JOHNS HOPKINS
KRIEGER SCHOOL
of ARTS & SCIENCES

MODEST-24, *Exploring Dense Stellar Systems Across Cosmic Time*
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SUPPORTED BY
ONASSIS FOUNDATION

Star cluster properties from intermediate-mass black hole mergers

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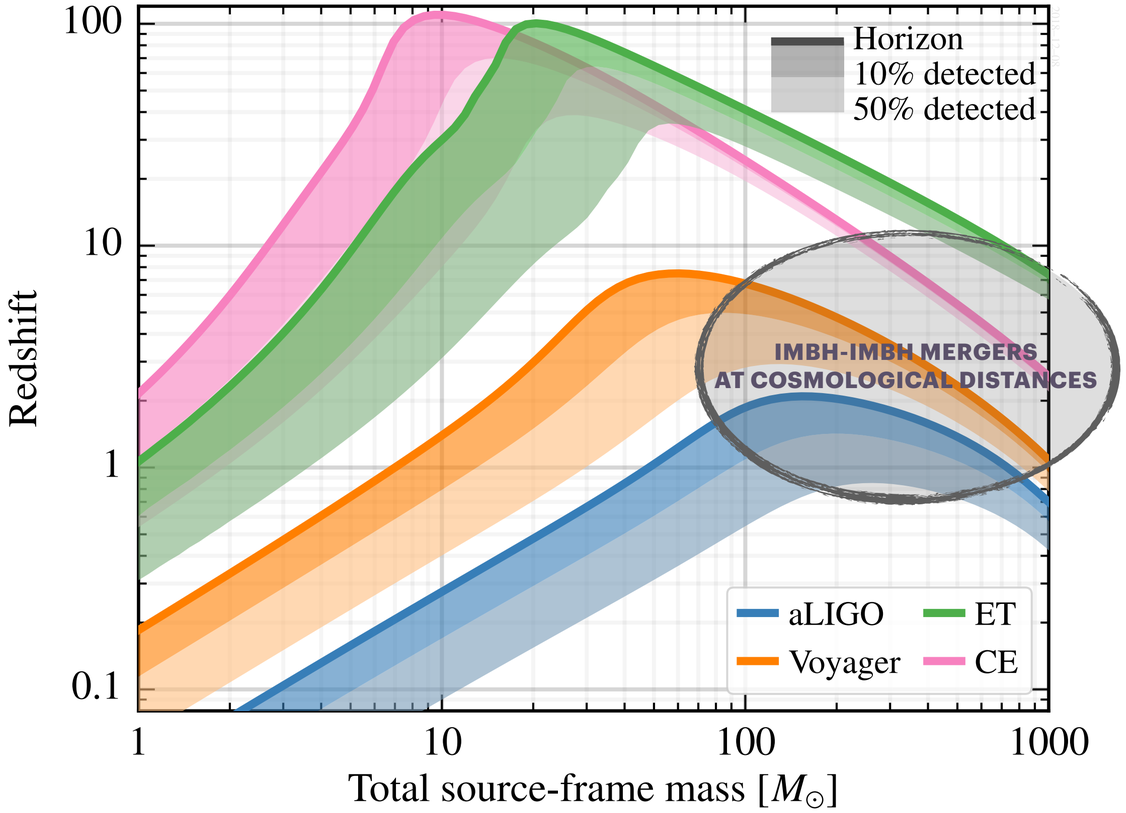
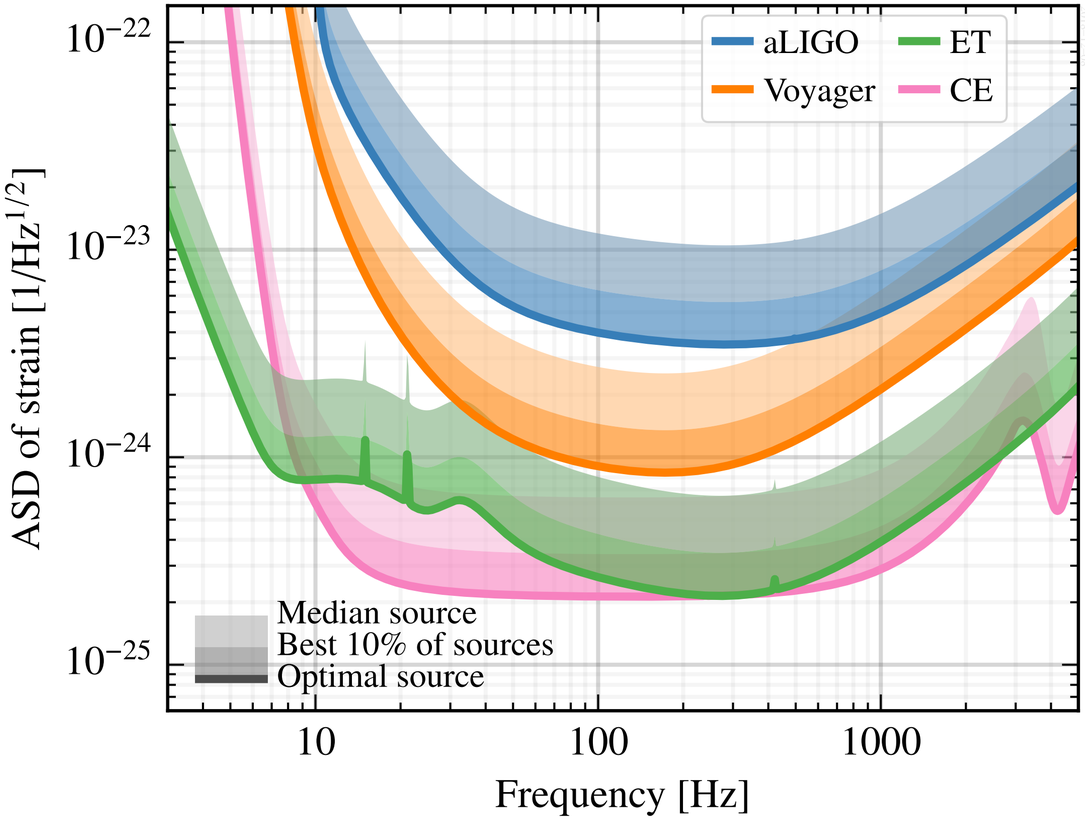
Collaborators: Luca Reali, Ken K.Y. Ng, Fabio Antonini, Emanuele Berti

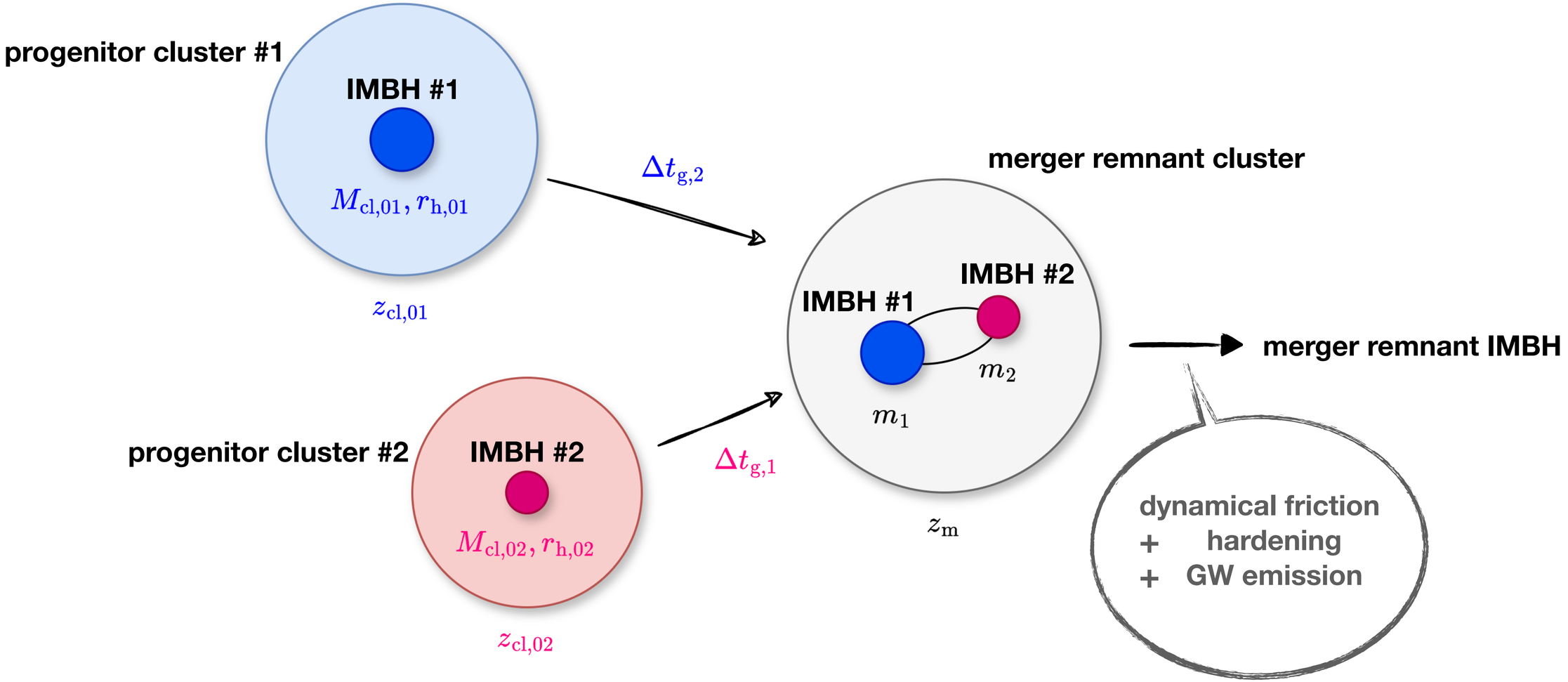
GROUND-BASED DETECTORS



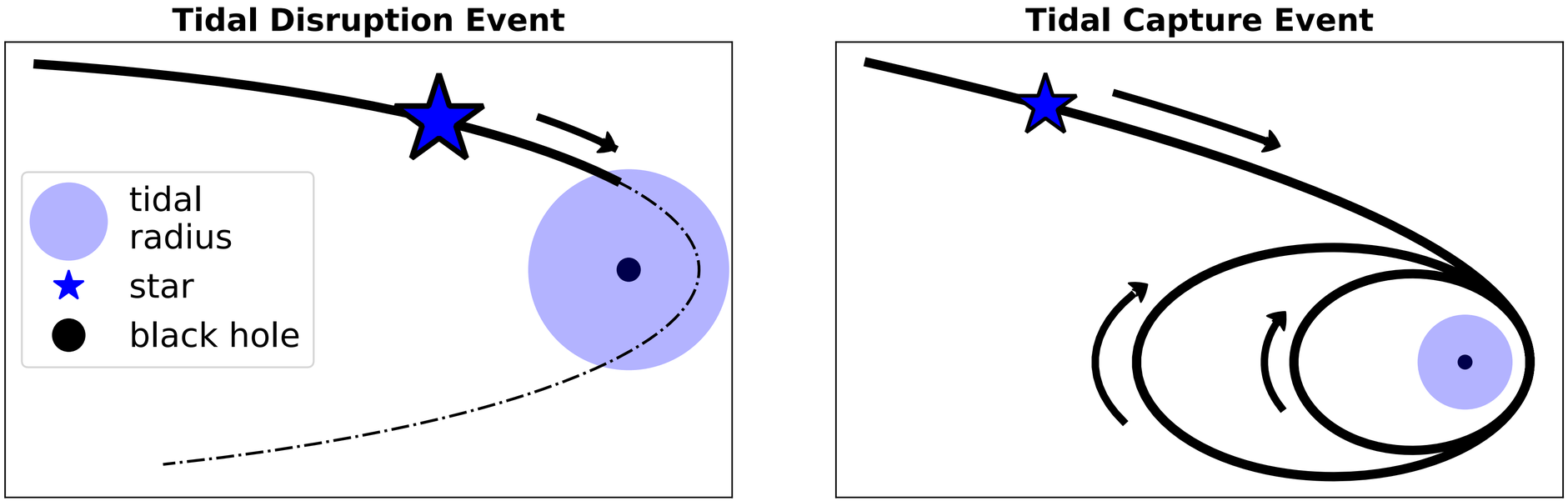


Hall & Evans (2019), 1902.09485

THE SCENARIO



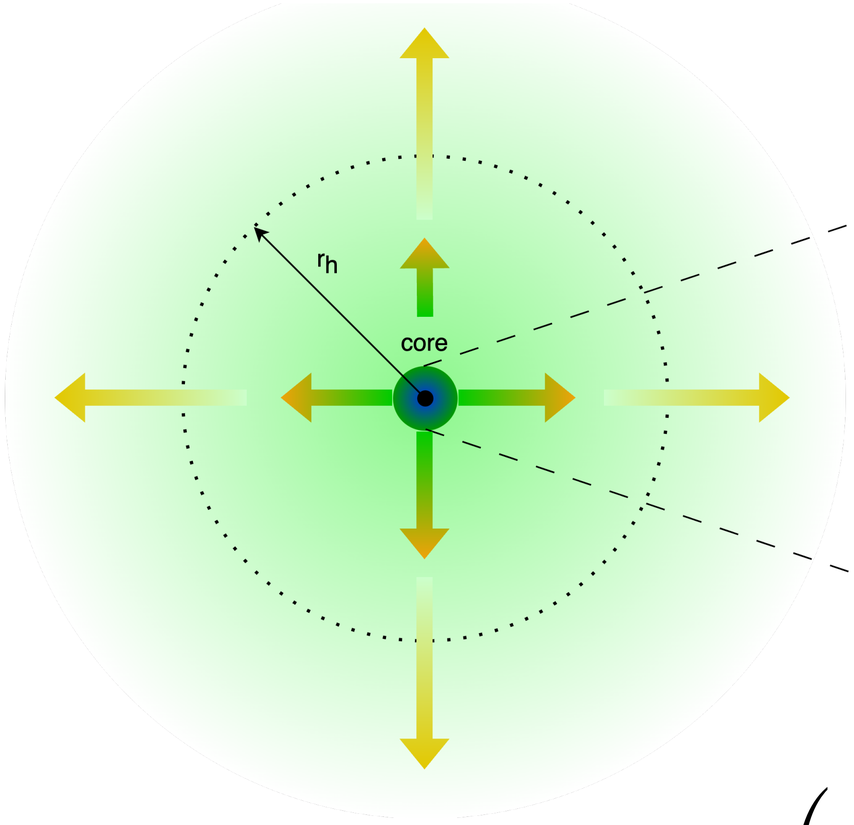
RUNAWAY TIDAL ENCOUNTERS



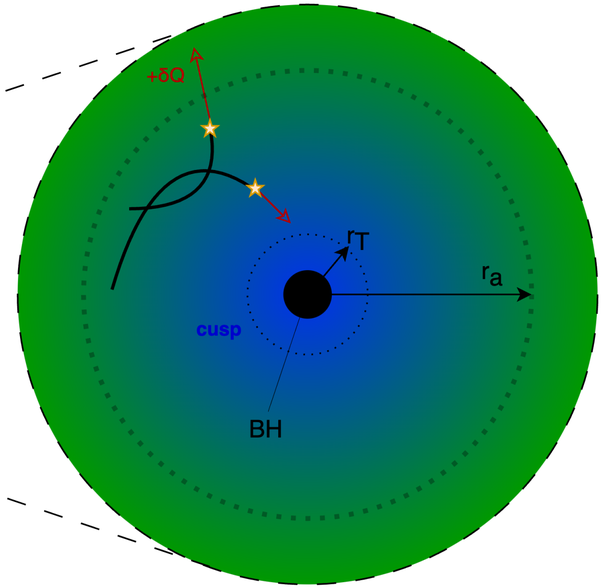
Rizzuto *et al.* (2022), 2211.13320

BLACK HOLE HEATING

MACROPHYSICS



MICROPHYSICS



Consumption rate: $\Gamma_C \simeq 53\,\mathrm{Myr}^{-1}\left(\frac{M_{BH}}{100M_\odot}\right)^{-2/3}\left(\frac{\sigma}{10\,\mathrm{km\,s}^{-1}}\right)^{5}$ Merritt 2013, pg. 294

CLUSTER MODEL

- $$\frac{d\overline{m}_\star}{dt} = -\nu\frac{\overline{m}_\star}{t}\Theta(t-\tau_{\rm se})$$
- $$\frac{dN_\star}{dt} = -\xi_{\rm e}\frac{N_\star}{\tau_{\rm rh}}\Theta(t-\tau_{\rm cc})$$
- $$\frac{dr_{\rm h}}{dt} = (\zeta-2\xi_{\rm e})\frac{r_{\rm h}}{\tau_{\rm rh}}\Theta(t-\tau_{\rm cc}) + \nu\frac{r_{\rm h}}{t}\Theta(t-\tau_{\rm se})$$

Alexander *et al.* (2014), 1405.1086

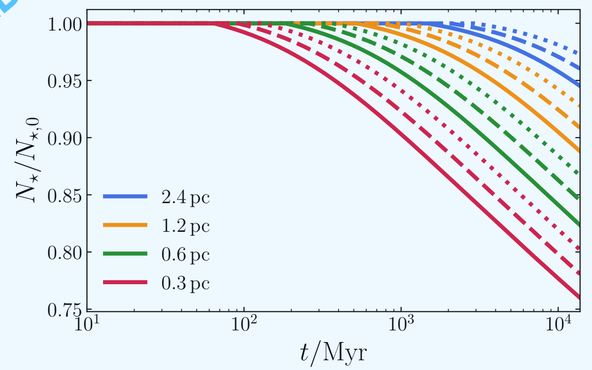
Antonini & Gieles (2019), 1906.11855

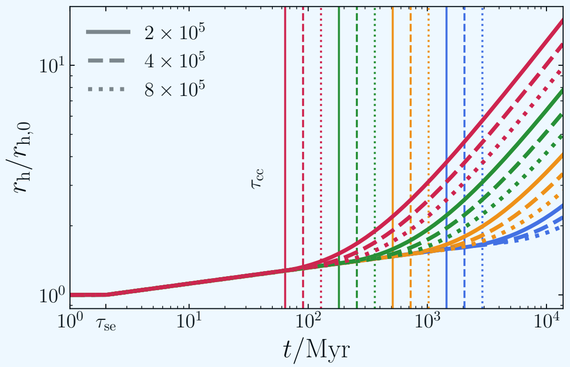
- $$\frac{dM_{\rm BH}}{dt} = f_{\rm s}\overline{m}_\star\Gamma_{\rm C}\Theta(t-\tau_{\rm BH})$$

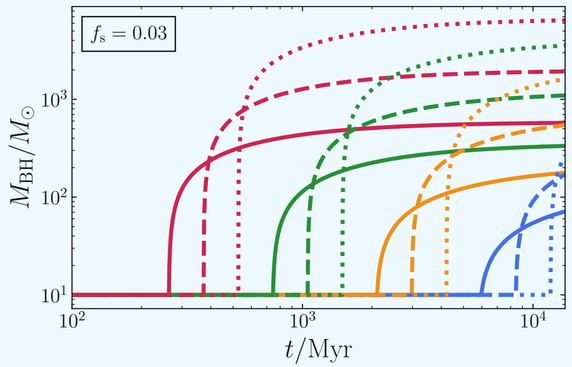
$$M_{\rm BH}(t) = \left\{ M_{\rm BH,0}^{5/3} + c_1 \left[x^{\frac{\nu}{3}+1}\,{}_2F_1\left(\frac{\nu+3}{3(\nu+1)}, \frac{5(\xi_{\rm e}-\zeta)}{7\xi_{\rm e}-3\zeta}; \frac{4\nu+6}{3(\nu+1)}; \left(\frac{x}{\tau_{\rm cc}}\right)^{\nu+1} \frac{1}{1-\frac{2(\nu+1)}{3\zeta-7\xi_{\rm e}}\frac{\tau_{\rm rh,0}}{\tau_{\rm cc}}\left(\frac{\tau_{\rm cc}}{\tau_{\rm se}}\right)^{2\nu}} \right) \right] \Bigg|_{\tau_{\rm BH}}^{t} \right\}^{3/5}, \quad t > \tau_{\rm BH}$$

CLUSTER EVOLUTION

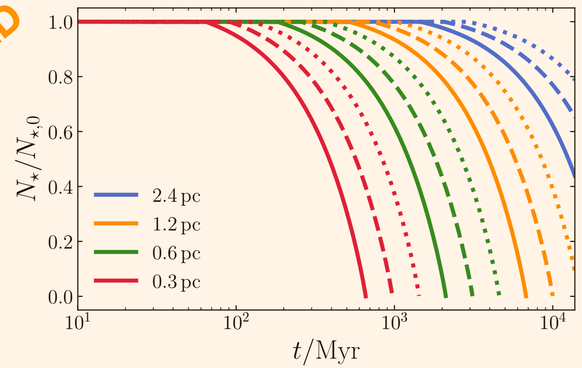
ISOLATED

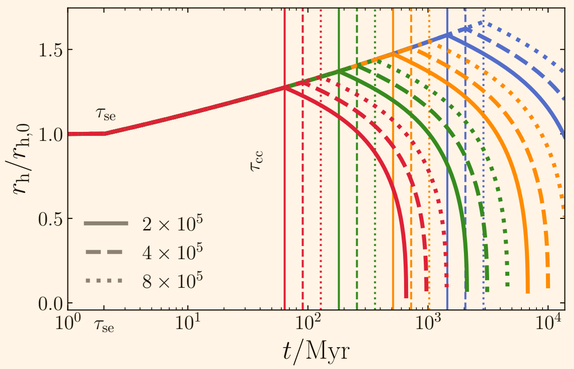


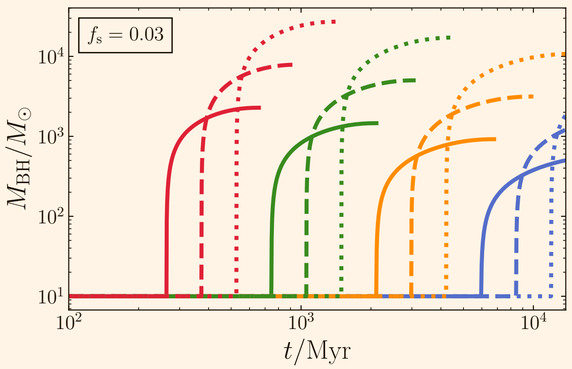




TIDALLY LIMITED

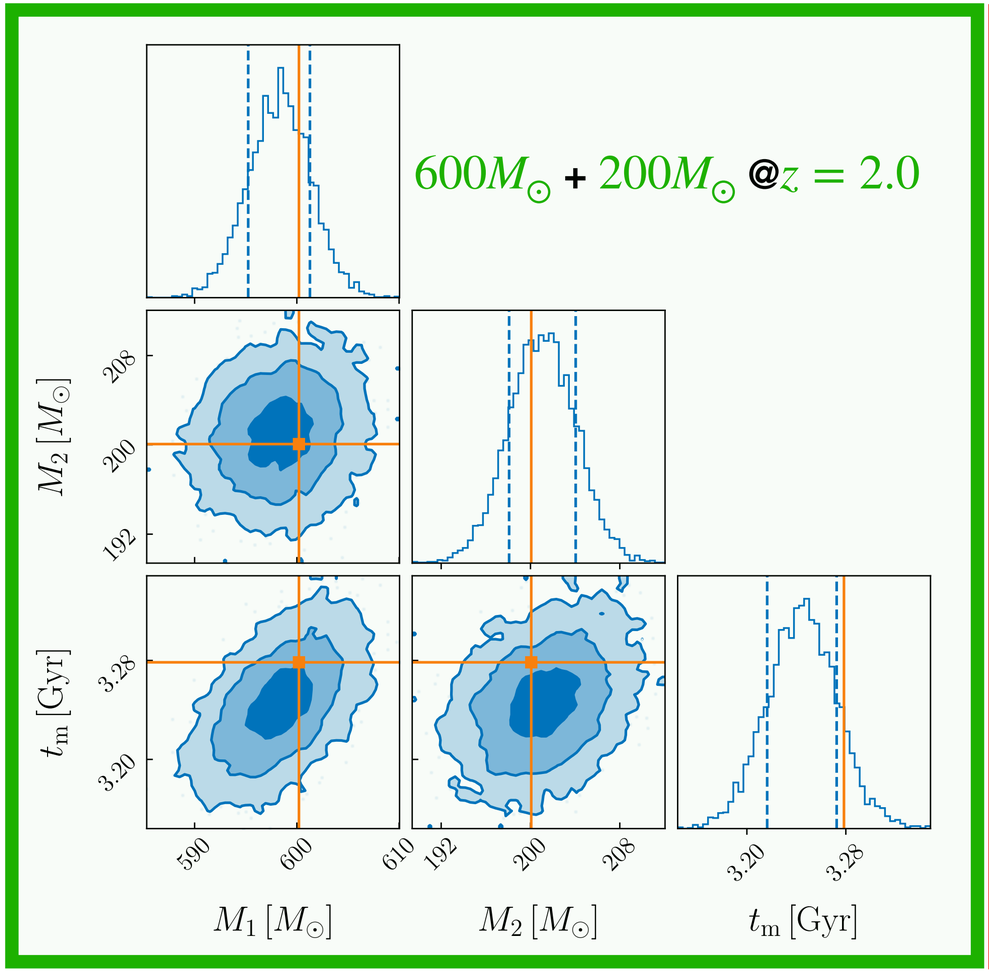


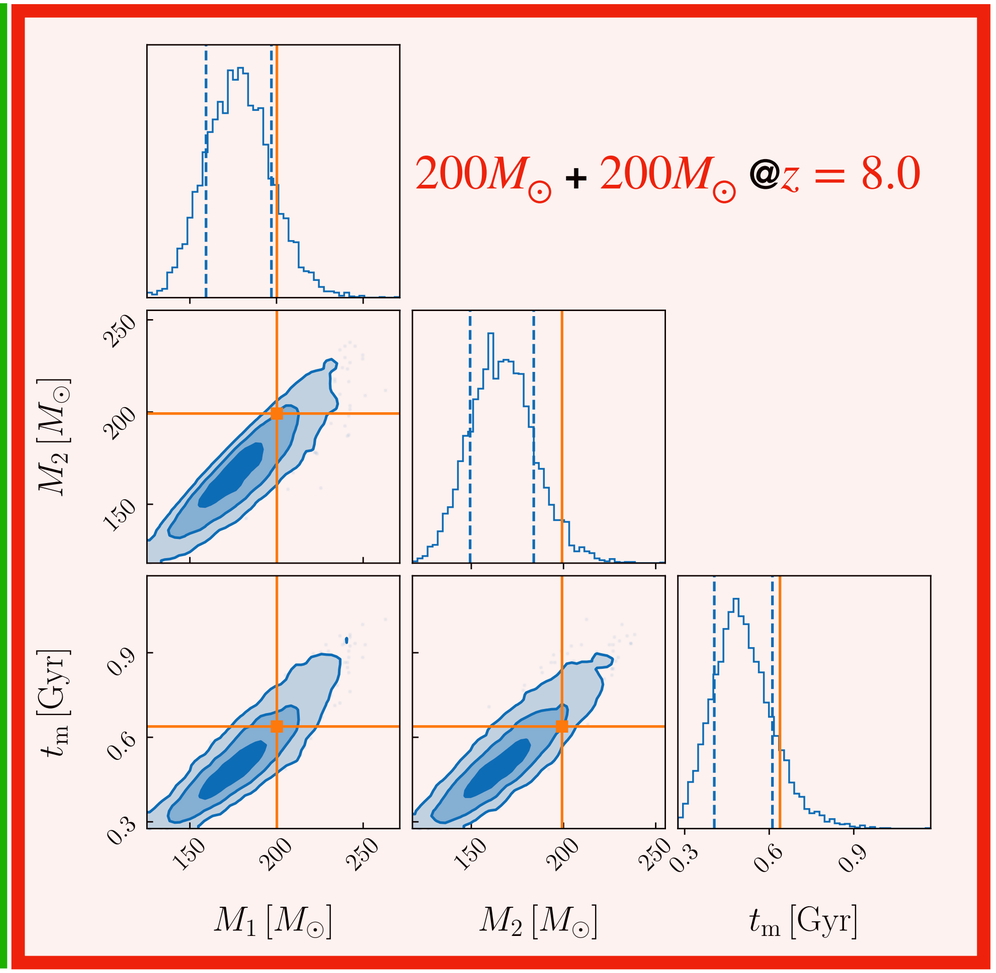


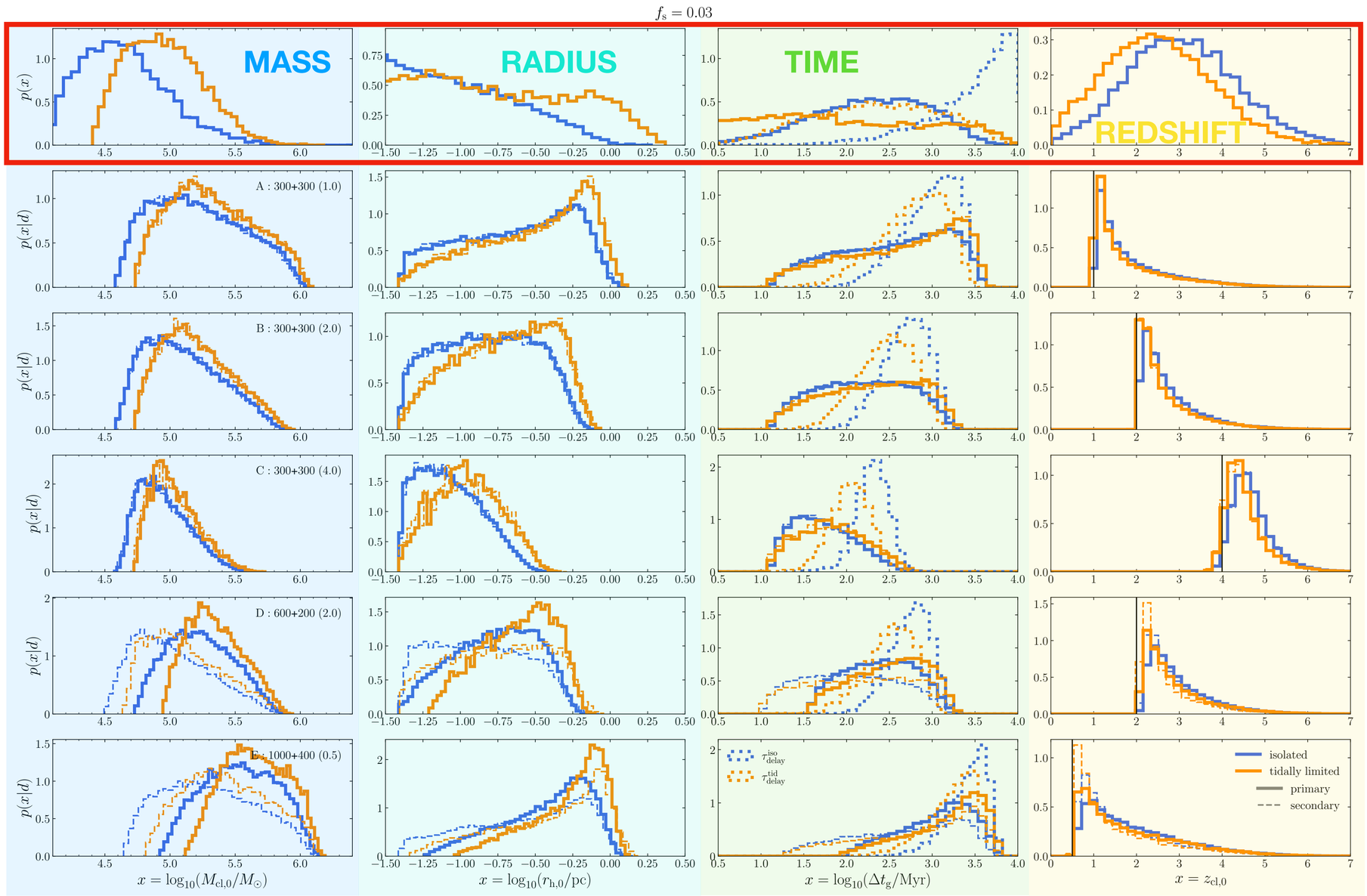


PARAMETER ESTIMATION

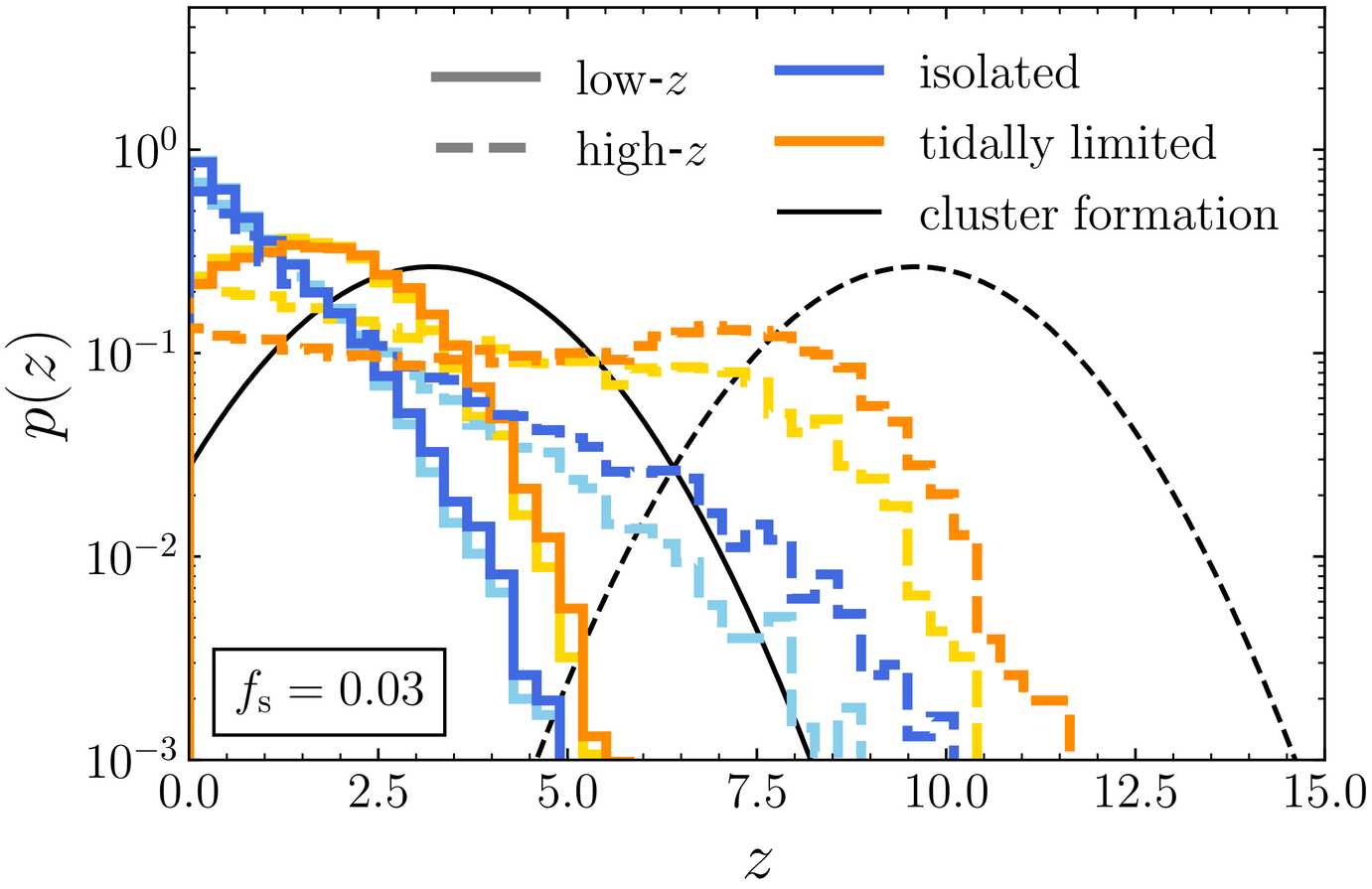
BILBY [Ashton *et al.* (2019)]**, IMRPhenomXPHM** [Pratten et al. (2021)]**, ET + 2 CE**






$f_s = 0.03$
MASS
RADIUS
TIME
REDSHIFT
PRIORS
A : 300+300 (1.0)
B : 300+300 (2.0)
C : 300+300 (4.0)
D : 600+200 (2.0)
E : 1000+400 (0.5)
$p(x)$
$p(x|d)$
$x = \log_{10}(M_{\rm cl,0}/M_\odot)$
$x = \log_{10}(r_{\rm h,0}/{\rm pc})$
$x = \log_{10}(\Delta t_{\rm g}/{\rm Myr})$
$x = z_{\rm cl,0}$
$\tau^{\rm iso}_{\rm delay}$
$\tau^{\rm tid}_{\rm delay}$
isolated
tidally limited
primary
secondary

MERGER POPULATION

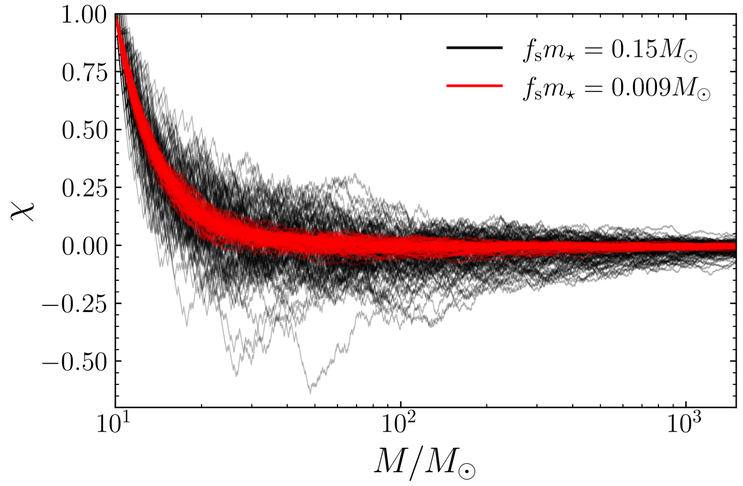


LIMITATIONS

- **Alternative IMBH growth models:**
  - Pop. III remnants
  - Runaway stellar collisions
  - Repeated BH mergers
  - Gas accretion

- **Comparison with N-body [Rizzuto *et al.* (2022), 2211.13320]:**
  we overestimate $M_{\rm BH}$ by factor of ~5

- **Spin asymptotes to zero (signature)**



CONCLUSIONS

- **Cluster structural parameters: poorly measured (due to model degeneracy)**
- **Redshift of cluster formation: more narrowly constrained**
- **Future work: how well can we infer the cluster formation history? (Population analysis)**

- **Contact: kkritos1@jhu.edu, or Slack me!**