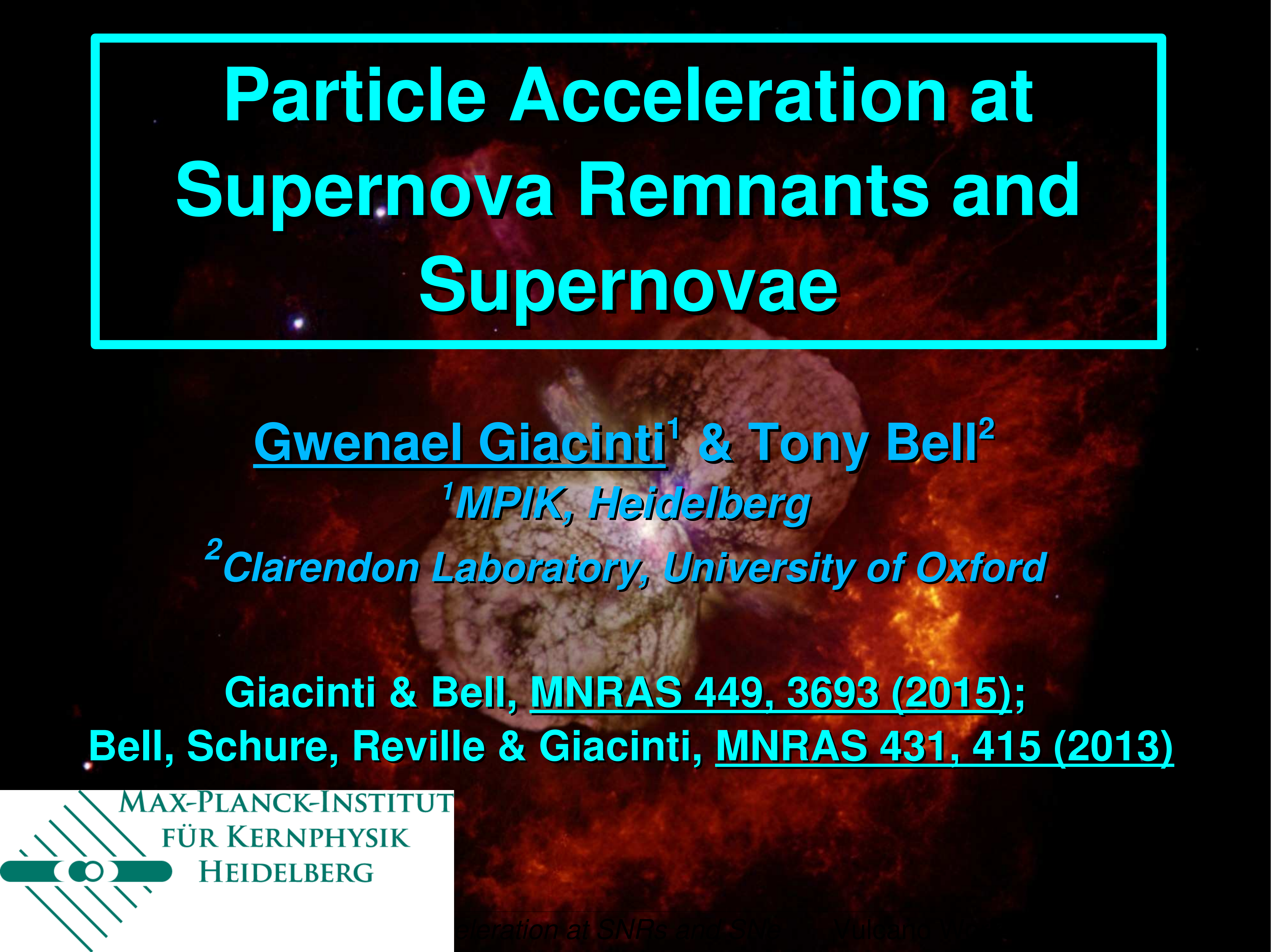

Particle Acceleration at Supernova Remnants and Supernovae

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

[1]MPIK, Heidelberg

[2]Clarendon Laboratory, University of Oxford

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

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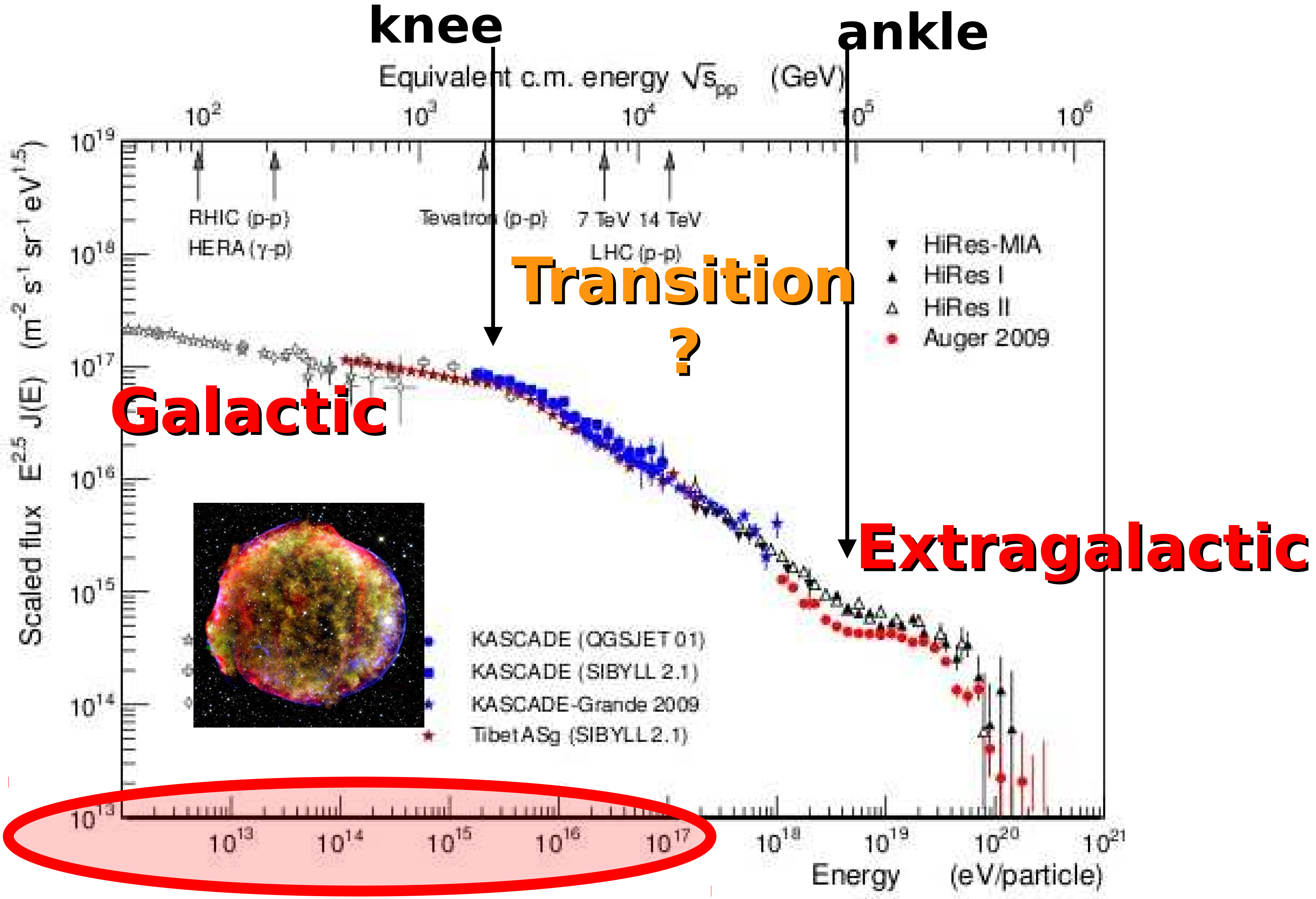
Cosmic ray spectrum



knee

ankle

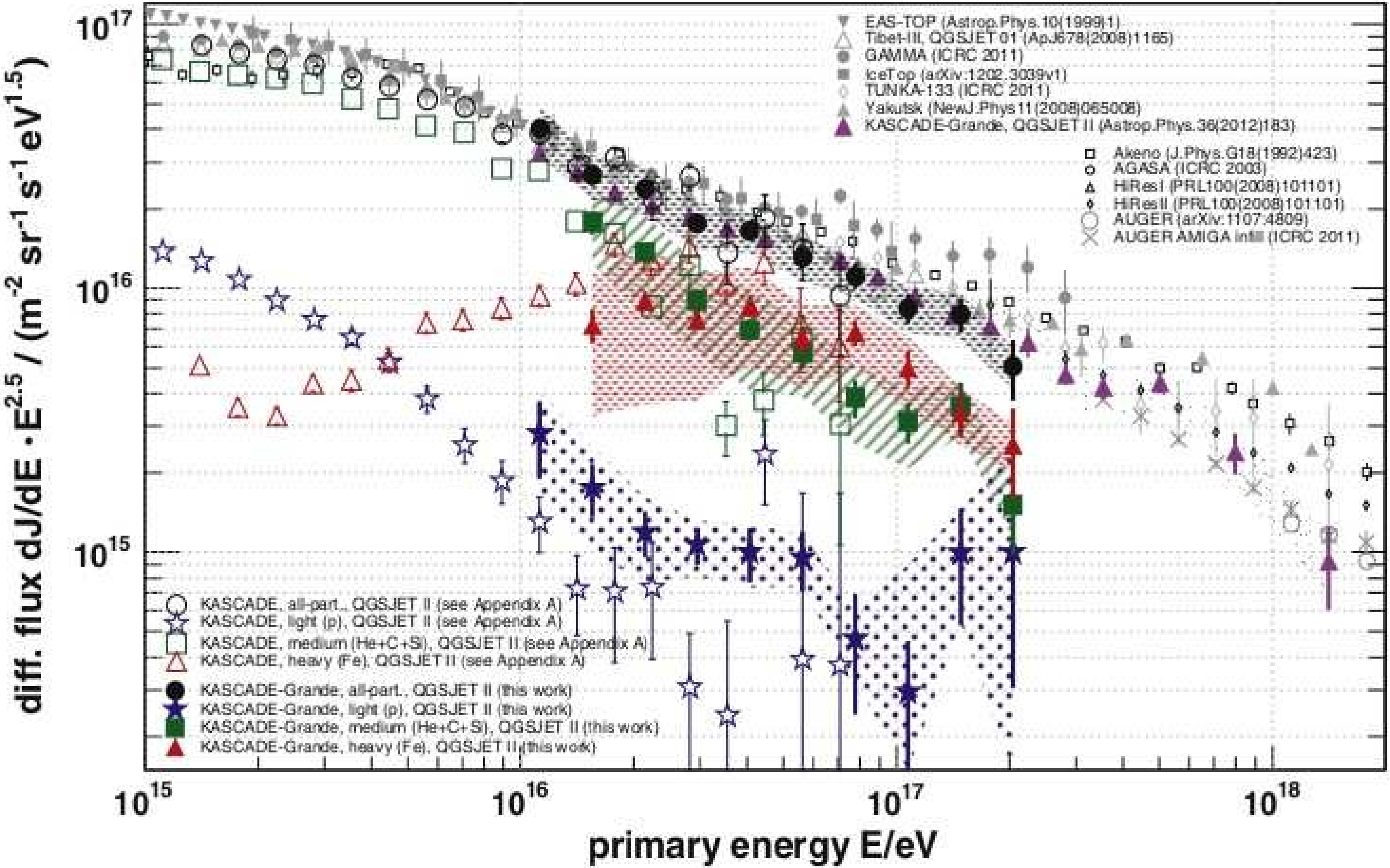
Transition ?

Galactic

Extragalactic

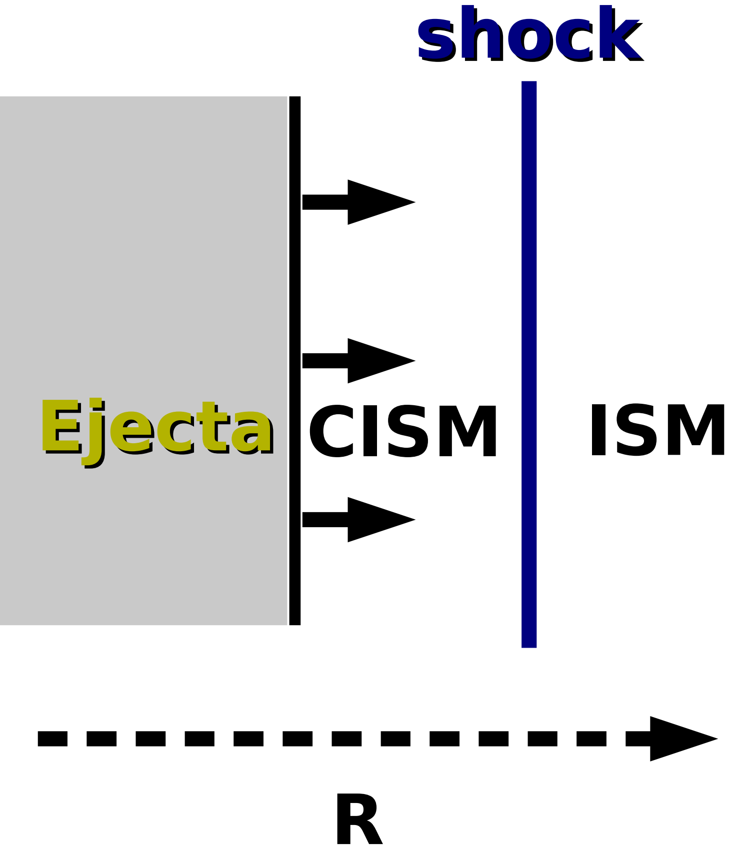
CR spectrum and knee

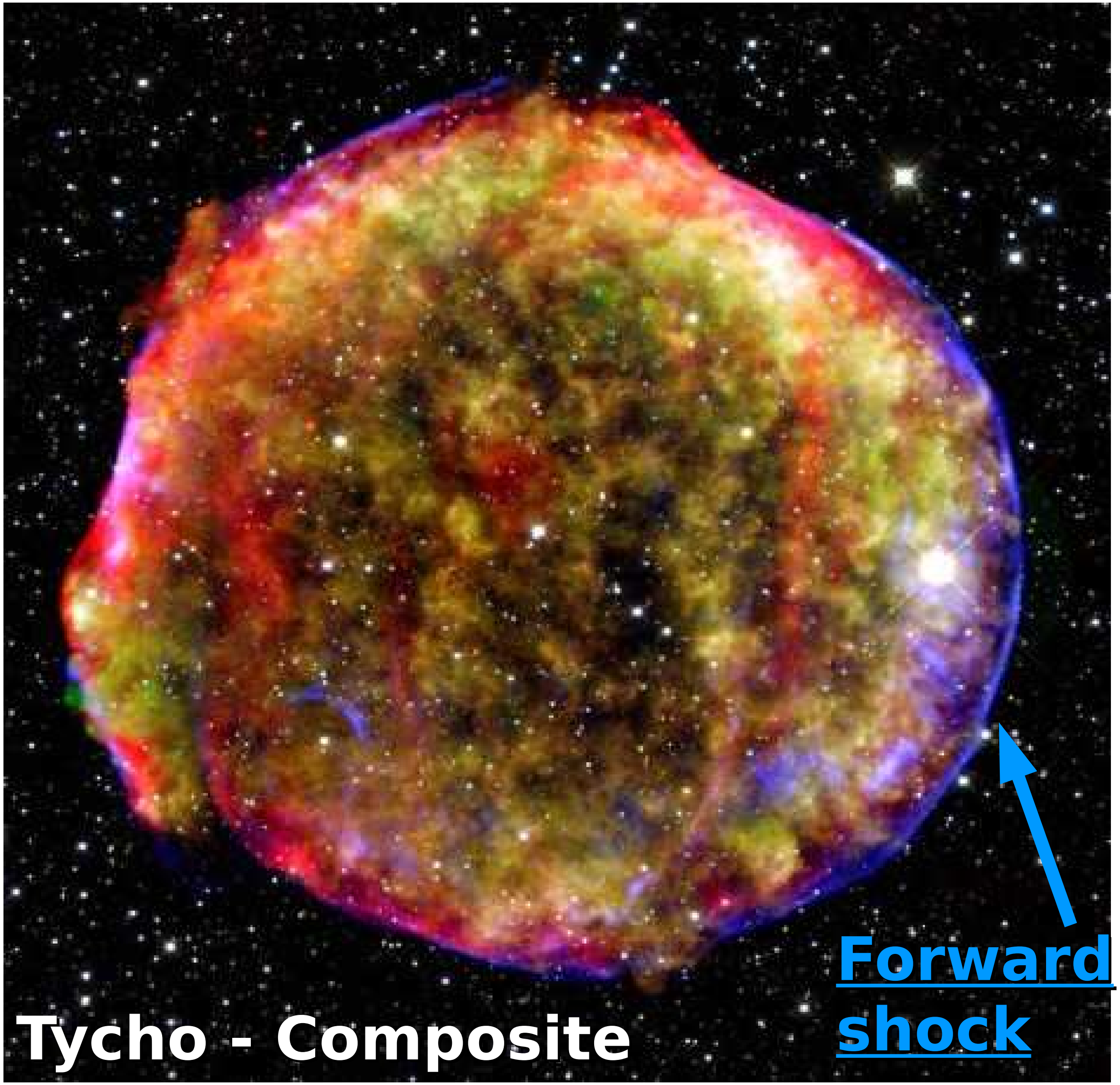
W.D. Apel et al. / Astroparticle Physics 47 (2013) 54–66



Sources, acceleration mechanism

Supernova remnants

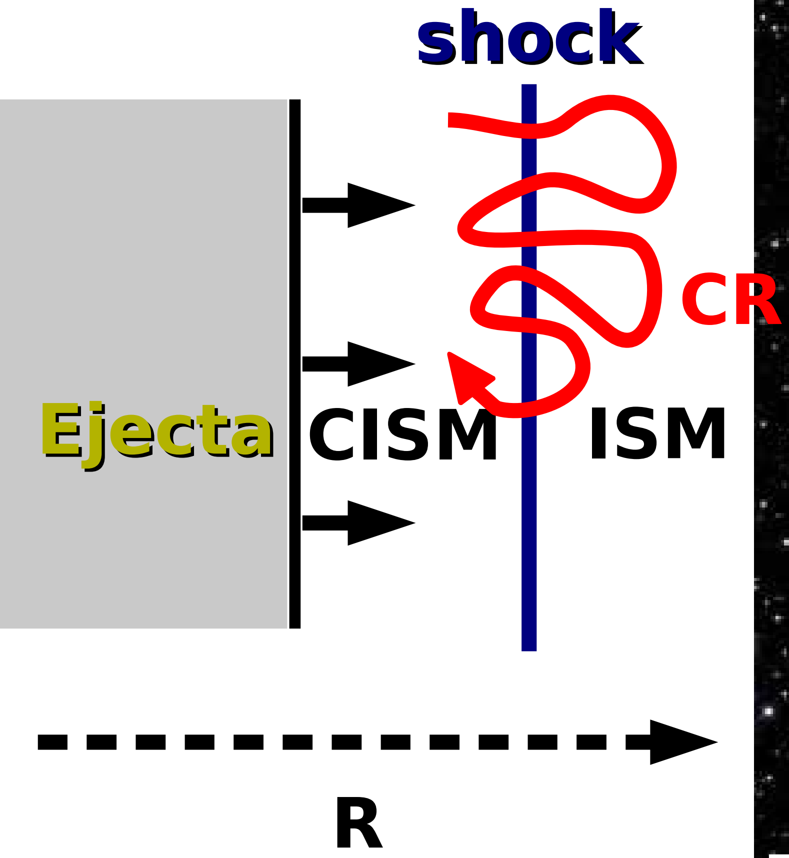


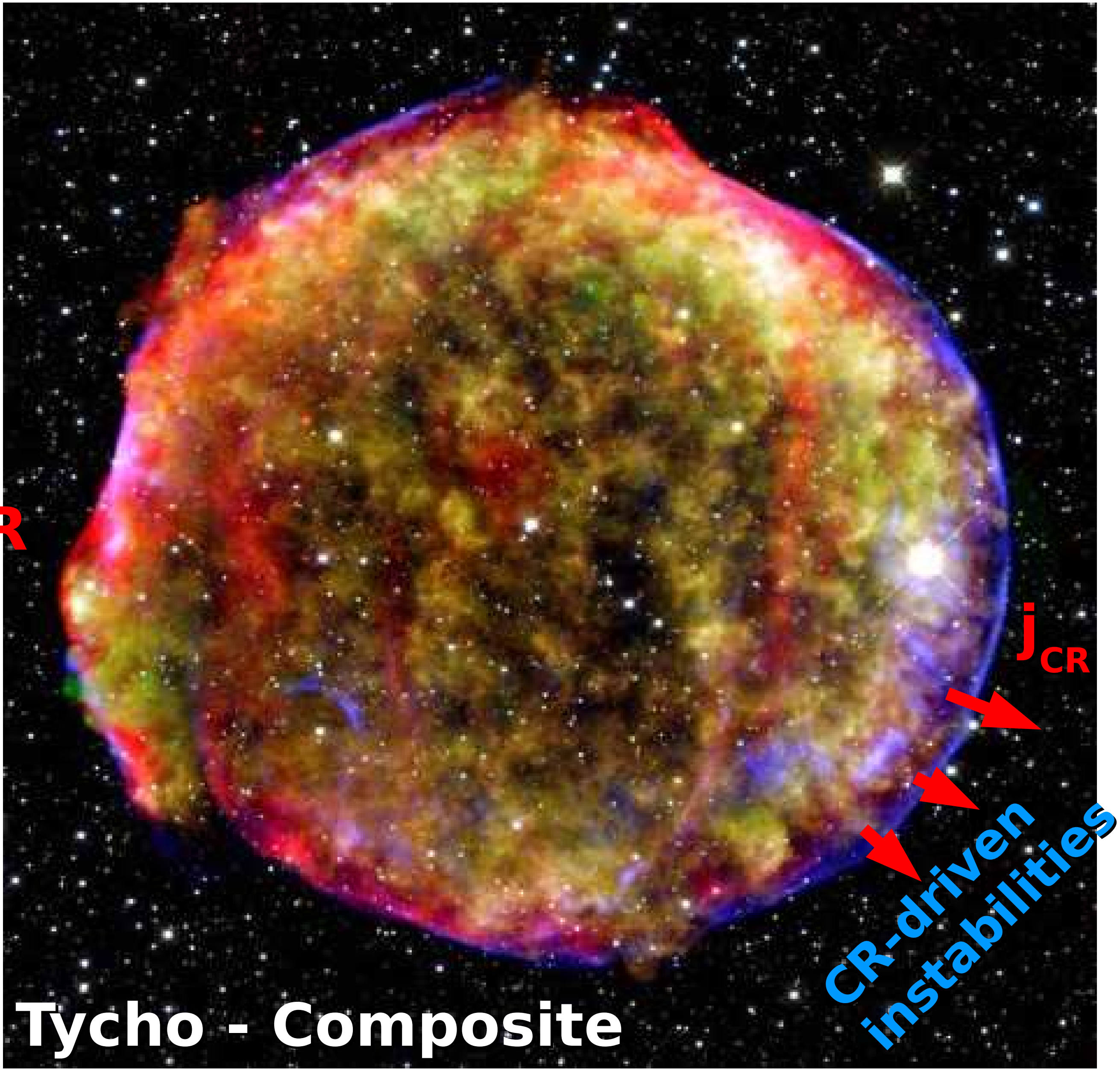


Tycho - Composite

Sources, acceleration mechanism

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





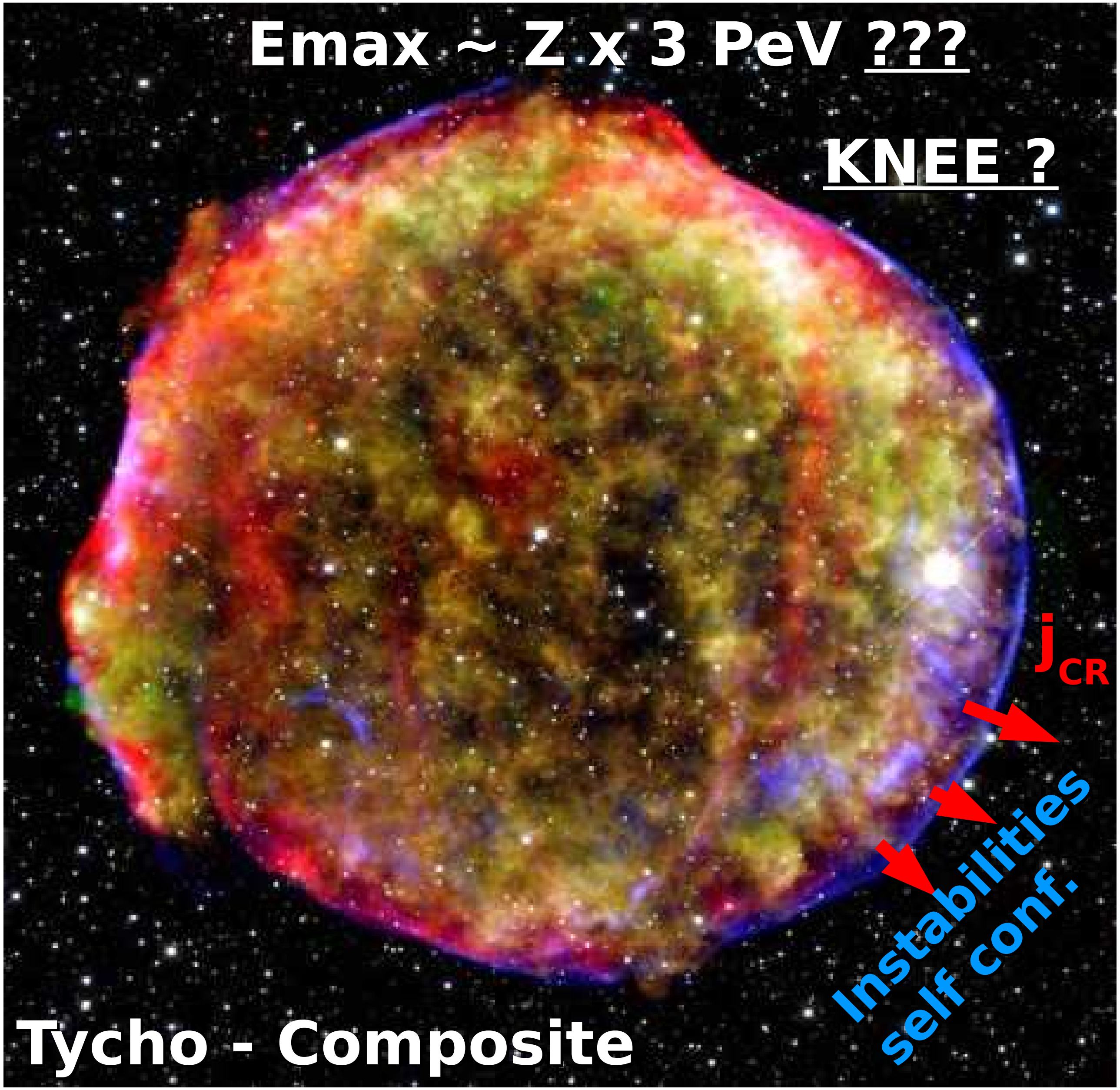
Sources, acceleration mechanism

Diffusive shock acceleration (Bell '78)

- E_{max} vs t : PeV ? When ?

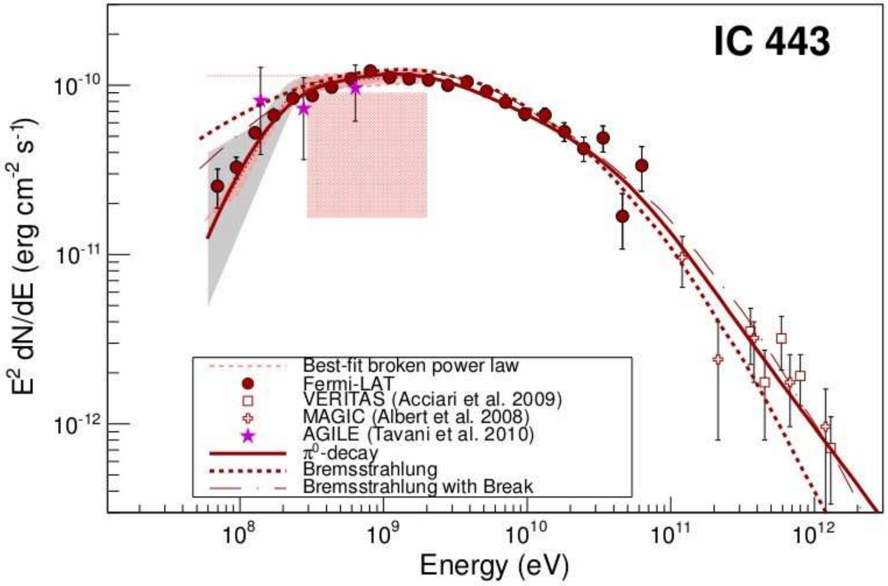
- How do CRs escape SNRs ?

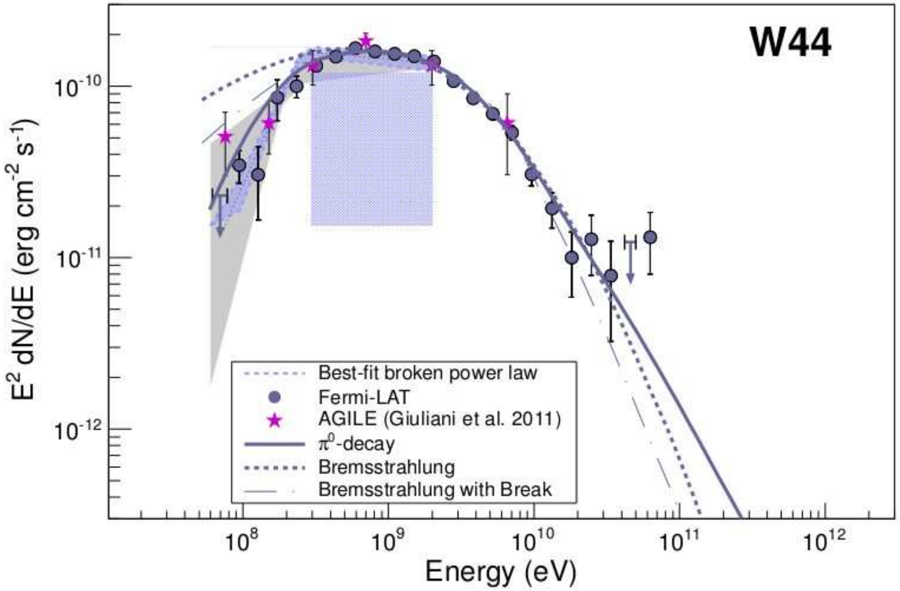
- Instabilities: Time to grow, MF amplification, ...

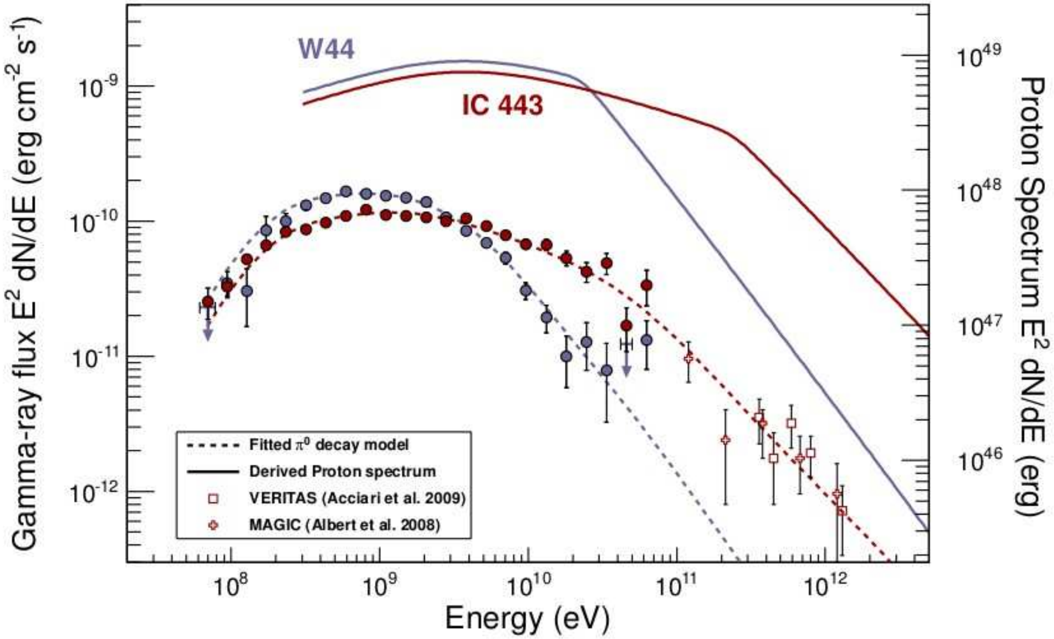


Pion bump

Fermi-LAT collaboration, Science **339,** 807 (2013)







… But 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

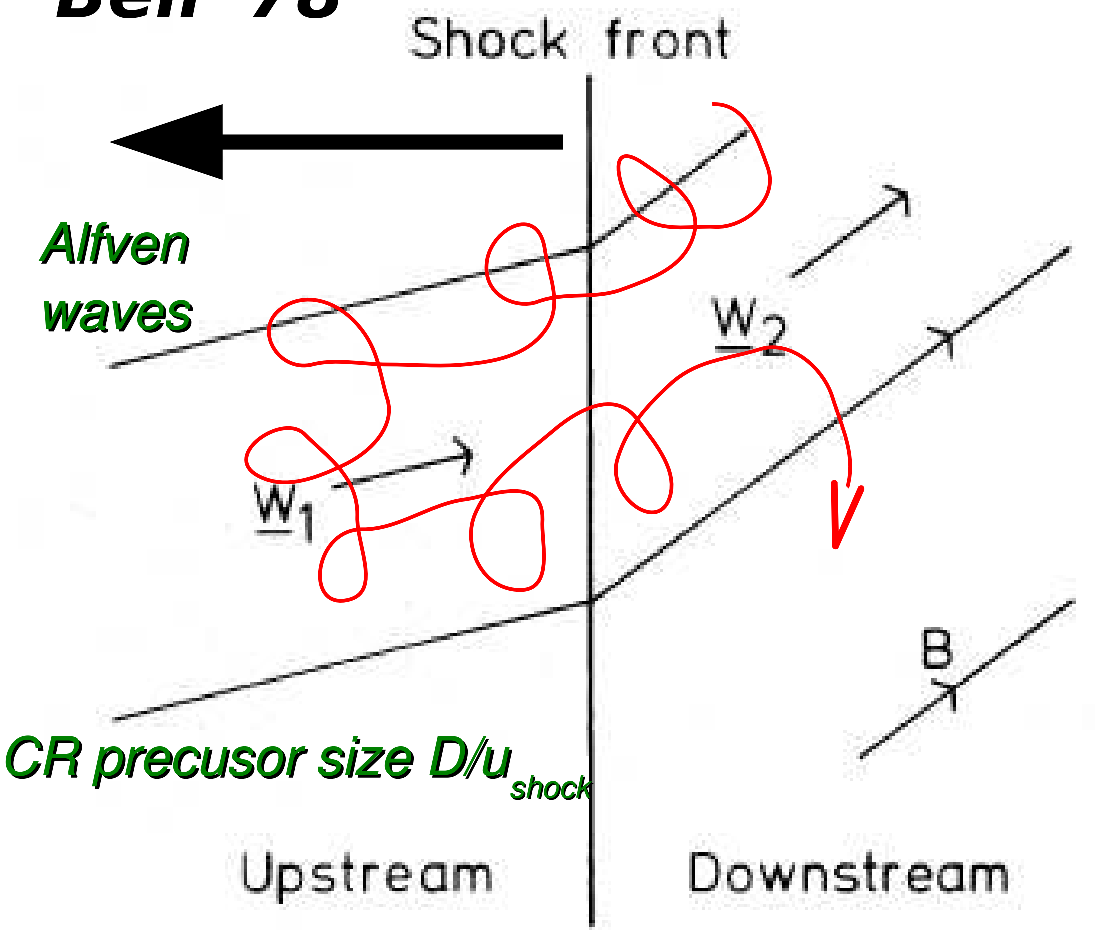
III – Particle Acceleration BEFORE SN Shock Breakout

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

Sources, acceleration mechanism

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

Bell '78



Alfven waves

CR precusor size D/u_{shock}

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

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}

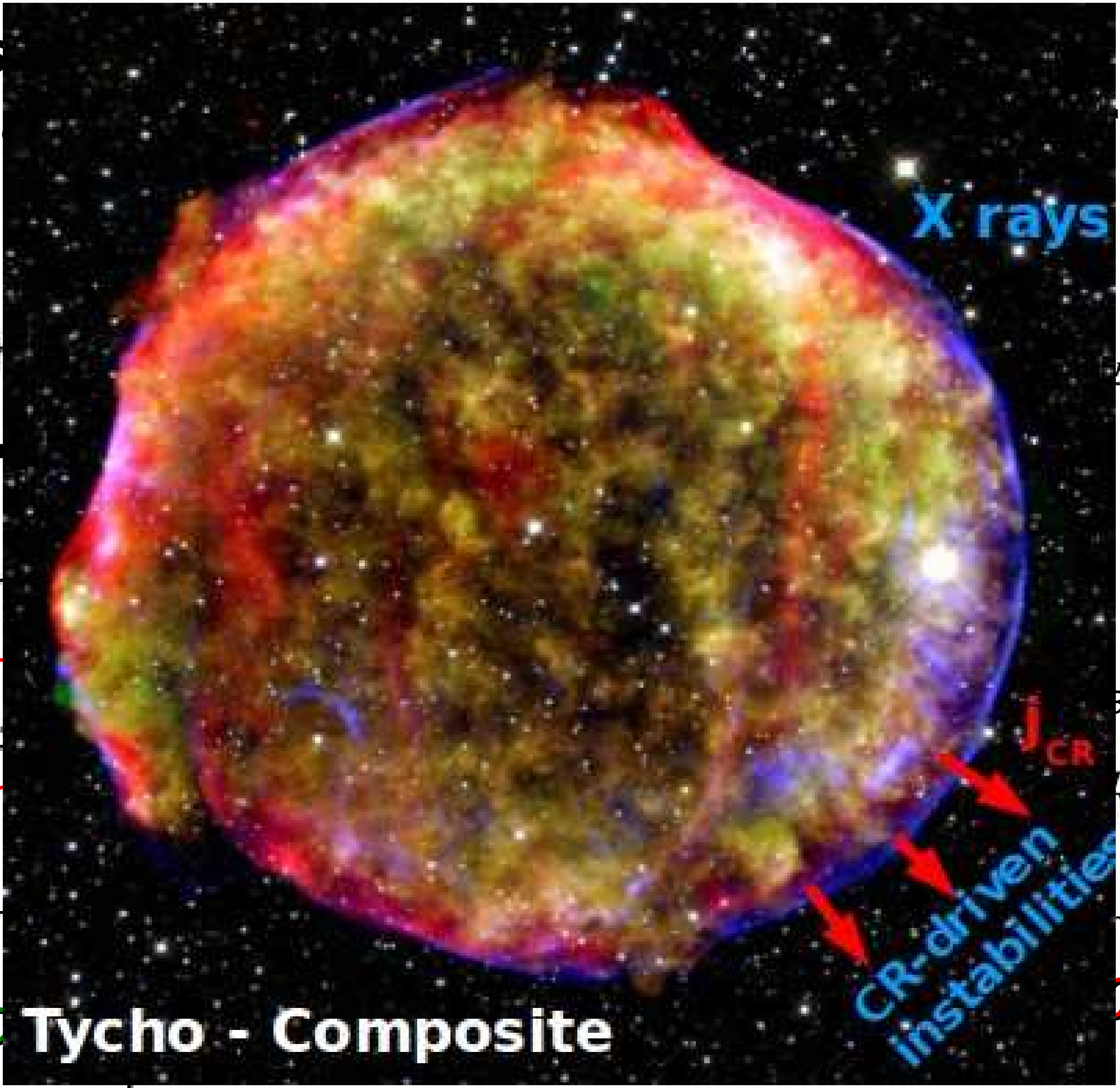
=> E_{max} ~ 10 TeV !!!

= > Need for MF amplification

Sources, acceleration mechanism

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

Bell '78



$$\frac{nstream}{/4)^2} \approx \frac{8D_{upstream}}{u^2_{shock}}$$

$\tau = R/u_{shock}$

$_{Bohm} = cR_g/3$

R

$_{hock}$ ~ 5000 km s^{-1}

0 TeV !!!

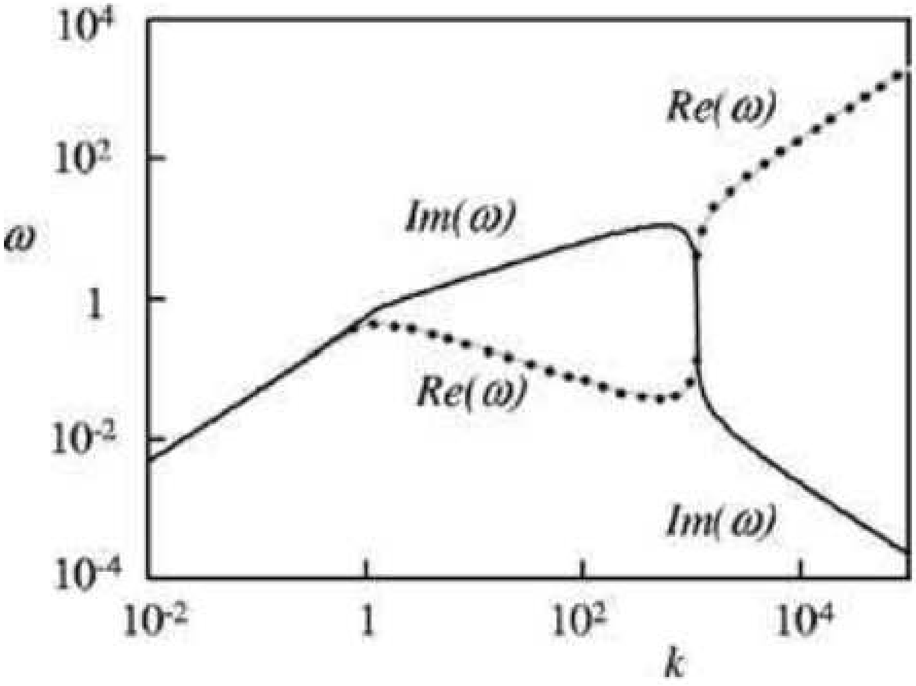
= > Need for MF amplification

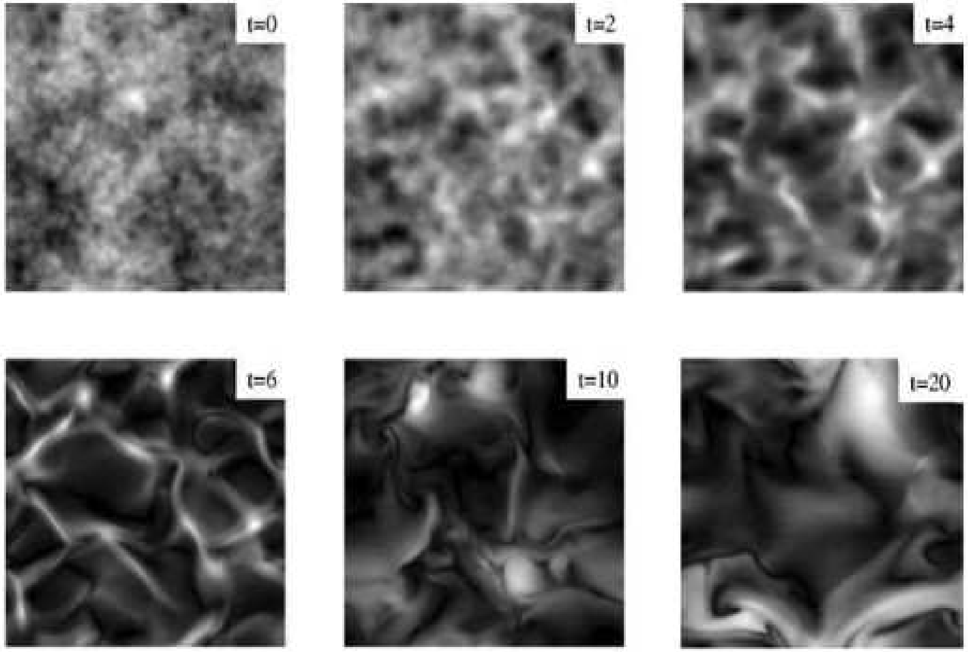
NRH instability (Bell '04)

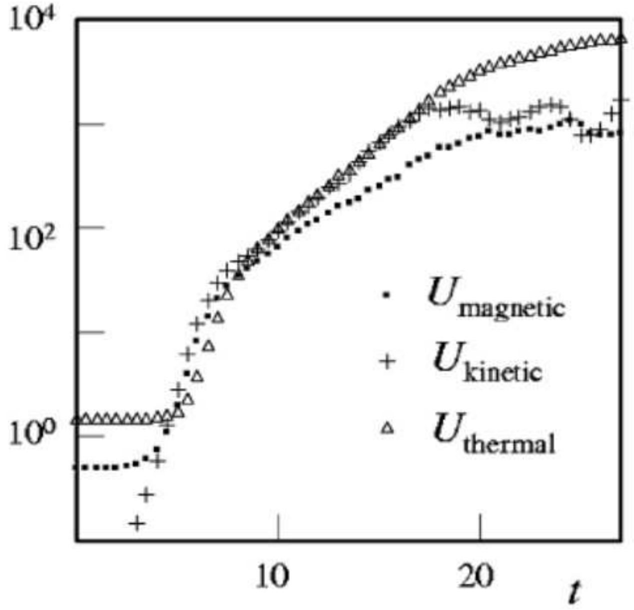
Large CR current densities : Non-resonant hybrid instability

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

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

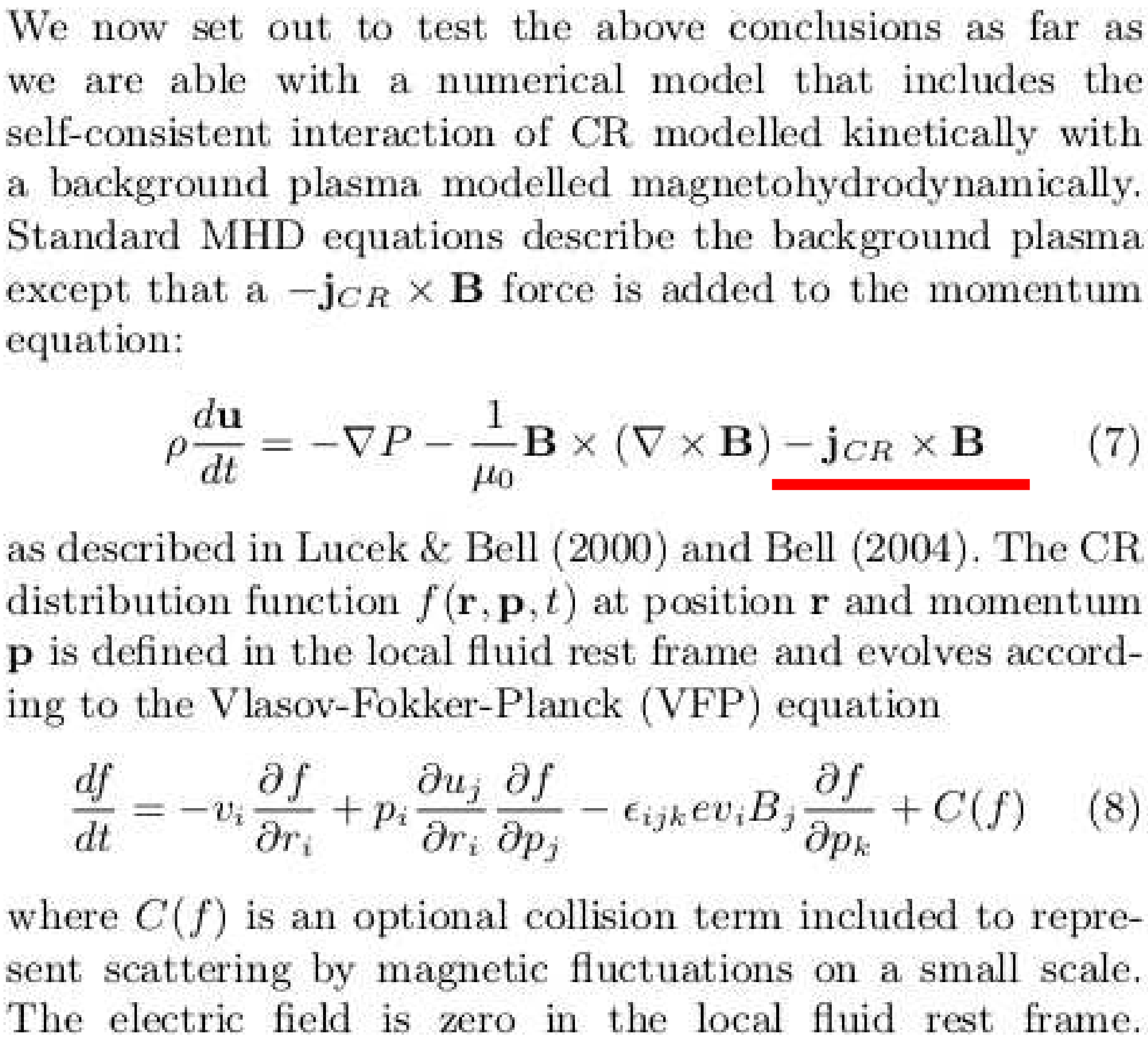






CR acceleration and escape

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

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

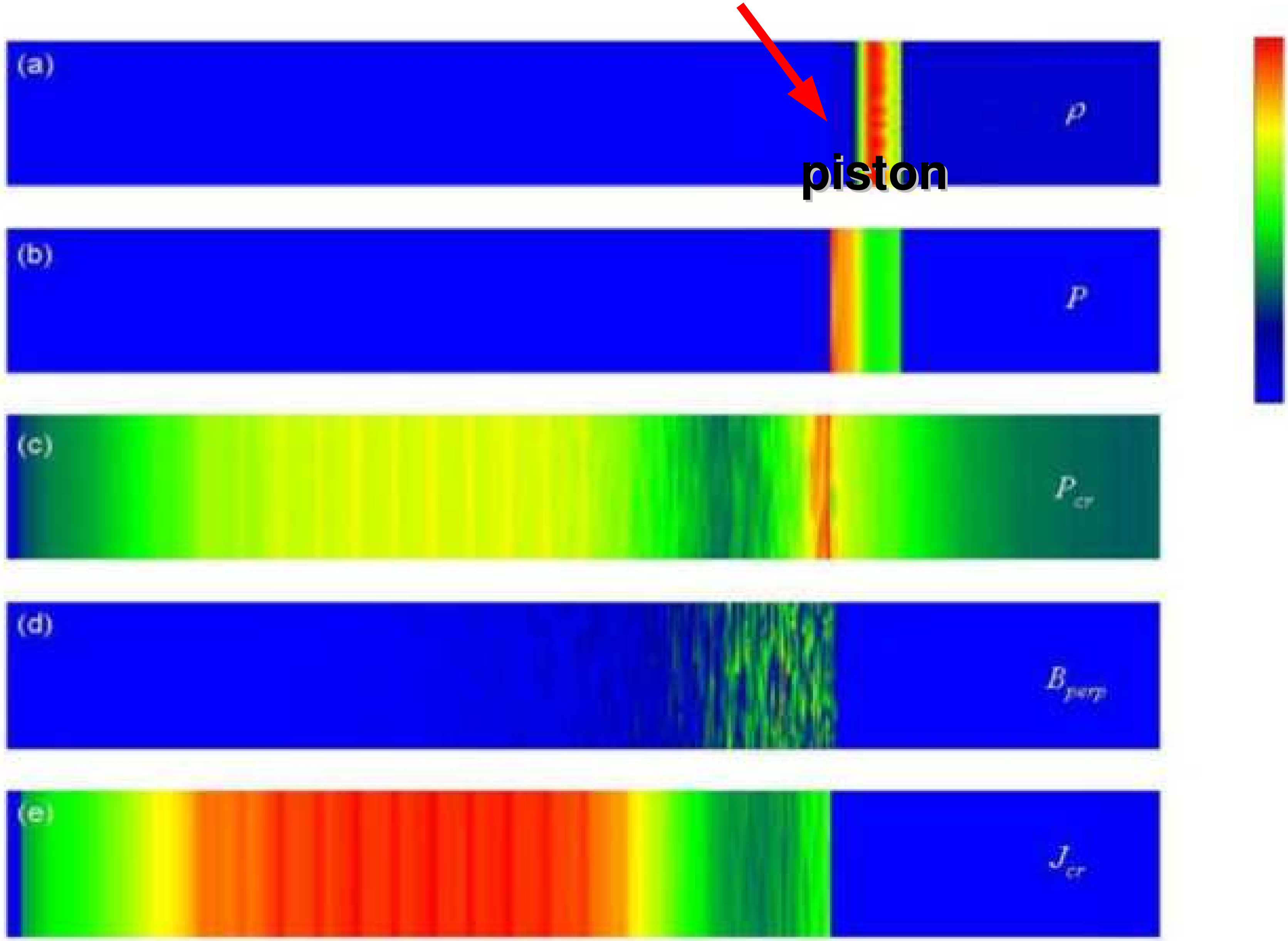
as described in Lucek & Bell (2000) and Bell (2004). The CR distribution function $f(\mathbf{r},\mathbf{p},t)$ at position $\mathbf{r}$ and momentum $\mathbf{p}$ is defined in the local fluid rest frame and evolves according to the Vlasov-Fokker-Planck (VFP) equation

CRs

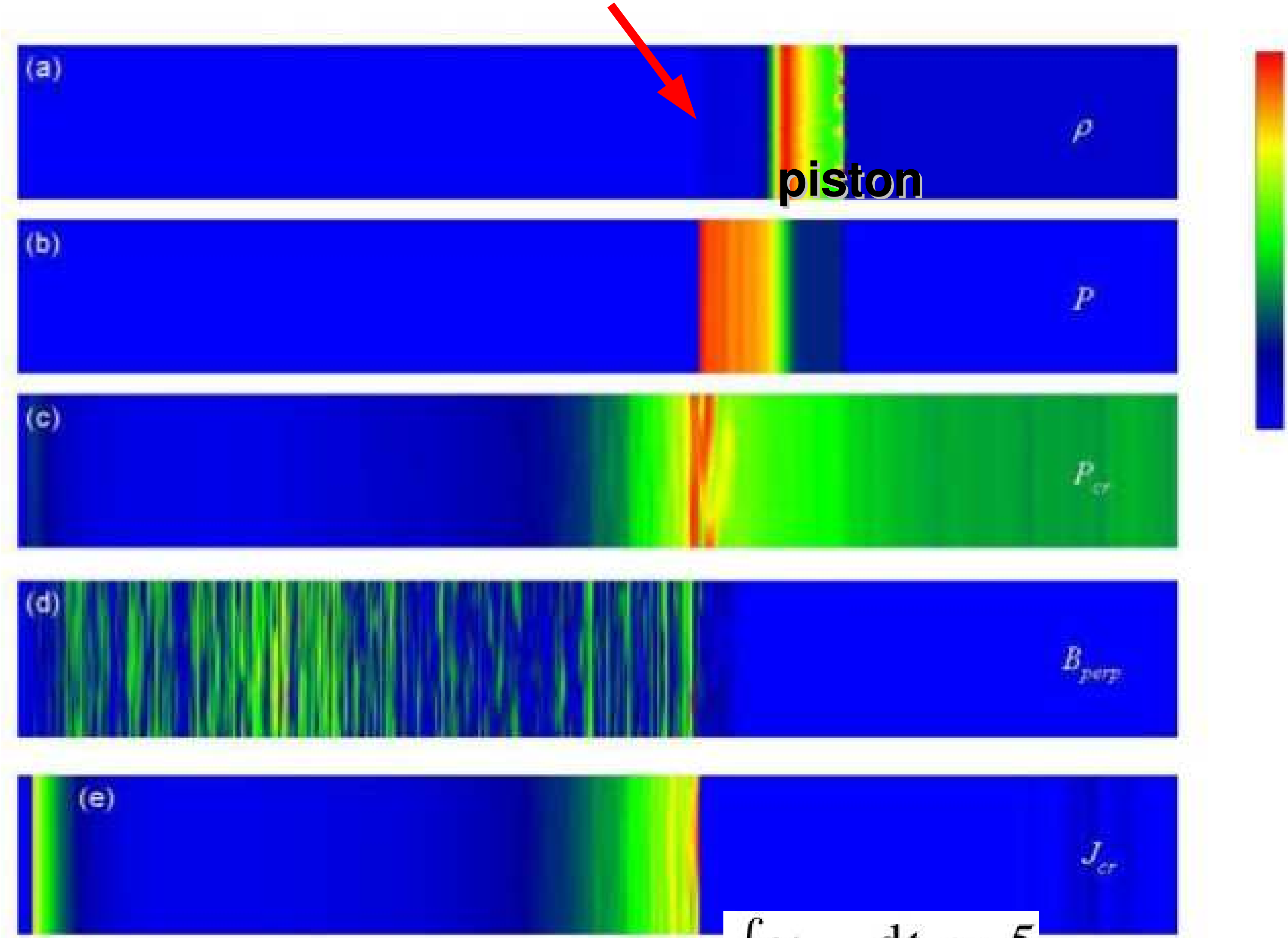
$$\frac{df}{dt} = -v_i\frac{\partial f}{\partial r_i} + p_i\frac{\partial u_j}{\partial r_i}\frac{\partial f}{\partial p_j} - \epsilon_{ijk}ev_iB_j\frac{\partial f}{\partial p_k} + C(f) \tag{8}$$

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



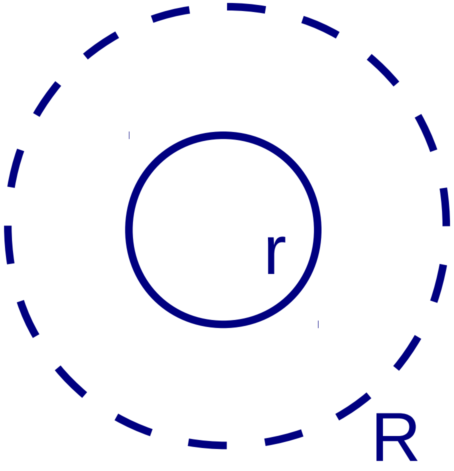
$$\int \gamma_{\max} \mathrm{d}t \sim 5$$

CR acceleration and escape

$$\int \gamma_{\mathrm{max}} \mathrm{d}t \sim 5$$

$$Q_{\mathrm{CR}} = \int j_{\mathrm{CR}} \mathrm{d}t = 10\sqrt{\rho/\mu_0}$$

CR charge through a unit surface, upstream



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

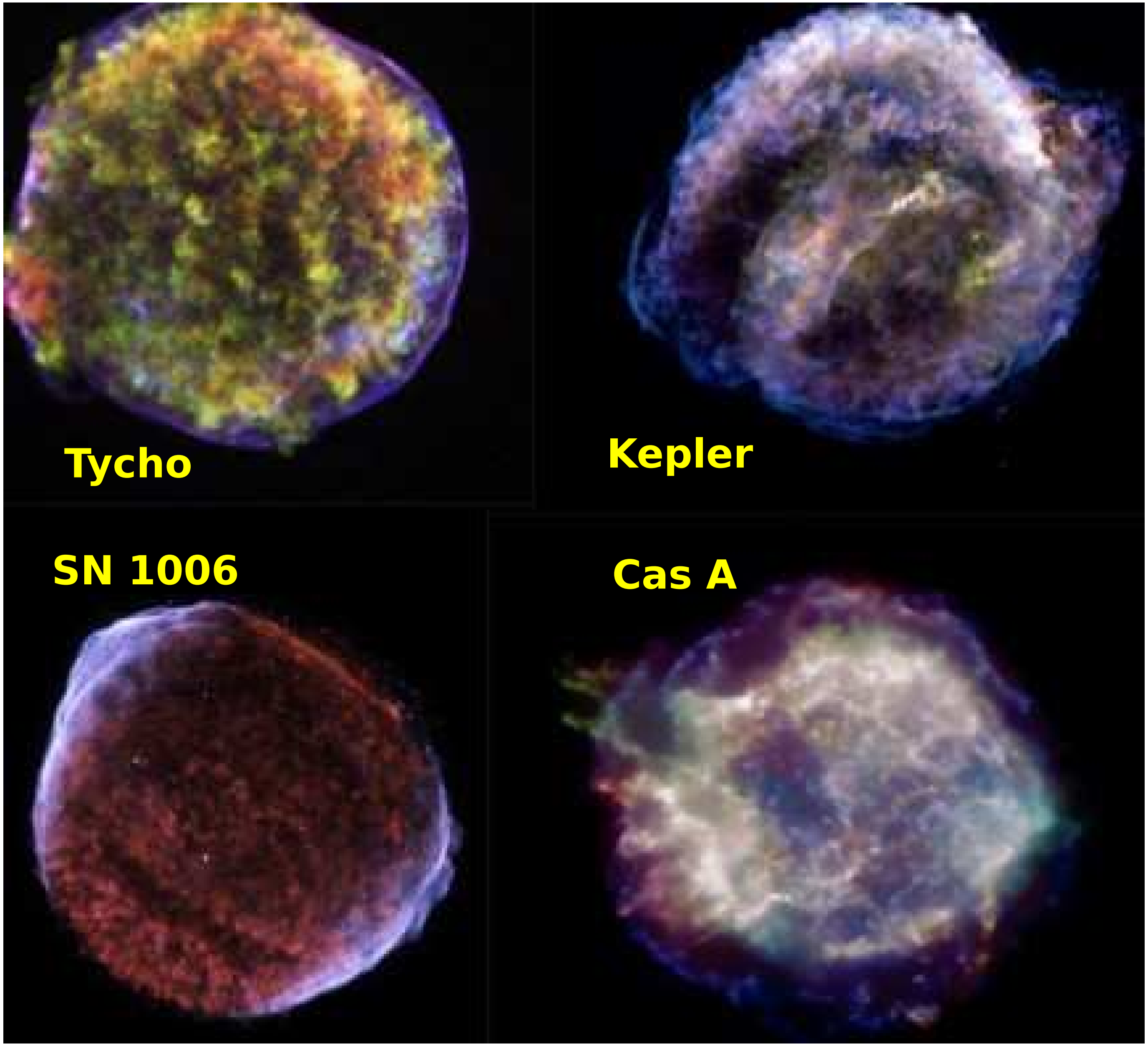
$$\int_0^R \frac{\eta \rho(r) u_{\mathrm{s}}^2(r)}{T(r)} r^2 \mathrm{d}r = 10 R^2 \sqrt{\frac{\rho(R)}{\mu_0}}$$

Diff. / R :

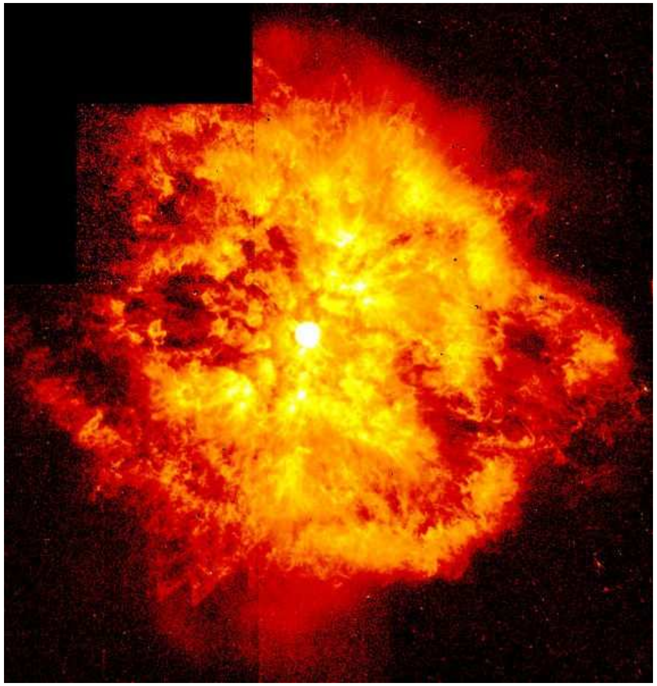
ρ = cst → $$\boxed{T = 230 \eta_{0.03} n_{\mathrm{e}}^{1/2} u_7^2 R_{\mathrm{pc}} \ \mathrm{TeV}}$$

Cas A : T ≈ 400 TeV !!!

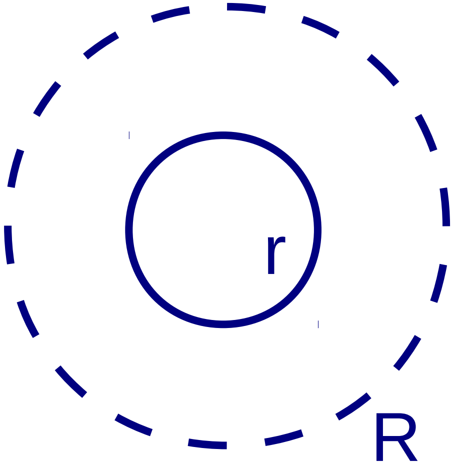
Nowadays, historical SNRs are <u>not</u> accelerating particles to the knee !



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 :

$\rho \propto r^{-2}$ →

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

Radio SNe

The Astrophysical Journal, 509:861–878, 1998 December 20
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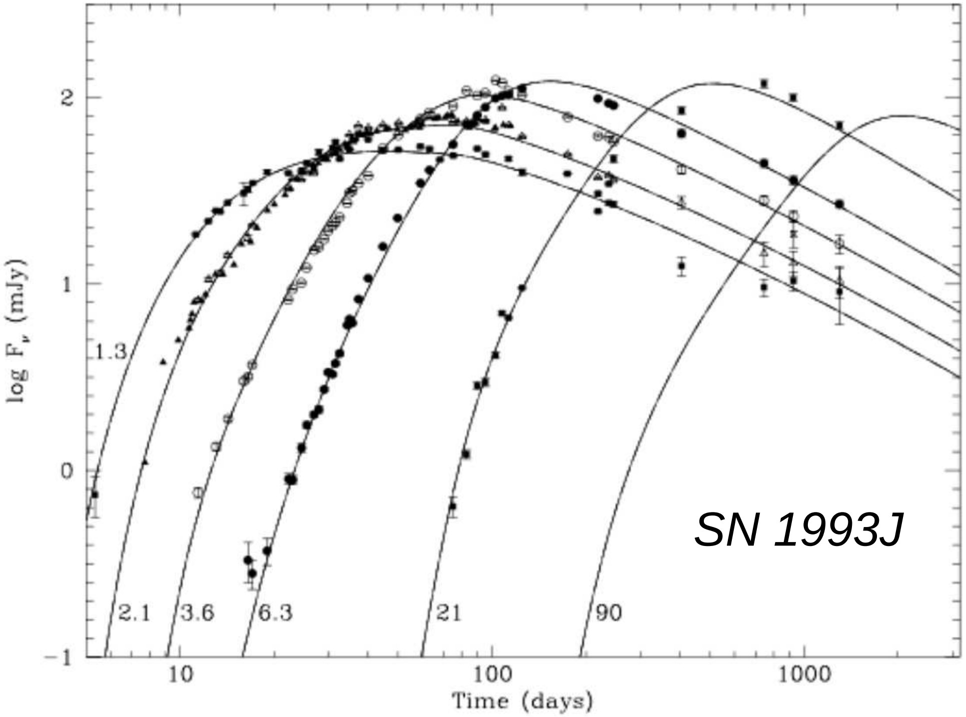
RADIO EMISSION AND PARTICLE ACCELERATION IN SN 1993J

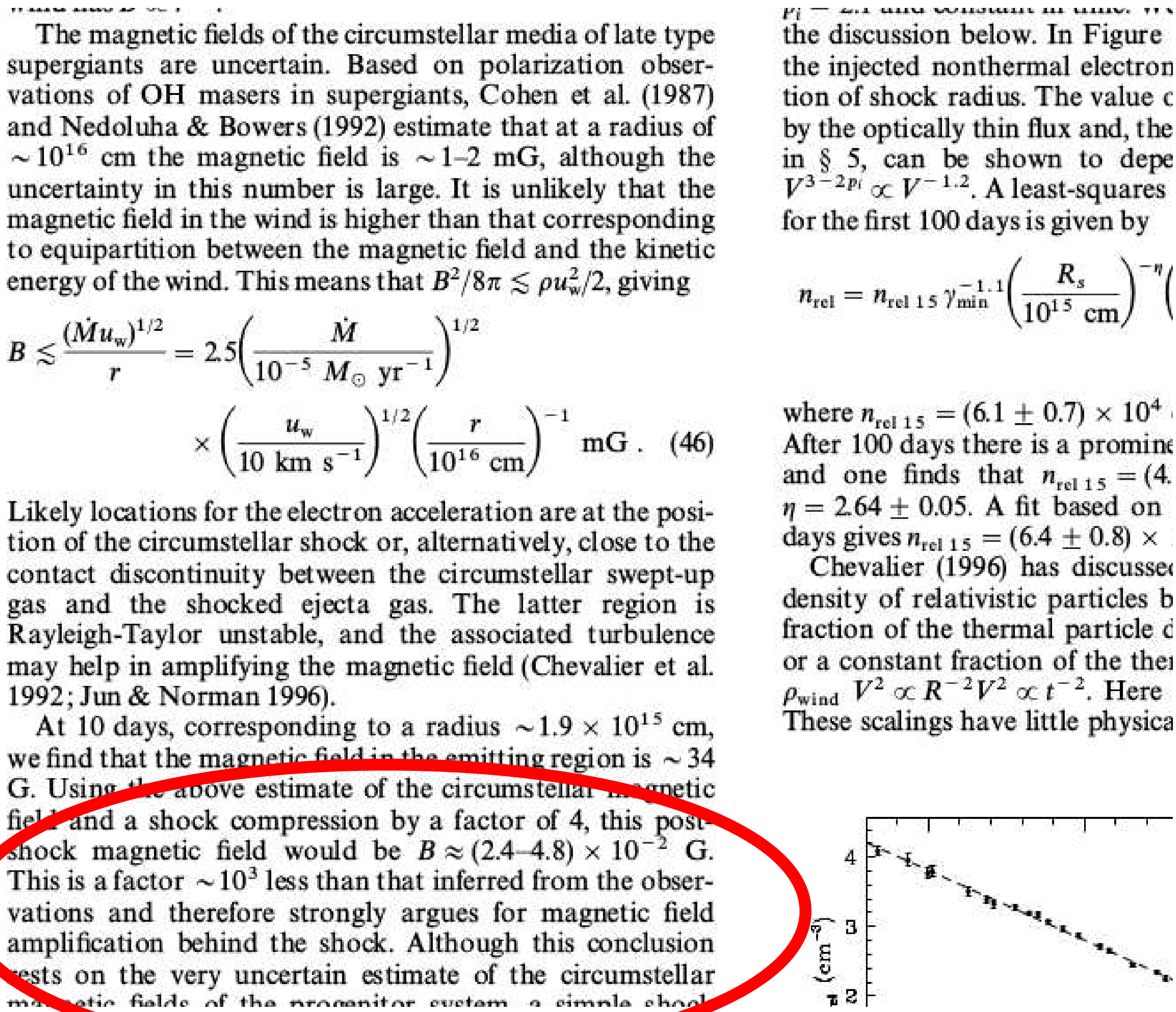
Claes Fransson[1] and Claes-Ingvar Björnsson[1]
Received 1998 April 27; accepted 1998 July 27



ABSTRACT

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
ck 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
~ 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



The magnetic fields of the circumstellar media of late type supergiants are uncertain. Based on polarization observations of OH masers in supergiants, Cohen et al. (1987) and Nedoluha & Bowers (1992) estimate that at a radius of ~10^{16} cm the magnetic field is ~1–2 mG, although the uncertainty in this number is large. It is unlikely that the magnetic field in the wind is higher than that corresponding to equipartition between the magnetic field and the kinetic energy of the wind. This means that $B^2/8\pi \lesssim \rho u_w^2/2$, giving

$$B \lesssim \frac{(\dot{M} u_w)^{1/2}}{r} = 2.5\left(\frac{\dot{M}}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2} \times \left(\frac{u_w}{10\ \mathrm{km\ s}^{-1}}\right)^{1/2}\left(\frac{r}{10^{16}\ \mathrm{cm}}\right)^{-1}\ \mathrm{mG}\,. \quad (46)$$

Likely locations for the electron acceleration are at the position of the circumstellar shock or, alternatively, close to the contact discontinuity between the circumstellar swept-up gas and the shocked ejecta gas. The latter region is Rayleigh-Taylor unstable, and the associated turbulence may help in amplifying the magnetic field (Chevalier et al. 1992; Jun & Norman 1996).

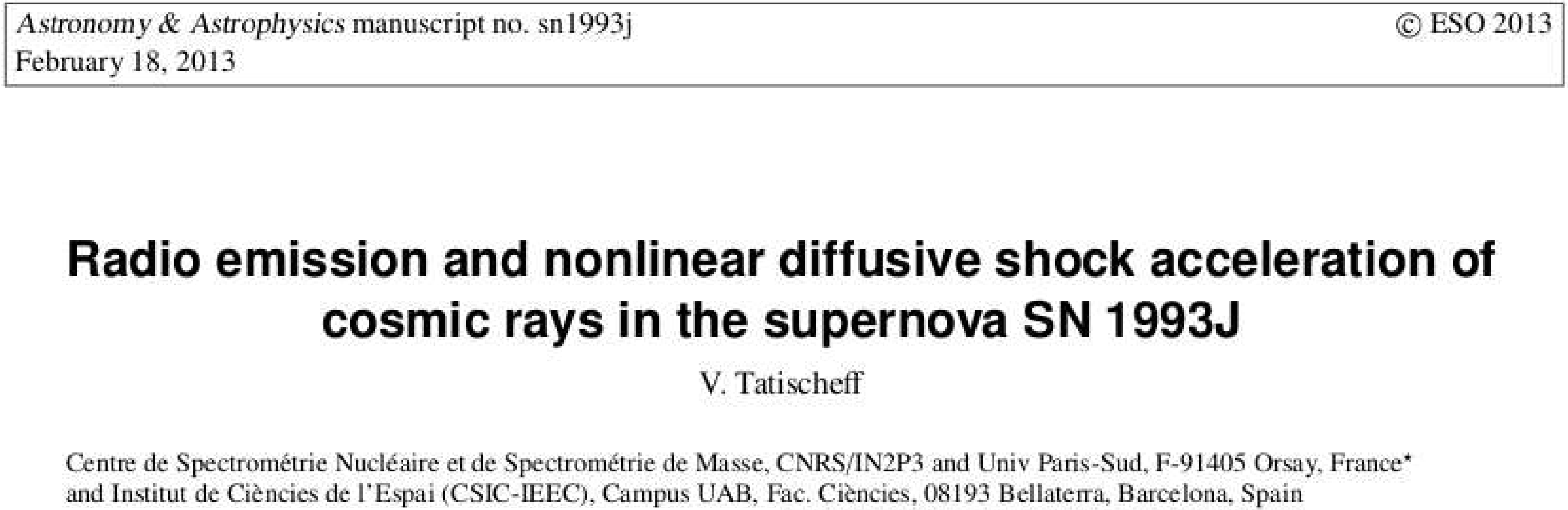
At 10 days, corresponding to a radius ~1.9×10^{15} cm, we find that the magnetic field in the emitting region is ~34 G. Using the above estimate of the circumstellar magnetic field and a shock compression by a factor of 4, this post-shock magnetic field would be $B \approx (2.4–4.8) \times 10^{-2}$ G. This is a factor ~10^3 less than that inferred from the observations and therefore strongly argues for magnetic field amplification behind the shock. Although this conclusion rests on the very uncertain estimate of the circumstellar magnetic fields of the progenitor system, a simple shock

the discussion below. In Figure
the injected nonthermal electron
tion of shock radius. The value c
by the optically thin flux and, the
in § 5, can be shown to depe
$V^{3-2p_i} \propto V^{-1.2}$. A least-squares
for the first 100 days is given by

$$n_{\mathrm{rel}} = n_{\mathrm{rel}\,15}\,\gamma_{\mathrm{min}}^{-1.1}\left(\frac{R_s}{10^{15}\ \mathrm{cm}}\right)^{-\eta}($$

where $n_{\mathrm{rel}\,15} = (6.1 \pm 0.7) \times 10^4$
After 100 days there is a promine
and one finds that $n_{\mathrm{rel}\,15} = (4.$
$\eta = 2.64 \pm 0.05$. A fit based on
days gives $n_{\mathrm{rel}\,15} = (6.4 \pm 0.8) \times$
Chevalier (1996) has discusse
density of relativistic particles b
fraction of the thermal particle d
or a constant fraction of the the
$\rho_{\mathrm{wind}}\ V^2 \propto R^{-2} V^2 \propto t^{-2}$. Here
These scalings have little physica

Radio SNe



Astronomy & Astrophysics manuscript no. sn1993j
February 18, 2013

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

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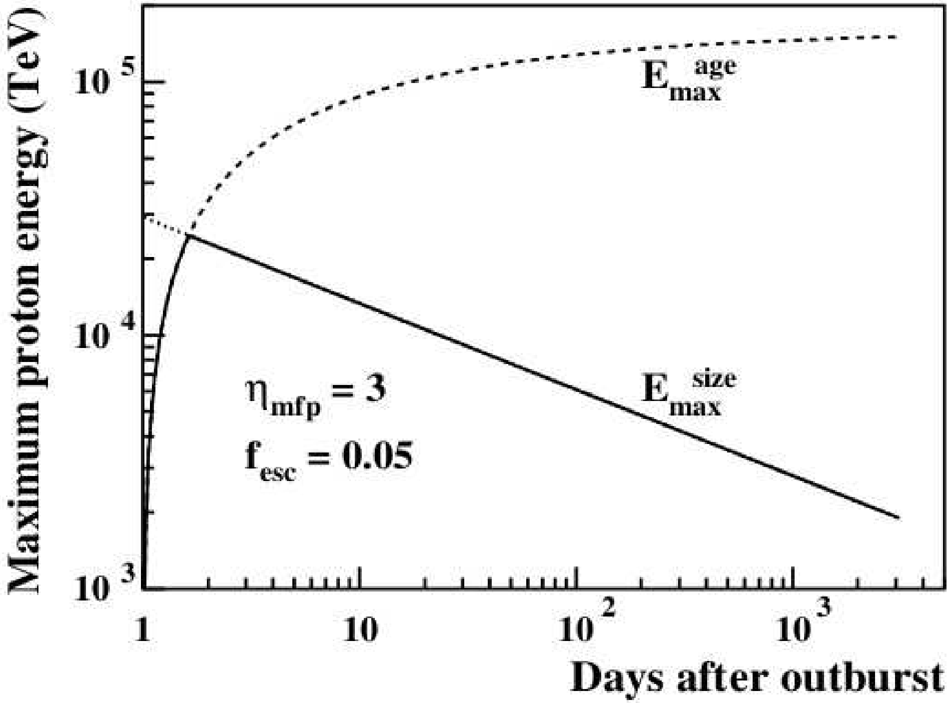
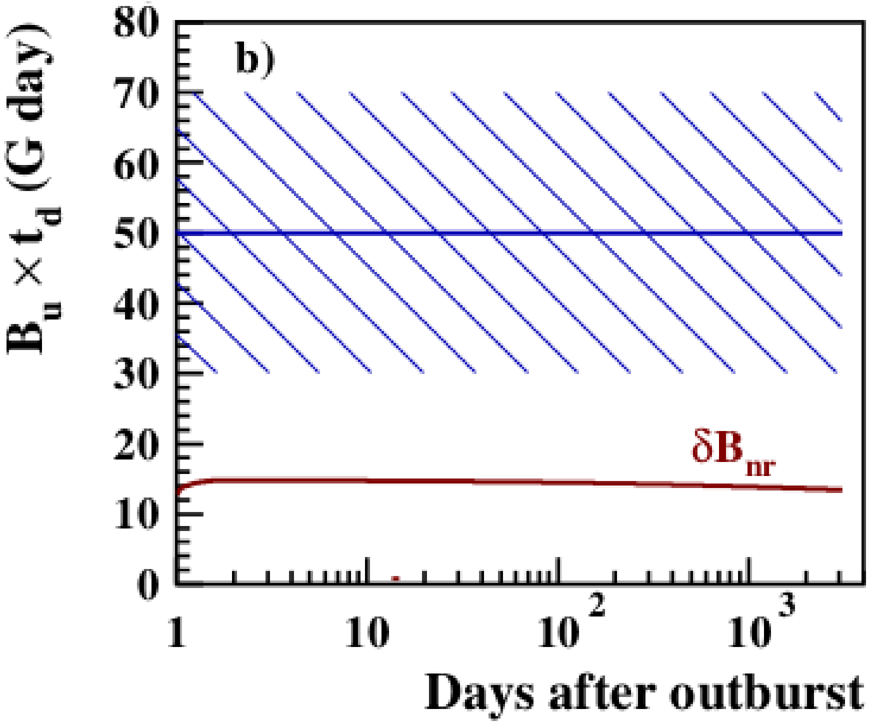
and Institut de Ciències de l'Espai (CSIC-IEEC), Campus UAB, Fac. Ciències, 08193 Bellaterra, Barcelona, Spain

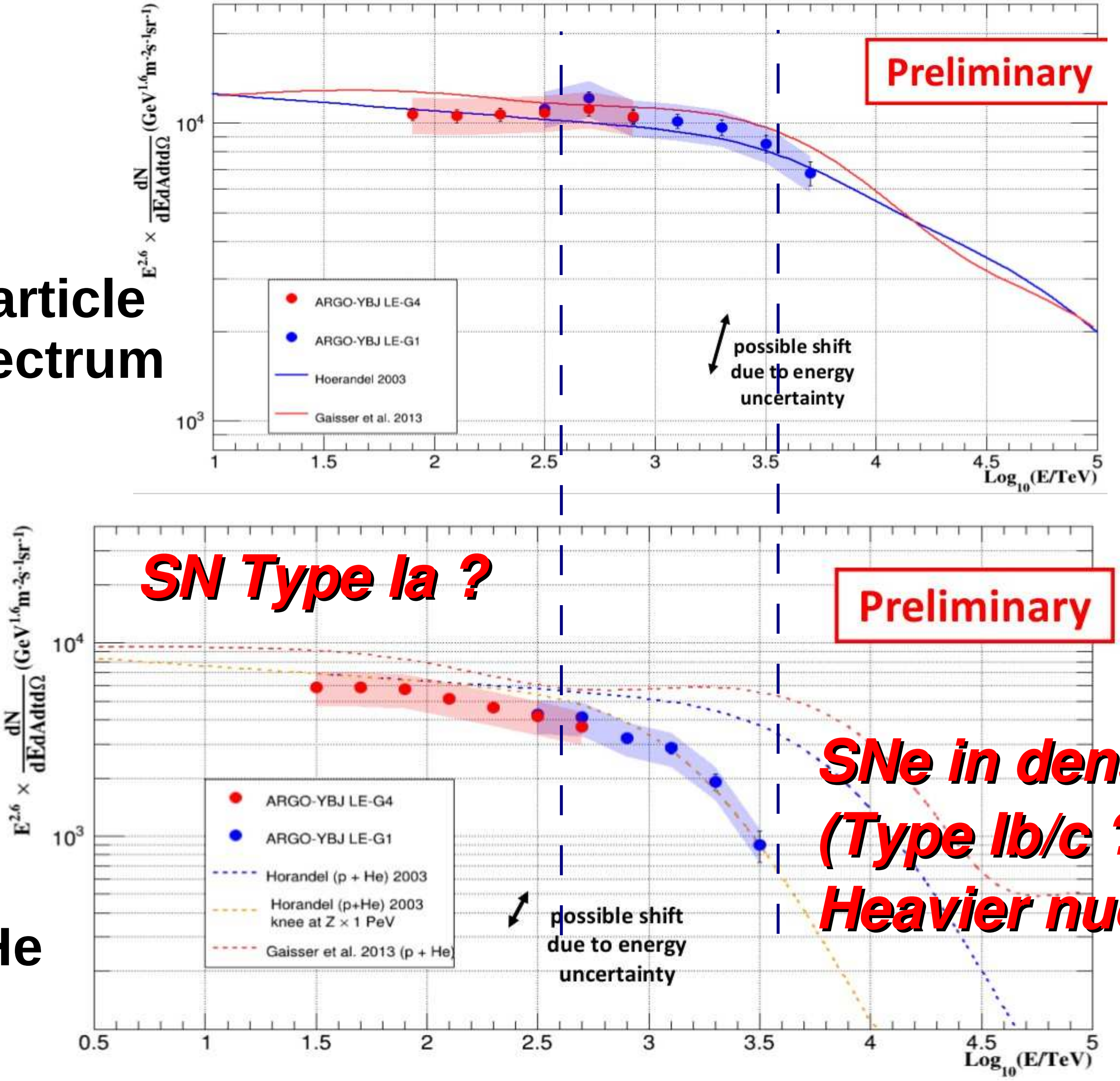




ARGO-YBJ : cutoff at ~ 700 TeV

All-particle spectrum

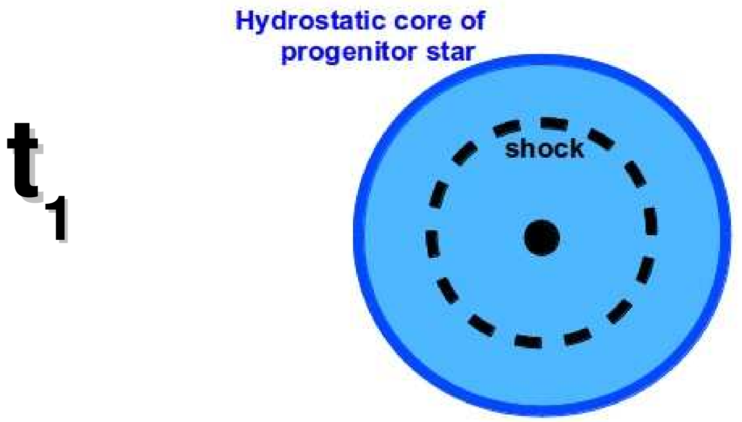
p+He

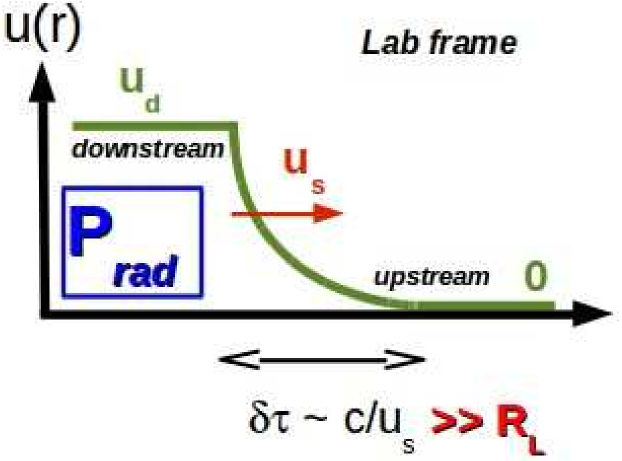


SN Type Ia ?

SNe in dense winds ?
(Type Ib/c ?, some II)
Heavier nuclei?

Formation of a collisionless shock

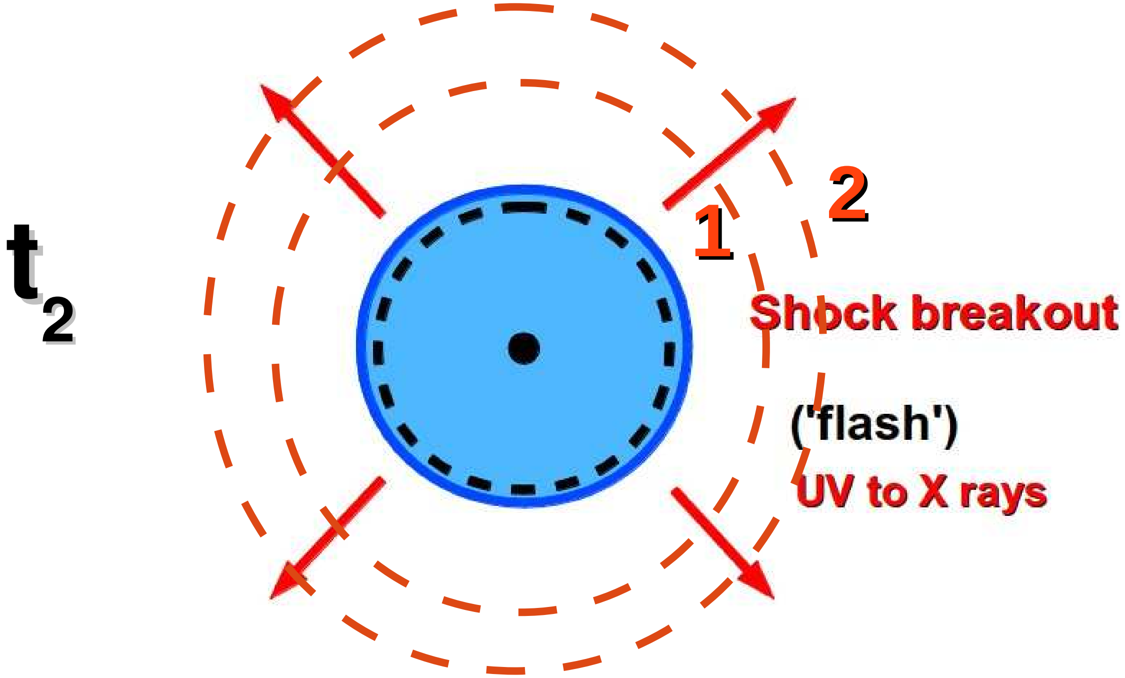




$\delta\tau \sim c/u_s \gg R_L$

Radiation-Mediated shock

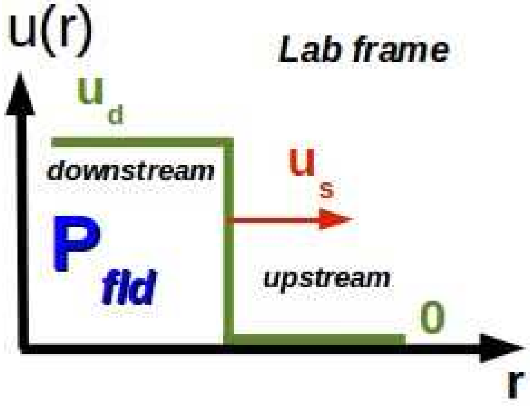
No CR acceleration



Shock breakout

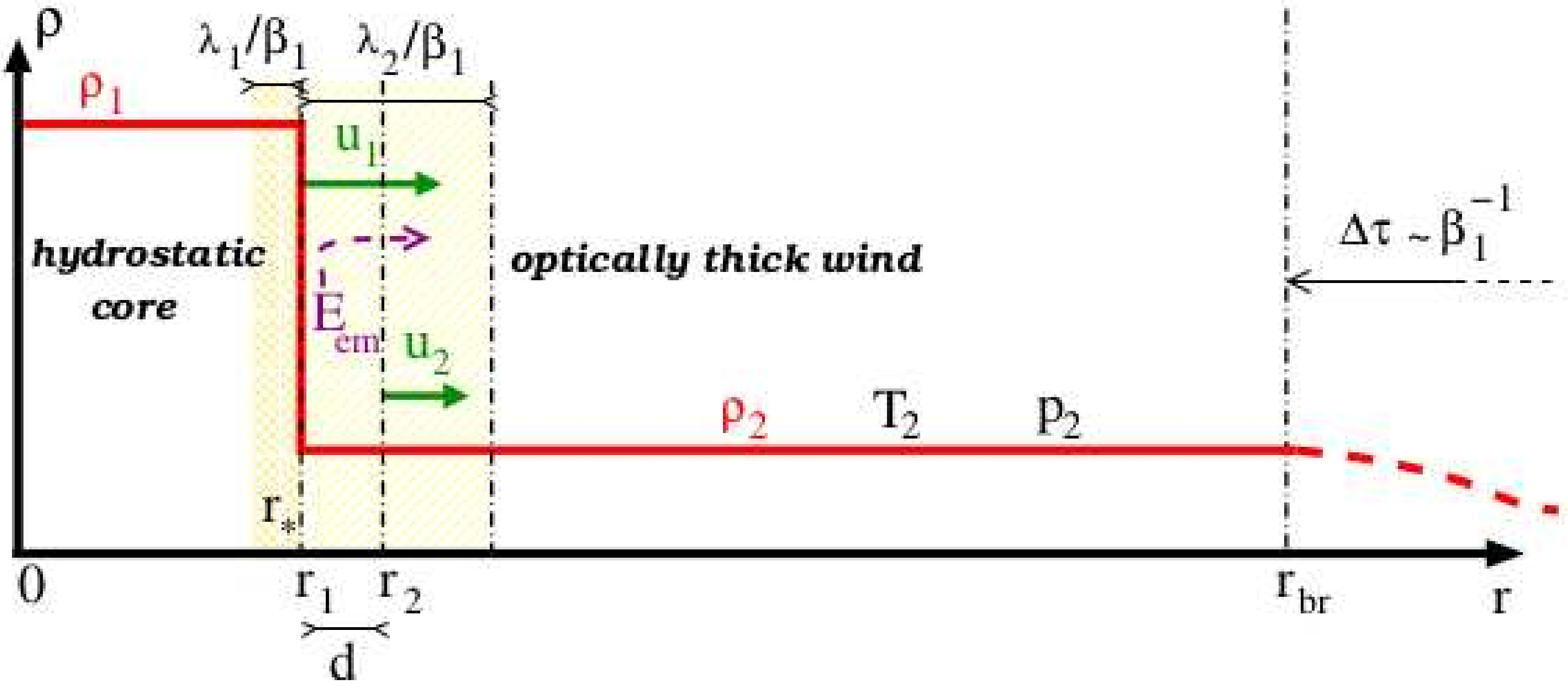
('flash')

UV to X rays



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

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



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

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

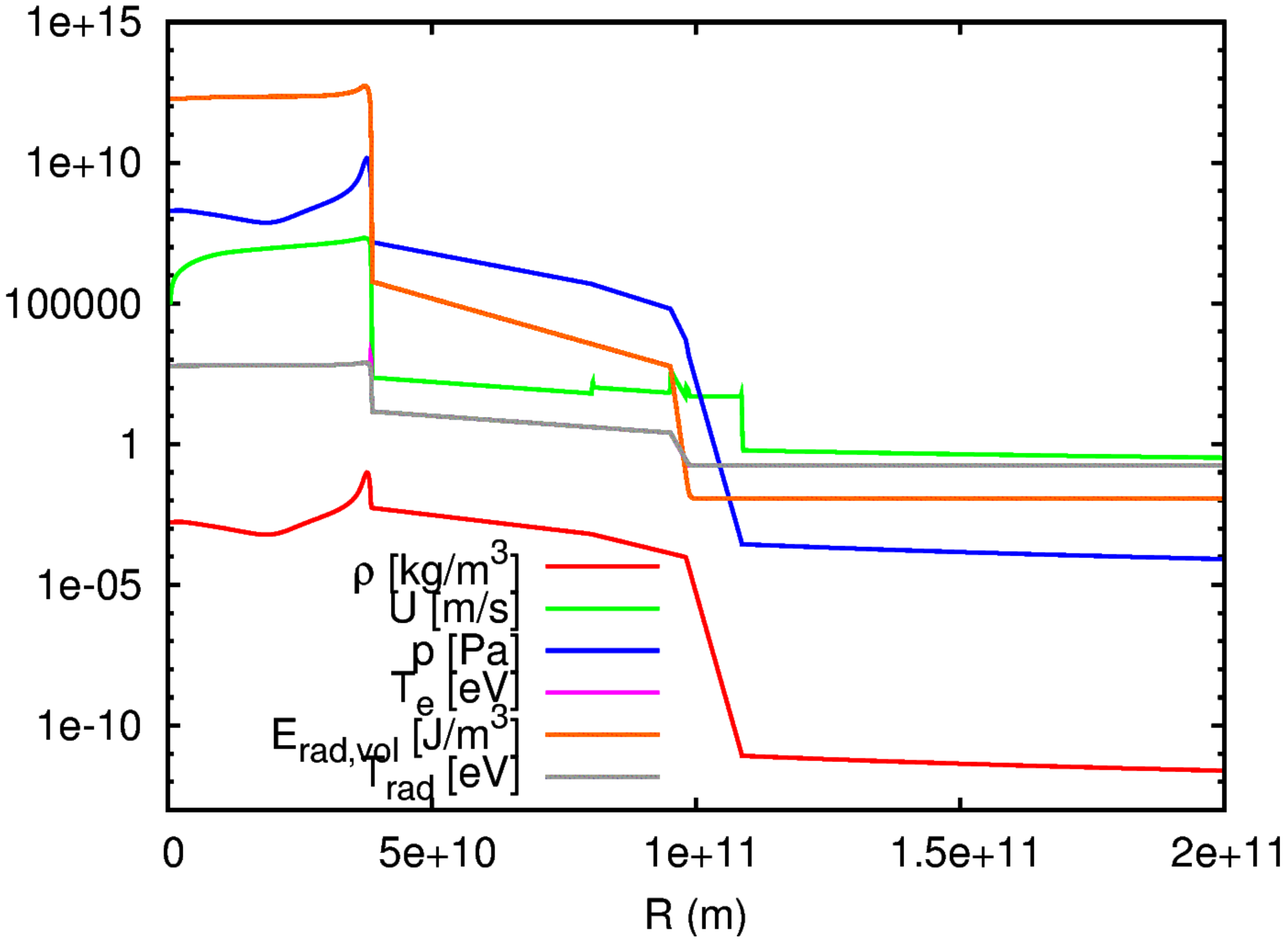
$u_2 < u_1$ ⇘

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

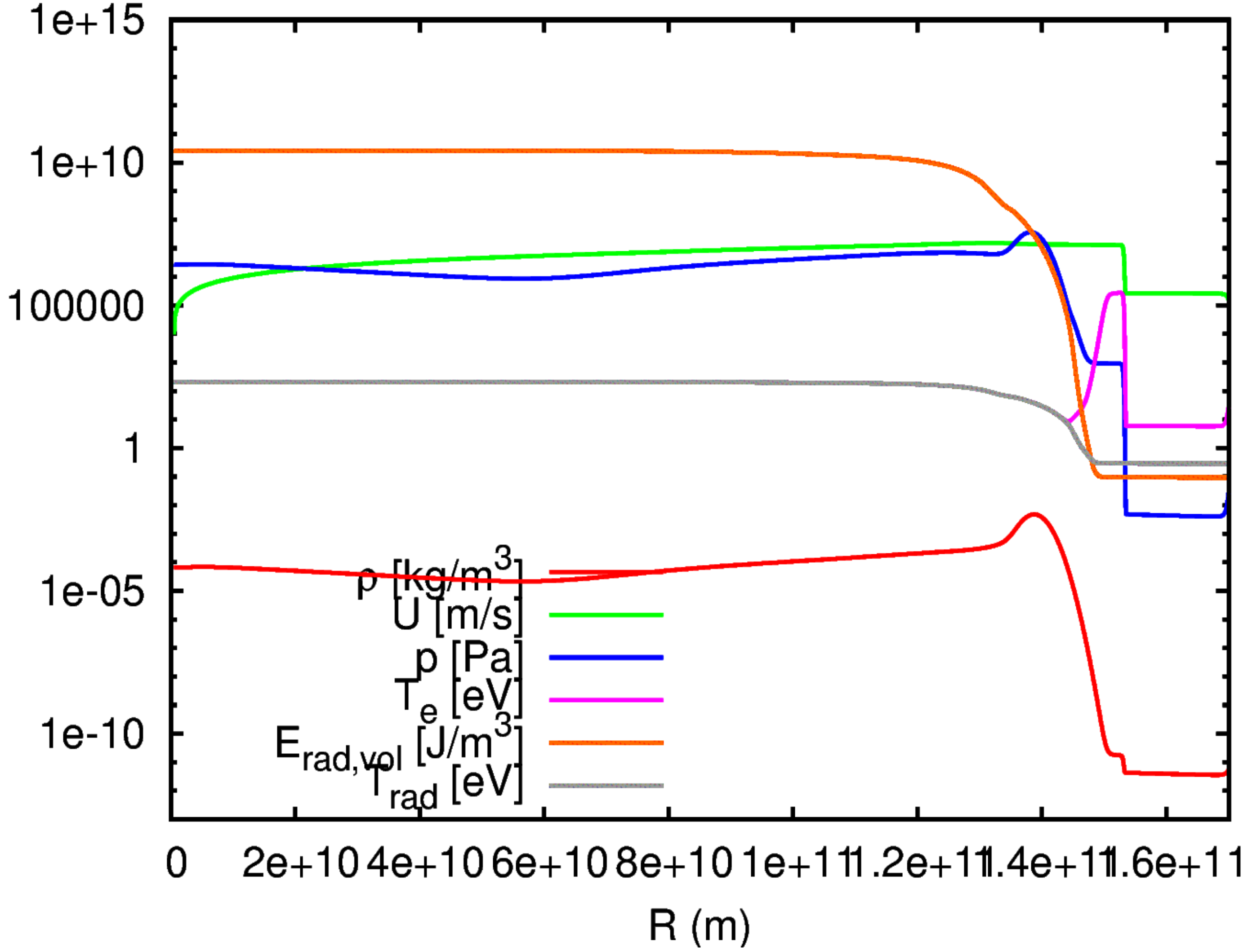
Progenitor with an optically THIN wind

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

Compton cooling + Bremsstrahlung **Thomson scattering**

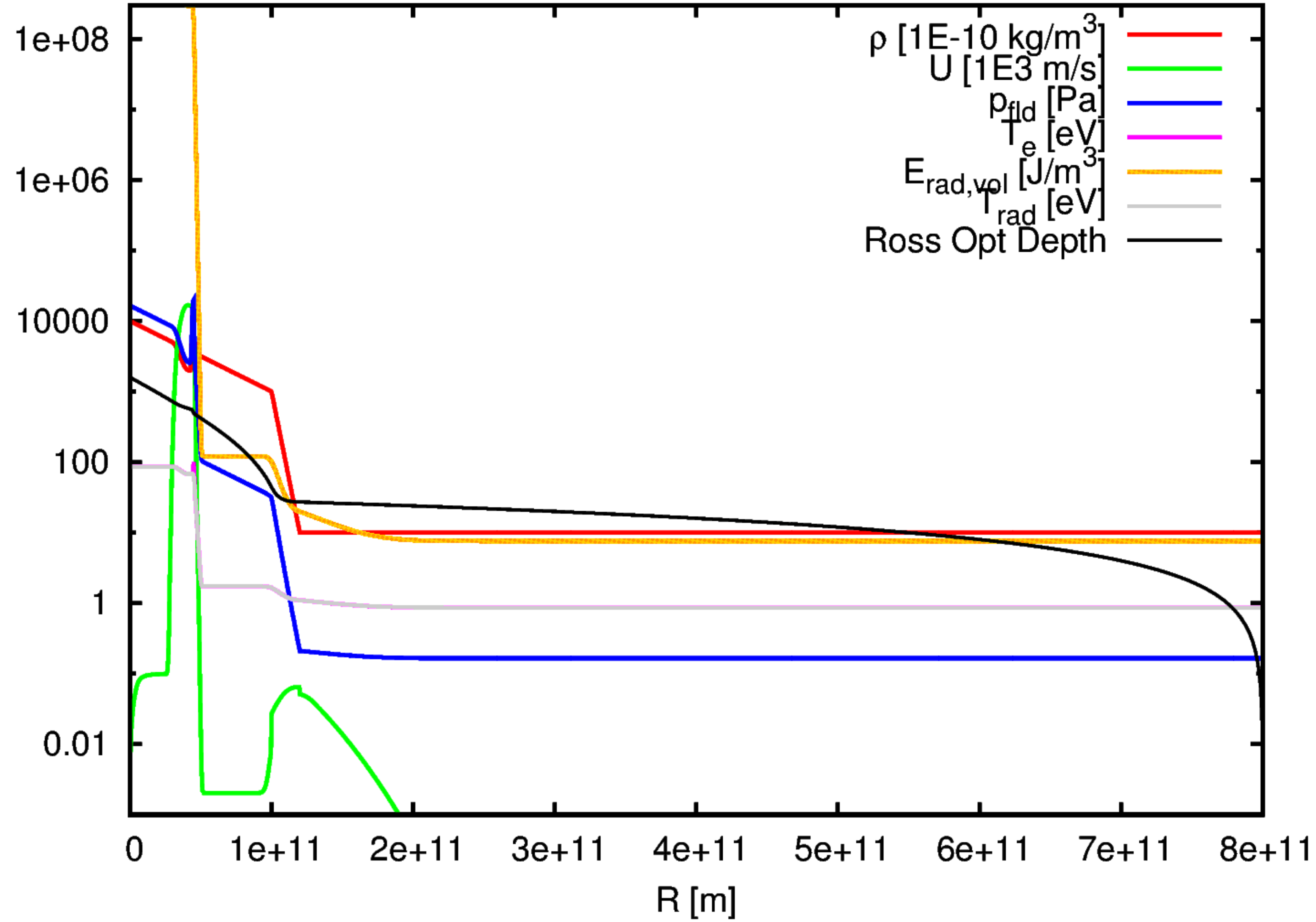


Progenitor with an optically THIN wind



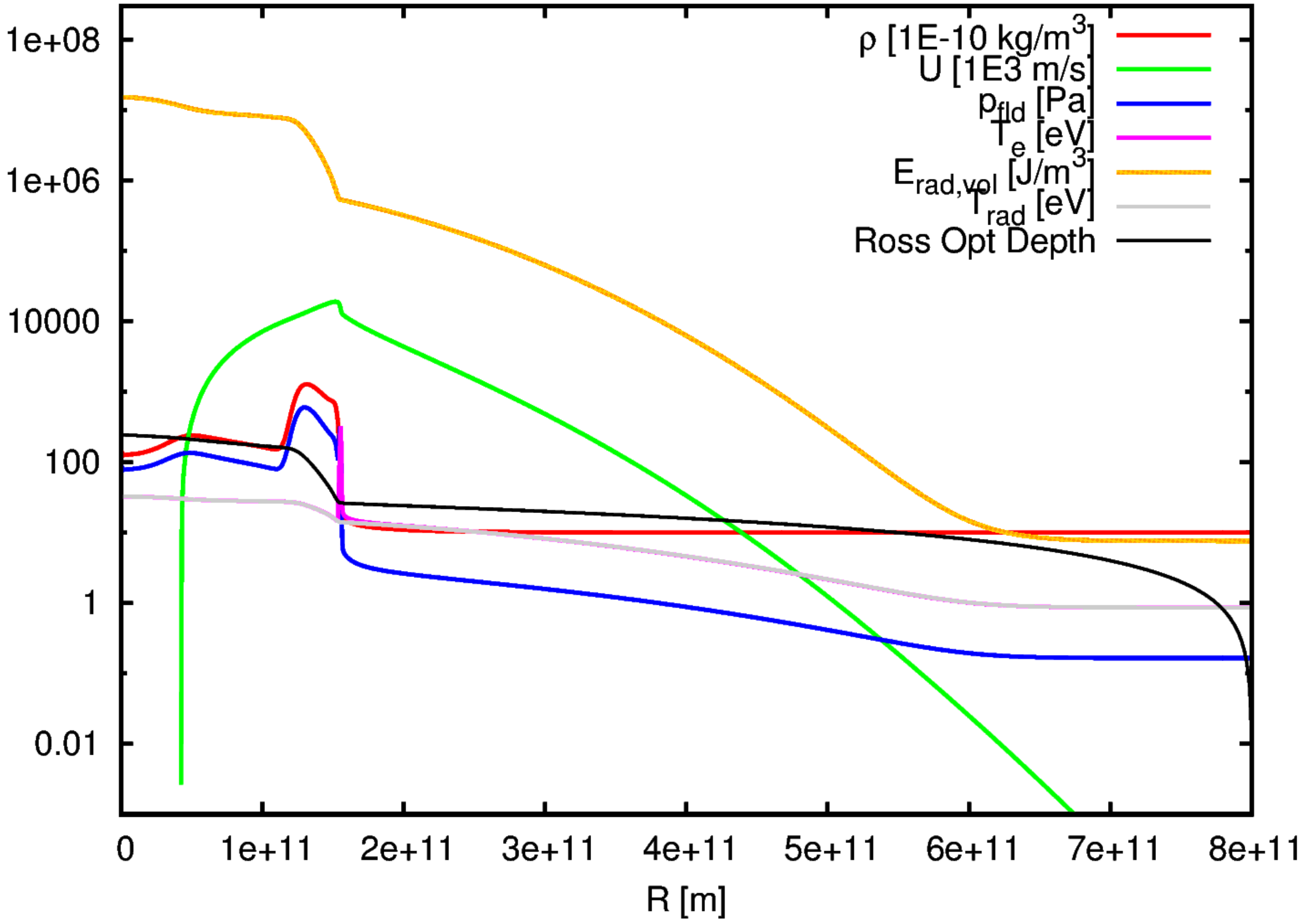
Progenitor with an optically **THICK** wind

Spherical 1D



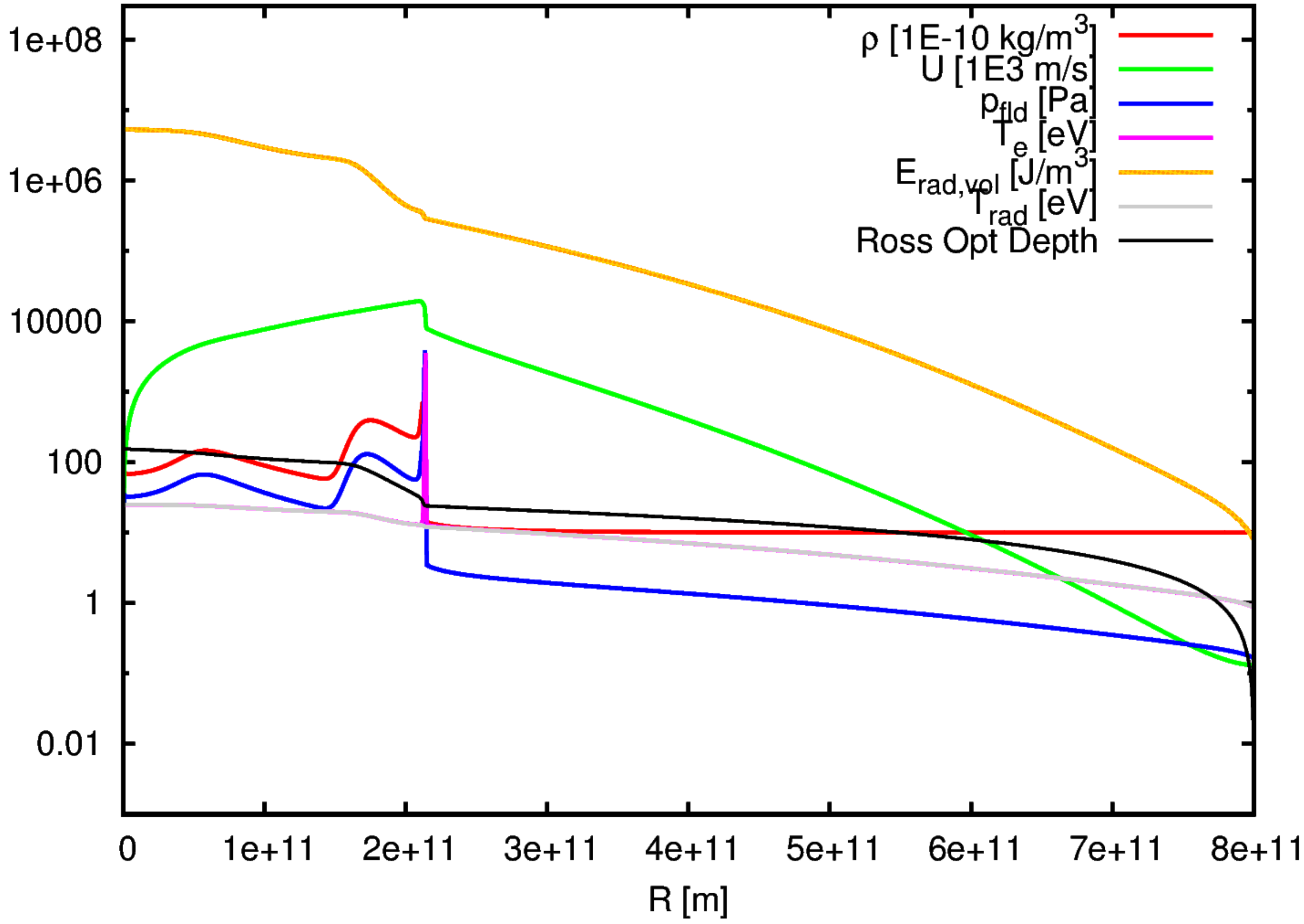
Progenitor with an optically THICK wind

Spherical 1D



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

Spherical 1D



Observational consequences

- 1 – 10 TeV CRs possible before breakout :

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

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

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

$< \;\rho u_{\rm s}^2/h\nu$ (For $10\,{\rm TeV}$ CRs, $\gtrsim 10\,{\rm keV}$)

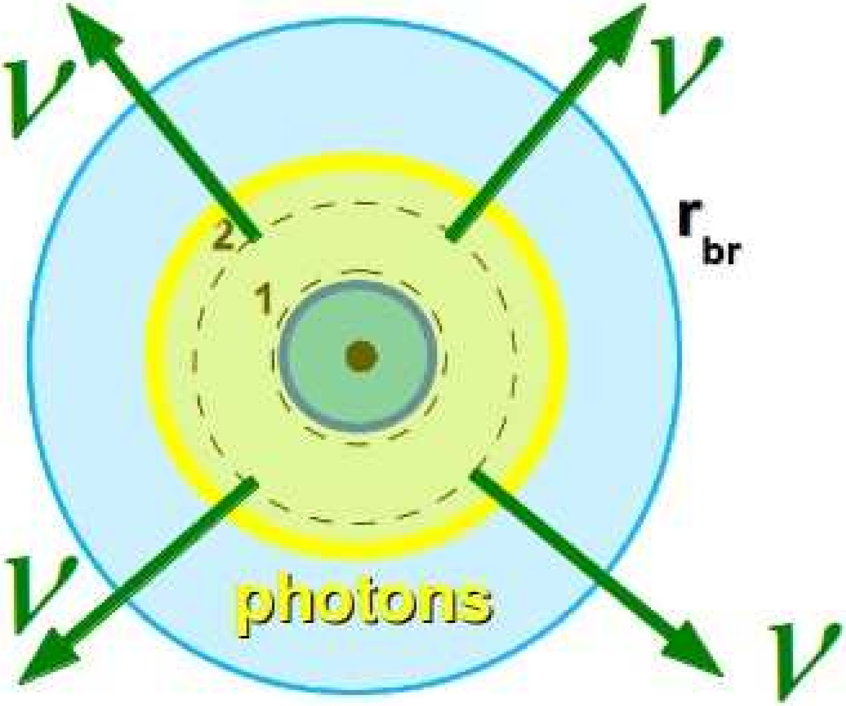
$\gtrsim (1-10)$ TeV CRs should be produced

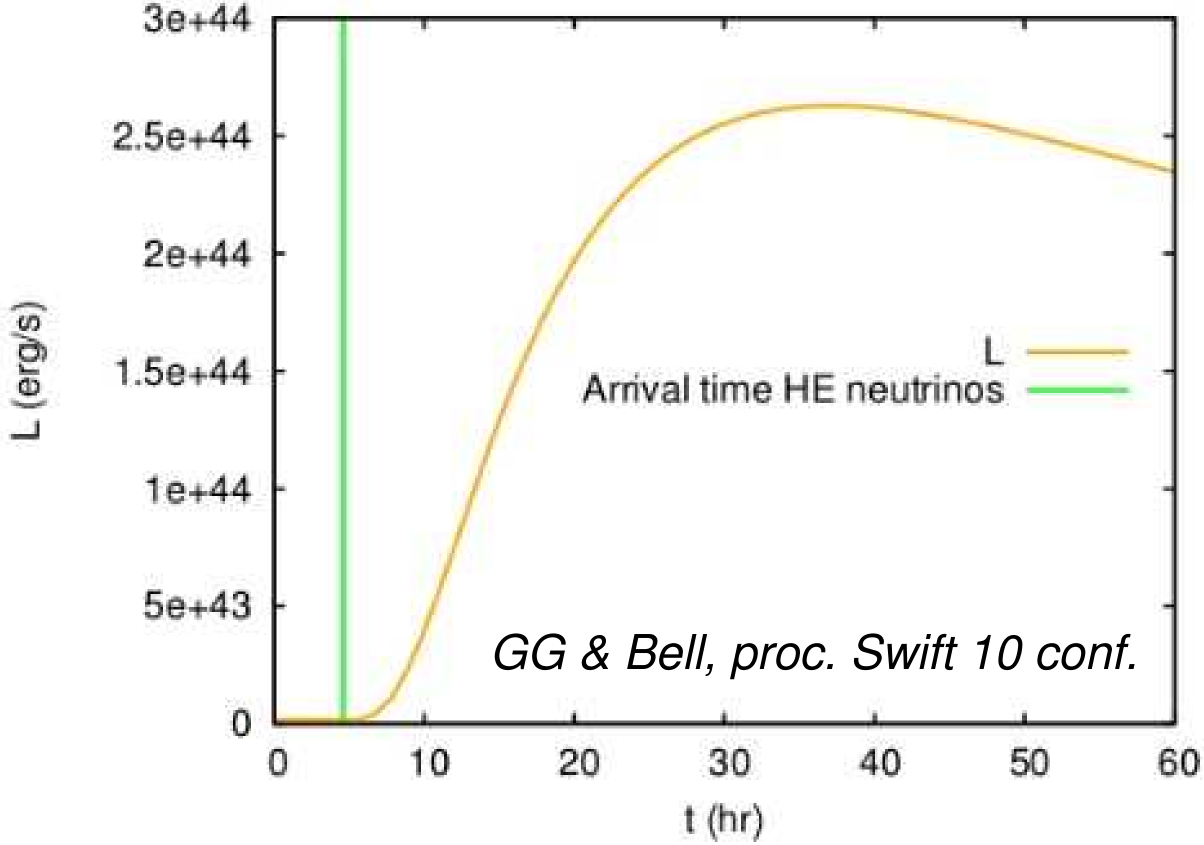
Observational consequences

1)

Neutrinos with energy $E_\nu > 100$ 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 $r < r_{br}$).



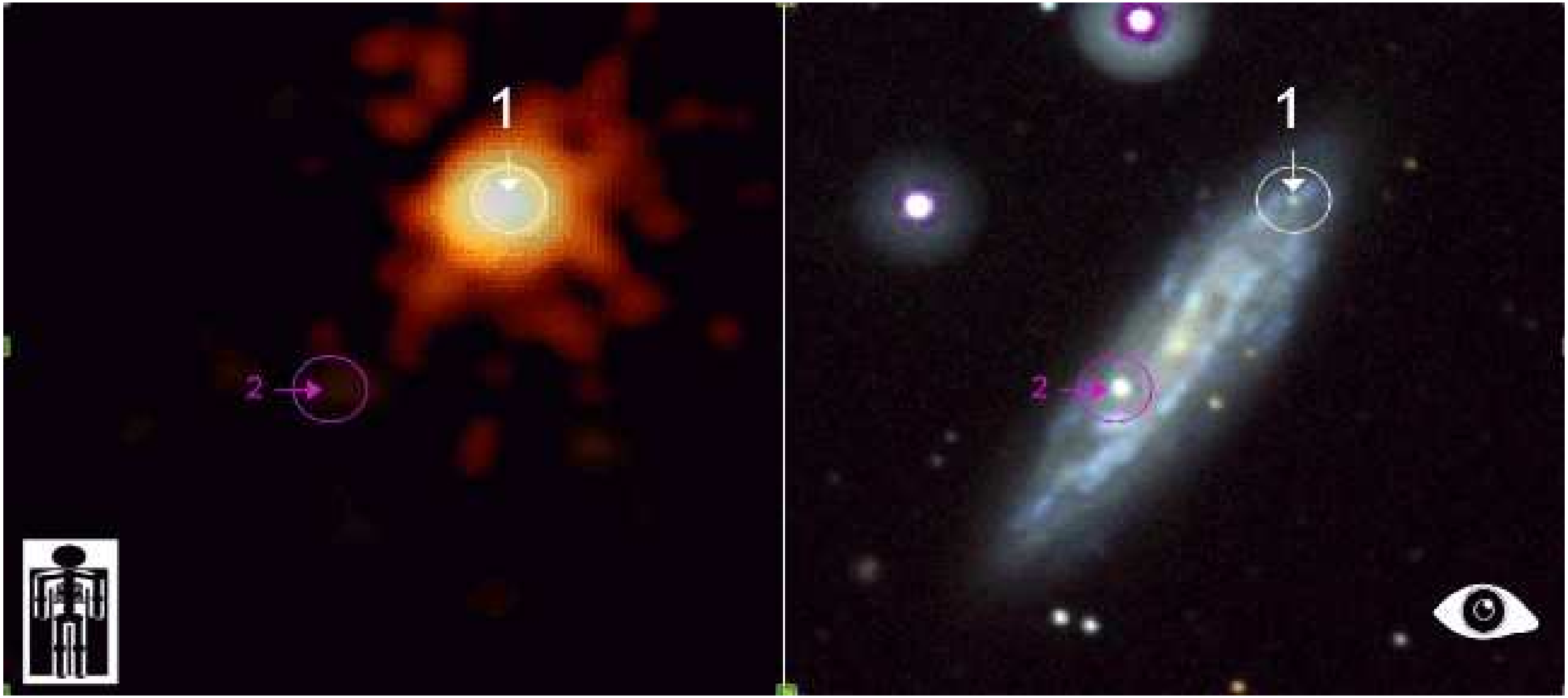


GG & Bell, proc. Swift 10 conf.

2) **X-Ray Flash**

Parameters of Svirski & Nakar, ApJL (2014) …

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



Conclusions and perspectives

- Summary of Bell's NR instability
- Instability growth / saturation => Limits CR E_{max}
- Tight link between CR Escape / E_{max} / MF amplification
- Type Ia fall short of reaching the knee
  => COMPOSITION ?
- First few decades of SNe in dense winds promising to reach knee and beyond

Conclusions and perspectives

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

- 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 → Probe of the poorly known optically thick regions of circumstellar winds