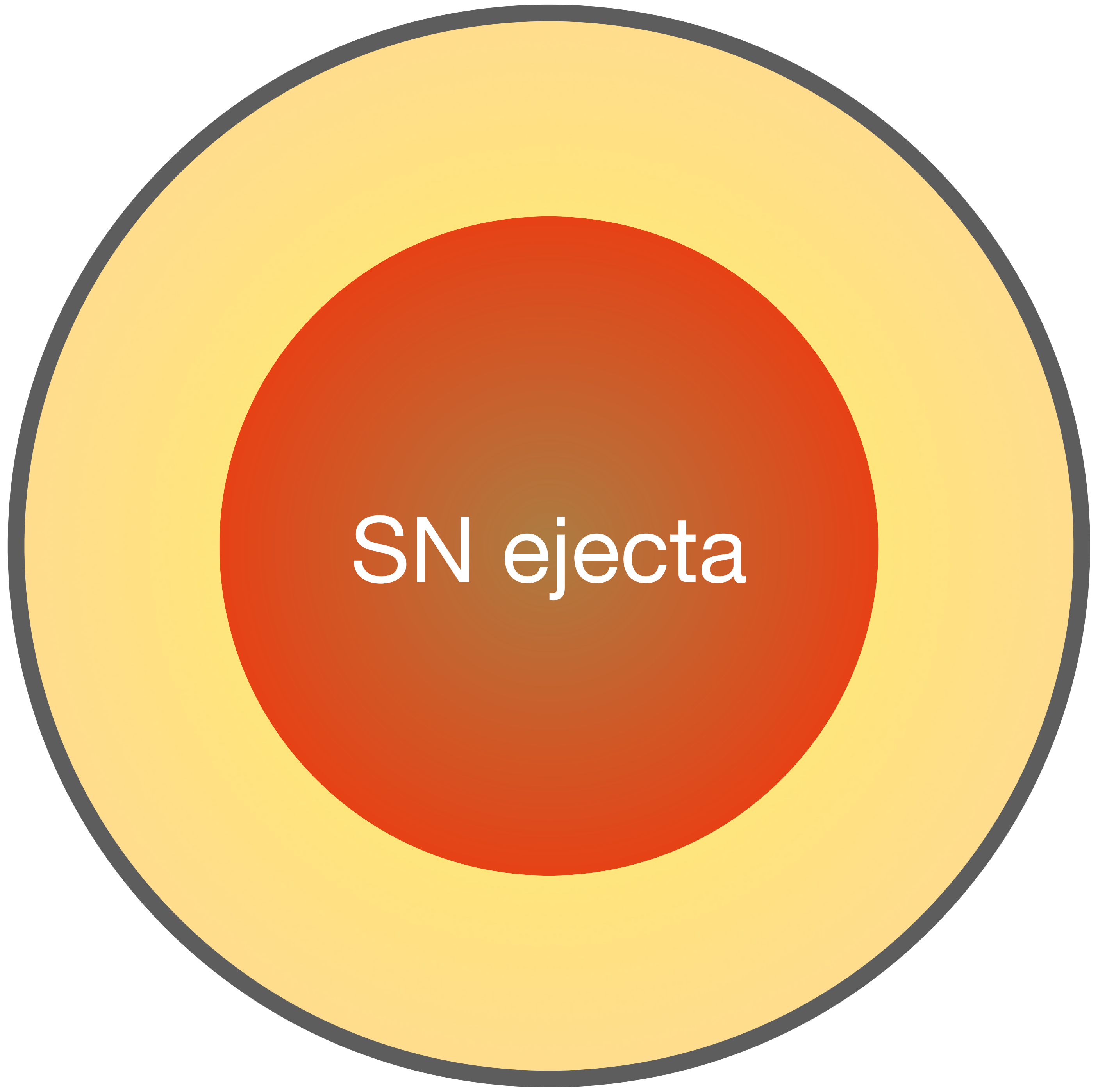
Inferring Dense Confined Circumstellar Medium around Supernova Progenitors via Long-term Hydrodynamical Evolution

<u>Tomoki Matsuoka</u> (ASIAA)

Keiichi Maeda (Kyoto Univ.)
Ke-Jung Chen (ASIAA)

中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics



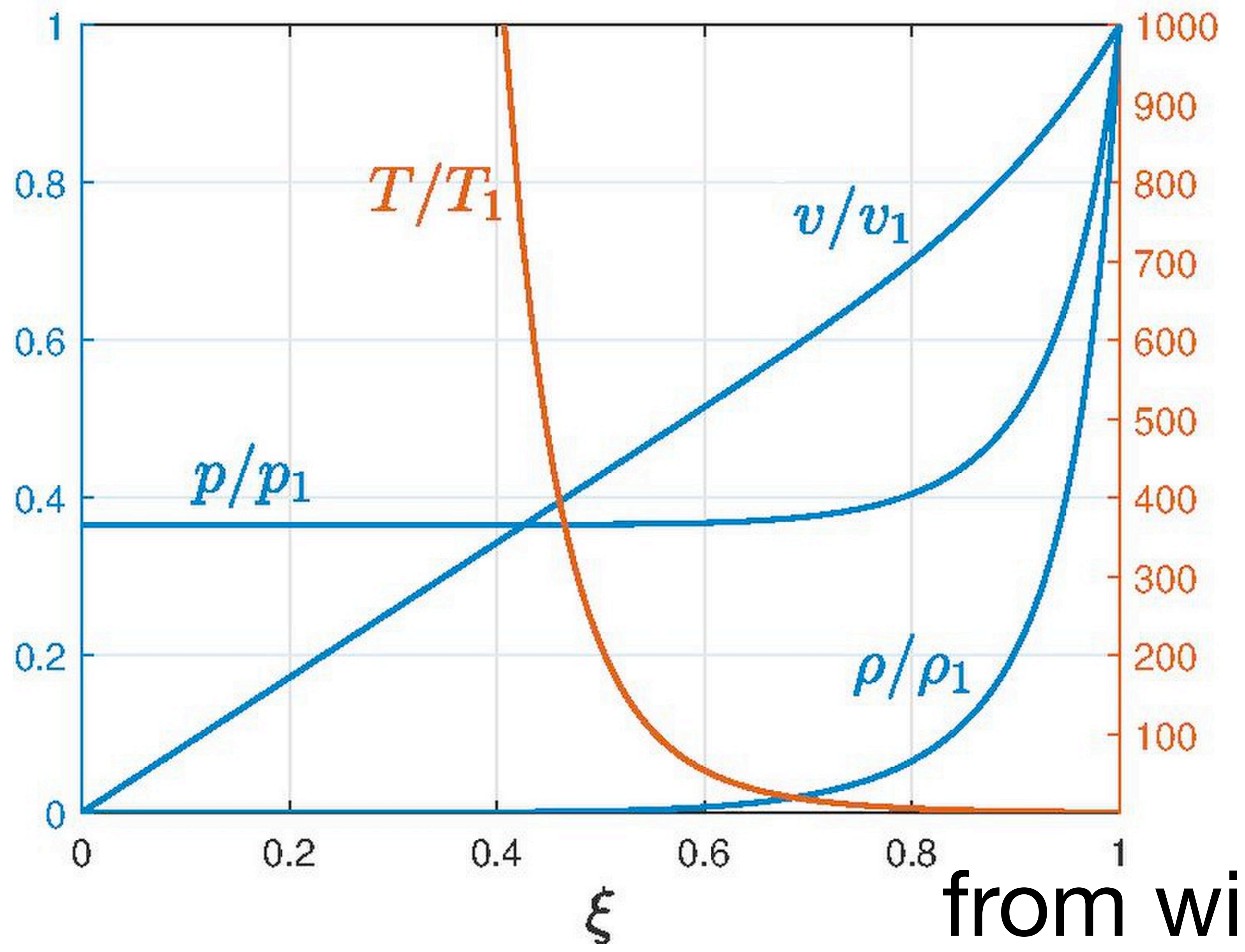
ambient;
circumstellar medium (CSM)

from Matsuoka et al., submitted to ApJL (arXiv: 2504.14255)

Self-similar solutions of SN hydrodynamics

Sedov (1959)
a point-source explosion of a mass-less material into ambient medium

- Application: Supernova remnant ($t \gtrsim$ tens of years)



from wikipedia

Chevalier (1982)
massive material expanding into ambient medium

- Application: young supernova ($t \lesssim$ a few years)

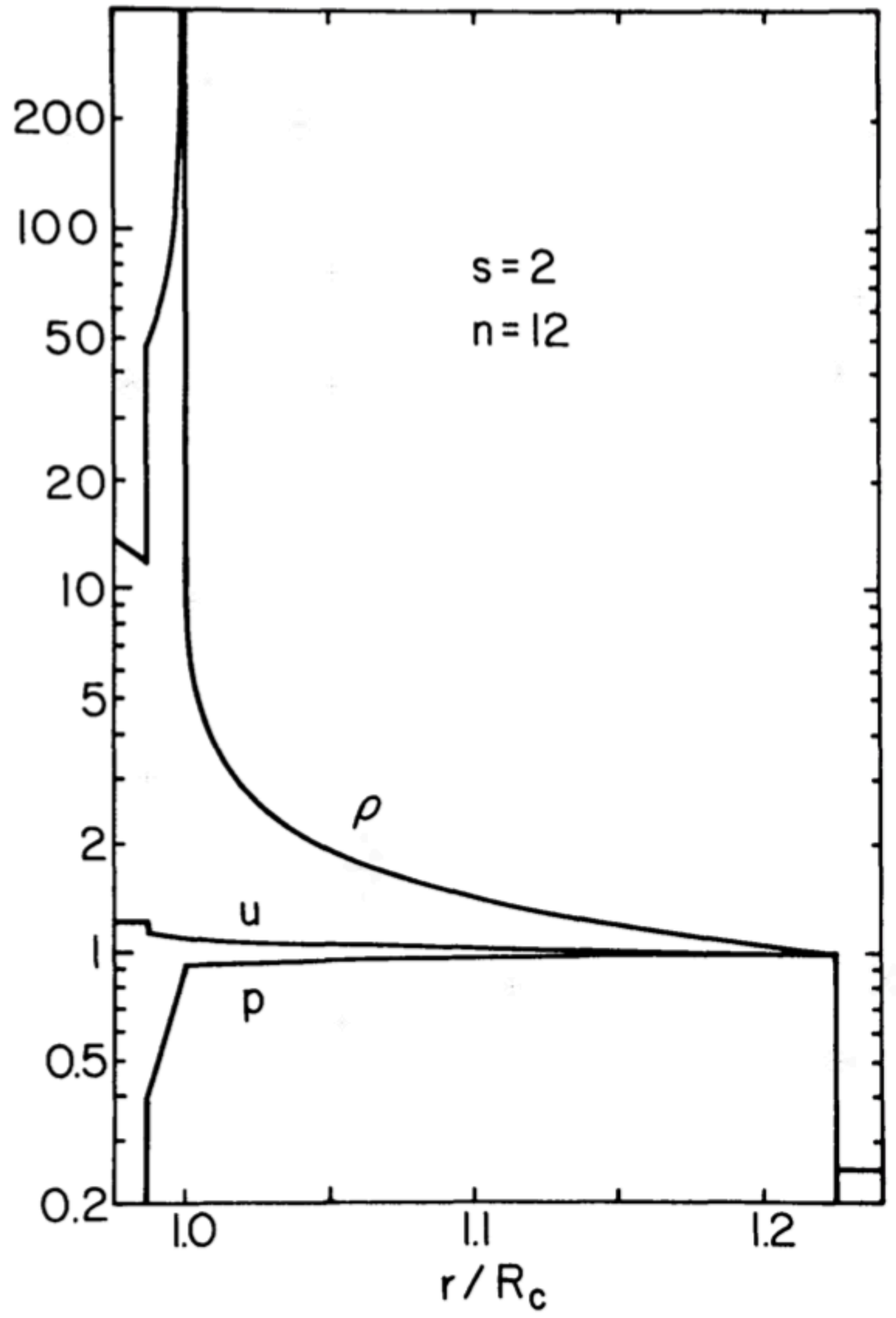
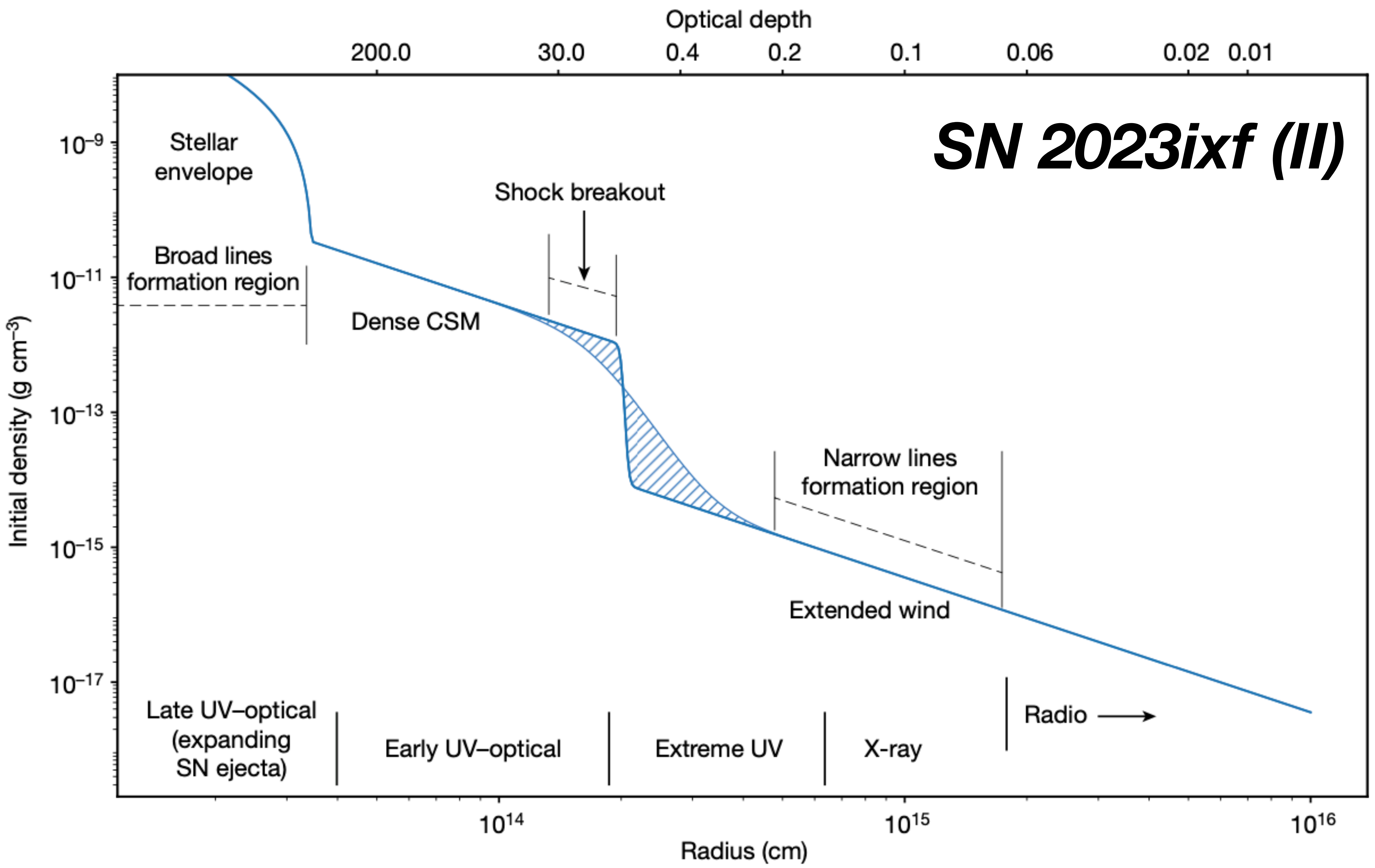


FIG. 4.—Same as Fig. 1 for $s = 2$, $n = 12$

Are these self-similar solutions applicable?

NO. CSM density profile is actually complicated (at least two component).



Zimmerman+24

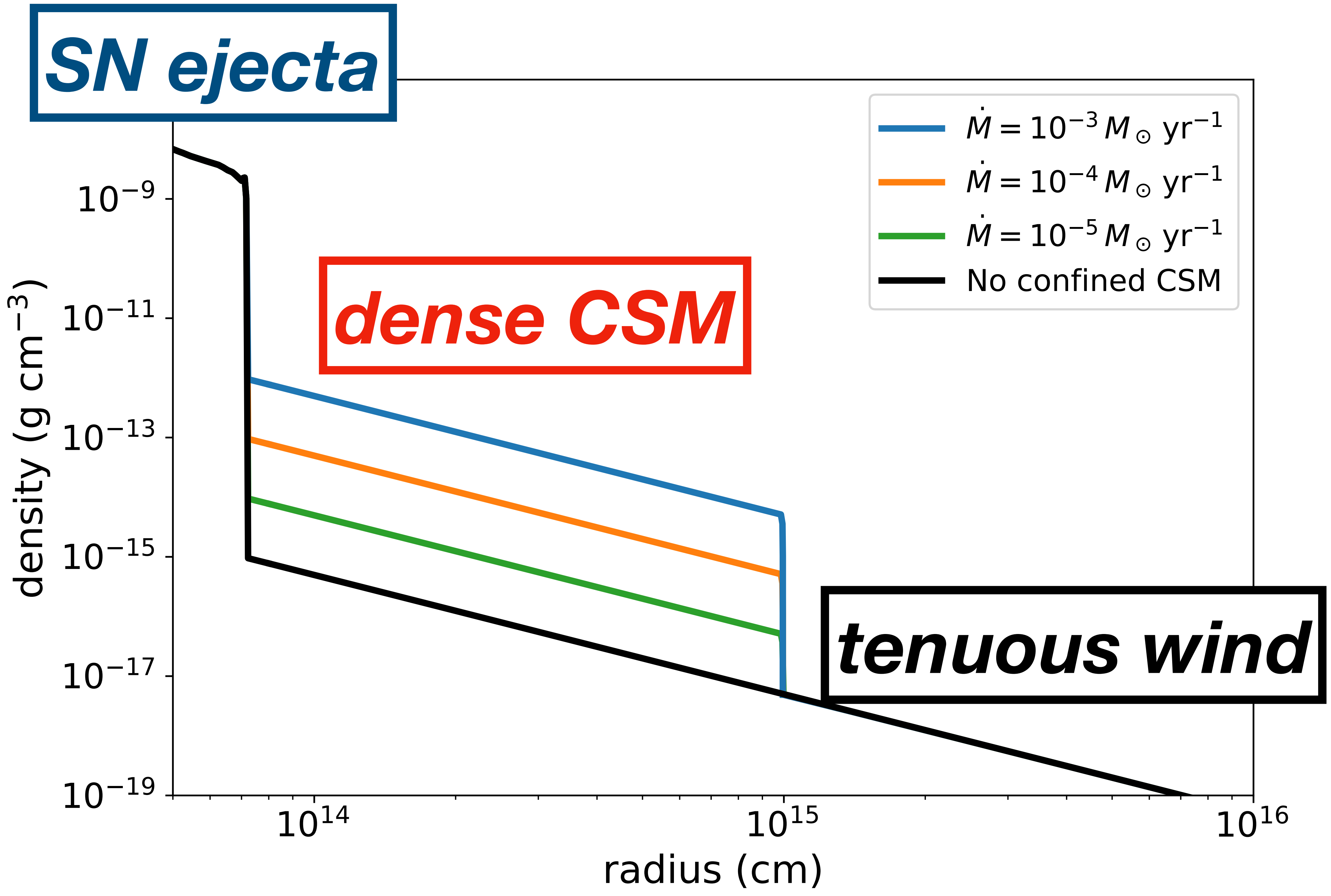
Q. What happens in SN-CSM interaction system if there is an additional dense CSM component near the star?

Start from numerical experiment.

- Numerically simulating 1D nonradiative hydrodynamics of SN-CSM interaction
  - open code SNEC (Morozova+15)
  - setup of an SN II progenitor with $M_{\rm ej} = 12\,M_\odot$, $E = 10^{51}\,{\rm erg}$
  - put dense CSM near the progenitor ($r < 10^{15}\,{\rm cm}$) with different corresponding mass-loss rates of $\dot{M} = 10^{-3}, 10^{-4}, 10^{-5}\,M_\odot\,{\rm yr}^{-1}$

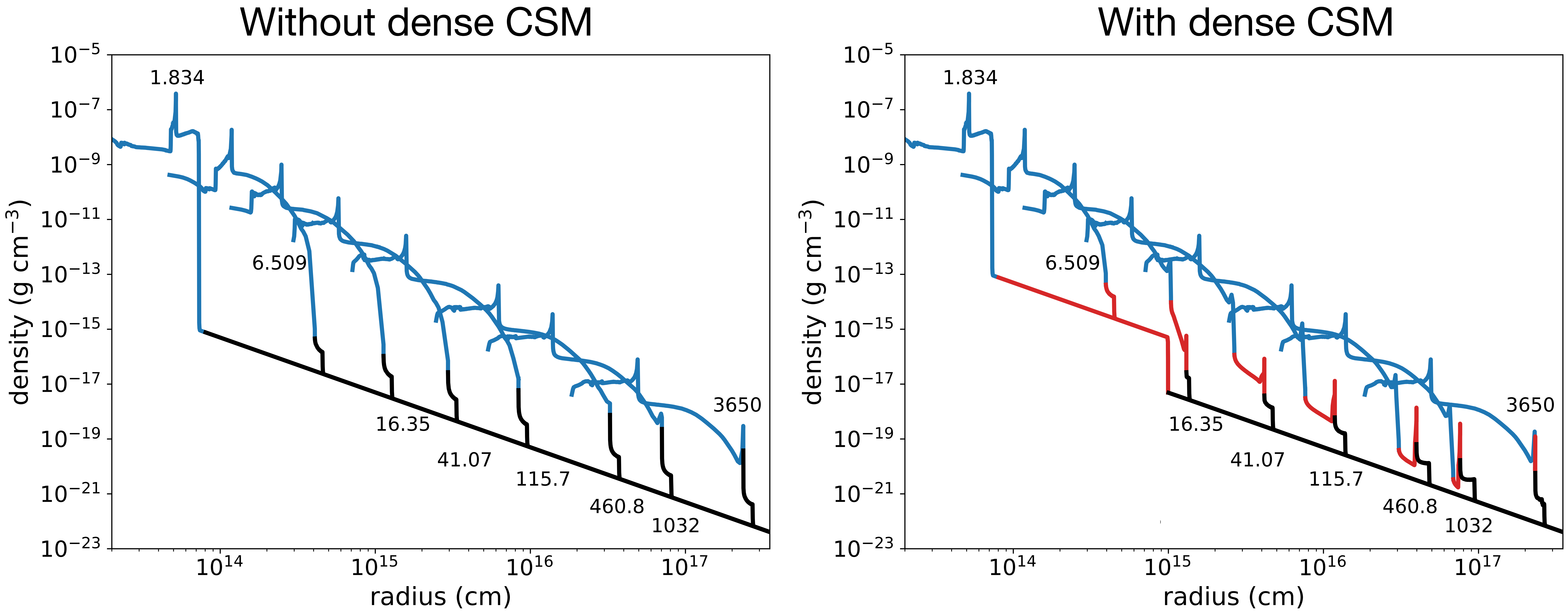
- Compare the evolutions and profiles between models with and without dense CSM

Initial density profiles examined in this study



Let me show you snapshots…

Blue: SN ejecta, Red: dense CSM, Black: tenuous wind



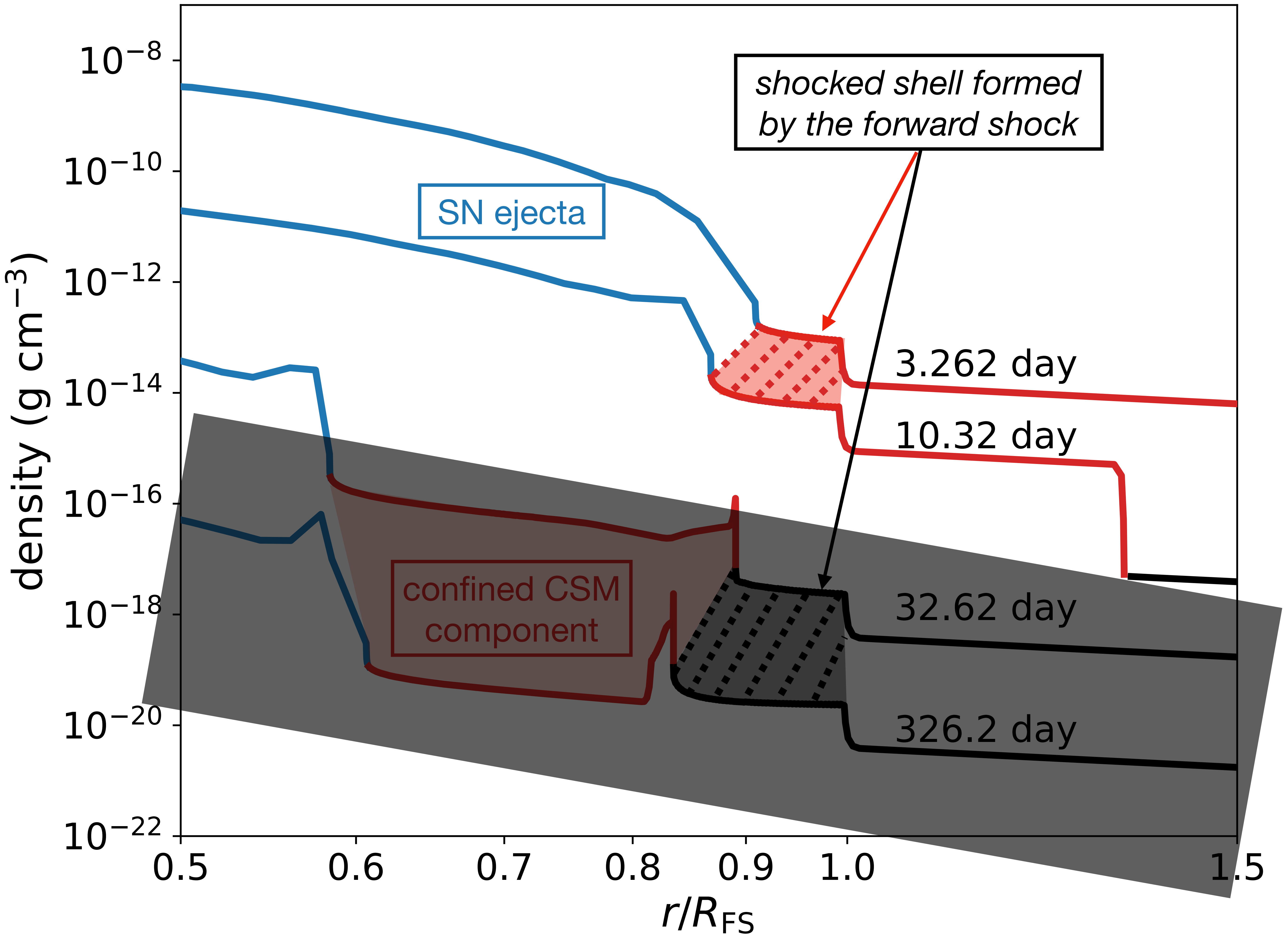
Contact me if you wanna see animations.

Who is driving the expansion?

- $t \lesssim 10\,\mathrm{days}$

SN shock sweeps ***dense CSM*** and the shell is pushed by ***SN ejecta***

Blue: SN ejecta, Red: dense CSM, Black: tenuous wind



Who is driving the expansion?

- $t \lesssim 10\,\mathrm{days}$

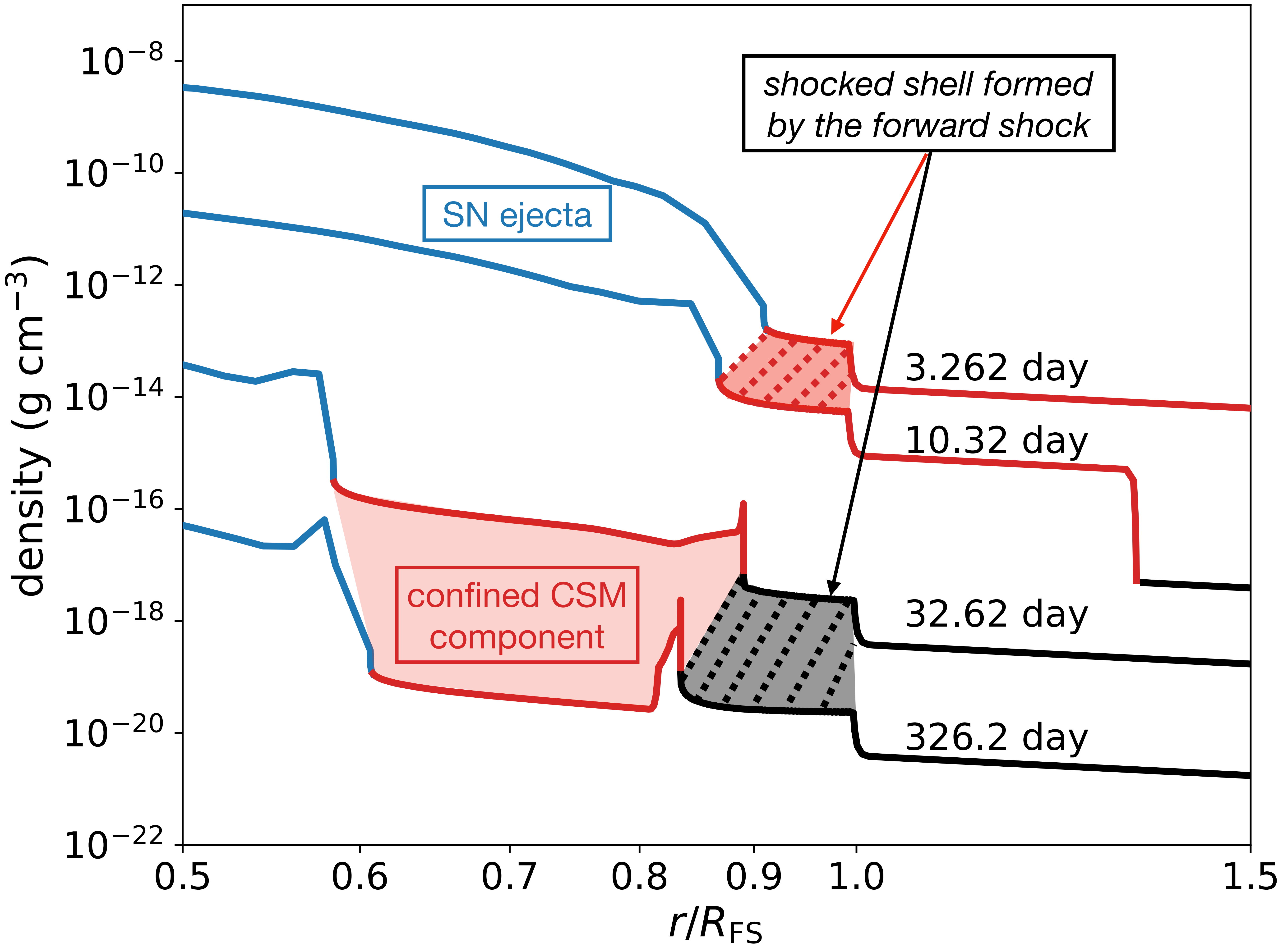
SN shock sweeps ***dense CSM*** and the shell is pushed by ***SN ejecta***

- $t \gtrsim 10\,\mathrm{days}$

SN shock sweeps **tenous wind** and the shell is pushed by ***dense CSM***

The dense CSM drives the expansion of the shocked shell. NOT the SN ejecta.

Blue: SN ejecta, Red: dense CSM, Black: tenuous wind

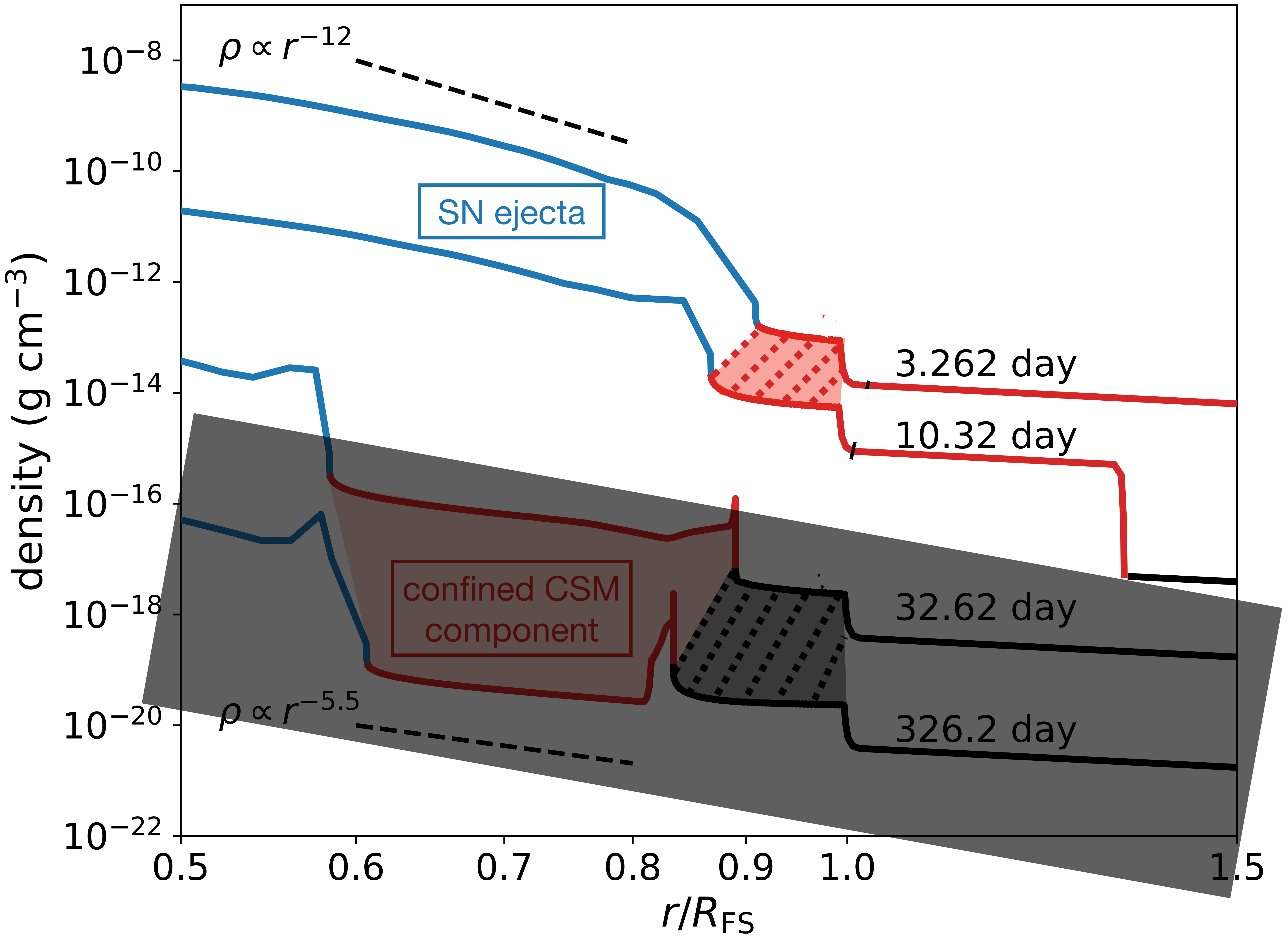


dense CSM material is flatter than SN ejecta

The density gradients of

- ***SN ejecta*** ($t \lesssim 10\,\mathrm{days}$)
  $\rho \propto r^{-12}$, as expected for SN II in Matzner+99

Blue: SN ejecta, Red: dense CSM,
Black: tenuous wind



dense CSM material is flatter than SN ejecta

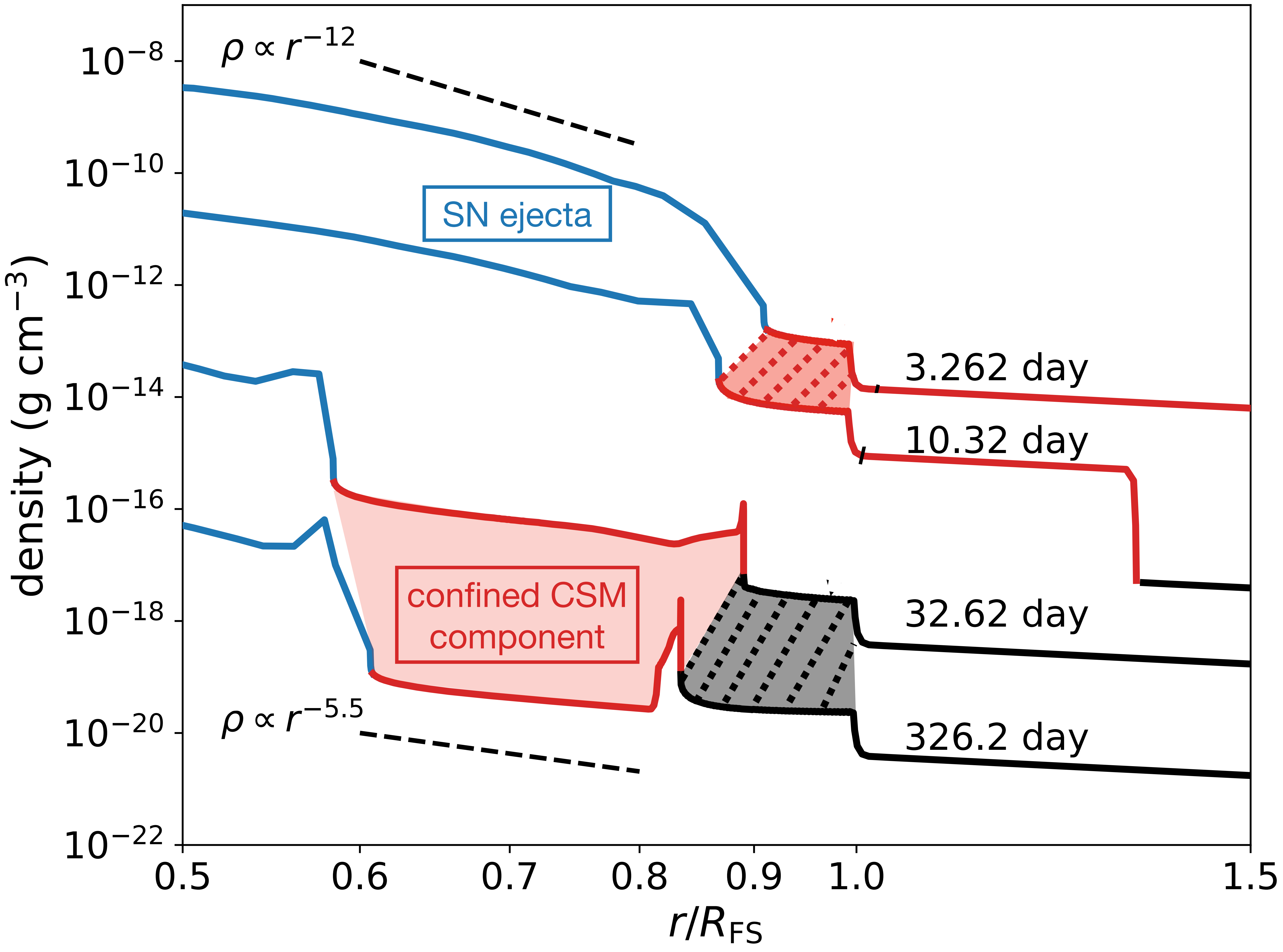
The density gradients of

- ***SN ejecta*** ($t \lesssim 10\,\mathrm{days}$)
  $\rho \propto r^{-12}$, as expected for SN II in Matzner+99

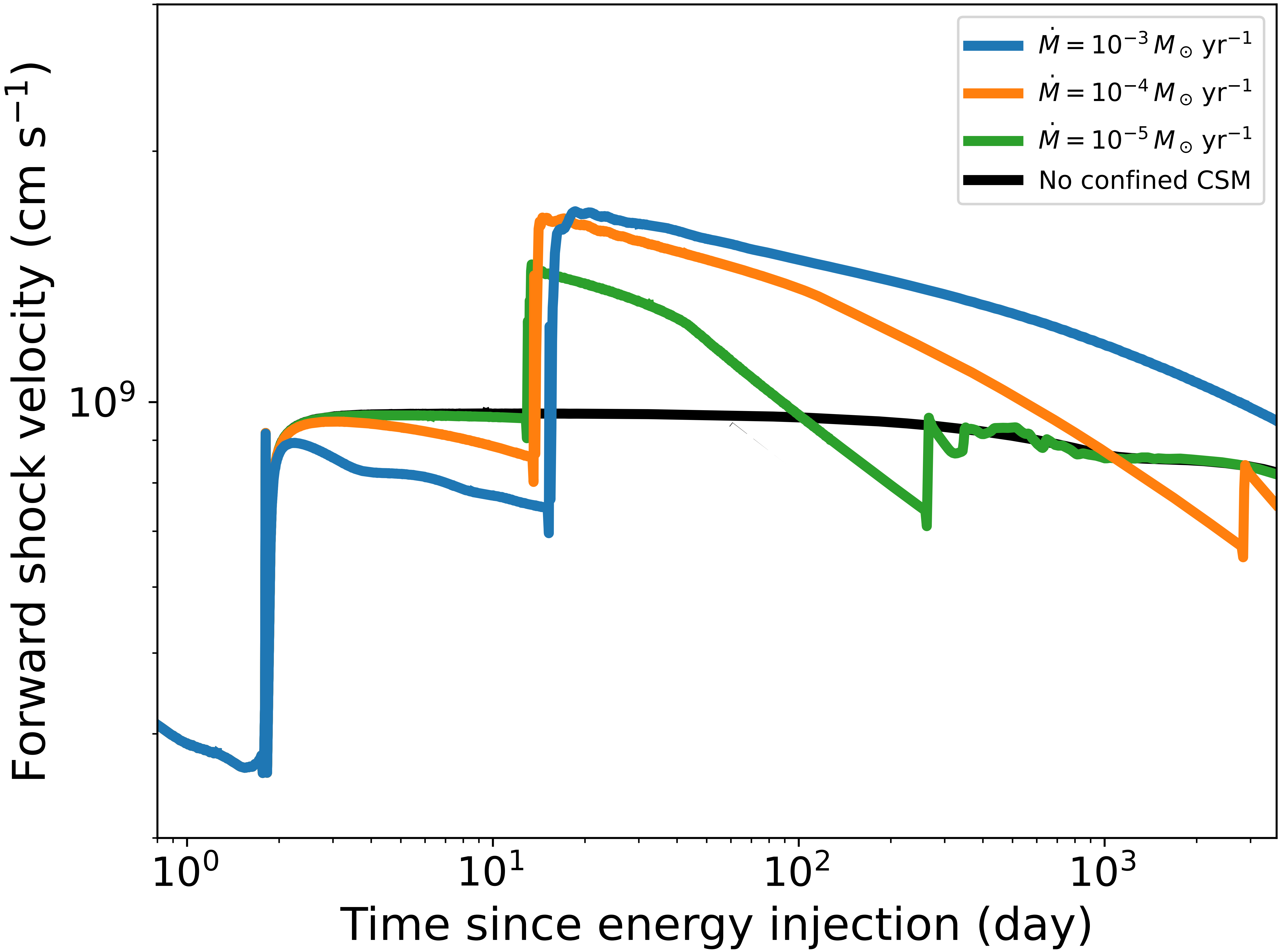
- ***dense CSM*** ($t \gtrsim 10\,\mathrm{days}$)
  $\rho \propto r^{-5.5}$, even flatter than the limiting case of SN ejecta ($7 \lesssim n \lesssim 12$)

The shell-pushing material (dense CSM) is actually flatter than SN ejecta.

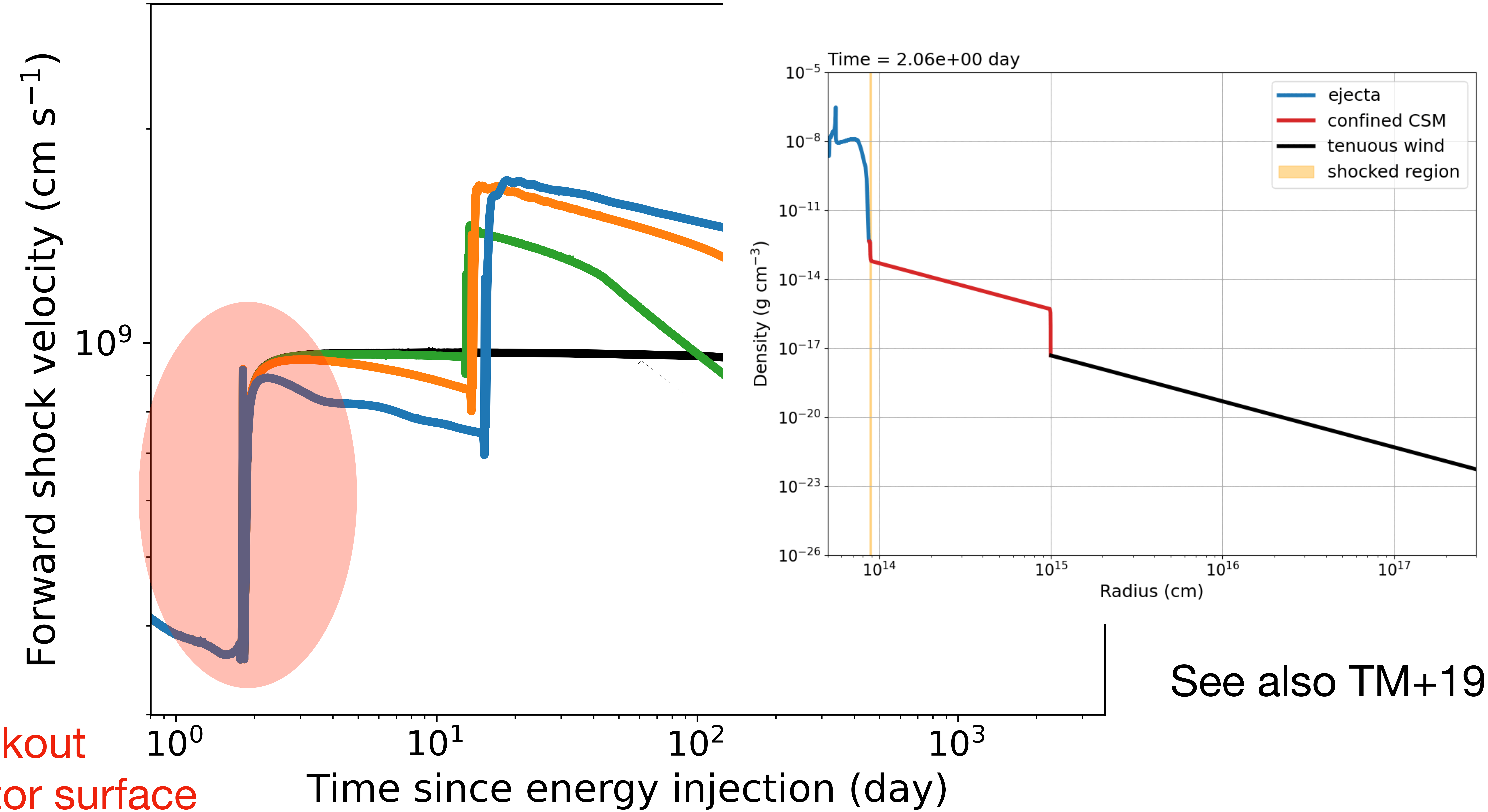
Blue: SN ejecta, Red: dense CSM, Black: tenuous wind



Influence on forward shock velocity $V_{\rm sh}$



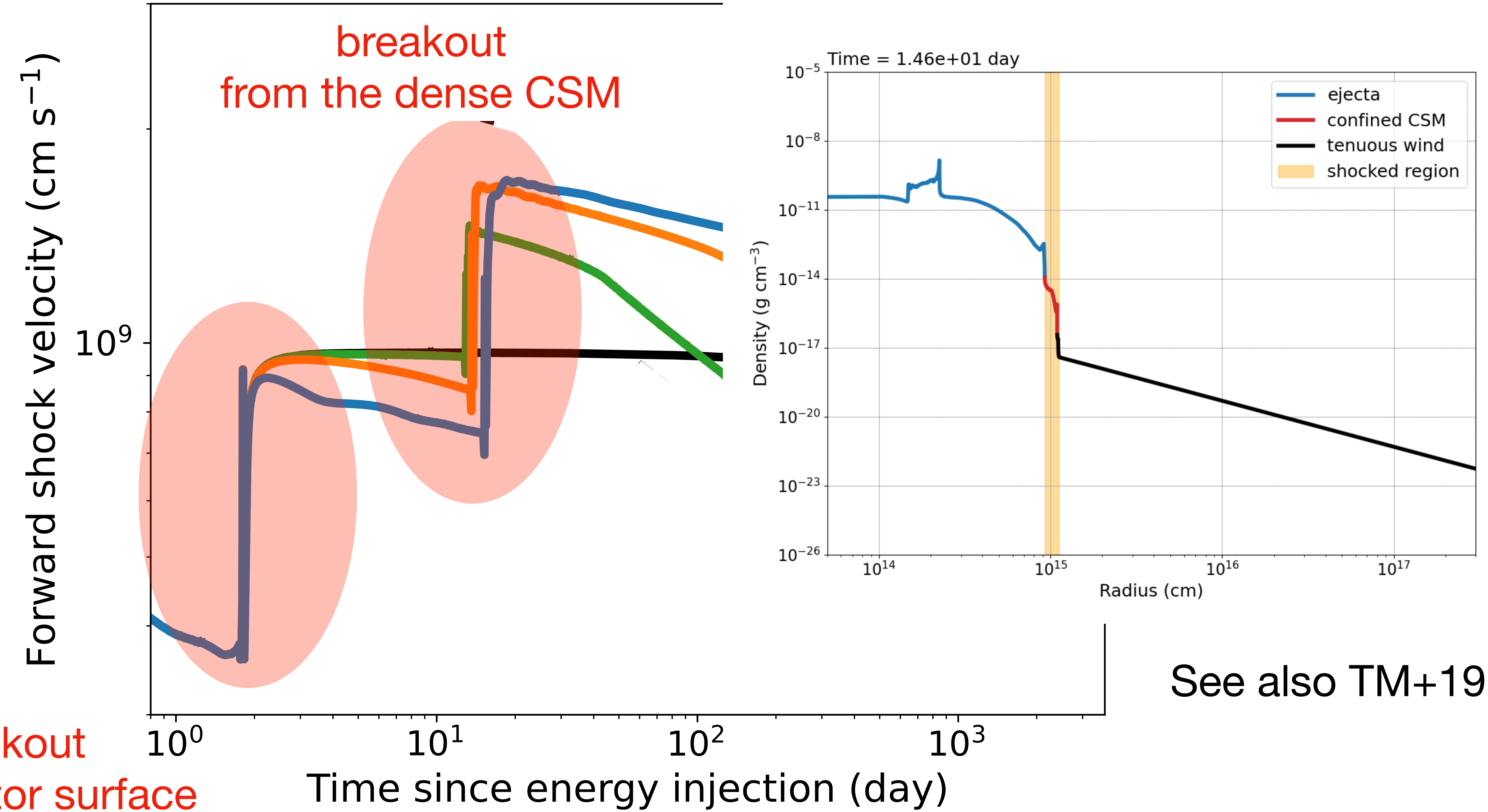
Influence on forward shock velocity $V_{\rm sh}$



Shock breakout
from the progenitor surface

See also TM+19

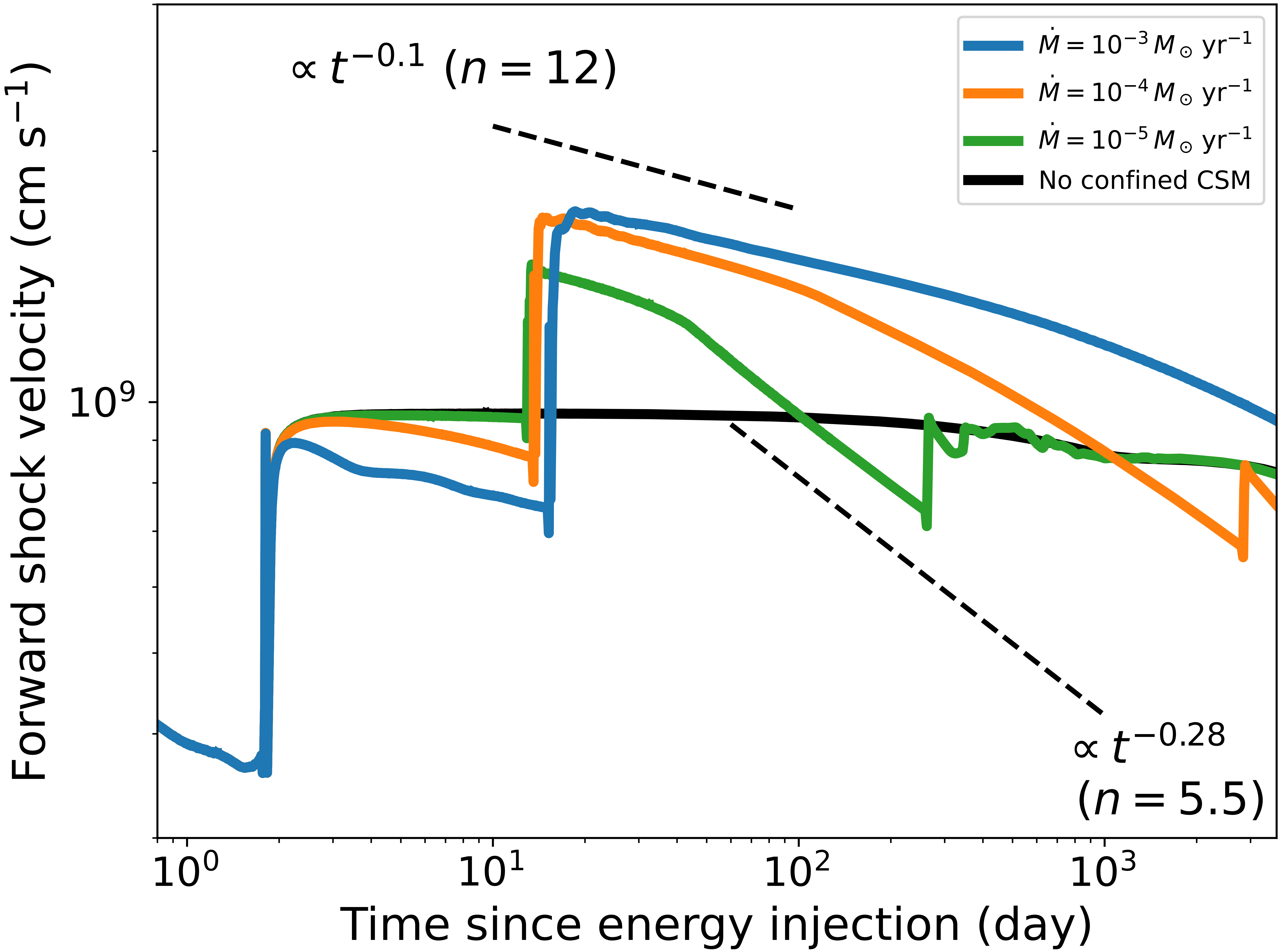
Influence on forward shock velocity $V_{\rm sh}$



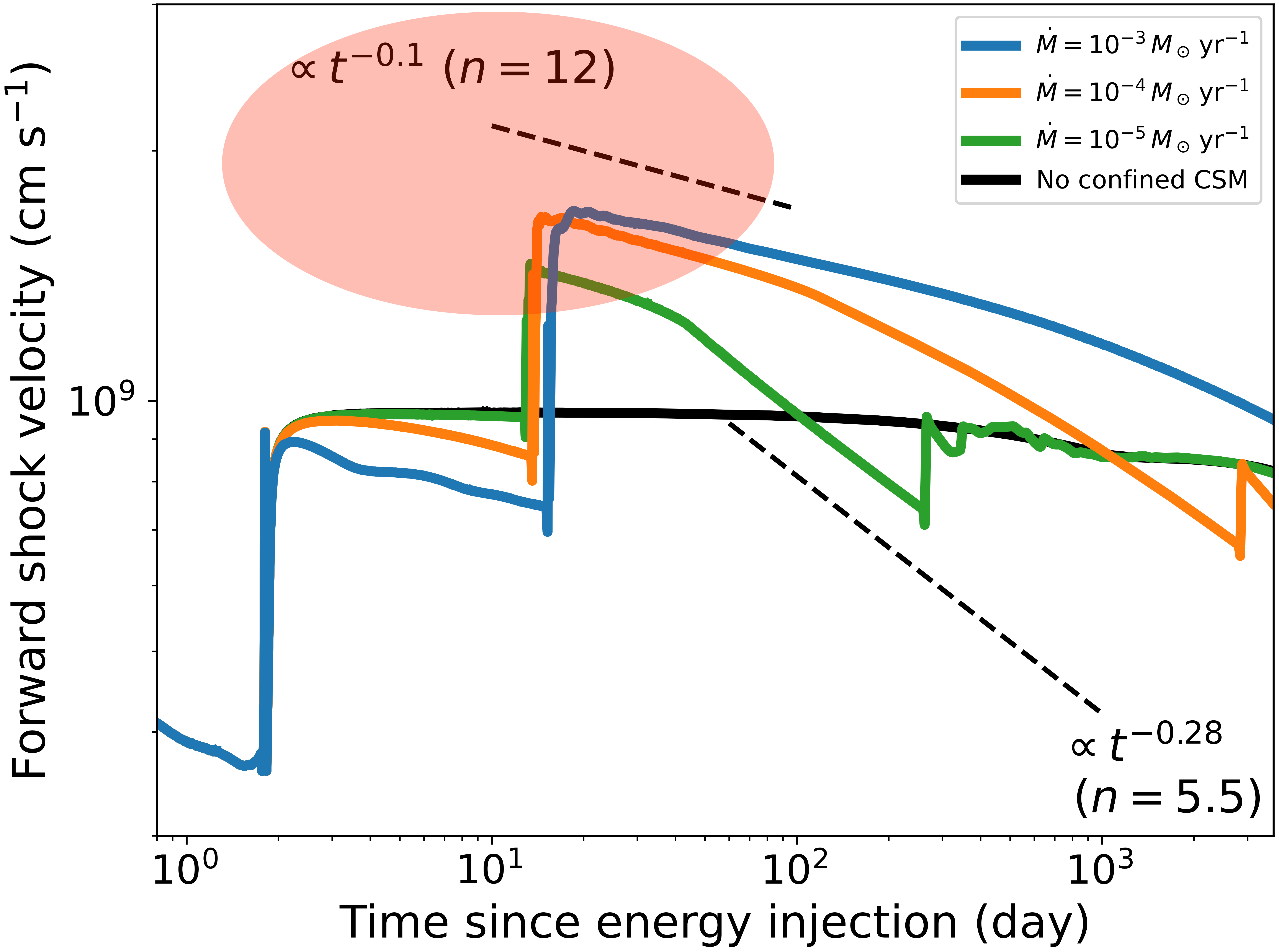
Shock breakout
from the progenitor surface

See also TM+19

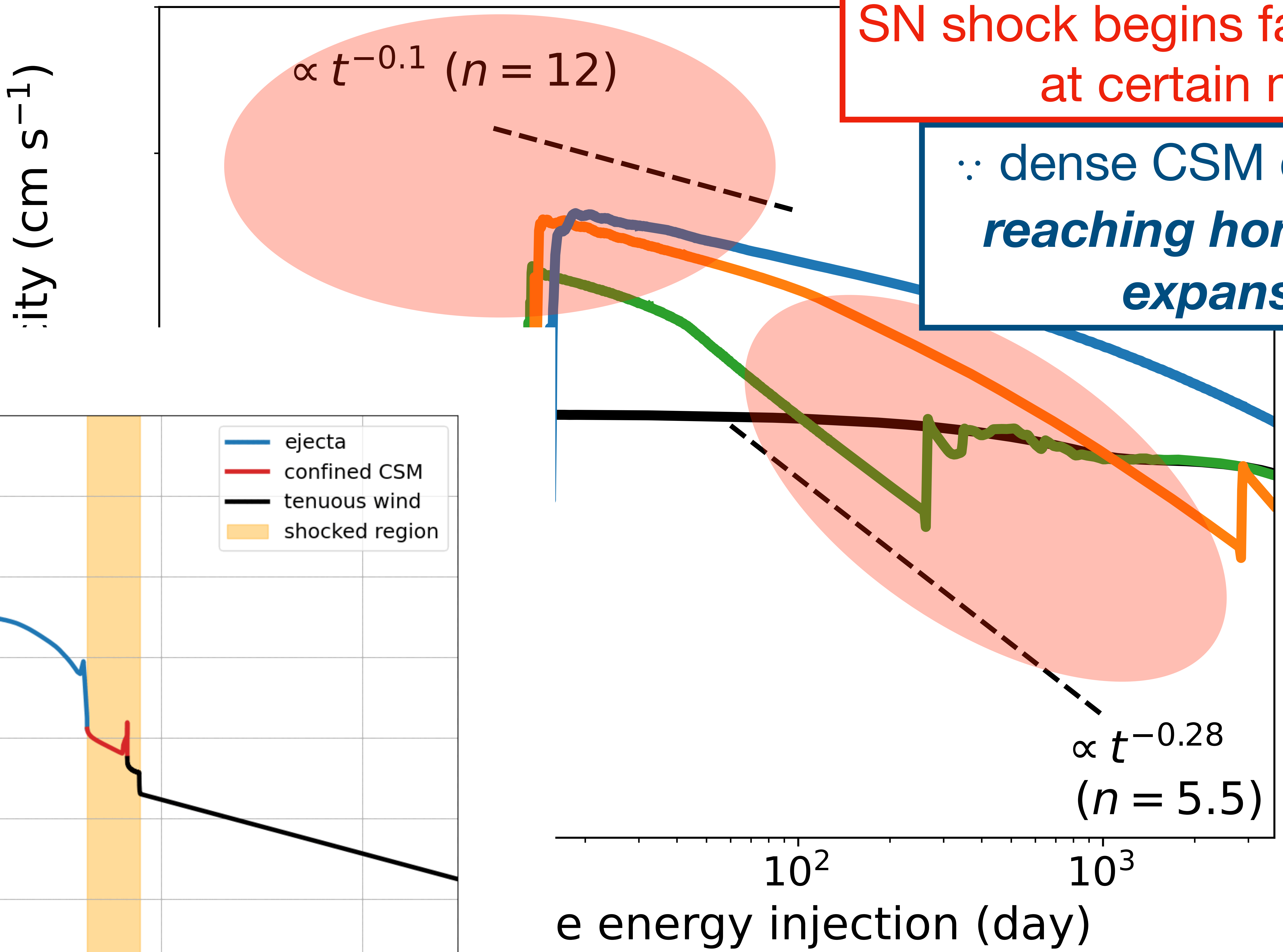
Influence on forward shock velocity $V_{\rm sh}$



Influence on forward shock velocity $V_{\rm sh}$

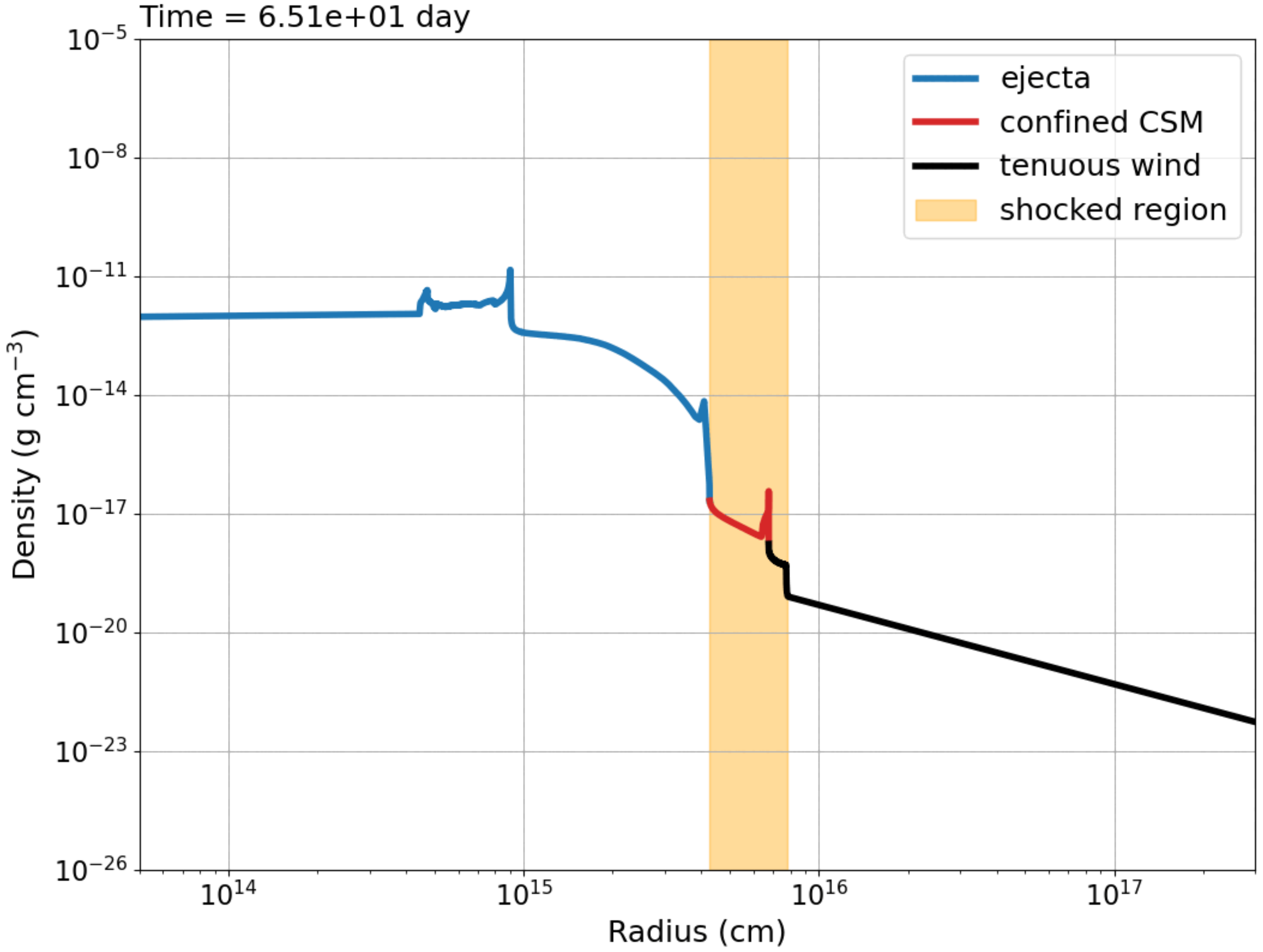


Influence on forward shock velocity $V_{\rm sh}$

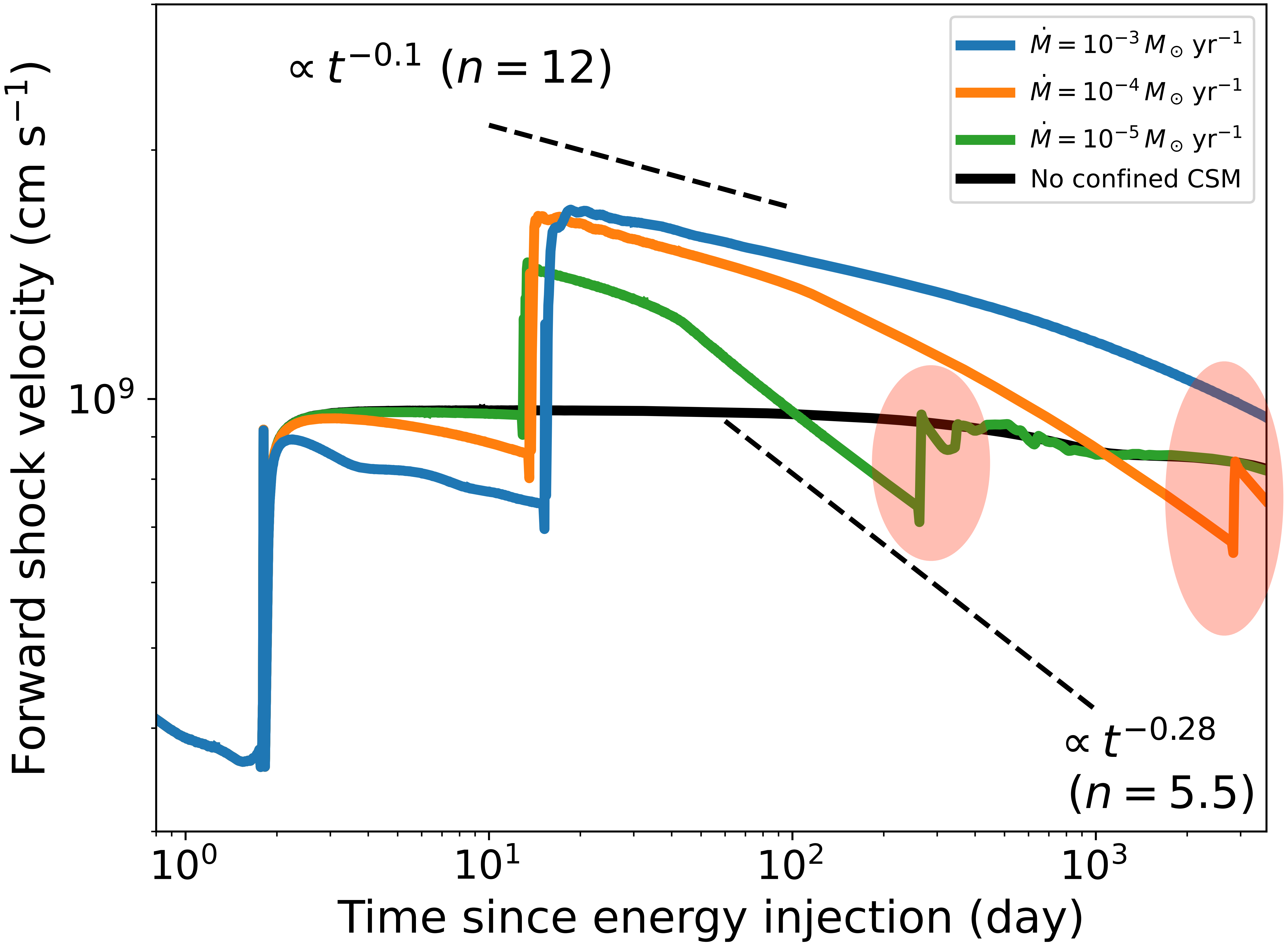


SN shock begins fast deceleration at certain moment

$\because$ dense CSM component ***reaching homologous expansion***



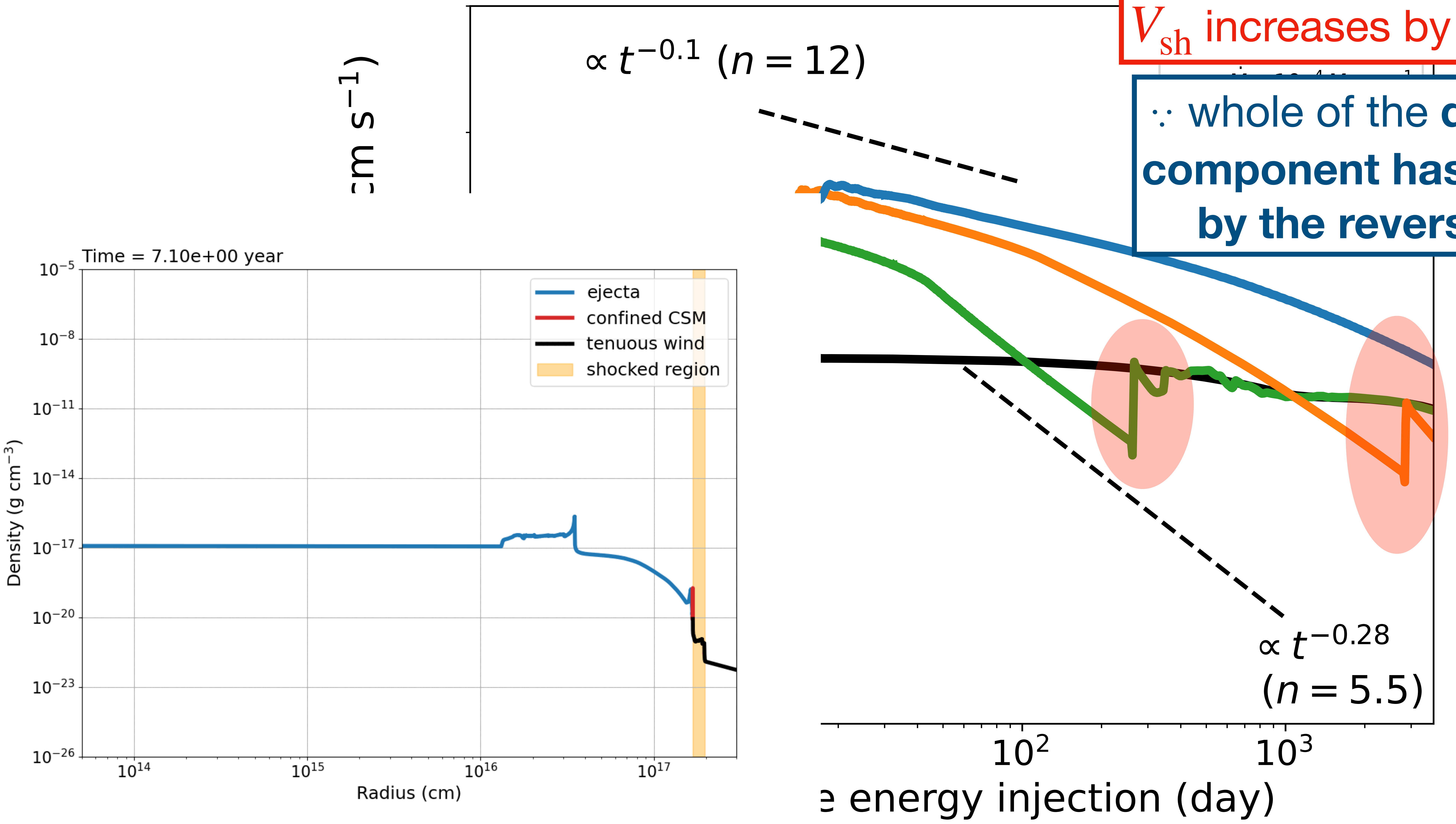
Influence on forward shock velocity $V_{\rm sh}$



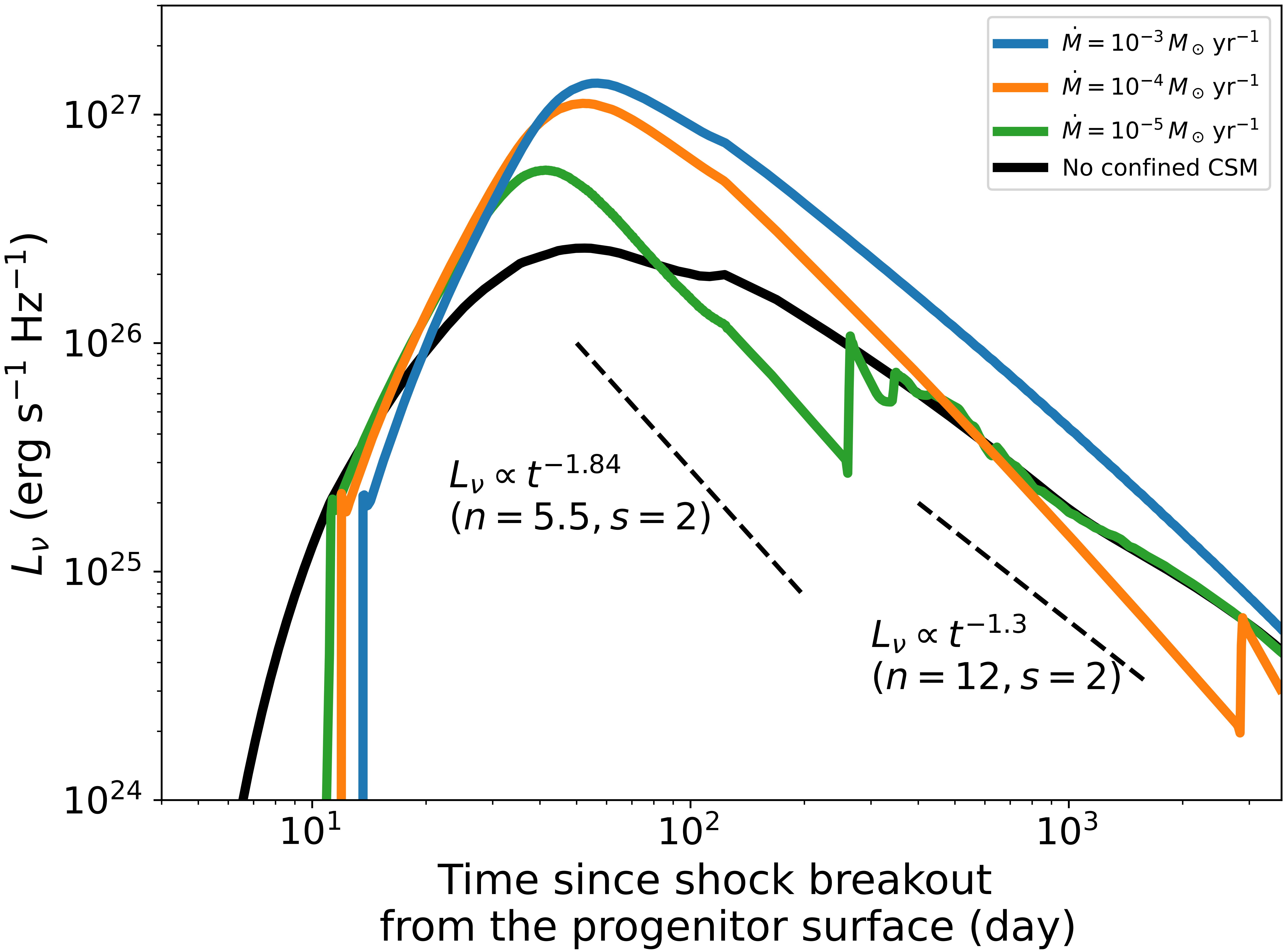
Influence on forward shock velocity $V_{\rm sh}$

$V_{\rm sh}$ increases by ~30% again

∵ whole of the **dense CSM component has heated up by the reverse shock**

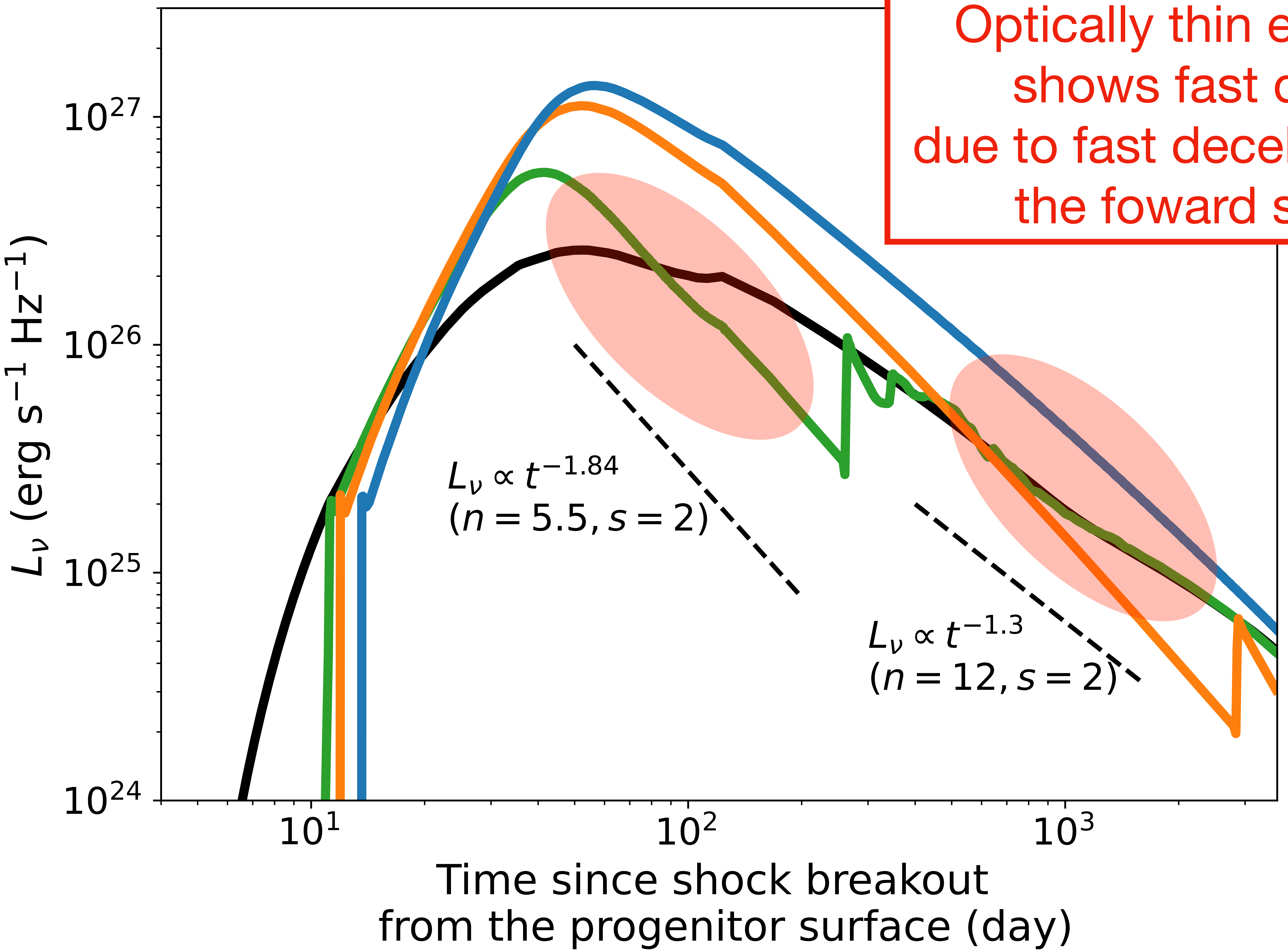


Observable signature: 5 GHz radio emission



See also TM+19

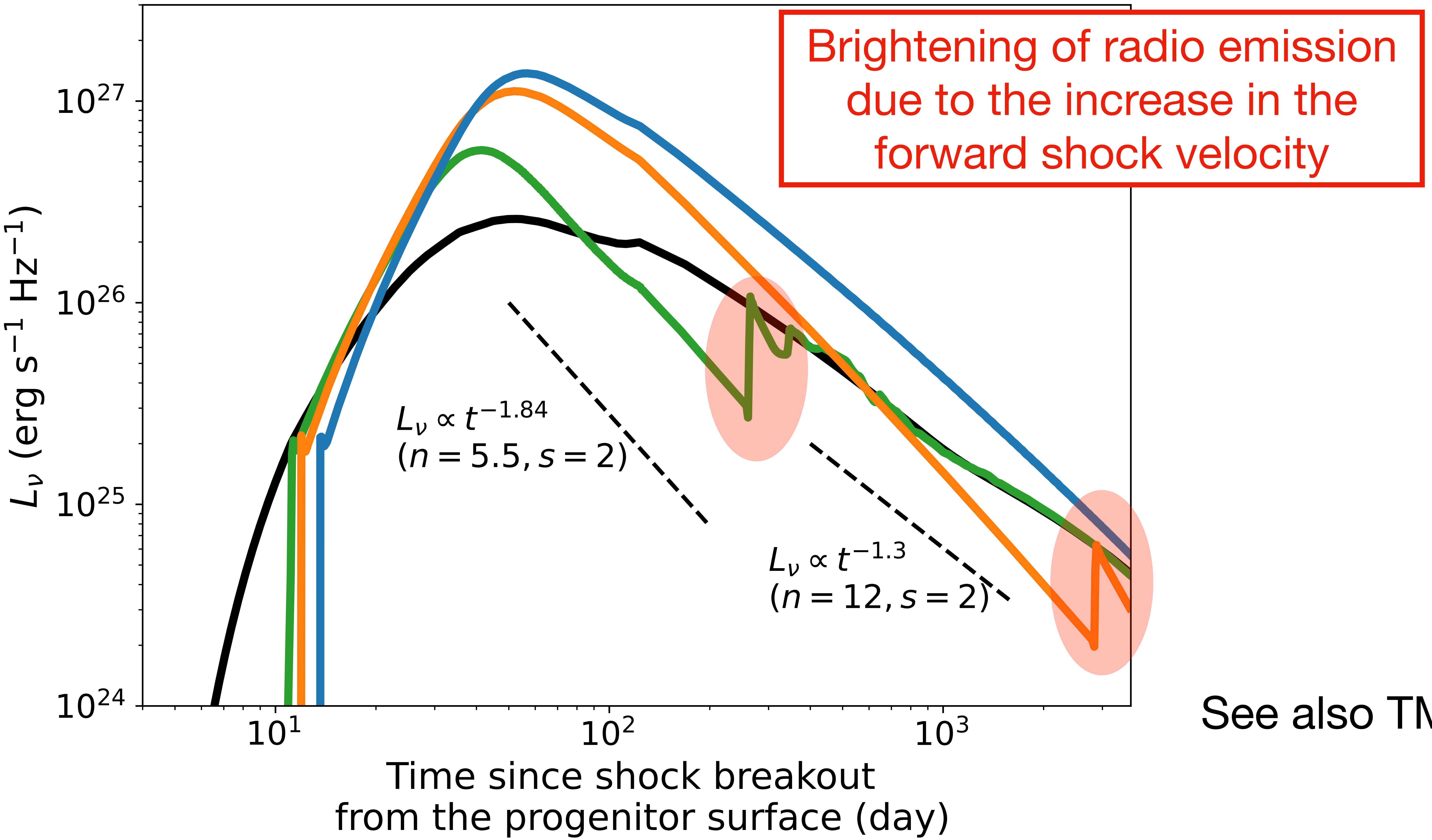
Observable signature: 5 GHz radio emission



Optically thin emission shows fast decay due to fast deceleration of the foward shock

See also TM+19

Observable signature: 5 GHz radio emission



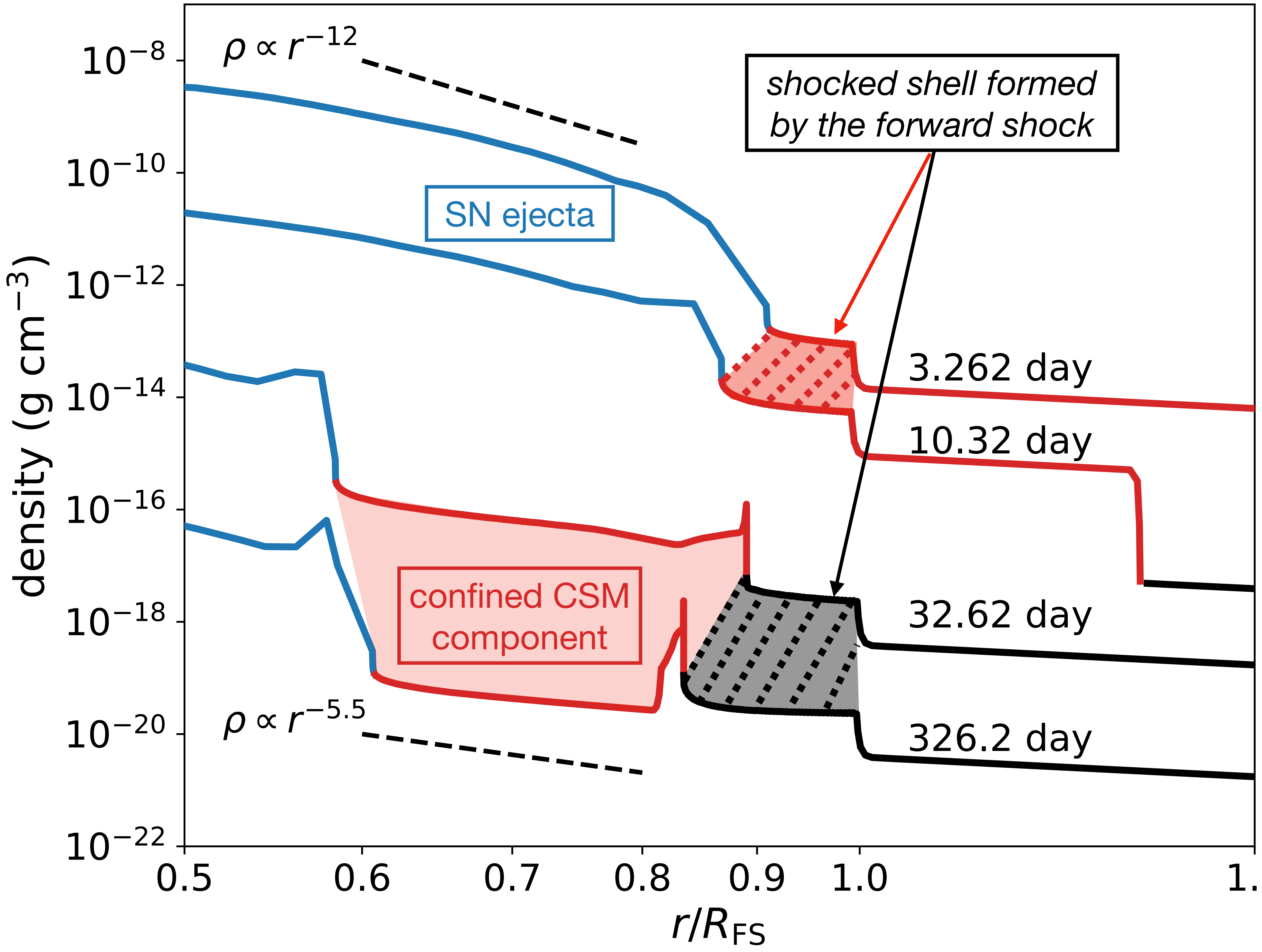
See also TM+19

Summary

- We have ***Tested the influence of dense CSM near the progenitor on the subsequent evolution***

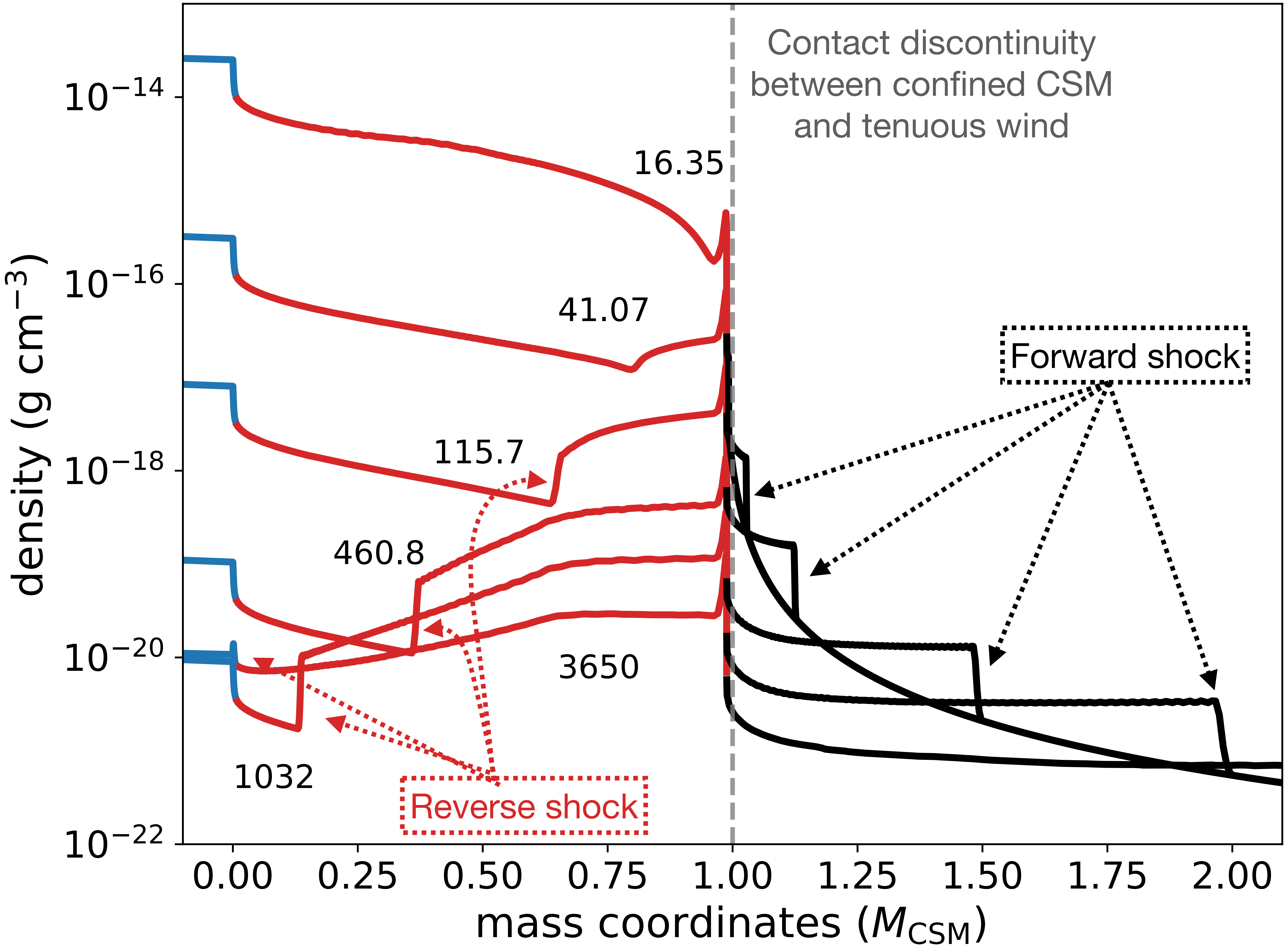
- Clear deviations from self-similar solution:
  - ***flatter density gradient*** of pushing material (Not ejecta, but dense CSM)
  - ***fast deceleration of*** $V_{\rm sh}$
    $\rightarrow$ fast decay of optically thin radio emission
  - ***increase in*** $V_{\rm sh}$ by a factor ***a few years after the explosion***
    $\rightarrow$ rebrightening of radio emission

- Next objective: Derive (semi-)analytic formulae of the profiles and shock evolutions (with consideration of whether we can do that).

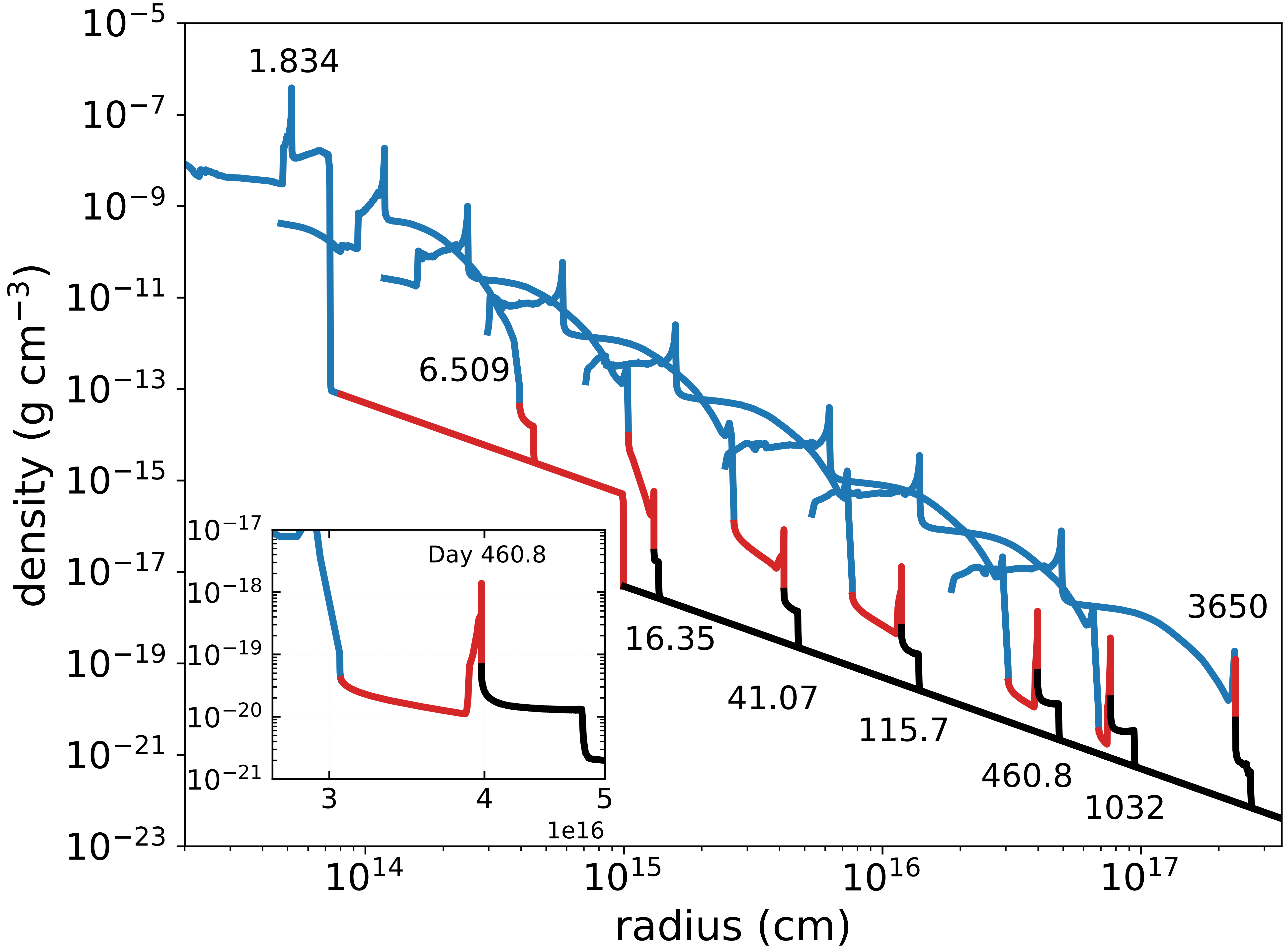


See TM+25a (arXiv:2504.14255)

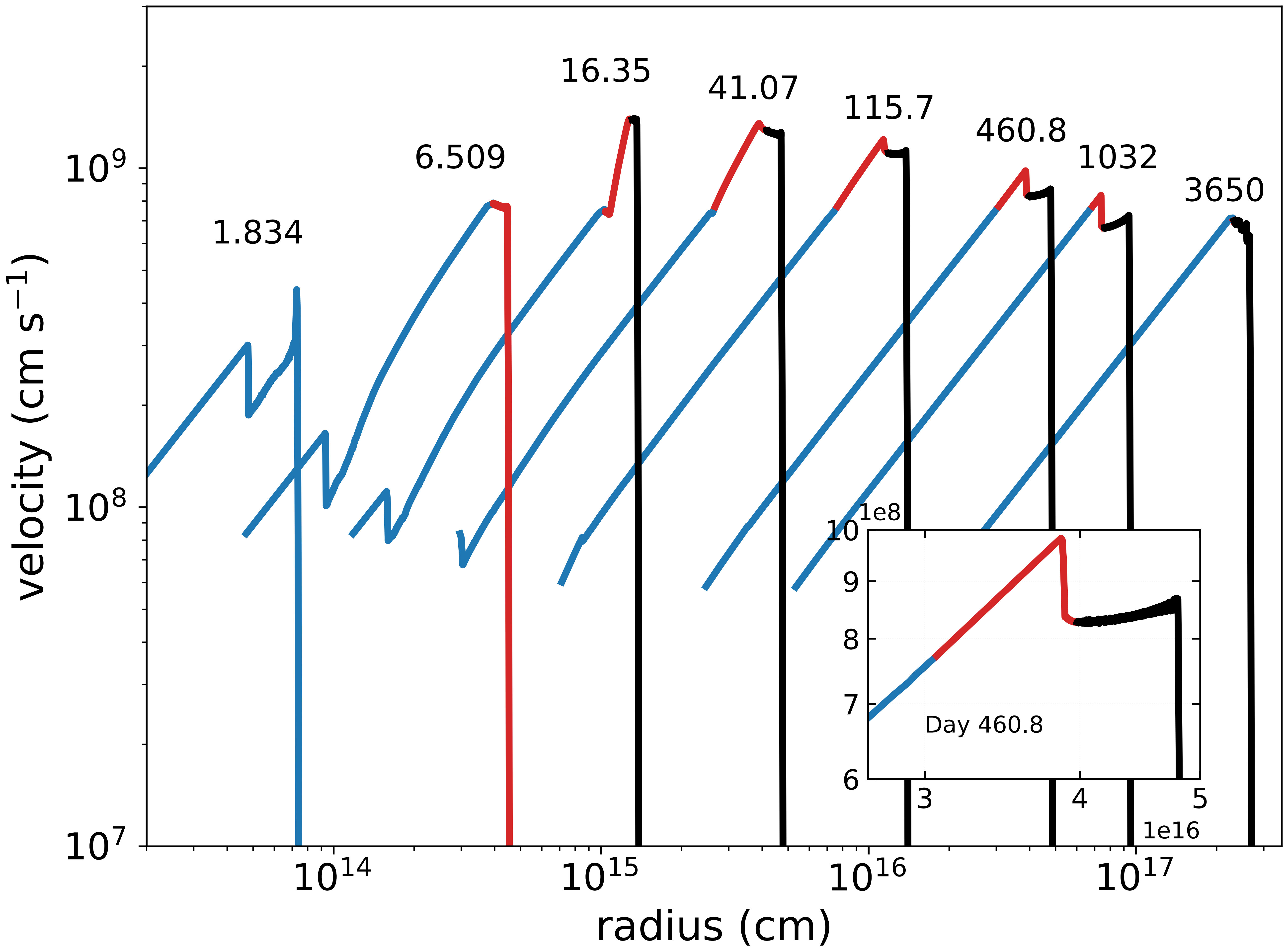
Density profile in mass coordinates



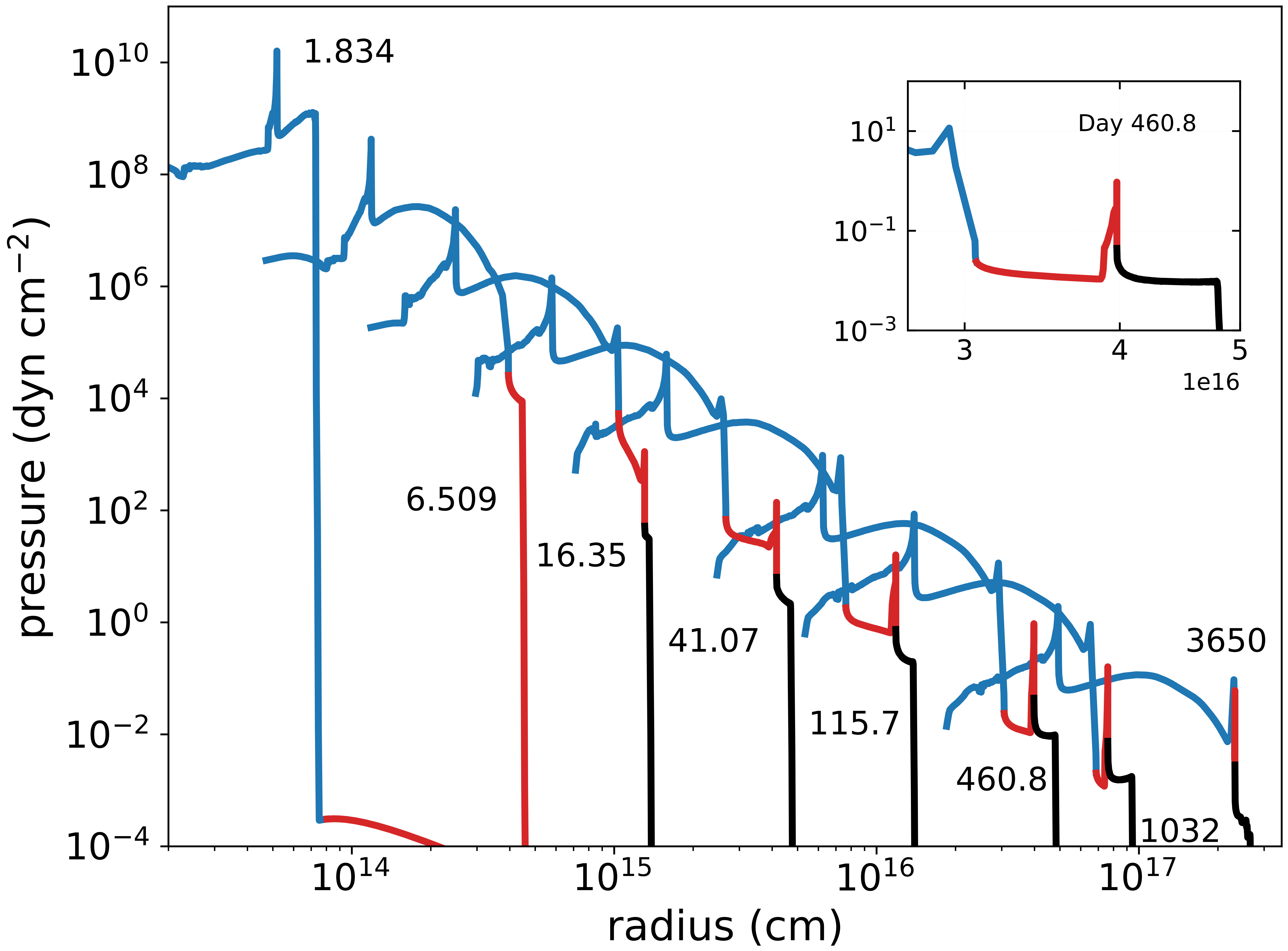
Density profile evolution



Velocity profile evolution



Ram pressure profile



Temperature profile evolution