Gamma-rays and Neutrinos from Efficient Cosmic-Ray Acceleration in Young Supernovae

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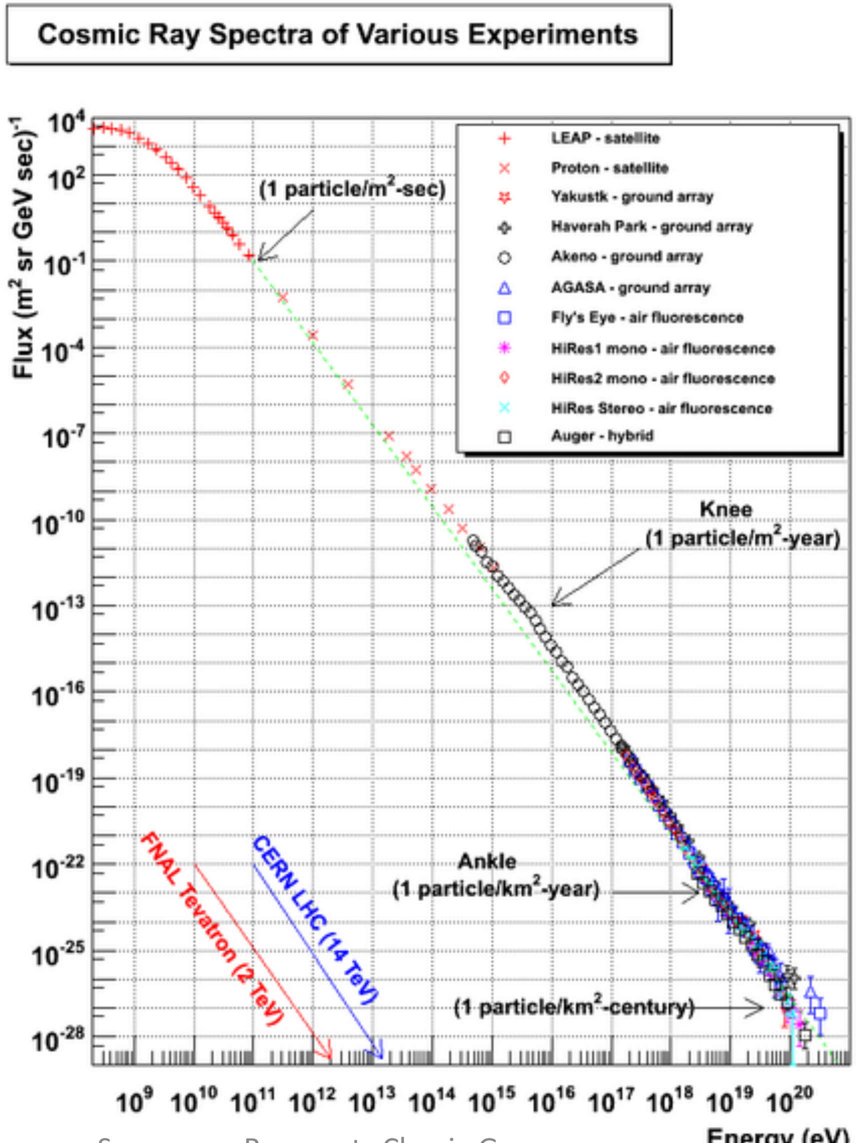
SNRs - Galactic Pevatrons?

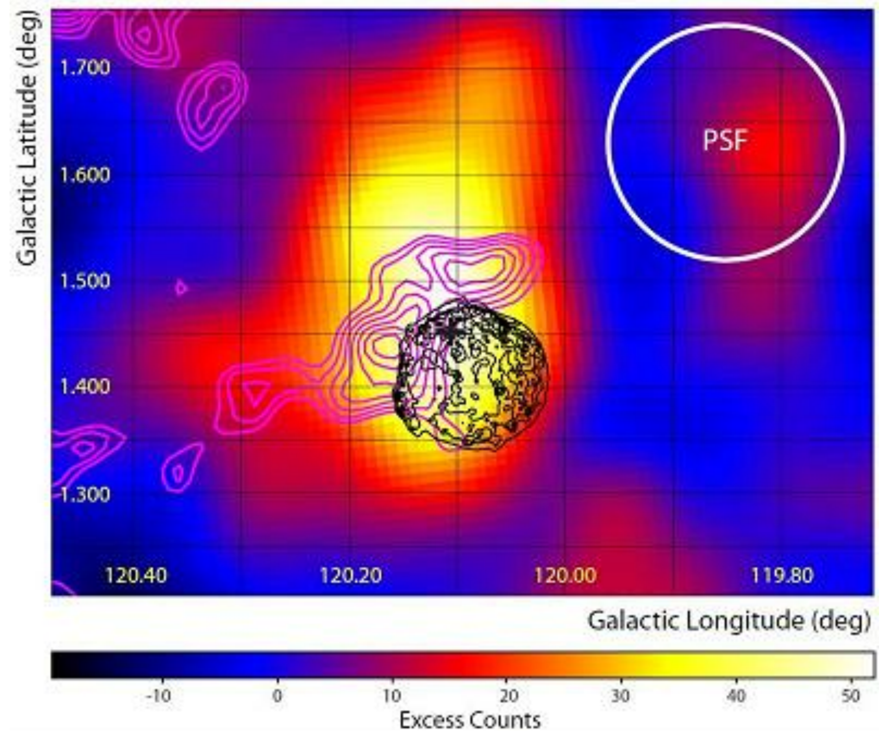
Can SNe accelerate particles up to the knee of the cosmic-ray spectrum – i.e. are they Galactic Pevatrons?

When are the PeV energy particles emitted?



SNRs as Particle Accelerators

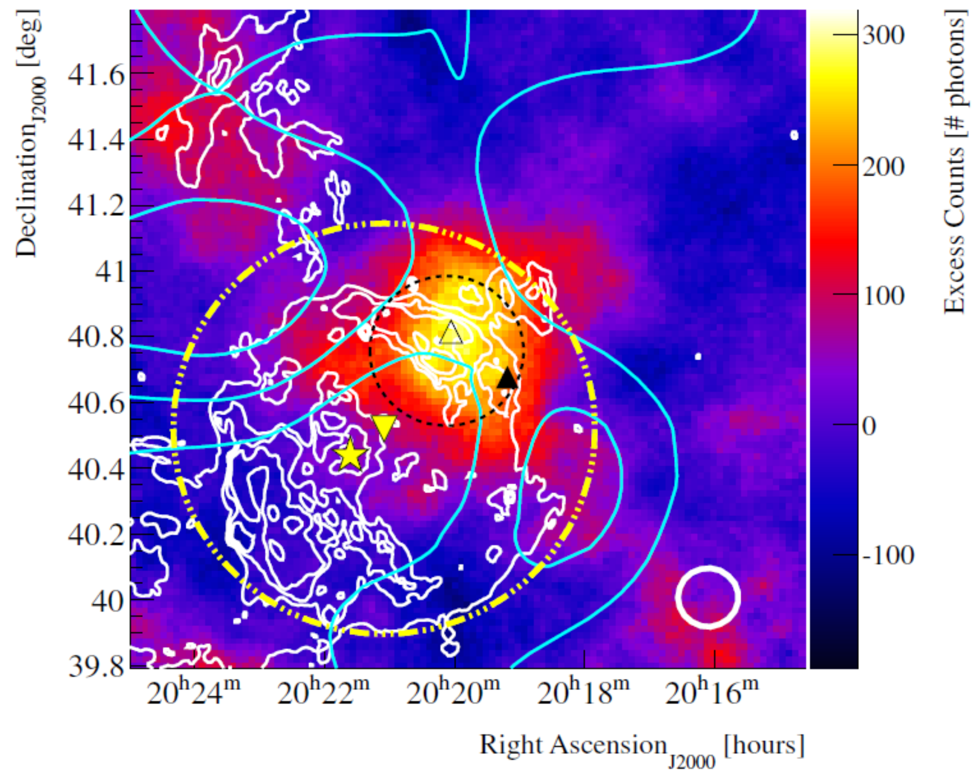
- $E_{max} \sim B\, R_{sh}\, v_{sh}$
- In general, not high enough to give Pevatrons using interstellar B values.
- Magnetic field must be amplified if high values of E_{max} are to be reached (Bell & Lucek 2001; Bell 2004)
- Bell instability – Resonant and Non-resonant modes



$$E_{\max} = Z(180\,TeV)\,u^2_{3000\,km/s}\,R_{sh,pc}\sqrt{n_{circ,cc}}$$

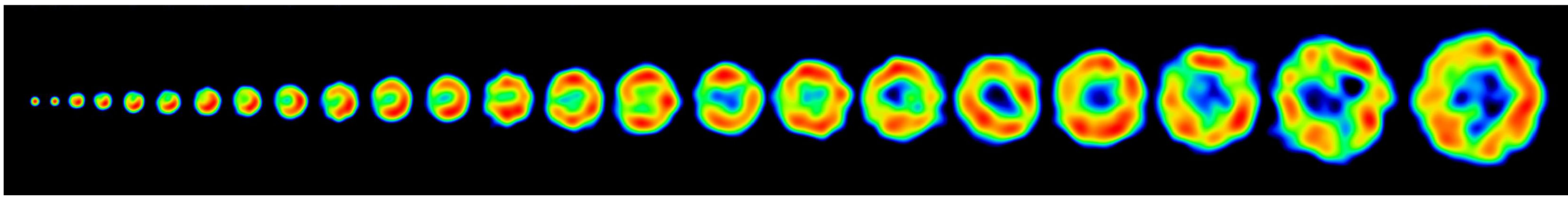
Gamma-rays from SNe

- We have started a large project to study various aspects of gamma-ray emission from SNRs.
- We look at the amplification of the magnetic field, maximum energy via various processes, and absorption of the emission in young SNRs.
- The goal is to understand particle acceleration in young SNe, and help to set the observing agenda for the Cerenkov Telescope Array (CTA) with regards to young SNe.
- In this talk I will consider the various arguments, using SN 1993J as an example.



SN 1993J

- Type IIb SN with possible RSG progenitor (Chevalier & Oishi 2003)
- VLBI observations provide information on expansion, radius and velocity



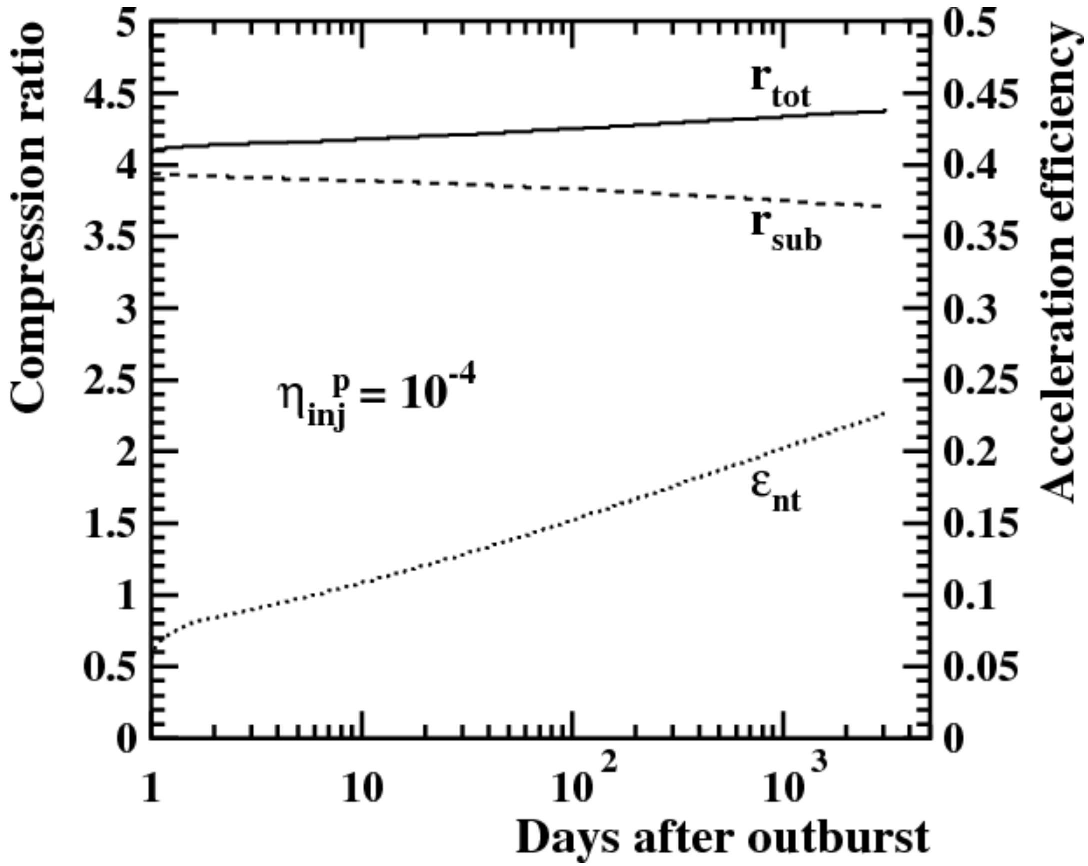
- Tatischeff (2009): $\langle B\rangle \approx \left[2.4 \pm 1G\right] \times \left(t/100d\right)^{-1.16\pm0.2}$
- Compare with equipartition magnetic field:

$$B_{eq} \cong \left[2.5mG\right] \times \dot{M}_{-5}^{1/2}\, u_{w,10}^{1/2} r_{16}^{-1}$$

- Magnetic field amplified almost 1000 times
- Chandra et al 2004: B_{eq} ~ 38 mG around day 3200

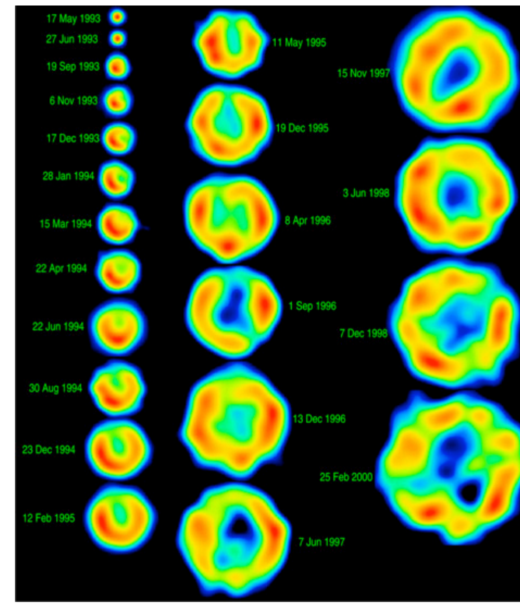
SN 1993J (Contd)

- Shock itself not highly modified
- Compression ratio close to 4
- Strong magnetic field amplification, driven by diffusive shock acceleration, at work at forward shock.
- Efficiency of accelerated particles increases with time to ~25%



SN 1993J (Contd)

- Shocks are not highly affected – assume Chevalier (1982) self-similar solution.
- Circumstellar medium formed by pre-SN RSG wind mass-loss. Wind fully ionized over 30 days of SN evolution.
- Mass-loss rate 3.8 x 10^{-5} $M_{\odot}$ yr^{-1}.
- Circumstellar density decreases as r^{-2}.



Streaming Instabilities

- Streaming of cosmic rays ahead of shock front produces magnetic fluctuations.
- Streaming modes can be in resonance with energetic particles ($k \sim r_L^{-1}$), or they can be non-resonant ($k > r_L^{-1}$). NR modes grow fastest in case of fast shocks, such as in young SNe:

$$\tau_{NR-st} = \frac{0.16(\phi/15)\varepsilon_{PeV} t_{days}^{1.17}}{(\xi_{cr}/0.05)u_{93J}^{3}\sqrt{n_{93J}}}\, days$$

Where $\phi = \ln(p_{max}/p_{inj}) \cong 15$, and $\xi_{CR} \cong 0.05$, i.e 5% of the kinetic energy goes into accelerated particles.

NR Modes (Contd)

- The growth timescale must be shorter than the advection timescale towards the shock $\tau_{ADV}=\kappa/v_{sh}^2$, where $\kappa=\eta\kappa_{B,}$
- $\kappa_B=cr_L/3$, r_L is the Larmor radius, and κ is calculated with the background magnetic field. We find: $\tau_{ADV} = 0.24\eta\varepsilon_{PeV}t_{days}^{1.17}$
- The condition $\tau_{NR\text{-}st} < \tau_{ADV}$ is necessary for the instability to develop and cosmic rays to be confined around the shock, but not sufficient.

Other Modes

- R instability has growth rate (Amato & Blasi 2009, MNRAS, 392, 1591):

  $\tau_{R\text{-}st} \cong (\pi\sigma/8)^{0.5}/r_{Lmax,}$ with $\sigma \sim 3\times10^{16}$ cm^2 s^{2}.
  Thus $\tau_{R\text{-}st} \cong 16\ \tau_{NR\text{-}st}$ at 1 PeV.

- Bykov et al (MNRAS, 410, 39) proposed a ponderomotive instability, that builds up magnetic fluctuations by the NR instability, with growth rate:

$$\tau_{LW} = \frac{0.29\varepsilon_{PeV} t_{days}}{\sqrt{u_{93J}^{3}\xi_{0.05}\phi_{15}^{-1}A_{10}}} days$$

Where $A_{10} = B_{NR}^2/B_0^2$ refers to increase in magnetic energy over background energy, (normalized to 10). Timescale is shorter than τ_{ADV} for $kr_{L,max} \cong 1$.

Maximum Energies

- At early times, maximum energy limited by SN age, and obtained by equating acceleration timescale with the age:

$t_{age} = \tau_{acc} = g(r)\, \kappa_u/u_{sh}^2$

where $g(r) = 3r/(r-1)\times(\kappa_d/\kappa_u r + 1)$.

$$E_{\max,age,PeV} \cong \frac{12.3}{\eta g(r)} \times \left(1 - t_{day}^{-0.17}\right)$$

Maximum Energies (Contd)

- If NR streaming instability is active:

$$E_{\max,NR,PeV} \cong 1 \times t_{day}^{-0.17}$$

- If long wavelength fluctuations due to ponderomotive instability (Maund et al 2004)

$$E_{\max,LW,PeV} \cong 55\left(\frac{\eta_{esc}}{0.1}\right) \times t_{day}^{-0.34}$$

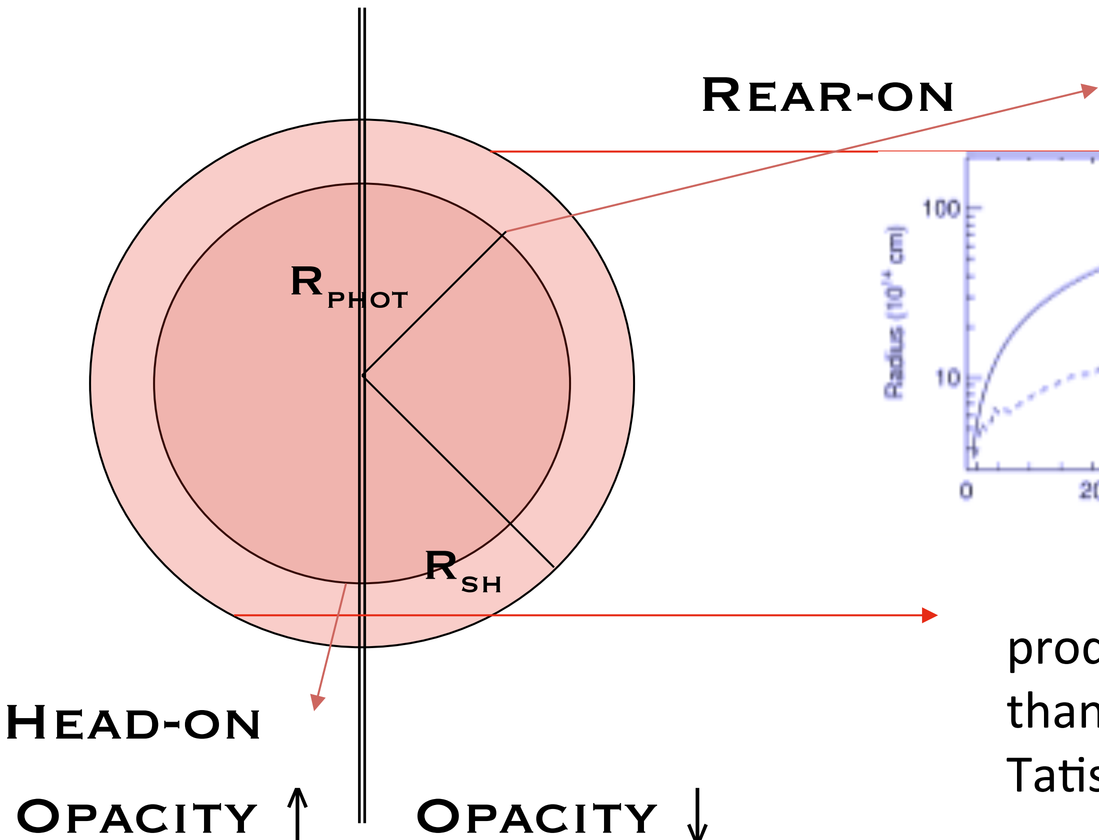
- Caveat: Highest Energy particles may not experience maximum B field.

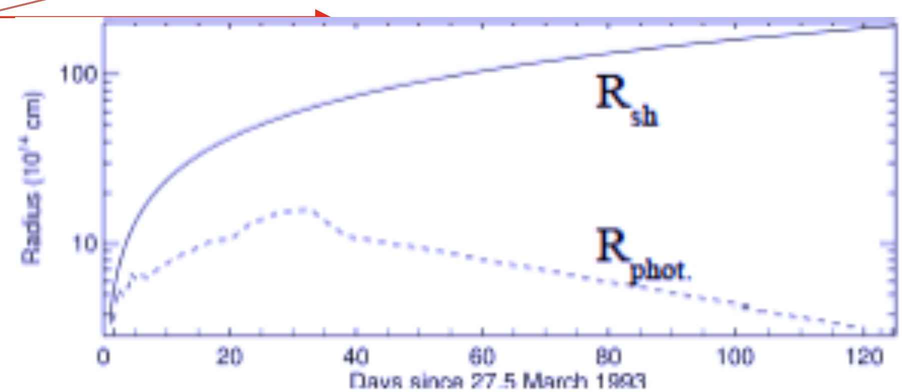
Particle Acceleration Modelling

- Procedure: [Renaud et al. (2016) in prep]
  - Using 1D solutions at the shock front:
    - Calculate $E_{max}(t)$ for protons and electrons (radiative losses) taking various instabilities into account
    - Inject a modified non-linear spectrum at the shock.
  - Downstream evolution (One-zone model):
    - Radiative + adiabatic losses
    - Pion production: Secondaries production (electron/positron, neutrinos)
  - Compute time dependent multi-wavelength spectra from primaries and secondaries.
    - GeV-TeV signal accounting from gamma-gamma absorption.

Gamma-ray Absorption

- Anisotropic Gamma-Gamma absorption over soft photons produced at the SN photosphere (UV,optical)





produces much less absorption than in isotropic calculations (eg Tatischeff, Kirk)

Gamma-Ray Absorption (Preliminary)

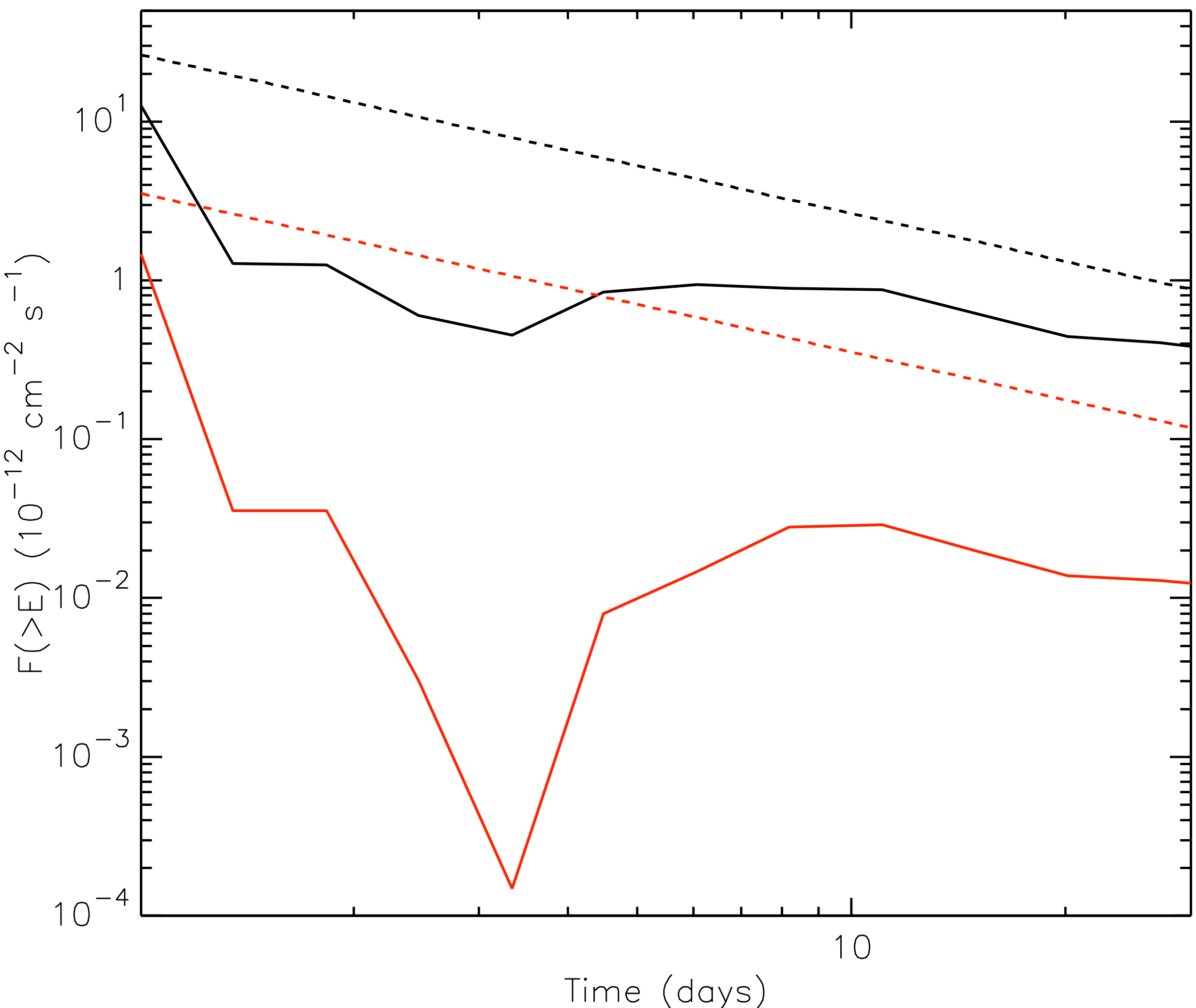
- Gamma- rays can be absorbed by soft photon fields to produce electron-positron pairs (gamma-gamma absorption).
- Photon source - SN photosphere. Full calculation of γ-γ opacity including geometrical effects due to anisotropic interaction.

Dashed line – unabsorbed flux

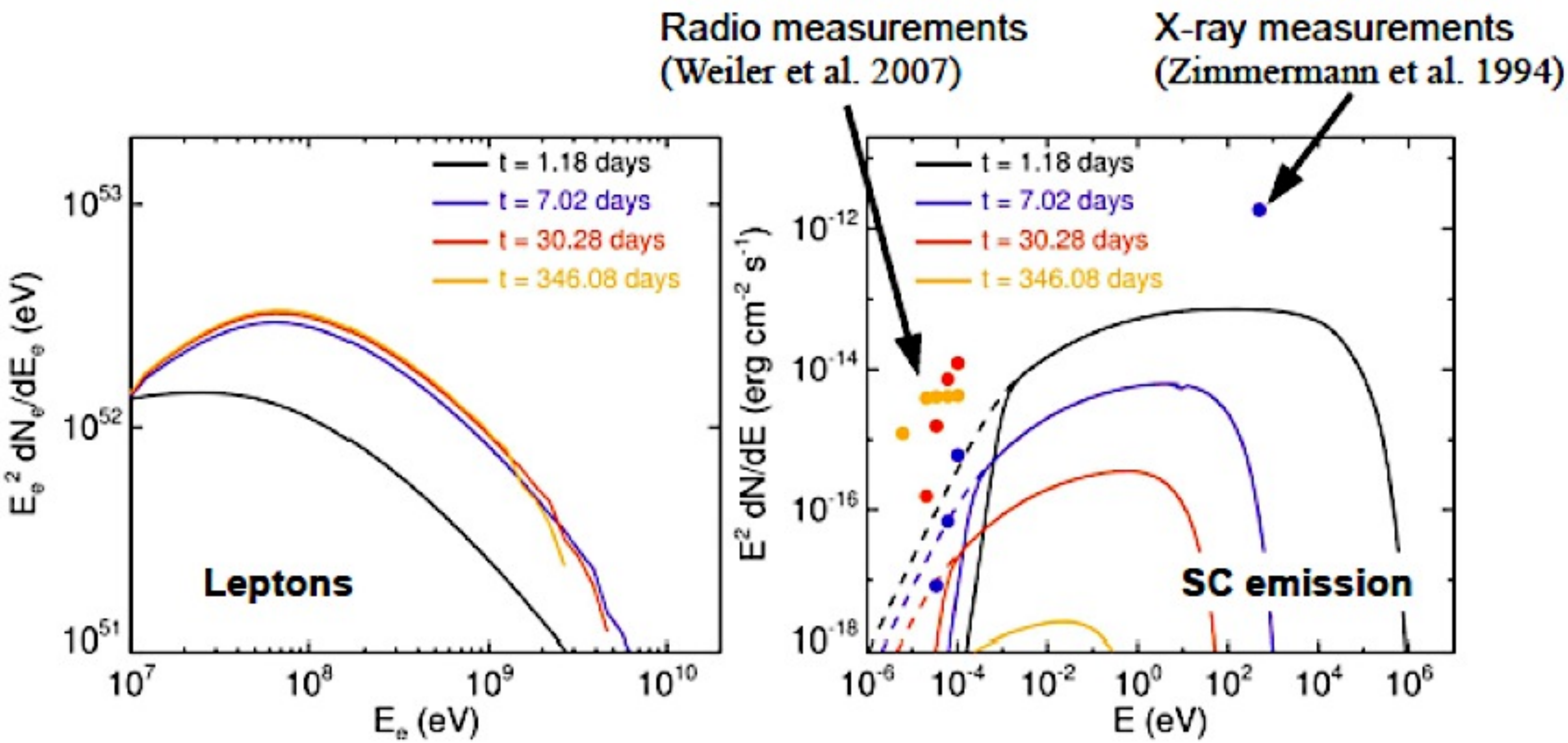
Solid line - Absorbed Flux

Above 0.1 TeV

Above 1 TeV

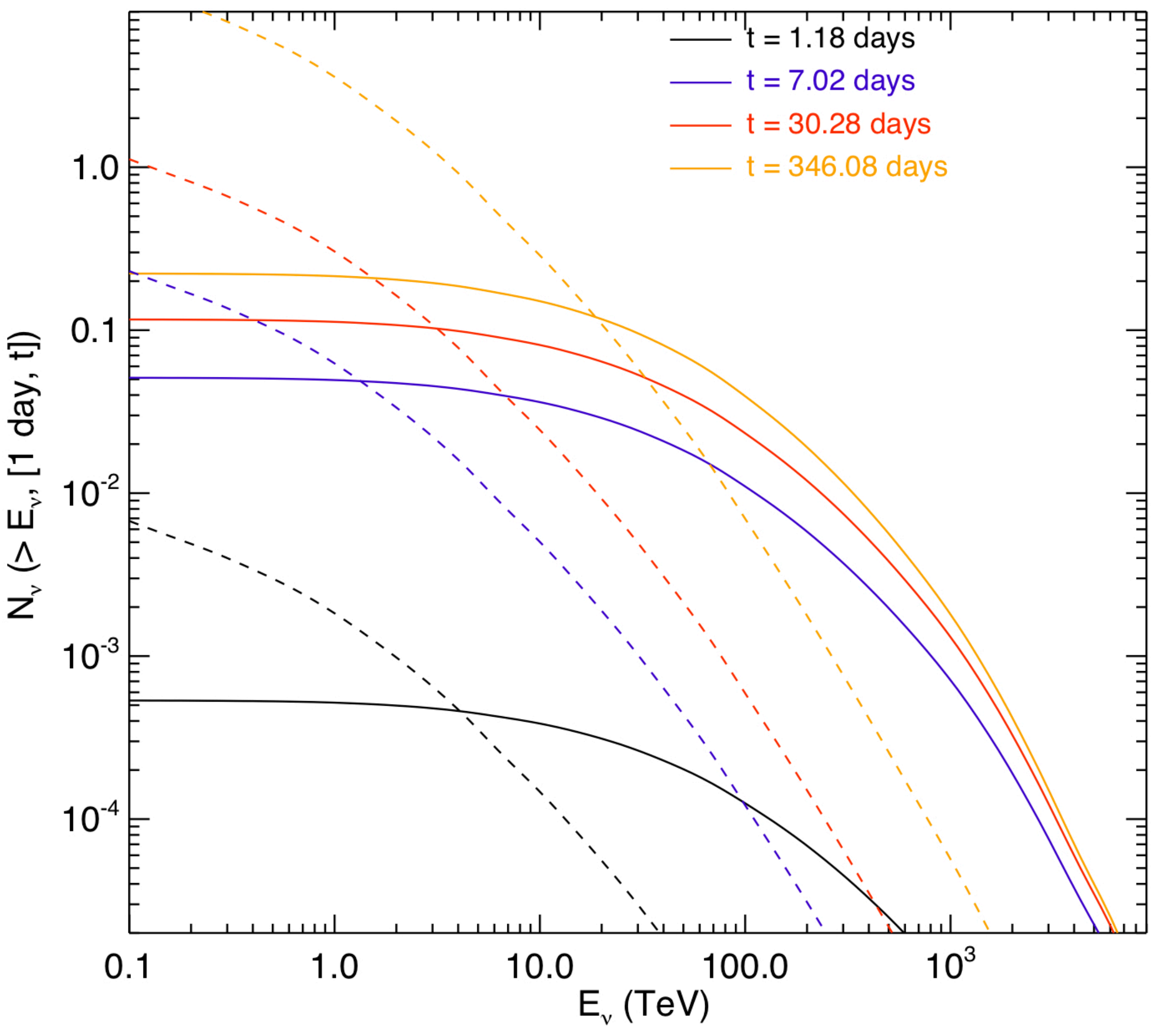


Emission from secondary leptons



Time dependent spectra from electron-positron secondaries at four different times after outburst. Radio data (Weiler et al., 2007, ApJ). X-ray data (Zimmerman et al., 1994, Nature), at about 7 days after outburst. Dotted lines represent unabsorbed synchrotron spectra while continuous lines include synchrotron self-absorption. The plot shows that the emission from the secondaries lies below the observed radio and X-ray levels.

Neutrinos



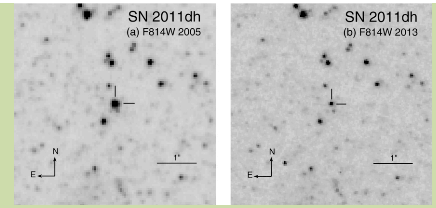
Neutrinos are by-products of pion production. Time dependent neutrino flux of SN 1993J above an energy E expected by an instrument equivalent to KM3NeT (solid lines) at four different times after the outburst. Dotted lines show the atmospheric neutrino backgrounds. In order to detect at least one neutrino from such a source, it must be at a distance < 1 Mpc, or the gamma-ray signal has to be ten times stronger.

Analysis of various effects

key parameters	main effects
Mass loss rate/wind velocity	CSM density and instability growth rate Target material and gamma-ray luminosity
Shock velocity	Instability growth rate and acceleration timescale
Local ionization degree	Composition, instability growth
Background magnetic field	Magnetization and obliquity
SN luminosity (peak and light curve)	Gamma-gamma absorption

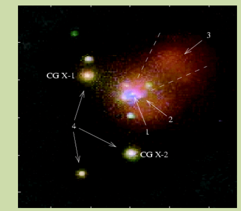
Analysis of SN Types

- SN IIb



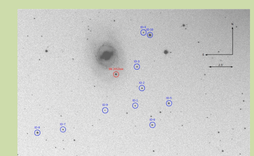
  – Interesting but rare events ~4-6% of core collapse SNe (Smartt+09). Some (IIb(e) - 93J) have higher ambient densities, other sub-types (IIb(c)) may have much lower densities.

- SN IIn



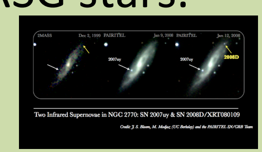
  – ~1-4% of Core-collapse SNe : more luminous, higher density. But not necessarily wind interaction; perhaps dense shell. Somewhat different hydrodynamical model required – cannot use self-similar solutions.

- SN IIP



  – around 50-55% of Core-Collapse SNe - less luminous, particularly in X-rays; suggests lower mass loss/wind velocity ratio than observed for RSG stars.

- SN Ib/Ic



  – mildly relativistic shocks. Associated with a WR phase, so low density ambient medium. X-rays presumably due to Inverse Compton, thus show evidence of particle acceleration already.

Conclusions

- Highest GCR energies are reached for fast shocks. Current driven instabilities grow the fastest in dense environments.

  Explore particle acceleration in very young SNe.

- Test case 93J:
  - Maximum energies: Up to few PeV for protons,
  - Gamma-gamma absorption reduces flux considerably, up to several orders of magnitude.
  - Gamma-ray detection of 93J-like SNe possible above 0.1TeV for CTA. Much higher ambient densities required for HESS, VERITAS and MAGIC.
  - High-energy neutrinos expected however the flux is low (depends on p-p interaction and surrounding density).
  - Our neutrino fluxes lower than some others (Murase et al., Zirakashvili etc) simply because these authors use very much higher ambient densities.
- Other SN classes:
  - Type IIn seem obvious targets – high density in surrounding medium.

Questions and Discussions