Early Time Signature of γ-ray Emission from Supernovae in Dense Circumstellar Media

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Abstract

We present our results on the γ-ray emission from interaction-powered supernovae (SNe), a recently discovered type of SN suggested to be surrounded by a Circumstellar Medium (CSM) with high densities $10^7 - 10^{12}$ cm^{-3} that favor the production of γ-ray photons through neutral pion decay as well as the photon production due to relativistic bremsstrahlung. Using a numerical code that includes synchrotron radiation, adiabatic losses due to the expansion of the source, photon-photon interactions, proton-proton collisions (pp) and proton-photon interactions, i.e. photopair ($p\gamma \to pe^{\pm}$) and photopion ($p\gamma \to p\pi^0$, $p\gamma \to p\pi^{\pm}$) production, we calculate the γ-ray emission (> 100 MeV) soon after the shock breakout and follow its temporal evolution until 100-1000 days. We show that > 100MeV γ-ray emission from pp collisions could be detectable by the Fermi-LAT telescope for nearby ($\lesssim$ 10 Mpc) SNe with dense CSM ($> 10^{10}$ cm^{-3}).

Physical Processes

We use the numerical code originally presented in Ref. [1], that includes:

- synchrotron emission
- inverse Compton scattering (ICS) on background photons and on synchrotron photons (i.e. synchrotron-self Compton)
- synchrotron-self absorption (SSA)
- photon-photon ($\gamma\gamma$) absorption
- photo-hadronic ($p\gamma$) interactions

Motivated by the idea of [2] that protons may play a primary role on the radiation of SNe, we expand the original code by including two physical processes, namely:

- proton–proton (pp) collisions, and
- adiabatic expansion of the source.

The inclusion of secondary particle production in pp collisions was based on Ref. [3]. The accelerated protons at the forward shock of an interaction-powered SN (e.g., SN IIn), may play a significant role in the γ-ray production because the source is surrounded by a very dense CSM. The shock-accelerated protons are advected in the downstream region of the shock where they can interact with the thermal (non-relativistic) protons of the shocked CSM producing energetic pions. These, in return, decay into other secondary particles:

- $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$
- $\mu^{\pm} \to e^{\mp} + \nu_e + \nu_{\mu}$
- $\pi^0 \to 2\gamma$

The pion-produced γ-rays and neutrinos are the smoking gun for proton acceleration at the source.

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Results

Following [4], we end up with an equation for the number density of the downstream medium and the relative magnetic field as a function of radius R:

$$n(R) \simeq 2 \cdot 10^{12} R_{in,14}^{-1} \beta_{-1.5}^{-1} \left(\frac{R_{in}}{R}\right)^{2} \text{ cm}^{-3} \quad \& \quad B(R) \simeq 46 \varepsilon_{B,-4}^{1/2} \beta_{-1.5}^{1/2} R_{in,14}^{-1/2} \left(\frac{R_{in}}{R}\right)^{\alpha_B} \text{ G}$$

where we introduced the notation $Q_x = Q/10^x$ in cgs units. R_{in} is the effective inner radius of the CSM, i.e. the shock breakout radius, ε_B is the ratio of the magnetic energy density over the post-shock thermal energy density and α_B is the decay slope of the magnetic field with the shock radius and will be considered unit.

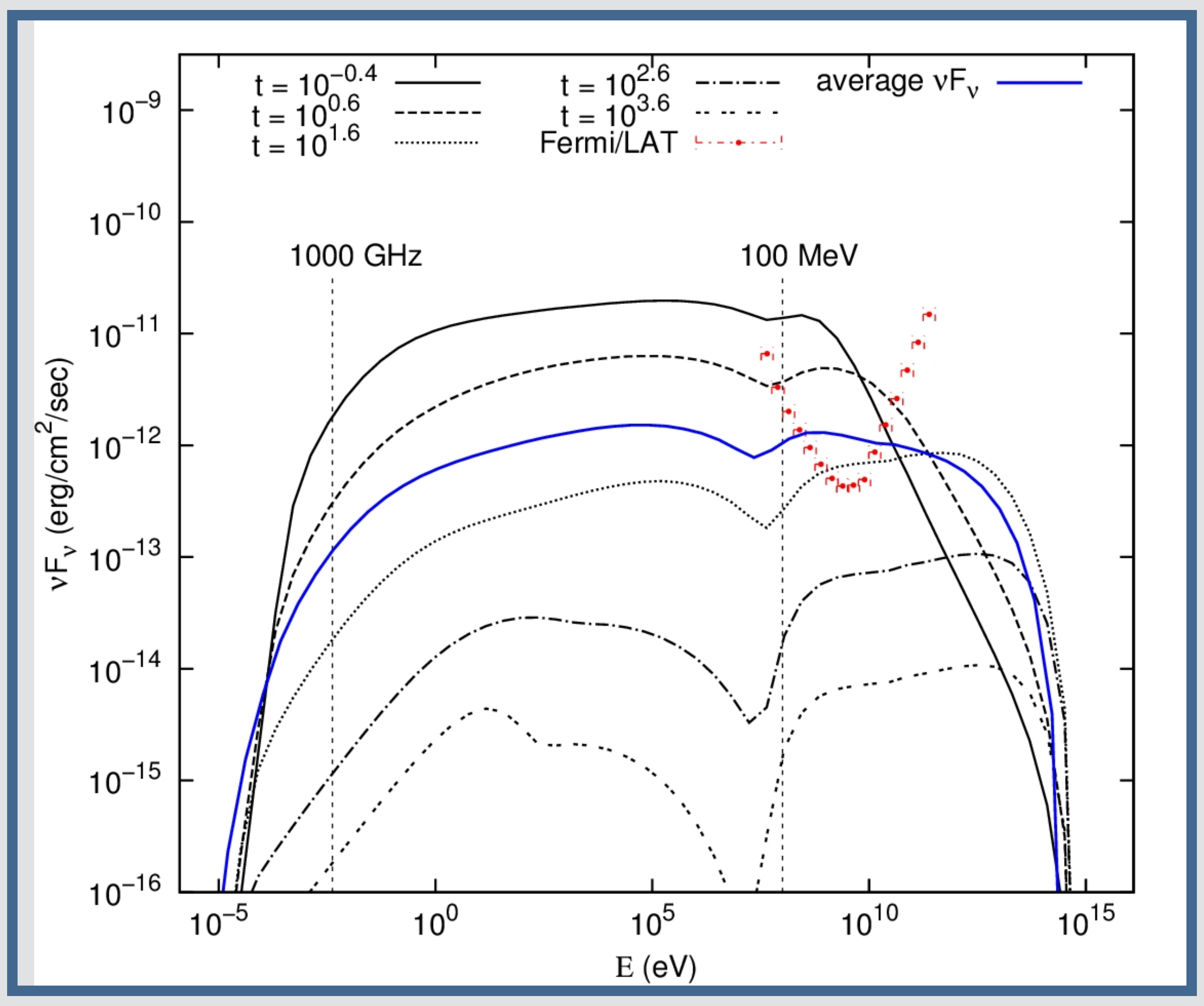

Fig. 1: Temporal evolution (for $t \leq 10^{3.6}$d $\simeq$ 11yr) of the multi-wavelength non-thermal spectrum of a SN IIn at a distance 5 Mpc. The radio emission is synchrotron self-absorbed at $E \sim 10^{-5}$eV, while the spectrum is dominated by the synchrotron emission of primary and secondary electrons up to $E \sim 10$ MeV. The pion-produced γ-ray emission extends from ~ 100 MeV up to $E \sim 1$ PeV for protons accelerated to ~ 1 PeV. The Fermi-LAT point-source sensitivity for a 10-yr exposure is depicted with red symbols (*http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm*). The average MW spectrum predicted by the model for a time interval of 10 yr is overplotted with a blue line.

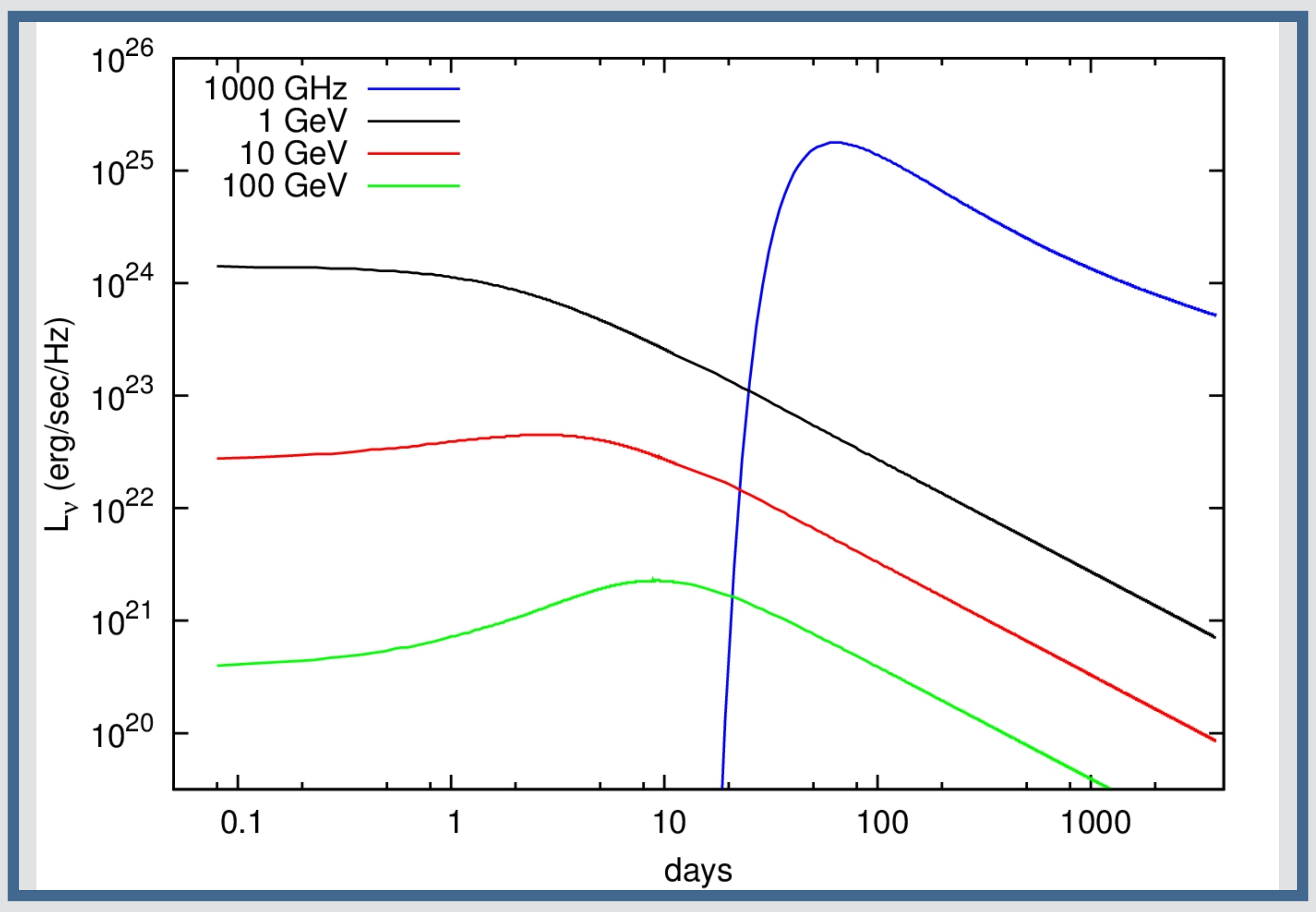

Fig. 2: Monochromatic light curves at 10^3 GHz, 1 GeV, 10 GeV and 100 GeV. The radio light curve is affected by free-free absorption on the thermal electrons of the unshocked CSM with $T_e = 10^5$ K. For display reasons, the GeV light curves are shifted upwards by a factor of 7 in logarithm. The luminosity decays as a power-law:

- $L_\nu \propto t^{-0.7}$ at 10^3 GHz and
- $L_\nu \propto t^{-1}$ at > 1 GeV.

Conclusion

- pp collisions may produce > 100MeV γ-rays for sufficiently dense CSM.
- the γ-ray attenuation due to internal $\gamma\gamma$ absorption is important only at early times (i.e. < 10d). We intend to include the SN optical radiation as a target for $\gamma\gamma$ absorption in a future work.
- $p\gamma$ interactions upon the non-thermal photons are negligible. The $p\gamma$ interactions with the X-ray bremsstrahlung photons produced by the hot shocked plasma will be considered in the future. Furthermore, the numerical code will be extended to include the relativistic bremsstrahlung radiation.
- a SN IIn at a distance < 10Mpc or with CSM density $\gtrsim 10^{12}$ cm^{-3} is detectable by the Fermi-LAT.

References

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