shock acceleration

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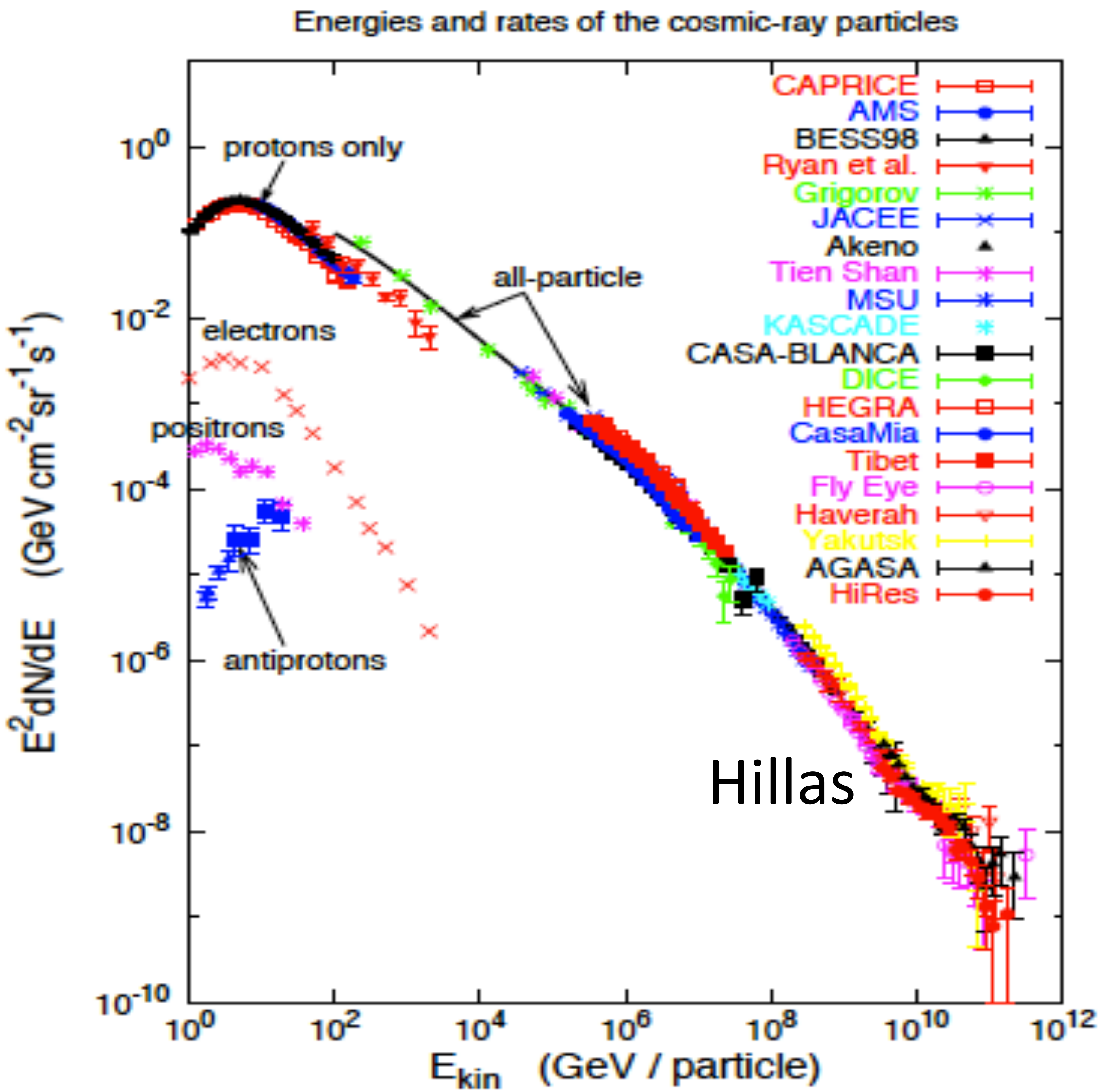
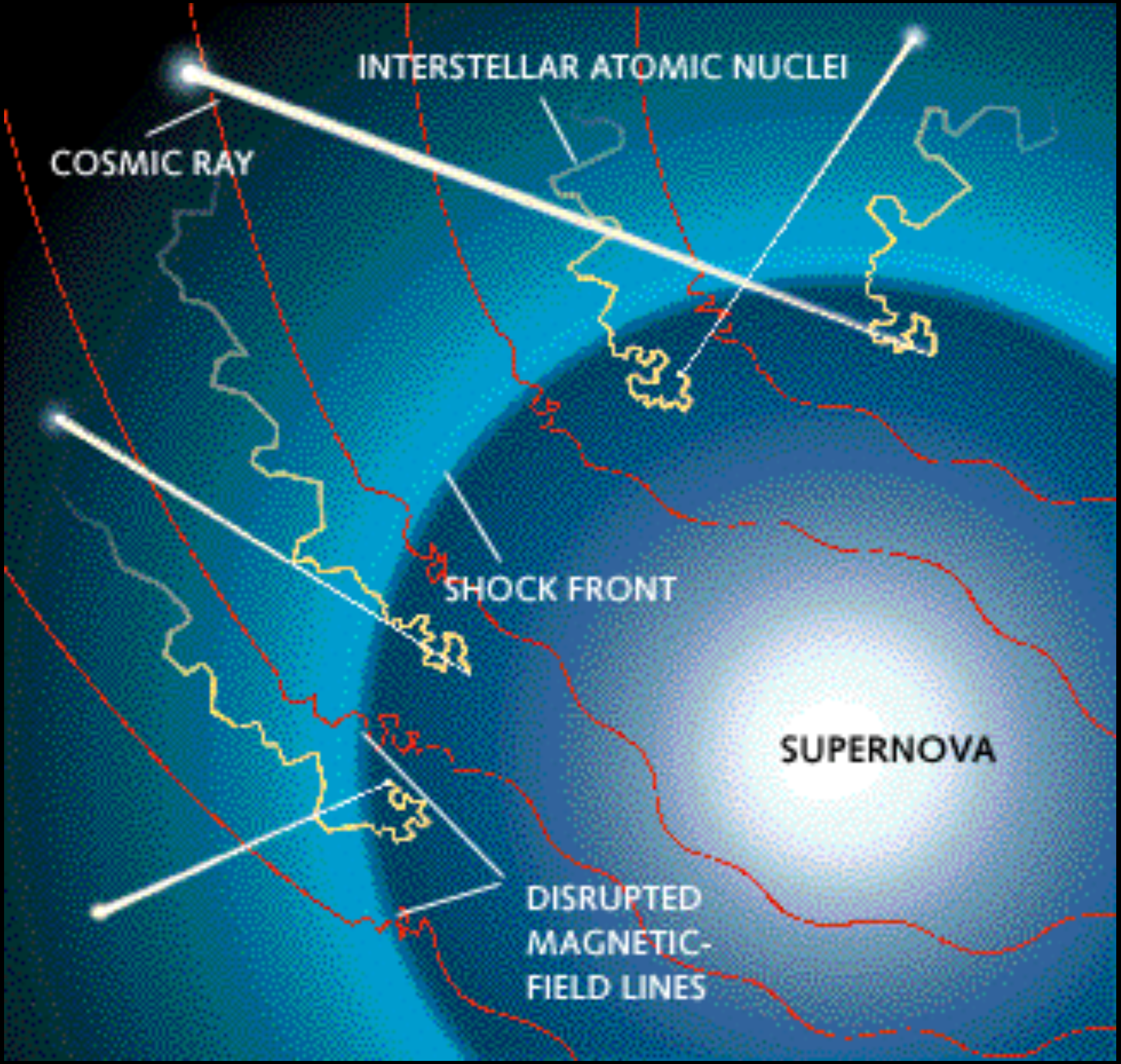
cosmic-ray spectrum



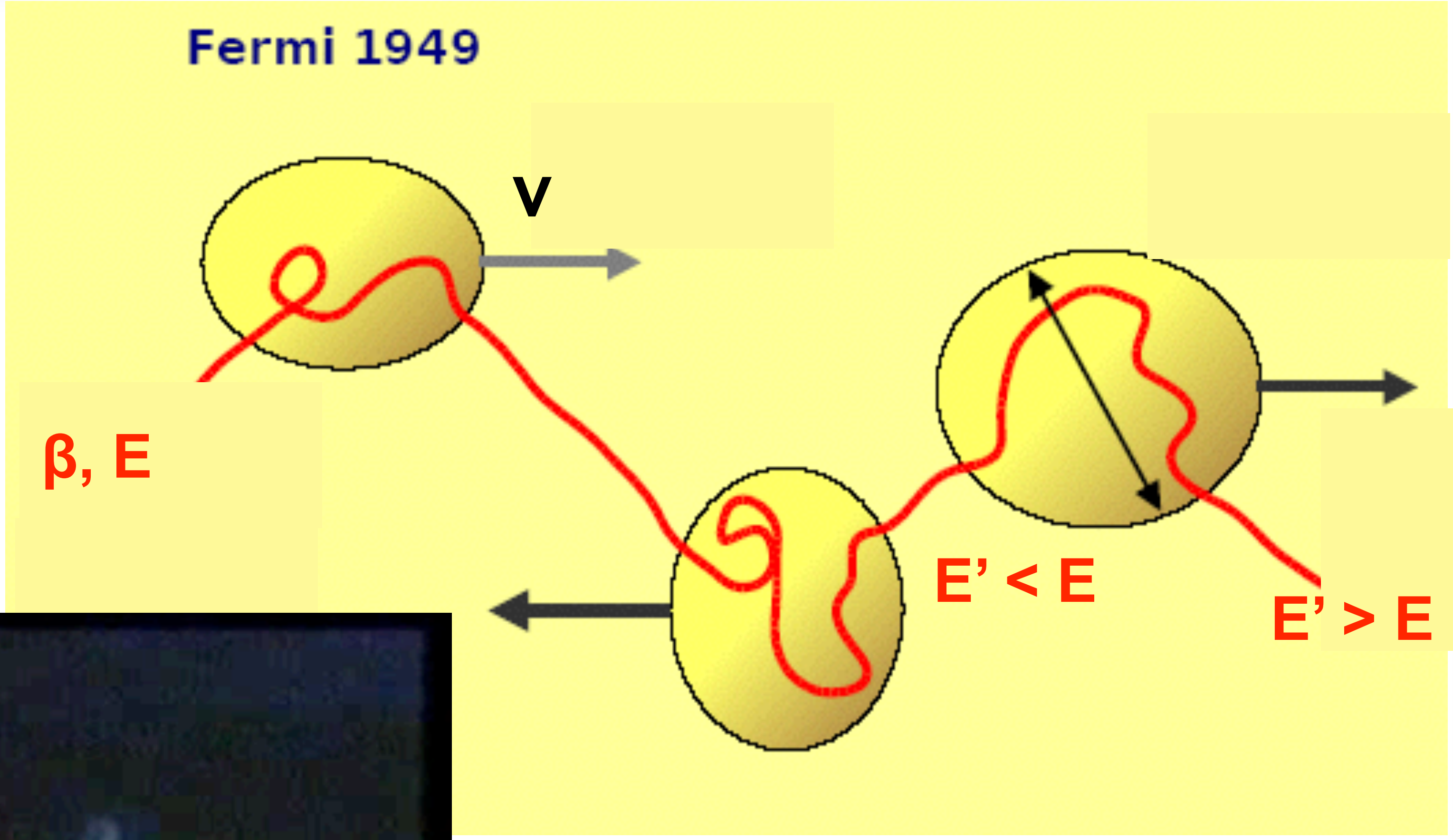
particle acceleration by shocks

- diffusion on magnetic field:
  change direction, but no work on the particle



2nd order Fermi acceleration

- uses bias towards head-on collisions
  to effect acceleration
  because more frequent head-on
  than trailing collisions
  (cf running in the rain)



the strange case
of cosmic rays
Frank Capra

1st order Fermi acceleration

downstream frame

$\vec{v_2'} = \mathbf{0}$

$\vec{v_s'} = \vec{v_s}/\mathbf{r}$

$\vec{v_1'} = \vec{v_1} - \vec{v_2} = -\vec{v_2}$

$\vec{v_1'} = -\vec{v_s}(\mathbf{1} - \mathbf{1}/\mathbf{r})$

shock frame

$\vec{u_2} = -\vec{v_s}/\mathbf{r}$

$\vec{u_1} = -\vec{v_c}$

upstream frame

$\vec{v_1'} = \mathbf{0}$

$\vec{v_s}$

$\vec{v_2} = \vec{v_s} + \vec{u_2}$

$\vec{v_2} = \vec{v_s}(\mathbf{1} - \mathbf{1}/\mathbf{r})$

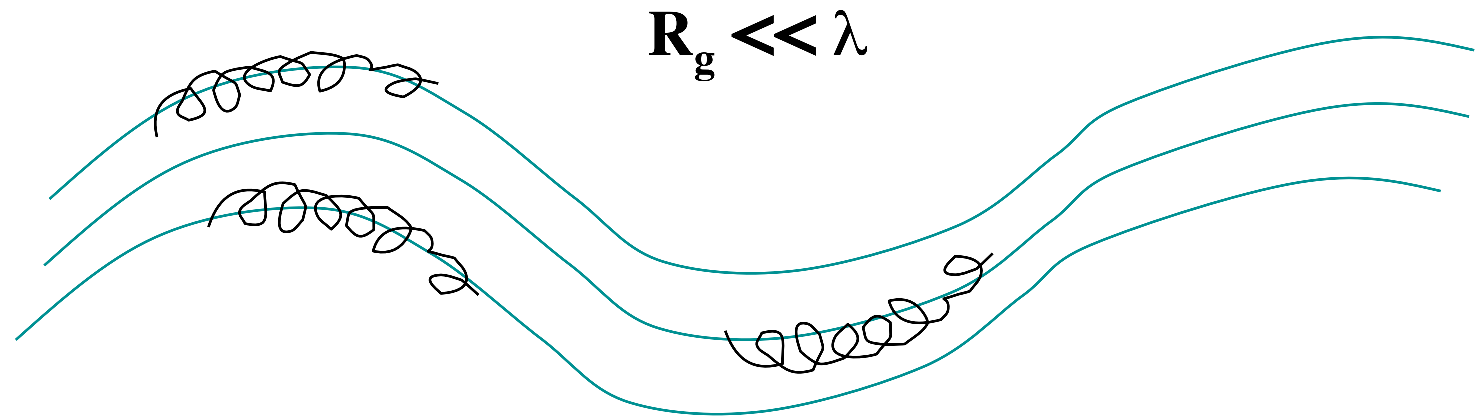
$\mathbf{v_2} < \mathbf{v_s}$

- opposite side symmetrically « arrives » at $v_s(1-1/r)$ = ¾ v_s if compression ratio r = 4
- magnetic diffusion (in angle) on δB waves in each medium => particles isotropized <v> = 0
  shock without collisions !
  => frontal racket swing at each crossing of the shock
- δB generation
  ✦ upstream: Alfven waves generated by the cosmic rays (stream instability)
  ✦ downstream: + turbulence
- mean free part (90°) and diffusion coefficient
  (random walk):

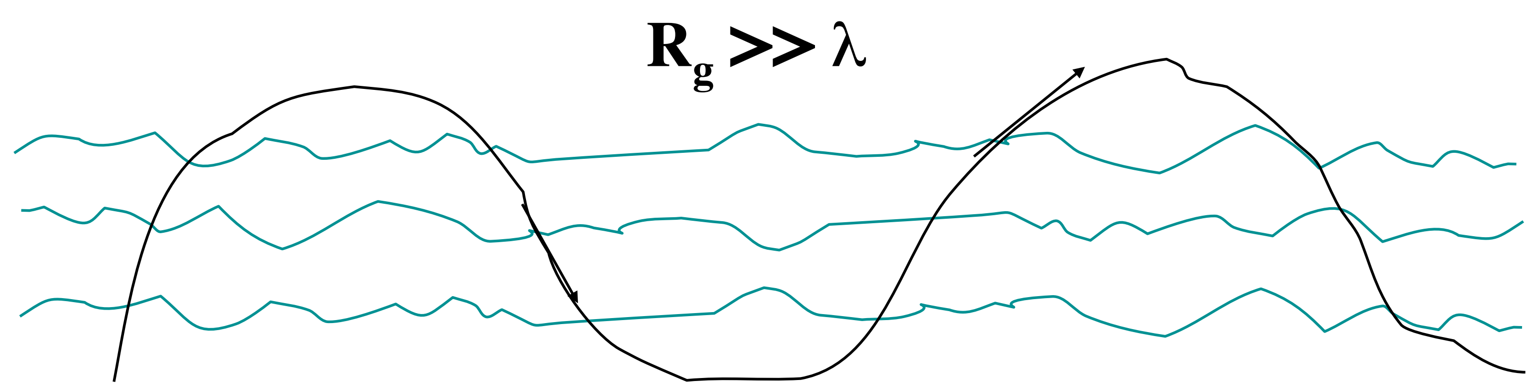
$$\lambda_{diff} = R_{giration}(B/\delta B)^2 \qquad D_{diff} \approx \tfrac{1}{3}\lambda_{diff} v_{part.}$$

B-particle interaction

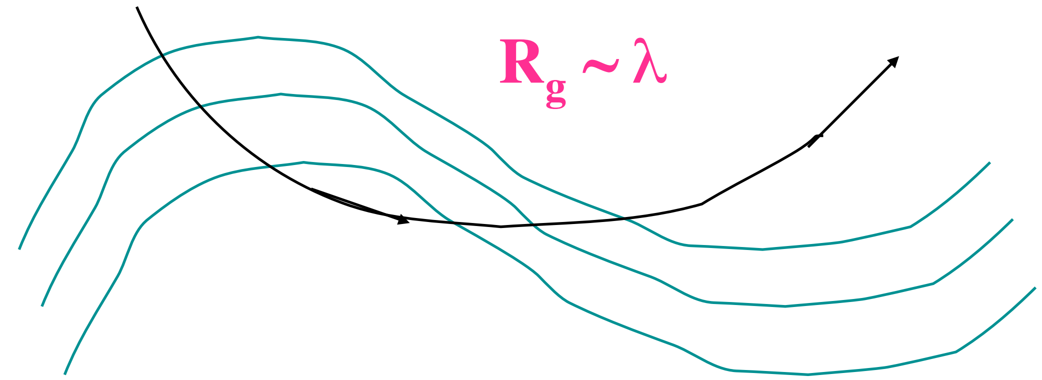
- adiabatic invariant $p_{\perp}^2/B$ = cte
  magnetic mirror…



- particule and B "ignore each other"



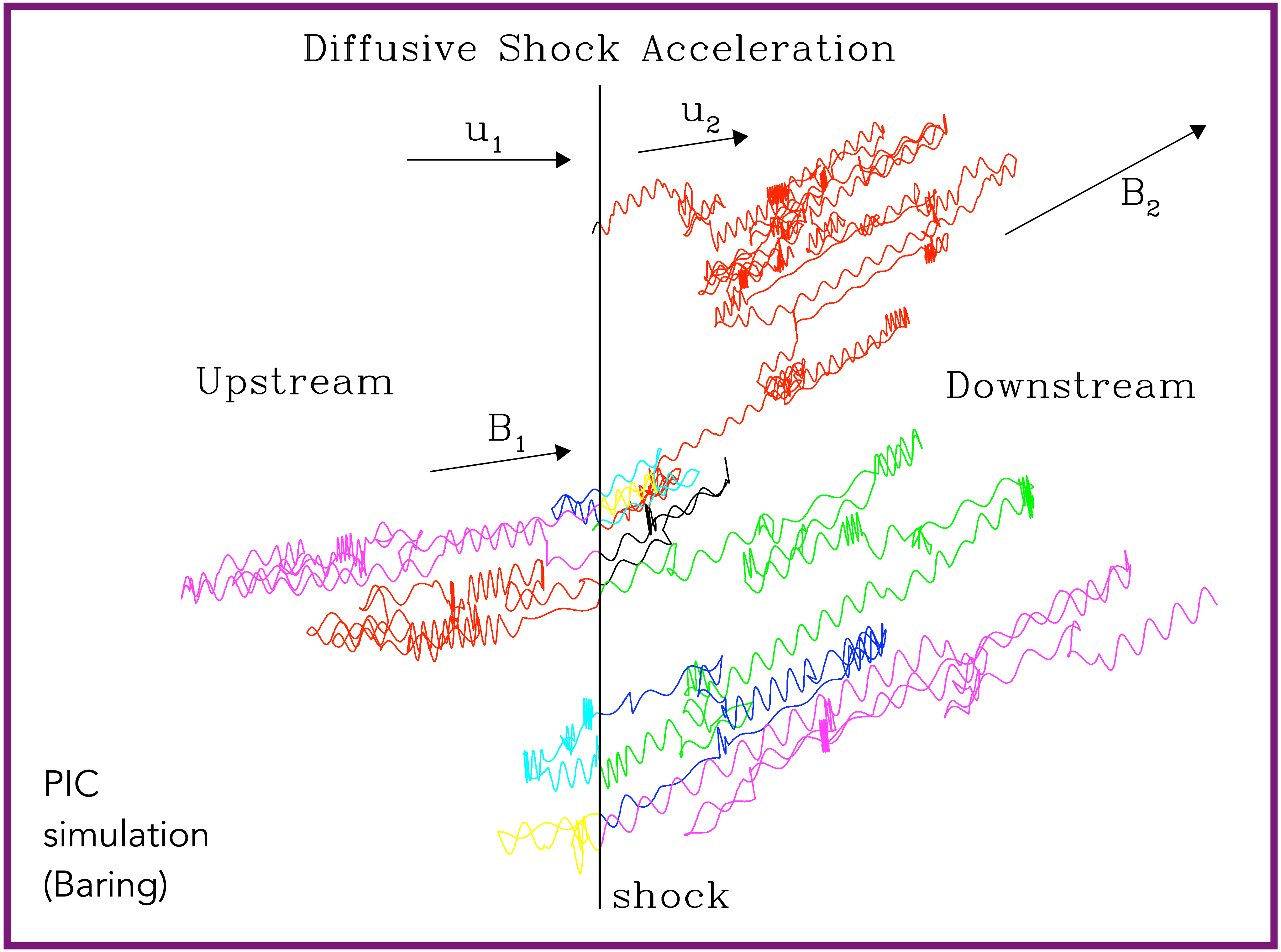
- angular diffusion
  $\Delta\alpha \sim \Delta B/B0$
  centre of curvature drifts
  $r \sim Rg\, \Delta\alpha$



- Bell '78, Axford '77, Blandford & Ostriker '78
  resonant scattering if $Rg \approx \lambda$ and growth of Alfven waves (λ) in the upstream medium

1st order Fermi acceleration

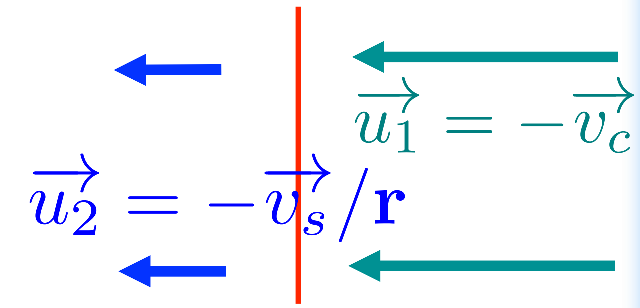
- kinematic gains in shock crossings to accelerate particles => diffusive shock acceleration
- net energy gains (increasing gyradii)



accelerated spectrum

- steady-state scenario, particle distribution function in momentum p:
- the integral F(p) follows the equation

shock frame



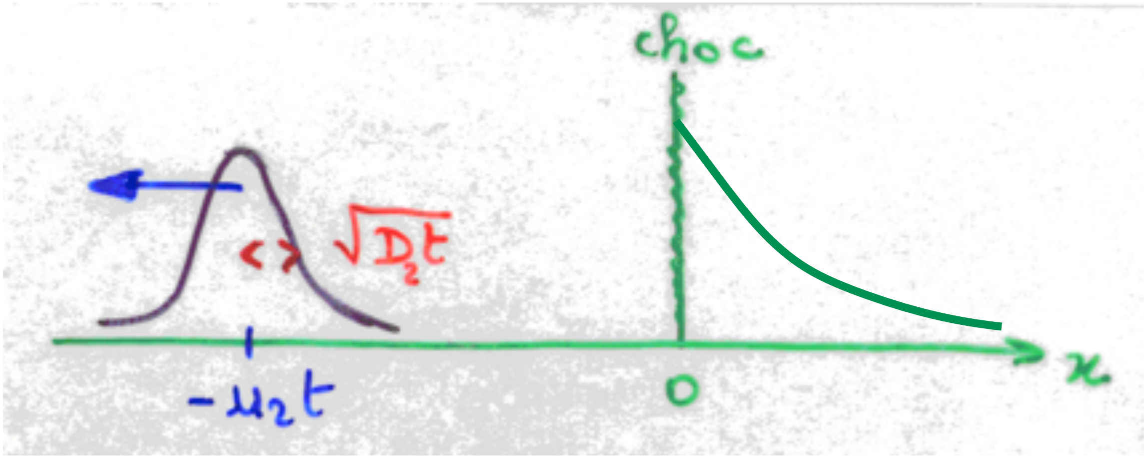
$$0 = t_{cyc} \frac{d\mathcal{F}}{dt} \equiv -\langle \Delta p \rangle \frac{d\mathcal{F}}{dp} - P_{\rm esc}\mathcal{F} , \quad \mathcal{F}(p) = \int_p^\infty f(p_1)\, dp_1$$

- diffusion upstream: equilibrium between diffusion outward and convection back to shock
  density n(x) of particles with velocity c

$$\mathbf{J} = -\mathbf{D_1} \overrightarrow{\nabla} \mathbf{n} + \overrightarrow{u_1}.\mathbf{n} \Rightarrow \mathbf{0} = -\mathbf{D_1} \frac{\partial \mathbf{n}}{\partial \mathbf{x}} - |\mathbf{u_1}|\mathbf{n} \Rightarrow \mathbf{n(x)} = \mathbf{n_0 e^{-u_1 x/D_1}}$$

- downstream advection with u_2 away from the shock
  ratio of fluxes crossing and downstream =>

$$\mathbf{P_{esc}} = \frac{\mathbf{4u_2}}{\mathbf{c}}$$



- for isotropic distributions on each side, average gain

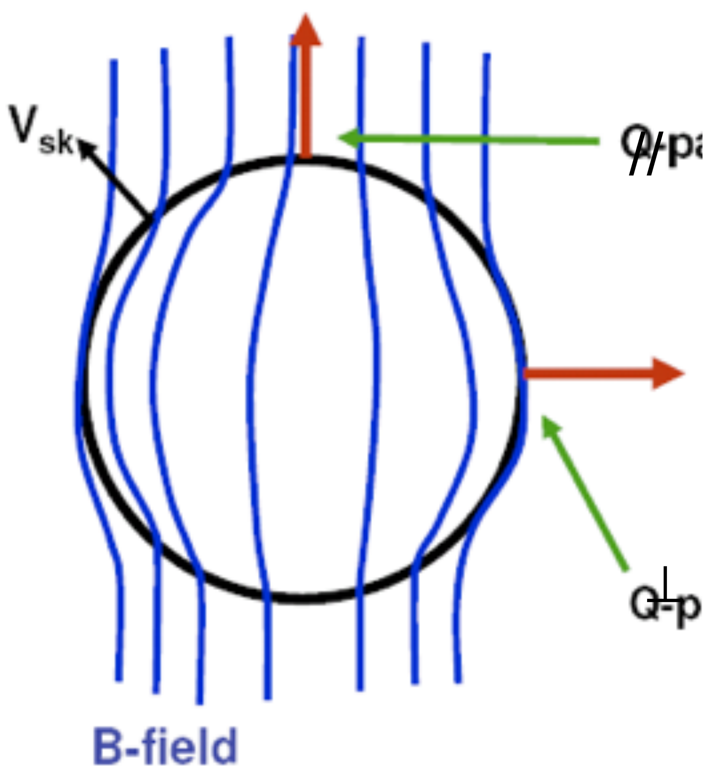
$$\frac{\overline{\Delta \mathbf{p}}}{\mathbf{p}} = \frac{\mathbf{4u_1(u_1 - u_2)}}{\mathbf{3u_2c}}$$

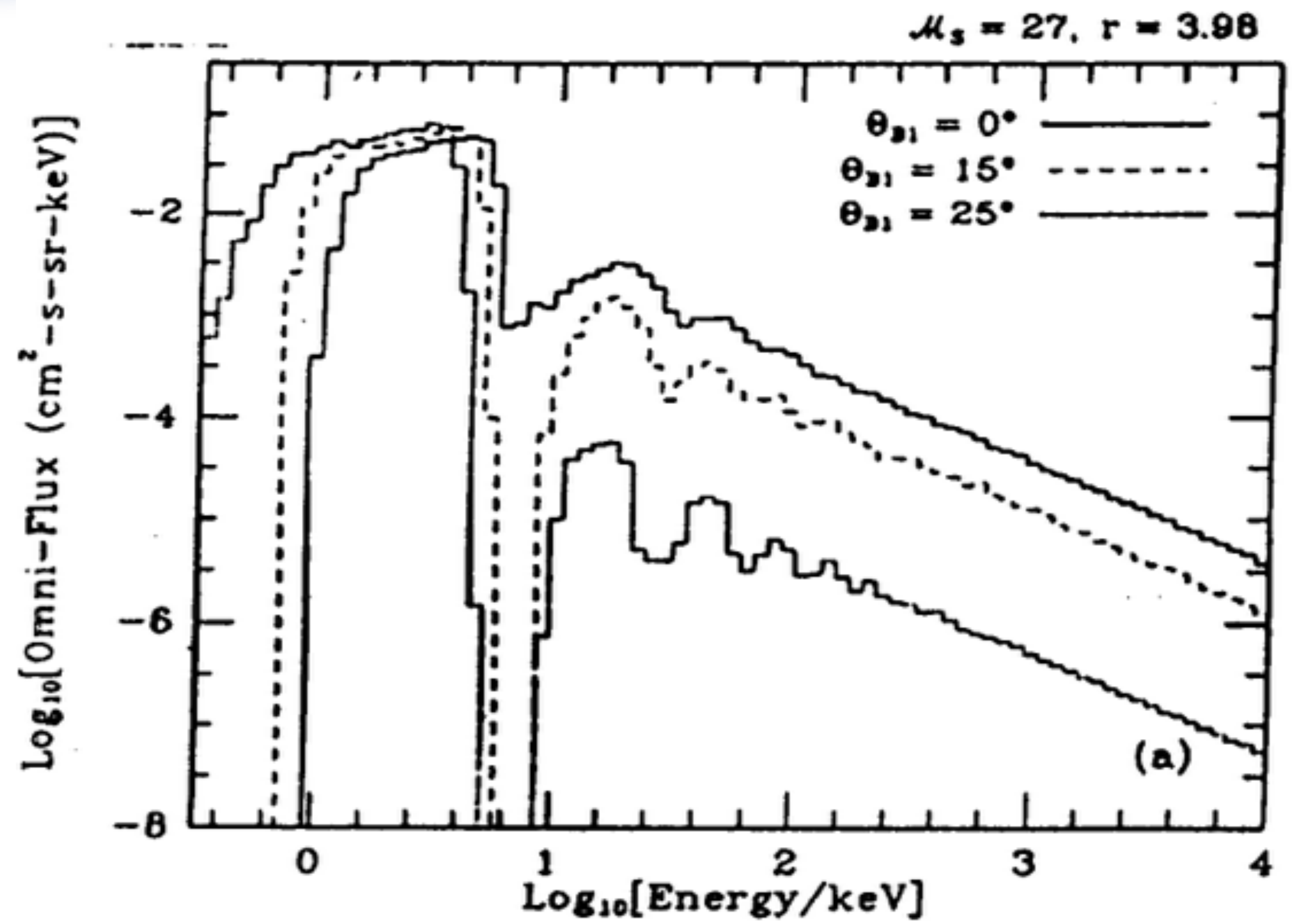
- power-law solution to the kinetic equation
  complete lack of energy scale
  spectral index independent of
  diffusion properties, B strength,
  obliquity… only gas compressibility

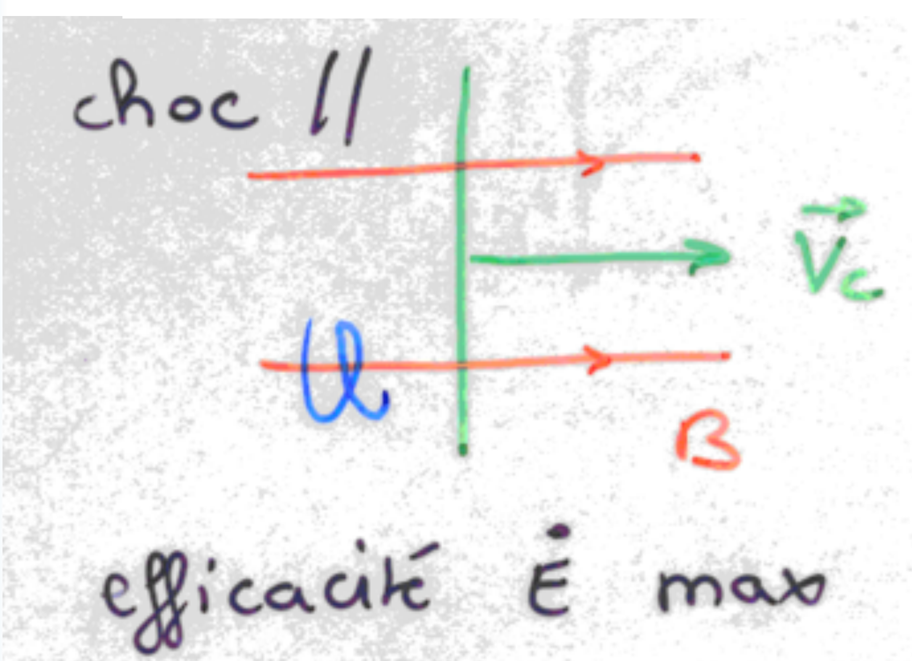
$$f(p) \propto p^{-\sigma} , \quad \sigma = 1 + \frac{p\, P_{\rm esc}}{\langle \Delta p \rangle} = \frac{r+2}{r-1} , \quad r = \frac{u_1}{u_2} .$$

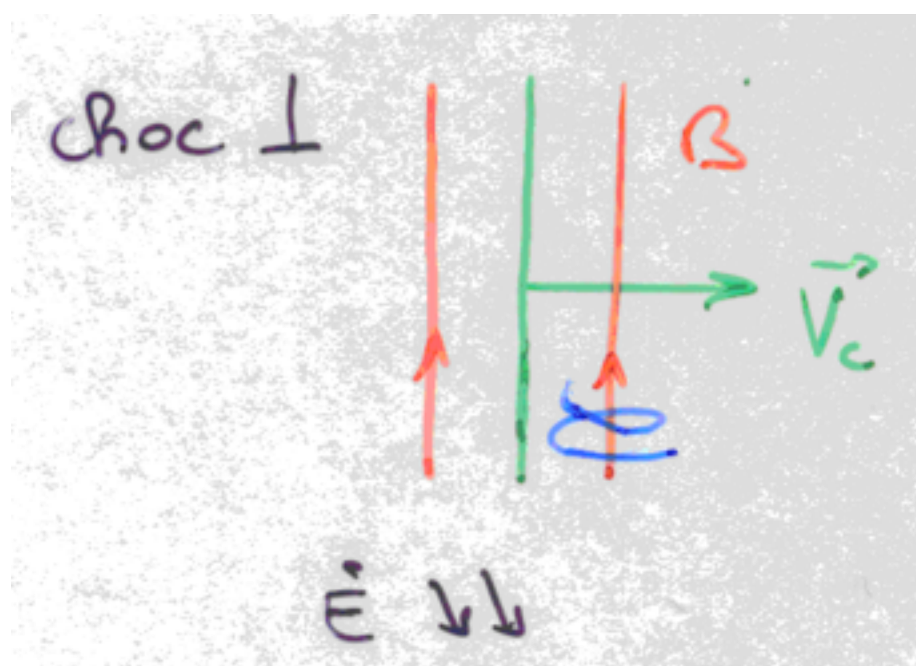
acceleration efficiency

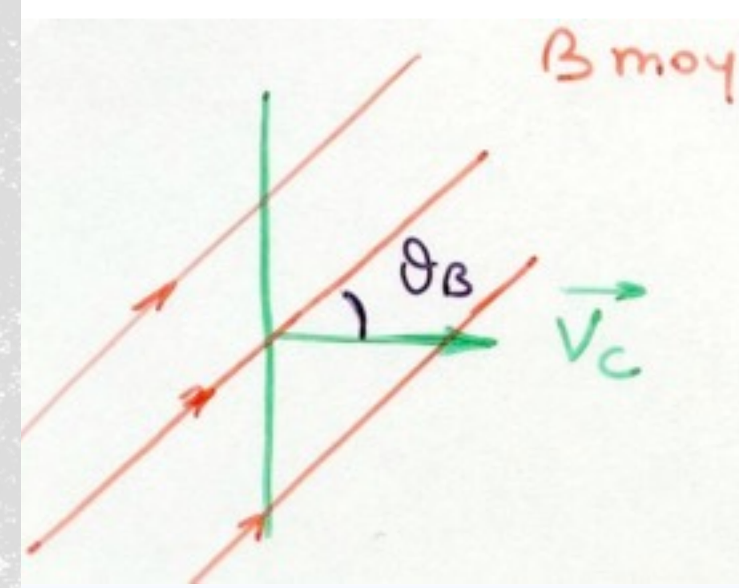
- spectral index ind. of θ_B
- $(dE/dt)_{acc}$ decreases as θ_B ↑ because injection rate depends on obliquity and Mach number











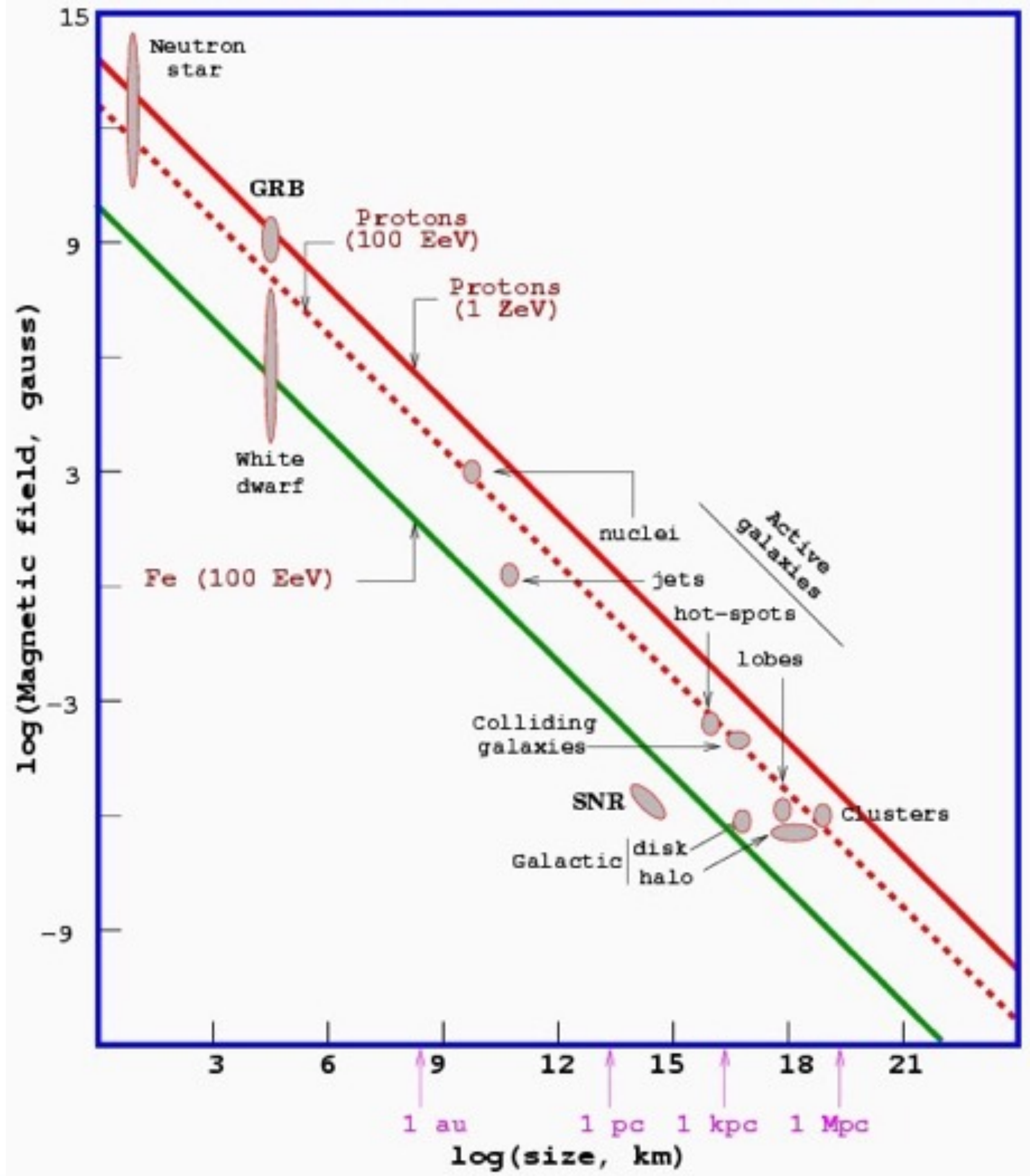
- crossing cycle duration: $$\langle T_{cycle} \rangle = \frac{4}{c}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right) = \frac{4}{cu_1}(D_1 + rD_2)$$
$$\langle T_{cycle} \rangle \propto D \propto E \text{ si } D_1 \sim D_2$$
- energy gain per cycle $$< \frac{\Delta E}{E} >= \frac{4(u_1 - u_2)}{3c}$$
- so constant acceleration rate in energy
  - ✦ just wait to get to the desired energy !

$$\dot{E}_{acc} =< \frac{\Delta E}{E} > \frac{E}{T_{cyc}} = cte$$

- maximum energy when
  - ✦ particle escapes: gyroradius ≈ shock size

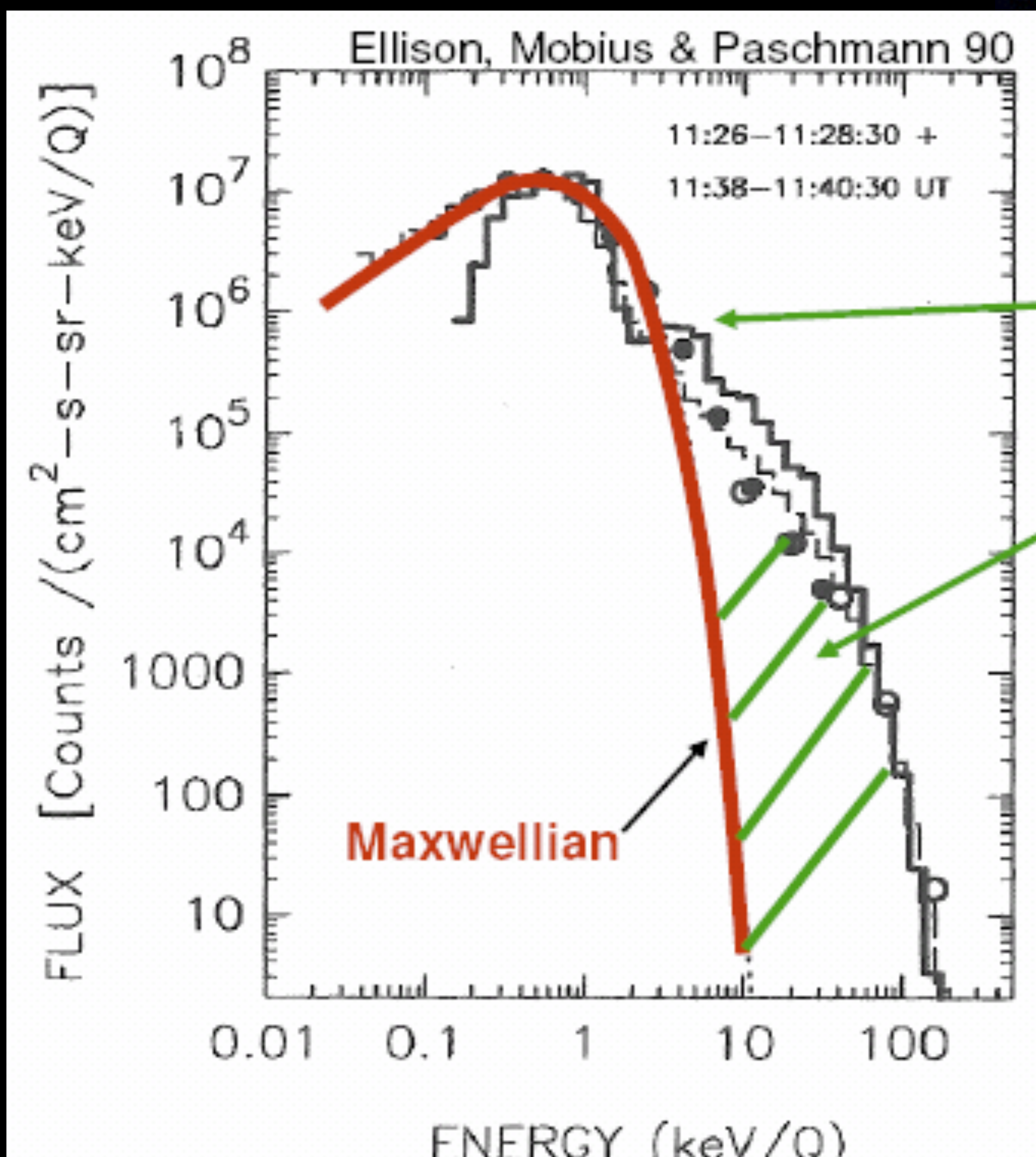
$$\frac{D_1}{u_1} < R_{SNR} \quad \Leftrightarrow \quad \frac{E}{3ZeB_1u_1} < R_{SNR}$$
$$\Rightarrow \quad E < 3ZeB_1u_1R_{SNR} \qquad \text{en S.I.}$$

  - ✦ acceleration time ≈ shock age
  - ✦ energy loss rate (radiation) balances the gain rate, particularly efficient for electrons



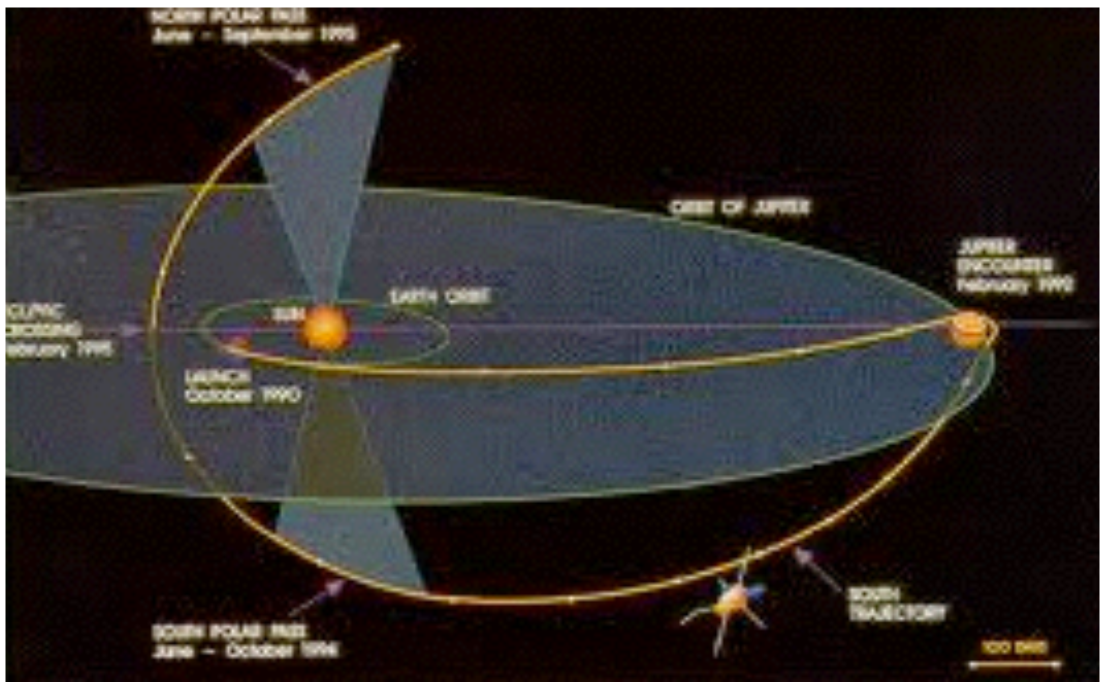
Earth bow shock

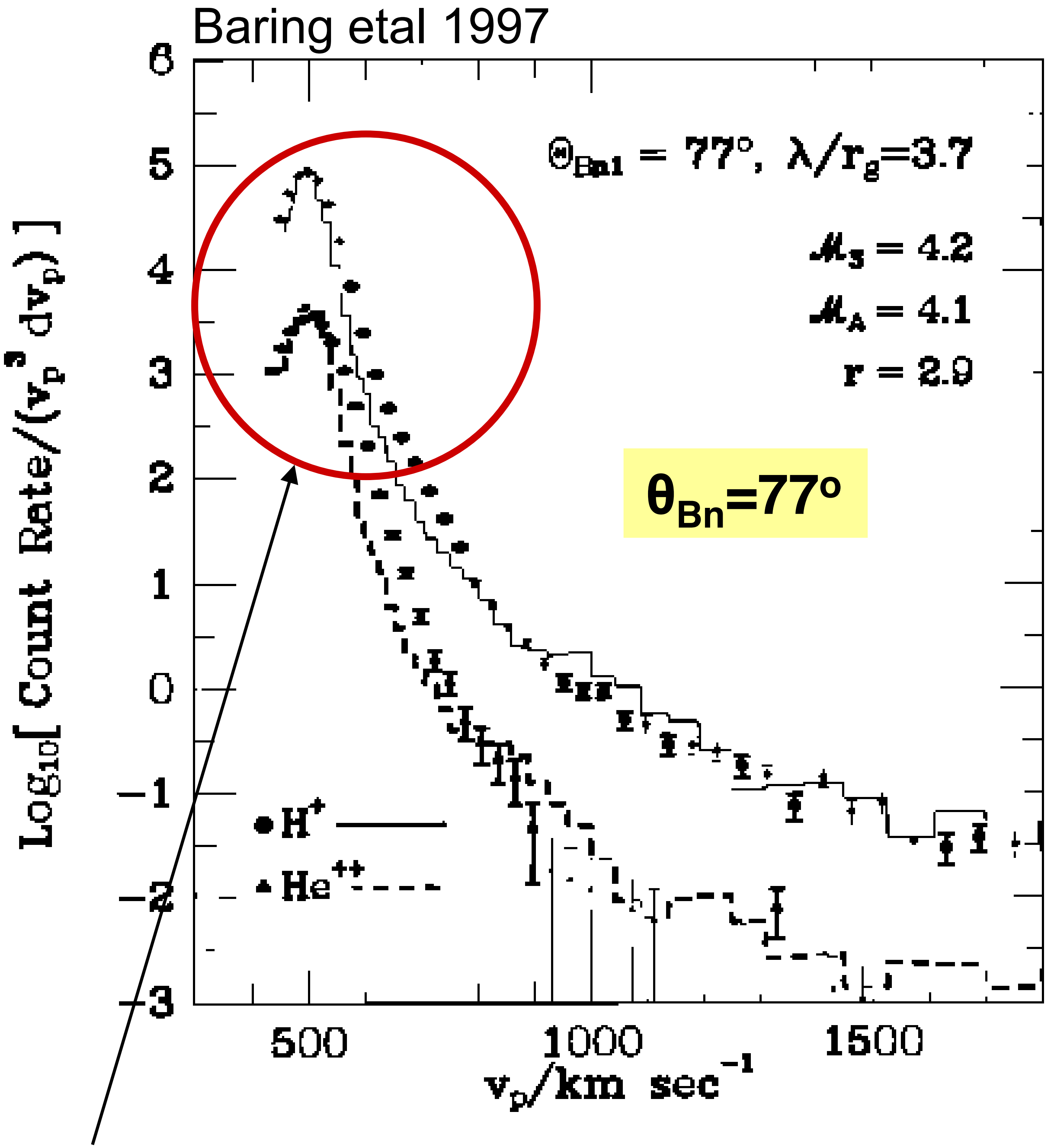
- very high acceleration efficiency above 4 keV
  - ⋆ ≈ 2.5% of proton density in suprathermal part
  - ⋆ > 25% of energy flux crossing the shock to supra thermal protons



interplanetary shocks

- highly oblique one (Ulysses)
- data consistent with acceleration model, but inefficient injection

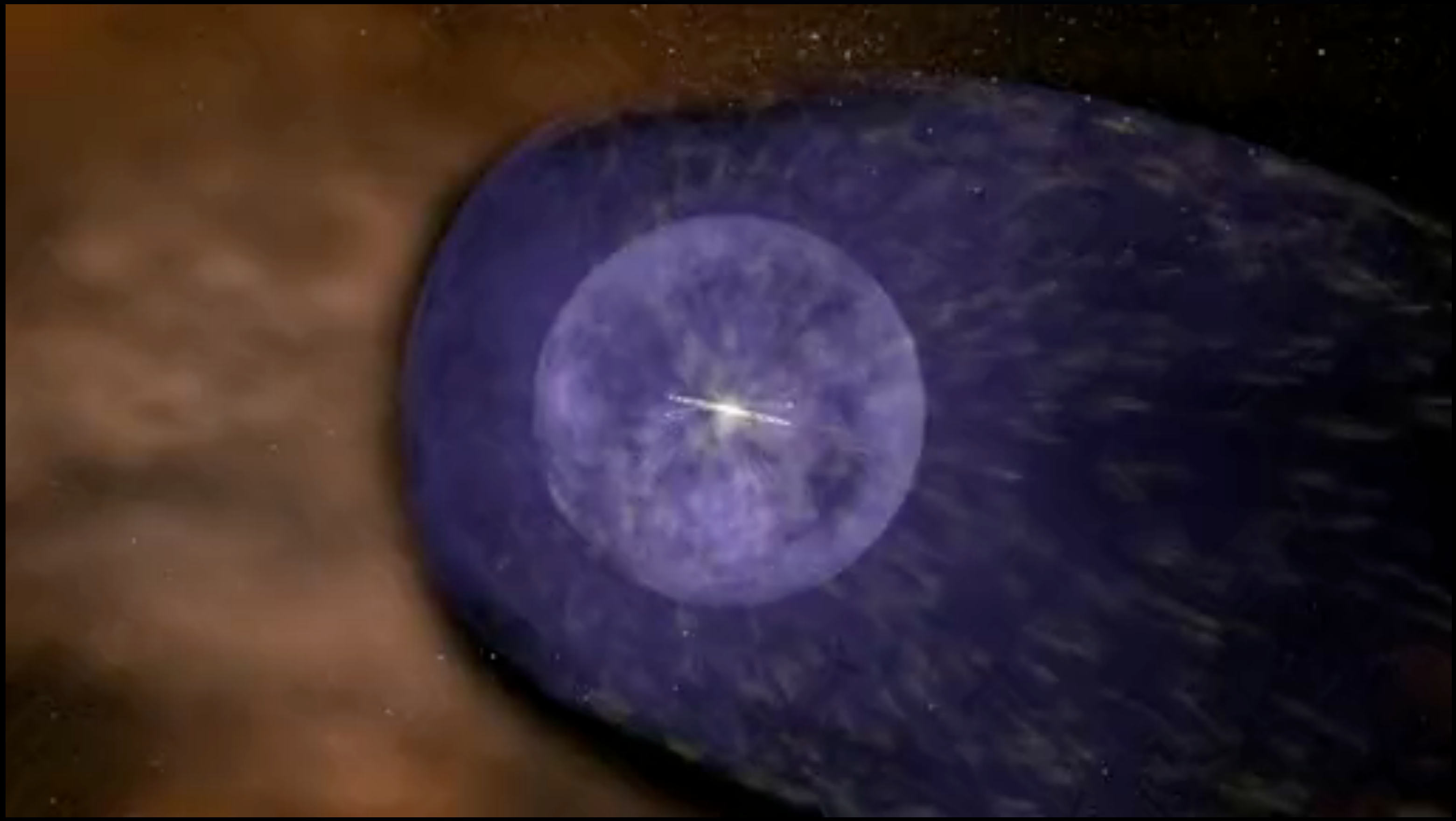




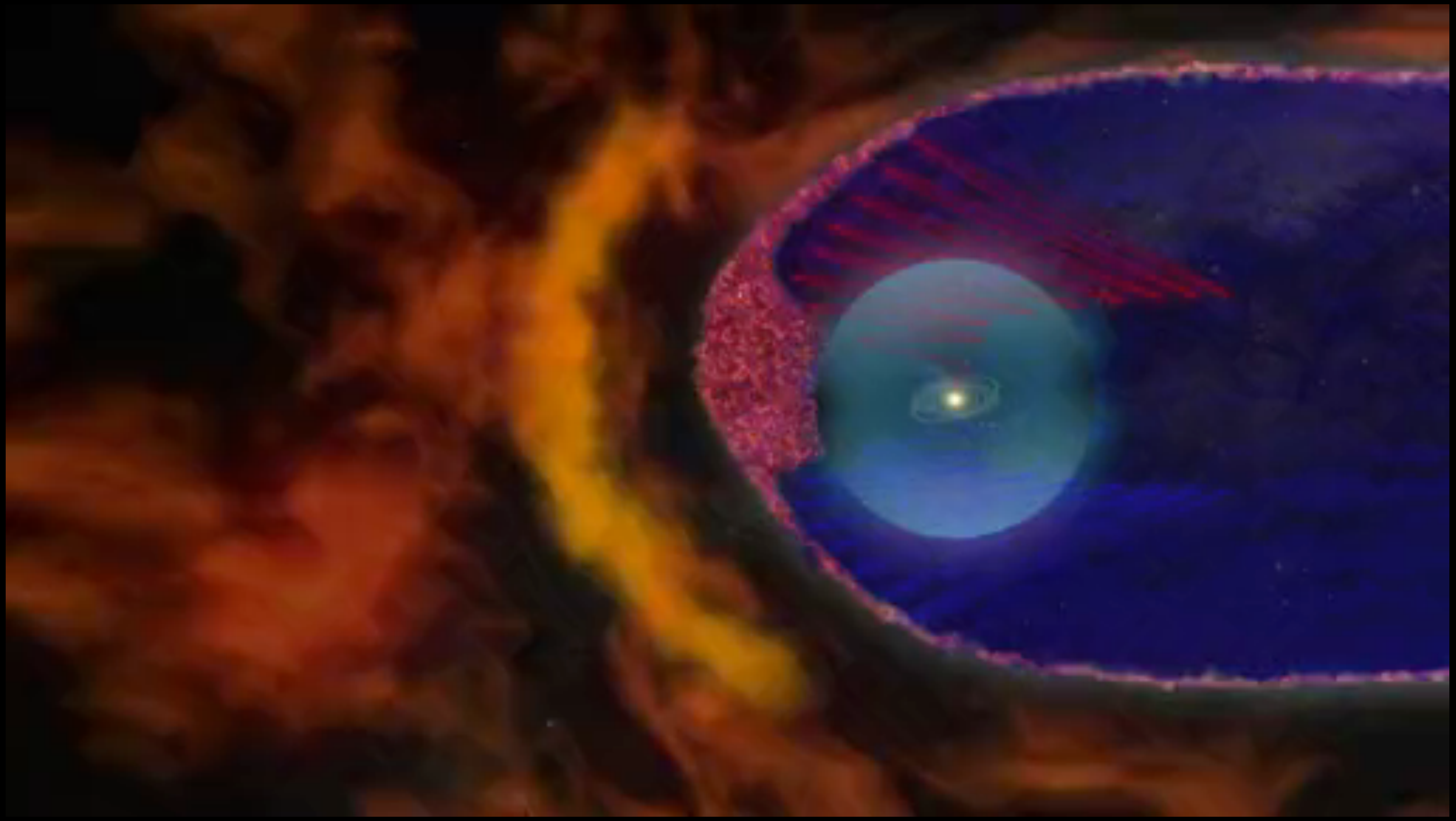
Critical range for injection

magnetic complexity ...

- old point of view



- magnetic "foam" reality



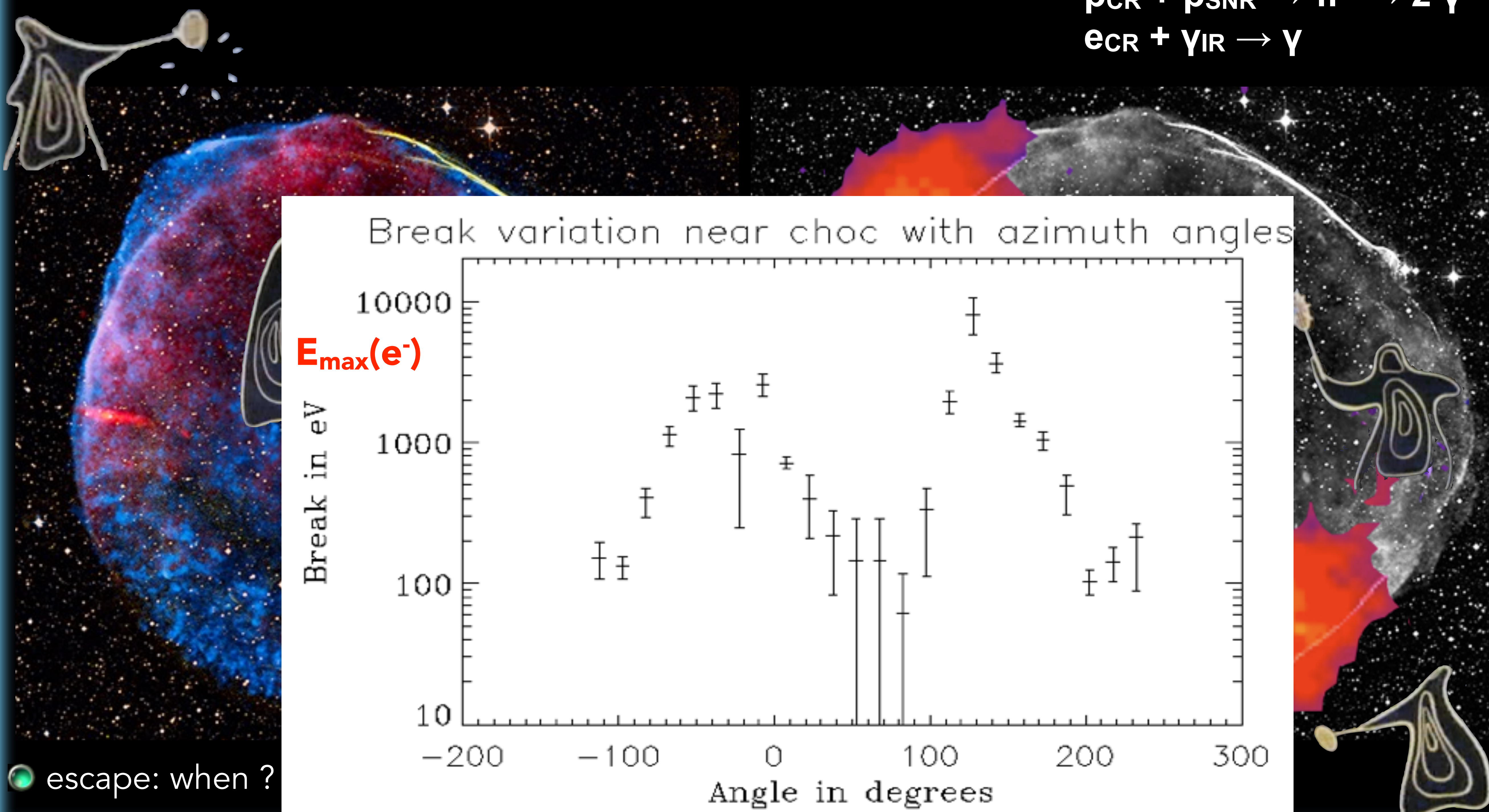
- SN1006

  radio, optical, X rays, γ rays (TeV)

- X-ray synchrotron radiation from ≈ few 10 TeV electrons accelerated at the shock

$p_{CR} + p_{SNR} \rightarrow \pi^0 \rightarrow 2\gamma$

$e_{CR} + \gamma_{IR} \rightarrow \gamma$



- escape: when ?

signature of proton acceleration

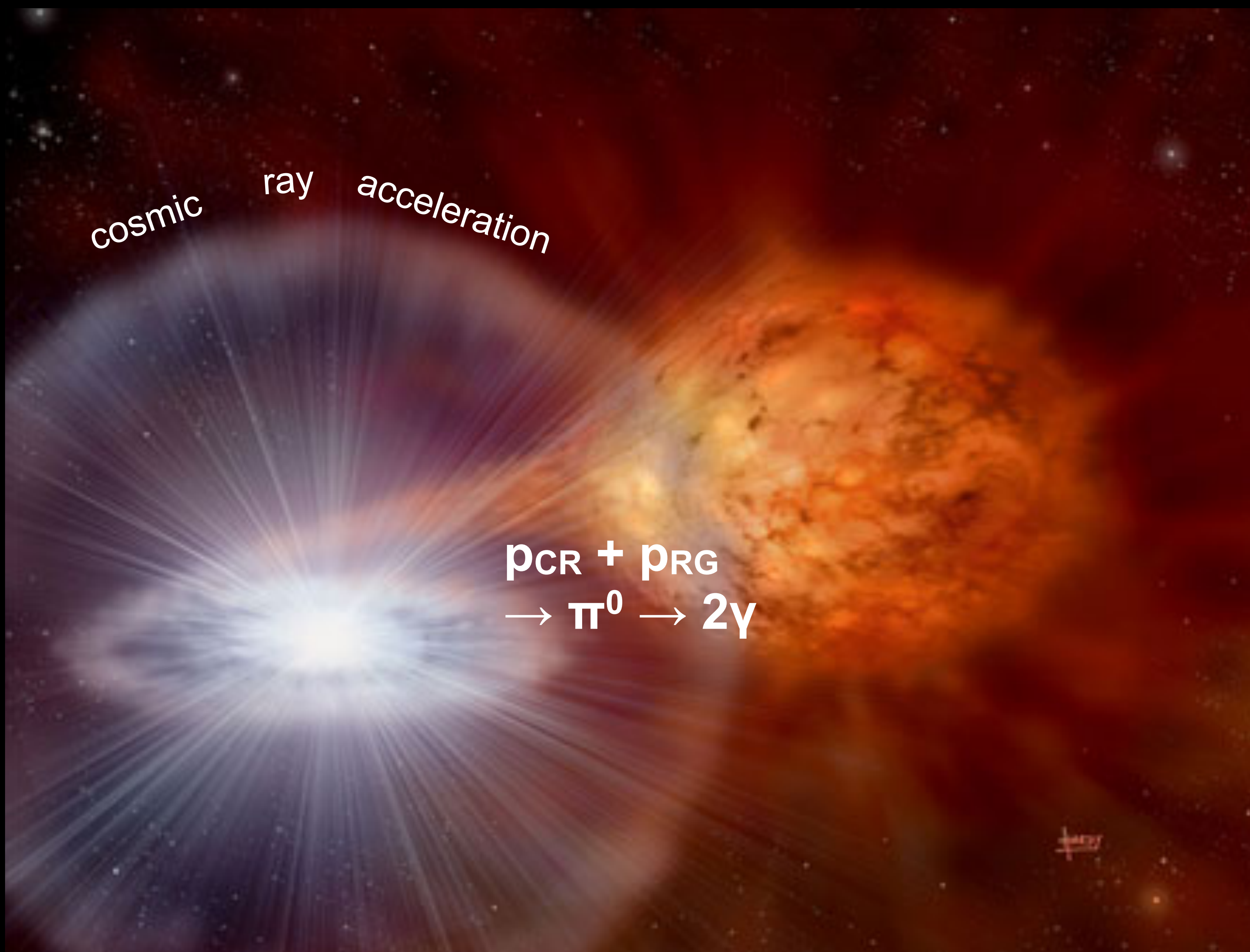
- Fermi sub-GeV spectrum: proton emission

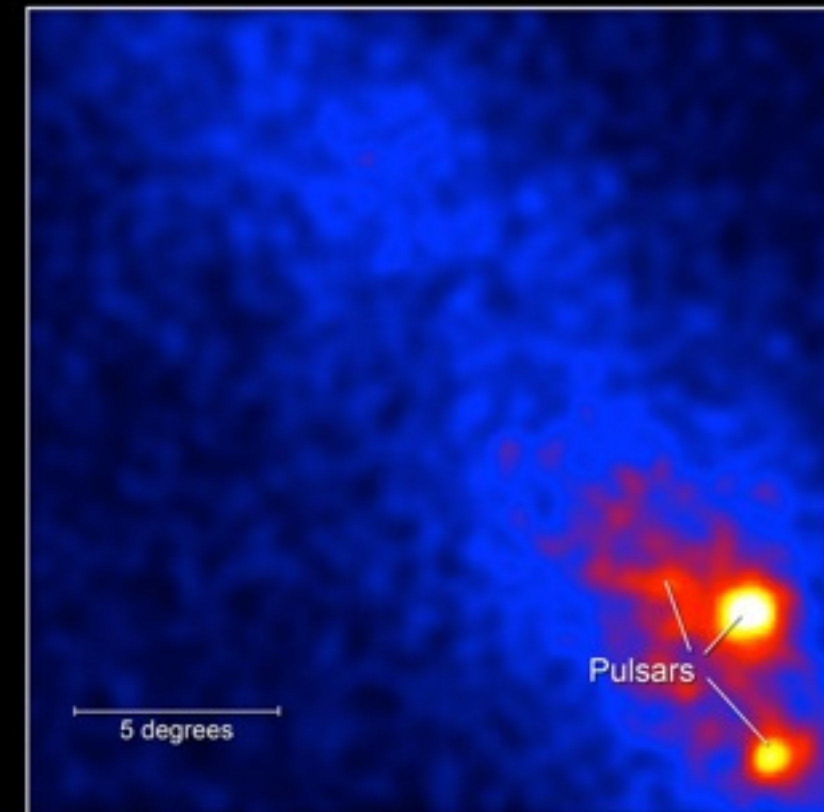
IR opt γ

$$p_{CR} + p \rightarrow \pi^0 \rightarrow 2\,\gamma$$

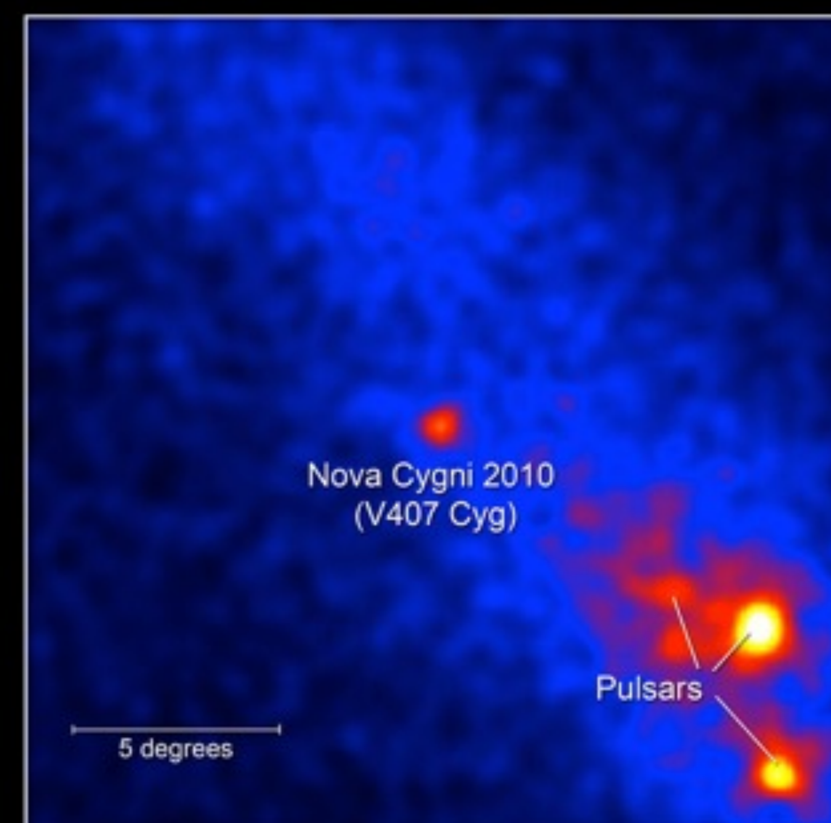
nova thermonuclear explosion

- nova 10^{37} J = P(Sun)*1000 years
- shock speed 44 Mkm/h
- 1 to 2 nova per year





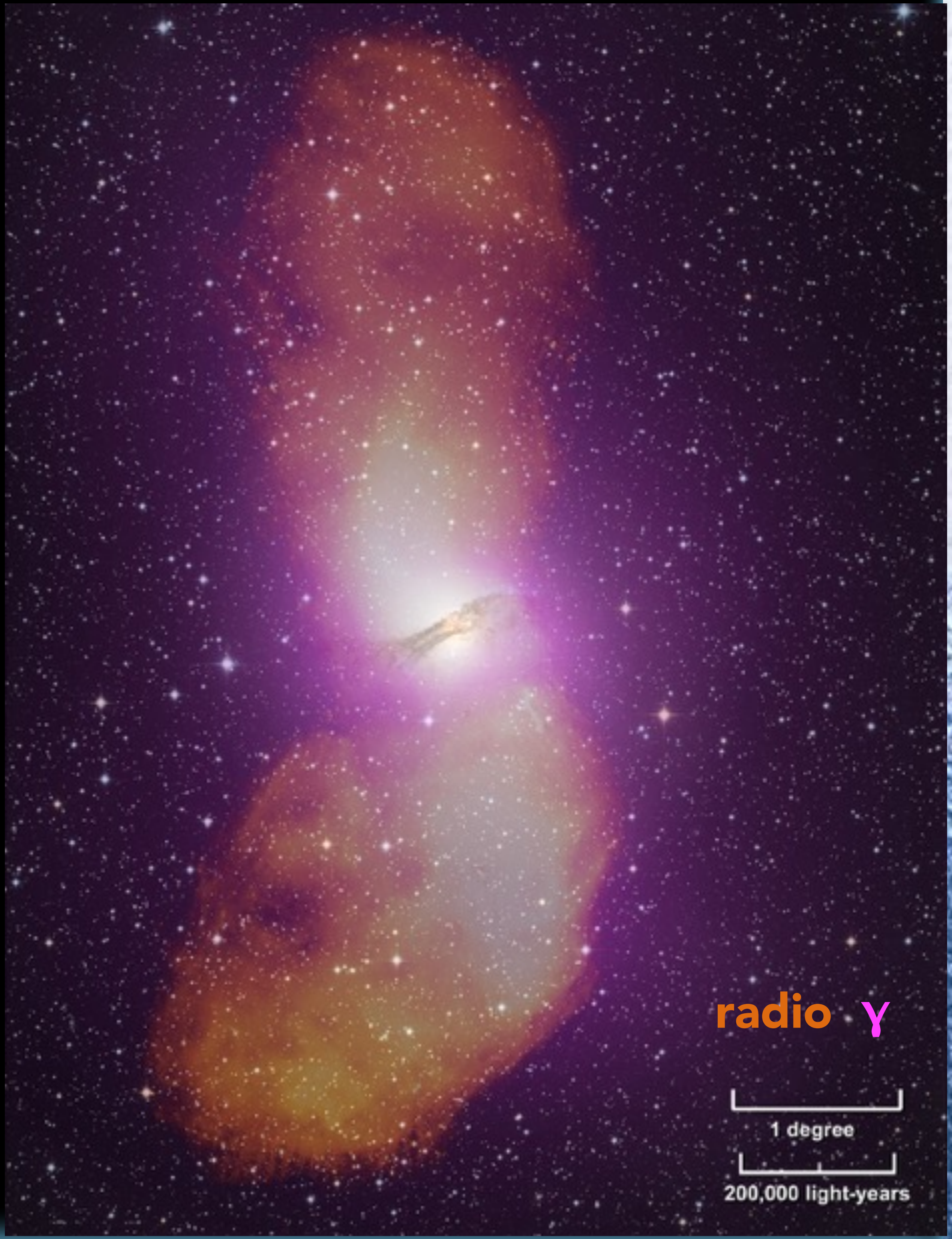
Feb. 19 to March 9, 2010



March 10 to 29, 2010

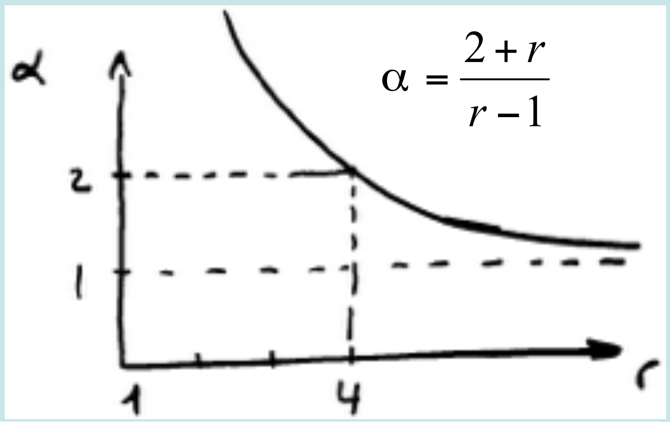
large scale acceleration

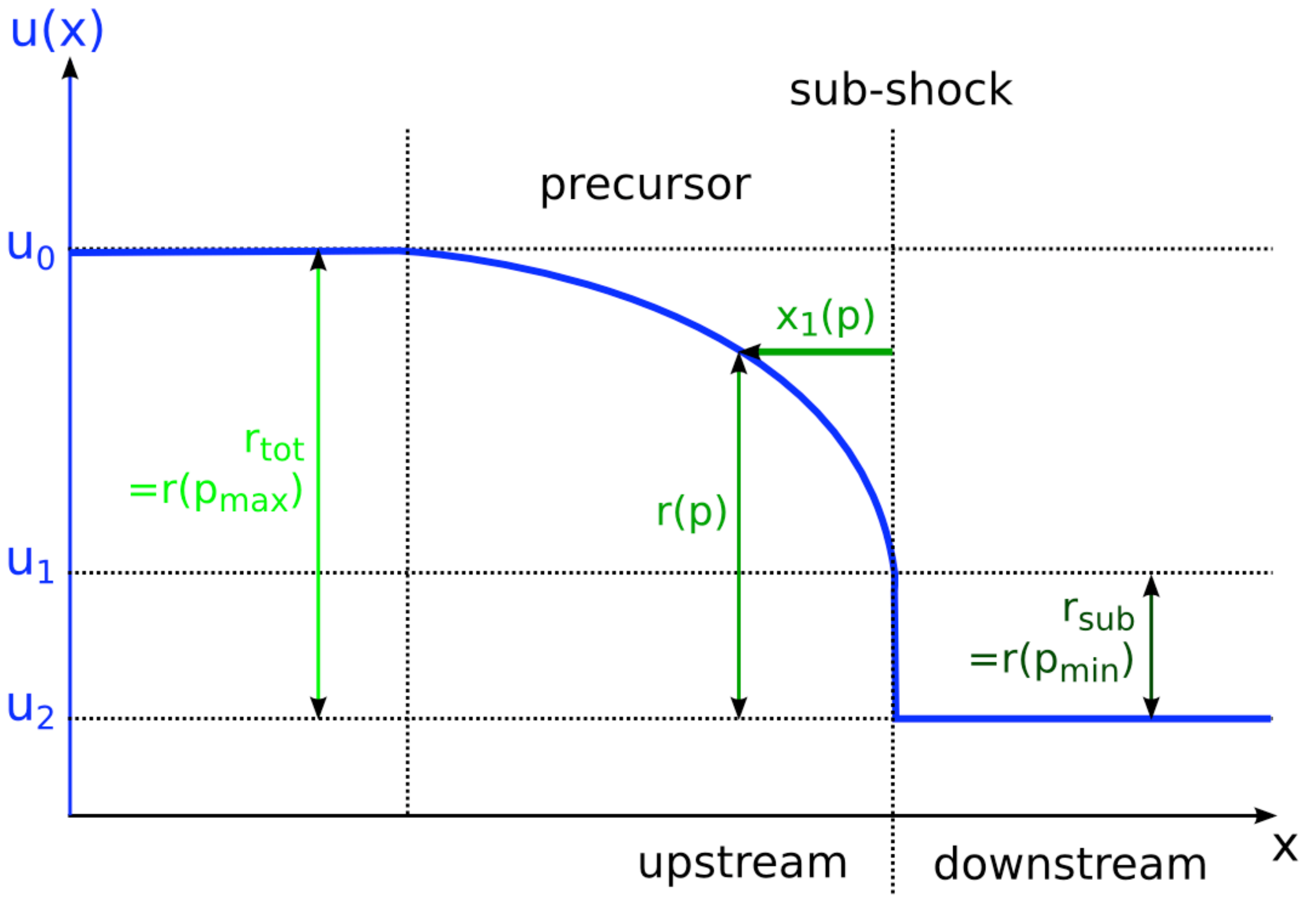
- Centaurus A jet lobes
-

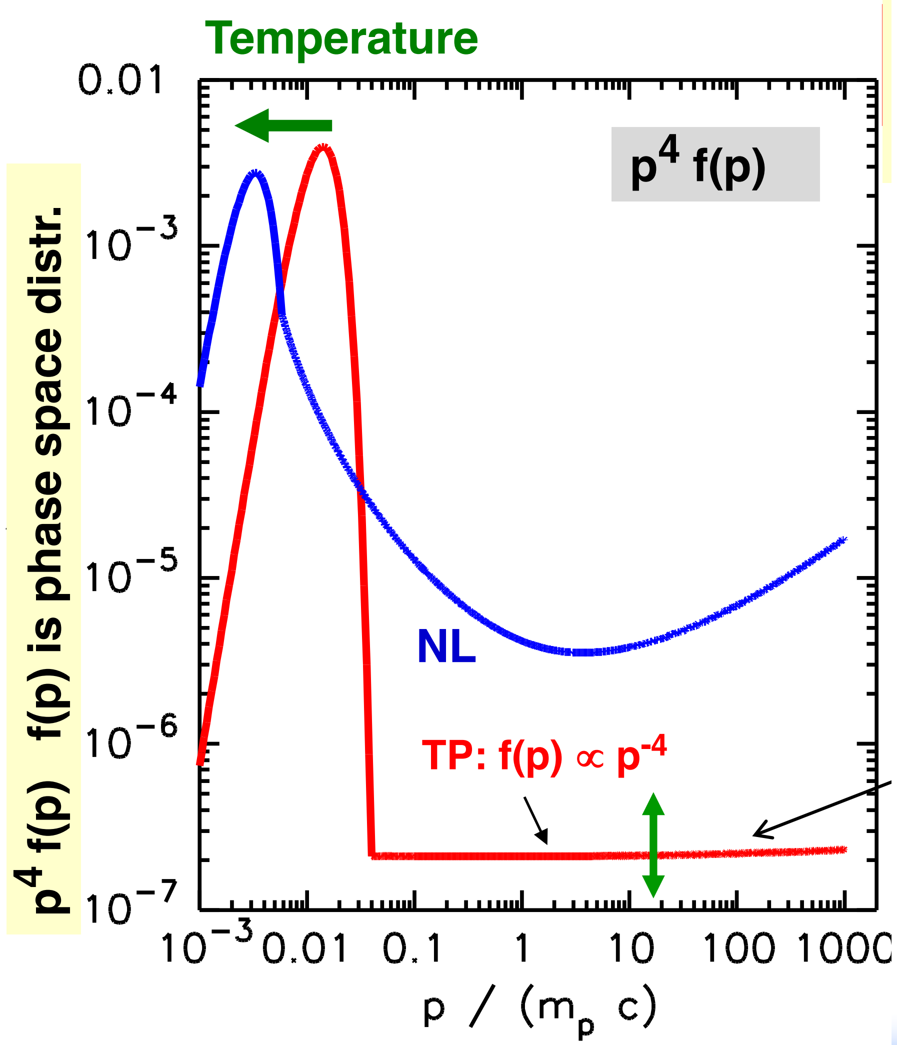


shock modification

- feedback of accelerated particles on the shock
  - ✦ gas adiabatic index γ = 5/3 —> 4/3 : more compressible (compression ratio r = 4 —> 7)
  - ✦ added particle pressure
  - ✦ shock precursor => particles with different gyroradii "see" different r ratios => different spectral indices
  - ✦ current leakage from escaping particles => Bell instability (Alfven wave spiraling along B, its radius grows as B increases) => strong B amplification $\delta B/B \approx 10$, then $\delta B/B$ —> 400 as loops advected near the shock



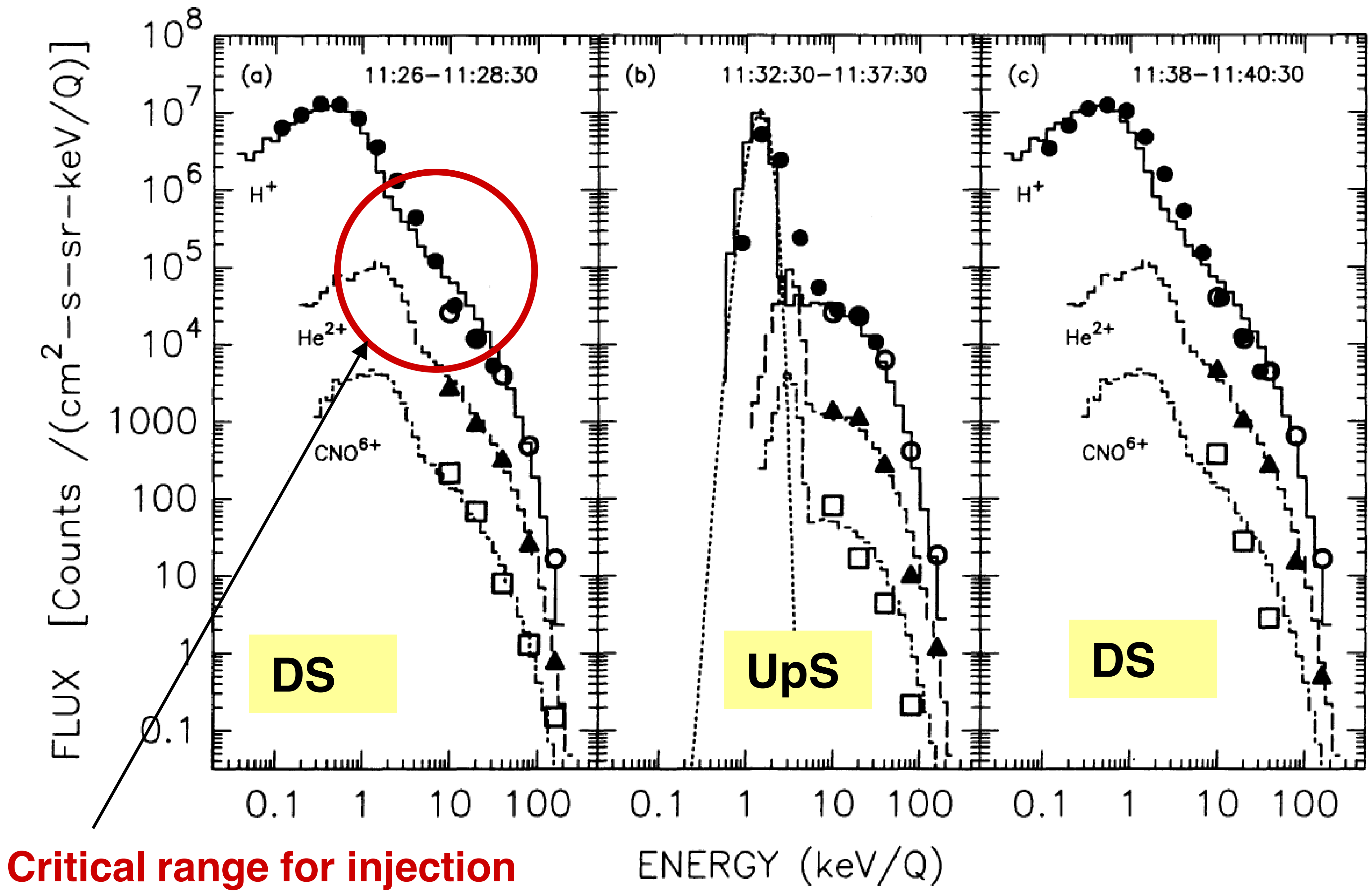




Earth bow shock

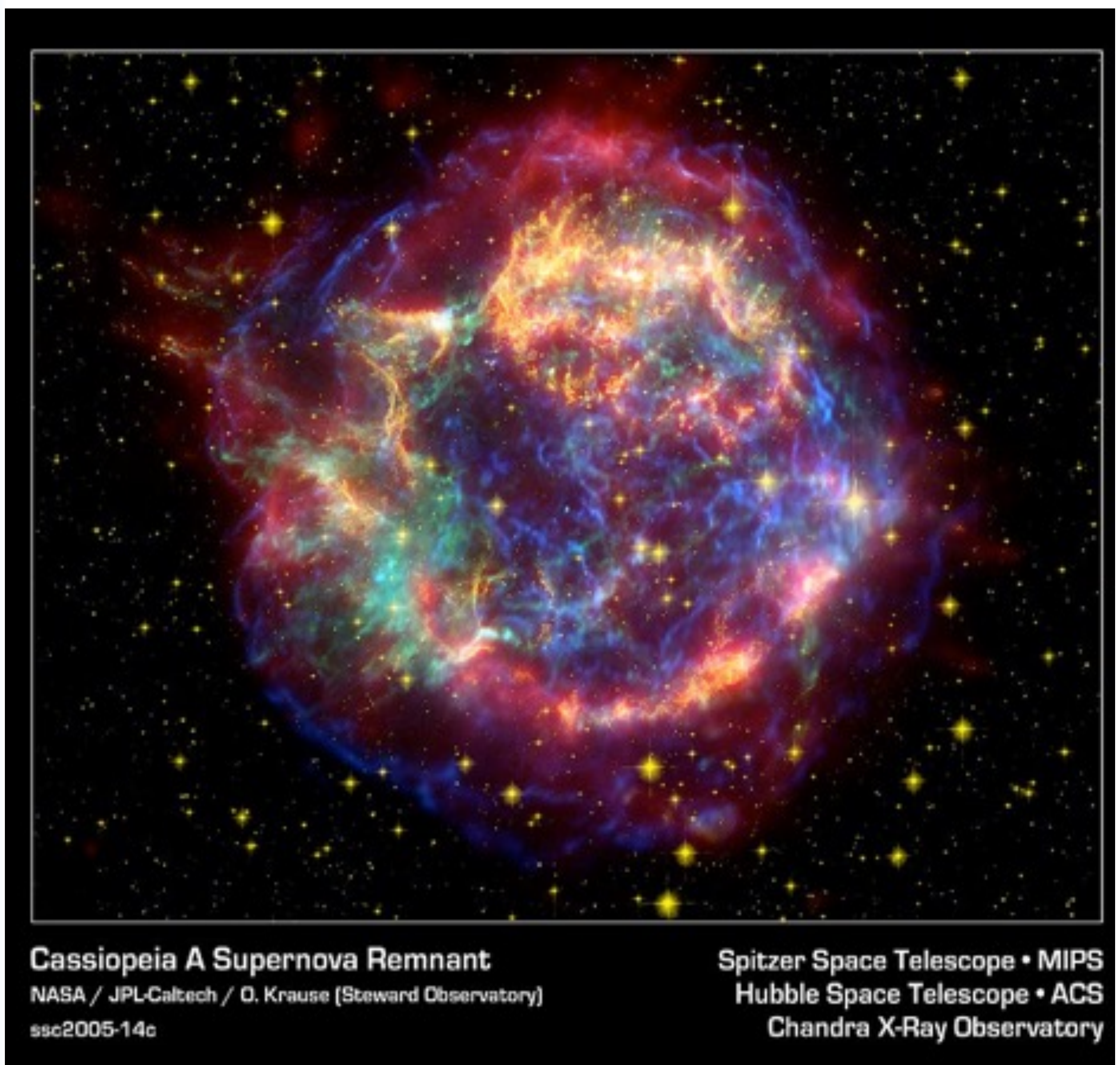
- quasi-parallel shock data (H^+, He^{2+}, CNO^{6+}, AMPTE data) consistent with non-linear (feedback) acceleration

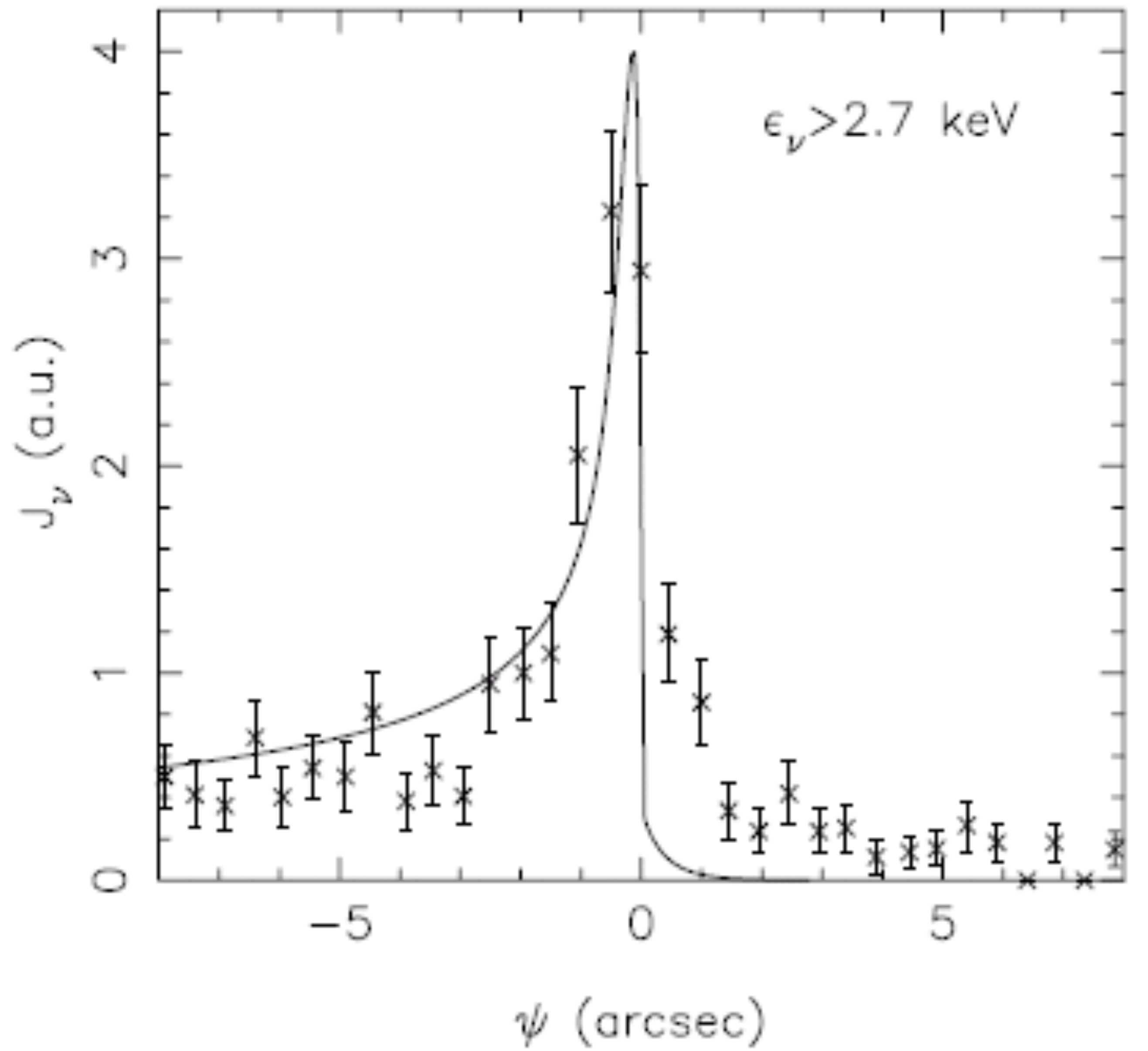
Ellison, Mobius & Paschmann 90



B amplification

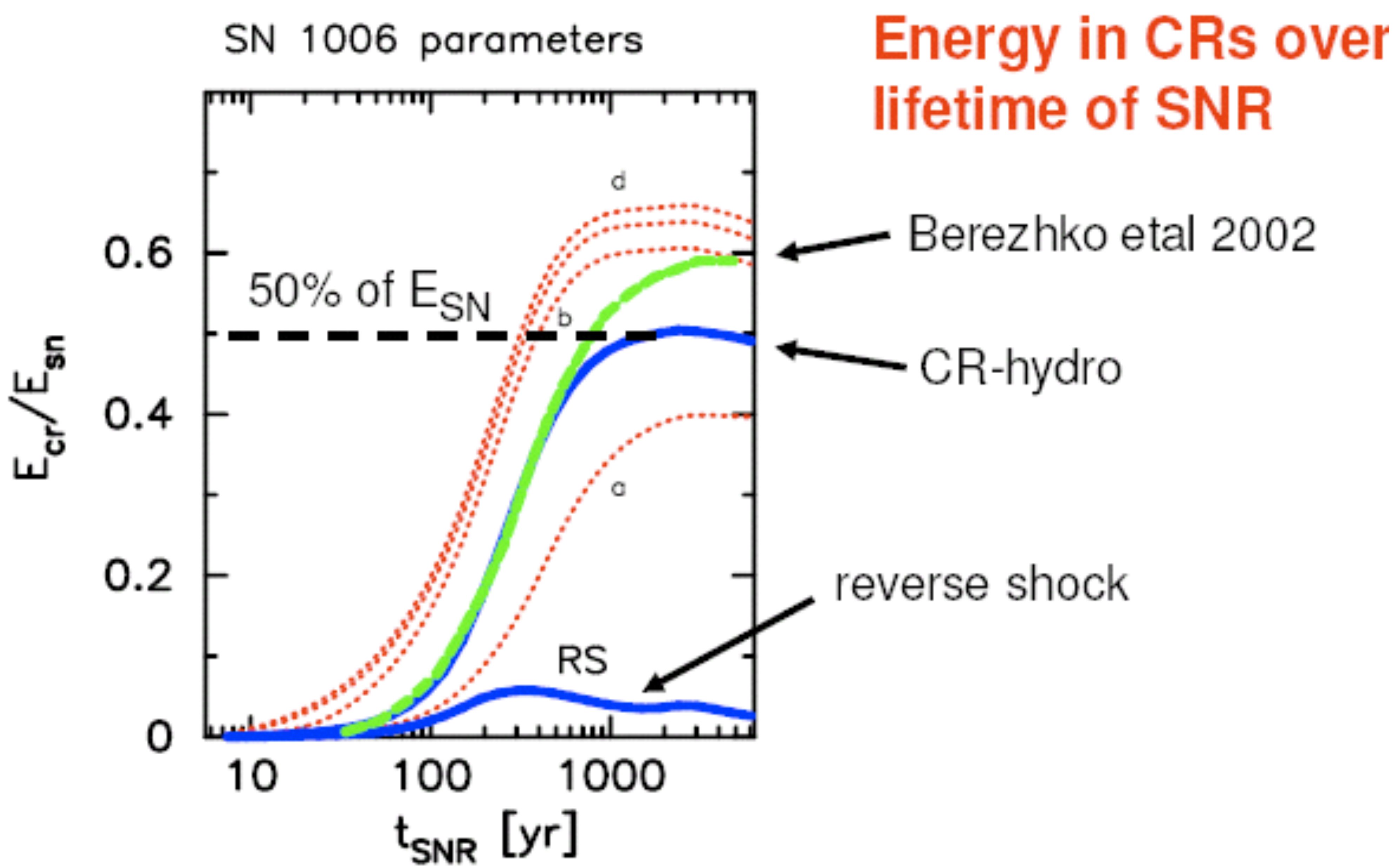
- thin X-ray synchrotron front
  => $B \sim 50$ nT $\gg r \times B_{ISM}$





1. The X-ray emissivity for X-ray energies $2.7 < \epsilon_\nu < 9$ keV

- large fraction of the shock energy goes to particle acceleration



Ellison, Decourchelle, & Ballet 2004

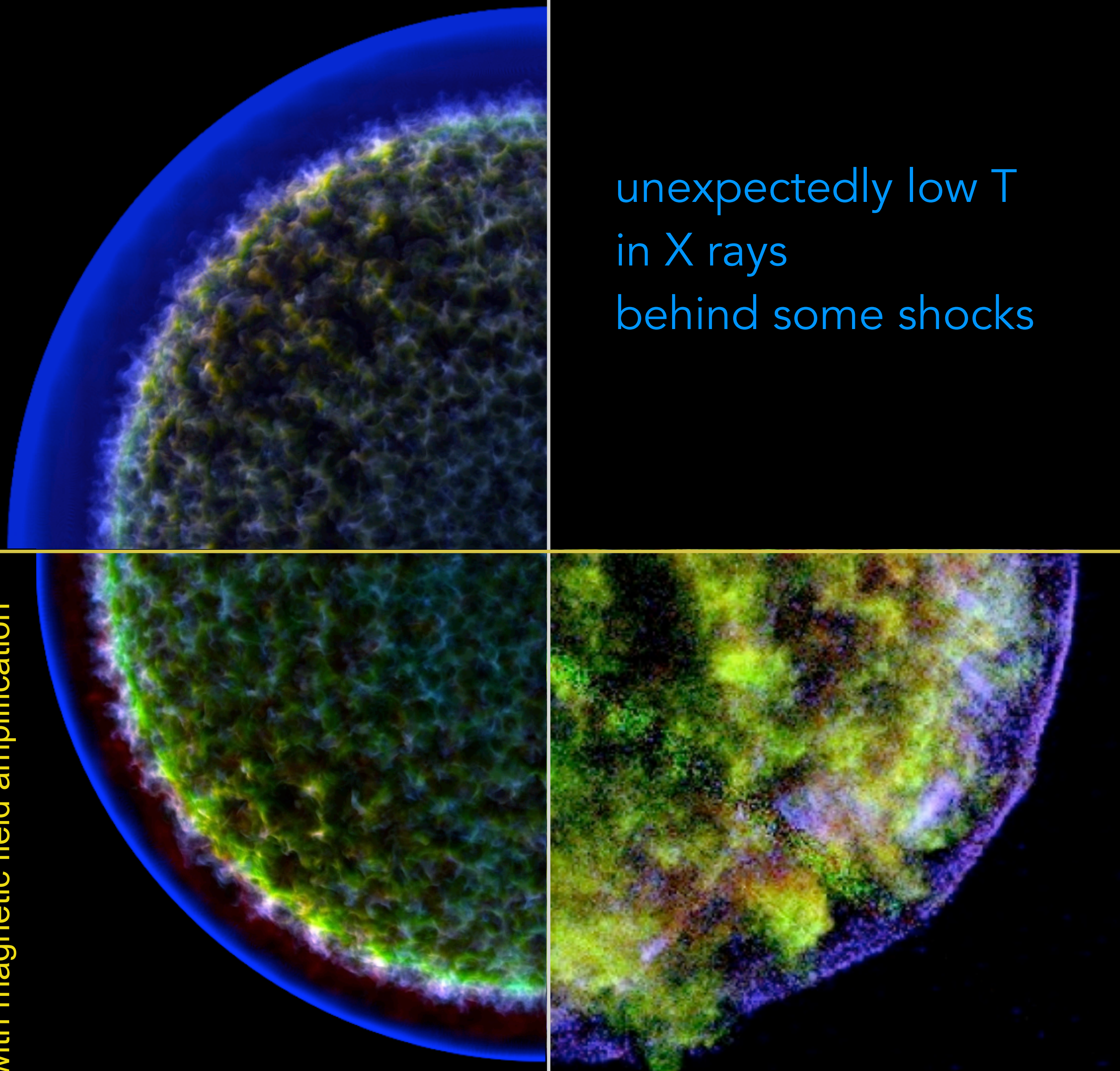
acceleration feedback on shock expansion

simulations

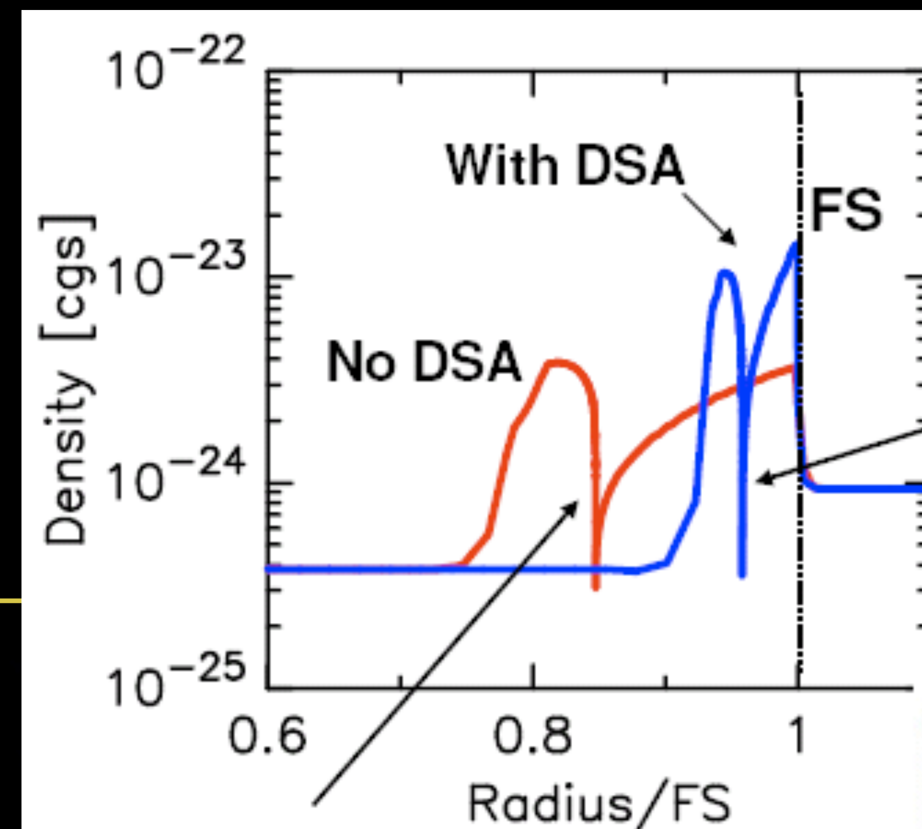
observations

un-modified shock

modified shock
with magnetic field amplification



unexpectedly low T
in X rays
behind some shocks



Ferrand et al. 2014