Dynamical Formation of Merging Binary Black Holes

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Future of GW Astronomy
ICTS
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tata institute of fundamental research

Plan of the talk

- Various formation channels for binary BHs and their inherent uncertainties
- The dynamical formation channel for binary black holes (BBHs)
  - Processes controlling formation efficiency and properties
  - Key differences from other channels
  - Implications for advanced LIGO
- A critical look at our understanding of the dynamical process (what's robust and what's not)
  - Initial binary properties, distribution of stars, etc. does not matter
  - BH formation physics, retention fraction, etc. matters
- Possible ways to improve our understanding of merging binary BH formation
- Summary & burning questions

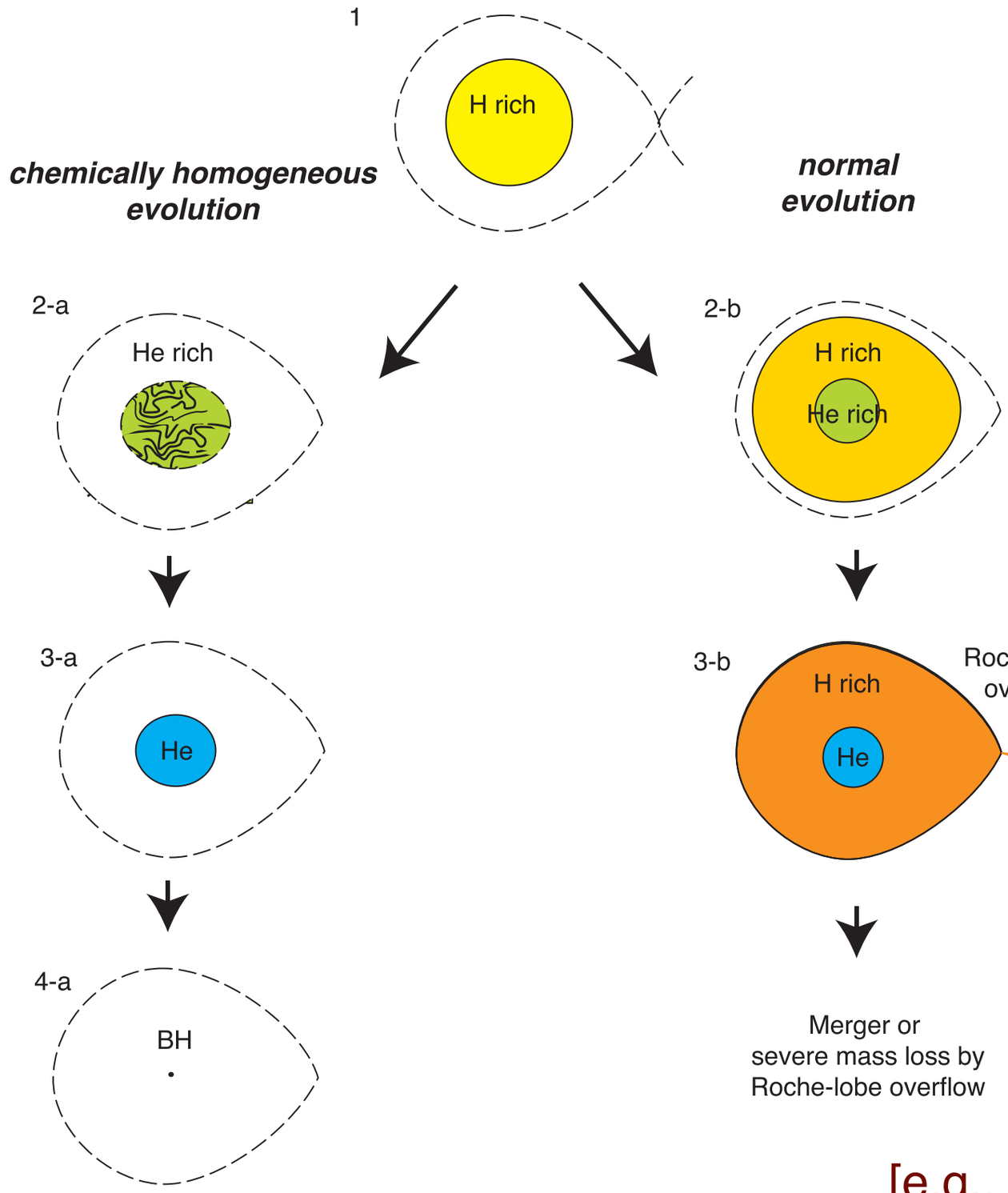
Isolated Binary Evolution

[Belczynski+ 16]

time [Myr]						a [$R_\odot$]	e
0.0000	**MS**	96.2 $M_\odot$		**ZAMS**	**MS**	60.2 $M_\odot$	2,463	0.15
3.5445	**HG**	92.2 $M_\odot$		**RLOF**	**MS**	59.9 $M_\odot$	2,140	0.00
3.5448	**HG** or **CHeB**	42.3 $M_\odot$			**MS**	84.9 $M_\odot$	3,112	0.00
3.8354	**He star**	39.0 $M_\odot$			**MS**	84.7 $M_\odot$	3,579	0.00
				direct BH				
3.8354	**BH**	35.1 $M_\odot$			**MS**	84.7 $M_\odot$	3,700	0.03
				CE				
5.0445	**BH**	35.1 $M_\odot$			**CHeB**	82.2 $M_\odot$	3,780	0.03
5.0445	**BH**	36.5 $M_\odot$			**He star**	36.8 $M_\odot$	43.8	0.00
5.3483	**BH**	36.5 $M_\odot$			**He star**	34.2 $M_\odot$	45.3	0.00
				direct BH				
5.3483	**BH**	36.5 $M_\odot$			**BH**	30.8 $M_\odot$	47.8	0.05
				merger				
10,294							0	0.00

Isolated Binary Evolution

Chemically homogeneous evolution



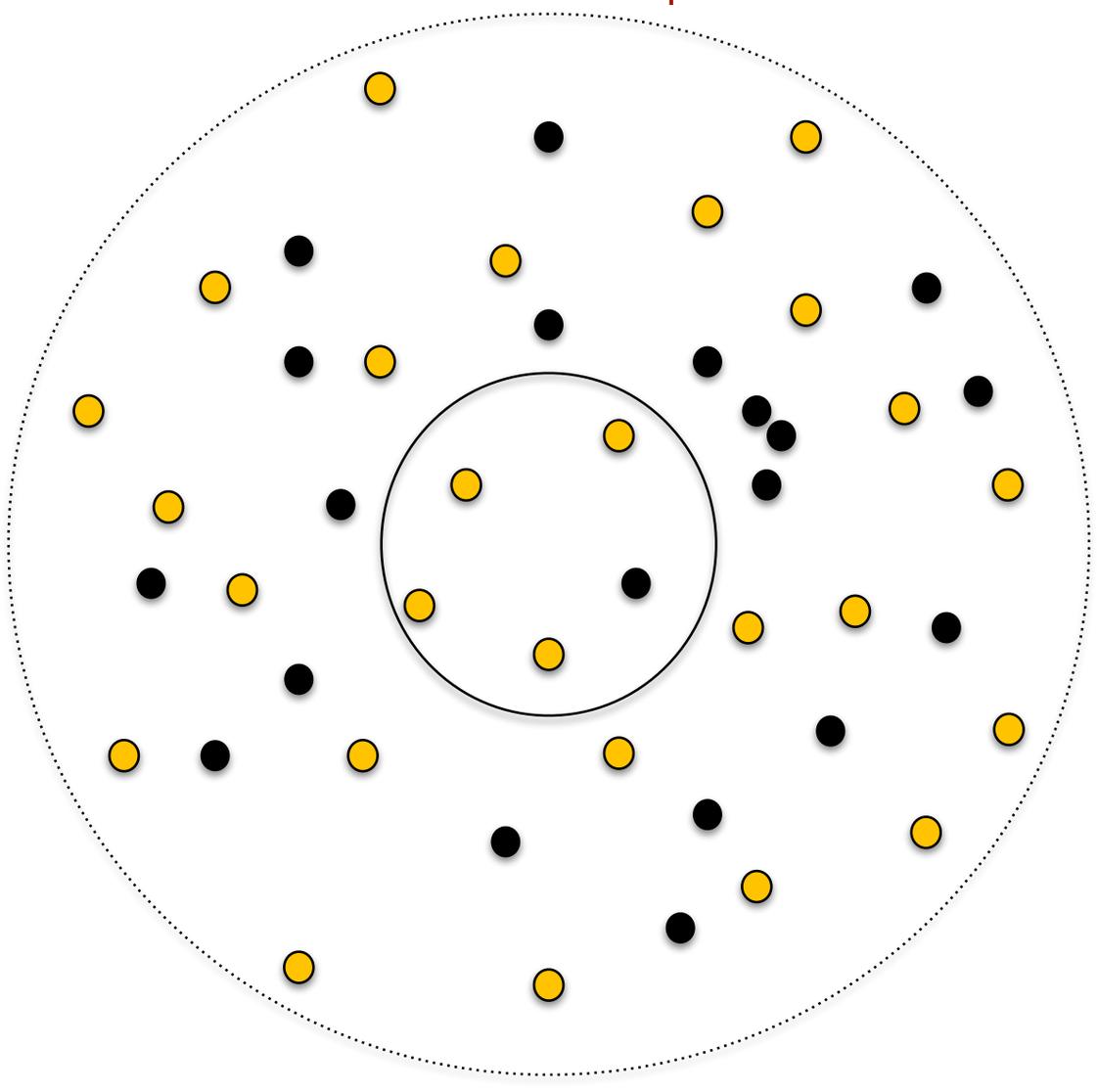
[e.g., Mandell & de Mink 16]

Dense Star Clusters

Physical Processes

Two-body relaxation

- Cumulative effect of a sequence of weak pair-wise gravitational interactions is a slow diffusion of energy
- Natural consequence is mass segregation



$$t_{\rm relax} \sim \frac{N}{\ln N}\, t_{\rm cross}$$

$$t_{\rm cross} << t_{\rm relax} < {\rm Age}$$

10^5 yr $\quad$ 10^9 yr $\quad$ 10^{10} yr

$$t_{\rm seg,i} \sim \frac{< M >}{M_i} t_{\rm relax}$$

Physical Processes

Two-body relaxation

Strong Scattering & Binary Burning

What makes GCs efficient factories of BBHs

- Most massive BHs sink to the center
- High density allows BBH formation
  - via exchange encounters
  - via three-body binary formation
  - via GW capture
- BBH orbits keep shrinking via super-elastic encounters potentially making them merge within a Hubble time
- The above process goes on until the binary is ejected due to recoil

Properties of BBHs are Determined by Dynamics

(*almost*) nothing else

From virial theorem:

$$\left\langle v^2 \right\rangle_r \sim \frac{GM(r)}{2r}$$

Escape speed:

$$\left\langle v^2_{\rm escape} \right\rangle_r = -2\phi(r) = \frac{2GM(r)}{r}$$

- Which binaries survive in the cluster?

$$E_B > \frac{1}{2}\langle m \rangle \left\langle v^2 \right\rangle \sim \frac{\langle m \rangle GM}{4r}$$

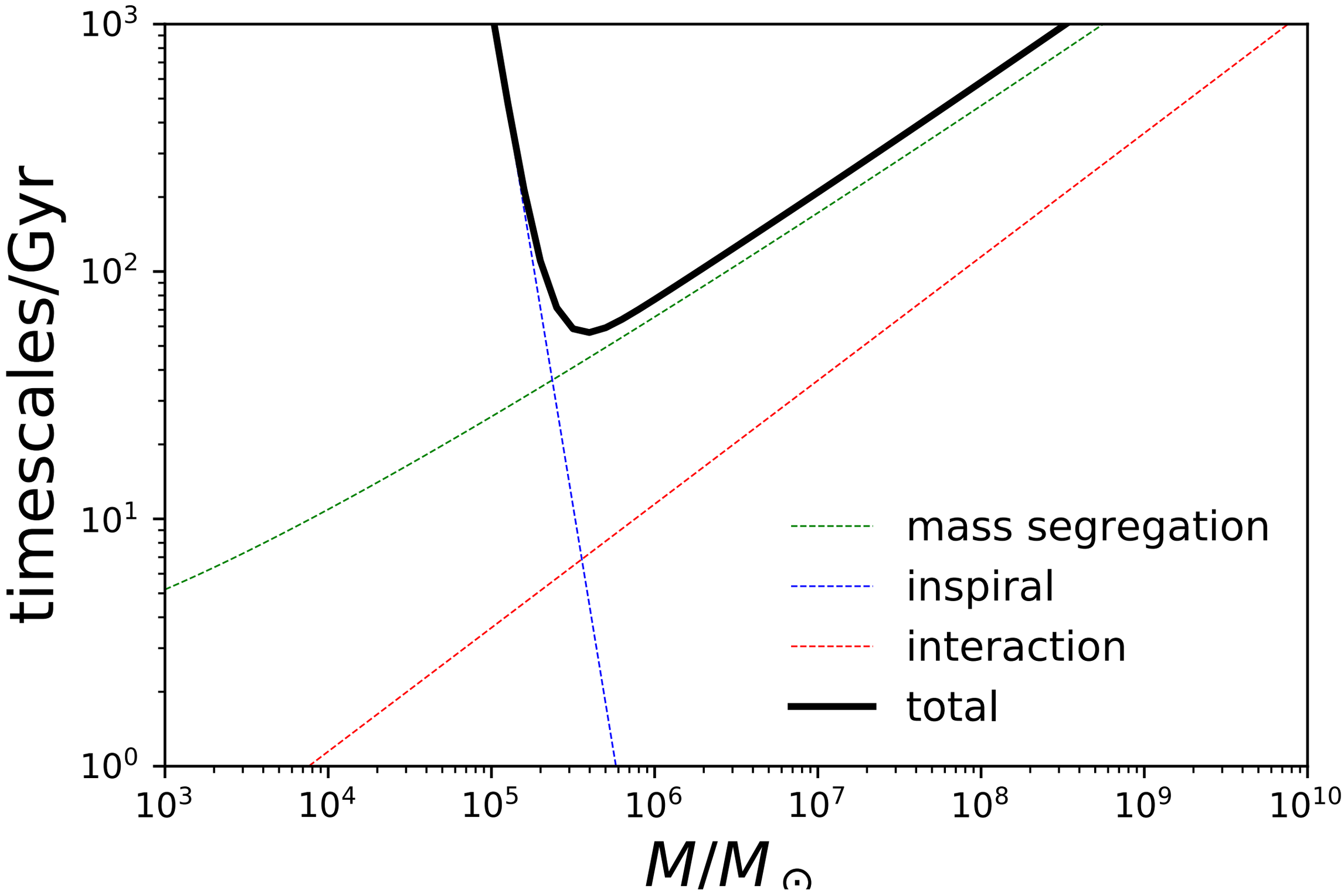
- Which binaries get ejected?

$$\left\langle v_{\rm recoil} \right\rangle \sim v_{\rm orb} > \left\langle v^2_{escape} \right\rangle^{1/2} \sim \left(\frac{2GM}{r} \right)^{1/2}$$

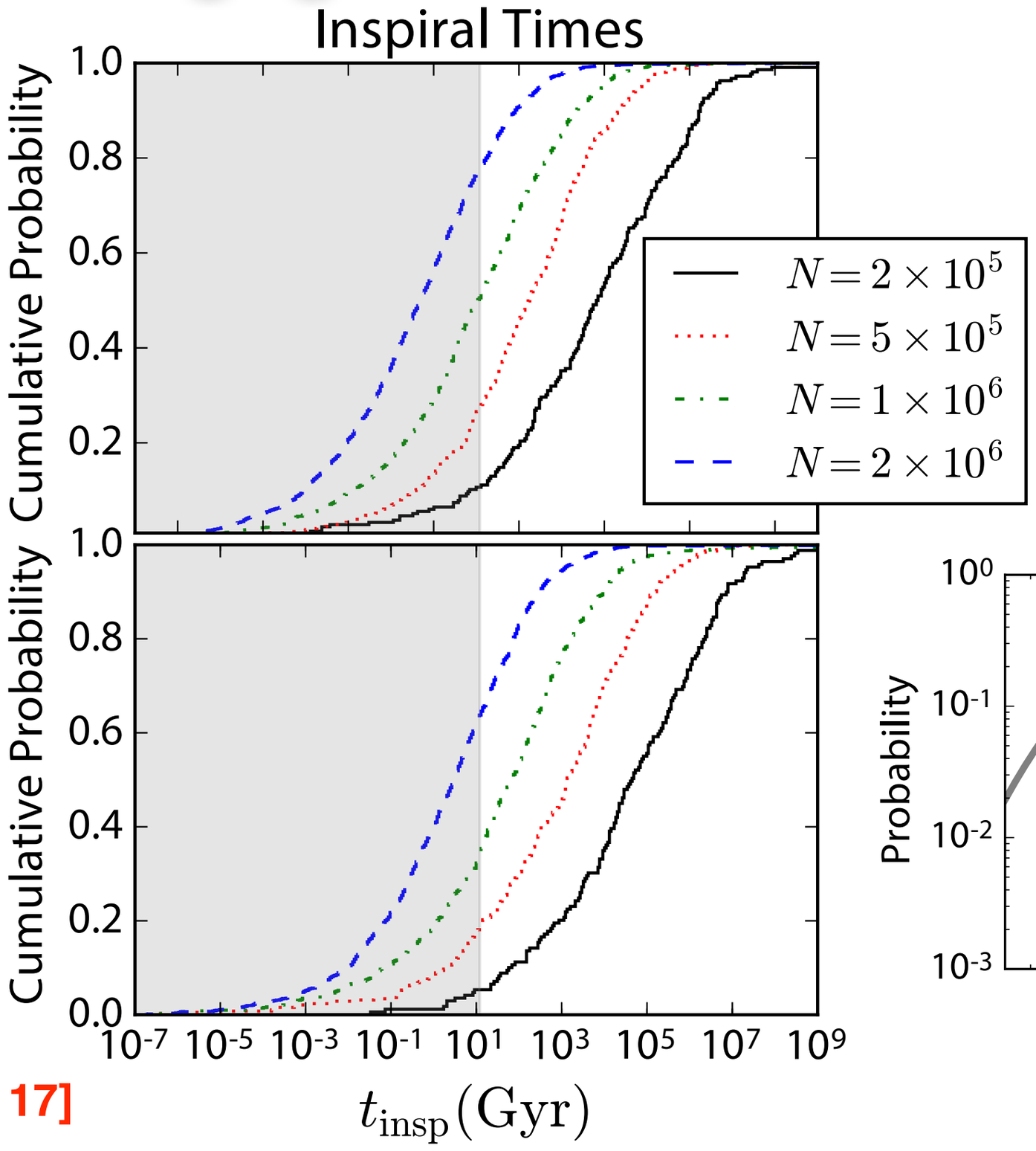
Separation and $t_{\rm inspiral}$

Properties of BBHs are Determined by Dynamics

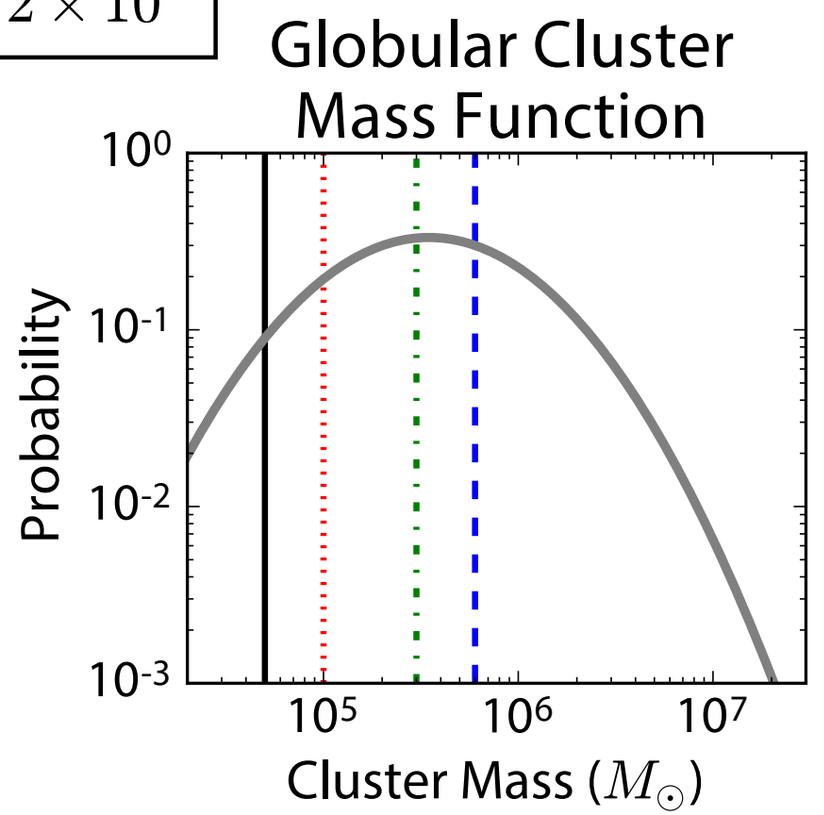
(*almost*) nothing else



Massive Star Clusters are Most Efficient in Merging BBH Production Per Star



[Rodriguez+ 17]



[Harris 14]

Unique Aspects of the Dynamical Formation Channel

- The merging binaries are *NOT* primordial
  - Not dependent on uncertain binary evolution stages
  - Initial binary fraction and properties have little effect

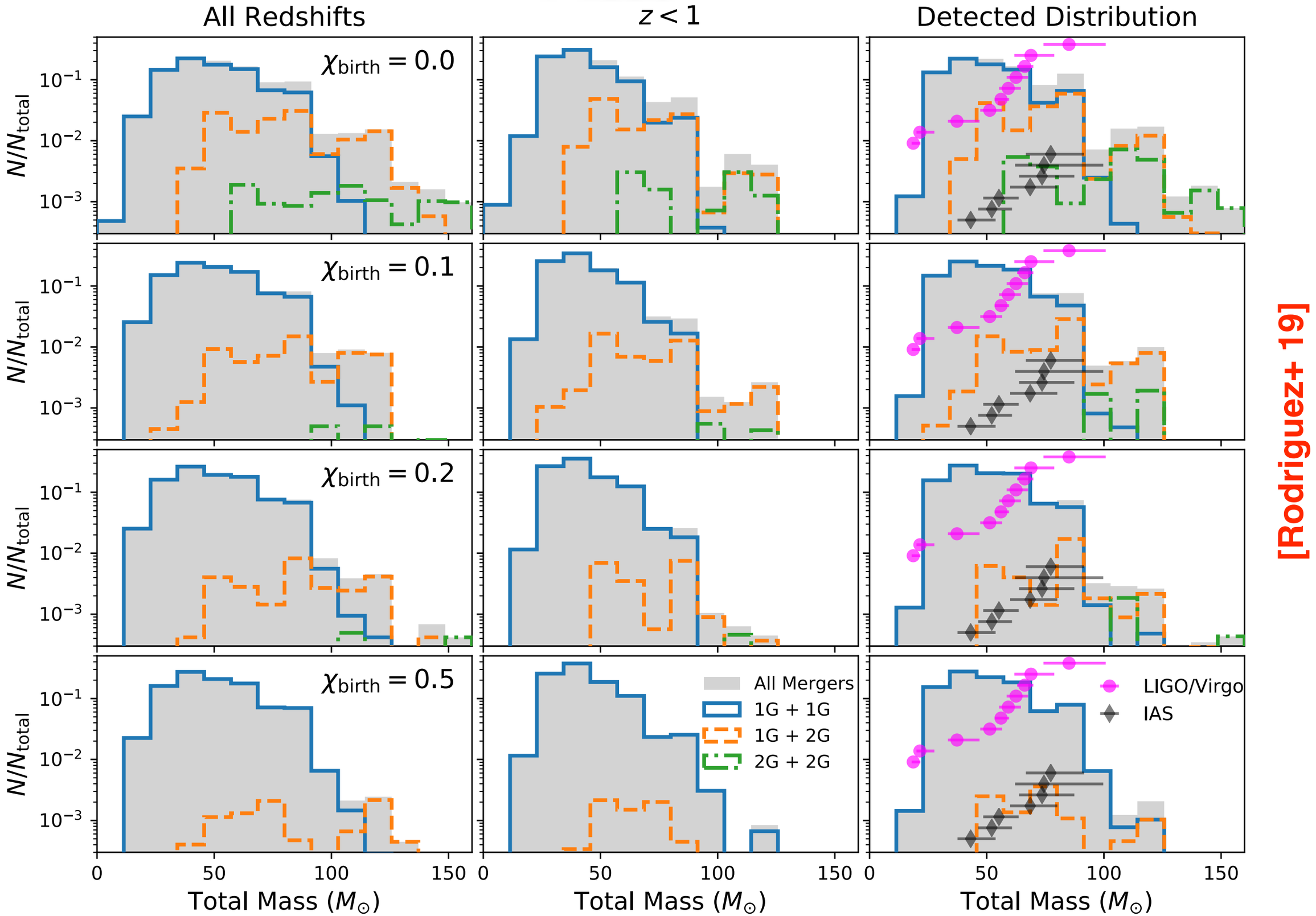
- BH spins are randomly oriented relative to the orbit

- High eccentricity during formation
  - Eccentricity can decay before reaching ~10 Hz
  - In some cases eccentricities can be very high even at high frequency (e.g., GW capture)

- Second generation (2G) mergers
  - If a merger is not ejected from cluster, it quickly acquires a BH companion and attains merging architecture

BBH Mergers

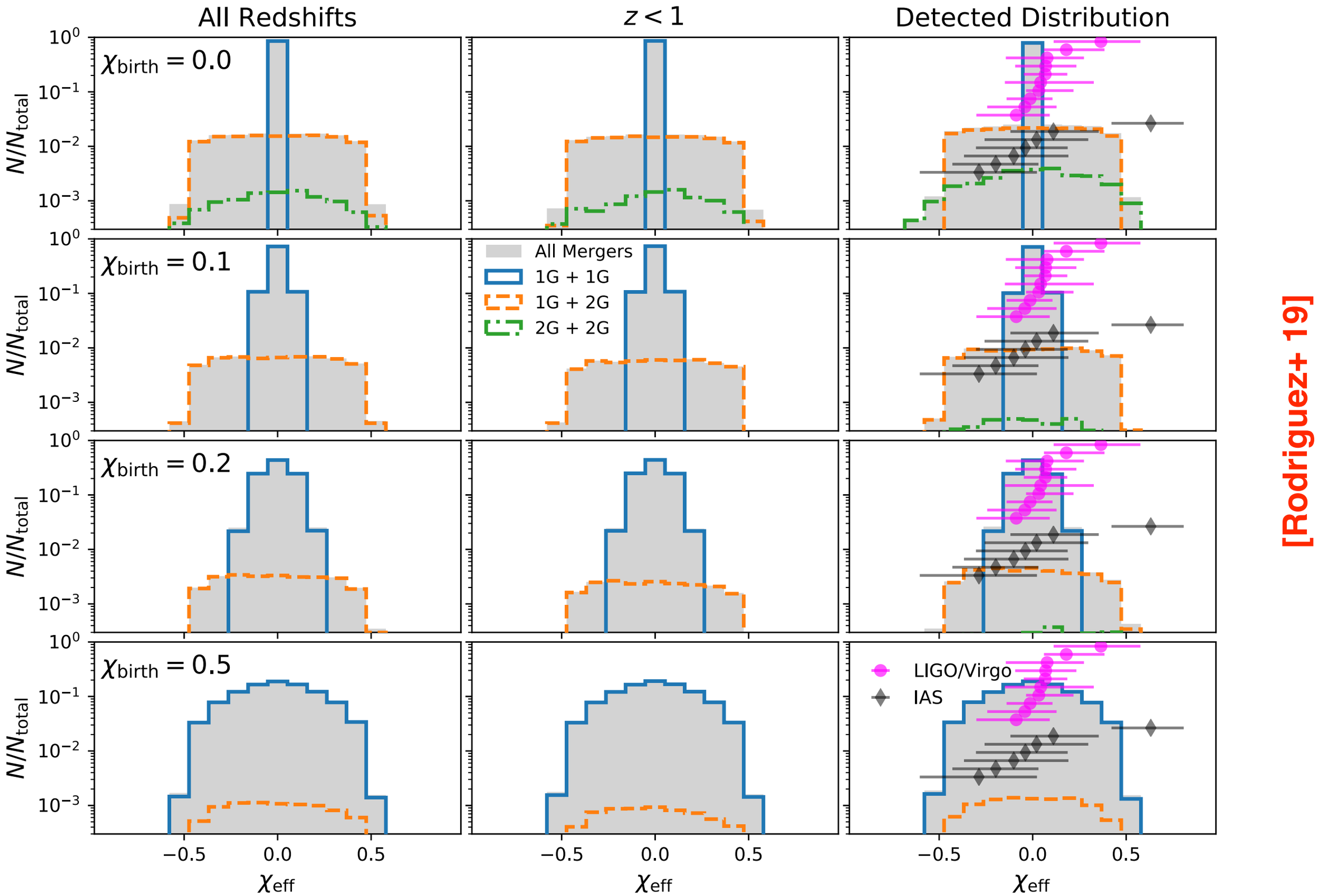
Mass



[Rodriguez+ 19]

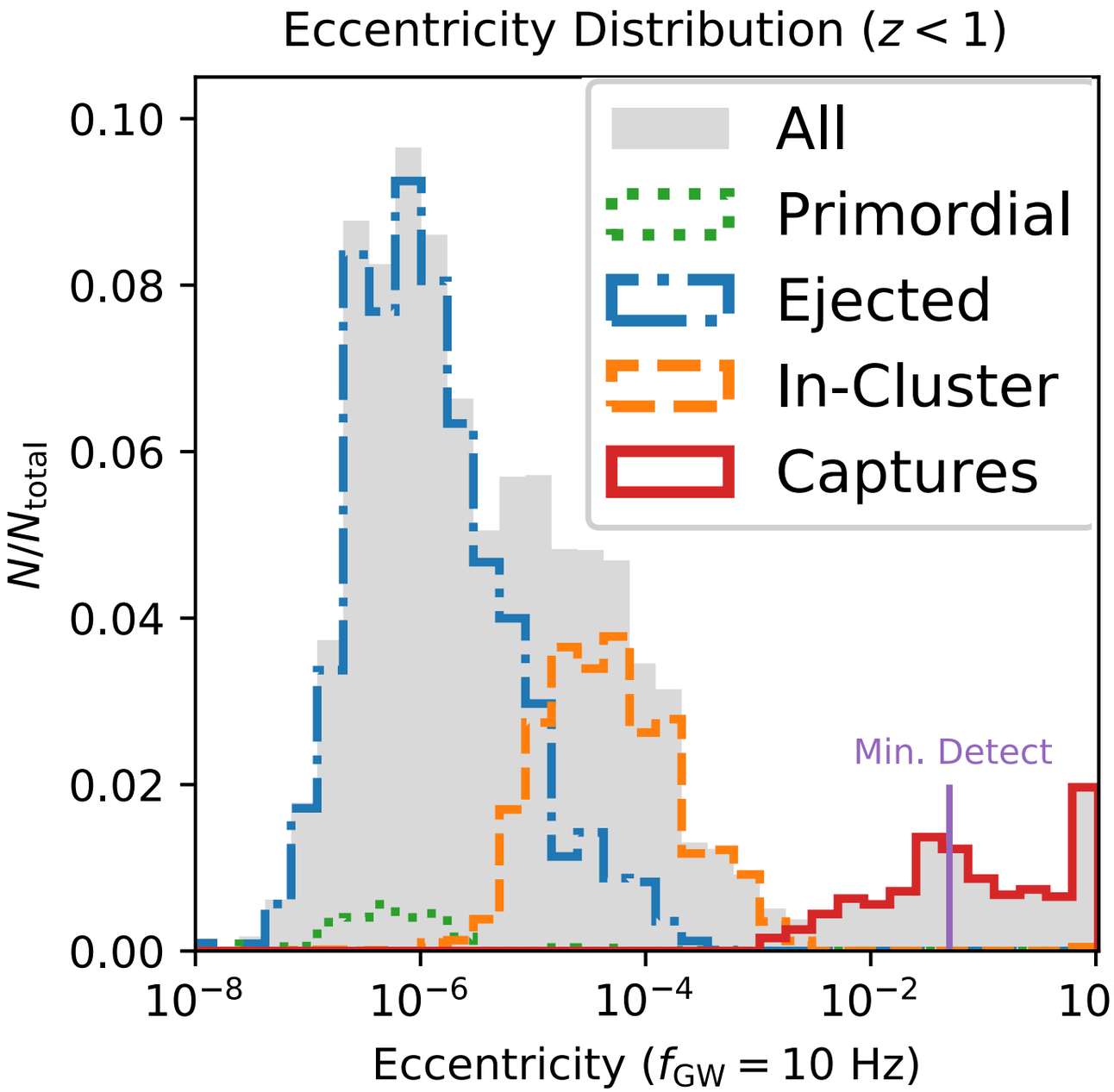
BBH Mergers

$\chi_{\rm eff}$

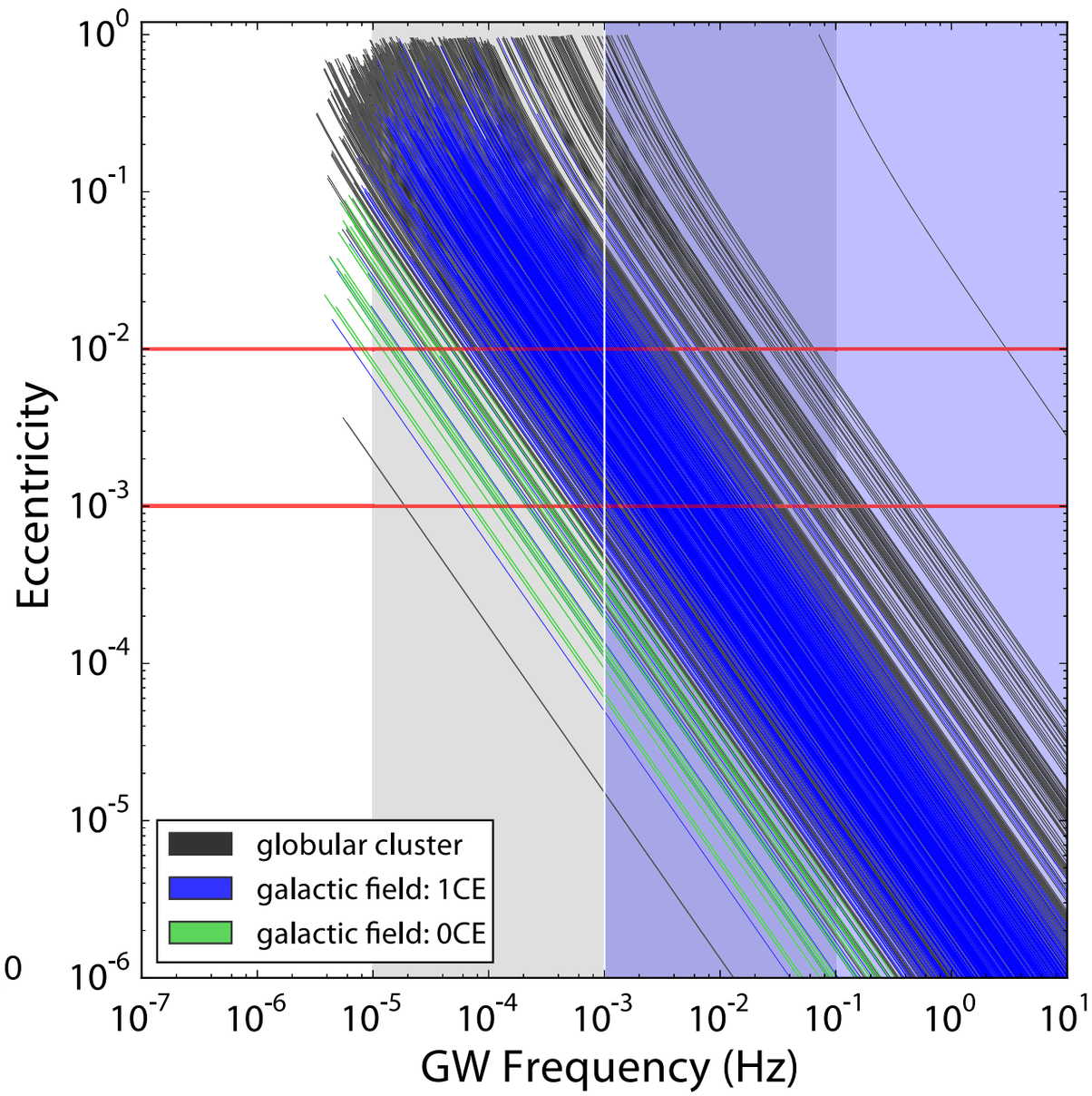


[Rodriguez+ 19]

BBH Mergers
Eccentricity



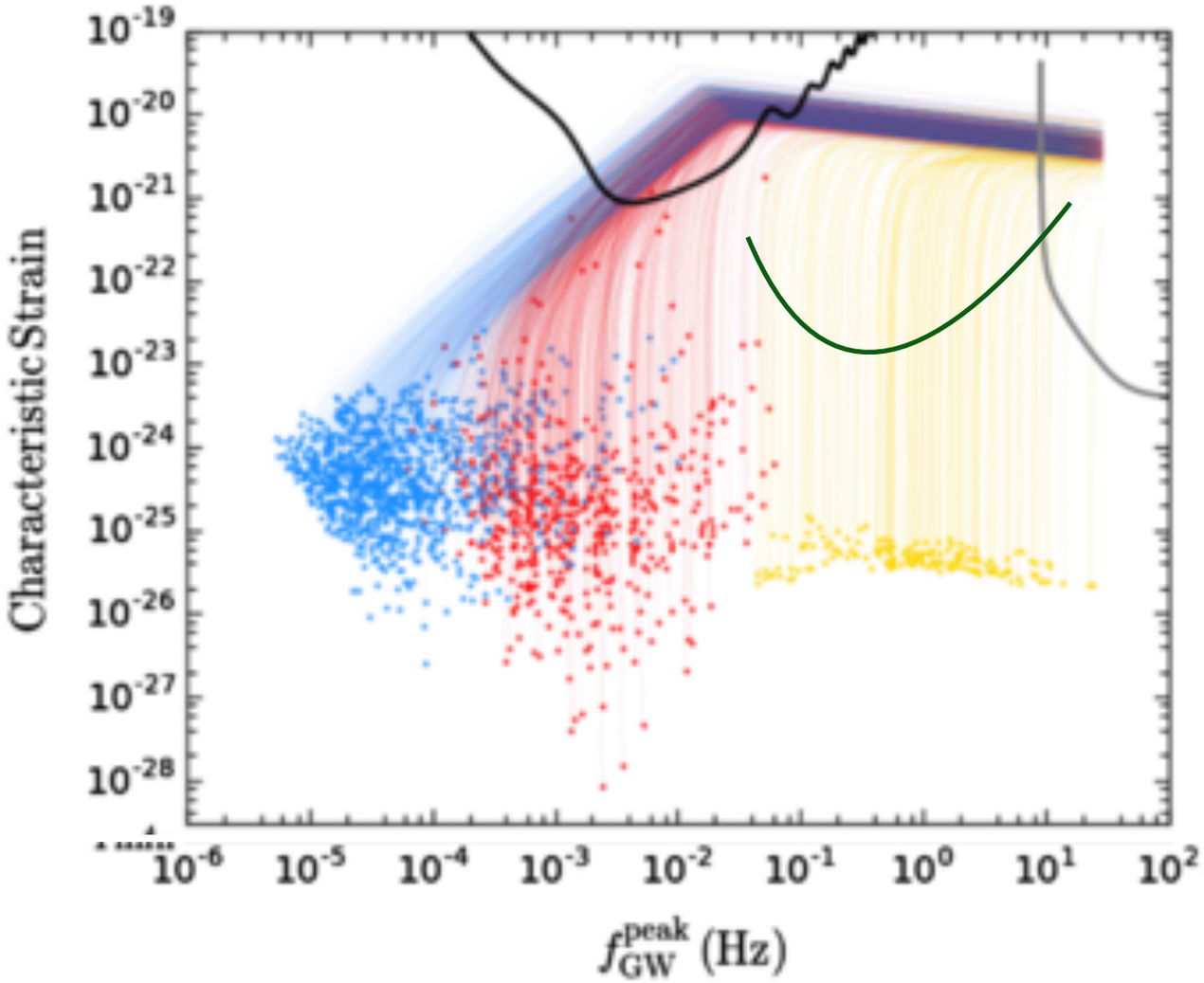
[Rodriguez+ 18]

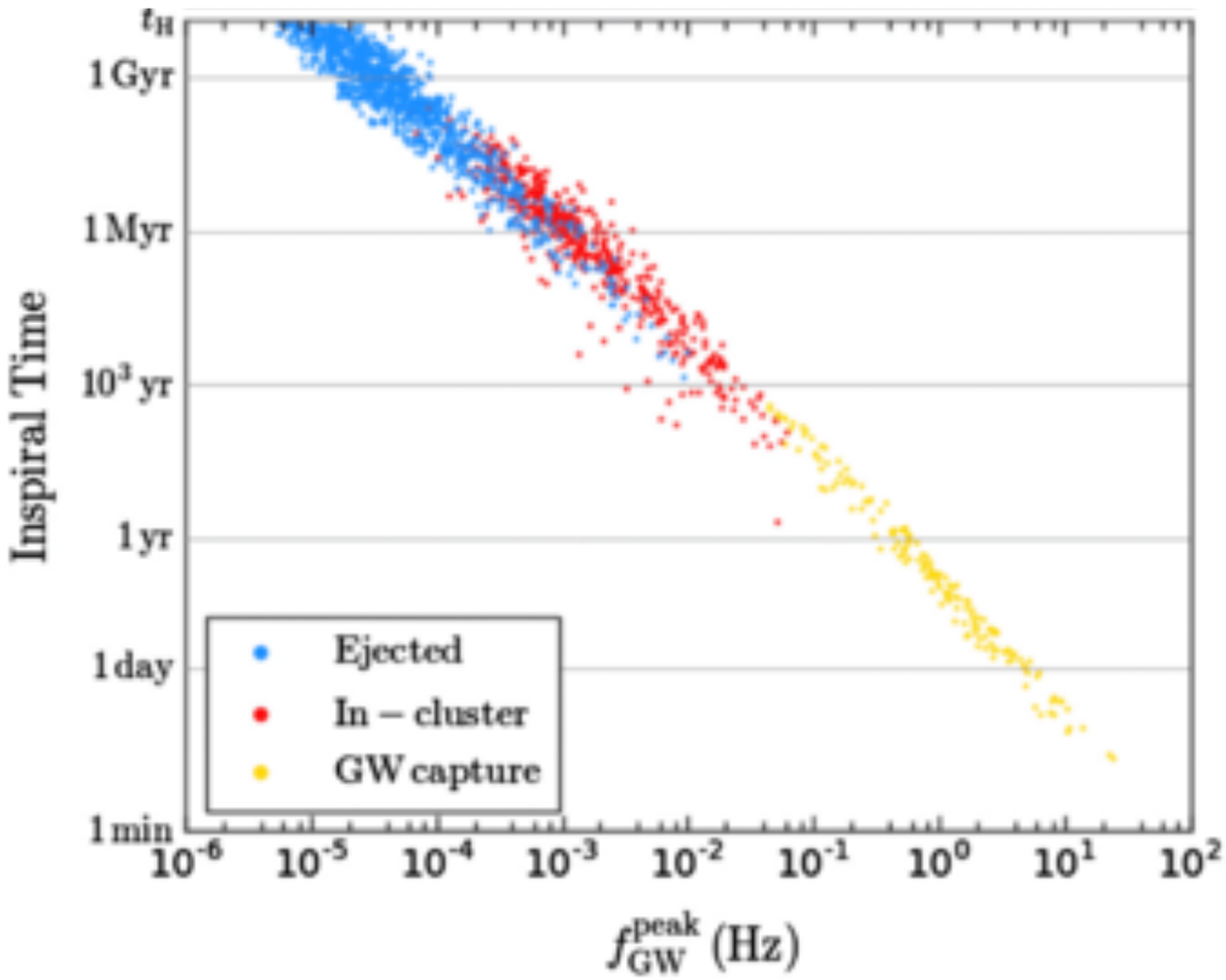


[Breivik+ 16]

BBH Mergers

Merger types: after ejection in-cluster GW capture





[Kremer+ 19]

The Burning Questions

- Retention fraction of BHs in GCs
  - hard to measure directly
  - depends on the above considerations *dynamical ages* of star clusters

Indirect Evidence!

- BH birth mass function
  - lacks observational constraints
  - models are not adequate to provide assumption-independent theoretical constraints

- BH birth kick distribution
  - lacks observational constraints; wh… able, constraints are confusing (e.g., Repetto+2012, 20… 2015)

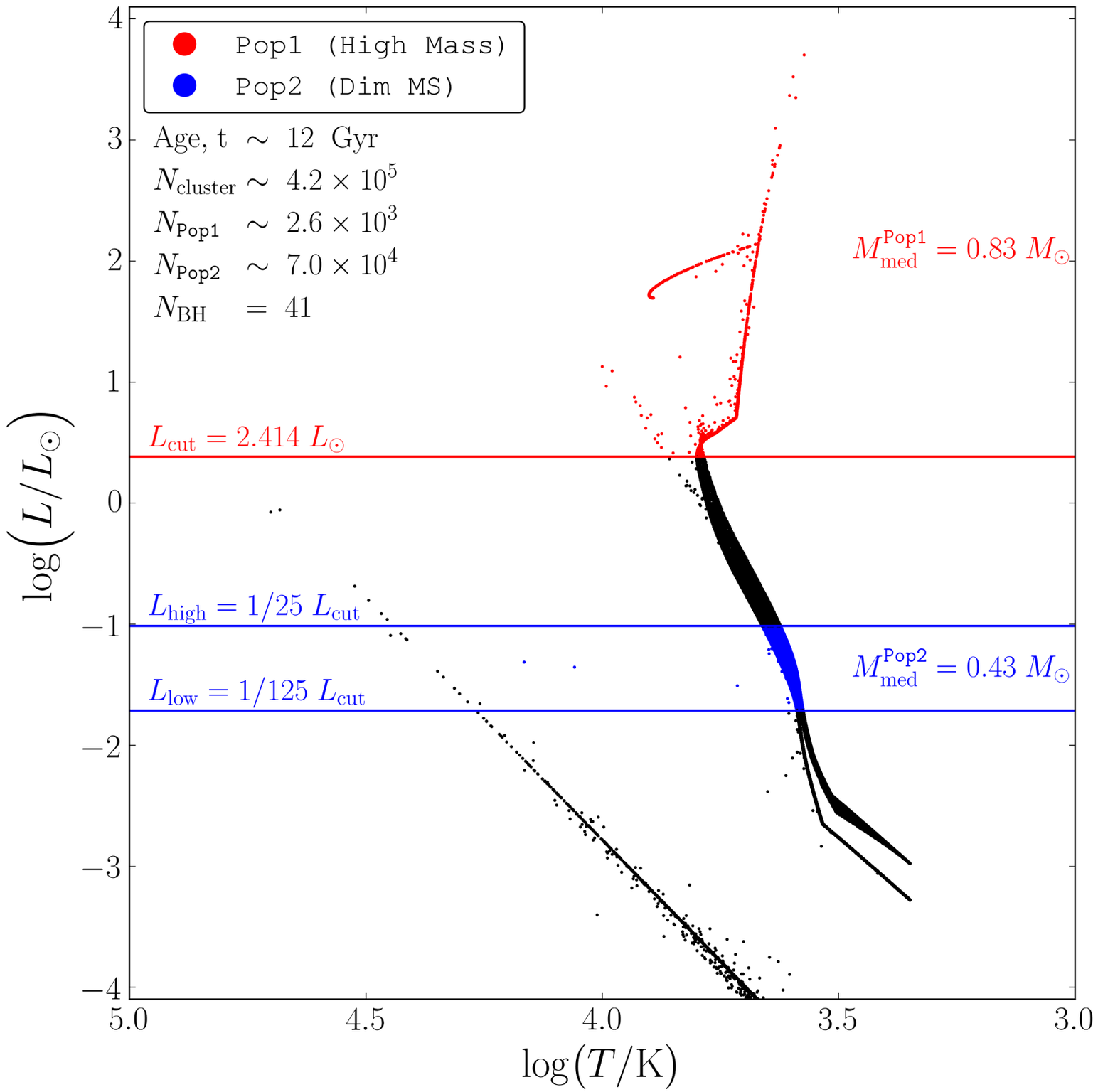
- Common-envelop… tion
  - parameterised pr… tions exist, results too sensitive on parameters

Needs large number of detections

Problem for all channels

Measuring BH Retention

Dynamical Signature e.g., Mass Segregation (Δ)



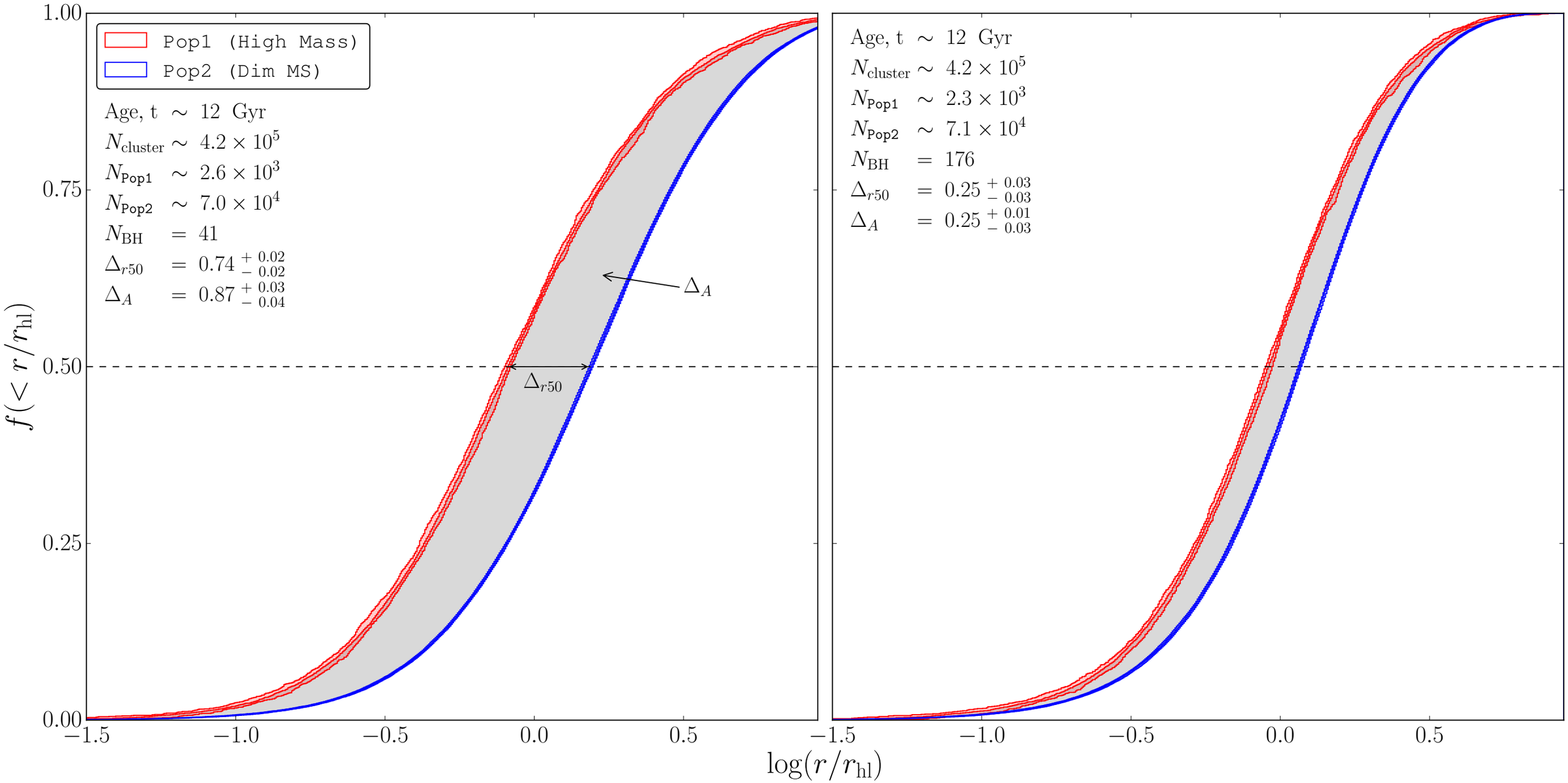
Requirements:

- Must be able to uniquely and consistently define groups in observed clusters and models
- Each group must have large memberships
- Need to be very careful about biases

[Weatherford+ 17]

Measuring BH Retention

Measuring Mass Segregation (Δ)



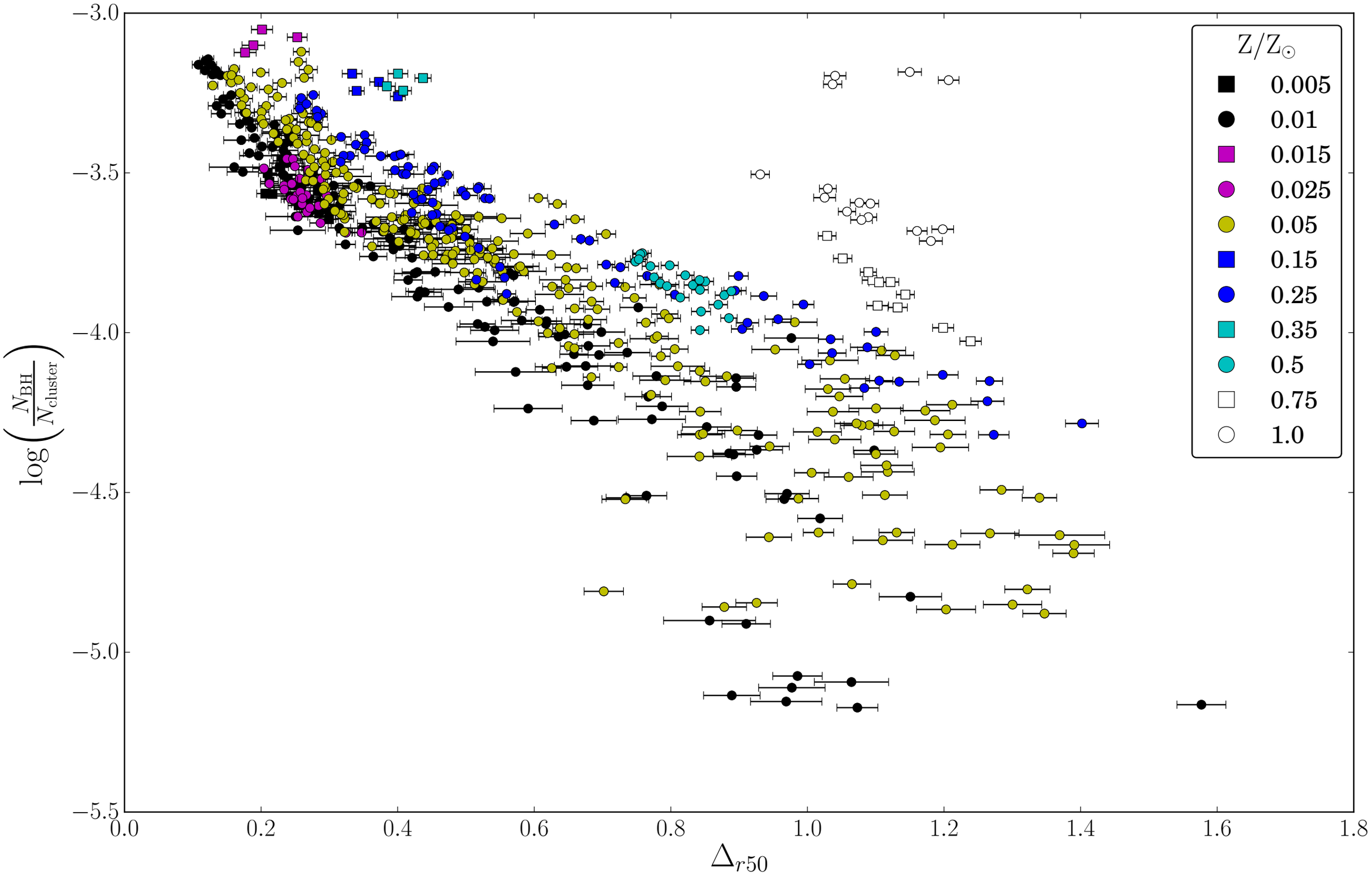
Low N_{BH} ➡ High Δ

High N_{BH} ➡ Low Δ

[Weatherford+ 17]

Strong Anticorrelation:

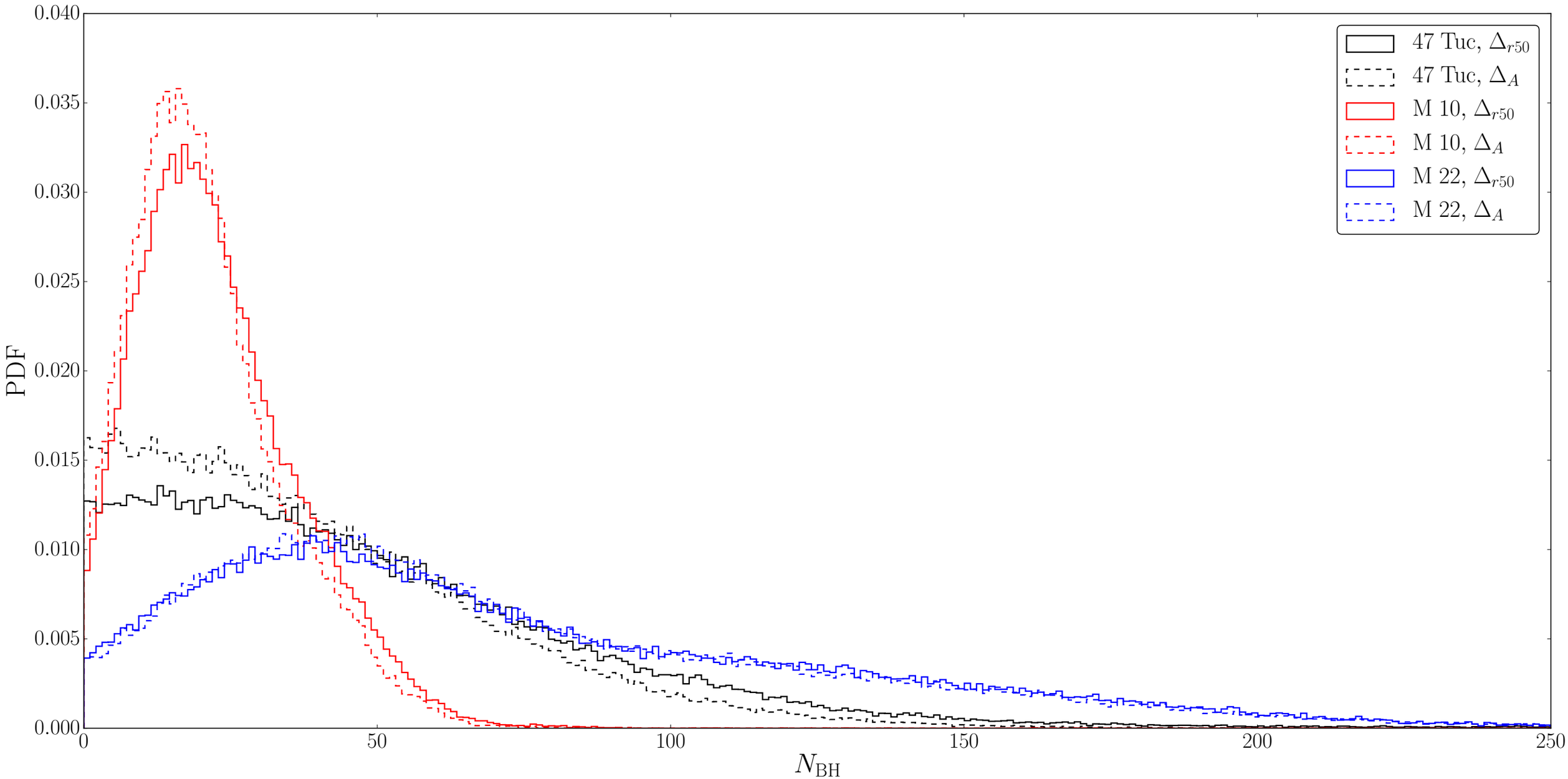
Δ vs N_{BH}



[Weatherford+ 17]

Strong Anticorrelation:

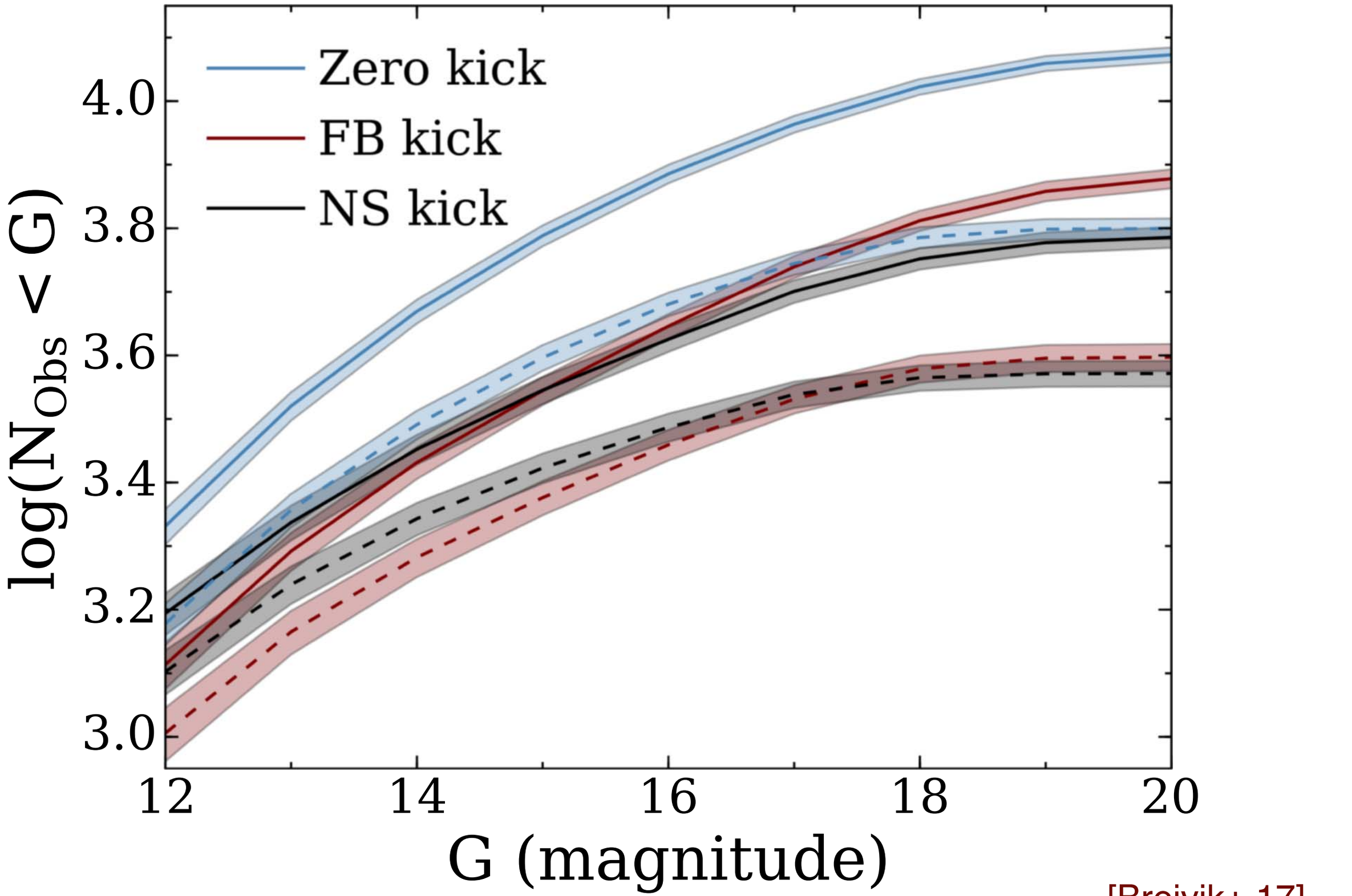
Inferred N_{BH} from measured Δ



[Weatherford+ 17]

Gaia

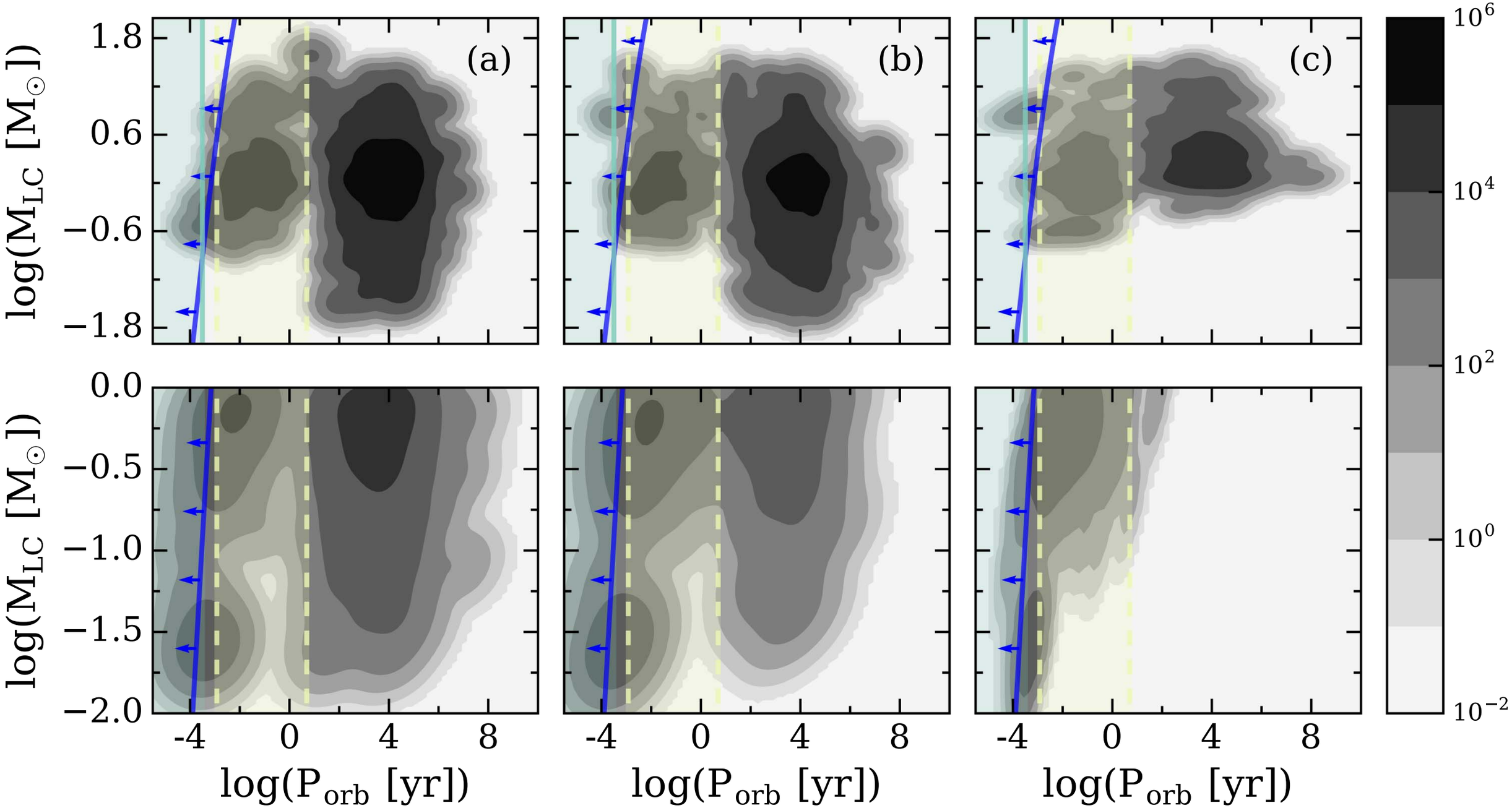
GAIA may detect thousands of BHs in the Milky Way



[Breivik+ 17]

GAIA's BHs

low detection biases & wider parameter space



[Breivik+ 17]

Summary

- Key features and uncertainties of formation channels
- The dynamical formation channel for binary black holes (BBHs)
  - Well understood processes control formation efficiency and properties
  - Key observable differences: mass, eccentricity, spin
- A critical look at our understanding of rates and properties
  - BH formation physics, BH retention fraction, etc.
- Possible ways to improve our understanding
  - Indirect measurements of BH population in today's GCs
  - Potential detection of many BHs and other compact binaries using *Gaia*.

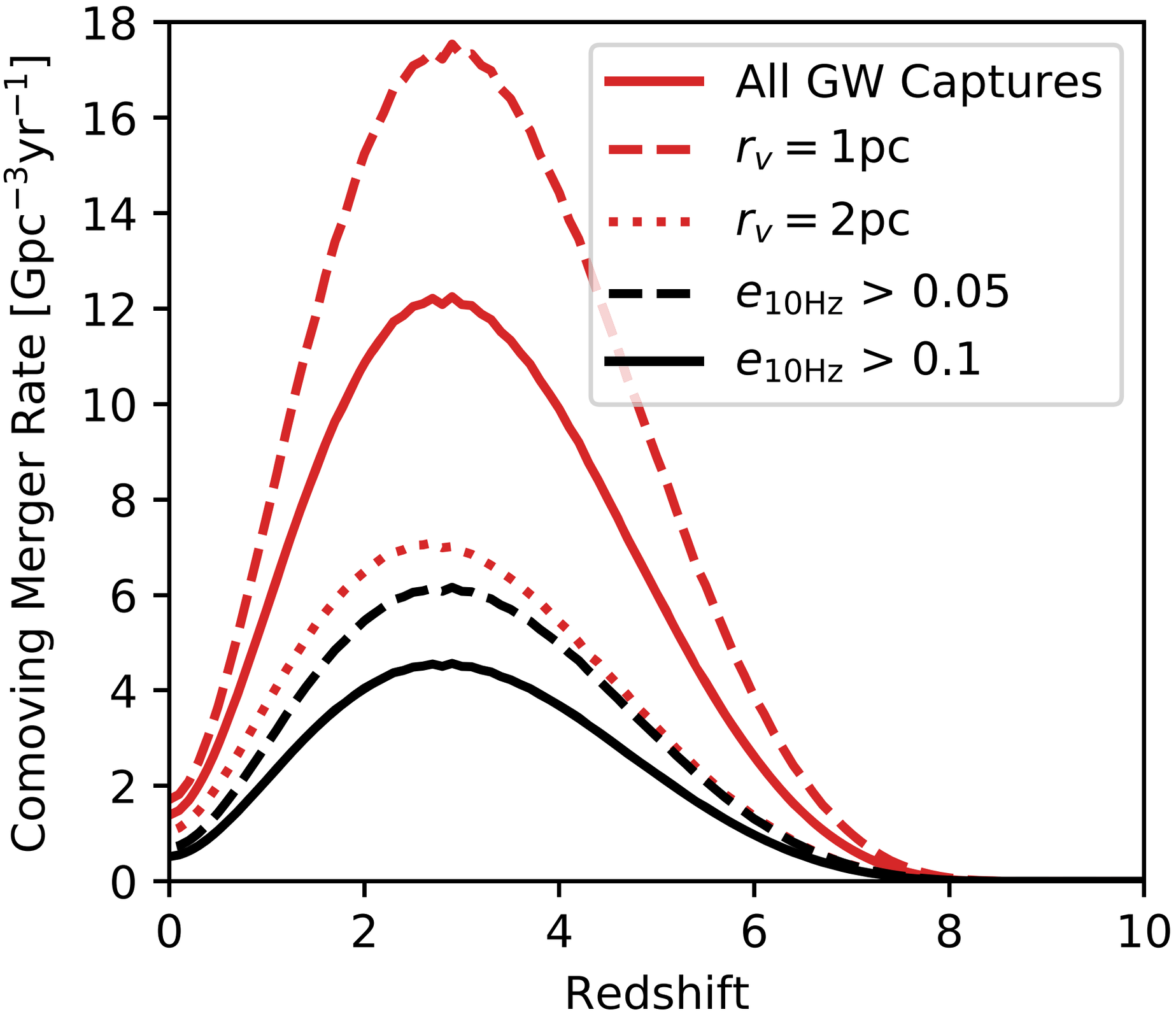
Burning Questions!!!

How much to trust our common-envelope evolution prescriptions?

We need better constraints for supernova physics

BBH Mergers

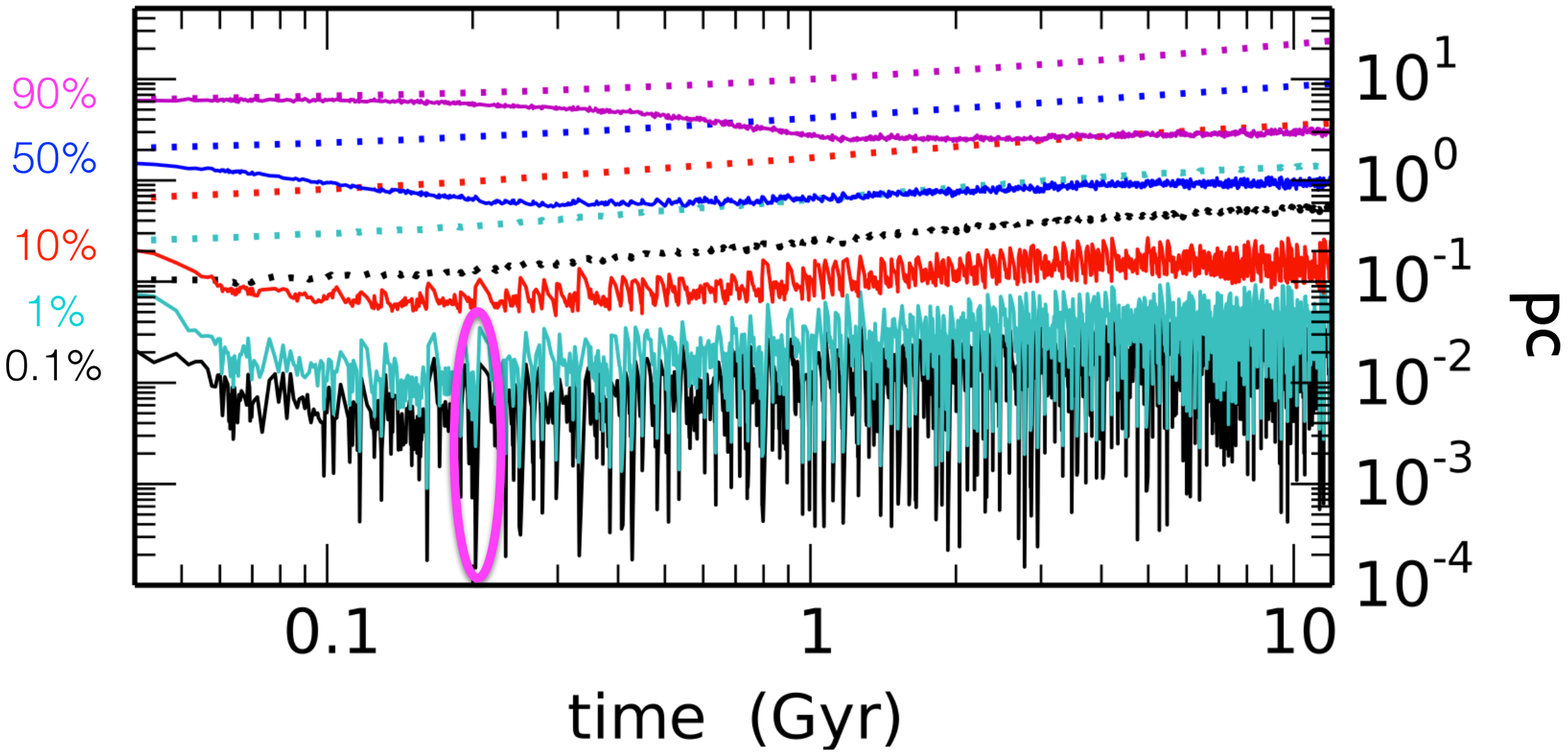
Merger rate



Rodriguez+ 18

What Really Happenes to the BHs in Clusters?

or Where Spitzer went wrong in the 60's



Morscher+ 2015

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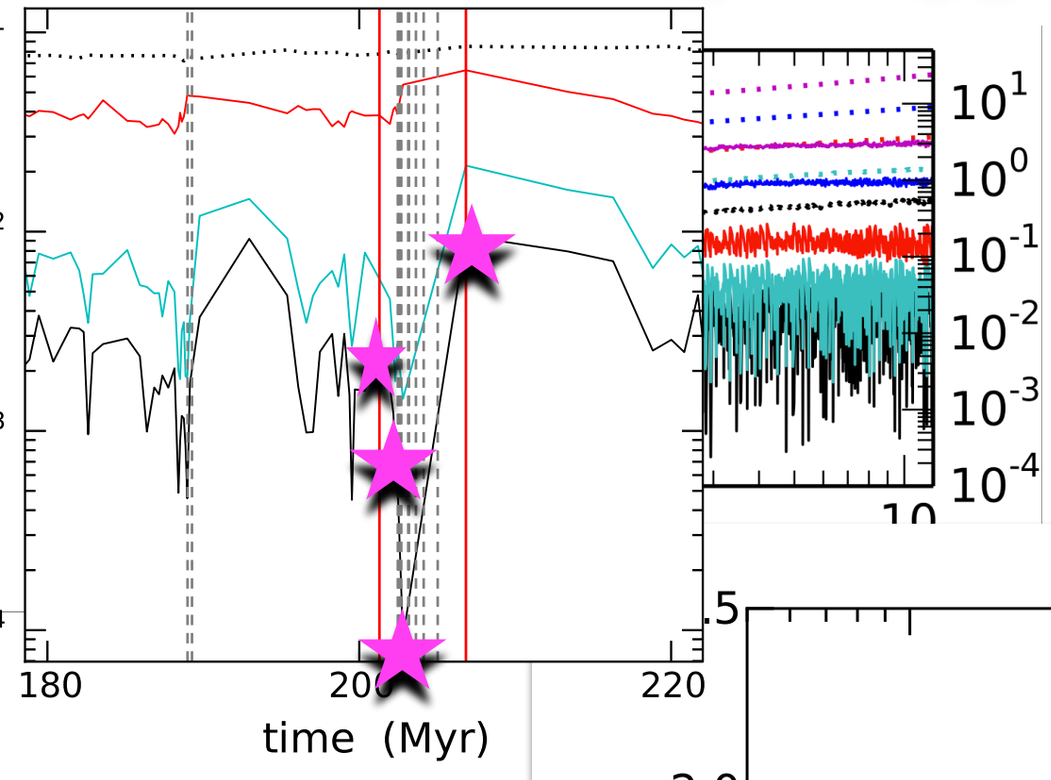
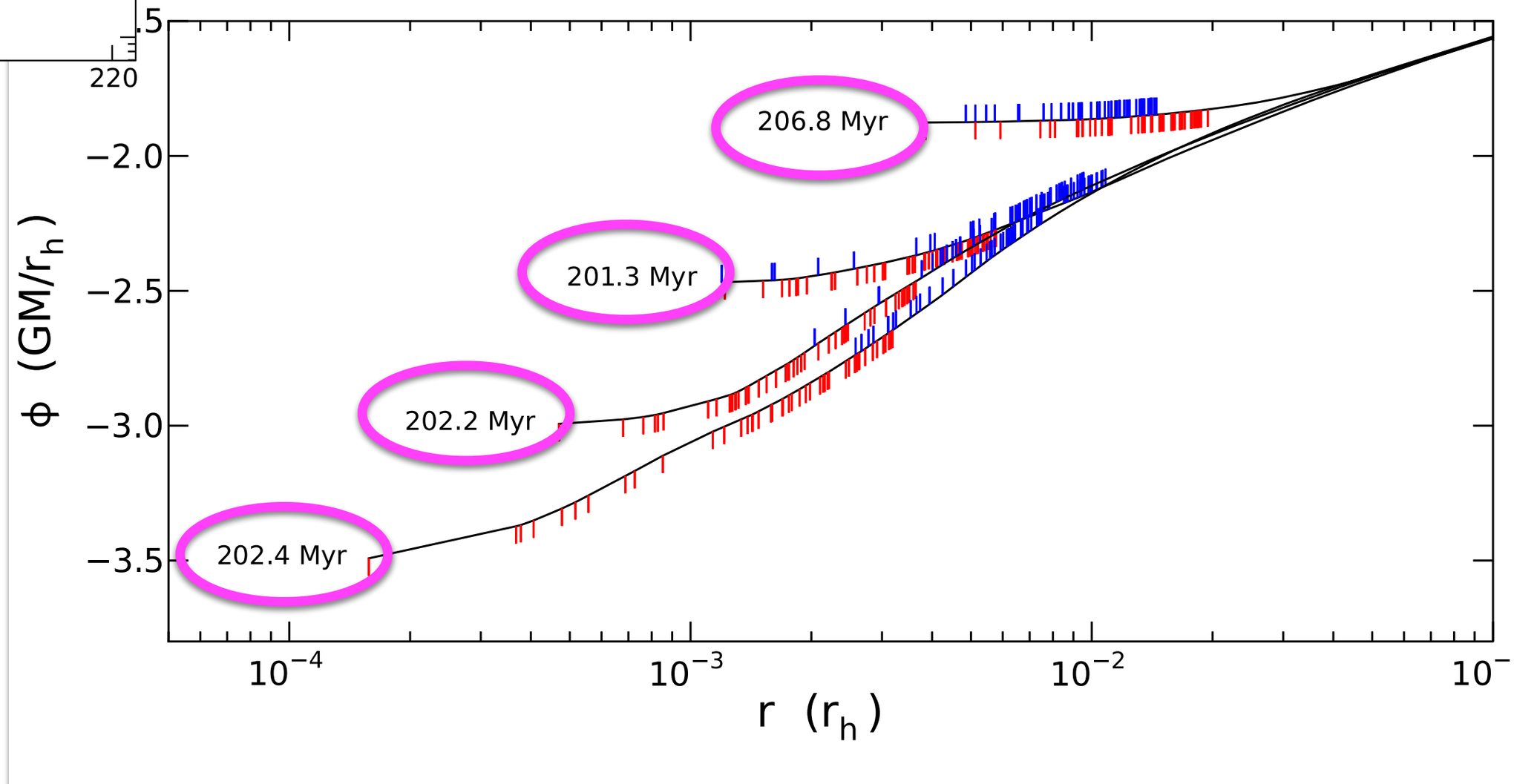
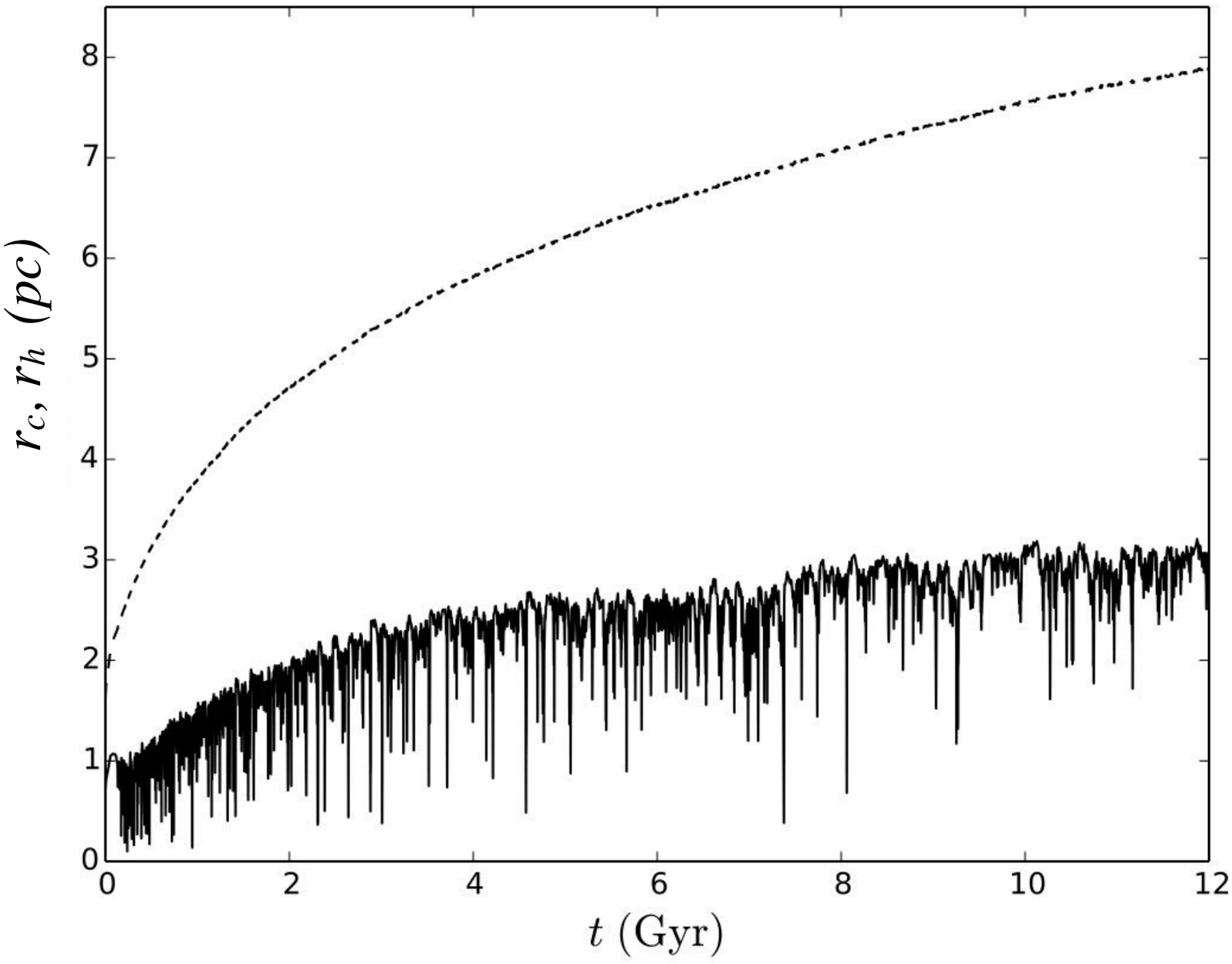




Morscher+ 2015

Challenges in Measuring BH Retention



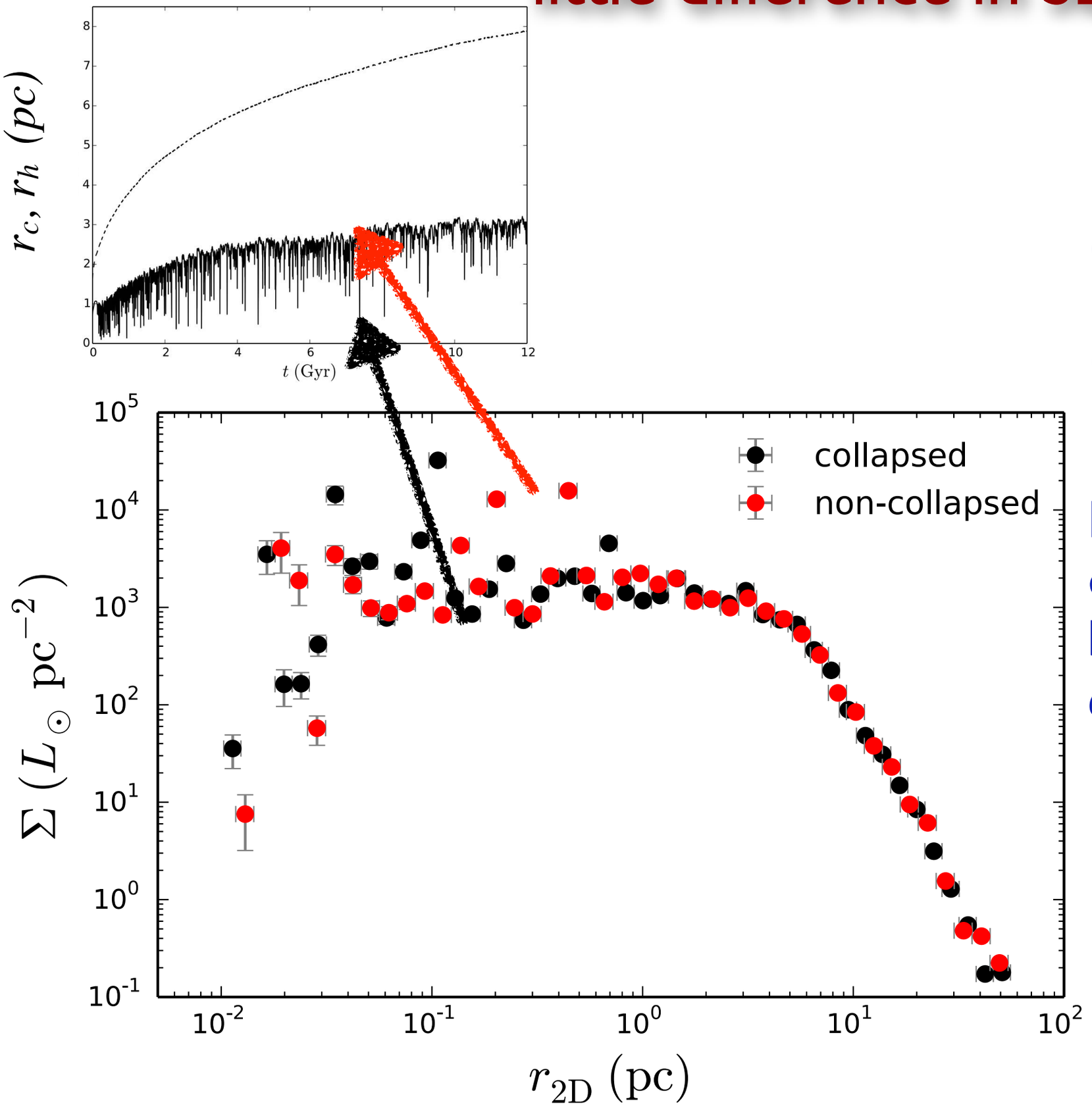
Repeated BH-driven collapse

Overall cluster expansion

Chatterjee+ 2017

Challenges in Measuring BH Retention

little difference in SBP



Repeated BH-driven collapse

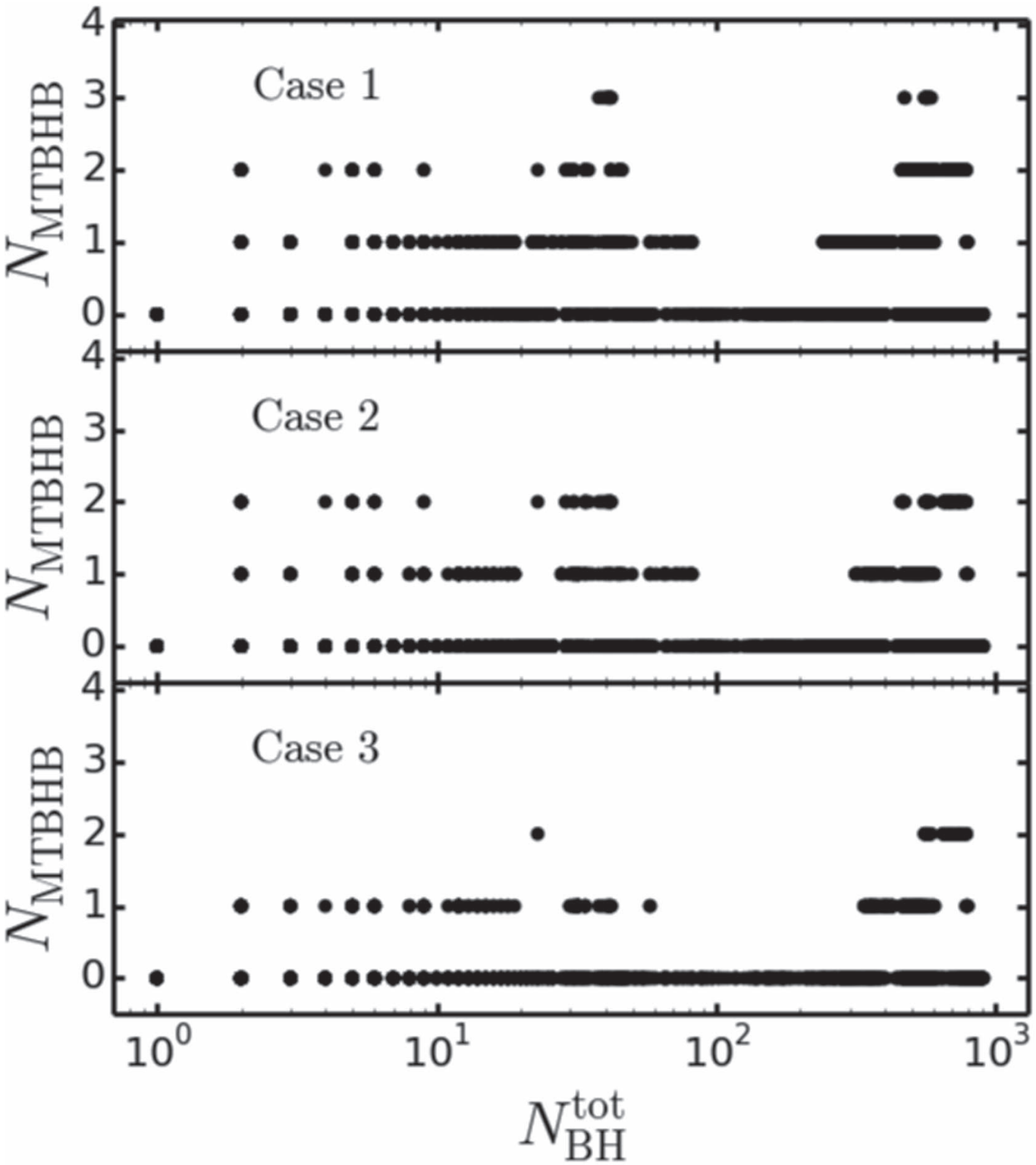
Overall cluster expansion

Little observable difference in surface brightness profile *in* and *out* of collapse

Chatterjee+ 2017

Challenges in Measuring BH Retention

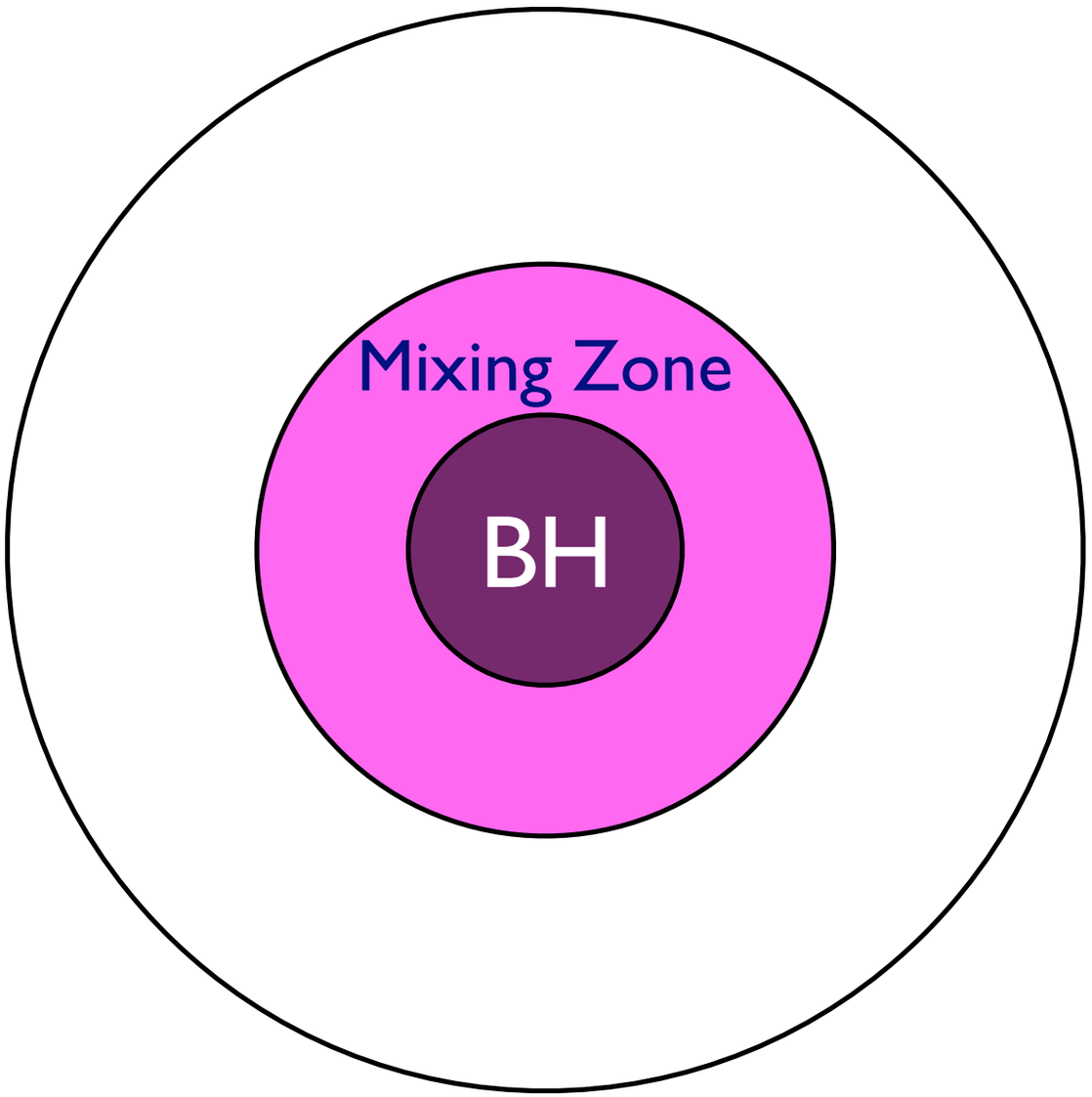
no correlation between N_{BH} and N_{BHMTB}



Kremer+ 2018

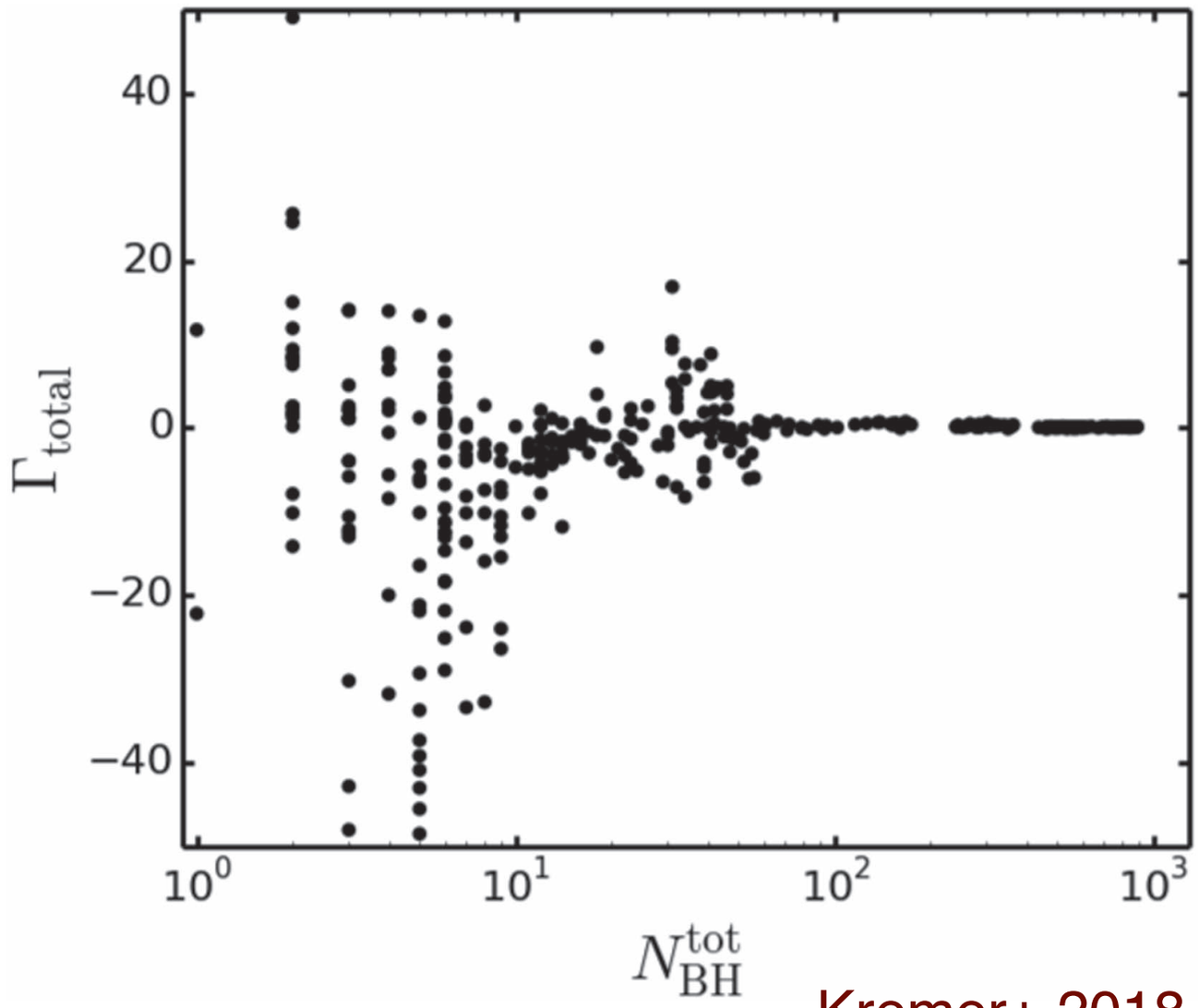
Challenges in Measuring BH Retention

no correlation between N_{BH} and N_{BHMTB}



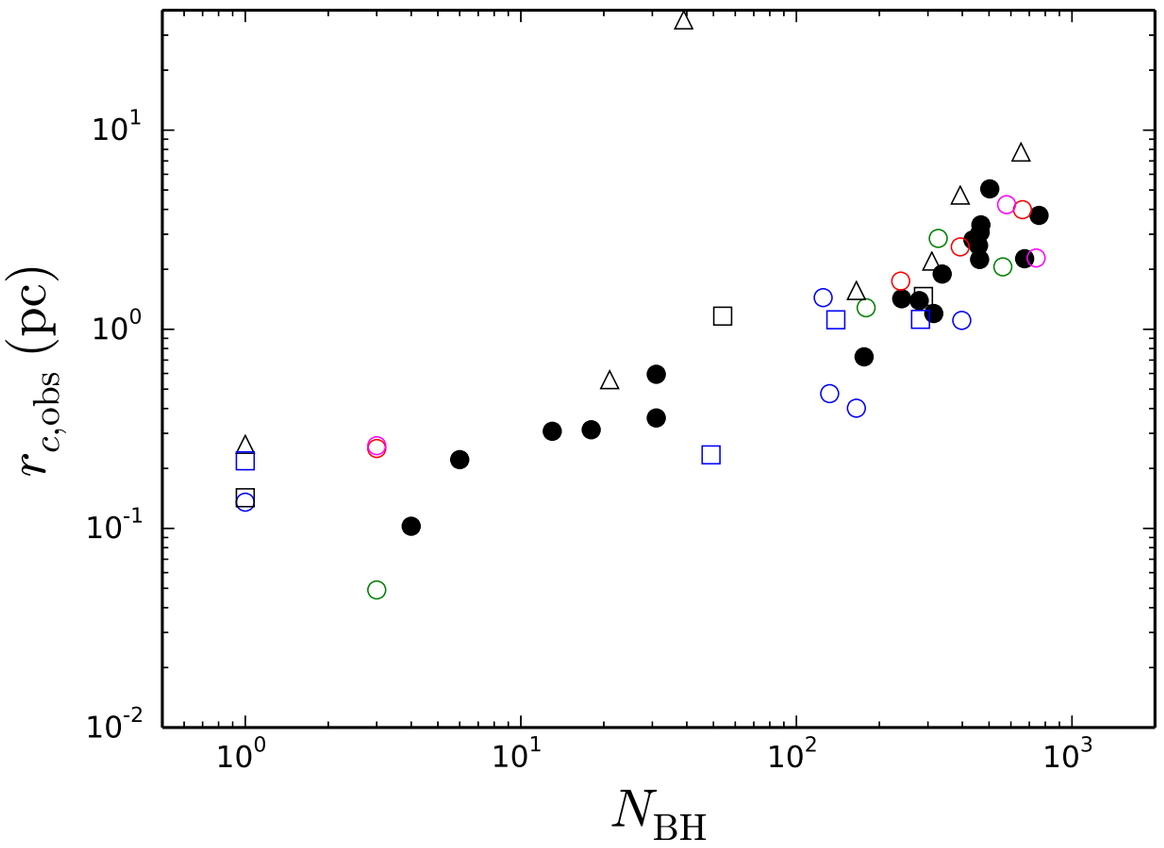
N_{BH} ↑

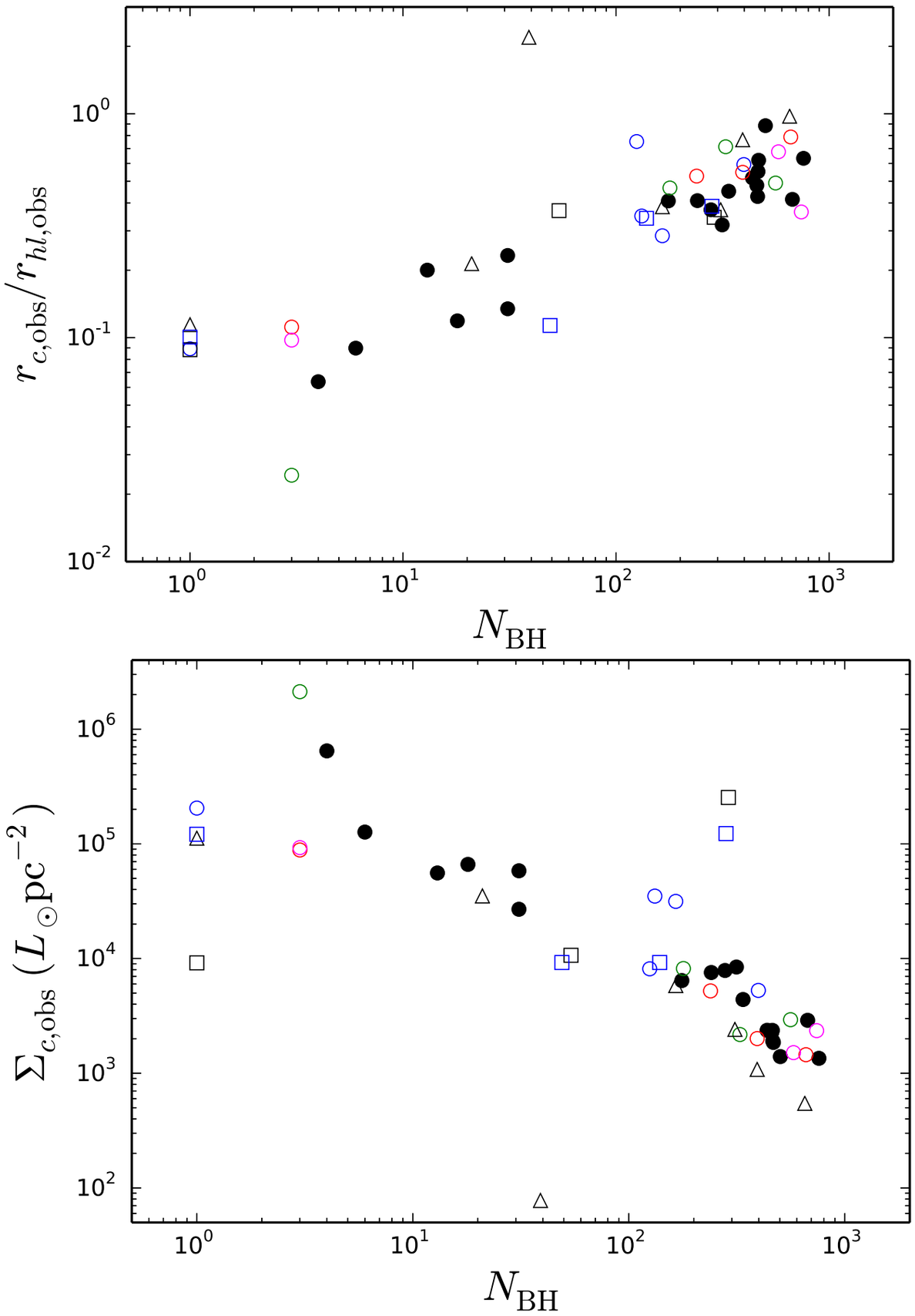
ρ_{MZ} ↓



Kremer+ 2018

Effects of BHs on Cluster Evolution





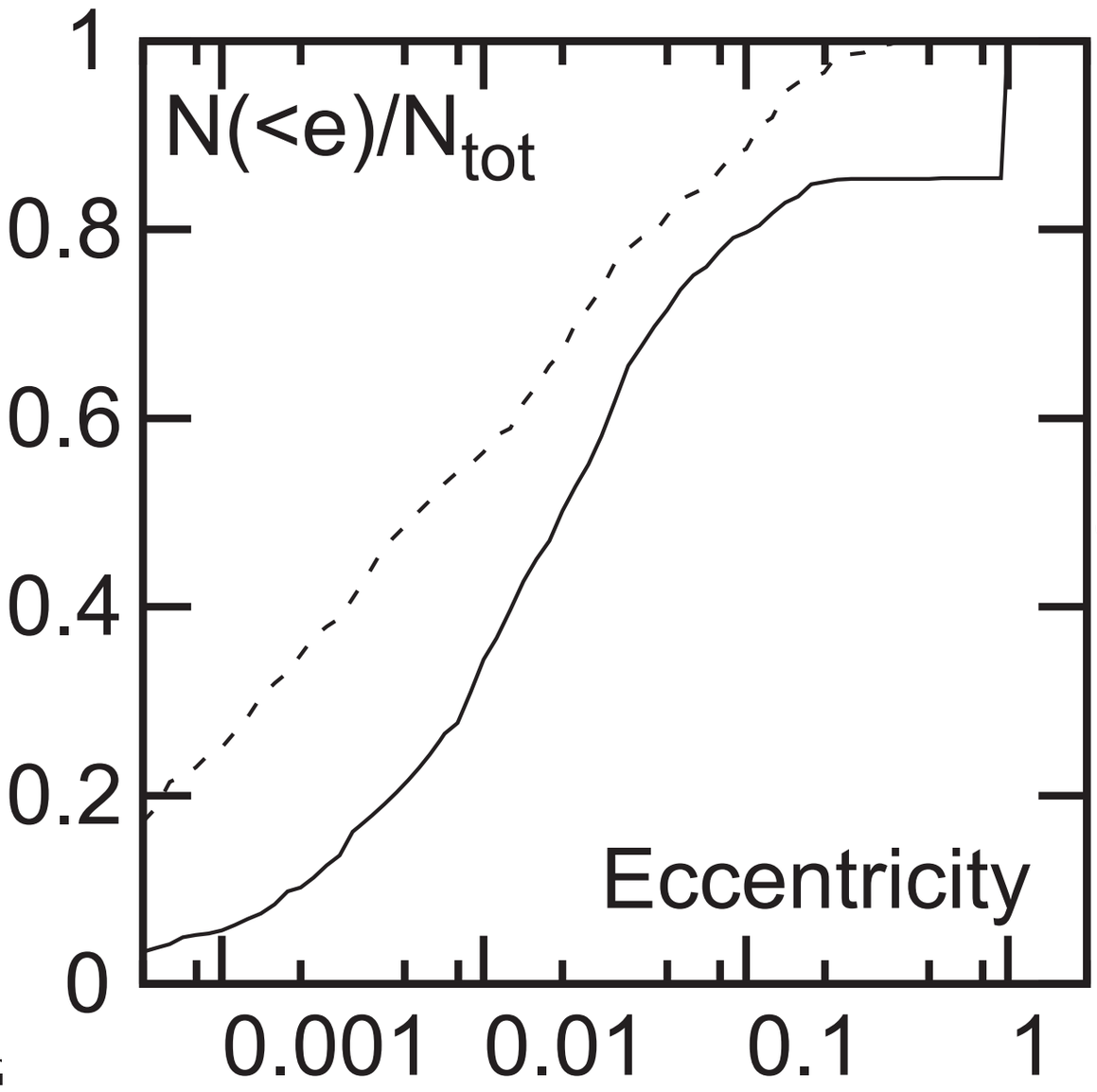
Chatterje+ 2017

While large N_{BH} is retained, GCs appear to have:

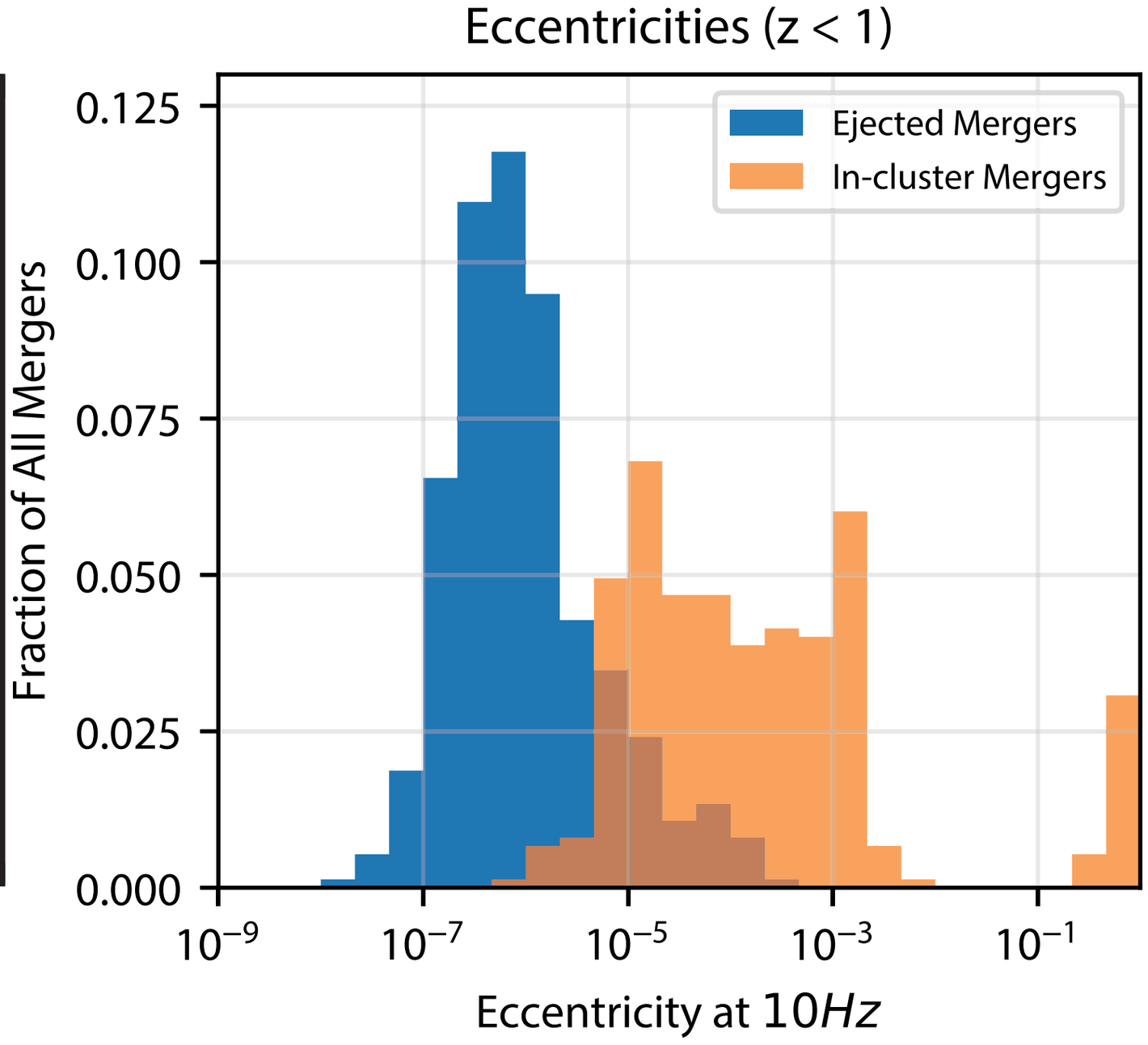
- Large core
- Low concentration
- Low central density
- Low velocity dispersion

Eccentricities of Merging BBHs

KL+GW capture



Antonini+ 2016



Rodriguez+ 2018

What are star clusters?

Star clusters in galaxies

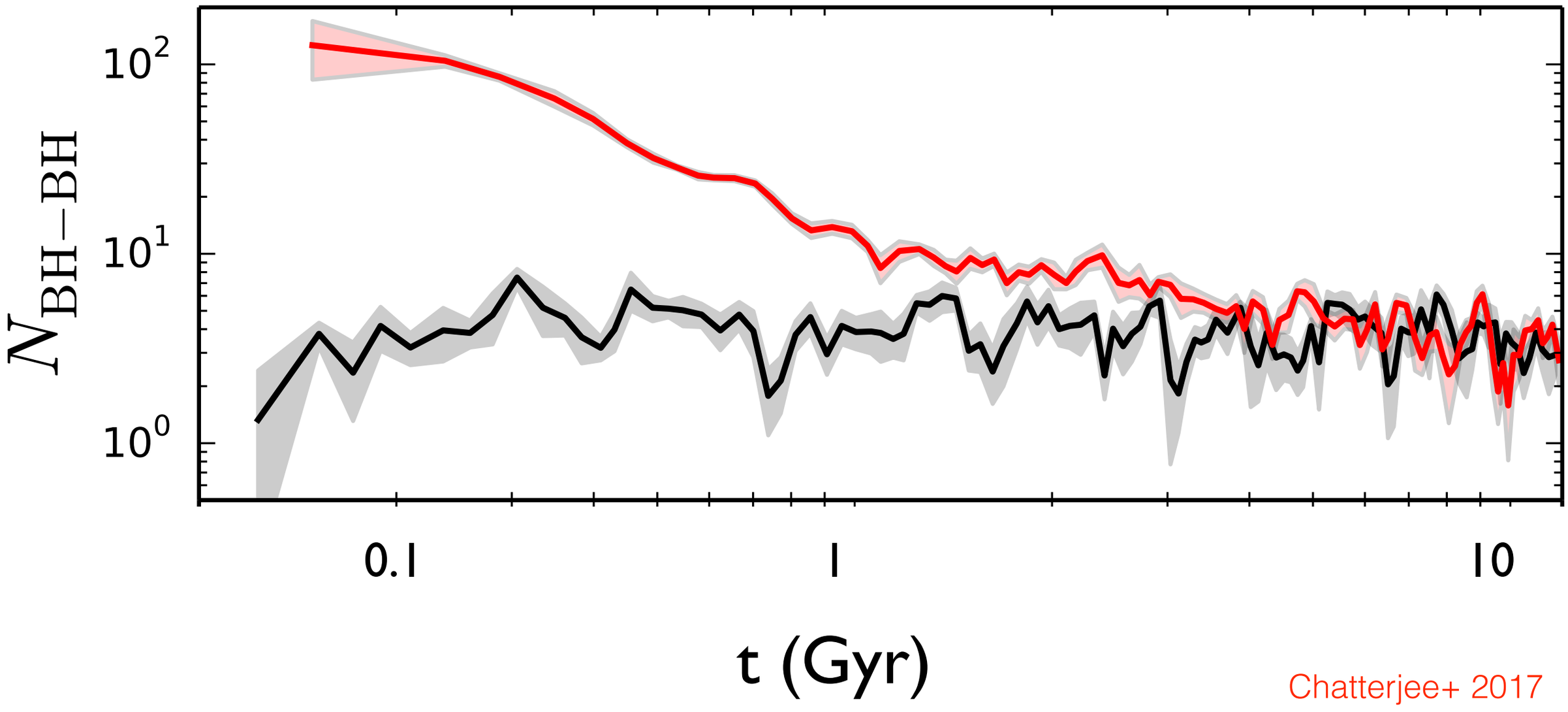
Property	Open Clusters	Globular Clusters
Mass ($M_\odot$)	up to ~ 10^3	typical ~ 10^5
ρ_c ($M_\odot pc^{-3}$)	up to ~ 10^2	typical ~ 10^4
Typical age	up to ~ 7 Gyr	9 - 12 Gyr
Binary fraction (f_b)	~ 50%	few - 20%
Metallicity	higher	low

Results Insensitive to Model Assumptions

A key difference between dynamical and non-dynamical formation channels

Initial $f_{b,\,\text{high-mass}} = 1$

Initial $f_{b,\,\text{high-mass}} = 0$



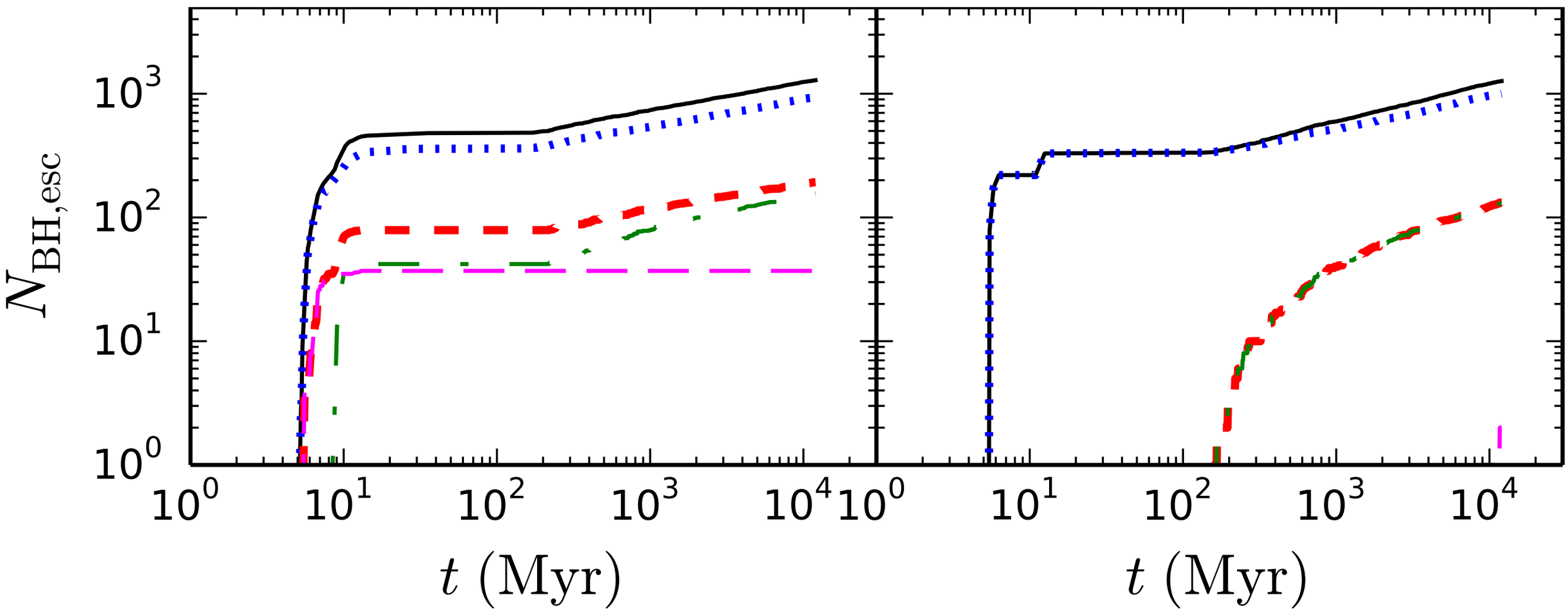
Chatterjee+ 2017

Results Insensitive to Model Assumptions

A key difference between dynamical and non-dynamical formation channels

Look at the green lines

Chatterjee+ 2017

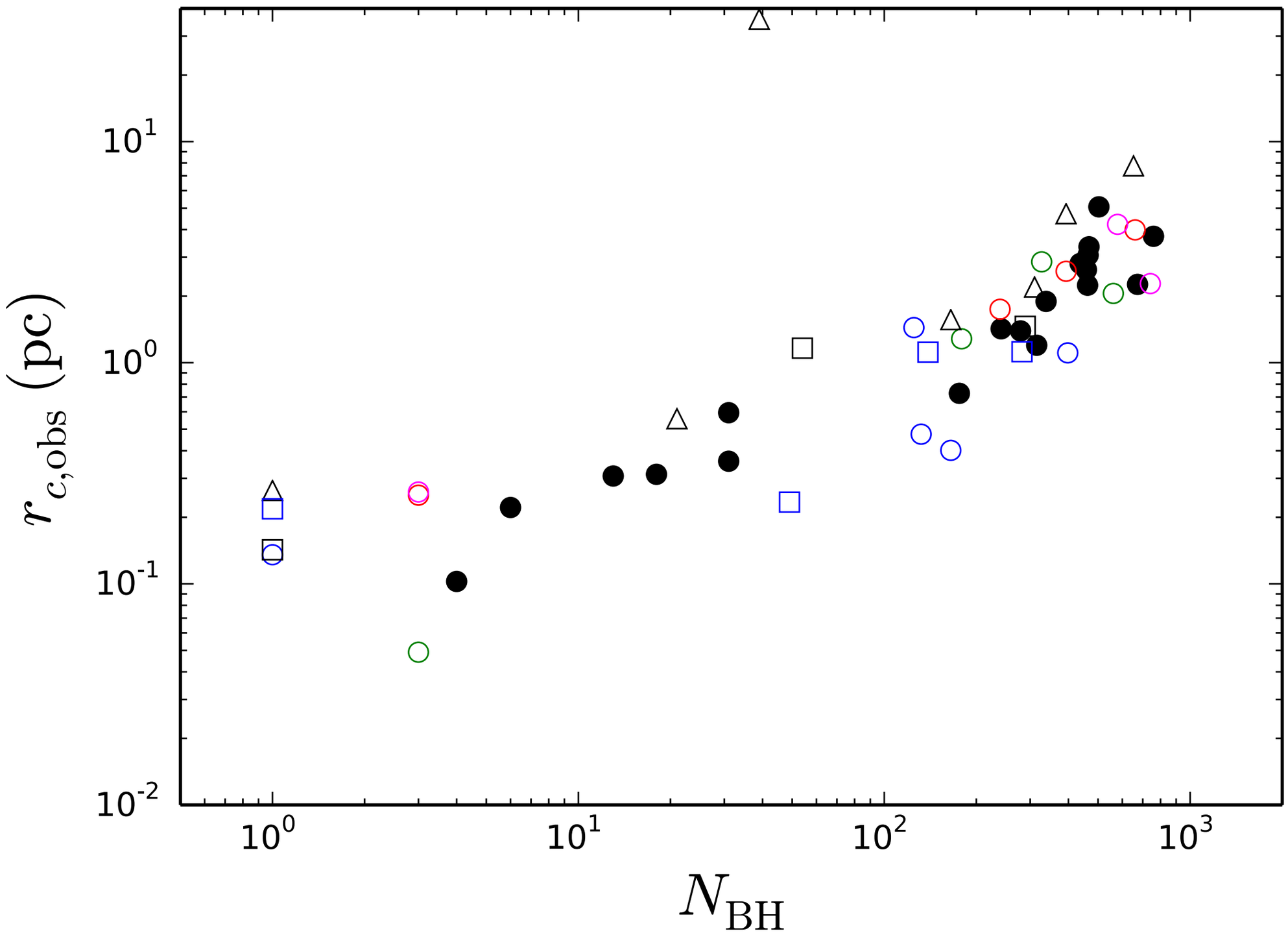


Initial $f_{b,\,\text{high-mass}} = 1$

Initial $f_{b,\,\text{high-mass}} = 0$

Number of Retained BHs and GC Properties

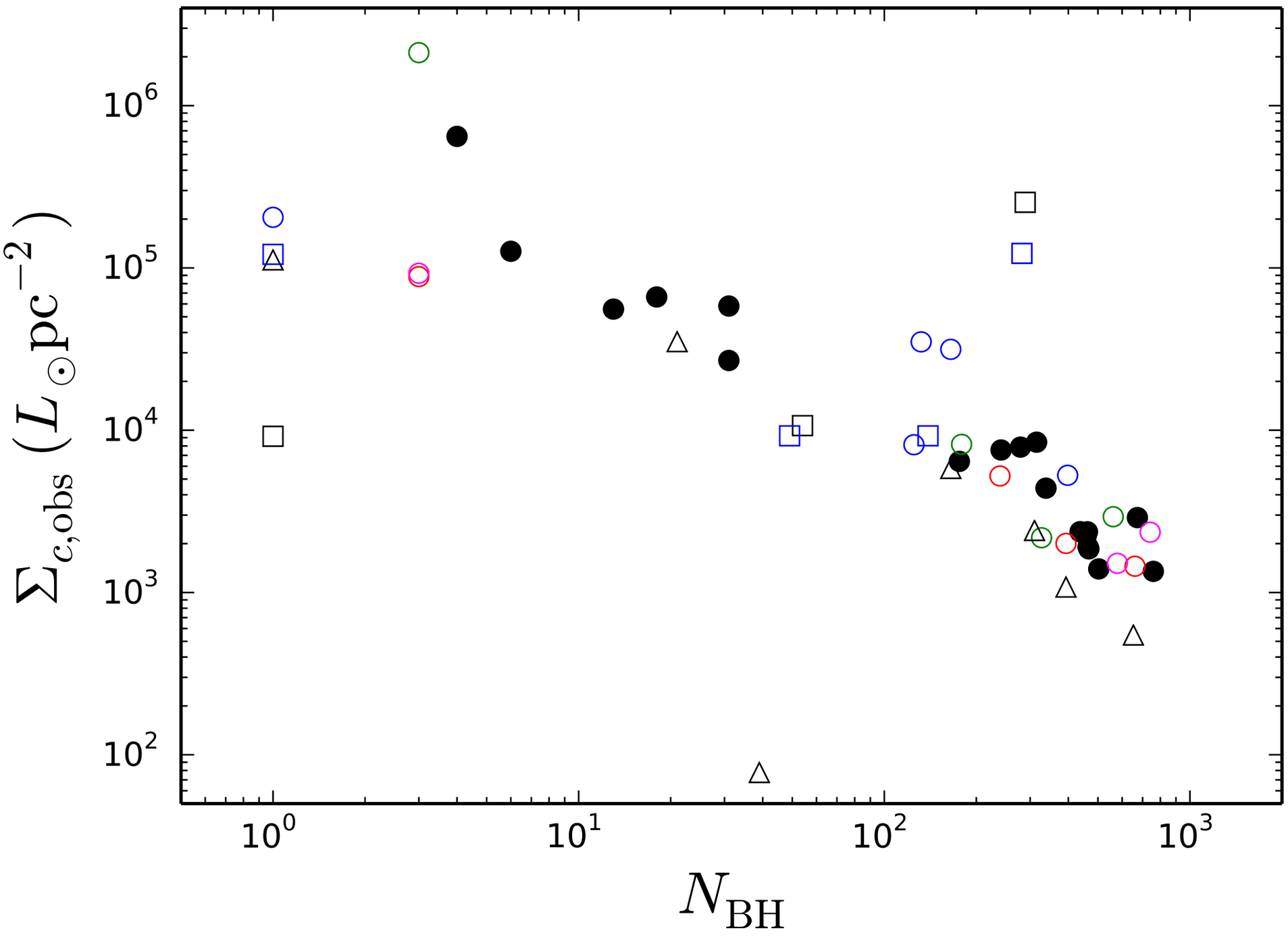
Correlation with core radius



Chatterjee et al. 2017

Number of Retained BHs and GC Properties

Correlation with central density



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