Collapse of rotating massive stars

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in collaboration with
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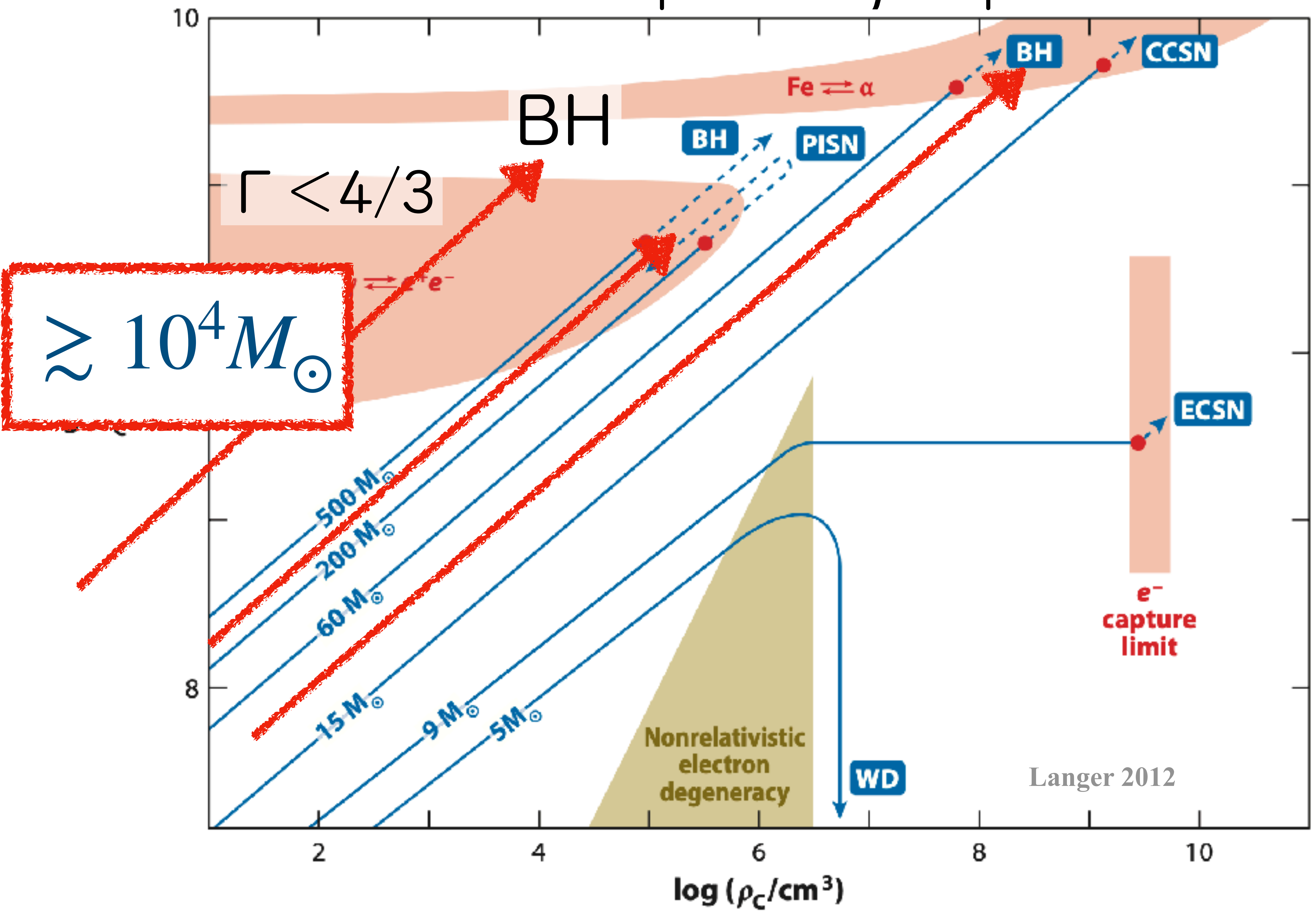
FRIS

Fate of massive stars

Evolutional paths in ρ-T plane



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

→ Iron core formation→Gravitational collapse

→ Core-collapse SNe (possible BH formation)

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

→ Unstable by $e^- e^+$ production

→ Pair instability SN

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

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

→ Collapse by GR instability

→BH formation

Fate of massive stars … with rotation

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

→ Iron core formation→Gravitational collapse

→ Core-collapse SNe (possible BH formation)

- Rapidly rotating NS (with B-field)
- Spinning BH with accretion disk

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→ Unstable by e^-e^+ production

→ Pair instability SN

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

- Change PISN explosion feature?
- Spinning BH with accretion disk

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

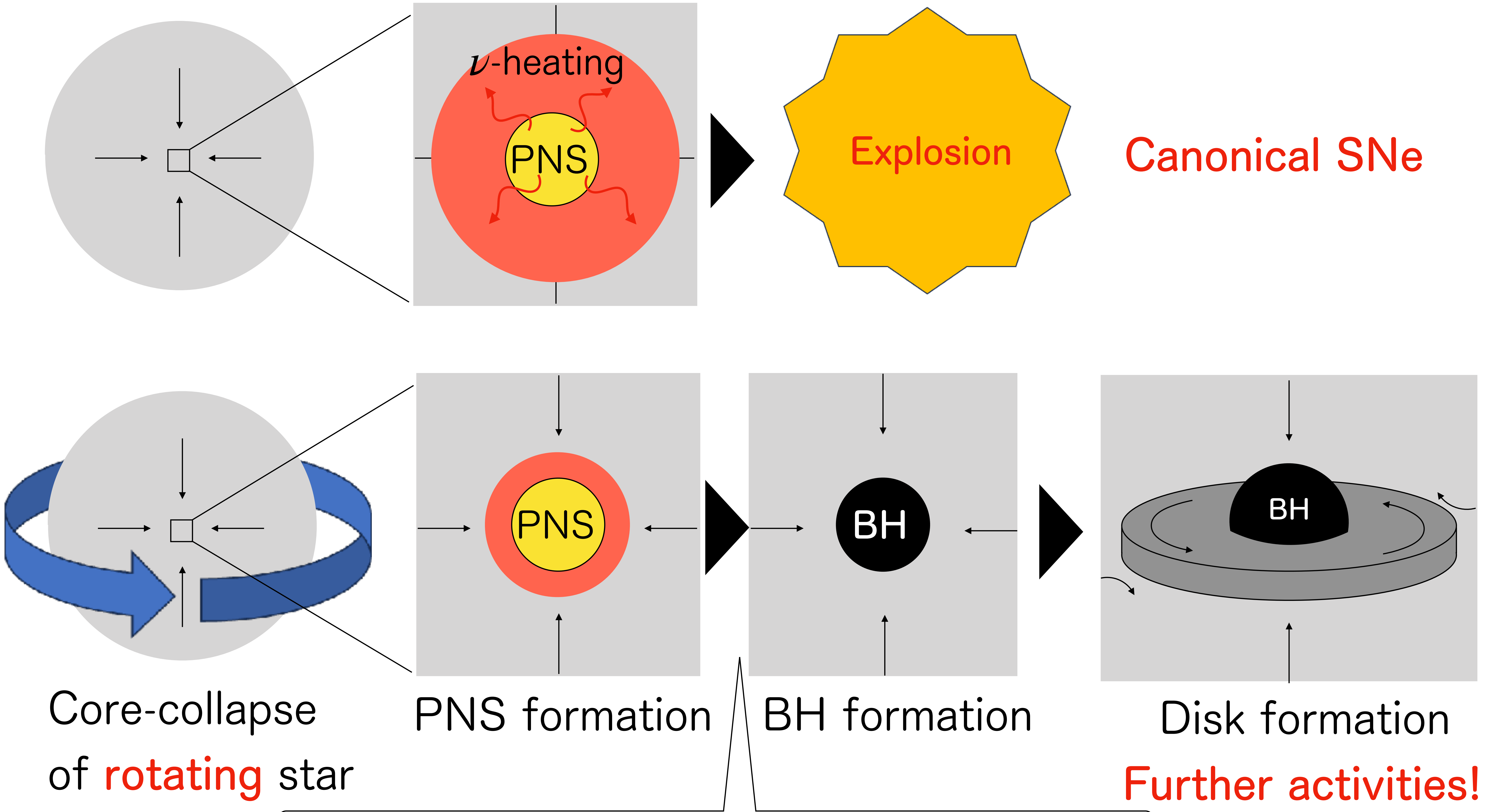
→ Collapse by GR instability

→BH formation

- Spinning BH with accretion disk

Usual massive star: $M \sim 10 M_\odot$

Collapsar



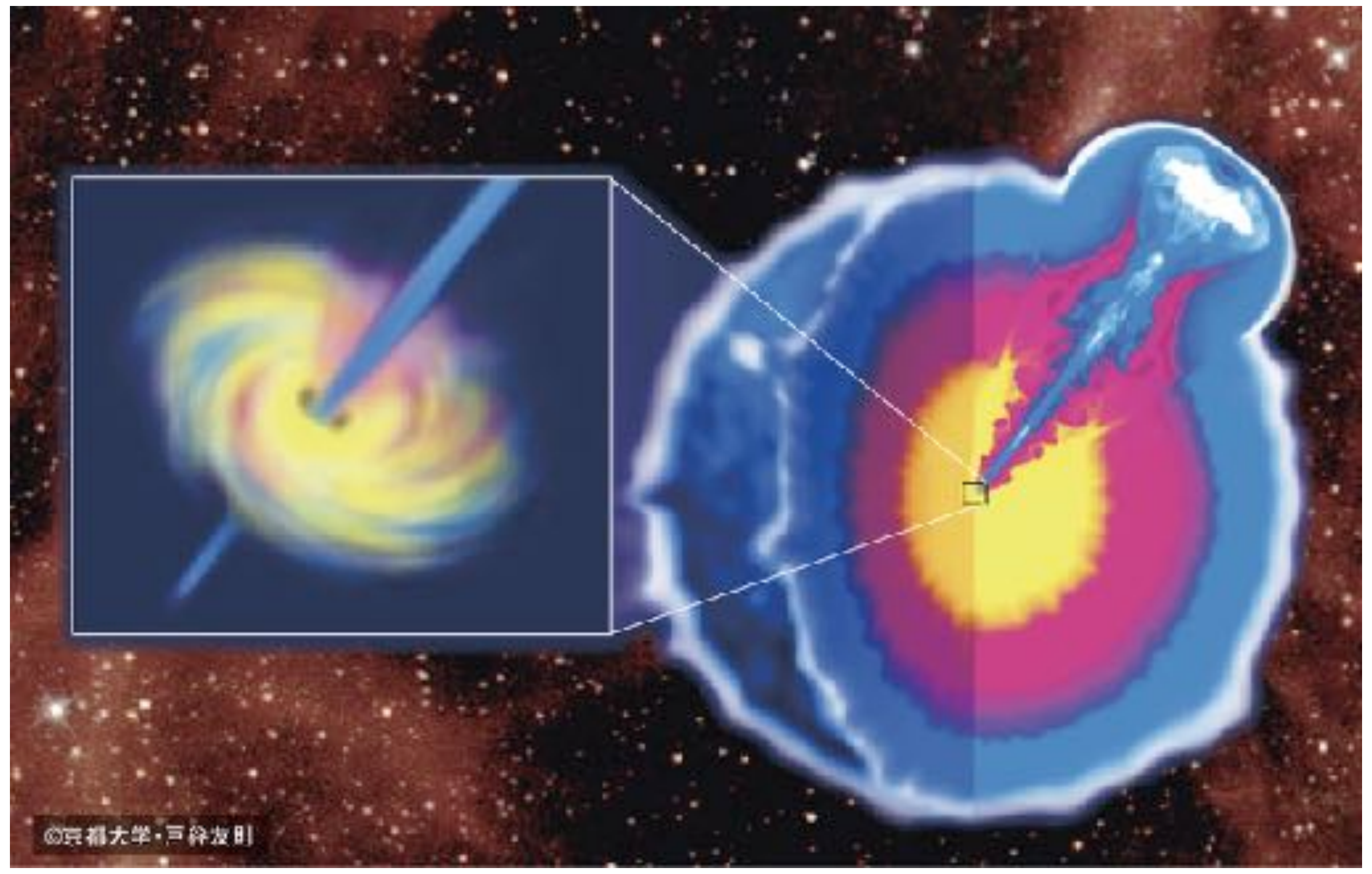
Explosion during PNS phase fails

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

Possible BH-disk activities

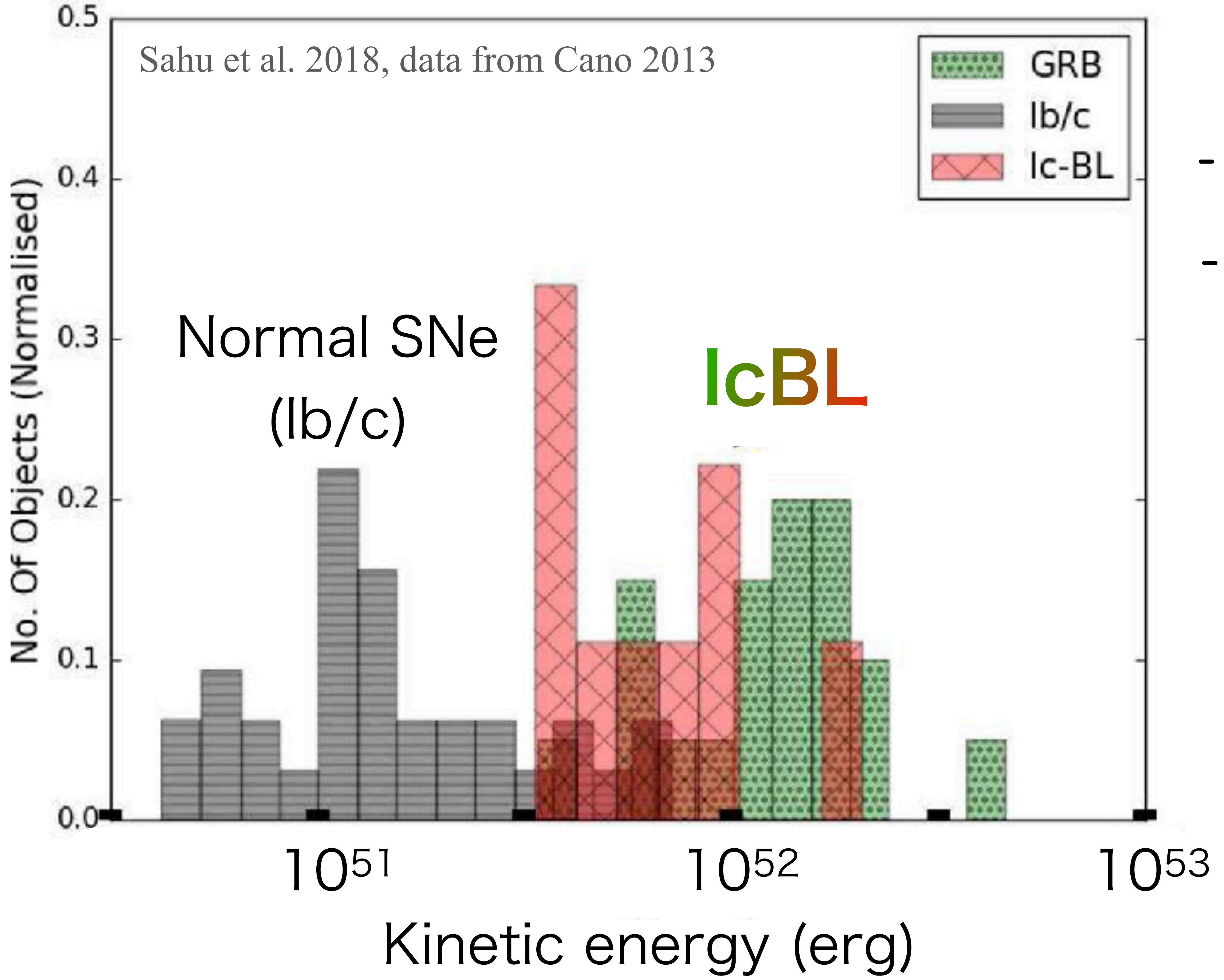
Gamma-ray bursts (GRBs)

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



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

A high-energy class of supernovae



- Explosion (kinetic) energy: ~10 times higher than normal SNe
- ^{56}Ni mass : larger than normal SNe

They are sometimes associated with long-GRBs
Something to do with BH-disk activity.

BH-disk activities and GRB-SN

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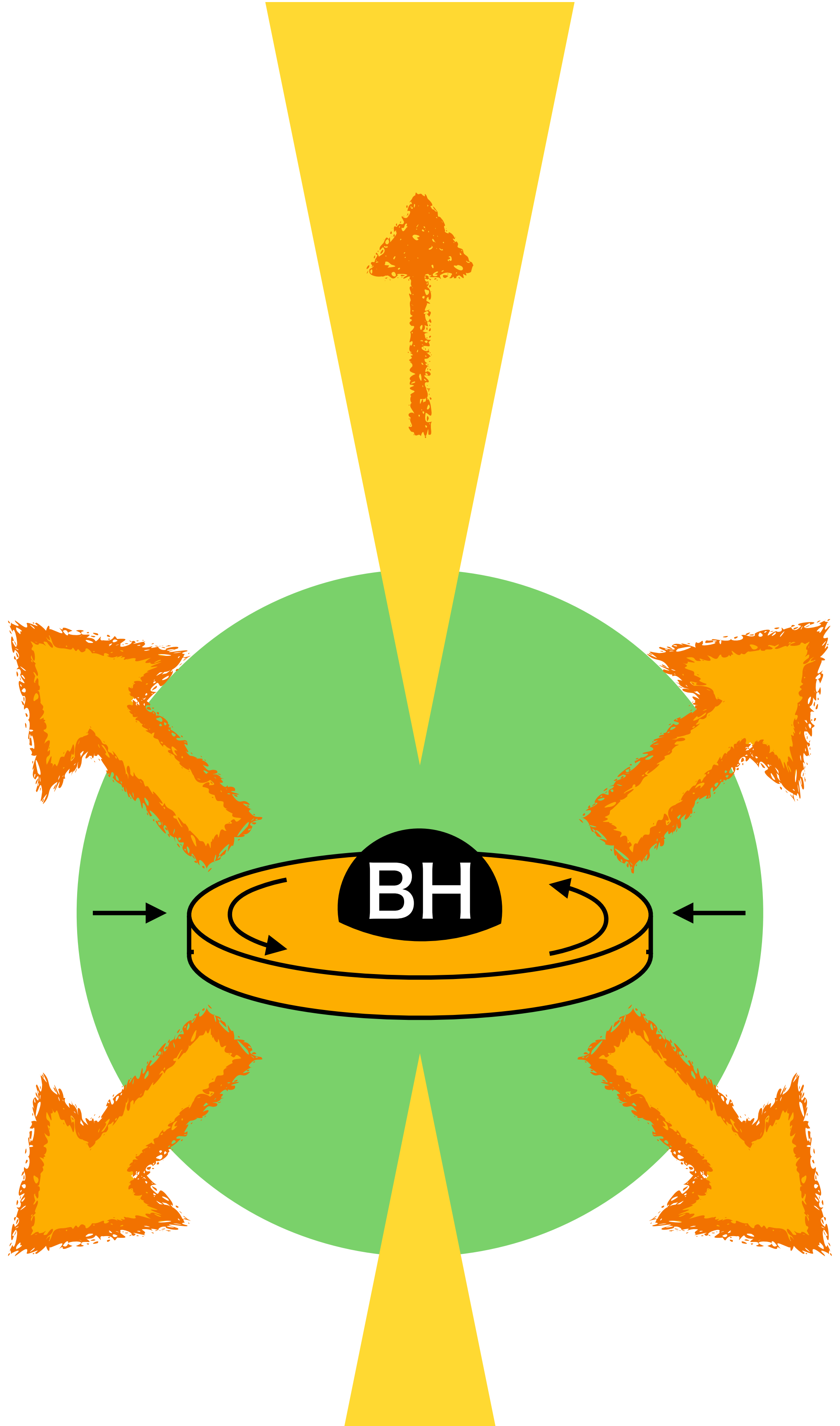
Disk outflow

(MacFadyen & Woosley 1999)

Energy generated by viscous accretion:

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

Viscosity-driven outflow from disk would naturally explain such SNe



MHD modeling of collapsar

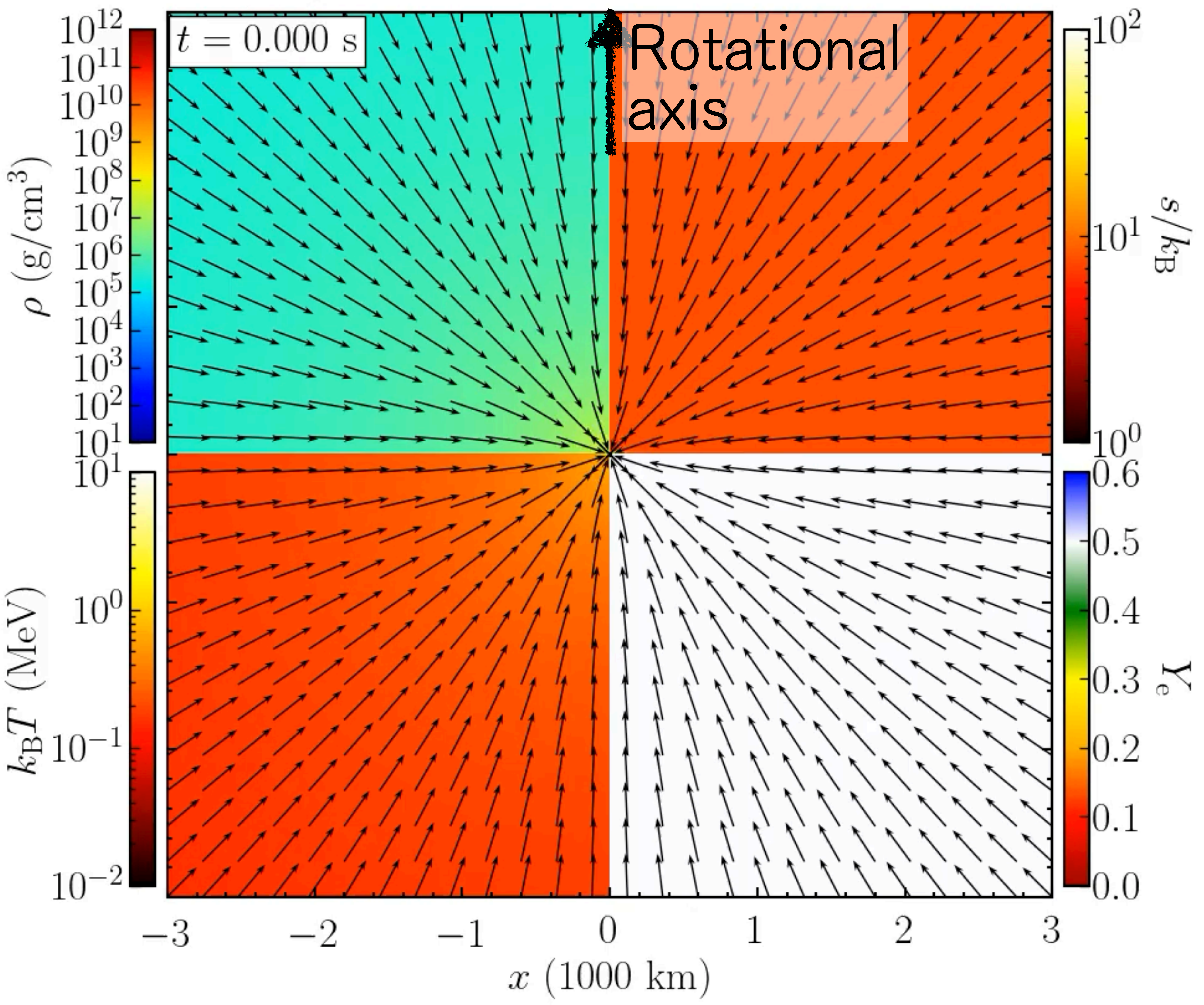
Shibata, SF+2025

2D-axisymmetric simulation with solving

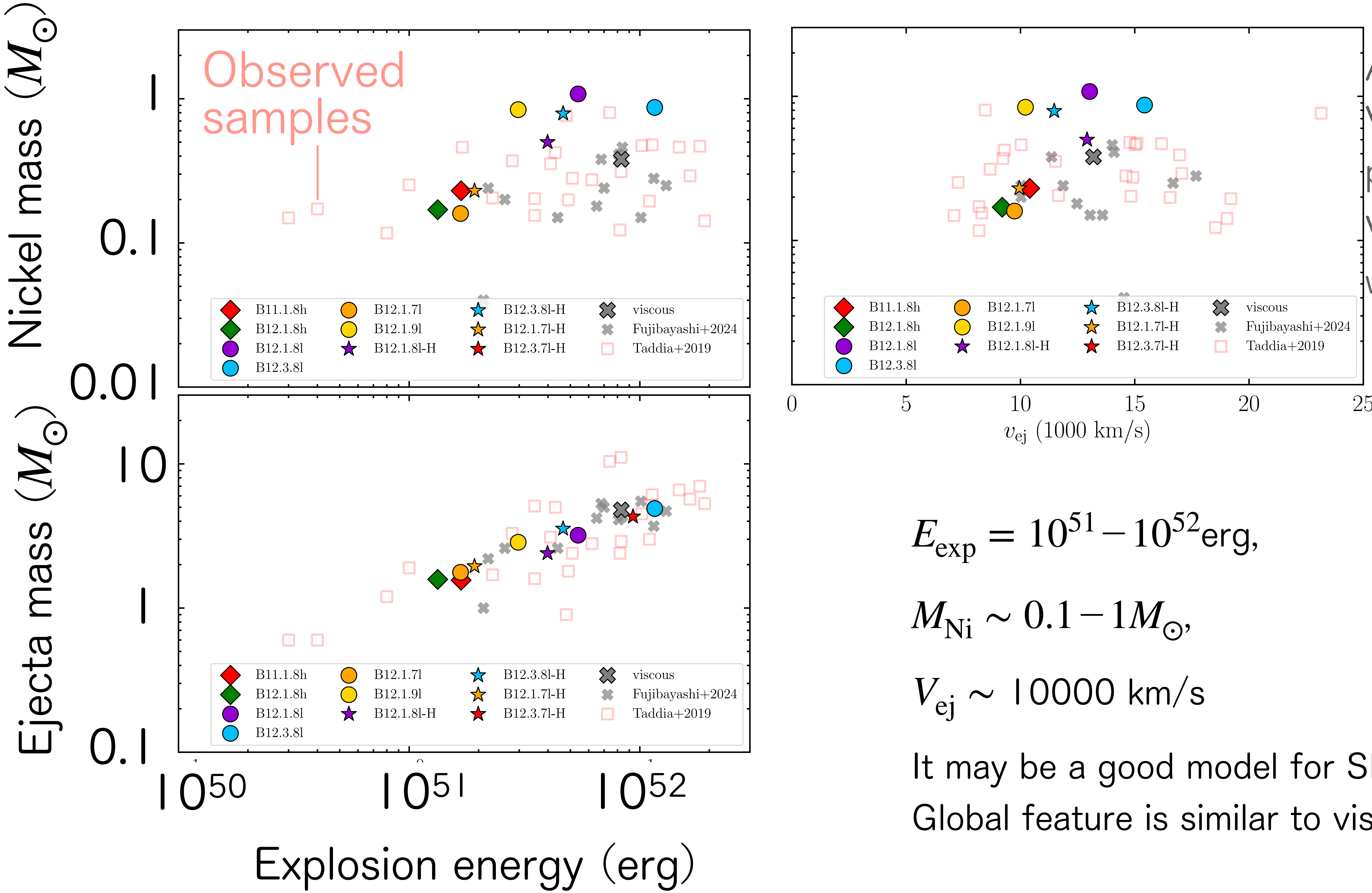
- ✓ Einstein's equation
- ✓ Neutrino radiation transfer equation
- ✓ Magneto-hydrodynamics equation

→BZ-driven Jet
+Spherical wind components

$M_{\rm ZAMS} = 35 M_\odot$ star, starting from toroidal field



Observables



All 35Msun models

Variation is made by parameters and resolution

Viscous models shown with grey color.

$E_{exp} = 10^{51} - 10^{52}$erg,

$M_{Ni} \sim 0.1 - 1 M_\odot$,

$V_{ej} \sim 10000$ km/s

It may be a good model for SNe Ic-BL.

Global feature is similar to viscous models.

Very massive and Supermassive stars:

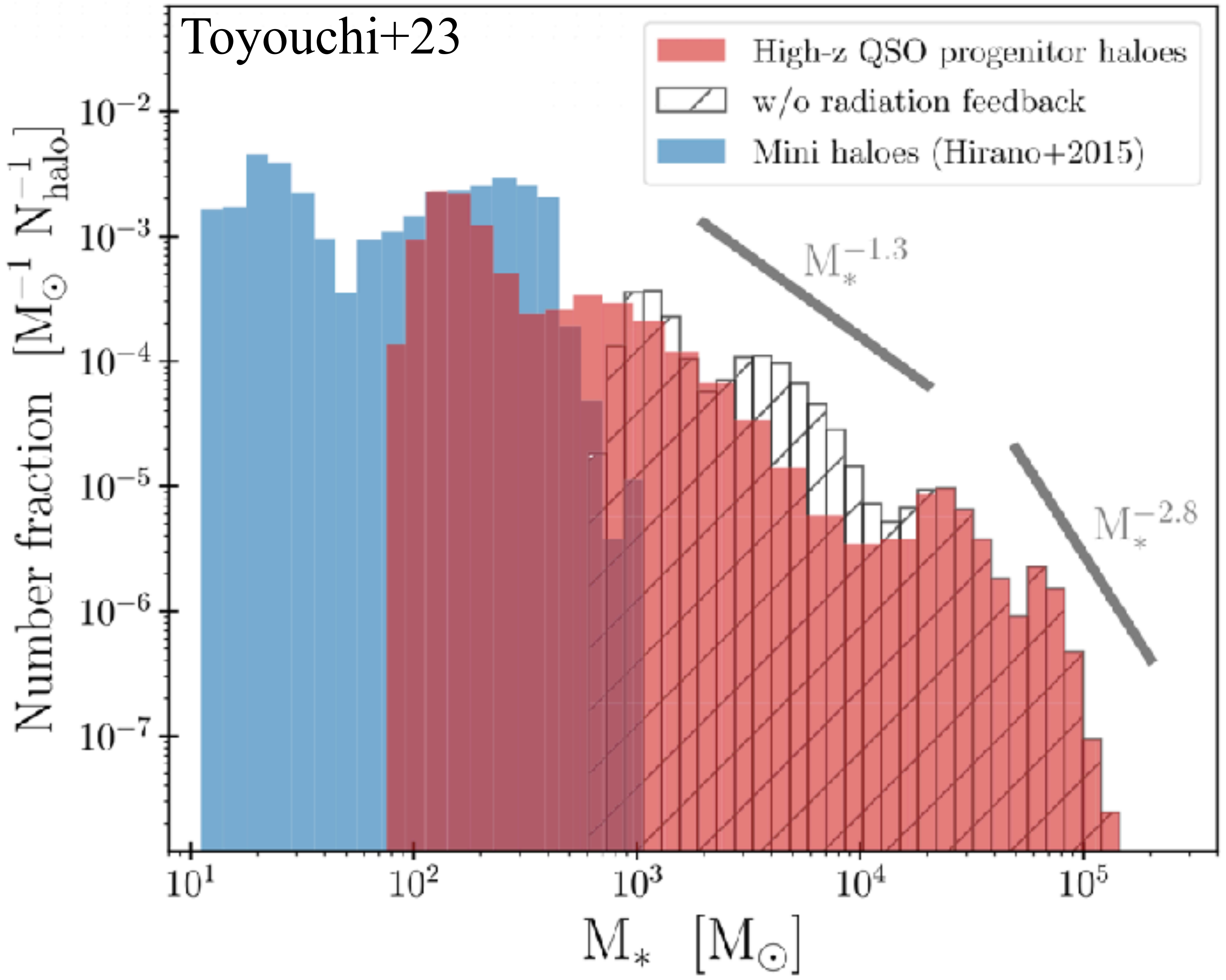
$$M \sim 10^3 - 10^6 M_\odot$$

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

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

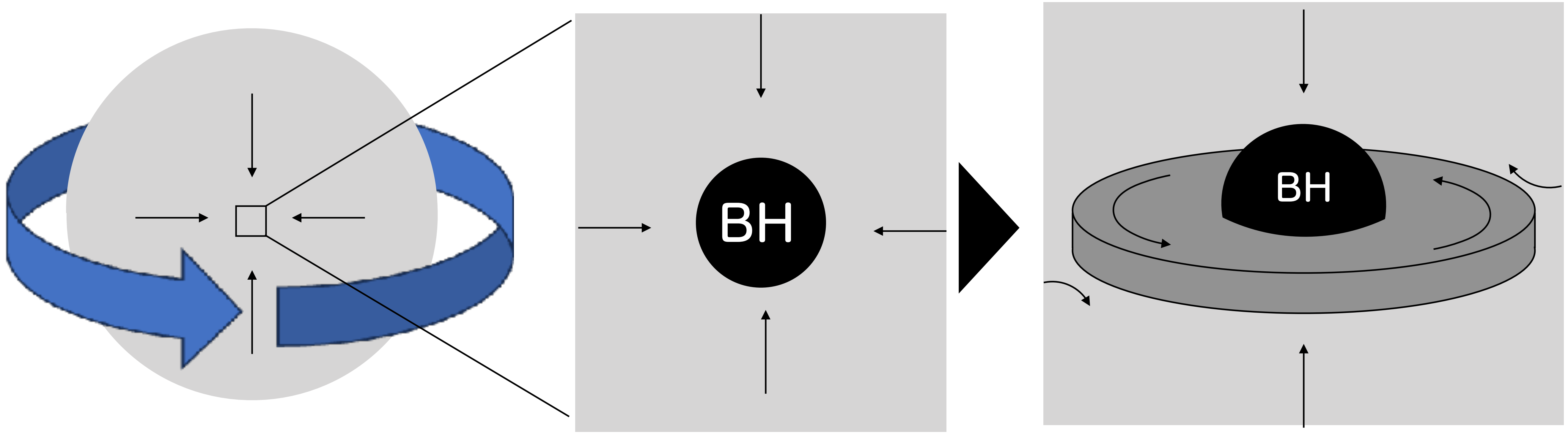
$M \lesssim 10^4 M_\odot$: Very massive star (collapse via pair instability)

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

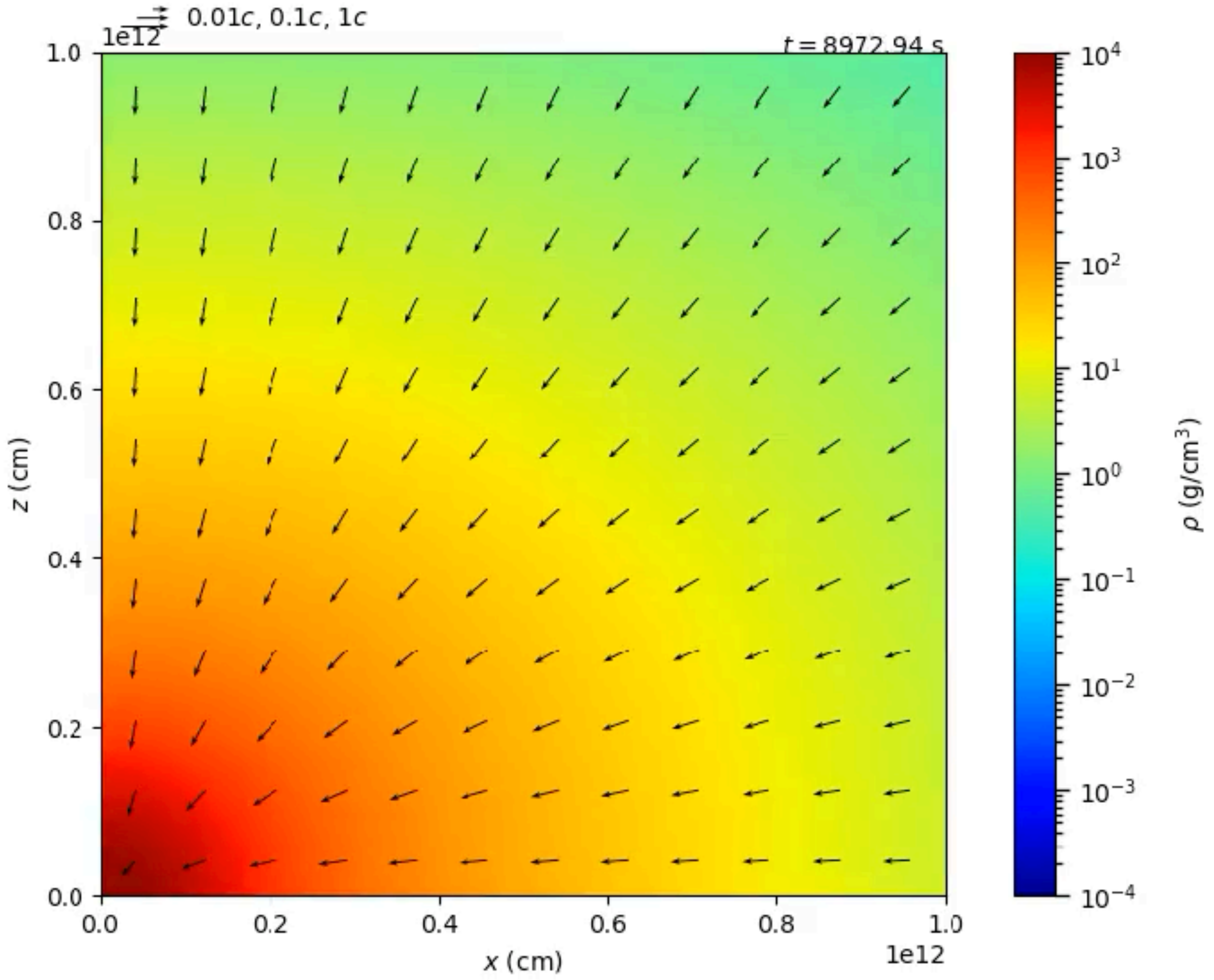


They just leave behind BHs....?

Something non-trivial occurs with rotation.



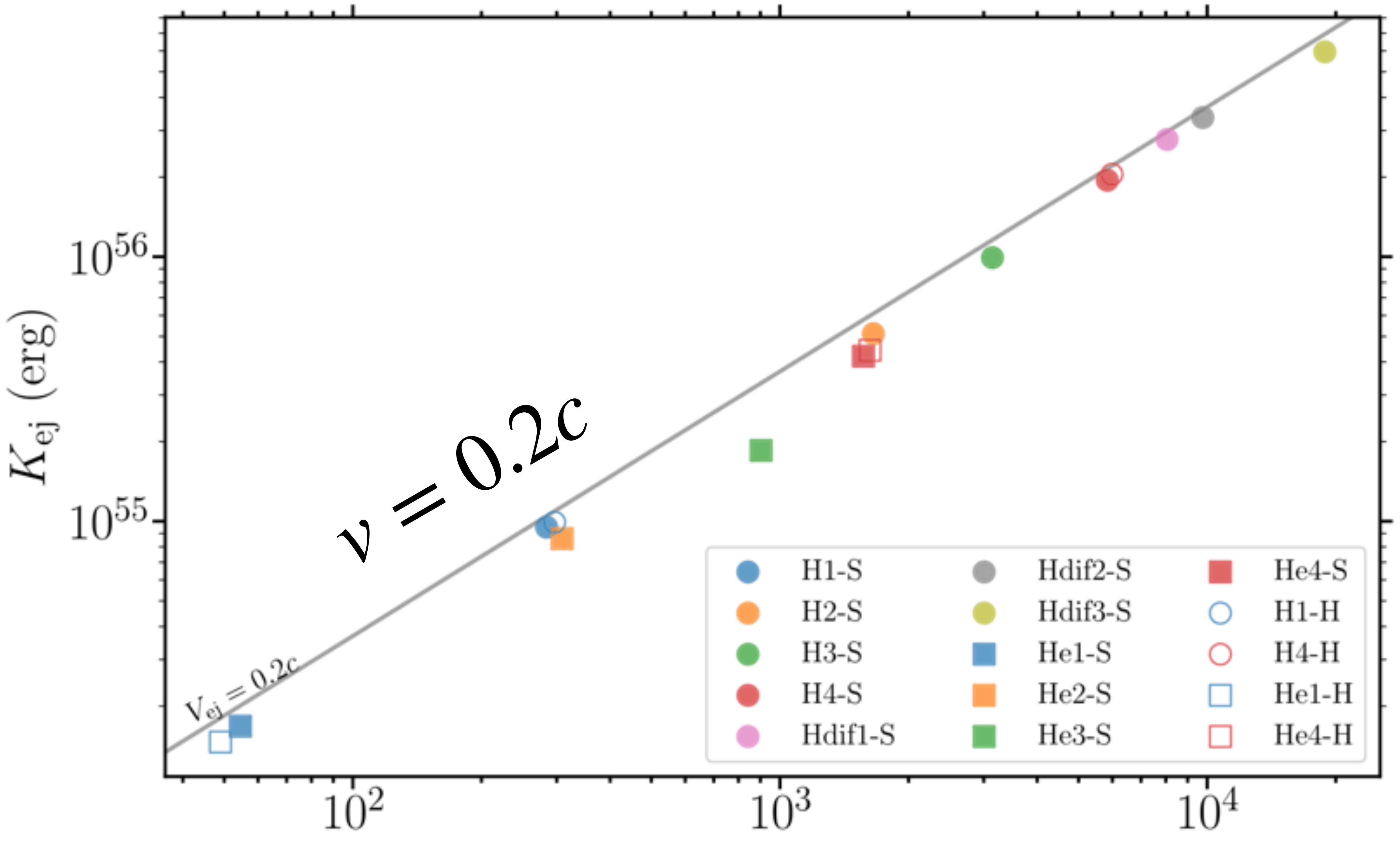
Disk bounce to mass ejection



Bounce of the disk just after the formation
→ A part of the disk becomes unbound.

Uchida et al. (2017)

Explosion energy (erg)



Ejecta mass $(M_\odot)$

Similar average velocity $v = 0.2c$

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

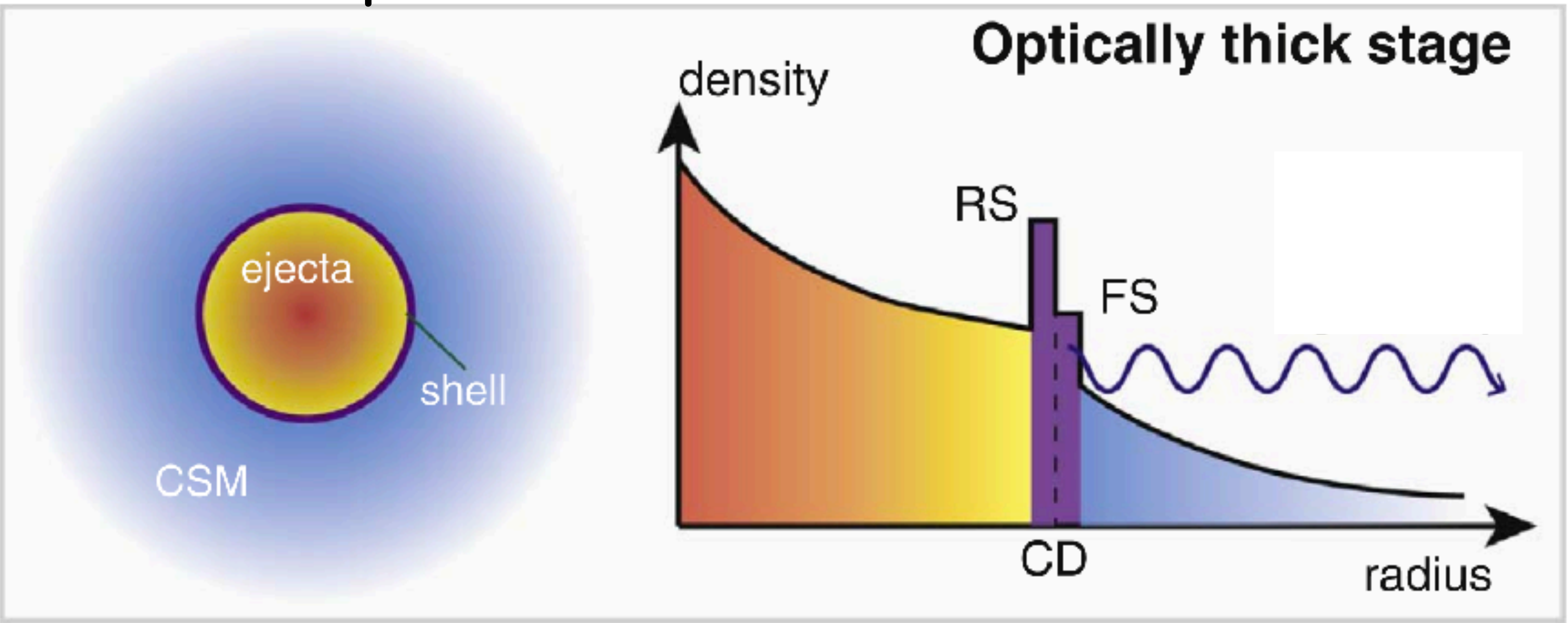
Similar escape vel. at disk formation (at ~ ISCO)
& Similar structure (n=3 polytrope)
& Coherent collapse

Observational properties

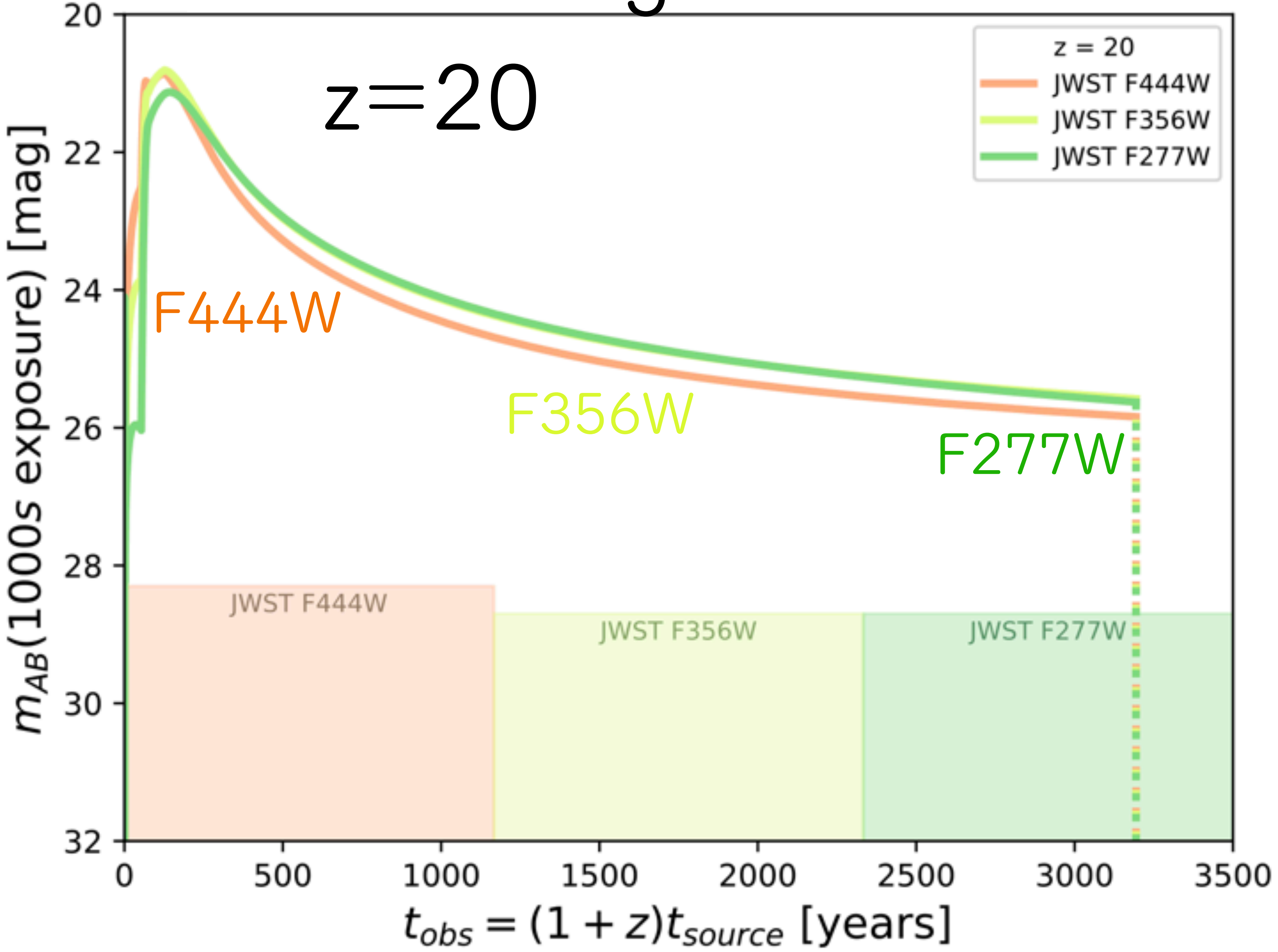
Jockel, Kawaguchi, SF, Shibata, arXiv:2507.15556 (in pres.)

Realistic picture

taken from Suzuki+2019



Magnitude



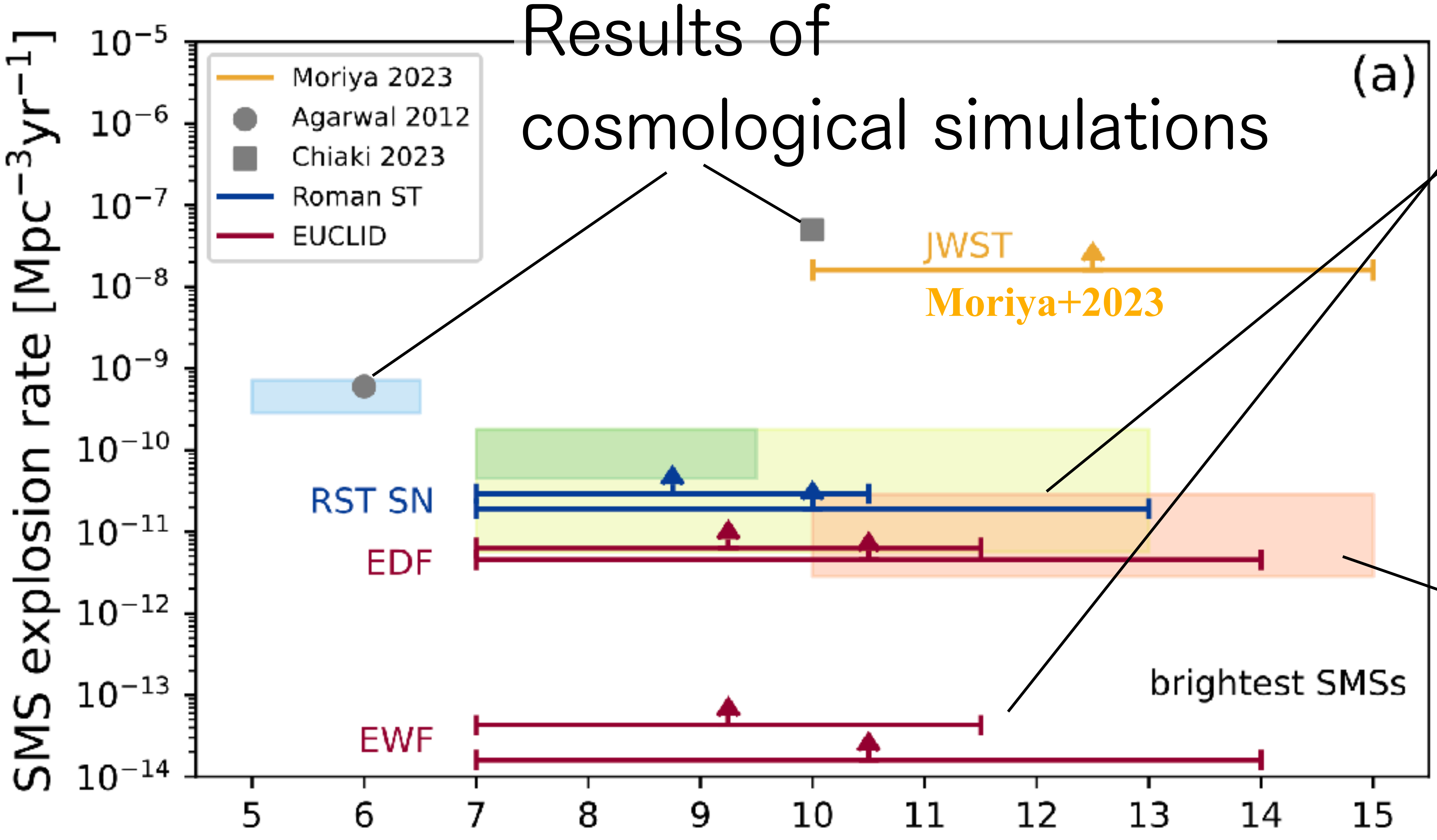
Most bright cases ($E_{\rm exp} \sim 10^{56}$erg) can be observed at z=20 (if found).

~10 yr timescale at **source frame.** → ~(1+z)10 yr for us.

→ Will be observed as nearly persistent "transients"

Detection prospects

Most bright cases (SMS mass $\sim 10^5 M_\odot$)



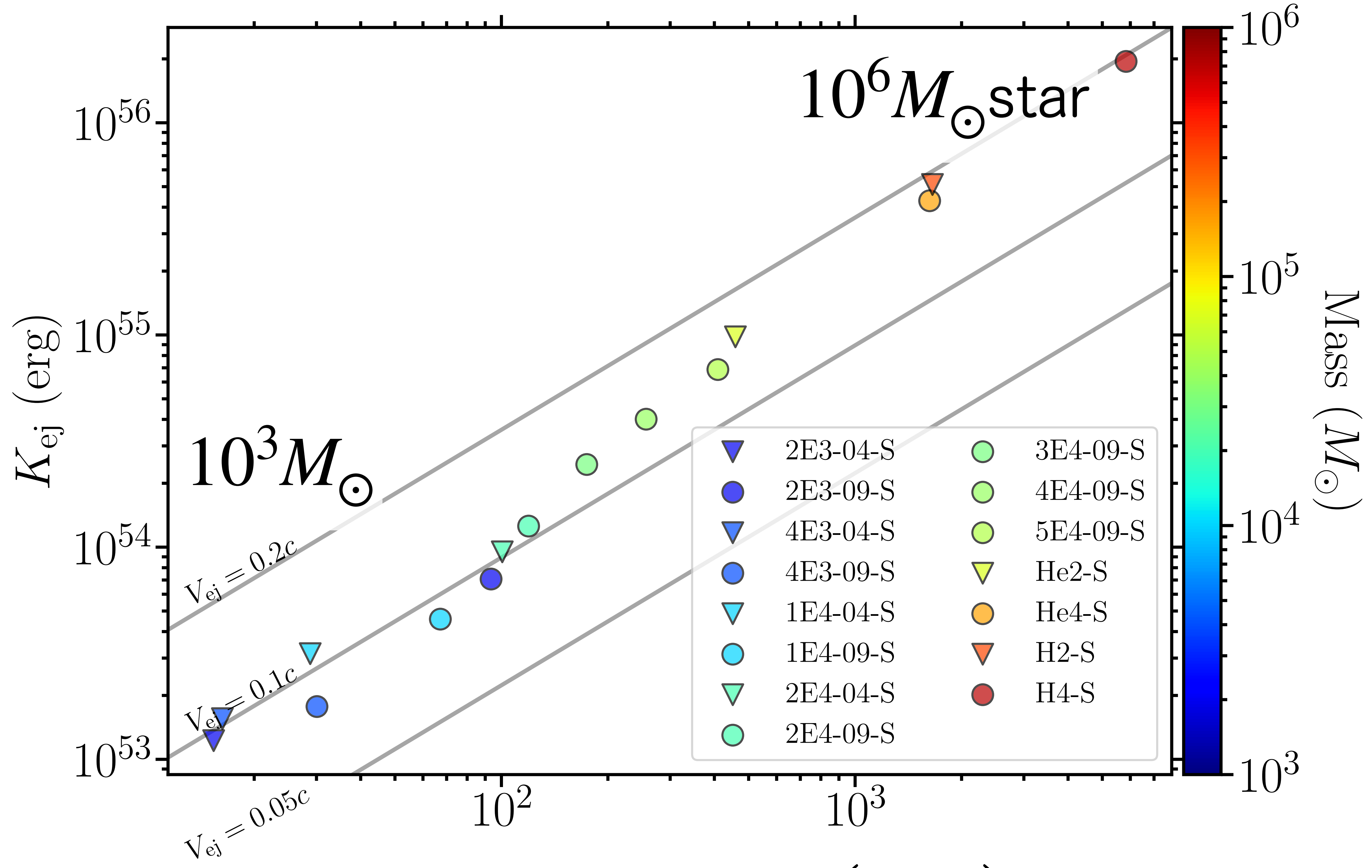
Results of cosmological simulations

Upper limit that can be set by each survey program of Roman or Euclid.

SFR x (ratio of $> 10^5 M_\odot$ stars)
(Harikane+23)
assuming Salpeter's IMF

Lower mass (down to $10^3 M_\odot$)

Explosion energy (erg)



Ejecta mass ($M_\odot$)

Slower average velocity
for smaller mass stars

Central region collapse earlier

→Smaller BH and disk masses
→Smaller energy available through bounce
compared to the stellar binding energy.

For ~$100 M_\odot$ star, the bounce cannot unbound matter
→ to **normal** collapsar

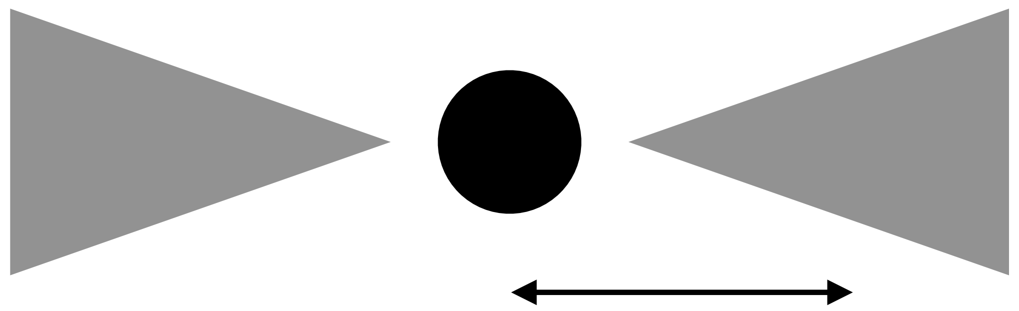
Summary

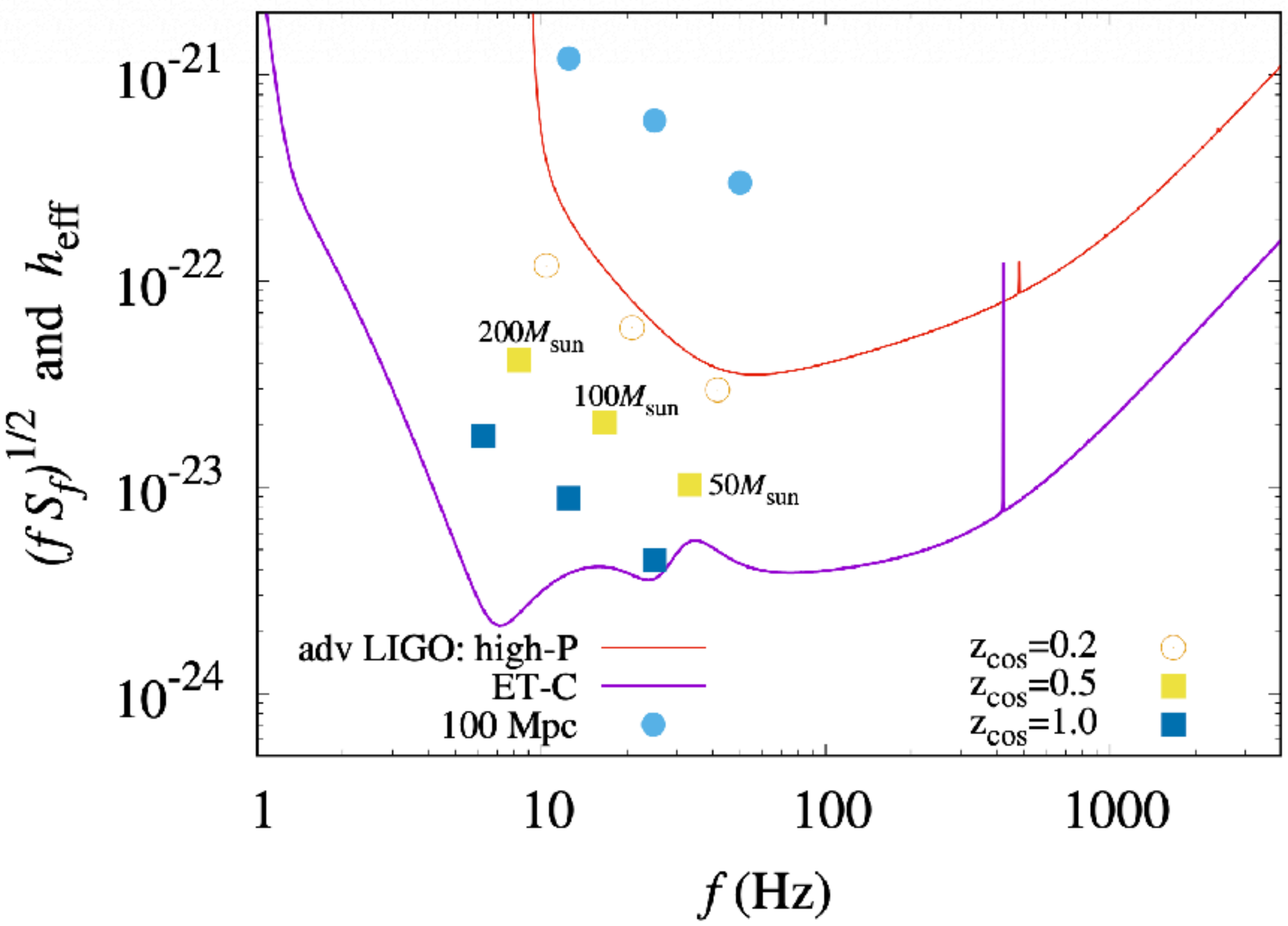
- Collapse of rotating normal massive star ($\sim 10 M_\odot$)
  - Outflow from disk around BH can power SNe Ic-BL.
  - BZ process could work for powering GRB jet.
- Collapse of rotating SMS and VMS ($\sim 10^3 - 10^6 M_\odot$)
  - Explosion induced by disk bounce:
    $M_{\rm ej} \approx 10^{-2} M$, $K_{\rm ej} \approx 10^{-4} M c^2$ $v/c \sim 0.2$ for high-mass end.
  - Scaled-up CSM-interacting SNe, can be target of JWST, Roman, EUCLID
  - Smaller average velocity for lower mass star.
    Even lower mass... normal collapsar.

Backup slides

Lower mass (down to $10^3 M_\odot$)

Lower mass → higher disk-to-BH mass ratio
→ Disk is unstable to non-axisymmetric deformation
→ Potential GW source





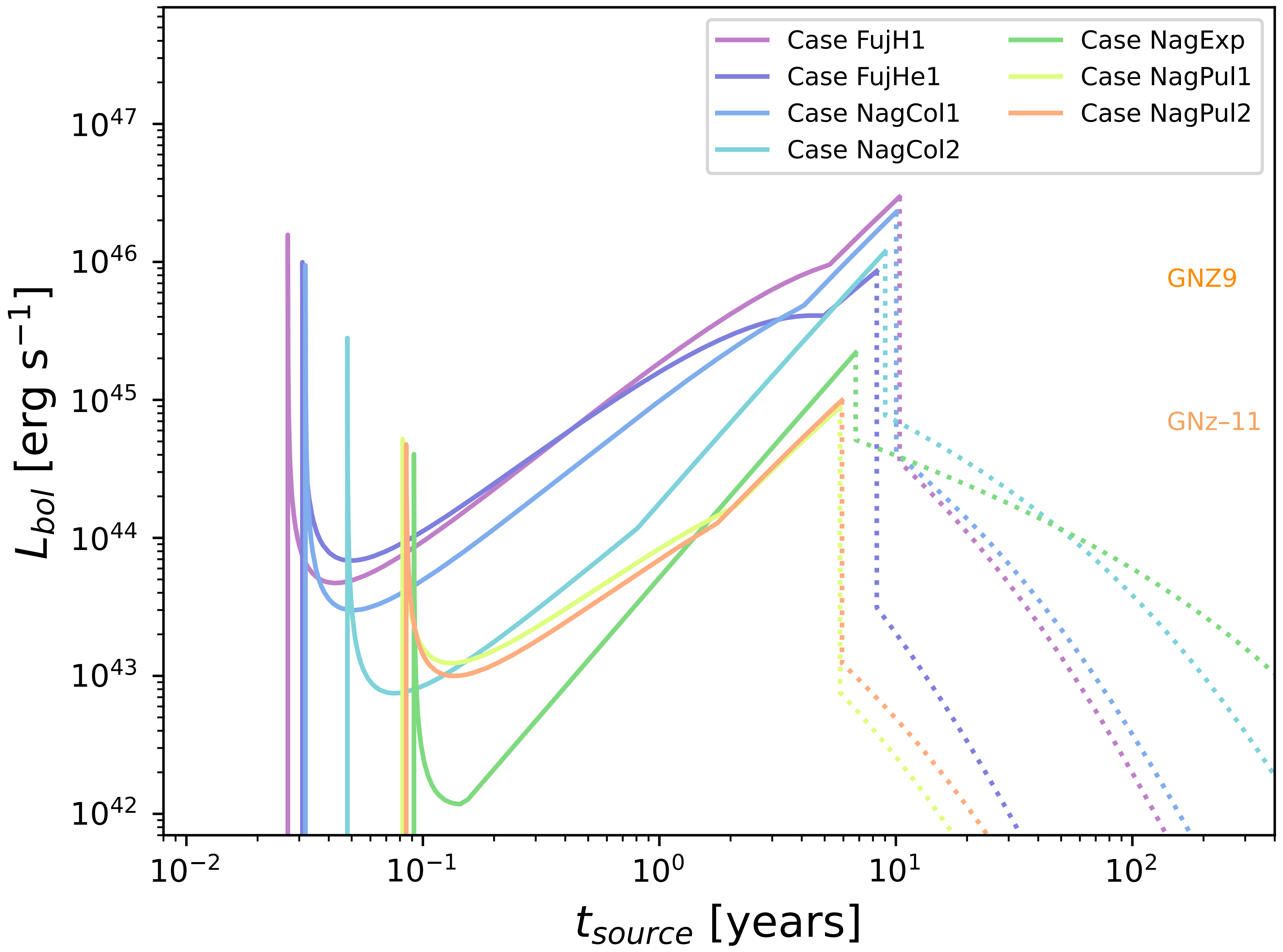
$$f_{\rm GW} \approx 0.8 \frac{c}{\pi r_g} \left(\frac{R_{\rm peak}}{r_g} \right)^{-3/2}$$

~ 30Hz for $100 M_\odot$ BH and $R_{\rm peak} = 7 r_{\rm g}$.

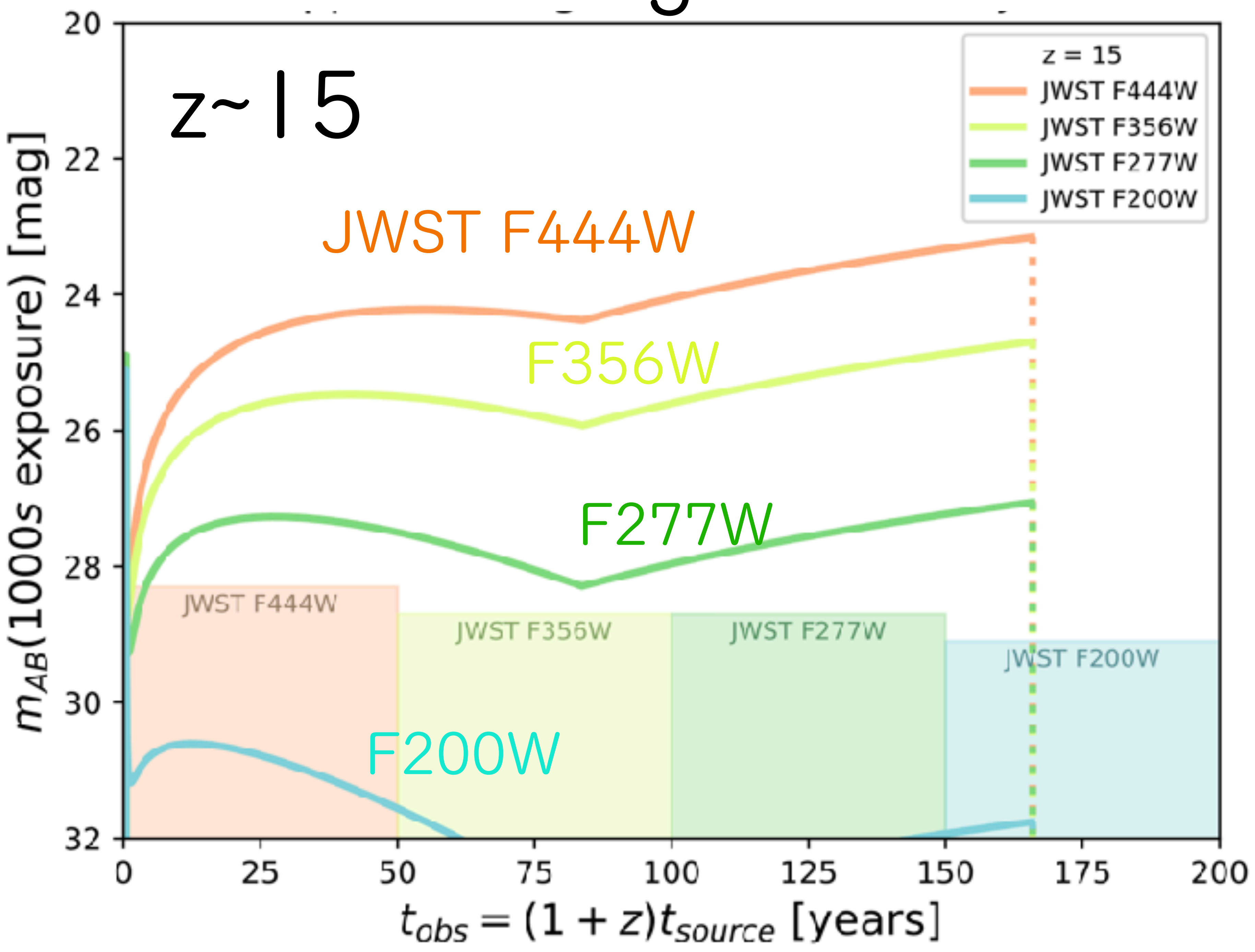
$$h_{\rm eff} = \epsilon \frac{G M_{\rm disk} r_g}{c^2 D R_{\rm peak}} \approx 3 \times 10^{-22} \left(\frac{\epsilon}{0.2} \right) \left(\frac{M_{\rm disk}}{20 M_\odot} \right) \times \left(\frac{R_{\rm peak}}{7 r_g} \right)^{-1} \left(\frac{D}{100\,{\rm Mpc}} \right)^{-1}$$

Detection prospects

Bolometric luminosity



Magnitude

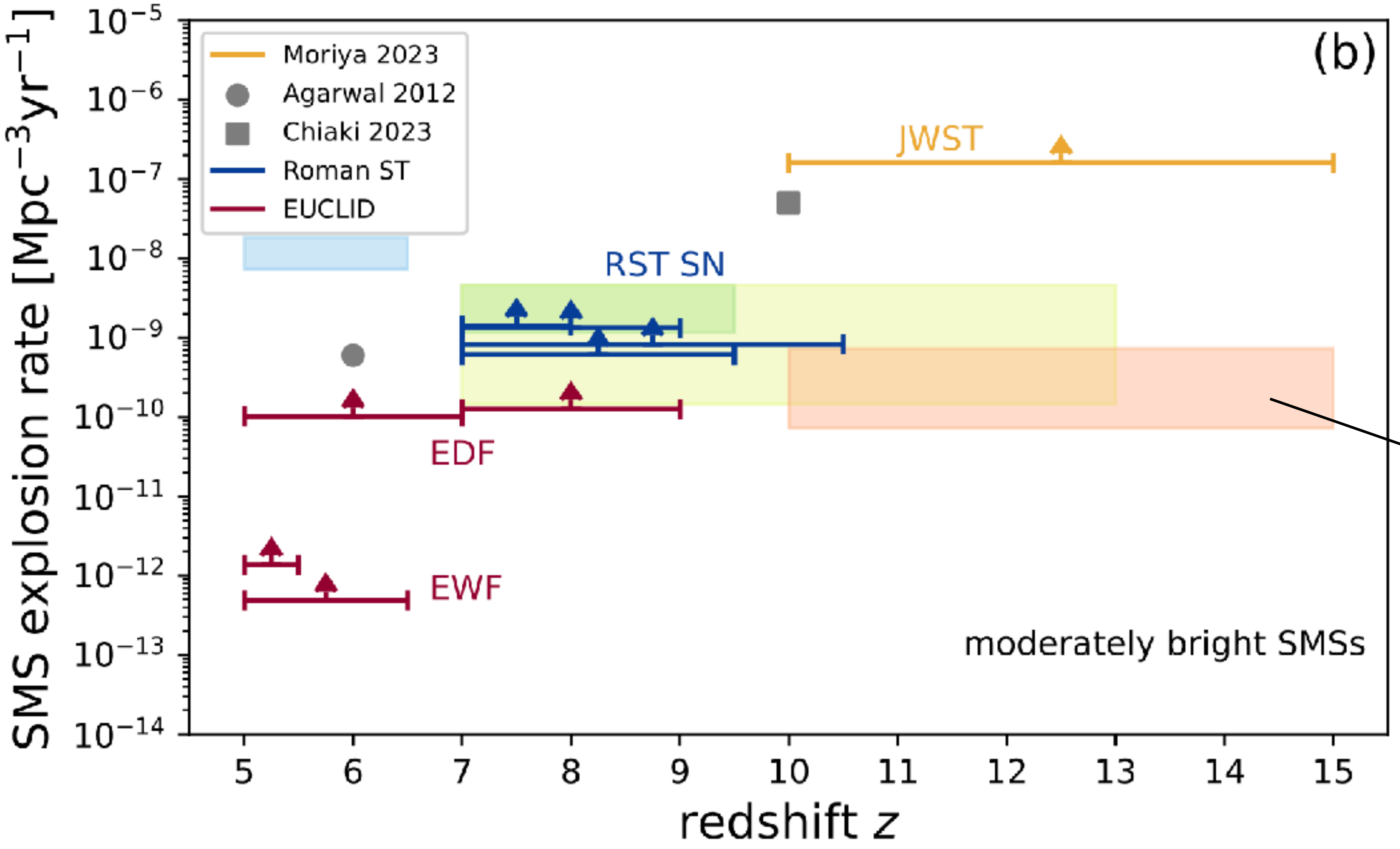


Even for more conservative cases $(E_{\rm exp} \lesssim 10^{55}{\rm erg})$,

the explosion can be observed at z~15

Detection prospects

More conservative cases (SMS mass $\sim 10^4 M_\odot$)



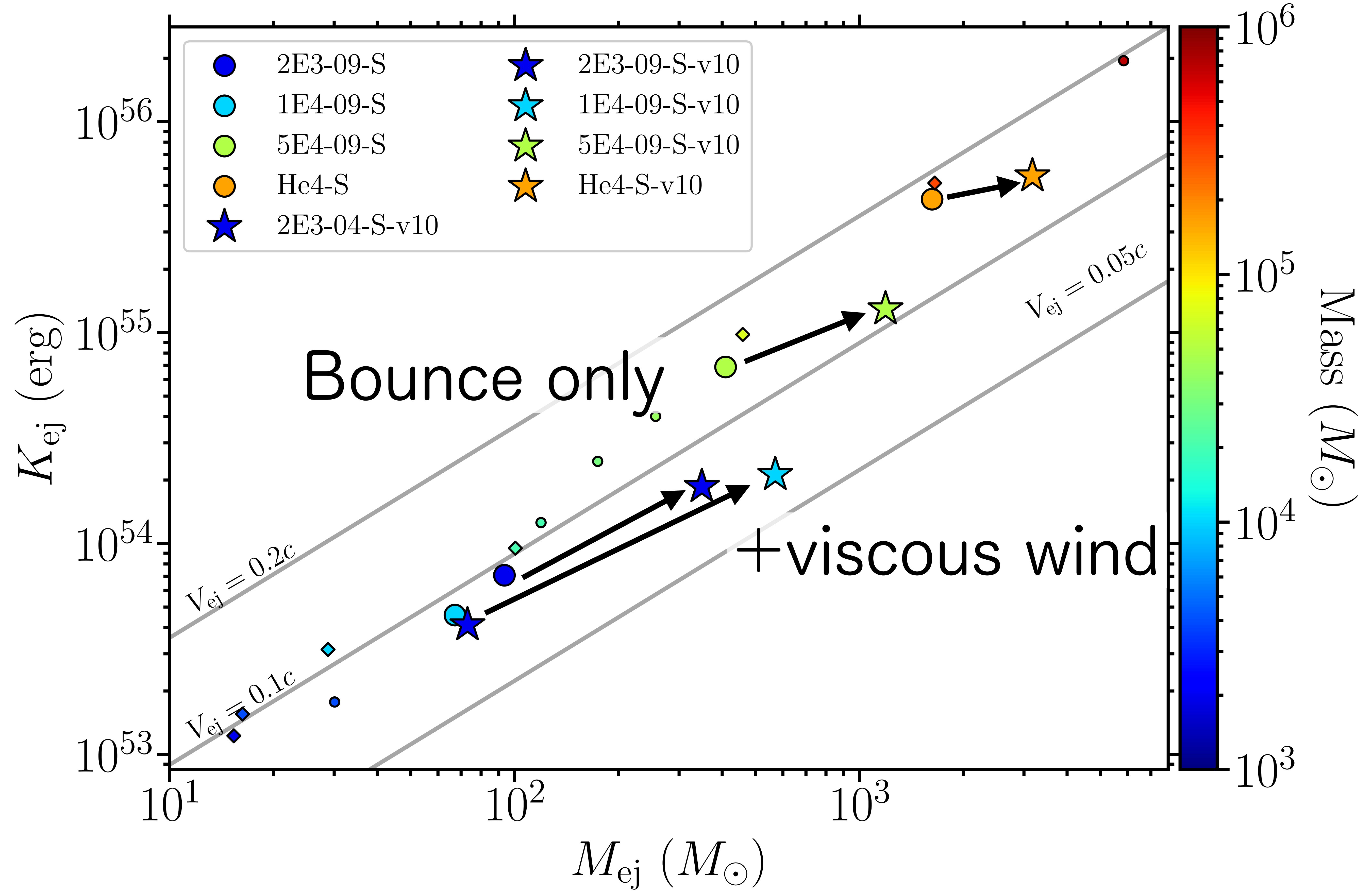
SFR (Harikane+23)

x ratio of $> 10^5 M_\odot$ stars

assuming Salpeter IMF

SMS explosion could be observed if SMS is formed at lower redshifts.

Effect of viscosity



Lower-mass star
→ less compact (large R/M)
→ envelope can have larger angular momentum
→ larger disk mass and its contribution