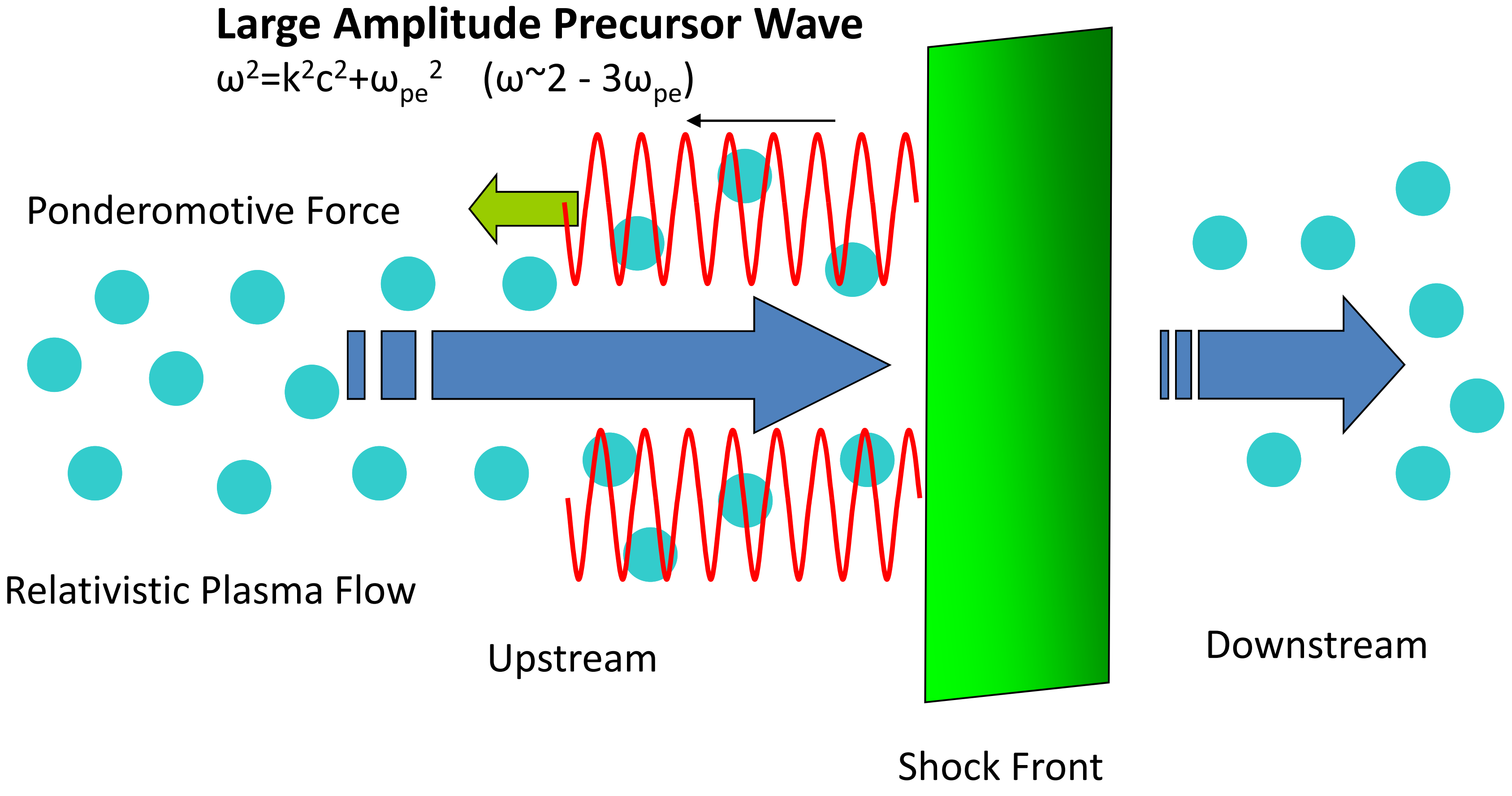


$$\omega = \frac{m_{e\pm} c^2}{E} \frac{eB_1}{m_{e\pm} c}$$

$$\gamma_1 m_{e\pm} c^2 \qquad E_{\max} = \frac{m_{p+}}{m_{e\pm}} (\gamma_1 m_{e\pm} c^2)$$

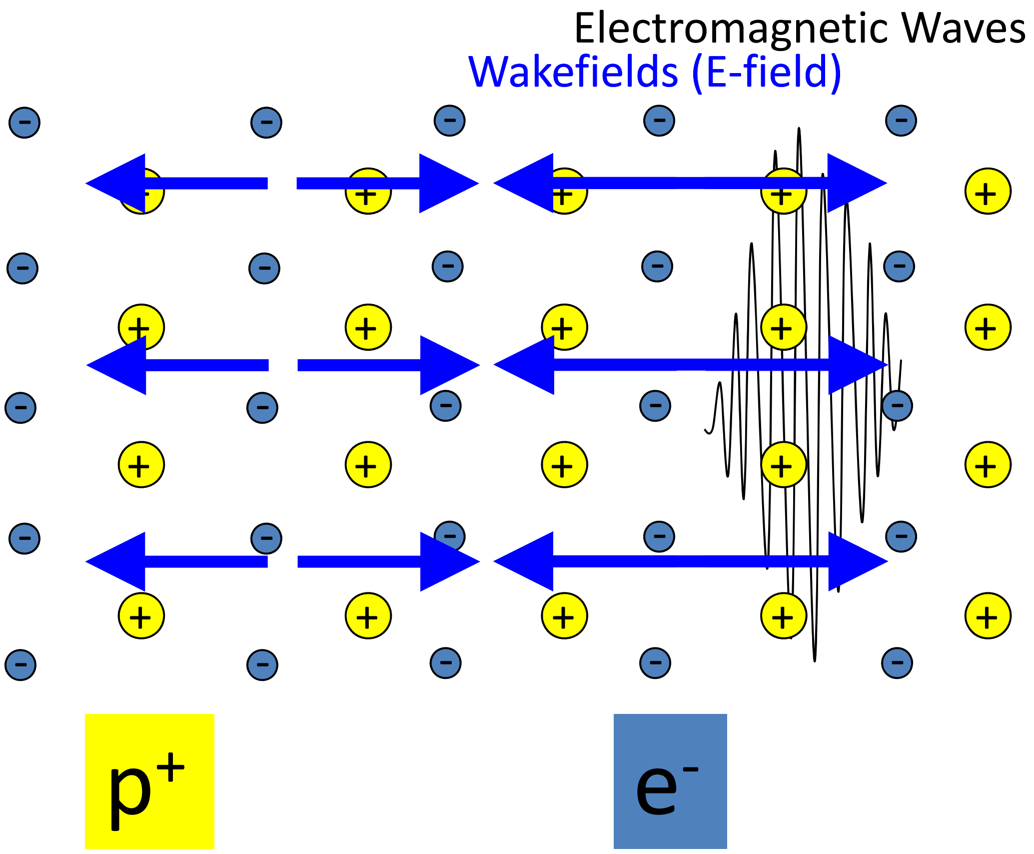
Wakefield Acceleration

Precursor Wave in Relativistic Shock



Chen et al. PRL 2003, Lyubursky ApJ 2007, MH ApJ 2008

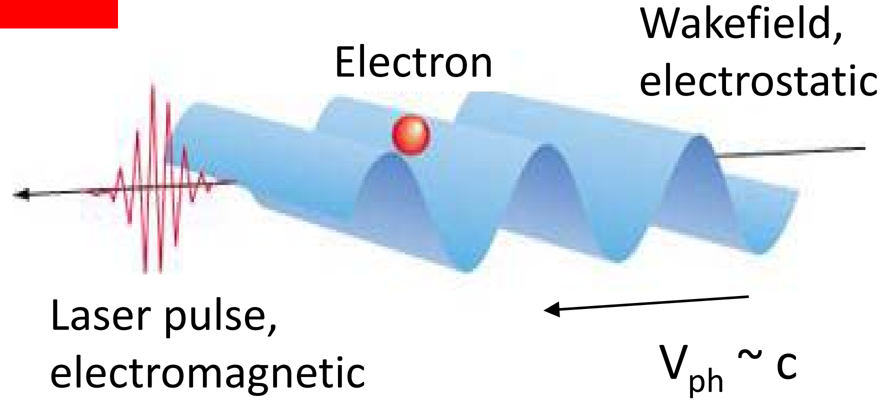
Ponderomotive Force in Precursor Wave



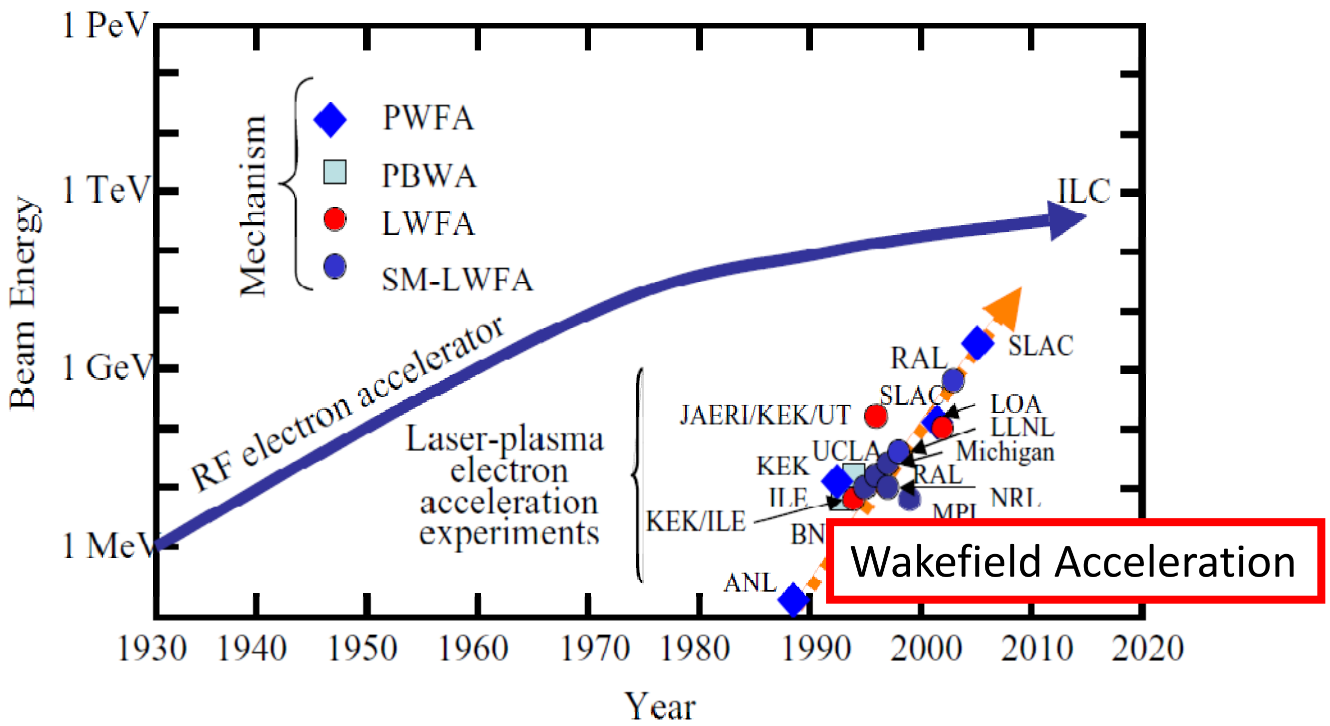
$$F_{ponderomotive} = \frac{e^2}{2m\omega^2}\nabla\left|\vec{E}_0\right|^2\left\langle \sin^2 \omega t\right\rangle$$

Wakefield Acceleration in Laboratory Laser Plasma

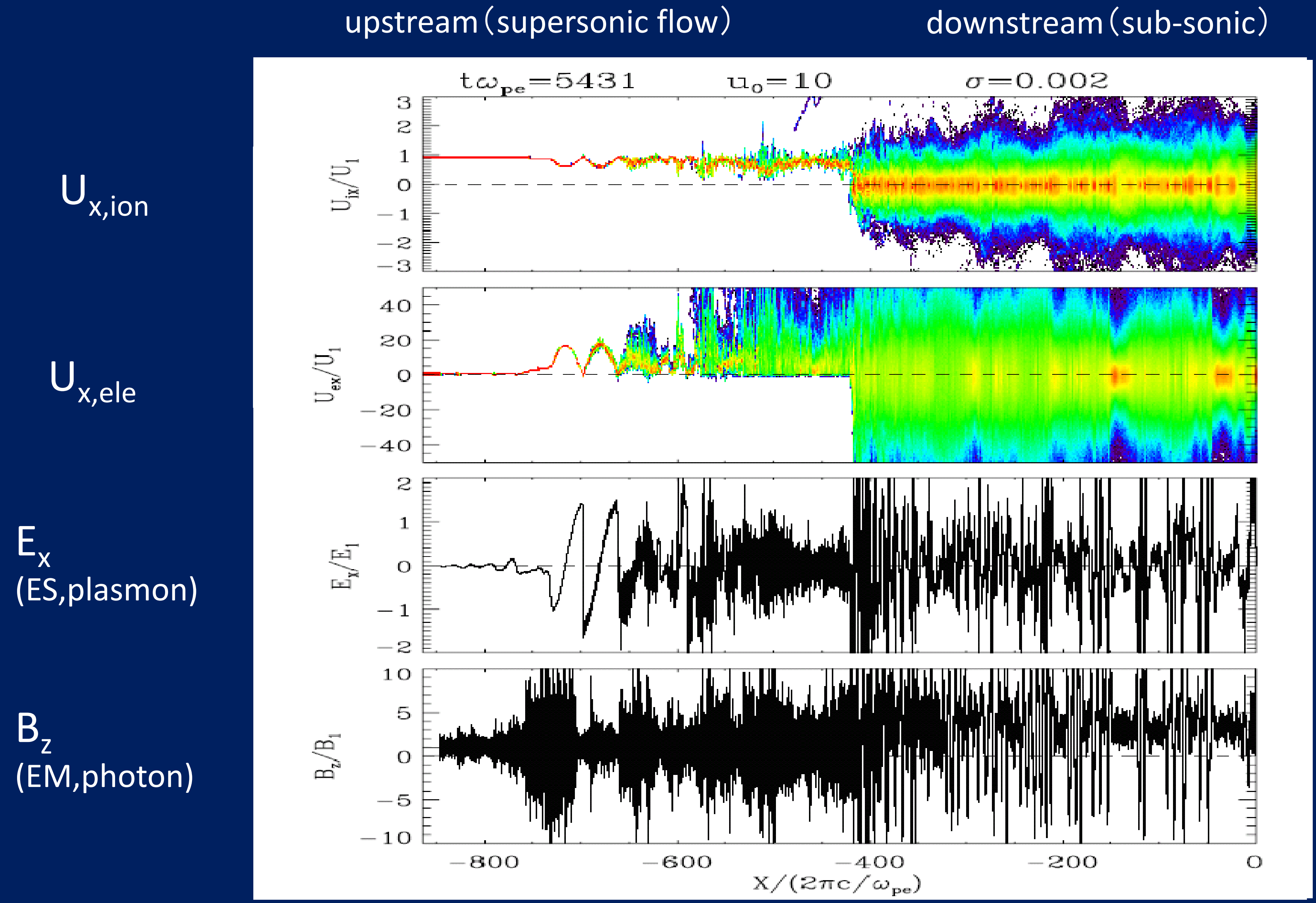
Tajima & Dawson, 1979



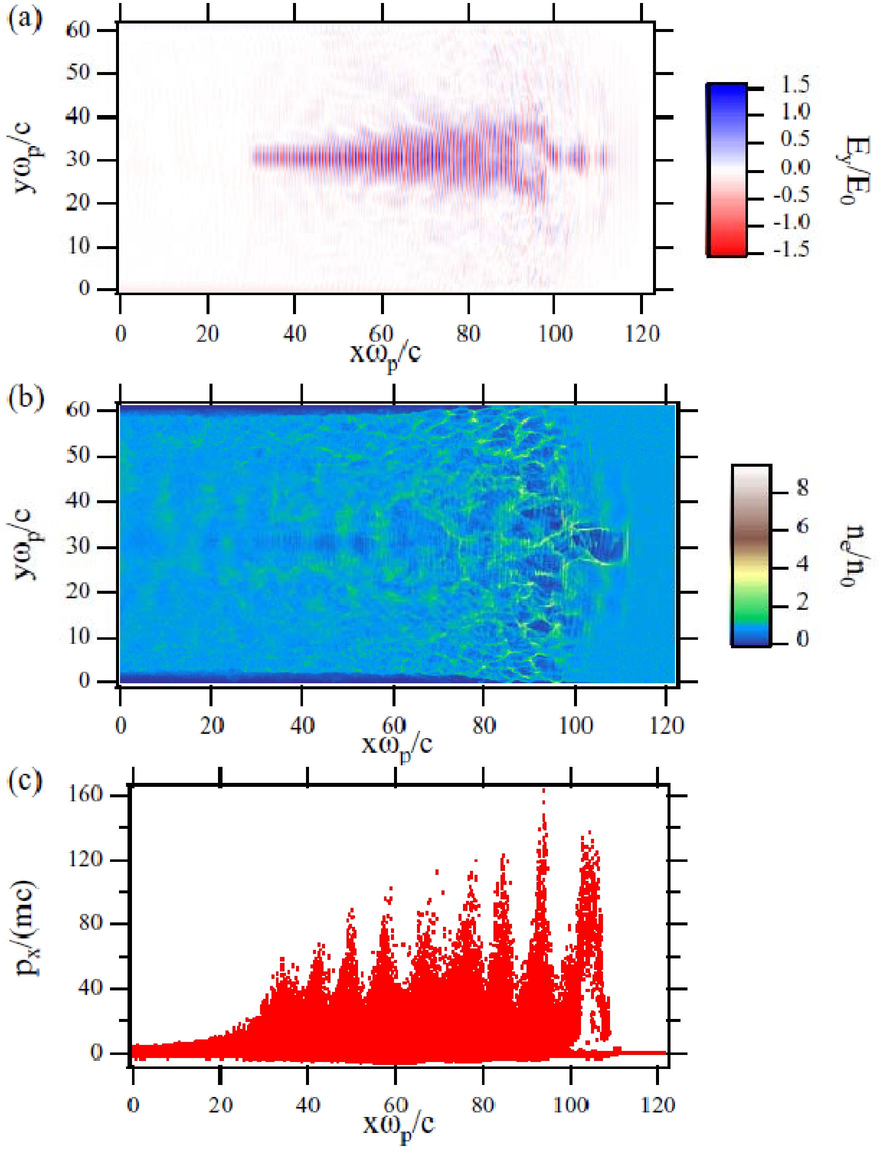
Livingston Chart



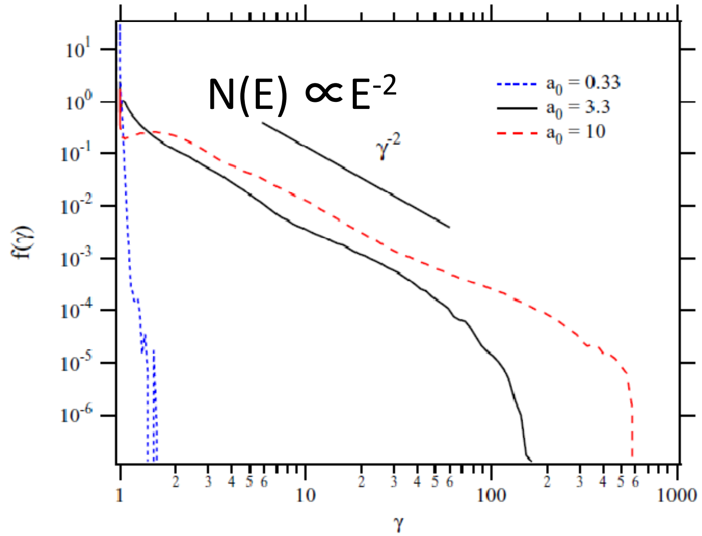
Particle (PIC) Simulation of Relativistic Shock

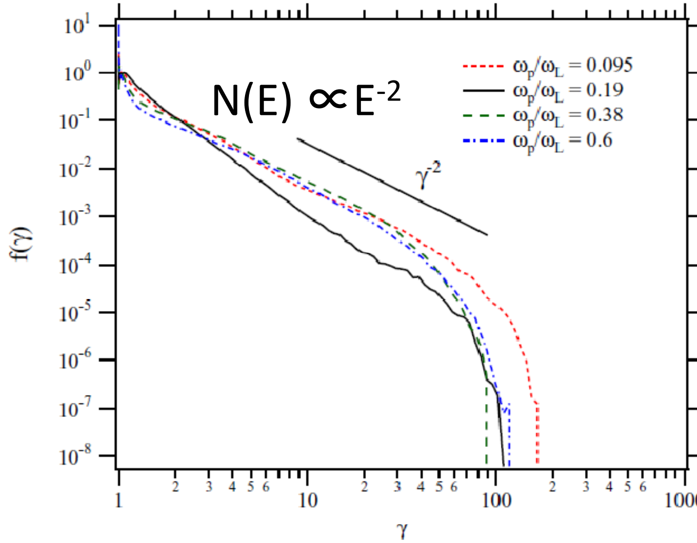


Energy Spectra in 2D Wakefield

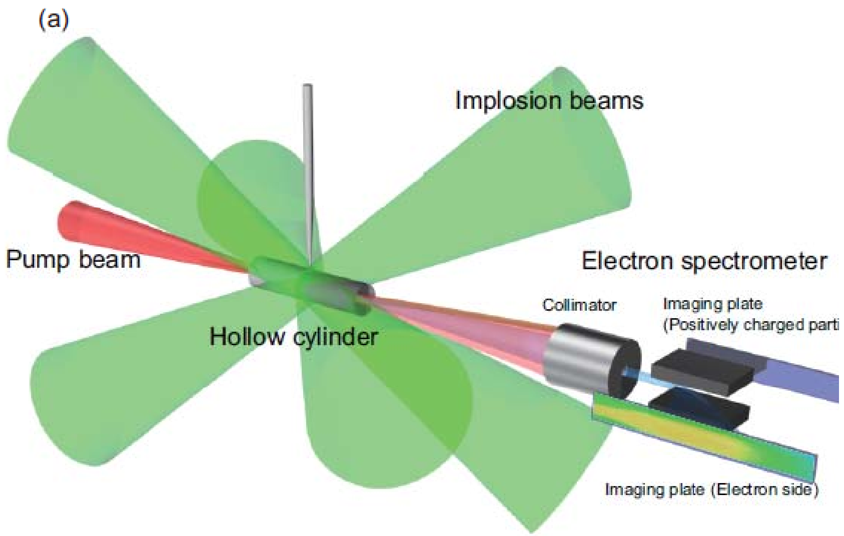


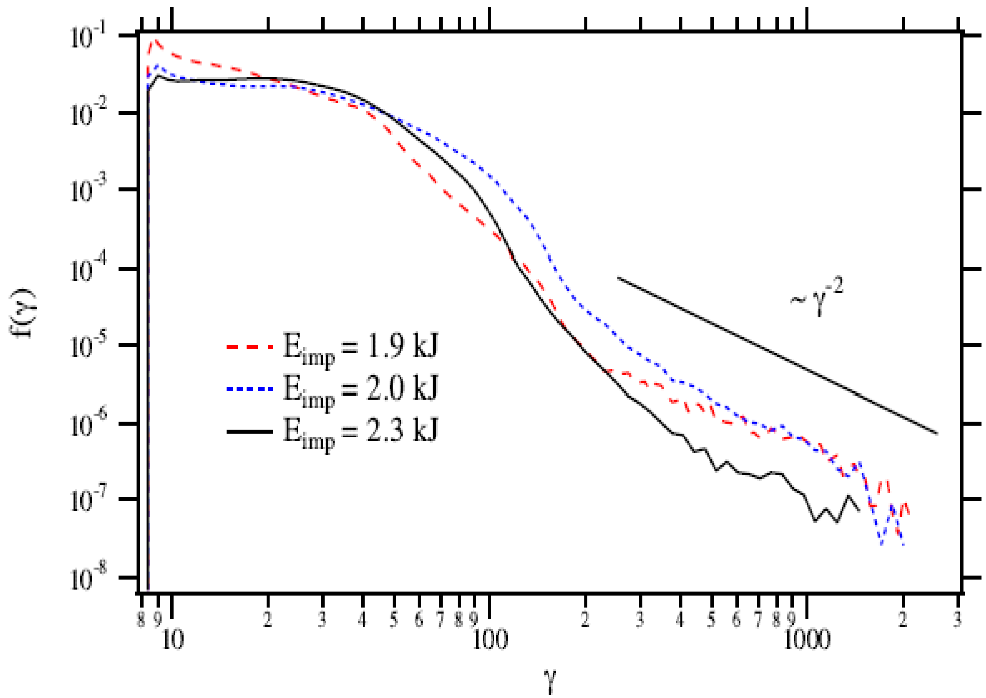
Kuramitsu et al., ApJ (2008)





Laboratory Experiment of Incoherent Wakefield Acceleration by an Intensive Laser Pulse





GEKKO XII Laser Plasma Experiment

Kuramitsu et al. submitted (2009)

Incoherent Wakefield Acceleration

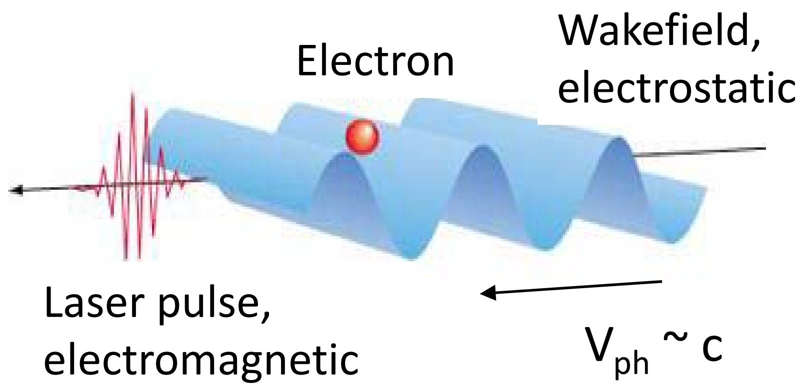
Wakefield Acceleration

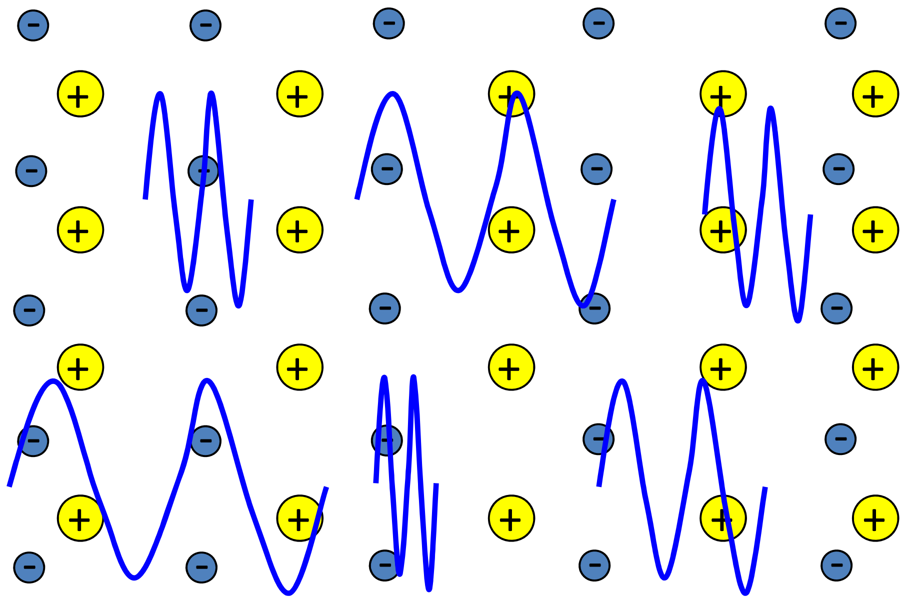
$$\varepsilon_{\max} \approx eE_{es}L\frac{c}{c-v_{ph}}$$

+

Turbulent scattering in upstream plasma frame

v_{ph} : propagation velocity of wakefield

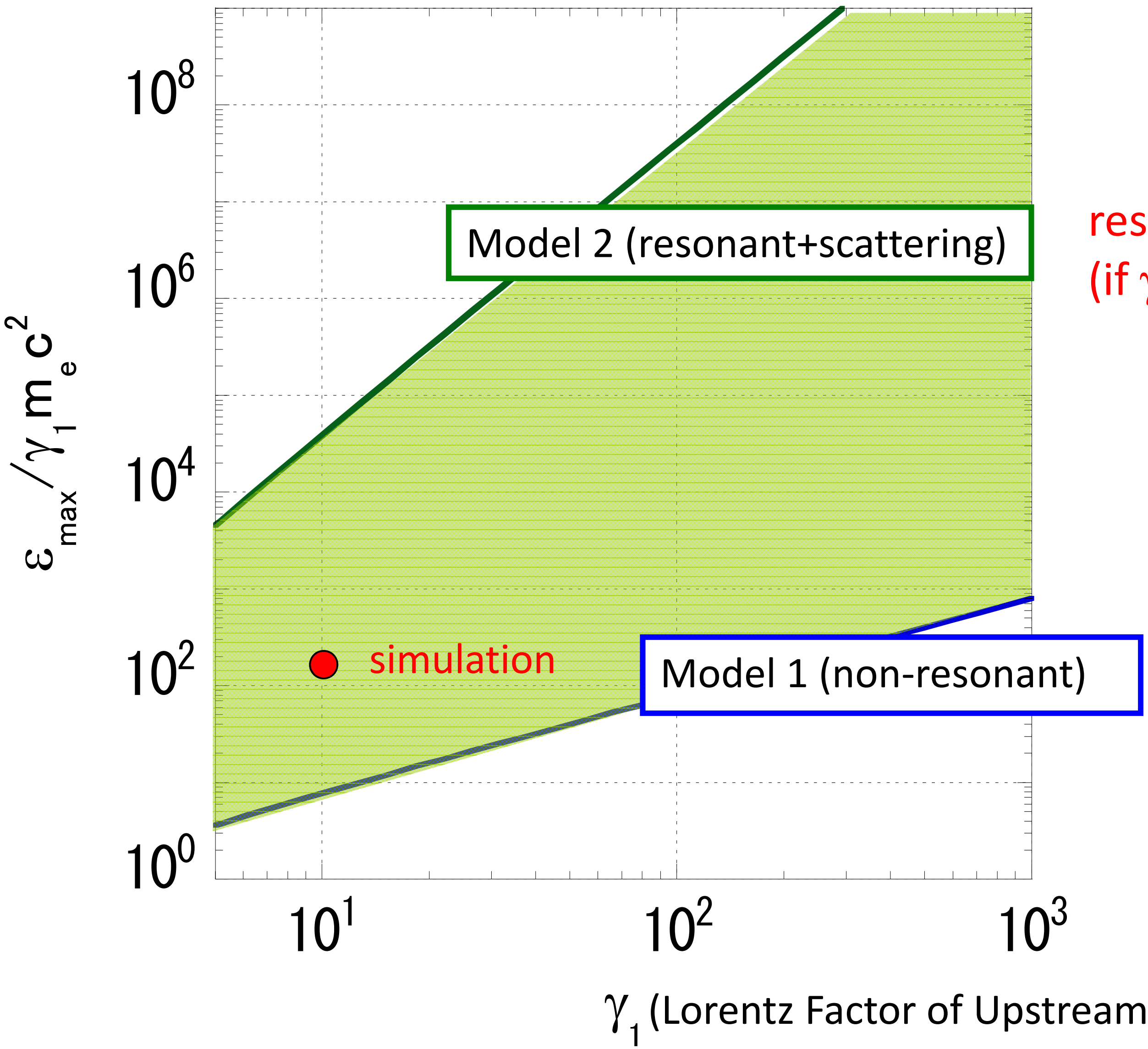




Tajima & Dawson, PRL (1979)

(confirmed in laboratory laser plasma experiments)

Maximum Attainable Energy



resonant+scattering model
(if $\gamma_1=10^3$, $\varepsilon_{max}=10^{20}$eV)

MH ApJ 2008

Summary

- Diffusive Shock Acceleration
  - can predict E^{-2} spectrum
  - maximum attainable energy problem
    - B field amplification
    - Nonlinear shock modification
- Wakefield Acceleration
  - acceleration by radiation pressure
- Resonant Absorption Acceleration
  - preferential positron acceleration