Supernovae as PeVatrons

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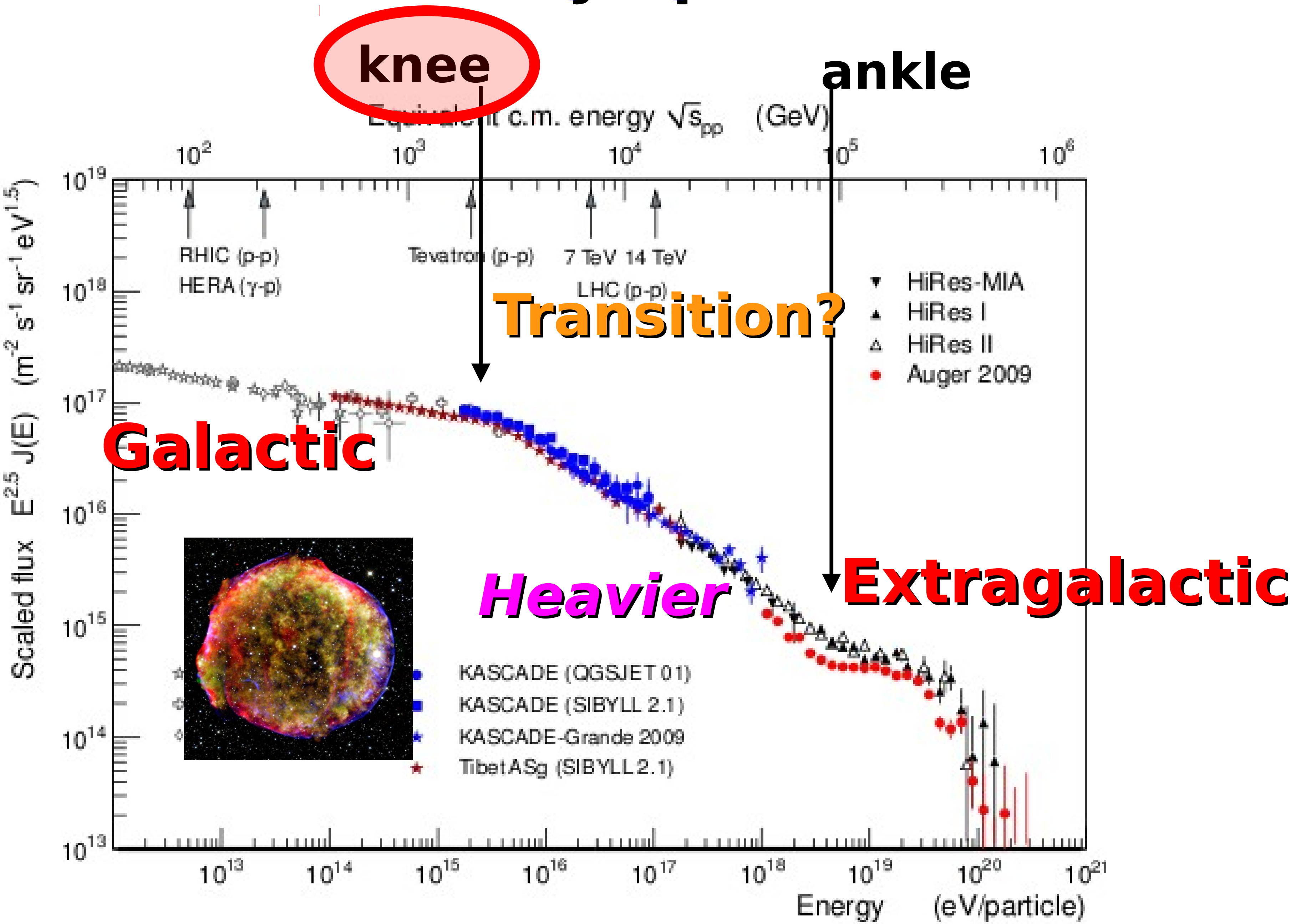
Giacinti & Bell, MNRAS 449, 3693 (2015);
Bell, Schure, Reville & Giacinti, MNRAS 431, 415 (2013)

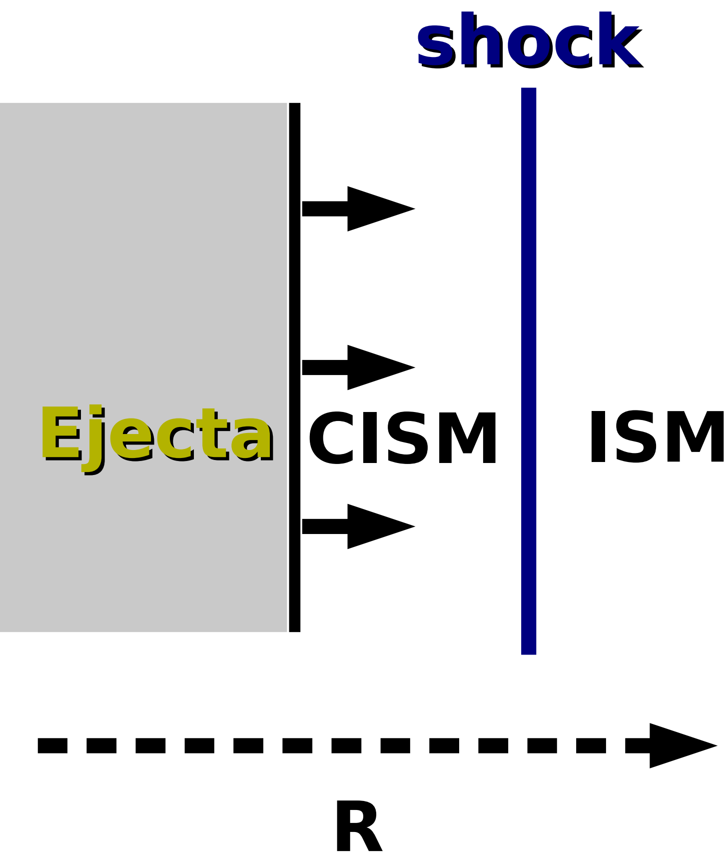
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

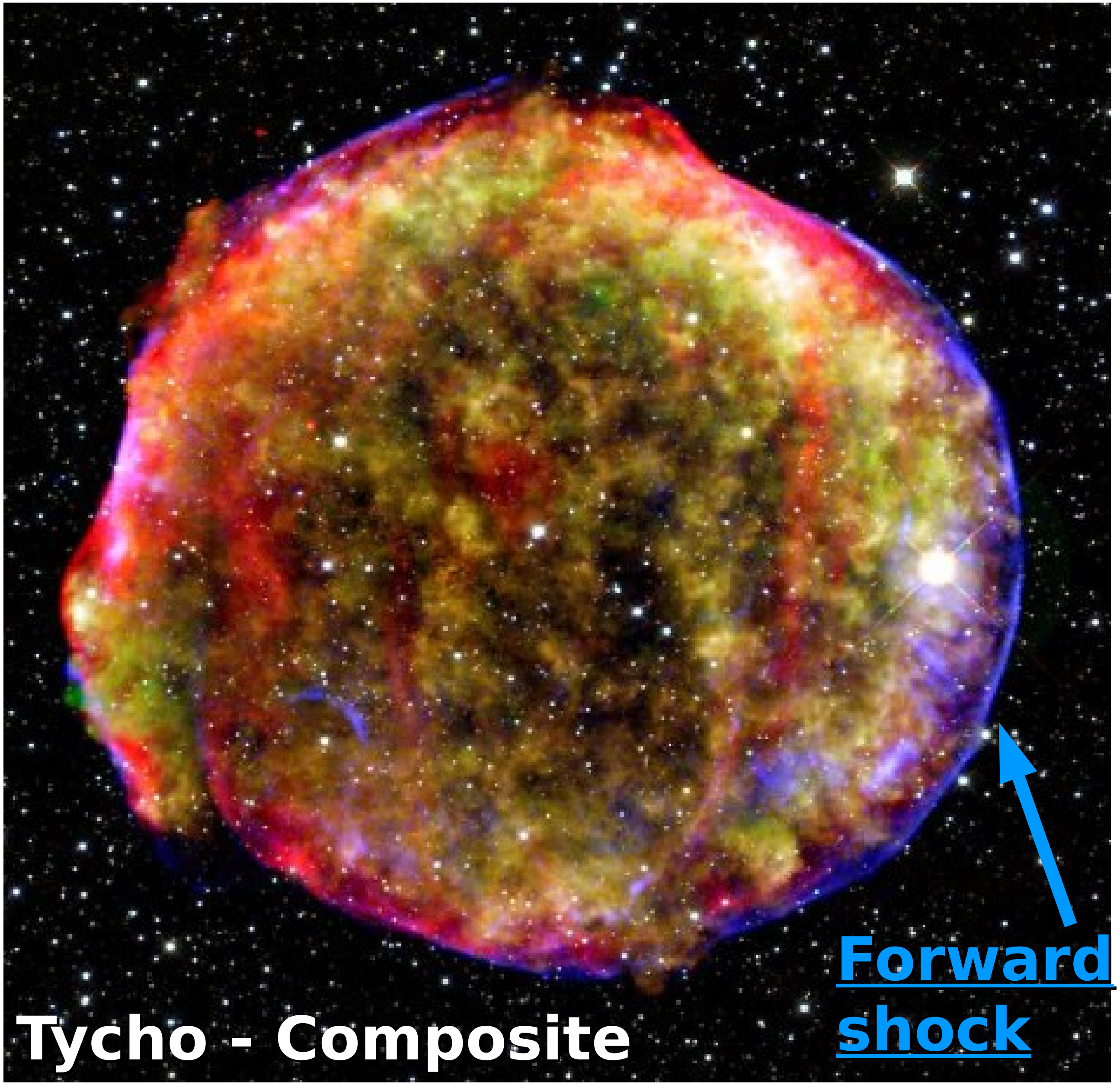
Cosmic ray spectrum



Sources, acceleration mechanism

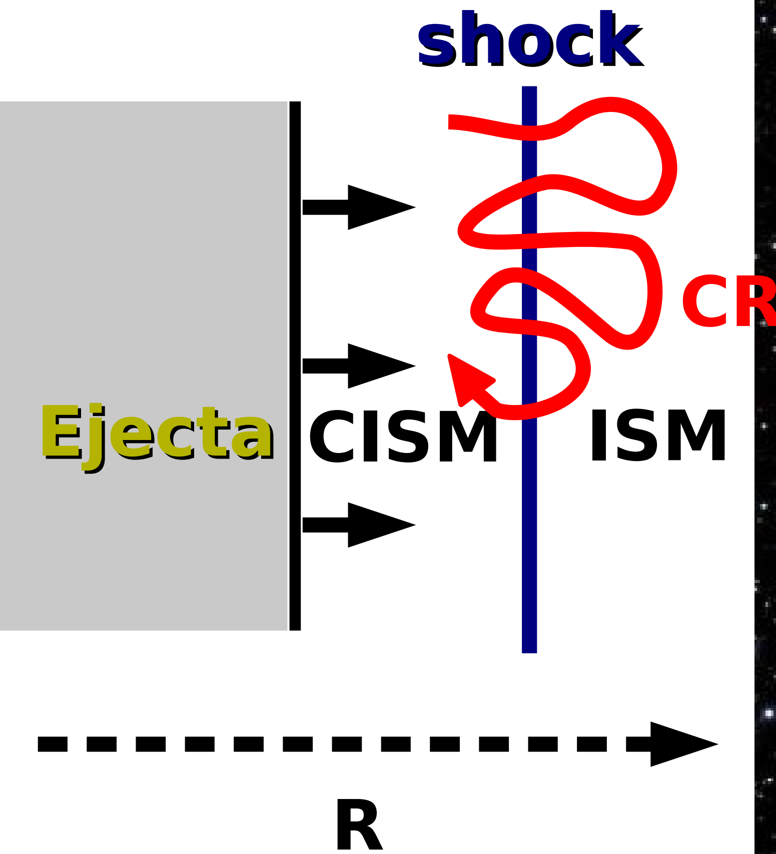
Supernova remnants

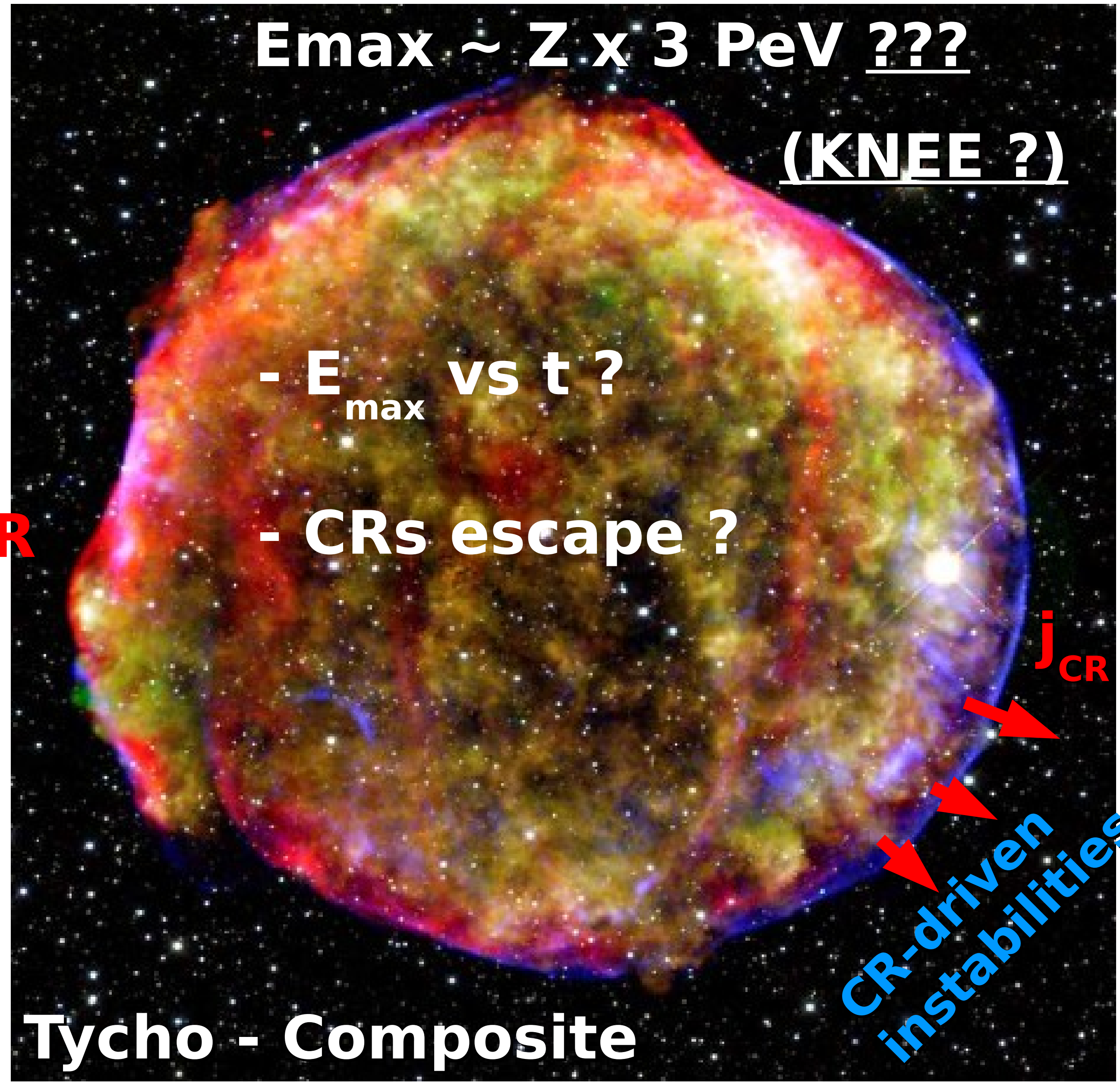




Sources, acceleration mechanism

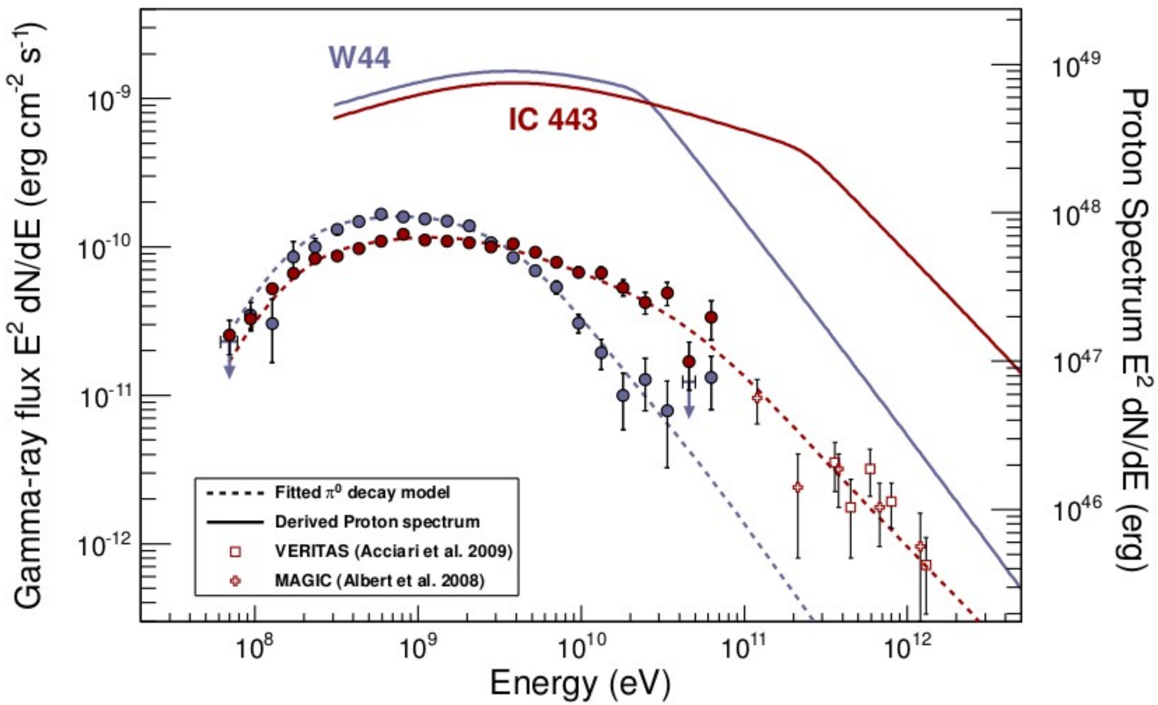
Diffusive shock acceleration (Krymskii; Axford *et al.* '77; Bell; Blandford & Ostriker '78)





In γ – rays :

→ Old SNRs : Fermi-LAT coll., Science **339,** 807 (2013)



→ Historical SNRs : Particles up to ~ 100's TeV only !

... So where are the PeVatrons ???

Outline

I – Cosmic Ray Acceleration at SNR / SNe

→ ***How do CR escape SNR ? magnetic field amplification ?***

→ ***Can SNR accelerate CR to > 1 PeV ... when ?***

II – SNe in dense winds as PeVatrons

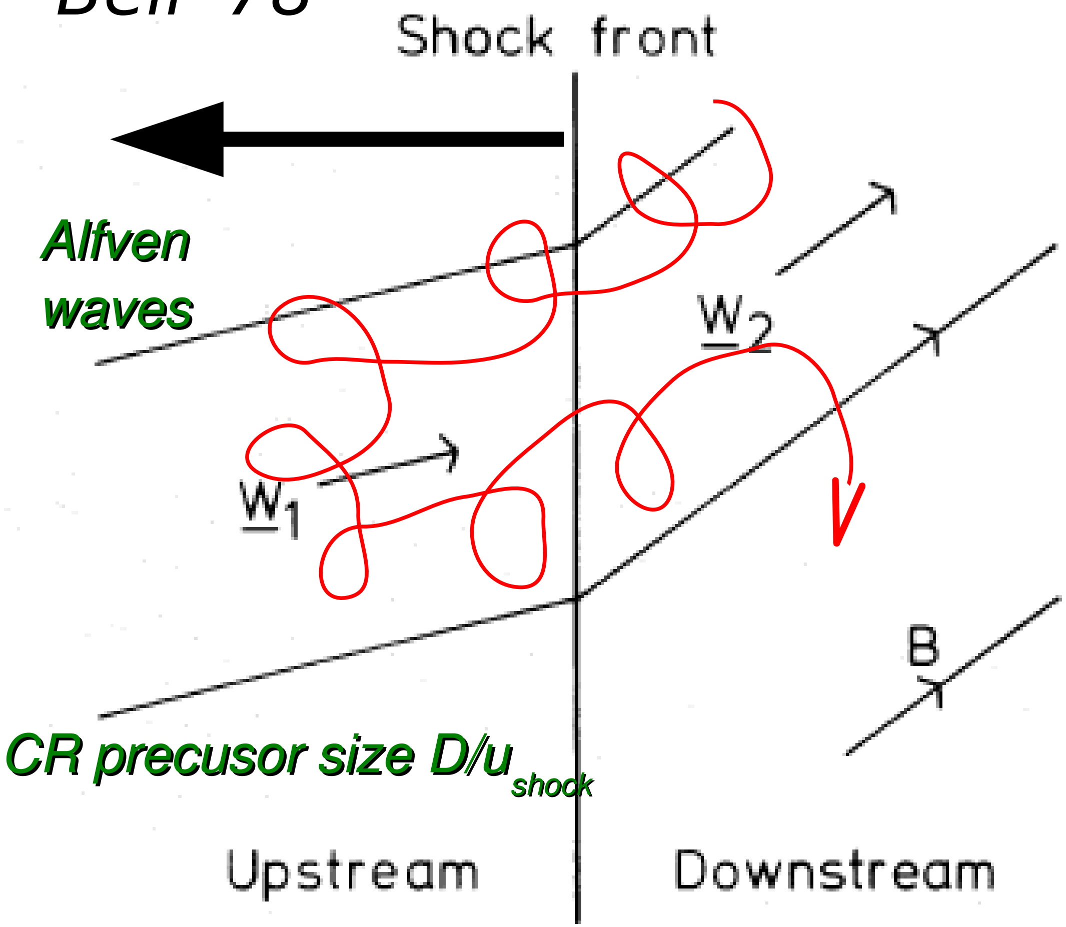
III – Particle Acceleration BEFORE SN Shock Breakout

→ ***When does particle acceleration start ?***

Sources, acceleration mechanism

Need for MF amplification

Bell '78



$$\tau = \frac{4D_{upstream}}{u_{shock}^2} + \frac{4D_{downstream}}{(u_{shock}/4)^2} \approx \frac{8D_{upstream}}{u_{shock}^2}$$

E_{max} *for :* $\tau = R/u_{shock}$

$D_{Bohm} = cR_g/3$

$$E_{max} = \frac{3}{8} u_{shock} BR$$

300 yrs, B ~ 3 μG, u_{shock} ~ 5000 km s^{-1}

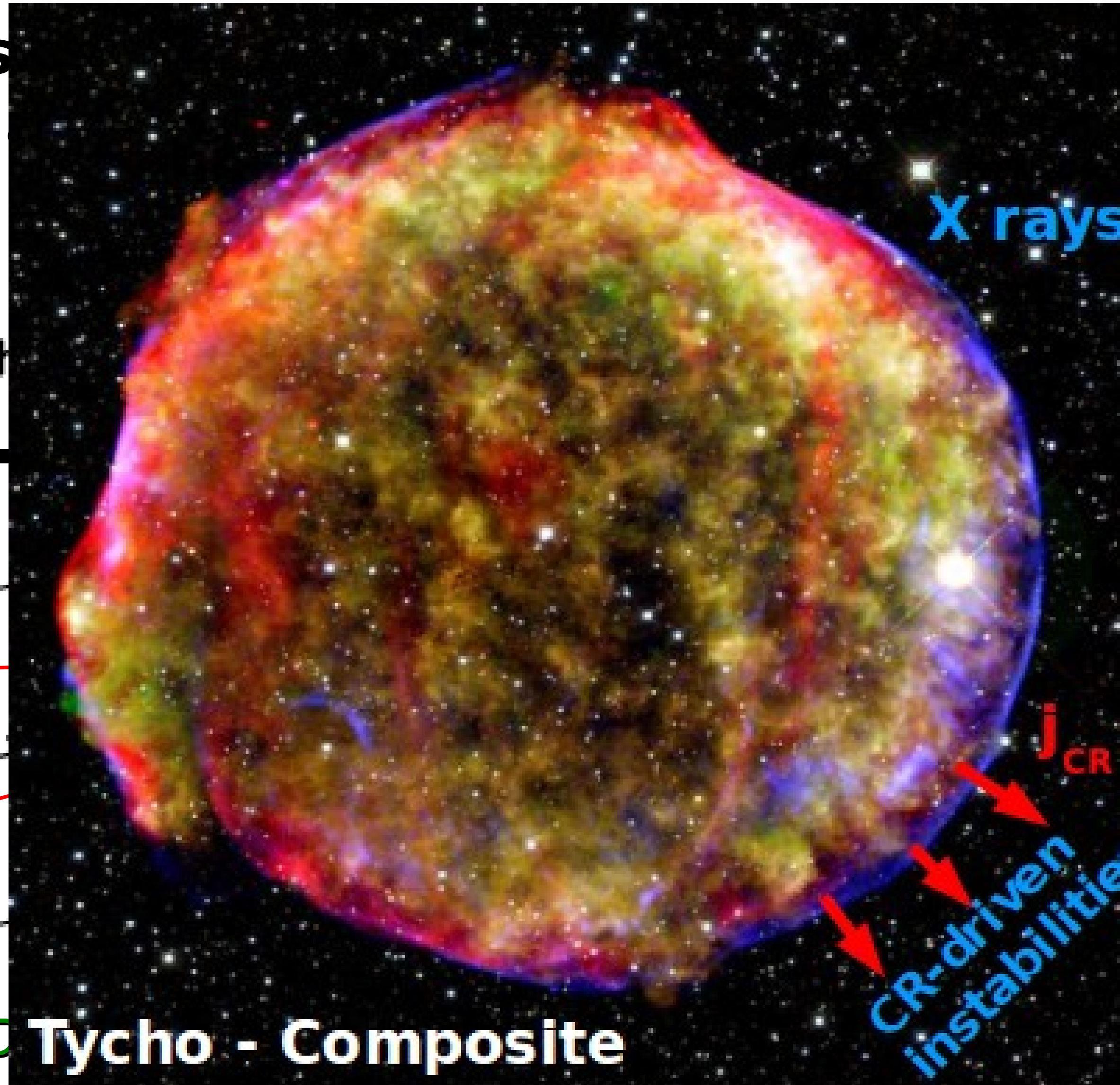
=> E_{max} ~ 10 TeV !!!

= > *Need for MF amplification*

Sources, acceleration mechanism

Diffus **'77;**
Axford *et* **iker '78)**

Bell '78



$\frac{...nstream}{(.../4)^2} \approx \frac{8D_{upstream}}{u_{shock}^2}$

$\tau = R/u_{shock}$

$..._{Bohm} = cR_g/3$

R

$..._{hock} \sim 5000$ km s^{-1}

0 TeV !!!

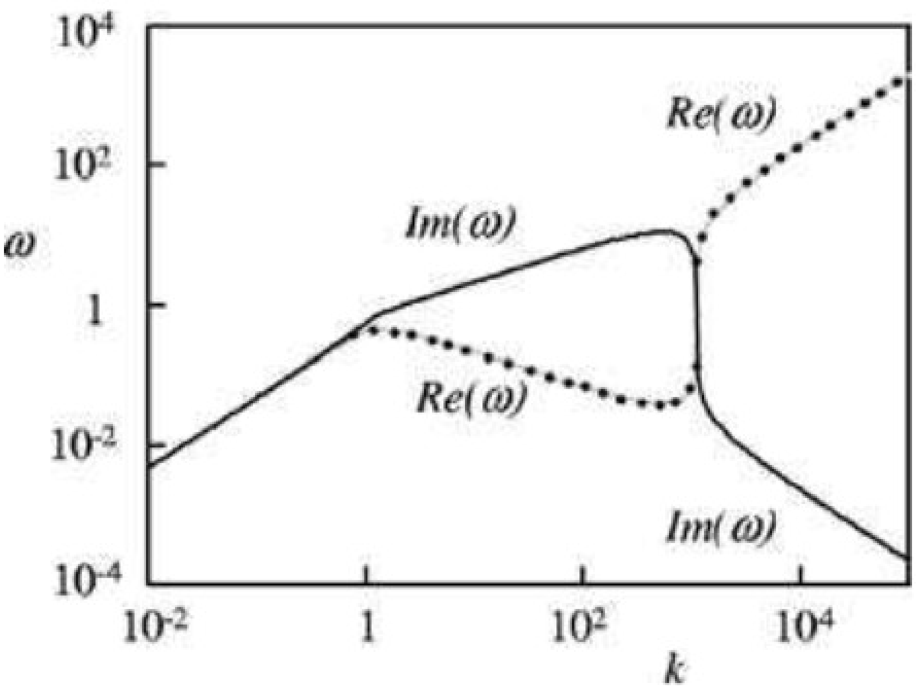
= > Need for MF amplification

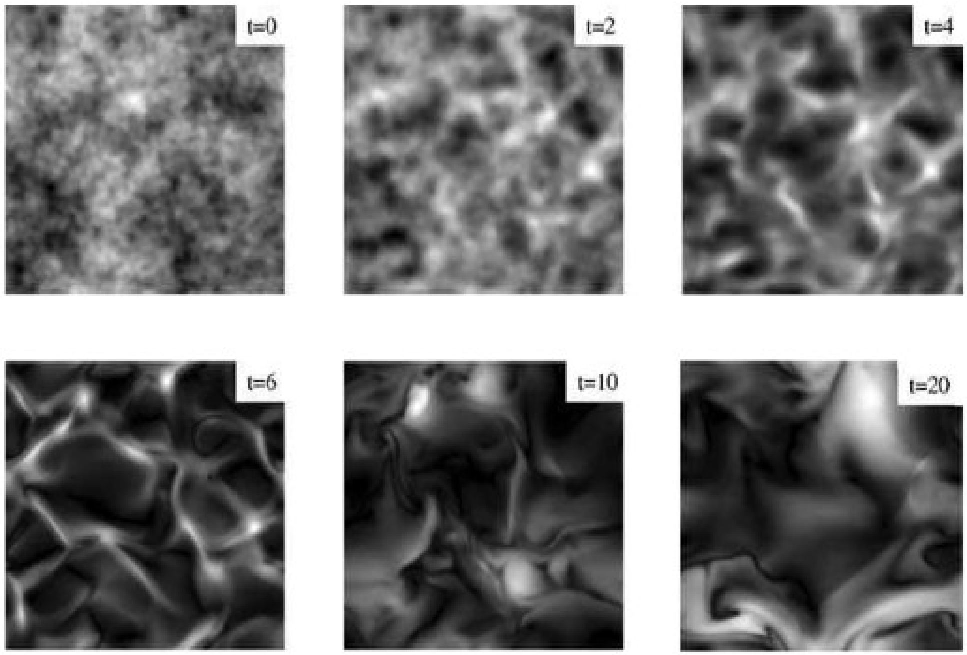
NRH instability (Bell '04)

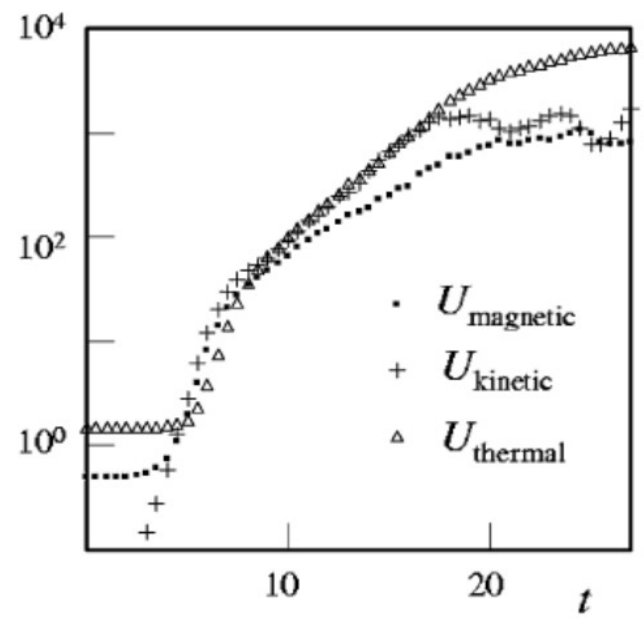
Large CR current densities : Non-resonant hybrid instability

if $B j_{\mathrm{CR}} r_{\mathrm{L}}/(\rho_{\mathrm{ISM}} v_{\mathrm{A}}^2) > 1$

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







CR acceleration and escape

MNRAS 431, 415 (2013)

We now set out to test the above conclusions as far as we are able with a numerical model that includes the self-consistent interaction of CR modelled kinetically with 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 →

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

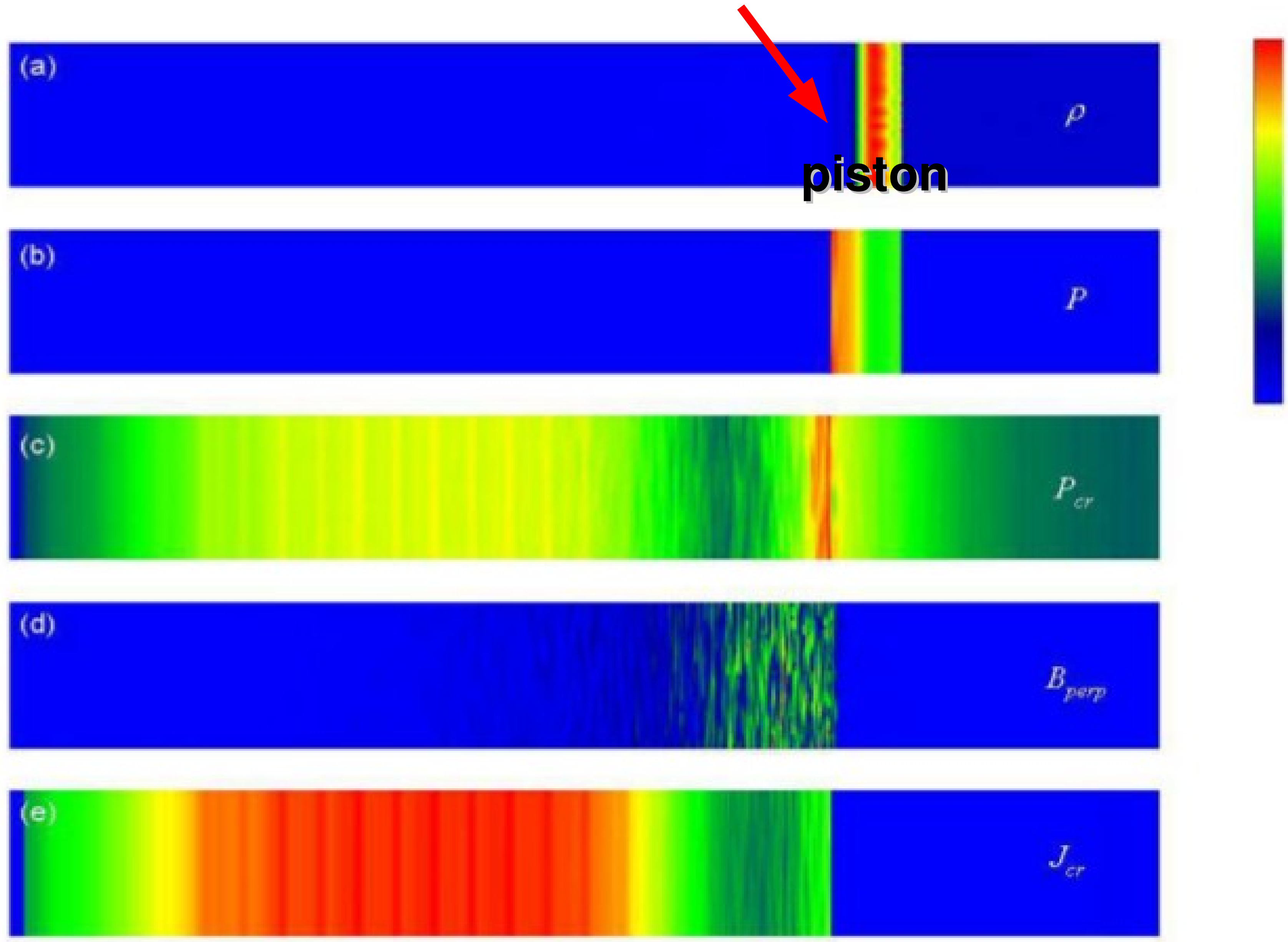
as described in Lucek & Bell (2000) and Bell (2004). The CR distribution function $f(\mathbf{r}, \mathbf{p}, t)$ at position $\mathbf{r}$ and momentum $\mathbf{p}$ is defined in the local fluid rest frame and evolves according to the Vlasov-Fokker-Planck (VFP) equation

CRs →

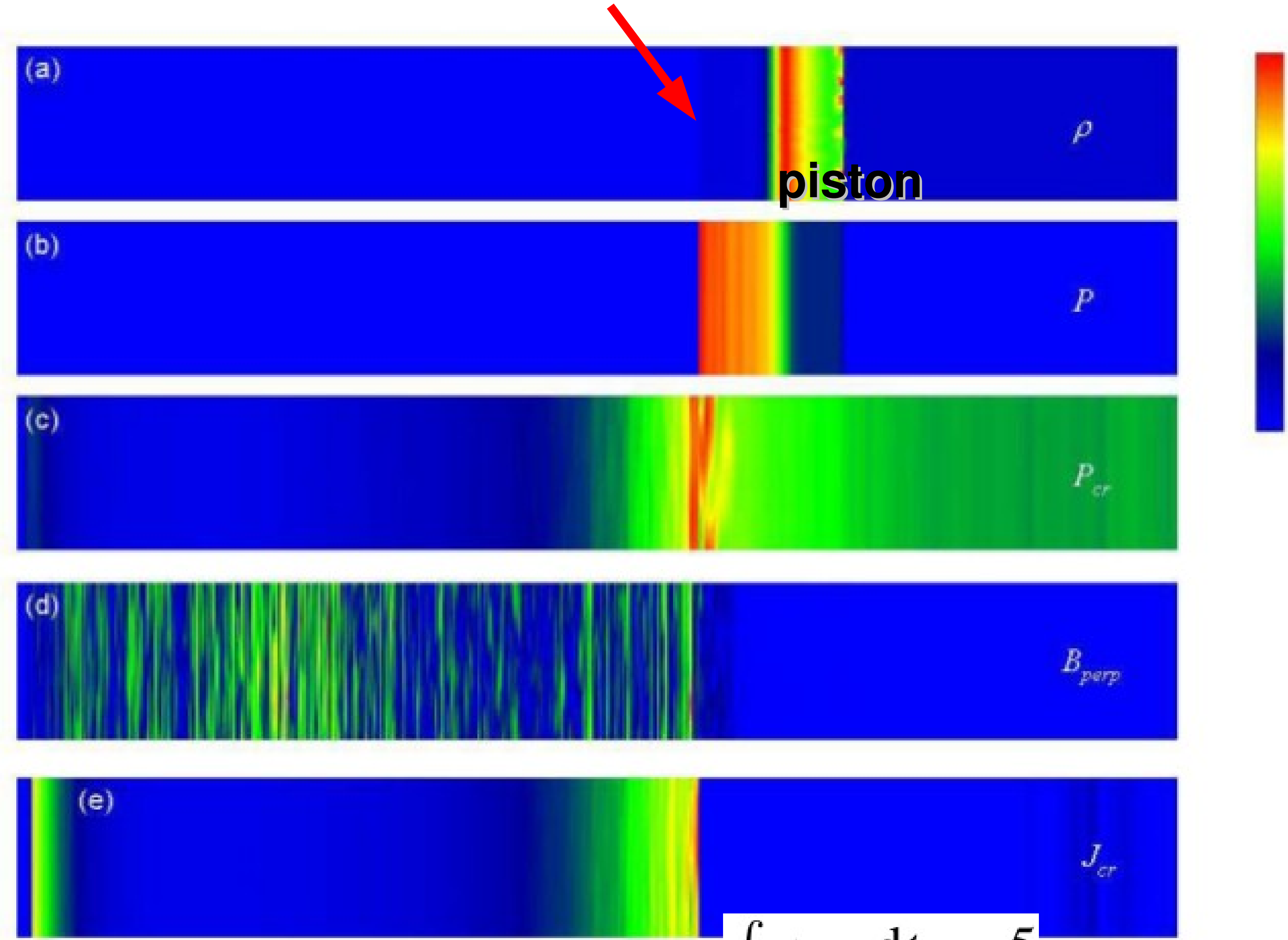
$$\frac{df}{dt} = -v_i \frac{\partial f}{\partial r_i} + p_i \frac{\partial u_j}{\partial r_i}\frac{\partial f}{\partial p_j} - \epsilon_{ijk} e v_i B_j \frac{\partial f}{\partial p_k} + C(f) \qquad (8)$$

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

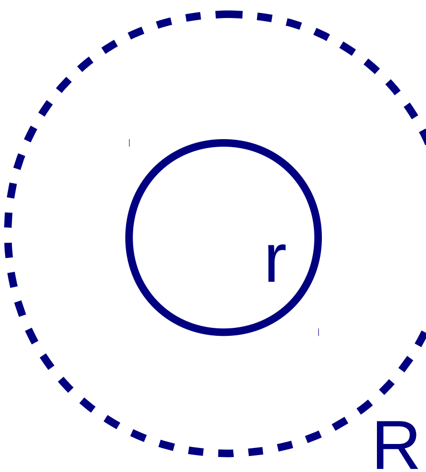


$$\int \gamma_{\max} dt \sim 5$$

CR acceleration and escape

$$\int \gamma_{\max} \mathrm{d}t \sim 5 \qquad\qquad Q_{\rm CR} = \int j_{\rm CR} \mathrm{d}t = 10\sqrt{\rho/\mu_0}$$

CR charge through a unit surface, upstream



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

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

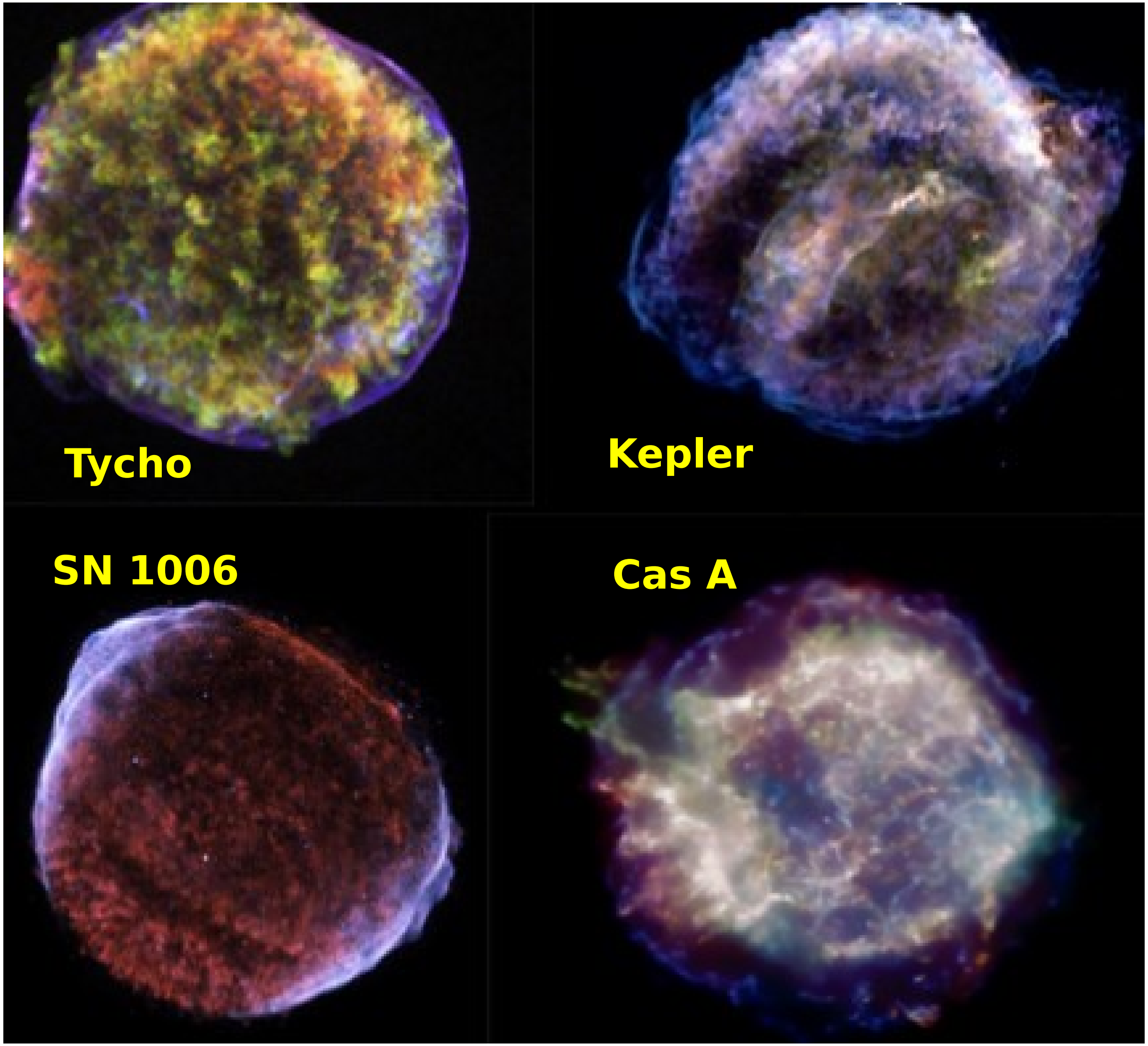
Diff. / R :

ρ = cst →

$$T = 230 \eta_{0.03} n_{\rm e}^{1/2} u_7^2 R_{\rm pc} \ \mathrm{TeV}$$

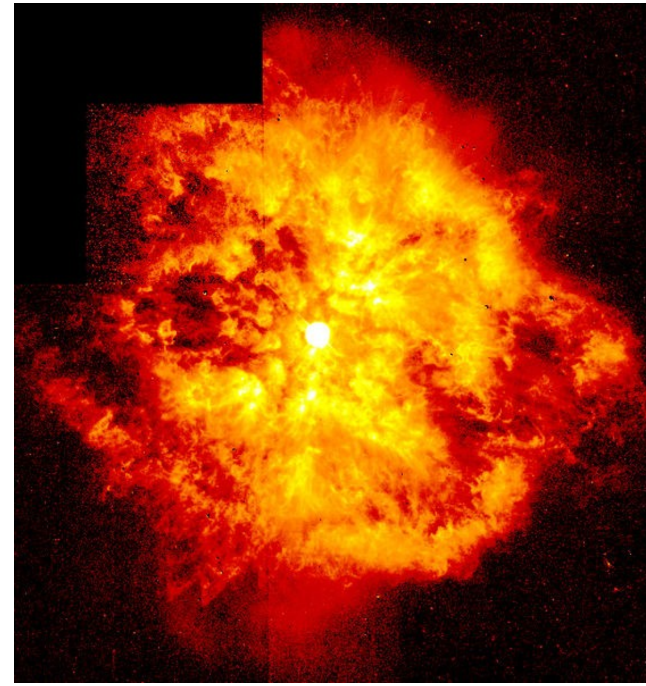
Cas A : $\quad T \approx 400$ TeV !!!

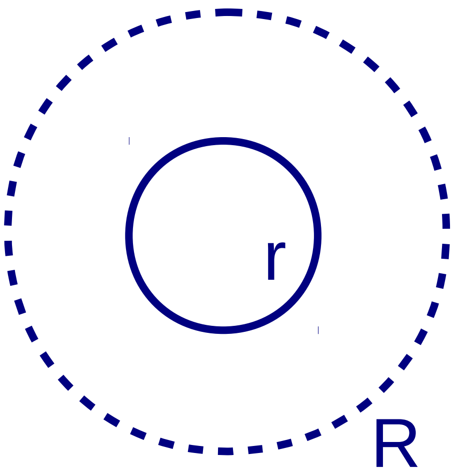
Nowadays, historical SNRs are <u>not</u> accelerating particles to the knee !



SNe in DENSE WINDS as PeVatrons

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 :

$\rho \propto r^{-2}$ →

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

Radio SNe

THE ASTROPHYSICAL JOURNAL, 509:861–878, 1998 December 20

RADIO EMISSION AND PARTICLE ACCELERATION IN SN 1993J

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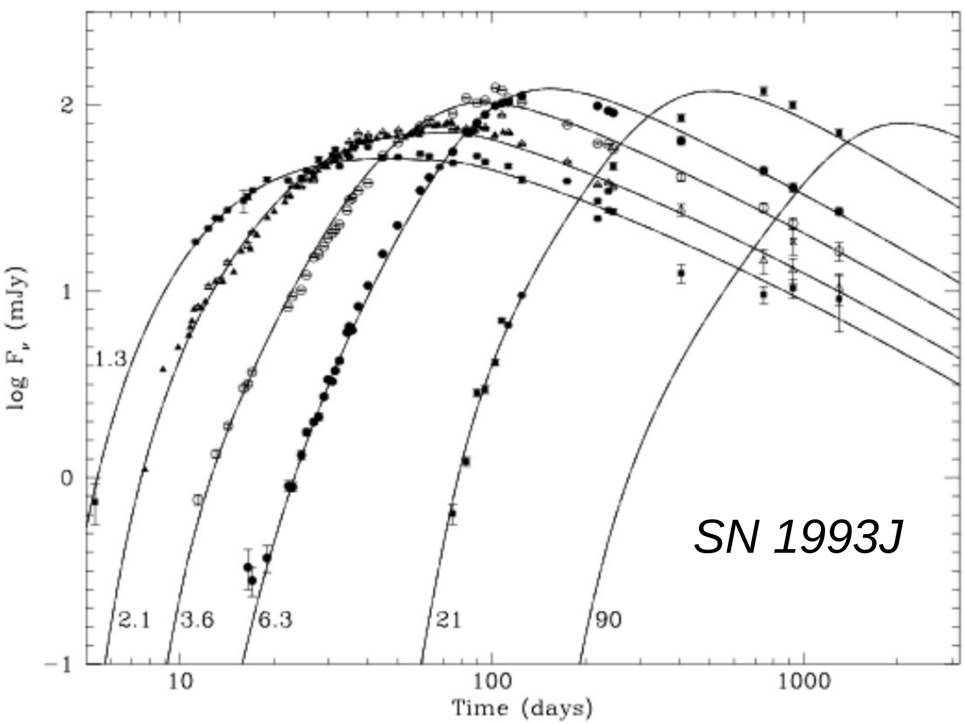
Received 1998 April 27; accepted 1998 July 27



ABSTRACT

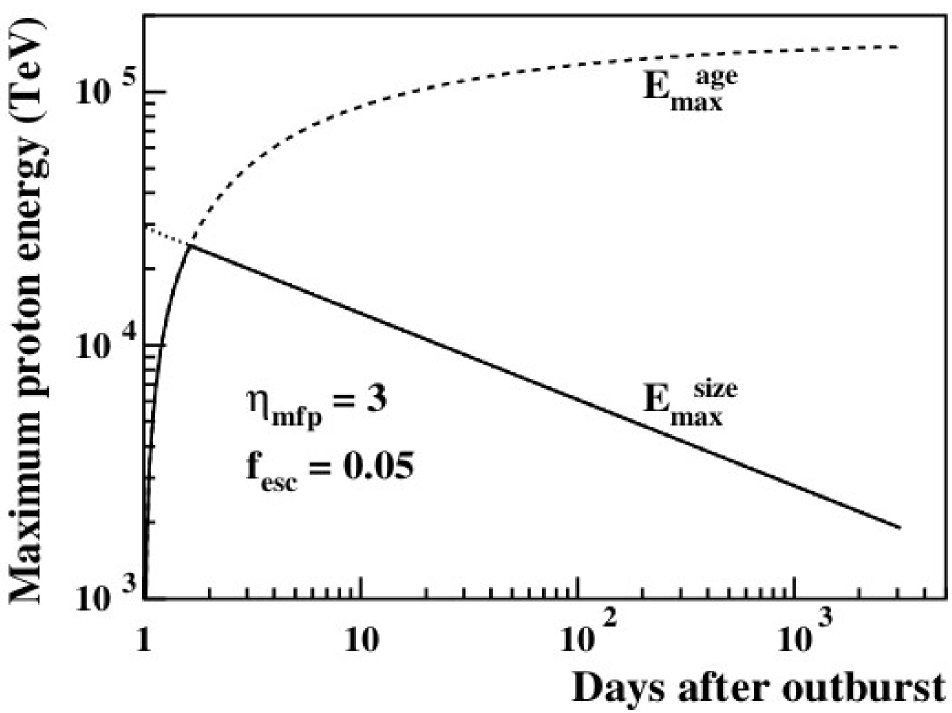
discussed. We find that a fit to the individual spectra by a
nal free-free absorption and synchrotron self-absorption, gives
ree-free absorption. A standard r^{-2} circumstellar medium is
om the flux and cutoff wavelength, the magnetic field in the
ock is determined to $B \approx 64(R_s/10^{15}\ \mathrm{cm})^{-1}$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

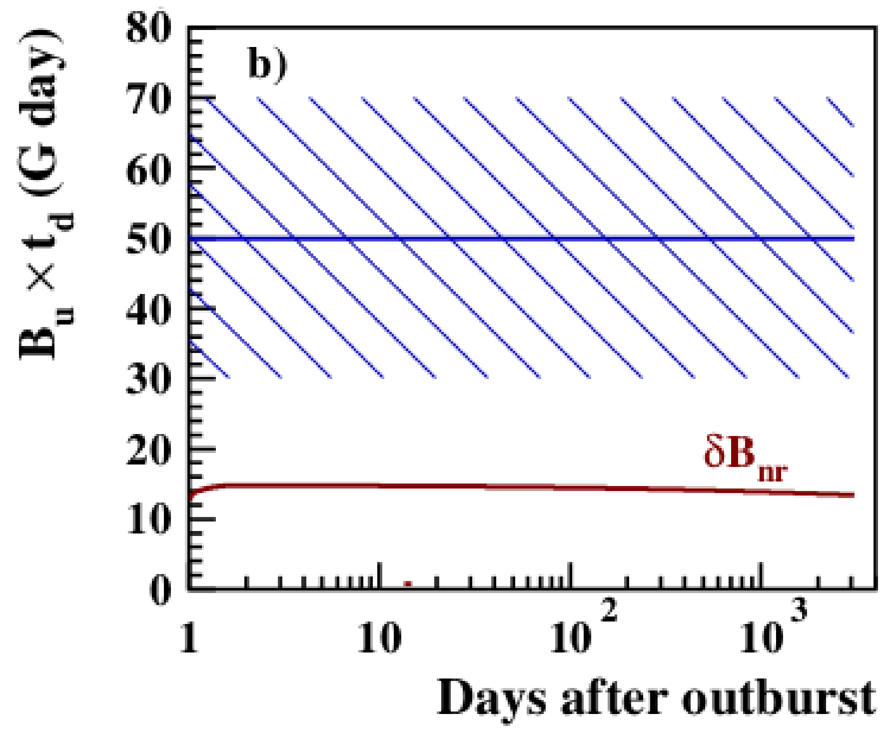
Radio SNe

Astronomy & Astrophysics manuscript no. sn1993j
February 18, 2013

Radio emission and nonlinear diffusive shock acceleration of cosmic rays in the supernova SN 1993J

V. Tatischeff





$$E_{CR} \cong \int_{t_0}^{t_f} \epsilon_{nt} \times \frac{1}{2}\rho_u V_s^3 \times 4\pi R_s^2 dt = 7.4 \times 10^{49} \text{ erg},$$

Fermi : <~ 1Mpc

Interaction-powered SNe

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Probing cosmic ray ion acceleration with radio-submm and gamma-ray emission from interaction-powered supernovae

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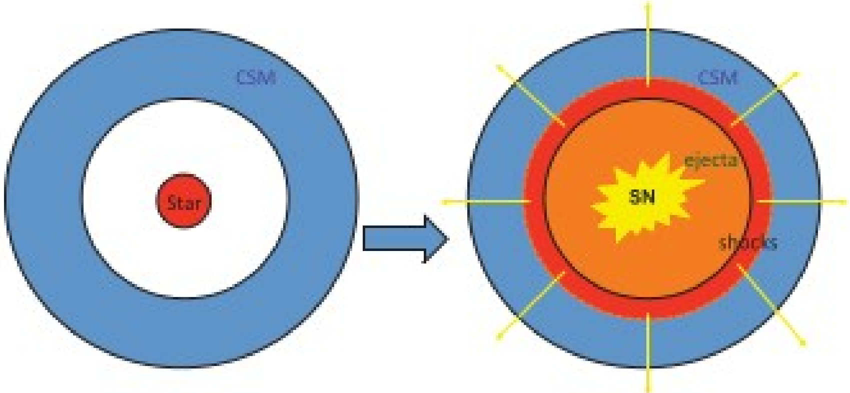

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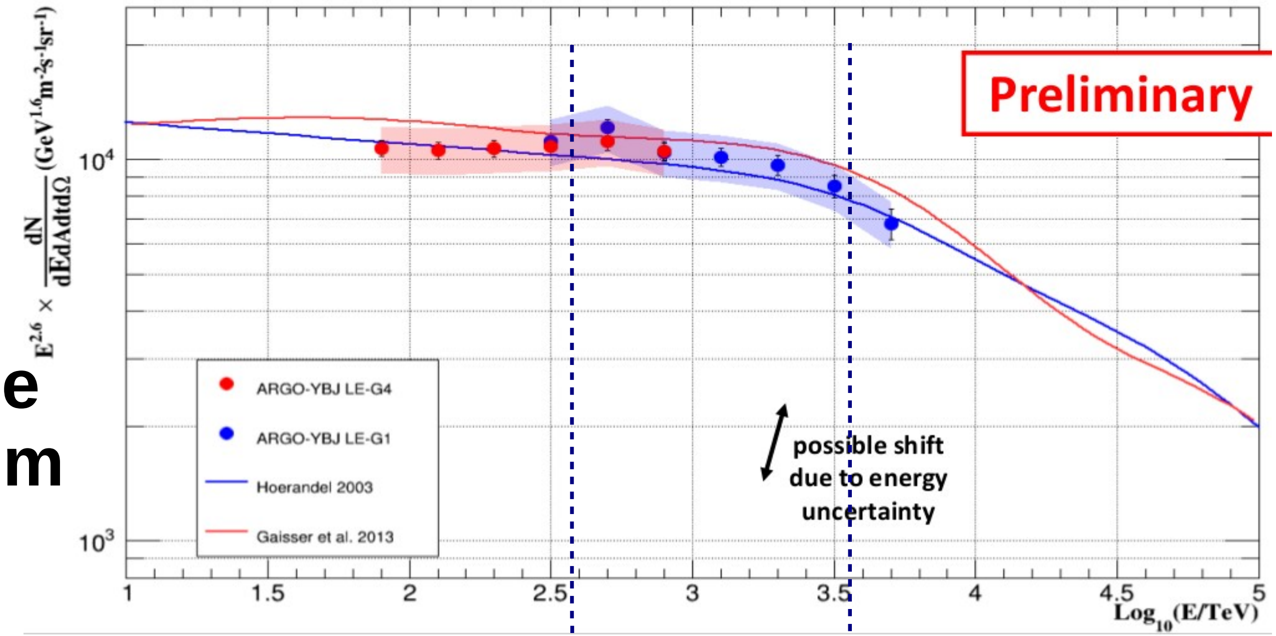
ABSTRACT

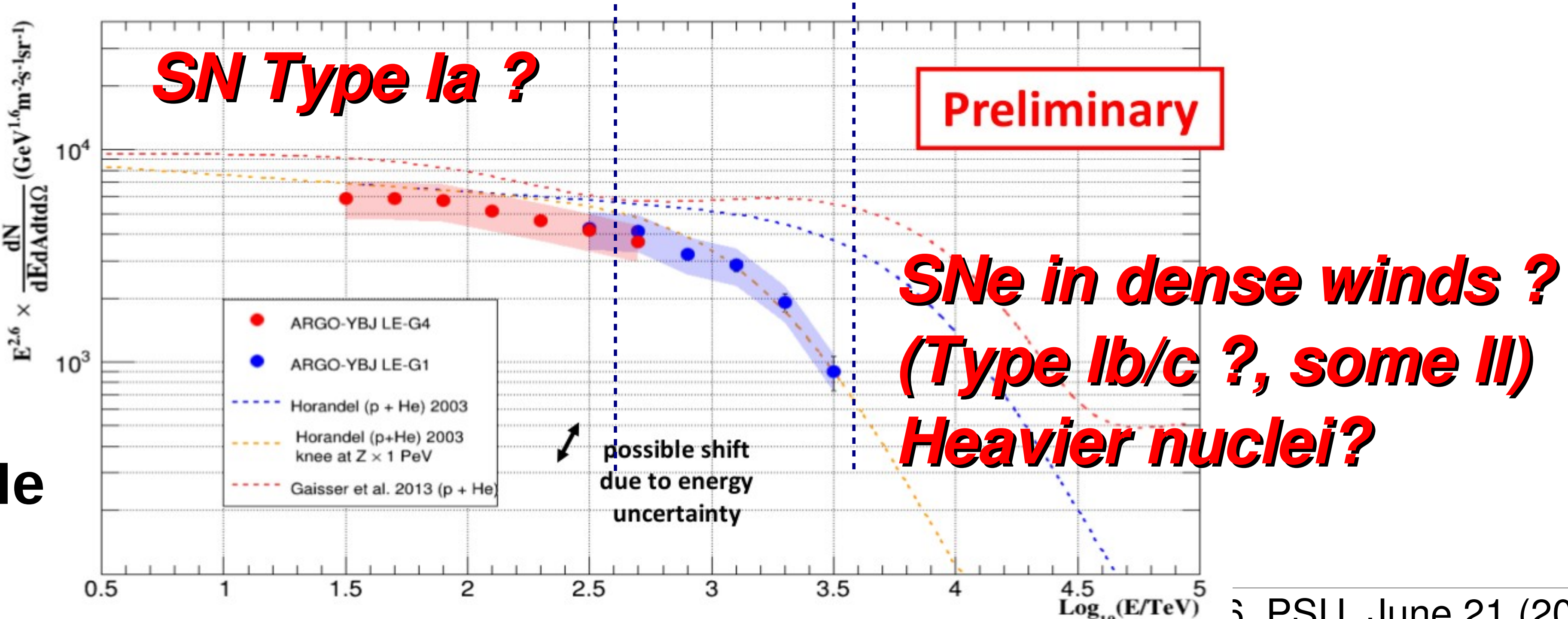
The optical and near-IR emission from some classes of supernovae (SNe), including Type IIn and possibly some super-luminous SNe, is likely powered by a collision between the SN ejecta and dense circumstellar material (CSM). We argue that for a range of CSM masses and their

ARGO-YBJ : cutoff at ~ 700 TeV

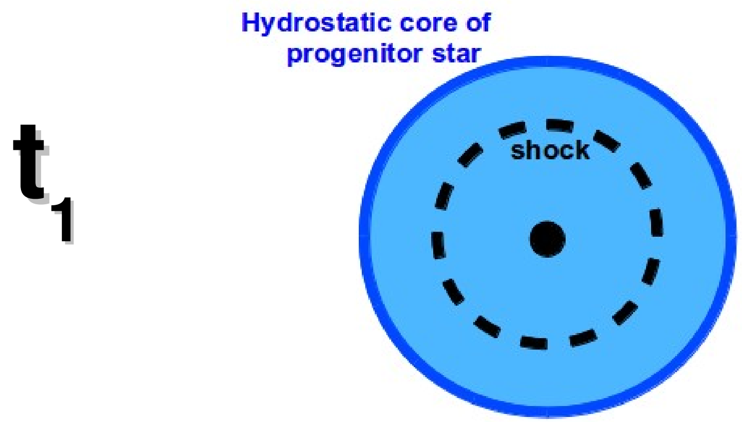
All-particle spectrum

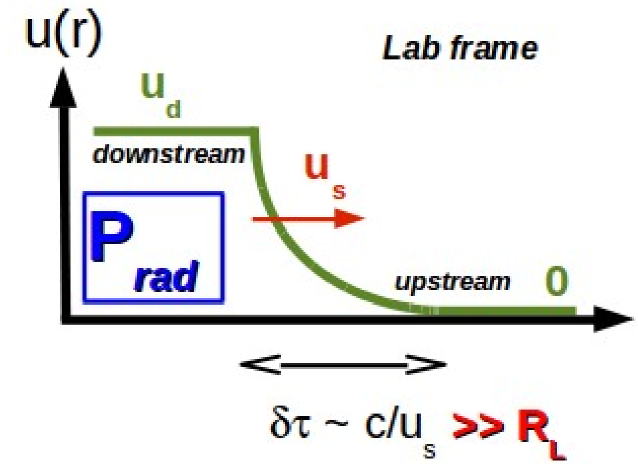


p+He



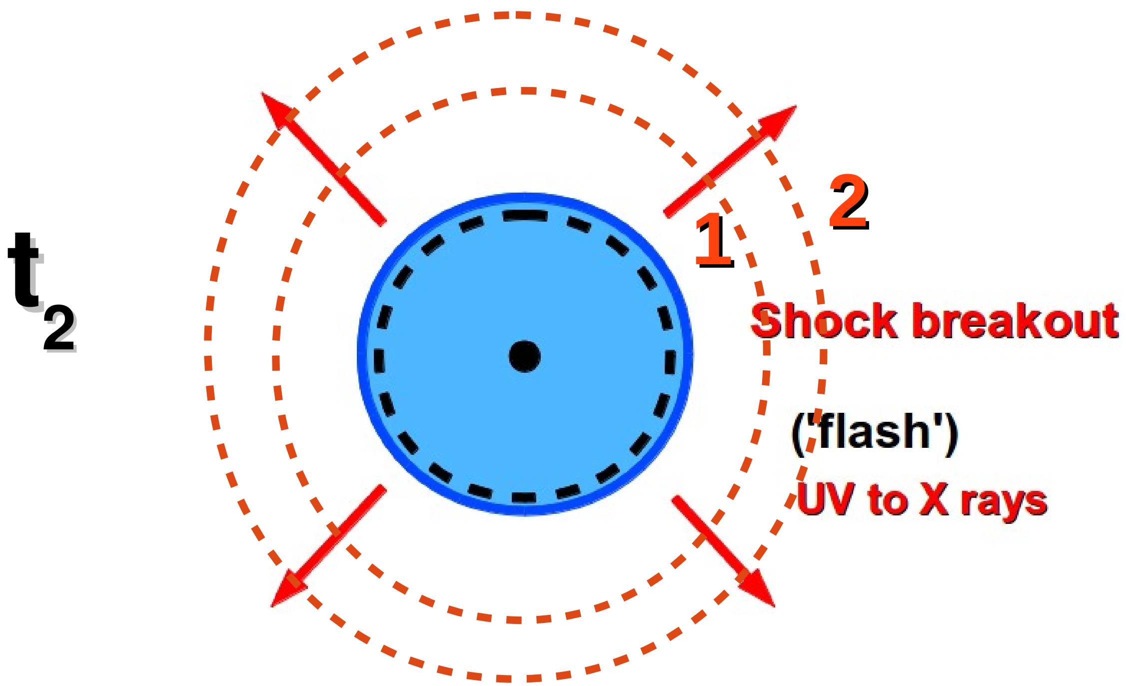
Formation of a collisionless shock

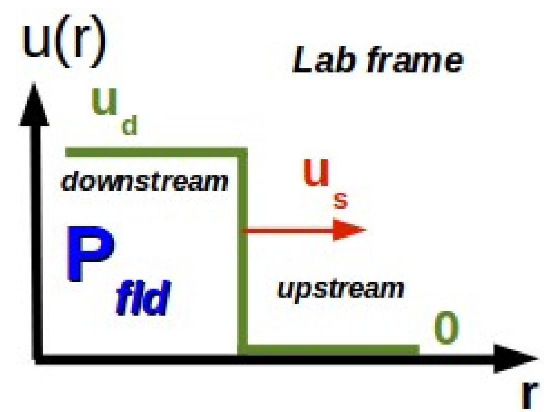




Radiation-Mediated shock

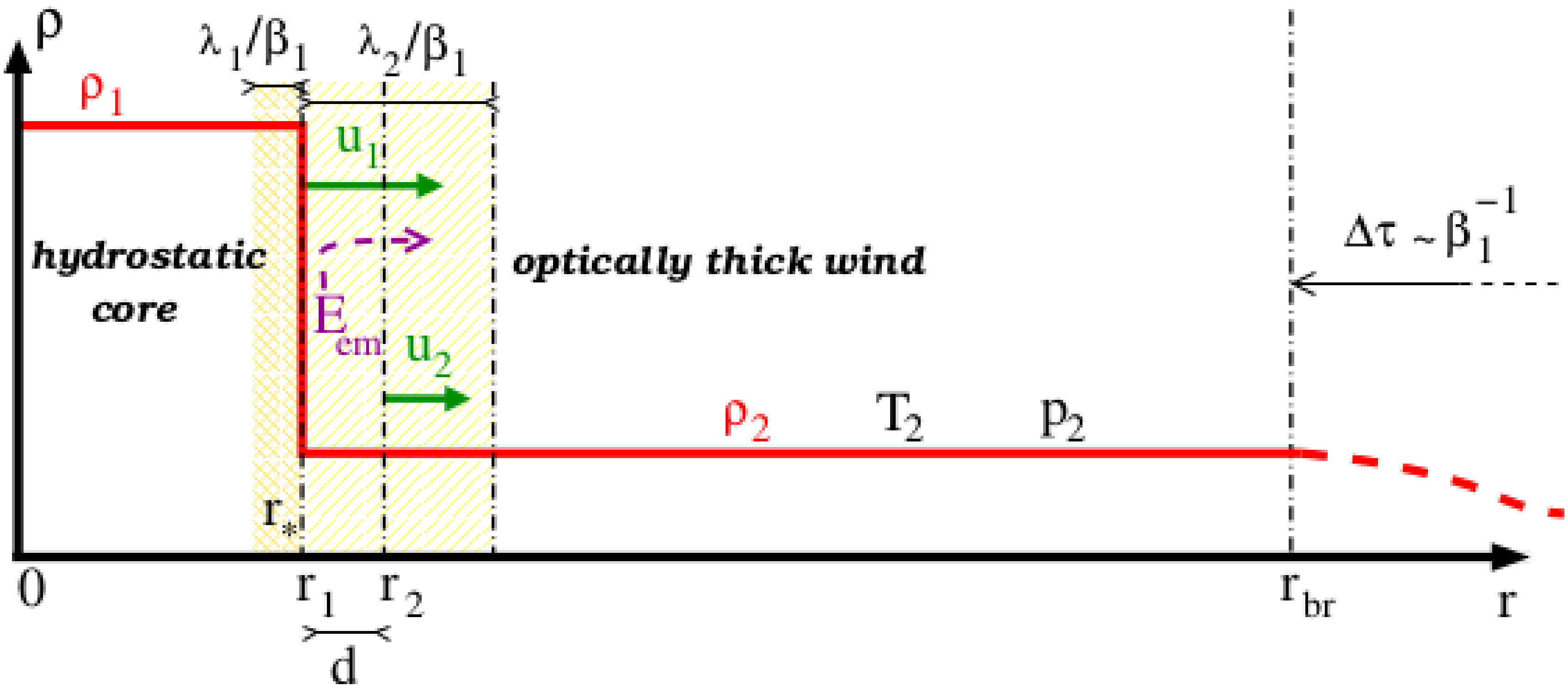
No CR acceleration





$$u_{\max,\gamma} = \kappa \int_{t_{\rm br}}^{\infty} \mathcal{F}_{\rm rad} dt/c < \kappa \int_{t_{\rm br}}^{\infty} \mathcal{L} dt/4\pi c r_{\rm i}^2 \propto r_{\rm i}^{-2}$$

($\mathcal{L}$: SN luminosity)



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

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

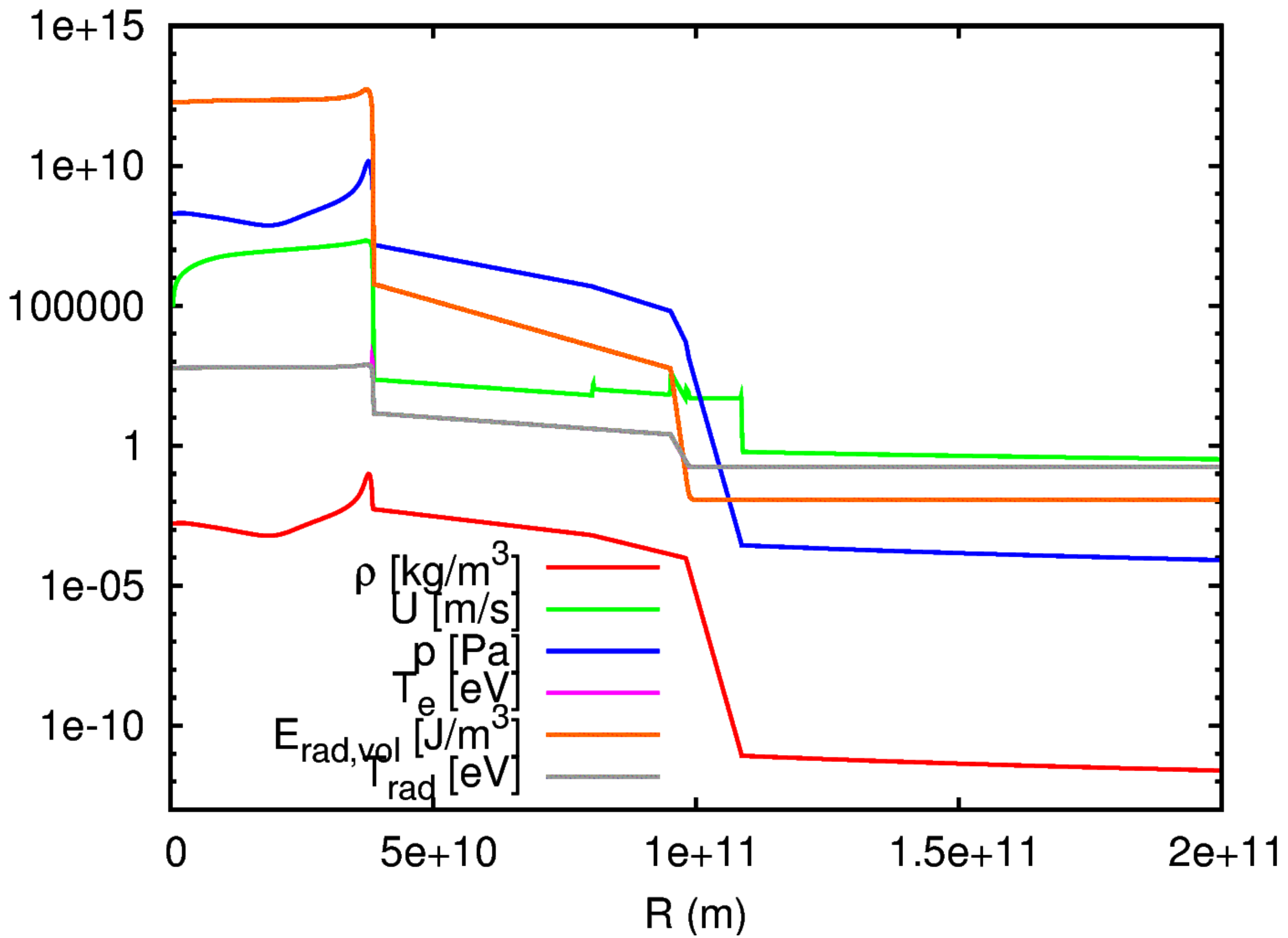
$u_2 < u_1$ ⇘

$$\beta_1 \lesssim 10\tilde{\lambda}_2 = 0.1\left(\frac{u_{\rm w}}{10\ {\rm km/s}}\right)\left(\frac{r_*}{10^{13}\ {\rm cm}}\right)\left(\frac{\dot{M}}{5\cdot 10^{-4}\ {\rm M_\odot/yr}}\right)^{-1}$$

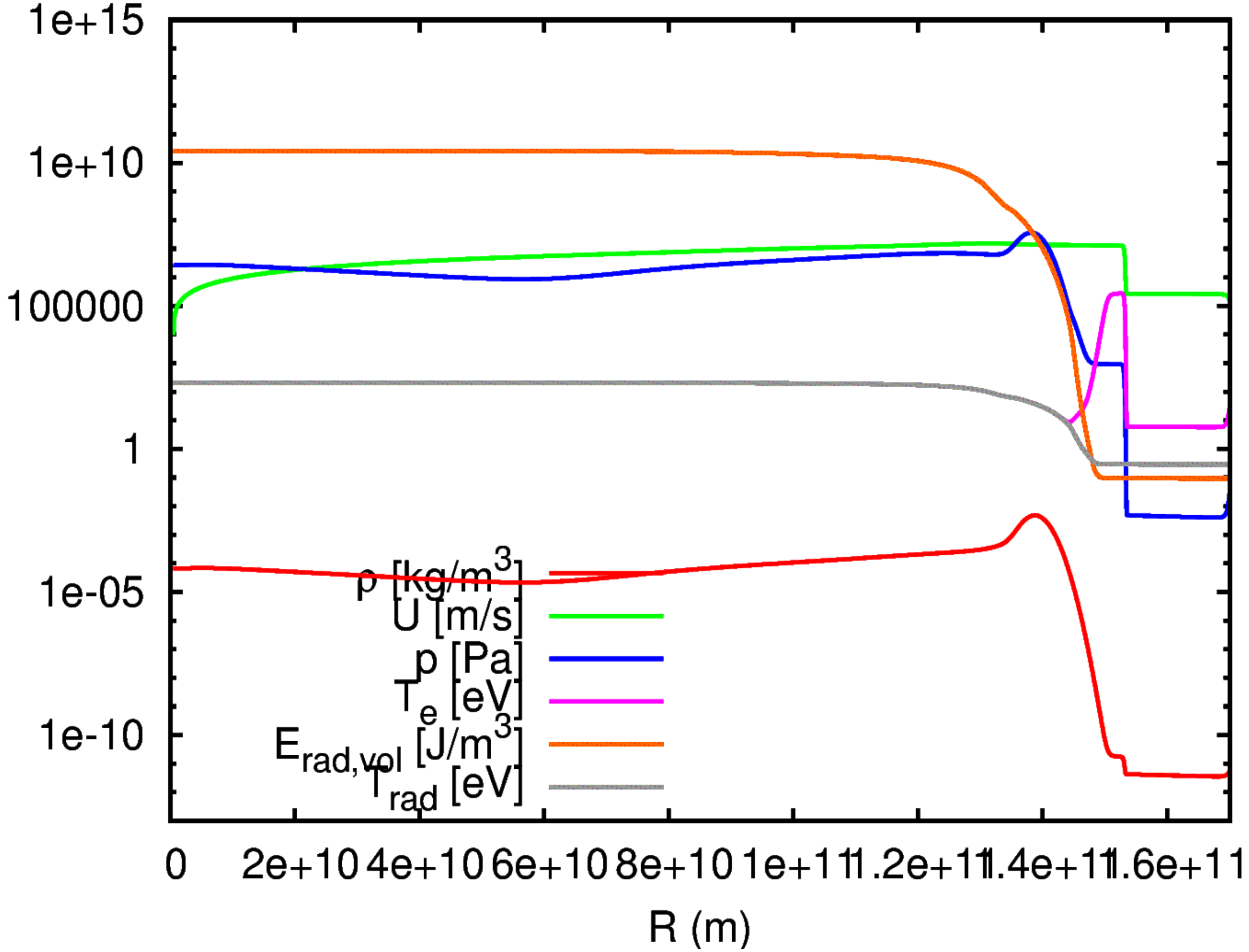
Progenitor with an optically THIN wind

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

Compton cooling + Bremsstrahlung **Thomson scattering**

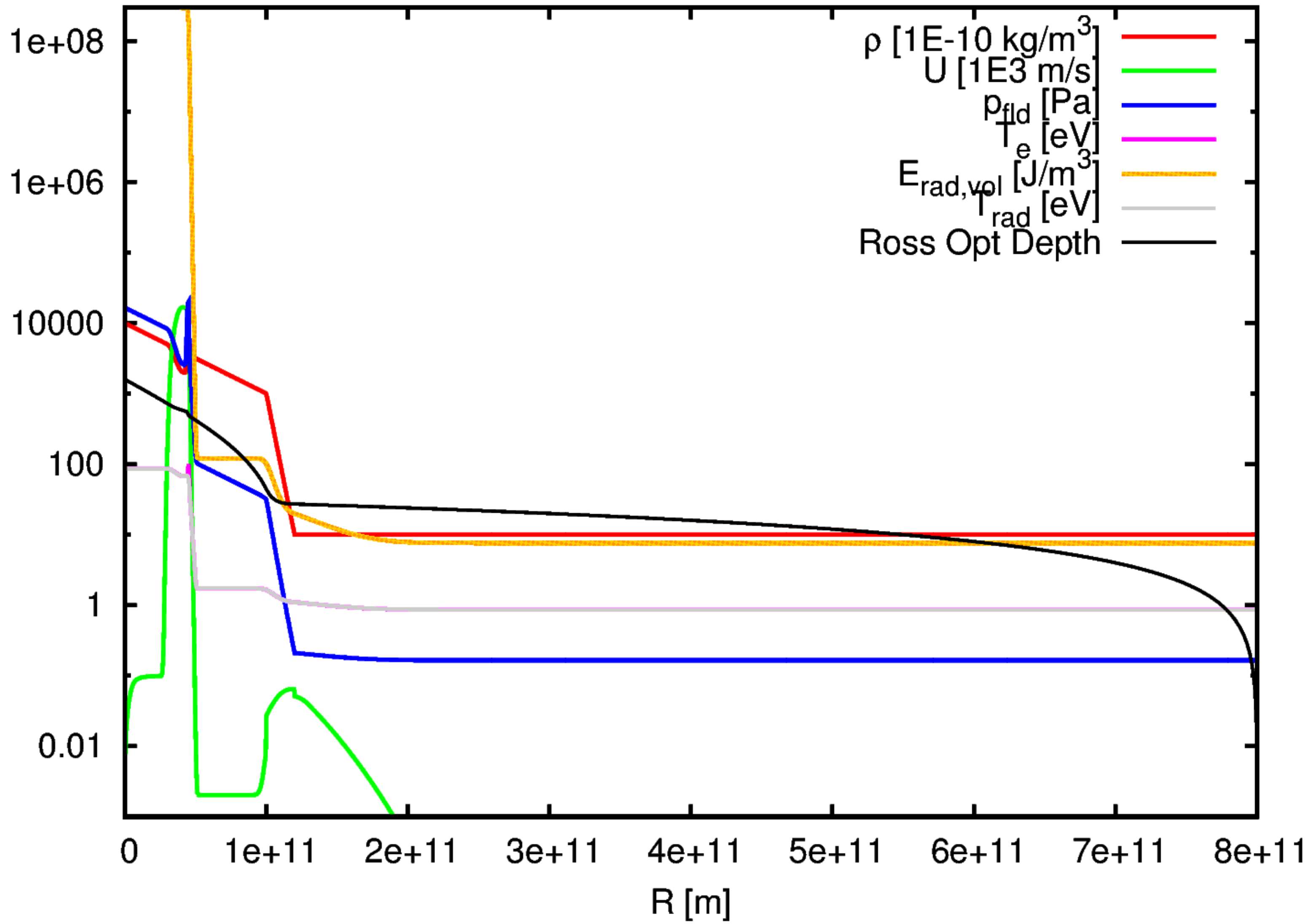


Progenitor with an optically THIN wind



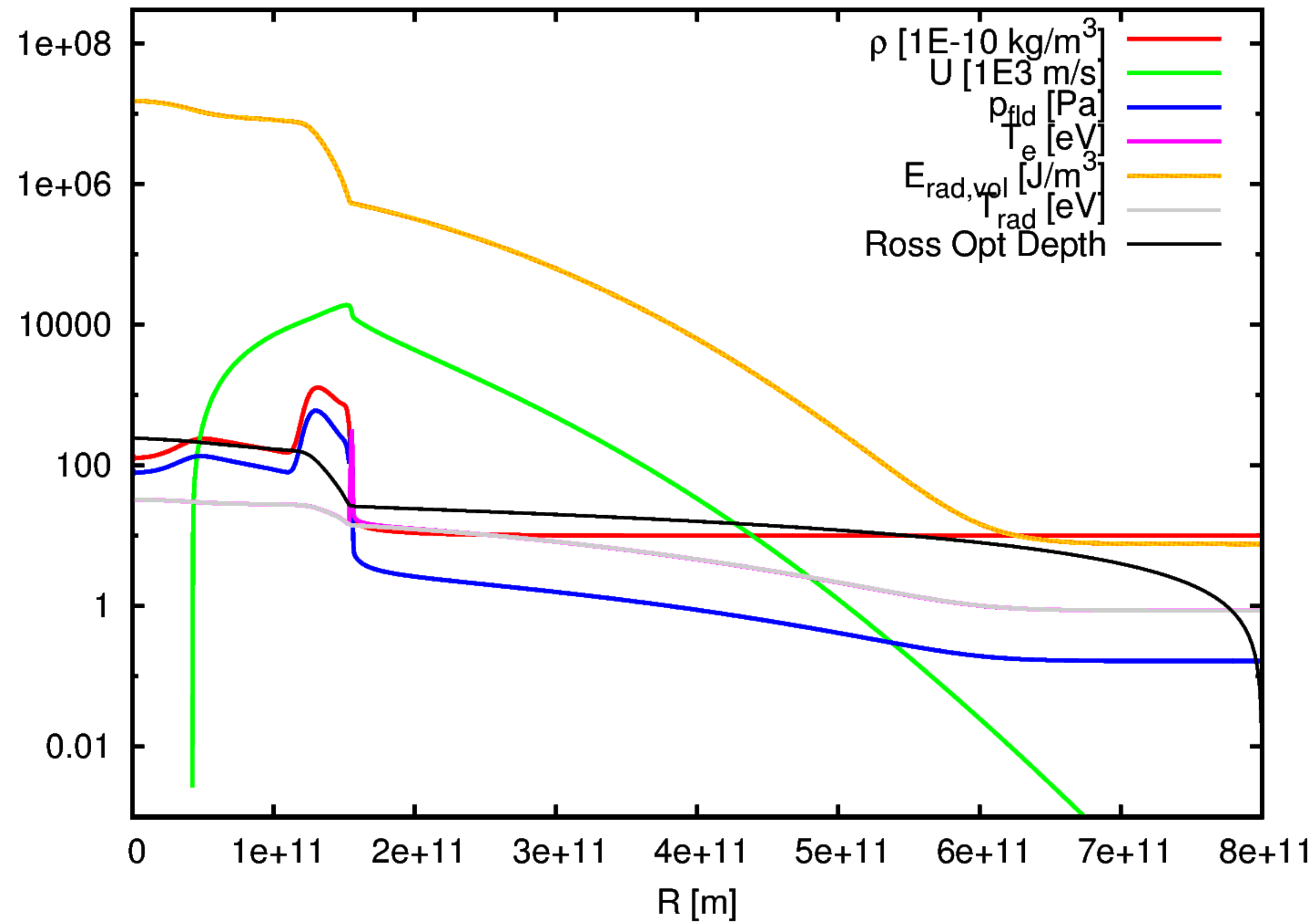
Progenitor with an optically <u>THICK</u> wind

Spherical 1D



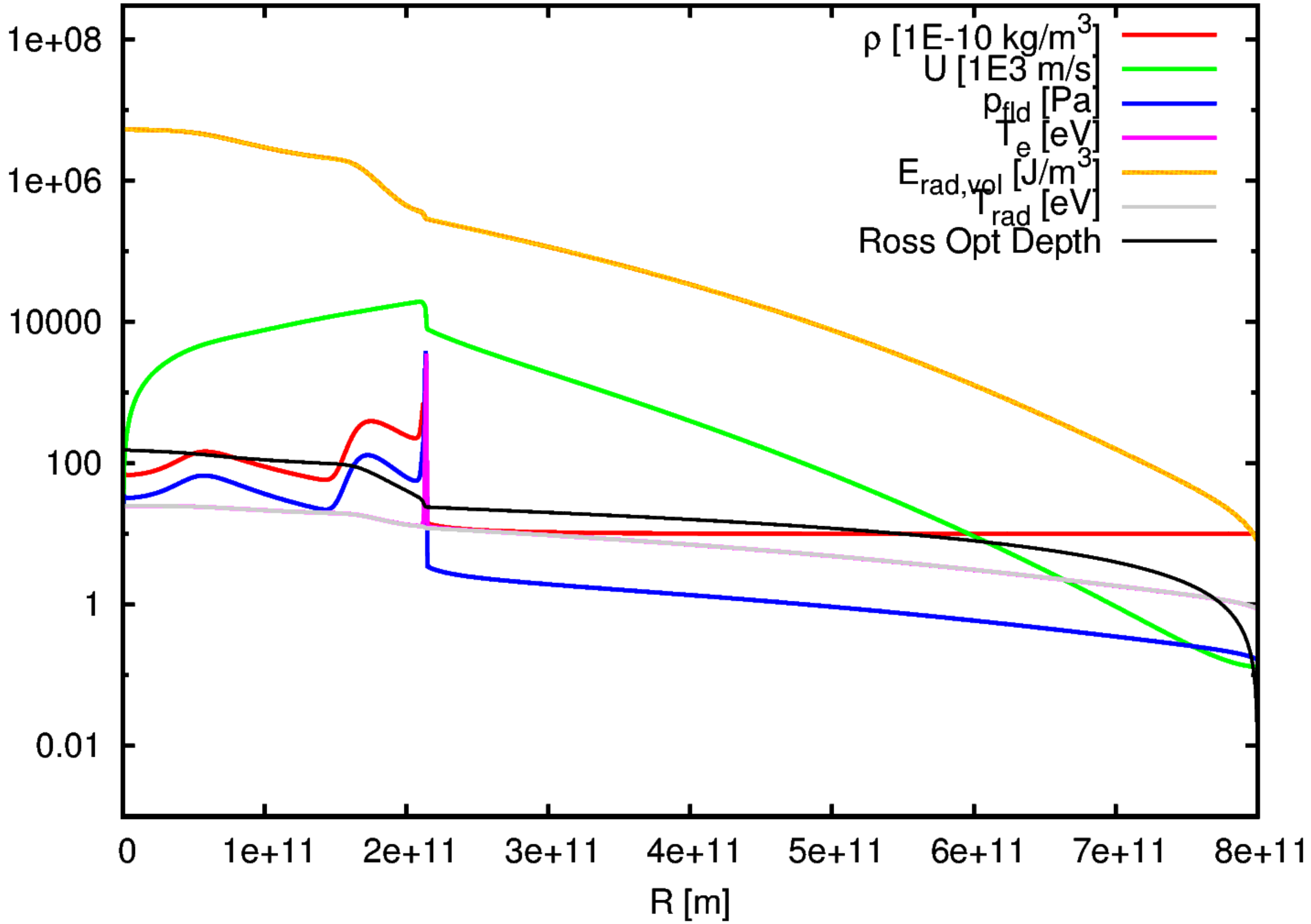
Progenitor with an optically <u>THICK</u> wind

Spherical 1D



Progenitor with an optically THICK wind

Spherical 1D



Observational consequences

- 1 – 10 TeV CRs possible before breakout :

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

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

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

(For $10\,{\rm TeV}$ CRs, $\gtrsim 10\,{\rm keV}$)

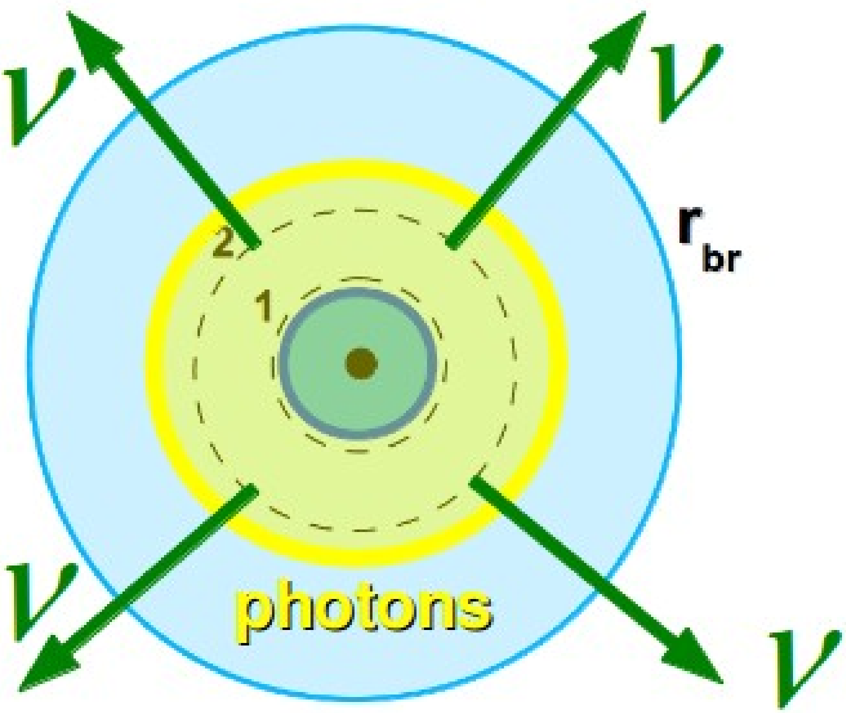
$\gtrsim (1-10)$ TeV CRs should be produced

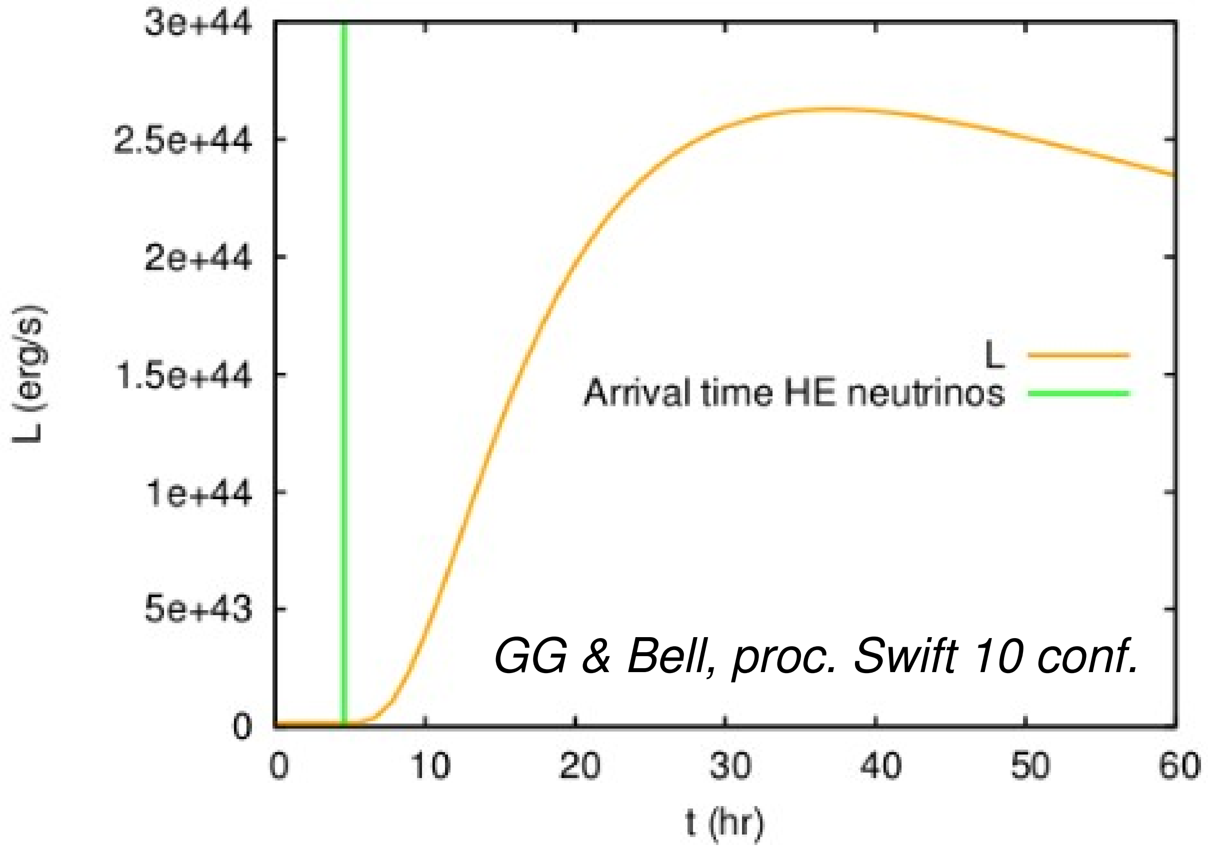
Observational consequences

(1)

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, $10^{-5}\,M_\odot$ processed at r < r_{br}).

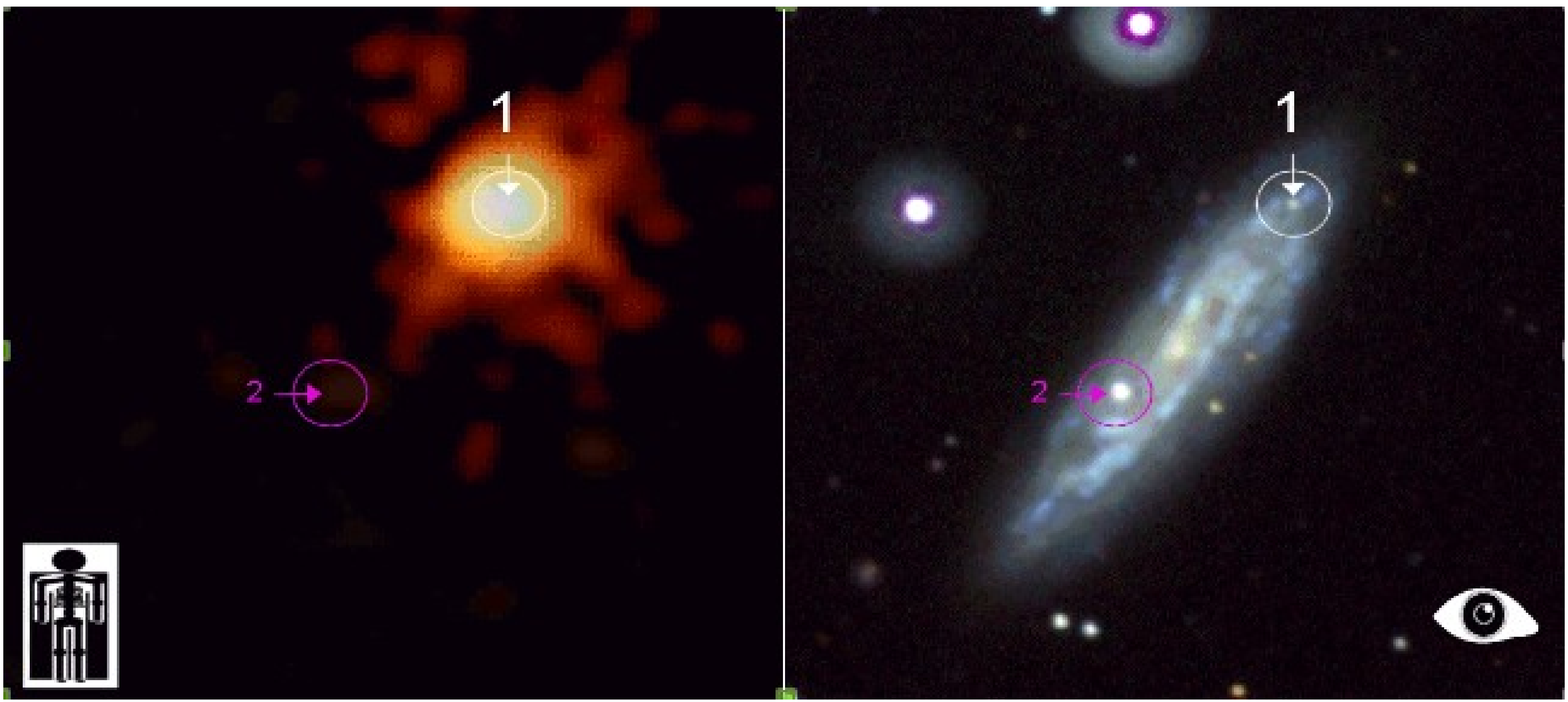




(2) X-Ray Flash

If one uses the parameters of Svirski & Nakar, ApJL (2014)…

SN 2008D / XRF 080109 may have been an event in which a CS is formed before SB



Conclusions and perspectives

- Tight link between CR Escape / E_{max} / MF amplification
- Type Ia fall short of reaching the knee
- First few decades of SNe in dense winds promising to reach knee and beyond
- First few decades of SNe in dense winds very promising
  -> Need to search for HE neutrino / (LE) γ-rays from SNe

- Optically thick winds : CS can form ***before*** breakout
- Observational consequences :
  - X-ray flashes
  - E > 100 GeV neutrinos → Probe of the poorly known optically thick regions of circumstellar winds