Hydrodynamical models for a successfull/failed jet from a massive star and implications to low-luminosity GRBs

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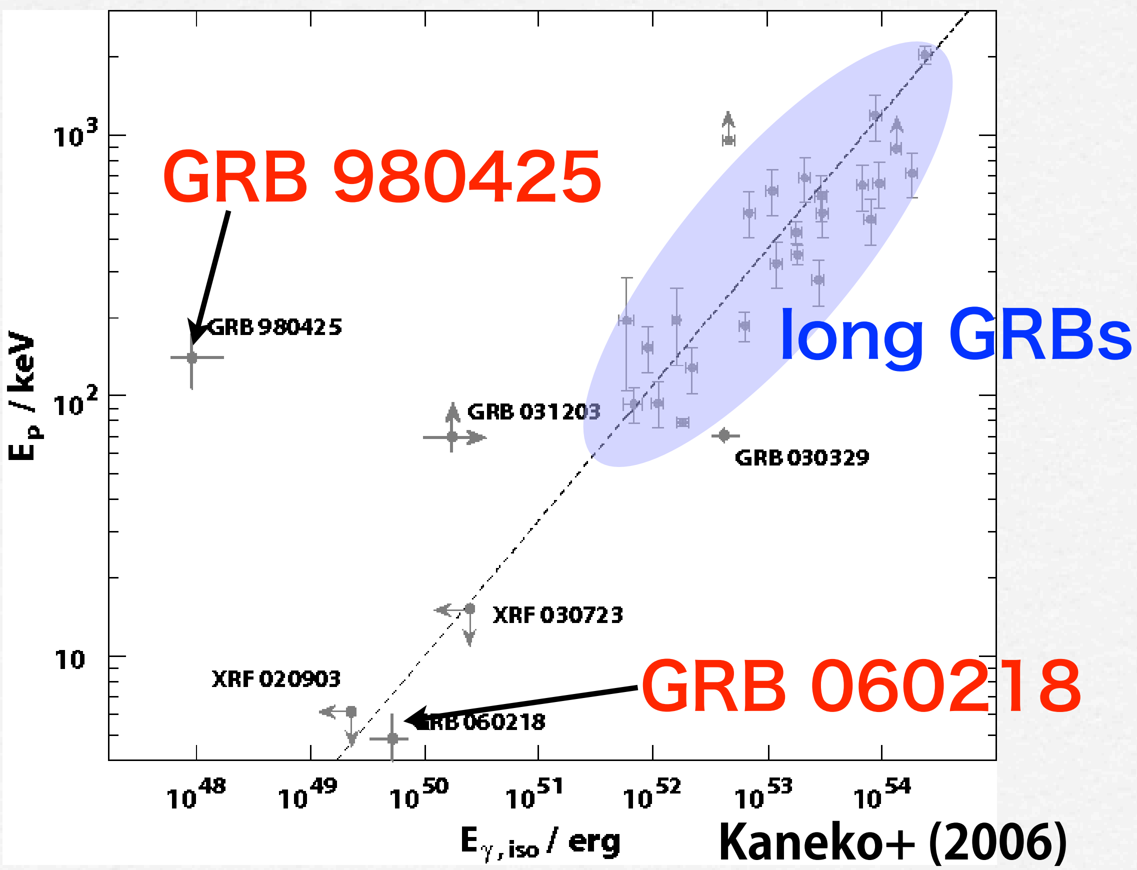
Outline

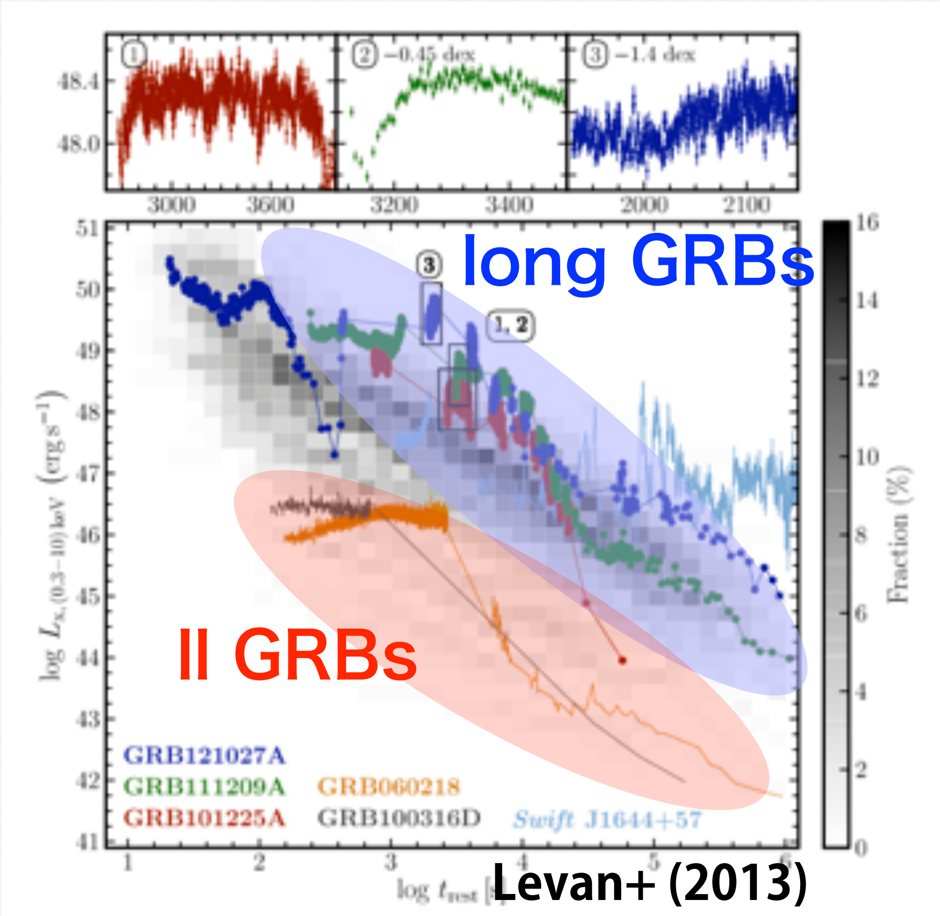
- ☑ Brief introduction of low-luminosity GRBs
- ☑ Jet models
- ☑ Implications to emission from low-luminosity GRBs
- ☑ Summary

Low-luminosity GRBs

- less energetic and less luminous subgroup of long GRBs
- They are found in the nearby universe. The event rate is high
  e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006), 100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)
- They are accompanied by broad-lined Ic supernovae
- Ex.) GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB100316D/ SN2010bh



Kaneko+ (2006)



Levan+ (2013)

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	Luminosity $L_{\gamma,iso}$	Isotropic energy E_{iso}	Duration T_{90}	peak energy E_p
GRB 980425 SN 1998bw	6×10^{46} erg/s	9×10^{47} erg	35 s	122 keV
GRB 060218 SN 2006aj	2×10^{46} erg/s	4×10^{49} erg	2100 s	4.7 keV
GRB 100316D SN 2010bh	5×10^{46} erg/s	6×10^{49} erg	1300 s	18 keV

from Hjorth (2011)

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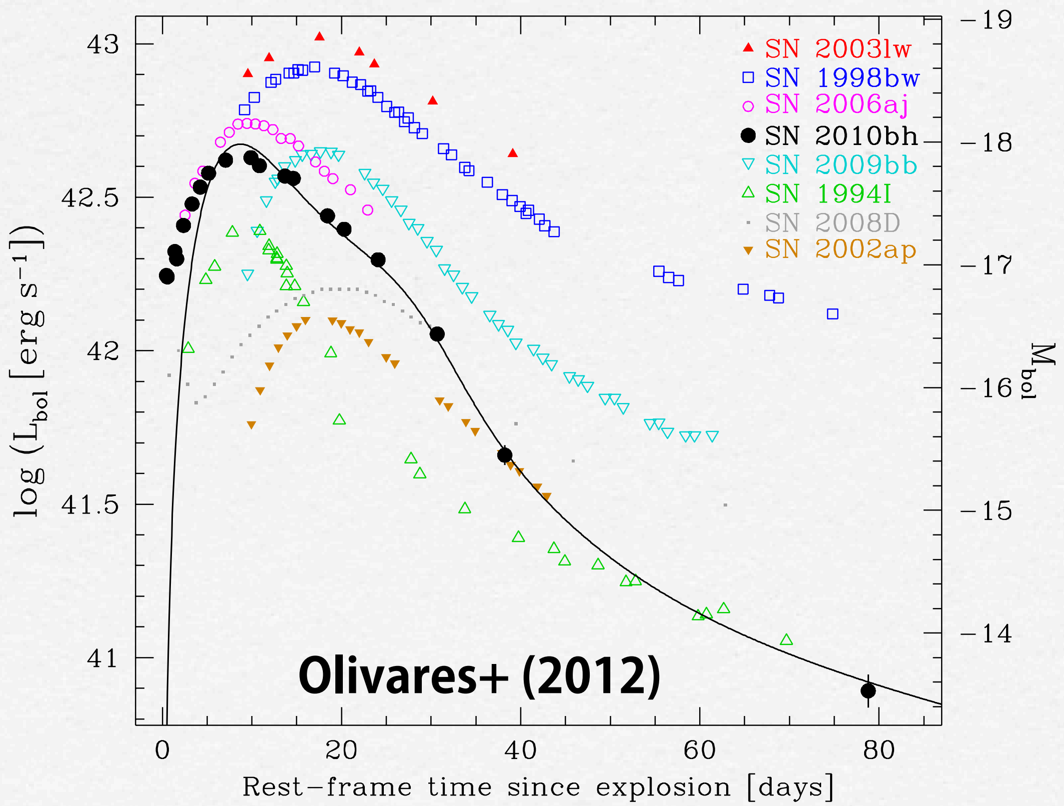
Question to answer: **What is their origin?**
What mechanism is responsible for X- and γ- ray emission

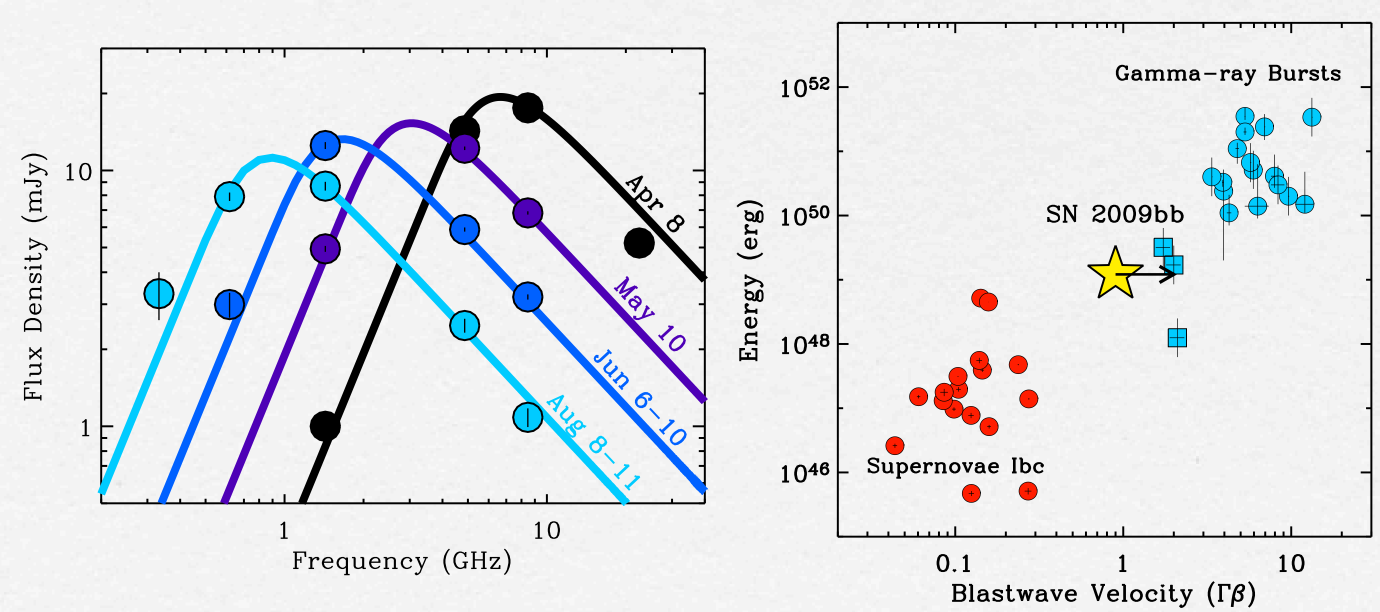
Connection to HNe, engine-driven SNe

- ☑ Optical observations: kinetic energy of non-relativistic ejecta is found by light curve modeling and spectroscopy : $v_{ph} \sim 0.1c$, $E_{kin} \sim 10^{52}$-10^{53} erg

- ☑ Radio observations: kinetic energy of the blast wave is found by using synchrotron emission model : $\Gamma v = (1\text{-}2)\ c$, $E_{kin} \sim 10^{49}$ erg



Soderberg+ (2010)



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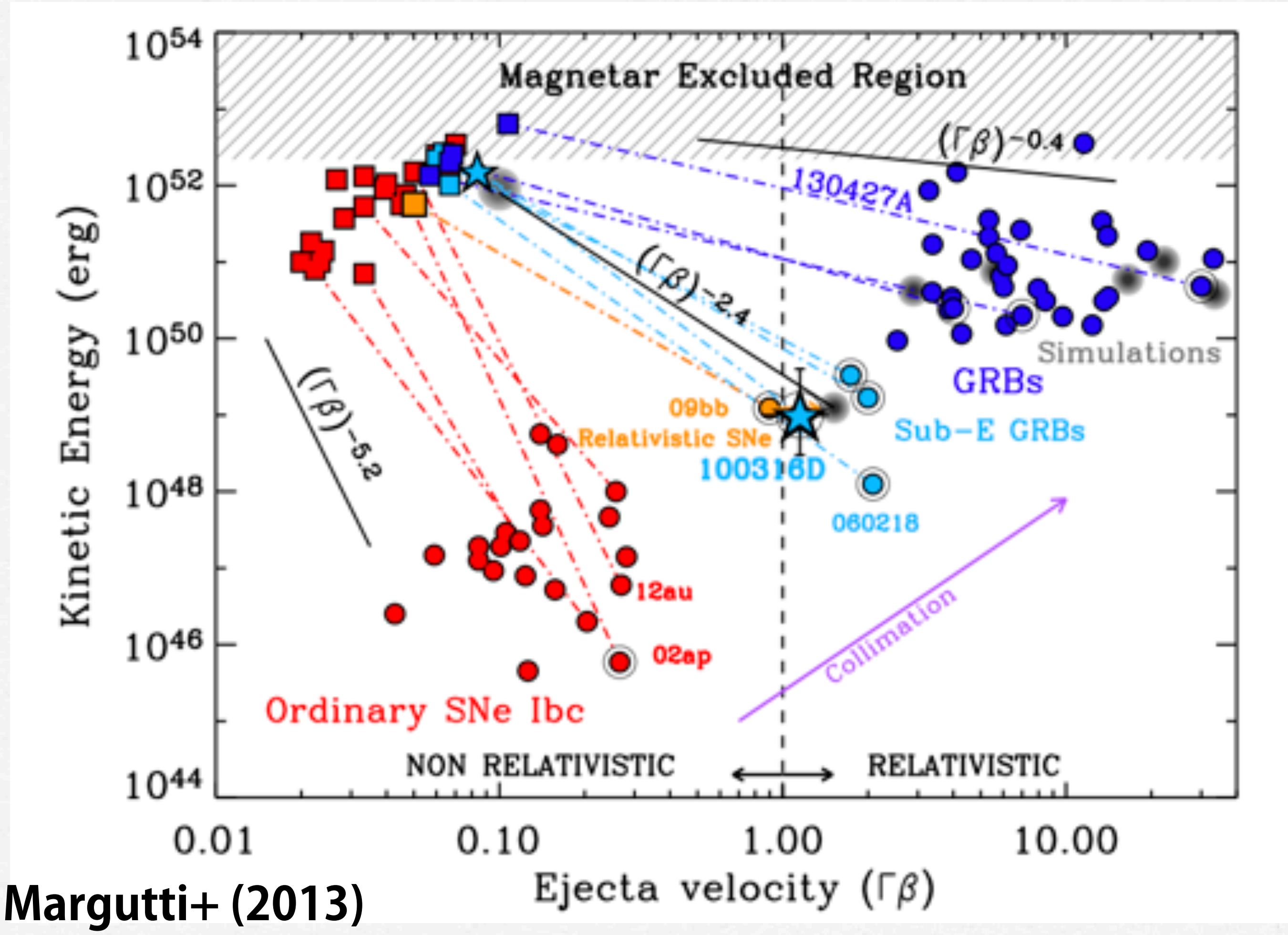
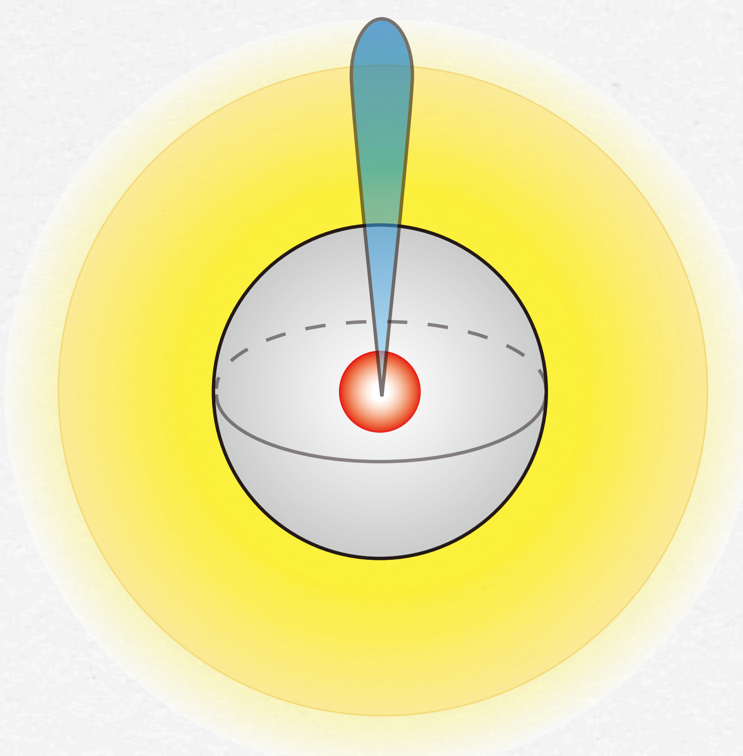


Margutti+ (2013)

Failed jet hypothesis

- ☑ E_{kin} for relativistic ejecta << E_{kin} for non-relativistic ejecta ➡ It is suggested that failed jet model produce such events.

Ultra-relativistic jet:
E_{kin} for rel. ejecta ~ E_{kin} for non-rel. ejecta



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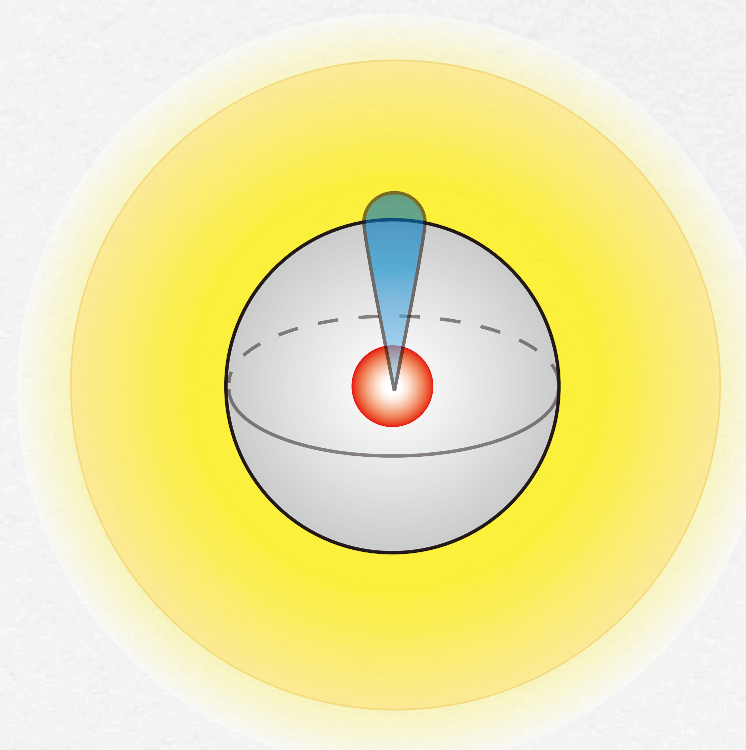

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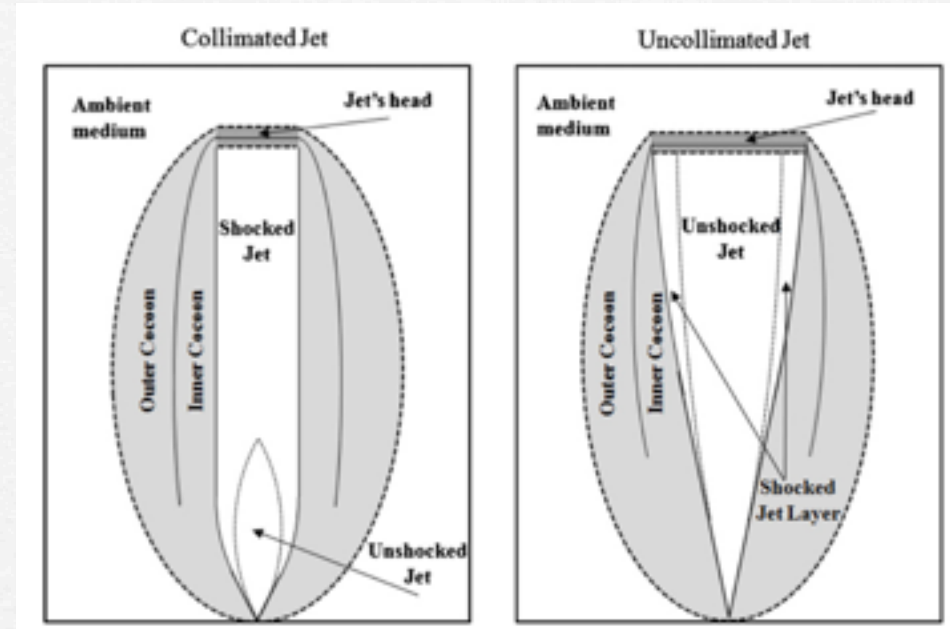
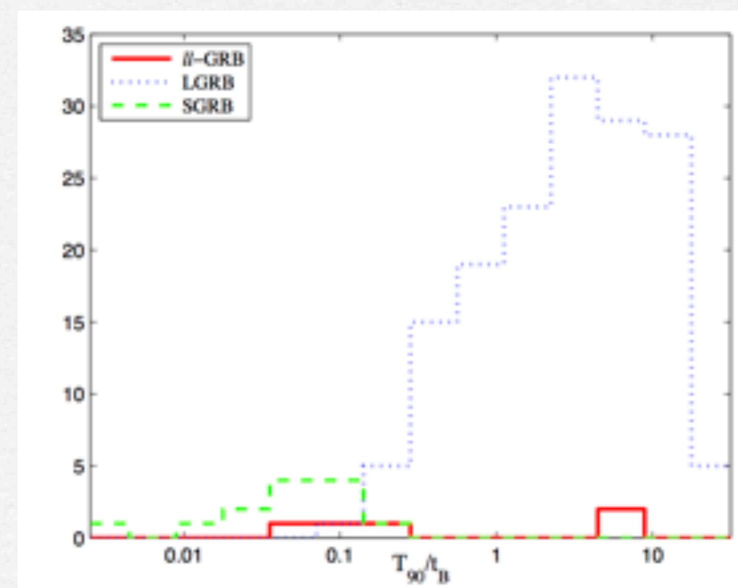
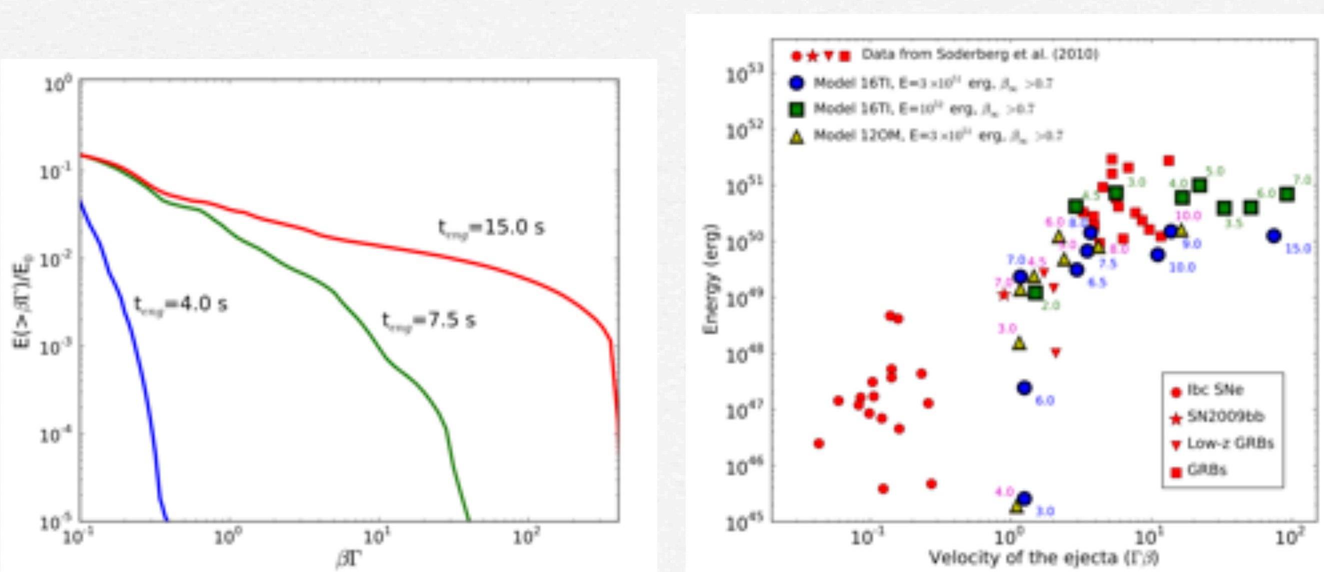
- ☑ E_{kin} for relativistic ejecta << E_{kin} for non-relativistic ejecta ➡ It is suggested that failed jet model produce such events.

- ☑ Many works to reveal whether or not an ultra-relativistic jet succeed in penetrating a massive star (e.g., Bromberg+2011a,b, Lazzati +2011)



Bromberg+ (2011a,b)





Lazzati+ (2011)

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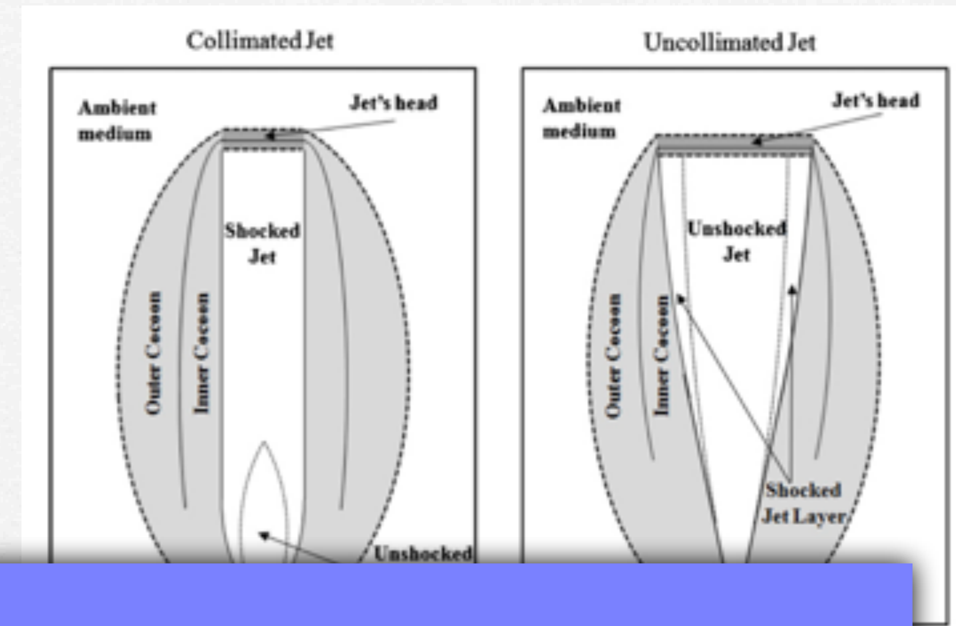

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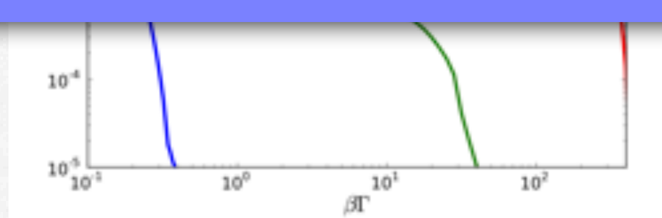
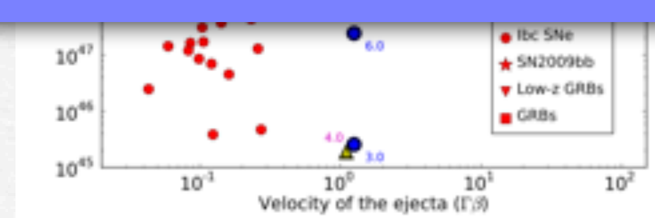
This study

1. carry out a series simulations of jet propagation in a massive star and identify a model corresponding to low-luminosity GRBs.

2. carry out further calculations to reveal the properties of the model, including nucleosynthesis calculations and CSM interaction.





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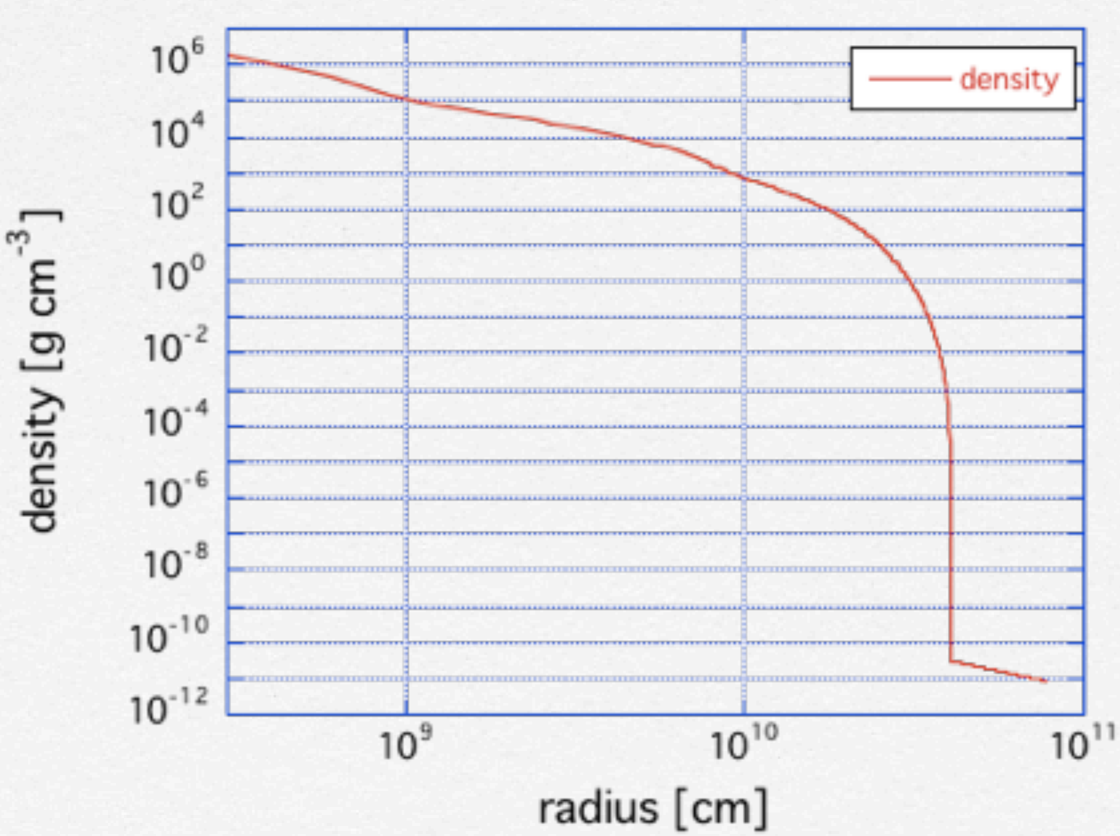
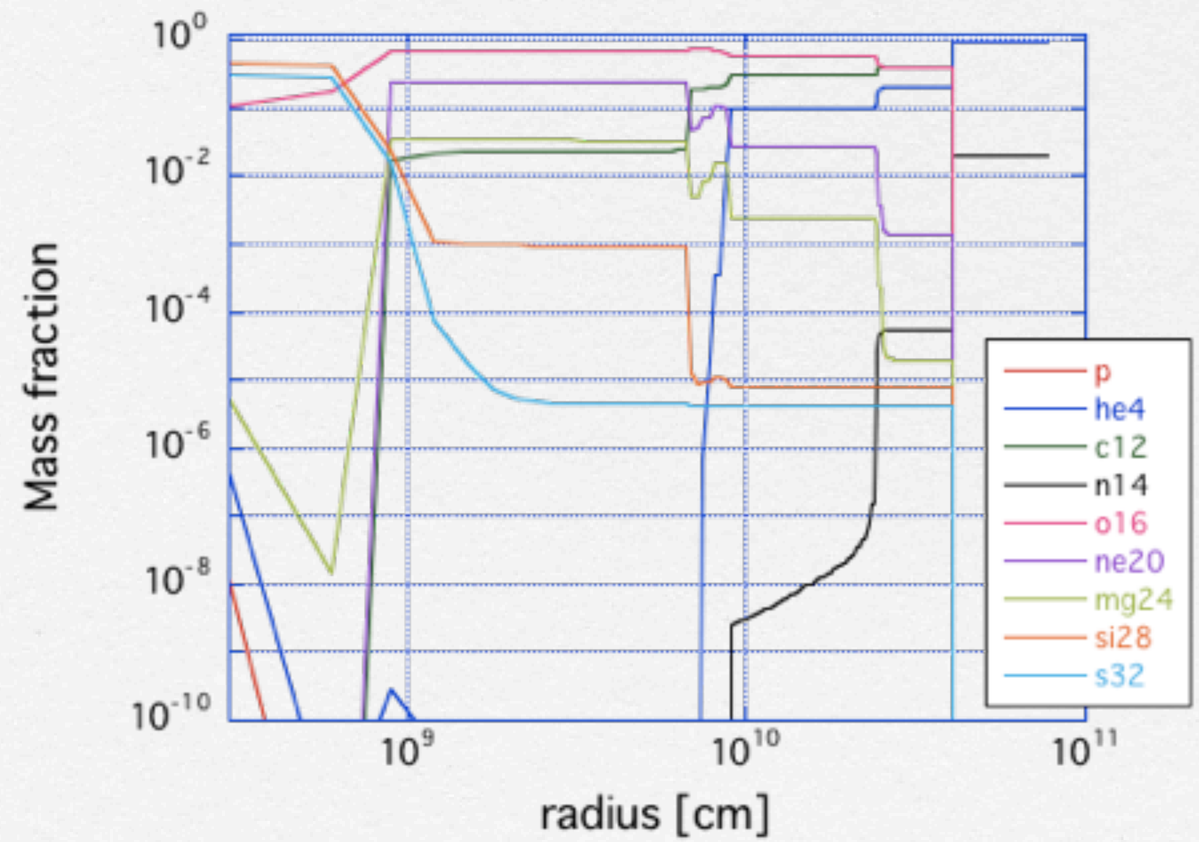
GRB jet simulation

- 4096×512 mesh
- Woosley&Heger(2006) 16TI model
- WR star
- final mass~14M⊙
- Radius ~ 3×10^{10}cm

$$\rho_{\rm ext} = \rho_{\rm w}(r) + \rho_{\rm ISM}$$
$$\rho_{\rm w} = \frac{\dot{M}}{4\pi r^2 v_{\rm w}}$$
$$\rho_{\rm ISM} = 100 m_{\rm u}\ {\rm g\ cm^{-3}}$$





Jet injection

- injection radius: $R_{in} = 3 \times 10^{8}$cm
- total energy: $E = 5 \times 10^{52}$ erg
- energy deposition rate: dE/dt=200, 100, 50, 20, 10, 5, 2, 0.5 $\times 10^{51}$ erg/s
- half opening angle: $\theta_j = 10°$
- initial jet Lorentz factor: $\Gamma_j = 5$
- specific internal energy: $\varepsilon_0/c^2 = 20$
- CSM: Mdot=10^{-7} $M_\odot$/yr, v_w=1000km/s

$$v_{\mathrm{j}} = \sqrt{1 - \frac{1}{\Gamma_{\mathrm{j}}^2}},$$

$$\rho_0 = \frac{\dot{E}}{2\pi R_{\mathrm{in}}^2 (1 - \cos\theta_{\mathrm{j}})} \frac{1}{v_{\mathrm{j}}[(1 + \gamma\epsilon_0)\Gamma_{\mathrm{j}}^2 - \Gamma_{\mathrm{j}}]},$$

$$p_0 = (\gamma - 1)\rho_0\epsilon_0.$$

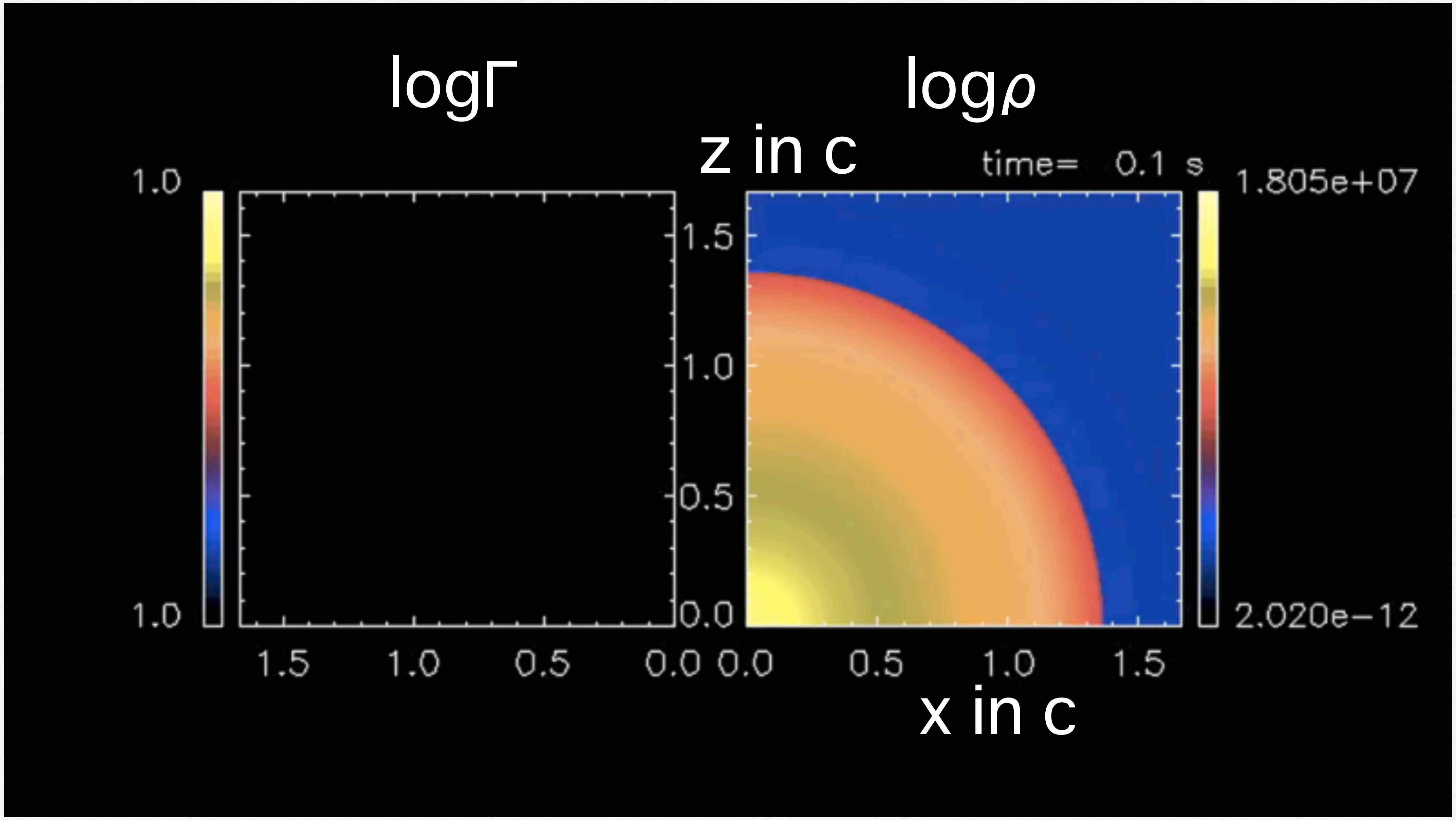
Jet models

- ultra-relativistic jet is formed successfully (jet break time < jet injection time)

low dE/dt (=0.5×10^{51}erg/s)

- left: Lorentz factor right: density

long t_{inj} (=50s)



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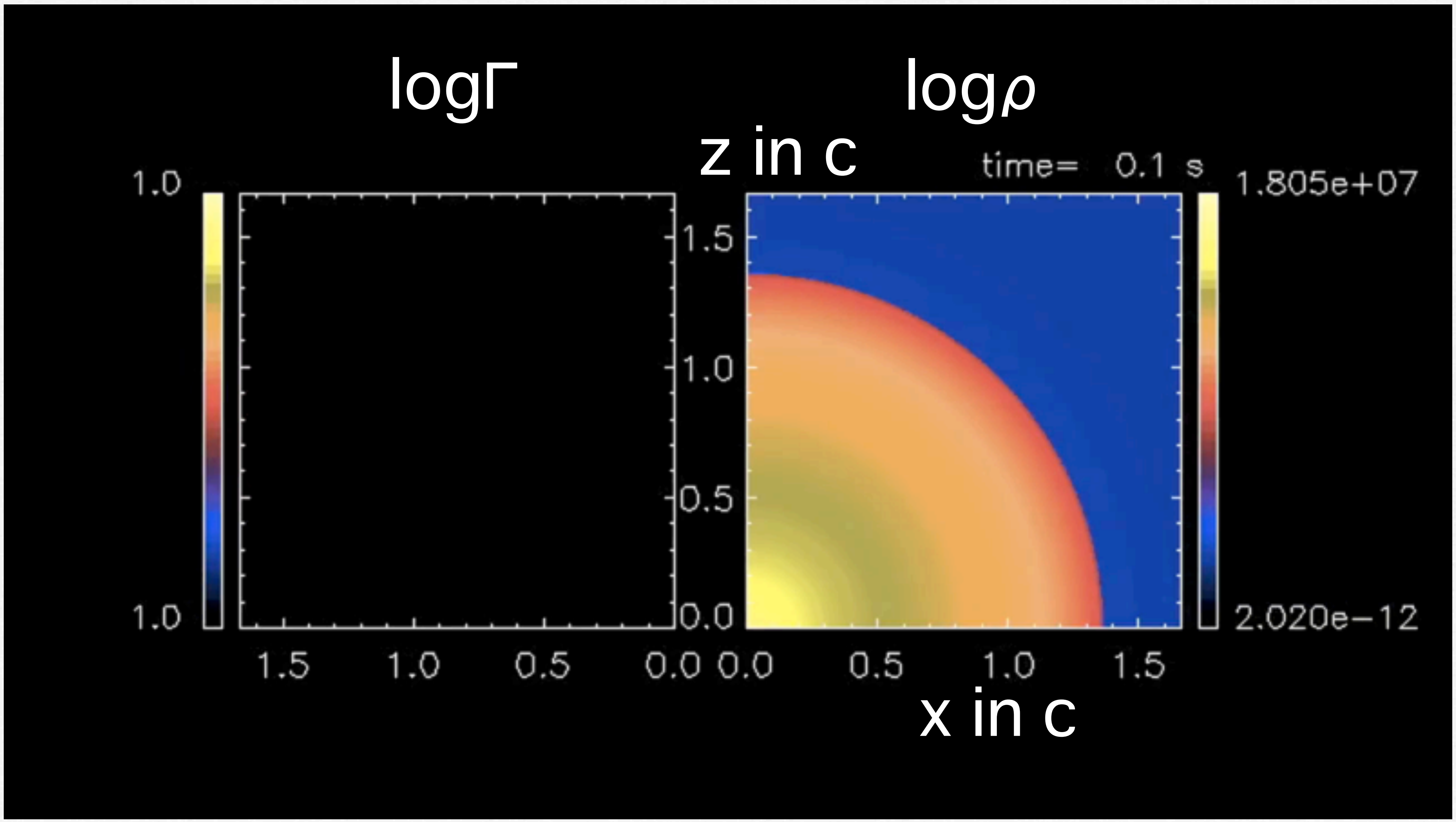


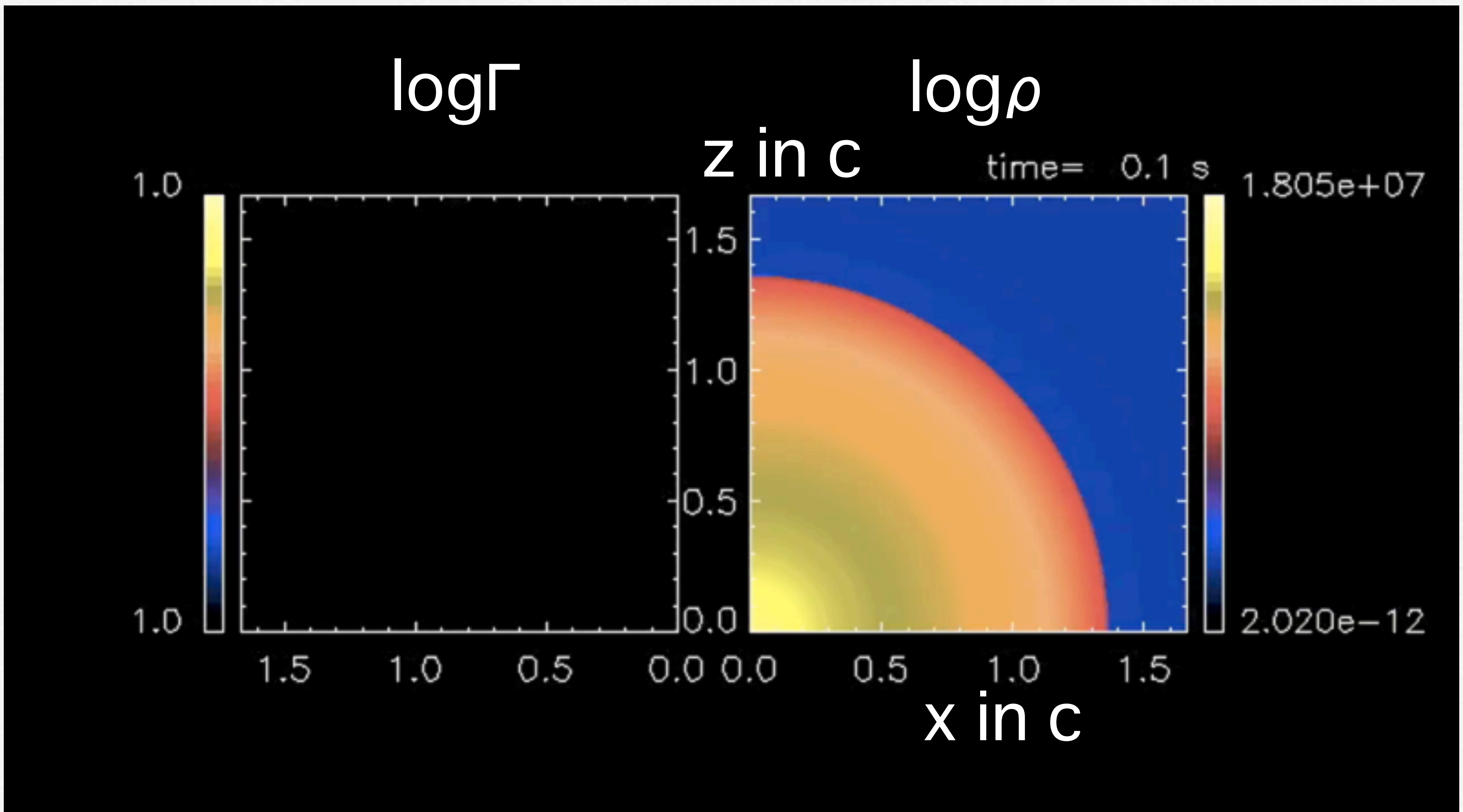
Jet models

- ☑ ultra-relativistic jet is not formed (jet break time > jet injection time)

  high dE/dt ($=50\times10^{51}$erg/s)

- ☑ left: Lorentz factor right: density

  short t_{inj} (=0.5s)



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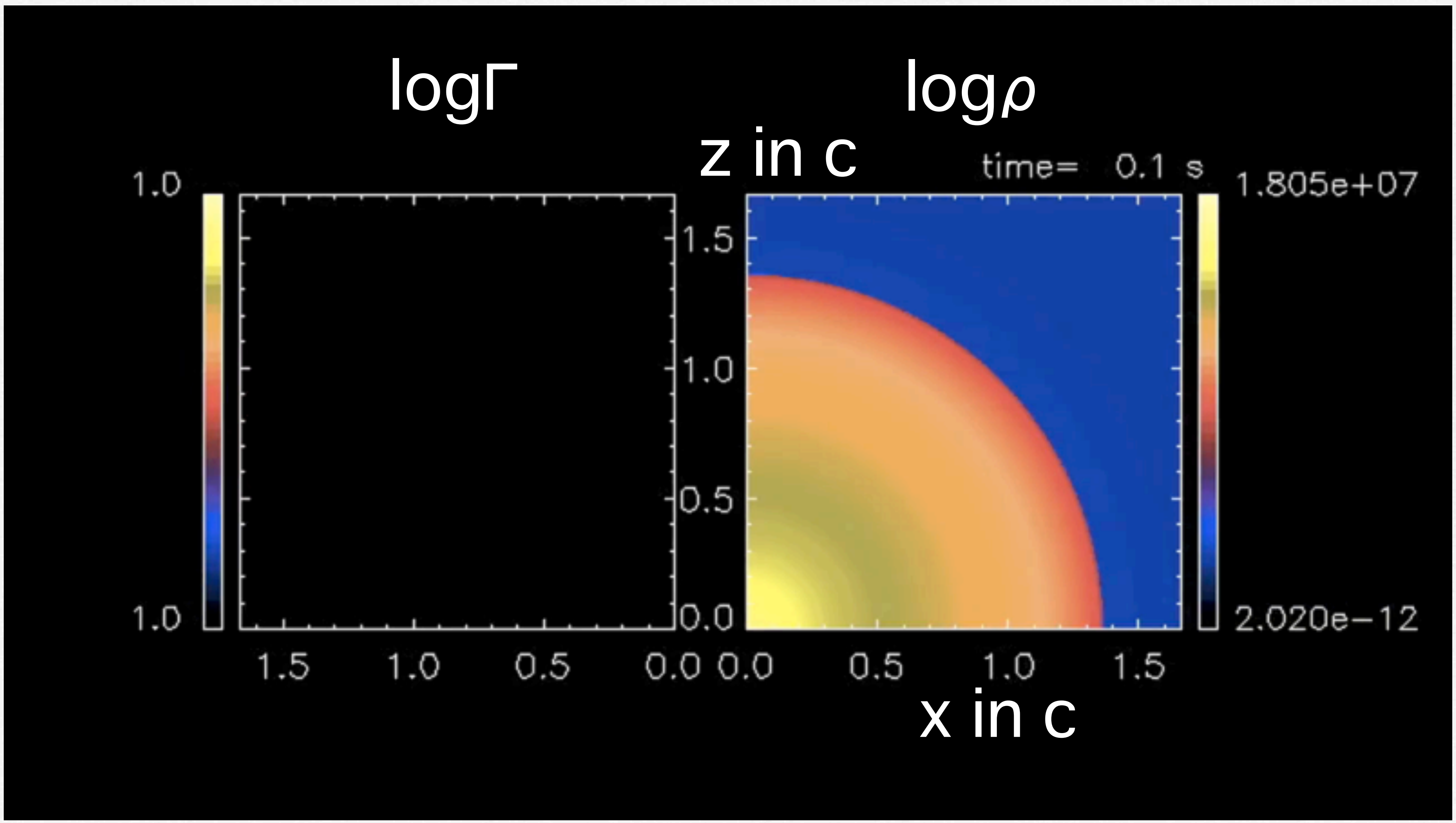
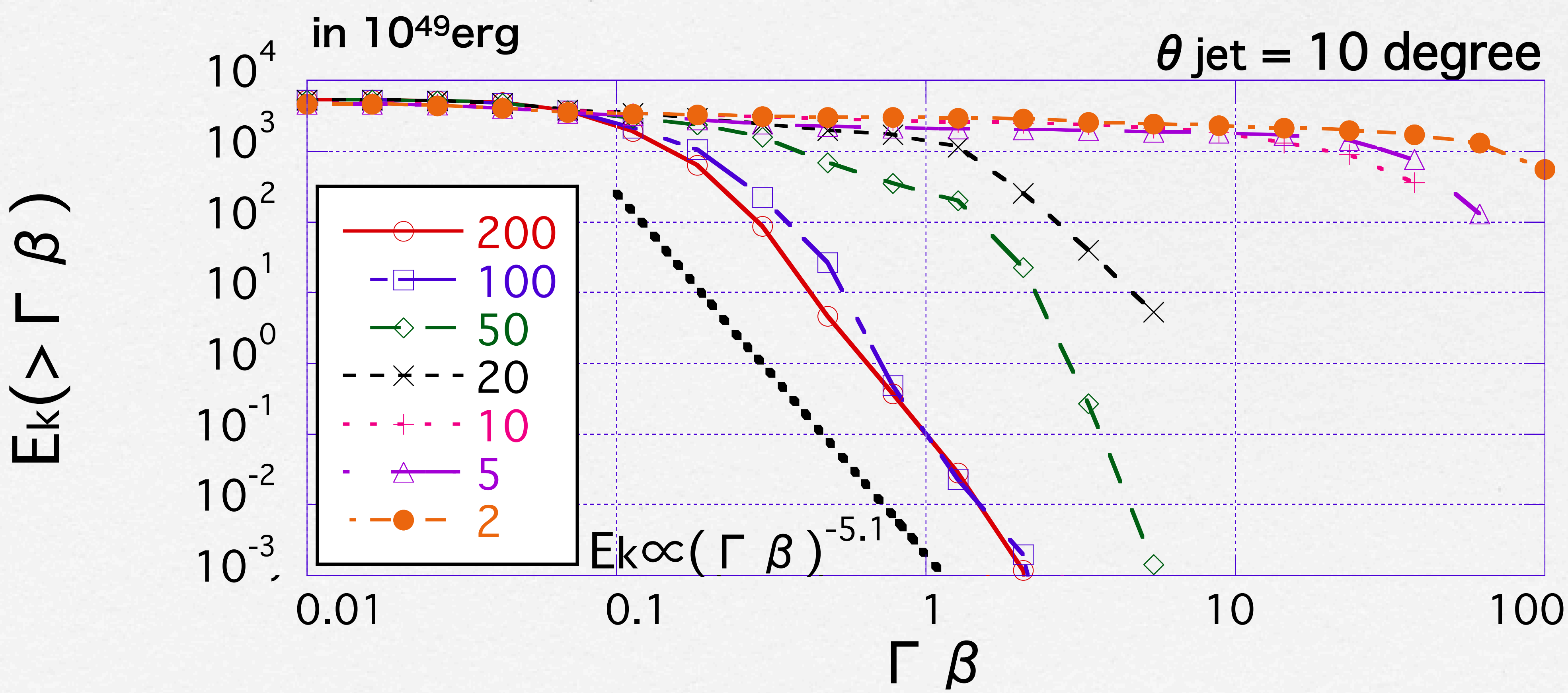


Kinetic energy distribution

- kinetic energy distribution of the ejecta at ~200 sec after the jet injection

$$E_{\mathrm{k}}(>\Gamma\beta) = \int \Gamma(\Gamma-1)\rho dV,$$

- Models with ultra-relativistic jet show flat distributions
- For models with nearly spherical blast waves, the distribution falls at $\Gamma\beta <$ a few



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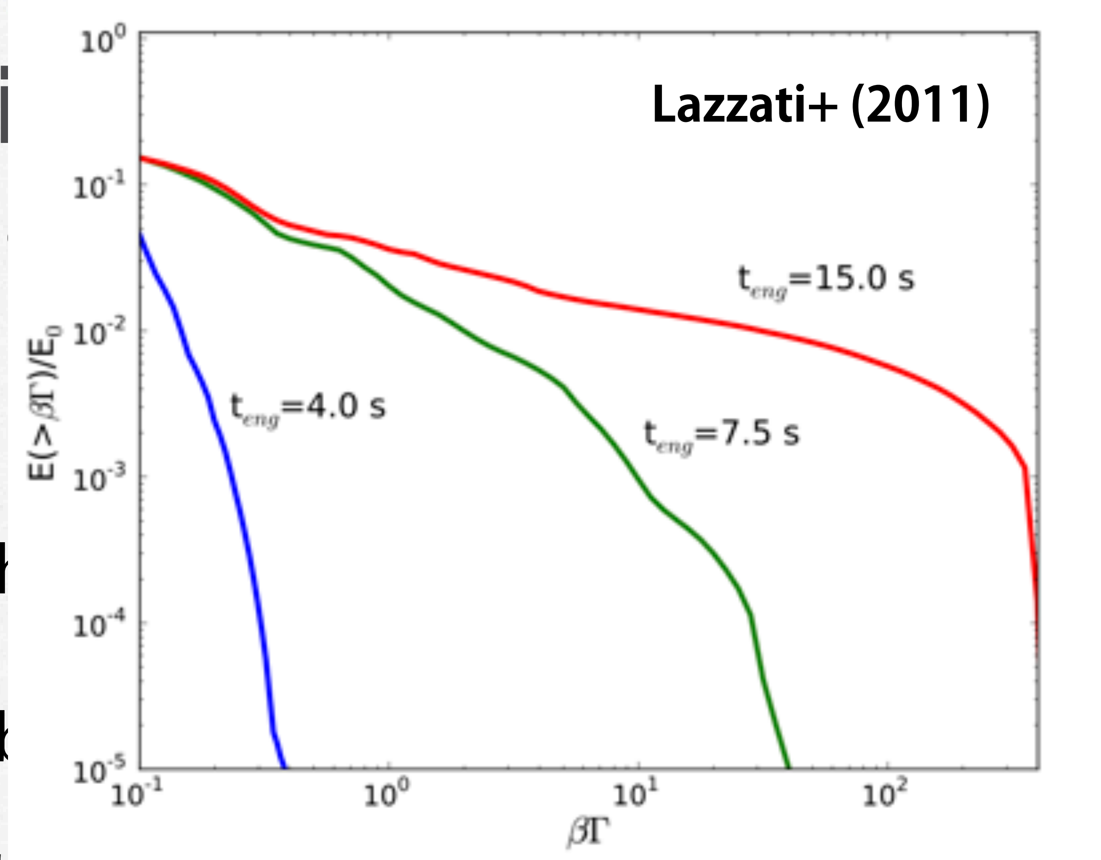

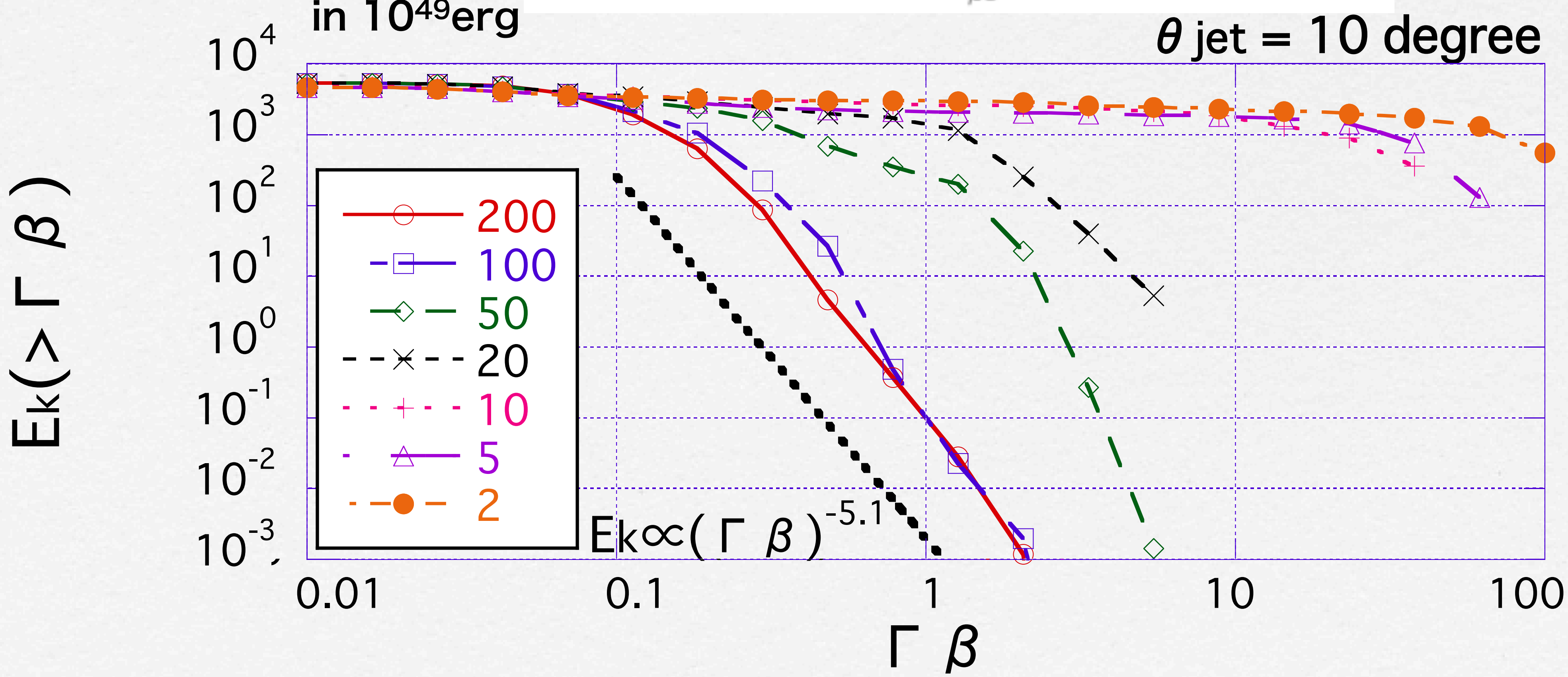

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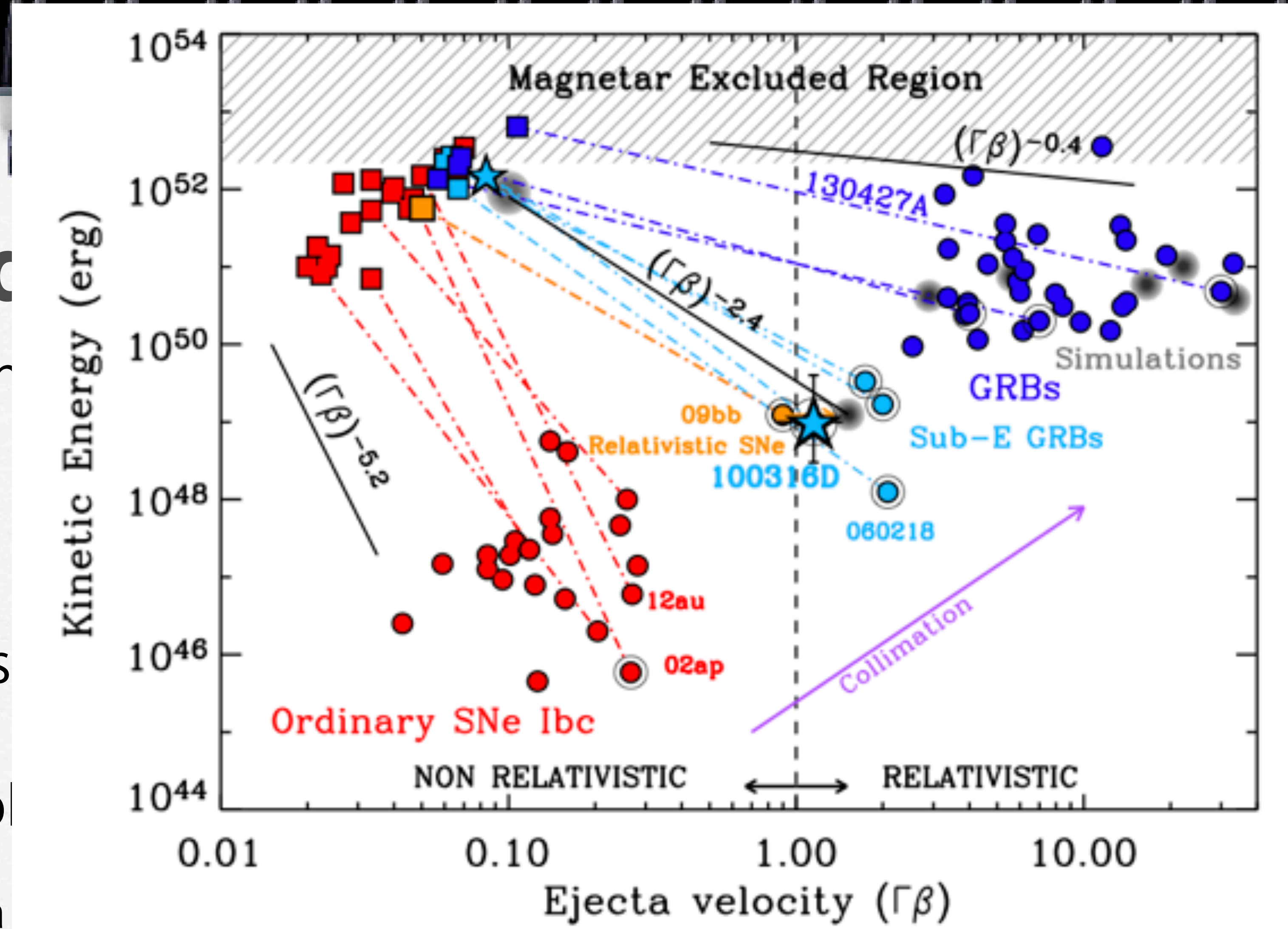

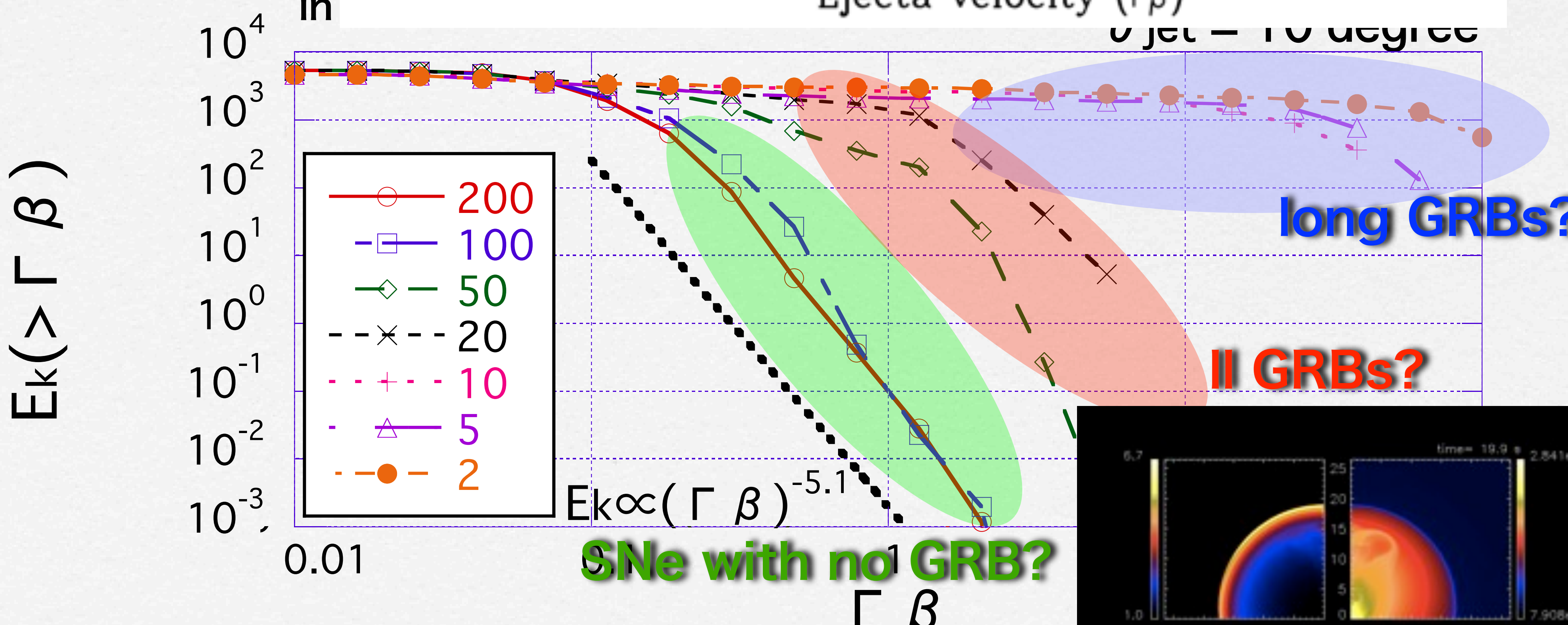

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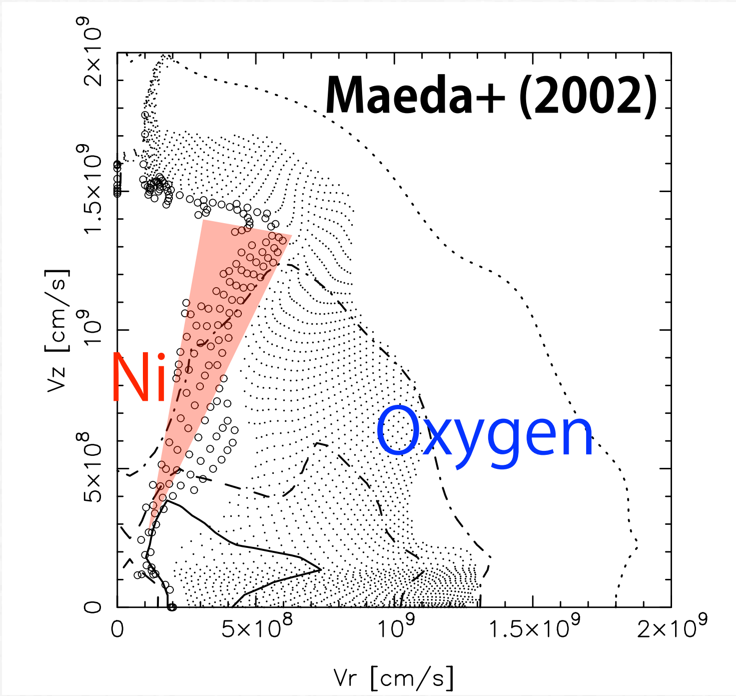
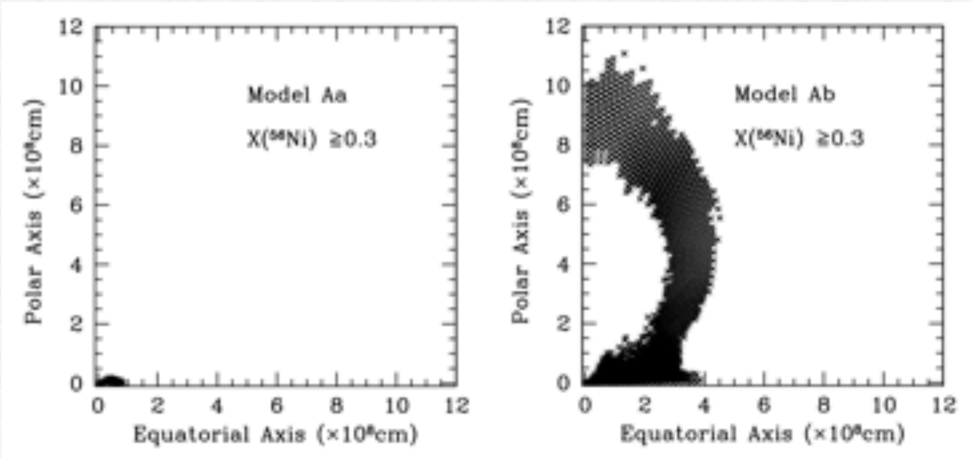
Nucleosynthesis

- Post-process nucleosynthesis calculations
- Many earlier works in the context of bipolar explosion in SNe (e.g., Nagataki+1997,2003,2005, Maeda+2002,Tominaga+2007)



- ^{56}Ni mass: (e.g.,Nagataki+2003,Tominaga+2007)
  slow energy deposition ➡ M(^{56}Ni)<<0.1M$_\odot$
  instantaneous energy injection ➡ M(^{56}Ni)~0.1M$_\odot$
- ^{56}Ni distribution:
  region with high X(^{56}Ni) is formed around the jet and a region with unburned ^{16}O is surrounding the region
  ➡ consistent with optical spectra of some HNe

Nagataki+ (2003)



Nucleosynthesis

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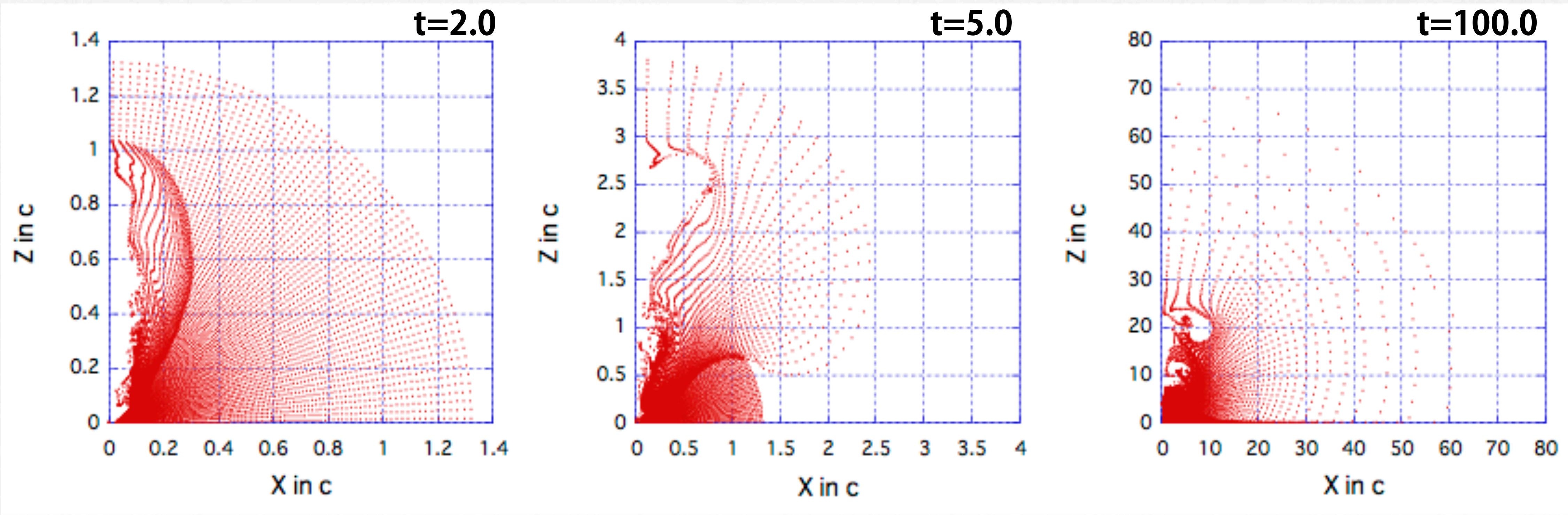
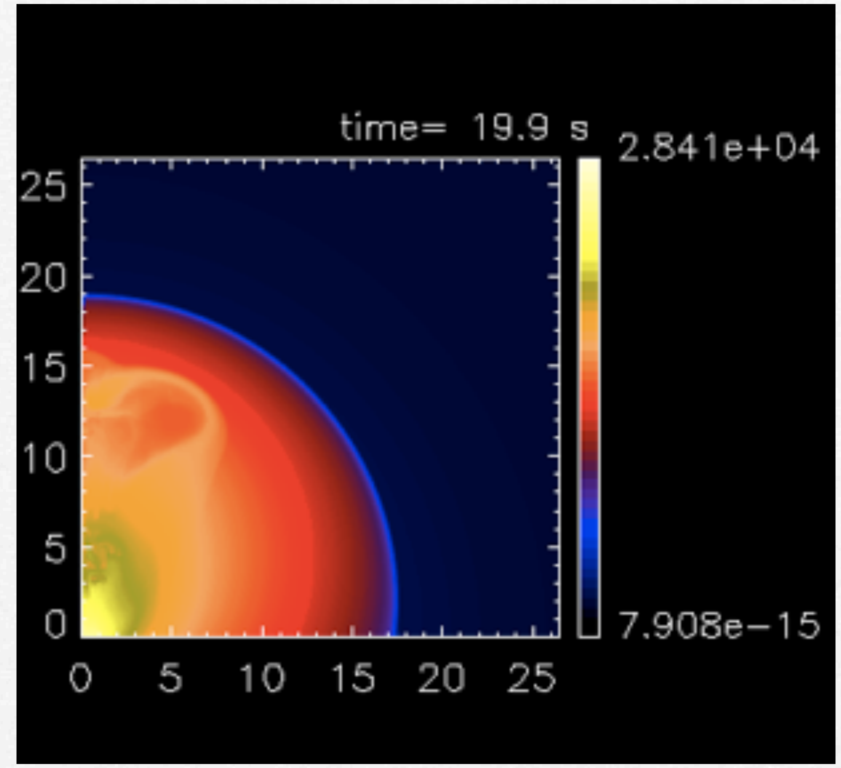
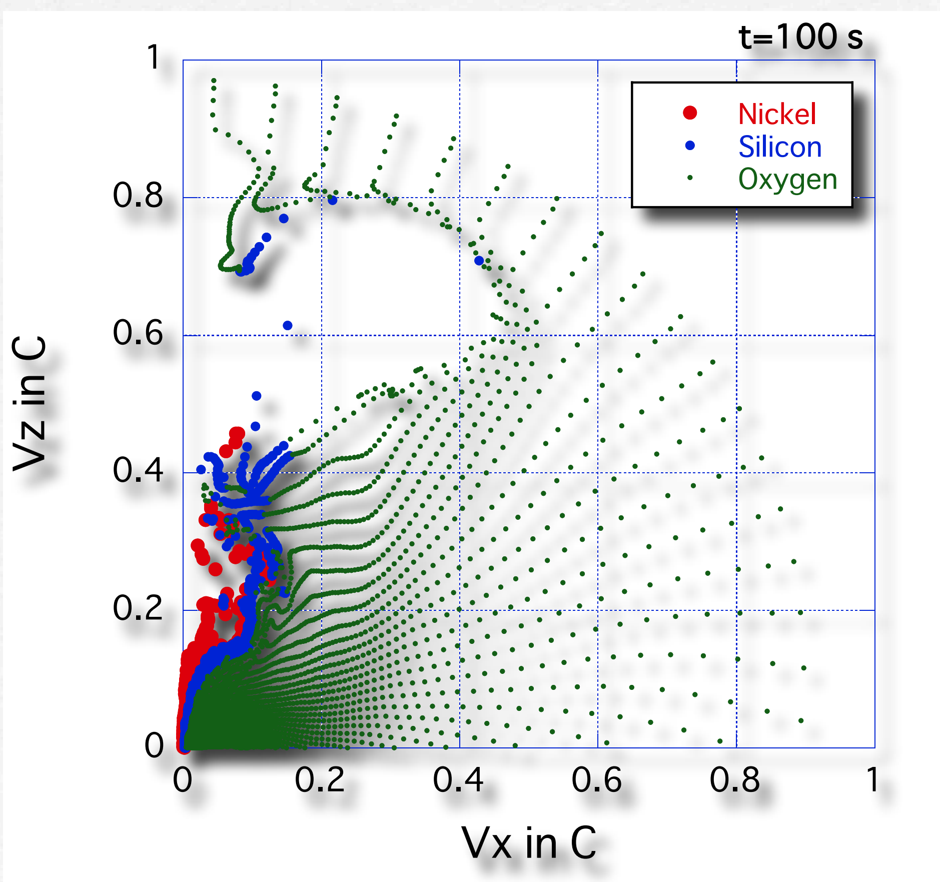
- Tracer particle method is employed



Nucleosynthesis

- ☑ Distributions of elements are similar to earlier works in the context of HNe.
- ☑ Particles that contains ^{56}Ni have velocities <0.3c
- ☑ Ni mass ~ 0.13 M$_\odot$, smaller by a factor of 2-3 than observed values

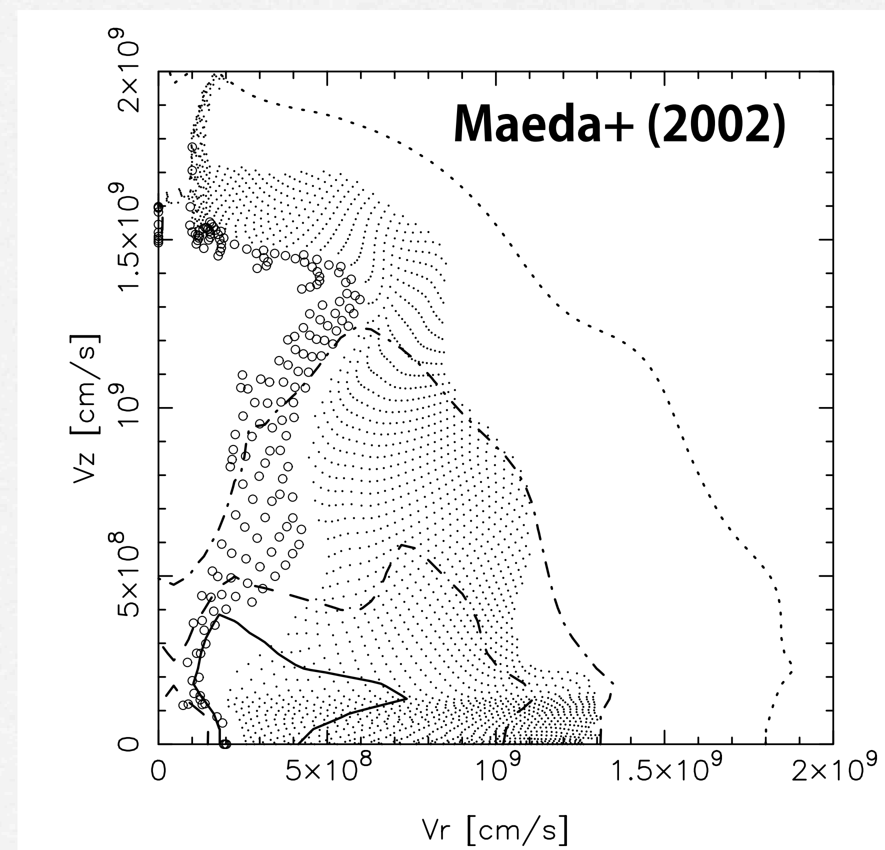




●: X(^{56}Ni) >0.1

●: X(^{28}Si) >0.1

●: X(^{16}O) > 0.1



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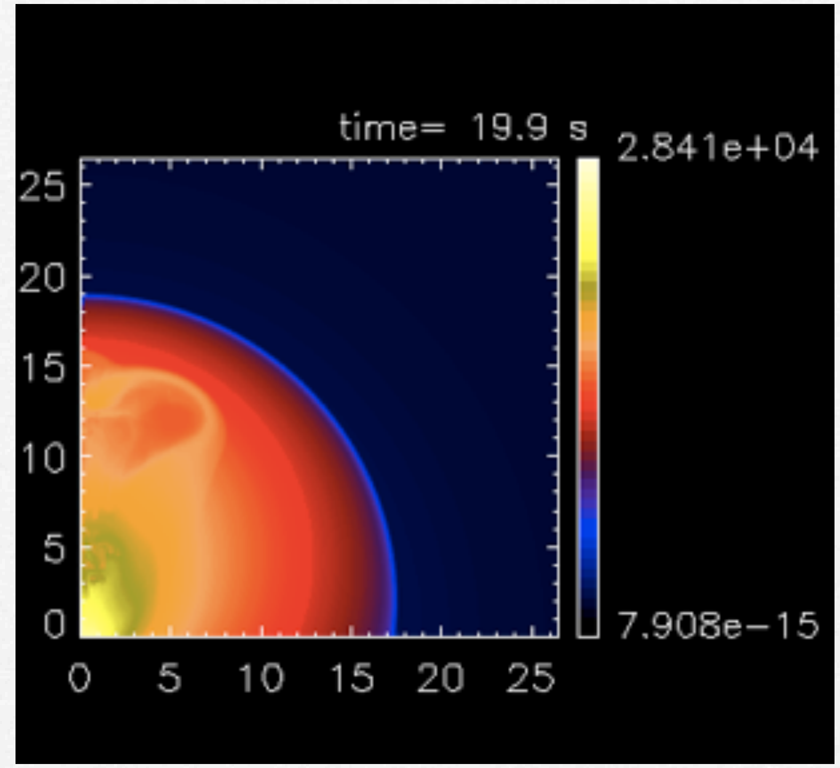
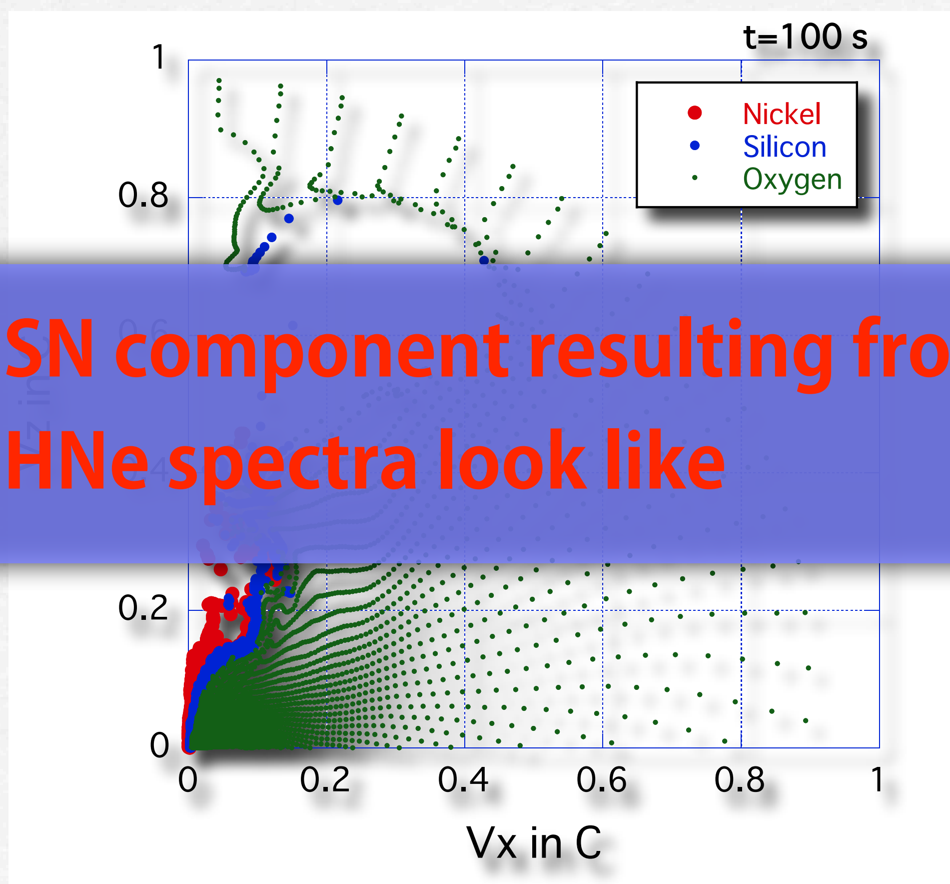
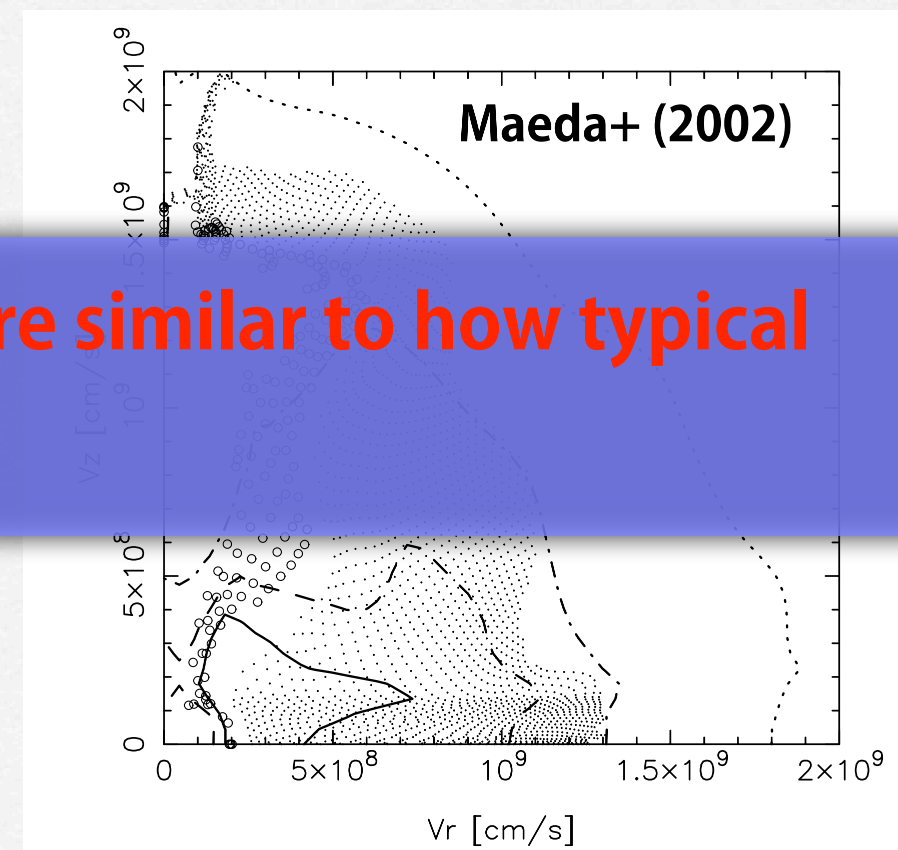




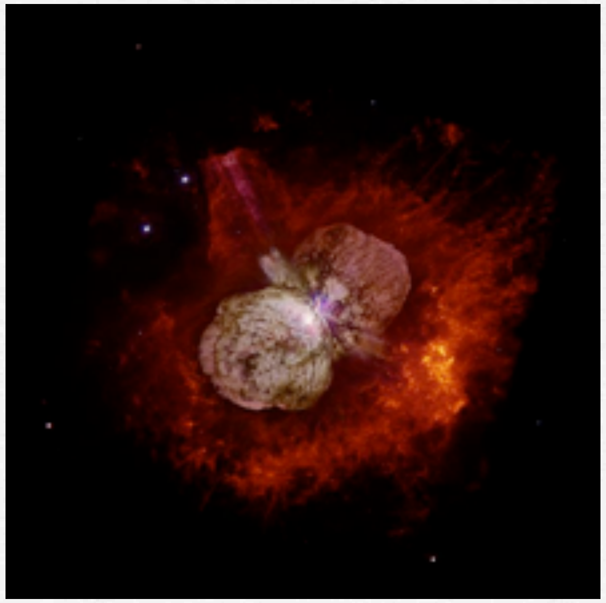
SN component resulting from failed jet are similar to how typical HNe spectra look like

- : X(^{56}Ni) >0.1
- : X(^{28}Si) >0.1
- : X(^{16}O) > 0.1



CSM interaction

- Dense circumstellar medium is expected around the progenitor star.
- ejecta-CSM interaction efficiently convert the kinetic energy of the ejecta into the internal energy and thus might give rise to bright emission in X-ray and gamma-ray.
- Some earlier works for the collision of mildly relativistic ejecta with CSM (e.g., Tan +2001).



η Carinae ©NASA

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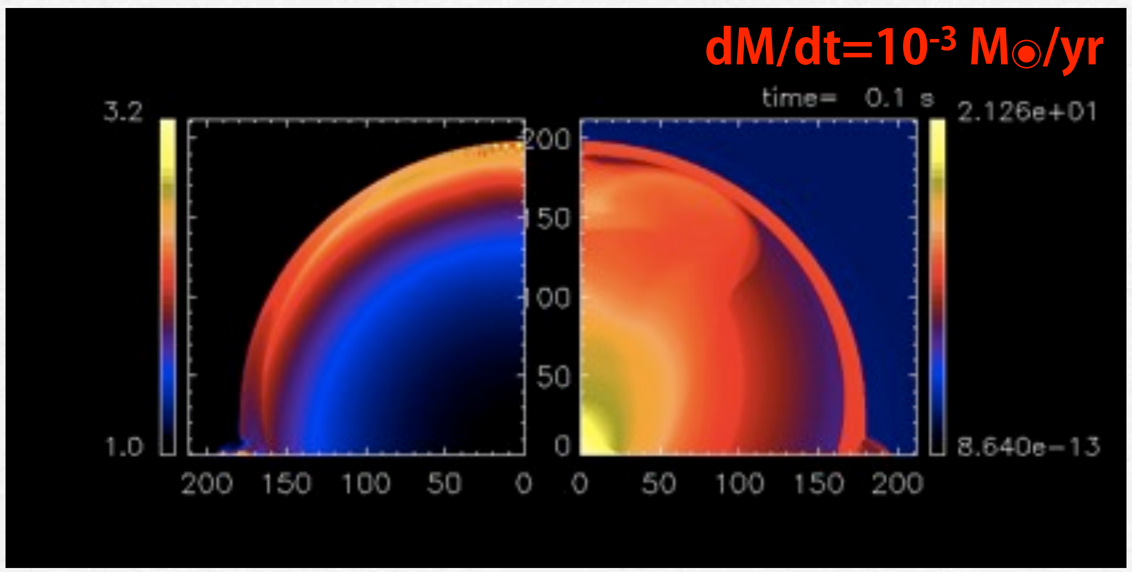
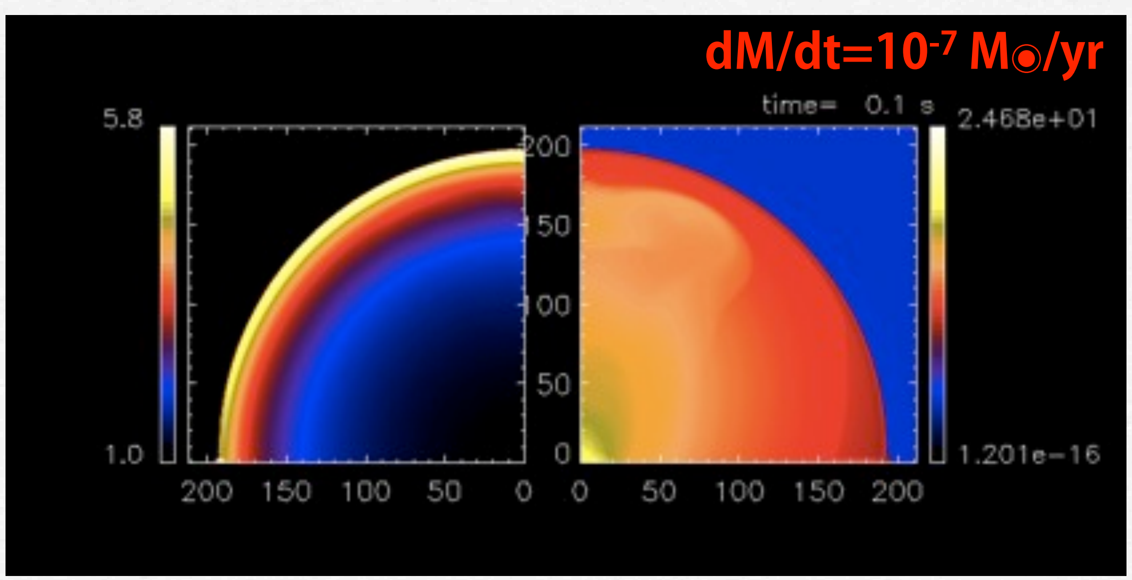
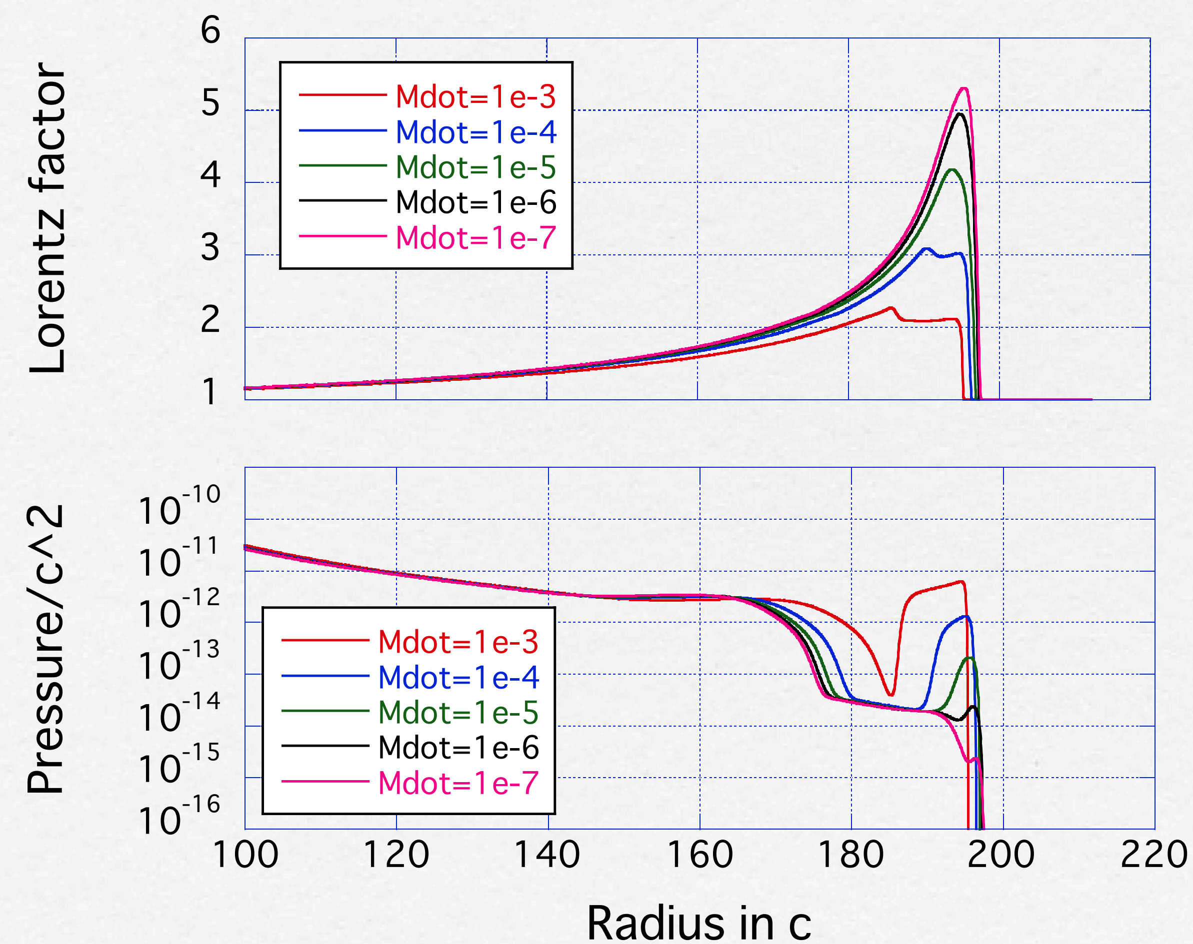
CSM interaction

- ☑ Models with dense CSM lead to “forward shock - reverse shock” system
- ☑ Models with dilute CSM lead to “forward shock - rarefaction wave” system







CSM interaction

- The internal energy flux F in the shocked region is of the order of 10^{20}-10^{21} erg/s/cm^2 for models with Mdot=10^{-3}, 10^{-4}, 10^{-5} $M_\odot$/yr

  flux : $F = P/(\gamma-1) \times \Gamma^2 v_r$

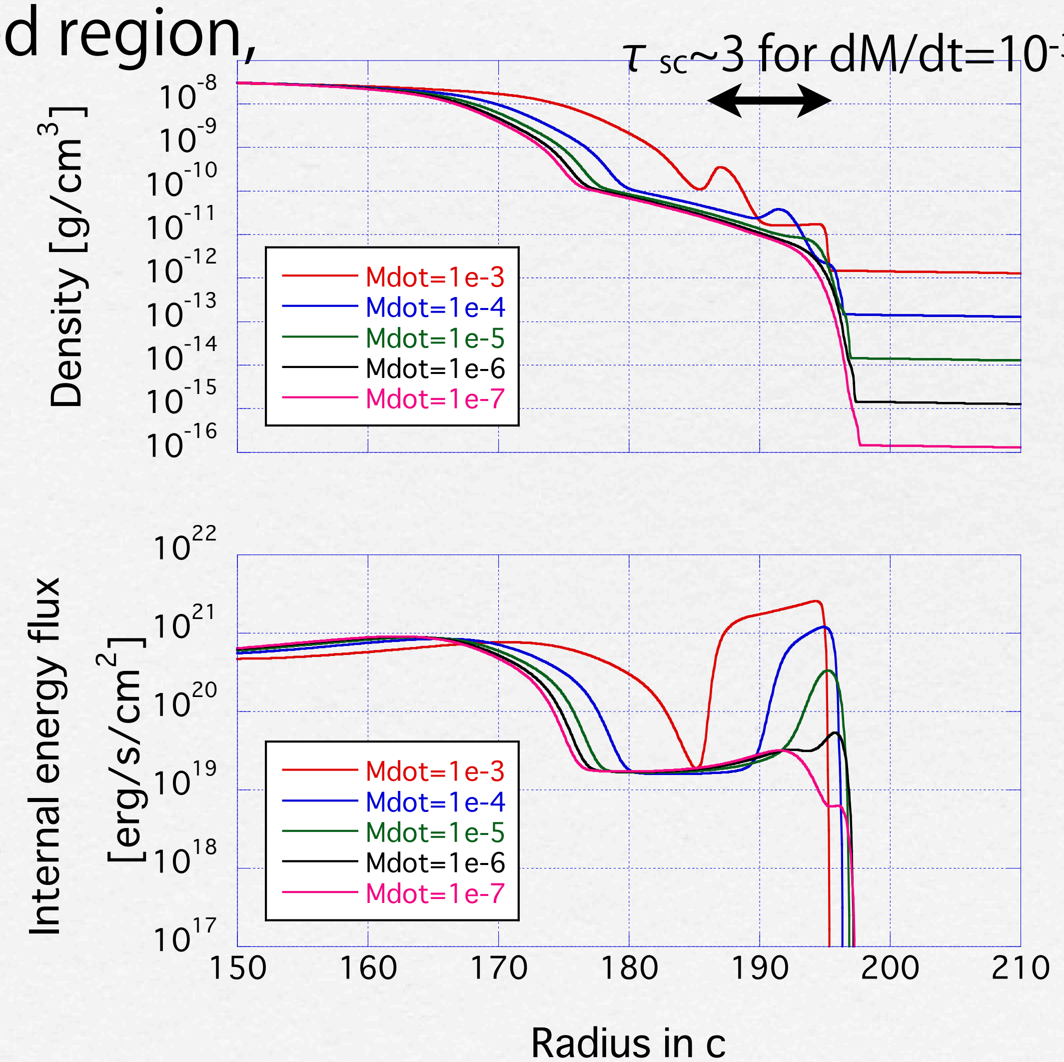
- assume the internal energy is dominated by photons and some fraction of photons can decouple from the shocked region,

ε : fraction of the energy emitted as photons

$L \sim 4\pi R^2 F \varepsilon$

$\sim 4 \times 10^{46}\ \varepsilon$ erg/s

$\times (R/6\times10^{12}\mathrm{cm})^2 (F/10^{20}\ \mathrm{erg\ s^{-1} cm^{-2}})$



However, thermal equilibrium between radiation and gas is not achieved!

CSM interaction has a potential to produce emission with L ~ $10^{46\text{-}47}$ erg/s

Summary

- Failed jet is promising to explain low-luminosity GRBs.

- Ultra-relativistic jet is failed to be created

  ➡ kinetic energy of the relativistic ejecta is much smaller than the kinetic energy of the non-relativistic one

- Explosive nucleosynthesis in the failed jet model

  ➡ similar result to HNe cases

- The interaction of the ejecta with dense CSM is investigated

  ➡ CSM interaction has a possibility in producing highly energetic emission with $L_{\gamma,iso} \sim 10^{46}$ - 10^{47} erg/s

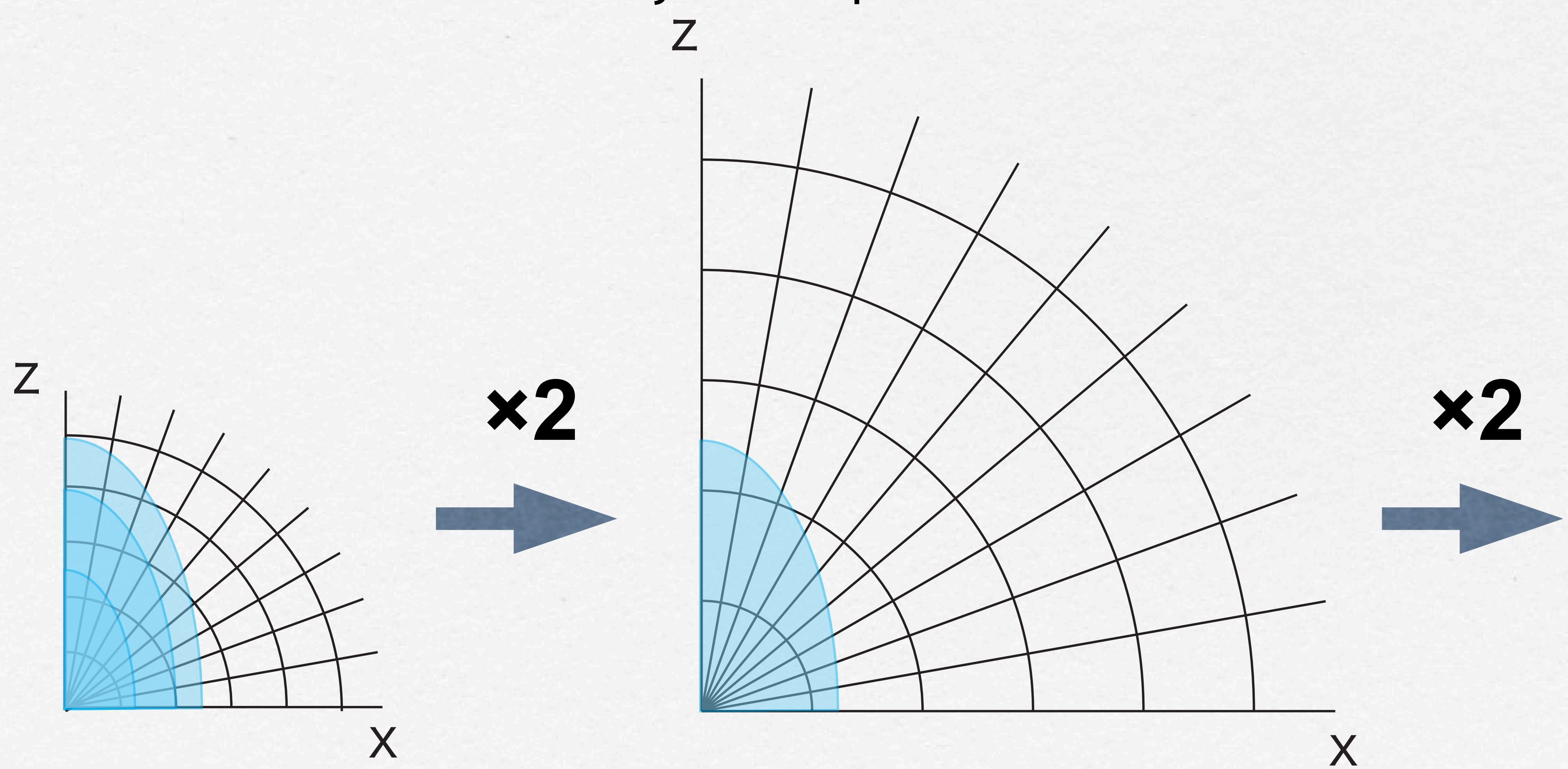
Mapping procedure

- dynamical range is huge

  ➡ jet ~ $10^{13\text{-}14}$ cm ⇄ Fe core ~ $10^{8\text{-}9}$ cm

- Courant condition limits the time step $\Delta t < c\Delta x$

- The numerical domain doubles as the ejecta expand. The resolution is halved.



Results

Ultra-relativistic jet

Mildly relativistic
blast wave