Supernovae brushstrokes in context of the OCEANS project

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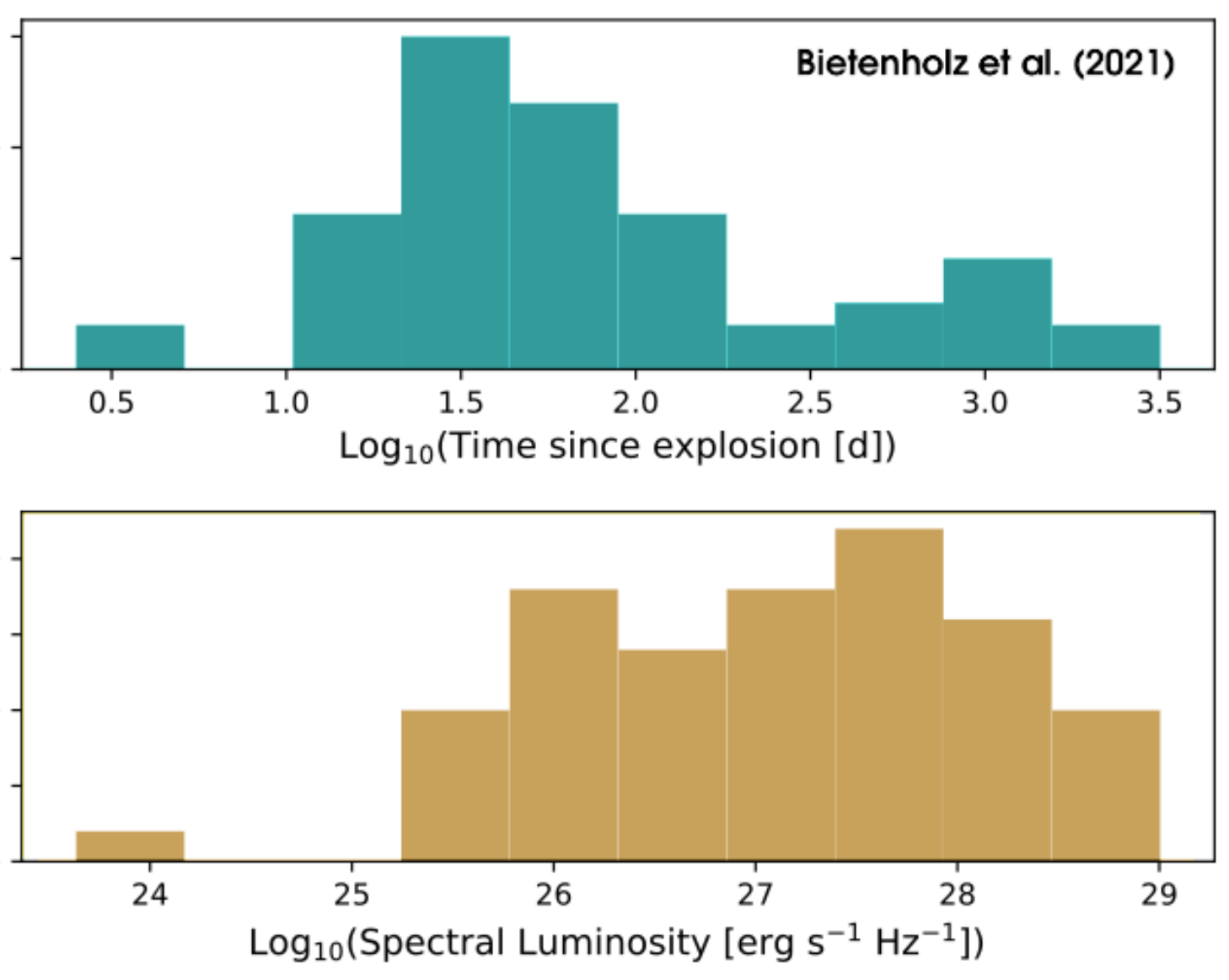
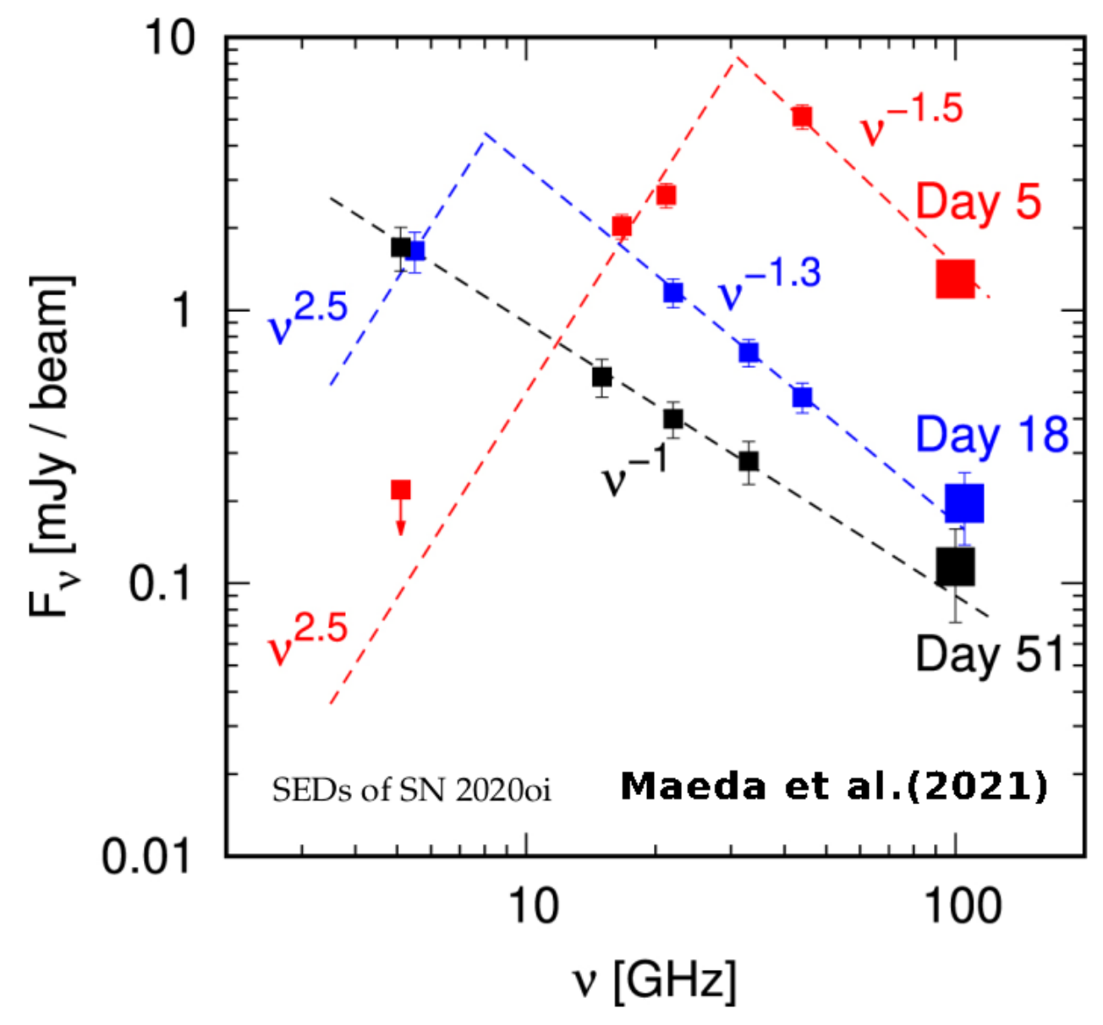
Supernovae are powerful stellar explosions that mark the final stage in the evolution of some stars. At optical wavelengths they are extremely luminous events that can be detected out to cosmological distances. Their study has an intricate connection with various astrophysical topics, and therefore they have deserved large investments in terms of observational campaigns. The methodology I have applied consists of explaining the thermal bolometric light curves calculated with a 1D radiation-hydrodynamic code with a long history of results already published.

A radio loud supernova (SN) is not as frequent. A key ingredient is the shockwave interaction with the circumstellar material (CSM) shed by the progenitor star before the explosion. In the best known cases the observations are well represented by a model of synchrotron emission from a shocked circumstellar shell initially suppressed by synchrotron self-absorption or a thermal free-free absorbing component. The interaction of the shock wave with a dense CSM gives rise to some processes that I would like to mention in this poster to encourage collaborations in the context of the *Overcoming Challenges in the Evolution And Nature of massive Stars*, OCEANS project, aiming to complement our findings.

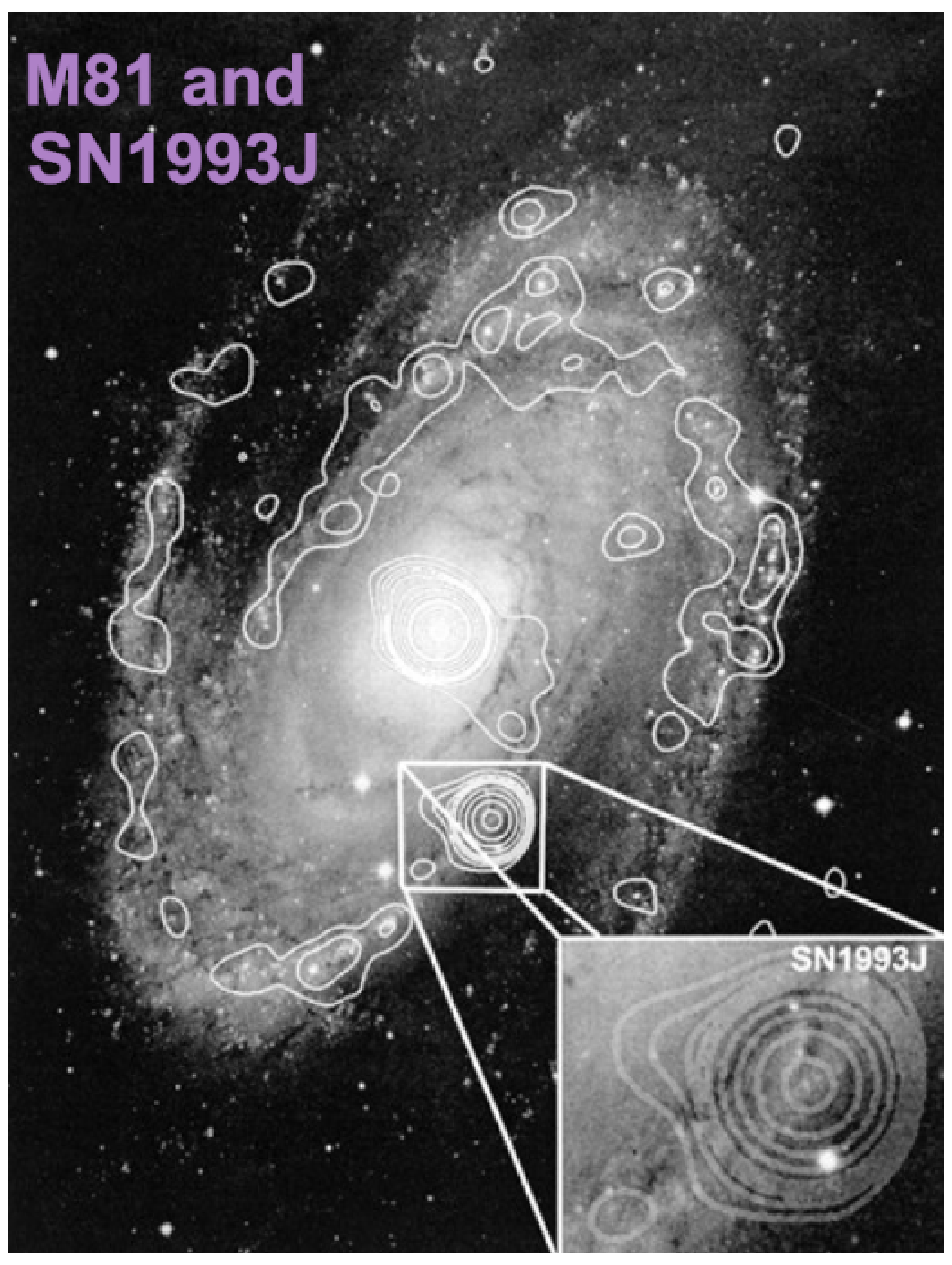
Literature of radio supernovae

A substancial collection of radio light curves was compiled by Bietenholz et al.(2021) and Mooley et al.(2022), as well as other analysis showing the luminosity vs. timescale and the energy vs. blastwave mean velocity. The studies illustrate a growing landscape where radio spectral luminosities range from $10^{25} - 10^{32}$ erg s^{-1} Hz^{-1} for 1–5 GHz frequencies.



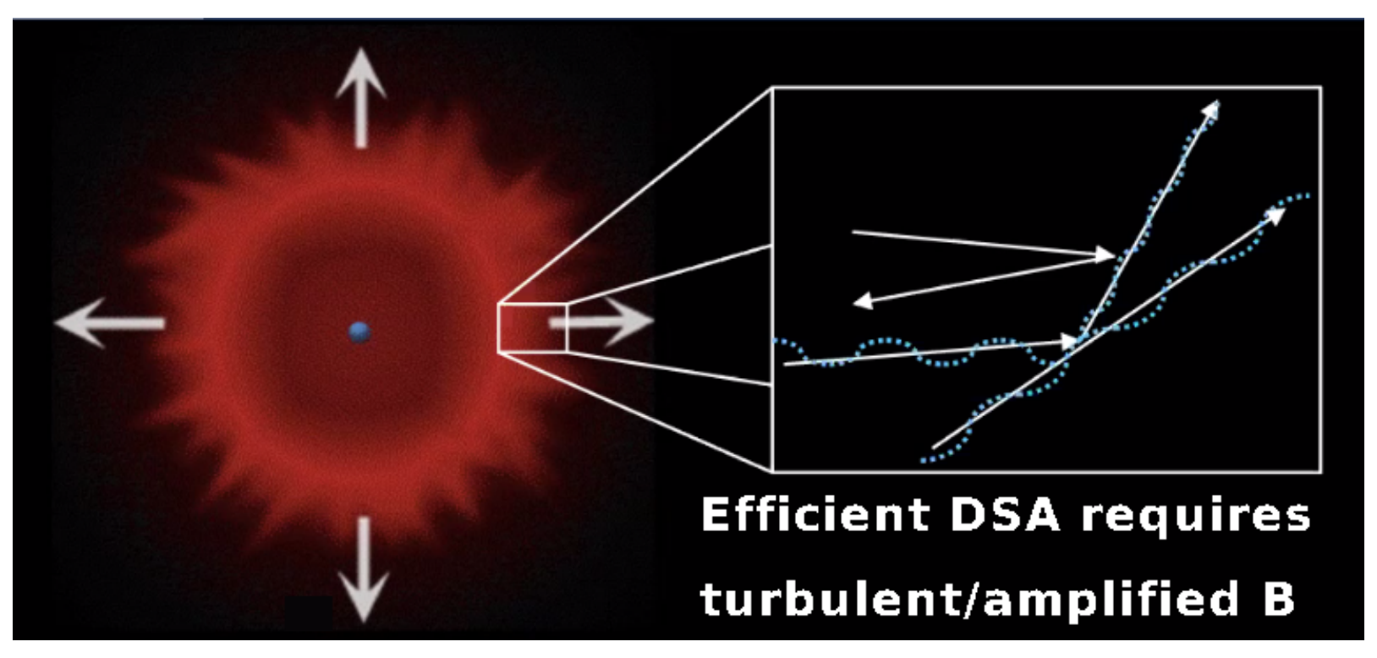


The figure provides some numbers for your consideration. The size of the sample is much smaller (2 to 4 orders of magnitude) than those of usual visual SNe. Studies of radio SNe are currently limited by the sensitivity of radio arrays and they are detectable only out to about 20 Mpc for normal supernovae and 100 Mpc for the very brightest objects.



The best studied case of a radio-loud supernova is SN1993J which exploded at a distance of 3.64 Mpc. The figure shows a visual image of M81 by Alan Sandage (1961) and radio contours by VLA obtained in 1997. Very few so bright and close SNe are resolved through Very Long Baseline Interferometry. In this outstanding case the SN was followed during the slow-down to around 30 % of its original expansion velocity. Nowadays is gently transitioning to a SN Remnant (SNR).

Note SNRs are usually older when first detected, being a great outlier the case of G1.9+0.3 aged around 200 yr since explosion.



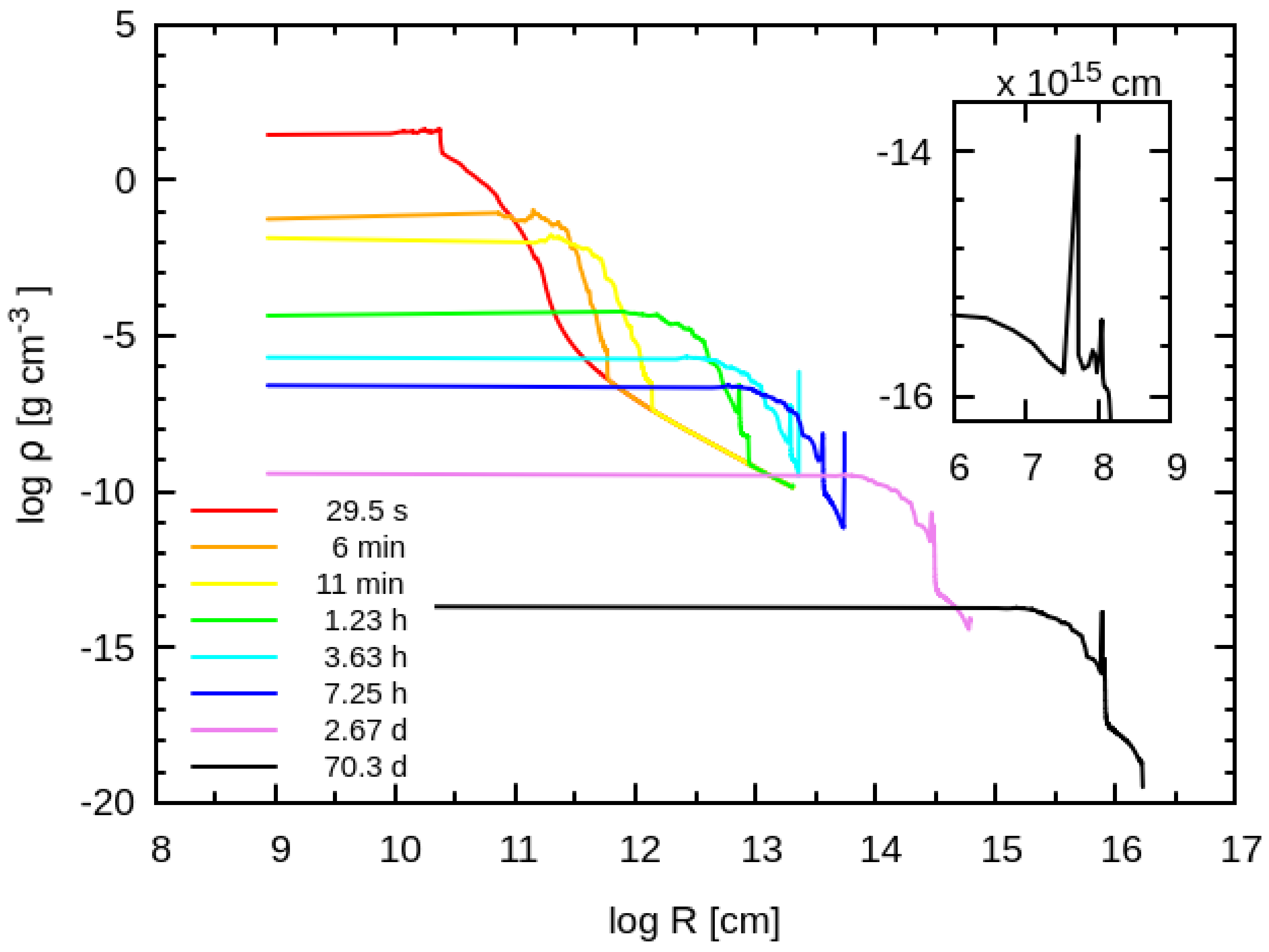
Magnetic field: another key ingredient

In interacting SNe, radio emission arises as nonthermal synchrotron emission from relativistically accelerated electrons in the forward shock.

The immediate surroundings of pre-SN stars carry the signature of the progenitors, and radio observations are one of the best ways to examine the ambient media. The radio emission mainly originates from the interaction of the supersonic ejecta with the circumstellar medium (CSM). According to diffusive shock acceleration theory (DSA), in the shocked region, the back-and-forth movements of charged particles across the shocks accelerate them.

Thermal emmission and previous results

Regarding the SN subtypes more promising for a detection, we point to SN IIb or Ibc which shown CSM interaction signatures at early phases. See Chandra (2025) for a multiwavelength update.



Changes in the density profile as a function of interior mass during the shock propagation. An overdense shell or contact discontinuity is formed. We can not treat properly the instabilities that likely occur behind the shock, however we gain a rough estimation of the shell where particle acceleration and magnetic field amplification should take place. The initial stellar density profile before SN explosion has an attached envelope of low mass. This is normally prescribed for type IIb explosions, see Orellana & Bersten (2024).

Optically based mass loss rate estimations for SN2016gkg (Bersten et al. 2018), were obtained through hydrodynamic calculations, considering a wind-like ambient medium. The figure above illustrates the shock propagation in a CSM with similar parameters, i.e. $M_{\rm env} = 0{,}01\, M_\odot$, $R_{\rm env} = 320\, R_\odot$. These are favored to reproduce the photometry and photospheric velocity evolution of SN2016gkg. The same SN was found to have a relatively compact progenitor in preexplosion imaging, and $\dot{M} \simeq 3{,}8 \times 10^{-6}$ M$_\odot$ yr^{-1} from radio analyses (Nayana et al. 2022), implying a lower CSM mass, of around $10^{-4}\, M_\odot$. Altogether, the published data and inferred properties of SN2016gkg call for a unifiying picture.

Nonthermal processes

A self-similar synchrotron model, as detailed by early by Chevalier, and later by Chandra, is the base for many studies considering synchrotron self-absorption (SSA) or free–free absorption (FFA) at radio wavelengths. Two important values are the fraction ϵ_e of the energy transferred to the nonthermal electrons and ϵ_B, the amplification efficiency; while less mentioned and yet important is the minimum energy of relativistic particles.

$$u_e = \epsilon_e \rho_{\rm sh}\, v_{\rm sh}^2$$

$$B = (8\pi \epsilon_B \rho_{\rm sh}\, v_{\rm sh}^2)^{1/2}$$

Following Matsuoka et al. (2019) the maximum energy of accelerated particles is determined by the various cooling processes and by imposing physical criteria.

work in progress

The job is in preliminary state, but the goal ahead is to predict the SN radio emission, specifically to model $F(\nu, t)$ flux. Next, to be aware if a nearby SN is potentially detectable with the observational facilities at hand, or use public data. The acceleration of charged particles and the amplification of magnetic fields, which play a crucial role in estimating the intensity of radio emission in SNe, are poorly constrained, leaving ample room for further exploration.

References:

- ⋆ Bersten, M. C., et al. 2018, Nature, 554, Issue 7693, 497
- ⋆ Bietenholz, M. F., Bartel, N., et al. 2021, ApJ, 908, 75
- ⋆ Chandra, P., 2025, Universe, Vol. 11, id.363
- ⋆ Green D.A., Gull S.F., 1984, Nature, 312, 527
- ⋆ Maeda et al. 2021, ApJ, 918,34
- ⋆ Matsuoka, T. et al. 2019, ApJ, 885, id. 41, 11
- ⋆ Mooley, K. P., et al. 2022, ApJ, 924, 16
- ⋆ Nayana, A. J., et al. 2022, ApJ 934 186
- ⋆ Orellana, M., 2024, BAAA, 65, 259
- ⋆ Orellana & Bersten, 2024 RMxAC, 56, 150

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