# Radio Emission from Supernovae in the Very Early Phase: Implications for the Dynamical Mass Loss of Massive Stars

**Tomoki Matsuoka*** (t.matsuoka@kusastro.kyoto-u.ac.jp), Keiichi Maeda* (keiichi.maeda@kusastro.kyoto-u.ac.jp), Herman Lee* (herman@kusastro.kyoto-u.ac.jp), Haruo Yasuda* (yasuda@kusastro.kyoto-u.ac.jp)
* Department of Astronomy, Kyoto University

Recent transient observations indicate that some massive stars have 'confined' circumstellar material (CSM), implying that they lose their own mass decades before their explosion. We investigate the time evolution of synchrotron radiation from a type II-P SN with confined CSM. Our simulations show that millimeter emission can be a diagnostic of the confined CSM. Furthermore we reveal that proton inelastic collisions, leading to a production of electrons and positrons, make a large contribution to the radio emission. We emphasize that this signal can be an interesting observational target for ALMA.

## 1. Introduction

**'Confined' circumstellar material (CSM)**

- a high density material
  $10^{-16}\ \mathrm{g/cm^3} \lesssim \rho \lesssim 10^{-12}\ \mathrm{g/cm^3}$
- only within a small radius
  $R_{\rm CSM} \lesssim 10^{15}\ \mathrm{cm}$

➡ Dynamical mass-loss decades before SN; $10^{-4}\ M_\odot/\mathrm{yr} \lesssim \dot{M} \lesssim 10^{-2}\ M_\odot/\mathrm{yr}$

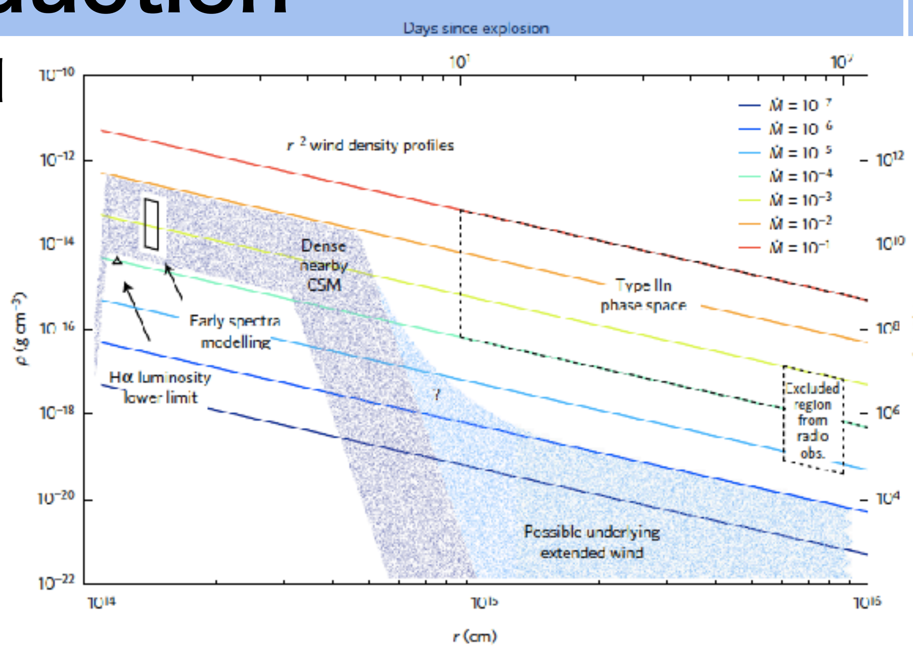

Figure 1 : The CSM density structure of the progenitor of SN 2013fs (Figure 6 in Yaron+ 2017)

Detected by recent transient surveys and flash spectroscopy follow-up observation (e.g., Gal-Yam+ 2014).

Instead of the flash spectroscopy, we have shown that **synchrotron signal can become a robust evidence of the confined CSM.**

Table 1 : Comparison of optical and radio

| | Flash spectroscopy (optical) | Radio |
|---|---|---|
| Characteristic tiimescale | $r_{\rm CSM}/c \sim$ hours | $r_{\rm CSM}/V_{\rm sh} \lesssim$ 10days |
| uncertainties of the density | large (Groh 2014) | small |

## 2. Method

### 1. Hydrodynamics

**A red super giant + confined CSM** w/ $\dot{M} = 10^{-2}, 10^{-3}, 10^{-4}\ M_\odot/\mathrm{yr}$ , to mimic the SN 2013fs (Yaron+ 2017, Figure 1)

Perform the hydrodynamics simulation by SNEC (Morozova+ 2015)

➡ obtain the time evolution of shockwave V_sh (Figure 2)

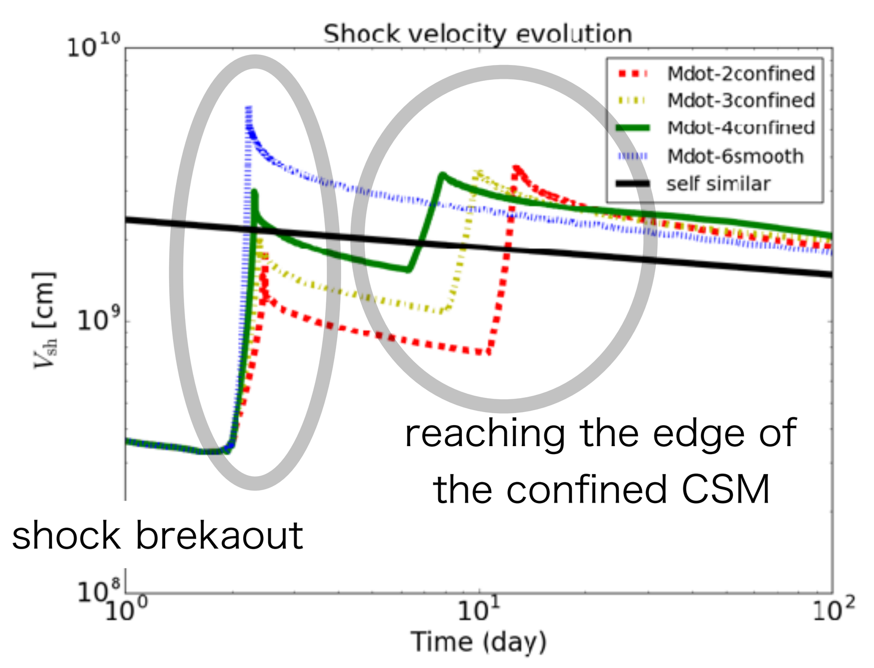

Figure 2 : Time evolution of forward shock

### 2. Particle acceleration and its energy loss

Parametrize the efficiencies of particle acceleration and magnetic field amplification at the forward shock front as follows;

$$u_{\rm e} = \epsilon_{\rm e}(\rho_{\rm sh} V_{\rm sh}^2),\ u_{\rm p} = \epsilon_{\rm p}(\rho_{\rm sh} V_{\rm sh}^2),\ \frac{B^2}{8\pi} = \epsilon_{\rm B}(\rho_{\rm sh} V_{\rm sh}^2)$$

Solve the particle energy distribution;

$$\frac{\partial}{\partial t}\left(\frac{dN_{\rm i}}{dE_{\rm i}}\right) = \frac{\partial}{\partial E_{\rm i}}\left(\frac{E_{\rm i}}{t_{\rm i,loss}}\frac{dN_{\rm i}}{dE_{\rm i}}\right) + \left(\frac{dN_{\rm i}}{dE_{\rm i}}\right)_{\rm in}$$

Cooling term: $\frac{\partial}{\partial E_{\rm i}}\left(\frac{E_{\rm i}}{t_{\rm i,loss}}\frac{dN_{\rm i}}{dE_{\rm i}}\right)$

Particle injection term: $\left(\frac{dN_{\rm i}}{dE_{\rm i}}\right)_{\rm in}$
- Power-law ( $i = e^-, p$ )
- proton inelastic collision ( $i = e^-, e^+$ )

### 3. Synchrotron radiation transfer

Radiative transfer; $\frac{dI_\nu}{dr} = -\alpha_\nu I_\nu + S_\nu$

w/
- synchrotron self-absorption (SSA) in the shocked region
- free-free absorption (FFA) in the unshocked region

## 3. Results

### 1. Light curves

Red : $10^{-2}\ M_\odot/\mathrm{yr}$ Yellow : $10^{-3}\ M_\odot/\mathrm{yr}$
Green : $10^{-4}\ M_\odot/\mathrm{yr}$ Blue : $10^{-6}\ M_\odot/\mathrm{yr}$, no confined CSM

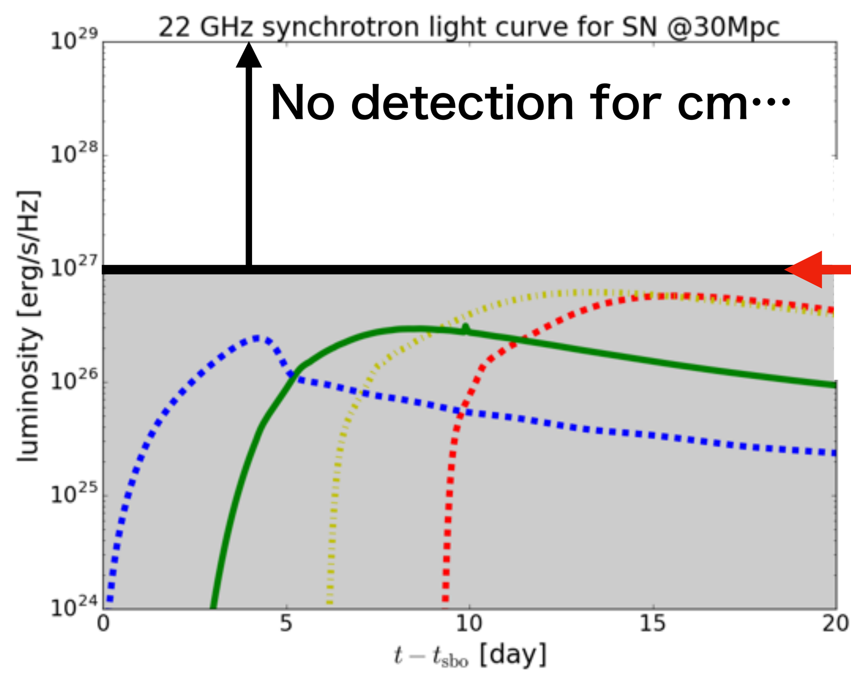

Figure 3 : Centimeter light curves; **damped** by SSA or FFA

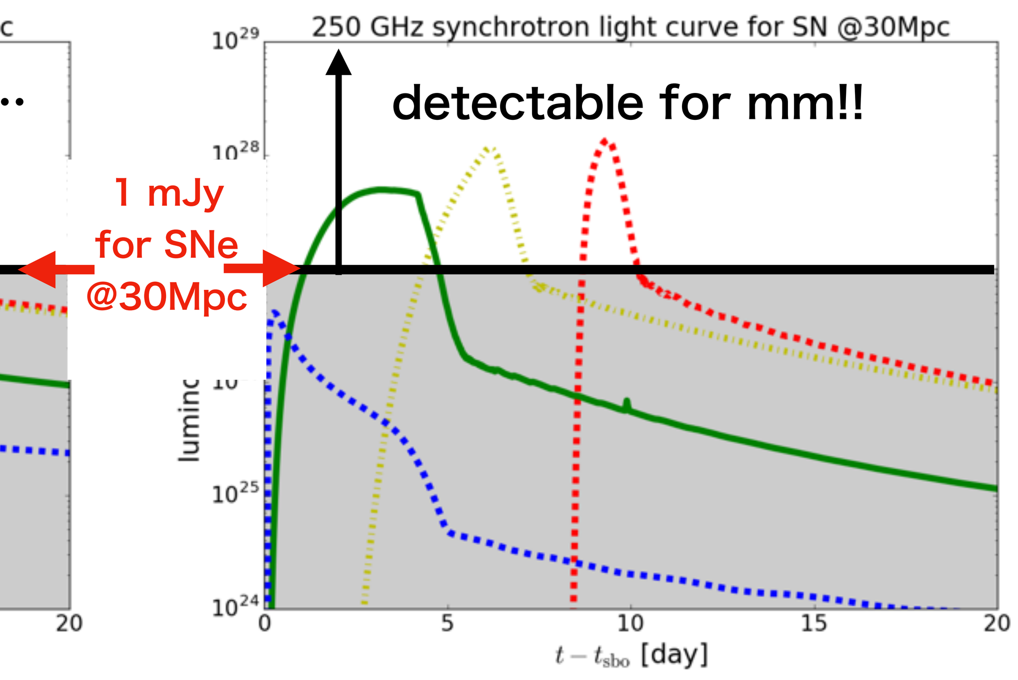

Figure 4 : Millimeter light curves; **detectable**

These light curves show that **the millimeter emission can be a diagnostic** for the confined CSM. This millimeter signal is **detectable by ALMA.**

### 2. Secondary particles

Blue : primary electron (accelerated by shock)
Red : secondary electron (produced by p-p collision)
Green : positron (produced by p-p collision)

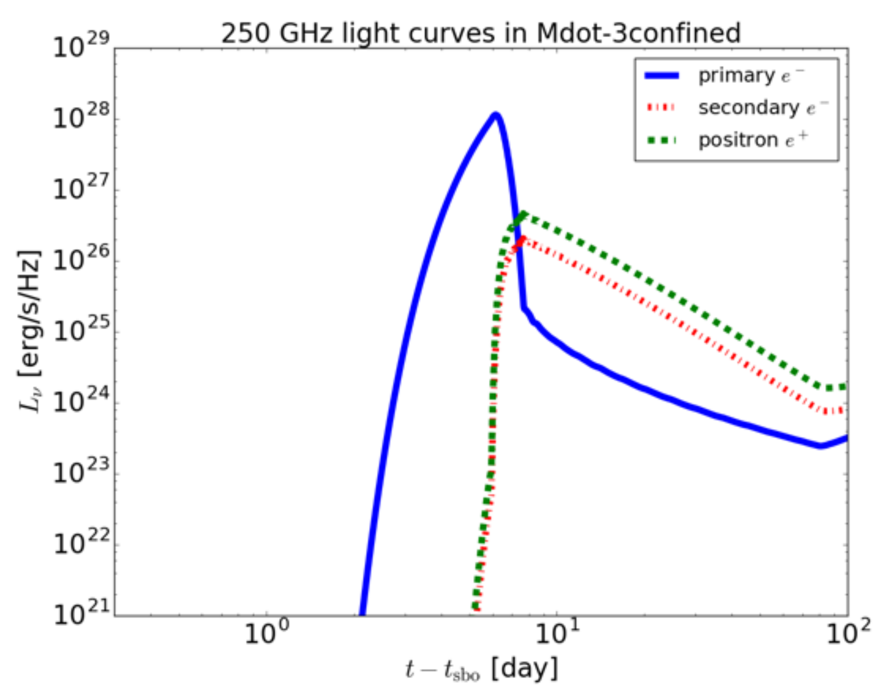

Figure 5 : Light curves for $\dot{M} = 10^{-3}\ M_\odot/\mathrm{yr}$ model, dividing into the different radiating particles

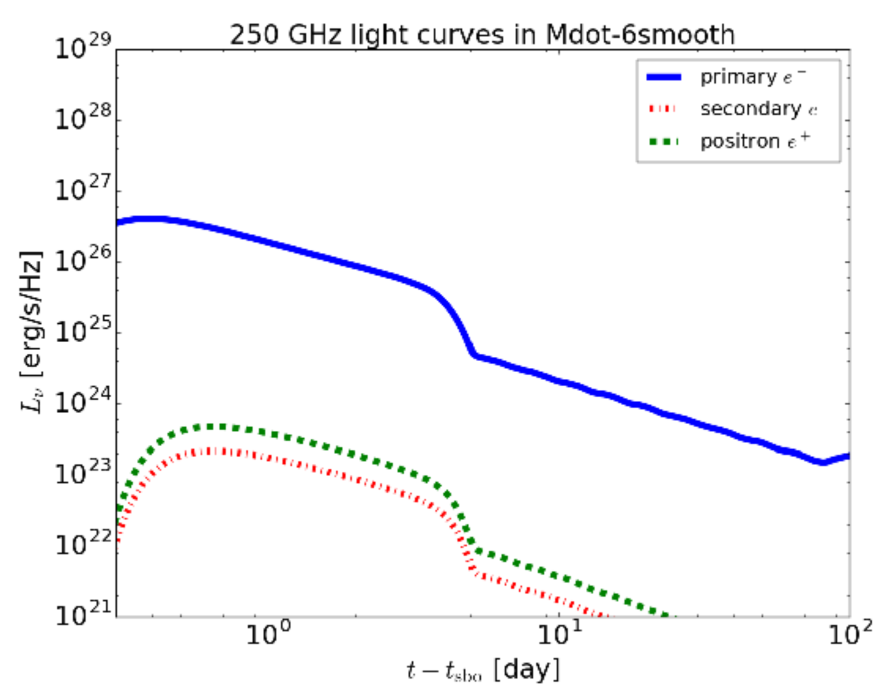

Figure 6 : Same as Figure 5, but for the smooth CSM

If the confined CSM exists, **secondary particles** ( $e^-, e^+$ ) produced by proton inelastic collisions **dominate the radio emission in the later phase** $t \gtrsim 1$ month .

## 4. Conclusions & Discussion

- We show that **synchrotron millimeter emission** can be a robust tracer of the confined CSM.
- If the confined CSM exists, the radio emission in the later phase ( $t \gtrsim 1$ month ) is dominated by **secondary particles**.
- The observation by **ALMA** will provide a robust evidence of the confined CSM, or the spatial structure of the CSM.

[1] Chevalier, R. A. 1982, ApJ, 259, 302
[2] Gal-Yam, A., Arcavi, I., Ofek, E. O., et al. 2014, Nature, 509, 471
[3] Groh, J. H. 2014, A&A, 572, L11
[4] Morozova. V., Piro, A. L., Renzom M., et al. 2015, ApJ, 814,63
[5] Yaron, O., Perley, D. A., Gal-Yam, A., et al. 2017, Nature Physics, 13, 510
[6] Matsuoka, T., Maeda, K., et al. 2019, ApJ, submitted