Central engine scenarios for extreme supernovae

Akihiro Suzuki (NAOJ fellow)

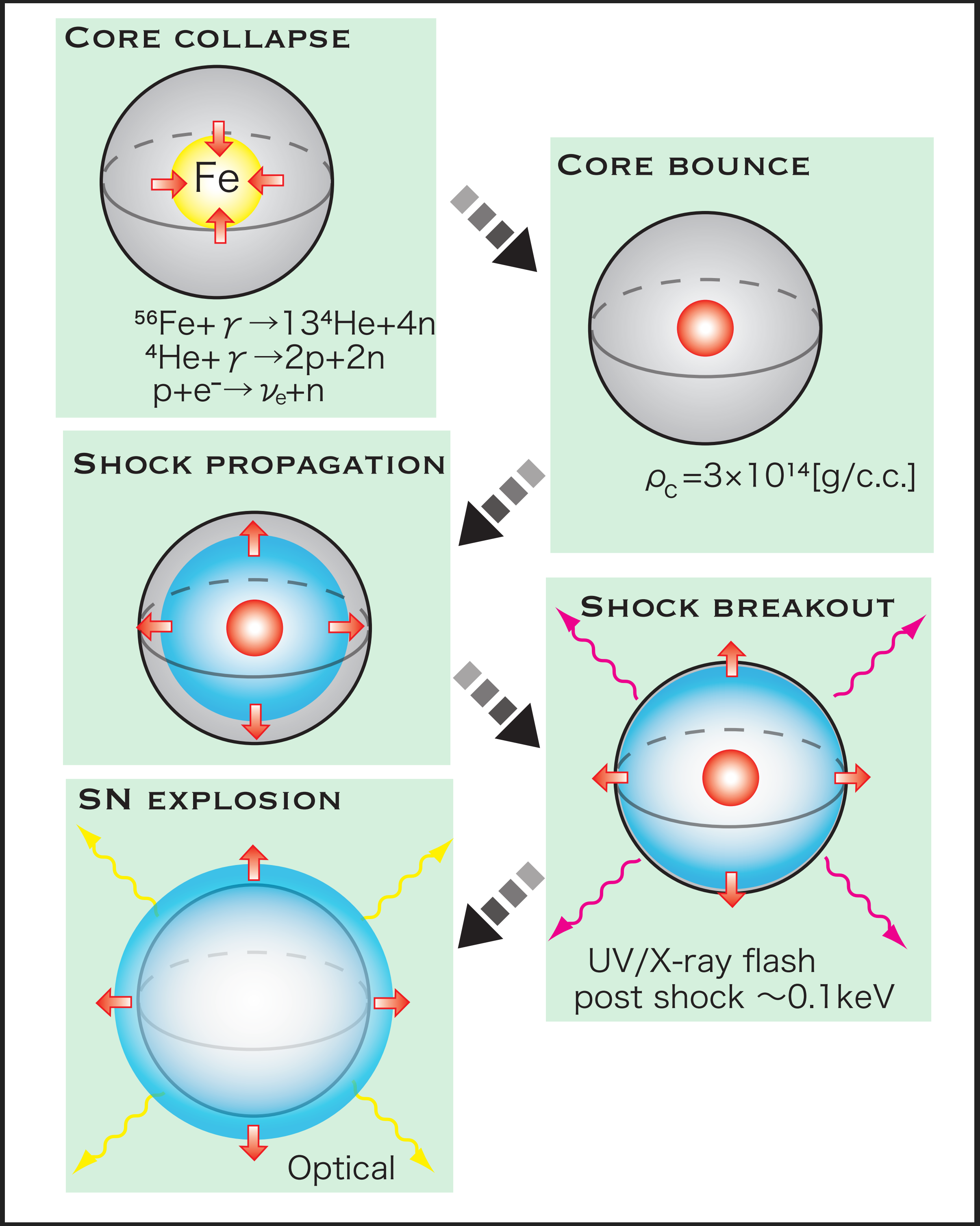
Neutron star workshop, Feb 20, 2019

Talk outline

- ordinary and extra-ordinary supernovae
- GRB-SNe and SLSNe: observational properties
- (magnetized) NS as an engine
- summary

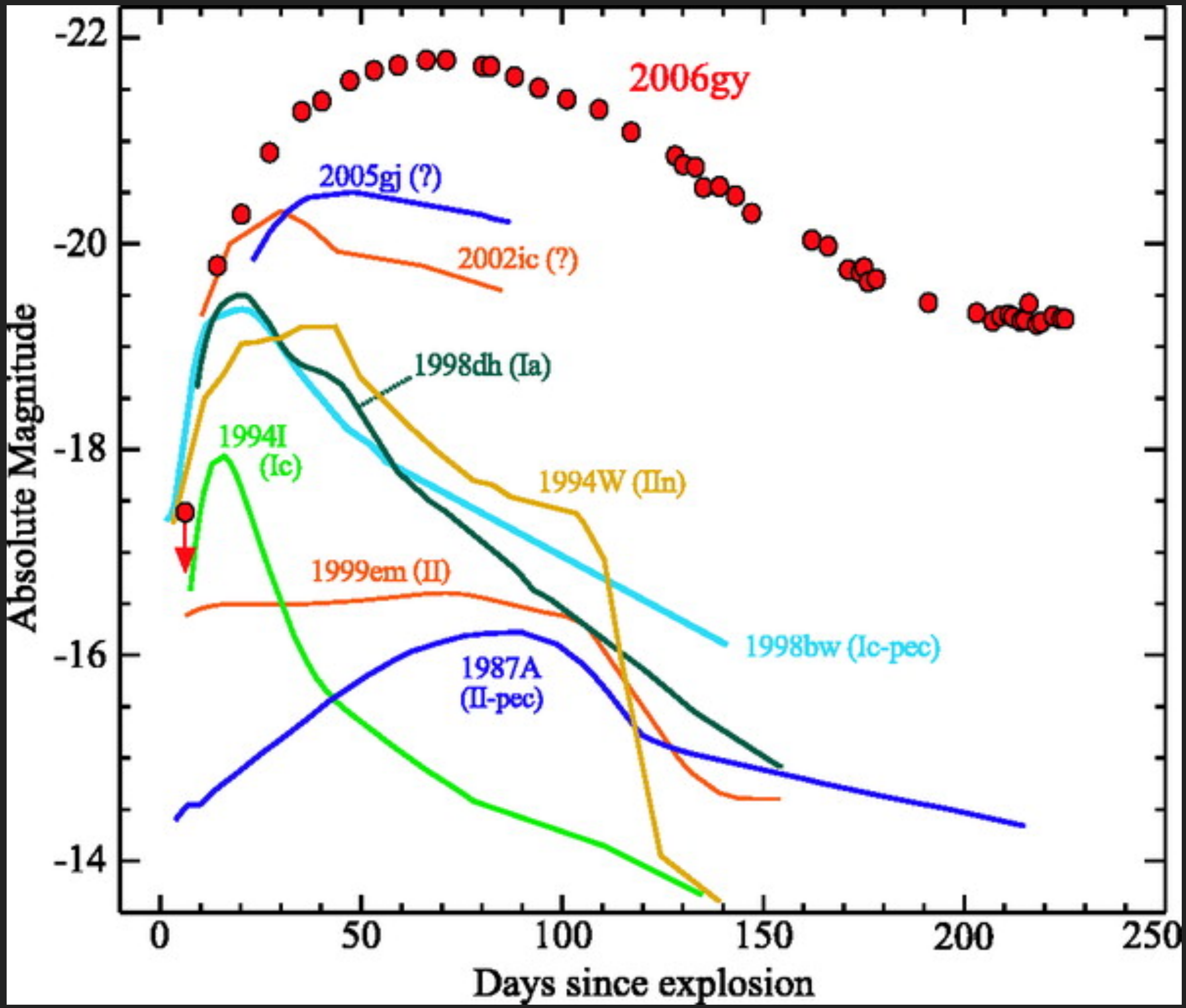
Core-collapse Supernova explosion

- iron core collapse of a massive star
- creation of proto-neutron star
- most of the released gravitational energy is radiated away as neutrino emission.
- But, a small fraction of the energy can be used to power the envelope outside the proto-NS.
- the energy injection leads to the formation of a blast wave.



Supernova explosion

- sudden emergence of a bright point source in the sky.
- they are outshining in optical for several 10 days up to ~100 days.
- super + novae (new star): it is like the appearance of a “new star”
- classical novae: surface explosion of WDs
- supernovae: explosions of stars → complete destruction



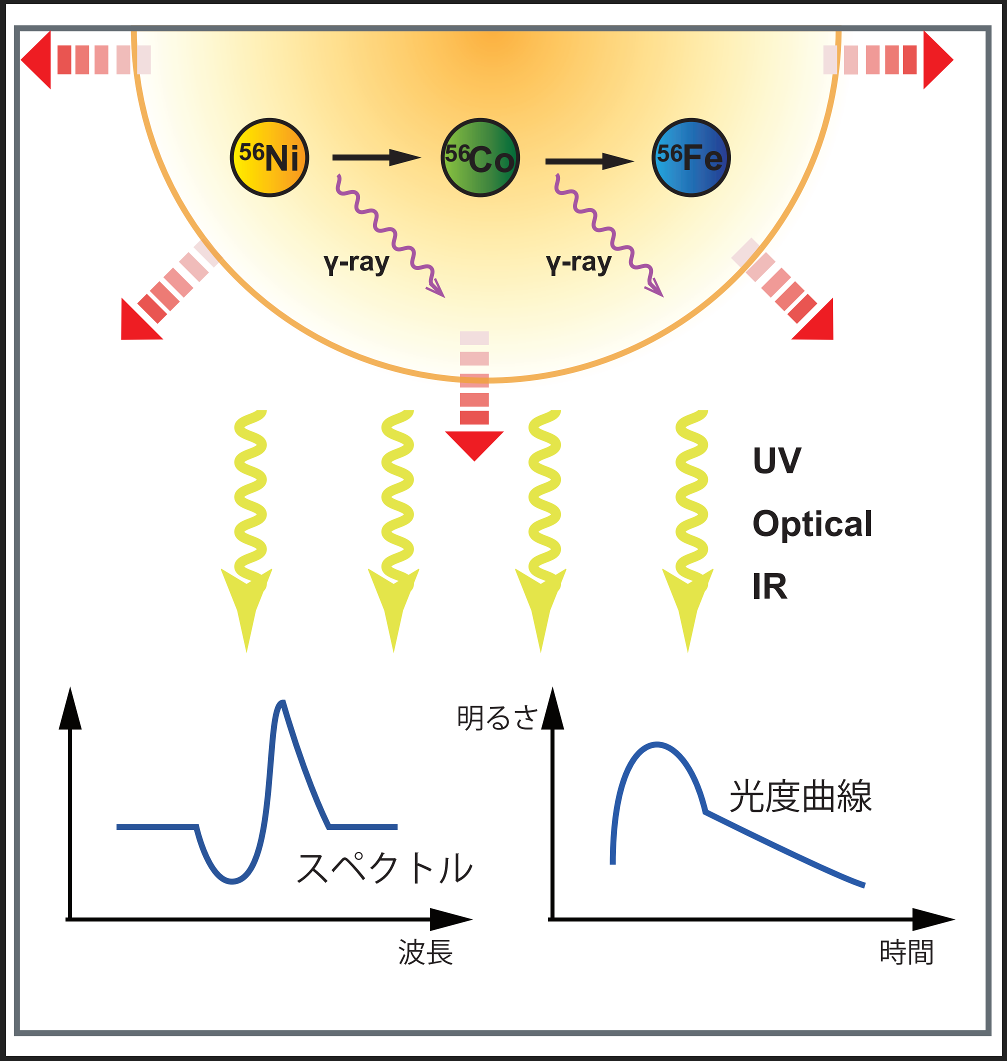
Light curves of various types of SNe

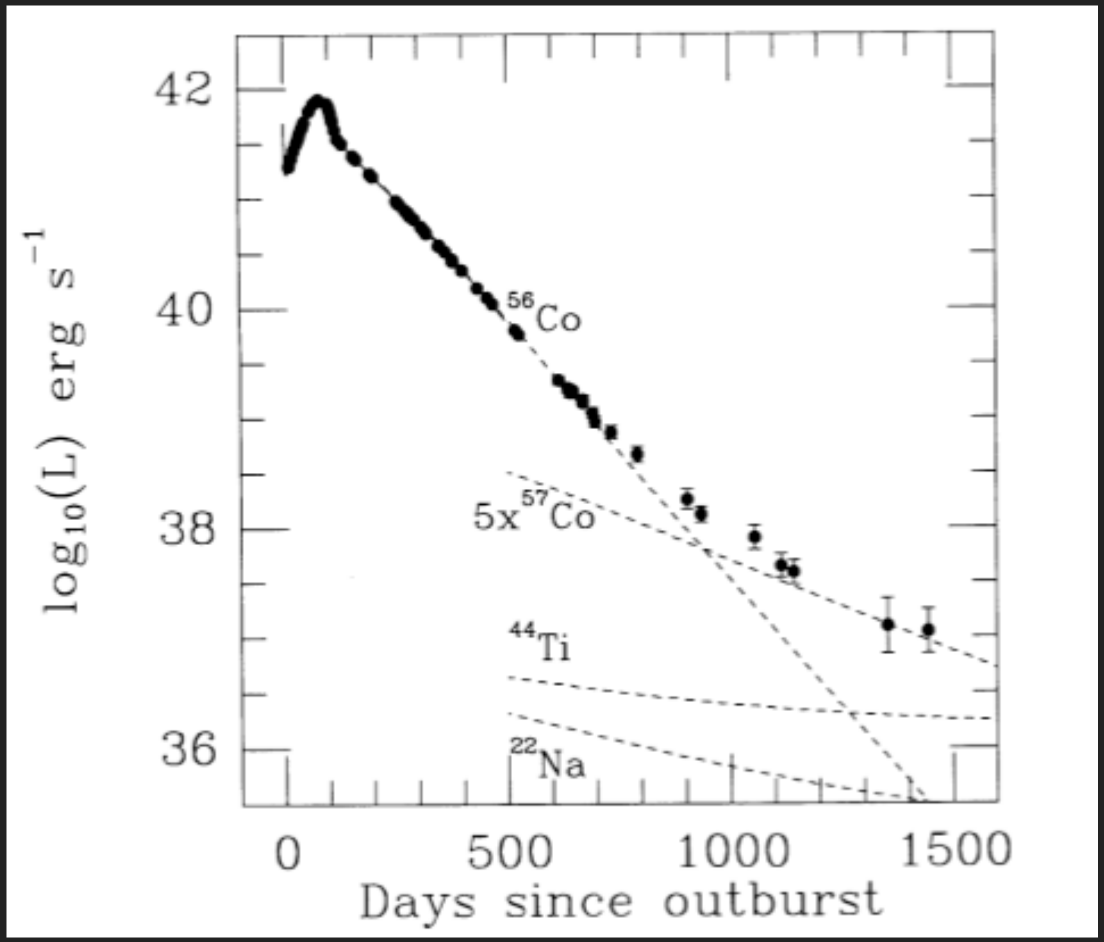
(SN Ia, II, Ibc, 1987A-like)

Smith+(2007)

Core-collapse Supernova explosion

- ^{56}Ni production in shocked hot gas
- radioactive decay of ^{56}Ni: primary energy source of SNe
- gamma-ray energy deposition in the ejecta → heating of the ejecta → thermal optical photons





SN1987A, Suntzeff+(1992)

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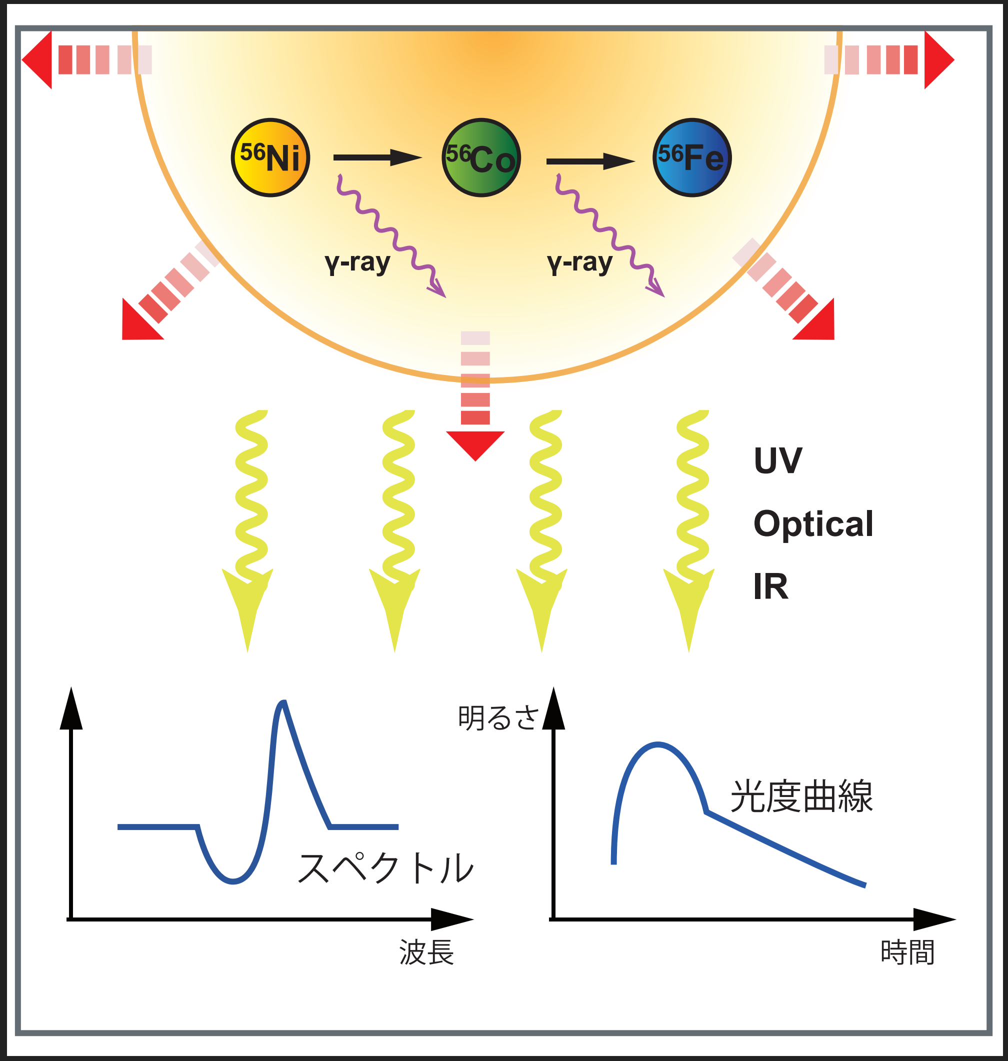
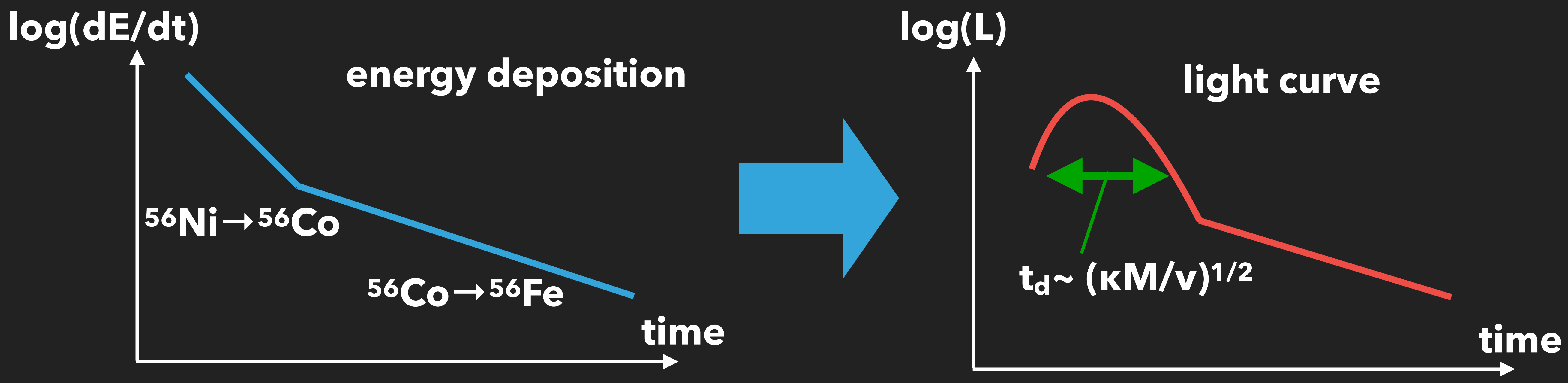
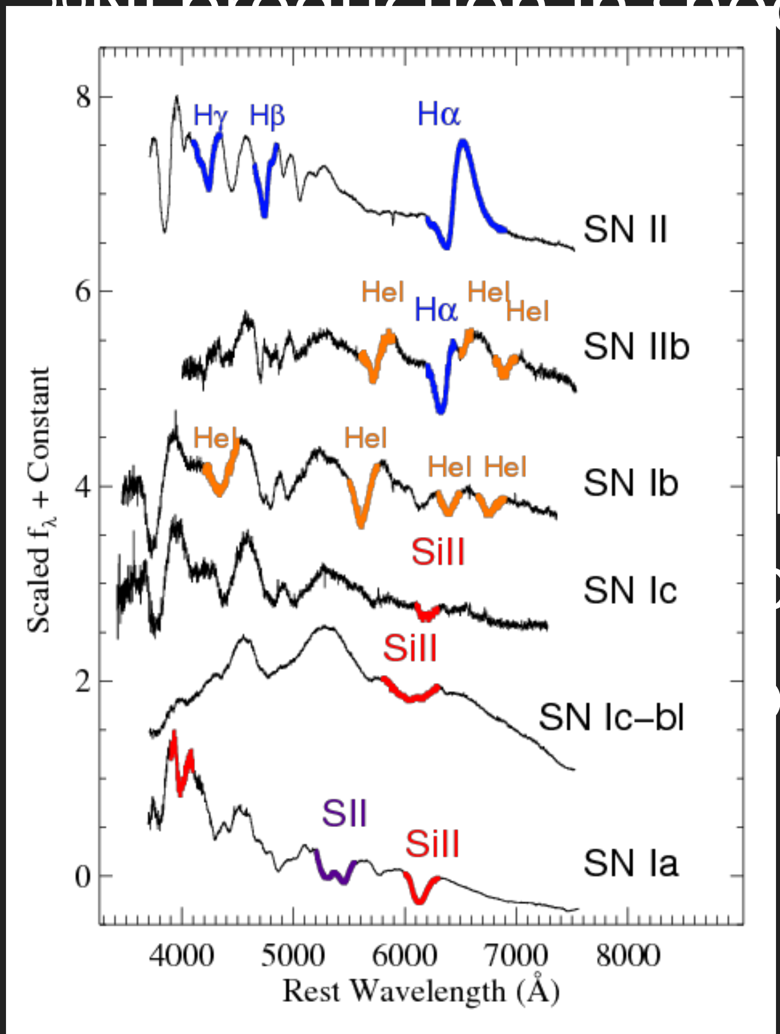


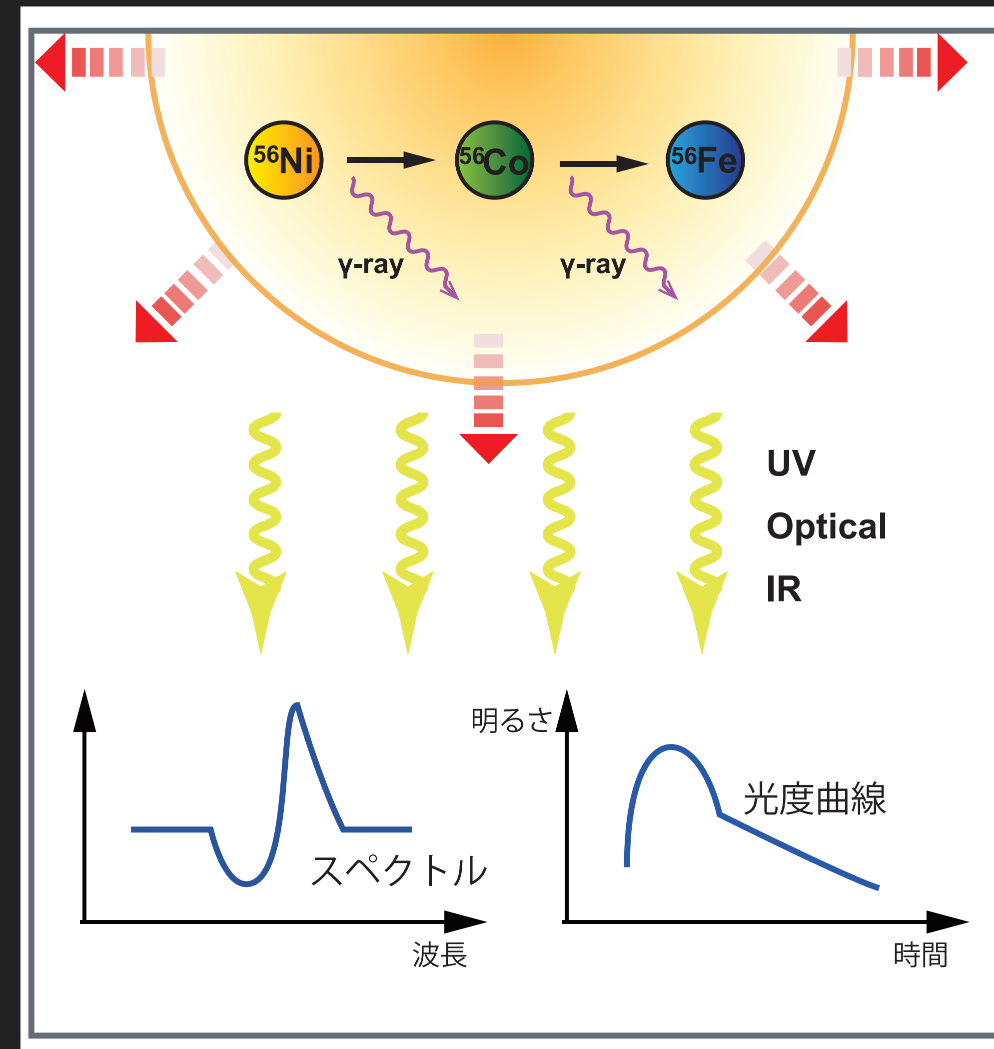


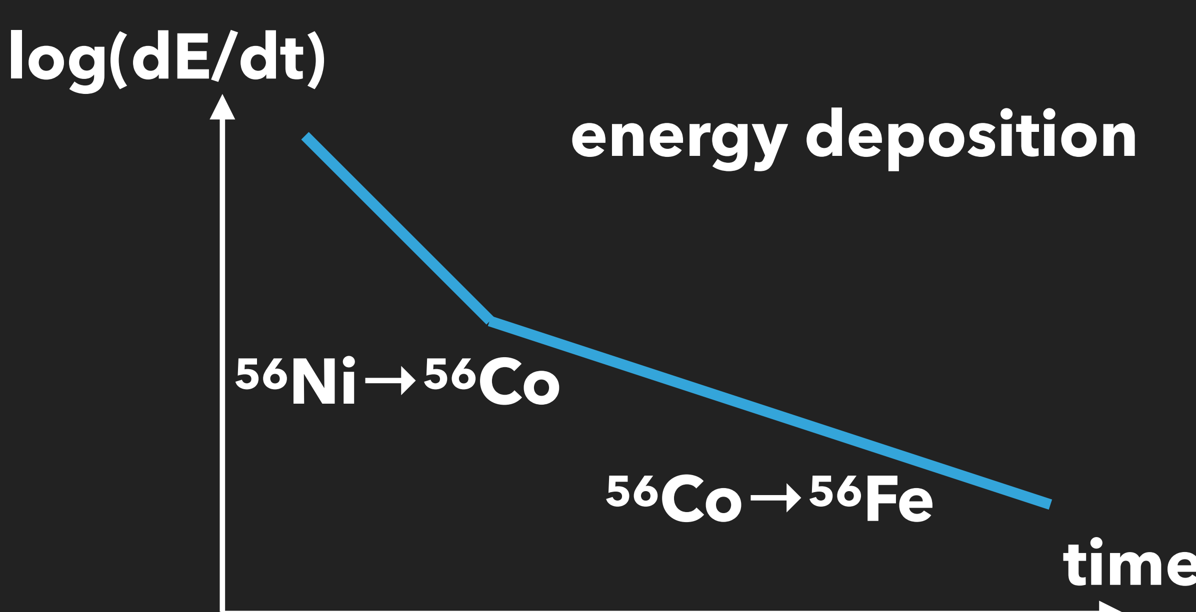
Core-collapse Supernova explosion

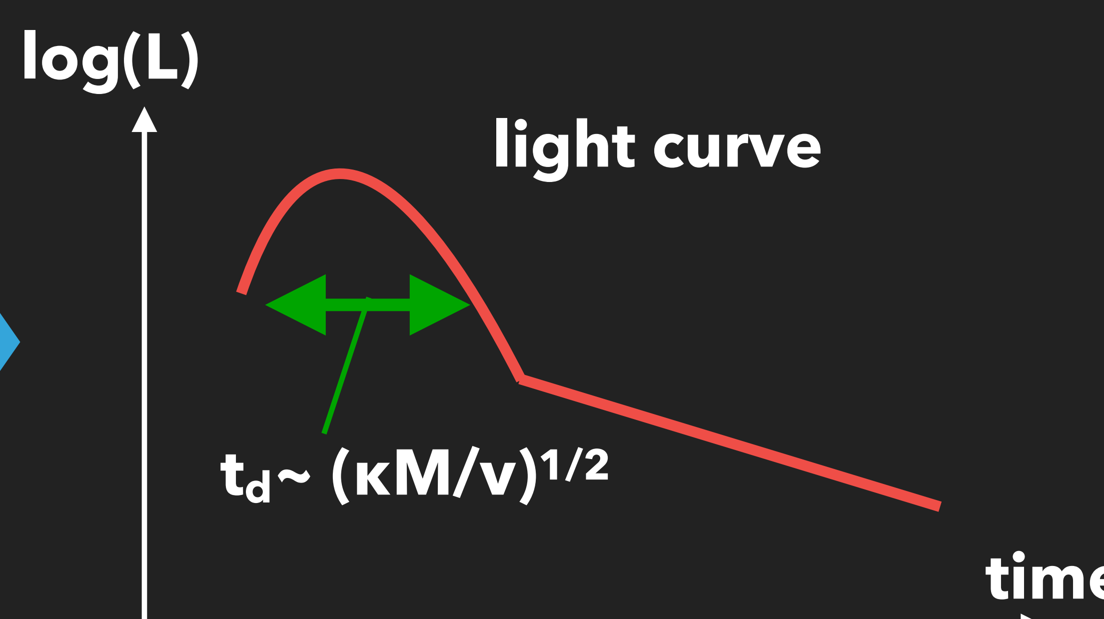
- ^{56}Ni production in shocked hot gas
- Ni: primary
- position in
  of the ejecta
  tons



$v \sim (E/M)^{1/2}$







Core-collapse Supernova explosion

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  - ➡ gravitational energy: $E_{grav} \sim GM_{ns}^2/R_{ns} \sim 10^{53}$ [erg]
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  - ➡ ejecta mass: $M_{ej} \sim 1 - 10$ [$M_\odot$]
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  - ➡ 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]

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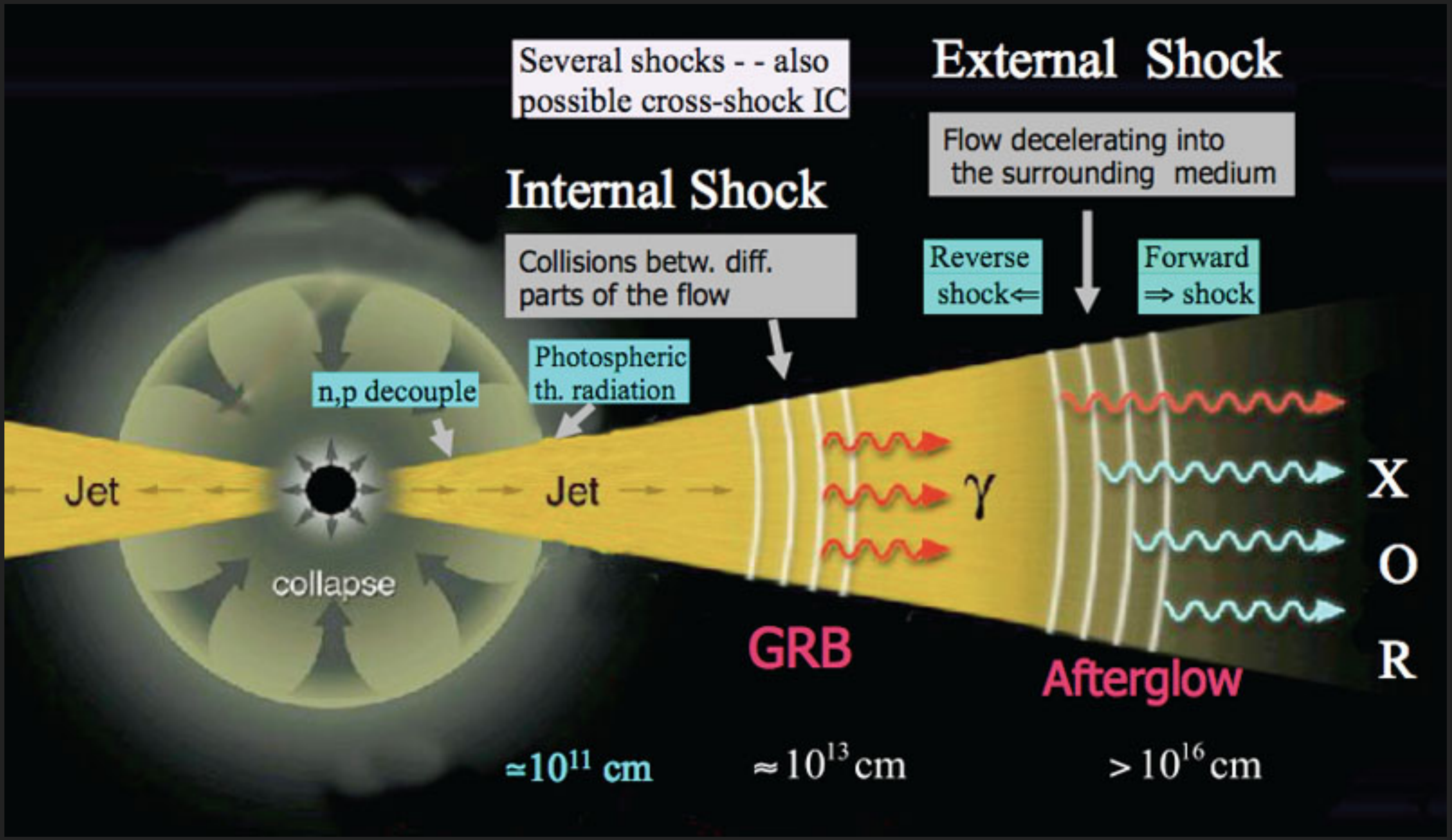
Broad-lined Ic SNe (Hypernovae)

- energetic SNe with the inferred kinetic energy of 10^{52} [erg]
- SNe associated with long gamma-ray bursts (GRBs) are always classified into this subclass



Meszaros&Rees (2014)

Broad-lined Ic SNe (Hypernovae)

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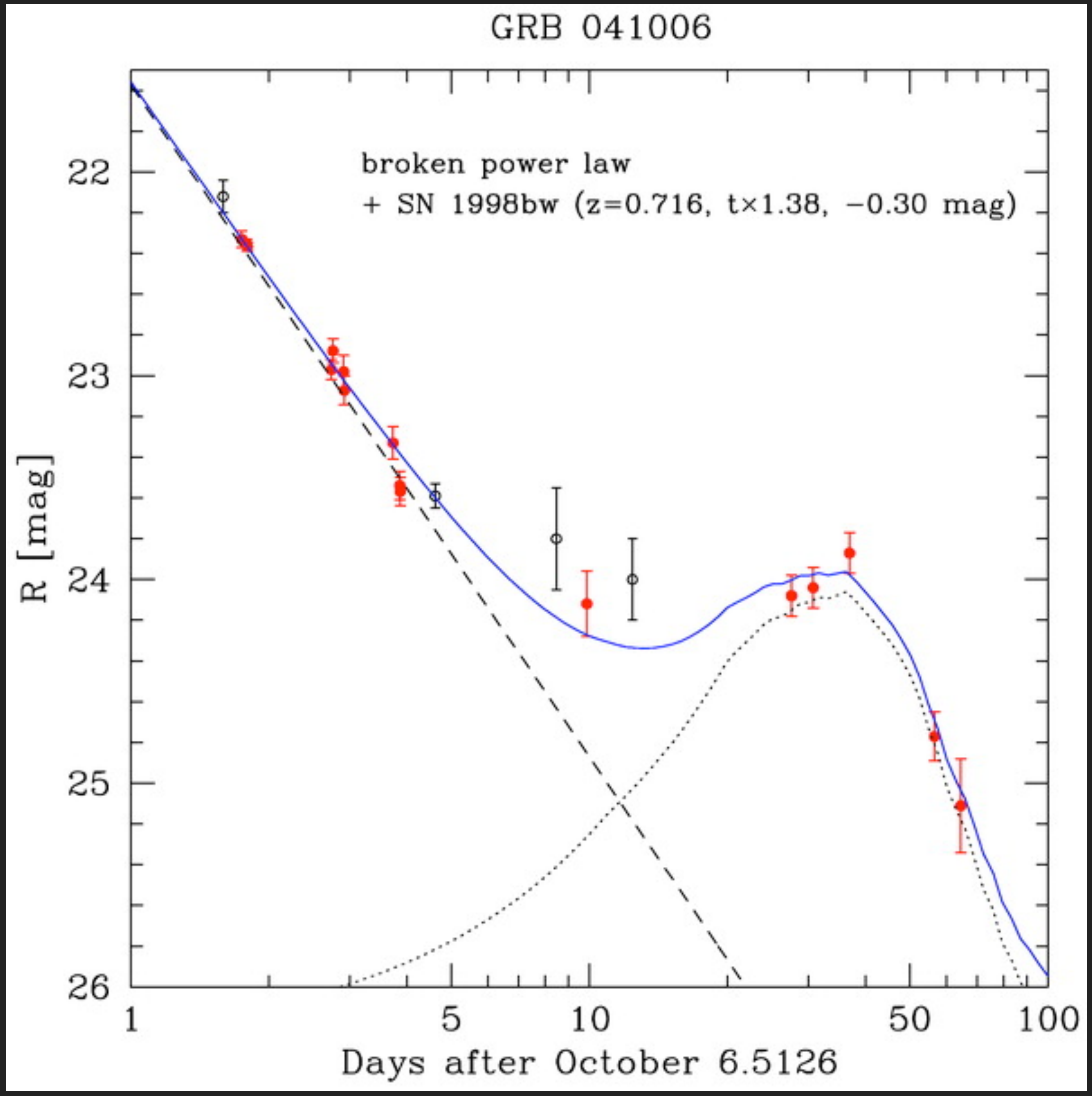
	associated SN	redshift
GRB 980425	SN 1998bw	z=0.0085
GRB 030329	SN 2003dh	z=0.1685
GRB 031203	SN 2003lw	z=0.1055
GRB 060218	SN 2006aj	z=0.0334
GRB 100316D	SN 2010bh	z=0.0591
GRB 120425A	SN 2012bz	z=0.283
GRB 130702A	SN2013dx	z=0.145
GRB 140606B	iPTF4bfu	z=0.384

GRB-SNe with spectroscopic confirmation

+GRB171205A/SN2017iuk



Stanek+ (2005)

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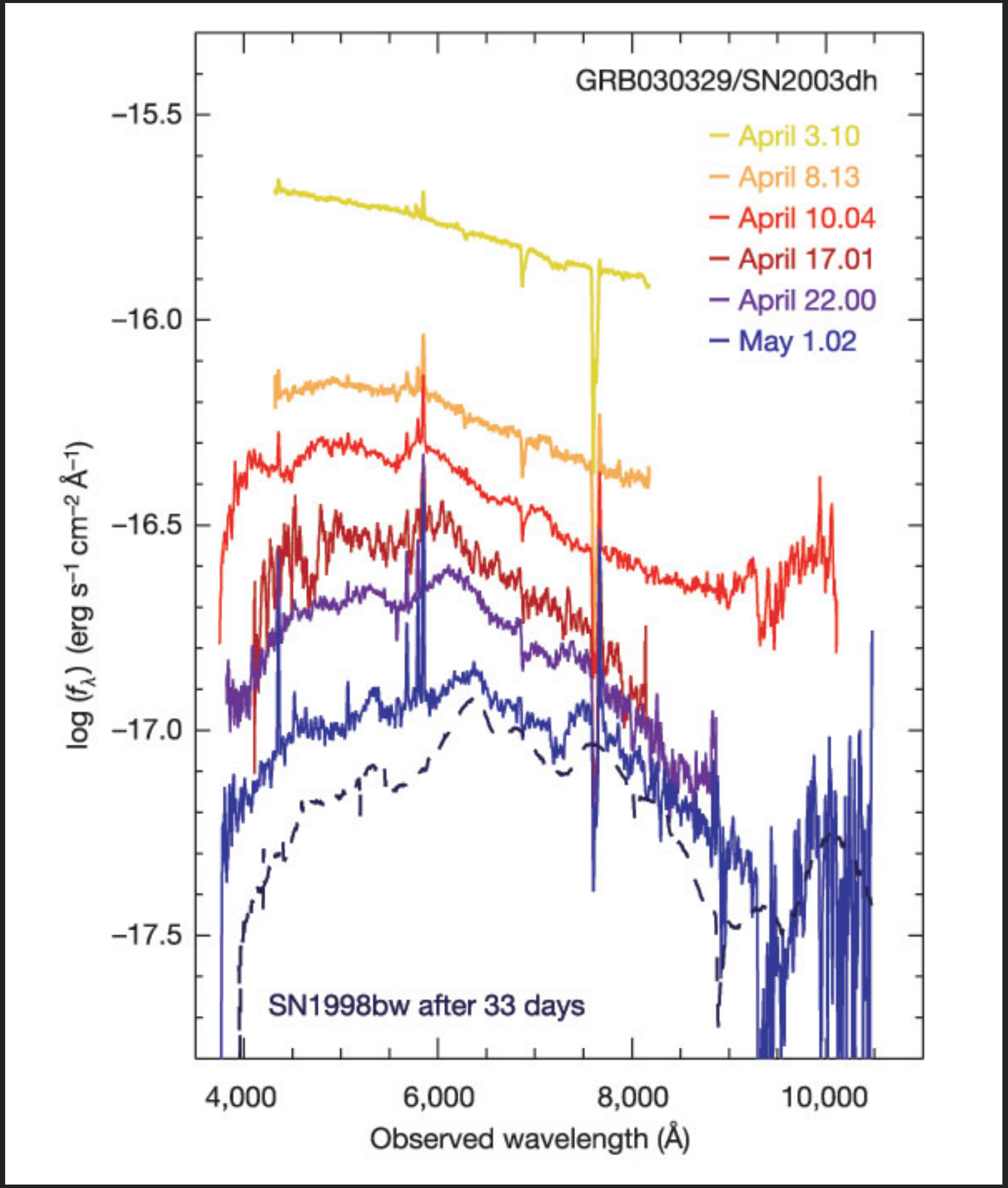


Hjorth+ (2003)

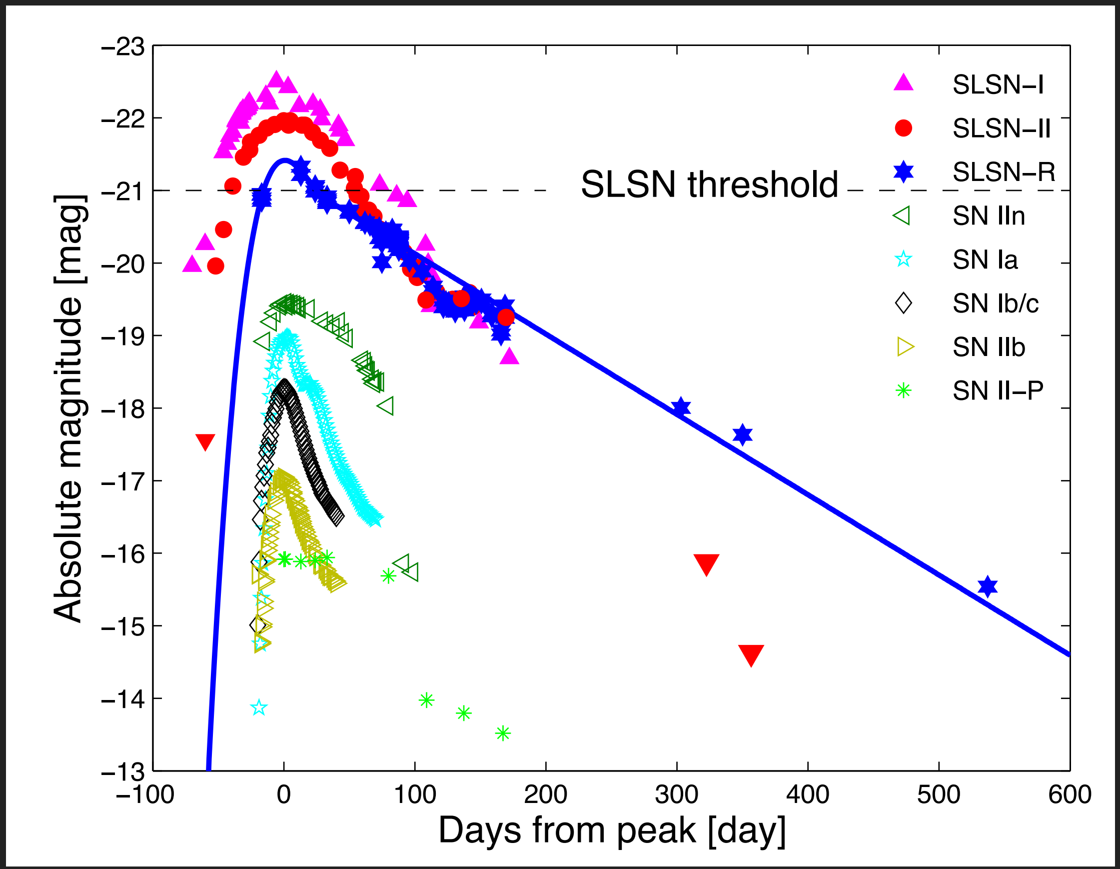
Superluminous Supernovae

- 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?

CSM? Central-engine?

or pair-instability SNe?



Gal-Yam (2012)

Superluminous Supernovae

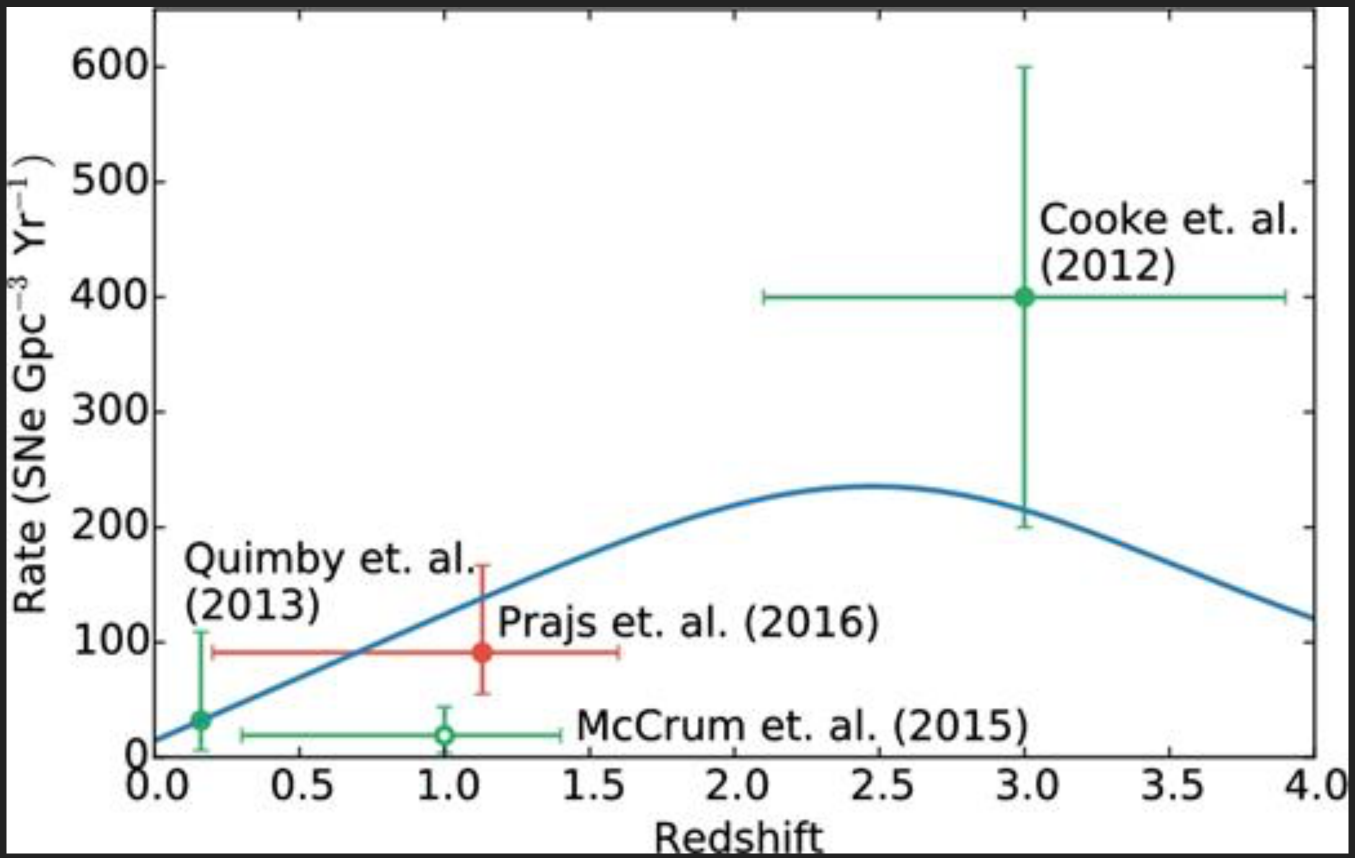
- event rate: they are extremely rare
- 0.01 - 0.1% of normal CCSNe
- CCSNe rate ~ 10^5 $Gpc^{-3}yr^{-1}$ at z~0.2 (e.g., Madau&Dickinson 2014)
- total SLSNe rate:

➡ 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)

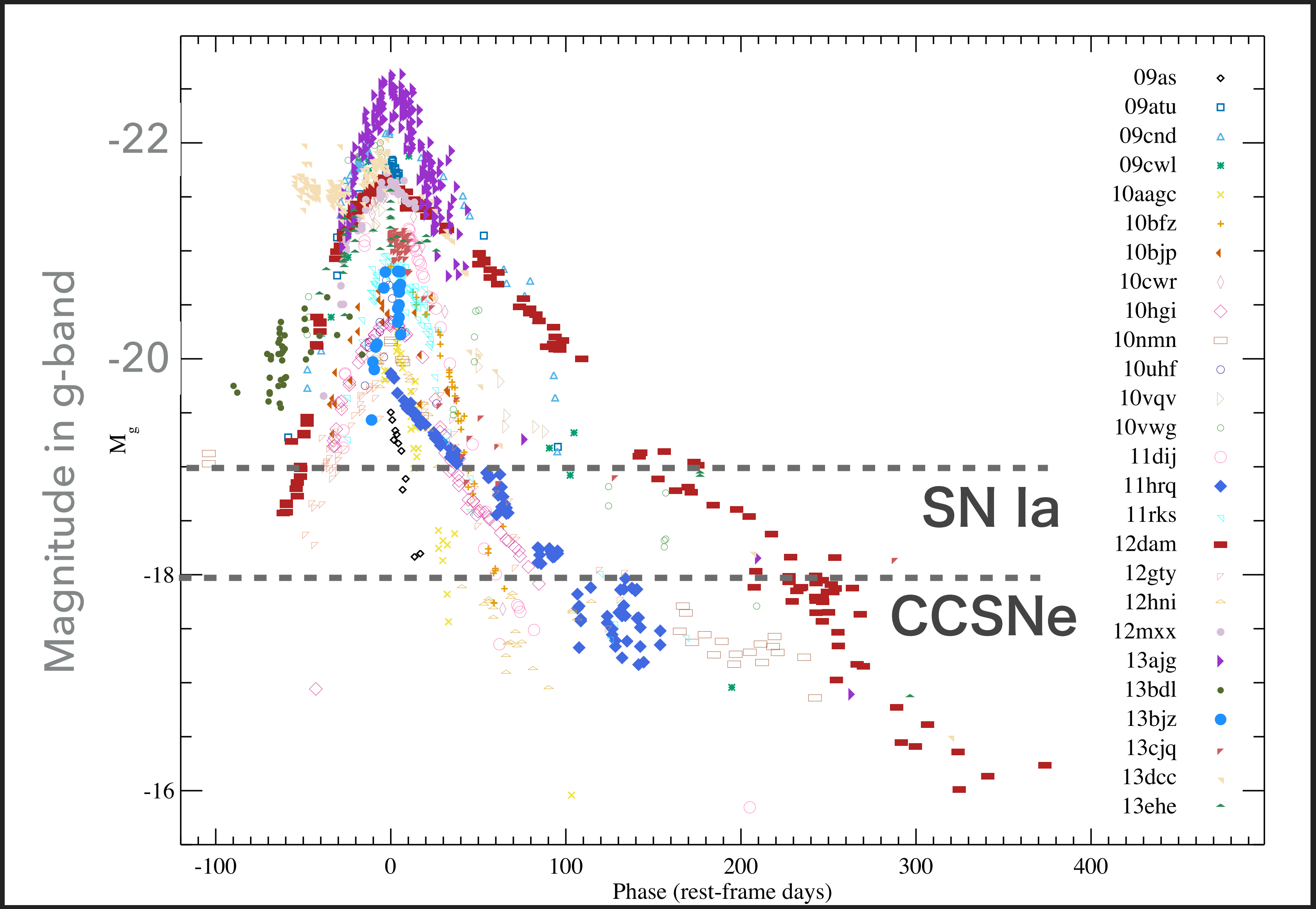
➡ SLSNe-I rate is even lower



↑SLSNe-I rate: Prajs+(2016)

Superluminous Supernovae

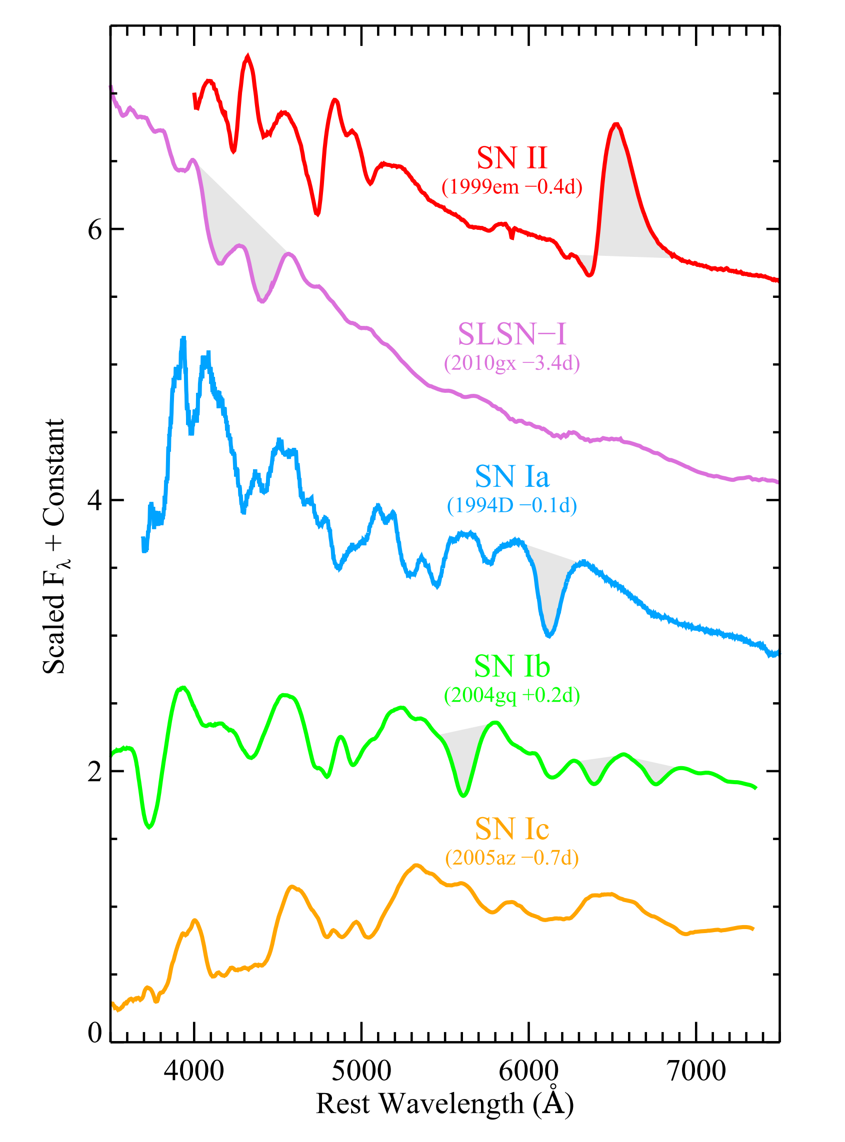
- SLSNe at maximum light: traditional threshold M_{abs}~-21
- the corresponding luminosity of L~10^{44}[erg/s]



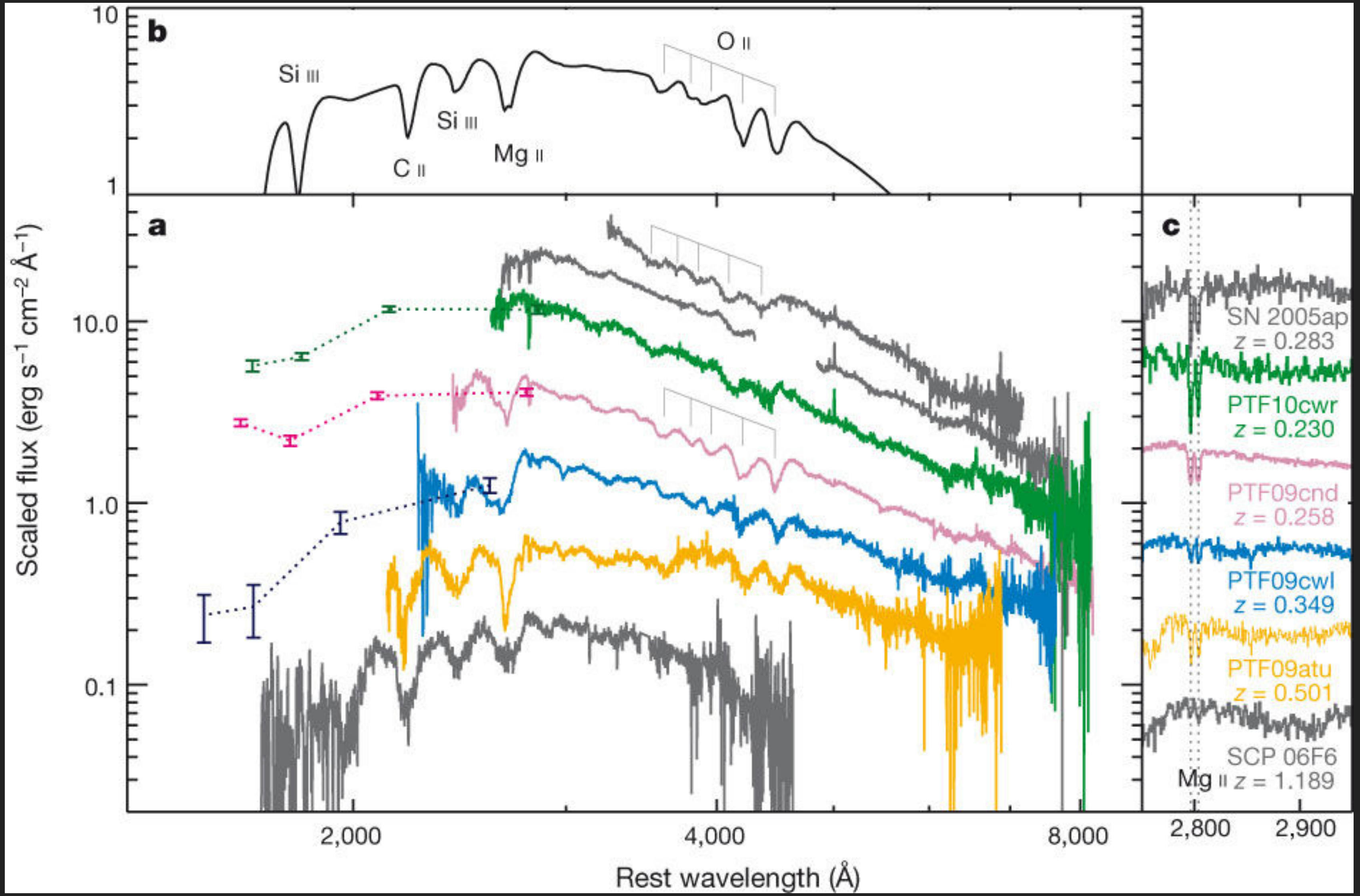
SLSNe-I from the PTF sample (De Cia+ 2017)

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])



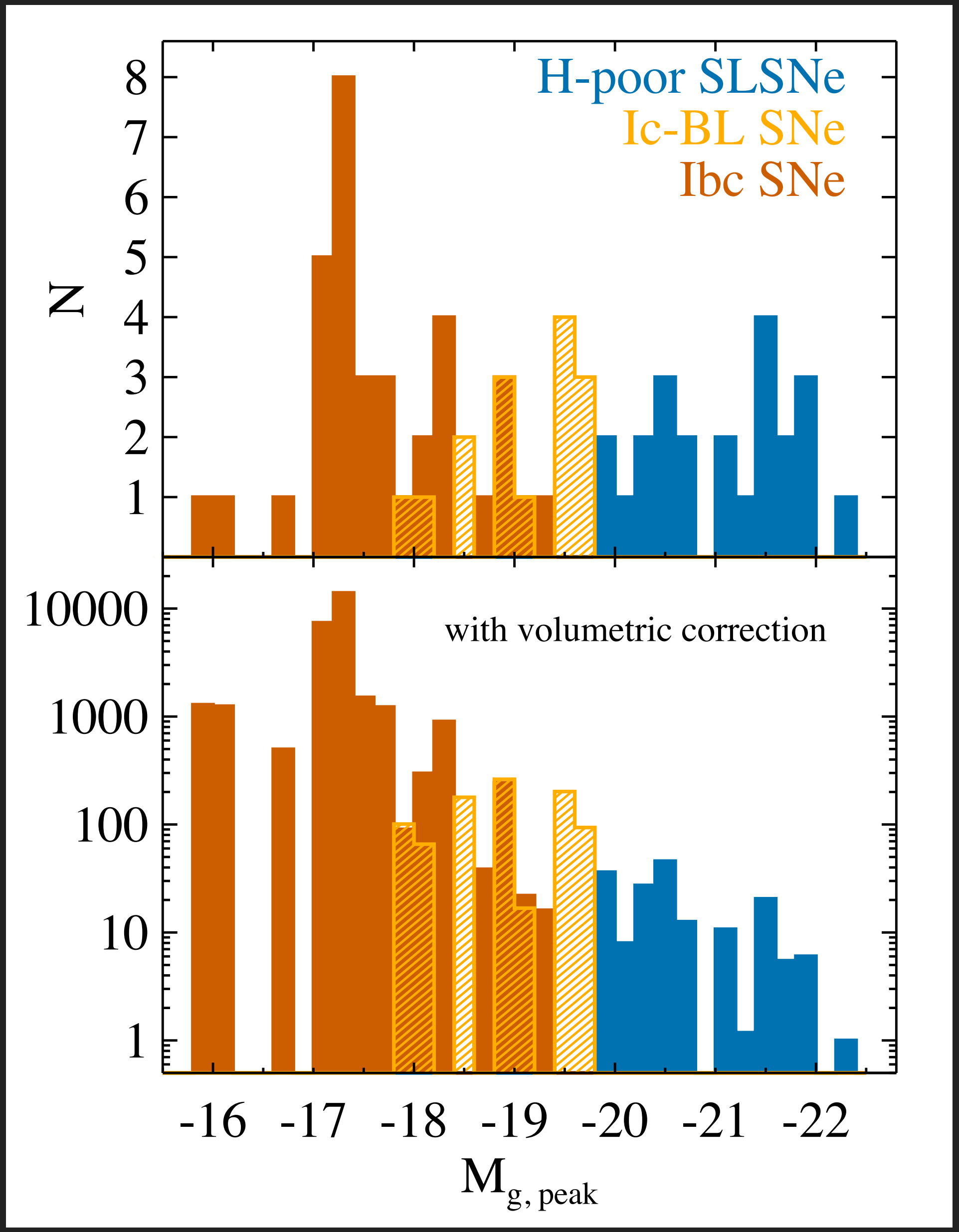
schematic SLSNe-I spectra (Quimby+2018)



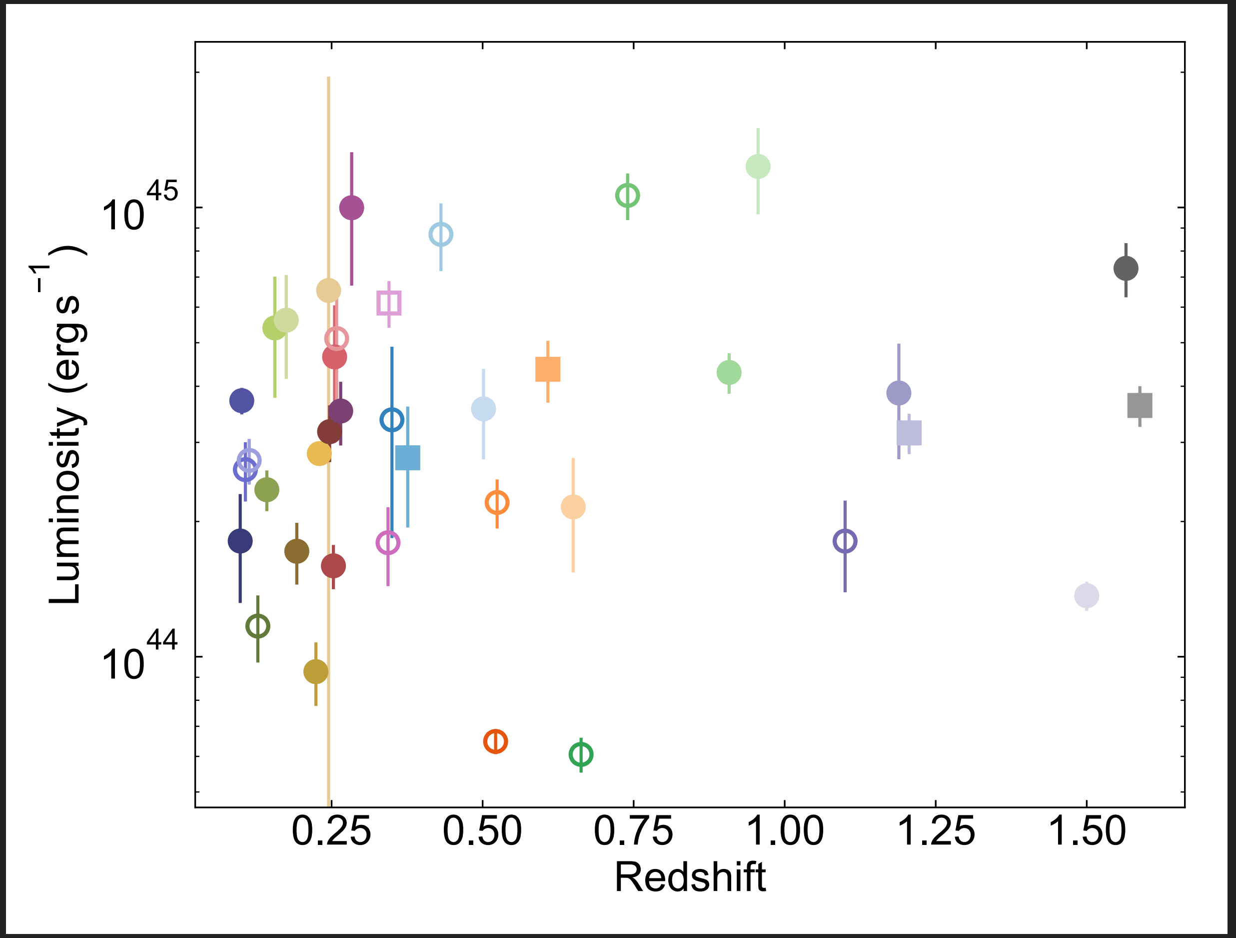
SLSNe-I spectra (Quimby+2011)

Superluminous Supernovae

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



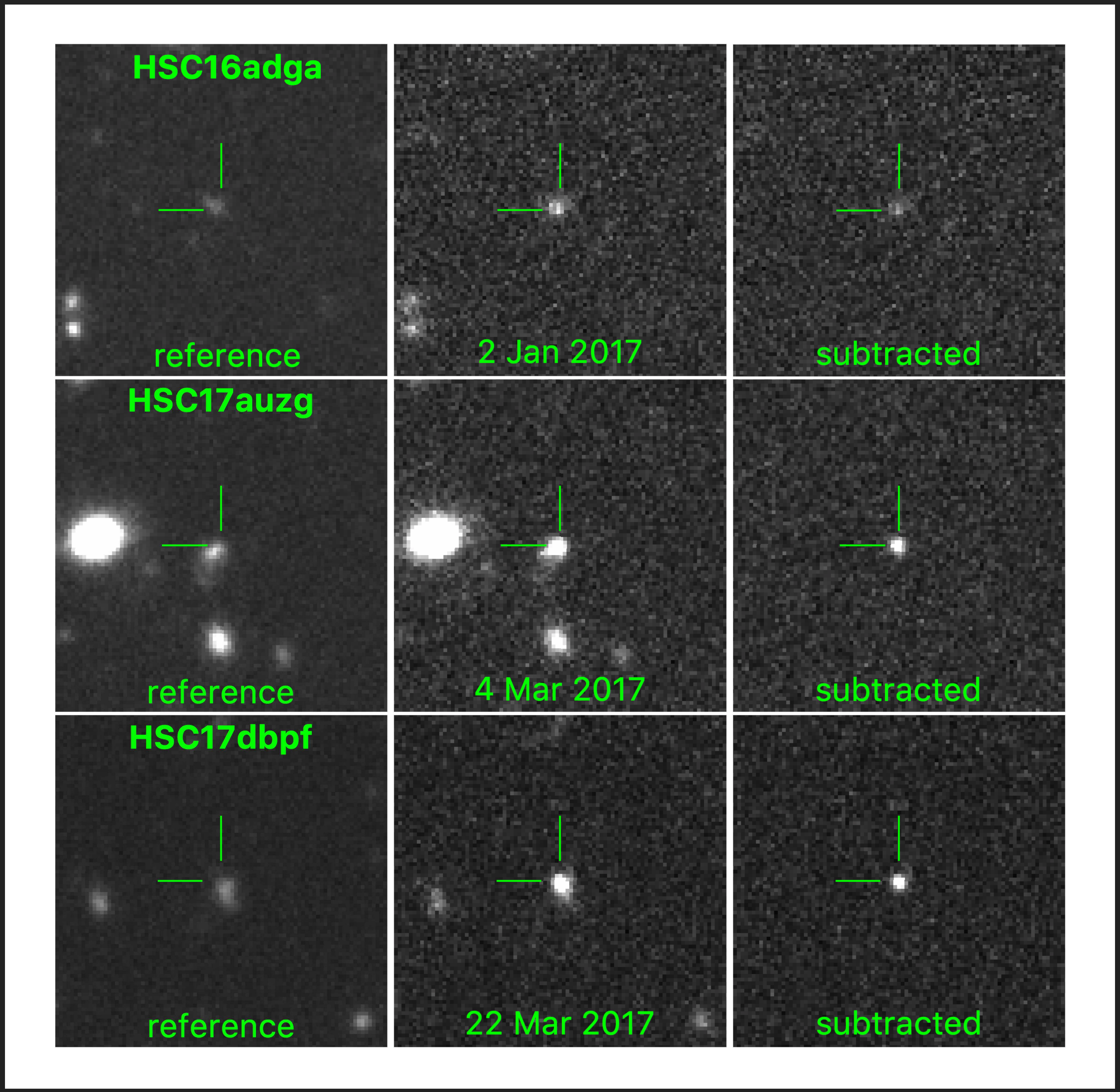
peak M_g distribution of PTF samples (De Cia+2018)



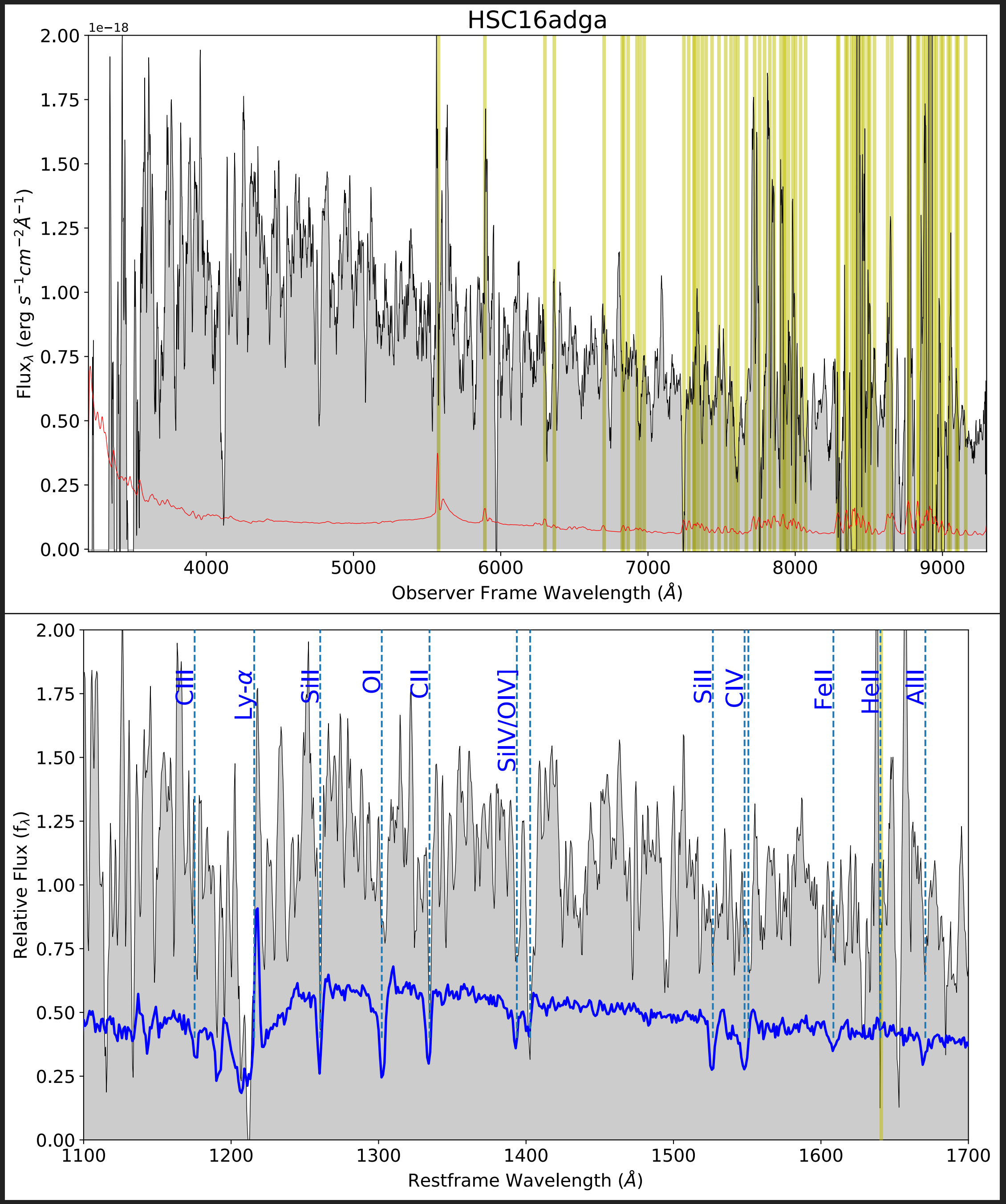
peak L vs redshift: Nicholl+(2017)

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)

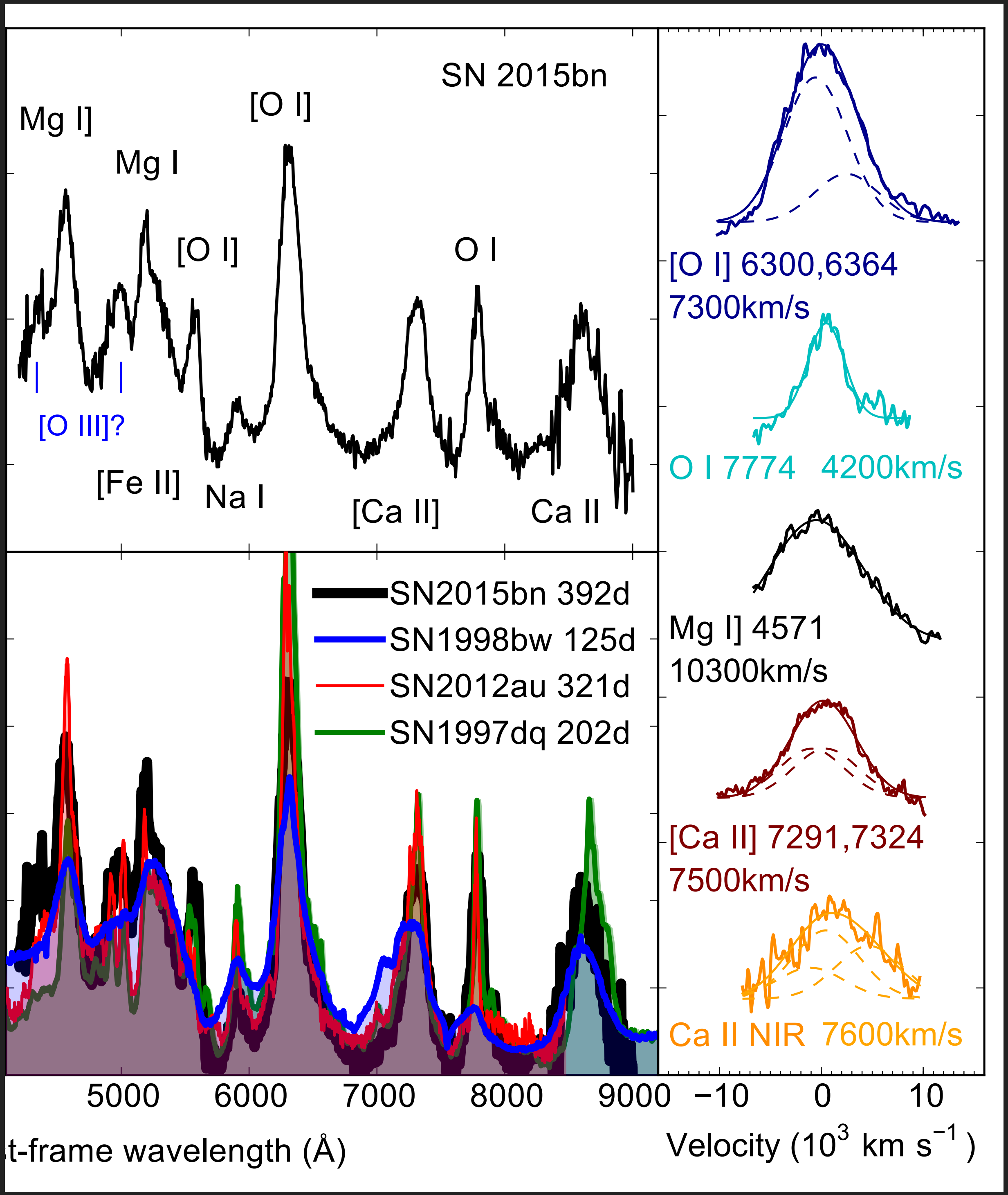


Keck spectra: Curtin+(2018)

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?

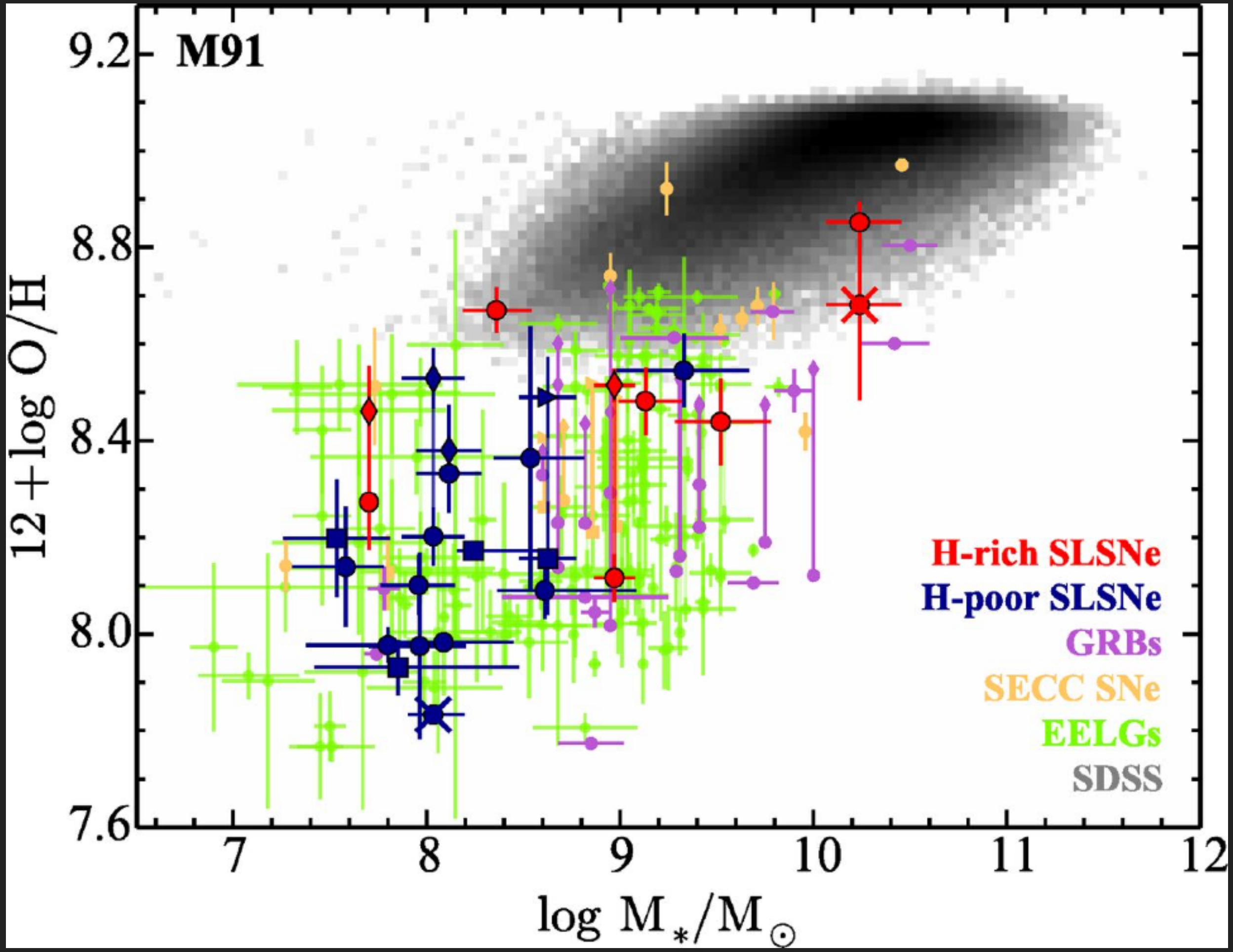


↑Nicholl+(2016)

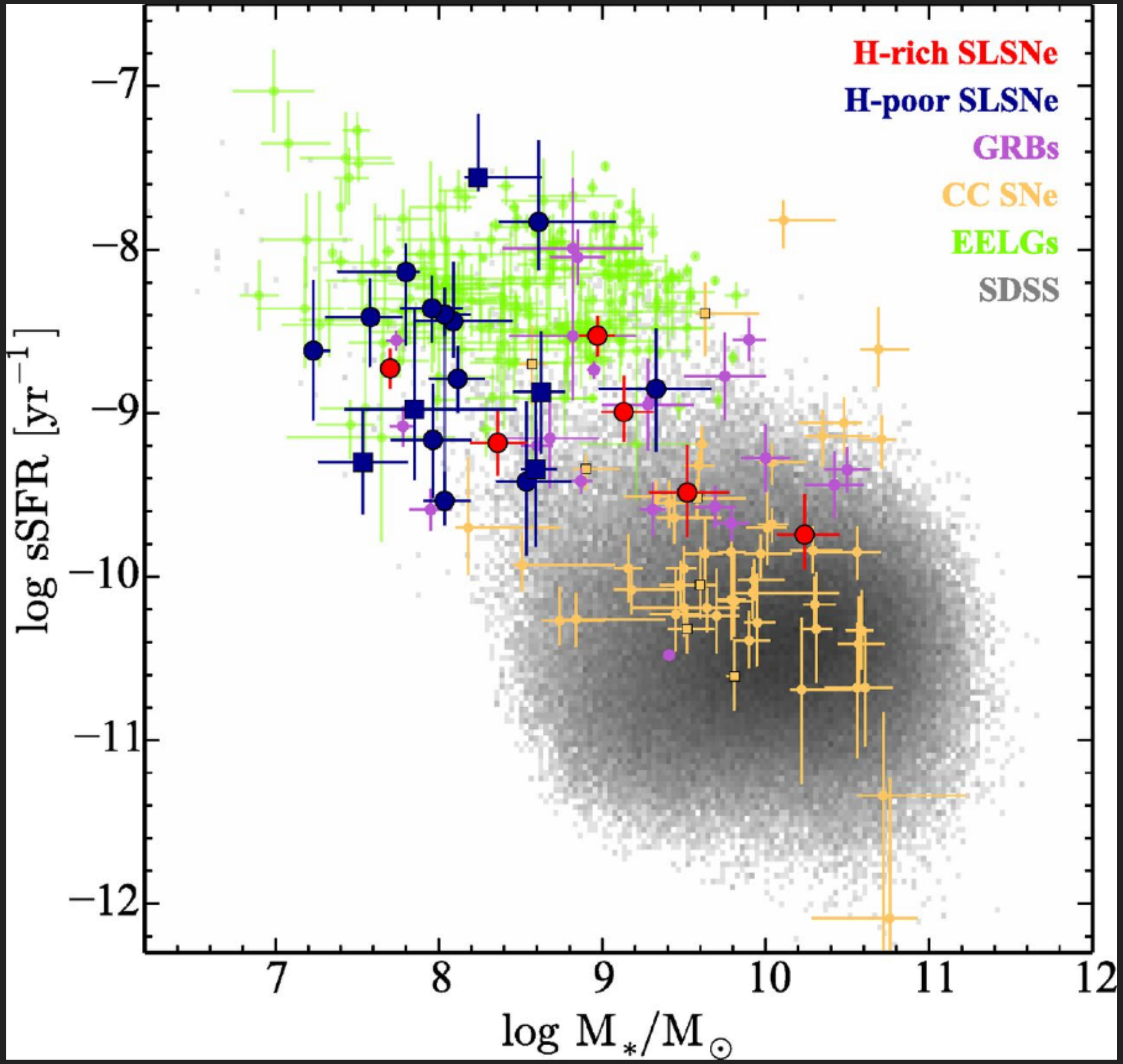
Superluminous Supernovae

- 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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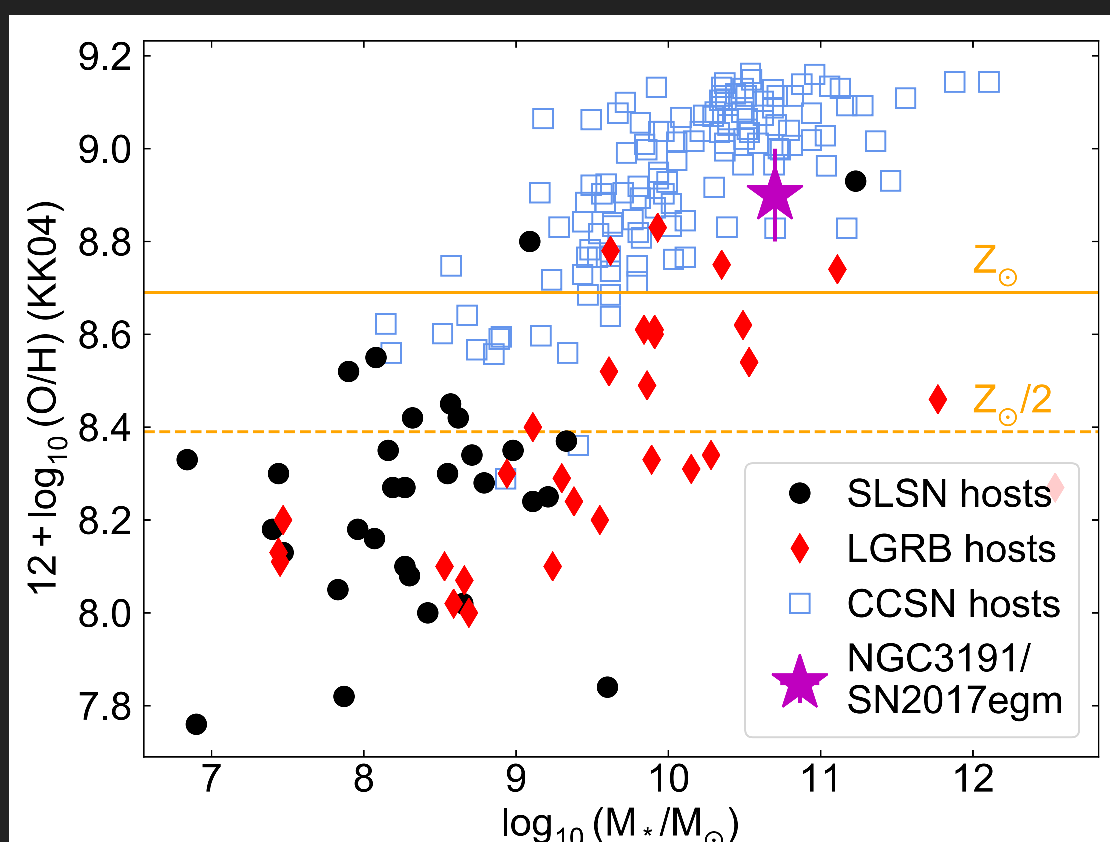
- **But**, recent discovery of SN2017egm in a massive galaxy with (super) solar metallicity



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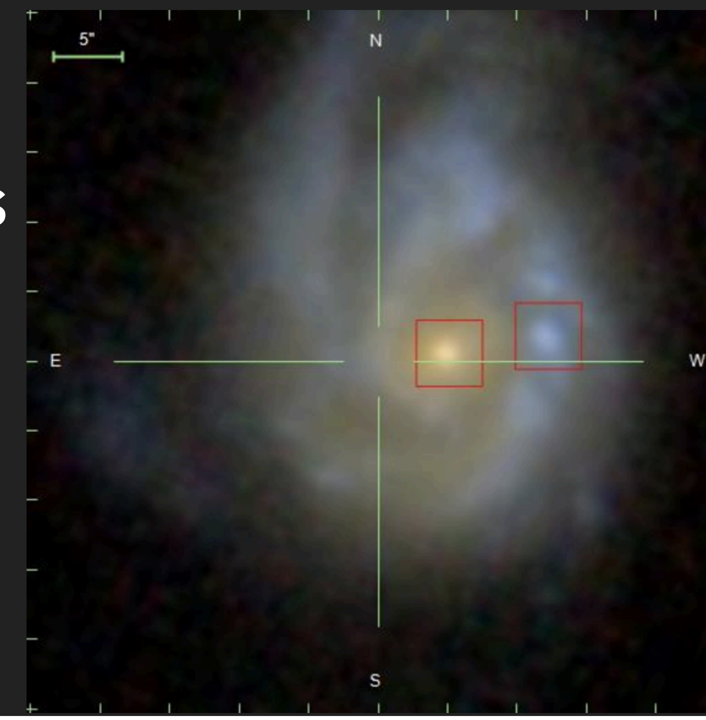
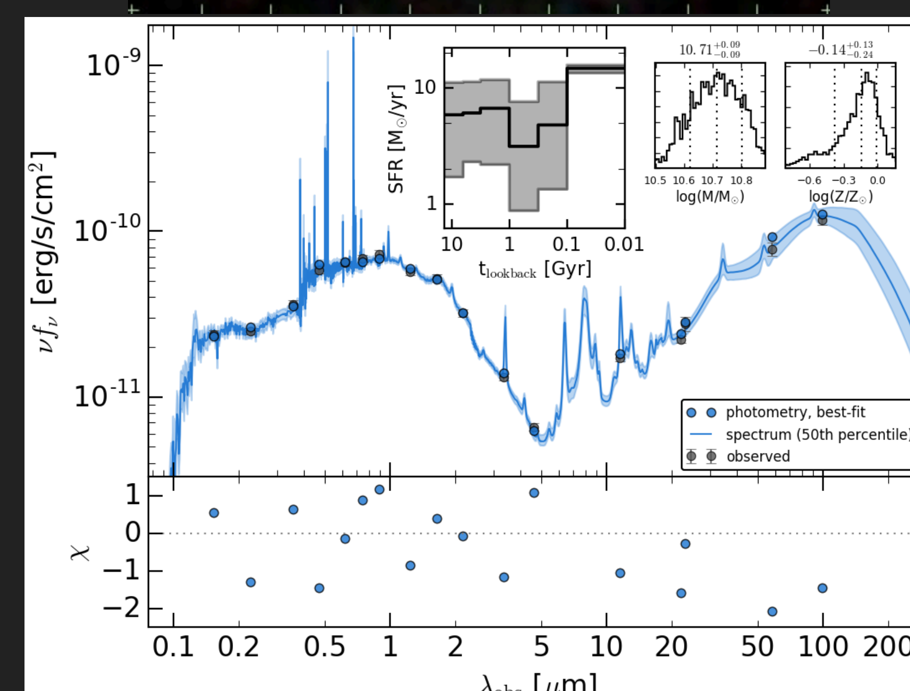
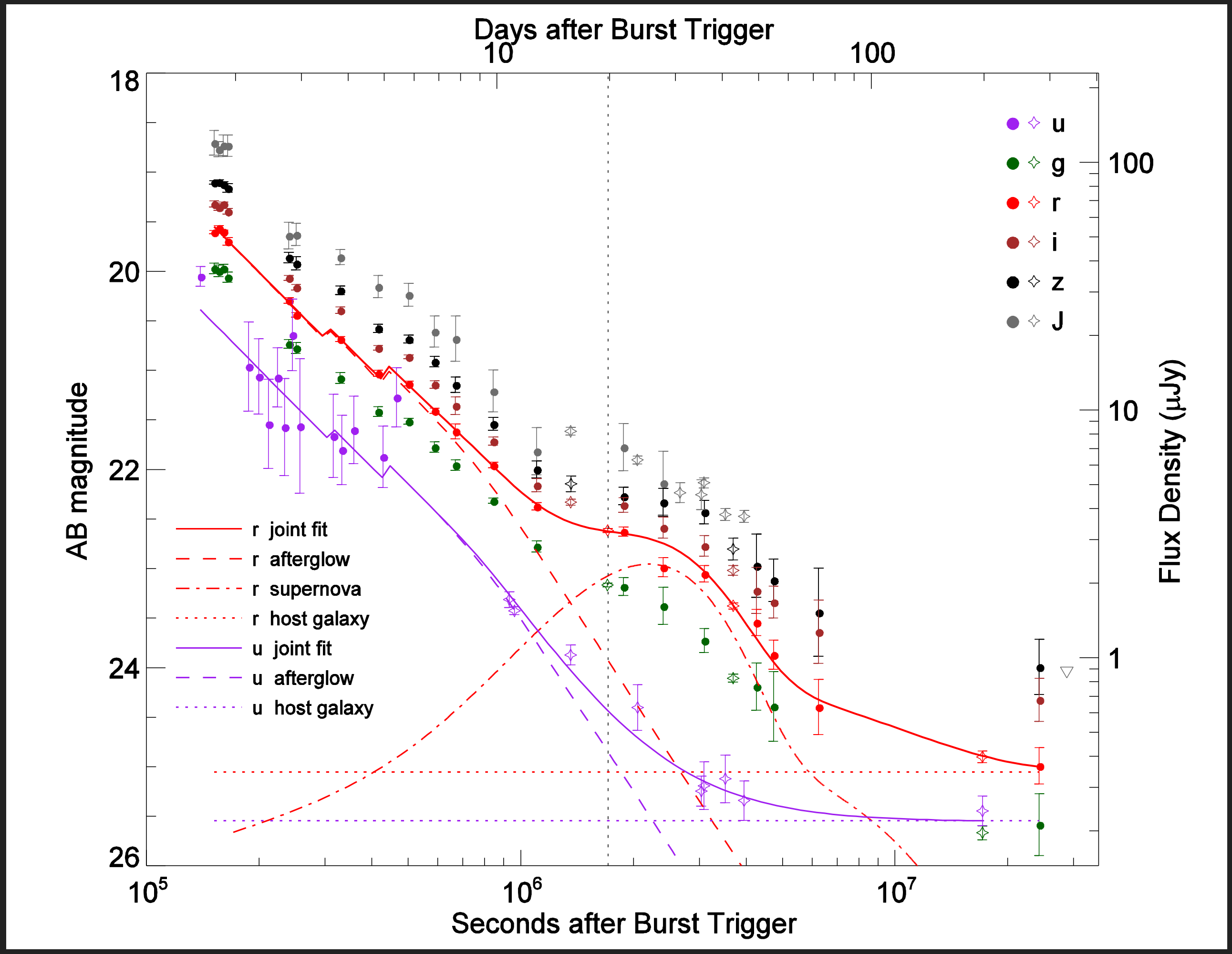


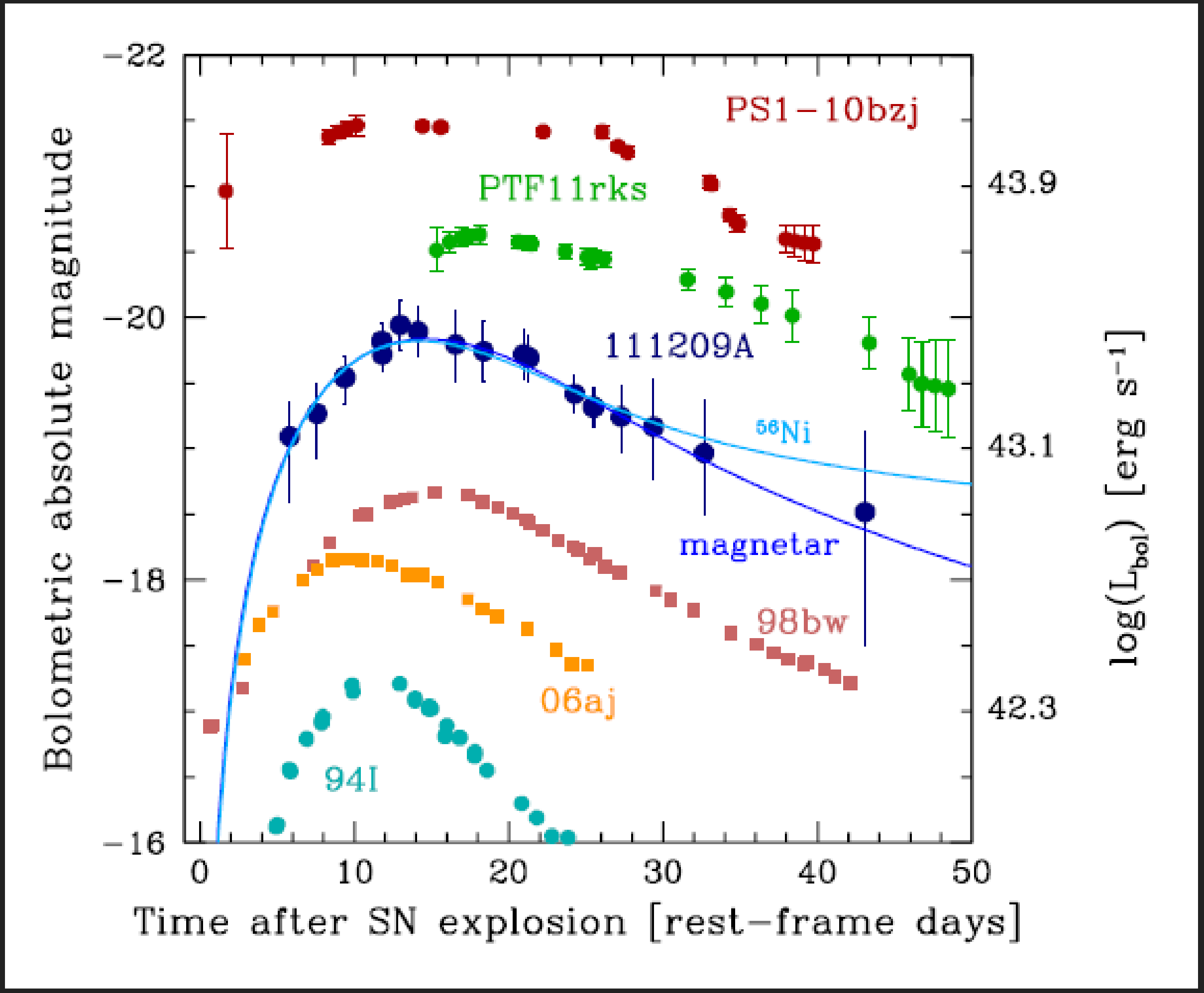


Nicholl+(2017)

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?

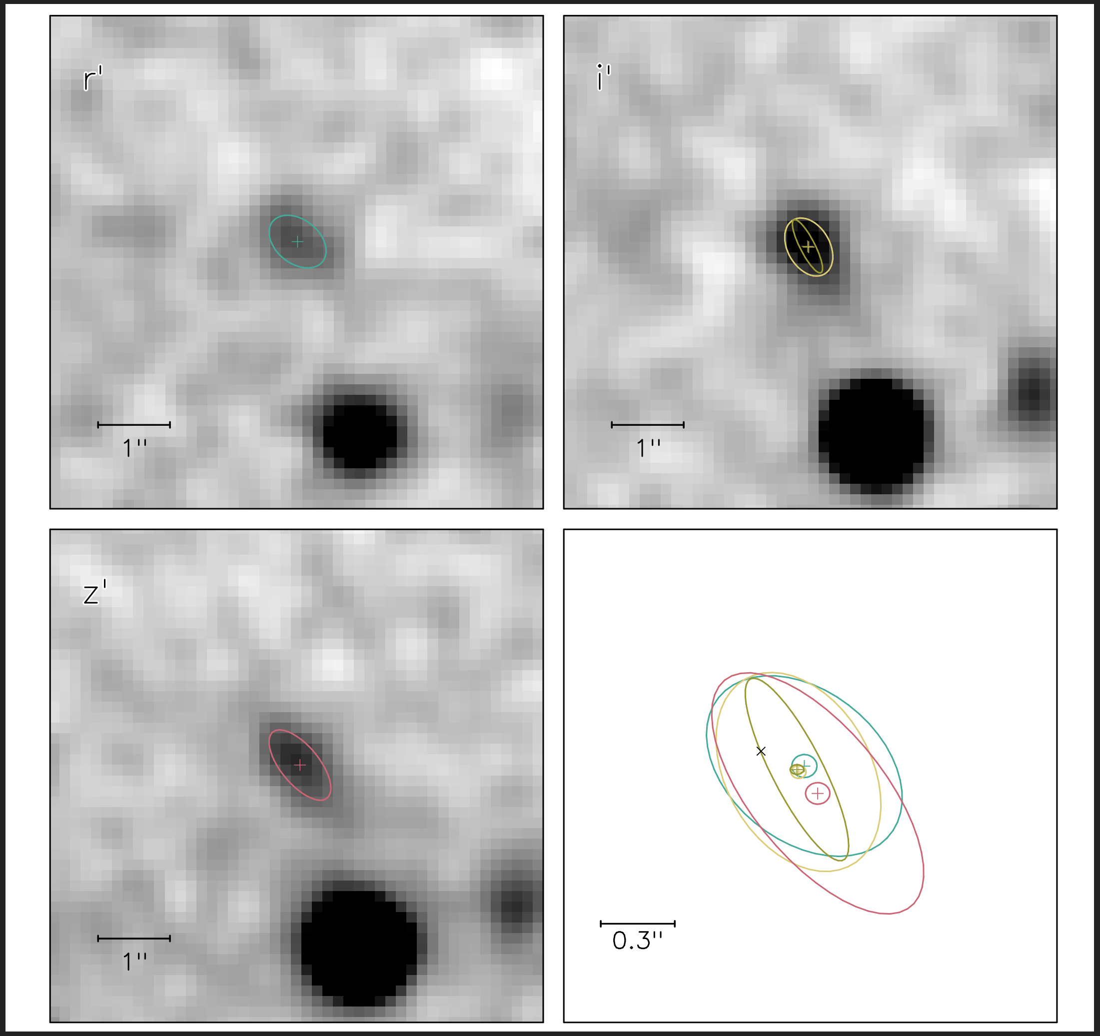




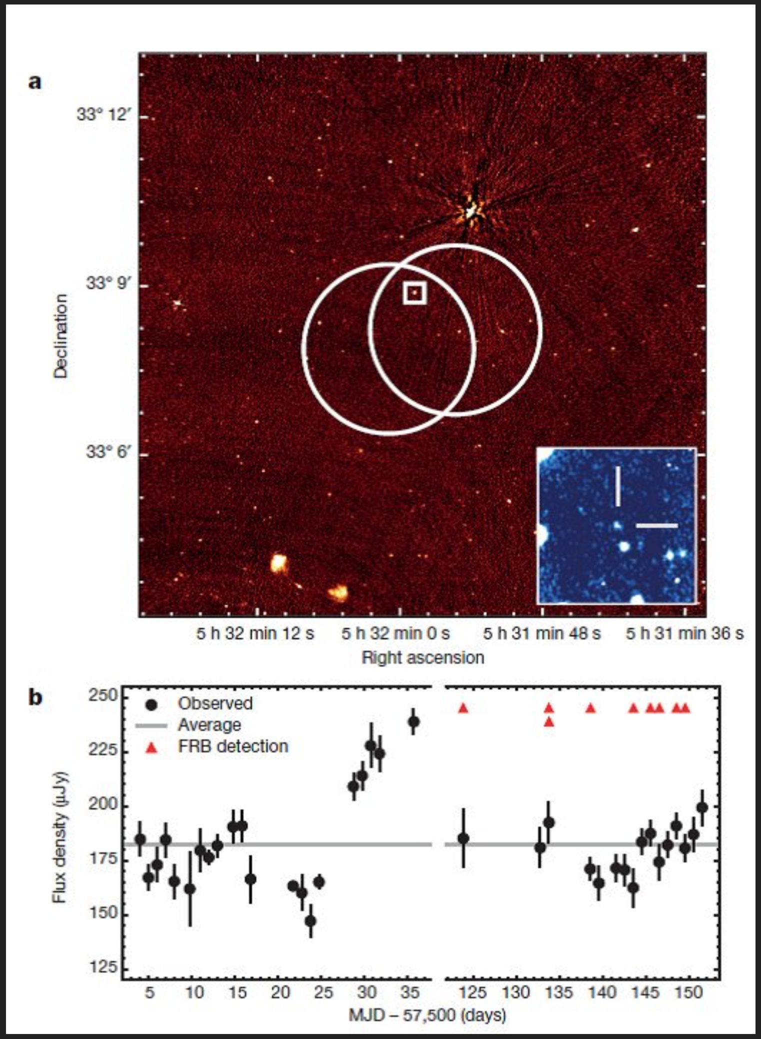
Greinar+(2015)

SLSN-GRB-FRB connection???

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



Tendulkar+(2017)



Chatterjee+(2017)

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  - ➡ typical ^{56}Ni mass: $M_{Ni} \sim 0.1 M_\odot$
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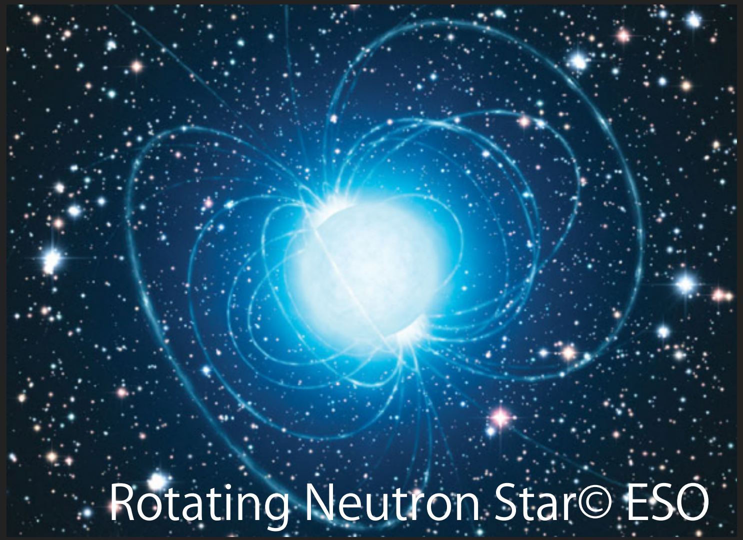
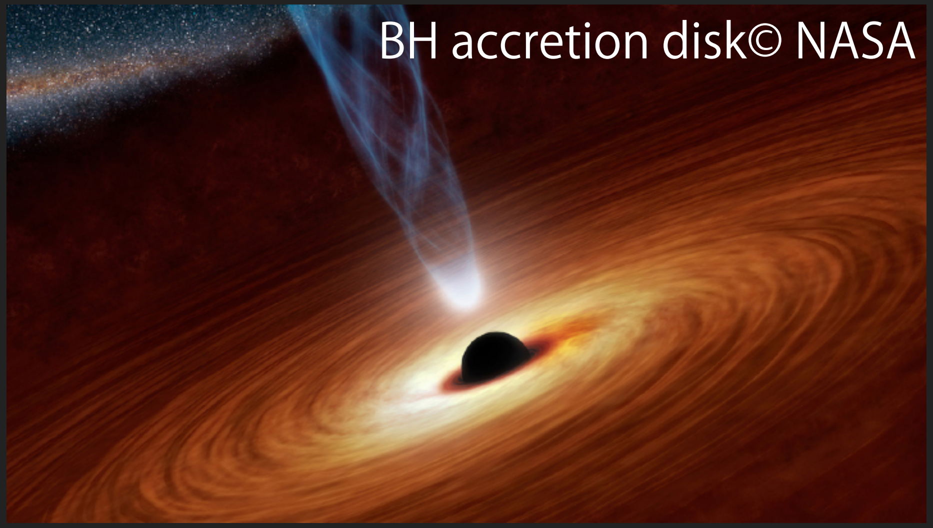
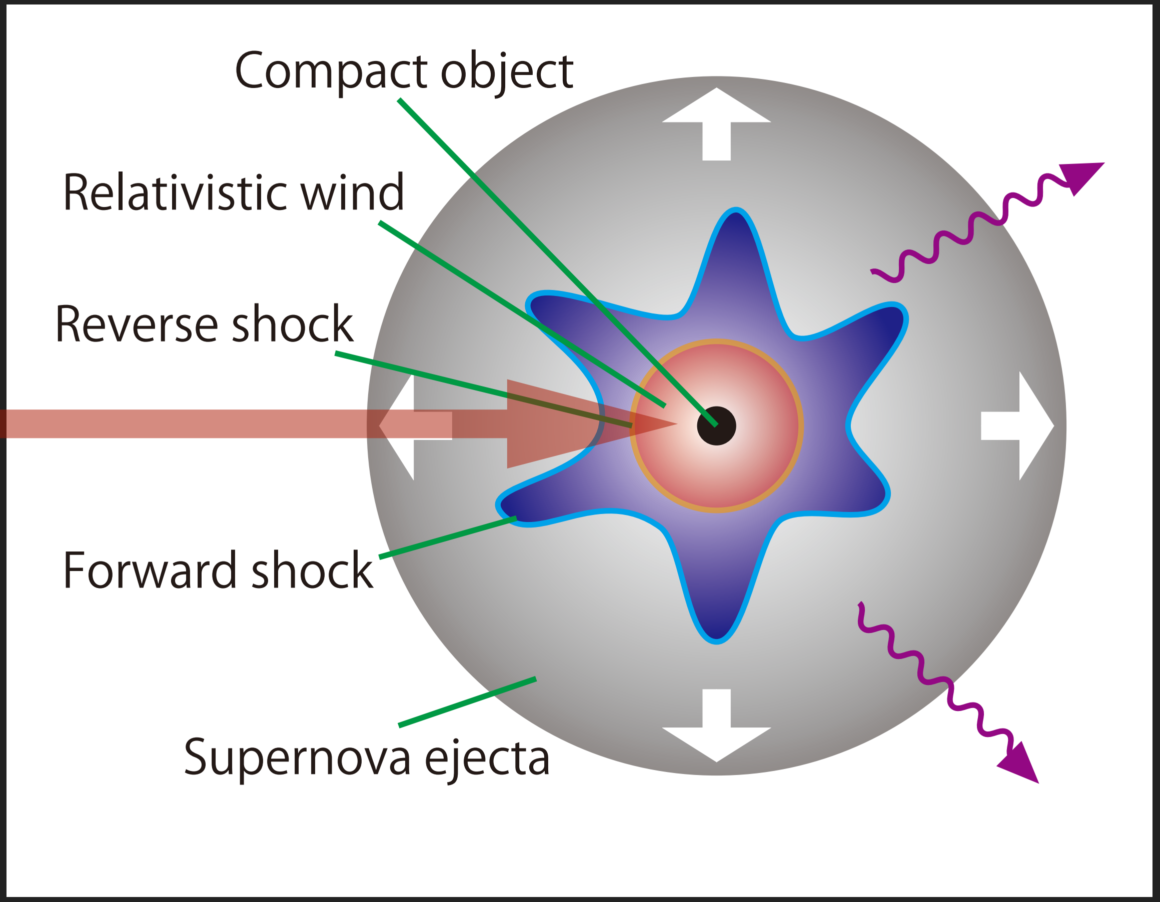
Models for type-I SLSNe

- 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)

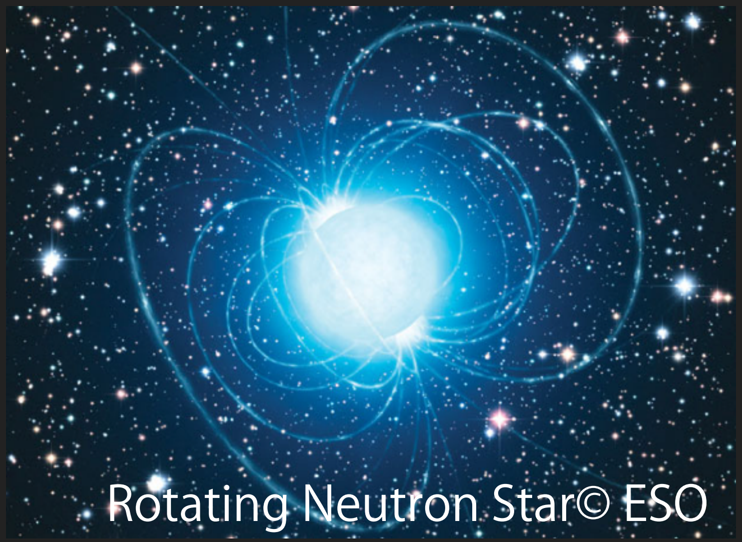






Magnetized neutron star scenario

- 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], $\Omega_i = 2\pi/P_i$~ 6x10^3 Hz
  - ➡ rotational energy: $E_{rot} = I_{ns}\Omega^2/2$~2x$10^{52}$ erg



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

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

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

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

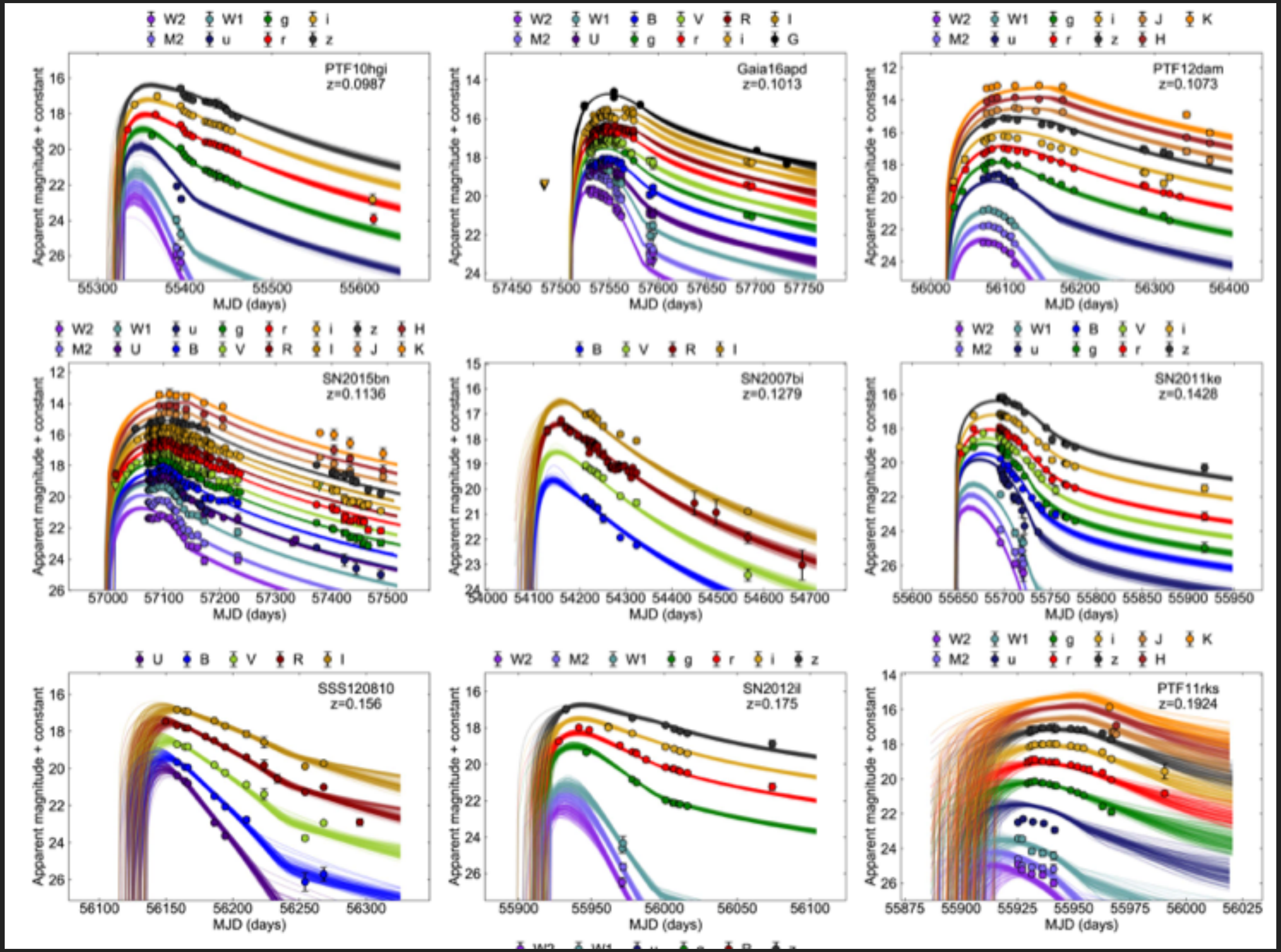
Magnetized neutron star scenario

- 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

Magnetized neutron star scenario

- 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)

Magnetized neutron star scenario

- 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

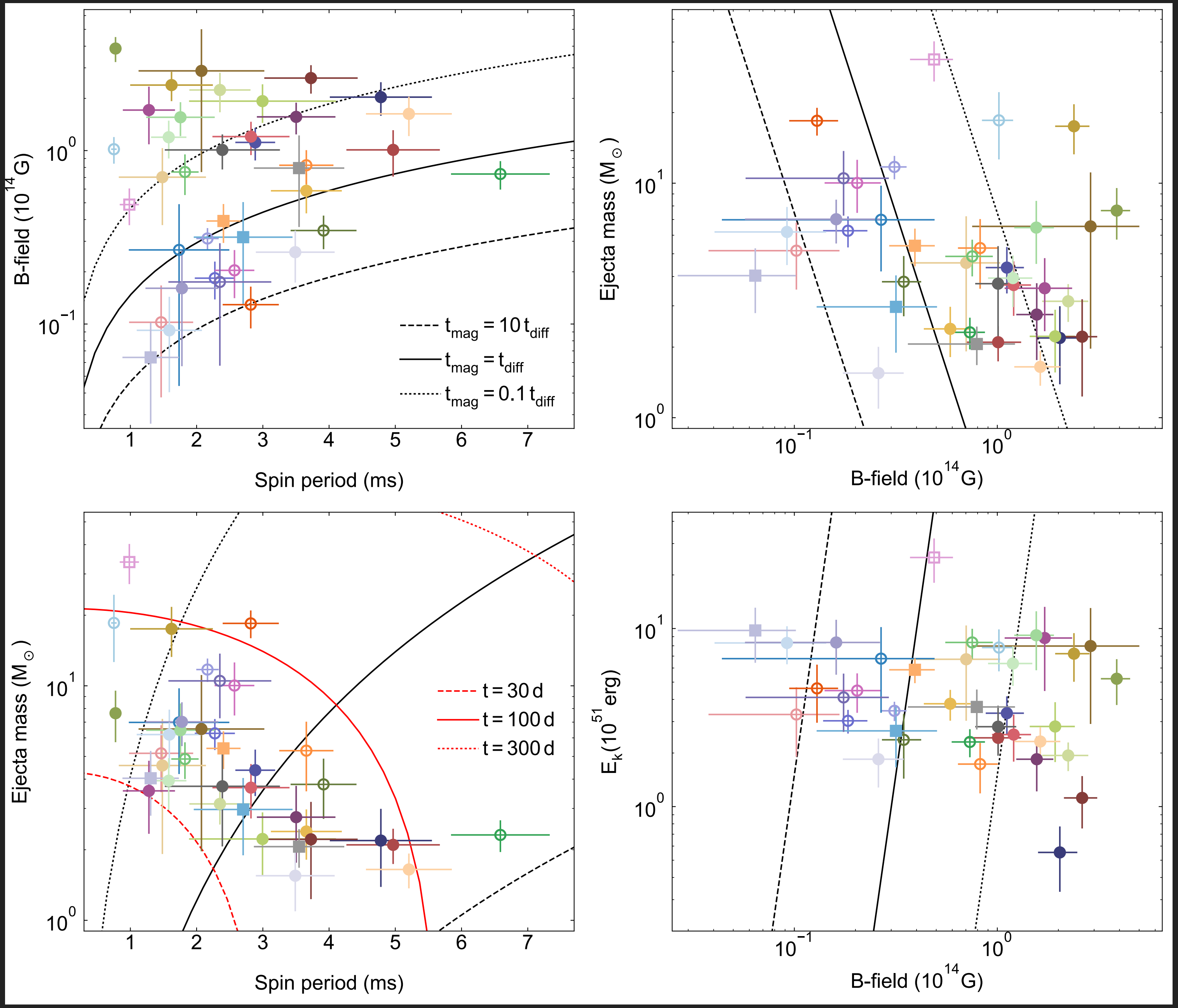
➡spin-period ~ 1 - 7 [ms]

➡B ~ 10^{13} - a few 10^{14} [G]

➡E_k ~ 10^{51} - 10^{52} [erg]

➡M_{ej} ~ 2 - 10 M◉

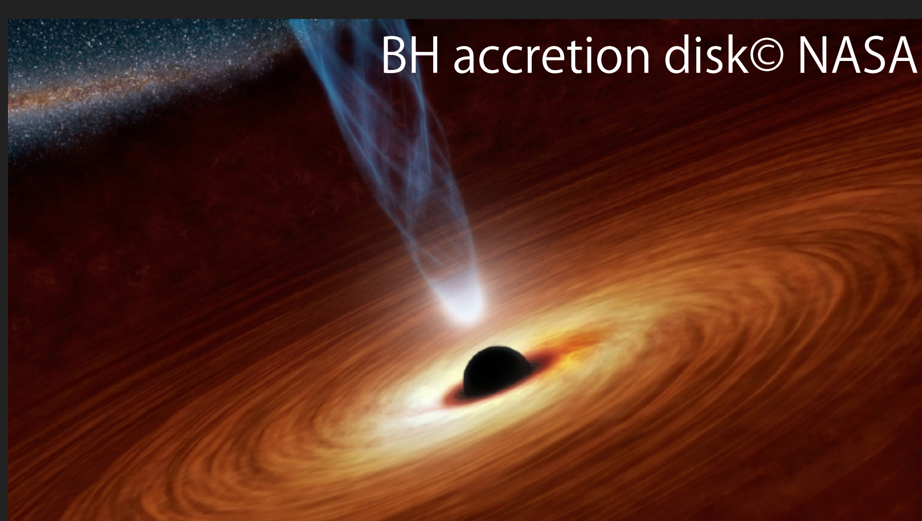
What is the "smoking-gun" of magnetar scenario?

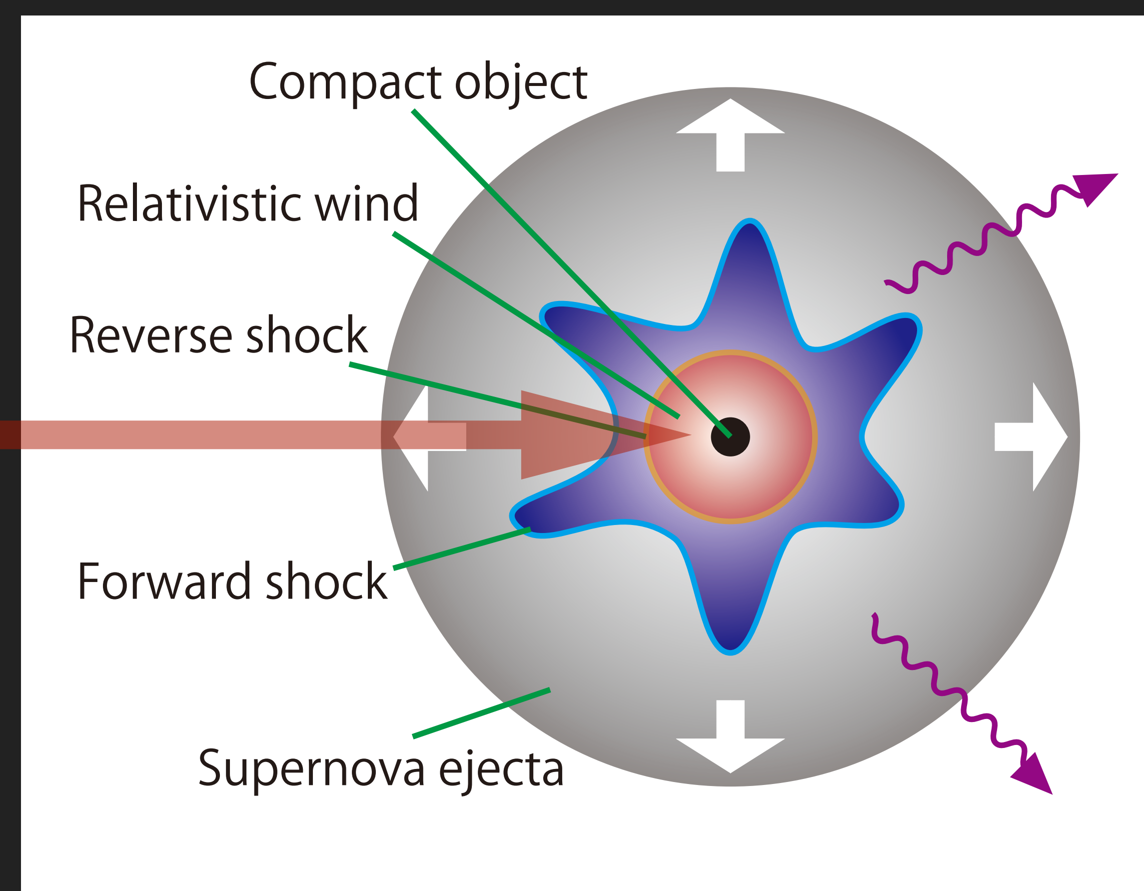


Nicholl+(2017)

How can we probe the powerful engine?

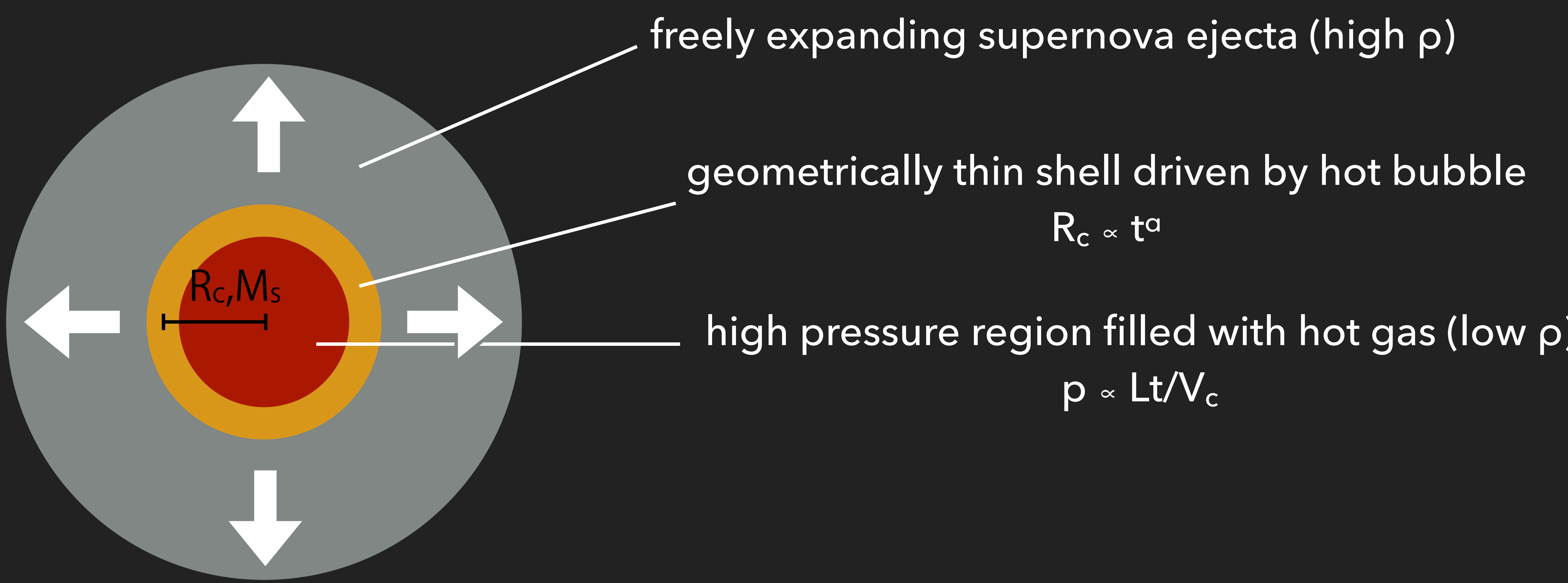
- Their impacts on SN ejecta : SN light curves and spectra
- Non-thermal emission from a wind nebula embedded in SN remnant (later times)





Impacts on SN ejecta

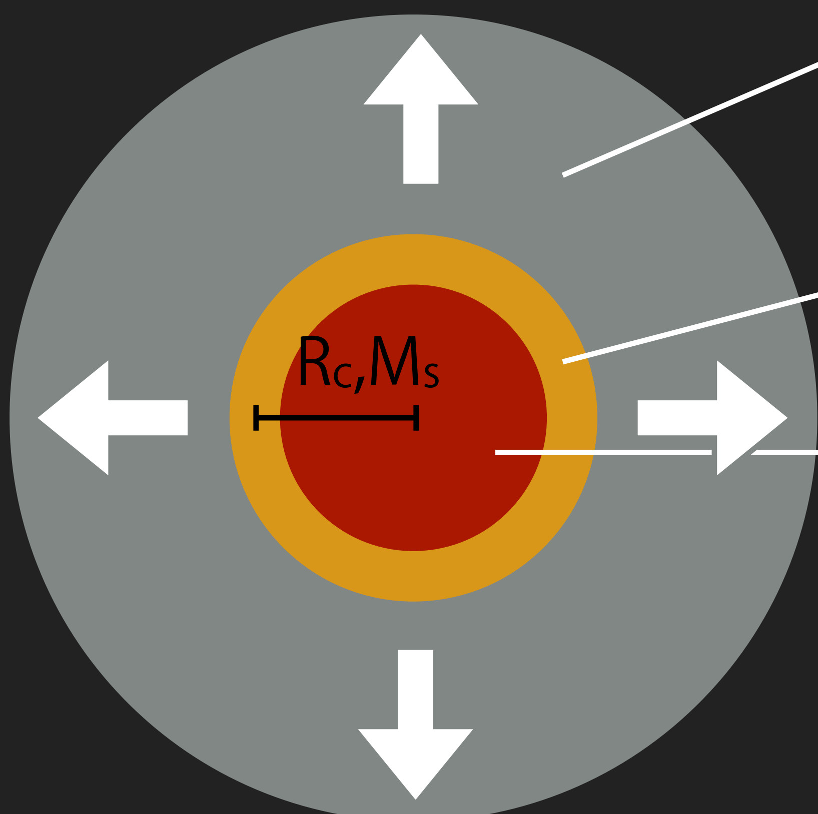
- 1D spherical picture of SN ejecta with a central engine
- analogy to galactic pulsar wind nebulae



e.g., Chevalier&Fransson (1992)

Impacts on SN ejecta

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



freely expanding supernova ejecta (high ρ)

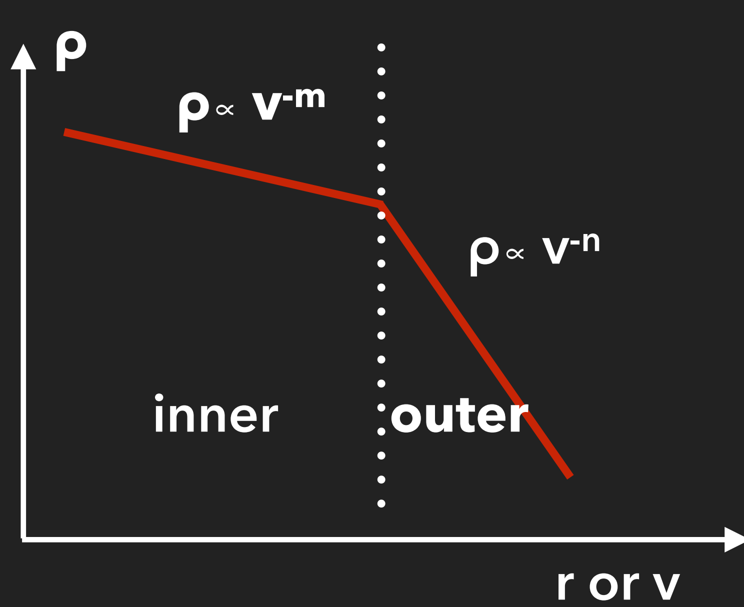
geometrically thin shell driven by hot bubble

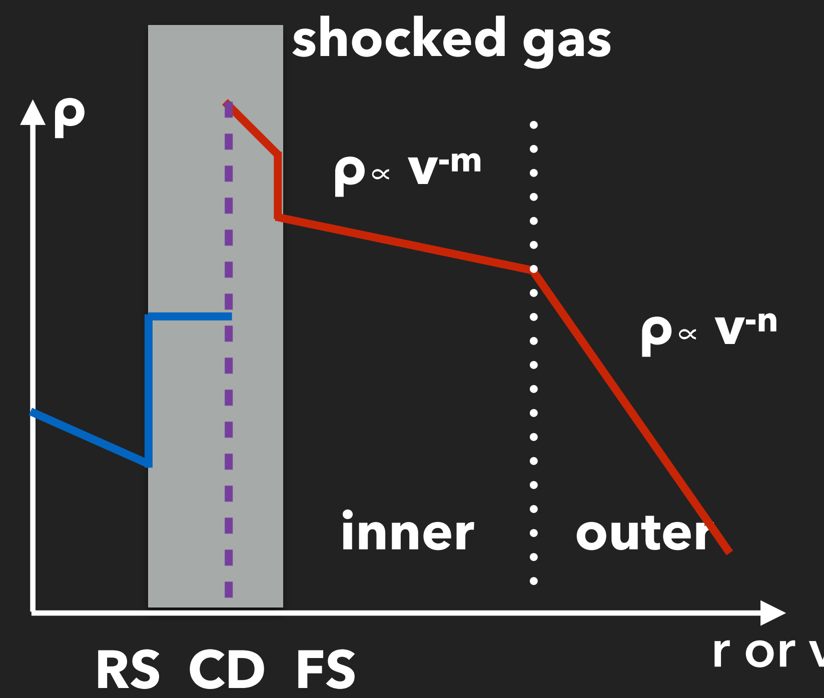
$R_c \propto t^a$

high pressure region filled with hot gas (low ρ)

$p \propto Lt/V_c$

Free expansion : v=r/t





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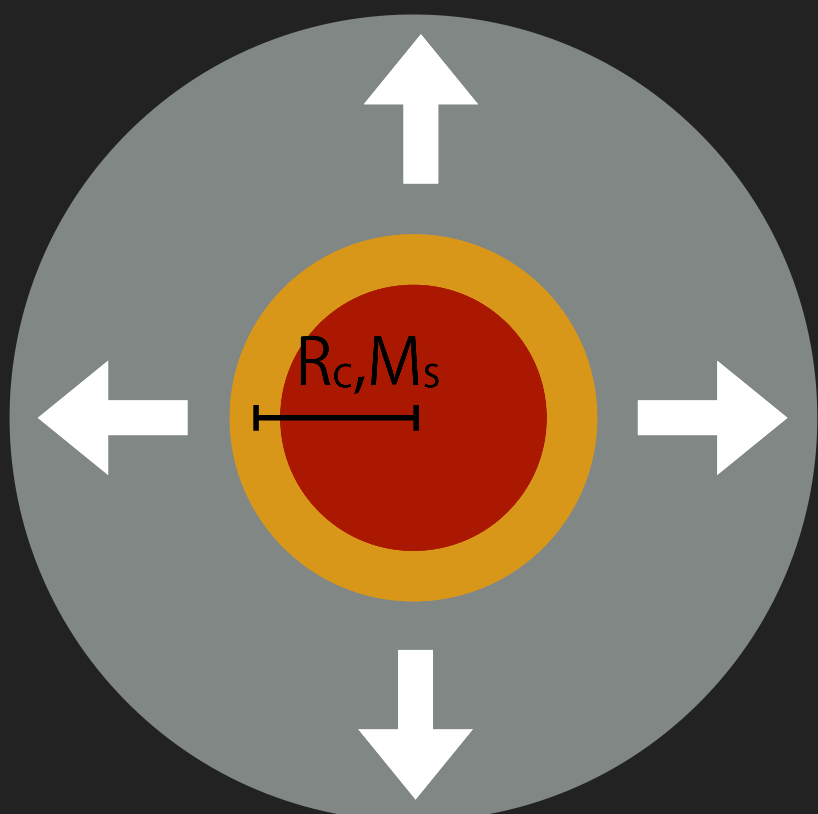
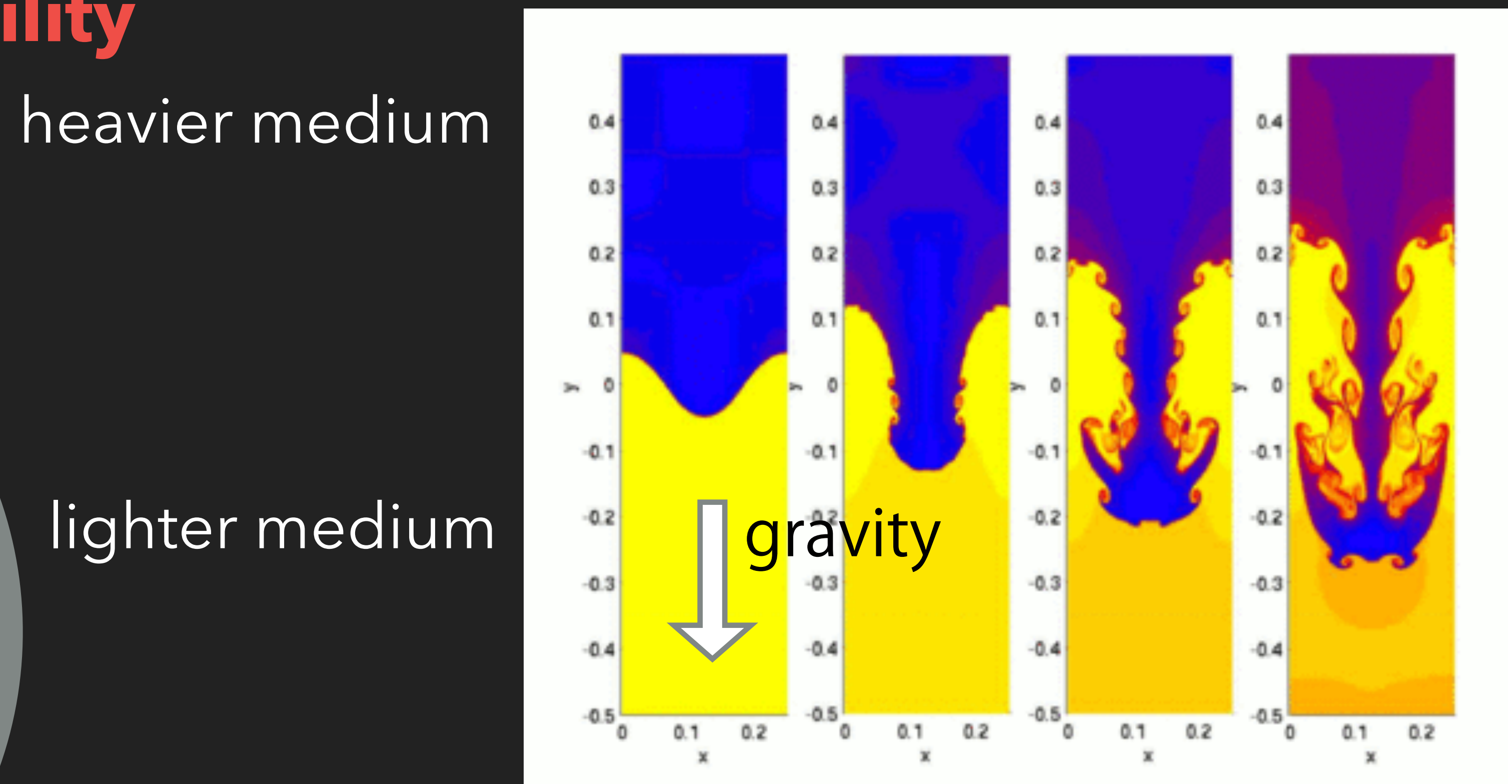
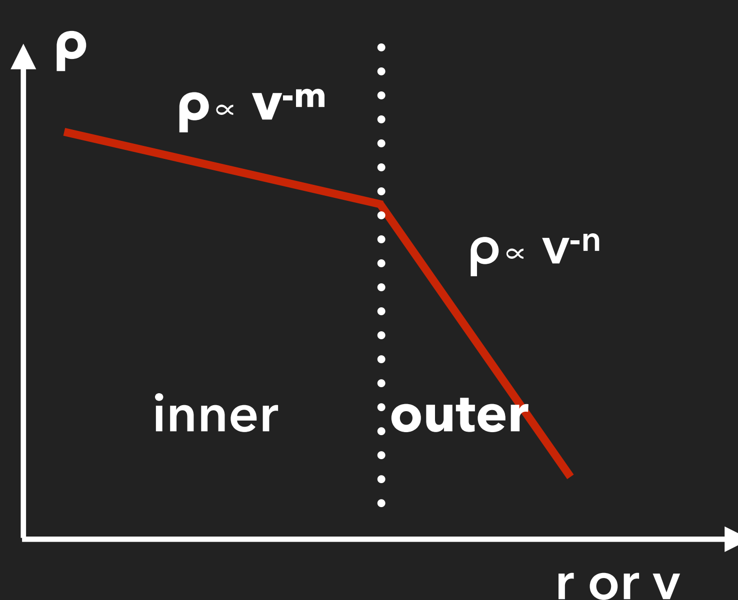
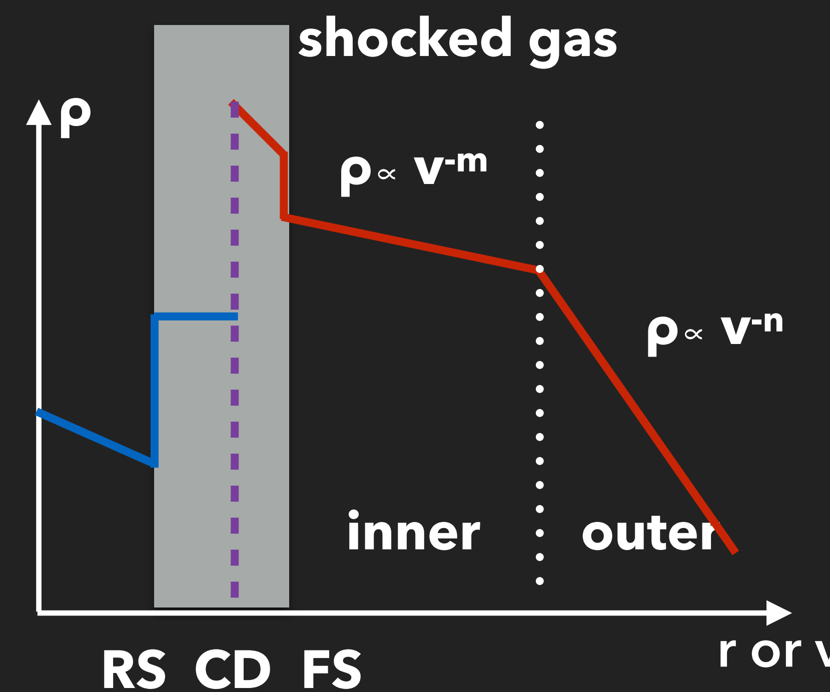
- Is1D spherical picture of SN ejecta with a central engine correct?
- Actually, No. **RT instability**









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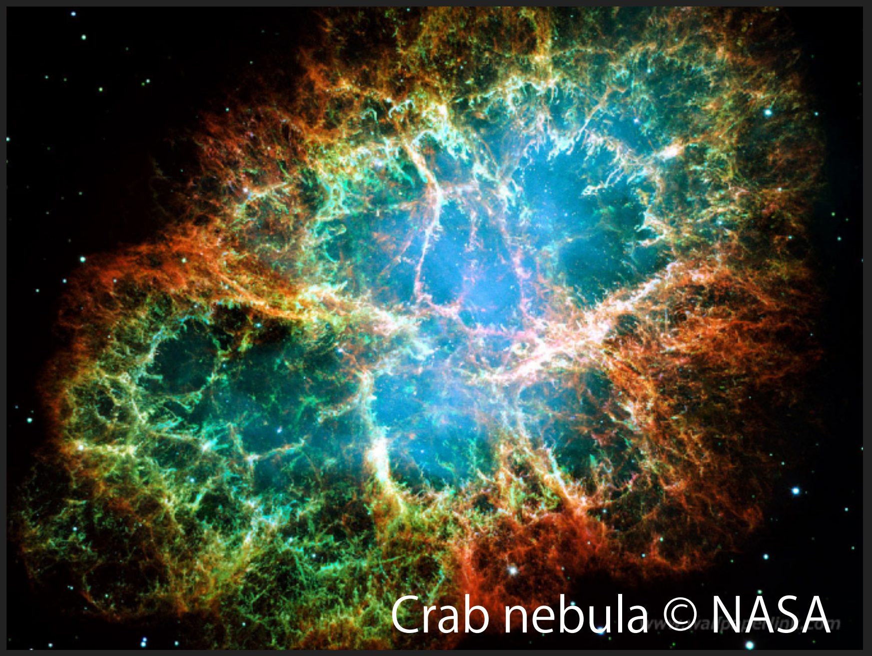

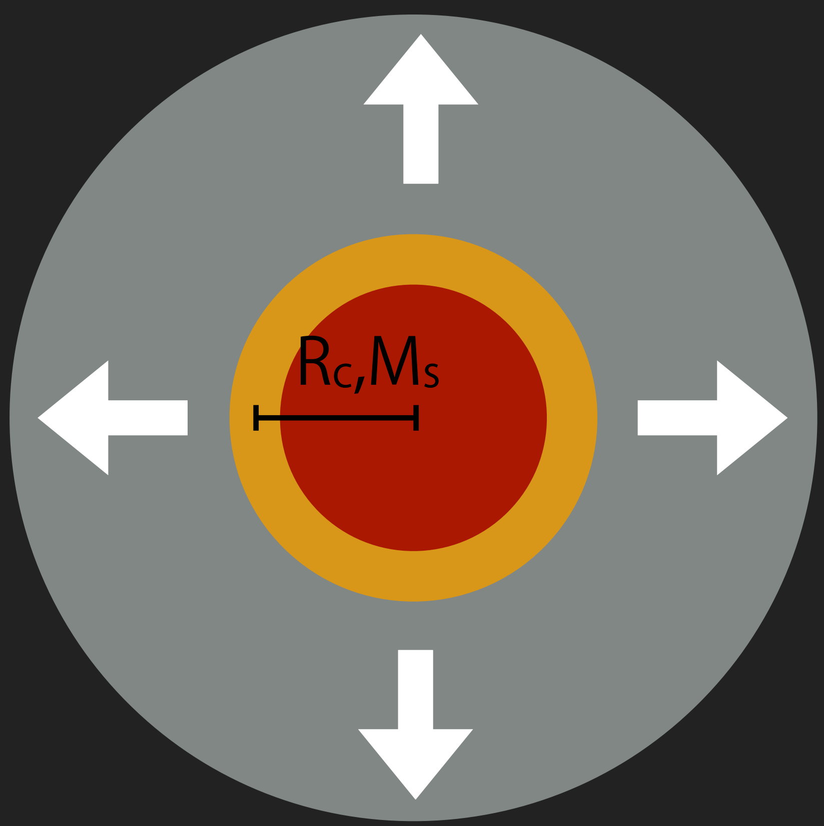

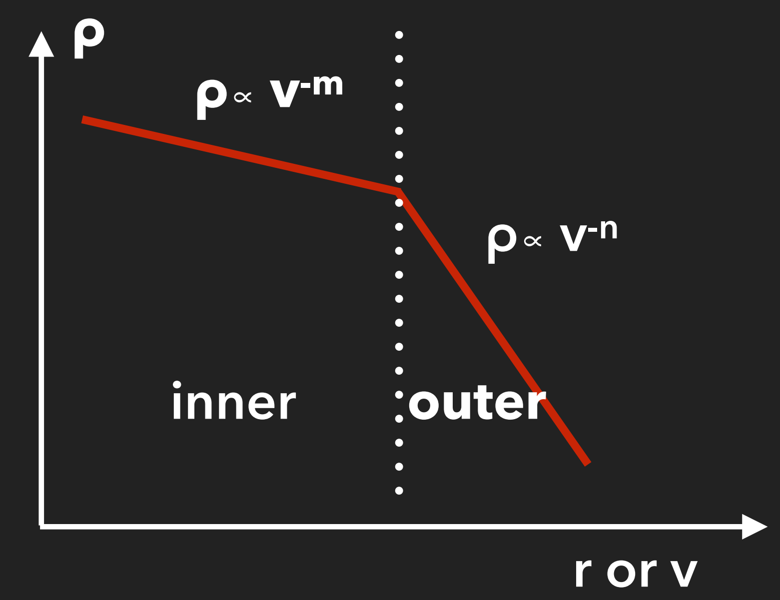

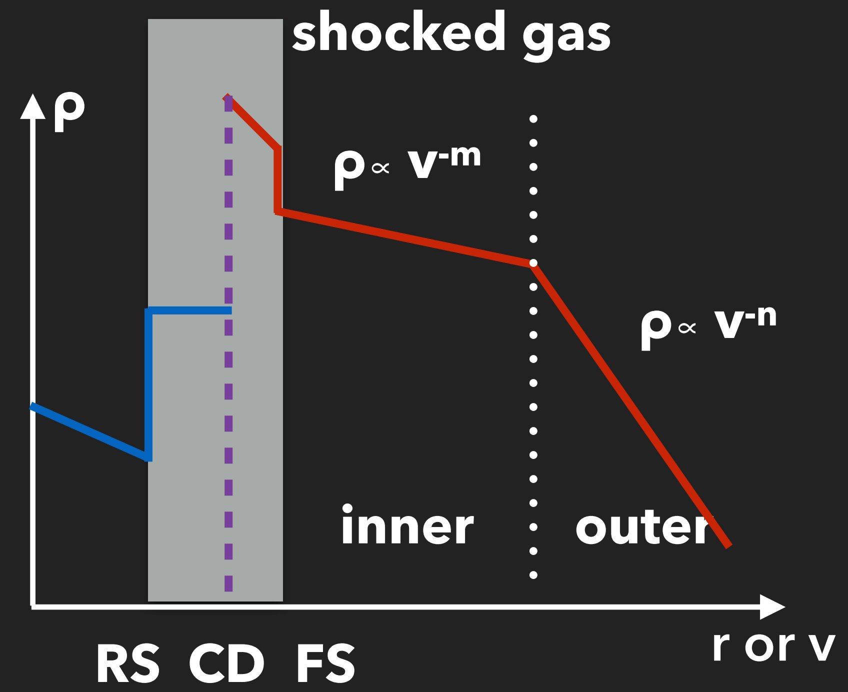

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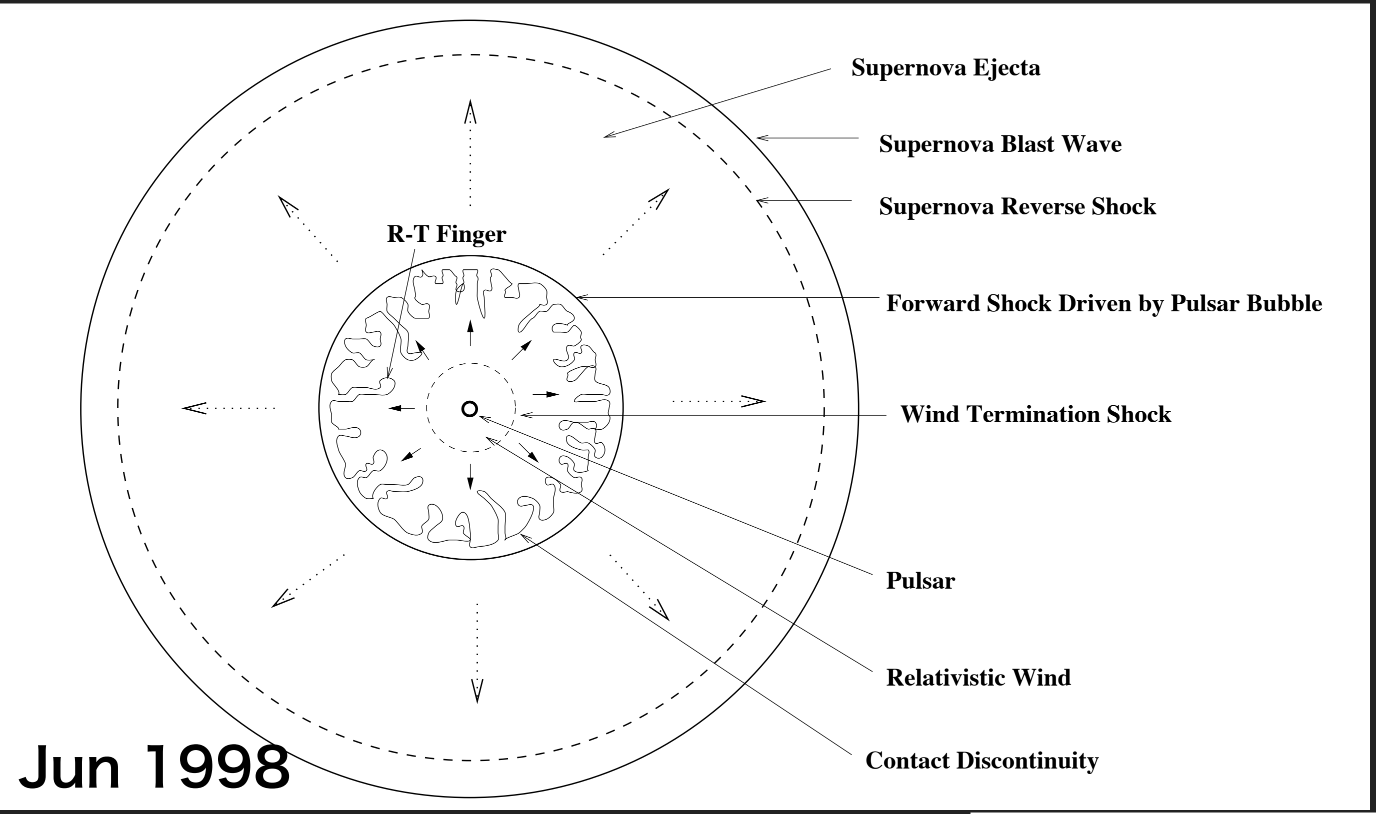
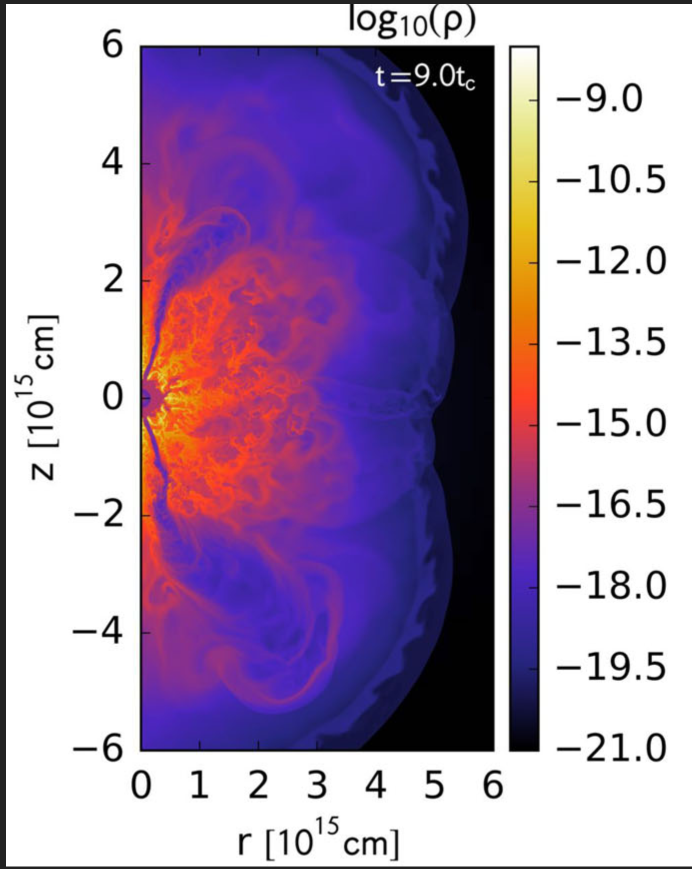
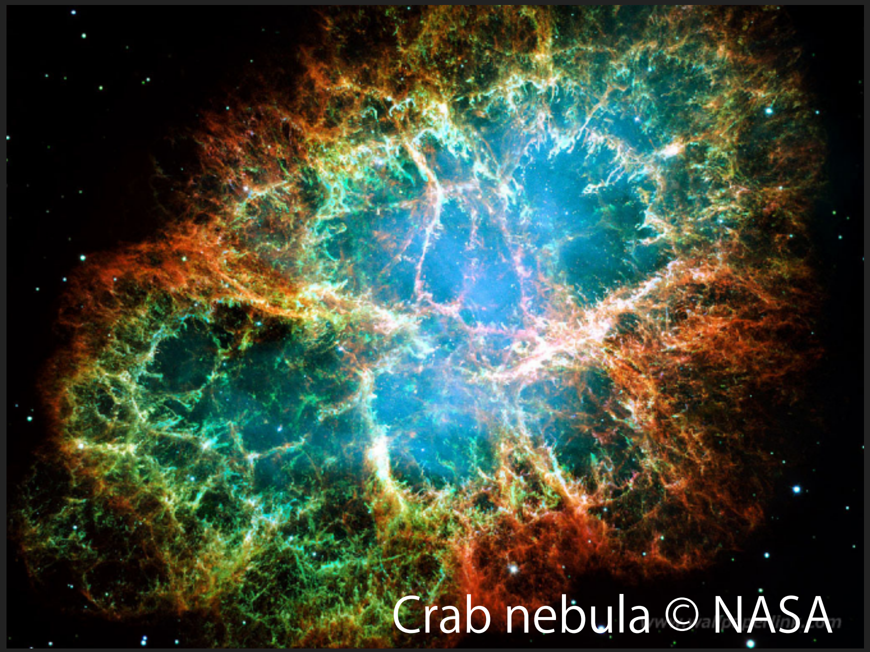
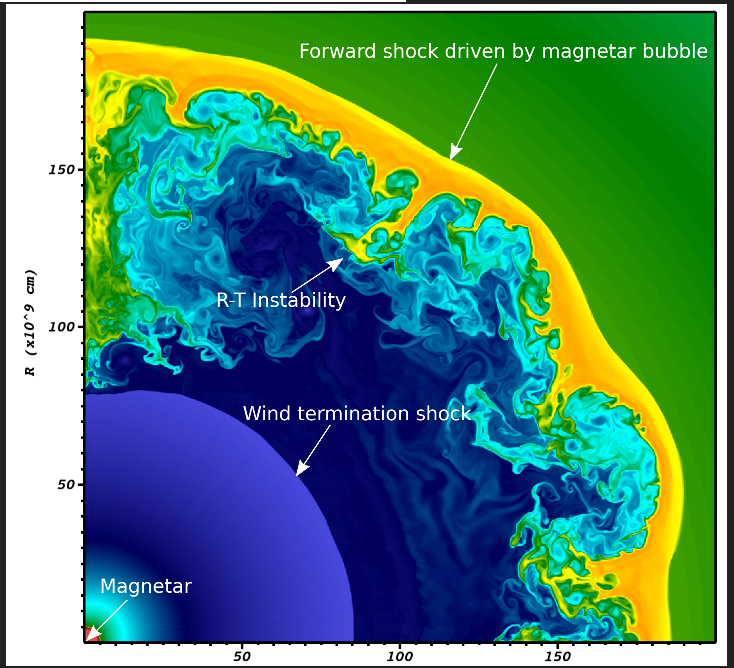


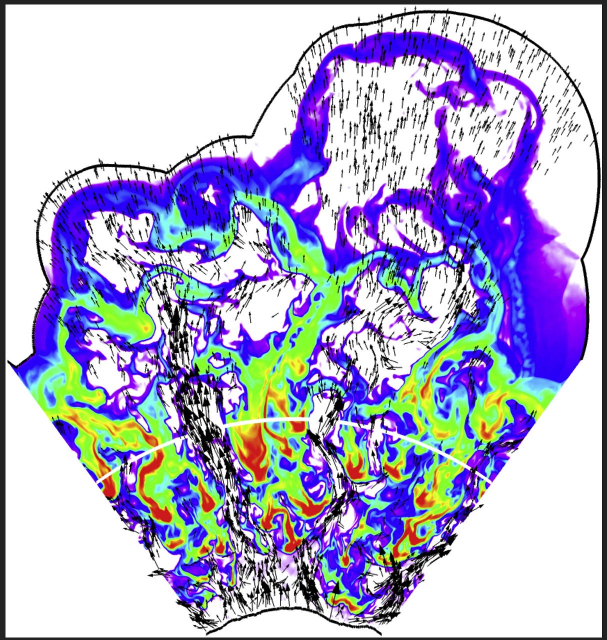
Suzuki & Maeda (2017)







Chen, Woosley, & Sukhbold (2016)

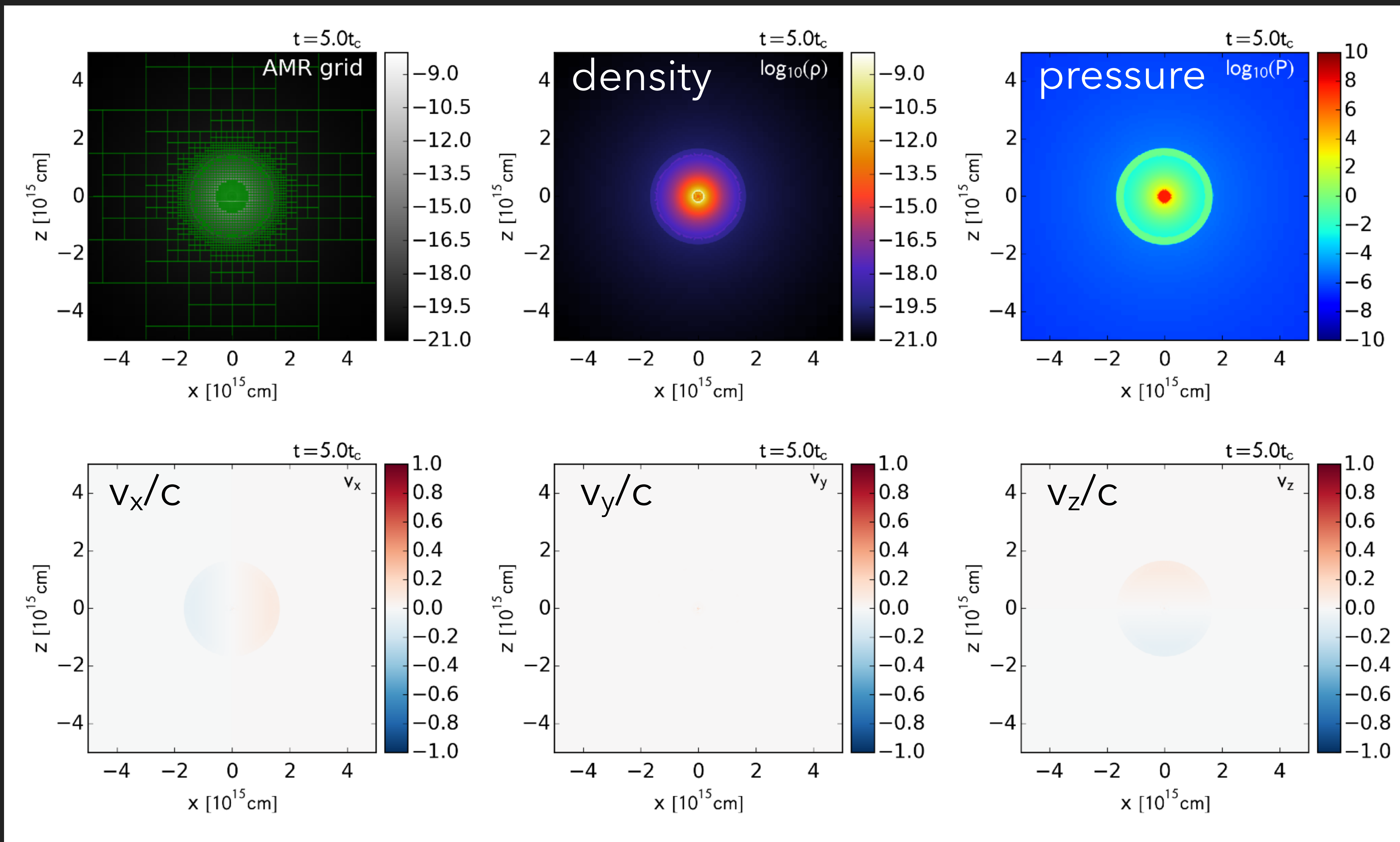


Blondin & Chevalier (2017)

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, in preparation)



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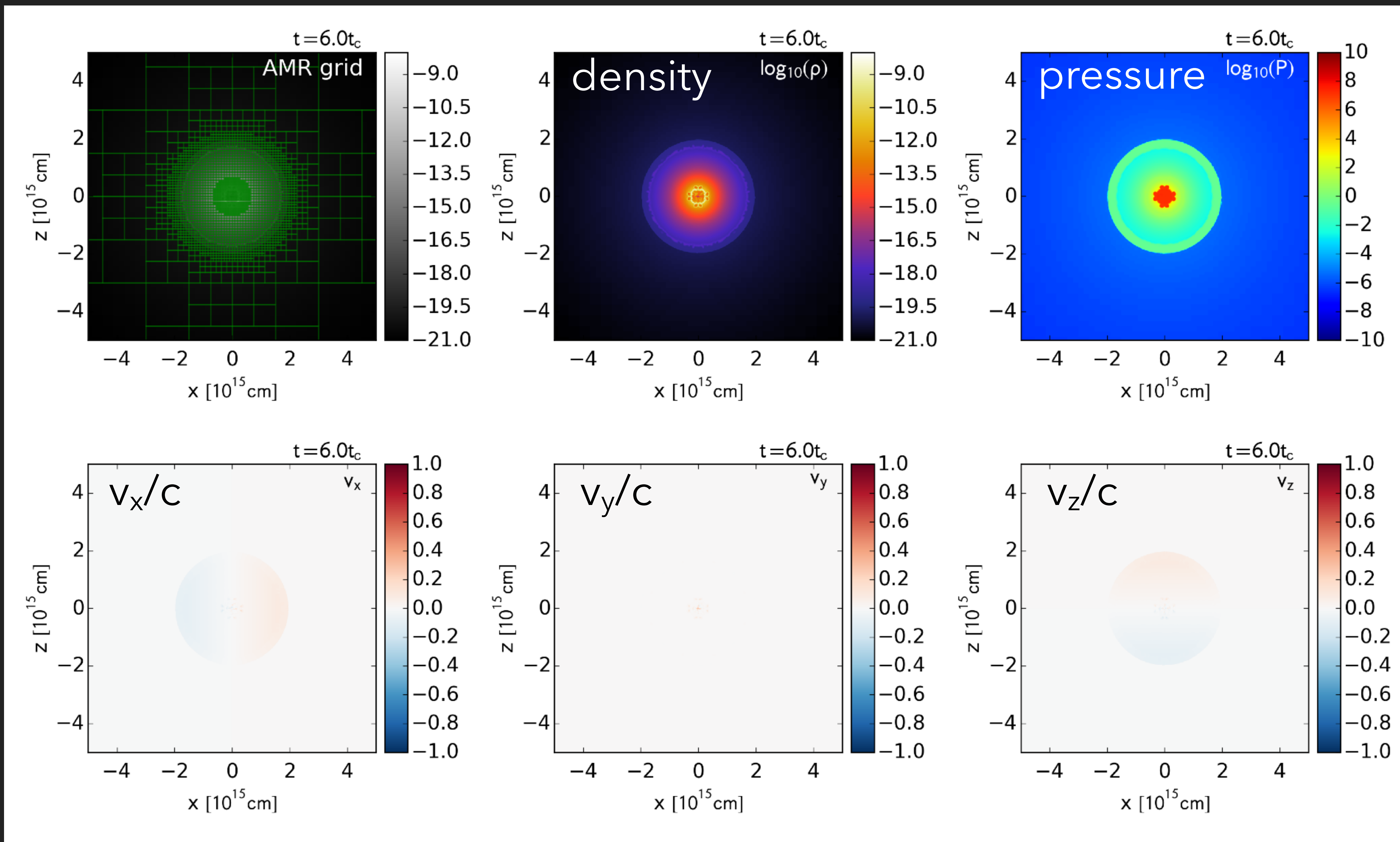

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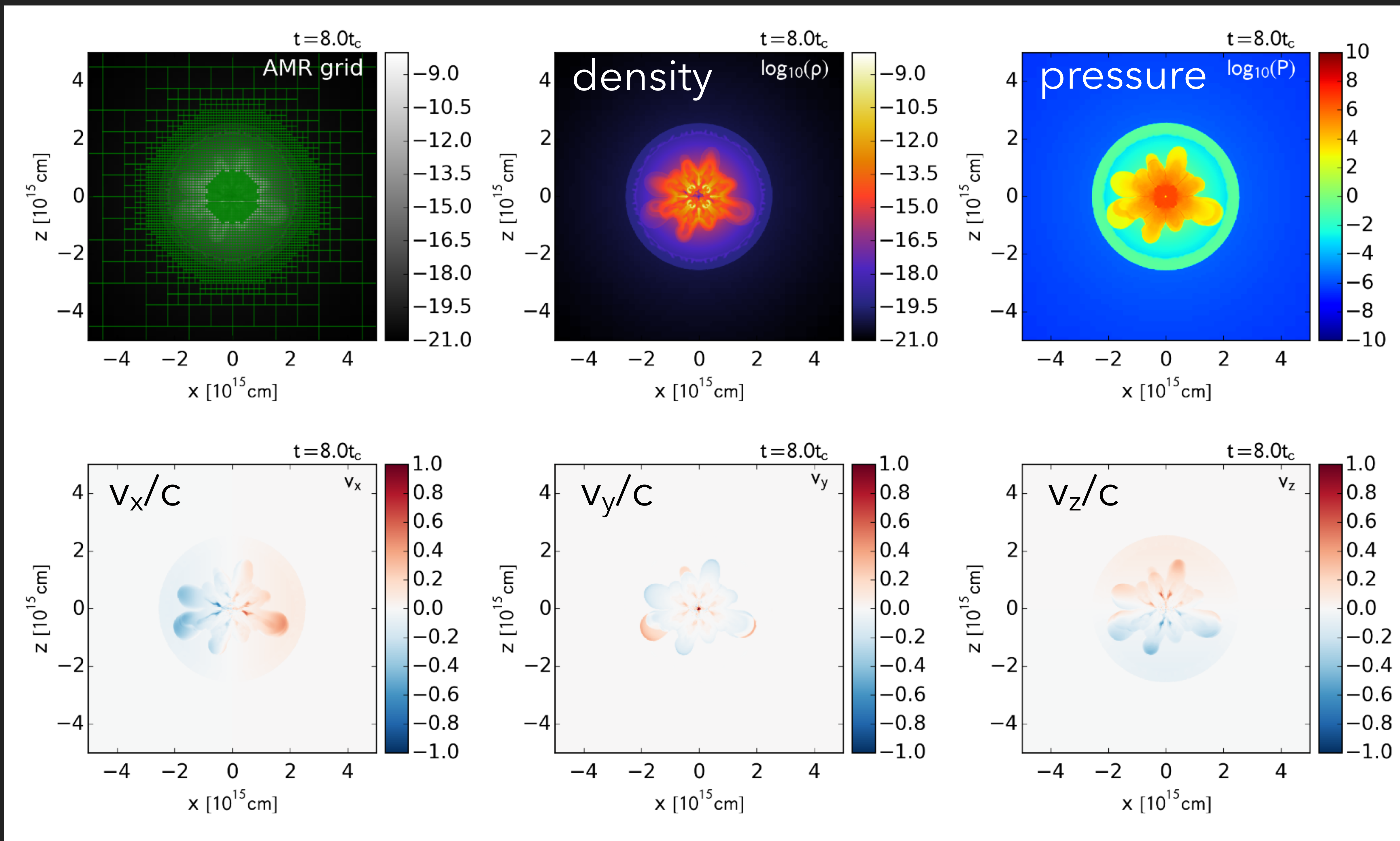

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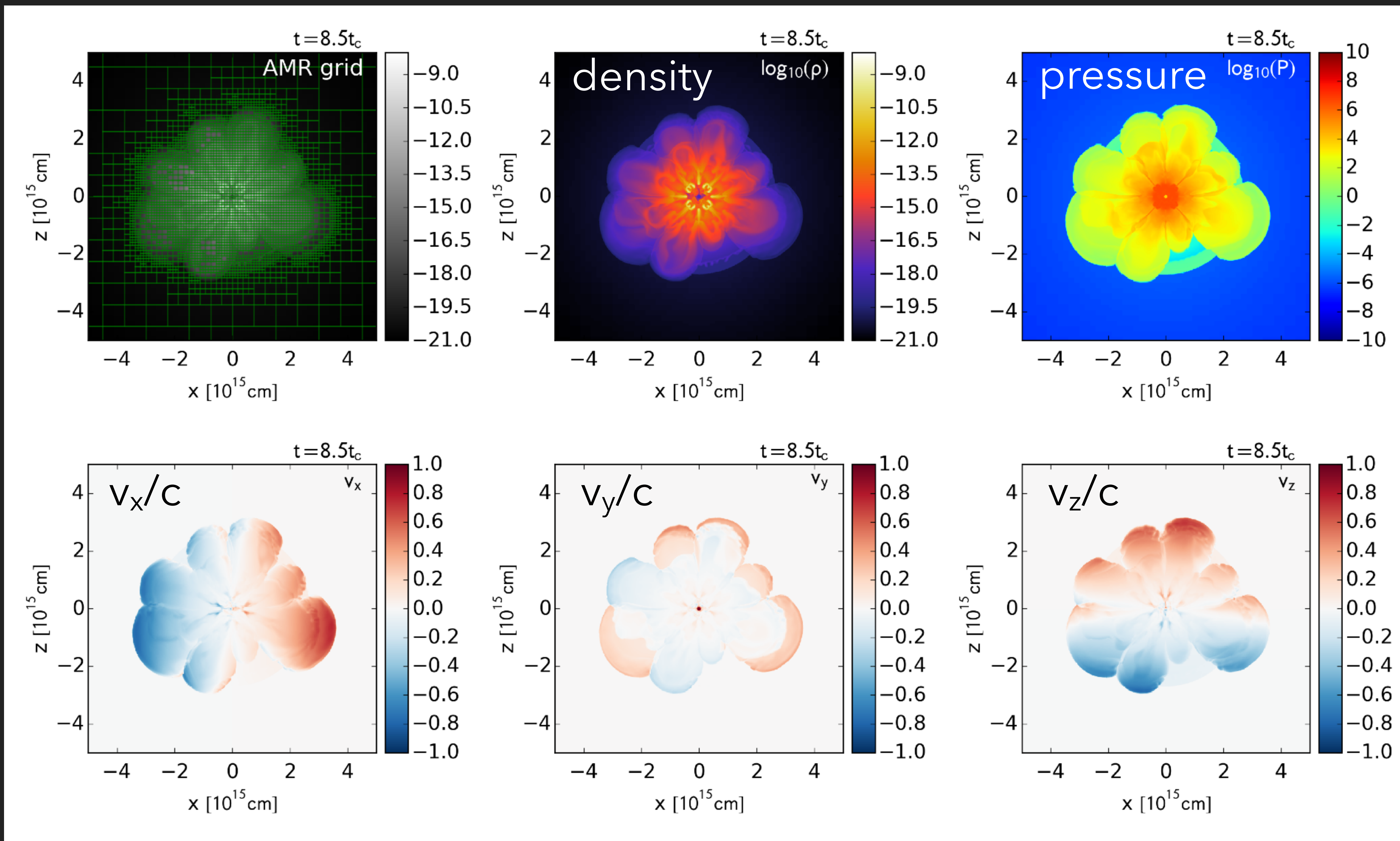

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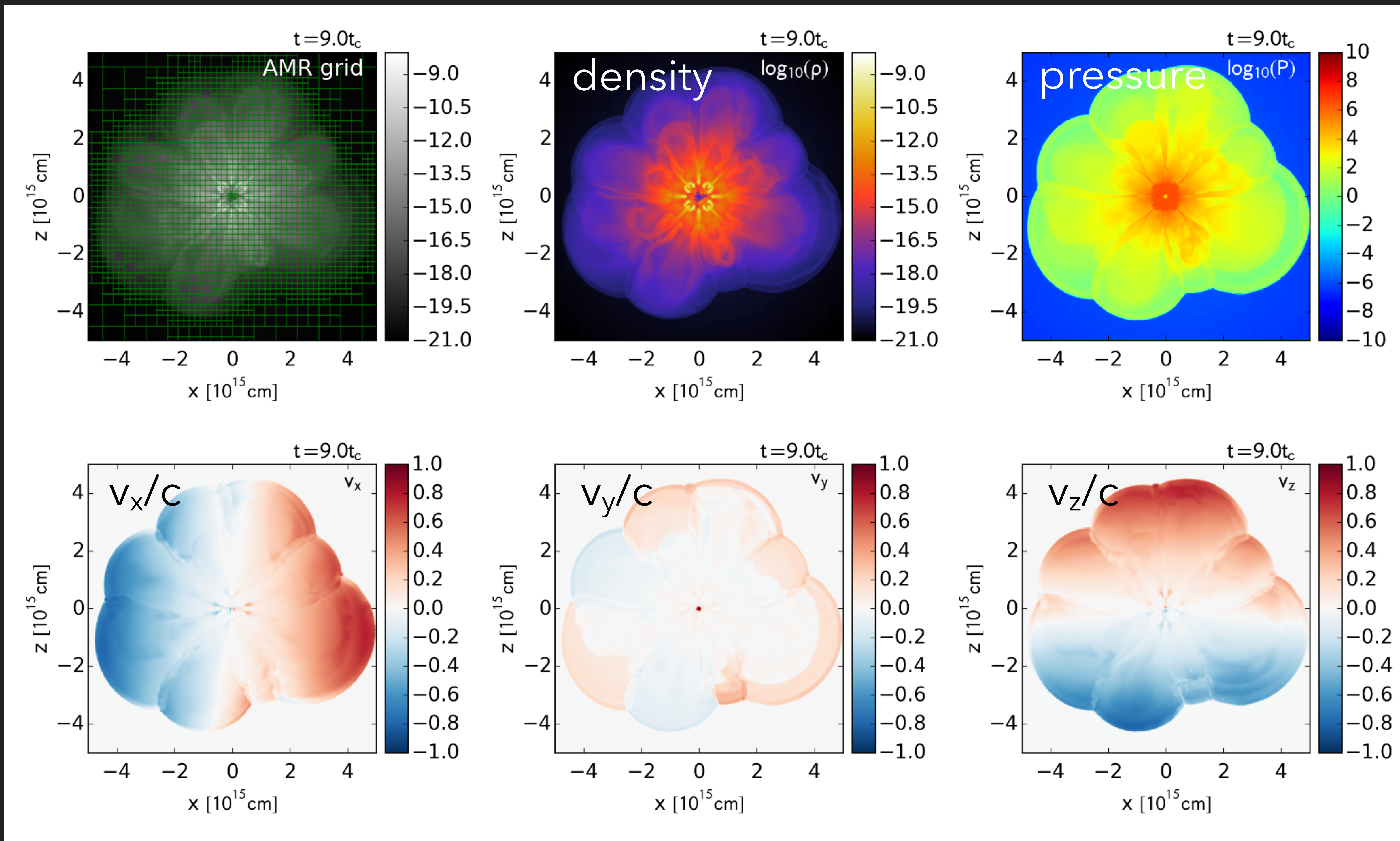

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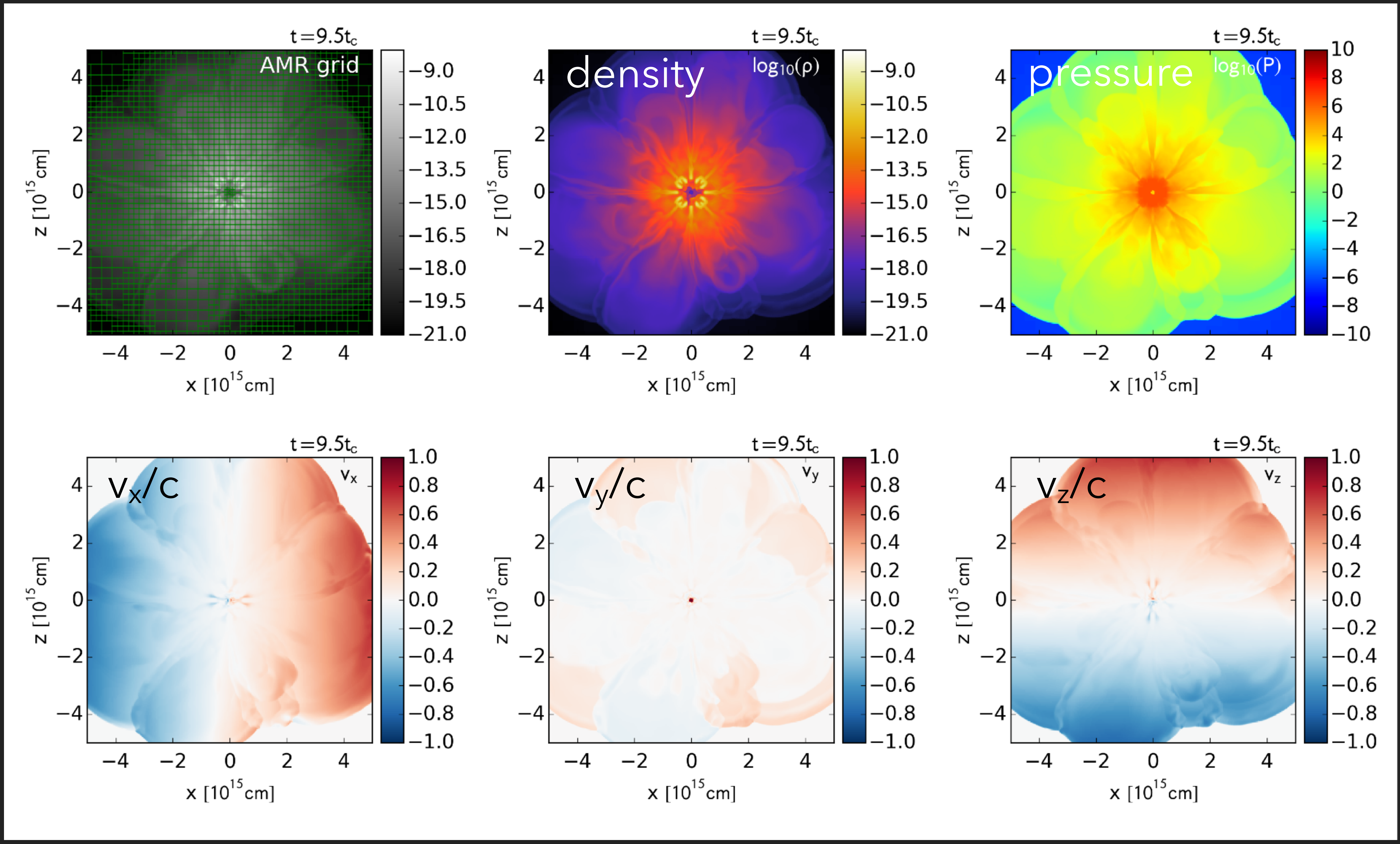

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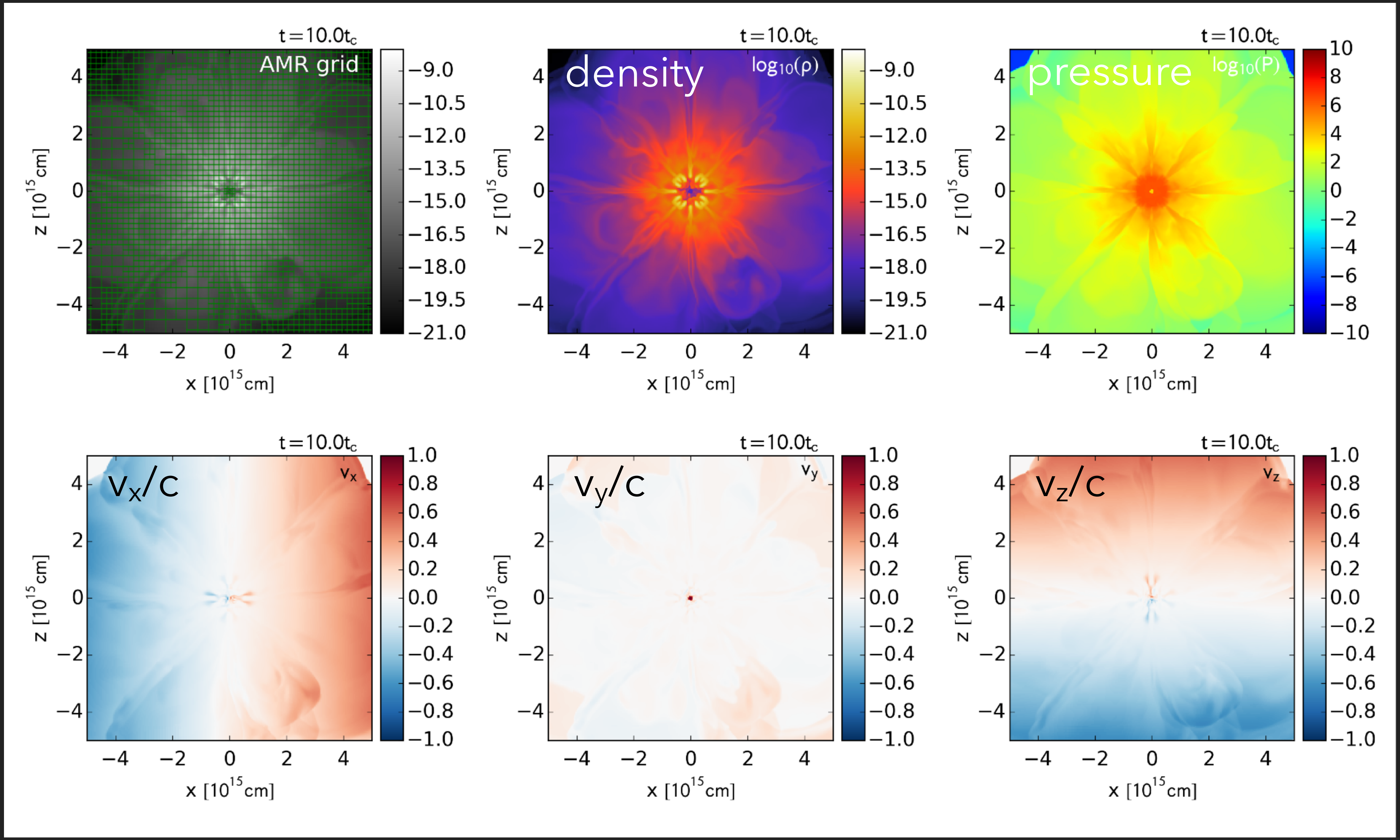

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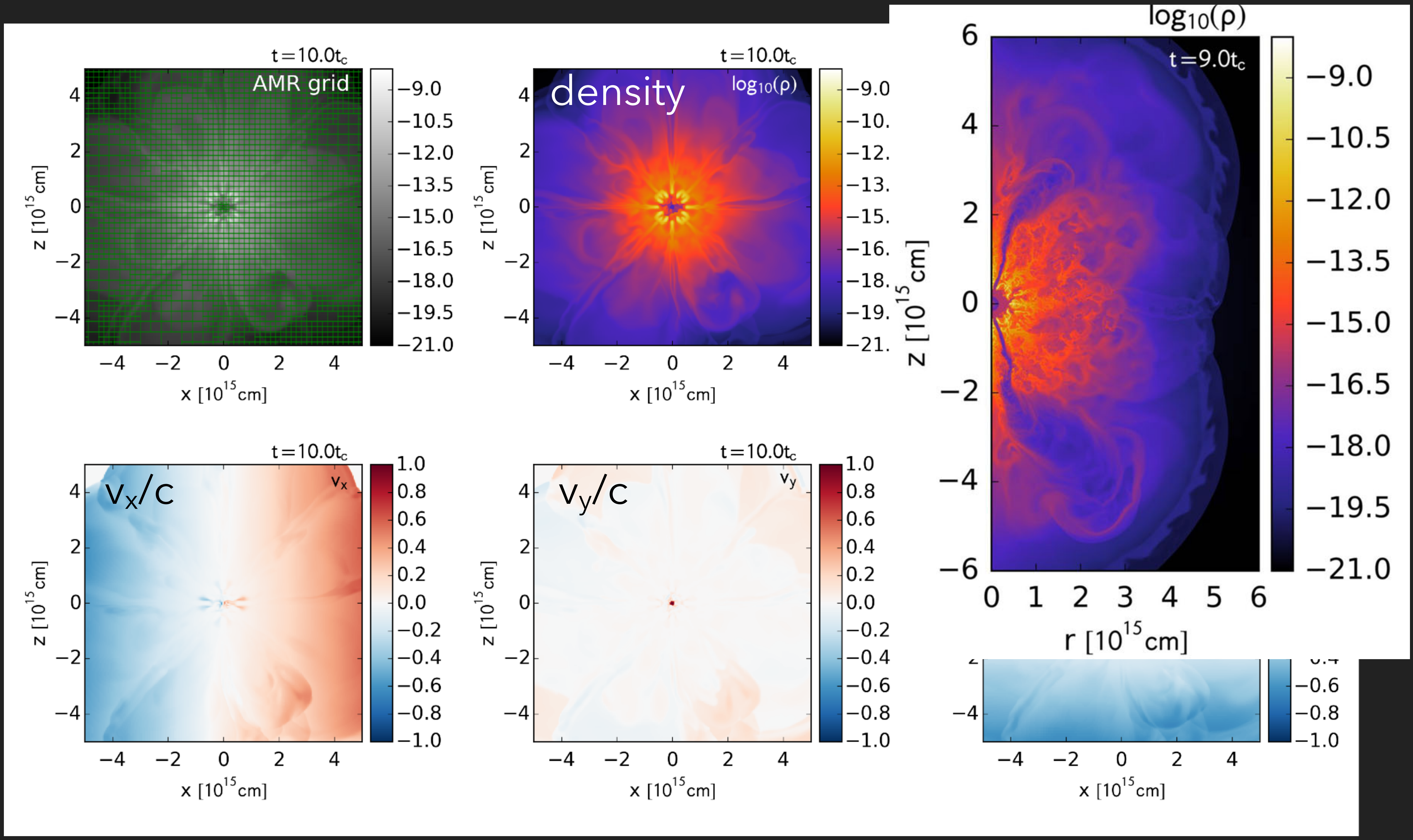
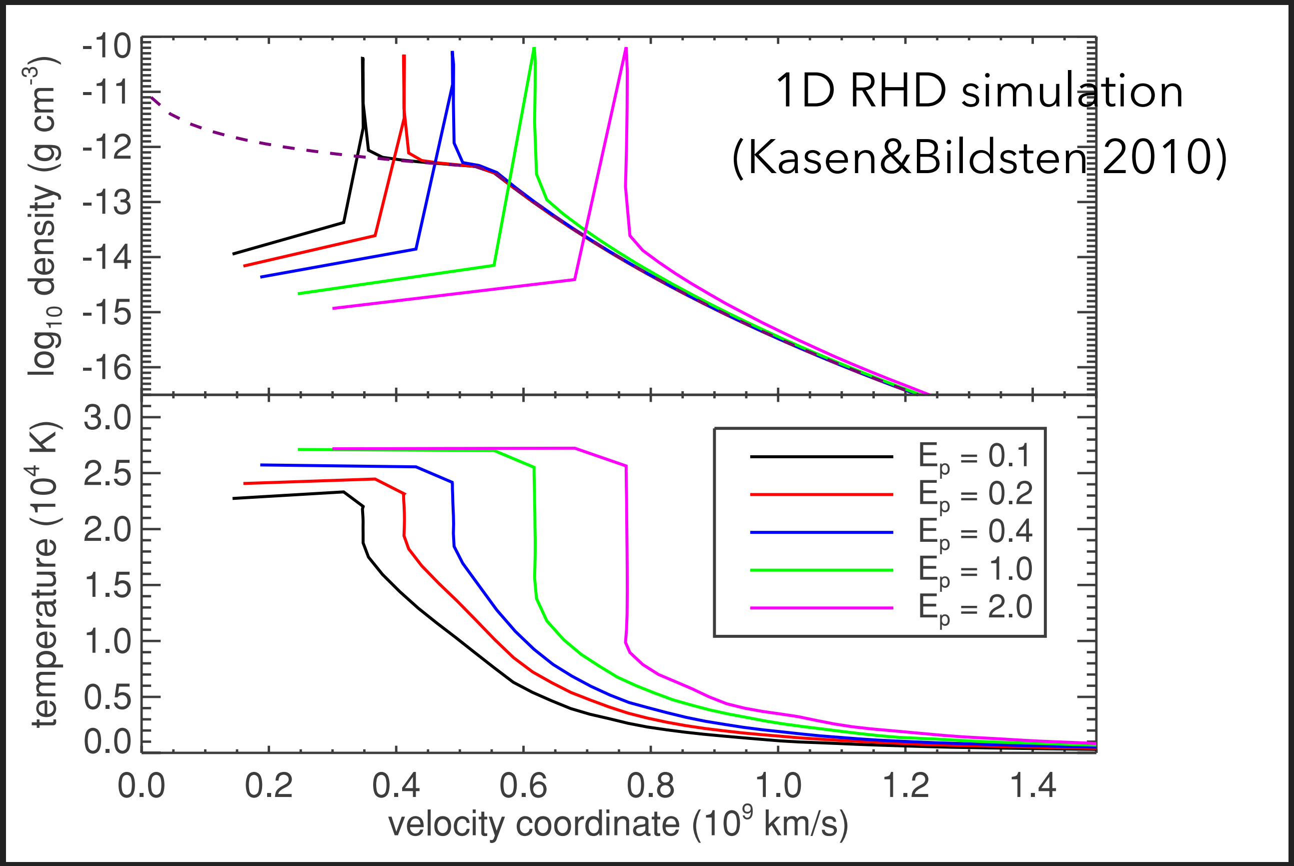
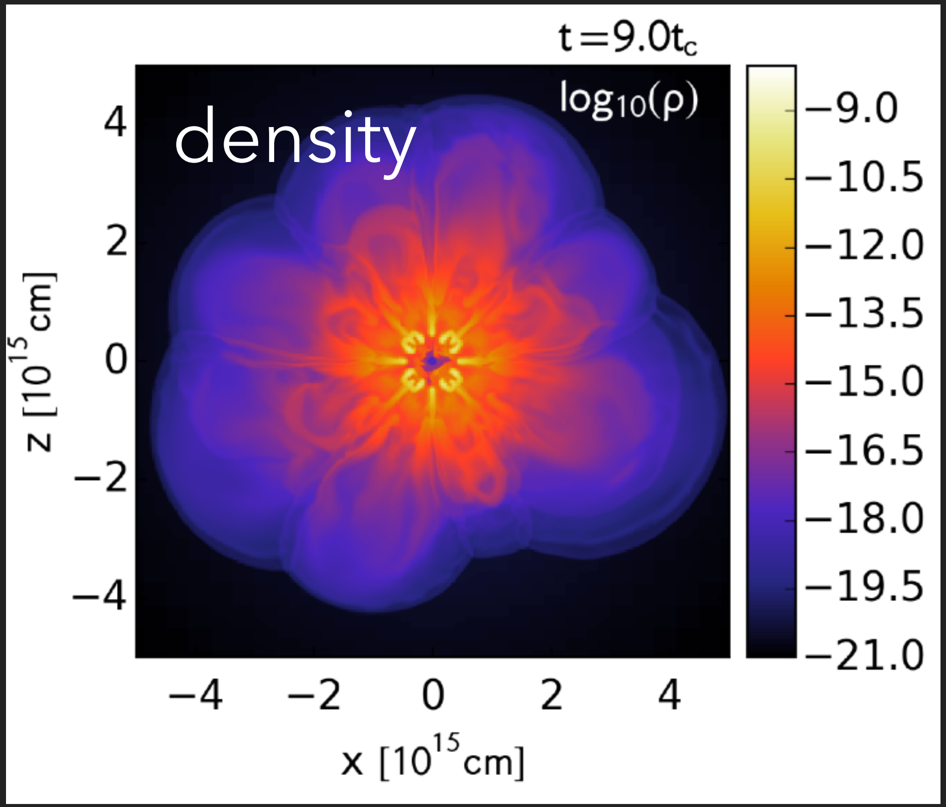
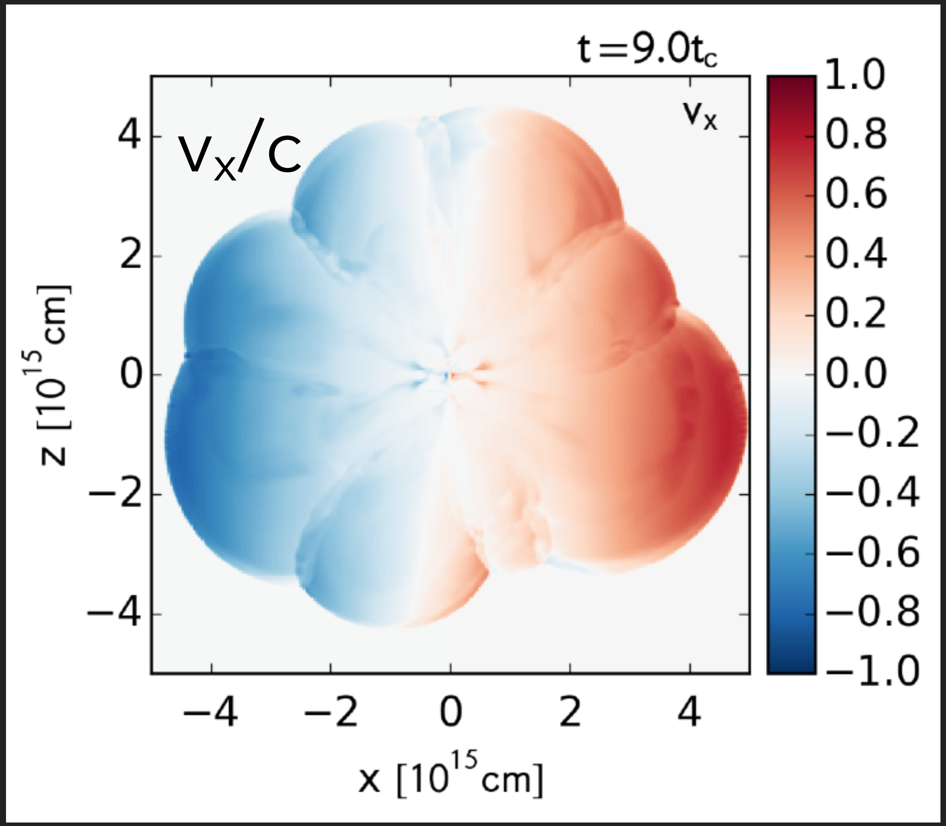


Density structure in 3D

- 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







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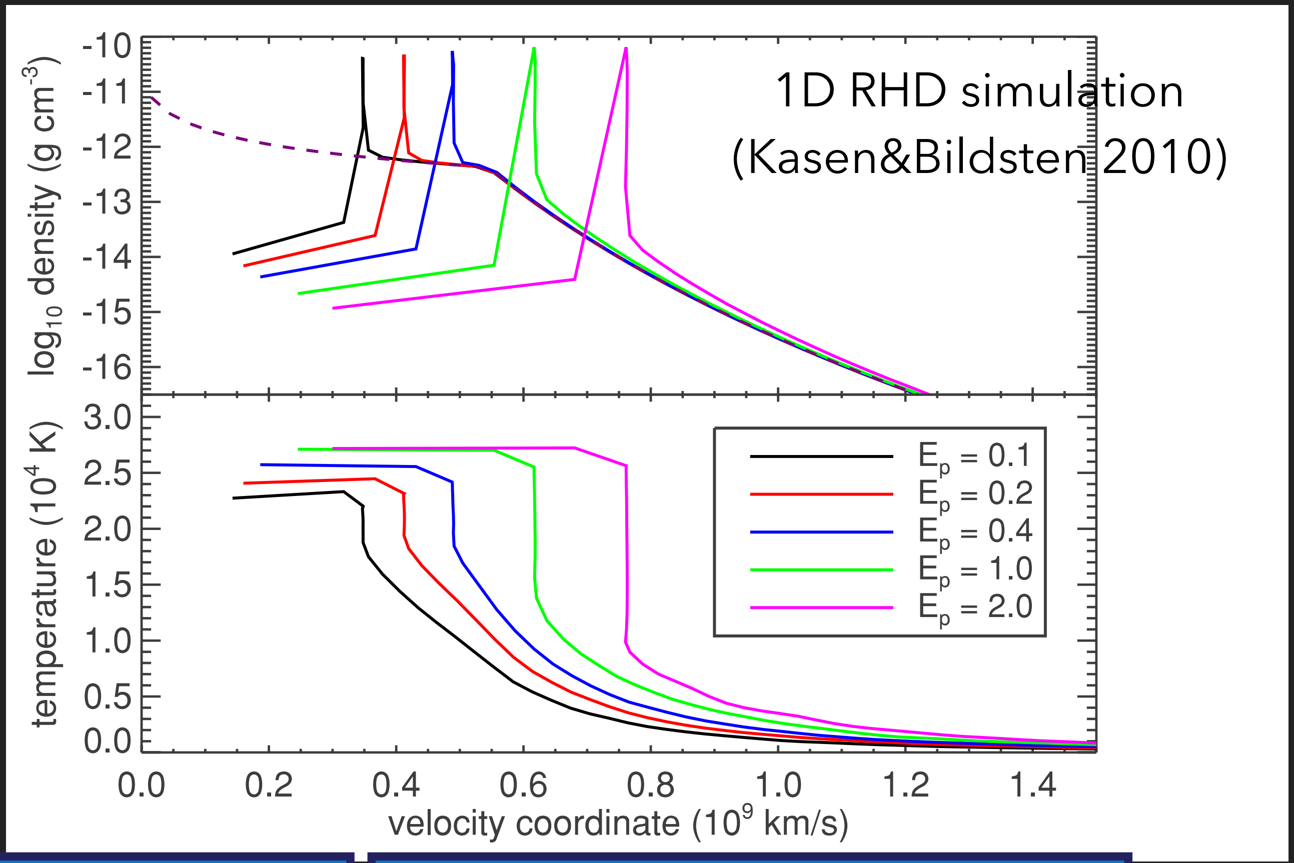
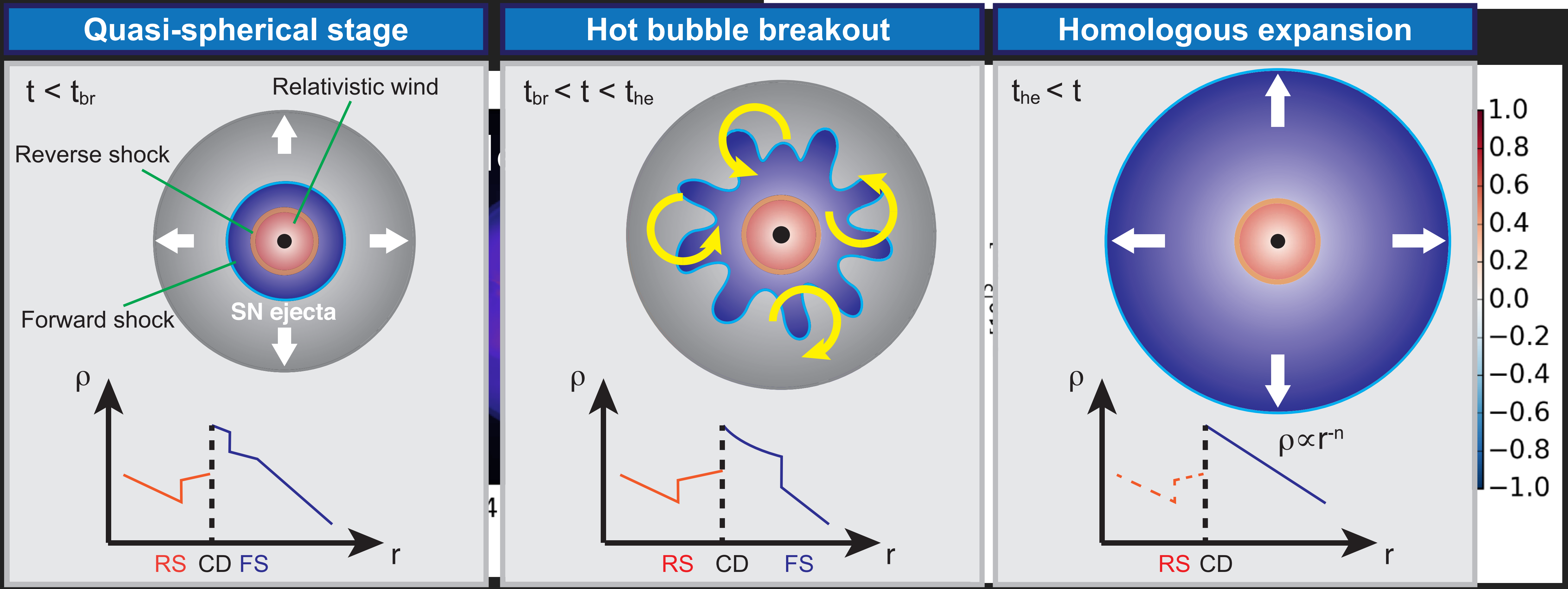
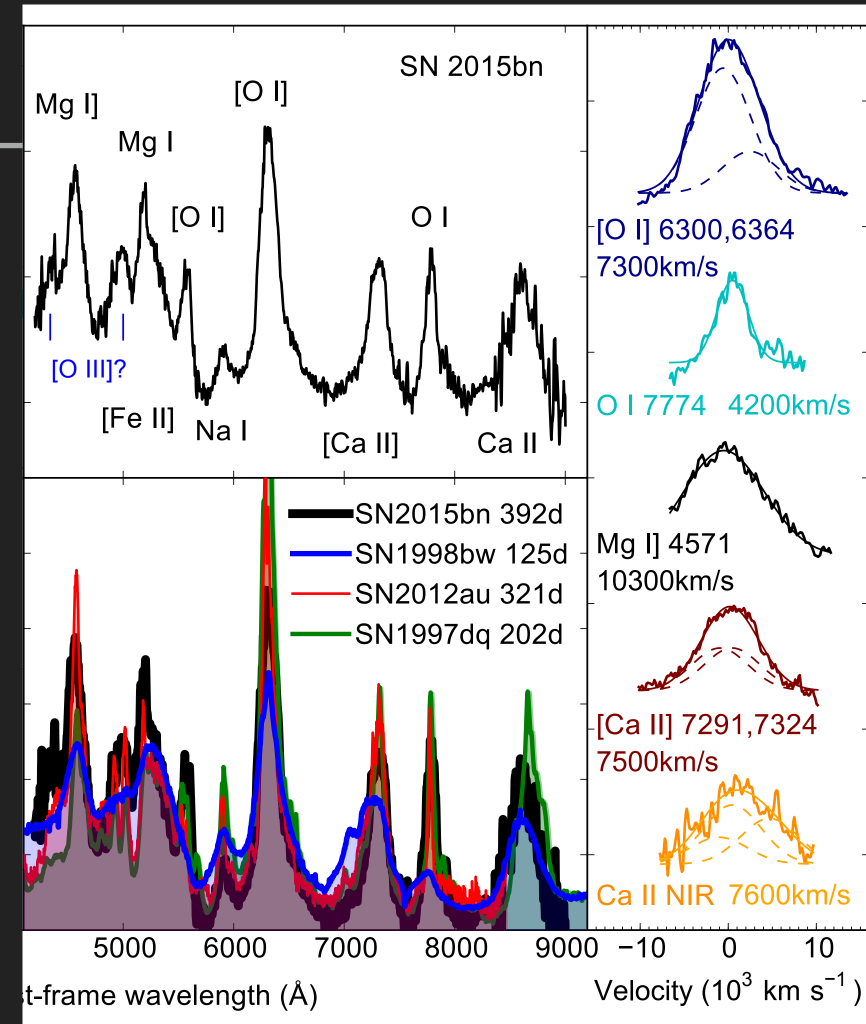


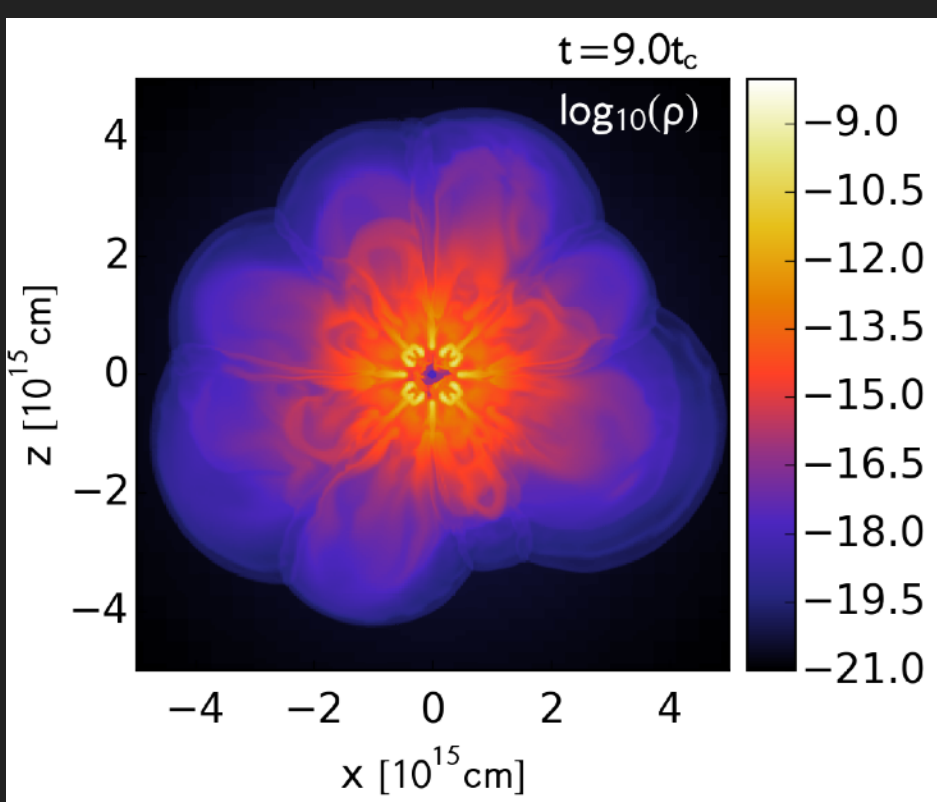


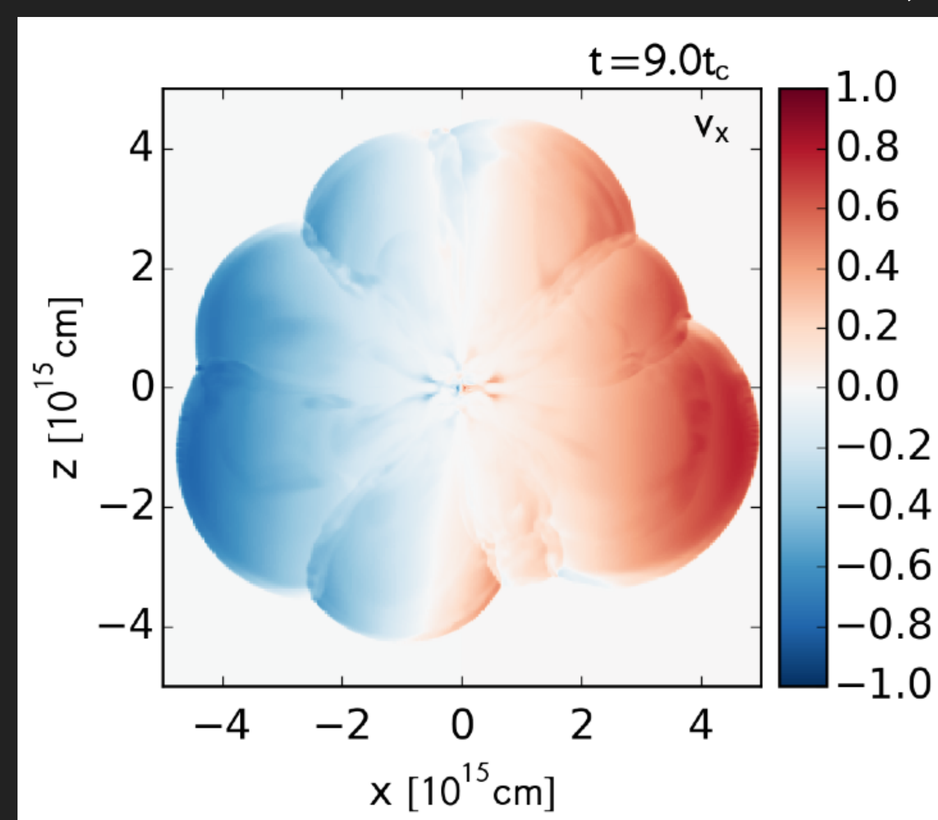
SLSN spectra in 3D

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



Nicholl+(2016)

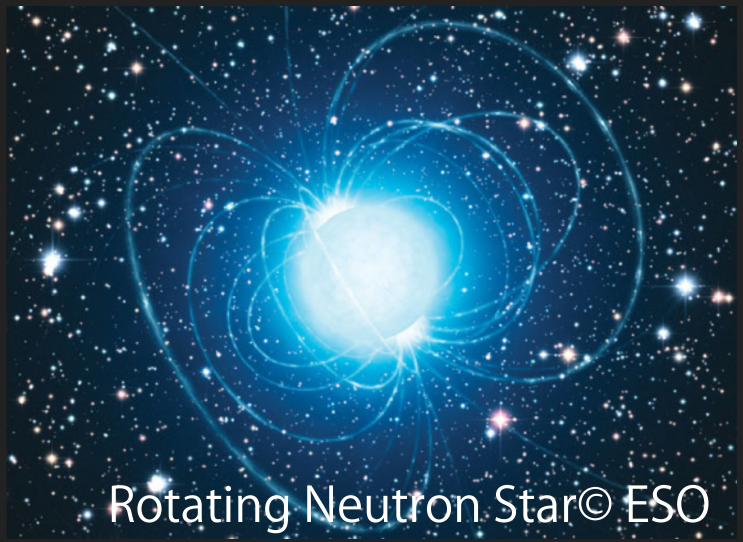


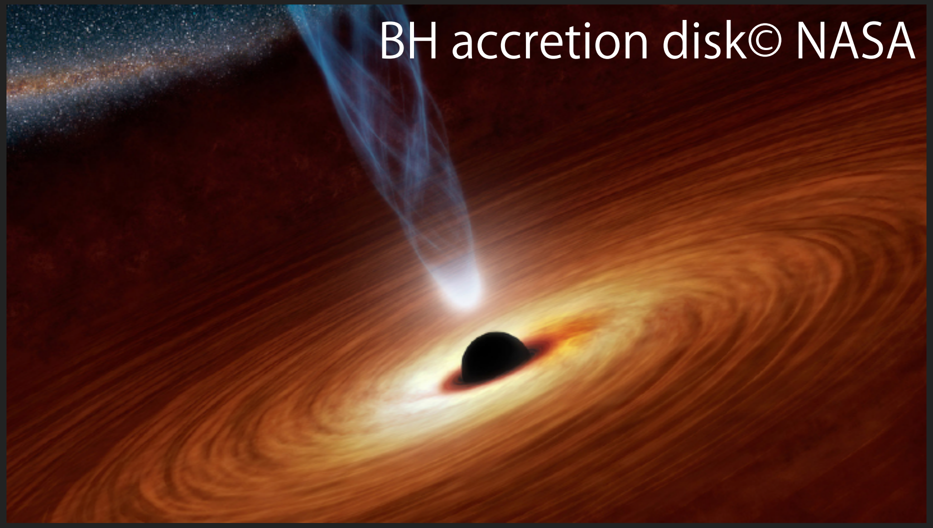


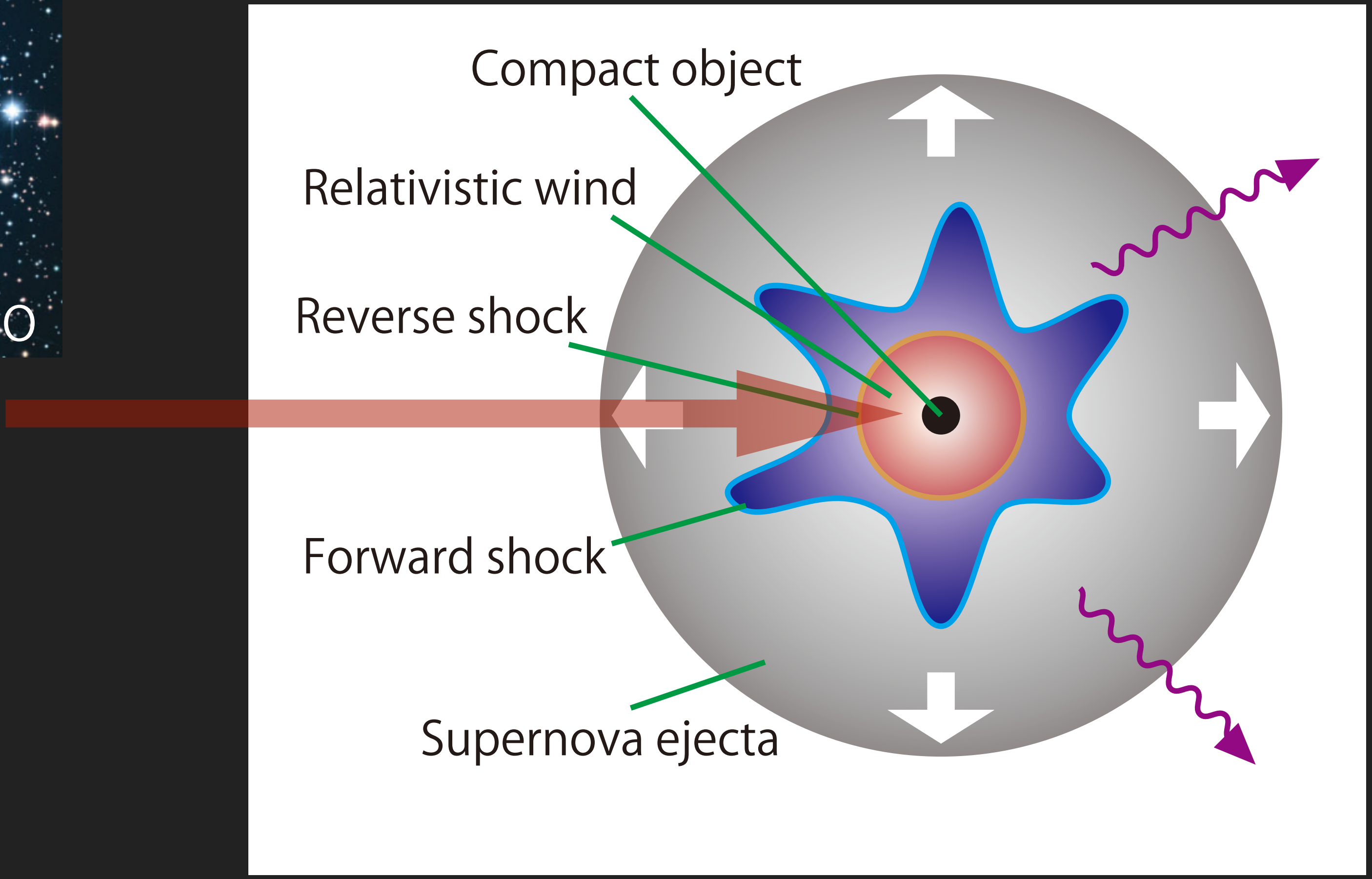
?

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)

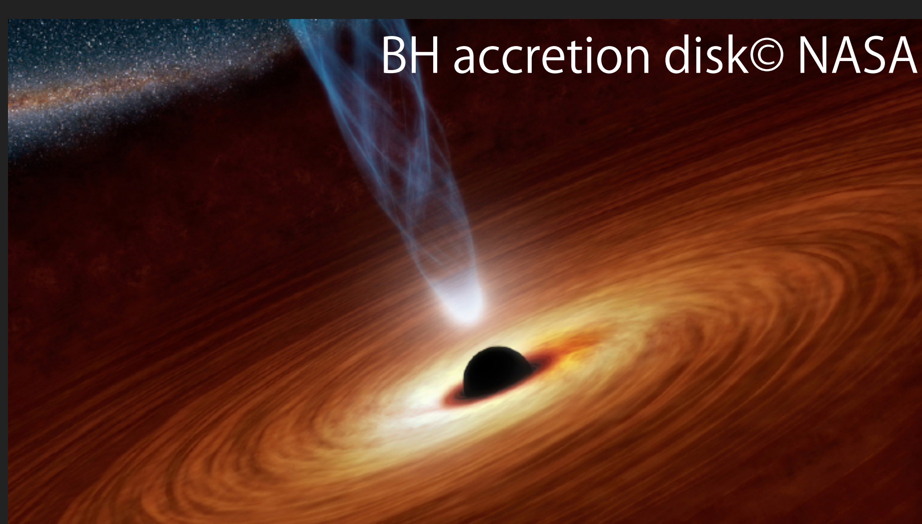


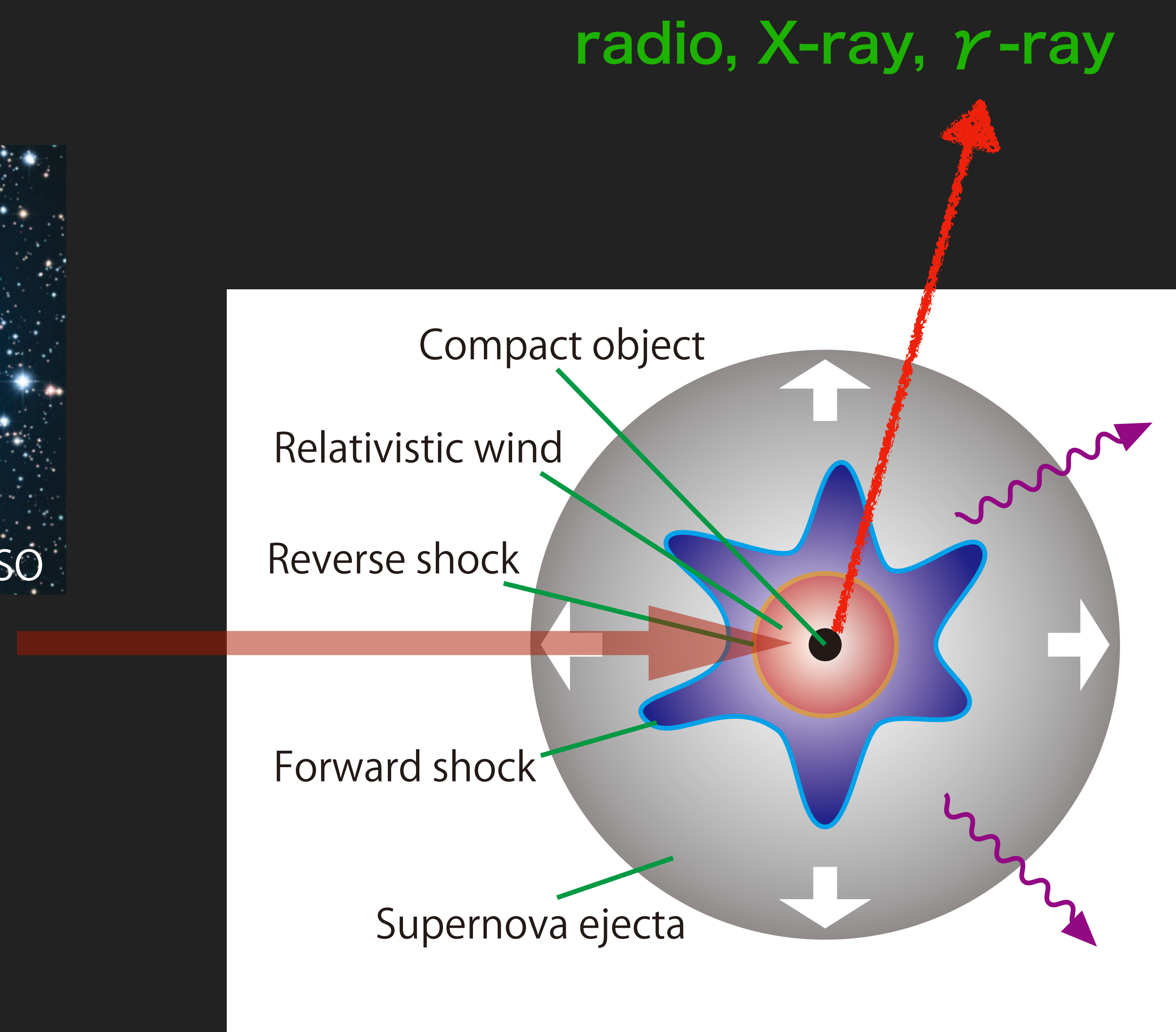




Pulsar wind nebula in SLSN ejecta

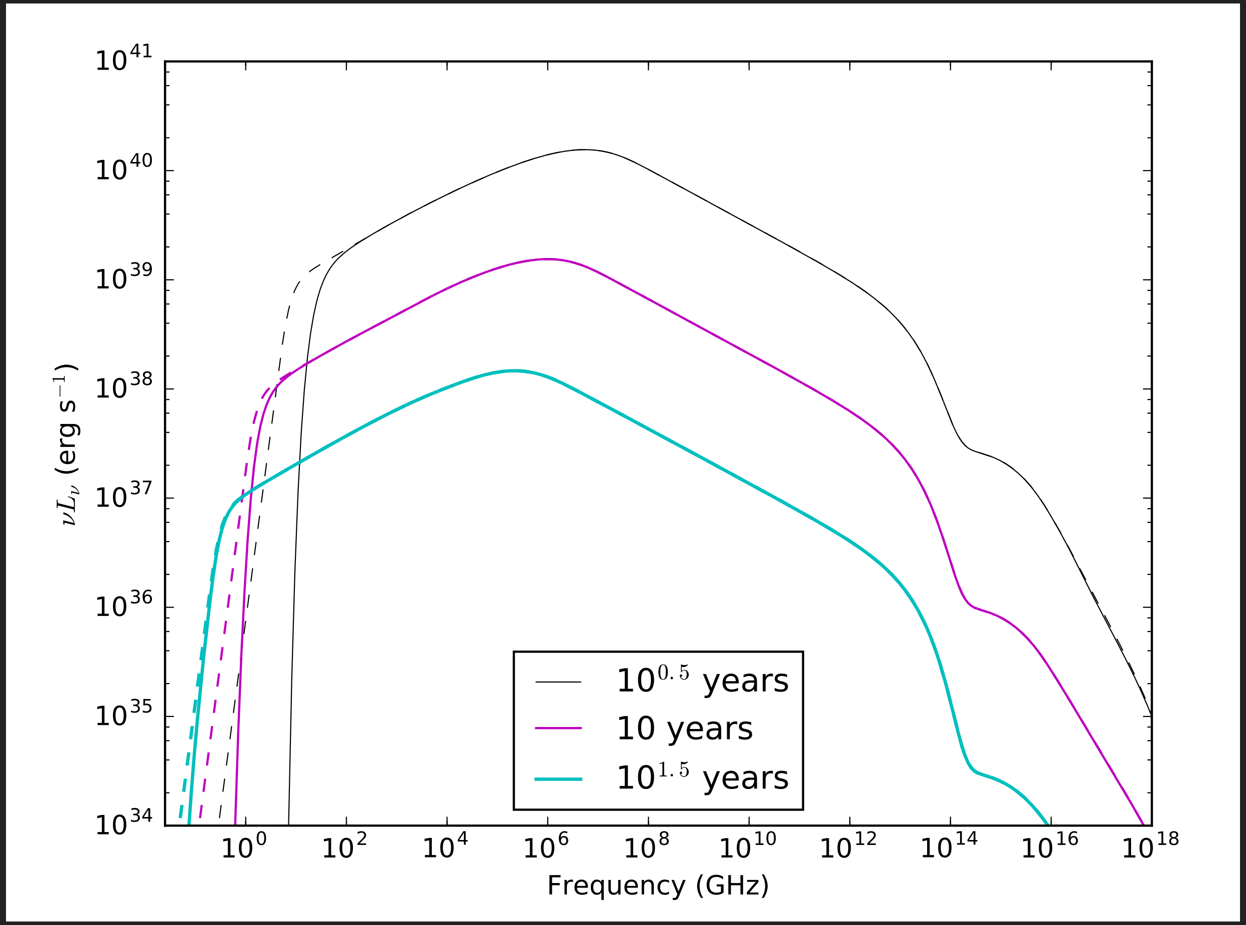
- If the putative rotating magnetized neutron star is enough powerful at later epochs :$L \sim (1+t/t_{sd})^{-2}$
- SLSNe could be bright sources in radio, X-ray, and γ-ray when SN ejecta becomes transparent

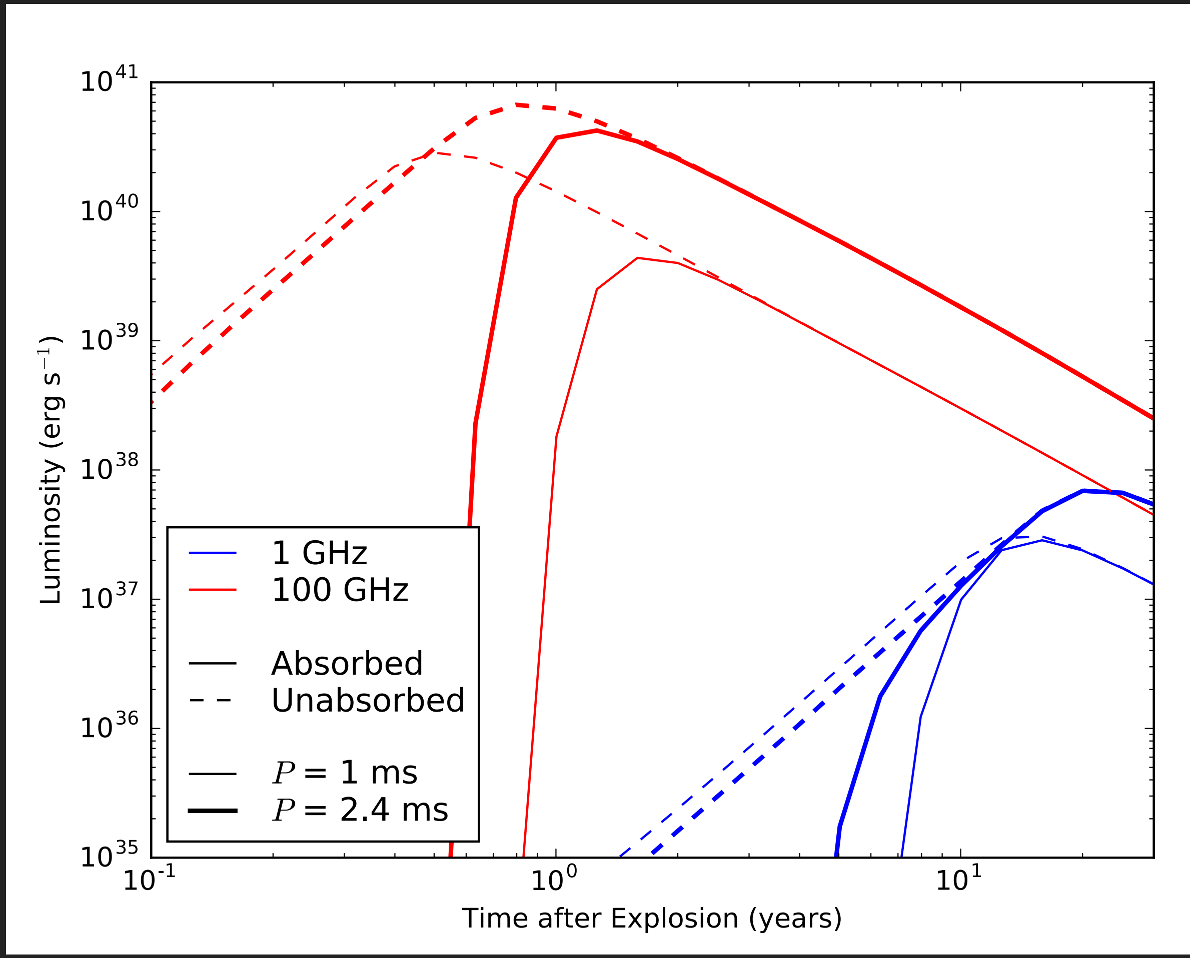




Pulsar wind nebula in SLSN ejecta

- Theoretical magnetar nebulae emission through SLSN ejecta (e.g., Murase+2015, Kashiyama+2016; see also Tanaka&Takahara 2010)
- late-time persistent radio emission (C. Omand+ 2017)
- bright X-ray emission? (ionization breakout; Metzger 201)

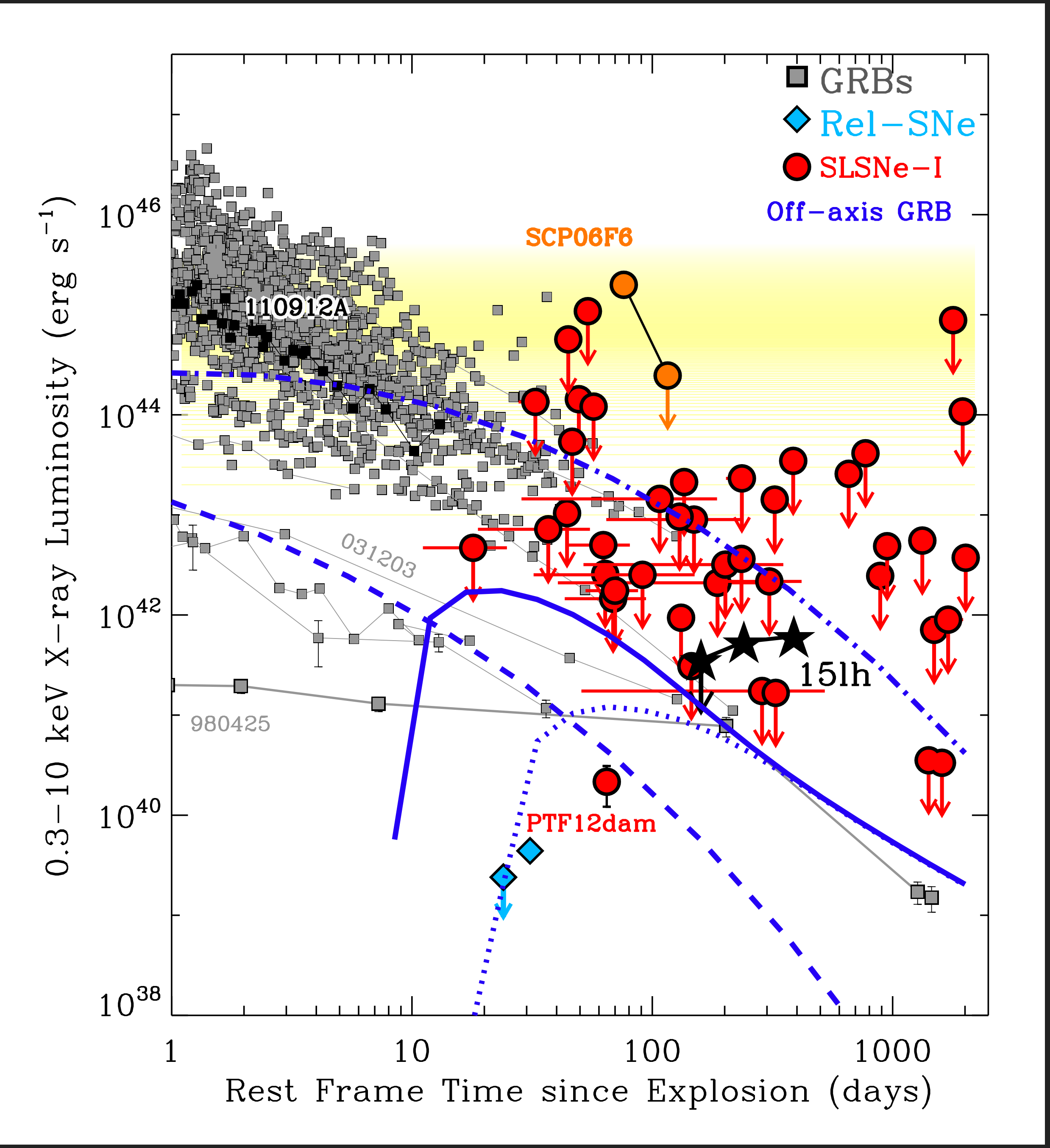




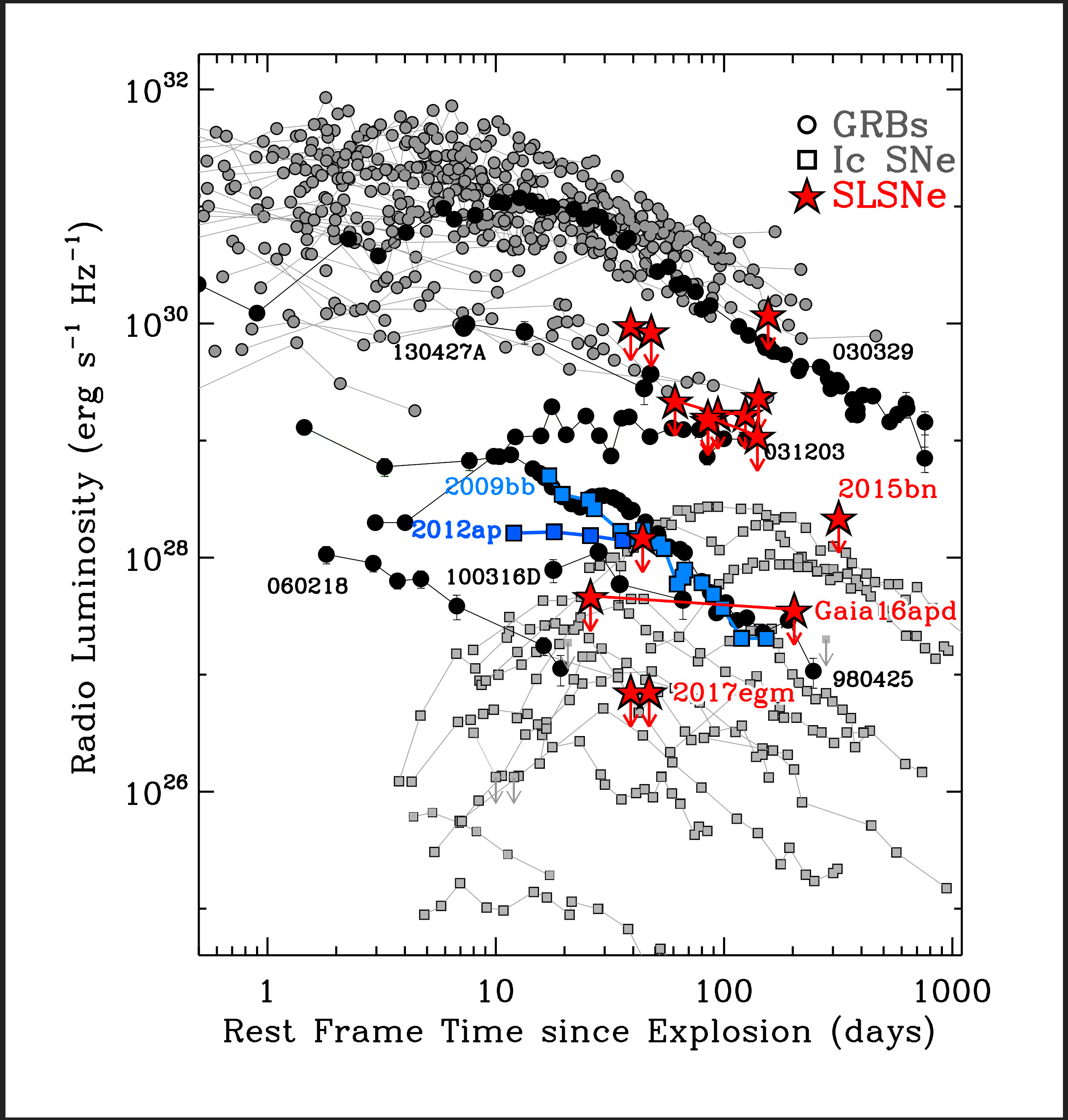
expected PWNe emission: Omand, Kashiyama, & Murase (2017)

No strong candidate

- Despite a lot of efforts, there has been no strong candidate source at SLSN site



X-ray constraint (Margutti+ 2018)



radio constraint (Coppejans+ 2018)

Until last month!

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

A RADIO SOURCE COINCIDENT WITH THE SUPERLUMINOUS SUPERNOVA PTF10hgi: EVIDENCE FOR A CENTRAL ENGINE AND AN ANALOGUE OF THE REPEATING FRB121102?

T. EFTEKHARI[1], E. BERGER[1], B. MARGALIT[2*], P. K. BLANCHARD[1], L. PATTON[1], P. DEMOREST[3], P. K. G. WILLIAMS[1], S. CHATTERJEE[4], J. M. CORDES[4], R. LUNNAN[5], B. D. METZGER[6], AND M. NICHOLL[7,8]

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[4]Cornell Center for Astrophysics and Planetary Science and Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
[5]The Oskar Klein Centre & Department of Astronomy, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden
[6]Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[7]Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
[8]Birmingham Institute for Gravitational Wave Astronomy and School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK

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+(arXiv: 1901.10479)

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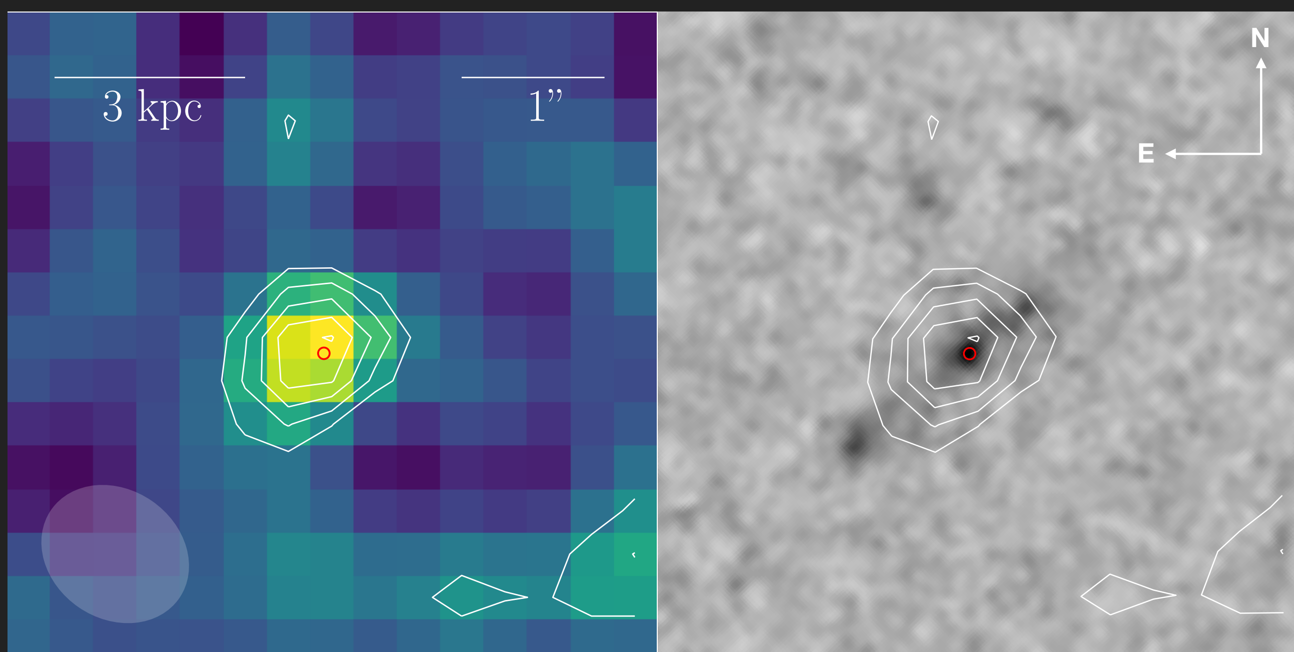

NCE FOR A CENTRAL

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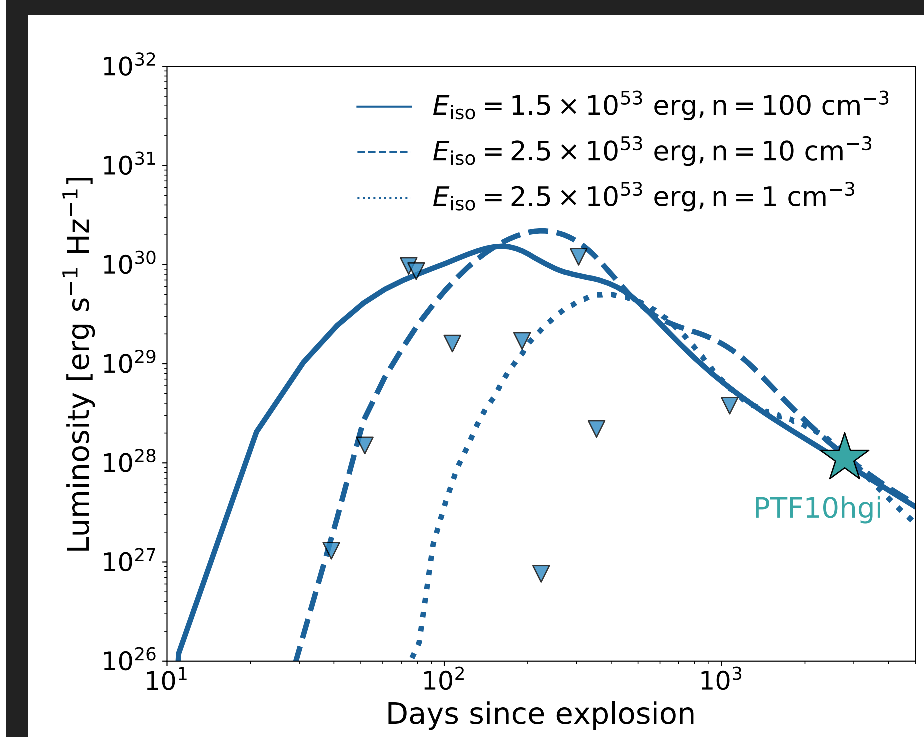

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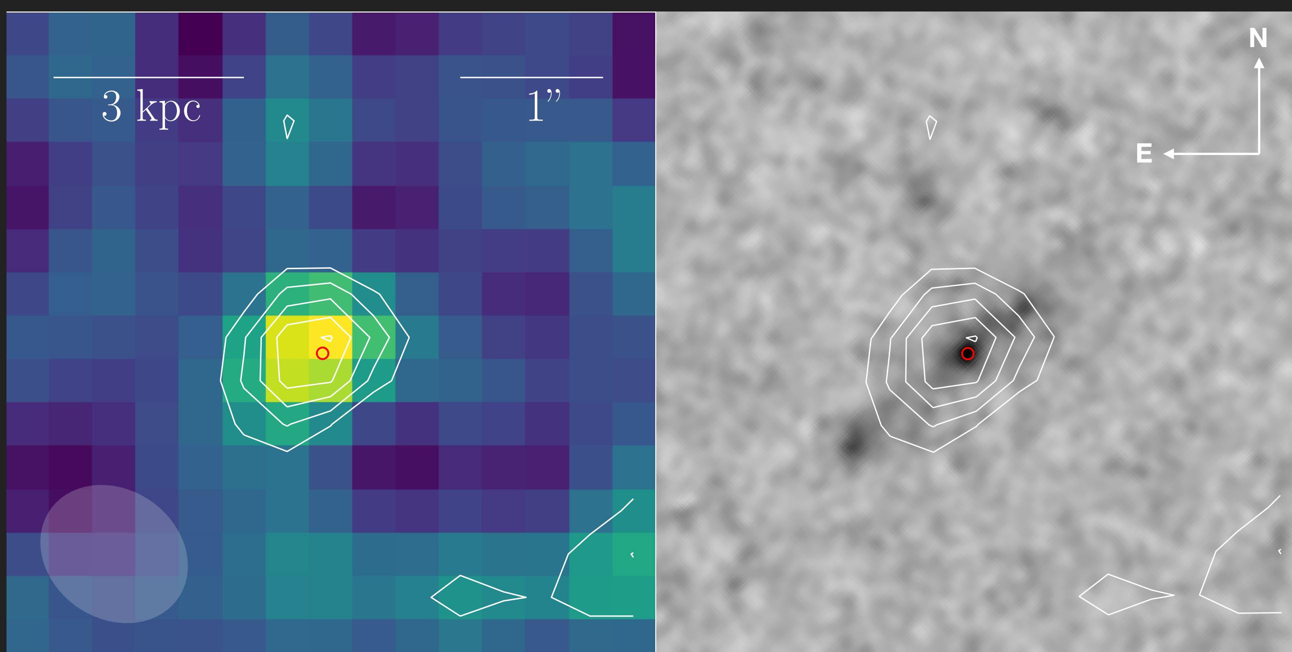

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stay tuned!

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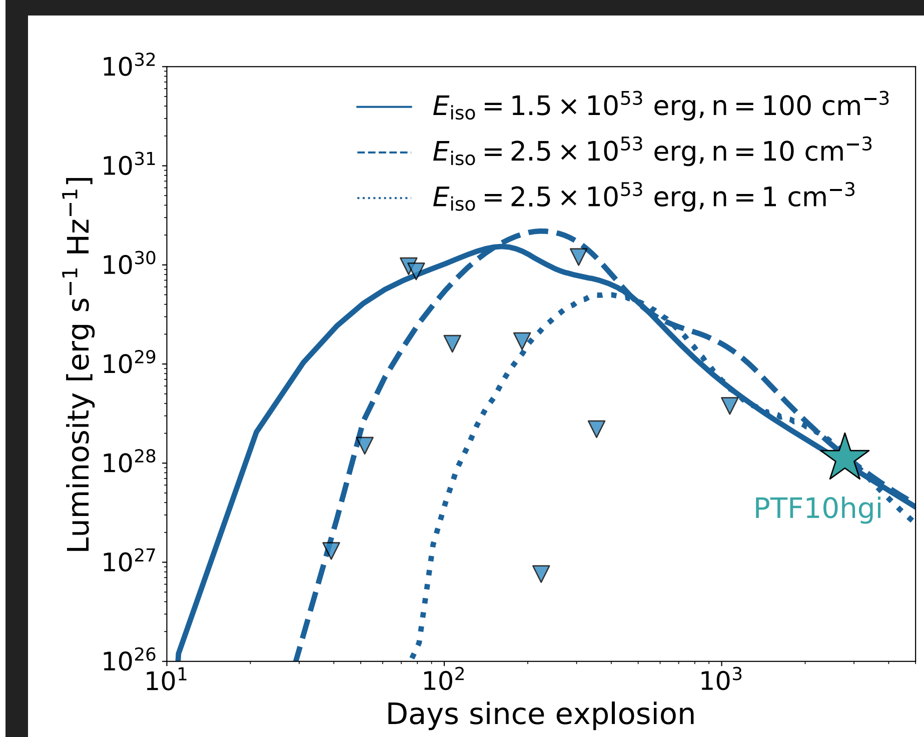
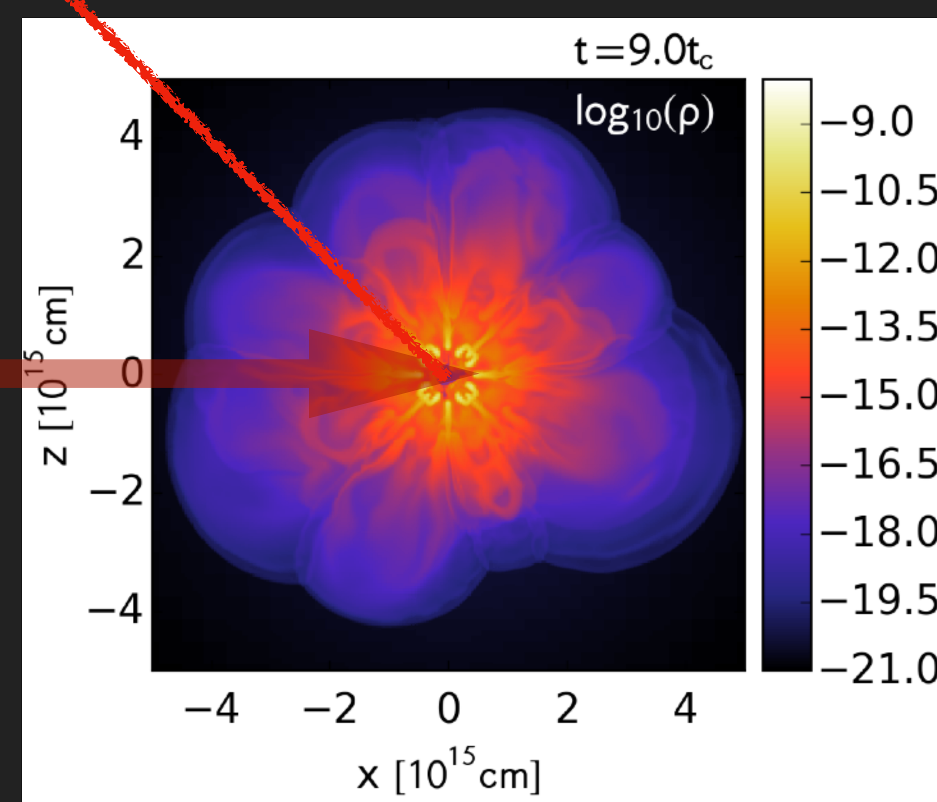


Eftekhari+(arXiv: 1901.10479)

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?

FRB?

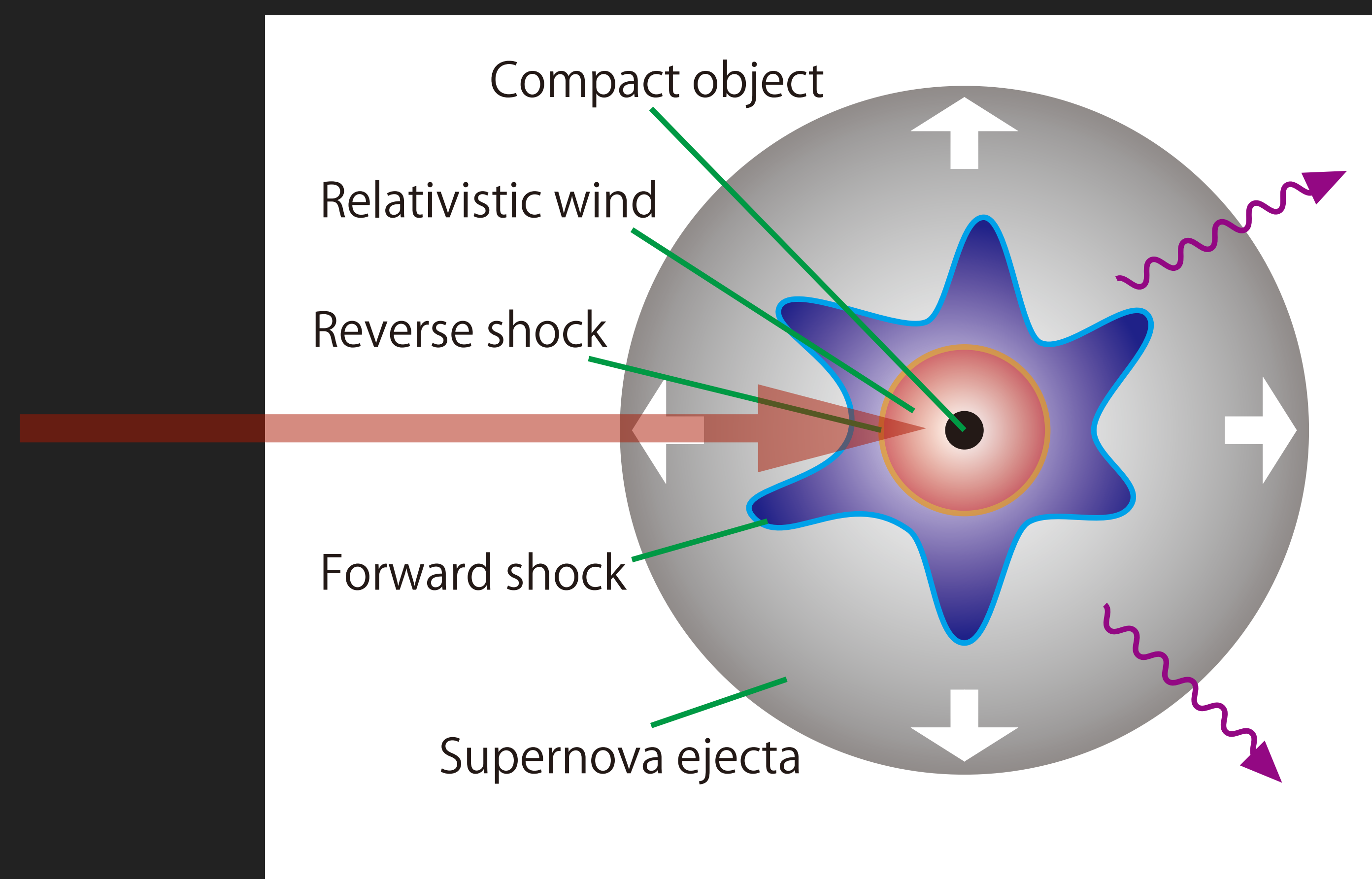


Talk outline

- ordinary and extra-ordinary supernovae
- GRB-SNe and SLSNe: observational properties
- (magnetized) NS as an engine
- summary

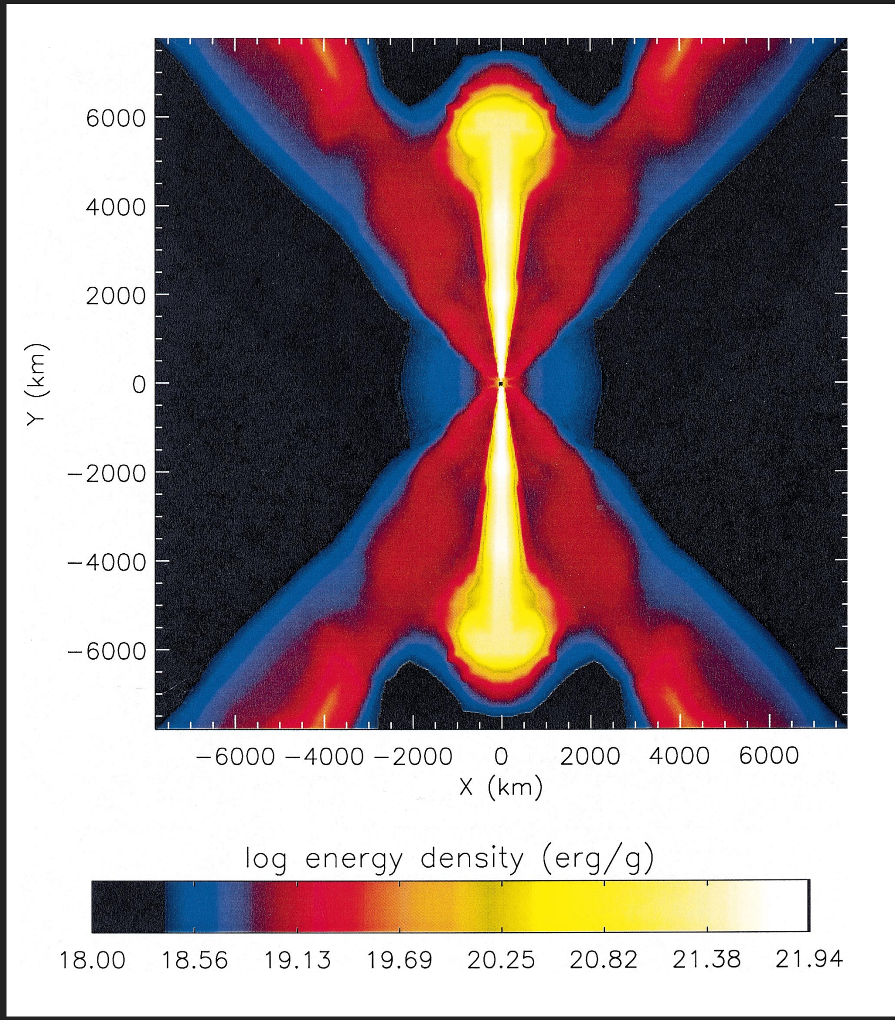
Extreme supernovae and neutron star as an engine

- 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?



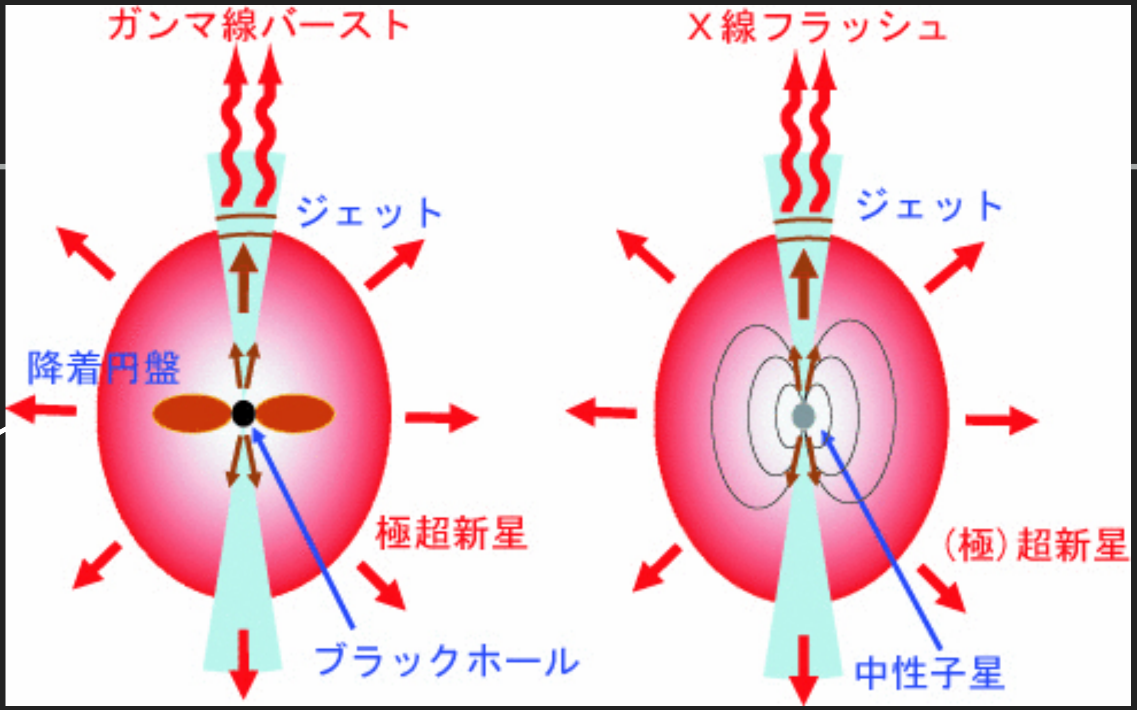
NS stars as GRB engine?

- 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?



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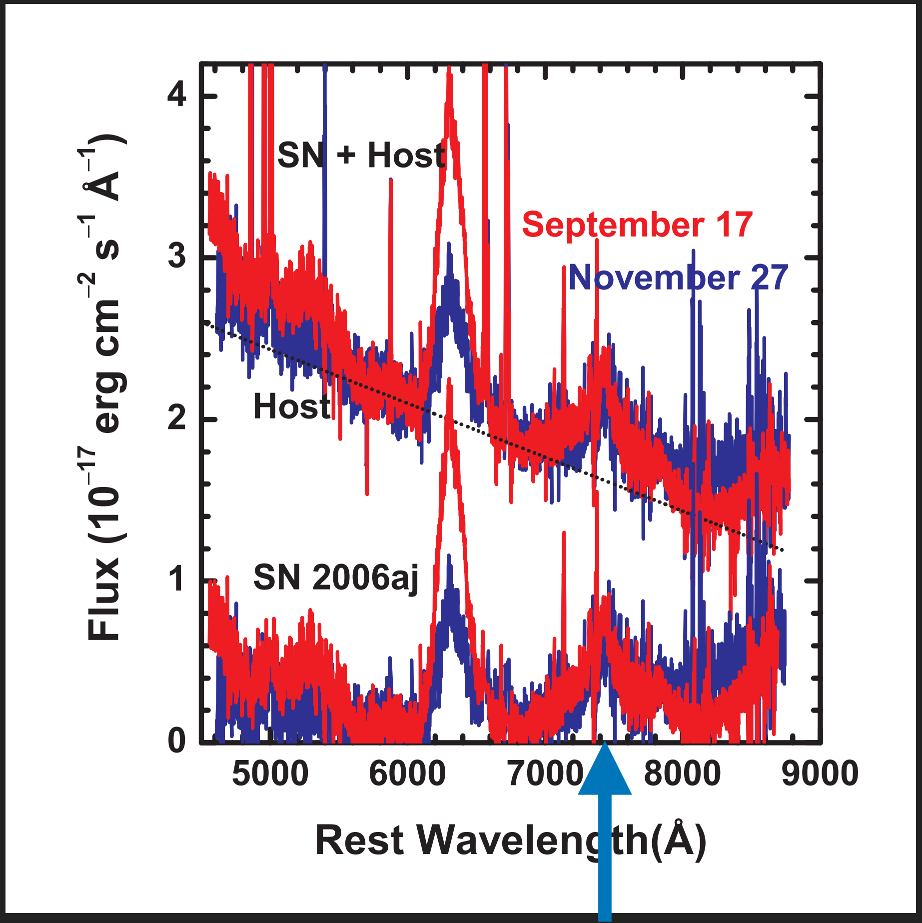
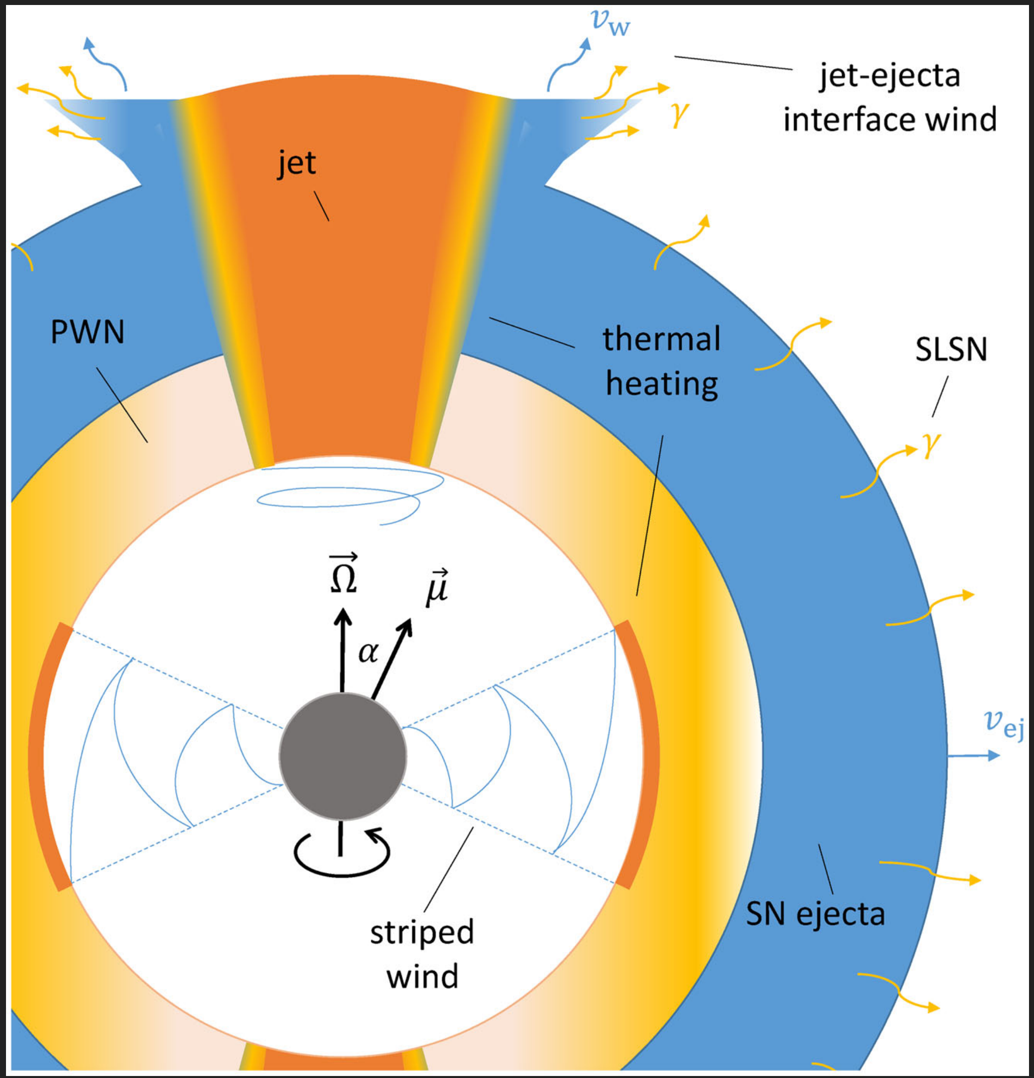
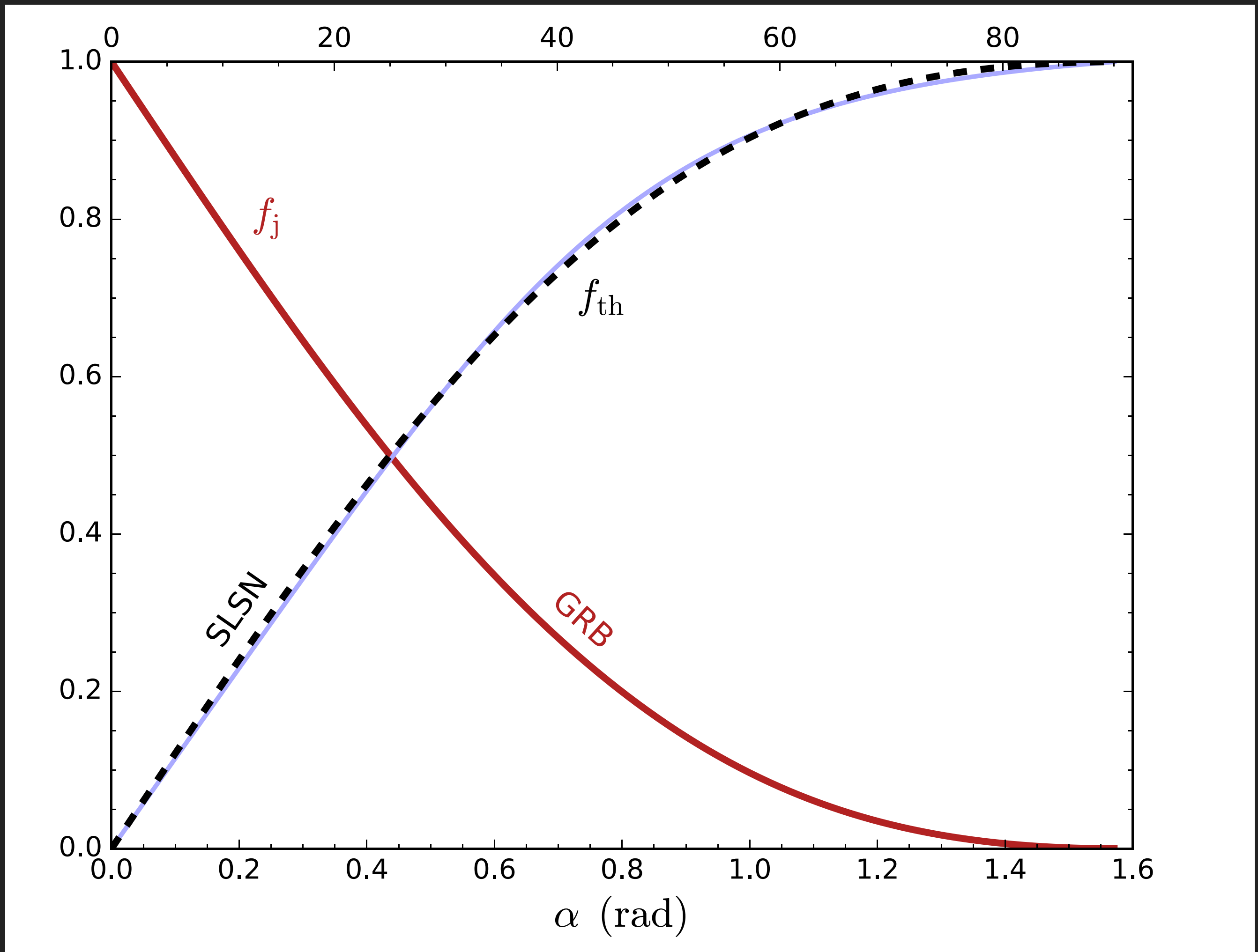


^{58}Ni emission line in SN 2006aj?
(Maeda+ 2007)

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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Relativistic SNe (without GRB)

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