arXiv: 1009.6001

Gamma-Ray Bursts of First Stars

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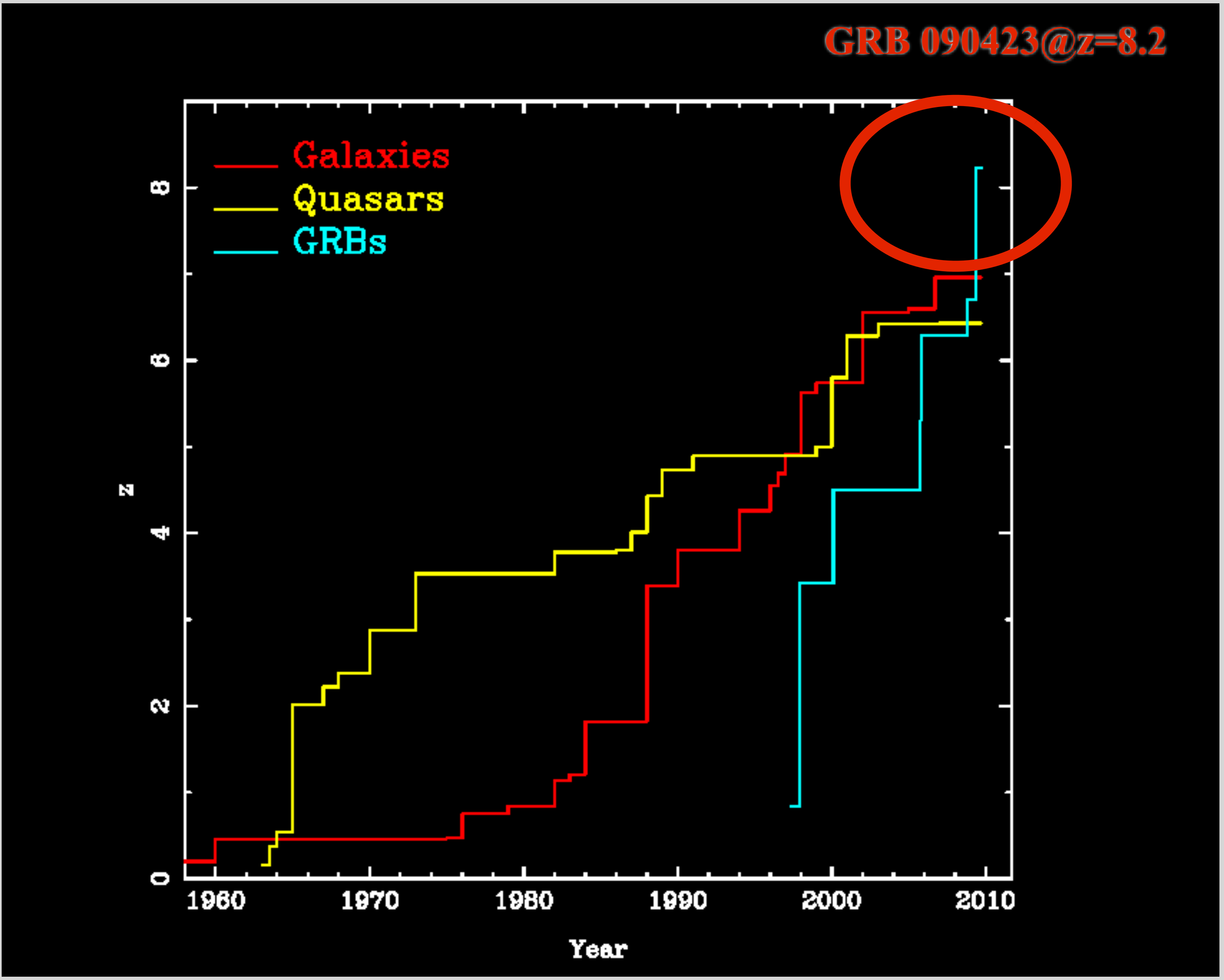
Collaboration with K. Ioka

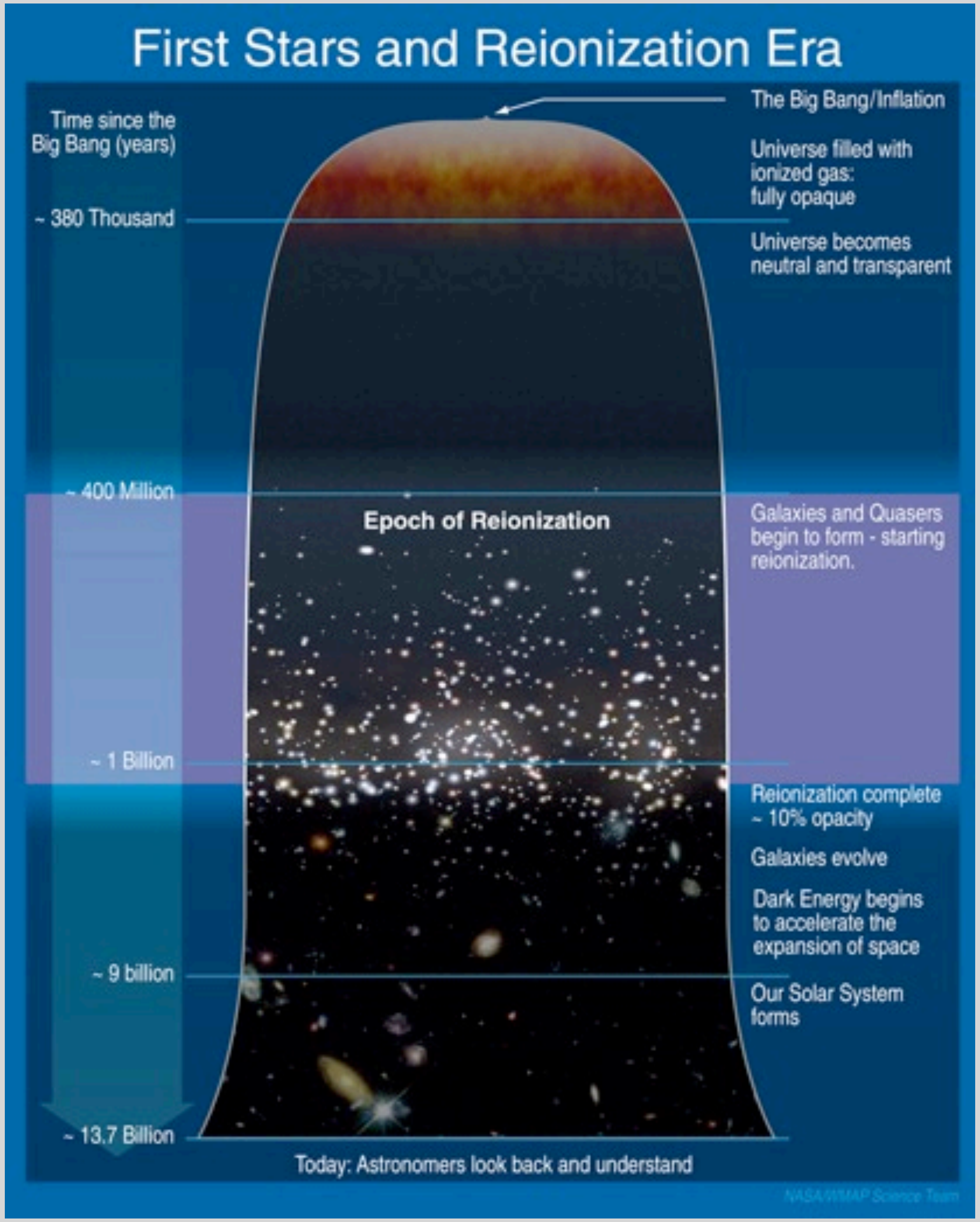
Most distant object?

Tanvir's talk @ Kyoto 2010



- We observed a high-z GRB 090423 (z~8.3), which was the most distant object we observed ever.
- Can we reach the first object in the universe?

The First Stars

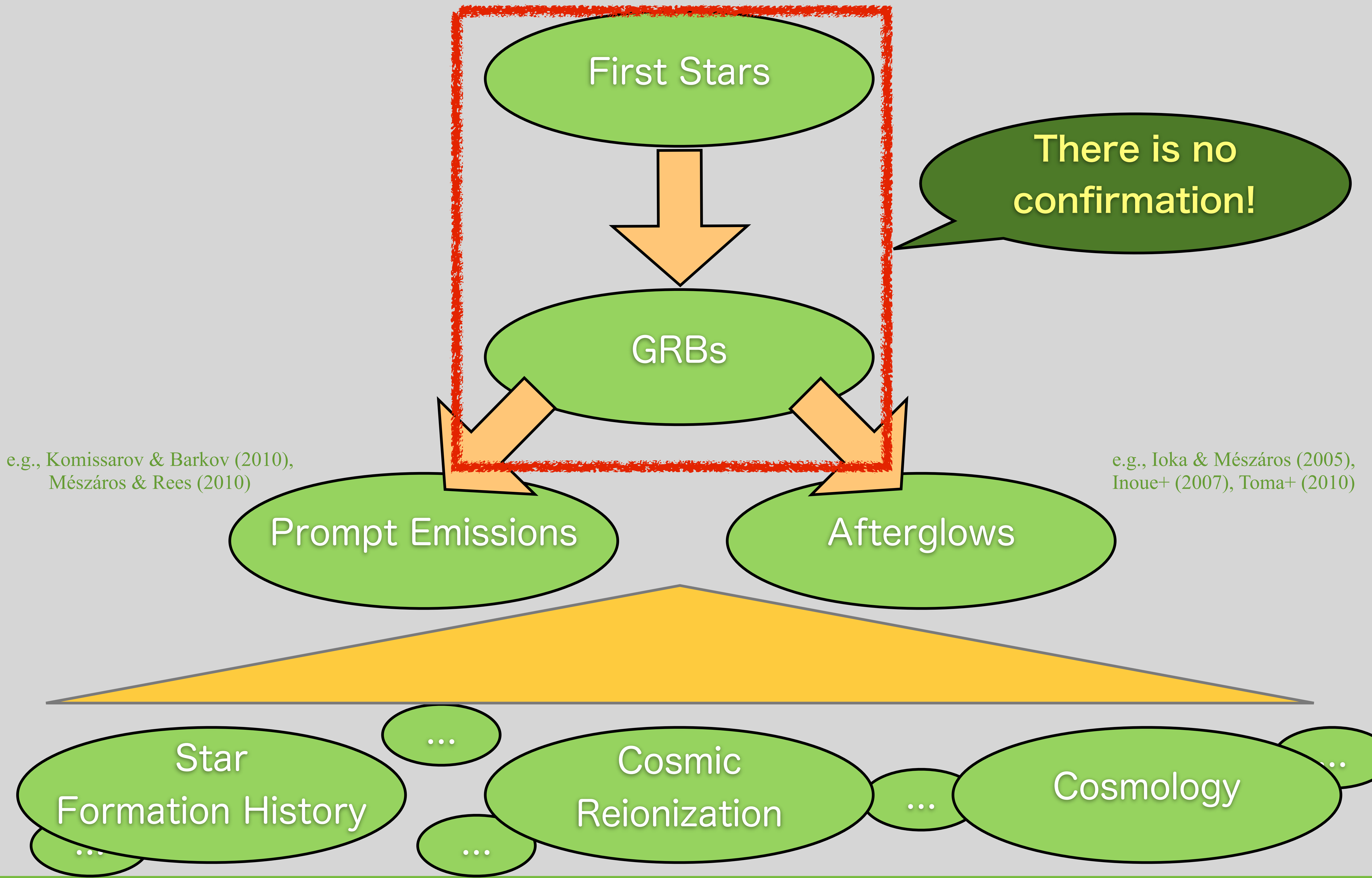


http://imagine.gsfc.nasa.gov/docs/sats_n_data/satellites/jwst_darkages.html

- Metal free
- Predicted to have been very massive(>~100M$_\odot$)
- The end of the cosmic "dark age"
- Related to reionization
- Difficult to observe

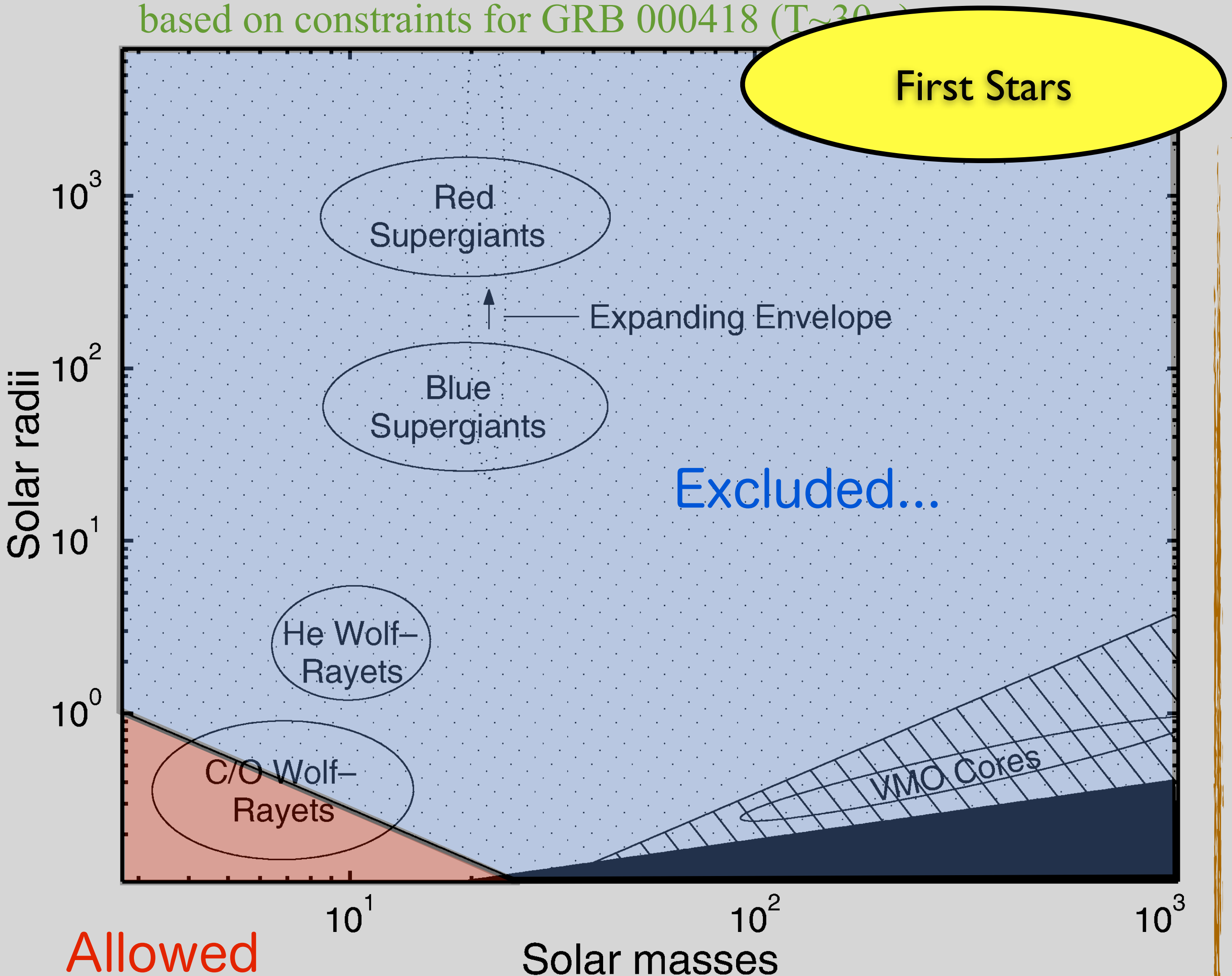
Can we observe the first stars using the "FIRST GRB"??

The First GRB studies so far



Can the First Stars Produce GRBs?

Matzner 03
based on constraints for GRB 000418 (T~30



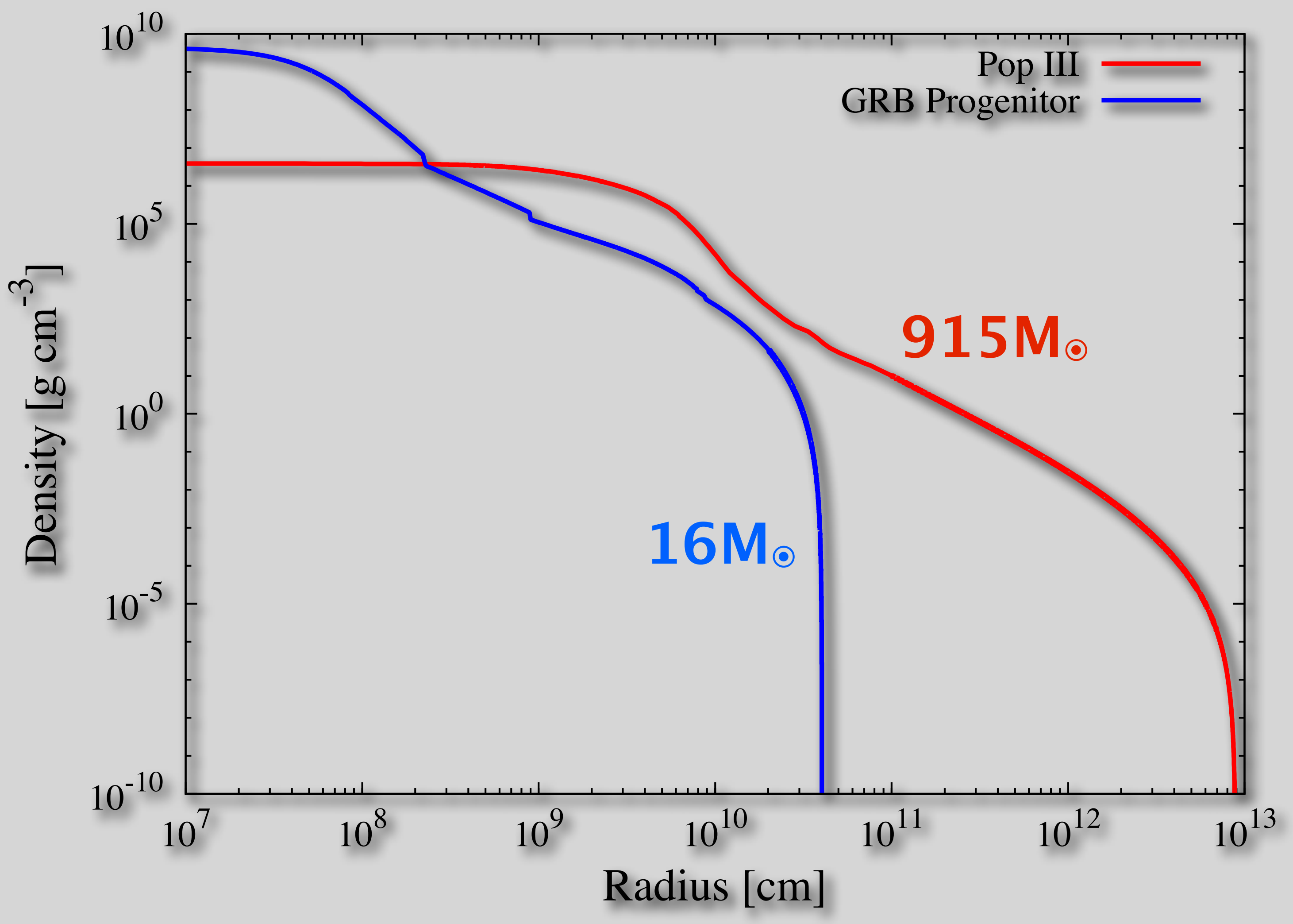
Allowed
☞ GRB progenitor

"Canonical" condition for *successful* GRB production

- Jet can penetrate the stellar envelope within the *duration*
  - ☞Star must be compact enough
  - ☞H envelope (expands to R~ $10^{13\text{-}14}$cm) should not be present (consistent with GRB-SN Ibc association)

☞The first star (with H envelope due to weak mass loss) could not produce a GRB??

Stellar Structure



Pop III: Ohkubo et al. (2009)
GRB: Woosley & Heger (2006)

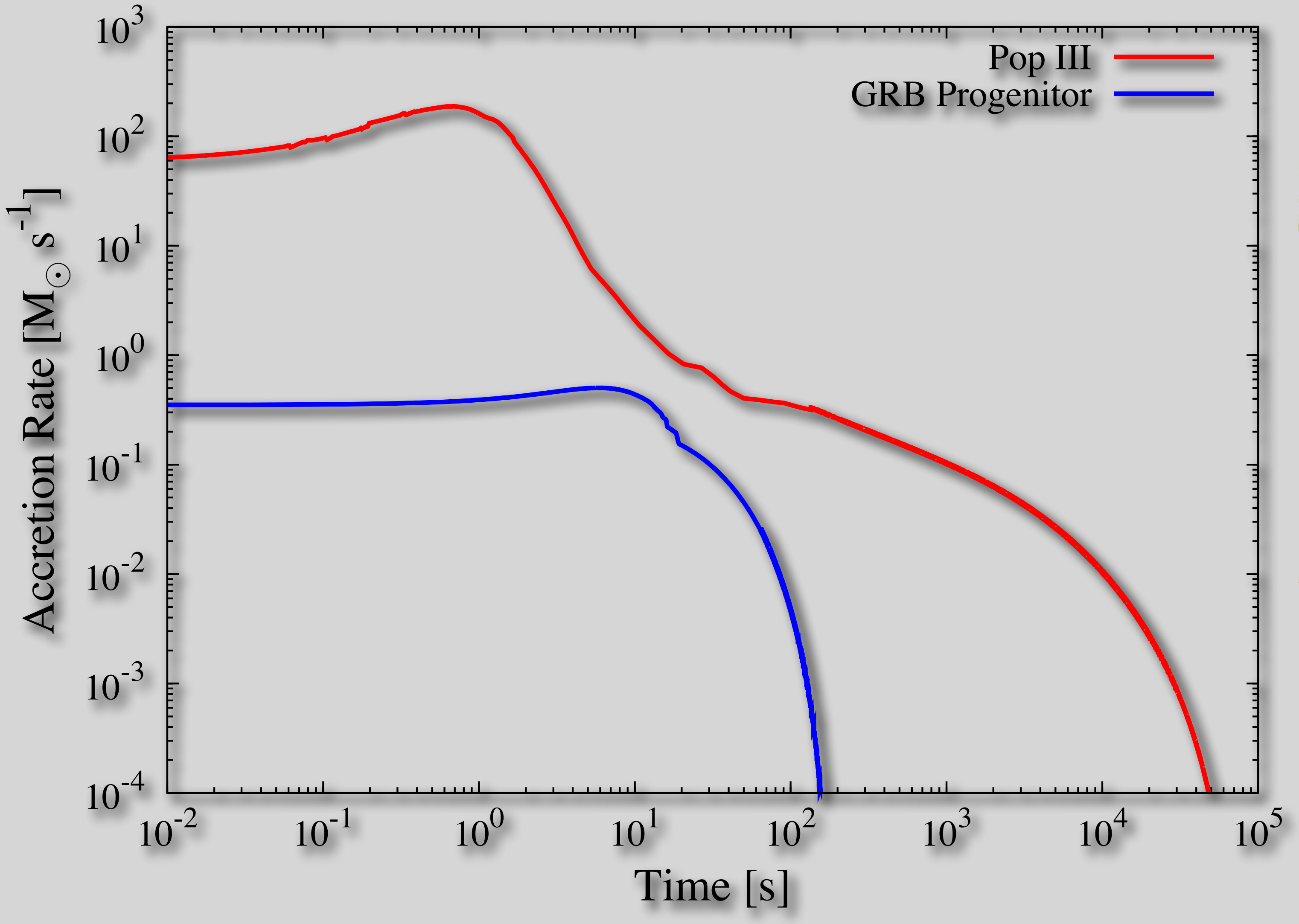
Stellar evolution calculations say...

- The first stars encounter the giant phase before core collapse (w/ radiative envelope; r~10^{13}cm)
- GRB progenitors are expected to be Wolf-Rayet stars (w/o large envelope)

Is it difficult for the first stars to produce successful GRBs?

- Question “Can the first stars produce GRBs?”
  - Absence of H envelope is required for successful GRB
  - But the first stars might not loose their massive envelope
  - More investigations are necessary

Accretion Rate

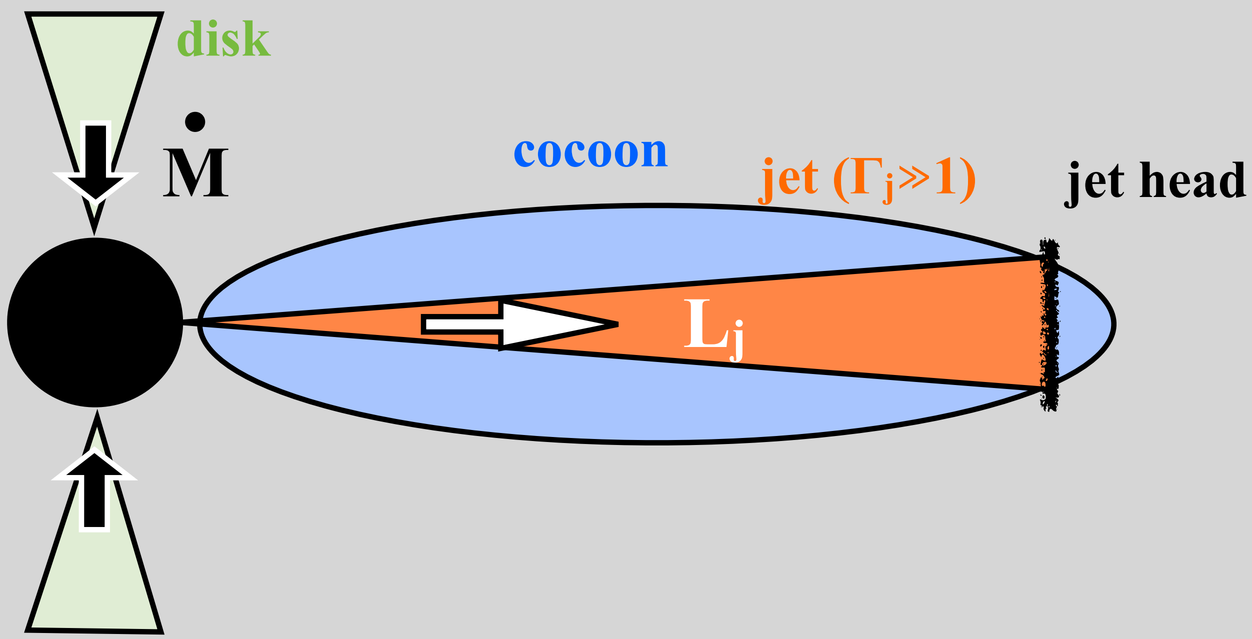


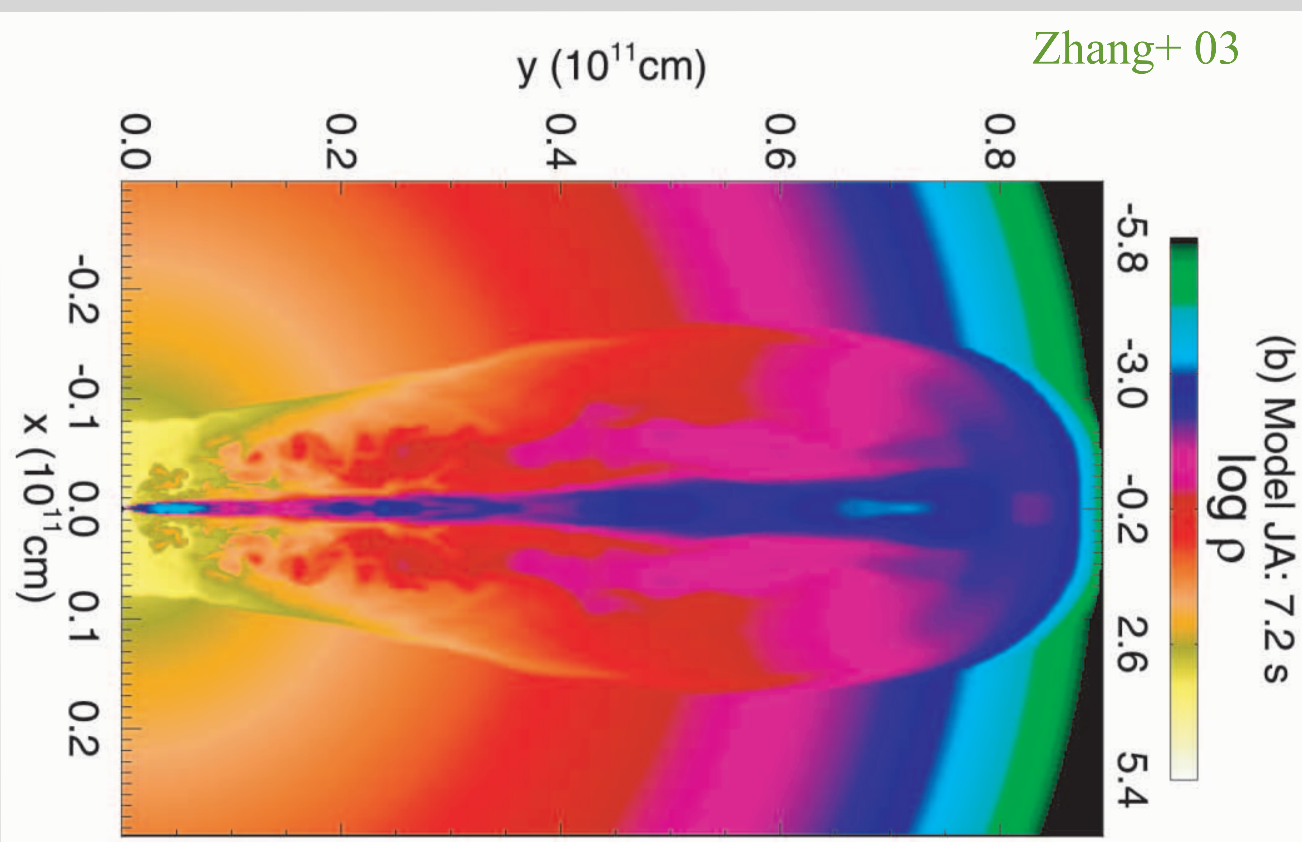
$$\dot{M} \sim \frac{\Delta M}{\Delta t_{acc}(M)} \qquad t_{acc}(M) \sim \sqrt{\frac{R^3}{GM}}$$

- **The first stars achieve larger accretion rate** than GRB progenitor at any time
- **Duration is also longer** (~10^4 s for $\gtrsim 0.01\ M_\odot$/s)

It looks hopeful to penetrate the massive stellar envelope!

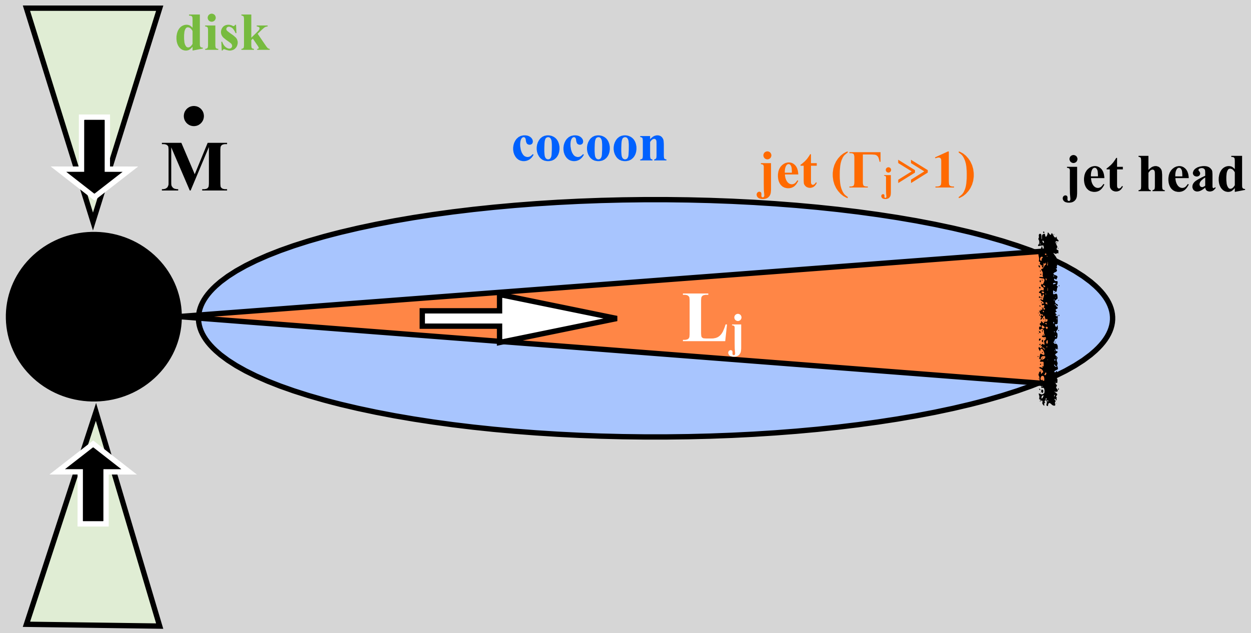
Collapsar Model





- Accreted matter is ejected as a relativistic jet
- If $\Gamma_h < \theta_j^{-1}$, the shocked material may escape sideways
  - Cocoon production
  - Avoidance of baryon loading problem
- If the jet head could break out the stellar surface, GRB will be produced!

Propagation of a Jet



- Energy balance around the shock
  - Non relativistic
  - Ultra relativistic

$$\beta_h \Gamma_h^2 \approx 18 \left(\frac{L_{\rm iso}}{10^{52}\ {\rm erg\ s^{-1}}} \right)^{1/2} \left(\frac{r}{10^{12}\ {\rm cm}} \right)^{-1} \left(\frac{\rho}{10^{-7}\ {\rm g\ cm^{-3}}} \right)^{-1/2}$$

- Propagation time of forward shock $t_h \approx \frac{r}{\Gamma_h^2 \beta_h c}$
- Combining these equations we obtain the necessary luminosity for the jet head to propagate outward

$$L_{\rm iso} \approx 3 \times 10^{54}\ {\rm erg\ s^{-1}} \left(\frac{r}{10^{12}\ {\rm cm}} \right)^4 \left(\frac{\rho}{10^{-5}\ {\rm g\ cm^{-3}}} \right) \left(\frac{t}{1\ {\rm sec}} \right)^{-2}$$

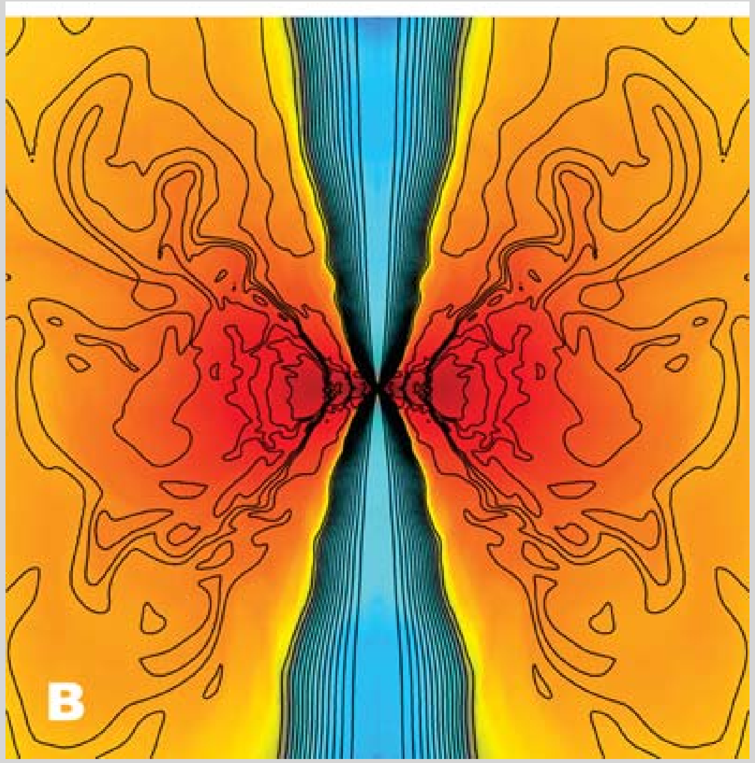
Jet Luminosity

- We do not have any concrete observational evidence of the central engine
- The well-discussed models;
  - Magnetic field (Blandford-Znajek process)
    $L_j \propto \dot{M} c^2$ [Komissarov & Barkov 09]
  - Neutrino annihilation
    $L_j \propto \dot{M}^{9/4} M_{BH}^{-3/2}$ [Zalamea & Beloborodov 10]

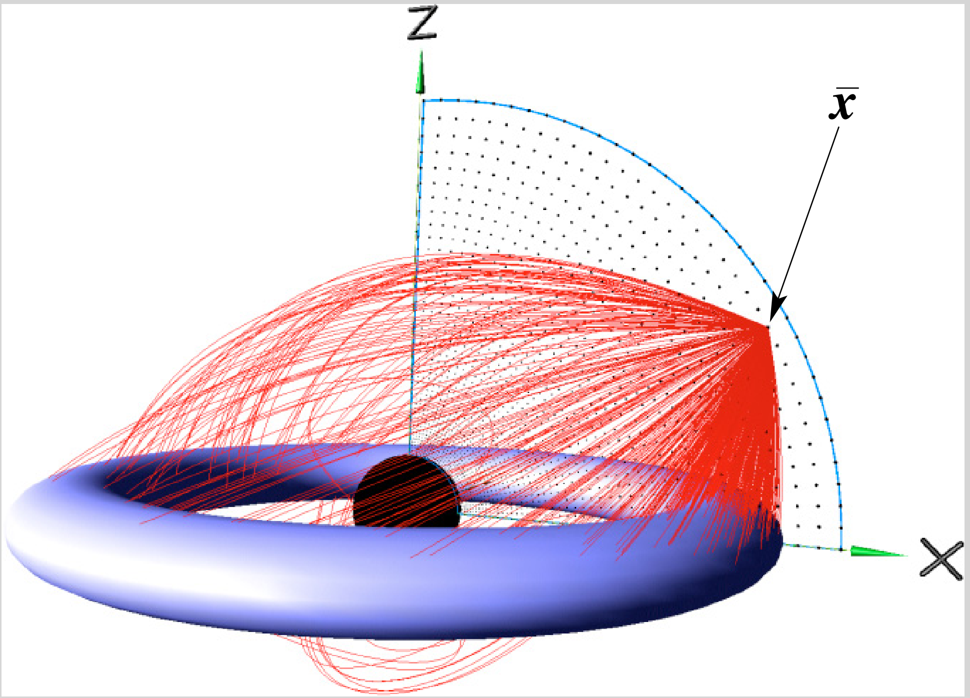
※ We calibrate the overall factor using the GRB progenitor to reproduce the observational characteristics

- The injected energy after the break out: $E_j = 10^{52}$ erg
- The jet opening angle: $\theta_j = 5^\circ$

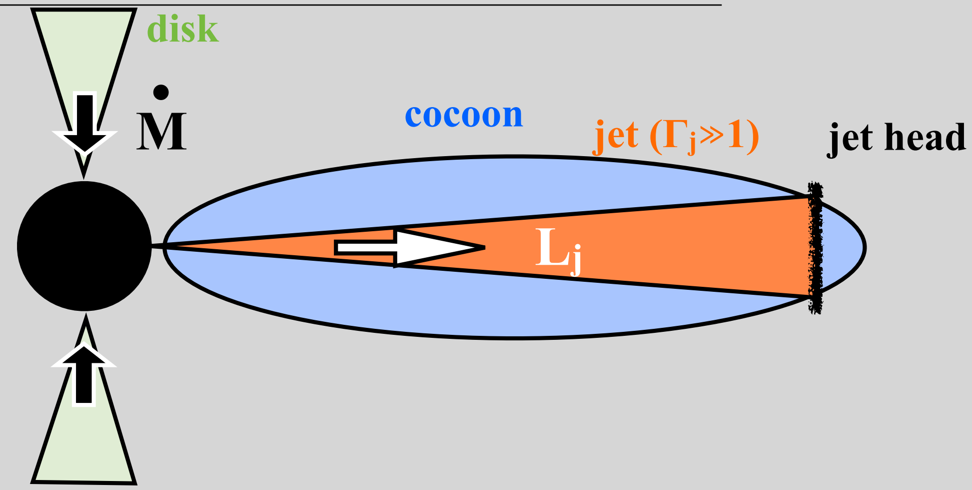
McKinney 07

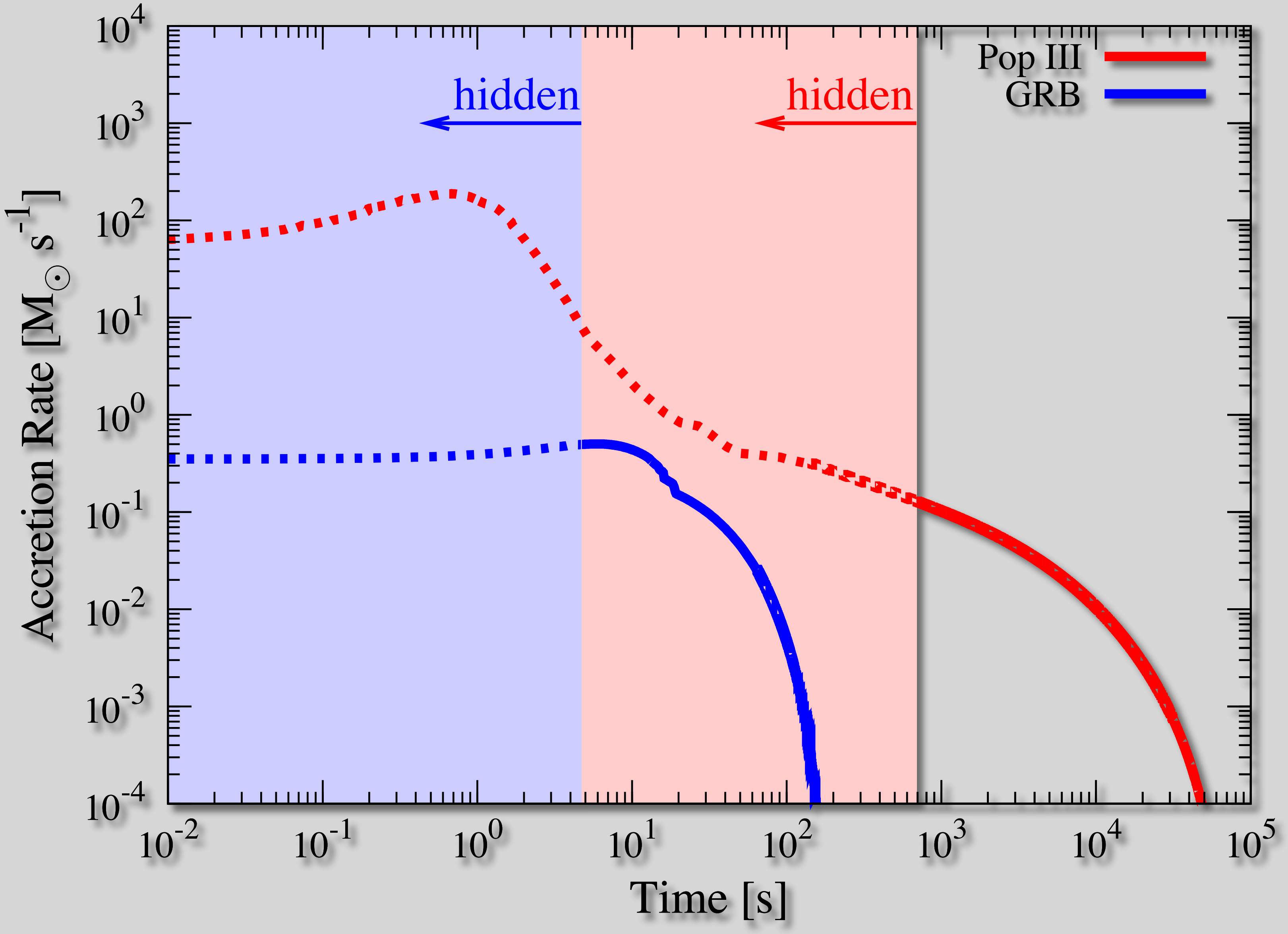


Birkl+ 07



Inside and Outside the Star



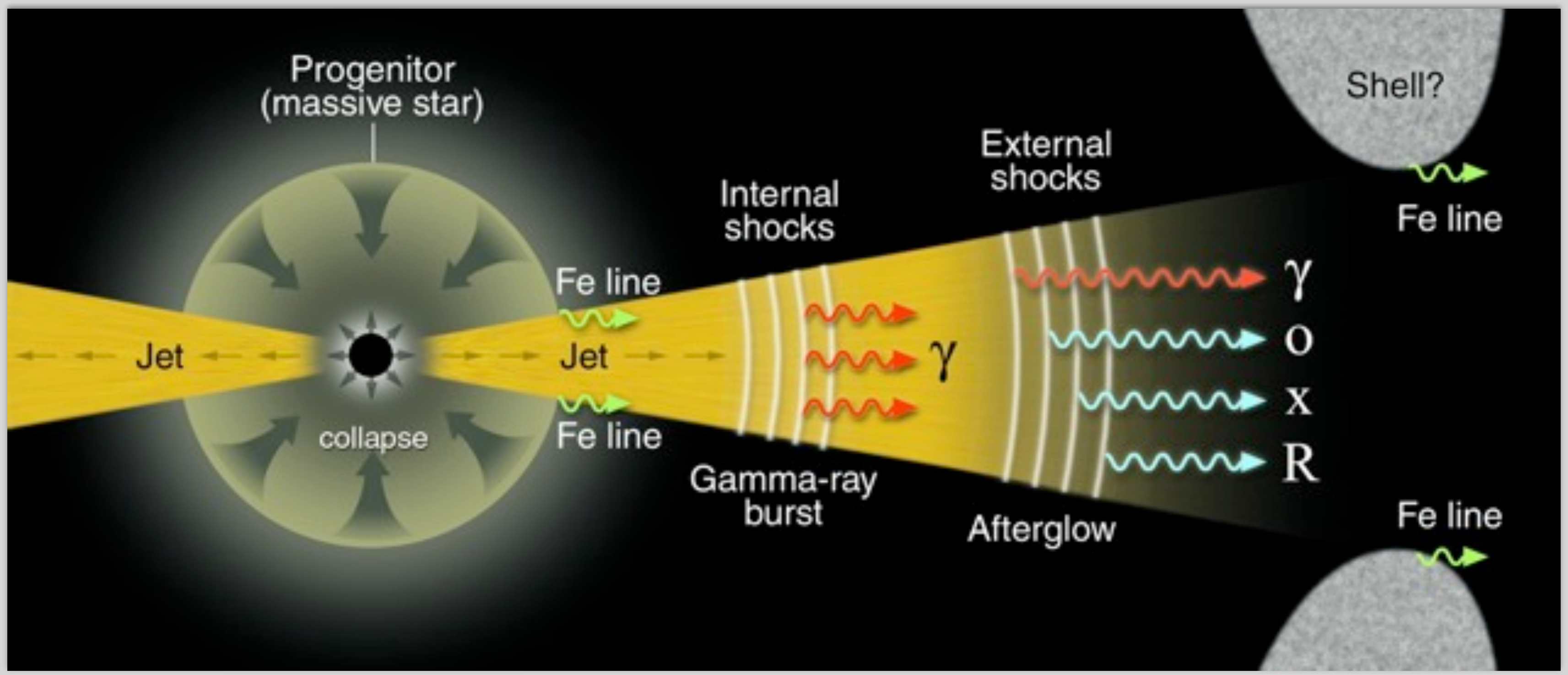


- A relativistic jet digs inside the star
- After the break out it will be observable as a GRB
- Before the break out jet energy goes to the cocoon

Jet Properties

<table>
<tr><th>Model</th><th>Mass [$M_\odot$]</th><th>Radius [10^{11}cm]</th><th>Mechanism</th><th>break time [s]</th><th>E_{GRB} [10^{52} erg]</th><th>E_{cocoon} [10^{52} erg]</th><th>T_{90}</th><th>E_{iso} [10^{54} erg]</th></tr>
<tr><td rowspan="2">Pop III</td><td rowspan="2">915</td><td rowspan="2">90</td><td>MHD</td><td>690</td><td>45</td><td>57</td><td>1500</td><td>120</td></tr>
<tr><td>Neutrino</td><td colspan="5">failed GRB</td></tr>
<tr><td rowspan="2">GRB</td><td rowspan="2">16</td><td rowspan="2">0.4</td><td>MHD</td><td>4.7</td><td rowspan="2">1.0</td><td>0.23</td><td>49</td><td rowspan="2">2.6</td></tr>
<tr><td>Neutrino</td><td>2.8</td><td>0.42</td><td>10</td></tr>
</table>

Observables



Mészáros 2002

- Assuming the conversion efficiency from the jet kinetic energy (E_j) to gamma rays (E_γ) as 10 %;

$$E_{\gamma,\mathrm{iso}} = \varepsilon_\gamma E_\mathrm{j} = 1.2 \times 10^{55} \left(\frac{\varepsilon_\gamma}{0.1}\right) \mathrm{erg}$$

- The peak energy of gamma rays for an observer (supposing E_p~0.5 MeV at GRB frame)

$$E_\mathrm{p} \simeq 25 \left(\frac{1+z}{20}\right)^{-1} \mathrm{keV}$$

- The observable flux just after the break out is ~10^{-9} erg cm^{-2} s^{-1} (@z=19 with WMAP parameters)

Summary

- Question “Can the first stars produce GRBs?”
  - Absence of H envelope is required for successful GRB
  - But the first stars might not loose their massive envelope
  - More investigations are necessary
- Stellar property “Powerful & long accretion”
  - The central engine keep its powerful activity for the long time
- Answer “It’s possible!”
  - But very dim…
  - How to trigger them?