The Onset of Particle Acceleration at Supernovae : From Shock Breakout to the First Decades

Gwenael Giacinti[1] **& Tony Bell**[2]

[1]*MPIK, Heidelberg*

[2]*Clarendon Laboratory, University of Oxford*

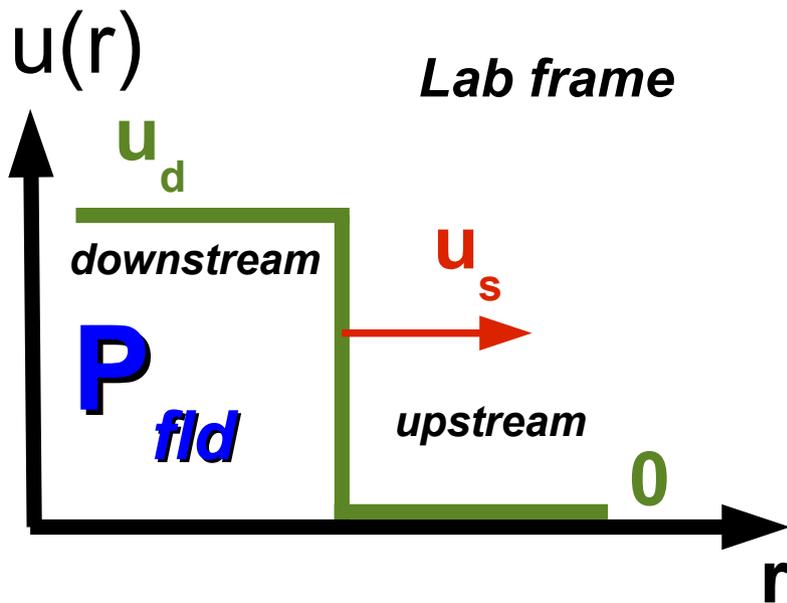**+ B. Reville & K. Schure**

Giacinti & Bell, MNRAS 449, 3693 (2015);
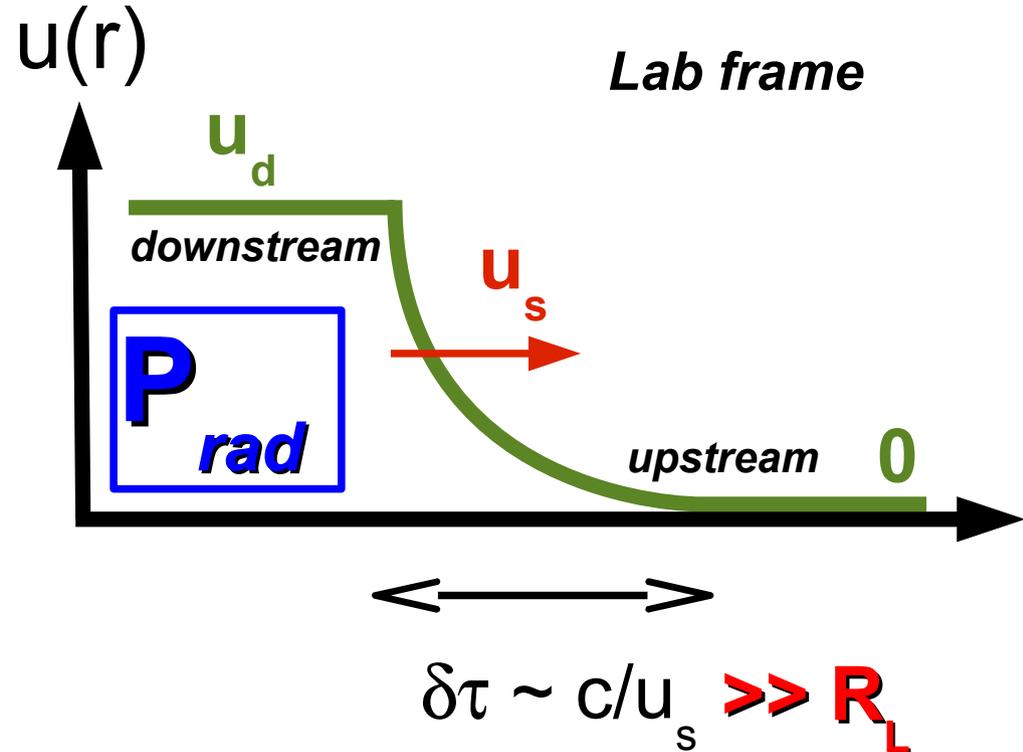
Bell, Schure, Reville & Giacinti, MNRAS 431, 415 (2013)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Outline

I – Particle acceleration *before* SN shock breakout

II – Supernovae in dense winds as PeVatrons

Radiation mediated shocks

u(r)

Lab frame

u_d

downstream

u_s

P_{fld}

upstream

0

r

Collisionless shock

u(r)

Lab frame

u_d

downstream

u_s

P_{rad}

upstream

0

$\delta\tau \sim c/u_s$ **>> R_L**

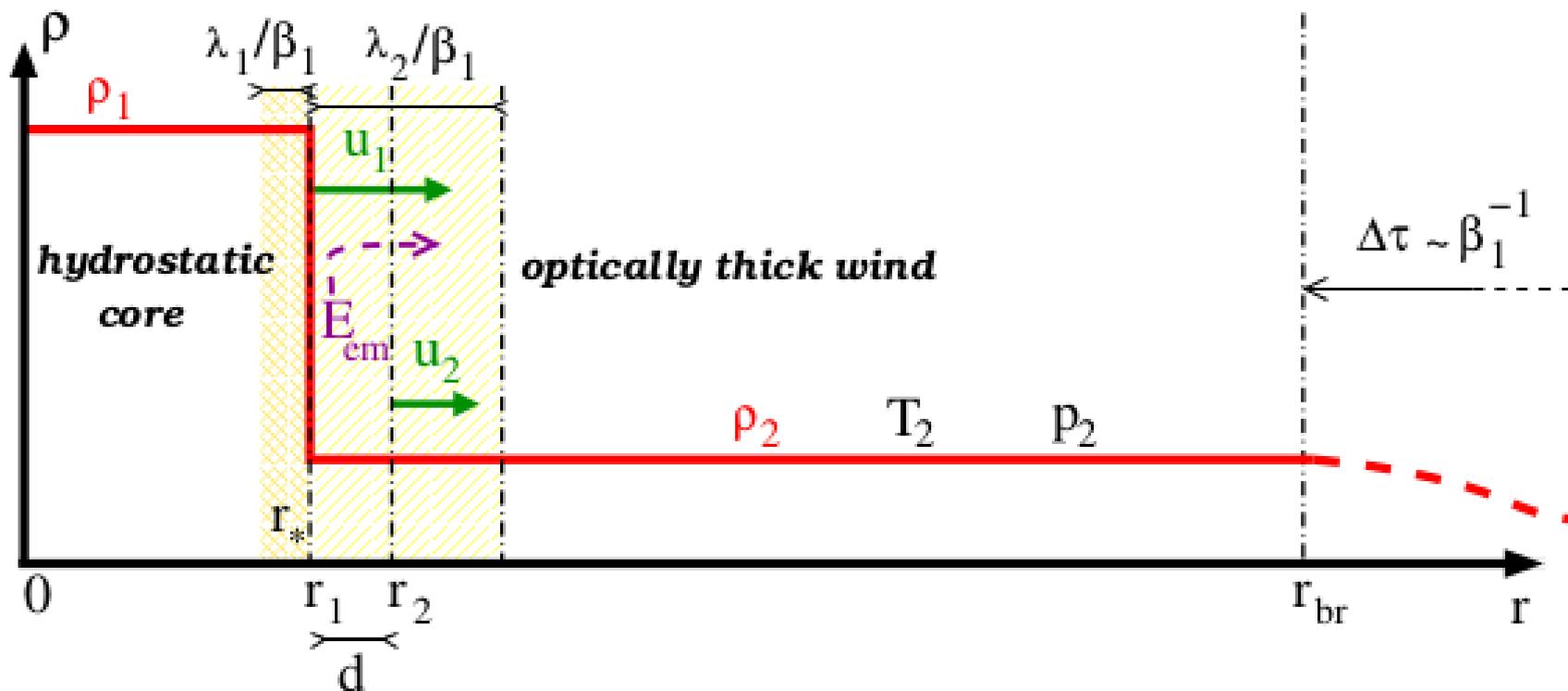**Radiation-Mediated shock**

No CR acceleration

The shell at r_2 cannot be accelerated by photons to a velocity larger than :

$$u_2 \leqslant u_1 \left(\frac{r_*}{r_* + d}\right)^2 + \frac{\kappa}{c} \frac{E_{em}}{4\pi(r_* + d)^2} \quad , \text{ where } \quad E_{em} \simeq \int_{r_*}^{r_* + d} 4\pi r^2 \frac{\rho_2}{2} u_1^2 \, dr$$

$u_2 < u_1$ ⟹

$$\boxed{\beta_1 \lesssim 10\tilde{\lambda}_2 = 0.1 \left(\frac{u_w}{10 \text{ km/s}}\right) \left(\frac{r_*}{10^{13} \text{ cm}}\right) \left(\frac{\dot{M}}{5 \cdot 10^{-4} \text{ M}_\odot/\text{yr}}\right)^{-1}}$$
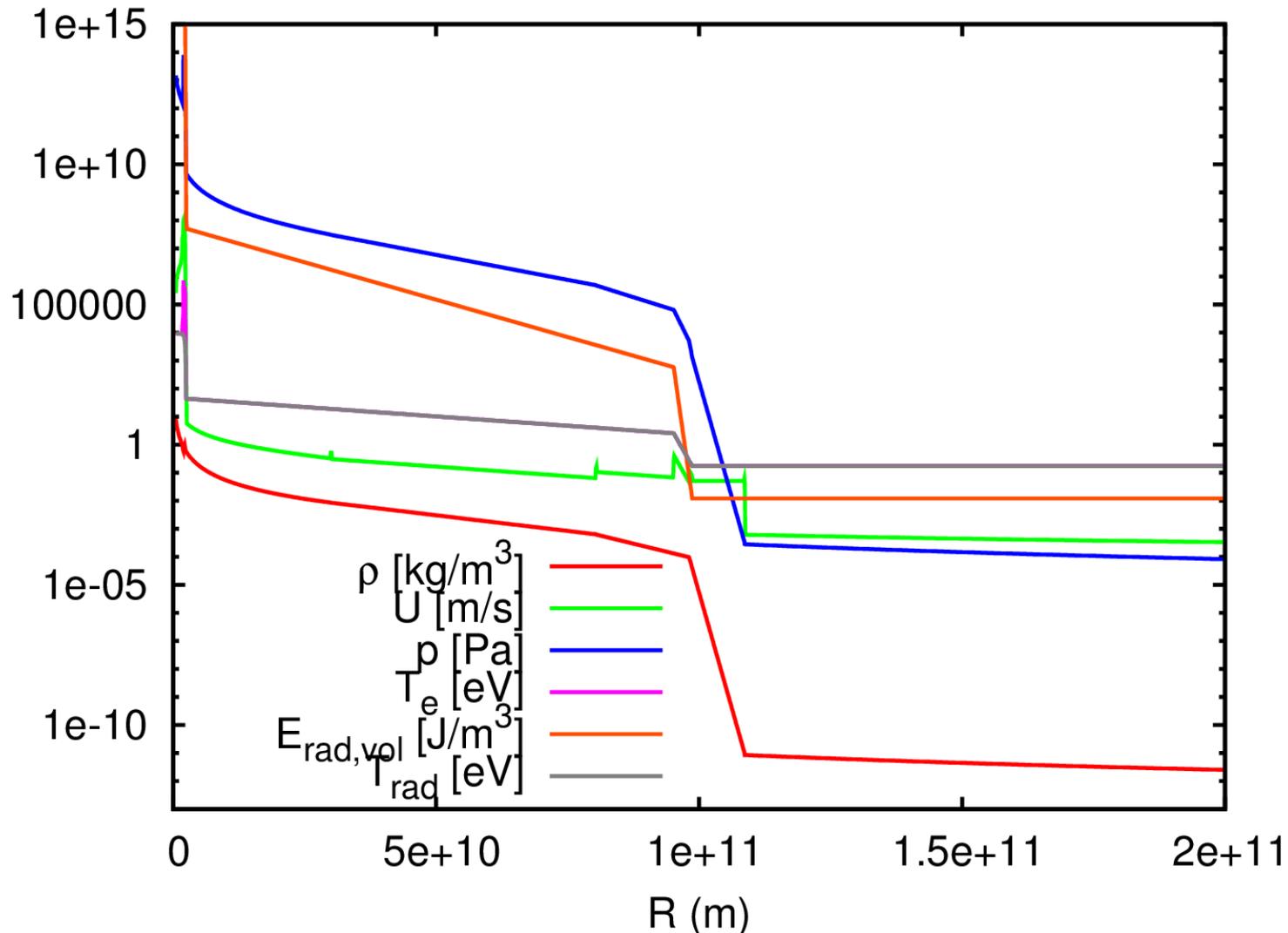
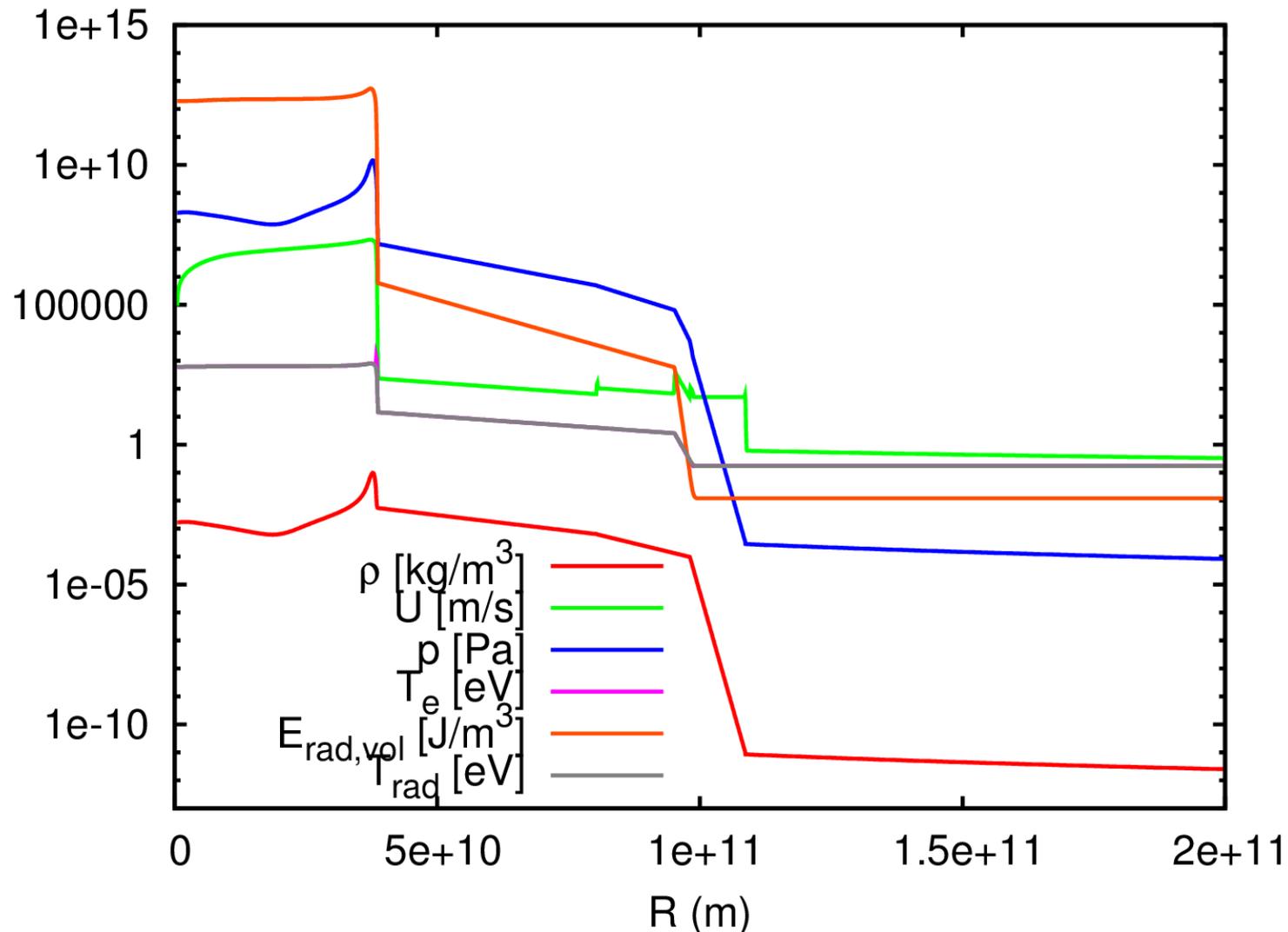# Progenitor with an optically THIN wind

1D – spherical $T_e = T_p$, but $T_e \neq T_{rad}$

Compton cooling + Bremsstrahlung   **Thomson scattering**

Legend:
- ρ [kg/m^3]
- U [m/s]
- p [Pa]
- T_e [eV]
- $E_{rad,vol}$ [J/m^3]
- T_{rad} [eV]
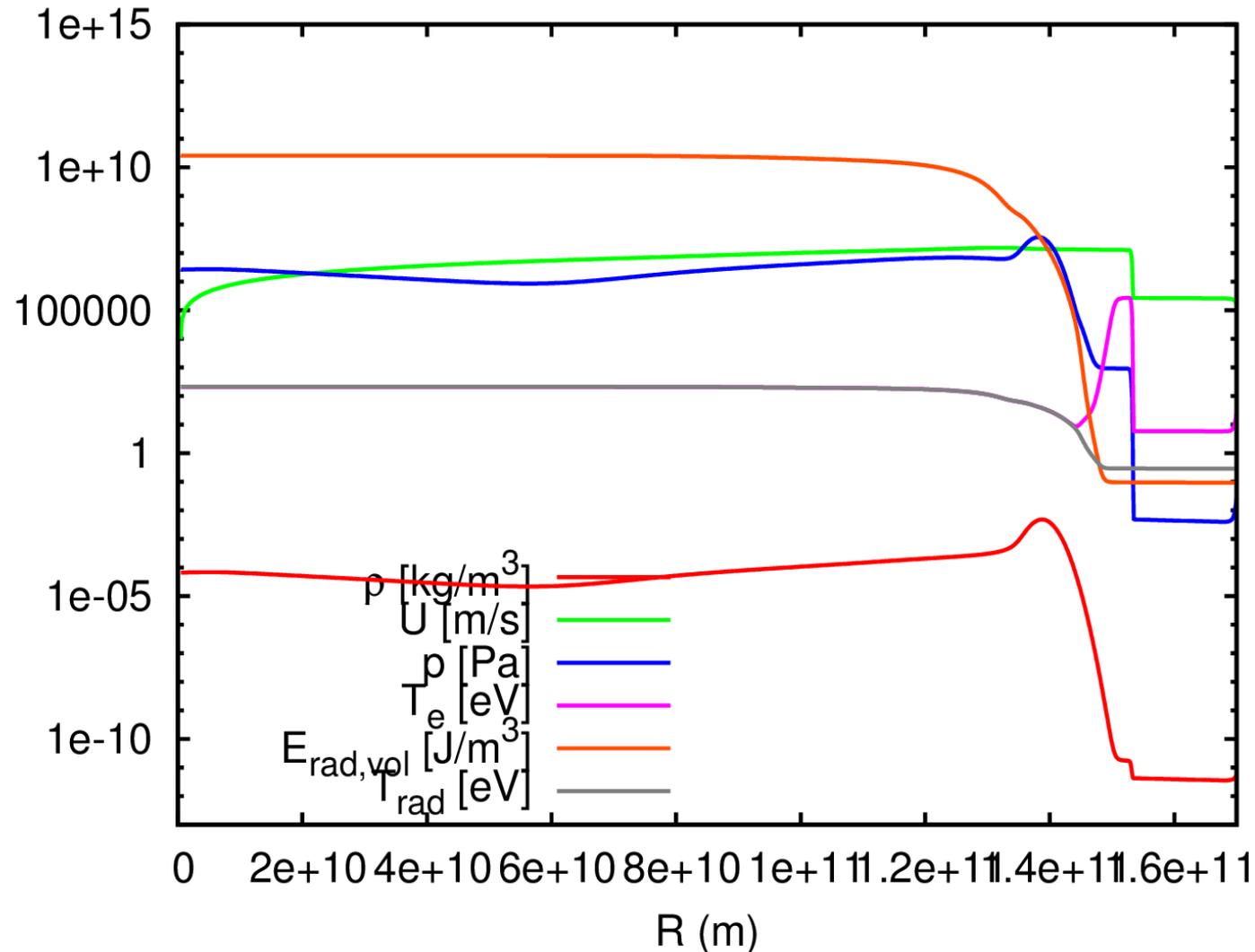
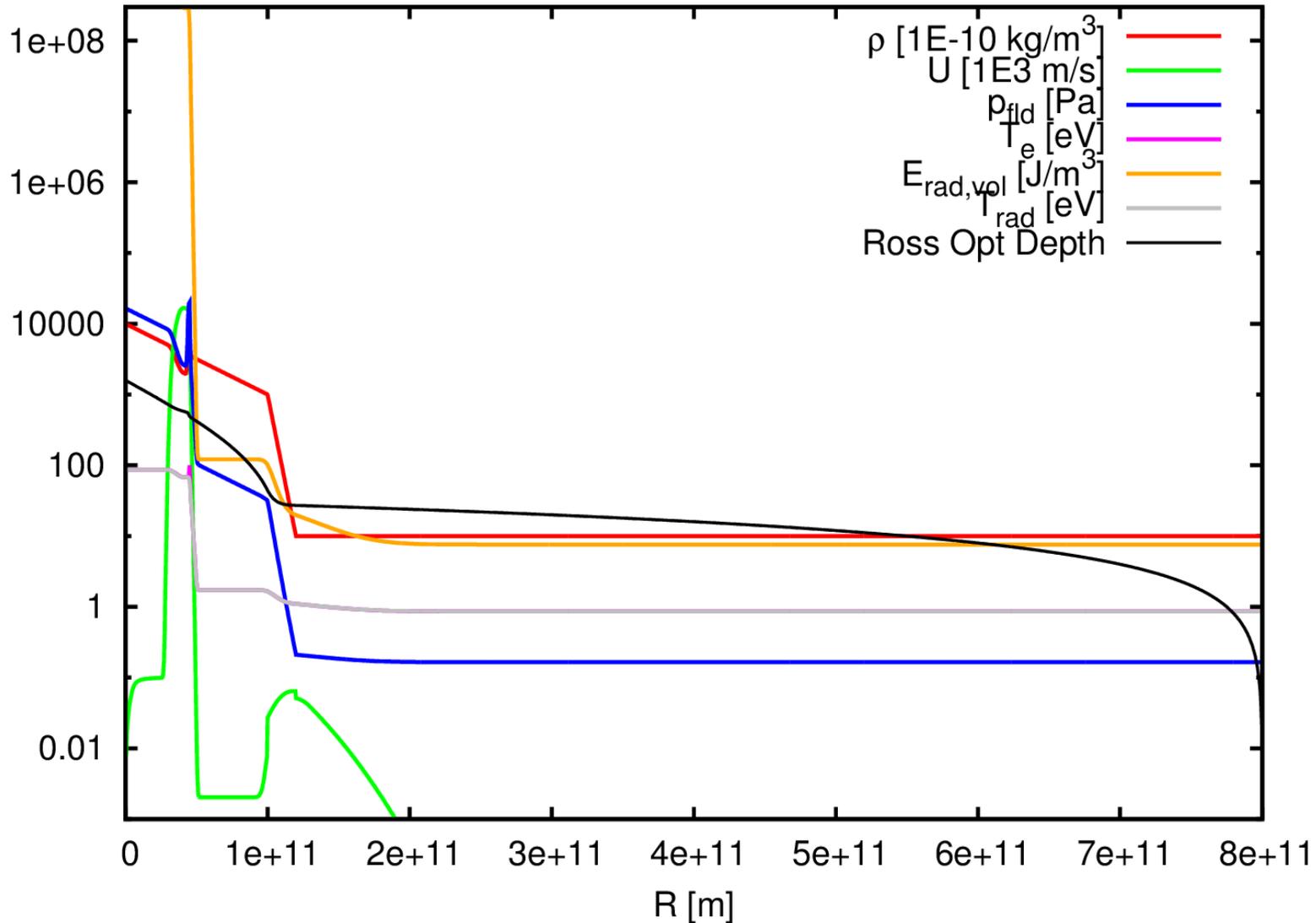# Progenitor with an optically THIN wind

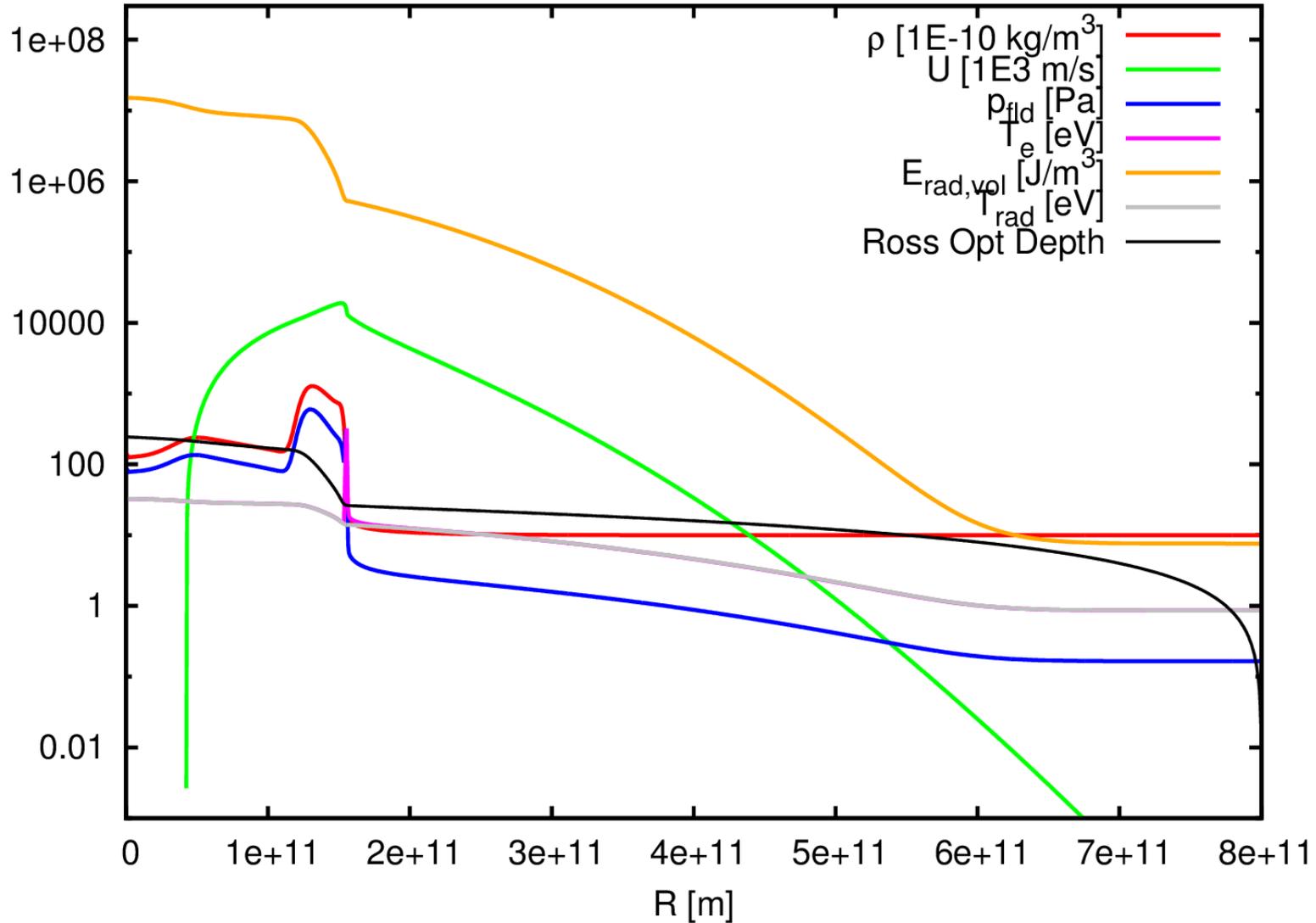# Progenitor with an optically THIN wind

Progenitor with an optically <u>THICK</u> wind

Spherical 1D

Progenitor with an optically <u>THICK</u> wind

Spherical 1D

Observational consequences

$$\tau_{\mathrm{CR}} = 8E_{\mathrm{CR}}/3eB_{\mathrm{s}}u_{\mathrm{s}}^2 \approx 30\,\mathrm{s}\left(\frac{E_{\mathrm{CR}}}{10\,\mathrm{TeV}}\right)\left(\frac{B_{\mathrm{s}}}{10\,\mathrm{G}}\right)^{-1}\left(\frac{\beta_{\mathrm{s}}}{0.1}\right)^{-2}$$

$$\tau_{\mathrm{pp}} \simeq m_{\mathrm{p}}/0.2c\rho\sigma_{\mathrm{pp}} \approx 4\,\mathrm{min}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)\left(\frac{r}{10^{13}\,\mathrm{cm}}\right)^2\left(\frac{\dot{M}}{5\cdot10^{-4}\,\mathrm{M_\odot/yr}}\right)^{-1}$$

$$\tau_{\mathrm{p\gamma}} \simeq 1/0.2cn_{\gamma}\sigma_{\mathrm{p\gamma}} \gtrsim 2\,\mathrm{min}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)\left(\frac{r}{10^{13}\,\mathrm{cm}}\right)^2\left(\frac{\dot{M}}{5\cdot10^{-4}\,\mathrm{M_\odot/yr}}\right)^{-1}\left(\frac{\beta_{\mathrm{s}}}{0.1}\right)^{-2}\left(\frac{E_{\mathrm{CR}}}{10\,\mathrm{TeV}}\right)^{-1}$$
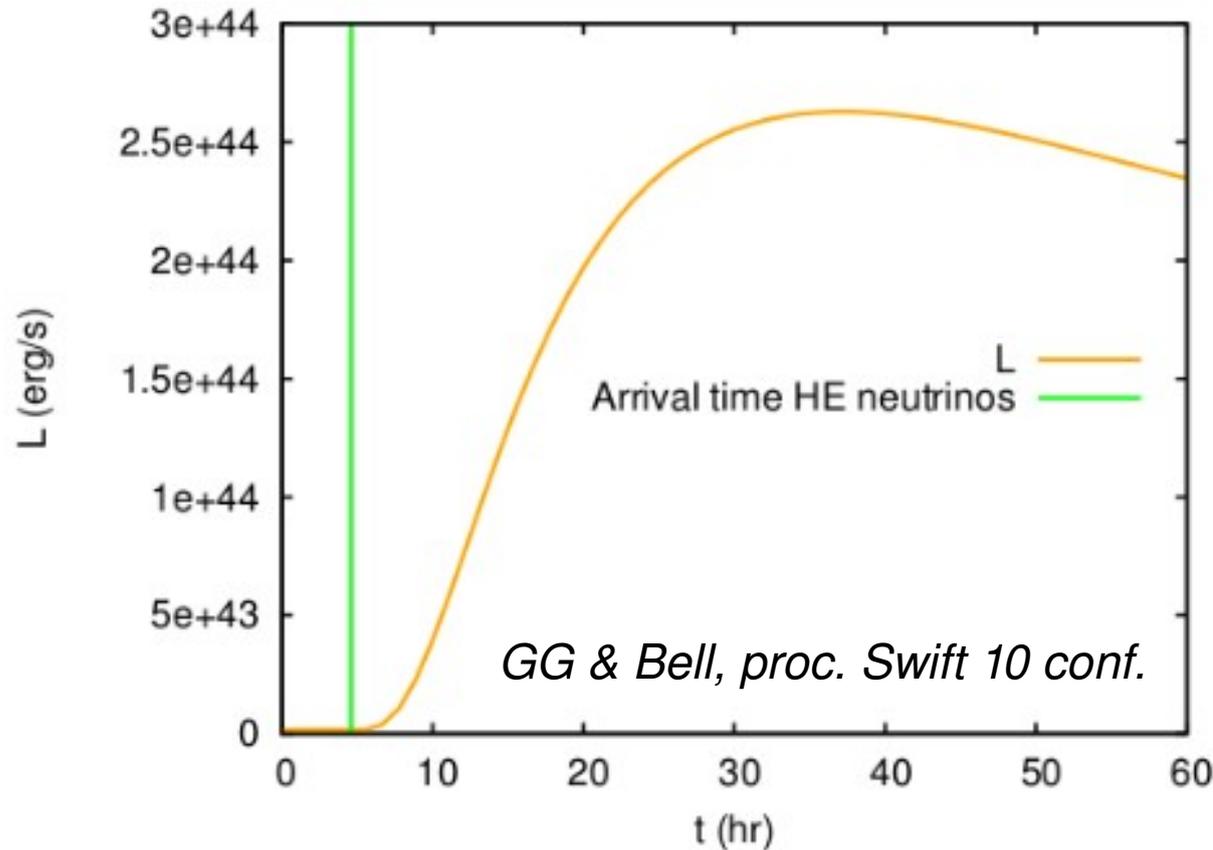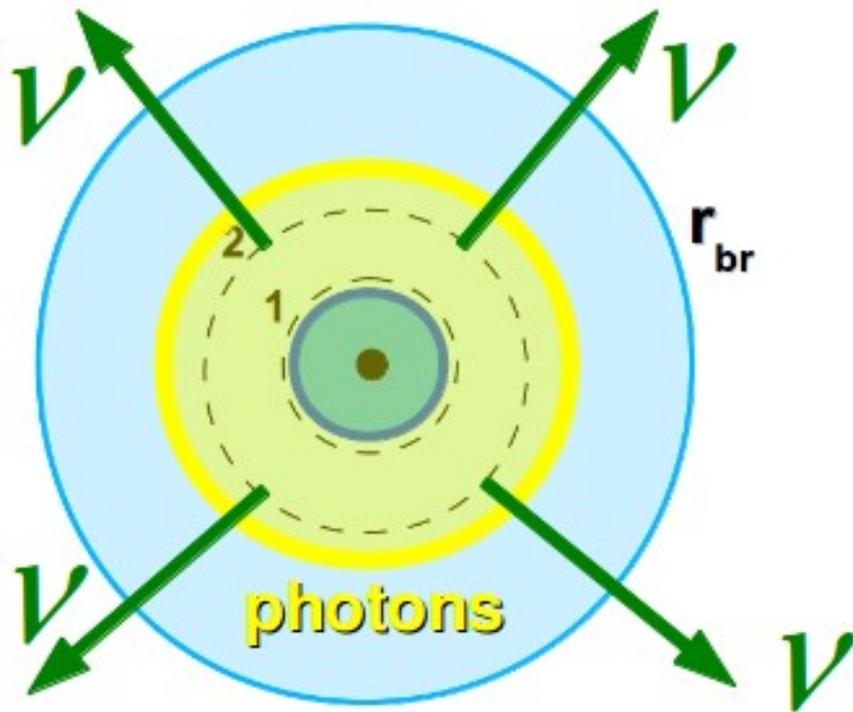
$\gtrsim (1-10)$ TeV CRs should be produced

Observational consequences

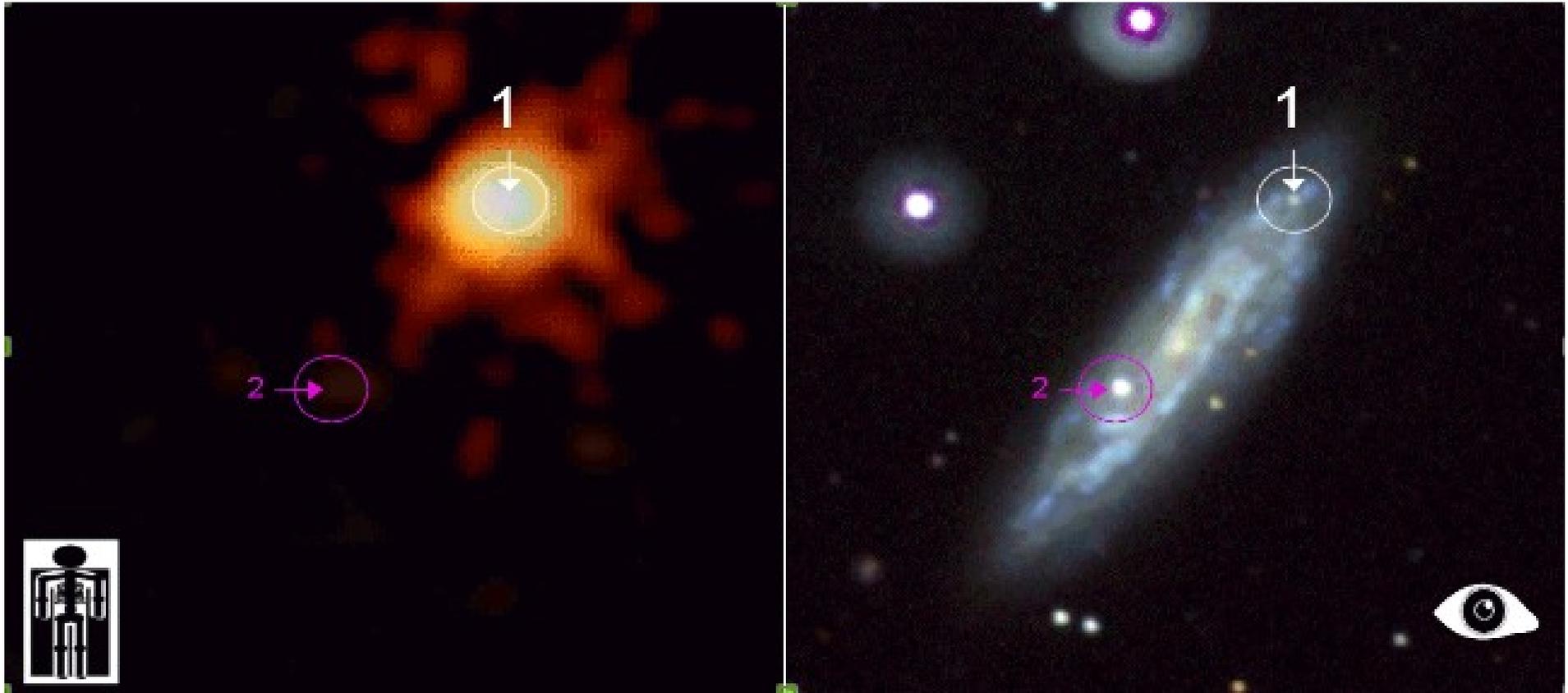**Neutrinos with energy E_ν > 100 GeV – 1 TeV ($\pi^\pm$ decay) arrive before the first photons from SB.**

Typically $\sim 10^3 \, (3\,\mathrm{kpc}/l)^2$ neutrinos (distance l, $r_{br} = 10 \, r_*$, 0.1c, $10^{-5}\mathrm{M}_\odot$ processed at $r < r_{br}$).

GG & Bell, proc. Swift 10 conf.

2) X-Ray Flash

Parameters of Svirski & Nakar, ApJL (2014) …

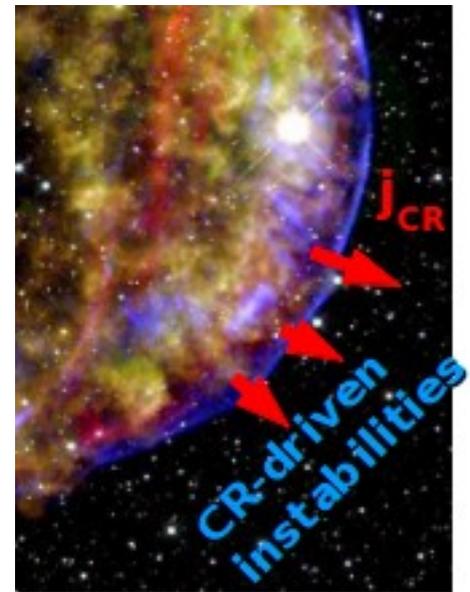<u>**SN 2008D / XRF 080109**</u> **may have been an event in which a CS is formed before SB**
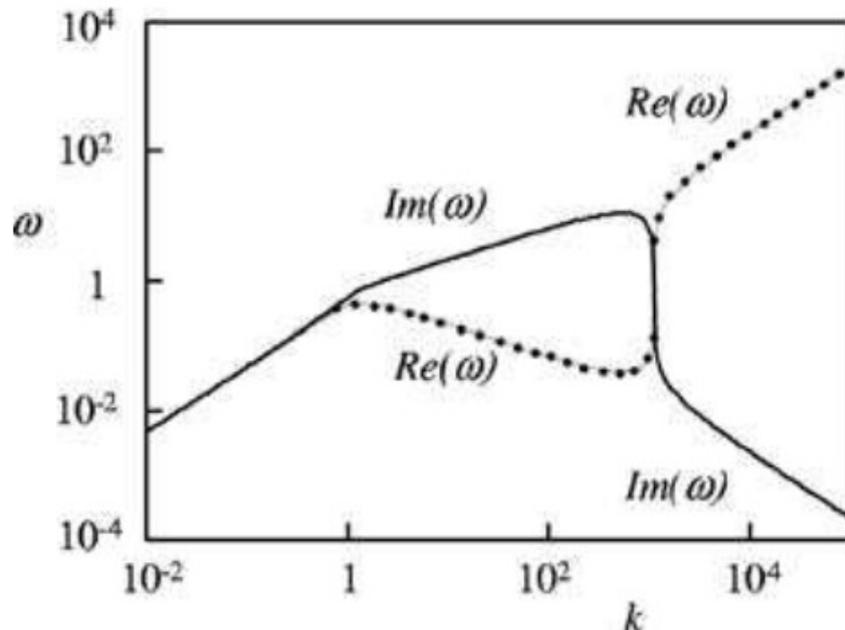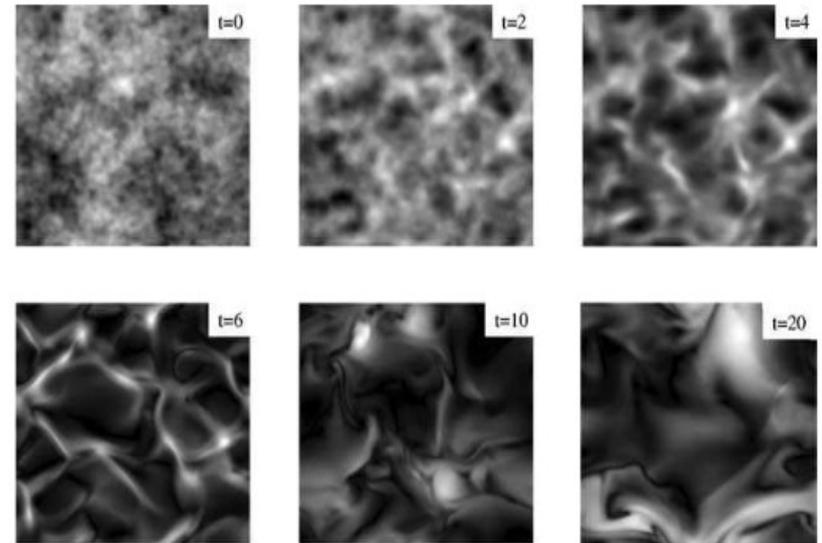
II – Supernovae in dense winds as PeVatrons

Bell's instability (Bell '04)

Large CR current densities :
Bell's non-resonant hybrid instability

$$\text{if } B j_{CR} r_L / (\rho_{ISM} v_A^2) > 1$$

$$\Gamma_{BNRH} = 0.5 j_{CR} \sqrt{\mu_0 / \rho_{ISM}}$$

CR acceleration and escape

Cosmic-ray acceleration and escape from supernova remnants

A. R. Bell,* K. M. Schure, B. Reville and G. Giacinti

Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

a background plasma modelled magnetohydrodynamically. Standard MHD equations describe the background plasma except that a $-\mathbf{j}_{CR} \times \mathbf{B}$ force is added to the momentum equation:

Bkg plasma ⟶

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla P - \frac{1}{\mu_0} \mathbf{B} \times (\nabla \times \mathbf{B}) - \mathbf{j}_{CR} \times \mathbf{B} \qquad (7)$$

as described in Lucek & Bell (2000) and Bell (2004). The CR distribution function $f(\mathbf{r}, \mathbf{p}, t)$ at position $\mathbf{r}$ and momentum $\mathbf{p}$ is defined in the local fluid rest frame and evolves according to the Vlasov-Fokker-Planck (VFP) equation
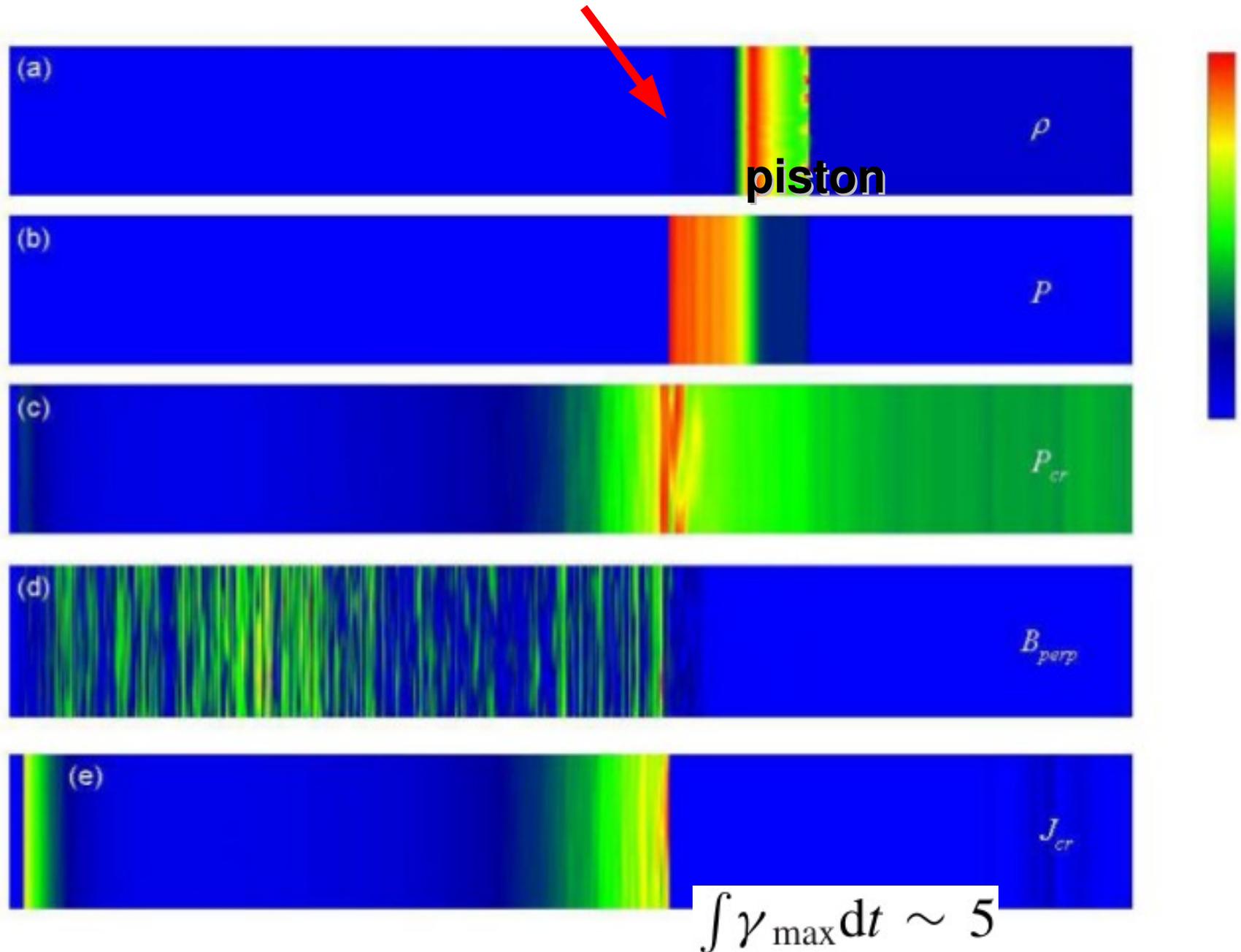
CRs ⟶

$$\frac{df}{dt} = -v_i \frac{\partial f}{\partial r_i} + p_i \frac{\partial u_j}{\partial r_i} \frac{\partial f}{\partial p_j} - \epsilon_{ijk} e v_i B_j \frac{\partial f}{\partial p_k} + C(f) \qquad (8)$$

where $C(f)$ is an optional collision term included to represent scattering by magnetic fluctuations on a small scale. The electric field is zero in the local fluid rest frame.
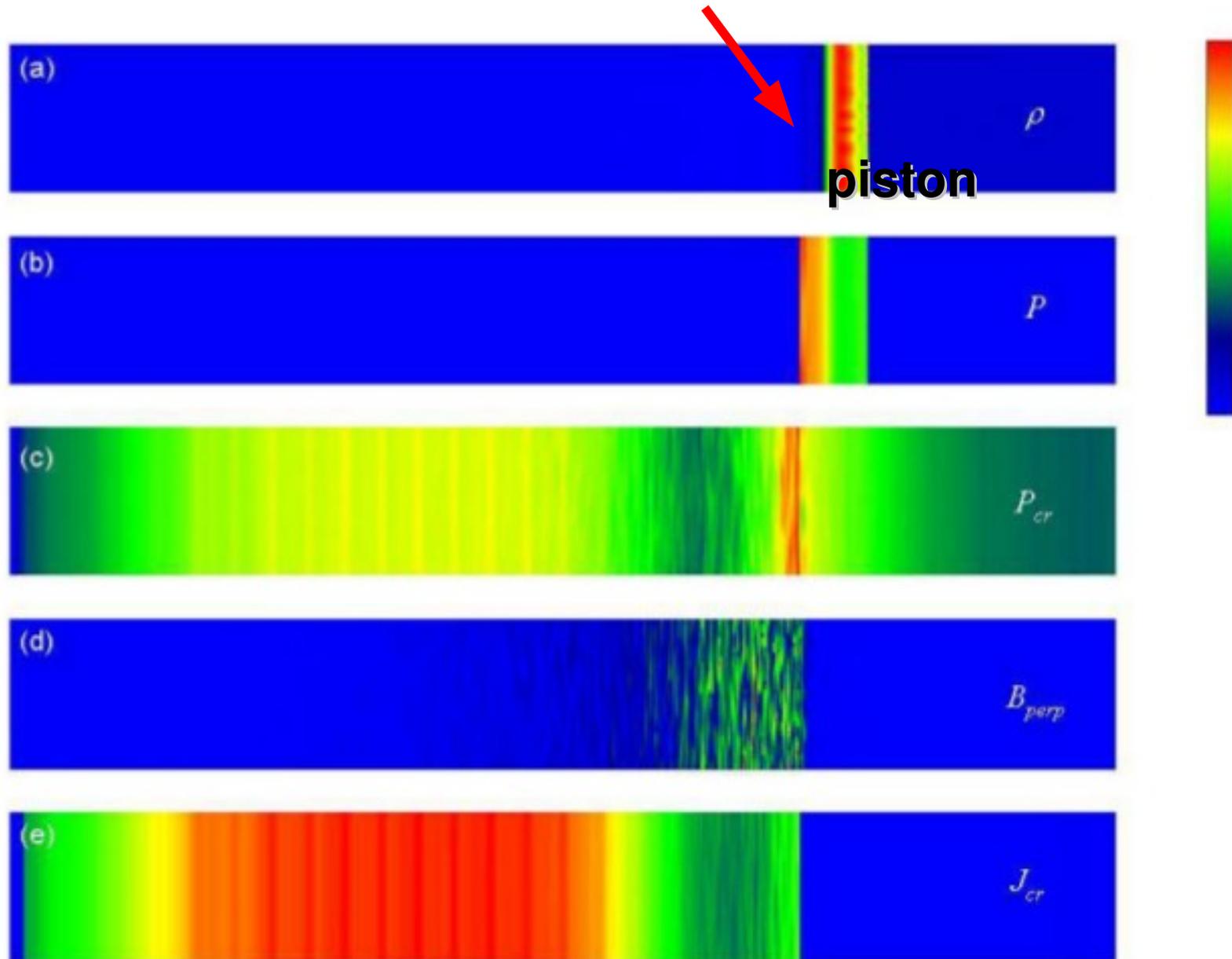
CR acceleration and escape
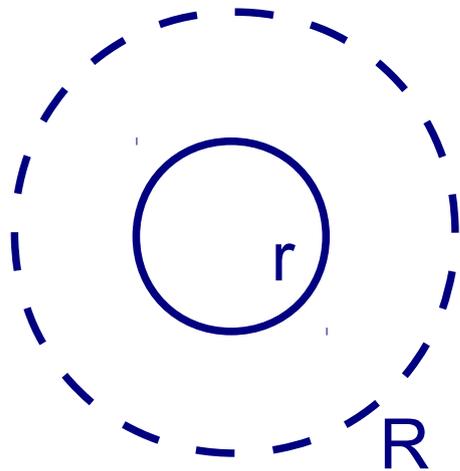
CR acceleration and escape

piston

ρ

P

P_{cr}

B_{perp}

J_{cr}

$$\int \gamma_{\max} dt \sim 5$$

CR acceleration and escape

$$\int \gamma_{max} dt \sim 5$$

$$Q_{CR} = \int j_{CR} dt = 10\sqrt{\rho/\mu_0}$$

CR charge through a unit surface, upstream

The CR current density at a radius R is $j_{CR} = \eta \rho u_s^3 r^2 / R^2 T$ (CRs accelerated to energy eT when the shock radius was r)

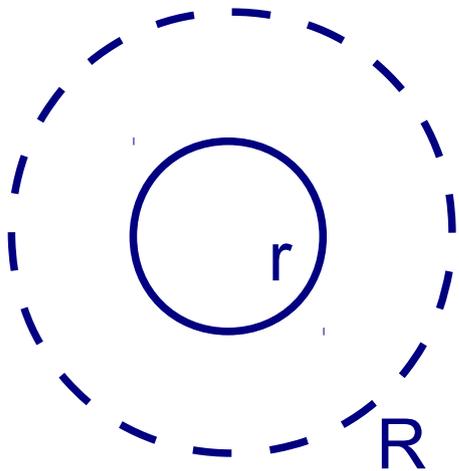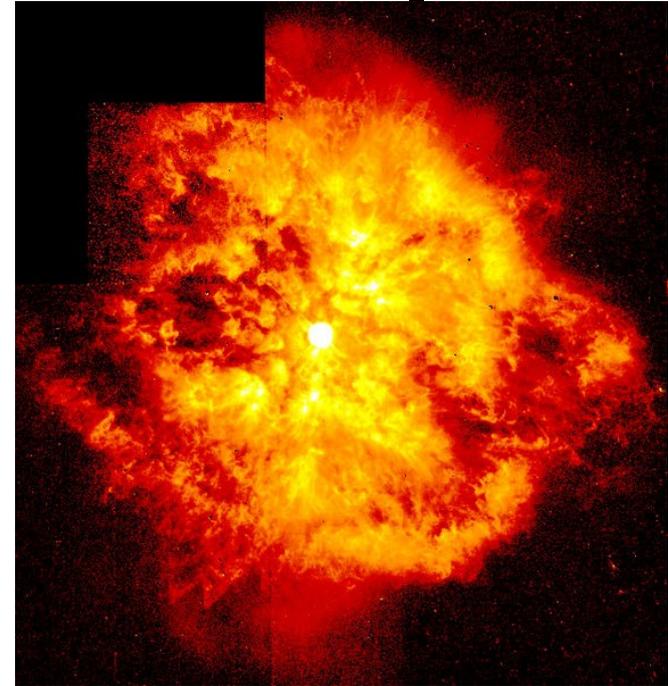$$\int_0^R \frac{\eta \rho(r) u_s^2(r)}{T(r)} r^2 dr = 10 R^2 \sqrt{\frac{\rho(R)}{\mu_0}}$$

Diff. / R :

ρ = cst $\rightarrow$

$$T = 230 \eta_{0.03} n_e^{1/2} u_7^2 R_{pc} \text{ TeV}$$

CR acceleration and escape

Bell et al. MNRAS 431, 415 (2013)

$$\int_0^R \frac{\eta\rho(r)u_s^2(r)}{T(r)}\, r^2 \mathrm{d}r = 10R^2\sqrt{\frac{\rho(R)}{\mu_0}}$$

Diff. / R :

$\rho \propto r^{-2} \rightarrow$

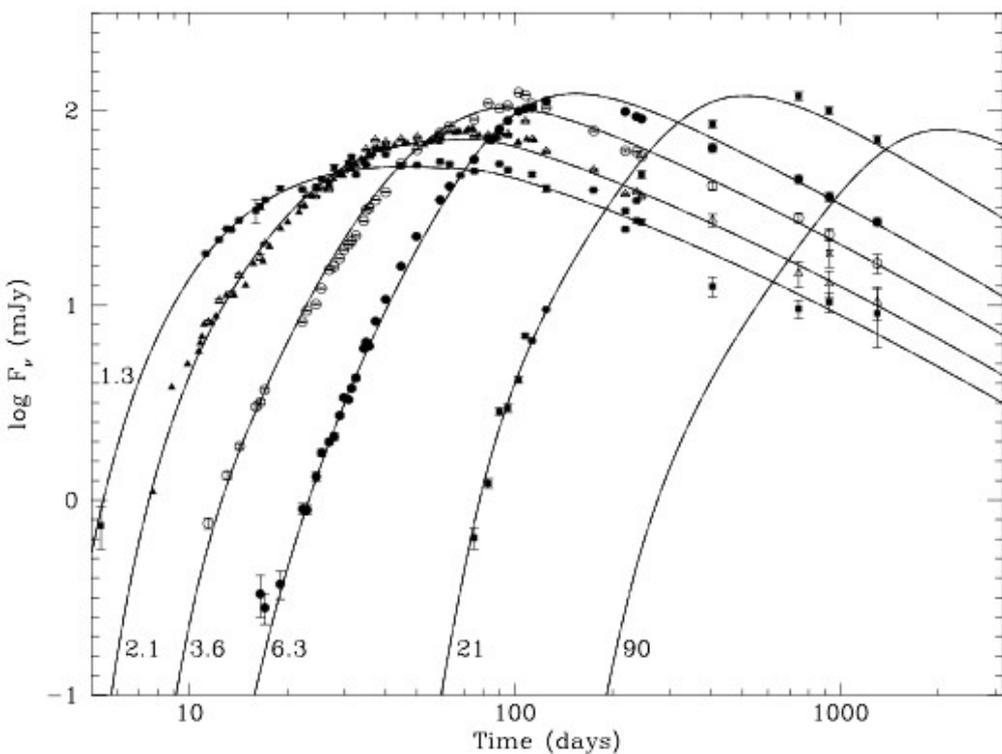$$T = 760\eta_{0.03}u_7^2\sqrt{\frac{\dot{M}_5}{v_4}}\ \mathrm{TeV}$$

Radio SNe

RADIO EMISSION AND PARTICLE ACCELERATION IN SN 1993J

CLAES FRANSSON[1] AND CLAES-INGVAR BJÖRNSSON[1]

Received 1998 April 27 ; accepted 1998 July 27

ABSTRACT

are discussed. We find that a fit to the individual spectra by a
xternal free-free absorption and synchrotron self-absorption, gives
re free-free absorption. A standard r^{-2} circumstellar medium is
. From the flux and cutoff wavelength, the magnetic field in the
shock is determined to $B \approx 64(R_s/10^{15} \text{ cm})^{-1}$ G. The strength of
amplification behind the shock. The ratio of the magnetic and
ck is ~ 0.14. Synchrotron losses dominate the cooling of the elec-
due to photospheric photons are less important. For most of the
spectrum. A model where a constant fraction of the shocked,
elerated, and subsequently lose their energy due to synchrotron
tion of the flux and number of relativistic electrons well. The
$c \, \gamma^{-2.1}$, consistent with diffusive shock acceleration. The injected
scales with the thermal electron energy density, ρV^2, rather than
x is strongly connected to the deceleration of the shock wave. The
electrons, if extrapolated to $\gamma \sim 1$, is $\sim 5 \times 10^{-4}$ of the thermal
n required is consistent with previous calculations of the circum-

Conclusions and perspectives

- <u>First few decades of SNe in dense winds very promising</u>
 <u>-> Need to search for HE neutrino / (LE) γ-rays from SNe</u>

- Studied transition from a radiation mediated shock to a collisionless shock,

- Optically thick winds : CS can form **significantly before** breakout

- Observational consequences :
  - X-ray flashes
  - E > 100 GeV neutrinos $\rightarrow$ Probe of the poorly known optically thick regions of circumstellar winds