Successful/failed GRB jets and explosive nucleosynthesis

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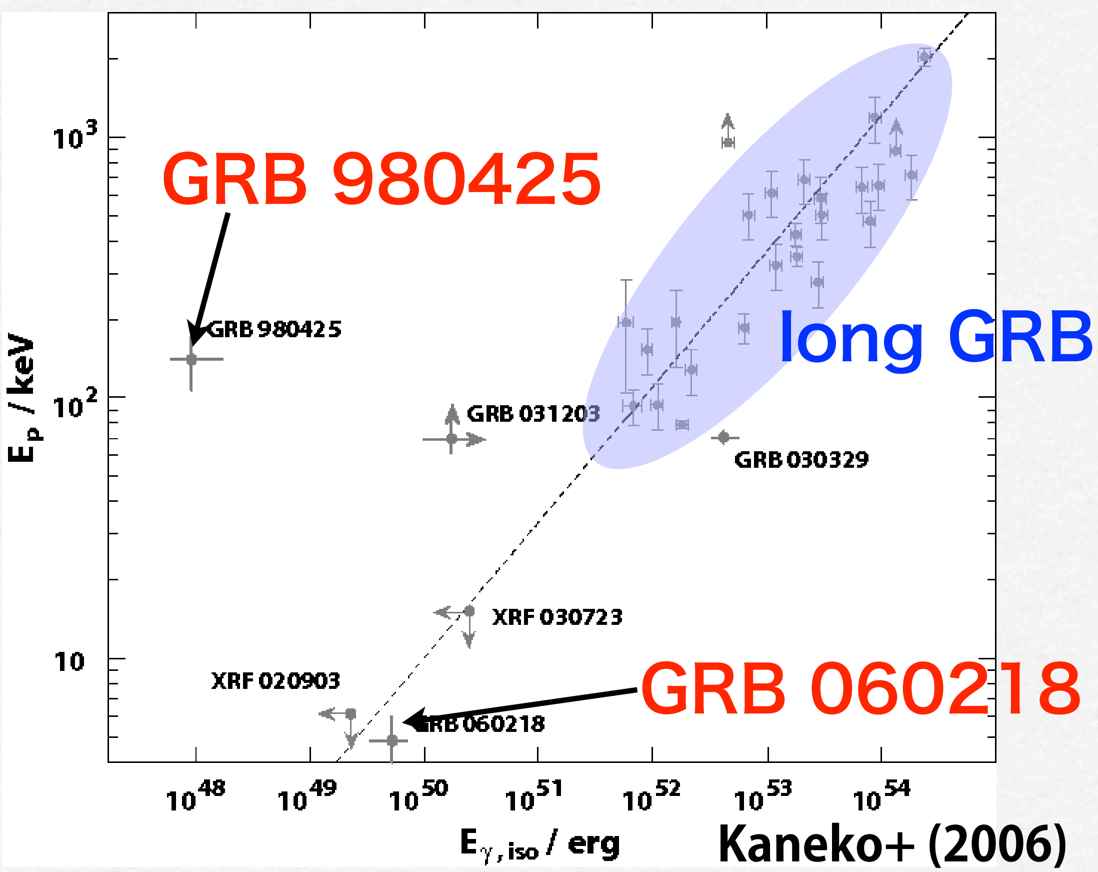
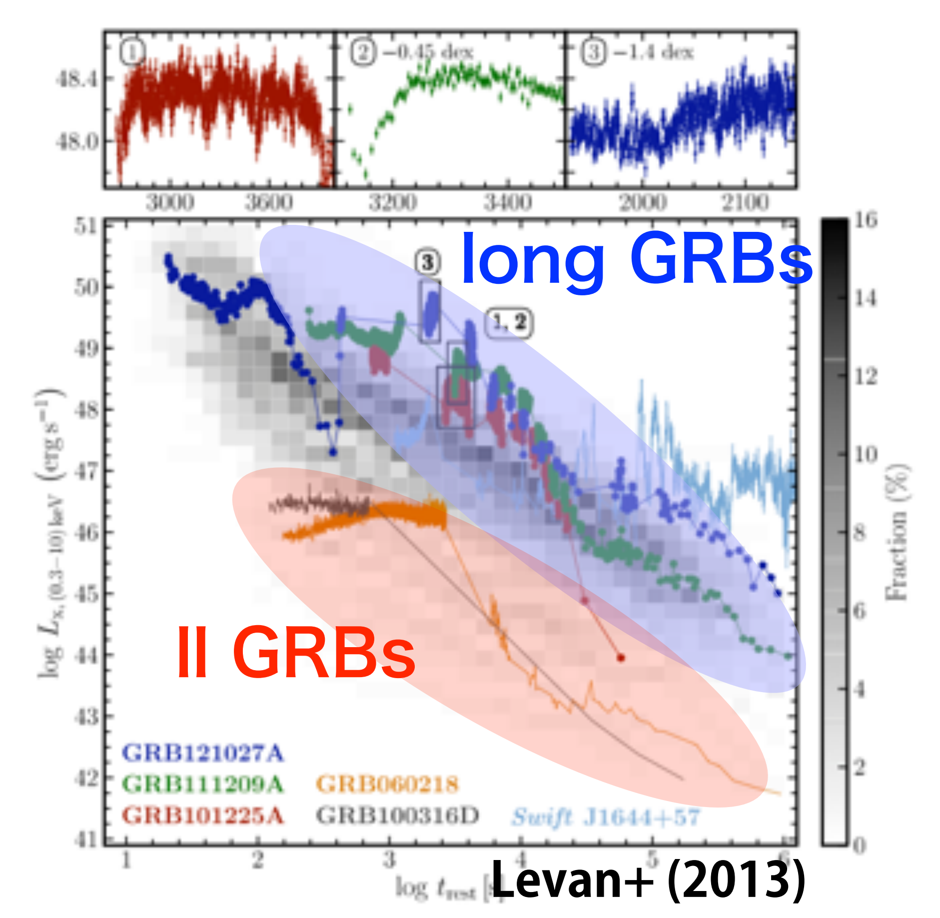
Outline

- ☑ Jet propagation in a massive star and GRBs
- ☑ Jet models
- ☑ Explosive nucleosynthesis as a result of jet injection
- ☑ Summary

GRBs and low-luminosity GRBs

- relativistic jet injected into a massive star as a origin of long GRBs
- llGRBS: less energetic and less luminous subgroup of long GRBs
- They are accompanied by broad-lined Ic supernovae
- Ex.) GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB100316D/ SN2010bh





Low-luminosity GRBs

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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

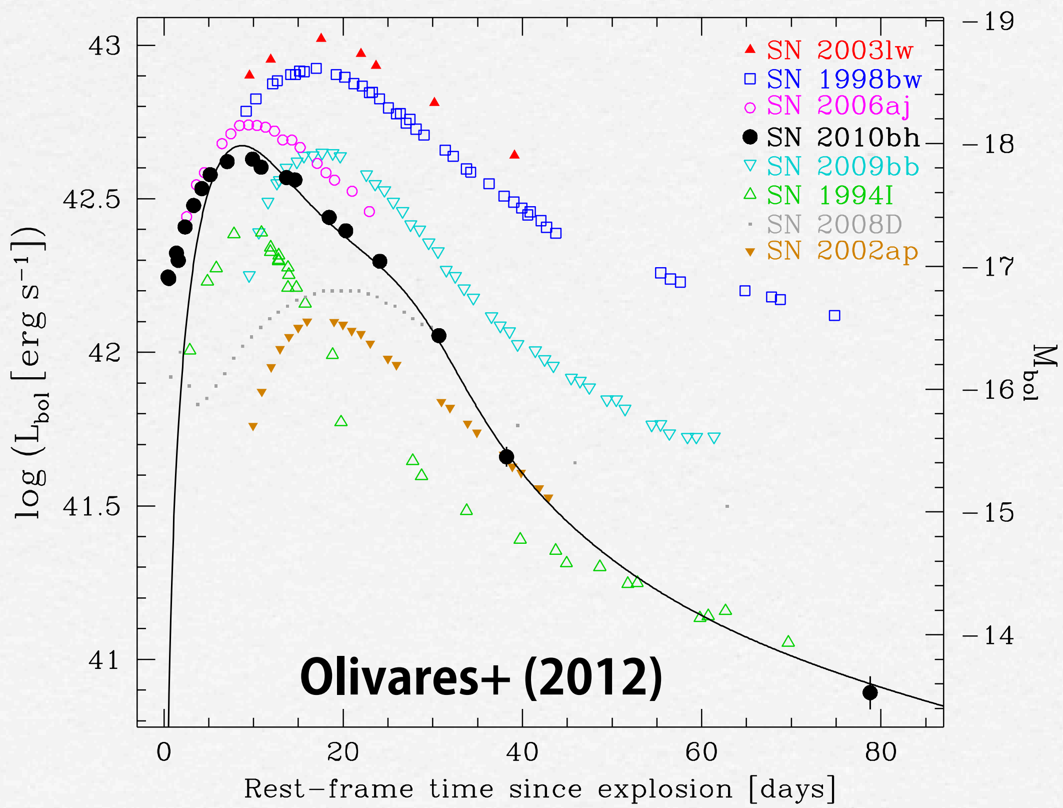
cf. Liso~10^{51} erg/s, Eiso~$10^{52\text{-}53}$ erg for standard GRBs from Hjorth (2011)

Question to answer: **What is the origin of the diversity of GRBs?**
What mechanism is responsible for X- and γ- ray emission

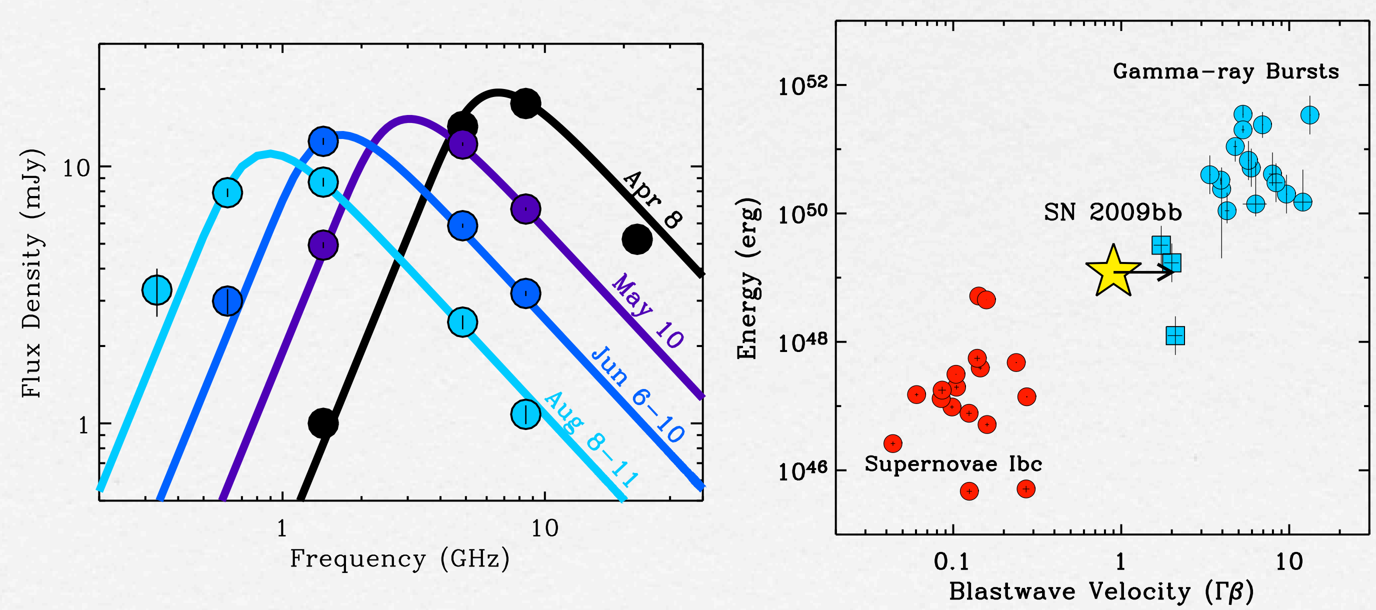
Connection to HNe, engine-driven SNe

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



Soderberg+ (2010)



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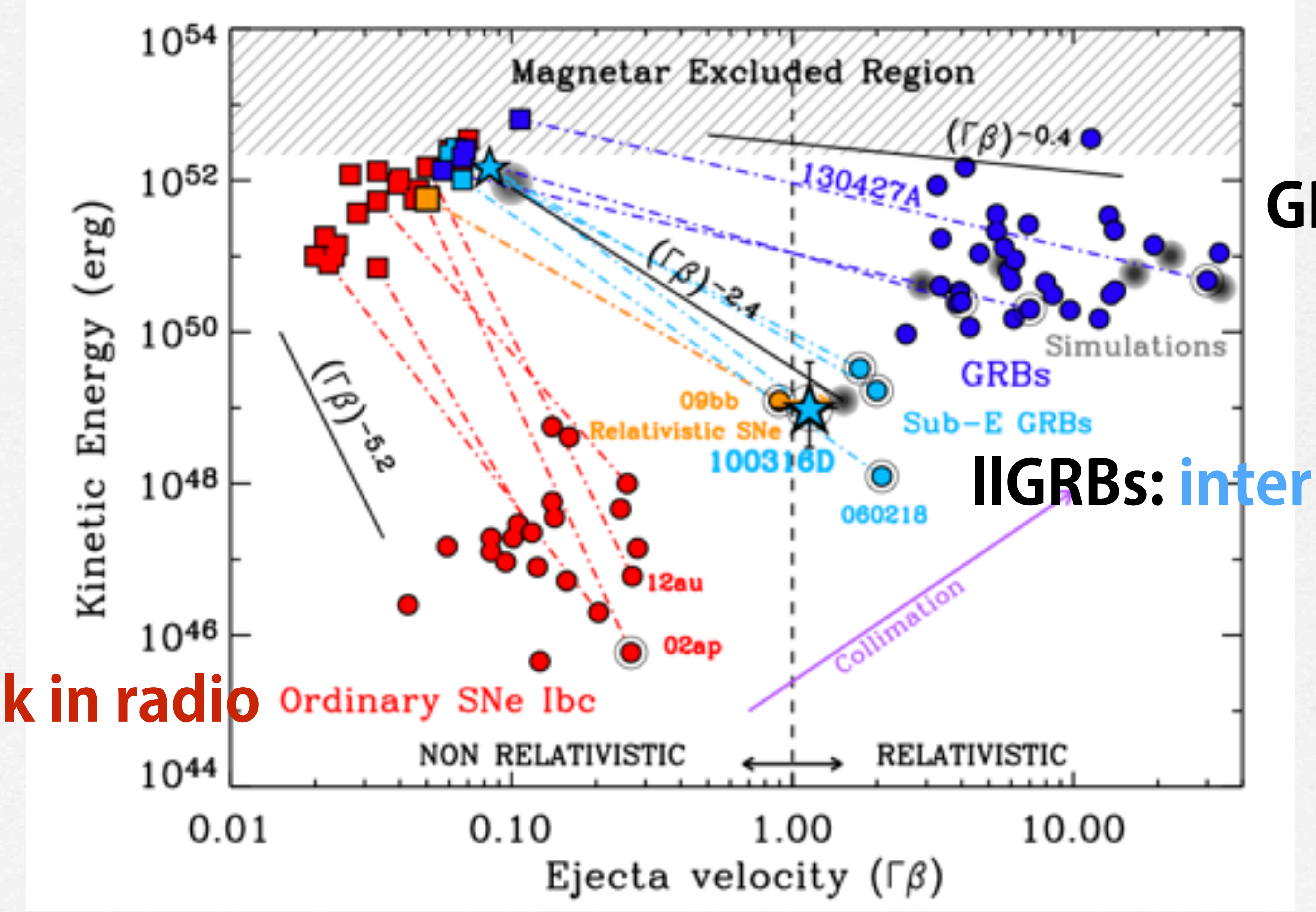

GRBS: bright in radio

llGRBs: intermediate

SNe Ibc: dark in radio

Margutti+ (2013)

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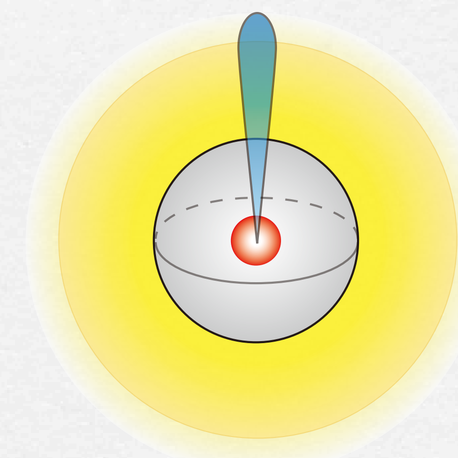
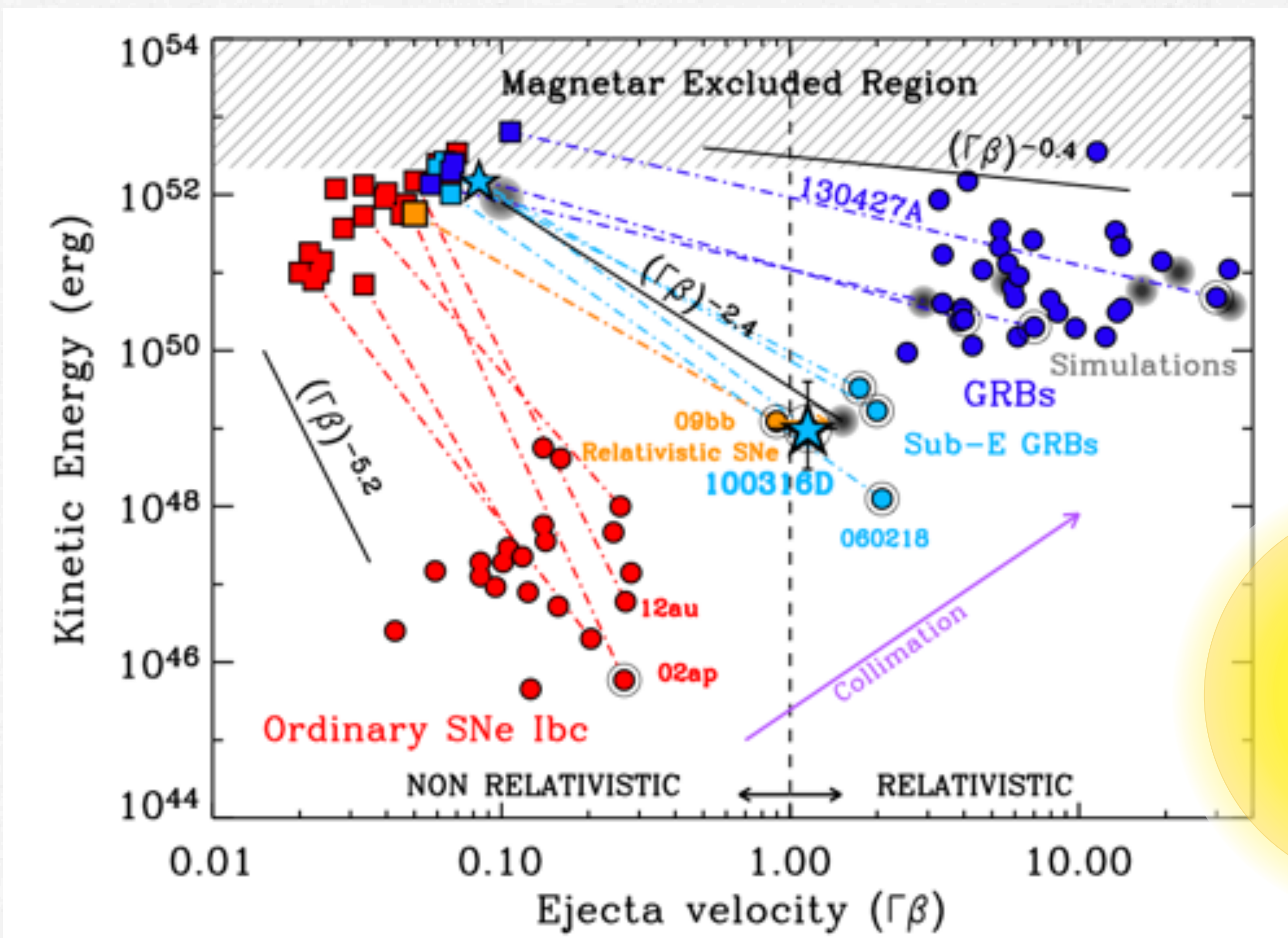
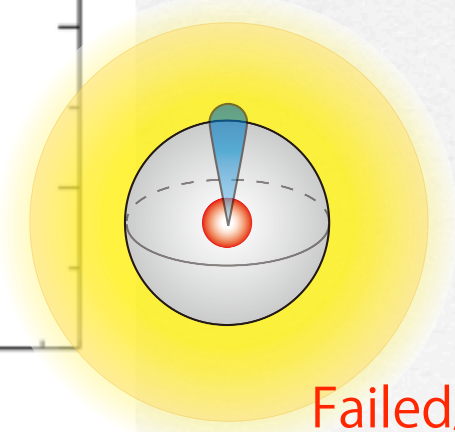
Ultra-relativistic jet?





No jet ?



Failed/Weak jet?

Margutti+ (2013)

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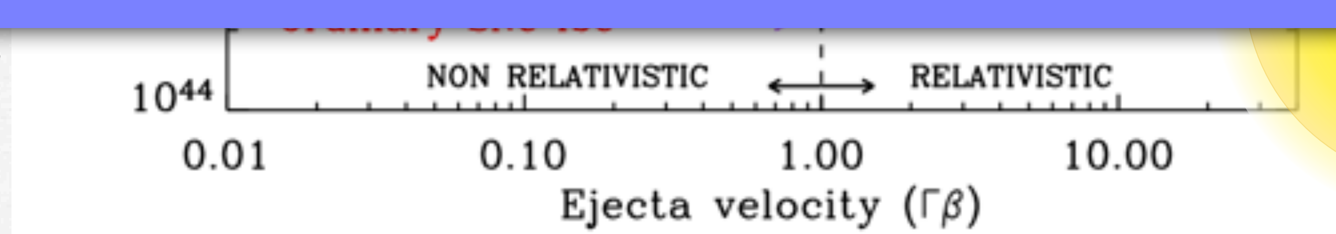
- Radio observations: kinetic energy of the blast wave is found by using synchrotron emission model : Γv =(1-2) c, $E_{kin} \sim 10^{49}$ erg

Ultra-relativistic jet?

This study

1. **We carry out a series simulations of jet propagation in a massive star with various injection conditions.**
2. **We carry out further calculations to reveal the properties of the models. Especially we focus on explosive nucleosynthesis as a result of the jet injection**

No jet ?



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Margutti+ (2013)

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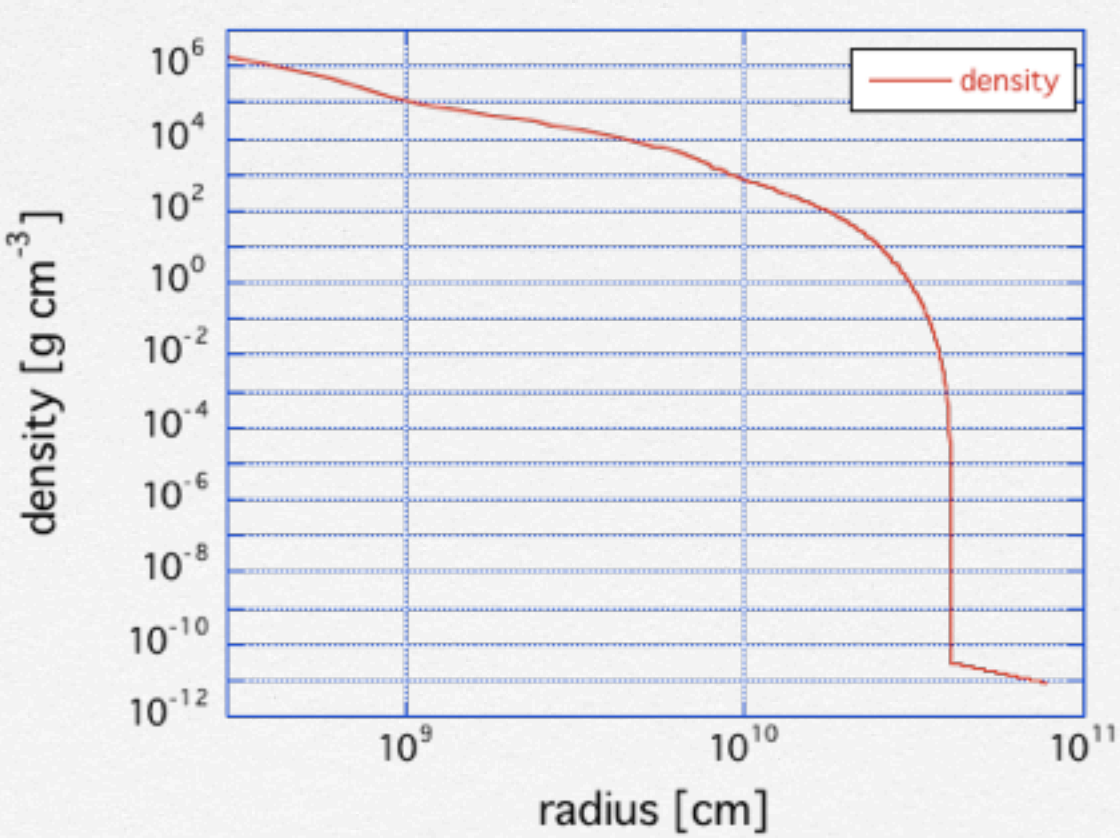
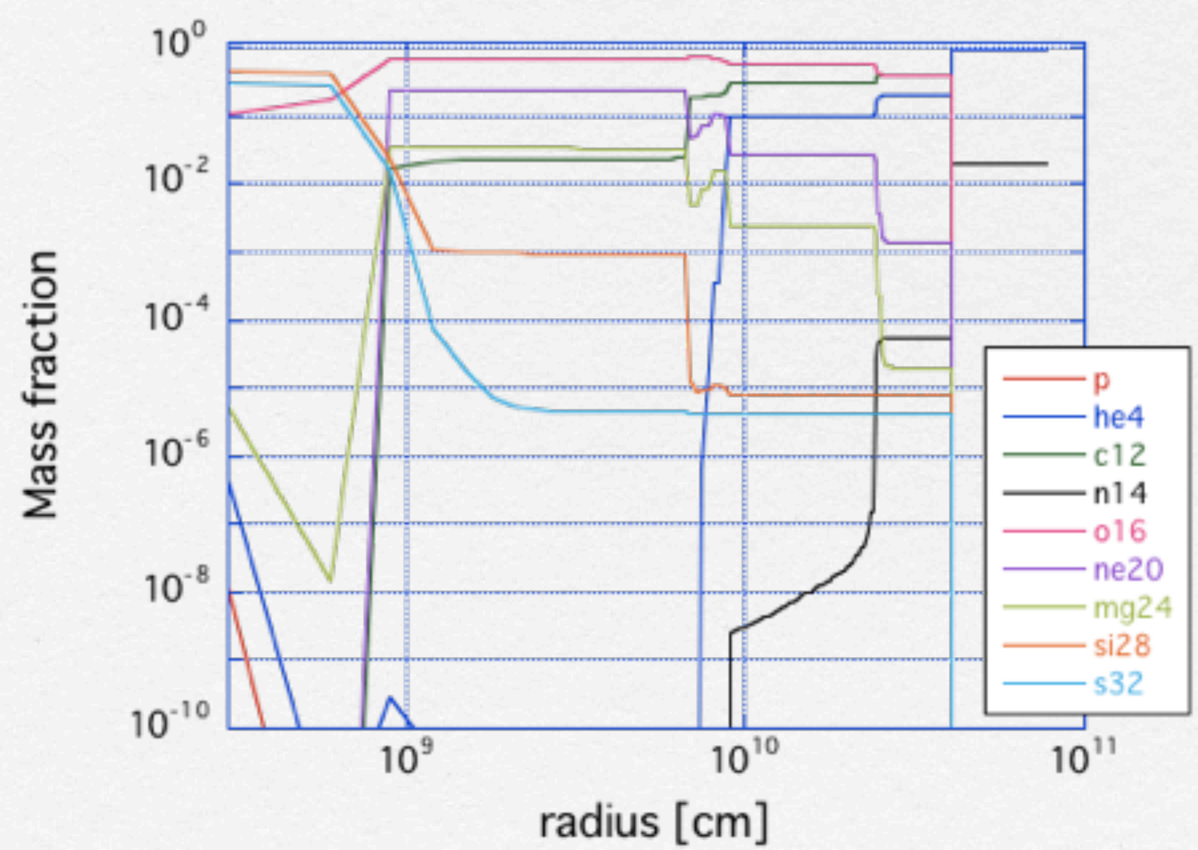
GRB jet simulation

- 2D SRHD simulations with 4096×512 mesh
- Woosley&Heger(2006) 16TI model
- WR star
- pre-supernova mass~14M$_\odot$
- Radius ~ 4×10^{10}cm

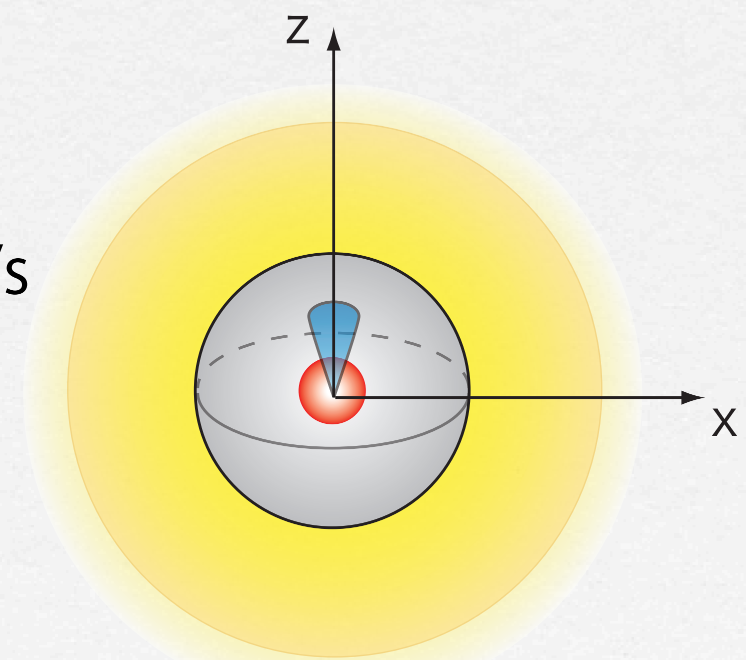
$$\rho_{\rm ext} = \rho_{\rm w}(r) + \rho_{\rm ISM}$$
$$\rho_{\rm w} = \frac{\dot{M}}{4\pi r^2 v_{\rm w}}$$
$$\rho_{\rm ISM} = 100 m_{\rm u}\ {\rm g\ cm^{-3}}$$





GRB jet simulation

- ☑ jet injection with various sets of free parameters
- ☑ injection radius: $R_{in} = 1.5\times10^{8}$cm and 1.0×10^{9}cm
- ☑ total energy: $E = 5\times10^{52}$ erg
- ☑ energy injection rate: dE/dt=2000, 1000, 500, 200, 100, 50, 20, 10, 5 $\times10^{50}$ erg/s
- ☑ half opening angle: $\theta_j = 10^\circ$
- ☑ initial jet Lorentz factor: $\Gamma_j = 5$
- ☑ specific internal energy: $\varepsilon_0/c^2 = 20$
- ☑ CSM: $dM/dt = 10^{-7}\ M_\odot$/yr, $v_w = 1000$km/s



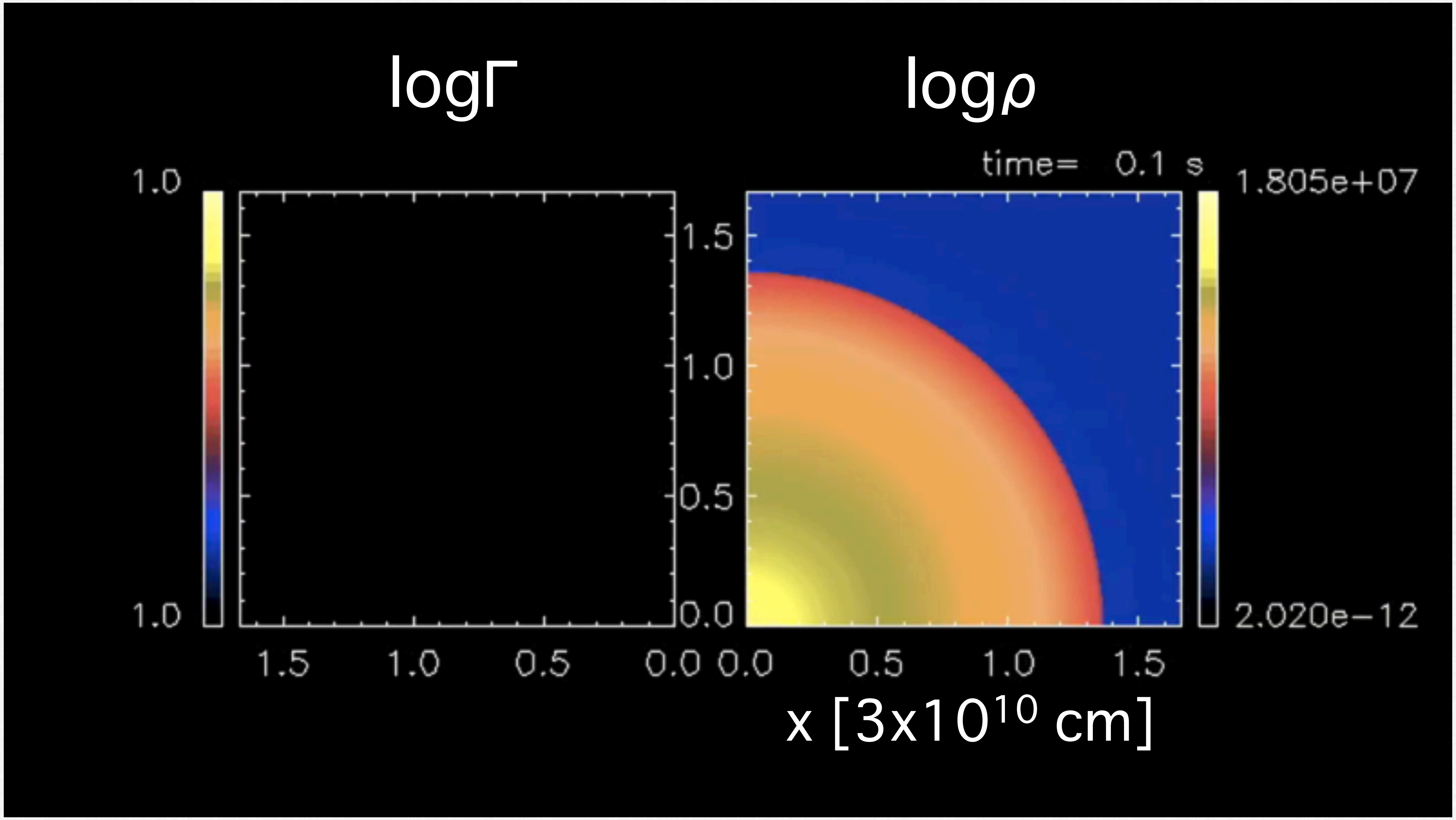
Jet models

- 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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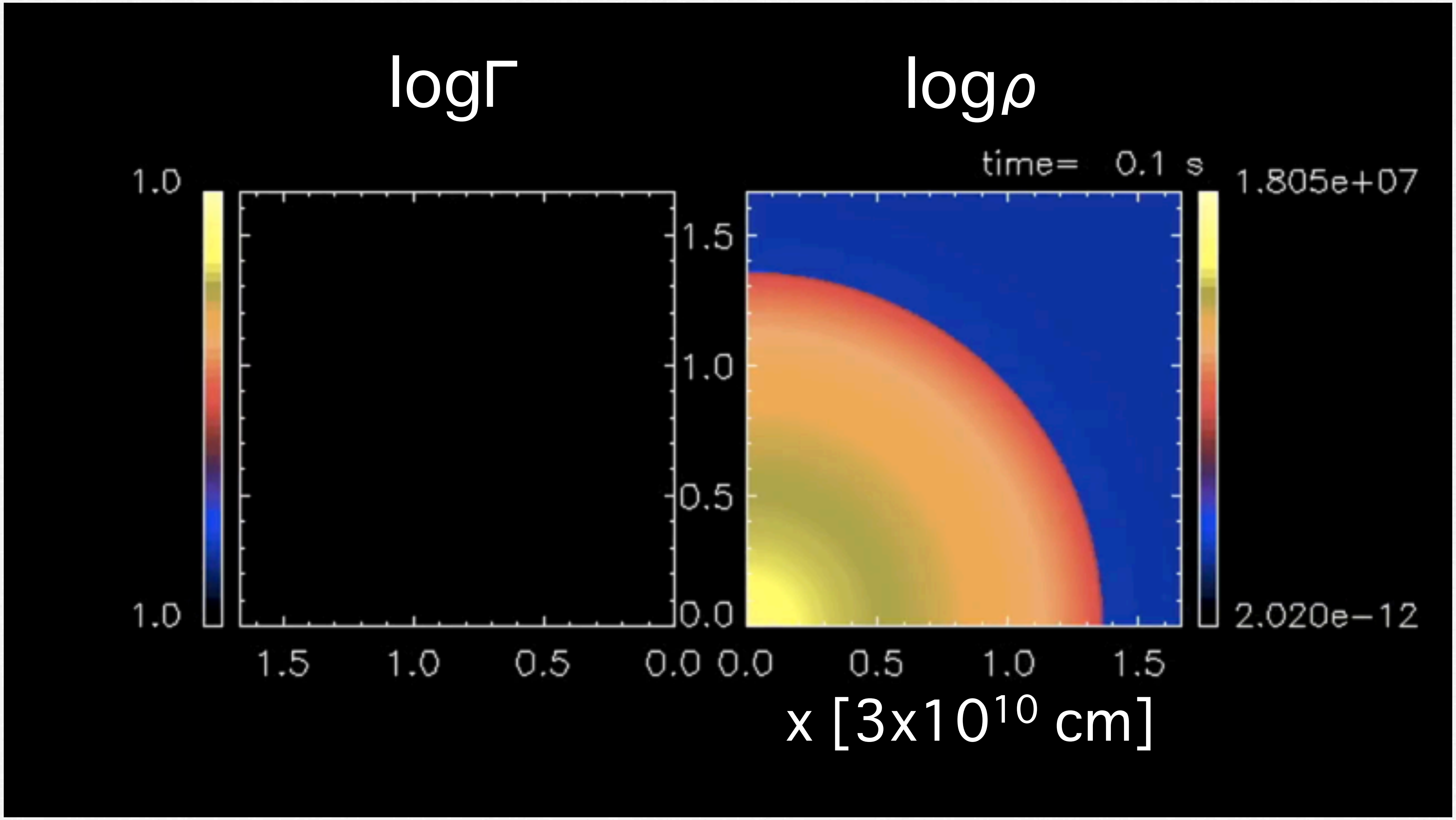


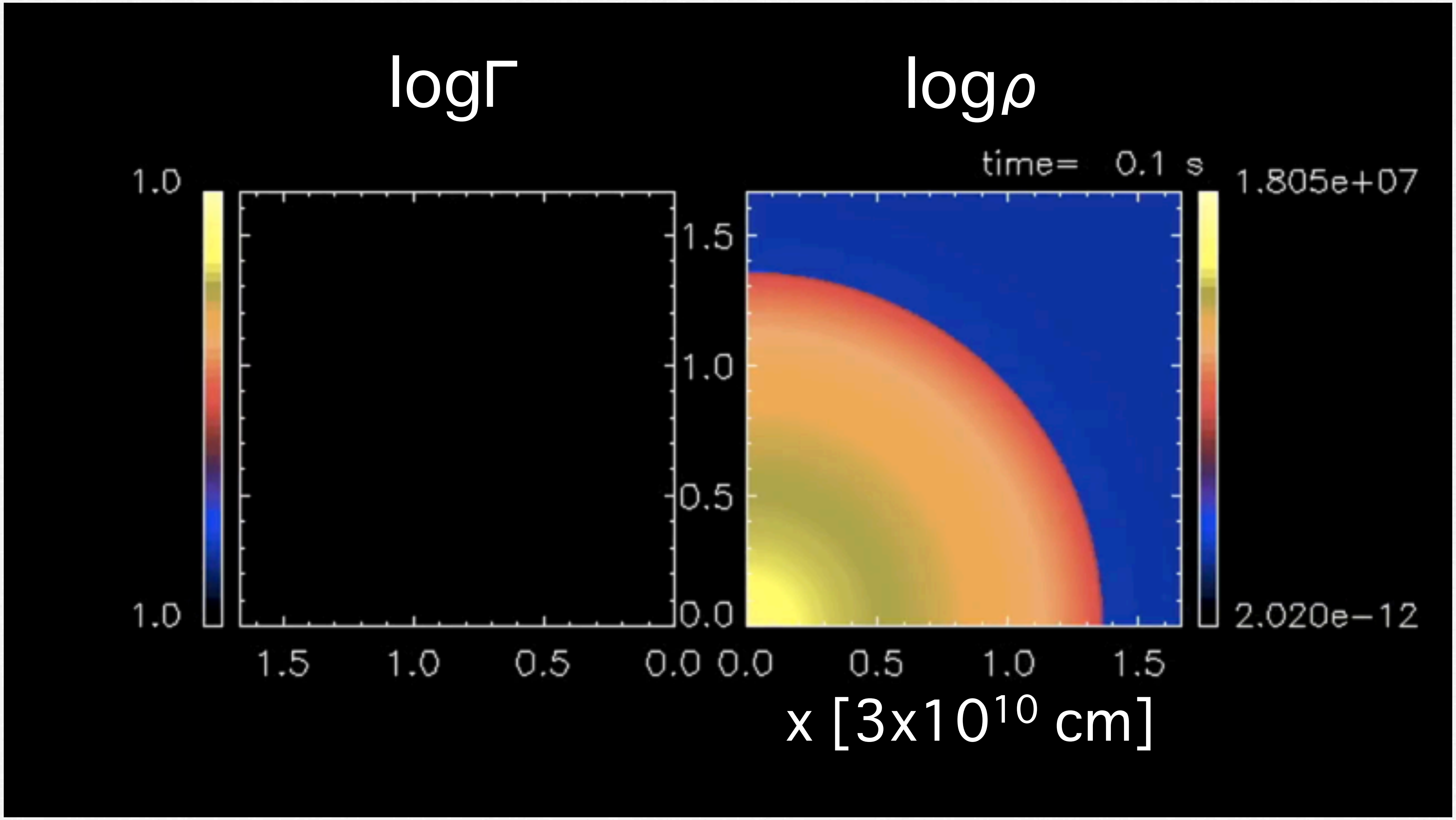
Jet models

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

high dE/dt (=50×10^{51}erg/s)

- ☑ left: Lorentz factor right: density

short t_{inj} (=0.5s)



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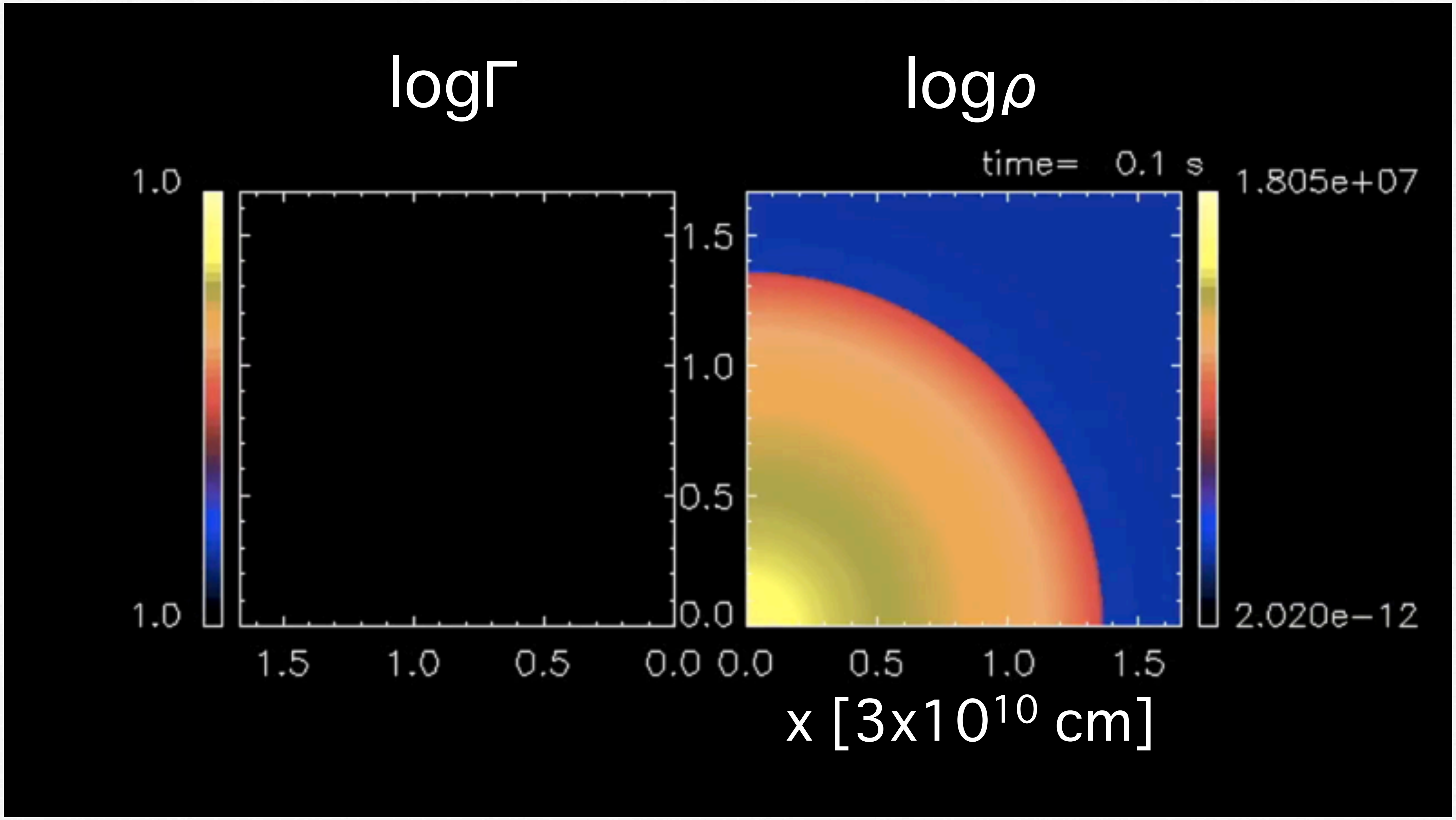


Successful/failed jets

- kinetic energy distribution of the ejecta at t=100 sec

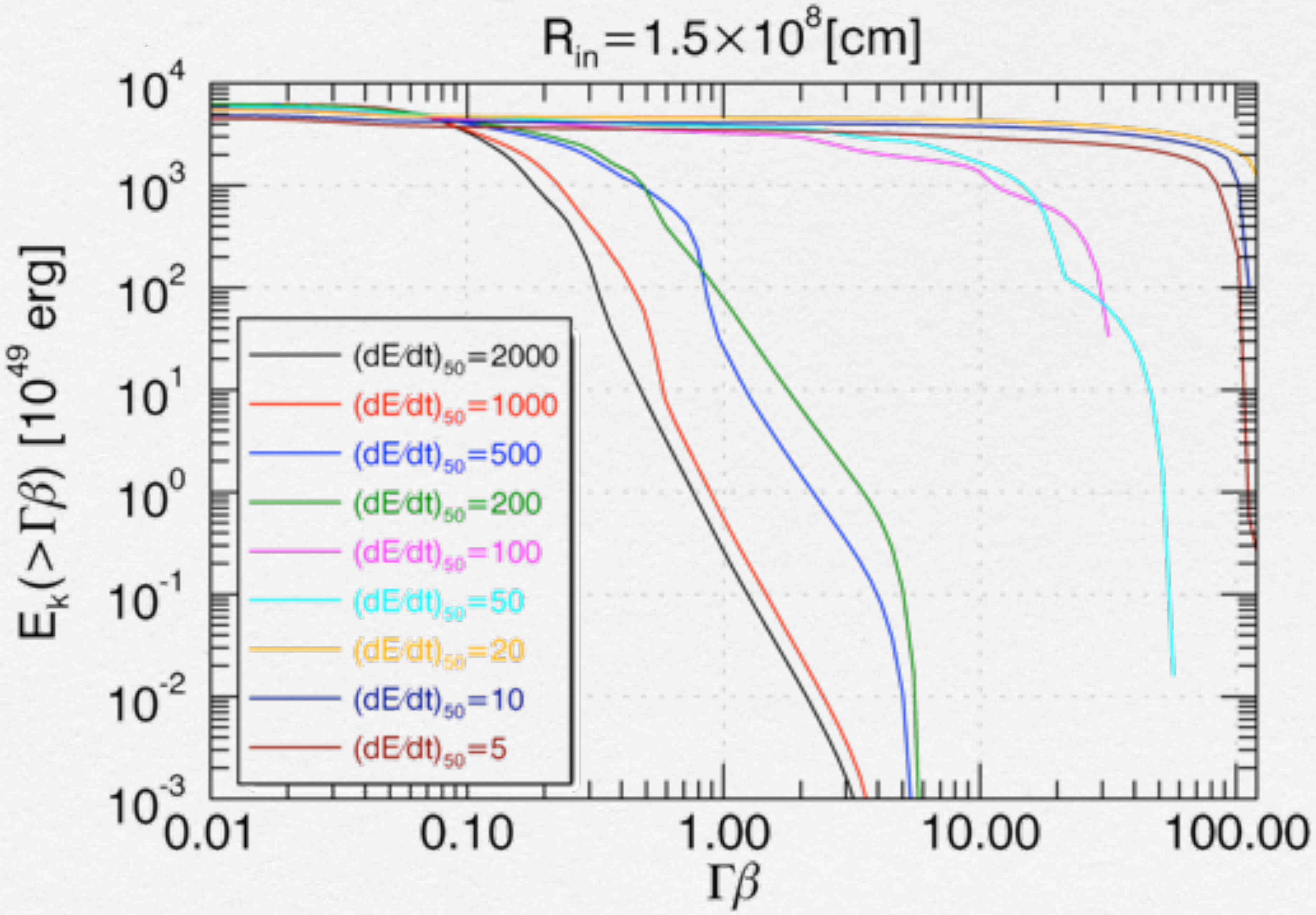
$$E_{\mathrm{k}}(>\Gamma\beta) = \int \Gamma(\Gamma-1)\rho dV,$$

- Models with successful jet → flat distribution
- Models with failed jet → steep distribution at around $\Gamma\beta = 0.1$ - 10

successful jet $\Gamma > 10$-20

relativistic ejecta, $E(\Gamma\beta>1)>10^{49}$ erg

non-rel. ejecta, $E(\Gamma\beta>1)<10^{49}$ erg



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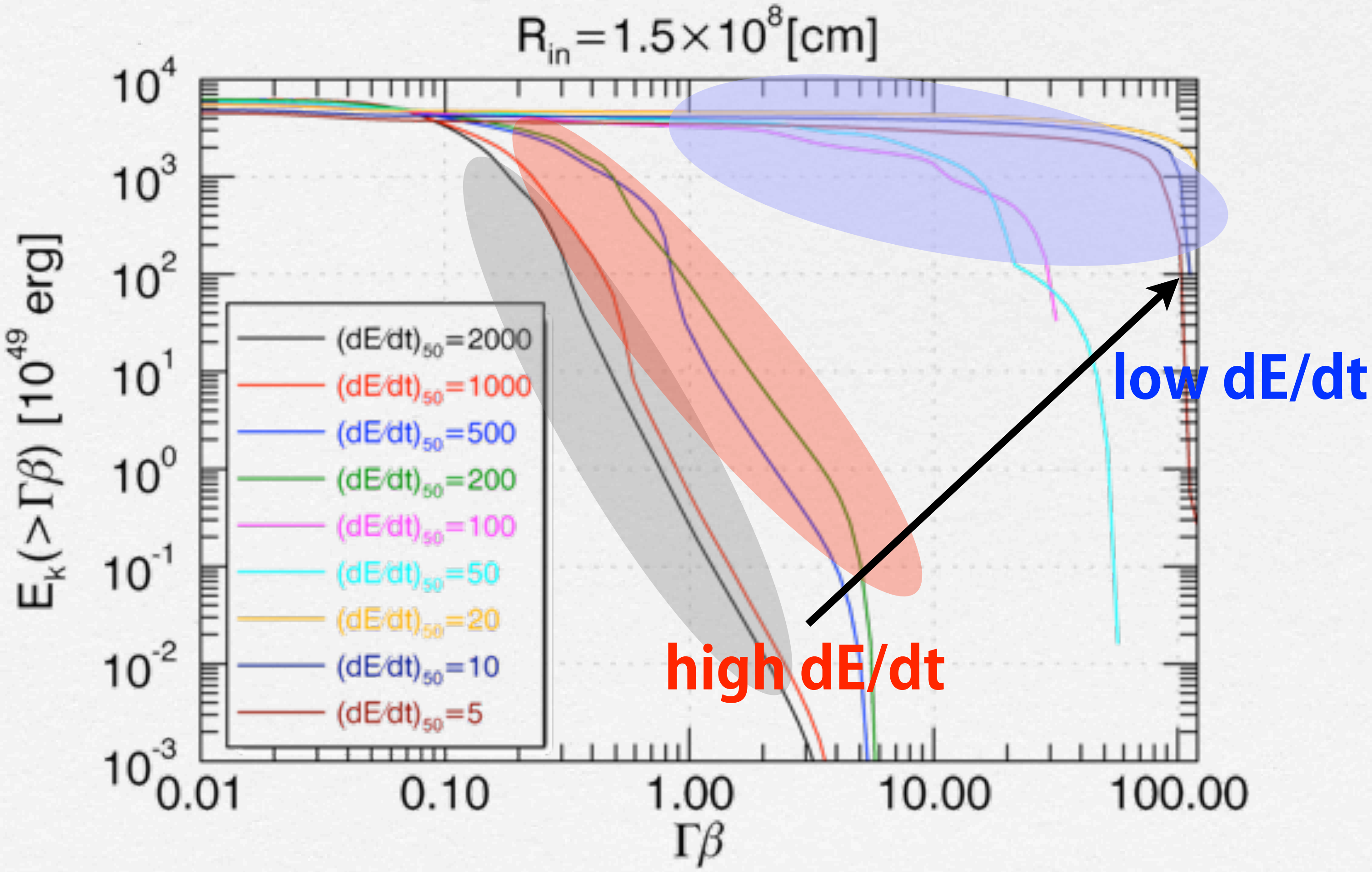
successful jet $\Gamma > 10\text{-}20$

relativistic ejecta, $E(\Gamma\beta > 1) > 10^{49}$ erg

non-rel. ejecta, $E(\Gamma\beta > 1) < 10^{49}$ erg



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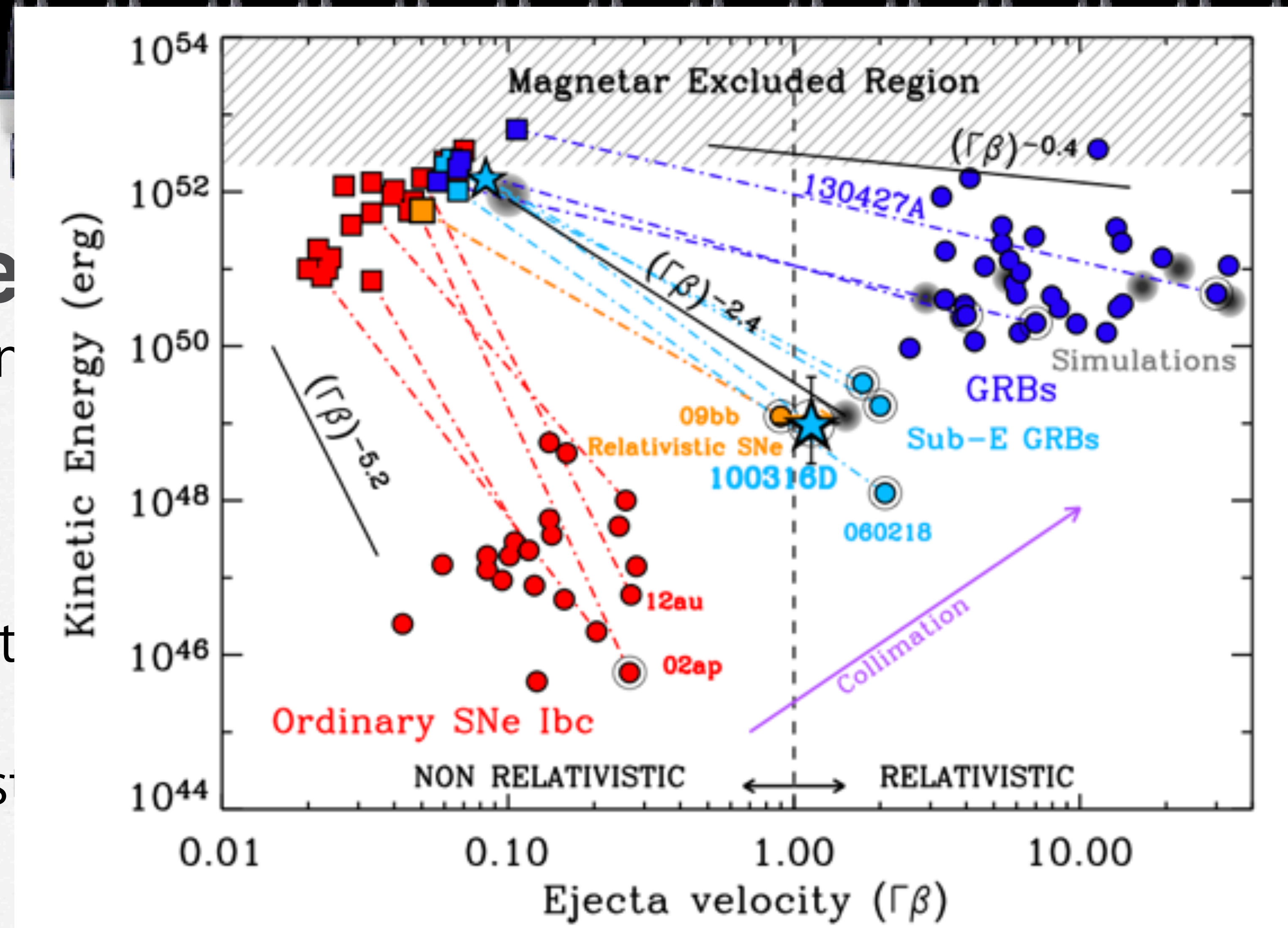

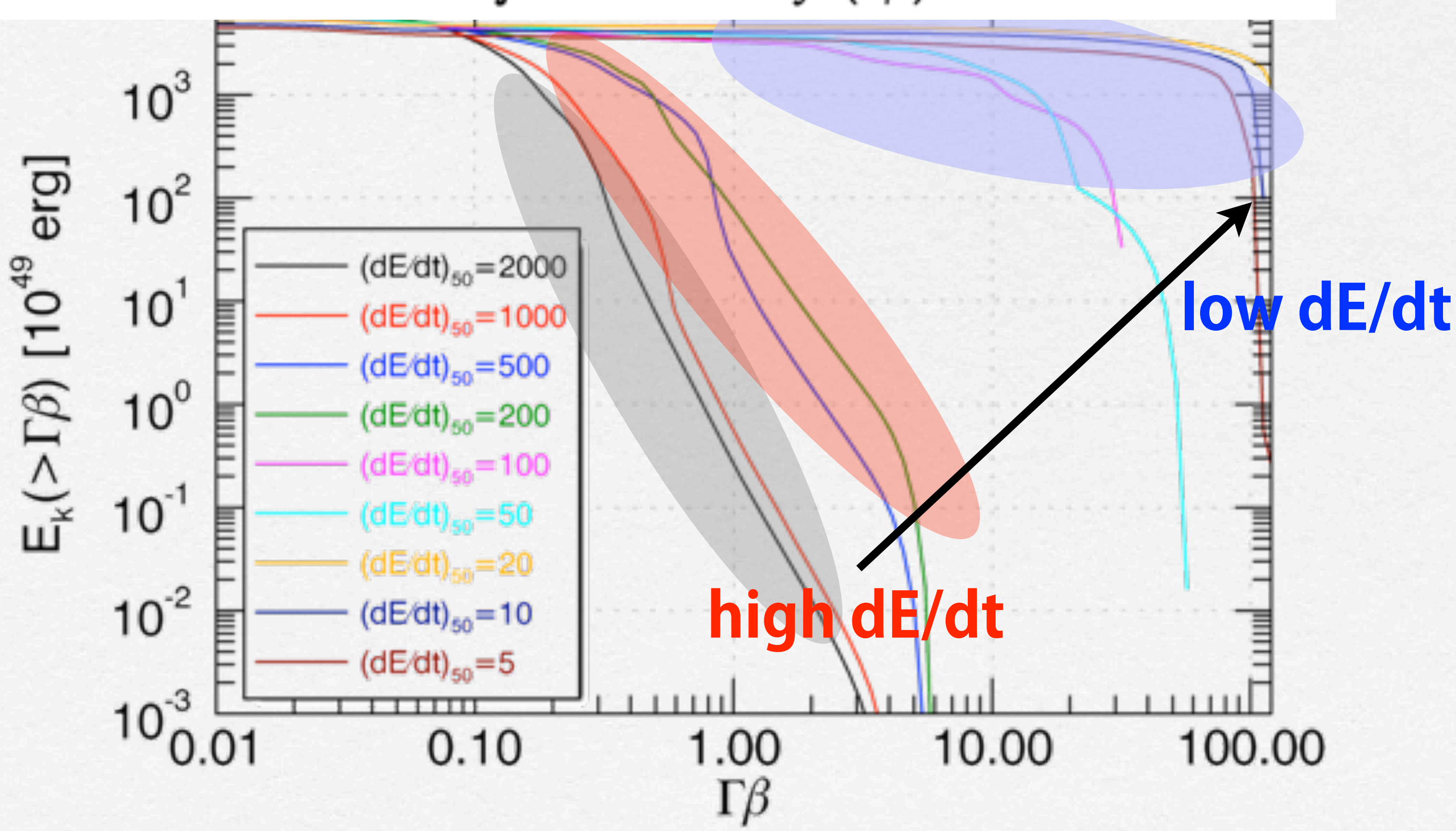

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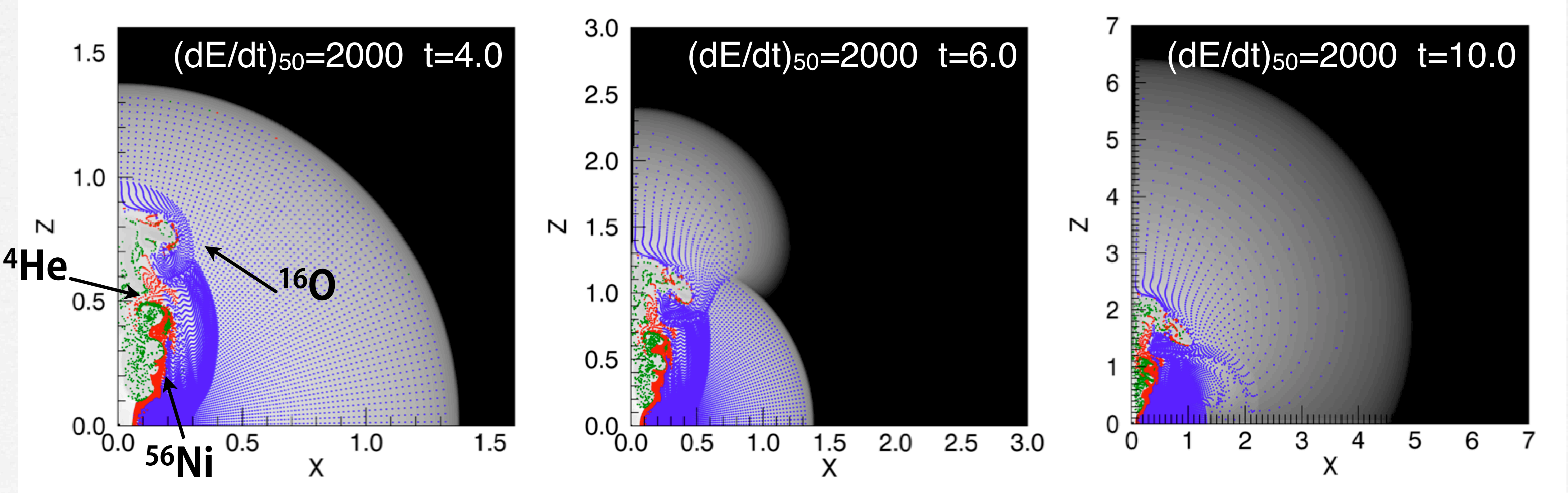
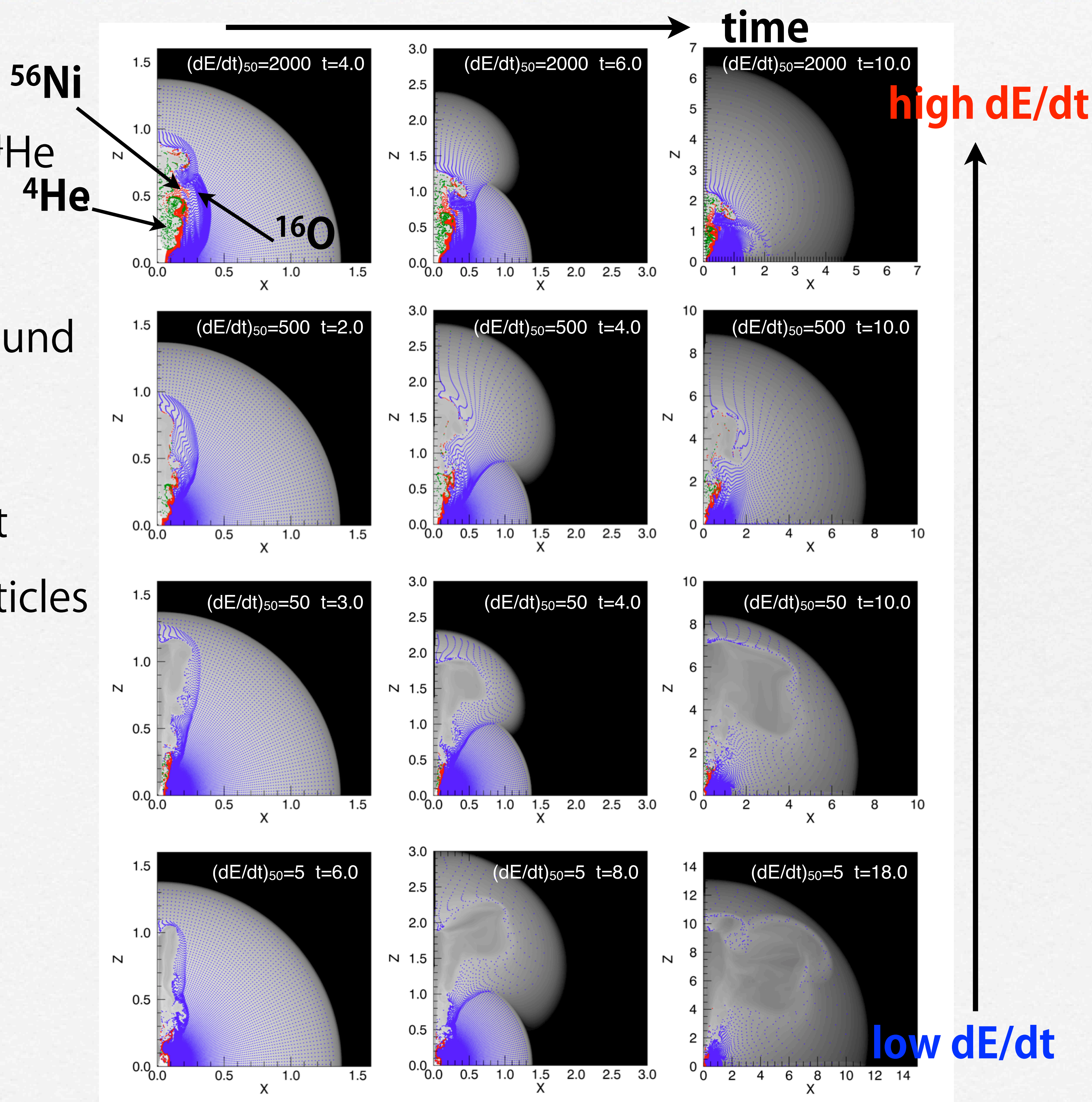
Explosive Nucleosynthesis

- tracer particle method: nucleosynthesis calculation as a post-process
- nuclear reaction network: from n,p up to Tc ~490 nuclei, ~6500 reactions
- tracer particles (~16000) are advected in the ejecta→the thermal history of the particles are used for nucleosynthesis calculation
- red: ^{56}Ni, blue: ^{16}O, green: ^{4}He



Results

- red: ^{56}Ni, blue: ^{16}O, green: ^{4}He
- high dE/dt models tend to produce more ^{56}Ni,^{4}He around the jet axis
- ρ_{peak}-T_{peak} plot: high dE/dt models produce more particles with higher maximum temperature



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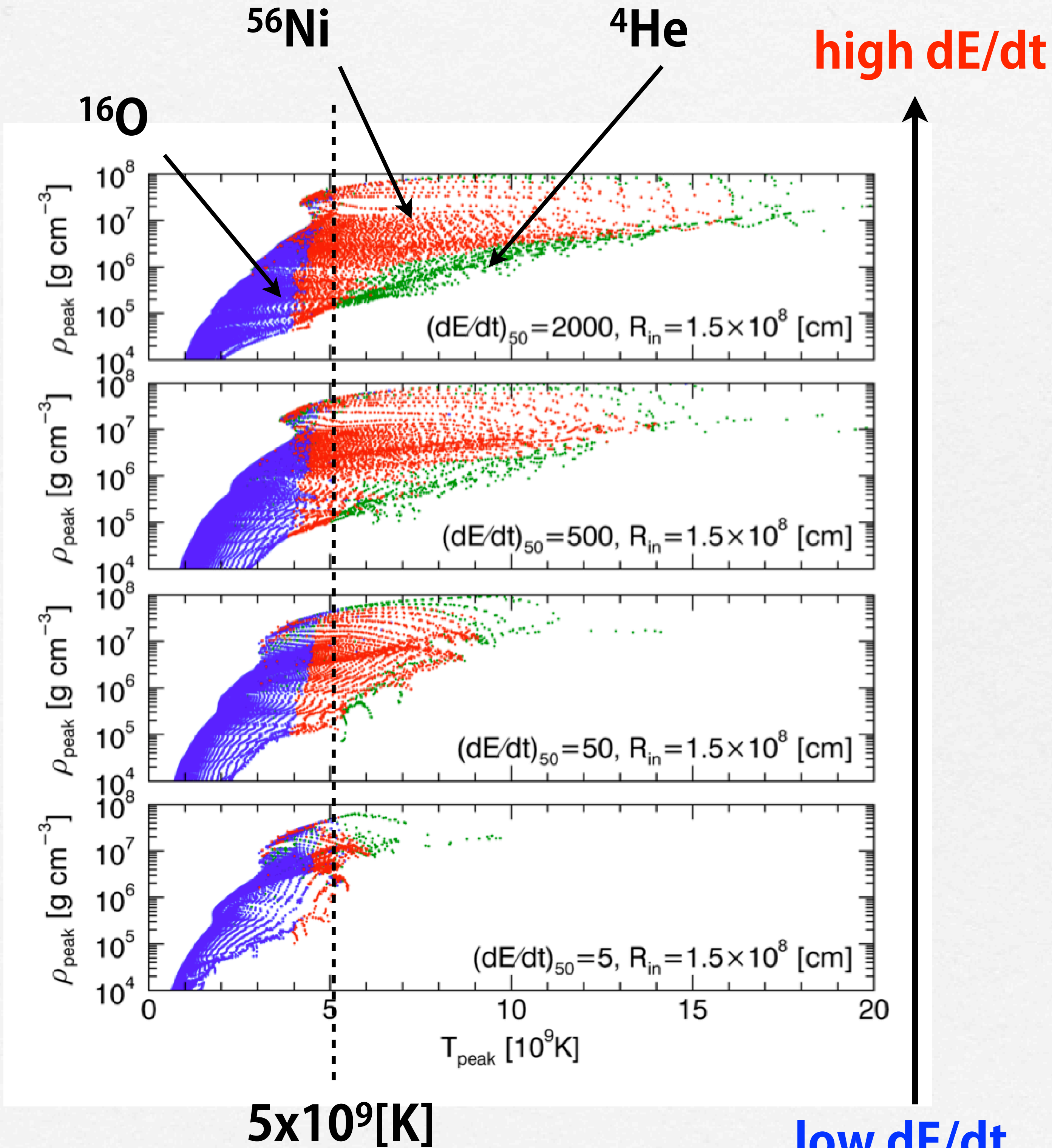
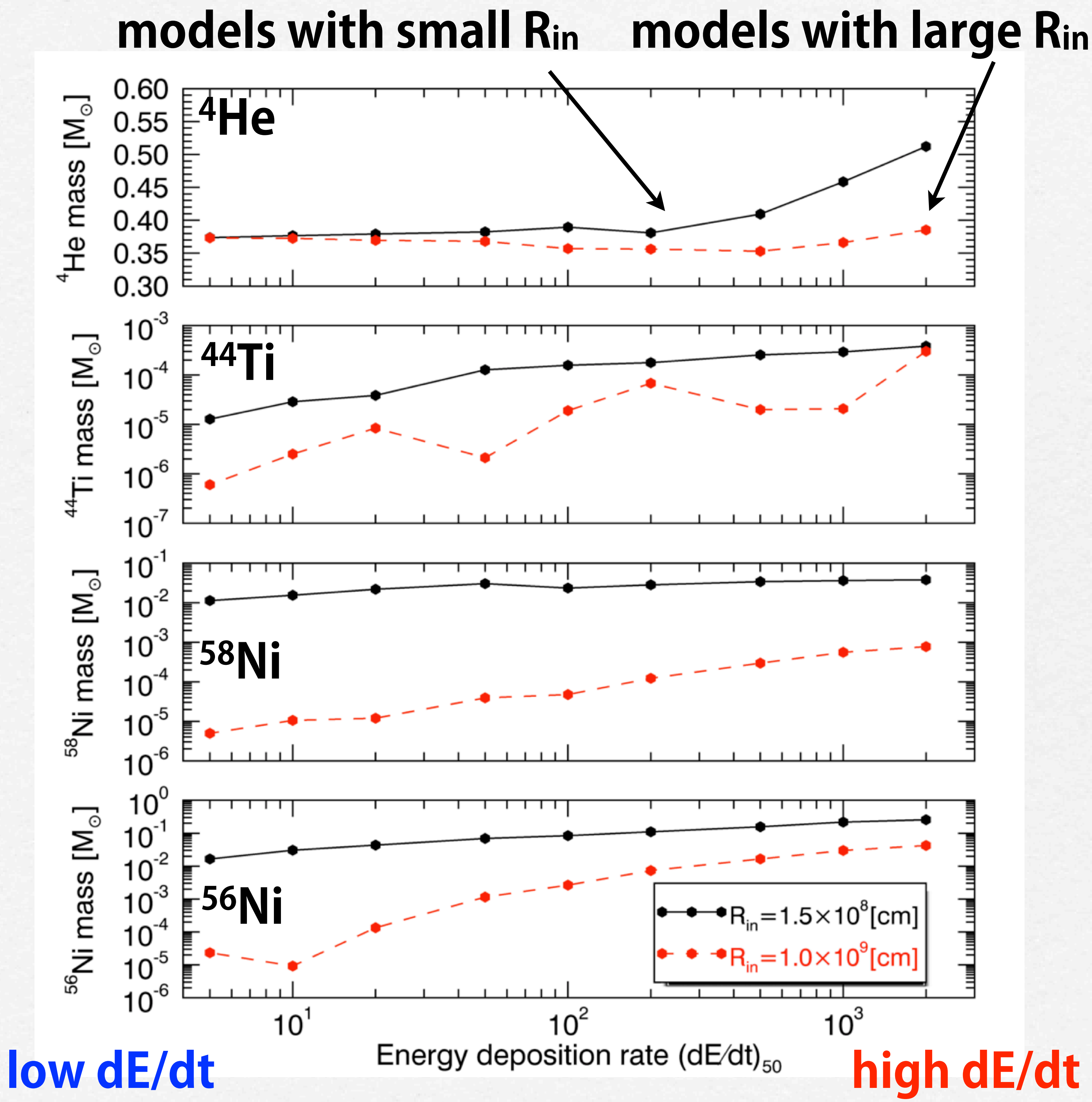


Results

- amount of some nuclei synthesized by the explosive nucleosynthesis
- M(^{56}Ni)>0.1M$_\odot$ =dE/dt>5x10^{52}[erg/s]
- the amount of ^{58}Ni reflect the injection radius.
- small injection radius models bring (low Ye) materials at the outermost layer of the iron core into the ejecta.



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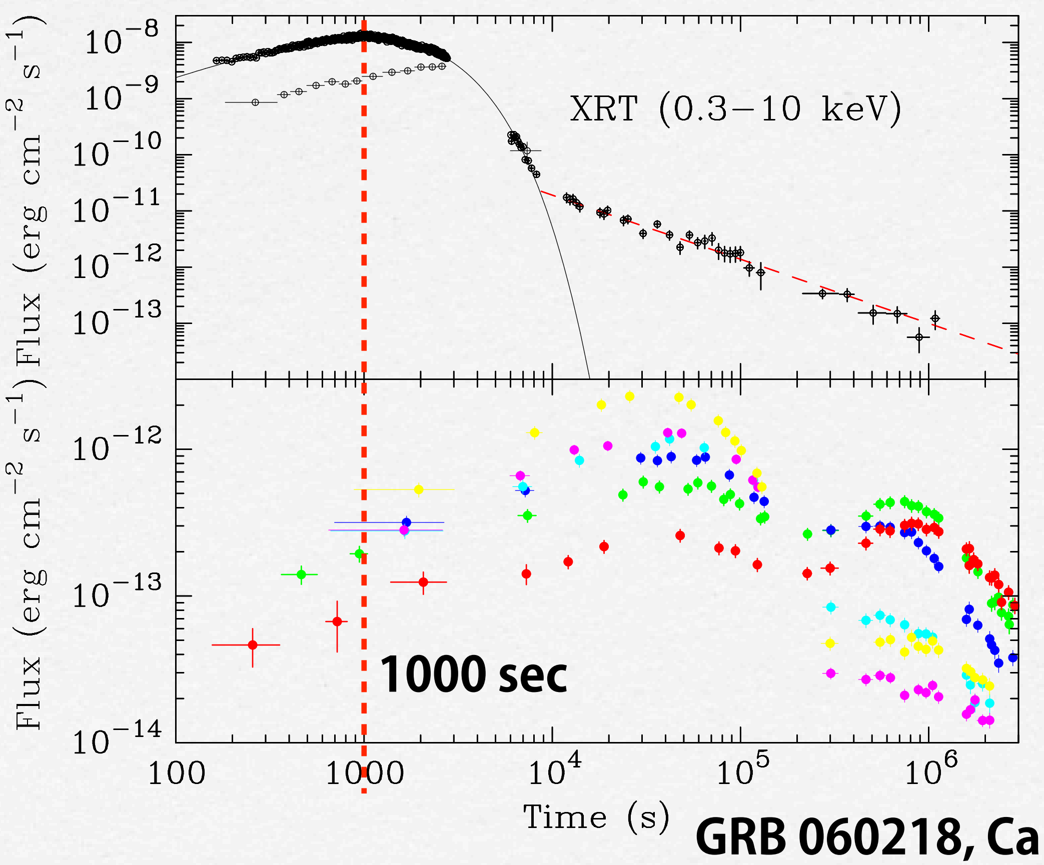
Summary

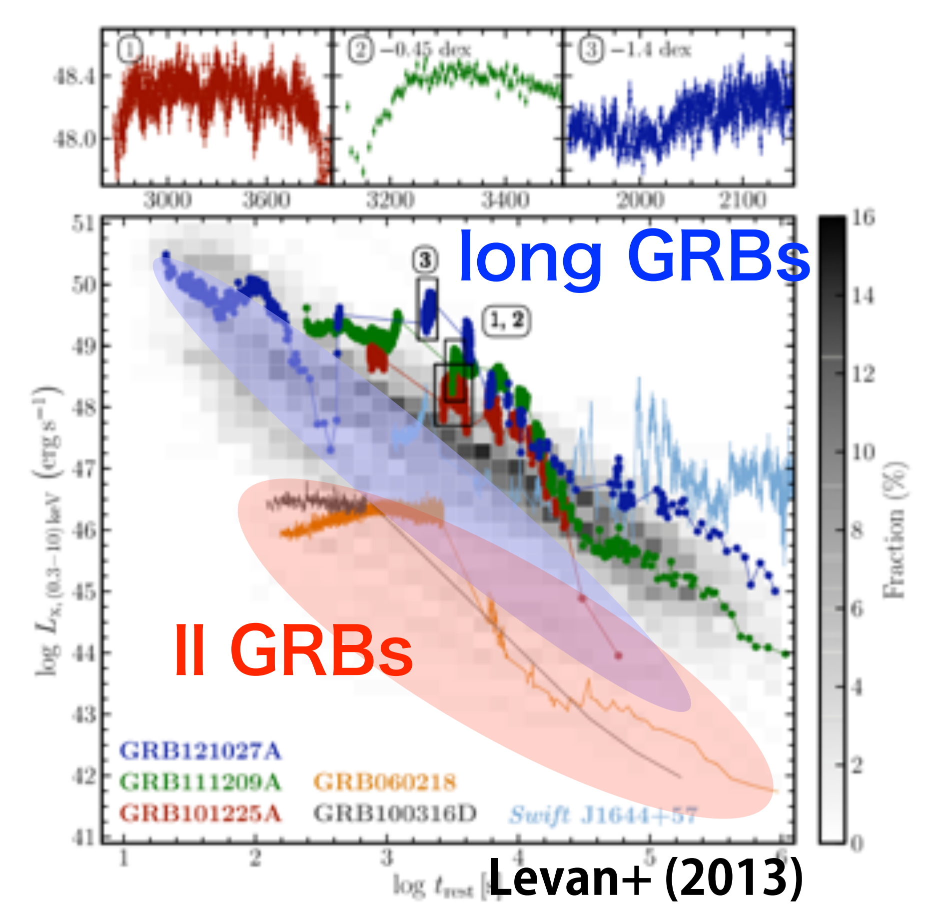
- Systematic studies of GRB jets with various sets of injection conditions and explosive nucleosynthesis in a context of standard/low-luminosity GRBs
- high dE/dt: ^{56}Ni -rich ejecta and ^{4}He production via alpha-rich freeze-out
- Extremely high energy injection rates are needed to produce sufficient amount of ^{56}Ni to explain the brightness of SN component associated with some GRBs: $M(^{56}\mathrm{Ni})>0.1M_{\odot} = dE/dt>5\times10^{52}$[erg/s]
- we need another ^{56}Ni production site? (e.g., disk wind)
- Some nuclei can be used as a tracer of the jet injection condition: ^{44}Ti, ^{58}Ni (possible ^{58}Ni detection in SN 2006aj: Maeda+(2007))

Low-luminosity GRBs

- llGRBS: less energetic and less luminous subgroup of long GRBs
- They are found in the nearby universe. The event rate seems to be 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



GRB 060218, Campana+ (2006)

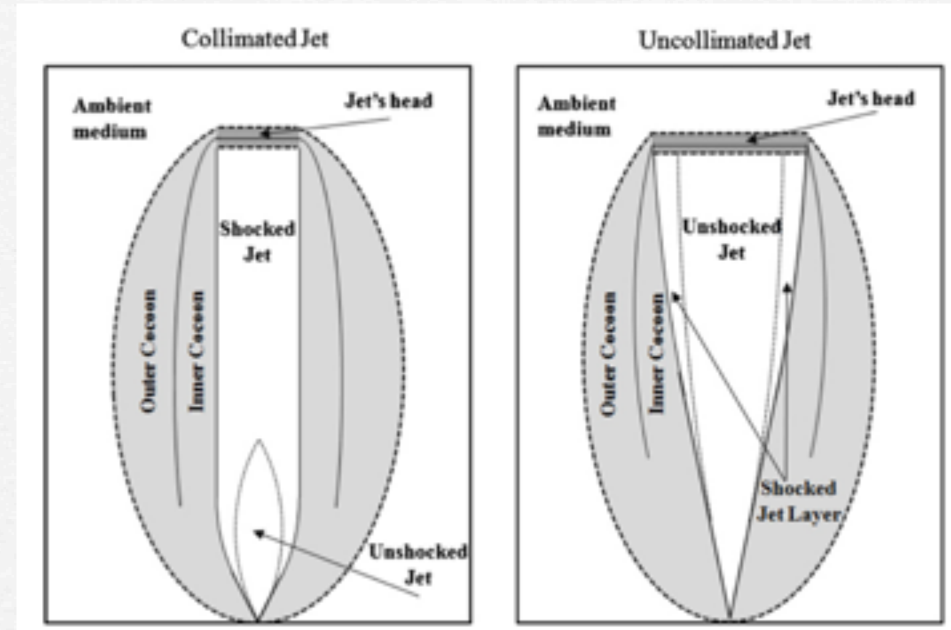


Levan+ (2013)

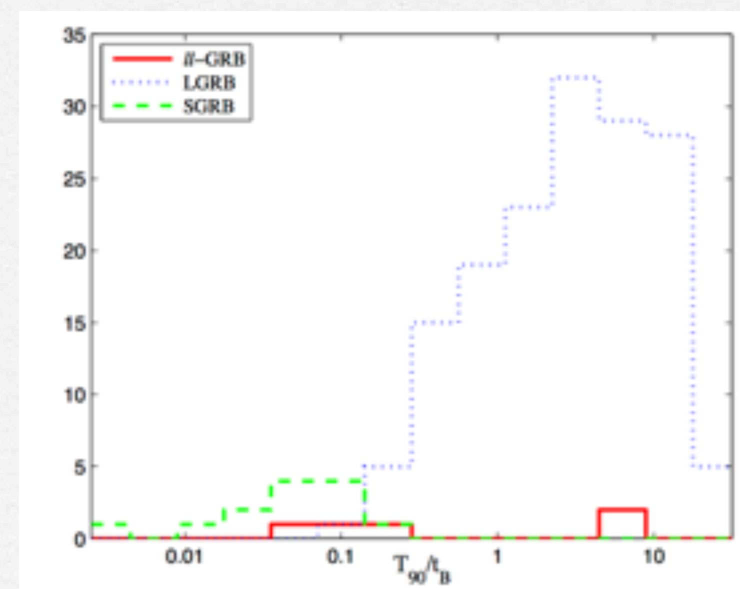
Failed jet hypothesis

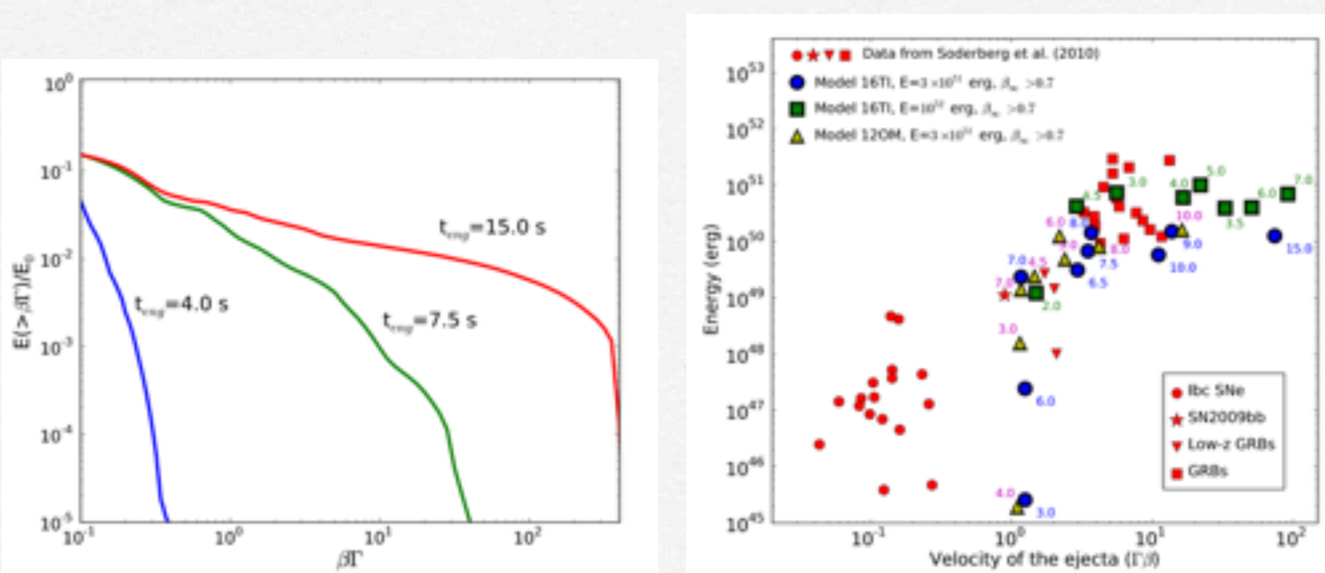
- E_{kin} for relativistic ejecta << E_{kin} for non-relativistic ejecta ➡ It is suggested that failed jet model produce such events.

- 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)

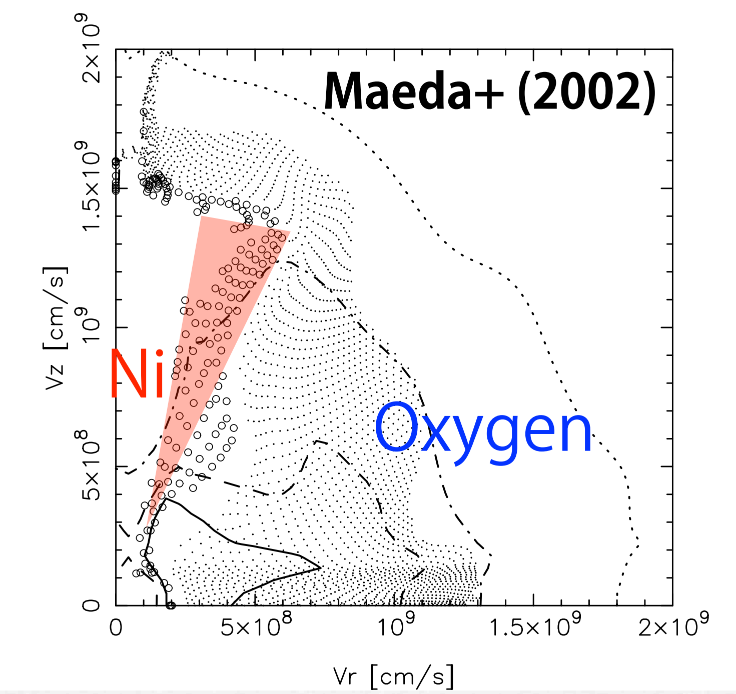




Lazzati+ (2011)

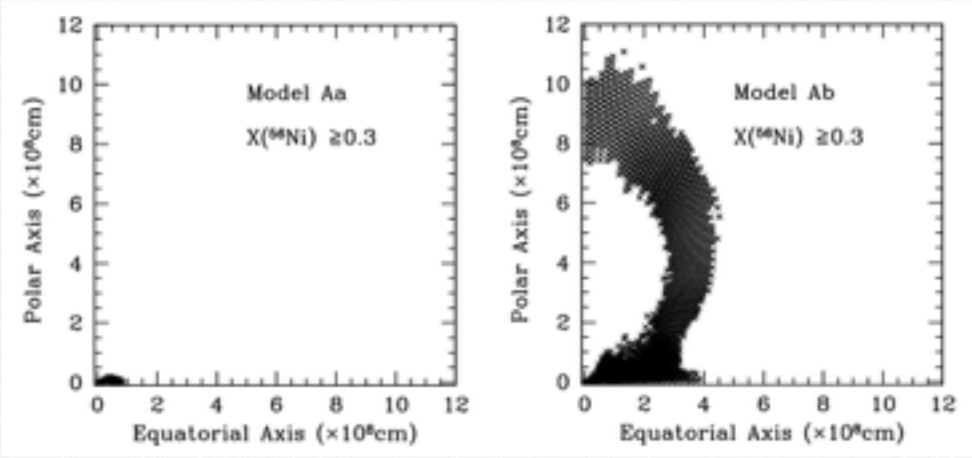
Explosive Nucleosynthesis

- 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 ➡ $M(^{56}Ni) << 0.1 M_\odot$
  instantaneous energy injection ➡ $M(^{56}Ni) \sim 0.1 M_\odot$
- ^{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)



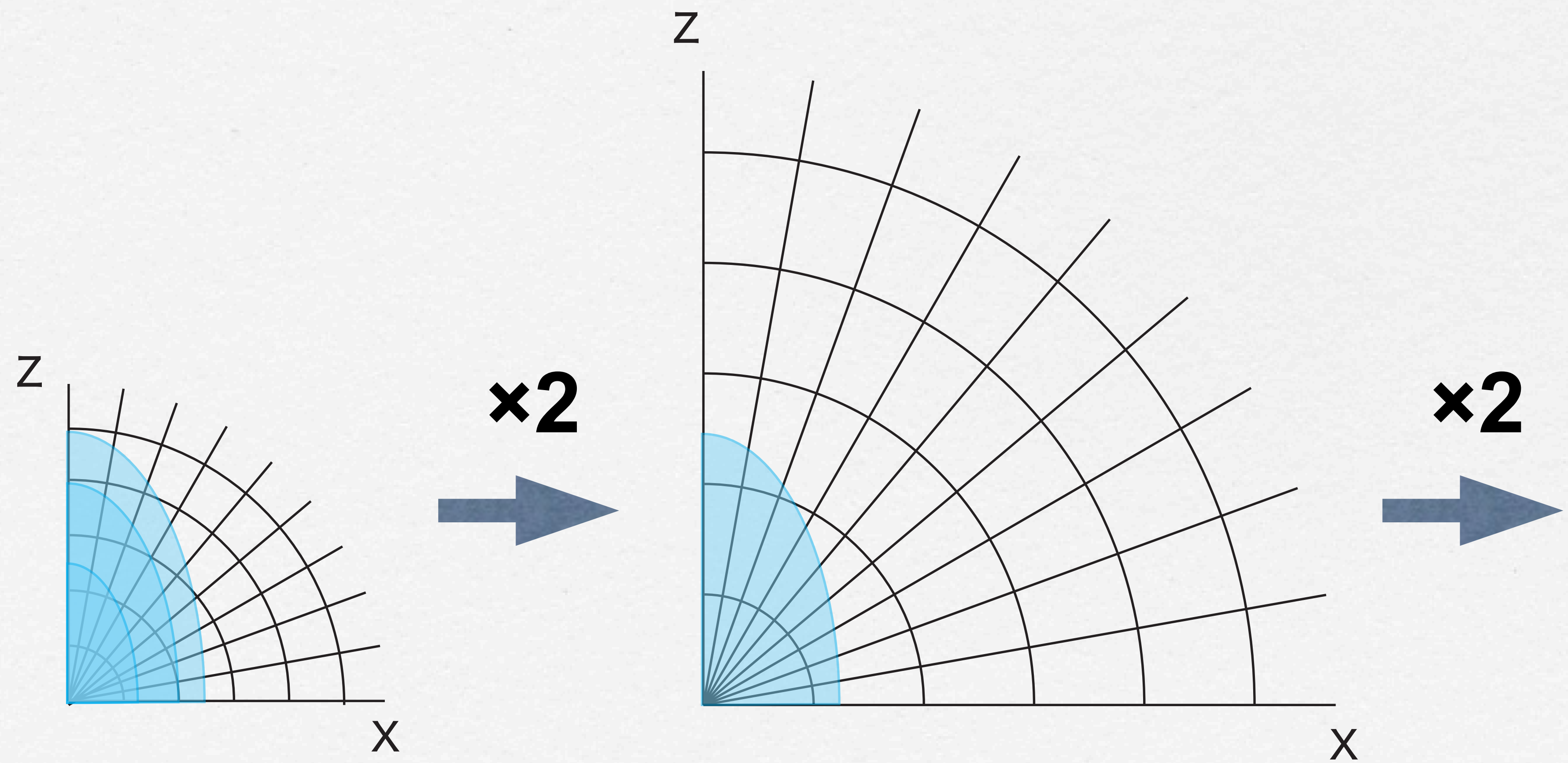
Mapping procedure

- 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