Supernova Shock Acceleration

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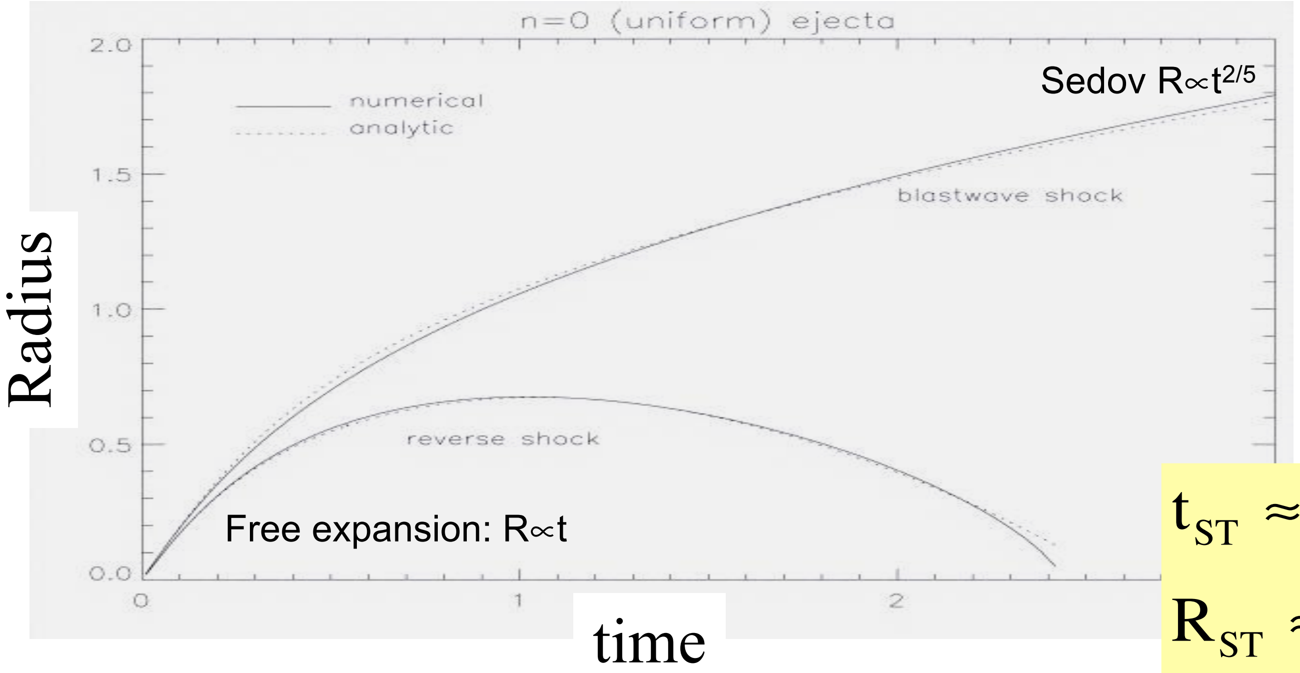
Outlines

- SNR evolution in the interstellar medium.
- Principles of diffusive shock acceleration.
  - Fermi acceleration mechanism, injection, maximum particle energy, source spectrum.
  - Magnetic field amplification and recent developments.
- Supernova shocks in interaction with molecular clouds.
  - Radiative shocks
  - Particle acceleration performances
- Conclusions.

SNR dynamics: adiabatic phases

Depends on the mass dominating the inertia: $M_{SNR}=M_{ej}+ 4\pi/3\ \rho_{ISM}\, R_{SNR}{}^3$

- Free expansion (ejecta dominated): $M_{SNR}=M_{ej}$
- Sedov (swept-up ISM dominated): $M_{SNR}= M_{swept\text{-}up}$



Sedov $R \propto t^{2/5}$

Free expansion: $R \propto t$

Truelove & Mckee'99

Uniform, ionised medium (SNIa)

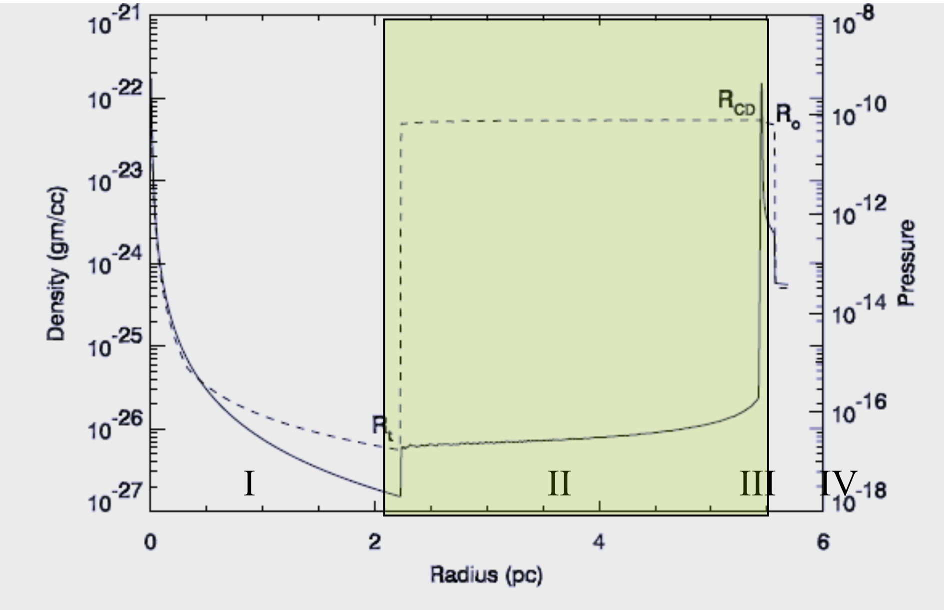
$$t_{ST} \approx (209\mathrm{yr}) E_{51}^{-1/2} M_{ej}^{5/6} n_{ism}^{-1/3},$$

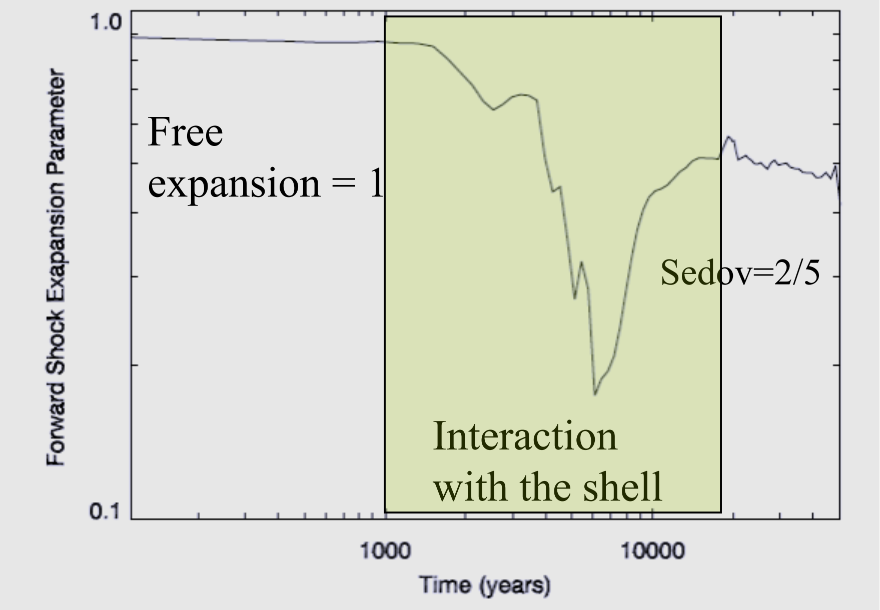
$$R_{ST} \approx (2.8\mathrm{pc}) M_{ej}^{1/3} n_{ism}^{-1/3}$$

SNR dynamics in a stellar wind

- Highly dependent on the main sequence star and post-main sequence phase (RSG, LBV) or further phases (Wolf-Rayet): SNII or SNIc/b (Dwarkadas'05)

Case: $M_{shell}/M_{ej} = 3.7$

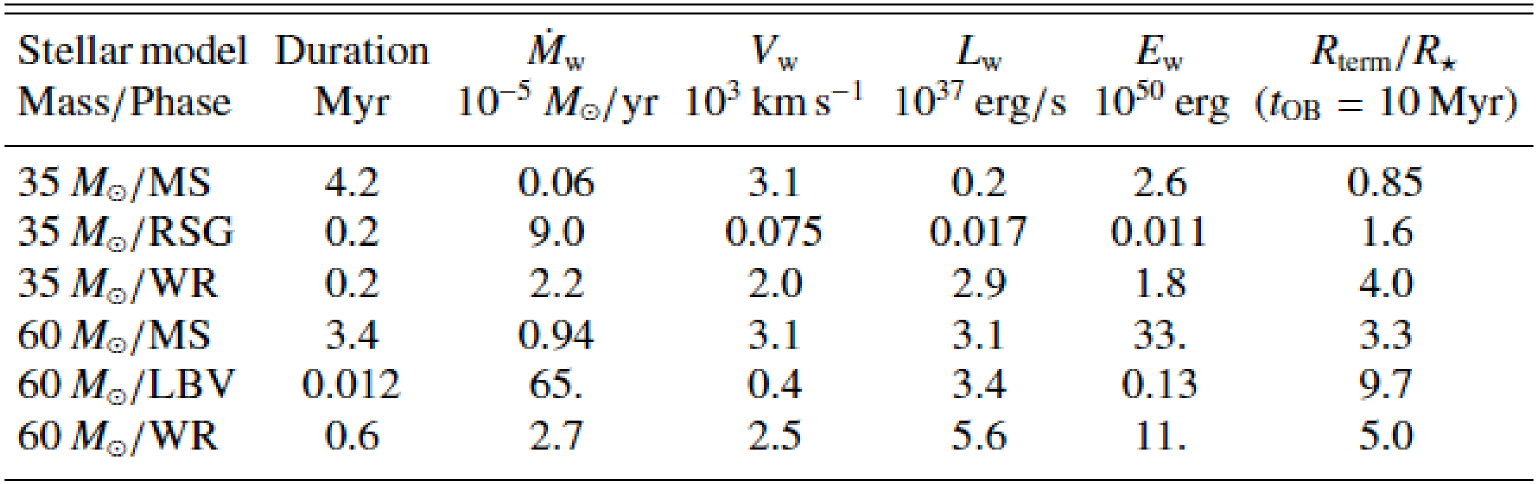




I: free stellar wind
II: shocked stellar wind
III: shocked ambient medium
IV: unshocked ambient medium

SNR in massive star forming regions & superbubbles

- Before the first SN explosion, stellar winds produce a cavity of hot (1 MK) and low density gas ($10^{-3/-2}$ cm^{-3})



Stellar model Mass/Phase	Duration Myr	$\dot{M}_w$ $10^{-5}\,M_\odot/\mathrm{yr}$	V_w $10^3\,\mathrm{km\,s^{-1}}$	L_w $10^{37}\,\mathrm{erg/s}$	E_w $10^{50}\,\mathrm{erg}$	$R_\mathrm{term}/R_\star$ ($t_\mathrm{OB} = 10\,\mathrm{Myr}$)
35 $M_\odot$/MS	4.2	0.06	3.1	0.2	2.6	0.85
35 $M_\odot$/RSG	0.2	9.0	0.075	0.017	0.011	1.6
35 $M_\odot$/WR	0.2	2.2	2.0	2.9	1.8	4.0
60 $M_\odot$/MS	3.4	0.94	3.1	3.1	33.	3.3
60 $M_\odot$/LBV	0.012	65.	0.4	3.4	0.13	9.7
60 $M_\odot$/WR	0.6	2.7	2.5	5.6	11.	5.0

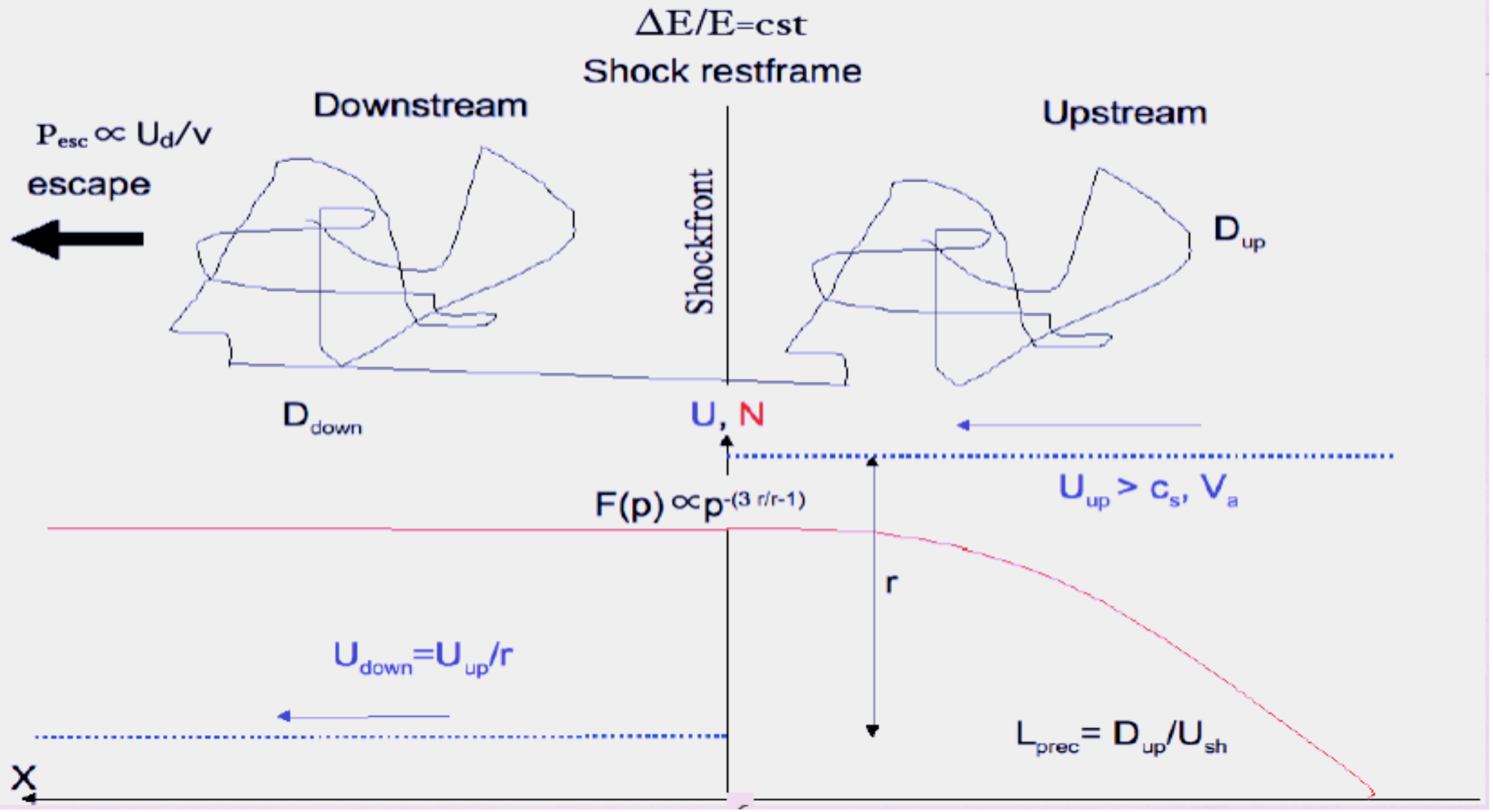
Parizot et al'04

- Termination shock radius R_term > mean distance between 2 stars R_* in a cluster
- A SN with blows off in a tenuous hot bubble:
  - R_SN larger and phases are delayed.
  - Radiative phases hardly reached; huge energy deposition in the ISM.

Principles of Diffuse Shock Acceleration (DSA)

- The Fermi acceleration mechanism
- Injection
  - Protons/ions
  - Electrons
- Maximum particle energy
  - Protons/ions
  - Electrons
- Generation of magnetic field in SNR.

Principles of DSA



$\Delta E/E = \mathrm{cst}$

Shock restframe

Downstream

Upstream

$P_{esc} \propto U_d/v$

escape

Shockfront

D_{up}

D_{down}

U, N

$U_{up} > c_s, V_a$

$F(p) \propto p^{-(3\,r/r-1)}$

r

$U_{down} = U_{up}/r$

$L_{prec} = D_{up}/U_{sh}$

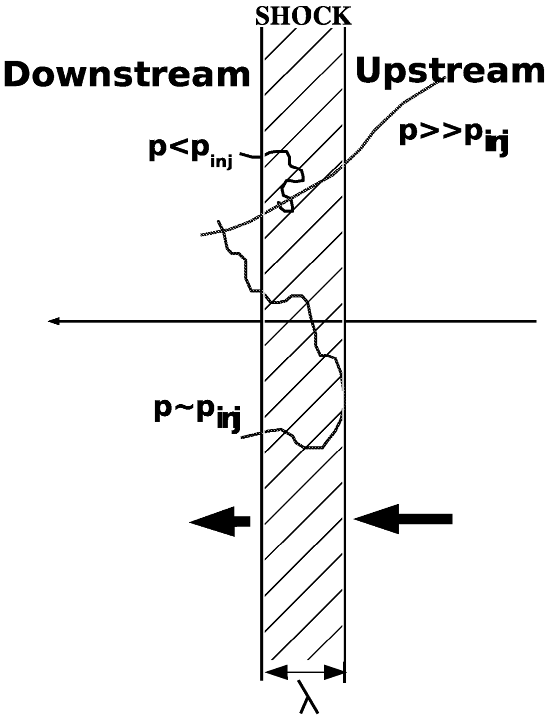
X

- Source spectrum: power-law with an index given by the compression ratio, for r = 4, the index is 4 = test particle solution.

Injection of suprathermal particles

- *Unsolved issue*: no self-consistent theory.
  - Depends on the magnetic field obliquity, plasma β parameter, Alfvenic Mach number ($V_{sh}/V_{a\text{-}loc}$), ionisation fraction, pre-existing non-thermal population, particle acceleration process itself (retroaction, heating …) … Malkov'98

- Ion injection: parametric models (kinematics)
  - η: fraction of the incoming flux of thermal particle ($10^{-4}/10^{-2}$)
  - P_{inj}: injection momentum ∝ $P_{th\text{-}d}$ (2-4)
  - Blasi et al'05: one parameter.
    - $P_{inj} = \xi P_{th\text{-}d}$
    - Normalisation / Maxwellian distribution



$\lambda = r_{g,\text{ thermal proton}}$

- Different processes to inject electrons or ions (microphysics)
  - Electron injection depends on the plasma modes produced by the ions in the precursor (foot region).

⇒ K_{ep} = fraction of electrons/ions

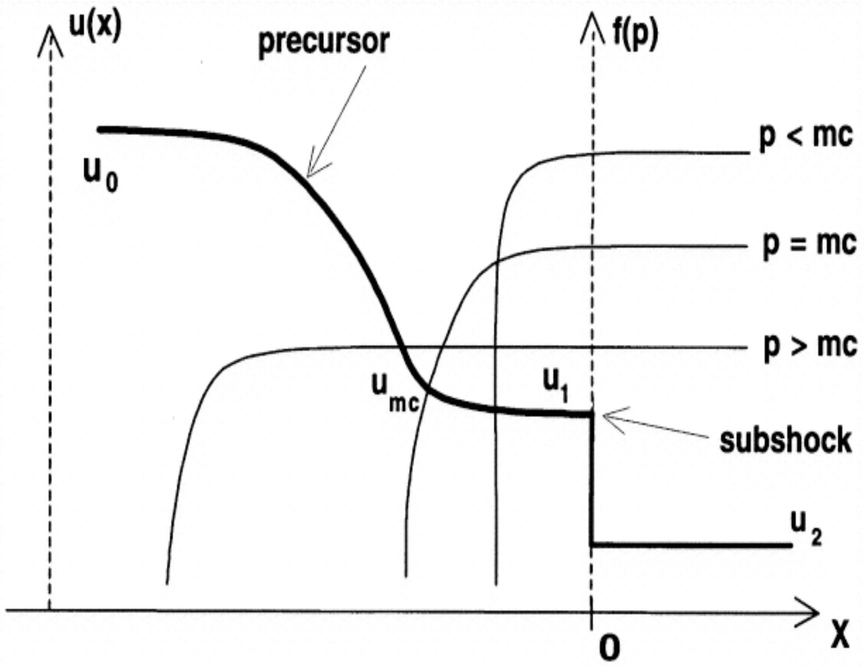
⇒ Intensity of synchrotron/Inverse Compton radiation.

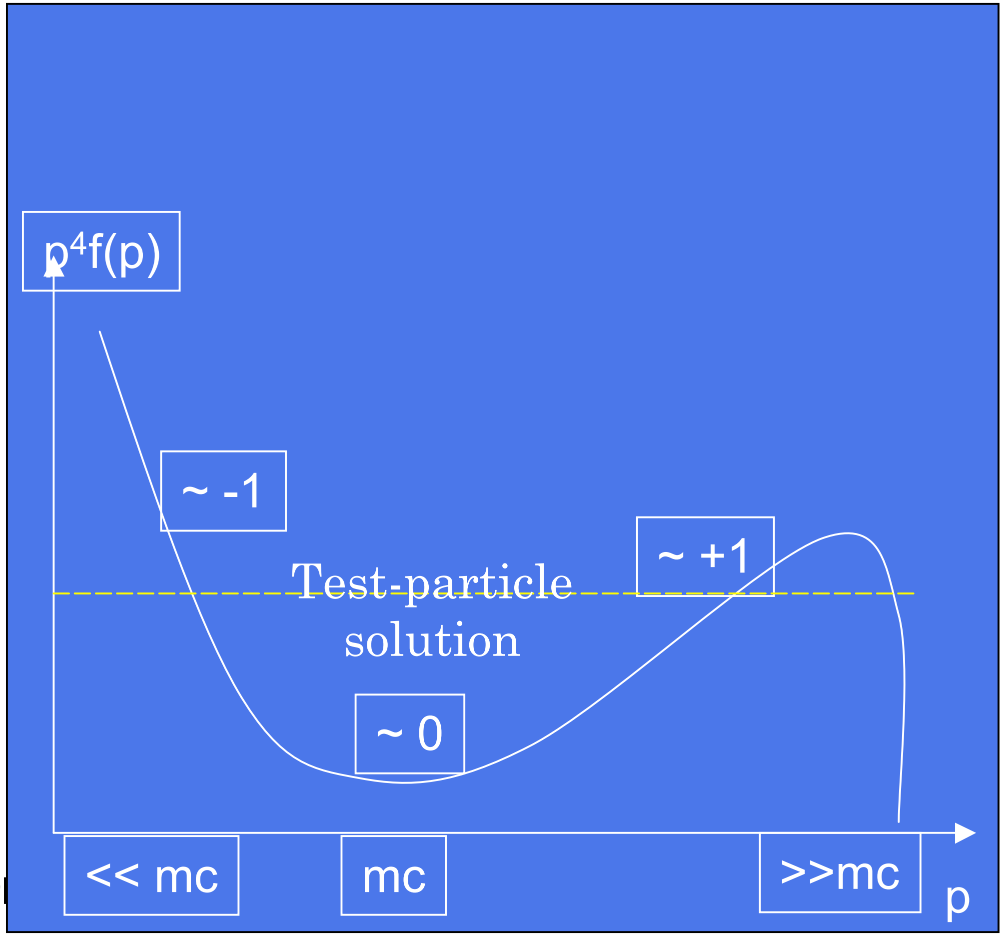
Particle transport & maximum energy

- Particle transport: controlled by the diffusion coefficient; *basically unknown:*
  - $T_{acc}= f(r)\, D(E)/V_{sh}{}^2$
- Diffusion coefficients: $D(E) = D_{norm}\,(E/E_{max})^a$; $a > 0$
  - Related to the properties of the turbulence (spectrum of fluctuating EM fields) $B(\lambda)/B_{ISM} = \eta\,(\lambda/\lambda_{max})^b$; e.g. Kolmogorov $b=5/3$
  - quasi-linear solutions !!!
    - $D_{norm} \propto \eta^{-1}$
    - $a = 2 - b$
    - $E_{max}\,(\lambda_{max})$ fixed by the geometry:
      - $\lambda_{max} \sim R_{sh}$ and $D(E_{max})/V_{sh} \sim R_{sh}$
      - $T_{acc}(E_{max}) \sim R_{sh}/V_{sh}$
- Lagage & Cesarsky (1983) limit in B_{ISM} $(\eta \sim 1)$: $E_{max} \sim Z\, 10^{14}$ eV

Source Composition & spectrum

- Source spectrum:
  - CR backreaction over the flow => concave spectrum.





$p^4f(p)$

~ -1

~ +1

Test-particle solution

~ 0

<< mc

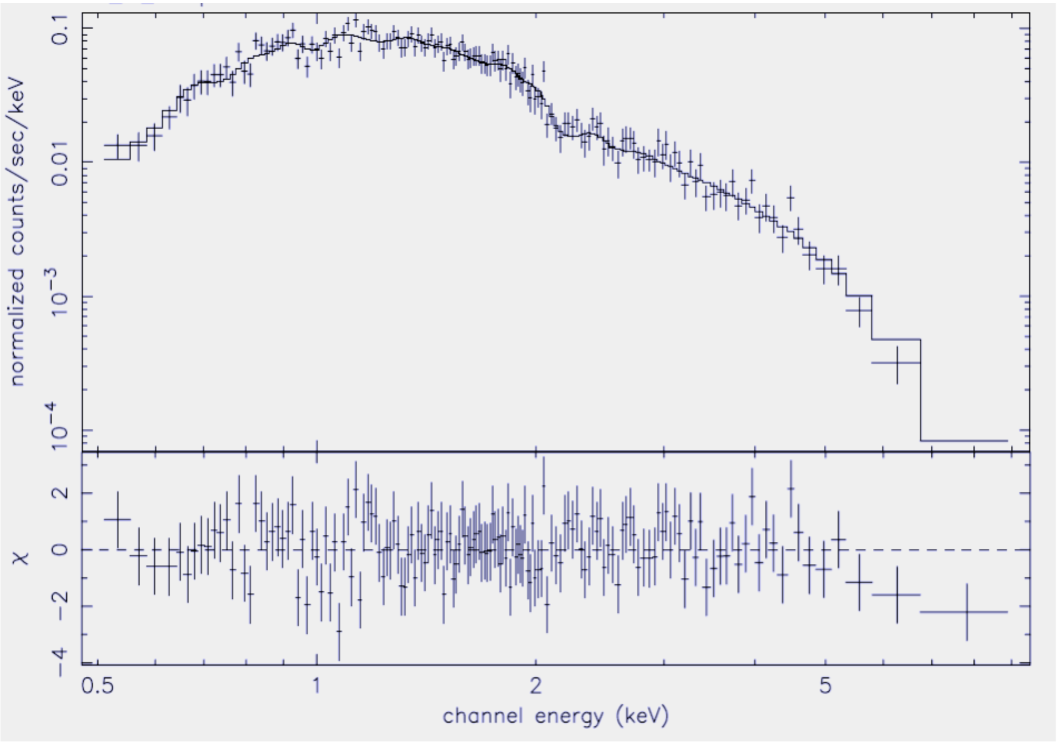
mc

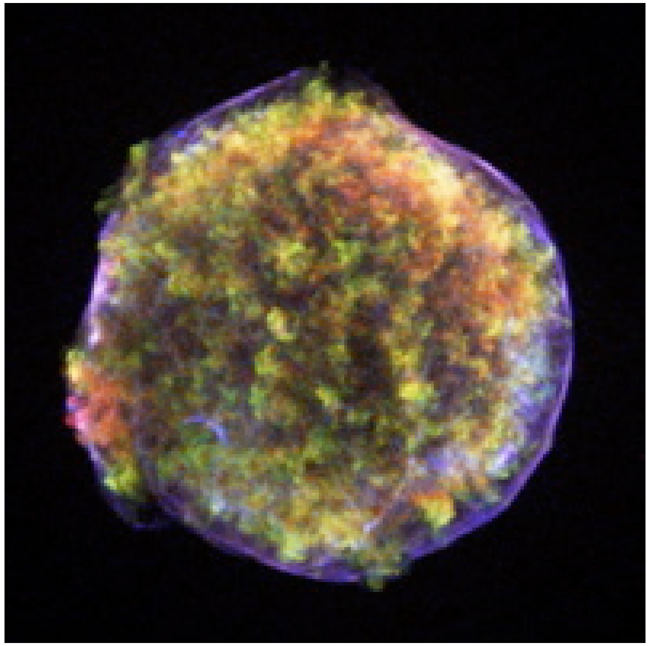
>>mc

p

X-ray filaments

- Thin filaments ~% SNR radius
- Non-thermal synchrotron radiation





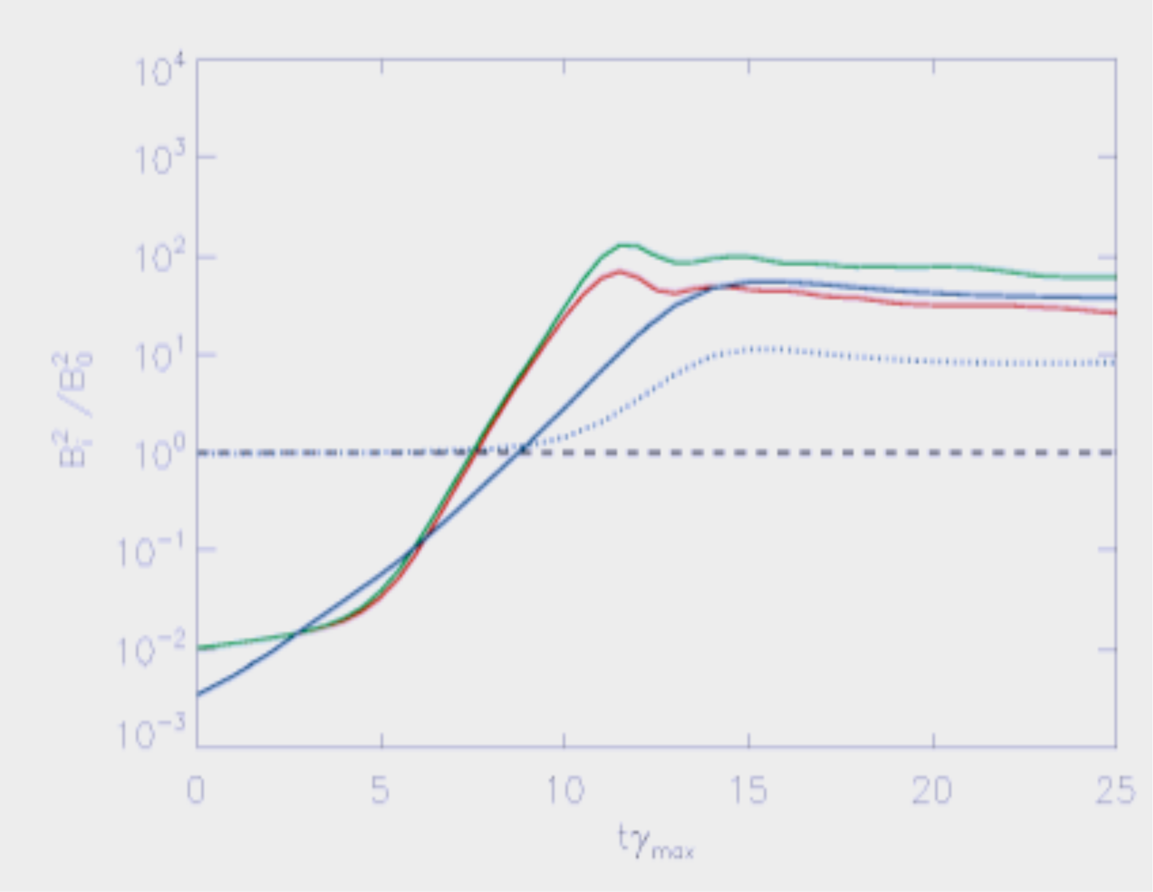
Tycho SNR as viewed in X-rays by Chandra.
Ejecta (red, green)
Outer shock (blue)

Hwang et al'02 (NW rim)

Magnetic field amplification

- Thin filaments => $B \sim 100\ B_{ISM}$
  - Compression $B \sim r\ B_{ISM}$ & $r < 10$
  - Need for amplification.
- Various processes invoked: self magnetic field generation
  - Streaming instabilities Skilling'75, Bell'78, Bell & Lucek'01, Bell'04, Pelletier et al'06… two regimes: resonant and non-resonant.
- Expected field values at the shock front: $M_{a\infty}=V_{sh/}V_{a\infty} > 100$ (ISM)
  - $B_{sat/Res}$:$(\delta B/B_{\infty})^2 = M_{a\infty}{}^2\ u_{sh/}/c\ (P_{CR}/\ \rho u_{sh}{}^2)$
  - $B_{sat/Nres}$: $(\delta B/B_{\infty})^2 = M_{a\infty}{}^2\ \ (P_{CR}/\ \rho u_{sh}{}^2)^2$
  - $B_{nres/Res}$: $(\delta B_{NR}/\delta B_R)^2 = (c/u_{sh/})\ (P_{CR}/\ \rho u_{sh}{}^2)$
- Non resonant instability dominates for fast shocks (V_{sh} -> 0.1 c) or early SN phases (SN 1993J see Tatischeff'09, SN 1987A …)

Numerical simulations



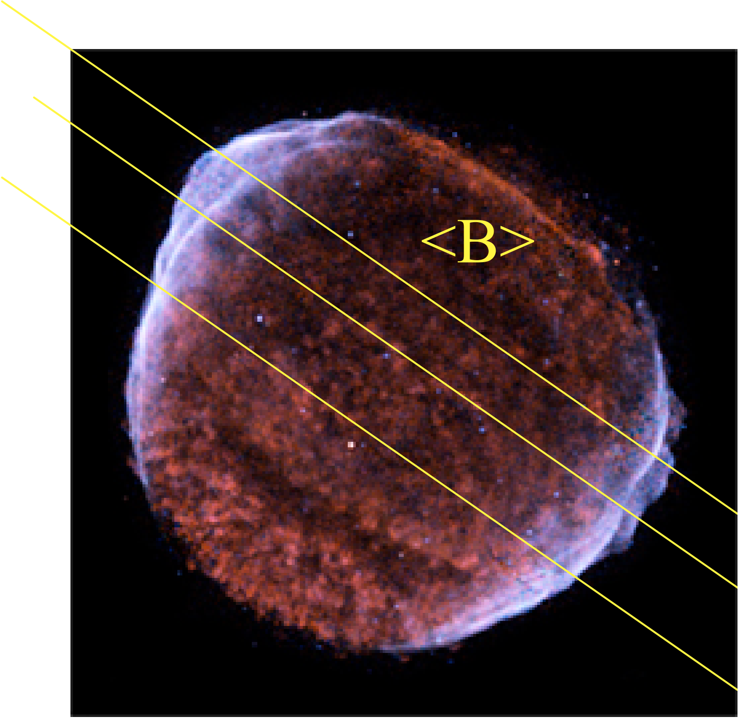
3D Particle-in-cell Simulations for the non-resonant instability.
Riquelme & Spitkovsky'09

Confirm $\delta B/B_{ISM} > 1$

Backreaction on J_{CR}
Blue 3D, red/green 1D
Solid: Perpendicular field
Dotted: Parallel field

Consequences of MF amplification

- Enhanced injection rate:
  - but mostly in the zones of parallel shock configuration (Voelk et al ‘03) => SN1006
- Enhanced acceleration efficiency: D ↓
- Higher energies => PeV in the Sedov phase even 100 PeV earlier.
- L_{sync}/L_{IC} ↑
- More plasma heating and less compressibility => source spectrum less modified (closer to the particle-test solutions)



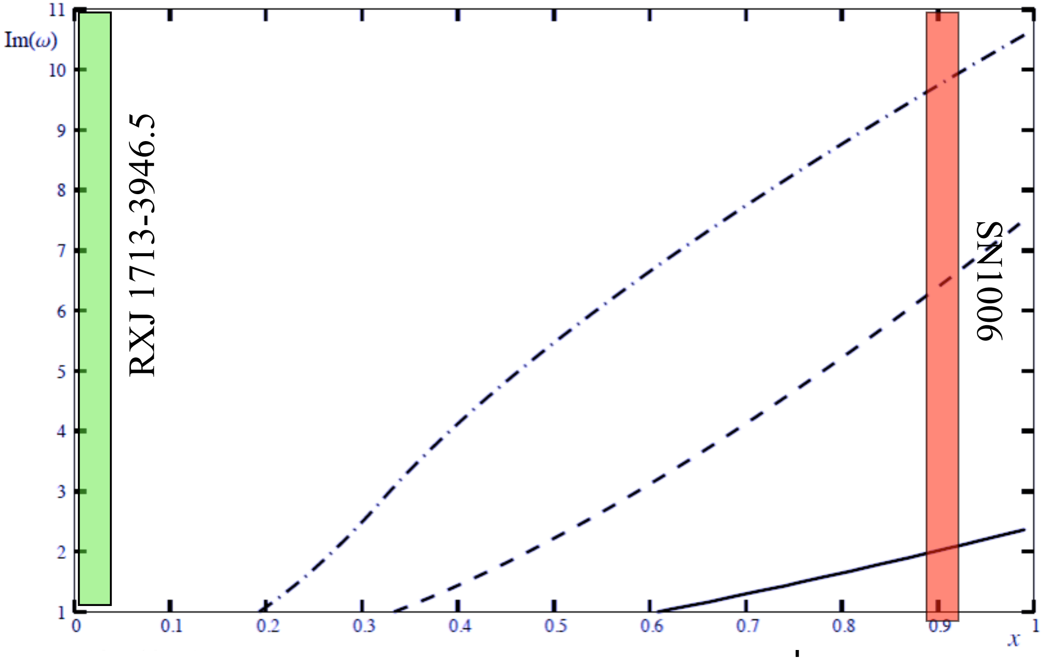
SN1006
by Chandra

Ion-neutral damping I

- If neutrals decouple from ions, the ion oscillations can be damped $\omega > \omega_i$

$$\gamma_{damp} = \frac{\omega^2}{\omega^2 + \omega_i^2}\omega_n ; \omega_{i/n} = n_{i/n}\langle \sigma v \rangle$$

- Effect on the non-resonant streaming instability (fast shocks a few thoudand km/s) Reville et al’07



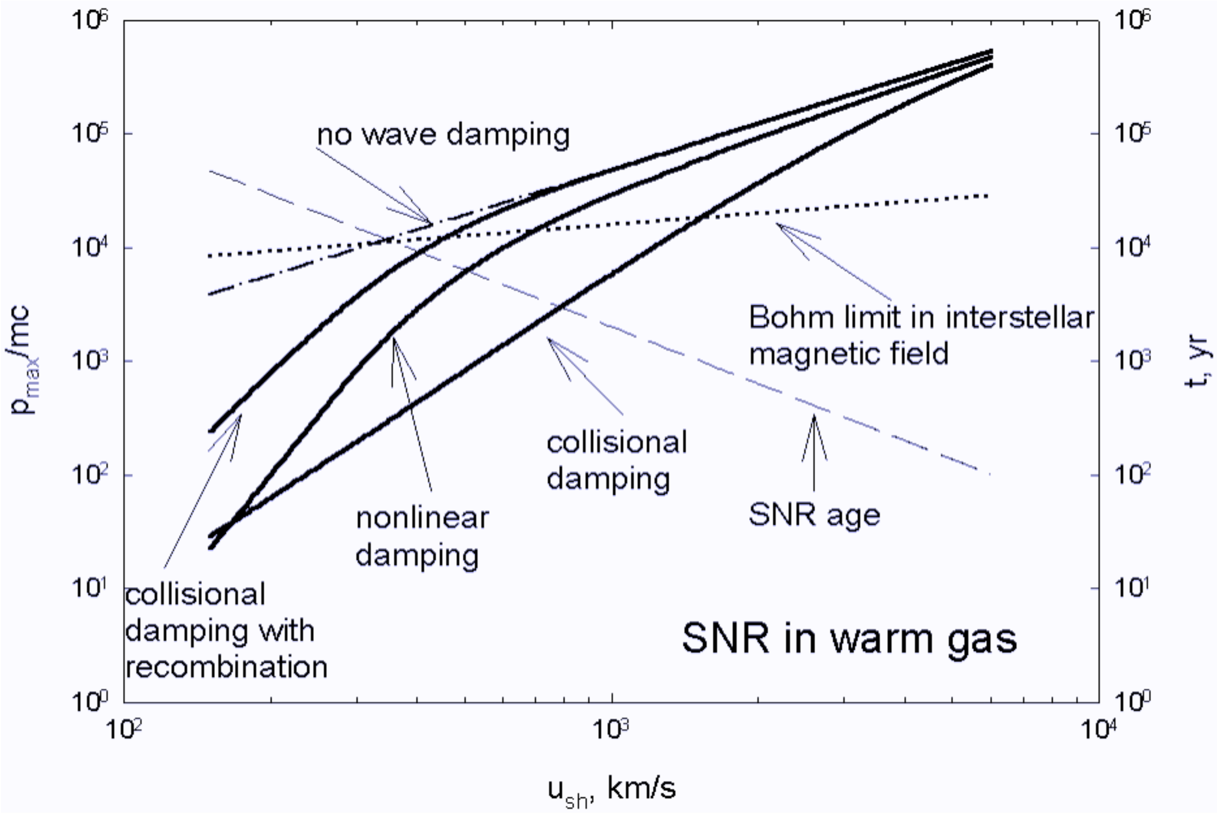
Growing rate vs ionisation fraction x

x= $n_i/(n_n+n_i)$

If Im(ω) < 1 the amplification is not effective anymore.

Argue that RXJ 1713-3946.5 (NW) is in the left part of the figure

Ion neutral damping II



Ptsukin & Zirakashvili'03

Maximum CR energy versus time and velocity in case of strong turbulence ($\delta B > B$)

Collisional damping limits the maximum energy to 100MeV-1 GeV at late Sedov phase.

n_n=0.4 cm^{-3}, n_i=0.03 cm^{-3}

Shock acceleration & interstellar medium

- Several configurations:
  - Isolated supernova
    - Homogeneous medium (type Ia): SN1006, Tycho
    - Stellar winds (type II): Cassiopeia A, RCW86

=> Illumination of nearby passive clouds (S.Gabici, F.Acero, Torres et al'08)

- $R_{SN} >> R_{cloud}$
- $R_{SN} <$ or $\sim R_{cloud}$

  - Supernova in interaction with a molecular cloud
    - $R_{SN} >> R_{cloud}$ (adiabatic solutions): Vela SNR
    - $R_{SN} <$ or $\sim R_{cloud}$ (radiative shock acceleration): IC443 Troja et al'06

Supernova shocks in interaction with molecular clouds

- Radiative shocks
- Particle acceleration performances- role of ionisation - magnetic field amplification ?

SNR dynamics - Radiative phases

Transition Sedov => Radiative phases (homogeneous medium)

$$t_{SP} \approx (2.9x10^4\,\mathrm{yr})E_{51}^{-4/17}n_{ism}^{-9/17},$$
$$R_{SP} \approx (18\mathrm{pc})E_{51}^{5/17}n_{ism}^{-7/17}$$

- Radiative (snowplow) phases:
  - Shell shrink through radiative losses
  - Internal Pressure drops <=> work done on the shell
- $R \propto t^{2/7}$, $V_{sh} \sim$ 100-200 km/s

Cioffi et al '88

Particle acceleration performances

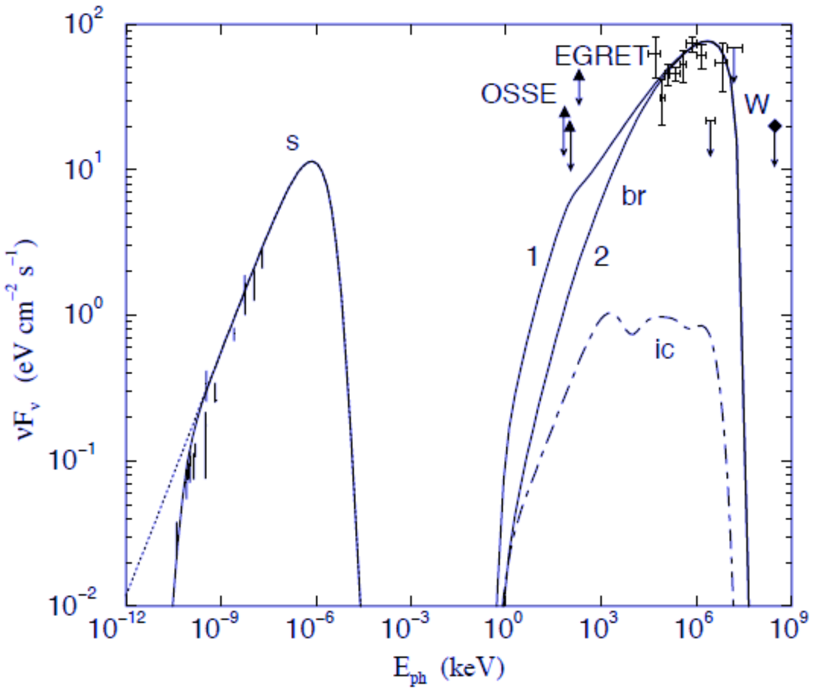
Homogeneous-ionised-'low density' medium

- Adiabatic high speed phases last longer.
- Streaming instability likely to generate strong magnetic fields (Reville et al'08)
- Internal injection from the heated thermal plasma unless propagating in massive star clusters regions (Ferrand et al '08).
- Acceleration up to very high energies (PeV and more).
- TeV particles observed in X and Gamma-rays.

Inhomogeneous-partially neutral-'dense' medium

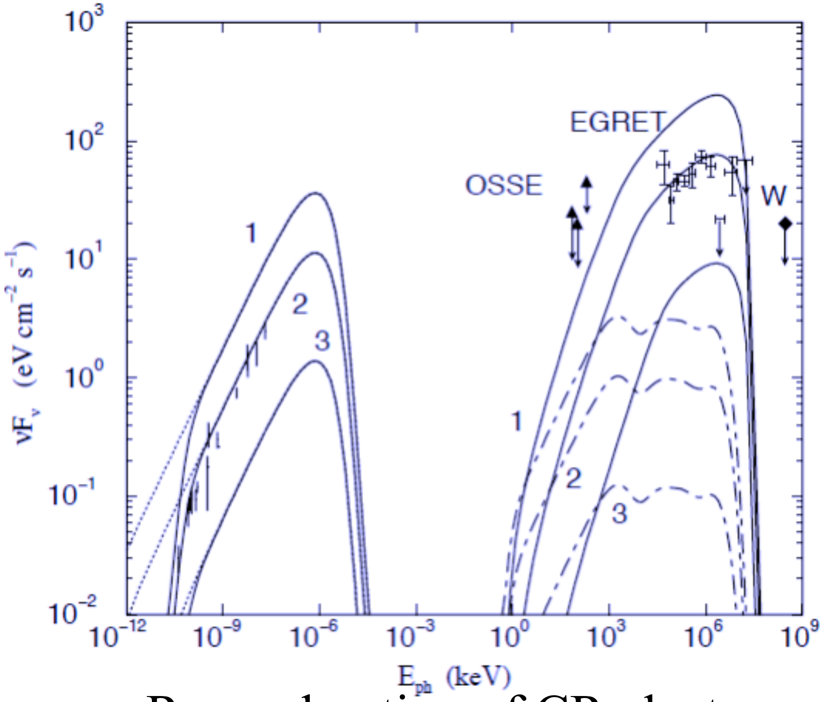
- Faster shock aging. Lower velocities.
- Ion-neutral damping over the Alfvèn waves (Tagger et al'95).
- Magnetic field compression ? The clouds can have magnetic fields > 10 μGauss.
- External energetic particles injection likely important (Bykov et al'00).
- Importance of reacceleration/Coulomb losses at low energy (keV-MeV) (Bykov et al '00).
- Acceleration performances to be tested versus wave damping and low shock velocities: GeV electrons in radio, where do TeV particles come from ?

Multiwavelength models for IC443



Injection from thermal pool
Min energy electron reacceleration
(stochastic)
1/ E=120 keV 2/ E=2 GeV

Bykov et al'00



Reacceleration of CR electrons
Max energy electron reacceleration
(shock)
1/E=0.5 GeV 2/E=0.05 GeV 3/case
of a dense clump

Ion-neutral damping

- Case of resonant Alfvén waves (in weak turbulence; $\delta B < B$) (Drury et al'96)
  - Typical energy where ion-neutral damping is the strongest: E_1
  - Maximum energy of particles if acceleration is limited by ion-neutral damping: E_2

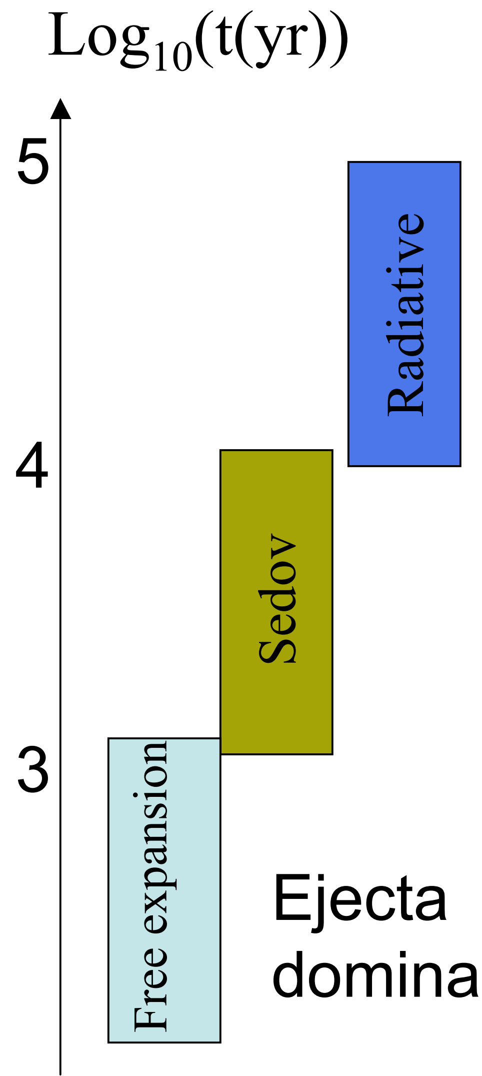
1. If $E_2 < E_1$ then acceleration highly reduced compared to the neutral free case.
2. If $E_2 > E_1$ then acceleration slightly reduced compared to the neutral free case.

$$E_1 = 8GeV \left(\frac{T}{10^4 K}\right)^{-0.4} \left(\frac{n_i}{1cm^{-3}}\right)^{-3/2} \left(\frac{B}{1\mu G}\right)^2$$

$$E_2 = 1TeV \left(\frac{U_{sh}}{10^3 km/s}\right)^3 \left(\frac{P}{0.1}\right) \left(\frac{T}{10^4 K}\right)^{-0.4} \left(\frac{n_i}{1cm^{-3}}\right)^{0.5} \left(\frac{n_n}{1cm^{-3}}\right)^{-1}$$

- High speed shocks ~1000 km/s are more likely in case 2.
- Low speed shocks ~100 km/s: $E_2 < 1$ GeV and likely in case 1.

SN-CRs-ISM and MCs



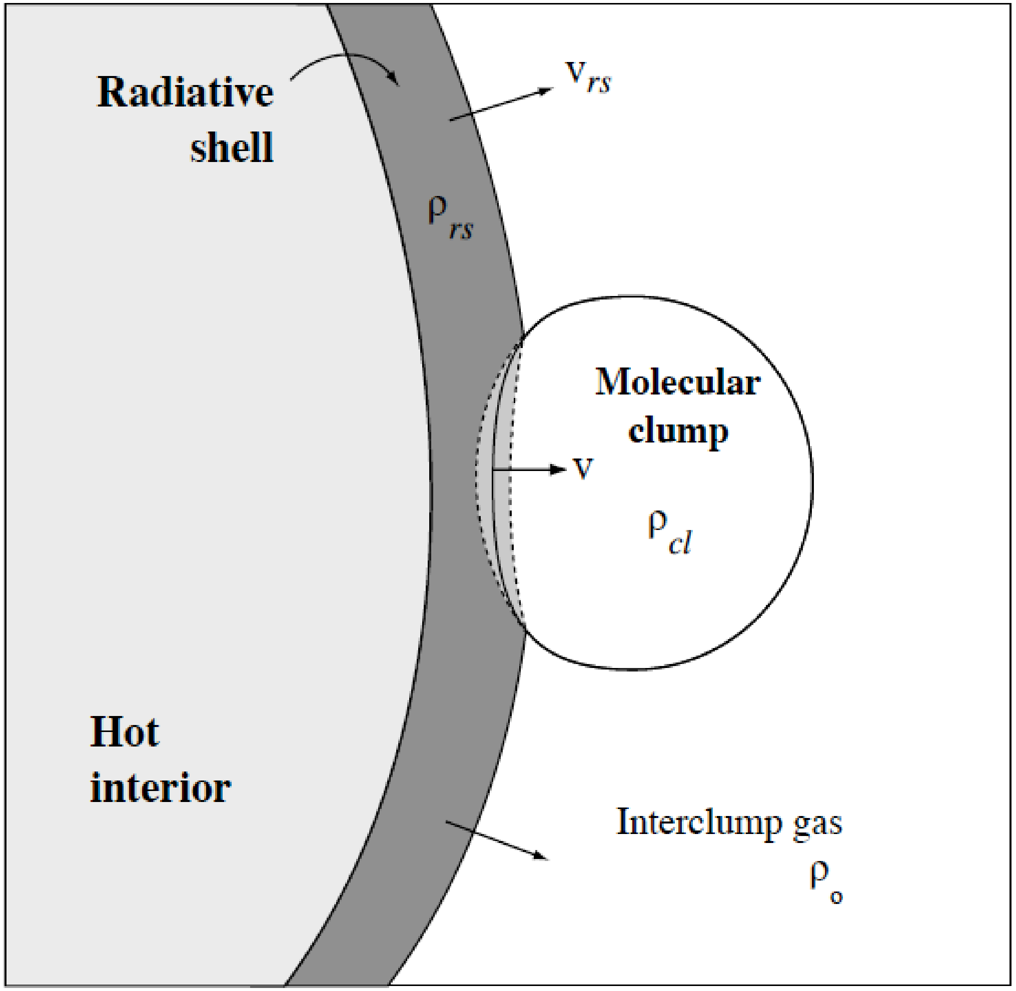
Homogen. ISM	Isolated Stell.Wind	SB MSF	E_{max}	E_{illu} MC?
		Sup. Shell	MeV	MeV
	ISM matter	SB	GeV?	TeV?
ISM matter				PeV?
	Stellar wind	Stellar winds	PeV?	100 PeV?
			100 PeV?	
Ejecta dominated	If massive shell even direct Transition FE => Radiative			

Conclusions

- SNR likely the sources of galactic CRs
  - Isolated or cluster effects ?
  - Important effects of the surrounding over the shock acceleration performances
    - Injection (thermal plasmas, pre-existing CRs)
    - Nature of the acceleration process
    - Magnetic field amplification (self-generated turbulence - pre-existing turbulence) … and damping (ion-neutral damping) likely to quench the acceleration process in low velocity shocks.
    - Maximum particle energy
- Need to rely on shock/medium properties to give any prediction.

Supplementary materials

Interaction with molecular clouds



- Dense clumps ($10^{4/5}$cm^{-3})
Filling factor: 0.02-0.08
(Shull'80, Blitz'93)
=> Buried SNR (R < 2 pc) peak emission in IR (grains)

- Inter clump medium (5-25 cm^{-3})
HII region
(Chevalier'99)

- The interclump medium may also be different: Superbubbles or massive star clusters + turbulent magnetic field (Parizot et al'04)
=> SNR never reach the radiative phase (low density, hot medium).

Numerical simulations

- Hydrodynamics:
  - 2D Klein et al'94.
  - 3D Xu & Stone'95.

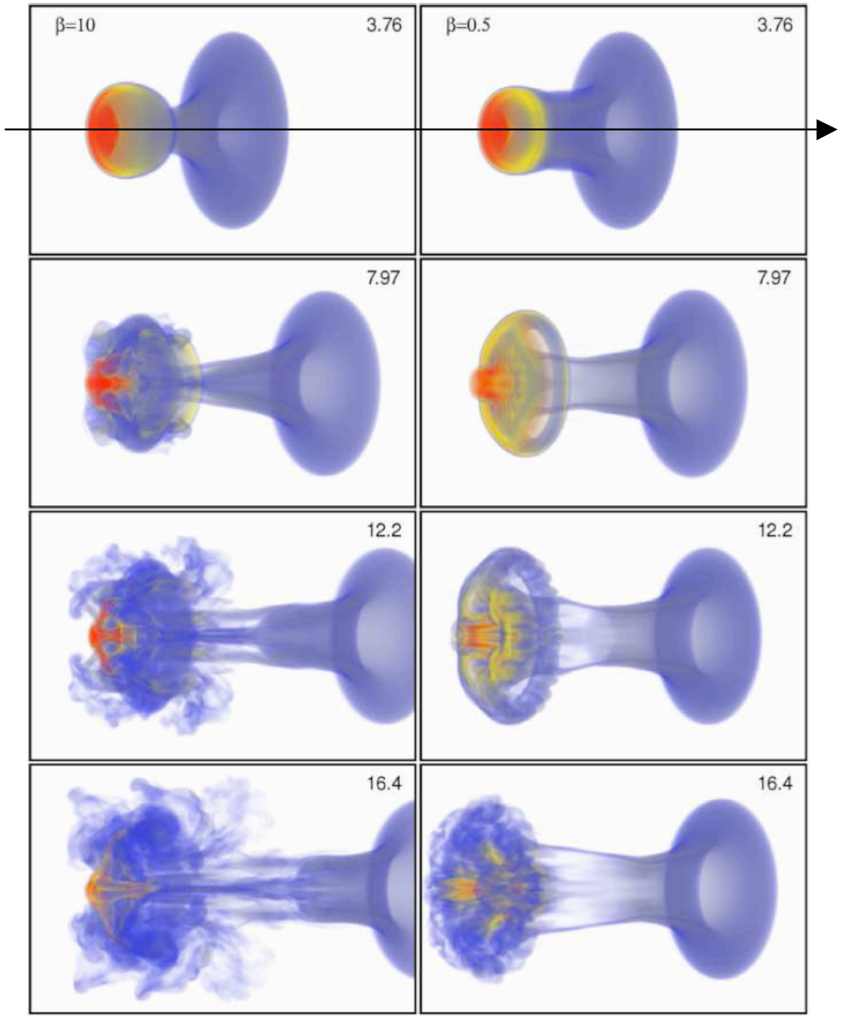
  + thermal conduction, autogravity: Fragile et al'04, Orlando et al'05.
- Magnetohydrodynamics:
  - 2.5D MacLow et al'94, Fragile et al'05, Van Loo et al'07.
  - 3D Shin et al'08
- Effects of magnetic fields over the cloud evolution:

  Simulations for different β (M_s=10):
  - Strong fields stabilise the structures and decrease the amplitude of turbulent motions.
  - Obliquity induces sheet like structures.

Cloud density versus cloud-crushing time

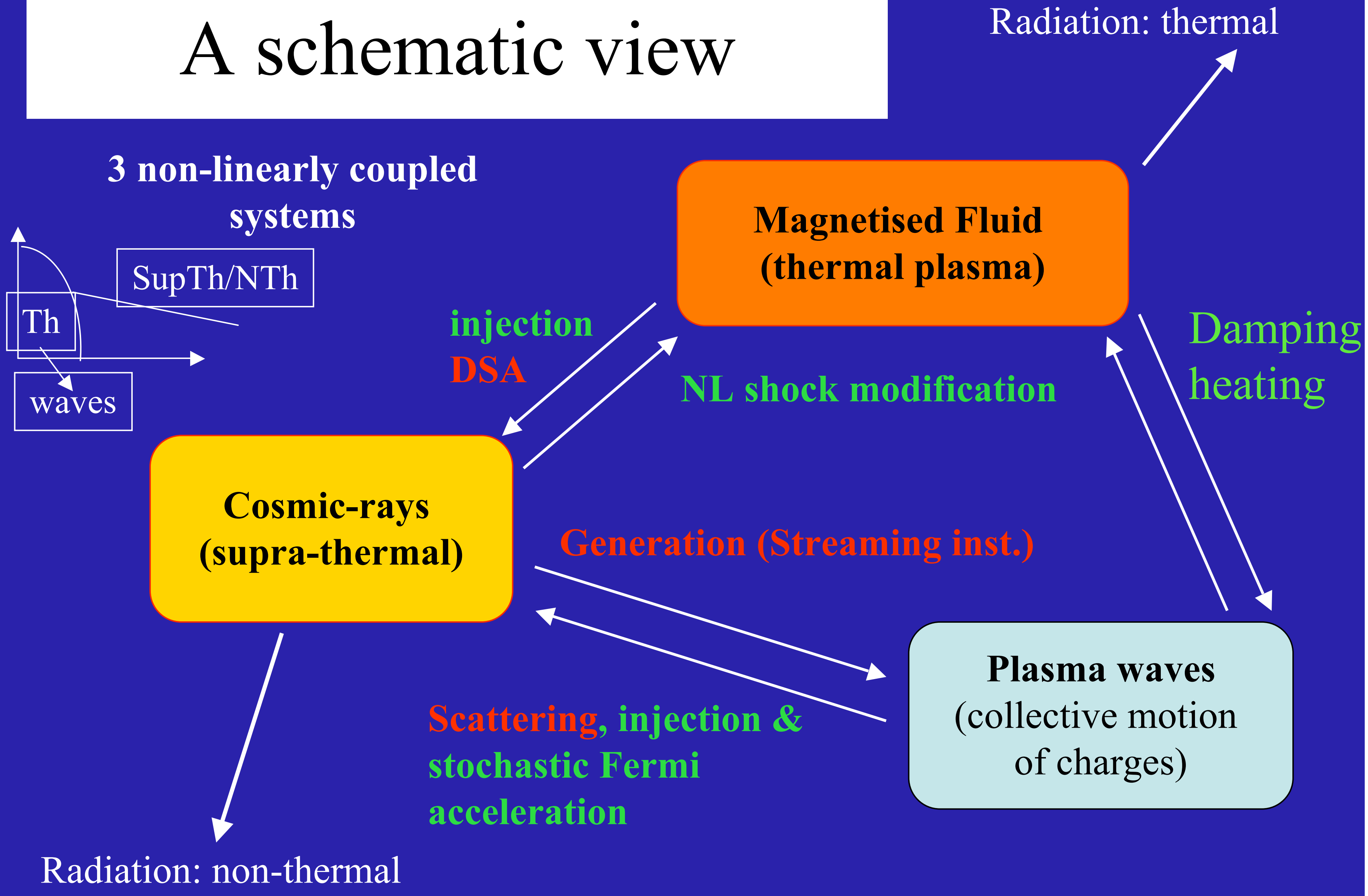
Parallel MF

Shin et al'08



Weak field Strong field

A schematic view



3 non-linearly coupled systems

Radiation: thermal

Magnetised Fluid (thermal plasma)

injection

DSA

NL shock modification

Damping heating

Cosmic-rays (supra-thermal)

Generation (Streaming inst.)

Plasma waves (collective motion of charges)

Scattering, injection & stochastic Fermi acceleration

Radiation: non-thermal