Cosmic Ray Acceleration and High-Energy Neutrinos at Supernova Explosions

From radiation-mediated shocks to collisionless shocks

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&

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Outline

I – Cosmic Ray Acceleration and escape at SNR shocks

II – Radio and X-Ray SNe : The onset of CR acceleration ?

III – What (we think) we know on formation of collisionless shocks and SN shock breakout

IV – Basics of radiation-hydrodynamics

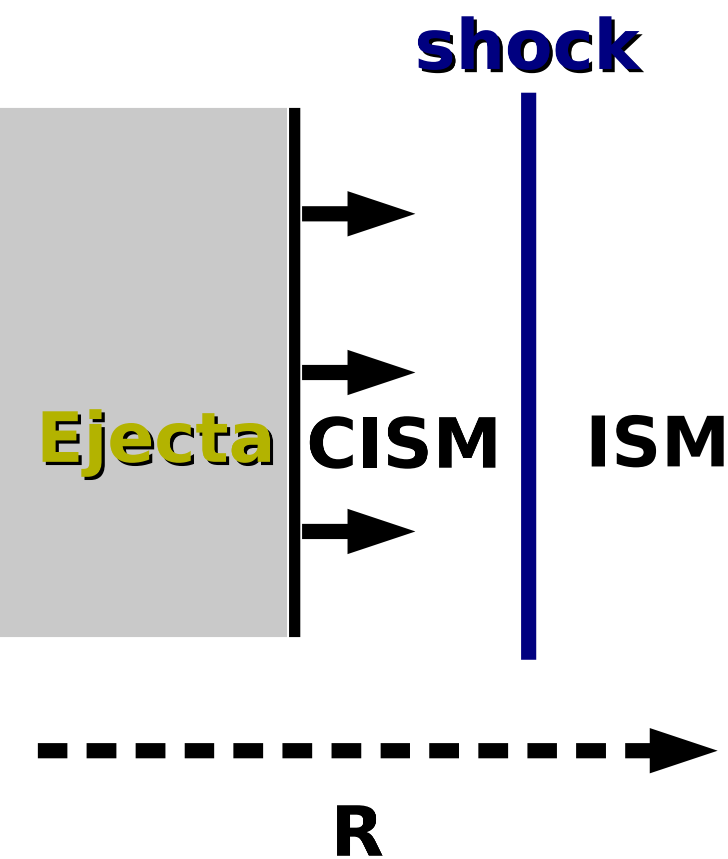
V – Results & Interpretation : *CR acceleration may start <u>SIGNIFICANTLY BEFORE</u> supernova shock breakout !!!*

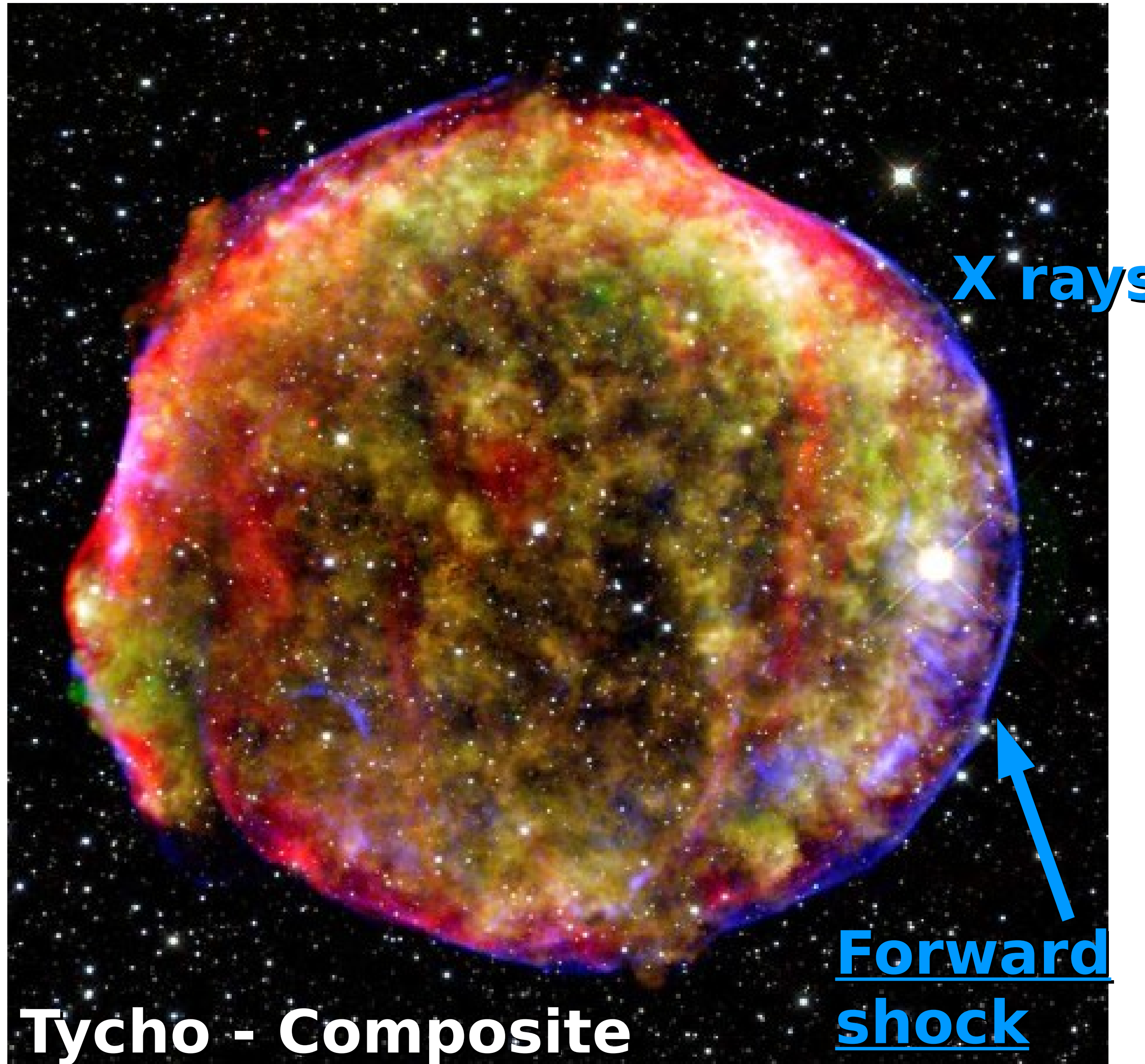
VI – Particle acceleration & Observational consequences : X-ray flashes + High-energy neutrinos

I – Cosmic ray acceleration and escape at SNR shocks

Sources, acceleration mechanism

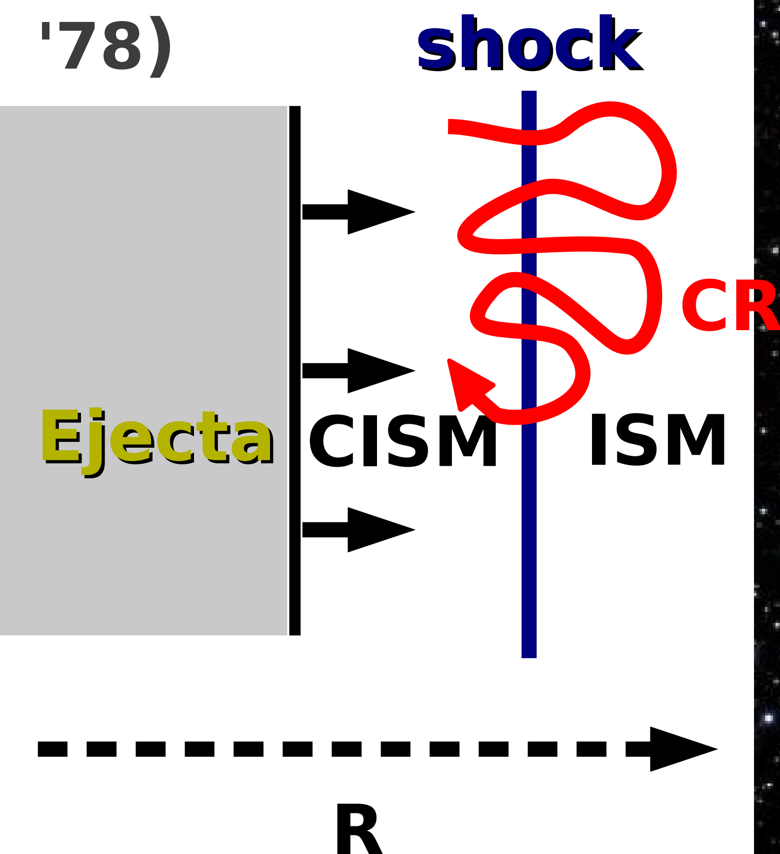
Supernova remnants

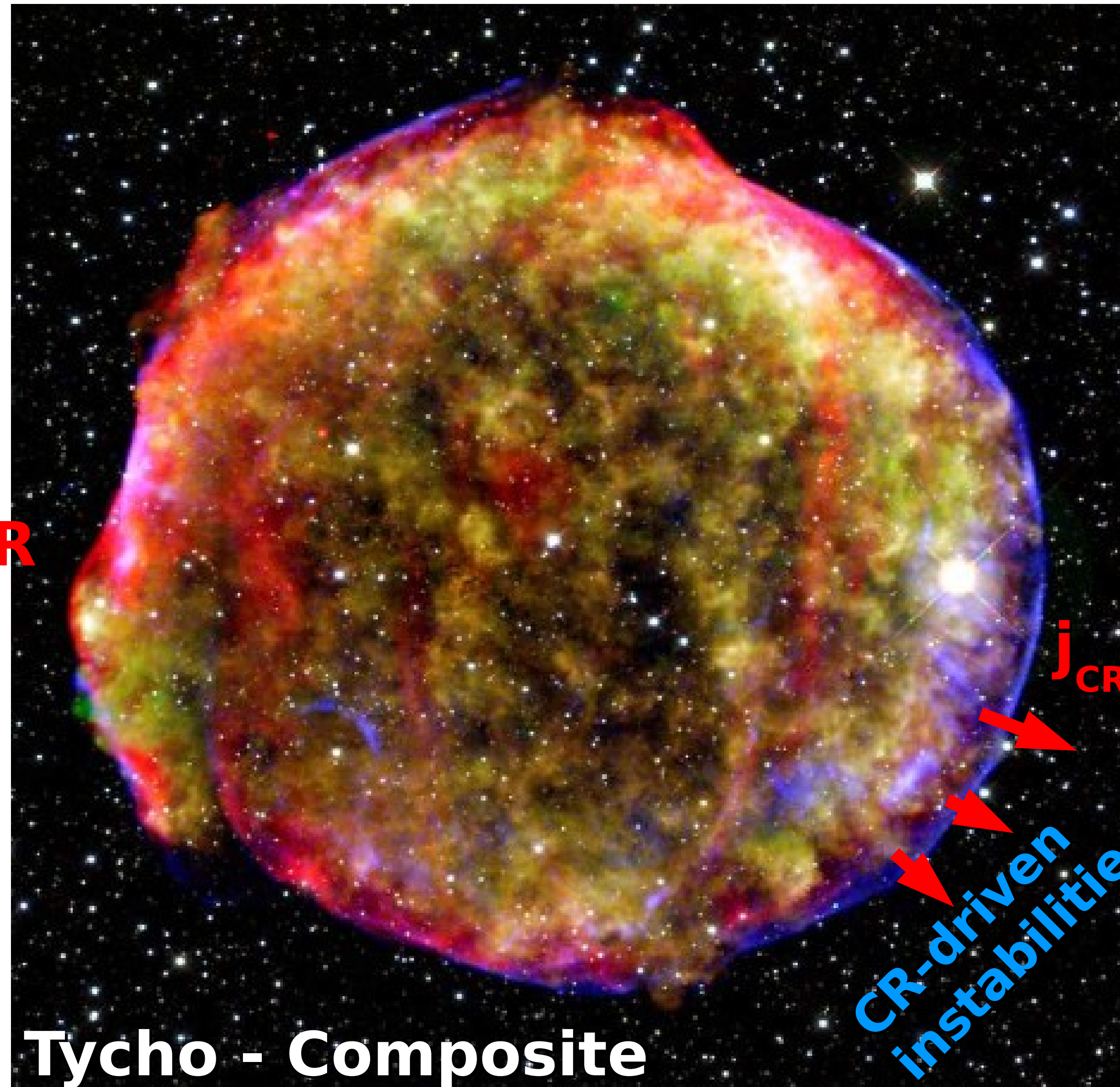


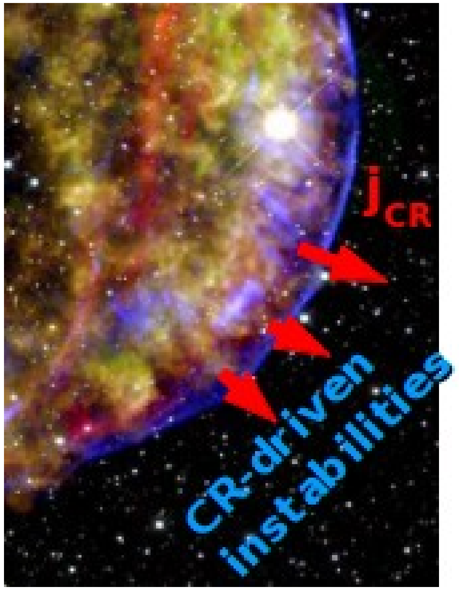


Sources, acceleration mechanism

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







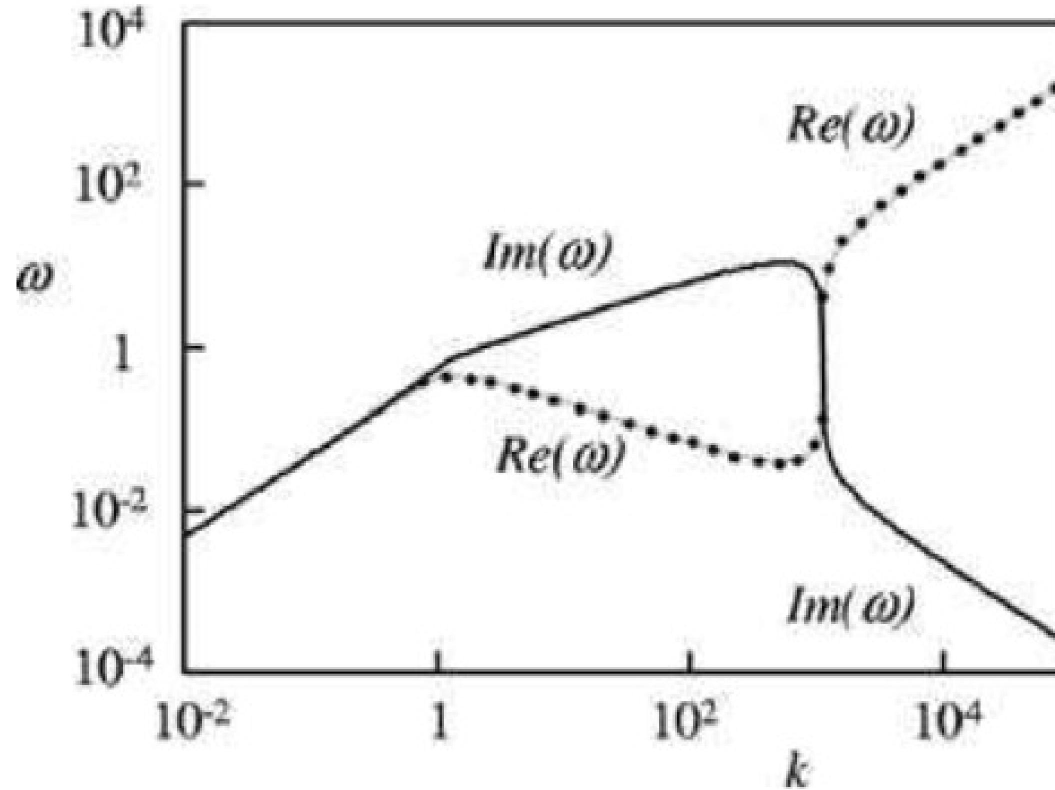
Bell's instability

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

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

$$\Gamma_{\mathrm{BNRH}} = 0.5 j_{\mathrm{CR}} \sqrt{\mu_0 / \rho_{\mathrm{ISM}}} \text{ and } \Gamma_{\mathrm{Alf}} \approx 0.3 j_{\mathrm{CR}} \sqrt{\mu_0 / \rho_{\mathrm{ISM}}}$$

(Bell '04)



Bell's instability

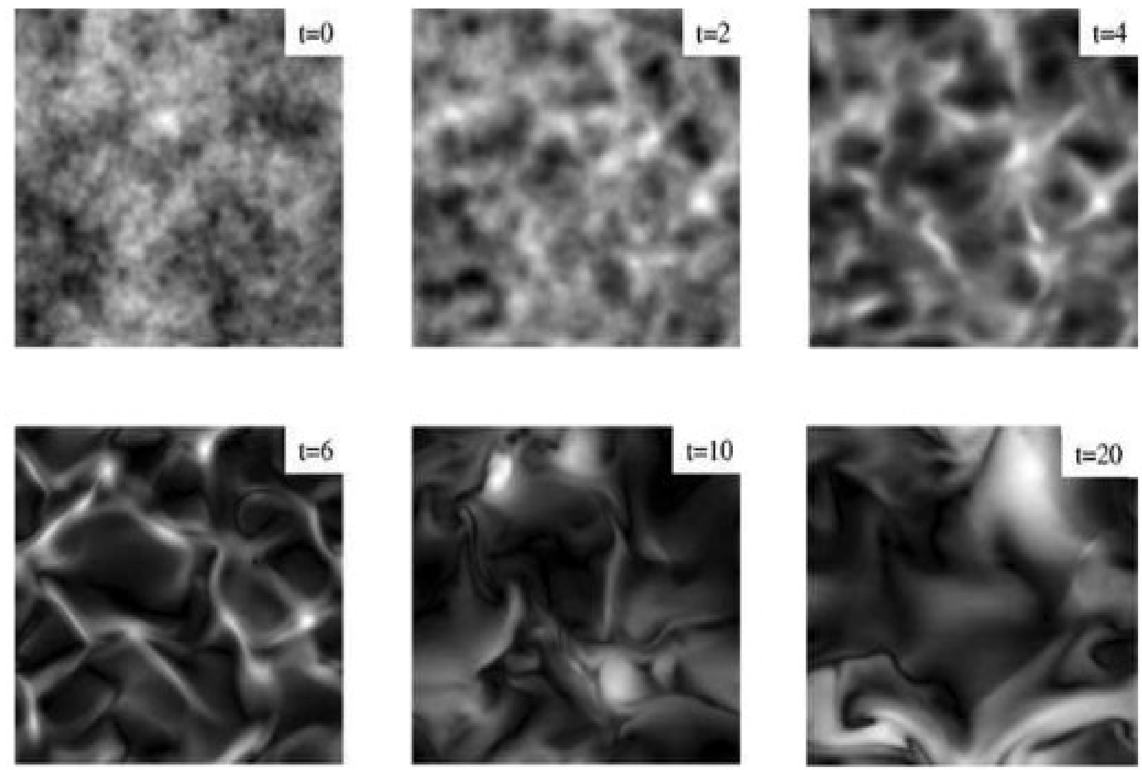
carries a charge density $-n_{cr}e$. If the background plasma carries a current density $\boldsymbol{j}$ in its local rest frame, then $\nabla \wedge \boldsymbol{B} = \mu_0(\boldsymbol{j}_{cr} + \boldsymbol{j} - n_{cr}e\,\boldsymbol{u})$ where $\boldsymbol{u}$ is the local plasma fluid velocity. Consequently, in the upstream rest frame (moving at speed v_s relative to the shock), the momentum equation for the background plasma is

$$\rho \frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = -\nabla P - \frac{1}{\mu_0}\boldsymbol{B} \wedge (\nabla \wedge \boldsymbol{B}) - \boldsymbol{j}_{cr} \wedge \boldsymbol{B} + n_{cr}e\boldsymbol{u} \wedge \boldsymbol{B}, \qquad (1)$$

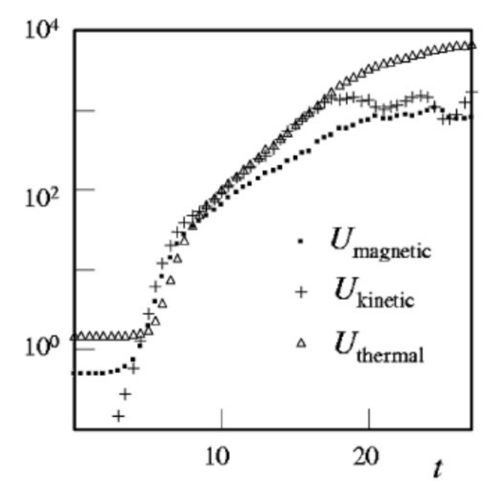
where P is the background plasma pressure. The plasma pressure plays no part in the linear calculation as the fluctuations are transverse in the cases we consider. The other MHD equations are unaffected by the presence of the CR:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \wedge (\boldsymbol{u} \wedge \boldsymbol{B}); \qquad \frac{\mathrm{d}\rho}{\mathrm{d}t} = -\nabla \cdot (\rho \boldsymbol{u}). \qquad (2)$$

These equations make it clear that the MHD turbulence is driven by the $-\boldsymbol{j}_{cr} \wedge \boldsymbol{B}$ force exerted in reaction to the $\boldsymbol{j}_{cr} \wedge \boldsymbol{B}$ force exerted on CR through the current they carry.



(Bell '04)



CR acceleration and escape

Mon. Not. R. Astron. Soc. **000**, 1–17 (2013) Printed 31 January 2013 (MN LATEX style file v2.2)

Cosmic ray acceleration and escape from supernova remnants

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ABSTRACT
Galactic cosmic ray (CR) acceleration to the knee in the spectrum at a few PeV is only possible if the magnetic field ahead of a supernova remnant (SNR) shock is strongly amplified by CR escaping the SNR. A model formulated in terms of the electric charge carried by escaping CR predicts the maximum CR energy and the energy spectrum of CR released into the surrounding medium. We find that historical SNR such as Cas A, Tycho and Kepler may be expanding too slowly to accelerate CR to the knee at the present time.

Key words: cosmic rays, acceleration of particles, shock waves, magnetic field, ISM: supernova remnants

CR acceleration and escape

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:

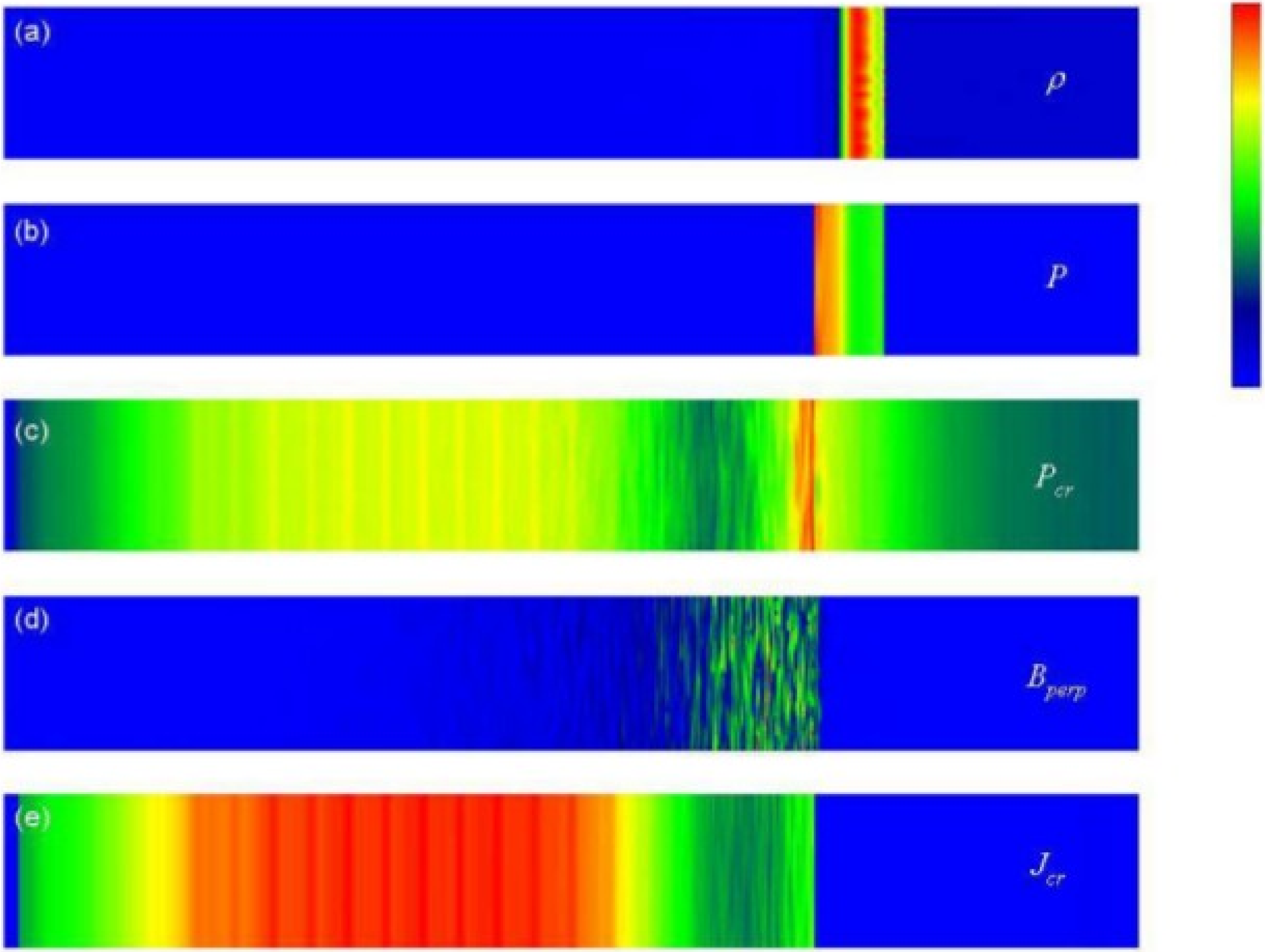
$$\rho \frac{d\mathbf{u}}{dt} = -\nabla P - \frac{1}{\mu_0}\mathbf{B} \times (\nabla \times \mathbf{B}) - \mathbf{j}_{CR} \times \mathbf{B} \qquad (7)$$

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

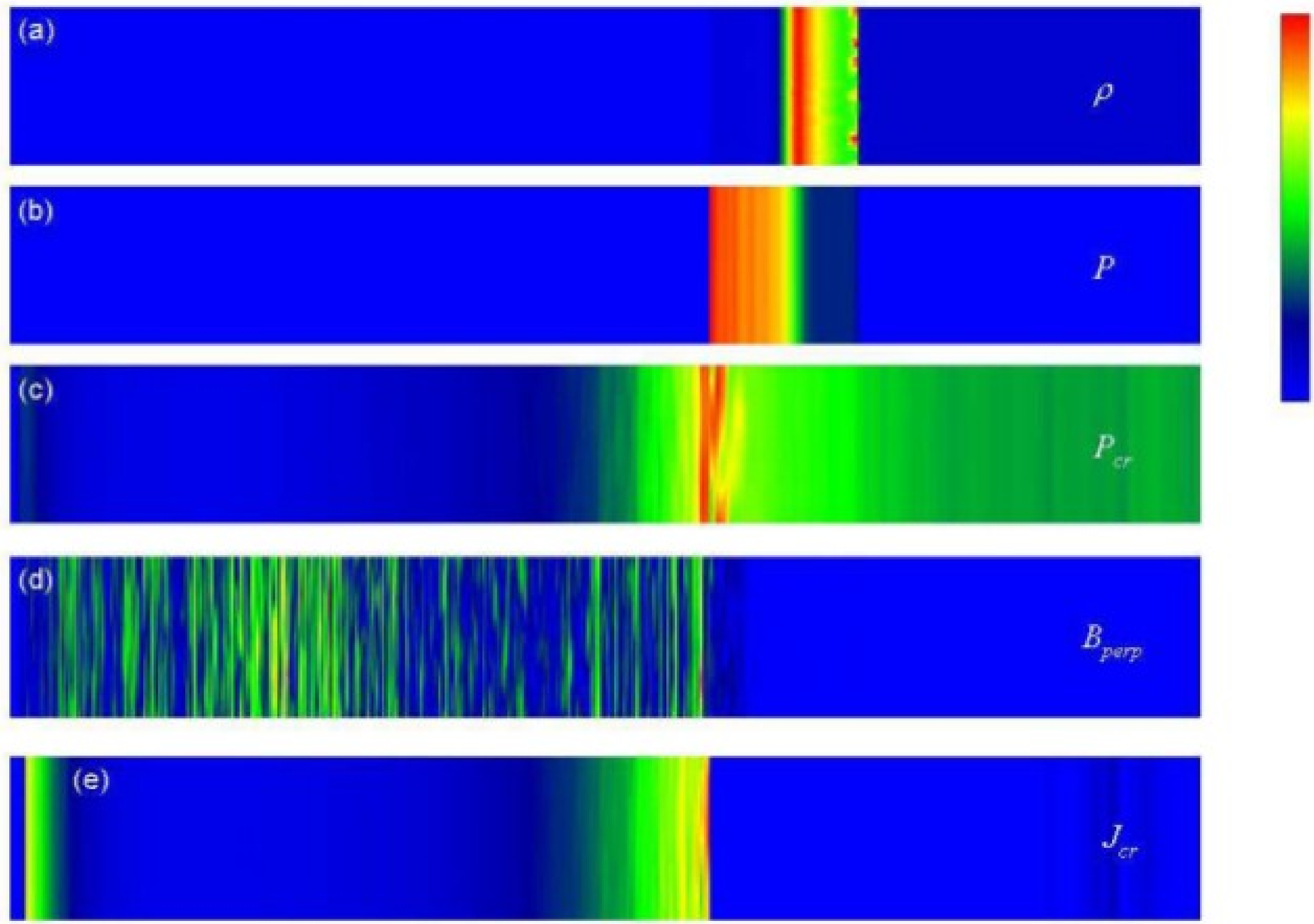
$$\frac{df}{dt} = -v_i \frac{\partial f}{\partial r_i} + p_i \frac{\partial u_j}{\partial r_i}\frac{\partial f}{\partial p_j} - \epsilon_{ijk} e v_i B_j \frac{\partial f}{\partial p_k} + C(f) \qquad (8)$$

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



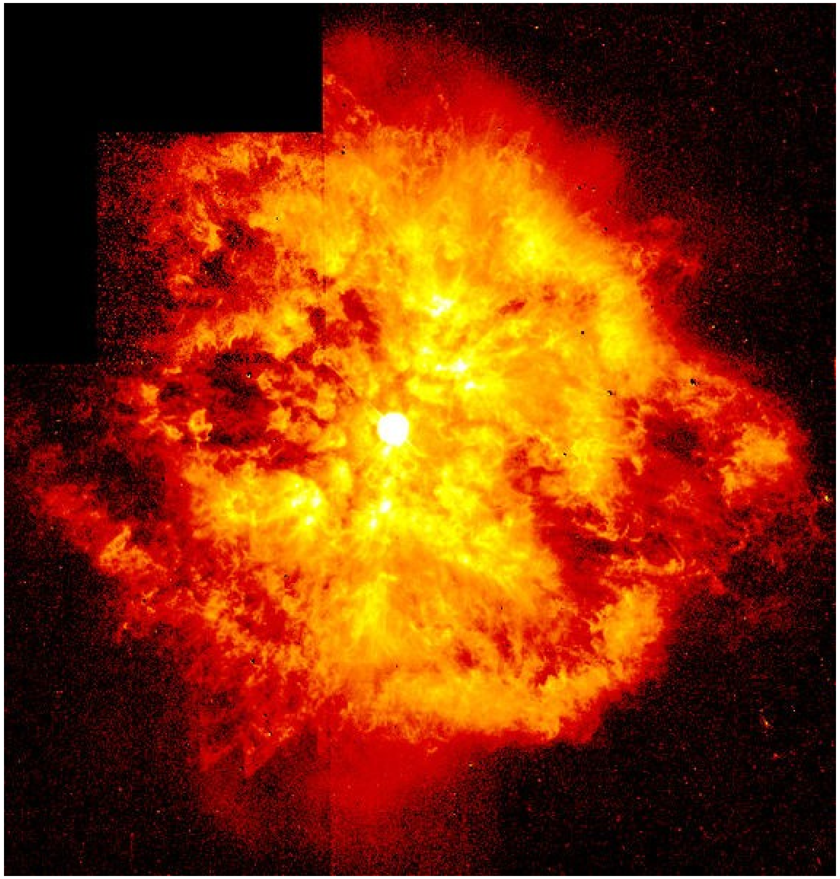
CR acceleration and escape

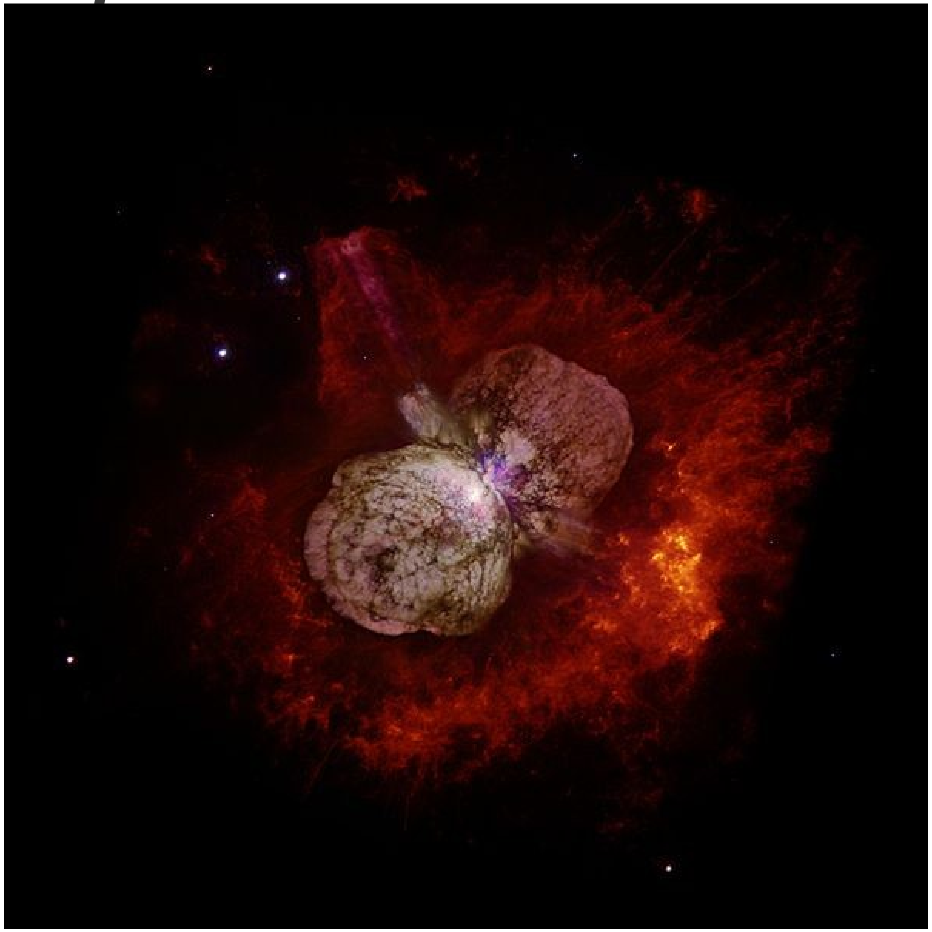


Core-Collapse SNe, Progenitors, Circumstellar winds

– Variety of progenitors and SNe types.

– Mass loss and circumstellar material :
Optically thin or thick winds possible





CR acceleration and escape

$$Q_{CR} = 10\sqrt{\rho/\mu_0}\ \text{Coulomb m}^{-2}$$

$$j_{CR} = \eta\rho u_s^3 r^2/R^2 T$$

η ~ 0.03

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

(m=0)

$$T(R) = \frac{\eta\sqrt{\mu_0}}{5(4-m)} u_s^2 R\sqrt{\rho}$$

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

(m=2)

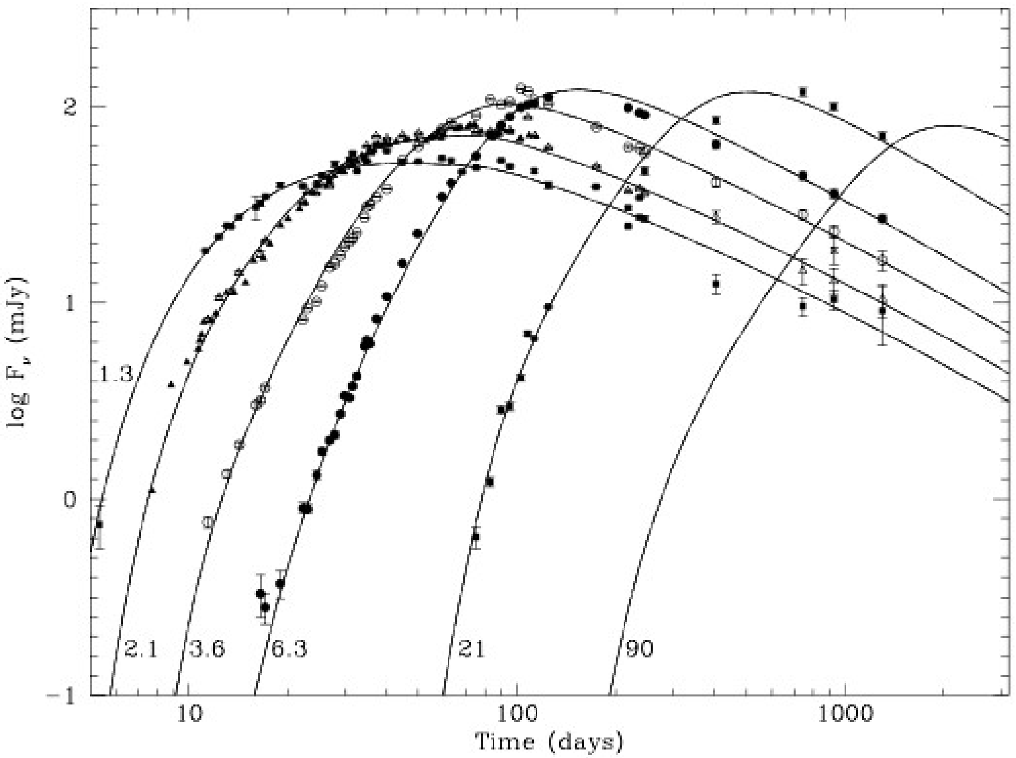
II – Radio and X-Ray SNe :
The onset of CR acceleration ?

Cosmic Ray electrons at fwd. shock & radio SNe

Radio :

→ Due to SSA

→ Sometimes a bit of free-free abs. further diminish the flux at early times



Fransson & Björnsson '98 - SN1993J

Cosmic Ray electrons at fwd. shock & radio SNe

THE ASTROPHYSICAL JOURNAL, 509:861–878, 1998 December 20
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RADIO EMISSION AND PARTICLE ACCELERATION IN SN 1993J

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Received 1998 April 27; accepted 1998 July 27

ABSTRACT

The radio light curves of SN 1993J are discussed. We find that a fit to the individual spectra by a synchrotron spectrum, suppressed by external free-free absorption and synchrotron self-absorption, gives a superior fit to models based on pure free-free absorption. A standard r^{-2} circumstellar medium is assumed and is found to be adequate. From the flux and cutoff wavelength, the magnetic field in the synchrotron-emitting region behind the shock is determined to $B \approx 64(R_s/10^{15}\ \mathrm{cm})^{-1}$ G. The strength of the field argues strongly for turbulent amplification behind the shock. The ratio of the magnetic and thermal energy density behind the shock is ~ 0.14. Synchrotron losses dominate the cooling of the electrons, whereas inverse Compton losses due to photospheric photons are less important. For most of the time also Coulomb cooling affects the spectrum. A model where a constant fraction of the shocked, thermal electrons are injected and accelerated, and subsequently lose their energy due to synchrotron losses, reproduces the observed evolution of the flux and number of relativistic electrons well. The injected electron spectrum has $dn/d\gamma \propto \gamma^{-2.1}$, consistent with diffusive shock acceleration. The injected number density of relativistic electrons scales with the thermal electron energy density, ρV^2, rather than the density, ρ. The evolution of the flux is strongly connected to the deceleration of the shock wave. The total energy density of the relativistic electrons, if extrapolated to $\gamma \sim 1$, is $\sim 5 \times 10^{-4}$ of the thermal energy density. The free-free absorption required is consistent with previous calculations of the circum-

Cosmic Ray electrons at fwd. shock & 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 $\sim 10^{16}$ cm the magnetic field is $\sim$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).

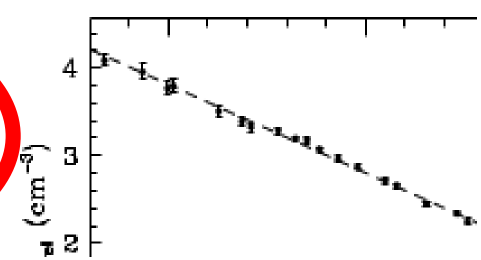
At 10 days, corresponding to a radius $\sim 1.9 \times 10^{15}$ cm, we find that the magnetic field in the emitting region is $\sim$34 G. Using the above estimate of the circumstellar magnetic field and a shock compression by a factor of 4, this post-shock magnetic field would be $B \approx (2.4–4.8) \times 10^{-2}$ G. This is a factor $\sim 10^3$ 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

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

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



Cosmic Ray electrons at fwd. shock & radio SNe

THE ASTROPHYSICAL JOURNAL, **333**:L65–L68, 1988 October 15
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MAXIMUM ENERGY OF COSMIC-RAY PARTICLES ACCELERATED BY SUPERNOVA REMNANT SHOCKS IN STELLAR WIND CAVITIES

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Received 1988 May 25; accepted 1988 July 28

ABSTRACT

In this *Letter* we demonstrate that diffusive shock acceleration, balanced by adiabatic losses, leads readily to particle energies of $\geq 10^{15}$ eV in the case of a supernova shock freely expanding into a stellar wind cavity. This process accelerates particles early on out of stellar wind material which is often enriched in certain elements (isotopes) and may thus contribute to explain elemental and isotopic anomalies in the cosmic rays. We speculate that the same process may produce particle energies up to 10^{19} eV in the case of a supernova explosion in a compact binary star.

Subject headings: cosmic rays: abundances — cosmic rays: general — nebulae: supernova remnants — particle acceleration — shock waves — stars: circumstellar shells

Cosmic Ray electrons at fwd. shock & 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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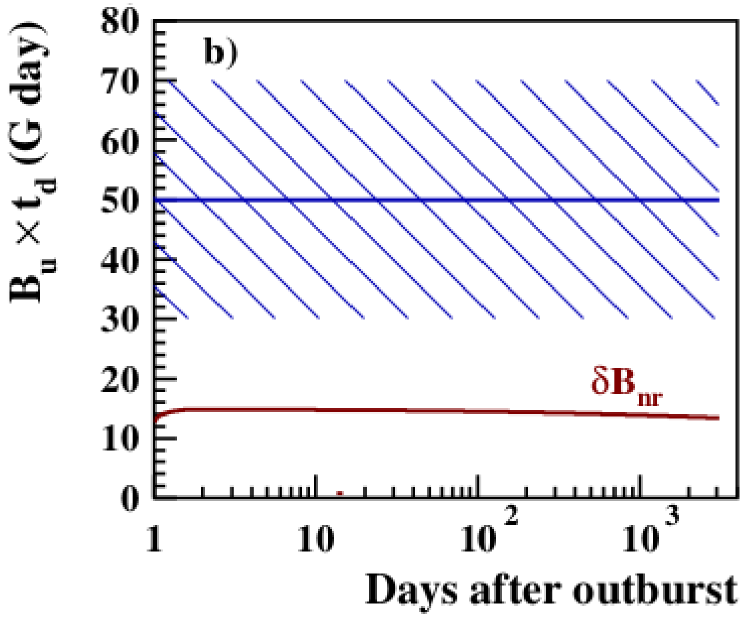
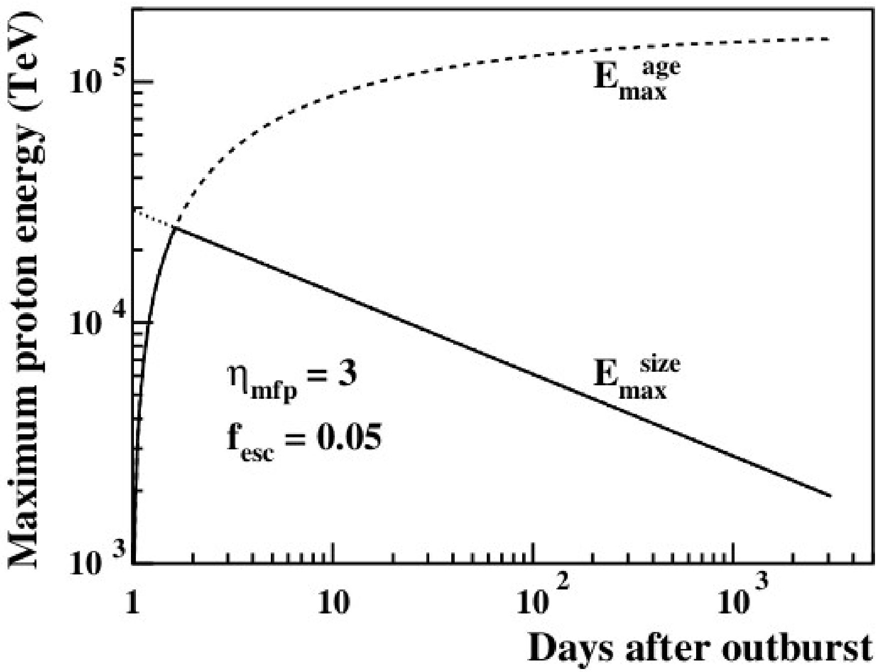


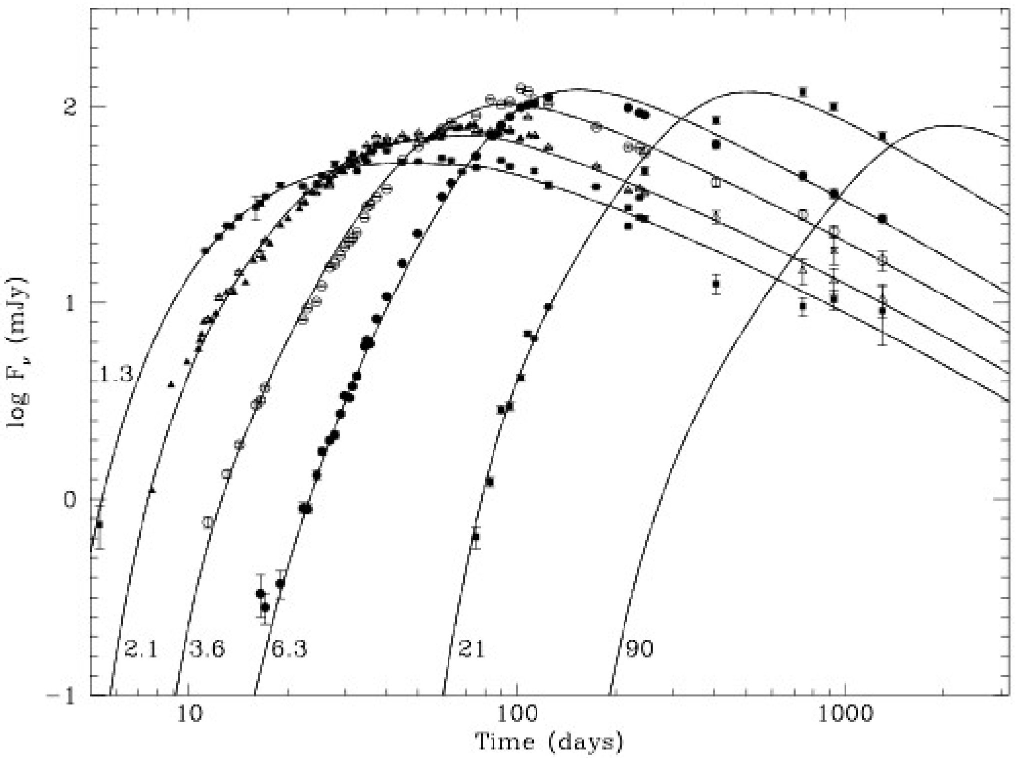


Cosmic Ray electrons at fwd. shock & radio SNe

Radio :

→ Due to SSA

→ Sometimes a bit of free-free abs. further diminish the flux at early times



Fransson & Björnsson '98 - SN1993J

X-rays :

→ Due to synchrotron (?) or Inverse Compton (more often)

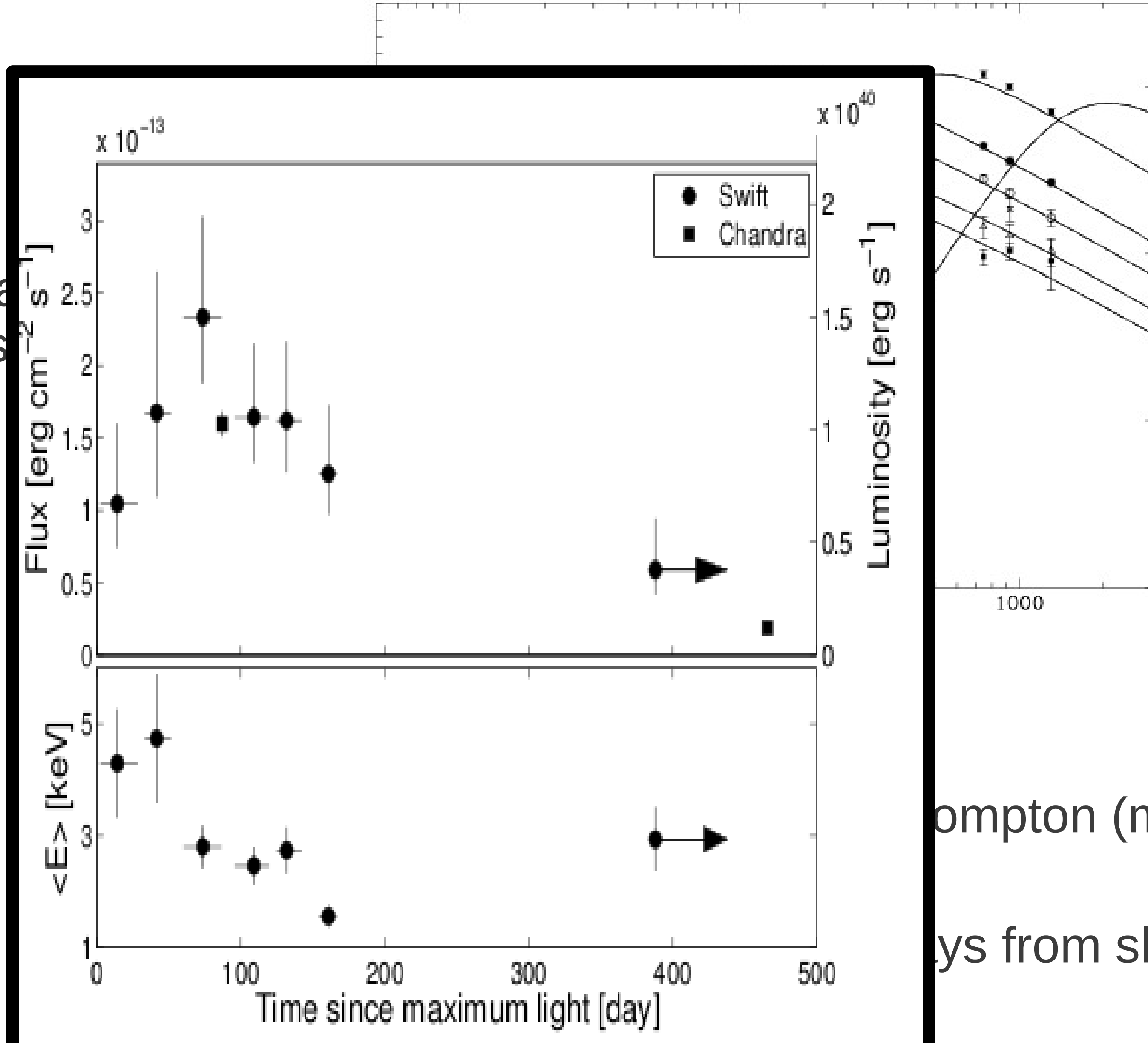
but often dominated by thermal X-rays from shock heated ISM

Cosmic Ray electrons at fwd. shock & radio SNe

<u>Radio :</u>

→ Due to SSA

→ Sometimes a
free-free abs
diminish the
early times



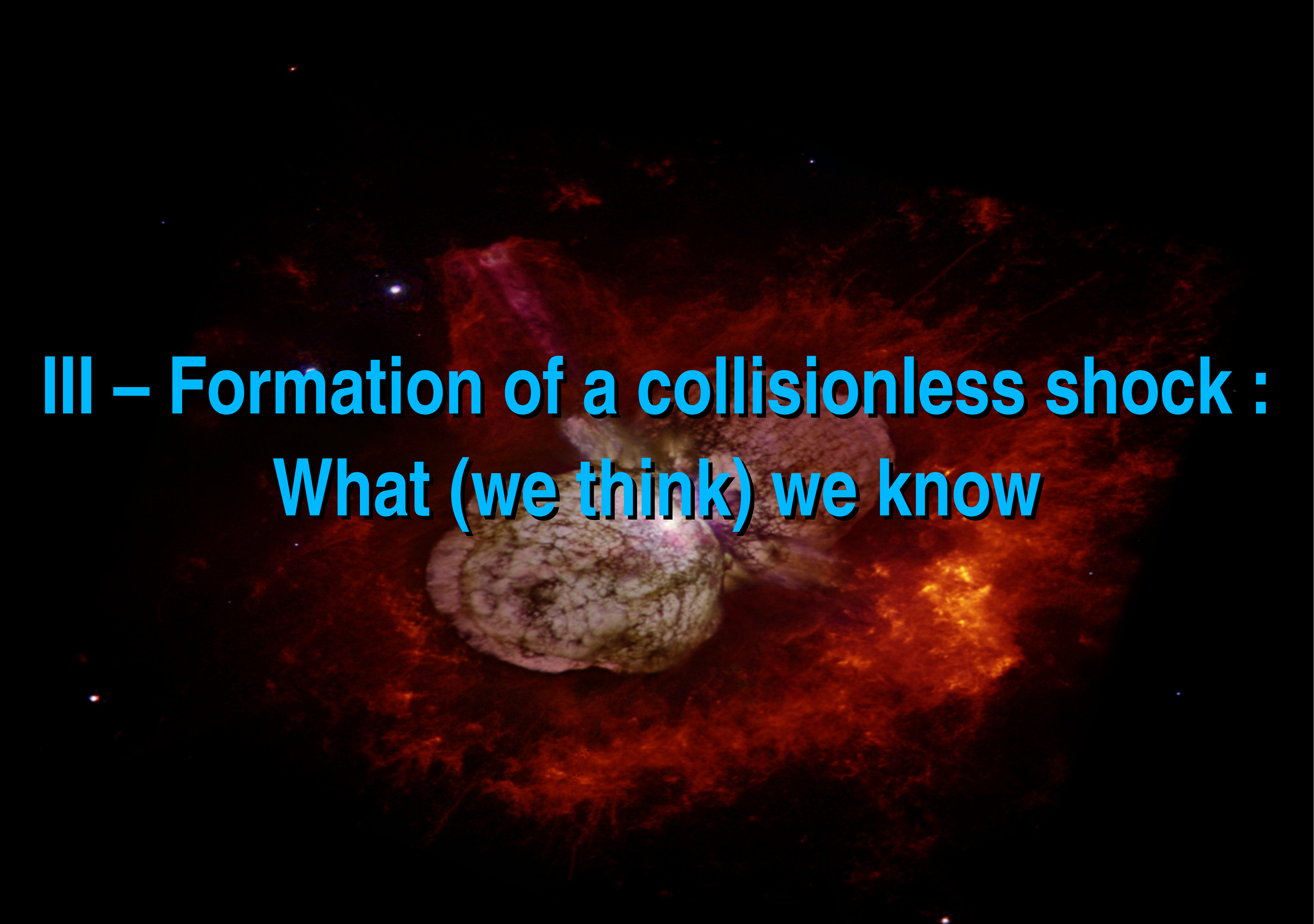
<u>X-rays :</u>

ompton (more

ys from shock

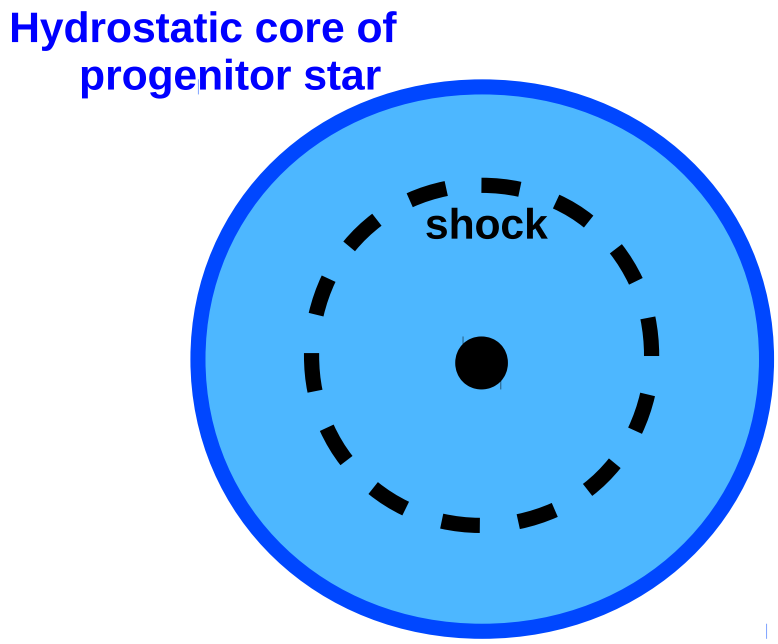
Ofek *et al.* '12

(SN 2006jc)



III – Formation of a collisionless shock : What (we think) we know

Shock Evolution and Shock Breakout



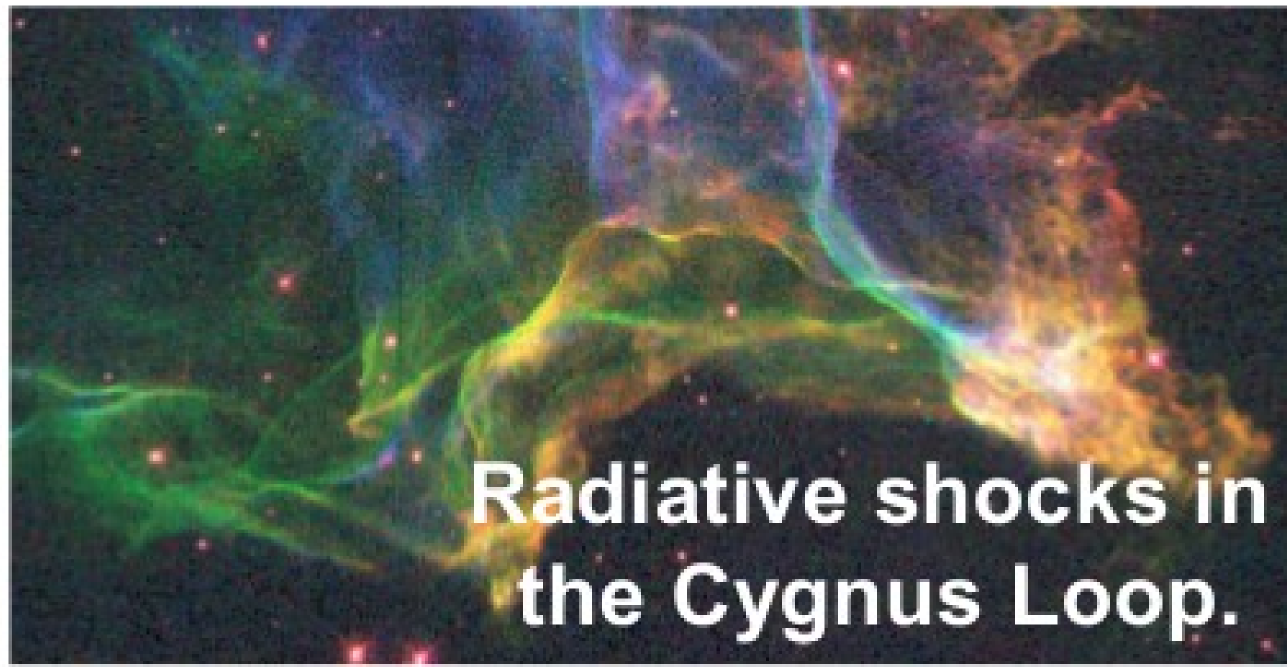
<u>Radiation Dominated (or Mediated) shock</u>

(*i.e.* $p_{rad} > p_{fl}$ downstr.)

Not the same as a *radiative* shock !

Shock Evolution and Shock Breakout

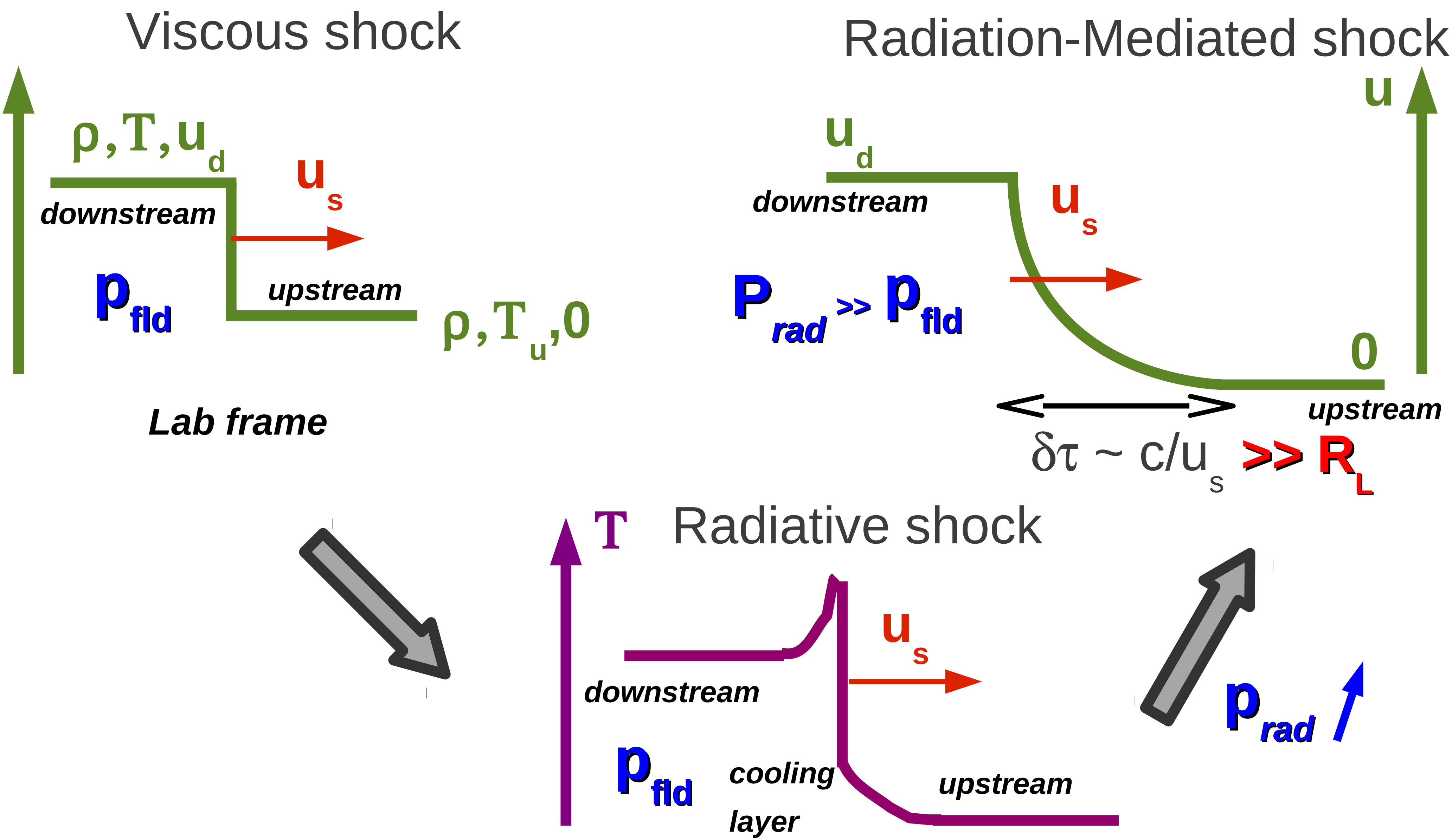
Ex. of *radiative* shock



McKee and Draine, Science ____

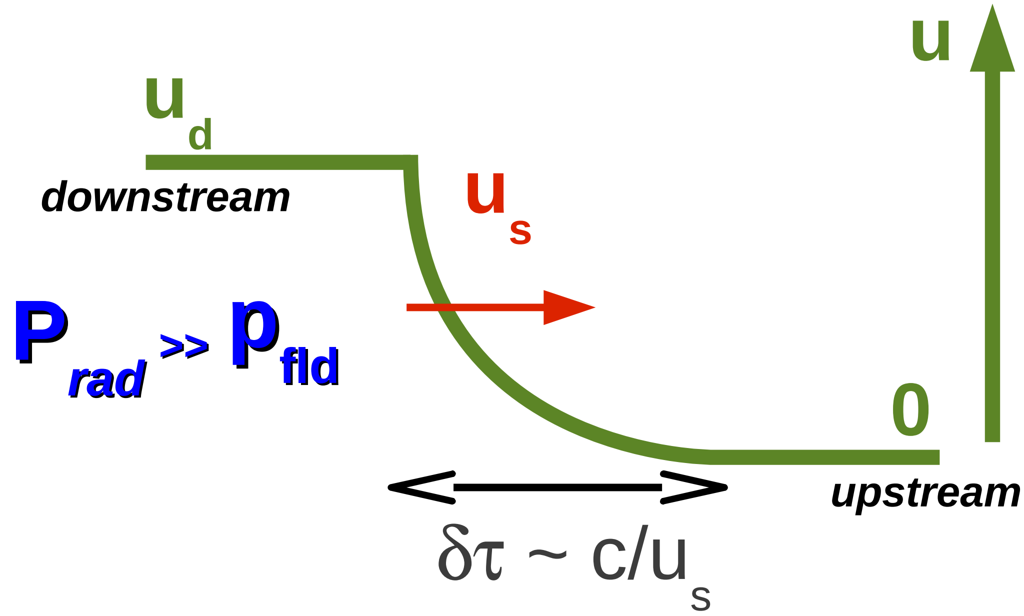
Not the sa
radiative shock !

Radiation mediated shocks



Radiation mediated shocks

Radiation-Mediated shock

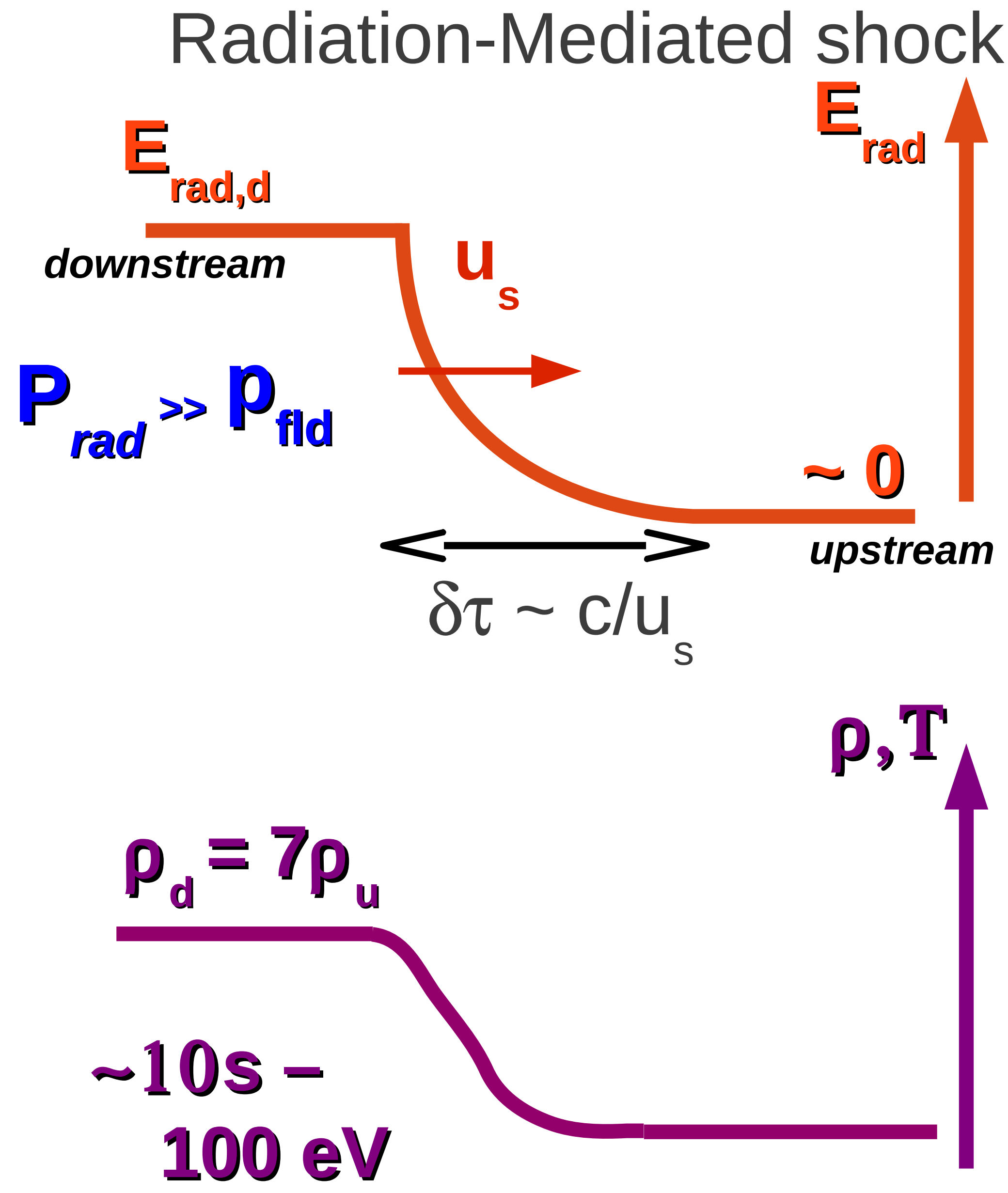


Radiation mediated shocks

Diffusive flux : $-D\, \delta E_{rad}/\delta r$

Advective flux : $-u_s\, E_{rad}$

$L_s \sim D/u_s \sim \lambda/\beta$



Radiation mediated shocks

See works of :

Zel'dovitch & Raizer '66

Colgate '74

Arnett '70s

Weaver '76

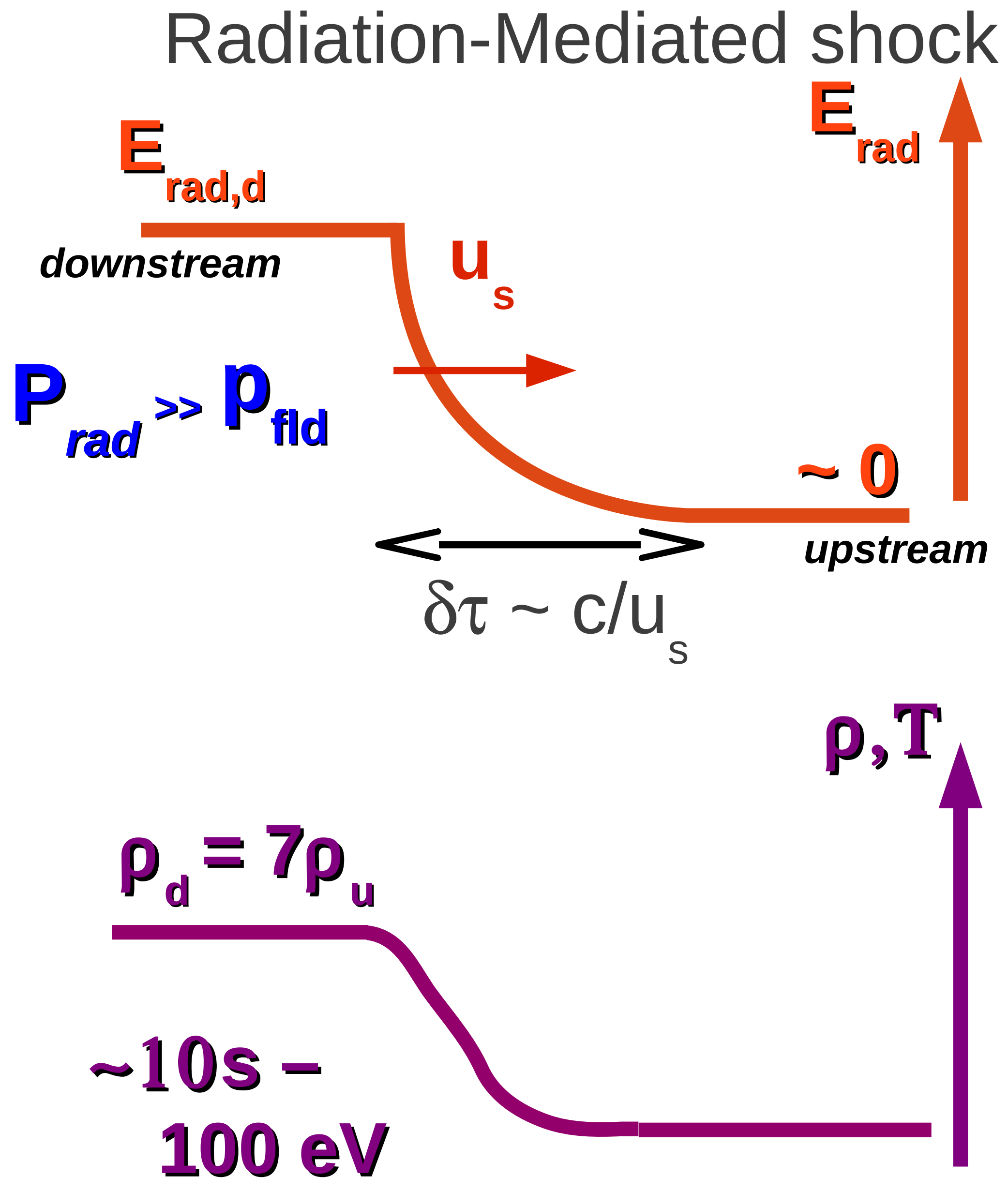
Falk '78

Klein & Chevalier '78

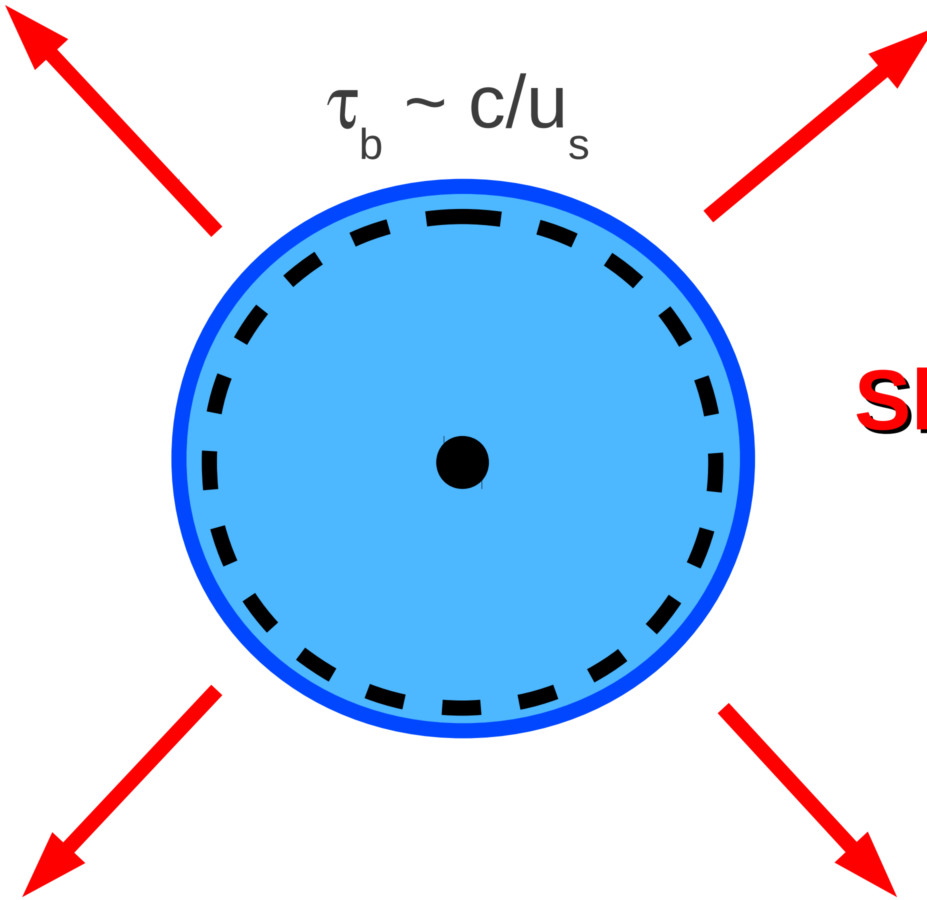
Matzner & McKee '99

Katz *et al.* 2010's

etc...



Shock Evolution and Shock Breakout

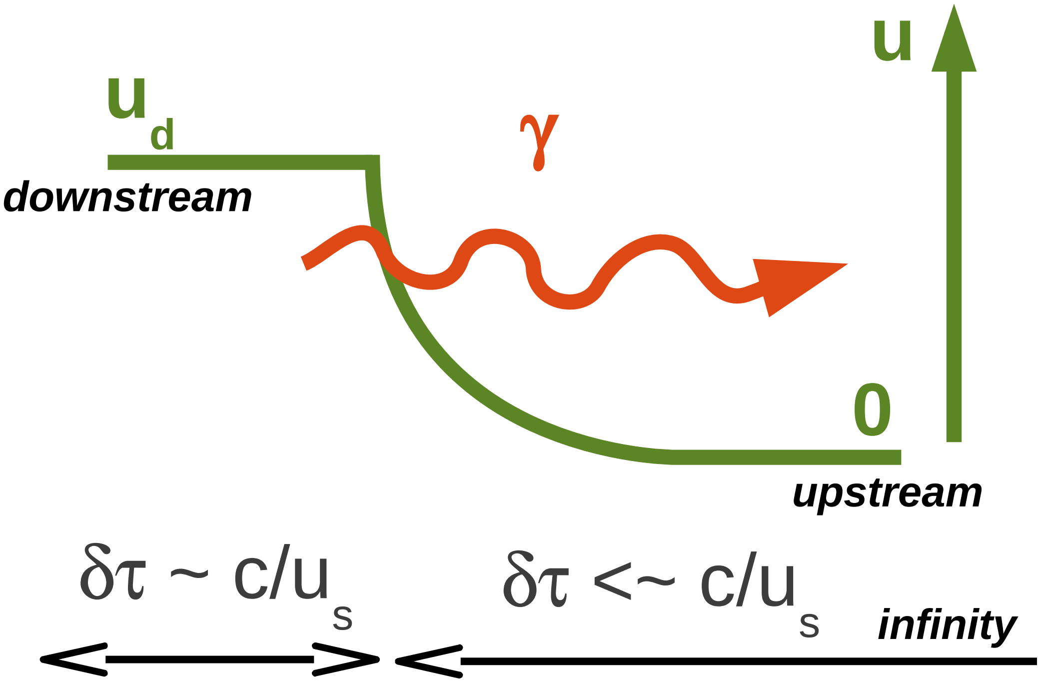


$\tau_b \sim c/u_s$

Shock breakout

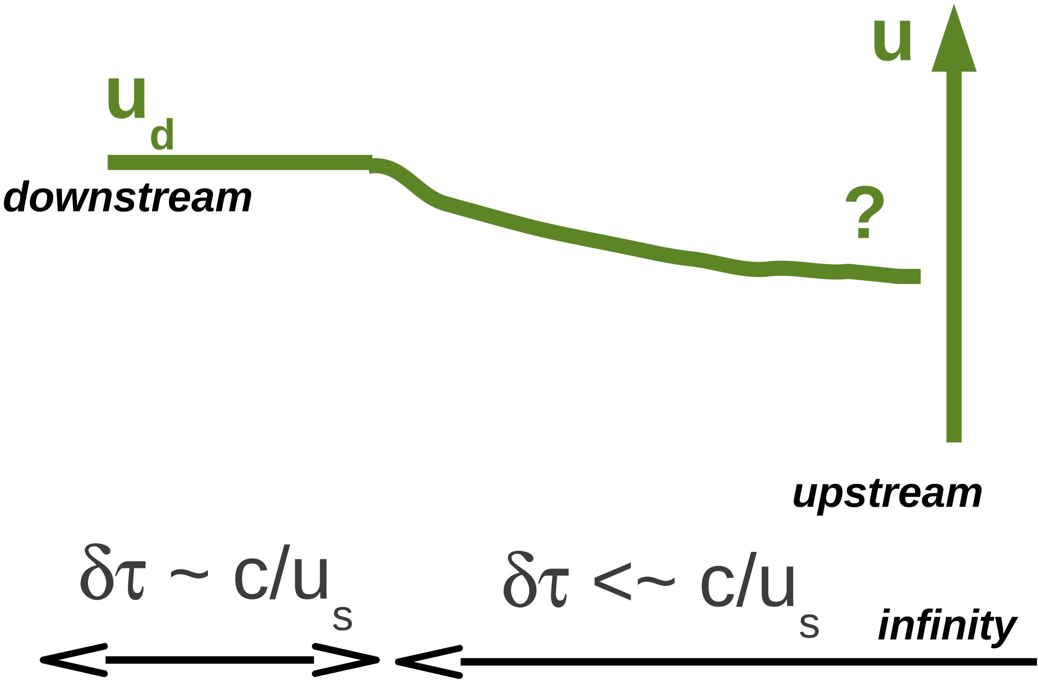
('flash')

Shock breakout



~ 10 – 100 eV
to X rays

Shock breakout



The radiation-mediated shock <u>disappears</u> !

THE ASTROPHYSICAL JOURNAL, 234:597–608, 1979 December 1
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NONEQUILIBRIUM PROCESSES IN THE EVOLUTION OF TYPE II SUPERNOVAE

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Received 1979 April 3; accepted 1979 June 21

ABSTRACT

The emergence of the shock wave from the envelope of a type II supernova is investigated in the approximation of gray radiative transfer. The calculations allow for nonequilibrium between the gas and the radiation field. It is found that the inclusion of flux-limiting does not play a large role in the radiative energy equation, while it is very important in the momentum equation. If the assumption of an isotropic radiation field is made in the momentum equation, the shock remains radiation dominated. The reduced radiative flux with a flux limiter reduces the momentum coupling between the radiation and the gas, and permits a transition from a radiation-dominated to a viscous shock wave as the shock moves into optically thin layers of the star. The occurrence of a viscous shock is important for the creation of hot gas ($T \approx 10^8$ K) in the outer layers of the atmosphere, which can radiate a substantial, hard X-ray flux.

After the completion of the hydrodynamic calculation, the emergent spectrum of the supernova at selected times was computed by solving the nongray time-independent radiative transfer equation on the assumption of coherent isotropic scattering and an LTE nonscattering source function. These calculations allowed the predictions of the X-ray flux from a Type II supernova by Klein and Chevalier. We have now found that the neglect of the time-dependent terms in the radiative transfer equation is moderately inaccurate so that our predictions can be regarded only as estimates of the X-ray burst.

Subject headings: shock waves — stars: supernovae — X-rays: bursts

THE ASTROPHYSICAL JOURNAL, 234:597–608, 1979 December 1
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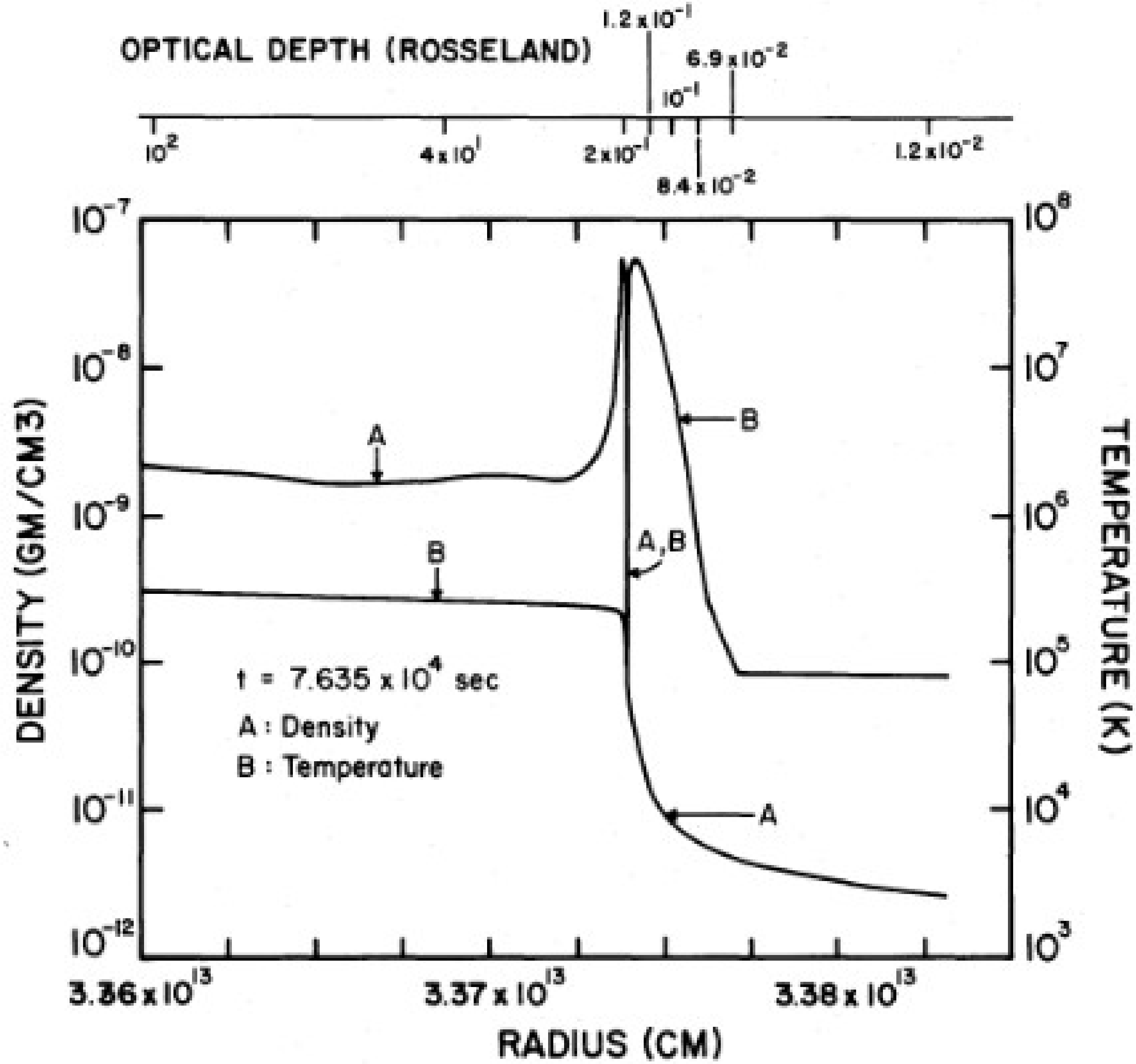

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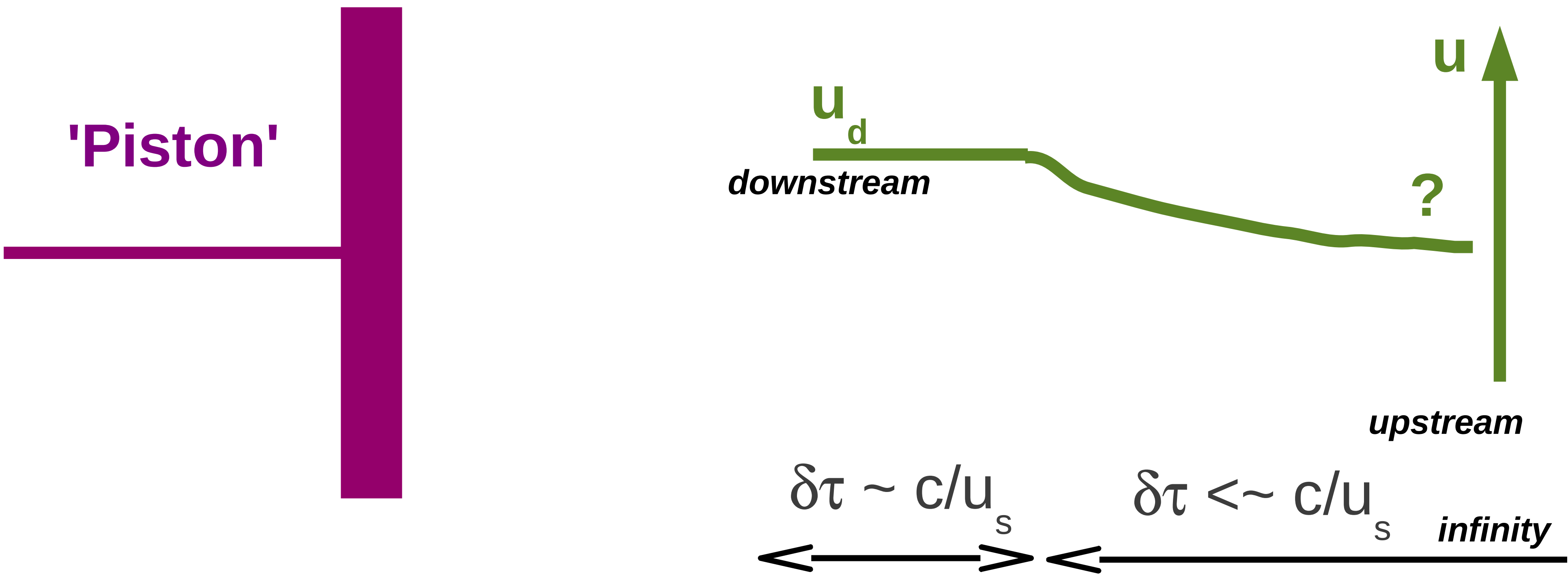
TeV Neutrinos and GeV Photons from Shock Breakout in Supernovae

Eli Waxman[†] & Abraham Loeb[⋆]
† *Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel; waxman@wicc.weizmann.ac.il*
⋆ *Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA; aloeb@cfa.harvard.edu*
(February 5, 2008)

We show that as a Type II supernova shock breaks out of its progenitor star, it becomes collisionless and may accelerate protons to energies > 10 TeV. Inelastic nuclear collisions of these protons produce a ~ 1 hr long flash of TeV neutrinos and 10 GeV photons, about 10 hr after the thermal (10 MeV) neutrino burst from the cooling neutron star. A Galactic supernova in a red supergiant star would produce a photon and neutrino flux of $\sim 10^{-4}$ erg cm^{-2} s^{-1}. A km^2 neutrino detector will detect ~ 100 muons, thus allowing to constrain both supernova models and neutrino properties.

PACS numbers: 97.60.Bw, 14.60.Pq, 98.70.Rz, 95.85.Ry

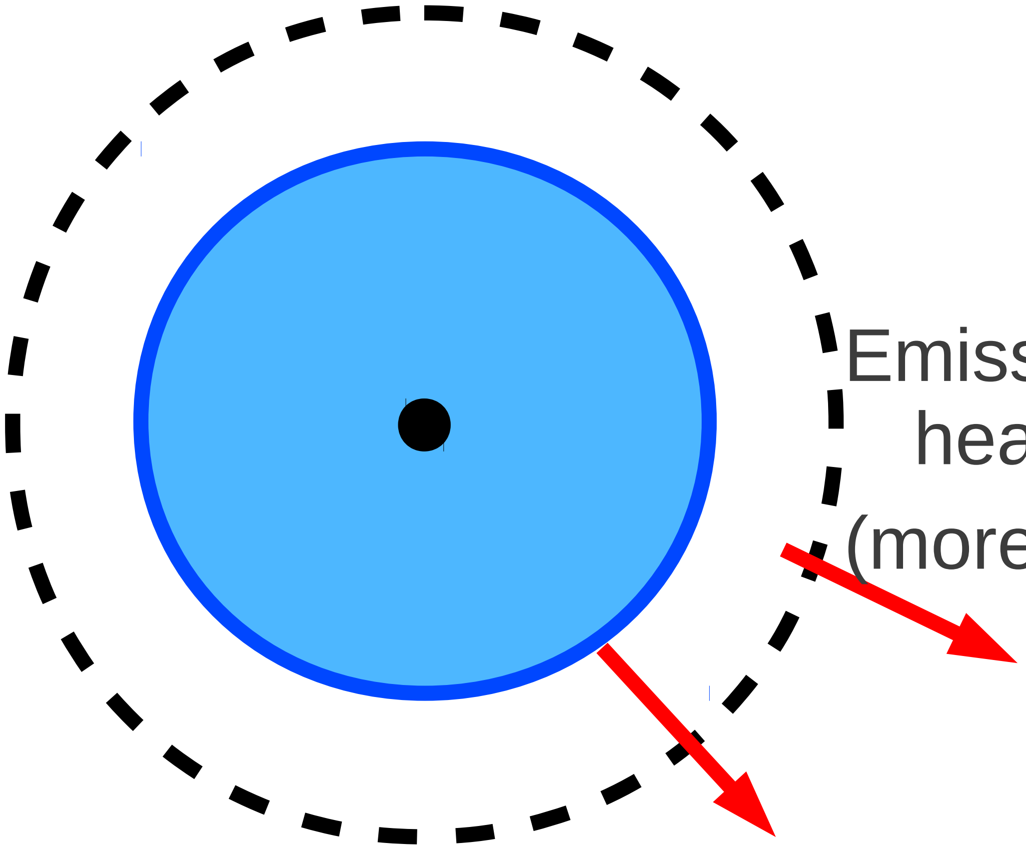
Shock breakout



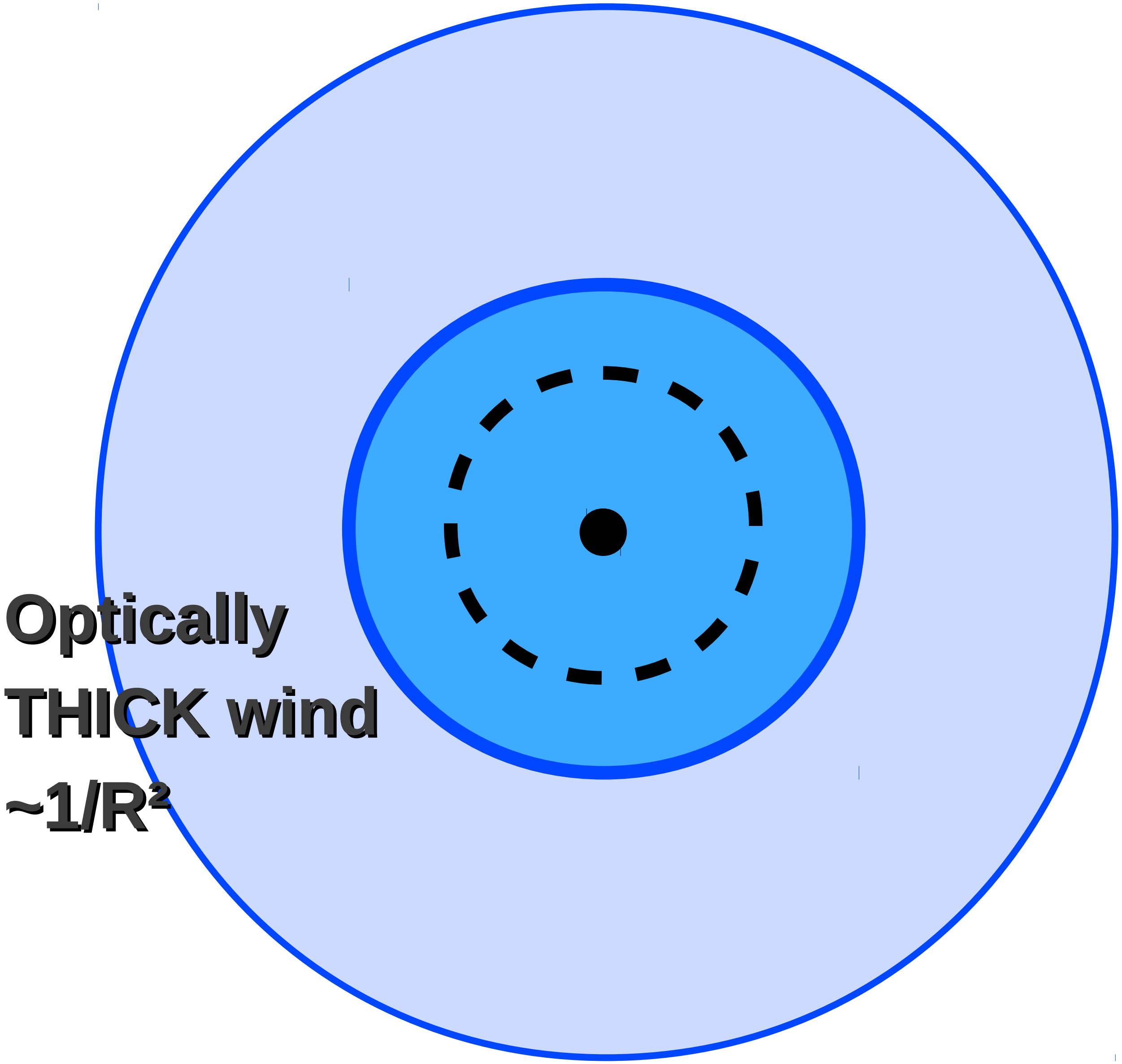
The radiation mediated shock disappears !

If **?** < u_d : 'Need to be accelerated to u_d & Radiation will not do it => Should be done by the fluid pressure => **C.S.**'

Shock Evolution and Shock Breakout

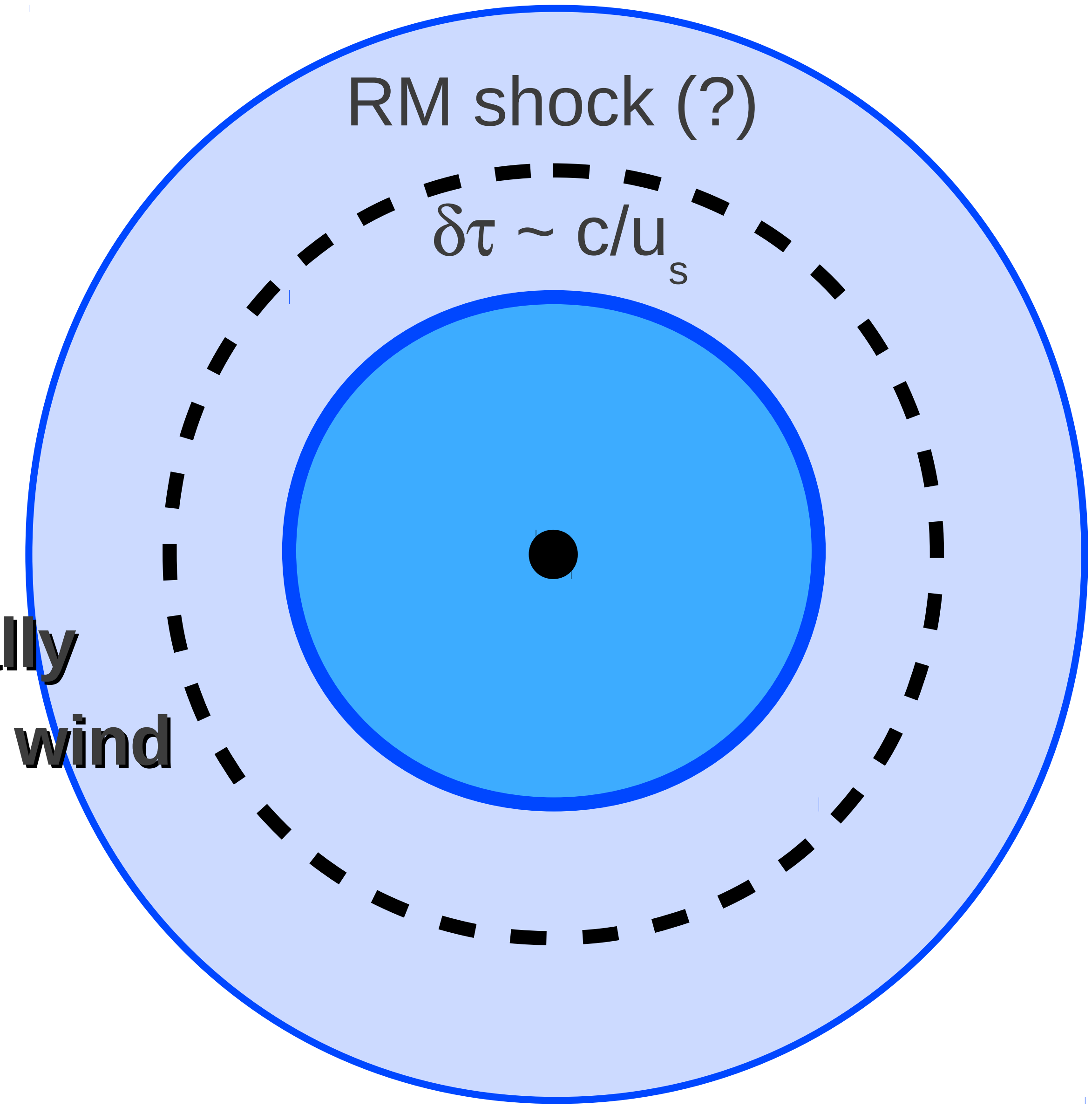


Shock Evolution and Shock Breakout



$$\tau \sim c/u_{\rm s} = \beta_{\rm s}^{-1}$$

Shock Evolution and Shock Breakout

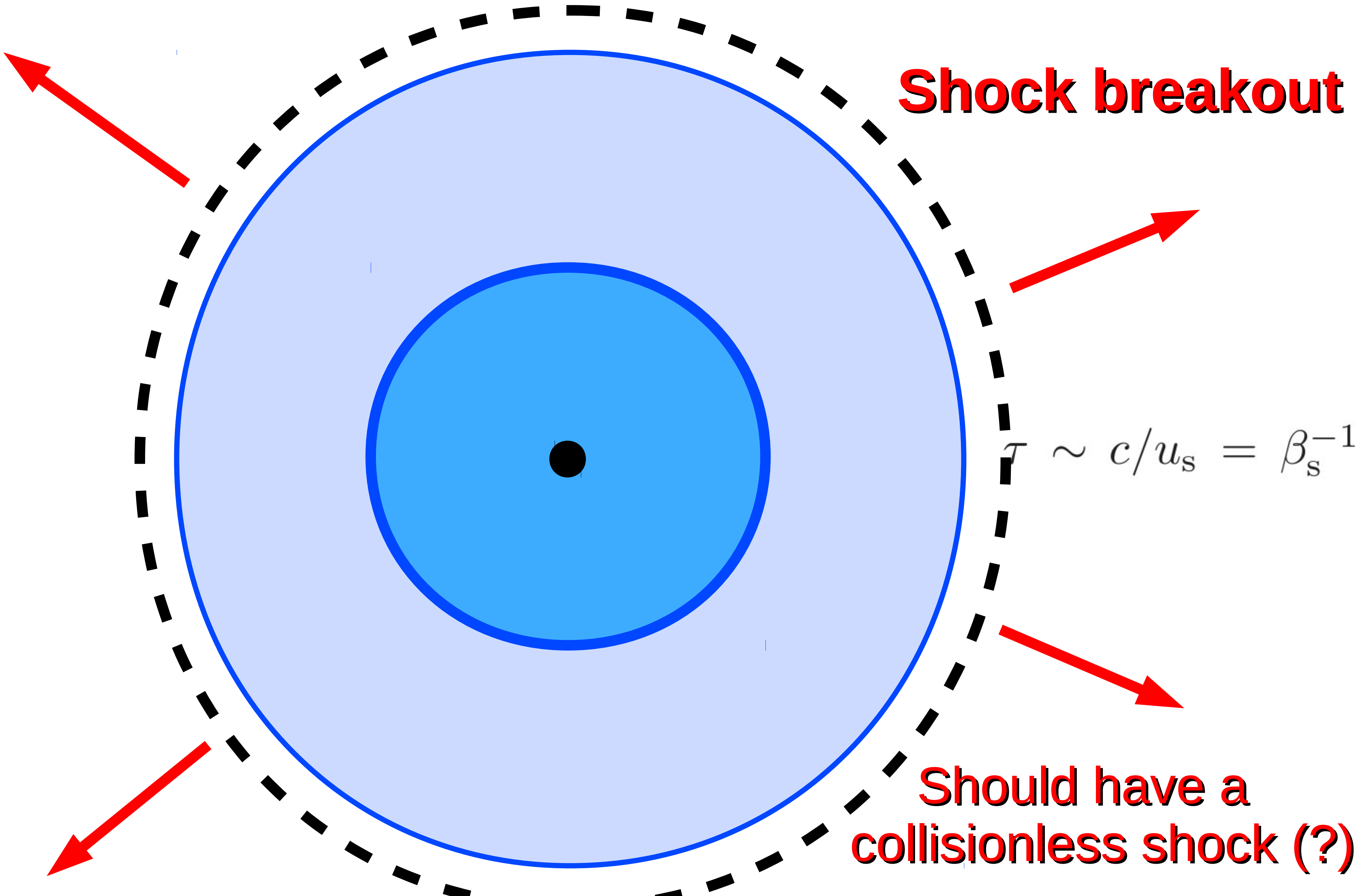


Optically THICK wind ~1/R²

$$\tau \sim c/u_\mathrm{s} = \beta_\mathrm{s}^{-1}$$

See works of Katz *et al.*, etc.

Shock Evolution and Shock Breakout



$$\tau \sim c/u_s = \beta_s^{-1}$$

X-rays, γ-rays and neutrinos from collisoinless shocks in supernova wind breakouts

Boaz Katz[1*], Nir Sapir[2], and Eli Waxman[2]
[1]*Institute for Advanced Study, Princeton, NJ 08540, USA and*
[2]*Dept. of Particle Phys. & Astrophys., Weizmann Institute of Science, Rehovot 76100, Israel*

We show that a collisionless shock necessarily forms during the shock breakout of a supernova (SN) surrounded by an optically thick wind. An intense non-thermal flash of $\lesssim 1$ MeV gamma rays, hard X-rays and multi-TeV neutrinos is produced simultaneously with and following the soft X-ray breakout emission, carrying similar or larger energy than the soft emission. The non-thermal flash is detectable by current X-ray telescopes and may be detectable out to 10's of Mpc by km-scale neutrino telescopes.

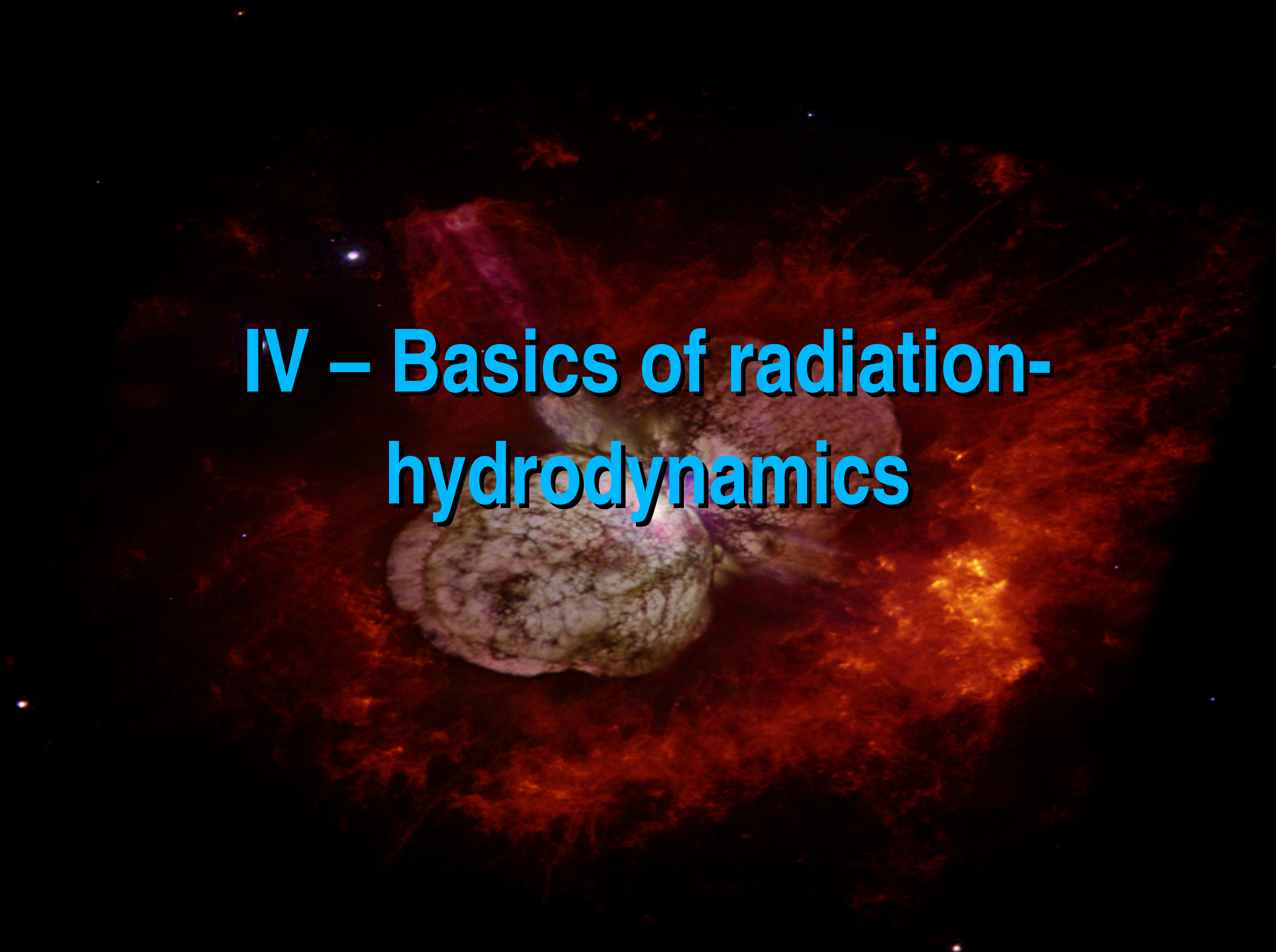
$$\rho(r) = \frac{c}{v}\frac{m_p}{\sigma_T R_{\rm br}}(r/R_{\rm br})^{-2}.$$

$$0.5M(r)v^2.$$

↘

$$v_{\rm max} = \frac{E_\gamma/c}{4\pi r^2}\frac{\sigma_T}{m_p} \quad < \quad 0.5(R_{\rm br}/r)v.$$

IV – Basics of radiation-hydrodynamics



Radiation-Hydrodynamics Code

Assumptions... and requirements :

- **1D – spherical** code sufficient,
- Two temperature code, and $T_e = T_p$,
- Allow NLTE ($T_e \neq T_{rad}$),
- For a reasonable and safe behaviour during the transition from optically thick to optically thin regions :
  => Use a flux limiter,
- Fluid fully ionized. Electron temperature between a few eV and a few 100s keV ($< m_e$)
  => Do not need to take into account atomic lines and Assume *Thomson scattering* for photons
  ---> No multigroup treatment of radiation (-> Gray diff.).

Radiation-Hydrodynamics Code

- Eulerian code.

- Architecture :

  \- > *Explicit :*

  1) Lagrangian terms,
  2) Advection terms,
  3) Energy exchange photons <-> fluid (Bremsstrahlung & Compton cooling).

  \- > *Implicit :*

  Photon diffusion term.

Radiation-Hydrodynamics Code

- **Mass Eqn. :**

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u\right) ,$$

- **Momentum Eqn. :**

$$\frac{\partial}{\partial t}(\rho u) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u \cdot u\right) - \frac{\partial}{\partial r}(p+q) + \frac{\mathcal{F}_{\rm rad}}{\lambda c} ,$$

where

$$\mathcal{F}_{\rm rad} = -\mathcal{D}_{\rm rad}^{\rm LIM}\frac{\partial E_{\rm rad}}{\partial r} ,$$

and $\mathcal{D}_{\rm rad}^{\rm LIM}$ is the flux-limited diffusion coefficient for photons

$$\mathcal{D}_{\rm rad}^{\rm LIM} = \frac{c}{\sqrt{\left(\frac{3}{\lambda}\right)^2 + \left(\frac{\partial E_{\rm rad}/\partial r}{E_{\rm rad}}\right)^2}} ,$$

so that $\mathcal{F}_{\rm rad} \leq c E_{\rm rad}$ in an optically thin medium. In an optically thick medium,

$$\mathcal{D}_{\rm rad}^{\rm LIM} \rightarrow \mathcal{D}_{\rm rad} = \frac{\lambda c}{3} \quad \text{and} \quad \frac{\mathcal{F}_{\rm rad}}{\lambda c} \rightarrow -\frac{1}{3}\frac{\partial E_{\rm rad}}{\partial r} = -\frac{\partial p_{\rm rad}}{\partial r} .$$

Radiation-Hydrodynamics Code

- **Mass Eqn. :**

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u\right) ,$$

- **Momentum Eqn. :**

$$\frac{\partial}{\partial t}(\rho u) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u \cdot u\right) - \frac{\partial}{\partial r}(p+q) + \frac{\mathcal{F}_{\rm rad}}{\lambda c} ,$$

where

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so that $\mathcal{F}_{\rm rad} \leq cE_{\rm rad}$ in an optically thin medium. In an optically thick medium,

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Radiation-Hydrodynamics Code

- **Total fluid energy Eqn. :**

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho u^2 + \frac{3}{2}p\right) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left(\frac{1}{2}\rho u^2 + \frac{3}{2}p\right)\cdot u\right\} - \frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left(p+q\right)\cdot u\right\} + u\cdot\frac{\mathcal{F}_{\rm rad}}{\lambda c} + \Lambda_{\rm C} + \Lambda_{\rm B}\,,$$

- Compton cooling (Chevalier & Klein '79) :

$$\Lambda_C = 8.07\epsilon_r\rho[T_e - (\epsilon_r/a)^{1/4}] \times [1 + (6.75\times10^{-10})T_e](\text{ergs s}^{-1}\text{ cm}^{-3})$$

where $a = 7.56\times10^{-15}$.

- Bremsstrahlung :

$$\Lambda_B = 1.42\times10^{-27}\frac{\rho^2}{\mu^2}T_e^{1/2}g_{\rm ff}\left(1 - \frac{\epsilon_r}{aT_e^4}\right)$$

(Gaunt factor ~ 1.25)

Radiation-Hydrodynamics Code

- **Total fluid energy Eqn. :**

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho u^2 + \frac{3}{2}p\right) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left(\frac{1}{2}\rho u^2 + \frac{3}{2}p\right)\cdot u\right\} - \frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left(p+q\right)\cdot u\right\}$$
$$+ u\cdot\frac{\mathcal{F}_{\rm rad}}{\lambda c} + \Lambda_{\rm C} + \Lambda_{\rm B}\,,$$

- **Radiation energy Eqn. :**

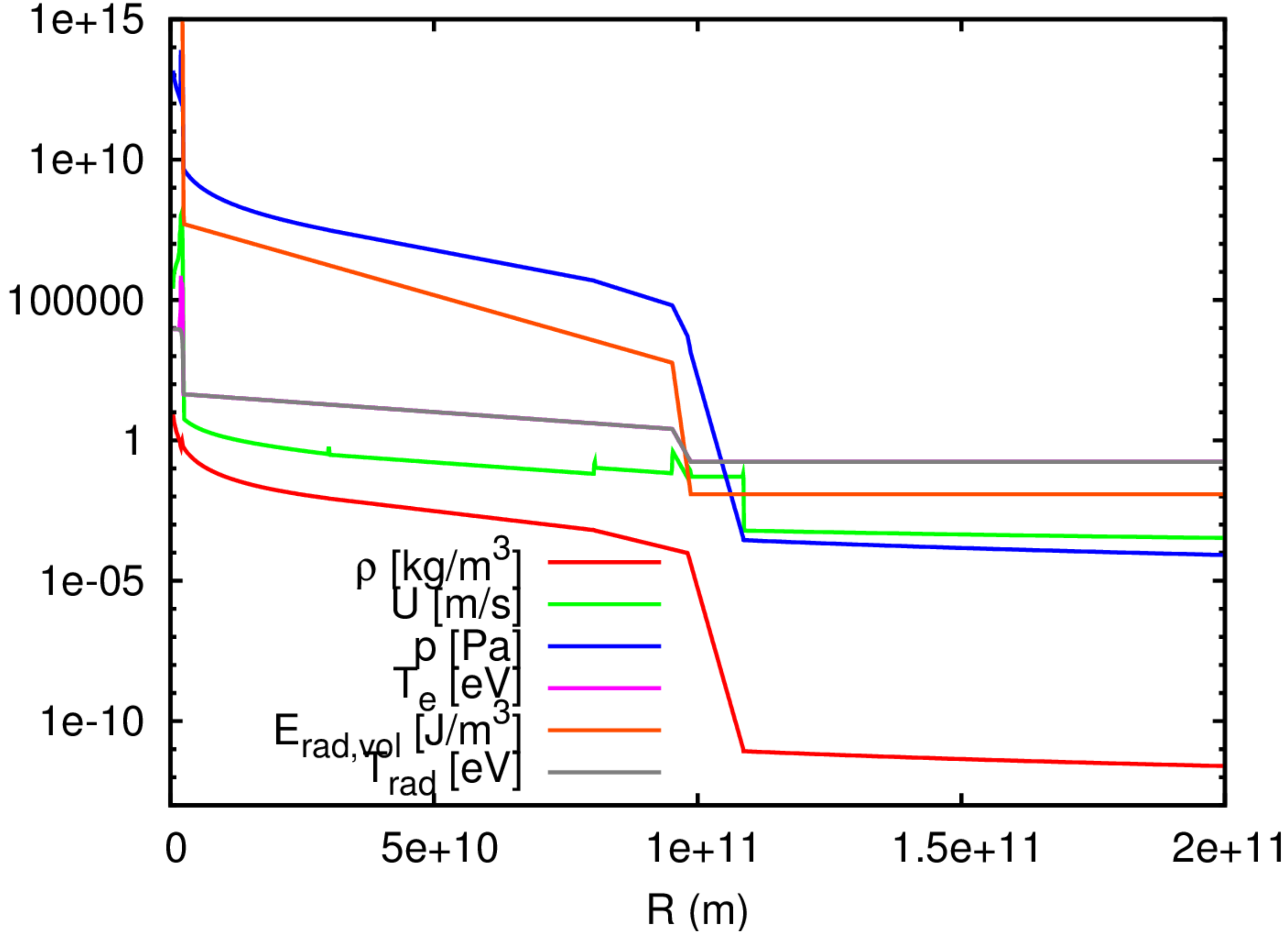
$$\frac{\partial E_{\rm rad}}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 E_{\rm rad}\cdot u\right) - p_{\rm rad}\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u\right)$$
$$+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\mathcal{D}_{\rm rad}^{\rm LIM}\frac{\partial E_{\rm rad}}{\partial r}\right) - \Lambda_{\rm C} - \Lambda_{\rm B}\,,$$

with $p_{\rm rad} \simeq E_{\rm rad}/3$. For safety reasons, $\mathcal{D}_{\rm rad}^{\rm LIM}$ may be replaced with $\mathcal{D}_{\rm rad} = \lambda c/3$.

V – Results & Interpretation

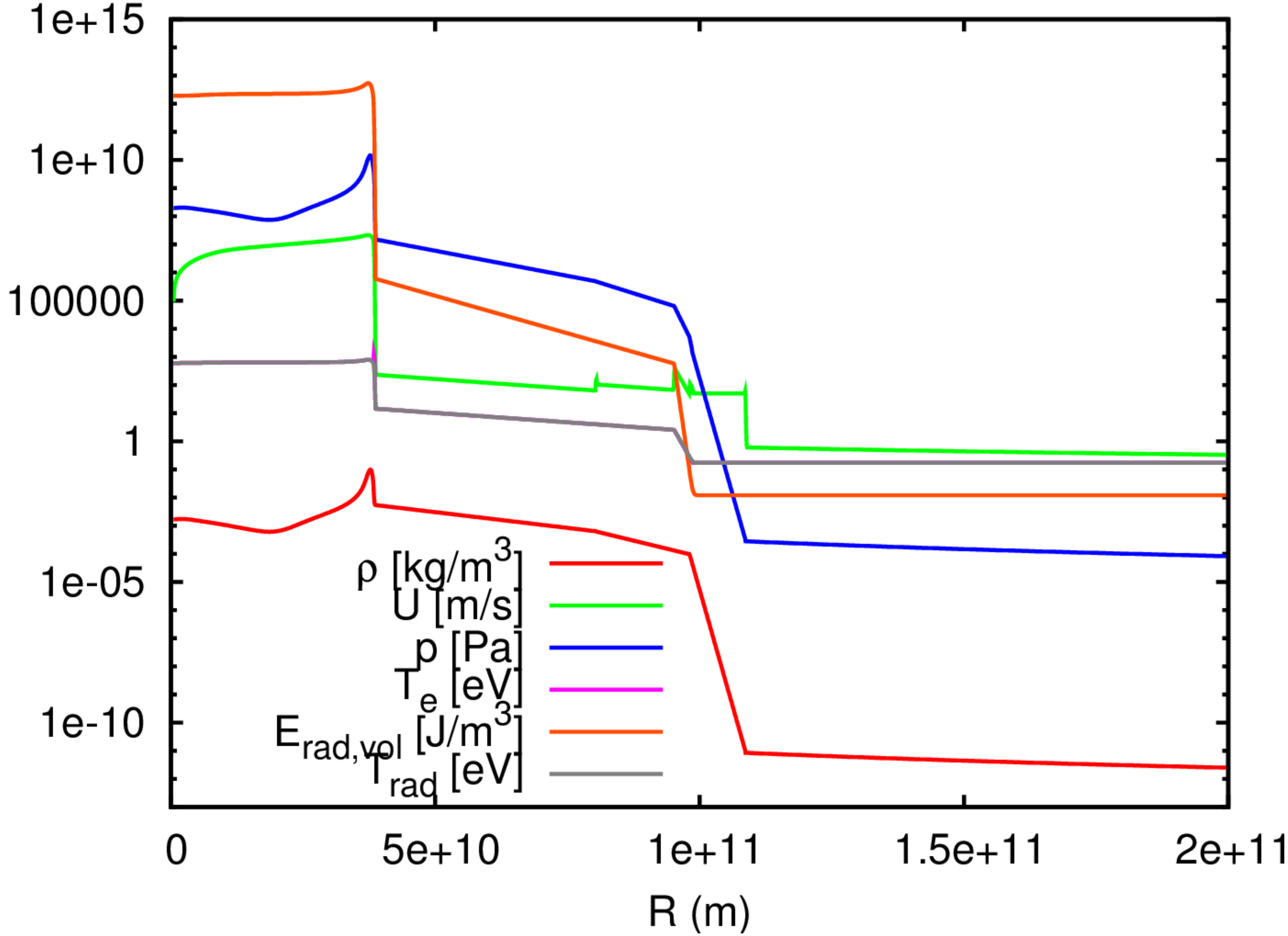
Progenitor with an optically THIN wind

Initial conditions at t = 0



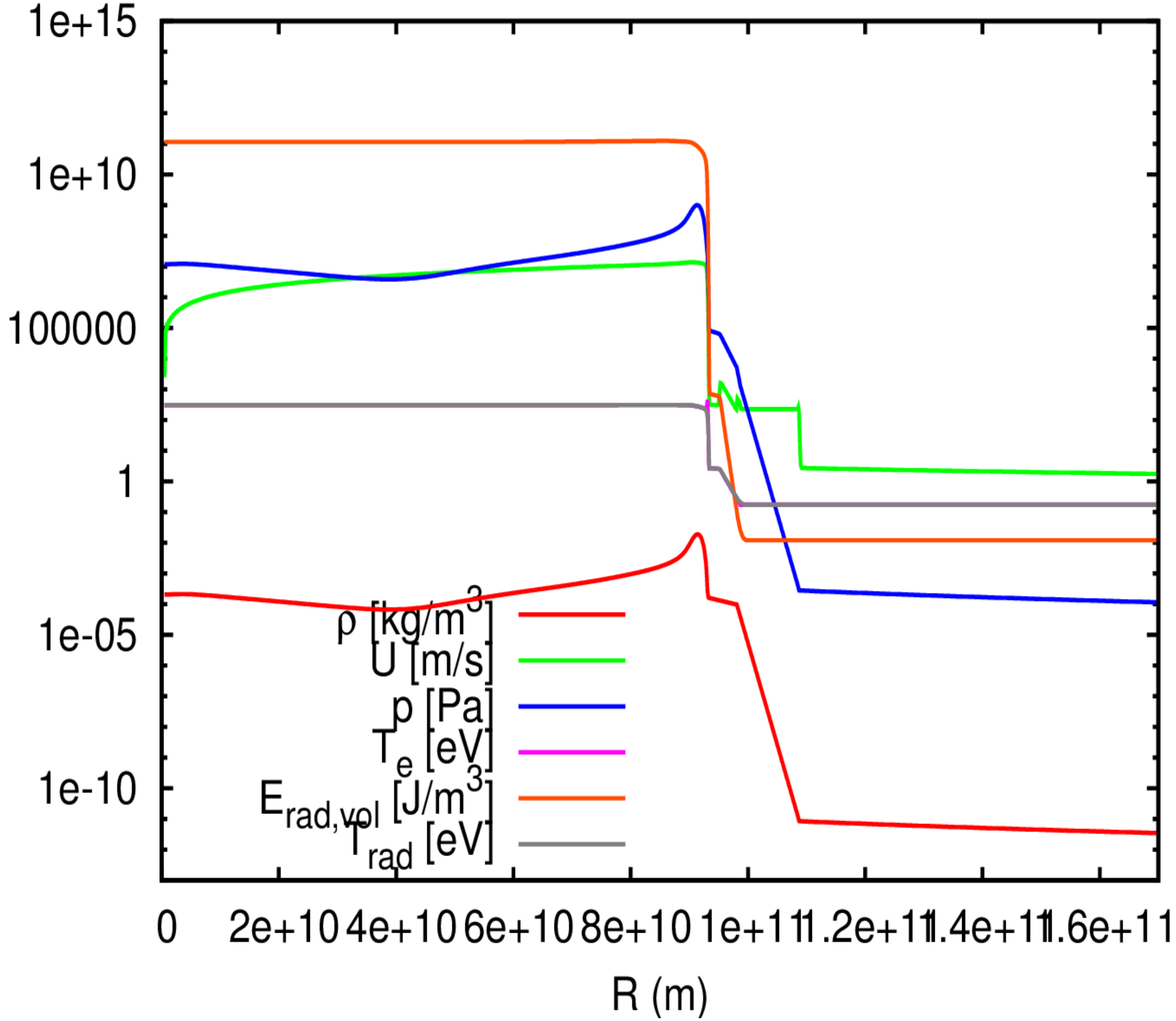
Progenitor with an optically THIN wind

t = 1 000 s



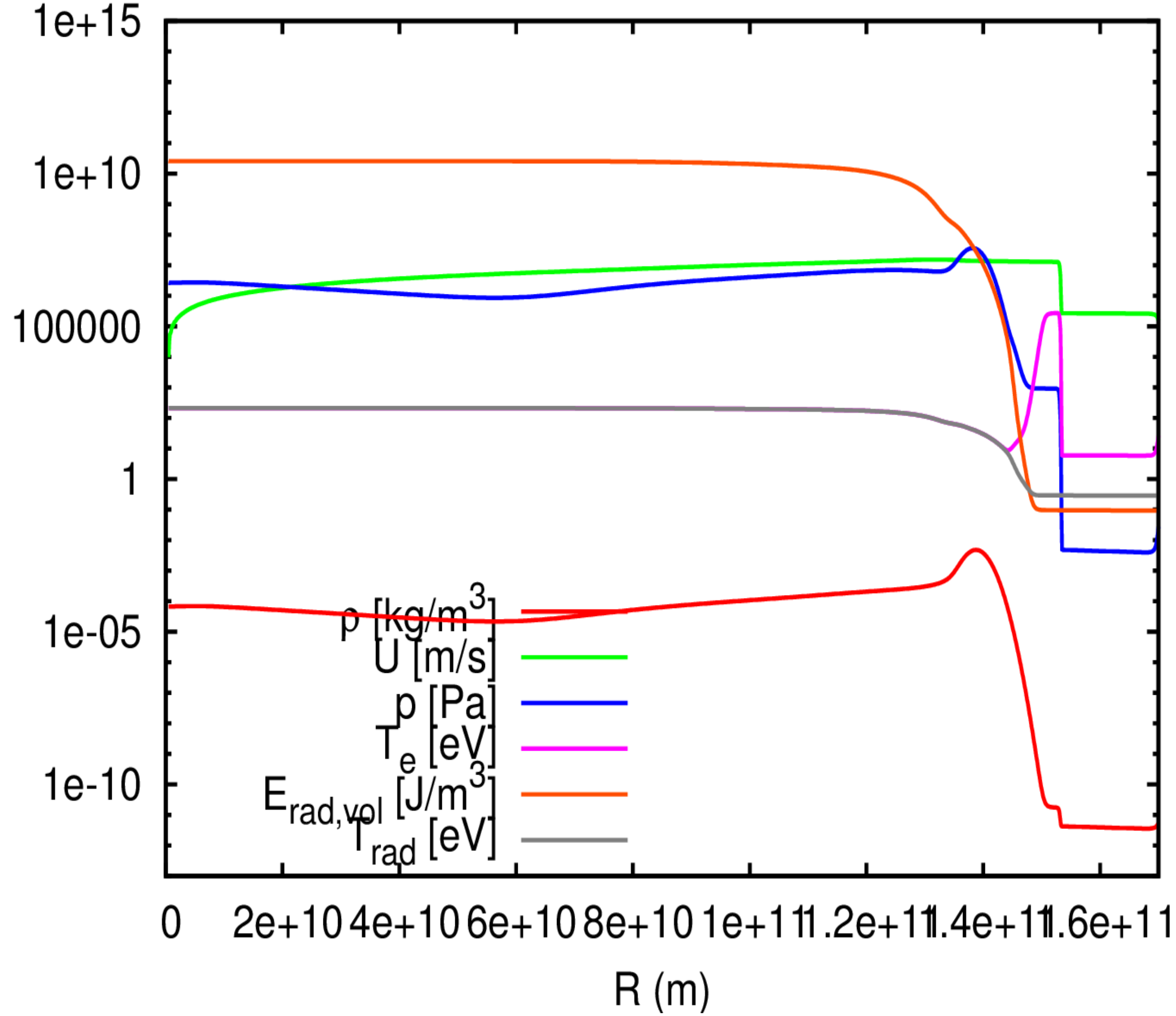
Progenitor with an optically THIN wind

t = 4 500 s



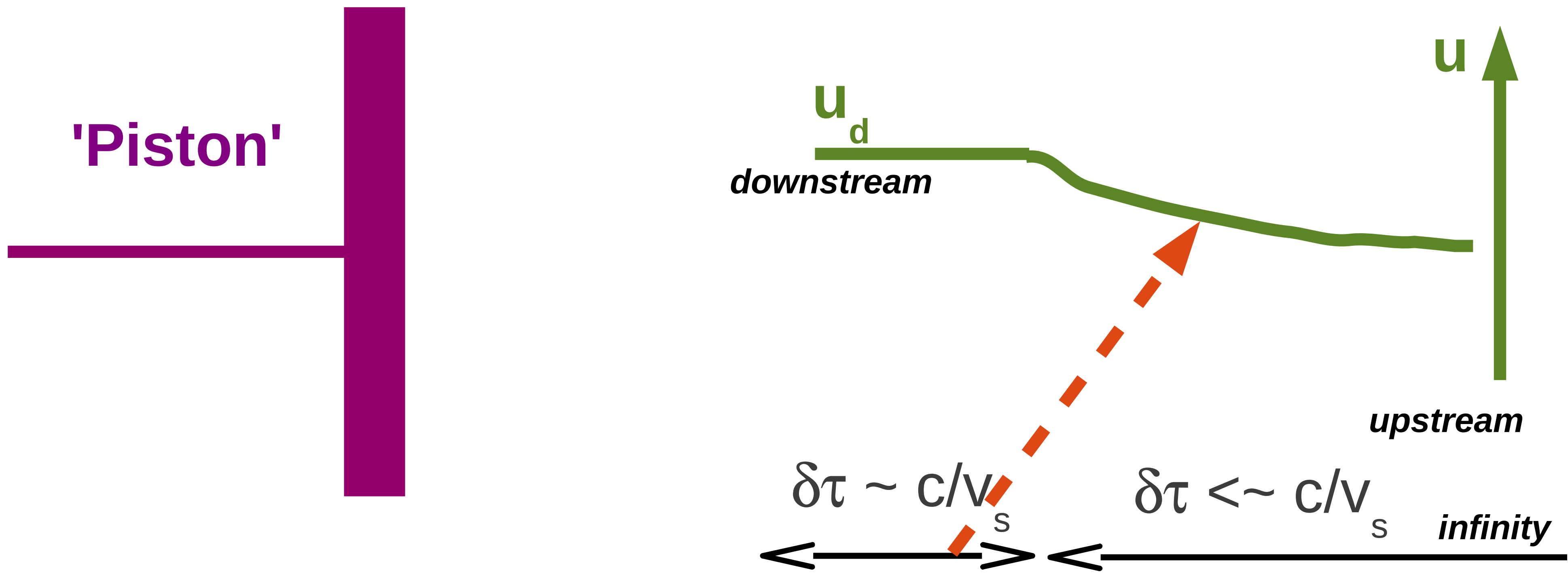
Progenitor with an optically THIN wind

T = 8 000 s



Movie

Shock breakout

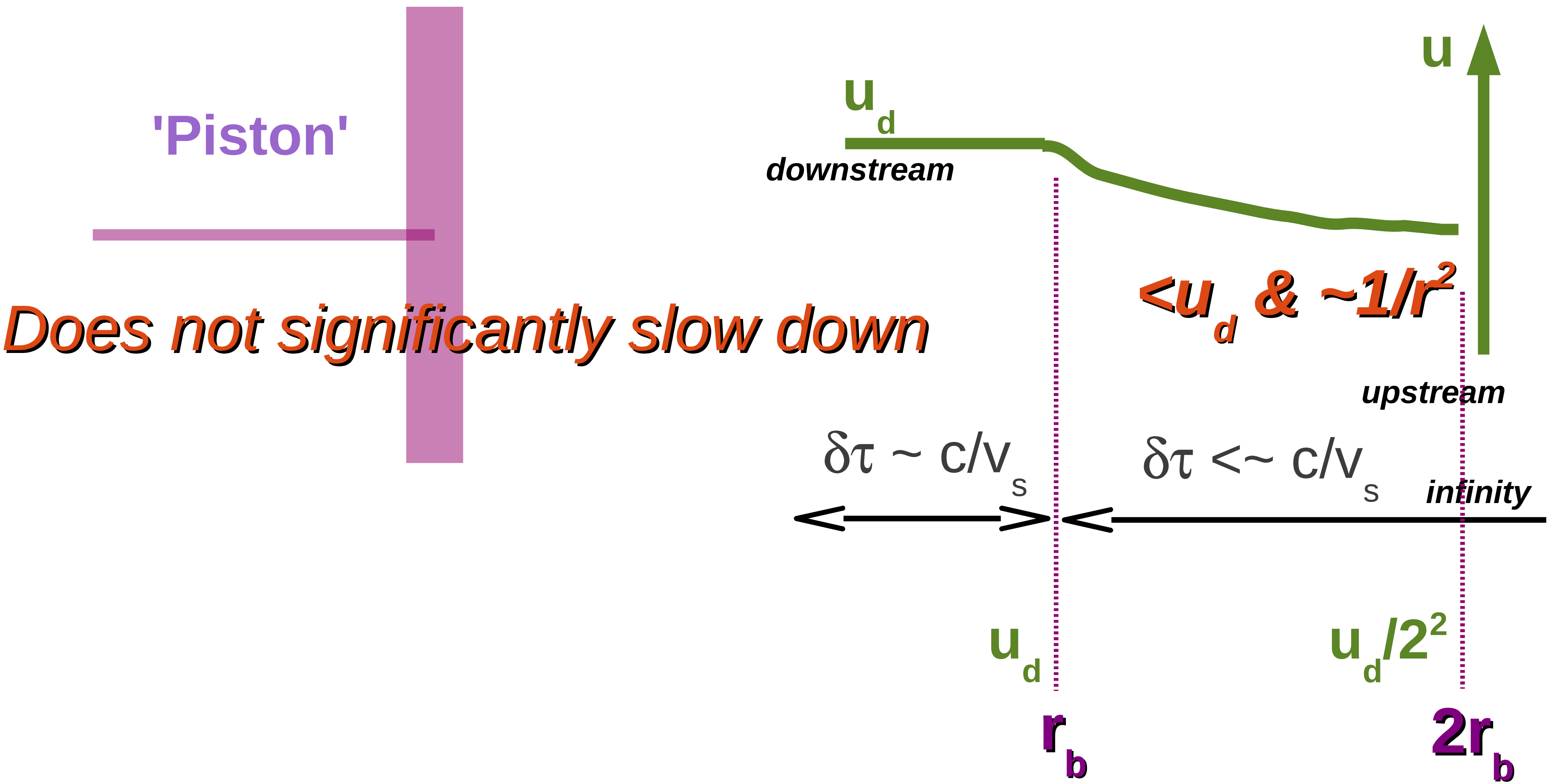


The radiation mediated shock disappears !

[E]/**[S]**[t]

Lagrangian : **$Du / Dt = \kappa F_{rad} / c$**

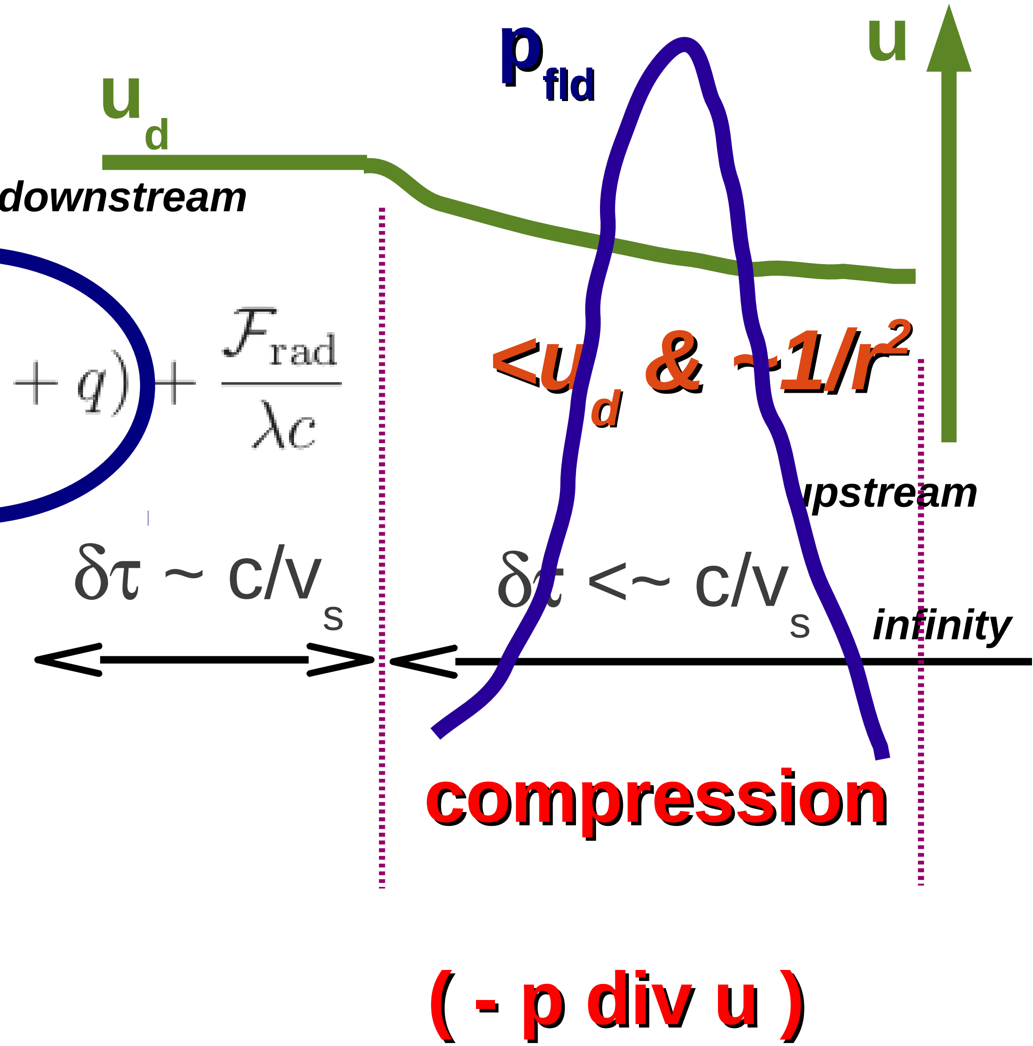
Shock breakout



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

Shock breakout

$$\frac{\partial}{\partial t}(\rho u) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u \cdot u\right) - \frac{\partial}{\partial r}(p+q) + \frac{\mathcal{F}_{\rm rad}}{\lambda c}$$



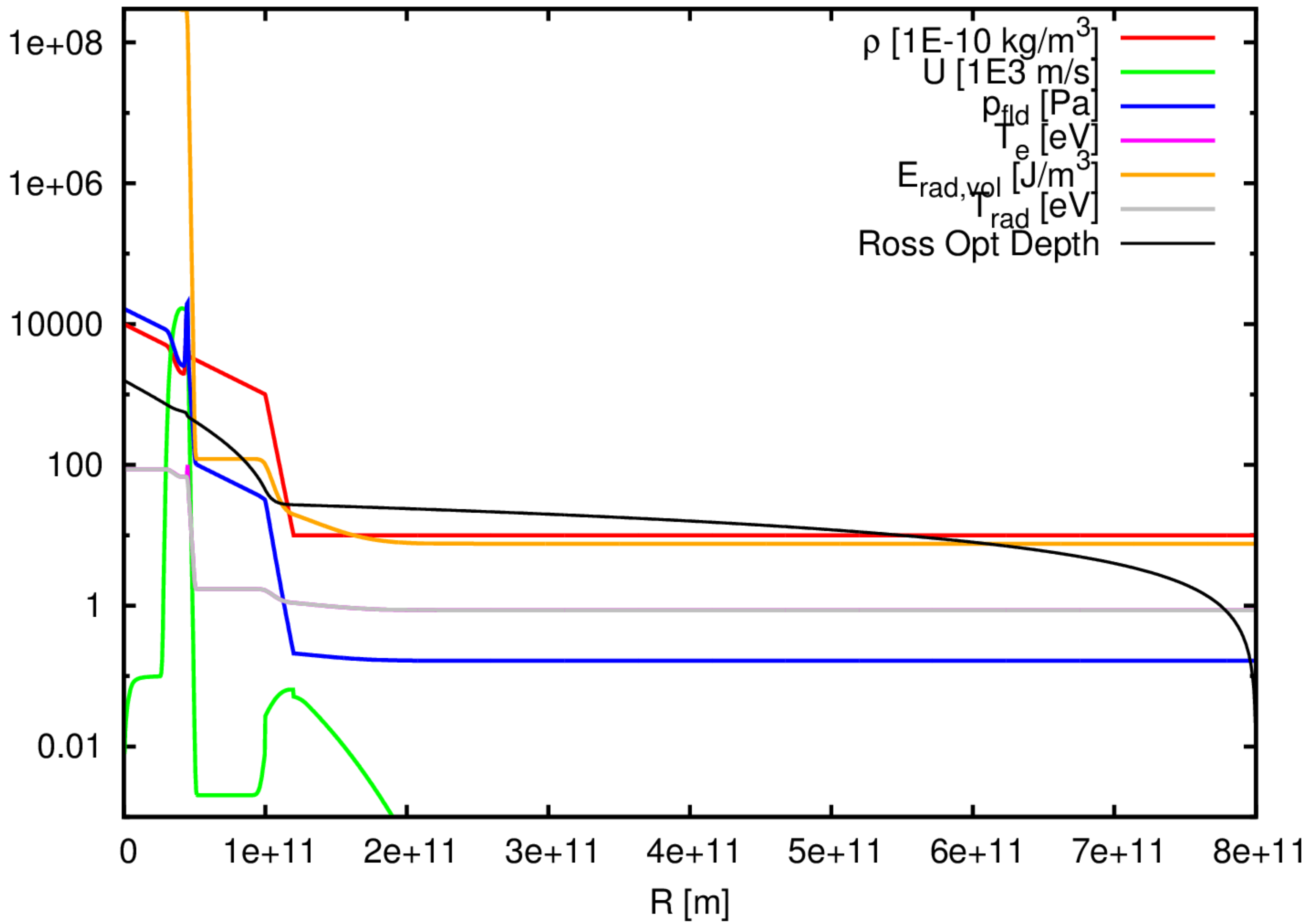
Mediated by the *fluid* pressure

=> VISCOUS shock (collisionless shock)

$$Du/Dt = \kappa \mathcal{F}_{\rm rad}/c - (1/\rho)\,\partial p/\partial r$$

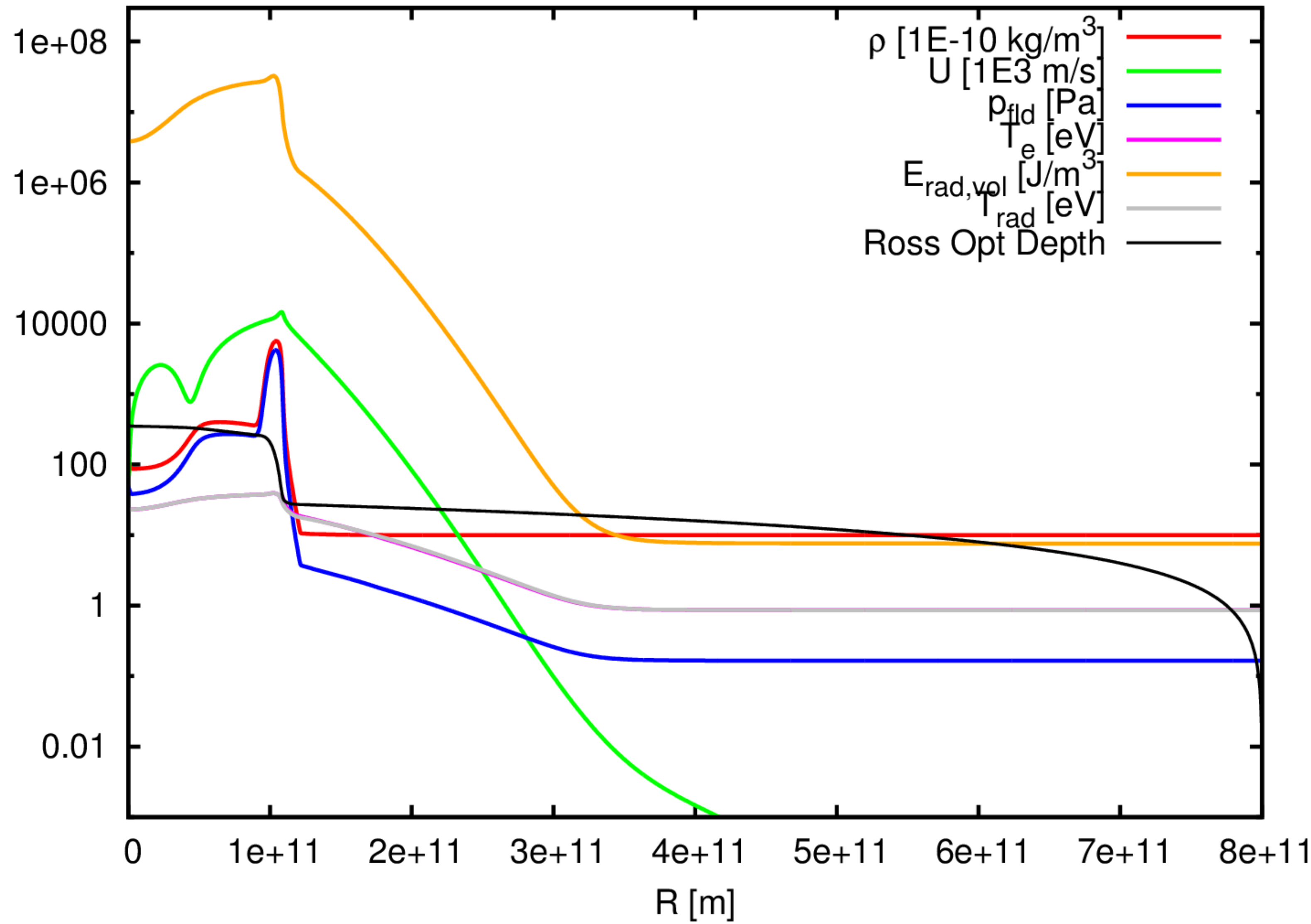
Progenitor with an optically THICK wind

Spherical 1D



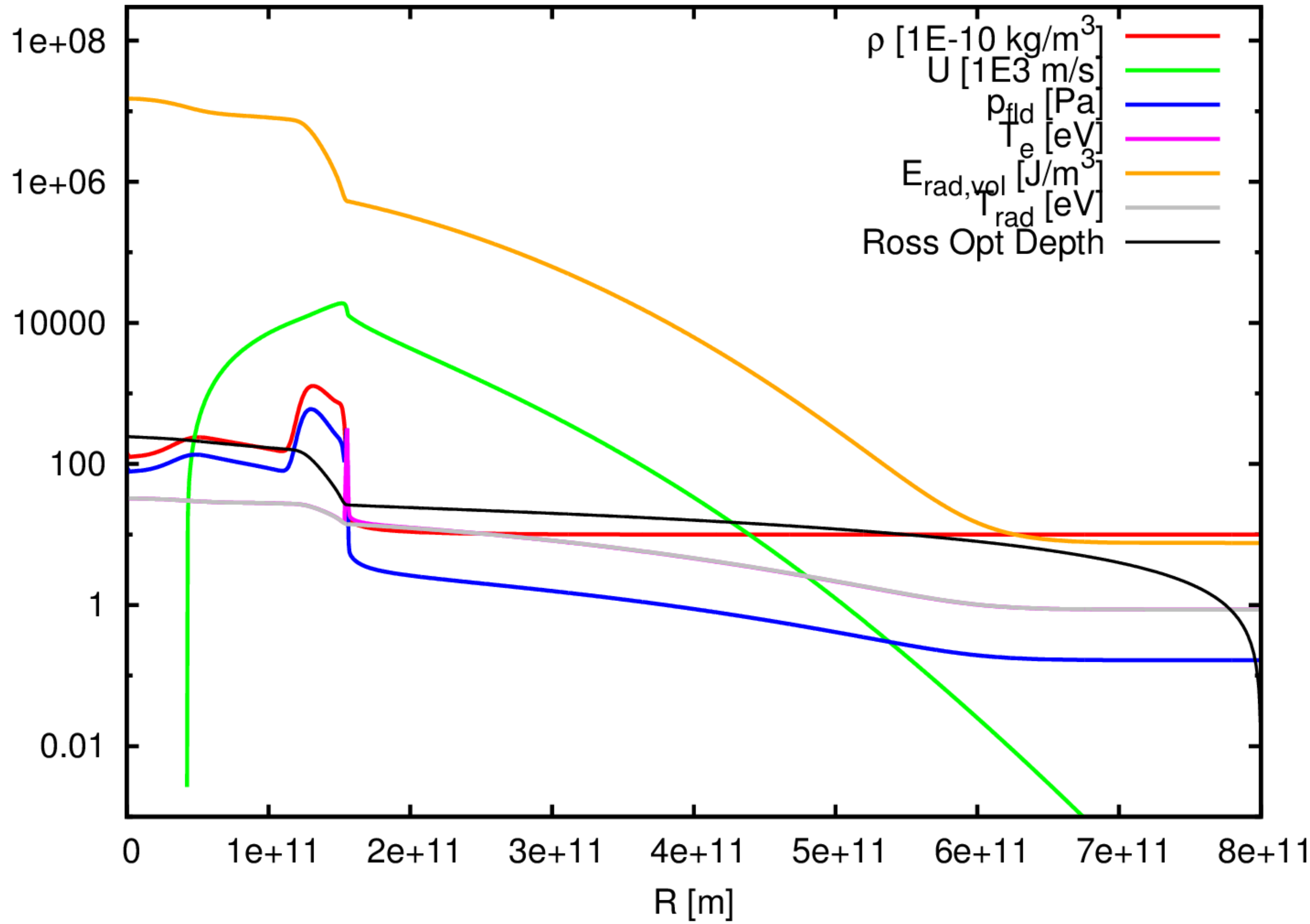
Progenitor with an optically <u>THICK</u> wind

Spherical 1D



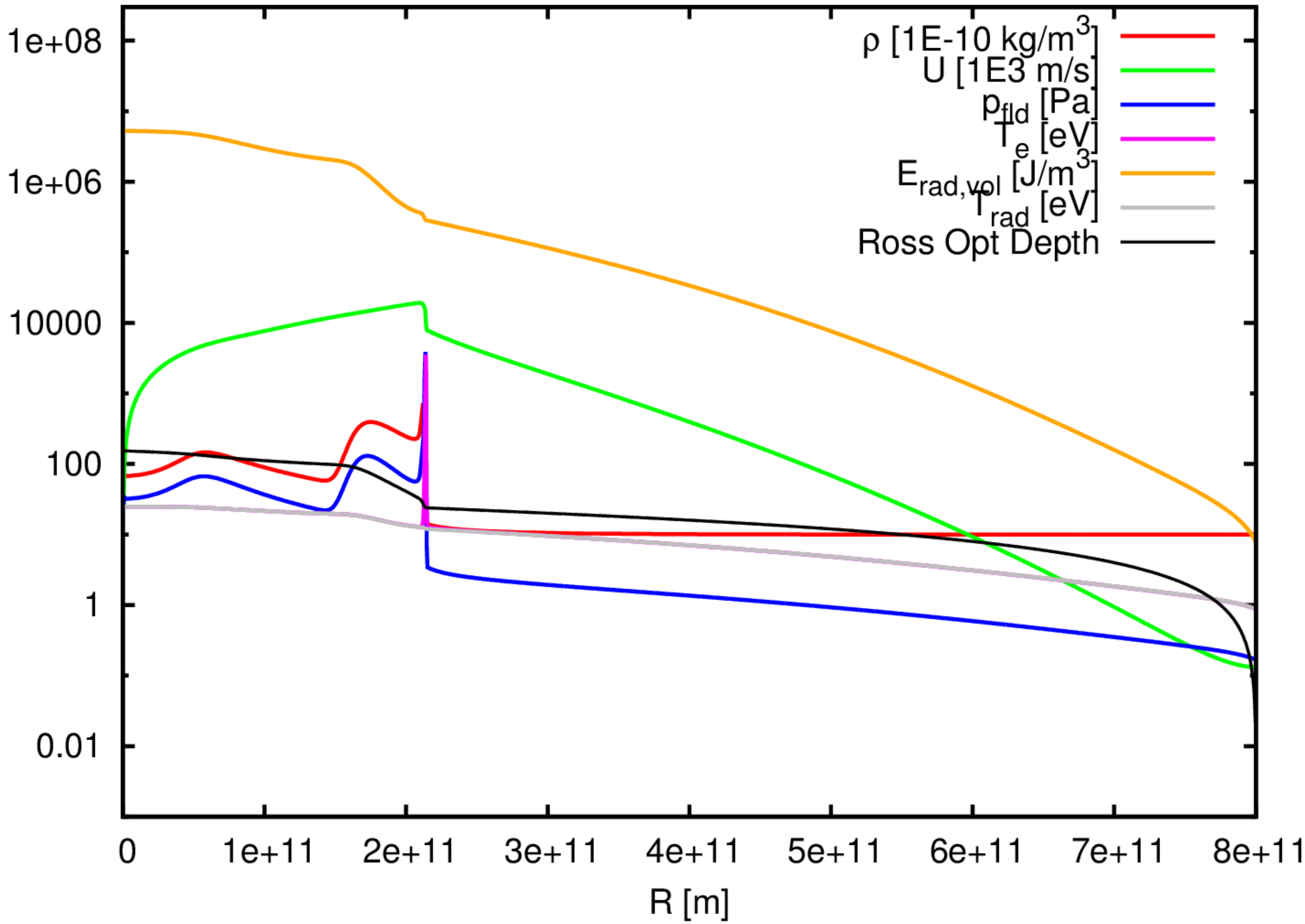
Progenitor with an optically THICK wind

Spherical 1D



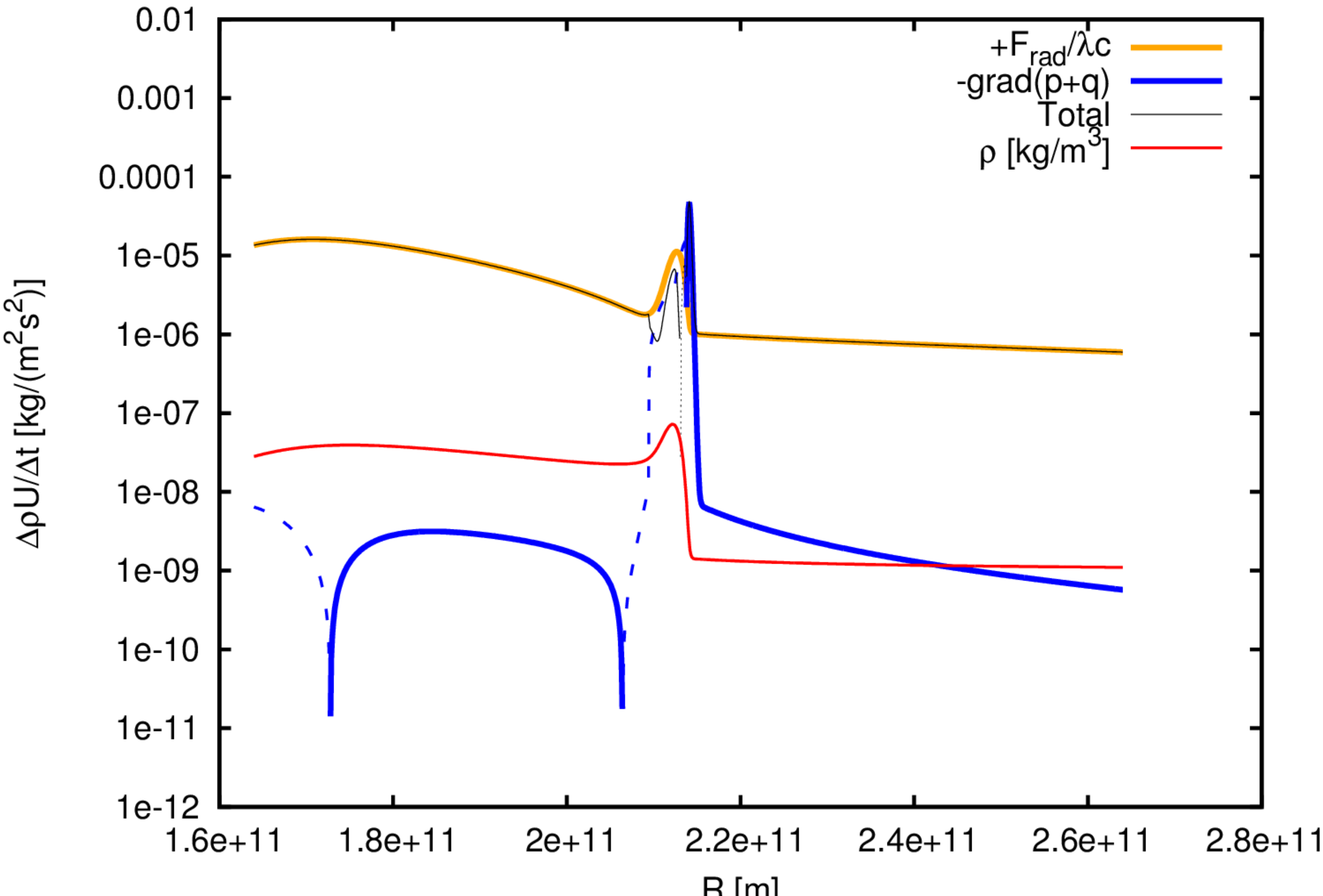
Progenitor with an optically THICK wind

Spherical 1D



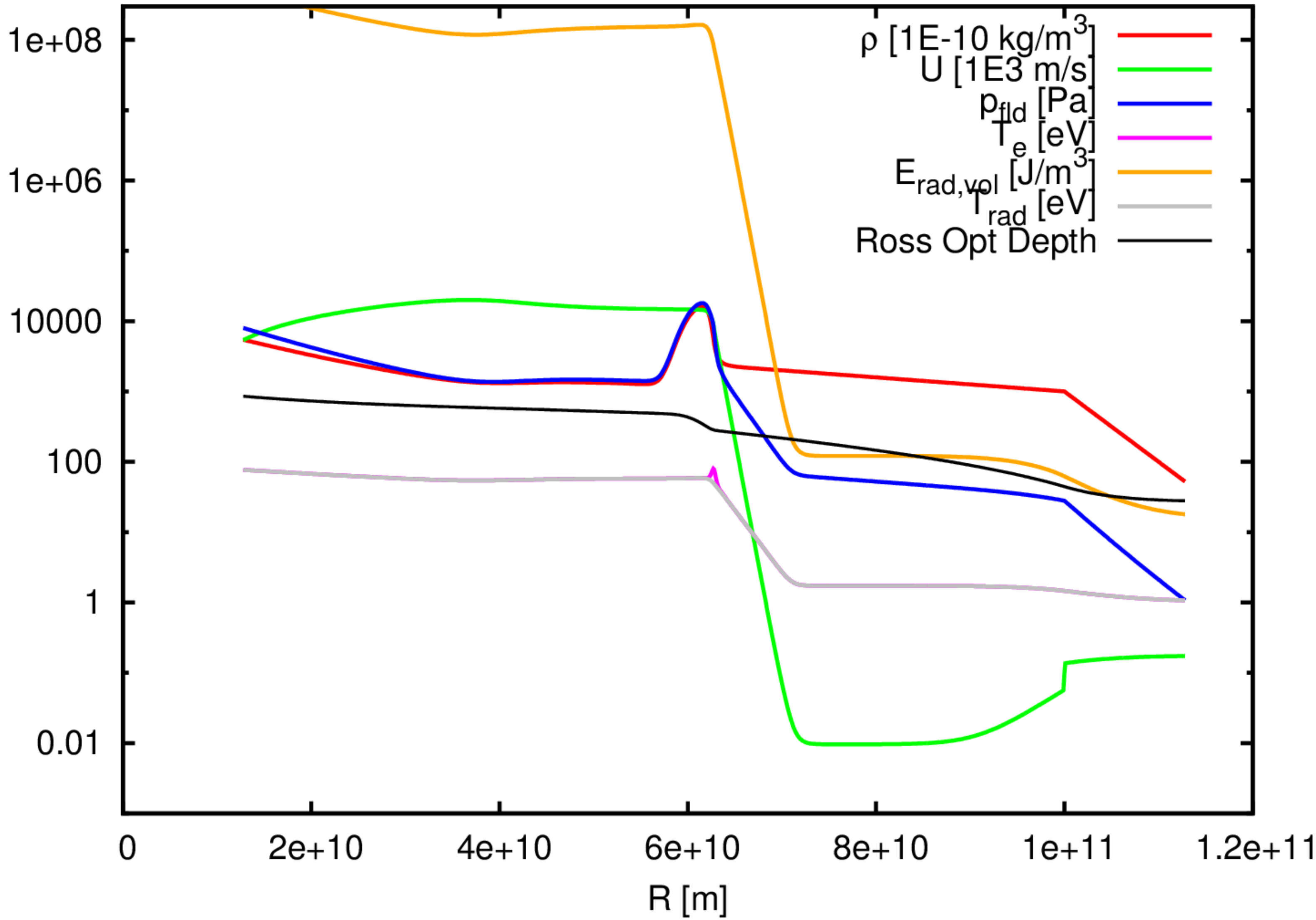
Progenitor with an optically THICK wind

Spherical 1D



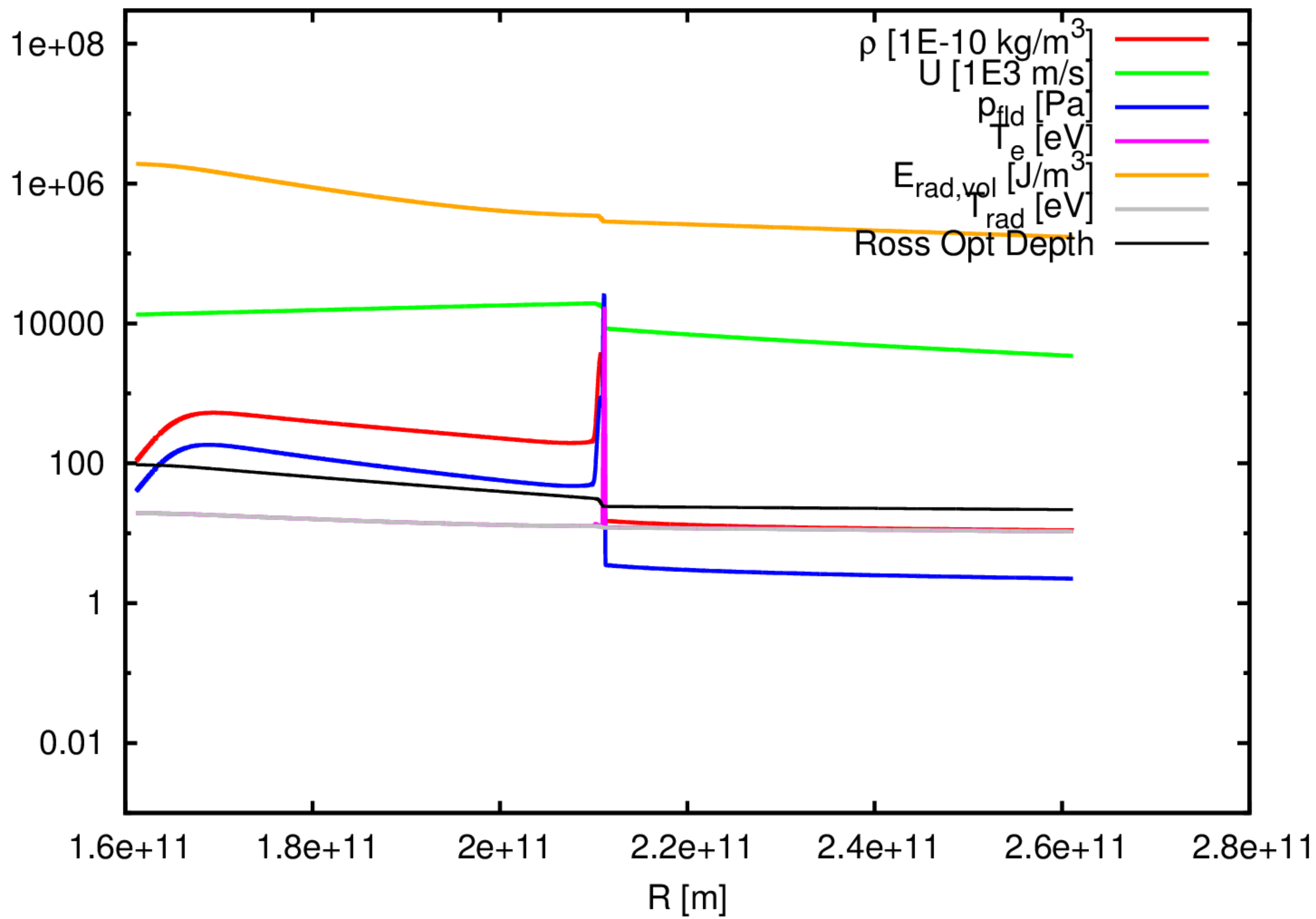
Progenitor with an optically <u>THICK</u> wind

Spherical 1D

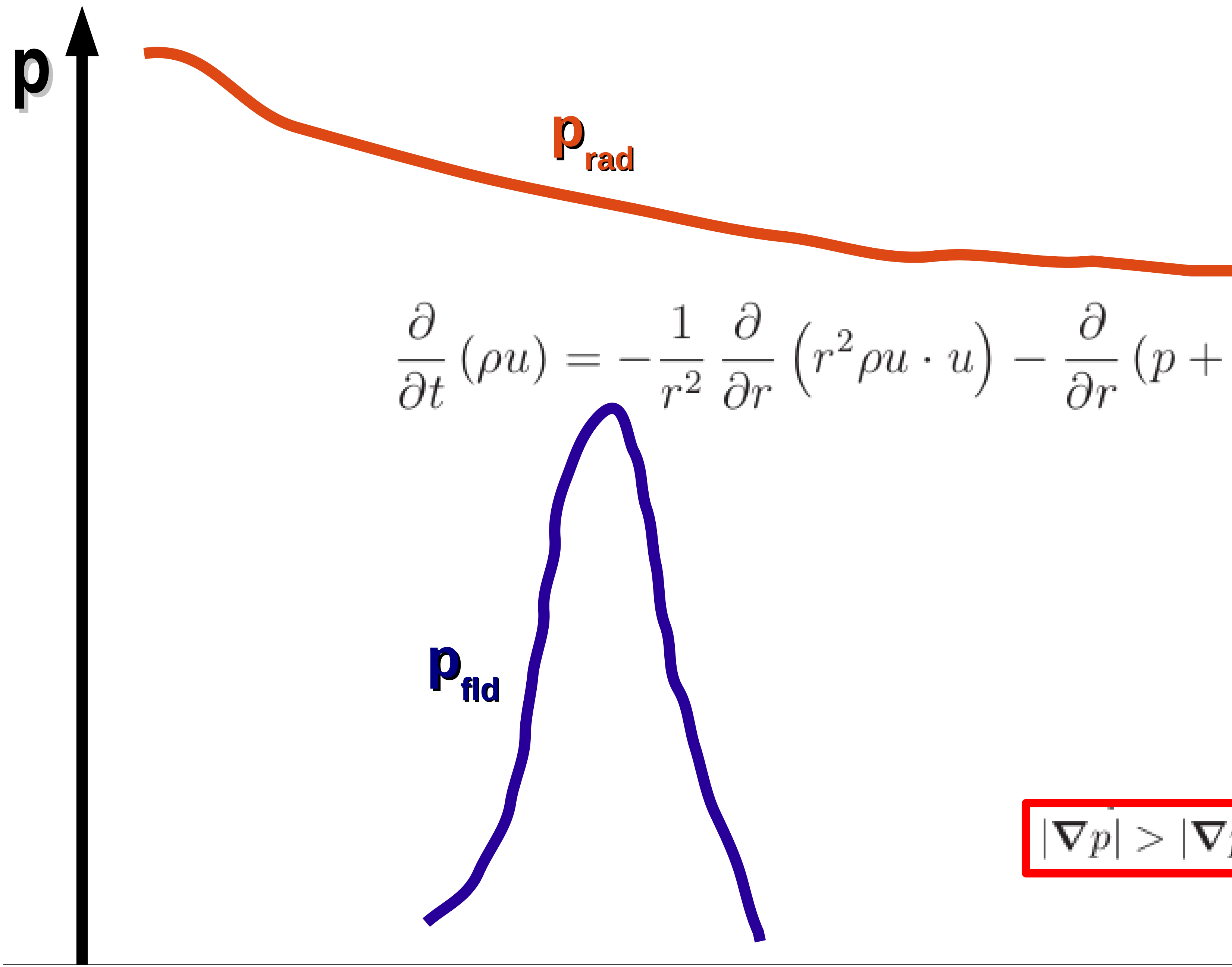


Progenitor with an optically <u>THICK</u> wind

Spherical 1D



Viscous shock formation in opt. thick medium ?

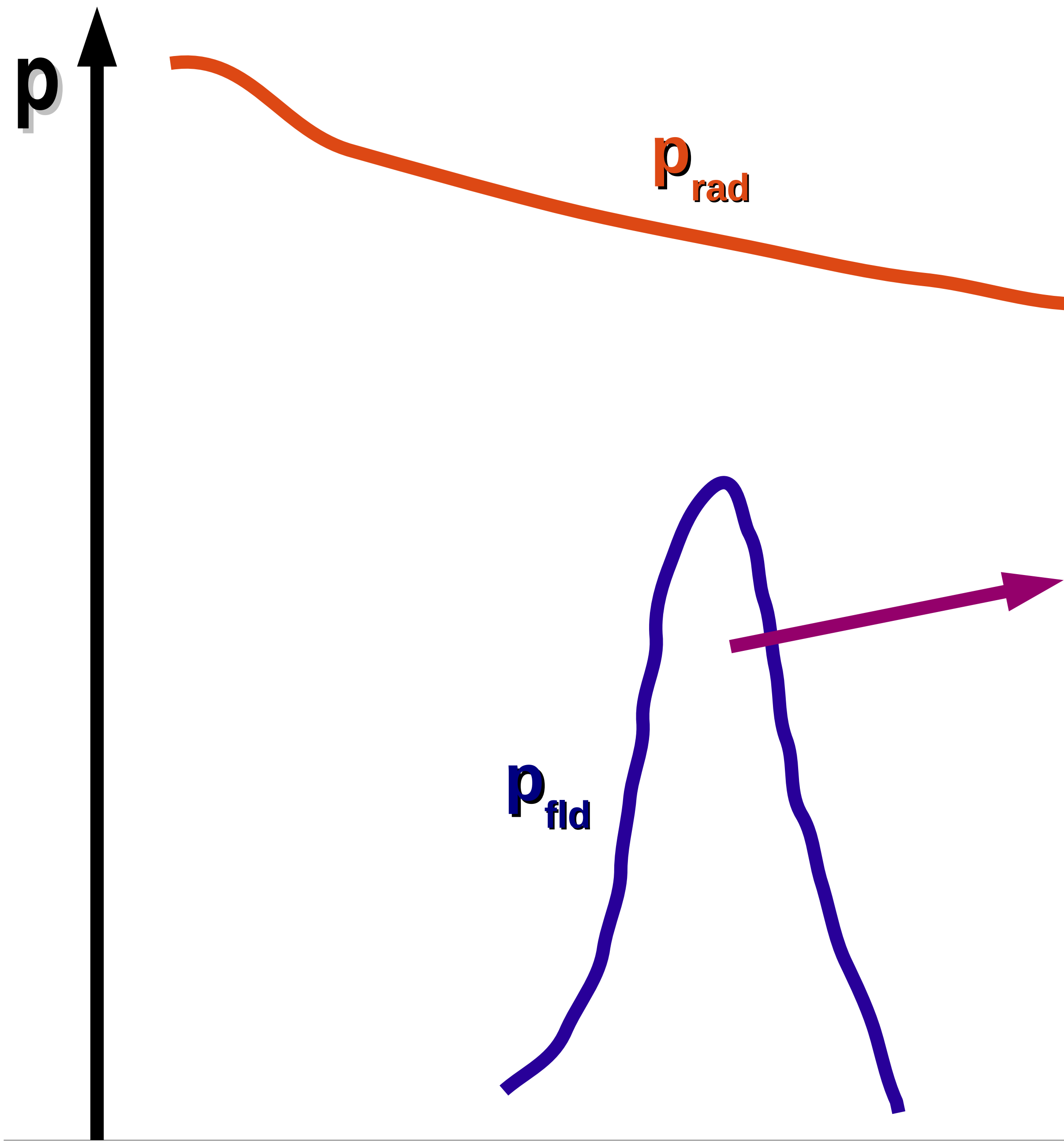


$$\frac{\partial}{\partial t}(\rho u) = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho u \cdot u\right) - \frac{\partial}{\partial r}(p+q) + \frac{\mathcal{F}_{\rm rad}}{\lambda c}$$

$$-\frac{\partial p_{\rm rad}}{\partial r}$$

$$|\nabla p| > |\nabla p_{\rm rad}|$$

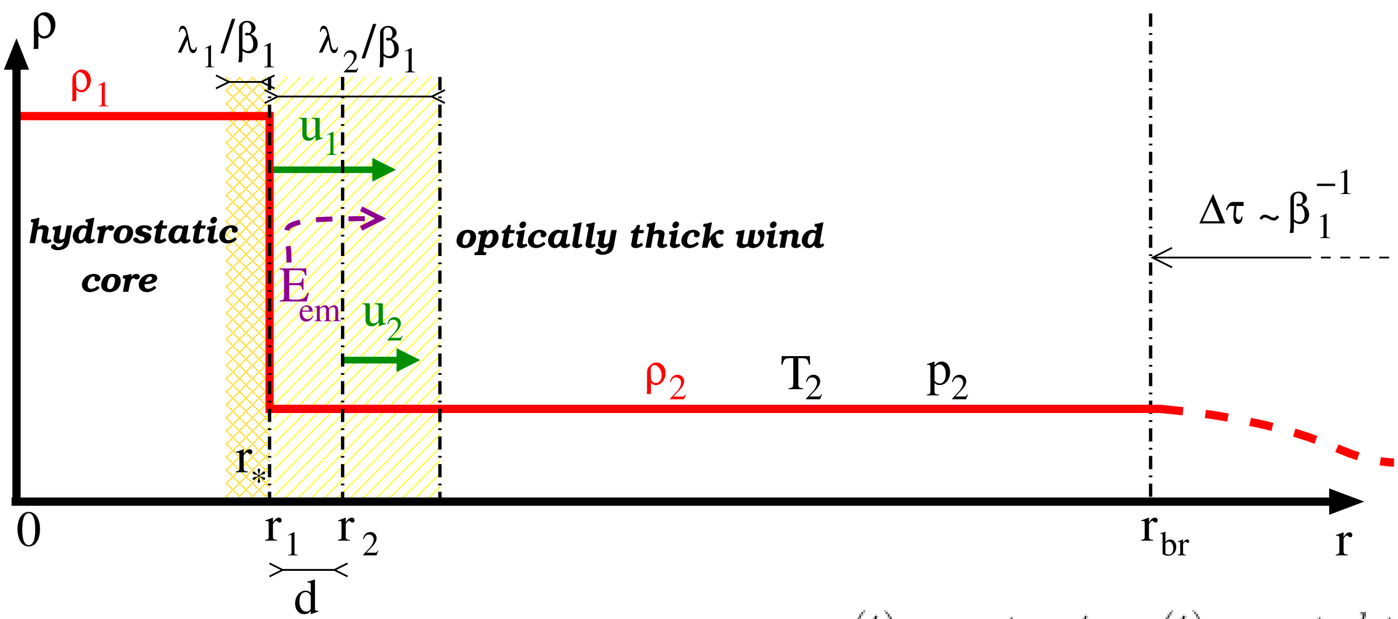
Viscous shock formation in opt. thick medium ?



Collisionless shock :

- From a viscous shock : NO
- From Radiation : NO
- ***From compression***

Viscous shock formation BEFORE sb



$$r_1(t) = r_* + u_1 t \; ; \; r_2(t) = r_* + d + u_2 t$$

$$\frac{Du}{Dt} = \left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial r}\right) u = \frac{\kappa}{c} j$$

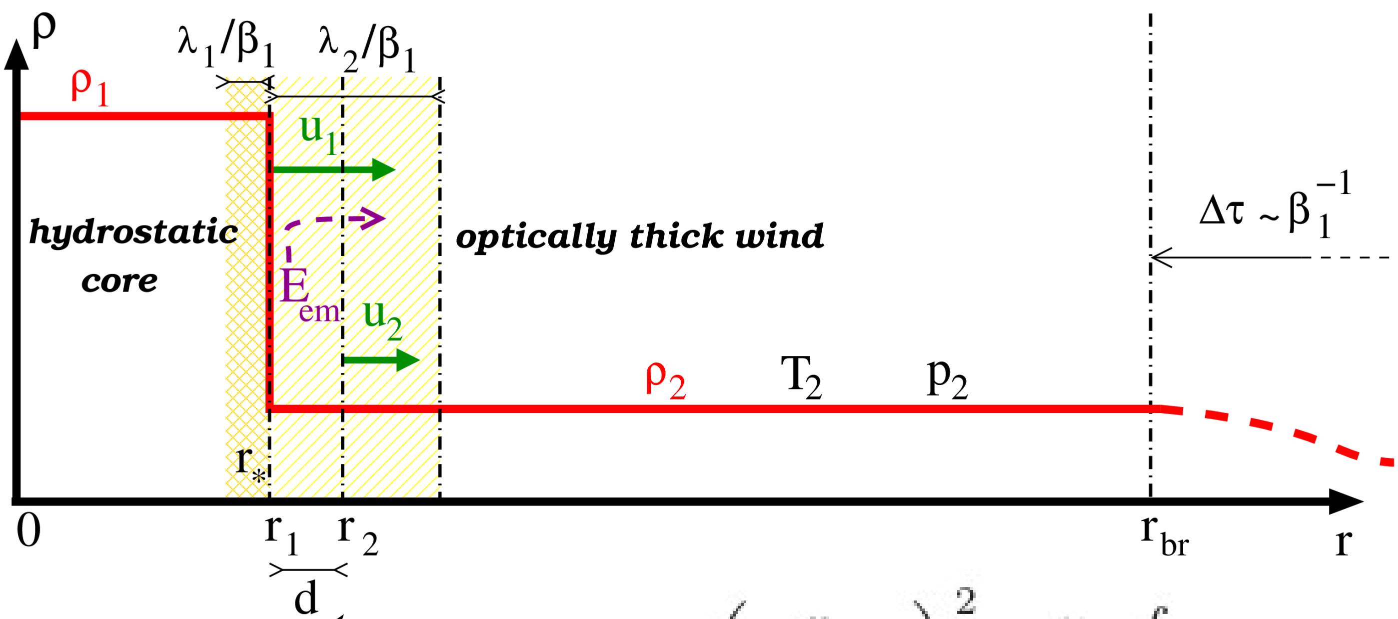
$$(r_2 - r_1)(t_{\rm eq}) = 0 = d + (u_2 - u_1) t_{\rm eq}$$

$$t_{\rm eq} = \frac{d}{u_1 - u_2}$$

$$u_{\rm max}(\tau) = \frac{\kappa}{c} \int_{t_0}^{t_{\rm max}} j(\tau) dt$$

$$r_1(t_{\rm eq}) = r_* + \frac{d}{1 - \frac{u_2}{u_1}} \leq r_{\rm br}$$

Viscous shock formation BEFORE sb



$$u_{2,\mathrm{sph}} \leq u_1 \left(\frac{r_*}{r_* + d}\right)^2$$

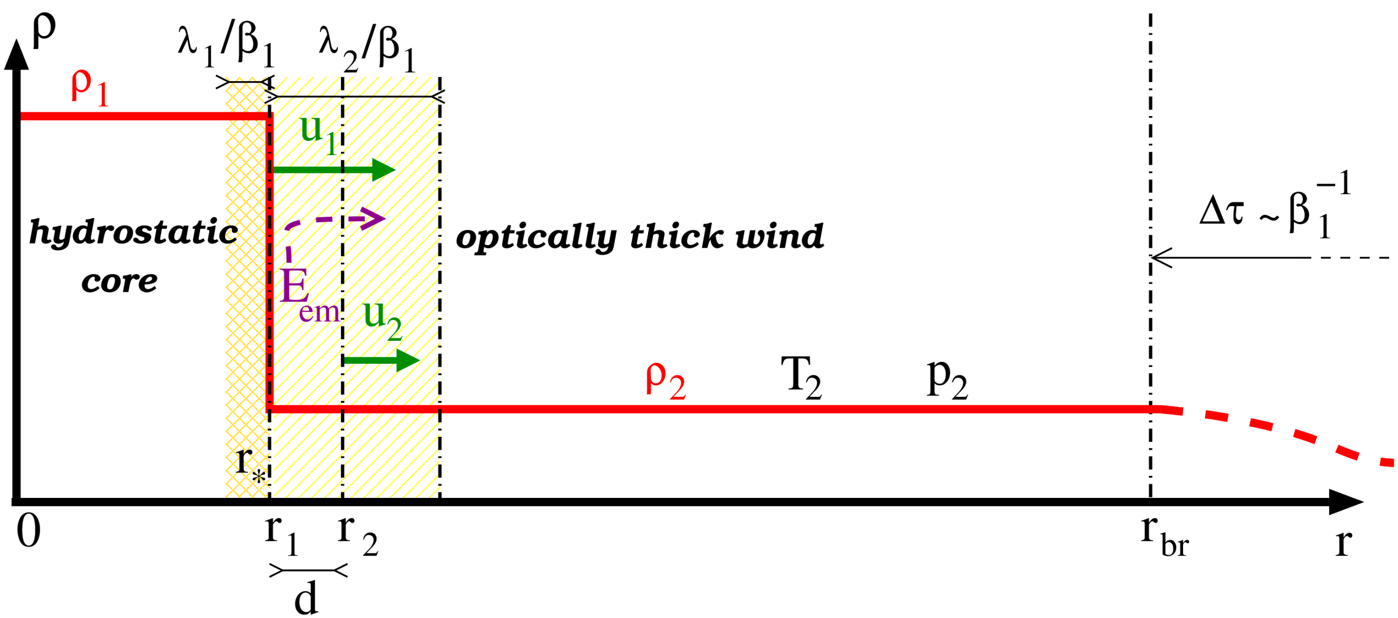
$$u_2 \leq u_1 \left(\frac{r_*}{r_* + d}\right)^2 + \frac{\kappa}{c} \int j_{\mathrm{em}} dt$$

$$u_2 \leq u_1 \left(\frac{r_*}{r_* + d}\right)^2 + \frac{\kappa}{c} \frac{E_{\mathrm{em}}}{4\pi (r_* + d)^2}$$

$$\leq u_1 \left(\frac{1}{1+\tilde{d}}\right)^2 \left[1 + \frac{\beta_1}{2\tilde{\lambda}_2} \left(\tilde{d} + \tilde{d}^2 + \frac{\tilde{d}^3}{3}\right)\right]$$

$$\tilde{x} = x/r_*$$

Viscous shock formation BEFORE sb



(i) $\beta_1 < 4\tilde{\lambda}_2$ **(ii)** $\beta_1 < 4\tilde{\lambda}_2[1 - 1/2(\tilde{r_{br}} - 1)]$

… But estimate rather conservative. Numerically, we find :

$\beta_1 \lesssim 10\tilde{\lambda}_2$ **i.e.** $\lambda_2/\beta_1 \gtrsim r_*/10$

Viscous shock formation BEFORE sb

$$\beta_1 \lesssim 10\tilde{\lambda}_2$$

With :

$$\dot{M} \approx 5 \cdot 10^{-4}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$$

$$\rho = \dot{M}/4\pi u_{\mathrm{w}} r^2$$

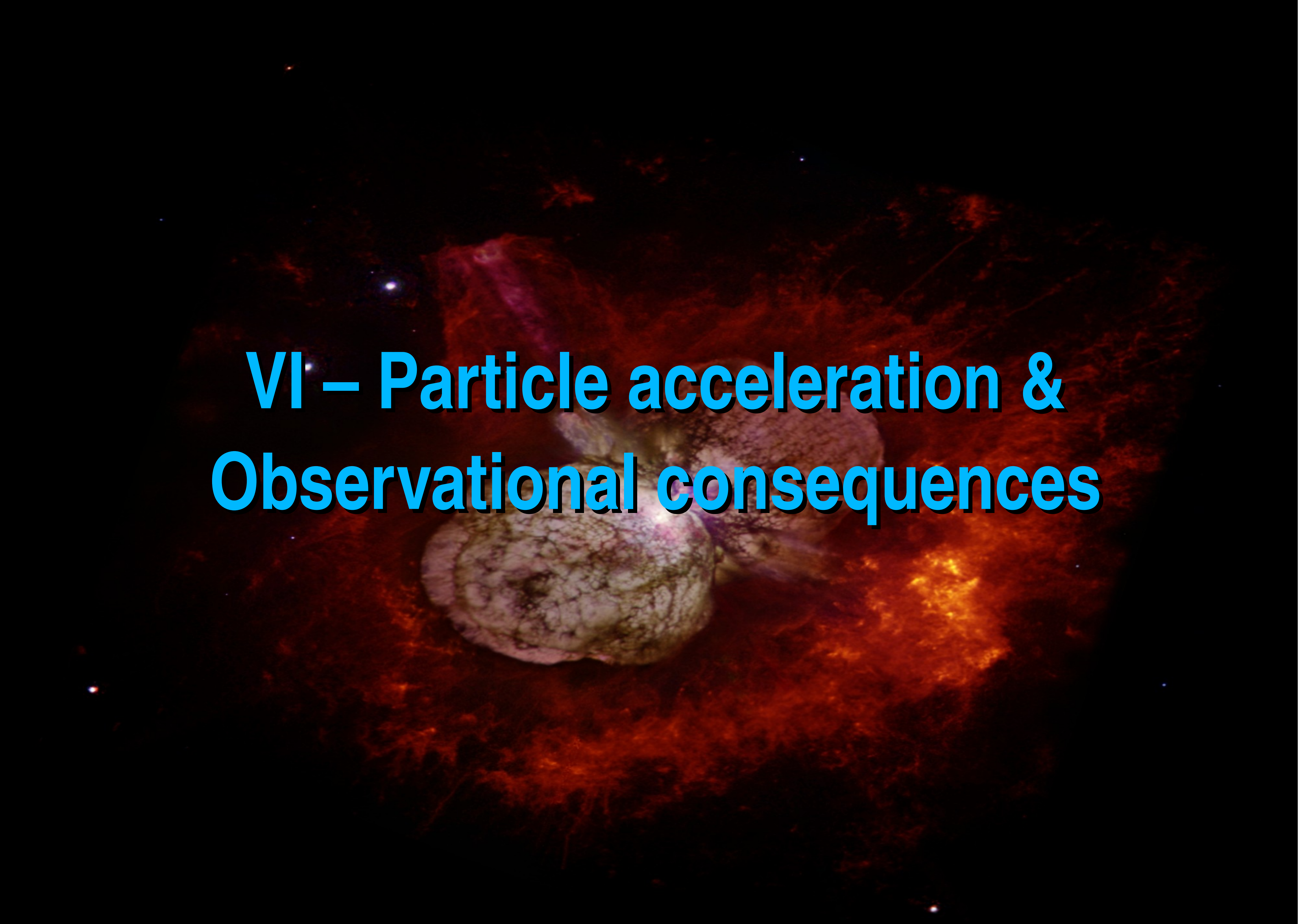
$$\rho \sim 10^{-11\,(-9)}\,\mathrm{g\,cm}^{-3}$$

=> $\beta_1 \lesssim 0.1$

($\tau = \kappa \int_r^\infty \rho dr,\ r_{\mathrm{br}} \approx \kappa \dot{M} \beta_{\mathrm{s}}/4\pi u_{\mathrm{w}}$

$r_{\mathrm{br}}/r_* \sim 10$ for $\beta_{\mathrm{s}} = 0.1$)

VI – Particle acceleration & Observational consequences



Observational consequences

- 1 – 10 TeV CRs possibly in a few seconds... (but do not contribute significantly to the Galactic CR flux)

$B_s \sim 10\,\mathrm{G}$, $\rho \sim 10^{-9,11}\,\mathrm{g\,cm^{-3}}$,

$u_A \sim (1-10)\,\mathrm{km\,s^{-1}} \lesssim u_s$ → Super-Alfvenic, OK.

$$\tau_{\rm CR} = 8E_{\rm CR}/3eB_s u_s^2 \approx 30\,\mathrm{s}$$ for $E_{\rm CR} = 10\,\mathrm{TeV}$ and $\beta_s = 0.1$

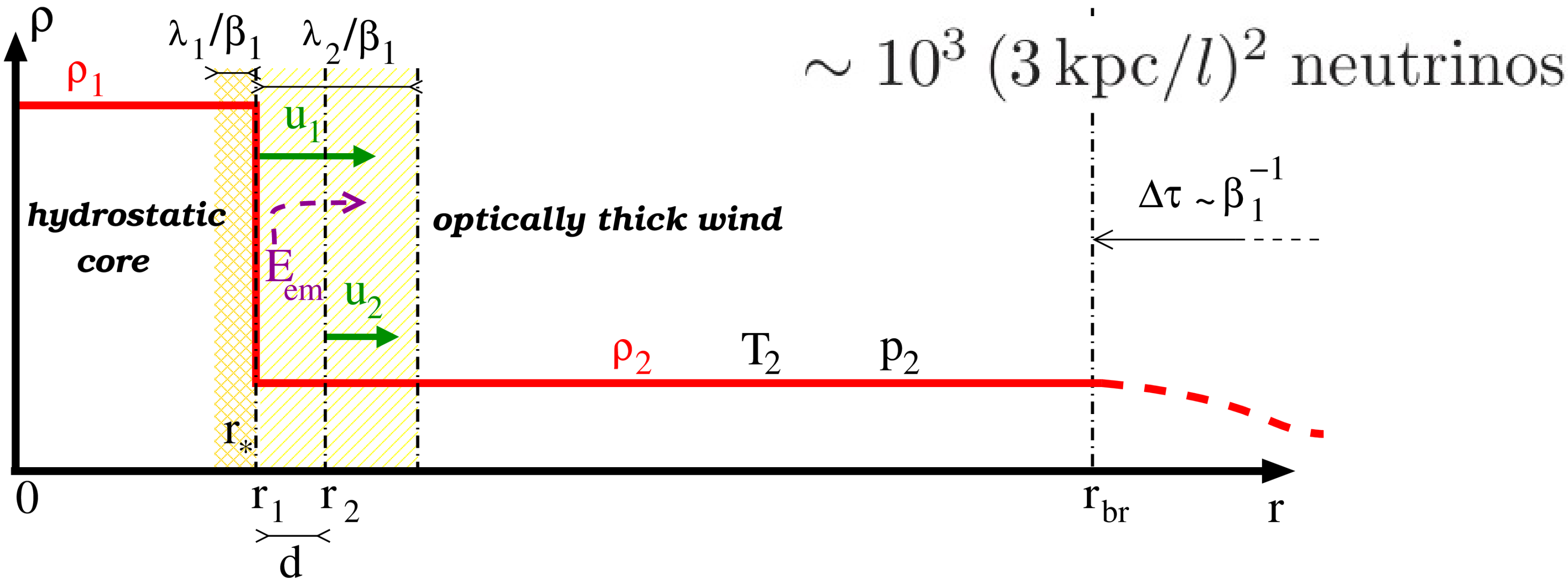
$$\tau_{\rm pp} \simeq m_{\rm p}/0.2c\rho\sigma_{\rm pp} \approx 10\,\mathrm{min}$$

$$\tau_{\rm p\gamma} \simeq 1/0.2cn_\gamma\sigma_{\rm p\gamma} \gtrsim 5\,\mathrm{min}$$ (For 10 TeV CRs, $\gtrsim 10\,\mathrm{keV}$)

$n_\gamma < \rho u_s^2/h\nu$ (+ $e^\pm$ pair creation due to $p\gamma$ interactions)

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

Observational consequences



- HE neutrinos from p – p interactions arrive SIGNIFICANTLY BEFORE photons from shock breakout : 10 hours or more !

- Flash harder than expected at shock breakout because of the viscous shock
(+ Secondary gamma-rays from pi0 decay. $\gamma\gamma_{\rm b} \rightarrow e^+e^-$)

Conclusions and perspectives

- Studied transition from a radiation mediated shock to a collisionless shock,
- Confirm that a collisionless shock forms (and why),
- Optically thick winds : Can form ***significantly before*** breakout
- Observational consequences :
  - X-ray flashes
  - >100 GeV neutrinos → Probe of the poorly known optically thick regions of circumstellar winds