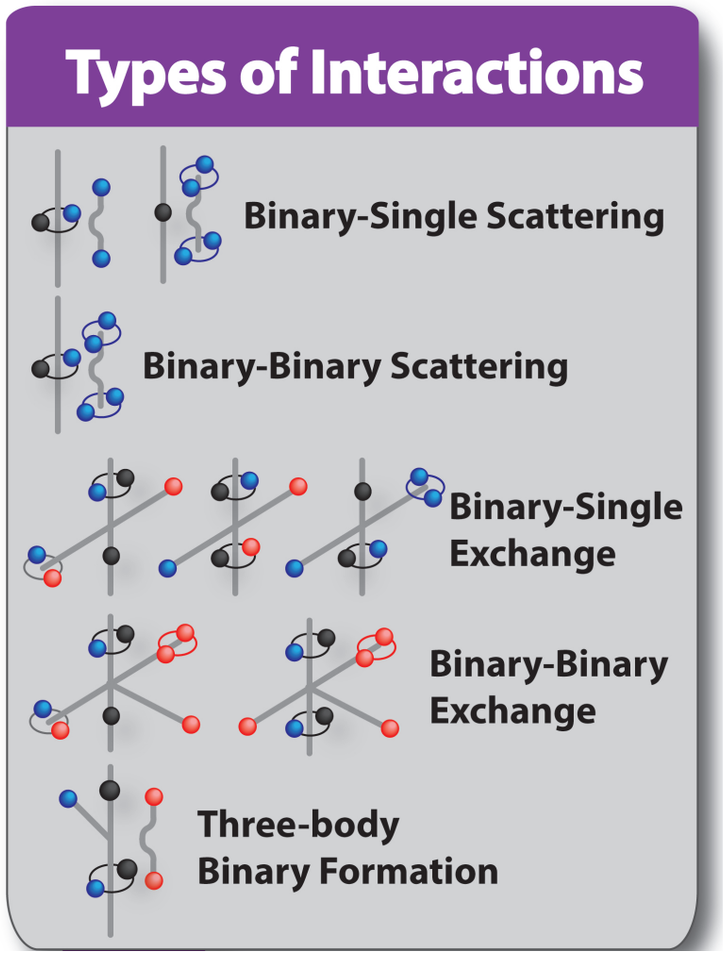
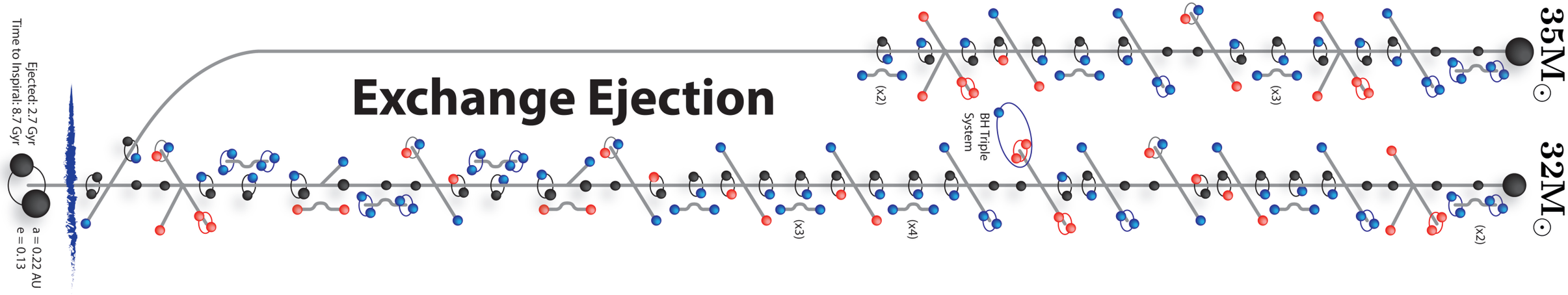
Dynamical formation: an example

e.g., Rodriguez et al. 2016



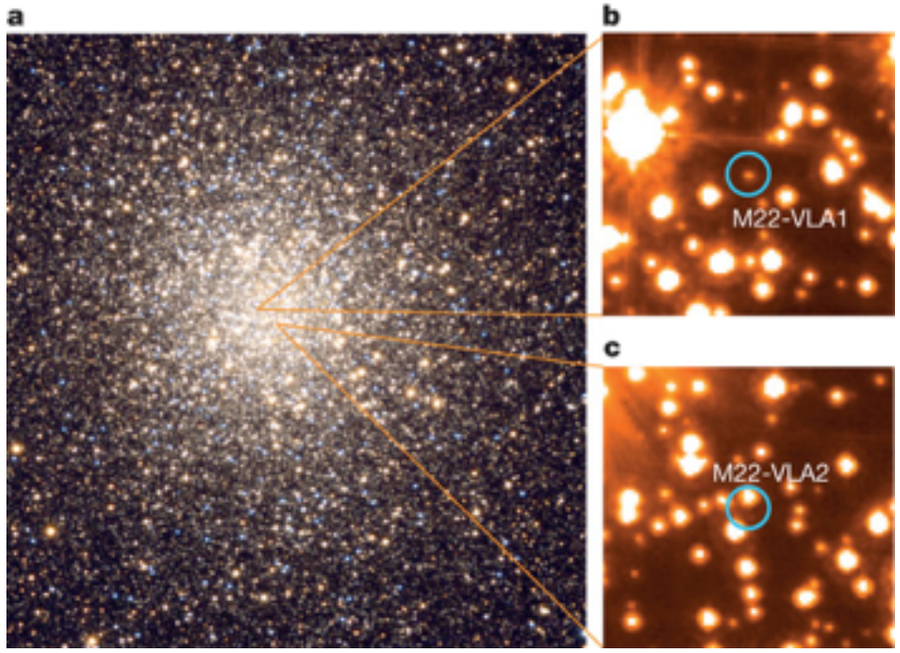


What are star clusters?

Star clusters in galaxies

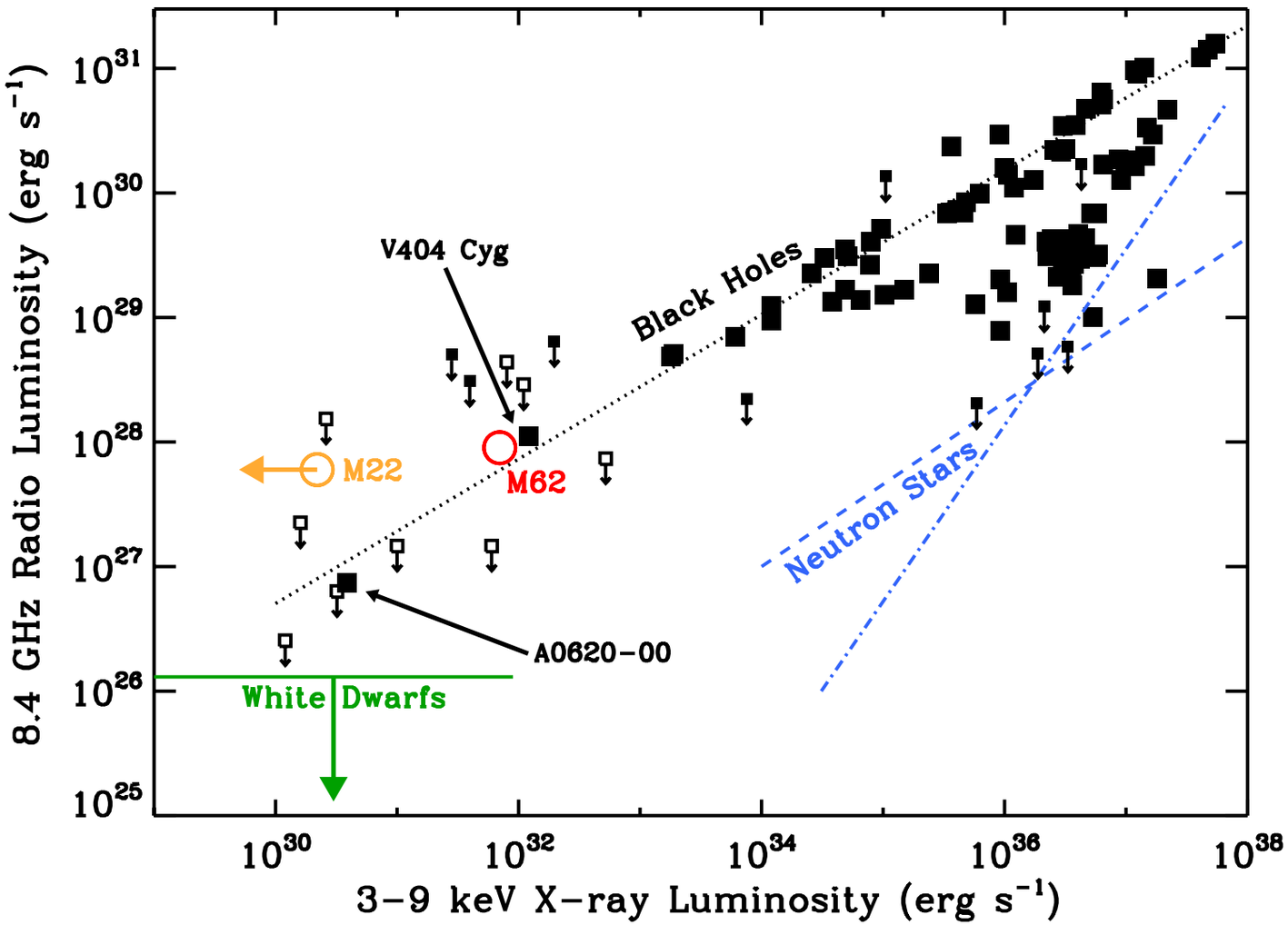
Property	Open Clusters	Globular Clusters
Mass ($M_\odot$)	up to ~ 10^3	typical ~ 10^5
ρ_c ($M_\odot pc^{-3}$)	up to ~ 10^2	typical ~ 10^4
Typical age	up to ~ 7 Gyr	9 - 12 Gyr
Binary fraction (f_b)	~ 50%	few - 20%
Metallicity	higher	low

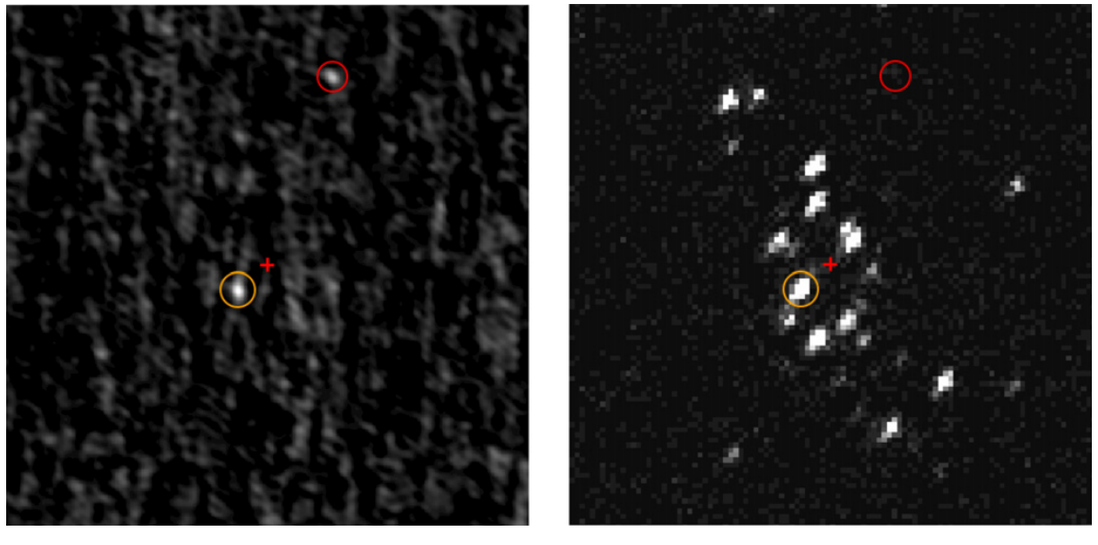
Stellar-Mass Candidate BHs *are Observed* in GCs



M22

Strader et al. 2012





M62

Chomiuk et al. 2012

Physical Processes

Physical Processes

Two-body relaxation

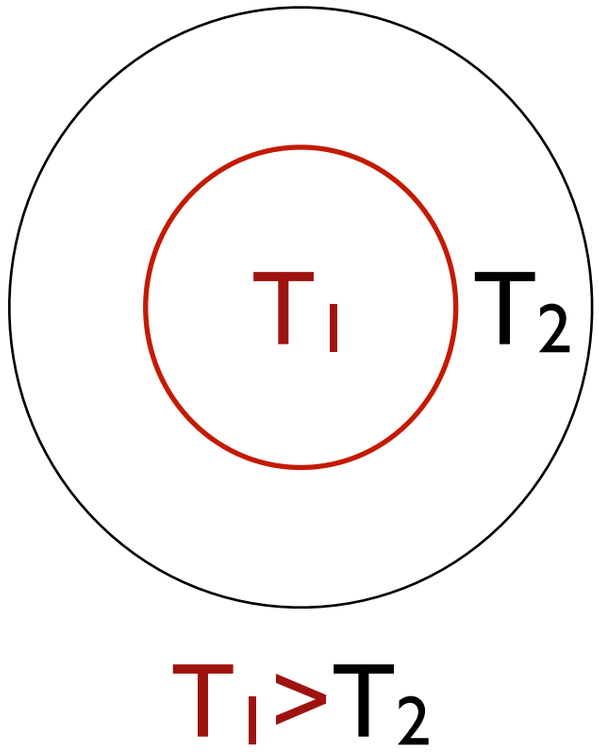
lose energy

↓

sink deeper into the potential

↓

speed up



$T_1 > T_2$

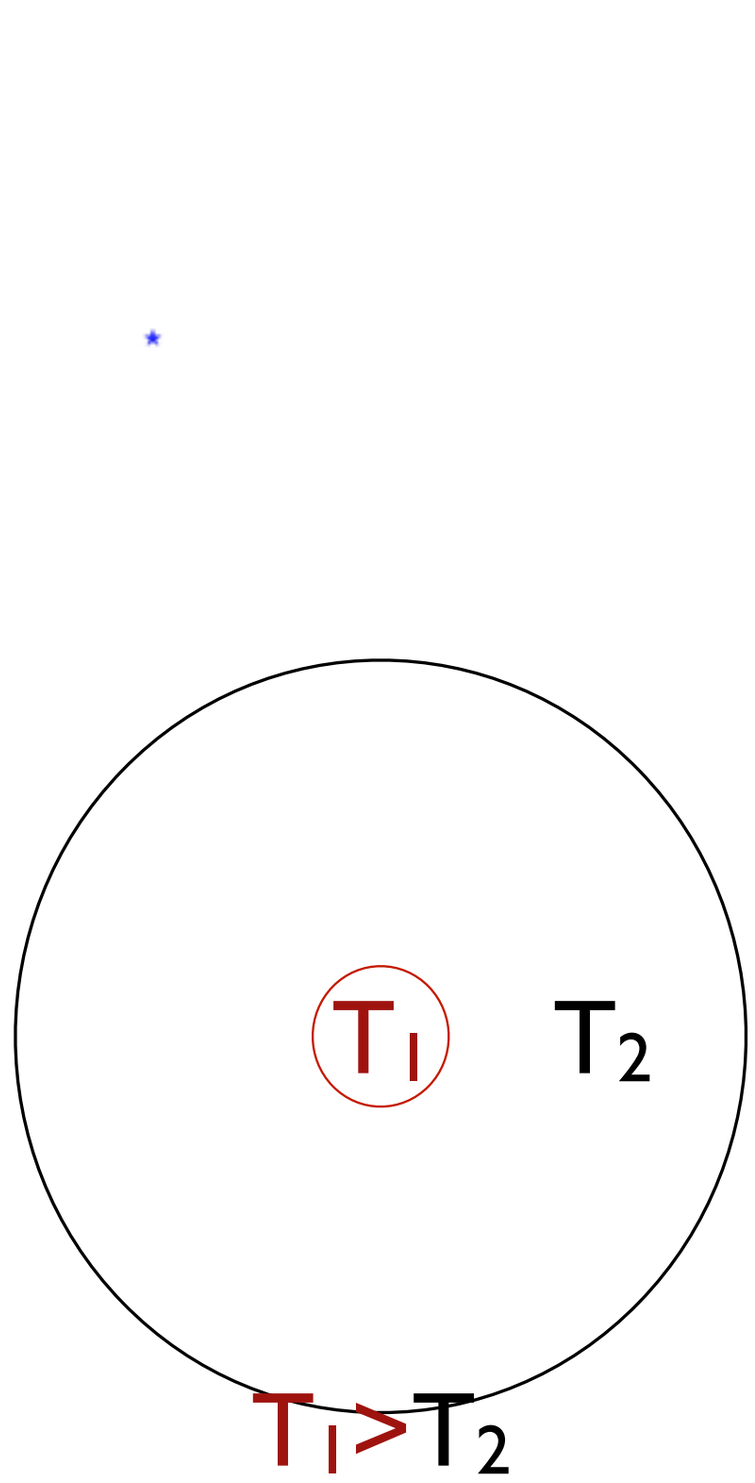
Physical Processes

Two-body relaxation

lose energy

sink deeper into the potential

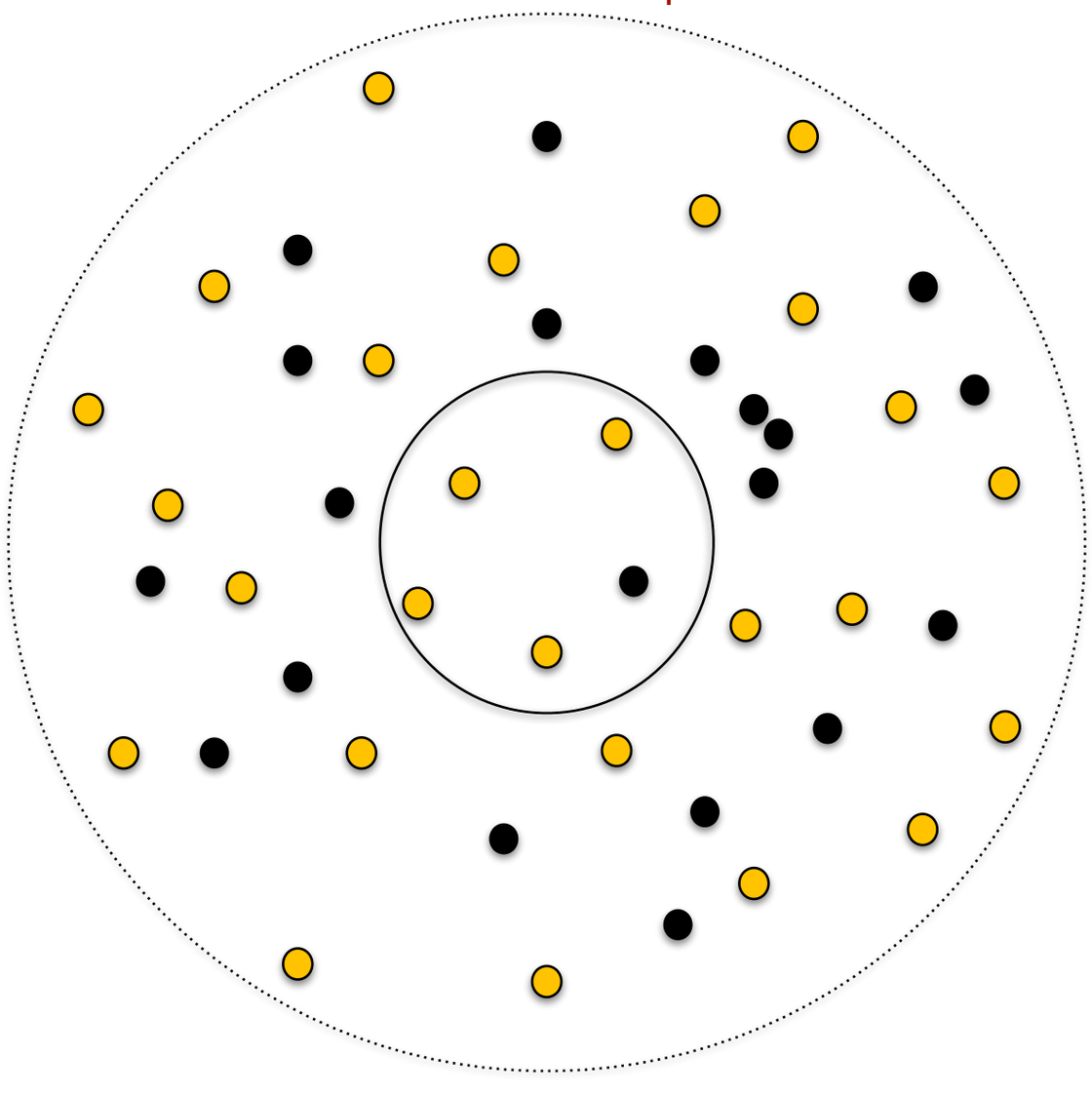
speed up



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



Physical Processes

Two-body relaxation

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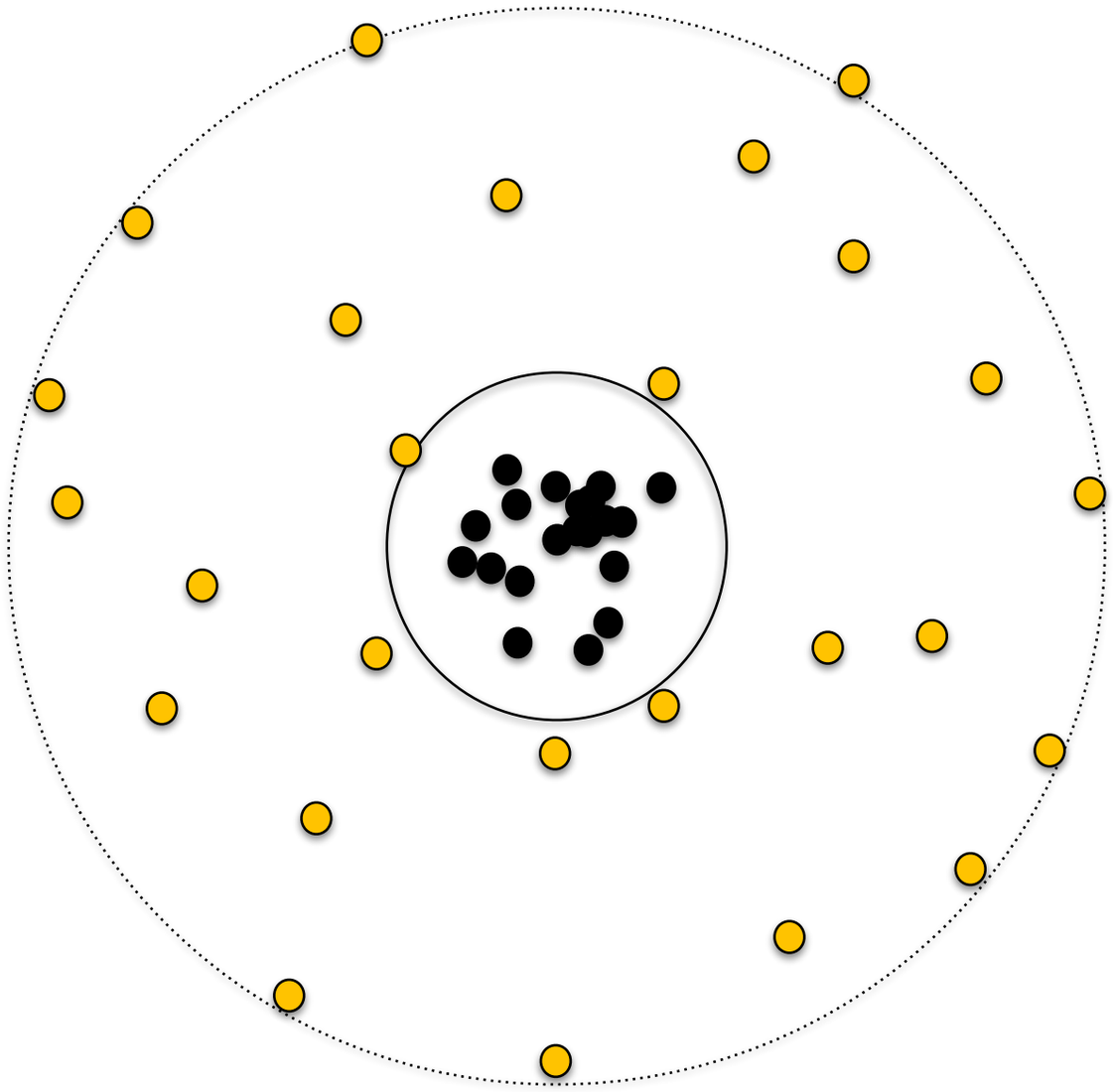


$$t_{\rm relax} \sim \frac{N}{\ln N}\, t_{\rm cross}$$

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

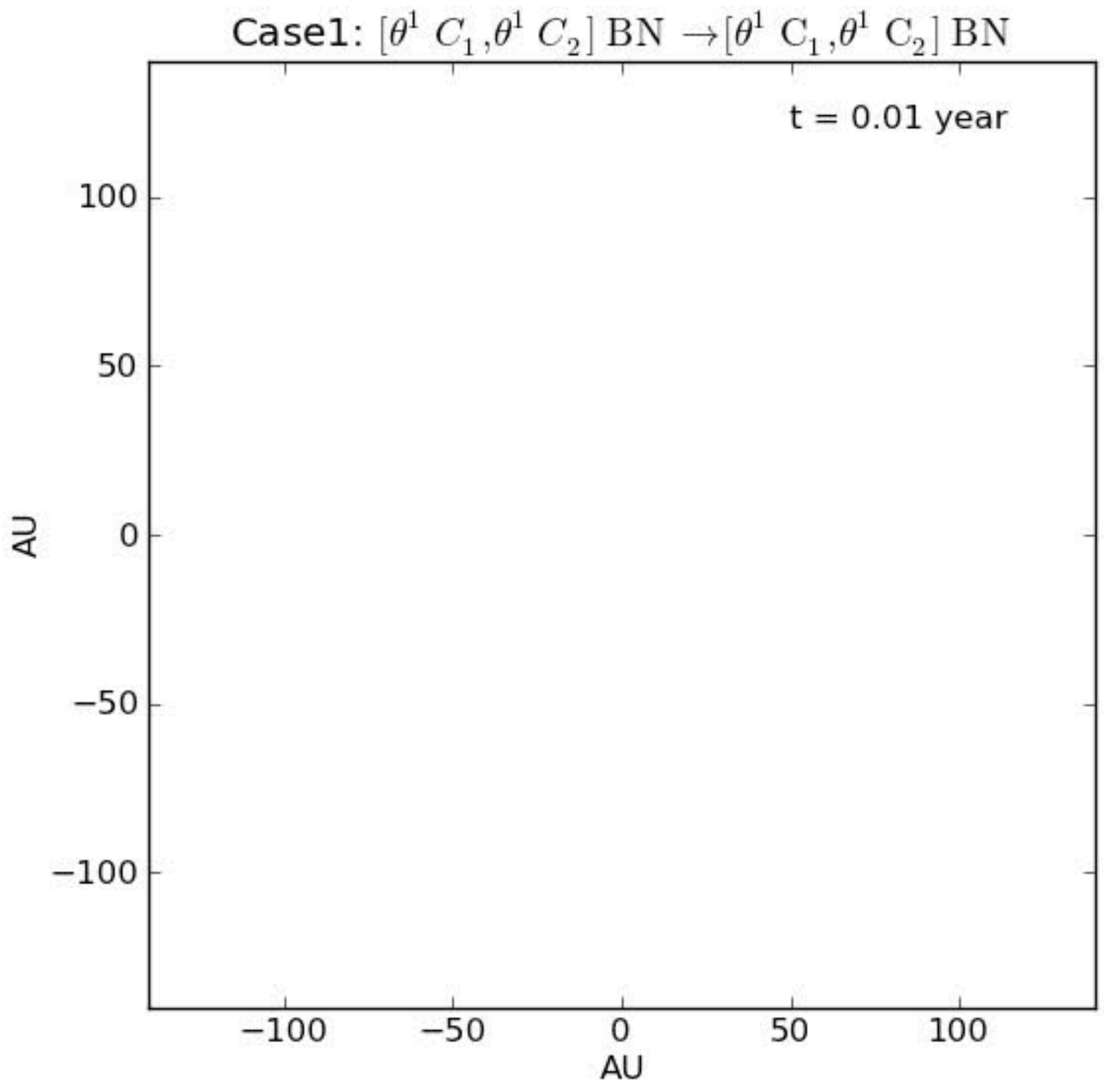
10^5 yr 10^9 yr 10^{10} yr

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

Physical Processes

Two-body relaxation

Strong Scattering &

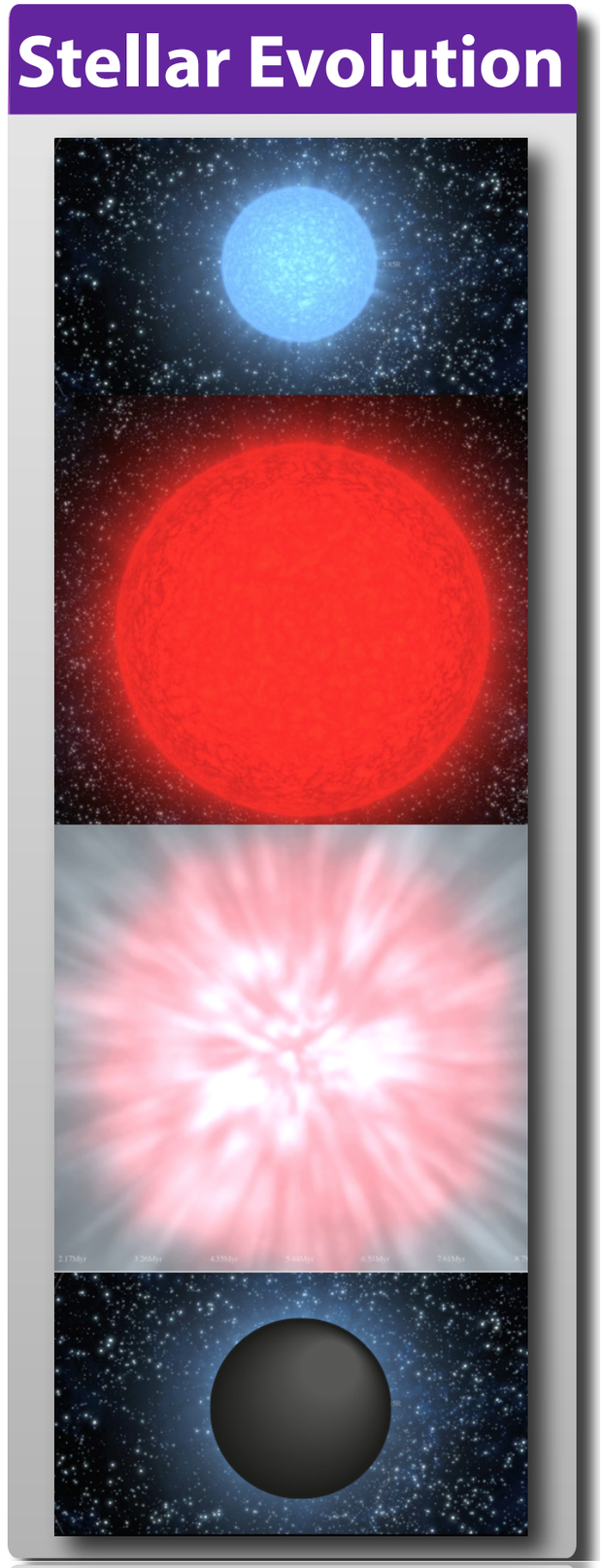


Physical Processes

Two-body relaxation

Strong Scattering & Binary Burning

Single & Binary Stellar Evolution

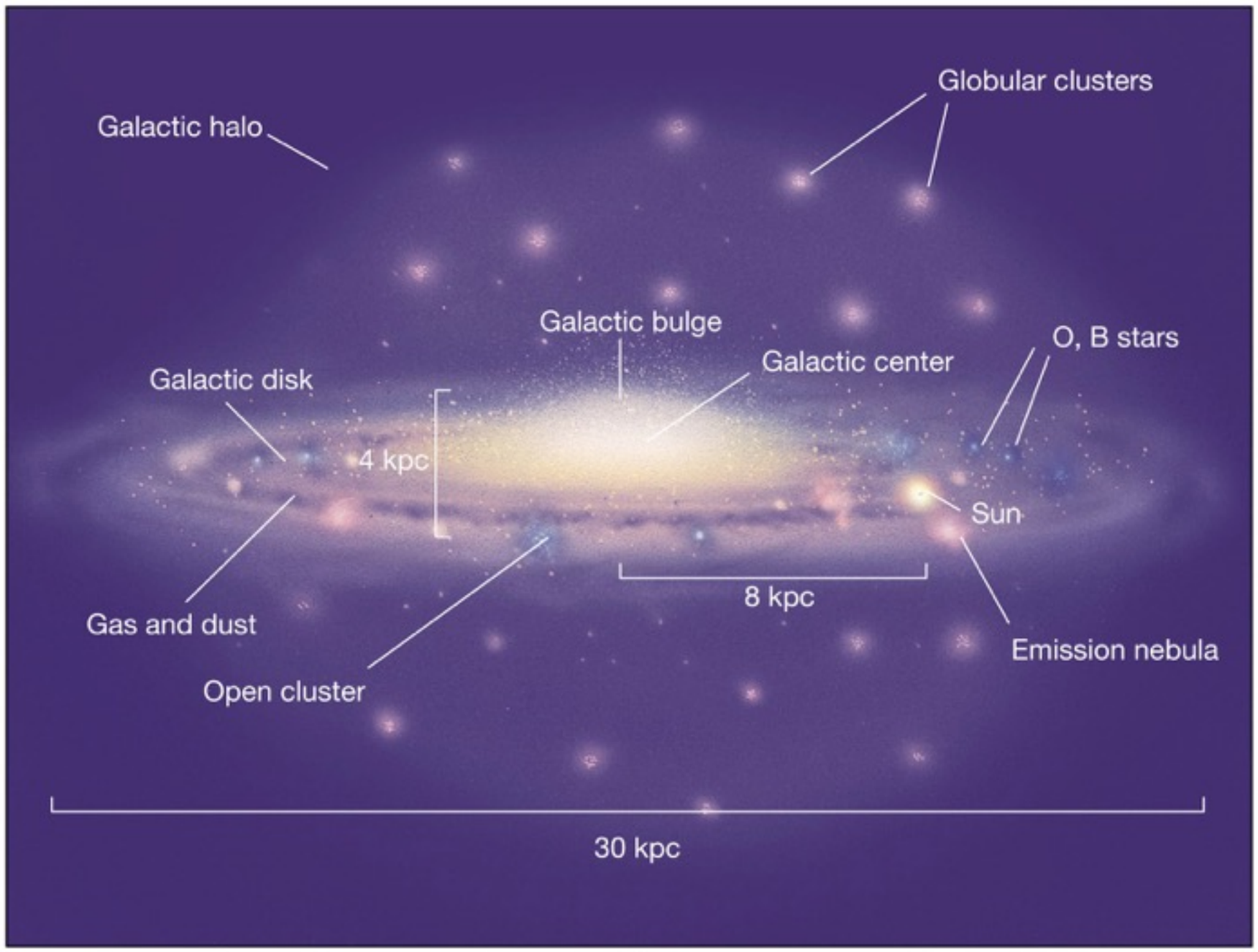


Physical Processes

Two-body relax

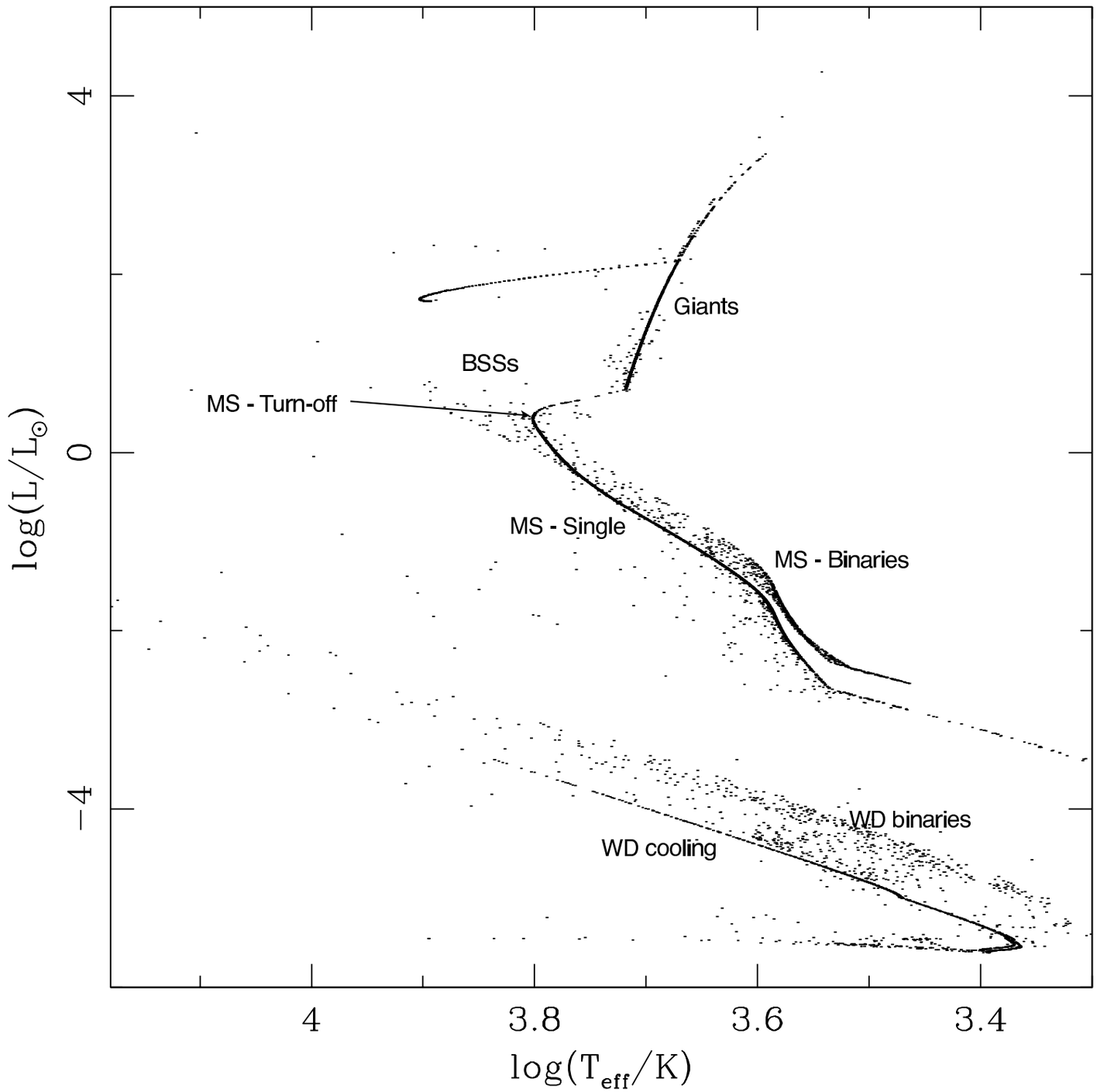
Strong Scatteri

Single & Binary



Tidal Stripping by the Galaxy

Results are Directly Comparable to Observations



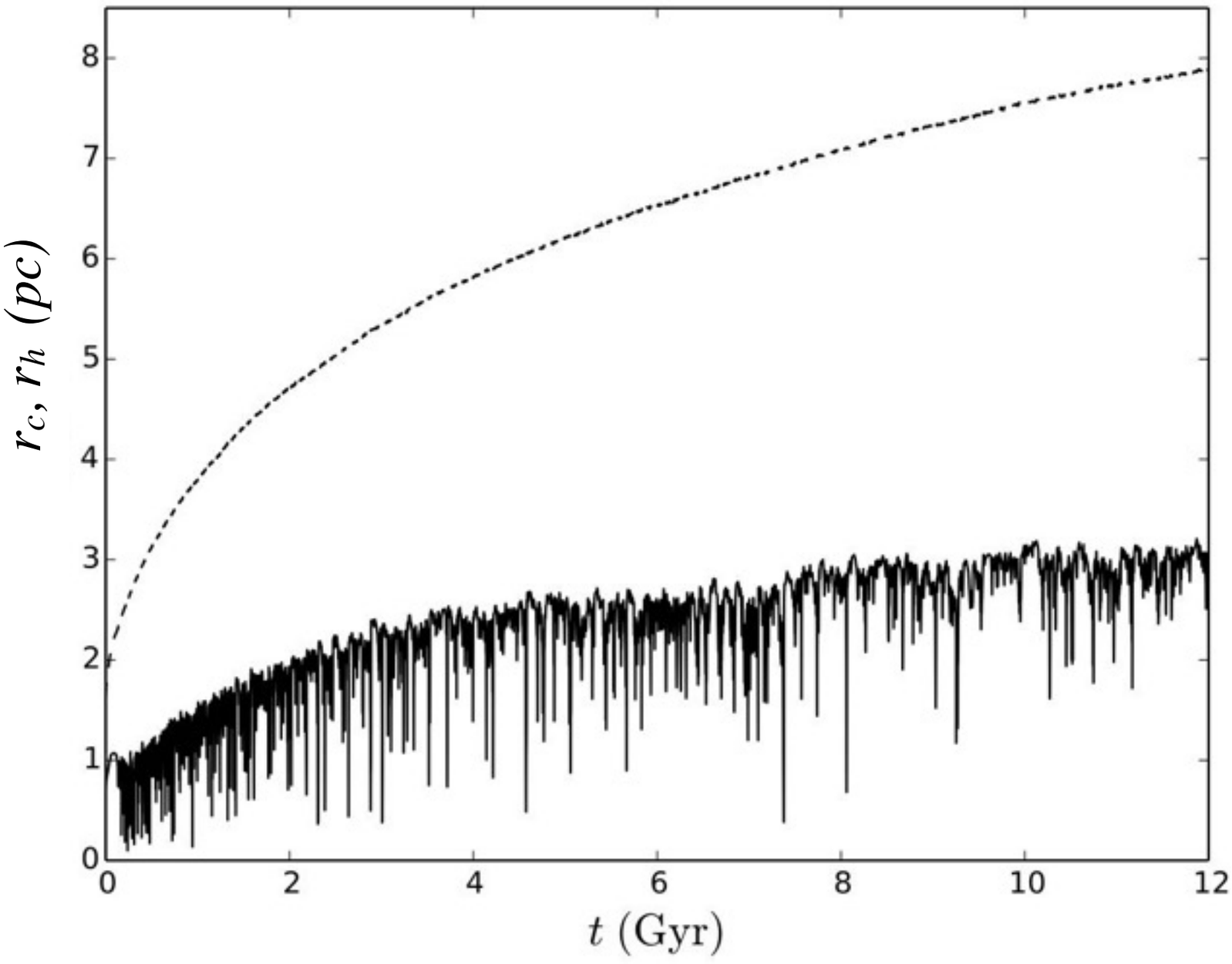
Chatterjee et al. 2013

Dynamical Formation of Binary Black Holes & Implications for aLIGO

Numerical Simulation Setup

- Hénon-type Monte Carlo simulations using *CMC*
- Coverage of a large parameter space
  - $N \sim 2\text{x}10^5$ to $2\text{x}10^6$
  - $Z \sim 0.0005, 0.001$
  - 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: weak winds (e.g., Vink 2001)

Typical Evolution

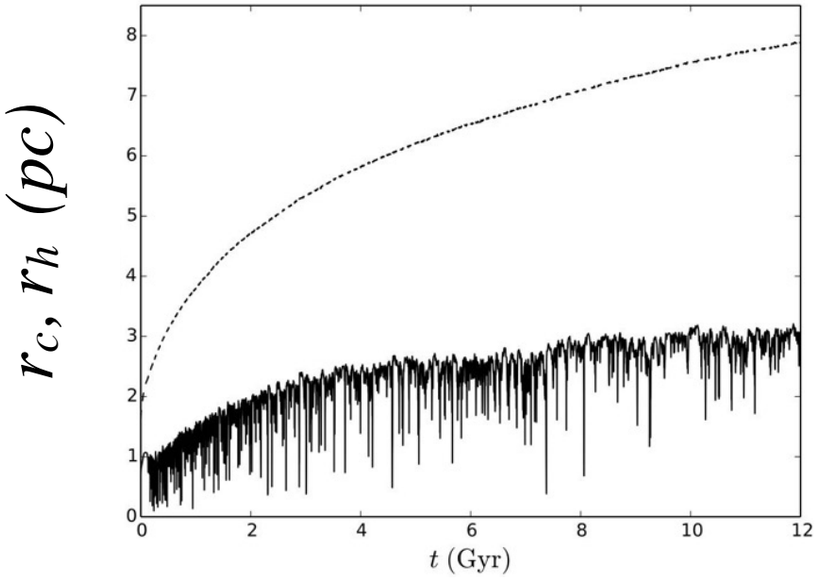


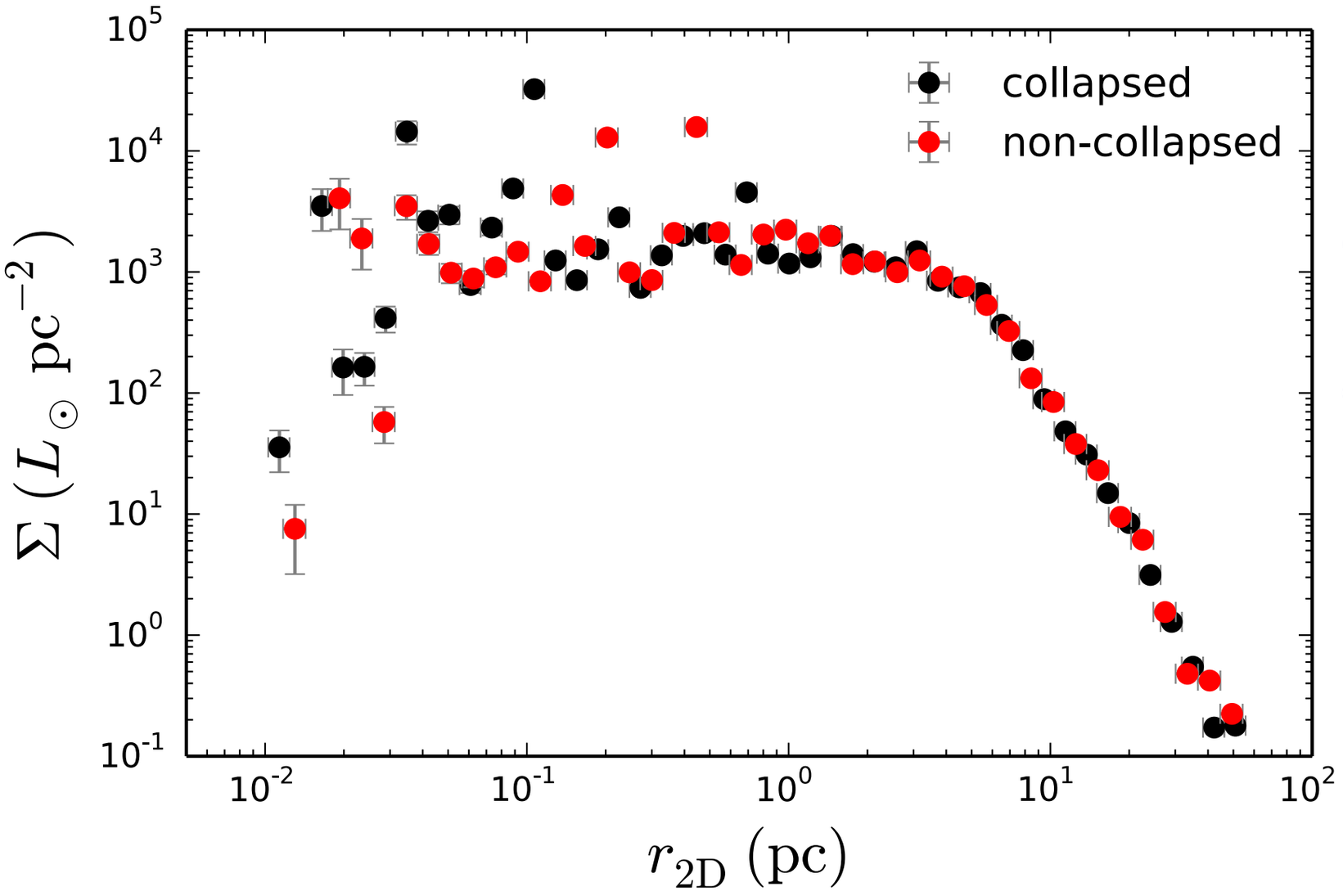
Repeated BH-driven collapse

Overall cluster expansion

CRoRa-16, ApJ (in press)

Typical Evolution





Repeated BH-driven collapse

Overall cluster expansion

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

CRoRa-16, ApJ (in press)

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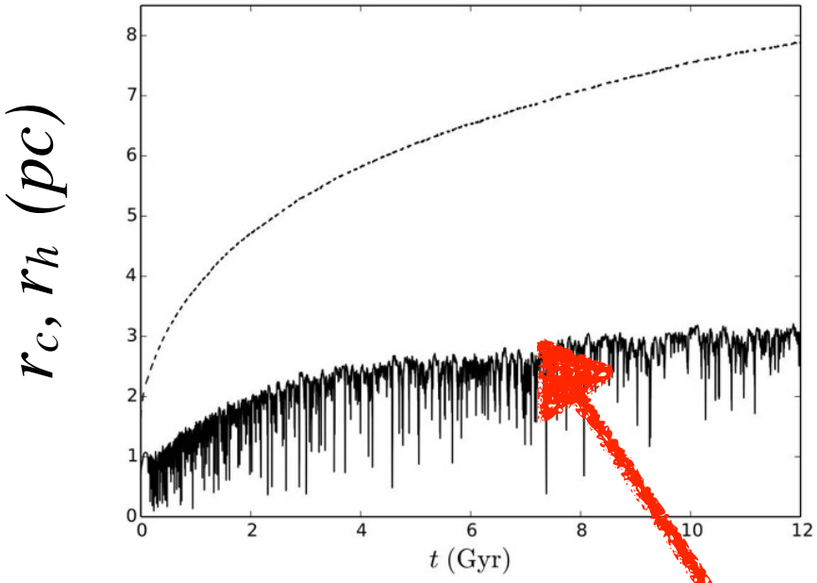

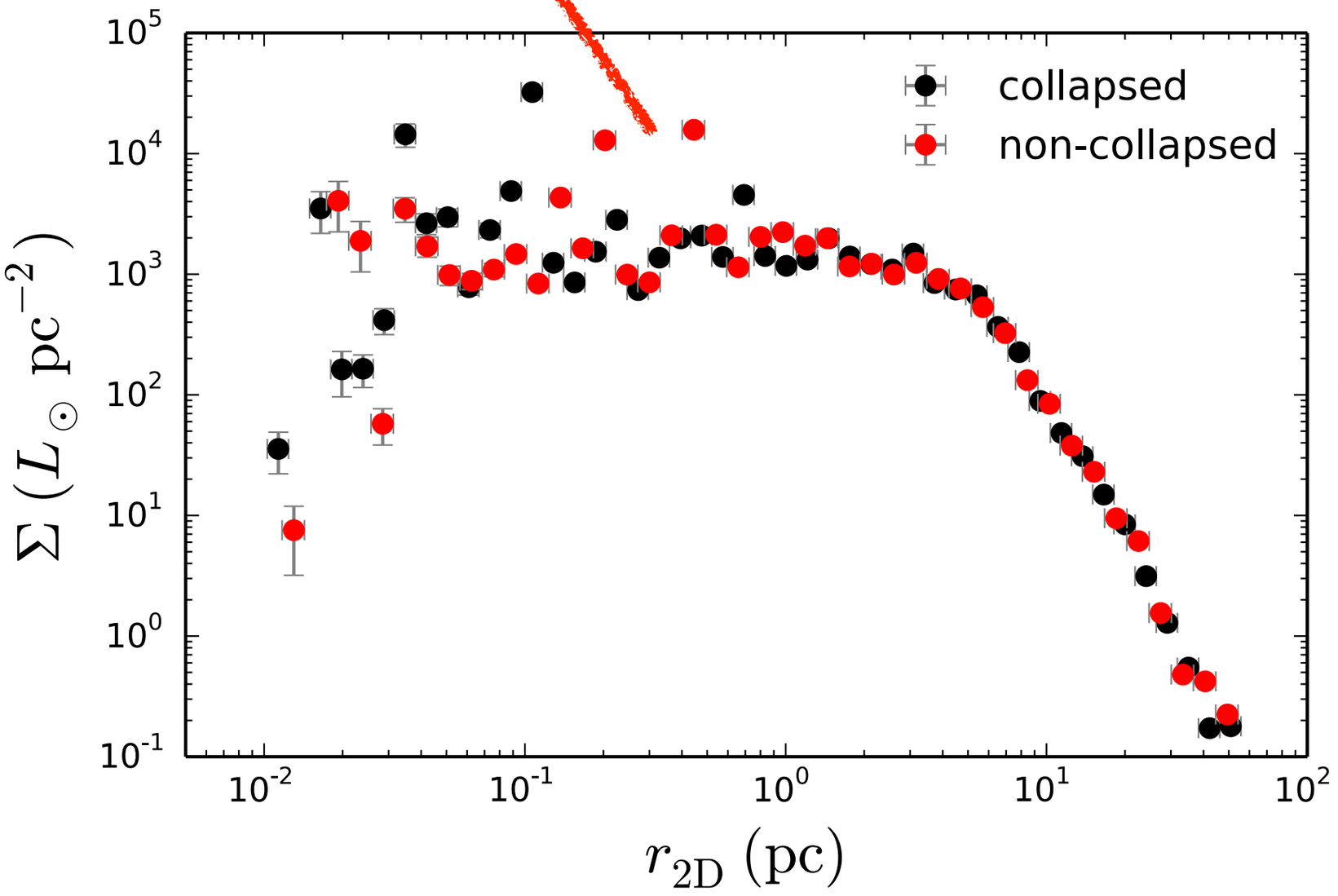

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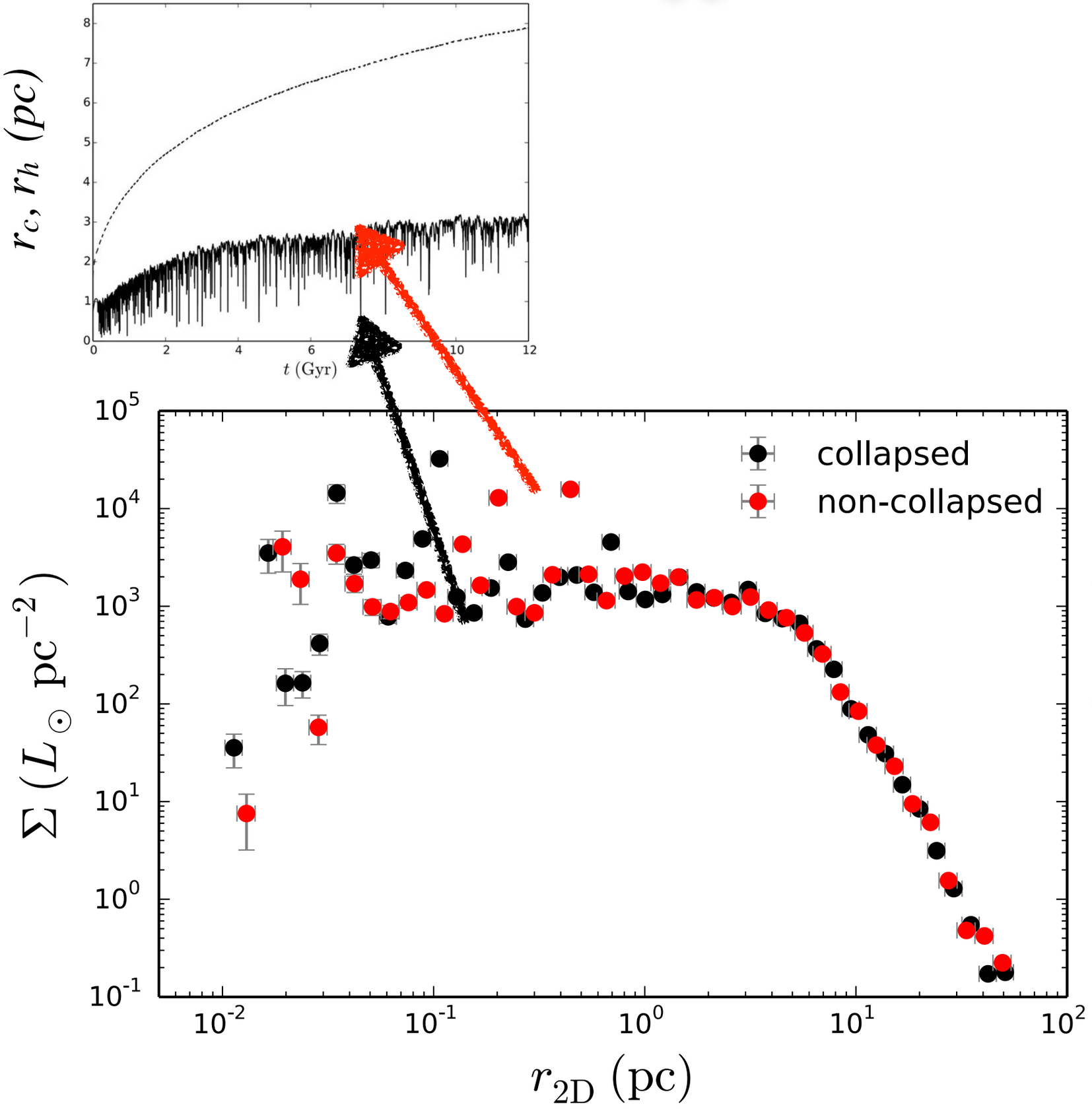

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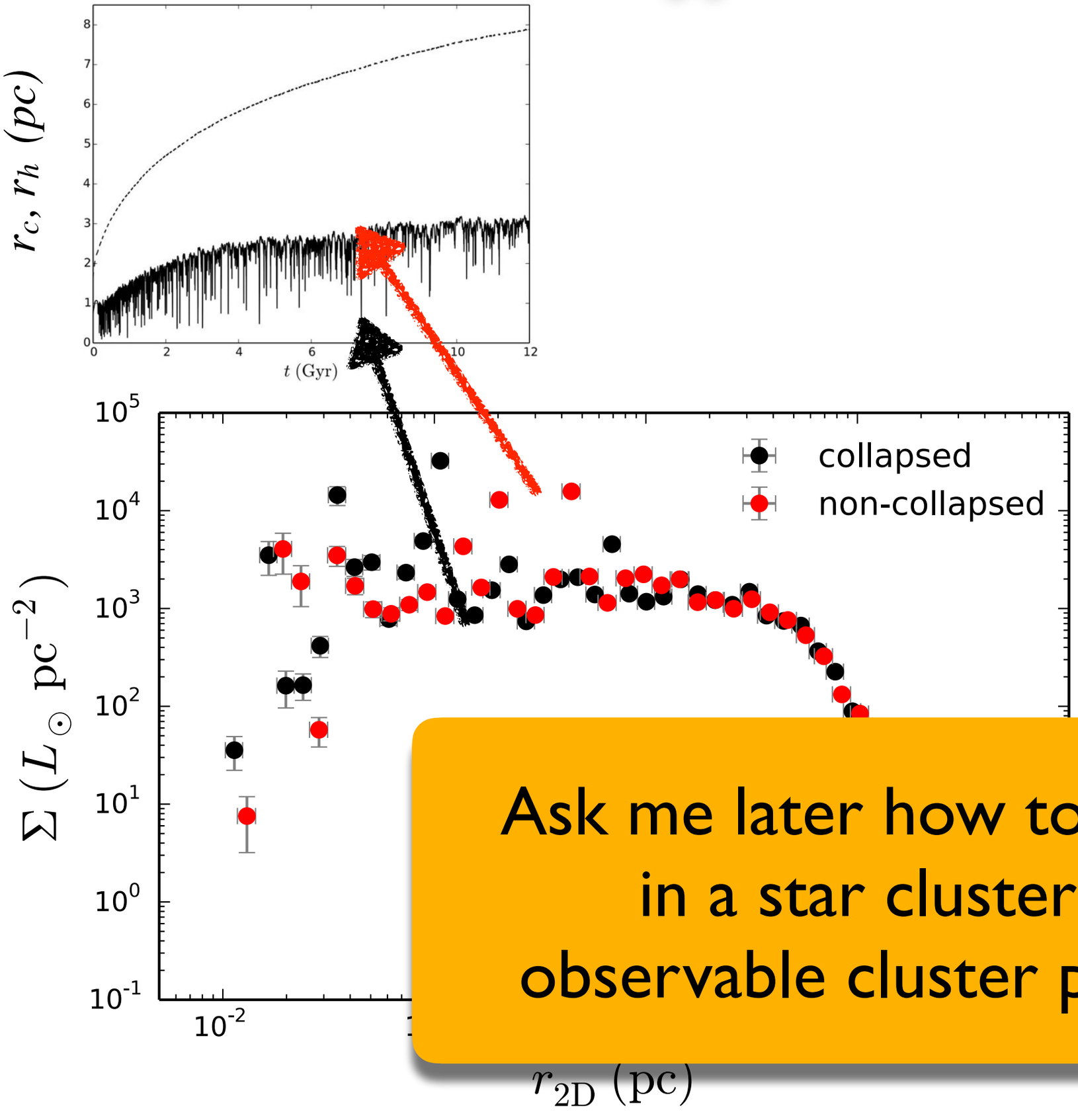


Repeated BH-driven collapse

Overall cluster expansion

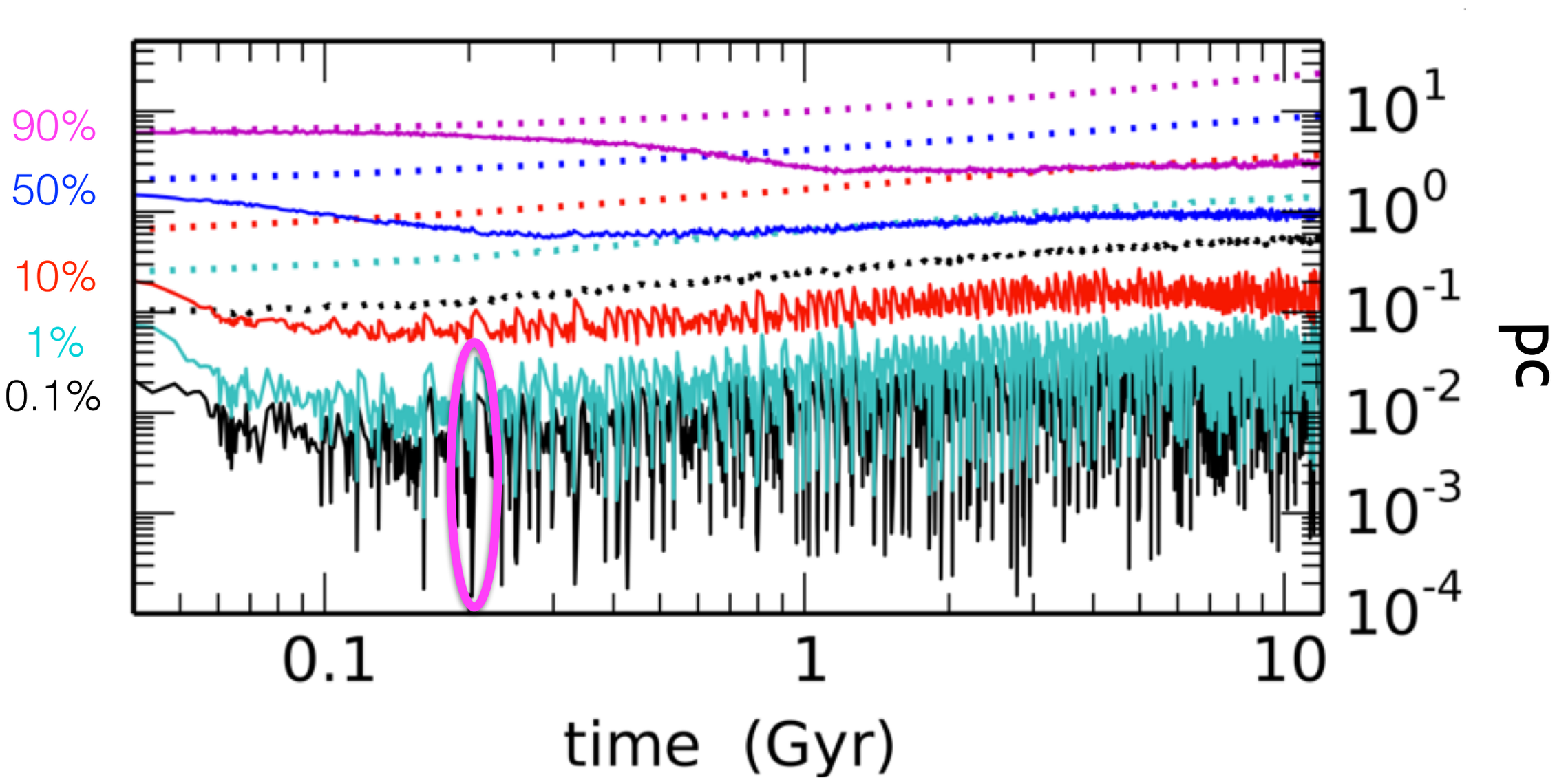
Little observable difference in surface brightness profile in and out of collapse

Ask me later how to infer BHs in a star cluster from observable cluster properties

CRoRa-16, ApJ (in press)

What Really Happenes to the BHs in Clusters?

Lagrange Radii: BHs and non-BHs



Morscher et al. (2015)

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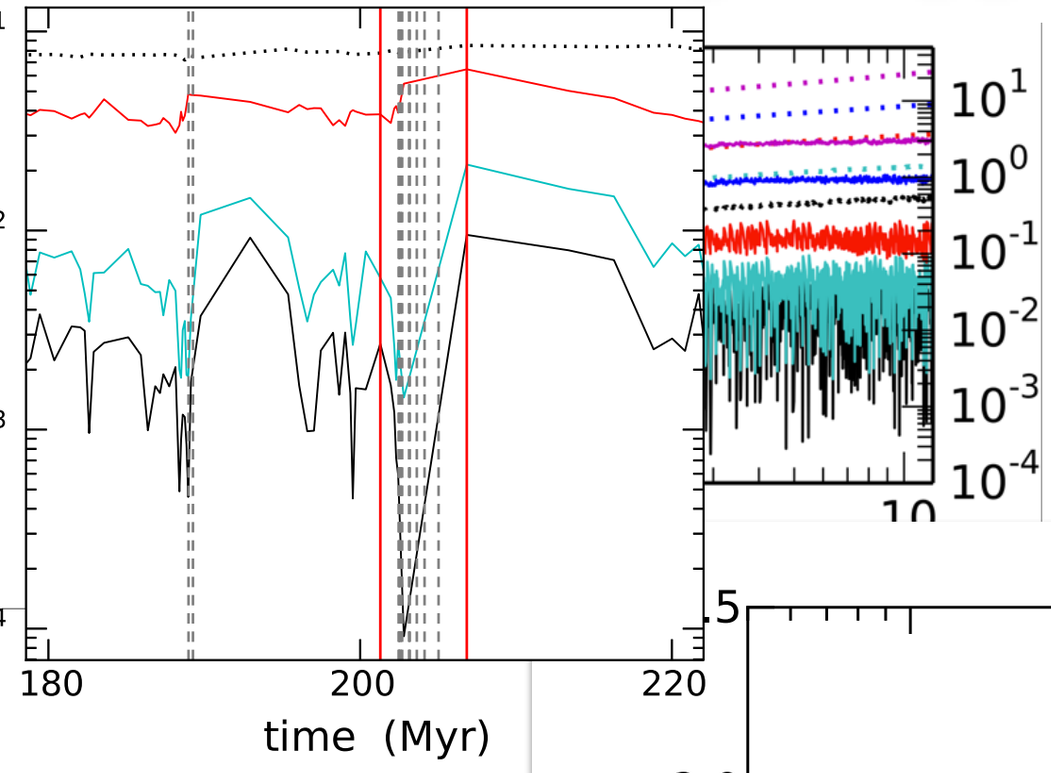

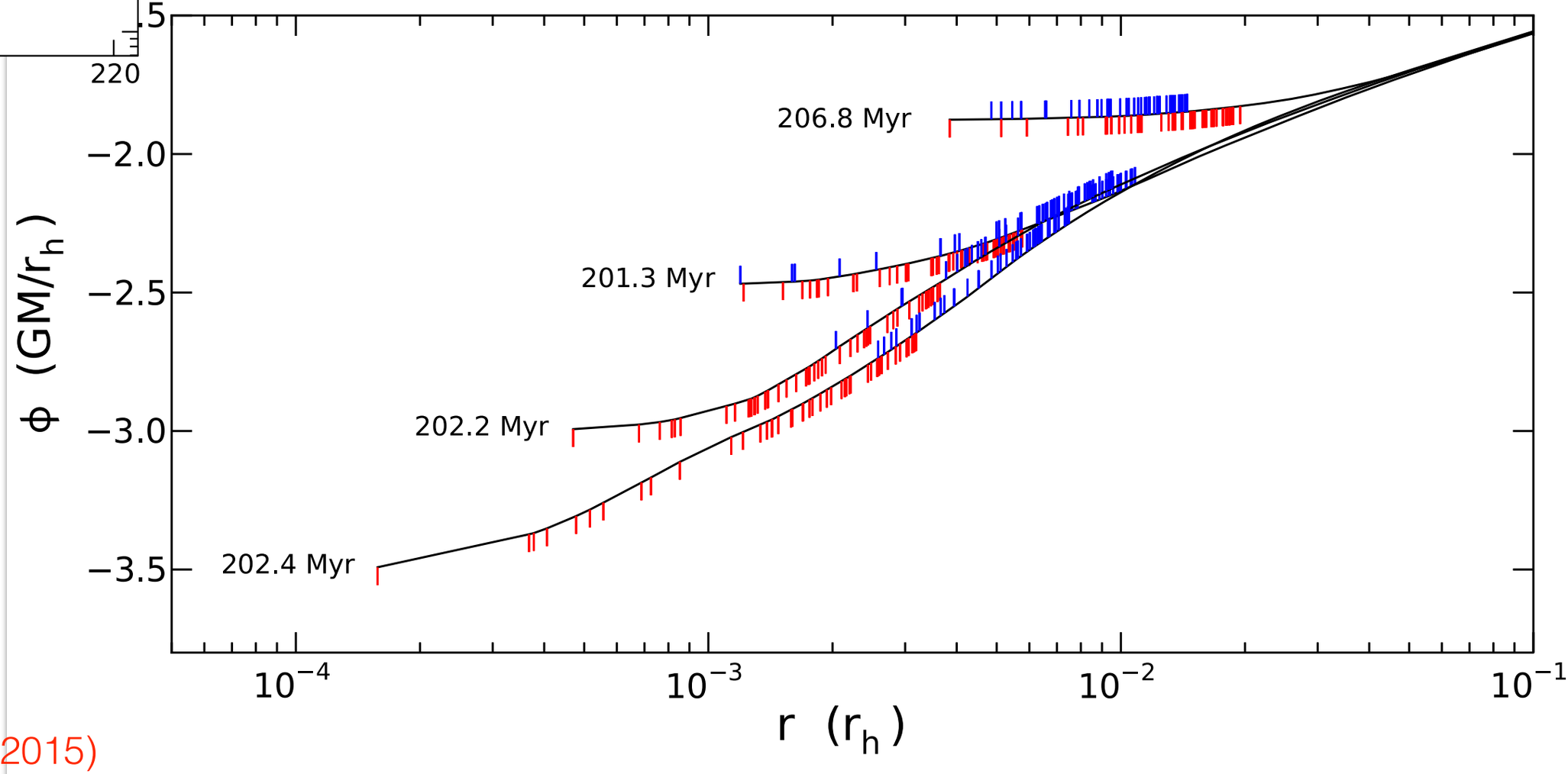

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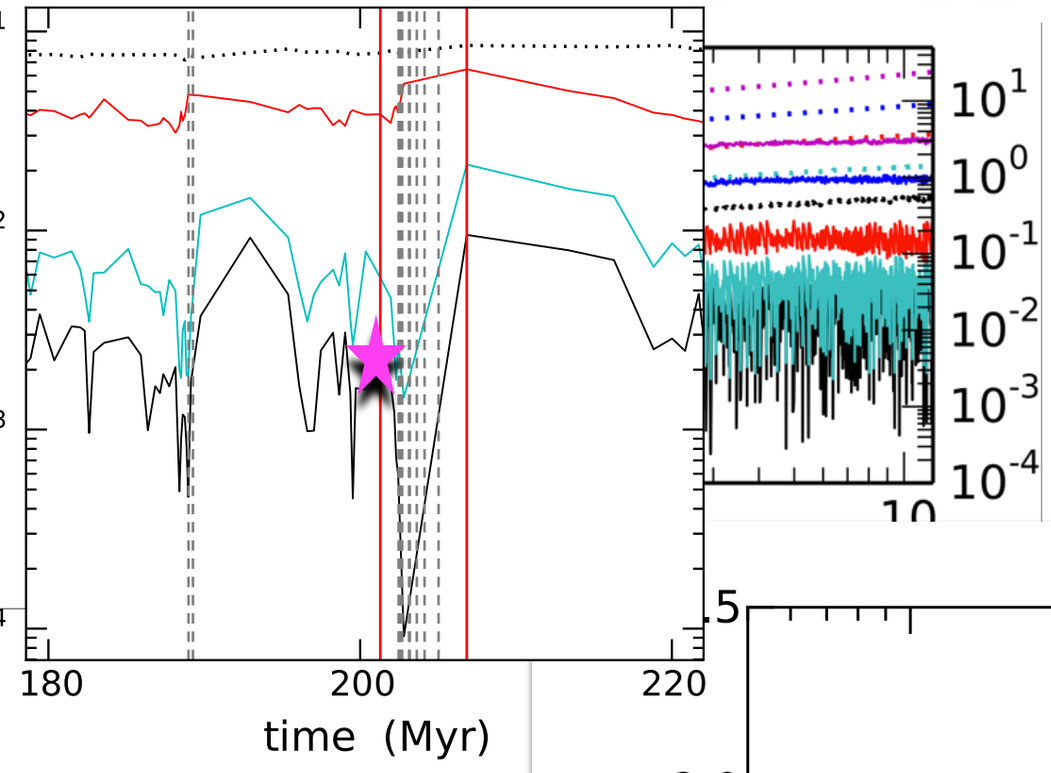

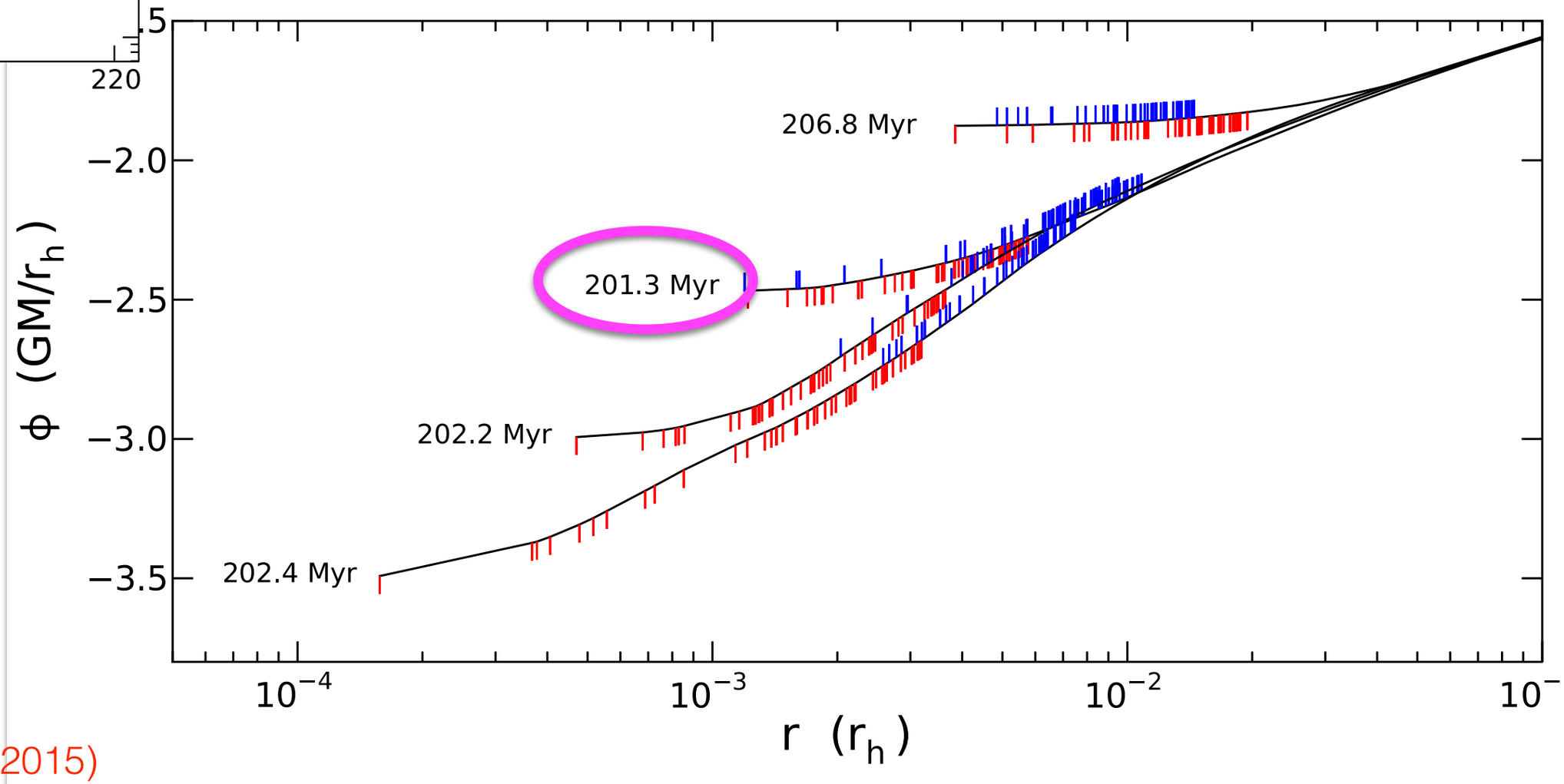

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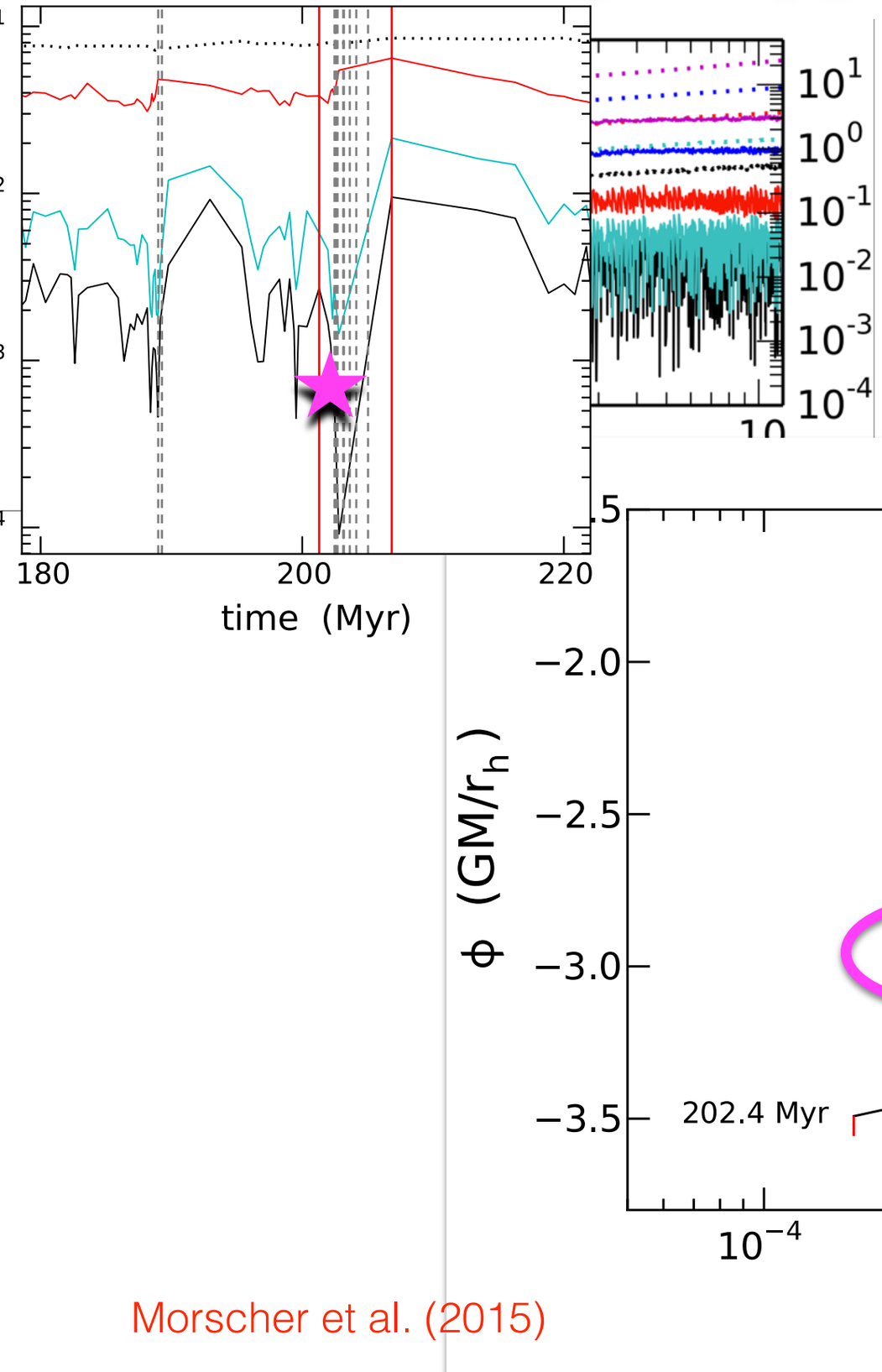

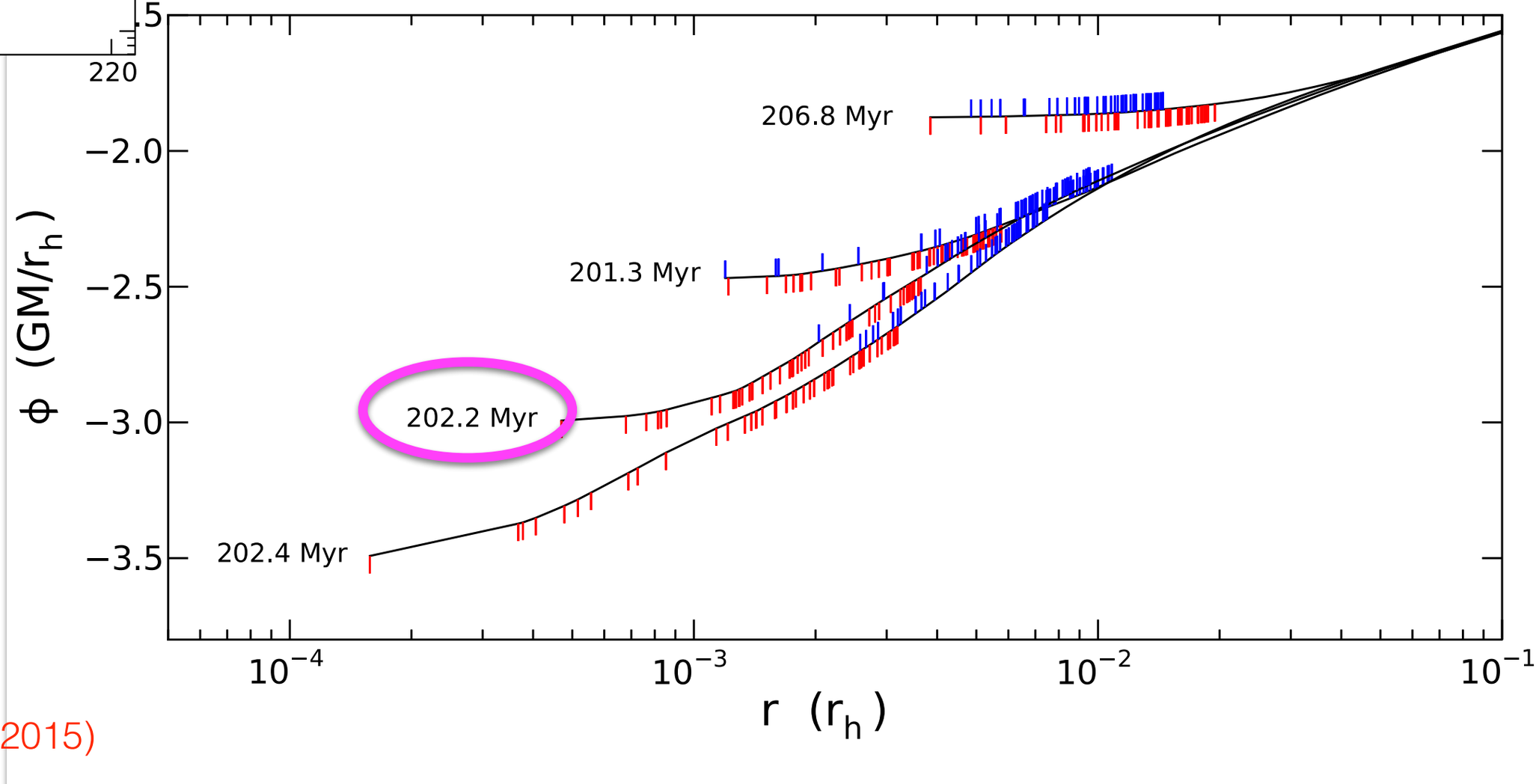

Morscher et al. (2015)