DYNAMICAL EVOLUTION OF SUPERNOVA EJECTA WITH A CENTRAL ENERGY SOURCE

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Suzuki & Maeda (2017) MNRAS, 466, 2633 (arXiv: 1612.03911)
Suzuki & Maeda (2018) MNRAS, 478, 110 (arXiv: 1804.05397)
Suzuki & Maeda (2019) ApJ, 880, 150 (arXiv:1906.07381)

Multi-Messenger Astrophysics in the Gravitational Wave Era, YITP, Oct. 24, 2019

Superluminous Supernovae

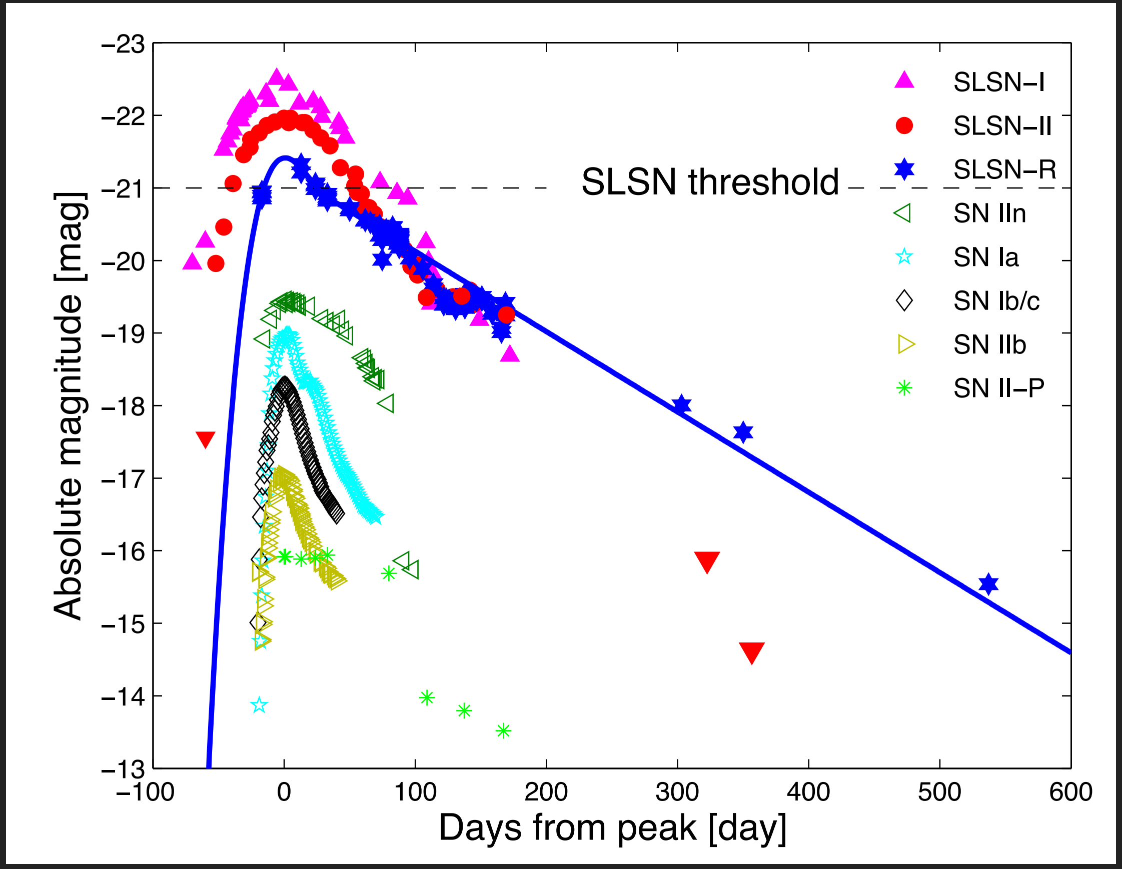
- SNe 10-100 times brighter than normal CCSNe (Quimby+2007, Barbary+ 2009, etc, see Gal-Yam 2012, Moriya+ 2017 for review)
- They are found by recent “unbiased” transient survey projects (e.g., Palomar Transient Factory, Pan-STARRS, etc)
- Spectral classifications (analogy to normal SNe)
  - ➡ SLSNe-I: no Hydrogen feature (no He)
  - ➡ SLSNe-II: Hydrogen feature
- Total radiated energy can be ~10^{51} [erg]

What is their origin?

ejecta-CSM interaction?

Central-engine?

or pair-instability SNe?



Gal-Yam (2012)

Superluminous Supernovae

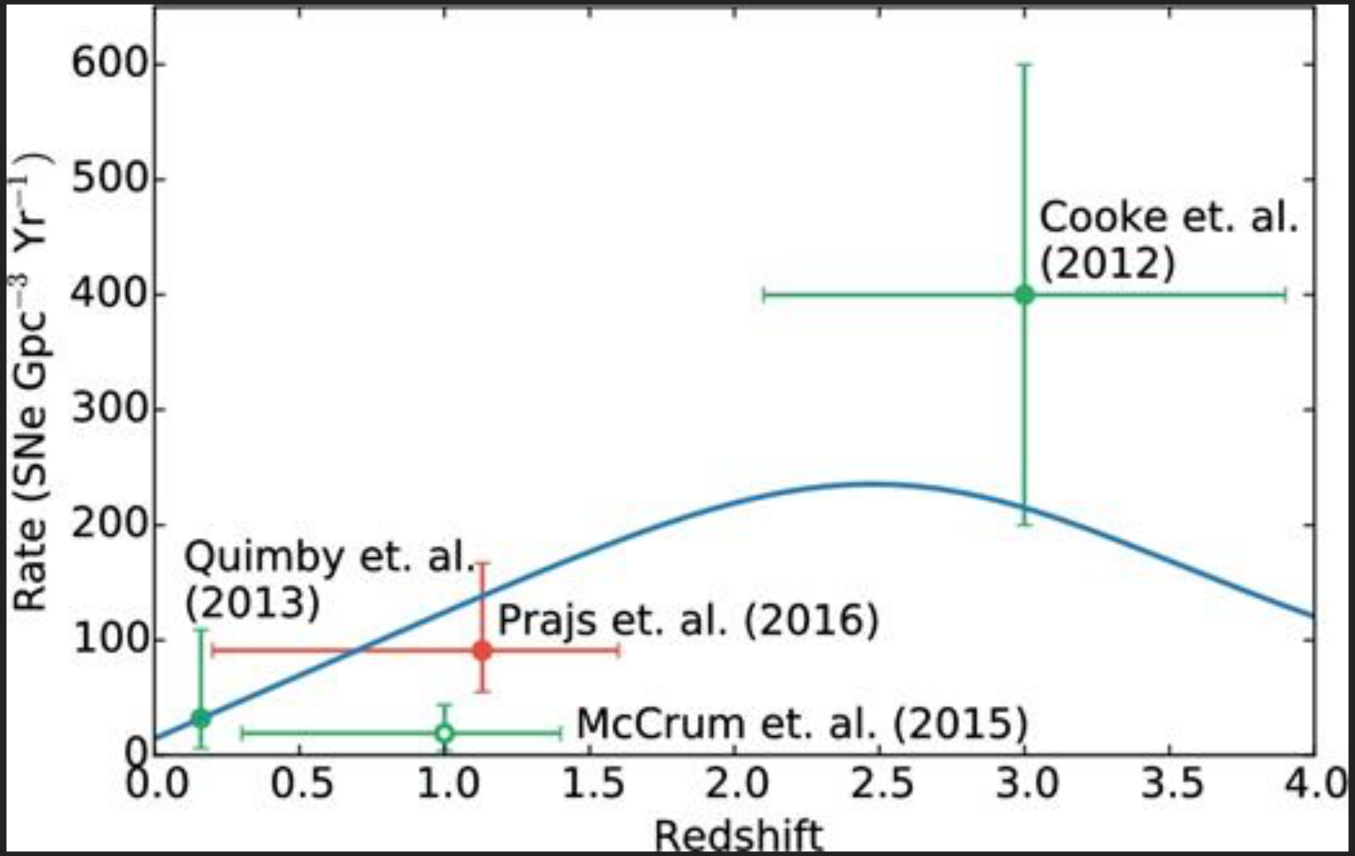
- event rate: they are extremely rare
- 0.01 - 0.1% of normal CCSNe
- CCSNe rate ~ 10^5 $Gpc^{-3}yr^{-1}$ at z~0.2 (e.g., Madau&Dickinson 2014)
- total SLSNe rate:

➡ 199^{+137}_{-86} $Gpc^{-3}yr^{-1}$ at z~0.2 (Quimby+2013)

➡ ~400 $Gpc^{-3}yr^{-1}$ at z=2-4 (Cooke+2012)

➡ ~900 $Gpc^{-3}yr^{-1}$ at z~2 (HSC: Moriya+2018)

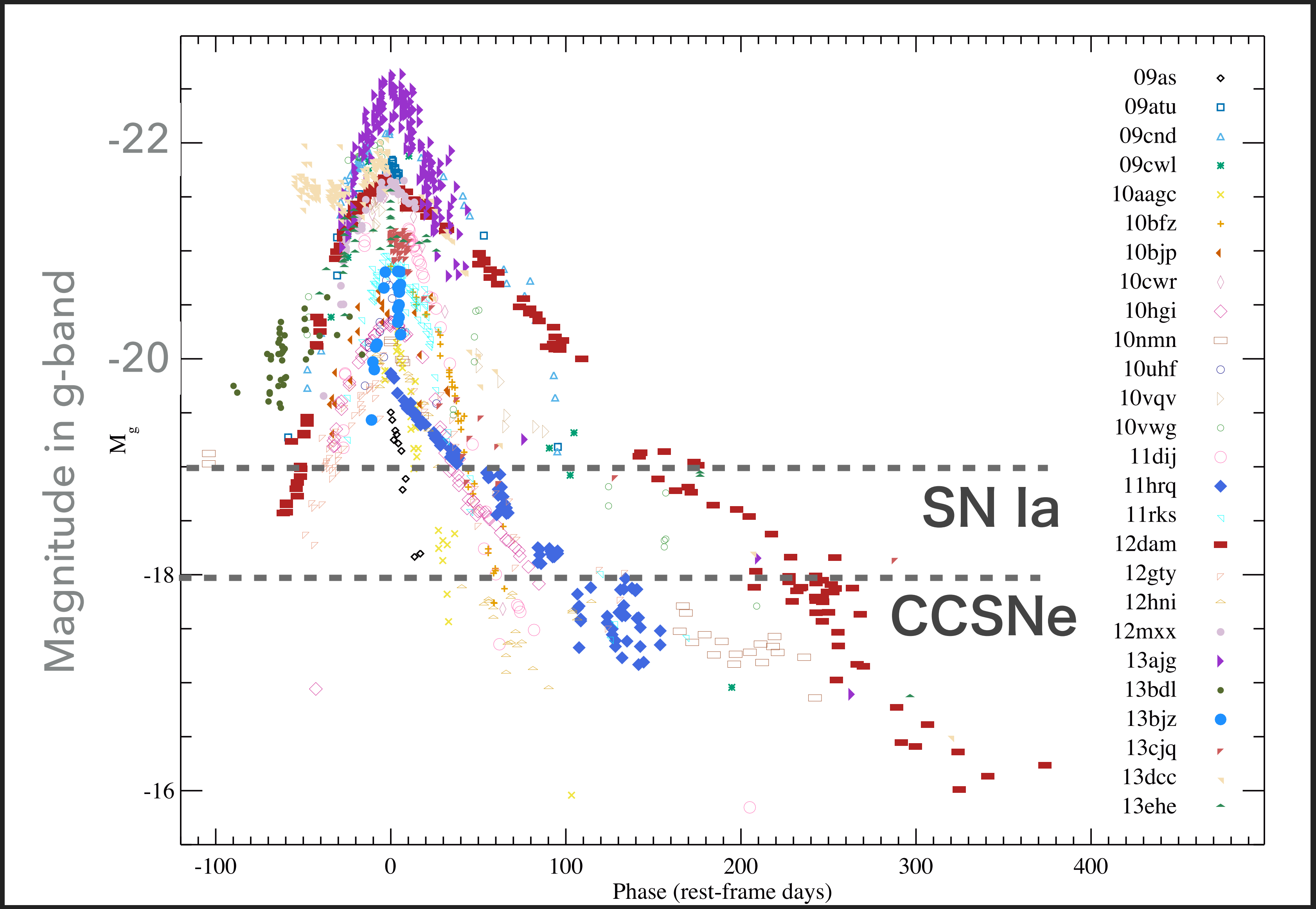
➡ SLSNe-I rate is even lower



↑SLSNe-I rate: Prajs+(2016)

Superluminous Supernovae

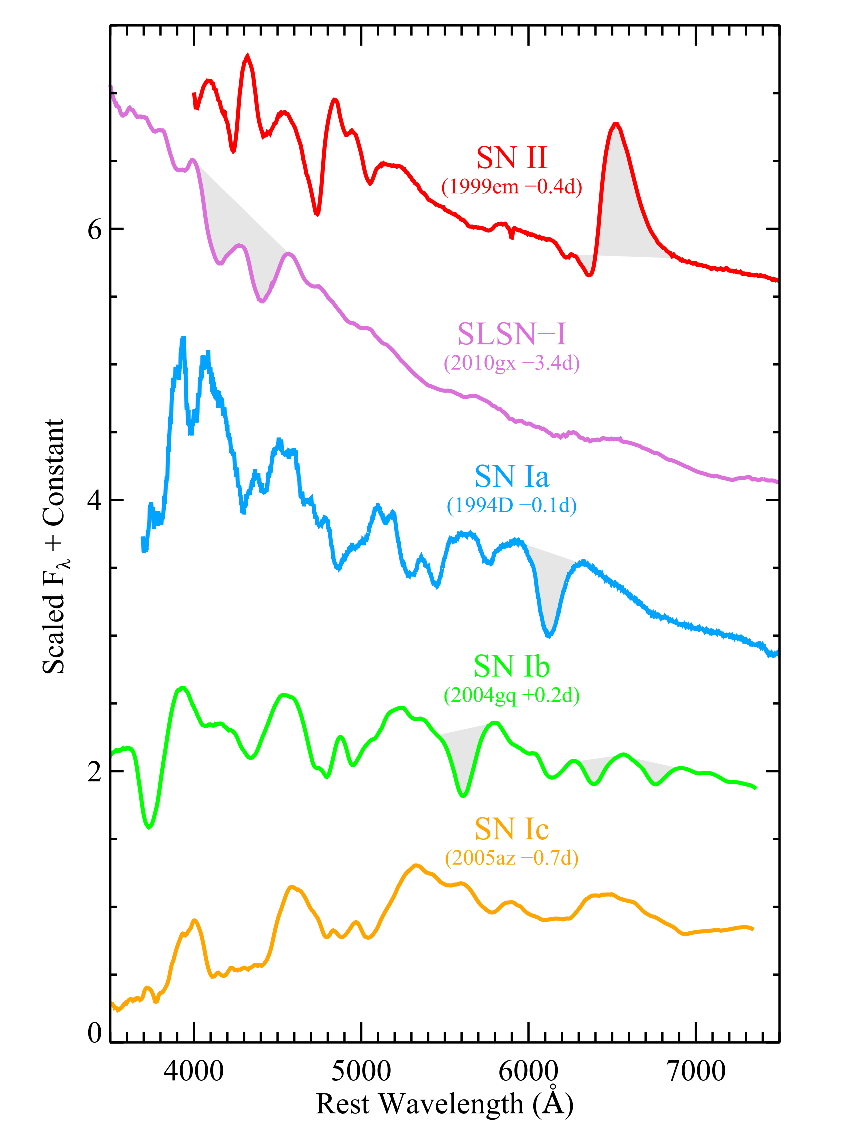
- SLSNe at maximum light: traditional threshold M_{abs}~-21
- the corresponding luminosity of L~10^{44}[erg/s]



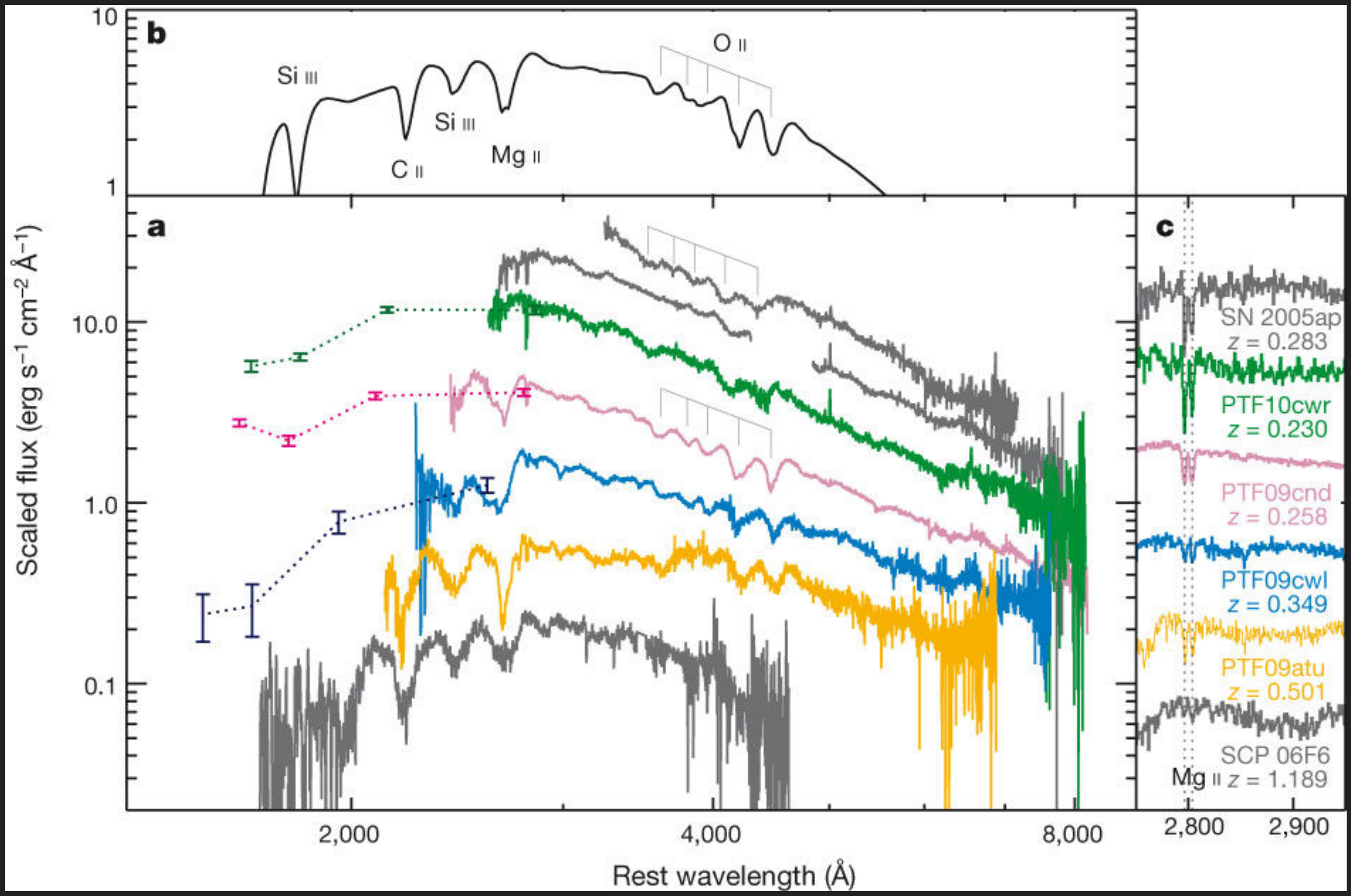
SLSNe-I from the PTF sample (De Cia+ 2017)

Hydrogen-poor Superluminous Supernovae

- spectrum: lack of hydrogen and helium
- blue continuum (T ~ several 10^4 K)
- broad-line
- "w"-shaped spectral feature (caused by O[II], O[III])



schematic SLSNe-I spectra (Quimby+2018)

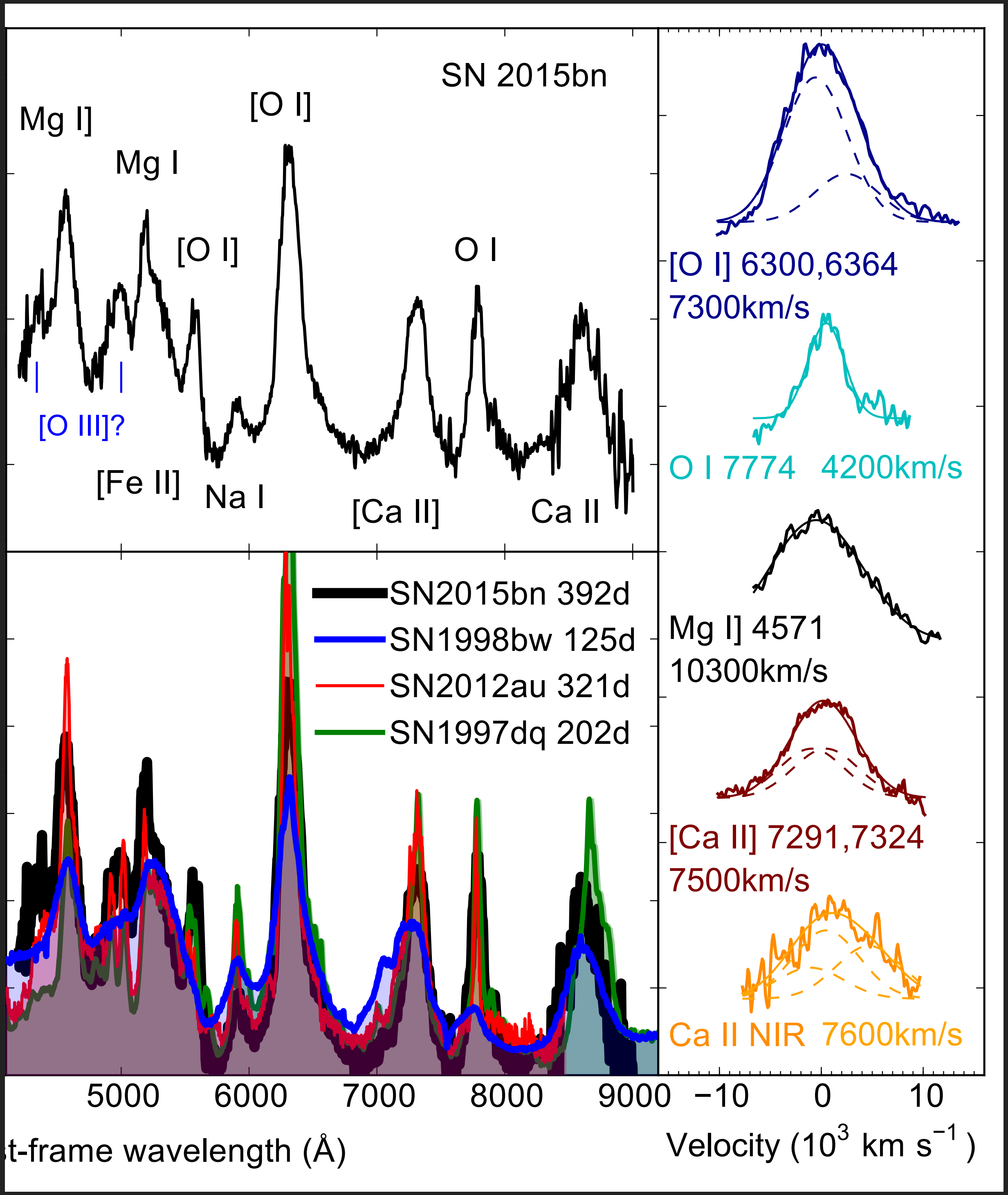


SLSNe-I spectra (Quimby+2011)

Hydrogen-poor Superluminous Supernovae

- Late-time (nebular) spectra
- nebular spectrum of SLSN 2015bn show a remarkable similarity to broad-lined Ic SN 1998bw
- possible link between SLSNe-I and broad-lined Ic (or GRB-SNe)

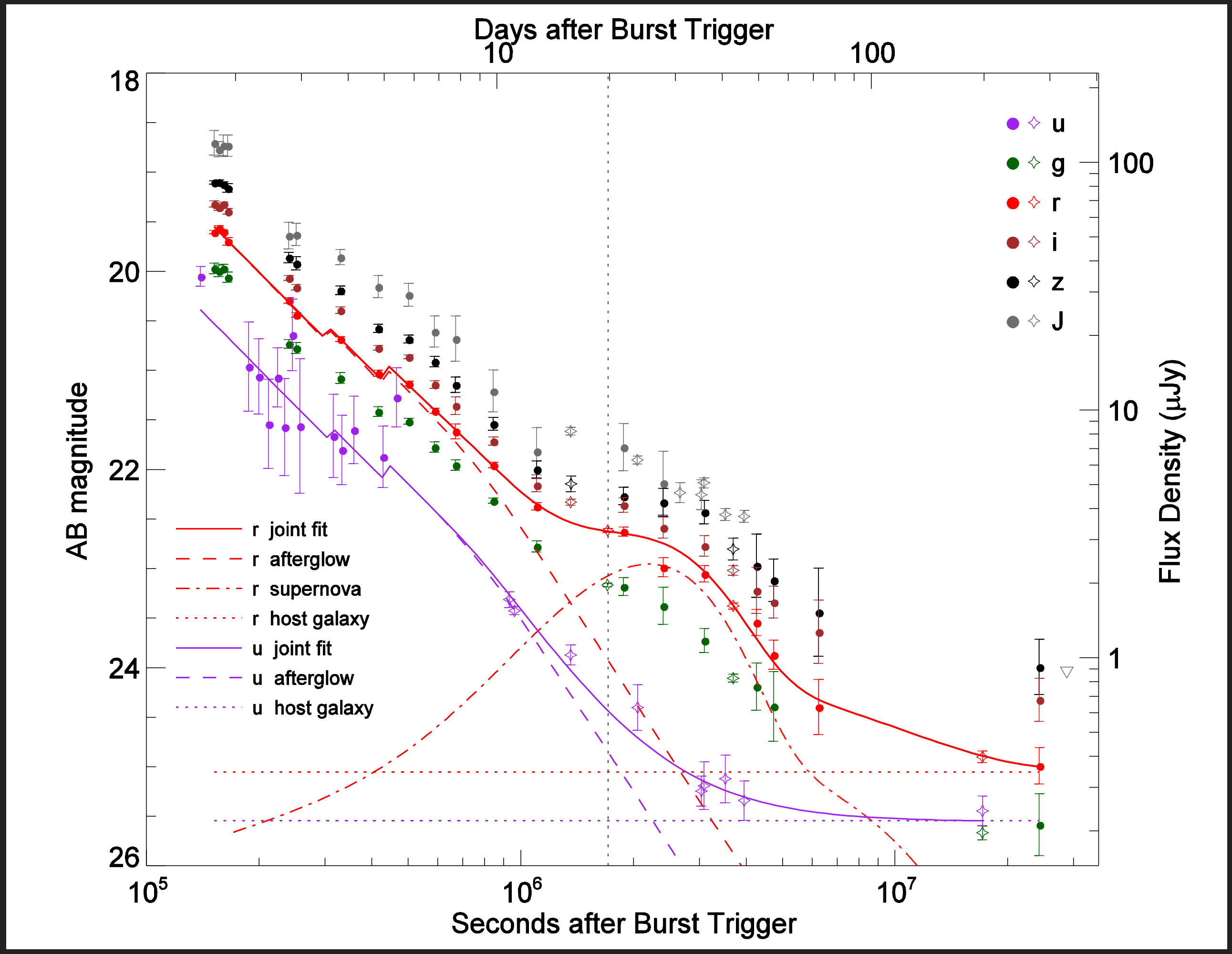
Central-engine in H-poor SLSNe?

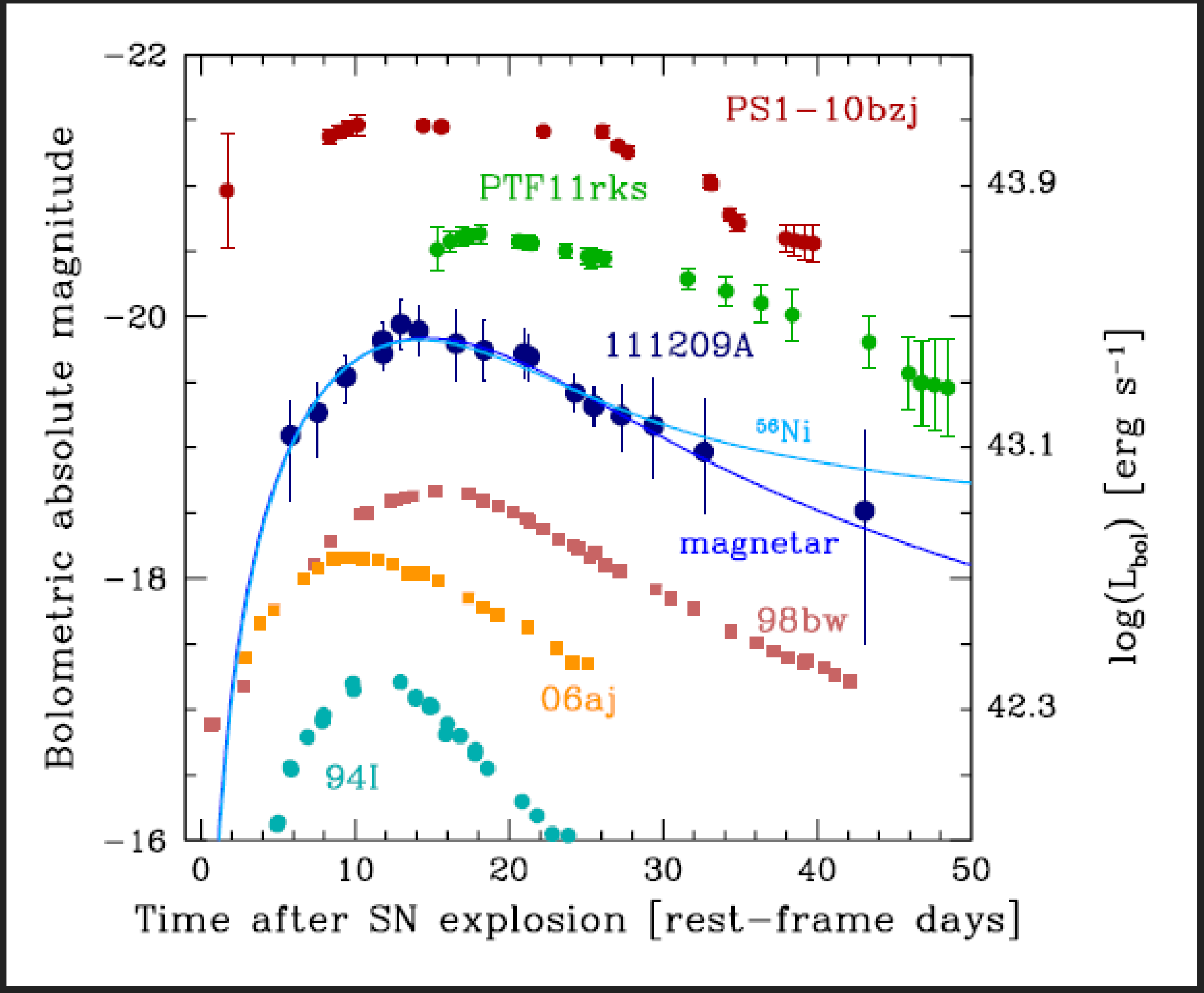


↑Nicholl+(2016)

SLSN-GRB connection?

- SN 2011kl associated with unusually long GRB 111209A
- SN 2011kl was ~3 times more luminous than other GRB-SNe
- similar spectral properties to SLSNe
- common mechanism to produce GRBs and SLSNe?

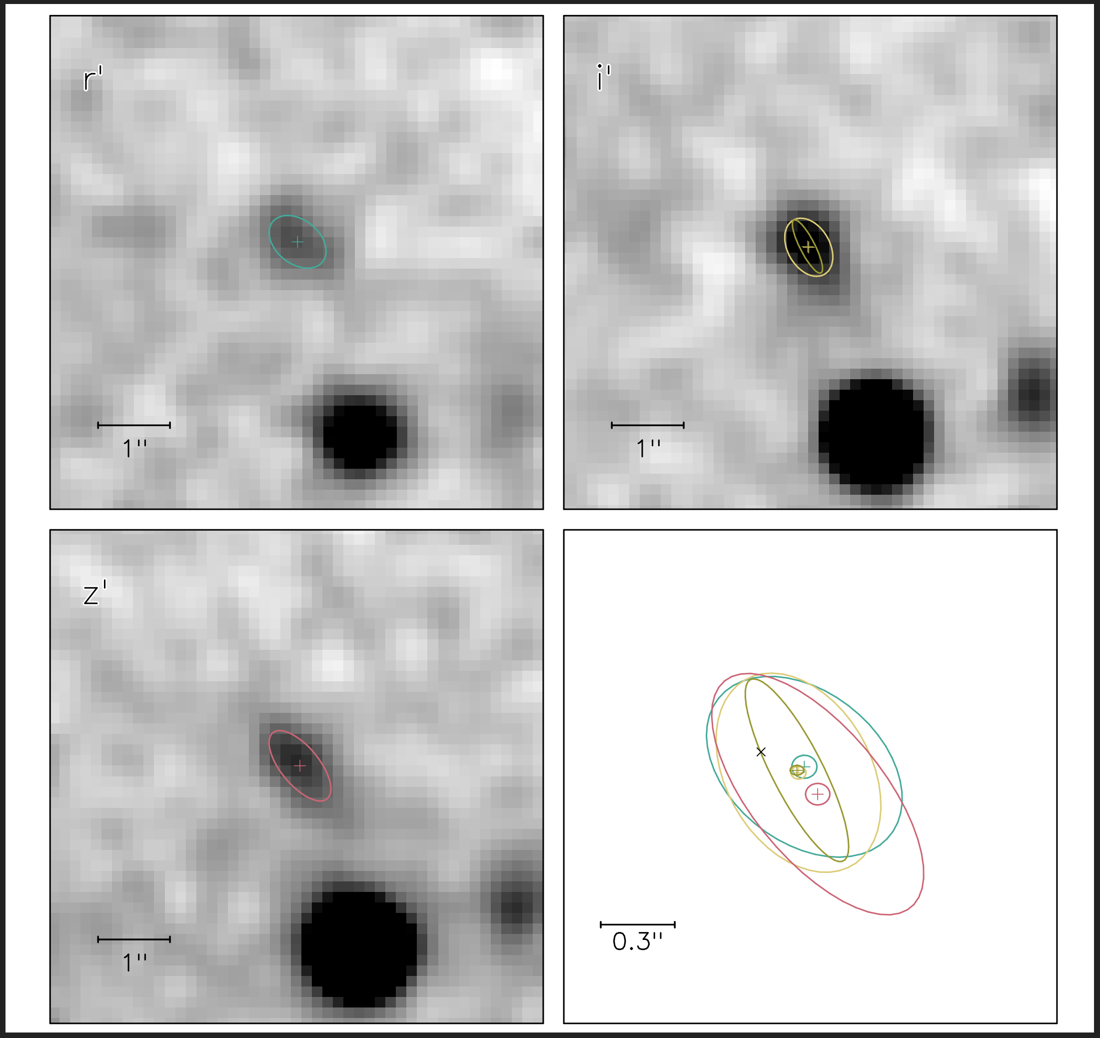




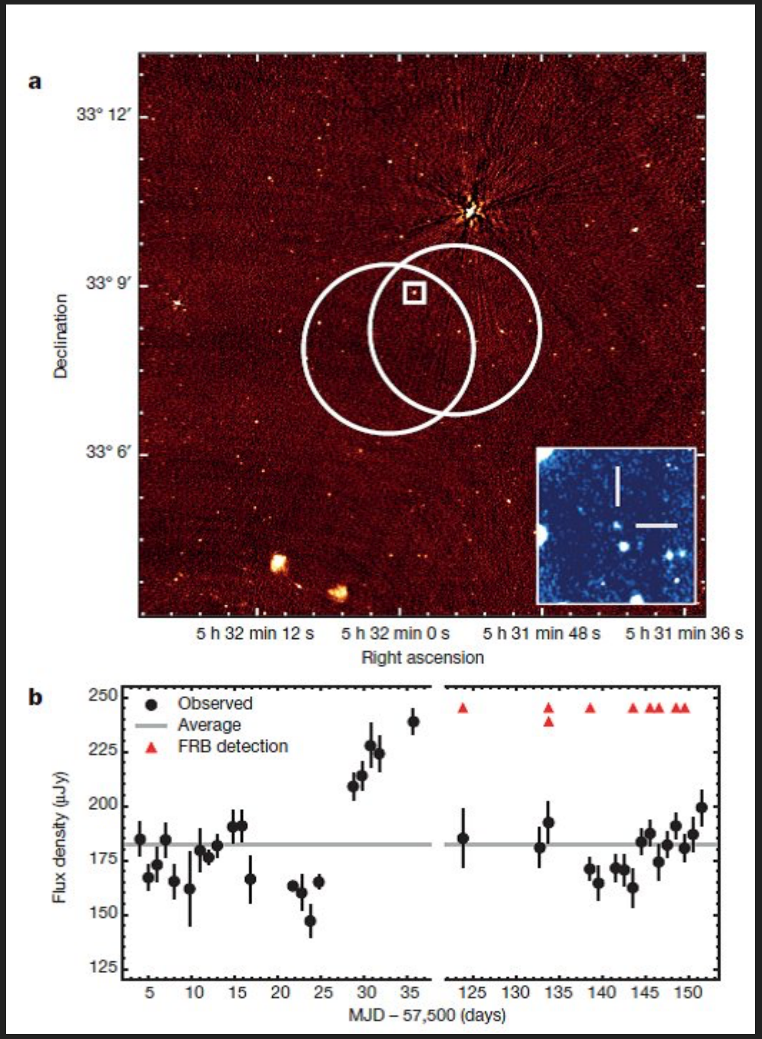
Greinar+(2015)

SLSN-GRB-FRB connection???

- Fast Radio Bursts(FRBs): radio emission lasting for <1ms, source unidentified
- localization of a repeating FRB 121102 (Chatterjee+,Marcote+,Tendulkar+,2017)
- host galaxy was similar to SLSN, GRB host galaxies



Tendulkar+(2017)

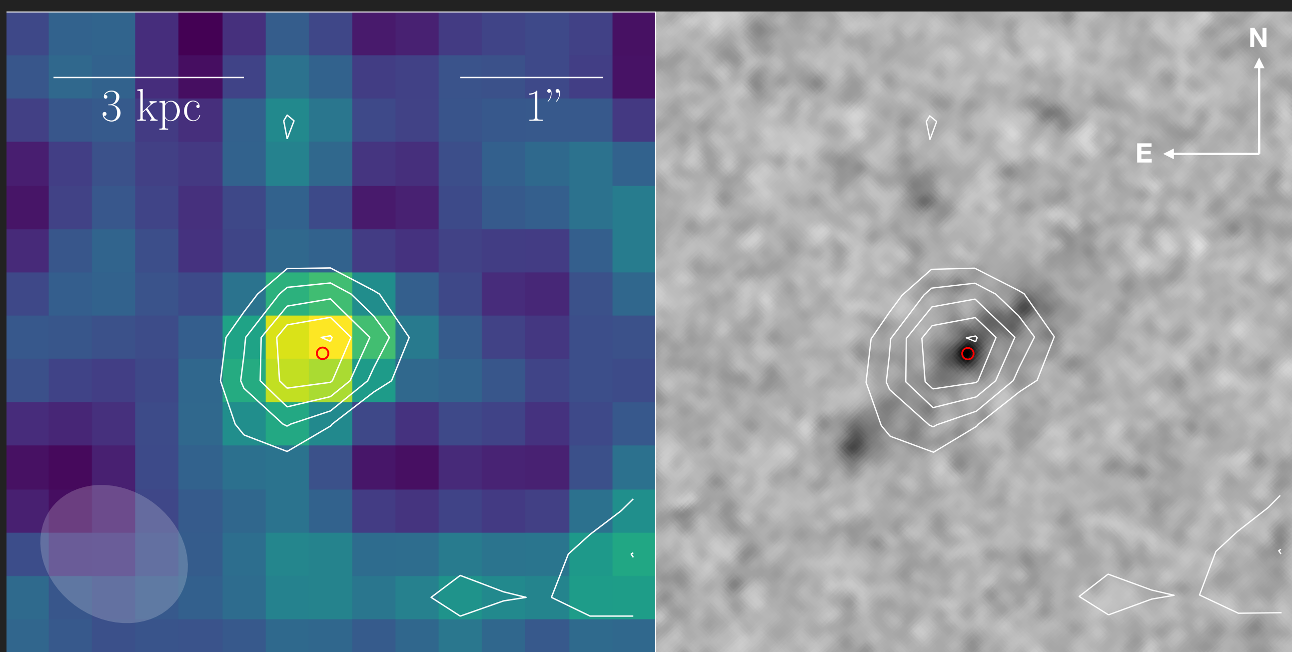


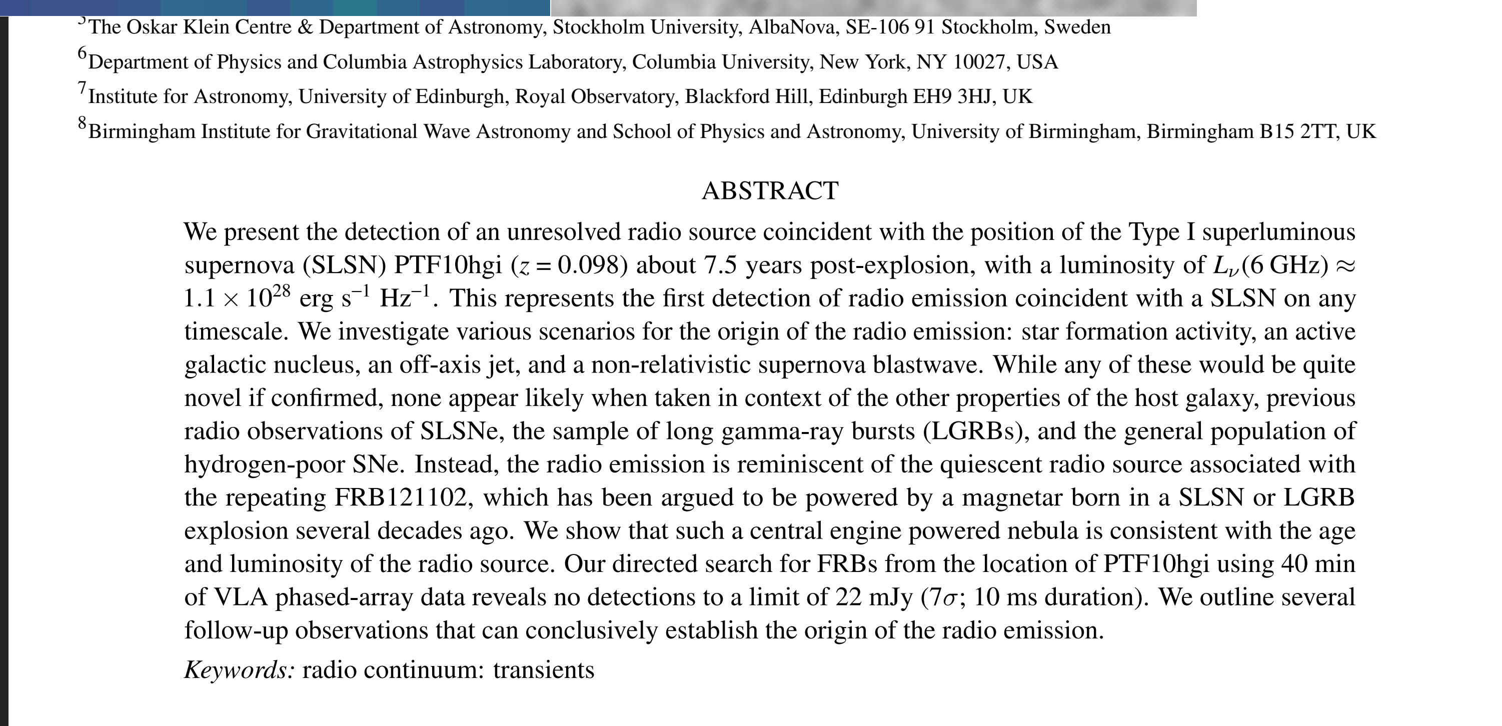
Chatterjee+(2017)

SLSN-GRB-FRB connection???

- first possible association of a persistent radio source with an SLSN site
- similar properties to a repeating FRB 121102 (persistent source + host galaxy)

see also talk by C. Omand





…NCE FOR A CENTRAL

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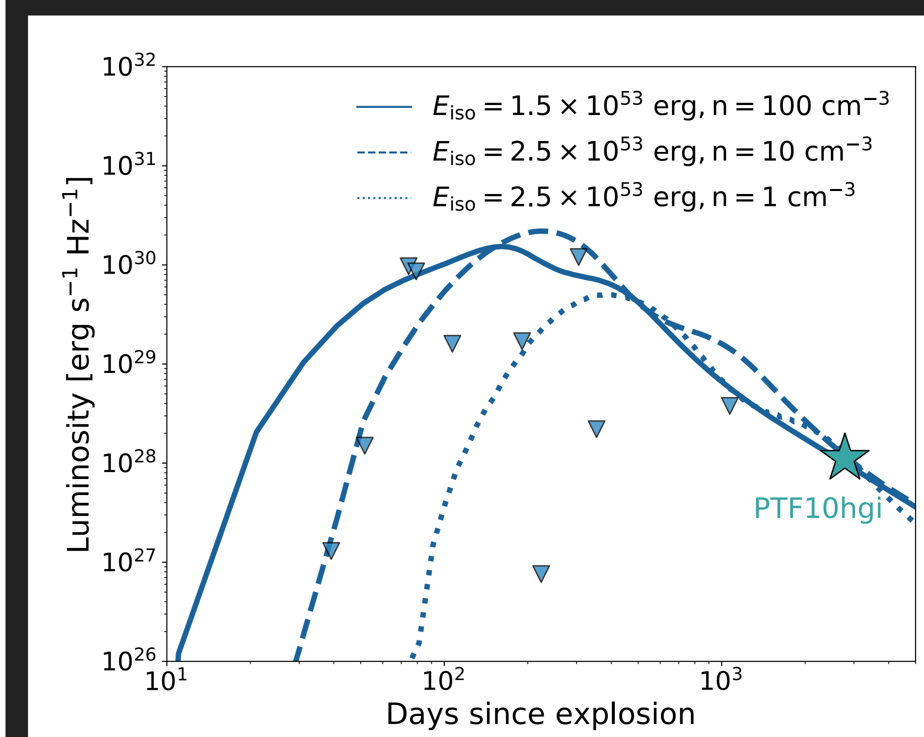
ABSTRACT

We present the detection of an unresolved radio source coincident with the position of the Type I superluminous supernova (SLSN) PTF10hgi ($z = 0.098$) about 7.5 years post-explosion, with a luminosity of $L_\nu(6\,\mathrm{GHz}) \approx 1.1 \times 10^{28}$ erg s^{-1} Hz^{-1}. This represents the first detection of radio emission coincident with a SLSN on any timescale. We investigate various scenarios for the origin of the radio emission: star formation activity, an active galactic nucleus, an off-axis jet, and a non-relativistic supernova blastwave. While any of these would be quite novel if confirmed, none appear likely when taken in context of the other properties of the host galaxy, previous radio observations of SLSNe, the sample of long gamma-ray bursts (LGRBs), and the general population of hydrogen-poor SNe. Instead, the radio emission is reminiscent of the quiescent radio source associated with the repeating FRB121102, which has been argued to be powered by a magnetar born in a SLSN or LGRB explosion several decades ago. We show that such a central engine powered nebula is consistent with the age and luminosity of the radio source. Our directed search for FRBs from the location of PTF10hgi using 40 min of VLA phased-array data reveals no detections to a limit of 22 mJy (7σ; 10 ms duration). We outline several follow-up observations that can conclusively establish the origin of the radio emission.

Keywords: radio continuum: transients

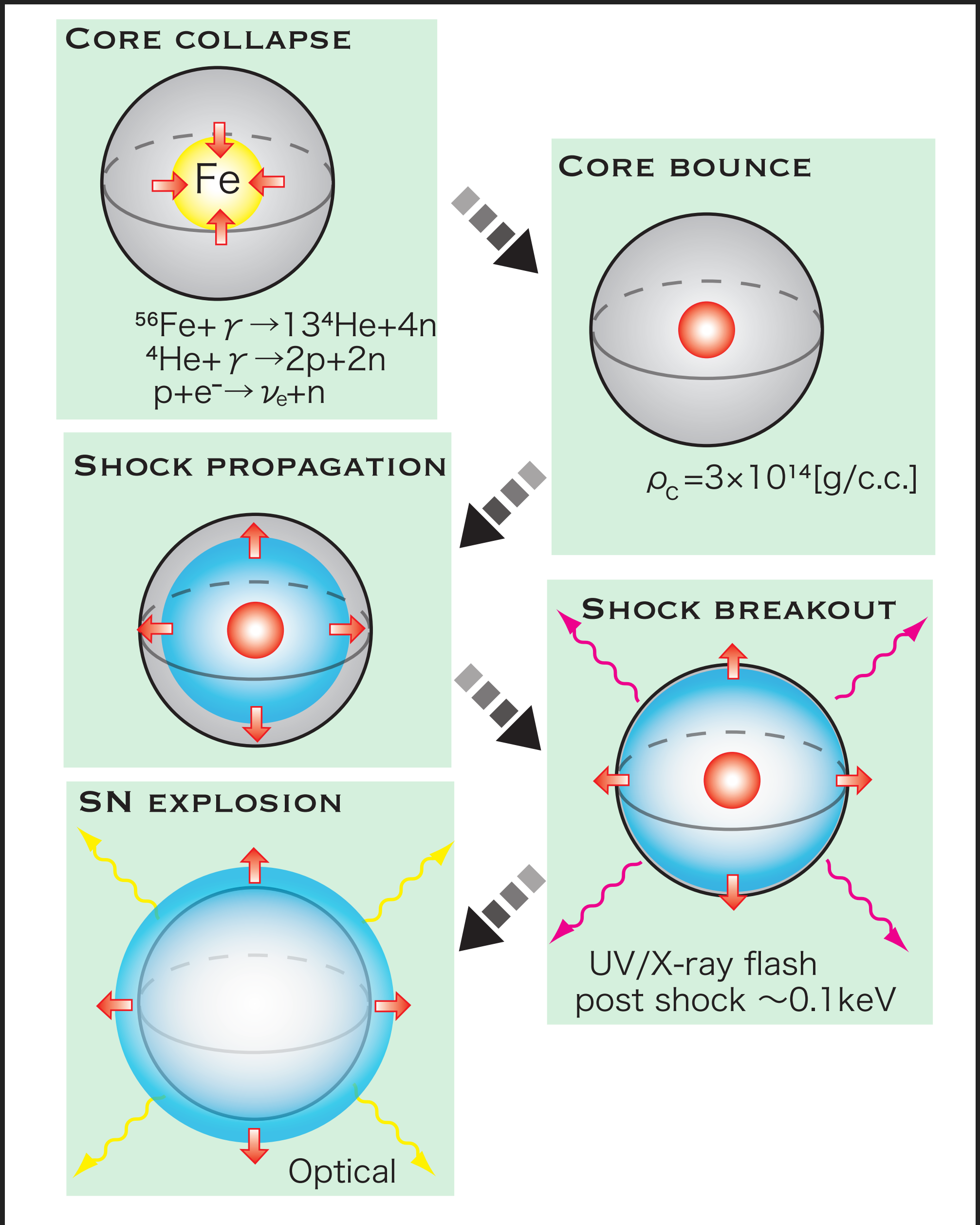
persistent radio emission
at an SLSN site (PTF10hgi)?



Eftekhari+ 2019

Core-collapse Supernova explosion

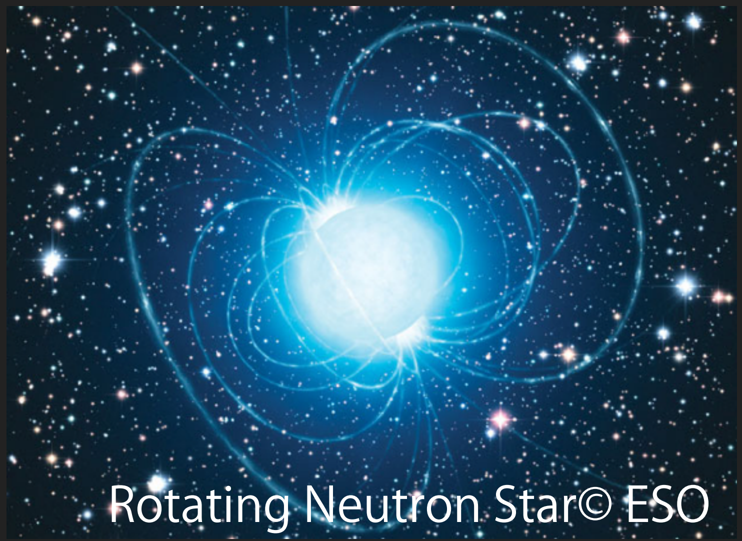
- CCSNe energetics: canonically,
  - ➡ gravitational energy: $E_{grav} \sim GM_{ns}^2/R_{ns} \sim 10^{53}$ [erg]
  - ➡ explosion energy: $E_{exp} \sim$ 1% of $E_{grav} \sim 10^{51}$ [erg]
  - ➡ radiation energy: $E_{rad} \sim$ 1% of $E_{exp} \sim 10^{49}$ [erg]
  - ➡ ejecta mass: $M_{ej} \sim 1 - 10\ [M_\odot]$
  - ➡ typical velocity: $v \sim (2E_{exp}/M_{ej})^{1/2}$ ~ several 1000 - 10000 km/s
  - ➡ typical ^{56}Ni mass: $M_{Ni} \sim 0.1 M_\odot$

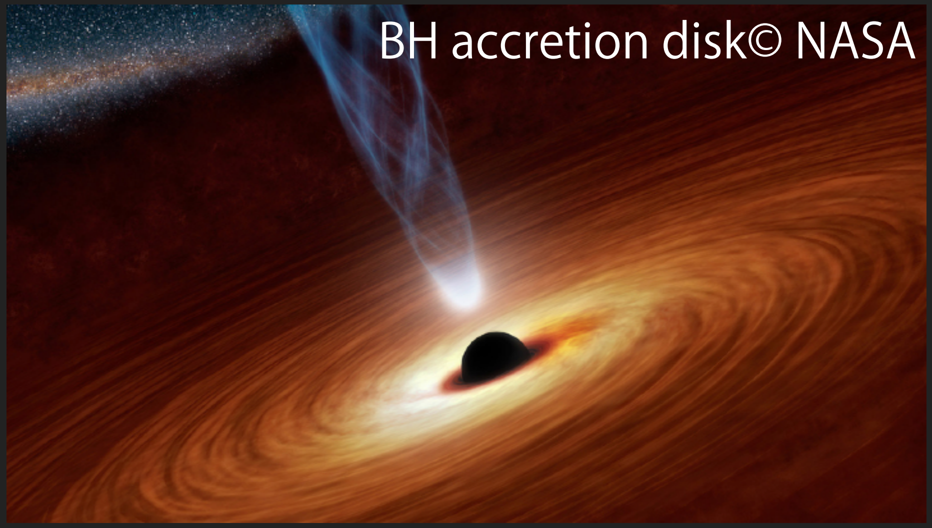


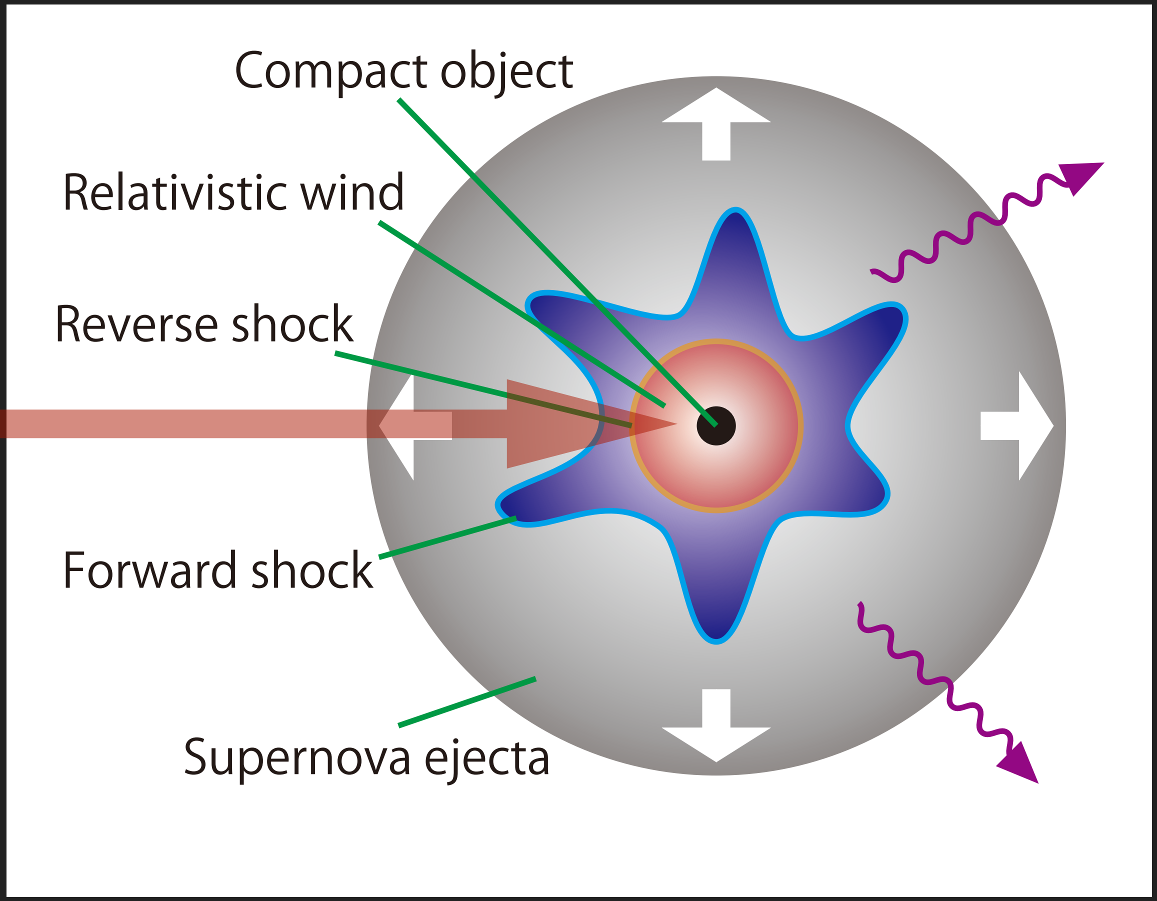
- But, extraordinary events are sometimes found
  - ➡ **broad-line Ic SNe**: ejecta mass and velocity appear to be larger, implying a larger kinetic energy of **10^{52}** [erg] > 10^{51} [erg]
  - ➡ **superluminous SNe**: extremely bright SNe with total radiated energies of **10^{51}** [erg] > 10^{49} [erg]

Scenarios for hydrogen-poor SLSNe

- pair-instability SNe (very massive progenitor with M~140-300 M$_\odot$)
- CSM (circum-stellar media) interaction
- additional energy injection from the central-engine :rotating neutron star (Kasen&Bildsten 2010, Woosley2010), or BH accretion (Dexter&Kasen 2013)

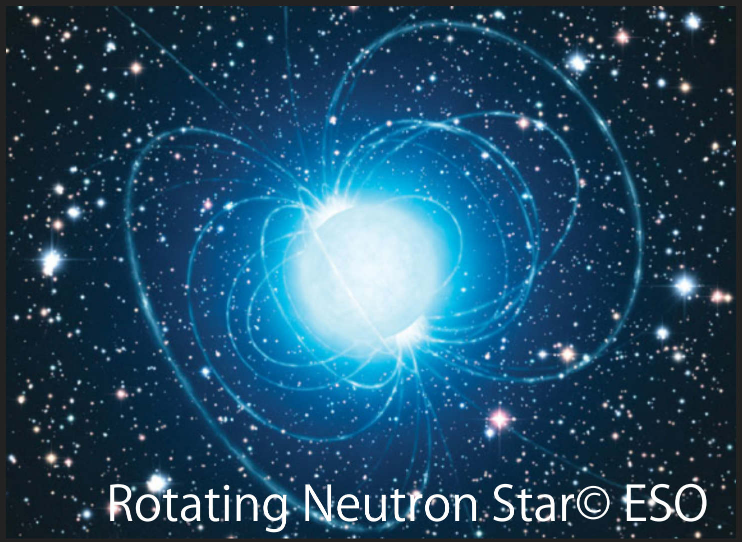






Rotating magnetized (proto-)neutron star hypothesis

- after the iron-core collapse, a massive star can leave a magnetized neutron star rotating at a high frequency
- a magnetized neutron star loses its rotational energy via dipole radiation
  - ➡ NS radius: R_{ns}~10 km
  - ➡ moment of inertia: I_{ns}~ 10^{45} g cm^2
  - ➡ initial period: P_i~1 [ms], Ω_i=2π/P_i~ 6x10^3 Hz
  - ➡ rotational energy: E_{rot}=$I_{ns}\Omega^2/2$~2x10^{52} erg



- spin-down of the new-born NS can power the SN ejecta

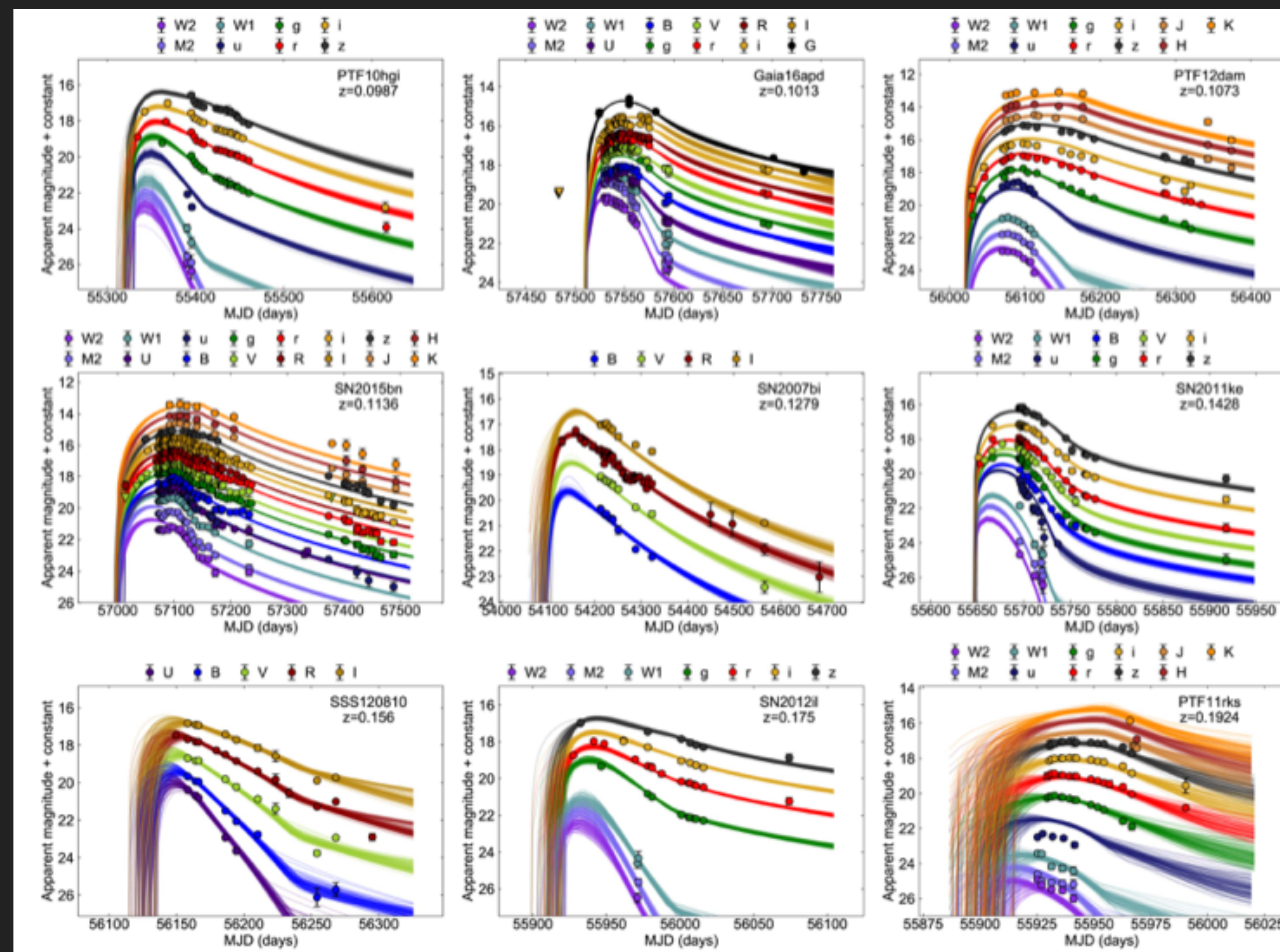
$$L = \frac{E_{\rm rot}/t_{\rm ch}}{(1+t/t_{\rm ch})^2}$$

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

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

Rotating magnetized (proto-)neutron star hypothesis

- one-box light curve model.
- injection of the spin-down energy into the SN ejecta
- the injected energy is instantaneously thermalized and diffusing out from the ejecta



Multi-color light curve fit: Nicholl+(2017)

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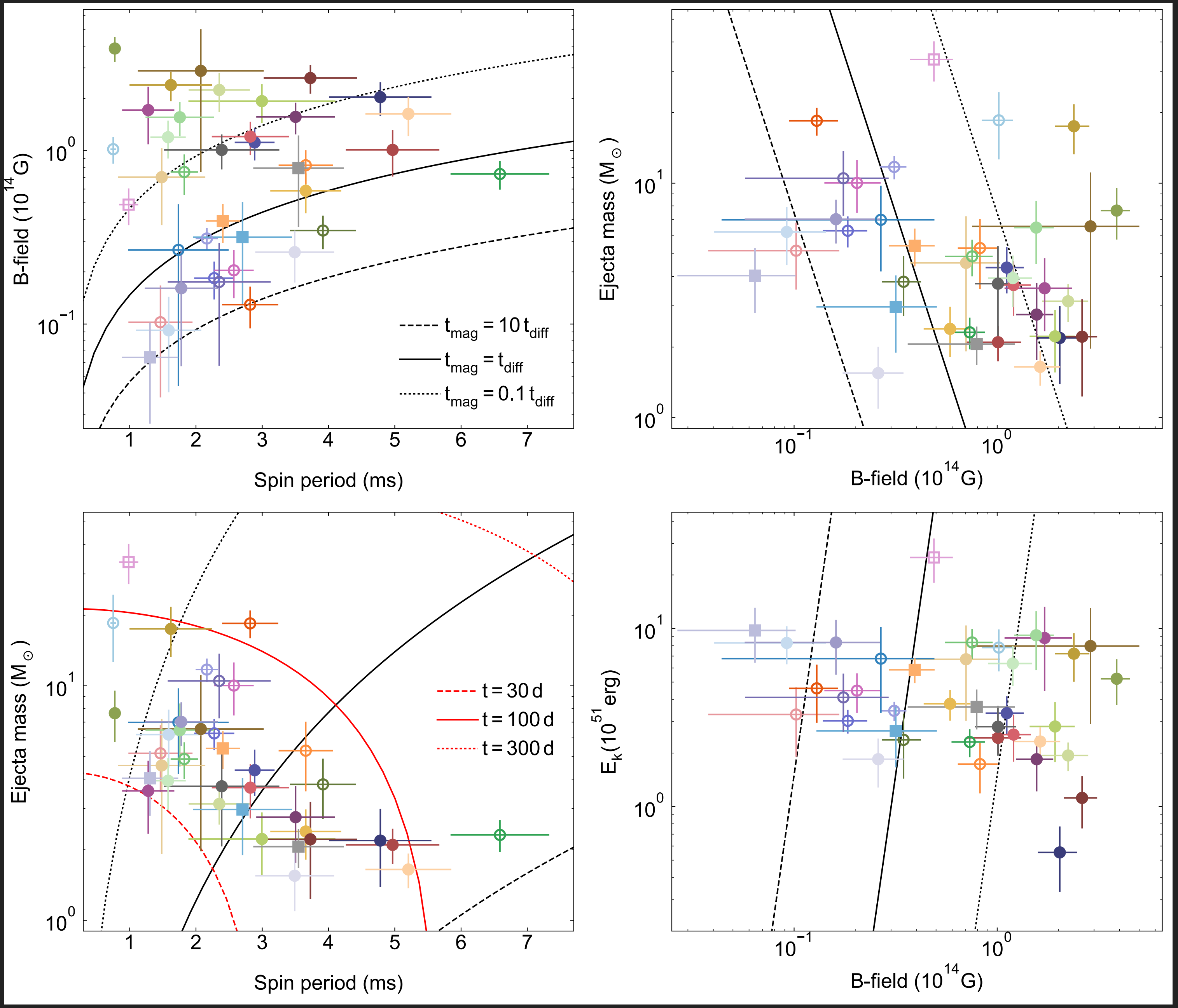
➡spin-period ~ 1 - 7 [ms]

➡B ~ 10^{13} - a few 10^{14} [G]

➡E_k ~ 10^{51} - 10^{52} [erg]

➡M_{ej} ~ 2 - 10 $M_\odot$

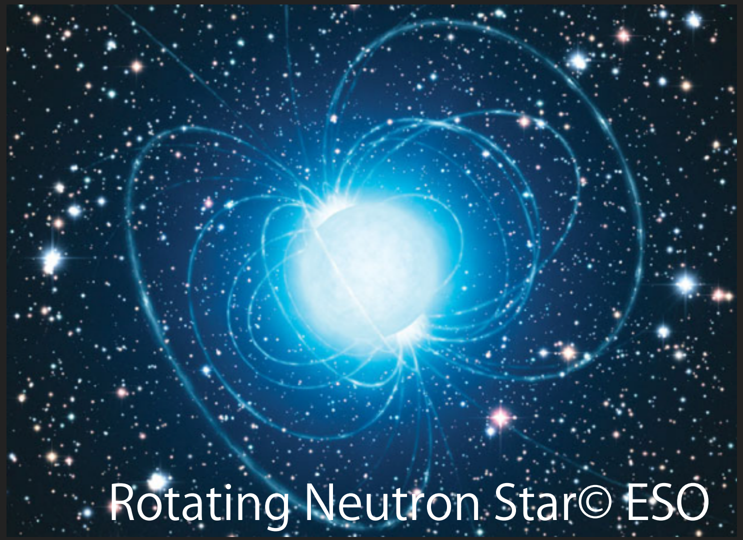
How we can prove magnetar hypothesis?

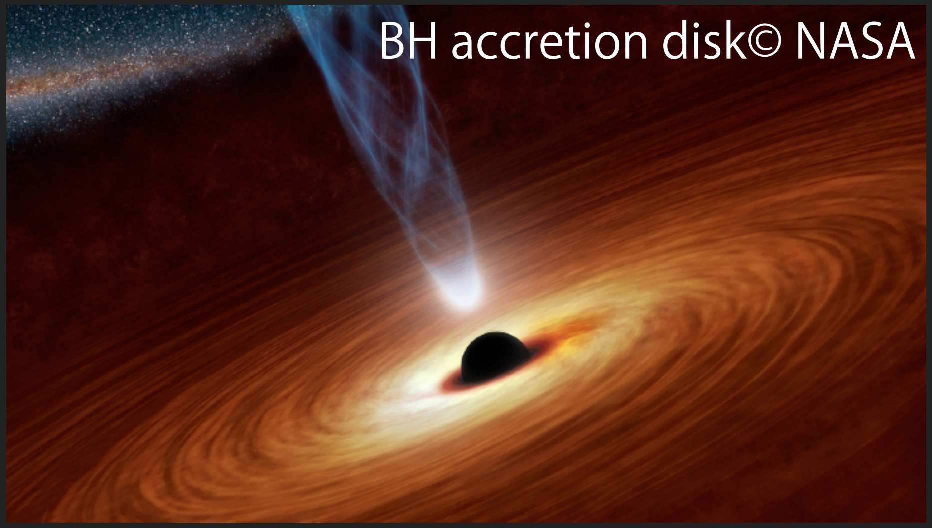


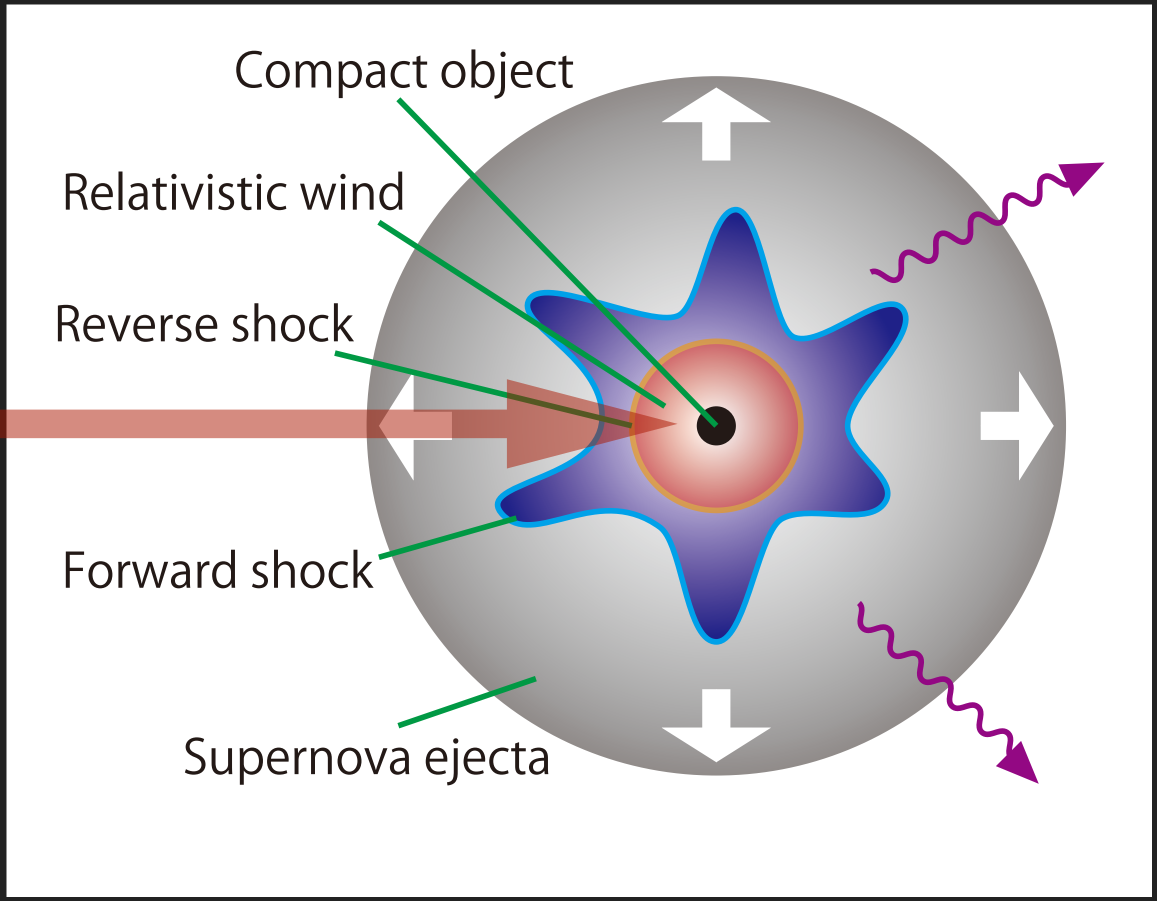
Nicholl+(2017)

How can we probe the powerful engine?

- Their impacts on SN ejecta : SN light curves and spectra
- Non-thermal emission from a wind nebula embedded in SN remnant (later times)


Rotating Neutron Star© ESO


BH accretion disk© NASA



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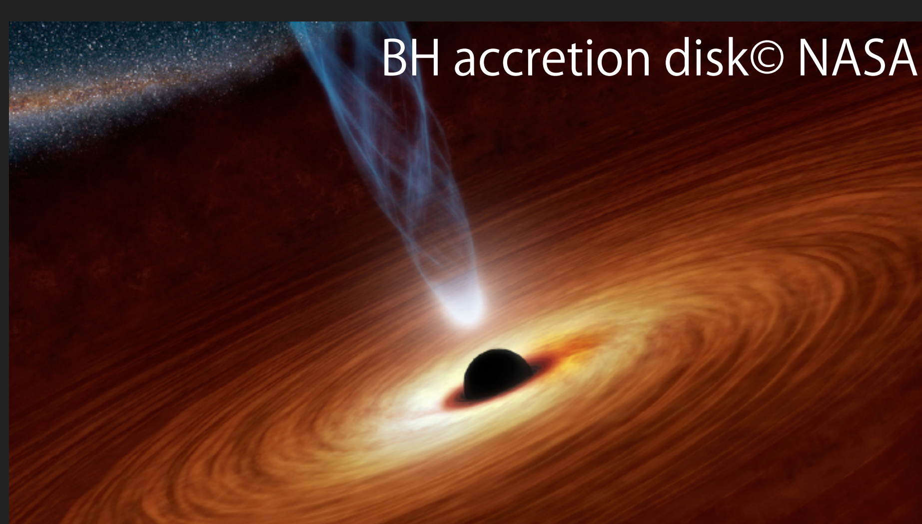
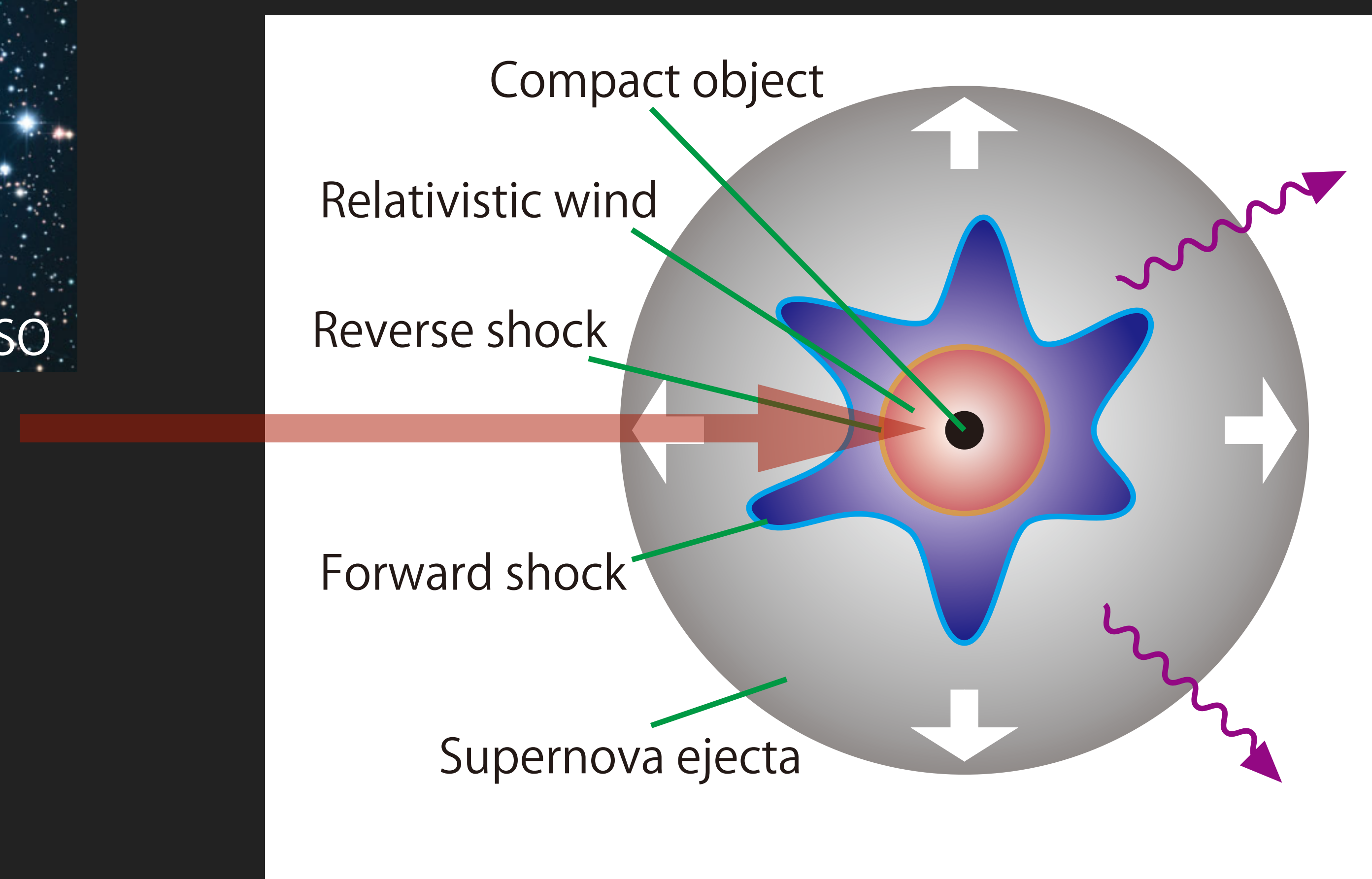
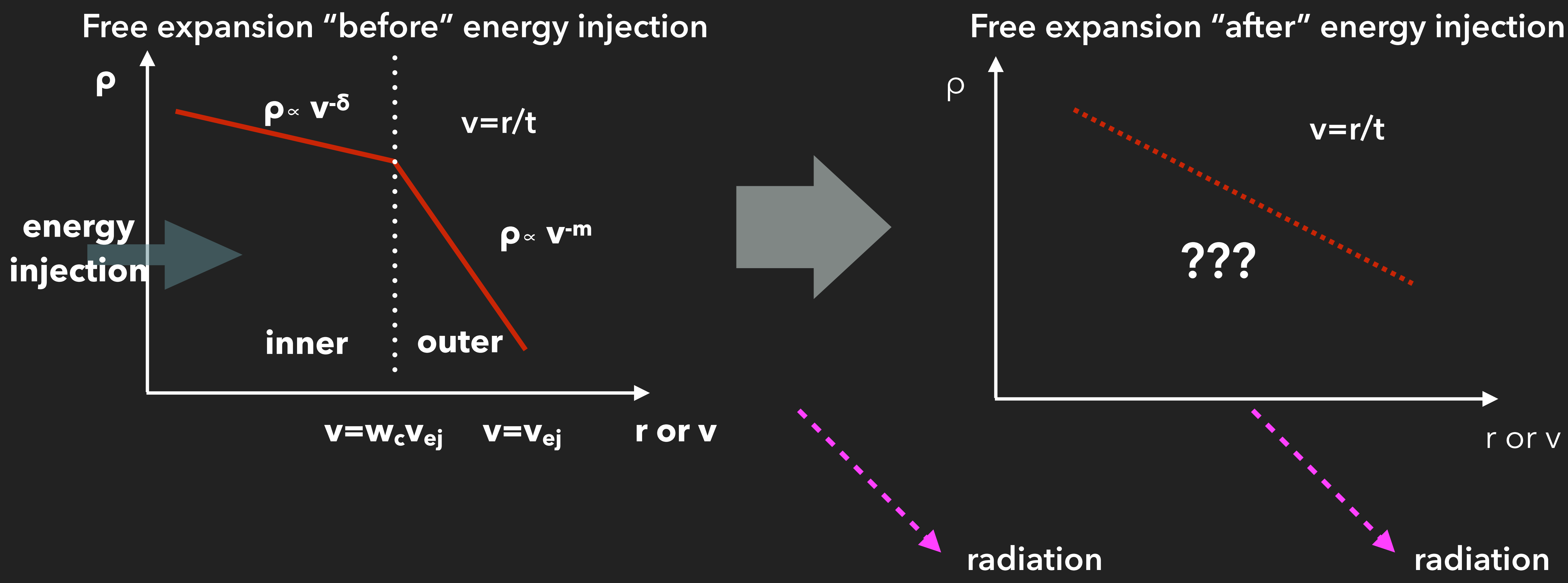




Energy re-distribution in SN ejecta



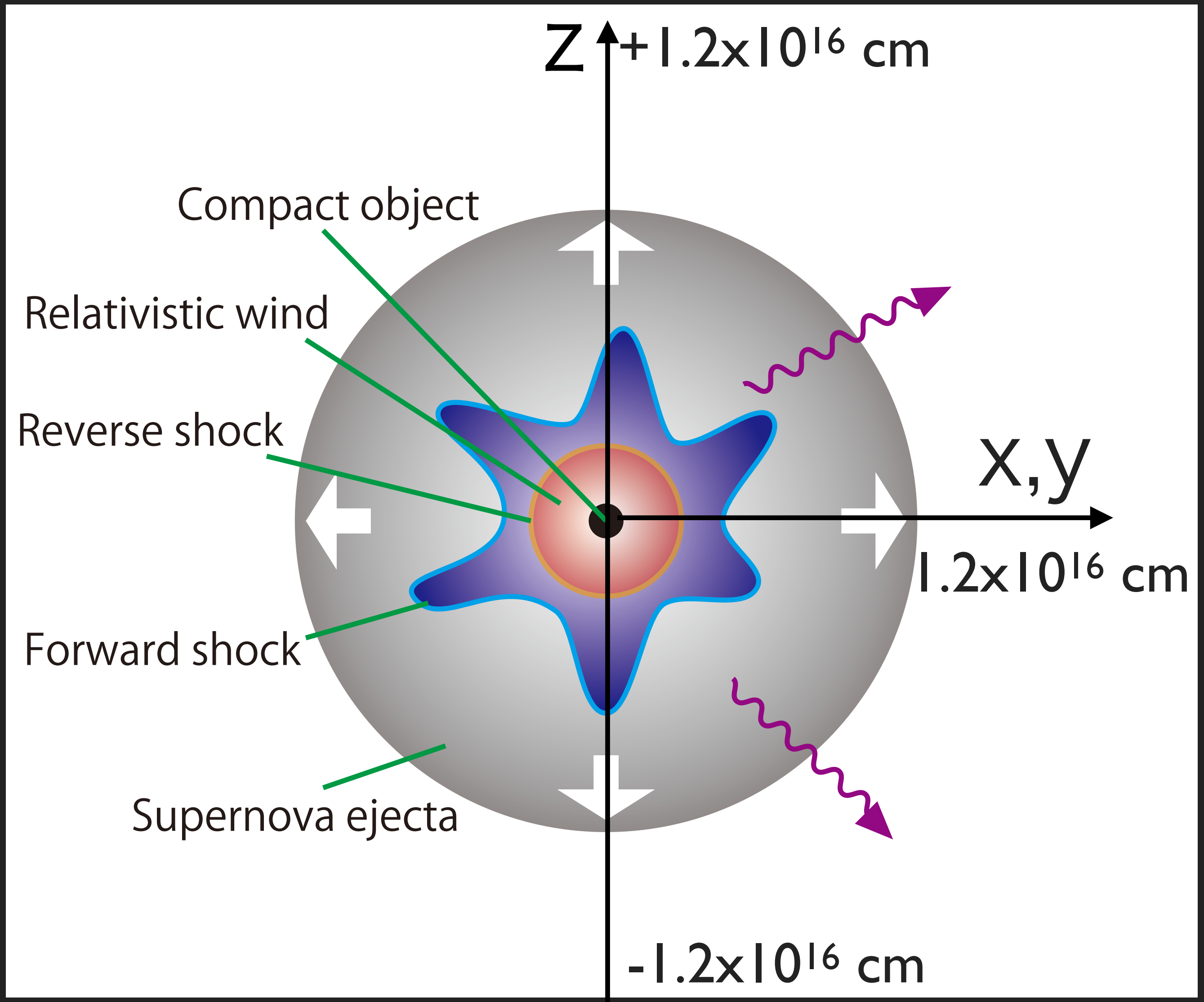
- We inject a relativistic wind from the central region
- How the injected energy is **transported** and **redistributed** in the SN ejecta
- What is the final density and kinetic energy distributions?
- (What about the conversion efficiency of the injected energy into radiation?)

Numerical setups (Suzuki&Maeda 2019)

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

- SR hydrodynamic simulation
- 3D cartesian coordinate (x,y,z)
- -4.8×10^{16}[cm]<x,y,z<4.8×10^{16}[cm]
- AMR technique
- ideal gas law with $\gamma=4/3$
- SN ejecta with $M_{ej}=10[M_\odot]$,

  $E_{sn}=10^{51}$ [erg]: broken power-law density profile with $\delta=1$ and m=10
- relativistic gas injection from a small region at the center
- injection rate $L=10^{46}$[erg/s] up to $Lt=10^{52}$ [erg]
- $dM/dt=0.05L/c^2$
- unit time $t_c=E_{sn}/L=10^5$s~1day
- simulation from $t=0.02t_c$ to $20t_c$



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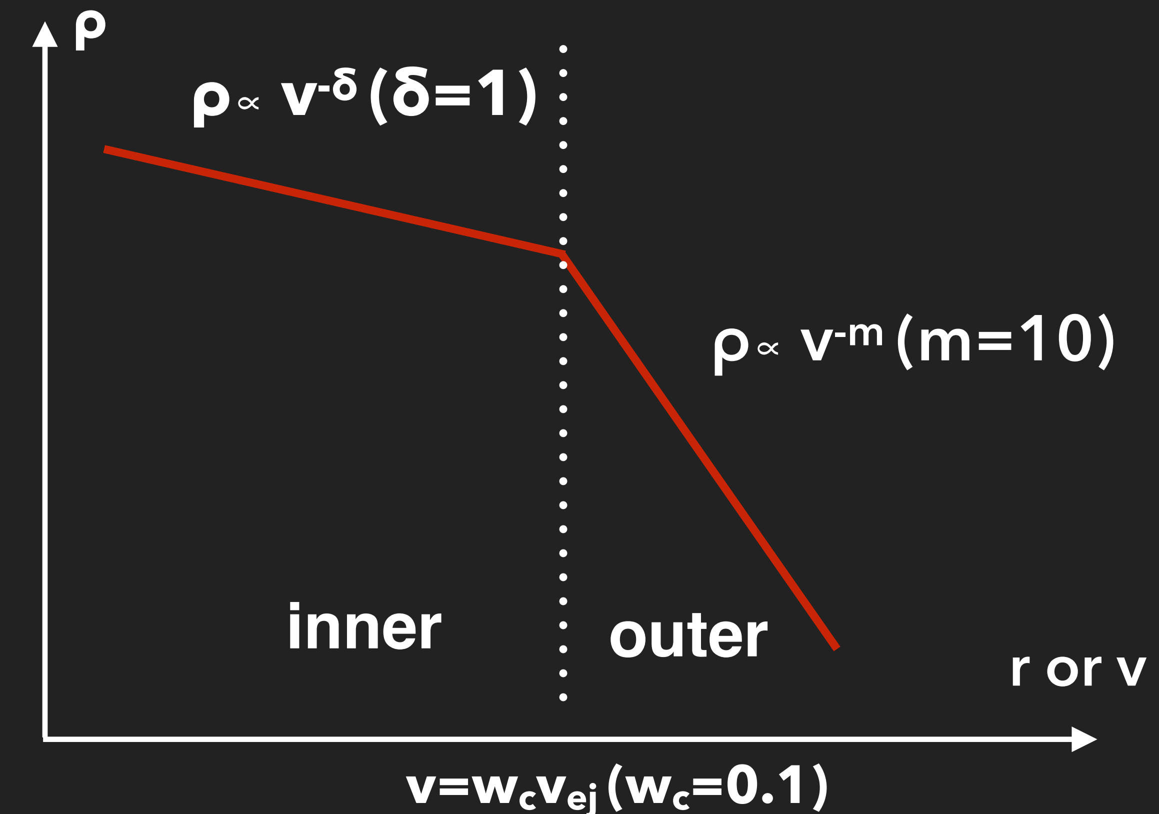
Free expansion : v=r/t



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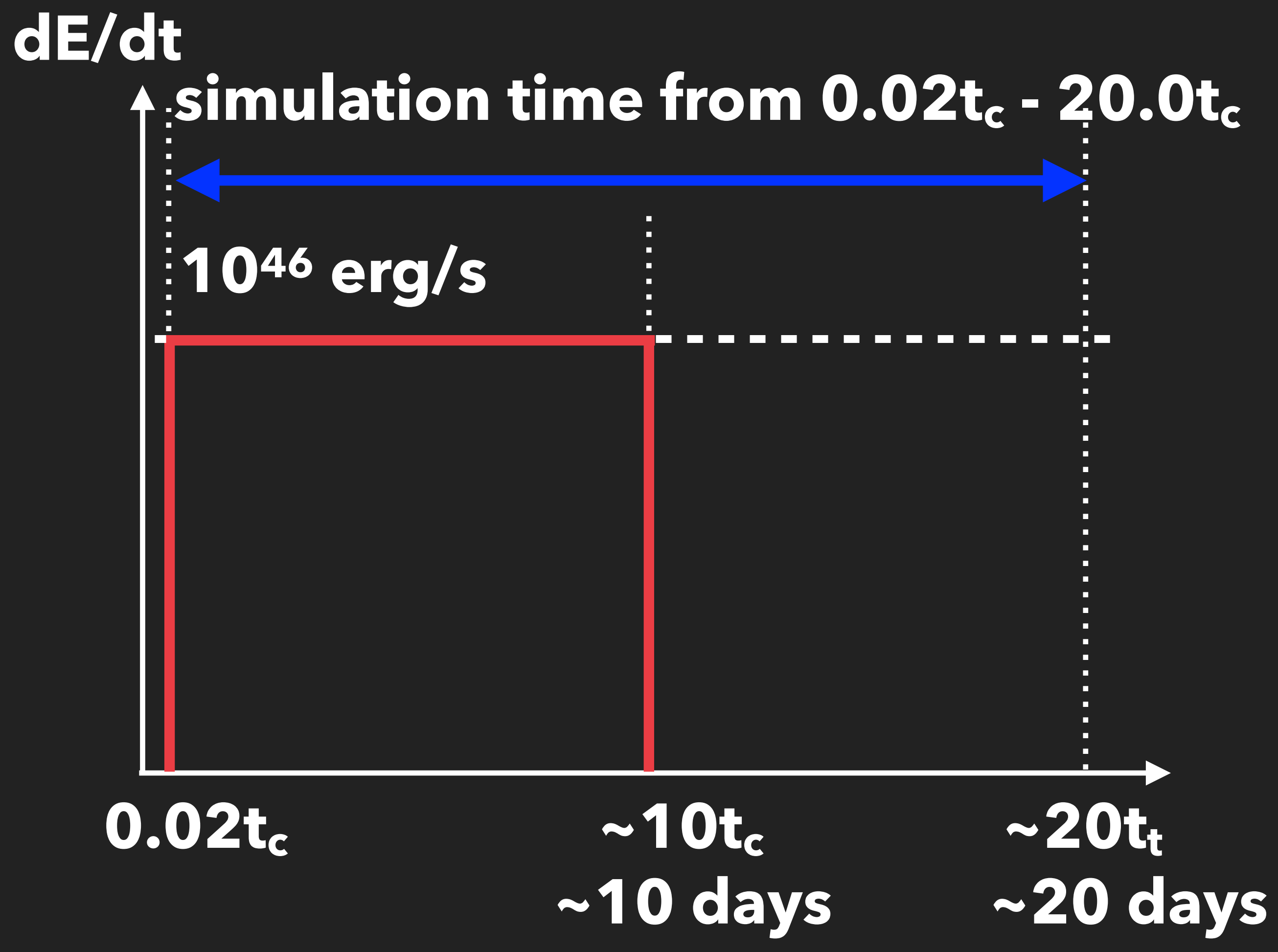
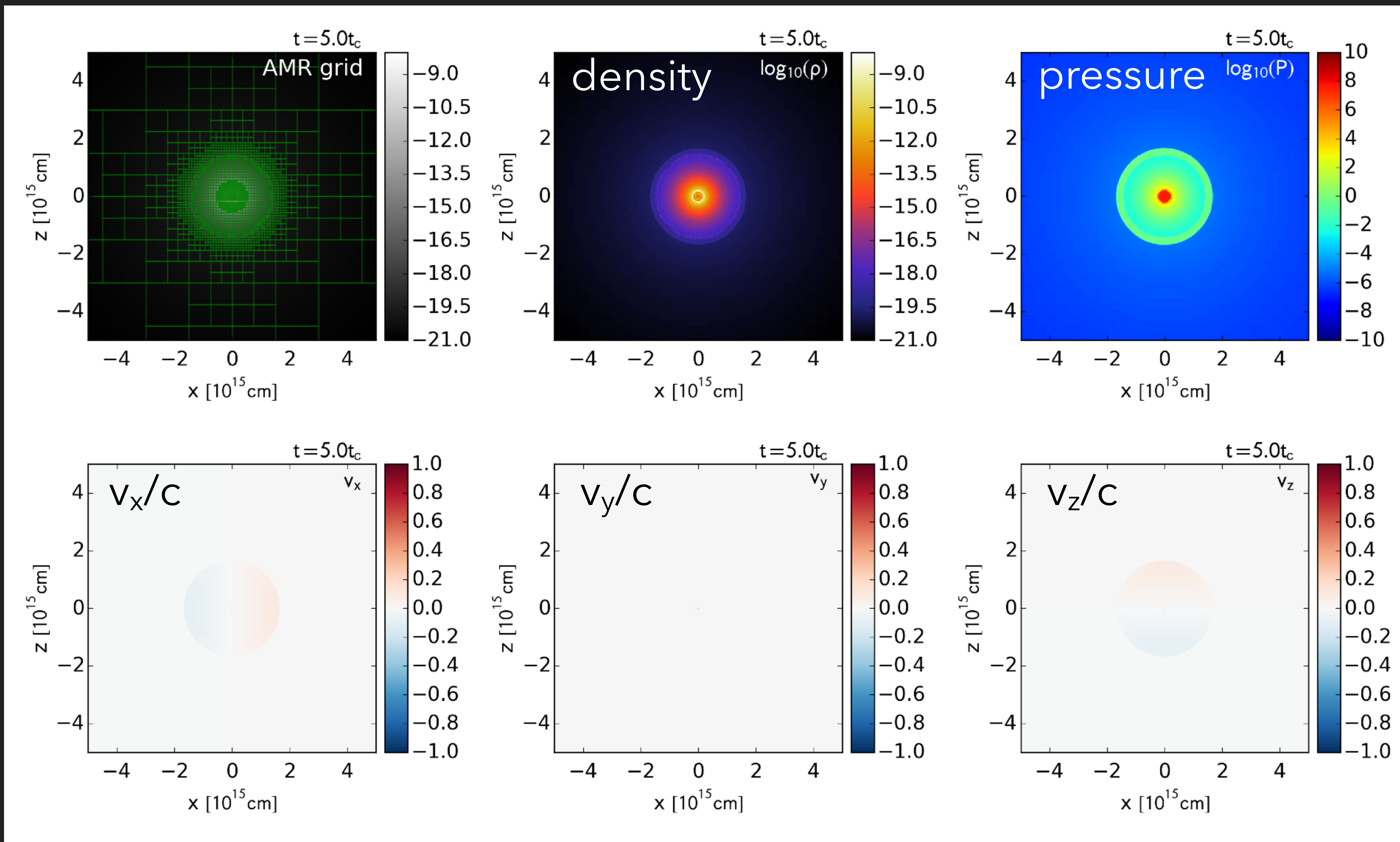


Impacts on SN ejecta

$E_{sn}=10^{51}$ [erg], $L=10^{46}$ [erg/s], $t_c=10^5$ [sec] → $Ein=10^{52}$[erg]

(Suzuki&Maeda 2017, 2019)



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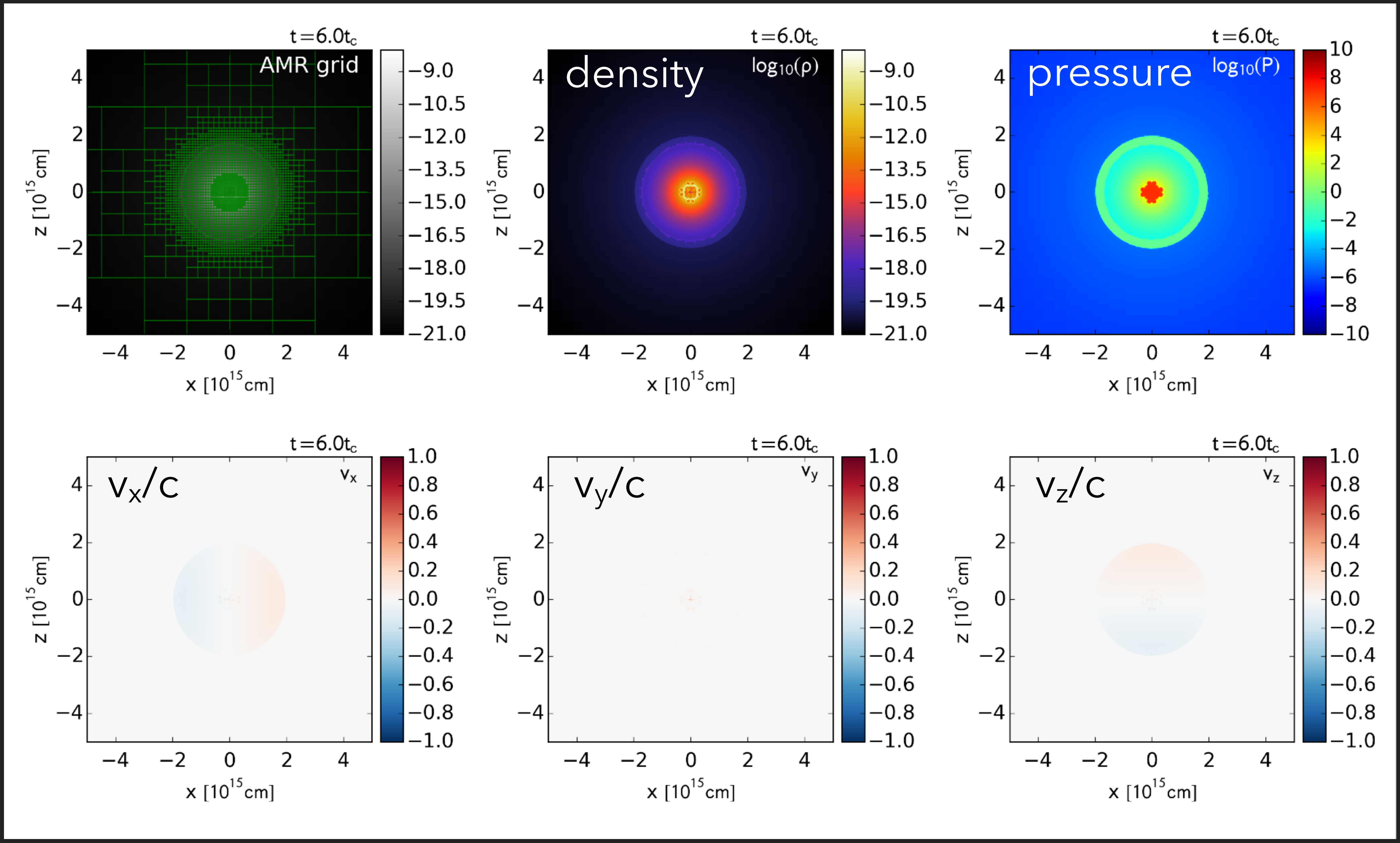

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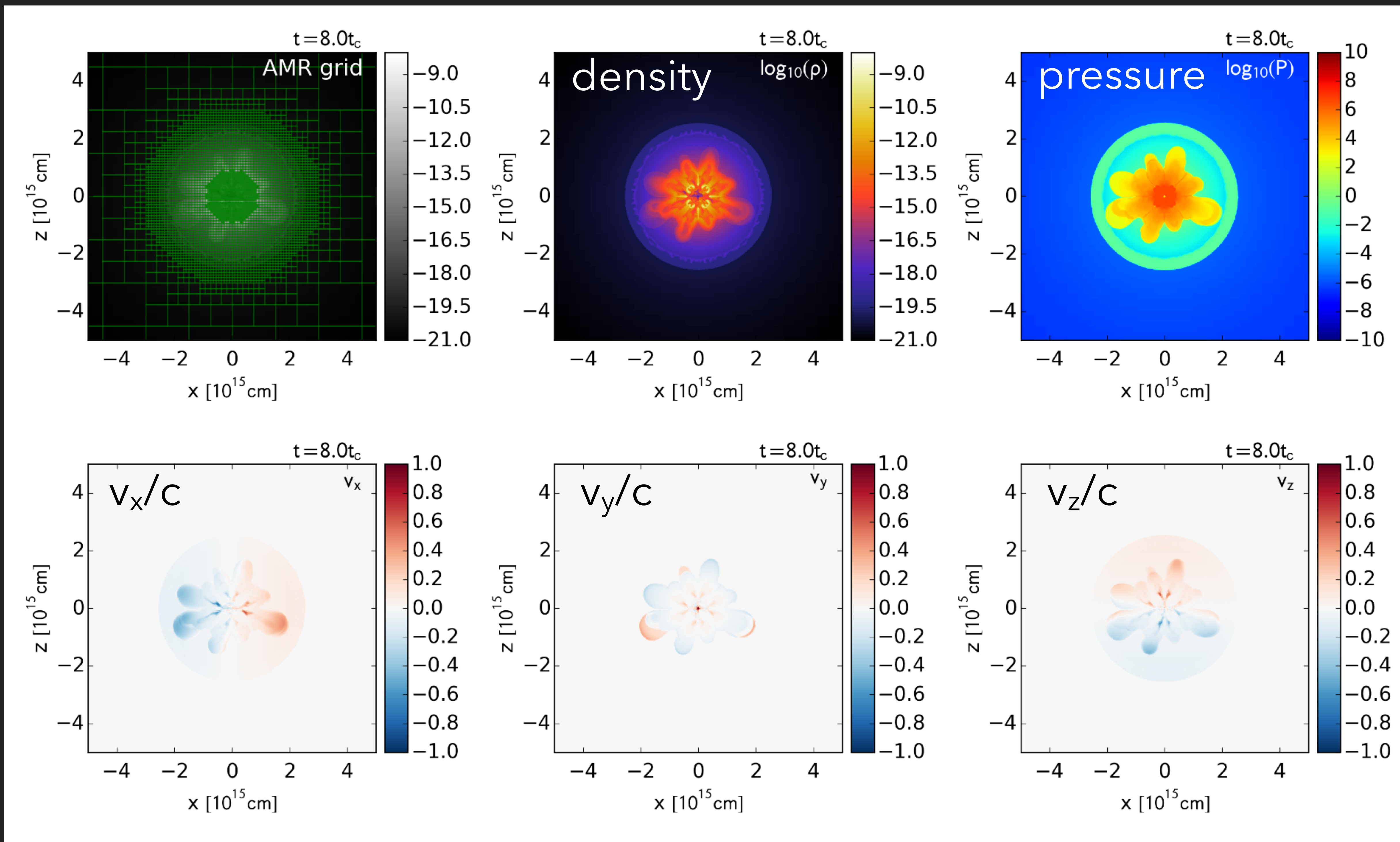

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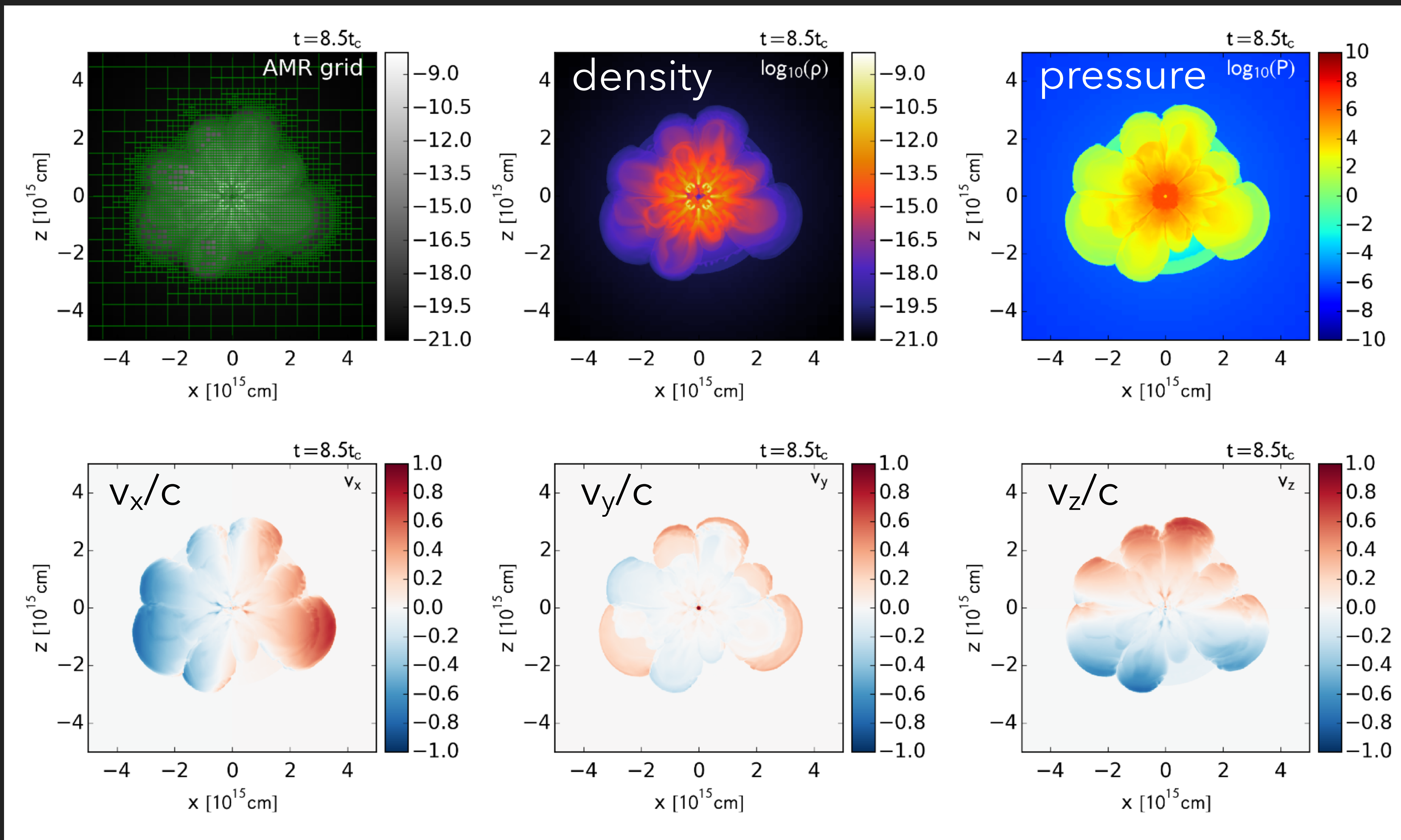

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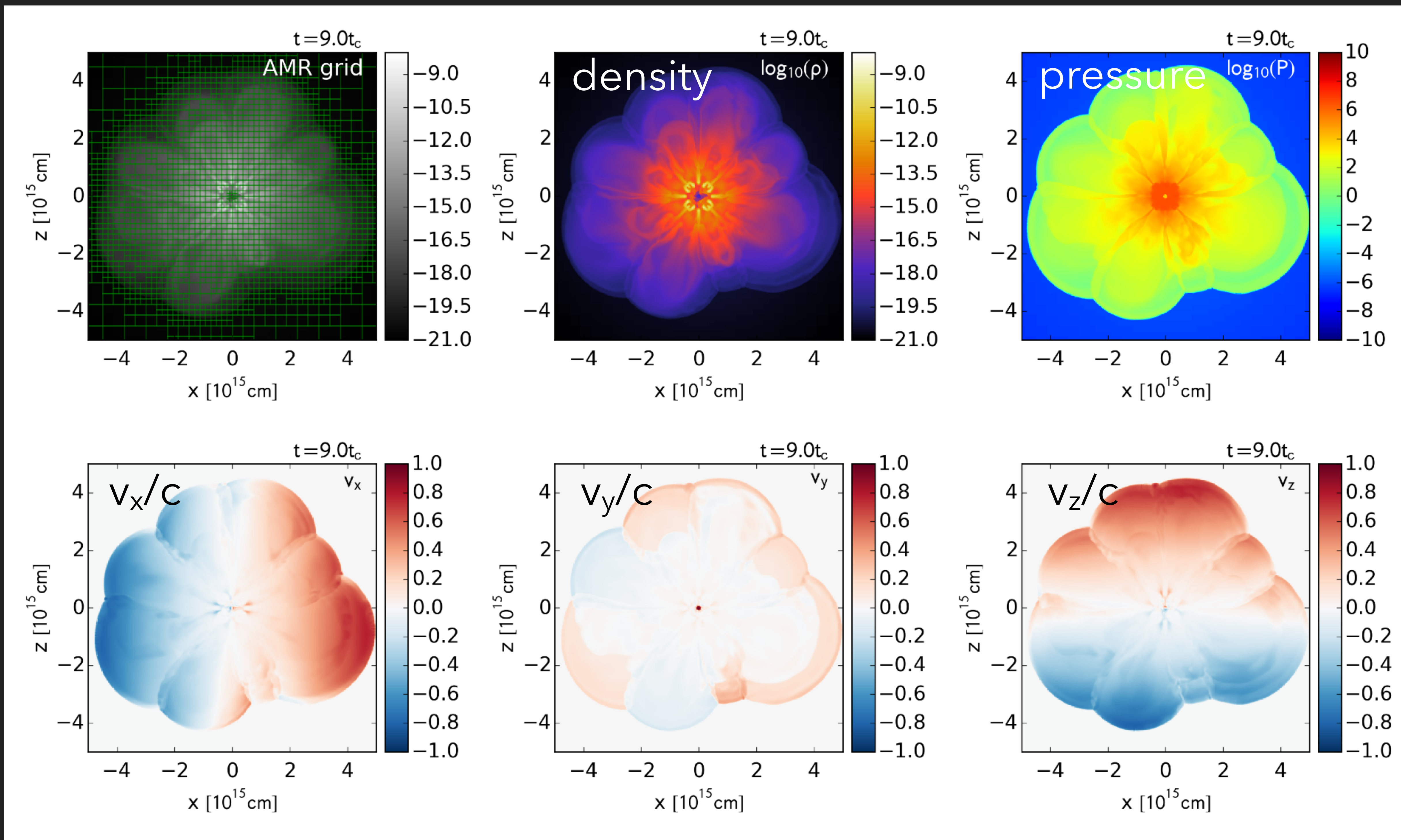

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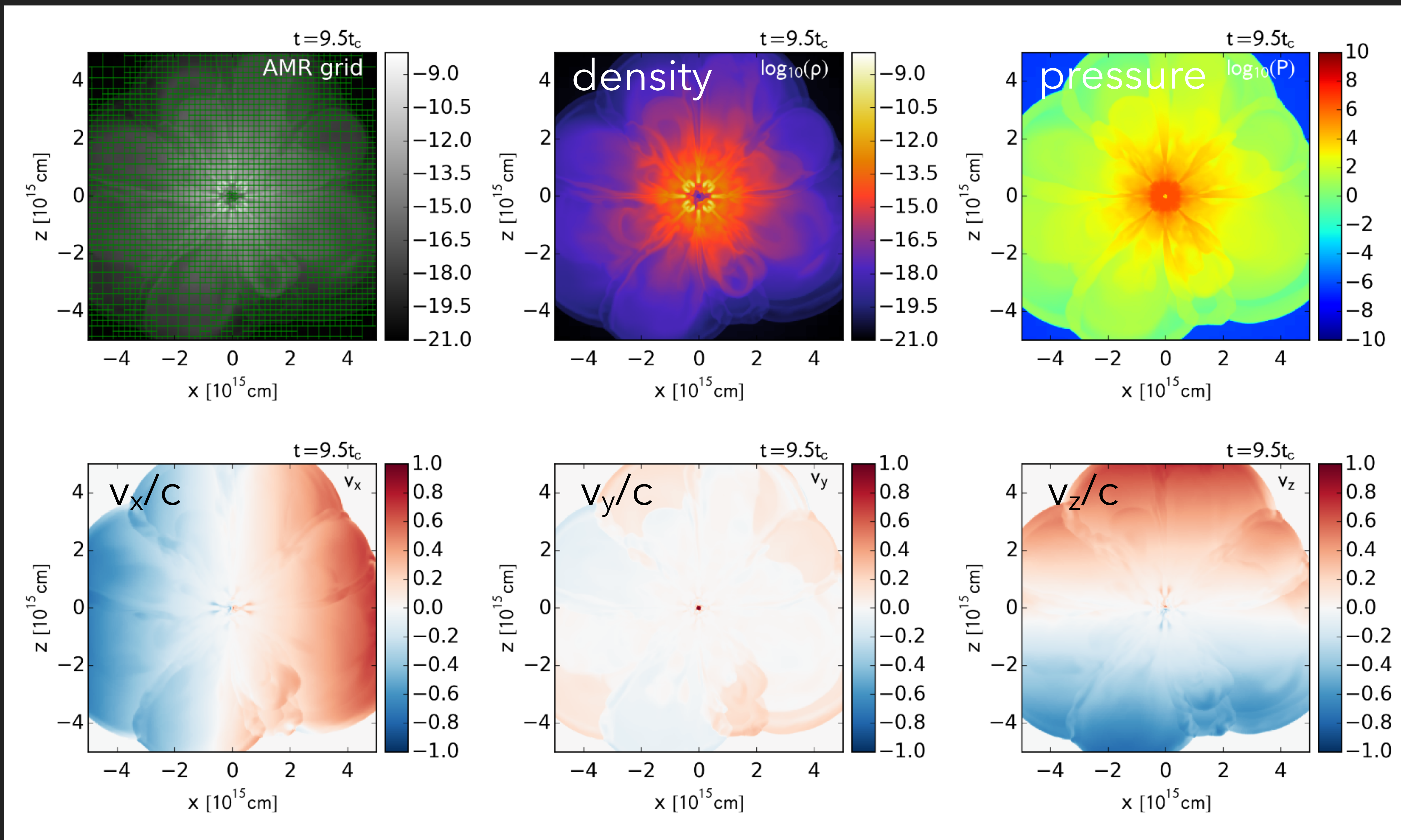

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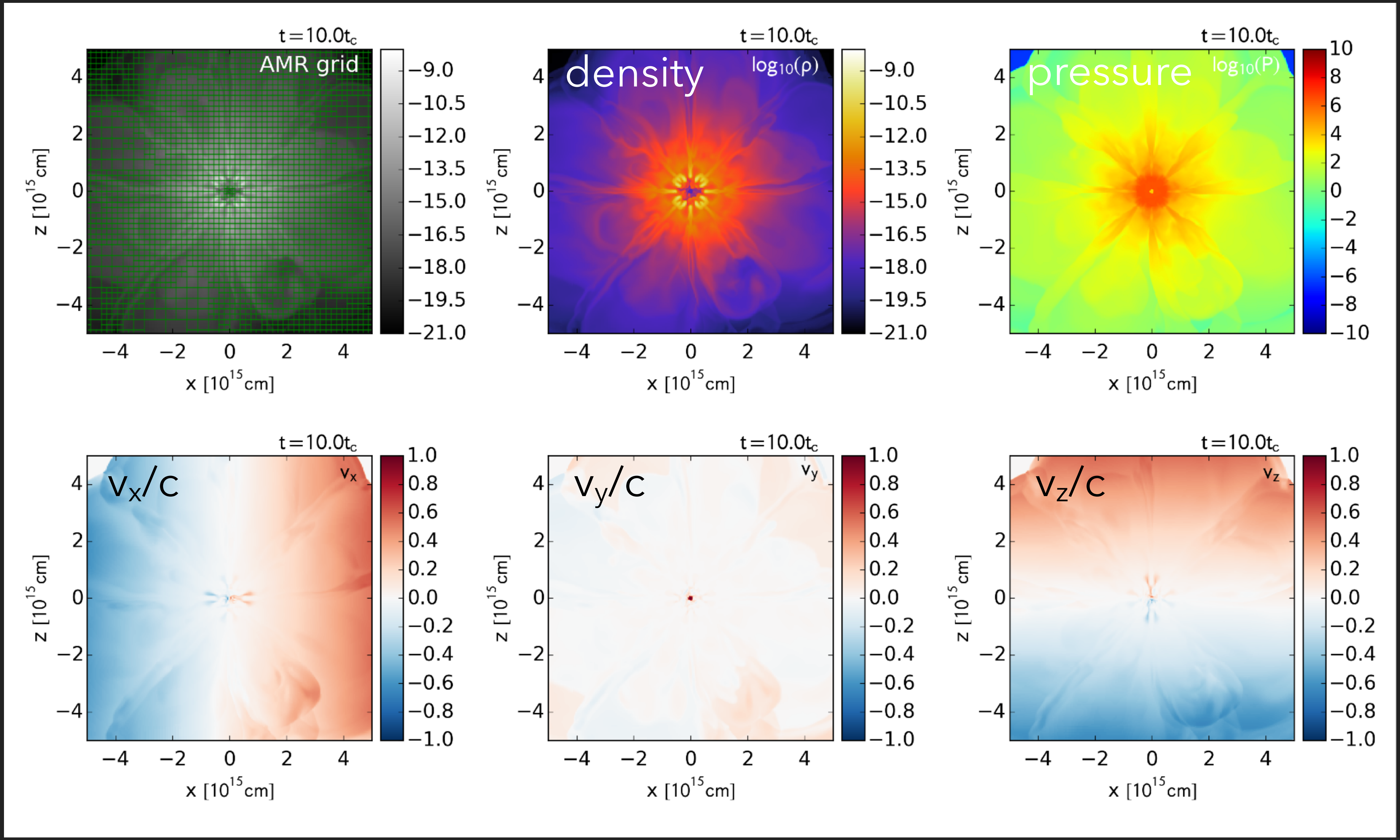

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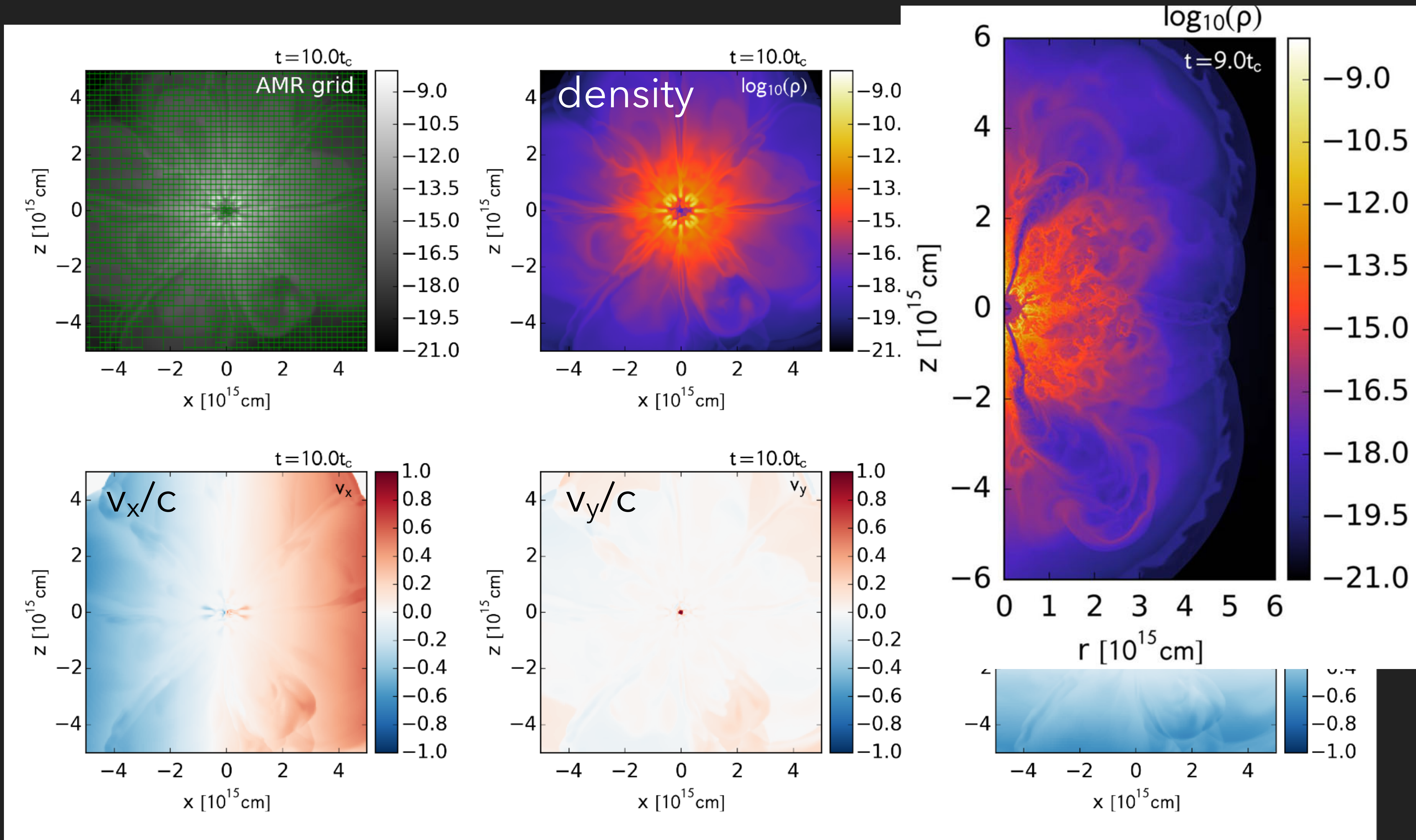
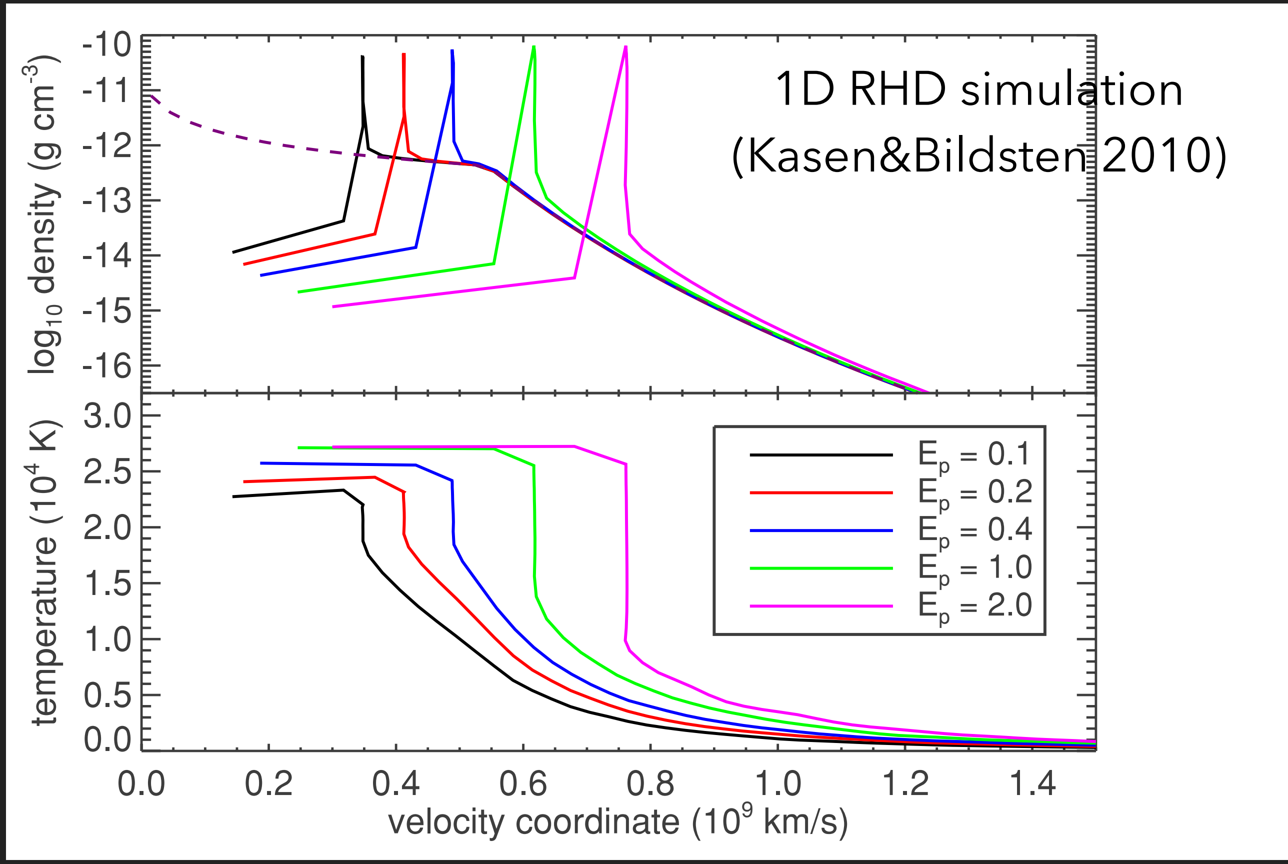
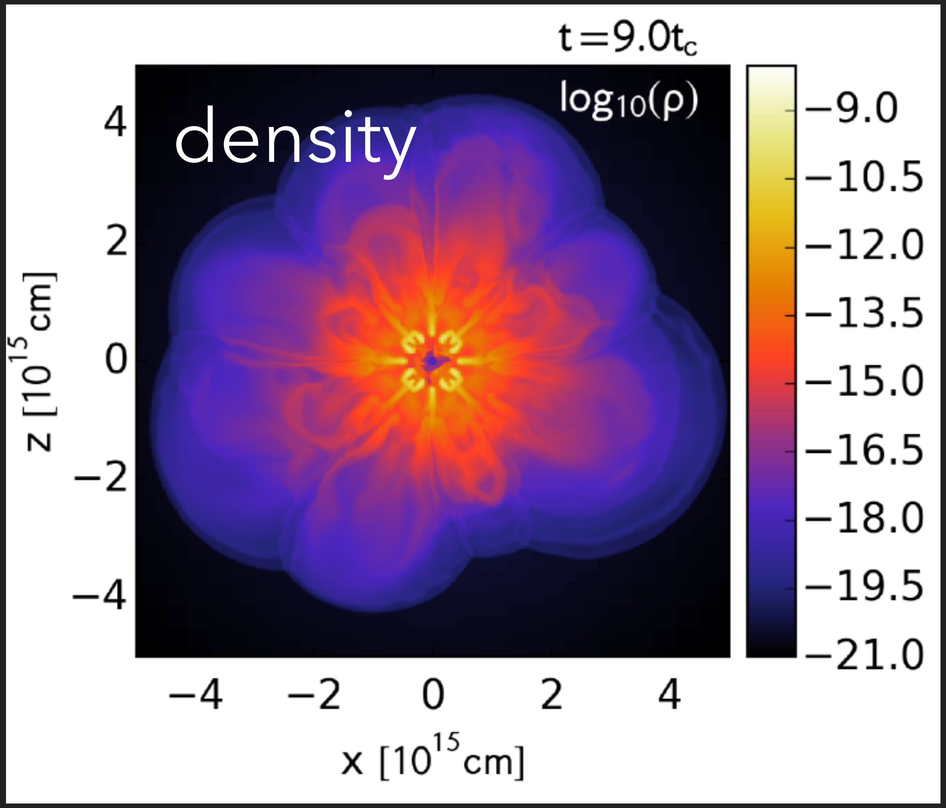
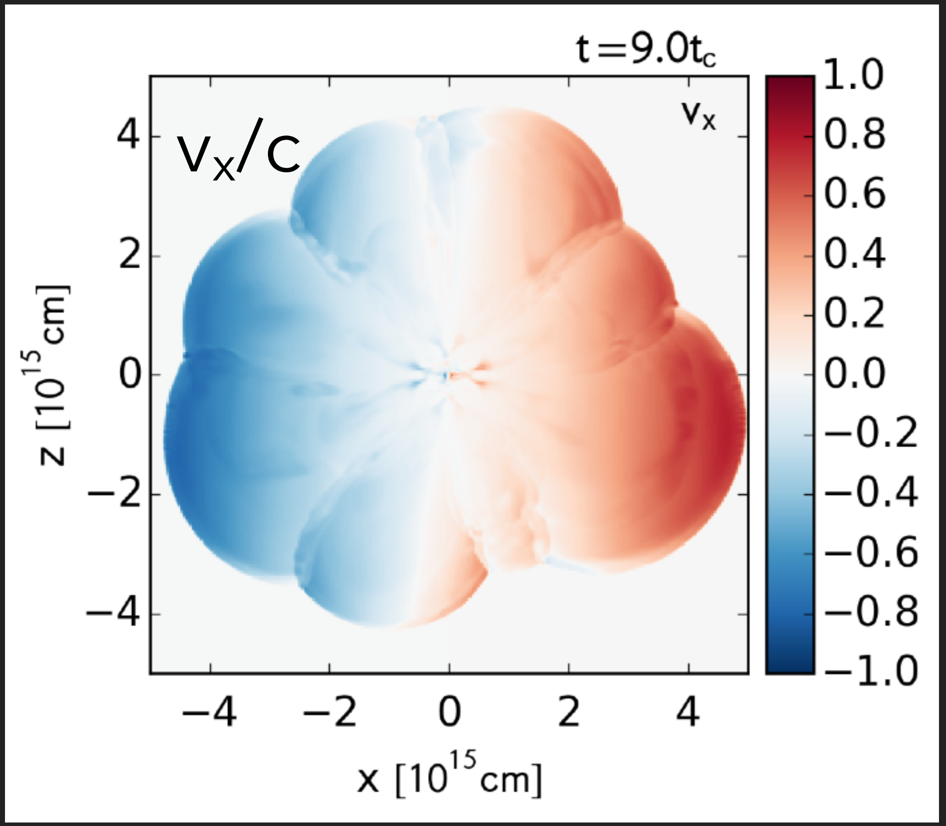


Density structure in 3D

- hot bubble breakout
- qualitatively different evolution from 1D spherical case
  → clumpy density structure
- development of R-T fingers
  → acceleration of forward shocks up to v~c

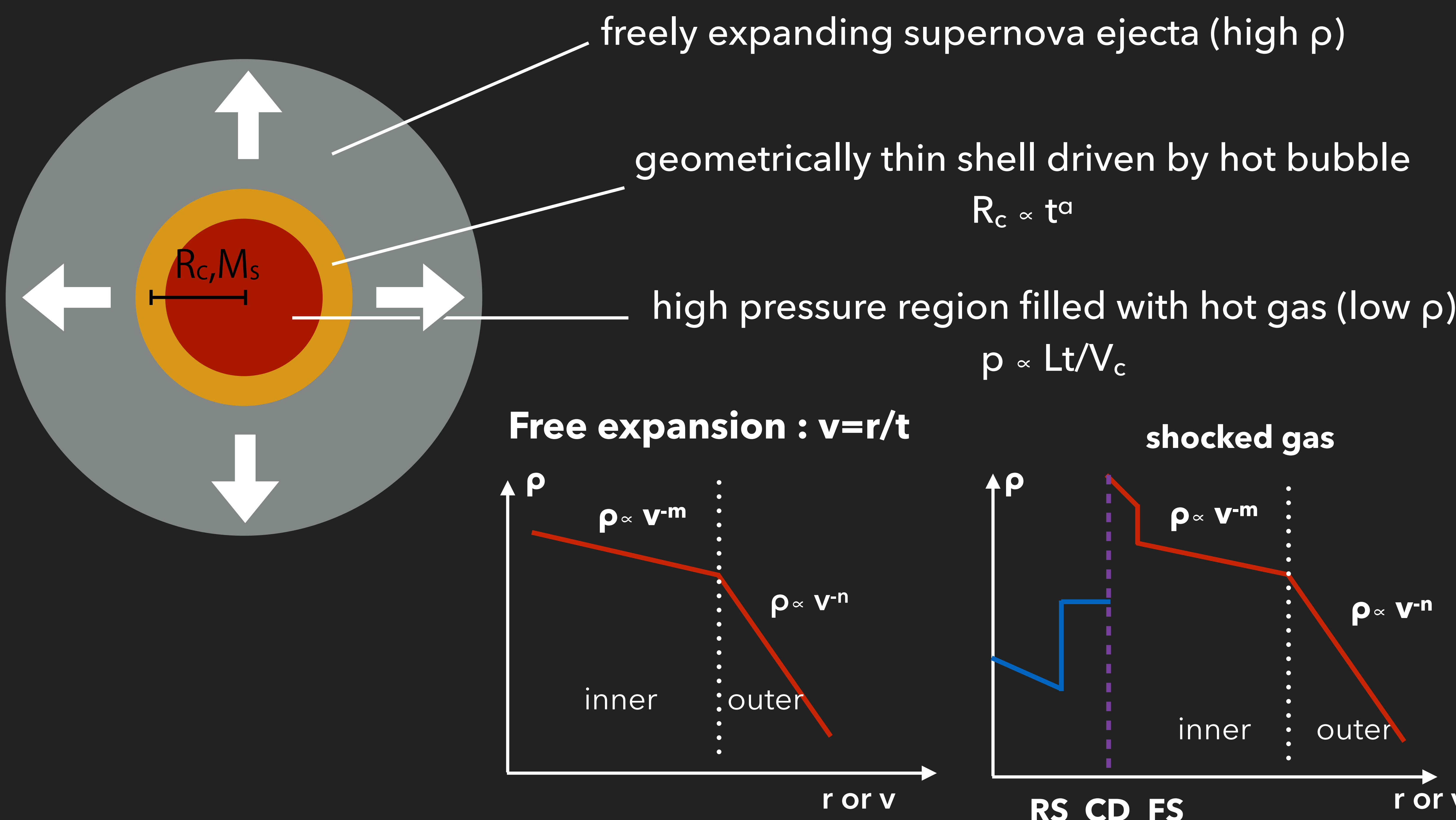




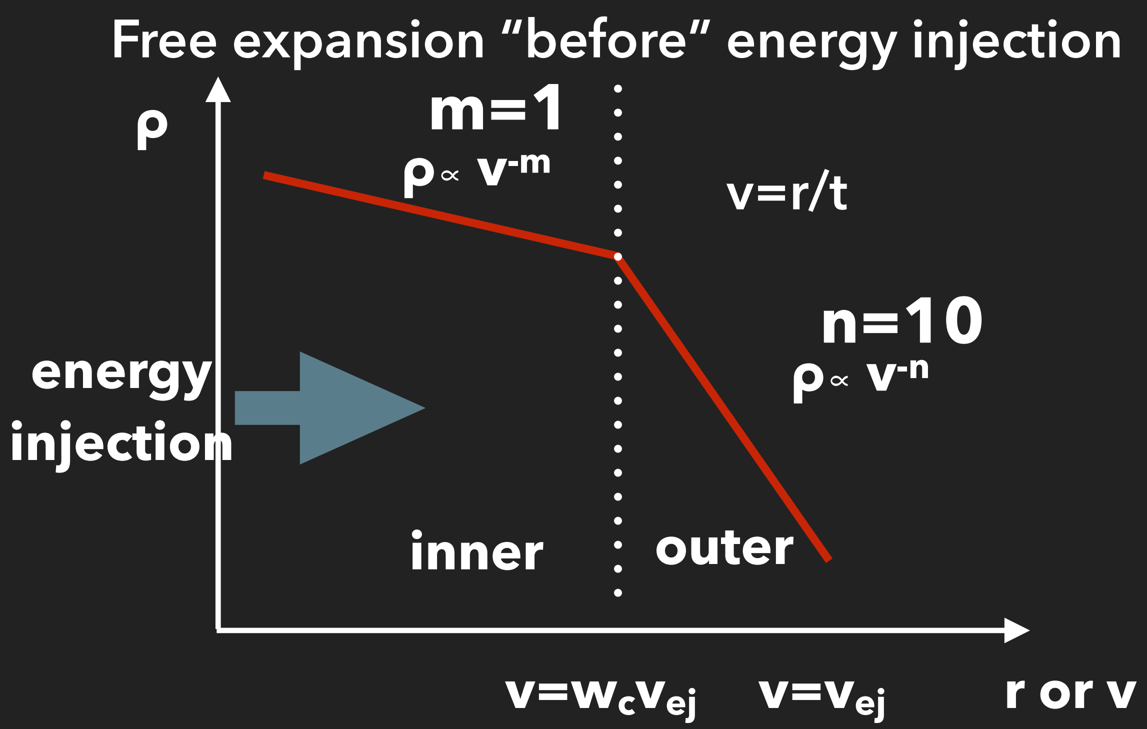


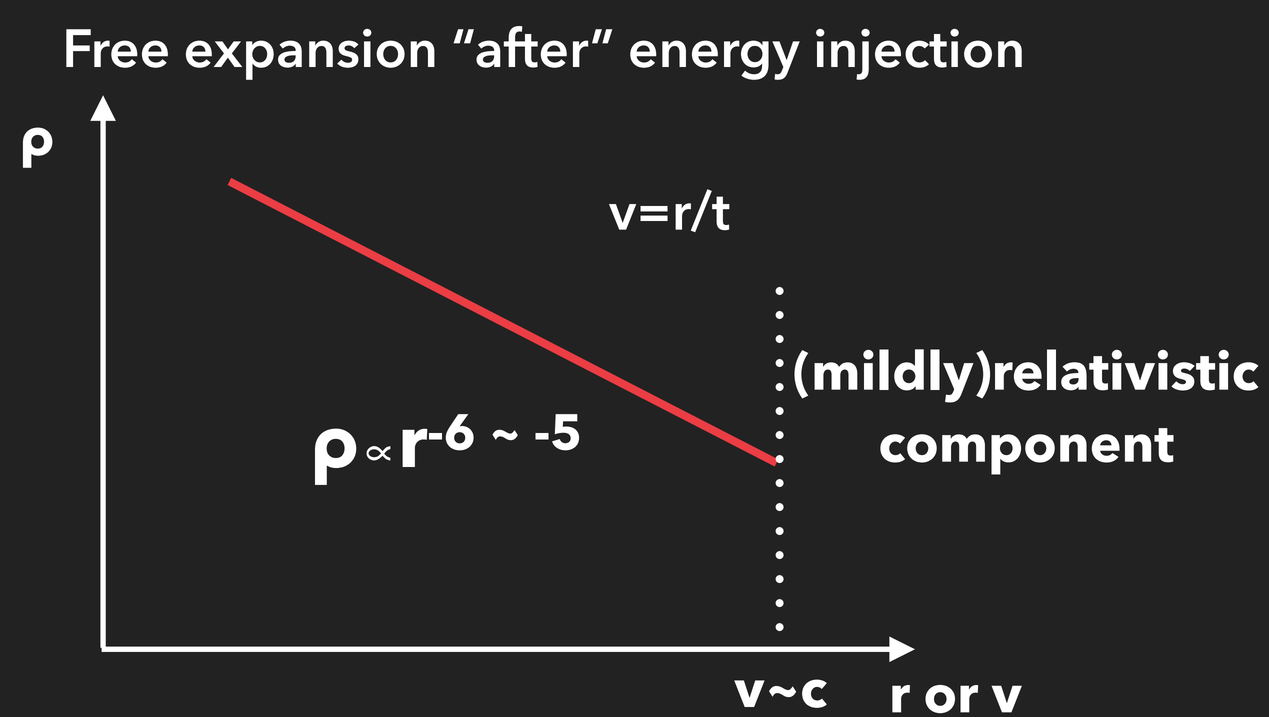
Impacts on SN ejecta

- 1D spherical picture of SN ejecta with a central engine
- analogy to galactic pulsar wind nebulae

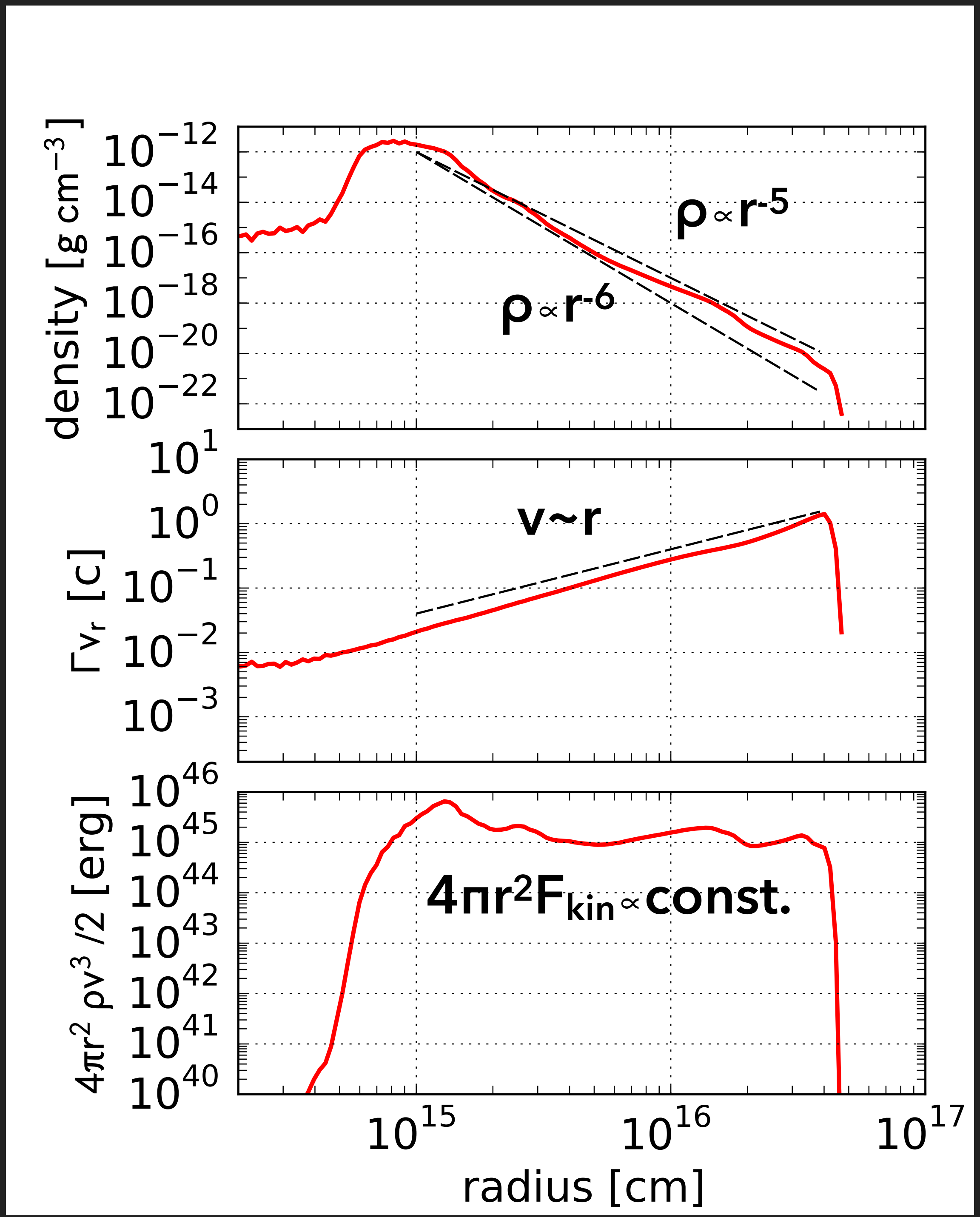


Radial profiles of physical variables





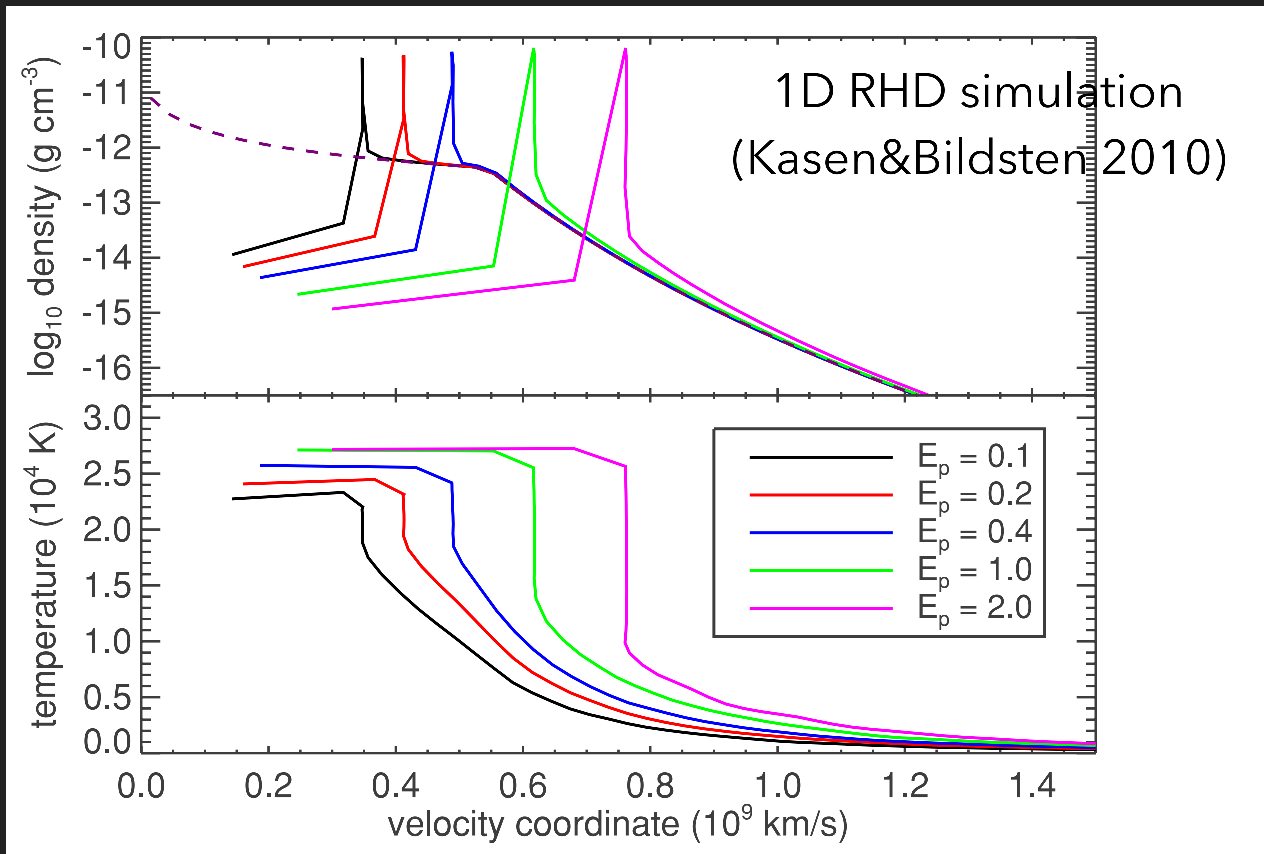
radial profiles at t=20t_c



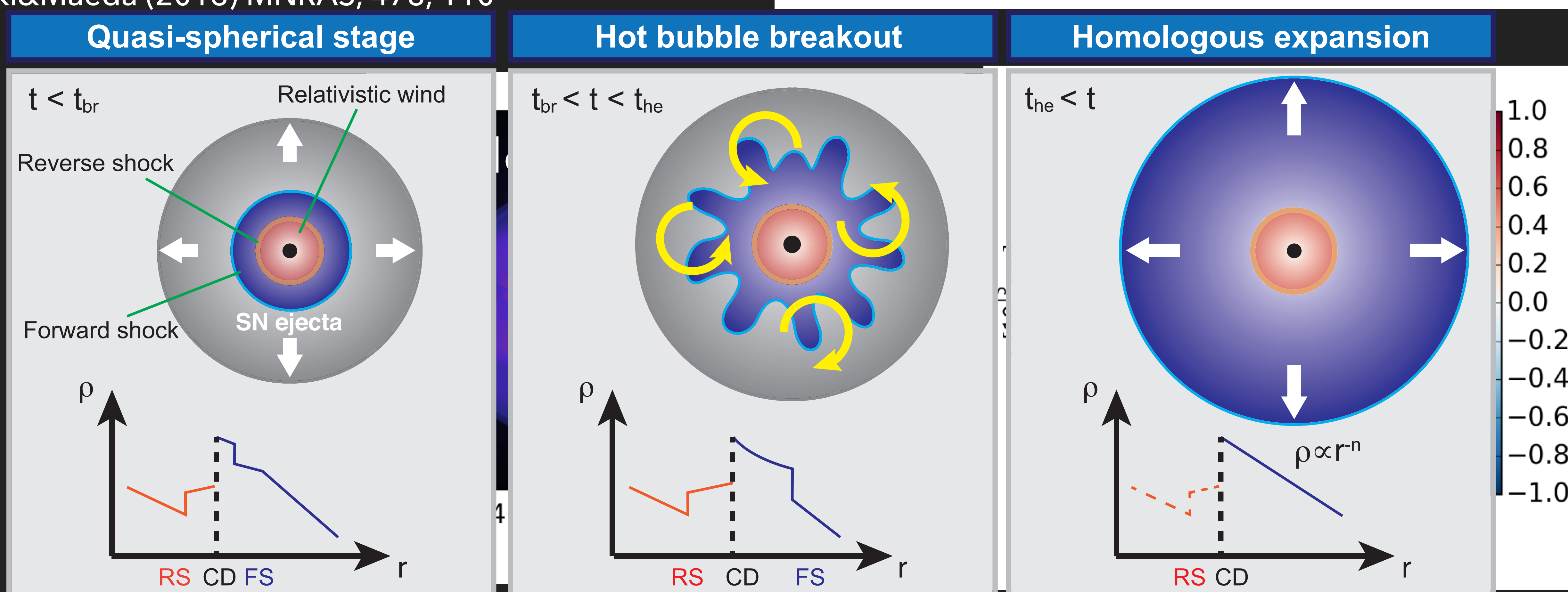
see Suzuki&Maeda (2017) for details

Density structure in 3D

- hot bubble breakout
- qualitatively different evolution from 1D spherical case
  → clumpy density structure
- development of R-T fingers
  → acceleration of forward shocks up to v~c

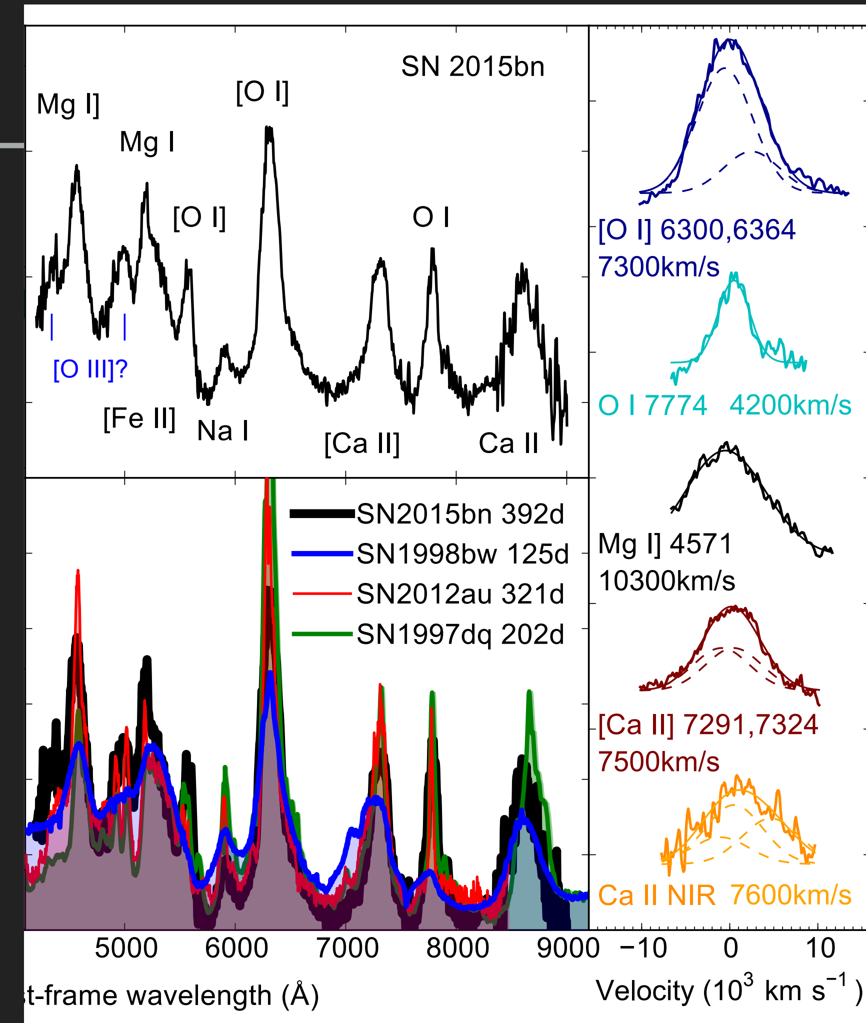


Suzuki&Maeda (2018) MNRAS, 478, 110

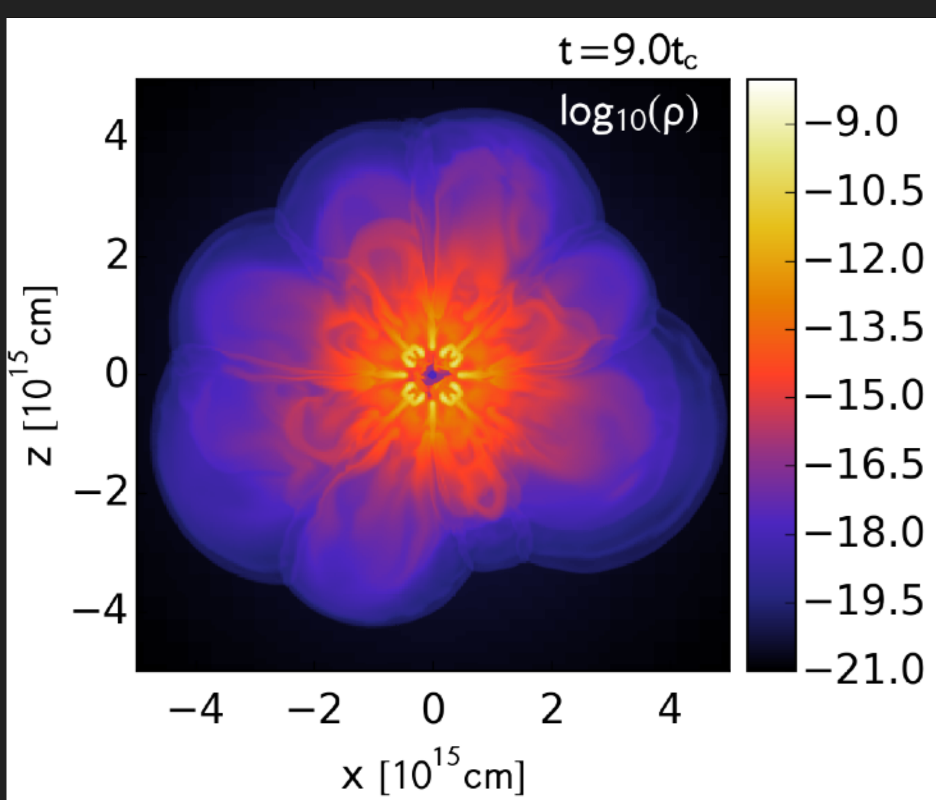


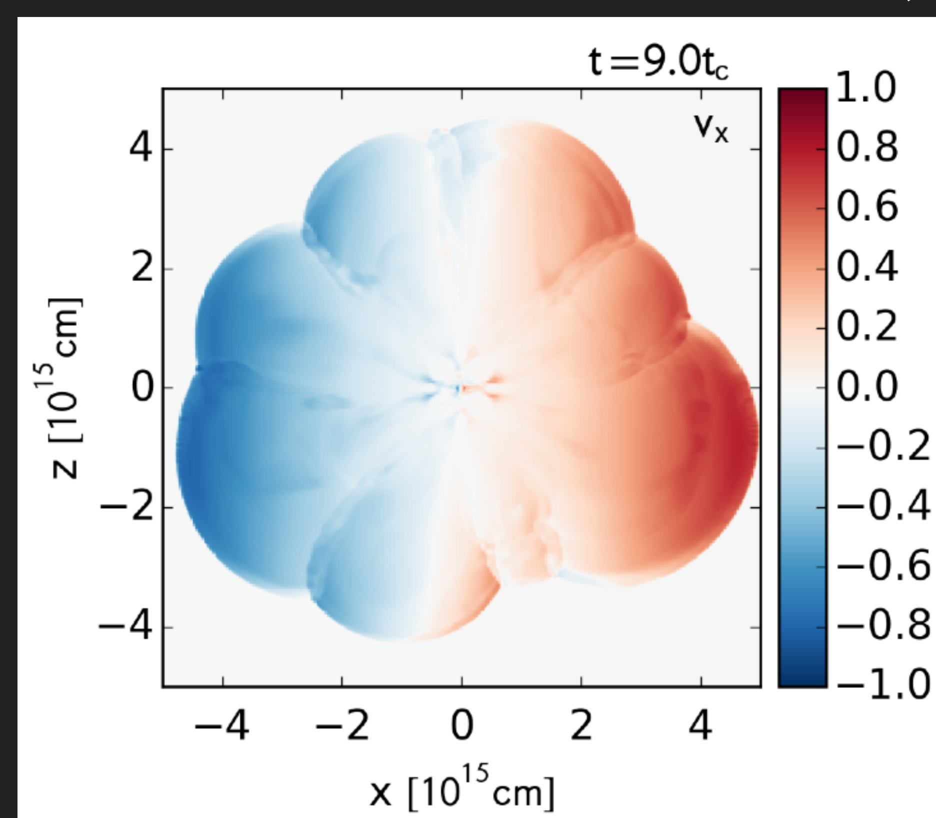
SLSN spectra in 3D

- spectral evolution should be different from normal CCSNe
- broad-lined nebular spectrum like HNe?
-



Nicholl+(2016)



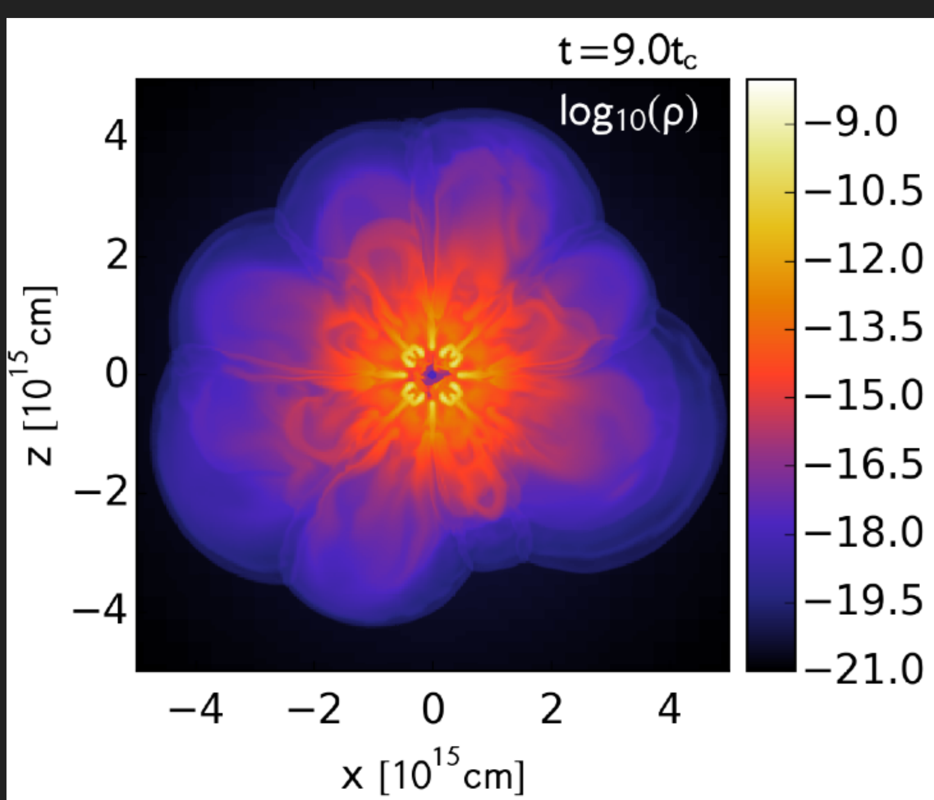


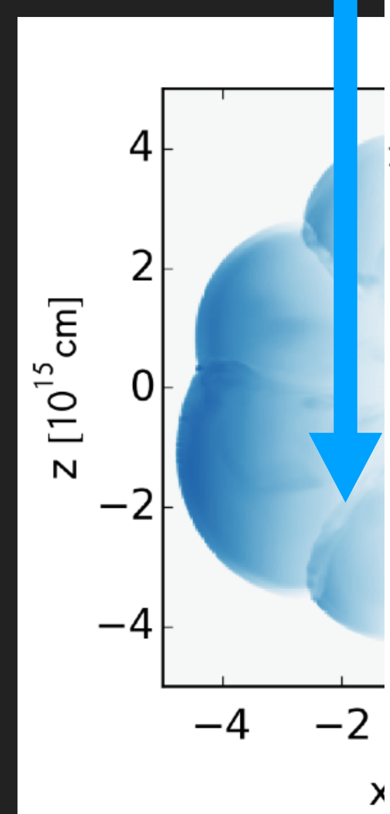
?

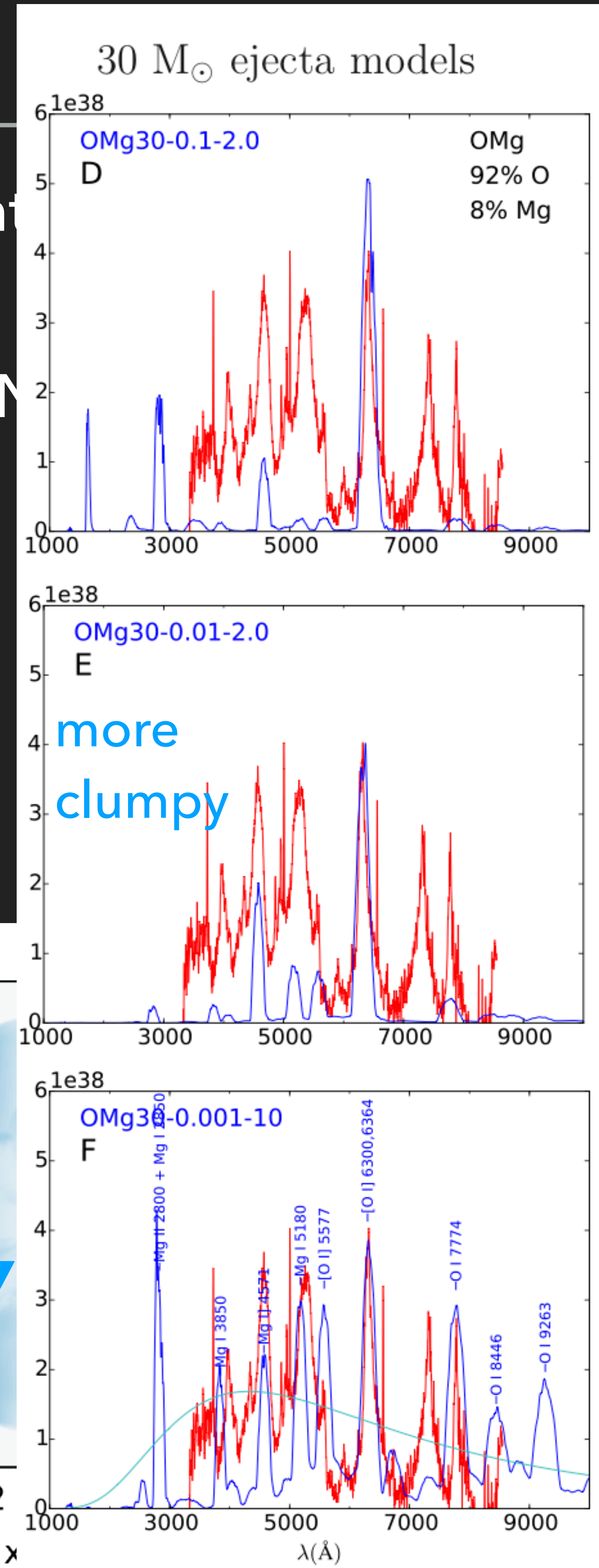
SLSN spectra in 3D

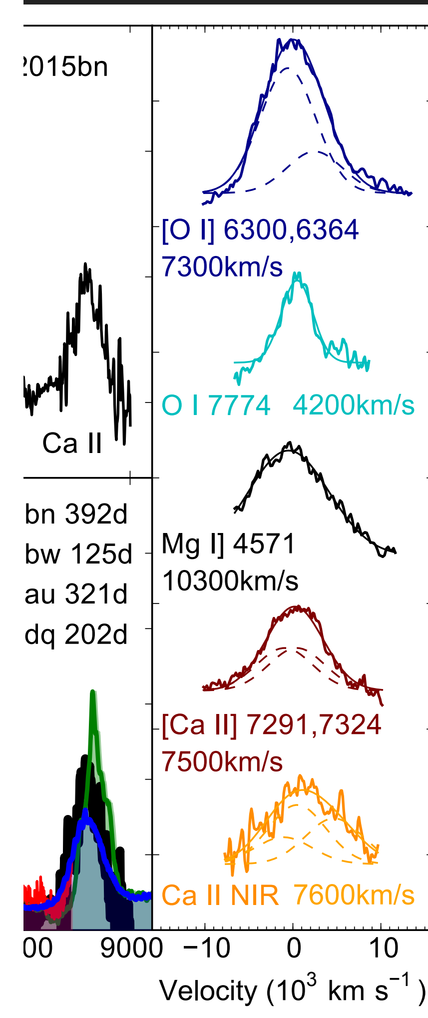
- spectral evolution should be different from normal CCSNe
- broad-lined nebular spectrum like HN
-

Clumpy ejecta?
Jerkstrand+(2017)





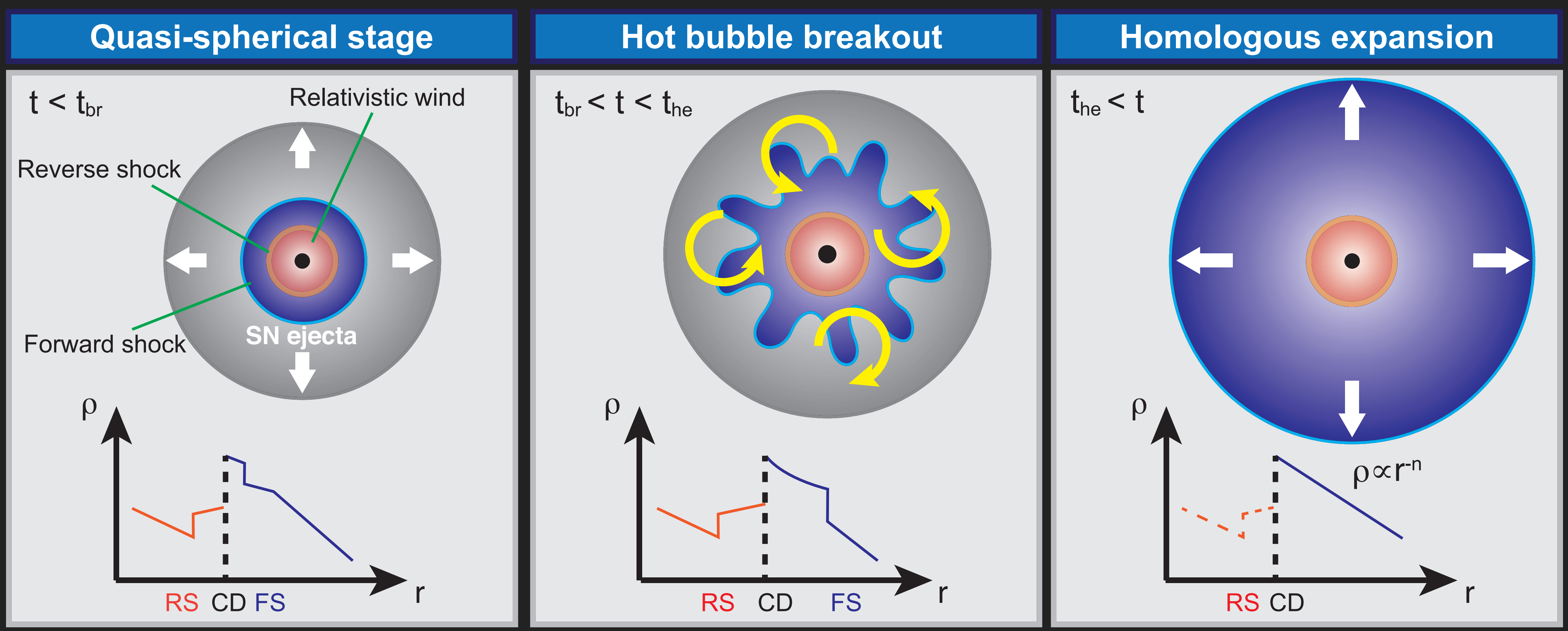




?

Summary and future work

- Superluminous SNe: a new class of extremely bright SNe
- central-engine SNe: promising scenario for SLSNe?
- multi-D simulations of SN ejecta with central energy injection
- hot bubble breakout → acceleration of the outermost layer
- more work to do: spectral modeling, radiation-hydro simulation

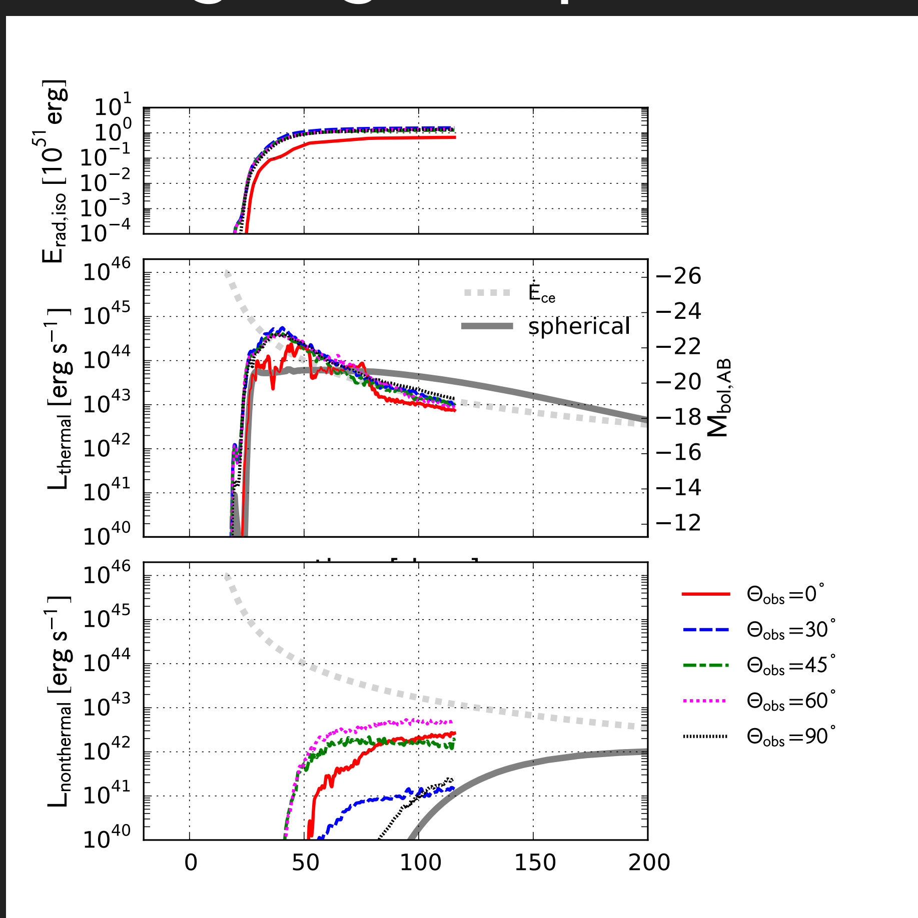


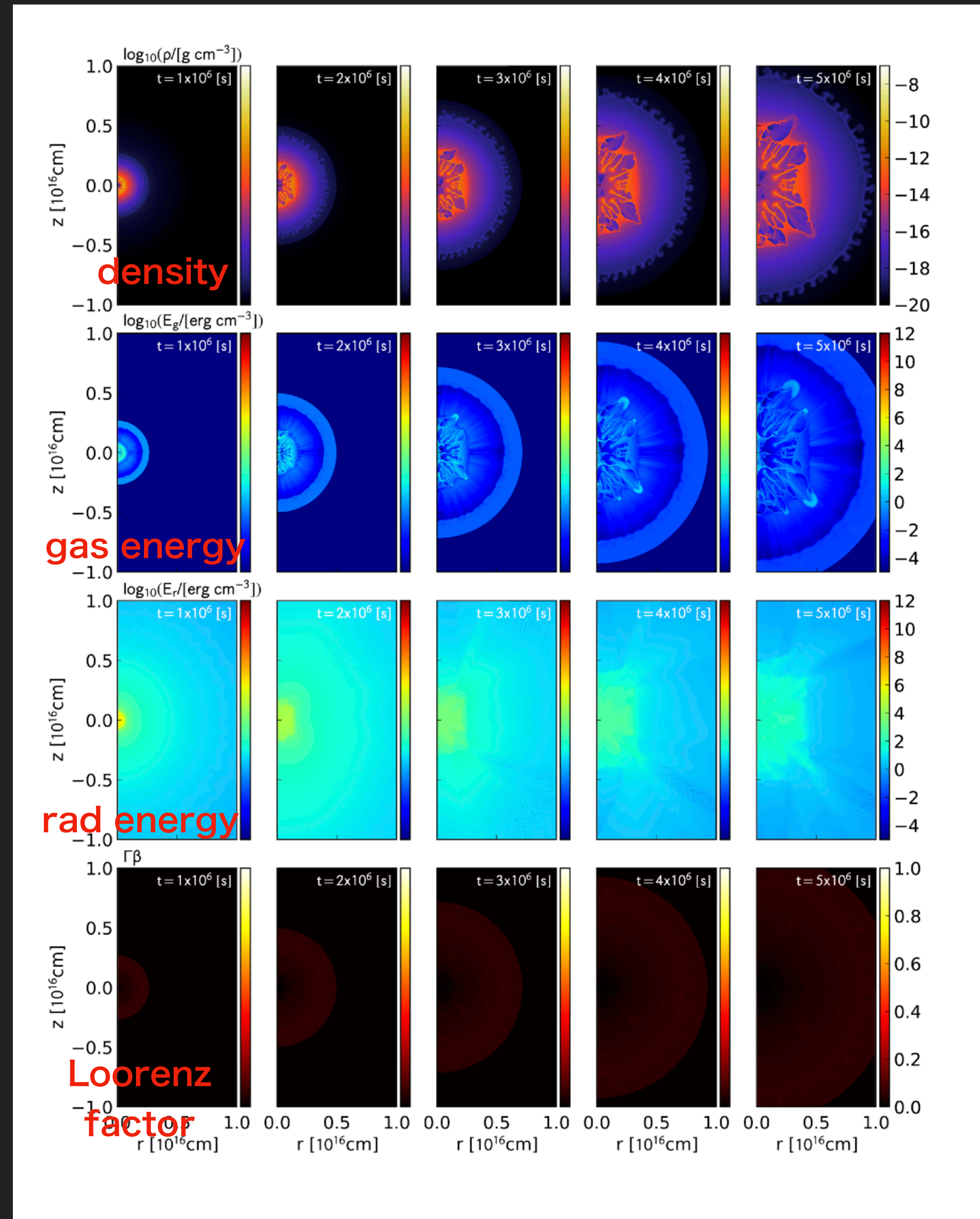
Suzuki&Maeda (2018) MNRAS, 478, 110

Summary and future work

Preliminary

- Radiation-hydrodynamic simulations in 2D cylindrical coordinates (Suzuki, Maeda, Shigeyama 2016)
- mixing processes similar to hydrodynamic simulations
- bolometric light curve and its viewing angle dependence





Summary and future work

Thank you.

Summary and future work

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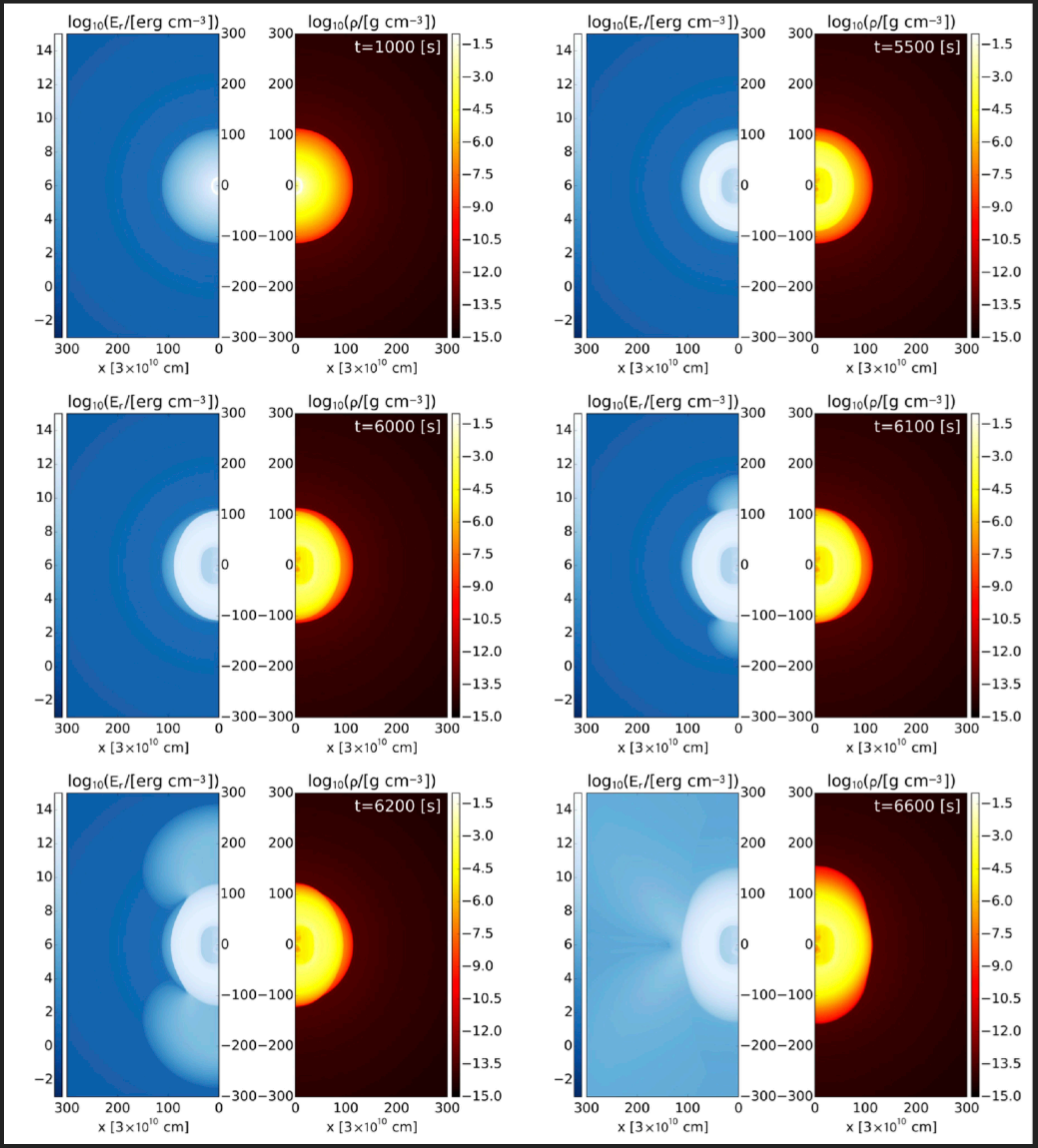
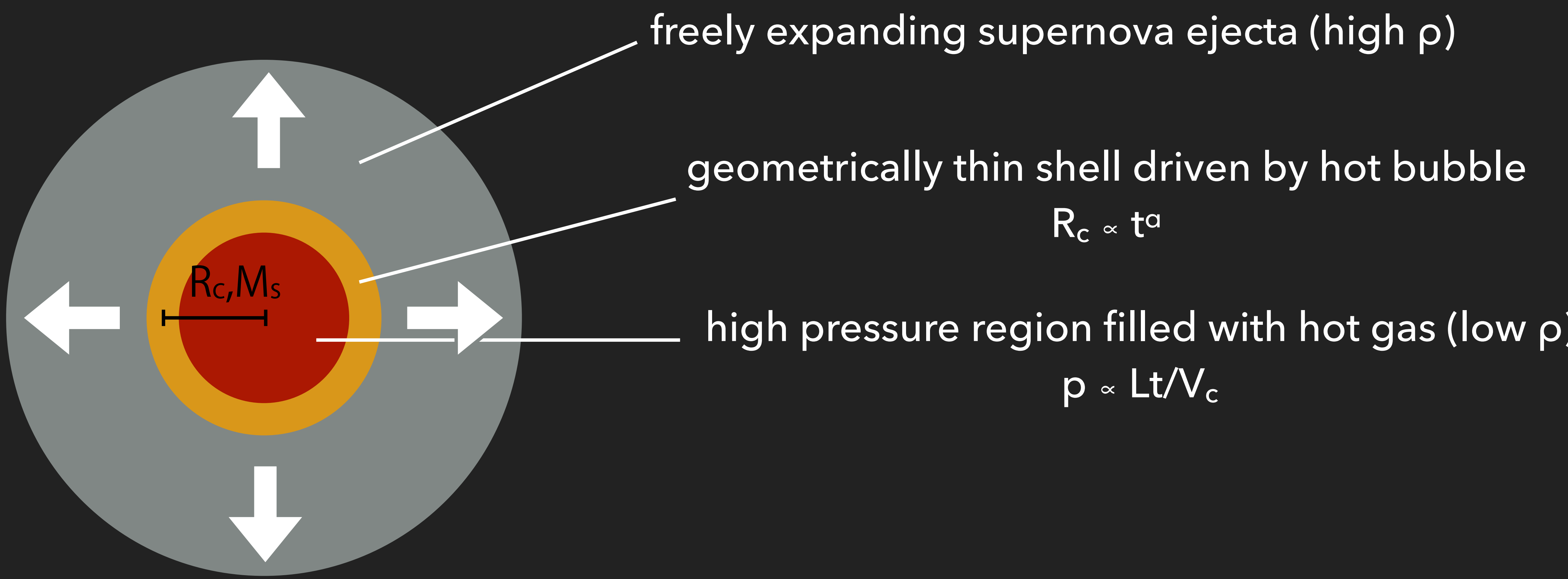


Impacts on SN ejecta

- 1D spherical picture of SN ejecta with a central engine
- analogy to galactic pulsar wind nebulae



e.g., Chevalier&Fransson (1992)

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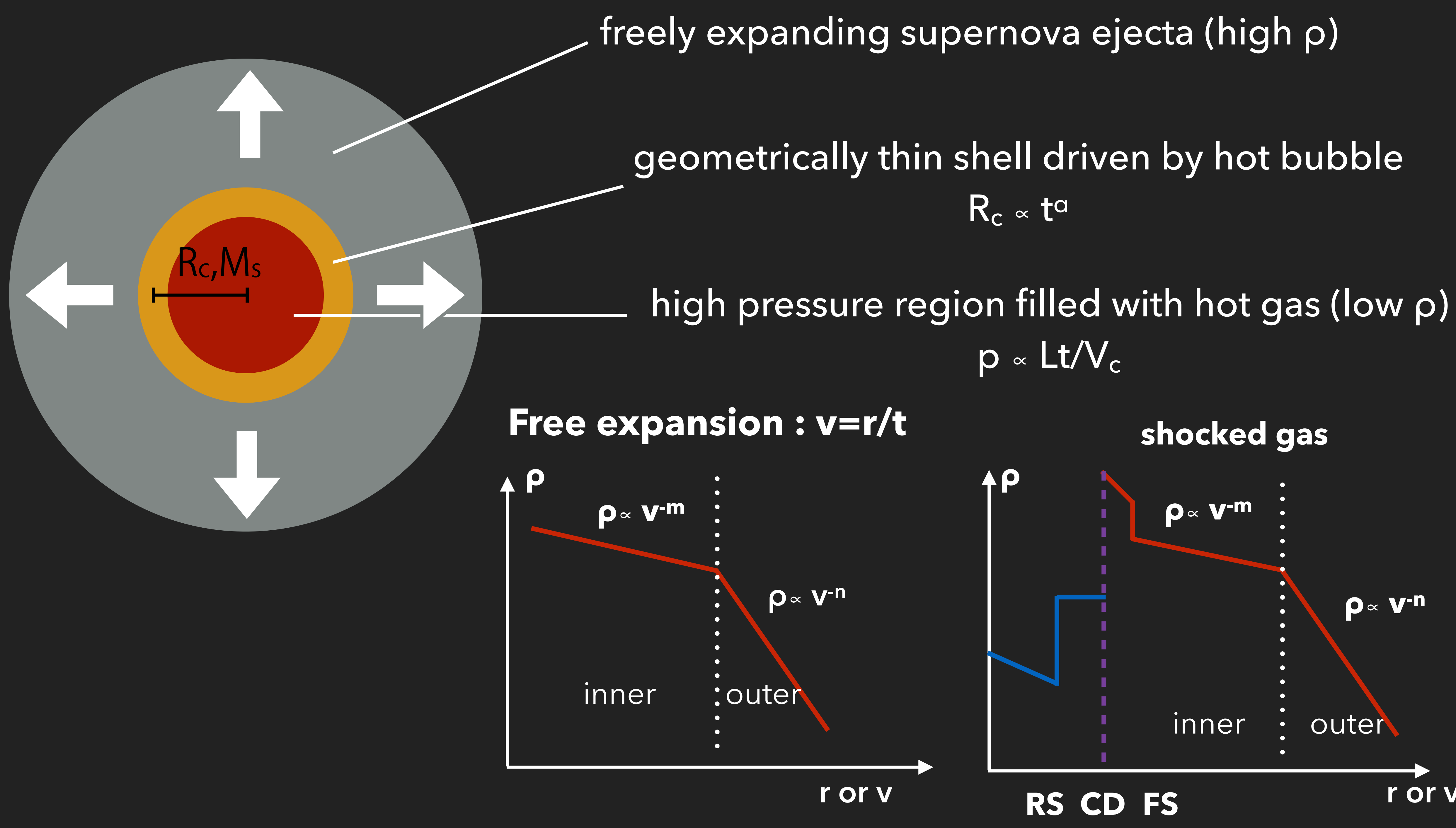
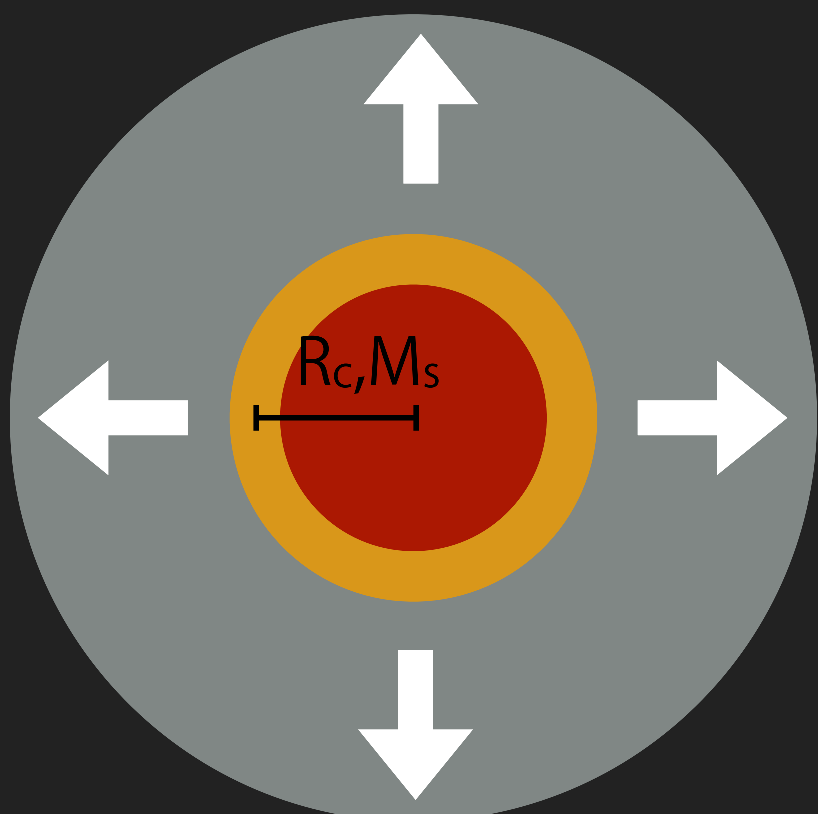


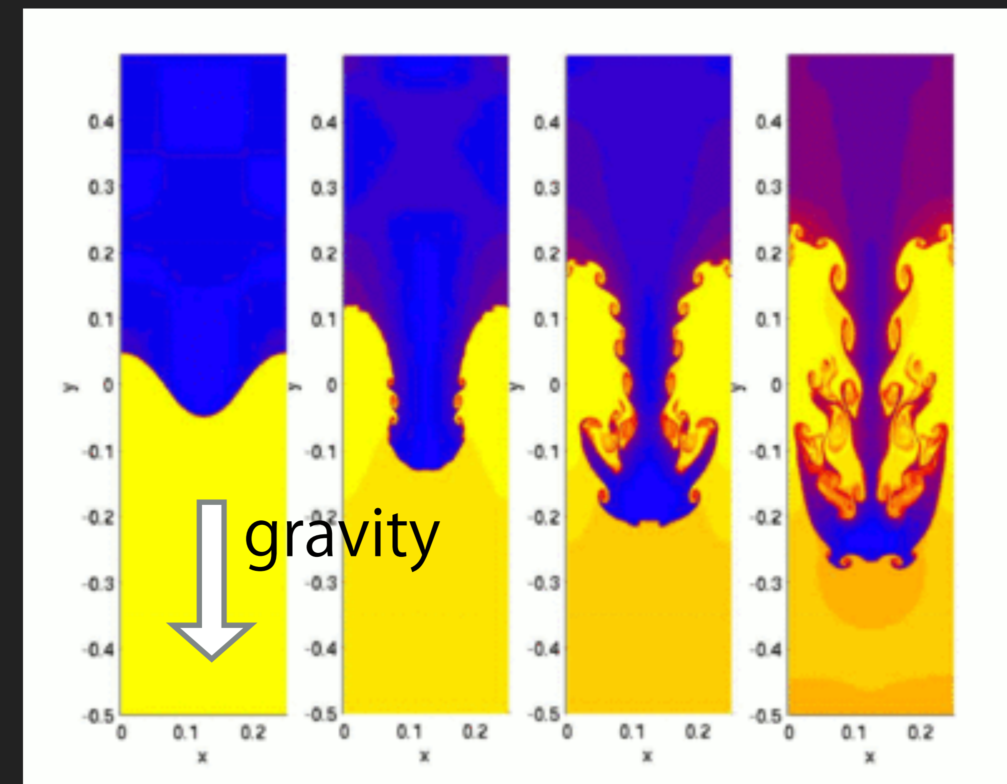
Impacts on SN ejecta

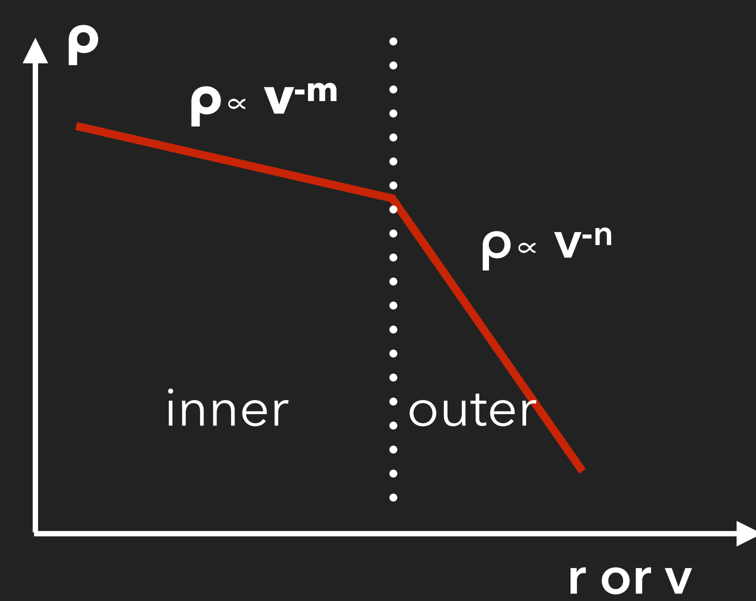
- Is1D spherical picture of SN ejecta with a central engine correct?
- Actually, No. **RT instability**

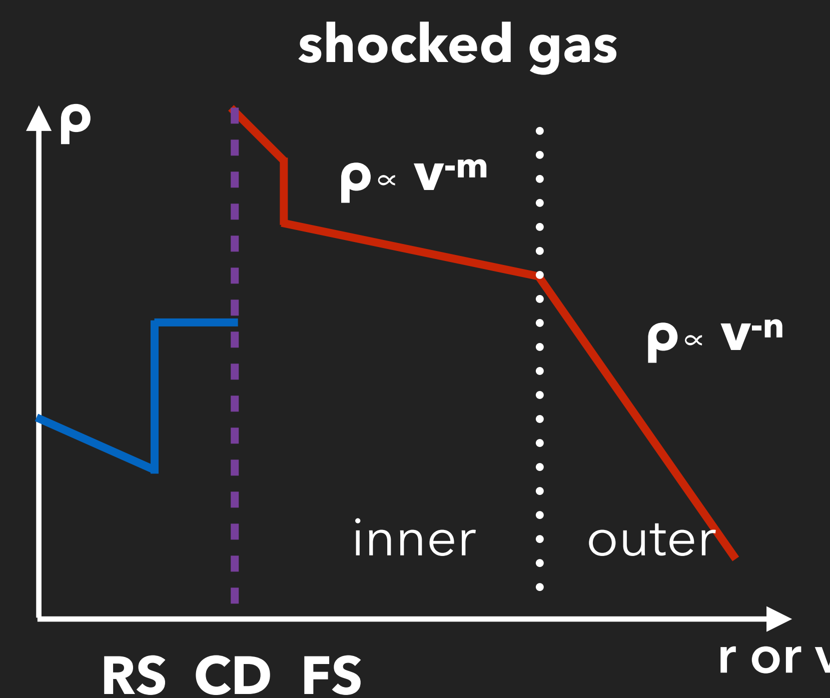


heavier medium

lighter medium







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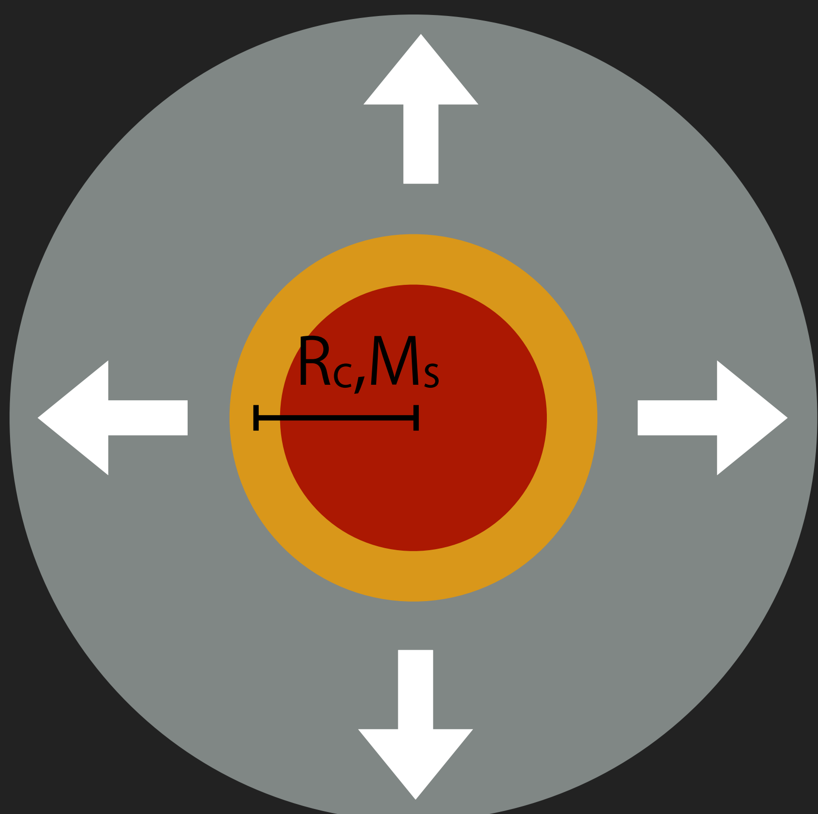
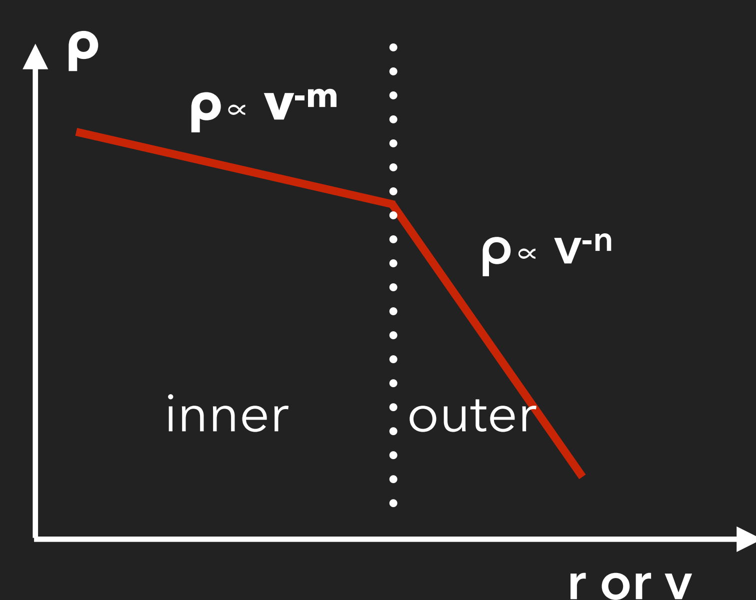
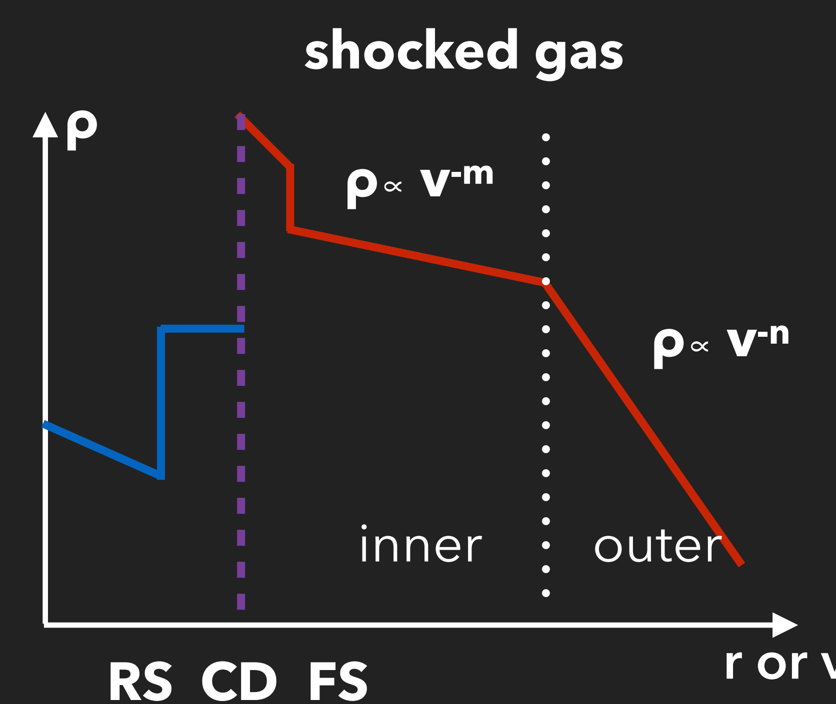



Crab nebula © NASA





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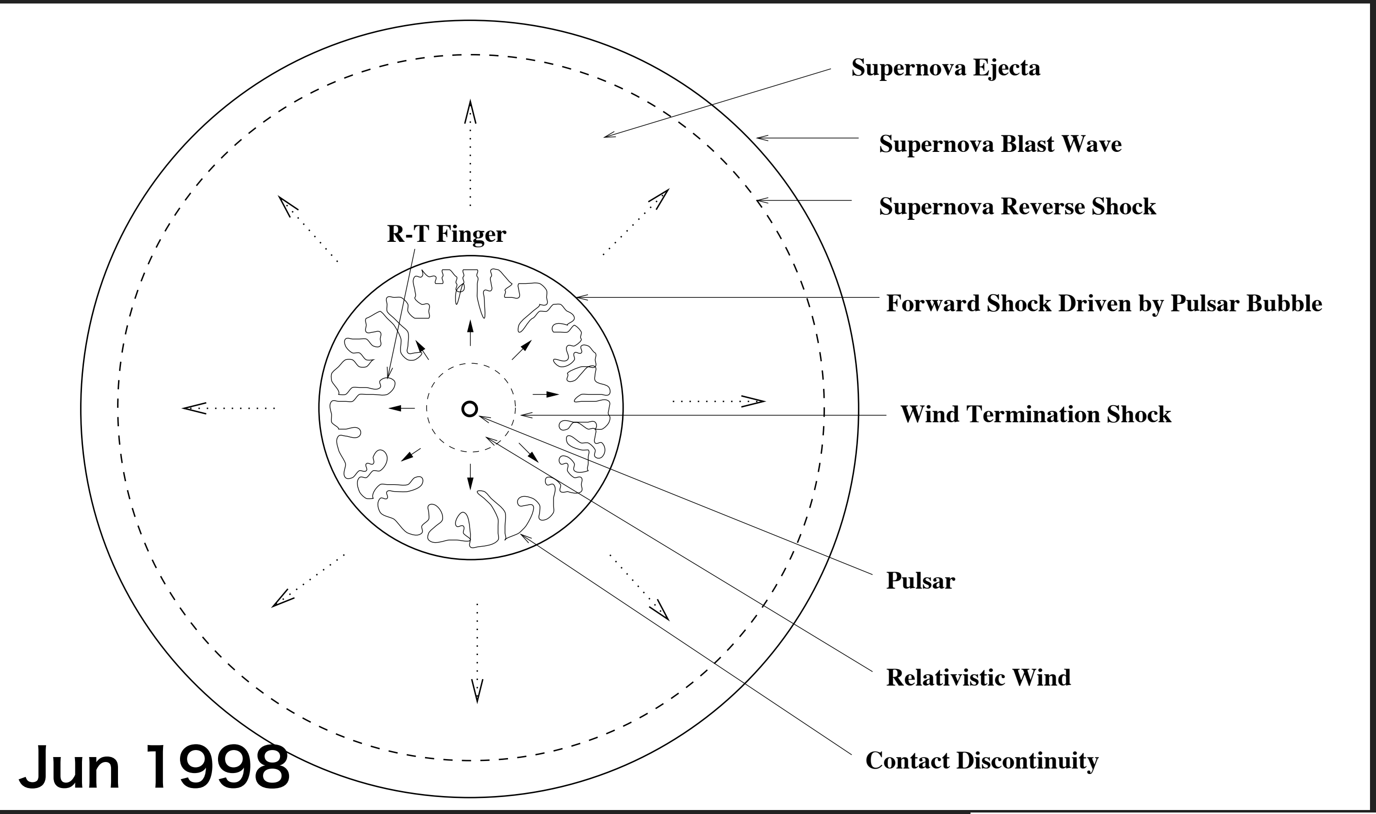
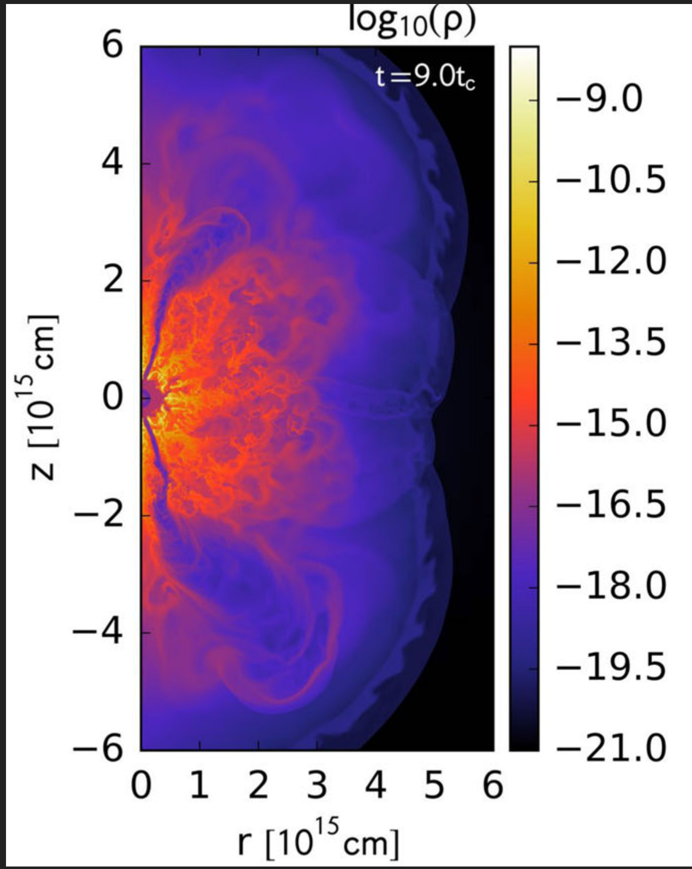
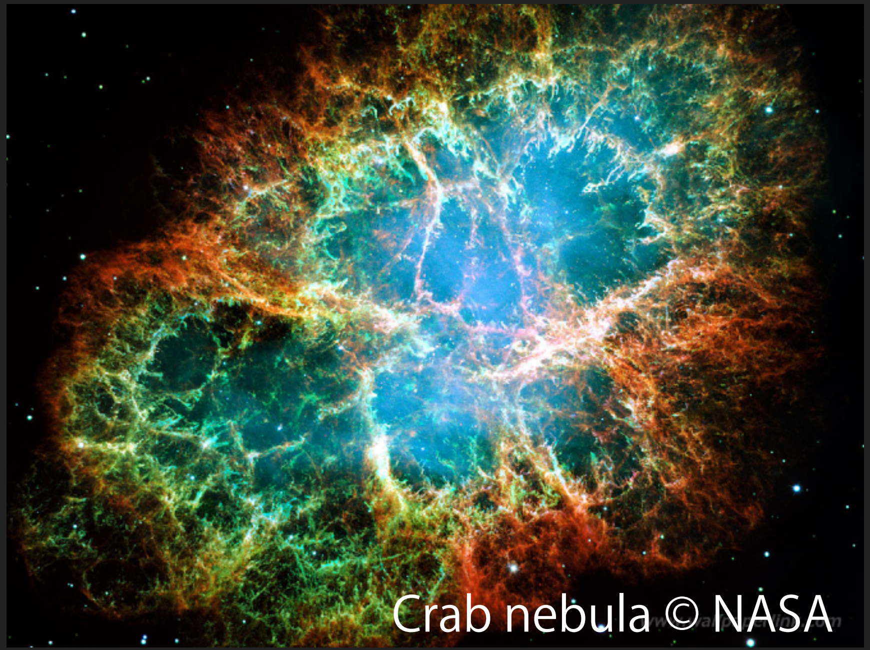
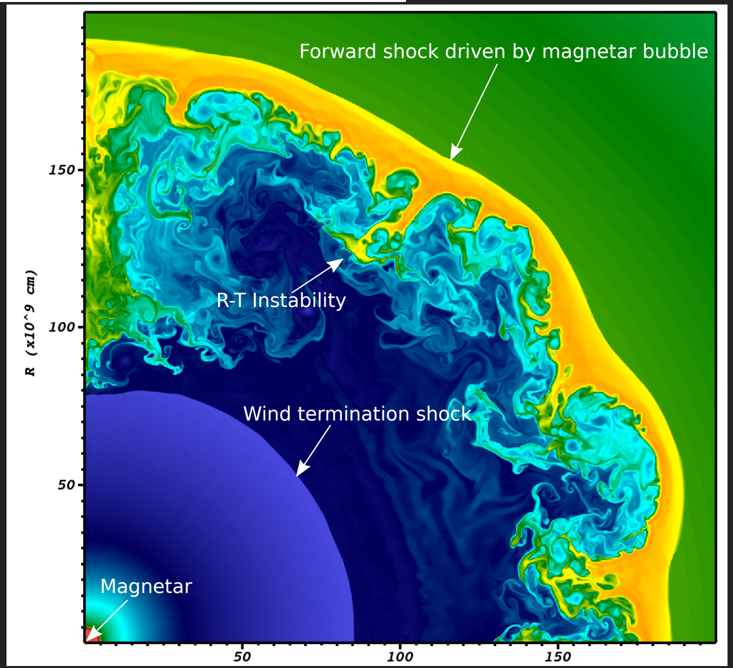
Suzuki & Maeda (2017)



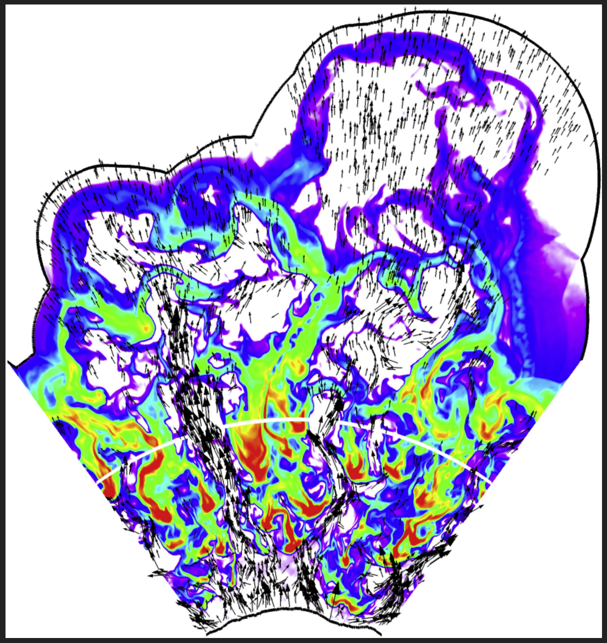




Crab nebula © NASA



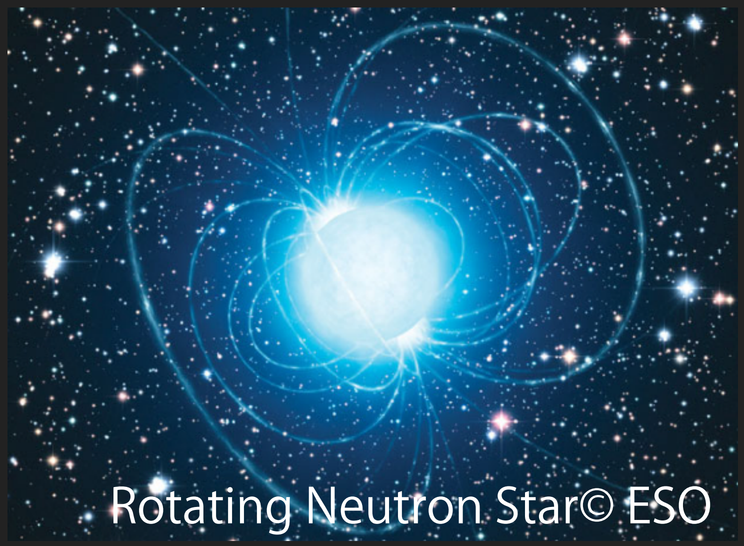
Chen, Woosley, & Sukhbold (2016)

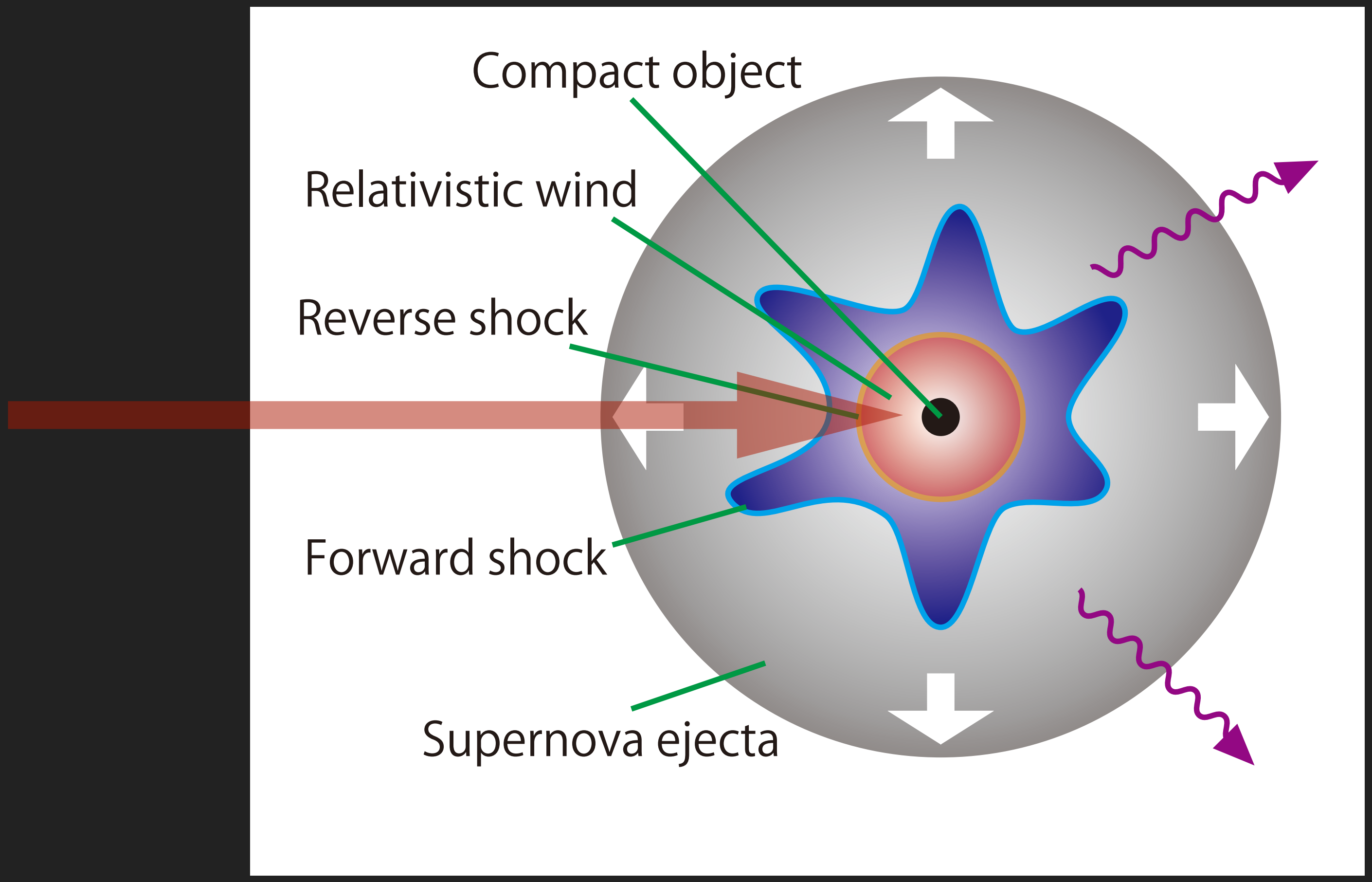


Blondin & Chevalier (2017)

Extreme supernovae and neutron star as an engine

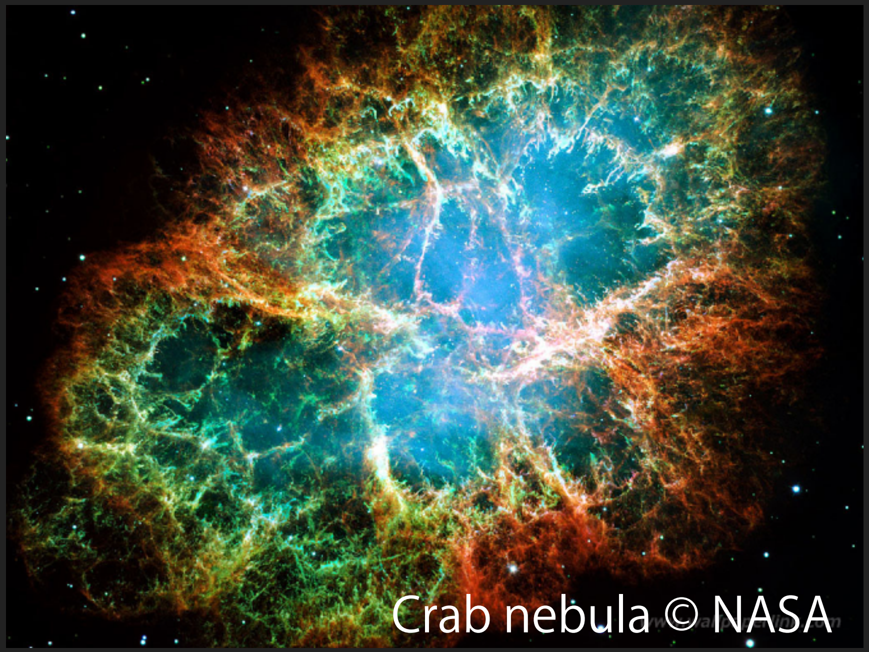
- How we can be sure about the presence of a highly rotating, magnetized neutron star in SN ejecta.
- Currently we are based on naive assumption
- NS physics can help?

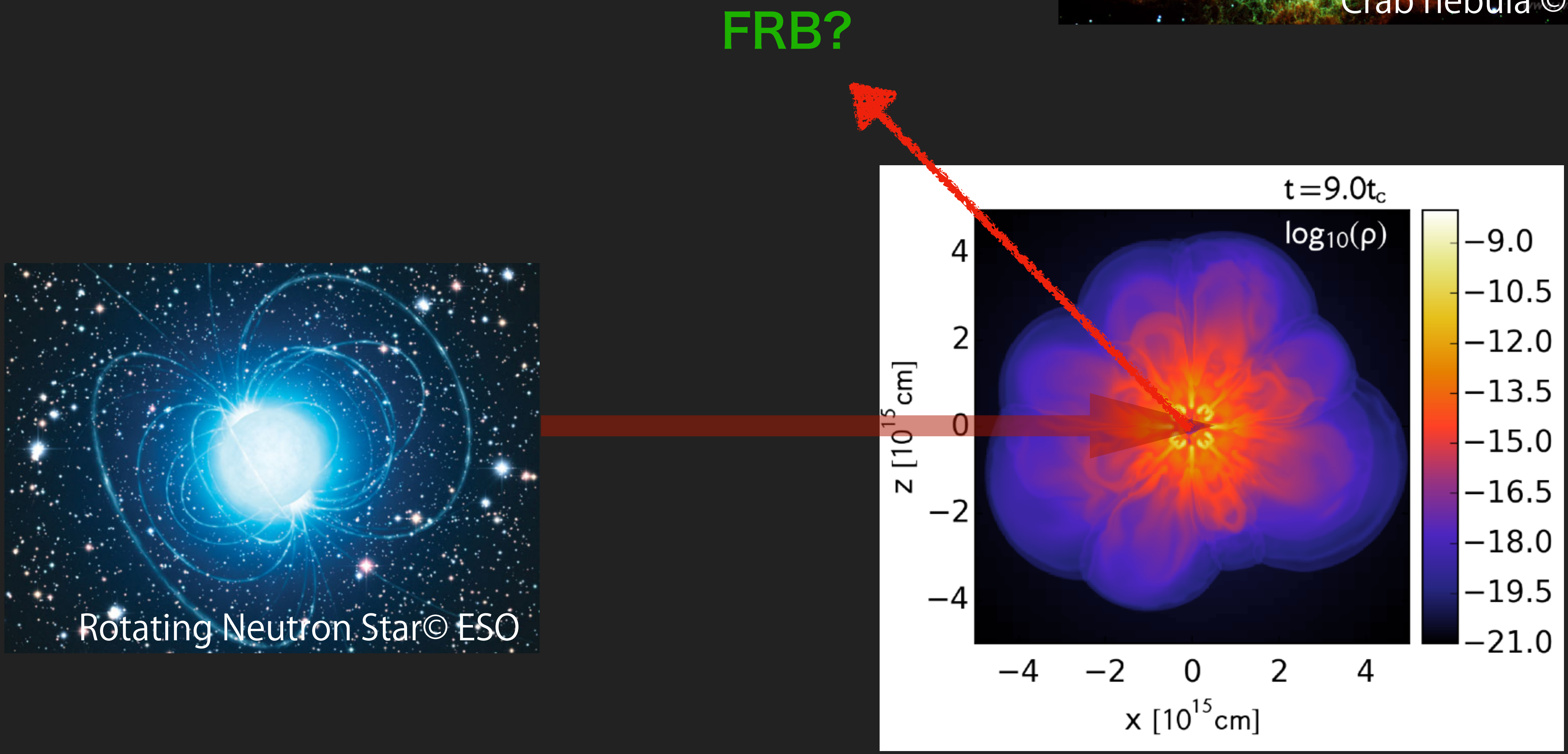




FRB in clumpy SLSN ejecta?

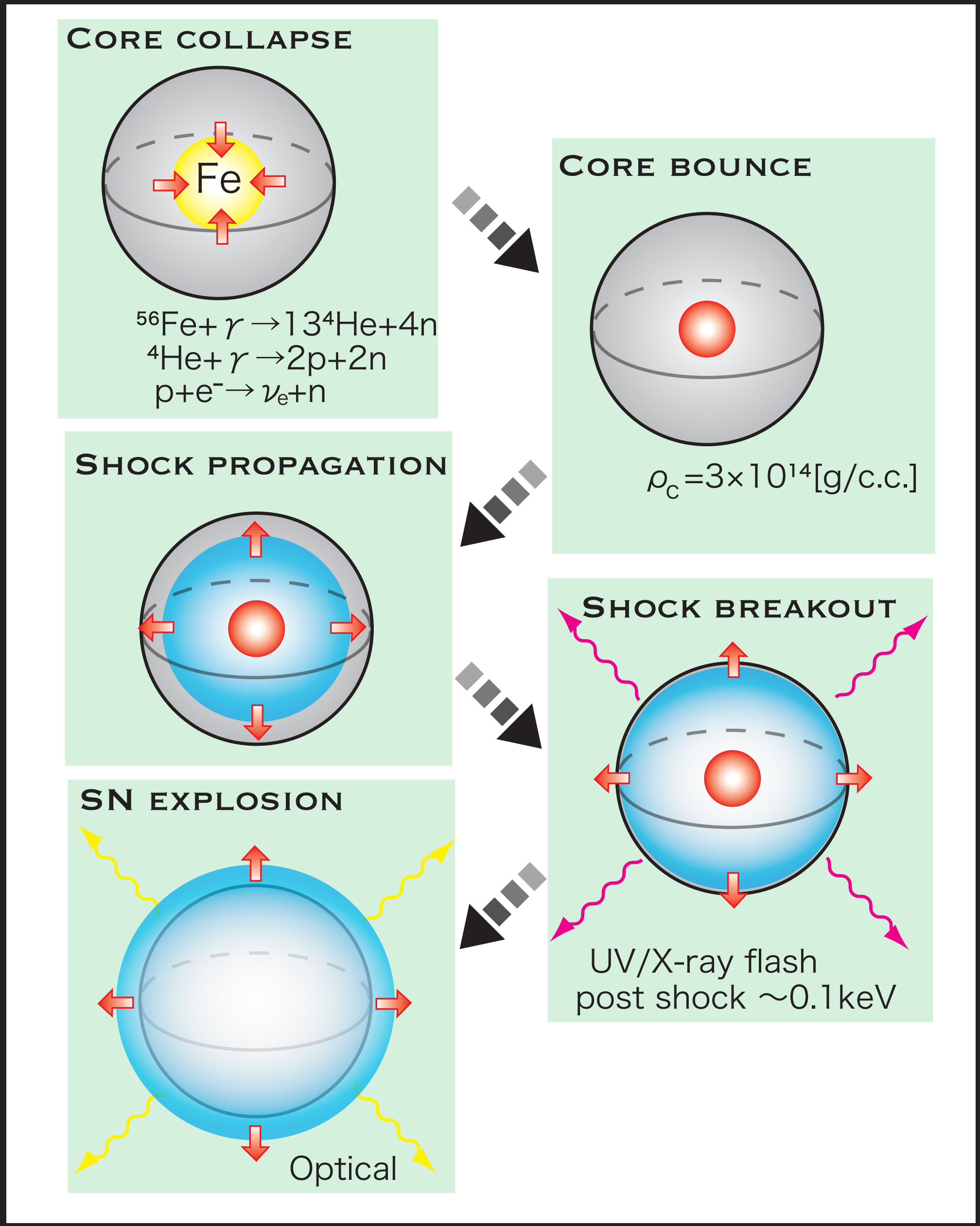
- If FRB-SLSN connection is true, FRB sources should be embedded in a clumpy SN ejecta
- SN ejecta contribute to DM and SM ?
- any idea?





Core-collapse Supernova explosion

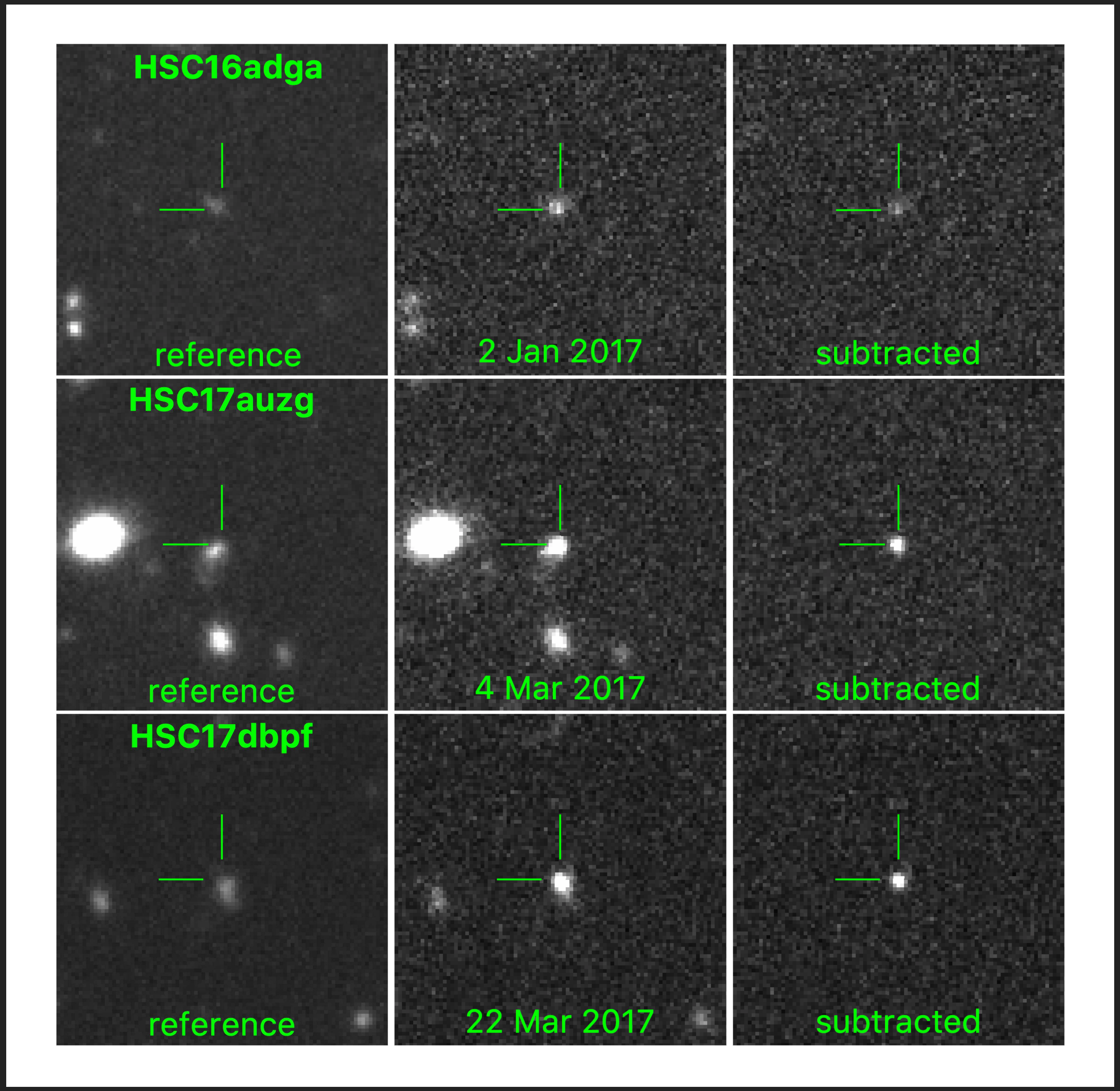
- CCSNe energetics: canonically,
  - ➡ gravitational energy: $E_{grav} \sim GM_{ns}^2/R_{ns} \sim 10^{53}$ [erg]
  - ➡ explosion energy: $E_{exp} \sim$ 1% of $E_{grav} \sim 10^{51}$ [erg]
  - ➡ radiation energy: $E_{rad} \sim$ 1% of $E_{exp} \sim 10^{49}$ [erg]
  - ➡ ejecta mass: $M_{ej} \sim 1 - 10$ [$M_\odot$]
  - ➡ typical velocity: $v \sim (2E_{exp}/M_{ej})^{1/2}$ ~ several 1000 - 10000 km/s
  - ➡ typical ^{56}Ni mass: $M_{Ni} \sim 0.1 M_\odot$



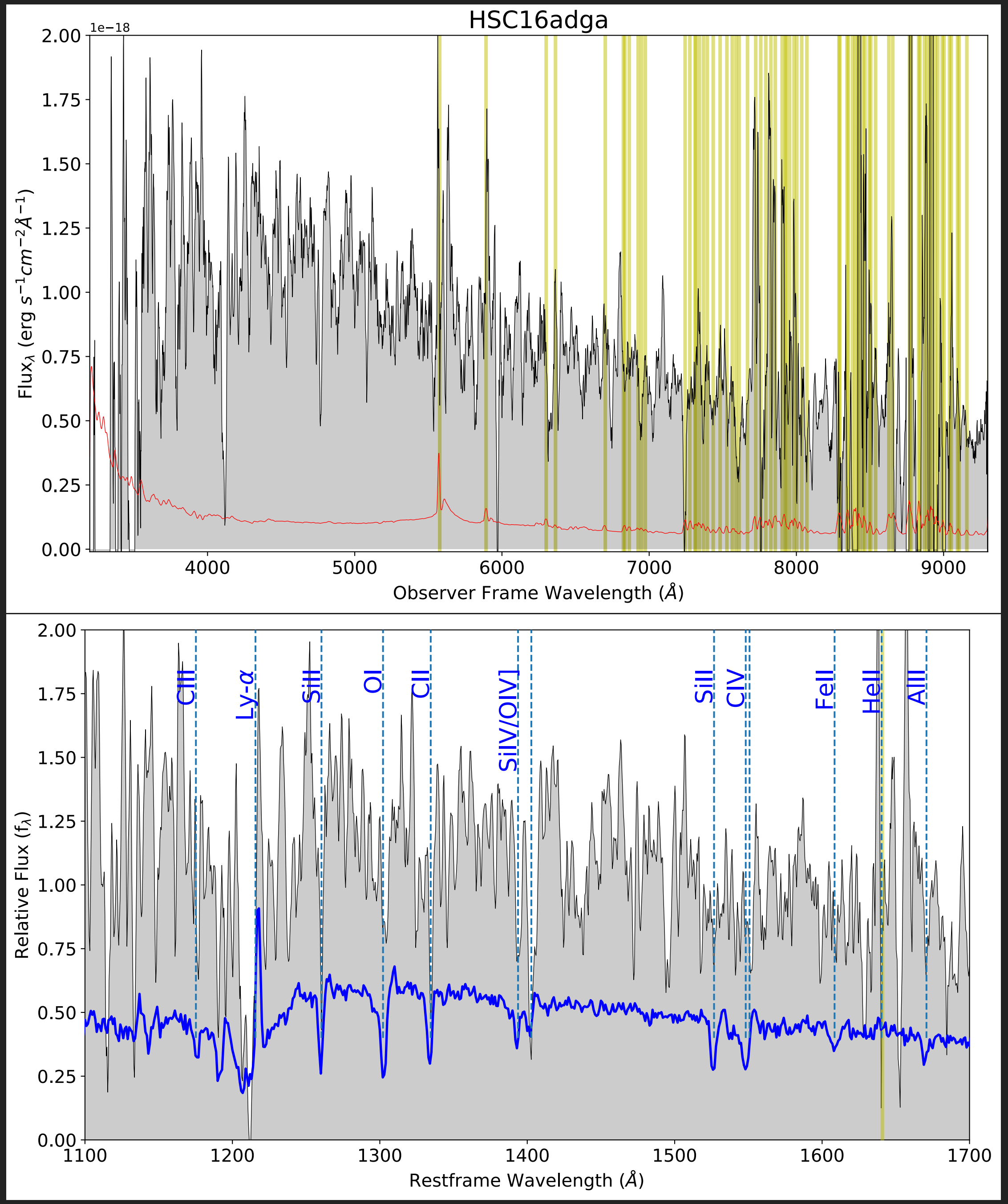
- But, extraordinary events are sometimes found
  - ➡ **broad-line Ic SNe**: ejecta mass and velocity appear to be larger, implying a larger kinetic energy of **10^{52}** [erg] > 10^{51} [erg]
  - ➡ **superluminous SNe**: extremely bright SNe with total radiated energies of **10^{51}** [erg] > 10^{49} [erg]

Superluminous Supernovae

- high-z event: three spectroscopically confirmed events at z=1.851, 1.965 and 2.399 (HSC: Moriya+2018, Curtin+2018)



HSC images: Moriya+(2018)



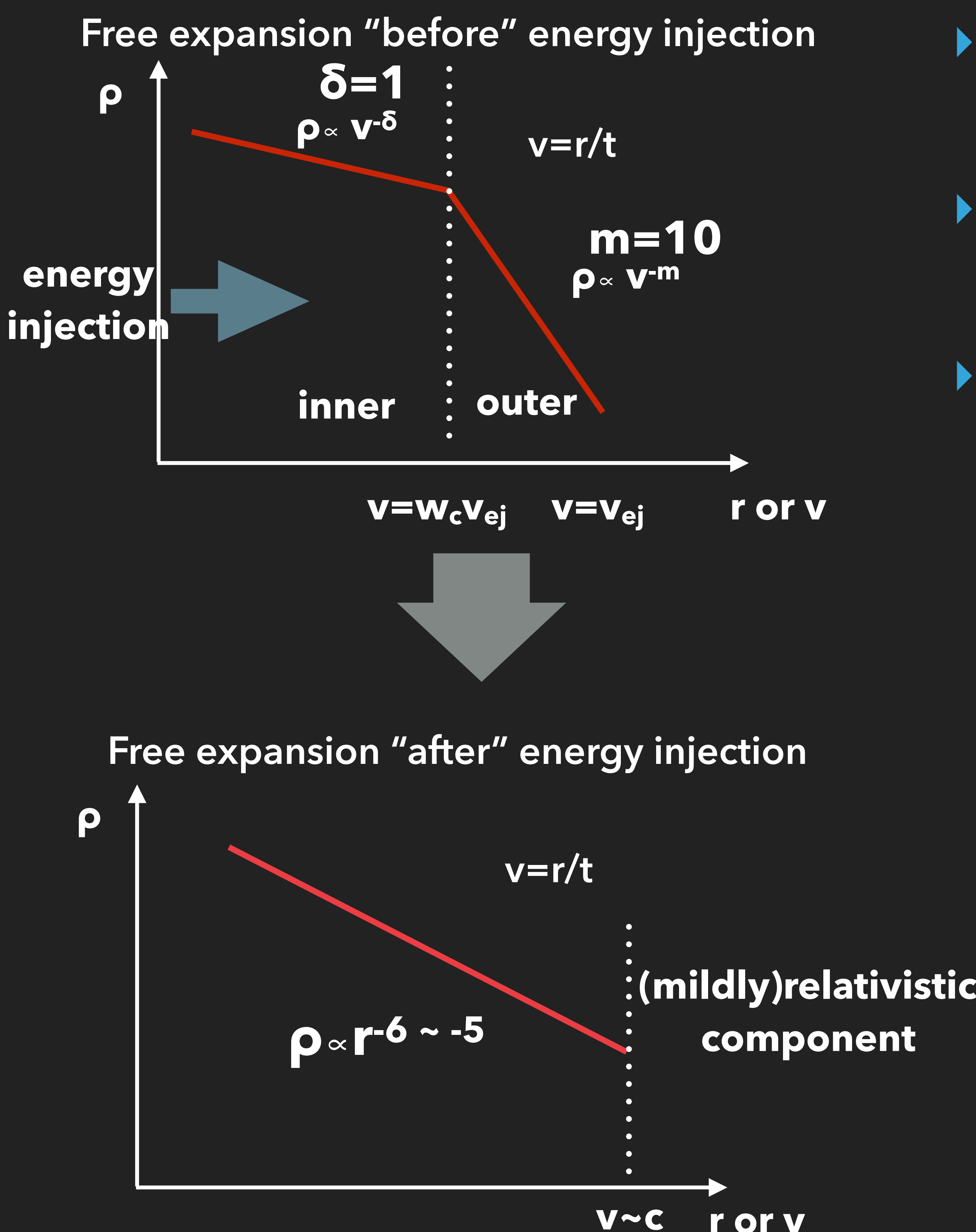
Keck spectra: Curtin+(2018)

Rotating magnetized (proto-)neutron star hypothesis

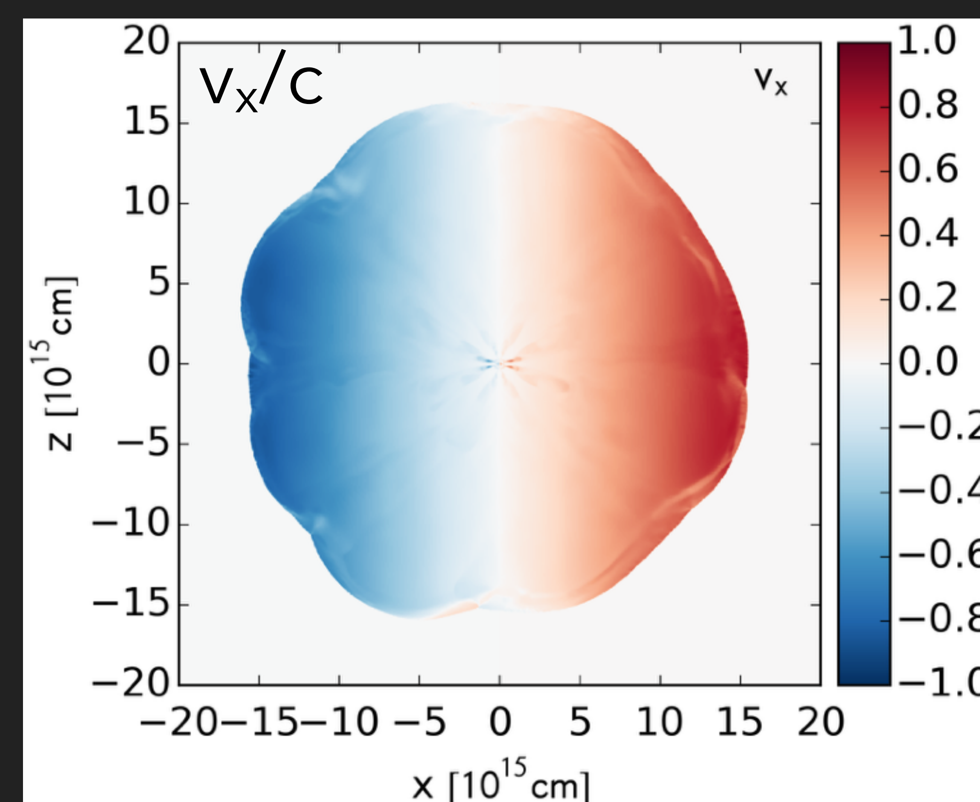
- **But**, how exactly the magnetized neutron star power the SN ejecta
- The magnetic braking is formulated by assuming a rotating neutron star with a dipole magnetic field surrounded by vacuum. What happens in highly dense environment? Can we apply the vacuum dipole formula?
- OK, we can assume that the energy extraction from the rotating neutron star is realized by the magnetic braking. But, the energy flux is "**Poynting-flux dominated**"
  → long-standing σ-problem (Rees&Gunn 1974, Kennel&Coroniti 1984, etc): how to convert Poynting-dominated flow to particle energy-dominated flow???

Usually, magnetar scenario is employed as a "working hypothesis" and see what happens

Non-thermal emission from CSM interaction



- The outermost layers are accelerated up to v~c
- non-thermal e^- production via shock acceleration
- SNe with a central engine can be bright radio emitter.



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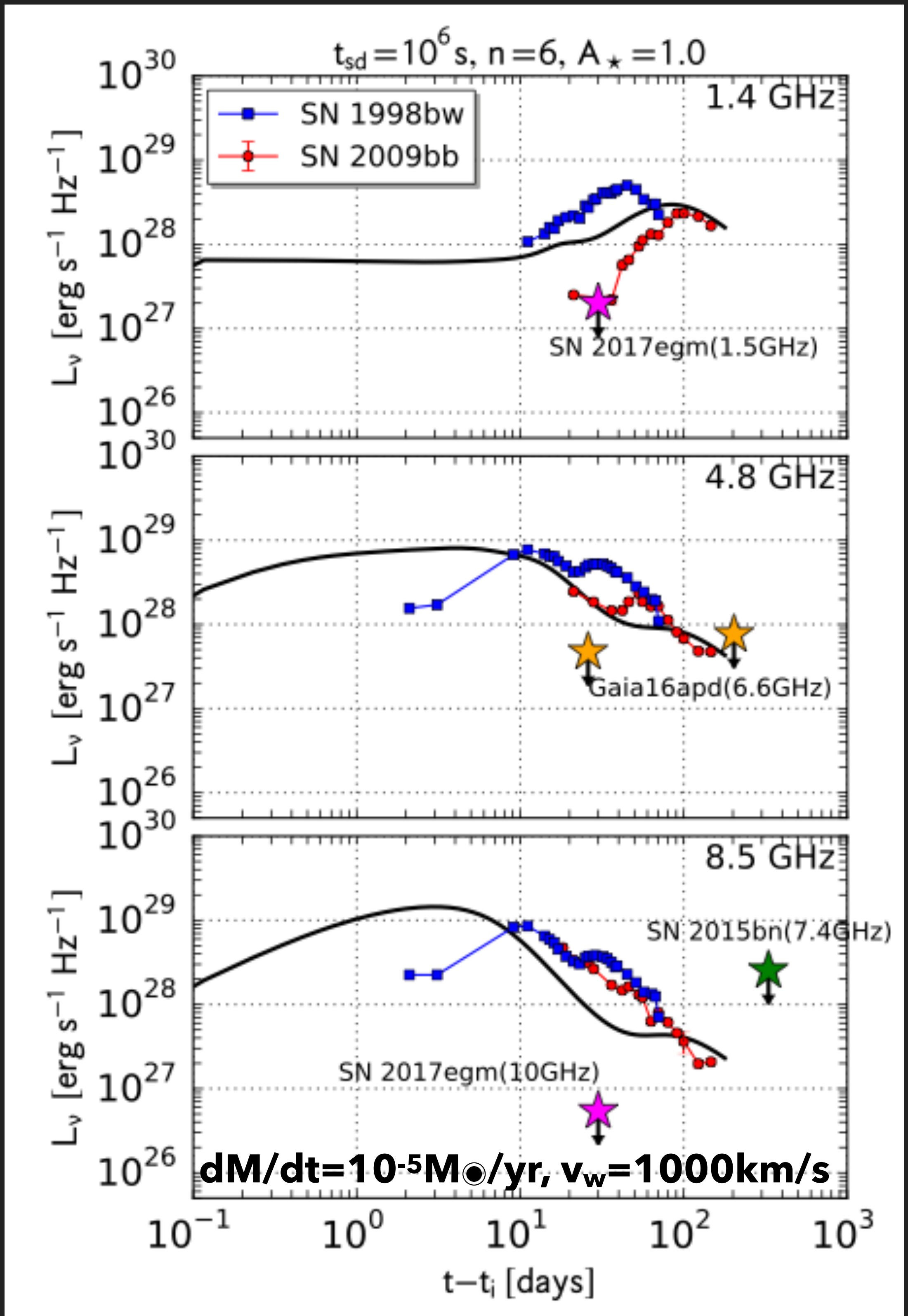


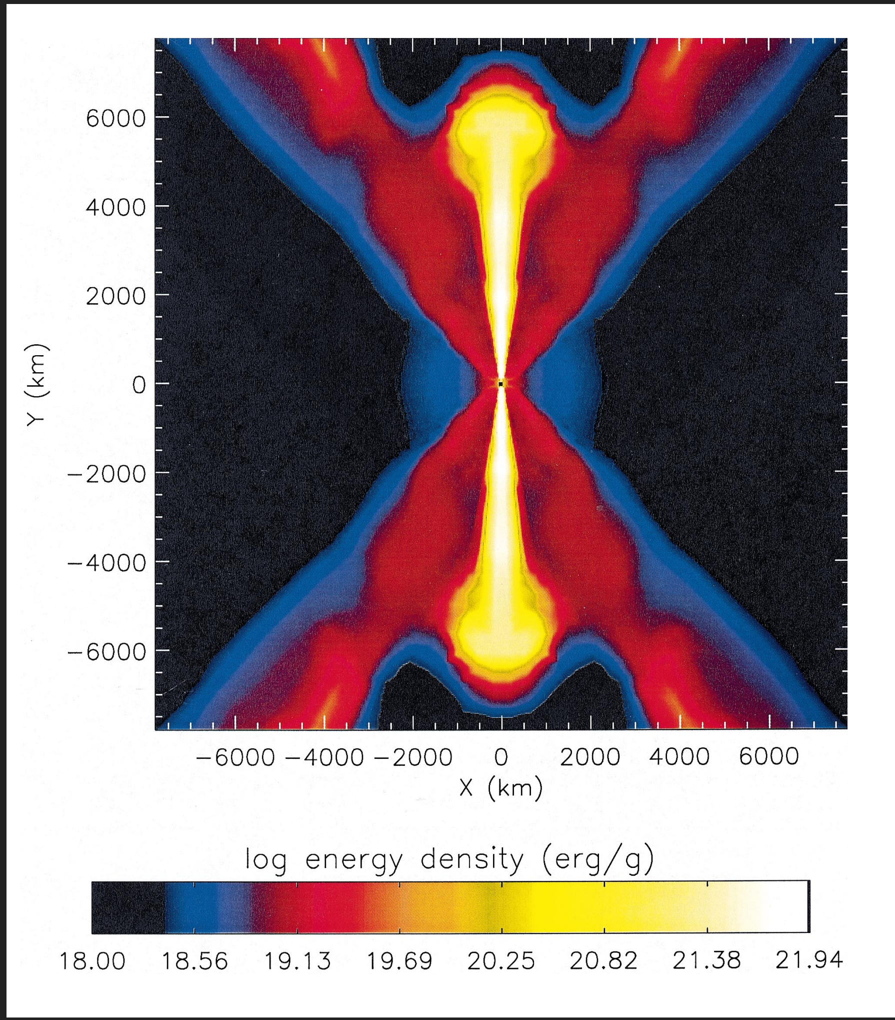
- The outermost layers are accelerated up to v~c
- non-thermal e$^-$ production via shock acceleration
- SNe with a central engine can be bright radio emitter.

- similar radio fluxes to radio-bright broad-lined Ic SNe (1998bw and 2009bb)
- tight radio upper limits are already available for some SLSNe
  → absence of relativistic ejecta in SLSNe?

Suzuki&Maeda (2018) MNRAS 478, 110
see also Metzger+ (2017), Omand+ (2018), Coppejans+ (2018)

NS stars as GRB engine?

- collapsar vs magnetar
- collapsar: BH accretion disk (Woosley 1993, MacFadyen&Woosley 1999)
- (proto-)magnetar: rotating magnetized neutron star (Usov 1992, Thompson 1994, Metzger+ 2007,2010, etc)
- magnetar engine for XRF/LLGRBs?: the case of GRB 060218/SN 2006aj (Mazzali+2006)



MacFadyen&Woosley (1999)

NS stars as GRB engine?

- collapsar vs magnetar
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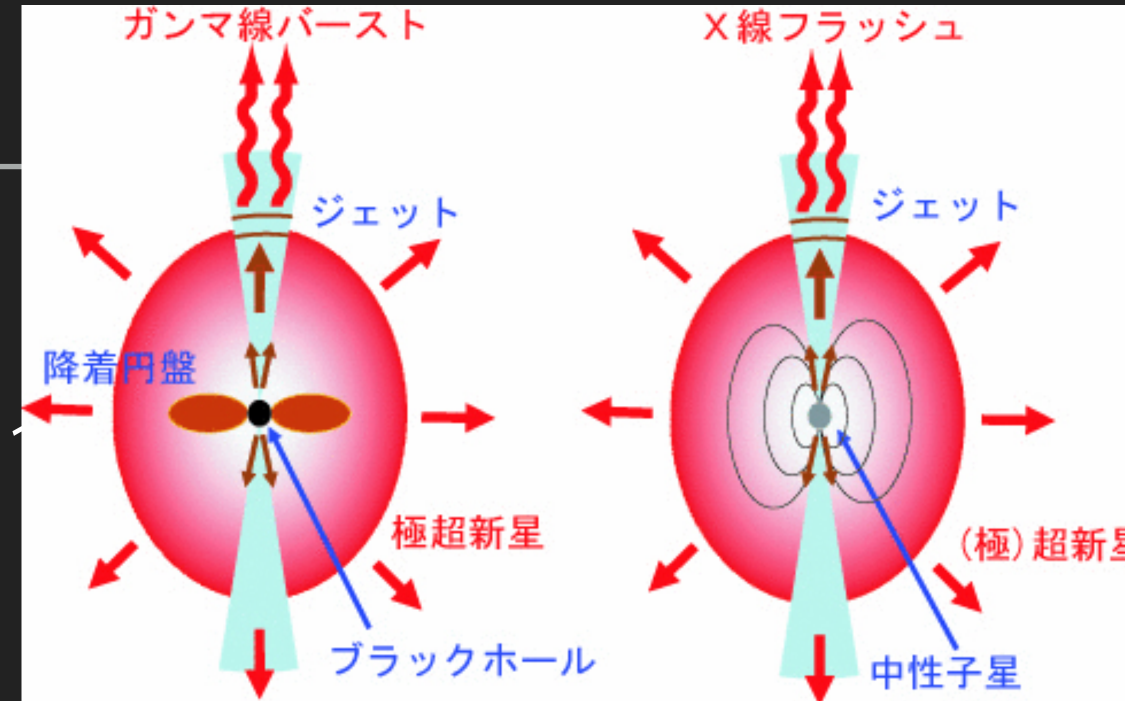
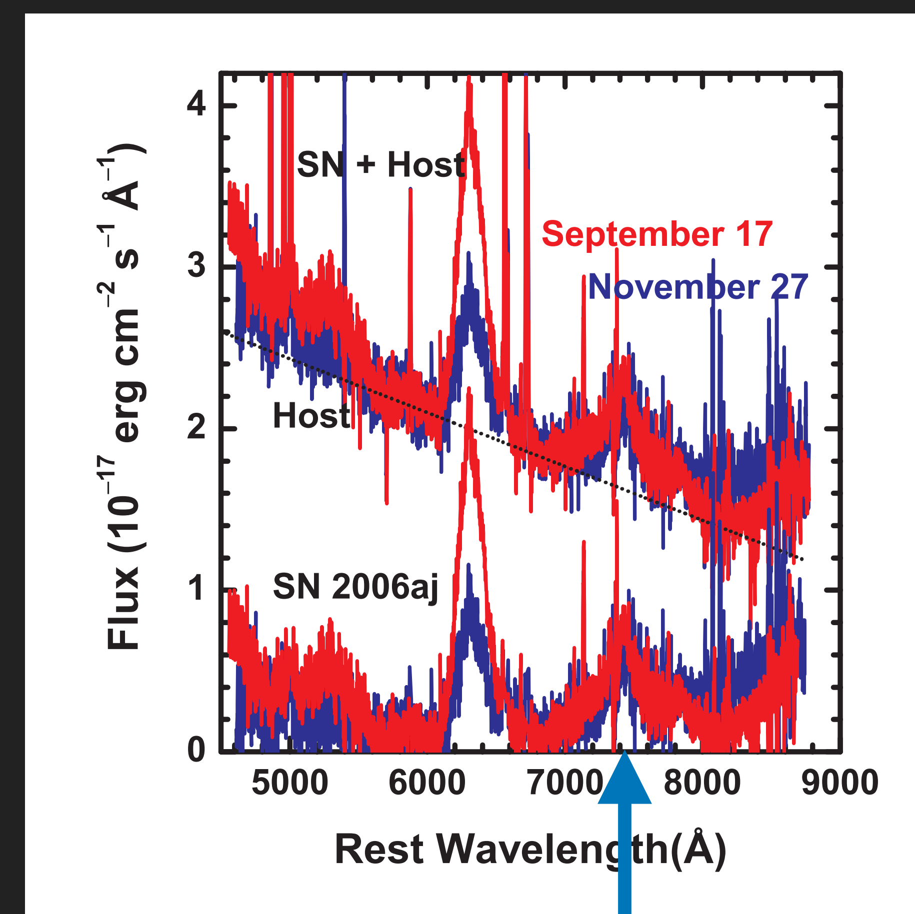
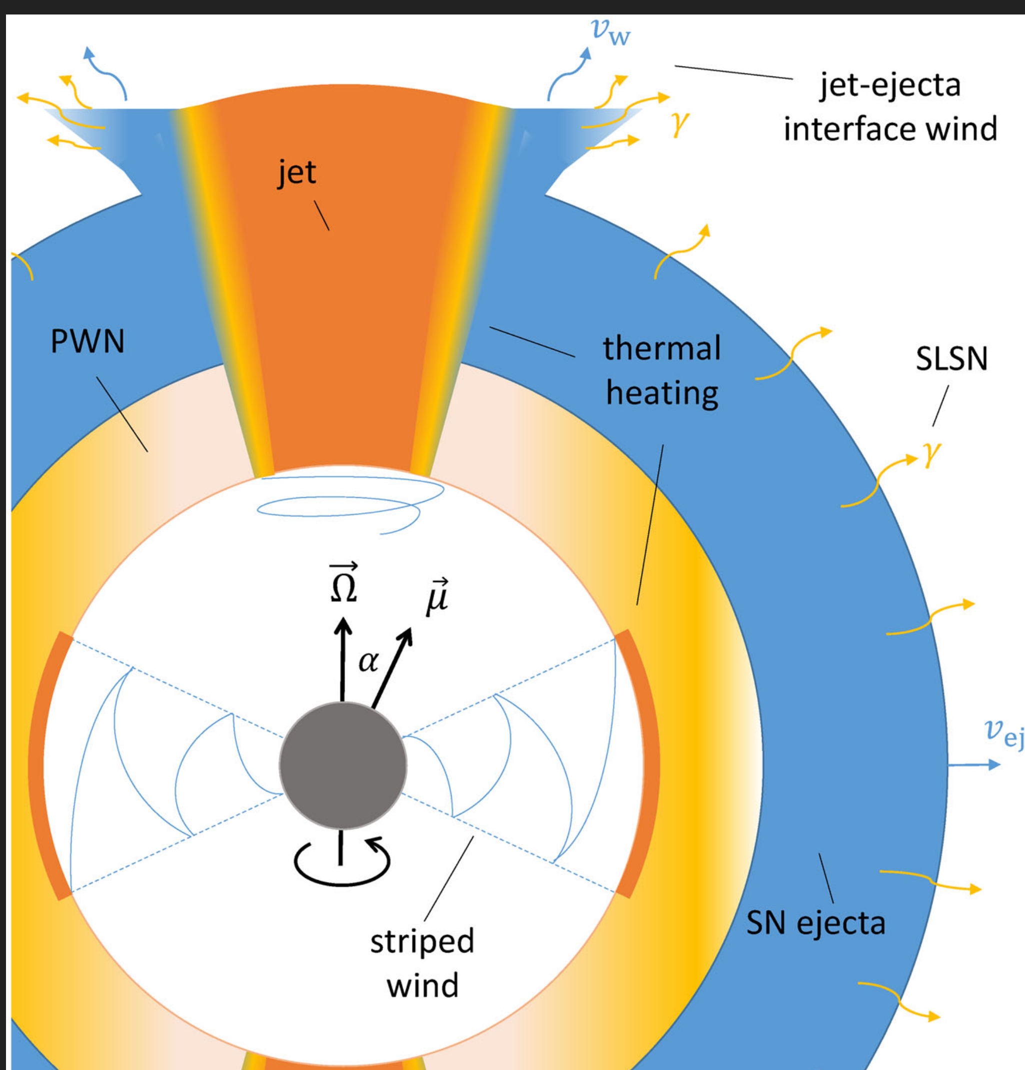


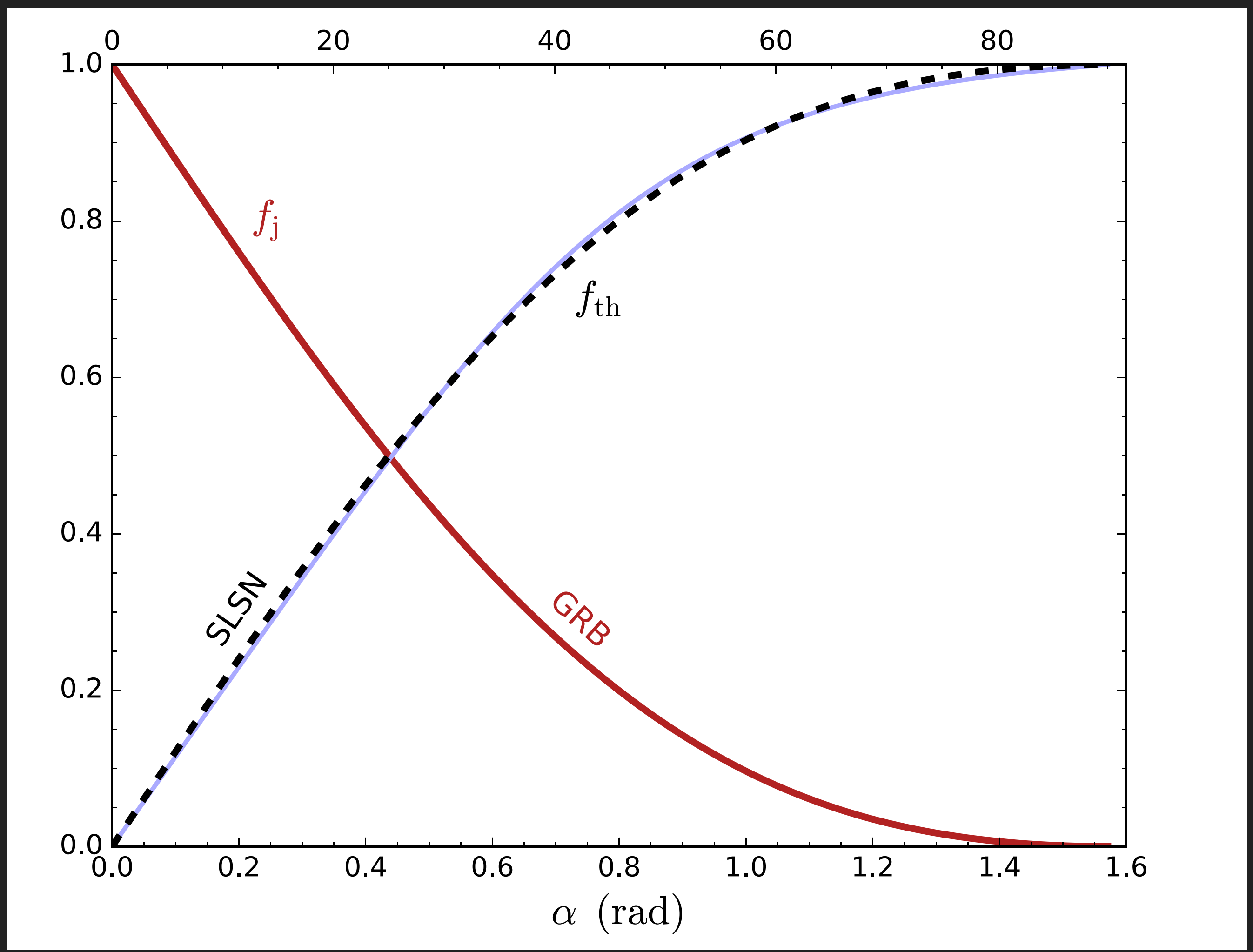


^{58}Ni emission line in SN 2006aj?
(Maeda+ 2007)

SLSN-GRB connection?

- SN 2011kl associated with unusually long GRB 111209A
- SN 2011kl was ~3 times more luminous than other GRB-SNe
- similar spectral properties to SLSNe
- common mechanism to produce GRBs and SLSNe?





Margalit+(2018)

Models for type-I SLSNe

- pair-instability SNe (very massive progenitor with M~140-300 $M_{\odot}$)
- CSM interaction
- additional energy injection from the central-engine :rotating neutron star (Kasen&Bildsten 2010, Woosley2010), or BH accretion (Dexter&Kasen 2013)

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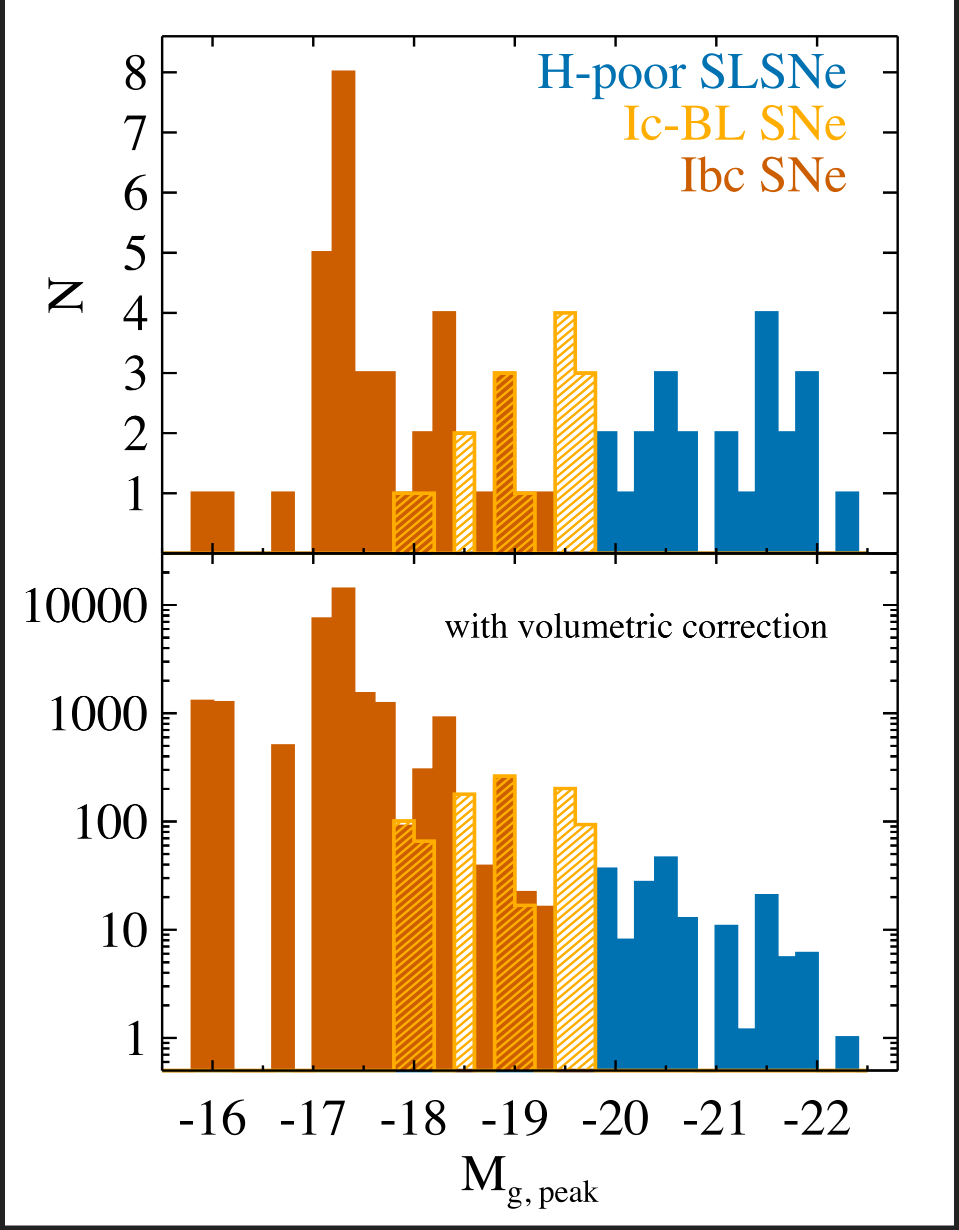
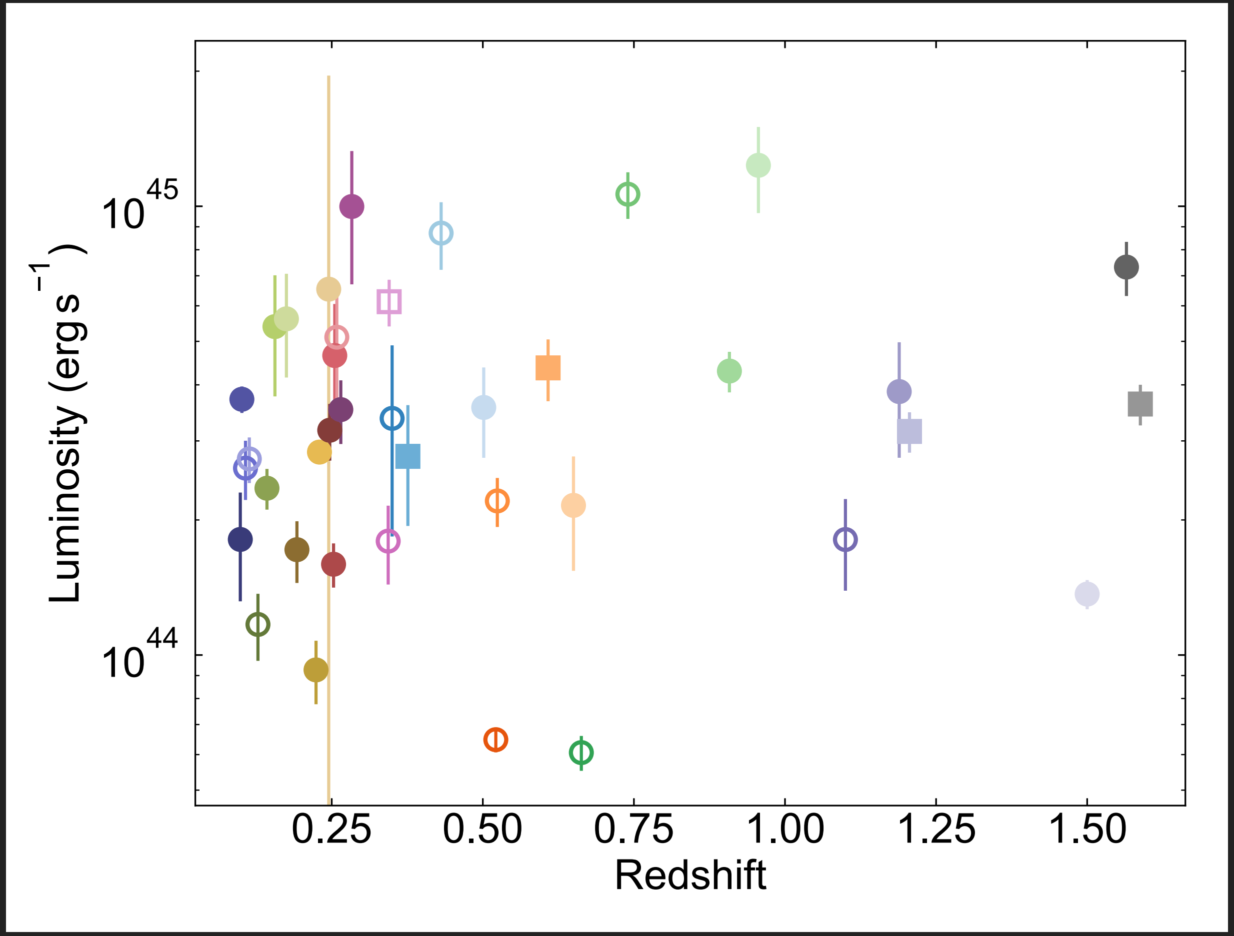
Superluminous Supernovae

- SLSNe at maximum light: traditional threshold M_{abs}~-21
- the corresponding luminosity of L~10^{44}[erg/s]
- "Gap-transient"? (Arcavi+2016)



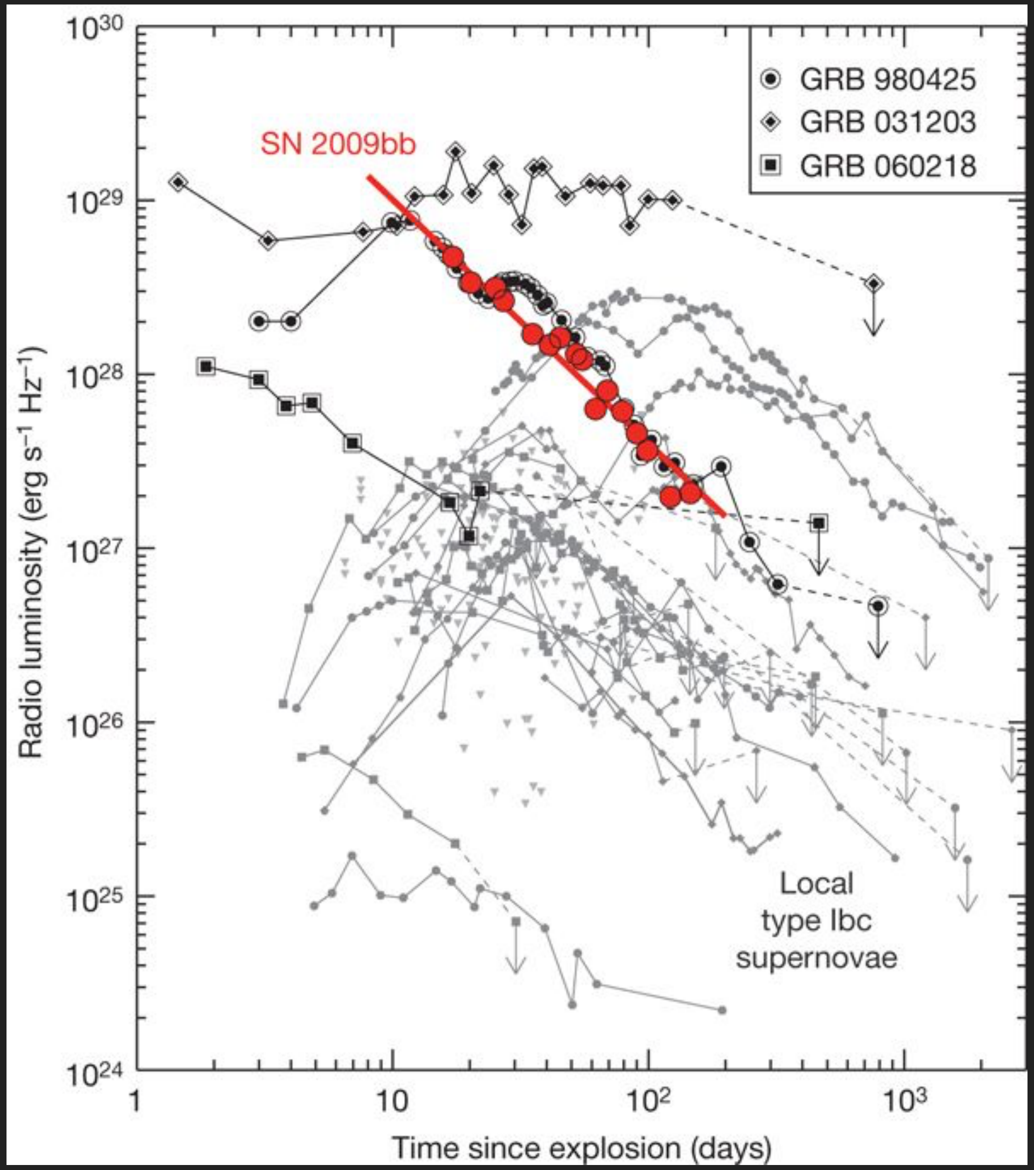
peak M_g distribution of PTF samples (De Cia+2018)

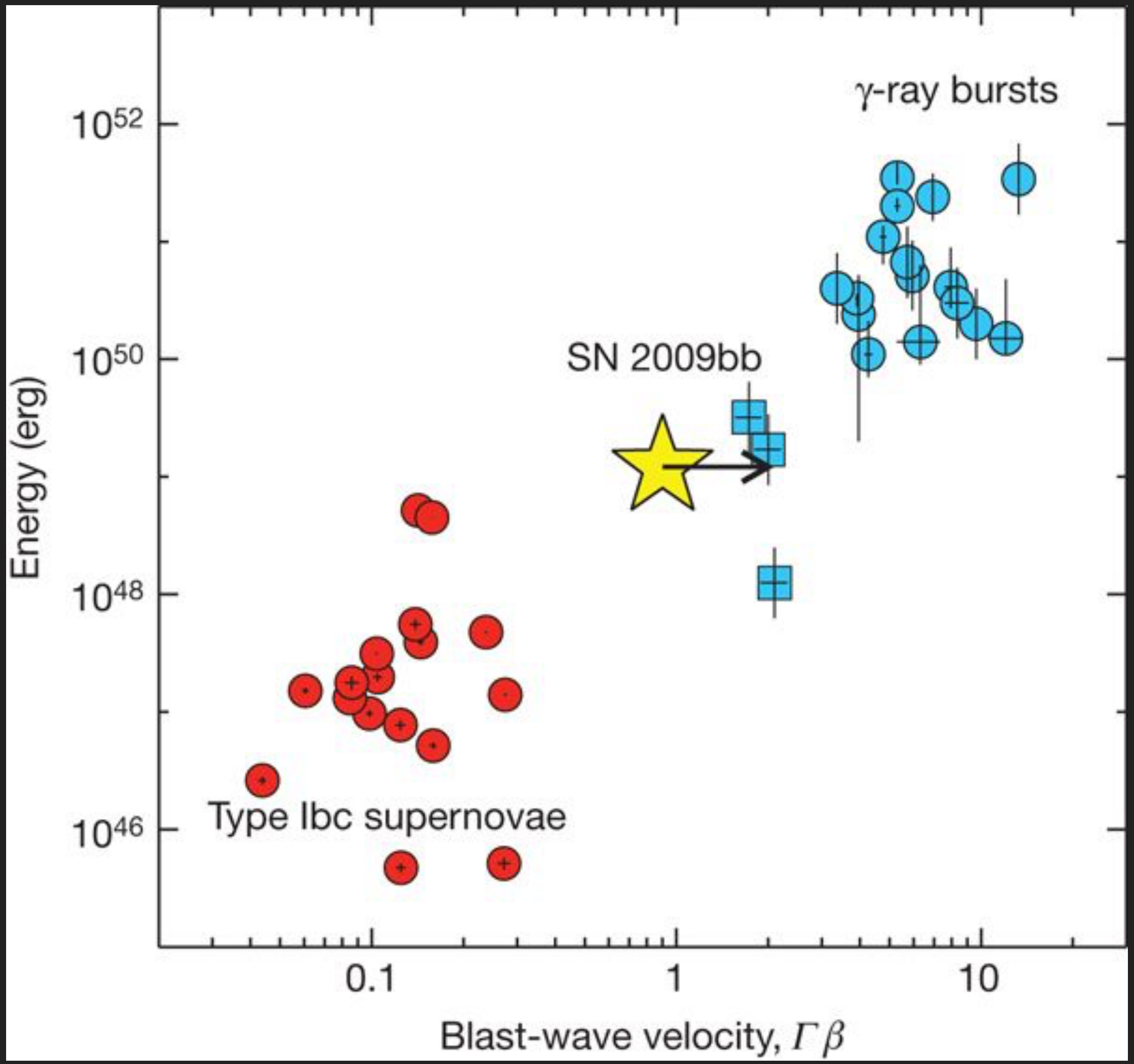


peak L vs redshift: Nicholl+(2017)

Relativistic SNe (without GRB)

- energetic SNe with bright radio emission similar to GRB-SNe
- But, without any GRB association
- relativistic SNe: SN 2009bb, 2012ap

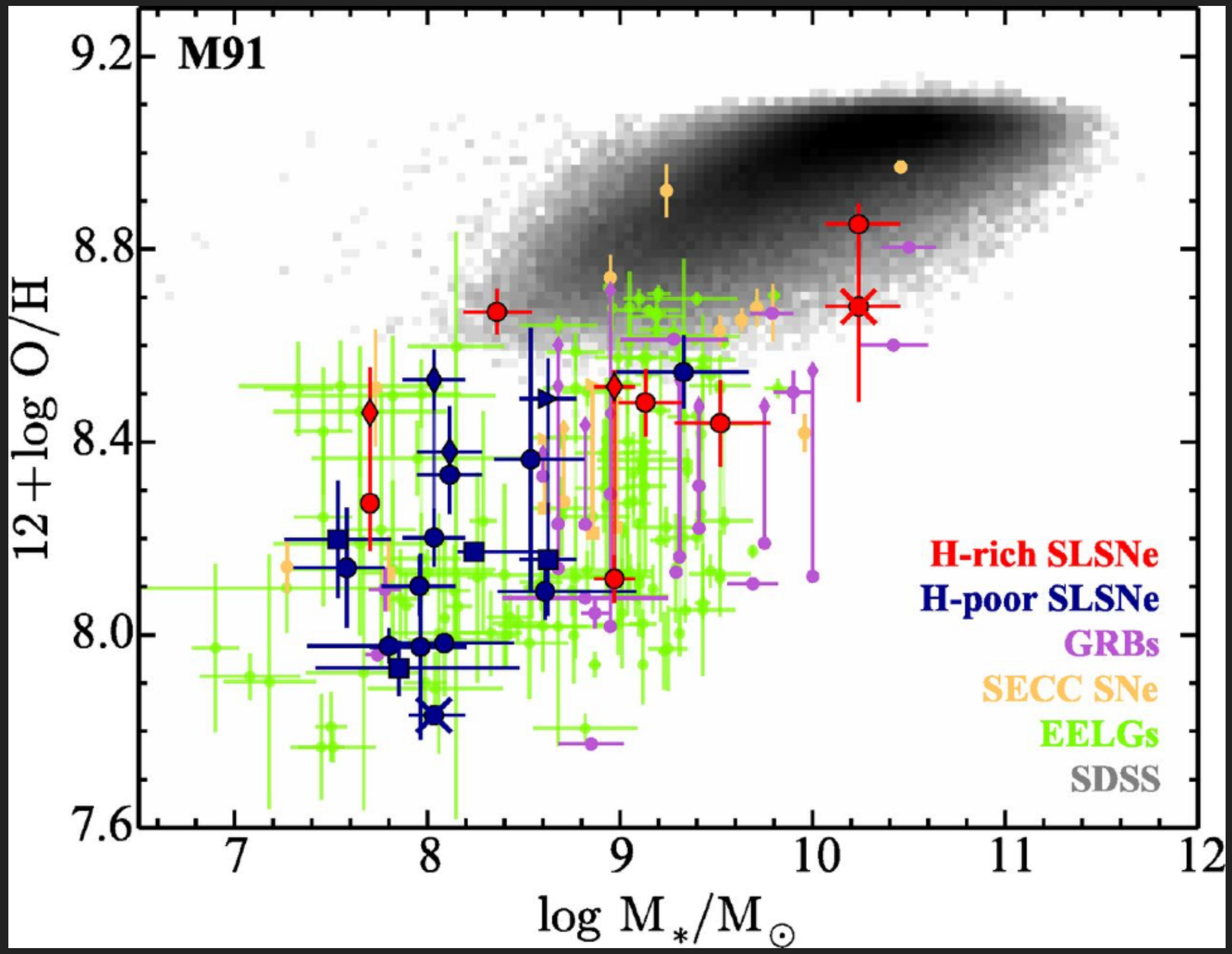




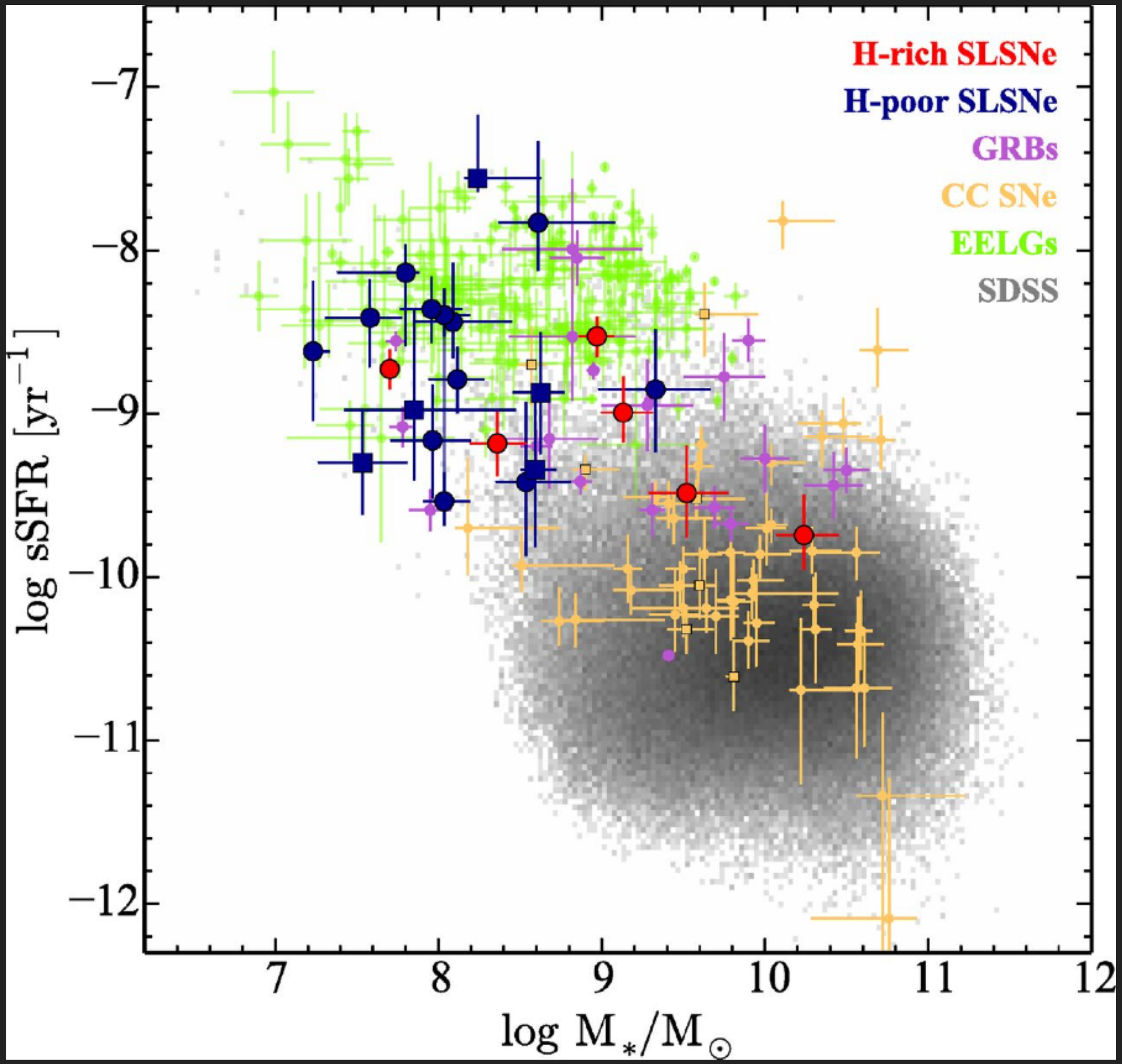
Superluminous Supernovae

- host galaxy demographics
- SLSNe-I prefer small dwarf galaxies with high specific SFRs
- low metallicity
- similar trend for GRB and SNe Ic-BL host galaxies

Leloudas+(2015)



↑stellar mass vs metallicity



↑stellar mass vs sSFR

Superluminous Supernovae

- host galaxy demographics
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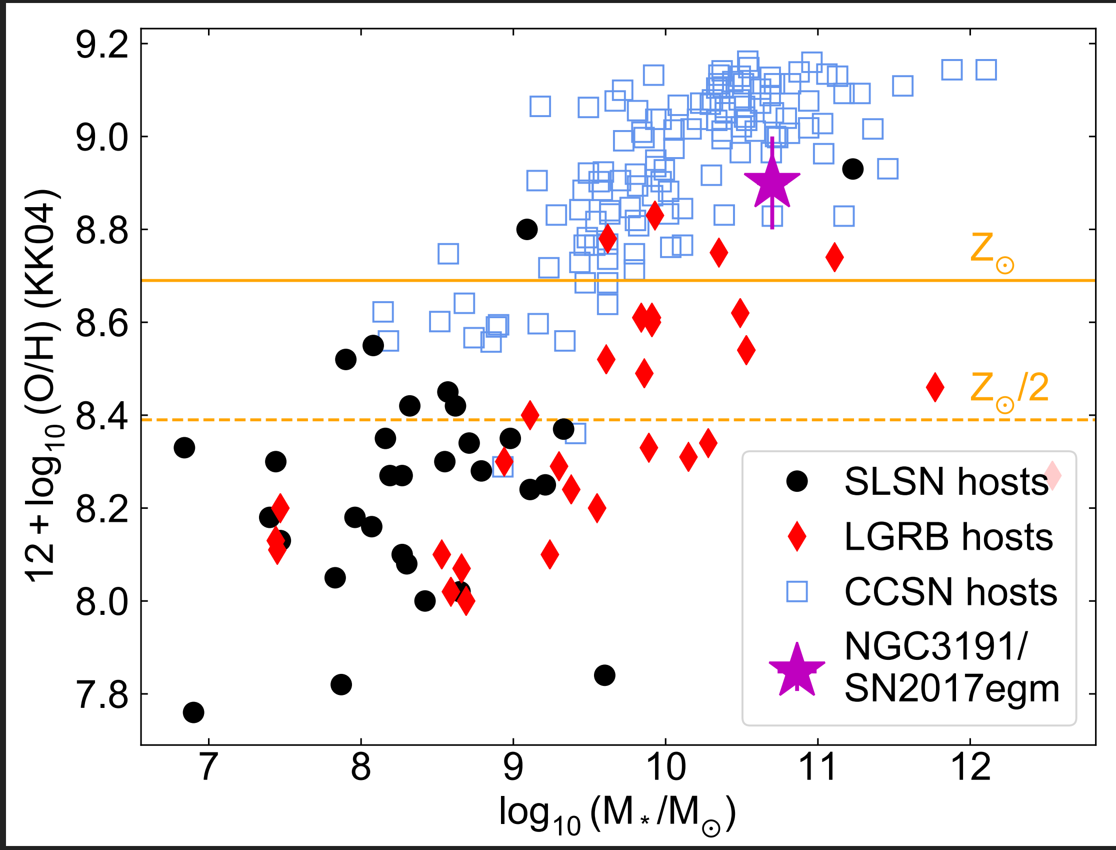
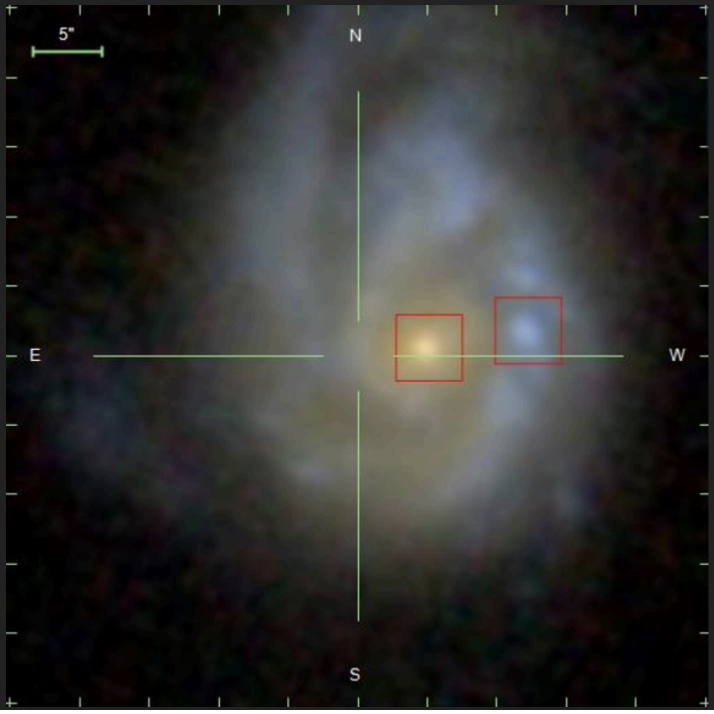
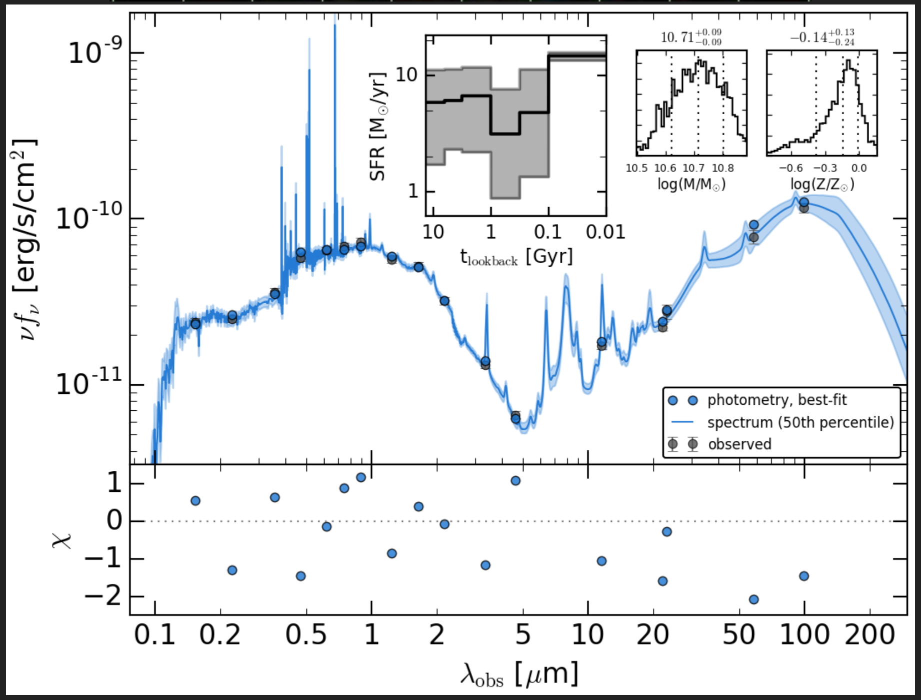
- similar trend for GRB and SNe Ic-BL host galaxies
- **But**, recent discovery of SN2017egm
  in a massive galaxy with (super) solar metallicity



↑stellar mass vs metallicity

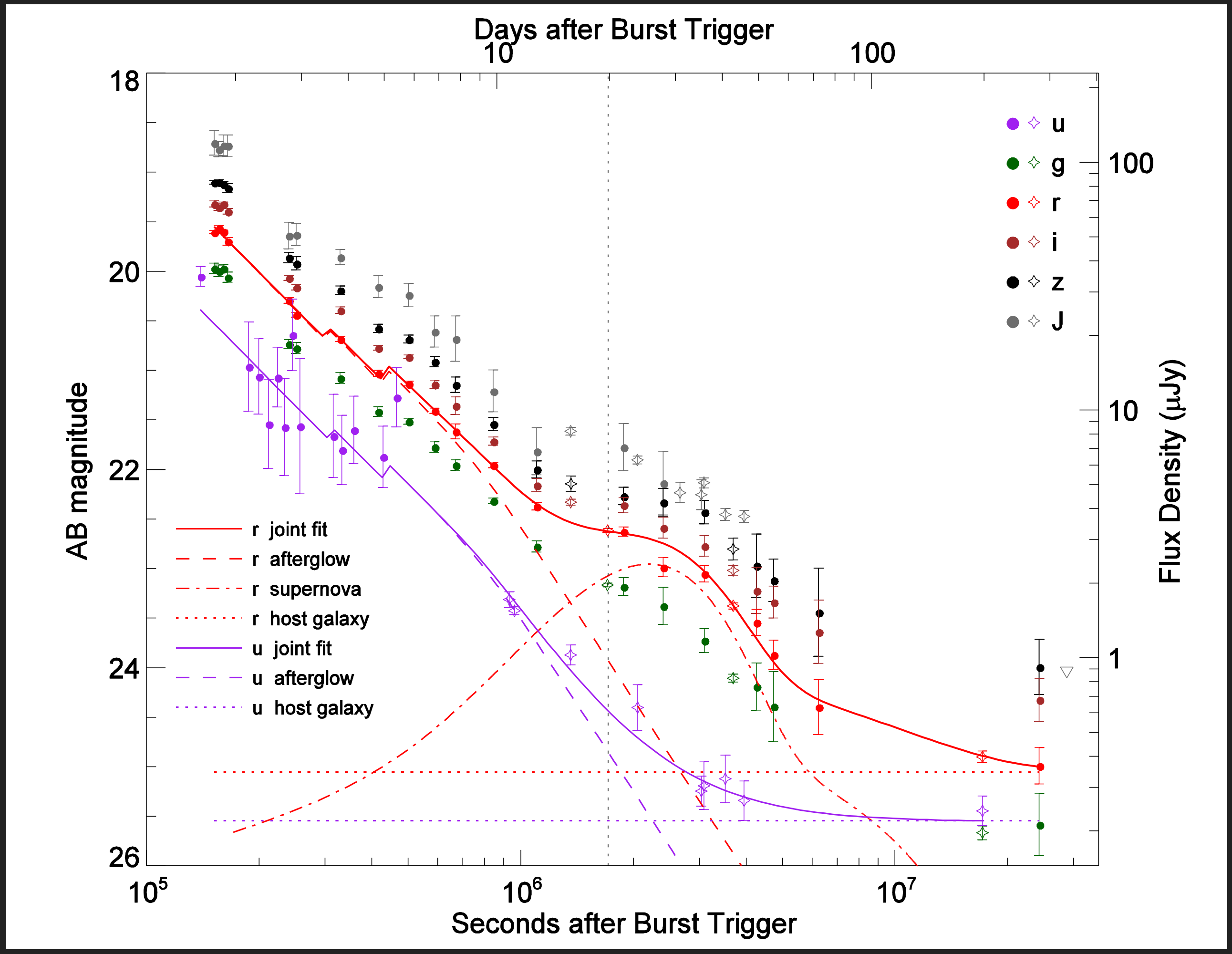


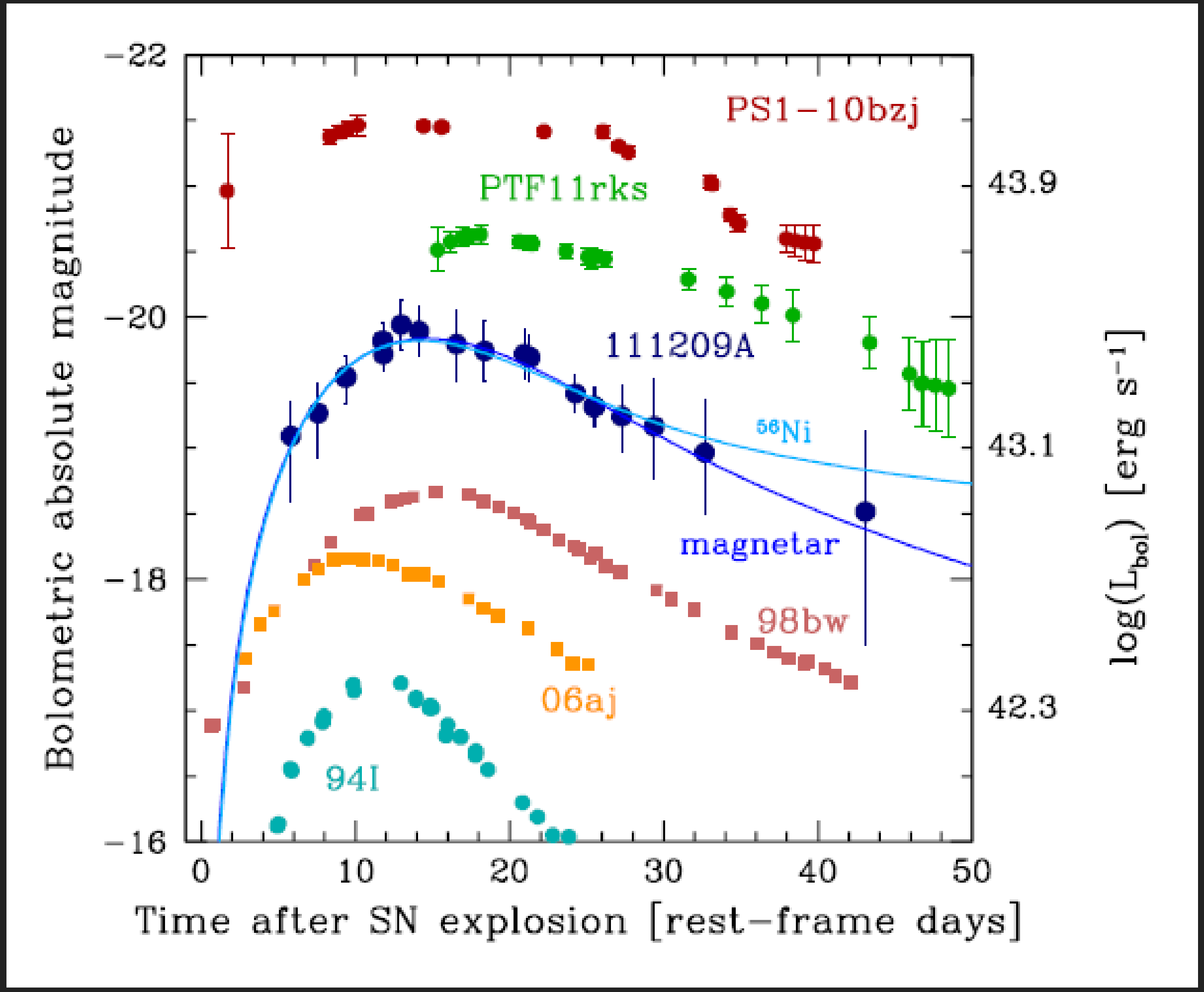


Nicholl+(2017)

SLSN-GRB connection?

- SN 2011kl associated with unusually long GRB 111209A
- SN 2011kl was ~3 times more luminous than other GRB-SNe
- similar spectral properties to SLSNe
- common mechanism to produce GRBs and SLSNe?





Greinar+(2015)