STATISTICS OF POPULATION III BINARIES AND THEIR IMPLICATIONS ON EARLY STRUCTURE FORMATION

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RECENT PAPERS

Collaborators: Volker Bromm[1], Anna Schauer[1,2], Georges Meynet[3]

- Liu B. Meynet G. & Bromm V., *Dynamical evolution of Population III stellar systems and the resulting binary statistics*, 2020, **arxiv:2009.05824**
- Liu B. & Bromm V., *The Population III origin of GW190521*, 2020, arxiv:2009.11447
- Liu B. & Bromm V., *Gravitational waves from Population III binary black holes formed by dynamical capture*, 2020, MNRAS, staa1362
- Schauer A. T. P., Liu B. & Bromm V., *Constraining First Star Formation with 21 cm Cosmology*, 2019, ApJ, 877, L5

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OUTLINE

Background

Our novel approach

Results & implications

Summary & discussion

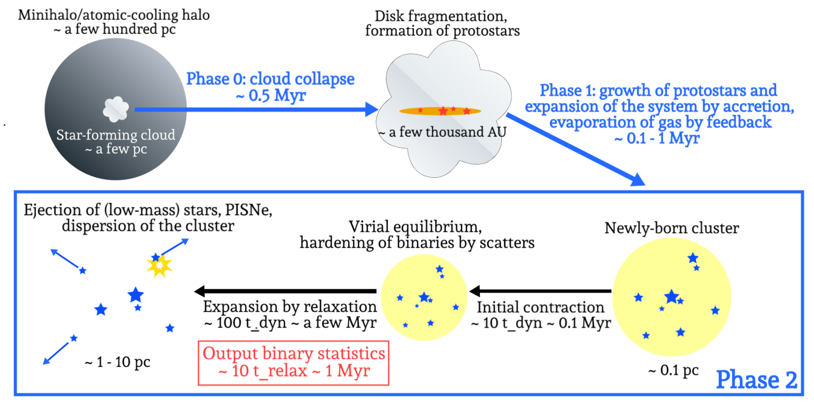
BACKGROUND

WHY BINARIES?

Binaries are important for understanding the observational signatures and imprints of the first stars:

- Different stellar evolution tracks under close binary interactions (e.g. mass transfer, tidal and common envelope evolution) → direct observation
- Contamination from the winds of companion stars, different supernova conditions in binaries → stellar archaeology
- Binary stars as progenitors of **X-ray binaries (XRBs)** and **black hole binaries (BHBs)**:
  - Feedback from X-ray binaries (formation of the first galaxies & thermal history of the IGM) → 21-cm signal
  - Binary black hole mergers → gravitational waves!

THE ‘STANDARD’ PICTURE OF POP III STAR FORMATION



Due to limited computation power, currently the link between Phase 1 and Phase 2 is still uncertain.

CAVEATS IN PREVIOUS STUDIES

Simplified assumptions/treatments for Pop III binaries:

- Pop III binaries are similar to their present-day (Pop I) counterparts (e.g. Kinugawa et al. 2014; Tanikawa et al. 2020a).
- Turn Pop III protostar systems (e.g. Greif et al. 2012; Stacy & Bromm 2013) into Pop III clusters by simply boosting the masses of protostars (e.g. Ryu et al. 2016; Belczynski et al. 2017)

Common problem: overproduction of close binaries
Binaries of protostars ***expand*** ($a \gtrsim 10^3$ AU) during accretion as the system gains angular momentum from infalling gas (e.g. Sugimura et al. 2020).

OUR NOVEL APPROACH

OVERVIEW

Initial condition model/generator for the end products of Phase 1 → pure N-body simulations (with AMUSE, Portegies Zwart & McMillan 2018) for Phase 2 → binary statistics

Elements of the initial condition model:

- Global properties (cluster size, total mass and number of stars): fragmentation and accretion timescales, $t_{\rm frag}$ and $t_{\rm acc}$
- IMF ($\propto m_\star^{-\alpha}$): minimum mass $M_{\rm min}$ and power-law slope α
- Internal structure (distribution of stars in the 6D phase space): hierarchical fragmentation

GLOBAL PROPERTIES

Quasi-scale-free nature of disk evolution → self-similar scaling relations ($P \propto \rho^{\gamma_\mathrm{eff}}$, $\gamma_\mathrm{eff} = 1.09$, Omukai & Nishi 1998):

$$R_c \propto t^{2-\gamma_\mathrm{eff}}\ , \quad M \propto t^{4-3\gamma_\mathrm{eff}}$$

Number of *surviving* fragments (in normalized time, Susa 2019):

$$N_\star \propto t^{0.3}$$

Universal solution for Pop III disk evolution:

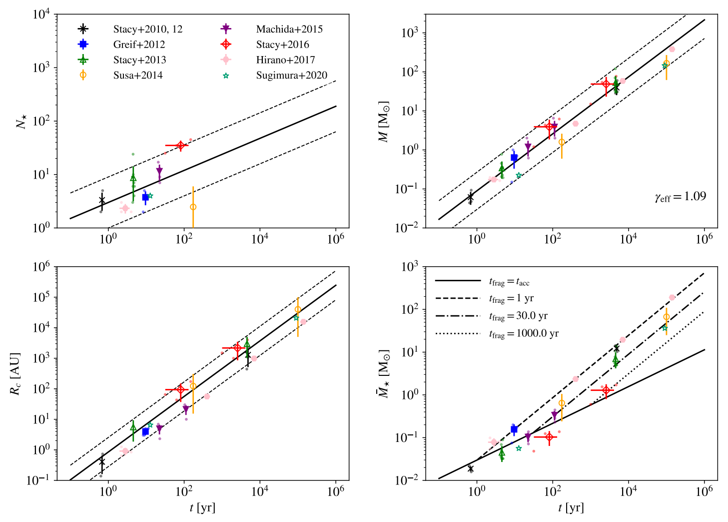
$$N_\star \simeq 3(t/\mathrm{yr})^{0.3} \tag{1}$$

$$R_c \simeq \mathrm{AU}\ (t/\mathrm{yr})^{2-\gamma_\mathrm{eff}} \tag{2}$$

$$M \simeq 400\ \mathrm{M}_\odot\ \left[t/(10^5\ \mathrm{yr})\right]^{4-3\gamma_\mathrm{eff}} \tag{3}$$

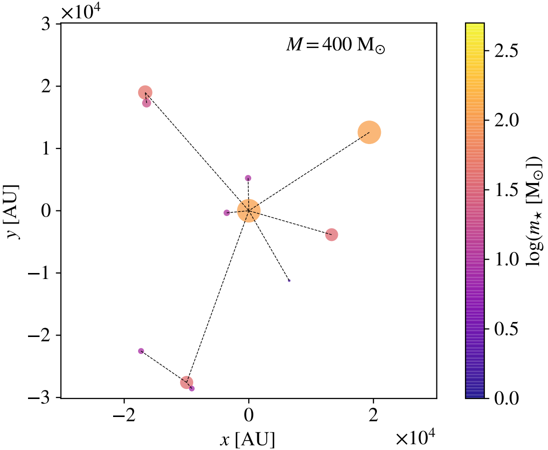
End of Phase 1: $N \sim N_\star(t_\mathrm{frag})$, $R_0 = R_c(t_\mathrm{acc})$, $M = M(t_\mathrm{acc})$

FITTING SIMULATION DATA



Scatters: within a factor of 3 (thin dashed)

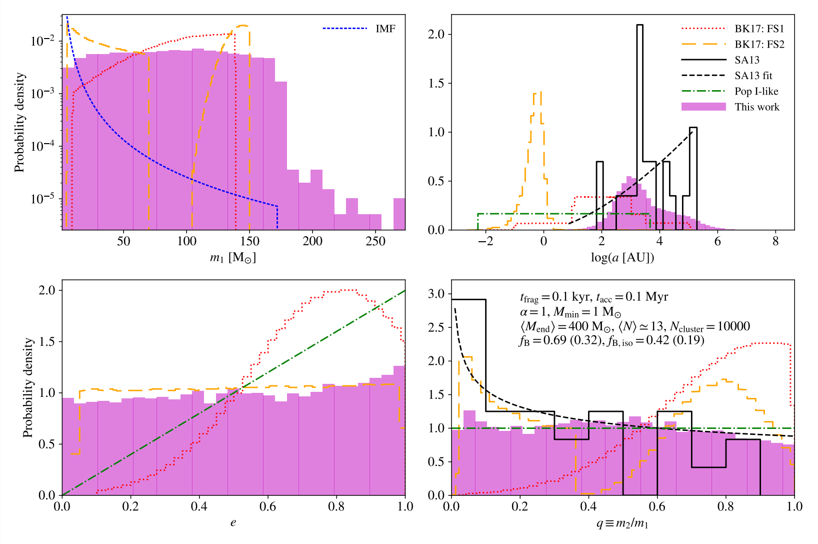
INTERNAL STRUCTURE: HIERARCHY OF BINARIES



Connections/binaries/pairs (branches) of stars (nodes) record their relative locations in the 6D phase space.

RESULTS & IMPLICATIONS

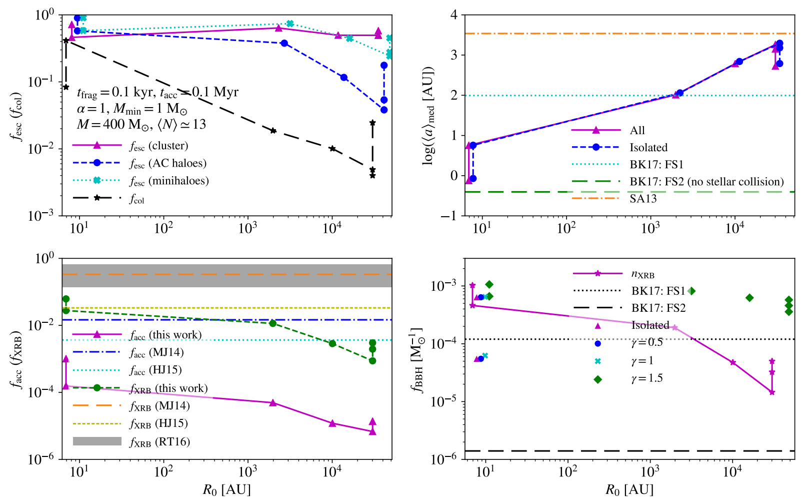
Fiducial model vs. previous studies



Fiducial (FD) model: $R_0 \sim 3 \times 10^4$ AU~ 0.15 pc, SA13 (protostars of a few M$_\odot$): Stacy & Bromm (2013), BK17 (mass enhanced protostar systems, Belczynski et al. 2017): FS1: $R_0 \sim 2000$ AU, based on Stacy & Bromm (2013), FS2: $R_0 \sim 7$ AU, based on Greif et al. (2012)

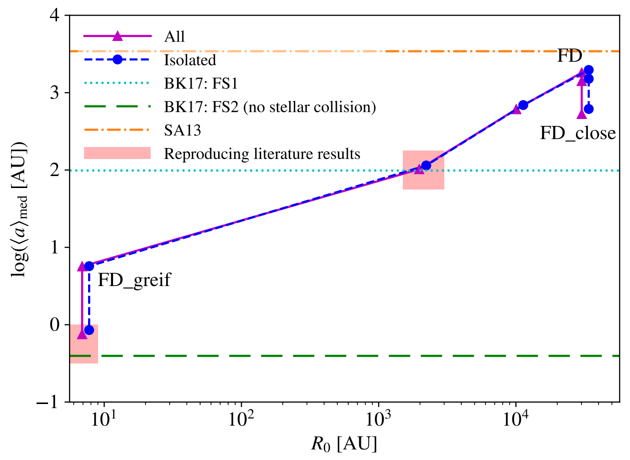
DEPENDENCE ON KEY PARAMETERS

Cluster size, internal structure, stellar collisions



MJ14: Jeon et al. (2014), HJ15: Hummel et al. (2015), RT16: Ryu et al. (2016)

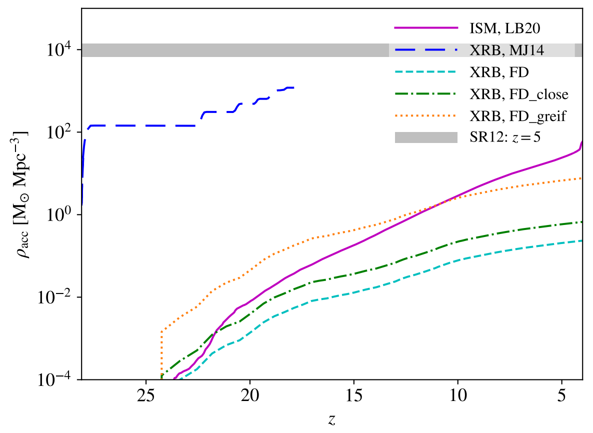
MEDIAN BINARY SEPARATION VS. INITIAL CLUSTER SIZE



SA13 (protostars of a few $\mathrm{M}_\odot$): Stacy & Bromm (2013), BKI7 (mass enhanced protostar systems, Belczynski et al. 2017): FS1: $R_0 \sim 2000$ AU, based on Stacy & Bromm (2013), FS2: $R_0 \sim 7$ AU, based on Greif et al. (2012)

IMPLICATIONS FOR POP III XRB FEEDBACK

Typical XRB properties: $n_{\rm XRB}\equiv N_{\rm XRB}/M_{\rm tot}\sim 10^{-5}-10^{-4}\ \rm M_{\odot}^{-1}$, $\langle m_{\rm BH}\rangle_{\rm med}=45\ \rm M_{\odot}$, $\langle t_{\rm XRB}\rangle_{\rm med}=0.3$ Myr, $\langle m_{\rm acc}\rangle_{\rm med}=0.37\ \rm M_{\odot}$



LB20: Liu & Bromm (2020b), MJ14: Jeon et al. (2014): 1/3 of binaries become high-mass XRBs with a duration of 2 Myr, Salvaterra12: upper limit placed by the unresolved cosmic x-ray background (Salvaterra et al., 2012)

SUMMARY & DISCUSSION

CONCLUSIONS

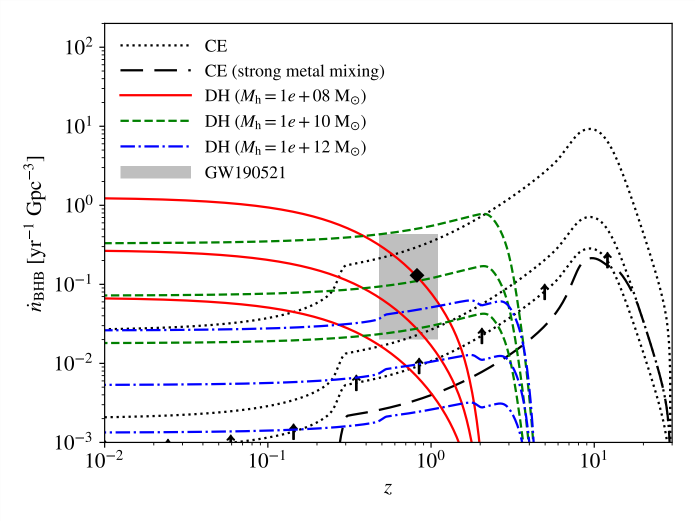
- Binary statistics are highly sensitive to the initial cluster size.
- Our models based on the universal solution of Pop III disk evolution predict much fewer close binaries ($a \lesssim 100$ AU) than in previous studies with simplified treatments of Pop III binary statistics (e.g. Kinugawa et al. 2014; Ryu et al. 2016).
- We predict significantly (by a factor of $10 - 10^3$) lower efficiencies of forming Pop III XRBs (only a few in every $10^5\ \mathrm{M}_\odot$) than assumed/predicted in previous studies (e.g. Jeon et al. 2014; Hummel et al. 2015; Ryu et al. 2016).
  The feedback from Pop III XRBs is likely unimportant for the global evolution of the IGM.

OUTLOOK

- Link between Phase 1 and Phase 2 with more advanced simulations
- Systematic investigations for the environments/modes of Pop III star formation → contribution from the outliers of the universal solution
- Ex-situ channels for the formation and evolution of Pop III BHBs (e.g. dynamical capture of Pop III BHs, 3-body interactions with surrounding low-mass stars in dense star clusters, Liu & Bromm 2020b,a)

THE POP III ORIGIN OF GW190521 (ABBOTT ET AL., 2020)

(Liu & Bromm, 2020a)



See also Kinugawa et al. (2020); Safarzadeh & Haiman (2020); Farrell et al. (2020); Tanikawa et al. (2020b)

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