Particle acceleration at astrophysical sources

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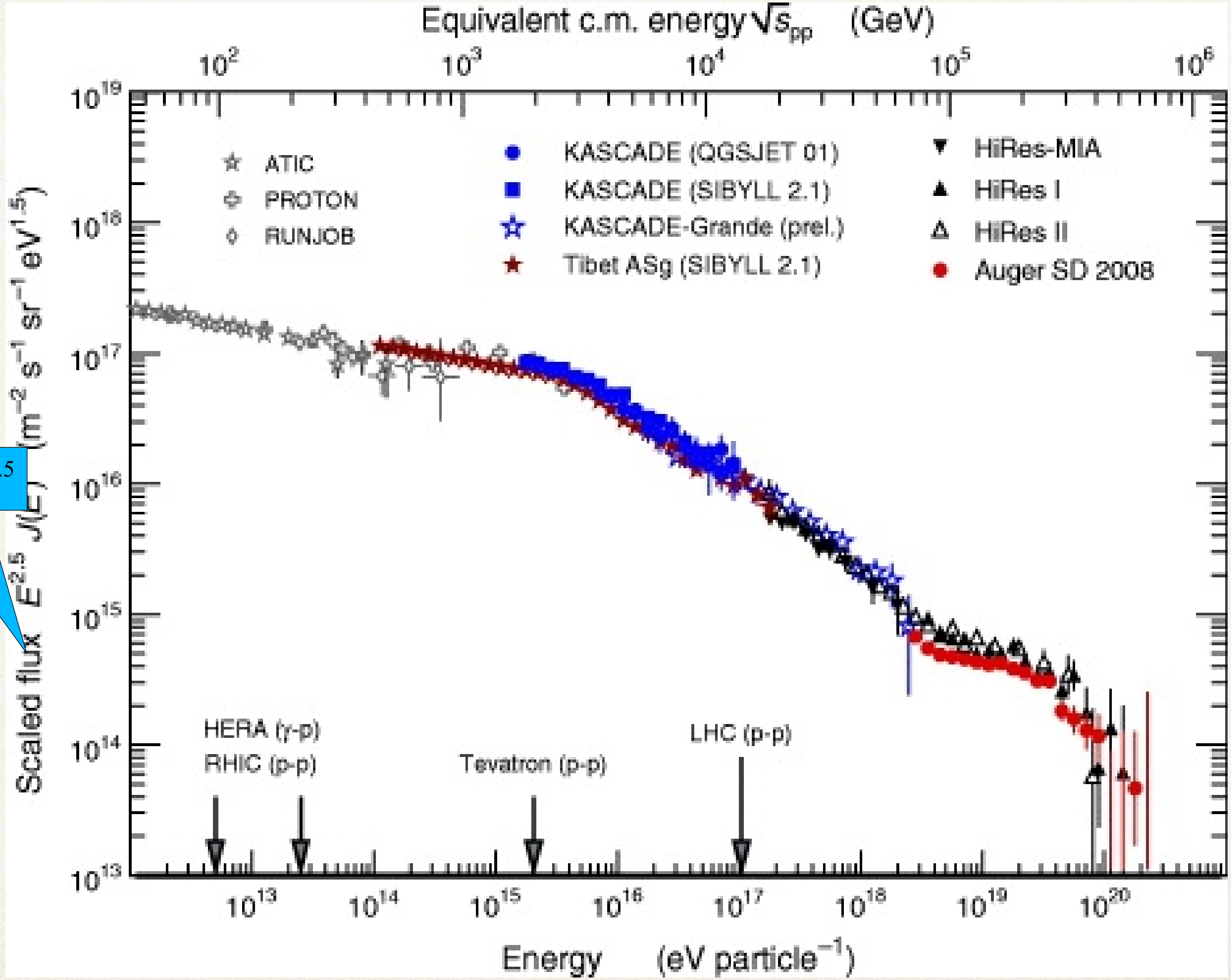
Summary

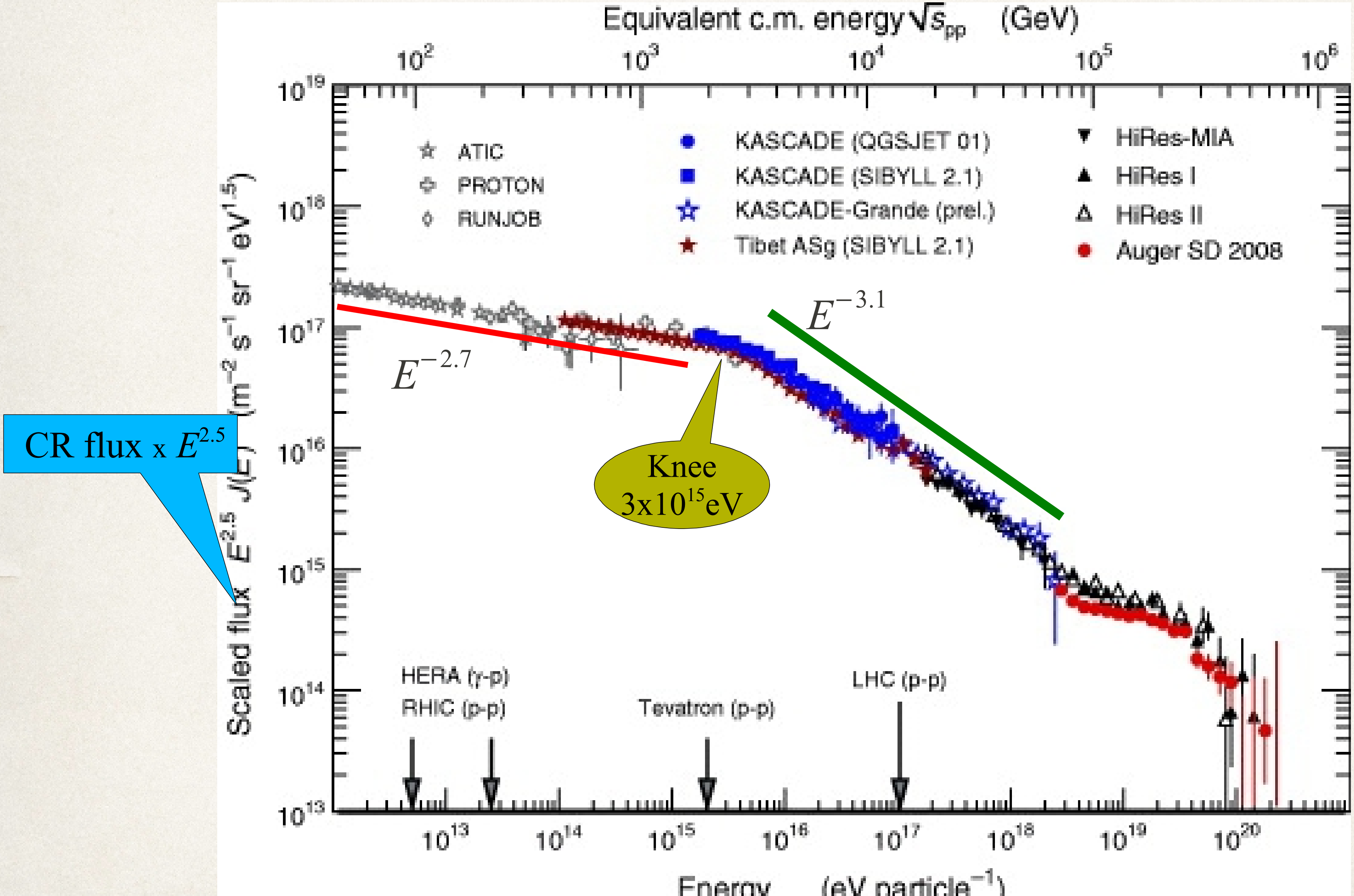
- A quick outlook to Cosmic Ray spectrum
- The SNR paradigm
- Diffusive shock acceleration
- Particle escape from sources
- PWN: Relativistic Shocks & Magnetic Reconnection

A quick view on cosmic ray spectrum

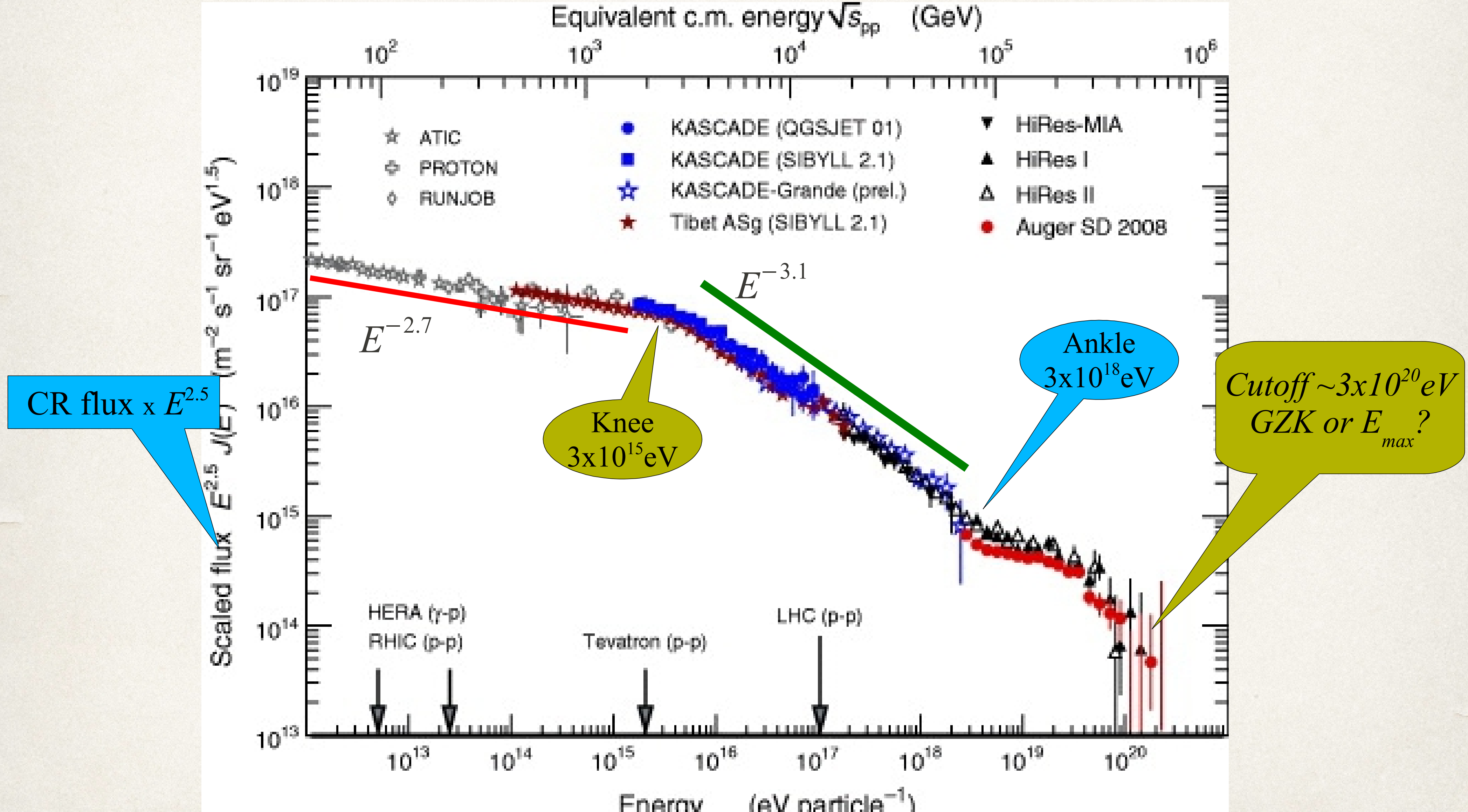


CR flux x $E^{2.5}$

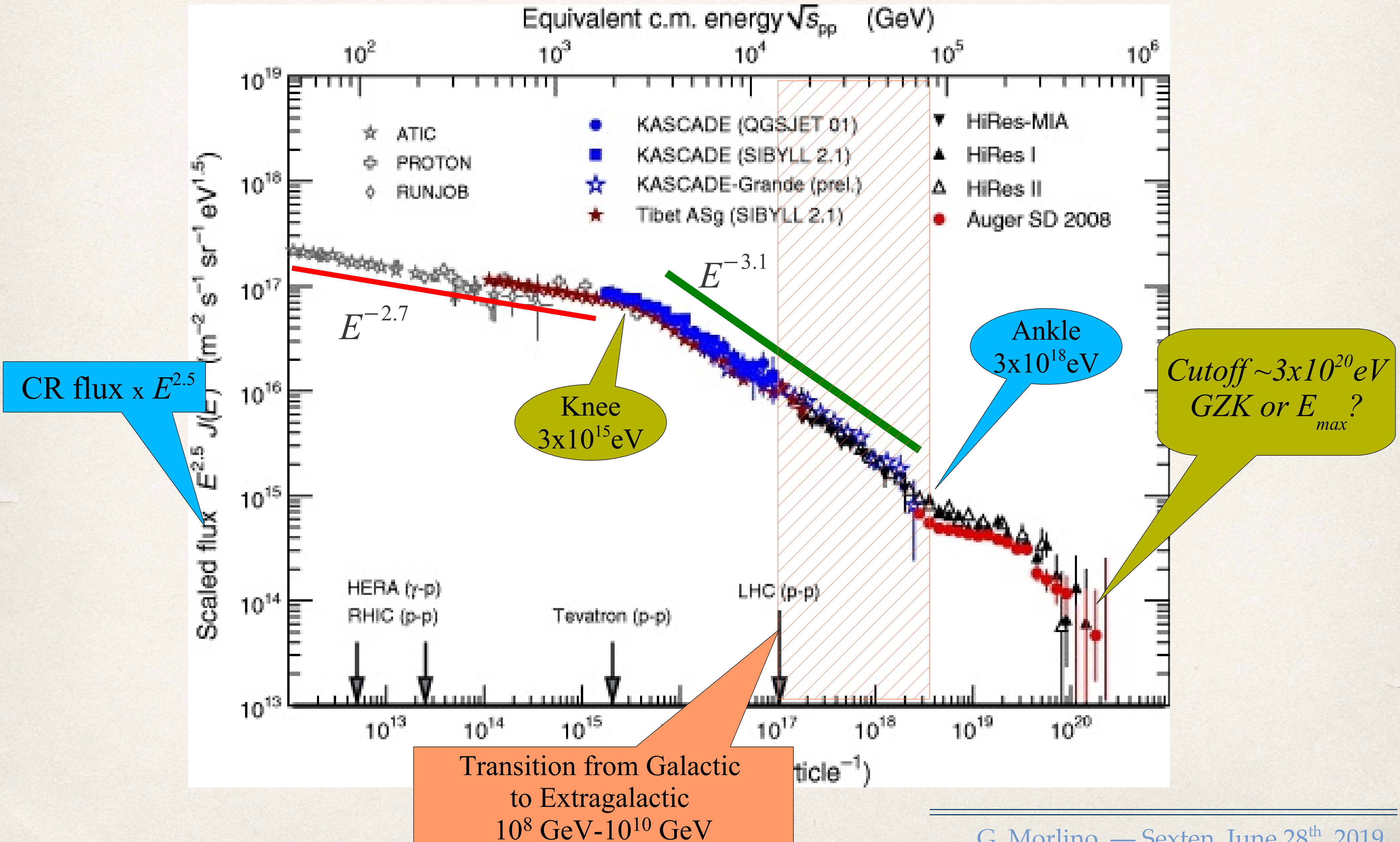
A quick view on cosmic ray spectrum



A quick view on cosmic ray spectrum



A quick view on cosmic ray spectrum



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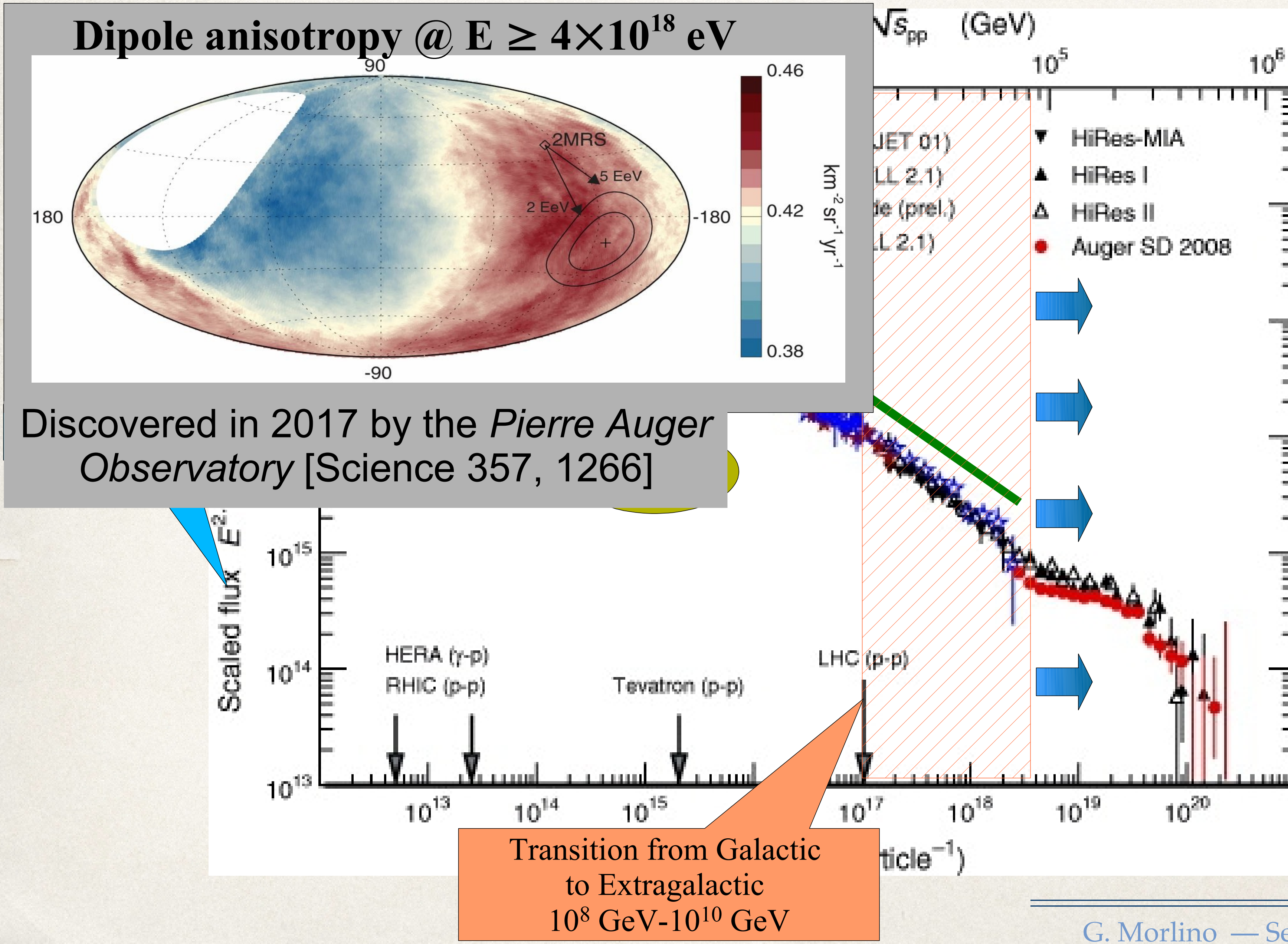
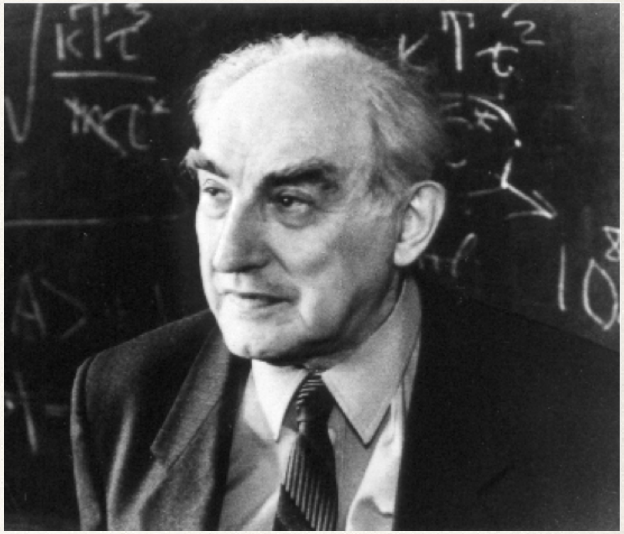


Origin of Galactic CRs

Zwicky & Baade were the first to postulate that SNR could be plausible sources of CRs (1934). But they concluded it was impossible because thought CR were extragalactic.



Vitali Lazarevich Ginzburg made the argument for SNRs as sources of galactic CR in the 60's in a more quantitative form.

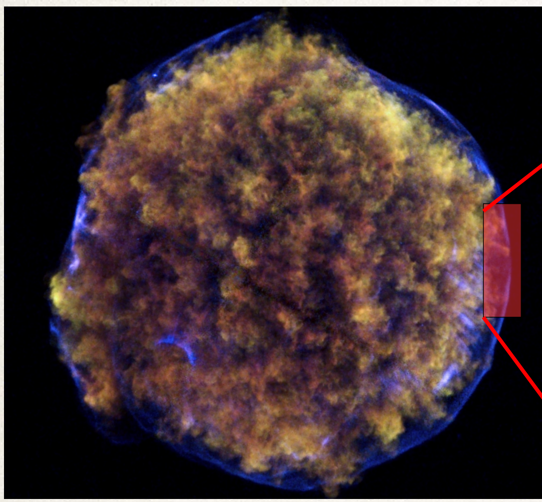
$$W_{CR} \sim U_{CR} Vol_{CR} / \tau_{res} \approx 10^{40}\, erg/s$$
$$W_{SN} \sim R_{SN} \;\; E_{SN} \approx 3 \cdot 10^{41}\, erg/s$$
$$\Rightarrow \quad \frac{W_{CR}}{W_{SN}} \approx 0.03 \div 0.3$$

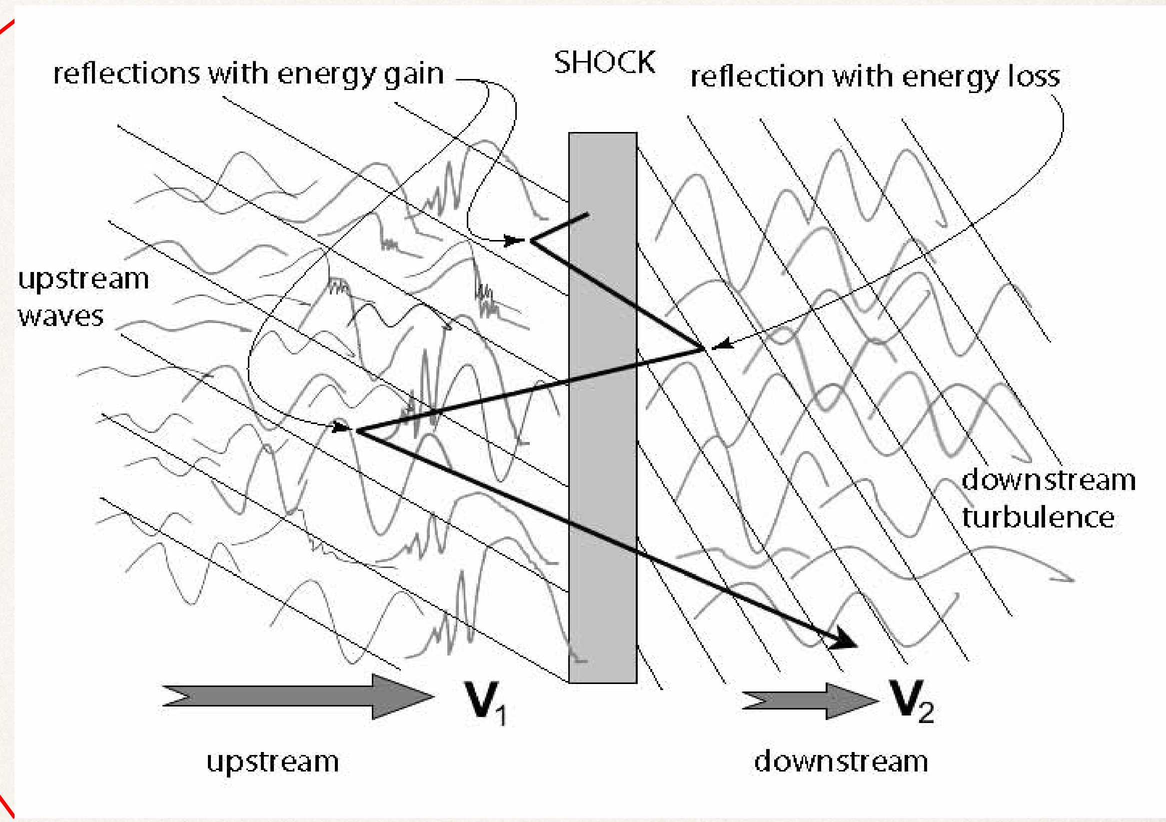
In principle ~10% of the SN kinetic energy is enough to explain the CR energy density

What kind of mechanism can transfer energy to non-thermal particle in a power law spectrum?

Where does acceleration occur?

Diffusive Shock Acceleration (proposed in the '70s)

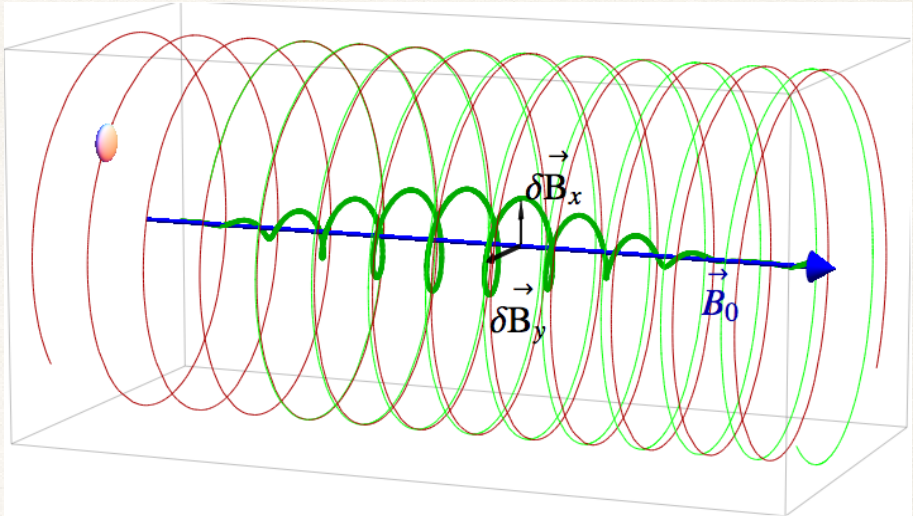




Repeated multiple scatterings produce small energy gain at each shock crossing

Why particles diffuse?

Particle motion in presence of magnetic perturbations



Equation of motion

$$\frac{d\boldsymbol{p}}{dt} = q\frac{\boldsymbol{v}}{c}\left(\boldsymbol{B}_0 + \delta\boldsymbol{B}\right);$$

$$p_z = mc\gamma\mu; \qquad \mu = \cos(\theta)$$

$$mc\gamma\frac{d\mu}{dt} = q\left(1-\mu^2\right)^{1/2}\left[\cos(\Omega t)\delta B_y - \sin(\Omega t)\delta B_x\right]$$

Average value of the variance over a time Δ*t*:

$$\left\langle \Delta\mu^2 \right\rangle = \frac{q^2(1-\mu^2)}{(mc\gamma)^2} B_k^2 \int dt \int dt' \cos[(\Omega - kv\mu)t + \phi]\cos[(\Omega - kv\mu)t' + \phi];$$

$$\left\langle \frac{\Delta\mu^2}{\Delta t} \right\rangle_\phi = \frac{q^2(1-\mu^2)\pi B_k^2}{(mc\gamma)^2} \frac{1}{v\mu}\delta\left(k - \frac{\Omega}{v\mu}\right)$$

Resonant condition

Many waves

IN A GENERAL CASE ONE DOES NOT HAVE A SINGLE WAVE BUT RATHER A POWER SPECTRUM:

$$P(k)=\delta B_k^2/8\pi$$

THEREFORE INTEGRATING OVER ALL OF THEM:

$$D_{\mu\mu}=\left\langle\frac{\Delta\mu^2}{\Delta t}\right\rangle=\frac{q^2(1-\mu^2)\pi}{(mc\gamma)^2}\ \frac{8\pi}{v\mu}\int dk\frac{\delta B_k^2}{8\pi}\delta\left(k-\frac{\Omega}{v\mu}\right)=\ \pi(1-\mu^2)\Omega\ \ k_{res}\frac{P(k_{res})}{B_0^2/8\pi}$$

OR IN A MORE IMMEDIATE FORMALISM: $D_{\theta\theta}=\pi\Omega k_{res}F(k_{res})$

THE DEFLECTION ANGLE CHANGES BY ORDER UNITY IN A TIME:

$$\tau\approx\frac{1}{\Omega k_{res}F(k_{res})}\quad\Rightarrow\quad D_{zz}=\frac{1}{3}v(v\tau)\approx\frac{v^2}{\Omega k_{res}F(k_{res})}$$

SPATIAL DIFFUSION COEFFICIENT

Particle scattering

- Each time that a resonance occurs, the particle changes pitch angle randomly by $\Delta\theta \sim \delta B/B$
- The resonance occurs only for right-hand polarized waves for particles moving to the right (and vice-versa)
- The resonant conditions tell us that:
  - If $k << 1/r_L$ particles surf adiabatically
  - If $k >> 1/r_L$ particles do not feel the waves

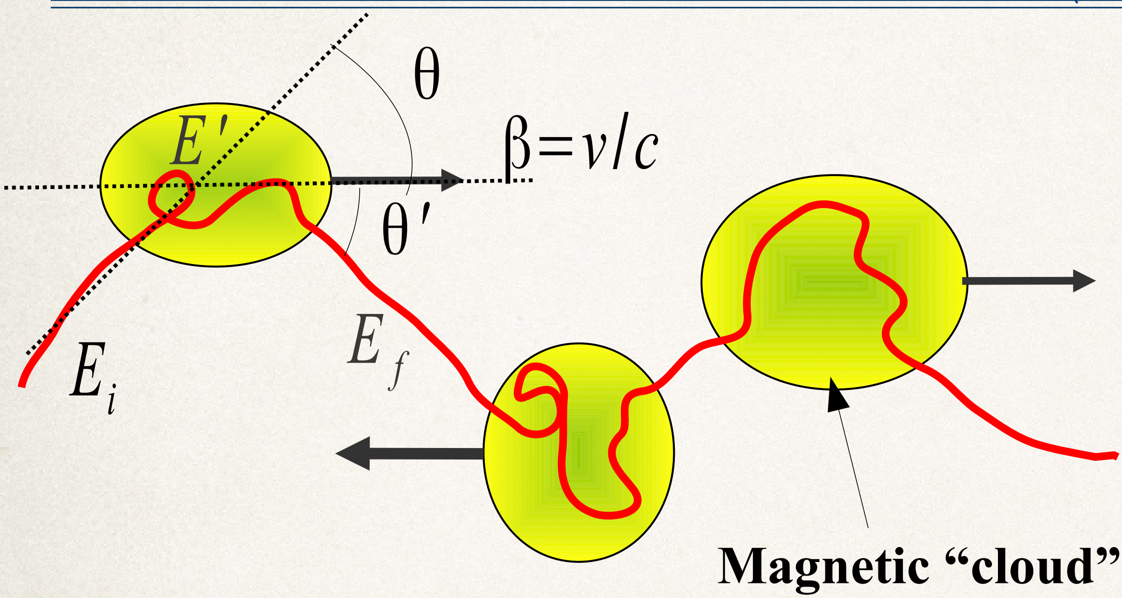
Where do the waves come from?

From diffusion to energy gain

- All acceleration mechanism are electromagnetic in nature
- Magnetic field do not makes work on charged particles!
- We need electric fields.
- But in the majority of astrophysical sources conductivity] ∞, hence $<E> = 0$
- The majority of acceleration mechanism are stochastic

$$\langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0$$

A quick look to 2nd order Fermi acceleration (Fermi, 1949)



Using Lorents transforations

$$E' = \gamma E_i (1-\beta\mu)$$
$$E_f' = E_i' = E'$$
$$E_f = \gamma E' (1+\beta\mu')$$
$$\rightarrow E_f = \gamma^2 E_i (1-\beta\mu)(1+\beta\mu')$$

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu'} = \int \frac{E_f - E_i}{E_i} d\mu' = 2\left[\gamma^2(1-\beta\mu)-1\right]$$

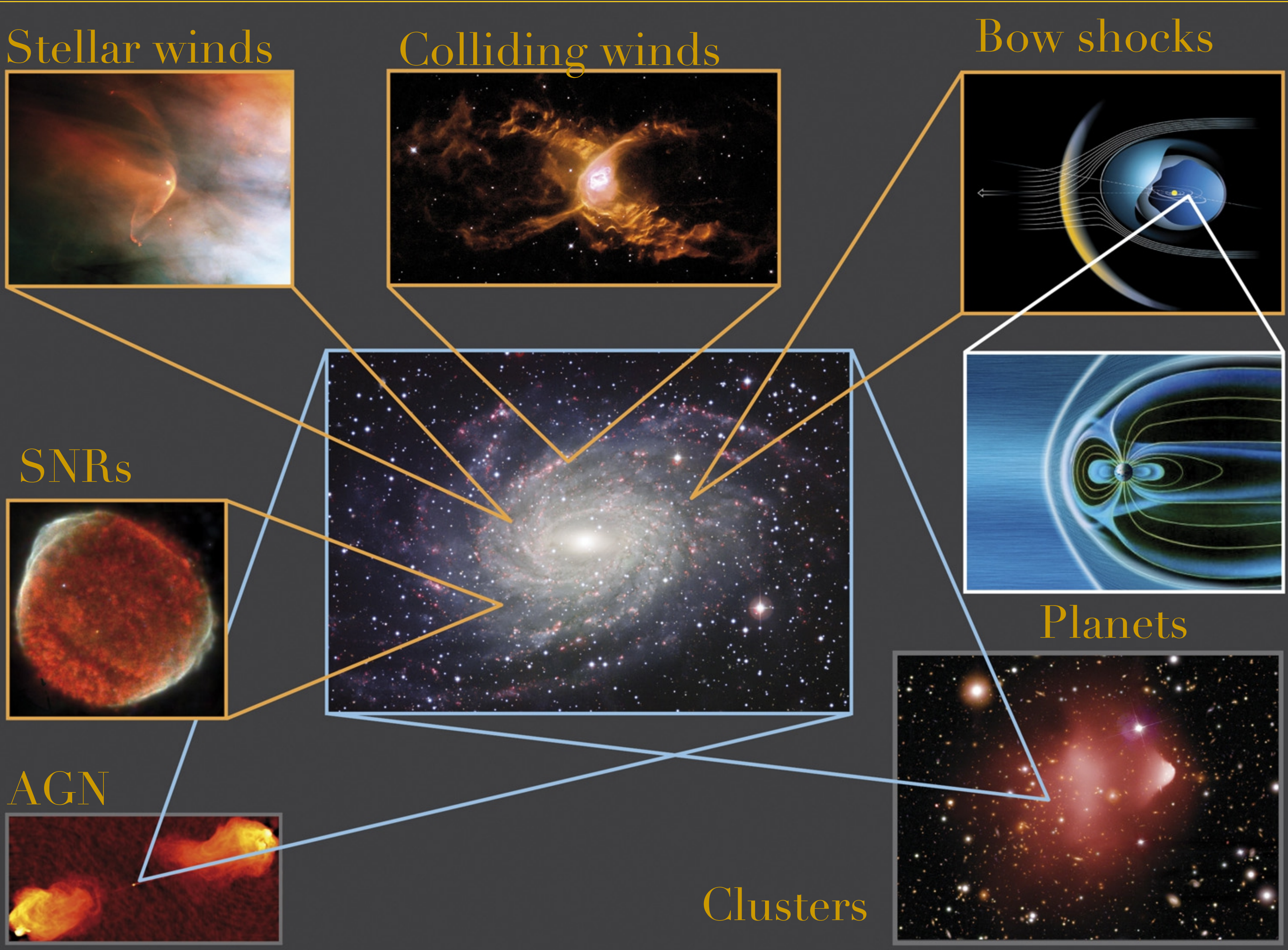
Assuming isotropy in the cloud's reference frame

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu'\mu} = \int_{-1}^{1} d\mu \frac{1}{2}(1-\beta\mu) 2\left[\gamma^2(1-\beta\mu)-1\right] \propto \beta^2$$

Losses and gains are both present but do not compensate exactly

The energy gain is too small to explain the CR spectrum

Shocks in the Universe



The nature of collisionless shock

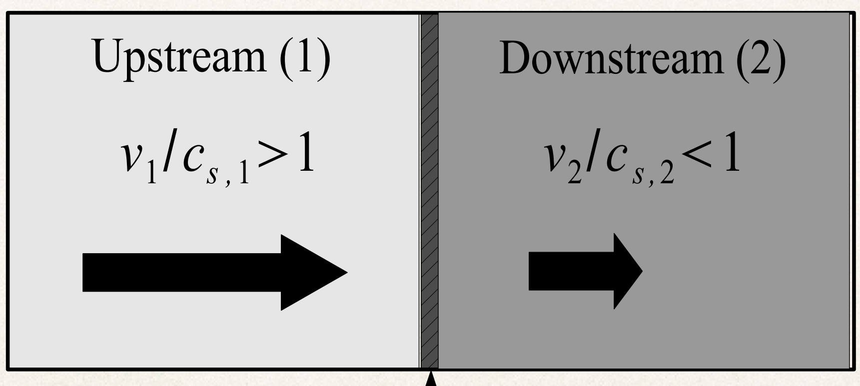
A shock is a discontinuity solution of the fluid equations where a supersonic fluid becomes subsonic (i.e. the entropy increases)

$$\left[\rho u\right]_1 = \left[\rho u\right]_2$$
$$\left[\rho u^2 + P\right]_1 = \left[\rho u^2 + P\right]_2$$
$$\left[\frac{1}{2}\rho u^3 + \frac{\gamma}{\gamma-1} P u\right]_1 = \left[\frac{1}{2}\rho u^3 + \frac{\gamma}{\gamma-1} P u\right]_2$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 - 1\right) \rightarrow \frac{2\gamma M_1^2}{\gamma+1}$$
$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1) M_1^2}{(\gamma-1) M_1^2 + 2} \rightarrow \frac{\gamma+1}{\gamma-1} \stackrel{\text{def}}{=} r$$
$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{\rho_1}{\rho_2}$$

$M_1 \gg 1$

$$M \stackrel{\text{def}}{=} v / c_s$$



Shock transition ~ λ

Caveats:
1) What produces the transition?
2) Does the fluid equations describe correctly astrophysical plasmas?

The nature of collisionless shock

What produce the shock transition?

$$\lambda_{mfp} \sim \frac{1}{n\sigma} = \begin{cases} \dfrac{1}{N_A \rho_{air} (2\pi a_0^2)} \sim \ 10^{-7}\, cm & \text{Collisions in air} \\[2ex] \dfrac{1}{n_{ISM}\, \sigma_{Coul}} \ > \ 1\, pc & \text{Collisions in the ISM} \end{cases}$$

But observationally
(from Balmer emission):

$$\lambda_{sh} \ll 10^{15}\, cm = \ 3 \times 10^{-4}\, pc$$

The nature of collisionless shock

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Length-scale for EM processes:

Electron skin depth $\quad \sigma_{pe} = \left(\dfrac{4\pi n_e e^2}{m_e}\right)^{1/2} = 5.3\times 10^5\, n_e^{-1/2}\, cm$

Ion skin depth $\quad \sigma_{pi} = \left(\dfrac{4\pi n_i e^2}{m_i}\right)^{1/2} = 2.3\times 10^7\, n_i^{-1/2}\, cm$

p's Larmor radius $\quad r_L(v_{sh}) = \dfrac{m_p v_{sh} c}{eB} = 10^{10} \left(\dfrac{v_{sh}}{3000\, km/s}\right)\left(\dfrac{B}{3\mu G}\right)^{-1} cm$

Shock thickness between these two lengthscale

Electro-magnetic instabilities in a shock

The shock transition is mediated by electromagnetic interactions.
Collisions have no role → the Mach number does not properly describe the shock properties

Alvénic Mach number is more appropriate:

$$M_A = \frac{v_{sh}}{v_A}; \qquad v_A = \frac{B}{\sqrt{4\pi\rho}} \approx 2 B_{\mu G} \left(\frac{n}{cm^{-3}} \right)^{-1/2} km/s$$

Alfvén waves are a combination of electromagnetic-hydromagnetic waves

Analogy with waves on a string: $v = \sqrt{T/\mu}; \quad T \to B^2/4\pi, \quad \mu \to \rho$

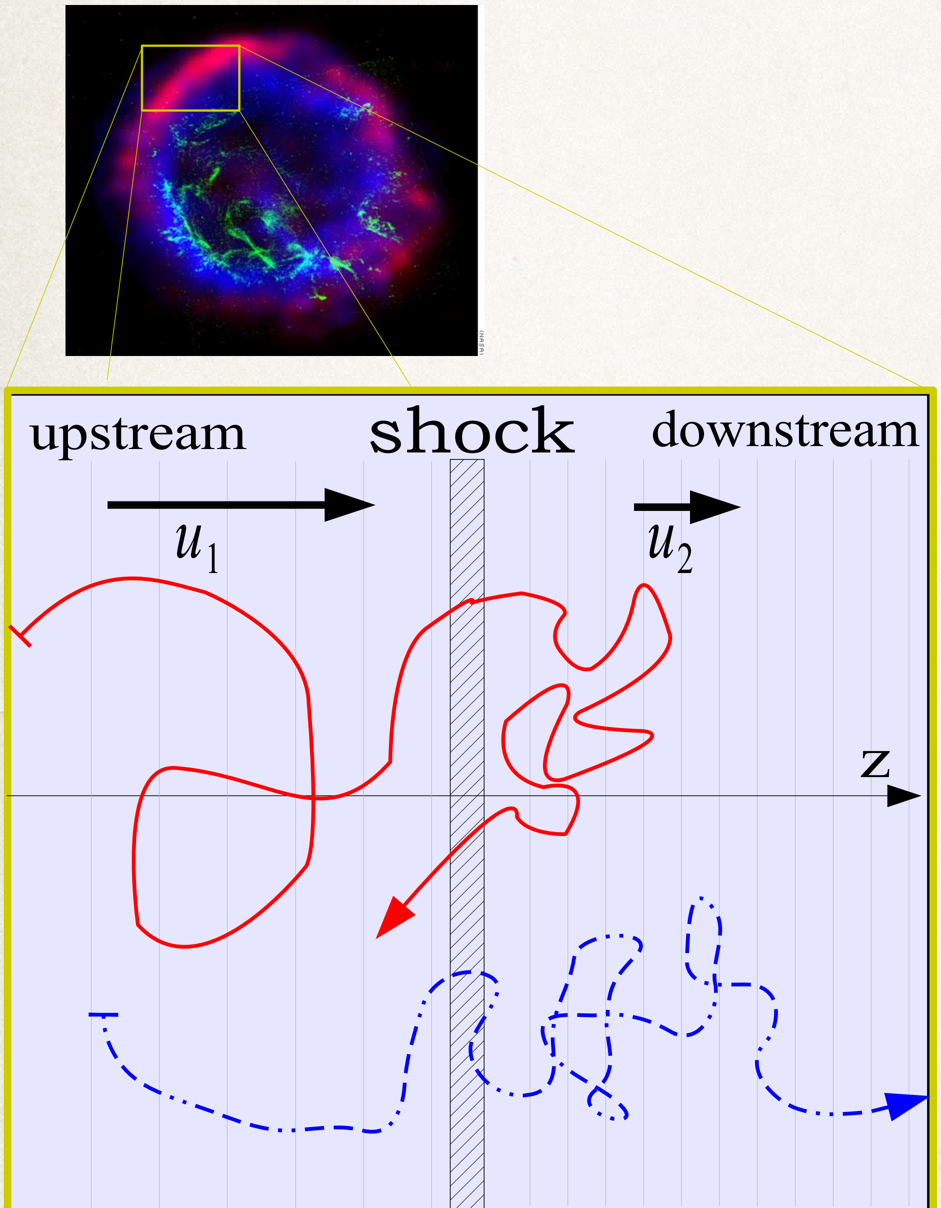
Collisionless shocks require $M_A > 1$

Which instability is responsible for the shock transition?

- Two stream instability
- Weibel instability
- Oblique instability
- Filamentation
- ...

The relative importance depends on the initial conditions of the plasma

Fermi mechanism applied to shocks: test particle approach



MICROSCOPIC APPROACH

Assuming isotropic distribution in all reference frames:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\frac{u_1 - u_2}{c}; \quad P_{esc} = 4\frac{u_1}{c};$$

Stochastic acceleration:

$$n(E) = \frac{dN}{dE} \propto E^{-\alpha};$$

$$\alpha = 1 - \frac{\ln P_{ret}}{\ln \Delta E/E} \approx 1 + \frac{P_{esc}}{\Delta E/E} = \frac{r+1}{r-1}$$

For strong shocks and mono-atomic gas:

$$r \equiv \frac{u_1}{u_2} \rightarrow 4$$

$$n(E) = E^{-2} \sim n(p) = p^{-4}$$

Maximum energy

The maximum energy is obtained comparing the acceleration time with the age of the accelerator and the energy losses

$$t_{acc} = min[t_{loss}, T_{age}] \Rightarrow E_{max}$$

Energy losses are usually negligible for protons but are important for electrons

Acceleration time: $$t_{acc} = \frac{t_{cycle}}{\Delta E/E}$$

Time for one cycle
upstream → downstream → upstream

$$t_{cycle} = \tau_{diff,1} + \tau_{diff,2}$$

Equating the particle injected from downstream with the particles upstream:

$$\frac{nc}{4}\Sigma\tau_{diff,1} = n\Sigma\frac{D_1}{u_1} \Rightarrow \tau_{diff,1} = \frac{4D_1}{c\,u_1} \quad \wedge \quad \tau_{diff,2} = \frac{4D_2}{c\,u_2}$$

$$t_{acc} = \frac{t_{cycle}}{\Delta E/E} = \frac{3}{u_1 - u_2}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right) \approx 8\,\frac{D_1}{u_{sh}^2}$$

Maximum energy

Maximum energy can increase only during the ejecta dominated phase of the SNRs because $u_{\mathrm{sh}} \sim const$

$$\begin{cases} t_{ST} = R_{ST}/u_{sh} \\ \frac{1}{2} M_{ej} u_{sh}^2 = E_{SN} \\ \frac{4\pi}{3} \rho_{ISM} R_{ST}^3 = M_{ej} \end{cases} \Longrightarrow \quad t_{\mathrm{ST}} \approx 50 \left(\frac{M_{\mathrm{ej}}}{M_\odot}\right)^{\frac{5}{6}} \left(\frac{E_{\mathrm{SN}}}{10^{51}\mathrm{erg}}\right)^{-\frac{1}{2}} \left(\frac{n_{\mathrm{ISM}}}{\mathrm{cm}^{-3}}\right)^{-\frac{1}{3}} \mathrm{yr},$$

Using the diffusion coefficient from quasi-linear theory:

$$D = \frac{1}{3} \frac{r_L v}{F(k_{res})}; \quad F(k) = \frac{\delta B^2}{B_0^2}$$

$$t_{acc} = t_{ST} \Longrightarrow \quad E_{\max} = 5 \times 10^{13} Z \mathscr{F}(k_{\min}) \left(\frac{B_0}{\mu\mathrm{G}}\right) \left(\frac{M_{\mathrm{ej}}}{M_\odot}\right)^{-\frac{1}{6}} \left(\frac{E_{\mathrm{SN}}}{10^{51}\mathrm{erg}}\right)^{\frac{1}{2}} \left(\frac{n_{\mathrm{ISM}}}{\mathrm{cm}^{-3}}\right)^{-\frac{1}{3}} \mathrm{eV}$$

High energies, up to PeV, can be achieved only if $F(k) \gg 1$.
This condition requires amplification of the Magnetic field

Predictions of *diffusive shock acceleration*

(1) ➡ **Spectrum:** $f_{CR}(p) \propto p^{-4} \rightarrow f_{CR}(E) \propto E^{-2}$

(2) ➡ **Acceleration efficiency: ~10%**

(3) ➡ **Maximum energy:** $E_{max} \simeq 50 \left(\frac{\delta B}{B_0}\right)\left(\frac{B_0}{\mu G}\right) TeV$

Strong dependence on magnetic field

High energies, up to PeV, can be achieved only if

$(\delta B/B_0)^2 >> 1$

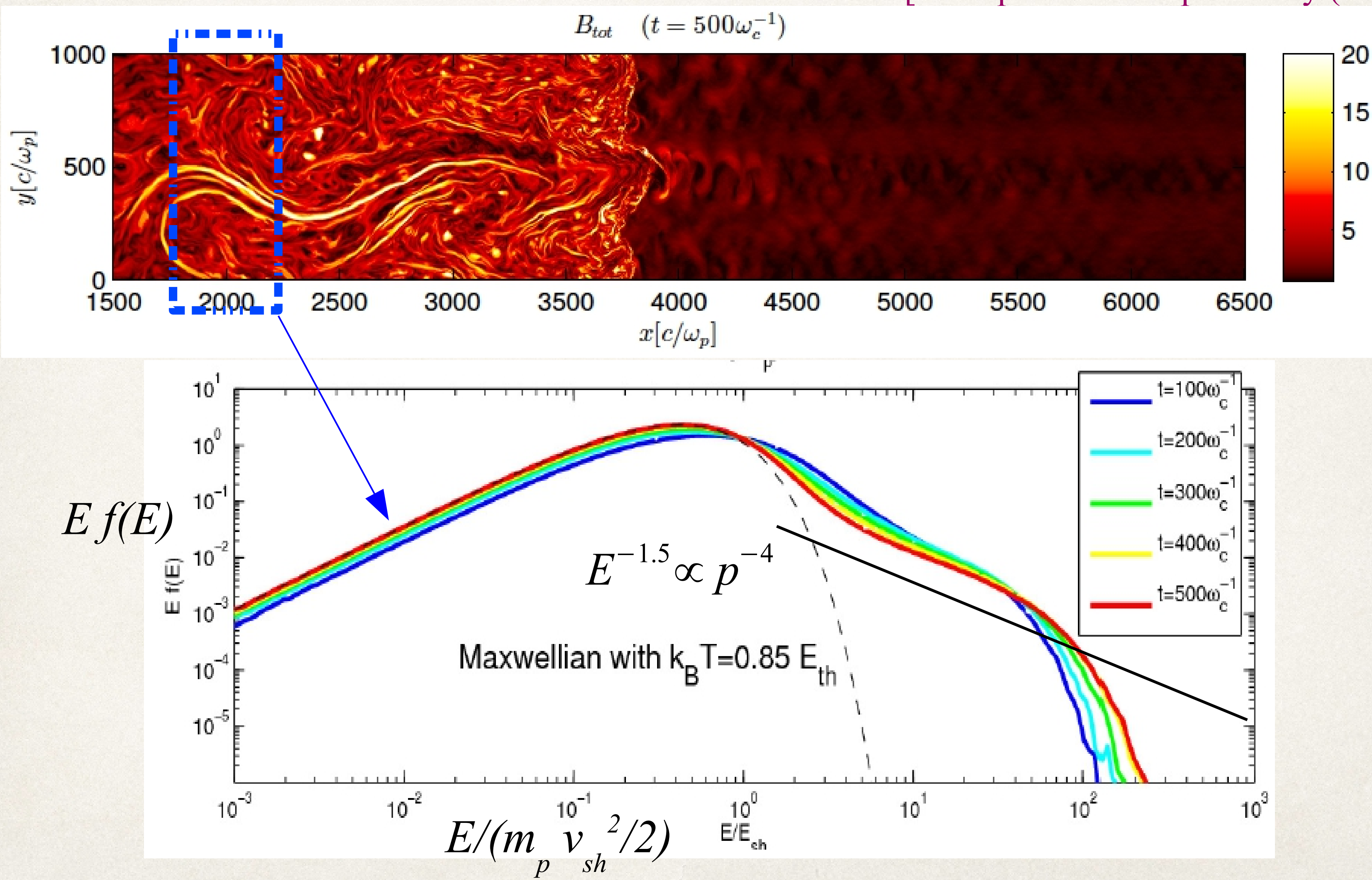
This condition requires amplification of the magnetic field

Fermi acceleration at work

[From Gargaté & Spitkovsky (2013)]

PIC simulation of particle acceleration

[D. Caprioli & A. Spitkovsky (2013)]

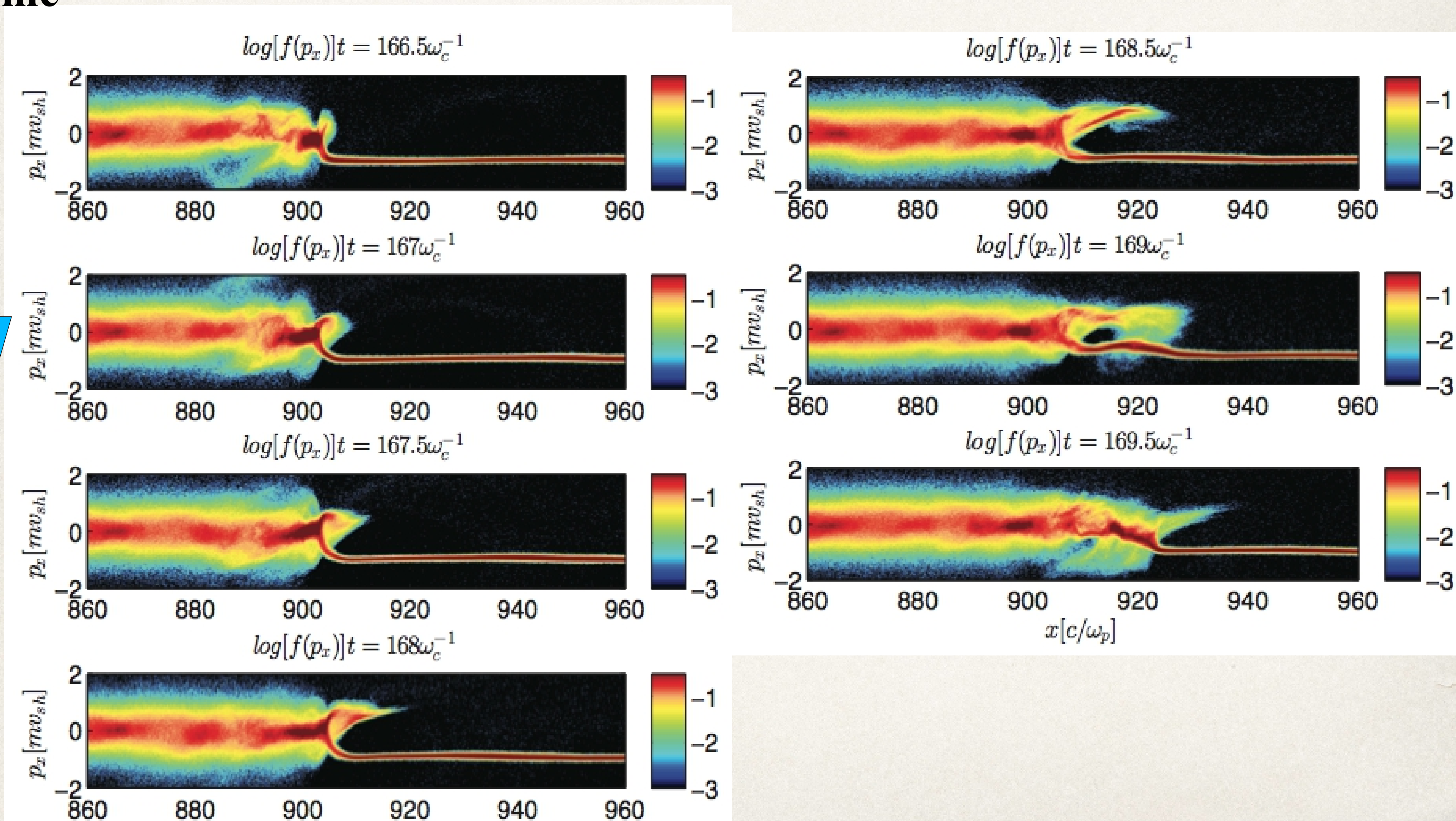


Particle injection and shock reformation

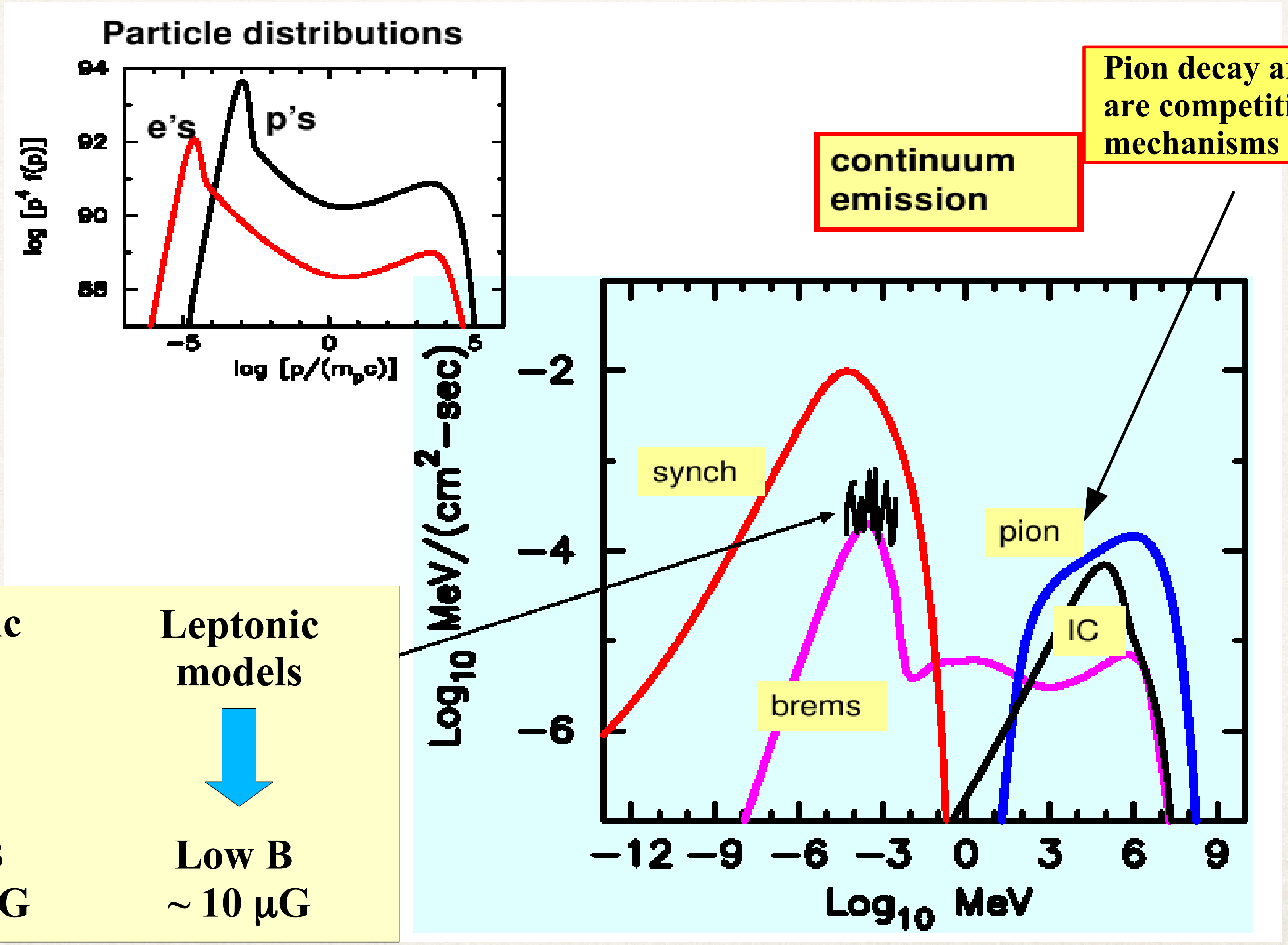
[From Caprioli, Pop & Spitkovsky (2015)]

Time

Hybrid simulation



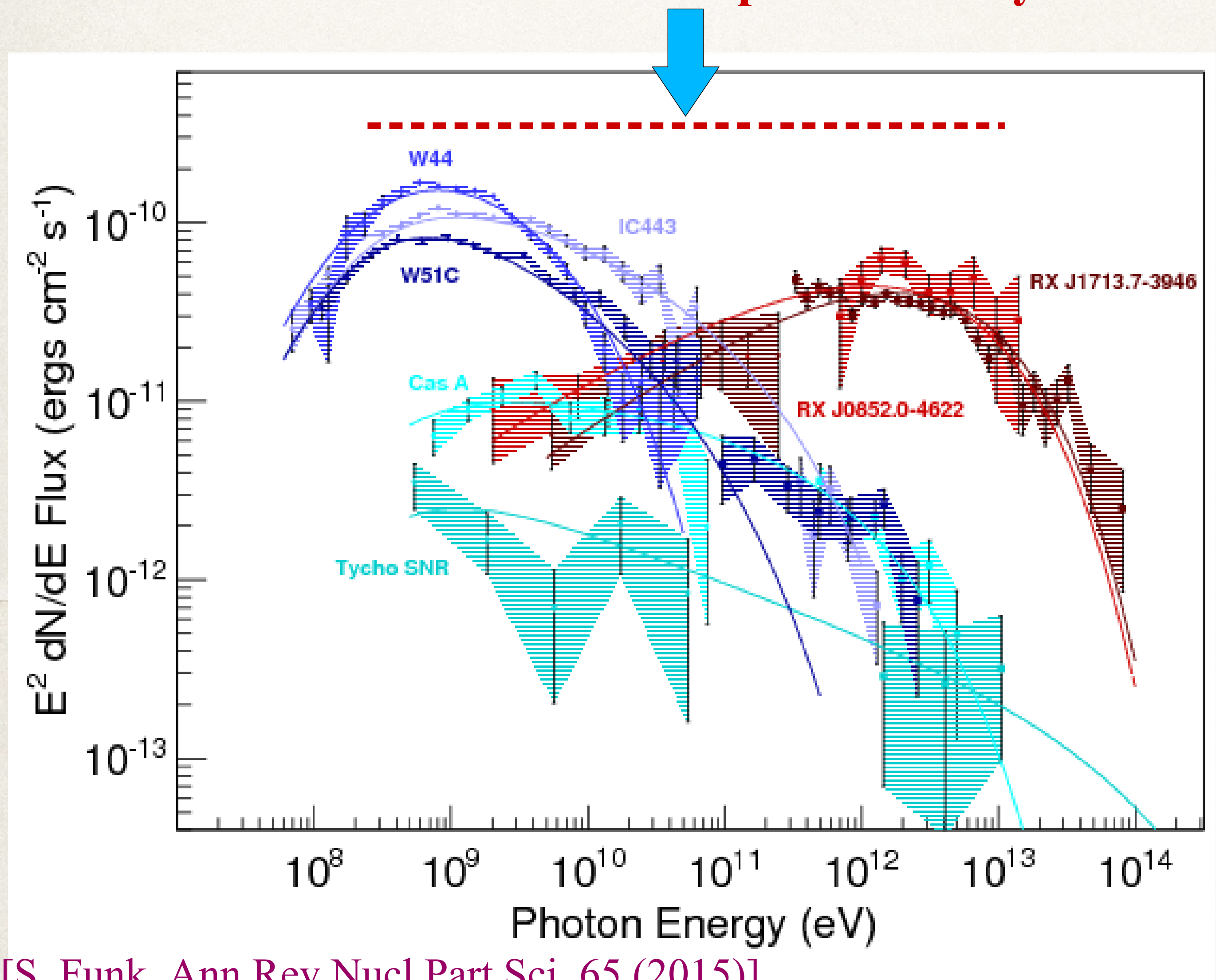
Non-thermal spectrum from SNRs



Hadronic models	Leptonic models
↓	↓
Large B >~ 100 μG	Low B ~ 10 μG

Gamma-rays from SNRs:
what's wrong with DSA?

Prediction of test prticle theory



[S. Funk, Ann.Rev.Nucl.Part.Sci. 65 (2015)]

Middle-aged SNRs (~20.000 yrs)

- hadronic emission
- steep spectra ~E^{-3}
- E_{max} < 1 TeV

Young SNRs (~2000 yr)

- Hadronic/leptonic?
- Hard spectra
- E_{max} ~ 10-100 TeV

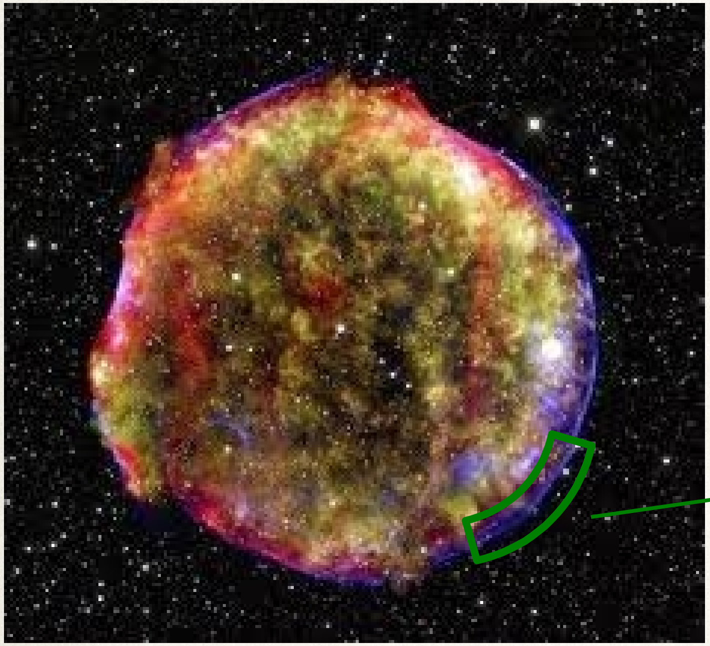
Very young SNRs (~300 yr)

- hadronic
- steep spectra ~$E^{-2.3}$
- E_{max} ~ 10-100 TeV

Not enough to explain the Knee at ~ PeV

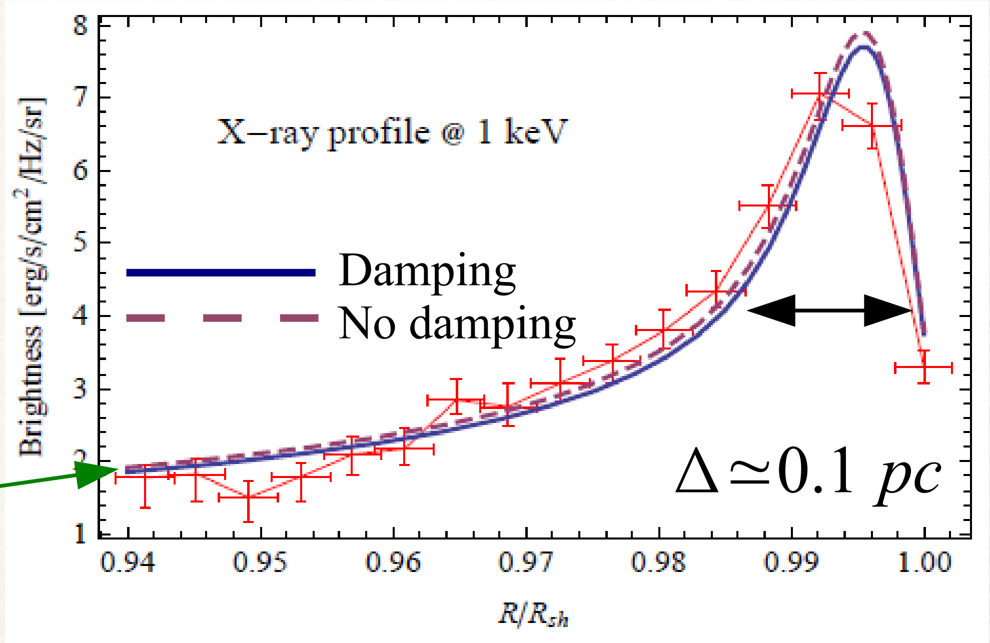
Magnetic field amplification: observations

Chandra X-ray map.
Data for the green sector are from Cassam-Chenaï et al (2007)



Thin non-thermal X-ray filaments provide evidence for magnetic field amplification

[Hwang el al(2002); Bamba et al (2005)]



X-ray thickness = Synchrotron losslength

$$\begin{cases} D = r_L c/3 \propto E B^{-1} \\ \tau_{syn} = \dfrac{3 m_e c^2}{4 \sigma_T c \gamma \beta^2 U_B} \propto E B^{-2} \end{cases}$$

$$\Delta \simeq \sqrt{D \tau_{syn}} \propto B^{-3/2}$$

⇒ ***B*~200-300 μG >> B_{ISM}**

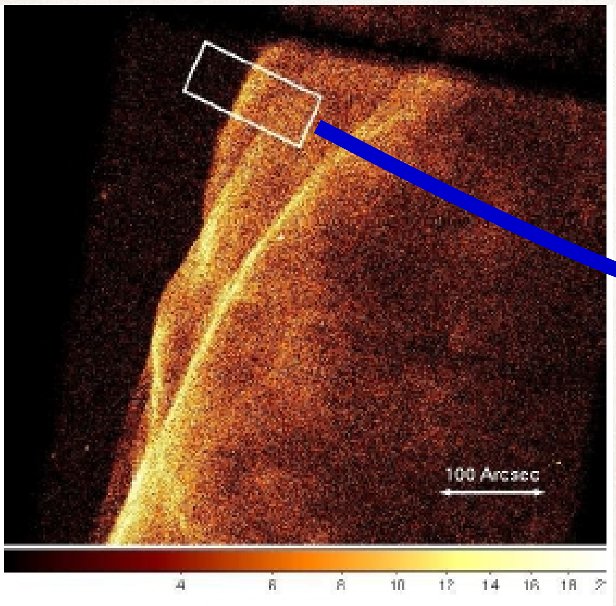
Where is the magnetic field amplified?

DOWNSTREAM: MHD instabilities (shear-like)

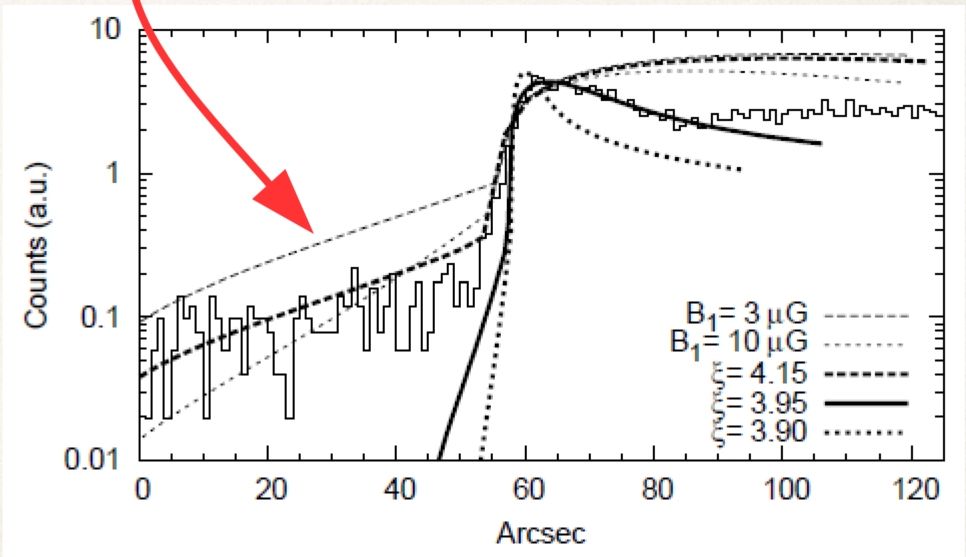
UPSTREAM: only through instabilities driven by CRs (Streaming, Bell)

BUT we need amplification upstream
of the shock to reach high energies

Low magnetic field upstream produces a more extended emission NOT OBSERVED!



SN1006 in X-rays (*Chandra*)



[from G.M., Amato, Blasi, 2009, MNRAS]

Magnetic field amplification: Theory

How is the magnetic field amplified?

Resonant Straming instability

[e.g. Skilling (1975), Bell & Lucek (2001), Amato & Blasi (2006), Blasi (2014)]

Particles amplify Alfvèn waves with wave-number

$k = 1/r_L(p)$

Fast growth rate but

$$\left(\delta B / B_0\right)^2 \simeq 1$$

$$E_{max} \approx 100\, TeV$$

A factor 10 below the knee

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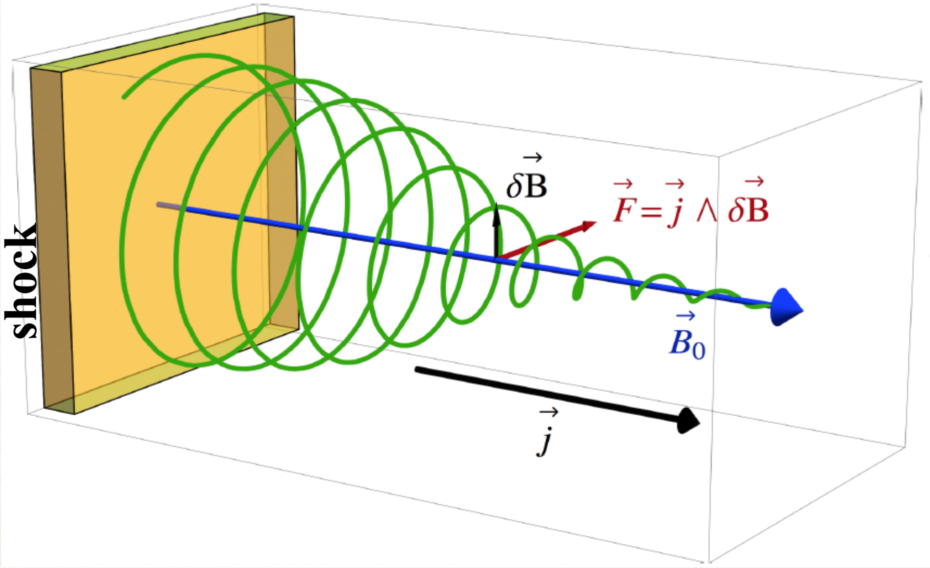
Non-resonant
***Bell* instability**

[Bell (2004)]

$E_{max} \propto \sqrt{\rho_{CSM}}$

Amplification due to $\vec{j} \wedge \vec{B}$ force



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Non-resonant *Bell* instability

[Bell (2004)]

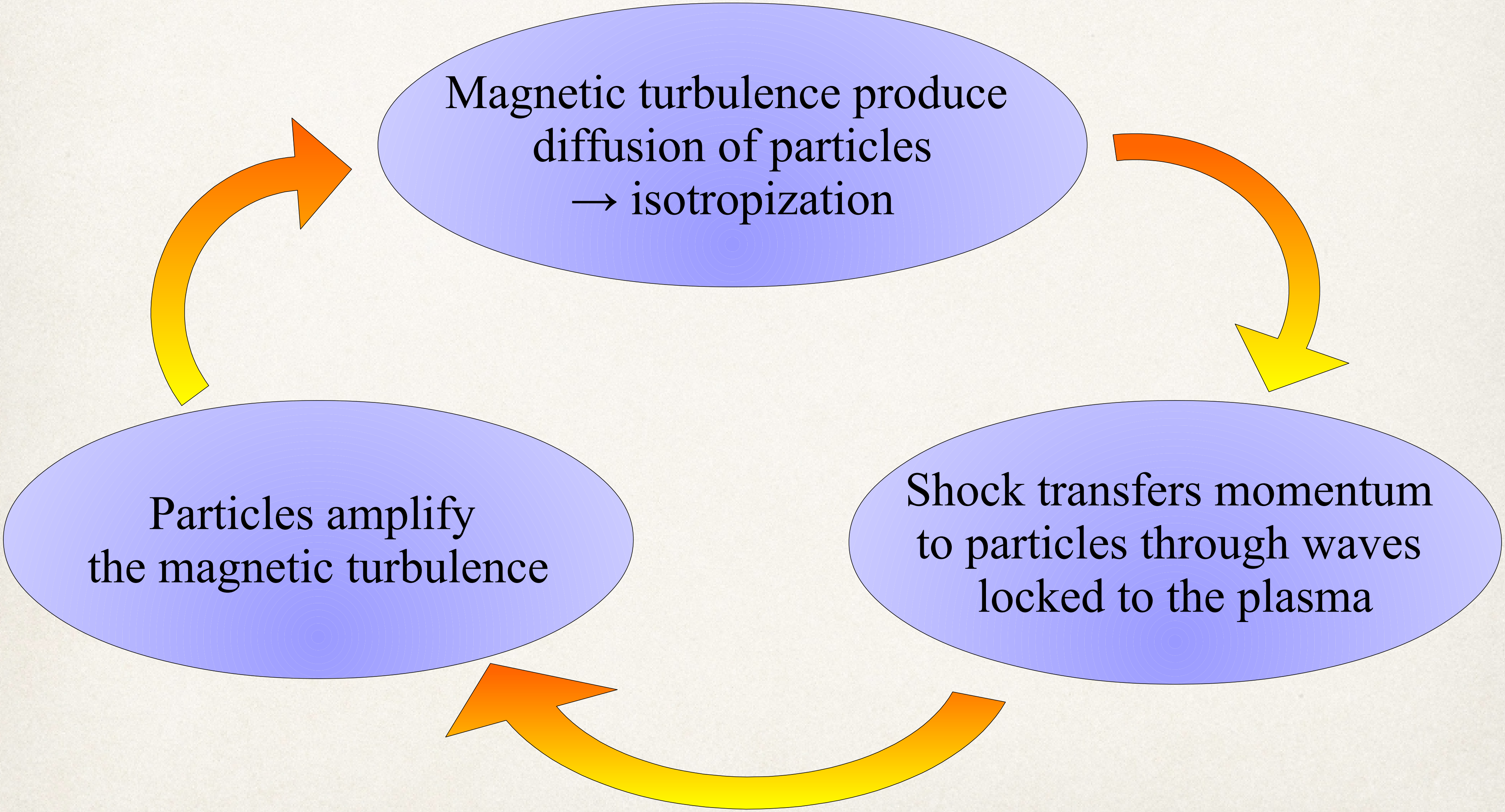
$$E_{max} \propto \sqrt{\rho_{CSM}}$$

Type Ia SNR expanding into a uniform medium → $E_{max} \approx 100\, TeV$

Core-Collapse SNR expanding into a red supergiant wind → $E_{max} \approx 2000\, TeV$

Right number, but this last only ~50 yr!

The non-linear fashion of DSA



Particle escape from SNRs

If particles are not released all at the same time, in general:

Spectrum injected into the Galaxy $\quad f_{esc}(p) \neq f_{SNR}(p) \quad$ Spectrum inside SNRs

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Assume that at time t only particles at maximum momentum $p_{\max}(t)$ can escape

$$4\pi f_{esc}(p)\, c\, p\, p^2\, dp = \xi_{esc}(t)\, \frac{1}{2}\rho V_{sh}^3\, 4\pi R_{sh}^2\, dt$$

Released energy

Converted fraction

Incoming energy flux

Particle escape from SNRs

If particles are not released all at the same time, in general:

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$$\Downarrow$$

$$f_{esc}(p) \propto p^{-4} V_{sh}(t)^{5\alpha-2}\, \xi_{esc}(t)$$

$$\Downarrow$$

$$\boxed{f_{esc}(p) \propto p^{-4}}$$

- Expantion in omogeneous medium with $R_{sh}(t) \propto t^{\alpha}$
- Escaping during the Sedov-Tayor phase (^ α=2/5)
- ξ_{esc}(t) ≈const

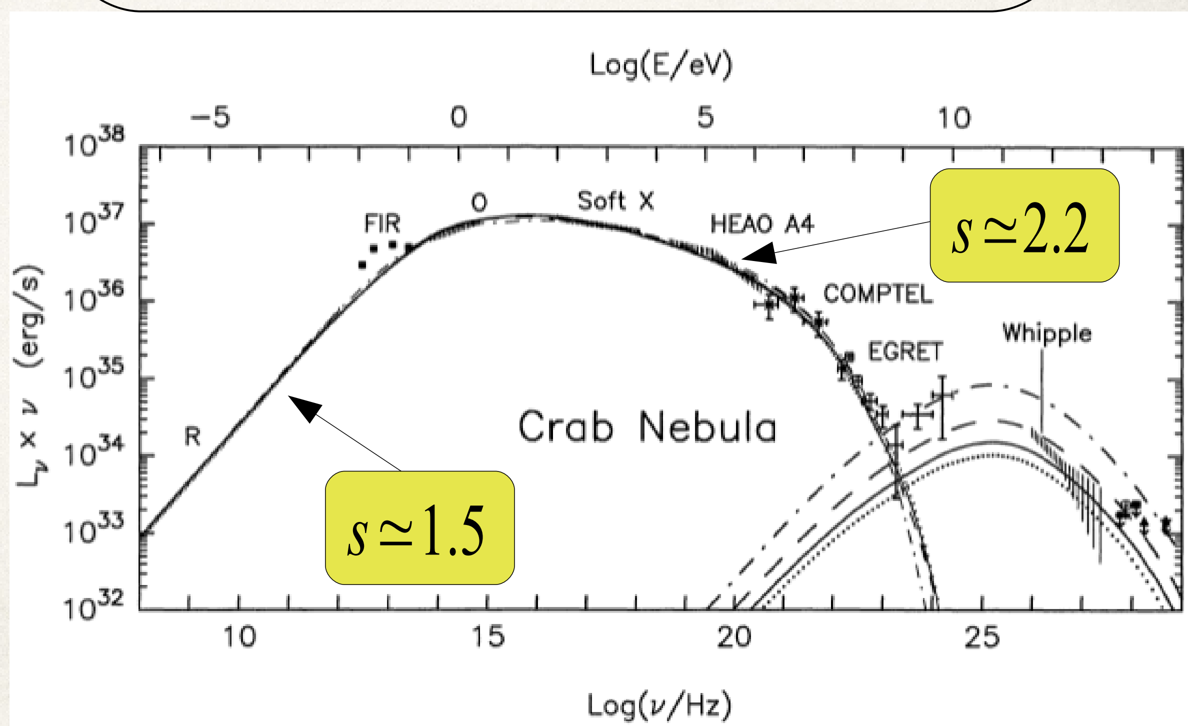
Spectrum NOT related to Fermi acceleration process!

Pulsar Wind Nebulae

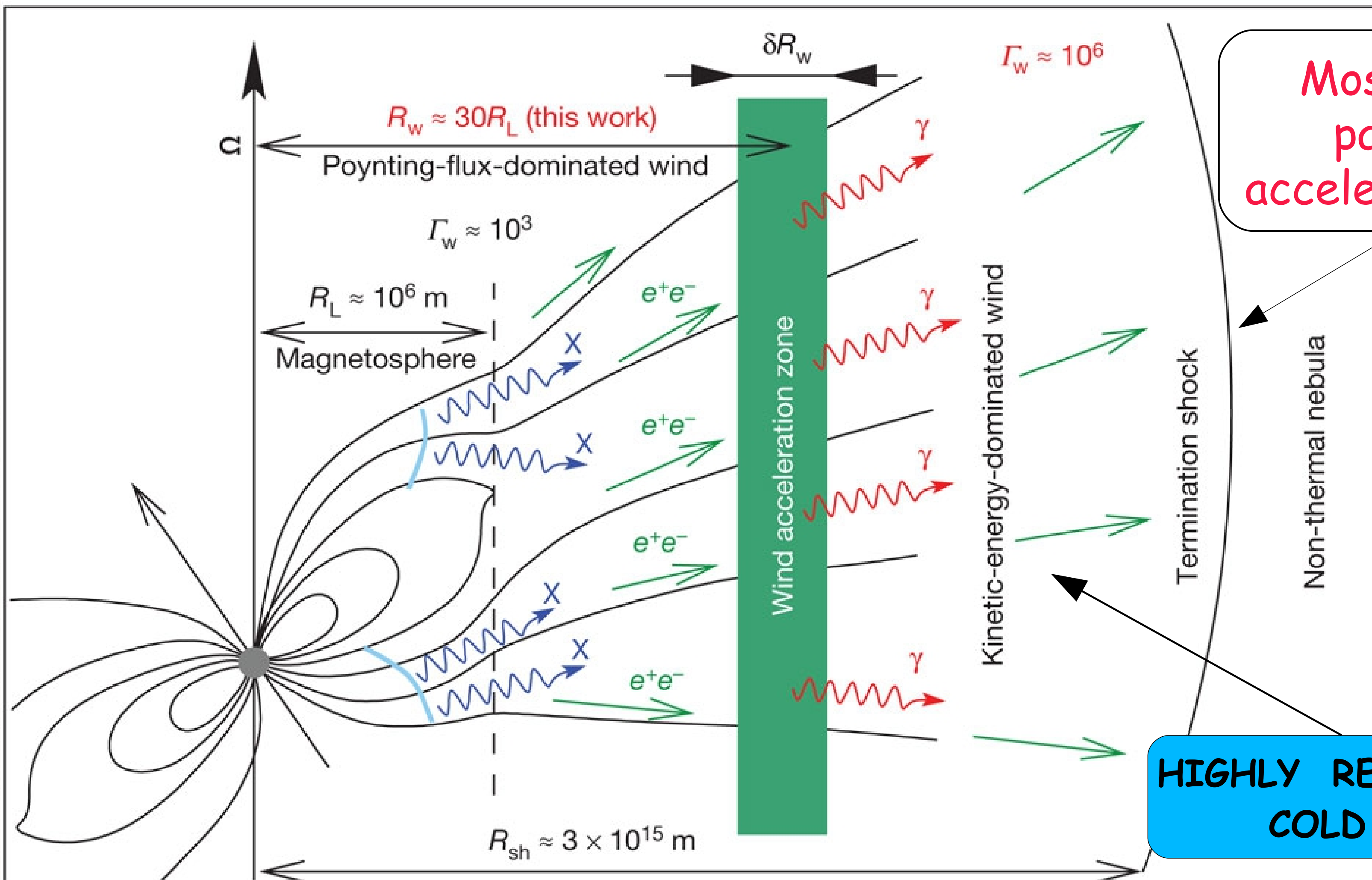
The Crab nebula
(where we have learnt most of what we know)

Primary emission mechanism:
synchrotron radiation by
relativistic particles in a
intense (>few x 100 B_{ISM}) *ordered*
(high degree of polarization, in radio,
optical and even γ-rays, Dean et al. 08)
magnetic field

Source of B field and
particles:
NS suggested before
pulsar discovery
(Pacini '67)



THE BASIC PICTURE



Most likely particle acceleration site

HIGHLY RELATIVISTIC COLD WIND

In Crab R_{TS} ~0.1 pc from pressure balance (e.g. Rees & Gunn 74)

F. A. Aharonian, S. V. Bogovalov & D. Khangulyan (2012)

THE TERMINATION SHOCK

THE RADIUS OF THE TERMINATION SHOCK CAN BE DERIVED FROM THE PRESSURE BALANCE BETWEEN THE RELATIVISTIC WIND AND THE NON-RELATIVISTIC NEBULA: $R_{TS} \sim R_N (V_N/C)^{1/2} \sim 10^9\text{-}10^{10}\ R_{LC}$ (REES & GUNN 74) – HERE WE ASSUMED THAT THE MAGNETIC PRESSURE IS NEGLIGIBLE, NOT TRUE IN GENERAL – In the Crab R_{TS} ~0.1 pc

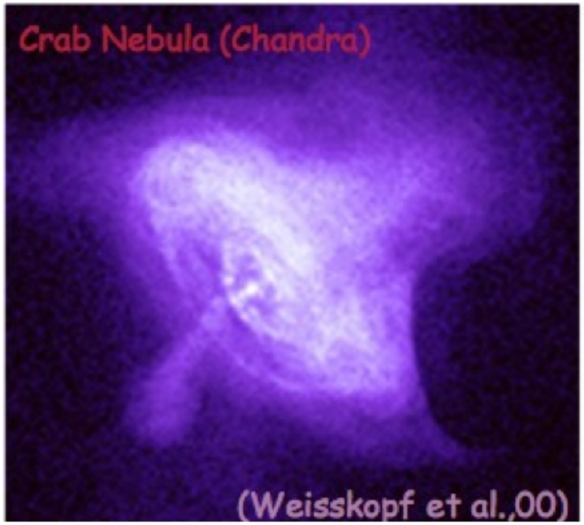
Composition: mainly pairs maybe a fraction of ions
Geometry: perpendicular where magnetized even if field not perfectly toroidal
Magnetization: $\sigma = B^2/4\pi n \Gamma m c^2 \rightarrow \sigma \sim V_N/c \ll 1$, a paradox

At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)

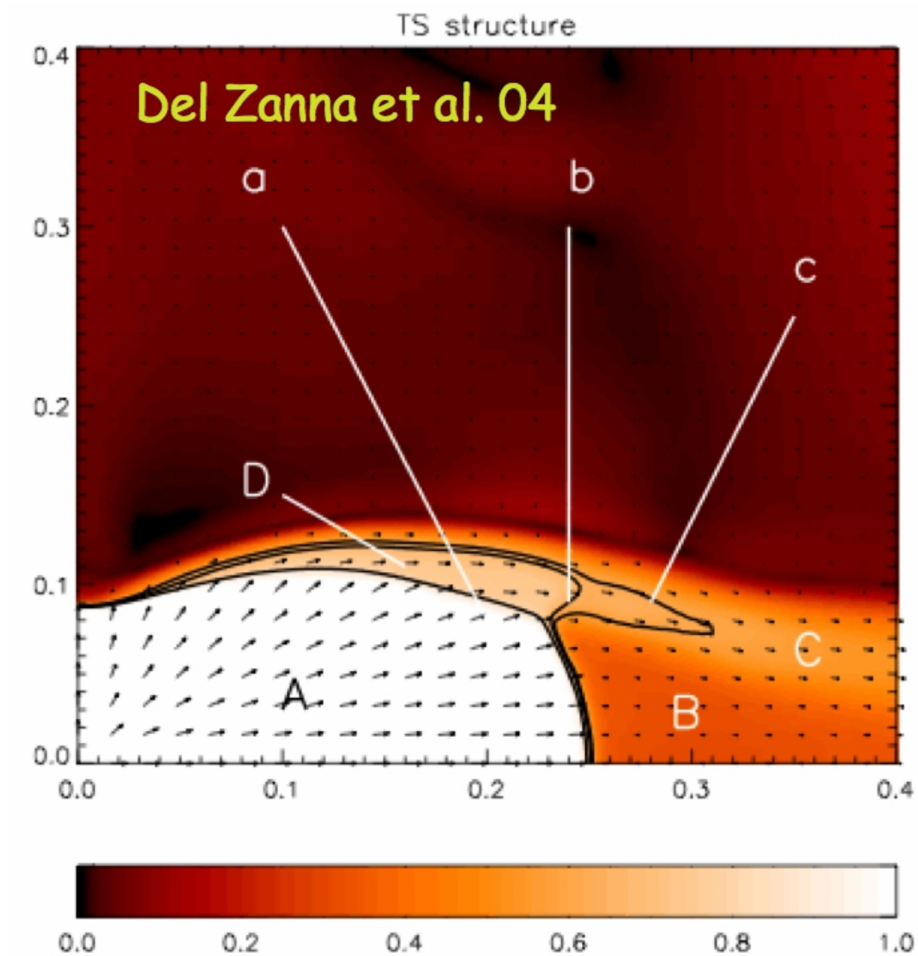
σ-paradox!

At R_{TS}: $\sigma \sim V_N/c \ll 1$(!?!) $\Gamma \in (10^4\text{-}10^7)$
(PWN theory and observations)

A MORE REALISTIC STRUCTURE OF THE TERMINATION SHOCK



The termination shock is not spherical

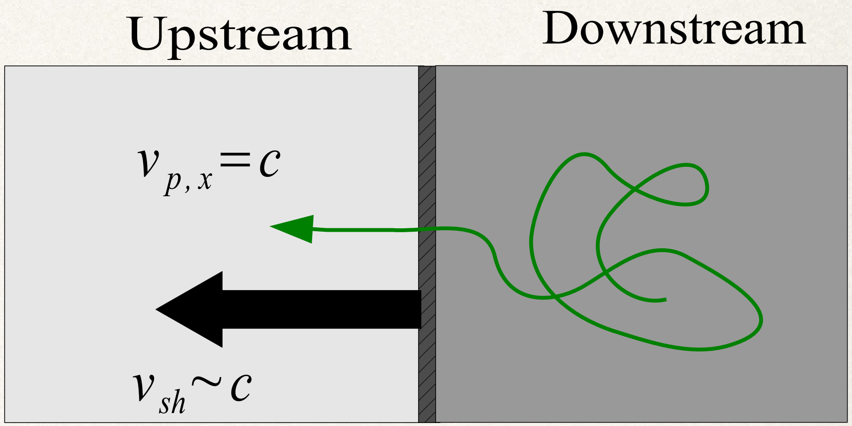


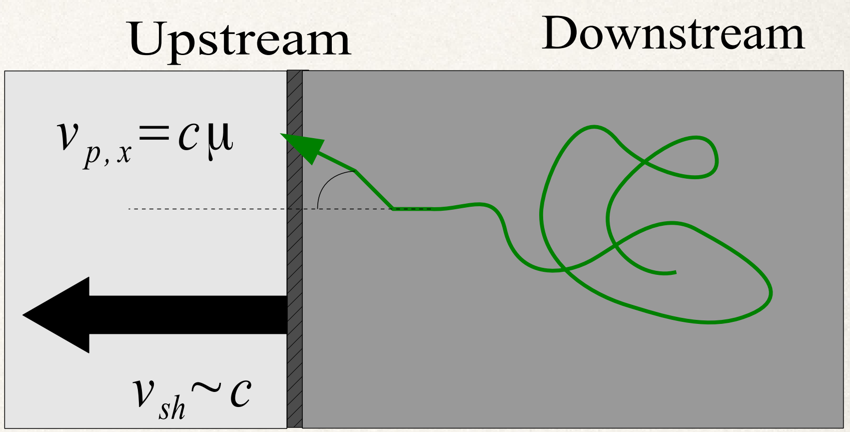
ACCELERATION AT THE TERMINATION SHOCK

Is the termination shock able to accelerate particles?

- Cold high relativistic wind: $\gamma > 10^5$
  $\rightarrow$ particles are catched by the shock as

$$\mu < 1/\gamma$$





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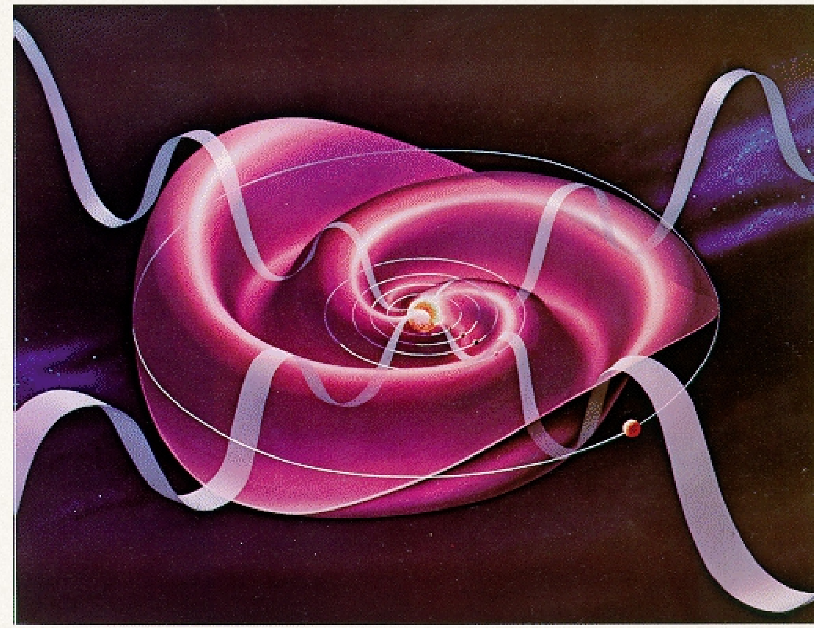
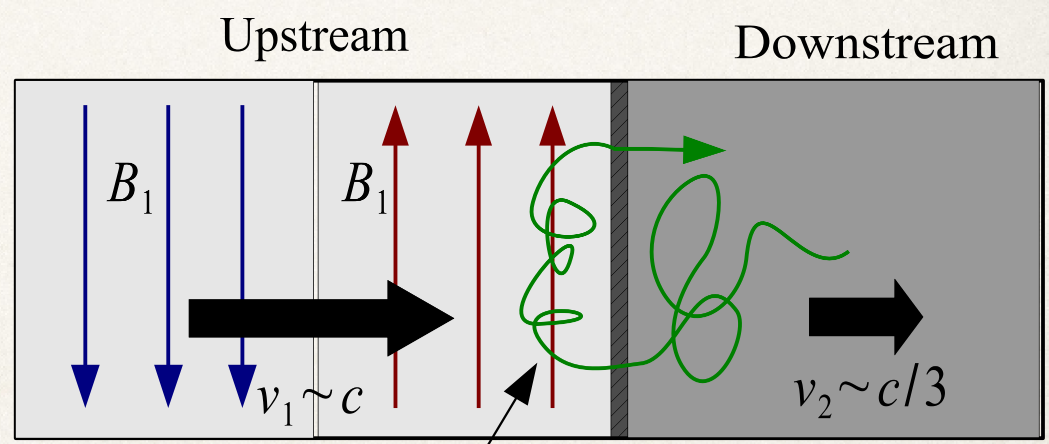
- Perpendicular shock configuration (Parker's spiral configuration)

Fermi-shock acceleration seems not suitable

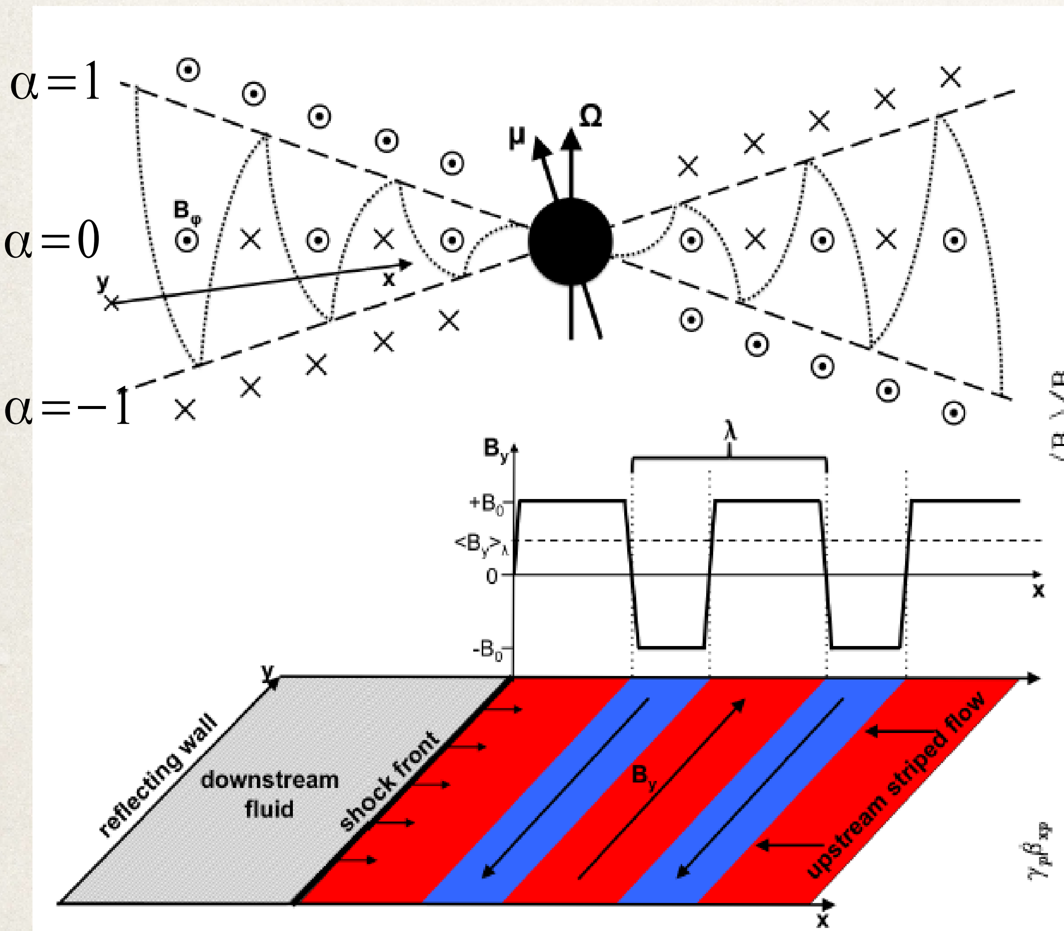


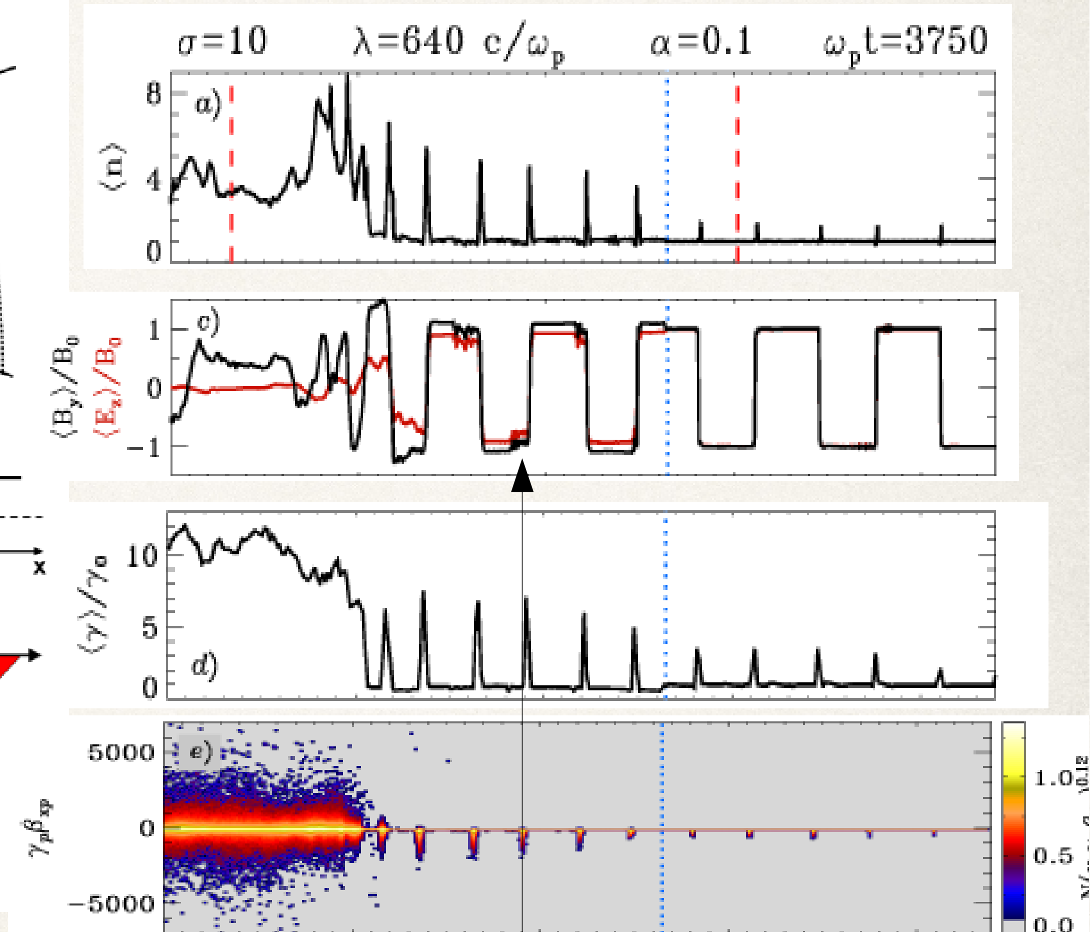


It is difficult for particles to diffuse upstream

STRIPED WINDS + TERMINATION SHOCK

From Sironi & Spitkovsky (2012)

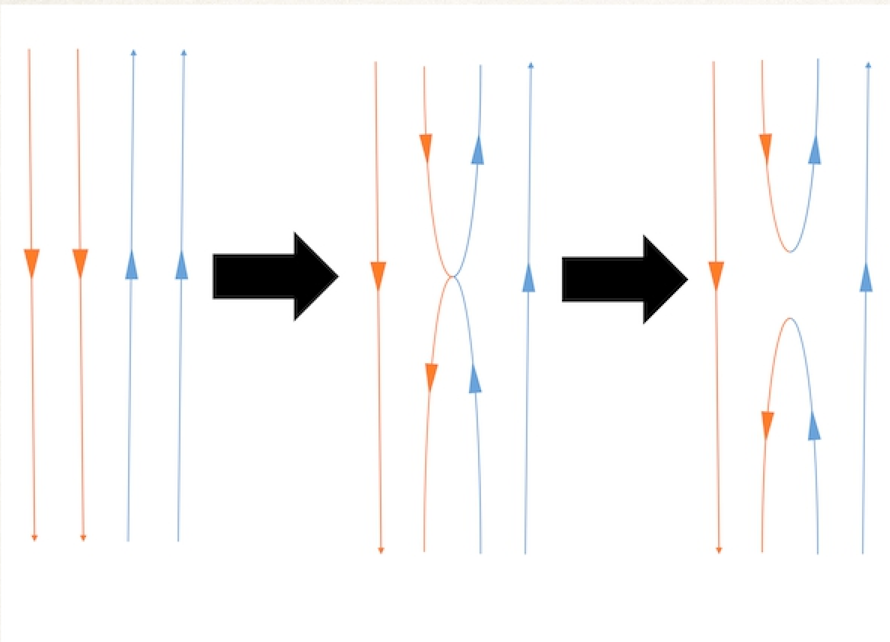




$$\frac{\langle B_y \rangle}{B_0} = \frac{\alpha}{2-|\alpha|} \rightarrow -1 < \alpha < 1$$

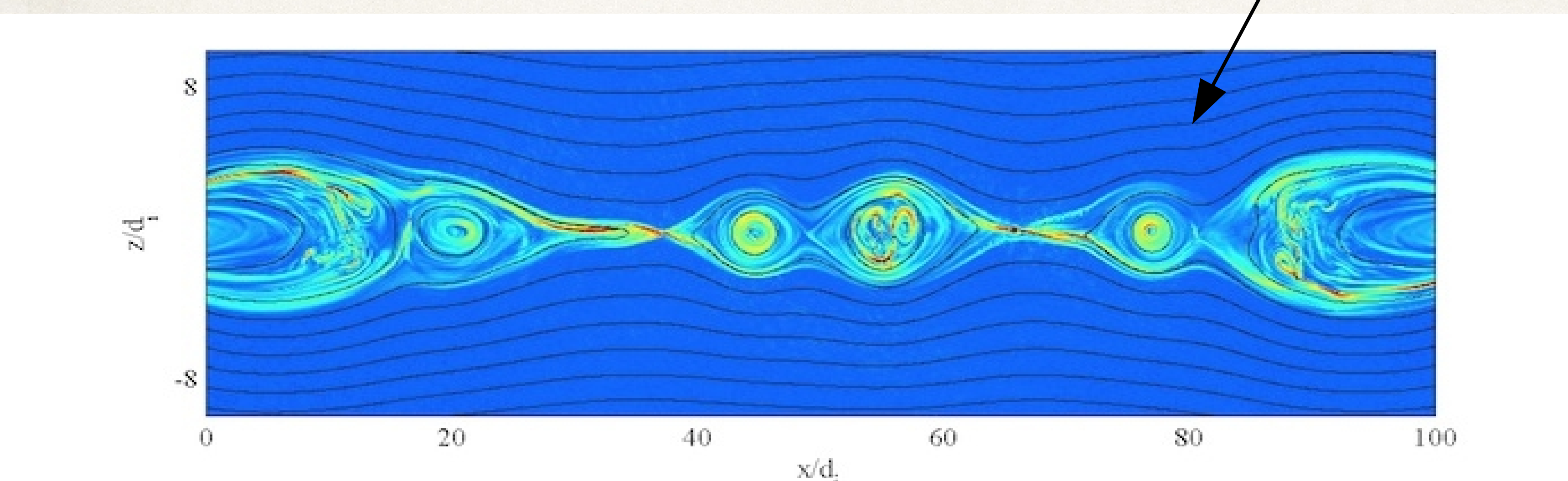
MHD shock drives the reconnection of magnetic field

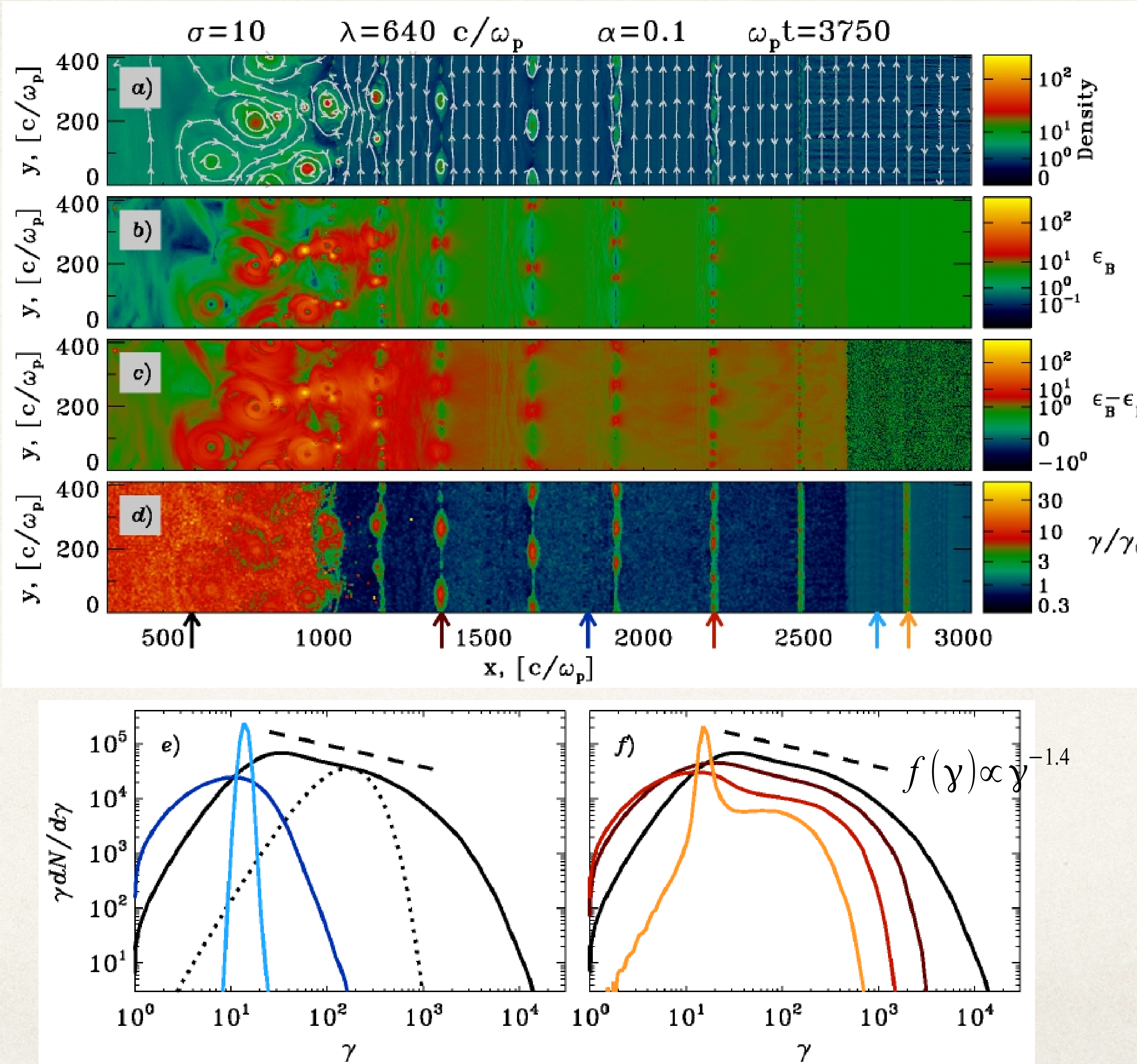
MAGNETIC RECONNECTION IN ONE SLIDE



Magnetic field lines compressed at the shock can reconnect

Magnetic islands is where particles' energization occurs

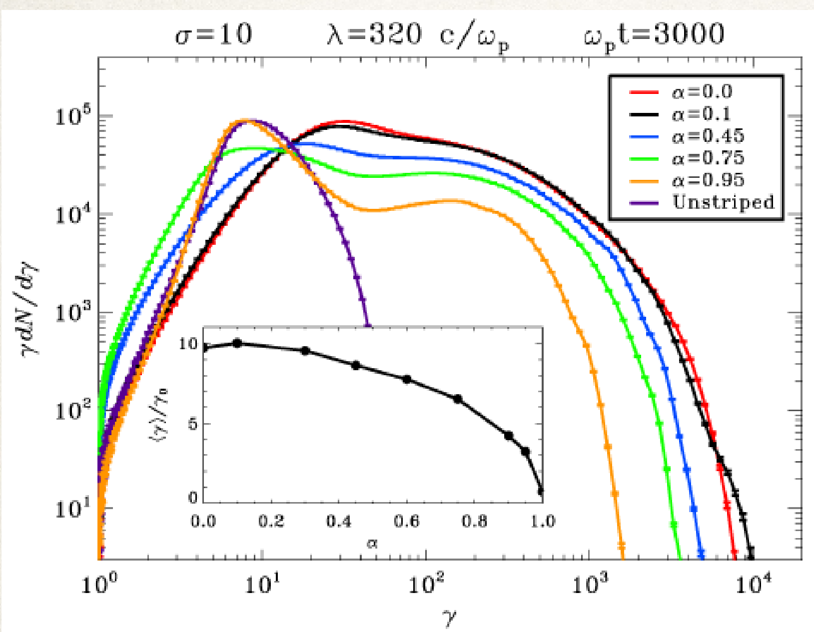


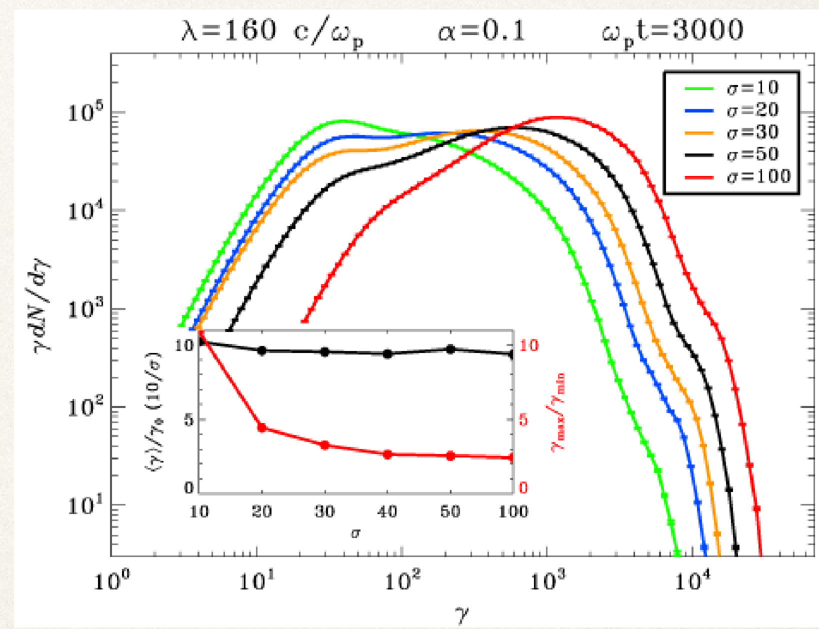


σ=10 λ=640 c/ω_p α=0.1 ω_p t=3750
a)
b)
c)
d)
e)
f)
Density
ε_B
ε_B−ε_E
γ/γ_0
y, [c/ω_p]
x, [c/ω_p]
γdN/dγ
γ
f(γ)∝γ^−1.4

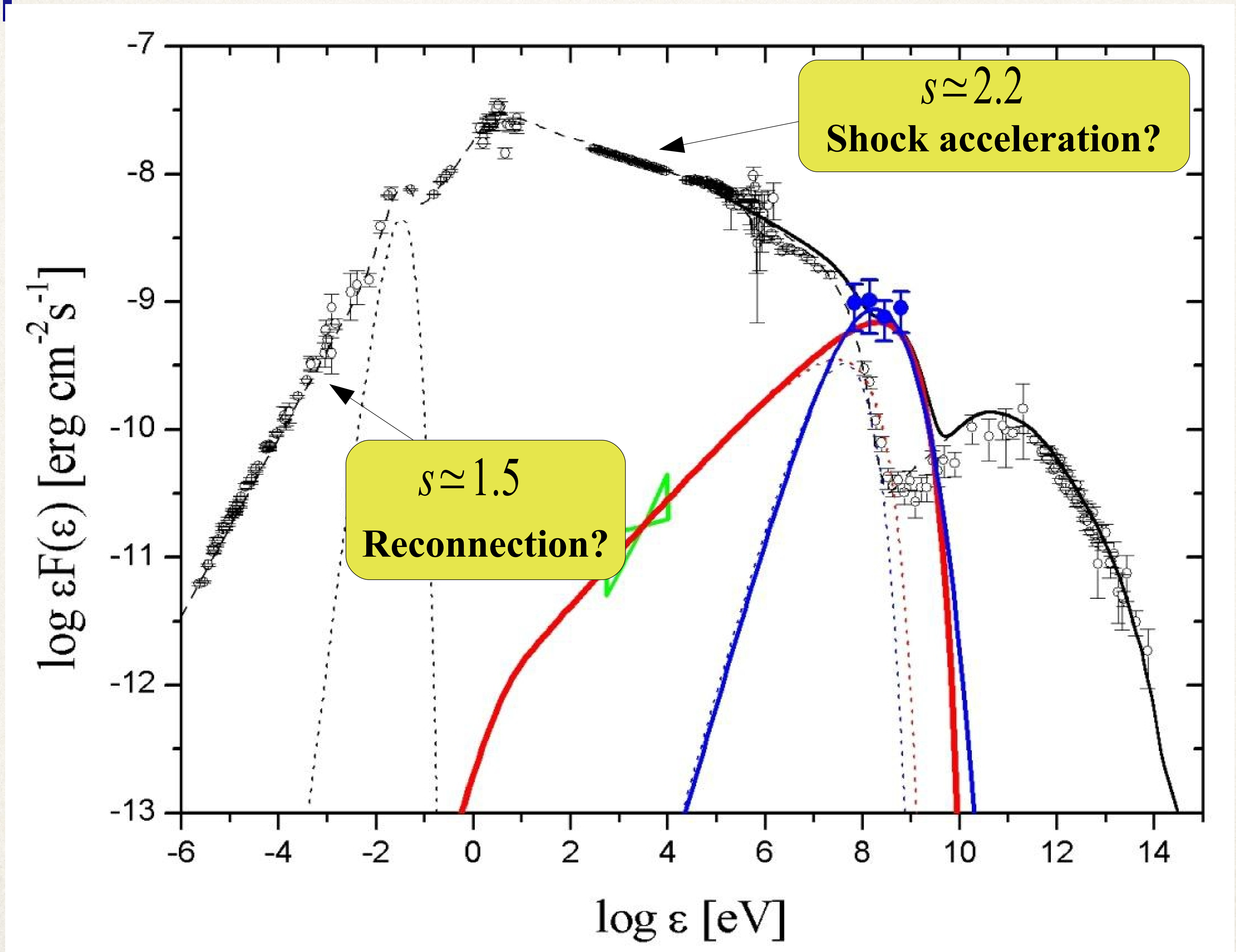
Particle spectrum from MF reconnection

- Slope of accelerated particles depends on magnetization σ
- For $\sigma \in$ [; : -; : :] $\rightarrow$ ***f(E) = E*** $^{-s}$ with ***s*** $\in$ **[1-2]**





SPECTRUM OF CRAB



Conclusions

Supernava Remnants

- Diffusive shock acceleration is the main way to produce non-thermal particles
- DSA makes important prediction
  - Power law spectra indipendent on the diffusion properties
  - Maximum energy that can reach ~ 1 PeV]   requires MFA
  - Strong evidence for magnetic field amplification induced by CRs
    - Gamma-ray emission more complex than expected (environmental effects?)
    - Lack of PeVatrons (very young SNR or other class of sources needed?)

Pulsar Wind Nebulae

- Shock acceleration is unlike to be efficient in relativistic shocks
- Magnetic reconnection can be the main acceleration mechanism at least for low energy particles (<~ TeV)

Thanks!