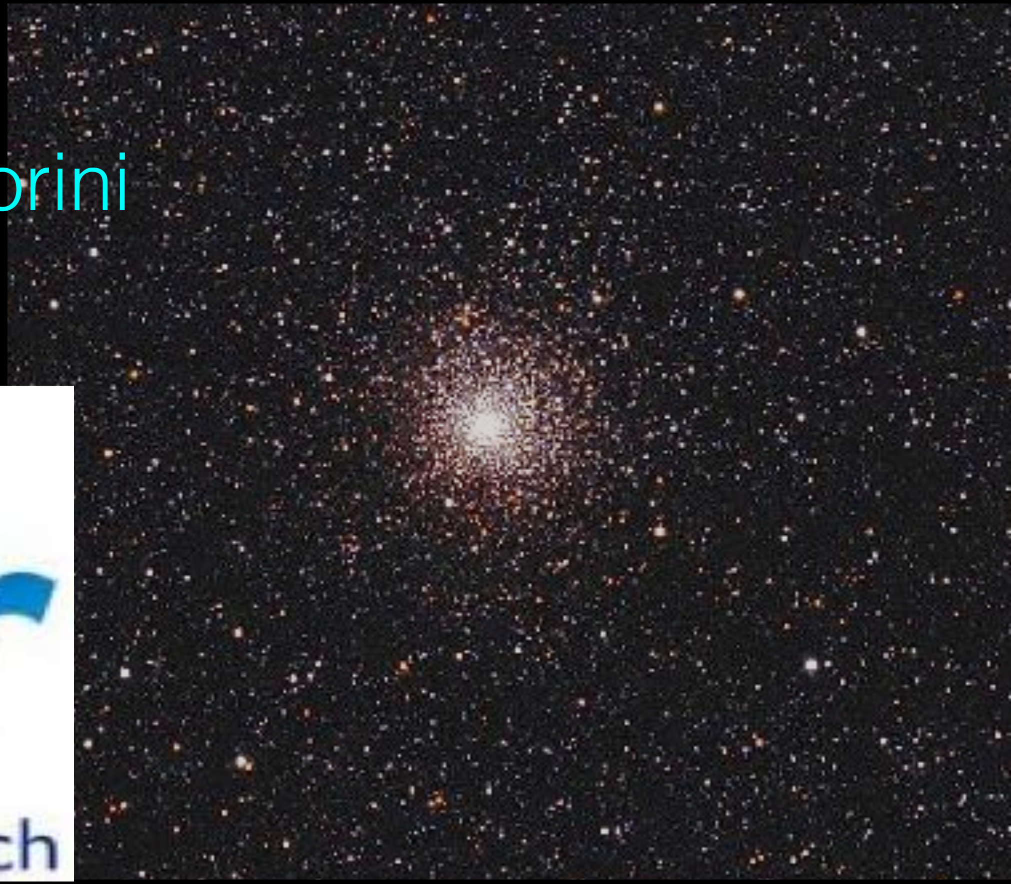
Monte Carlo Models of Dense Star Clusters

Sourav Chatterjee

MODEST 18, Firá, Santorini
June 26, 2018

tata institute of fundamental research



Hénon-type Monte Carlo

N-body model

spread all masses in spherical shells (E, J)

approximate the total effects of many weak
fly-bys by a super encounter between neighbors

update E, J; calculate new orbits

Monte Carlo new positions and
velocities in these orbits to get back new N-body model

add physics (e.g., strong scattering, stellar evolution, tides, etc.)

2-body relaxation

Hénon-type Monte Carlo

N-body model

spread all masses in spherical shells (E, J)

Mon. Not. R. Astron. Soc. **000**, 1–10 (2002) Printed 24 November 2014 (MN LaTeX style file v2.2)

Michel Hénon’s contributions to collisional stellar systems

Douglas C. Heggie[1]

[1] *University of Edinburgh, School of Mathematics and Maxwell Institute for Mathematical Sciences, King’s Buildings, Edinburgh EH9 3JZ, UK; d.c.heggie@ed.ac.uk*

24 November 2014

velocities in these orbits to get back new N-body model

add physics (e.g., strong scattering, stellar evolution, tides, etc.)

World's Only DMP Parallel Monte Carlo Code
CMC

- 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)
- Parallelized using MPI & CUDA (Pattabiraman et al. 2012)
- Rate-based 3-Body binary formation (Morscher et al. 2015)
- Up to 2.5 PN GR effects for all strong encounters (Rodriguez et al. 2018; Antognini et al. 2014; Amaro-Seoane et al. 2016)

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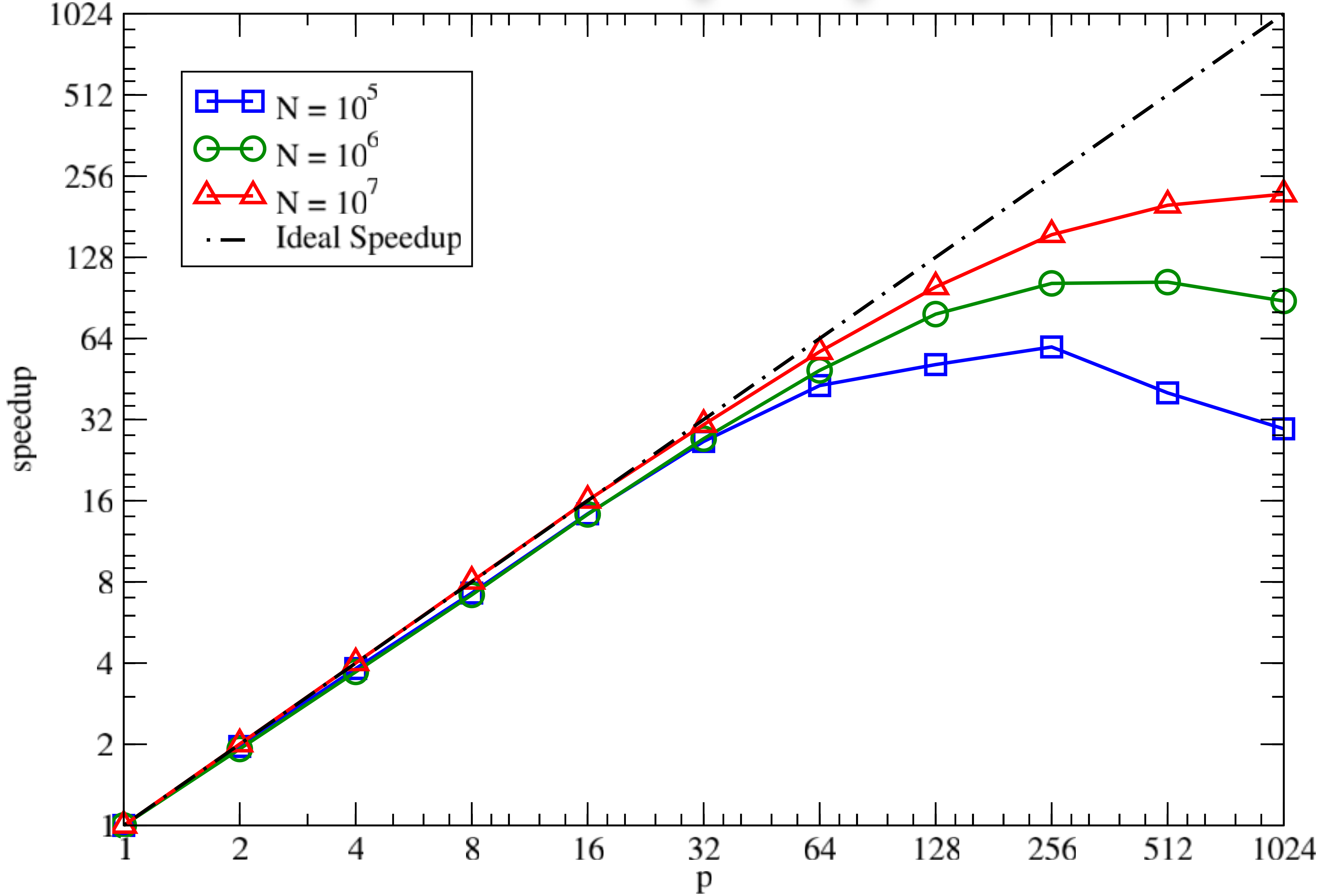
Performance of Parallel CMC

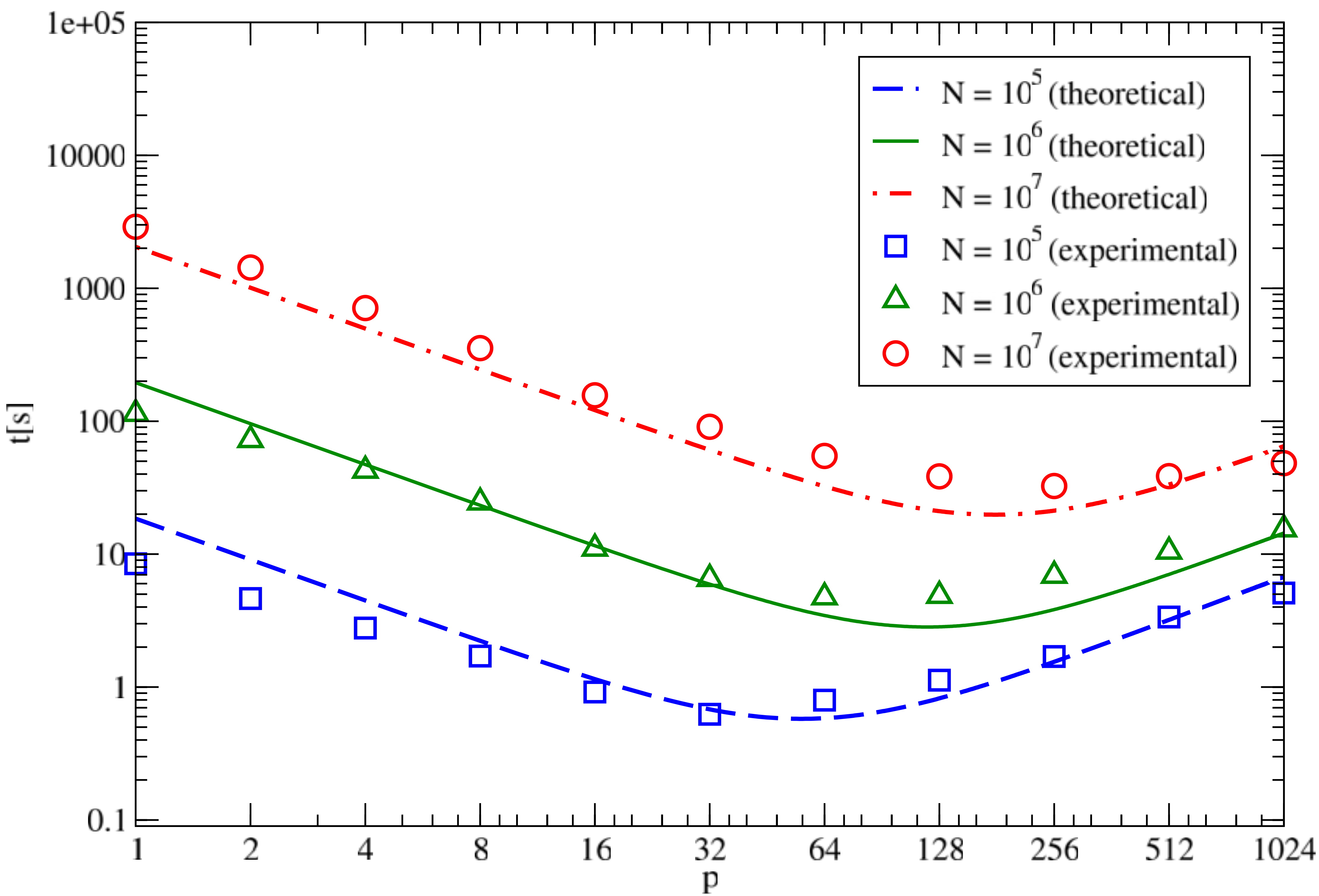
Overall Speedup



Pattabiraman et al. 2013

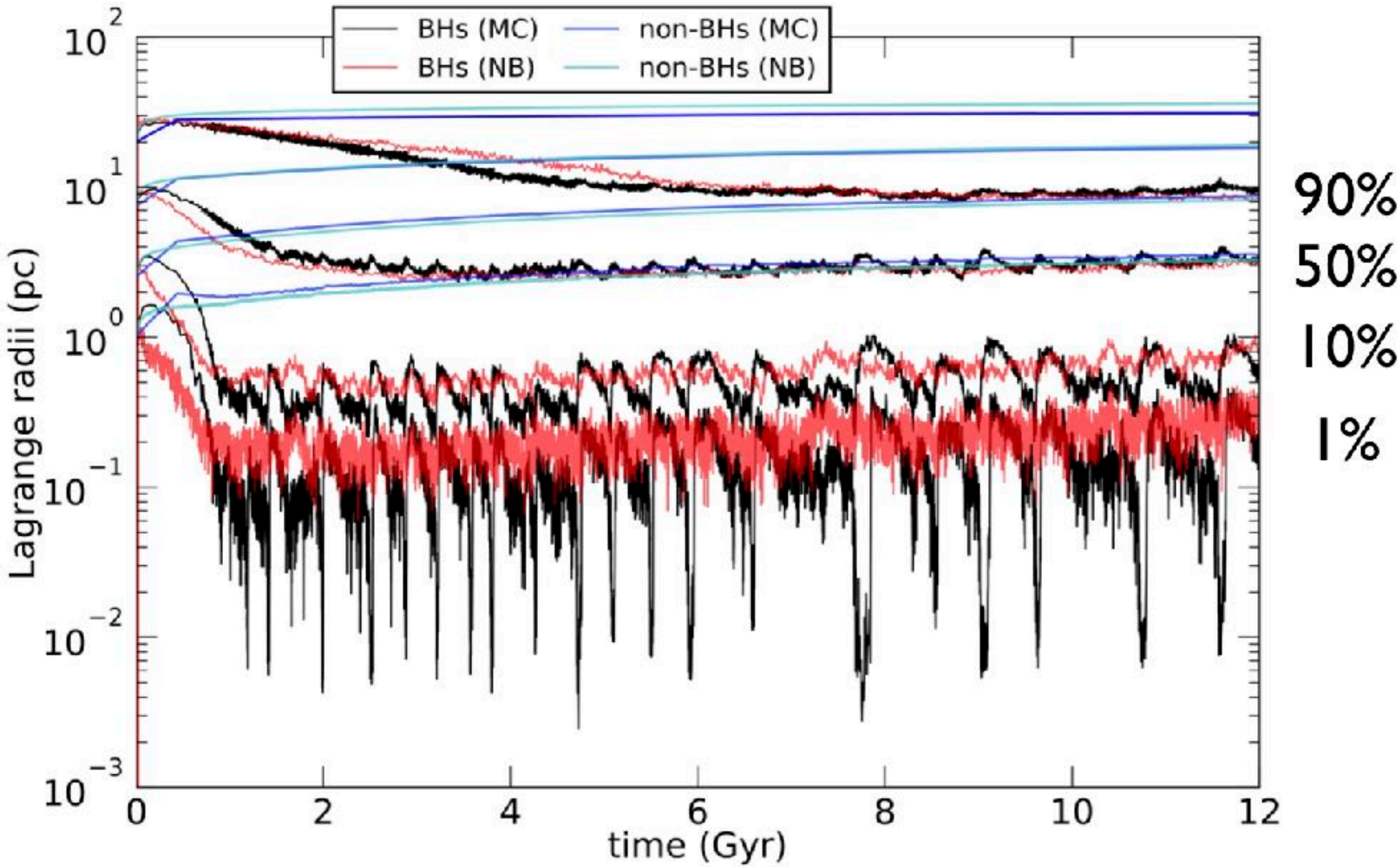
Performance of Parallel CMC

Speedup for the Sorting Module



Pattabiraman et al. 2013

Comparison to Direct *N*-body (Dragon) Results



Rodriguez et al. 2016

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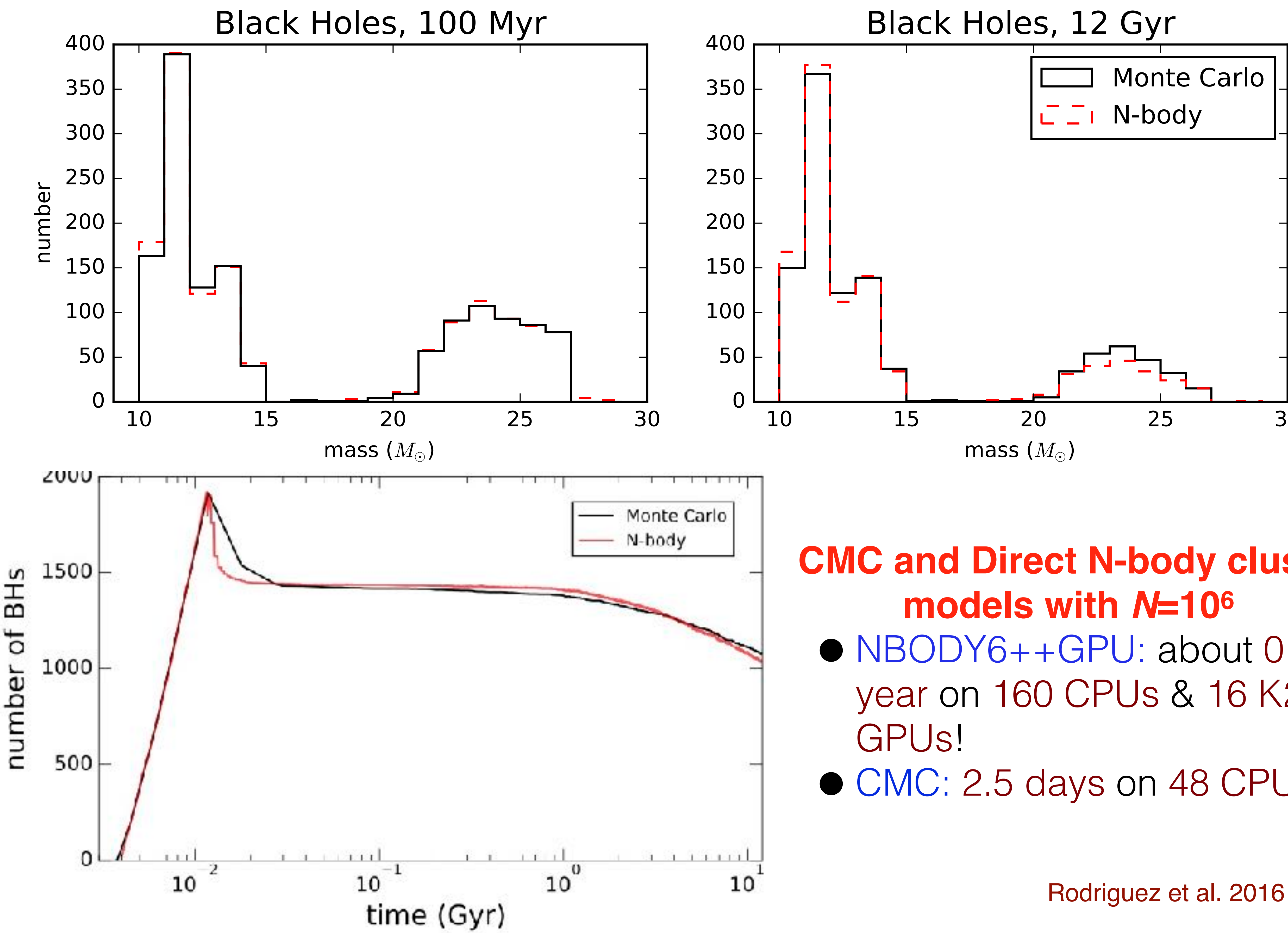

CMC and Direct N-body cluster models with *N*=10^6

- NBODY6++GPU: about 0.5 year on 160 CPUs & 16 K20m GPUs!
- CMC: 2.5 days on 48 CPUs

Rodriguez et al. 2016

Research Highlights Using CMC

In the era of GAIA, LIGO, & LISA

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

Research Highlights Using CMC

In the era of GAIA, LIGO, & LISA

- 8 journal papers using CMC results since MODEST 17
  - Clusters affecting production of stellar exotica: E.g., merging BBHs, BH XRBs, LISA sources from GCs, MSPs, Subsubgiants, Blue Stragglers
  - Compact remnants affecting clusters: E.g., effects of BH retention on cluster's observable and dynamical properties, ways to detect BH retention

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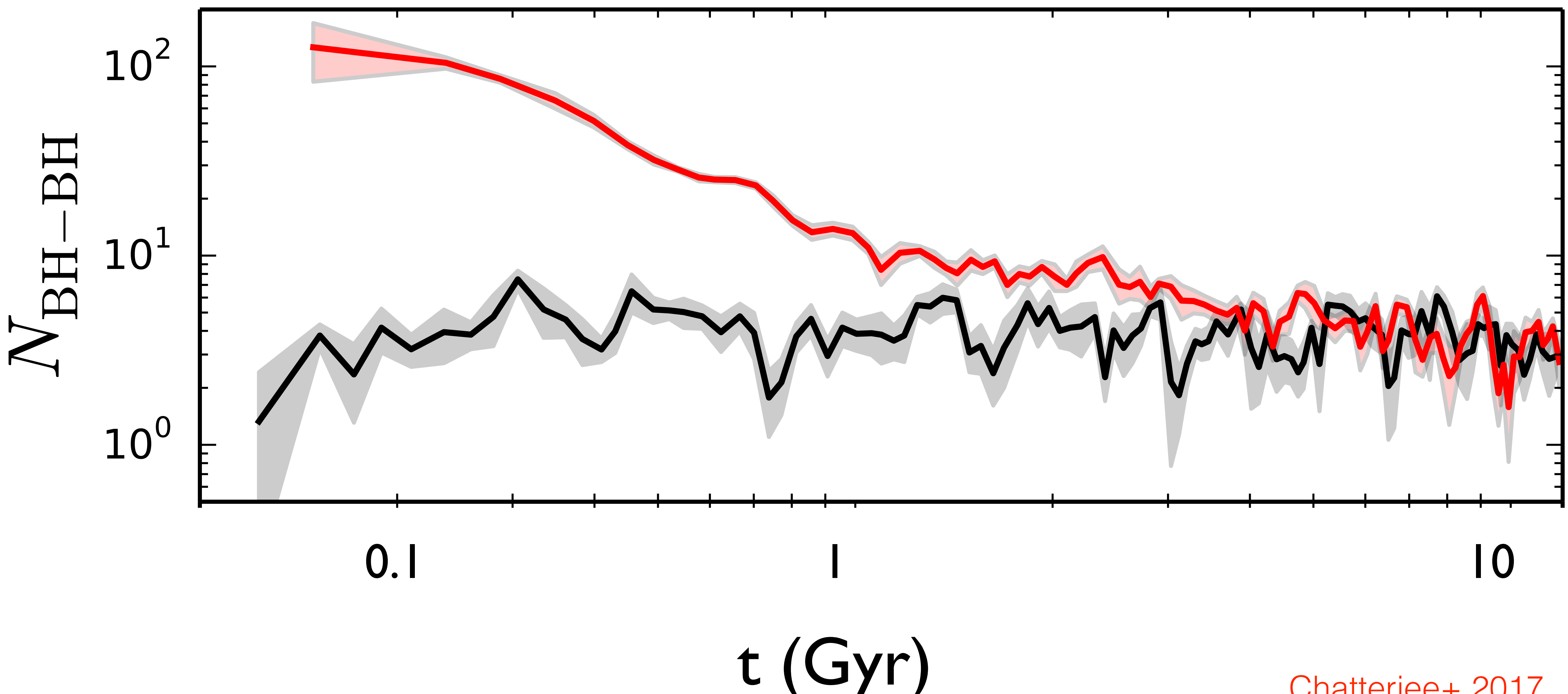
- Critically question 'standard assumptions:'
  - E.g., Assumptions on BH natal kicks, initial binary properties, IMF, etc.
  - Metallicities and formation redshifts of massive clusters

Results Insensitive to Model Assumptions

BH-BH binaries in the cluster

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

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

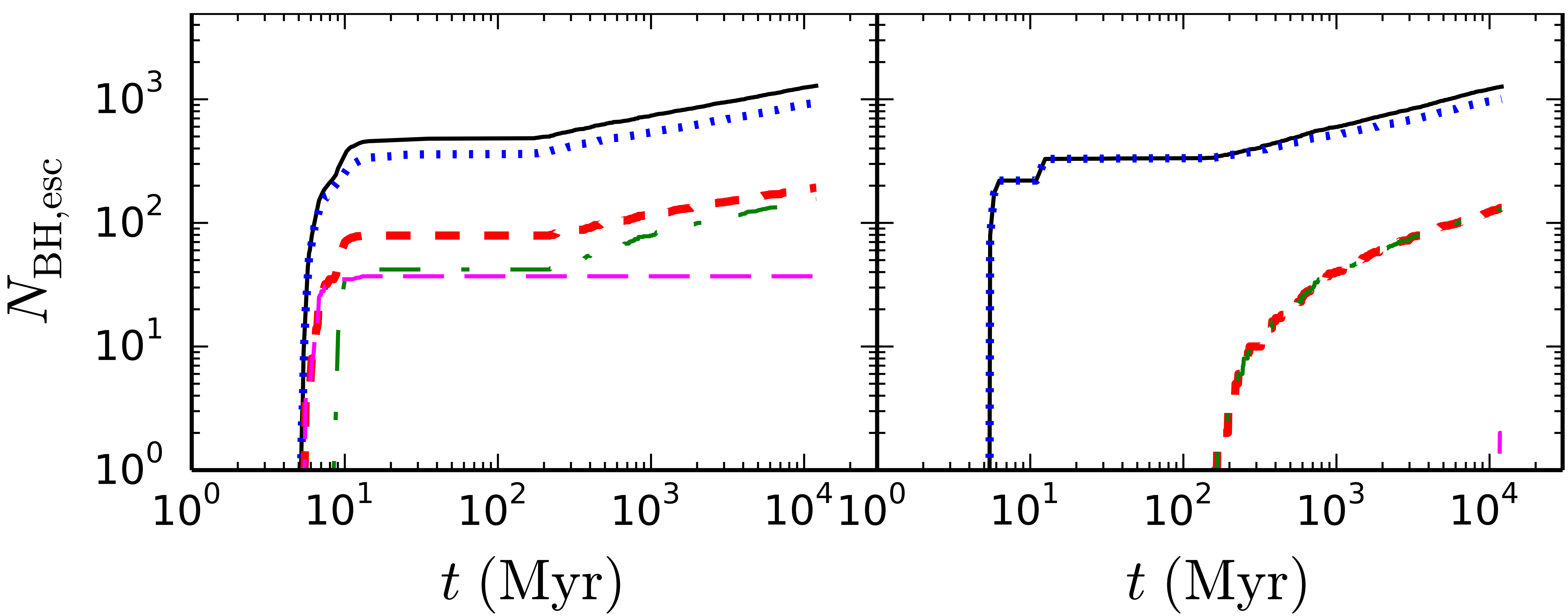


Chatterjee+ 2017

Results Insensitive to Model Assumptions

Escaped BH-BH binaries

Chatterjee+ 2017



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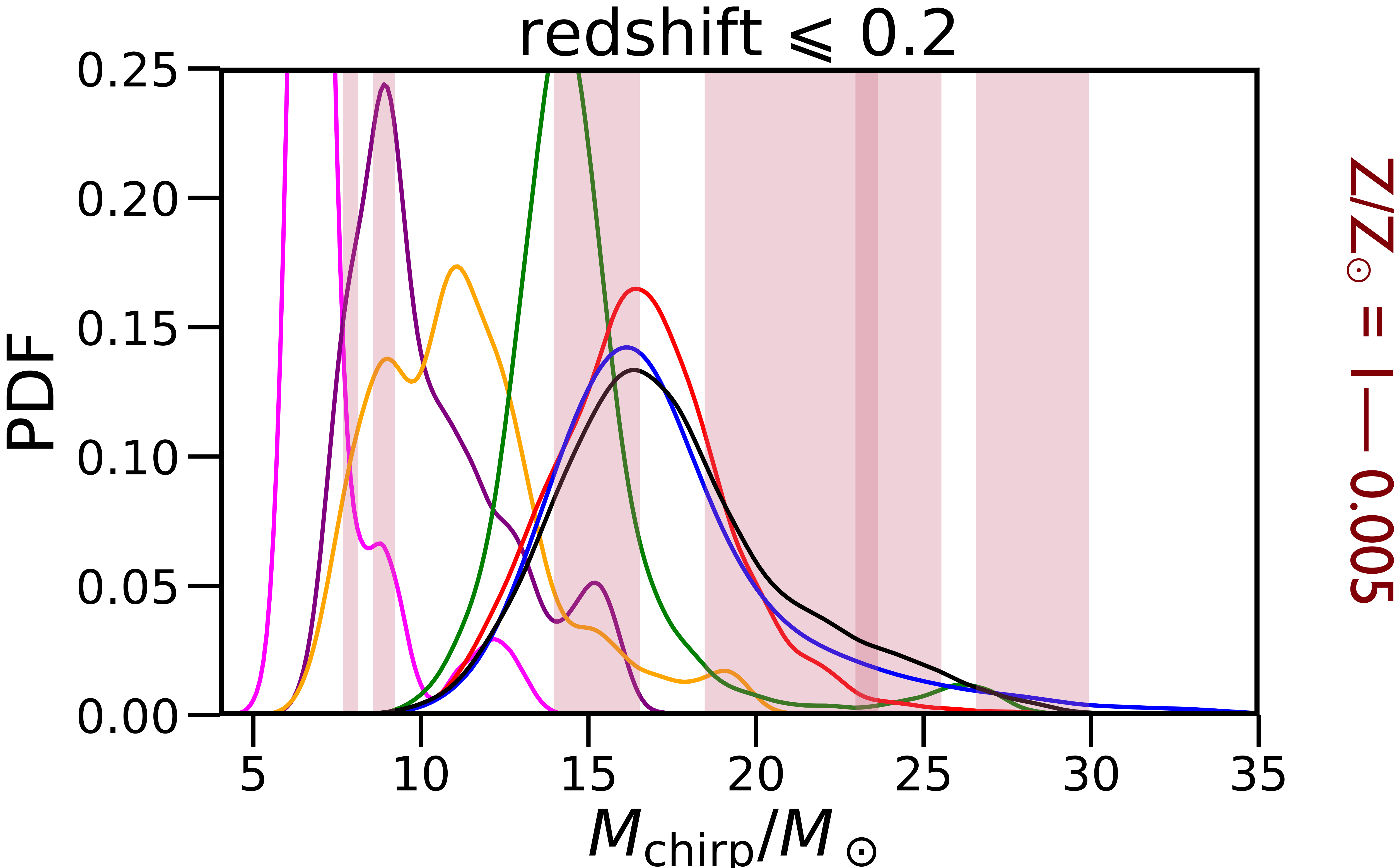
BH-BH Merger Properties as LIGO source

Masses



Chatterjee et al. 2017

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  - Metallicities and formation redshifts of massive clusters
- Biggest source of uncertainty is from BH formation physics
  - Deviced ways to detect BH retention in today's GCs
  - More BH observations needed to get meaningful constraints

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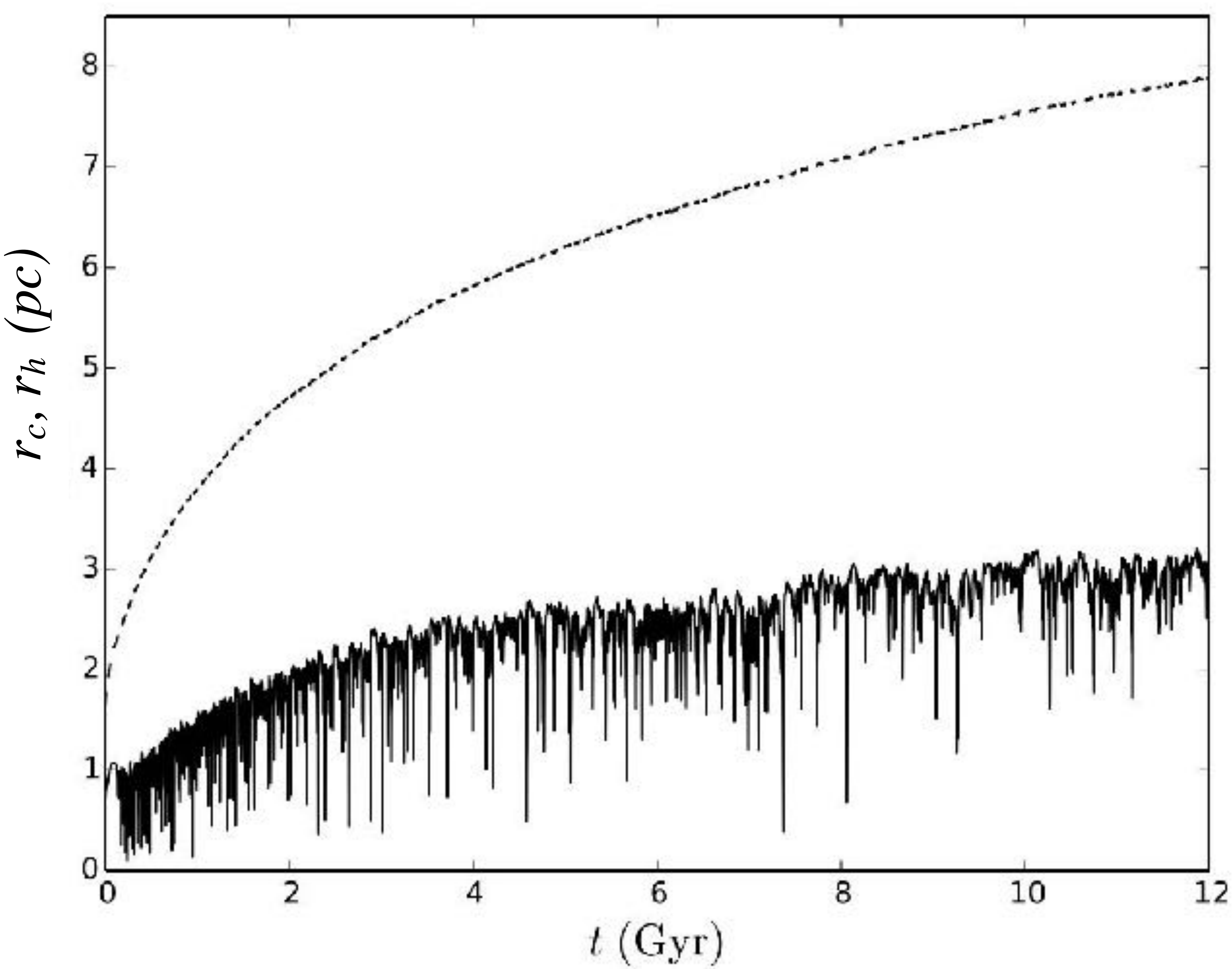
Challenges in Measuring BH Retention



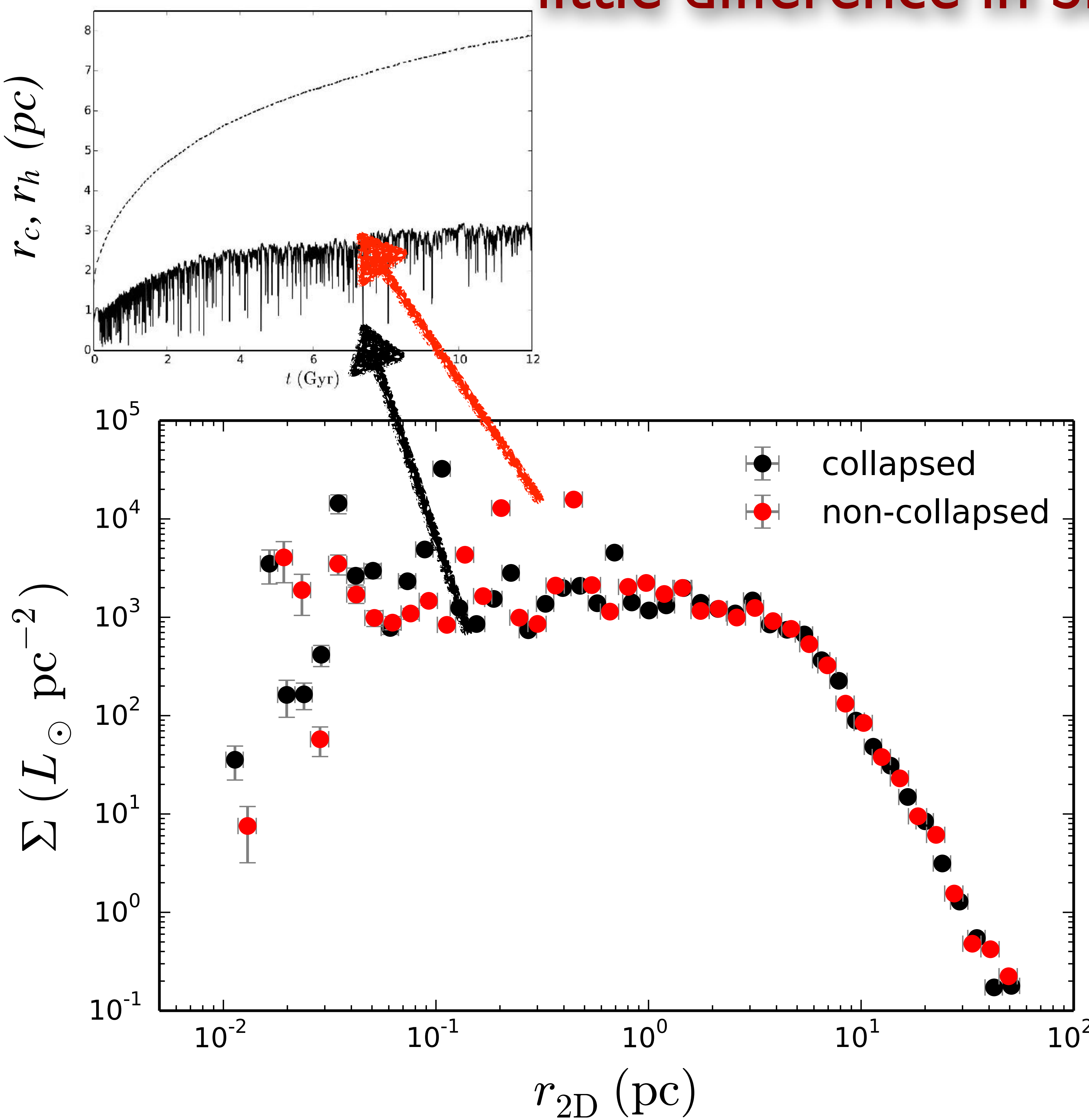
Repeated BH-driven collapse

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

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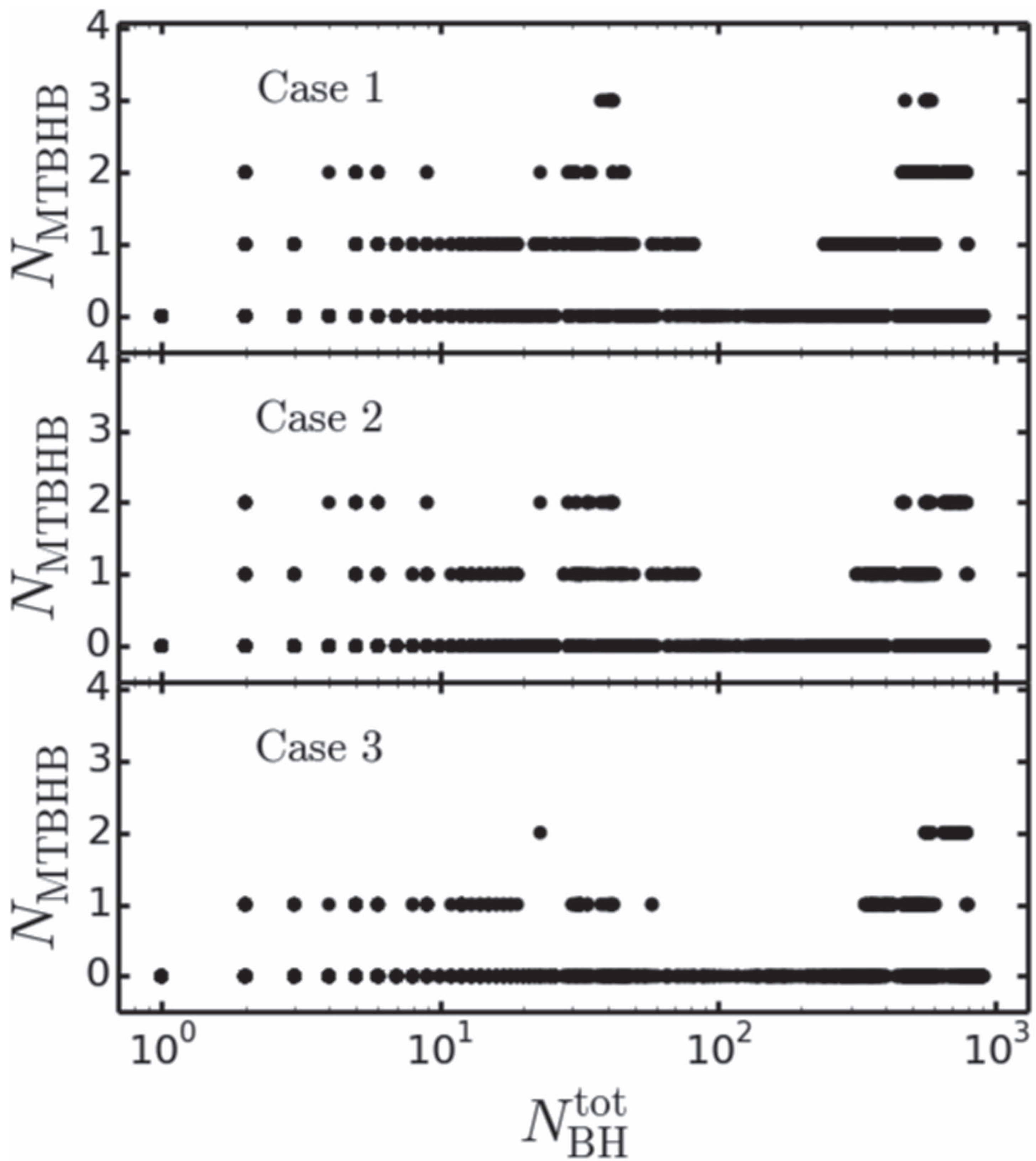
Challenges in Measuring BH Retention

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



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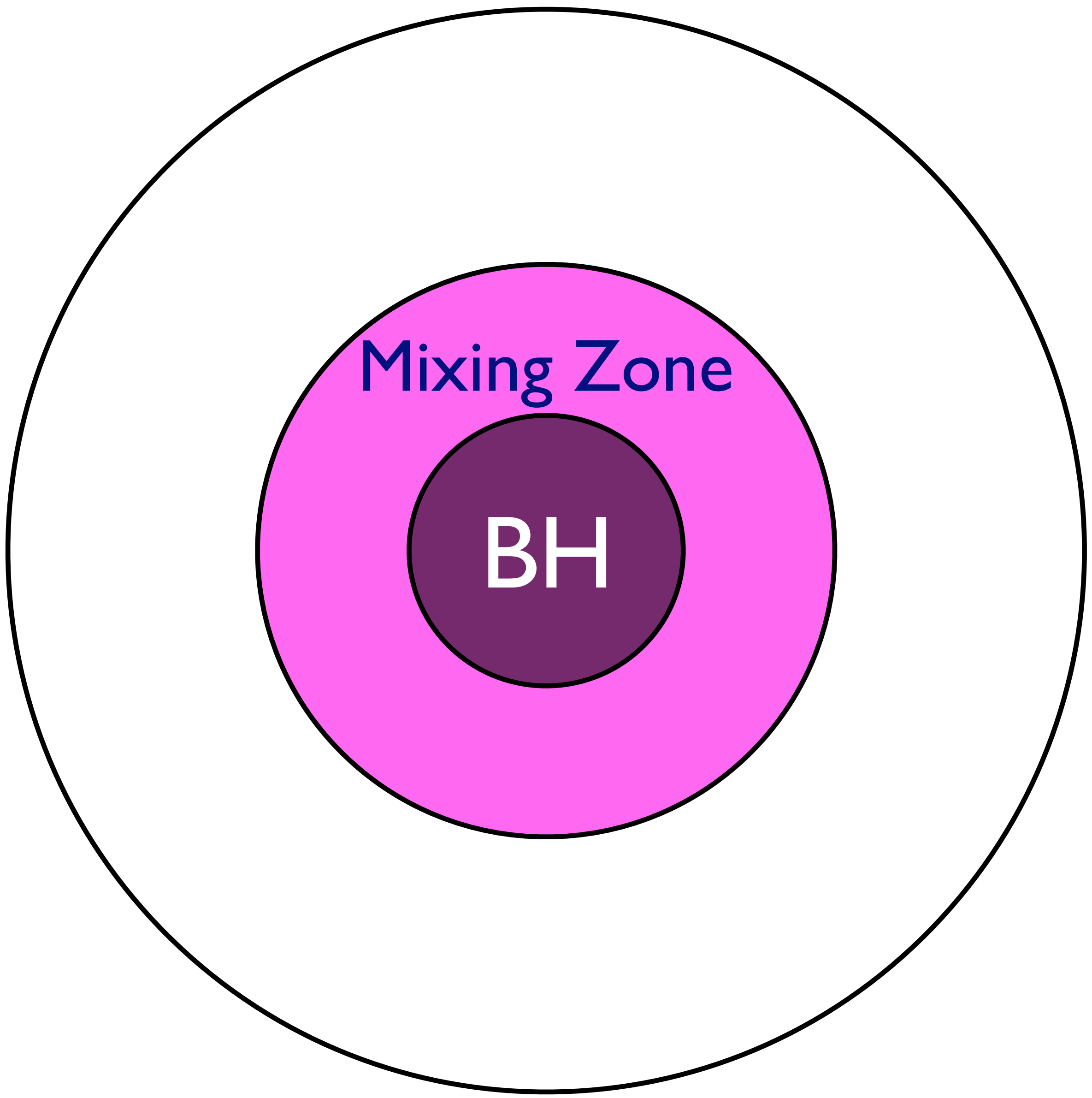
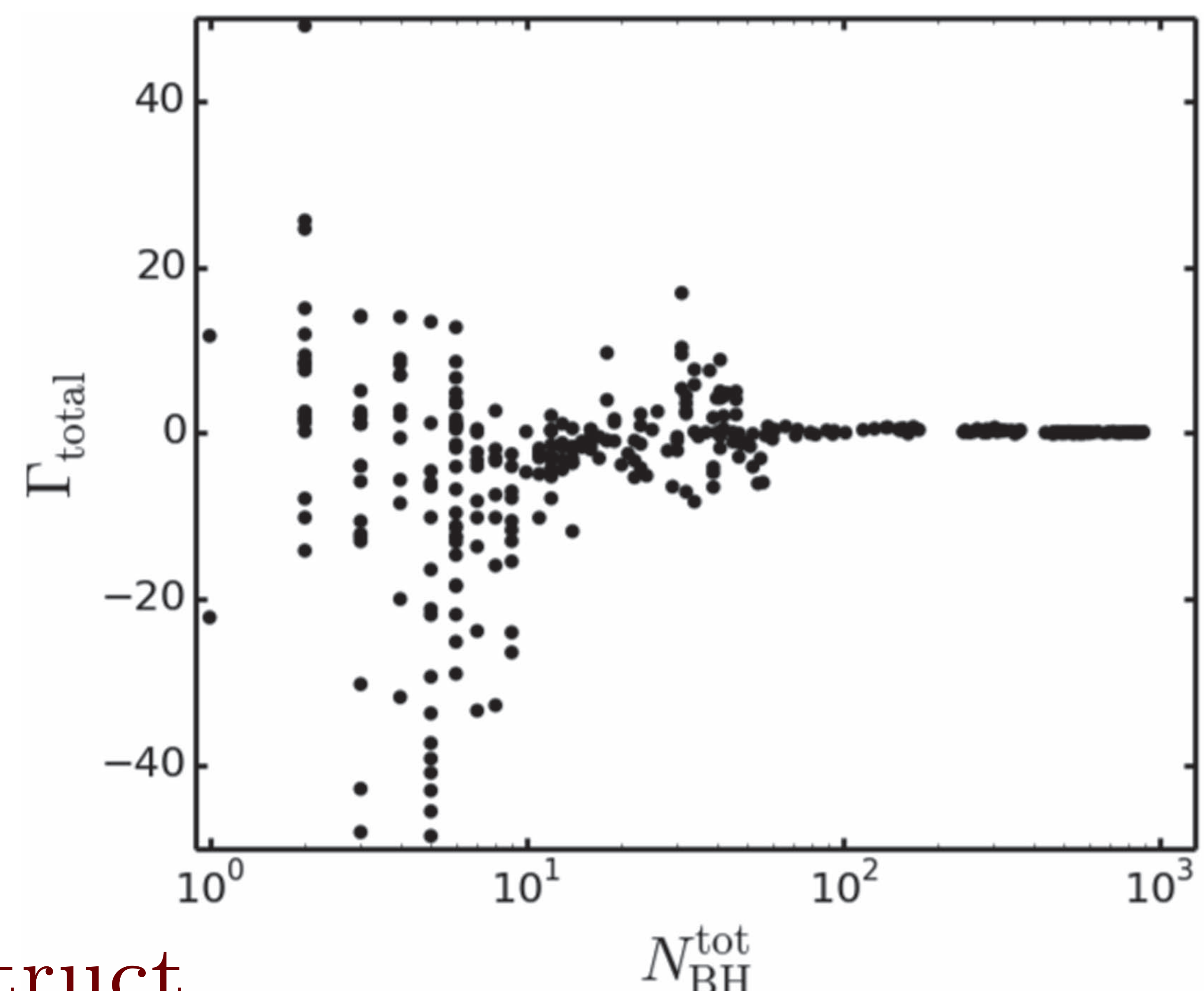
Challenges in Measuring BH Retention

no correlation between N_{BH} and $N_{\mathrm{BH\text{-}nonBH}}$

N_{BH} ρ_{MZ}



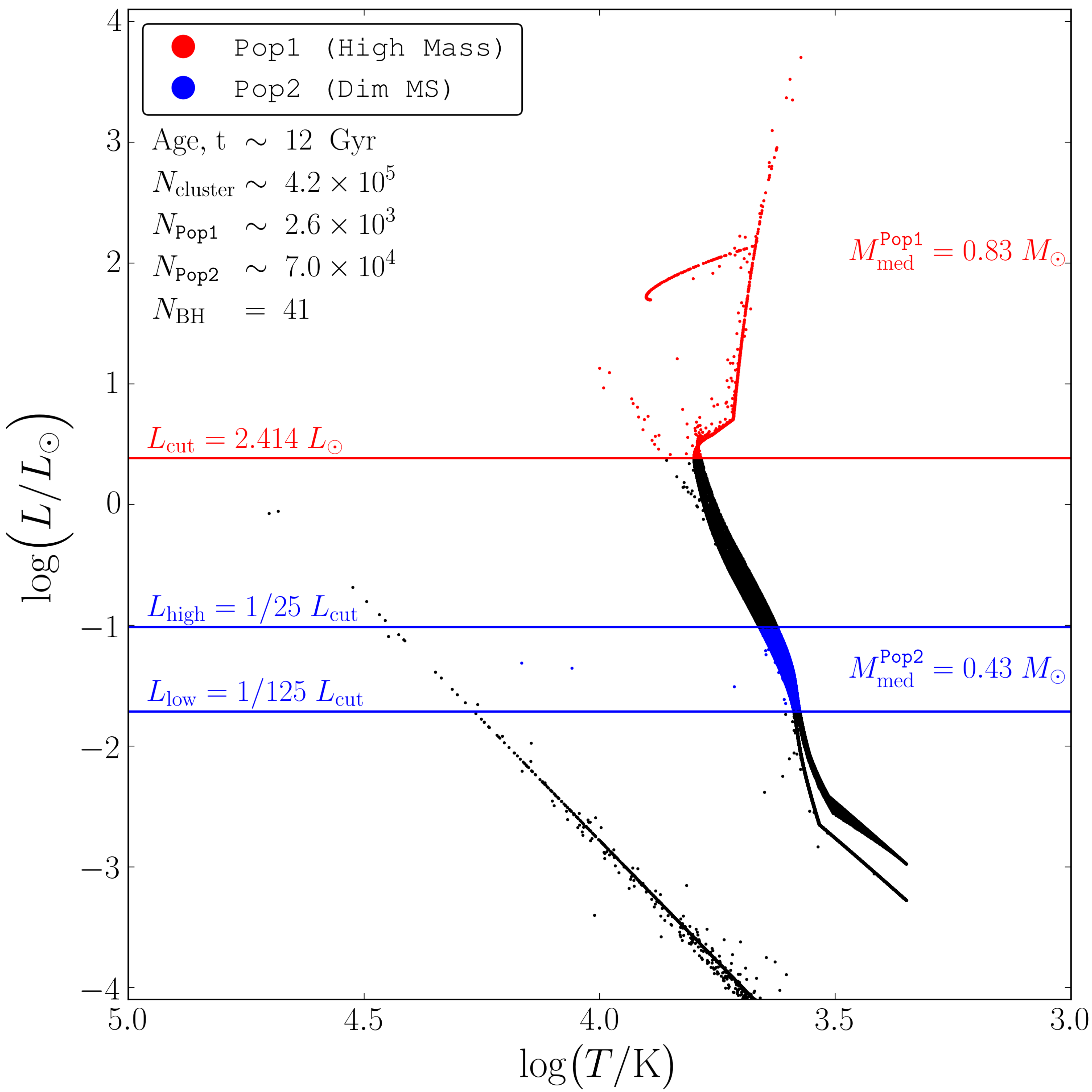


$$\Gamma_{\mathrm{total}} \equiv \Gamma_{\mathrm{form}} - \Gamma_{\mathrm{destruct}}$$

Kremer+ 2018

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 and incompleteness differences

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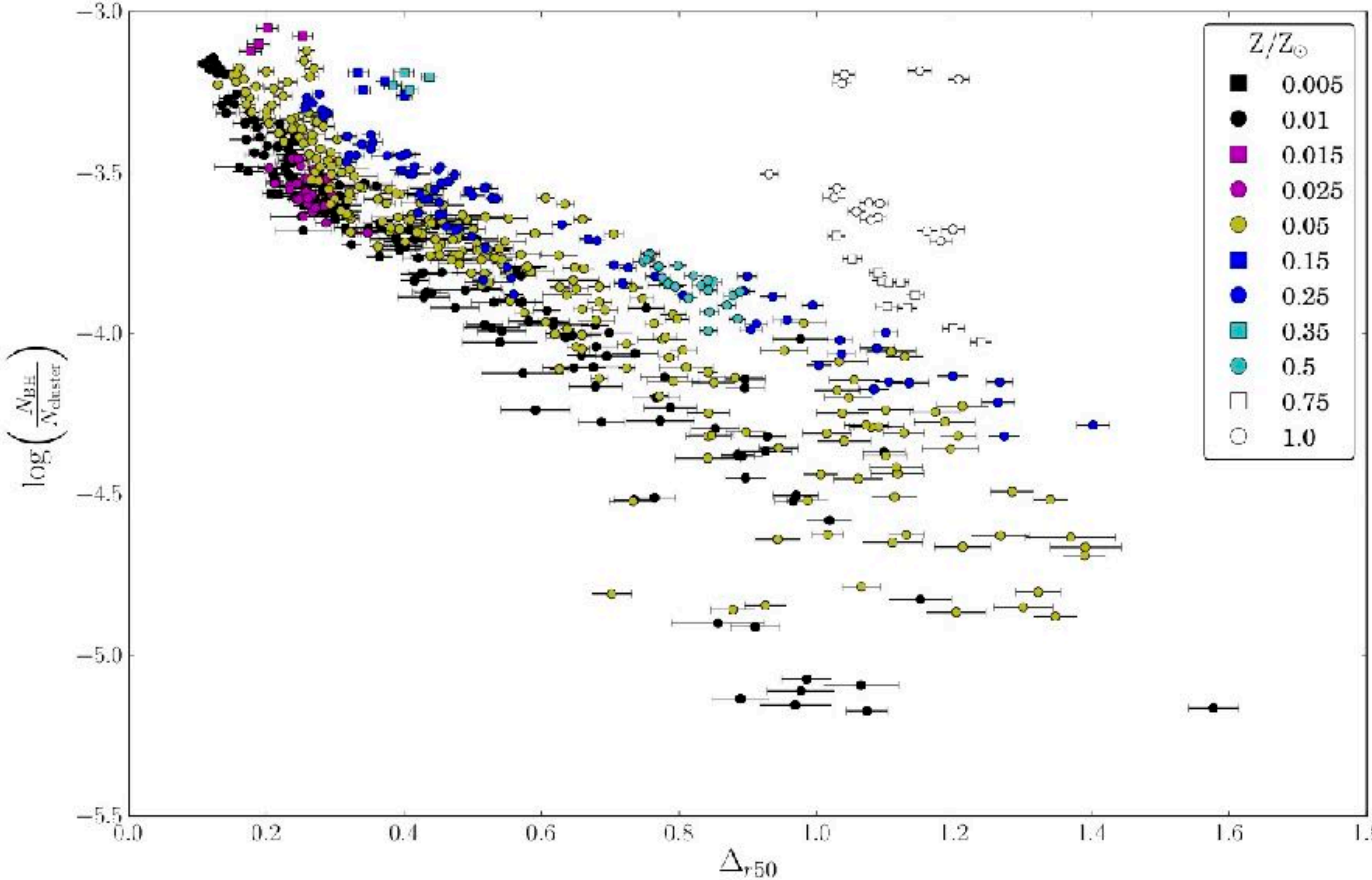
Strong Anticorrelation:

Δ vs N_{BH}



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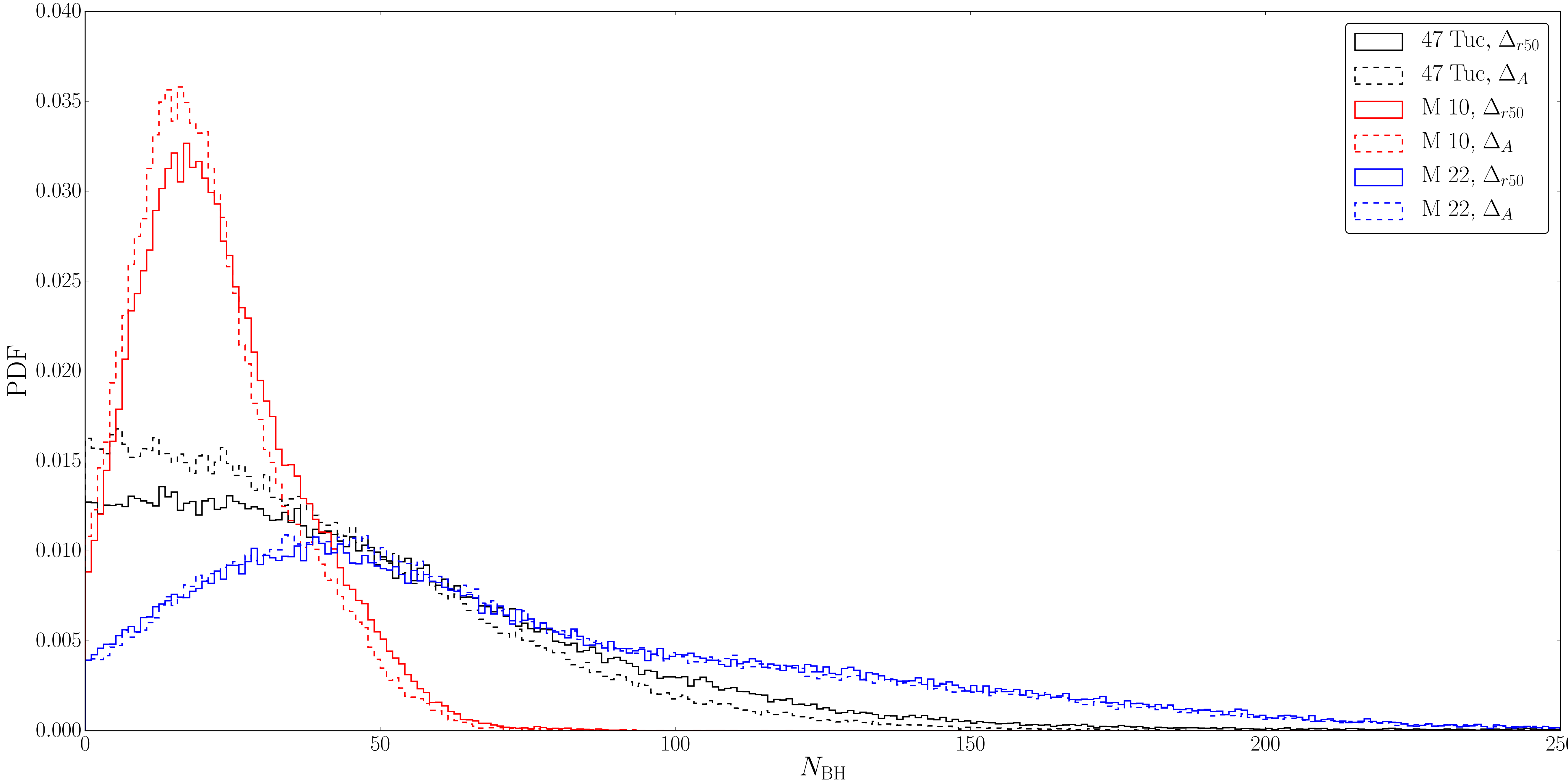
Strong Anticorrelation:

Inferred N_{BH} from measured Δ



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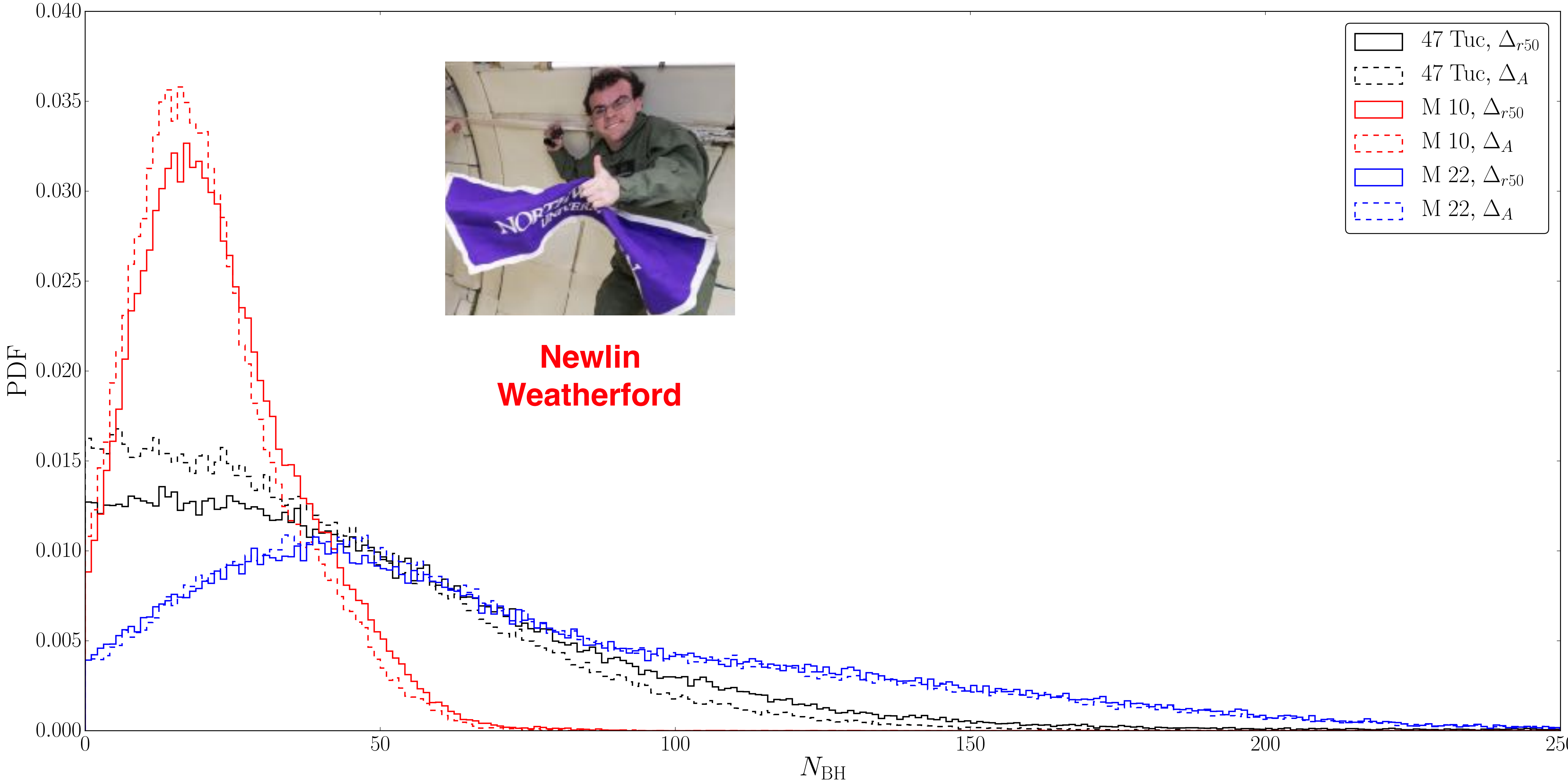

Newlin Weatherford

Weatherford+ 2017

Upcoming Improvements to CMC

- We are now getting ready to create a grid of simulations using up to PN 2.5 terms and all code improvements (~ few months)
  - State-of-the-art prescriptions for BHs, e.g., fallback modulated natal kicks, delayed supernova, Z-dependent maximum BH mass, etc.

- Addition of octuple-order effects from hierarchical triples (~ this year)
  - Effects are expected to be small, but strange systems may form

Other Talks & Posters Using CMC

In the era of GAIA, LIGO, & LISA

Talks

Carl Rodriguez

Wed. Evening
PN effects & Repeated BBH Mergers in GCs

Kyle Kremer

Wed. Morning
BHs shaping the fate & properties of GCs

Katie Breivik

Wed. Evening
LISA sources in GCs

Claire (Shi) Ye

Thu. Morning
Modeling MSPs in GCs

Posters

Newlin Weatherford

Predicting stellar-mass BH populations in GCs

Katie Breivik

Revealing BH binaries with GAIA