Collapses and explosions of rotating massive stars (BH-forming cases)

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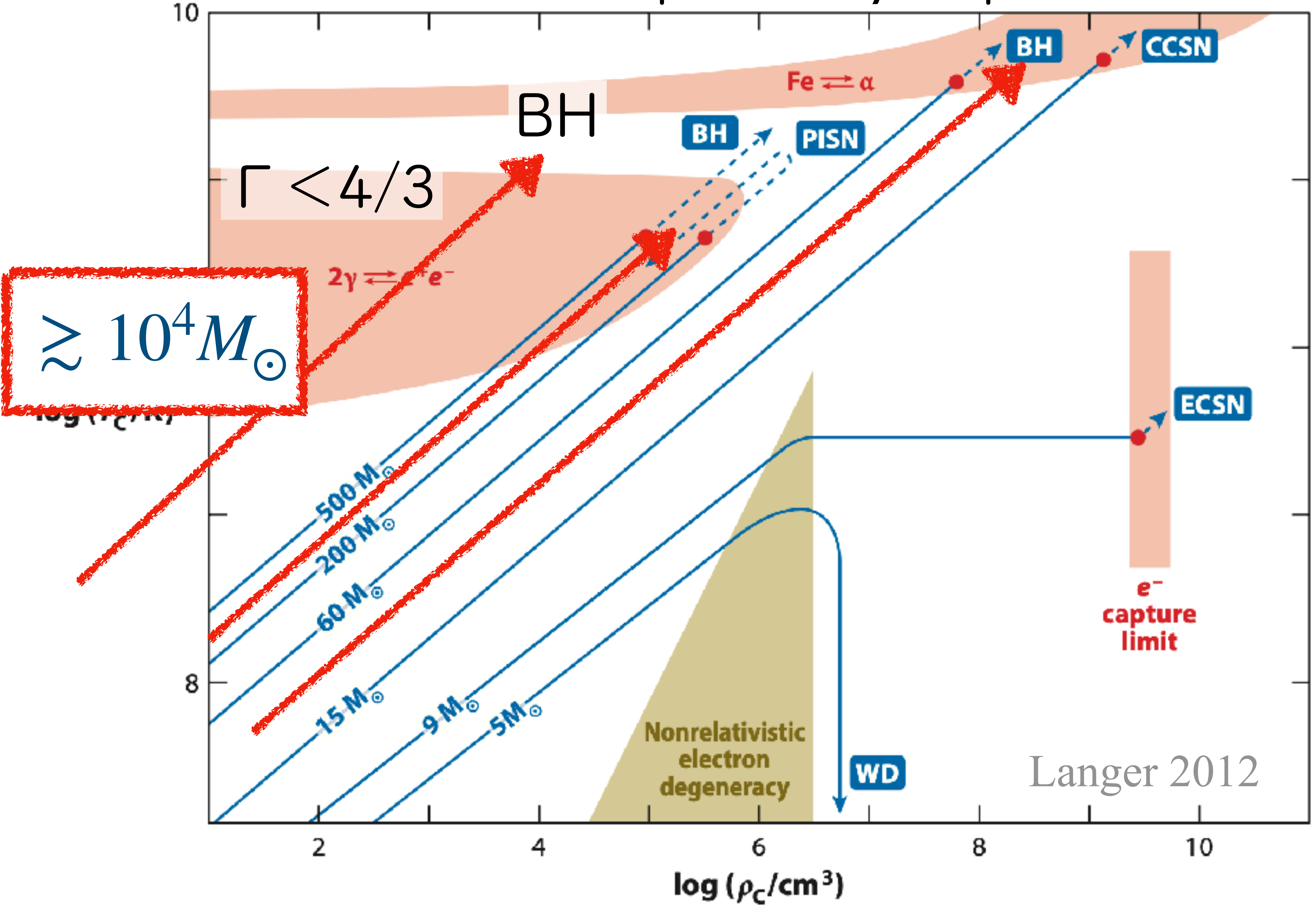
YITP long-term workshop
Multi-Messenger Astrophysics in the Dynamic Universe (2nd week)
2026.02.06, YITP, Kyoto, Japan

TOHOKU UNIVERSITY
FRIS

Evolution of stars with various masses

Evolutional paths in ρ-T plane



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

→ Iron core → Collapse

✓ $M_{\mathrm{ZAMS}} \gtrsim 130 M_\odot$ (Very massive star; VMS)

→ $e^- e^+$ production → Collapse

$M_{\mathrm{ZAMS}} \gtrsim 260 M_\odot$ → BH formation

✓ $M_{\mathrm{ZAMS}} \gtrsim 10^4 M_\odot$ (Supermassive star; SMS)

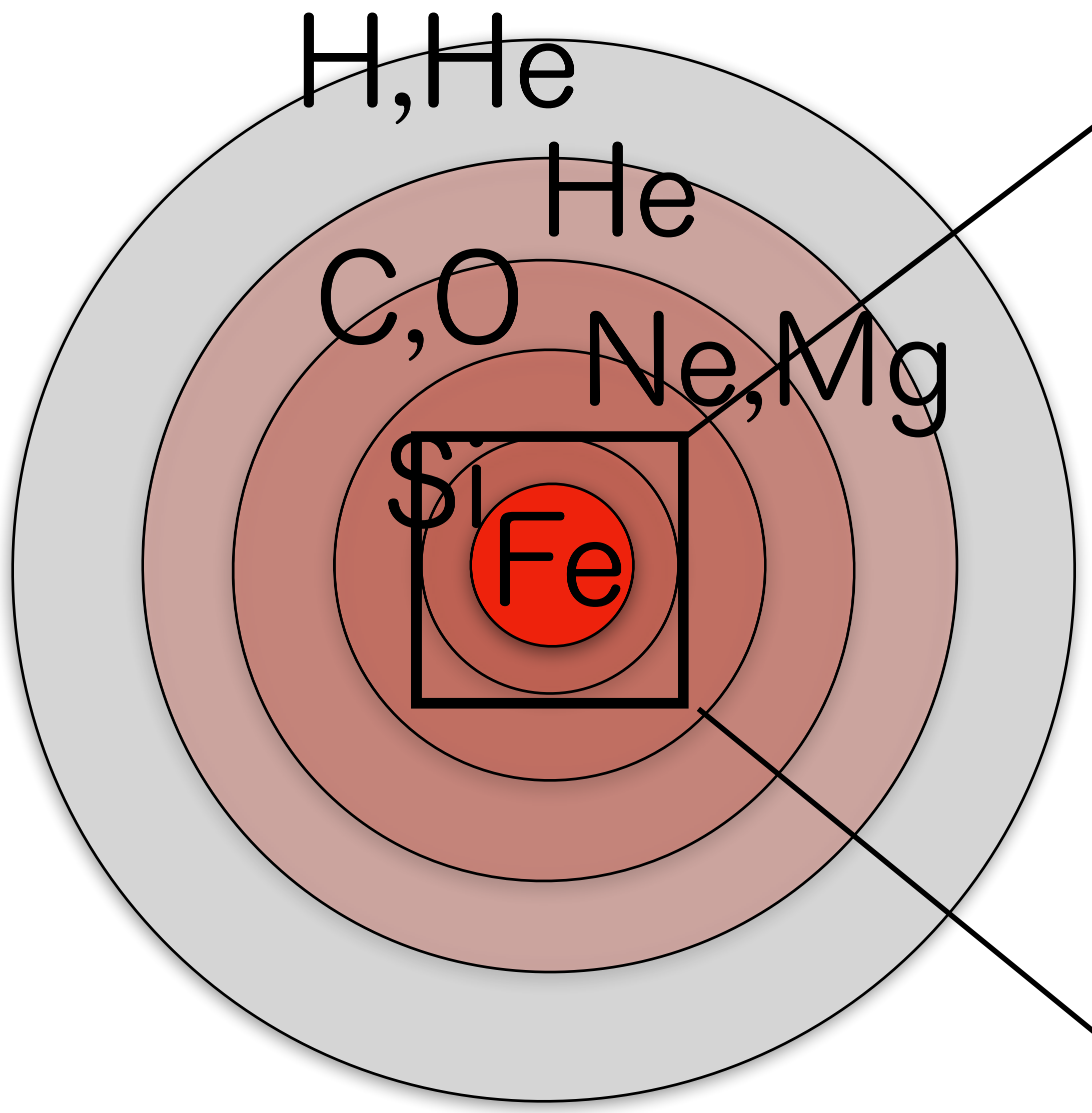
→GR instability → Collapse

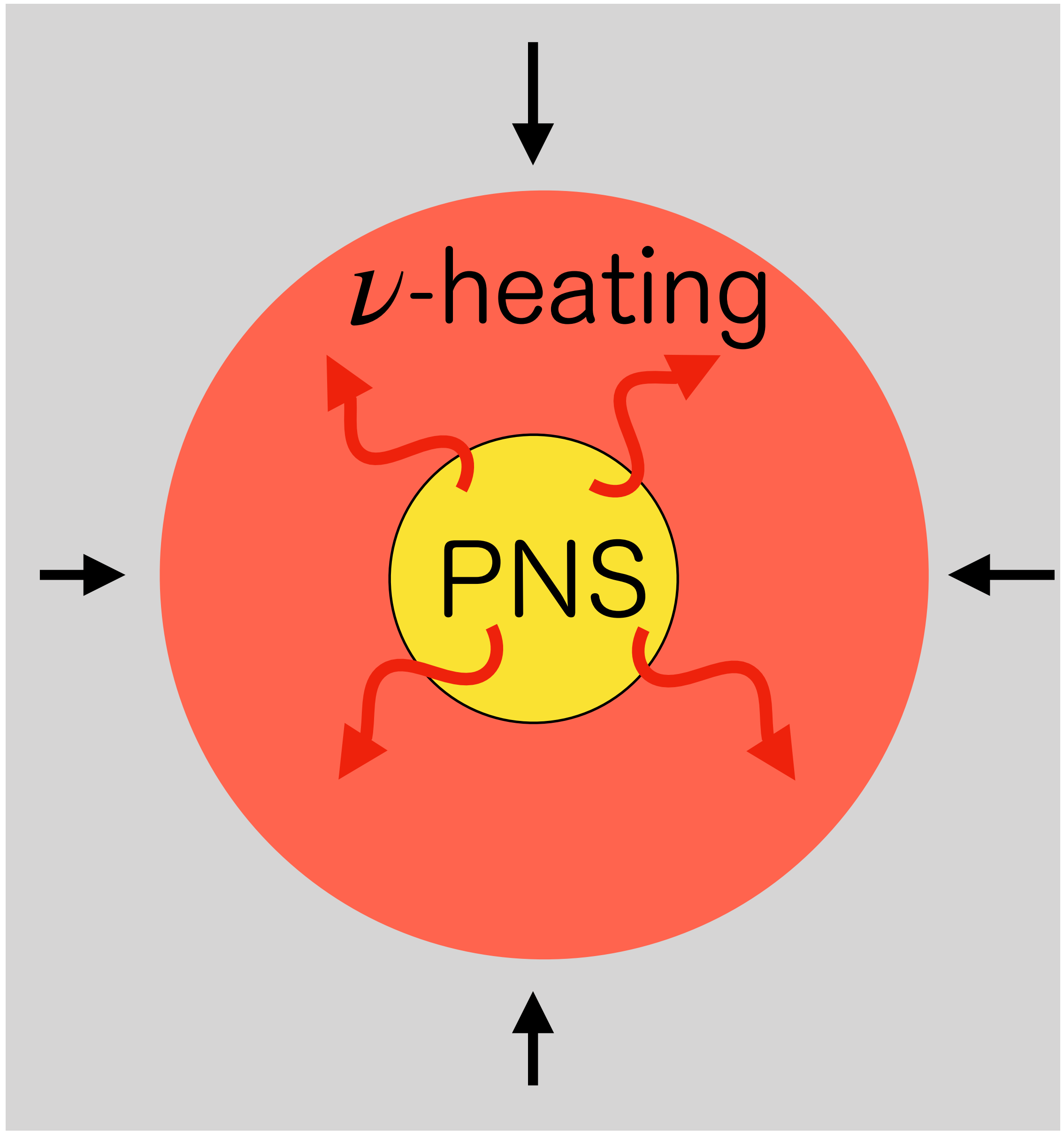
→(Direct) BH formation

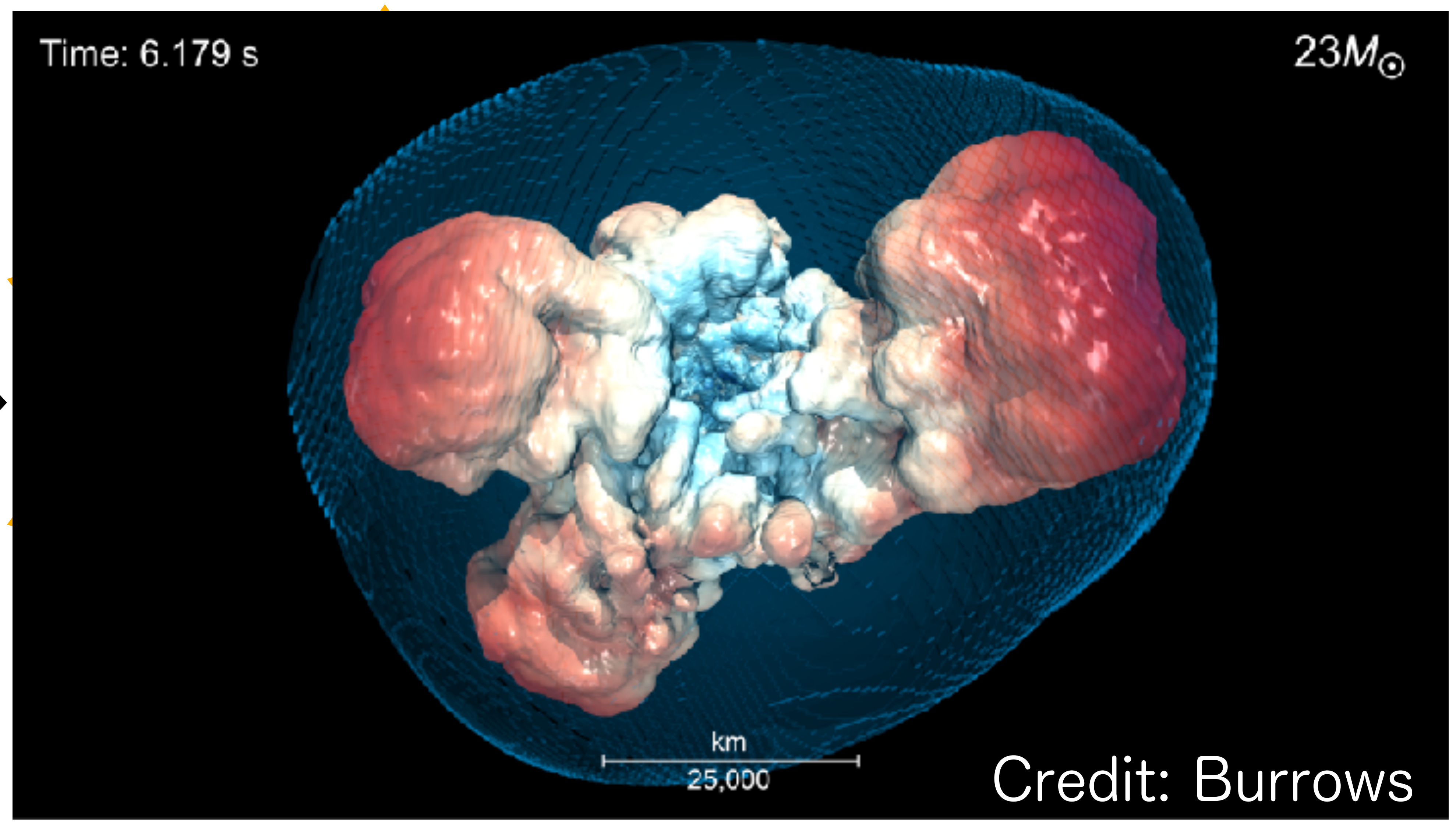
Outline

1. Collapse of usual massive stars (~$10M_\odot$)
2. Collapse of Supermassive stars ($\gtrsim 10^4 M_\odot$)
3. Collapse of Very massive stars ($\lesssim 10^4 M_\odot$; preliminary)

Collapse of massive stars





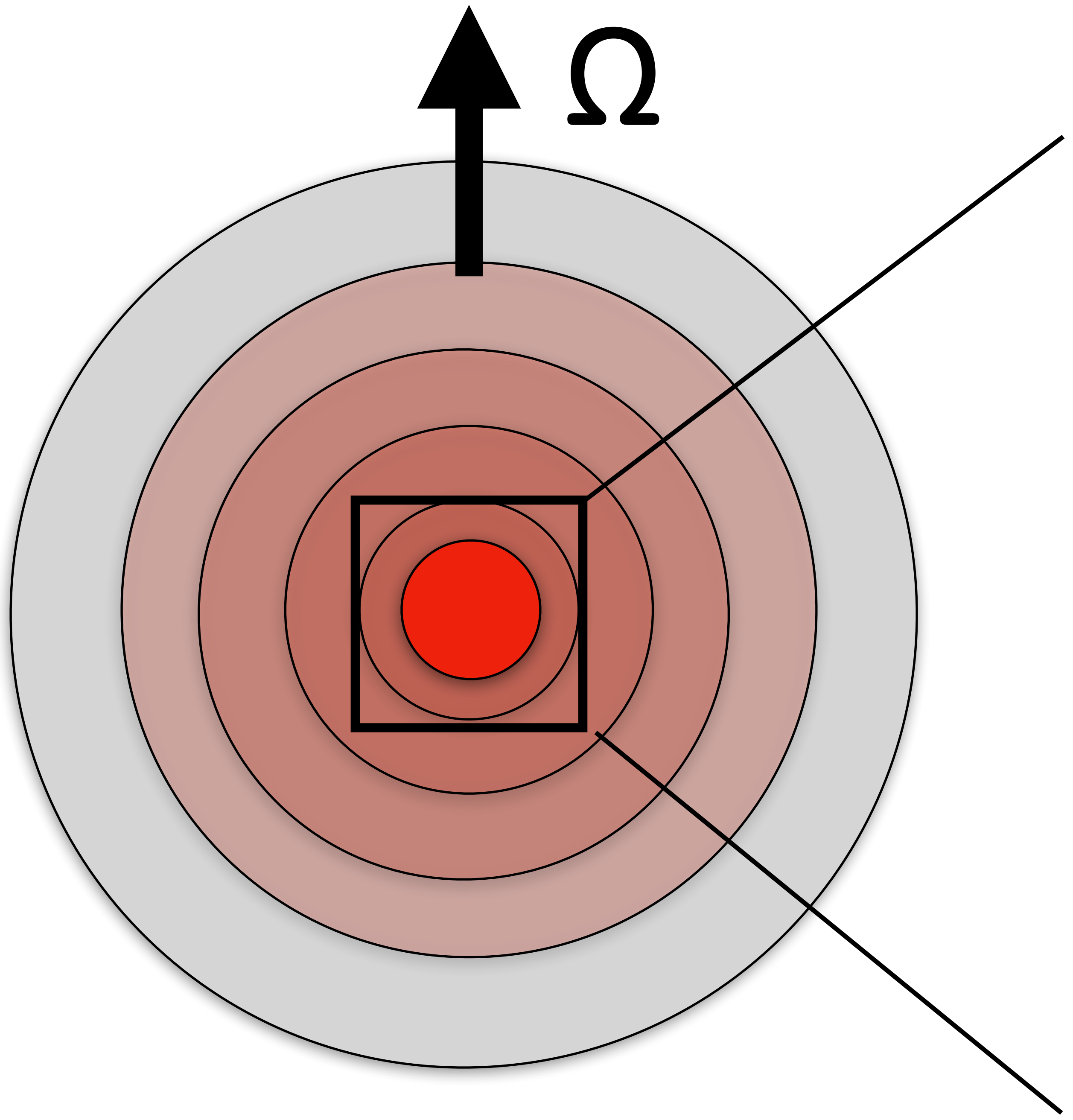


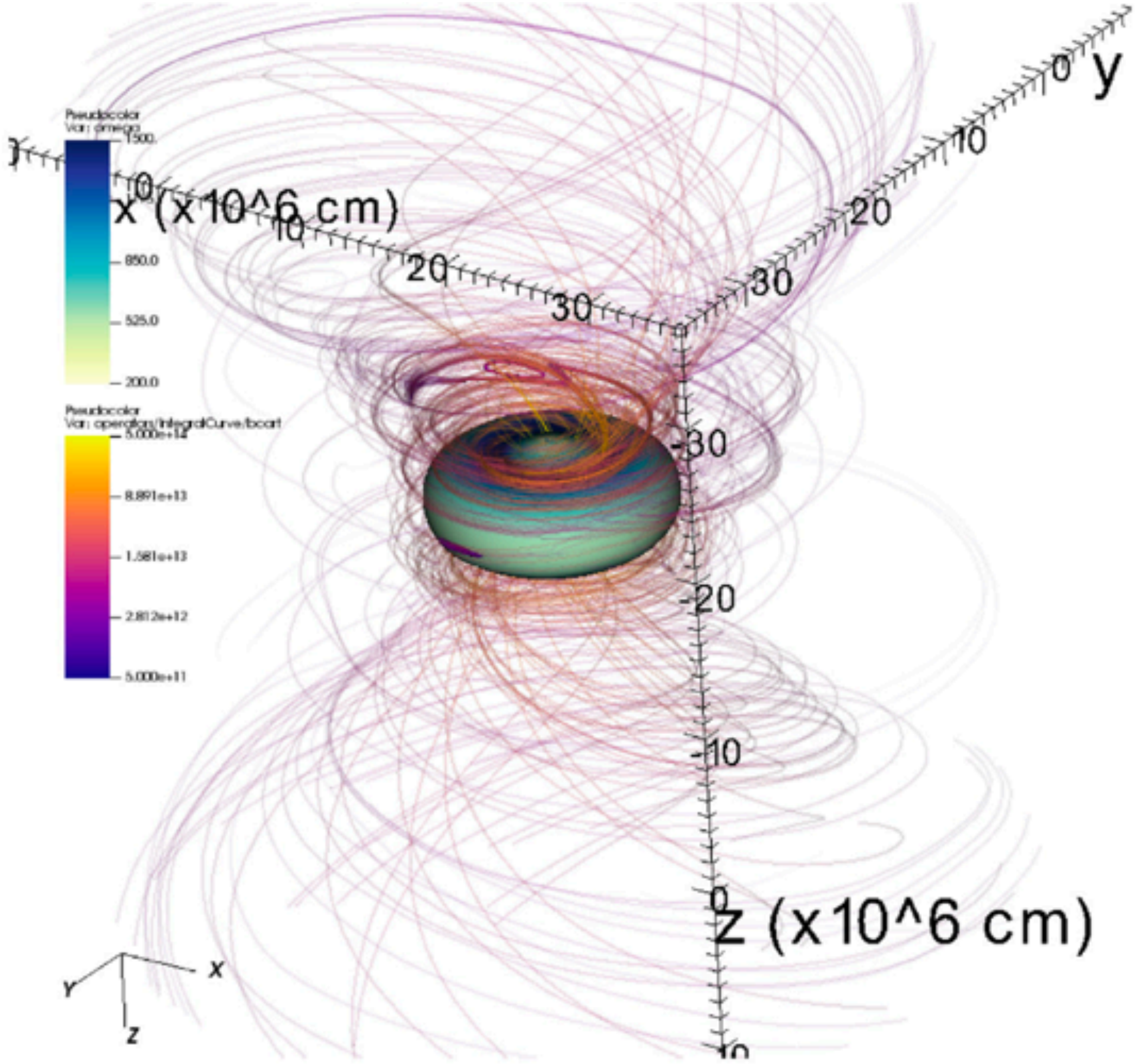
"Normal" SN

Gravitational Collapse

Proto-neutron star
shock formation…
Neutrino heating

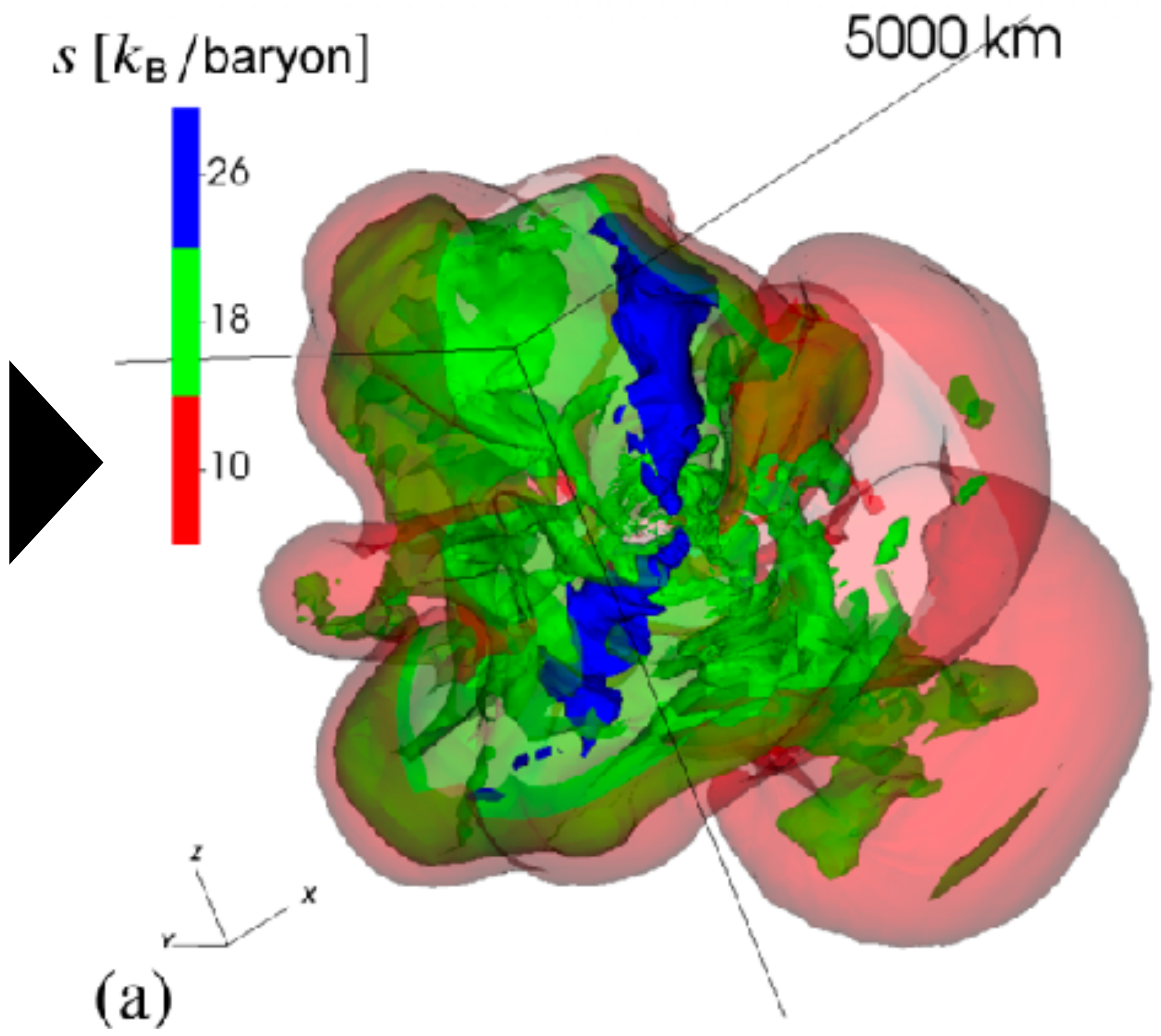
Collapse of massive stars





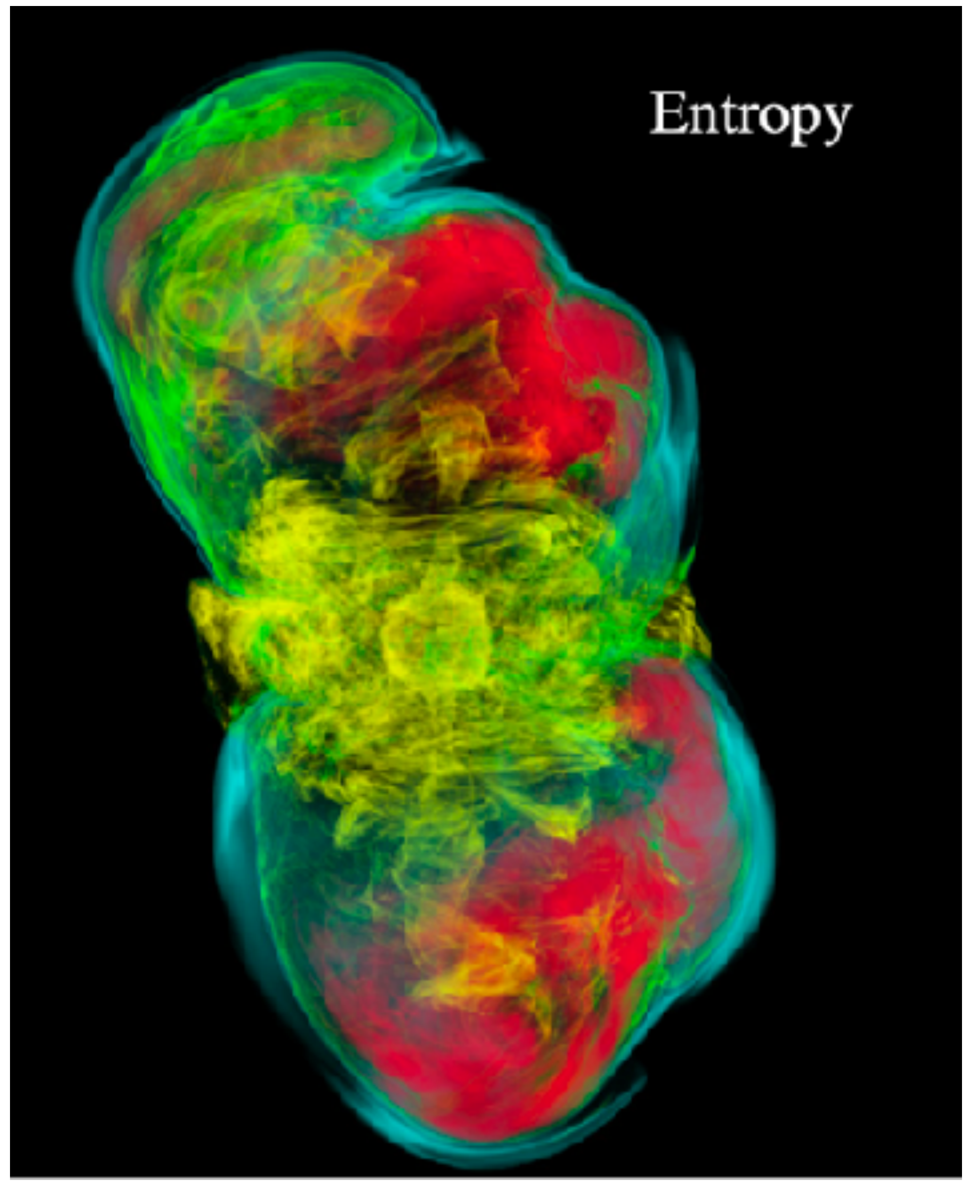
→Aloy's talk

Aloy & Obergaulinger 2021

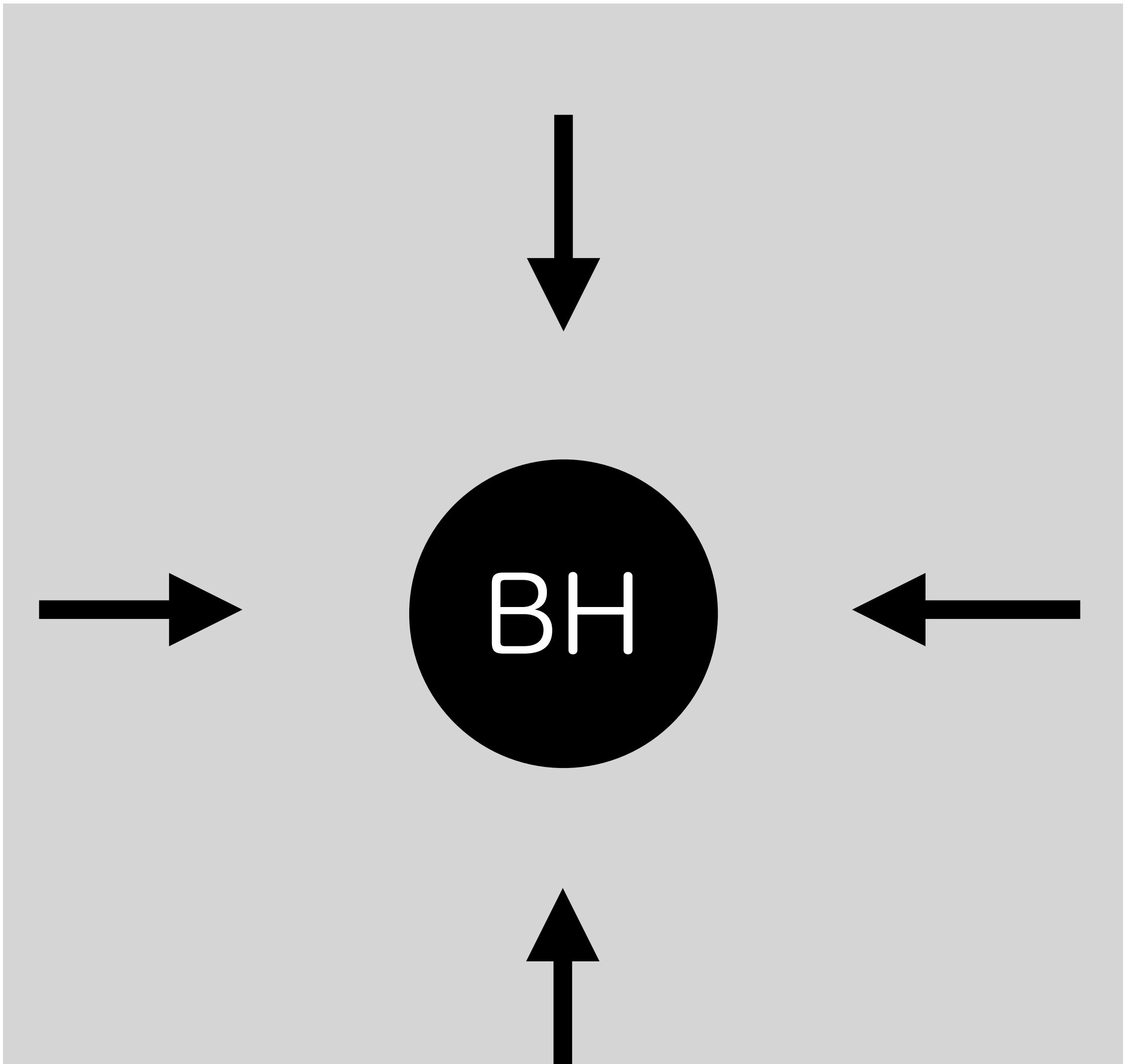


→Mösta's talk

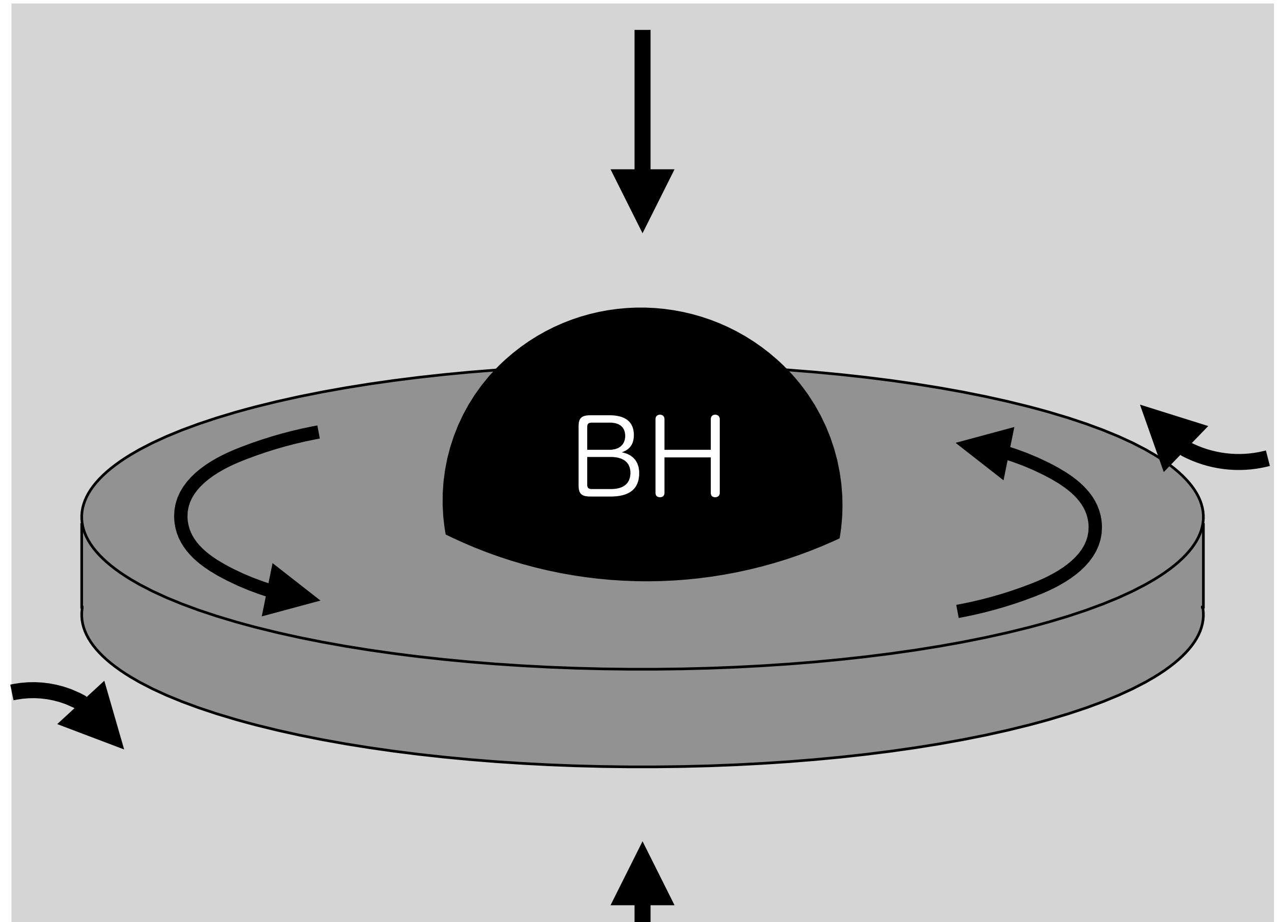
Mösta+2014



e.g., Core is too compact
BH formation before
successful explosion.



Activities after BH formation



Transient from collapses of rotating massive stars

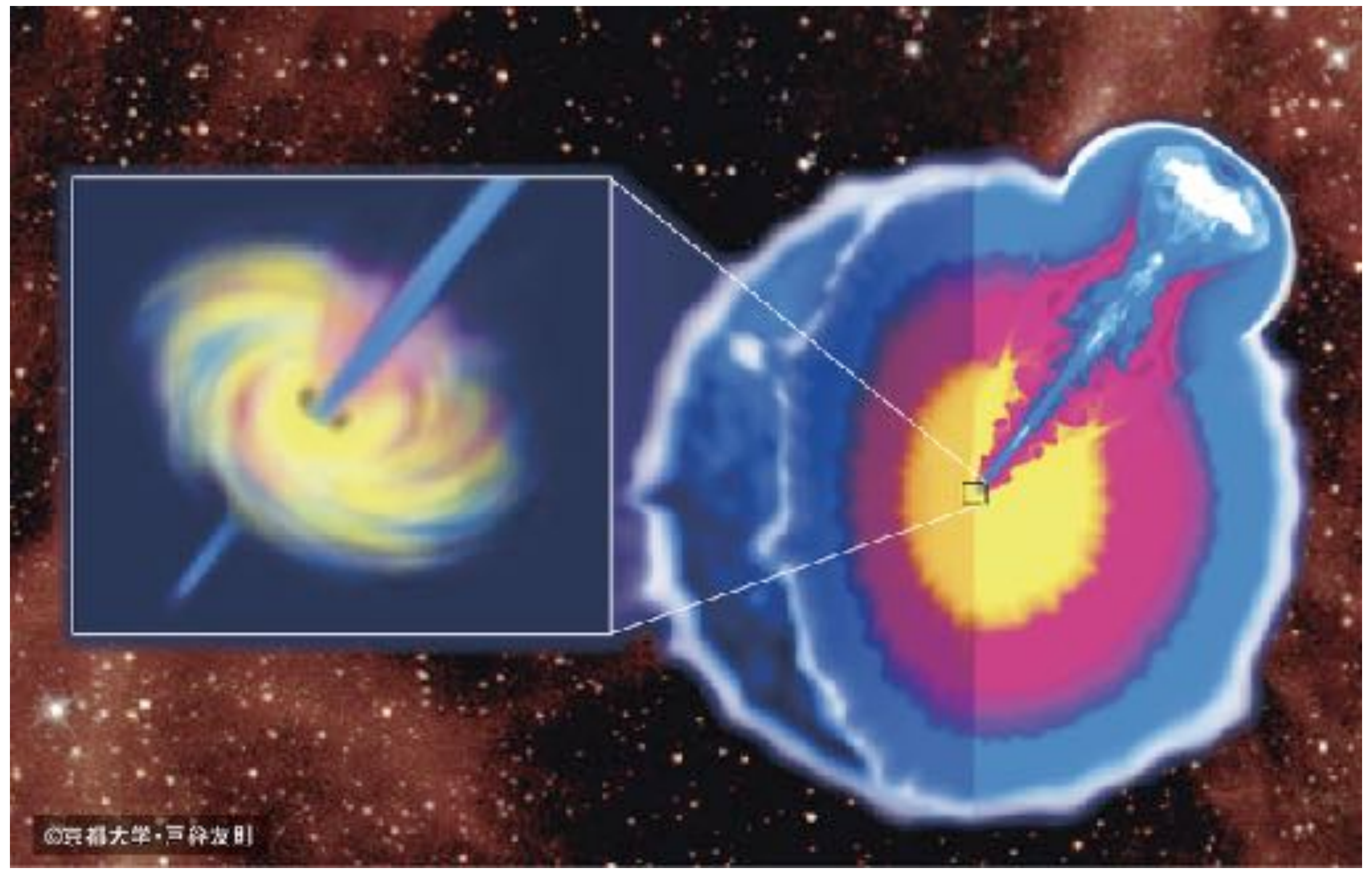
Gamma-ray burst (GRB)

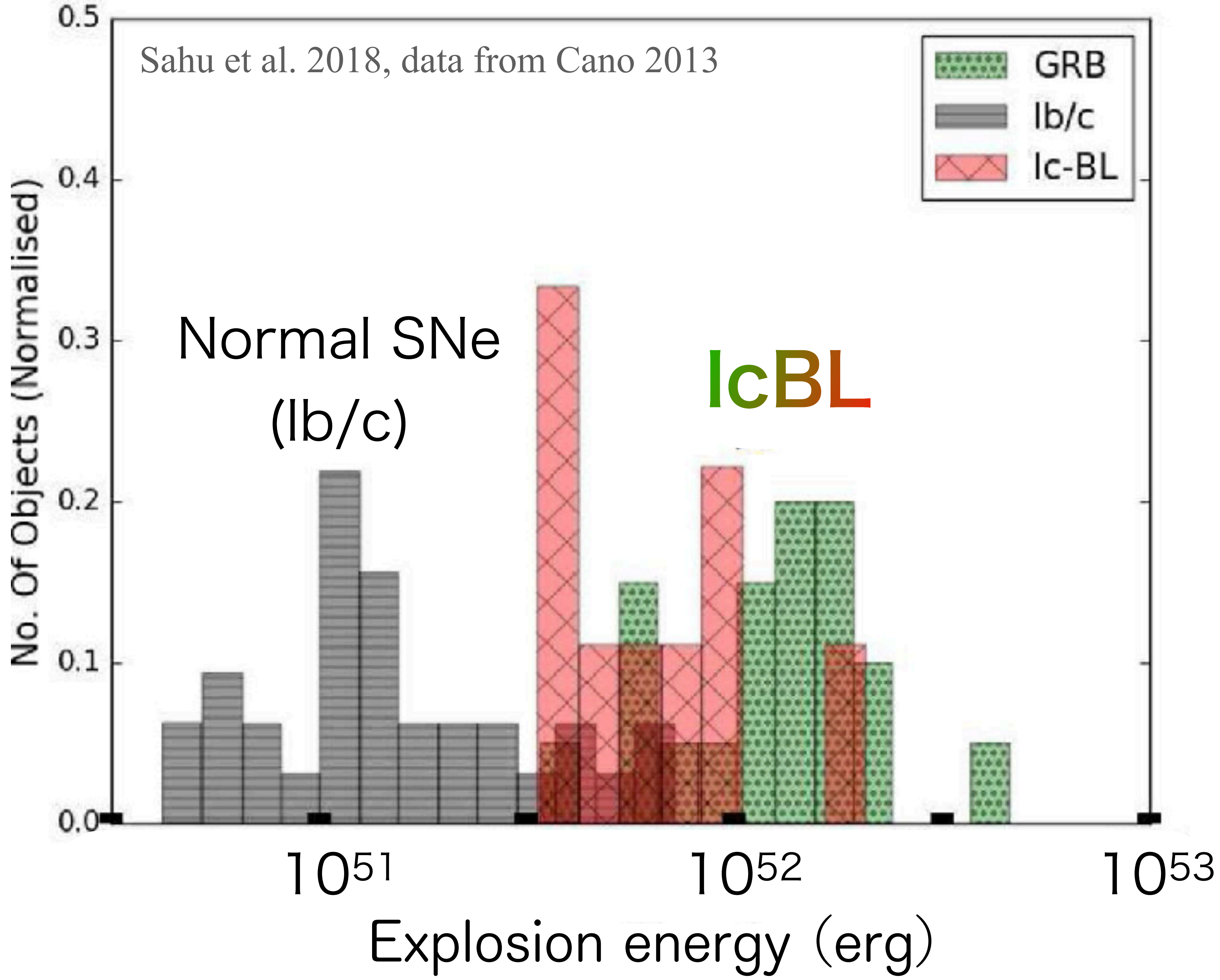
Bright γ-ray flash (0.1 – 100 s, L_{iso}~10^{50} – 10^{55} erg/s)

BH-disk system is promising "central engine"

(e.g., Woosley et al. 1993...)

→**Janiuk's talk, Płonka's poster**





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

More energetic class of SNe

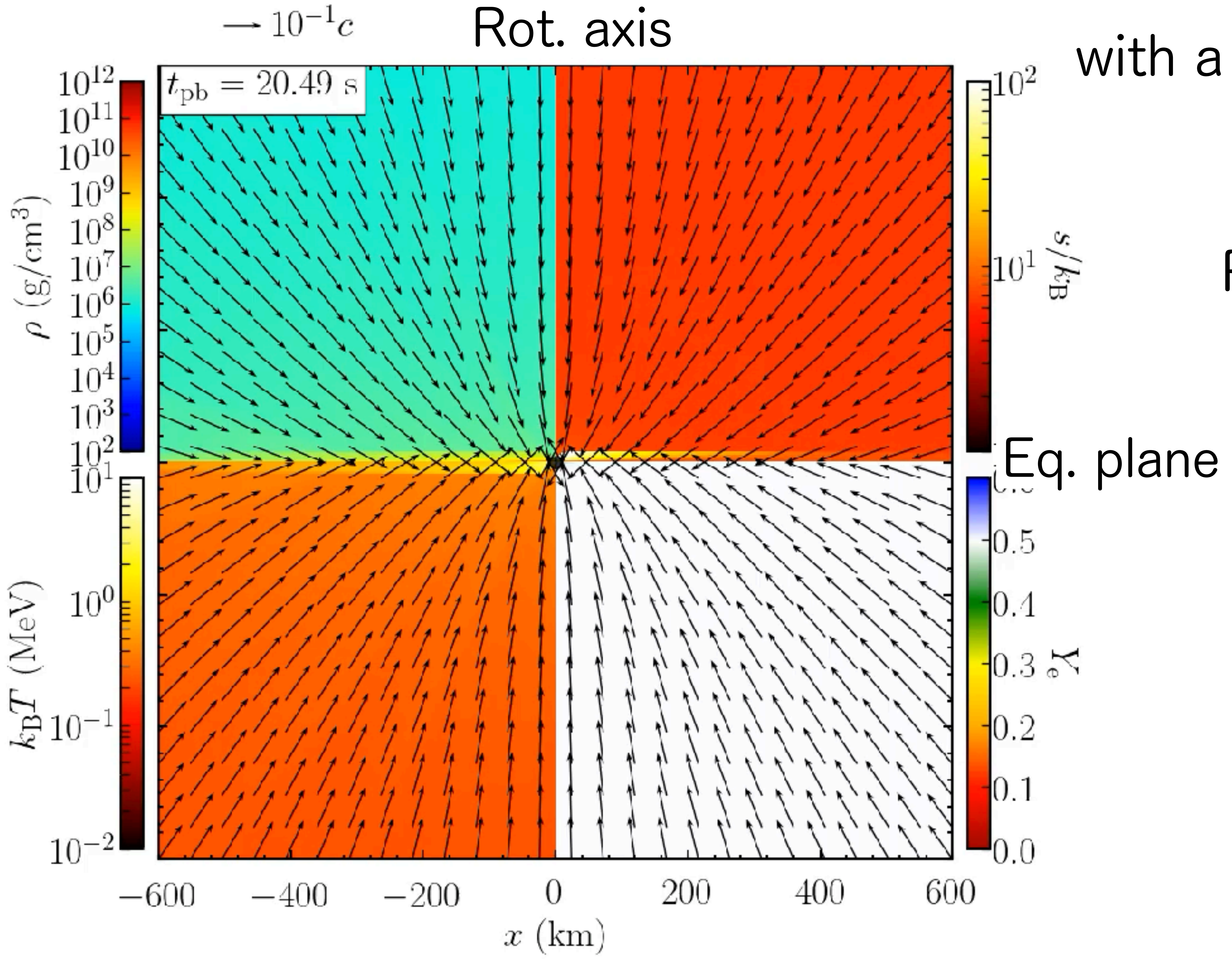
- ~ x10 higher explosion energy
- Large ^{56}Ni mass
- Association with GRBs
- Something to do with BH-disk activity?

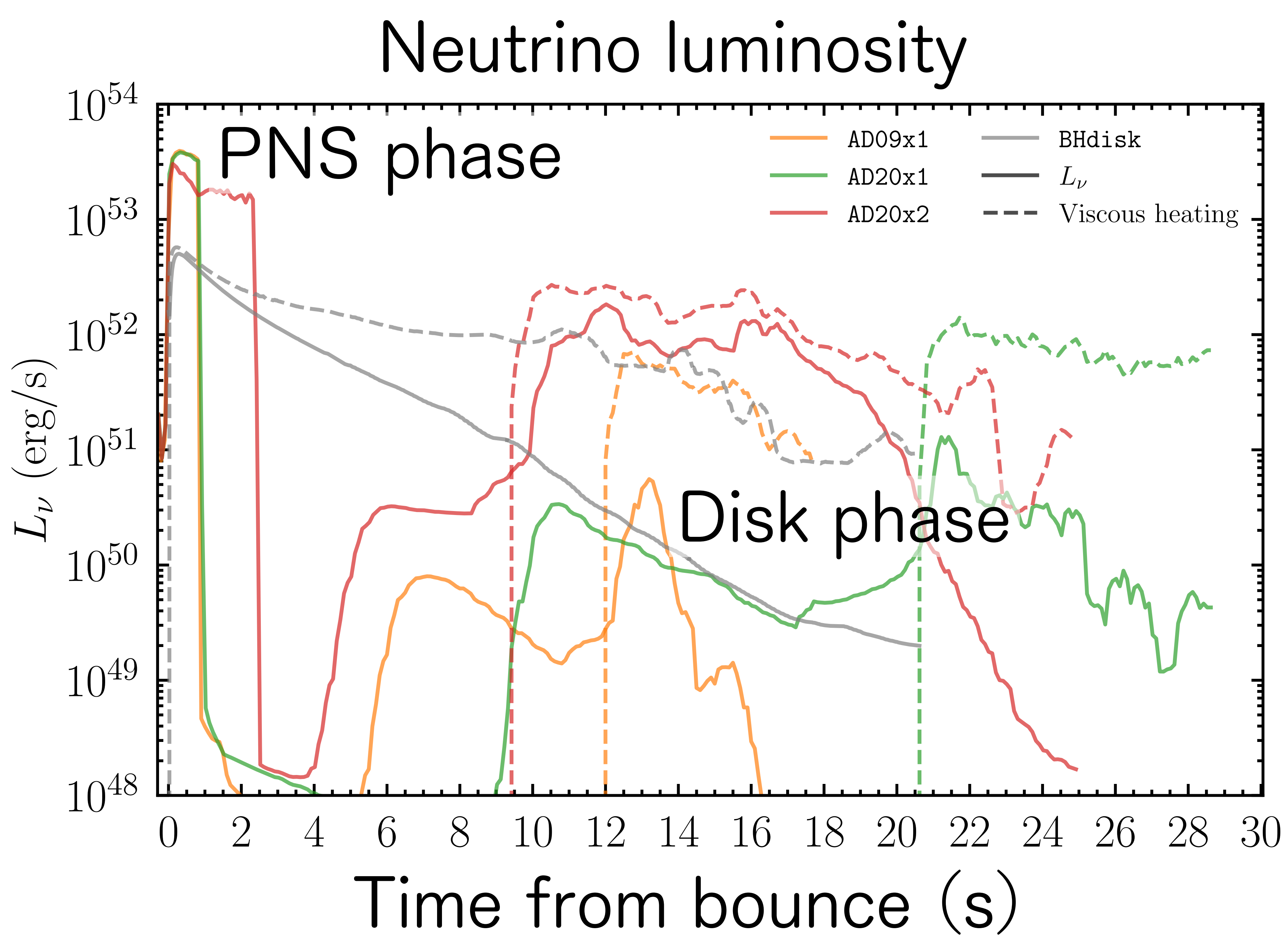
An example

Numerical relativity axisymmetric 2D simulation with a neutrino transport and viscous hydro.

SF+2023

PNS→BH→disk formation→Outflow





SF+2023, Dean & Fernandez +2024

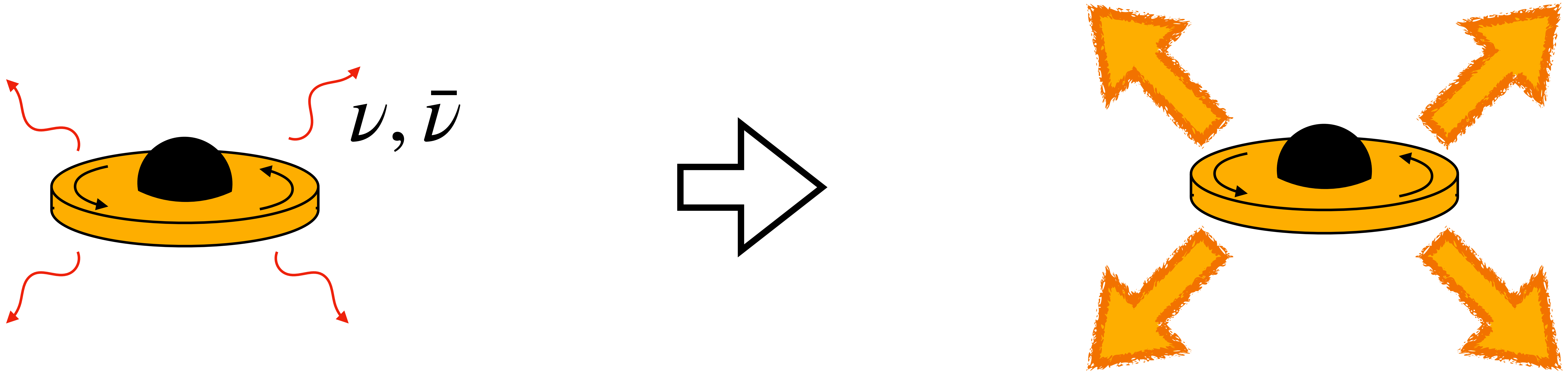
Neutrino cooling vs viscous heating

- Neutrino emission cooling

$$t_{\rm weak} \sim \frac{1}{{G_{\rm F}}^2 T^5} \approx 1\,{\rm s} \left(\frac{kT}{1\,{\rm MeV}}\right)^{-5}$$

- MHD turbulence → Viscous angular momentum transport/heating

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

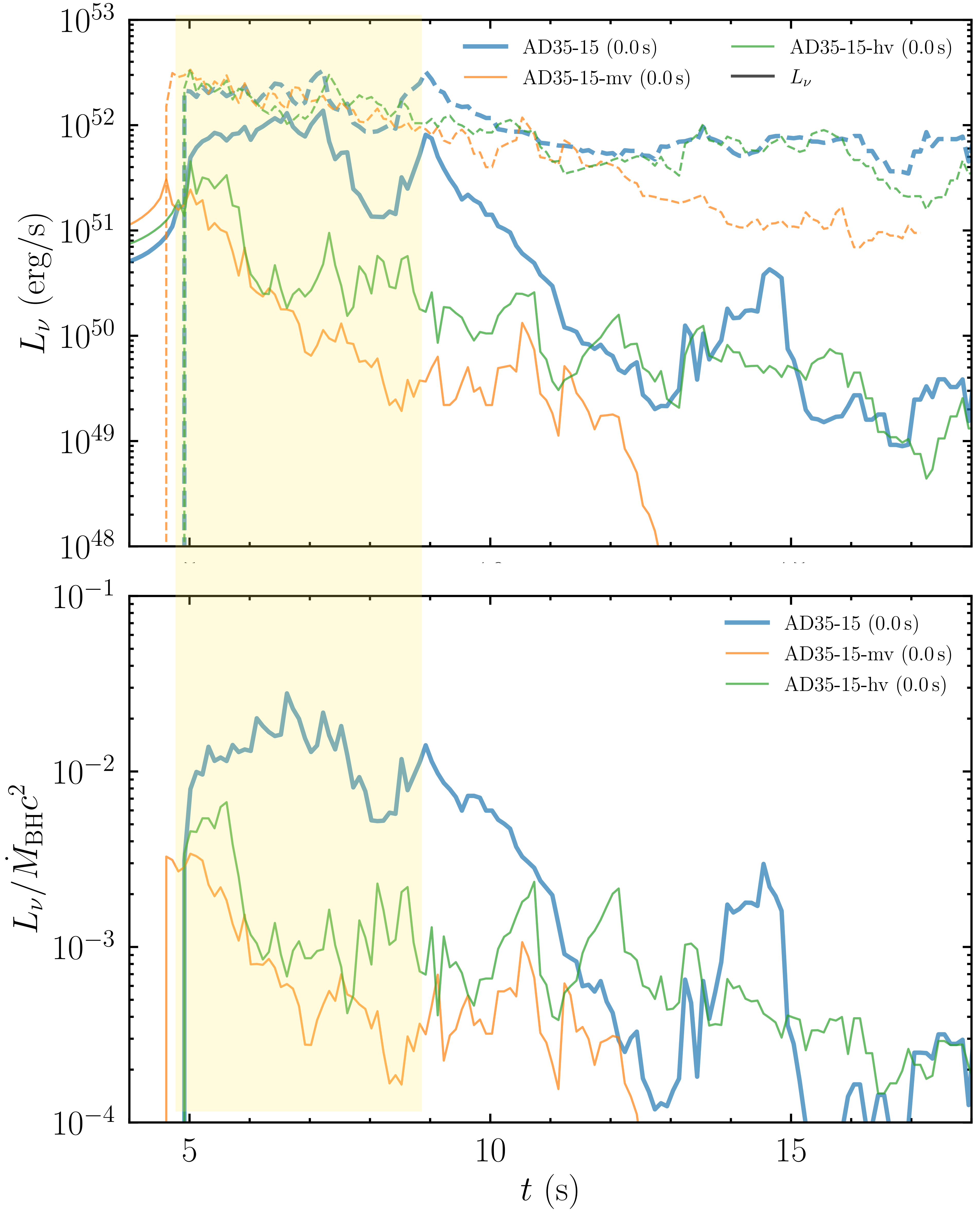


✓ $t_{\rm weak} \lesssim t_{\rm vis}$ weak/no outflow

✓ $t_{\rm weak} \gg t_{\rm vis}$ viscosity can drive outflow

Very similar to BNS merger remnant disk

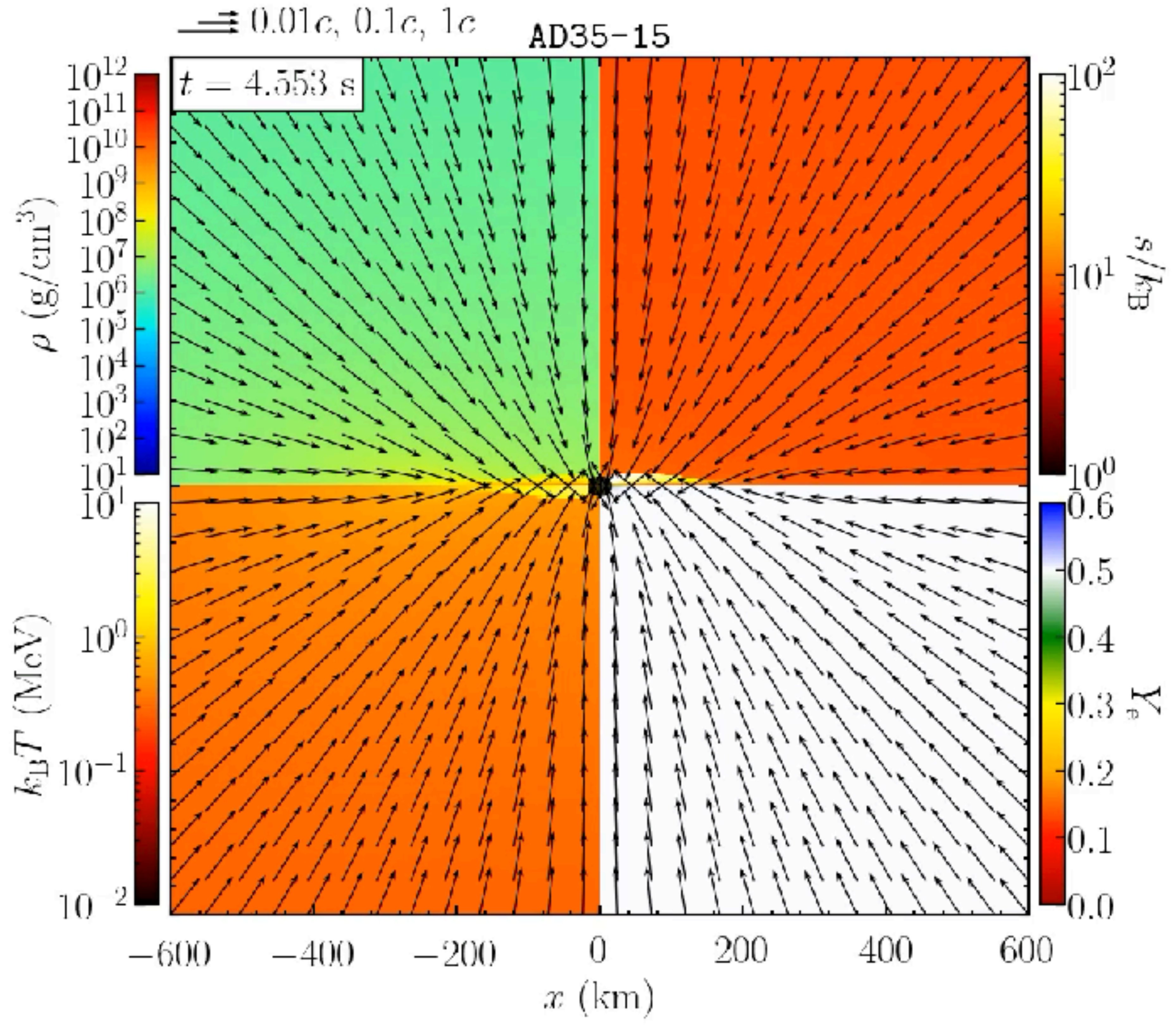
Neutrino emission vs viscous heating



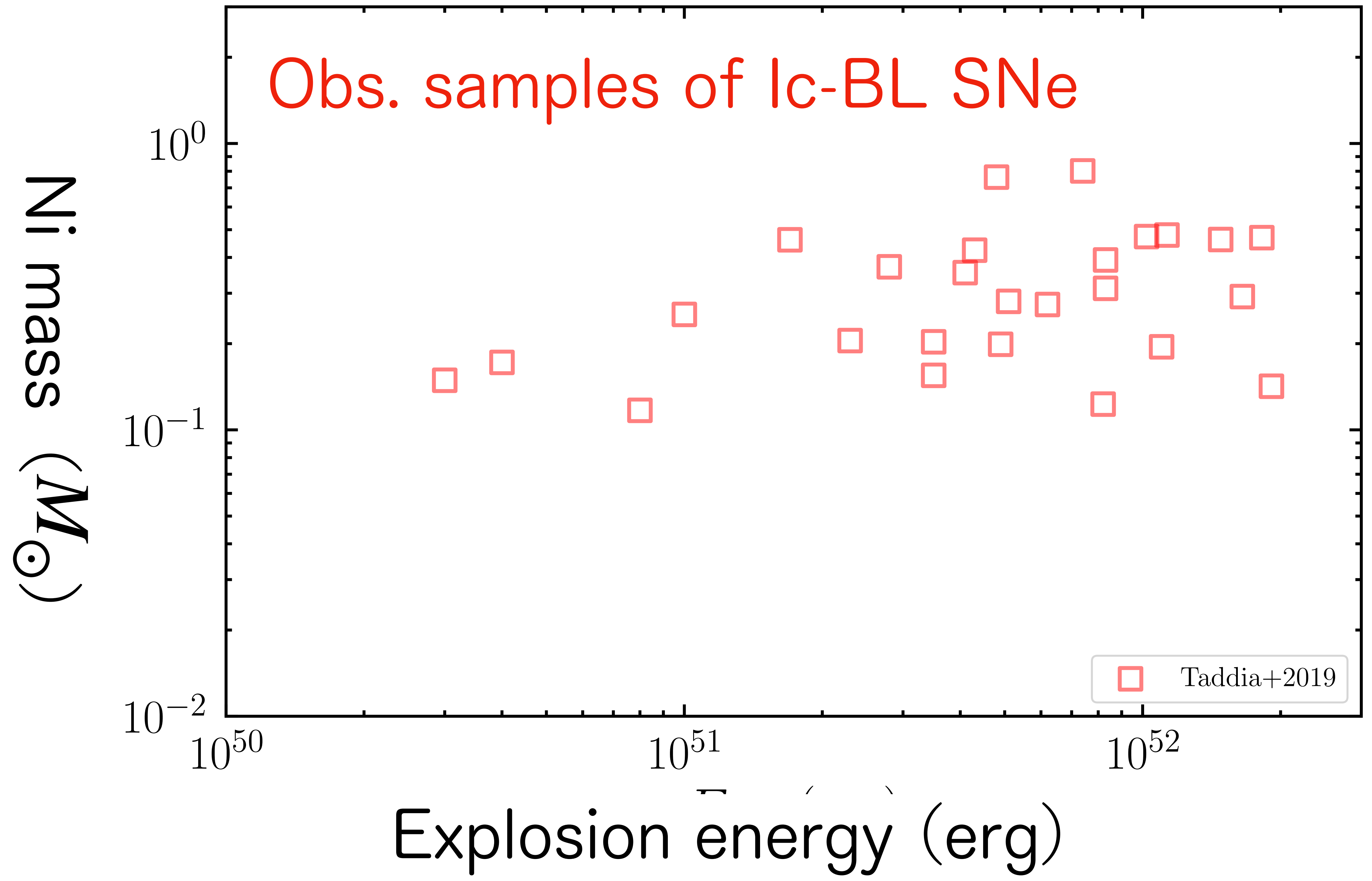
(See blue lines)

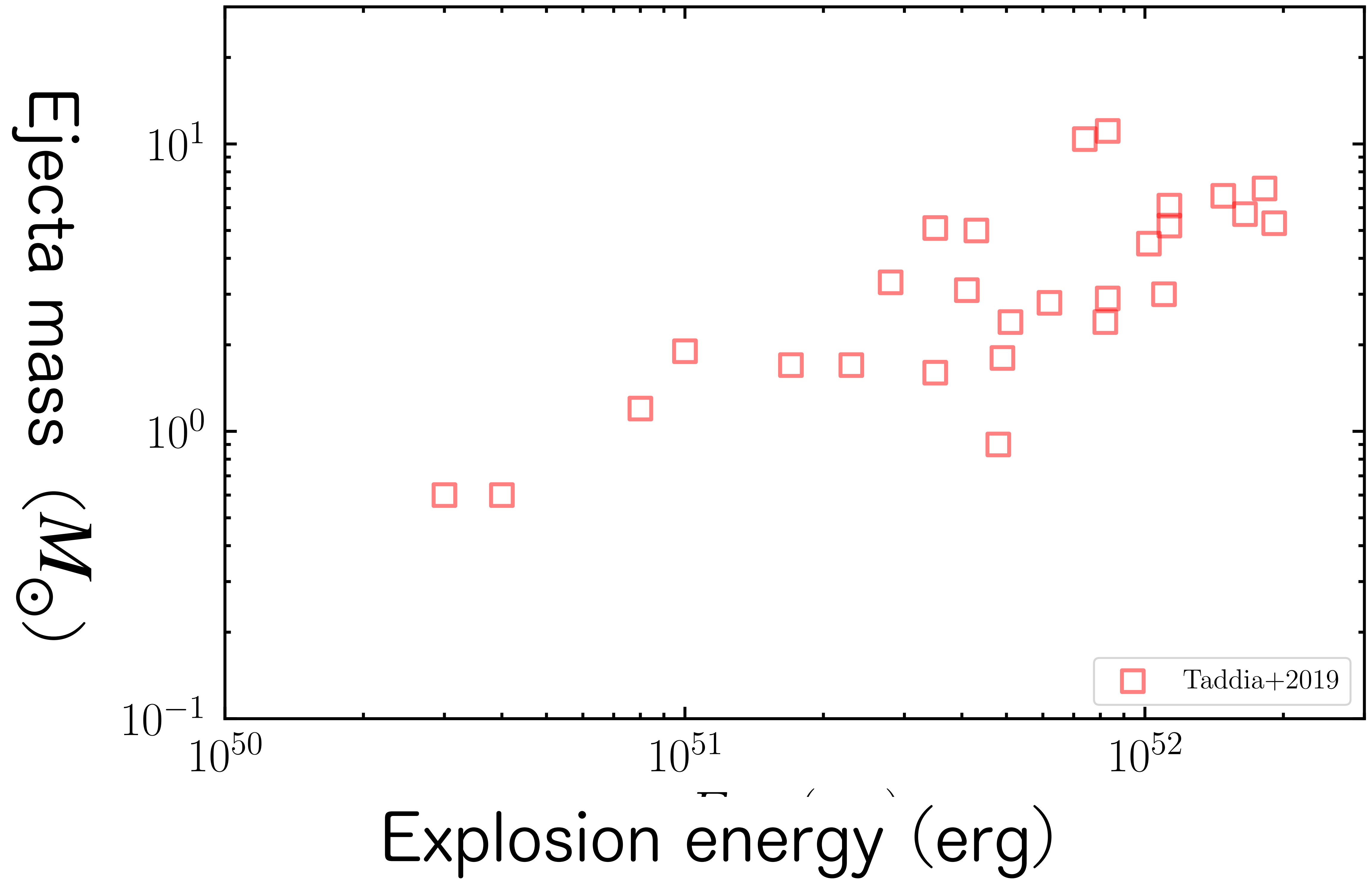
NDAF phase ~ several seconds.

Cooling efficiency drops → Disk outflow



Comparison with Observation





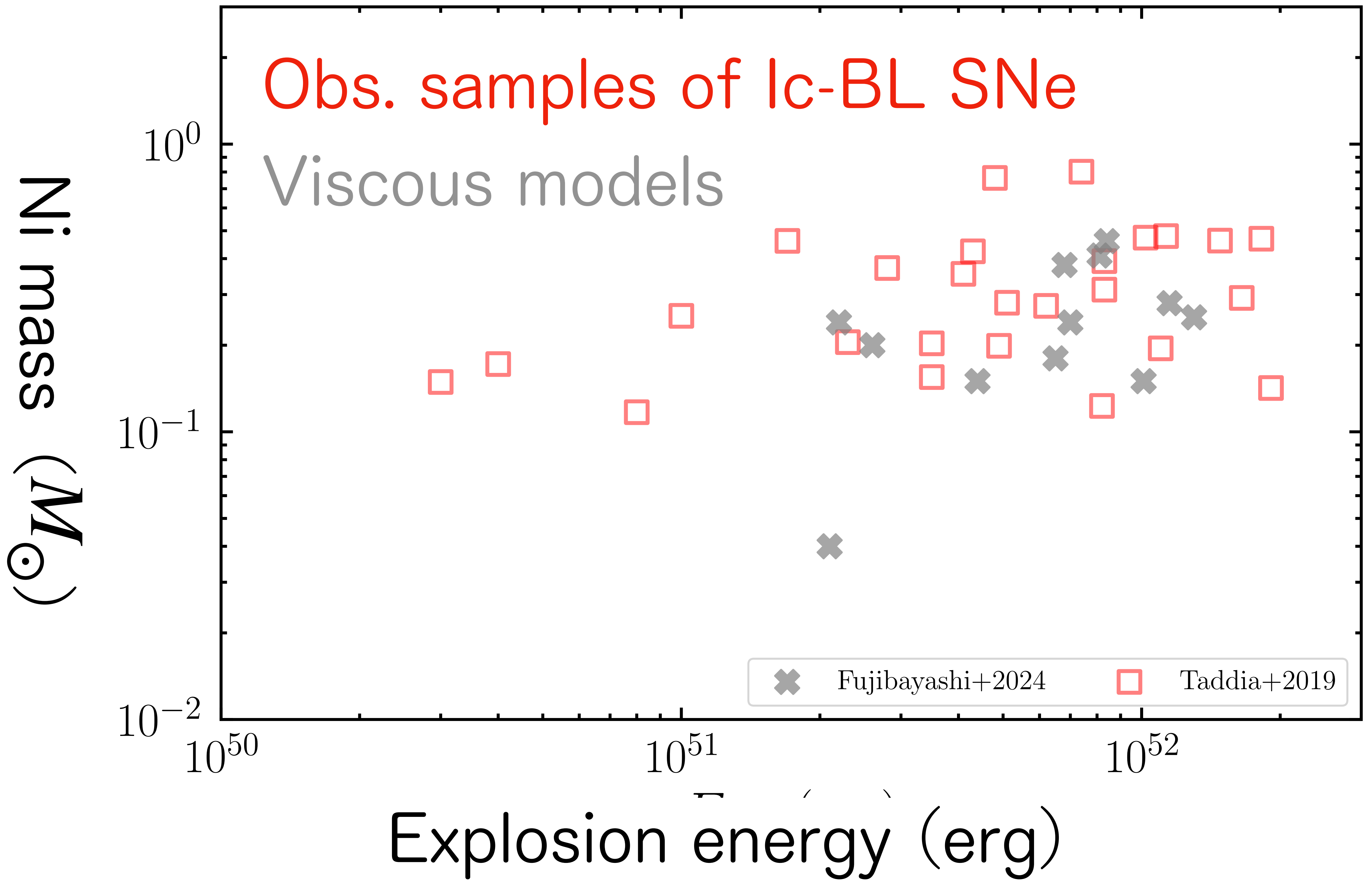
Observations typically show...

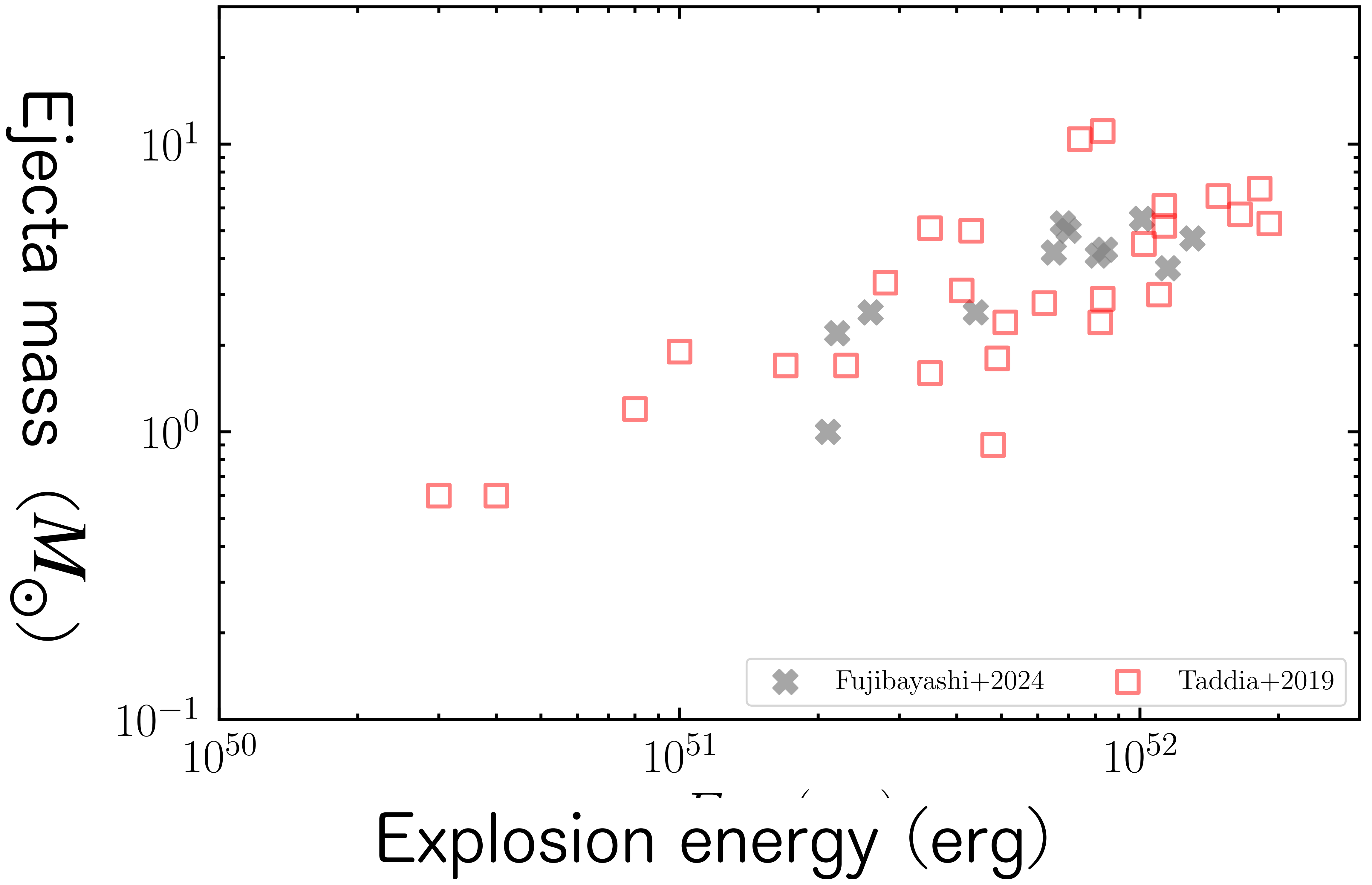
Explosion energy of 10^{52} erg

Ejecta mass of $1 - 10M_\odot$

Ni mass of $0.1 - 1M_\odot$

Comparison with Observation



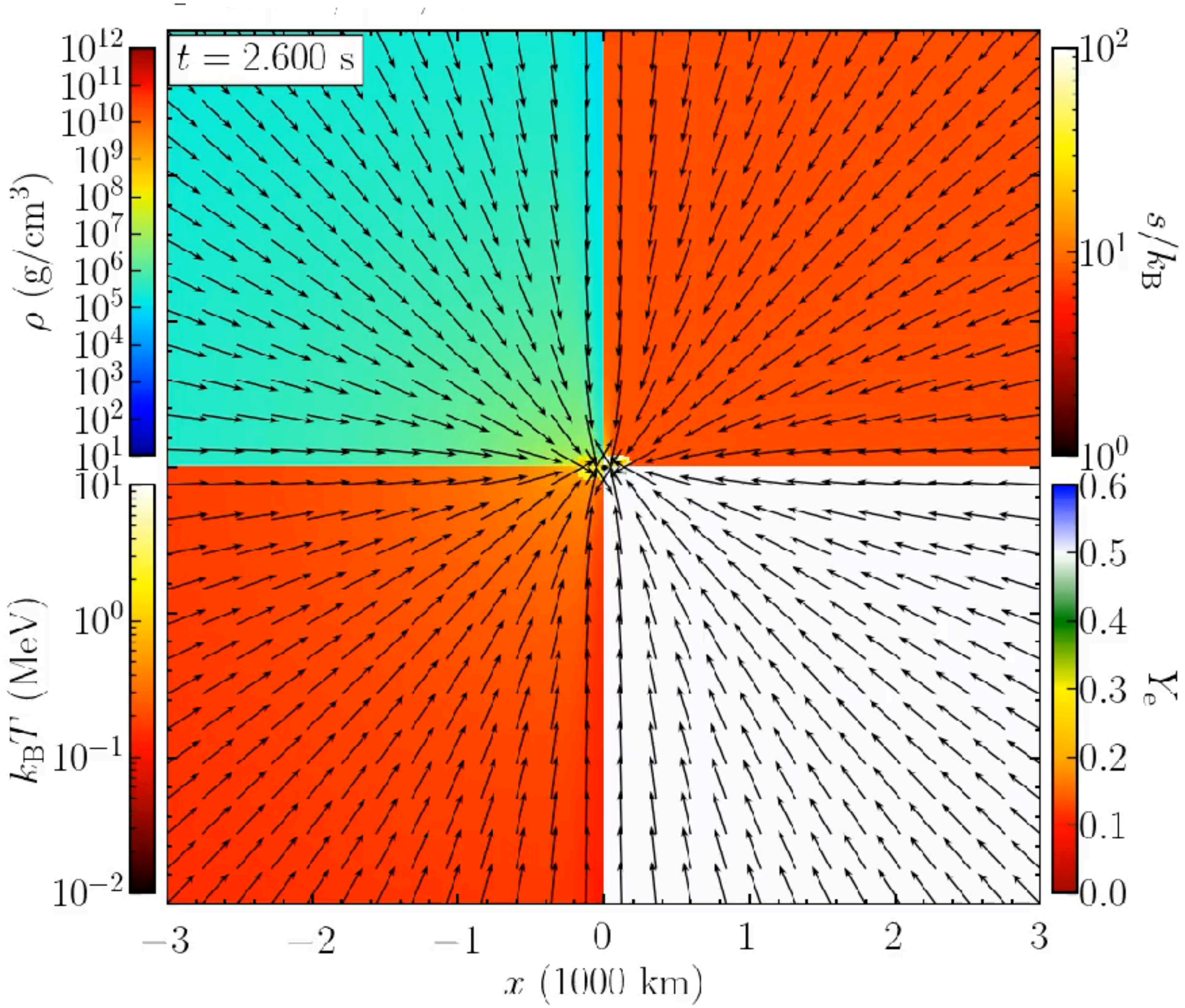


Post-process nucleosynthesis

Collapsar disk scenario can explain the observational feature consistently.

MHD effects

$M_{\rm ZAMS} = 35 M_\odot$ star, Poloidal field



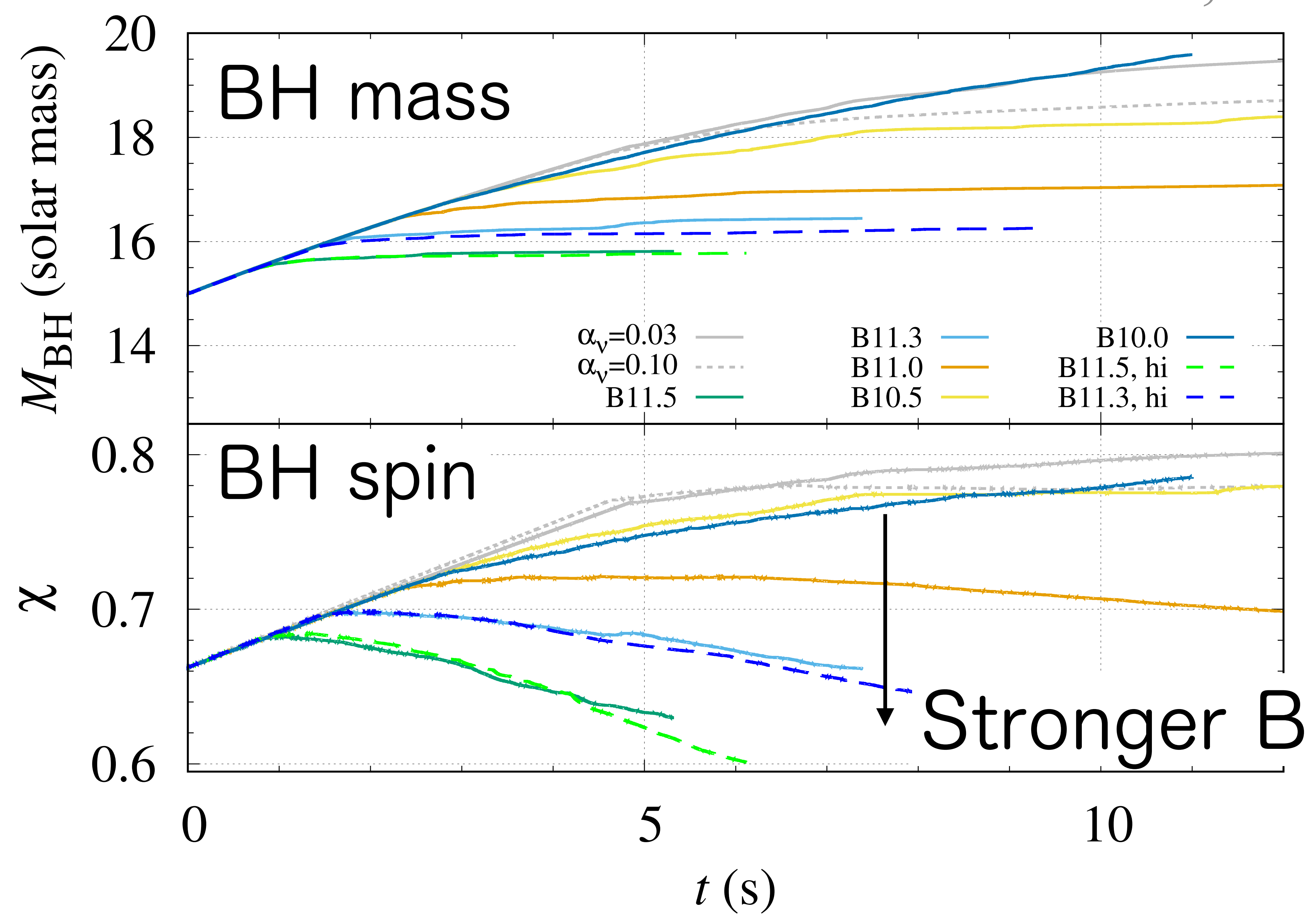
Viscous→ (ideal) Magneto hydro.

Fossil field

→ Jet launch by Blandford-Znajek (BZ) process

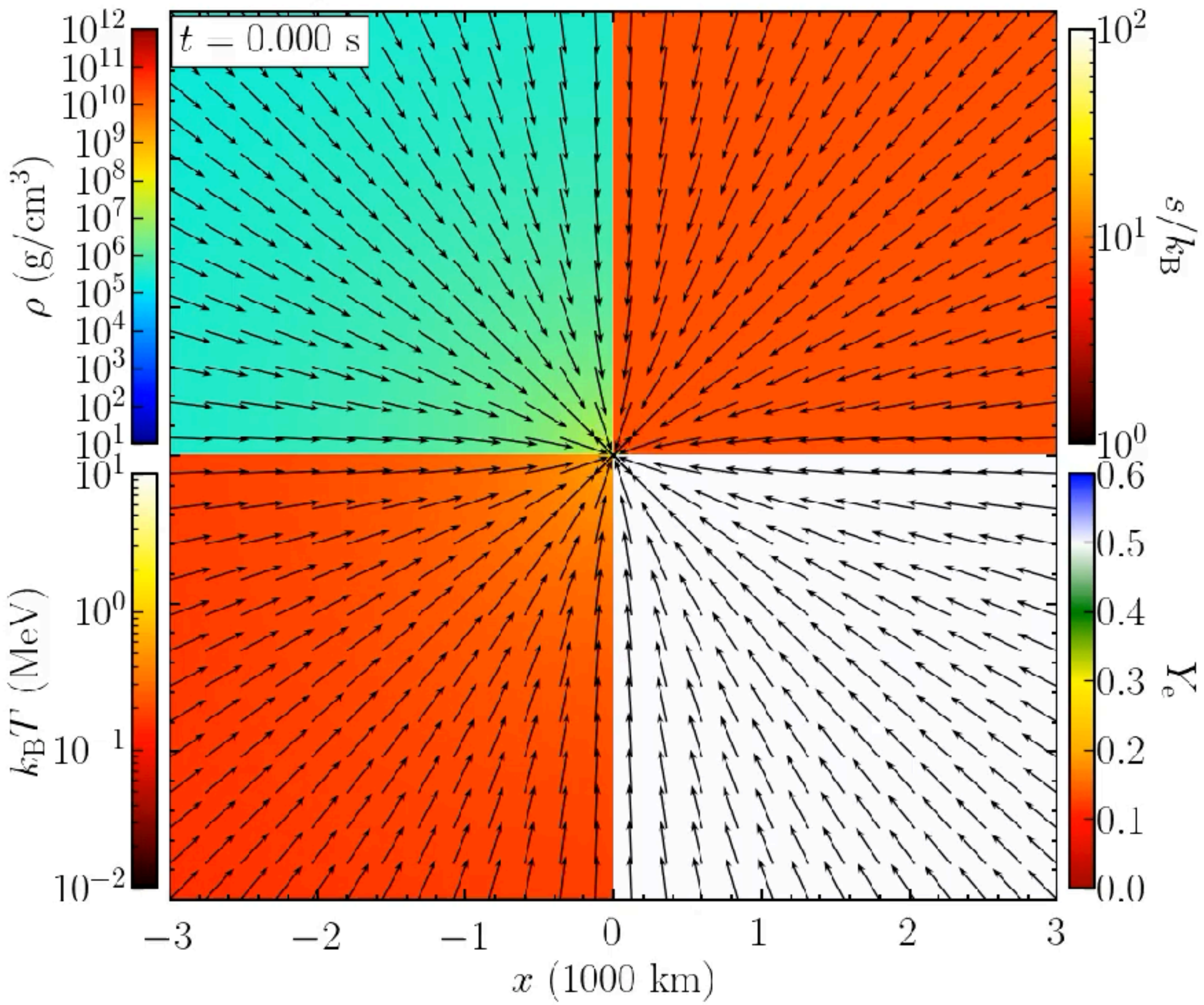
We observed BH spin down by BZ process!

Shibata, SF+2024



MHD+dynamo term

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



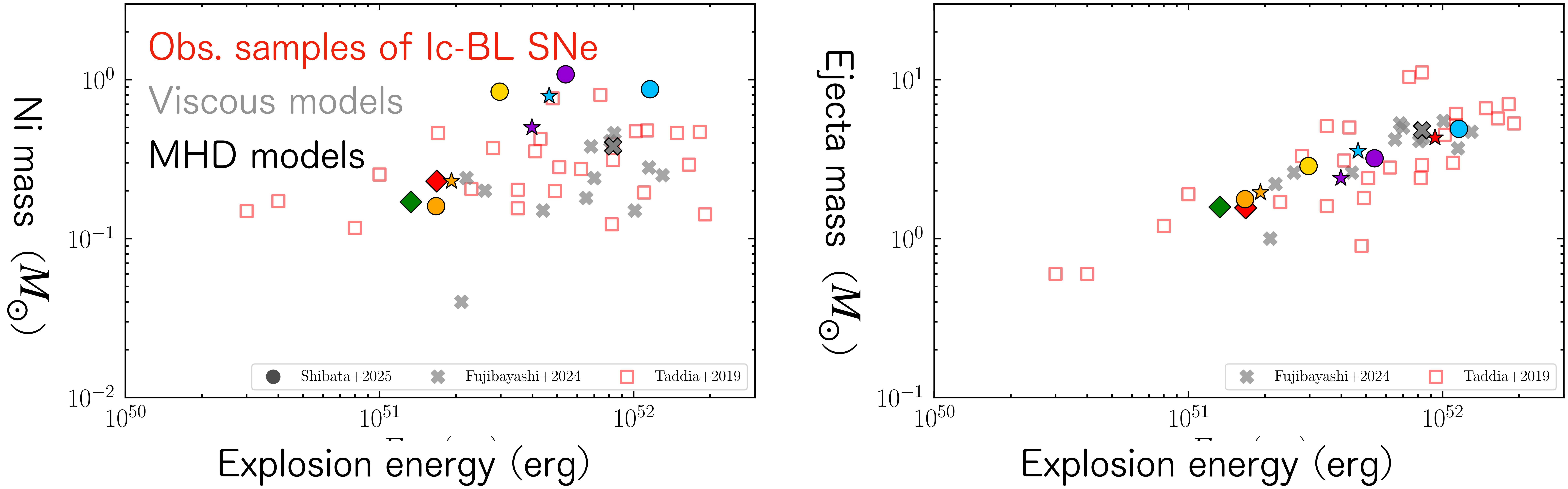
Resistive MHD
+ phenomenological dynamo term.
to consider dynamo action in 2D simulation

Shibata, SF+2025

Poloidal field amplified in the disk is advected to BH.

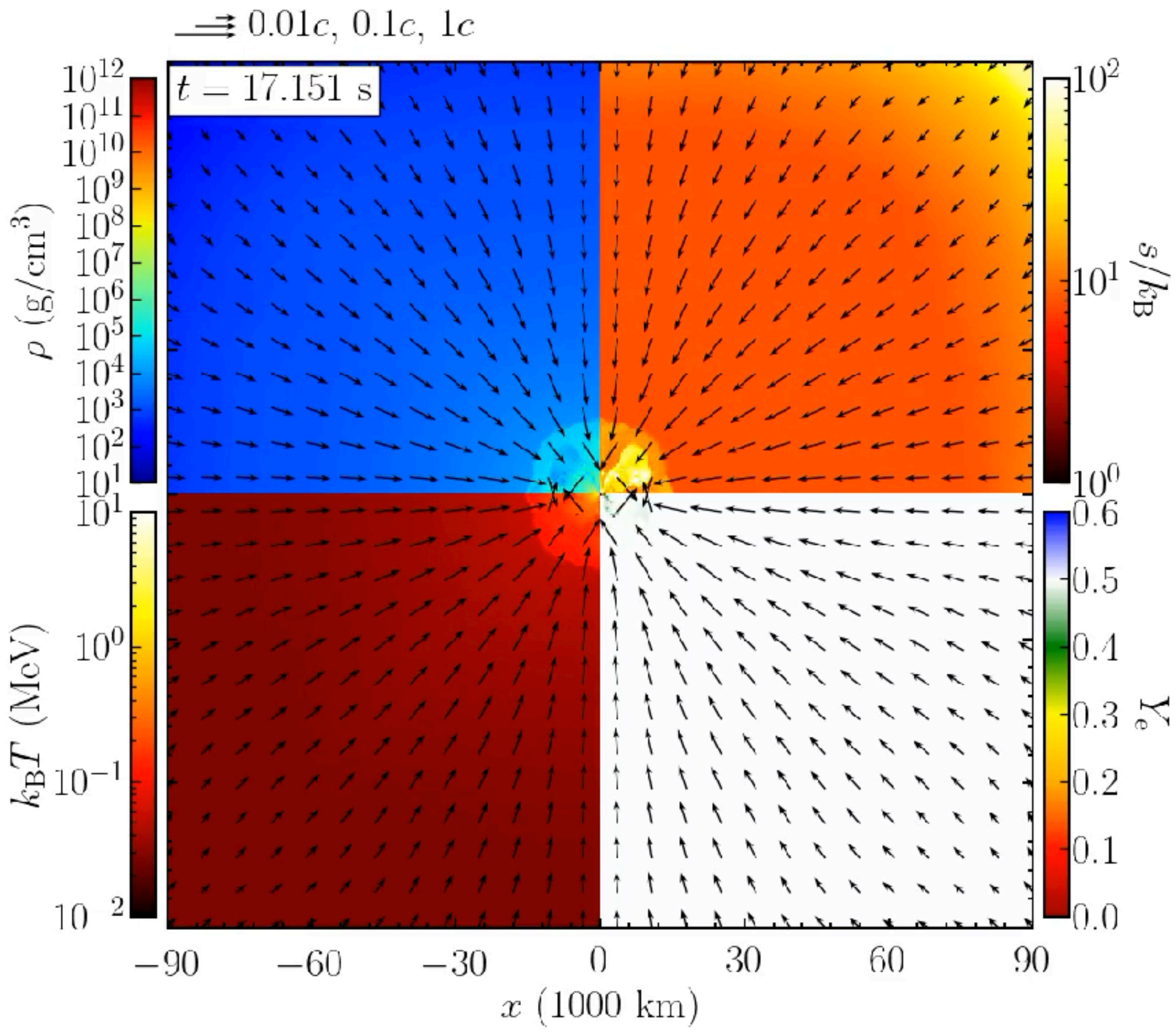
→Jet by BZ process＋Viscosity-driven outflow

Comparison with Observation



Similar to viscous hydro case.
Collapsar disk scenario can explain the observational feature consistently.

Heavy element synthesis

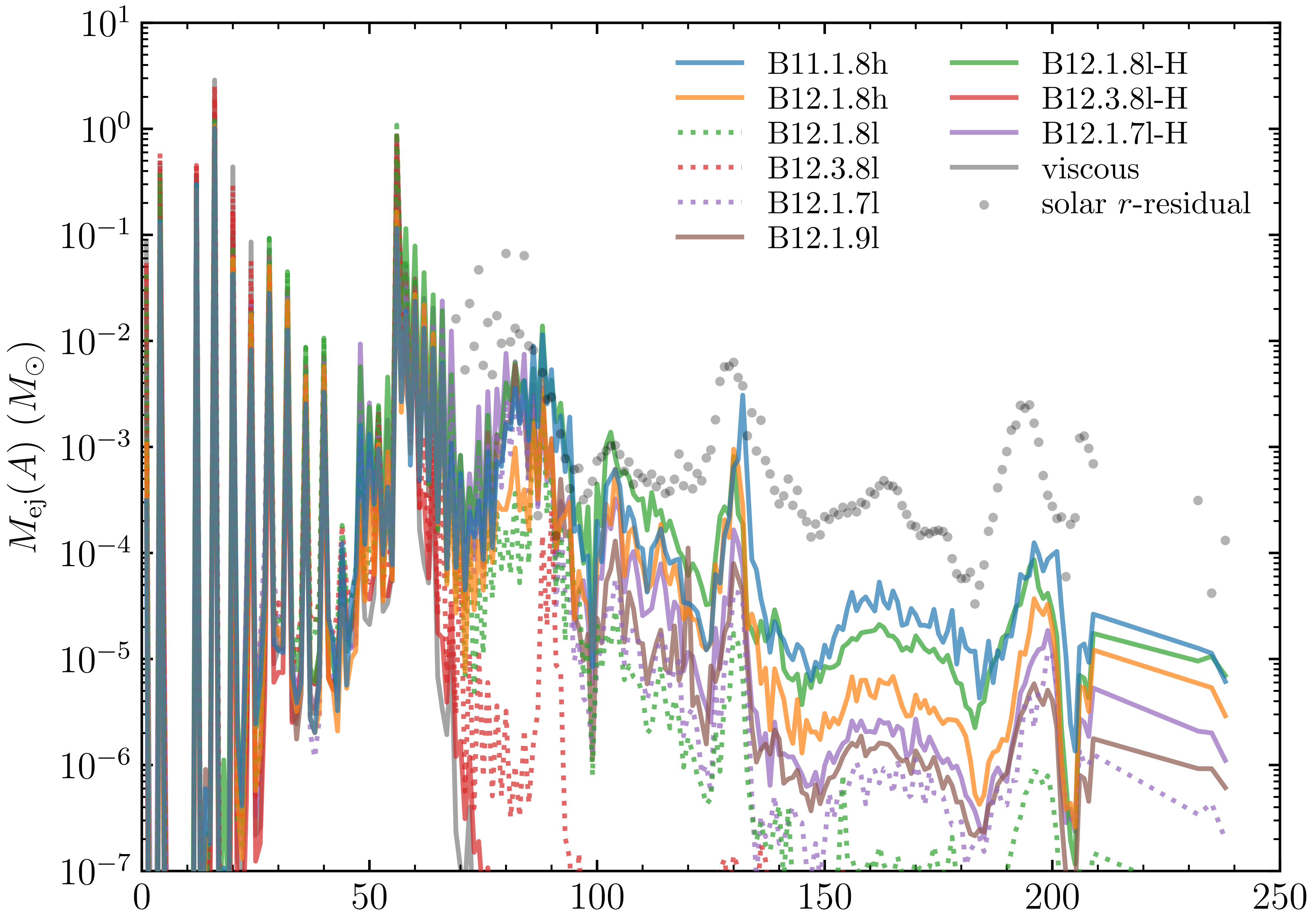


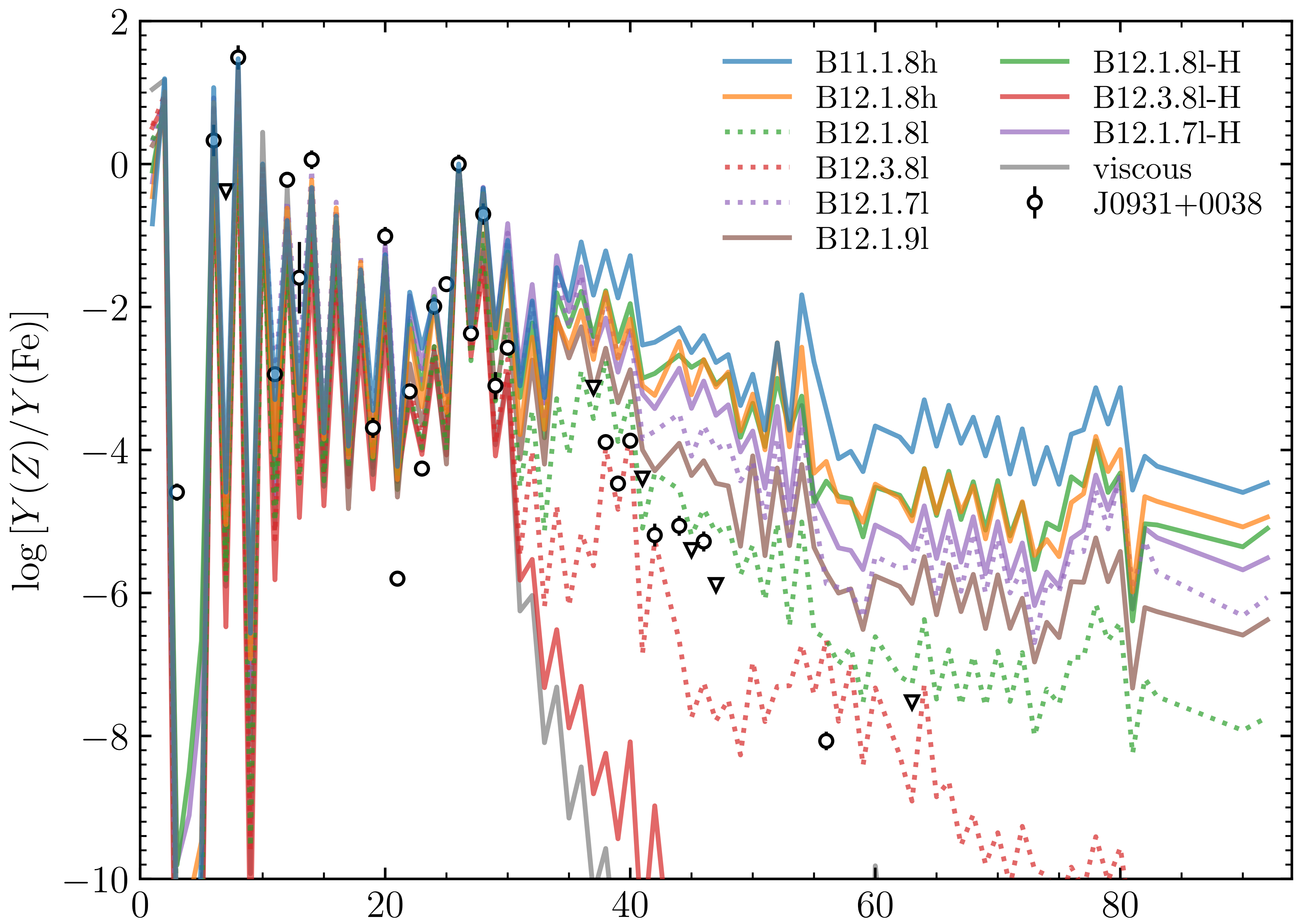
Amplified B-field blows up
a low-Ye (~0.4) component inside
the disk when a jet is launched.
The component has a high entropy.
→ r-process occurs.

Just+2022, Dean-Fernandez 2024

→Saji's poster

Heavy element synthesis





Mass number

Atomic number

- Lighter r-process nuclei are main products.
- Agreement with patterns of some metal-poor stars?

J0931+0038 (Ji+2024)

SMSS J0224−5737 (Okada+2025)

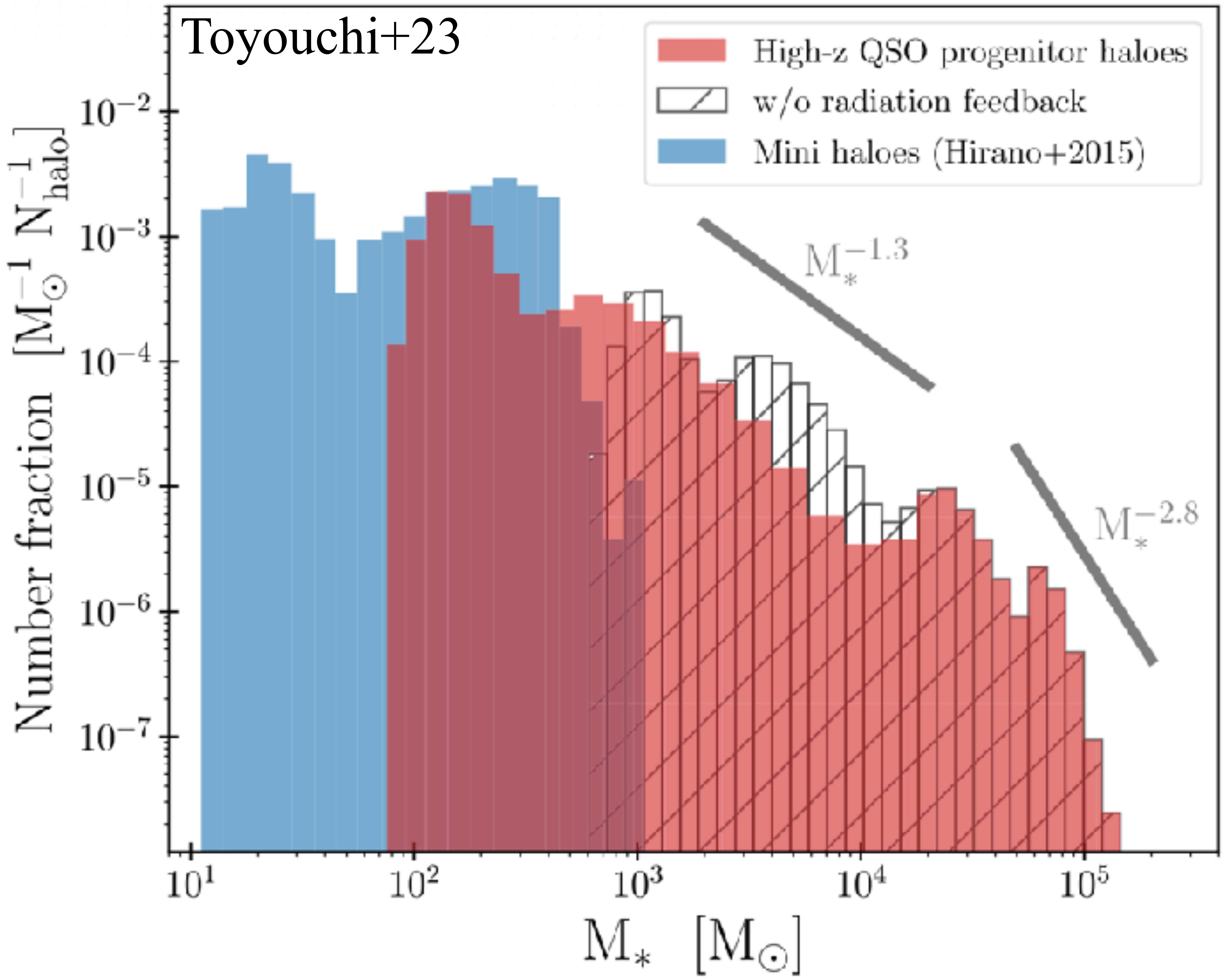
Collapse of Supermassive Stars and Very Massive Stars

Fate of rotating stars with $M \gtrsim 10^3 M_\odot$

Hypothetical object in the early universe (potential seed of high-z SMBH)

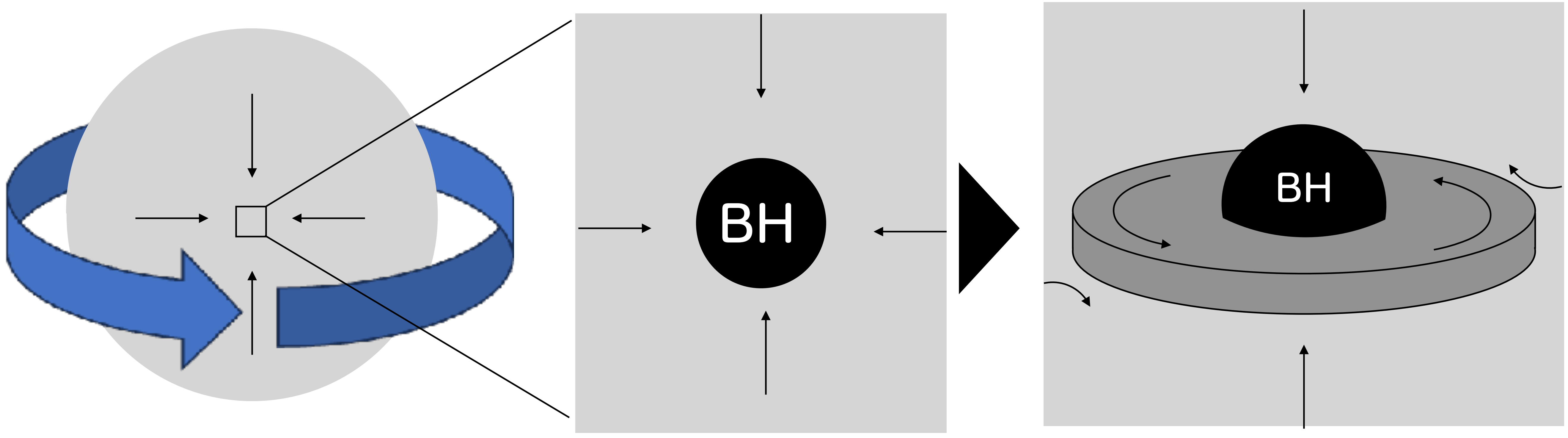
$M \lesssim 10^4 M_\odot$: Very massive star (collapse via pair instability)

$M \gtrsim 10^4 M_\odot$: Supermassive star (collapse via GR instability)

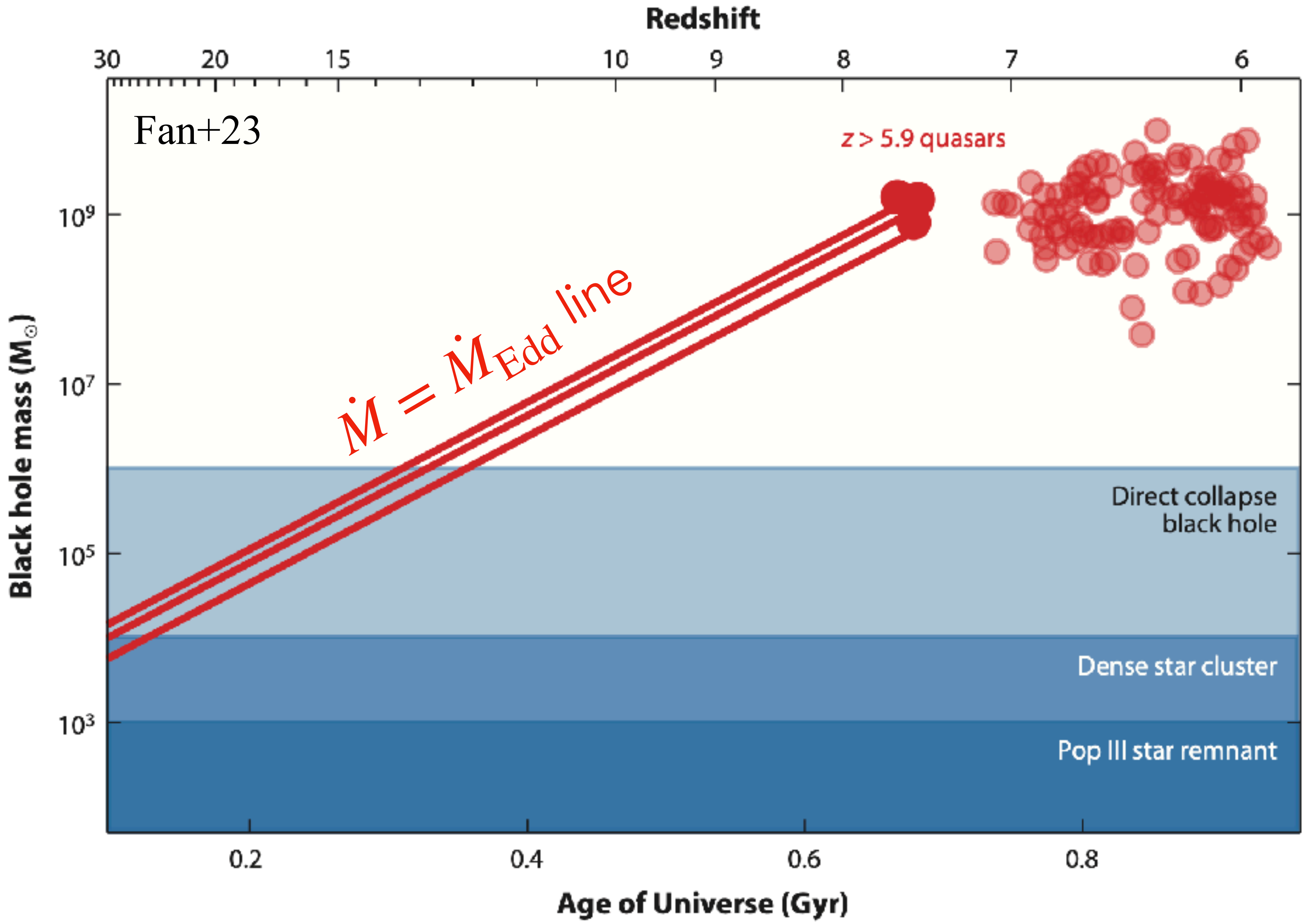


They just leave behind BHs....?

Something non-trivial occurs with rotation.



SMBHs in early universe



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

How are they formed?

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

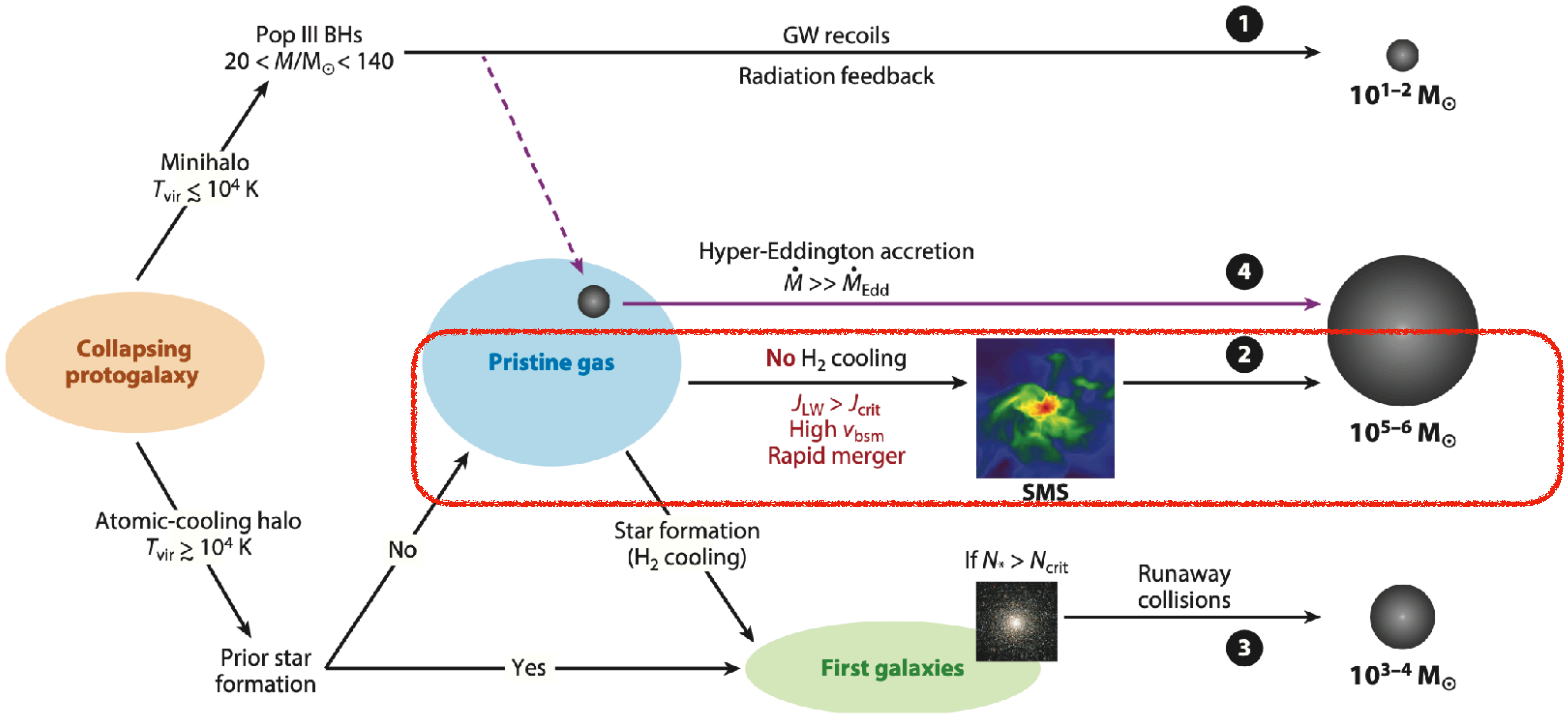
(Super/hyper-Eddington accretion may be possible)

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 SMSs

- By nuclear burning
  (Explosion of entire star)

Chen et al. (2014) : $\sim 5 \times 10^4 M_\odot$ SMS

Nagele et al. (2022) : $\sim 2 \times 10^4 M_\odot$ SMS

(partial explosion by pulsation is also possible)

- Fast rotation→disk bounce→explosion
  (Partial explosion)

Uchida et al. (2017)

I revisited this mechanism with our updated numerical relativity code.

Method: Numerical setup

General relativistic gravity

Hydrodynamics with nuclear reaction

$$\varepsilon = \varepsilon_{\rm int} + \sum_I (m_I - A_I m_{\rm u}) c^2 \frac{X_I}{A_I}$$

Burning → Change in mass excess

→ Increase $\varepsilon_{\rm int}$

Takahashi+2016
Uchida+2017, 2019,
Cheong & Fryer 2025

H →(CNO cycle)→ He →(triple-α)→ C (Only forward reaction)

Equation of state

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

Timmes & Swesty (2000)

Neutrino loss

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

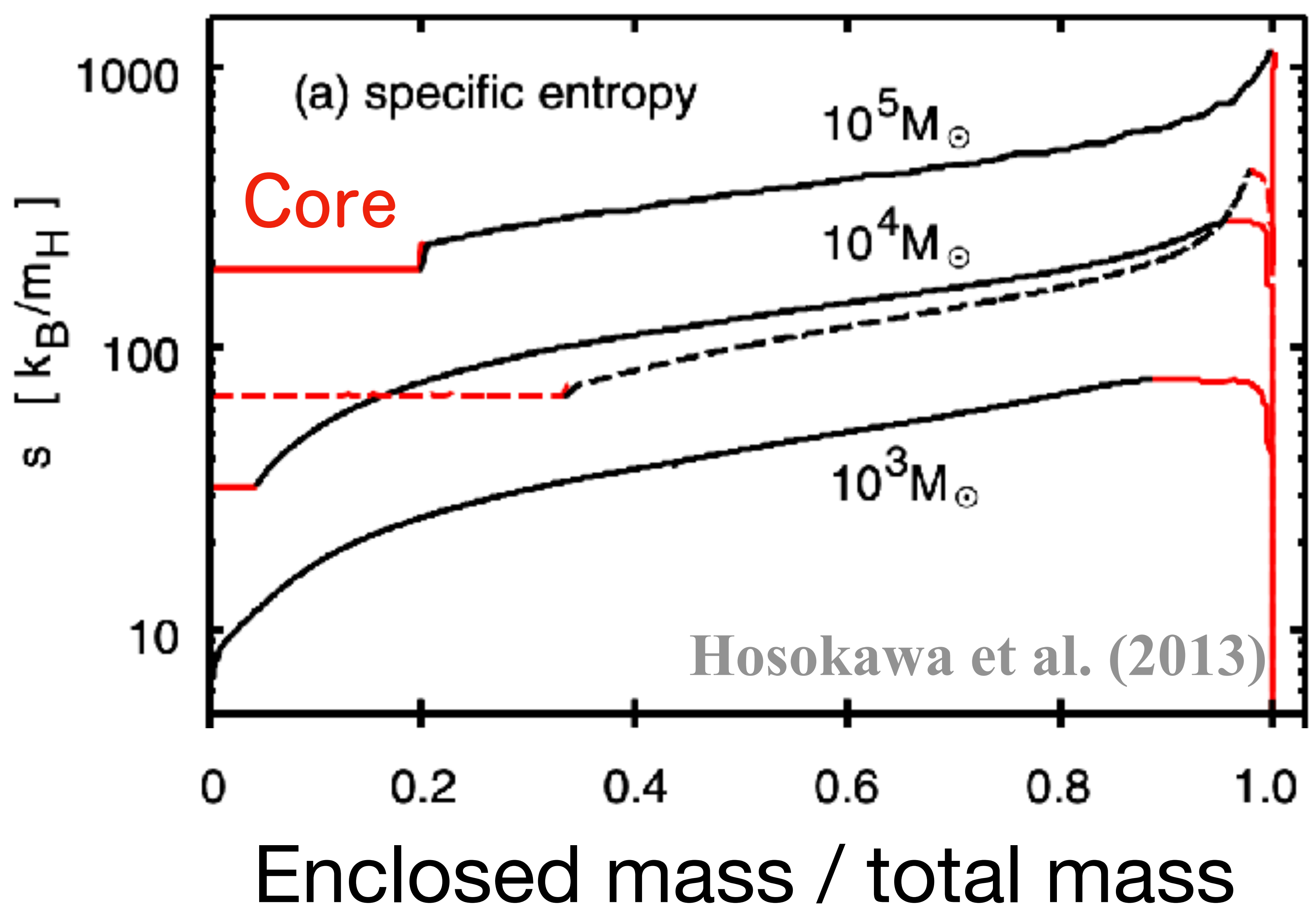
Method: Initial supermassive star models

Marginally stable rotating equilibrium body with n=3 polytrope

Shibata+2016, 2025

Mass at the onset of instability increases with rotation
decreases for evolved star

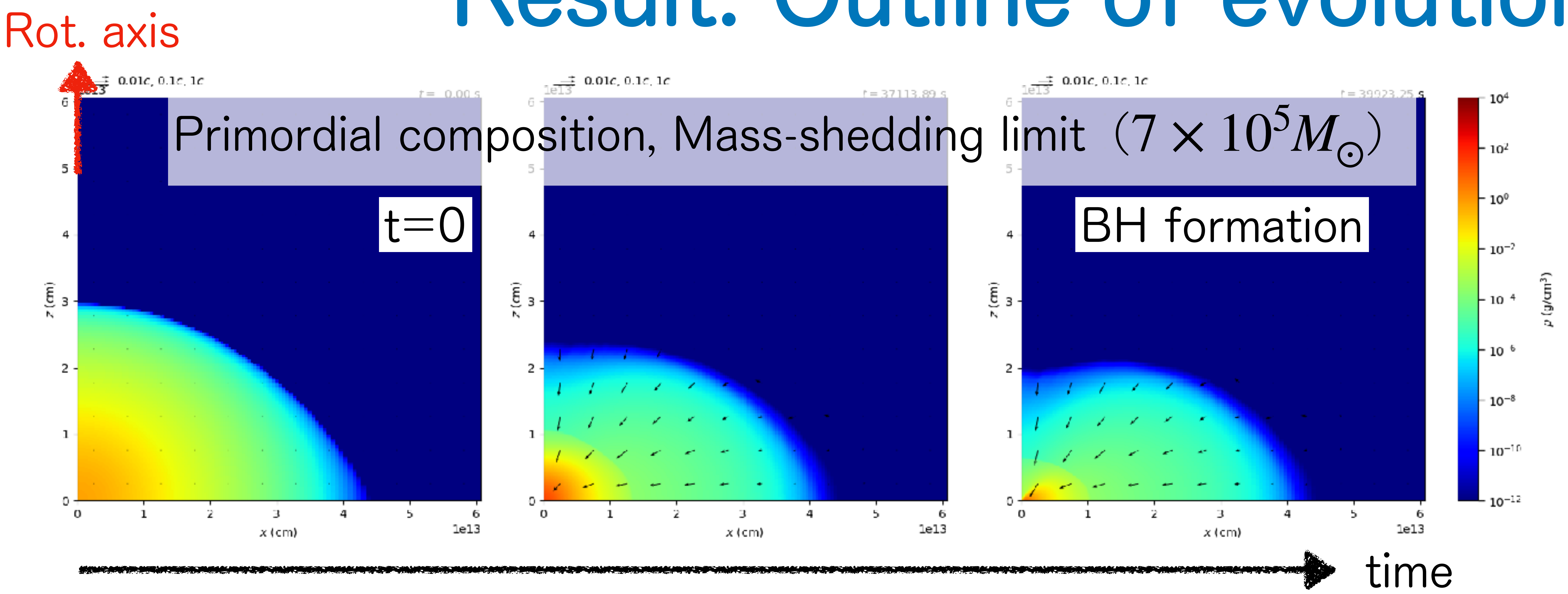
For pristine gas, $M = 2 \times 10^6 M_\odot$ for rigidly rotating mass-shedding star



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

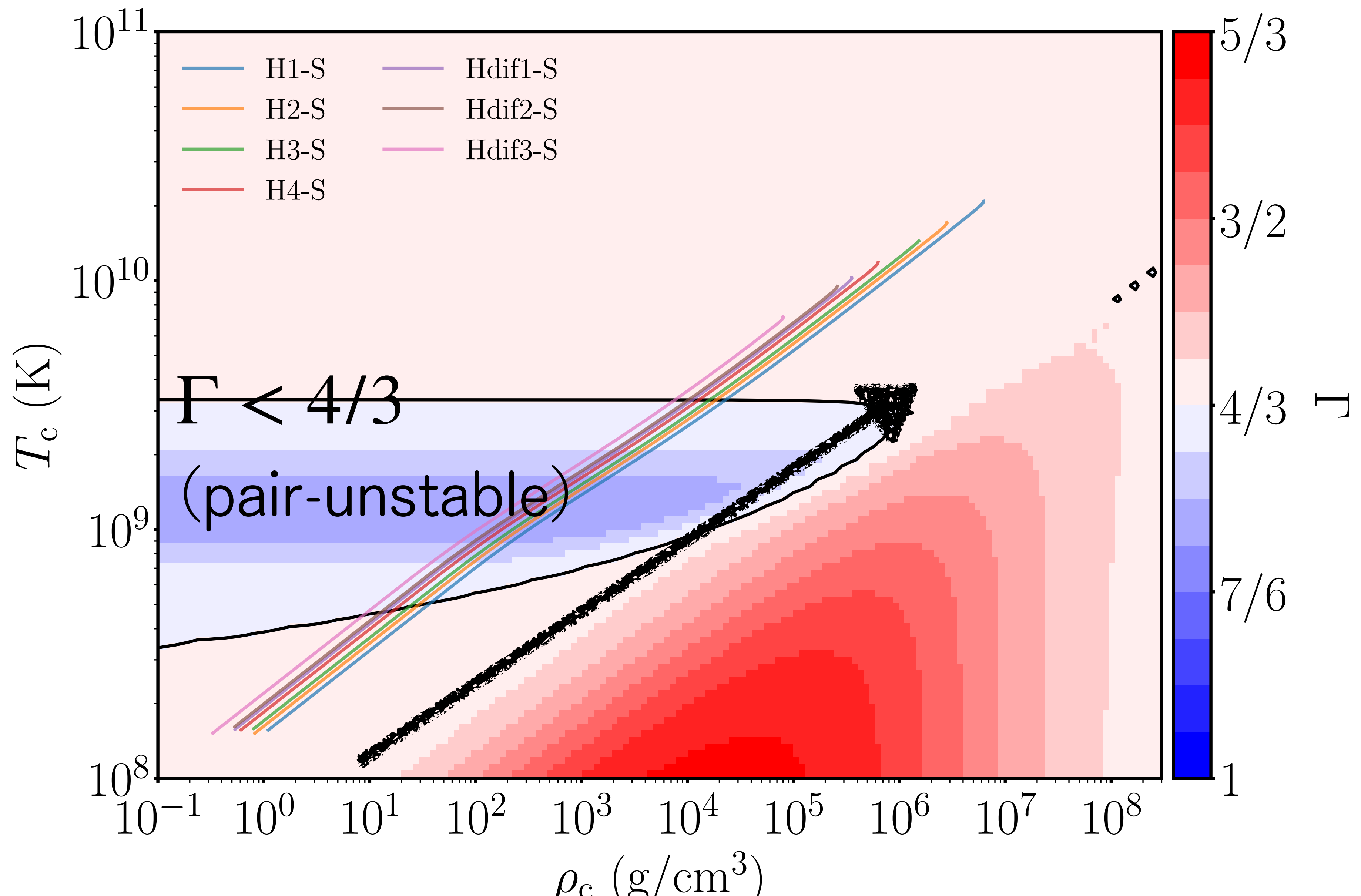
Realistic SMSs have inflated envelope

Result: Outline of evolution



Coherent collapse
(←GR instability)

time

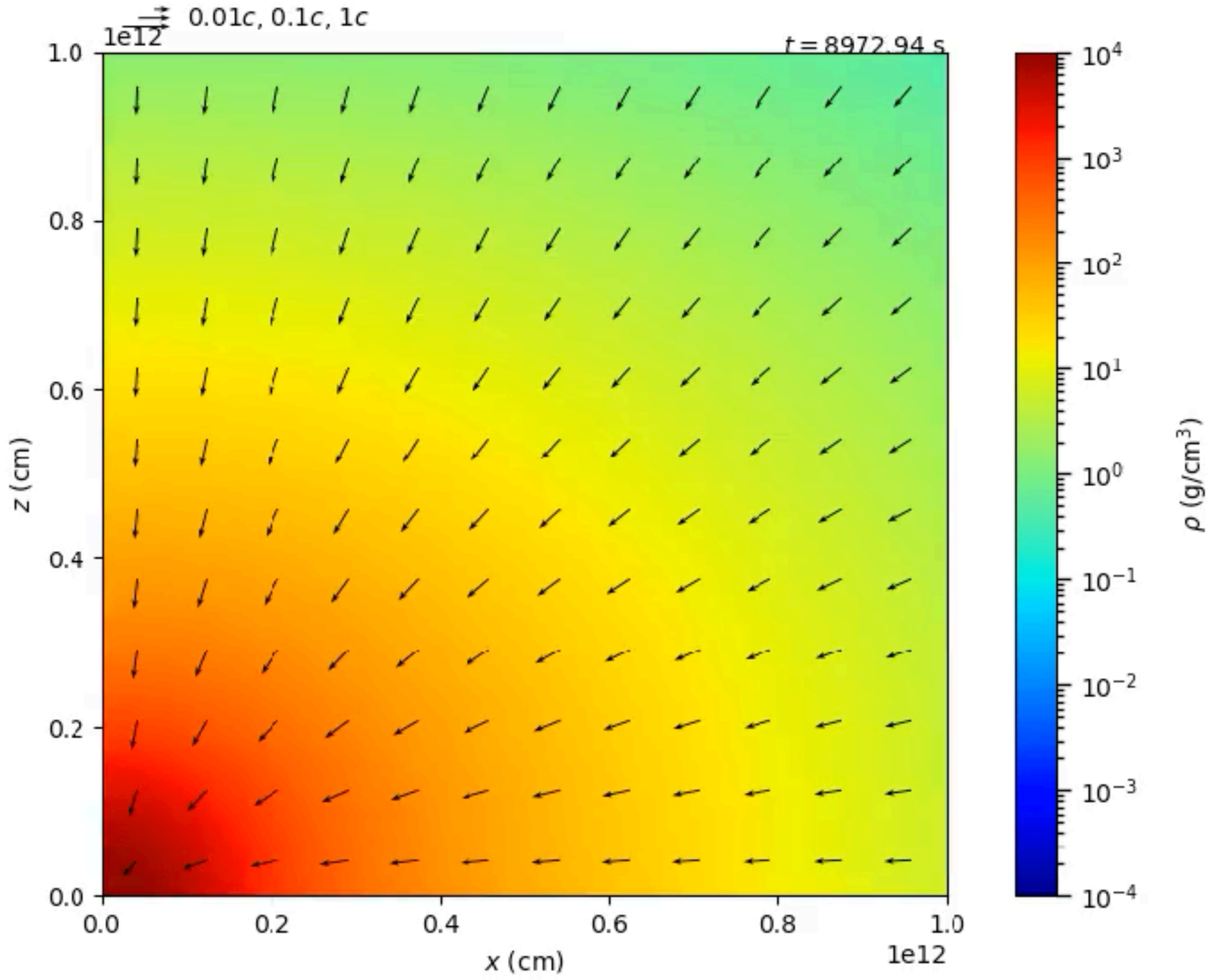


Central density-temperature

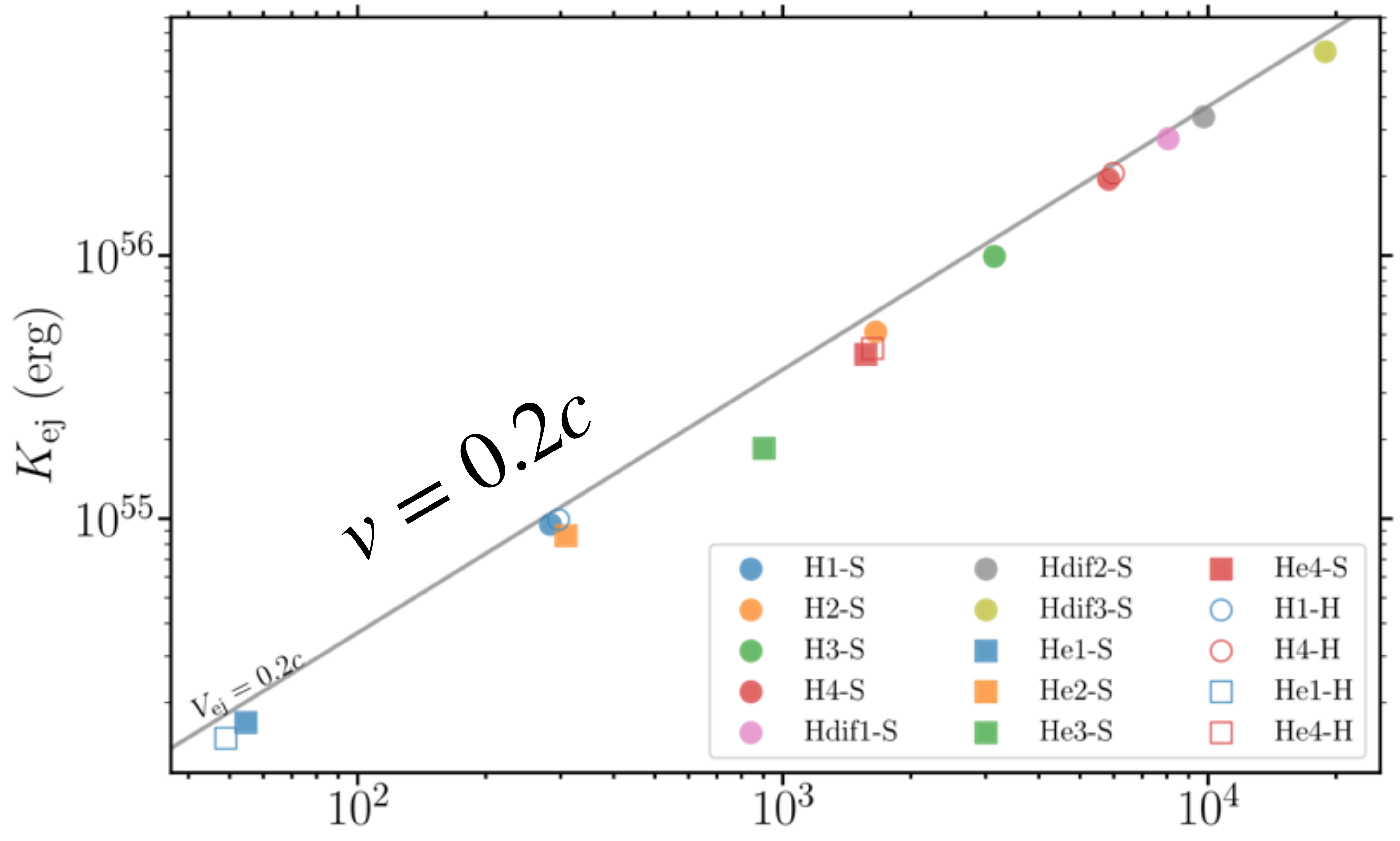
Proceed the collapse outside PI region
(←GR instability)

Explosion mechanism

Sudden formation of a disk induces its bounce
→ Mass ejection



Explosion energy (erg)



Ejecta mass ($M_\odot$)

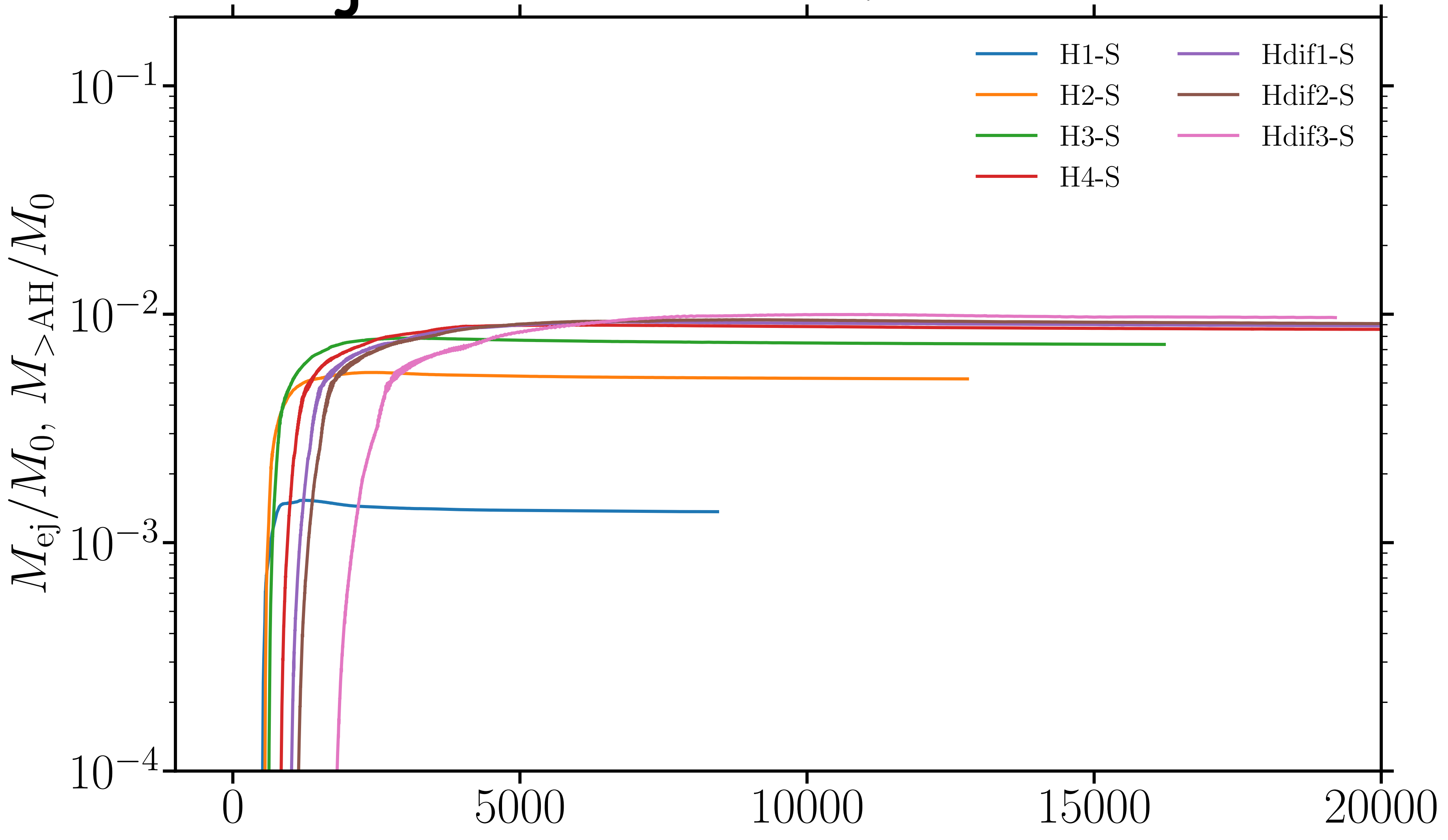
Ejecta mass and energy scales with core mass

$$M_{ej} \approx 10^{-2} M,\ K_{ej} \approx 10^{-4} M c^2 \ \rightarrow v = 0.2c$$

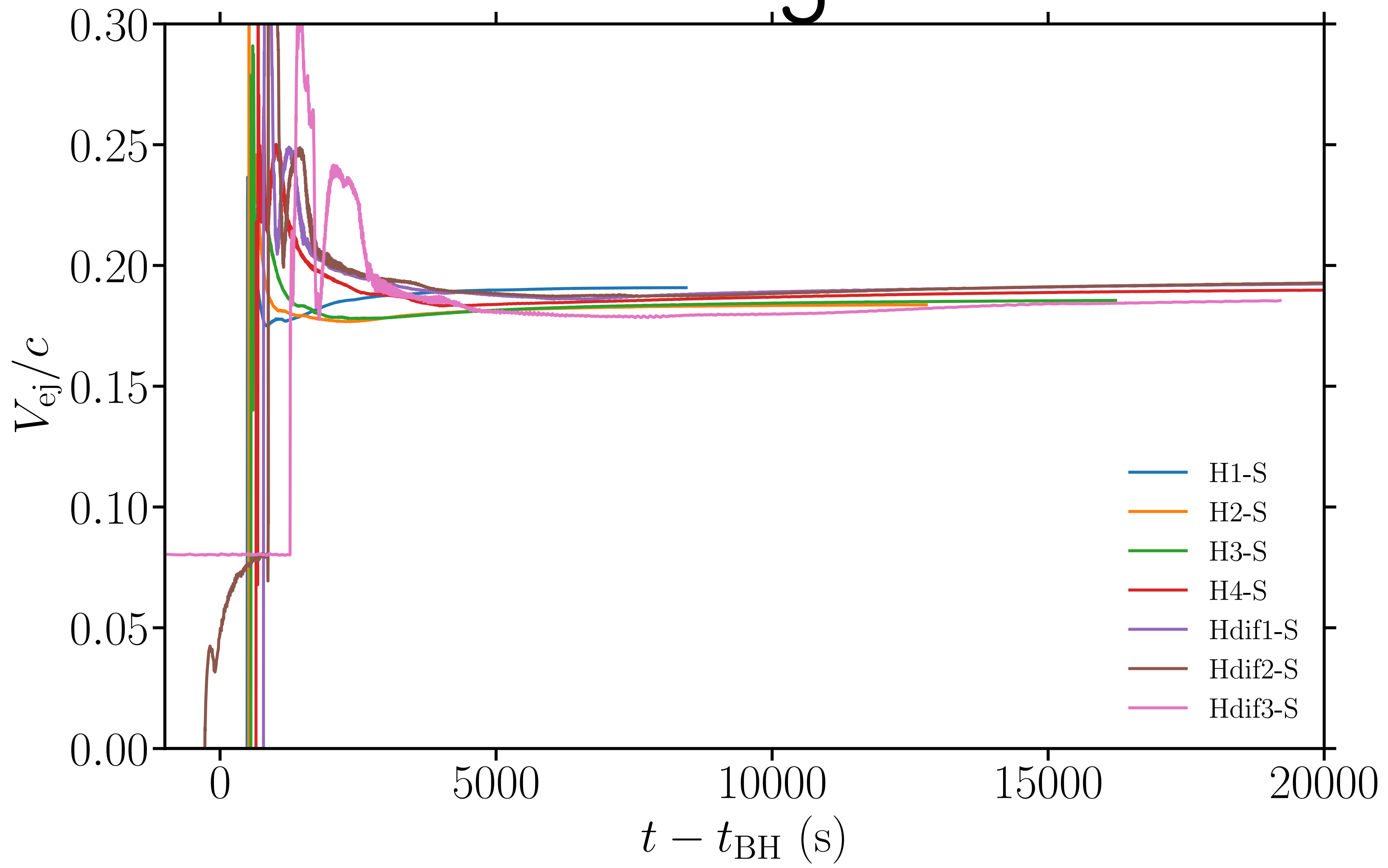
Similar escape velocity of the disk (at ~ ISCO)
& Similar core structure (n=3polytrope)
& GR instability (coherent collapse)

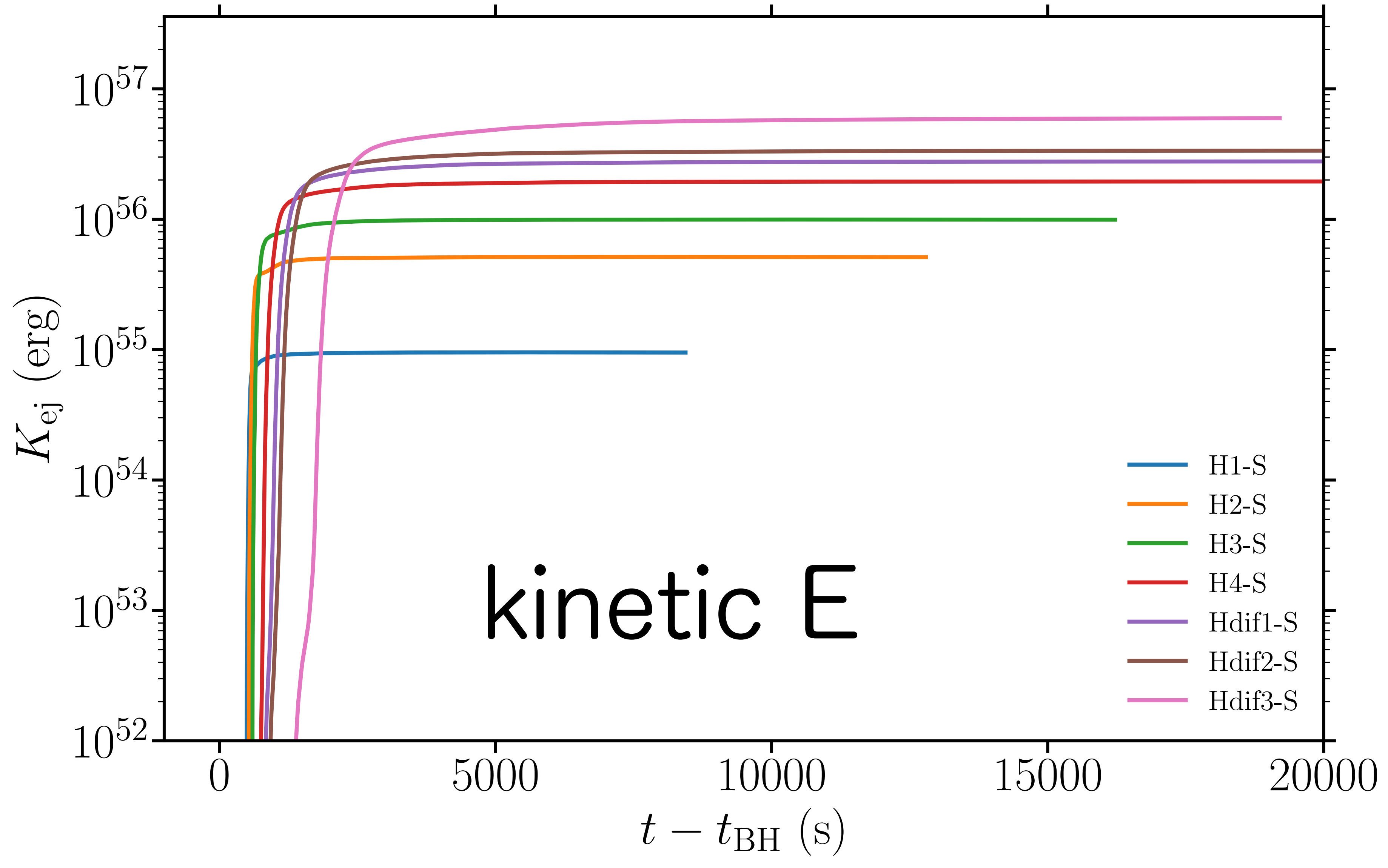
Result: Properties of ejecta

ejecta mass / Total mass

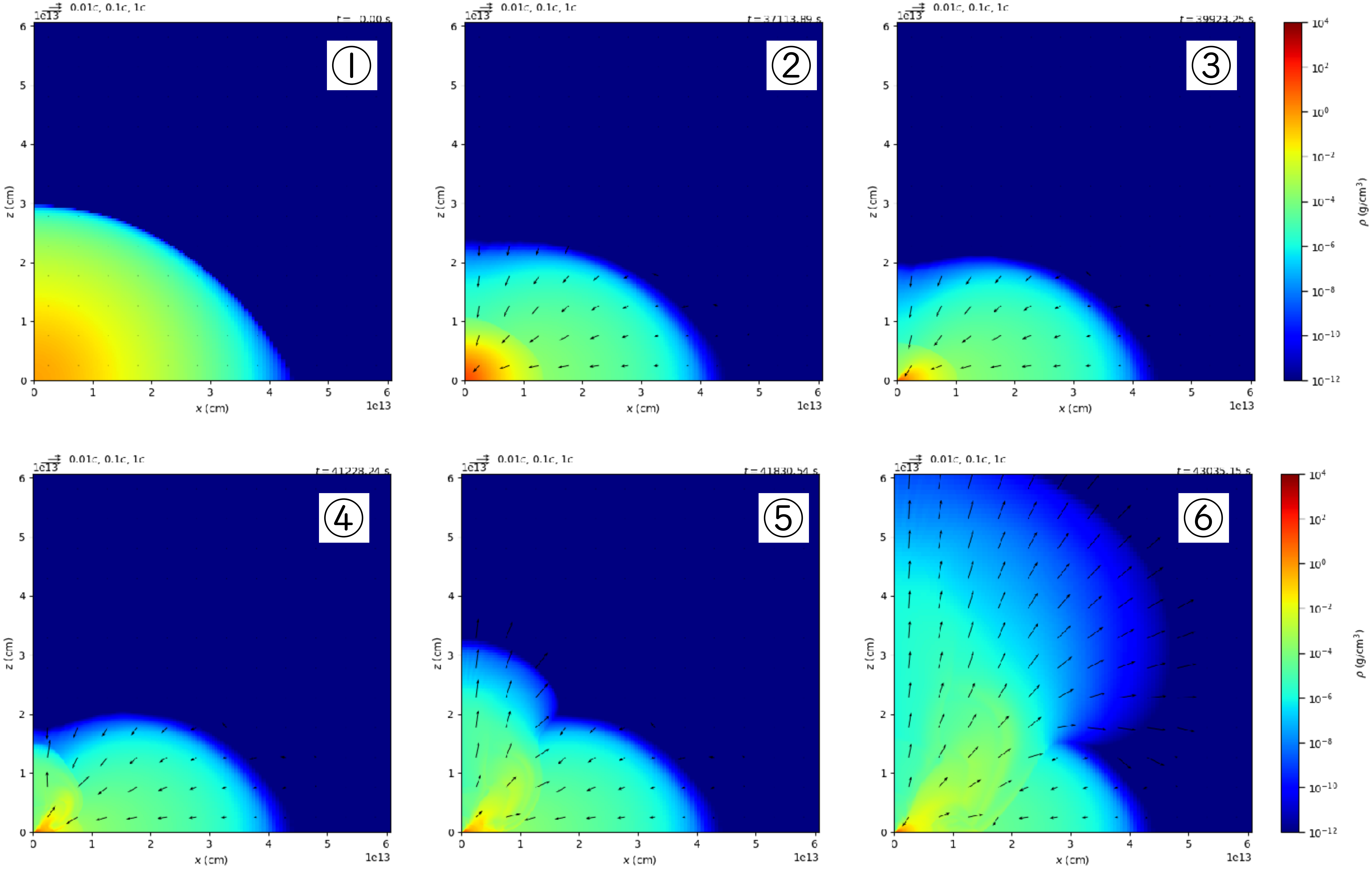


Average V





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



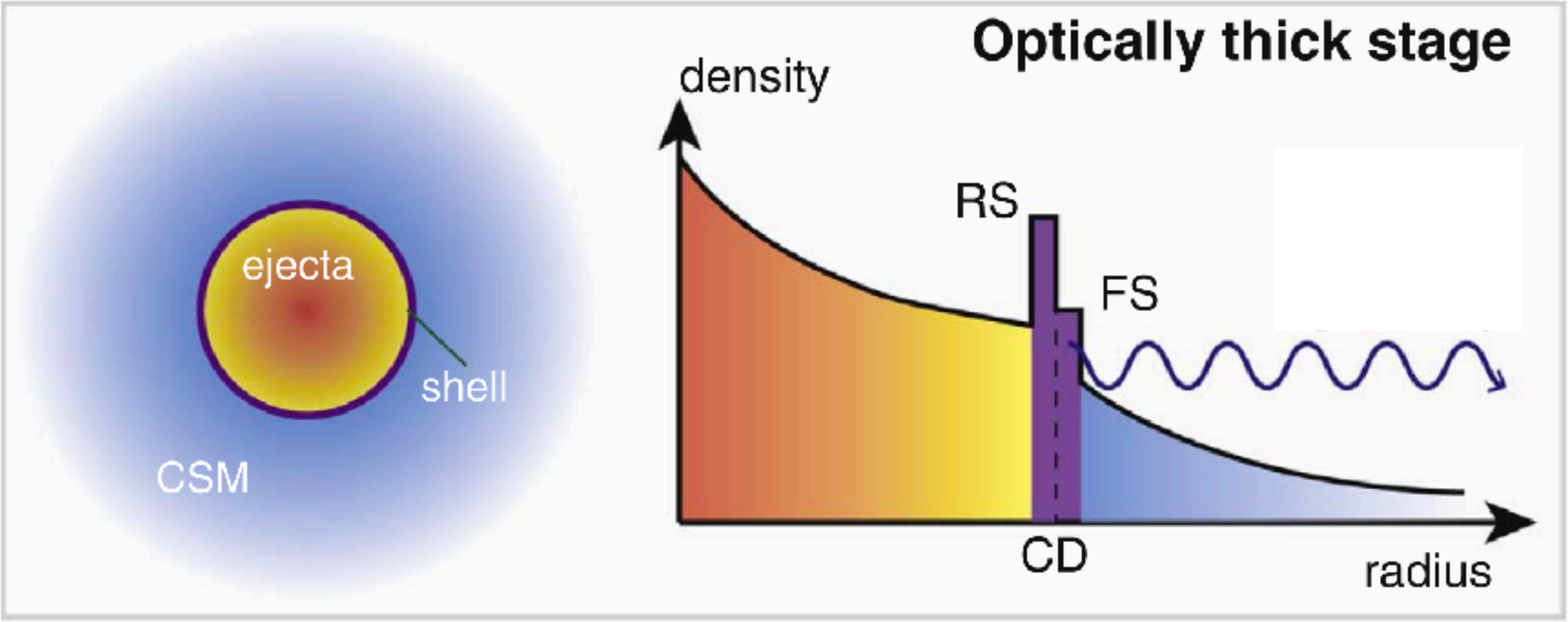
0.01c, 0.1c, 1c
1e13
t = 0.00 s
t = 37113.89 s
t = 39923.25 s
t = 41228.24 s
t = 41830.54 s
t = 43035.15 s
①
②
③
④
⑤
⑥
z (cm)
x (cm)
1e13
ρ (g/cm³)

Observational properties

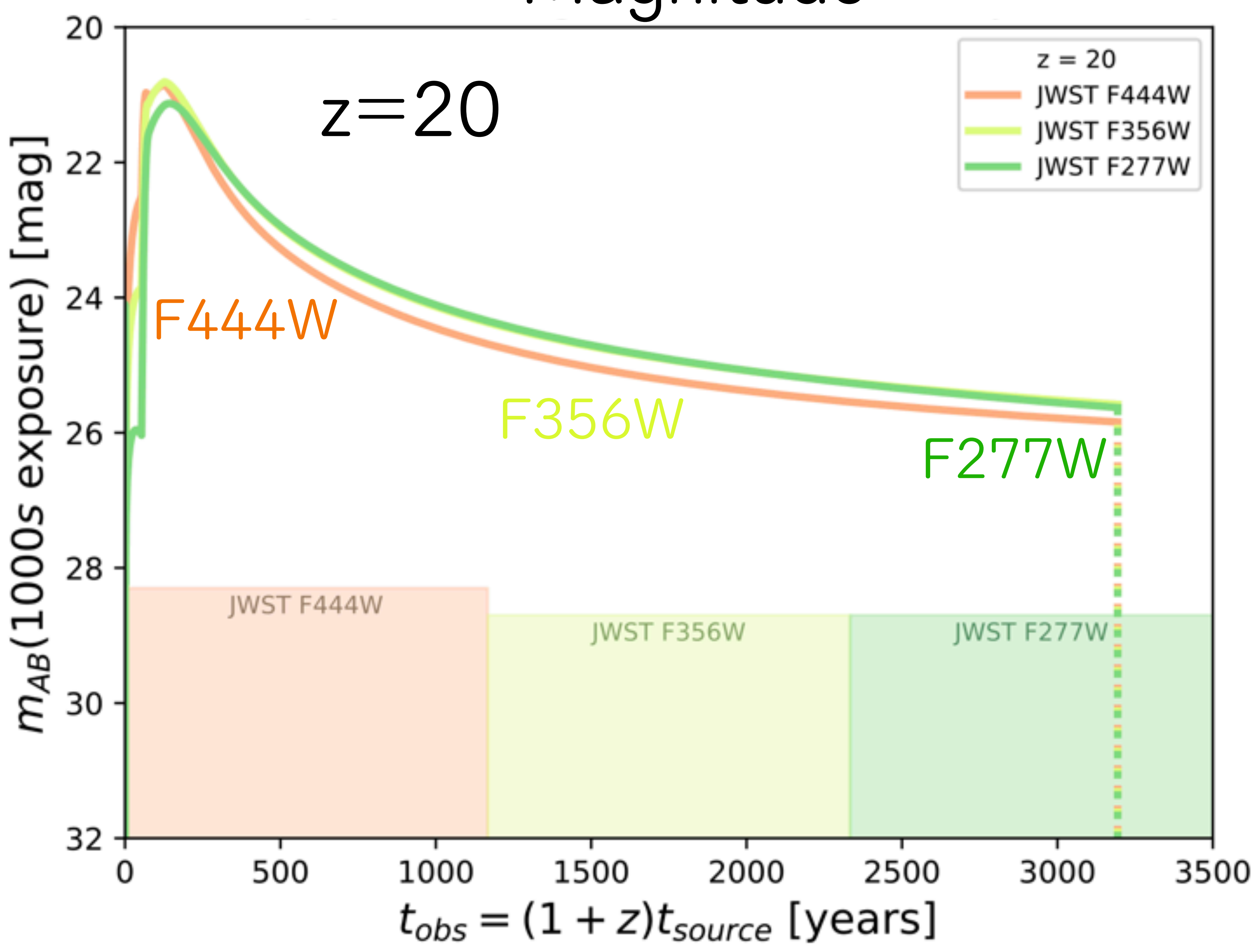
Jockel, Kawaguchi, SF, Shibata (2026)

Realistic picture

taken from Suzuki+2019



Magnitude

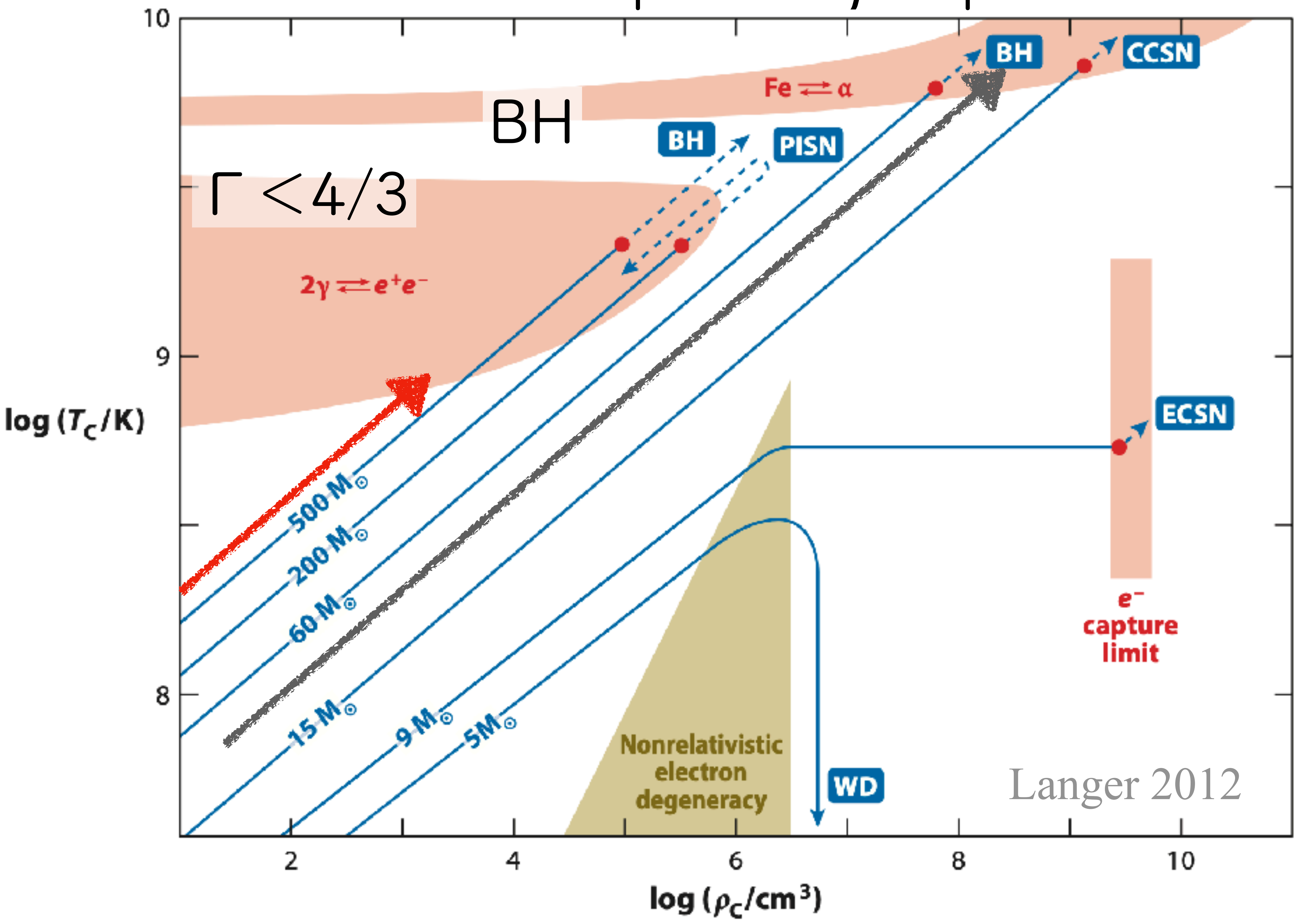


Most bright cases ($E_{\rm exp} \sim 10^{56}$erg) can be observed at z=20 (if found).

~10 yr timescale at **source frame.** → ~(1+z)10 yr for us.
→ Will be observed as nearly persistent "transients" Jockel's talk (4th week)

Very massive stars

Evolutional paths in ρ-T plane



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

→ Iron core → Collapse

✓ $M_{\rm ZAMS} \gtrsim 130M_\odot$ (Very massive star; VMS)

→ e^-e^+ production → Collapse

$M_{\rm ZAMS} \gtrsim 260M_\odot$ → BH formation

✓ $M_{\rm ZAMS} \gtrsim 10^4 M_\odot$ (Supermassive star; SMS)

→GR instability → Collapse

→(Direct) BH formation

They can be formed under low-metallicity environment such as early universe.

Method: Numerical setup

SF+ in prep.

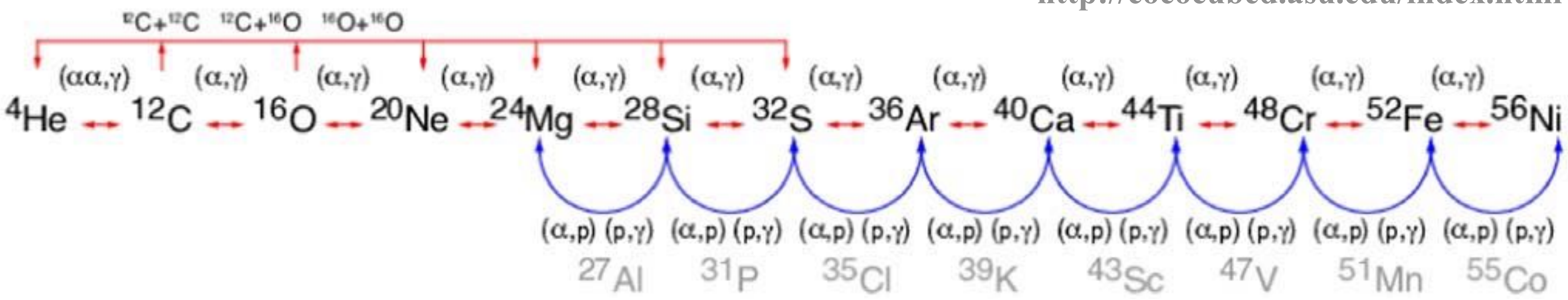
General relativistic gravity

Hydrodynamics with nuclear reaction

Higher density and temperature
→ More microphysics come into play.

http://cococubed.asu.edu/index.html

α-chain network



Equation of state

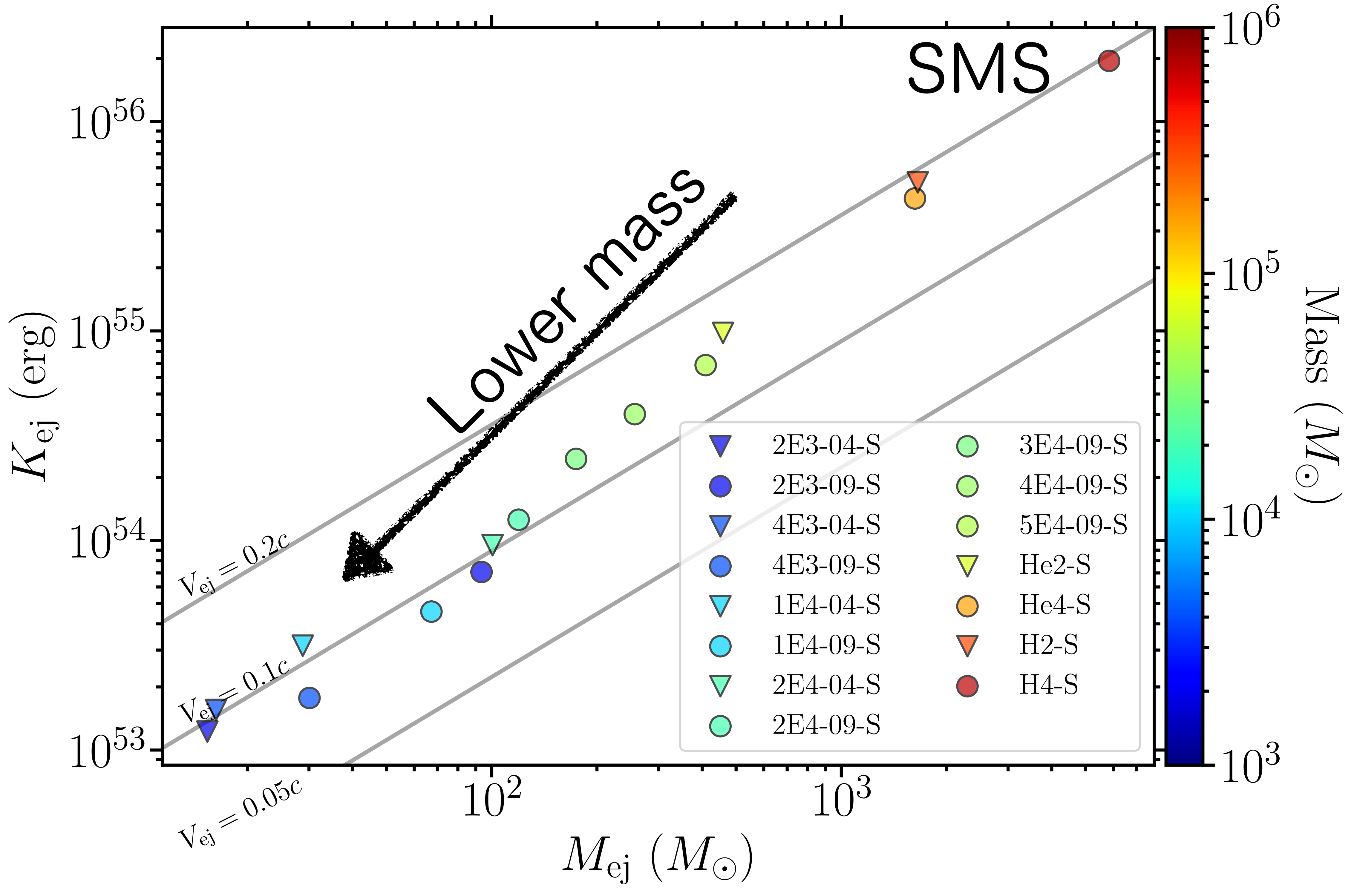
Composite of ions, photons, electrons and positrons

Timmes & Swesty (2000)

(optically thin) Neutrino loss

Pair-process (pair, plasma, photo neutrinos) Itoh+1996

Explosion properties



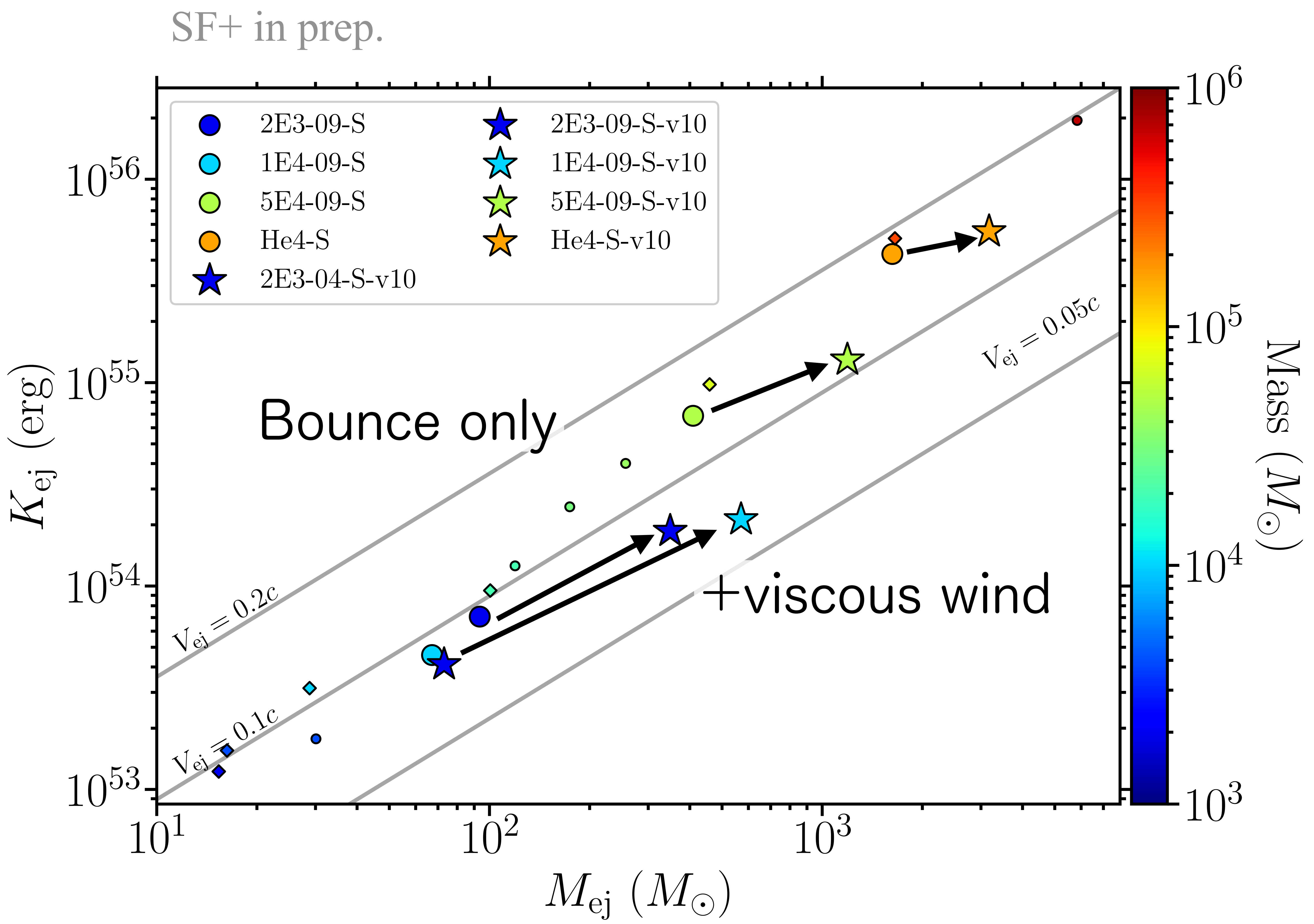
Lighter mass→smaller velocity

Less compact (smaller M/R),
or, more inflated at the collapse onset.

Have more angular momentum for a given rotation.
Initial BH-disk is small
→ Energy attained by the bounce becomes smaller compared with the total binding energy

For ~100Msun stars, no explosion by bounce → "collapsar" in canonical gravitational collapse

Viscous evolution



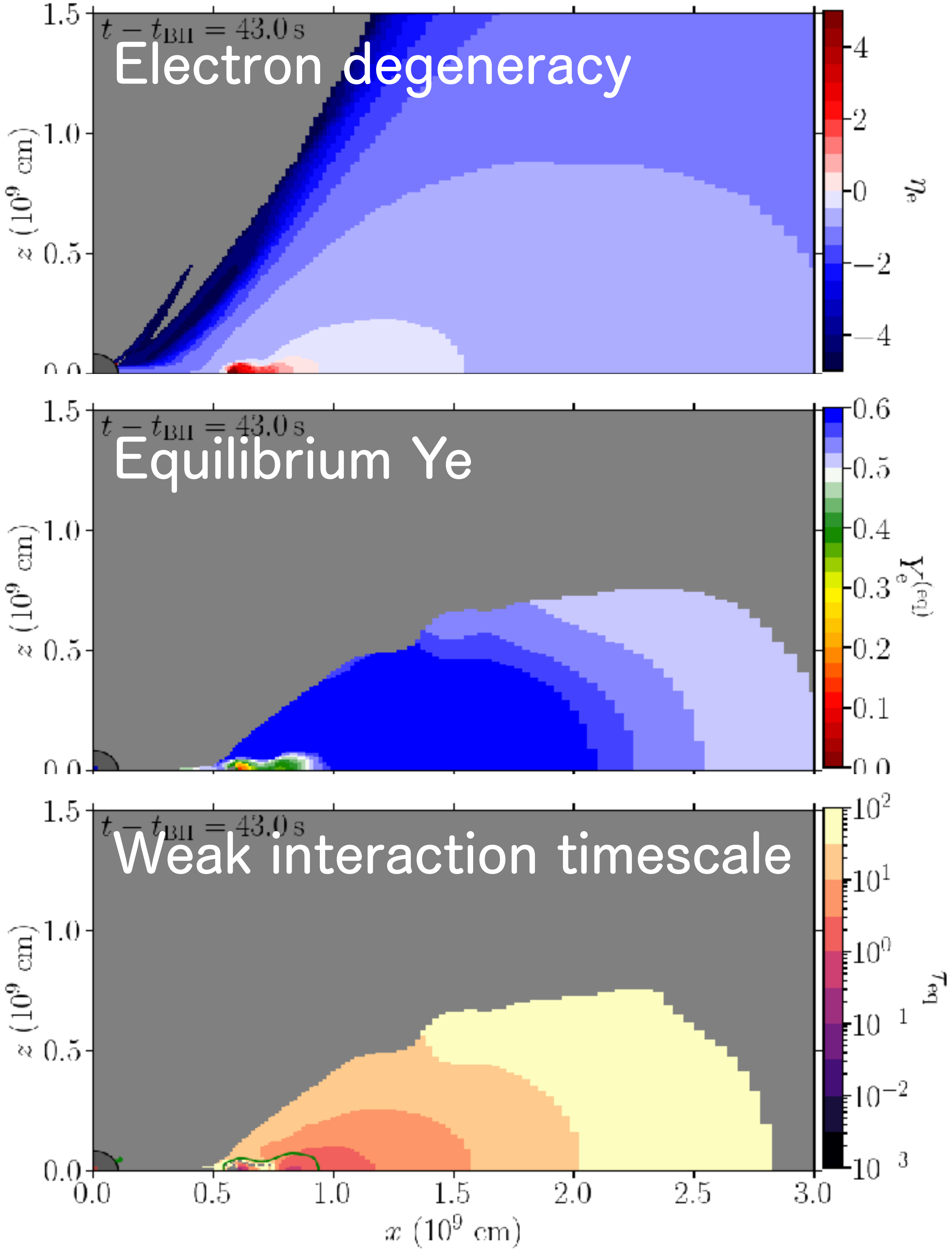
Lower mass (still $10^3 - 10^4 M_\odot$ though) :

Larger viscosity-driven ejecta

Less compact (smaller M/R),
or, more inflated
at the collapse onset.

Have more angular momentum.
More matter can form disks.

Possible neutronization



For $M_{\rm core} \sim 10^3 M_\odot$, electron degeneracy in the formed disk becomes high enough for deleptonizing.

Ye at emission equilibrium $(\dot{n}_{\rm ec} = \dot{n}_{\rm pc})$ becomes < 0.4

Timescale to achieve equilibrium:
~1 sec < Viscous time (~10 s) → Neutronization can work

The high-density part is swallowed by BH
→ low-Ye domain vanishes in 10 s.
(systematic study needed)

→Agarwal's talk

→Hernández-Morales's poster

Summary

Collapse of ...

- Usual massive star with rotation
  - Outflow from BH-disk by viscous heating
  - MHD+dynamo: BZ-driven jet
  - Ejecta properties in agreement with SNe Ic-BL
- Supermassive star (GR unstable)
  - Bounce after disk formation → Explosion
  - Long-lasting, very bright "transient" in early universe
- Very massive star (pair unstable)
  - Ejecta is less energetic
  - More investigation is necessary →**Lam's talk**