Core Collapse Supernovae as Cosmic Ray Sources

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Core-Collapse Supernovae (SNe)

- Arise from Massive Stars

- These stars have strong winds throughout their lifetimes

- If the wind mass-loss rate $\dot{M}$ and the wind velocity v_w are constant, then the wind density $\rho_w = \dot{M}/(4\pi r^2 v_w) \propto r^{-2}$

- ➡ The density is maximum at small radius, i.e. close in to the star.
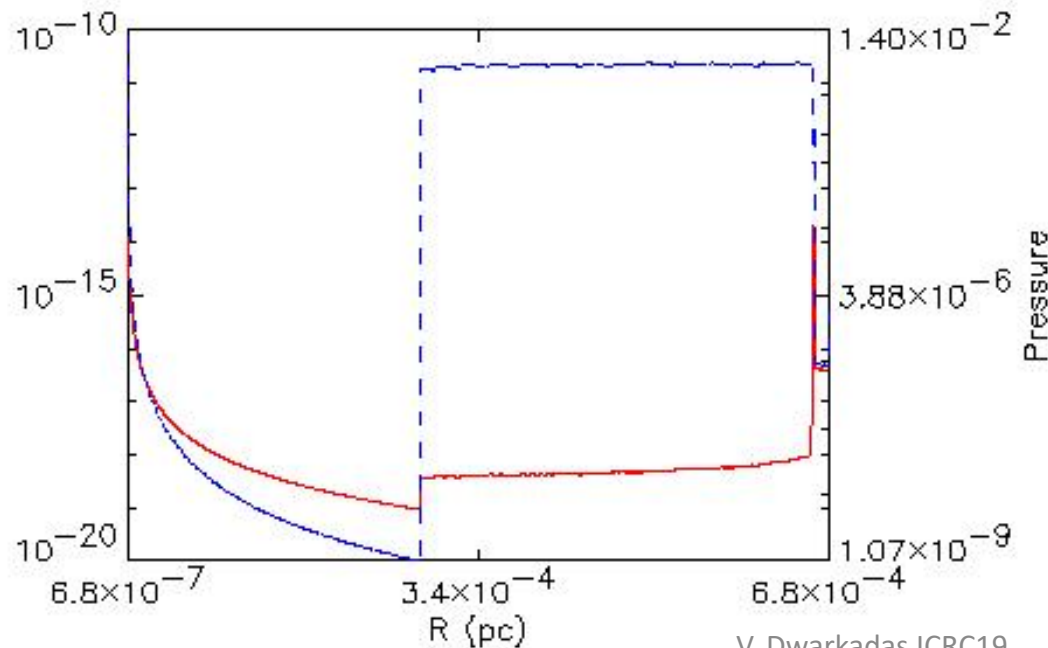
Red=Density
Blue=Pressure
Simulation shows the density and pressure structure around a star, from a simulation of a stellar wind interacting with the Interstellar medium. Note that the density is very high close in to the star.

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Gamma-Ray Emission from Young SNe

- The SN shock expands with high velocity in these high density winds.

- Protons accelerated by the SN shock wave interact with protons in the surrounding medium, giving rise to hadronic γ-ray emission via pion decay.

- Hadronic emission depends on the proton density of the target material, and thus the density of the medium.

- The hadronic emission will be highest where the density is the largest, i.e close-in to the star.

- The high radio emission from young SNe points to large magnetic fields.

- The combination of accelerated particles, large magnetic fields and high density indicates high gamma-ray emission.

- We have started a project to study the acceleration of particles due to various cosmic-ray instabilities in young SNe, growth rate of the instabilities, the maximum energy of the accelerated particles, and the gamma-ray emission.

(Marcowith, VVD et al 2018, MNRAS, 479, 4470)

Shock Dynamics

- Assume SN ejecta and circumstellar medium both evolve as a power-law with time.
- Shock radius is given by self-similar solution (Chevalier 82).
- If we start from initial time t_0 where shock radius is R_0 then

$$R_{sh}(t) = R_0 \left[\frac{t}{t_0}\right]^m, \qquad V_{sh}(t) = \frac{R_0 m}{t_0} \times \left(\frac{t}{t_0}\right)^{m-1}$$

Wind density:

$$\rho_{CSM}(t) = \rho_0 \left[\frac{R_{sh}(t)}{R_0}\right]^{-s} = \rho_0 \left[\frac{t}{t_0}\right]^{-ms}, \text{ s=2 for steady wind}$$

$$\rho_0 = \frac{\dot{M}(R_0)}{4\pi v_w(R_0) R_0^2} \cong 1.3 m_p n_H$$

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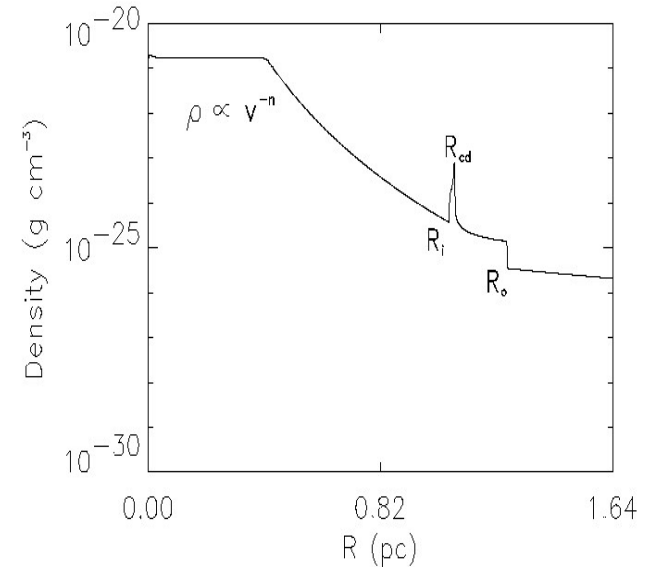
Magnetic Field Strength

- Magnetic field strength at stellar surface, obtained by balance between magnetic energy density and kinetic energy density:

$$B_{eq,0} = \left[\frac{2.5 \times 10^{13}}{R_0} \, G \right] \dot{M}_{-5}^{1/2} V_{w\,10}^{1/2}$$

CSM magnetic field proportional to $B_{eq,0}$

$$B_w(t) \cong \varpi B_{eq,0} \left[\frac{t}{t_0} \right]^{\frac{-ms}{2}}, \text{ where } \varpi = B_w(t_0)/B_{eq,0} \sim 0.1\text{-}10.$$

Acceleration Model

- We adopt a model based on the theory of Diffusive Shock Acceleration (DSA).

- Timescale to advect frozen CR-magnetized fluid to shock front is:

$$T_{adv,u} = \frac{\kappa_u}{v_{sh}^2}$$

Parallel shocks: $\kappa_u = \kappa_{II} = \frac{\eta R_L v}{3}$, where R_L = Larmor radius $\cong E/eB_w$

Writing $R_L = 3.3 \times 10^{12} \, E_{PeV} B_{w,G}^{-1}$ cm, we get

$$T_{adv,u,P} \cong \left[\frac{1.3 \times 10^9 \, \eta_P R_{0,cm}}{V_{0,\frac{cm}{s}}^2 \, \varpi} \right] \times \frac{E_{PeV}}{\dot{M}_{-5}^{\frac{1}{2}} v_{w,10}^{\frac{1}{2}}} \left(\frac{t}{t_0} \right)^{2(1-m)+ms/2}$$

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Acceleration timescale

$$T_{acc,P} = g(r)T_{adv,u,P} = g(r)\frac{\kappa_u}{v_{sh}^2}$$

Where $g(r) = \frac{3r}{r-1} \times \left(1 + \frac{\kappa_d r}{\kappa_u}\right)$ depends on shock compression ratio r and ratio of downstream to upstream coefficients.

Ratio $\frac{\kappa_d}{\kappa_u} = r_B^{-1}, r_B = \frac{B_d}{B_u}$ is ratio of magnetic fields in postshock region.

For parallel shock, $r_B \cong 1 \ and \ g(r) = 3r(r+1)/(r-1)$

Observed Magnetic Field Strength

Magnetic fields in Young SNe difficult to interpret. One usually gets synchrotron radio emission, and from there needs to deduce the magnetic field depending on the volume and other unknown parameters. But almost always seems much higher than the interstellar field by orders of magnitude.
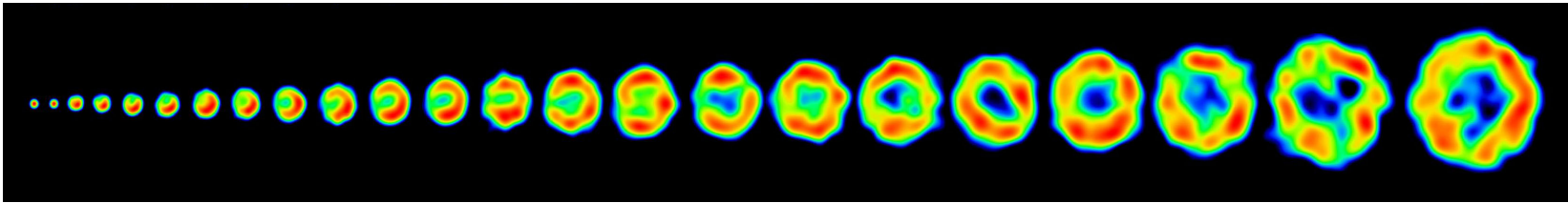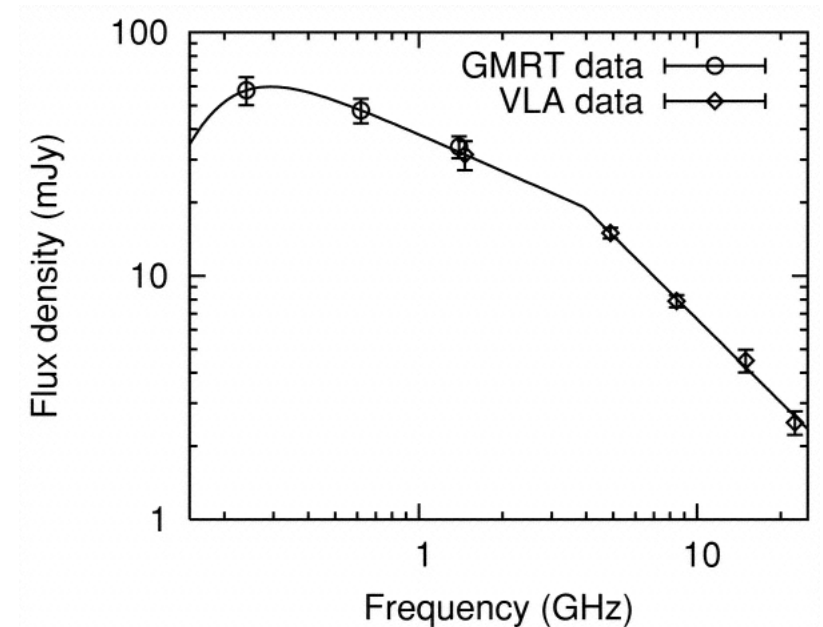

Chandra et al 2004, ApJ, 604, L97
Magnetic field for SN 1993J can be deduced from synchrotron break in the spectrum to be 0.33G, at 3200 d.

Comparable to field deduced by Fransson & Bjornsson 1998 from analysis of radio emission.

The field is much larger than the interstellar magnetic field.

Cosmic-Ray Driven Instabilities

- These operate on the forward shock and generate magnetic field fluctuations necessary for the DSA process to operate efficiently.

1. Bell Non-resonant Instability (Bell 2001, 2004)
   - ➤ Currents produced by the streaming of CRs ahead of the shock front.
   - ➤ CR streaming induces a return current in the background plasma.
   - ➤ Triggers magnetic fluctuations at scales $l \ll R_L$
   - ➤ Is non-resonant, and can be treated using modified MHD code.
   - ➤ The minimum growth time-scale (corresponding to maximal growth rate)

$$T_{min,NRS} \cong \left[\frac{2.2 \times 10^{18} R_0}{V_0^3} \right] \frac{\emptyset_{14}}{\xi_{CR,0.05}} E_{PeV} \times \dot{M}_{-5}^{-1/2} V_{w,10}^{1/2} \left(\frac{t}{t_0} \right)^{2(1-m)+(ms)/2}$$

Note: The acceleration time is inversely proportional to V_{sh}^3, thus it is lowest at the highest velocities, i.e. just after explosion. Since m<1, it is increasing with time.

Where $\emptyset_{14} \equiv \dfrac{\ln\left(\frac{E_{max}}{m_p c^2} \right)}{14}$, ξ_{CR} is fraction of shock ram pressure imparted to CRs
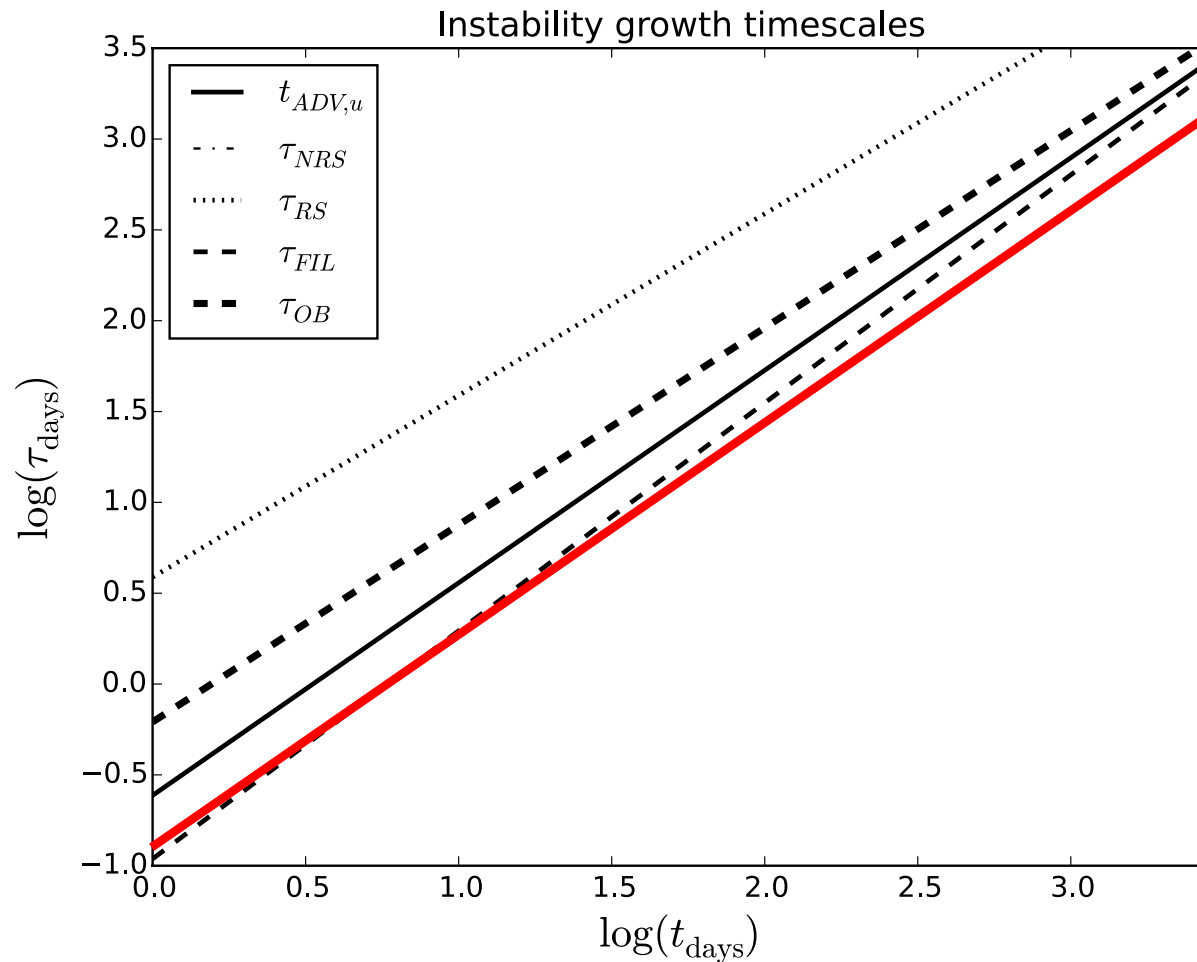
Cosmic-ray Driven Instabilities

❑Resonant streaming Instability: Streaming of Cosmic Rays faster than the local Alfven speed produces long-wavelength modes at scales $l \sim R_L$ (Amato & Blasi 2009)

❑Filamentation Instability: Reville & Bell (2012) demonstrate that CRs form filamentary structures in the precursors of SNR shocks due to their self-generated magnetic fields. The filamentation results in growth of a long-wavelength instability.

❑Instabilities generating long oblique modes: Bykov et al.(2011) show that presence of turbulence with scales shorter than the CR gyroradius enhances growth of modes longer than gyroradius for particular polarizations.

Instability Growth timescales
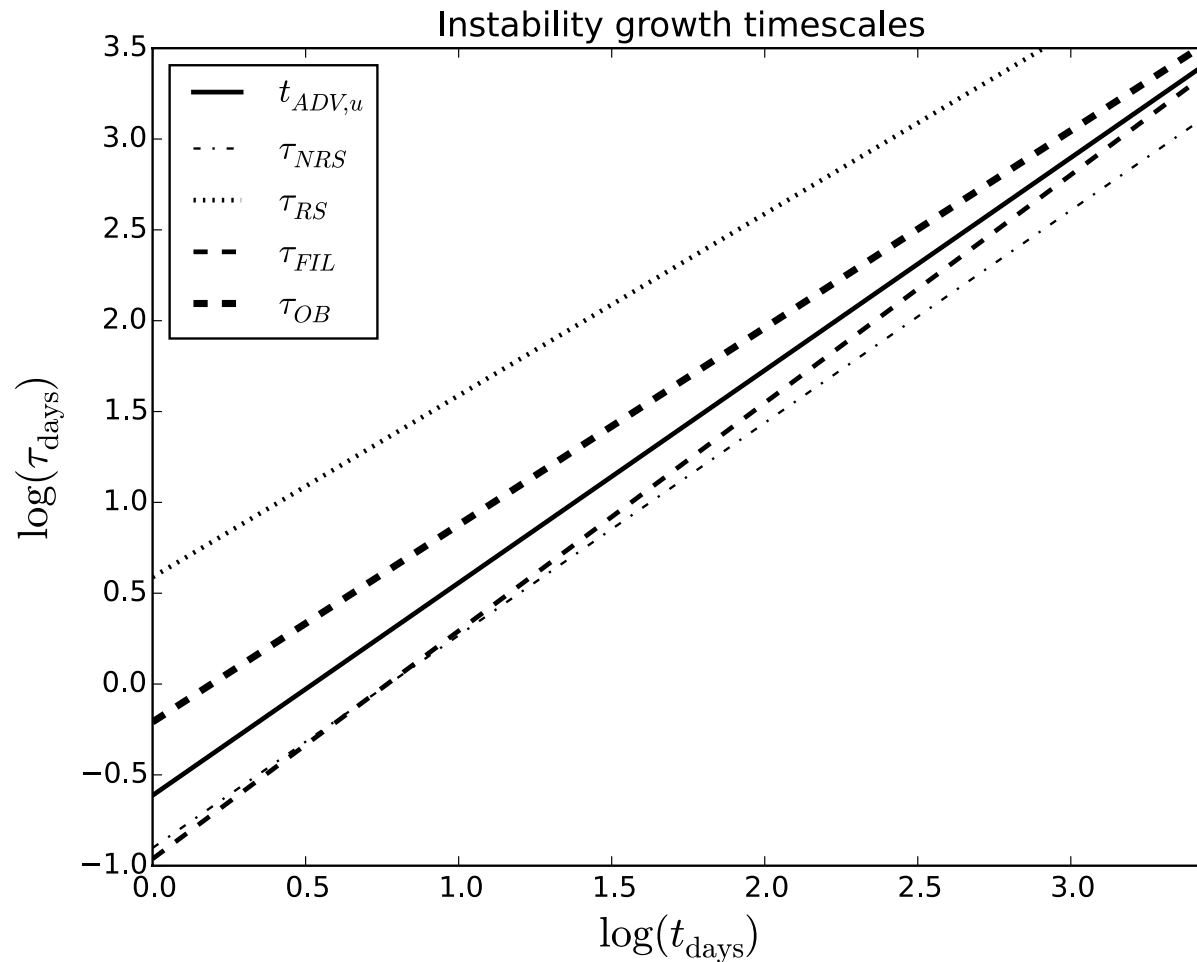
Instability growth timescales

Main instability growth timescales as a function of the time in days for the fiducial case SN 1993. We have assumed $\eta = \varpi = 1$, E = 1 PeV, $\phi = 14$, $\xi_{CR} = 0.05$.

Instability Growth timescales

Instability growth timescales

Legend:
- $t_{ADV,u}$ (solid line)
- τ_{NRS} (dash-dot line)
- τ_{RS} (dotted line)
- τ_{FIL} (dashed line)
- τ_{OB} (heavy dashed line)

x-axis: $\log(t_{\mathrm{days}})$
y-axis: $\log(\tau_{\mathrm{days}})$

Main instability growth timescales as a function of the time in days for the fiducial case SN 1993.
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Maximum Cosmic-Ray Energies

❖ Age limitation - $T_{acc} = (\frac{1}{E}\frac{dE}{dt})^{-1}$ -acceleration limited by shock age

❖ Geometrical losses due to finite spatial extent of the shock

❖ Current-driven maximum energy: If NRS instability operates, $\frac{t}{T_{min.NRS}} = N, N \in [1, \ln A]$, where A corresponds to amplification of magnetic field by factor A.

❖ Nuclear Interaction losses: High-energy CRs interact with ambient material via p-p interactions. (Mainly relevant for PeV energies).

❖ Adiabatic Losses: CRs suffer from adiabatic losses in rapidly expanding flow

Maximum Cosmic-Ray Energies
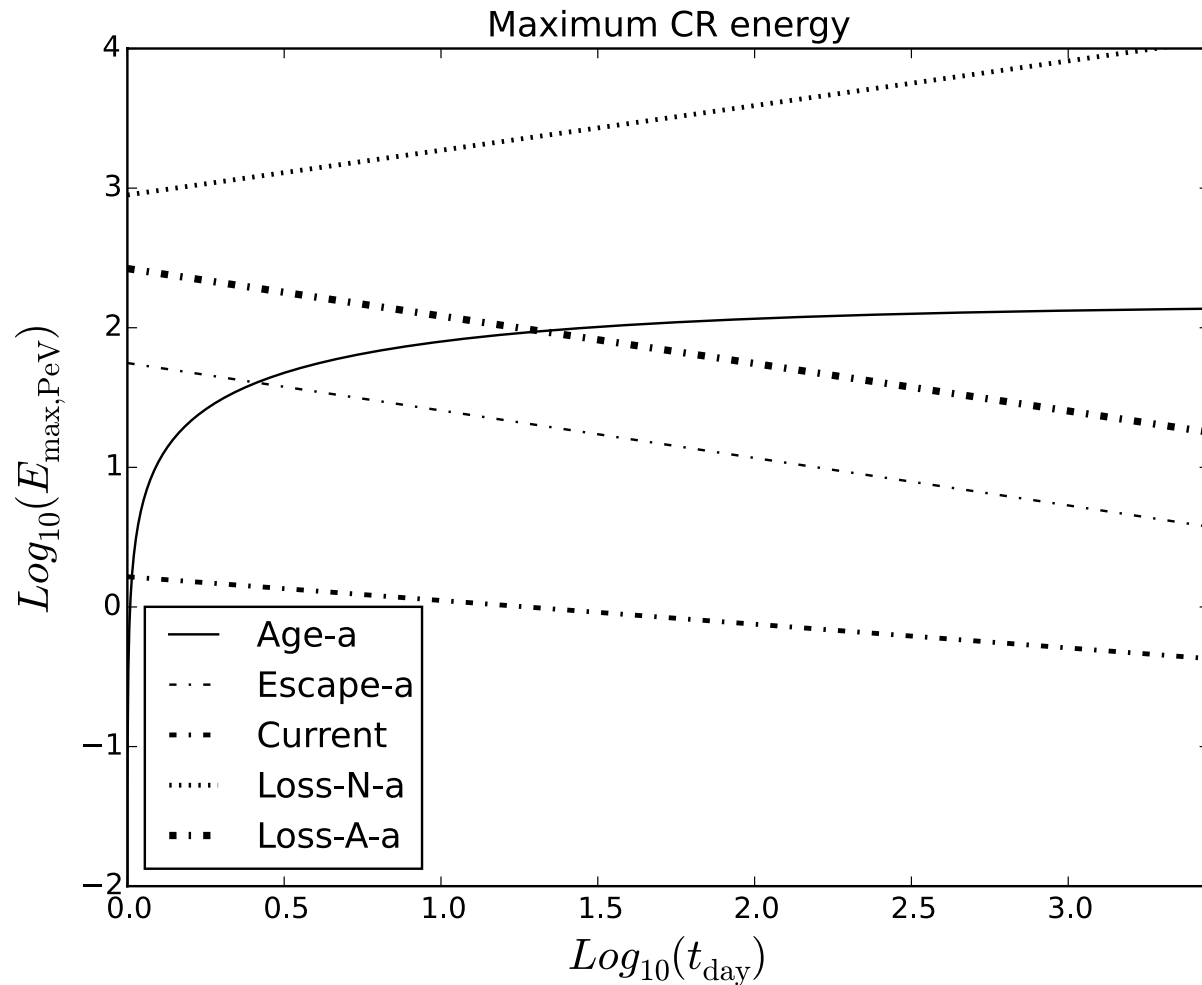
Maximum CR energy

Maximum CR energy limits in PeV units for Parallel shock model as a function of time after shock breakout for SN 1993J. The background field has been amplified up to $B_{sat,NRS}$. The dotted line plots $E_{max,nuc}(t)$, the large dot-dashed line plots $E_{max,adi}(t)$, the intermediate dot-dashed line plots $E_{max,cur}(t)$, the small dot-dashed line plot $E_{max,esc}(t)$, the solid line plots $E_{max,age}(t)$ We use: $\varpi = 1$, $\eta = 1$, $N = 5$, $\phi = 14$, $\sigma_{pp} = 1.87$.

Maximum Cosmic-Ray Energies
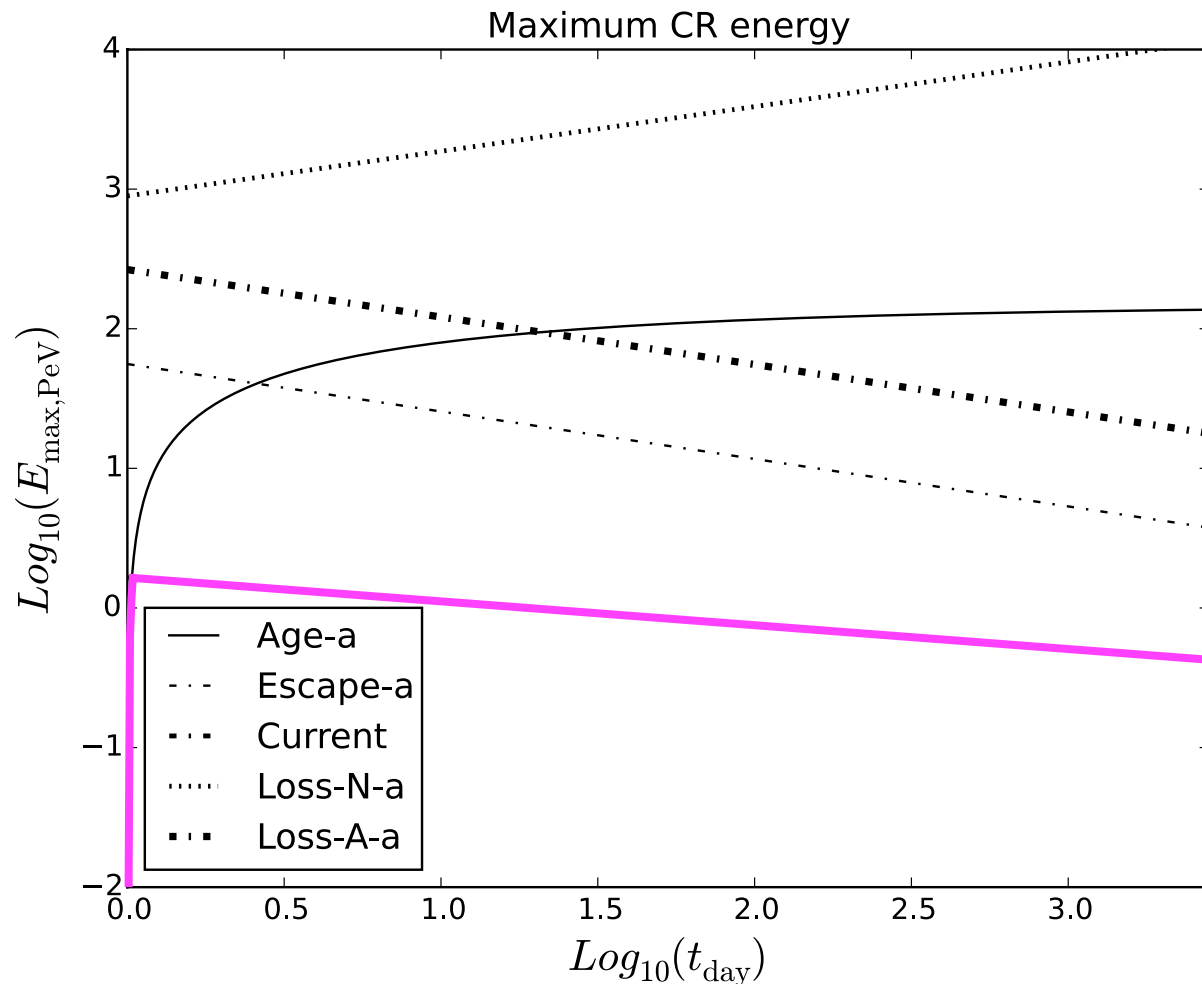
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The case for Young SNe

- The non-resonant streaming instability, that amplifies the magnetic field, is proportional to V_{sh}^{-3}, and thus the acceleration time is minimum when velocity is maximum, i.e. just after explosion, and increases with time.

- The B field gets amplified to a high value in a short time, and decreases with time.

- The density drops as r^{-2} and thus is maximum close in to the star.

- The combination of fast shocks in a high density medium results in a short acceleration timescale, highly amplified fields and a high level of gamma-ray emission in the initial stages of SN expansion.

- Thus young SNe are the most likely to accelerate particles to PeV energies
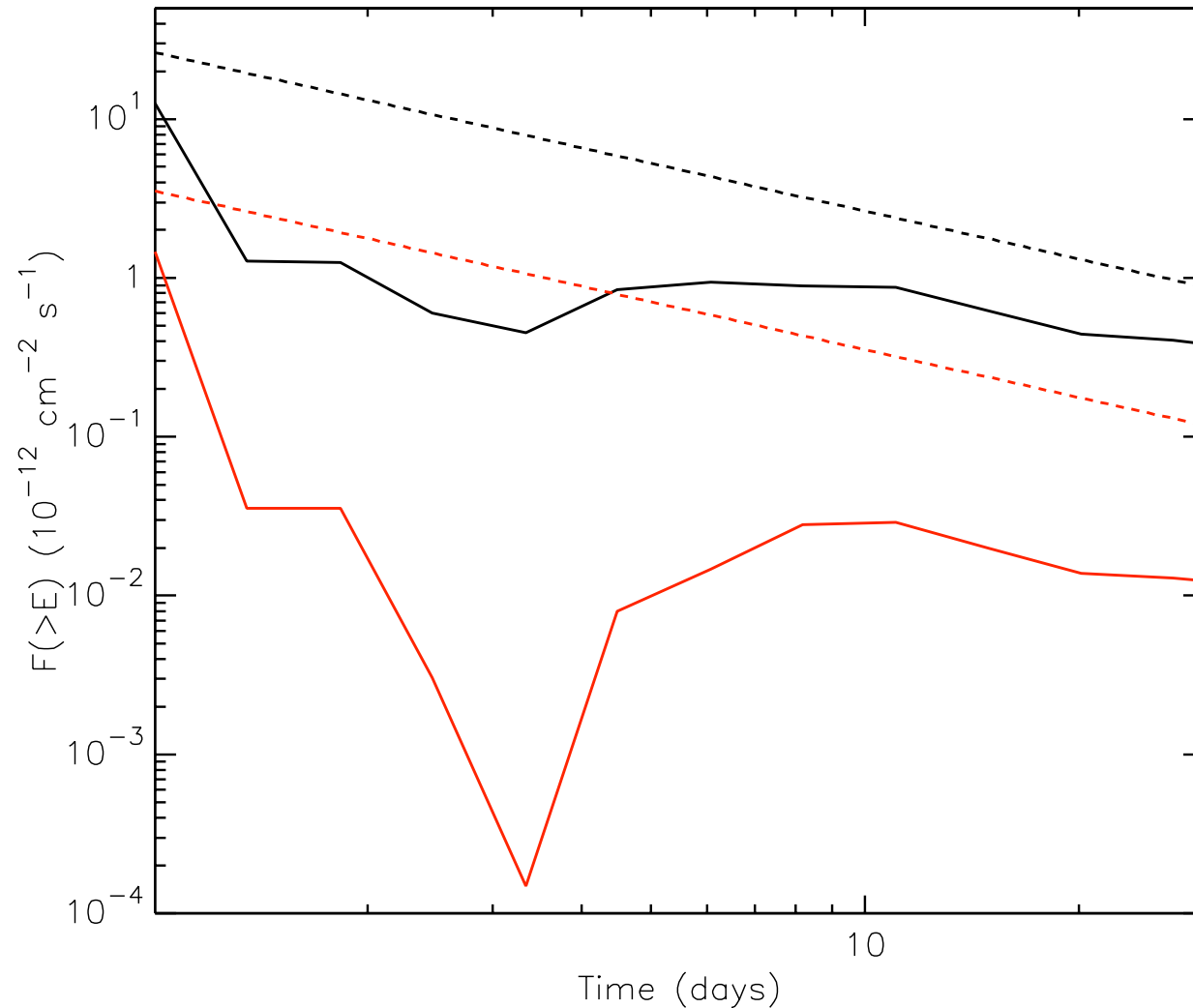
Gamma-Ray Absorption (Preliminary)

- Gamma- rays can be absorbed by soft photon fields to produce electron-positron pairs (gamma-gamma absorption).

- Photon source - SN photosphere. Full calculation of γ-γ opacity including geometrical effects due to anisotropic interaction.

Dashed line – unabsorbed flux
Solid line - Absorbed Flux

Above 0.1 TeV
Above 1 TeV

Conclusions

- Young core-collapse SNe interact with a dense medium, which can lead to high-energy particles and production of gamma-rays via pion-decay.

- Due to CR driven instabilities, magnetic fields can be amplified up to factors of several hundred.

- CR-driven instabilities, if triggered, can contribute up to 50% of magnetic field strength.

- Consequently, particles with maximum cosmic-ray energies up to or > 1 PeV can be produced.

- **Young SNe may be the long-sought Pevatrons in the Galaxy.**

- For further details, see Marcowith, VVD, et al. (2018, *MNRAS*, **479**, 4470).

- Numerical simulations, see Giacinti et al., Poster Session 2, Sat July 27, Cosmic Ray Direct, Main lounge

Questions, Discussion