中心エンジン駆動超新星エジェクタの多次元シミュレーション

Multi-dimensional simulations of central-engine powered supernova ejecta

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Suzuki & Maeda (2017) MNRAS 466 2633 and recent updates

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Ordinary and Extra-ordinary CCSNe

- CCSNe energetics: Canonically,
  - gravitational energy $E_{grav} \sim GM_{ns}^2/R_{ns} \sim$ **10^{53} [erg]**
  - kinetic energy $E_{kin} \sim$ **1%** of $E_{grav} \sim$ **10^{51} [erg]**
  - total radiated energy $E_{rad} \sim$ **less than 1%** of $E_{kin} \sim$ **$<10^{49}$ [erg]**
  - ejecta mass: **a few - 10 $M_\odot$**
  - photospheric velocity: typically, ~**10,000 [km/s]**

- However, some unusual SNe have been found:
  - **broad-lined Ic SNe (Ic-BL)**: photospheric velocity larger by a factor of 2-3 ~ **a few 10^4 [km/s]**, which implies $E_{kin} \sim$ **10^{52} [erg]** > 10^{51} [erg]
  - **Superluminous SNe (SLSNe)**: $E_{rad} \sim$ **10^{51} [erg]** > 10^{49} [erg]

Superluminous SNe

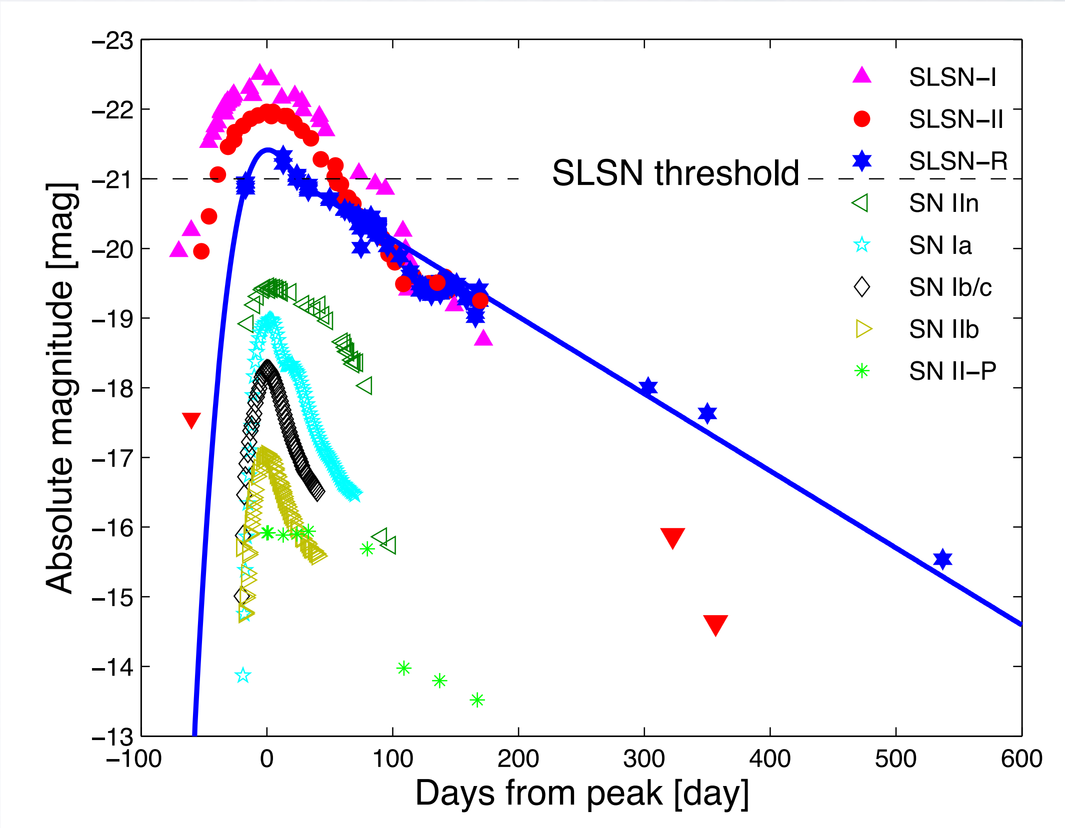
- Superluminous supernovae(SLSNe): SNe **10-100 times brighter** than normal SNe (Quimby+2007, Barbary+2009 etc, see Gal-Yam+2012 for review)

- They are found by recent “unbiased” transient survey projects (e.g., Palomar transient factory, Pan-STARRS).

- The following classification based on their optical spectra has been proposed (analogy to standard SNe).

  1) **SLSN-I** : no Hydrogen feature
  2) **SLSN-II** : Hydrogen feature
  3) **SLSN-R** : subclass of SLSN-I, their light curves can be explained by the decay of radioactive ^{56}Ni (e.g., 3M$_\odot$ Ni for SN 2007bi)

- Total radiated energy can be ~ 10^{51} [erg]
  (~ explosion energy of normal CCSNe)

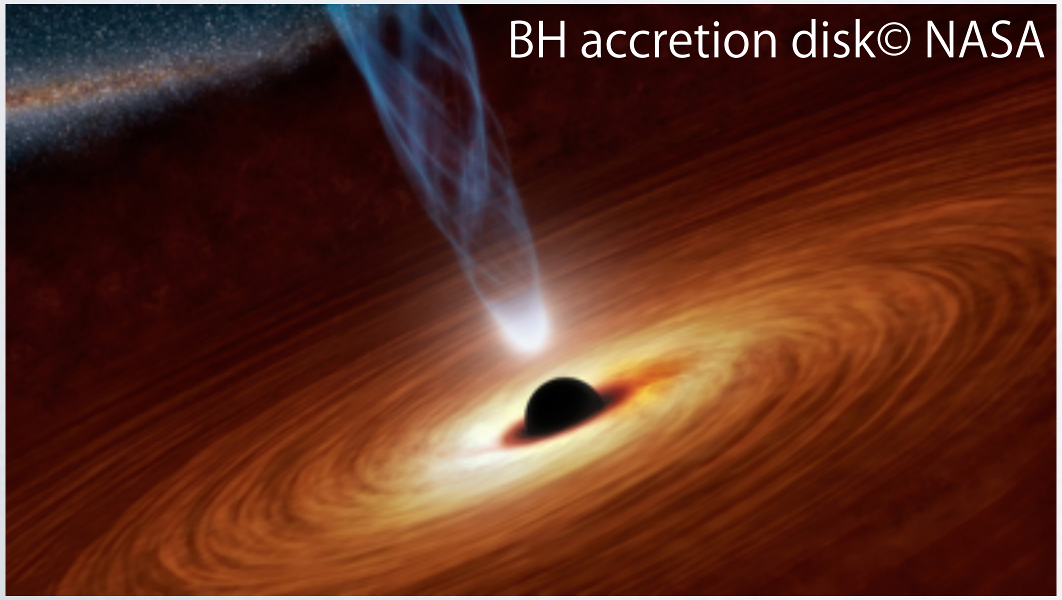


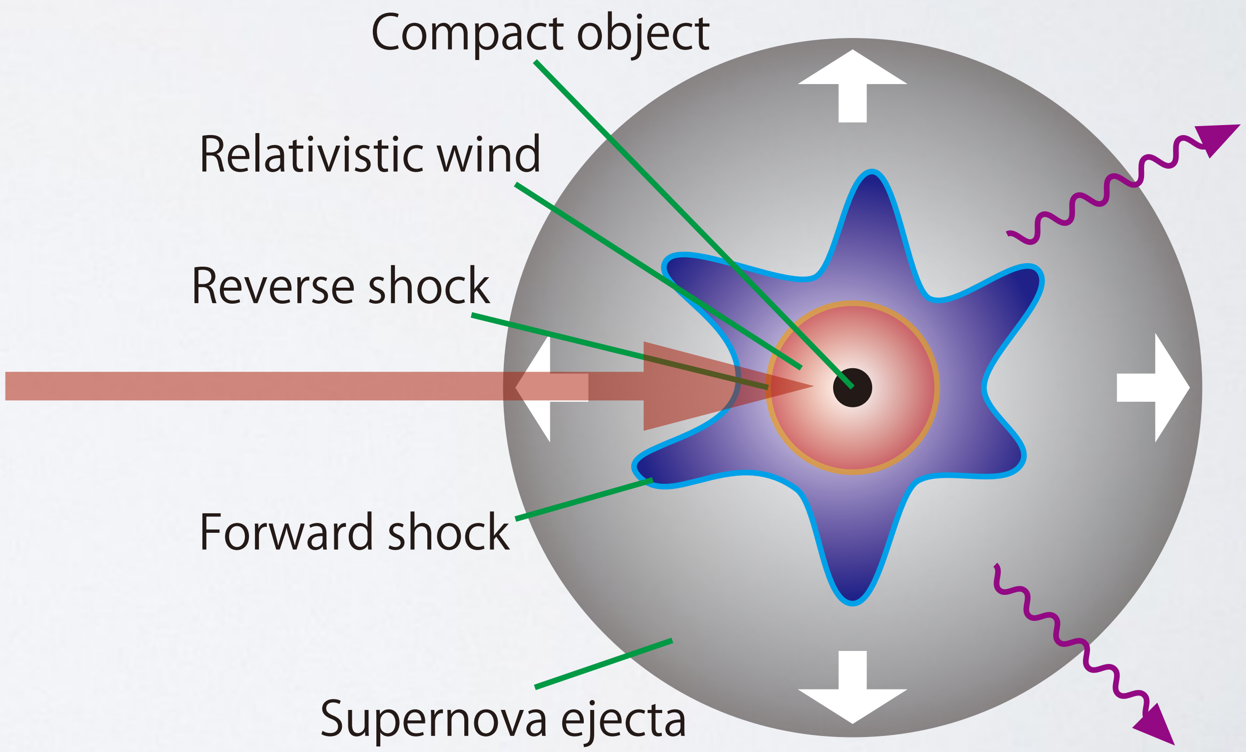
What is the origin of SLSNe-I?

↑ light curves of standard SNe, SLSNe (Gal-Yam 2012)

Proposed models and progenitors for SLSNe

- CSM interaction
- pair-instability SNe (very massive progenitor with ~ 100-300$M_\odot$ at ZAMS)
- additional energy injection from the central engine : magnetar spin-down (e.g., Kasen&Bildsten 2010, Woosley 2010) or BH accretion (Dexter&Kasen 2013)





mili-second Magnetar scenario

- After the gravitational collapse of the iron core, a massive star experience the core bounce and its outer layer with mass M_{ej} is expelled by neutrino-driven explosion with $E_{kin}=10^{51}$[erg] (standard scenario for CCSNe).

- a neutron star with a strong dipole magnetic field is assumed to form immediately after the neutrino-driven explosion.

  radius $R_{\rm ns}$ ~ 10km

  $\text{moment of inertia } I_{\rm ns} \sim 10^{45} \text{ g cm}^2$

  $\text{initial period of } P_{\rm i} \sim 1 \text{ ms}$

  $E_{\rm rot} = I_{\rm ns}\Omega_{\rm i}^2/2 \simeq 2\times 10^{52} \text{ erg.}$

- spin-down of the new-born magnetar is expected to power the SN ejecta

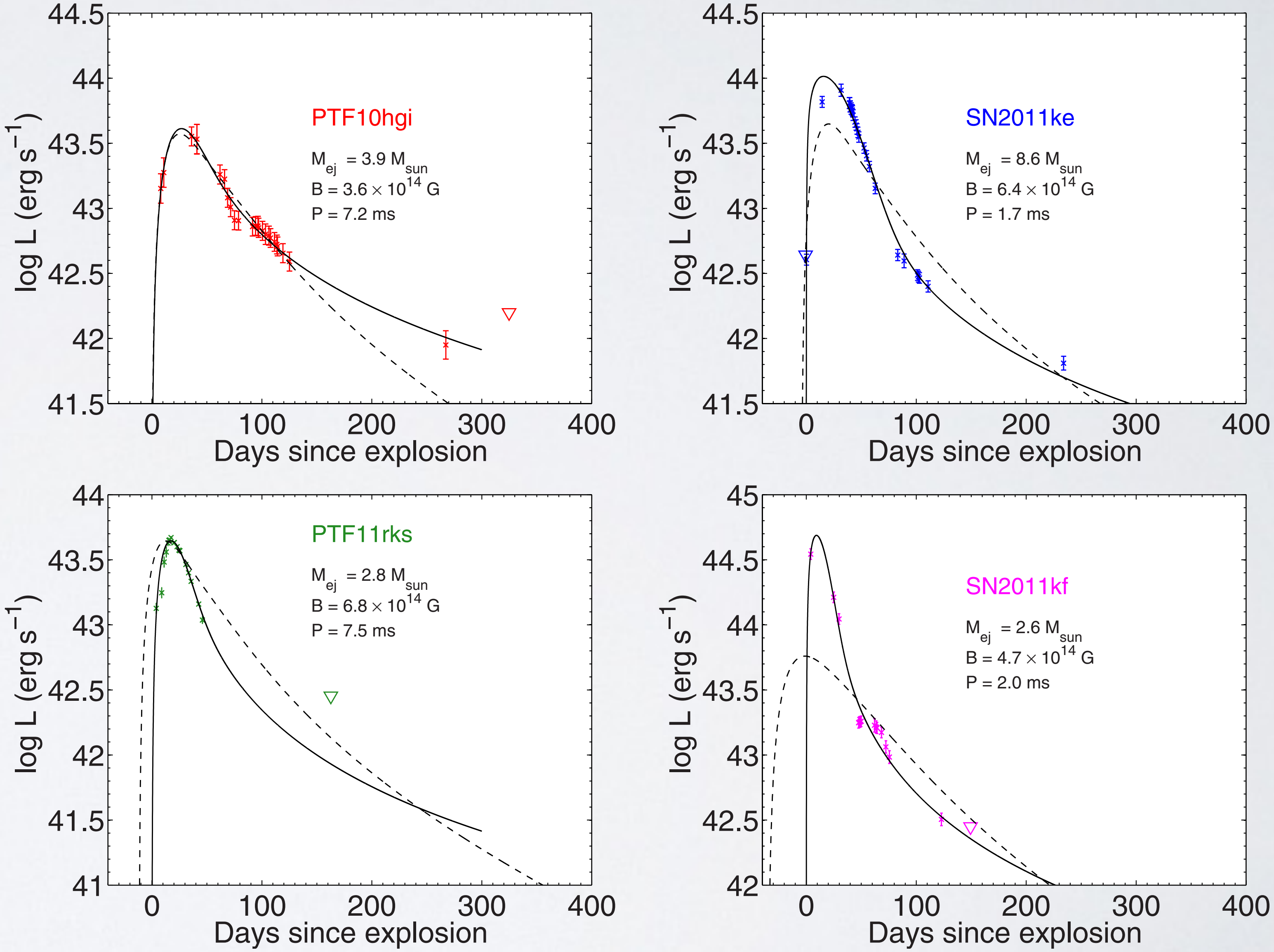
$$L = \frac{E_{\rm rot}/t_{\rm ch}}{(1+t/t_{\rm ch})^2}$$

$$L \simeq \frac{B^2 R_{\rm ns}^6 \Omega_{\rm i}^4}{6c^3} \sim 10^{49} B_{15}^2 R_{\rm ns,6}^6 P_{\rm i,-3}^{-4} \text{ erg s}^{-1}$$

$$t_{\rm ch} = \frac{6 I_{\rm ns} c^3}{B^2 R_{\rm ns}^6 \Omega_{\rm i}^2} = 4.1\times 10^3 I_{\rm ns,45} B_{15}^2 R_{\rm ns,6}^6 P_{\rm i,-3}^2 \text{ s.}$$

mili-second Magnetar scenario

- one-box light curve model for SNe with magnetar energy injection
- LCs are explained by "tuning" several free parameters, M_{ej}, B, and P_i.
- Magnetar scenario looks successful when one-box model is considered.



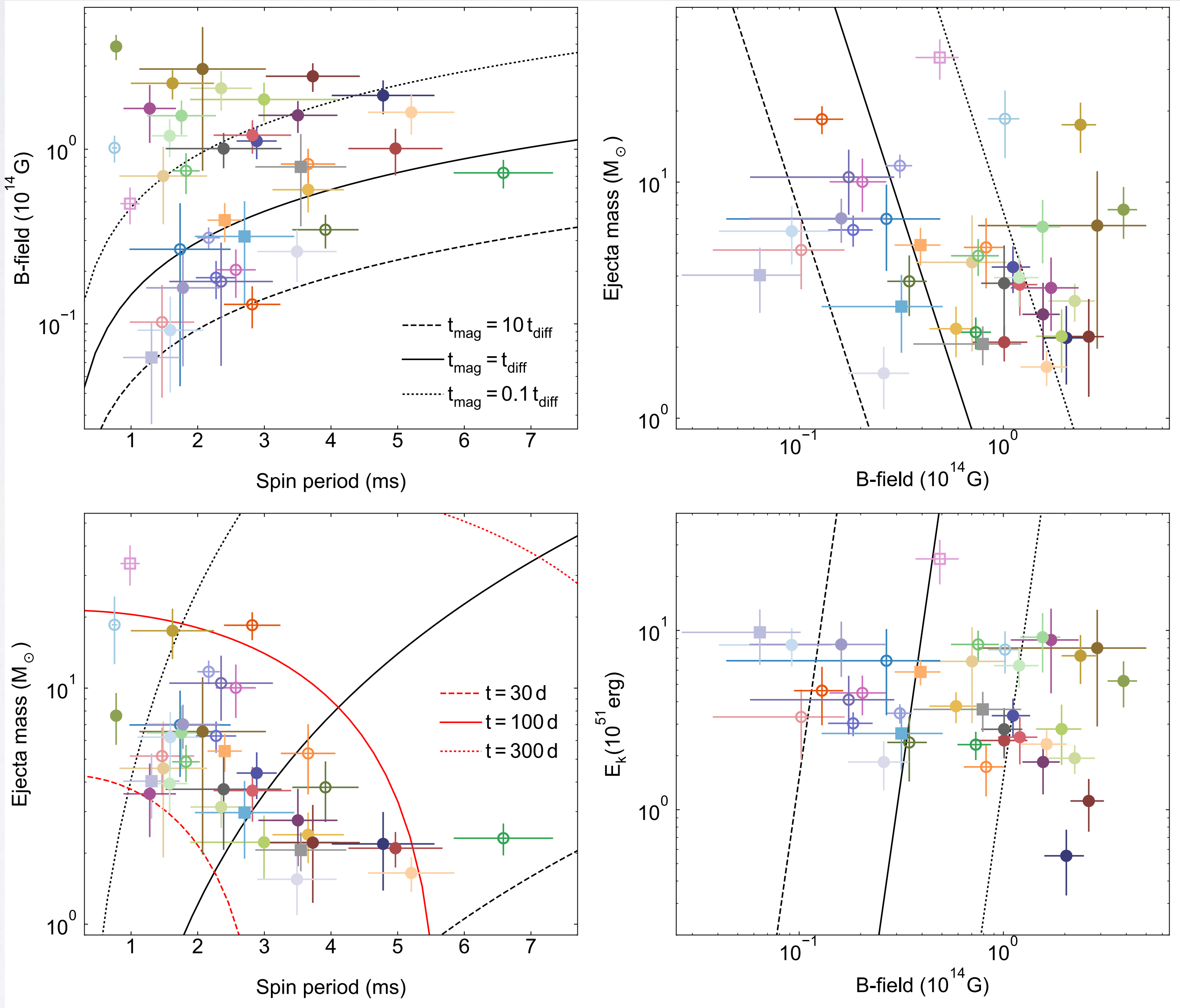
↑Magnetar model fit to SLSNe-I (Inserra+2013)

Magnetar scenario

- one-box light curve model for SNe with magnetar energy injection
- LCs are explained by "tuning" several free parameters, M_{ej}, B, and P_i.
- Magnetar scenario looks successful when one-box model is considered.
- Magnetar fit :

- spin-period ~ 1 - 7 [ms]
- B ~ 10^{13} - a few 10^{14} [G]
- time-scale ~ a few 10-100 days
- E_k ~ 10^{51} - 10^{52} [erg]
- M_{ej} ~ 2 - 10 $M_\odot$

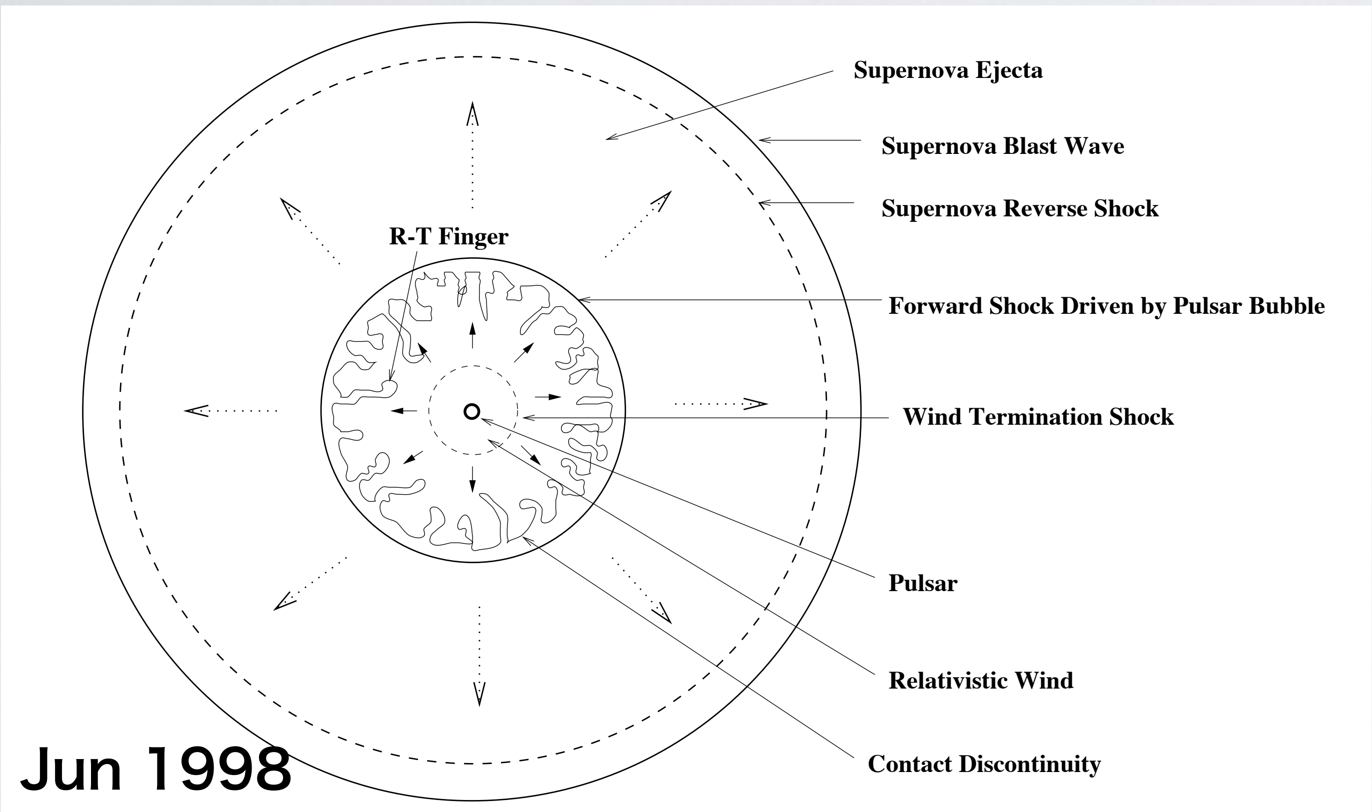
(e.g., Nicholl+2017)

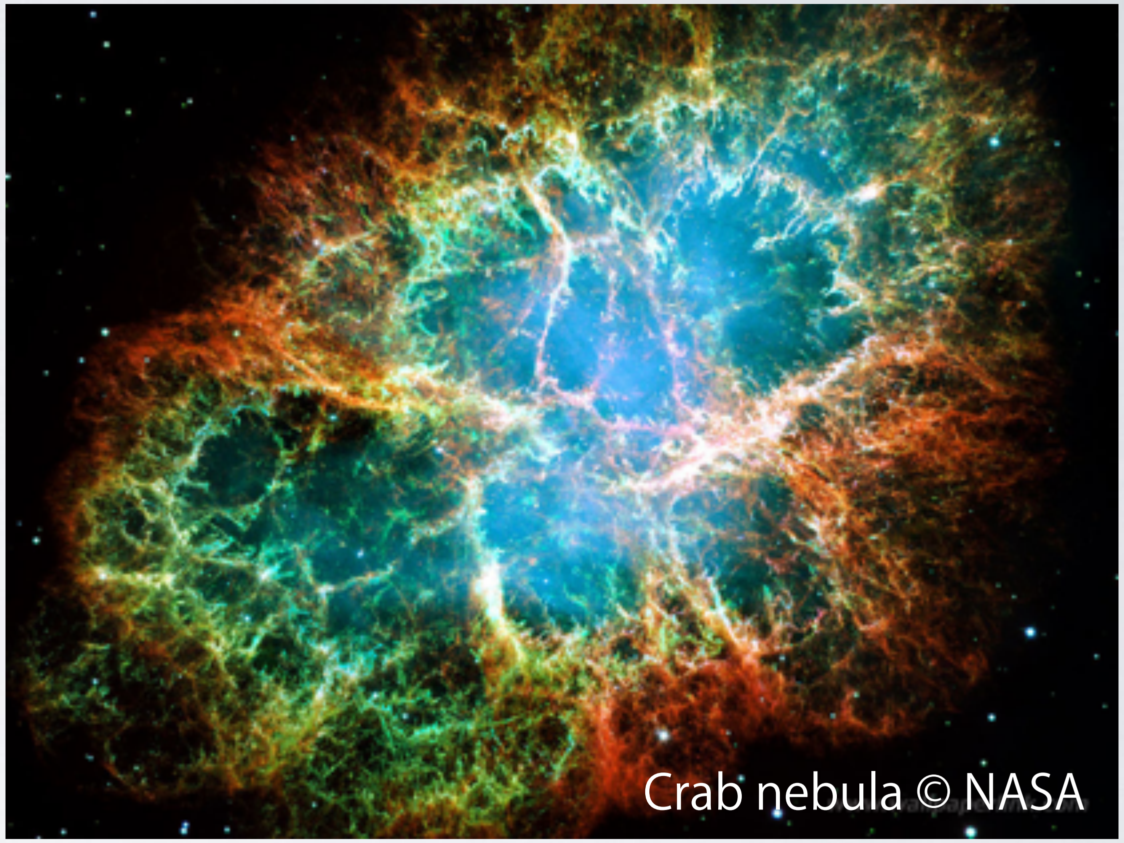


↑ Magnetar model fit to SLSNe-I (Nicholl+2017)

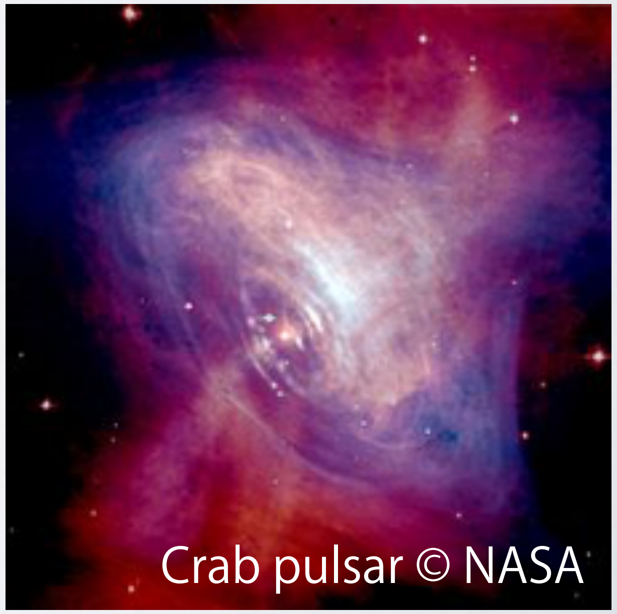
Relativistic wind from magnetized NS

- SN ejecta (or SNR) pushed by a pulsar wind nebula
- e.g., Crab nebula





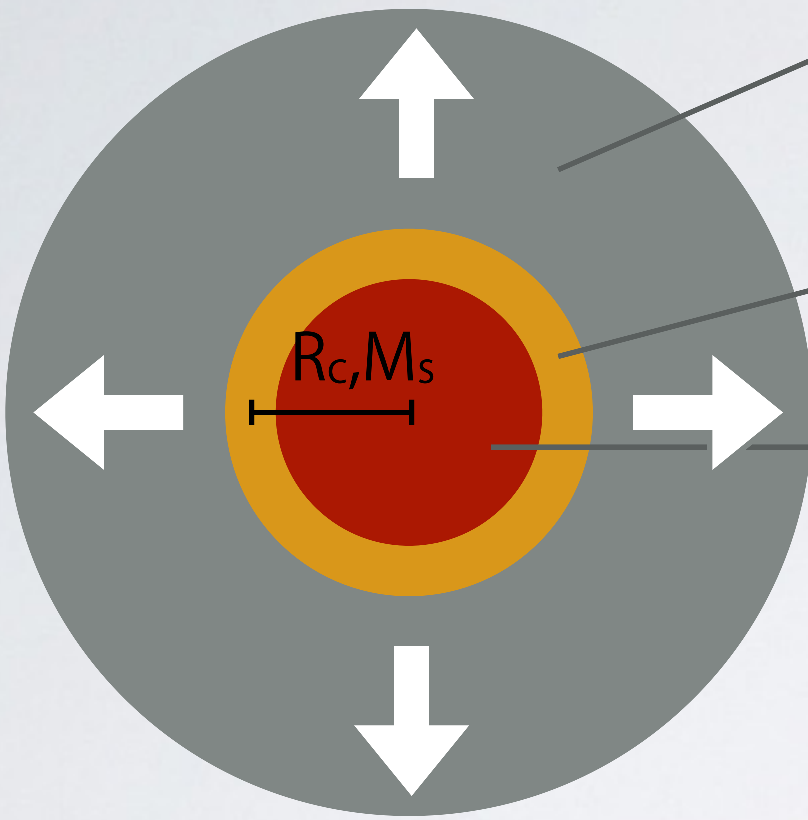
- galactic PWNe: injected energy E_{inj} < SN explosion energy E_{exp}



What happens when $E_{inj} > E_{exp}$?
(or maybe $E_{inj} \gg E_{exp}$)

1D spherical picture of SN-wind interaction

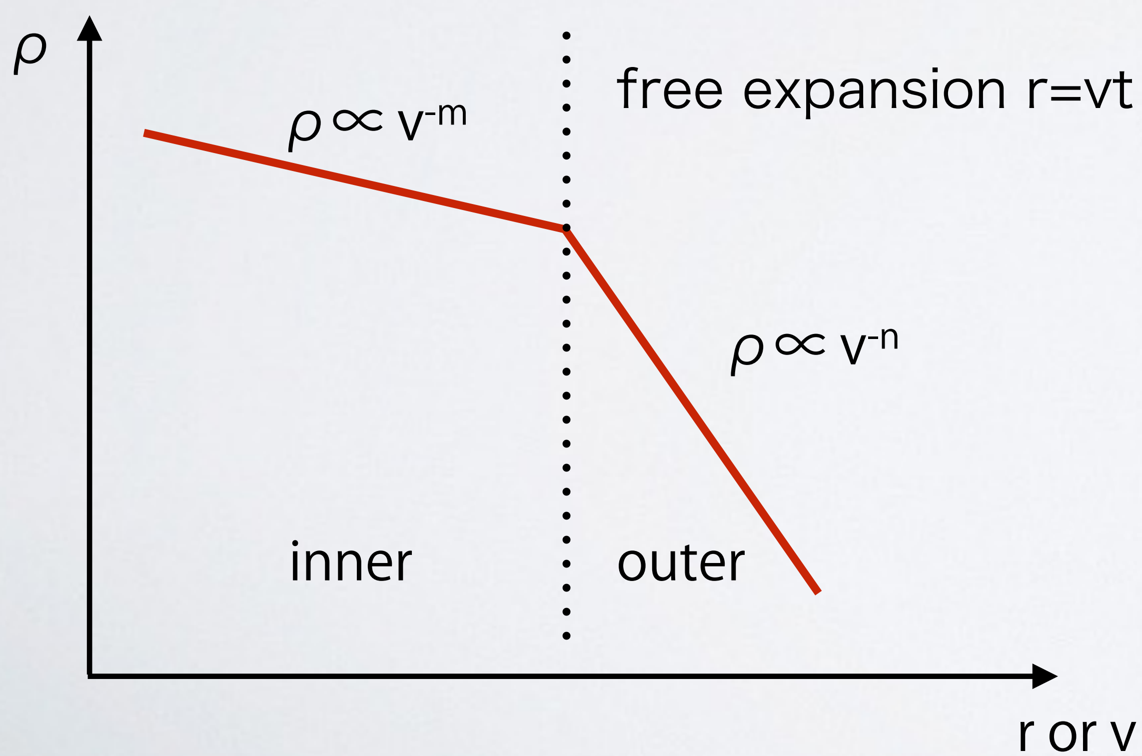
e.g., Chevalier (1992), Jun (1998)

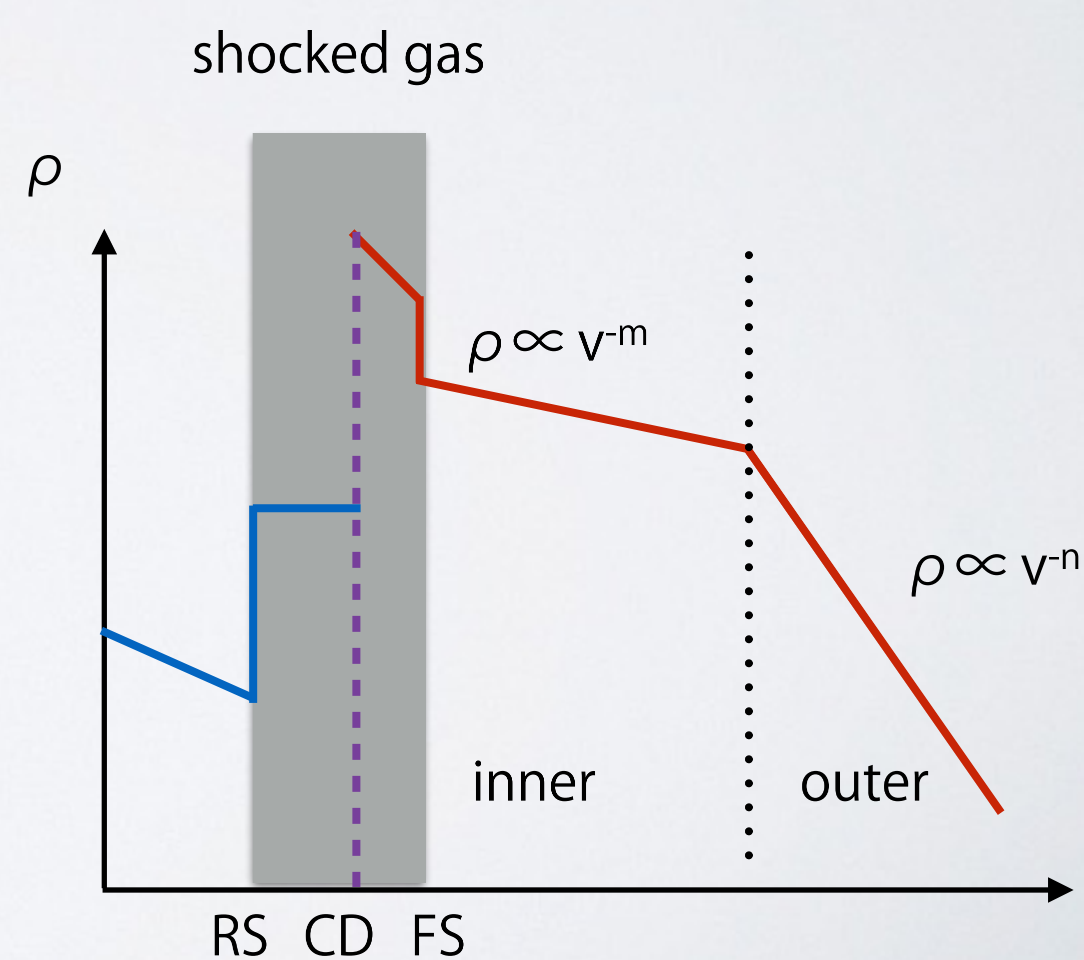


freely expanding supernova ejecta (high ρ)

geometrically thin shell driven by hot bubble
assume $R_c \propto t^{\alpha}$

high pressure region filled with hot gas (low ρ)
$p \propto Lt/V_c$





1D analytic model

e.g., Chevalier (1992), Jun (1998)

pressure of the hot bubble

$$p_{\rm c} = \frac{3(\gamma-1)E_{\rm th}}{4\pi R_{\rm c}^3} = \frac{3(\gamma-1)(2-\gamma)}{1+3\alpha(\gamma-1)} \frac{Lt}{4\pi R_{\rm c}^3}$$

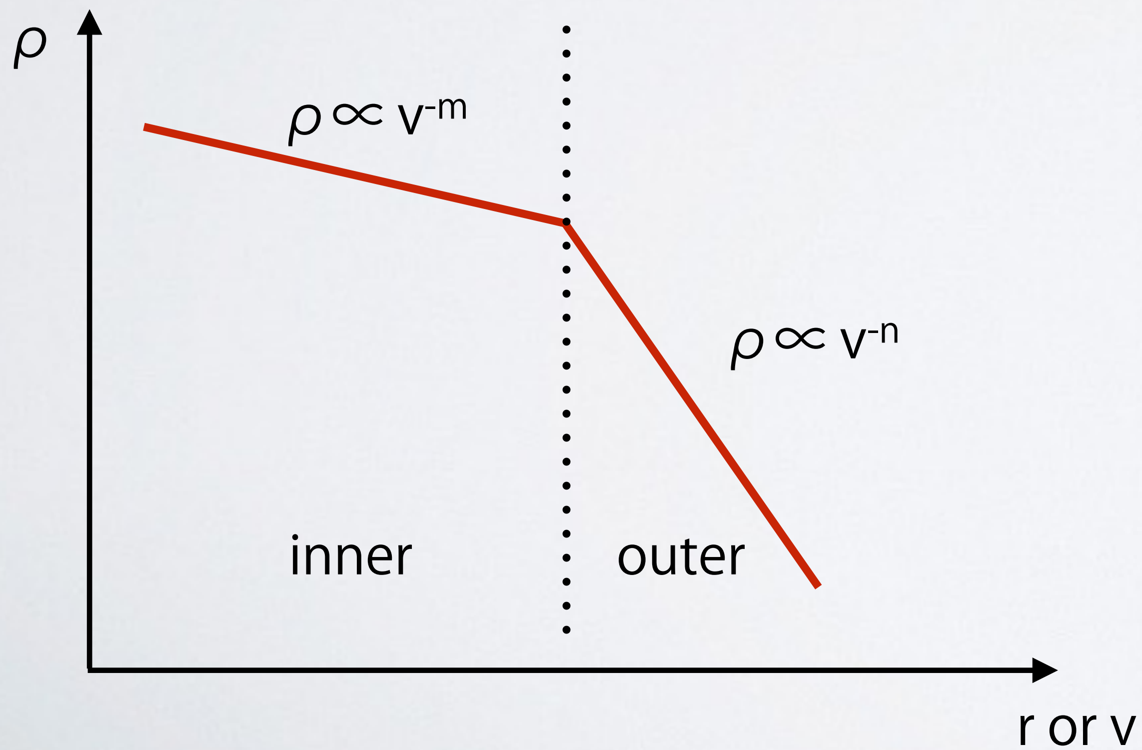
Eq. of continuity

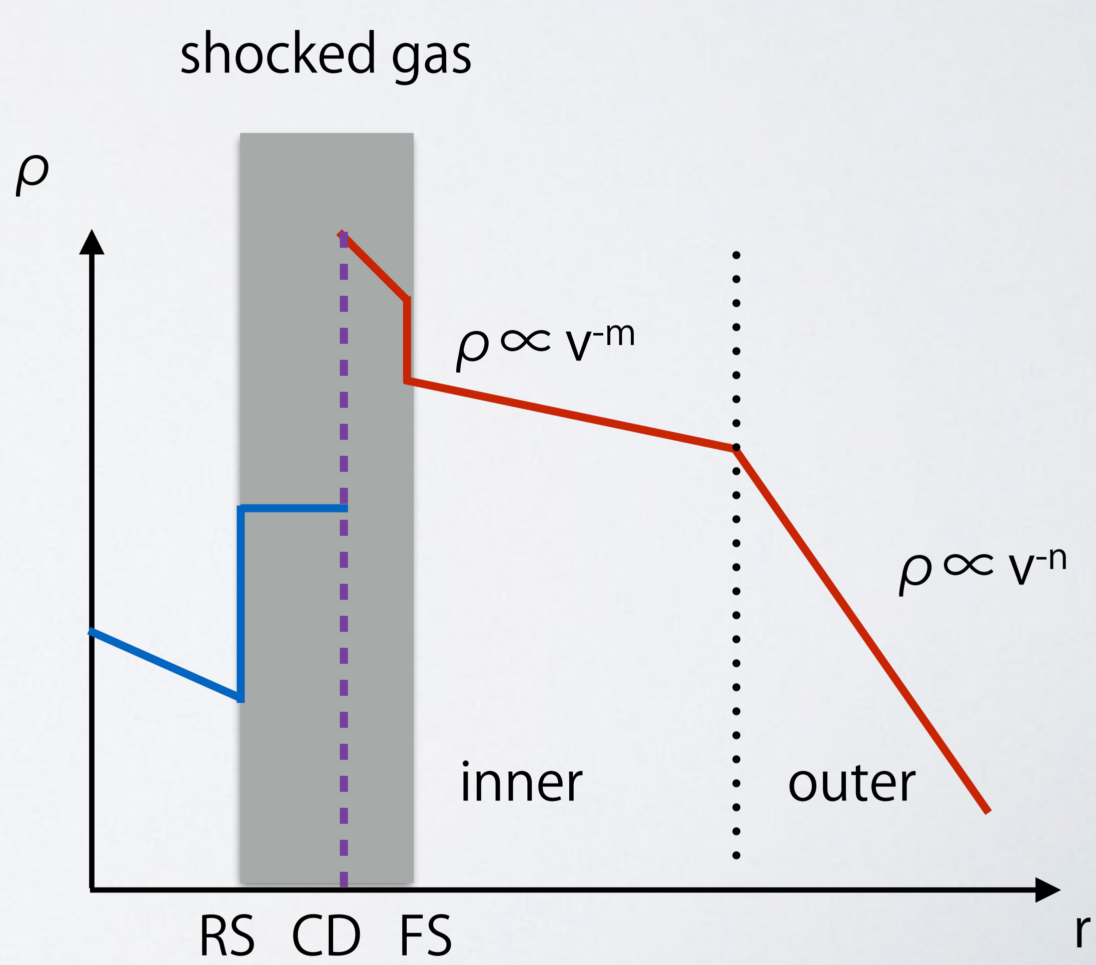
$$M(t) \propto \int_0^r \rho(t,r) r^2 dr \propto t^{m-3} r^{3-m}$$

Eq. of motion

$$M(t)\frac{d^2 R_{\rm c}}{dt^2} = 4\pi R_{\rm c}^2 p_{\rm c} \propto \frac{t}{R_{\rm c}}$$

$$R_{\rm c}^{5-m} \propto t^{6-m} \quad \Rightarrow \quad R_{\rm c} \propto t^{\alpha}, \quad \text{with } \alpha = \frac{6-m}{5-m}$$





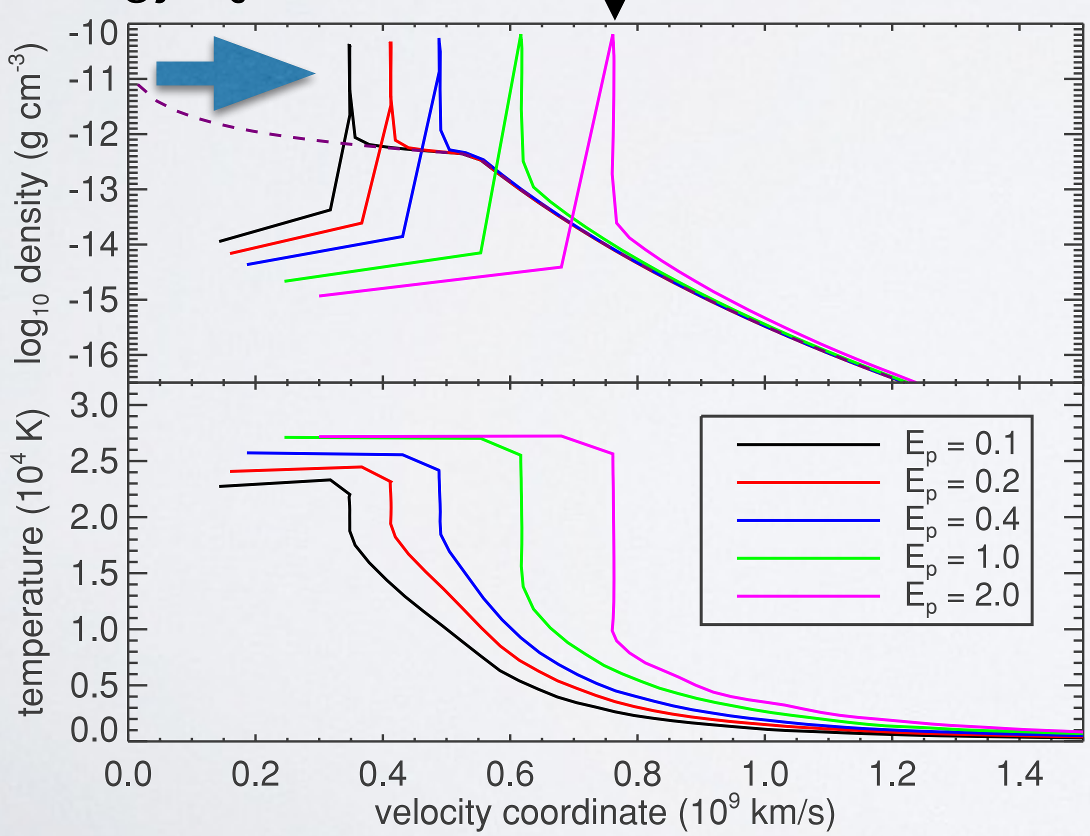
1D spherical picture of SN-wind interaction

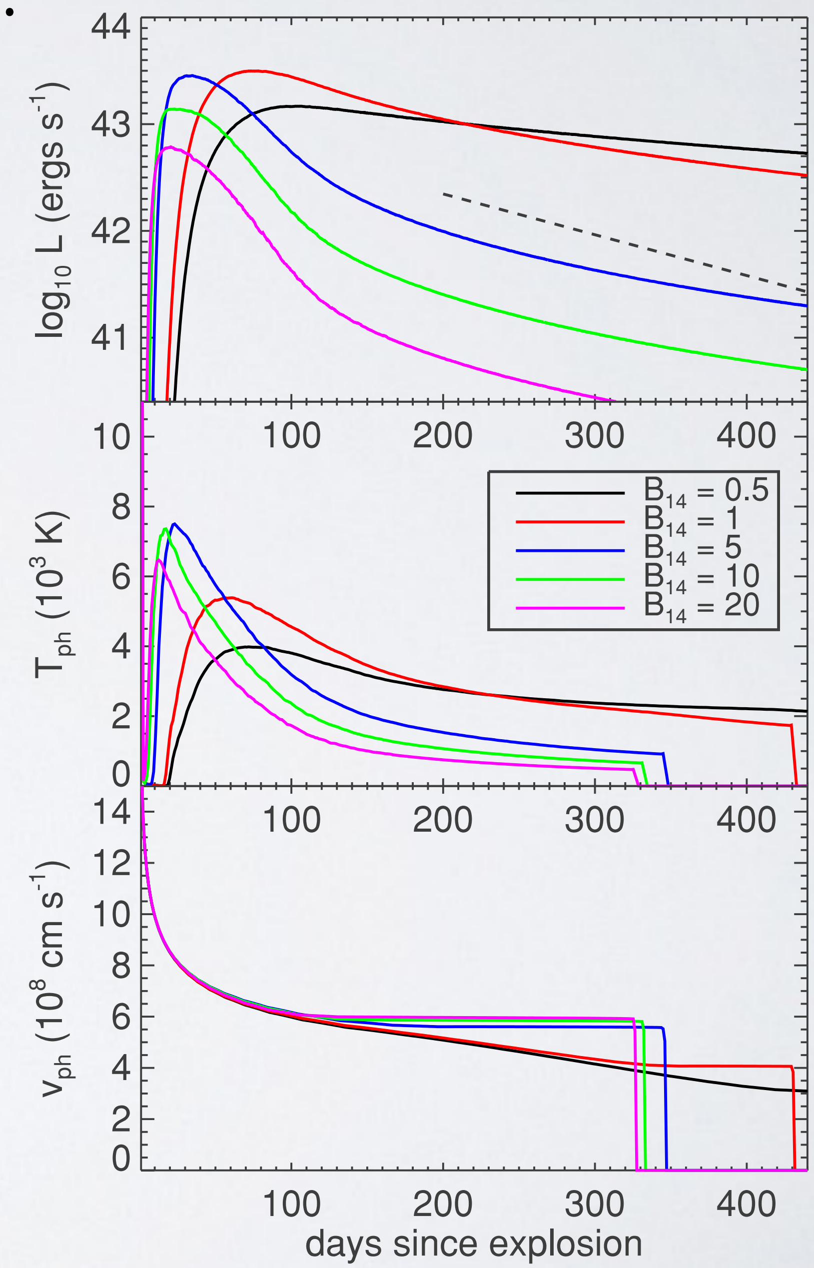
- In 1D spherical case, the energy redistribution is realized by a geometrically thin shell (swept up materials by the energy injection) and the radiation diffusing out from the shell.
- It seems OK to explain the high brightness of SLSNe.

1D RHD simulation by Kasen&Bildsten (2010)

geometrically thin shell

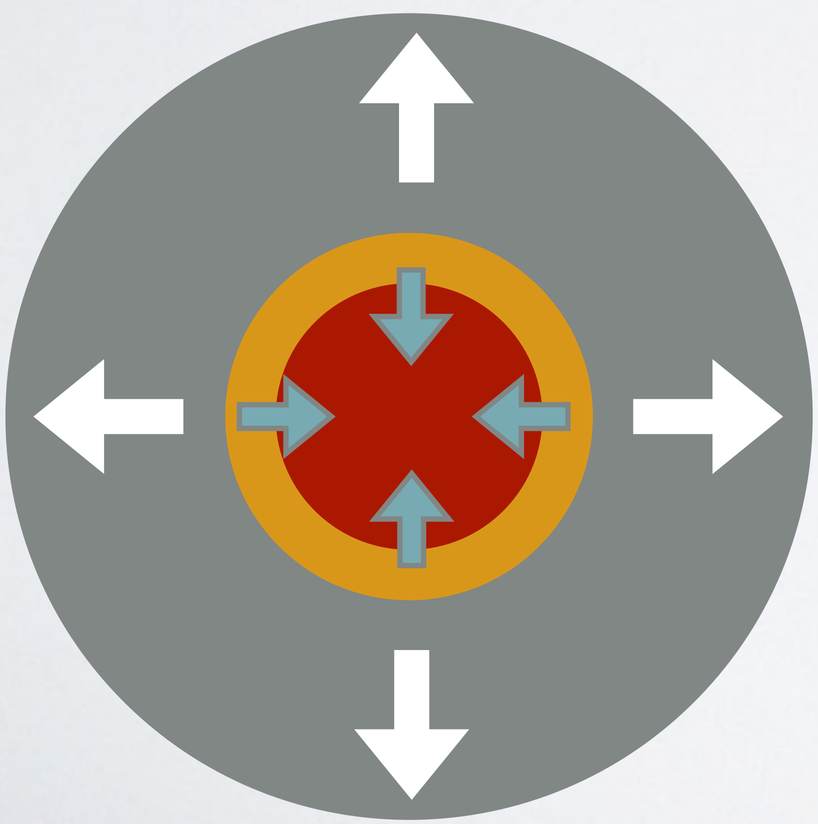
magnetar energy injection

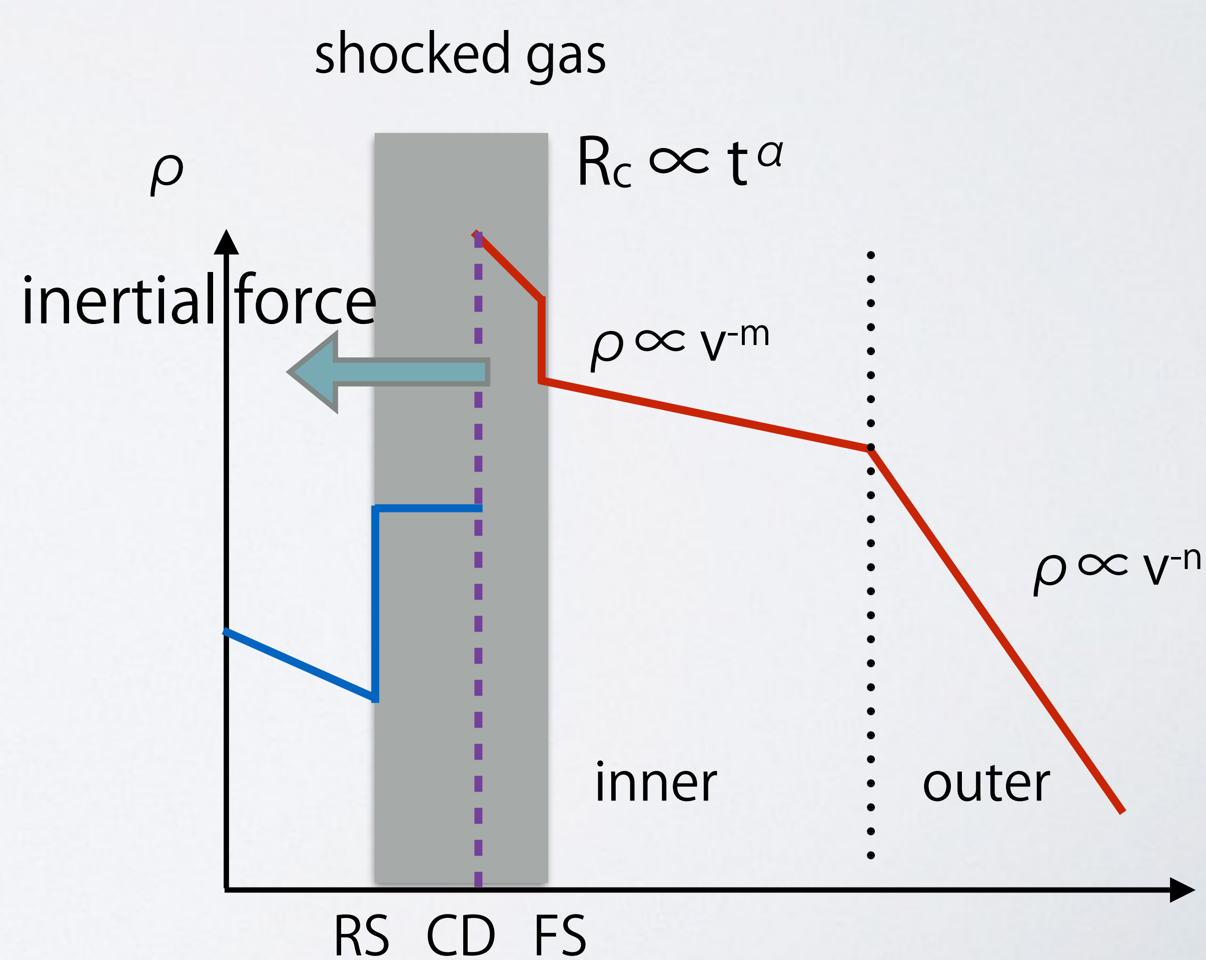




Q: Is 1D picture correct?

- No.
- From 1D analysis, we see that the shell is accelerating (α >1)
- an accelerating spherical shell is Rayleigh-Taylor unstable!
- more precisely, the unstable condition is "(dp/dr) x (d ρ /dr) <0"





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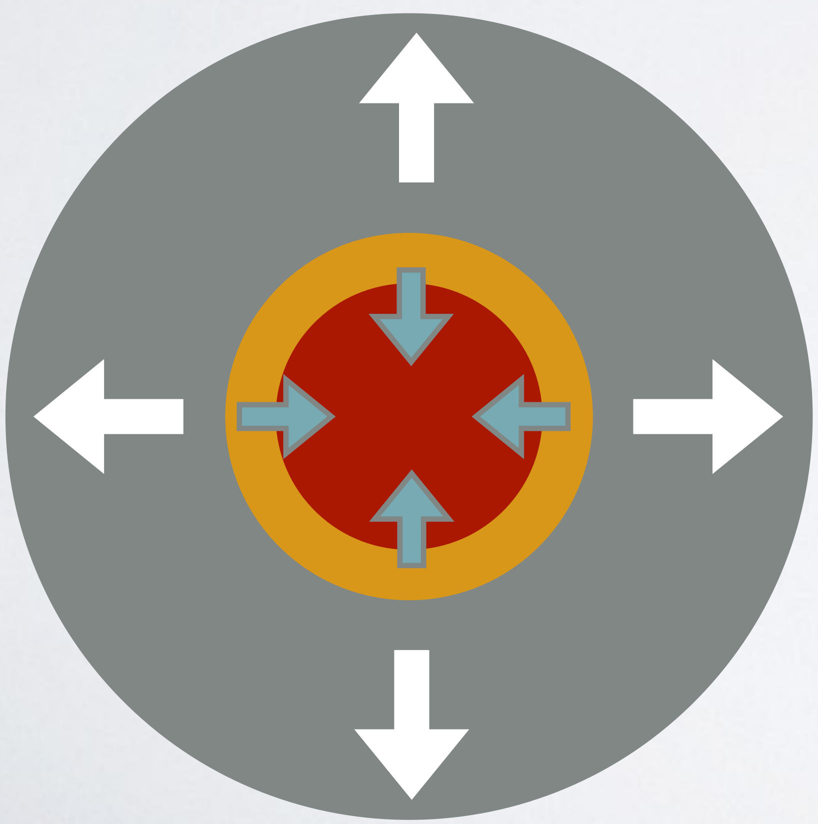
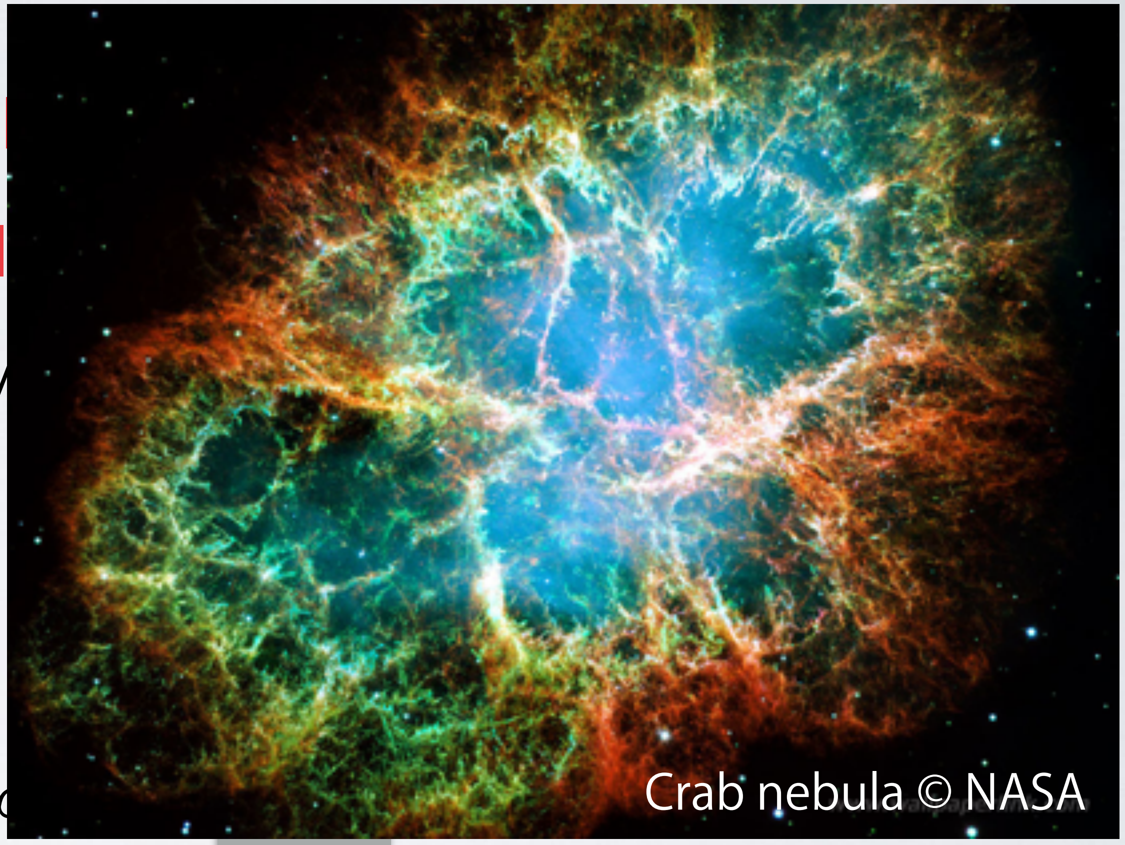
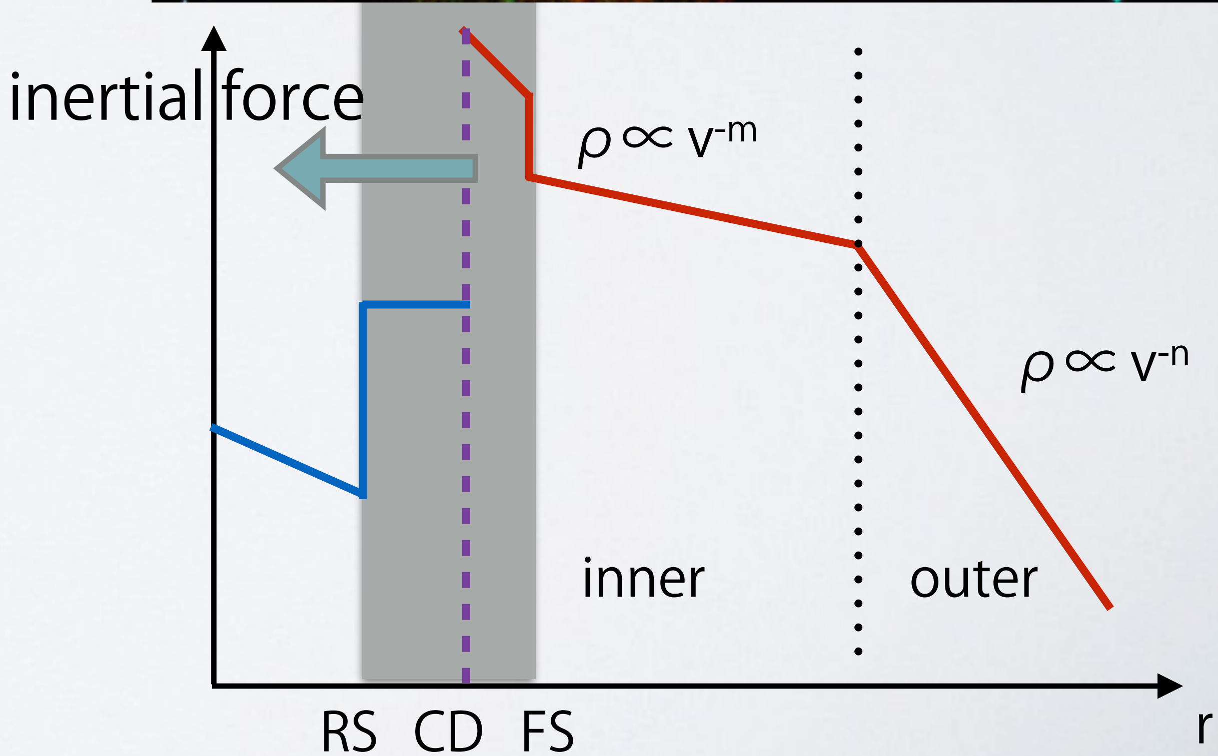




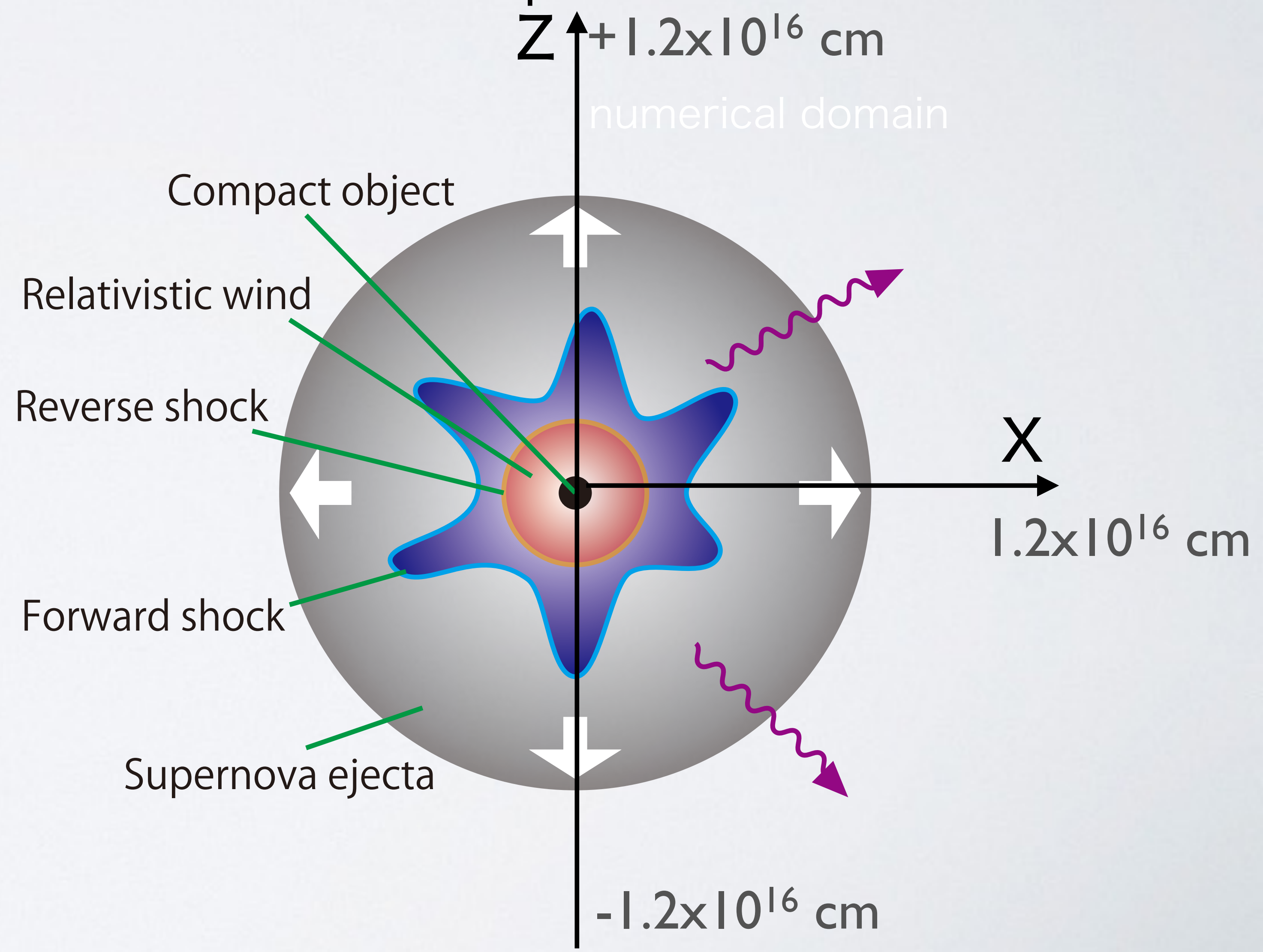


3D simulation (Suzuki&Maeda, in prep.)

cf. 2D cylindrical simulation (Suzuki&Maeda 2017)

- cartesian coordinate (x,y,z)
- x,y,z in [0,1.2x10^{16} cm]
- AMR technique.
- ideal gas law γ =4/3
- relativistic gas injection within 3x10^{12} [cm] : L=10^{46} [erg/s] up to 10^{52} [erg]
- dM/dt=0.05L/c^2

- SN ejecta with 10[$M_\odot$] and 10^{51} [erg]
- unit time t_c=E_{sn}/L = 10^5sec
- from t=0.1t_c up to t=20.0t_c



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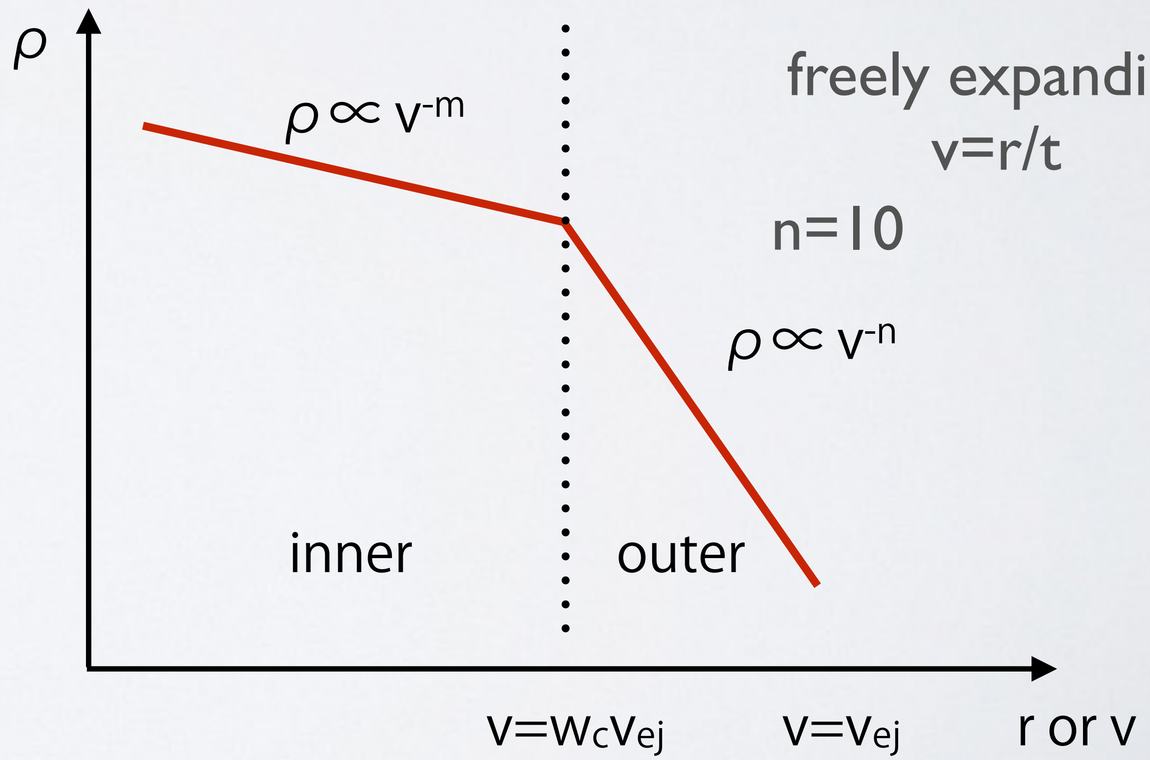

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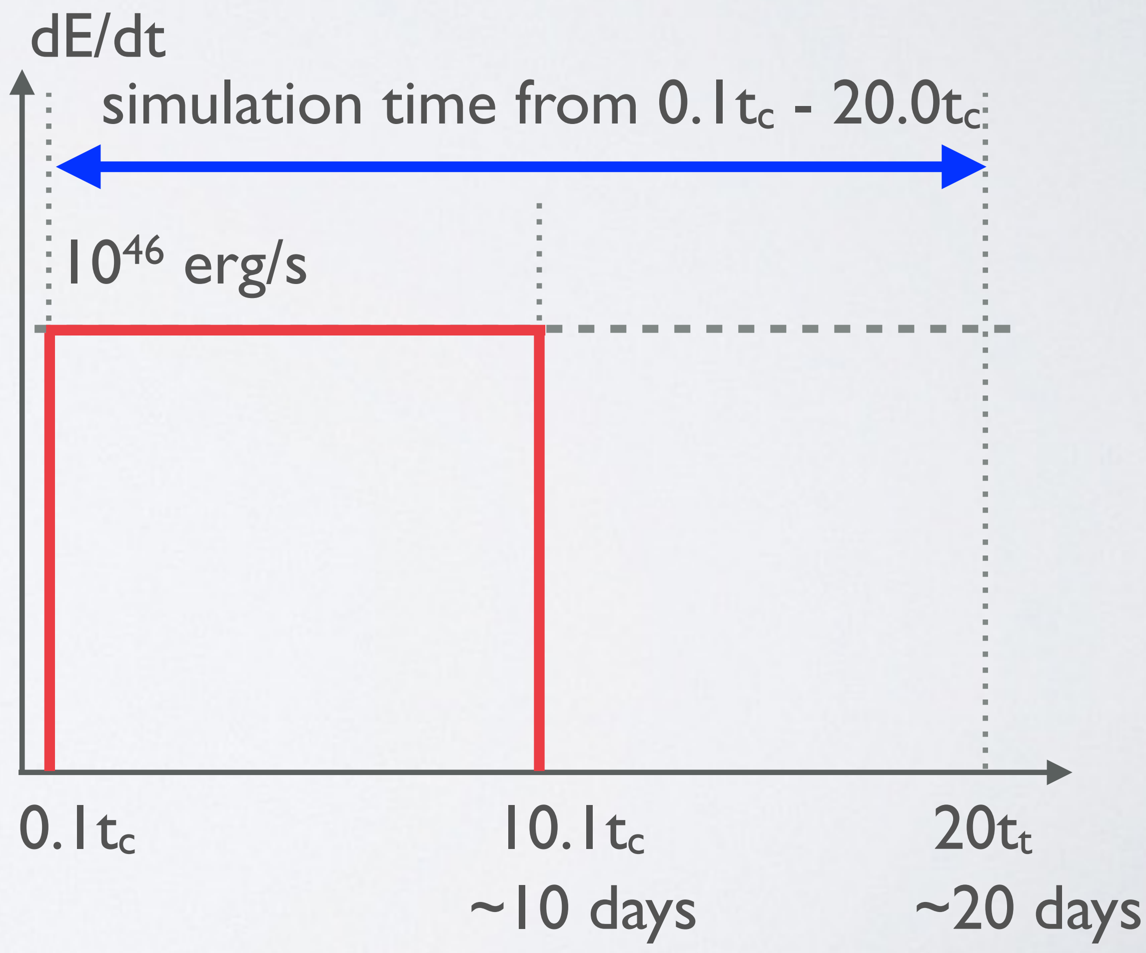

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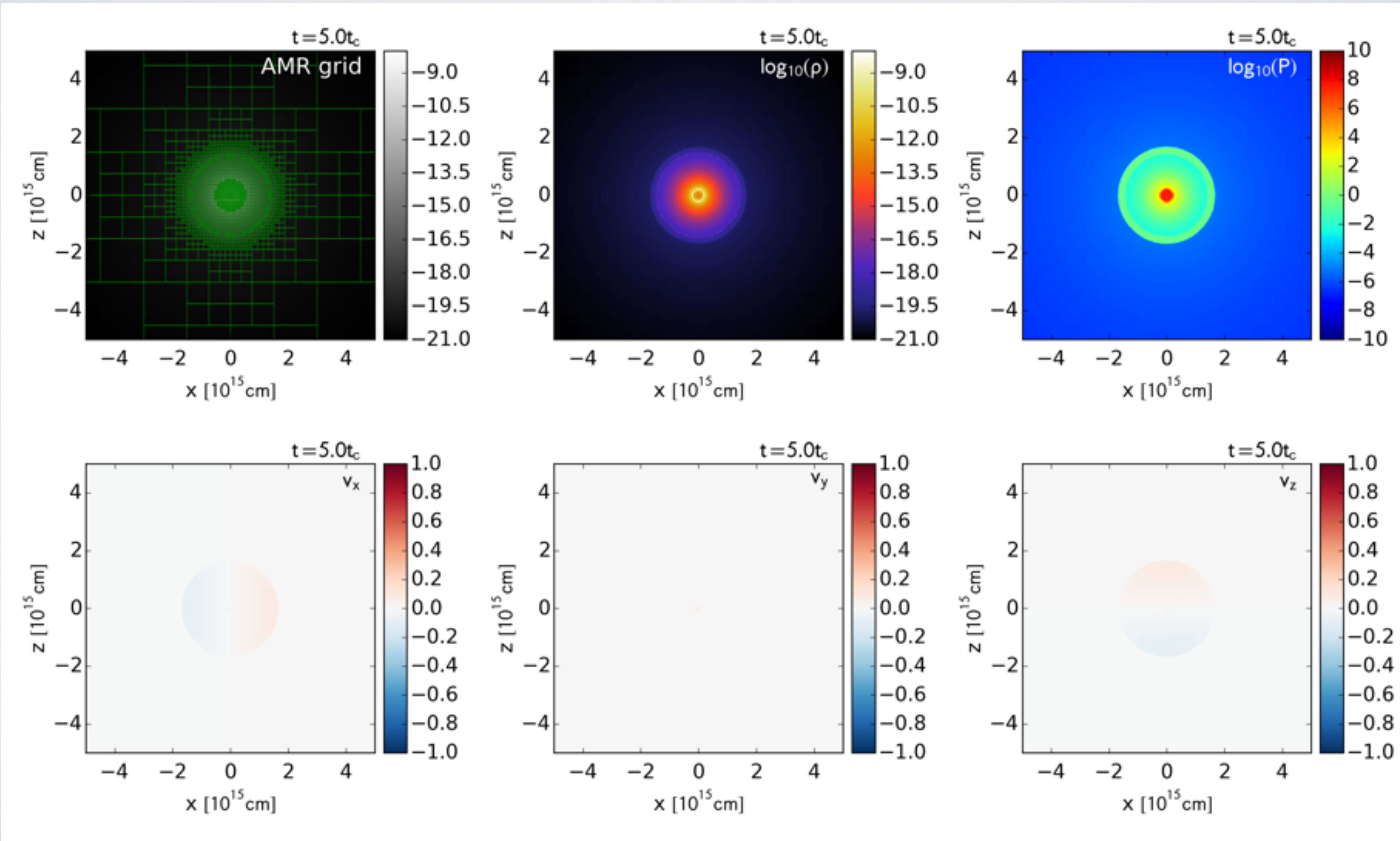

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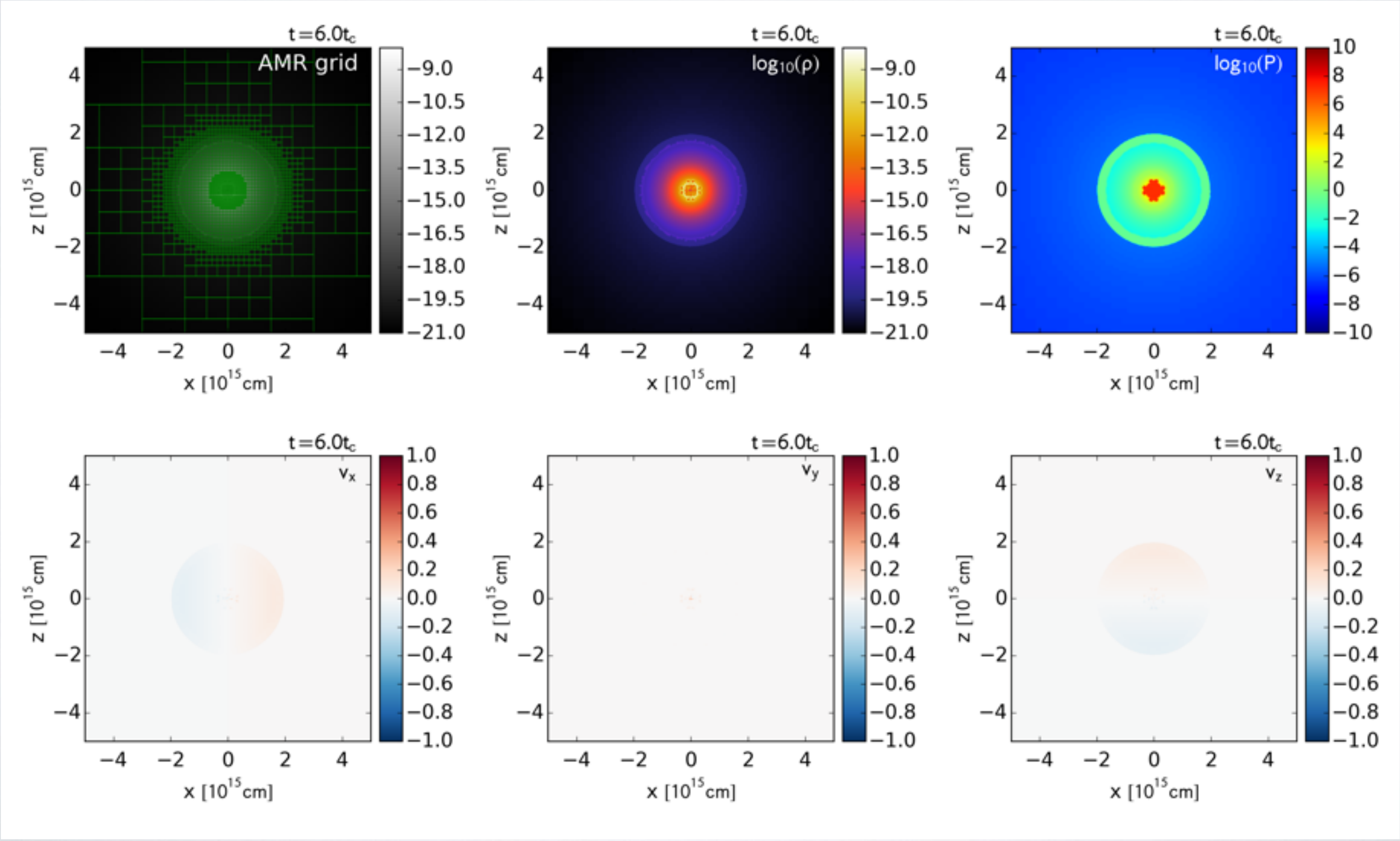

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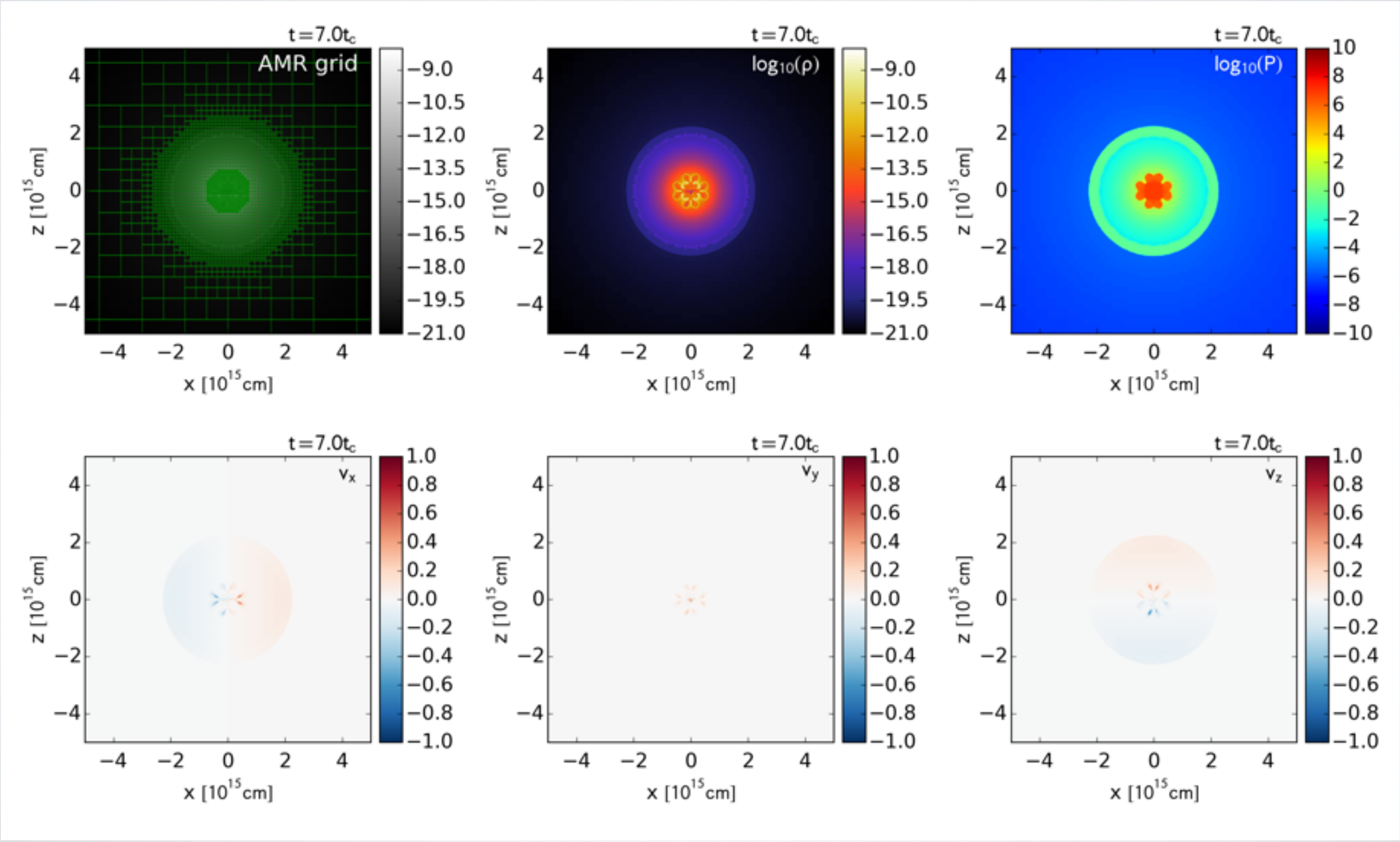

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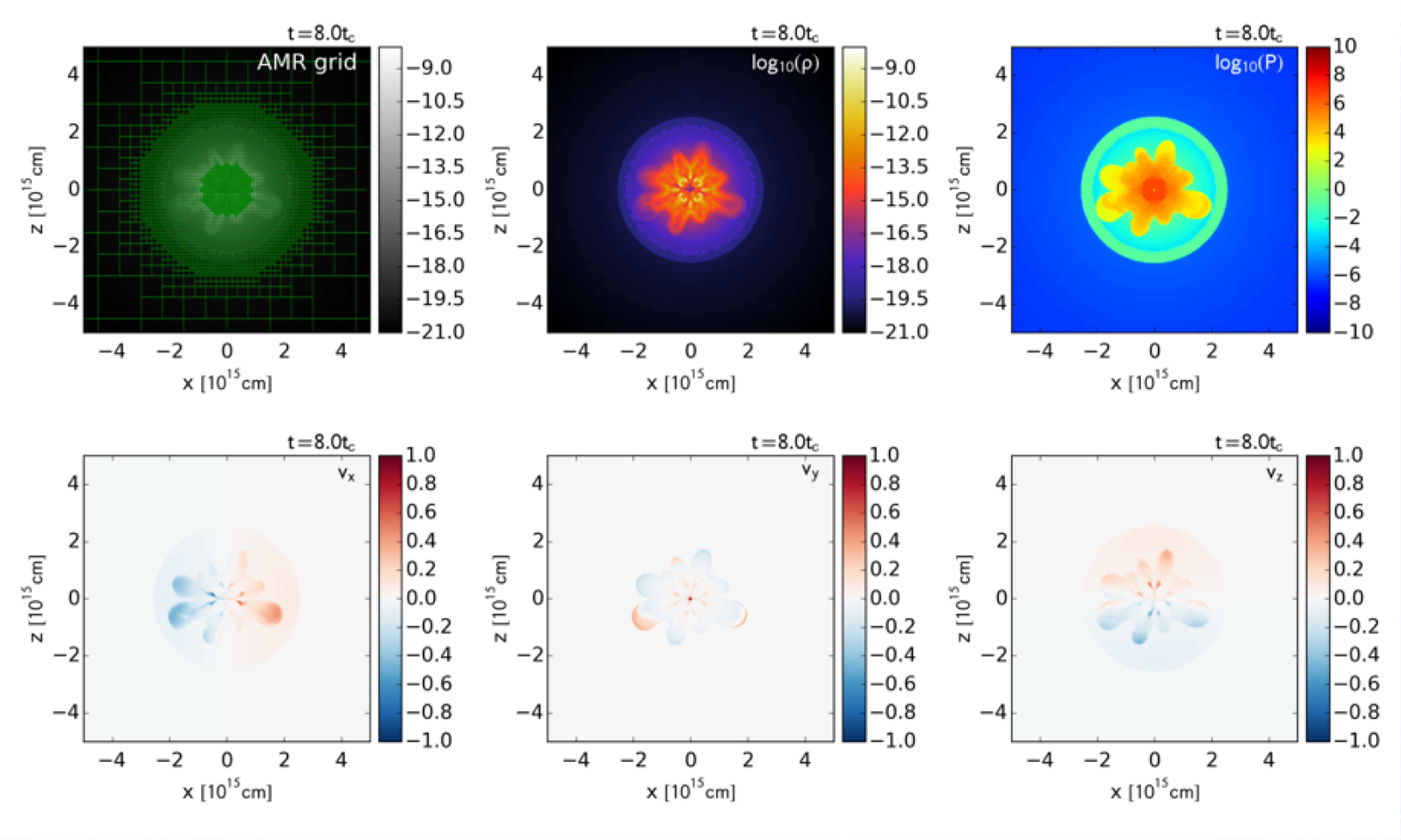

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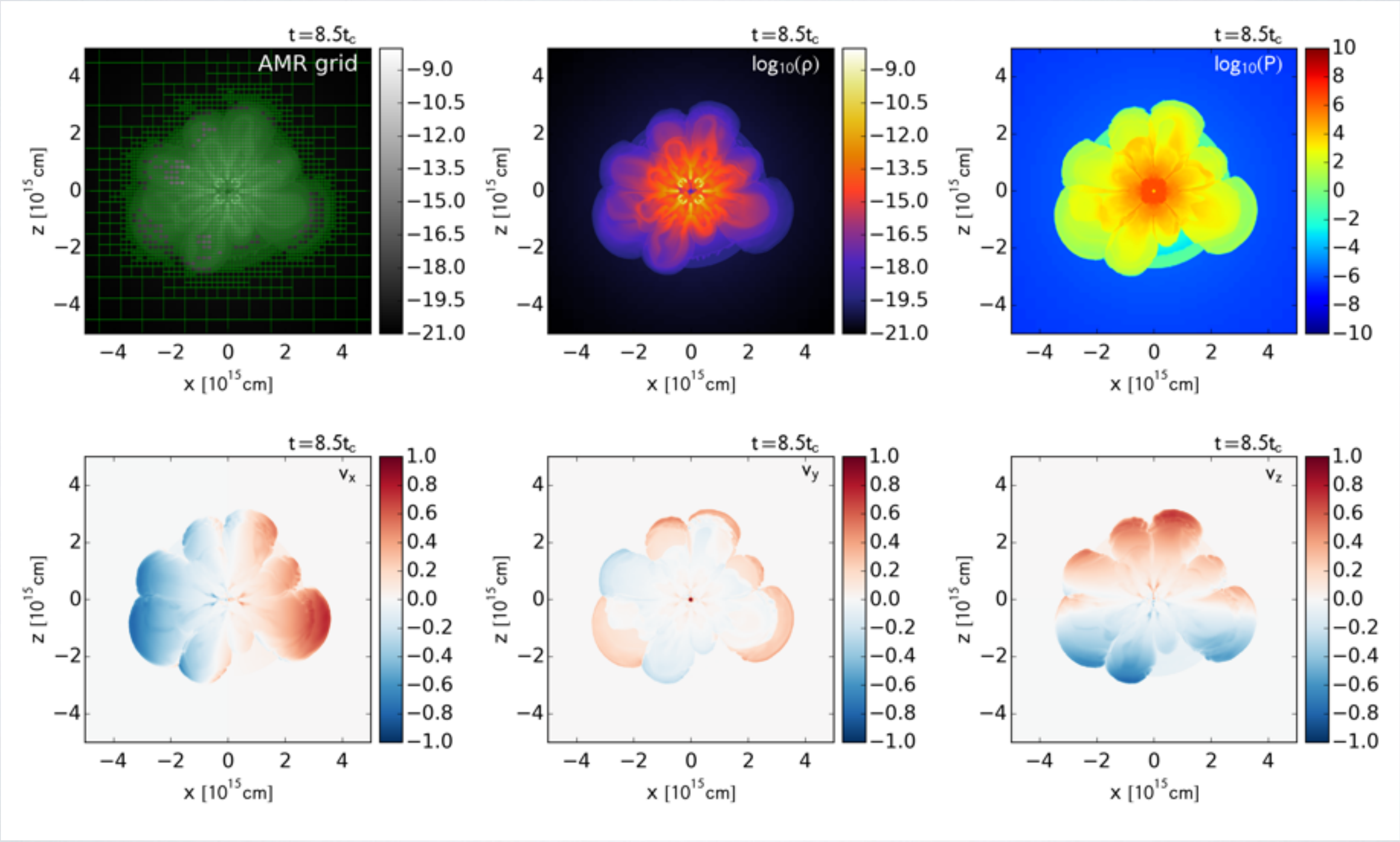

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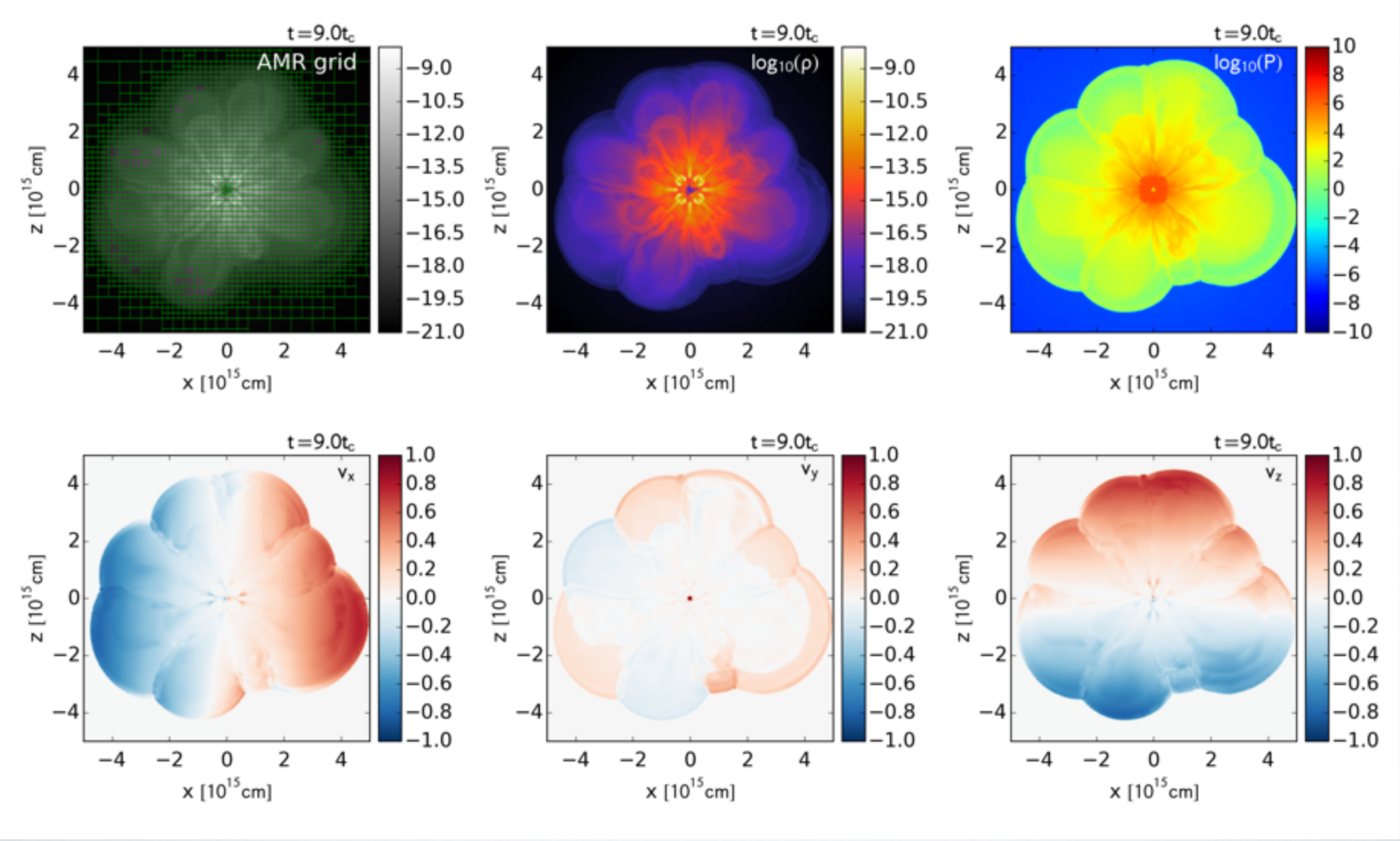

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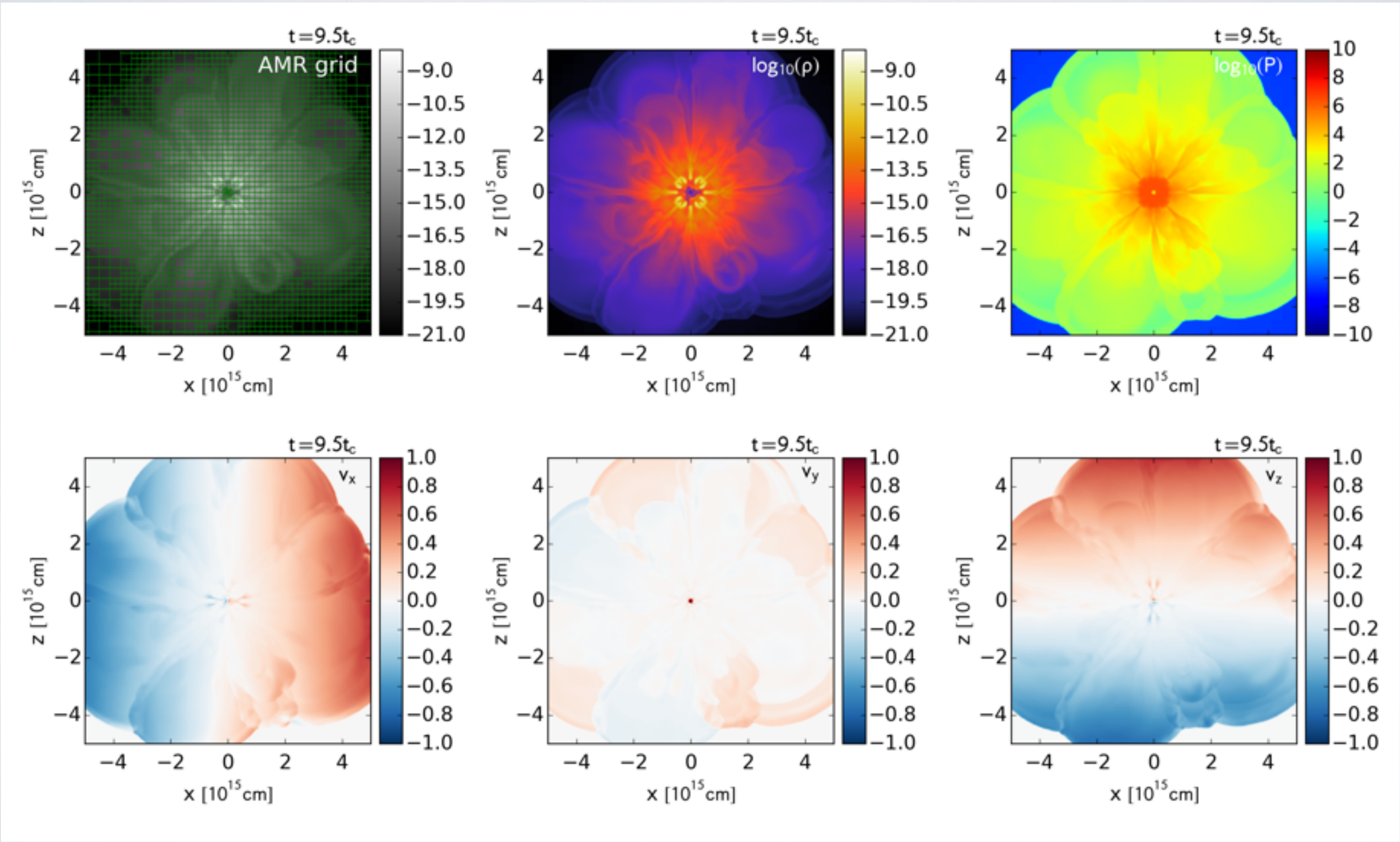

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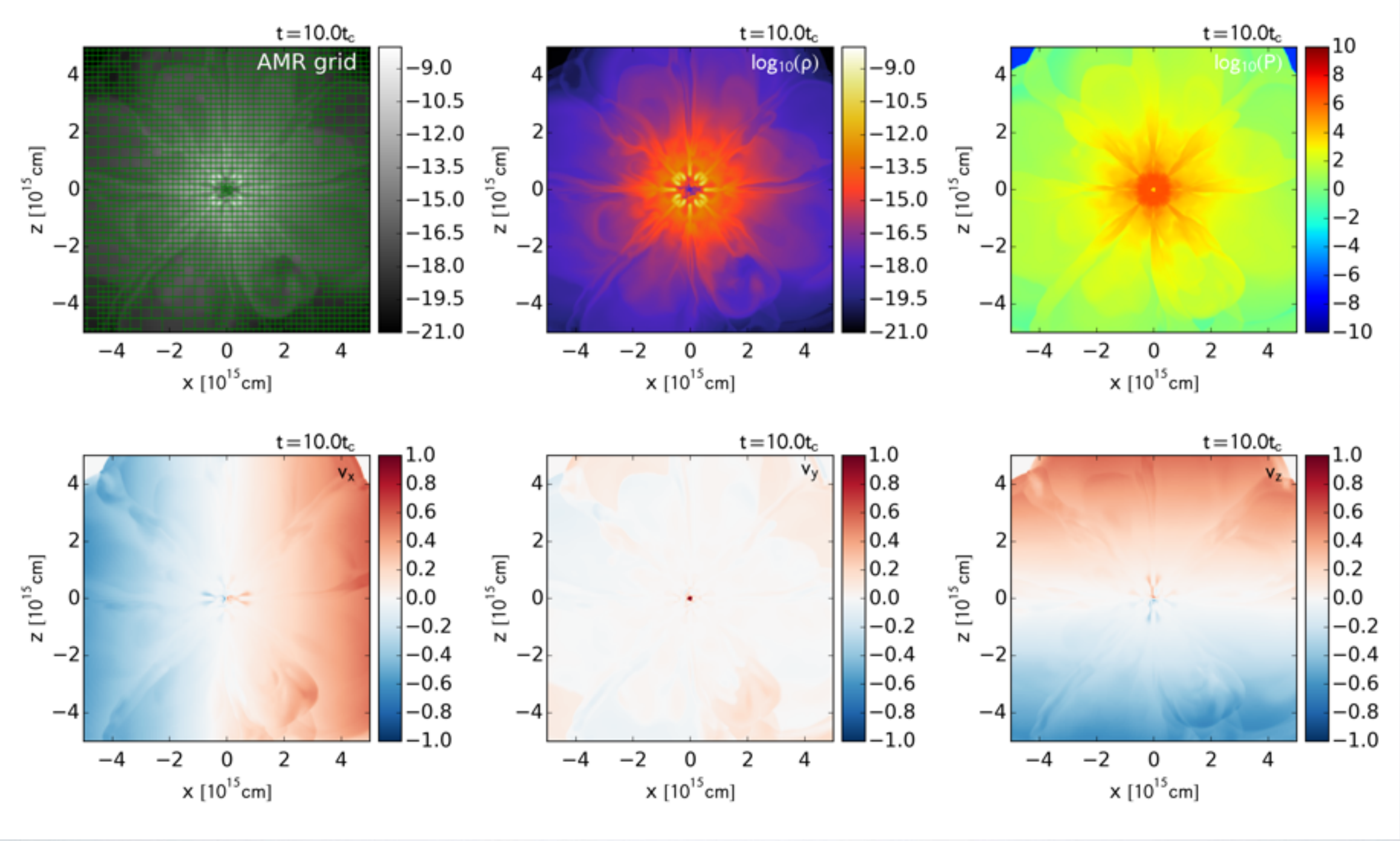
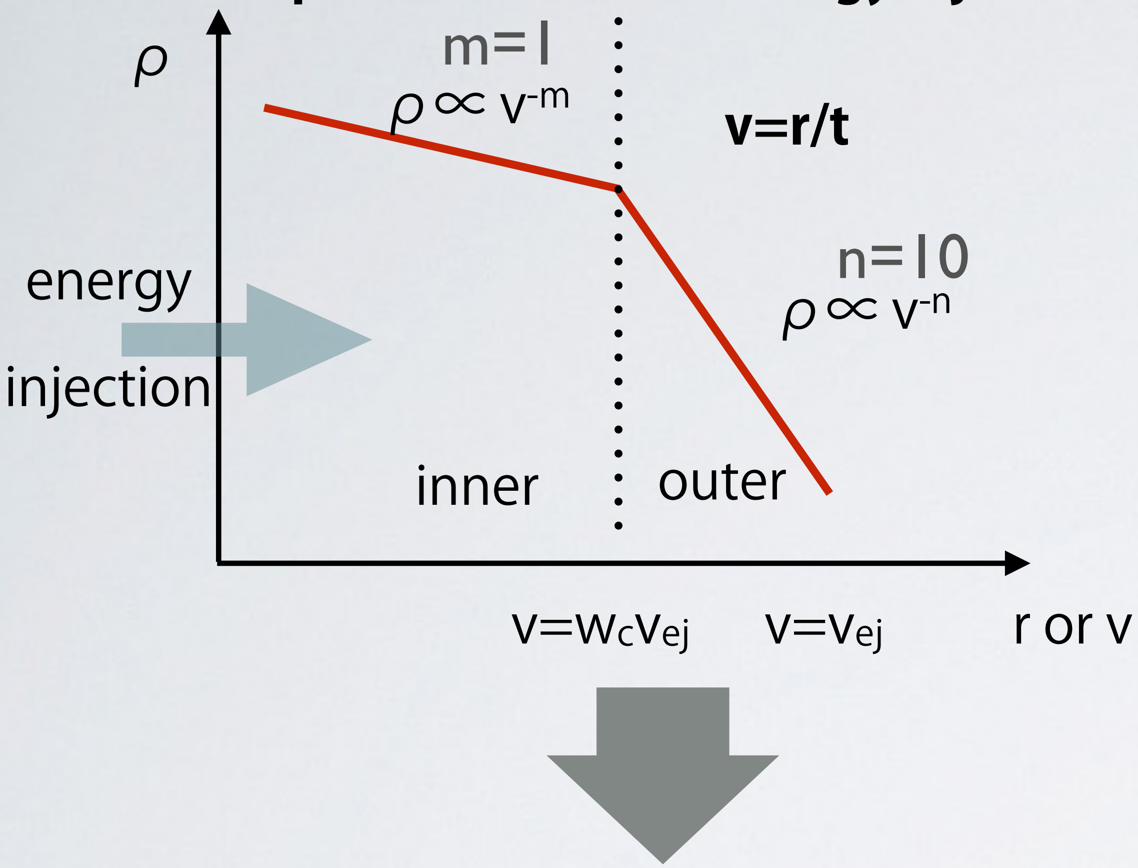


Density structure

radial profiles at t=20t$_c$

Free expansion "before" energy injection



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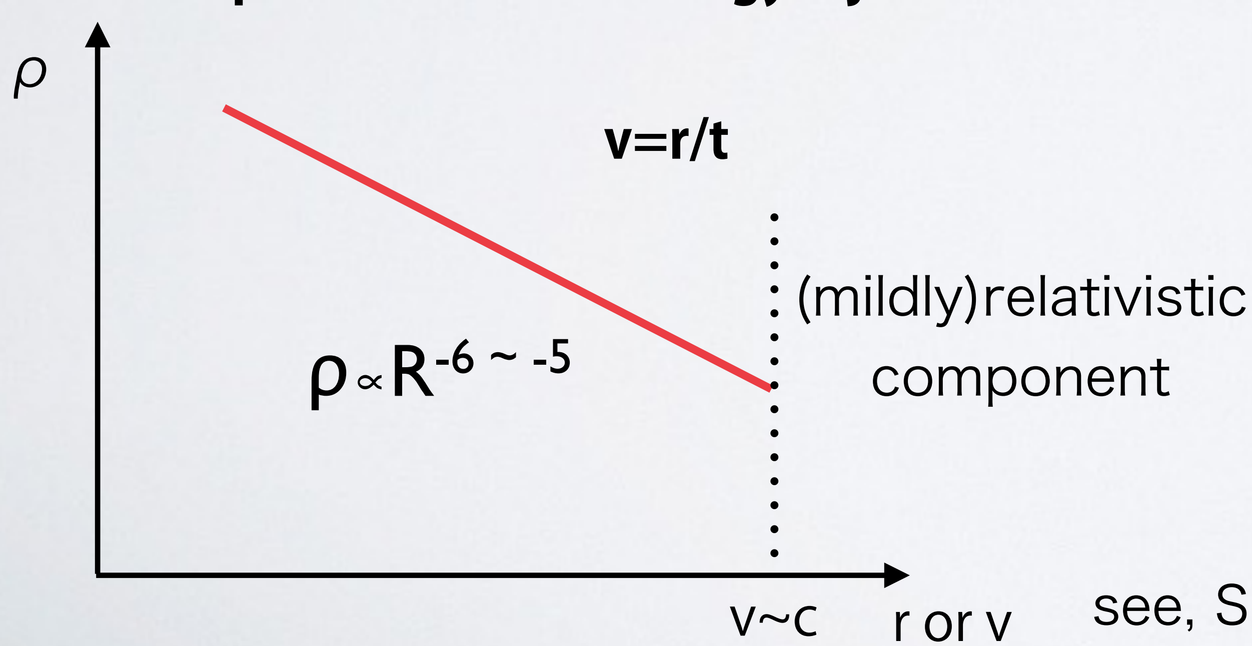
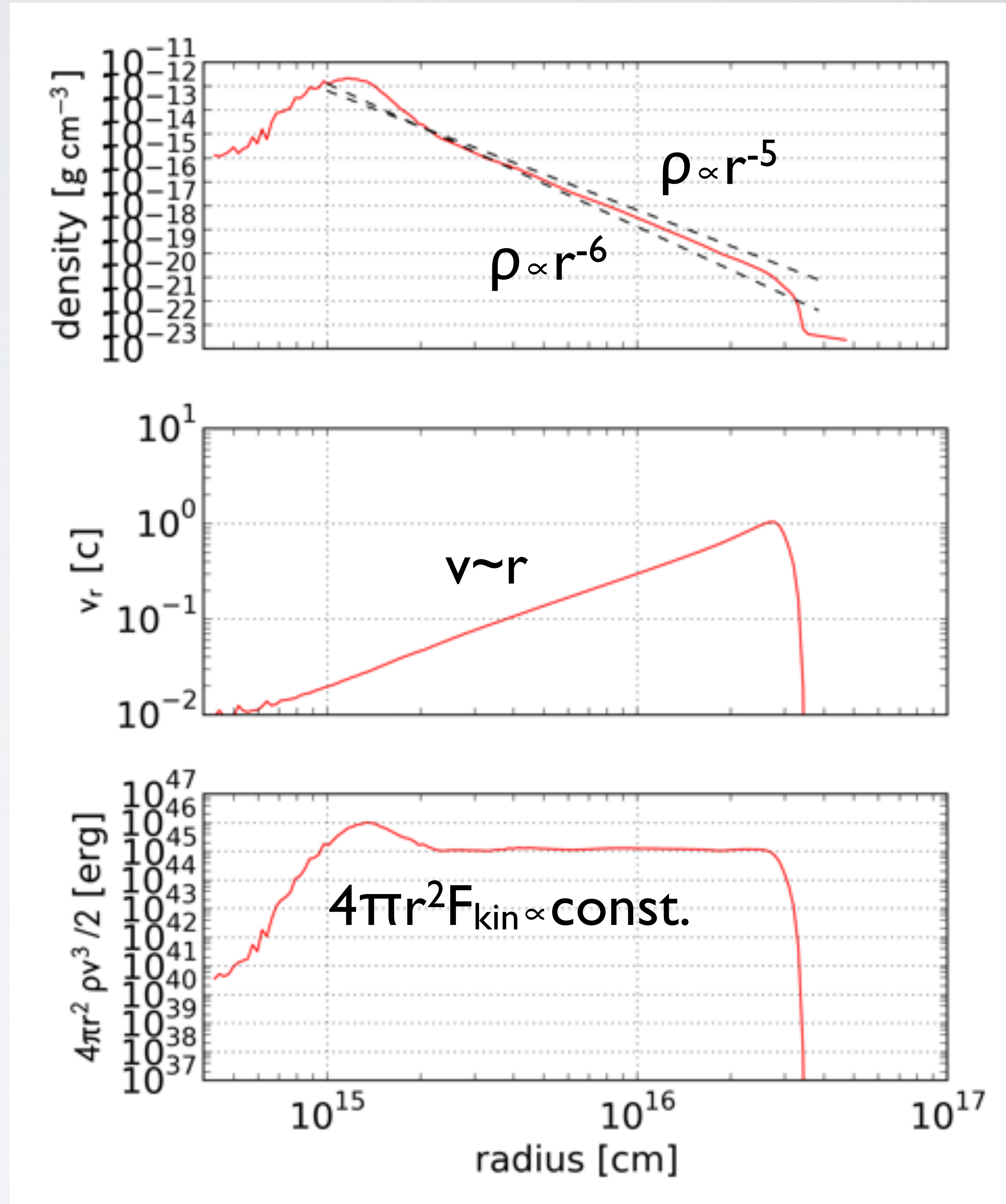
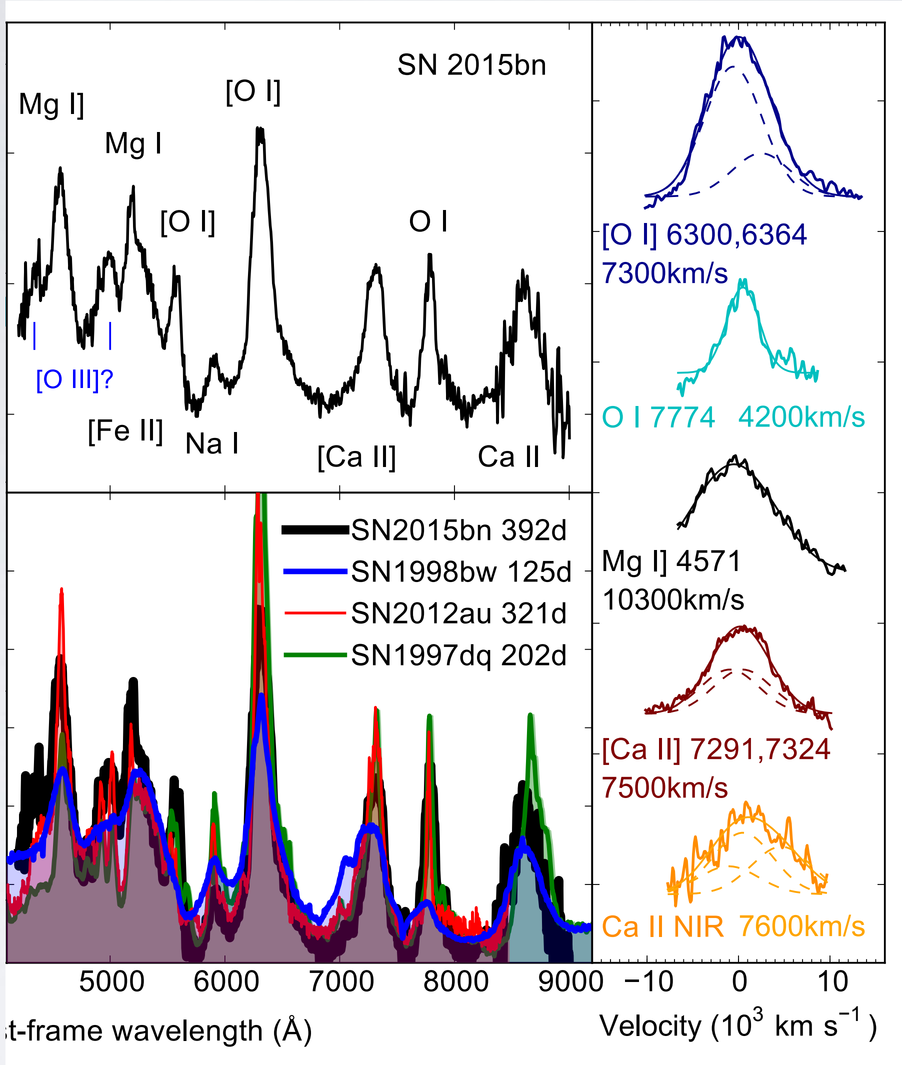




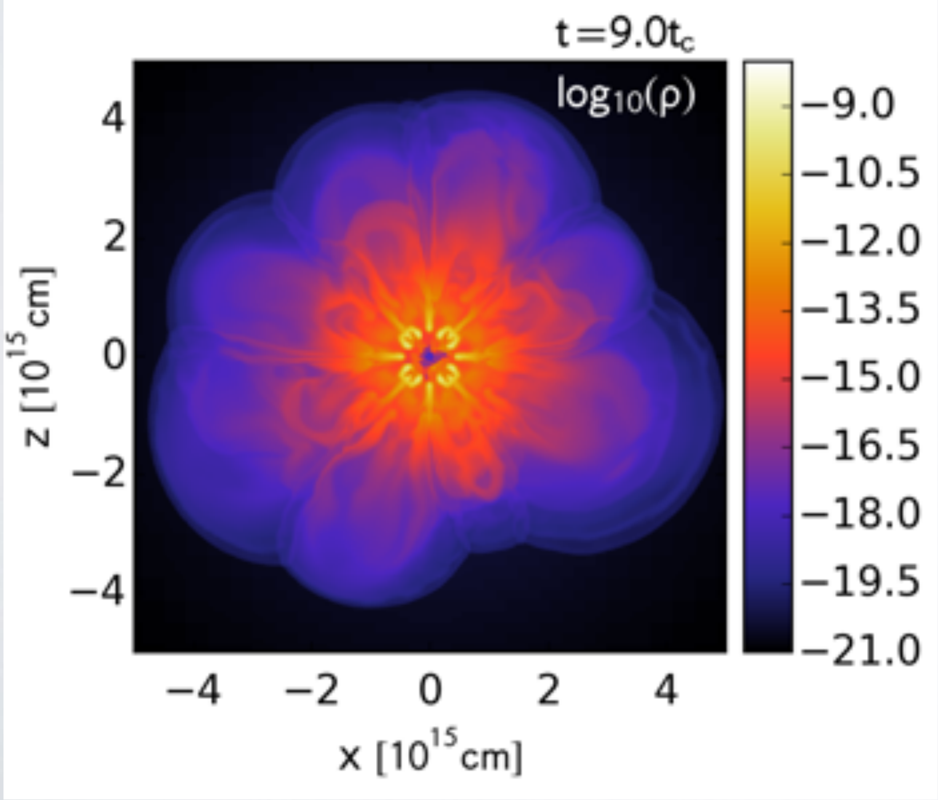
see, Suzuki&Maeda (2017)

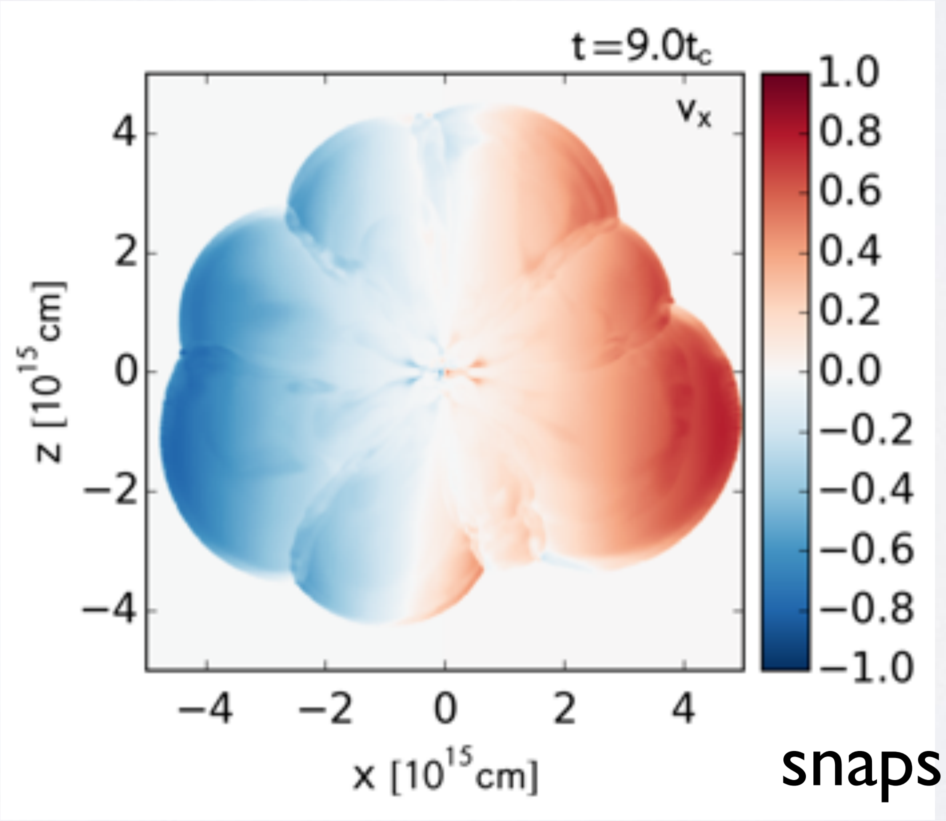
Density structure

- shredding by hot bubble breakout
- efficient matter mixing + high photospheric velocity
- broad-line feature in optical spectrum(?)
- $\rho \propto v^{-7}$ is favored for SLSNe-I (Mazzali+2016)



Nicholl+ (2016)





?

今後、可視光
スペクトルを計算

snapshot at $t=9t_c\sim9$ days

Summary: central-engine SNe in multi-D

- Dynamical evolution of SN ejecta + additional energy injection is multi-dimensional
- Hot bubble breakout leads to violent mixing (+ precursor?)
- final radial density structure of the ejecta is a simple power-law function
- we have started 3D simulations and confirmed the picture