HIGH-ENERGY PARTICLE ACCELERATION AT ASTROPHYSICAL SHOCKS: RECENT PROGRESSES

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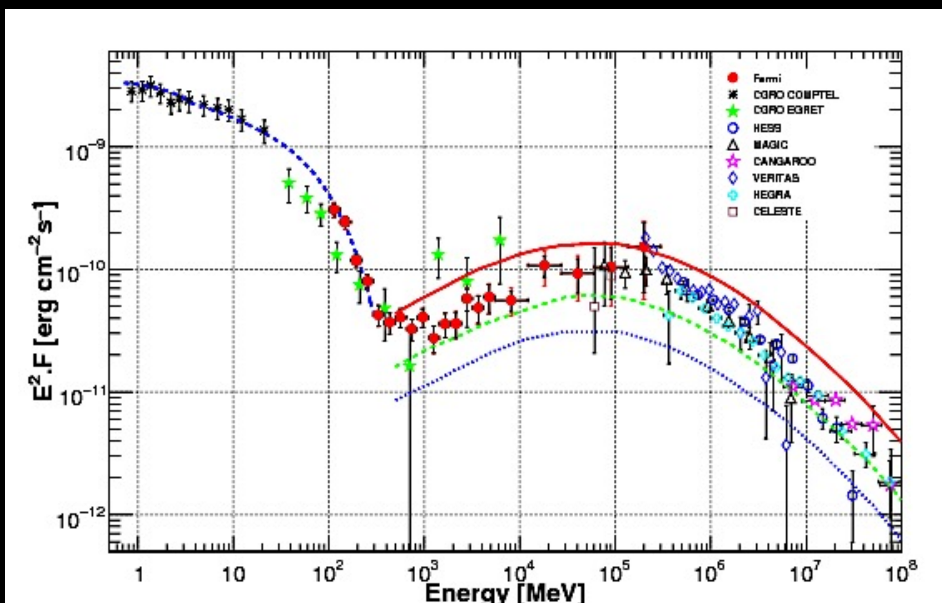
OUTLINES

- Astrophysical contexts
- Particle acceleration at non-relativistic shocks: Case of supernova remnants
  - Diffusive shock acceleration
- Particle acceleration at relativistic shocks
  - Fermi acceleration at last ?
- Conclusions

ASTROPHYSICAL CONTEXT.

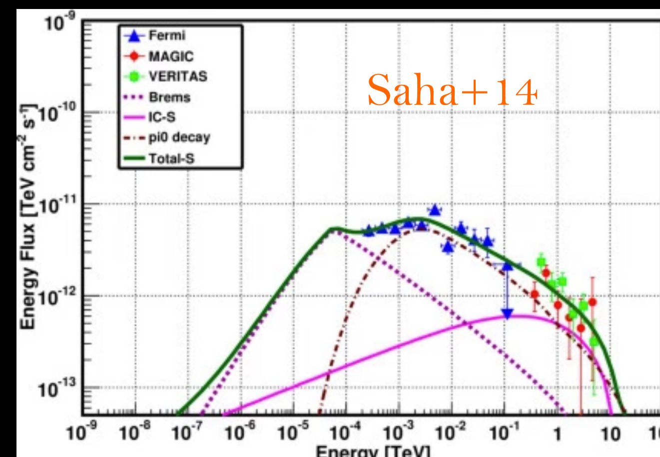
- Shocks are ubiquitous + energetic particles (GeV-TeV) and non-thermal radiation (radio-gamma-rays) are found in many astrophysical objects.

RELATIVISTIC SHOCKS



Crab nebula SED
Abdo+09

NON-RELATIVISTIC SHOCKS



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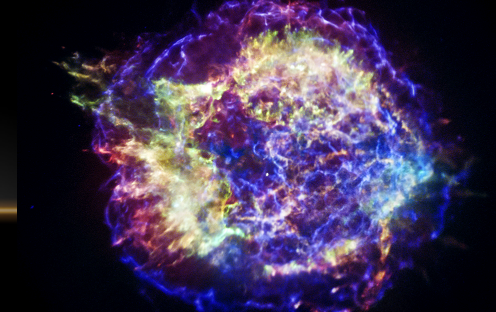


SNR & GRB are candidate sources for cosmic ray production

PARTICLE ACCELERATION AT SHOCKS: ASTROPHYSICAL INTERESTS

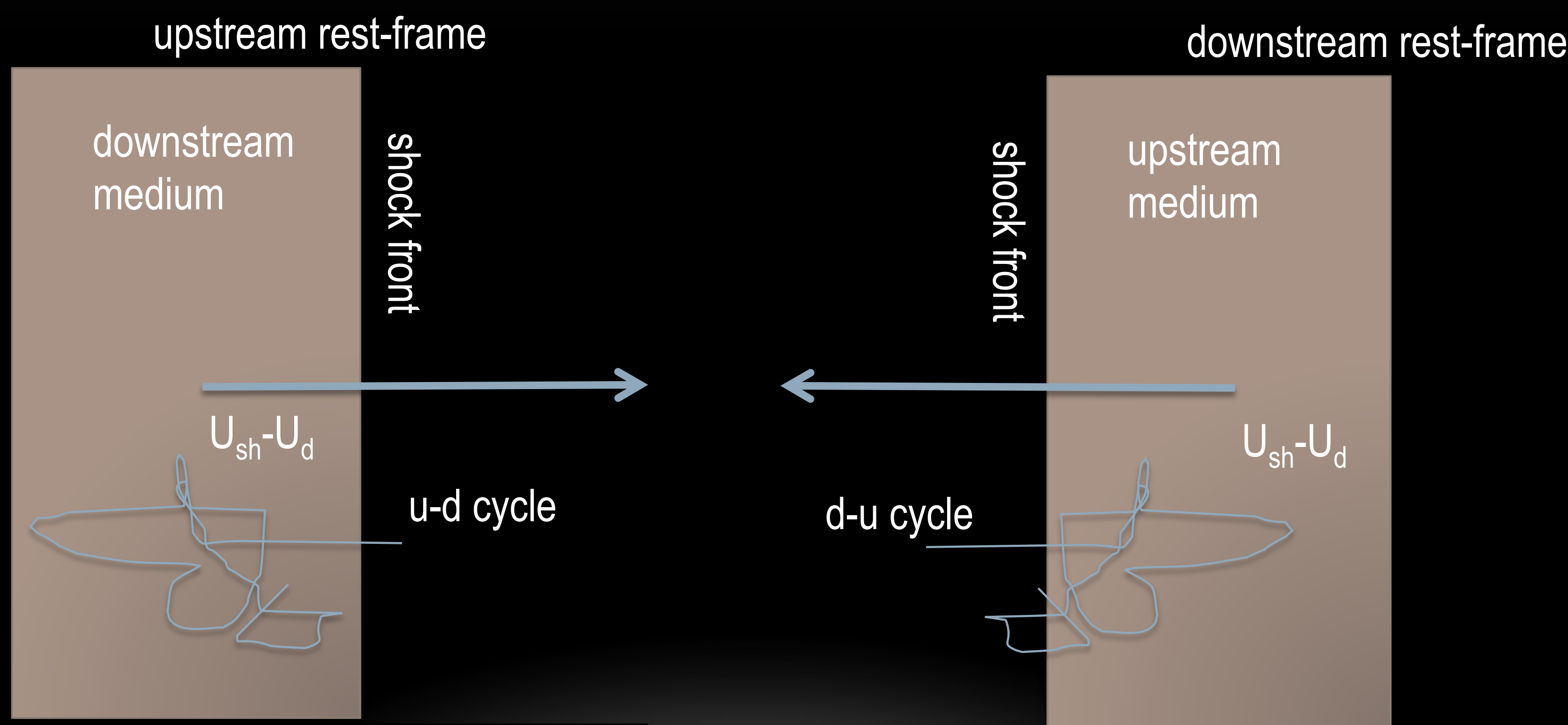
1. Explain the observations:
   - SED: particle content, energetics
   - Variability: acceleration mechanism
2. The highest energies:
   - Link with the origin of cosmic rays: where are the sources ?
3. Shocks are parts of complex systems:
   - What back-reaction over shock, jet, accretion … dynamics ?
4. Injection of non-thermal component in inter-stellar/galactic media:
   - Contribution to diffuse background emissions
   - Non-linear effects over structure dynamics

SUPERNOVA REMNANTS (SNR)

- Known as non-thermal sources since late 40's (Ryle & Smith 1948).
- 12 SNR identified by Fermi (third Fermi catalogue: Acero+15), 11 SNR identified by Cerenkov instruments (http://tevcat.uchicago.edu/)
- Potential sources of galactic cosmic rays (GCR): MeV-PeV (EeV ?). Not the only one although (see eg this afternoon).
- X-ray observations (especially high-resolution by Chandra): particle acceleration at work ⇔ magnetic amplification ⇔plasma microphysics.
- <u>Favorite acceleration process</u>: diffusive shock acceleration (Krymsky'77, Bell'78, Drury'83).

DIFFUSIVE SHOCK ACCELERATION

- Particles can reach high energies with repeated high number shock crossings.



crossing from upstream:
first interaction is head-on =>
energy kick ~(U_{sh}-U_d)/U_{sh}

crossing from downstream:
first interaction is head-on =>
energy kick ~(U_{sh}-U_d)/U_{sh}

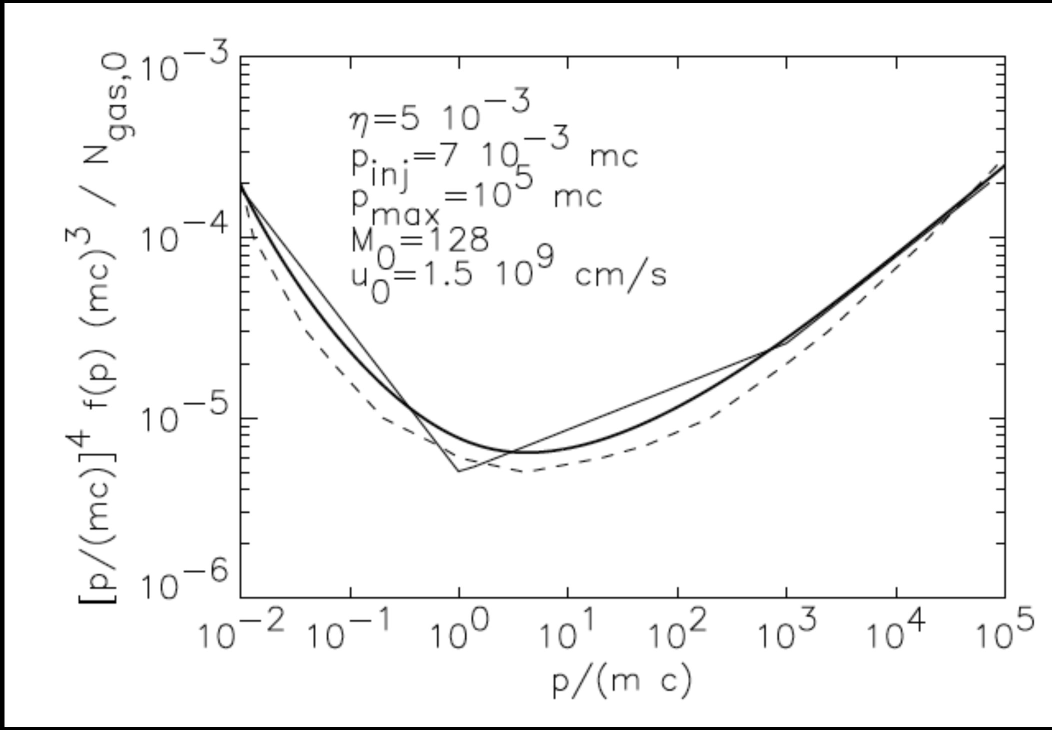
MAIN RESULTS … BUT MODIFIED BY NON-LINEAR EFFECTS

1. The relative energy gain $\Delta E/E \sim (1-r)$, $r=\rho_d/\rho_u=4$ (strong supersonic adiabatic shocks)
2. At each cycle particles have a finite probability to escape downstream

Points 1 and 2 => particle distribution at the shock front only dependent on r:

Index $s_E = -d\log(N)/d\log(E) = (r+2)/(r-1) = 2$ for $r=4$ (or $s_p = -d\log(N)/d\log(p) = 4$).

It soon appeared (Drury & Voelk'81) that this solution produced too efficient particle acceleration.



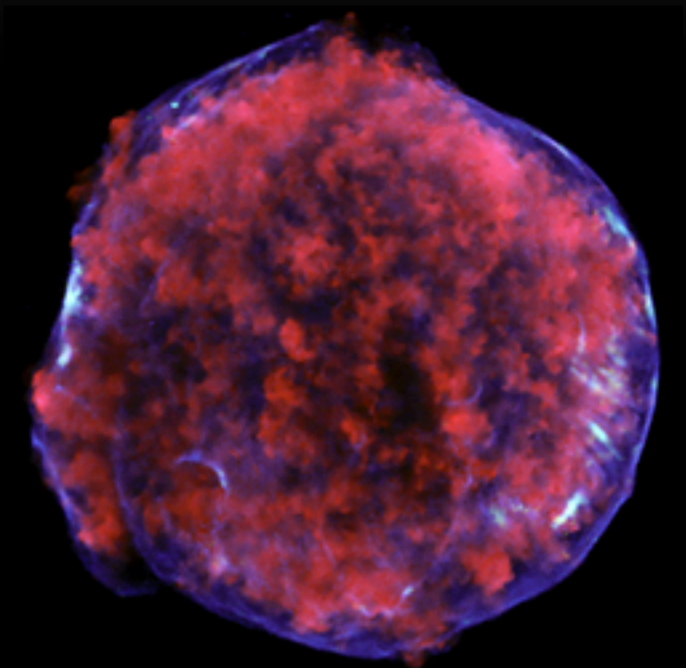
Non-linear solution (Blasi'02)

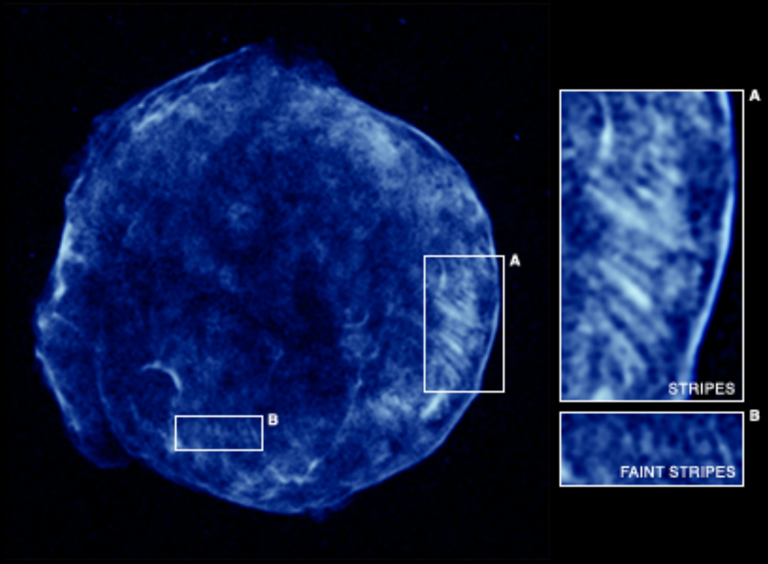
- CR escaping upstream => escaping flux => increase compression (and r)
- CR overpressure => increase compression.
- Conservation laws => sub-shock compression < 4 => softer low energy CR spectrum

=> Concave shape in $p^4 f(p)$

SUB-STRUCTURES IN X-RAYS

Tycho SNR by Chandra in 4-6 keV band





Filaments (Hwang+02) and stripes (Eriksen+11)

Filament size ~0.01 pc (% shock radius) ~ distance between 2 stripes

MAGNETIC FIELD AMPLIFICIATION

L_X =deprojected filament size

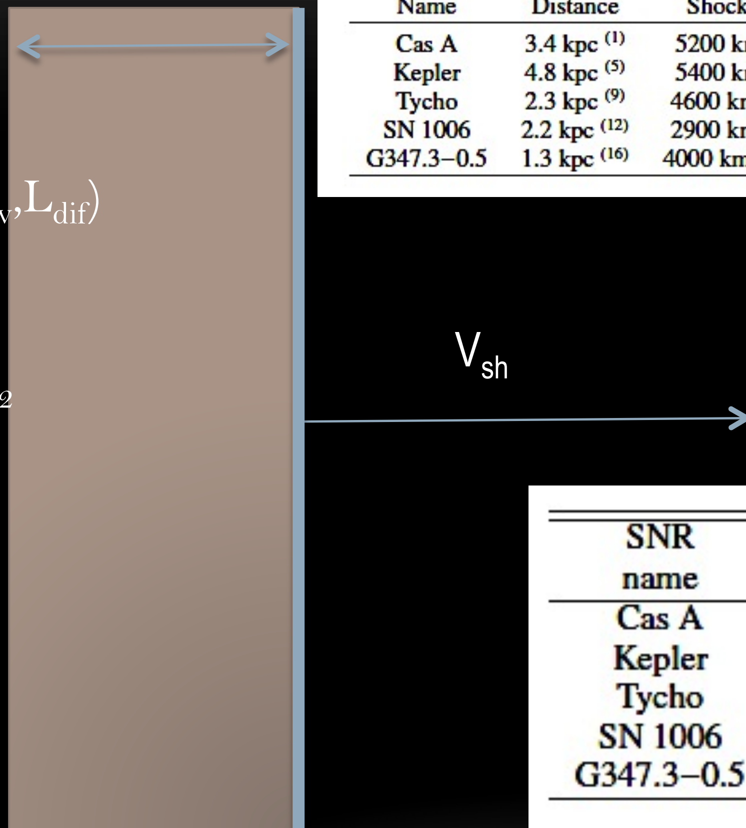
Name	Distance	Shock speed	Projected width	Age	Cut-off energy
Cas A	3.4 kpc [1]	5200 km s^{-1} [2]	0.05 pc (3″) [3]	320 yr ? [4]	1200 eV [3] (whole SNR)
Kepler	4.8 kpc [5]	5400 km s^{-1} [6]	0.07 pc (3″) [7]	400 yr	900 eV [8]
Tycho	2.3 kpc [9]	4600 km s^{-1} [10]	0.05 pc (4″) [7]	430 yr	290 eV [11]
SN 1006	2.2 kpc [12]	2900 km s^{-1} [13]	0.2 pc (20″) [14]	1000 yr	3000 eV [15]
G347.3–0.5	1.3 kpc [16]	4000 km s^{-1} ? [17]	0.25 pc (40″) [18]	1620 yr ? [19]	2600 eV [18]

$L_X = \mathrm{MIN}(L_{adv}, L_{dif})$

$L_{adv} = U_d\, t_{syn}$

$L_{dif} = (D_d t_{syn})^{1/2}$

=> B_d



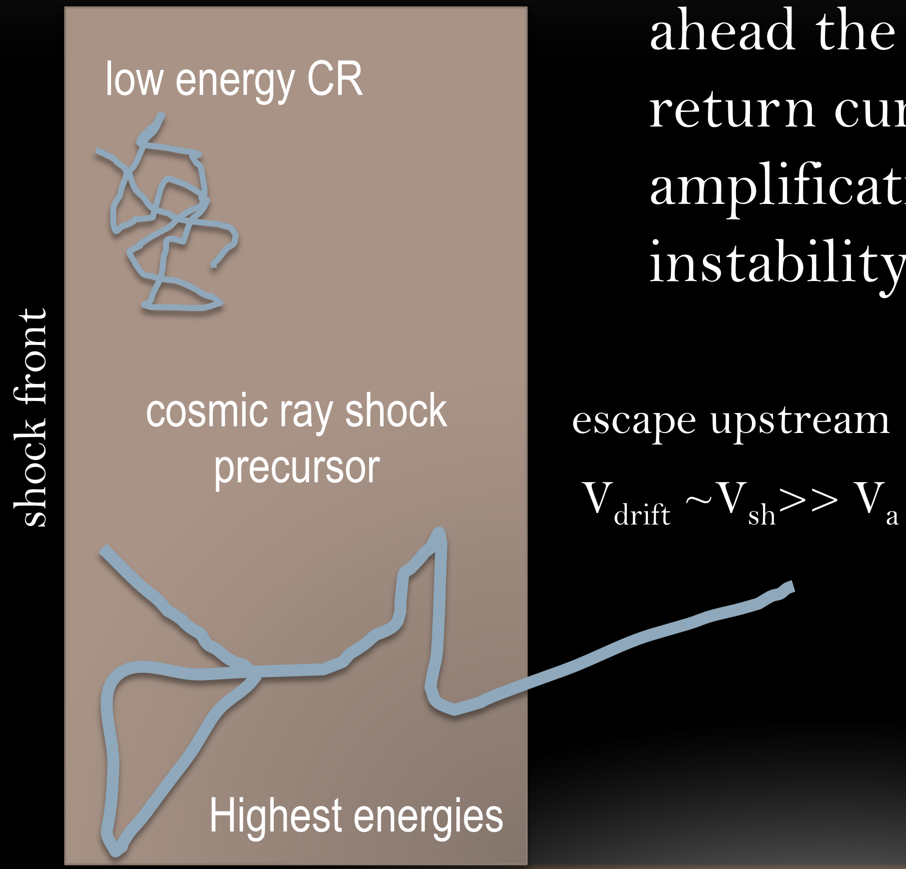
Parizot+06

SNR name	τ_{syn}^{max}/t_{SNR} $(\times 4\bar{P}/r)$	B_{adv} (μG)	B_{diff} (μG)	$\rho_B = \frac{\Delta R_{diff}^{(B)}}{\Delta R_{adv}}$
Cas A	<2.6%	210	230	1.1
Kepler	<2.8%	170	180	1.1
Tycho	<2.1%	200	230	1.2
SN 1006	<5.9%	57	90	2.0
G347.3–0.5	<3.3%	61	77	1.4

We must find a way to amplify the ISM magnetic field by more than one order of magnitude …

Magnetic field amplification produces softer spectra: $s > 2$

MAGNETIC FIELD AMPLIFICATION PROCESS

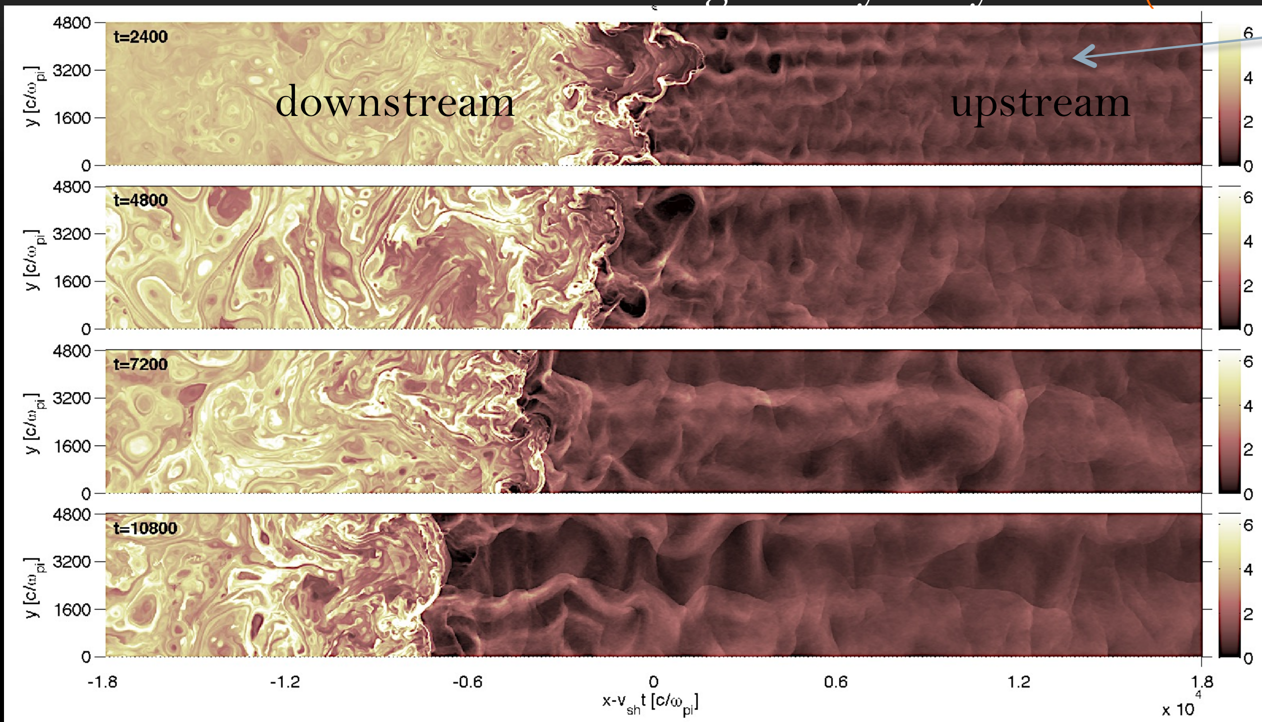


<u>High energy particles</u>: free streaming ahead the shock front => CR current => return current => magnetic field amplification: Non-resonant streaming instability (Bell'04).

- Modes generated at scales $l << r_L$ with a fast growth rate $G \sim 100\ \mathrm{yr}\ E_{PeV}\, n_{cc}^{-1/2}\, V_{sh,3}^{-3}$
- Very fast growth in fast shocks moving in dense media.

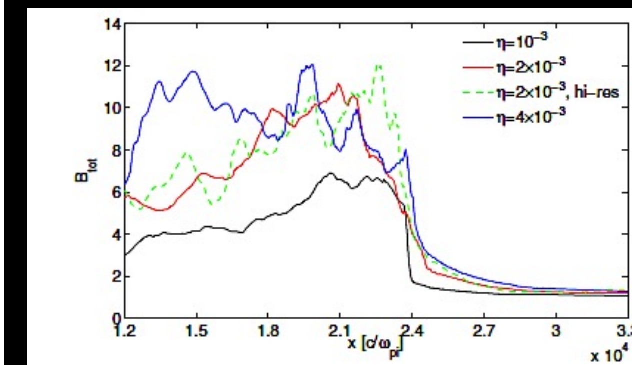
NUMERICAL SIMULATIONS

Particle-in-cell/Magneto-hydrodynamics (Bai+15)

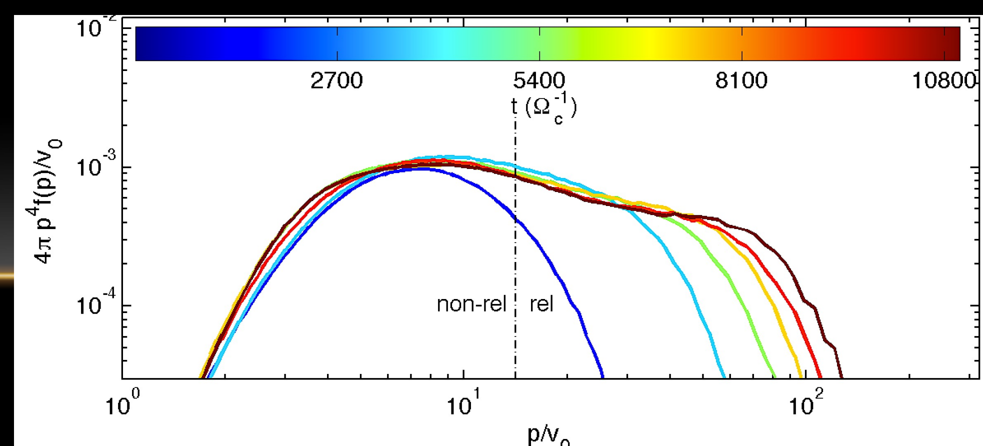


filamentary structures (non-linear stage of the streaming instability

magnetic field amplification



a transition towards diffusive shock acceleration ?



NON-RELATIVISTIC SHOCKS: ORIGIN OF (GALACTIC) COSMIC RAYS

- Several hot topics:

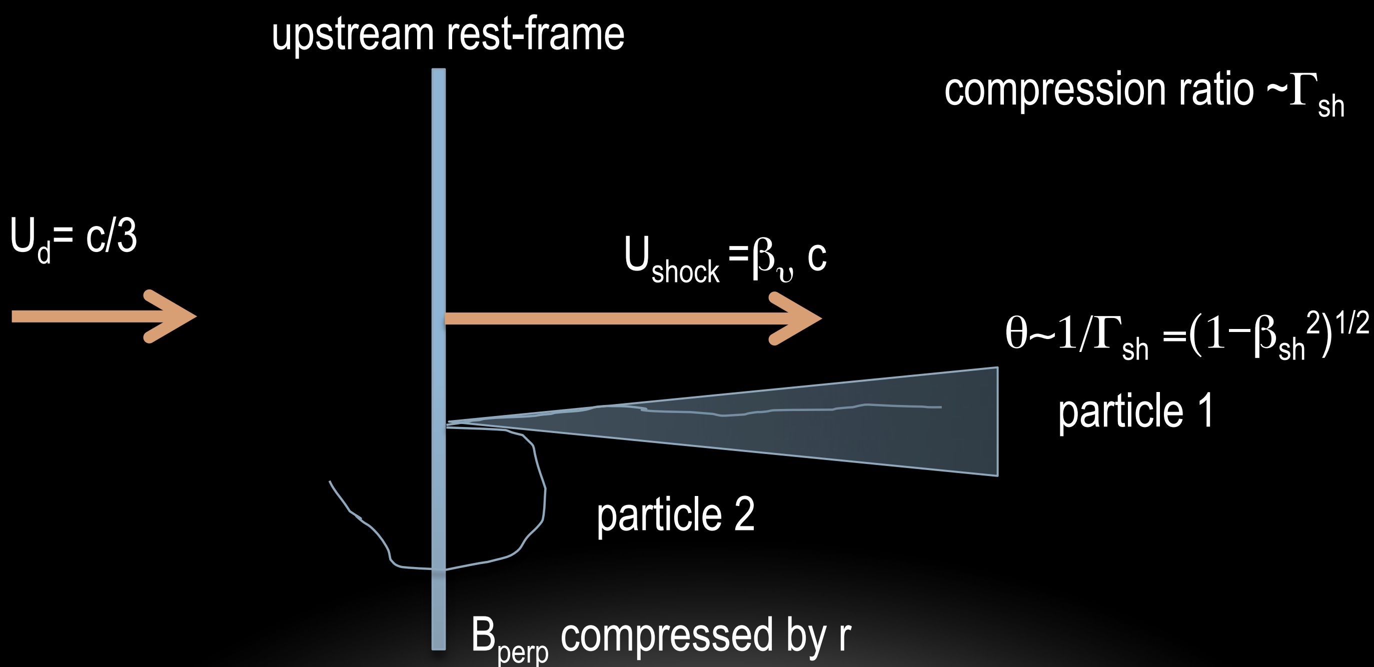
1. Injection and acceleration efficiency: effect of magnetization M_a), magnetic field obliquity (Riquelme & Spitkovsky'11, Caprioli+14)

2. Maximum energies: If the non-resonant streaming instability dominates: reach at early times (Bell+13, AM+14) => PeV could be reached.

3. Escape process: Strongly dependent on the ambient medium, possibility to have CR halos for timescales a few 10 000 years (Nava+15)

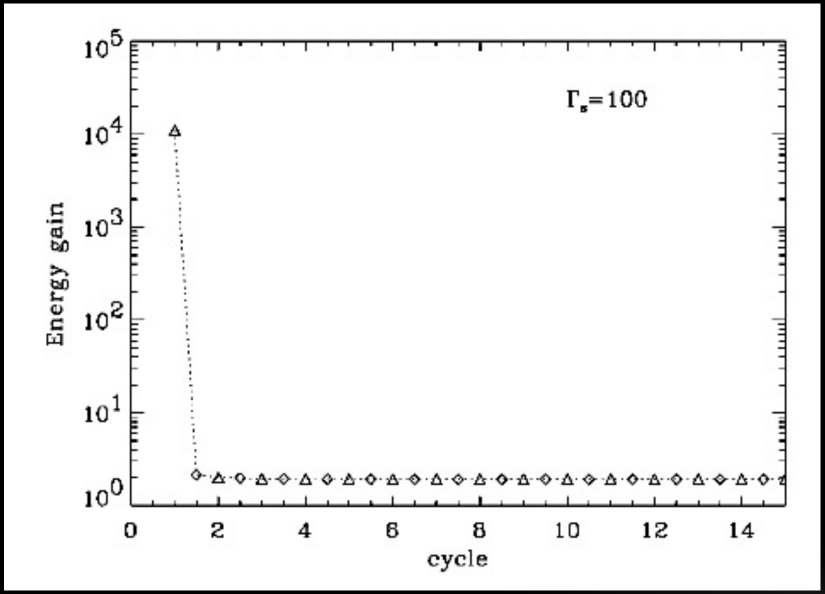
RELATIVISTIC SHOCK ACCELERATION: FERMI ACCELERATION AT LAST ?

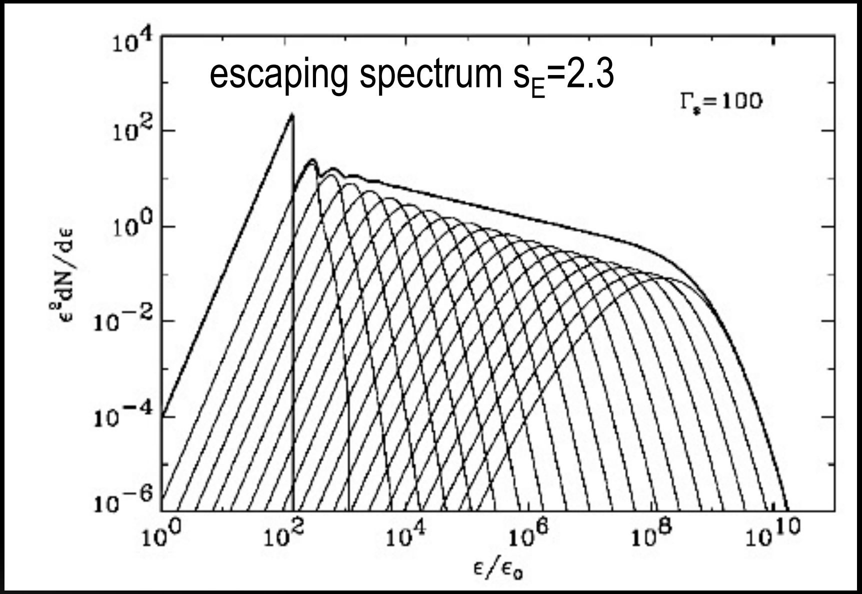
- Relativistic shocks are intrinsically different because $V_{sh} \sim c$ = particle velocity => different kinematics.



FERMI CYCLES IN RELATIVISTIC SHOCKS

- No need for many crossings to gain much energy … in one cycle a particle can gain Γ^2, but hence due to anisotropy=> gain factor *2*.





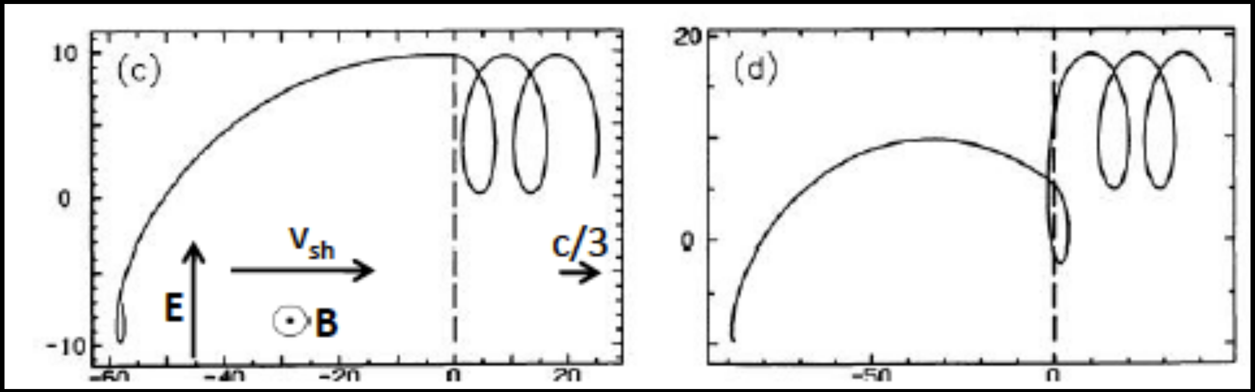
Lemoine & Pelletier'03

solution obtained with pure(no mean magnetic field) Kolmogorov type turbulence

Consistent with particle distribution => X- & gamma-ray spectrum from Crab nebula

FERMI CYCLES IN RELATIVISTIC SHOCKS

But the magnetic field in the shock rest-frame is quasi-perpendicular and likely superluminal => escape downstream 3/2 cycle at max.
Begelman & Kirk'90



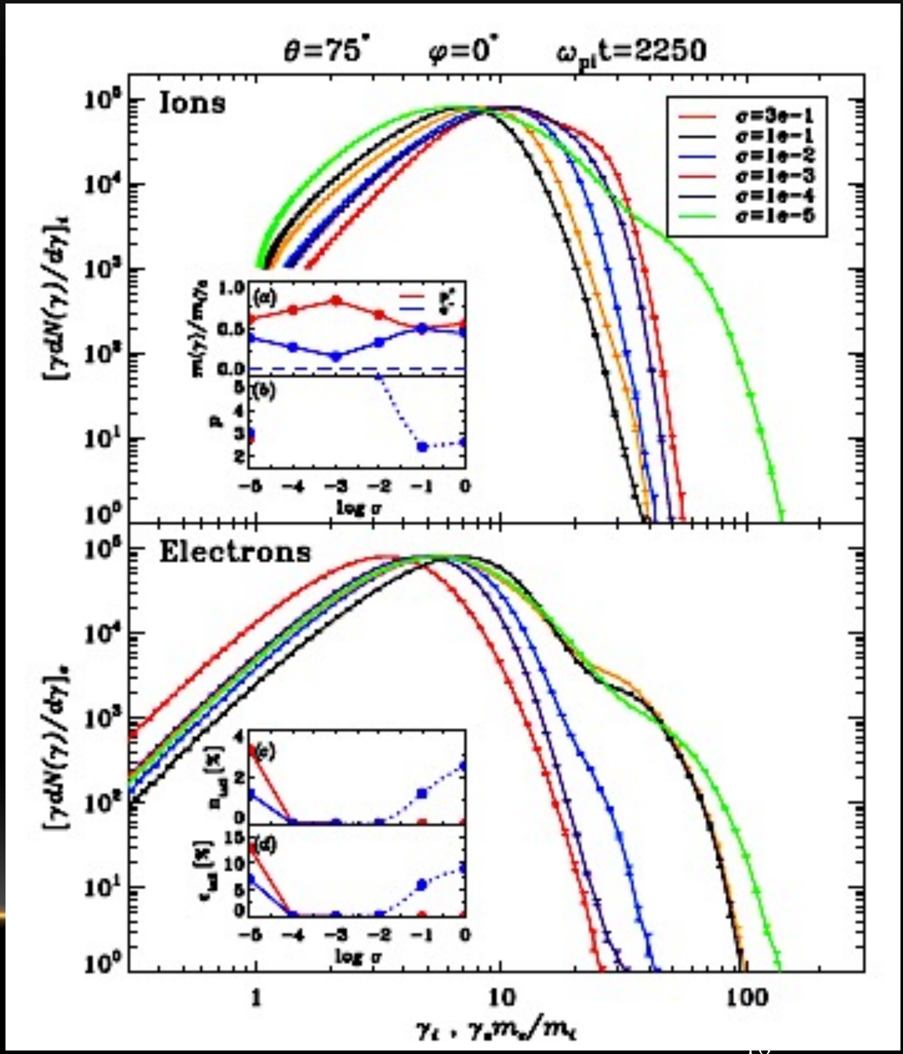
To unlock the effect of guiding large scale field the turbulence has to be generated at small scales (Pelletier, Lemoine, AM'09)

- Turbulence amplitude $\delta B/B >> 1$
- Turbulent wavelengths $<< r_L$

Challenging but possible …

NUMERICAL SIMULATIONS

Particle-in-cell simulations



Strong effect of background plasma magnetization (magnetic energy density/rest mass energy) (Sironi & Spitkovsky'11)

ASTROPHYSICAL IMPLICATIONS: UHE-CRS

- Relativistic shock acceleration performances:
  - Massive star wind magnetization is very low (GRB afterglow)

$$\sigma = \frac{B_{\mathrm{W}}^2}{4\pi n m_i c^2} \simeq 1.7 \times 10^{-8} B_{\mathrm{W},-5}^2 n_{-0.5}^{-1}$$

Sironi+13
Plotnikov+13

  - Typical maximum energy for protons

$$\gamma_{\mathrm{sat},i}^{\mathrm{up}} \simeq 1.3 \times 10^7\, E_{0,54}\, A_{11.5}^{-1}\, \sigma_{-8}^{-1/4}\, R_{16}^{-1}$$

(= 13 PeV)

and $g_e \sim 10^8$ (50 TeV) for electrons => 30 GeV photons.

- How to accelerate EeV-ZeV CRs ?
  - Mildly relativistic shocks (larger precursors, obliquity is less a problem, MHD instabilities could arise (Pelletier+09, Casse+13).
  - Ion acceleration in young millisecond pulsar winds ? Lemoine+15

CONCLUSIONS

- Linear theories of HE CR acceleration predict power-law solutions

  $s_E=(r+2)/(r-1)$ (non-relativistic shocks), $s_E=2.2$ (relativistic shocks with isotropic turbulence).

  - NB: These solutions are valid in the test-particle limit, in case the turbulence is isotropic: none of these are realistic in the nature …

- <u>Non-relativistic shocks</u>:

  - fast (but still NR) are sites of magnetic field amplification possibly explained by the streaming effect of the highest energies, final source spectra should give $s>2$.
  - PeVatrons are more likely to be found at early stages of SNR evolution.

- <u>Relativistic shocks</u>:

  - Fermi acceleration only possible with micro-turbulence requires weak magnetization to proceed.
  - Maximum energies however are limited because of weak diffusion. Solutions to reach EeV or more: mildly relativistic shocks or contribution from young millisecond pulsars.