Cosmic Rays - Acceleration

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Realistically only two sources of free energy for charged particle acceleration in astrophysical systems.

- Differential motion of magnetised plasma

⇒ Fermi mechanisms

- Magnetic field energy

⇒ Magnetic reconnection

(of course magnetic energy usually comes from differential motion also!)

Another useful way to think about it:

- Need to get around the "no electric field" problem to get acceleration (locally $E + v \wedge B = 0$)
  - Either violate pure MHD (reconnection or charge separated magnetosphere).
  - Or use the fact that E only vanishes locally and not globally (Fermi).

Theory has mainly concentrated on Fermi processes because:

- they seem to be more important in most systems and more direct (KE to Particle *v* KE to B to Particle if B from dynamo action) - also do not need any special conditions.

- we have a well-developed (we think!) non-relativistic theory and can, at least in principle, calculate models.

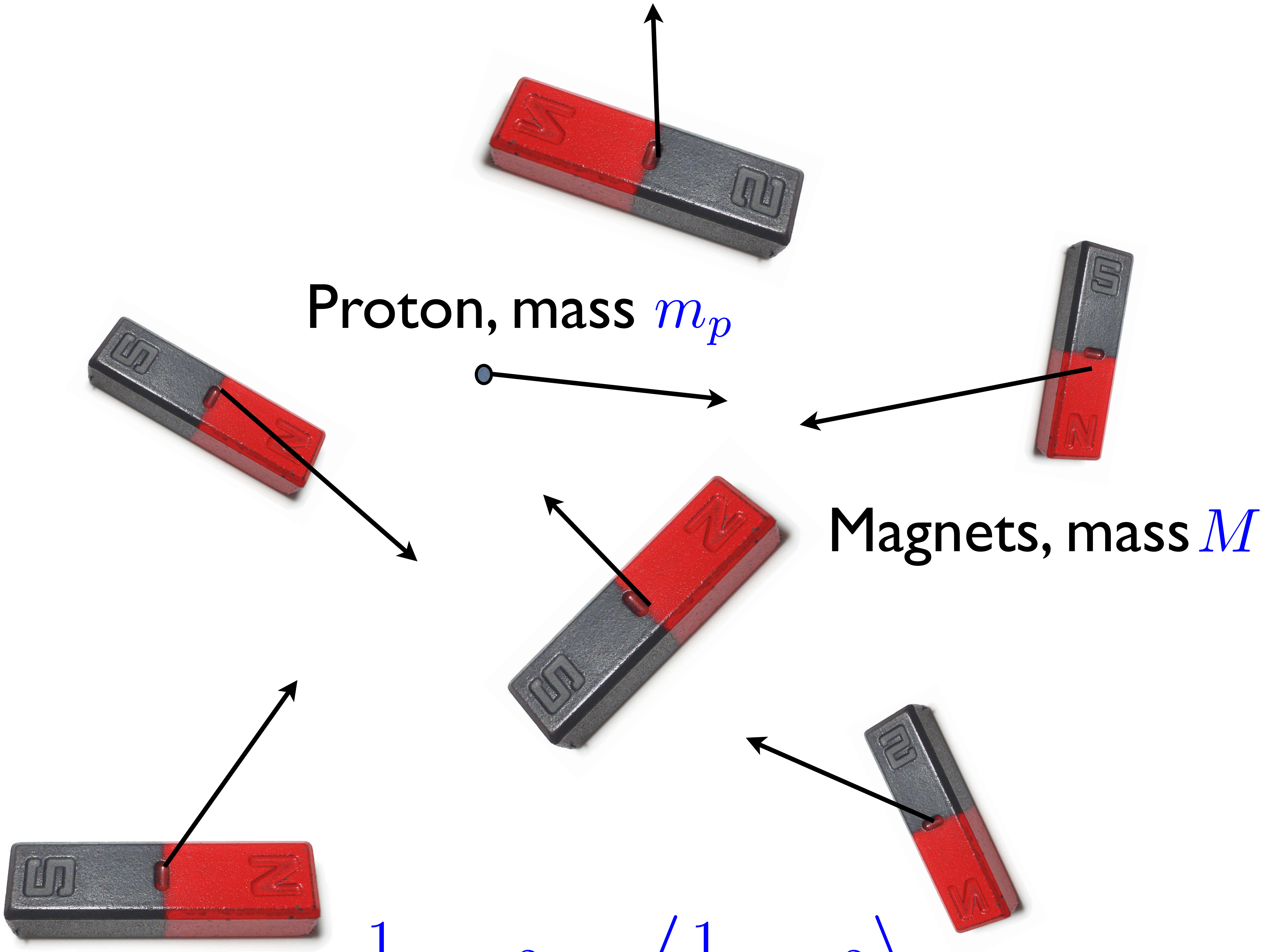
Reconnection should not be forgotten however!

Works in the sun, Earth's magnetotail, laboratory experiments and probably pulsar magnetospheres (note that hybrid models are perfectly possible).

More at end of talk…

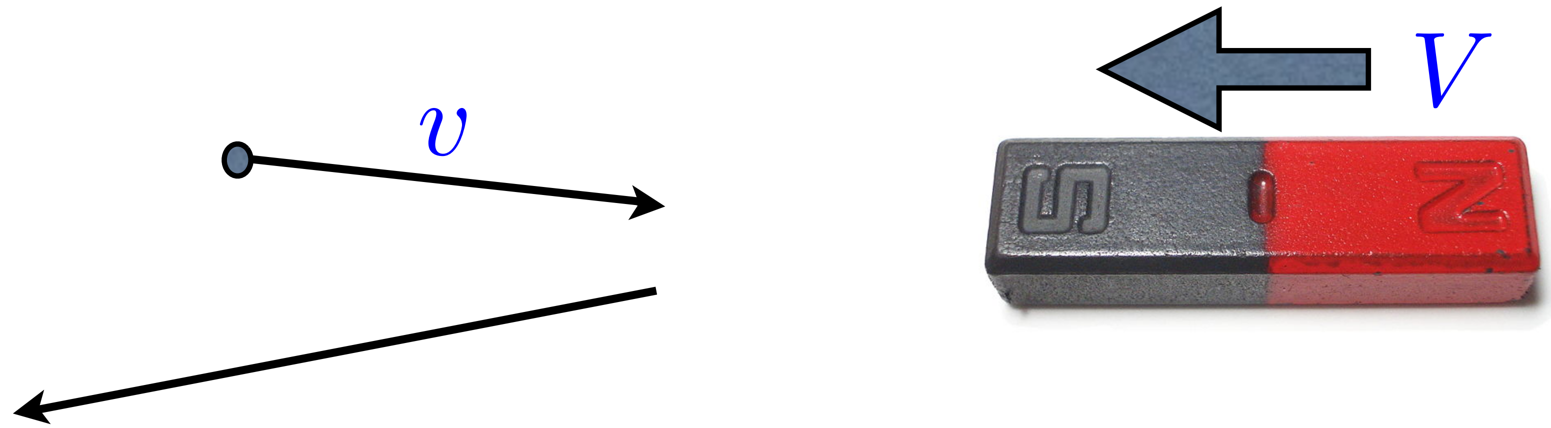
Fermi's great insight.....

- Magnetic fields have a unique ability to couple microscopic degrees of freedom of individual charged particles to macroscopic bulk motion of plasma.
- Attempt to achieve equilibrium inevitably leads, on average, to energy transfer to particles.
- *Gedanken* experiment - think of "gas" of bar magnets plus one proton....



$$\frac{1}{2}m_p v^2 \to \left\langle \frac{1}{2} M V^2 \right\rangle$$

`Head on' collisions give an energy (or momentum) gain of order



$$\frac{\Delta p}{p} \approx \frac{V}{v}$$

but of course time-reversed process gives energy loss!

NB importance of elastic scattering off very heavy magnetic mirror!

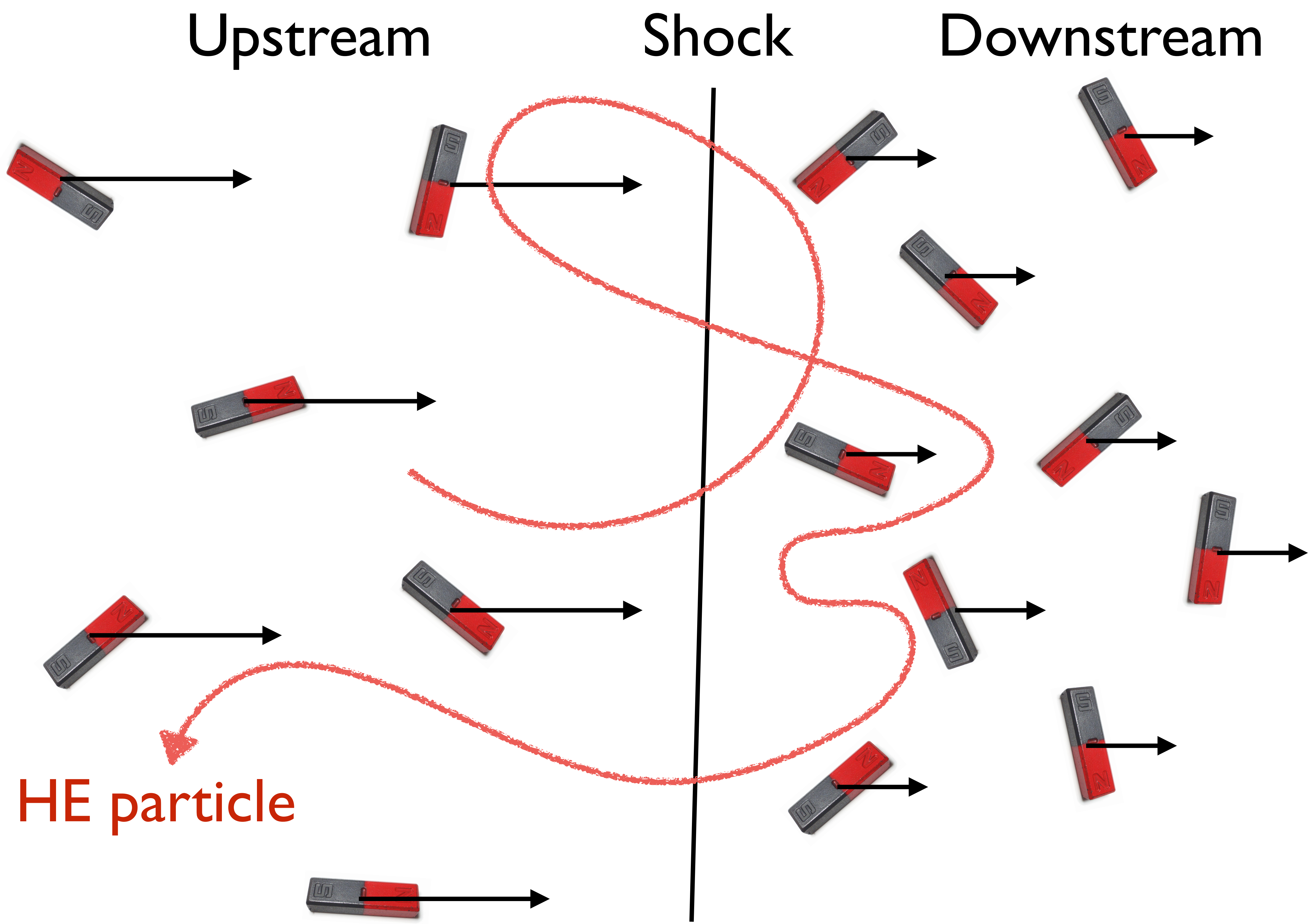
- But if collisions are random this merely gives a random walk (diffusion) of the charged particles in phase space (second order Fermi).

- Very slow normally, $t_{\rm acc} \approx \left(\frac{c}{V}\right)^2 t_{\rm coll}$ especially if $V \approx v_{\rm Alfven}$

- Can only work if all loss processes are even slower.

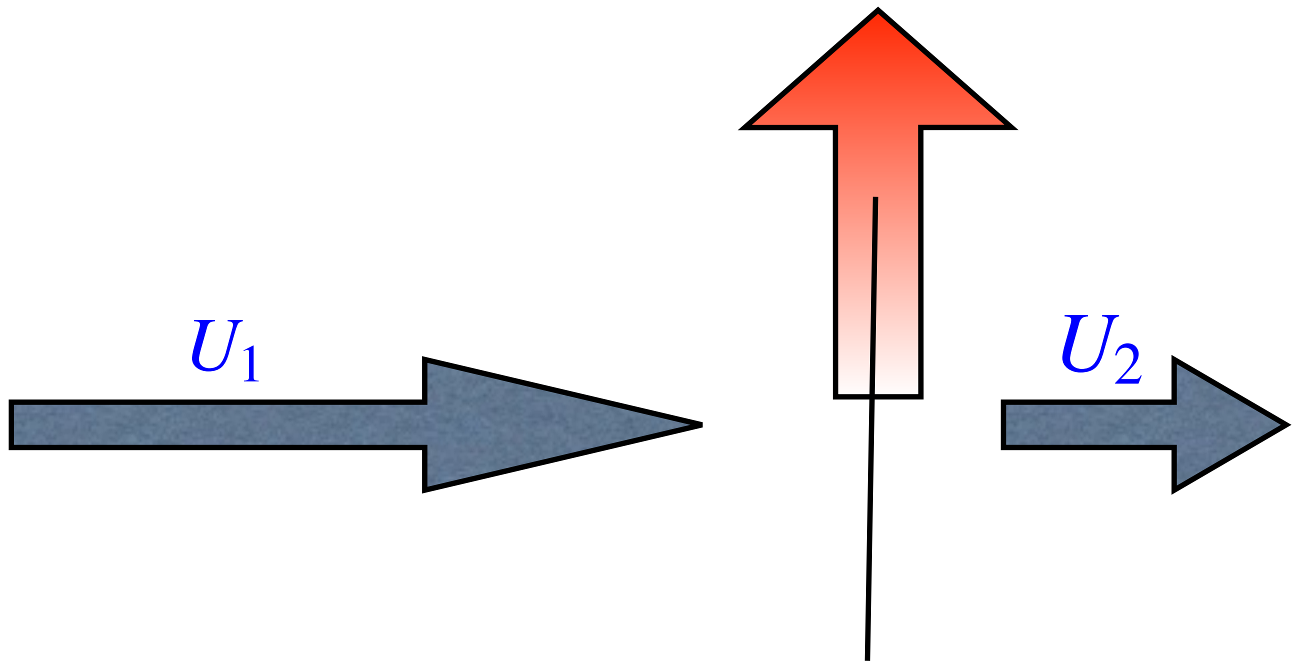
- Big discovery in 1977 - fast and efficient version of Fermi acceleration associated with shock waves

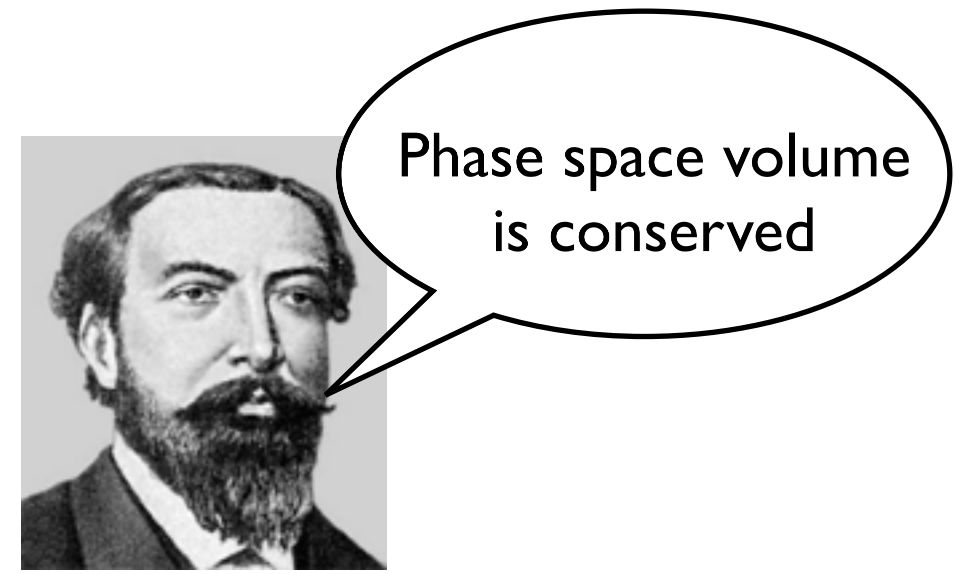
$\Rightarrow$ Diffusive Shock Acceleration


Upstream
Shock
Downstream
HE particle

Acceleration flux upwards in momentum space at shock is given by

$$\Phi(p) = \frac{4\pi}{3} p^3 f(p) \left(U_1 - U_2\right)$$





J. Liouville

Loss by advection downstream is $4\pi p^2 f(p) U_2$

$$\frac{\partial \Phi}{\partial p} = -4\pi p^2 f(p) U_2$$

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Divergence (in momentum space) of acceleration flux equals loss of particles by advection (in physical space).

Substituting for the acceleration flux this implies,

$$p\frac{\partial f}{\partial p} = -\frac{3U_1}{U_1 - U_2} f$$

with power-law solutions

$$f(p) \propto p^{-3\frac{U_1}{U_1 - U_2}}$$

Time scales

$$t_{\rm acc} = \frac{3}{U_1 - U_2}\left(\frac{\kappa_1}{U_1} + \frac{\kappa_2}{U_2}\right)$$

follows heuristically from

$$(L_1 + L_2)\, 4\pi p^2 f\, dp = \Phi dt$$

or rigorous mathematical analysis

If scattering in Bohm limit

$$\kappa \approx \frac{1}{3} r_g c$$

$$t_{\rm acc} \approx \frac{r_g}{c} \left(\frac{c}{U}\right)^2 \approx \beta^{-2} t_g$$

saturates Hillas limit!

$$t_{\rm acc} \approx t_{\rm dyn} \implies \frac{p}{eBc} \left(\frac{c}{U}\right)^2 \approx \frac{R}{U}$$

$$\implies pc \approx eBRU$$

Maximum particle rigidity = (magnetic field scale)X(velocity scale)X(length scale)

Scaling in Supernova Remnants

- RV is almost constant in Sedov phase.

$$R \propto t^{2/5} \implies V \propto t^{-3/5} \implies RV \propto t^{-1/5}$$

- At start of Sedov:
  - R fixed by ejecta mass and ambient density

    $$R \propto (M_{\rm ej}/\rho_0)^{1/3}$$

  - V fixed by explosion energy and ejecta mass

    $$V \propto (E_{\rm SN}/M_{\rm ej})^{1/2}$$

- RV only has weak dependencies on parameters!

$$RV \propto E_{\rm SN}^{1/2}\, M_{\rm ej}^{-1/6}\, \rho_0^{-1/3}\, (t/t_{\rm sw})^{-1/5}$$

- Leads to well known Lagage-Cesarsky problem
  - Maximum plausible rigidity with standard ISM magnetic fields and SNR parameters is only about 0.1 PV.
  - Even this requires scattering in the Bohm limit and very strong wave excitation.
  - Only hope if we want to accelerate to the “knee” and beyond in the GCR spectrum is to increase B.

Important recent series of papers by Caprioli and Spitkovsky

arXiv 1310.2943, 1401.7679, 1407.226

- Large scale hybrid simulations of collision-less non-relativistic shocks confirm:
  - long standing theoretical expectations of "Bohm" scaling for the diffusion coefficients;
  - magnetic field amplification (by approx square root of Alfvén Mach number);
  - efficient injection of ions with ca 20% of shock energy going into accelerated particles.

A historical note...

- Remarkable paper by Fred Hoyle in 1960 (MNRAS 120, 338) suggested that ISM shocks could dissipate kinetic energy into either thermal energy, non-thermal particles or magnetic field energy!
- But no physical mechanisms identified and Hoyle just supposed that the dominant component upstream took everything.
- 50 years on we are just beginning to understand what determines the balance between the three components...

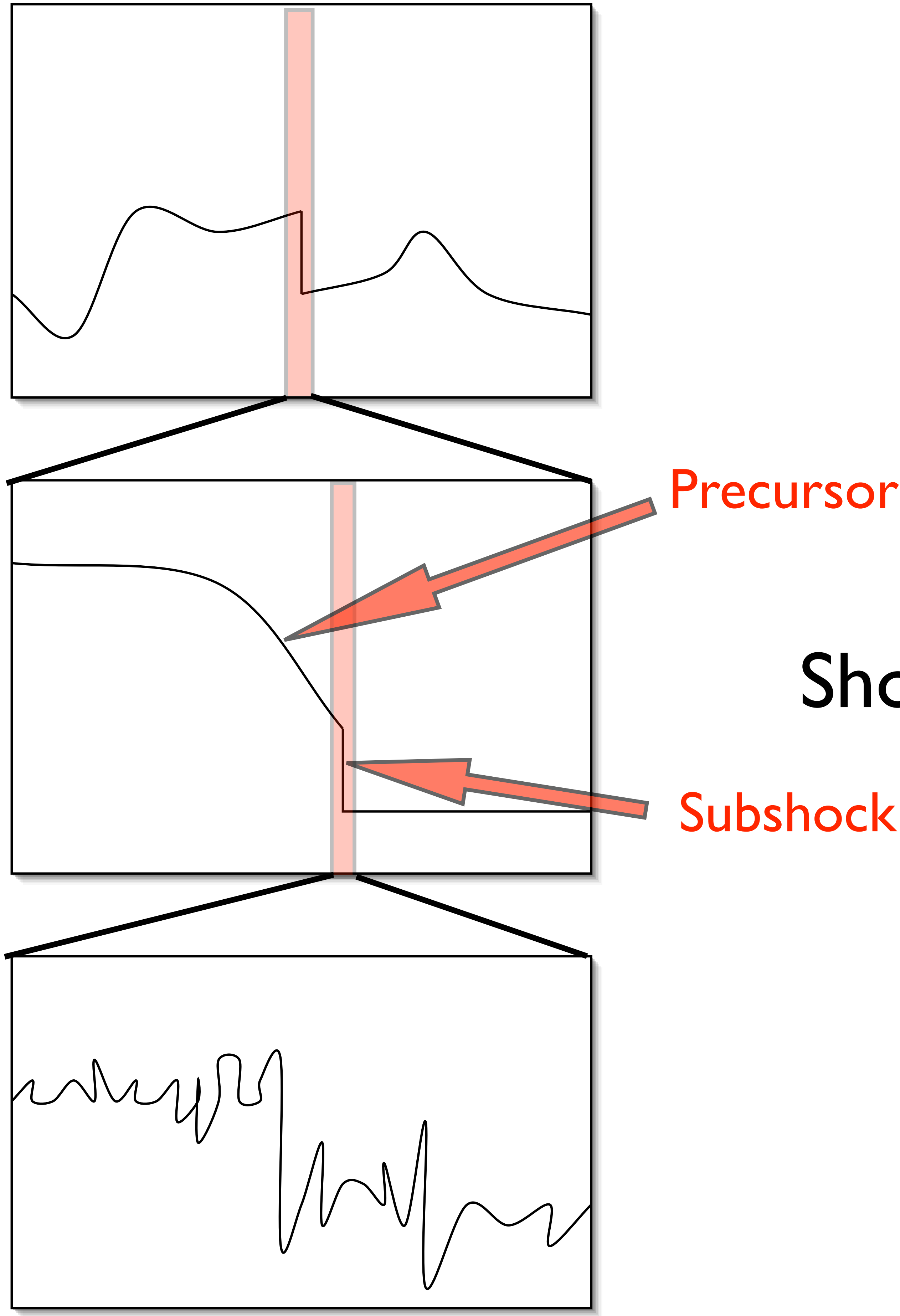
Issues

- Nonlinear modifications
- Magnetic field effects and amplification
- Relativistic effects
- Plasma physics of the subshock
- Injection mechanisms
- Second order Fermi terms
- Neutrals and charge exchange

In reality all coupled!

Nonlinear Reaction Effects

- The “big issue” for first twenty years of DSA
- Now regarded as “solved” (but with, in my view, serious caveats) for non-relativistic shocks
- Shock structure has to be modified if the accelerated particles take a significant part of the energy dissipated in the shock (as has to be the case for many models) - cannot ignore particle pressure.
- Usefully thought of as a mesoscopic phenomenon...



Outer scale:
Astrophysics

Intermediate scales:
Shock acceleration theory

Inner scale:
Plasma physics
Injection!

Consensus view...

- Spectra are generically curved, softer at low energies, hardening in the ultra-relativistic region before cutting off quite abruptly.
- Hardening at high energies at most changes spectral index from 4 to 3.5, so not too extreme.
- Subshock is reduced to point where injection matches capacity of shock to accelerate; suggests minimum subshock compression ratio of about 2.5.
- Significantly reduced shock heating.

But...

- All approaches assume steady structure on the mesoscopic scale.
- In fact exist many possible instabilities.
- However can hope that theory still applies in mean sense - basic physics is very robust.
- Also not all bad news - offers exciting prospect of amplified B fields and thereby reaching higher energies (as well as enhanced synchrotron emission from accelerated electrons)

- Shock precursors are almost certainly highly “turbulent” - not clear what implications this has for the modification theories (which all assume steady structures).

- But certainly easy to amplify small-scale magnetic field by CR pressure gradients (Downes and Drury, arXiv:1407.5664) as well as current-driven (Bell-type) and plasma (Weibel, filamentation etc) instabilities.

- Field can plausibly be increased by orders of magnitude, if not to equipartition (Bell predicts saturation a factor U/c below).

- Strong observational indications of amplified fields in young SNRs from narrow nonthermal X-ray rims (with possible U^3 scaling according to J Vink).

- Allows acceleration of protons to "knee region" with ease - otherwise as known since Lagage and Cesarsky problematic (but scale issue? Not enough to just make small scale fields).

- NB - upstream field amplification is needed to reach higher energies, but the observational evidence to date is for downstream fields!

Aside on relativistic shocks

See arXiv:0807.3459 by Pelletier, Lemoine and Marcowith for a good account as well as work by Kirk, Ostrowski, Achterberg etc. Also recent work by Lemoine et al in arXiv:1405.7360

- In principle the same basic acceleration process, multiple shock crossings with magnetostatic scattering on either side, should work.
- But there are a number of major differences as well as at least one serious problem - very hard to get particles back from downstream.

Injection and plasma physics of the subshock

- Promising progress with PIC and (for ions) hybrid simulations.
- No problem for protons at quasi-parallel shocks.
- Many mechanisms for electron injection - unclear whether any one process dominates, but certainly possible (actually easier for relativistic shocks; rest mass matters less).
- Heavier ions should be even easier than protons as appears to be reflected in the GCR composition.

Summary: Fermi acceleration and GCRs

- Consensus that DSA at SN driven shocks is main production mechanism in Galaxy.
- Need models for confinement and escape from SNRs; post-shock spectrum is not source spectrum for propagation models! (Drury, 2011).
- Second order Fermi possible in Galactic propagation at low energies (cf Galprop etc; Thornbury and Drury, 2014).
- Other contributions at 10% level not ruled out.
- Location and nature of transition to extragalactic UHE component is hotly debated at moment.

Finally, some recent hints of very rapid magnetically driven acceleration?

- Gamma-ray flares in the Crab nebula detected by Agile and Fermi (Abdo et al, 2011; Tavani et al, 2011; Balbo et al 2011; Ackermann et al 2013).
- Short time scales (days) imply very compact acceleration sites.
- Flares have very hard spectra cutting off sharply at GeV energies - no detection in other bands.
- GeV cutoff is very hard to explain without either strong electric fields or relativistic beaming (or both) - cf Udzensky et al, 2011.