Collapses of rotating supermassive stars

and associating transient

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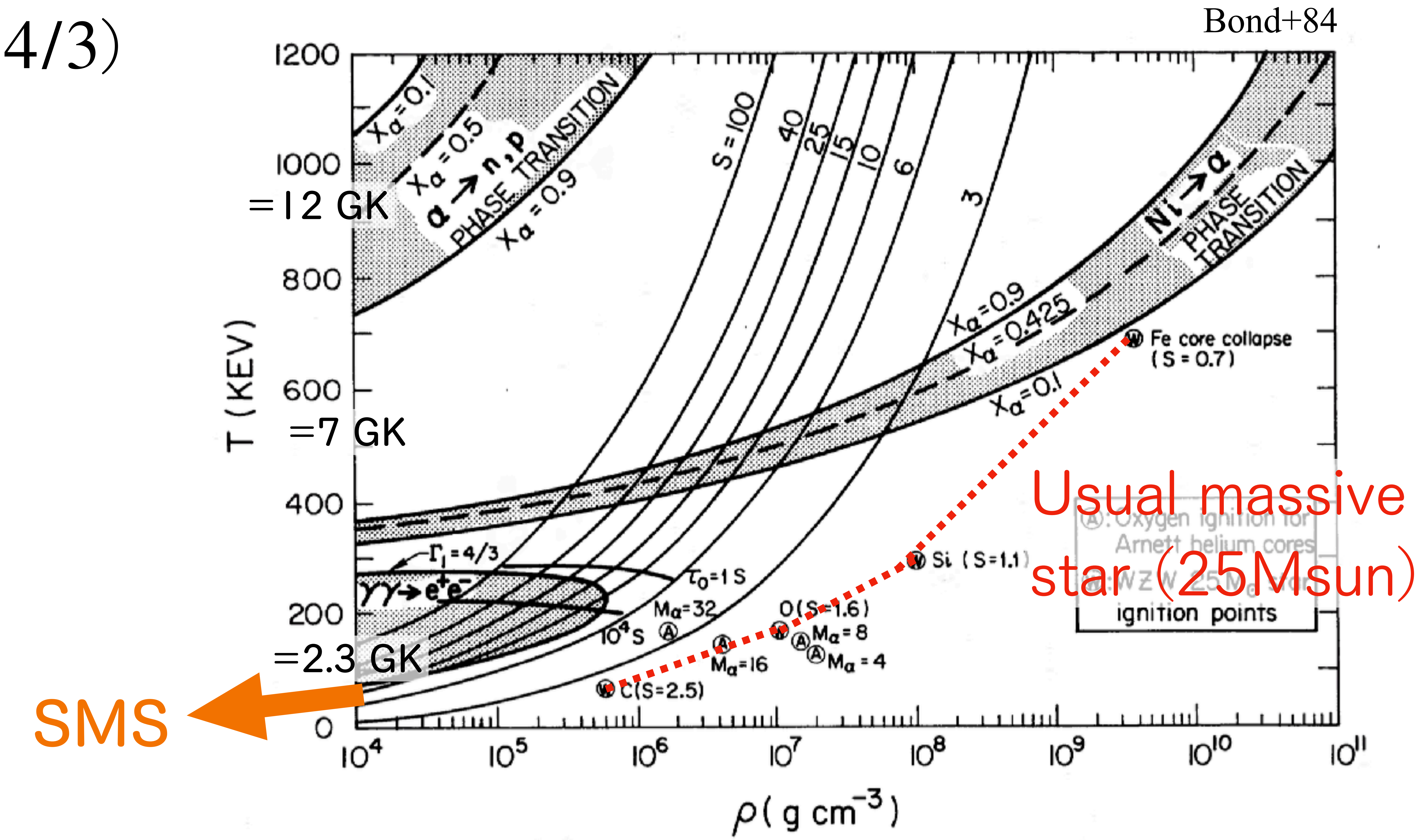
FRIS

Outline

- Collapse and explosion of supermassive stars (~10^5Msun)
  - Introduction
  - Numerical setup
  - Results
- Collapse of usual massive star (~10Msun)

Supermassive star

- Hypothetical very massive ($\gtrsim 10^4 M_\odot$) star
- High-s, $P_{\rm rad}$-dominant $(\Gamma \approx 4/3)$
- Dies likely by GR instability



Supermassive star

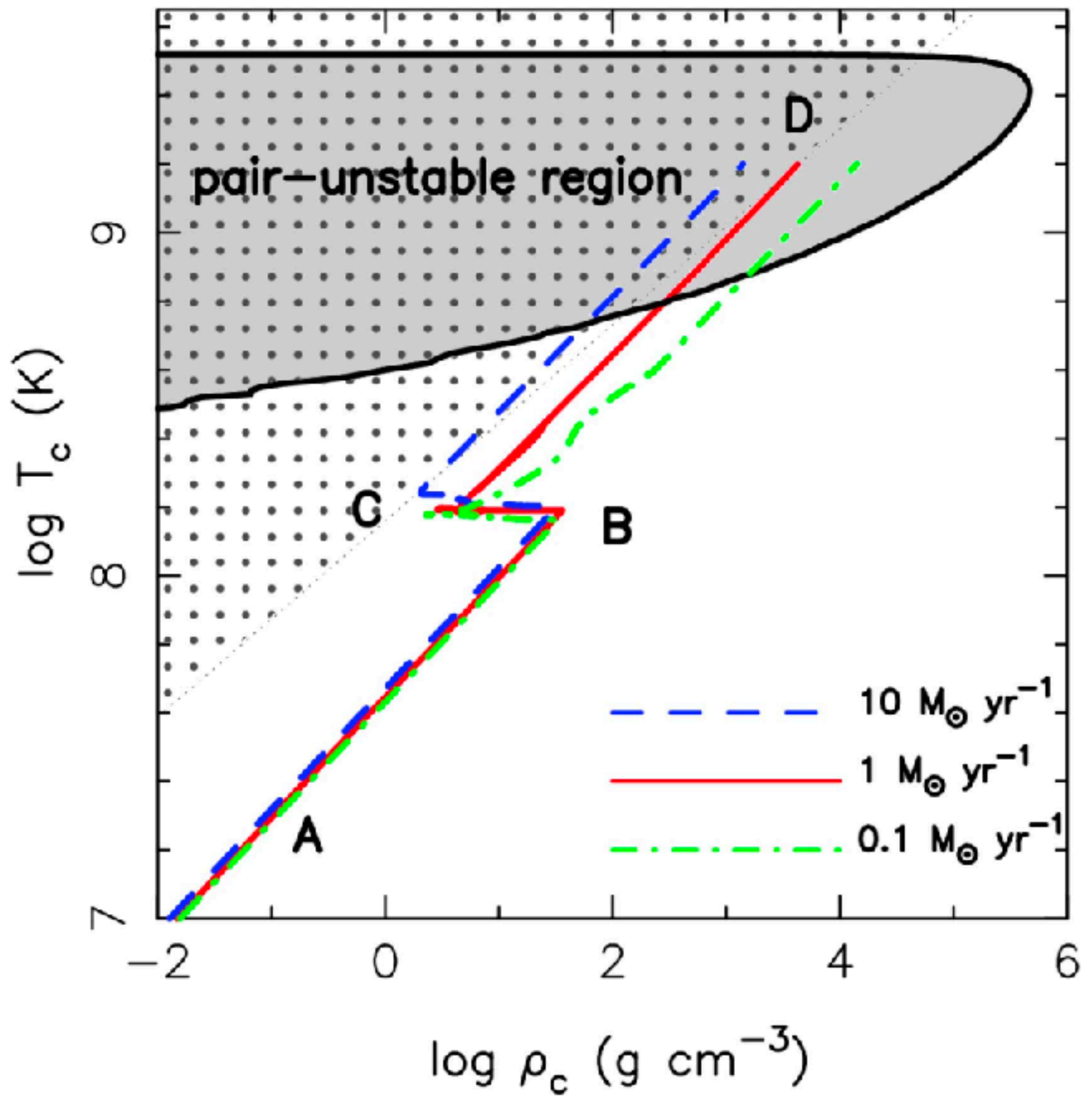
- Hypothetical very massive ($\gtrsim 10^4 M_\odot$) star
- High-s, $P_{\rm rad}$-dominant $(\Gamma \approx 4/3)$
- Dies likely by GR instability

$$\rho_{\rm crit} \approx 1.994 \times 10^{18} \left(\frac{0.5}{\mu}\right)^3 \left(\frac{M_\odot}{M}\right)^{7/2} \ {\rm g\ cm^{-3}}$$

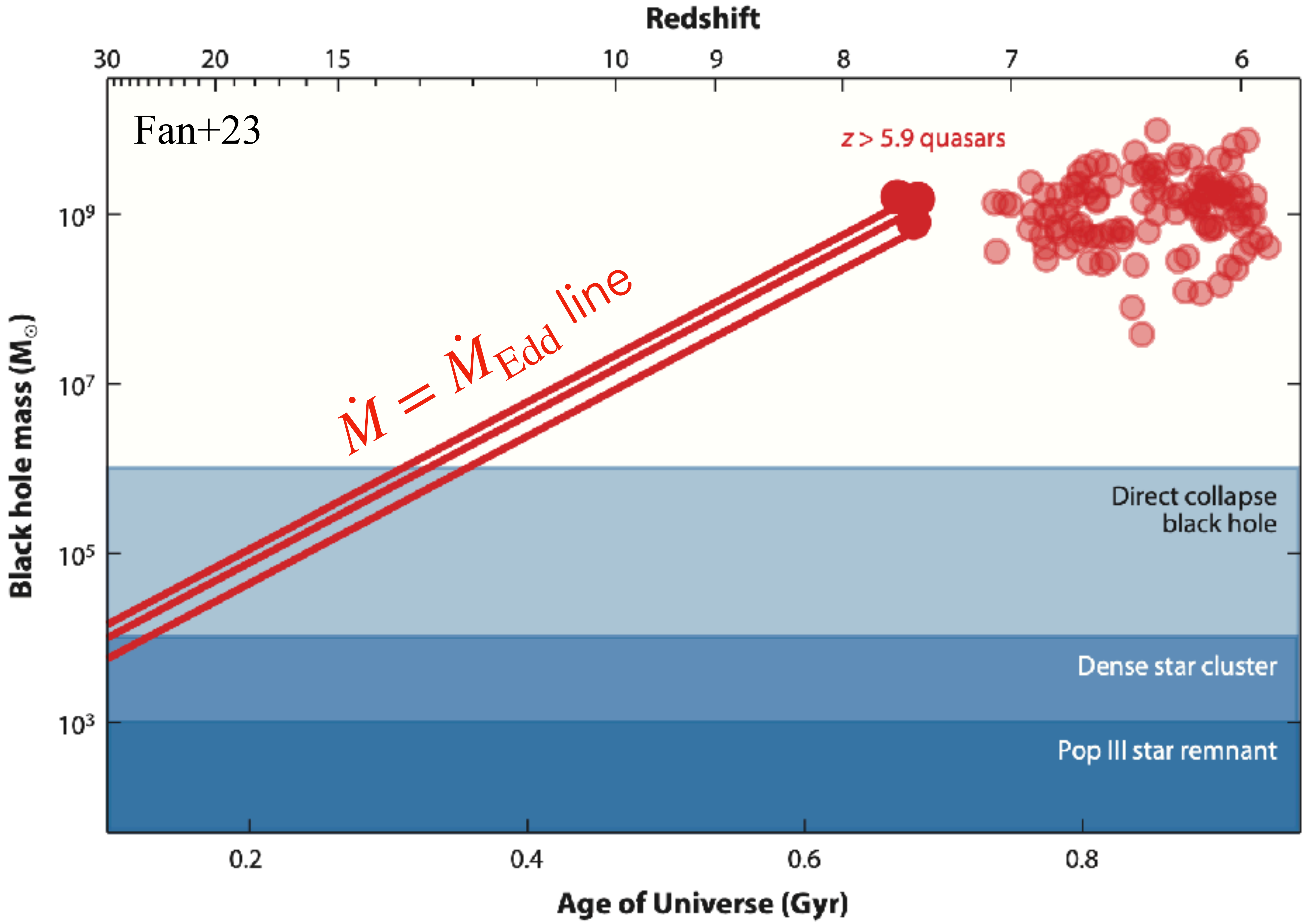
$$\approx 4\ {\rm g/cm^3}\ (M/10^5 M_\odot)^{-3.5} (\mu/0.59)^{-3}$$

(Shapiro-Teukolsky 83, Fuller+86)

Umeda+16



SMBHs in early universe



Distant (high-z) SMBH with $M \sim 10^9 M_\odot$

How are they formed?

Basic idea: $\dot{M} \lesssim \dot{M}_{\rm Edd} \propto M$.

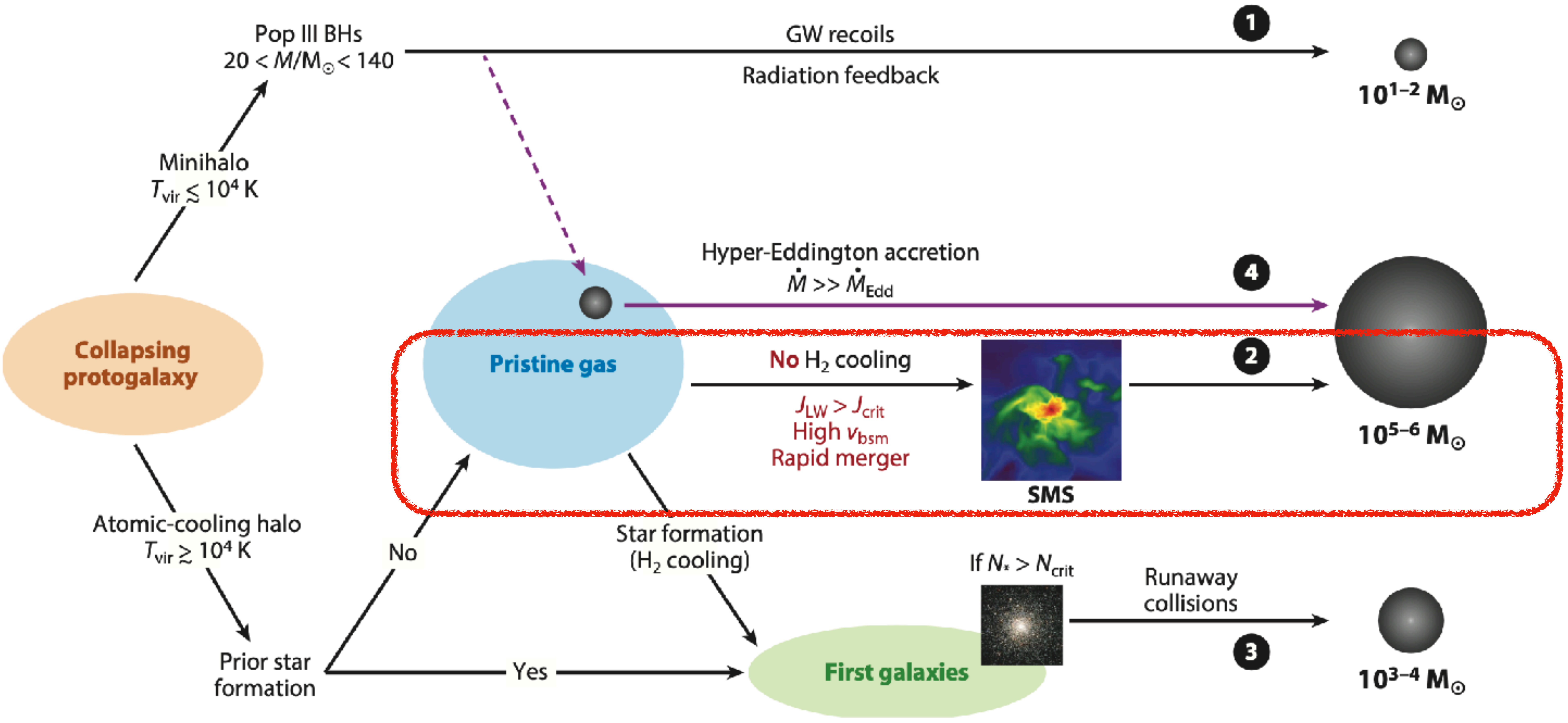
(Super/hyper-Eddington accretion may be possible)

Keeping a high Eddington ratio $\dot{M}/\dot{M}_{\rm Edd}$

from $10^2 M_\odot$ to $10^9 M_\odot$ may not be easy

Initial high mass of BH may make it easier!

Direct collapse scenario for SMBHs in early universe

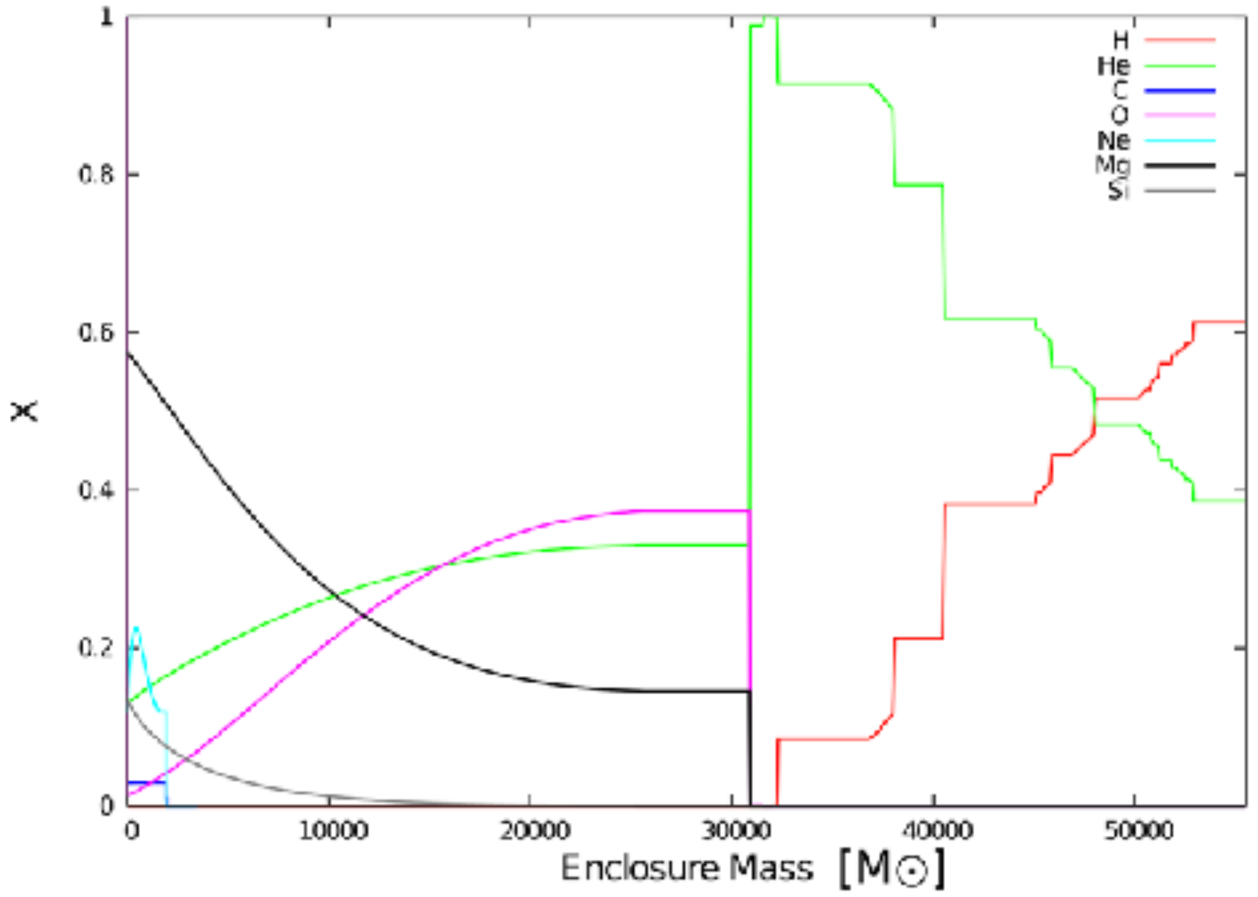


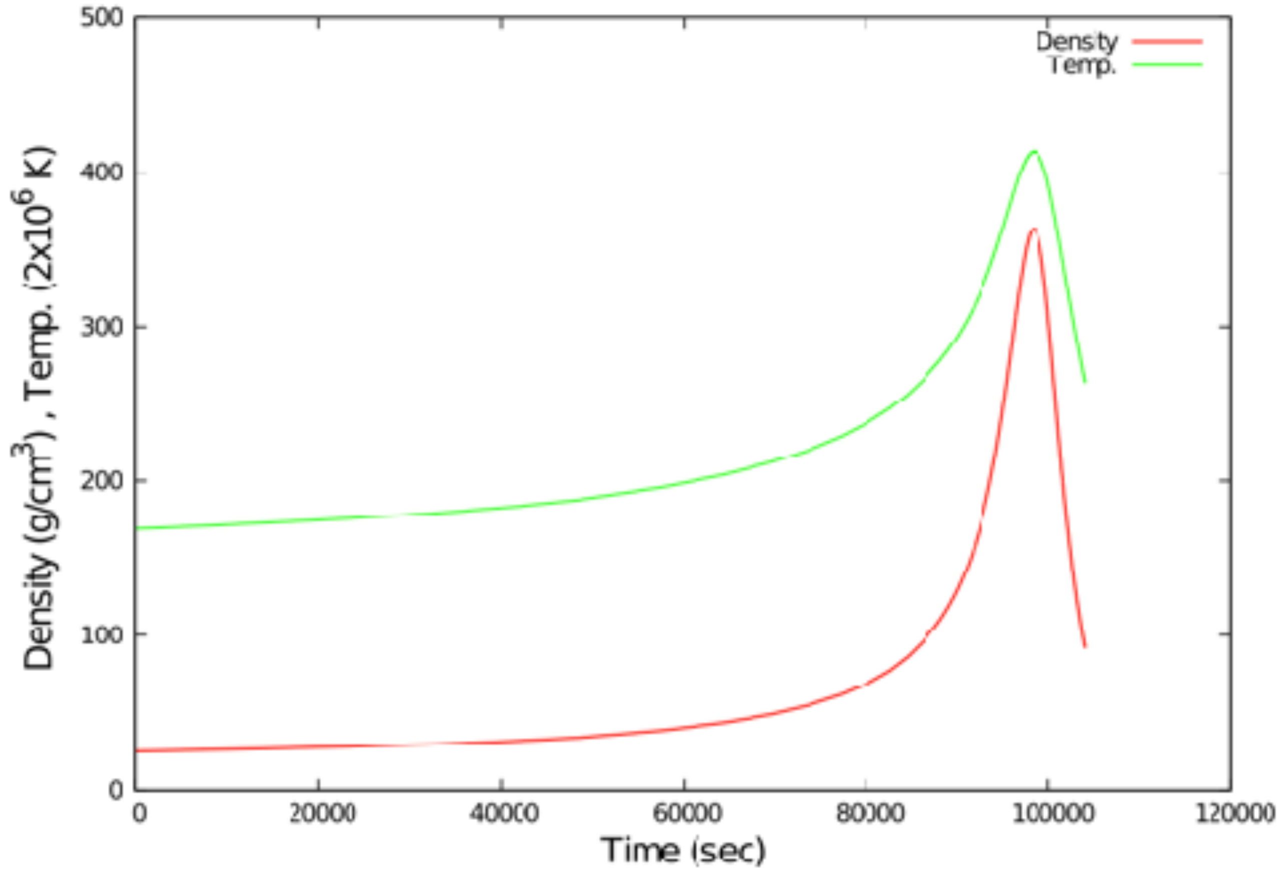
Inayoshi+20, see also Rees 1978

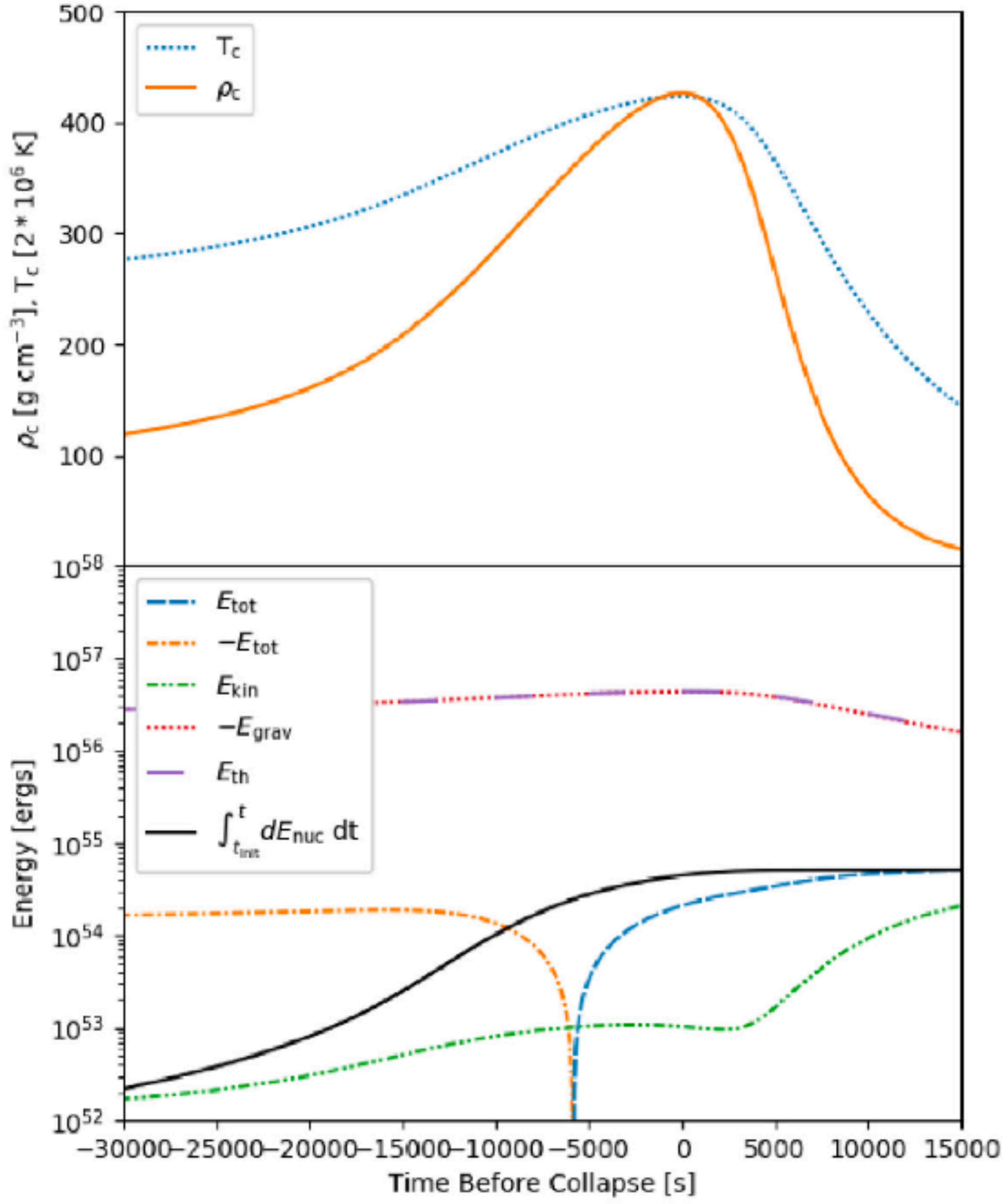
Explosion of supermassive stars: thermonuclear case

Chen+14

Nagele+20, 22







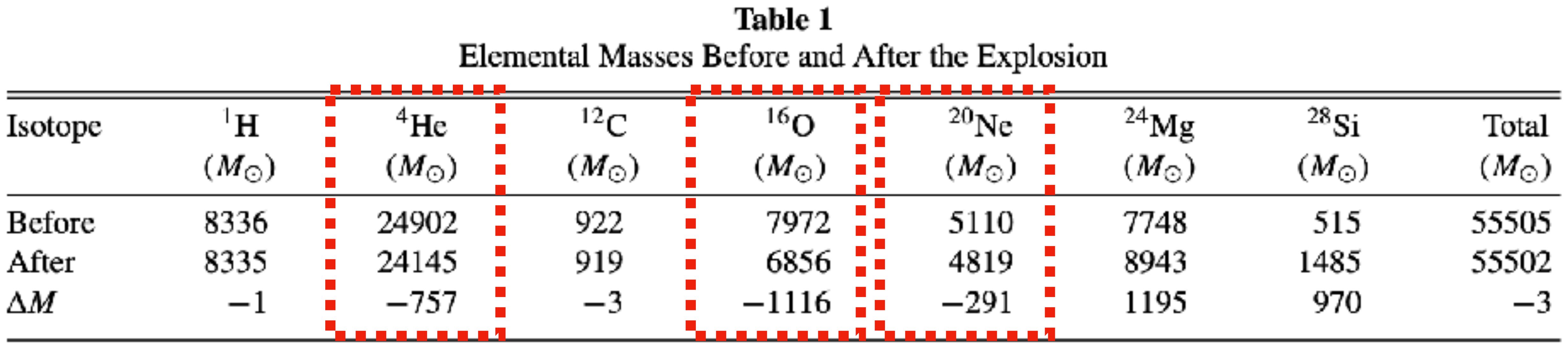


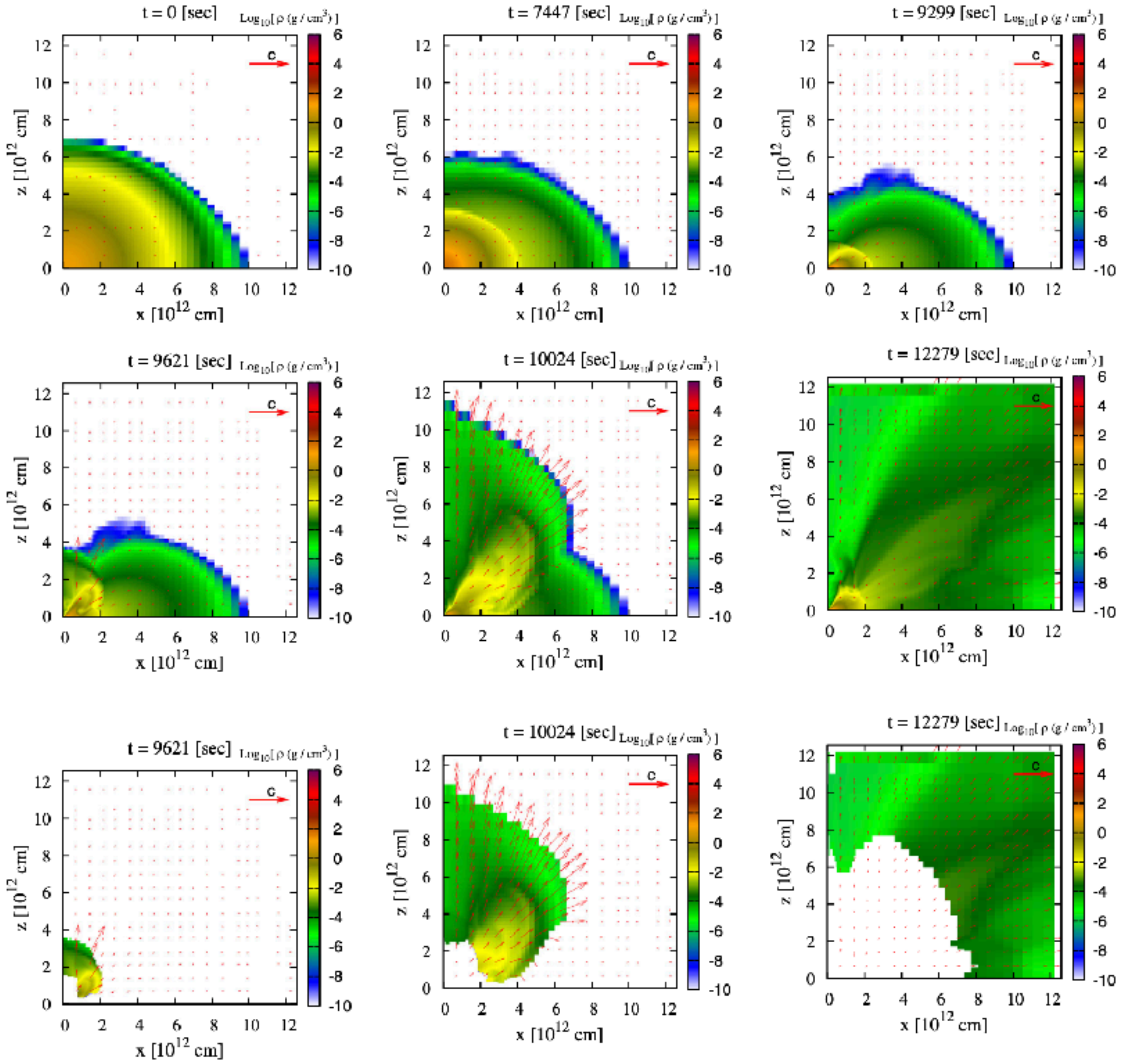
Table 1
Elemental Masses Before and After the Explosion

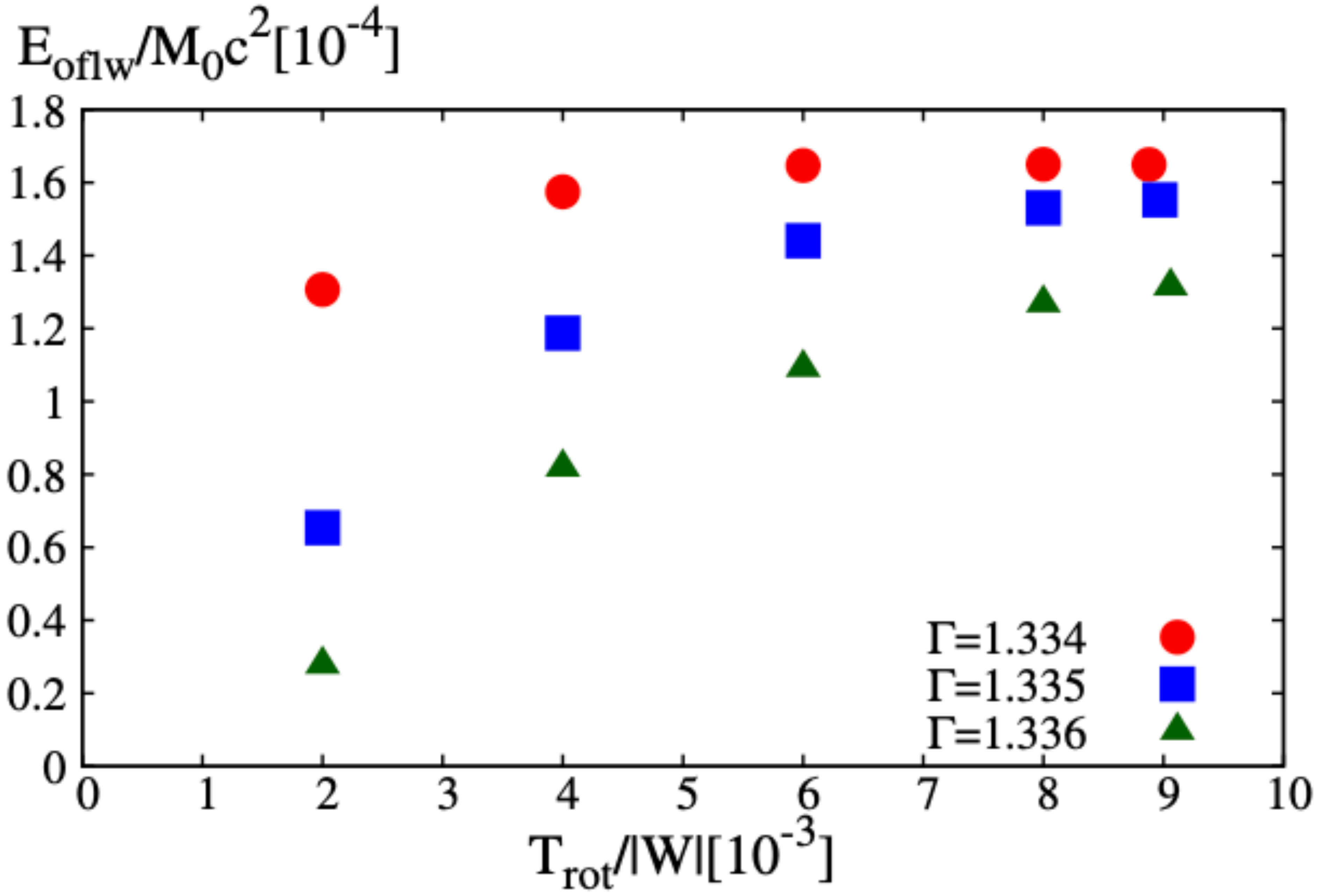
Isotope	^{1}H ($M_\odot$)	^{4}He ($M_\odot$)	^{12}C ($M_\odot$)	^{16}O ($M_\odot$)	^{20}Ne ($M_\odot$)	^{24}Mg ($M_\odot$)	^{28}Si ($M_\odot$)	Total ($M_\odot$)
Before	8336	24902	922	7972	5110	7748	515	55505
After	8335	24145	919	6856	4819	8943	1485	55502
ΔM	−1	−757	−3	−1116	−291	1195	970	−3

$^{16}O(\alpha,\gamma)^{20}Ne(\alpha,\gamma)^{24}Mg$ is responsible for explosion

Effects of rotation: bounce-induced explosion

Uchida+17





Method: Numerical setup

General relativistic gravity

Hydrodynamics with nuclear reaction

H → He → C （Only forward reaction）

CNO cycle triple-α

Equation of state

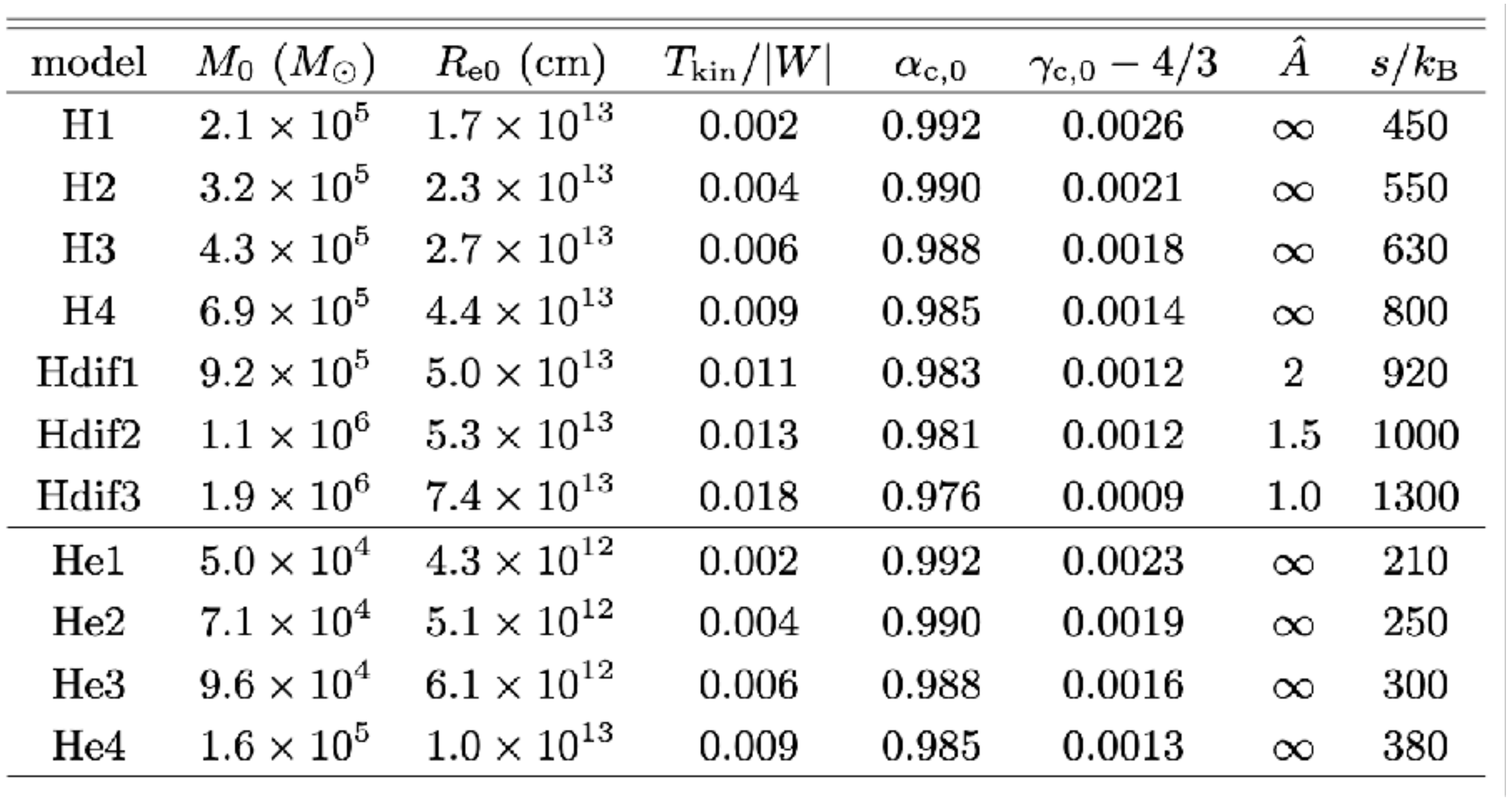
Composite of ions（H, He, C）, photons, electrons and positrons

Neutrino radiation

Only for neutrinos emitted by CNO cycle ~8% of heating rate

Method: Initial supermassive star models

Marginally stable SMS with rotation.



model	M_0 $(M_\odot)$	R_{e0} (cm)	$T_{\rm kin}/\|W\|$	$\alpha_{c,0}$	$\gamma_{c,0} - 4/3$	$\hat{A}$	s/k_B
H1	2.1×10^5	1.7×10^{13}	0.002	0.992	0.0026	∞	450
H2	3.2×10^5	2.3×10^{13}	0.004	0.990	0.0021	∞	550
H3	4.3×10^5	2.7×10^{13}	0.006	0.988	0.0018	∞	630
H4	6.9×10^5	4.4×10^{13}	0.009	0.985	0.0014	∞	800
Hdif1	9.2×10^5	5.0×10^{13}	0.011	0.983	0.0012	2	920
Hdif2	1.1×10^6	5.3×10^{13}	0.013	0.981	0.0012	1.5	1000
Hdif3	1.9×10^6	7.4×10^{13}	0.018	0.976	0.0009	1.0	1300
He1	5.0×10^4	4.3×10^{12}	0.002	0.992	0.0023	∞	210
He2	7.1×10^4	5.1×10^{12}	0.004	0.990	0.0019	∞	250
He3	9.6×10^4	6.1×10^{12}	0.006	0.988	0.0016	∞	300
He4	1.6×10^5	1.0×10^{13}	0.009	0.985	0.0013	∞	380

Primordial composition

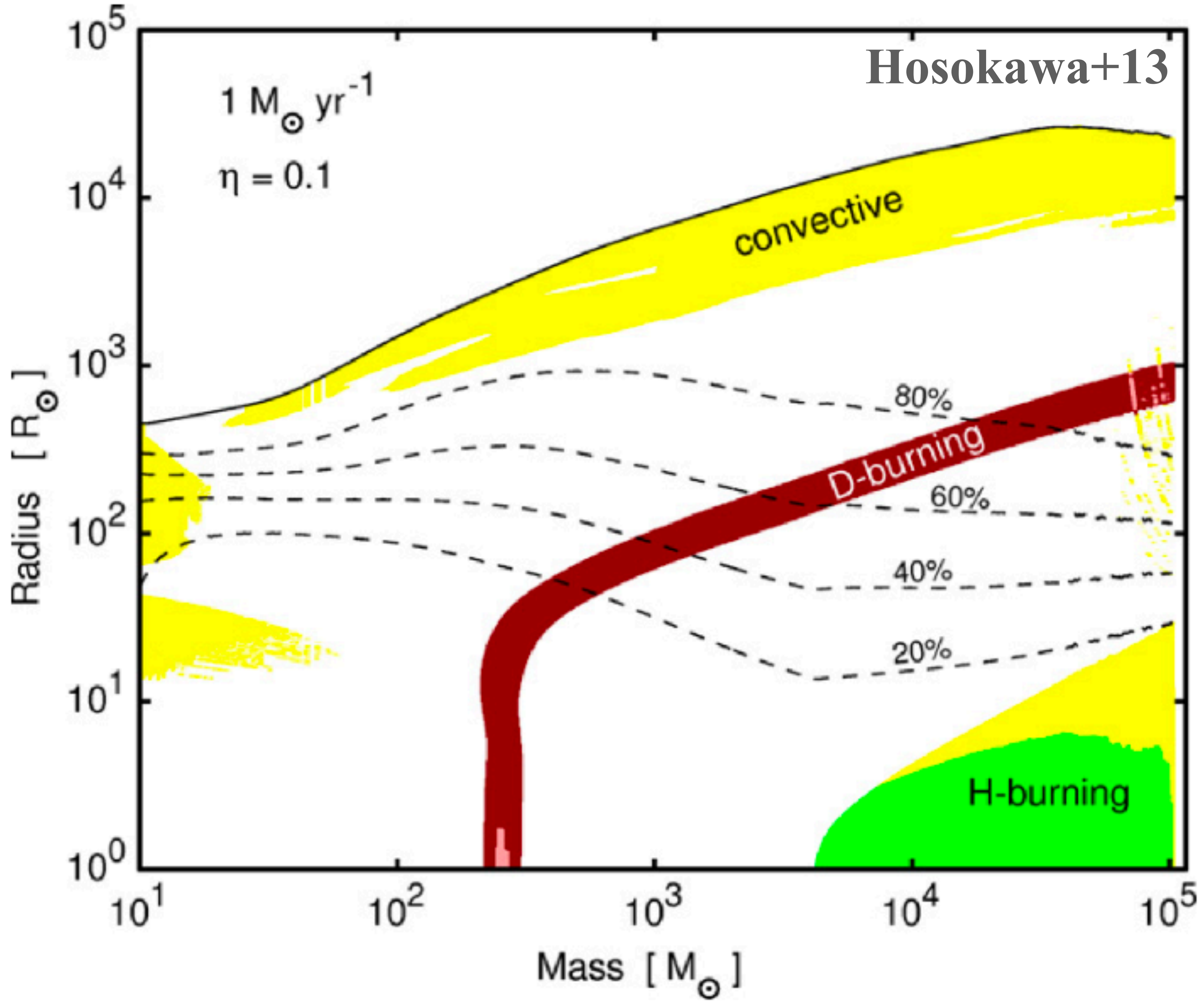
X(H)=0.25, X(He)=0.75

Purely He star

X(He)=1

Method: Initial supermassive star models

Caution: here are only the isentropic "core" of SMS

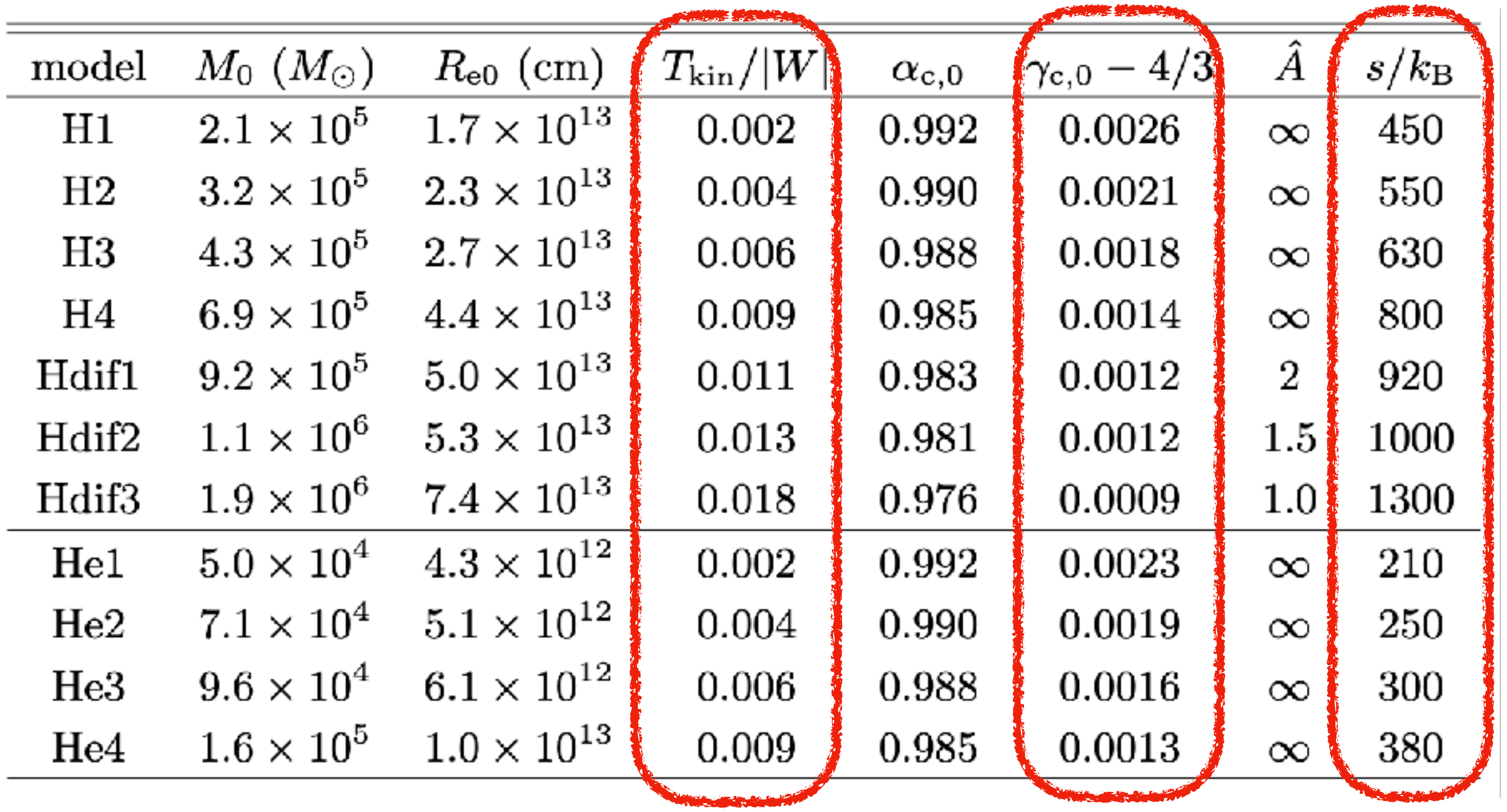


Realistic SMS may have inflated envelope

Method: Initial supermassive star models

Marginally stable SMS with rotation.

rotation



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More massive

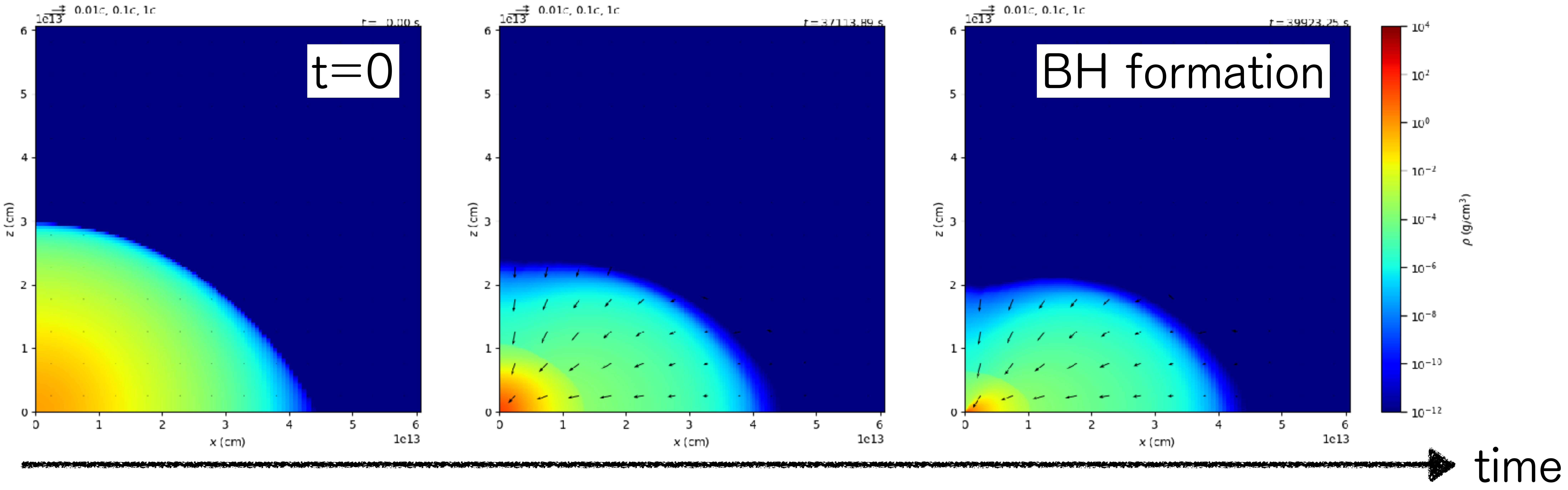
- more radiation-dominant
- $\gamma \rightarrow 4/3$
- higher entropy

More rapid rotation - more stable

larger mass for being unstable

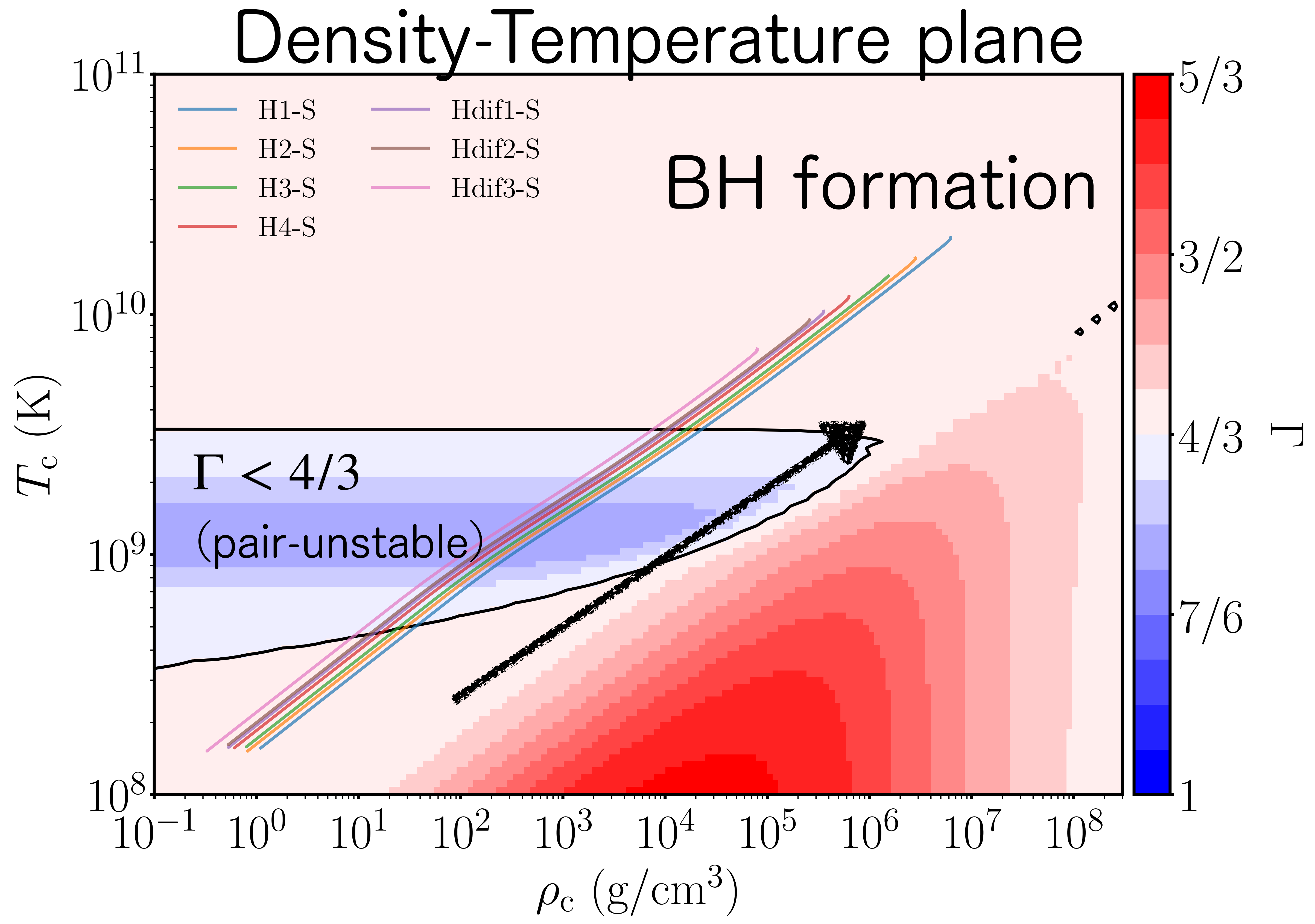
Result: Outline of evolution

Primordial composition, mass-shedding case



Collapsing motion is ~ coherent (characteristic of GR instability)

Result: Outline of evolution

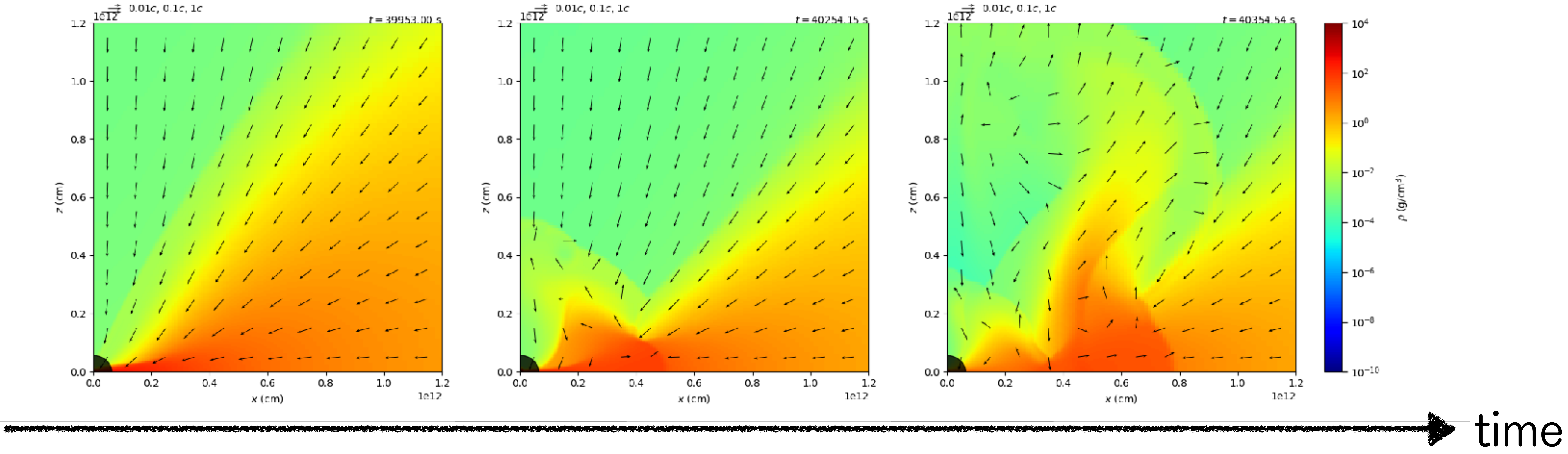


Collapse proceeds outside pair-unstable region.

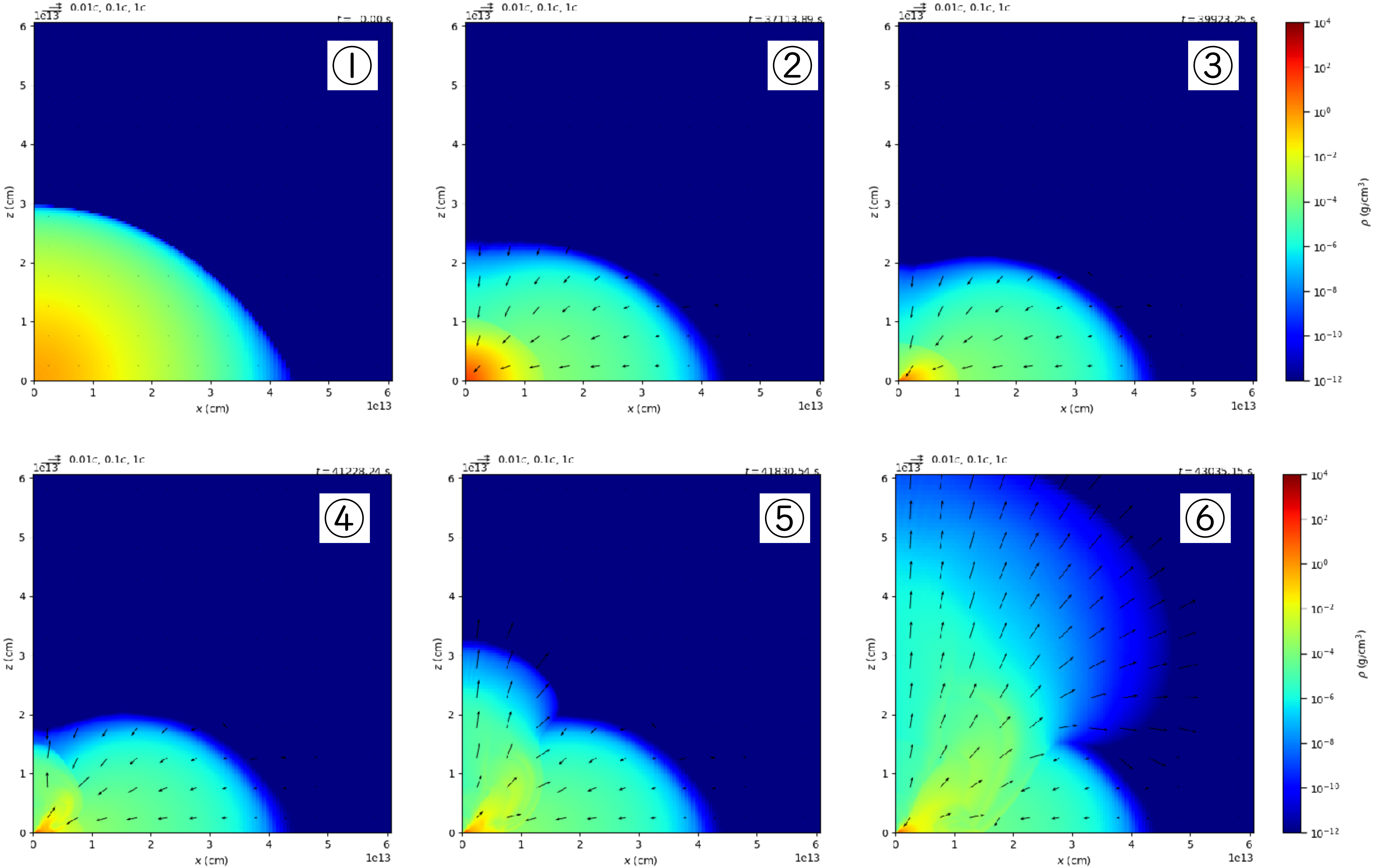
→ GR instability

Result: Bounce-shock-induced ejecta

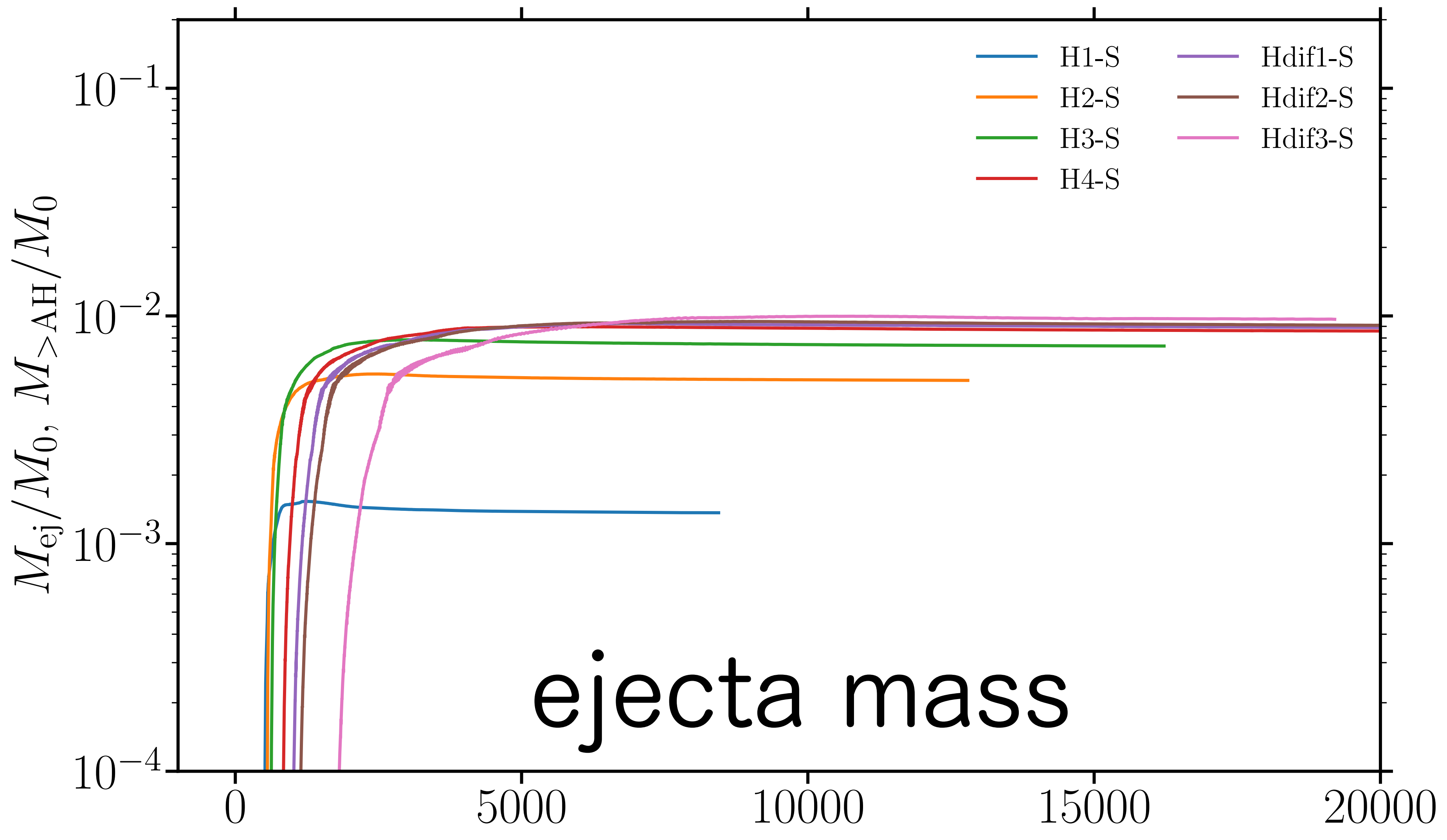
Density snapshots around torus formation time.

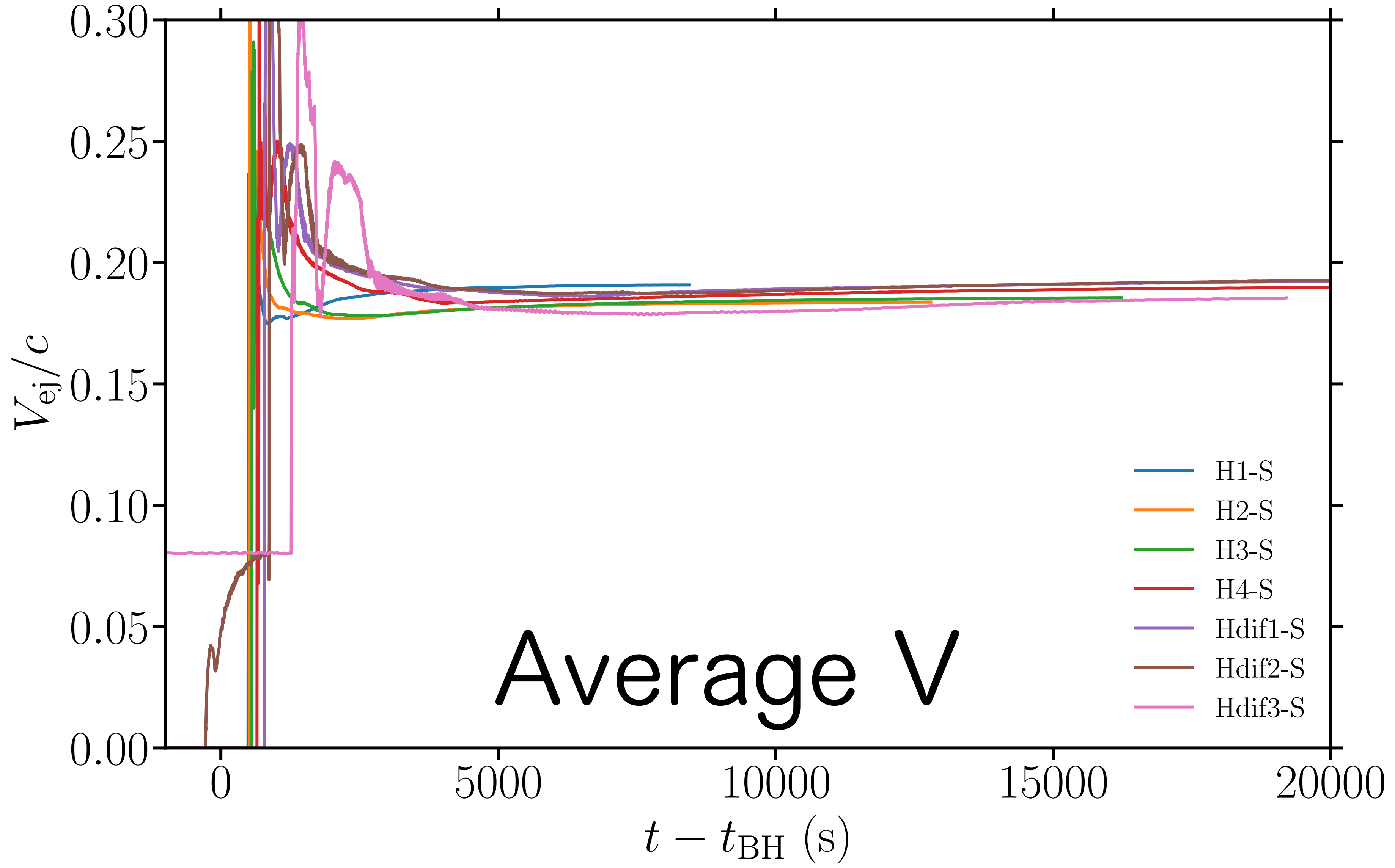


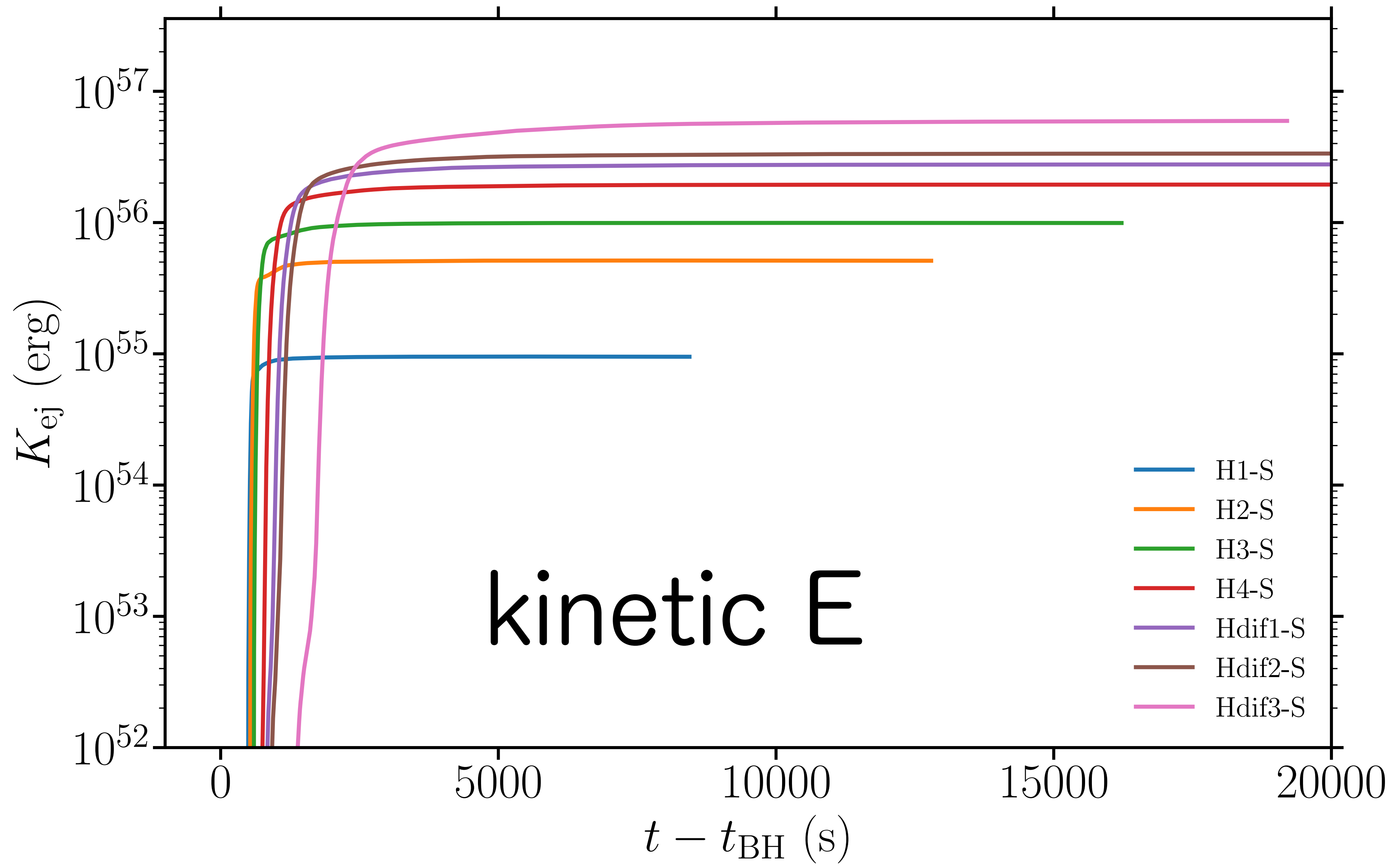
Sudden formation of centrifugally supported torus induces its bounce


①
②
③
④
⑤
⑥
1e13 0.01c, 0.1c, 1c
t = 0.00 s
t = 37113.89 s
t = 39923.25 s
t = 41228.24 s
t = 41830.54 s
t = 43035.15 s
z (cm)
x (cm)
1e13
0
1
2
3
4
5
6
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
ρ (g/cm^3)

Result: Properties of ejecta

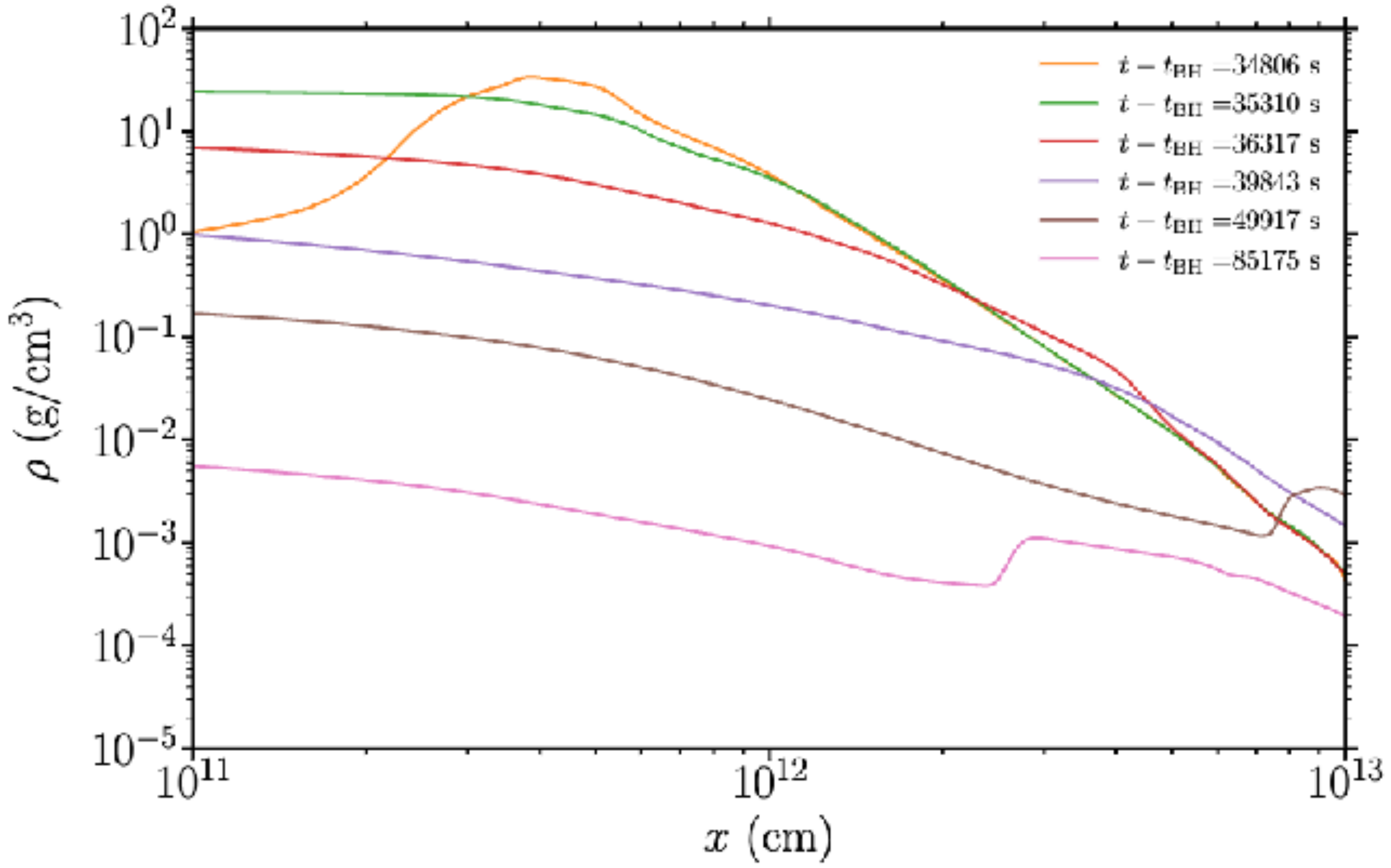


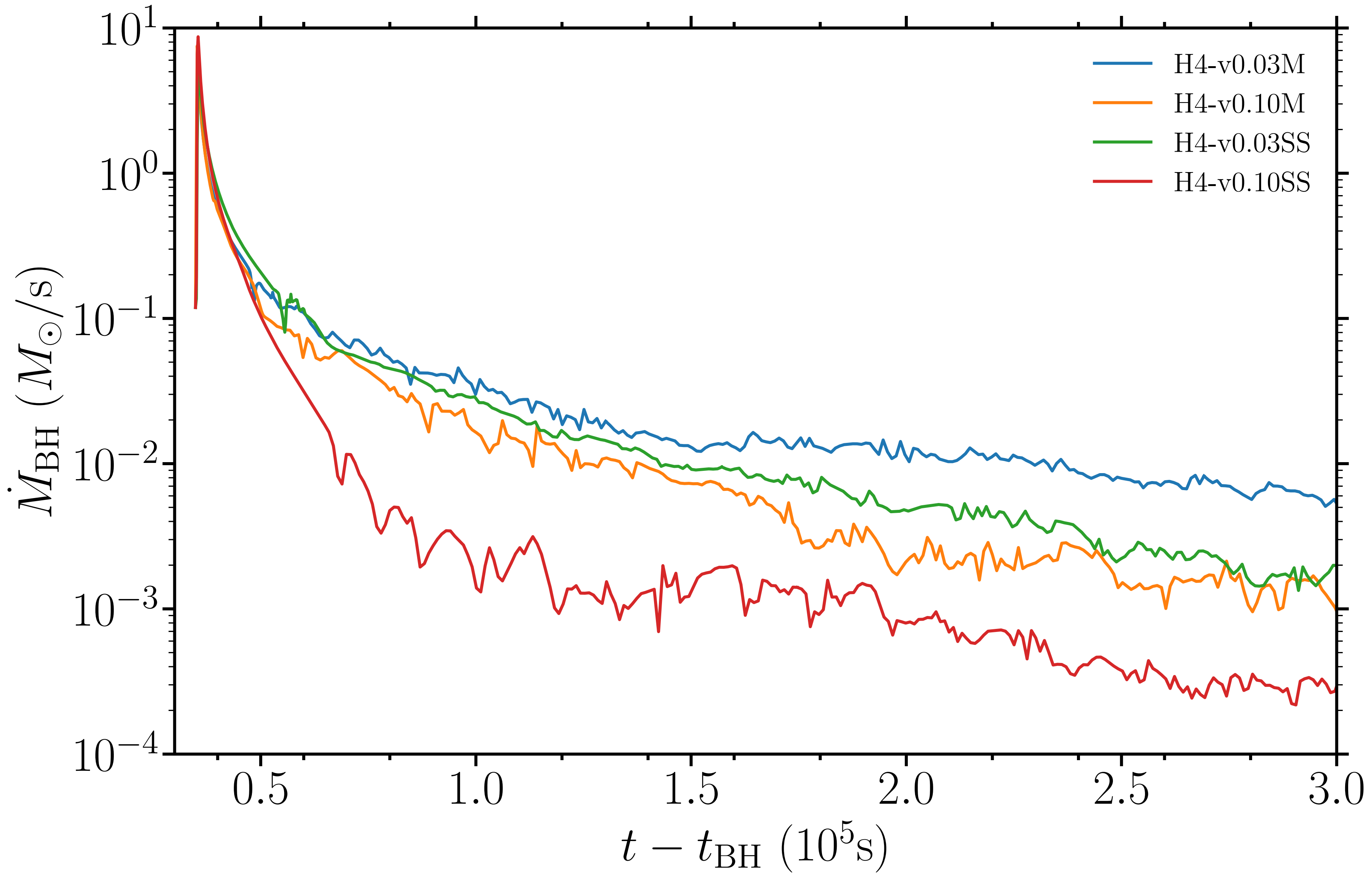


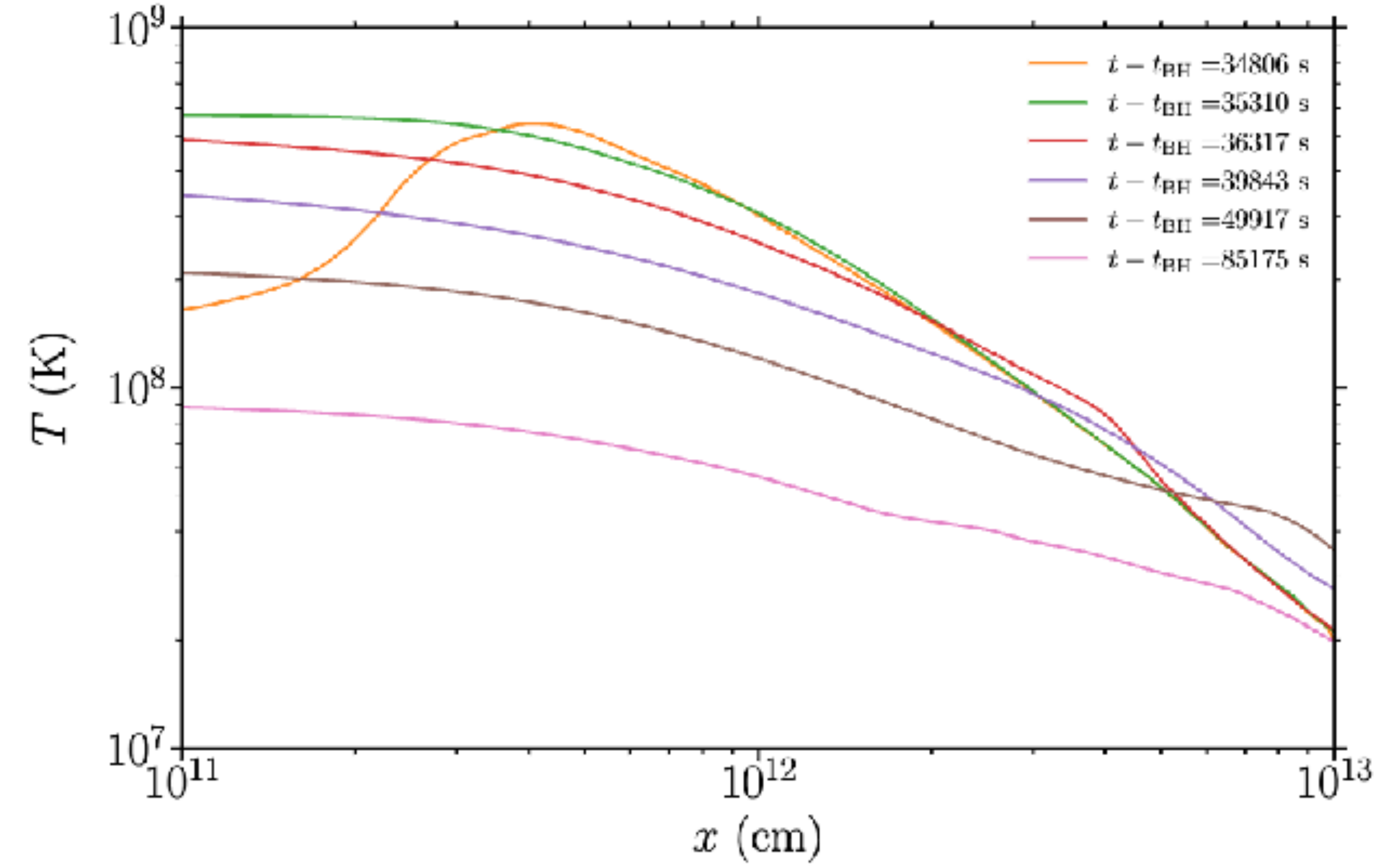


- Ejecta mass ~ 1% of initial SMS mass for fast-rotating SMS.
- Velocity ~ 0.2 c
- Kinetic E ~ $10^{-4}Mc^2$

Result: Viscous evolution of the disk



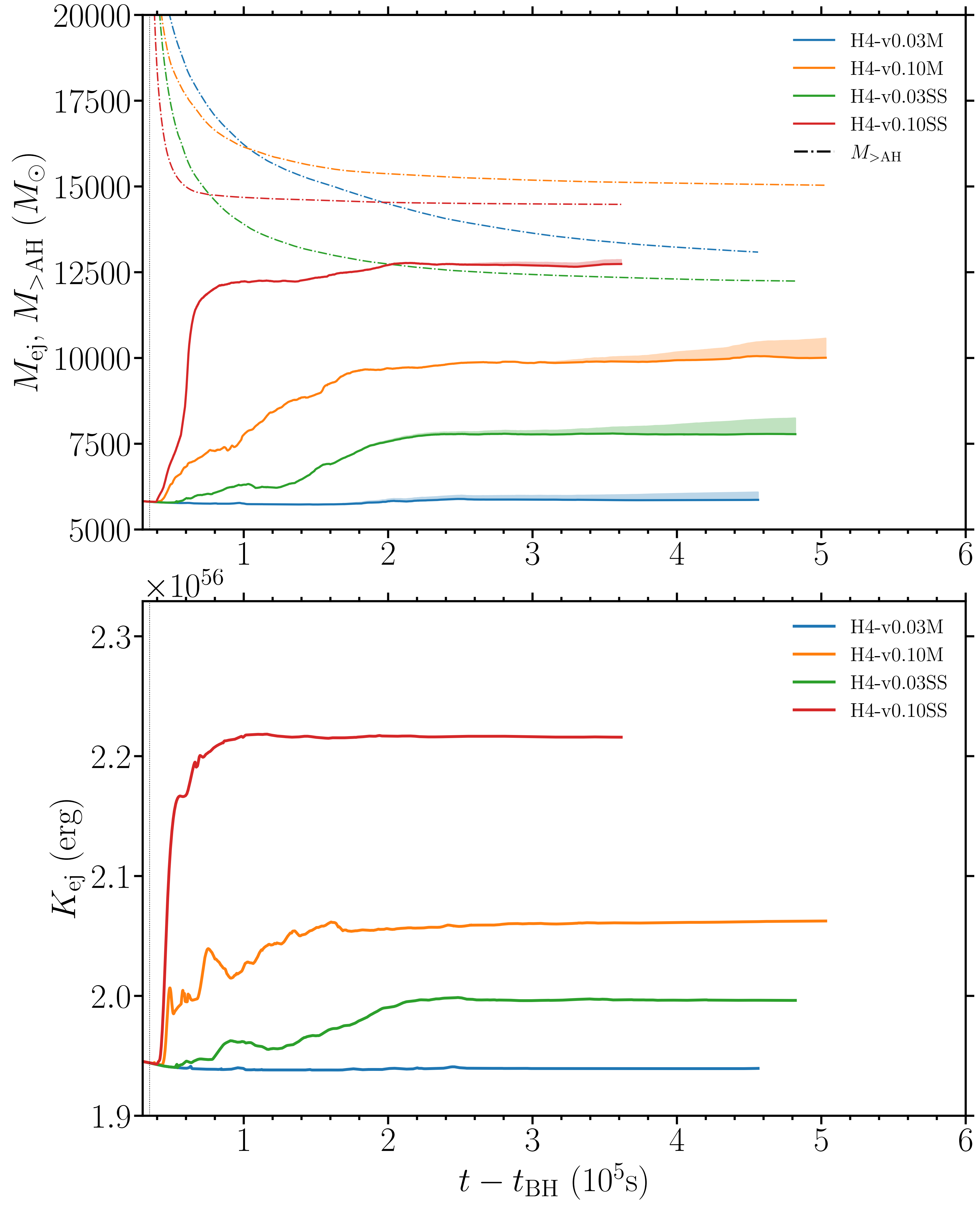




Accretion timescale ~10^4 s

Upto $\sim 10 M_\odot/{\rm s} \sim 10^{13}\dot{M}_{\rm Edd}$ (Hyper-Eddington)

Result: Viscous evolution of the disk

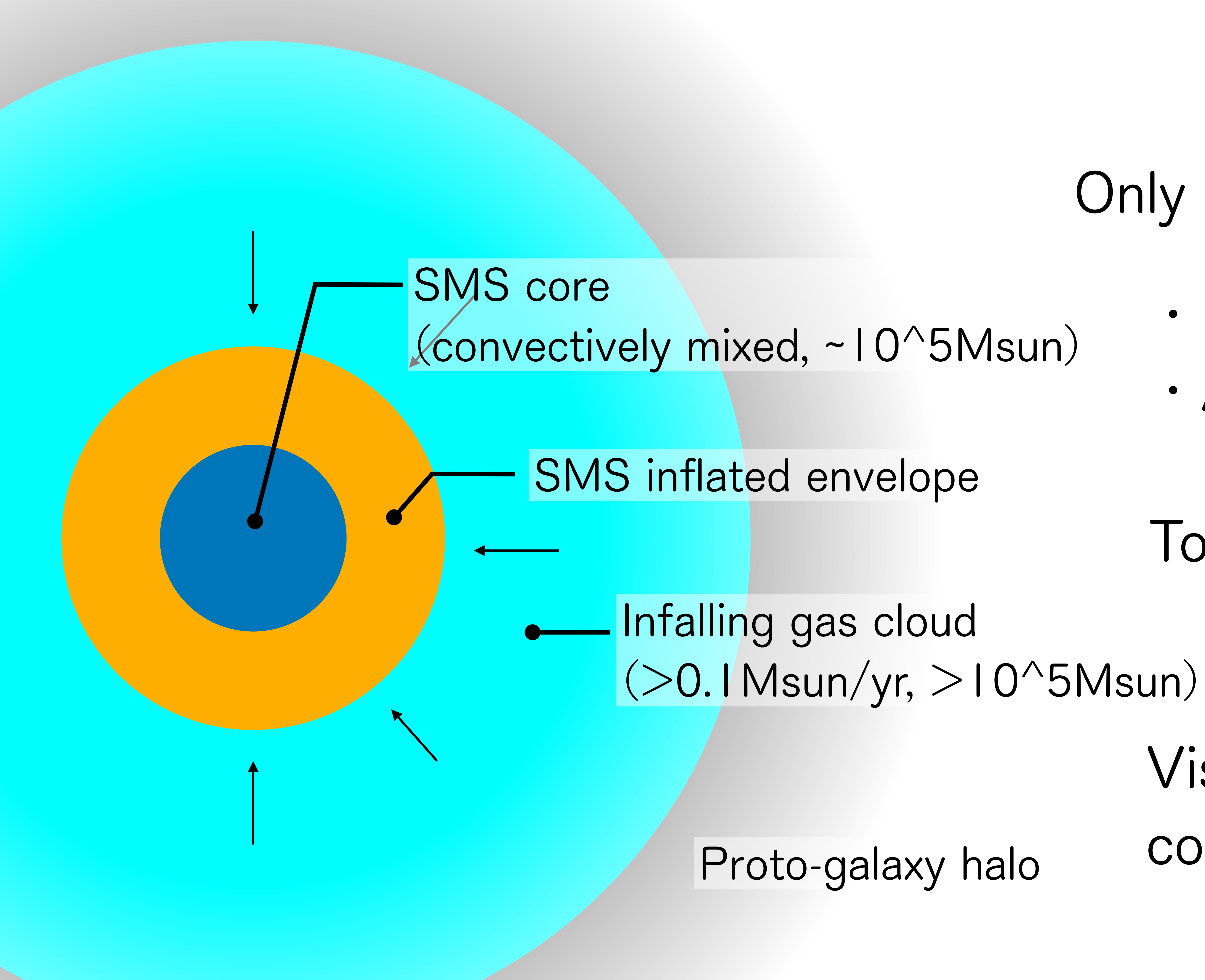


Viscosity-driven ejecta
(with different prescription & strength)

Ejecta mass can be ~3× bounce-driven ejecta

Velocity ~0.05 c ≈1/4×bounce-driven ejecta
→effect is minor in kinetic energy

Discussion: Realistic environment



SMS core
(convectively mixed, ~10^5Msun)

SMS inflated envelope

Infalling gas cloud
(>0.1Msun/yr, >10^5Msun)

Proto-galaxy halo

Only the collapse of SMS core is simulated.

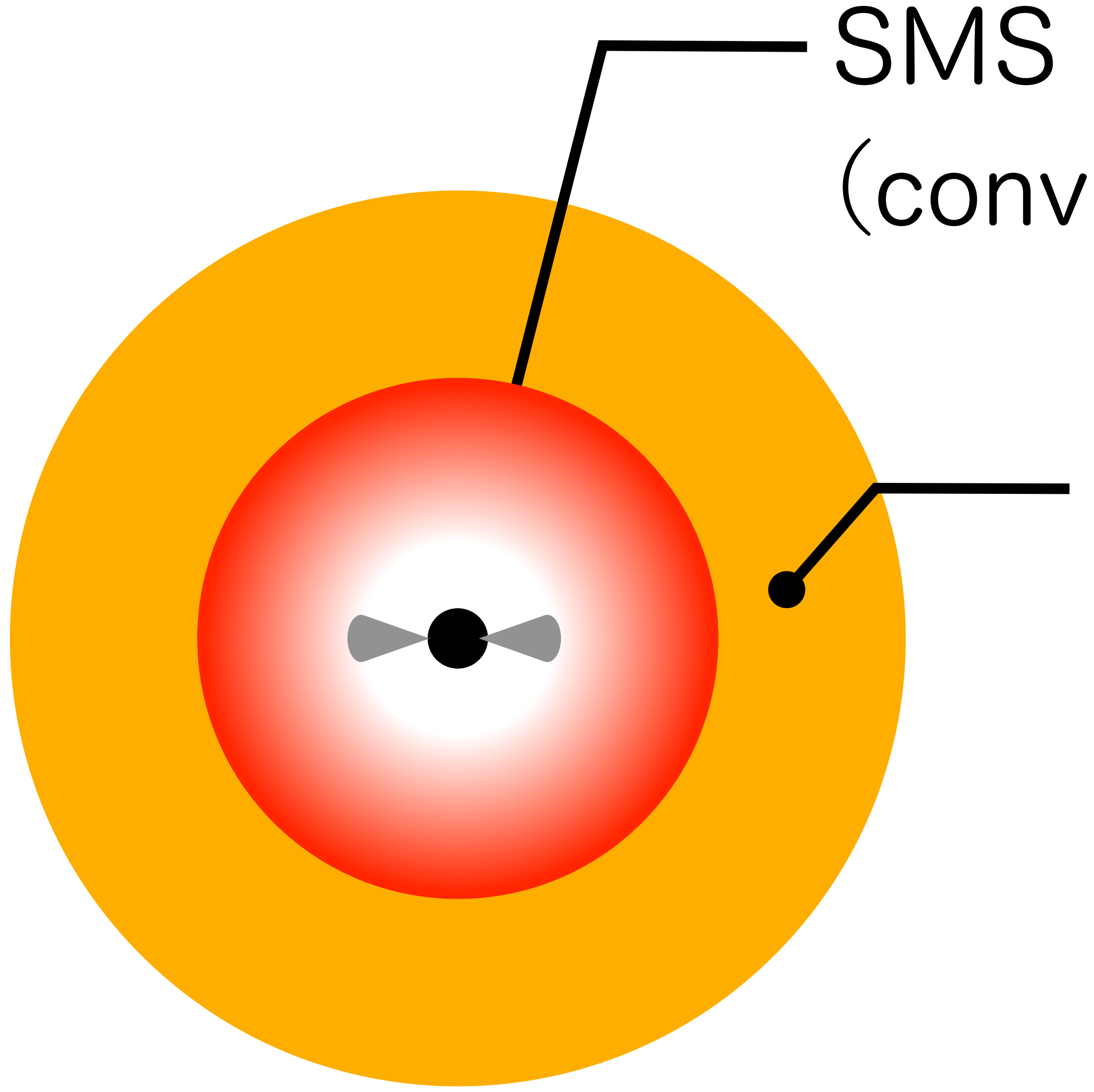
- Envelope
- Atomic cooling cloud ~ SMS mass

Total ejecta mass ~ 10^5 Msun

Viscosity-driven ejecta does not contribute much to total ejecta property

Discussion: Realistic environment

Only the collapse of SMS core is simulated.



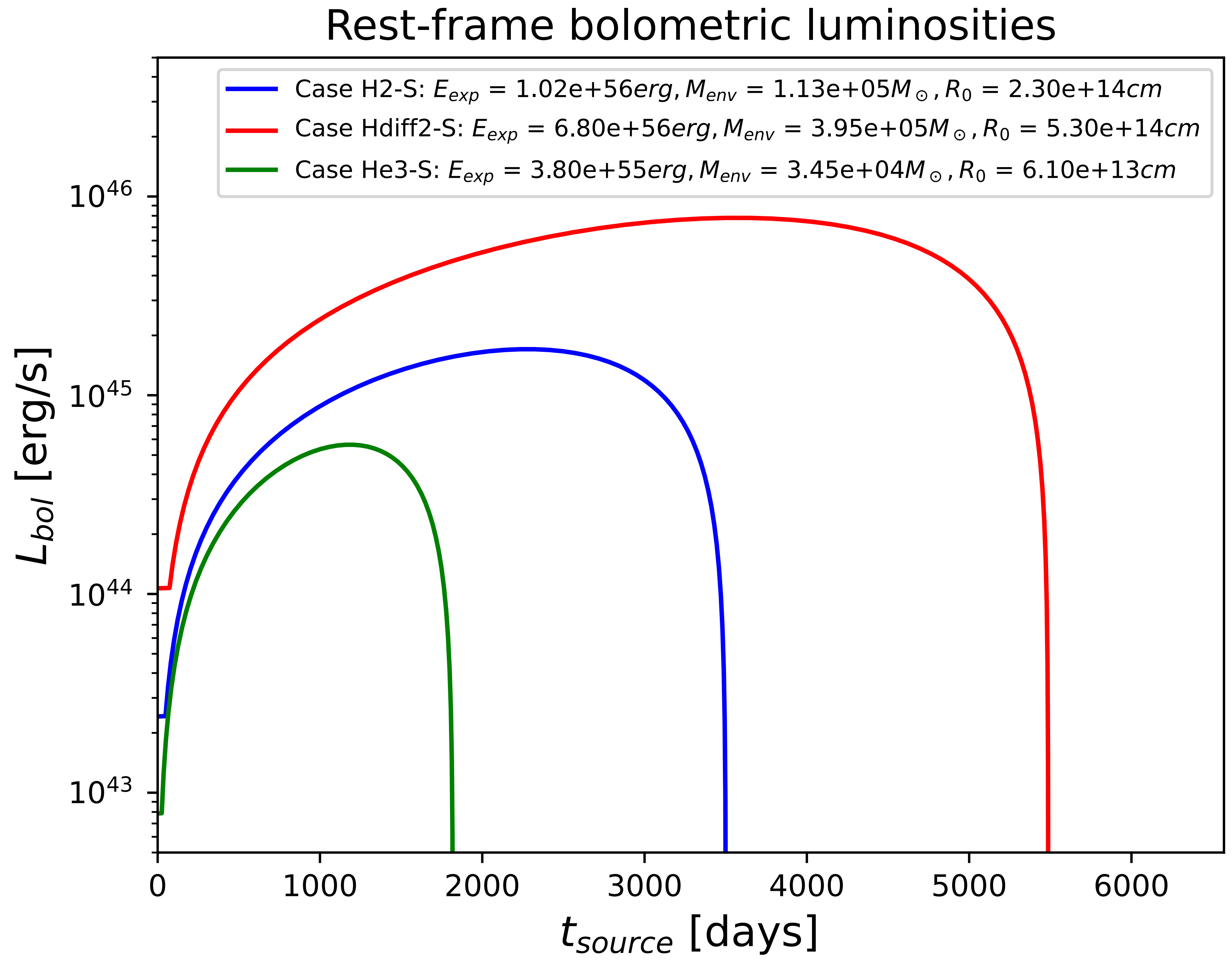
SMS core

(convectively mixed, ~10^5Msun)

SMS inflated envelope

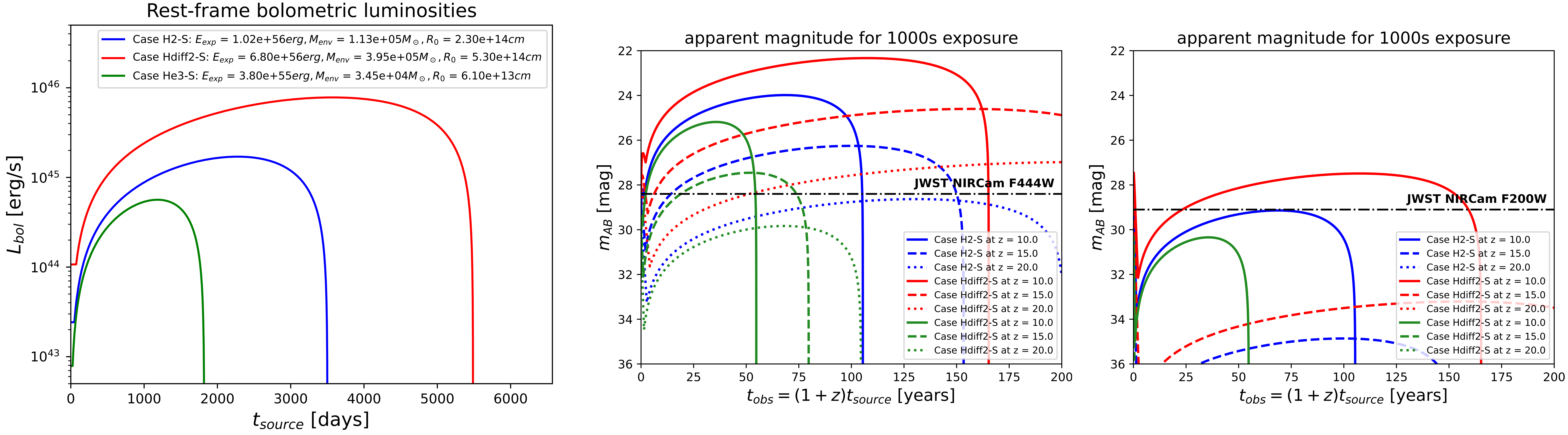
- Envelope ~10% of mass of SMS

Luminous H-rich SN (IIP) cf. Moriya+21



Discussion: Possible outcome of the explosion

Jockel, SF+ in prep.

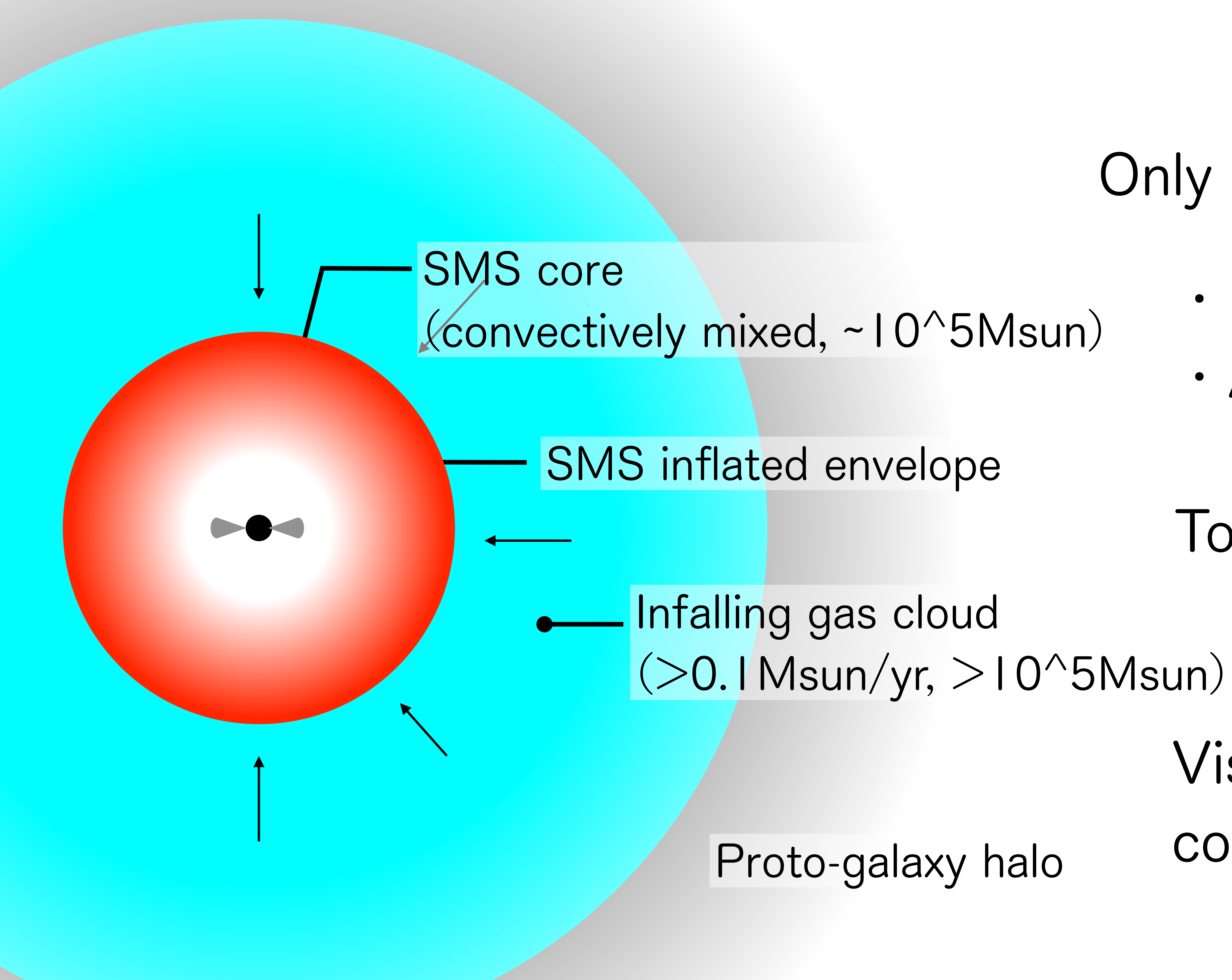


→ source time (d)

→ obs. time (yr)

Long duration (10-100 yrs), red object.

Discussion: Realistic environment



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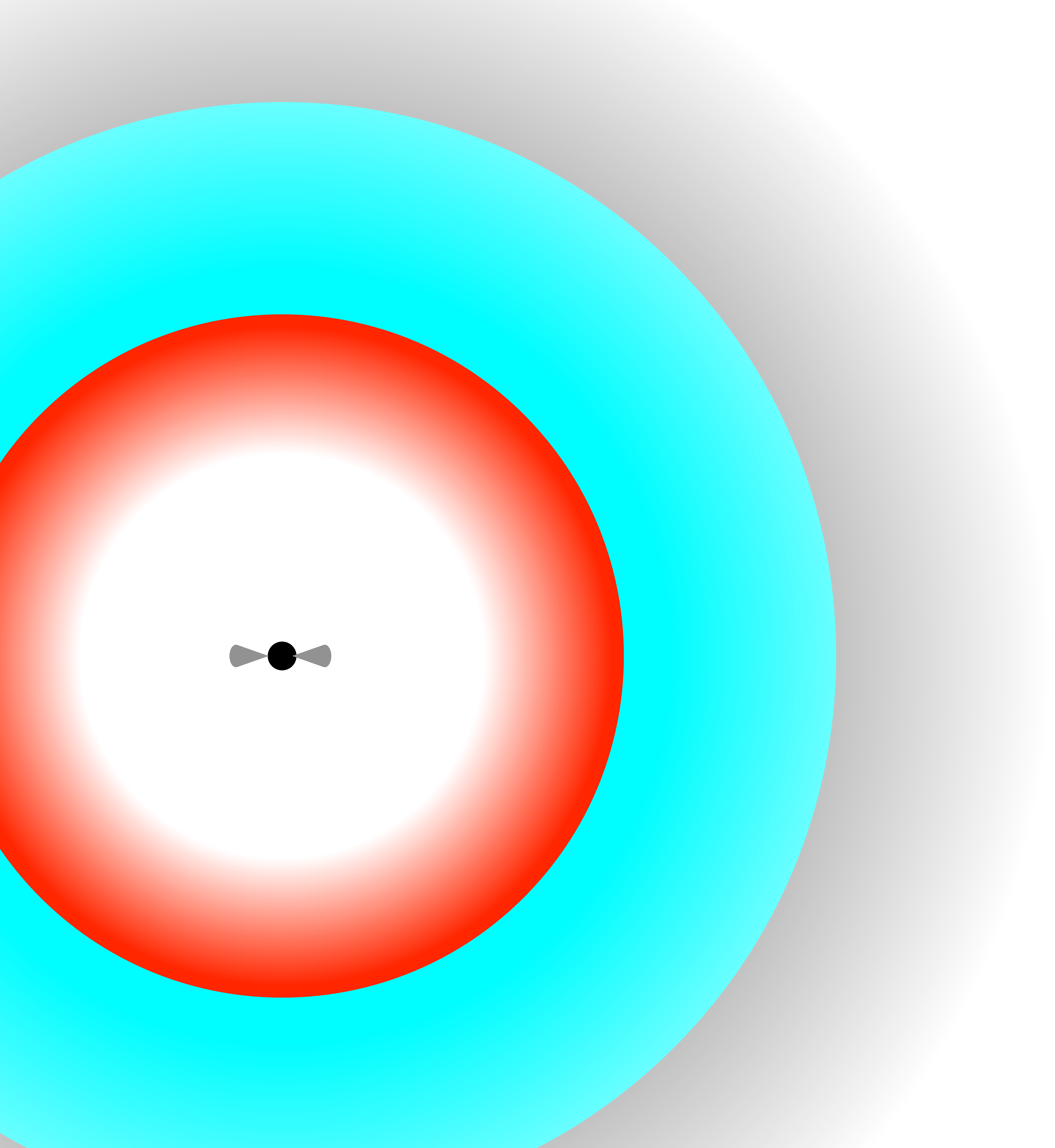


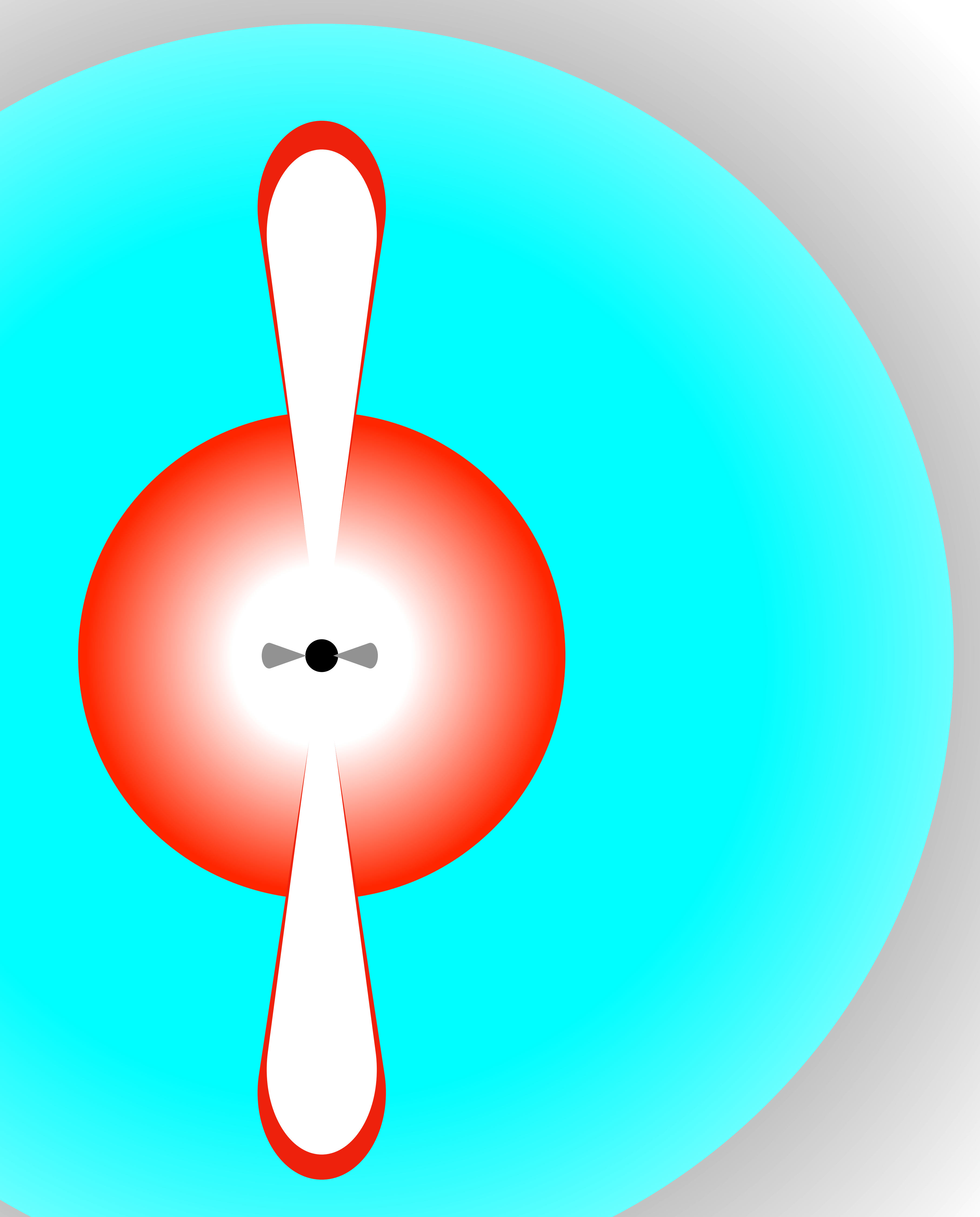
The ejecta have to sweep inflated envelope.

...breaks out the SMS surface (photosphere)

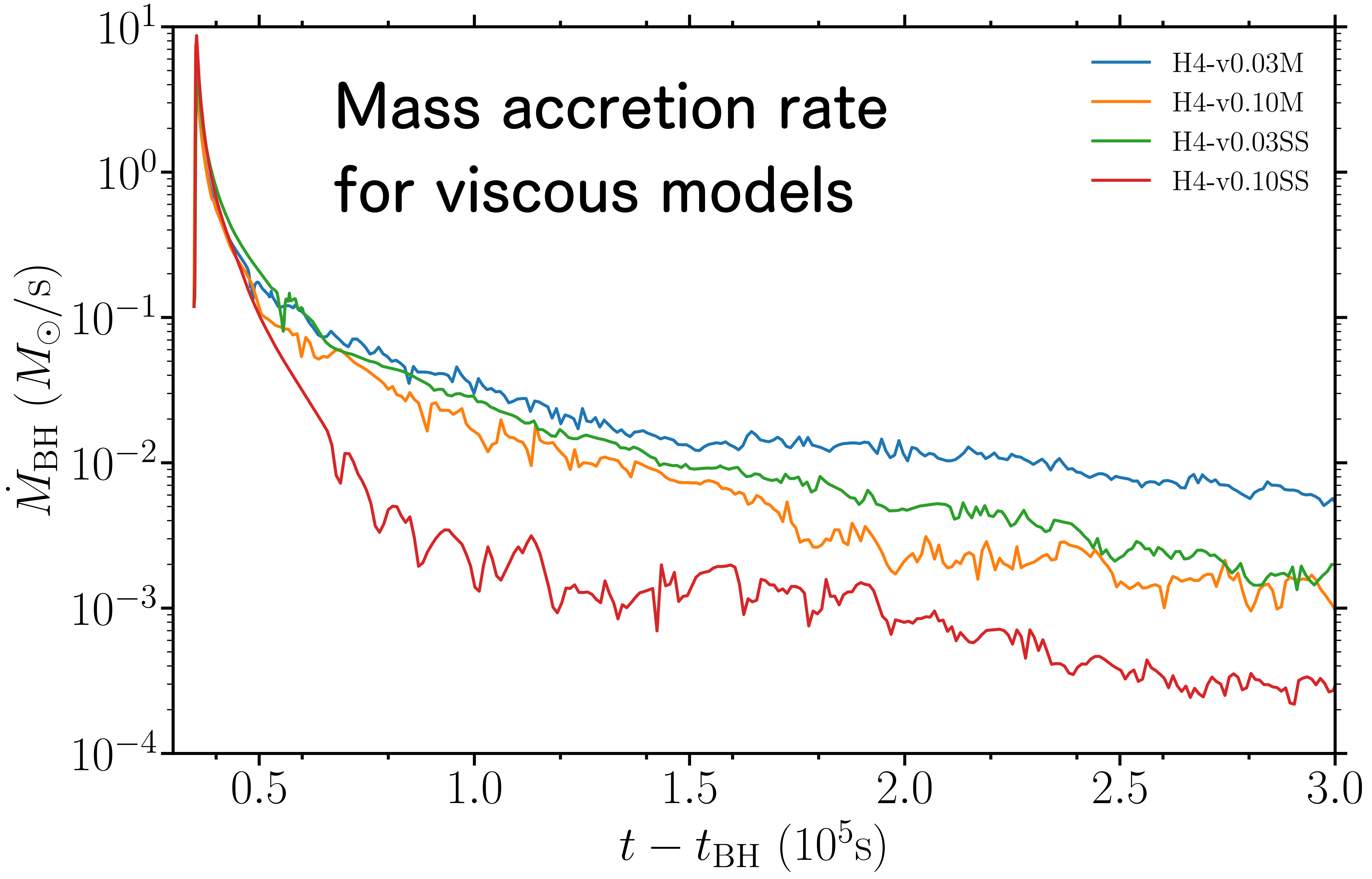
The ejecta then sweeps up the infalling gas cloud, with photon radiation. photosphere may locate at the shock front.

~ CSM-interacting supernova
(with E~1e55--1e56 erg, M_CSM ~ 10^5Msun)

Discussion: Jet driven by BH-disk

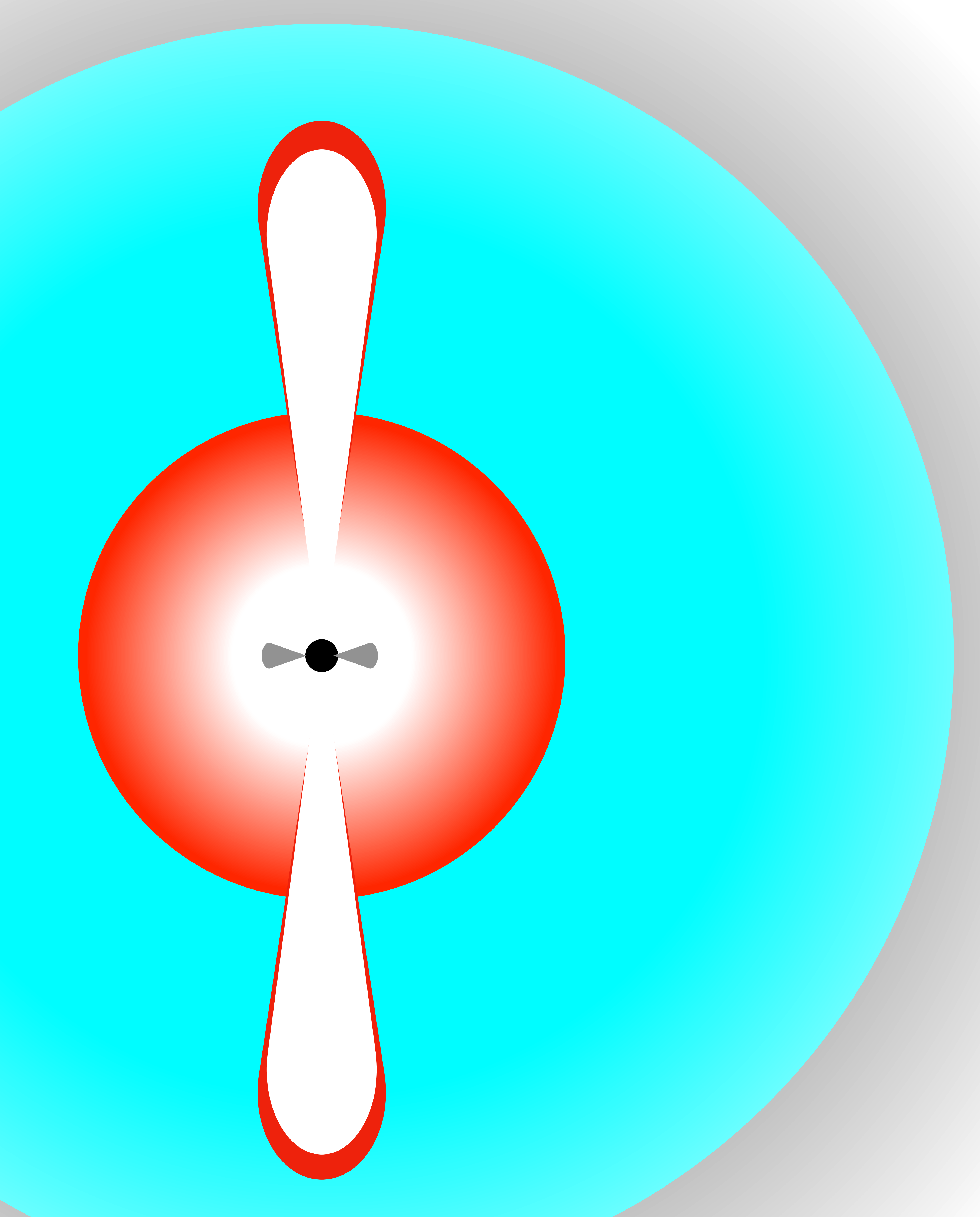


Disk accretion onto BH could drive relativistic jet **cf. Matsumoto+15,16**



Mass accretion rate
for viscous models

Discussion: Jet driven by BH-disk



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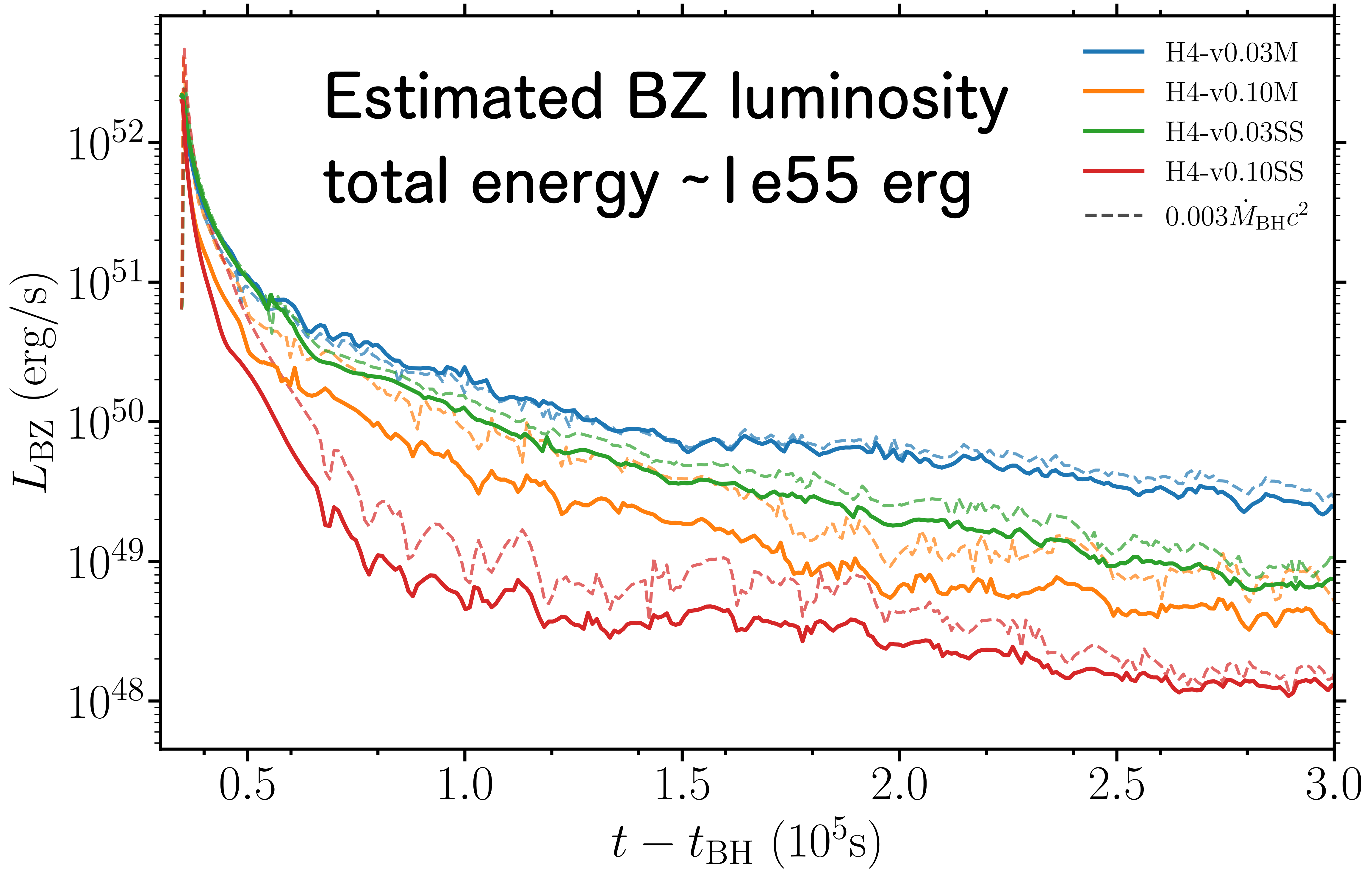
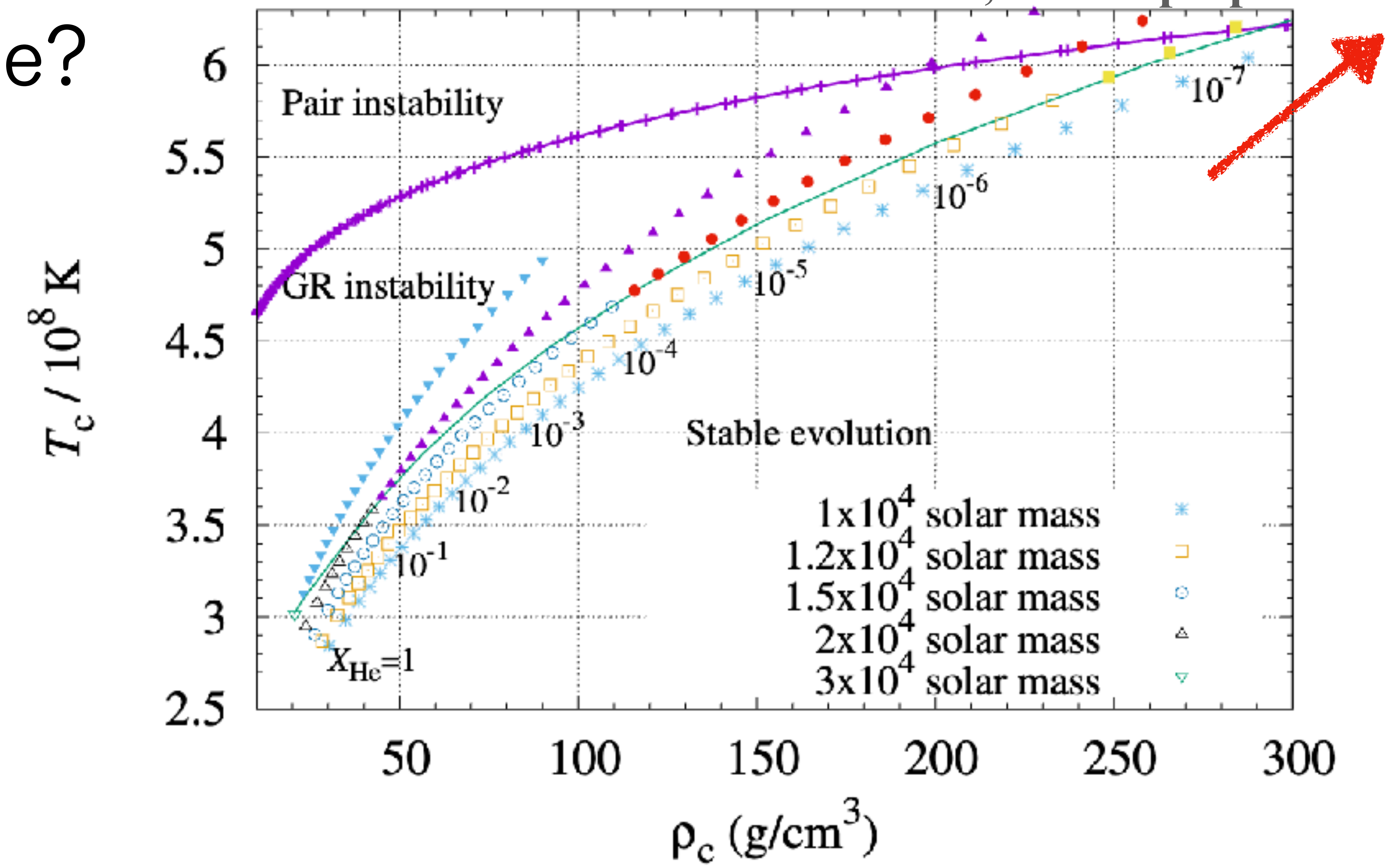


Estimated BZ luminosity
total energy ~1e55 erg

Prospects: Lower-mass SMS

- Lower-mass SMS: higher density, temperature at the collapse
- They may be more subject to pair-instability (thermal creation of. e-e+ pairs)
- Nuclear burning and neutrino energy loss become more significant
- Effect of rotation on pair-unstable collapse?



Shibata, SF+ in prep

Can SMS fast rotate?

Balance of radiation pressure, gravitational and centrifugal force:

$$\frac{\kappa}{c}\frac{L}{4\pi R^2} = \frac{GM}{R^2} - R\Omega^2_{\rm crit}$$

$$\frac{GM}{R^2}(1 - \Gamma_{\rm Edd}) = R\Omega^2_{\rm crit},\ \text{where}\ \Gamma_{\rm Edd} = \frac{L}{L_{\rm Edd}}$$

Allowed rotation is limited for $L \sim L_{\rm Edd}$

$$\Omega_{\rm crit} = \sqrt{\frac{GM}{R^3}}\sqrt{1 - \Gamma_{\rm Edd}}$$

“SMSs are slow rotators” **Haemmerlé+2018**

Core-collapse supernovae: neutrino-driven scenario

Stars with $\gtrsim 10M_\odot$

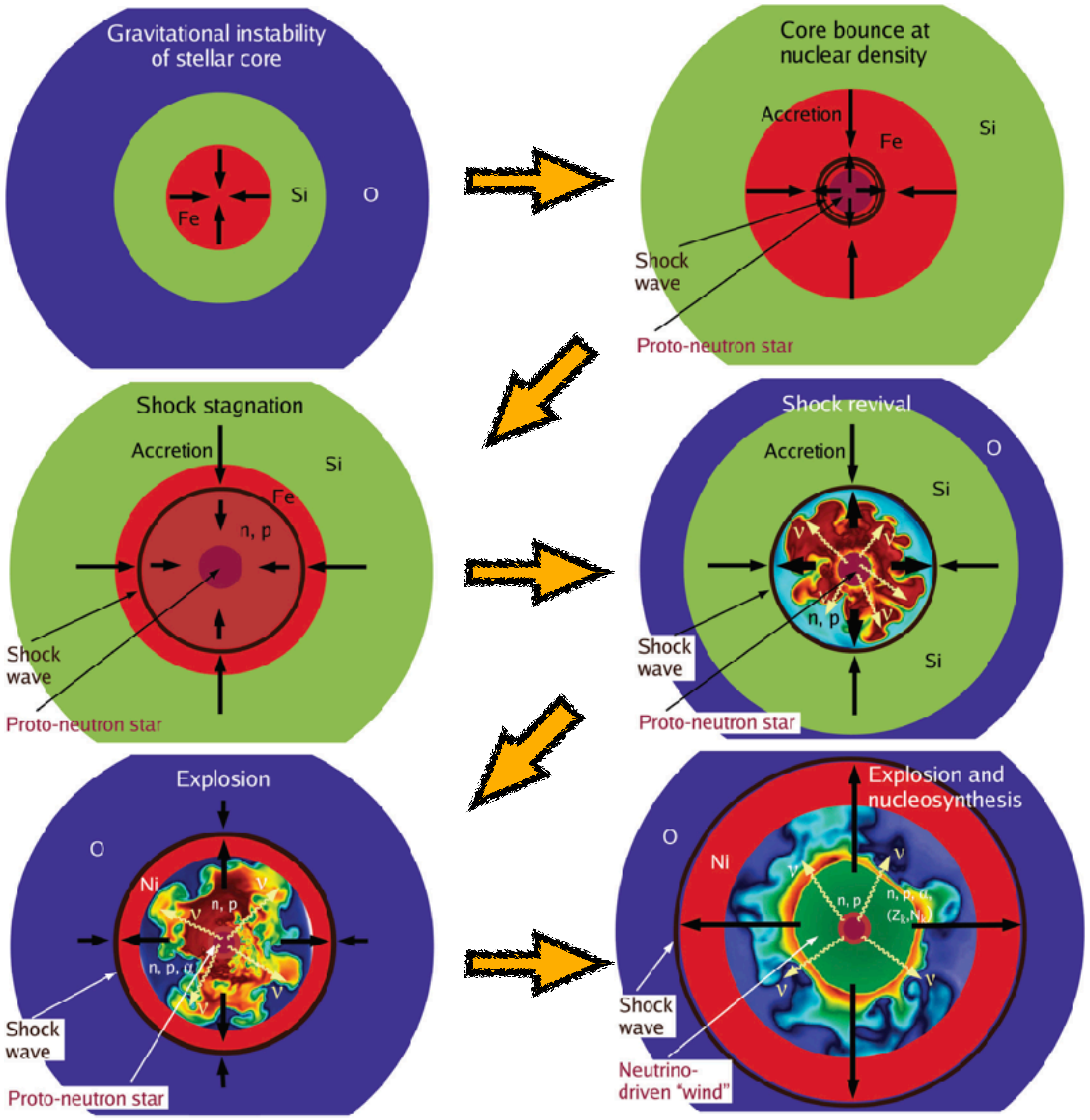
Collapse of iron core

Proto-neutron star formation

Shock developed
→ stall

Shock re-energized by neutrino heating

Successful breakout
→ observed as SN



Figures taken from Janka (2012)
(layers not drawn to scale)

BH formation

e.g. O’Connor & Ott 2011

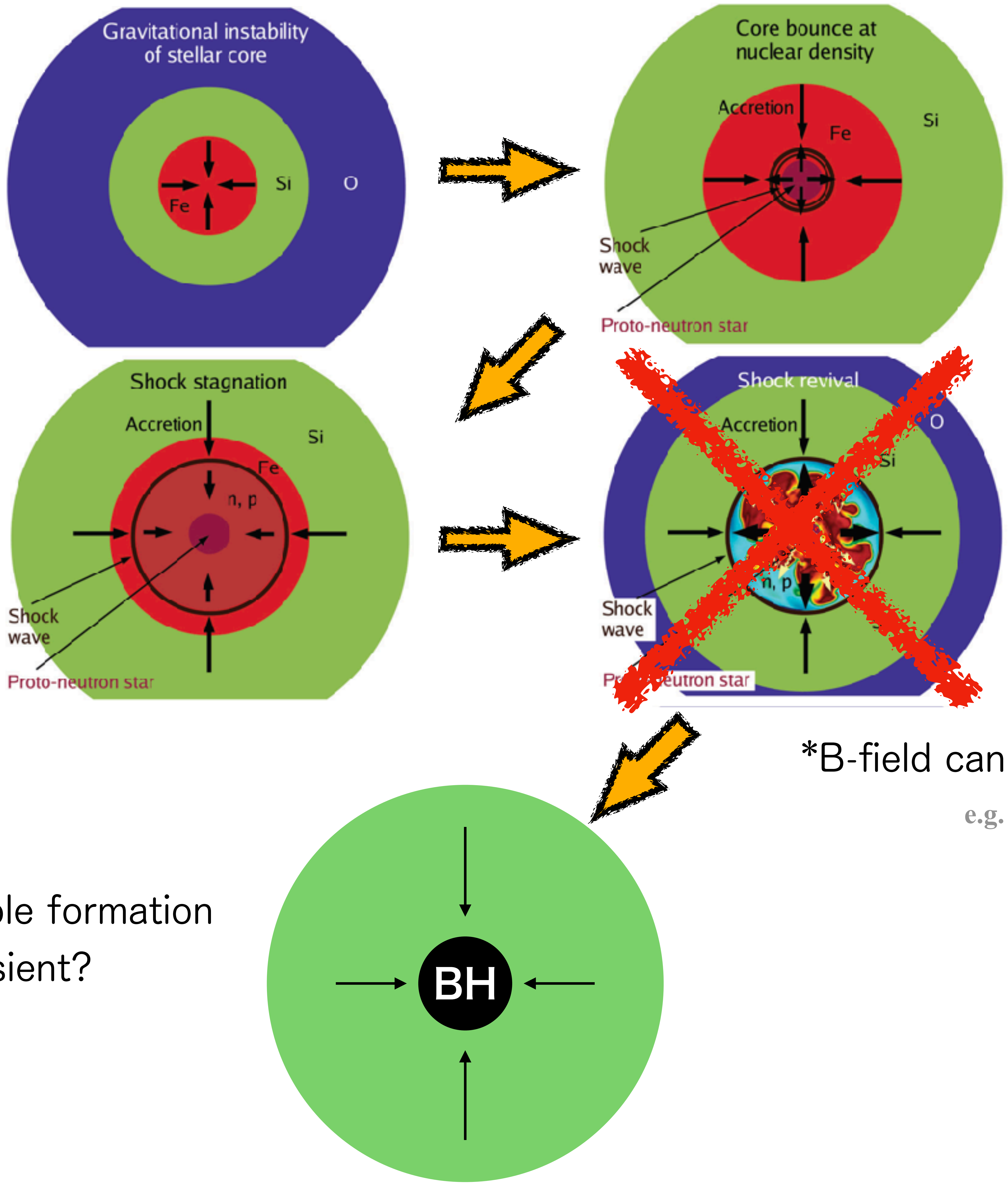
e.g., those with
too compact cores

Collapse of iron core

Proto-neutron star
formation

Shock developed
→ stall

Fail to re-energize
the shock



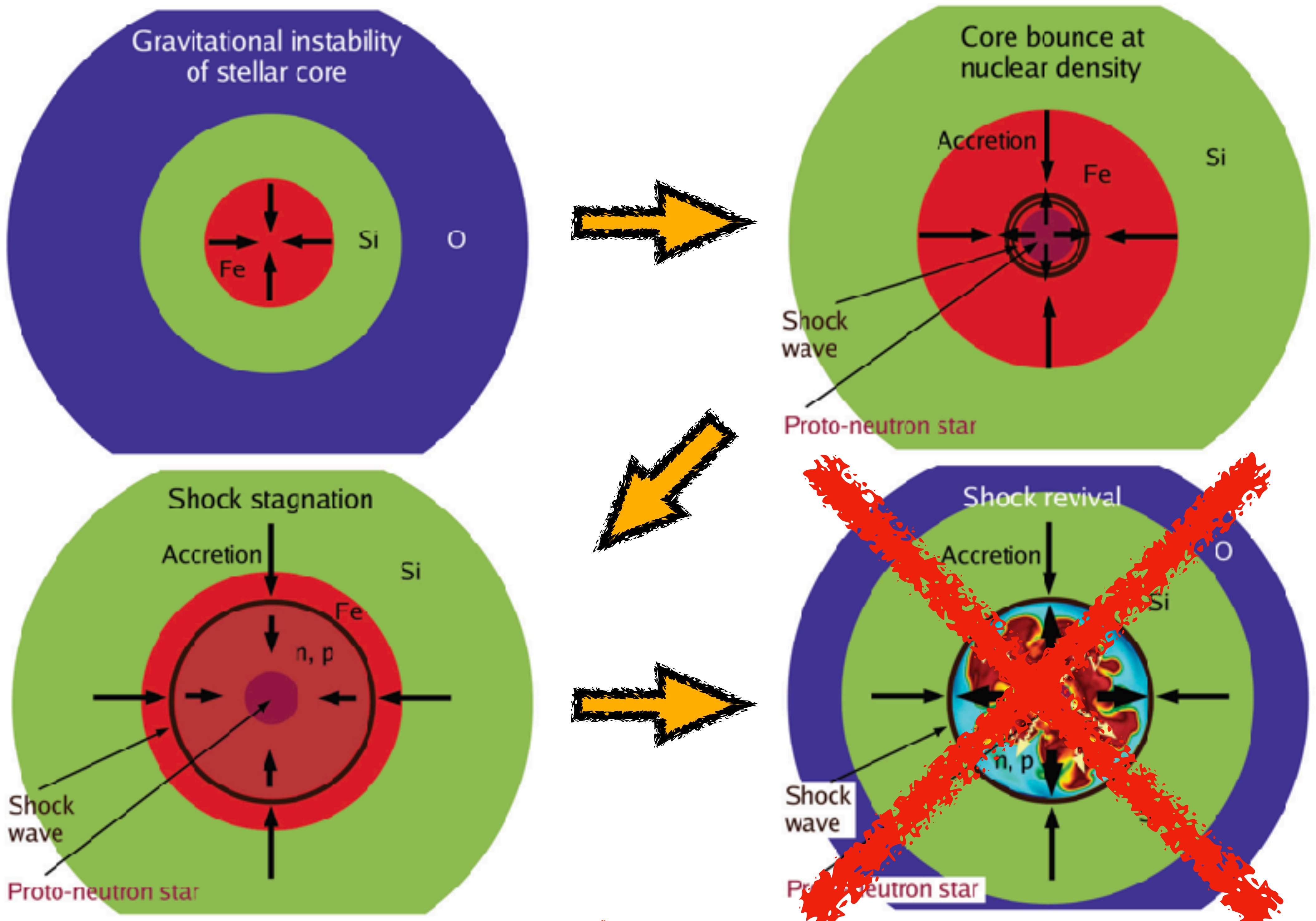
*B-field can also help explosion

e.g. Obergaulinger & Aloy 2021

Black hole formation
No transient?

Collapse of rotating star

e.g., those with
too compact cores



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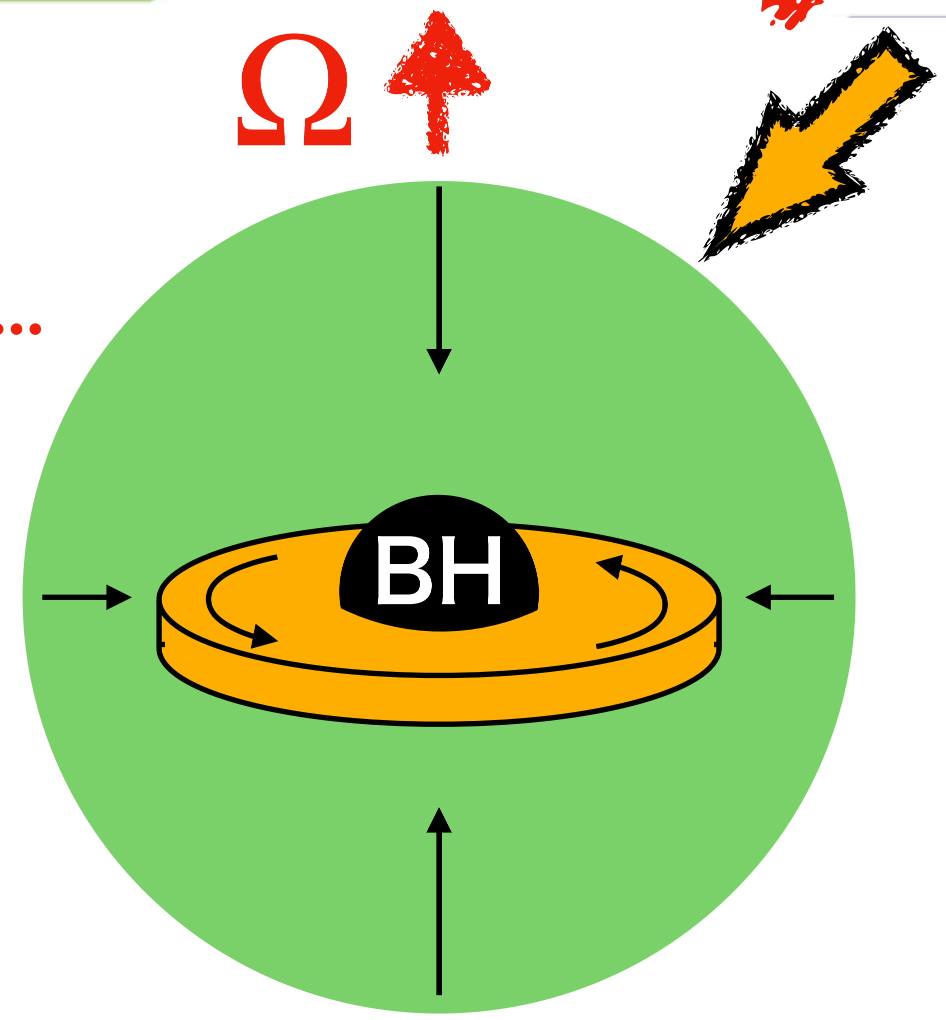


If the star has sufficient rotation...

Accretion disk formed
around the BH.
Further activities possible.

BH-disk activities

- Gamma-ray bursts (GRBs)

BH-disk is one of the promising central engines (e.g., Woosley et al. 1993...)

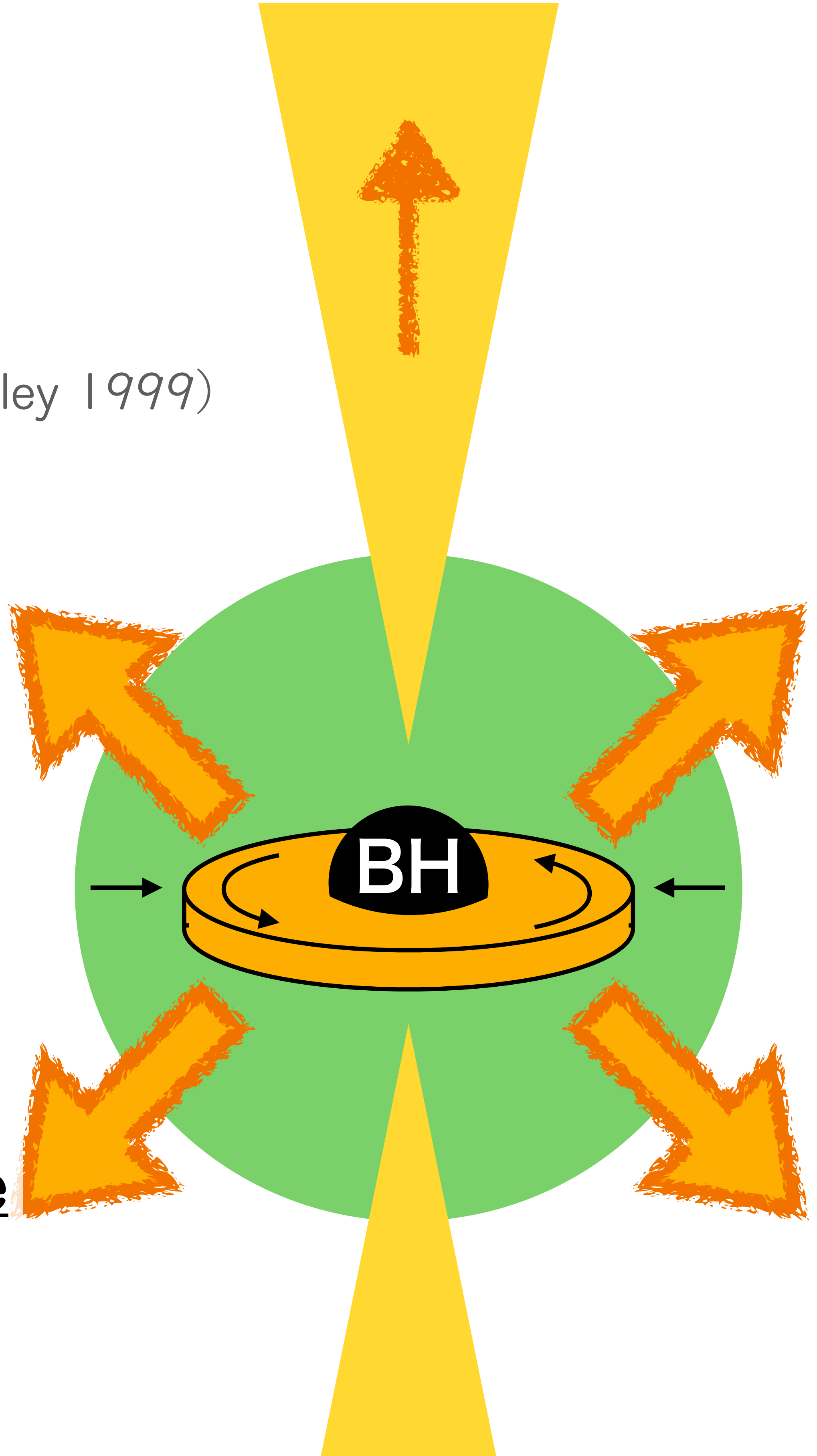
Energy liberated by viscous accretion:

$$GM_{\rm BH}M_{\rm disk}/r_{\rm disk} \approx 3\times10^{52}\,{\rm erg}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{M_{\rm disk}}{0.1M_\odot}\right)\left(\frac{r_{\rm disk}}{10^7{\rm cm}}\right)^{-1}$$

It can drive an energetic outflow from disk. (MacFadyen & Woosley 1999)

(at least some) long GRBs are accompanied by energetic SNe (Ic-BL)

- Explosion energy $E_{\rm K} = (0.8-4.4)\times10^{52}\,{\rm erg}$
- ^{56}Ni mass $M_{\rm Ni} = (0.2-0.5)\,M_\odot$ (Cano et al. 17)



<u>Viscosity-driven outflow from disk would naturally explain such SNe</u>

Neutrino cooling vs viscous heating

For high temperatures, （$kT \gtrsim 1\,\mathrm{MeV}$） neutrino emission cools down the disk.

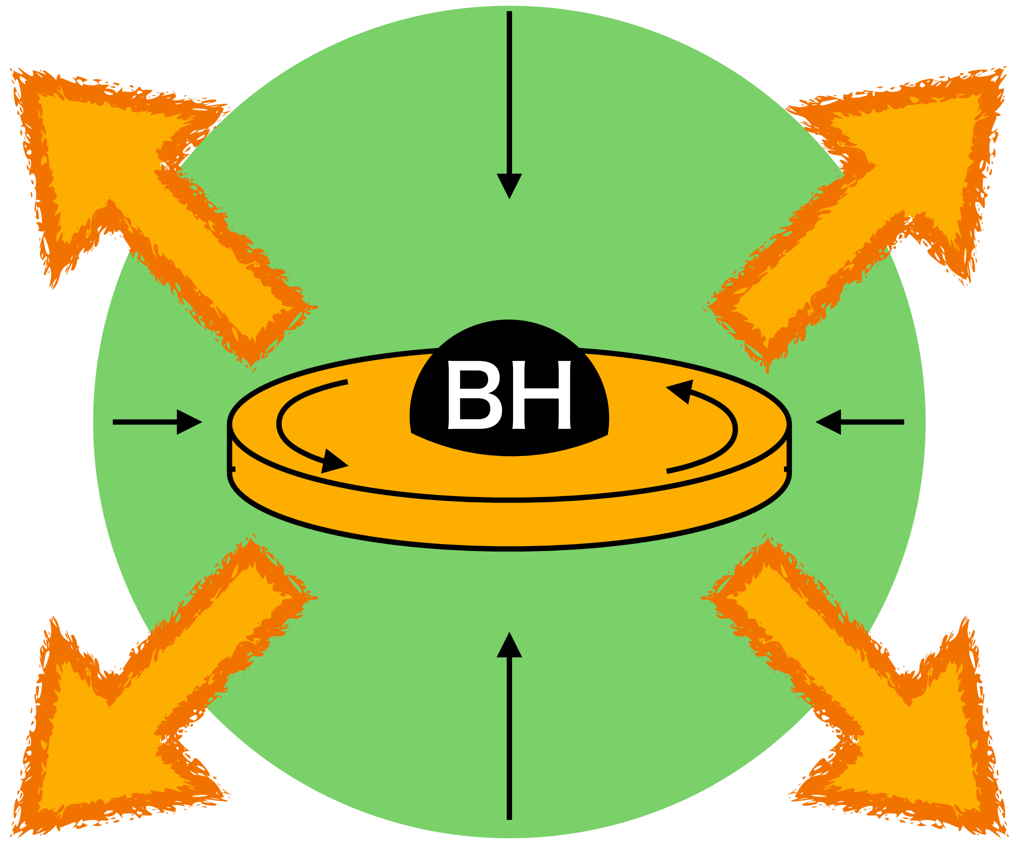
Neutrino emission timescale：$t_{\rm weak} \sim 1\,\mathrm{s}\left(\dfrac{kT}{1\,\mathrm{MeV}}\right)^{-5}$

$t_{\rm weak} \lesssim t_{\rm vis}$ （NDAF） phase: weak/no outflow

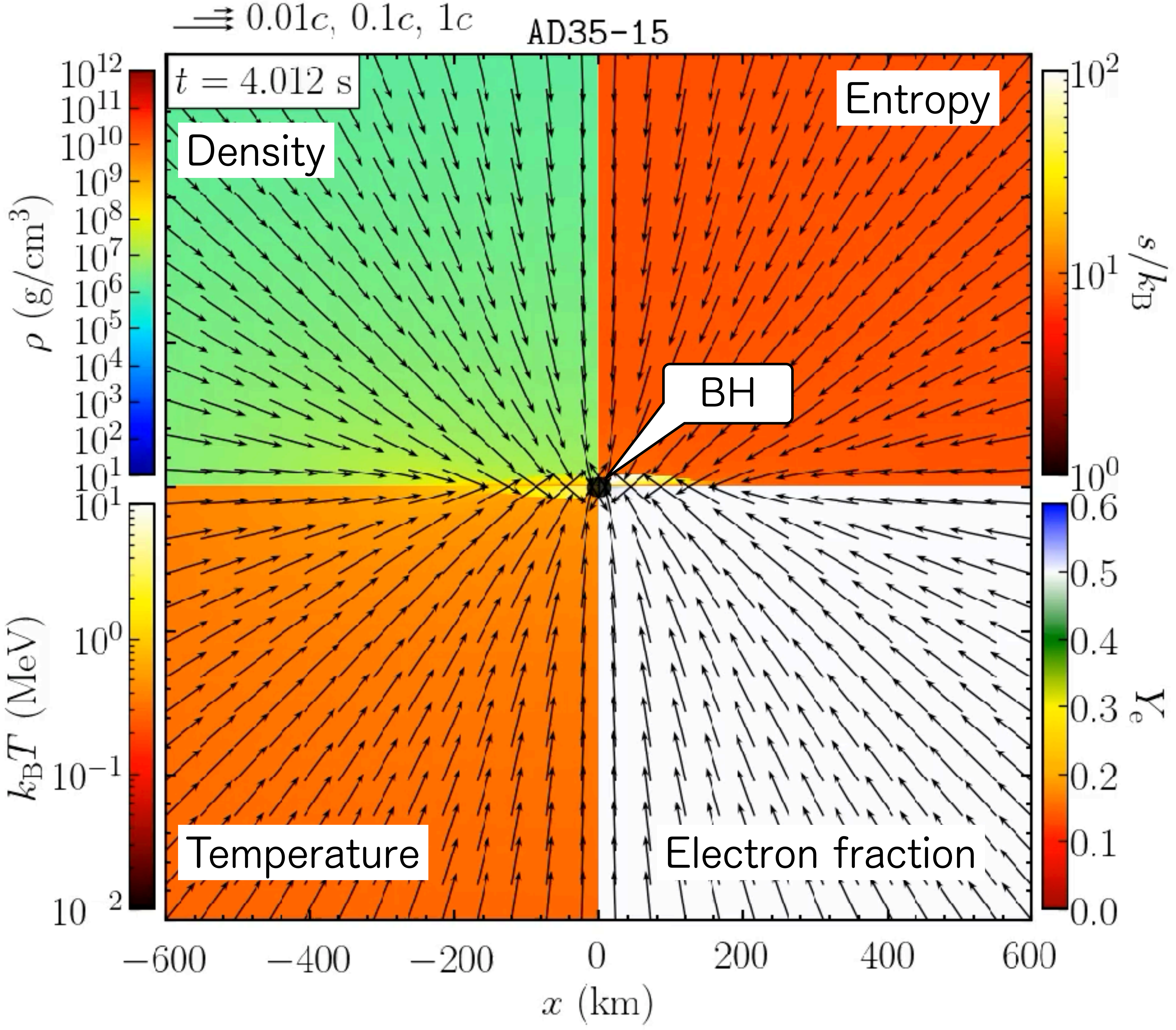
$t_{\rm weak} \gg t_{\rm vis}$ phase: strong outflow would be driven

I performed simulations of the post-merger remnant with

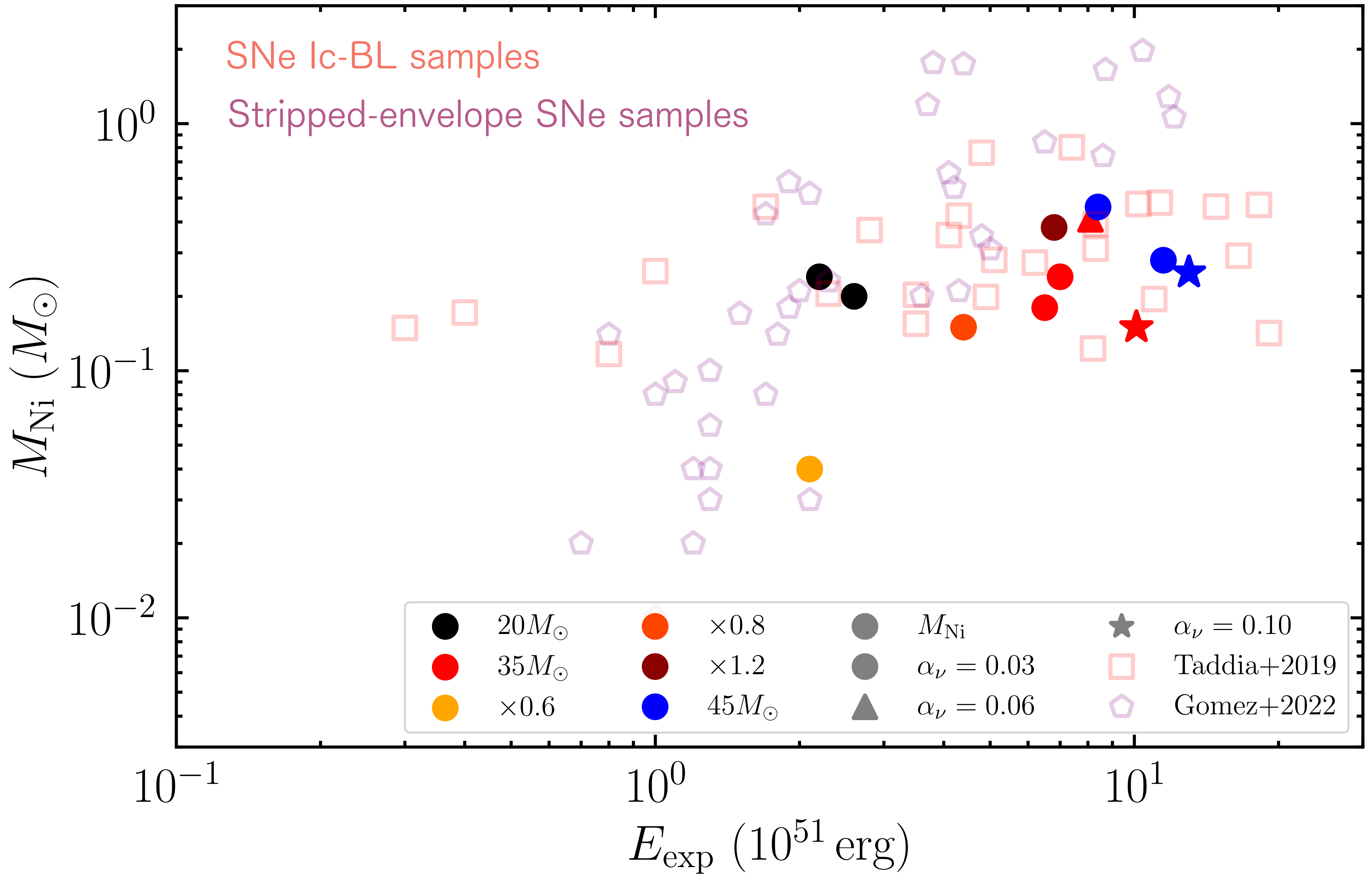
- GR gravity
- Neutrino cooling
- Viscous angular momentum transport



Disk formation→NDAF→Outflow



Comparison with observations

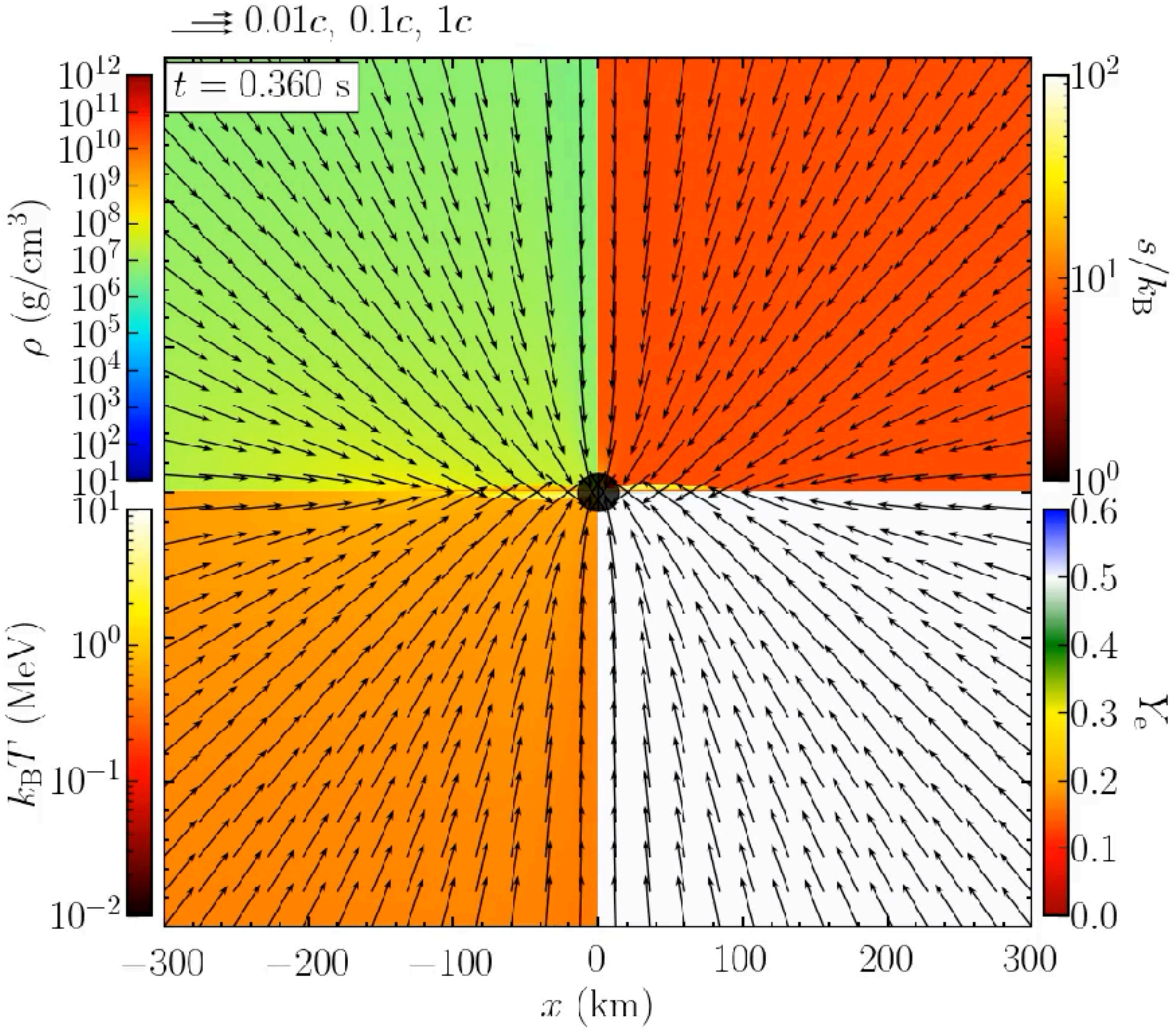


Nucleosynthesis calculation in the ejecta → $M_{\rm Ni} \gtrsim 0.1M_\odot$

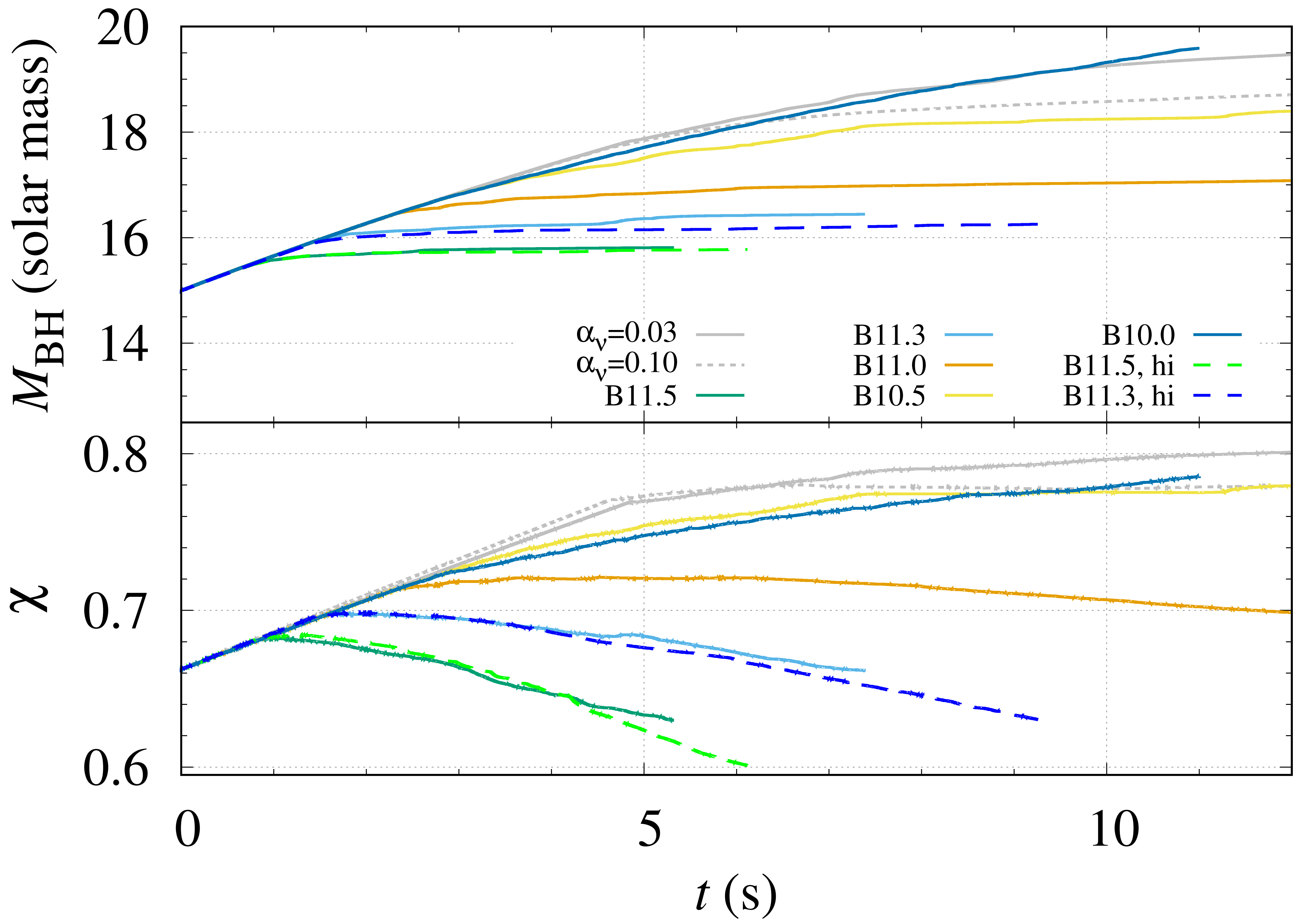
BH-disk can be an engine of the energetic explosion.

MHD models for GRB jets

Shibata, SF+24



MHD models for GRB jets



Spin down of BH by the feedback of energy extraction is numerically observed(!)

Summary

Numerical-relativity simulations of the collapses of rotating supermassive stars

Bounce-shock-induced ejecta with mass up to 1% of initial star, v~0.2c

Kinetic energy ~ $10^{55} - 10^{56}$ erg

(Mass is likely dominated by the swept-up cloud surrounding the star)

Bounce-shock-induced ejecta with mass up to 1% of initial star, v~0.2c

Numerical relativity simulations of collapses of rotating massive stars:

- It can explode with $E\sim10^{52}$ erg driven by disk outflow (←viscous model)
- It can synthesize sufficient amount ($\gtrsim 0.1M_\odot$) of ^{56}Ni (←viscous model)
- It can drive a jet (←MHD model with an ideal config.)
- No significant r-process in the ejecta