Numerical Modeling of Massive Star Clusters: An Evolving Story of the Black Holes

Sourav Chatterjee

Carl L. Rodriguez, Meagan Morscher, Fabio Antonini, Frederic A. Rasio

Stefan Umbreit, John M. Fregeau

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C I E R A

Center for Interdisciplinary Exploration and Research in Astrophysics

Plan of the talk

- Introduction
  - Motivation, physical processes active in clusters, numerical techniques
- Modeling star clusters using the Hénon-type Monte Carlo Code *CMC*
  - Validation of CMC
- BHs in clusters: the evolving story & current understanding
- BHs are affected by cluster dynamics
  - Properties, difference from field (undisturbed) population, aLIGO implications
- Cluster is affected by its BHs
  - Effects of uncertain BH-related physics
- Summary and conclusion

Star clusters Properties

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

Why study dense star clusters?

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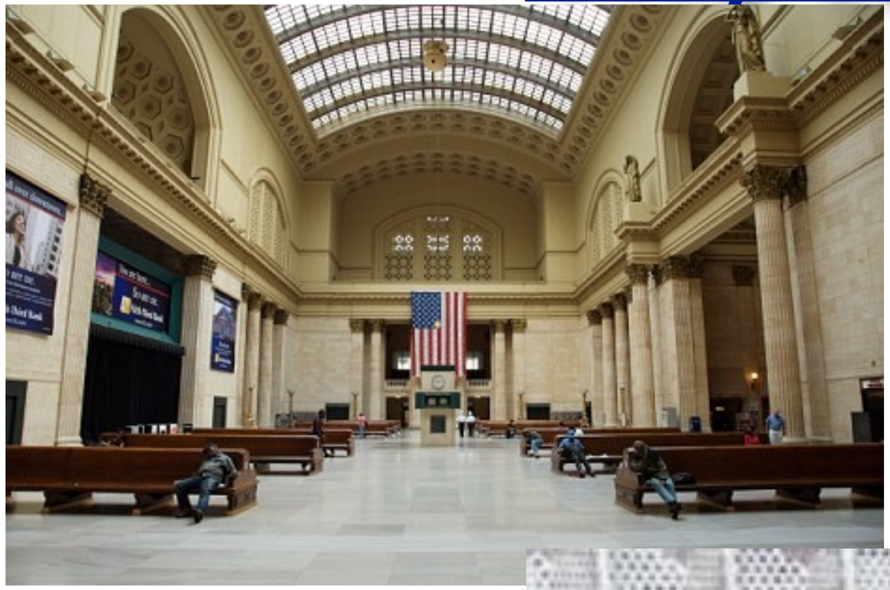


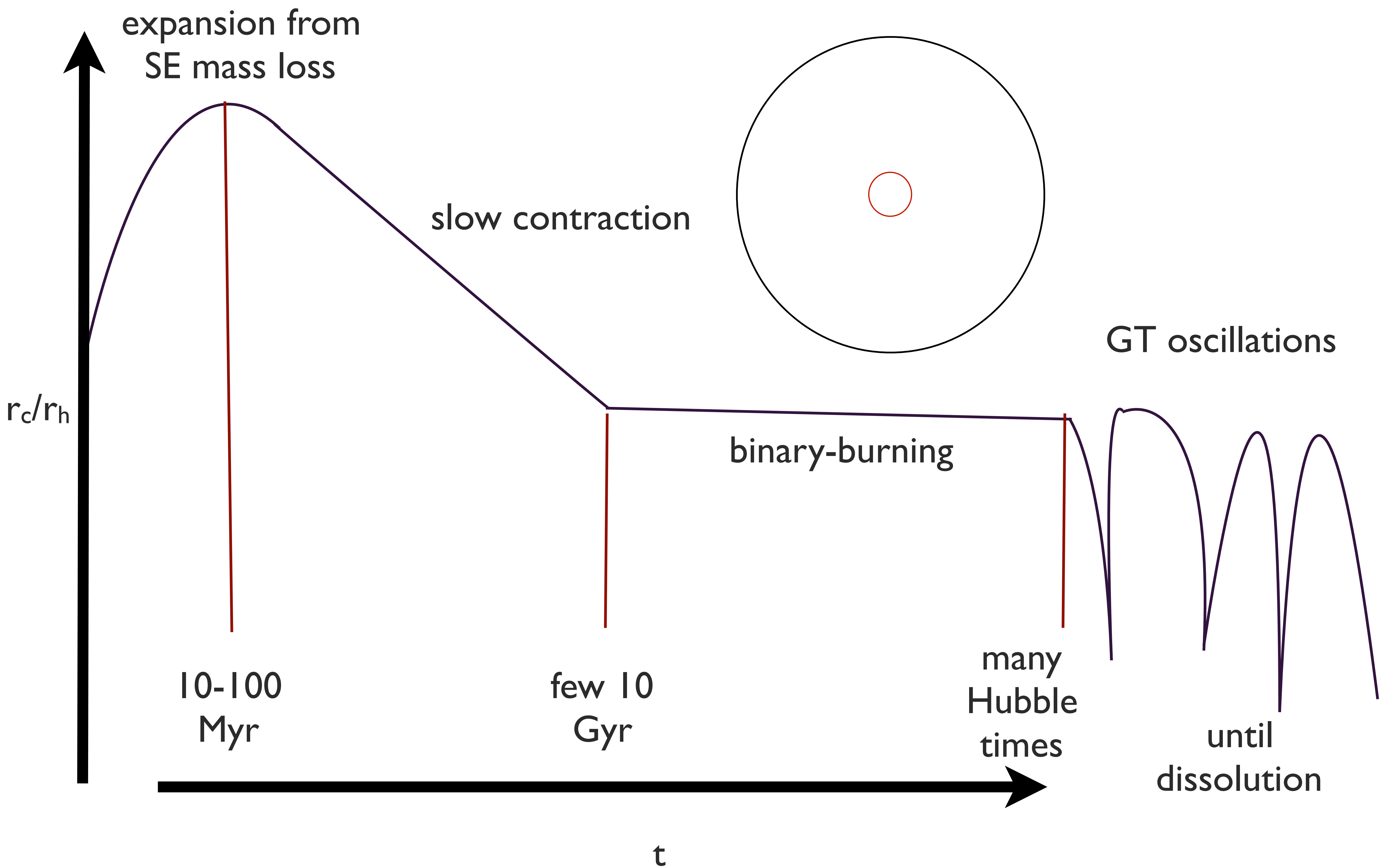
Why study dense star clusters?

- Clusters are dense stellar environments
  - Higher formation rates of exotic stars in GCs compared to elsewhere in the galaxy, e.g., blue stragglers, X-ray binaries, cataclysmic variables, & BH binaries (e.g., Clark 1975, Pooley & Hut 2006; Rodriguez et al. 2015)
- Massive GCs are important targets in distant galaxies
  - The dynamical history of clusters provides important clues to the hierarchical formation of the Galaxy (e.g., Brodie & Strader 2006 for a review)
  - Spatial distribution can constrain the dark matter halo radius
  - Typical old ages provide a direct window to early major star formation episodes in the local universe (e.g., Brodie & Strader 2006)
- All stars are born in clusters of some size
  - All clusters lose stars from galactic tides
  - Low mass clusters dissolve completely within Hubble time (e.g., Giersz & Heggie 1997; Odenkirchen et al. 2003; Gieles et al. 2005; Lamers et al. 2005)

Physical Processes

- Two-body relaxation
  - Cumulative effect of a sequence of weak pair-wise gravitational interactions is a slow outward diffusion of energy
  - Mass segregation is a natural consequence as the system evolves towards equipartition of energy
  - Typical timescale for Galactic GCs ~ 10^9 yr
- Binary-burning
  - Energy production from strong super-elastic scattering involving hard binaries
  - Interactions happen on a dynamical timescale
- Stellar evolution
  - Massive stars evolve on much shorter timescales compared to GC ages
  - Wind mass loss, mass loss from compact object formation
- Galactic tidal stripping

Evolutionary stages of dense star clusters



Numerical modeling of dense star clusters

Methods

Method	Advantage	Disadvantage
Fokker-Planck	Fastest among the three	Hard to implement additional physics
Hénon-type Monte Carlo	Fast, easy to implement additional physics, as accurate as direct N-body for $N \gtrsim 10^4$	Assumptions may not be valid for low $N \sim 10^2$
Direct N-body	Exact gravitational forces	Computationally expensive, $\sim N^3$

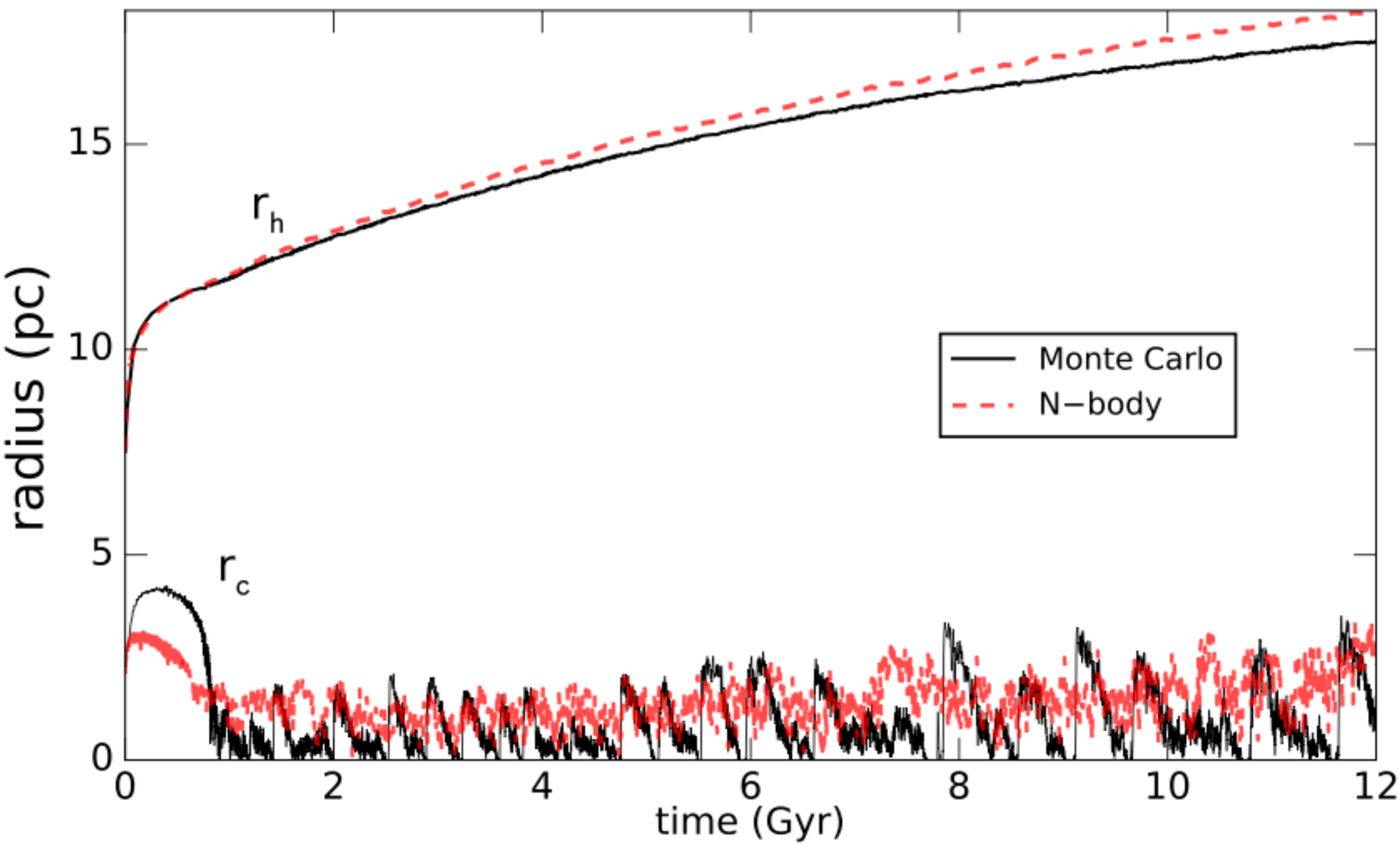
Monte Carlo Code CMC

Physical Processes & Parallelization

- Two-body relaxation (Joshi et al. 2000)
- Strong interactions: physical collisions, binary-mediated interactions (Fregeau & Rasio 2007)
- Galactic tidal stripping (Joshi et al. 2001; Chatterjee et al. 2010)
- Stellar evolution using BSE (Hurley et al. 2000, 2002; Chatterjee et al. 2008, 2010)
- Central IMBH with loss-cone physics (Umbreit et al. 2012)
- Rate-based 3-Body binary formation (Morscher et al. 2015)
- Parallelized using MPI & CUDA (Pattabiraman et al. 2012)

Million-body Simulation

CMC & NBODY6++GPU



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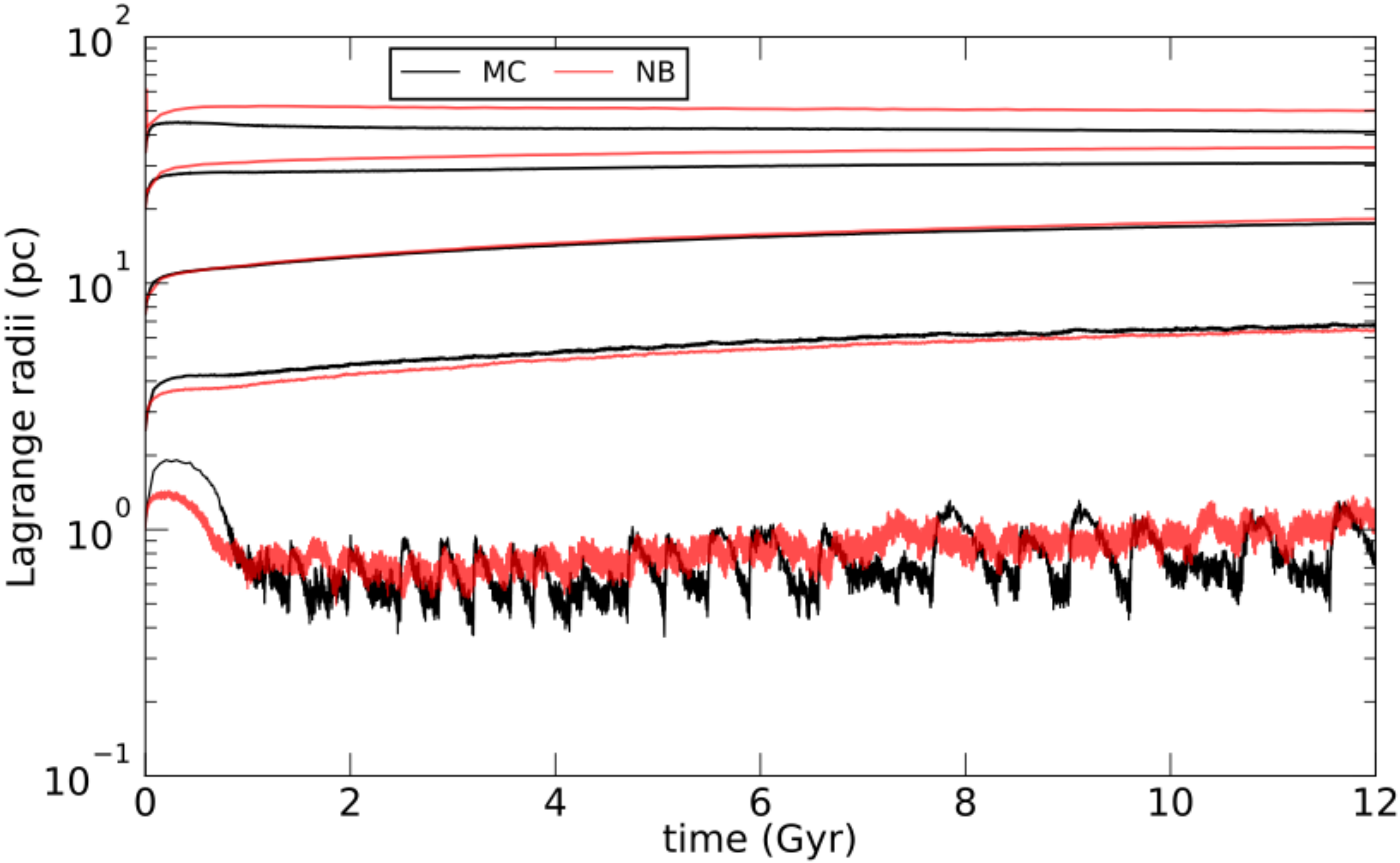
Million-body Simulation

Comparison Between CMC & NBODY6++GPU



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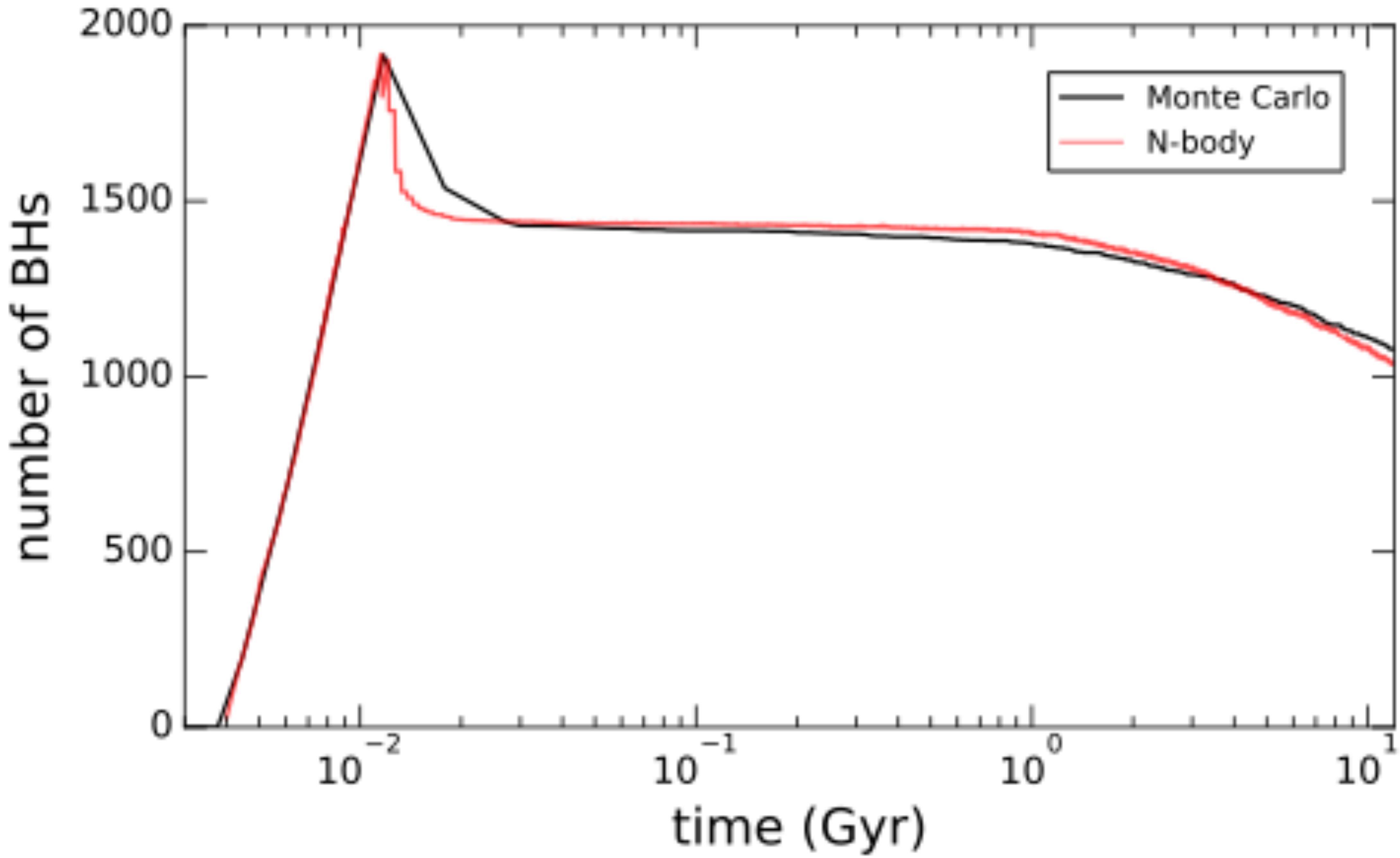

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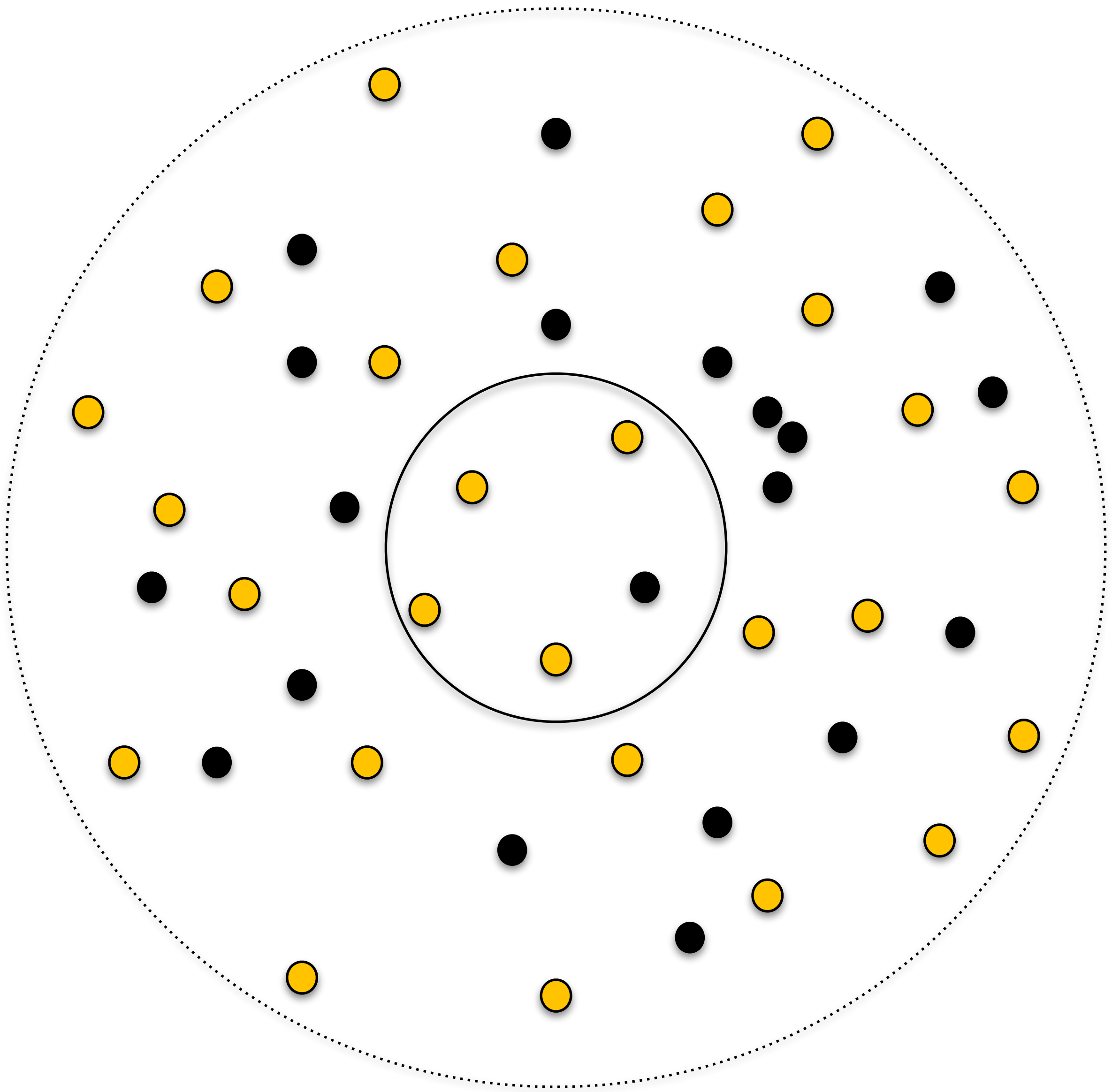
The Evolving Story of Stellar-Mass BHs in Old Star Clusters

BHs in Star Clusters

Massive GC-like clusters are born with N~10^5 — 10^6 stars, leading to hundreds to thousands of BH progenitors.

What happens to these BHs is still an evolving story.

- Past understanding: Mass segregation followed by rapid dynamical ejections deplete GCs of BHs on ~ Gyr timescales (e.g., Spitzer 1969; Kulkarni et al. 1993; Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000; Kalogera et al. 2004)



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

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

10^5 yr 10^9 yr 10^{10} yr

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

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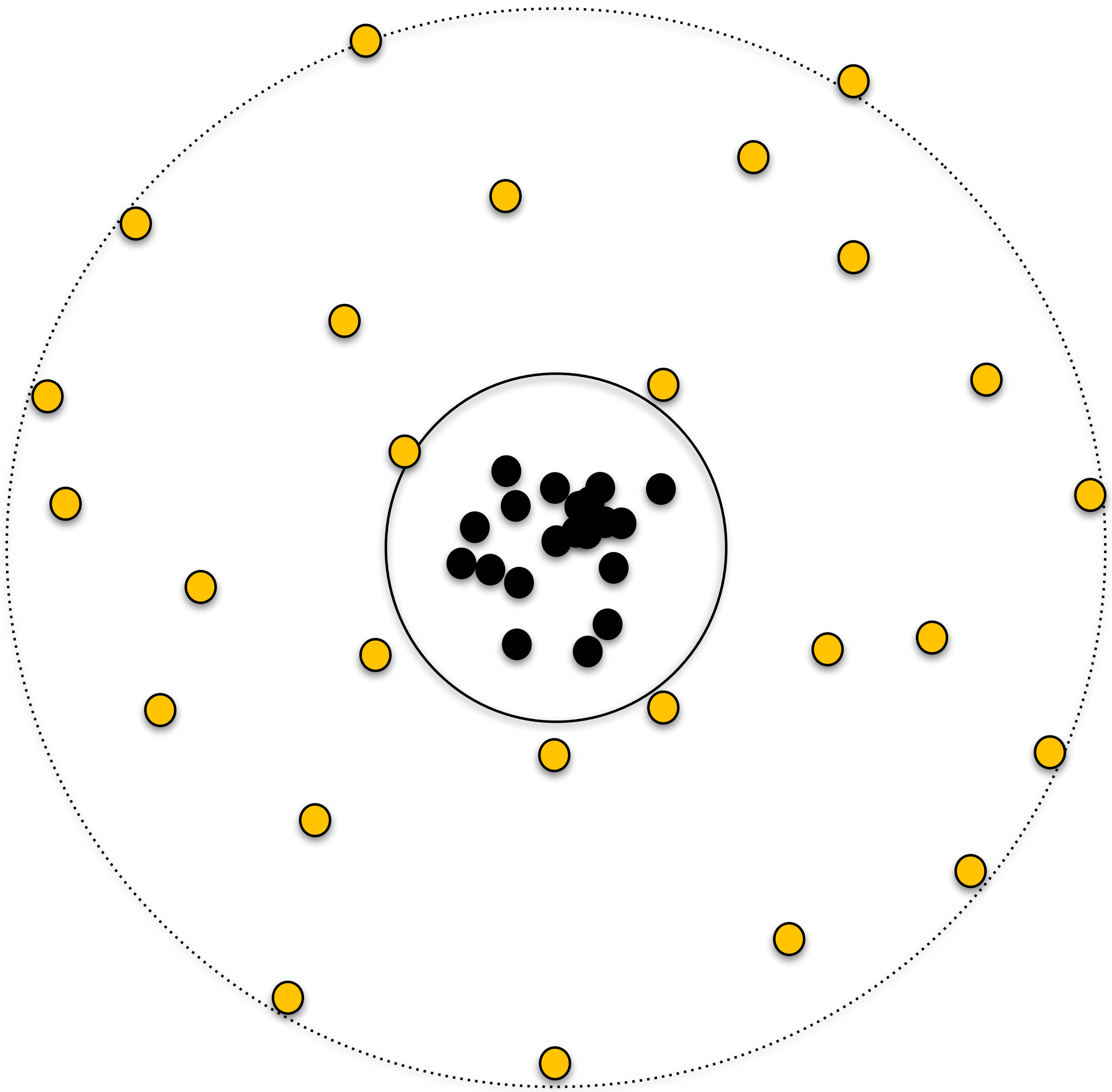

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Stellar-Mass Candidate BHs *are Observed* in GCs

Vol 445 | 11 January 2007 | **doi:10.1038/nature05434** nature

LETTERS

A black hole in a globular cluster

Thomas J. Maccarone[1], Arunav Kundu[2], Stephen E. Zepf[2] & Katherine L. Rhode[3,4]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **410,** 1655–1659 (2011) doi:10.1111/j.1365-2966.2010.17547.x

A new globular cluster black hole in NGC 4472

Thomas J. Maccarone,[1★] Arunav Kundu,[2] Stephen E. Zepf[3] and Katherine L. Rhode[4]

[1]*School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ*
[2]*Eureka Scientific, 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[4]*Department of Astronomy, Indiana University, 727 East 3rd Street, Bloomington, IN 47405-7105, USA*

REINSTATING THE M31 X-RAY SYSTEM RX J0042.3+4115 AS A BLACK HOLE X-RAY BINARY AND COMPELLING EVIDENCE FOR AN EXTENDED CORONA

R. Barnard[1], M. R. Garcia[1], and S. S. Murray[2]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[2] Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, Maryland, MD 21218, USA

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X-ray sources in GCs in NGC 4472, and M31 with

- Super Eddington luminosities
- High variability

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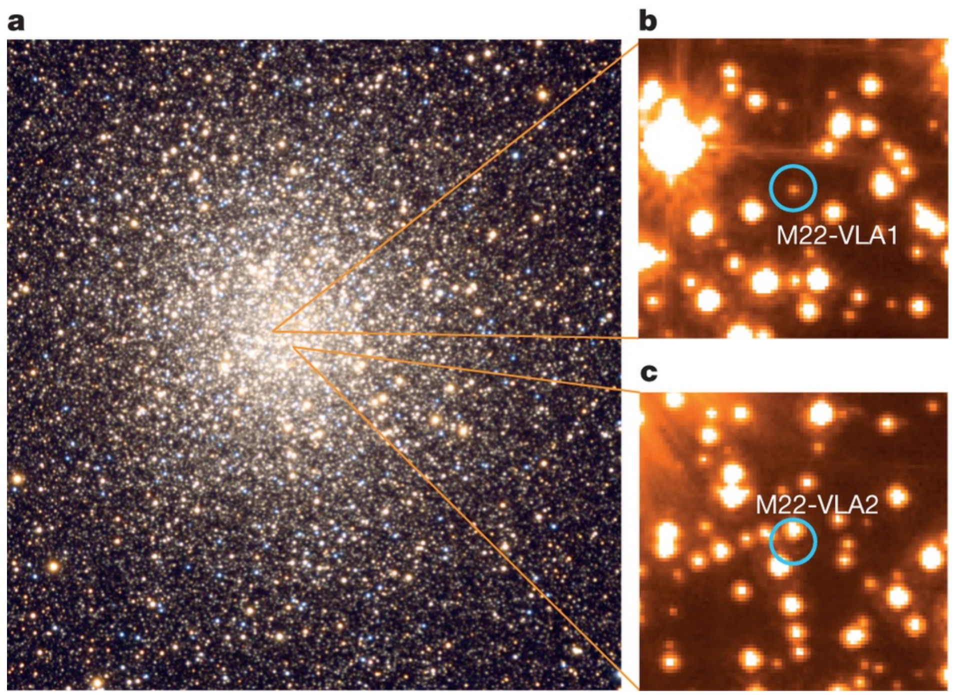
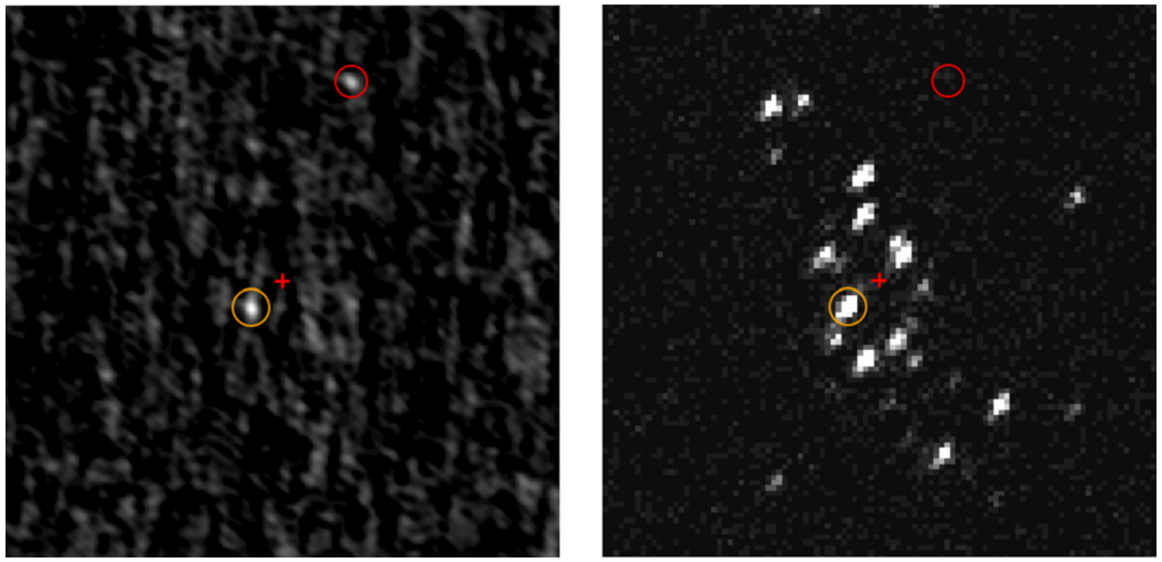
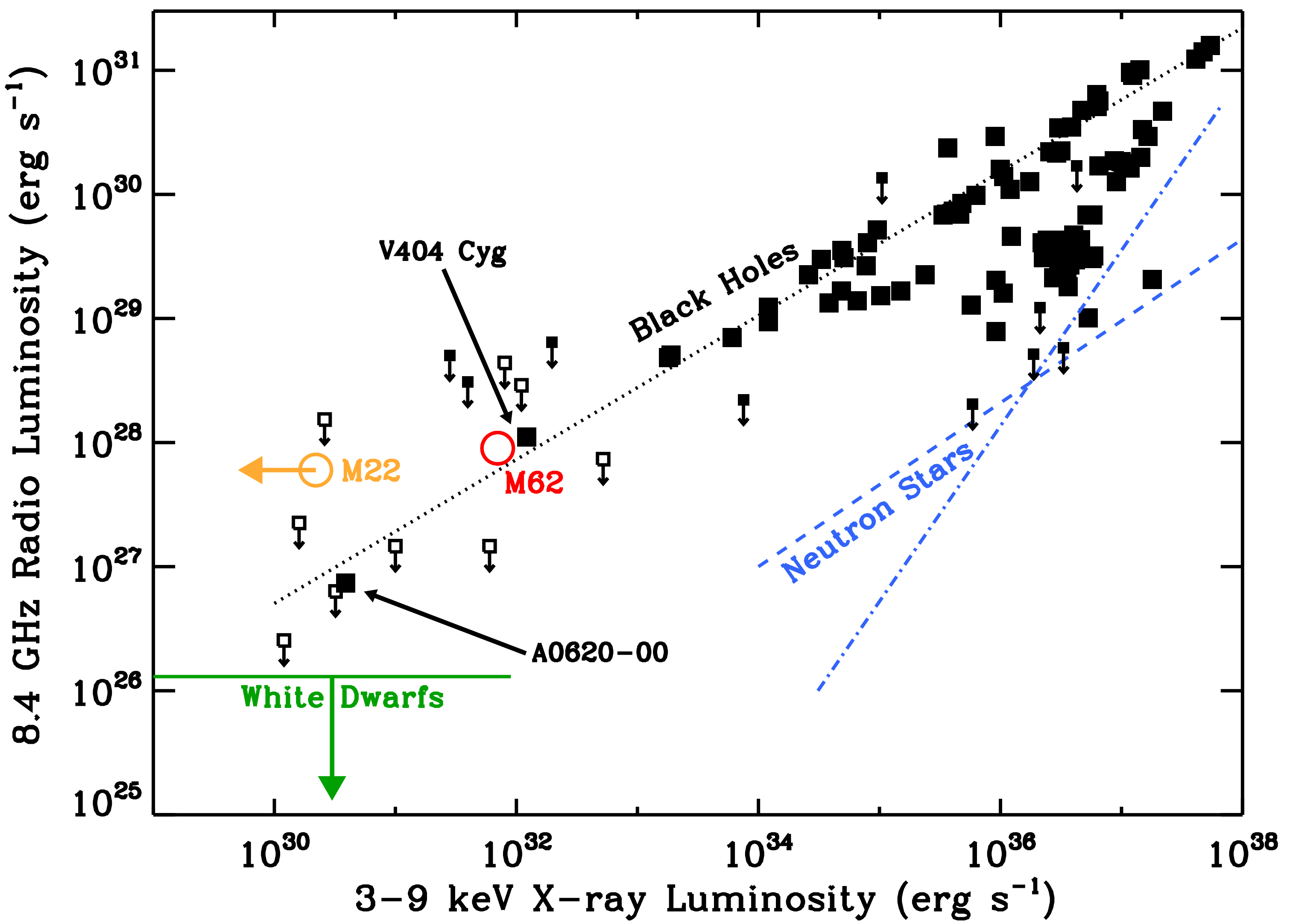


M22

Strader et al. 2012





M62

Chomiuk et al. 2012

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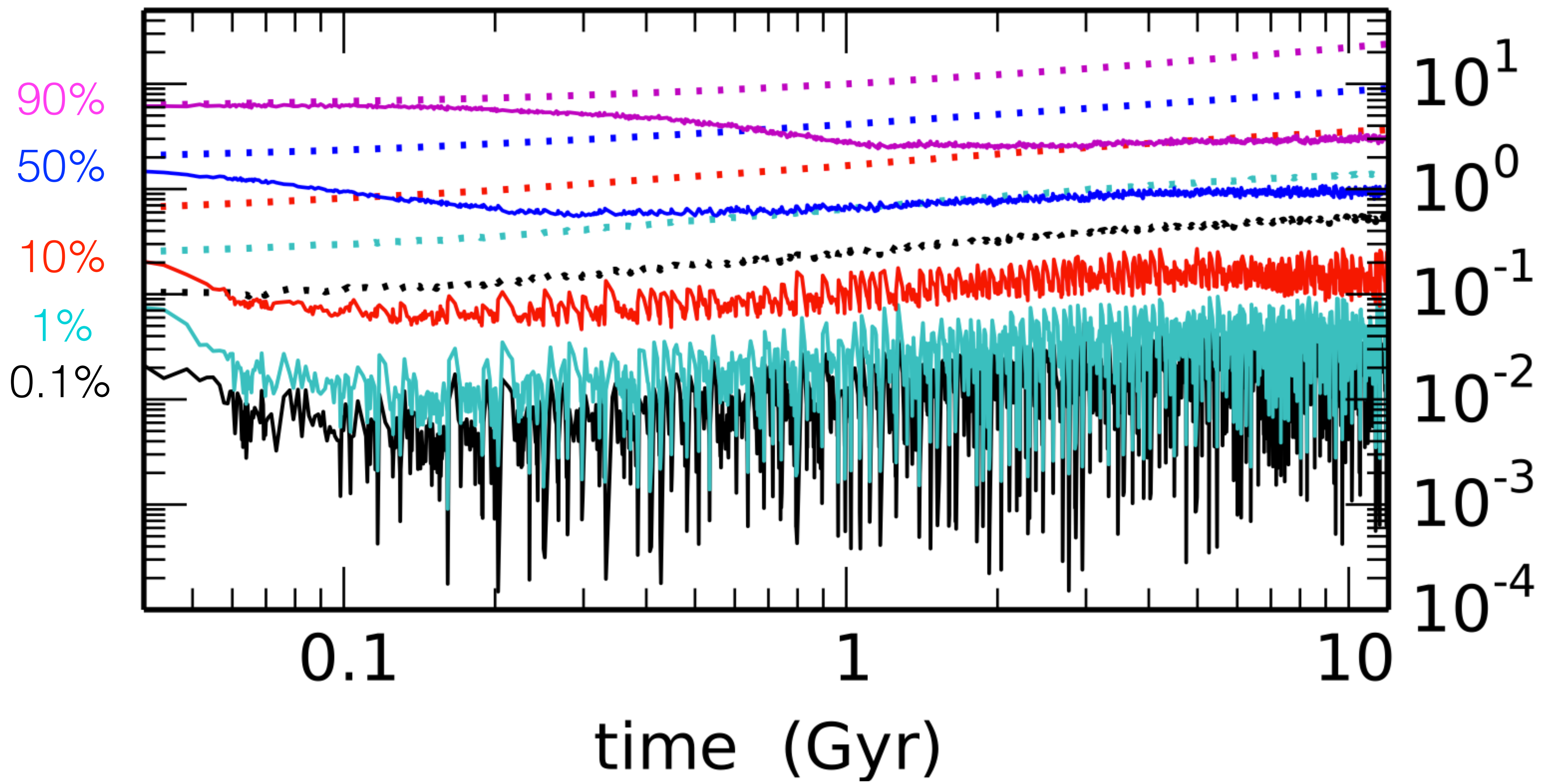
What Really Happenes to the BHs in Clusters?



Morscher et al. (2015)

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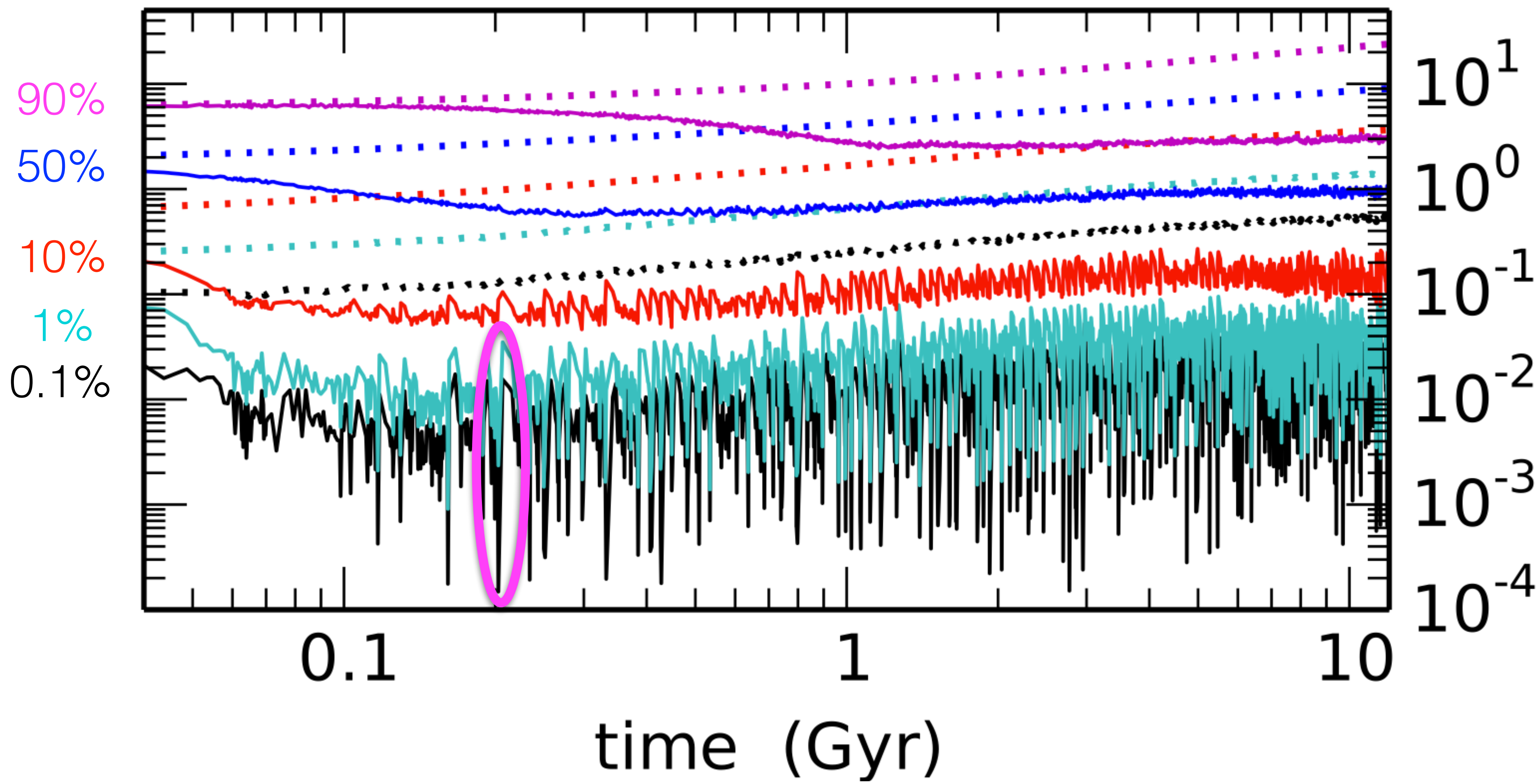

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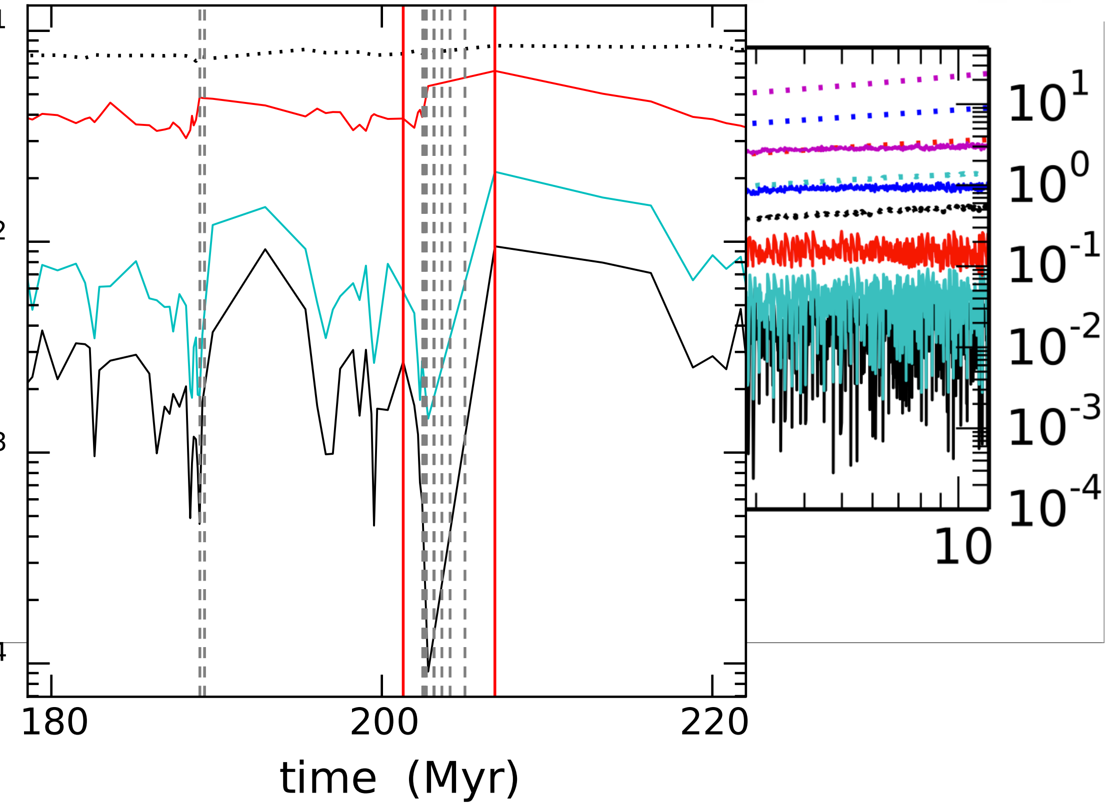

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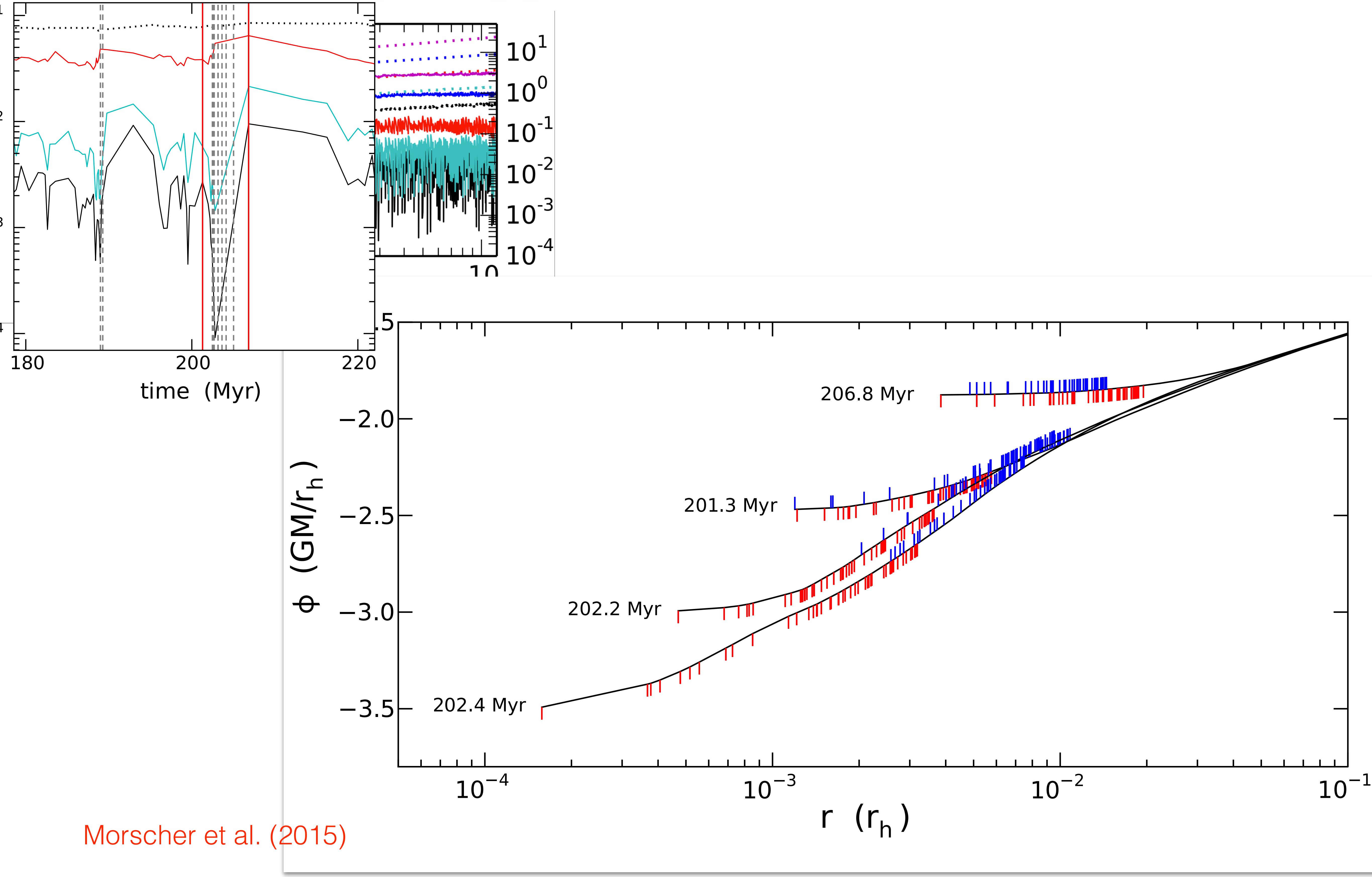

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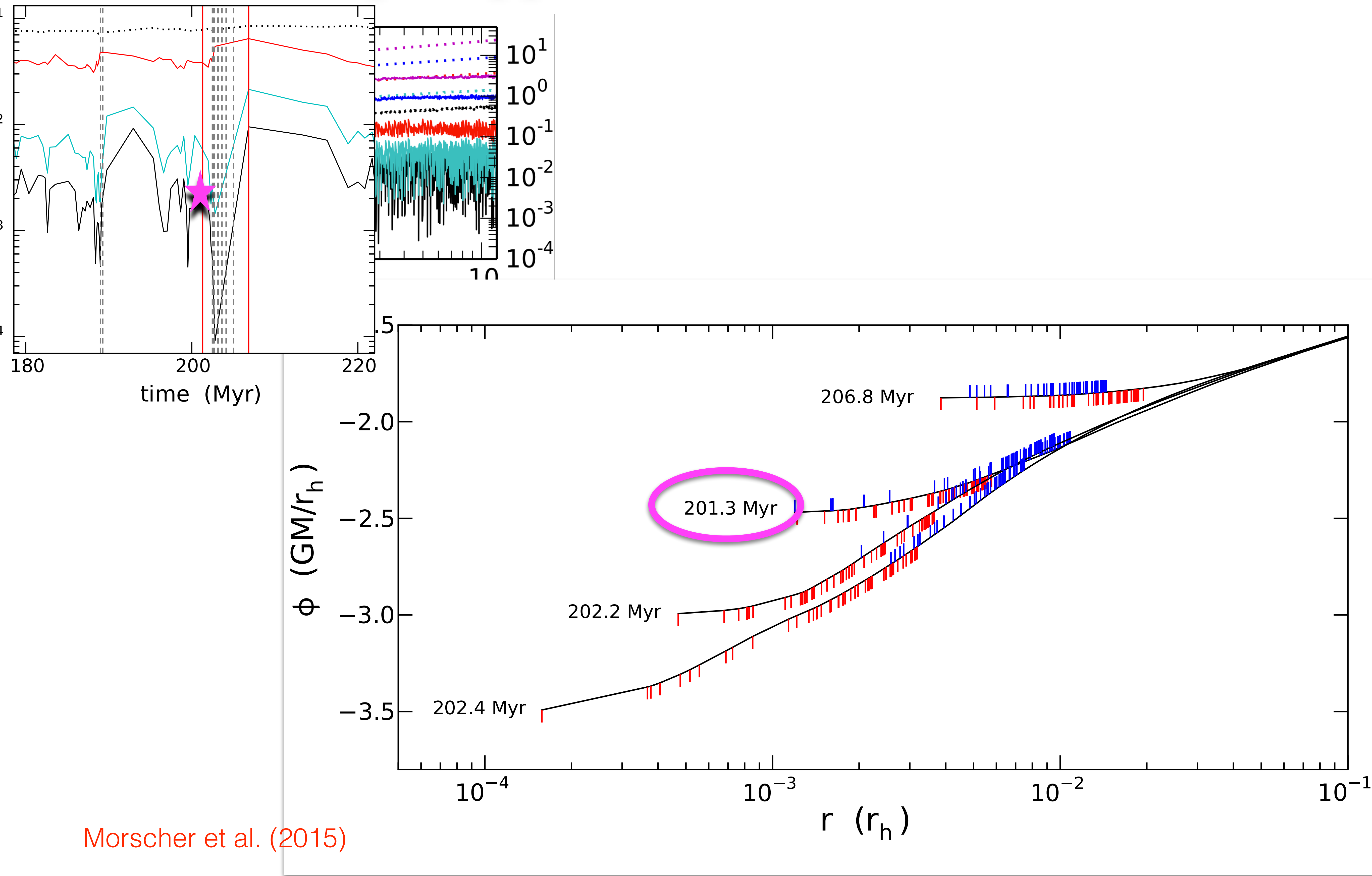

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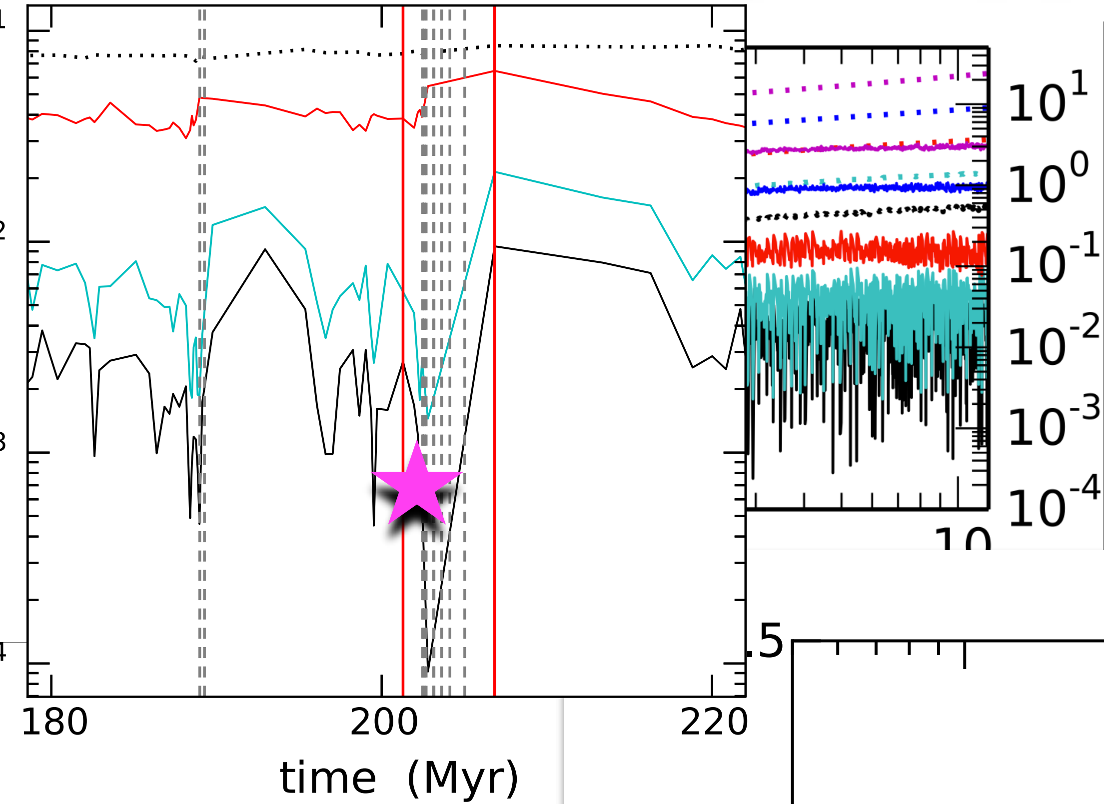

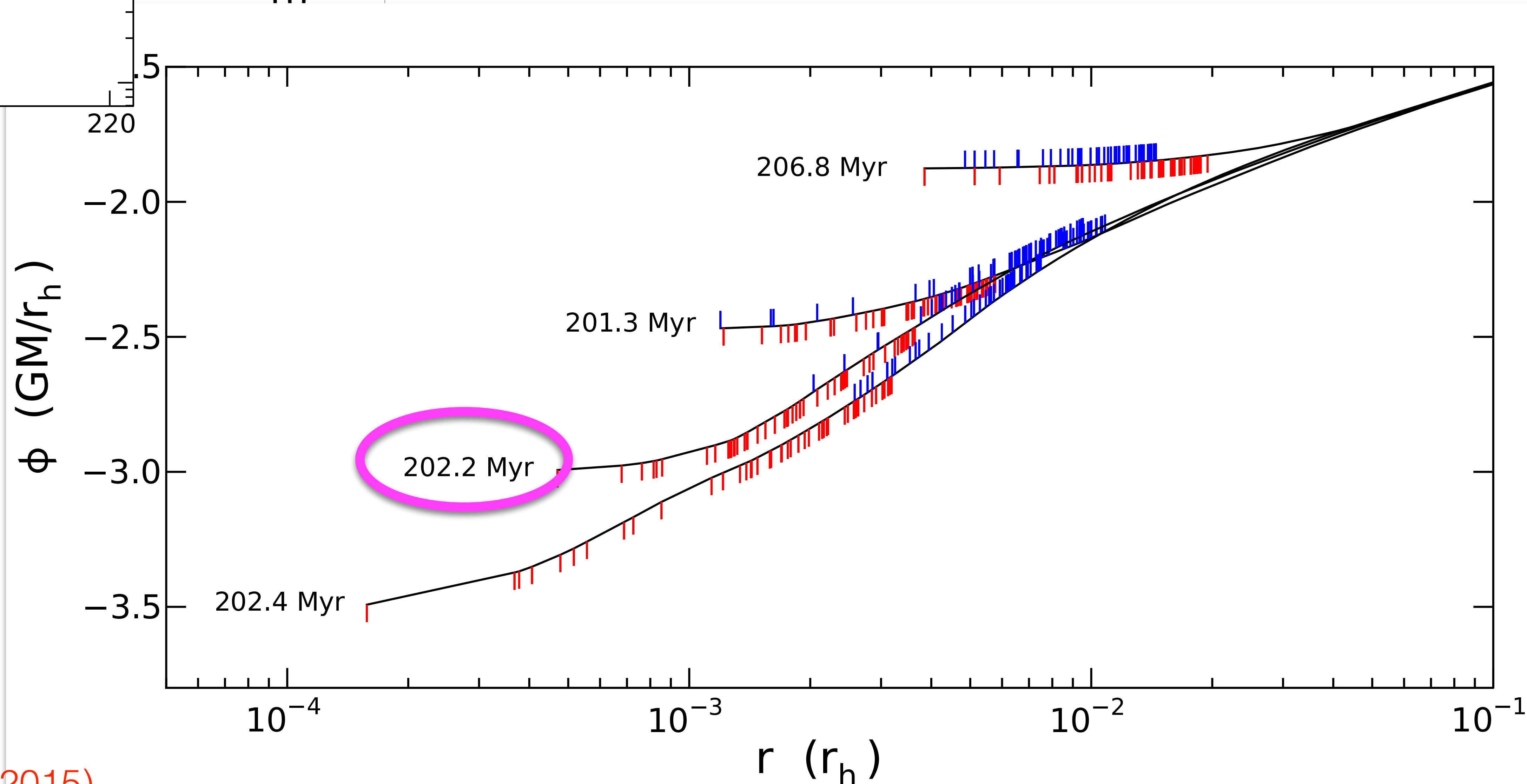

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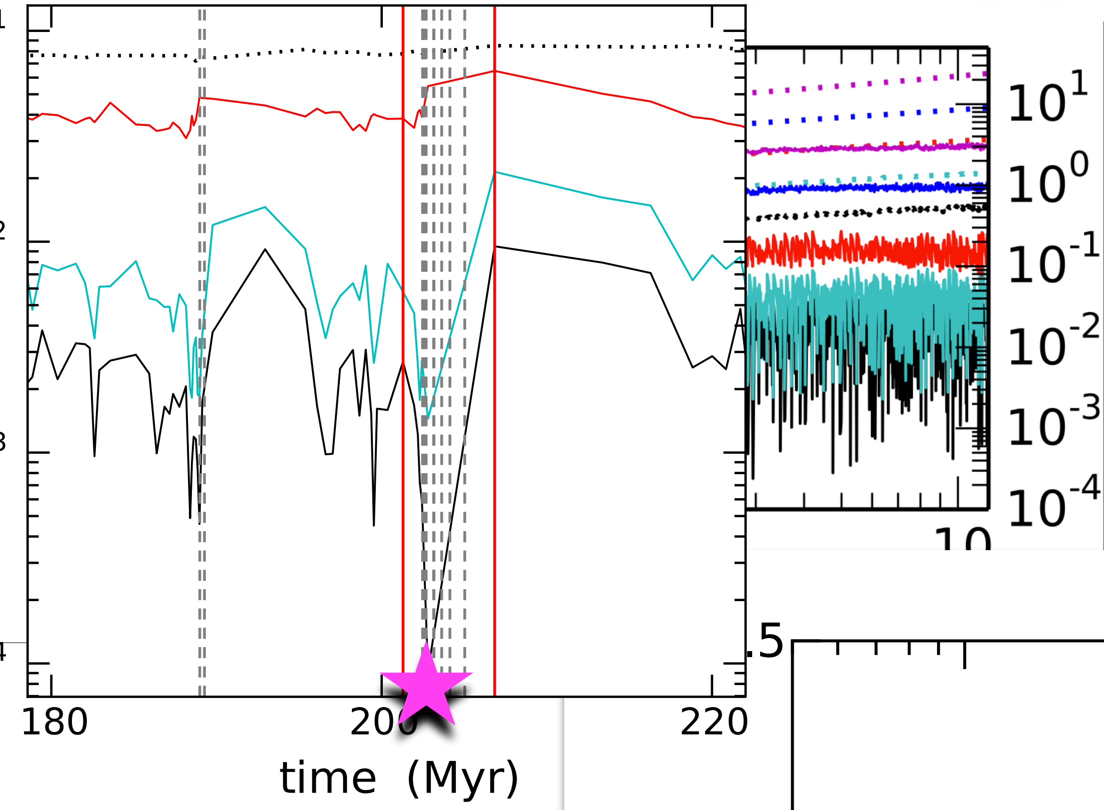

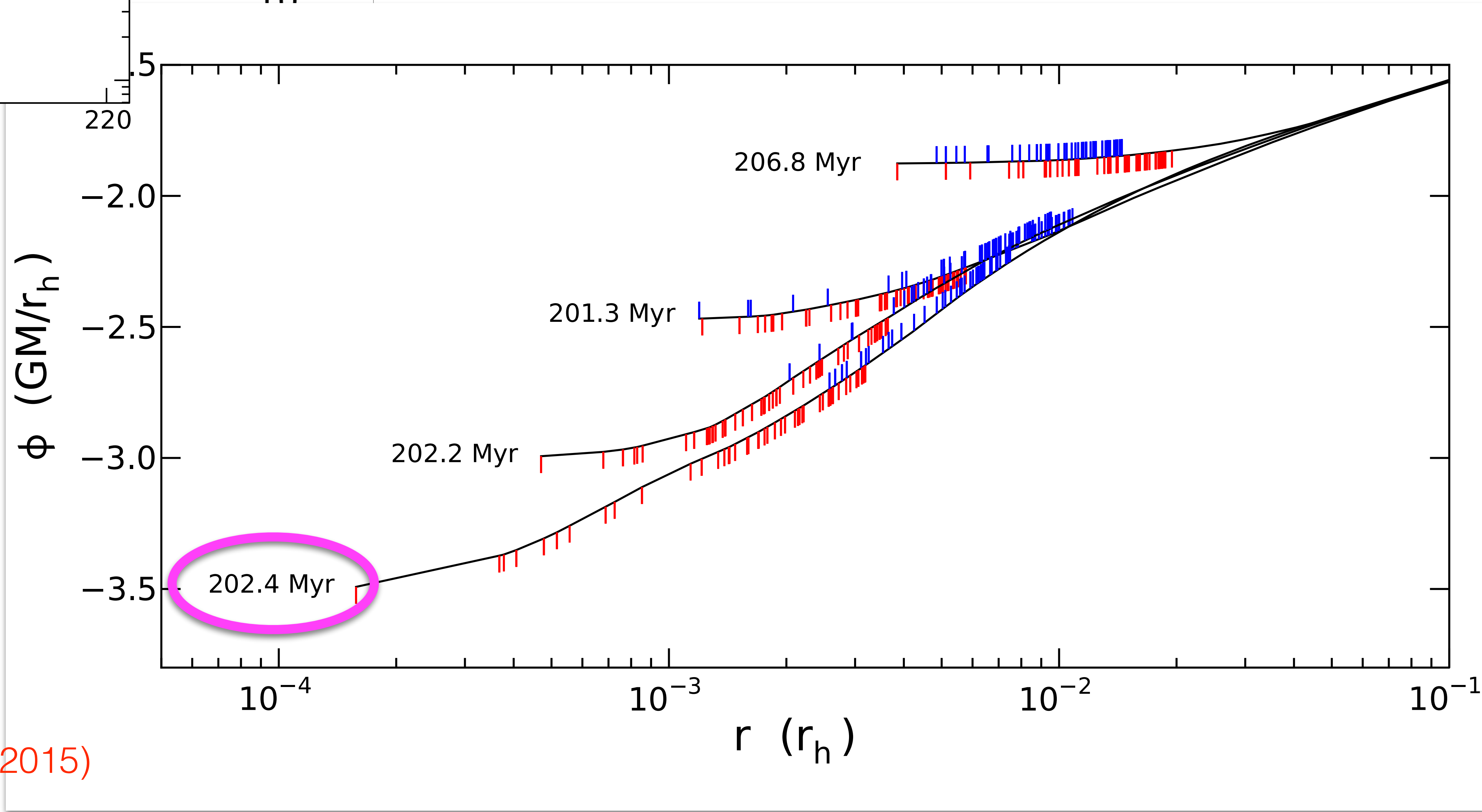

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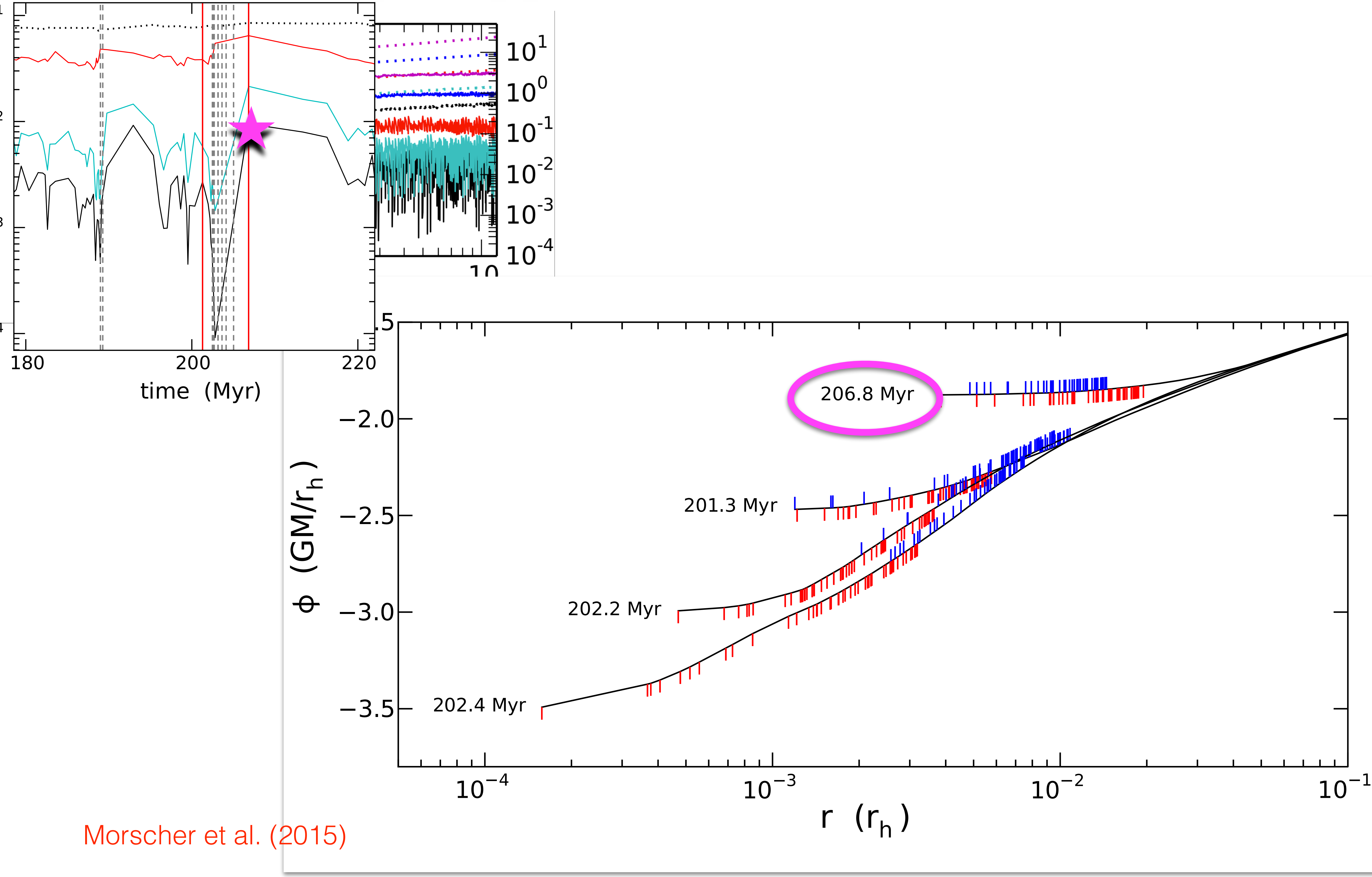

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and *do interesting things*

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BHs act as a significant and persistent energy source at the cluster center.

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- BH can … Maccarone et al. 2007; …
- Modern …

BHs act as a significant and persistent energy source at the cluster center.

Cluster dynamics affects the BH properties.

What happens to a cluster is intimately related to what happened to the BHs in it.

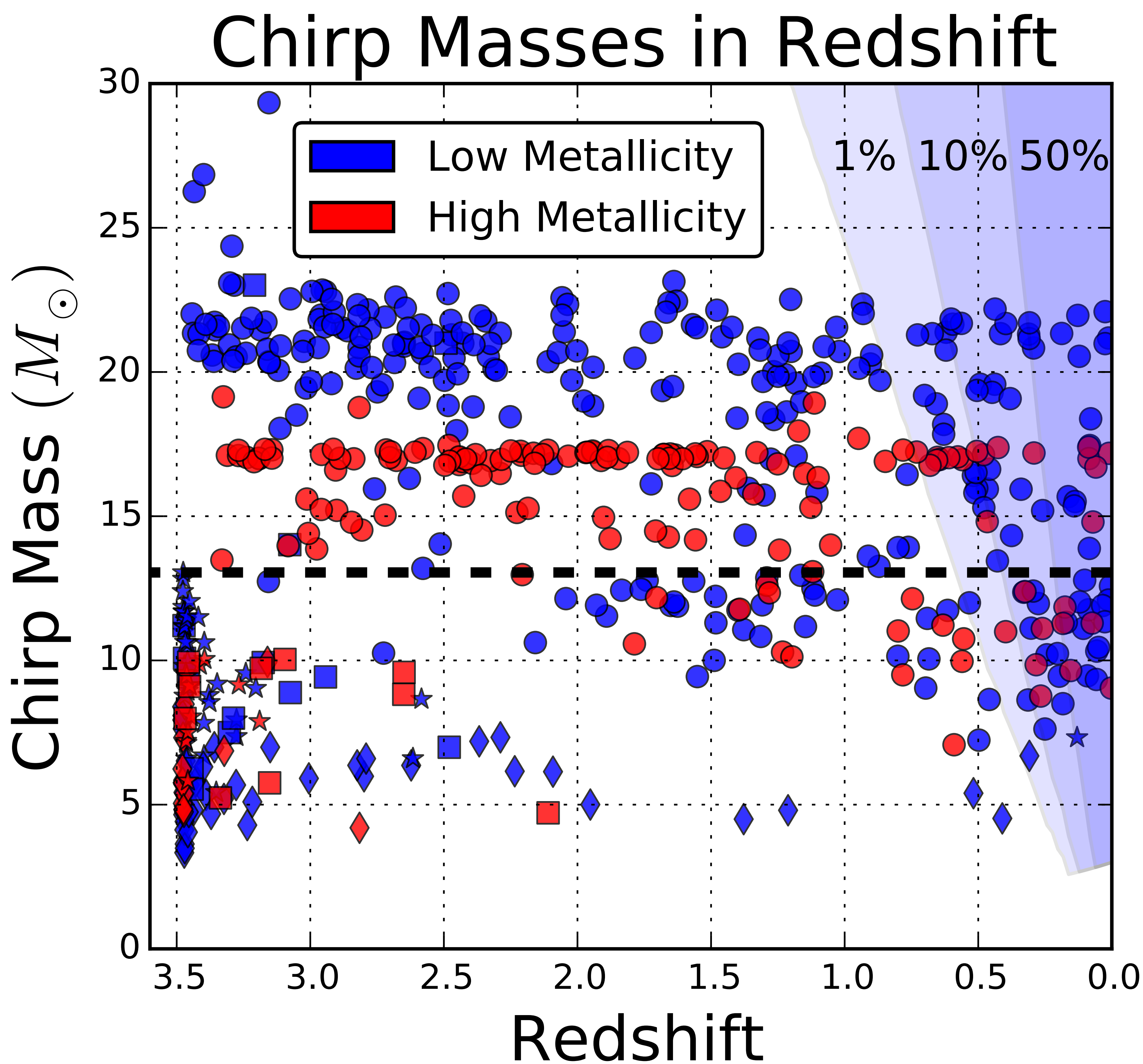
Effects of Cluster Dynamics on BHs & Implications for aLIGO

Numerical Simulation Setup

- Hénon-type Monte Carlo simulations using *CMC*
- Coverage of a large parameter space
  - $N \sim 2\times10^5$ to 2×10^6
  - $Z \sim 0.0005, 0.001$
  - King profile with $w_0 = 5$
  - Initial f_b = 5 to 10%
  - Kroupa (2001) IMF between 0.08 to 150 $M_\odot$
- BH formation kick distribution
  - Momentum conserving, dependent on progenitor mass and *Z* (Belczynsky 2012)
- Wind mass loss prescription

BH-BH Merger Properties as LIGO source

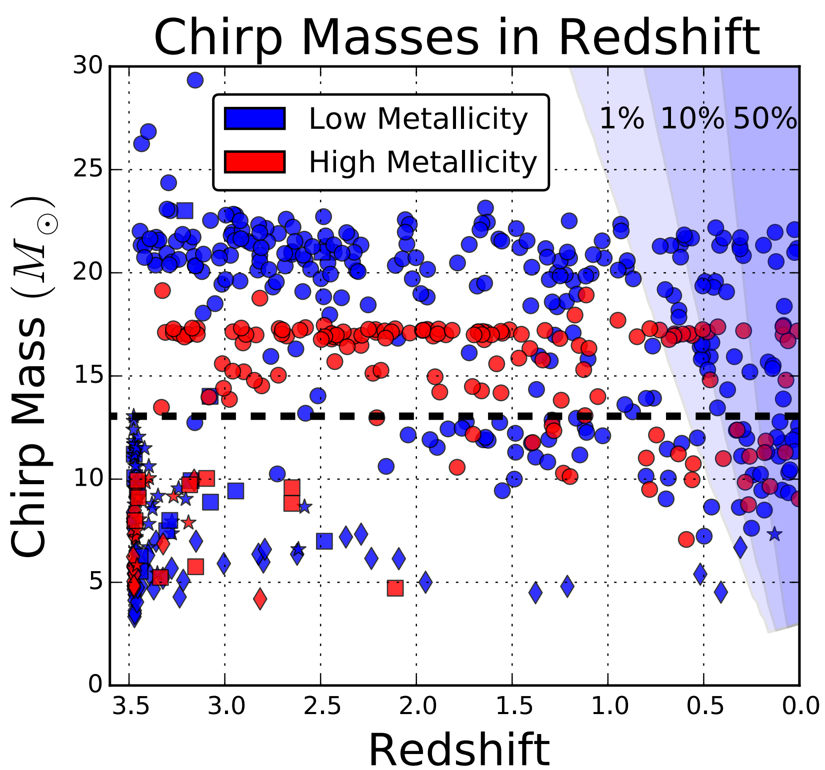
Masses

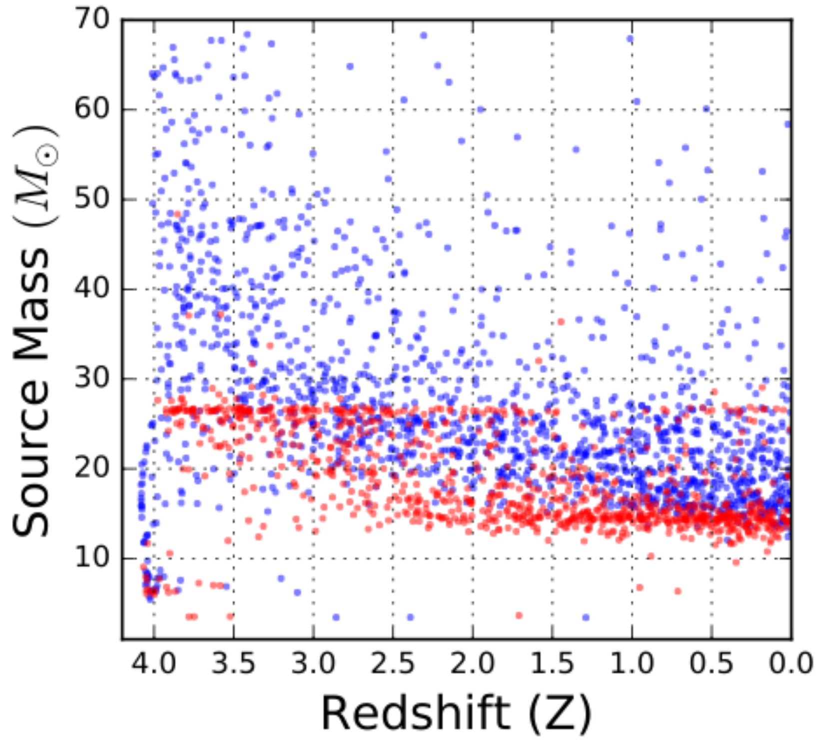


RMPCHR15

BH-BH Merger Properties as LIGO Source

Masses: Assumptions Make a Difference





RCR16 (in prep.)

BH-BH Merger Properties as LIGO Source

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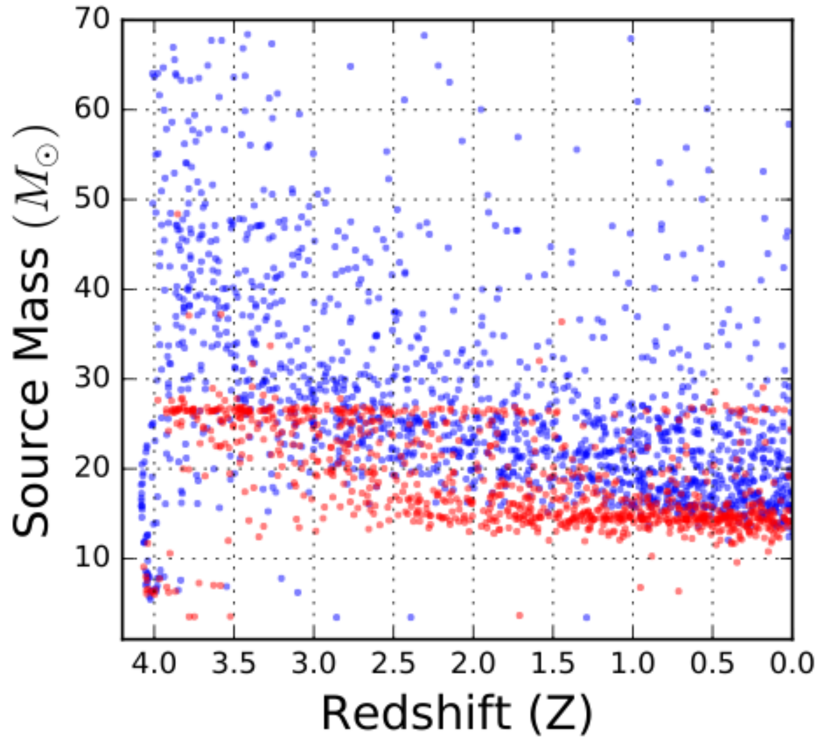

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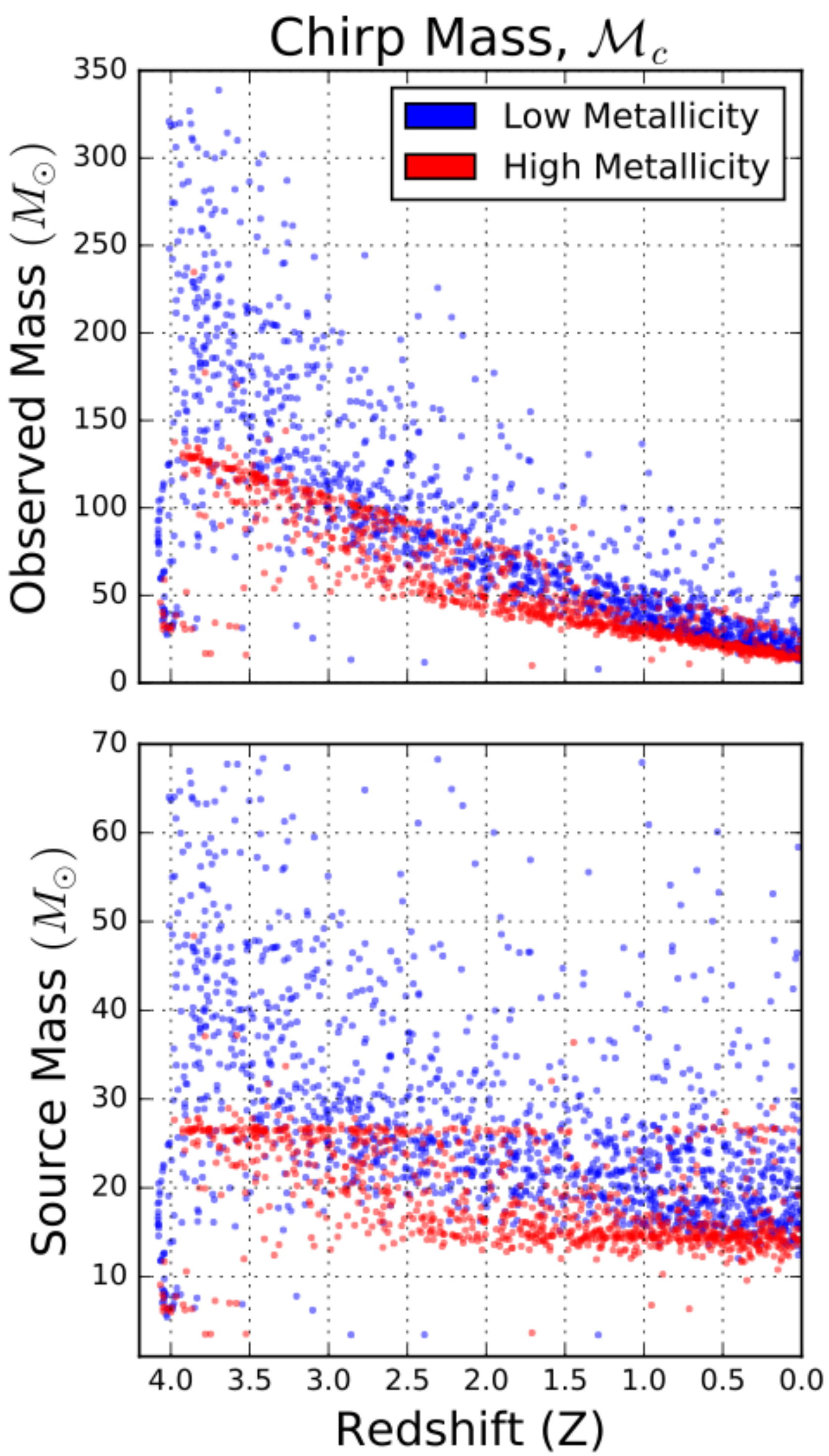

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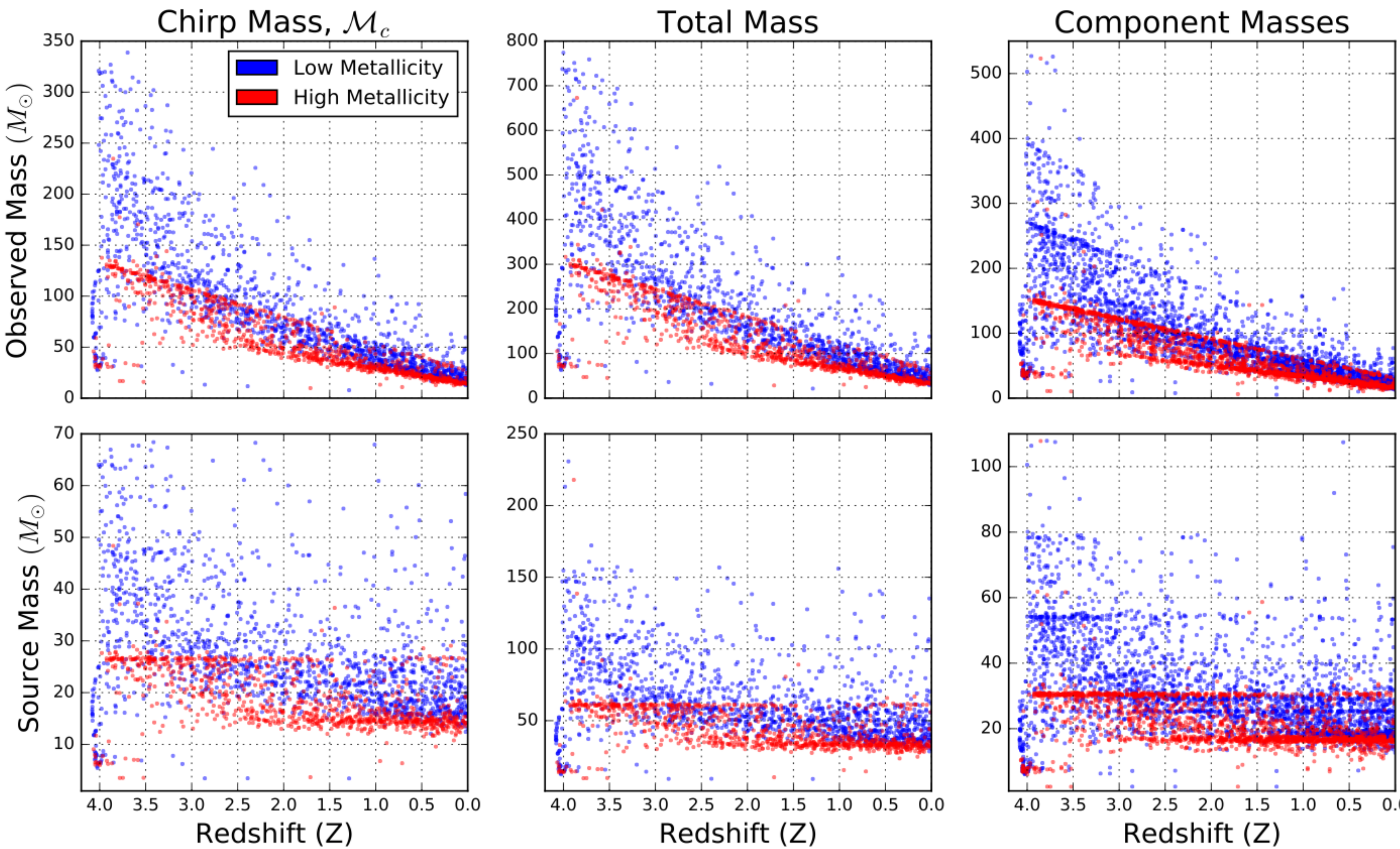

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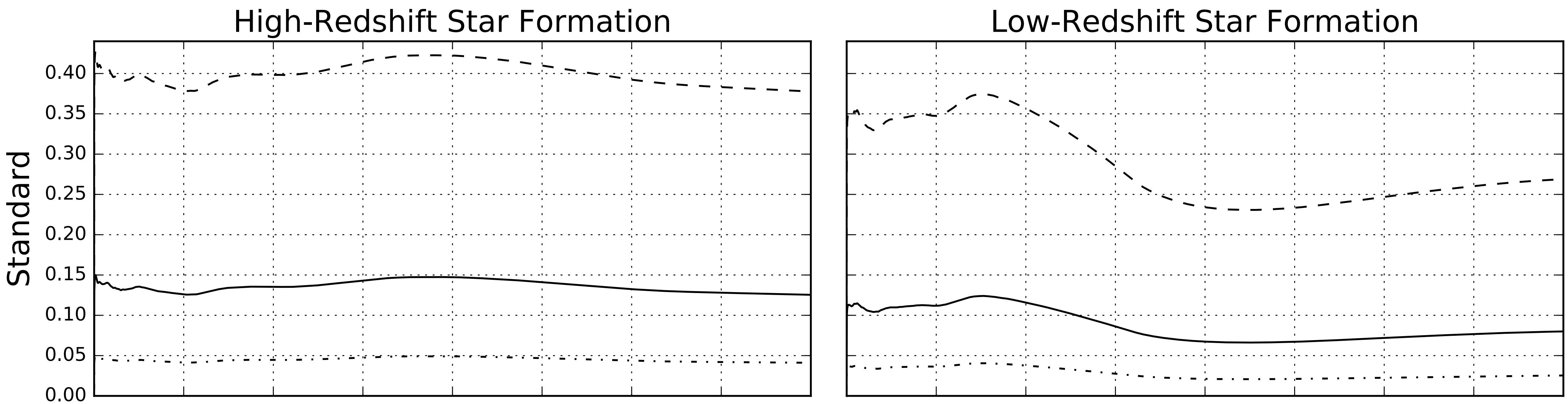
Cluster Source vs Field Source



Redshift (z)

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RCR16 (in prep.)

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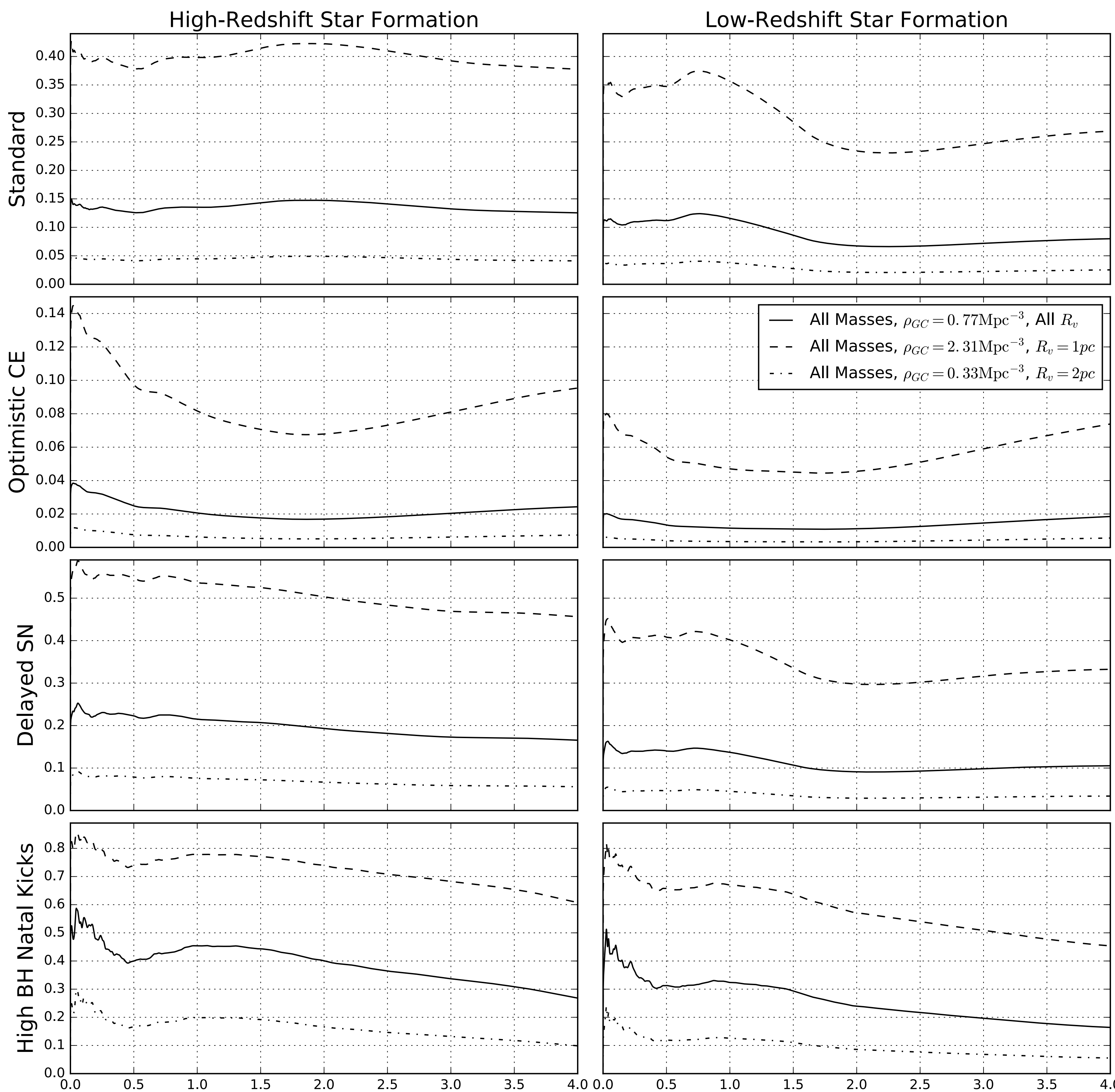
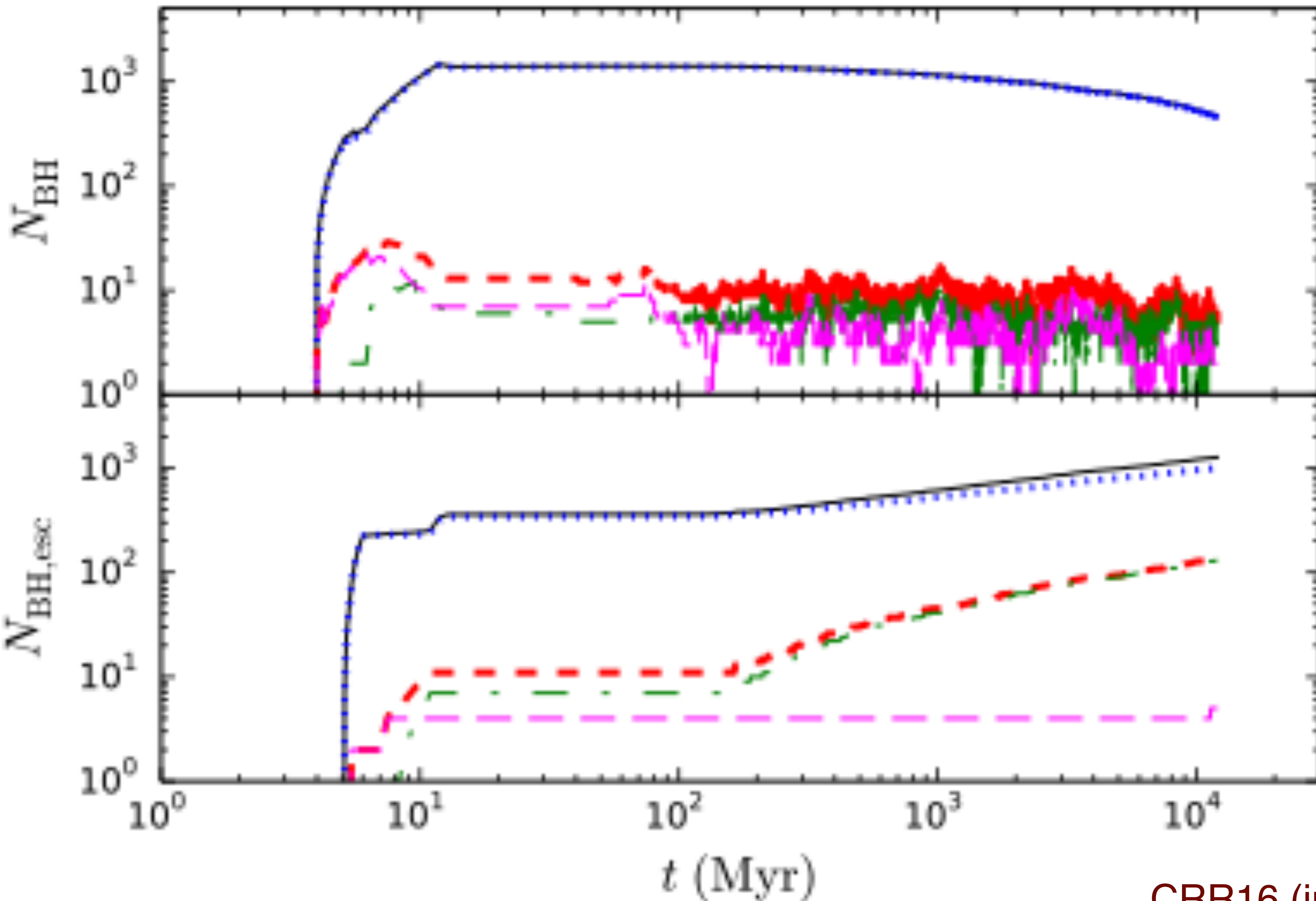


Redshift (z) Redshift (z) RCR16 (in prep.)

BHs:

Binarity, Retention and Ejection



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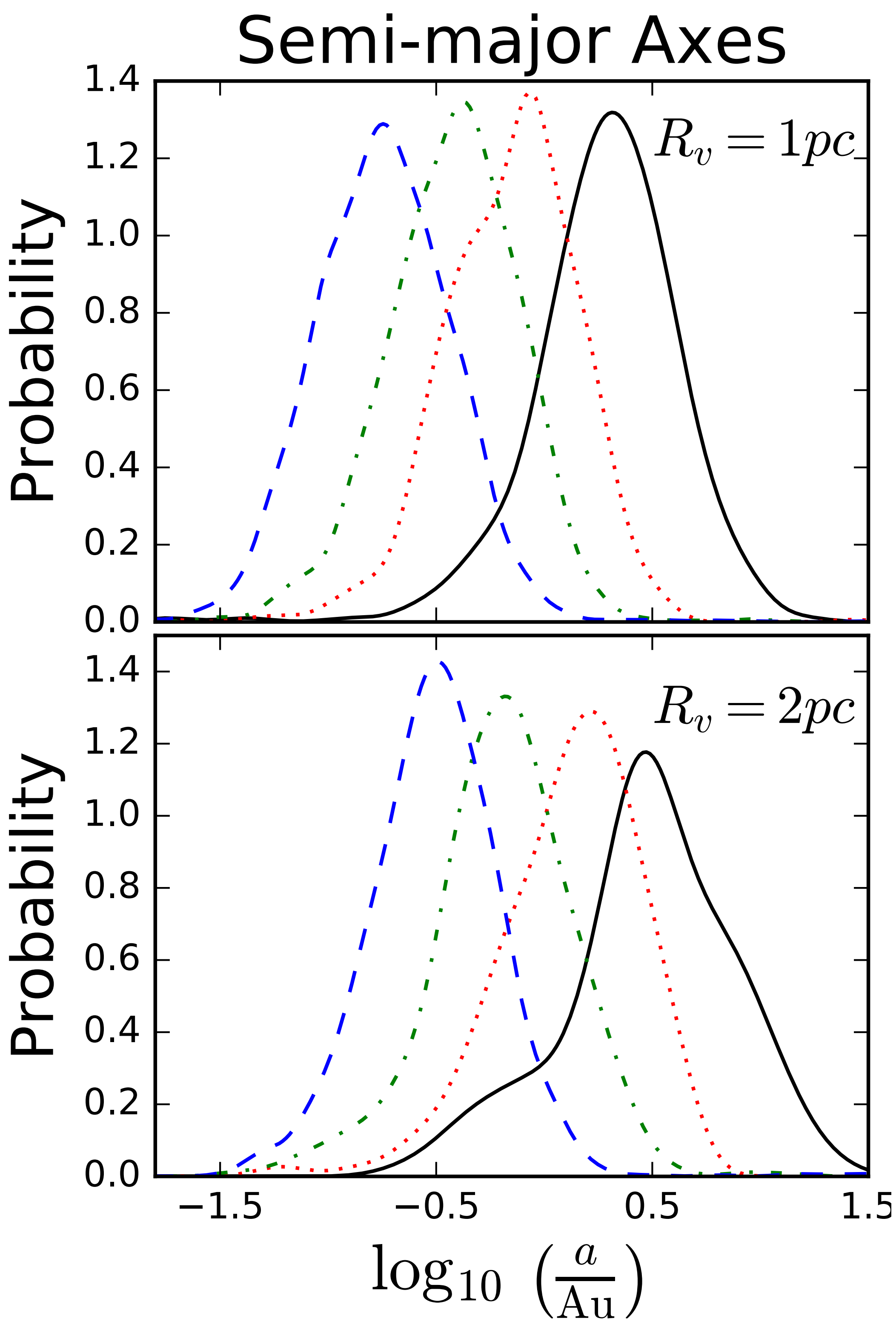
BH-BH Merger Contributions
from Clusters of Different Masses



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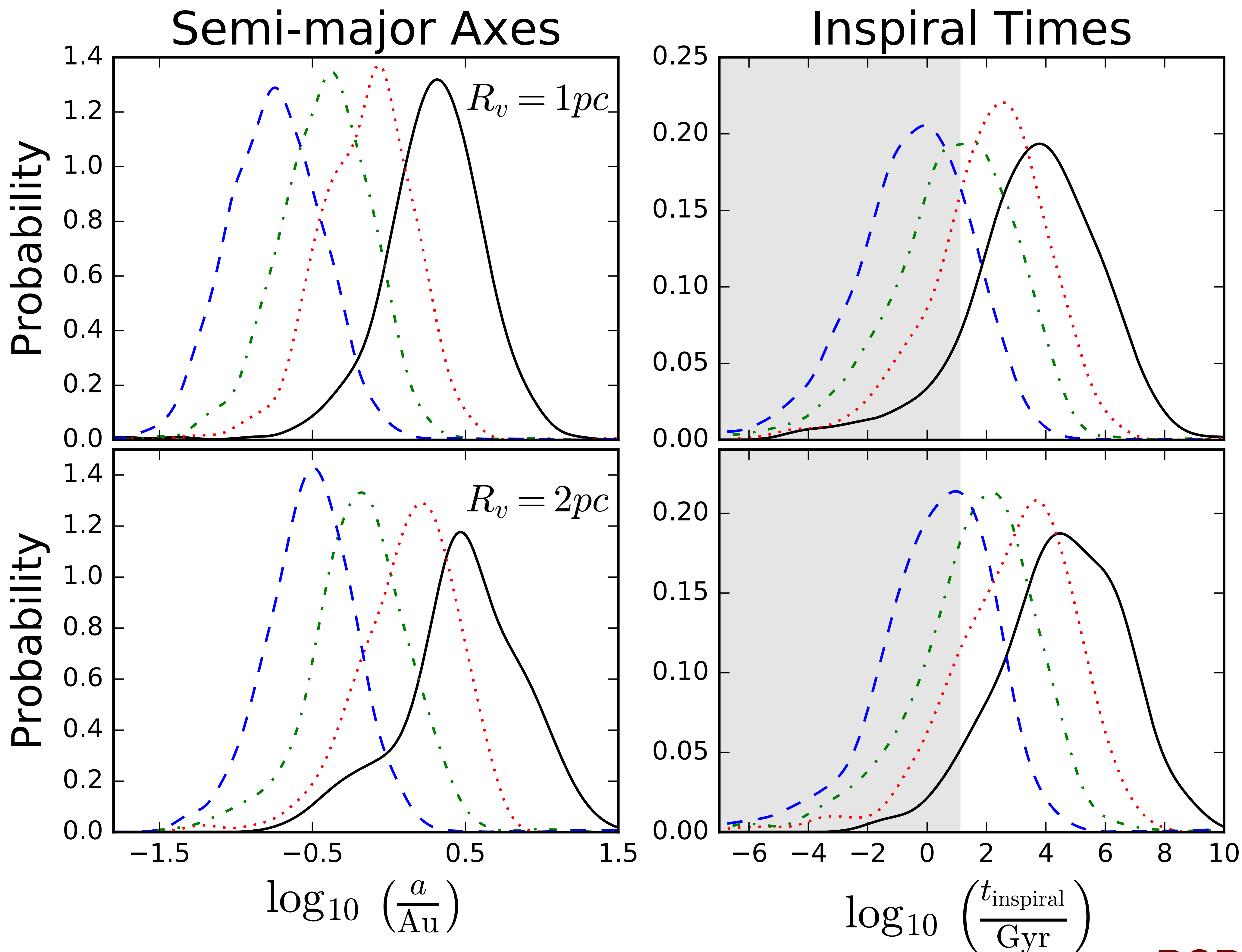

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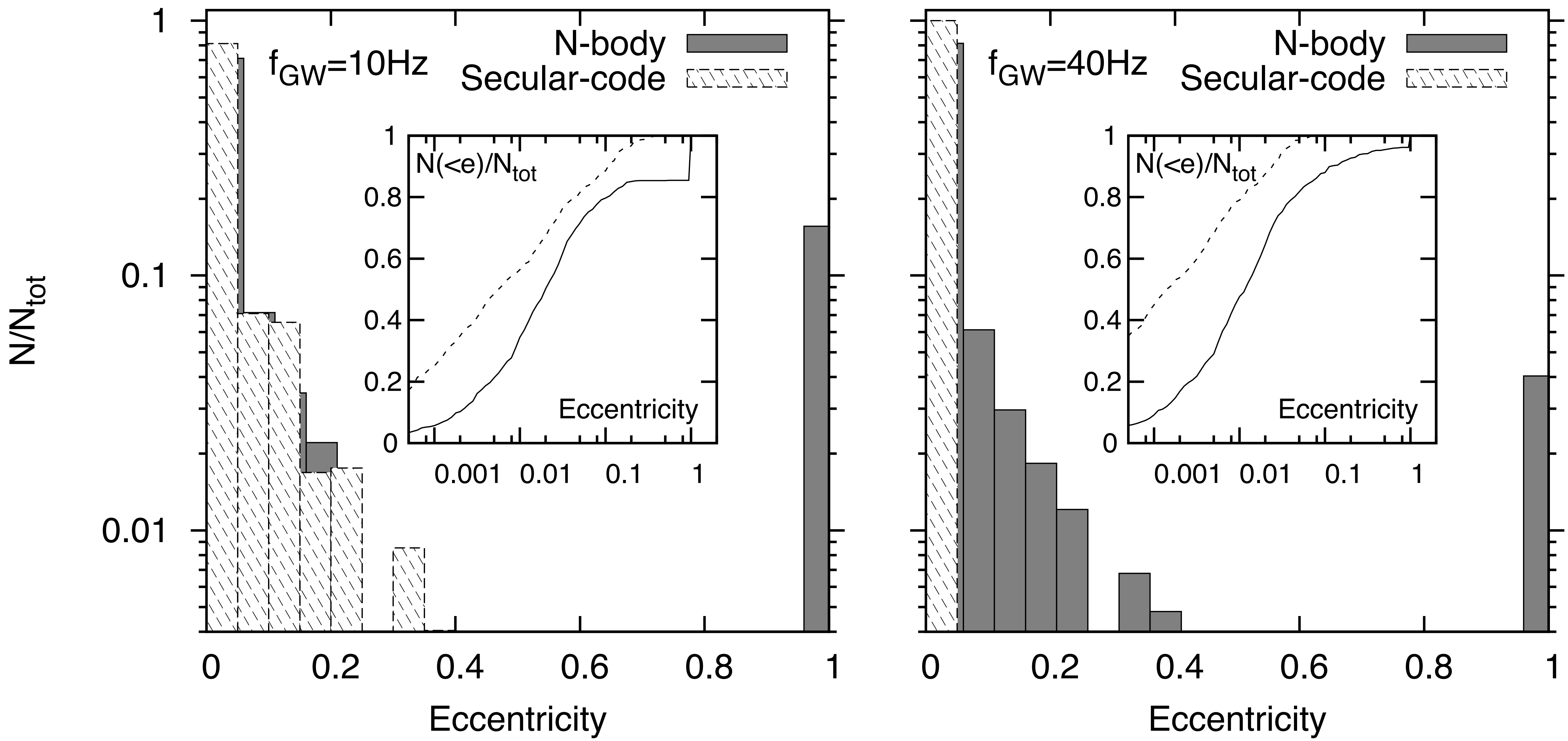
BH-BH Merger Properties

Eccentricity



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Uncertain BH Physics & Their Effects on Star Cluster Evolution

Numerical Simulation Setup

- Hénon-type Monte Carlo simulations using CMC
- Understand how uncertain BH physics affects the cluster's evolution and survival.
- Same initial star cluster model, different assumptions of BH physics
  - **$N = 8e5$, $r_v = 2$ pc, King profile, $w_0 = 5$, $f_b = 5\%$, Kroupa IMF ($0.1 - 100\ M_\odot$)**
  - Formation kick distribution
  - IMF variations within published uncertainties
  - Binarity and binary properties of high-mass stars
  - Wind mass loss prescription

How Does the Story Depend on *Uncertain* BH Physics?

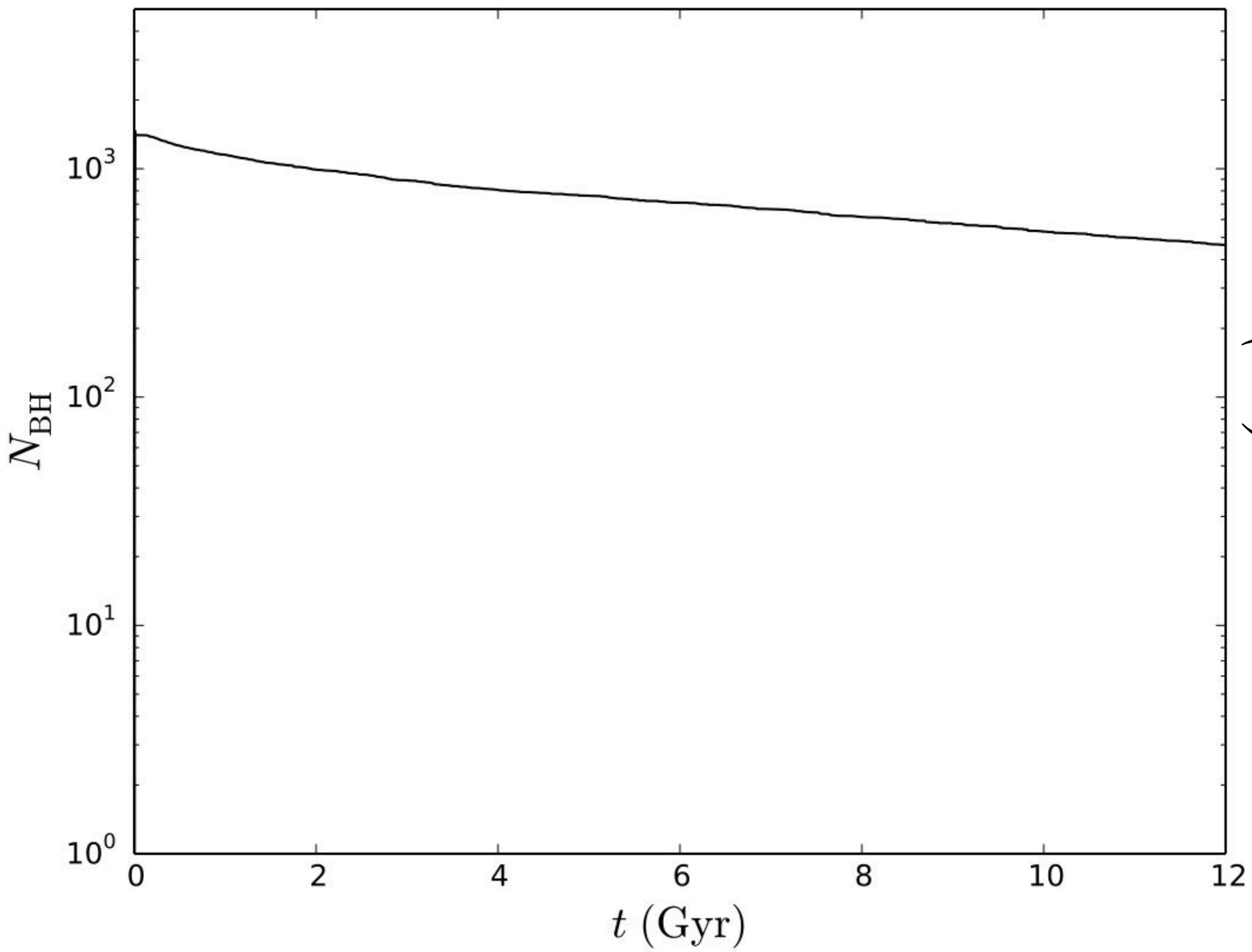
BH birth kicks:

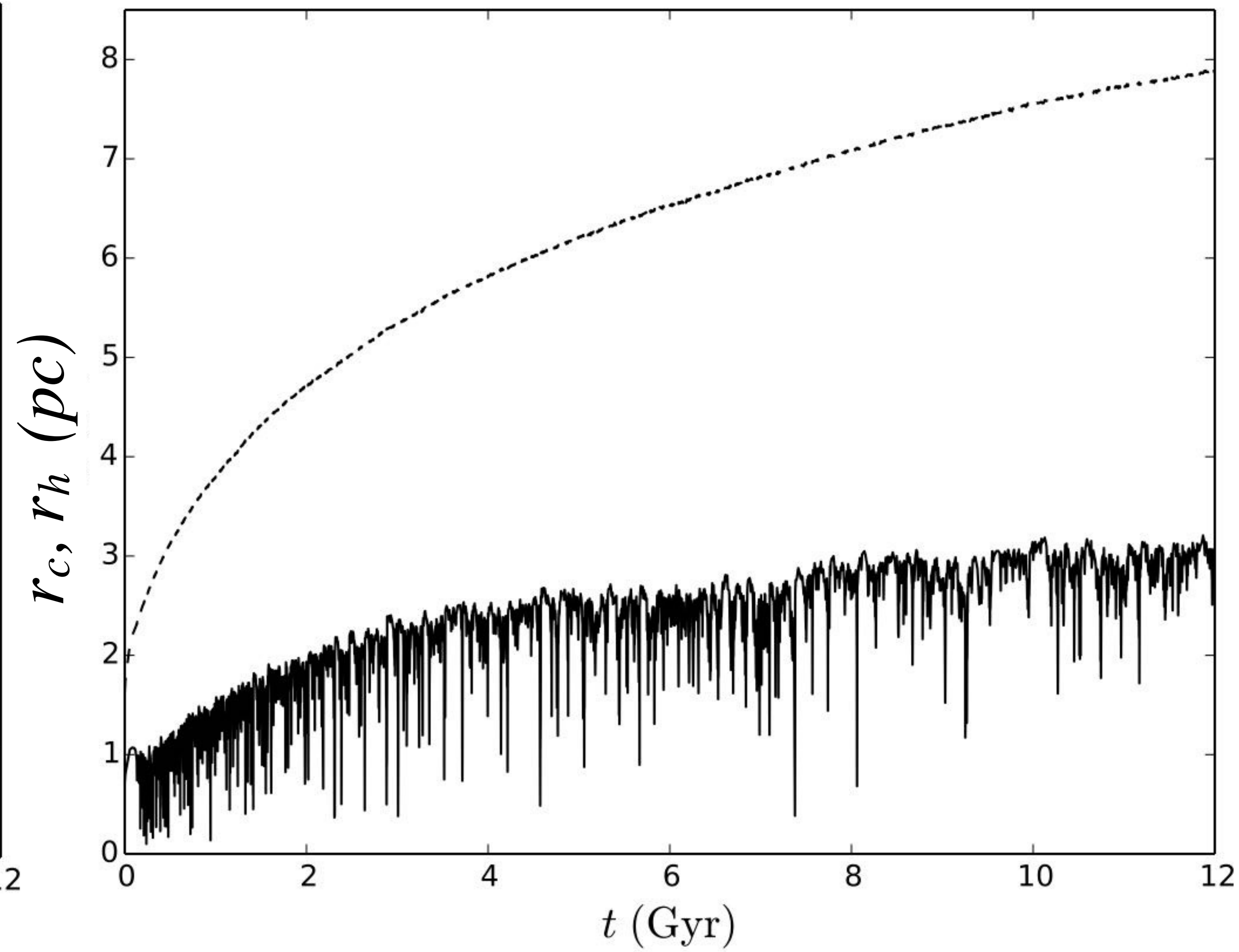
- Do BHs get large kicks similar to NSs?
  - Wide range in magnitudes from individual observed BH X-ray binaries (e.g., Brandt et al. 1995; Nelemans et al. 1999; Willems et al. 2005; Gualandris et al. 2005; Dhawan et al. 2007; Fragos et al. 2009; Wong et al. 2012, 2014).
- Mass-dependent kicks?
  - **YES,** should depend on the details of SN physics including fallback mass fraction (Fryer & Kalogera 2001; Belczynski et al. 2002)
  - MAYBE NOT (Repetto et al. 2012; Pejcha & Thompson 2015)

Effects of BHs on Cluster Evolution

BH birth kicks

M & Z dependent
(Belczynsky+02)





Number of retained BHs

r_c and r_h

CRR16 (in prep.)

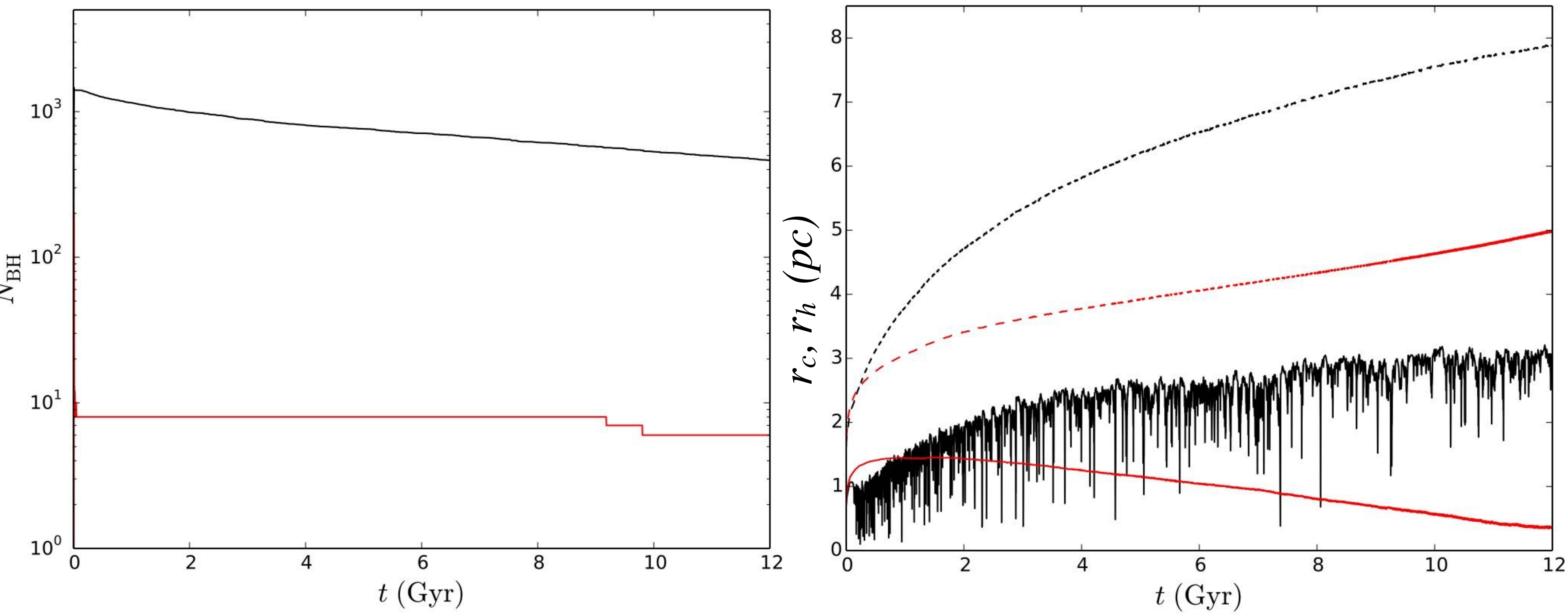
Effects of BHs on Cluster Evolution

BH birth kicks

BH kicks are as large as NSs

M & Z dependent (Belczynsky+02)

CRR16 (in prep.)



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CRR16 (in prep.)

Effects of BHs on Cluster Evolution

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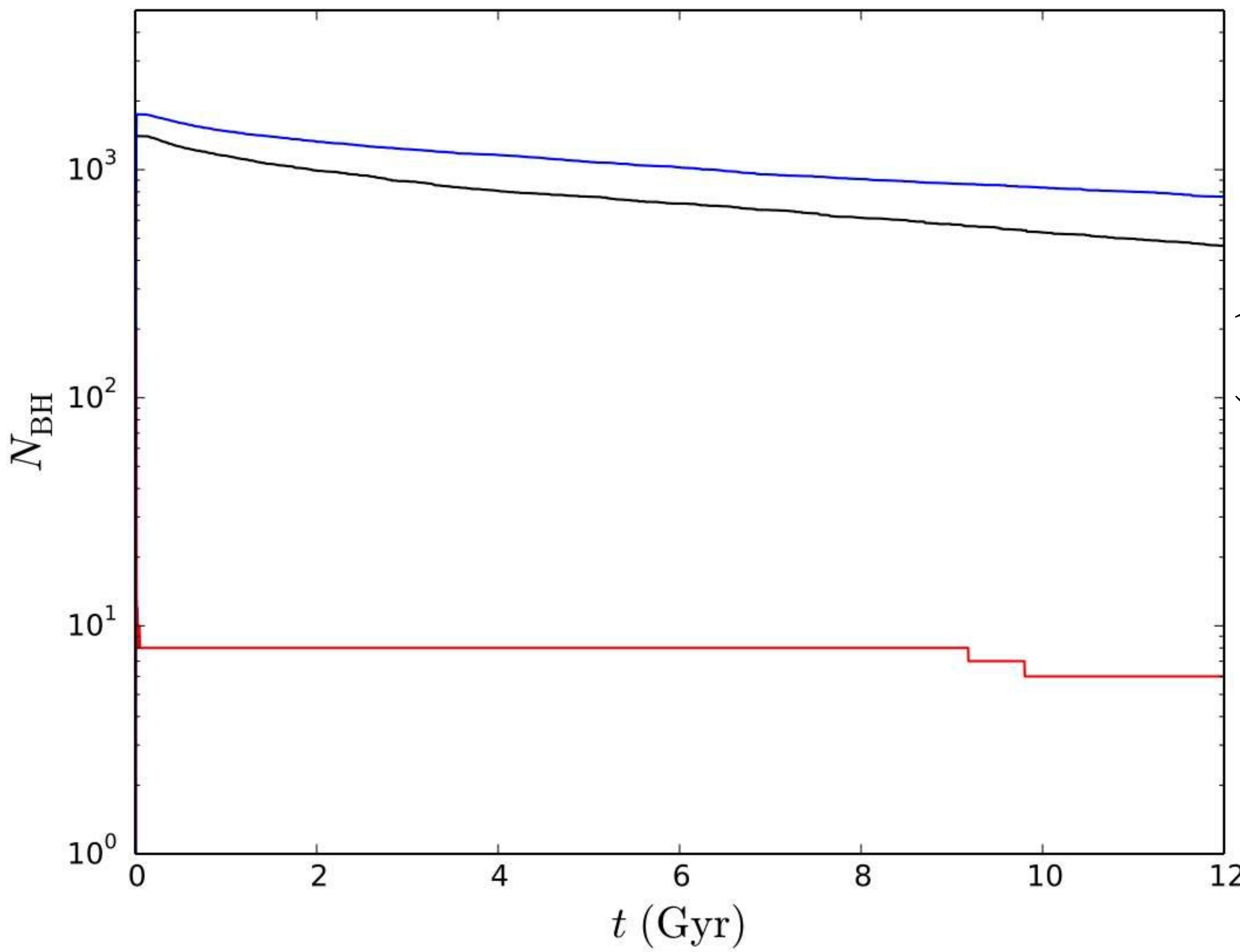
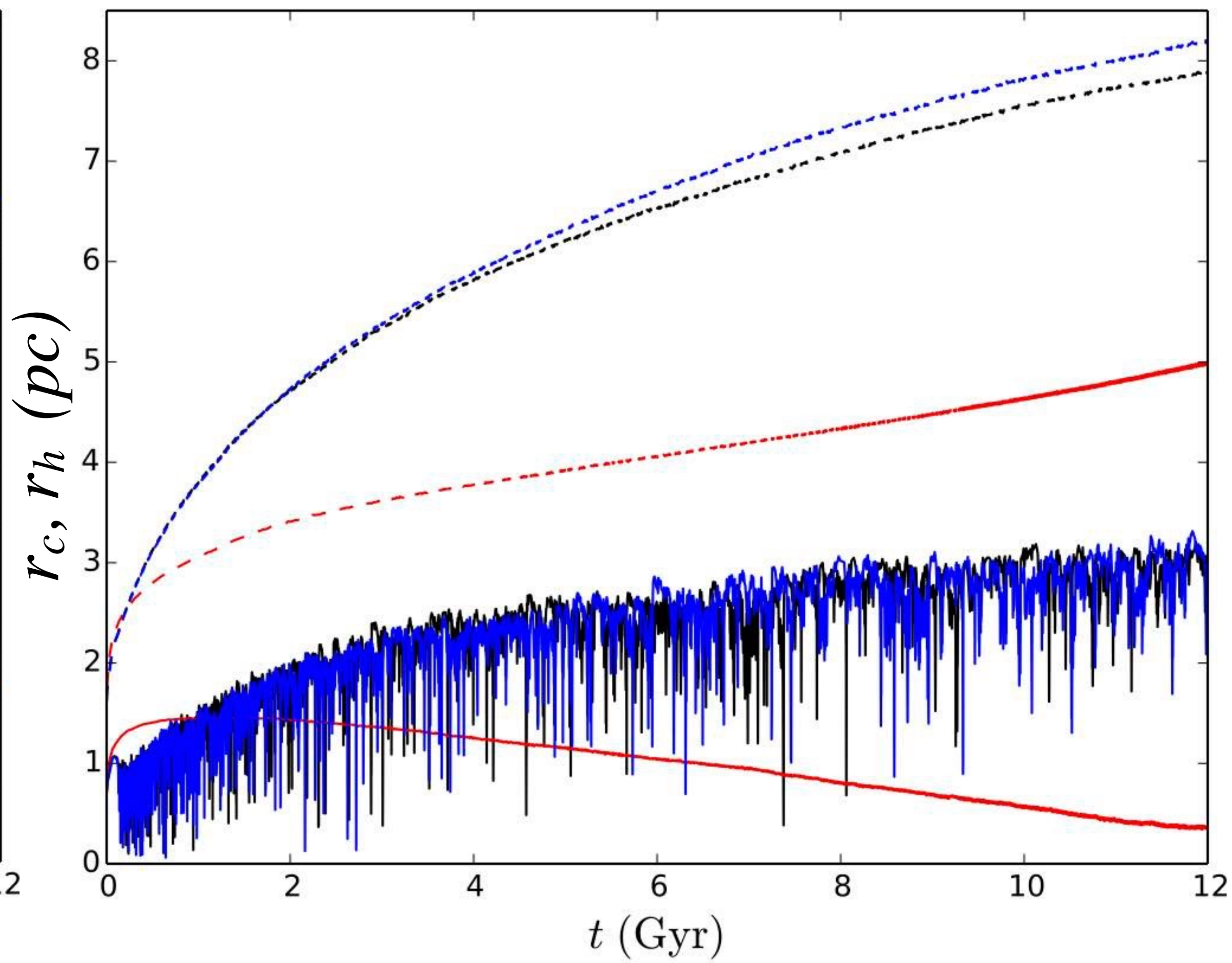
BH kicks are ~1% of NSs





Number of retained BHs

r_c and r_h

CRR16 (in prep.)

Effects of BHs on Cluster Evolution

BH birth kicks

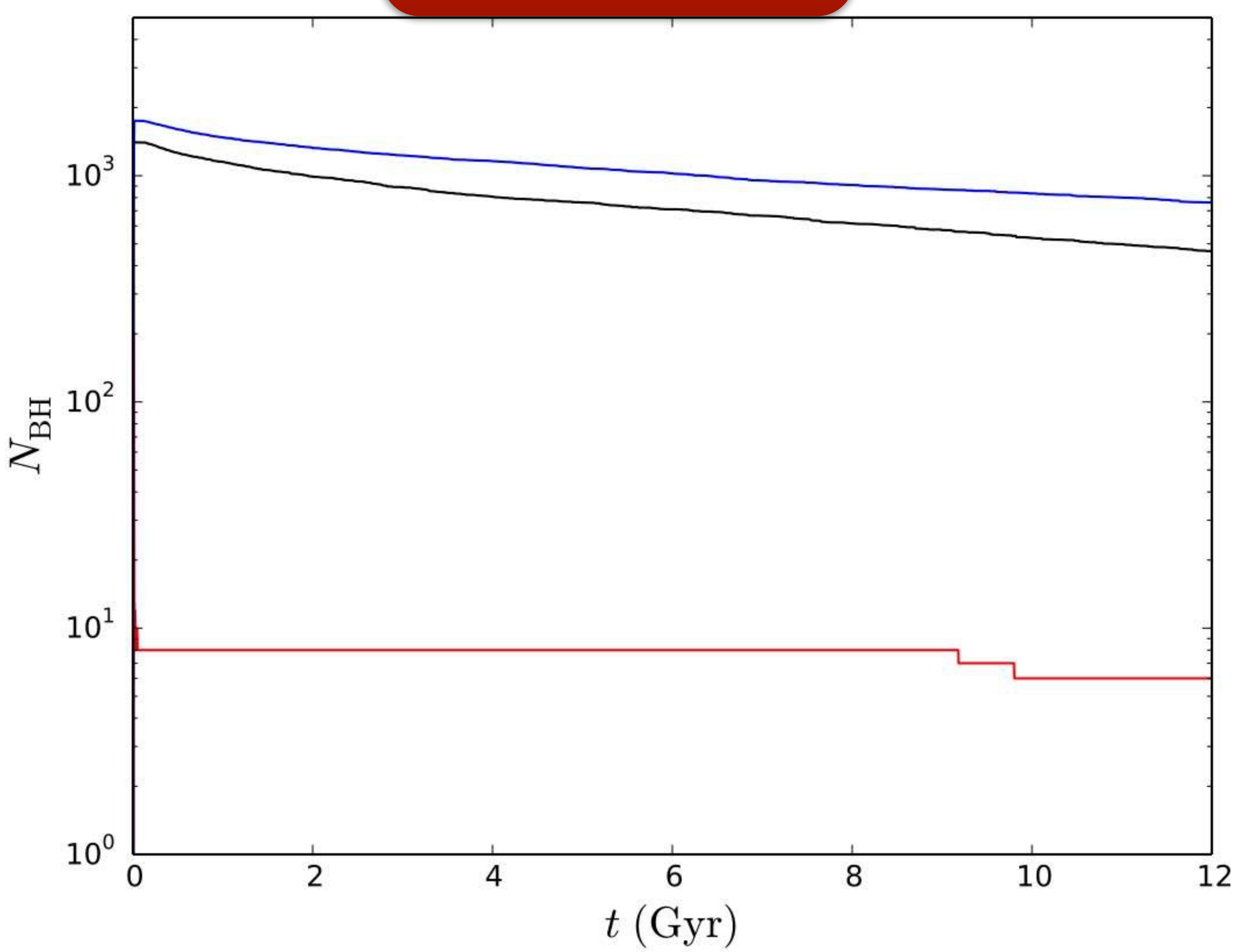
BH kicks are as large as NSs

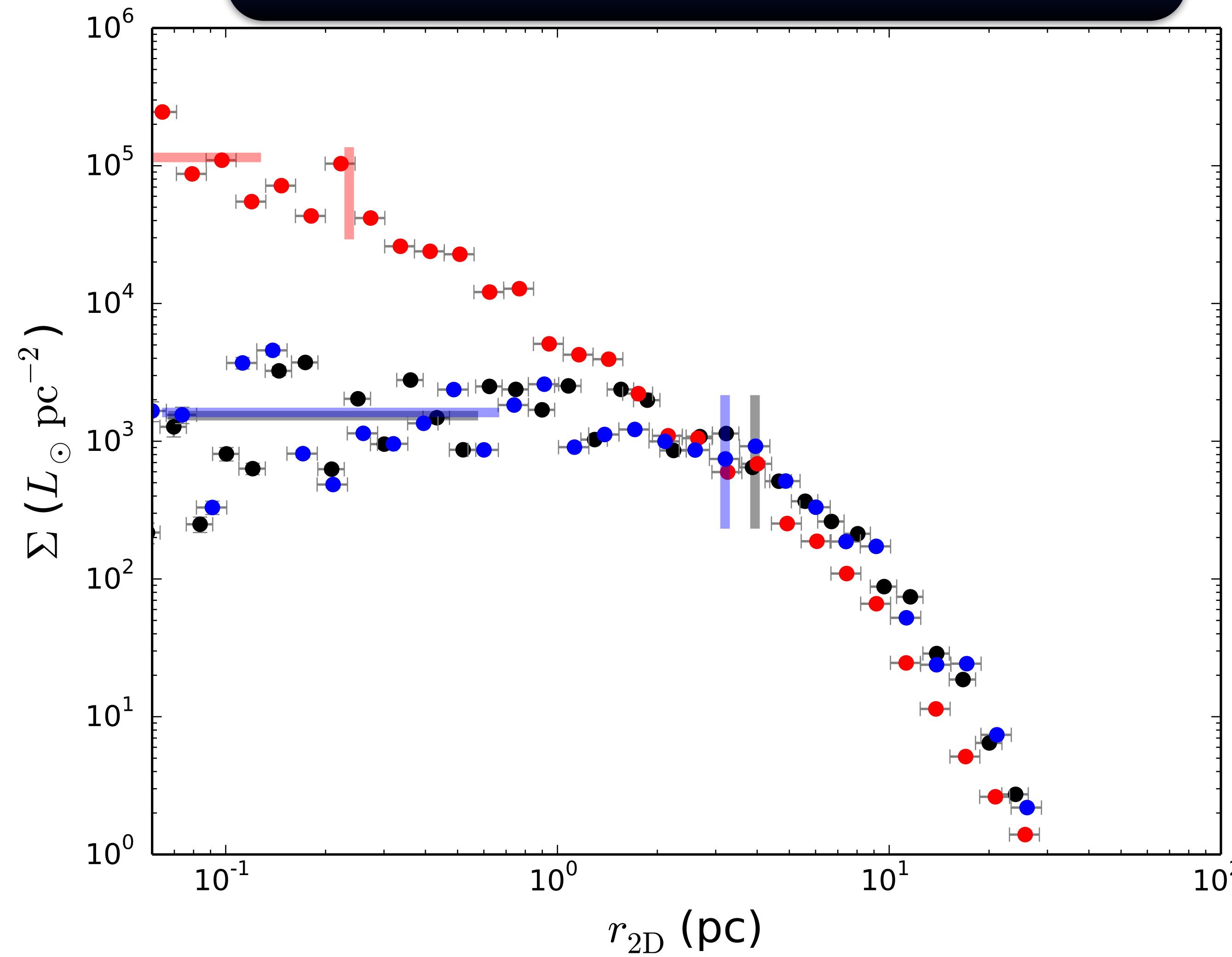
Core-collapsed cluster

M & Z dependent (Belczynsky+02)

BH kicks are ~1% of NSs

Puffy clusters with large cores and low central brightness





Number of retained BHs

Brightness Profile

CRR16 (in prep.)

How Does the Story Depend on *Uncertain* BH Physics?

BH birth kicks:

- Do BHs get large kicks similar to NSs?
  - Wide range in magnitudes from individual observed BH X-ray binaries (e.g., Brandt et al. 1995; Nelemans et al. 1999; Willems et al. 2005; Gualandris et al. 2005; Dhawan et al. 2007; Fragos et al. 2009; Wong et al. 2012, 2014).
- Mass-dependent kicks?
  - YES, should depend on the details of SN physics including fallback mass fraction (Fryer & Kalogera 2001; Belczynski et al. 2002)
  - MAYBE NOT (Repetto et al. 2012; Pejcha & Thompson 2015)

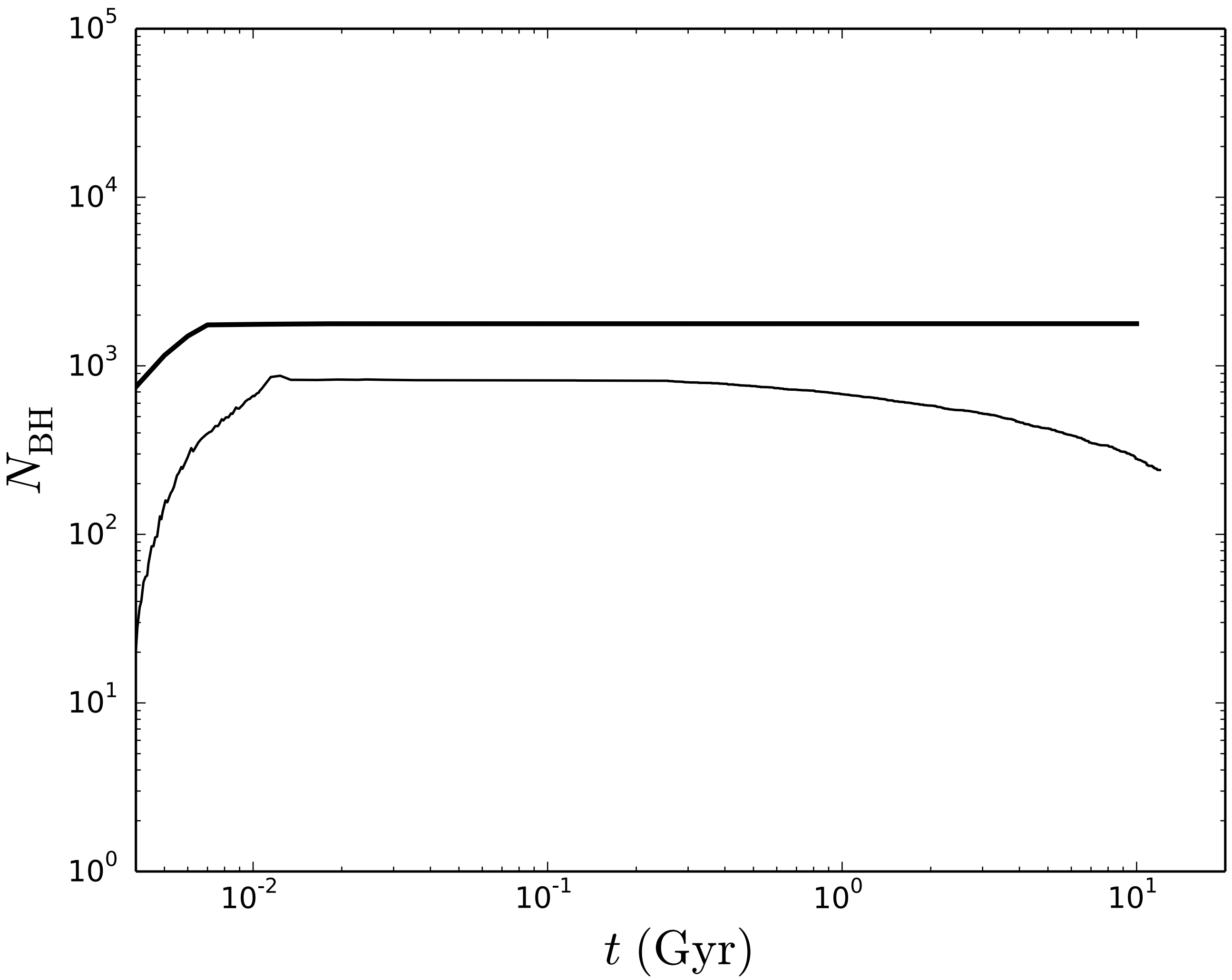
IMF

- Standard IMFs have large uncertainties in the high-mass end
  - $\alpha = 2.3 \pm 0.7$ for $m>1\ M_\odot$ where $dn/dm = m^{-\alpha}$ (Kroupa 2001)

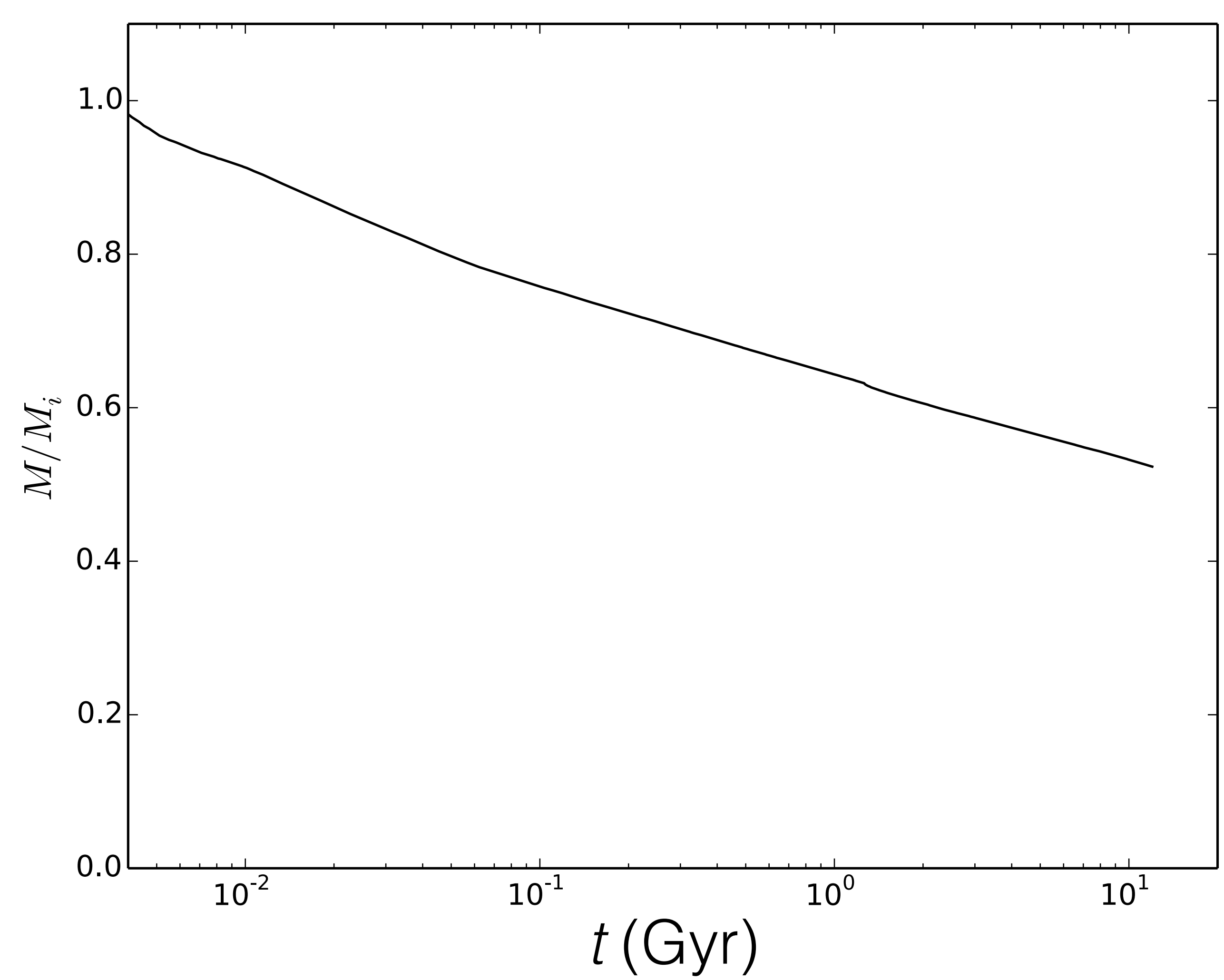
Effects of BHs on Cluster Evolution

IMF & Cluster Dissolution

$dn/dm \sim m^{-2.3}$



Number of retained BHs



Cluster Mass

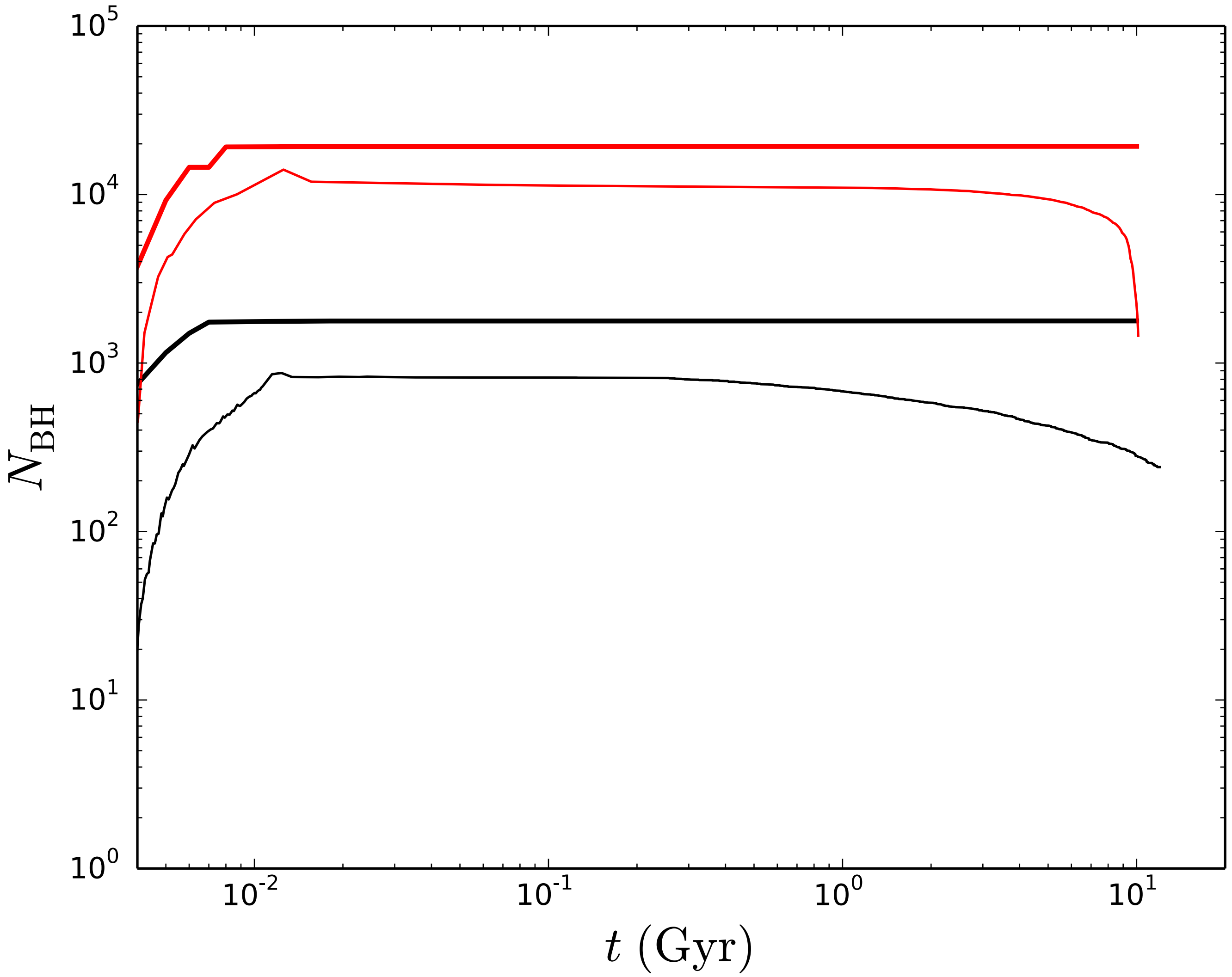
CRR16 (in prep.)

Effects of BHs on Cluster Evolution

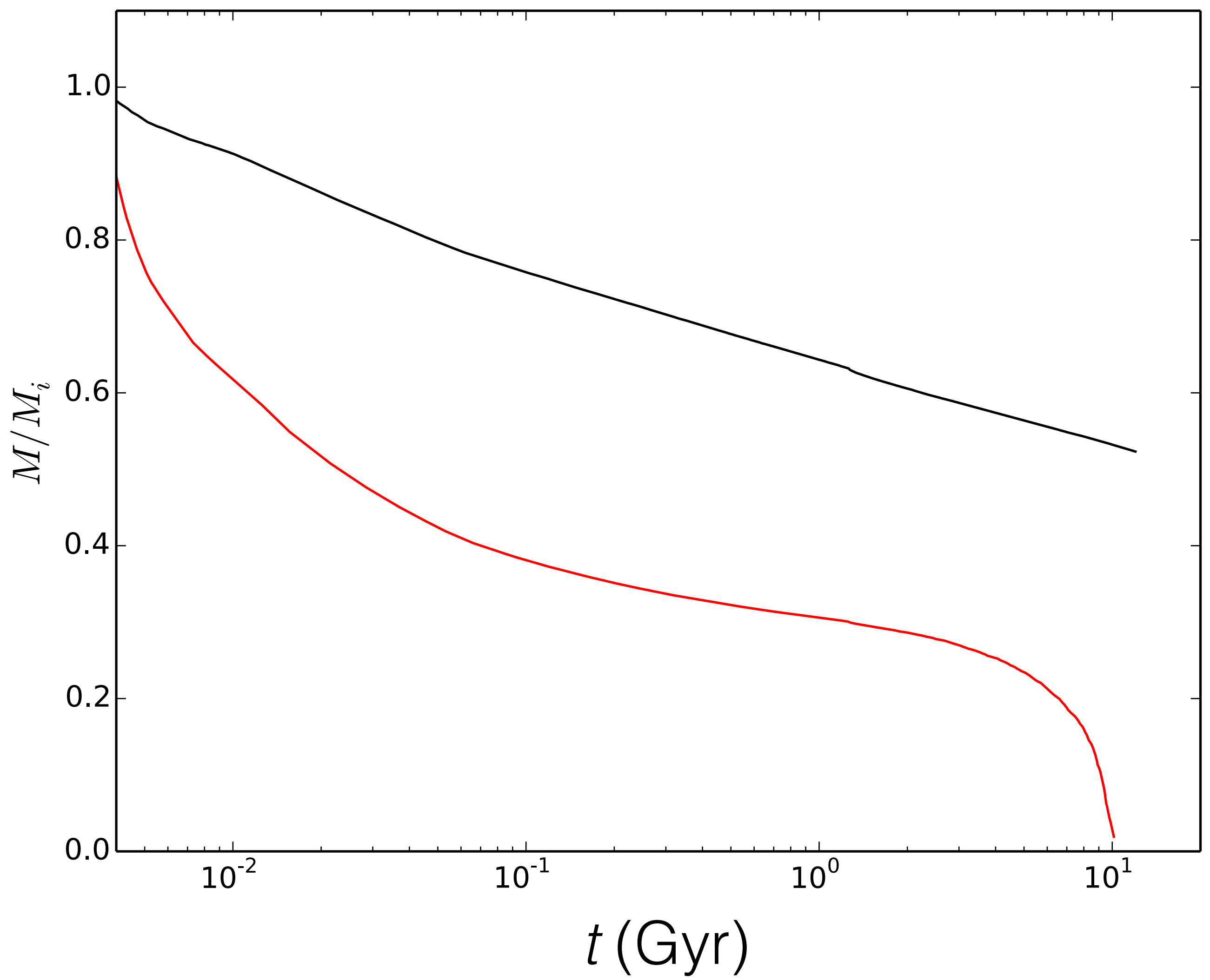
IMF & Cluster Dissolution

dn/dm ~ $m^{-1.6}$

dn/dm ~ $m^{-2.3}$



Number of retained BHs



Cluster Mass

CRR16 (in prep.)

Effects of BHs on Cluster Evolution

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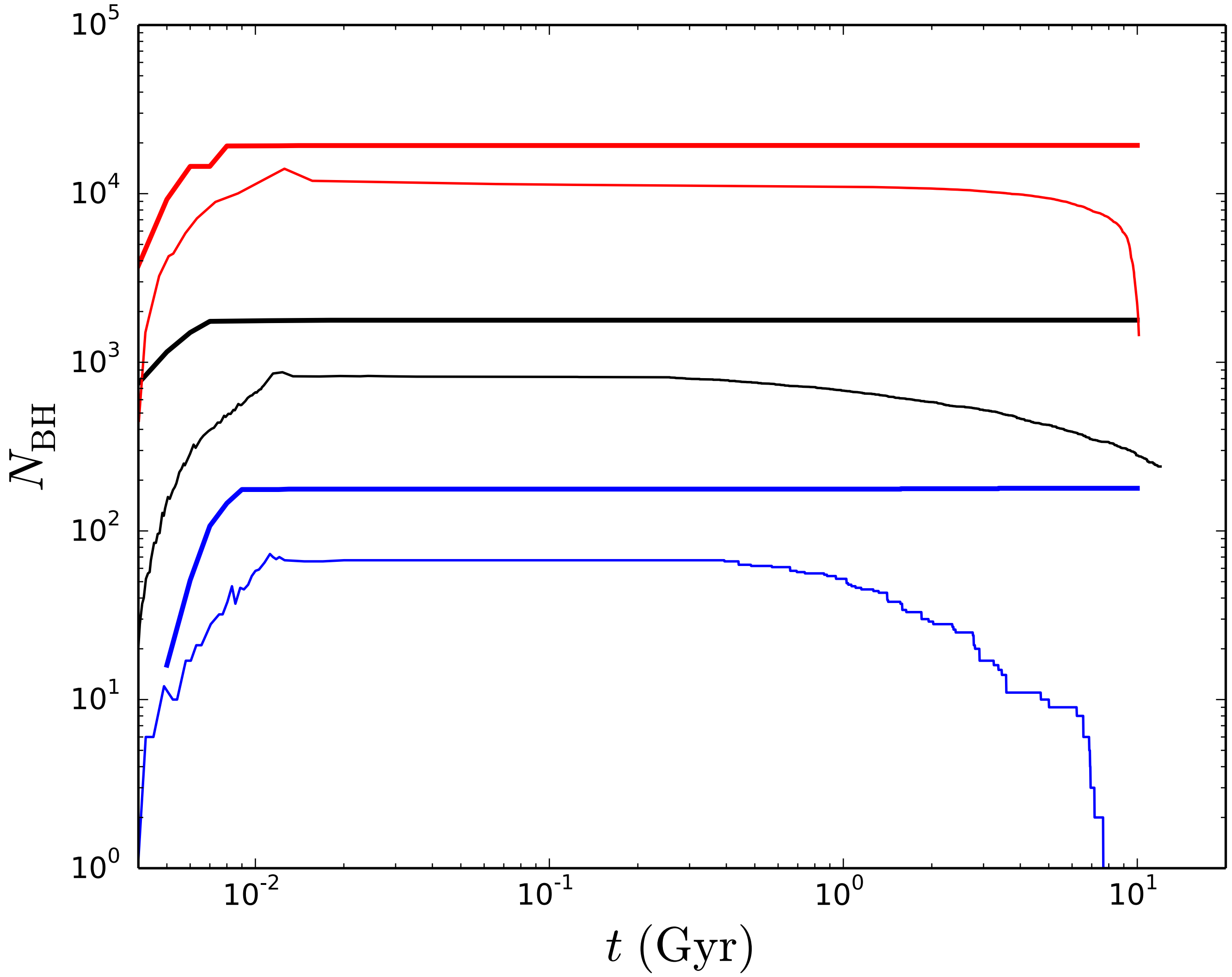
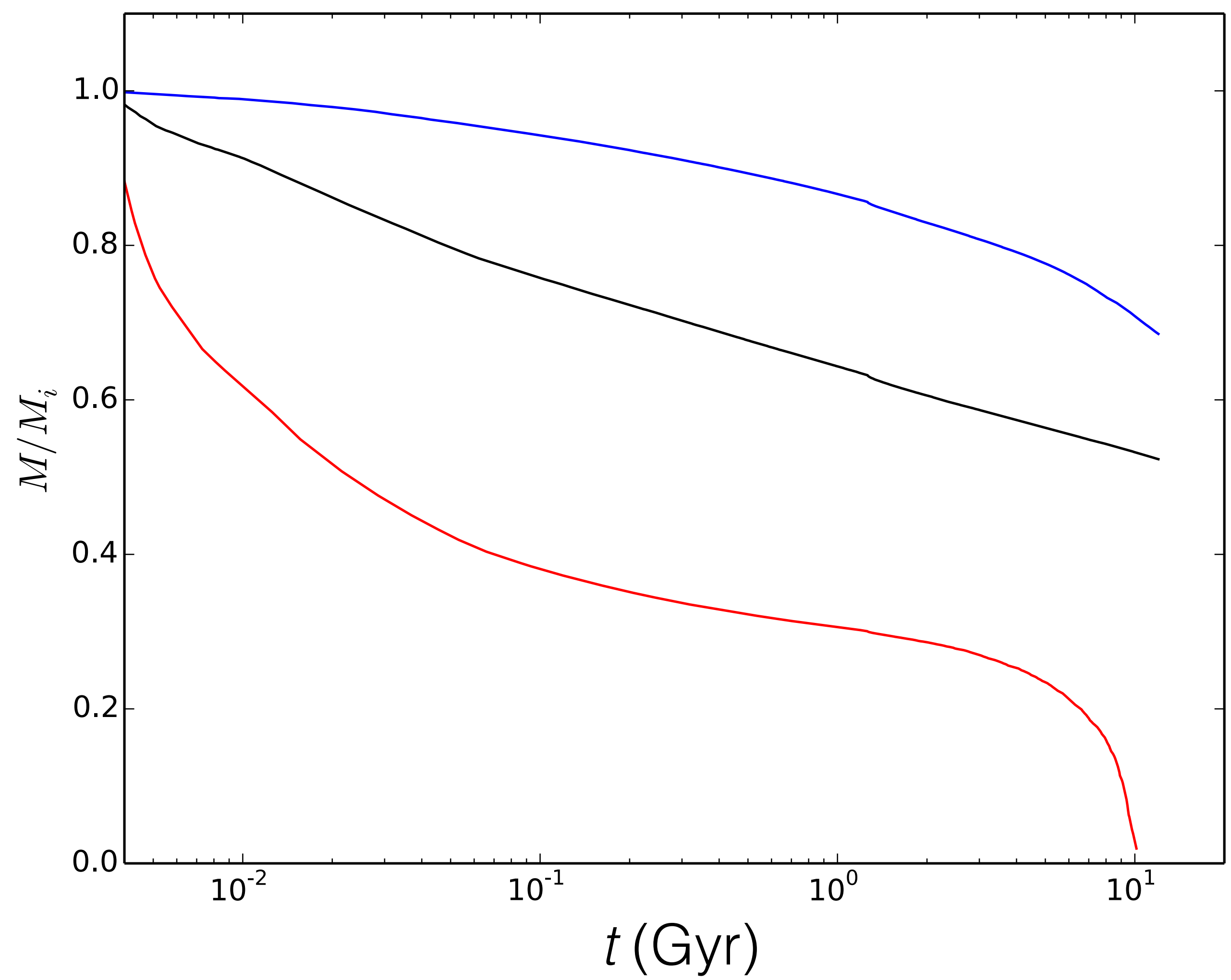


Number of retained BHs

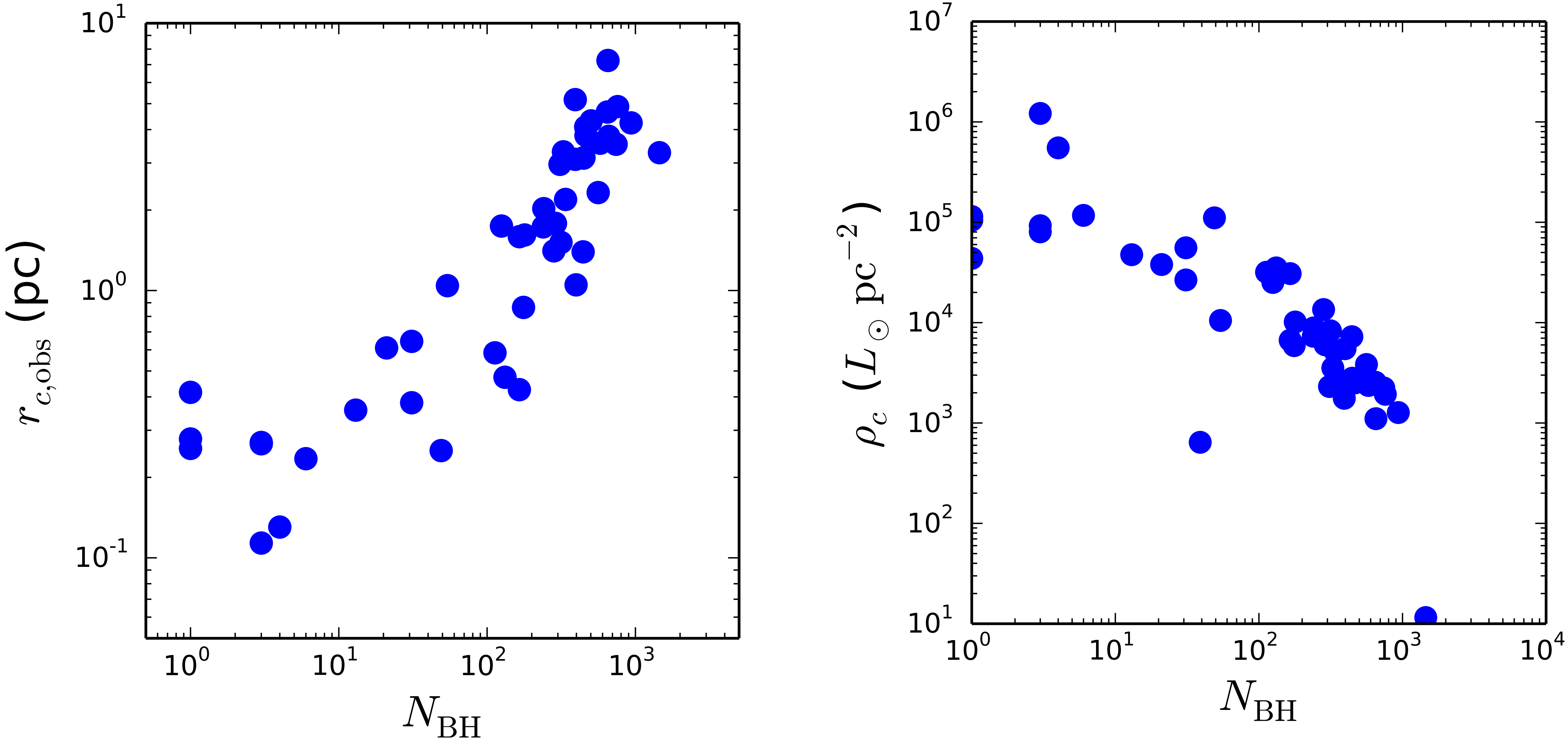


Cluster Mass

CRR16 (in prep.)

Number of Retained BHs and GC Properties

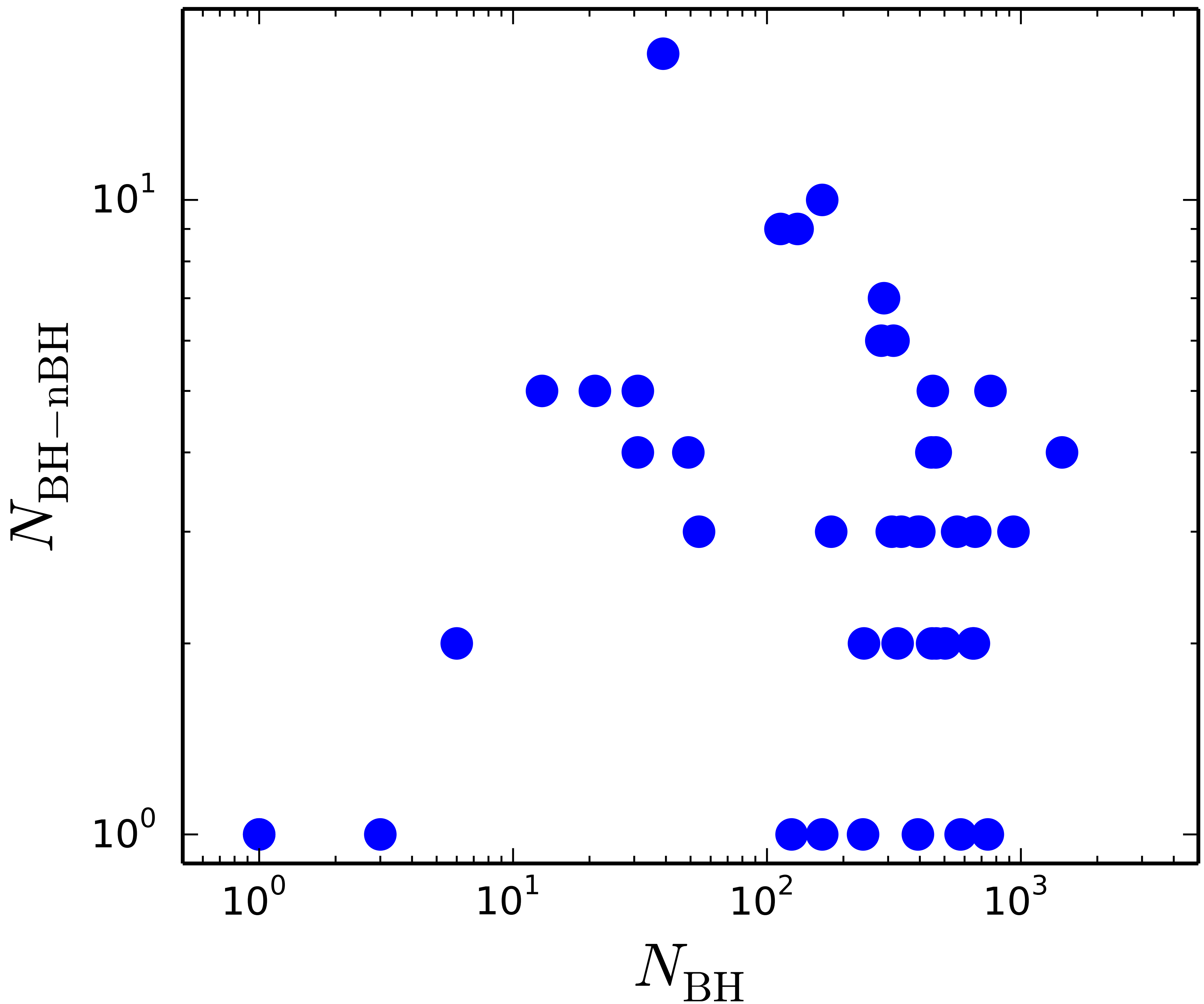
Total number of Retained BHs vs r_c and ρ_c



CRR16a (in prep.)

Identifying Clusters that Host BHs

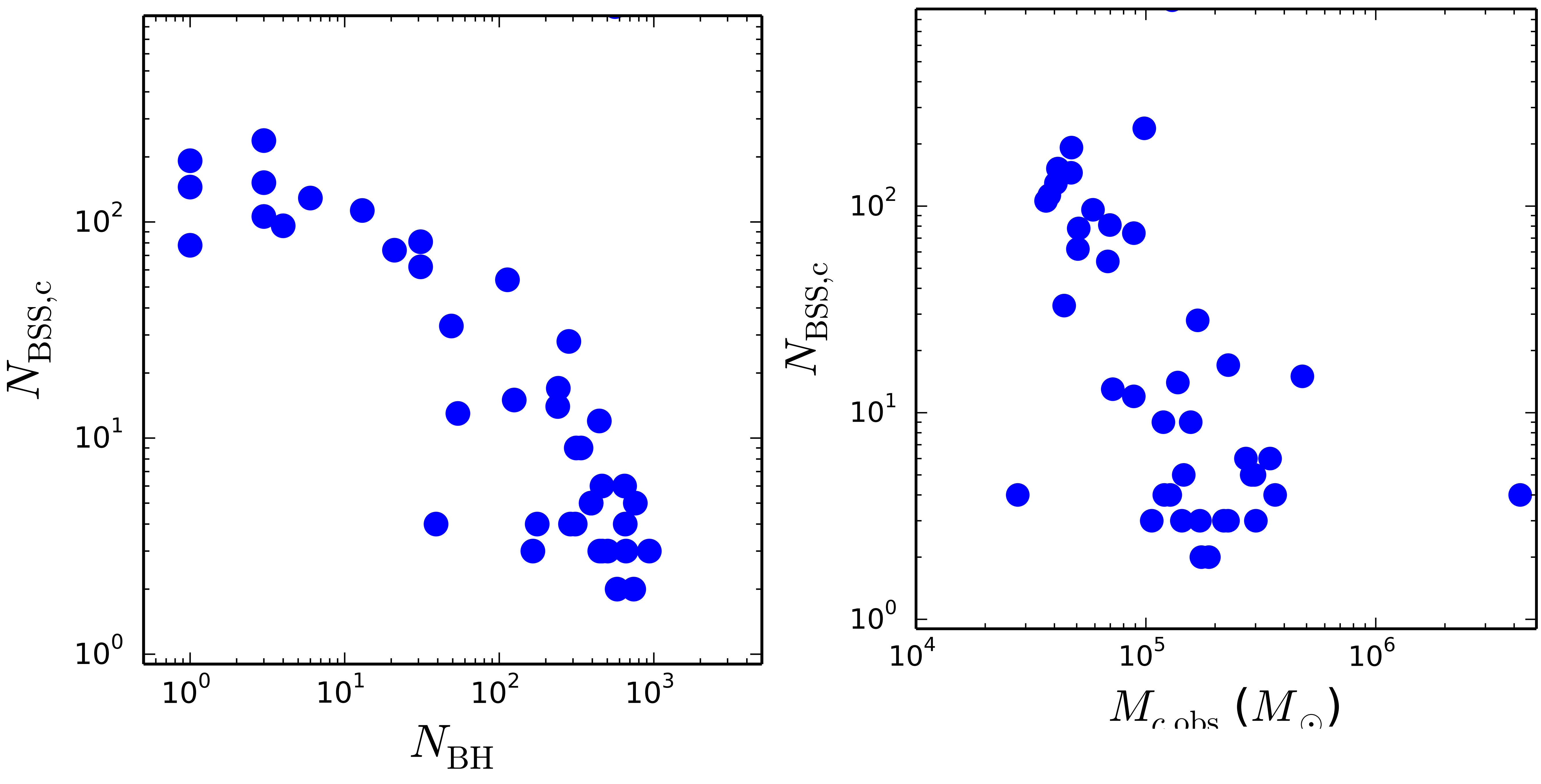
Little Correlation Expected Between N_{BH} and $N_{BH\text{-}nBH}$



CRR16a (in prep.)

Identifying Clusters that Host BHs

Other Dynamical Populations May Provide Important Clue



CRR16a (in prep.)

Summary

- Overview of physical processes, & different numerical approaches.
- Old GCs still can retain large numbers of BHs (unless they are all ejected due to SN kicks).
- Cluster dynamics modify binary BH properties:
  - Implications for LIGO sources.
- Effects of uncertain physics that affects BHs and in turn can dramatically changes host cluster's evolution.
- Challenges in identifying GCs that may host large numbers of BHs. Some possible solution (e.g., BSSs).

非常感谢