超高輝度超新星の中心エンジンモデル

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

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)

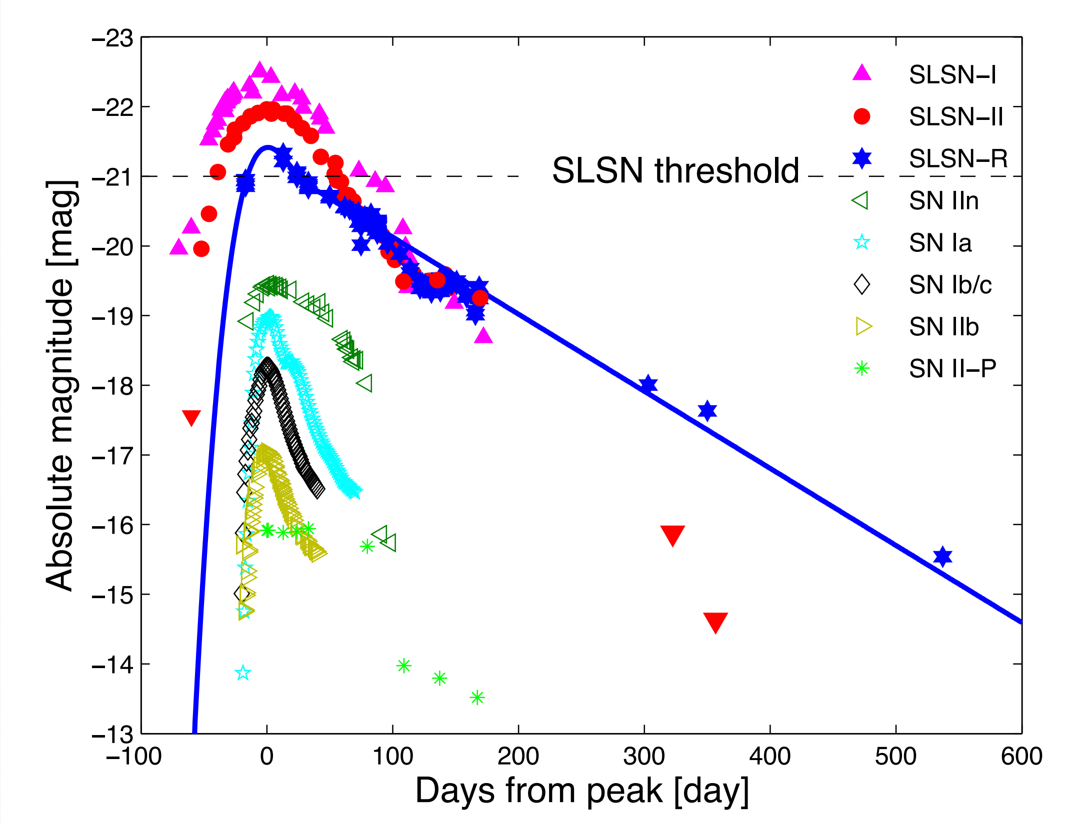
- They are found by recent “unbiased” transient survey projects (e.g., Palomar transient factory, Pan-STARRS).

- 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., 3$M_\odot$ Ni for SN 2007bi)

- Total radiated energy can be ~ 10^{51} [erg]

  (~ explosion energy of normal CCSNe)

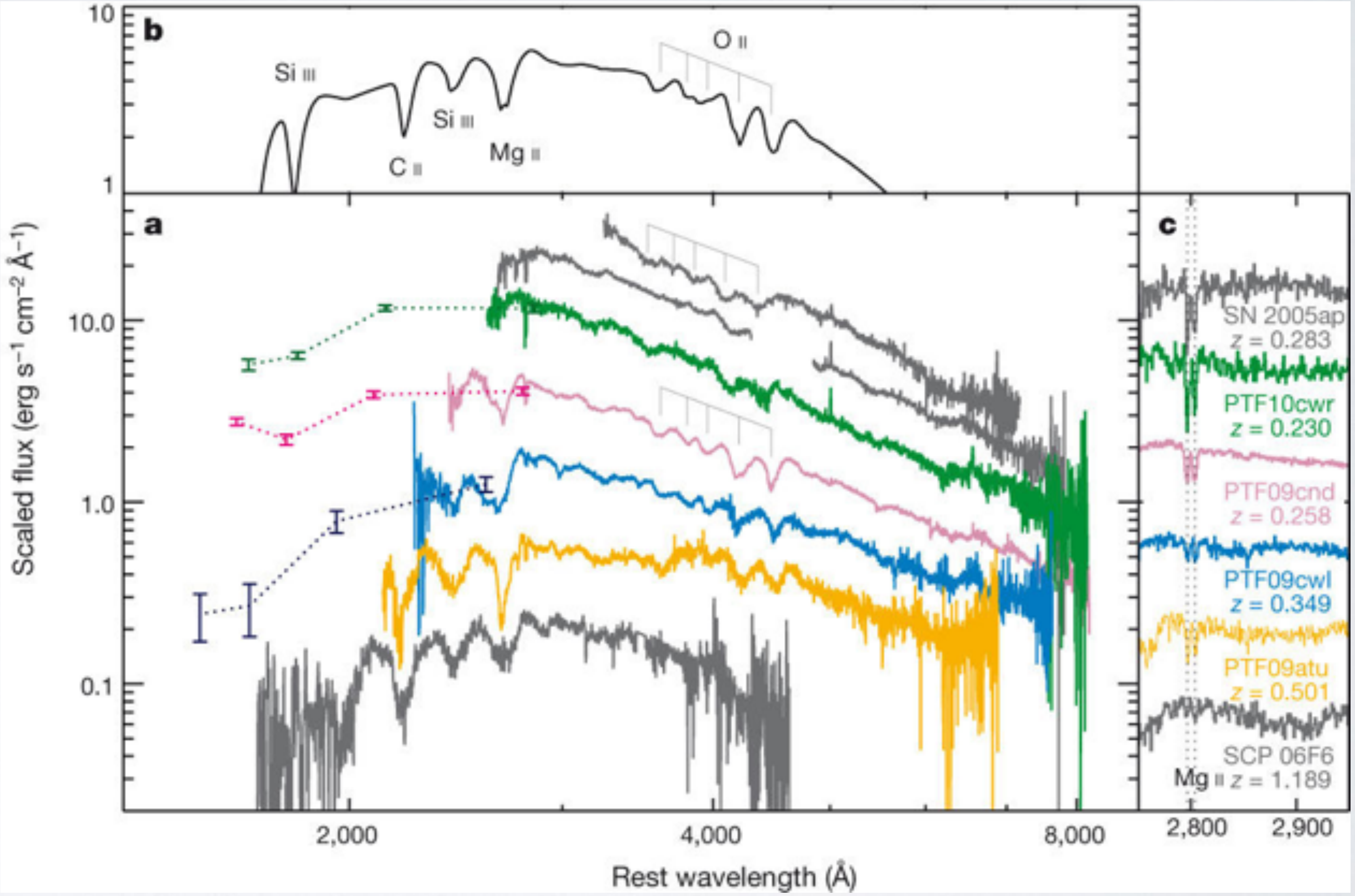


What is the origin of SLSNe-I?

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

Early-time spectra

- blue continuum
- broad-line
- “w”-shape spectral feature (by [OII])

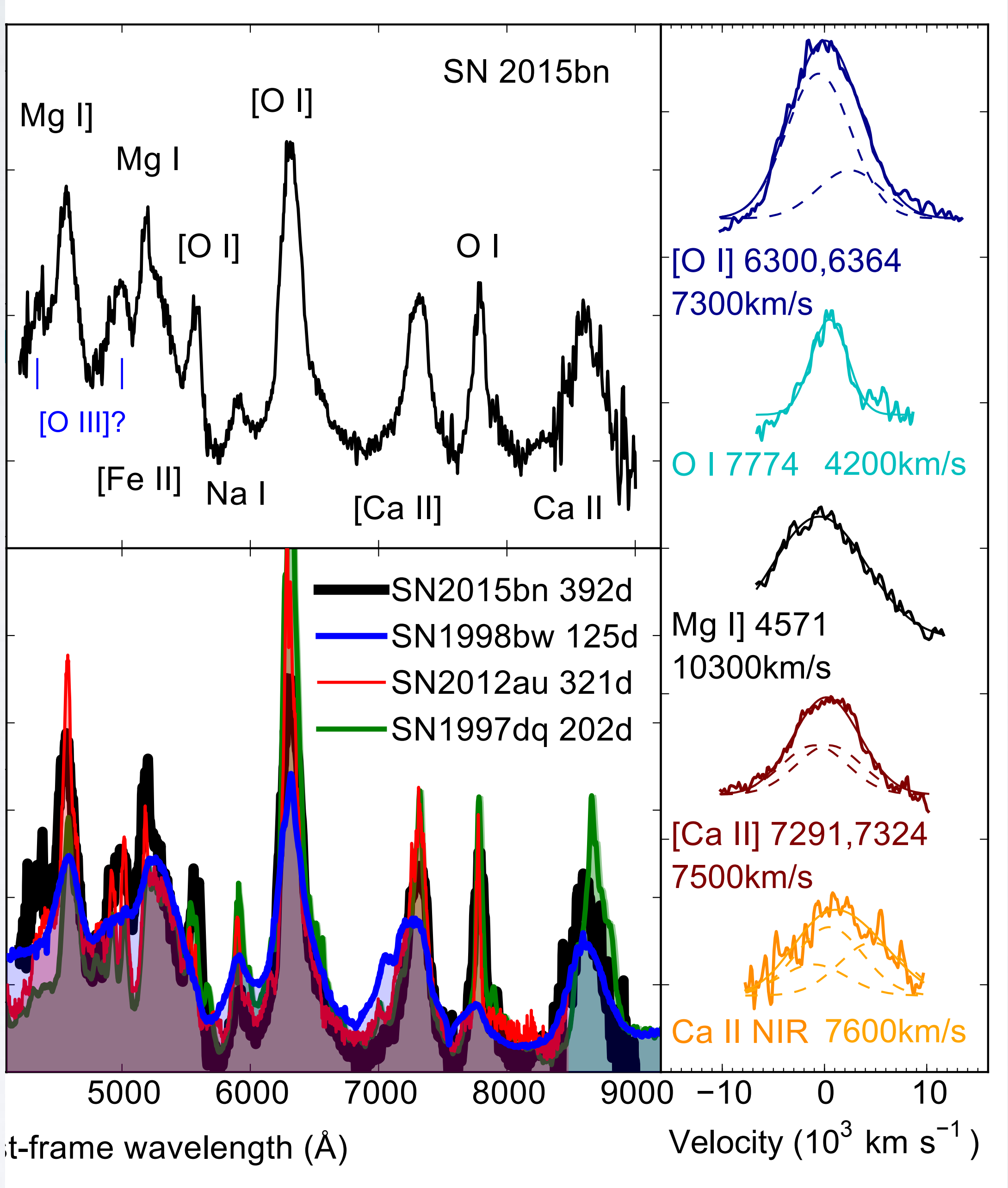


↑SLSNe-I spectra (Quimby+ 2011)

Late-time spectra

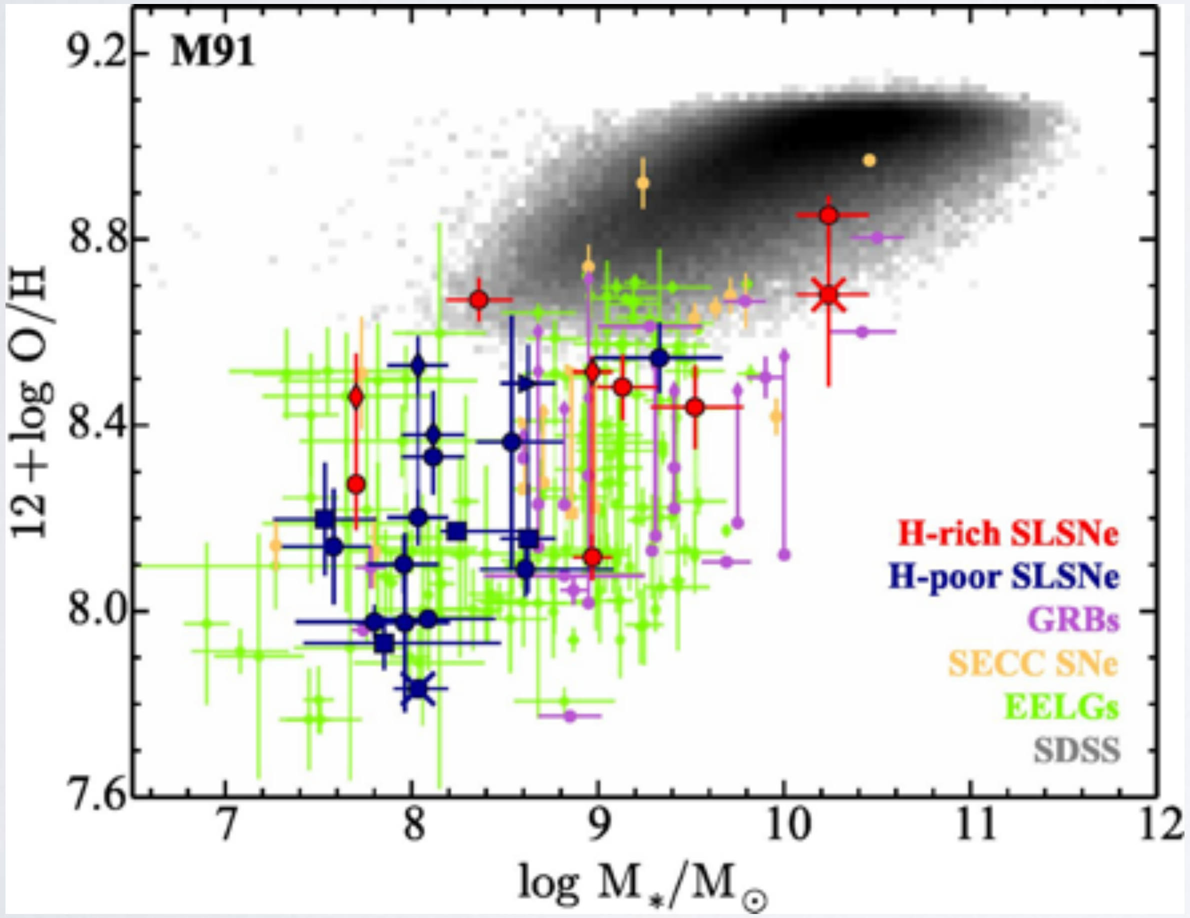
- Late-time spectra of SNe are dominated by nebular lines
- ionization of elements by radioactive decay
- Nebular spectrum of SLSNe-I 2015bn similar to broad-lined Ic SNe? → severe line-blending
- a possible link between Ic-BL SNe and SLSNe-I?

Nicholl+ (2016)

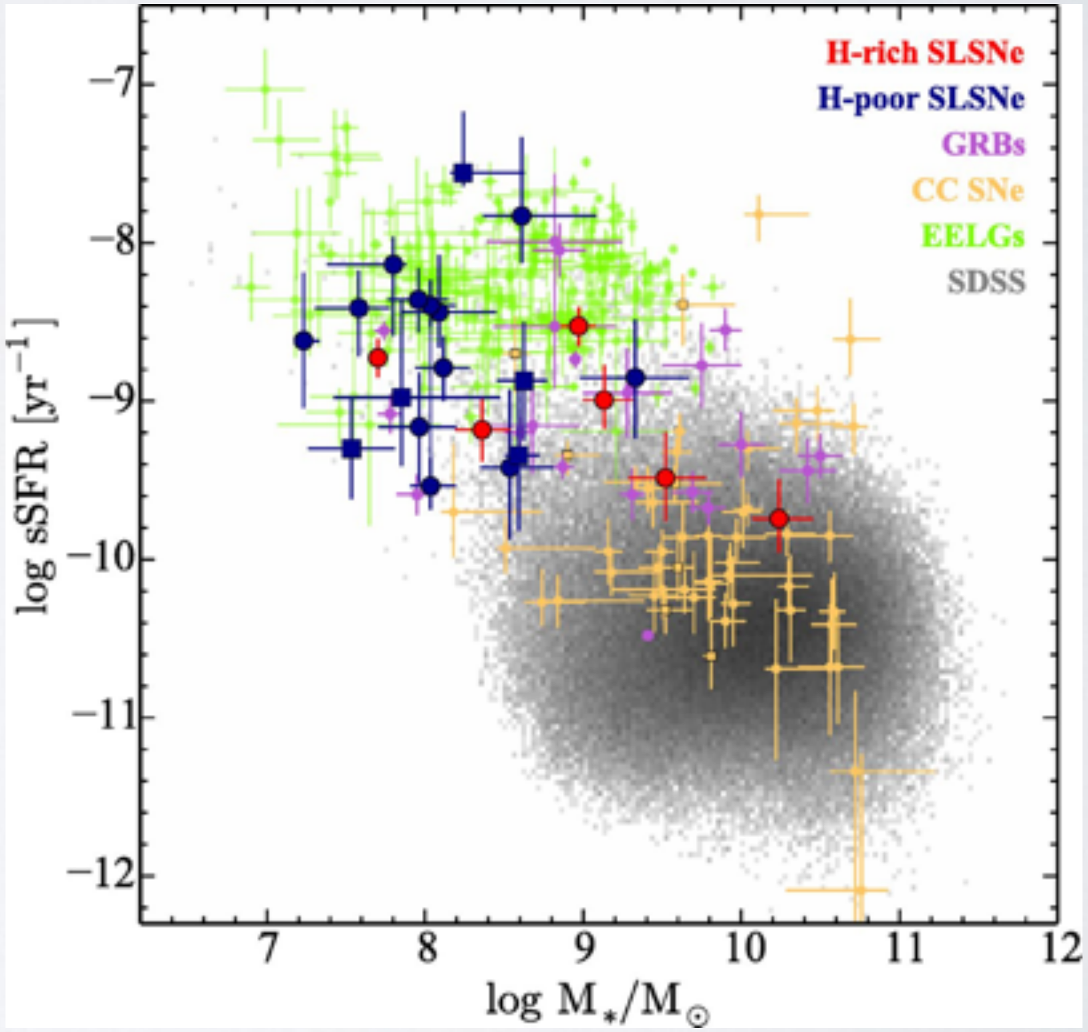


Host galaxy demographics

- star-forming dwarf galaxy (small stellar mass)
- high specific star formation rates (SFR/M★)
- low metallicity
- host galaxies of Ic-BL SNe and SLSNe-I are similar



↑stellar mass M★ vs metallicity (Leloudas+ 2015)

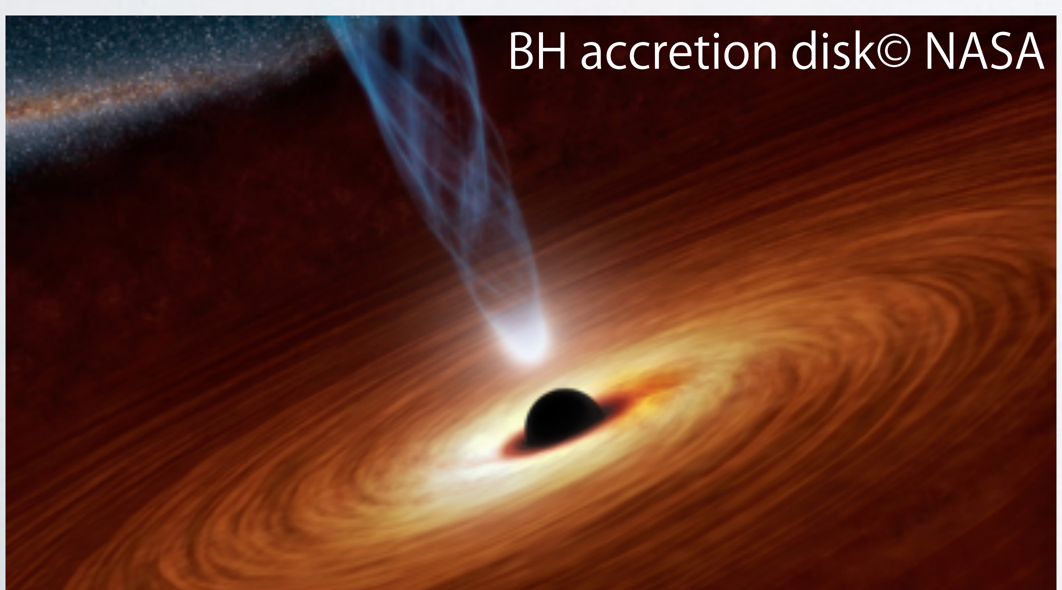


↑stellar mass M★ vs sSFR (Leloudas+ 2015)

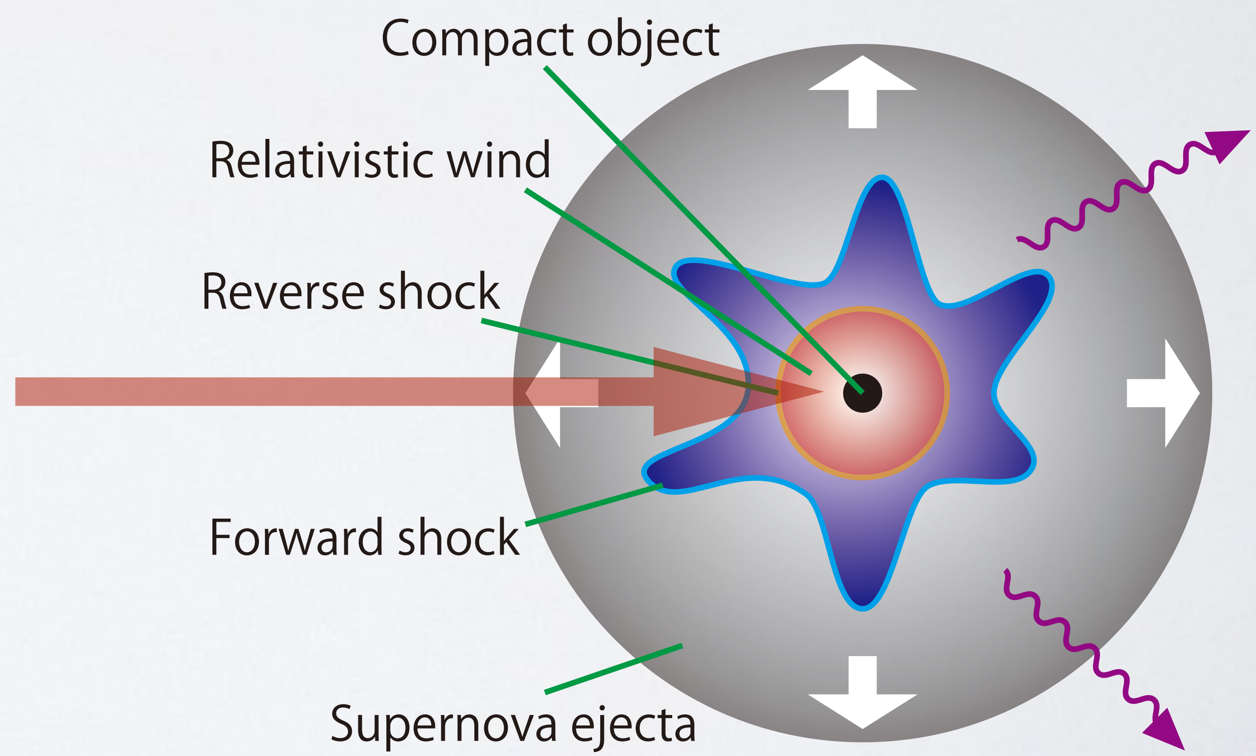
Proposed models and progenitors for SLSNe

- CSM interaction
- pair-instability SNe (very massive progenitor with ~ 100-300M$_\odot$ 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)

Rotating Neutron Star© ESO



BH accretion disk© NASA



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.

$$\text{radius } R_{\rm ns} \sim 10\text{km}$$
$$\text{moment of inertia } I_{\rm ns} \sim 10^{45} \text{ g cm}^2$$
$$\text{initial period of } P_{\rm i} \sim 1 \text{ ms}$$
$$E_{\rm rot} = I_{\rm ns}\Omega_{\rm i}^2/2 \simeq 2 \times 10^{52} \text{ erg.}$$

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

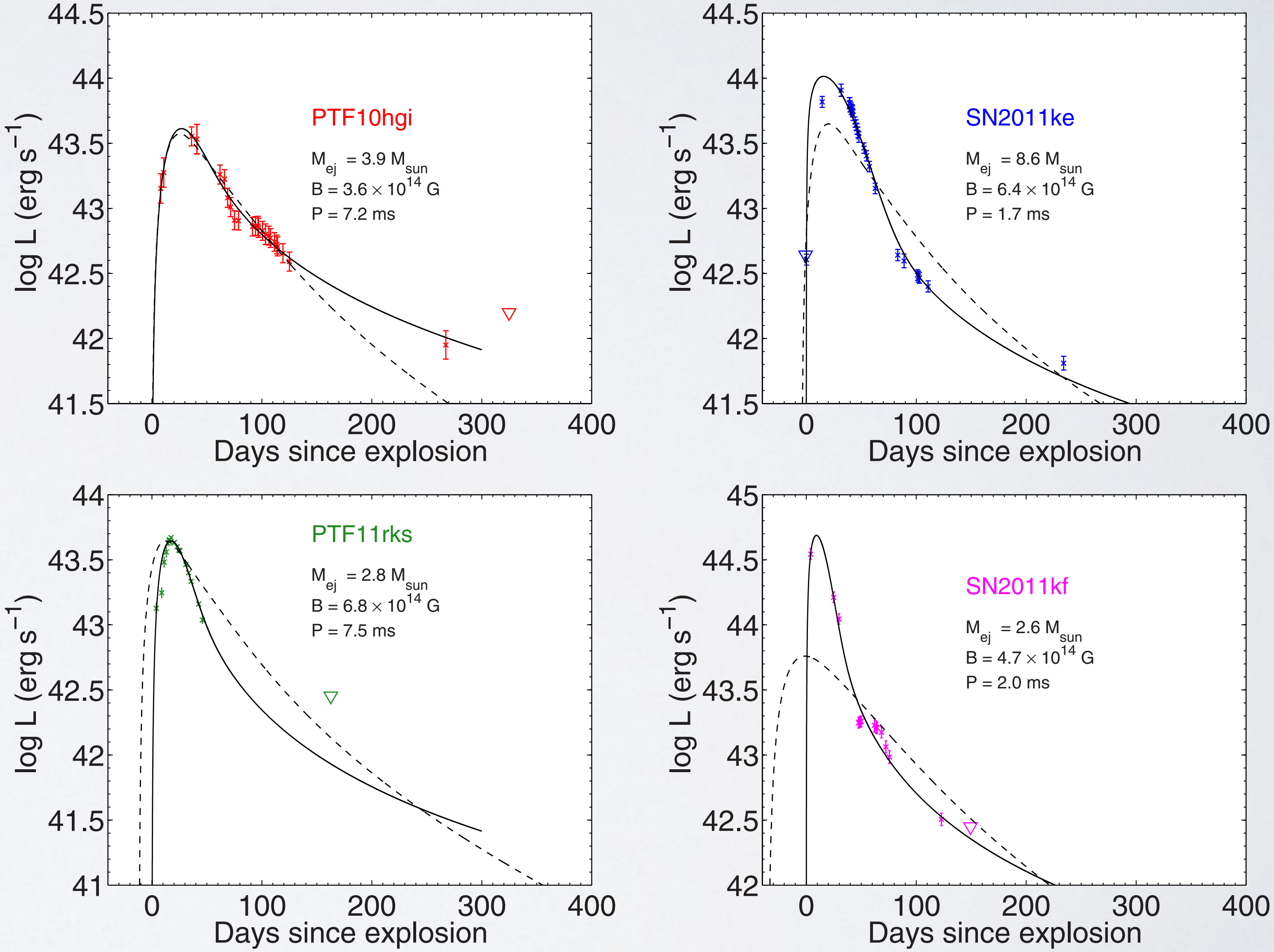
$$L = \frac{E_{\rm rot}/t_{\rm ch}}{(1+t/t_{\rm ch})^2}$$

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

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

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)

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- one-box light curve model for SNe with magnetar energy injection
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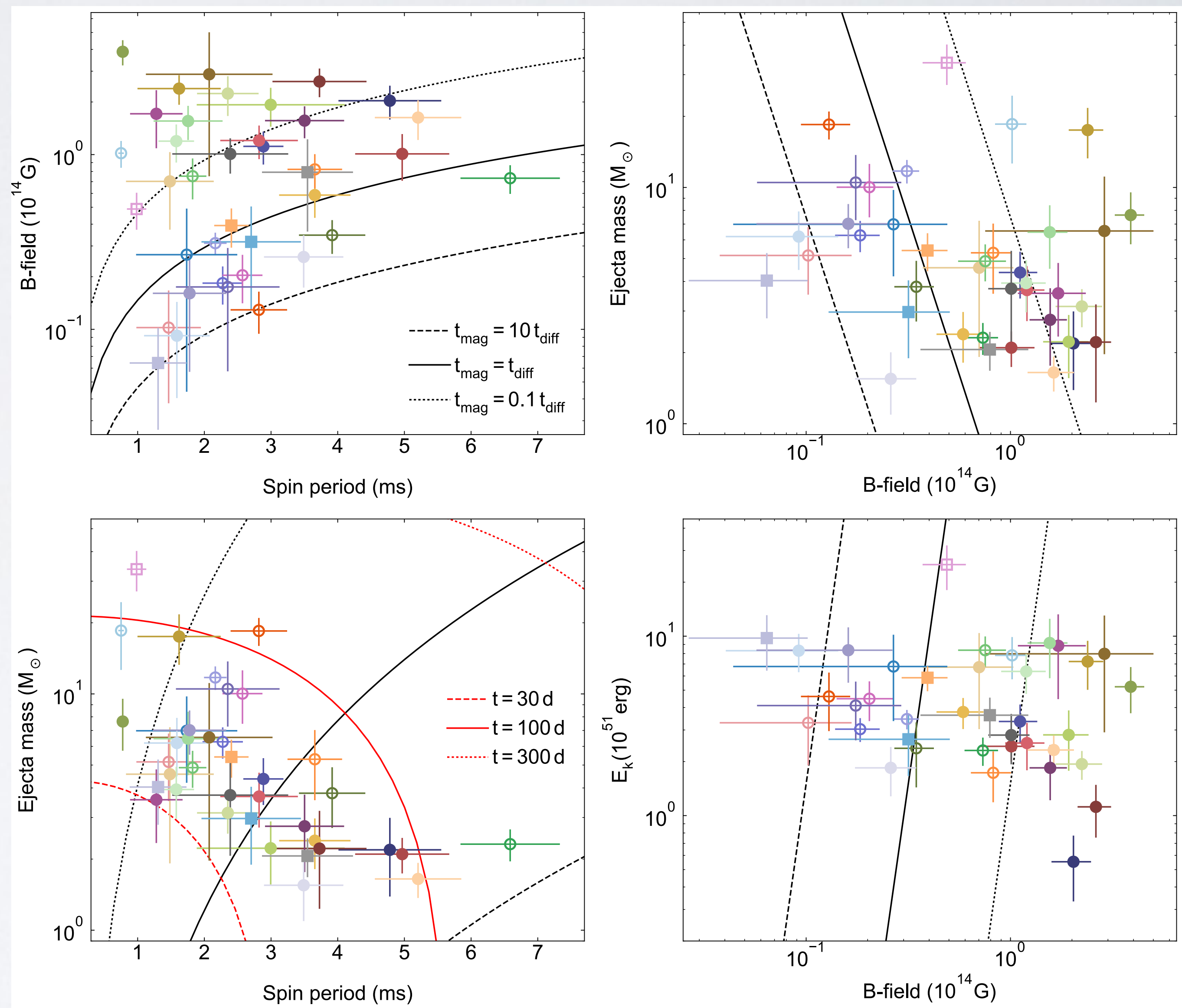
- Magnetar fit :



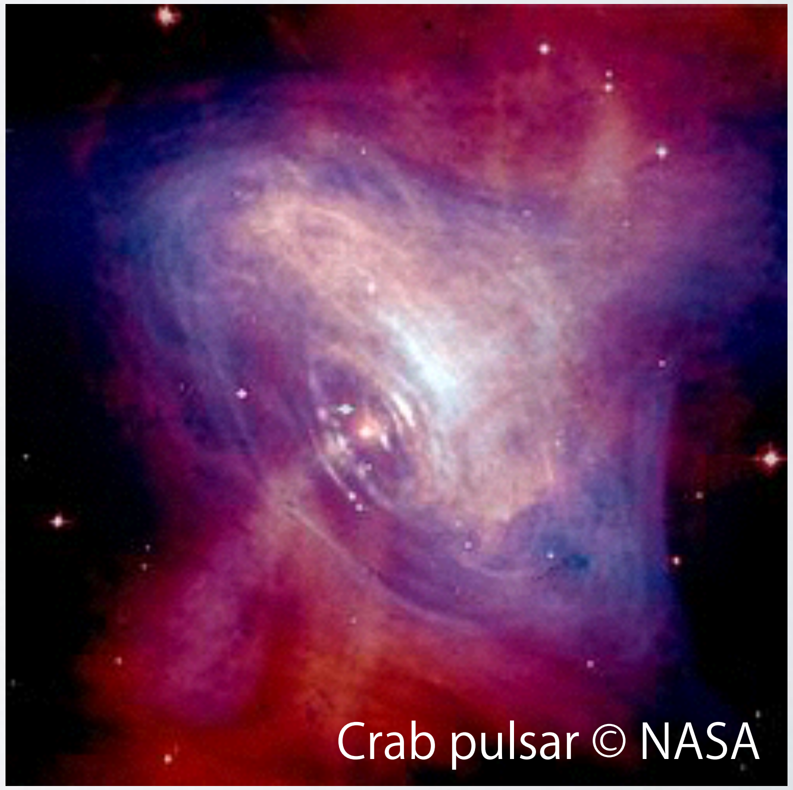
- spin-period ~ 1 - 7 [ms]
- B ~ 10^{13} - a few 10^{14} [G]
- time-scale ~ a few 10-100 days
- E_k ~ 10^{51} - 10^{52} [erg]
- M_{ej} ~ 2 - 10 $M_\odot$

(e.g., Nicholl+2017)

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

Q: But, how the magnetar power the ejecta?

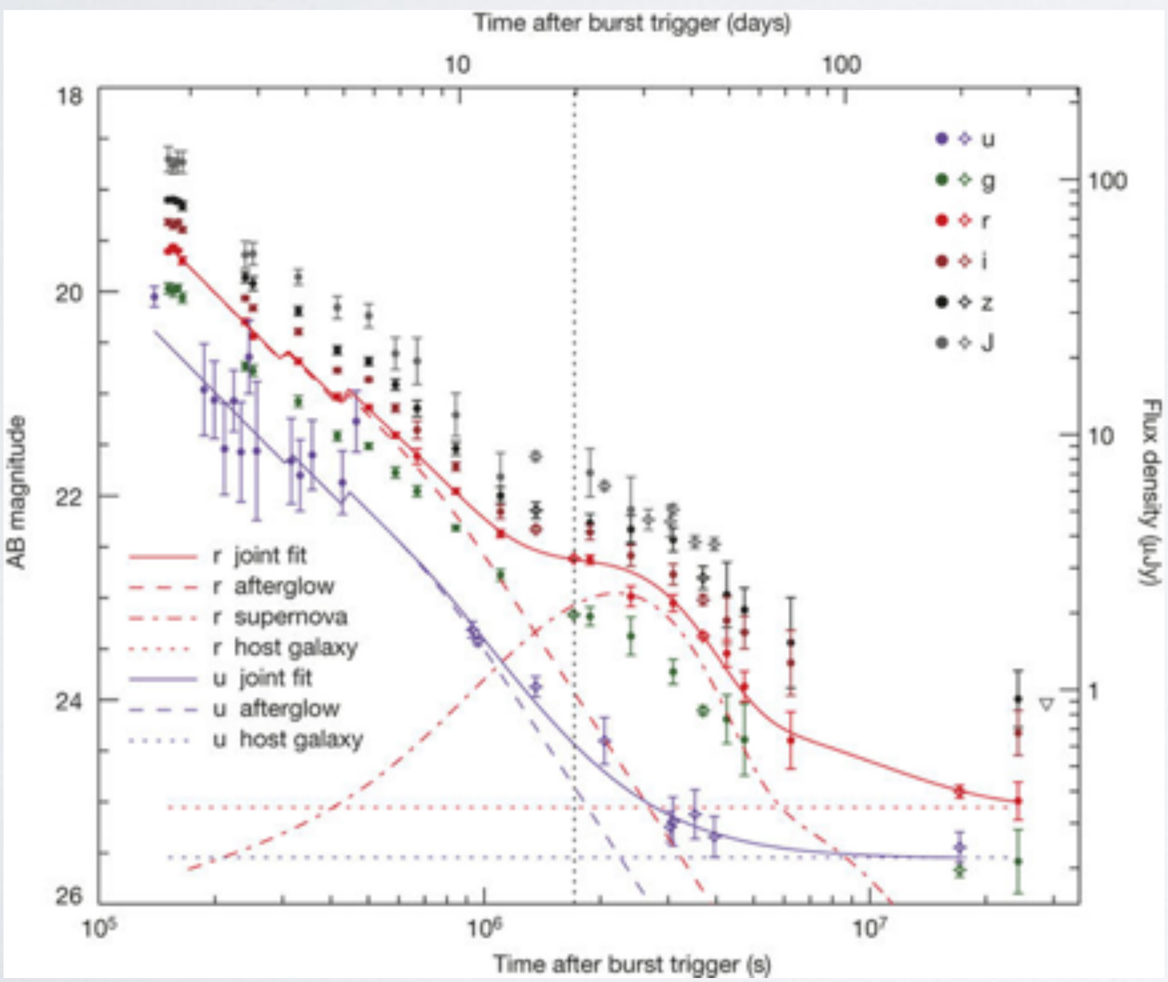
- The magnetic braking is formulated by assuming a **rotating neutron star with a dipole magnetic field** surrounded by **vacuum**. What happens in highly dense environment? Can we apply the vacuum dipole formula?
- OK, we can assume that the energy extraction from the rotating neutron star is realized by the magnetic braking. But, the energy flux is "**Poynting-flux dominated**" → long-standing (notorious) **σ-problem**: how to convert Poynting-dominated flow to particle energy-dominated flow???
- OK, we can assume the energy flux is dominated by some form (thermal or kinetic) of the particle energy at some distant region. But, **what kind of spectrum** is expected? The flow is composed of electron-positron pair or high energy ions? The flow may also be baryon-rich (no CR or pair acceleration).

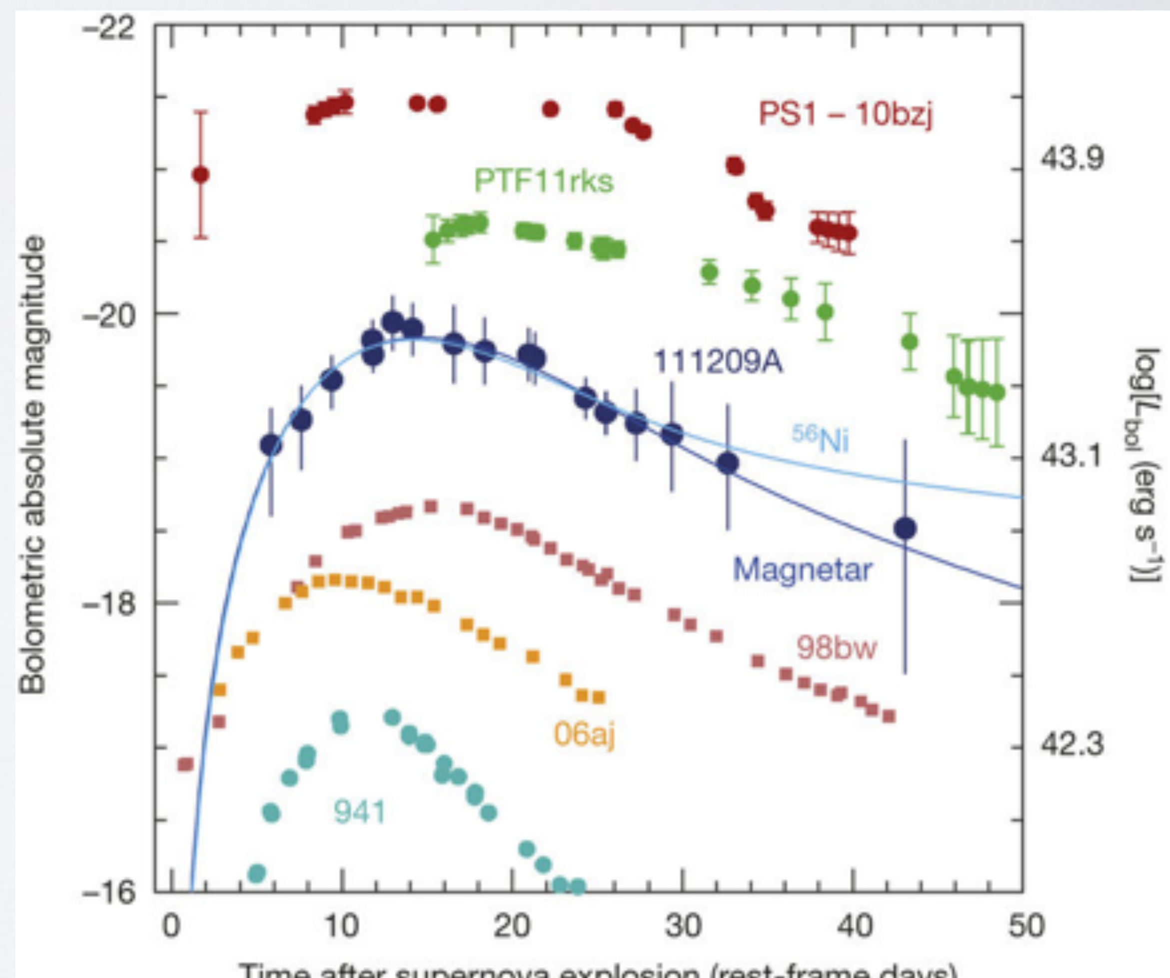


SLSNe - ultra-long GRB connection?

- GRB 111209A - SN 2011kl association
- SN 2011kl: “over-luminous” (not super-luminous) supernova. a few times more luminous than 1998bw (GRB980425)
- a similar central engine for GRB and SLSNe?

↓afterglow light curve of GRB111209A (Greinar+ 2015)





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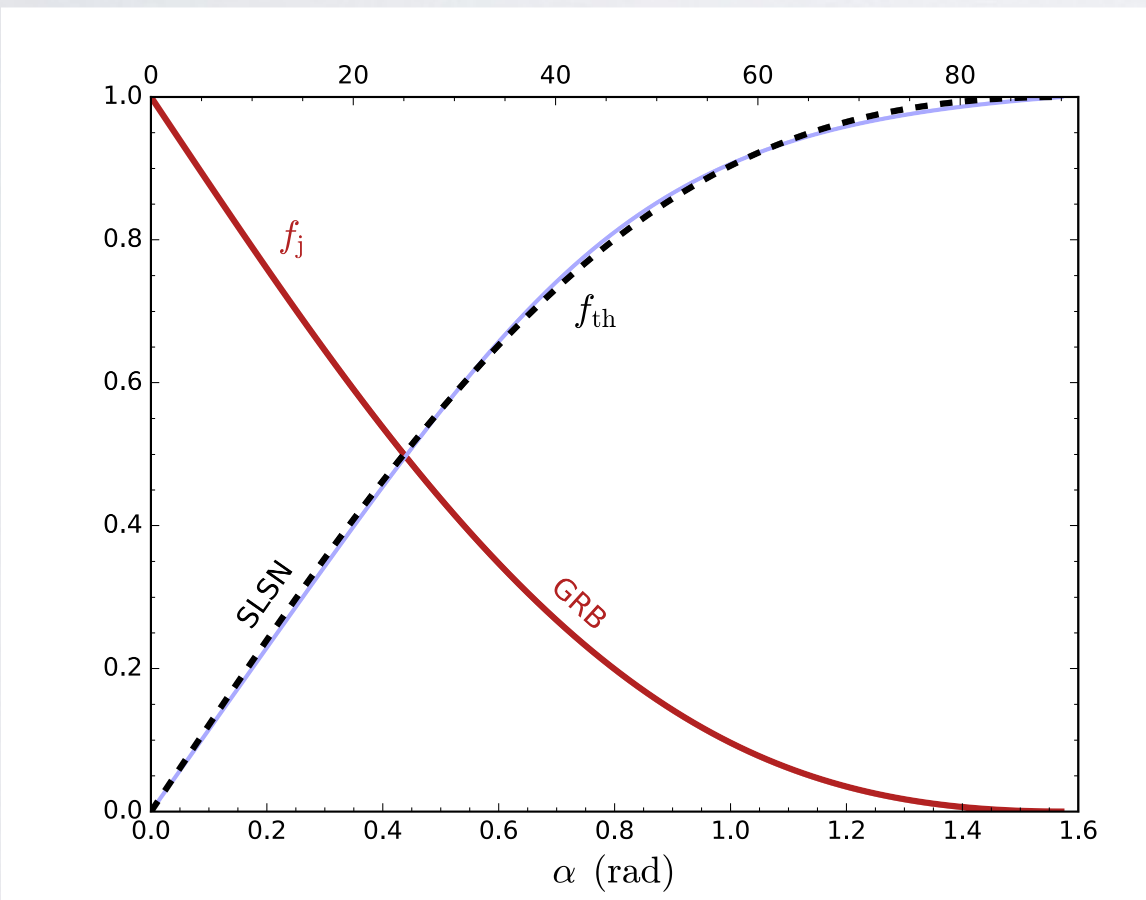
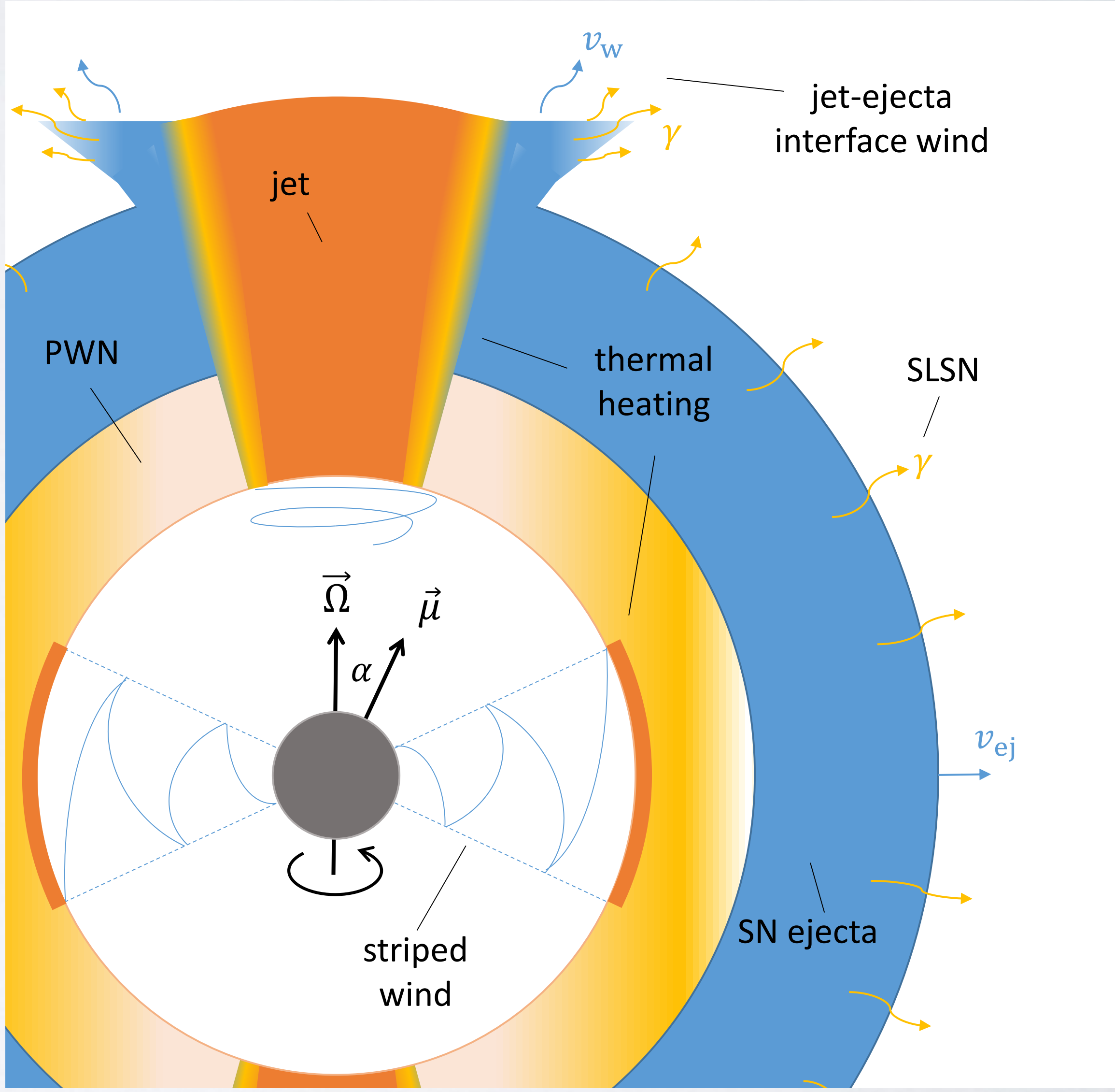


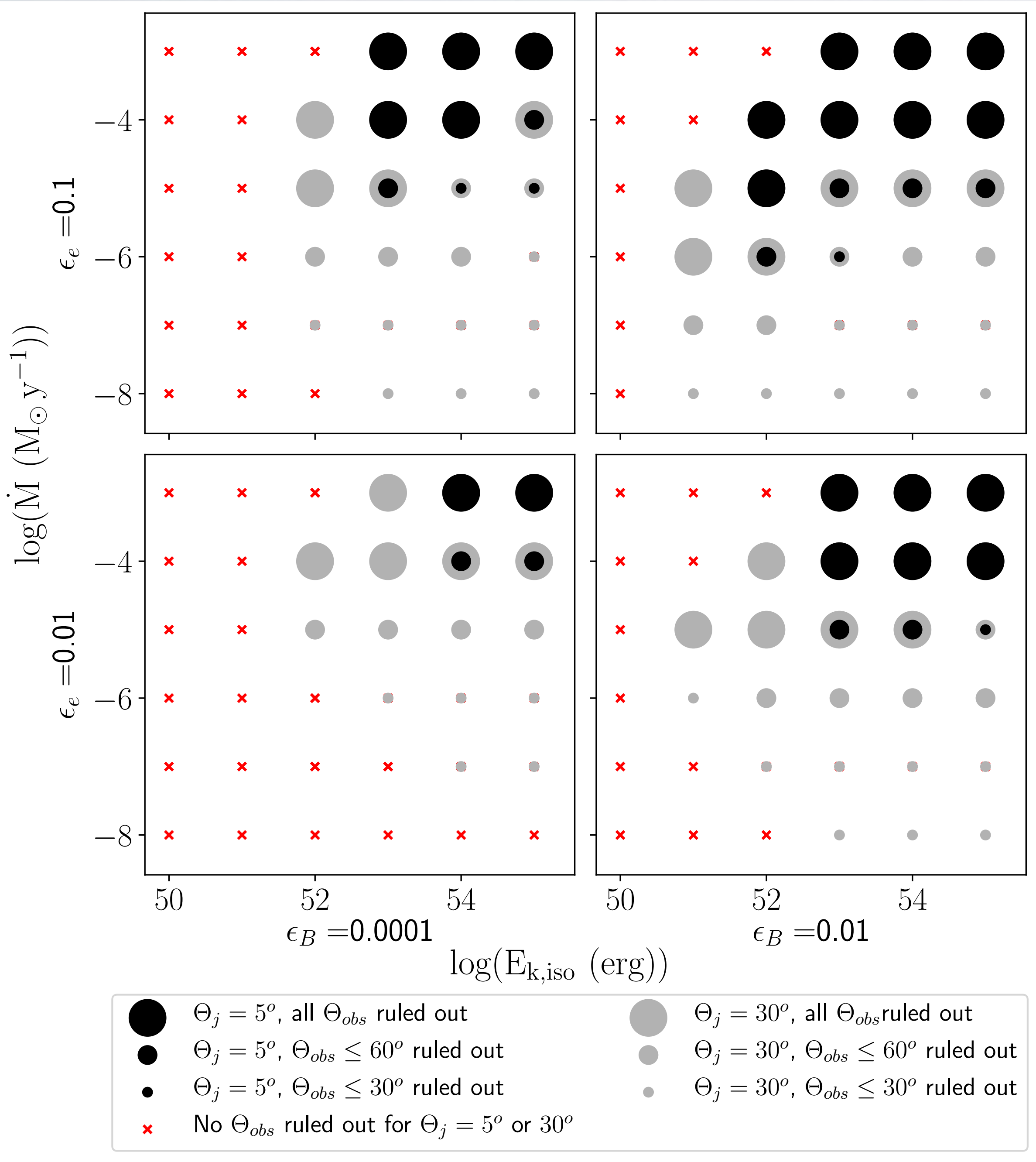
回転軸と磁場のなす角



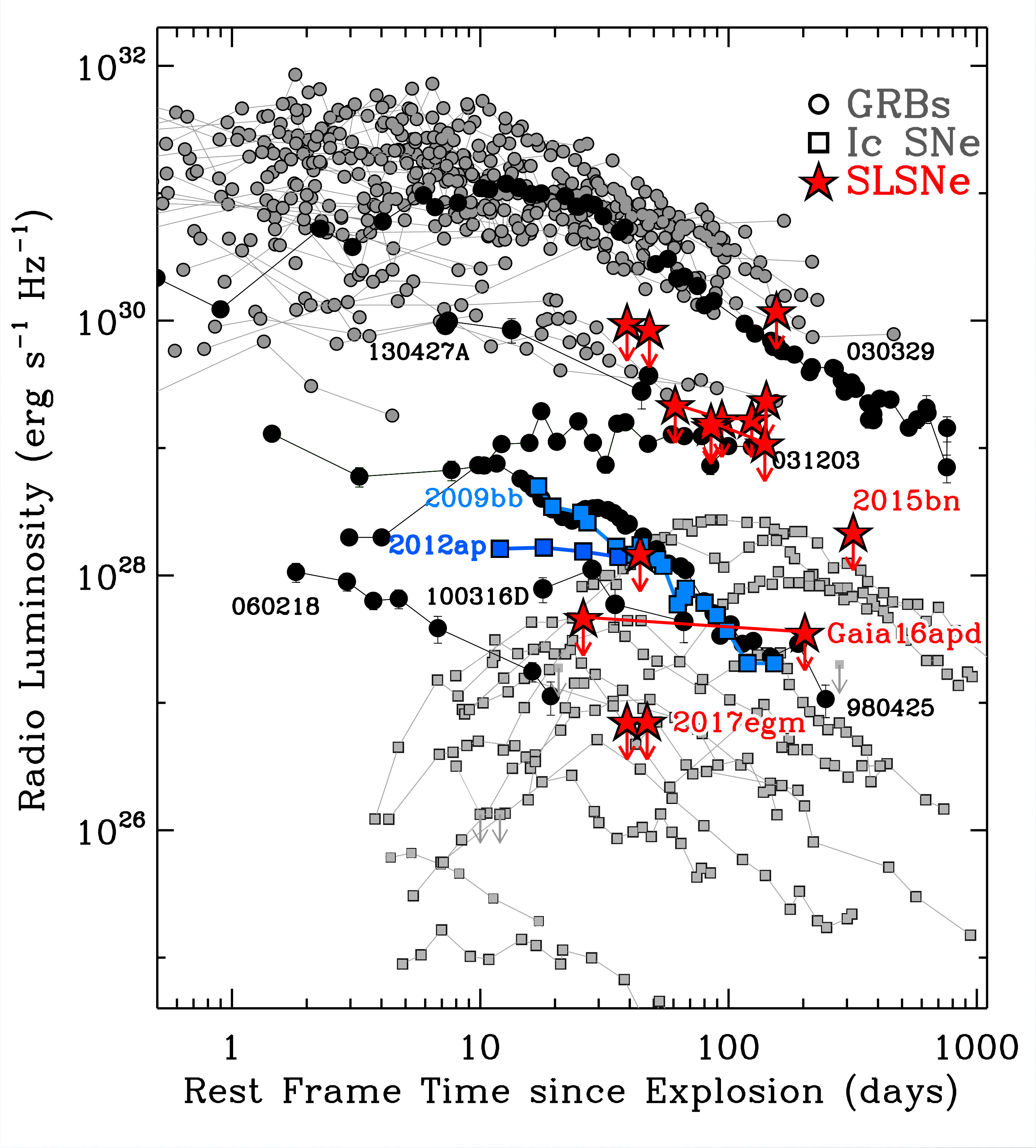
Margalit+ arXiv:1705.1103 ↑→

SLSNe - ultra-long GRB connection?

- radio non-detection → constraints for off-axis relativistic jets

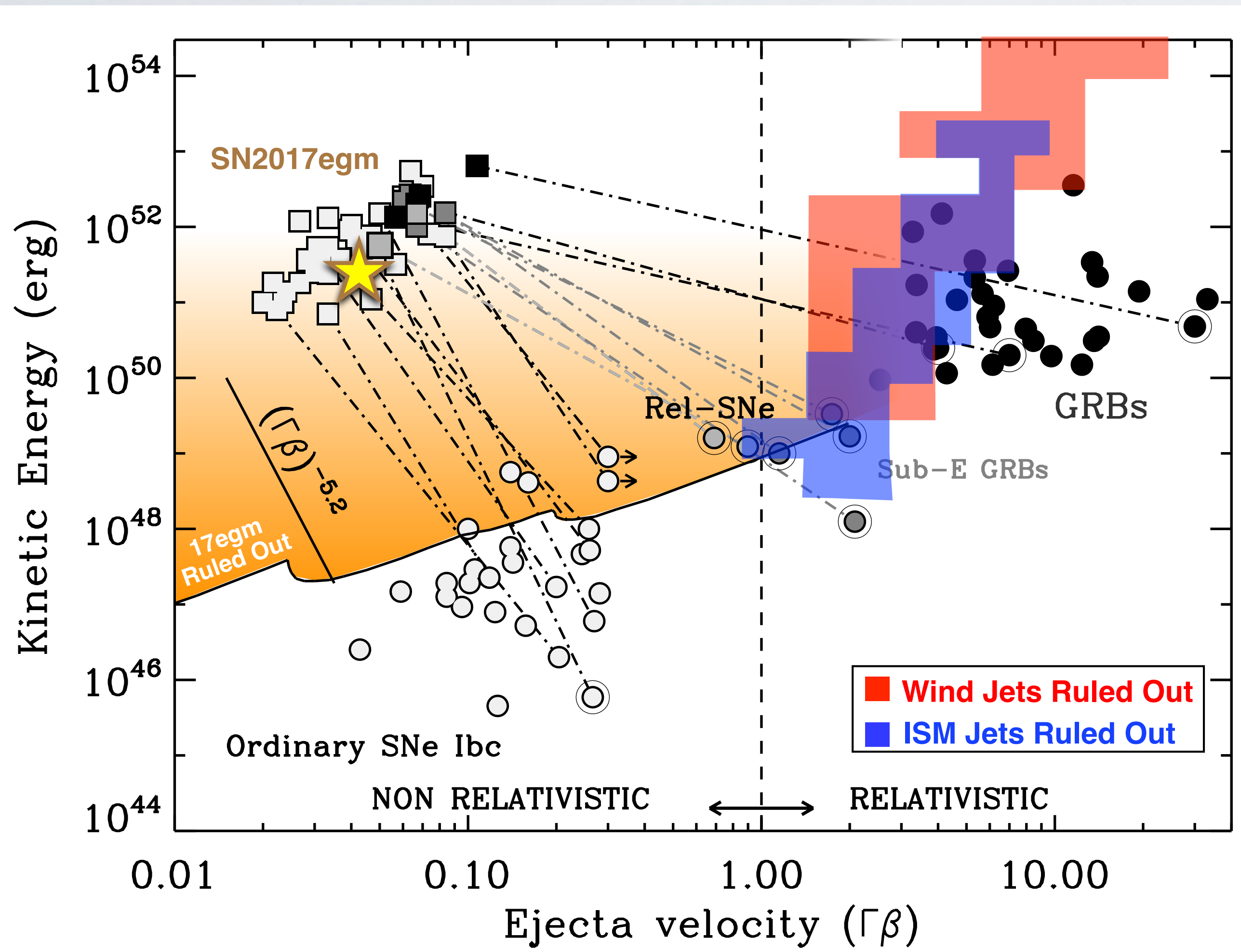


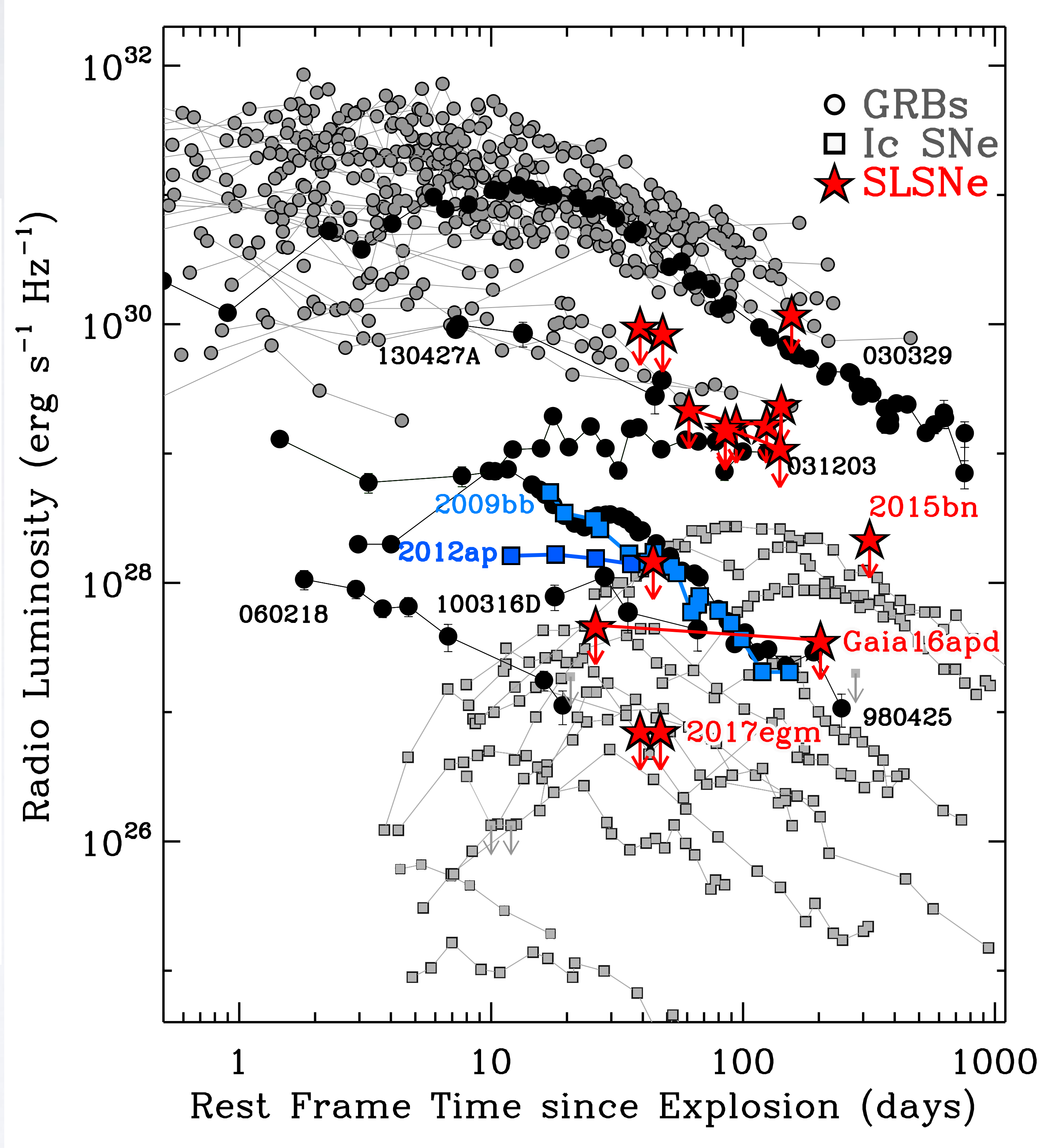
Coppejans+ arXiv:1711.03428



SLSNe - ultra-long GRB connection?

- radio non-detection → constraints for off-axis relativistic jets
- 電波の性質はGRB-SNeと異なる?

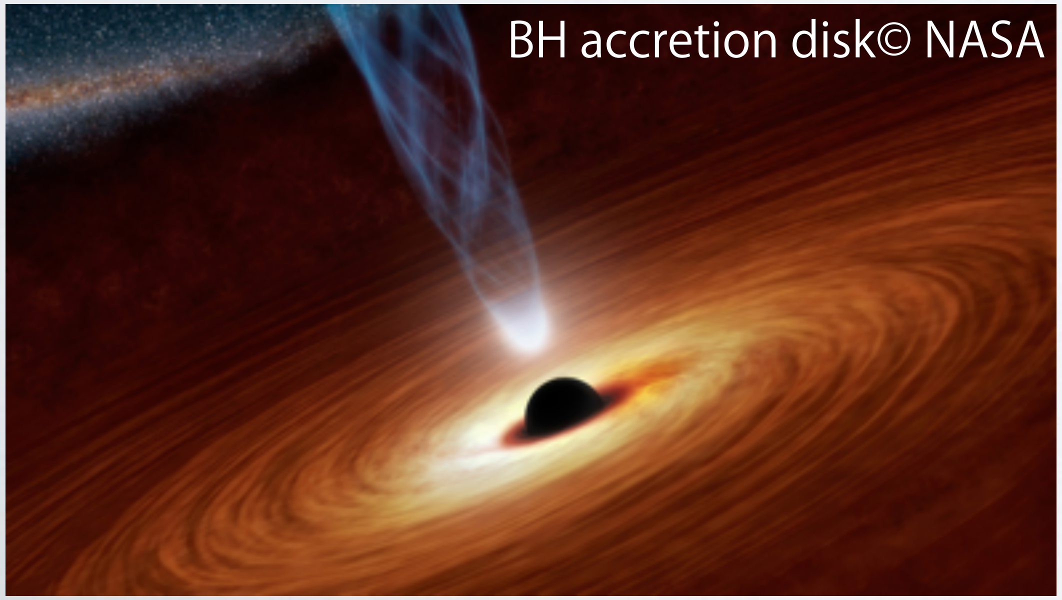


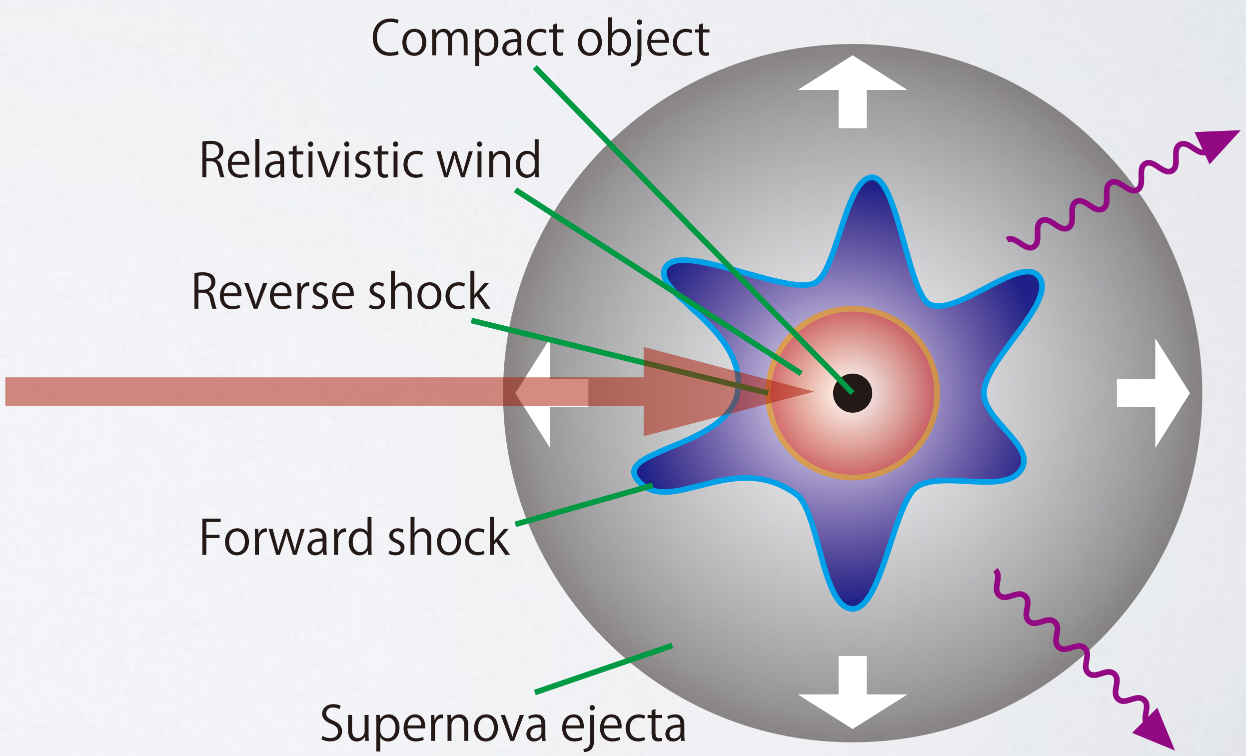


Coppejans+ arXiv:1711.03428

GRB Fireball in SN ejecta

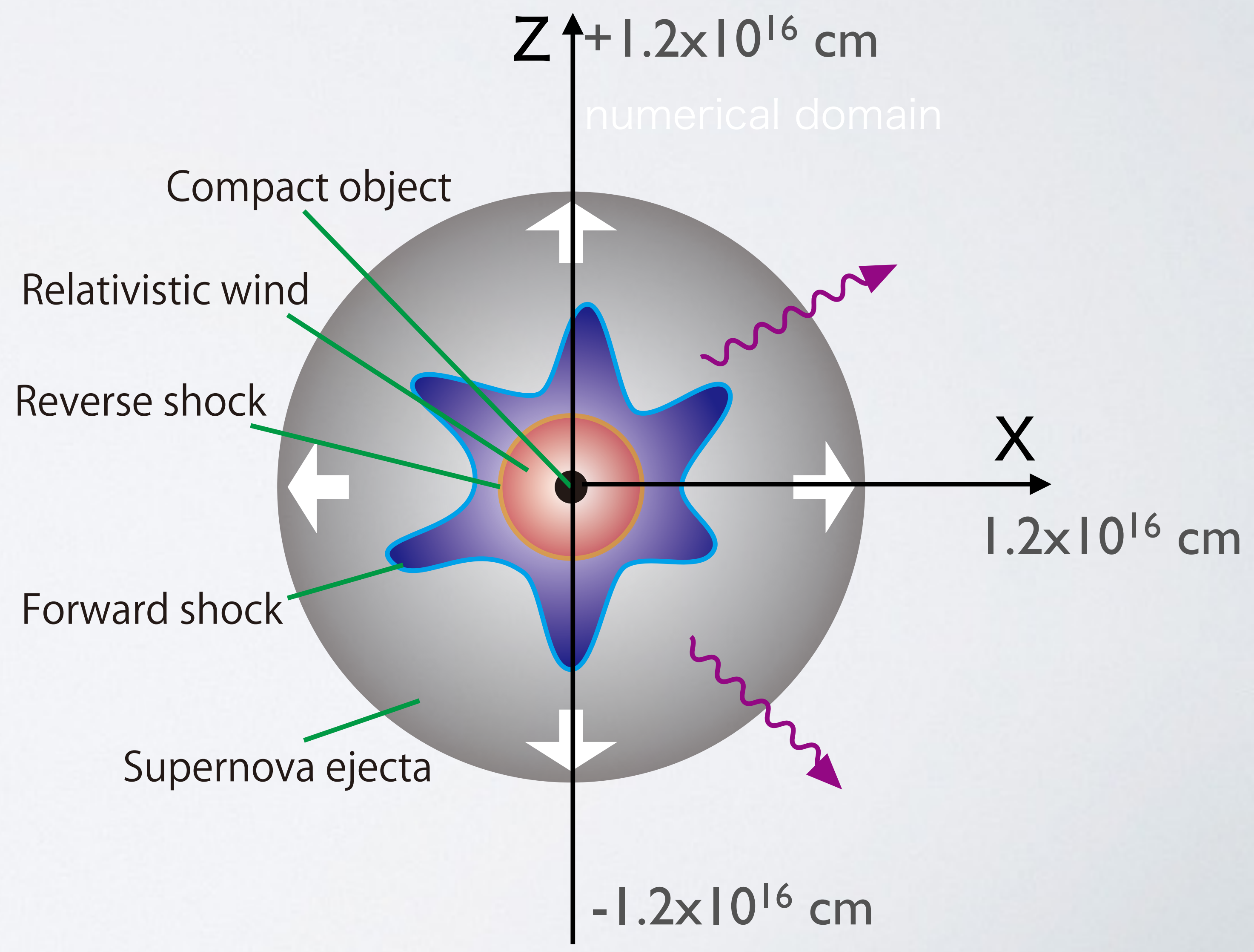
- SN ejecta中にexplosion energyより十分大きなエネルギーを注入した際に何が起こるのか?
- Extraordinary SNe (SLSNe, SNe Ic-BL)はこのようなシナリオで説明できるのか?
- 等方的なGRB fireball(的なもの)をSN ejecta中心に用意する





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

- 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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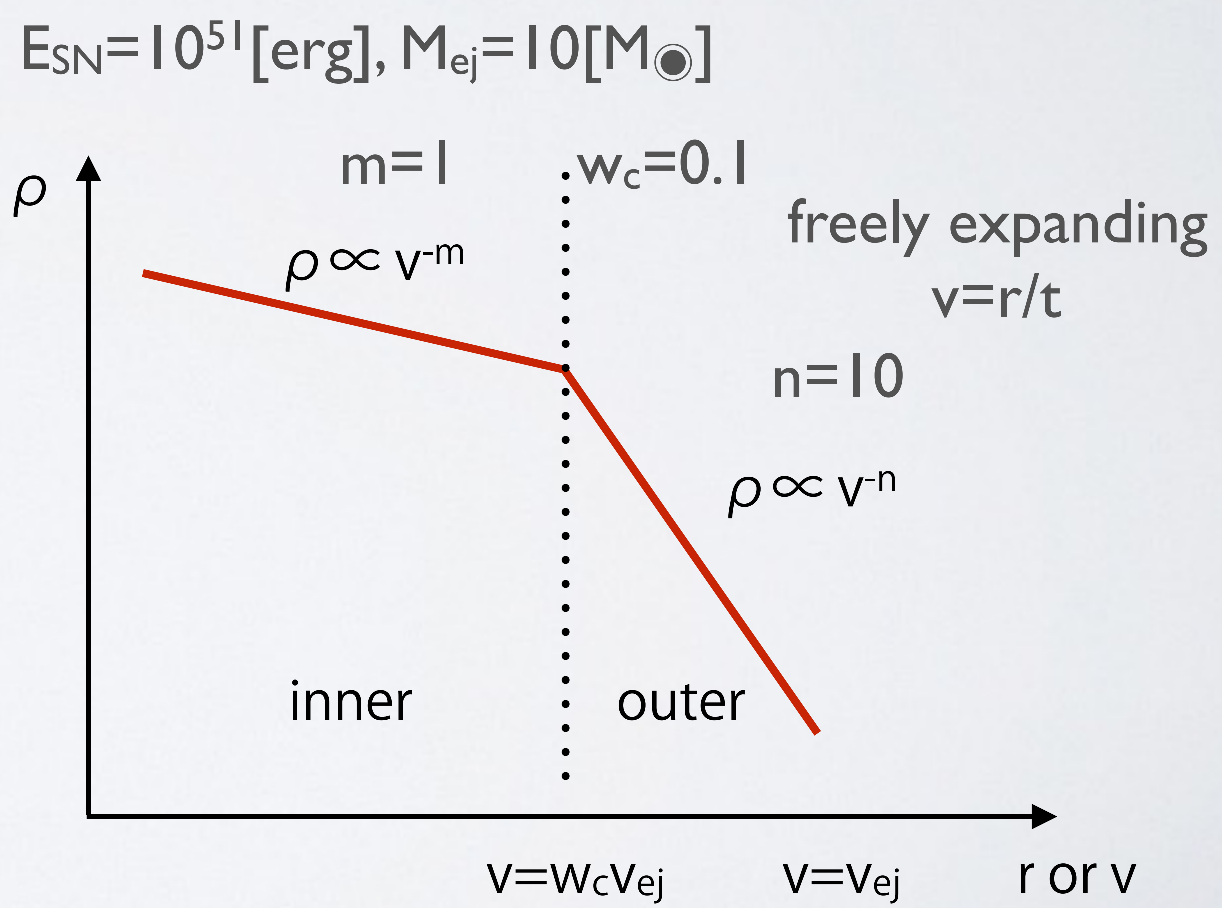

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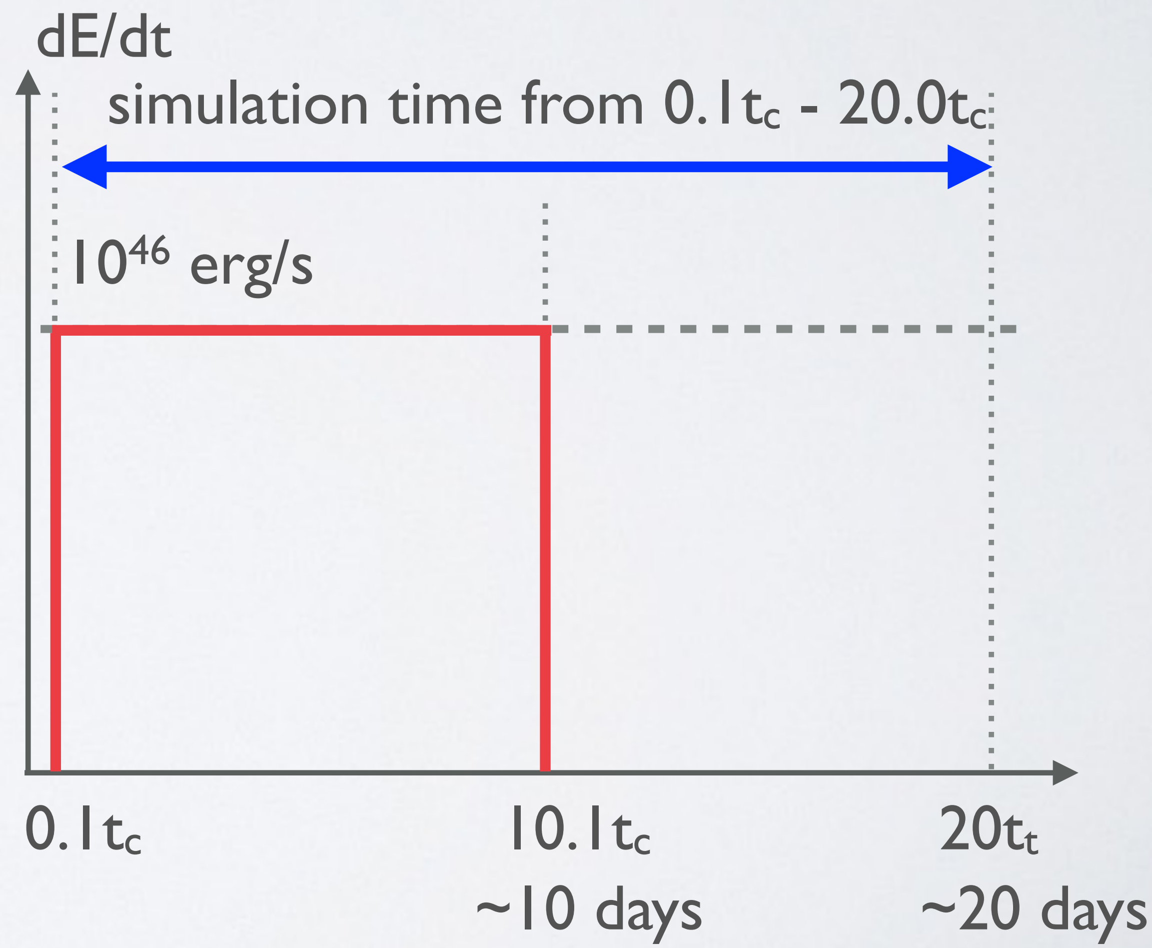

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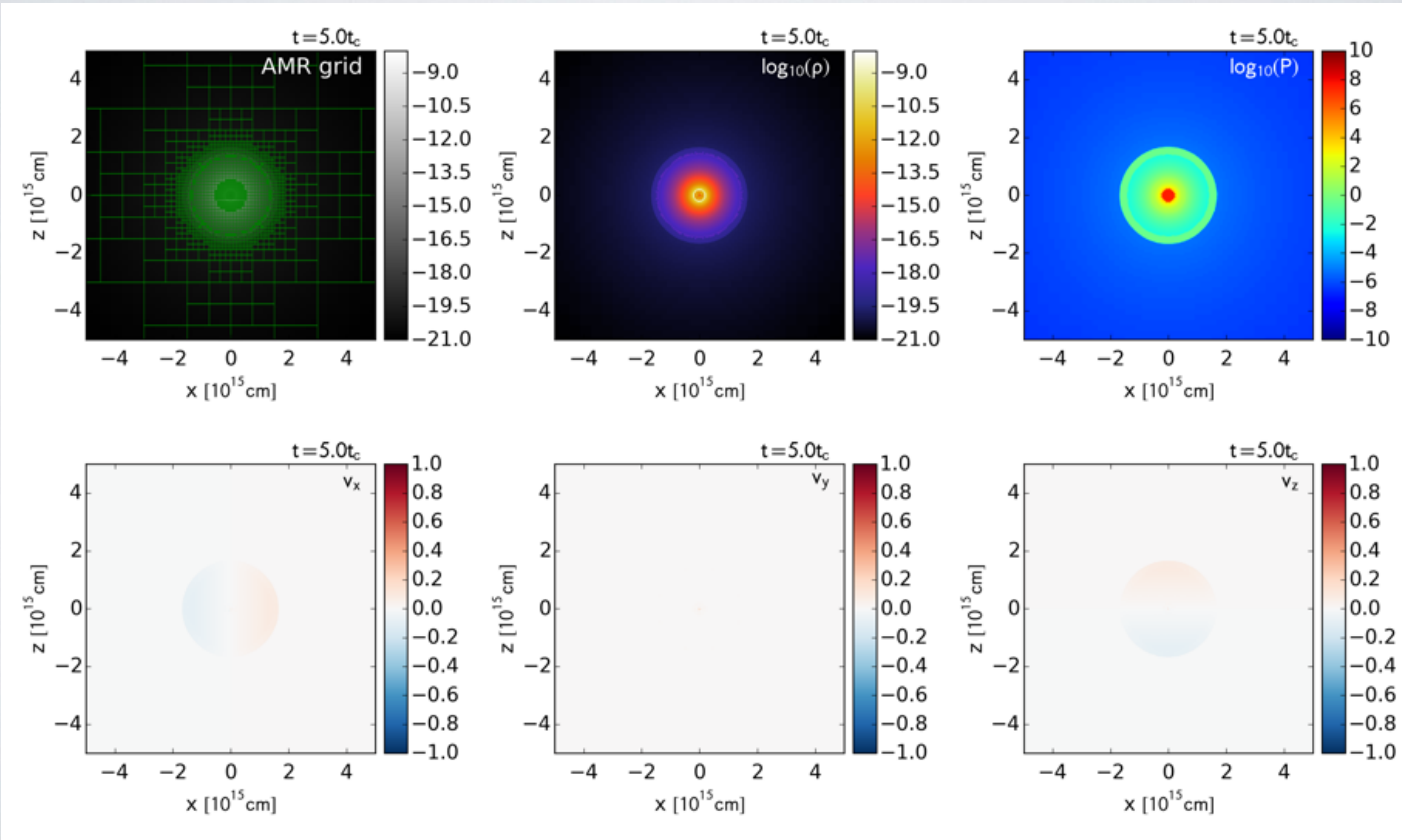

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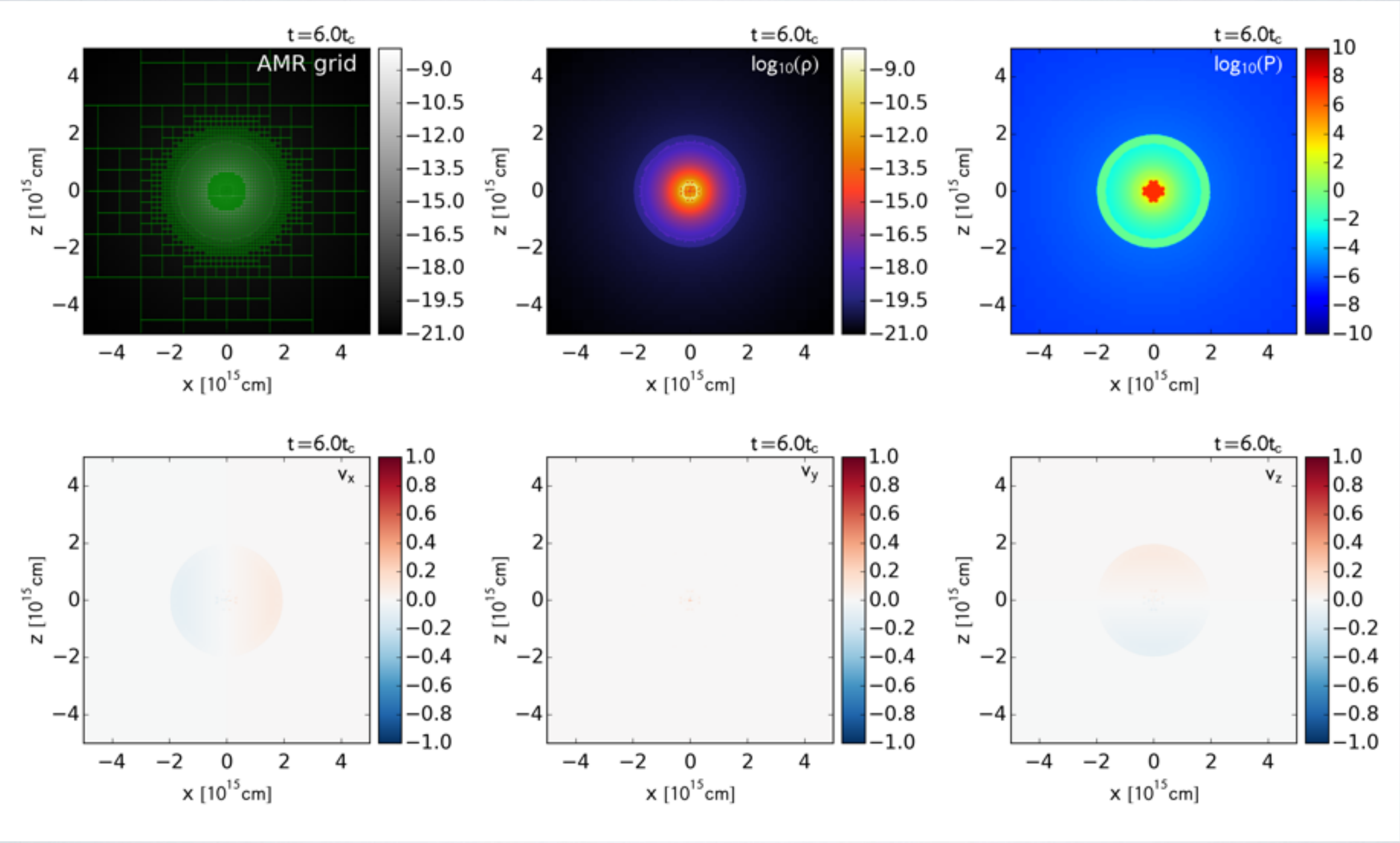

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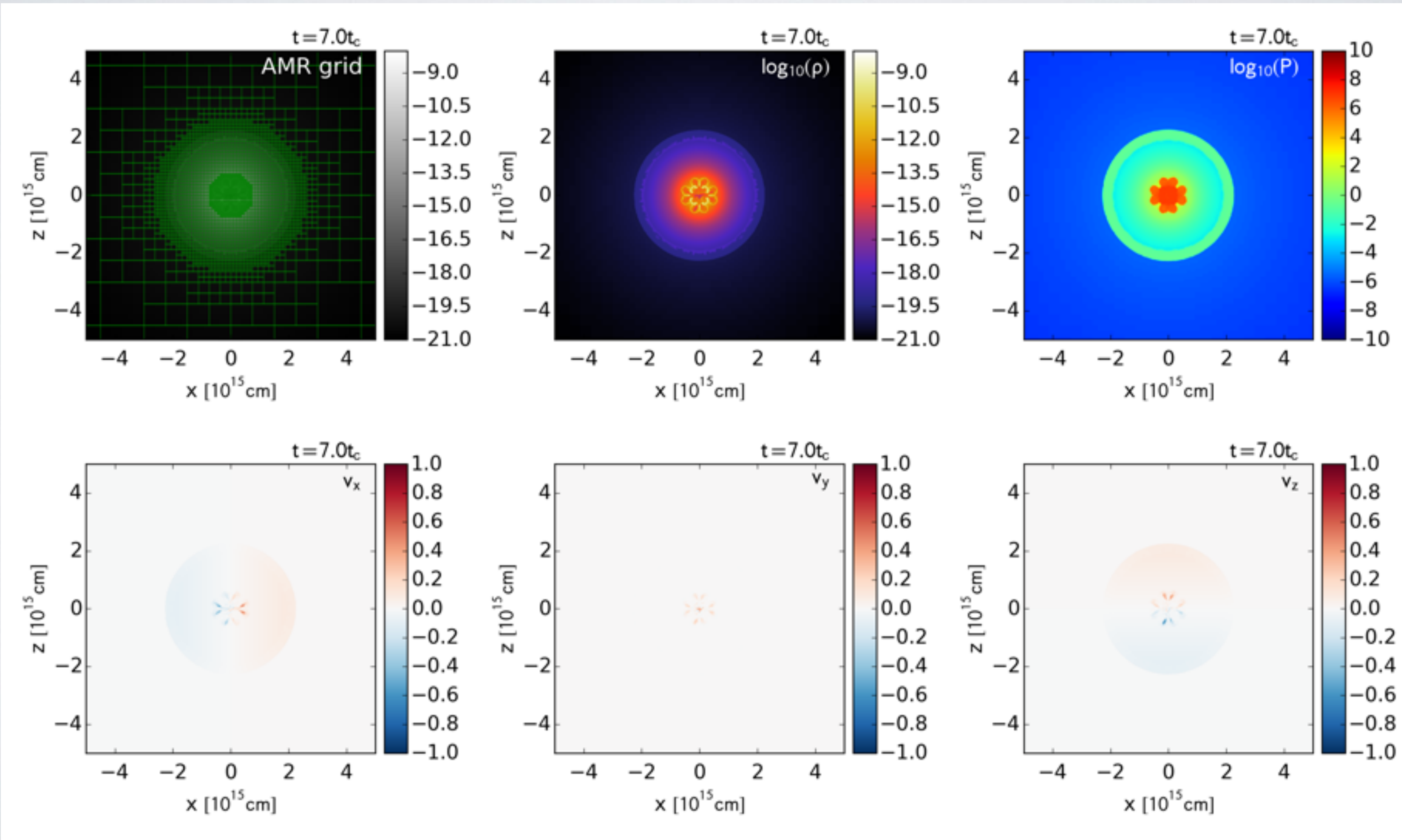

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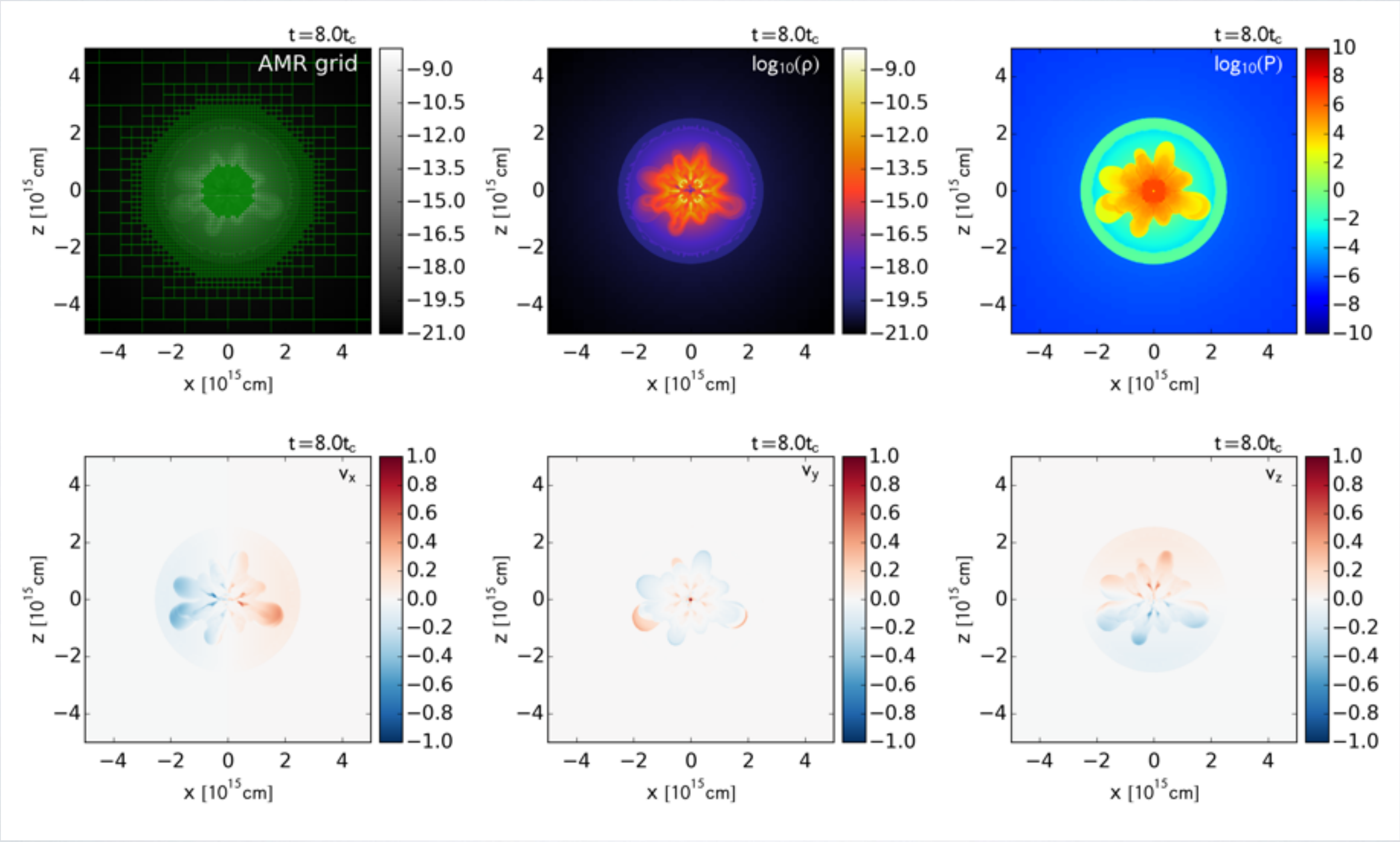

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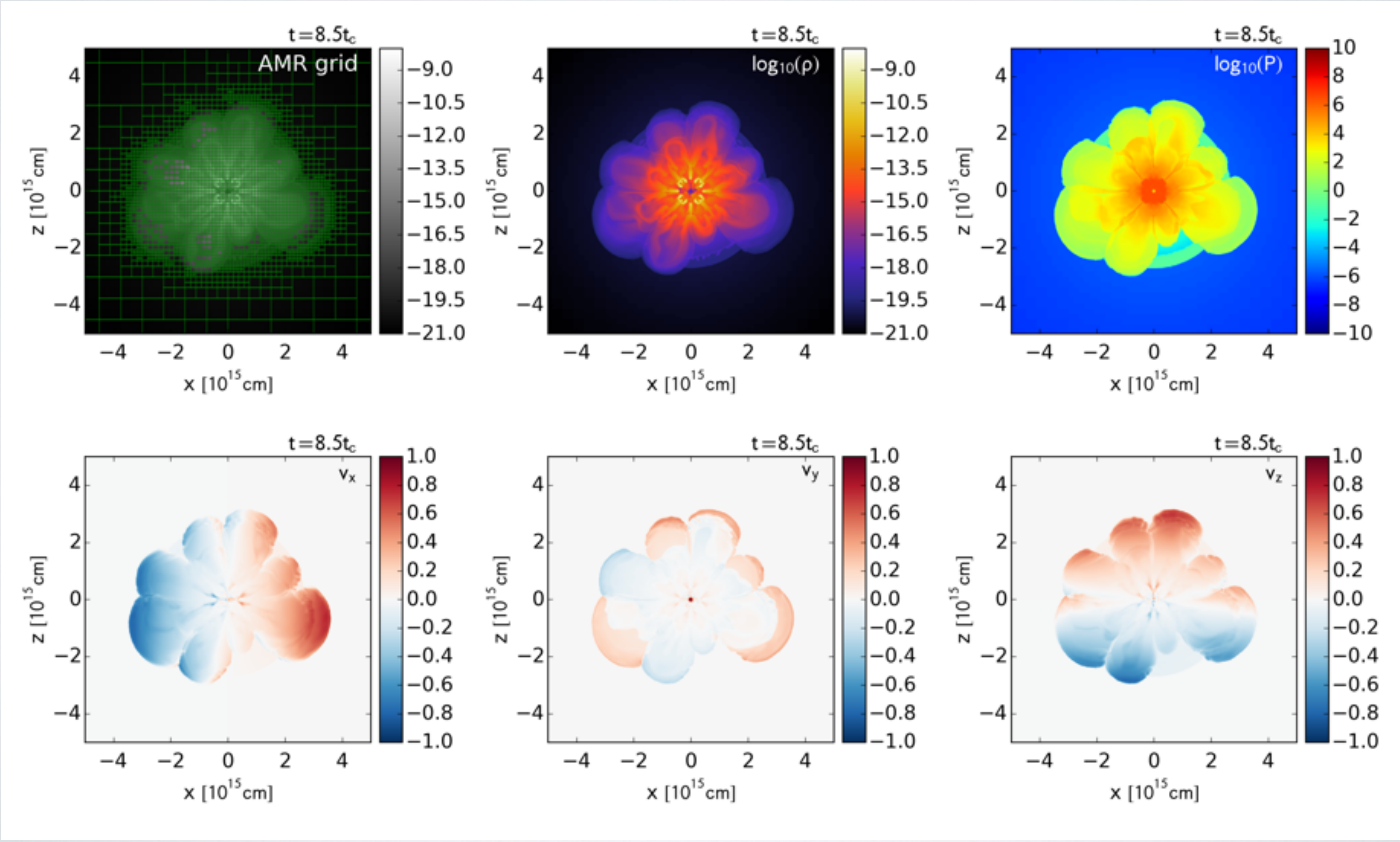

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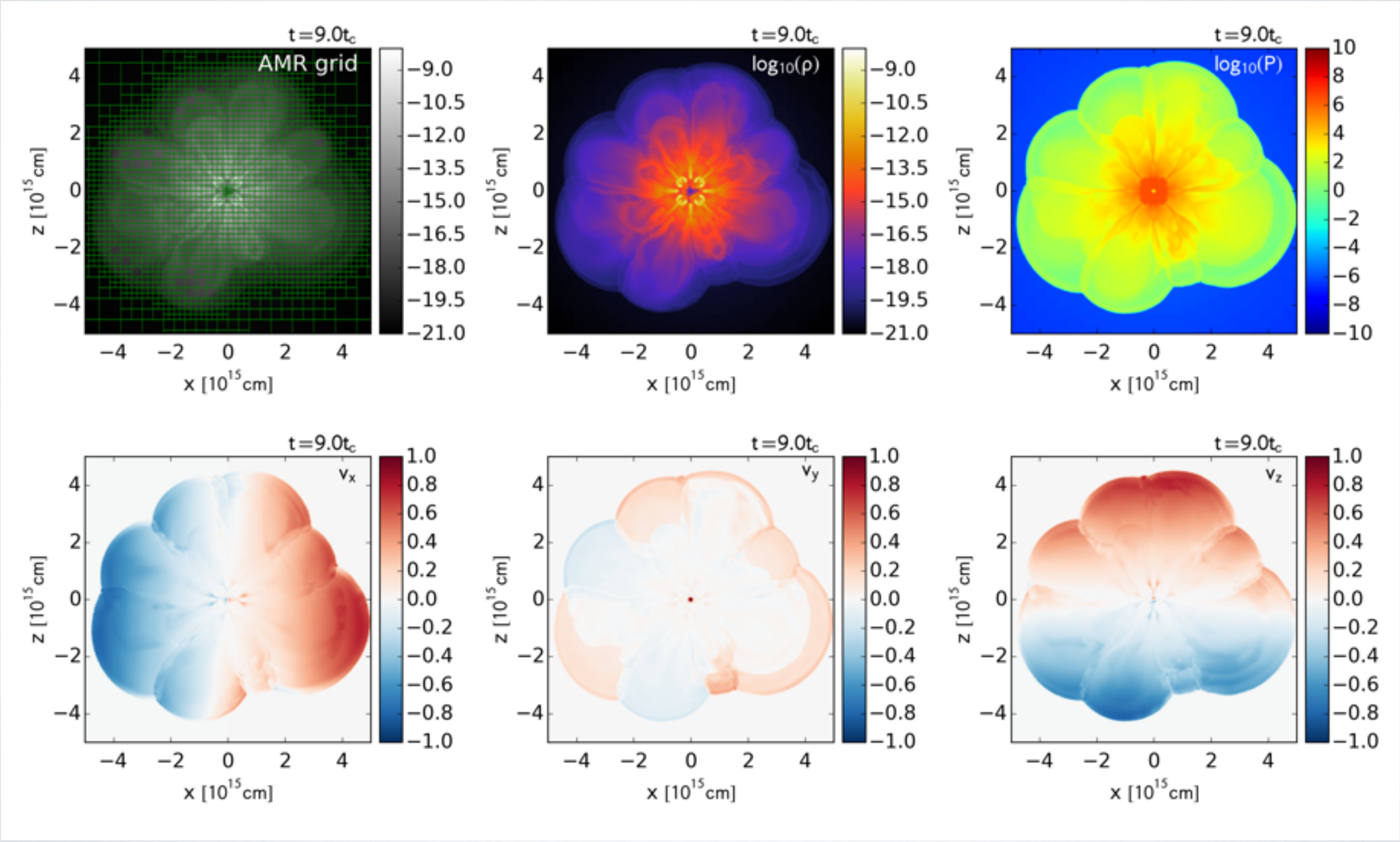

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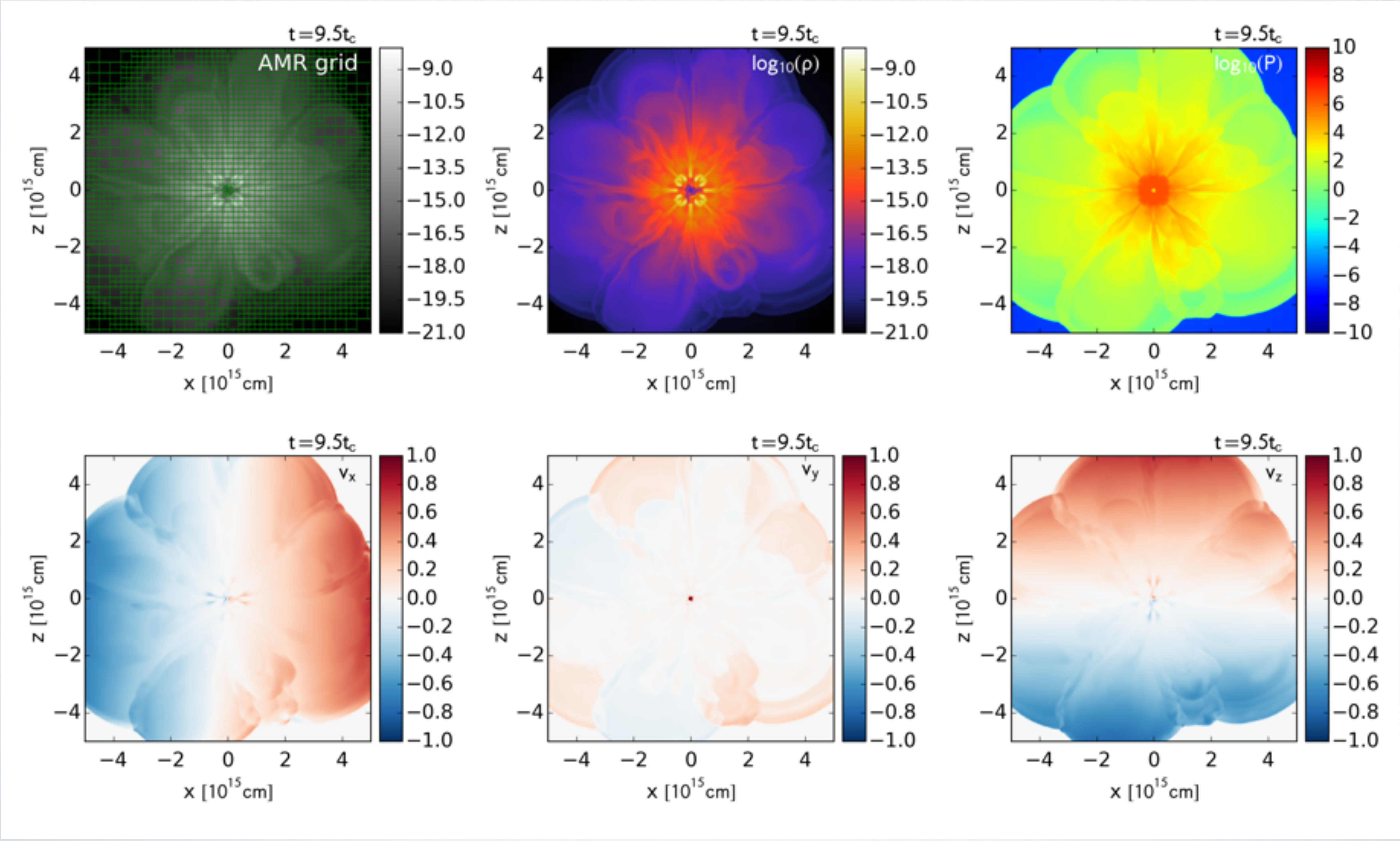

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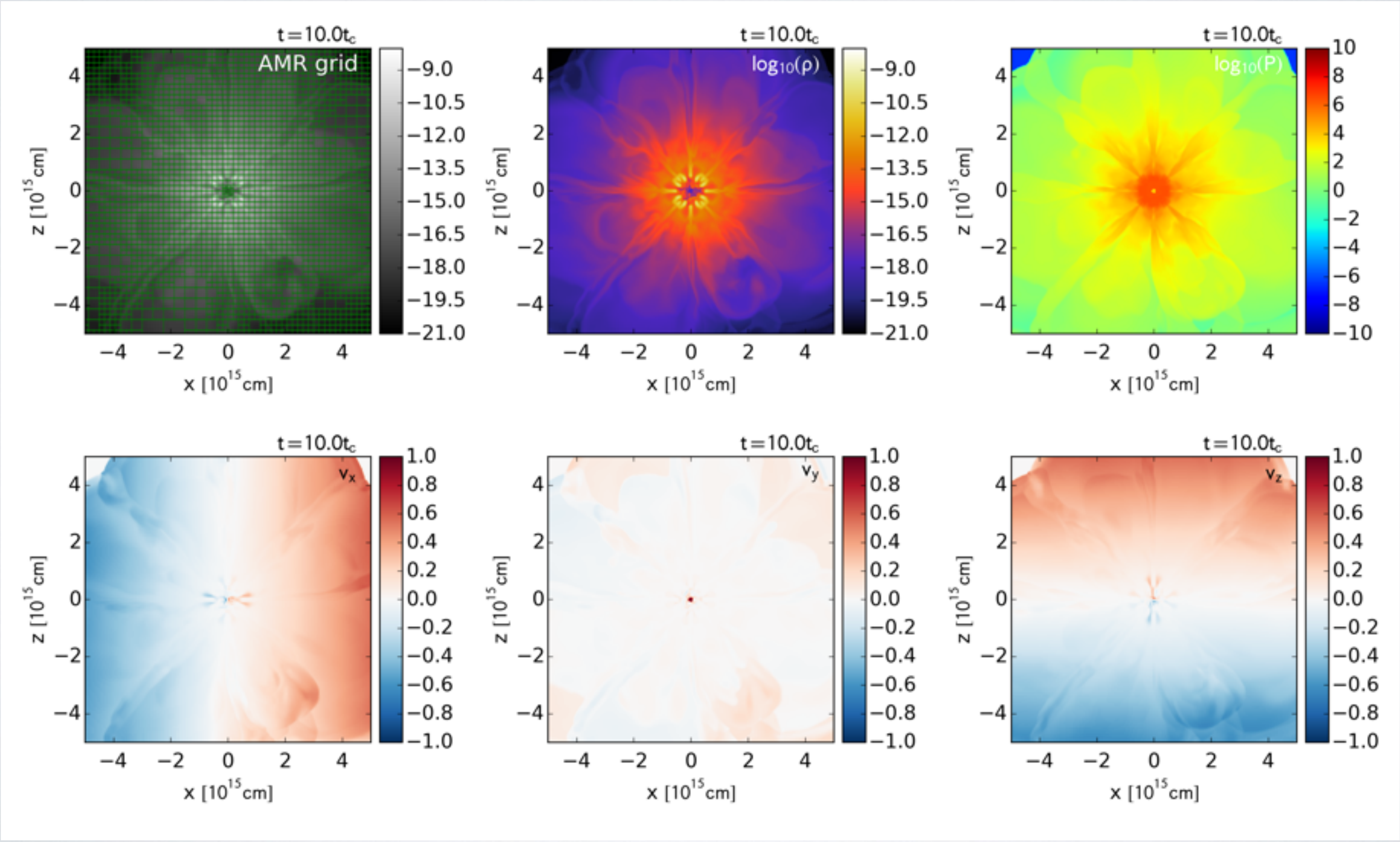
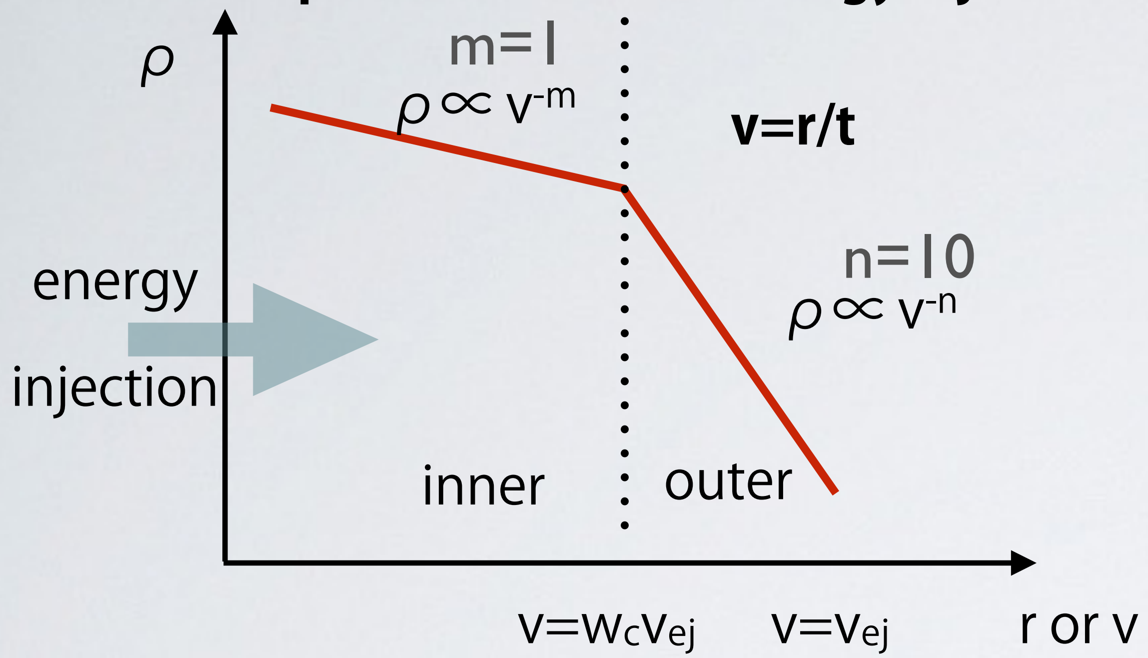


Density structure

radial profiles at $t=20t_c$

Free expansion “before” energy injection



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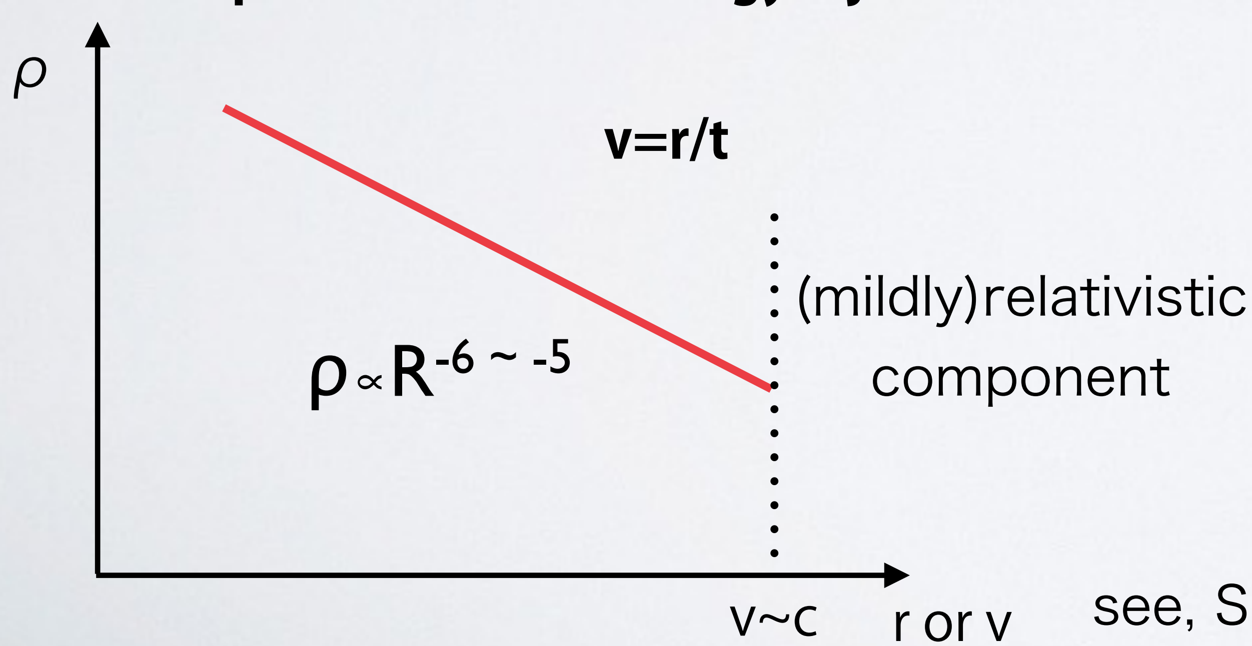
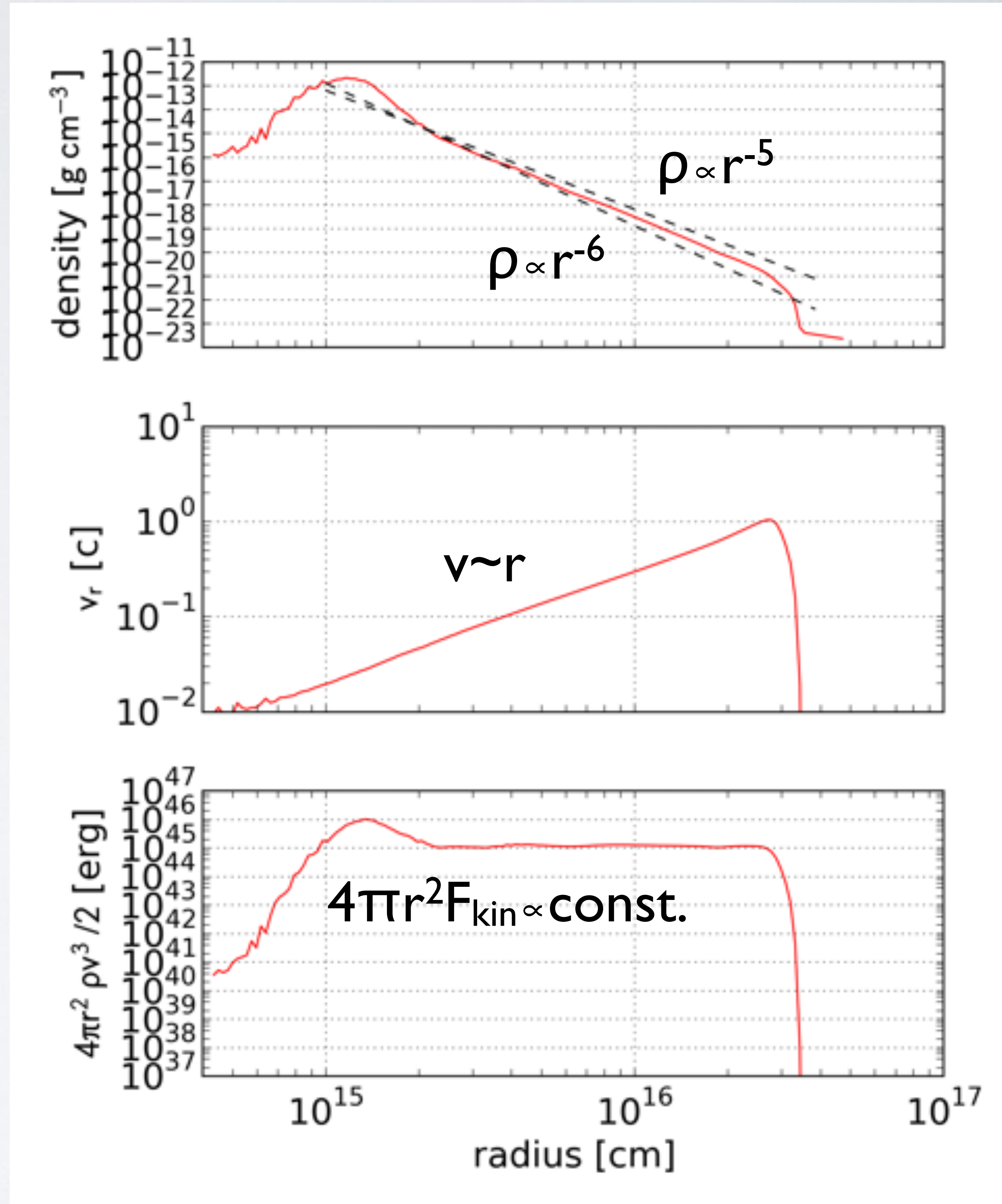
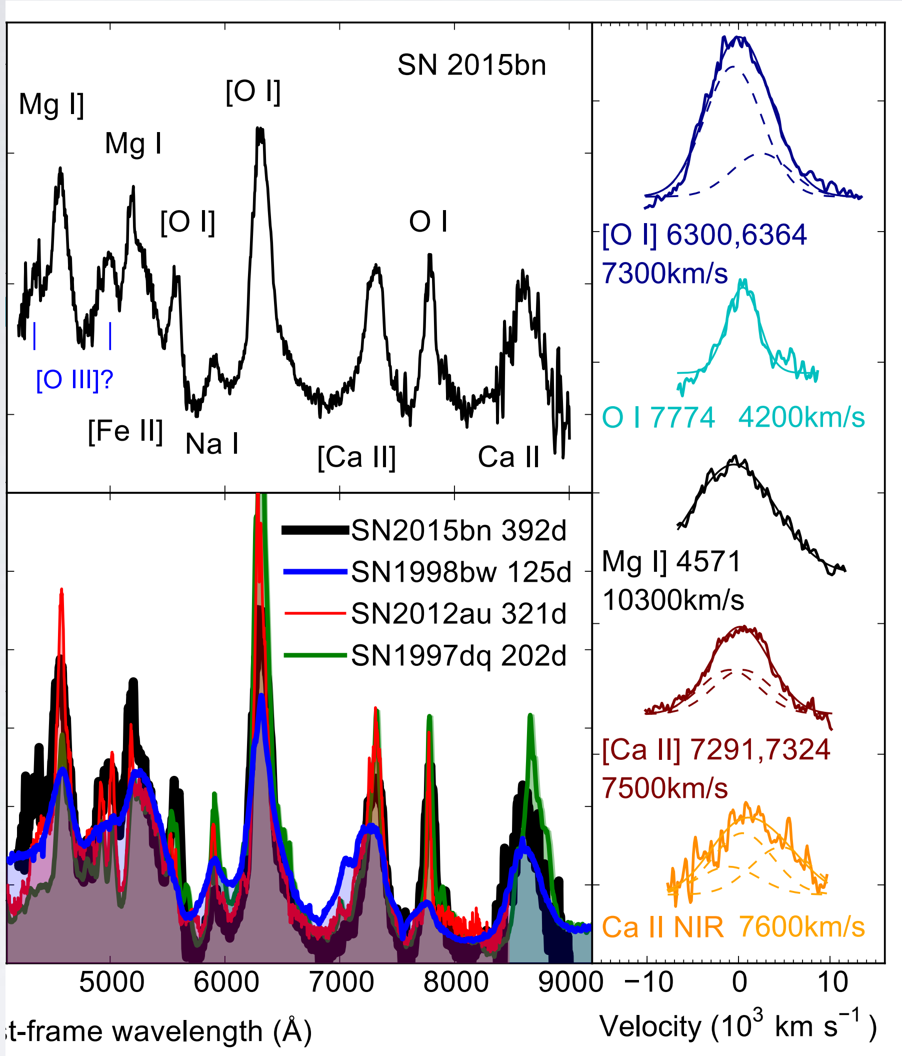




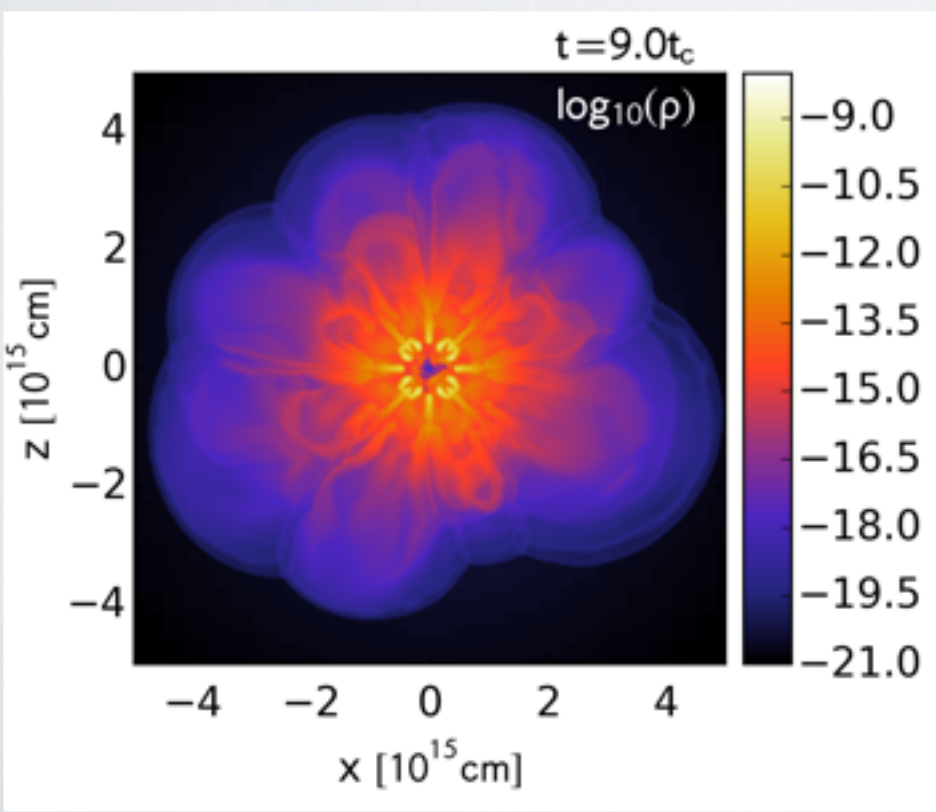
see, Suzuki&Maeda (2017)

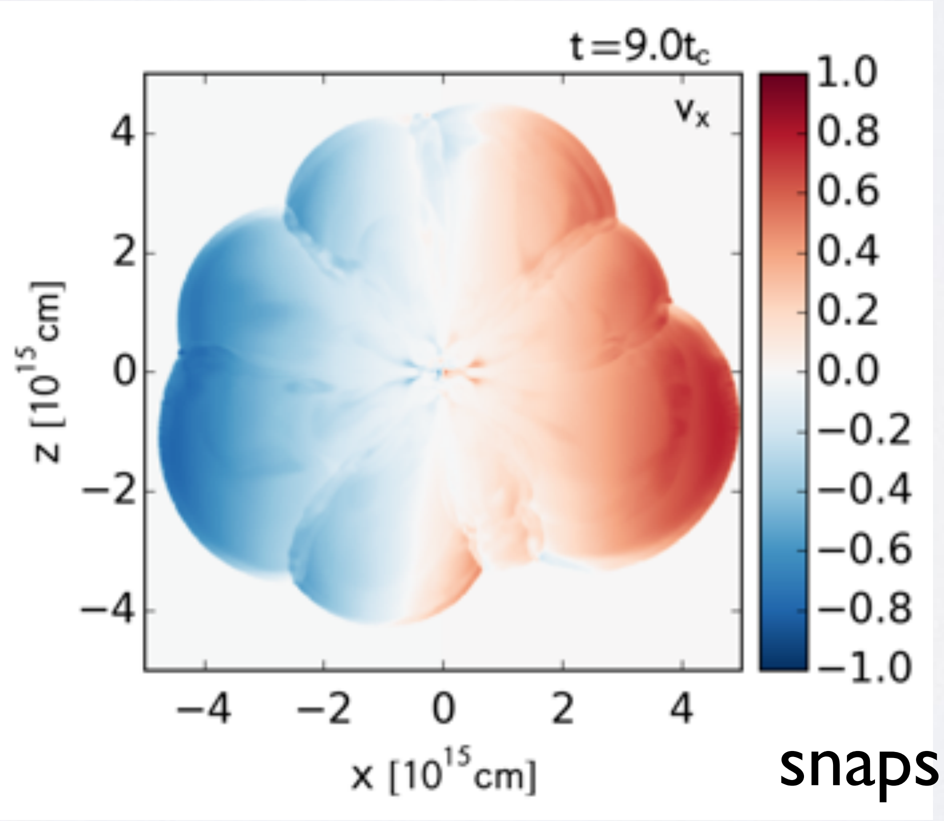
Density structure

- 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

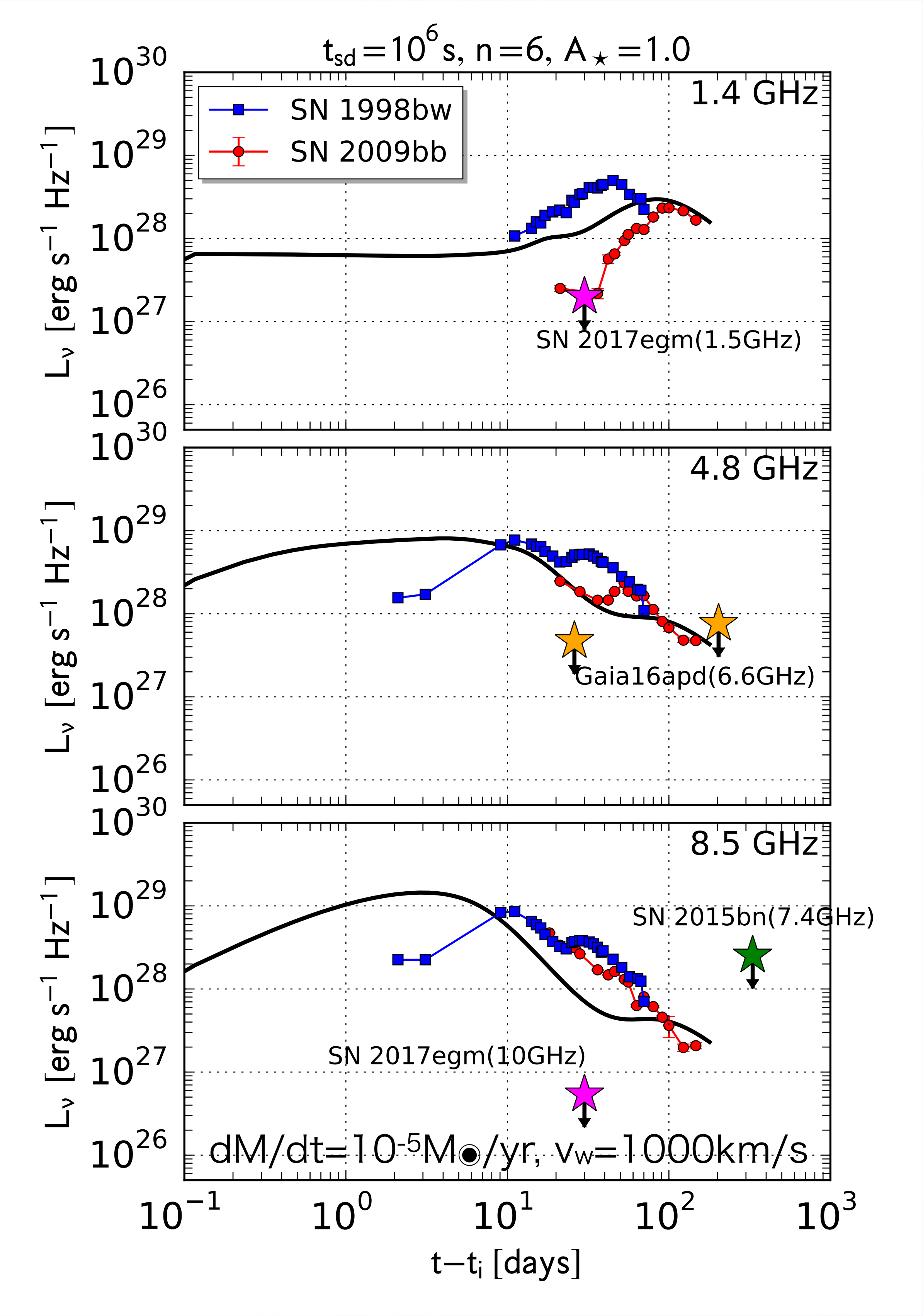
snapshot at $t=9t_c \sim 9$ days

Synchrotron emission

- central engine-powered SN ejecta embedded in a CSM
- synchrotron emission from non-thermal electrons.
- radio emission as bright as radio-loud SNe Ic-BL (1998bw, 2009bb) is expected.
- radio observations of SLSNe can constrain the central engine scenario.
- …but, the radio luminosity depend on the CSM density

Suzuki & Maeda, in prep.

ε_e=0.1, ε_B=0.03, p=3.0



Inverse Compton emission

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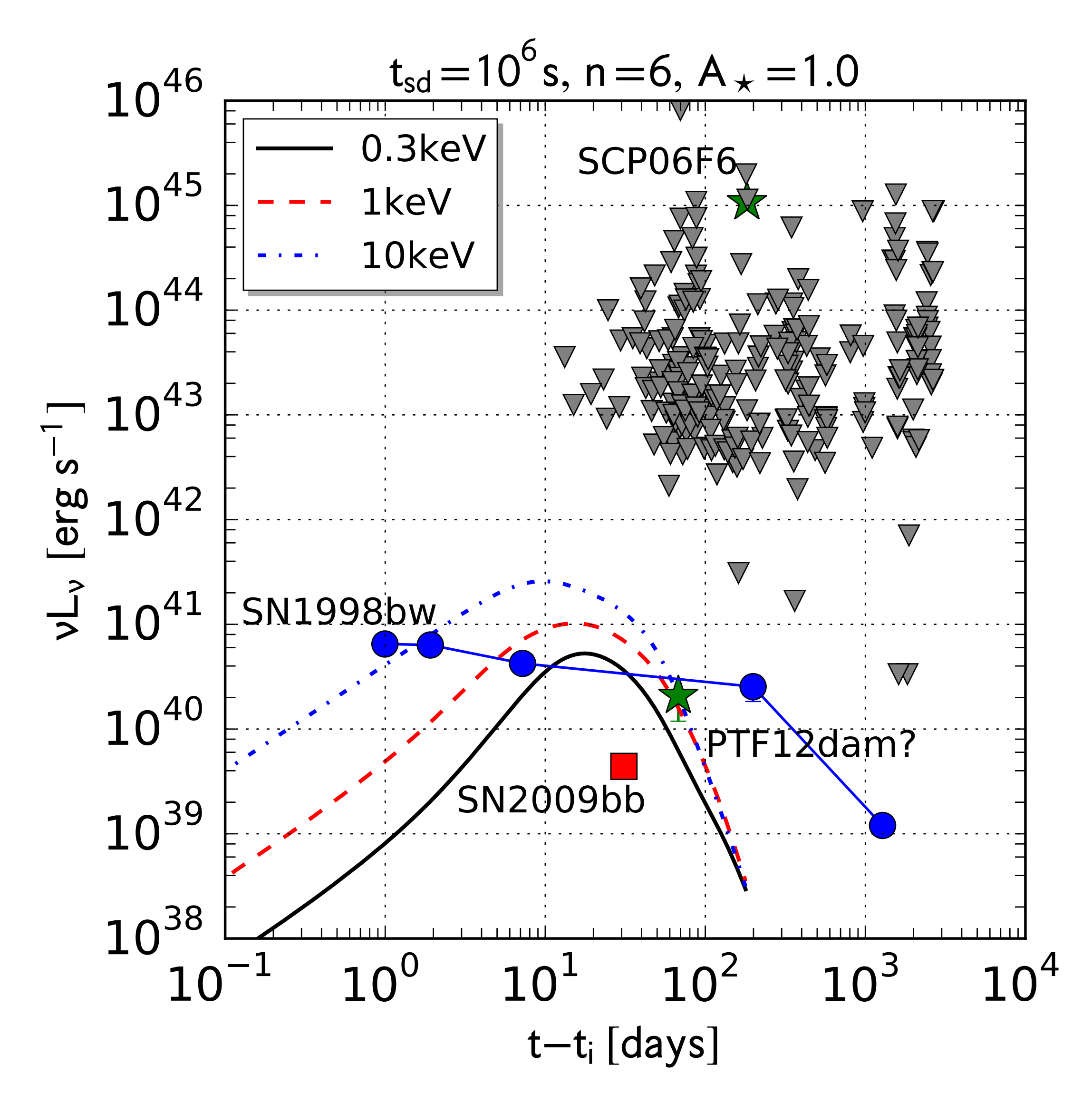
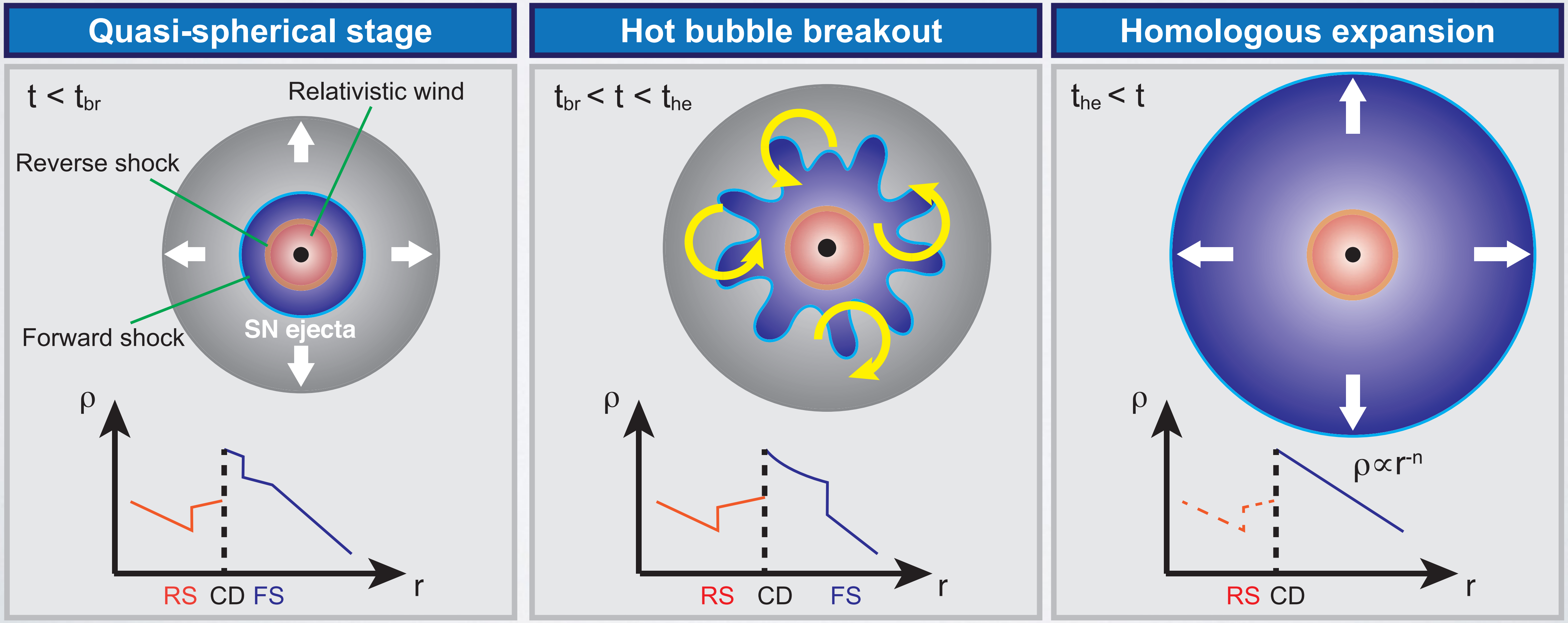


dM/dt=10^{-5}M$_\odot$/yr, v_w=1000km/s

ε_e=0.1, ε_B=0.03, p=3.0

Summary: central-engine SNe in multi-D

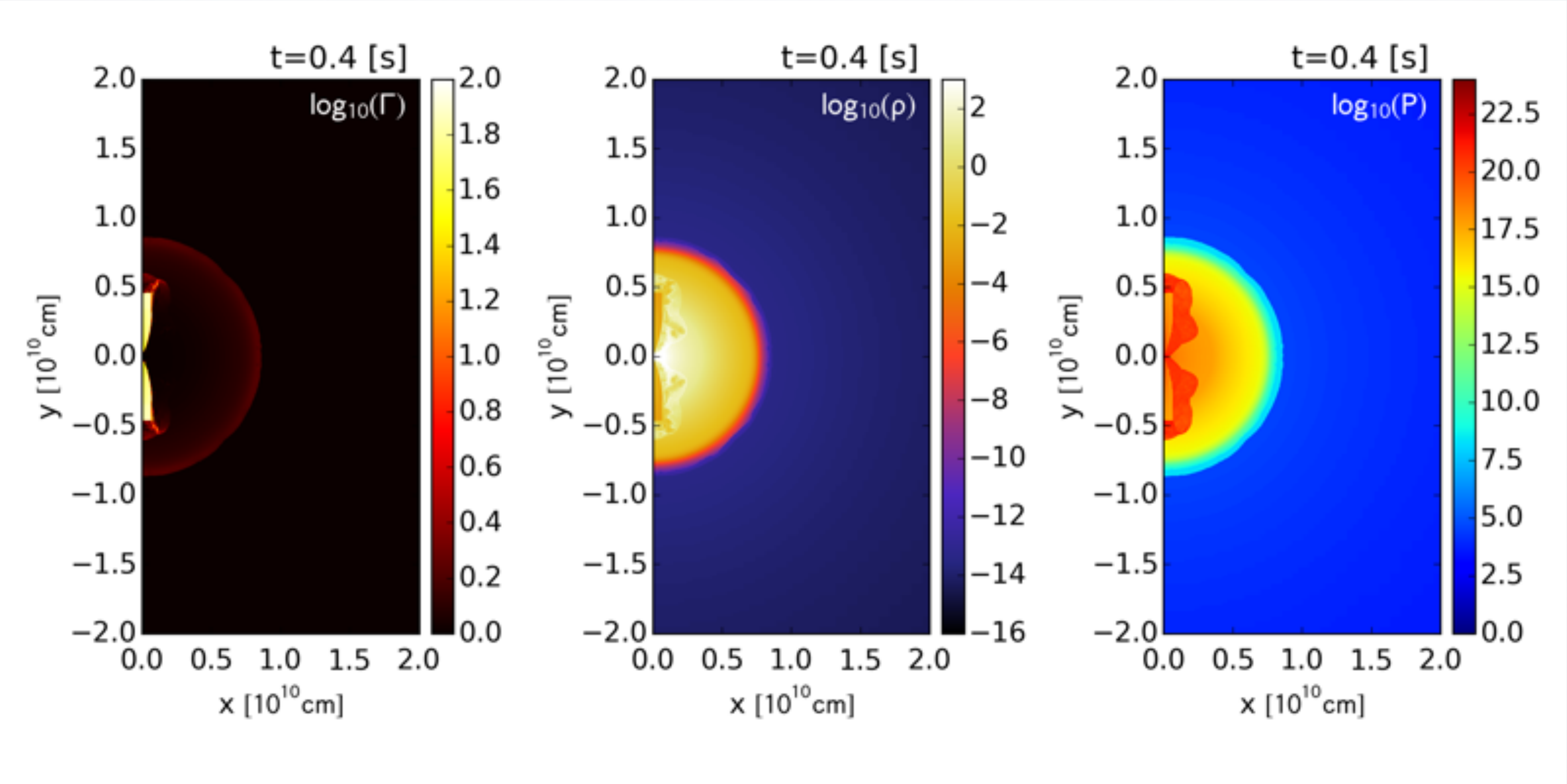
- Dynamical evolution of SN ejecta + additional energy injection is multi-dimensional
- Hot bubble breakout leads to violent mixing (+ precursor?)
- final radial density structure of the ejecta is a simple power-law function
- we have started 3D simulations and confirmed the picture



Future plans

- GRB Jets in SN ejecta → ultra-long GRB + over-luminous SN bump?
- short GRB (dynamical ejecta + sGRB jet)とのanalogy: freely expanding ejecta中での相対論的ジェット伝搬

short GRB jet in 0.01M$_\odot$ dynamical ejecta (preliminary)



Future plans

- GRB Jets in SN ejecta → ultra-long GRB + over-luminous SN bump?
- short GRB (dynamical ejecta + sGRB jet)とのanalogy: freely expanding ejecta中での相対論的ジェット伝搬

short GRB jet in $0.01M_{\odot}$ dynamical ejecta (preliminary)