Will we ever see any GRBs from the very first stars?

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Paper
Morales-Rivera, G., R.G., Jane, Beniamini, Granot
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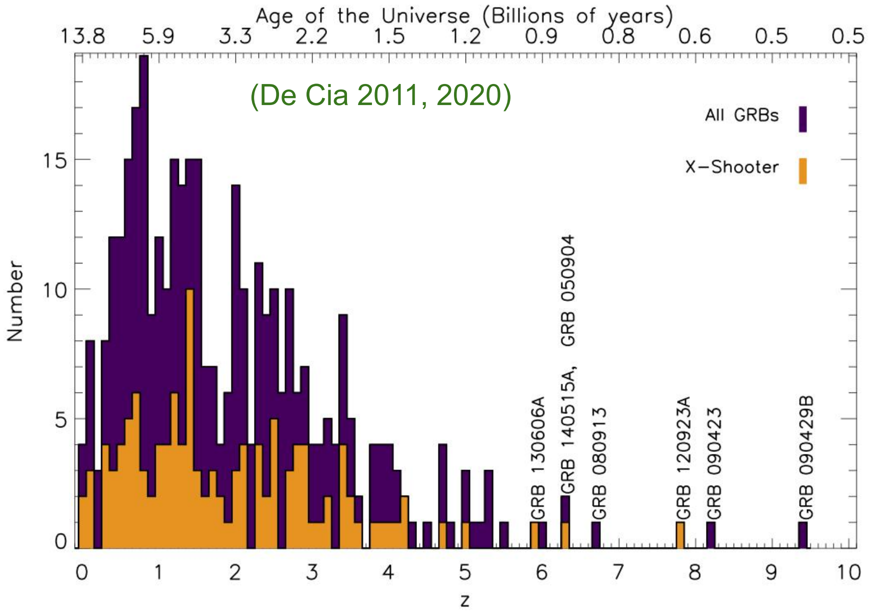
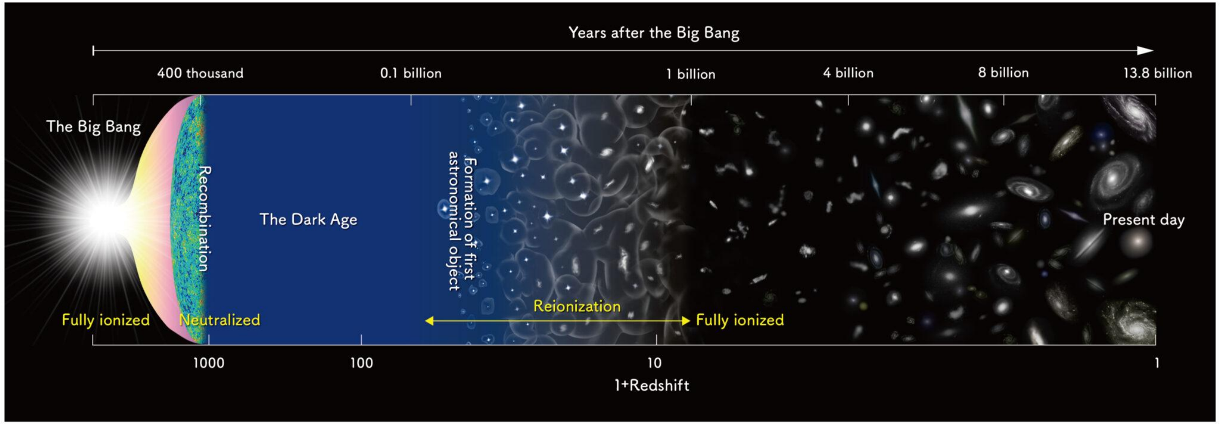
GRBs as cosmological probes



- The intrinsic high luminosity of GRBs allows them to be observed to very high redshifts.
- The prompt gamma-ray emission can be detected up to **z ~ 100** (Lamb & Reichart 2000) and afterglows to **z ~ 30** (IR, X-rays, Radio) (Ciardi & Loeb 2000; Ioka 2003; Inoue 2004)
- This makes GRBs useful probes of the early Universe, that can provide constraints on:
    - Star formation history
    - Stellar evolution
    - Extragalactic background light
    - Lorentz invariance violation

GRBs as probes of the first stars



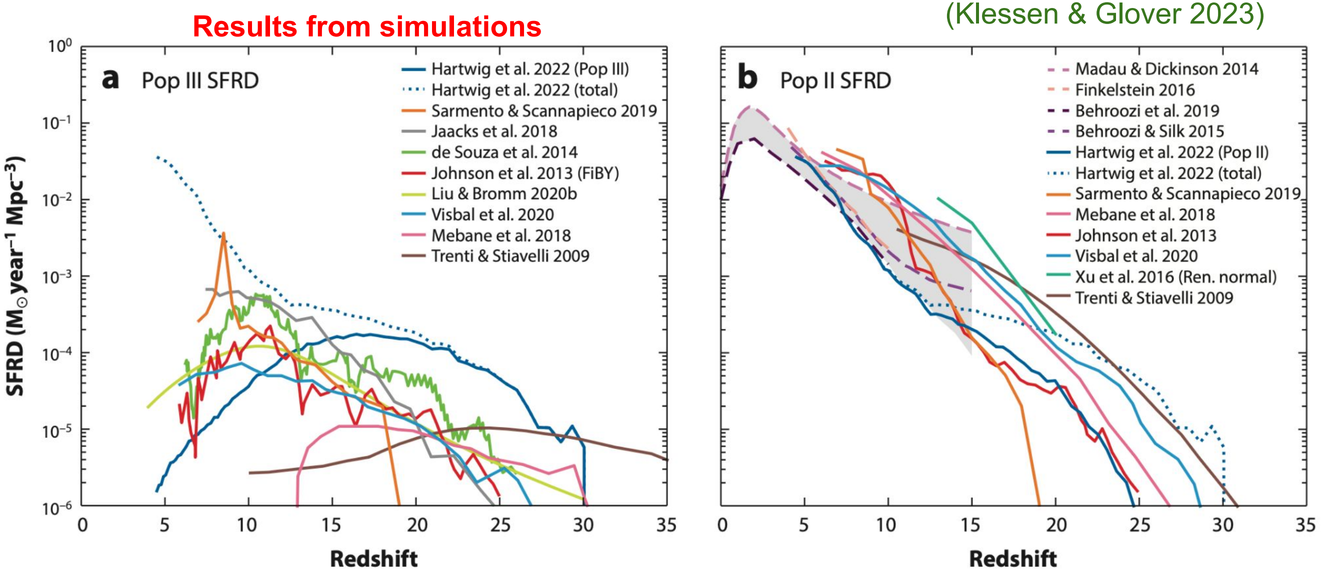
(NAOJ/NOAO)

- The very first stars (Pop III) are very challenging to observe directly, even with JWST!
- In the collapsar channel, long GRBs originate in the core collapse of massive stars that only live for ~ $10^{6.5}$ - 10^7 yr
- Since stars tend to be more massive in the past, some are expected to produce bright GRBs

Pop III stars

- Pop III stars formed from the **metal-free** primordial gas comprising H + He.
- The ΛCDM model predicts their **formation at z ~ 30**, where they **dominated the SFRD at z ~ 15 - 20**, with peak around z ~ 10.

(Klessen & Glover 2023)



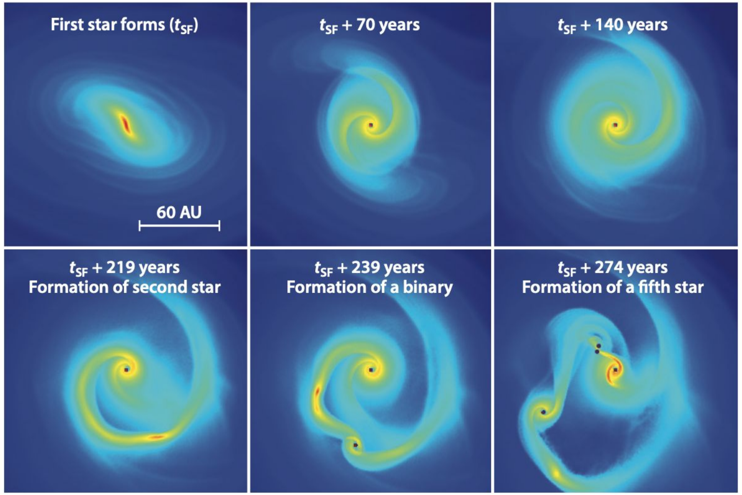
Pop III stars: Initial mass function

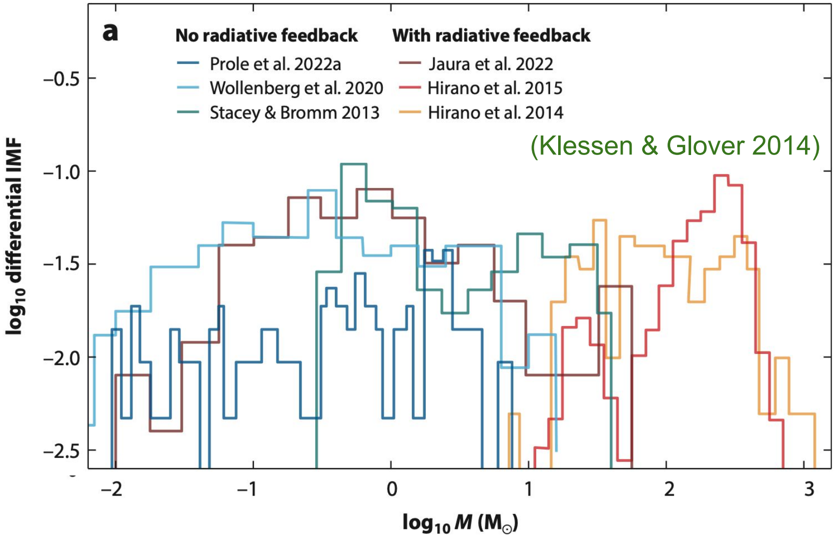
- The IMF of Pop III is expected to be **top-heavy**, with $\alpha \sim 1.13$ (Stacy+2016; Wollenberg+2020), and masses in the range $1 \lesssim M/M_\odot \lesssim 10^3$ (Hirano+2014; Hosokawa+2016)

$$\frac{dN}{d\ln M} \propto M^{1-\alpha}$$

- The present-day IMF is **bottom-heavy** with $\alpha = 2.35$ (Salpeter 1955) with average mass $\langle M \rangle = 0.5 M_\odot$

(Clark+2011)

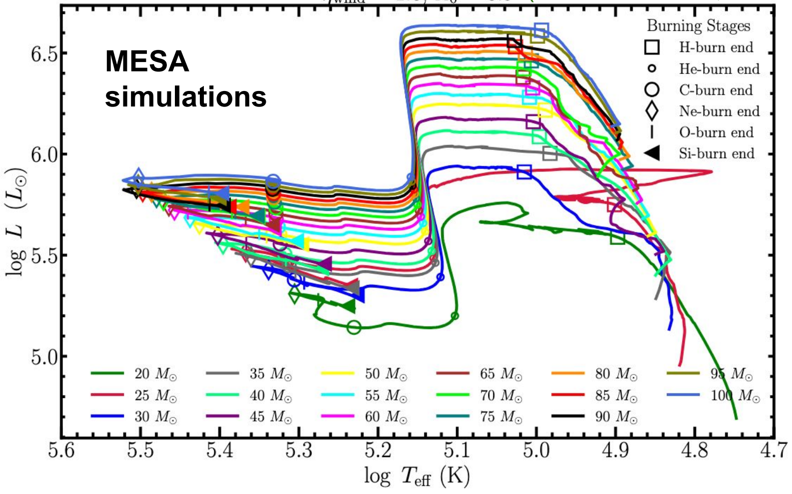




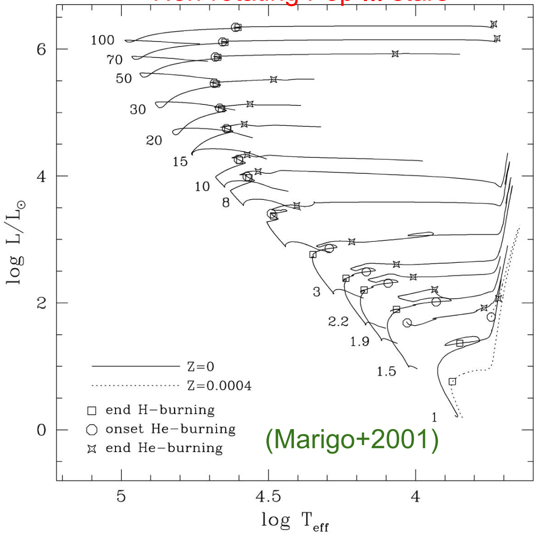
Stellar evolution of rapidly rotating stars

- Pop III stars were also expected to be rapid rotators, with surface equatorial angular velocities approaching the critical limit: $$\frac{\Omega_0}{\Omega_{\rm crit}} \lesssim 1 \qquad \Omega_{\rm crit} = \left(1 - \frac{L}{L_{\rm Edd}}\right)^{1/2} \Omega_k \qquad \Omega_k = \sqrt{\frac{GM}{R_\star^3}}$$
- Rapid rotators undergo a **chemically homogeneous evolution**, that leads to a bluward evolution on the HR diagram resulting in hotter, luminous stars with more massive cores.

$\eta_{\rm wind} = 1.0;\ \hat{\Omega}_0 = 0.9$ (Morales-Rivera, **RG** +2025)



Non-rotating Pop III stars

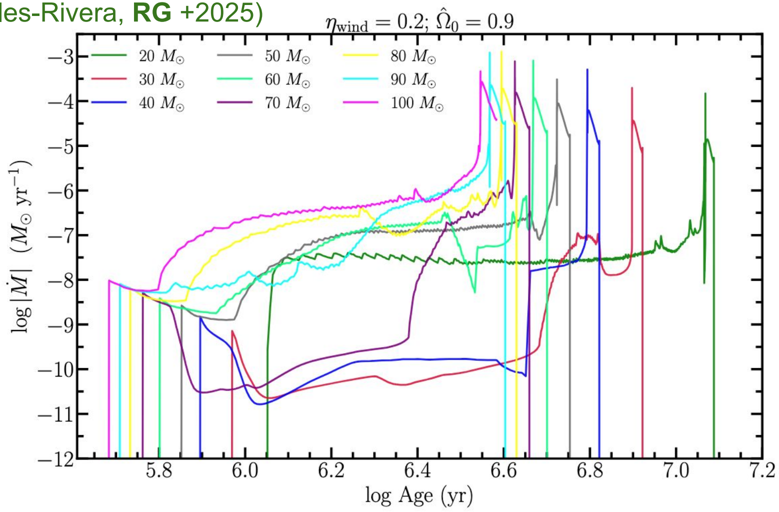


(Marigo+2001)

Mass loss

- Pop III stars can also **lose mass both mechanically and to line-driven winds** even though they initially don't have any metals in their atmospheres.
- Rapid rotation lowers the threshold to mechanical mass loss by providing additional centrifugal acceleration.
- Rotation also drives CHE that mixes metals produced in the core with outer stellar layers.

(Morales-Rivera, **RG** +2025)

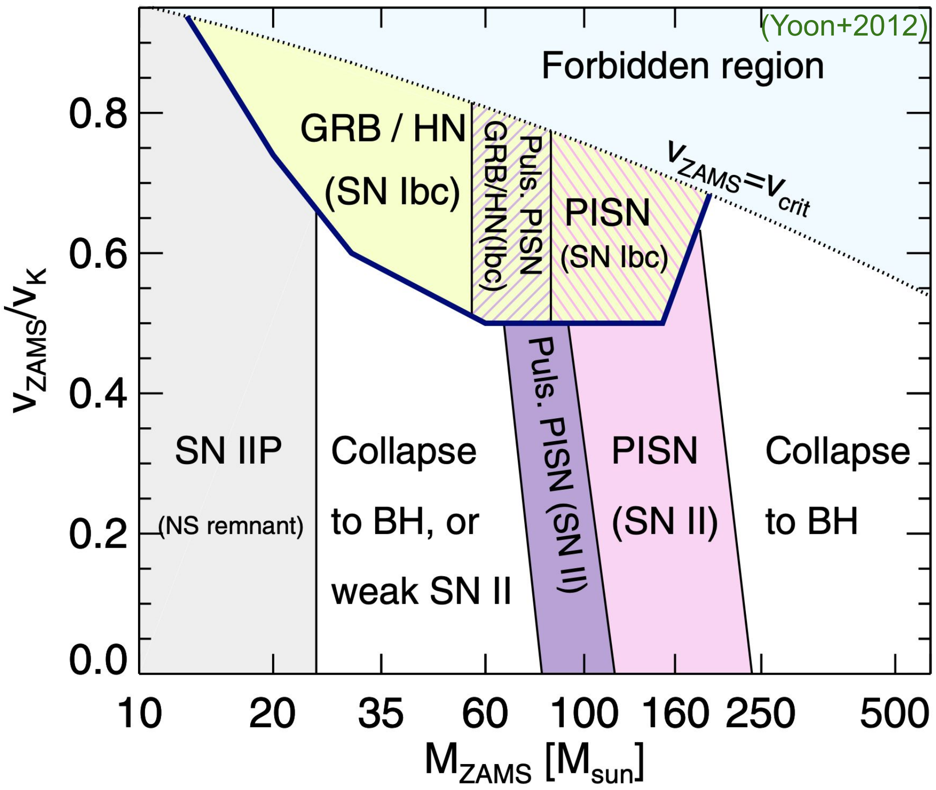


- **How much mass should be lost to line-driven winds** depends on the wind scheme and its efficiency.
- We use the Dutch wind scheme:

$$\dot{M}_{\rm wind} = \eta_{\rm wind}\dot{M}_{\rm Dutch}$$

- The amount of mass loss is consistent with that expected in more metal-rich Wolf-Rayet stars

Final outcome of rotating Pop III stars



Requisites to produce a GRB

- The collapsar engine requires the formation of a **rapidly spinning BH** accreting stellar material at **high mass accretion** rates
- This requires that the specific angular momentum of the infalling stellar material exceeds

$$j \gtrsim 3 \times 10^{16}\,\mathrm{cm\,s}^{-1}$$

for a BH with mass $M_{\rm BH} = 5M_\odot$

- The jet power exceeds a critical value below which the jet can be choked.
- The engine remains active for long enough to break out of the star and power the GRB:

$$t_{\rm eng} = t_{\rm bo} + t_{\rm GRB}$$

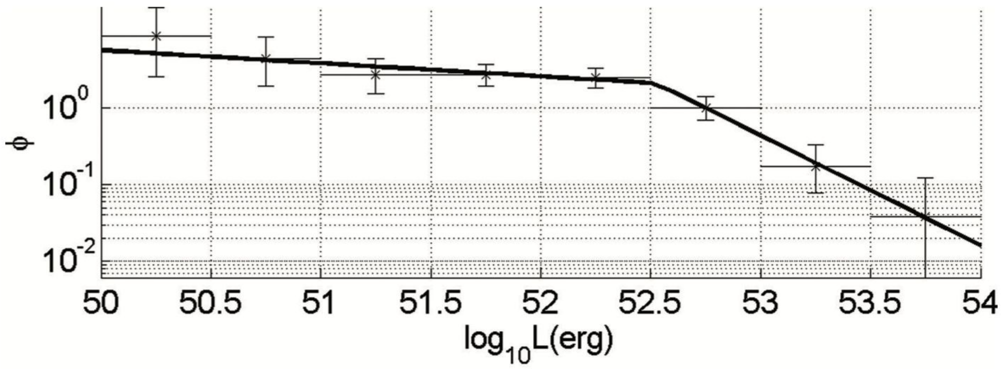
Detection rate of Pop III GRBs

- The observed rate of GRBs is obtained from: $\frac{dN_{\mathrm{GRB}}}{dt_{\mathrm{obs}}} = \eta_{\mathrm{beam}} \int_0^z dz\, \Psi(z) \int_{L_{\mathrm{lim}}(z)} \Phi(L) d\log L$

$\eta_{\mathrm{beam}} = \frac{\Delta\Omega}{4\pi} \approx \frac{\theta_j^2}{2} \sim \frac{1}{500}$ = beaming fraction (Frail+2001)

$\Phi(L)$ = luminosity function of GRBs above a detector-dependent limiting threshold luminosity $L_{\mathrm{lim}}(z)$

(Wanderman & Piran 2010)



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- The local comoving rate of GRBs at any redshift is given by:

$$\Psi(z) = \frac{d^2 N_{\rm GRB}}{dt_{\rm obs}\, dz} = \eta_{\rm GRB}(z) \frac{\dot{\rho}_\star(z)}{1+z} \frac{dV}{dz}$$

$\dot{\rho}(z)$ = local SFR, $\frac{dV}{dz}$ = local volume element per unit redshift

- **The efficiency of producing GRBs per unit stellar mass depends on the IMF and the rotation distribution of Pop III stars:**

$$\eta_{\rm GRB} = \frac{\int_{m_{\rm low}}^{m_{\rm high}(\hat{\Omega}_0)} \xi(m)\, P_{\rm rot}\left(\hat{\Omega}_0\right) dm\, d\hat{\Omega}_0}{\int_{m_{\rm min}}^{m_{\max}} m\, \xi(m)\, dm} \qquad P_{\rm rot}\left(\hat{\Omega}_0\right) \propto \hat{\Omega}_0^\delta \qquad 0.6 \leq \hat{\Omega}_0 \leq 1$$

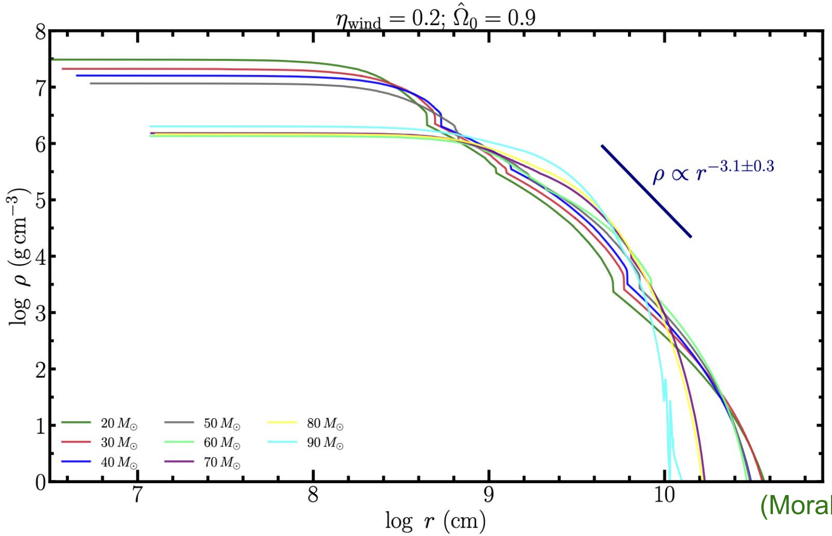
MESA simulations: Stellar structure at core collapse

- We perform MESA simulations for a grid of Pop III stars with:

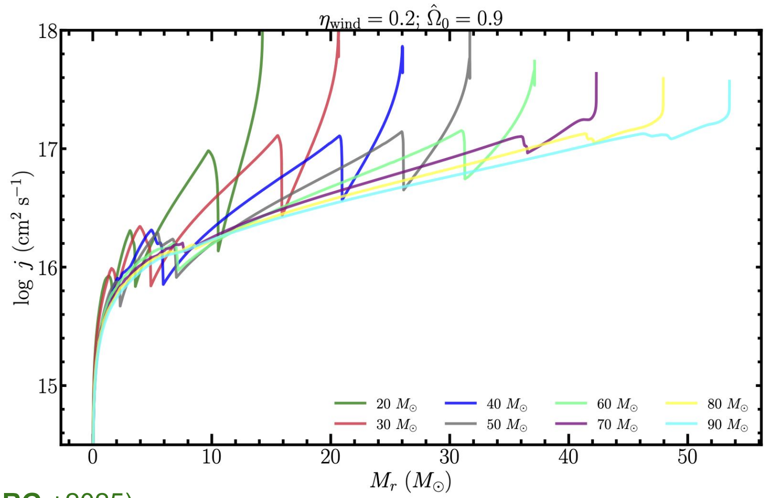
Initial stellar mass: $20 \leq \frac{M_{\rm ZAMS}}{M_\odot} \leq 100$ rotation rate: $0.6 \leq \frac{\Omega_0}{\Omega_{\rm crit}} \leq 0.9$ Wind efficiency: $0.2 \leq \eta_{\rm wind} \leq 1$

- Stars are evolved to just before core-collapse or depletion of core Silicon in the advanced burning stage.

Stellar density profile



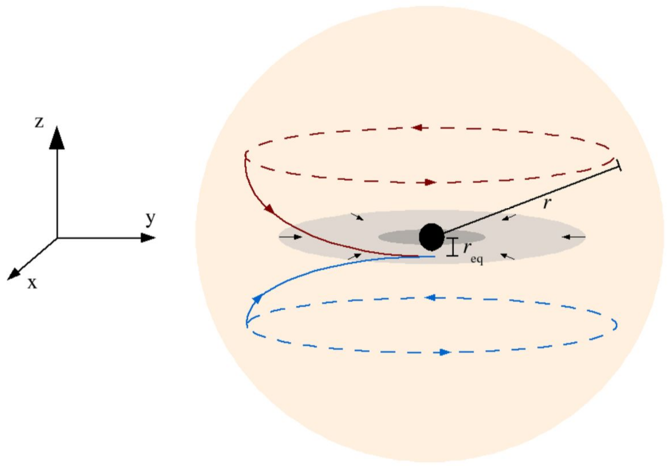
Specific angular momentum profile

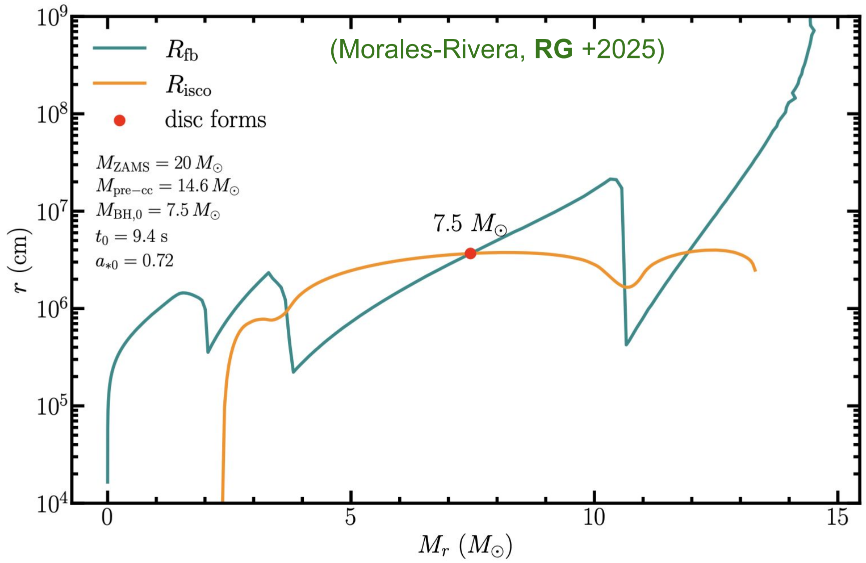


(Morales-Rivera, **RG** +2025)

Model of fallback and accretion

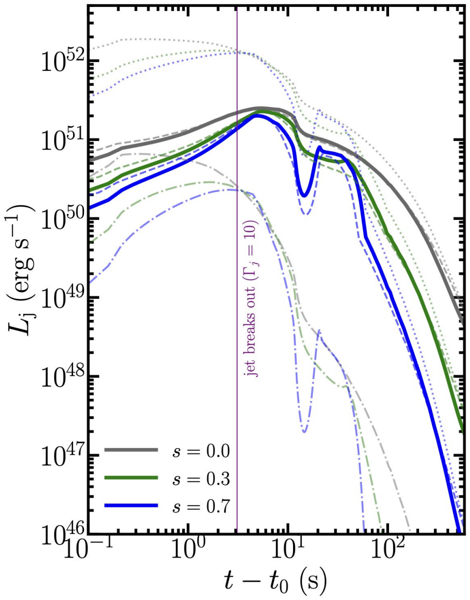
- We construct a semi-analytical model of stellar material fallback onto the equatorial plane and BH if lacking sufficient angular momentum (Kumar, Narayan, Johnson 2008).
- Initially, the core forms a proto-NS that promptly collapses into a BH due to fallback accretion
- Material continues to plunge directly into the BH until it circularizes outside of R_{ISCO} and forms a disc.





BH properties & jet power

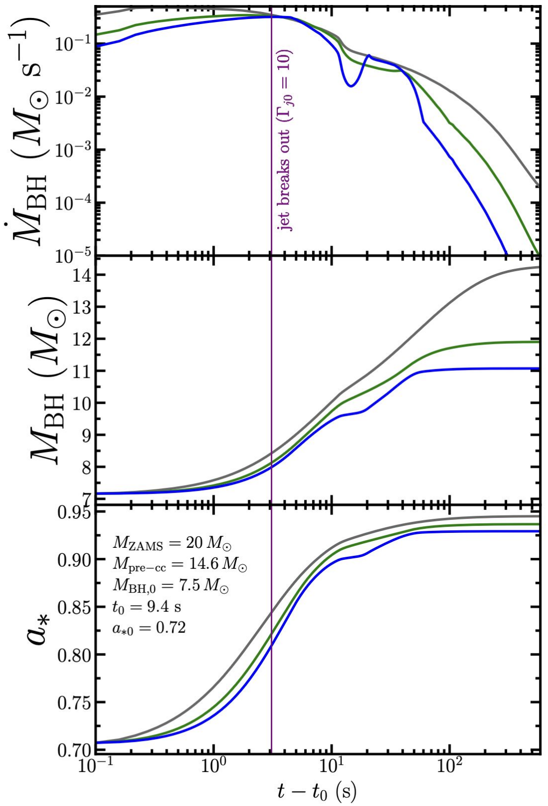
- From the mass fallback rate, we calculate the rate of accretion and growth of BH mass and its spin.
- We account for the mode of accretion: NDAF, ADAF, or combination, and disc-driven outflows.



- Since we don't know how GRB jets are launched, we calculate the jet power for two launching mechanisms:
  - Neutrino and anti-neutrino annihilation
  - Jet efficiency obtained from GRMHD simulations

$$L_j = \eta_j(a_\star)\dot{M}c^2$$

  - Jets from magnetically arrested discs

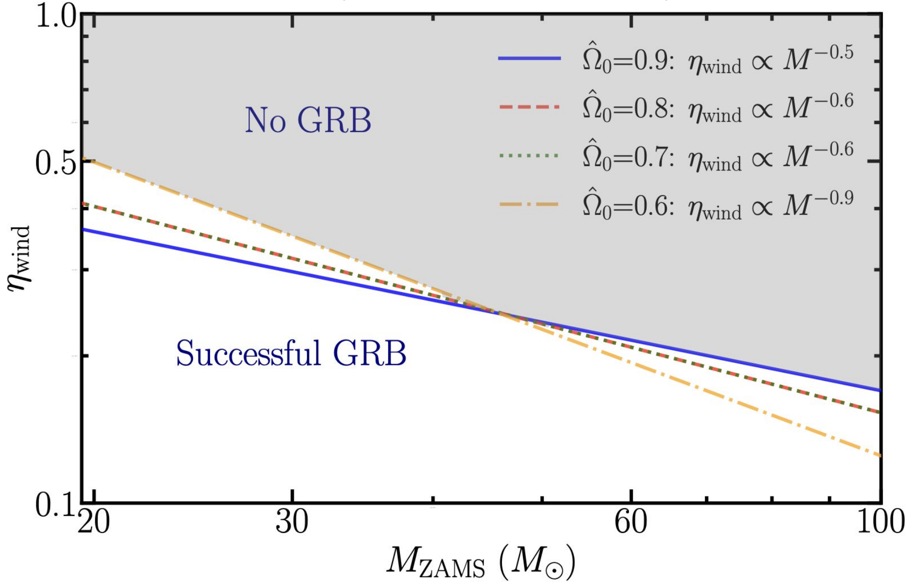


(Morales-Rivera, **RG** +2025)

Phase space for producing a GRB

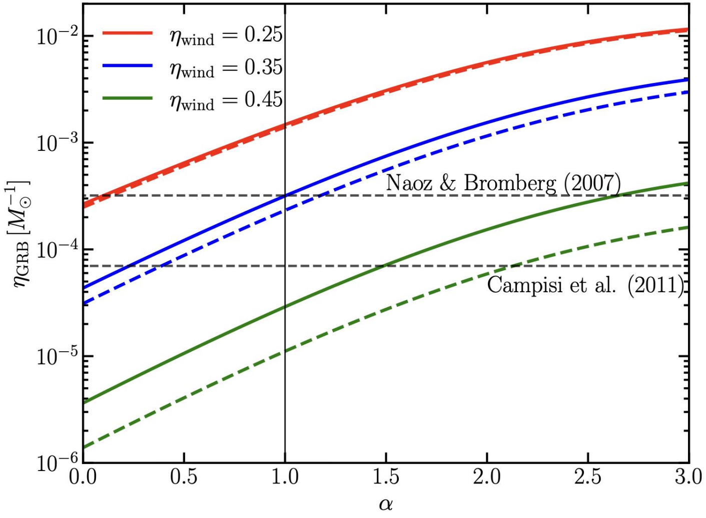
- This new phase space factors into the effects of **rotation**, **wind mass loss**, **jet launching** and **breakout**.
- For any given mass, the wind efficiency must be smaller than some critical value. Otherwise, the star will lose too much mass and angular momentum.
- The maximum ZAMS mass up to which Pop III stars can produce a GRB depends on the initial rotation rate for a given wind efficiency.

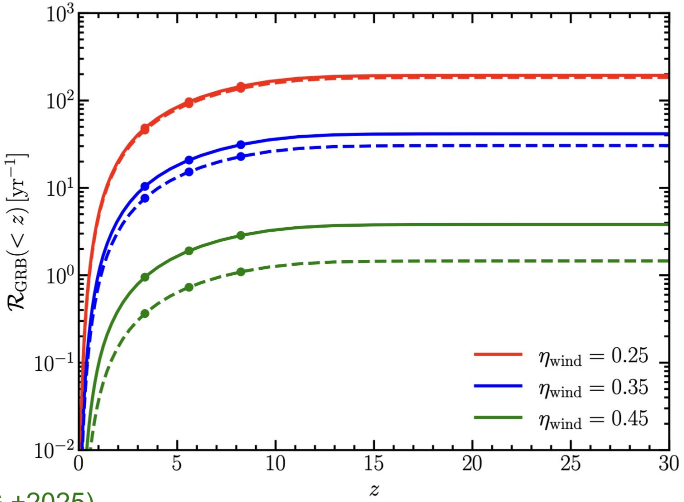
(Morales-Rivera, **RG** +2025)



GRB production efficiency & rate

- GRB production rate drops with increased wind mass-loss efficiency as more angular momentum is lost.
- Top-heavy IMF also leads to a low production efficiency due to the cap on the high-mass for a given wind mass-loss efficiency.
- 75% of the GRBs in the total integrated rate come from z < 8.





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Conclusions

- The efficiency of GRB production per unit mass (or rate of GRBs) is very sensitive to the wind mass-loss efficiency and/or scheme.
- Observed rate of high-z GRBs can constrain this highly uncertain mass-loss efficiency.
- For $\eta_{\rm wind} = 0.45$ and a flat IMF, $\eta_{\rm GRB} \sim 10^{-5} M_\odot^{-1}$ that yields a **detection rate of ~4 - 5 Pop III GRBs over the past 20 years of Swift/BAT**

- We find that GRBs from Pop III progenitors are **similar in their intrinsic properties with standard GRBs**, which makes it hard to discern their high-z origin.
- This degeneracy may be broken with **high-resolution IR spectroscopy** and by looking for absence of absorption from iron-group elements.

- If we don't detect an all-sky rate of 2 GRBs per year for a Swift/BAT-type detector, then the wind mass-loss must be high and/or these stars are born as slow rotators.
- In that case, only **progenitors in a binary** may be able to produce the right conditions for GRB production.