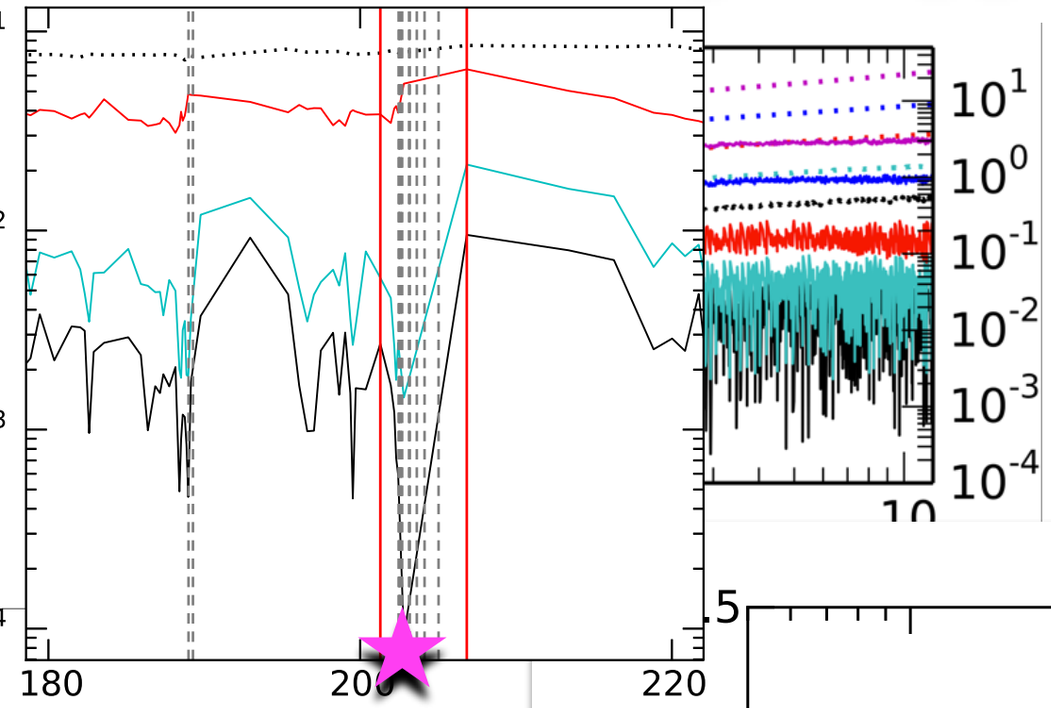
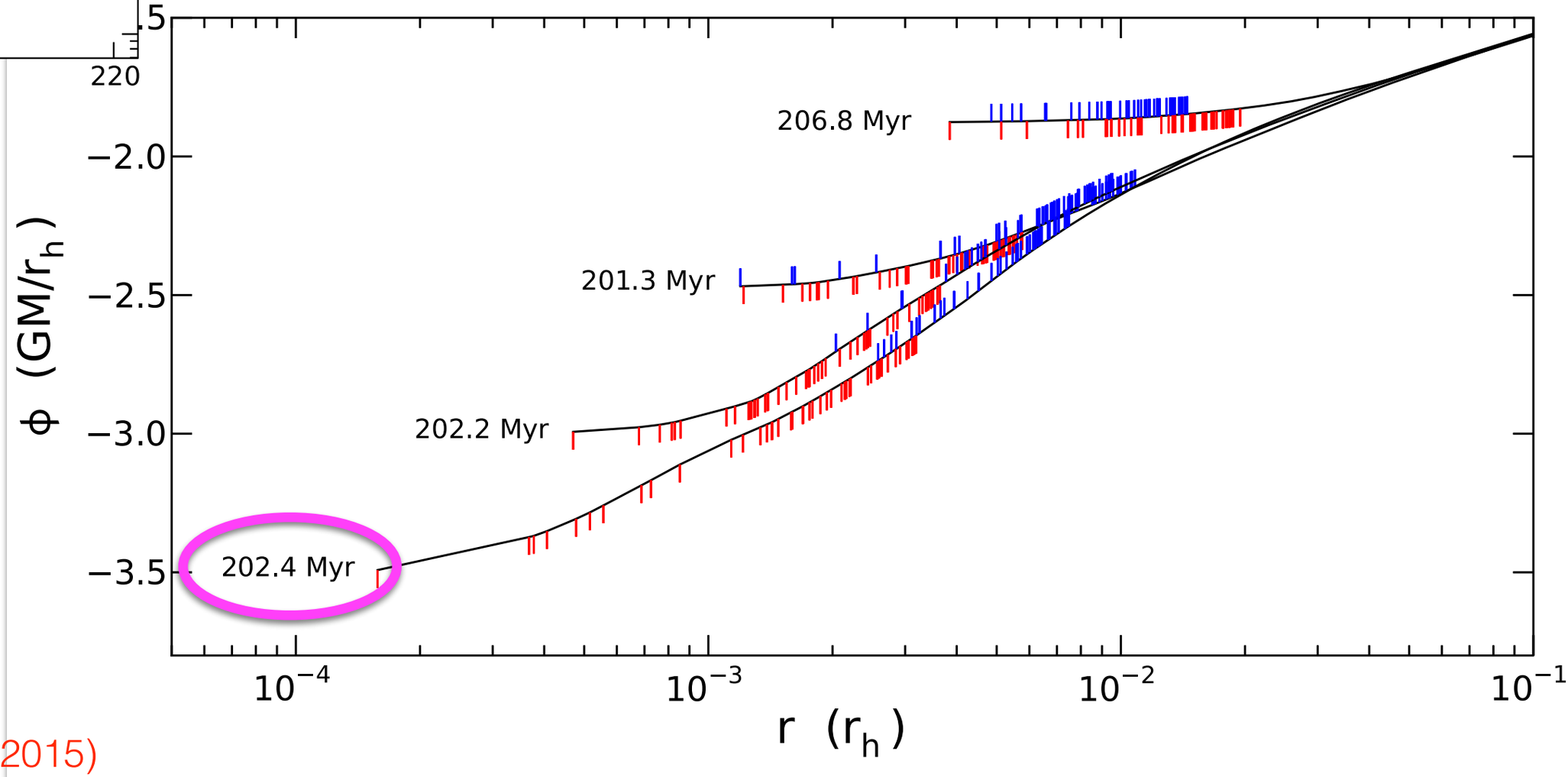
# What Really Happenes to the BHs in Clusters?










Morscher et al. (2015)

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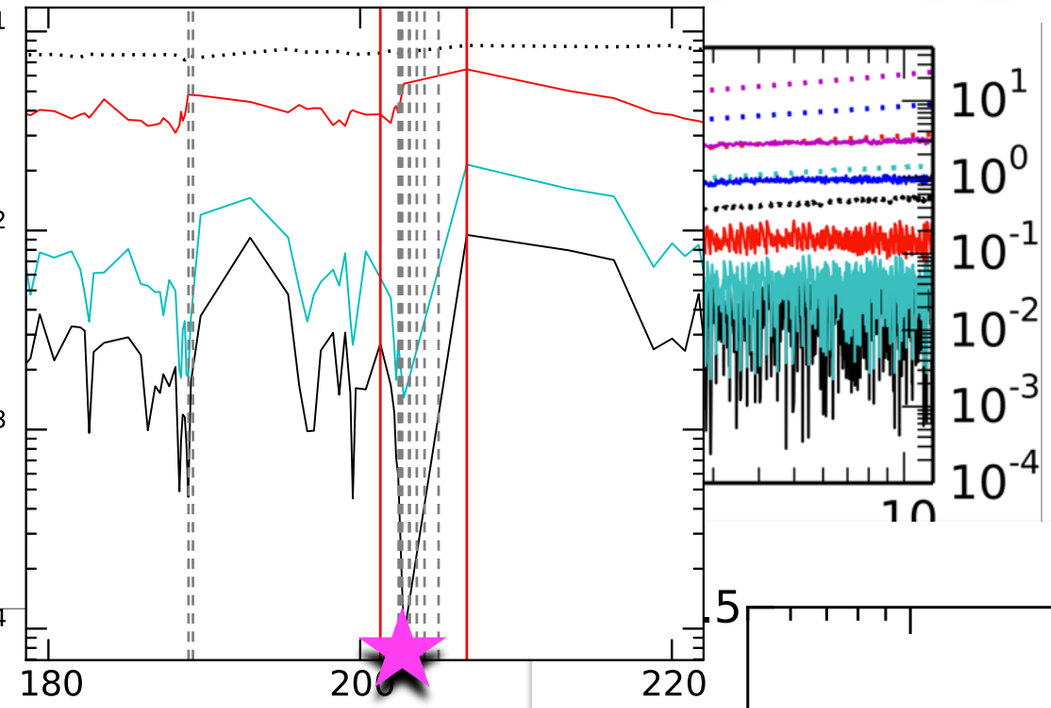





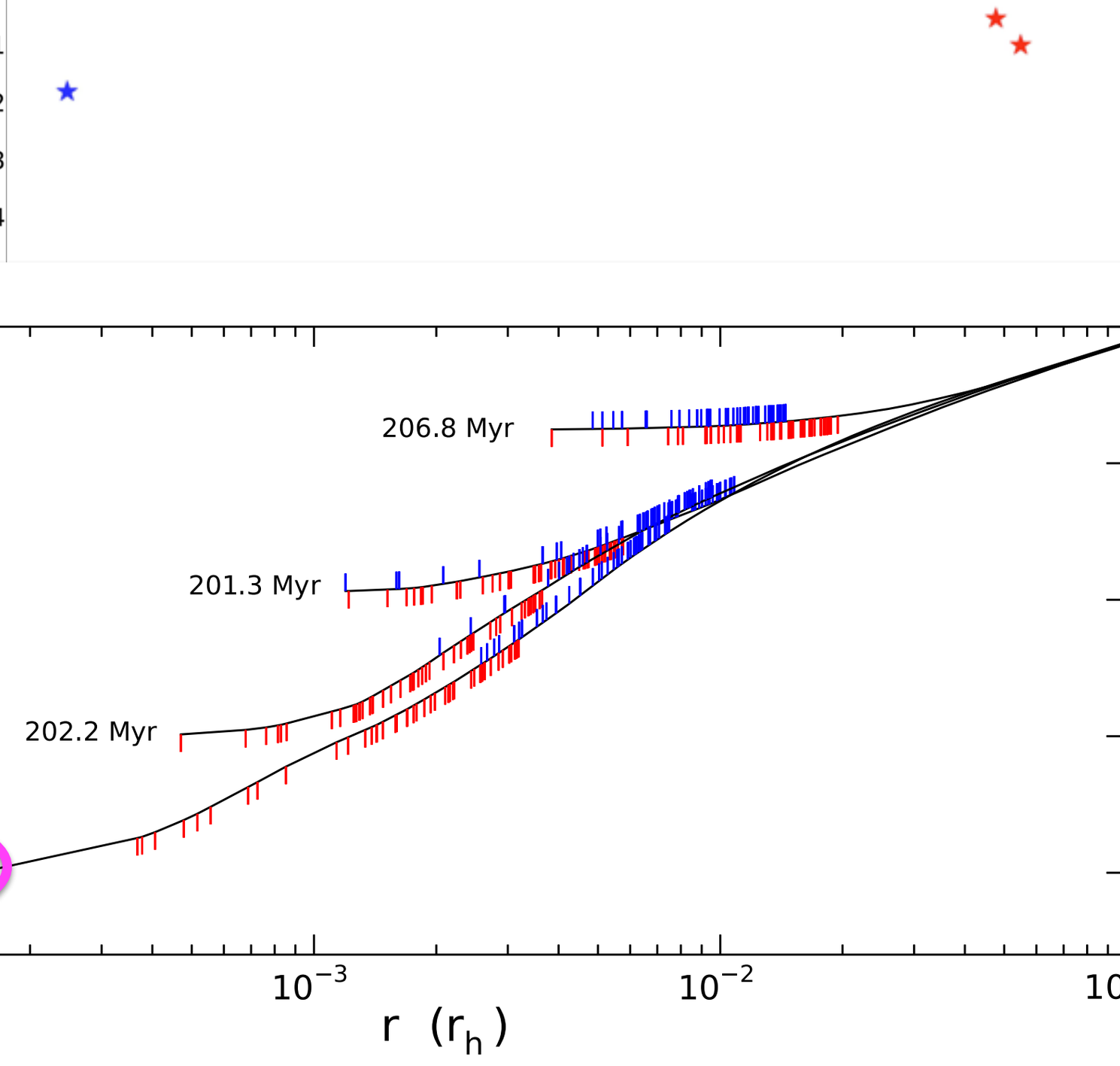


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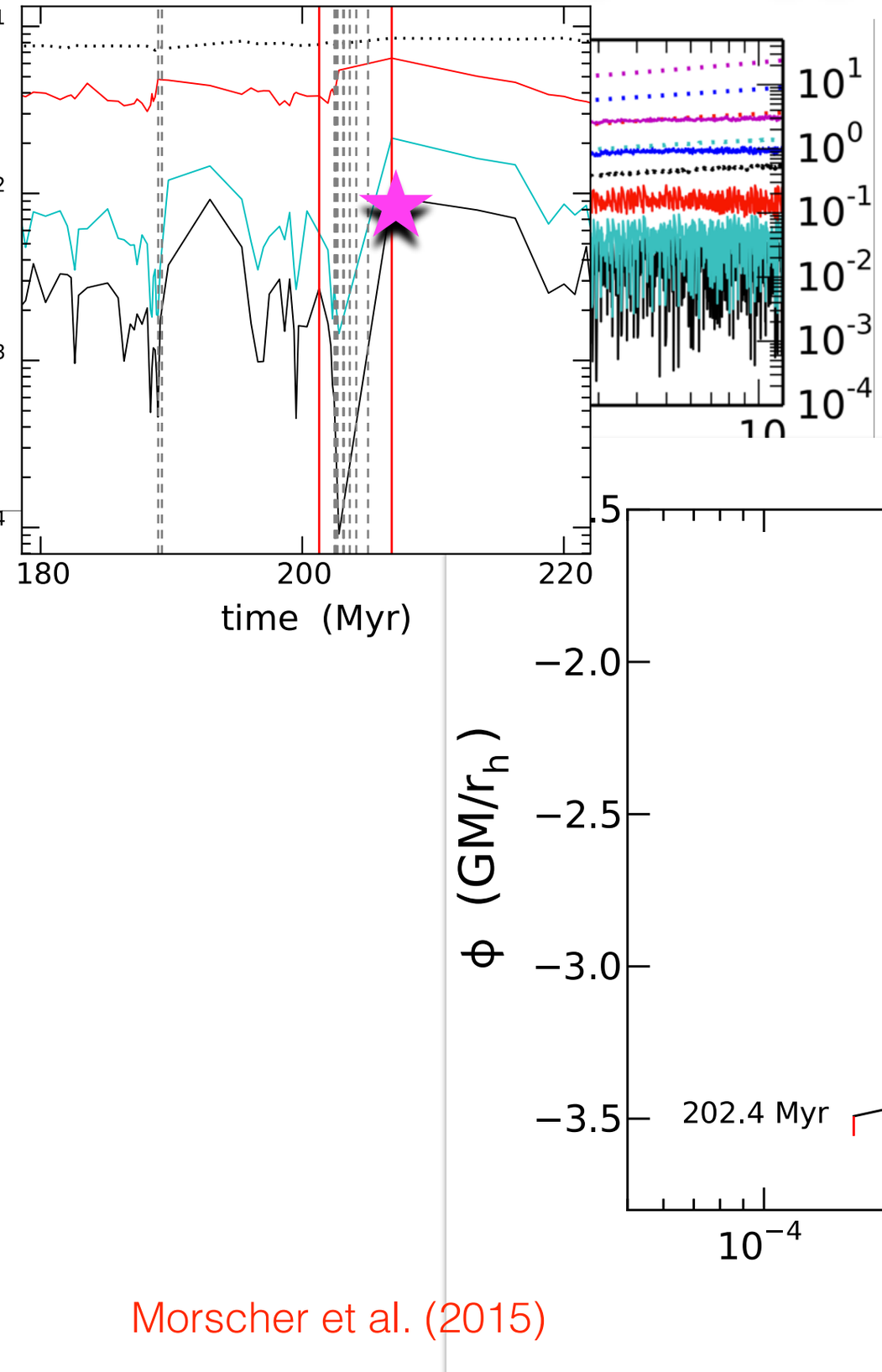
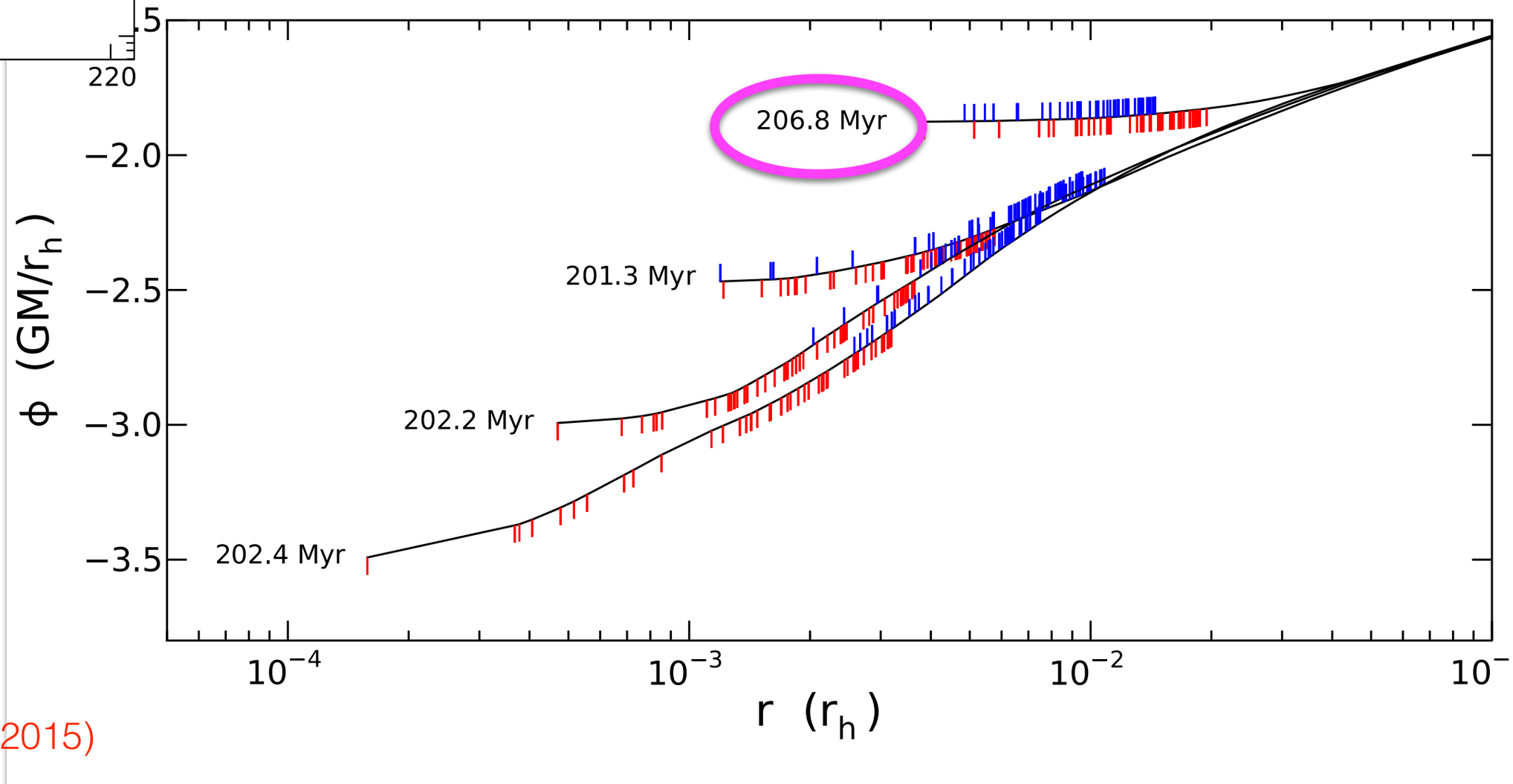




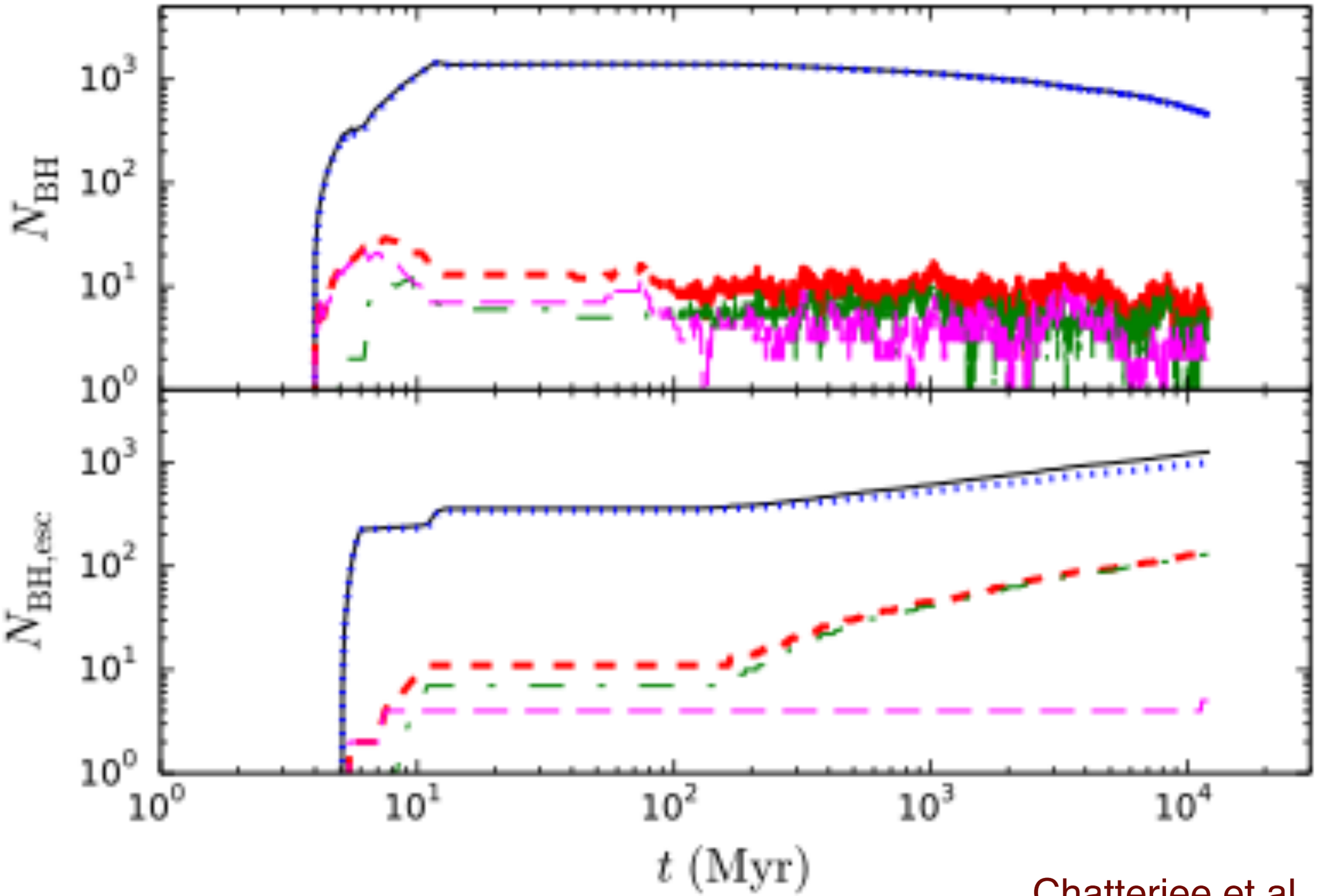





Morscher et al. (2015)

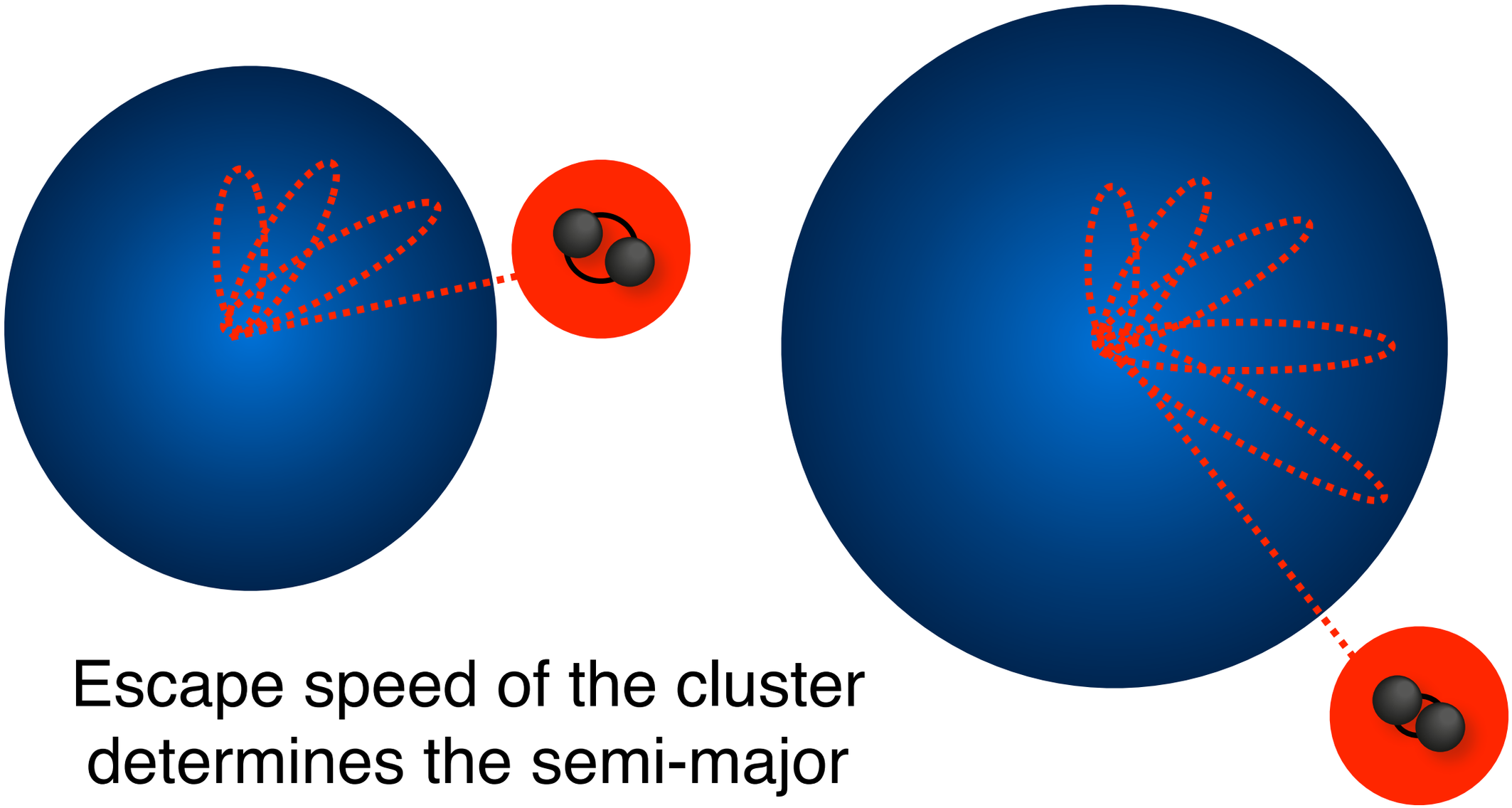
# BHs:

## Binarity, Retention and Ejection



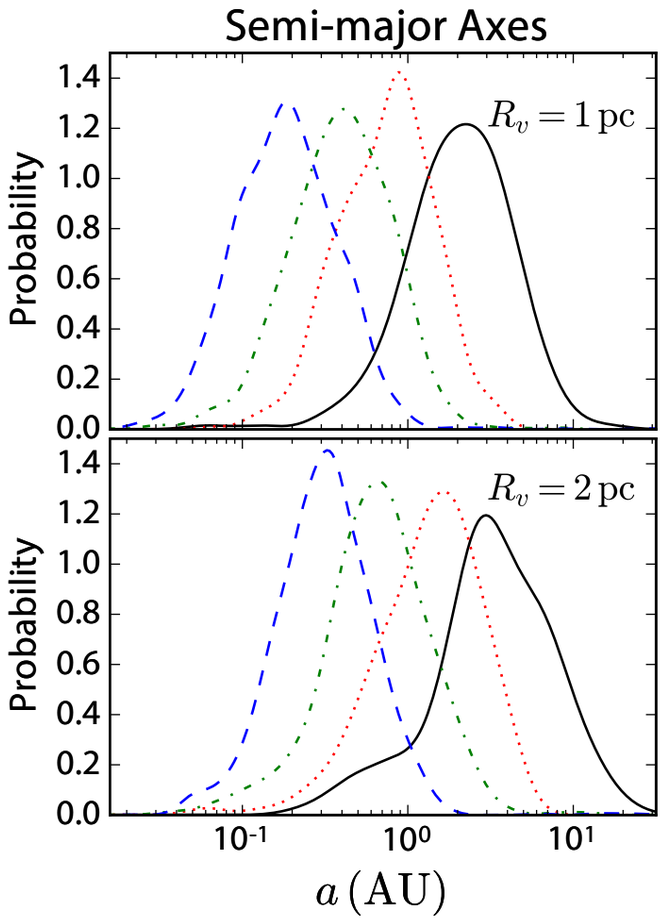

Chatterjee et al. 2016

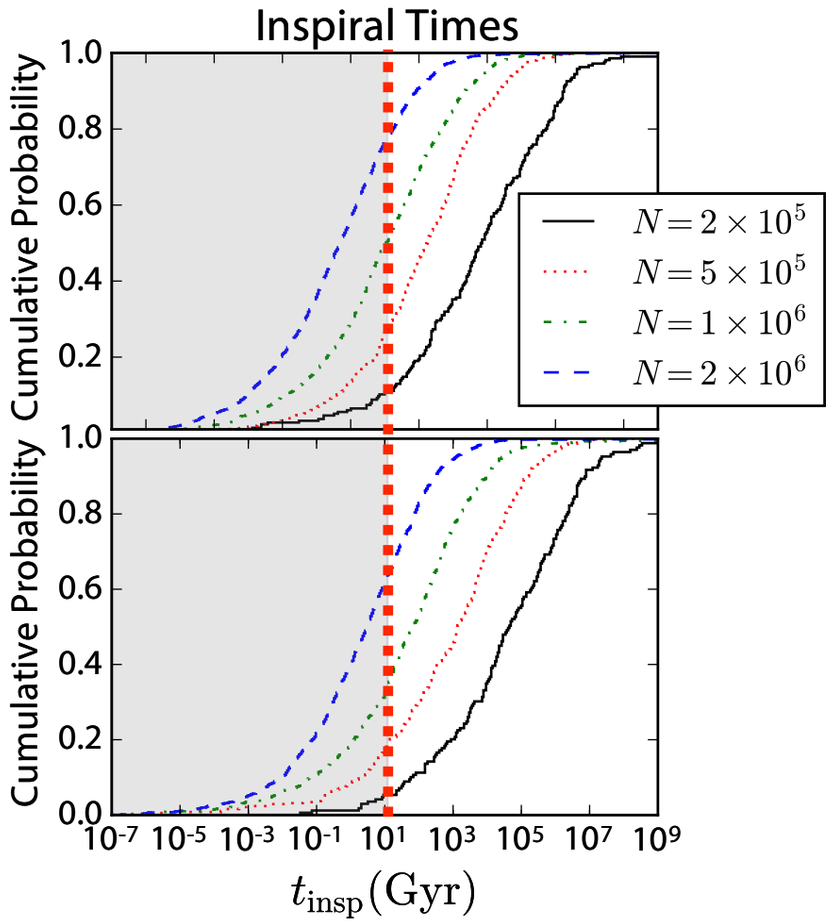
# Chaotic Interactions

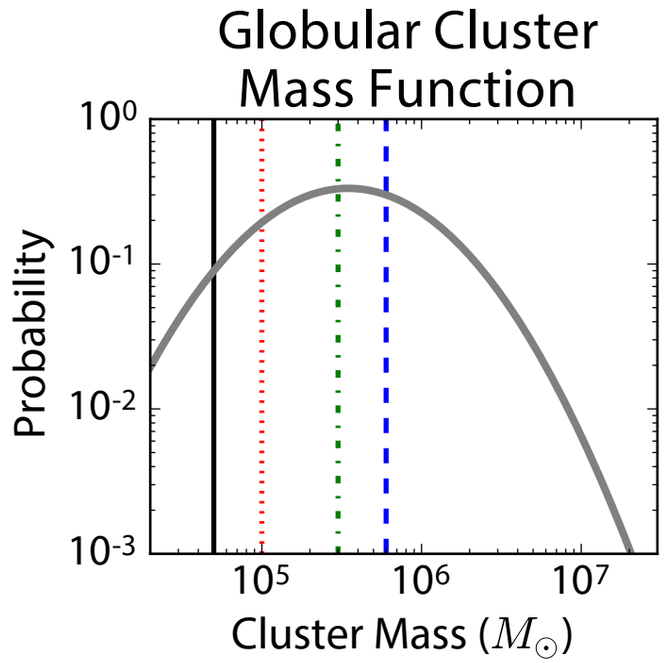


Escape speed of the cluster determines the semi-major axis of the ejected binaries

# Chaotic Interactions

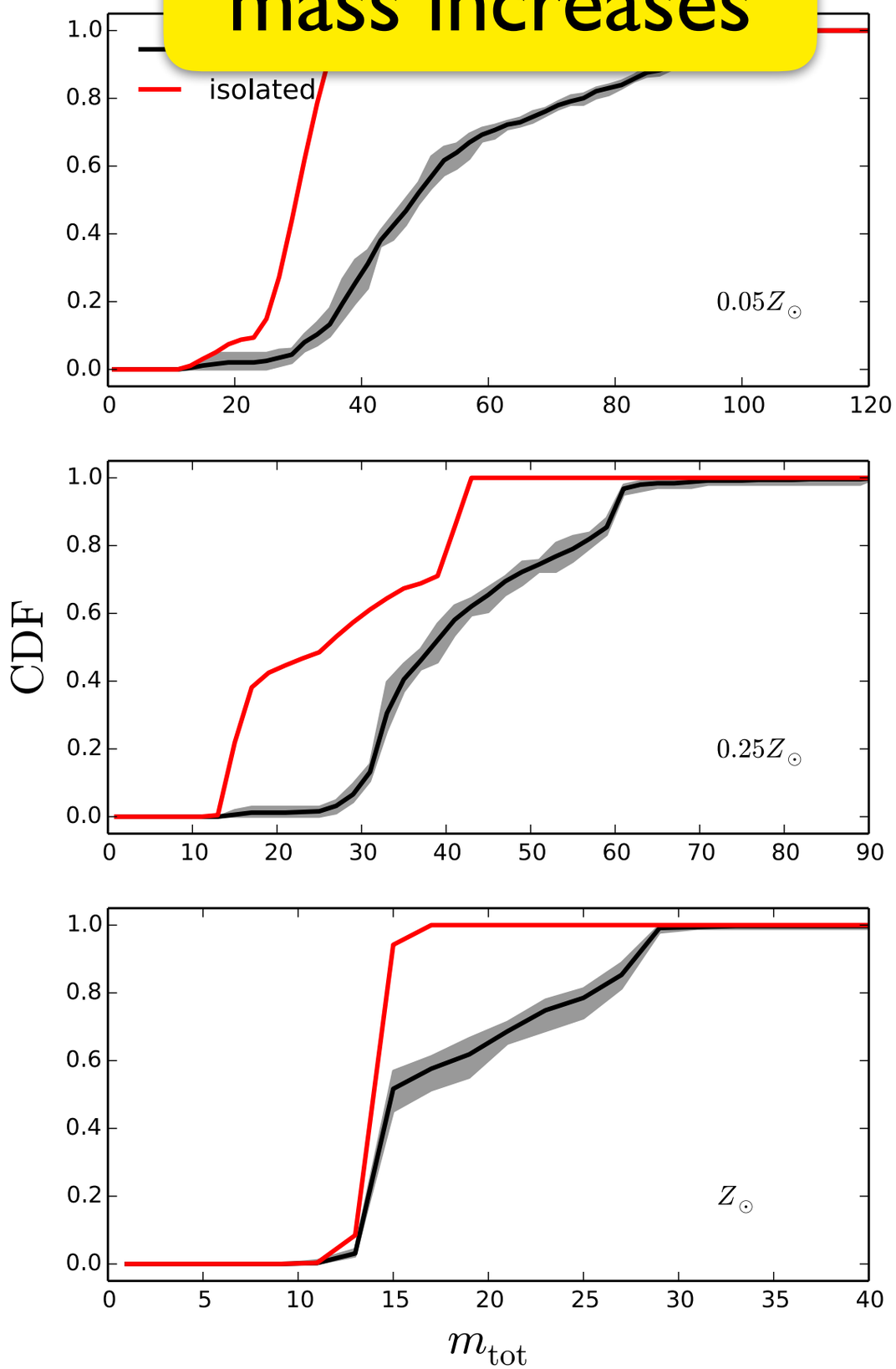


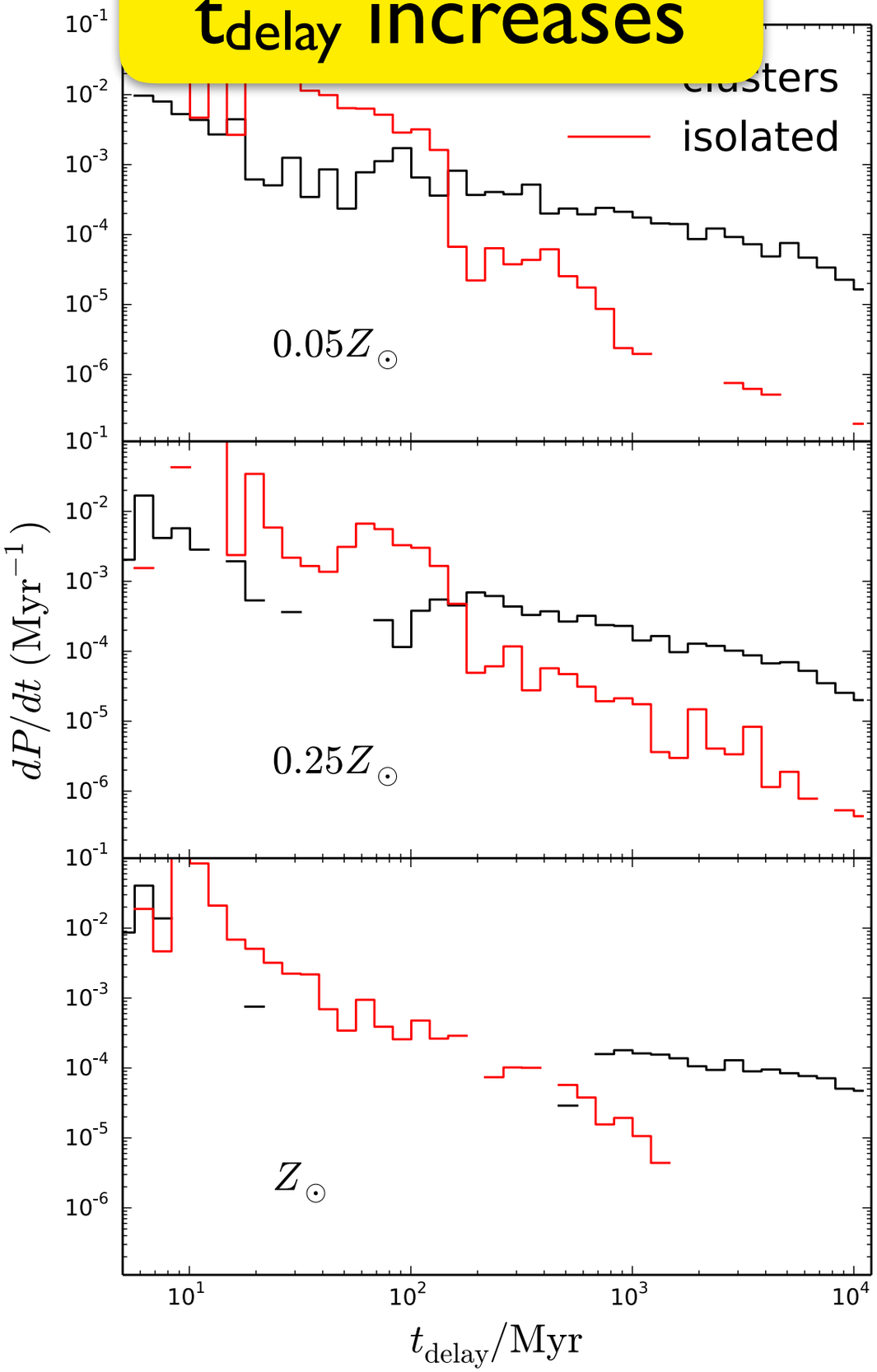



# What are the consequences?

**mass increases**




**$t_{delay}$ increases**



# Our most detailed predictions for LIGO came out just before the first detection …

PRL **115,** 051101 (2015) PHYSICAL REVIEW LETTERS week ending 31 JULY 2015

## Binary Black Hole Mergers from Globular Clusters: Implications for Advanced LIGO

Carl L. Rodriguez,[1] Meagan Morscher,[1] Bharath Pattabiraman,[1,2] Sourav Chatterjee,[1]
Carl-Johan Haster,[1,3] and Frederic A. Rasio[1]

[1]*Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Rd, Evanston, Illinois 60208, USA*

[2]*Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208, USA*

[3]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*

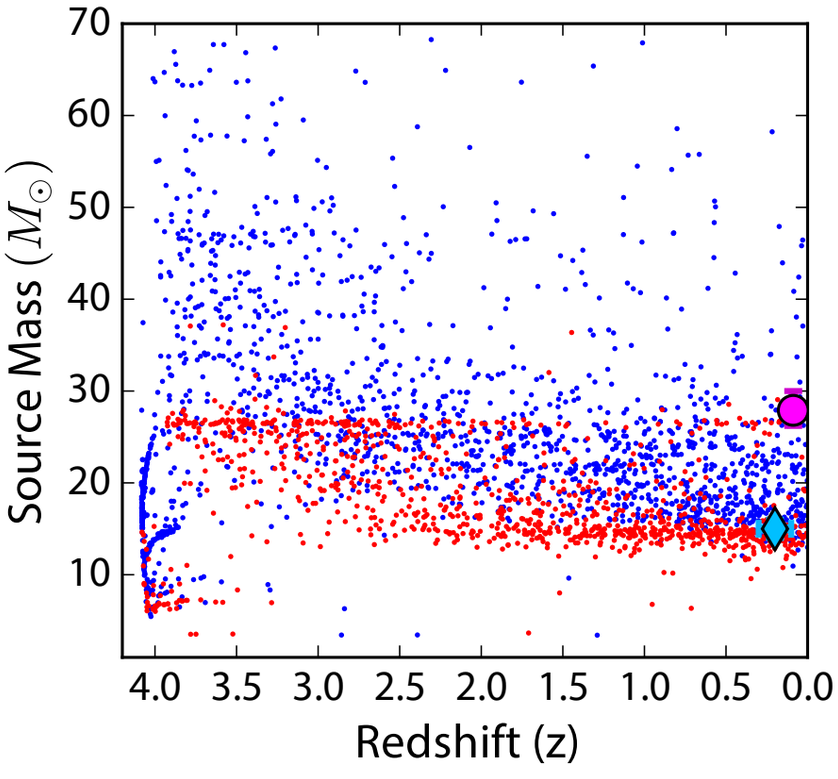
(Received 2 May 2015; published 30 July 2015)

The predicted rate of binary black hole mergers from galactic fields can vary over several orders of magnitude and is extremely sensitive to the assumptions of stellar evolution. But in dense stellar environments such as globular clusters, binary black holes form by well-understood gravitational interactions. In this Letter, we study the formation of black hole binaries in an extensive collection of realistic globular cluster models. By comparing these models to observed Milky Way and extragalactic globular clusters, we find that the mergers of dynamically formed binaries could be detected at a rate of ~100 per year, potentially dominating the binary black hole merger rate. We also find that a majority of cluster-formed binaries are more massive than their field-formed counterparts, suggesting that Advanced LIGO could identify certain binaries as originating from dense stellar environments.

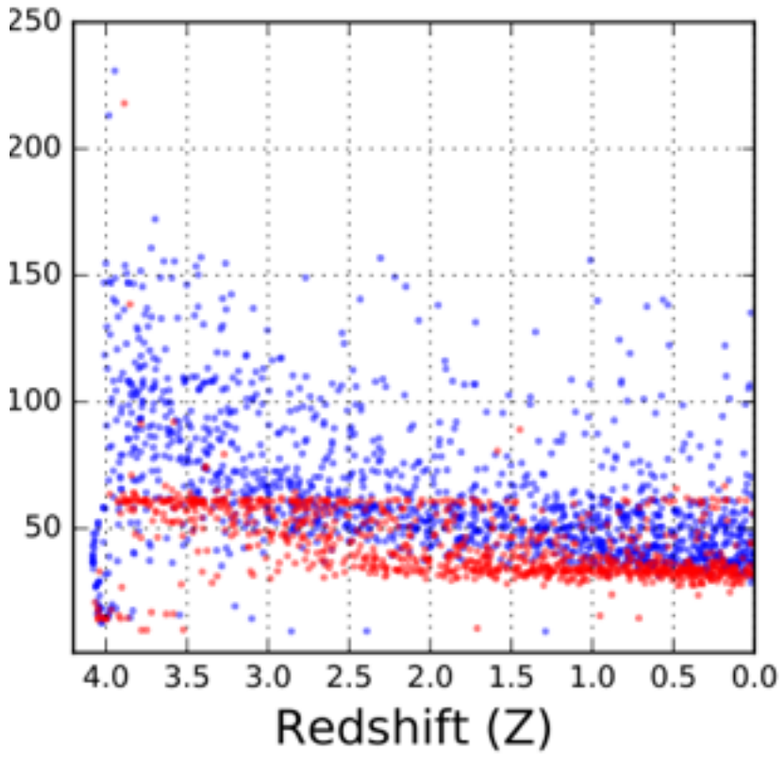
DOI: 10.1103/PhysRevLett.115.051101 PACS numbers: 04.30.Db, 98.20.-d

# BH-BH Merger Properties as LIGO source Masses

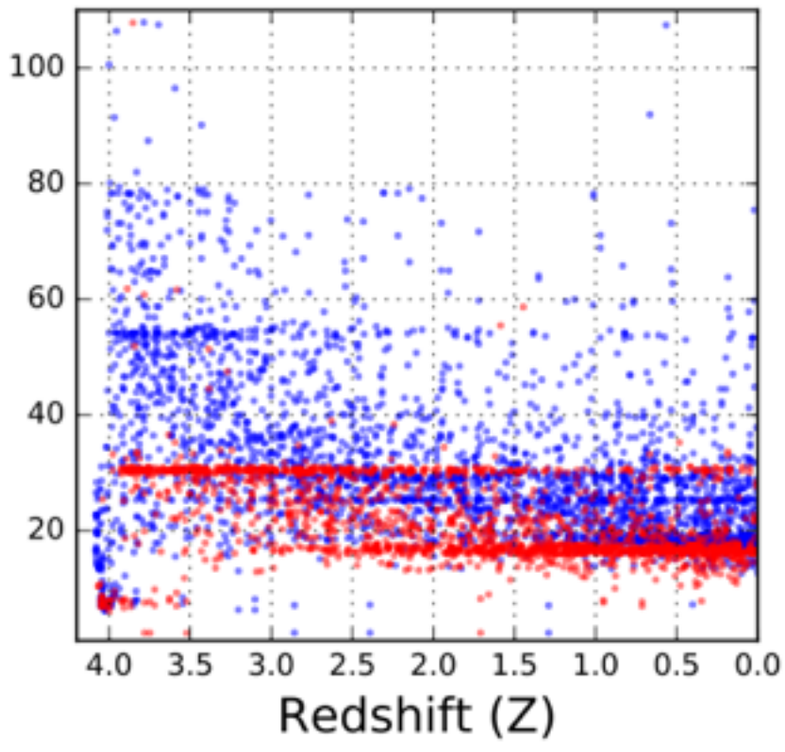
## Chirp Mass




## Total Mass




## Component Masses




Low Z
High Z

GW150914
LVT151012

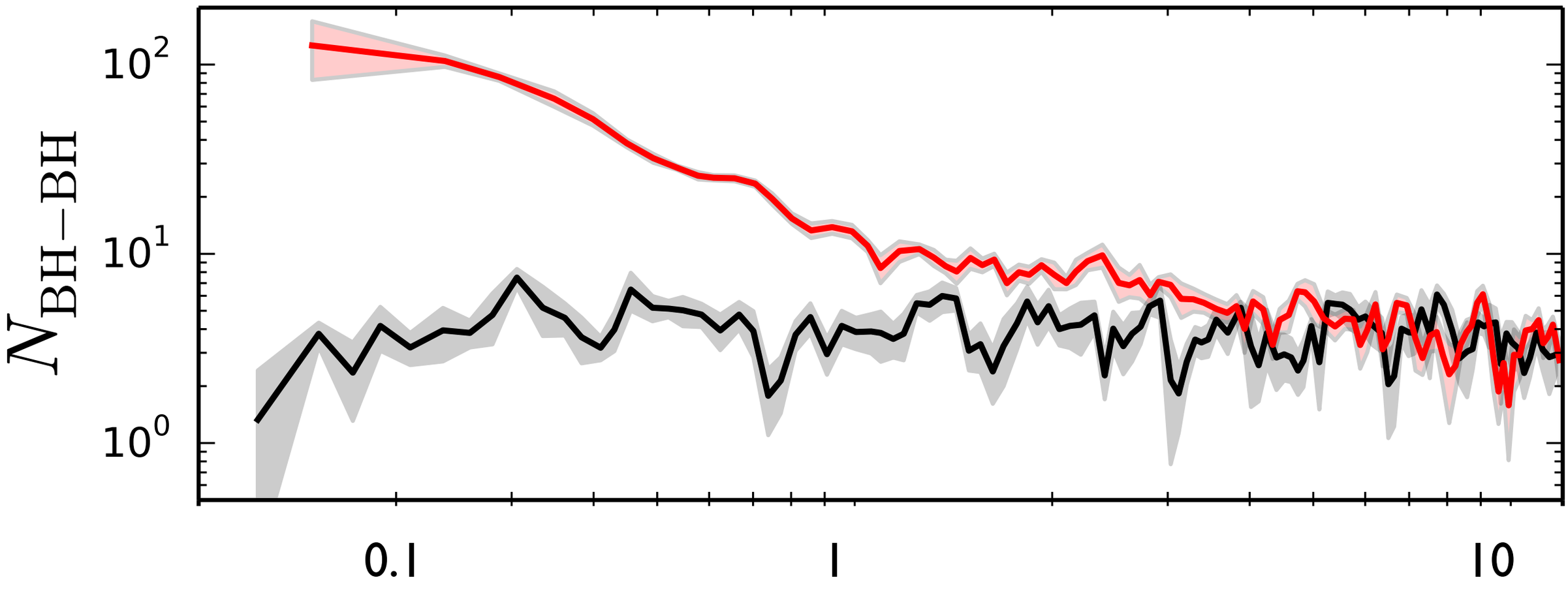
RoCRa-16, PRD

# Results Insensitive to Model Assumptions

## A key difference between dynamical and isolated formation channels

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

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




Chatterjee et al. 2016

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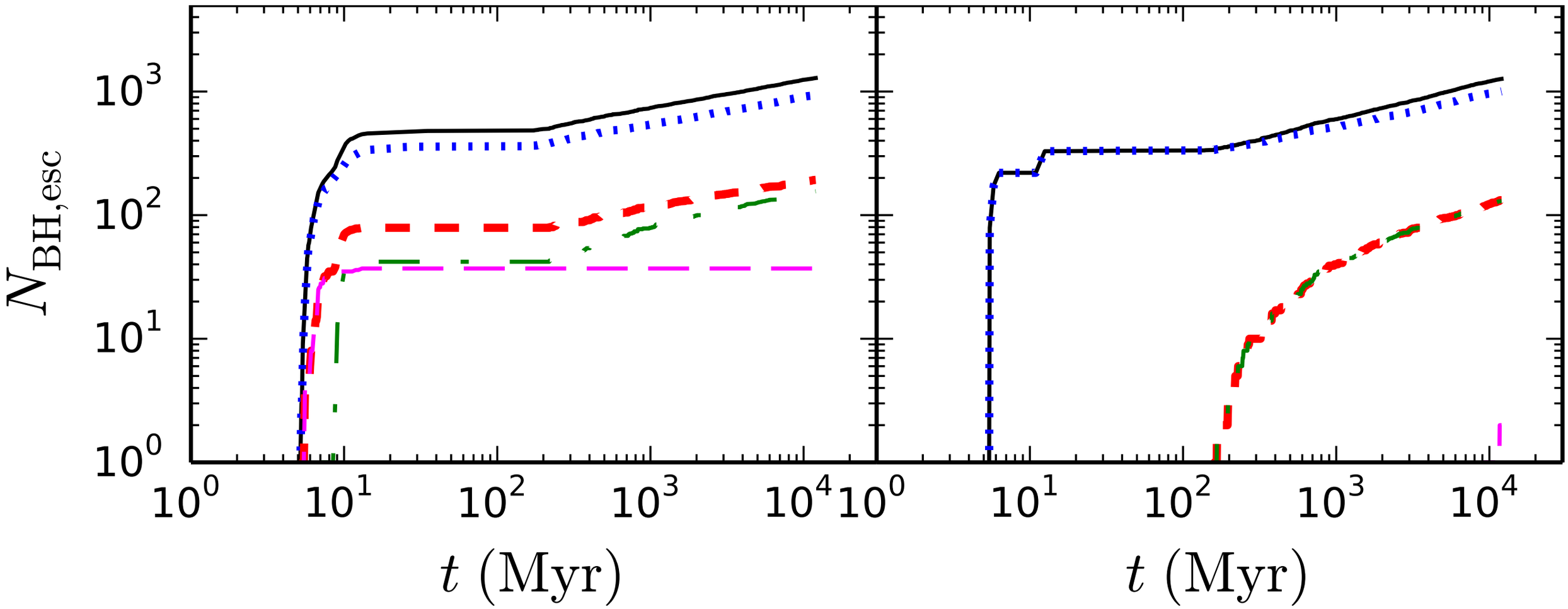
Chatterjee et al. 2016

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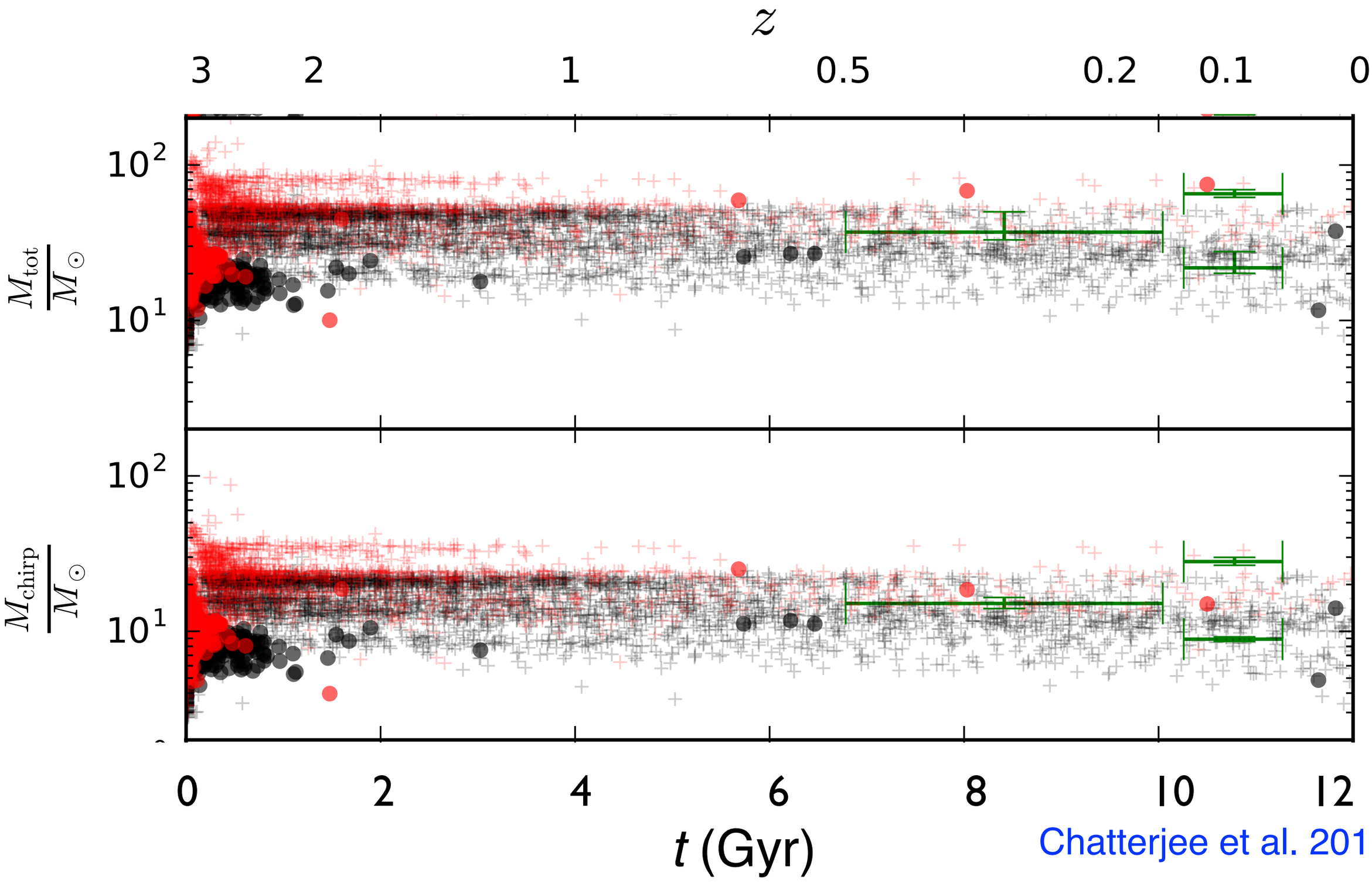
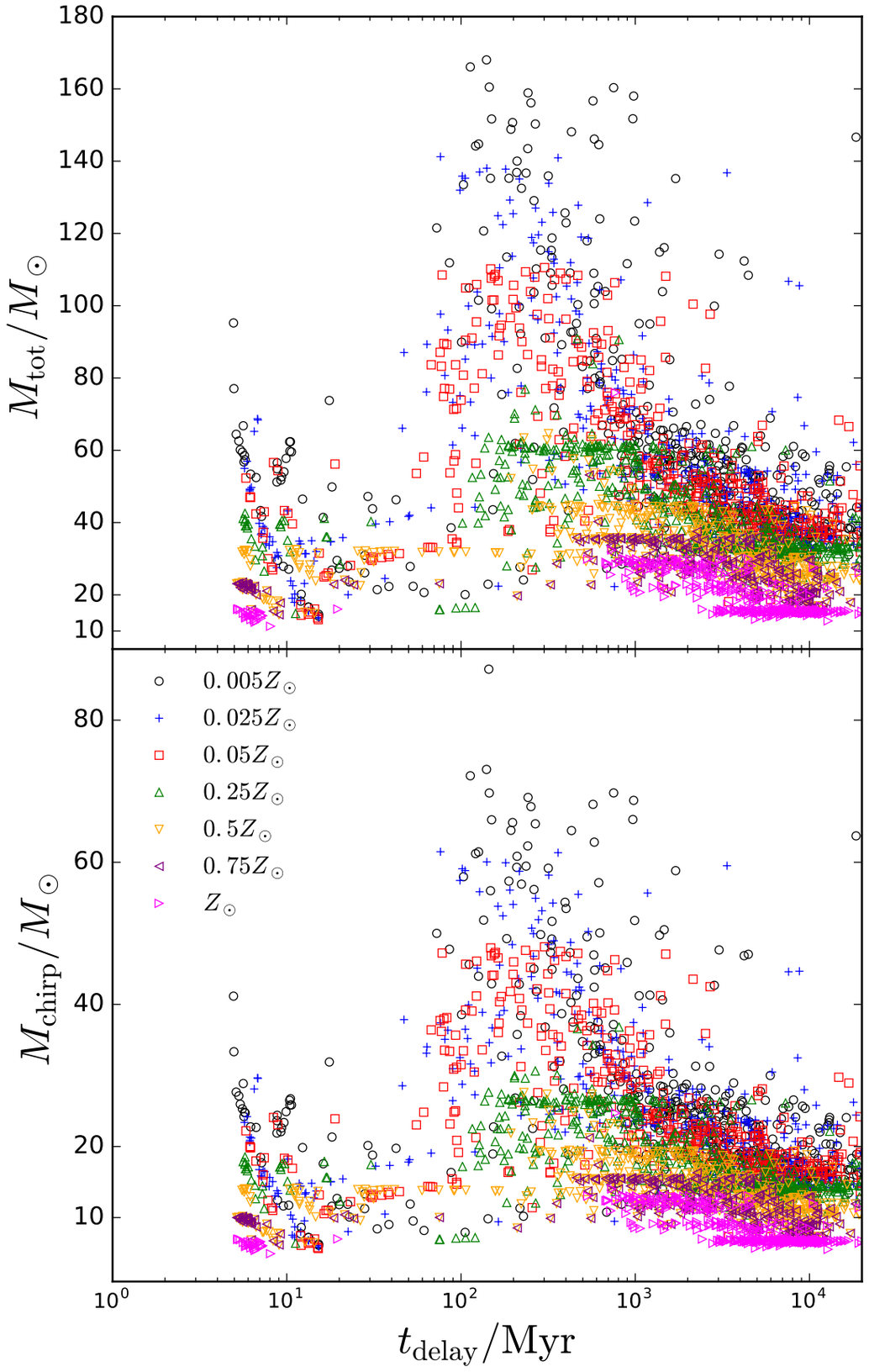



Chatterjee et al. 2016

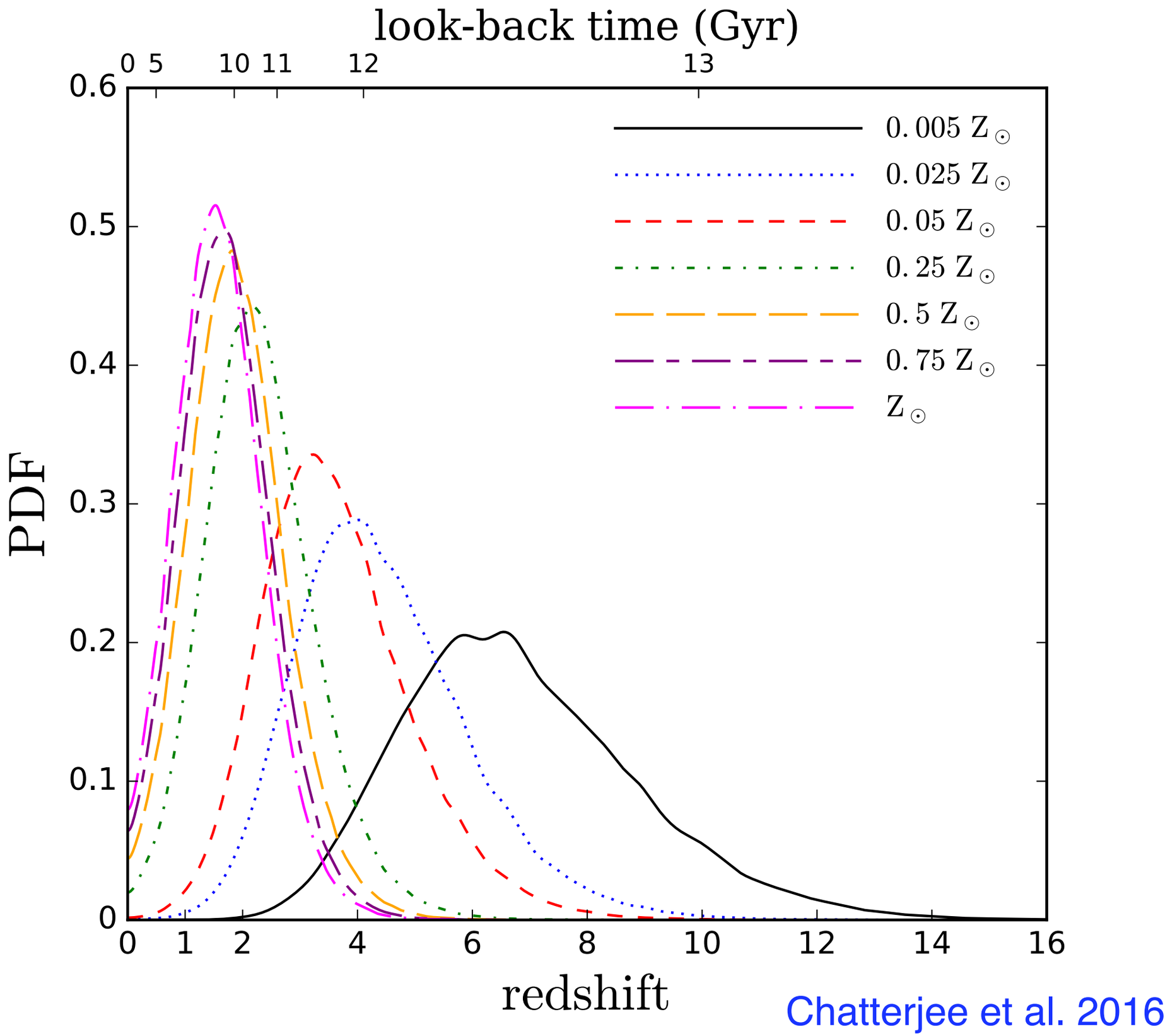
# Results Insensitive to Model Assumptions

## source of variations: metallicity and cluster age




Chatterjee et al. 2016

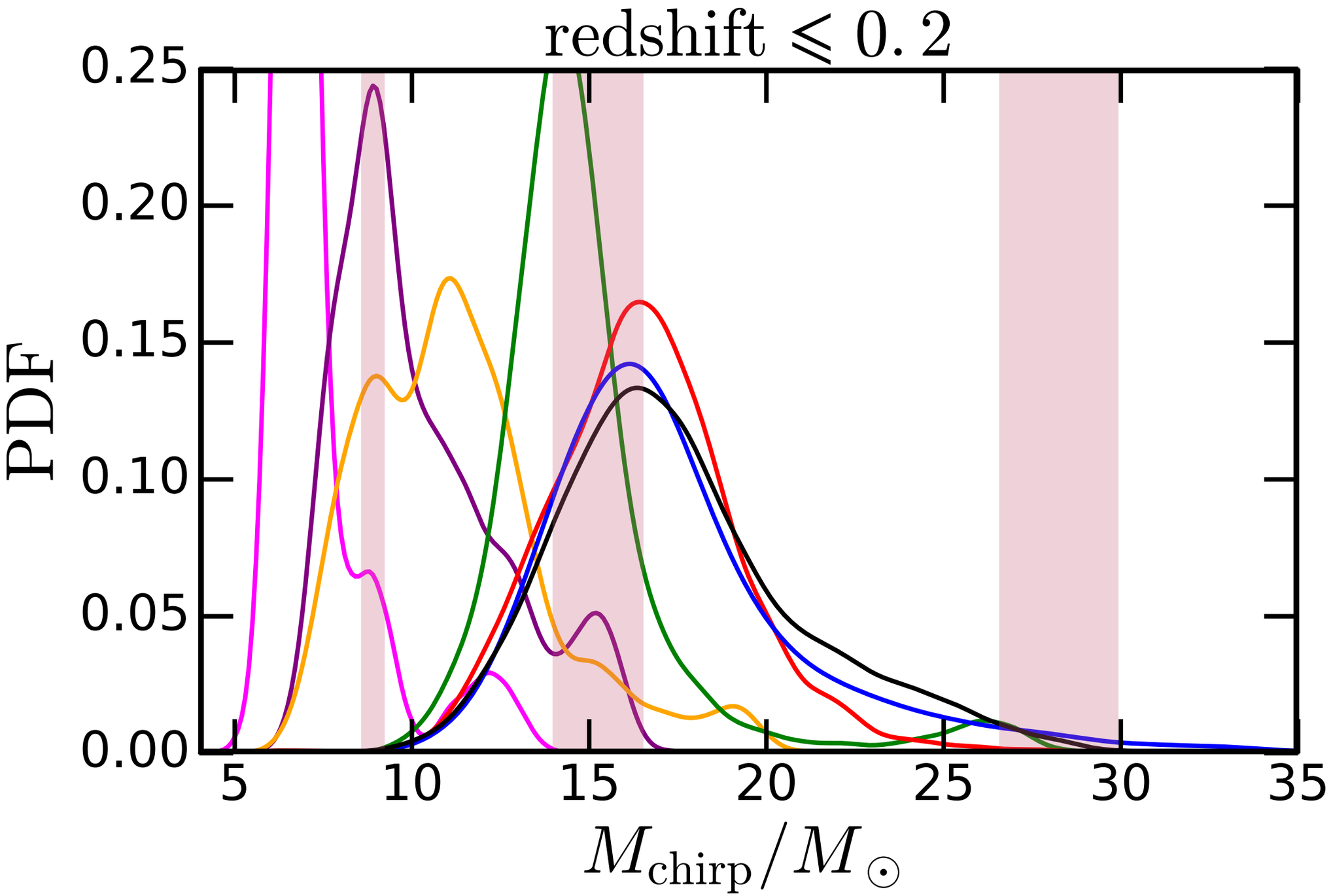
# Converting $t_{delay}$ to $z_{merger}$




Chatterjee et al. 2016

# BH-BH Merger Properties as LIGO source

## Masses




Chatterjee et al. 2016

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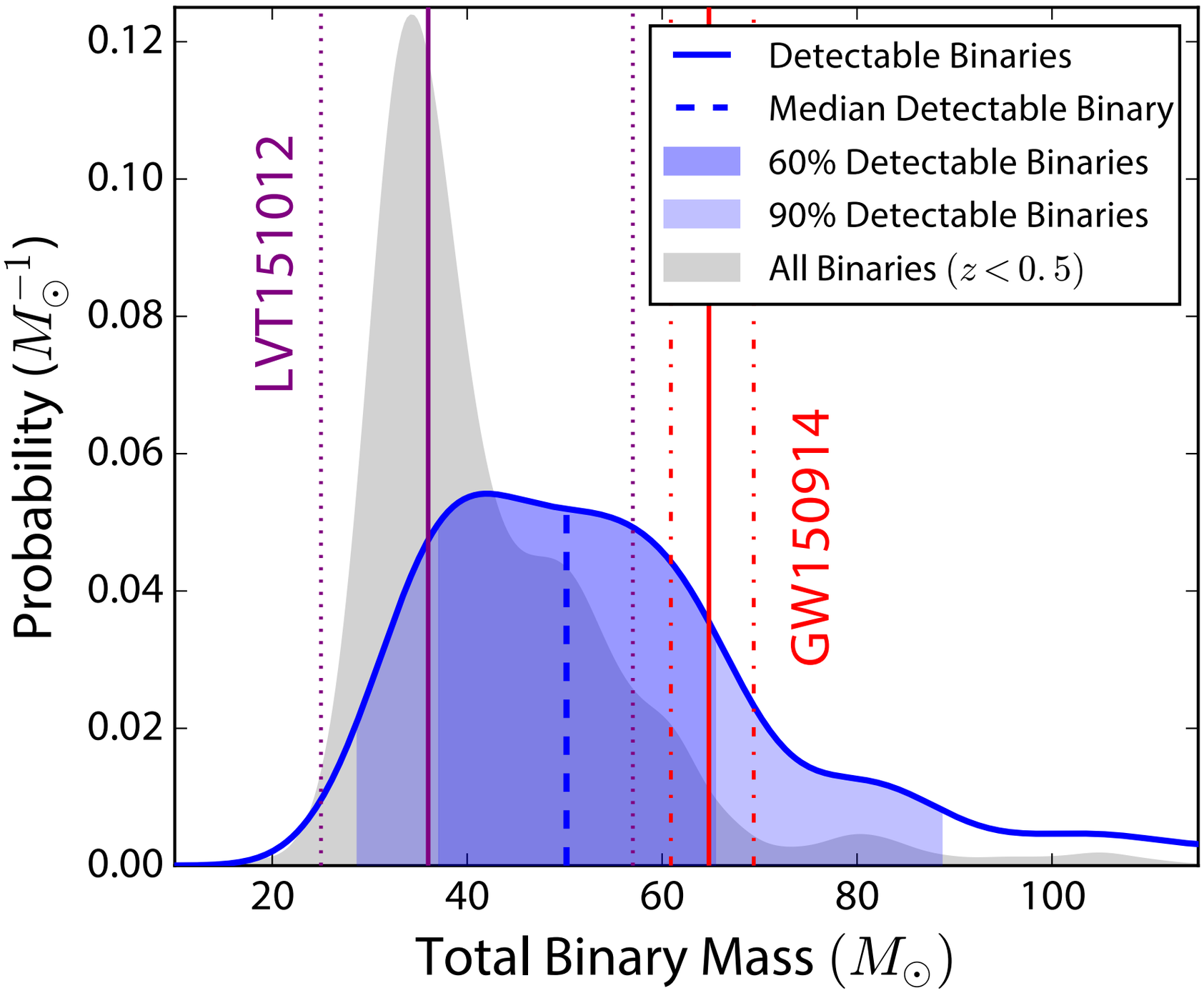
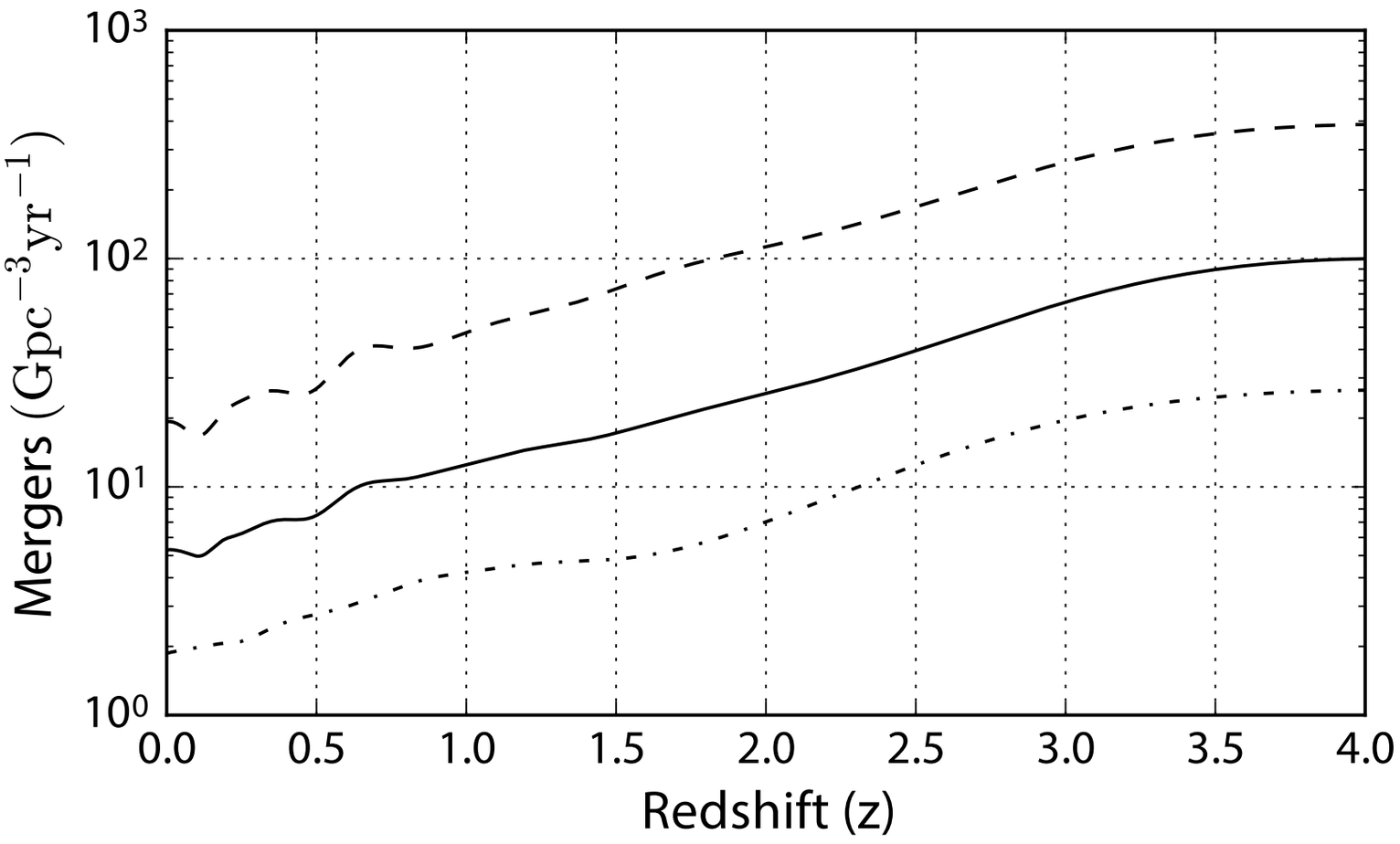



RoCjCRa16, ApJL

# BH-BH Merger Rates in aLIGO

| **Mergers** | **Pessimistic** | **Realistic** | **Optimistic** |
|---|---|---|---|
| O1 (Detections / 16 Days) | 0.05 | 0.2 | 0.7 |
| O1 (Detections / 50 Days) | 0.2 | 0.5 | 2 |
| O2 (Detections / Year) | 4 | 15 | 60 |
| Design Sensitivity (Detections / Year) | 30 | 100 | 400 |




$5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

RoCRa-16, PRD

# What's in the future on this topic?

- More detectors will lead to better sky localization (many planned, several under construction)
- Hundreds of detections
  - distributions of properties to constrain models

- How to uniquely identify the formation channel of a specific observed event
  - masses—not promising (e.g., CRoKRa-16,ApJL, submitted)
  - mass ratios—can have uncertainties (in prep)
  - eccentricities—needs LISA (e.g., Breivik et al. 2016; Chatterjee et al. 2016- ApJL, in press)
    - fortuitous discovery of high-e systems!!!
  - spins (promising, but hard to constrain observationally; e.g., Rodriguez et al. 2016, ApJL, submitted)
- Potential electro-magnetic counterparts??
- Ways to identify clusters hosting large numbers of undetected stellar BHs
- More interesting dynamically active stellar systems, e.g., nuclear clusters