回転大質量星の重力崩壊と爆発現象

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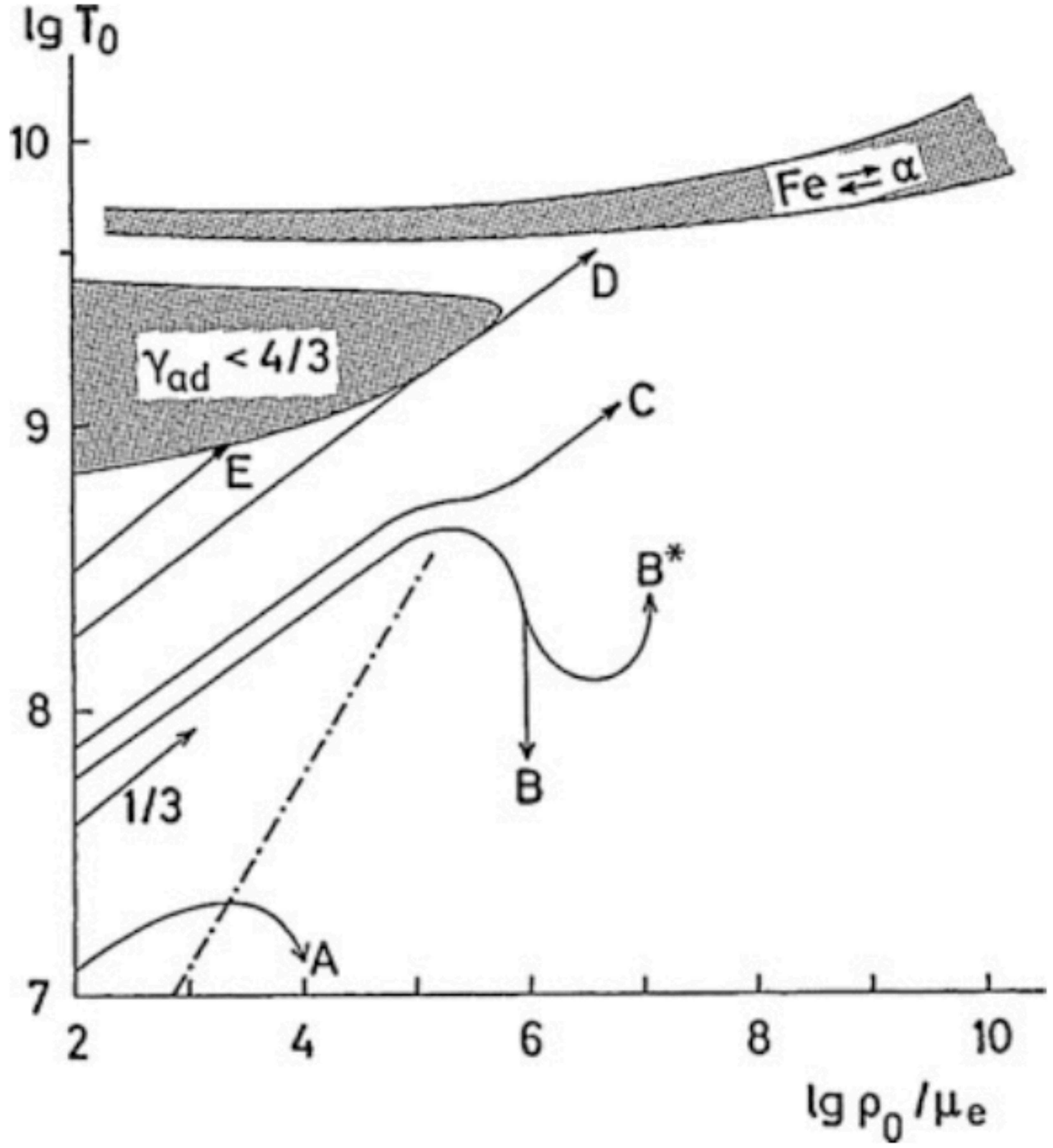
FSFG2024, 2024/11/13, Shinshu U, Nagano

Fate of massive stars



SMS

For single, non-rotating star...

- $M_{\rm ZAMS} \lesssim (8-10)M_\odot$

  → Degeneracy pressure support before Fe-formation

- $M_{\rm ZAMS} \gtrsim (8-10)M_\odot$

  → Fe-core formation → Gravitational collapse

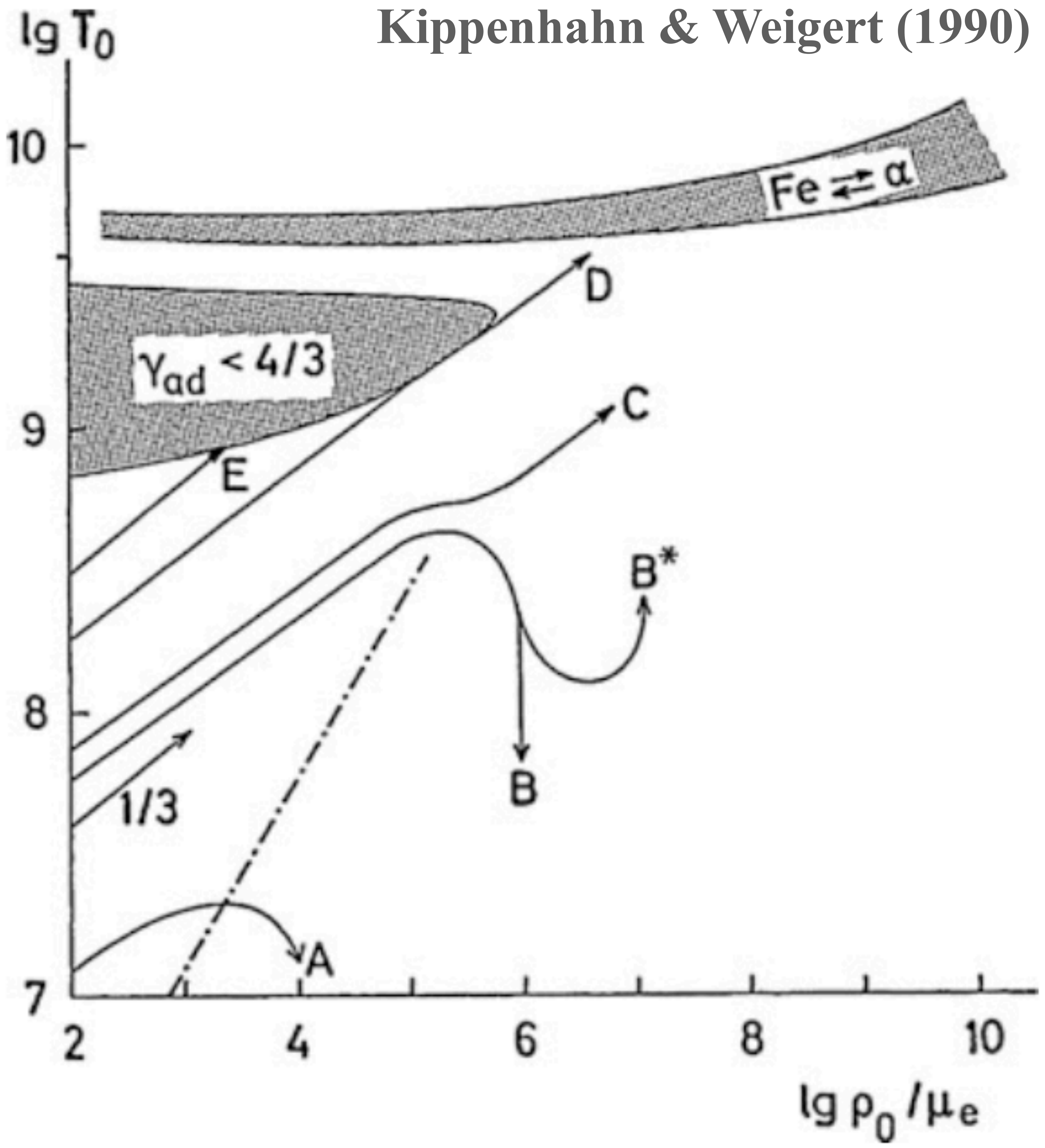
- $M_{\rm ZAMS} \gtrsim 130M_\odot$

  → e^-e^+ pair production → Gravitational collapse

- $M_{\rm ZAMS} \gtrsim 10^4M_\odot$

  → General relativistic instability → Gravitational collapse

Fate of massive stars



Kippenhahn & Weigert (1990)

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  → General relativistic instability → Gravitational collapse

Outline

- ✓ Collapse of rotating **supermassive** stars (~10^5Msun, ~10^3Msun)
- ✓ Collapse of rotating massive star (System~10Msun, ejecta~Msun)

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Supermassive star

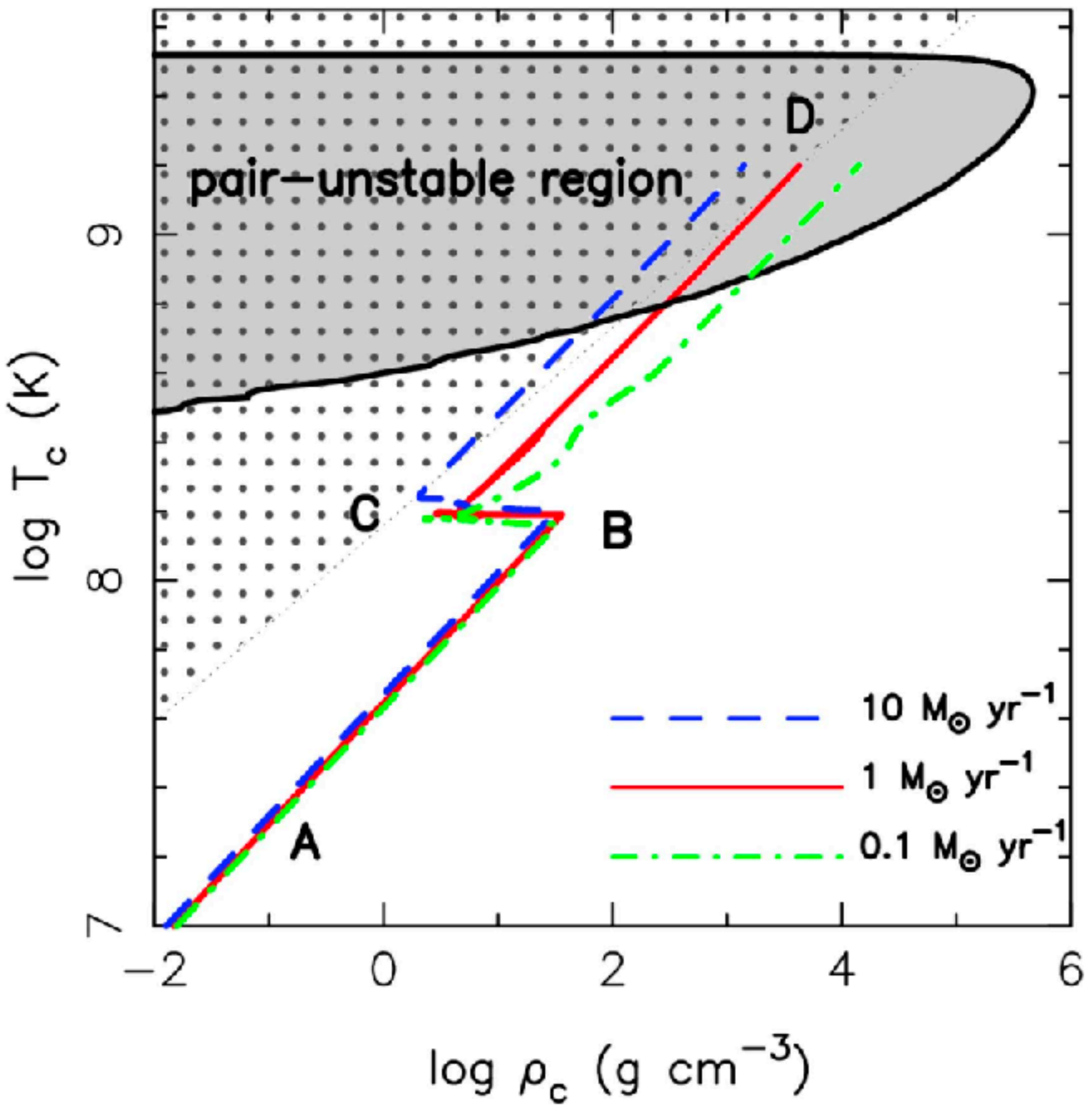
- Hypothetical very massive ($\gtrsim 10^4 M_\odot$) star
- High-s, P_{rad}-dominant $(\Gamma \approx 4/3)$
- Dies likely by GR instability

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

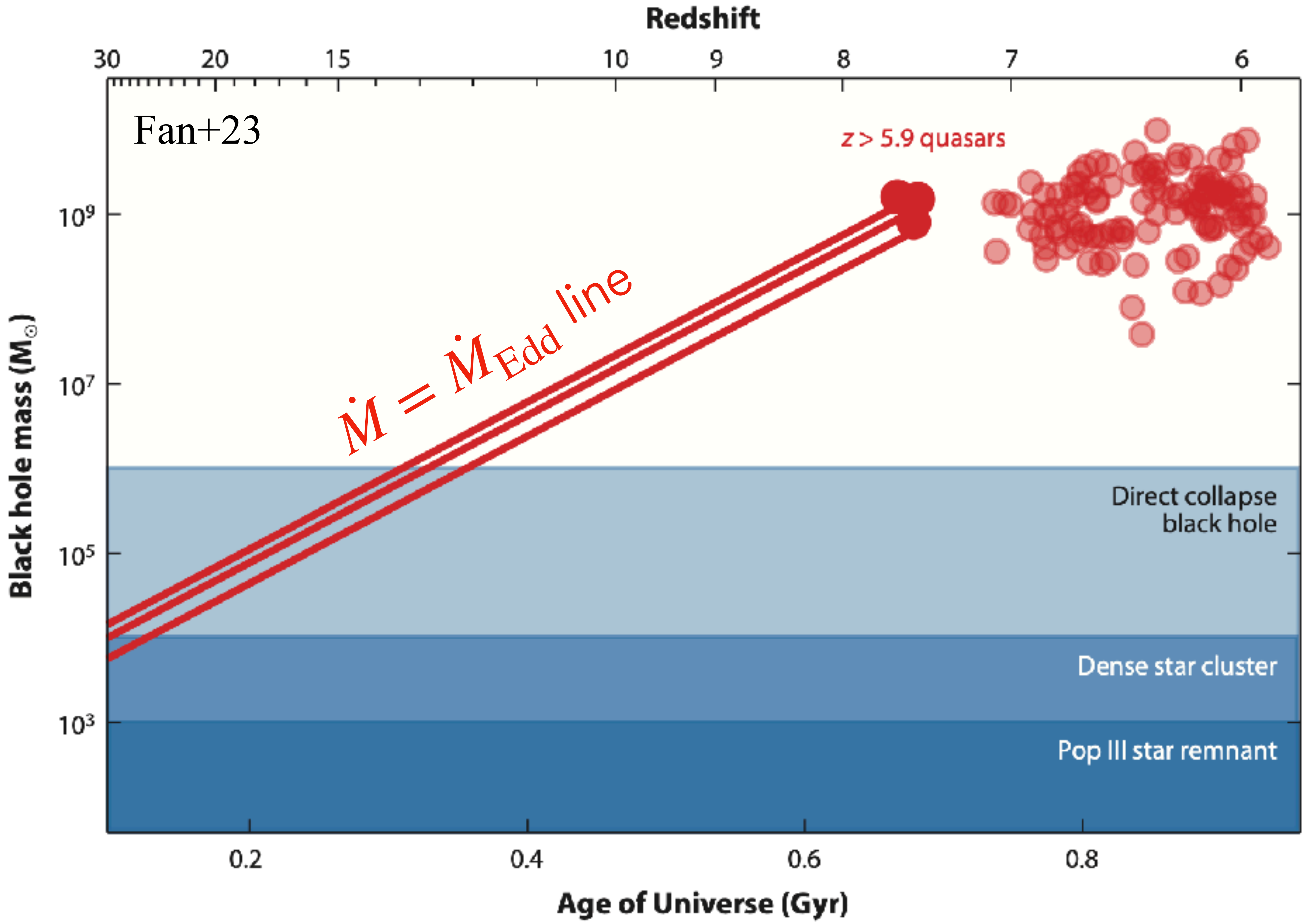
$$\approx 4\ \mathrm{g/cm^3}\ (M/10^5 M_\odot)^{-3.5} (\mu/0.59)^{-3}$$

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

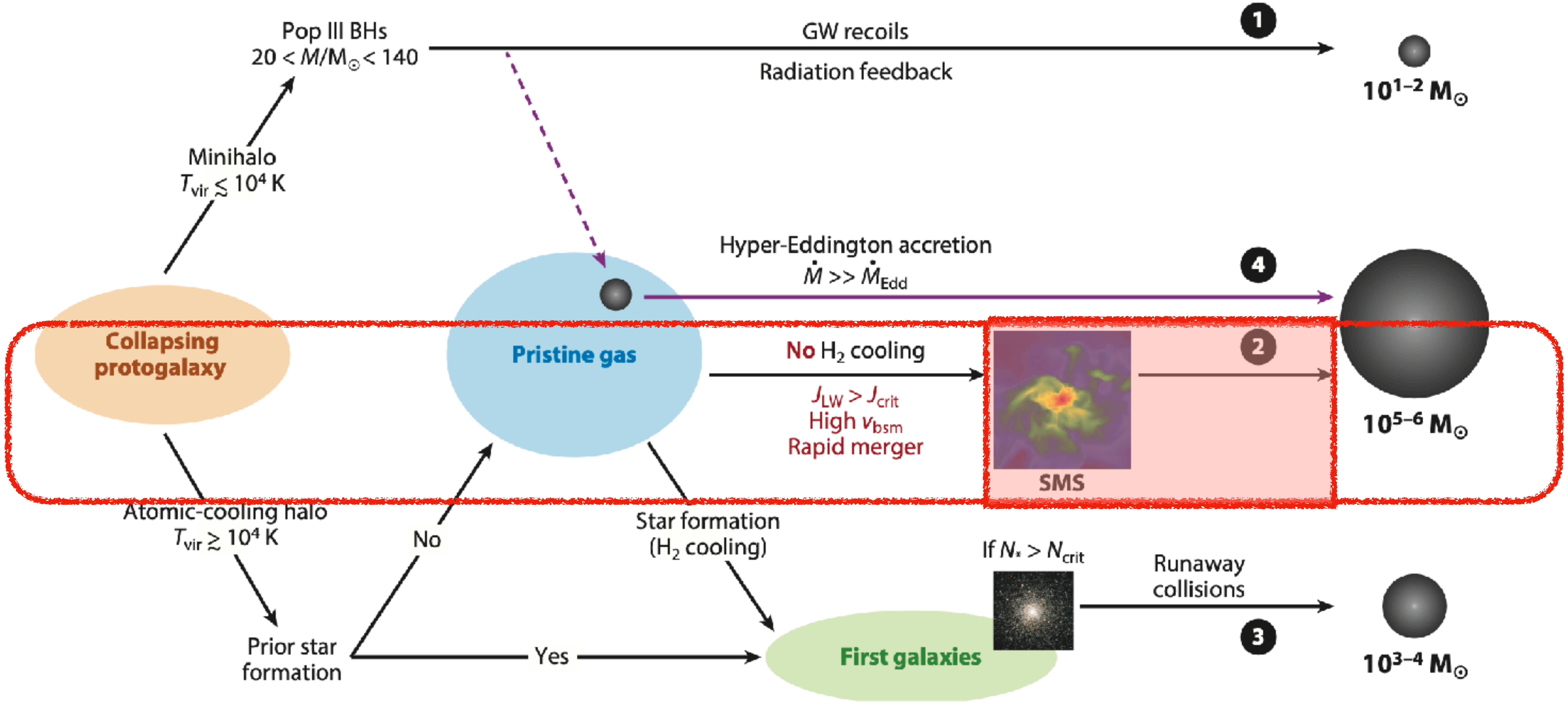
(Super/hyper-Eddington accretion may be possible)

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!

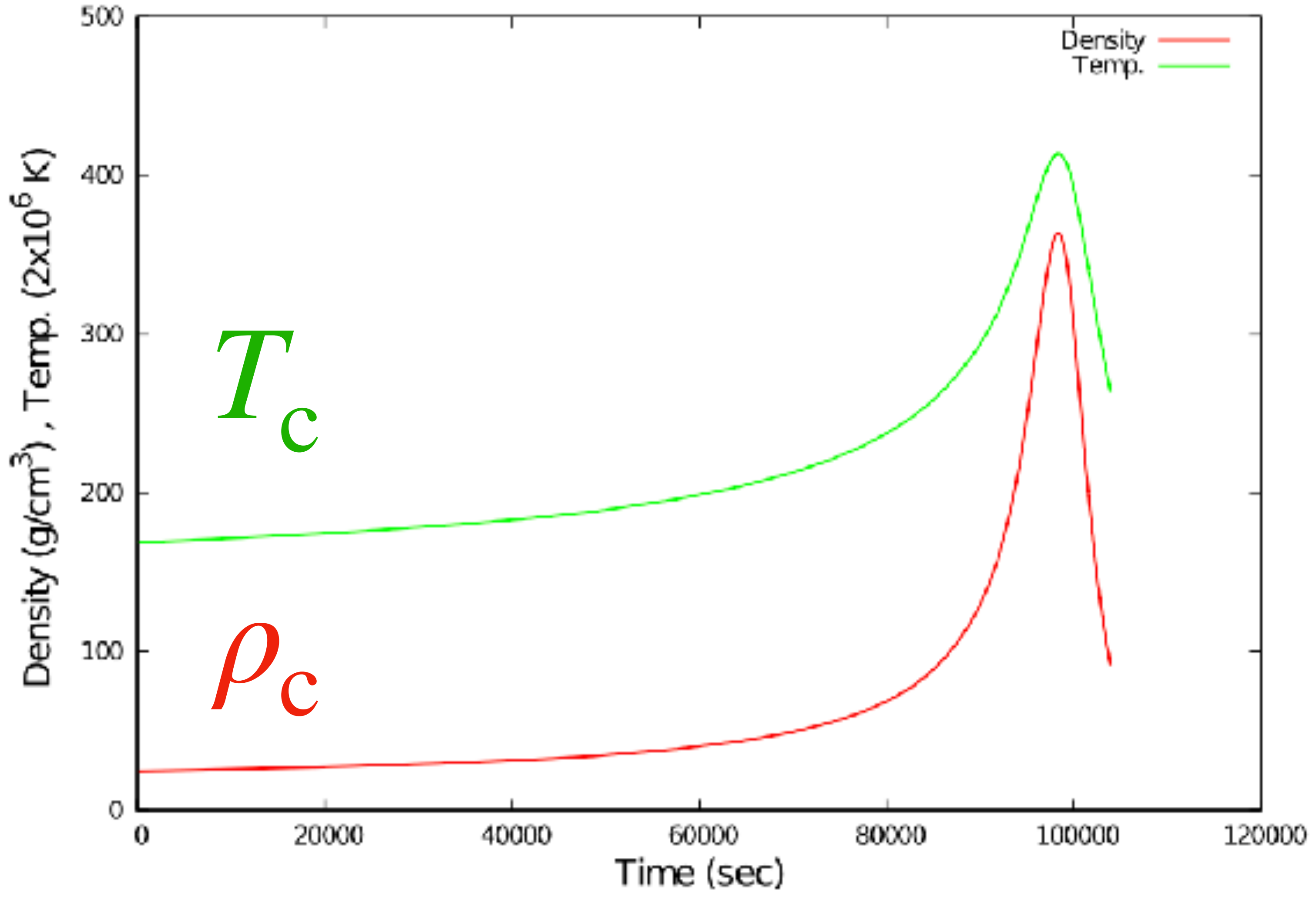
Direct collapse scenario for SMBHs in early universe



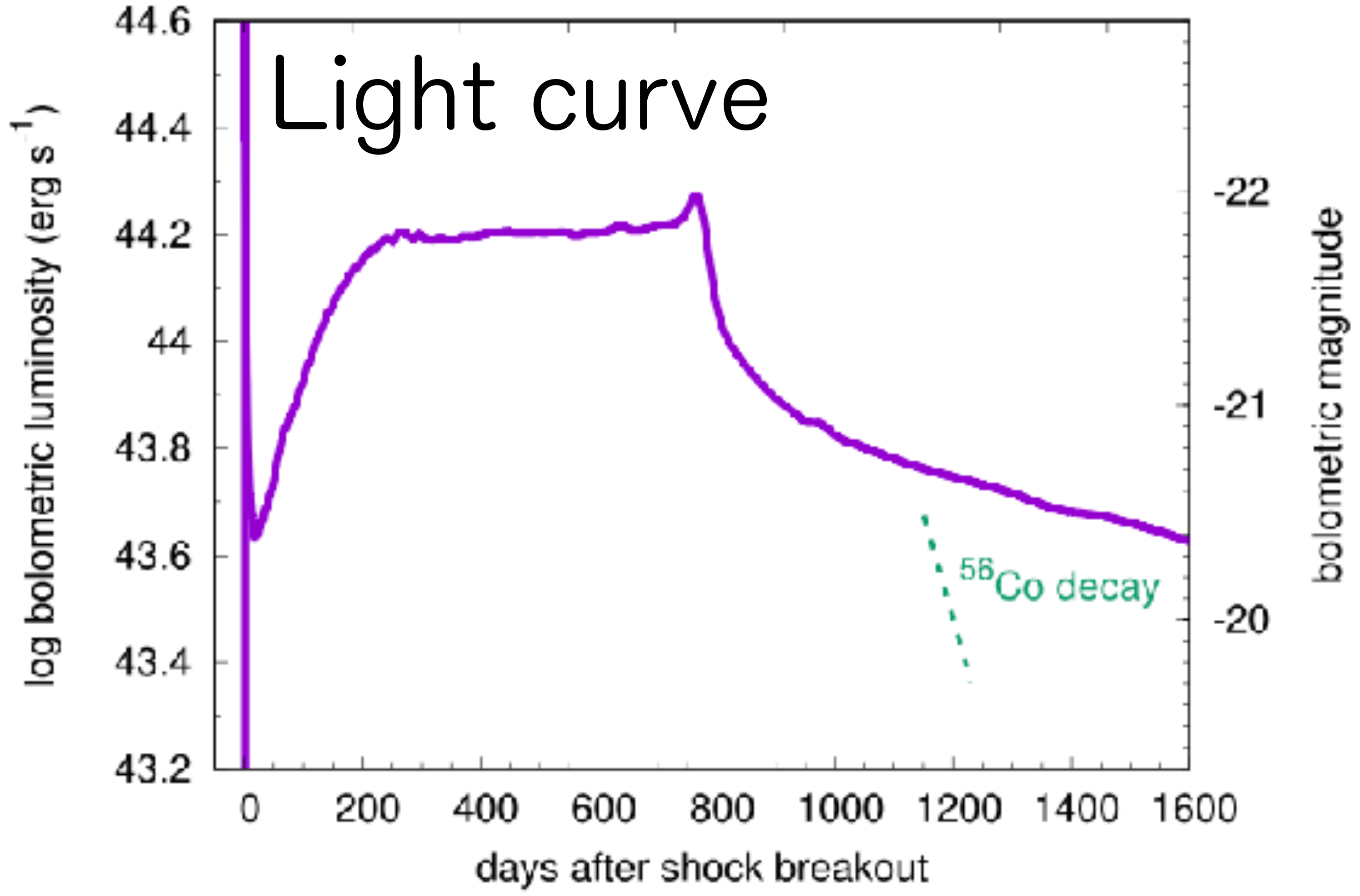
Inayoshi+20, see also Rees 1978

Explosion of supermassive stars: thermonuclear case

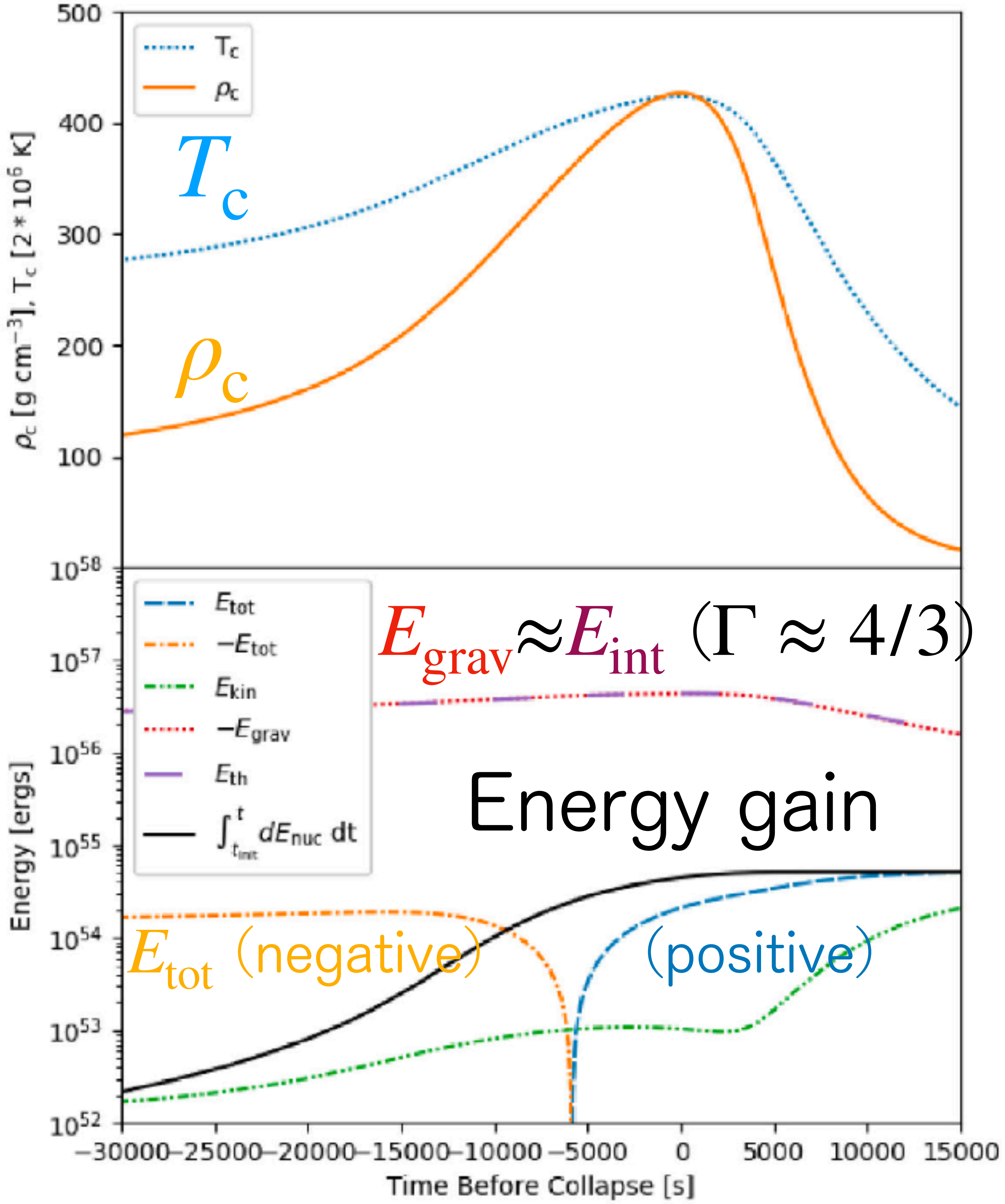
Chen+14



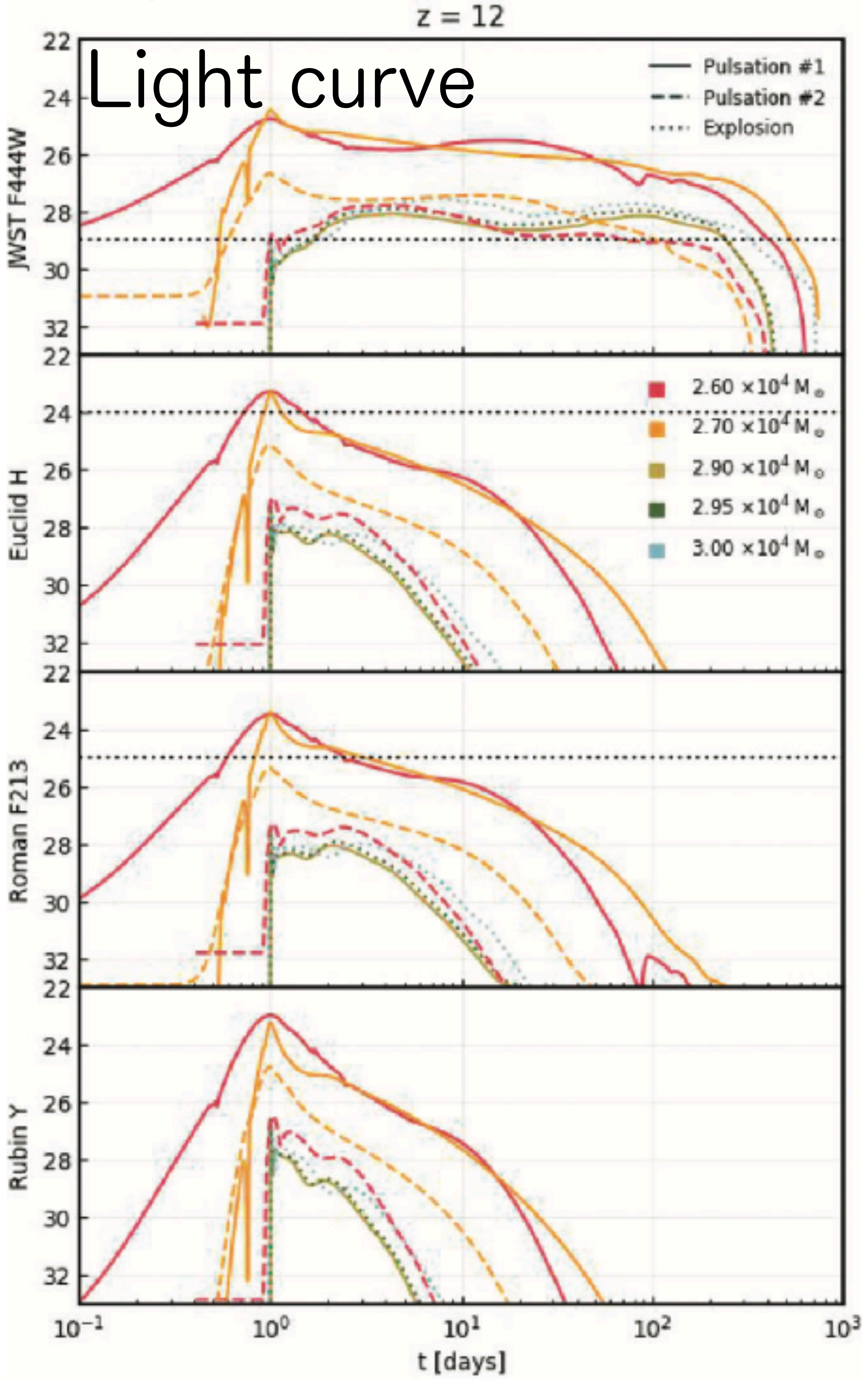
Moriya+21 (see also Whalen+13)



Nagele+20

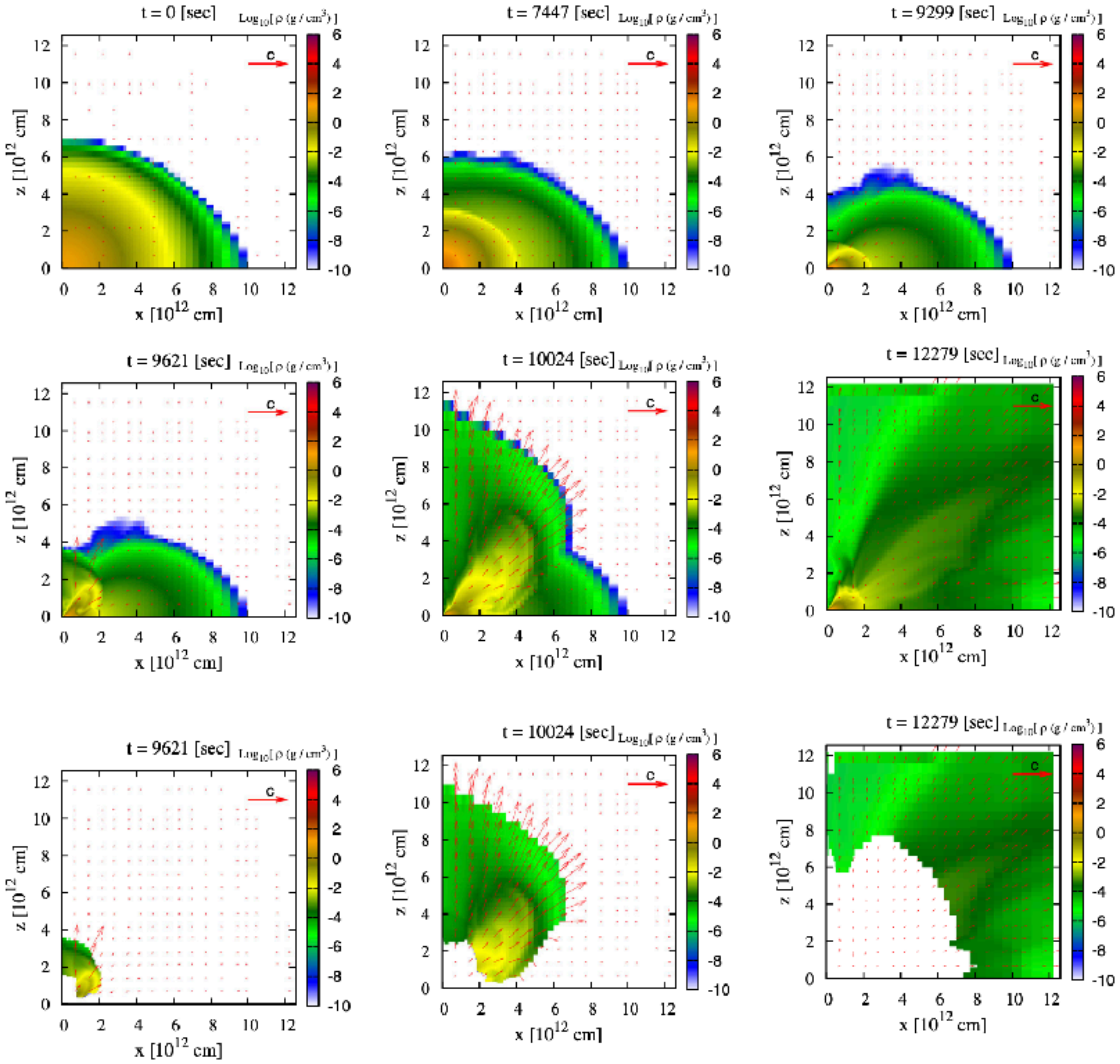


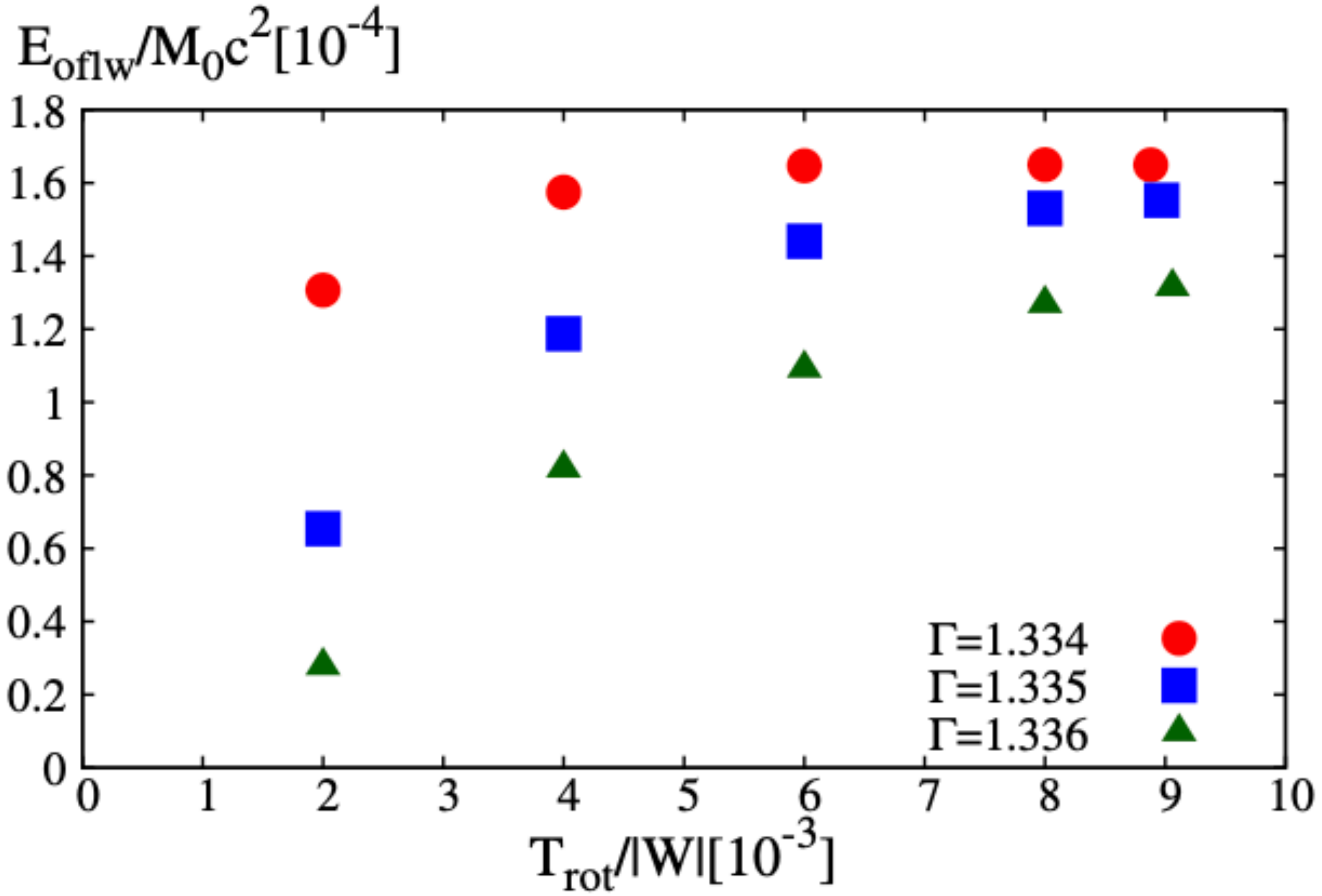
Nagele+23 (incl. pulsation)



Effects of rotation: bounce-induced explosion

Uchida+17





Let us revisit this scenario
as the first step toward the understanding
collapse of very massive stars

Method: Numerical setup

General relativistic gravity

Hydrodynamics with nuclear reaction

H → He → C （Only forward reaction）

CNO cycle triple-α

Equation of state

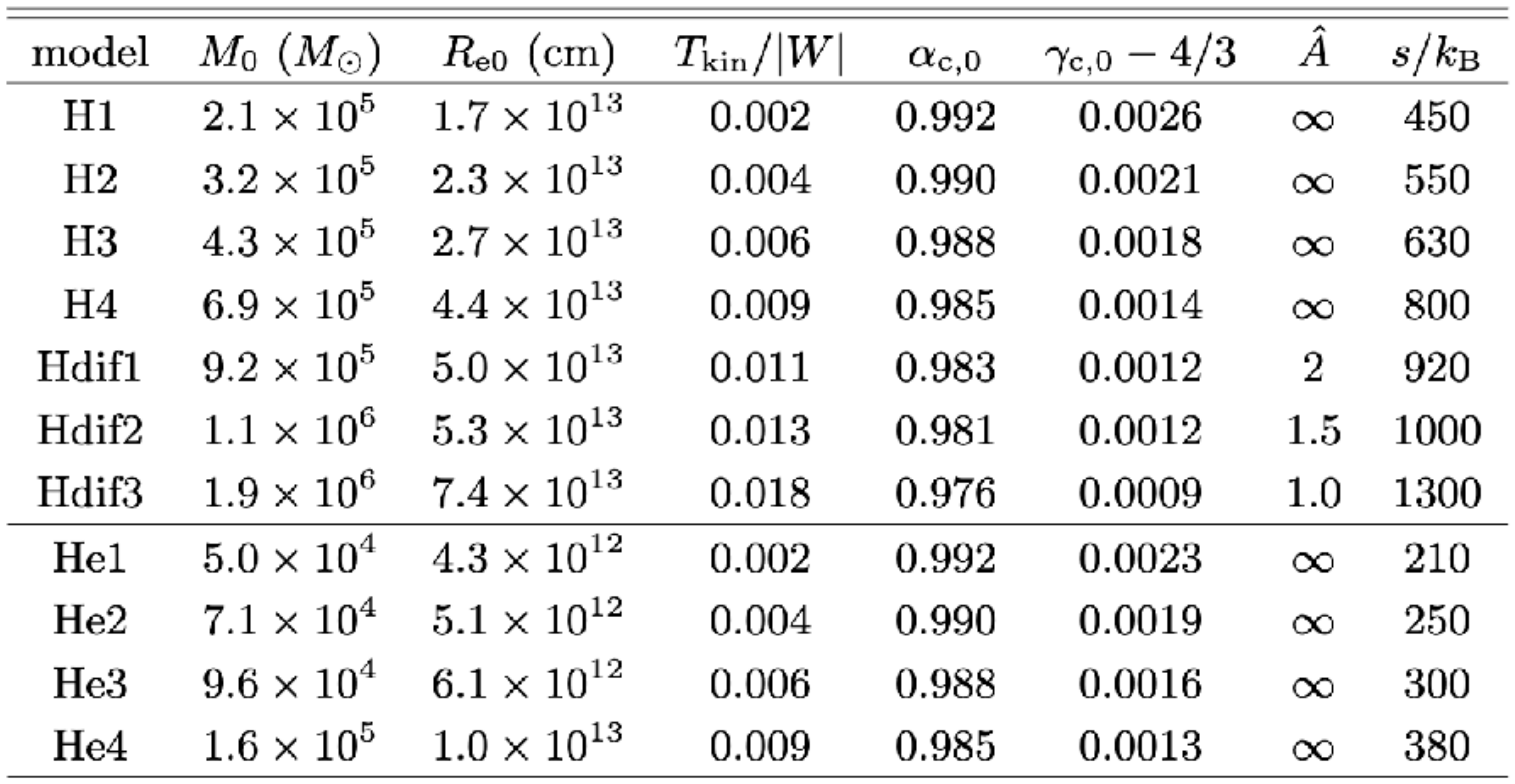
Composite of ions(H, He, C), photons, electrons and positrons

Neutrino radiation

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

Method: Initial supermassive star models

Marginally stable SMS with rotation.



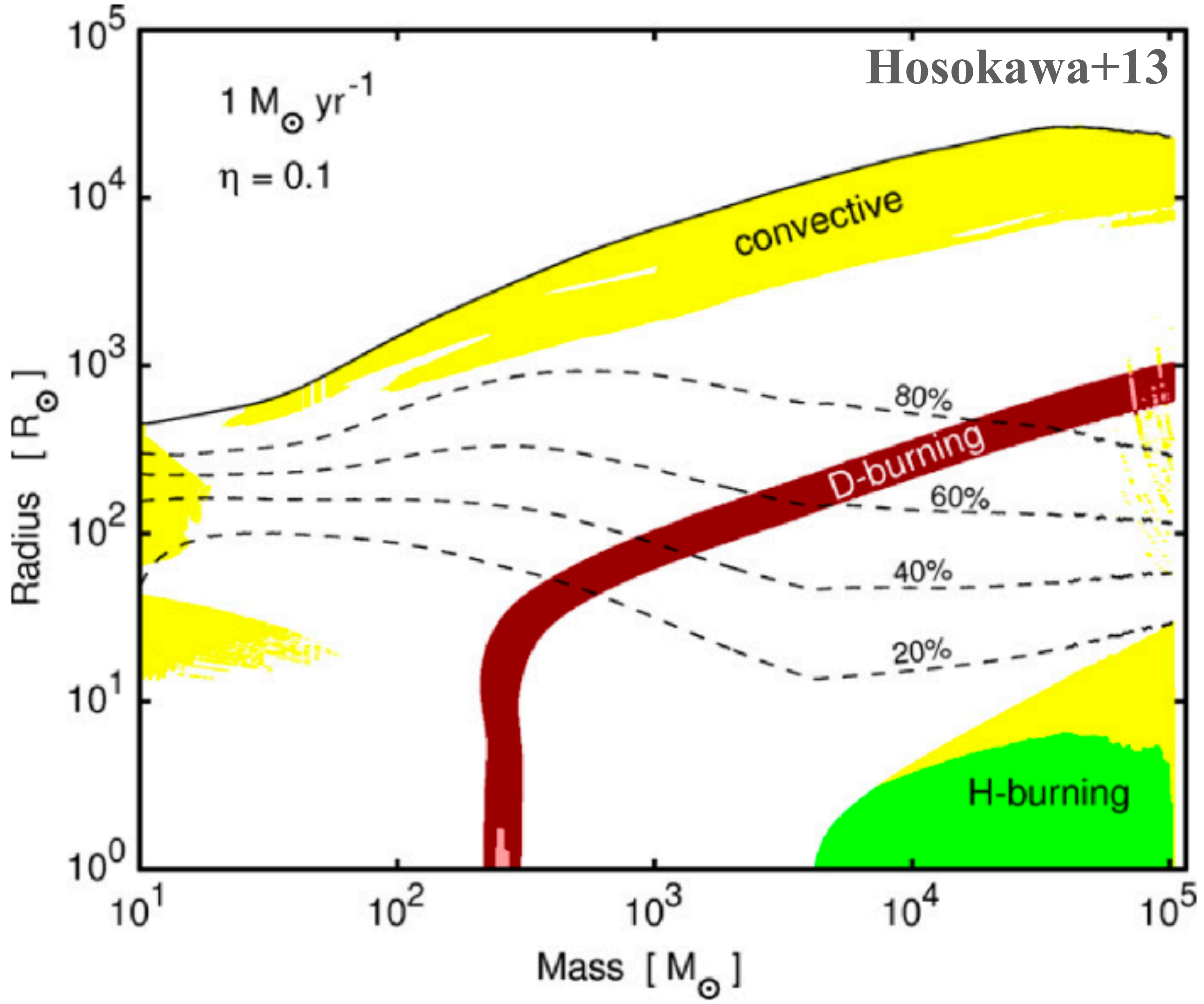
model	M_0 ($M_\odot$)	R_{e0} (cm)	$T_{\rm kin}/\lvert W\rvert$	$\alpha_{c,0}$	$\gamma_{c,0}-4/3$	$\hat{A}$	$s/k_{\rm B}$
H1	2.1×10^{5}	1.7×10^{13}	0.002	0.992	0.0026	∞	450
H2	3.2×10^{5}	2.3×10^{13}	0.004	0.990	0.0021	∞	550
H3	4.3×10^{5}	2.7×10^{13}	0.006	0.988	0.0018	∞	630
H4	6.9×10^{5}	4.4×10^{13}	0.009	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

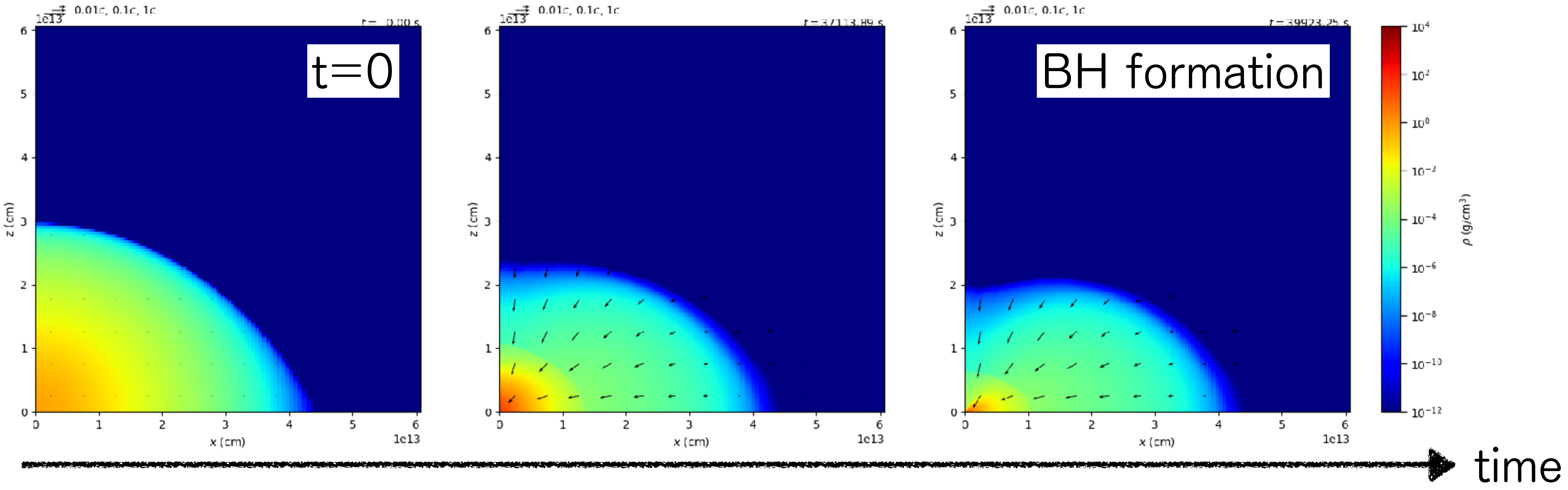
Caution: here are only the isentropic “core” of SMS



Realistic SMS may have inflated envelope

Result: Outline of evolution

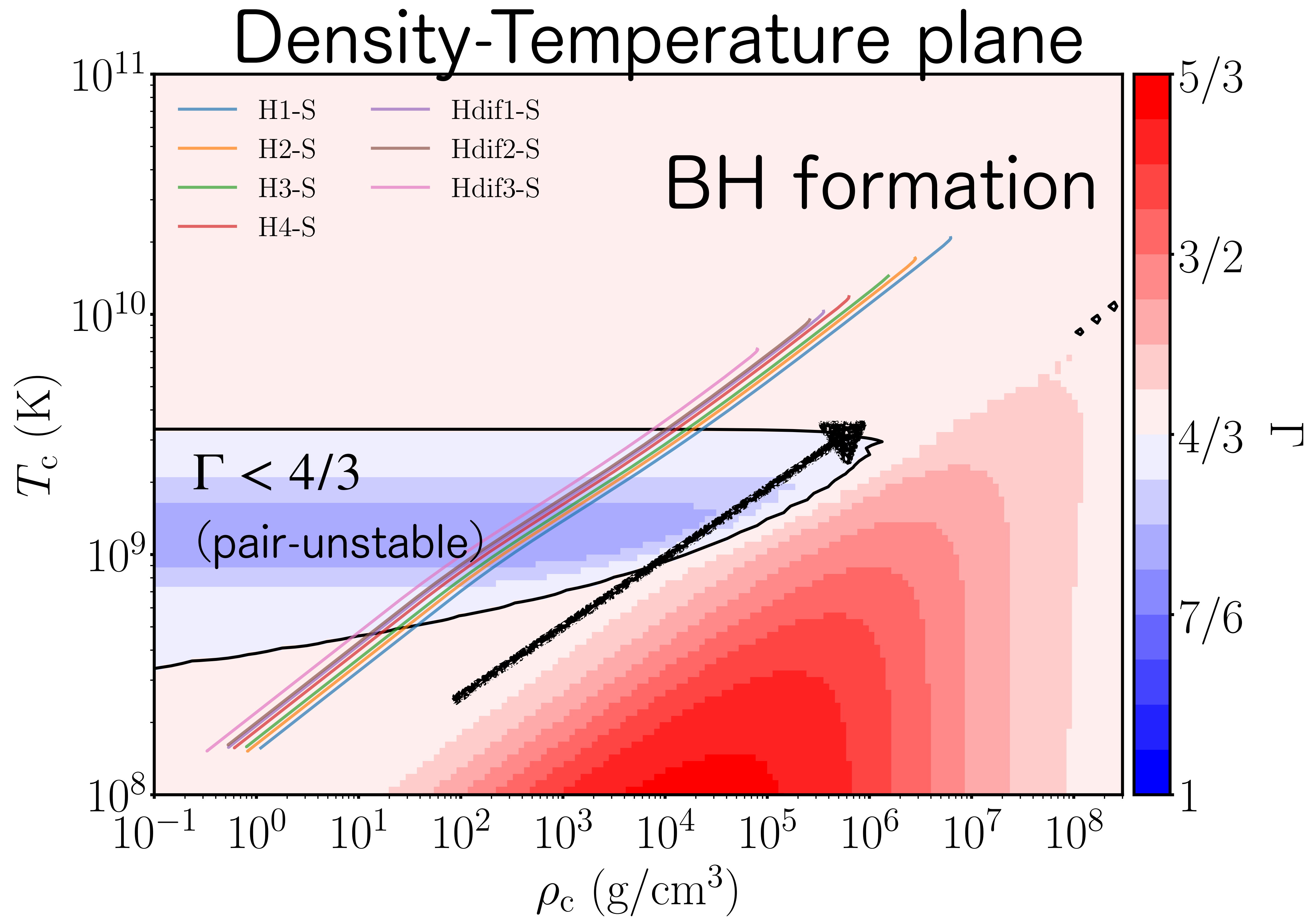
Primordial composition, mass-shedding case



Collapsing motion is ~ coherent (characteristic of GR instability)

Result: Outline of evolution

Density-Temperature plane

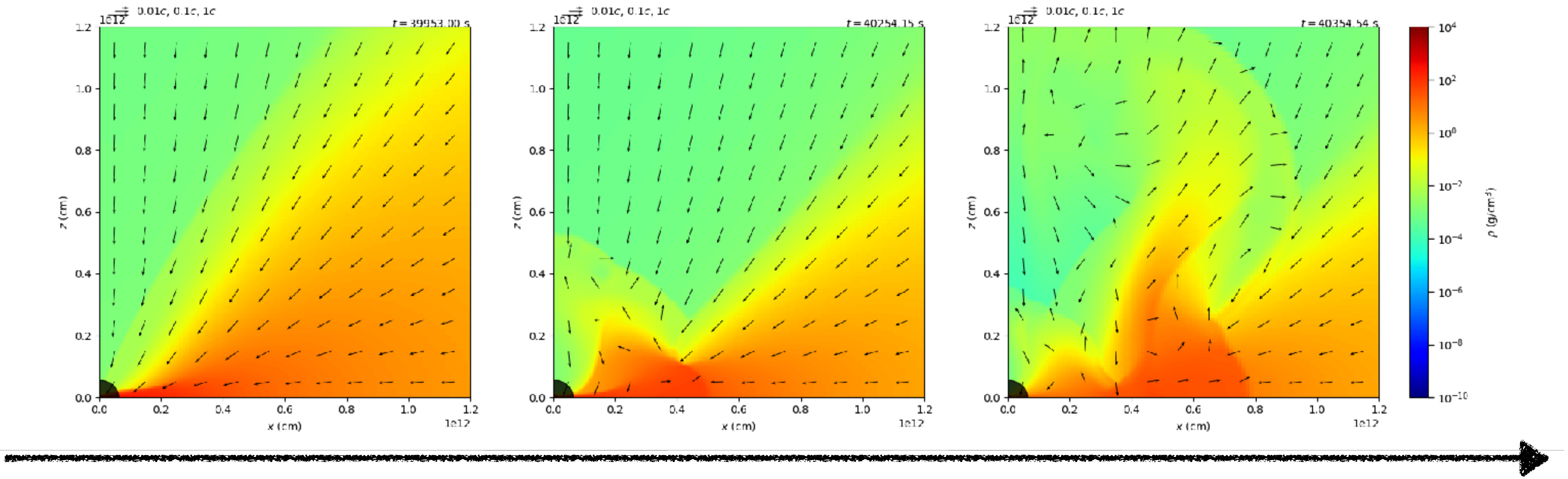


Collapse proceeds outside pair-unstable region.

→ GR instability

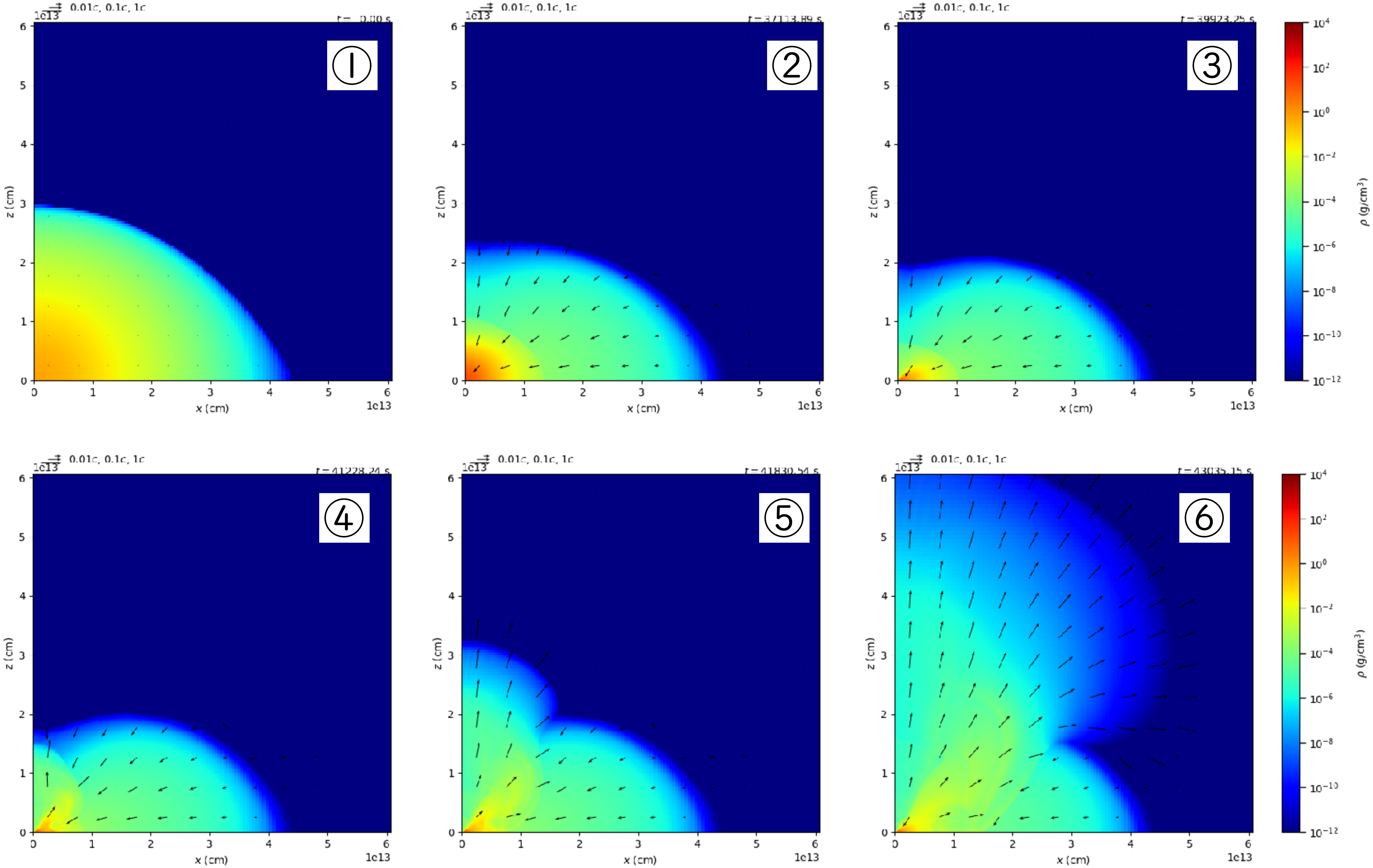
Result: Bounce-shock-induced ejecta

Density snapshots around torus formation time.



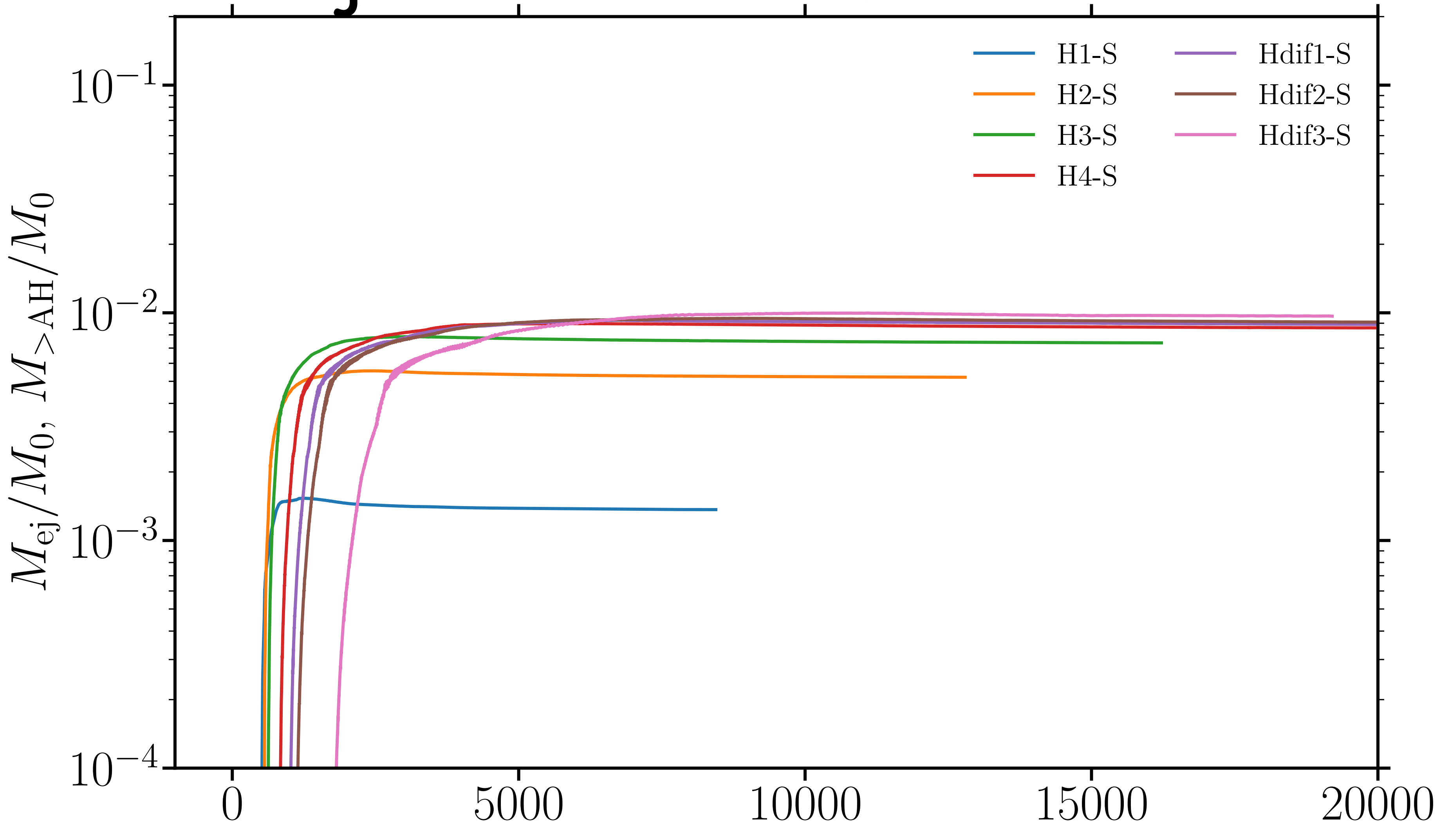
time

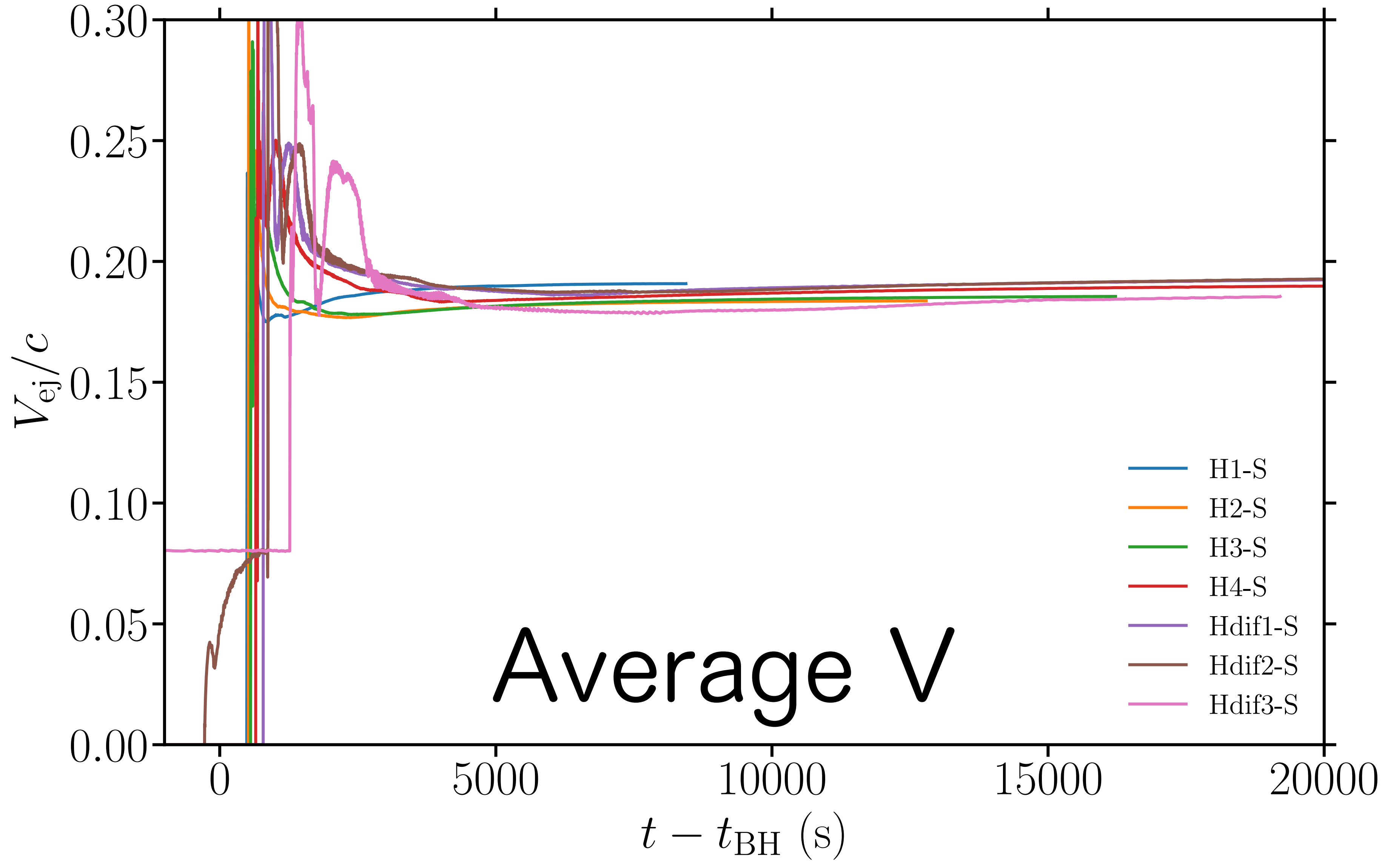
Sudden formation of centrifugally supported torus induces its bounce

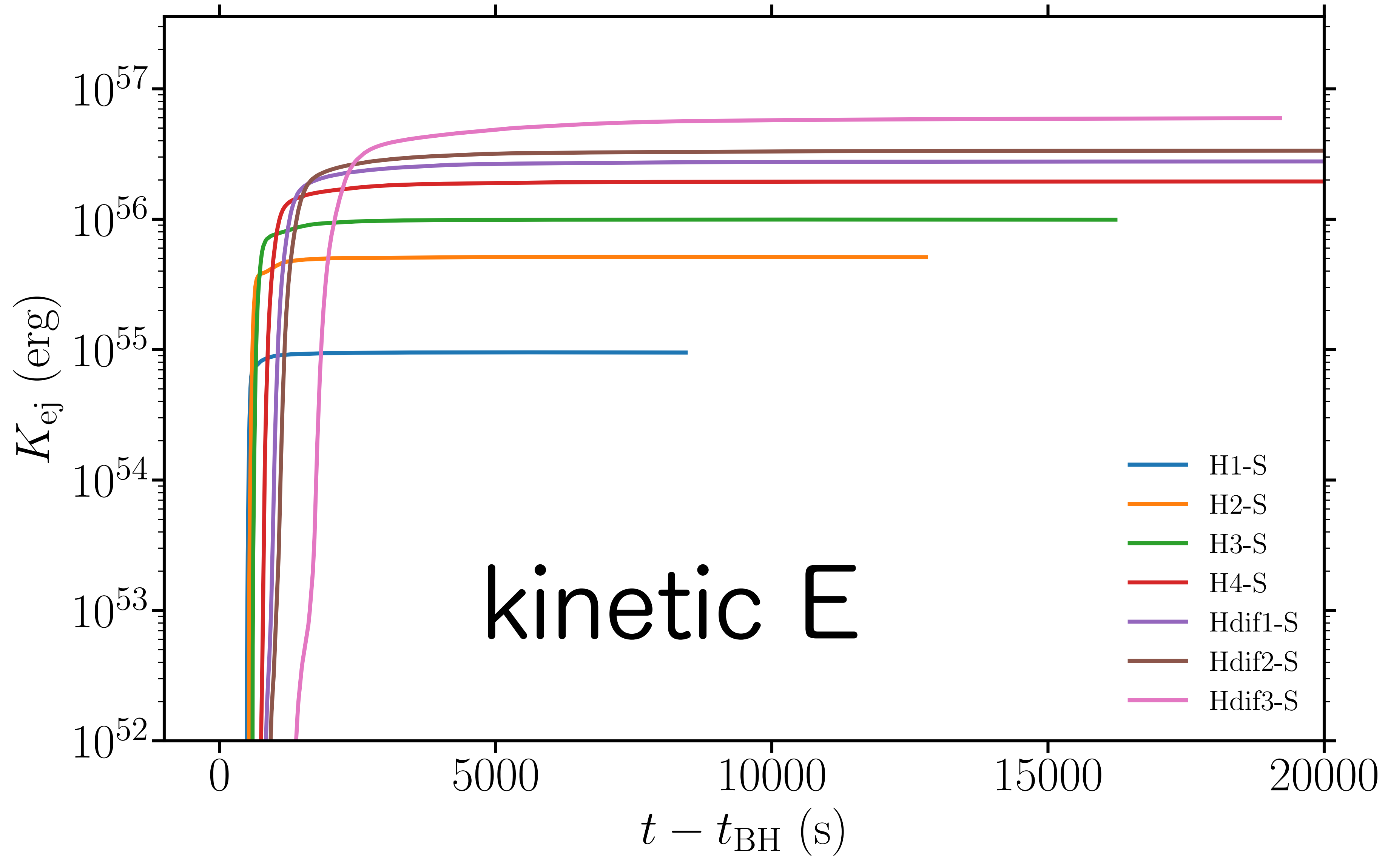
①
t = 0.00 s
②
t = 37113.89 s
③
t = 39923.25 s
④
t = 41228.24 s
⑤
t = 41830.54 s
⑥
t = 43035.15 s
0.01c, 0.1c, 1c
1e13
x (cm)
z (cm)
0
1
2
3
4
5
6
ρ (g/cm³)
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12

Result: Properties of ejecta

ejecta mass / total mass

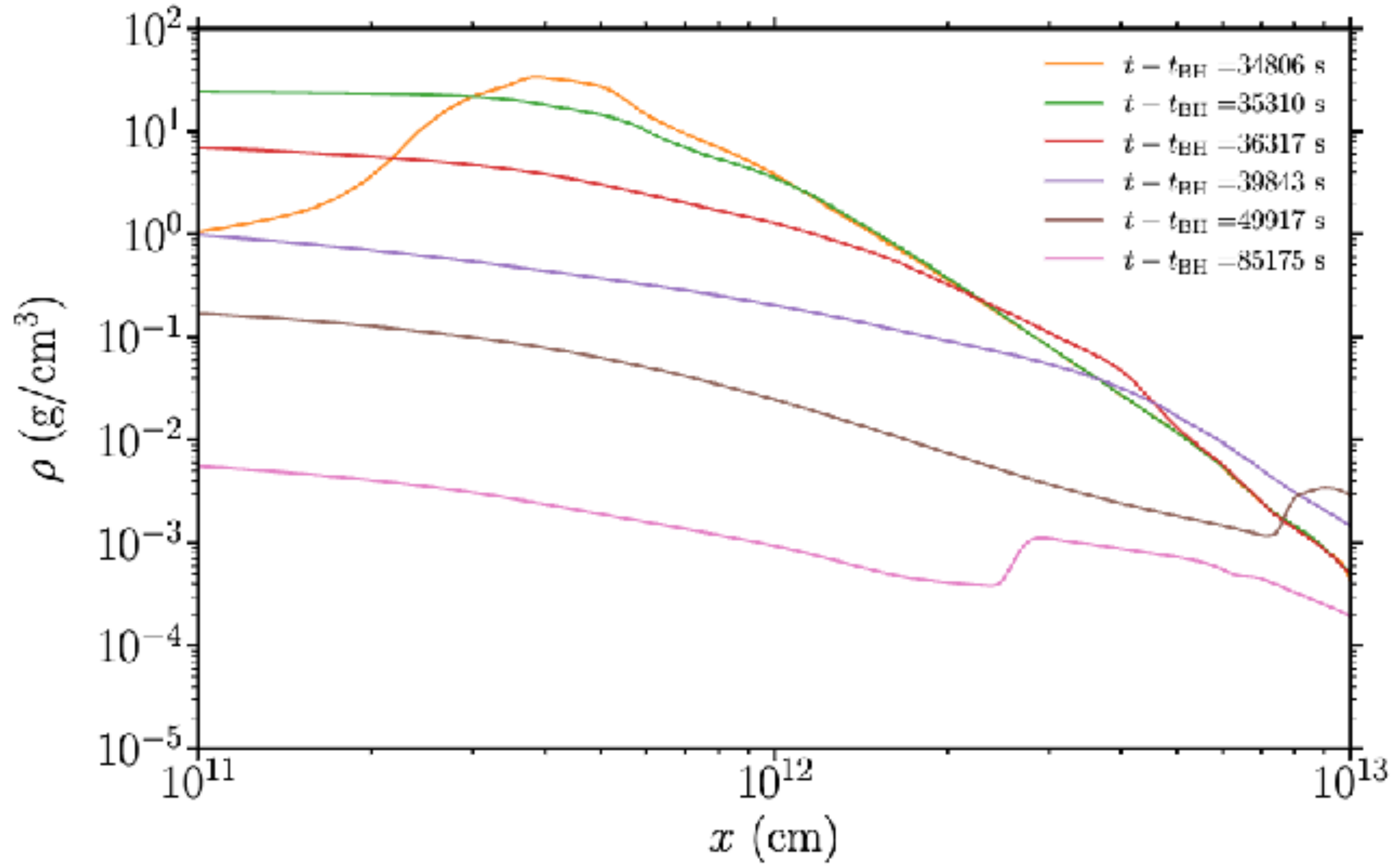


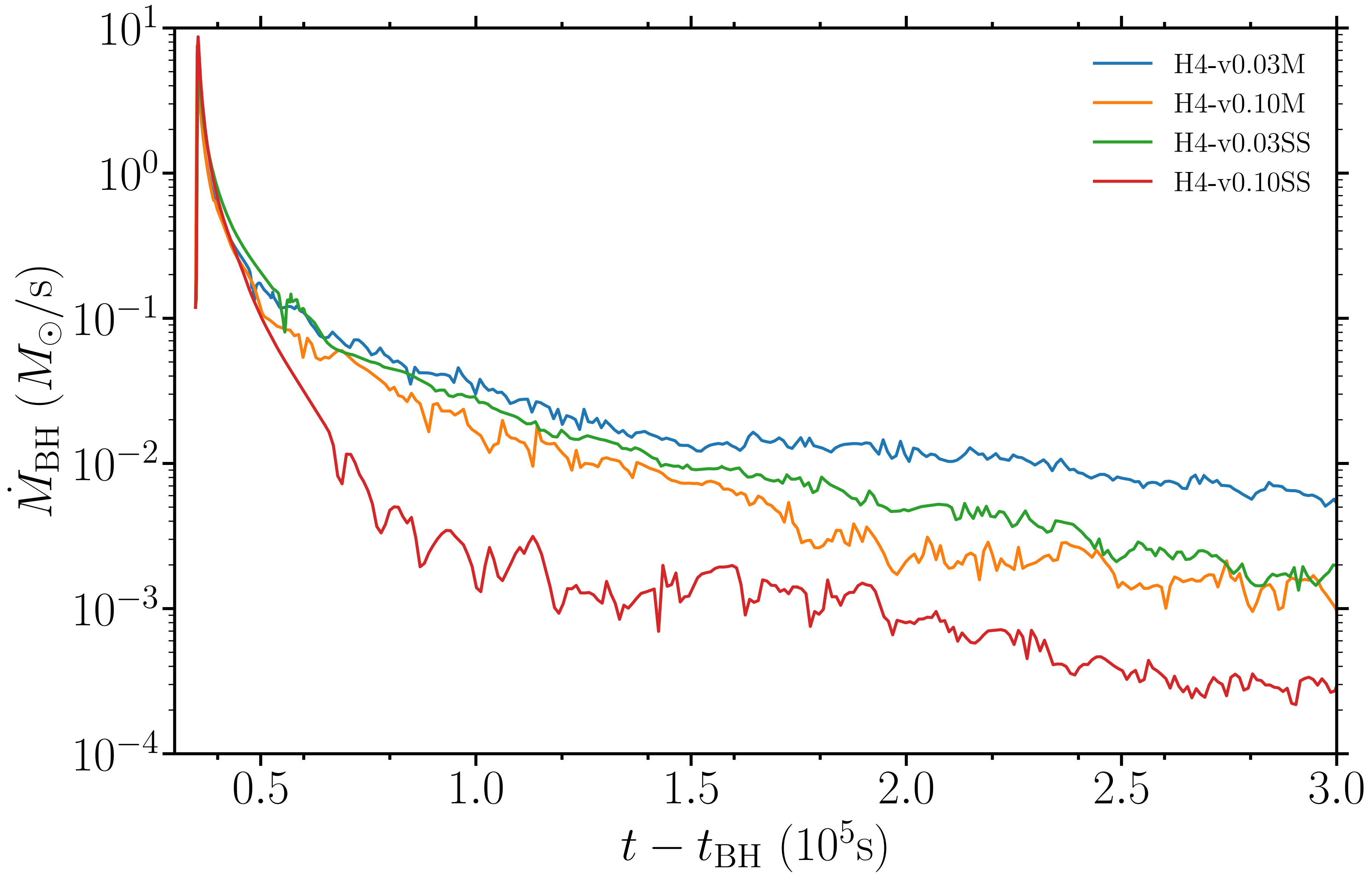


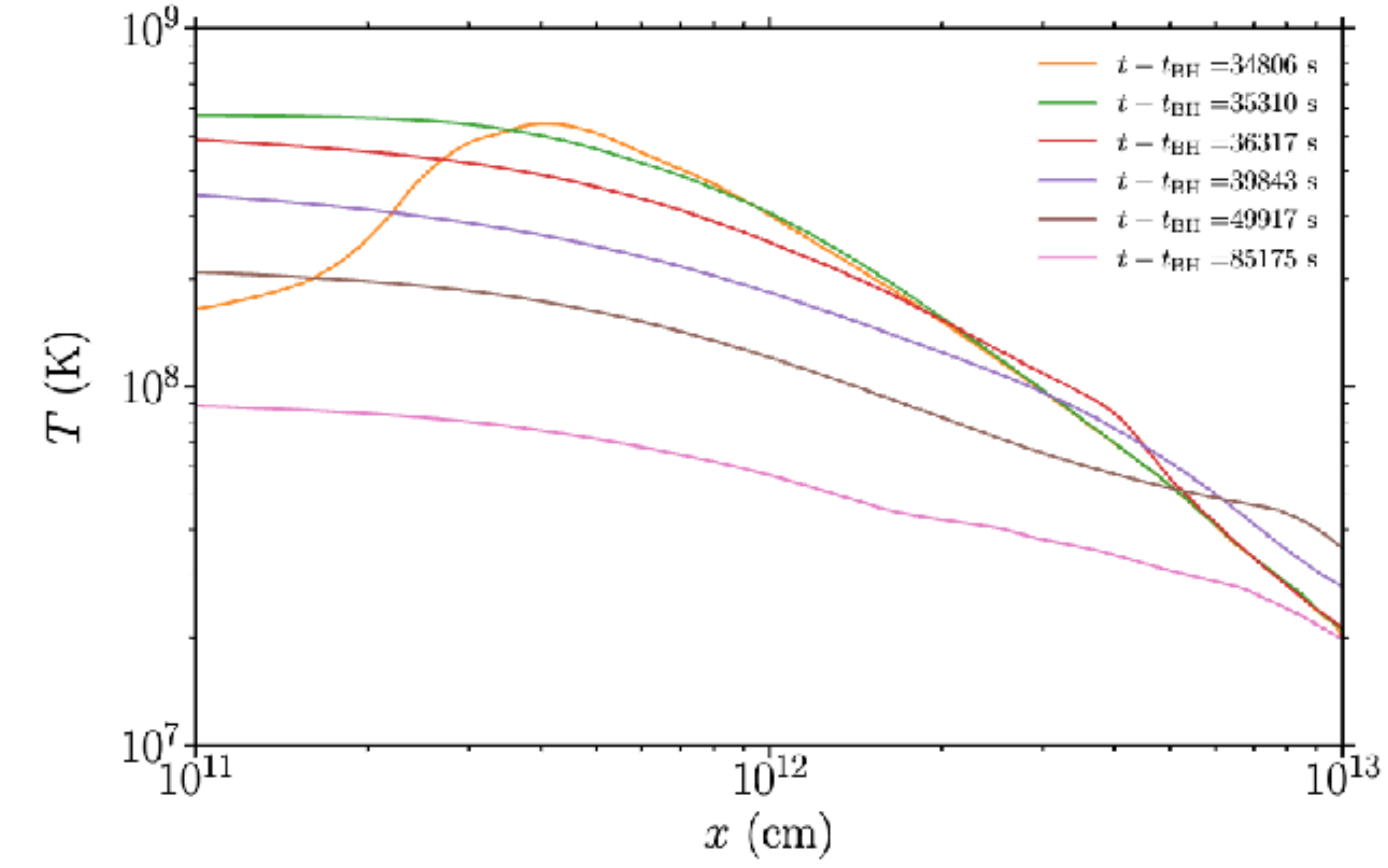


- Ejecta mass ~ 1% of initial SMS mass for fast-rotating SMS.
- Velocity ~ 0.2 c
- Kinetic E ~ $10^{-4}Mc^2$

Result: Viscous evolution of the disk



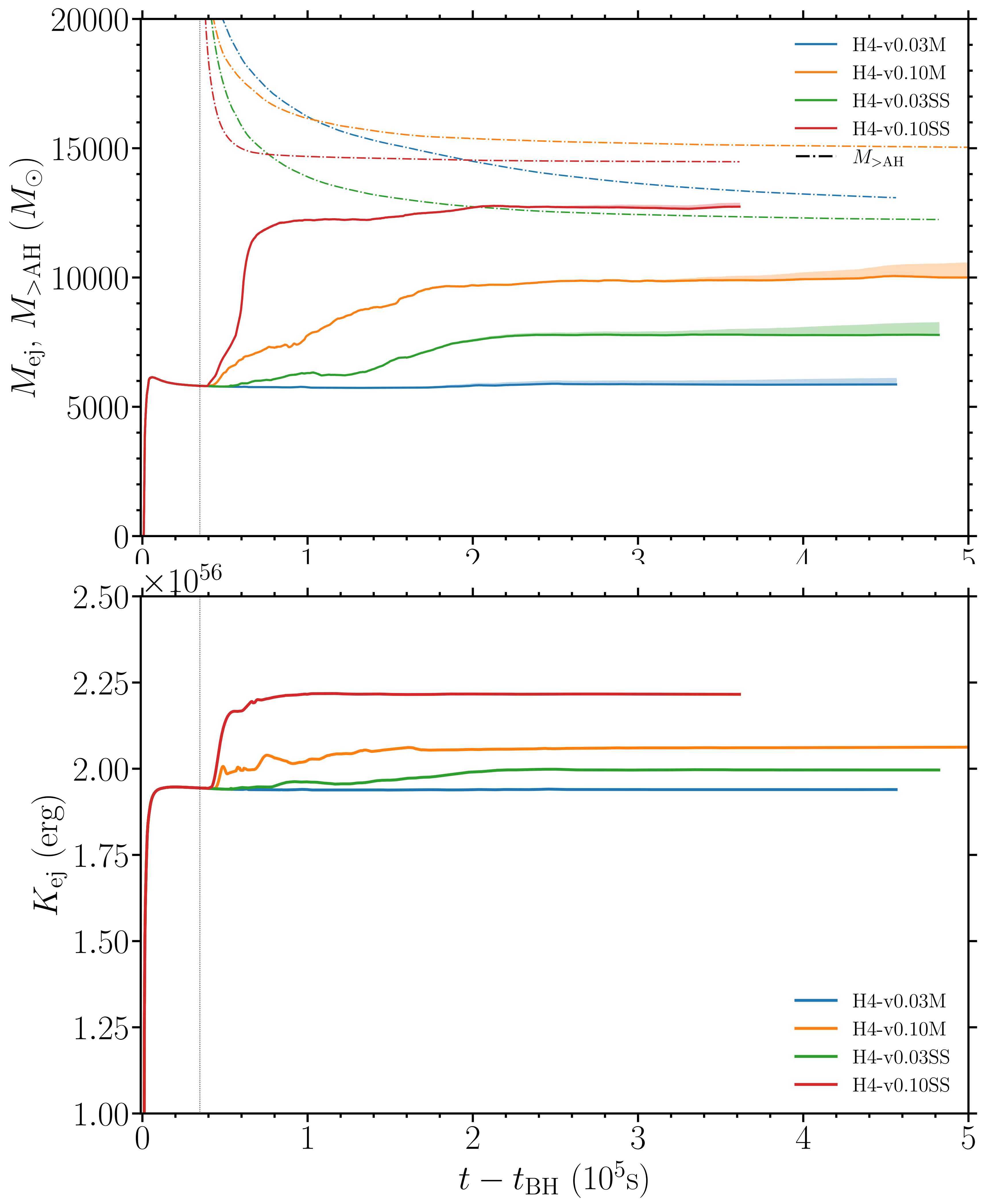




Accretion timescale ~10^4 s

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

Result: Viscous evolution of the disk

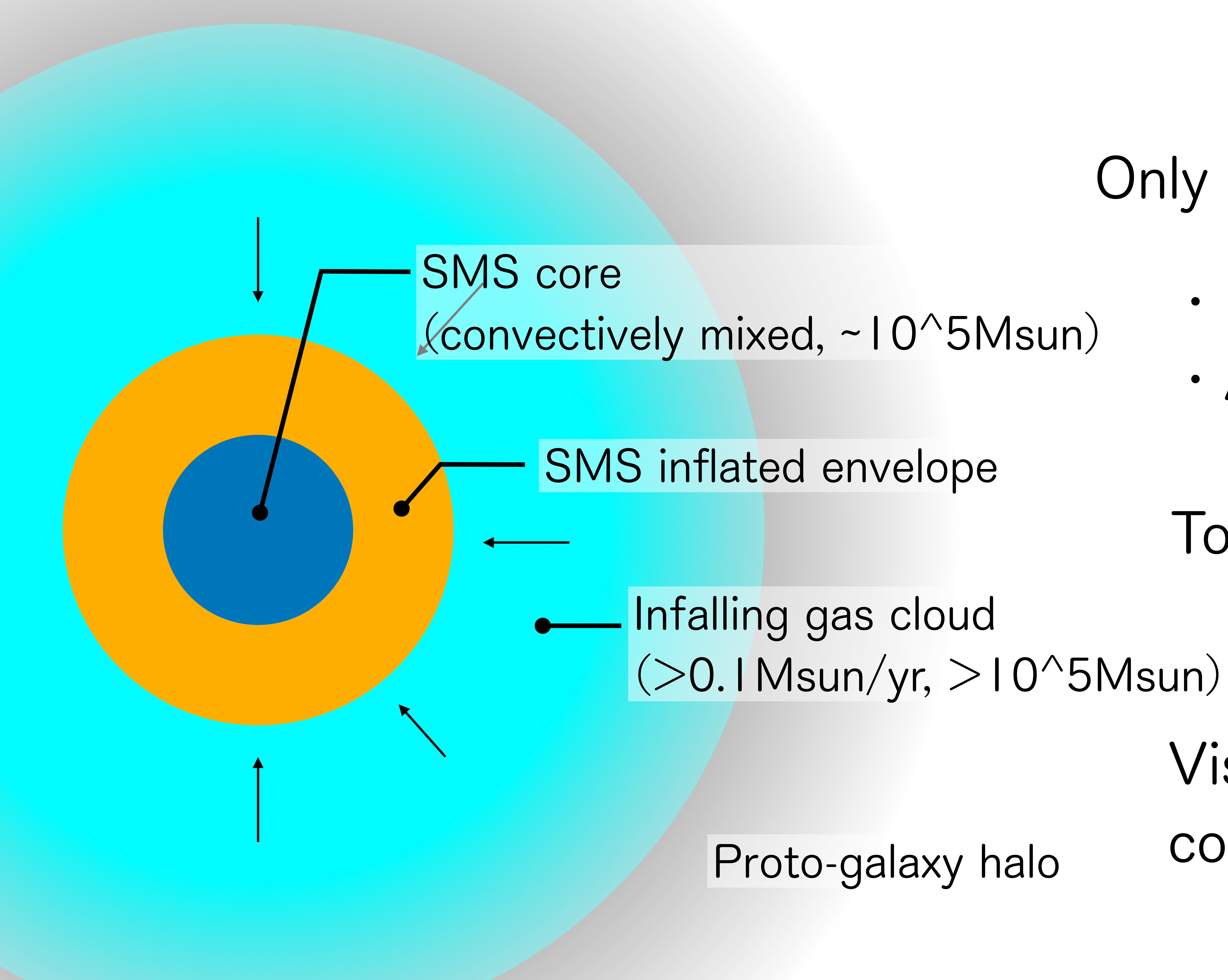


Viscosity-driven ejecta
(with different prescription & strength)

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



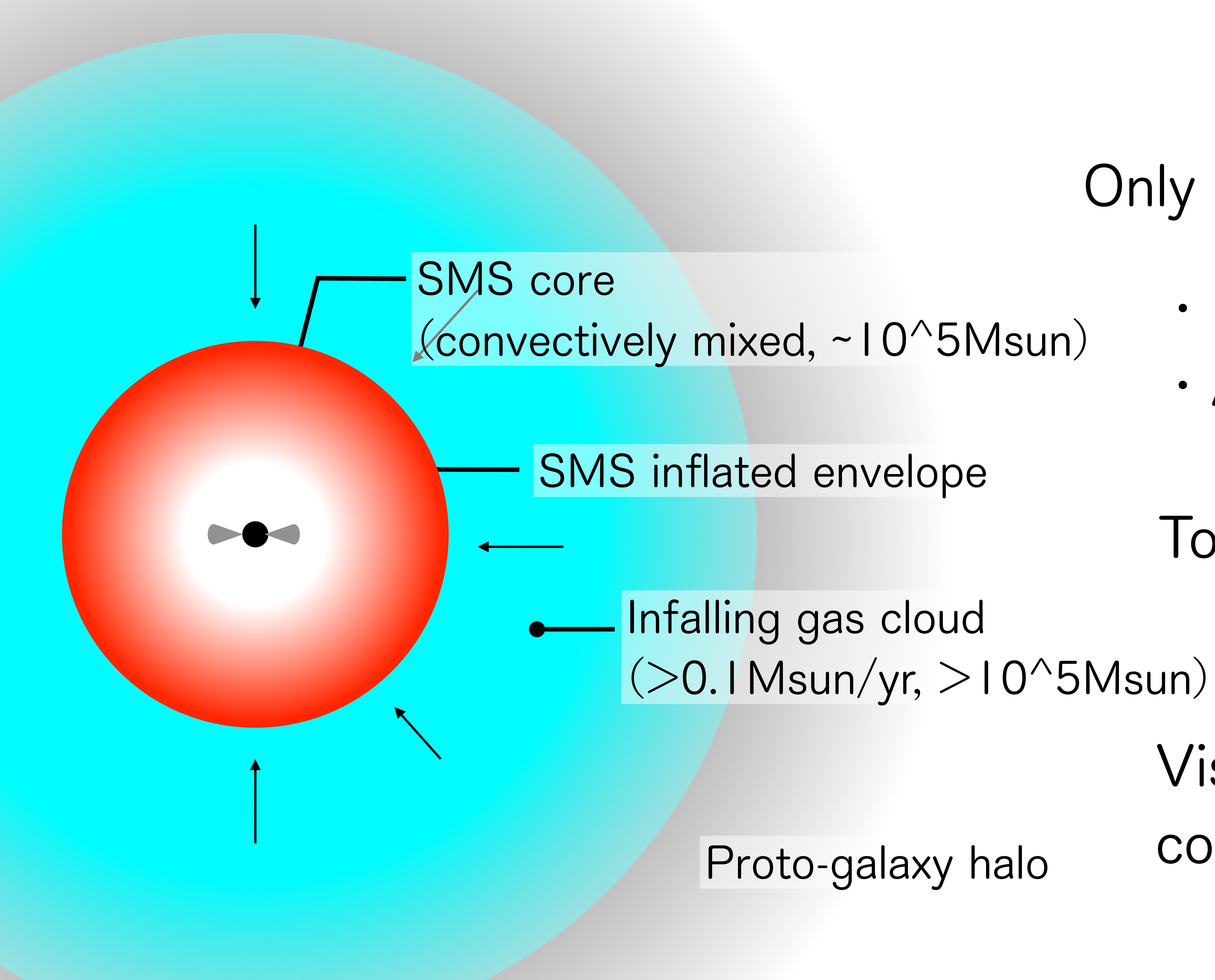
Only the collapse of SMS core is simulated.

- 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



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

SMS inflated envelope

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

Proto-galaxy halo

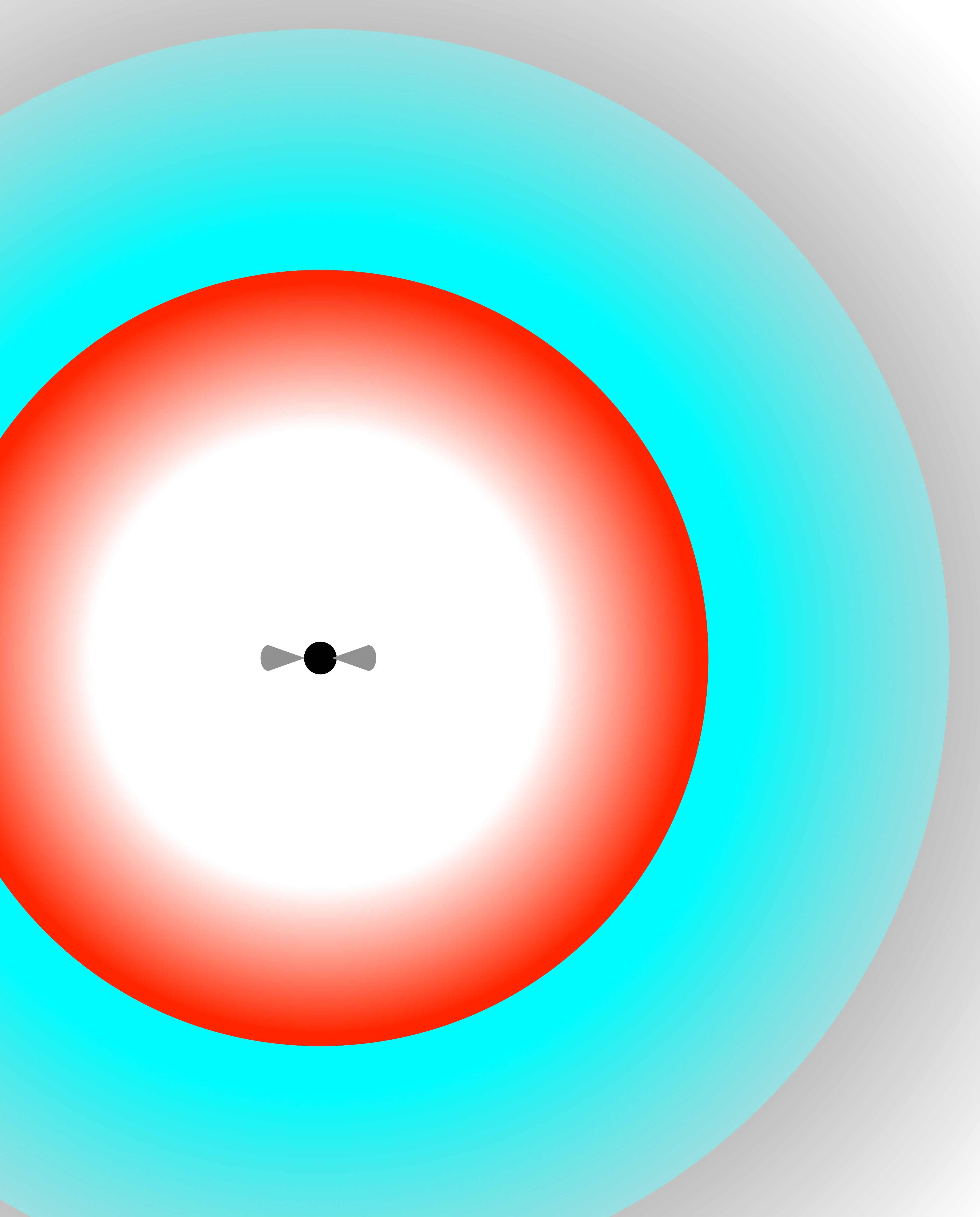
Only the collapse of SMS core is simulated.

- 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

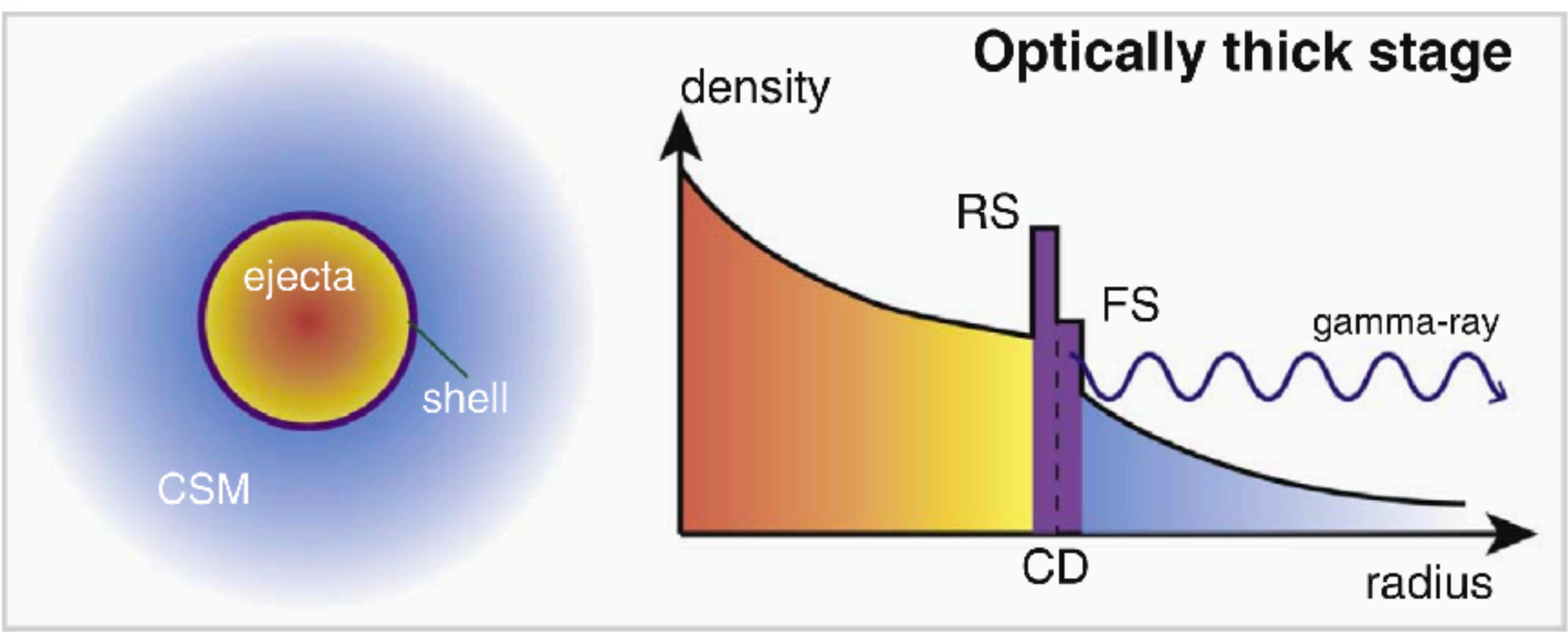


The ejecta sweep up inflated envelope

→ break out from SMS surface

The ejecta sweep up the infalling gas cloud

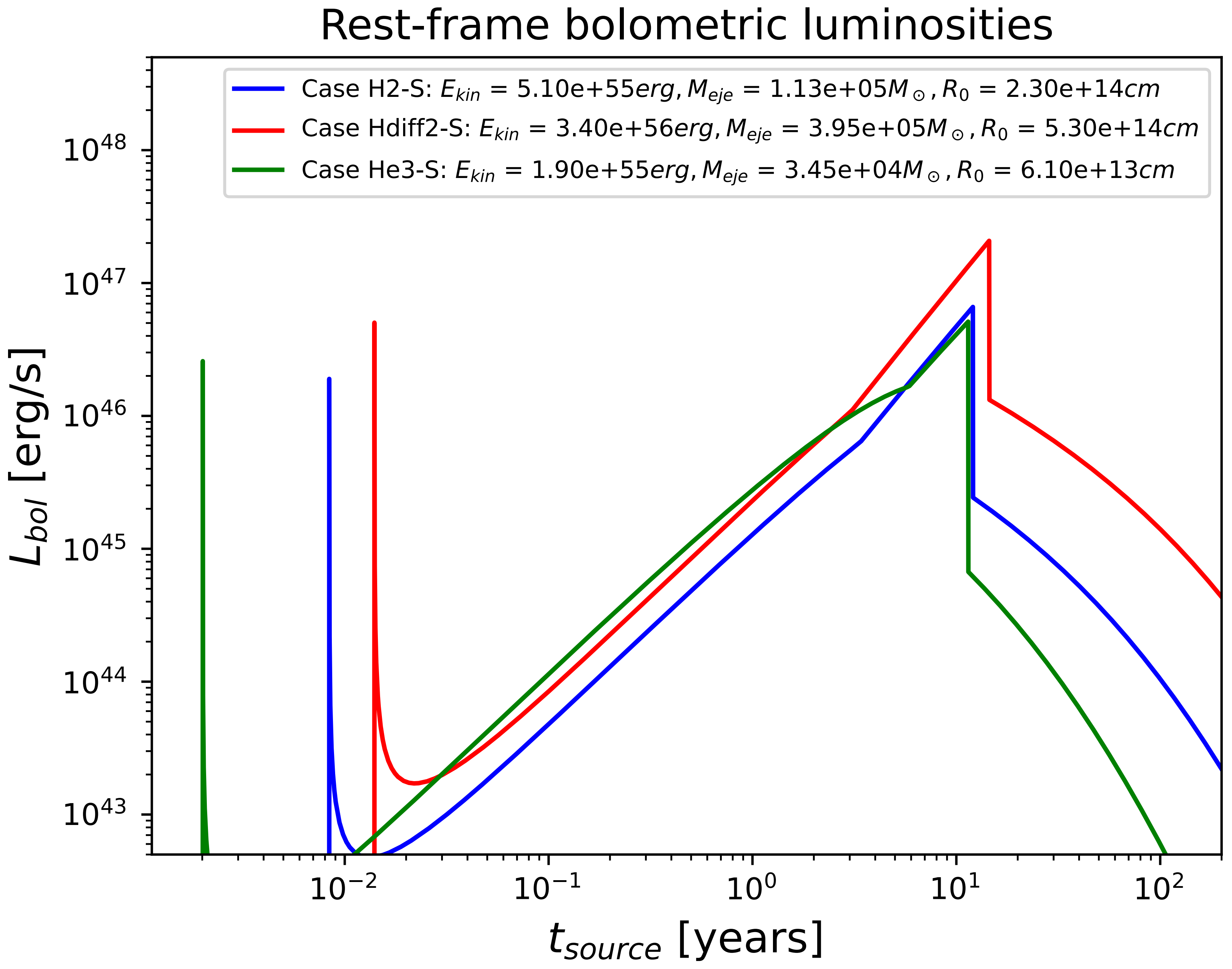
~ CSM-interacting SN
(with E~1e55--1e56 erg, M_CSM ~ 10^5Msun)

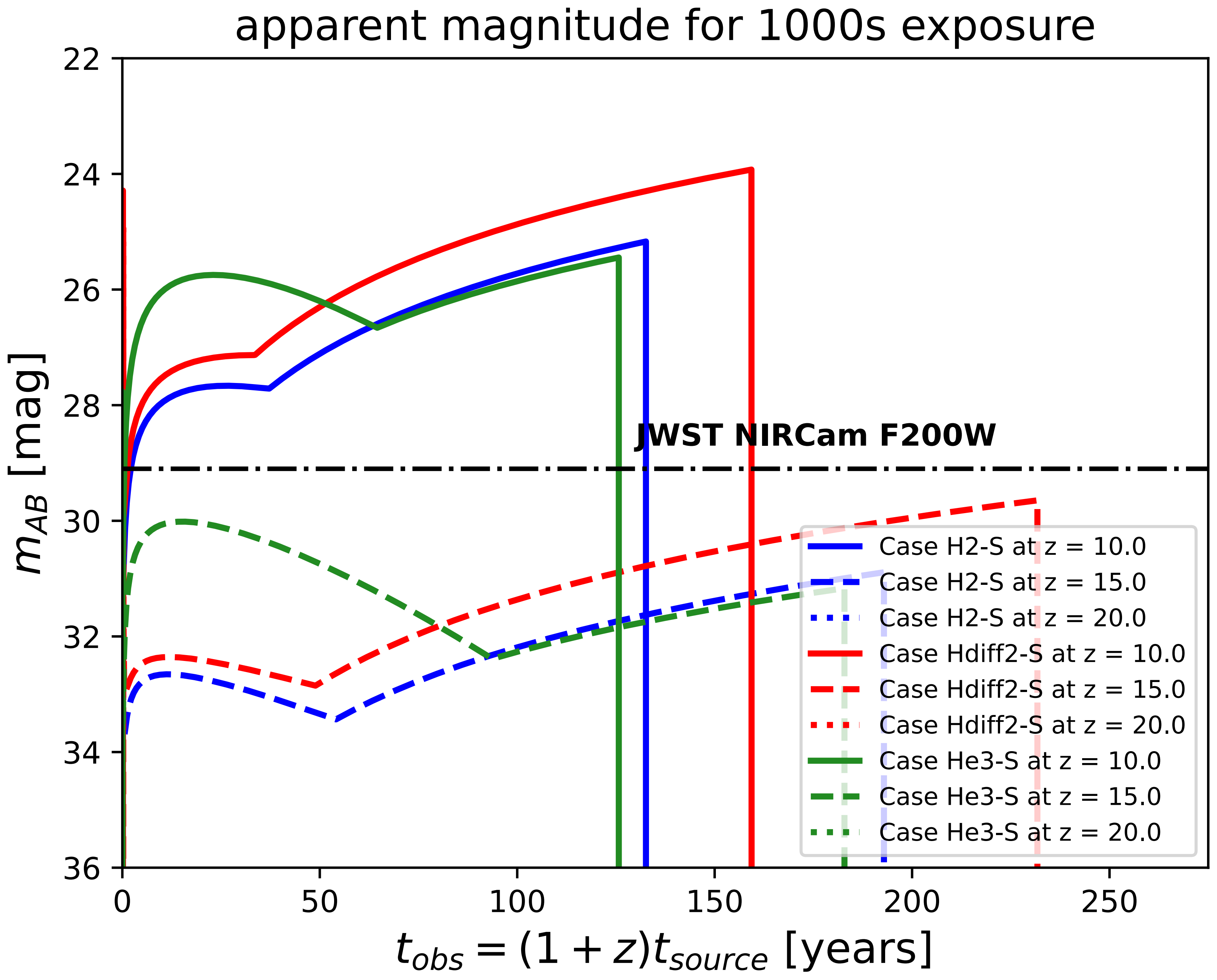


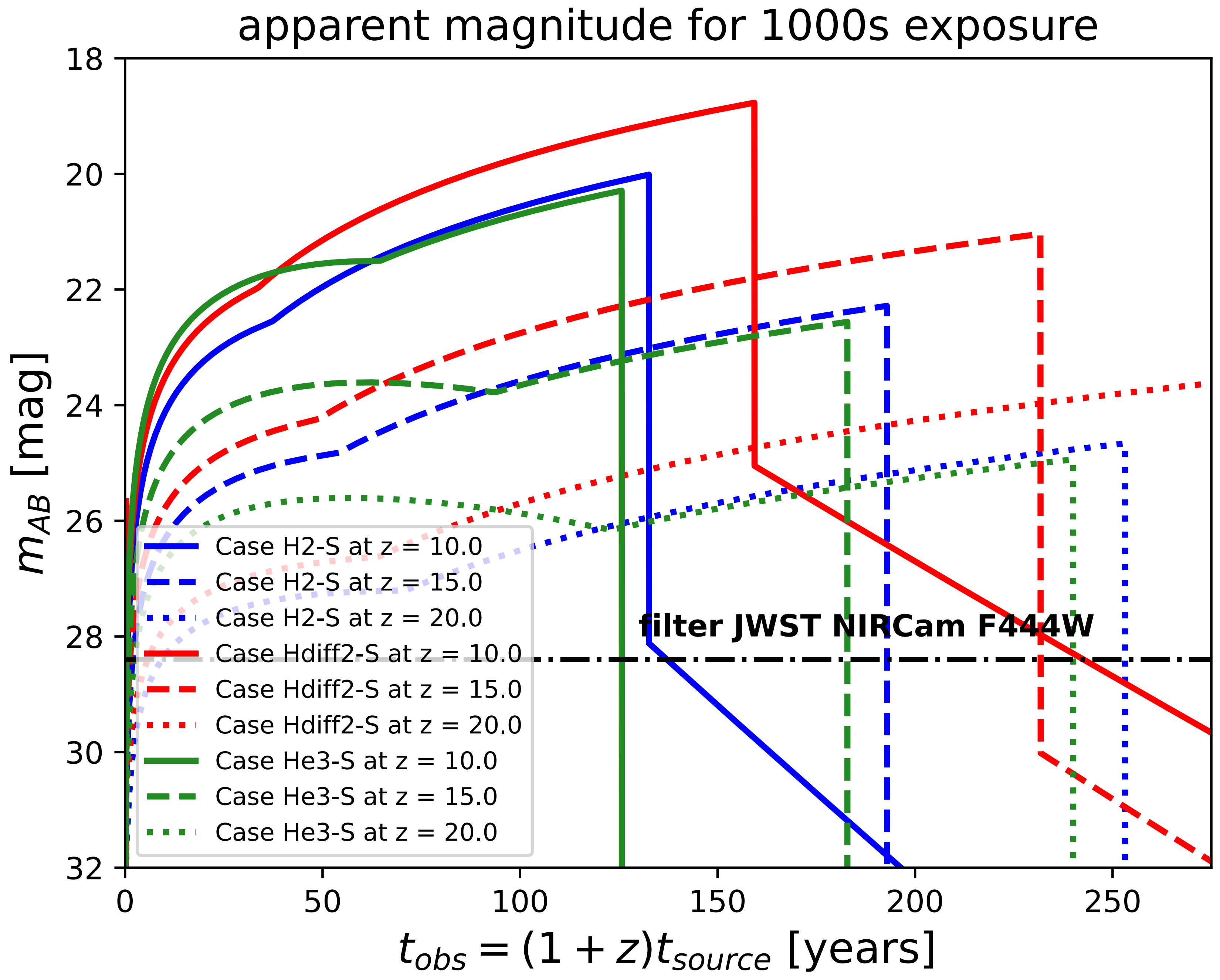
Suzuki+2019

Observational feature

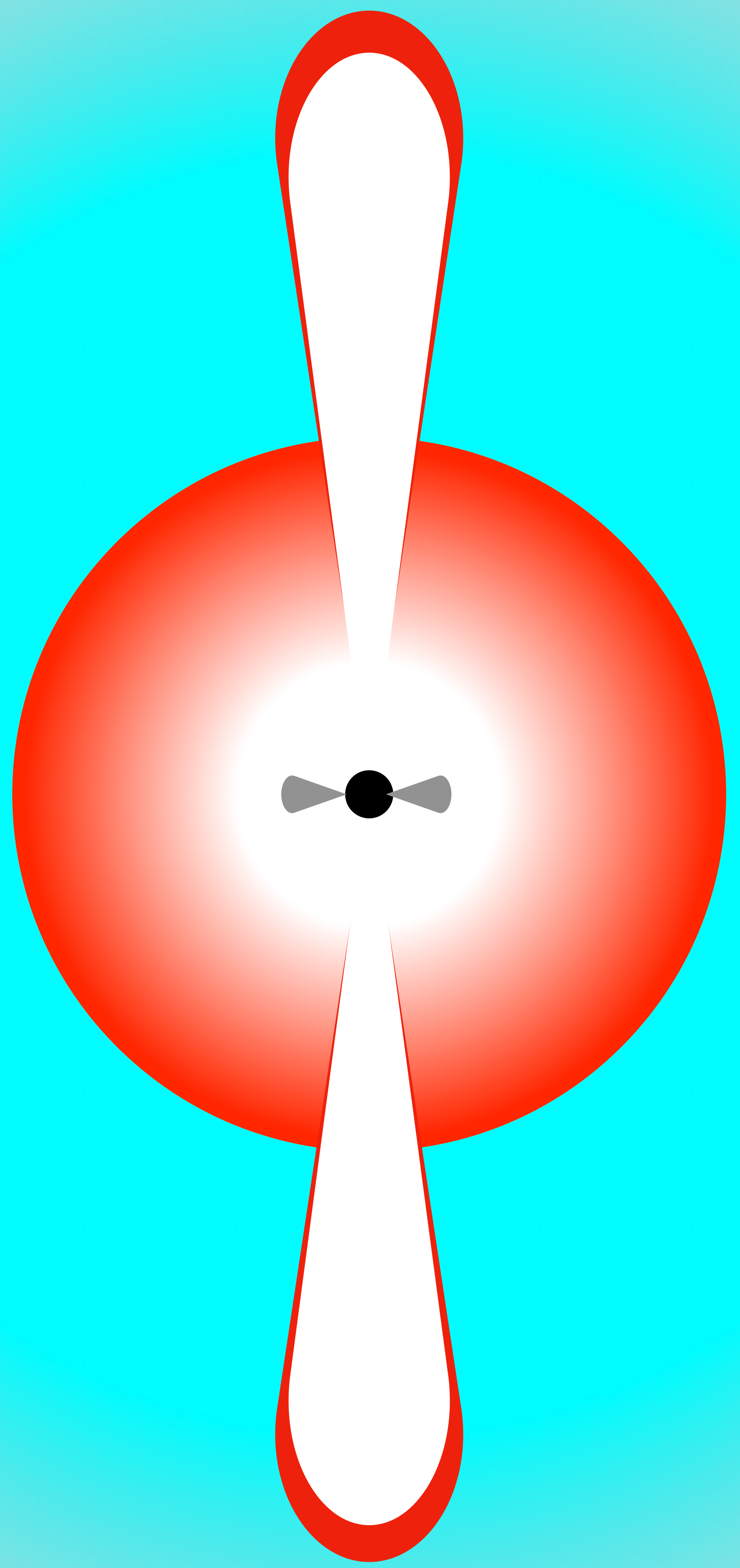
Jockel, SF+ in prep.



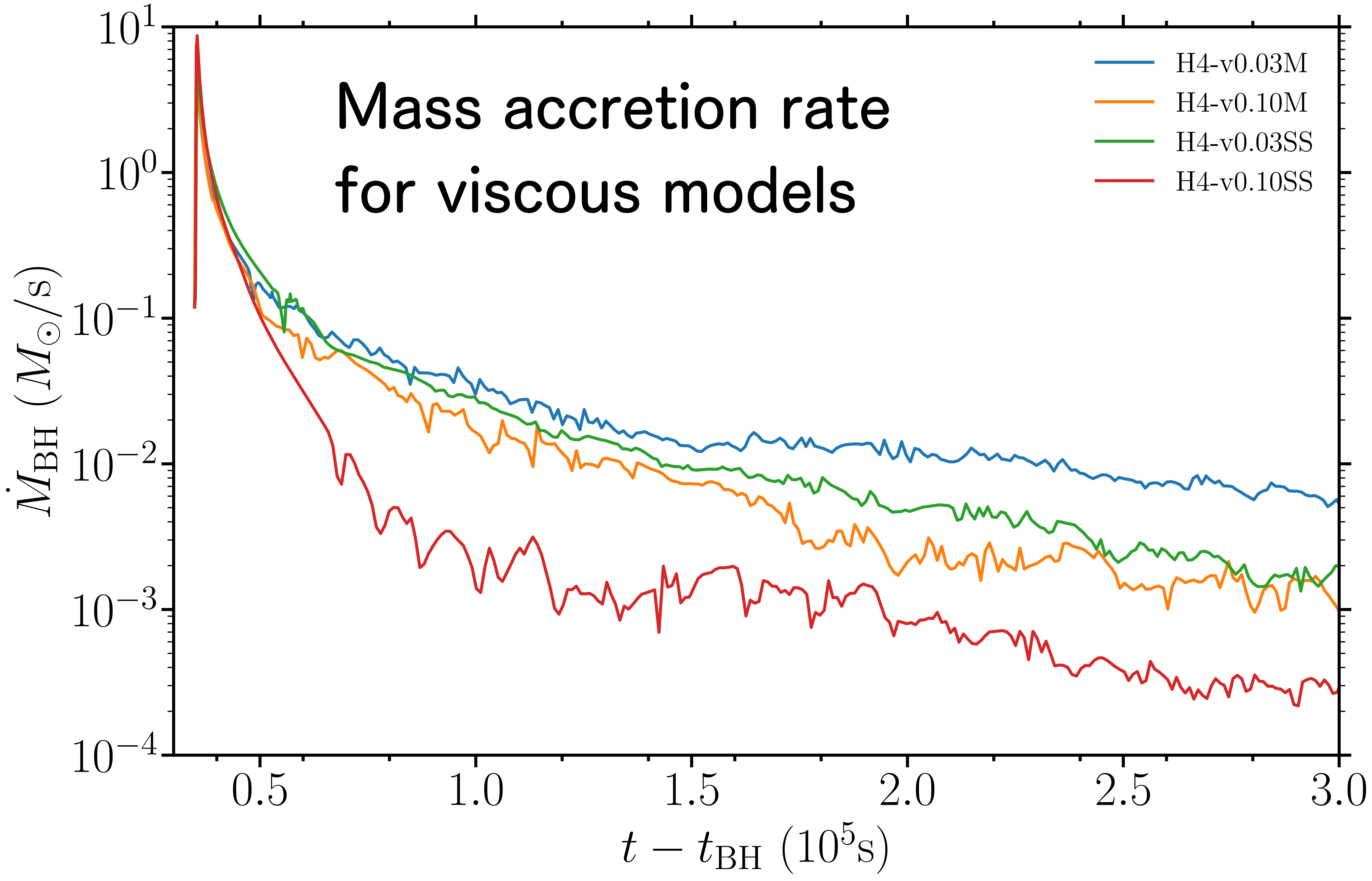




Discussion: Jet driven by BH-disk



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



Summary (Part I)

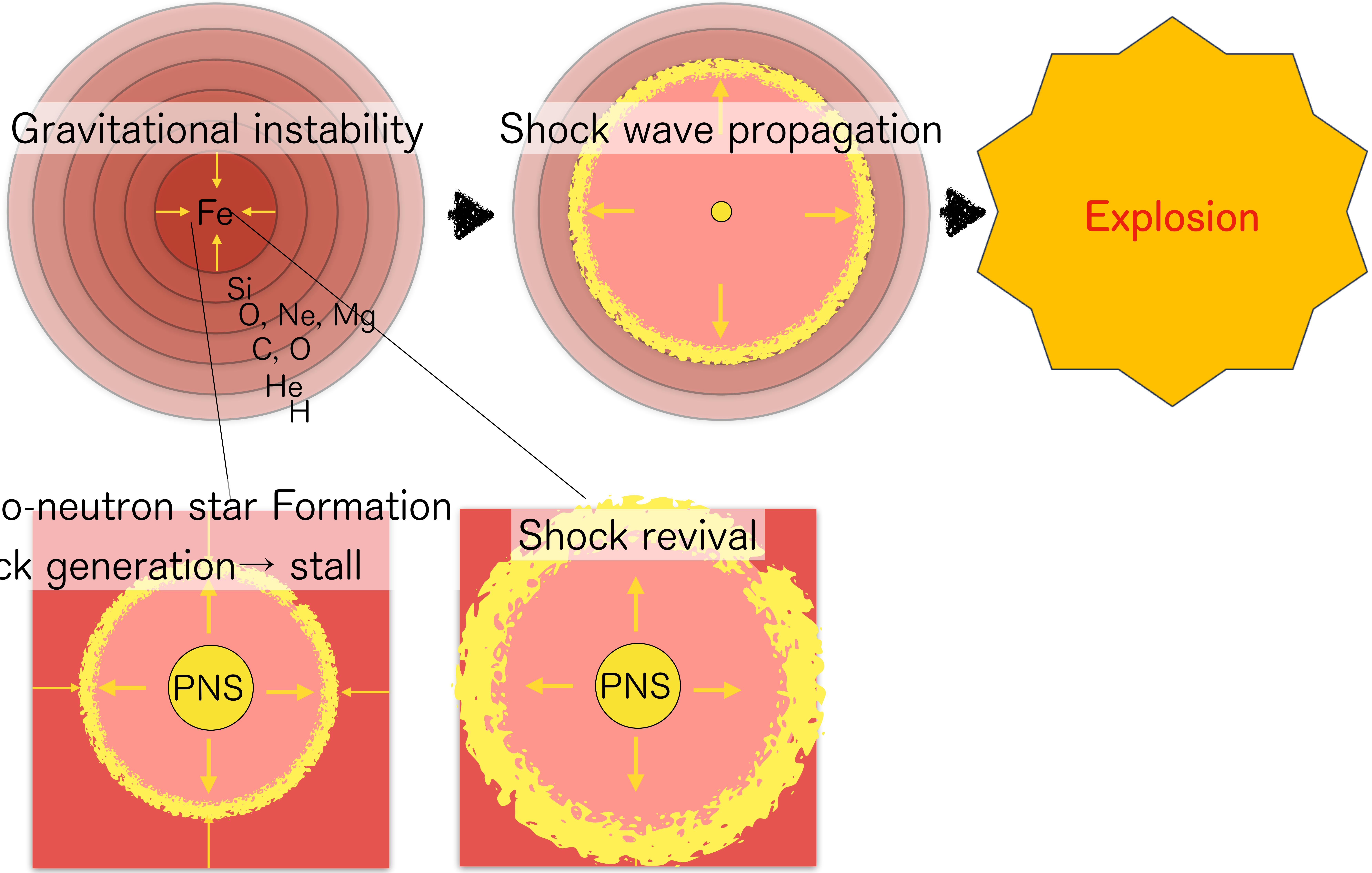
- ✓ Numerical-relativity simulations of the collapses of rotating supermassive stars
- ✓ Bounce-shock-induced ejecta up to 1% of core mass $(10^{-2}M_{\rm core})$, $v \approx 0.2c$
  (Mass is likely dominated by the swept-up cloud surrounding the star)
- ✓ Kinetic energy ~ $10^{55} - 10^{56}$ erg $(10^{-4}M_{\rm core}c^2)$
- ✓ Bright CSM-interacting SNe with duration ~10 (1+z) yr

Outline

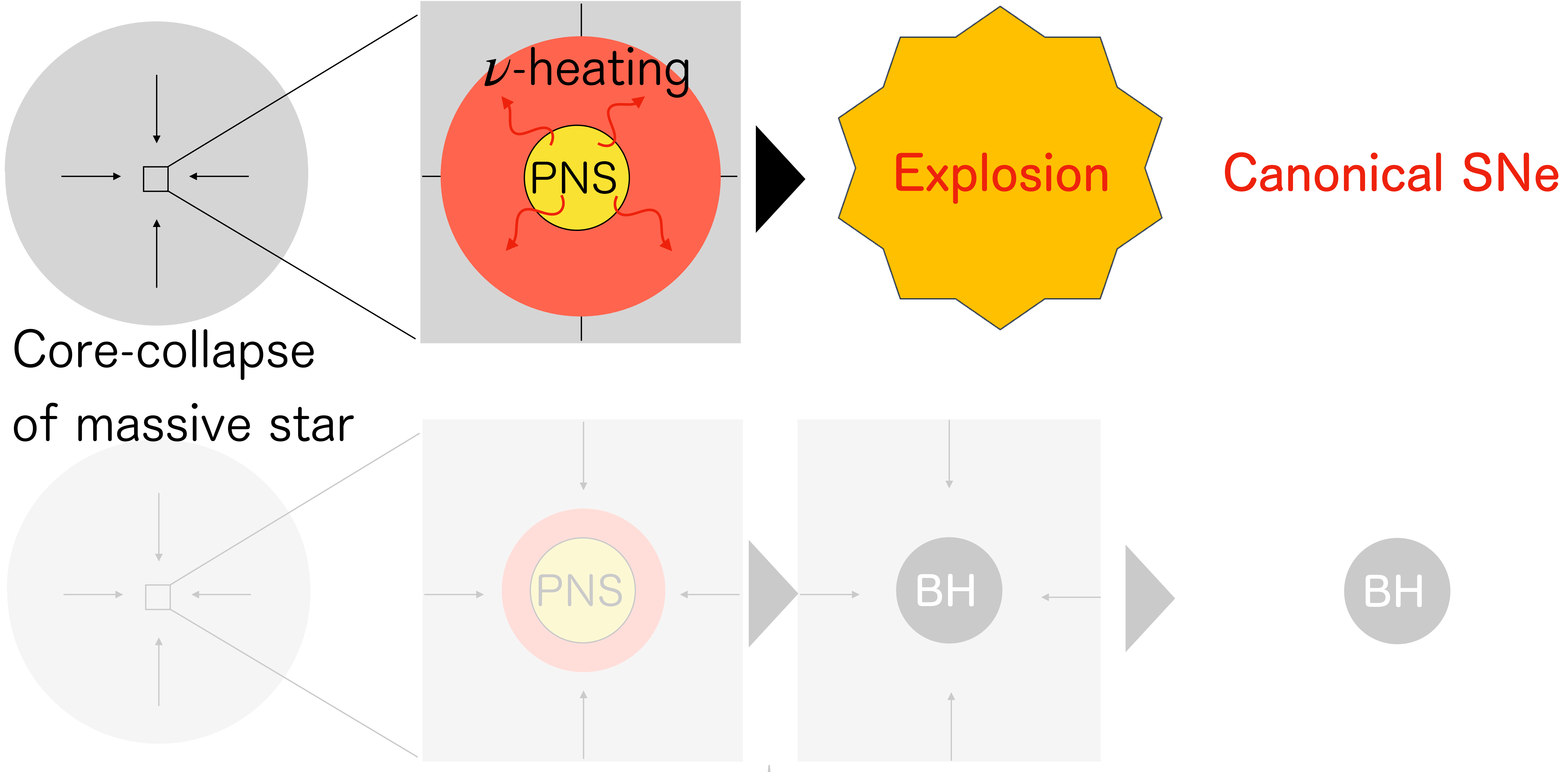
- ✓ Collapse of rotating **supermassive** stars (~10^5Msun, ~10^3Msun)
- ✓ Collapse of rotating massive star (System~10Msun, ejecta~Msun)

Core-collapse supernovae

Stars with mass $\gtrsim 10\,M_\odot$



Collapsar



Core-collapse
of massive star

Canonical SNe

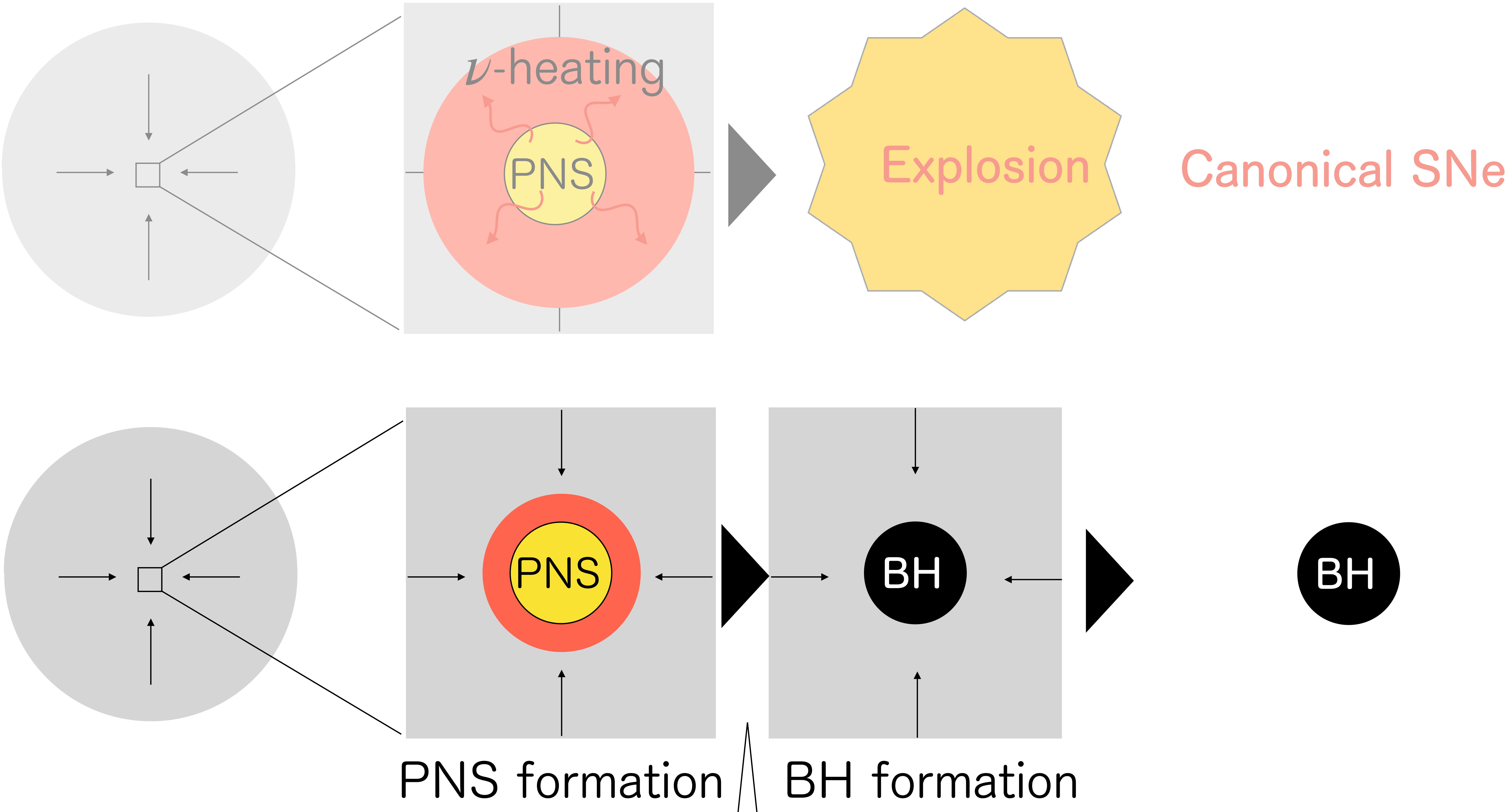
PNS formation

BH formation

Isolated BH

Explosion during PNS phase fails
if, e.g., the core compactness is too high.

Collapsar



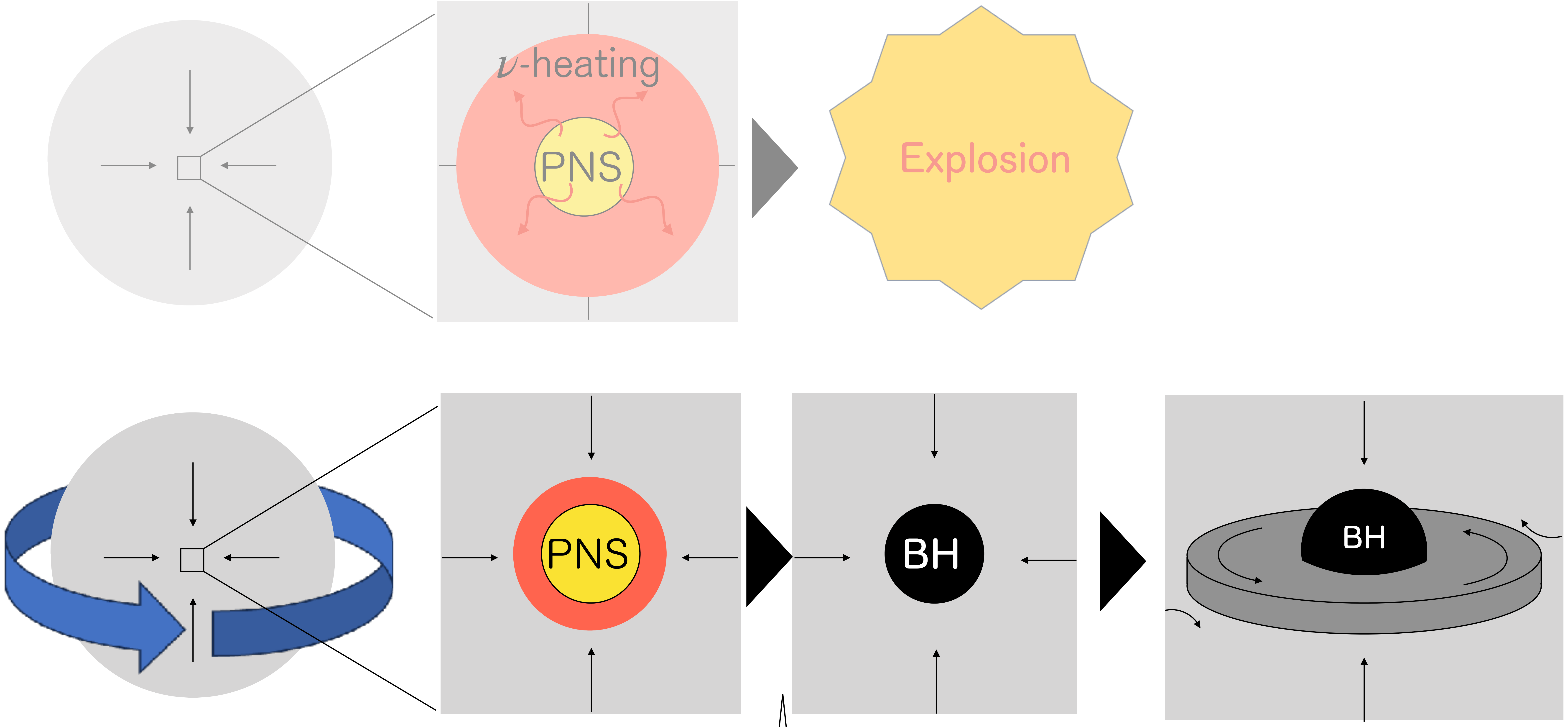
Explosion during PNS phase fails

if, e.g., the core compactness is too high.

Note: MHD process
can help explosion

e.g., Obergaulinger & Aloy

Collapsar



Core-collapse
of rotating star

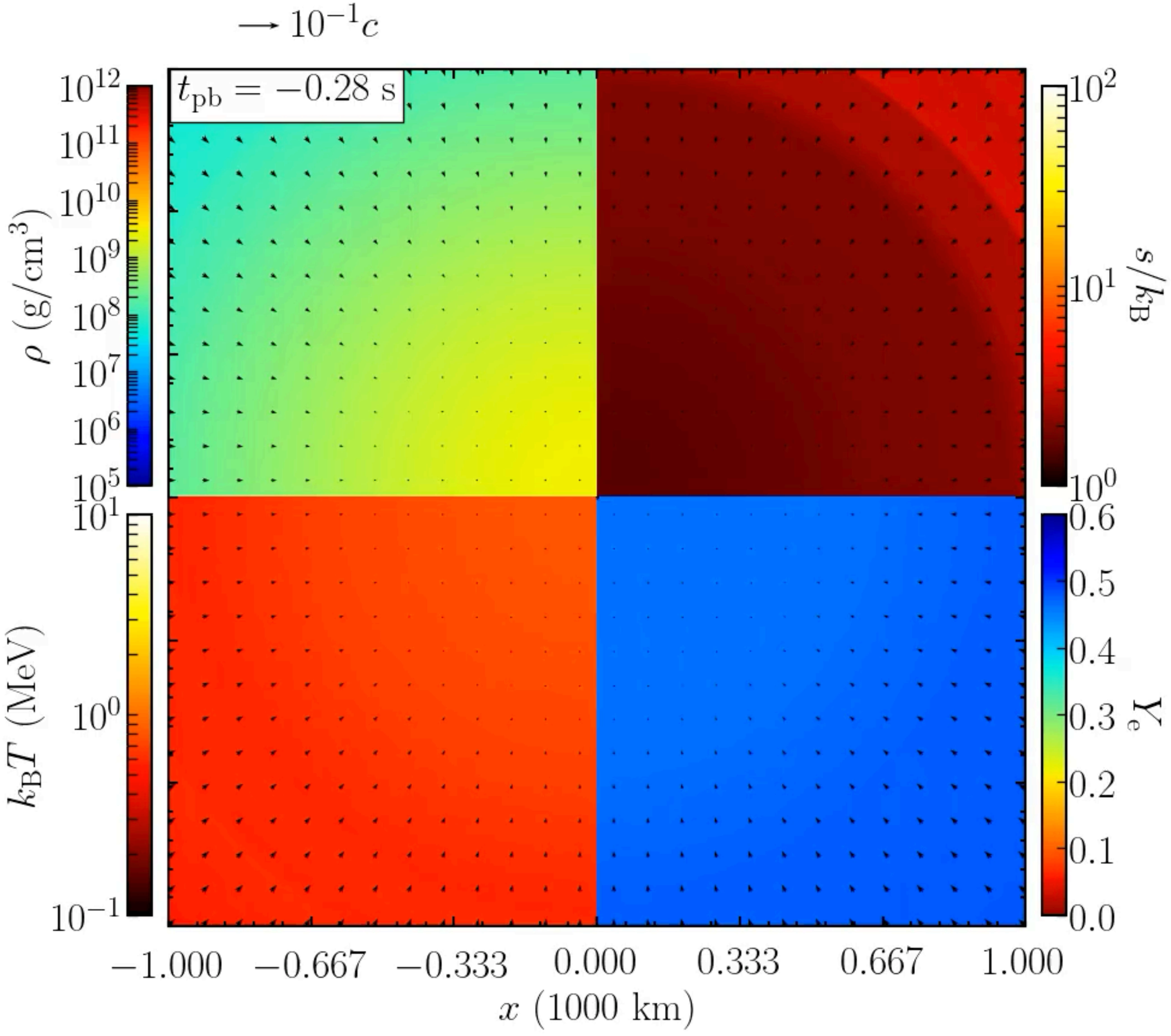
PNS formation

BH formation

Disk formation
Further activities!

Explosion during PNS phase fails
if, e.g., the core compactness is too high.

Collapsar



An example **SF+2023**

Collapse of $M_{\rm ZAMS} = 20M_\odot$ star

(taken from Aguilera-Dena+2020)

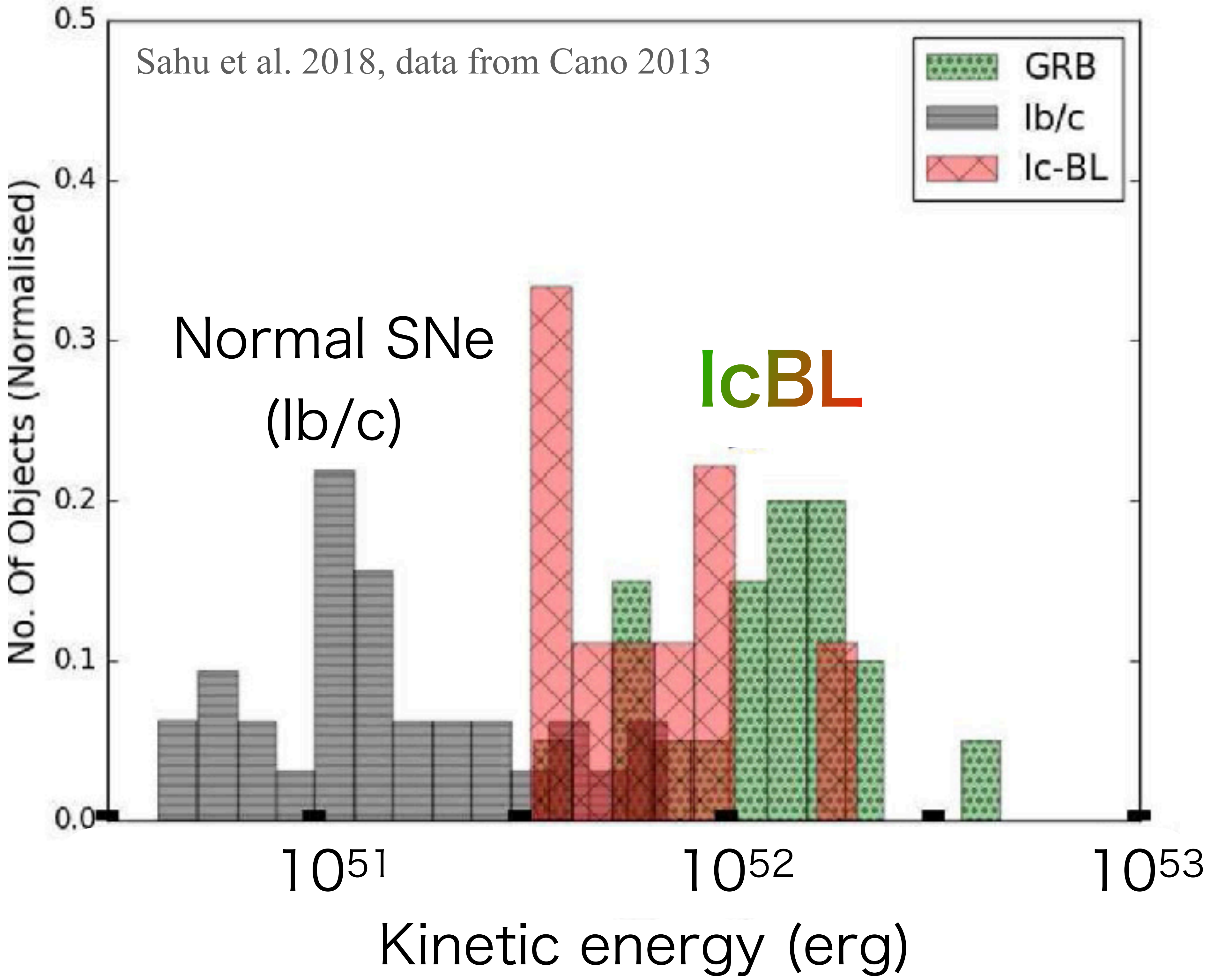
BH-disk activities and GRB-SN

Gamma-ray bursts (GRBs)

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

Broad-lined type Ic SNe (SNe Ic-BL; Hypernovae)

Long GRBs are accompanied by energetic SNe (Ic-BL)



- Explosion (kinetic) energy $E_K = (0.8 - 4.4) \times 10^{52}$ erg
- ^{56}Ni mass $M_{Ni} = (0.2 - 0.5) M_\odot$ (Cano et al. 17)

BH-disk activities and GRB-SN

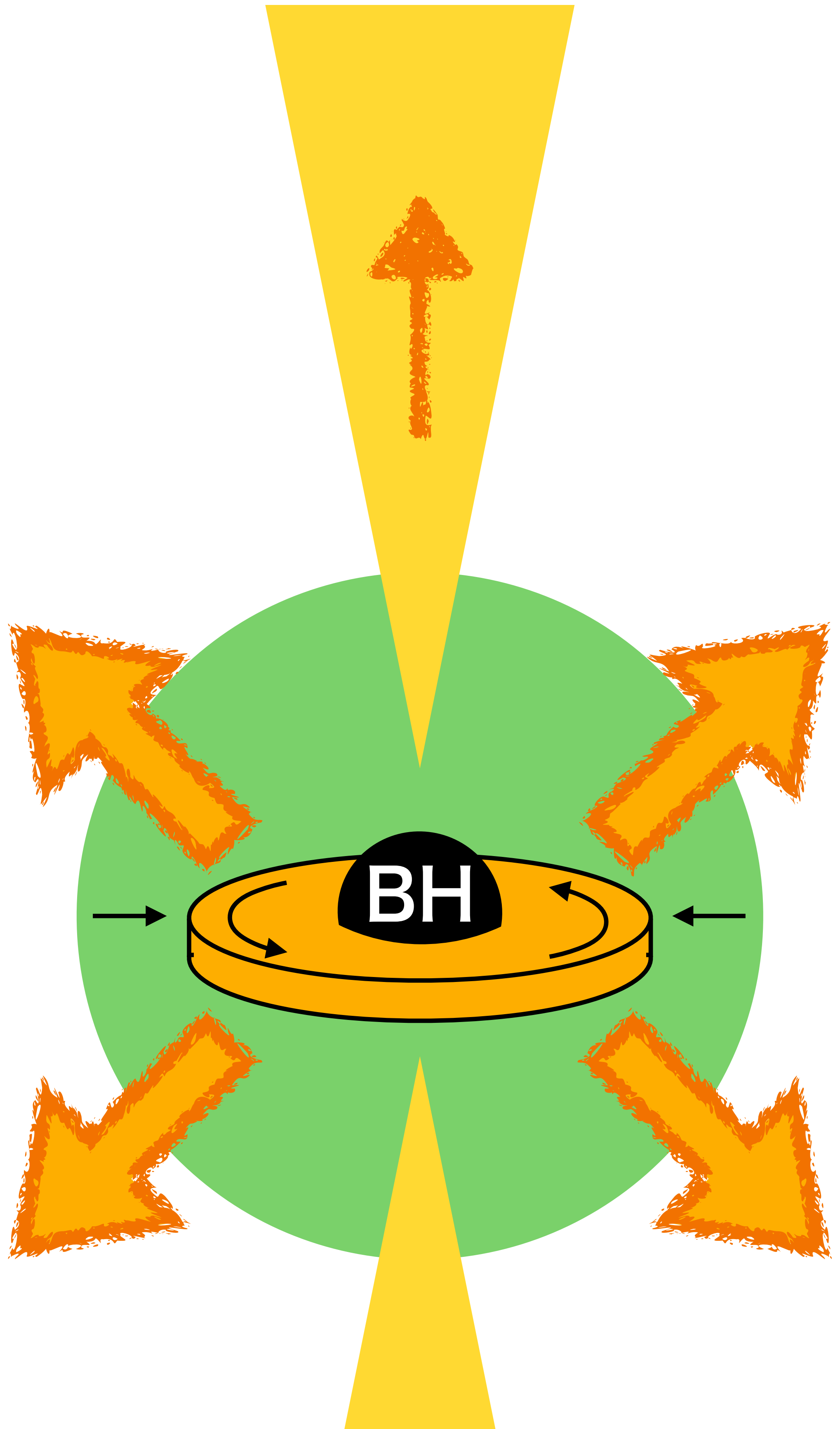
Disk outflow

(MacFadyen & Woosley 1999)

Energy generated by viscous accretion:

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

Viscosity-driven outflow from disk would naturally explain such SNe

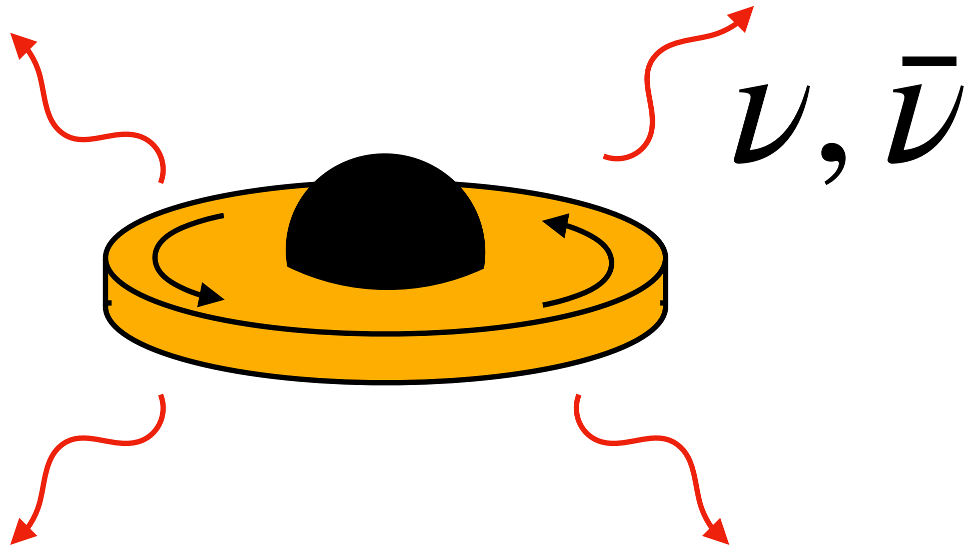


Neutrino cooling vs viscous heating

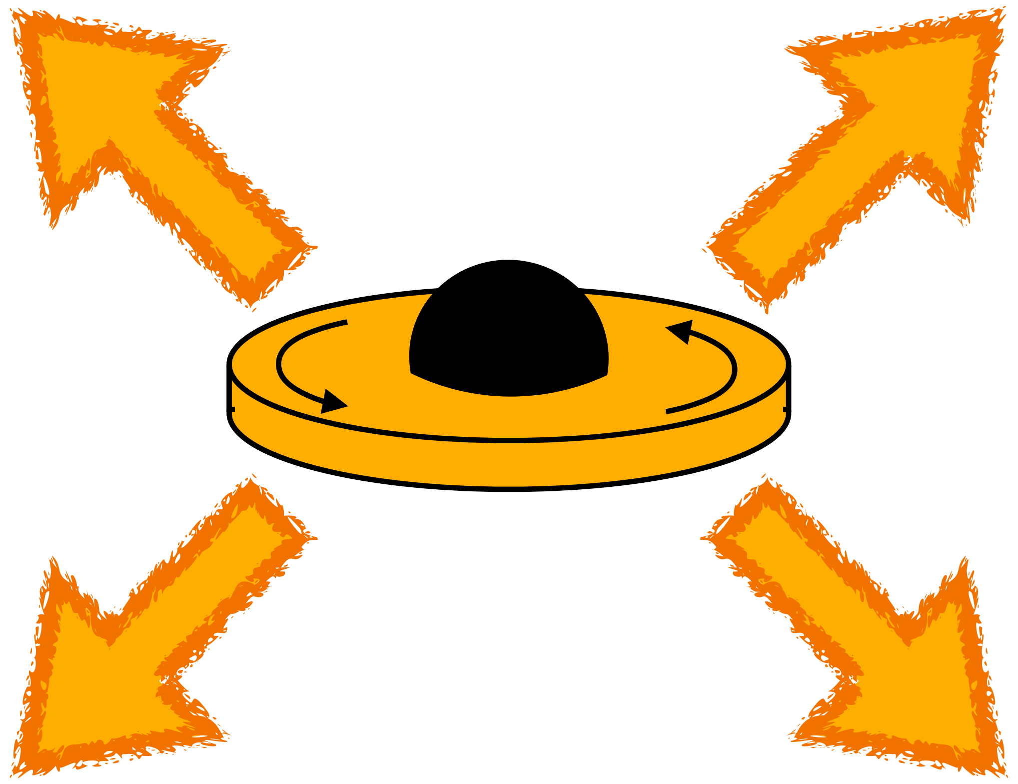
- Neutrino emission cooling $t_{\mathrm{weak}} \sim \frac{1}{G_{\mathrm{F}}{}^{2} T^{5}} \approx 1\,\mathrm{s}\left(\frac{kT}{1\,\mathrm{MeV}}\right)^{-5}$
- MHD turbulence → Viscous angular momentum transport/heating

$$t_{\mathrm{vis}} \sim \frac{R^2}{\nu} = 1\ \mathrm{s}\left(\frac{R}{10^{7}\mathrm{cm}}\right)\left(\frac{c_s}{10^{9}\mathrm{cm/s}}\right)^{-1}\left(\frac{\alpha}{0.03}\right)^{-1}\left(\frac{H/R}{0.3}\right)^{-1}$$

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



✓ $t_{\mathrm{weak}} \gg t_{\mathrm{vis}}$ phase: viscosity can drive outflow



Same as NS-merger remnant disk

Methods

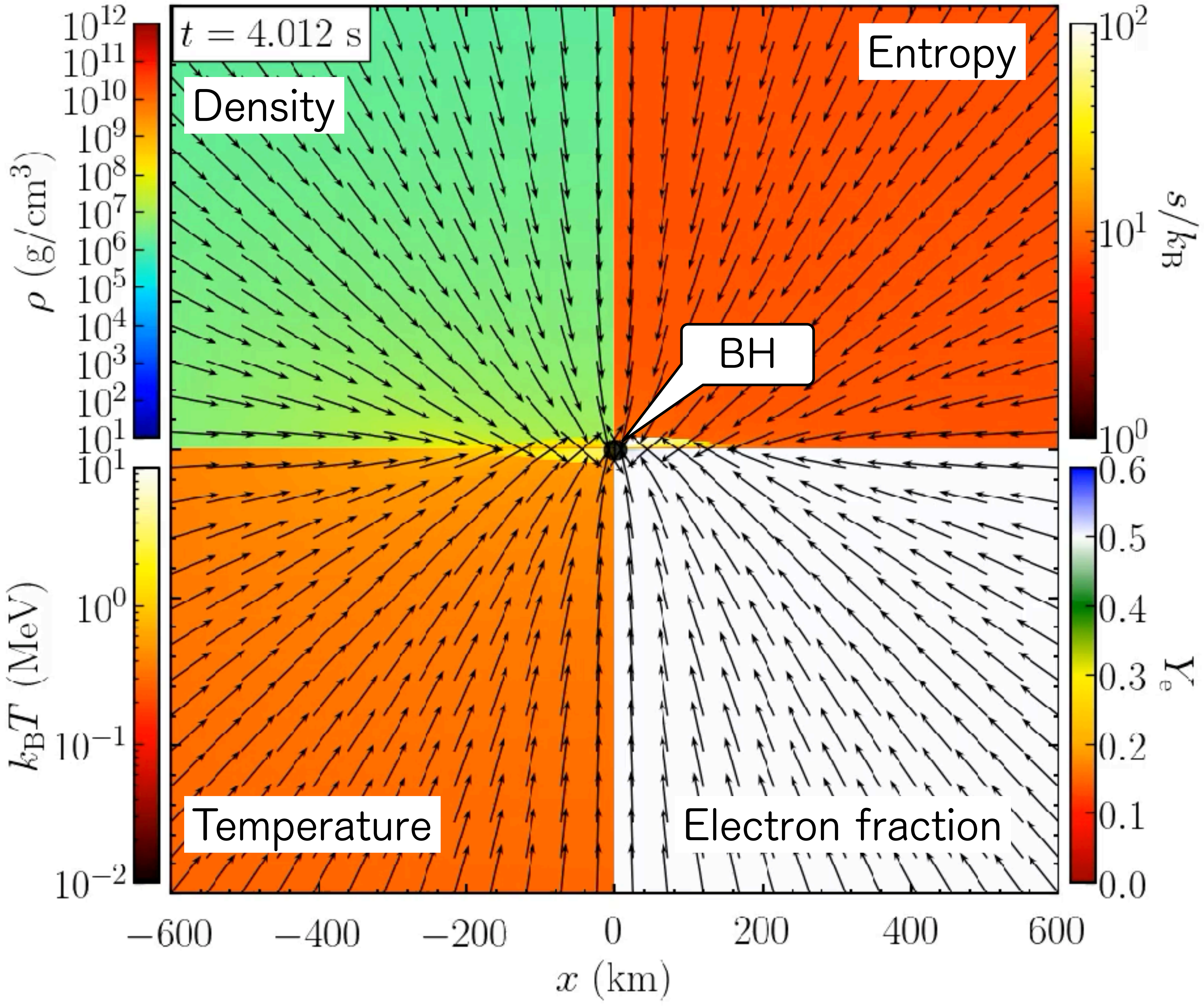
Sekiguchi 10, Sekiguchi & Shibata 11, Sekiguchi+12

2D-axisymmetric simulation with solving

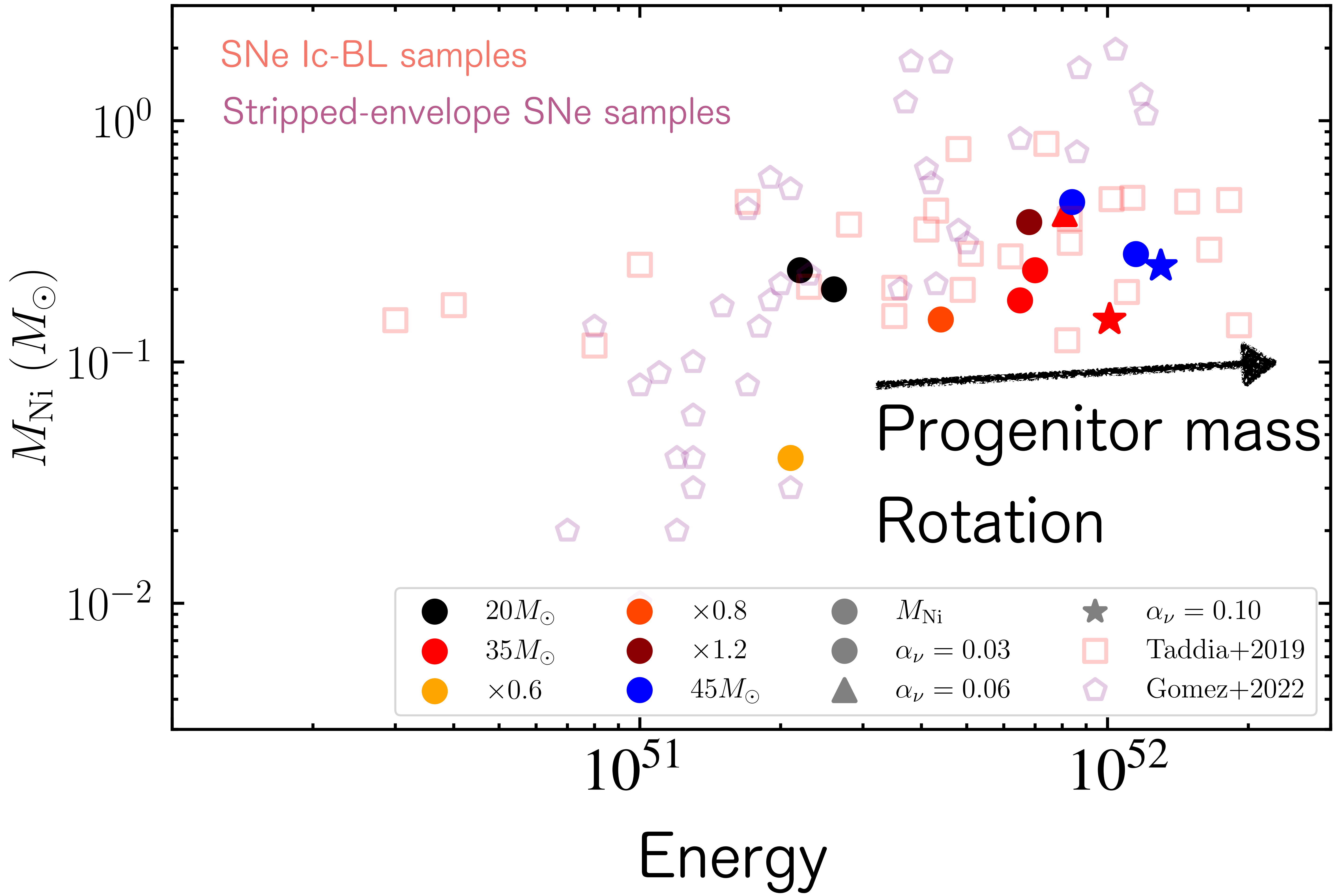
- ✓ Einstein's equation Nakamura & Shibata 95, Baumgarte & Shapiro 99
- ✓ Neutrino radiation transfer equation Thorne 81, Shibata et al. 11
- ✓ Viscous hydrodynamics equation Israel & Stuart 79, Shibata et al. 17, Shibata & Kiuchi 17
  (to mimic MHD turbulence)

Disk formation→NDAF→Outflow

Progenitor: $M_{\rm ZAMS} = 35M_{\odot}$ star



Comparison with observations



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

BH-disk can power the energetic explosion.

MHD models for GRB jets

Only with viscosity, jet cannot be produced.

With MHD, we have Blandford-Znajek (BZ) process Blandford & Znajek (1977)

$$L_{\rm BZ} \sim (BM\chi)^2 \sim 10^{50}{\rm erg/s}\left(\frac{\chi}{0.7}\right)^2\left(\frac{M}{10M_\odot}\right)^2\left(\frac{B}{10^{14}{\rm G}}\right)^2$$

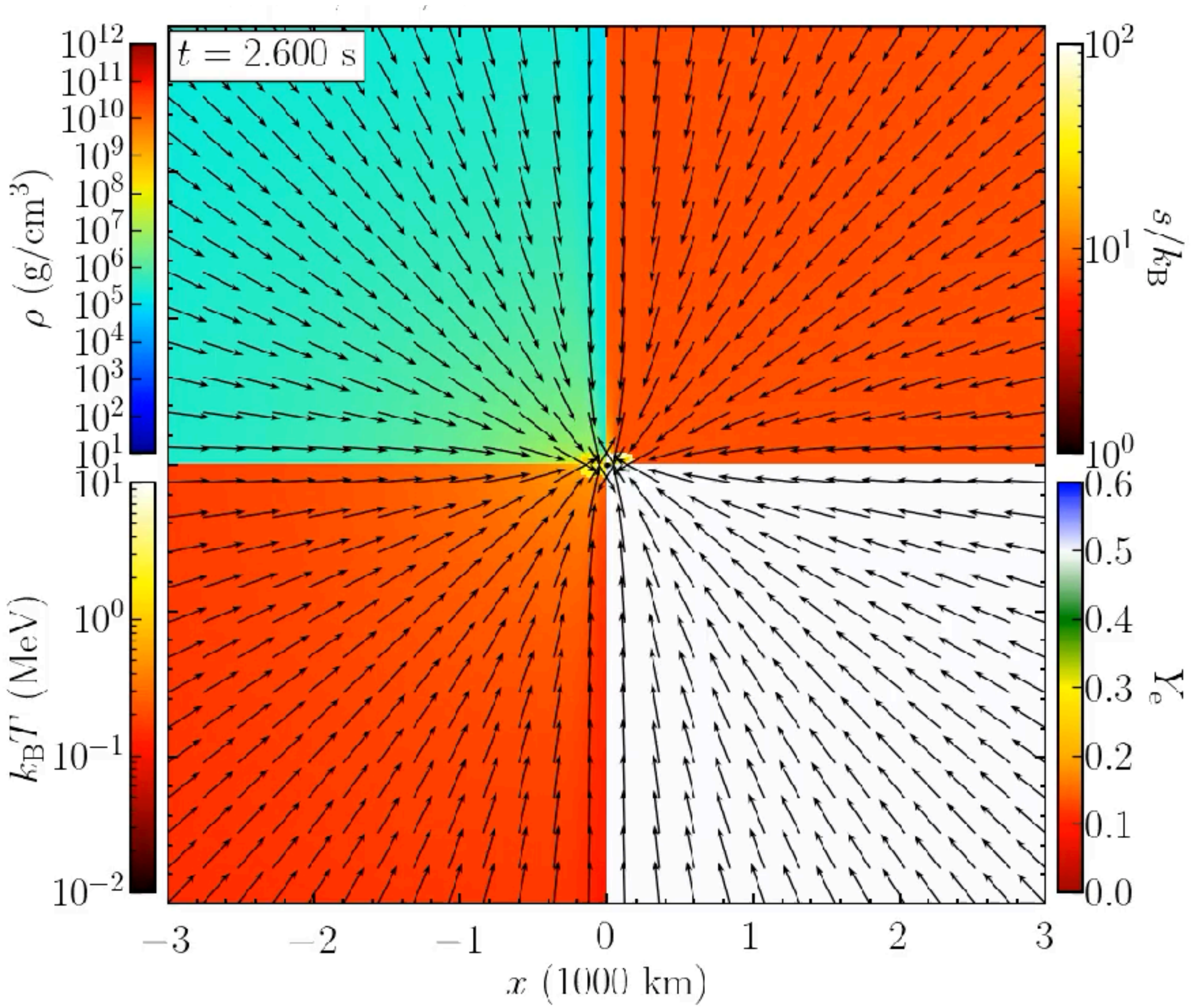
2D-axisymmetric simulation with solving

- ✓ Einstein’s equation Nakamura & Shibata 95, Baumgarte & Shapiro 99
- ✓ Neutrino radiation transfer equation Thorne 81, Shibata et al. 11
- ✓ Magneto-hydrodynamics equation Shibata, SF+21

MHD models for GRB jets

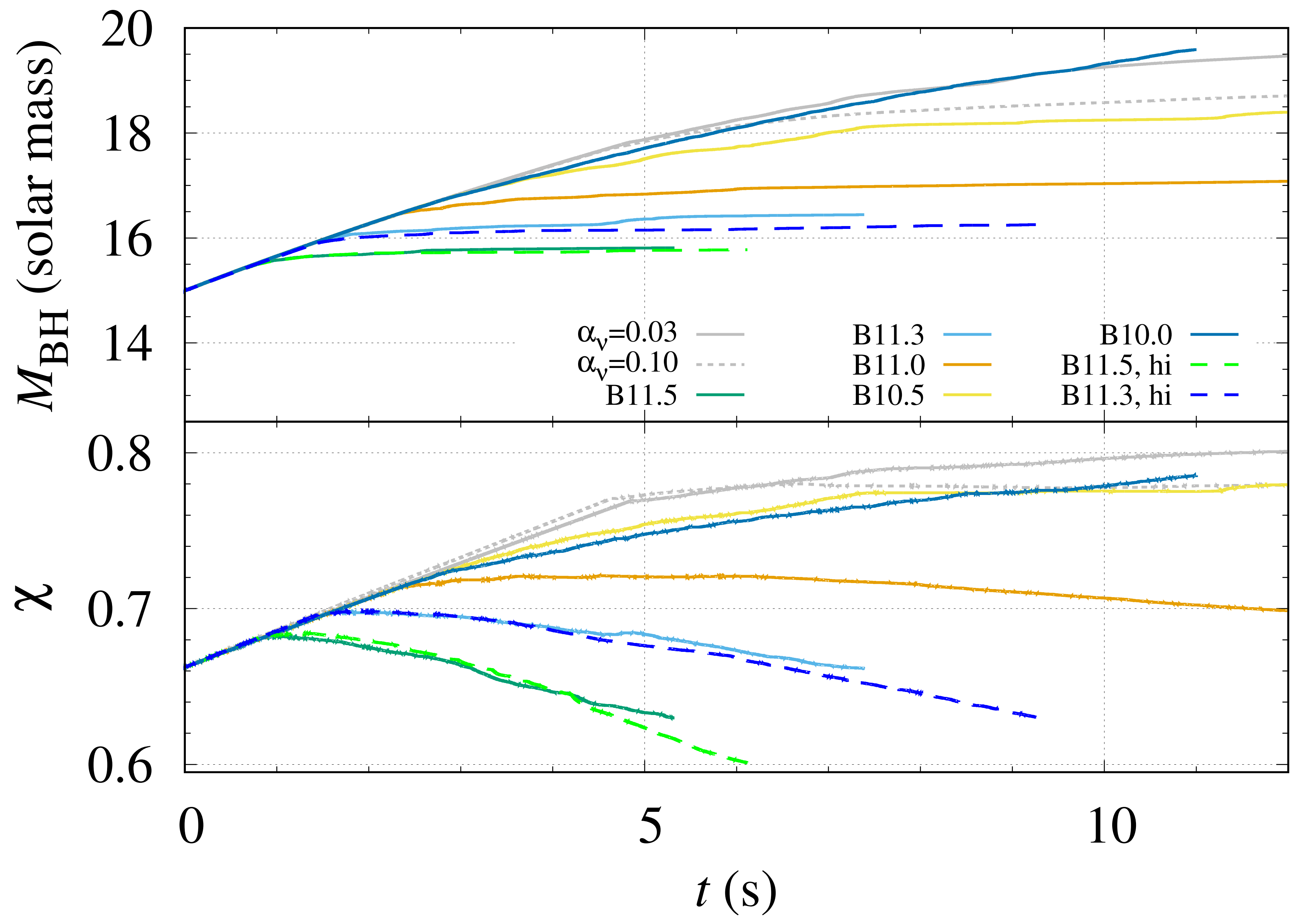
Shibata, SF+24

Progenitor: $M_{\mathrm{ZAMS}} = 35 M_{\odot}$ star, Poloidal field



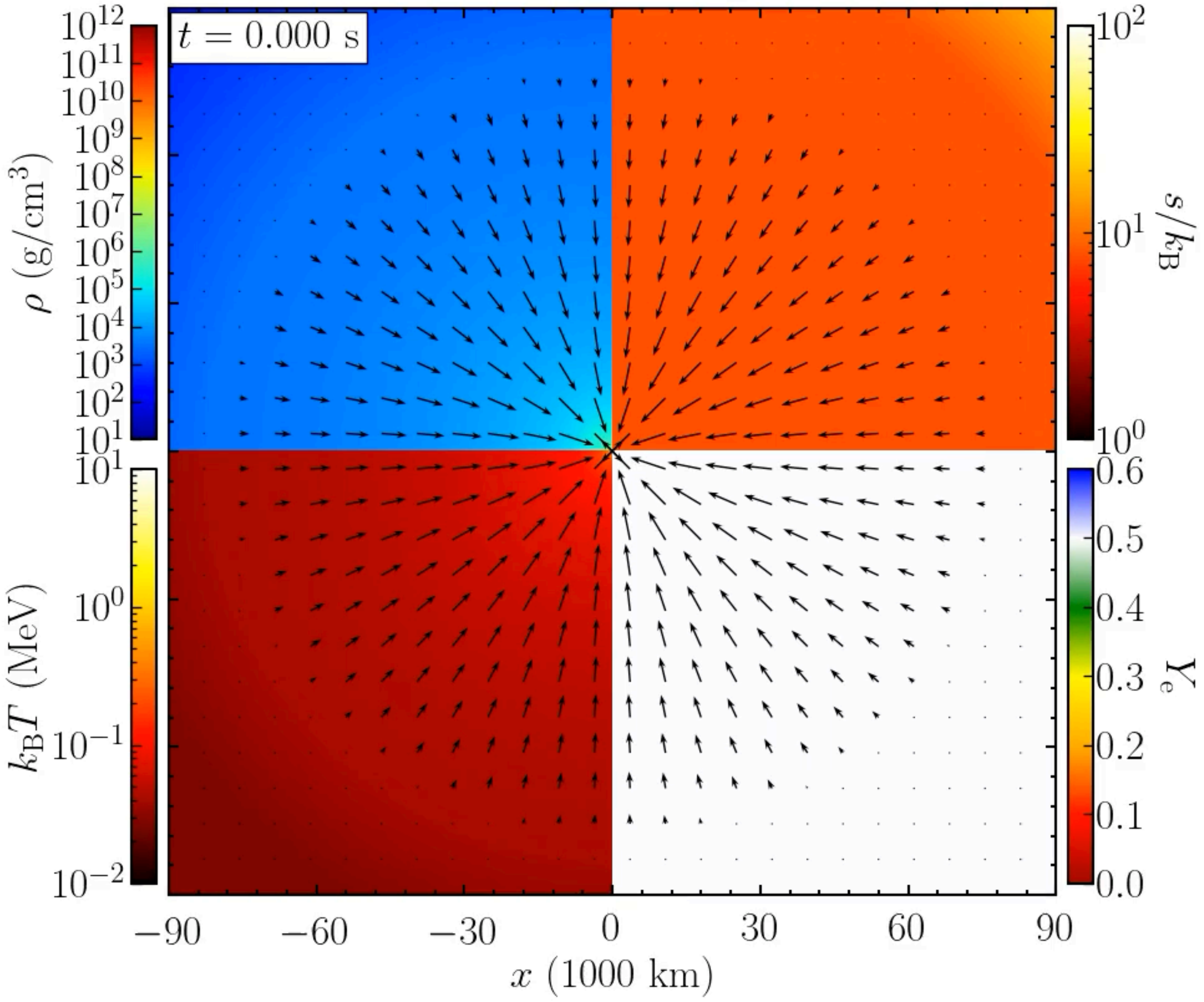
Fossil field → BZ jets

Feedback on BH spin is numerically observed



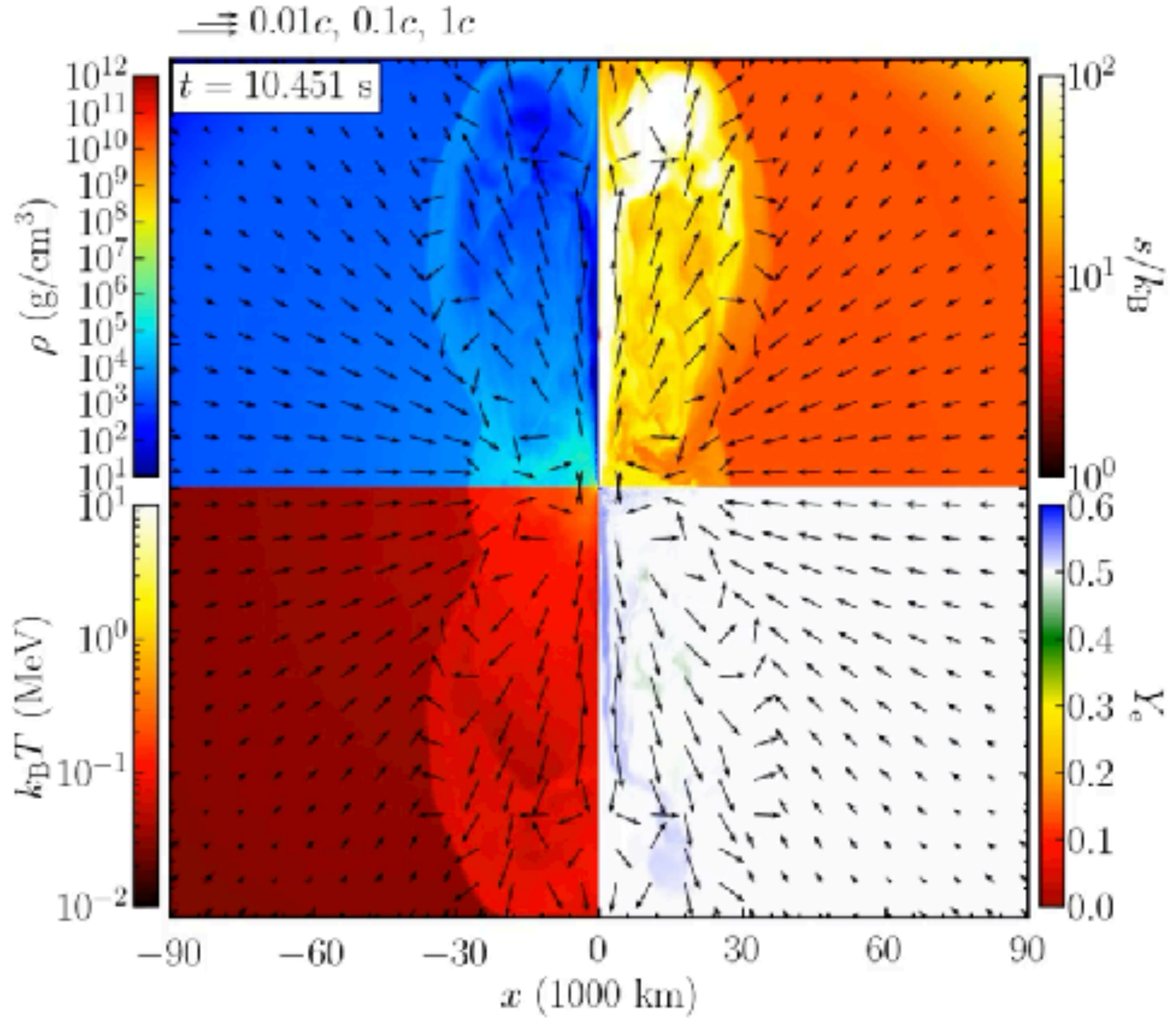
Collapsar with MHD+dynamo

Progenitor: $M_{\mathrm{ZAMS}} = 35 M_\odot$ star, toroidal field



Jet + spherical components

cf. Ideal MHD case



Summary (Part II)

Numerical relativity simulations of collapses of rotating massive stars

- ✓ It can explode with E~10^{52} erg driven by disk outflow (←viscous model)
- ✓ It can synthesize sufficient amount ($\gtrsim 0.1 M_\odot$) of ^{56}Ni (←viscous model)
- ✓ It can drive a jet (←MHD model with an ideal config.)
- ✓ MHD+phenomenological dynamo model will come soon.
- ✓ No significant r-process in the ejecta