Explosions of Supermassive Stars at High Redshift

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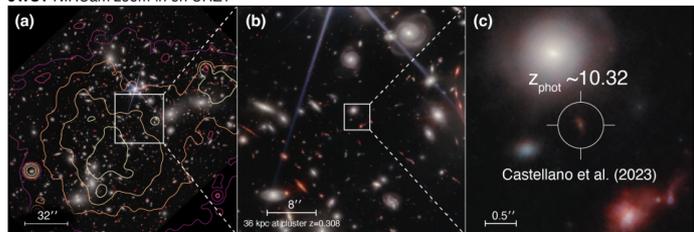## Max Planck Institute for Gravitational Physics (Potsdam)

MAX PLANCK INSTITUTE
FOR GRAVITATIONAL PHYSICS
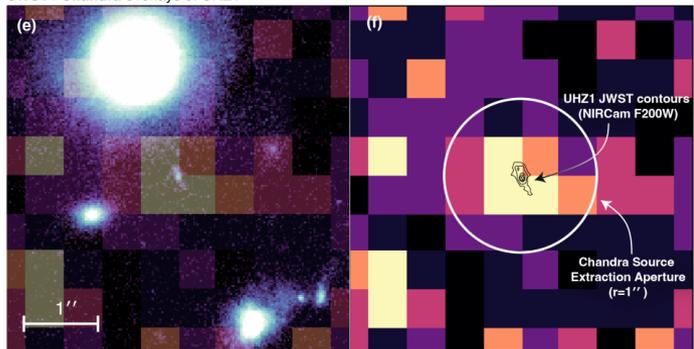(Albert Einstein Institute)
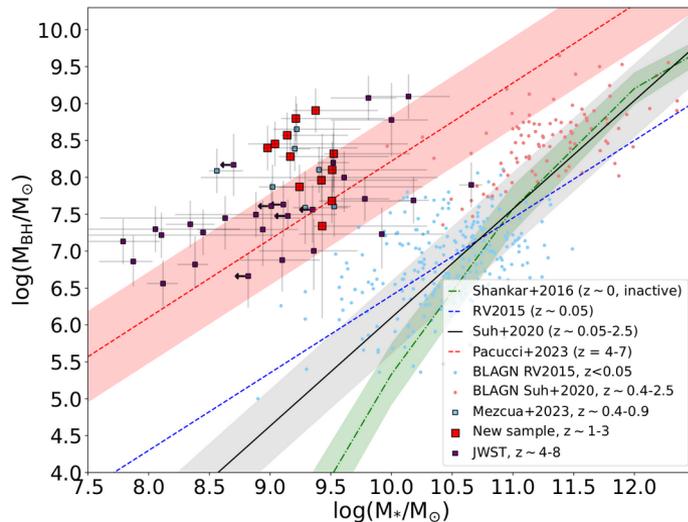
High-Redshift Discoveries

JWST NIRCam zoom-in on UHZ1
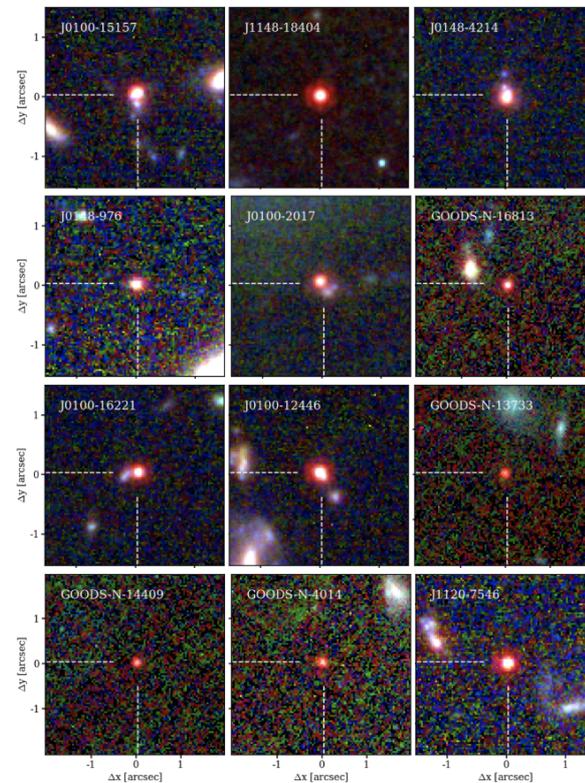
JWST NIRCam UHZ1 images

JWST / Chandra overlays of UHZ1
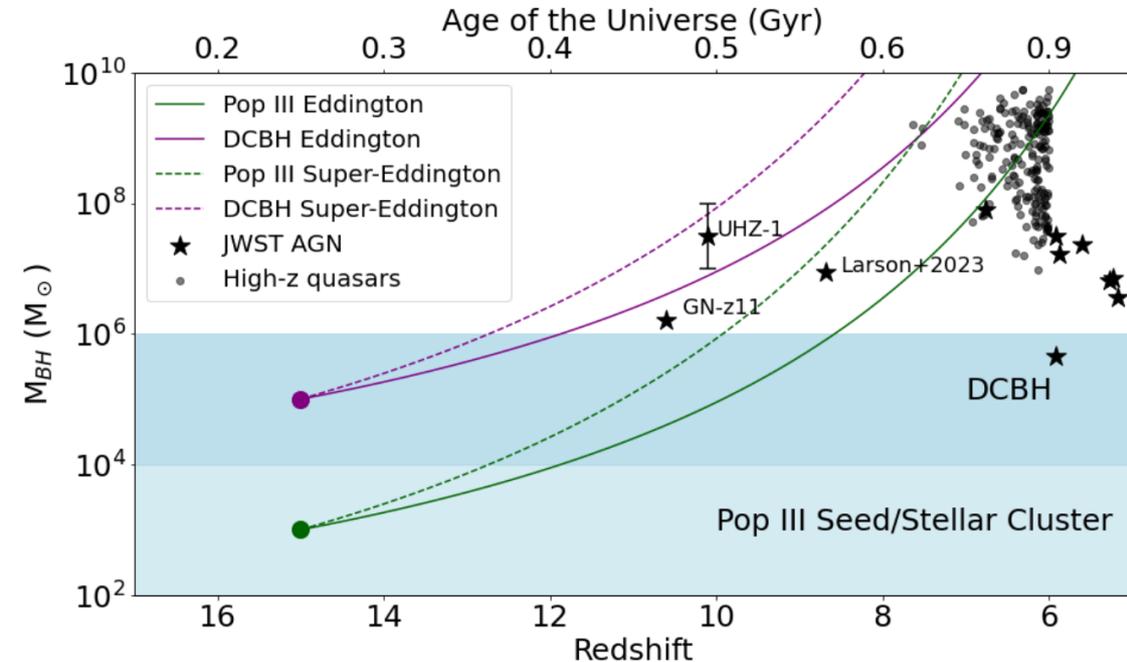
High-z SMBH ~10^{7-8} M$_{sun}$ [Bogdán2023]

Over-massive BHs [Mezcua2024]

Spatially unresolved little red dots
[Matthee2024]

SMBH formation
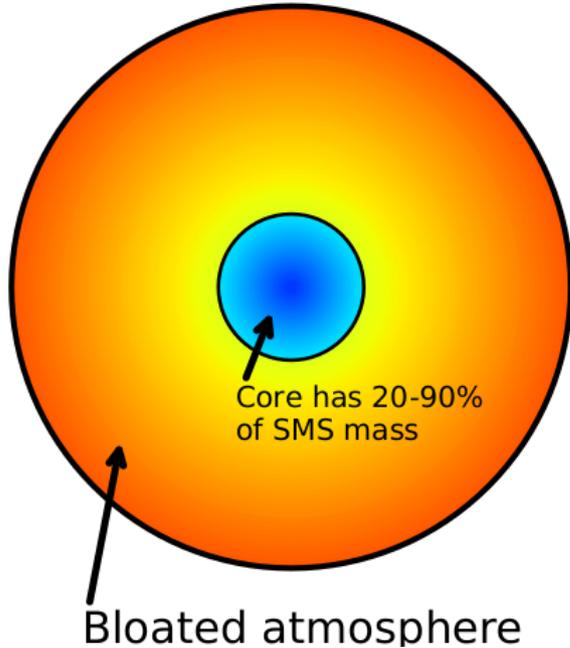

[Jeong2024]

→ How does SMBH formation at z>11 (400Myr after Big Bang) work?

→ Large Eddington rate (mergers and accretion) from a ~10^2 M_{sun} BH might be difficult to achieve over a long time

→ Growth channels unclear...

But larger initial mass might make growth easier!

"Direct" Collapse Black Holes

Core has 20-90% of SMS mass

Bloated atmosphere

→ **Supermassive PopIII stars** (SMSs) would be intermediate stage in pristine cloud collapse before SMBH formation (see talks and review paper by K. Inayoshi + Y. Harikane)

→ SMSs grow until GR instability ($\sim 10^{4\text{-}6}$ M_{sun}), then monolithic collapse

→ Explosion mechanisms: by nuclear burning (cf. Nagele, Chen) or torus disk bounce (see talk by Sho Fujibayashi, week 2)

→ Exploding supermassive stars as **signatures of SMBH birth?**

SMS Explosion Light Curve Pipeline
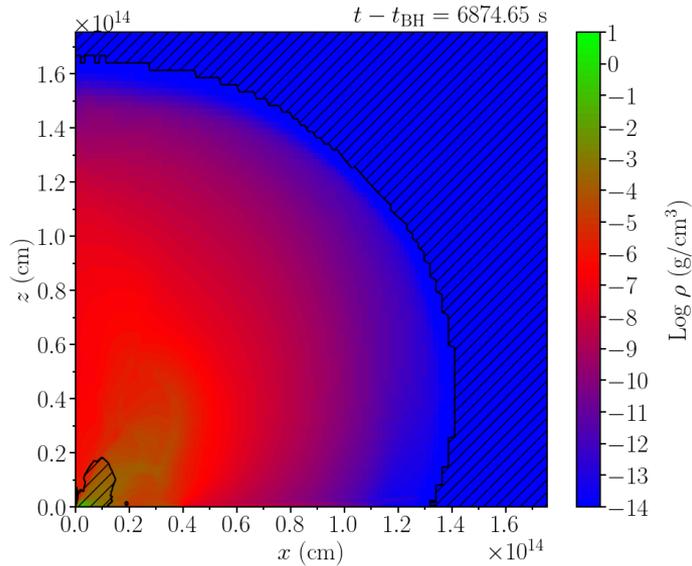
→ Numerical collapse simulation
 [cf. Fujibayashi24, Nagele24]

→ Get ejecta properties M_{eje} & E_{kin}

SMS Explosion Light Curve Pipeline
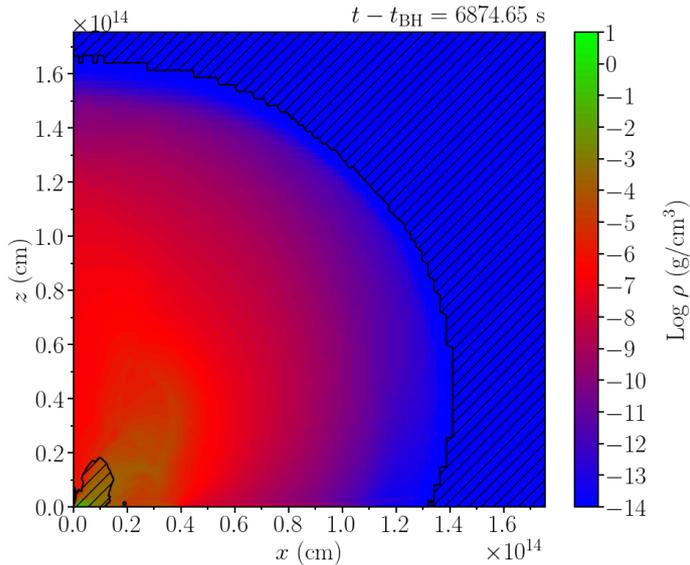
→ Light curve model takes M_{eje} & E_{kin} + CSM

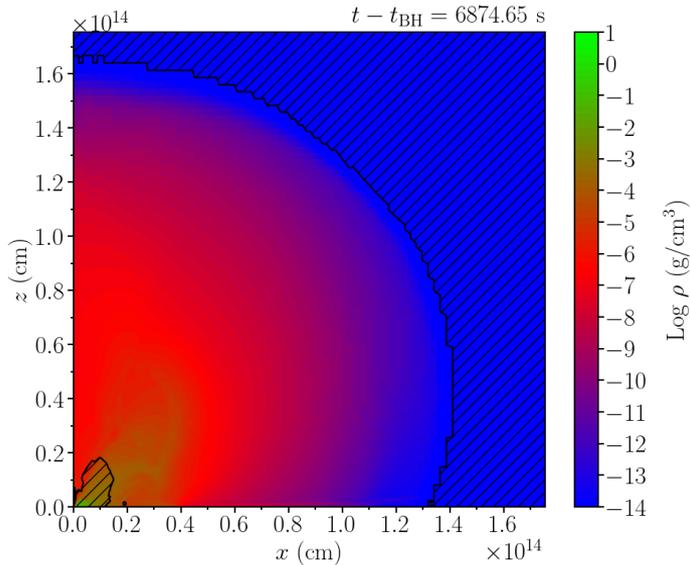→ Ejecta **interacts with CSM** through optically thick shock

→ Model shock + EM radiation

→ Numerical collapse simulation [cf. Fujibayashi24, Nagele24]

→ Get ejecta properties M_{eje} & E_{kin}

$$L_{bol} = \frac{4\pi c R_{sh}}{3\kappa M_{sh}} E_{int}$$

SMS Explosion Light Curve Pipeline

→ Light curve model takes M_{eje} & E_{kin} + CSM

→ Get **luminosity L_{bol}(t)**

→ Get **spectrum**

→ Ejecta **interacts with CSM** through optically thick shock

→ Ionising photon flux

→ Model shock + EM radiation

→ observable photometric light curves

→ Numerical collapse simulation [cf. Fujibayashi24, Nagele24]

→ Get ejecta properties M_{eje} & E_{kin}

$$L_{bol} = \frac{4\pi c R_{sh}}{3\kappa M_{sh}} E_{int}$$

Bright Bolometric Light Curves
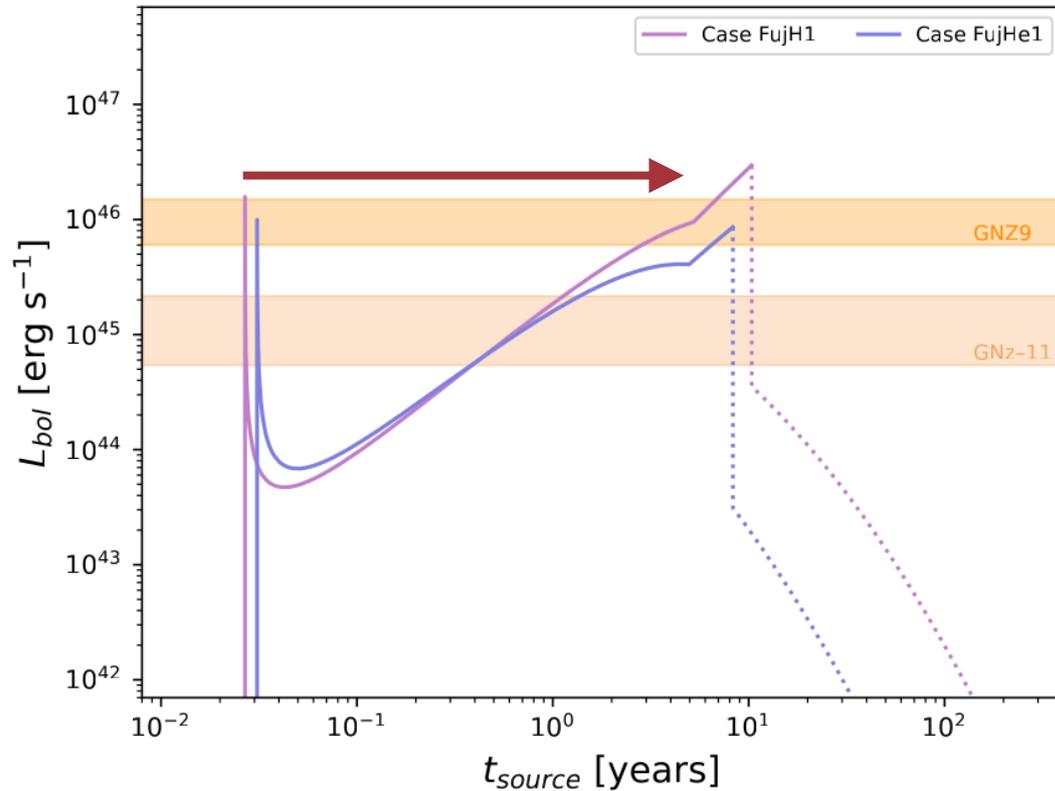
→ Possible initial radiation flash

→ Luminosity rising and temperature cooling

Bright Bolometric Light Curves

Rest-frame bolometric luminosity

→ Possible initial radiation flash

→ Luminosity rising and temperature cooling

→ Late time H recombination phase with constant $T_{eff} \sim 6000K$ ($L_{bol}(t) \sim R^2 \sim t^2$)

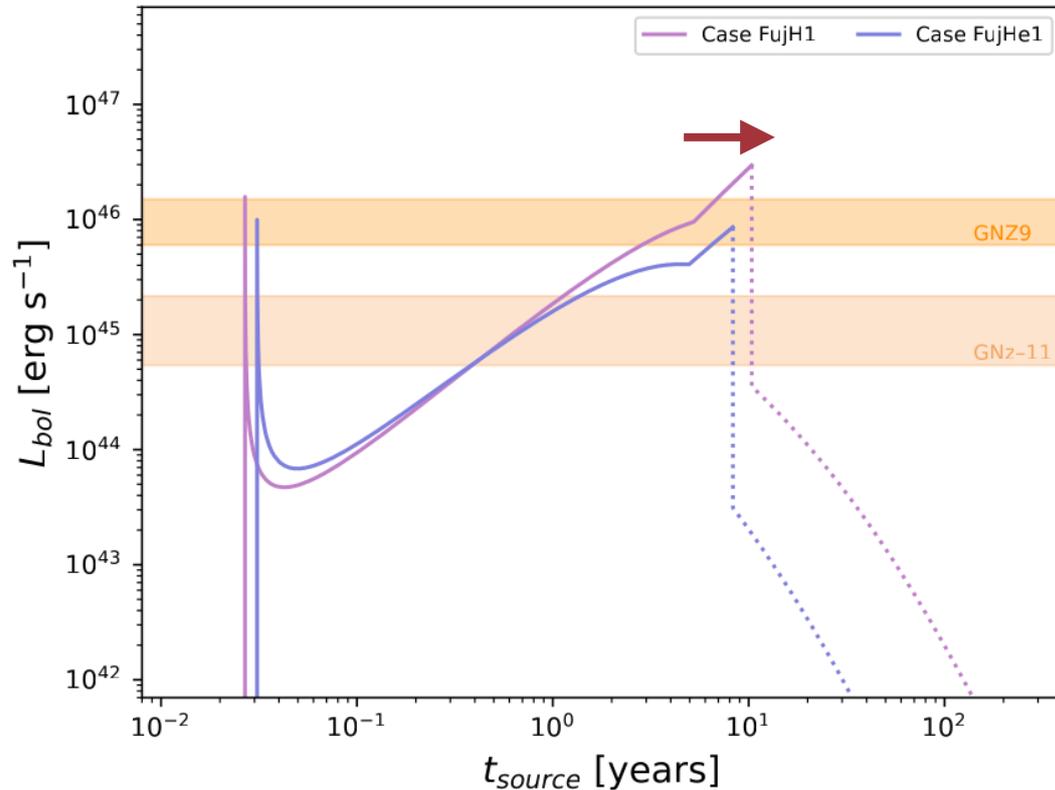→ Non-thermal emission after shock is transparent (not modelled in detail)
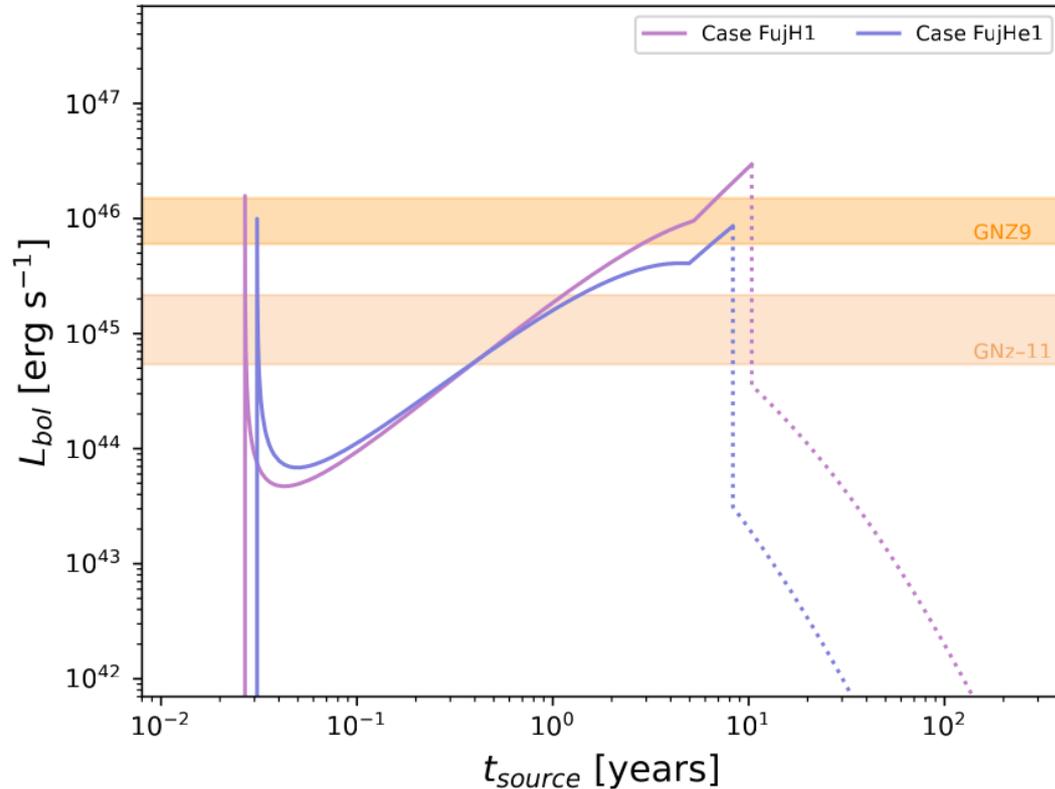
Bright Bolometric Light Curves

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→ Non-thermal emission after shock is transparent (not modelled in detail)

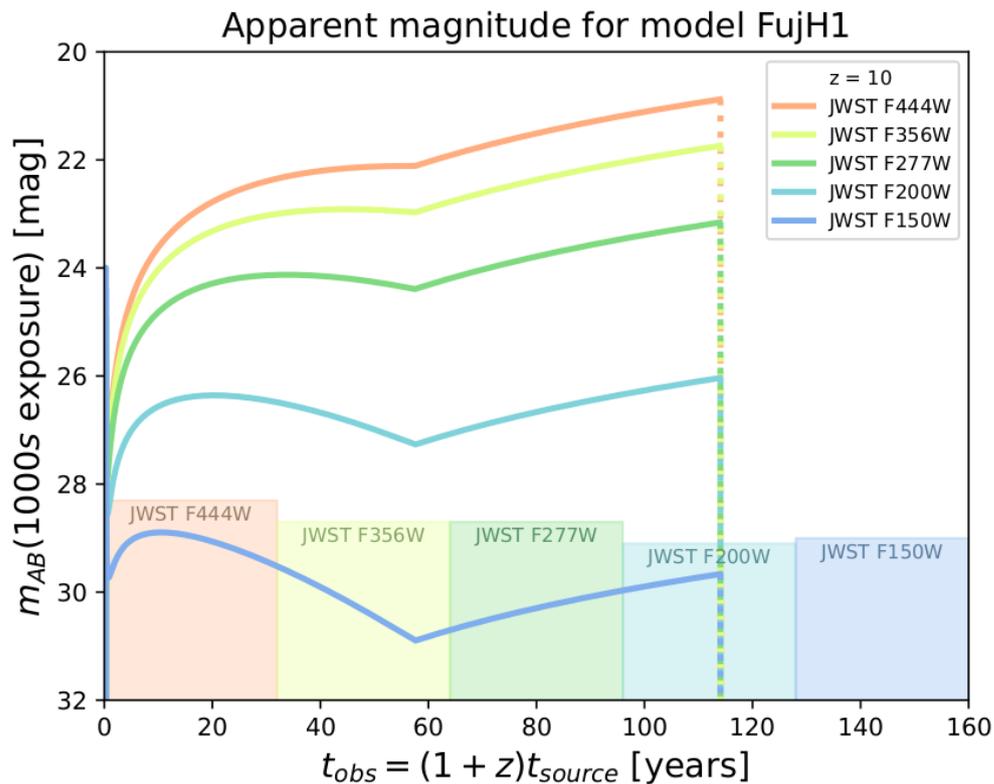→ Comparable luminosity to high-z AGN

→ Timescale ~10–15 years **in rest frame** until shock becomes transparent

Visibility of SMS explosions using JWST

Apparent magnitude for model FujH1
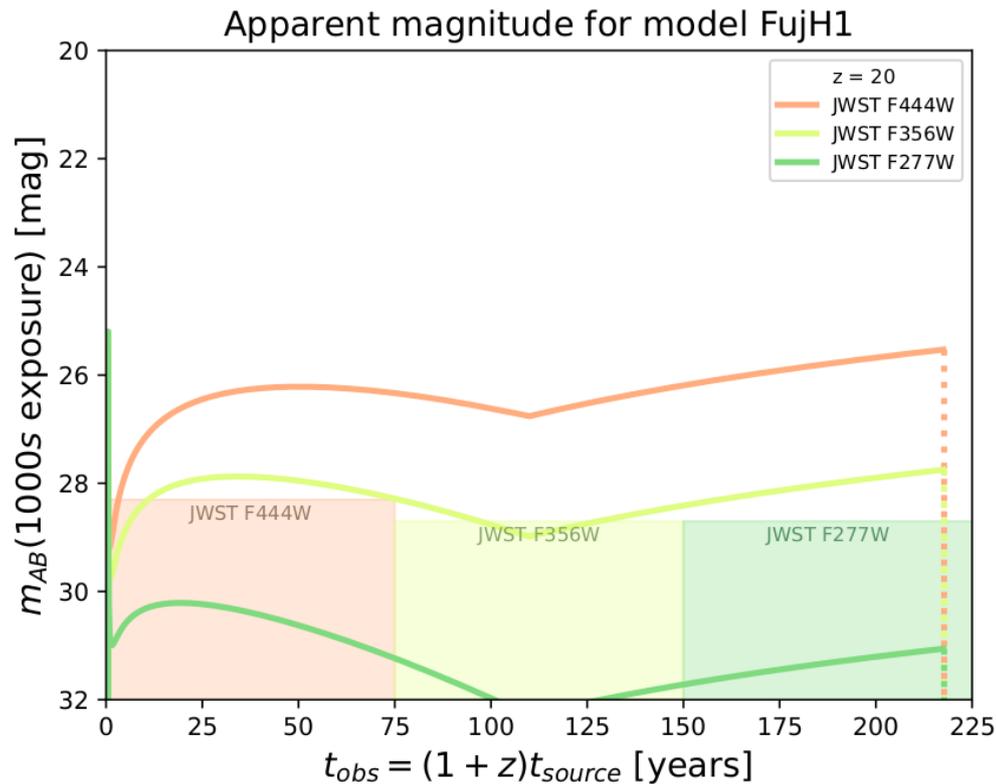
Visibility of SMS explosions using JWST

Photometric Detection Possible

Colour magnitude diagram
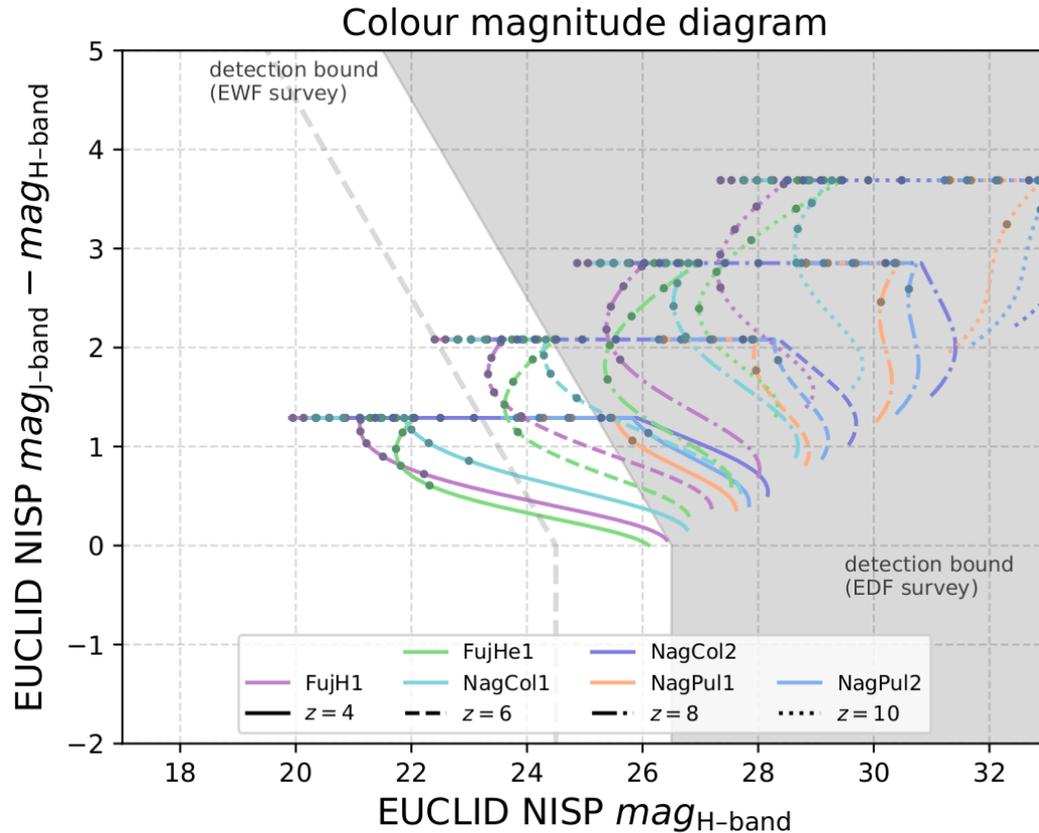
→ Bright and red sources with slow colour evolution due to time-dilatation

→ For EUCLID (and Roman Space Telescope), detection still possible to redshift z~6-7 (even higher z in JWST)

→ Detectability strongly depends on intrinsic explosion rate, telescope survey and sky area (next slide)

→ Large survey area might lead to good observation opportunities (next slides)

Prospects for SMS Detection

→ Detectable intrinsic rates derived from light curve model

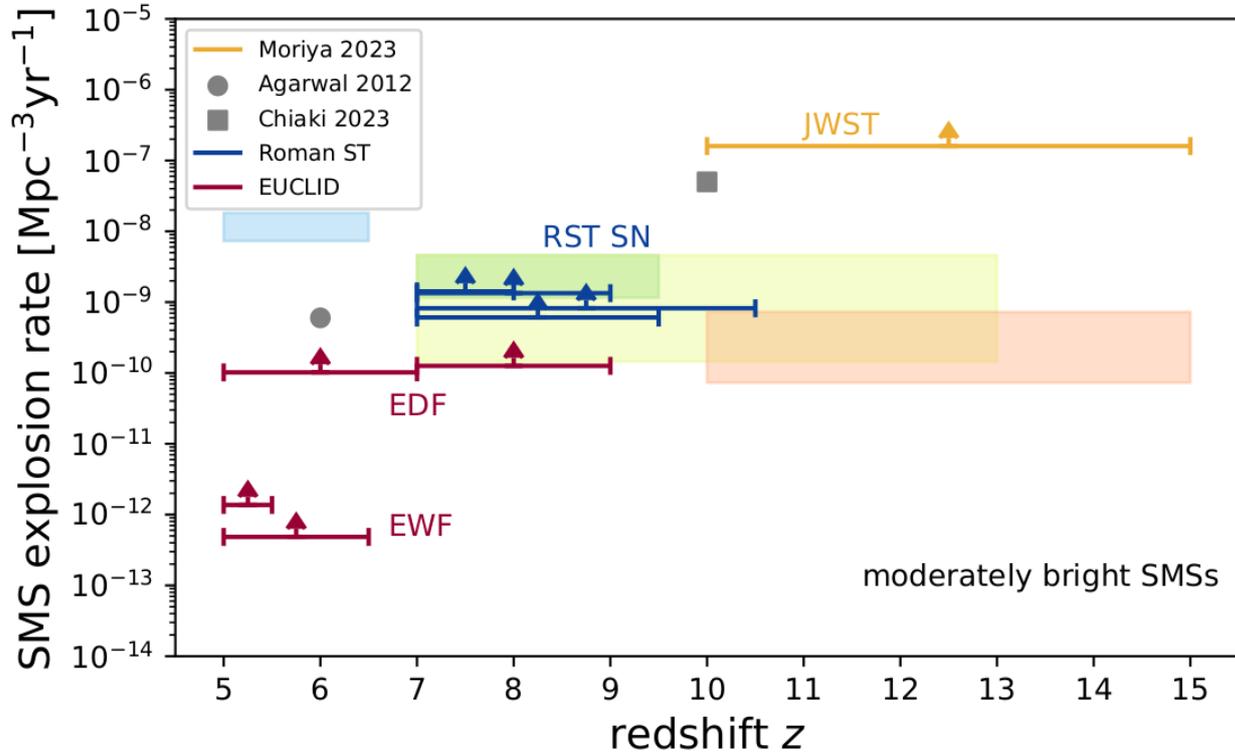→ EUCLID wide+deep field more constraining than JWST due to sky area coverage

→ Expected detections based on cosmological simulations and star formation rates

→ Up to **10–1000 detections** in EUCLID wide+deep fields !
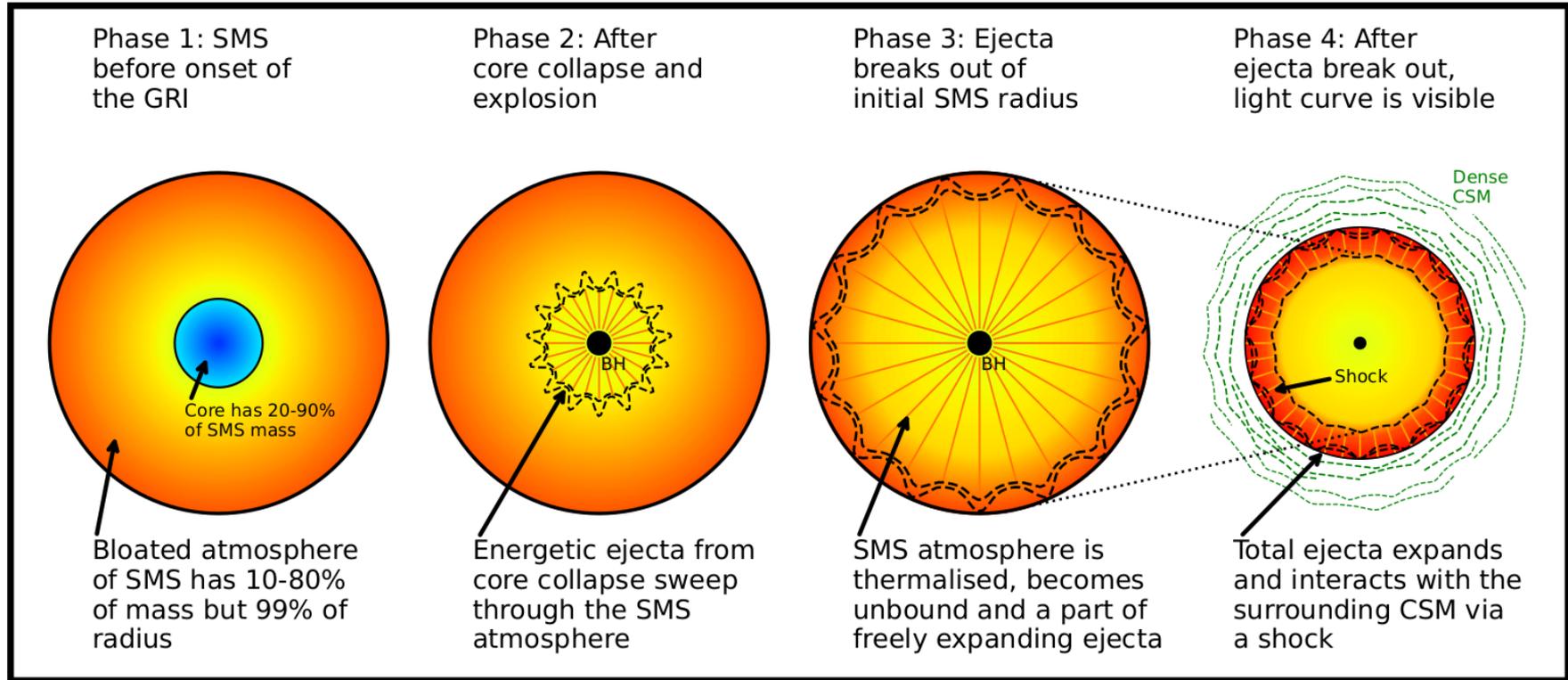
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Conclusion

Supermassive PopIII stars in the early universe

→ SMSs offer an interesting pathway to explain early SMBH formation

→ The collapse of SMSs can produce powerful and bright explosions

→ The resulting light curves could be visible in JWST, EUCLID and Roman Space Telescope as quasi-persistent red transients

→ Sky surveys by EUCLID and Roman ST could detect multiple SMSs (10-1000)

→ With a population study one could infer if SMSs are abundant enough to solve the problem of high-z over-massive AGN

**Thank you for your attention!**

Backup Slides

Supernova-Like Explosions

Phase 1: SMS before onset of the GRI

Core has 20-90% of SMS mass

Bloated atmosphere of SMS has 10-80% of mass but 99% of radius

Phase 2: After core collapse and explosion

BH

Energetic ejecta from core collapse sweep through the SMS atmosphere

Phase 3: Ejecta breaks out of initial SMS radius

BH

SMS atmosphere is thermalised, becomes unbound and a part of freely expanding ejecta

Phase 4: After ejecta break out, light curve is visible

Dense CSM

Shock

Total ejecta expands and interacts with the surrounding CSM via a shock

→ Model the expanding ejecta with $M_{eje,tot}$, R_{SMS} , $E_{kin,eje}$

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Photometric Detection Possible

Colour magnitude diagram
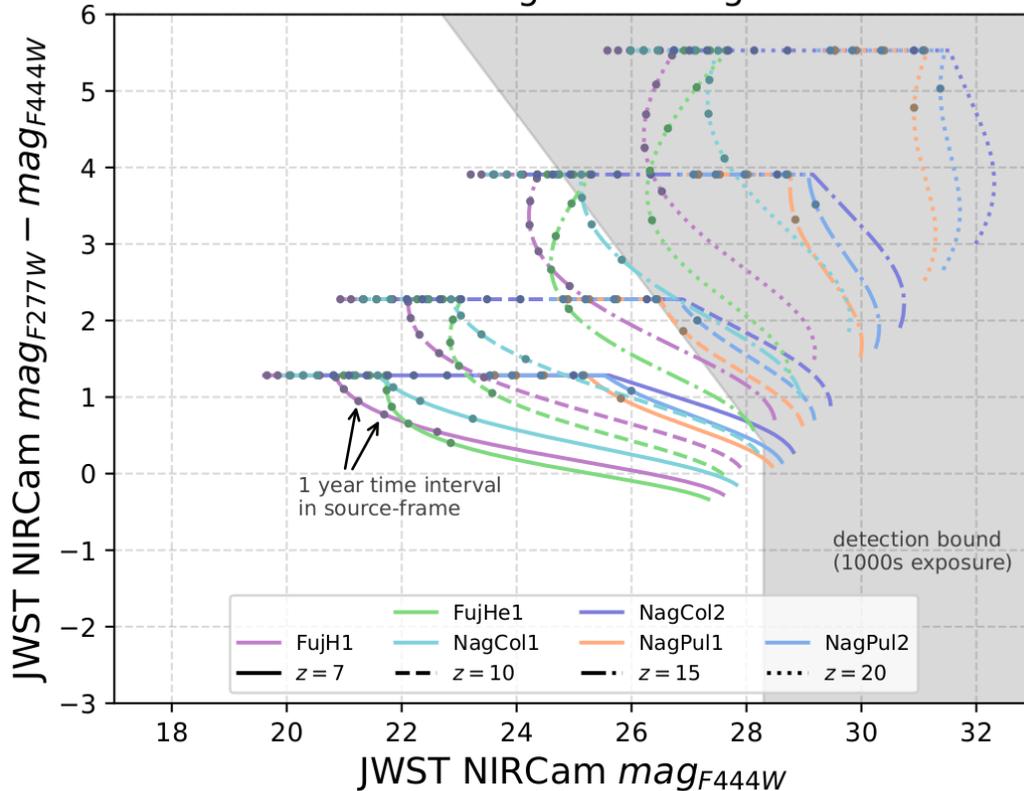
→ Supermassive star explosions are easily detectable using JWST in principle

→ Bright and red sources with slow colour evolution due to time-dilatation

→ Source brightens and reddens over several decades

→ JWST only covers small sky area, practical visibility might be difficult
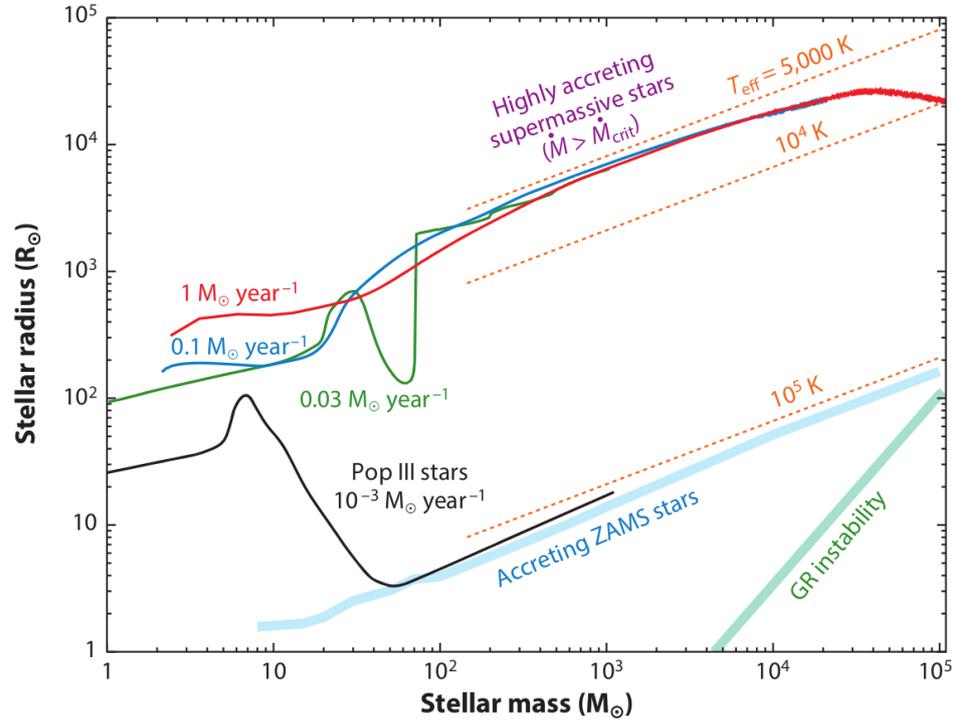
SMS Smoking Gun Signals

Strömgen sphere and shock radius
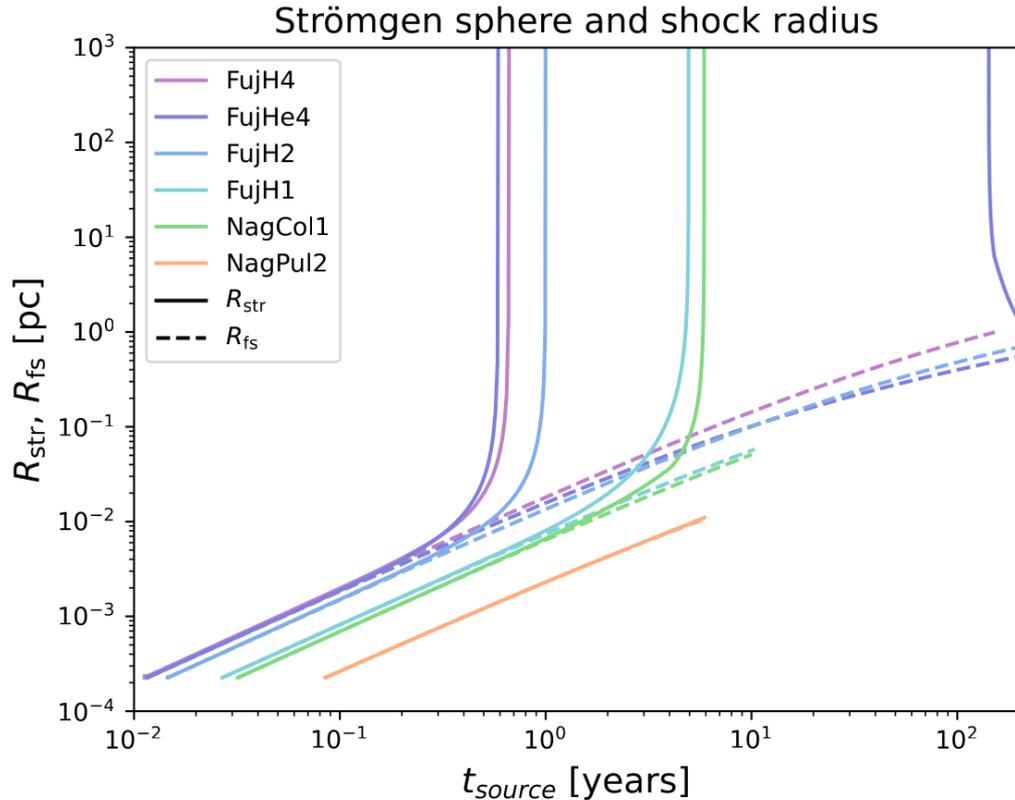
From Photometry:
→ red colour
→ colour evolution
→ very long time scale

From spectrum:
→ primordial chemical composition
→ Narrow H & He lines (P-Cygni?)
→ self-Ionising CSM
→ (emerging) electron-scattering line-broadening
→ (vanishing) Balmer break

Rapidly accreting protostars

[Inayoshi2020]

→ Continuous fast accretion

→ Two stellar evolution paths red vs blue giant depending on accretion rate

→ Bloated low-density atmosphere, convective H- or He-burning core

→ Stars eventually grow until they become **Supermassive stars** $> 10^{4\text{-}5}$ M_{sun}

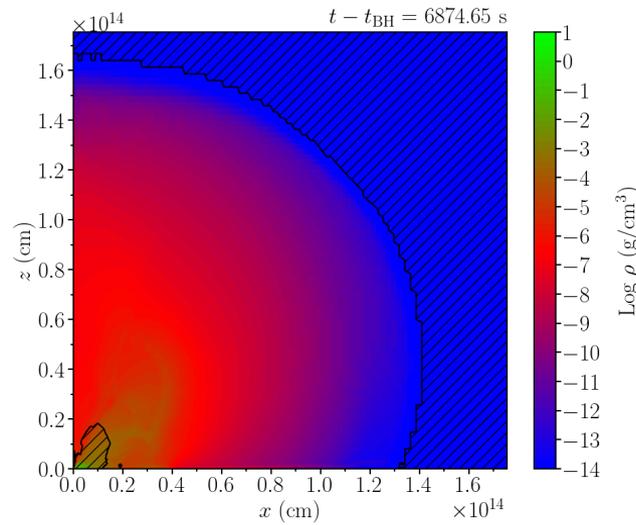→ At $\sim 10^{5\text{-}6}$ M_{sun} GR instability, then monolithic collapse

Collapse and explosion
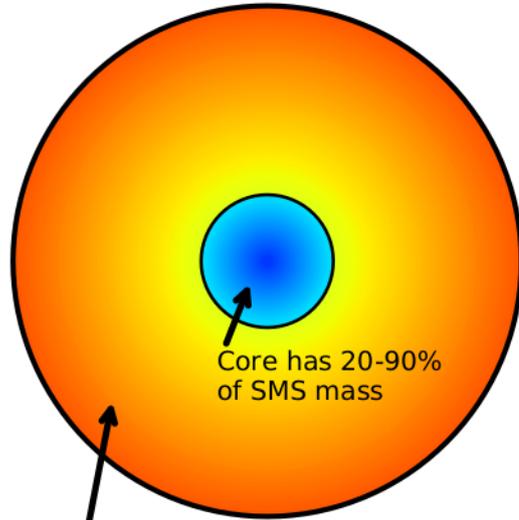
→ Two-zone structure of SMS before H/He-core collapse

→ Kerr BH is quickly formed from monolithic core collapse

→ Accretion torus forms, infalling matter bounces off

Core has 20-90% of SMS mass

Bloated atmosphere of SMS has 10-80% of mass but 99% of radius

$t - t_{\mathrm{BH}} = 6874.65$ s

$\times 10^{14}$

z (cm)

x (cm) $\times 10^{14}$

$\mathrm{Log}\ \rho\ (\mathrm{g/cm^3})$

→ Highly energetic massive ejecta will be produced

[Simulation by Fujibayashi 2024 shows bound region (torus) + ejecta]
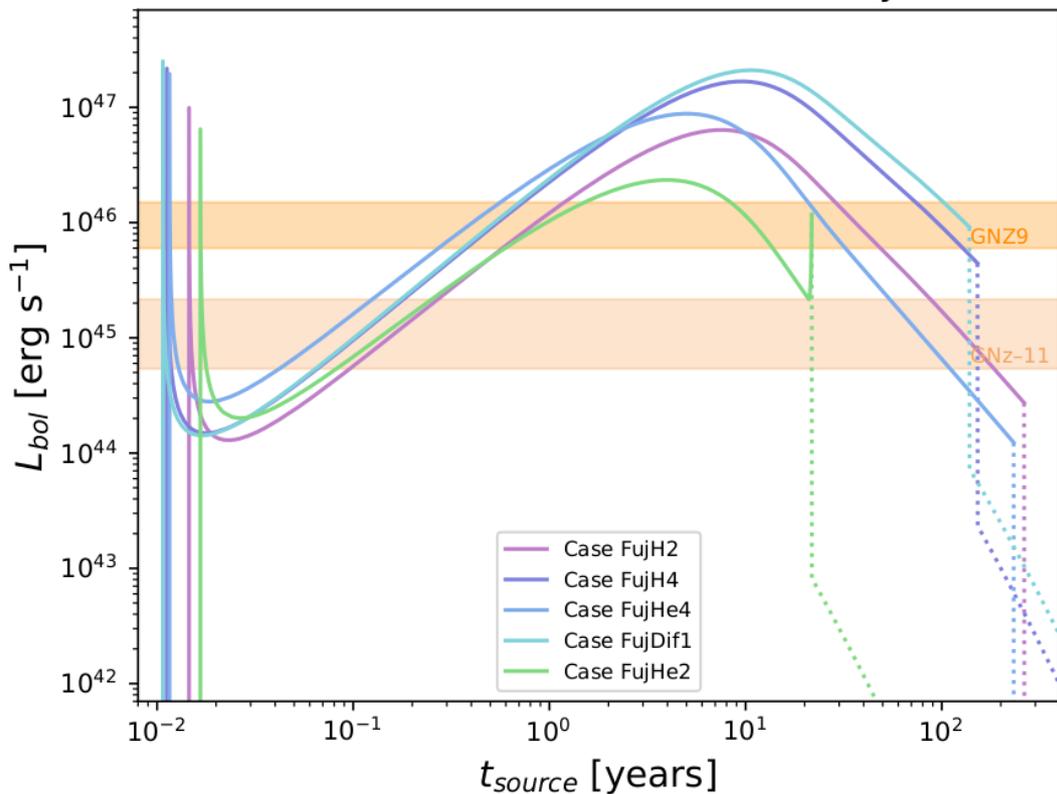
Ejecta properties
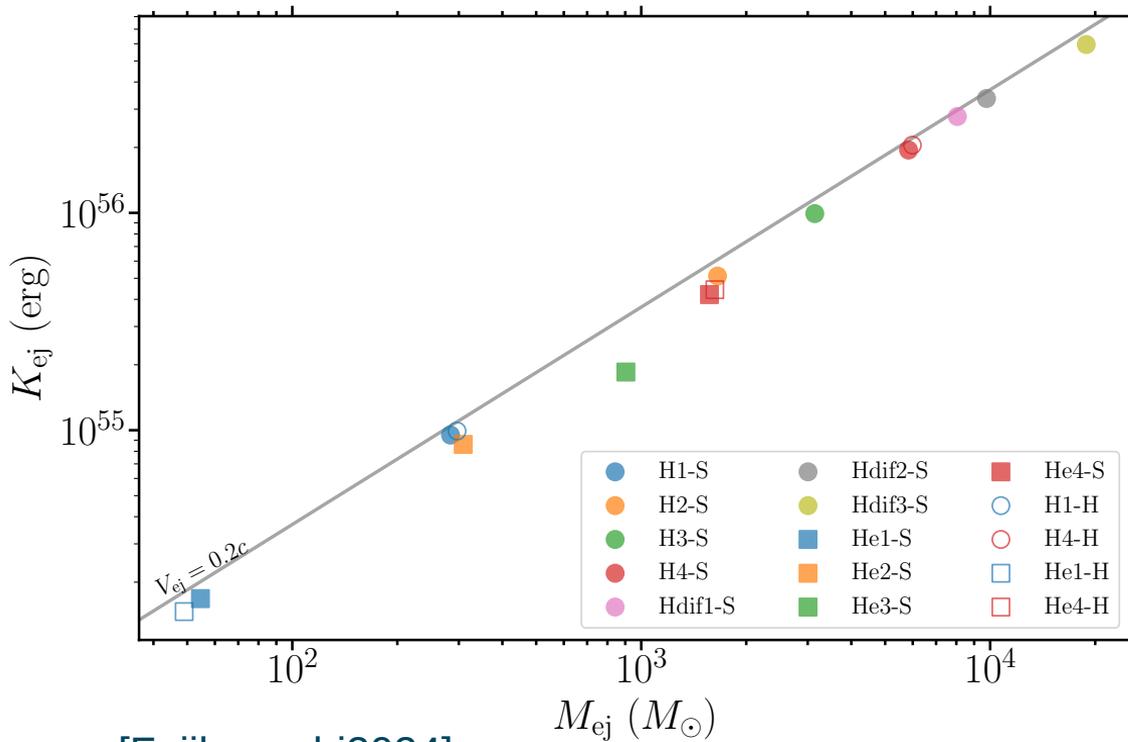
[Fujibayashi2024]

→ Similar to very large Hydrogen rich supernova explosion

→ 10^{55-56} erg typical explosion energy

→ High ejecta masses 10^{3-4} M_{sun} !

→ Average velocity around 0.2c

→ Ejecta from core then sweep through bloated SMS atmosphere (pick up additional ejecta mass)

Bright Bolometric Light Curve

Rest-frame bolometric luminosity

→ Very bright cases ~10^{47} erg/s fall out of thermal equilibrium

→ Photon and electron temperatures rise

→ Recombination phase is prevented

→ Light curve timescale significantly longer, up to 200 years

→ Even longer visibility than less bright cases
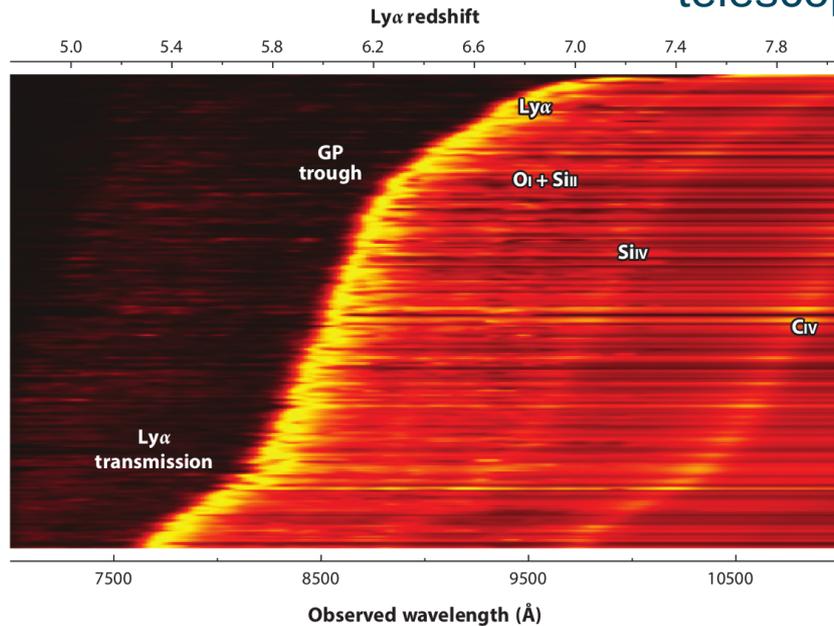
Observing the early universe

$L_{bol}(t)$, T_{eff}, R_{ph},
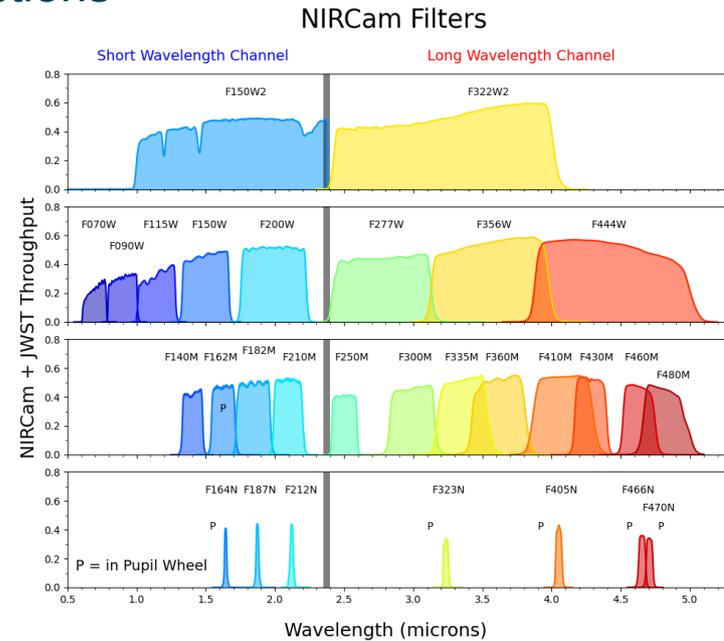i.e. flux F_ν

redshift signal (cosmology)
apply intergalac. absorption
telescope filter functions

final apparent
magnitude

[Fan2023] intergalactic light absorption


[NASA JWST] filter transmission functions

Rate estimation

→ How to compute the intrinsic explosion rate? [Mpc^{-3} yr^{-1}]

→ (1) get volume from survey area and observable redshift depth

→ (2) get time from intrinsic visibility timescale of the light curve

Visible timescale
(e.g. 10 yrs)

Explosion

Survey observation starts

→ assuming non-detection: e.g. with 10^5 Mpc^3 & 10 yrs   we get 10^{-6} Mpc^3 yr^{-1}

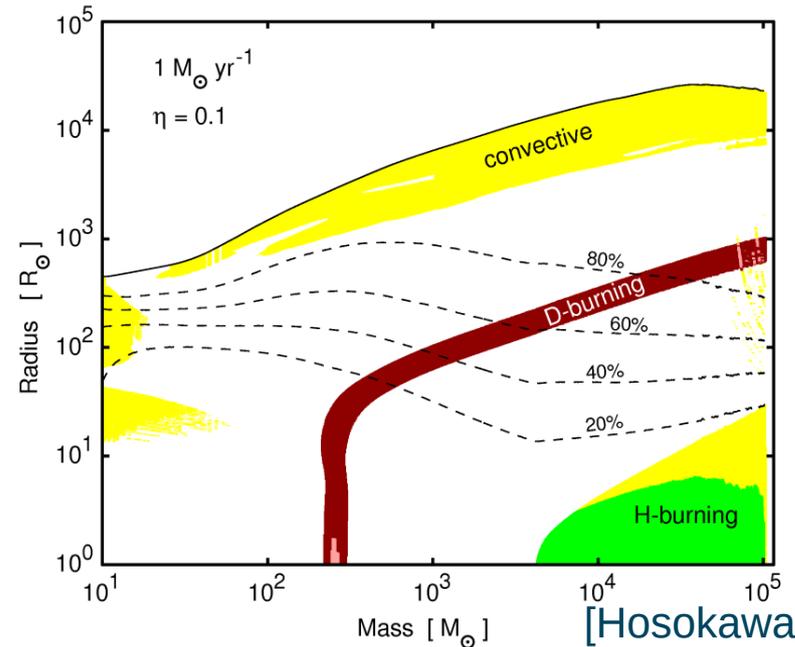# Formation channels for AGN

[Inayoshi2020]
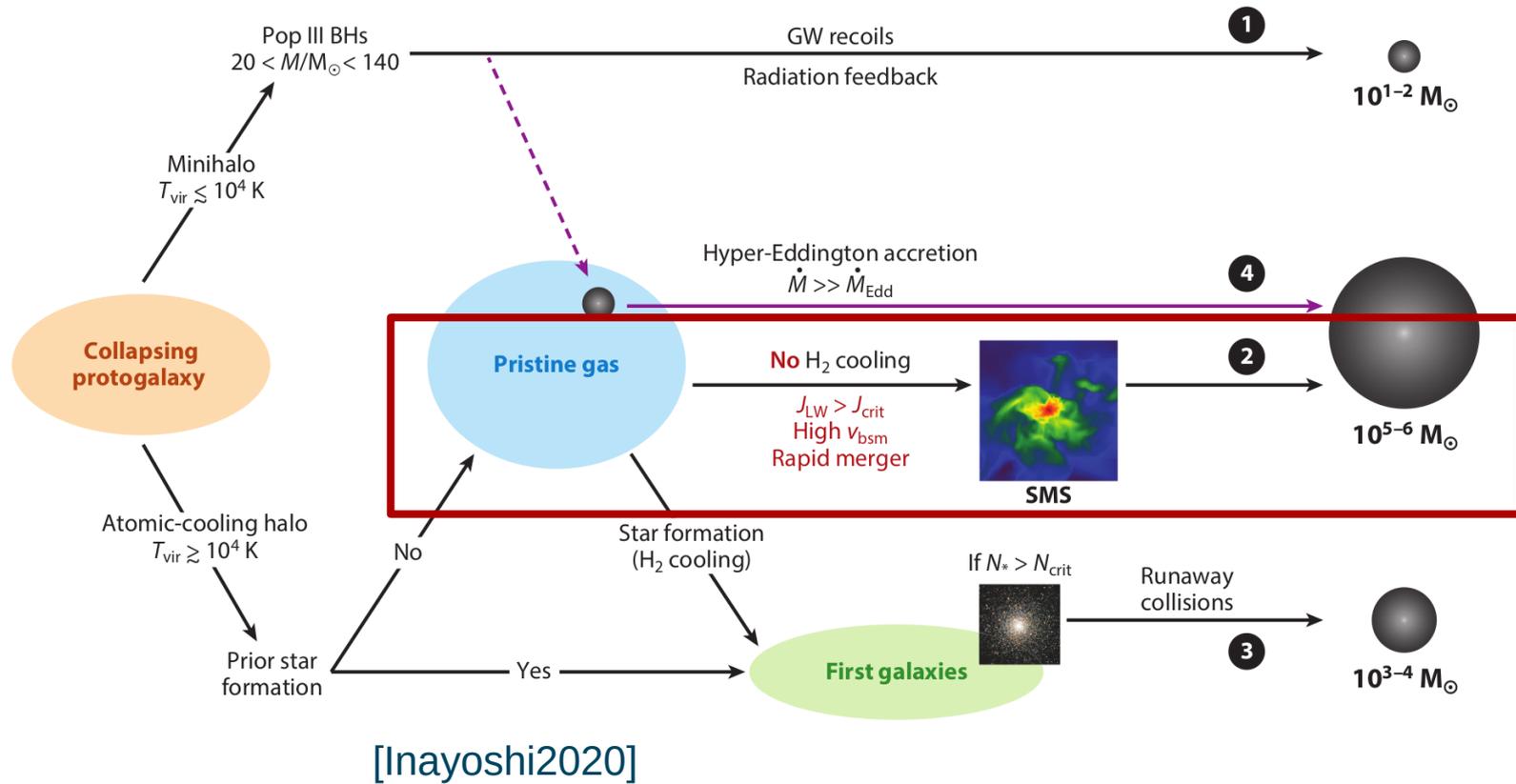
Evolution of supermassive stars

→ Continuous fast accretion, bloated low-density atmosphere
→ Convective H-burning core
→ SMS grow until GR instability ($\sim 10^{5\text{-}6}$ M_{sun}), then monolithic collapse
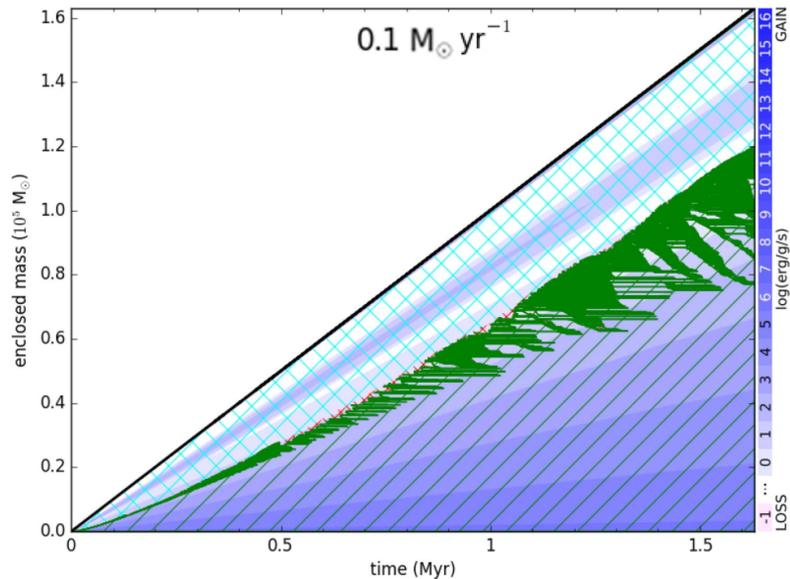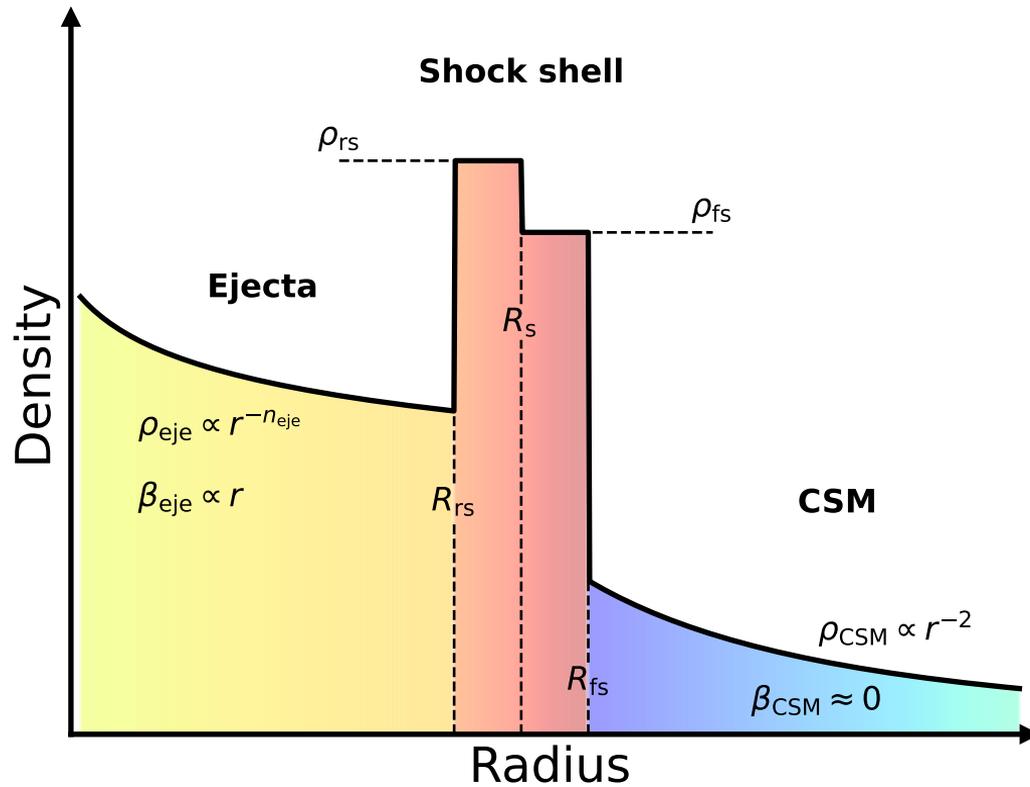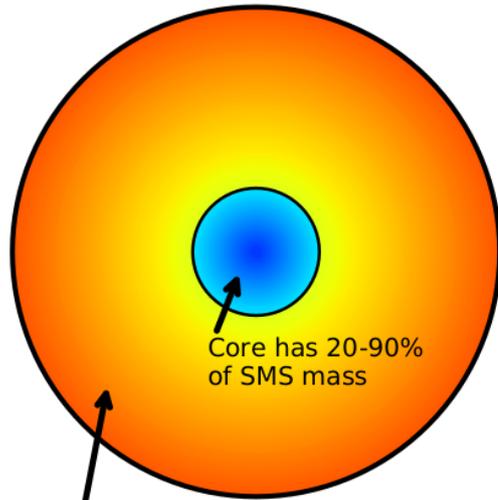

[Woods2017]

[Hosokawa2018]

Shock Structure

Core Collapse and Explosion

Core has 20-90% of SMS mass

Bloated atmosphere of SMS has 10-80% of mass but 99% of radius

→ State of supermassive star before H/He-core collapse

→ Spinning BH ~ 10^{4-5} M_{sun} with accretion torus is formed
→ Infalling stellar atmosphere matter bounces off torus
→ Launch energetic massive ejecta **~10^{54-56} erg**, 10^{3-4} M_{sun}
→ Hydrogen rich ejecta: similar to TypeII supernova explosion

→ Interaction with dense CSM via **optically thick shock:**

Figure from [Suzuki2018]
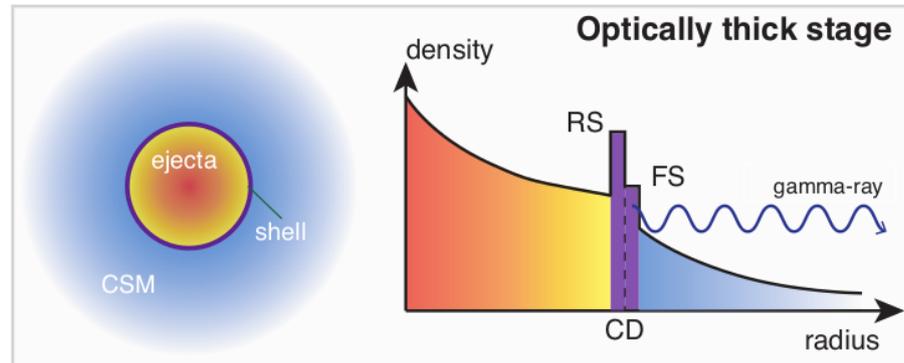
→ SMS in centre of collapsing halo
→ n ~ 10^{10} cm^{-3}
→ $v_{t=0}$ ~ 0.2c
→ Shock-interaction powered supernova light curve