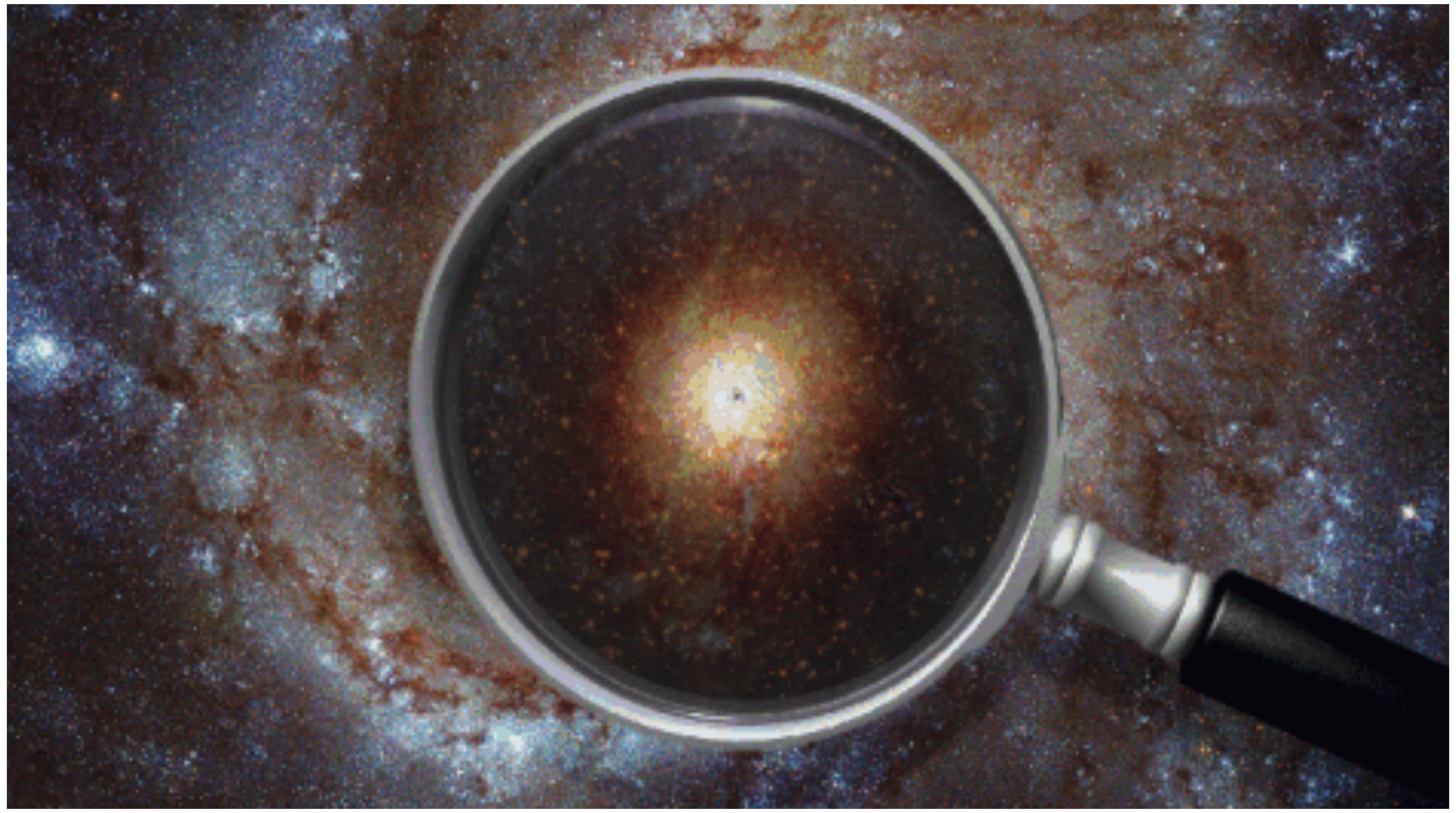
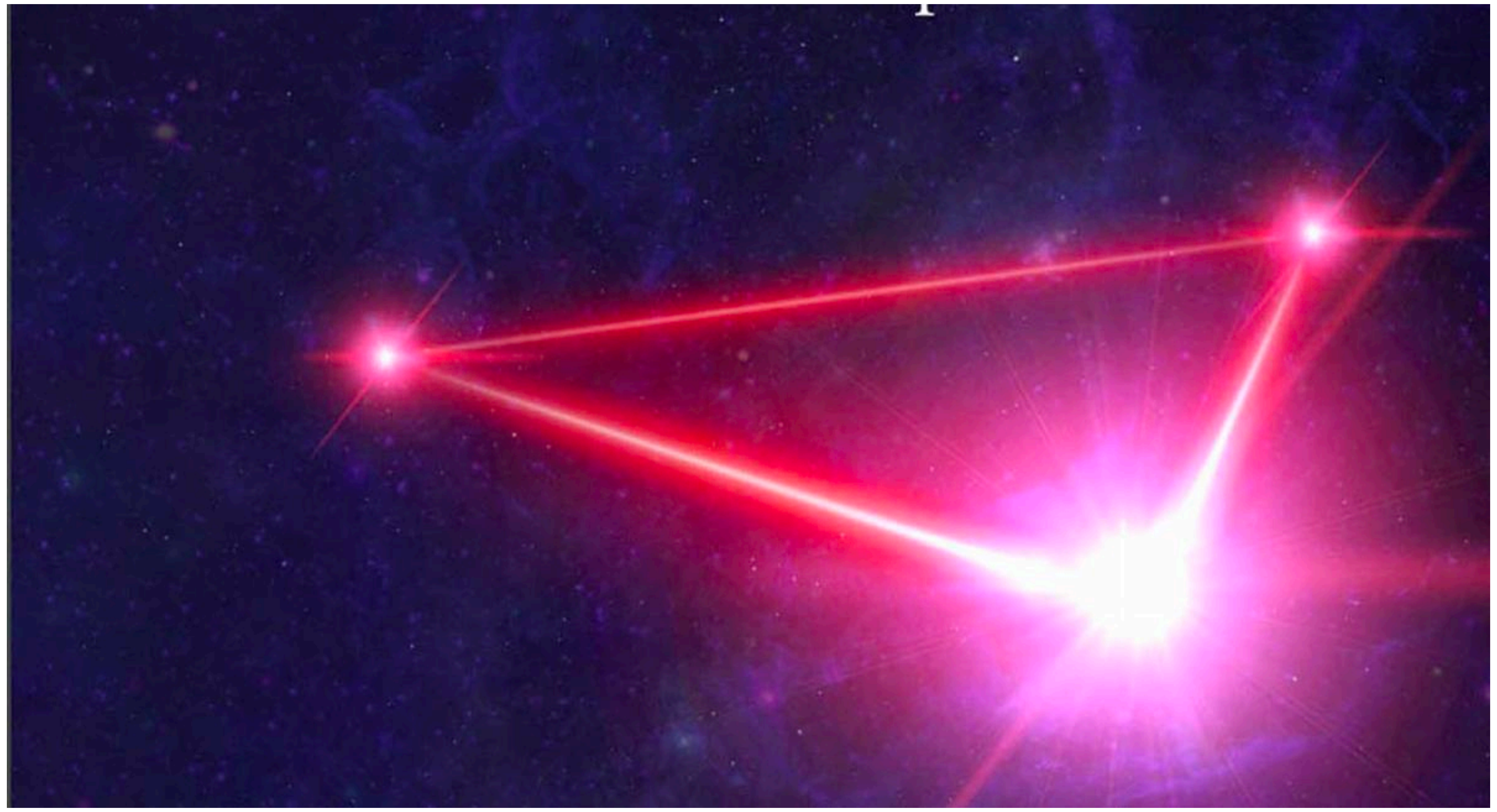
Formation & Growth of Supermassive Black Holes in Galactic Nuclei: LISA Binaries & Intermediate-Mass Ratio Inspirals





Credit: LISA (NASA/Simon Barke)

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MARIE CURIE ACTIONS

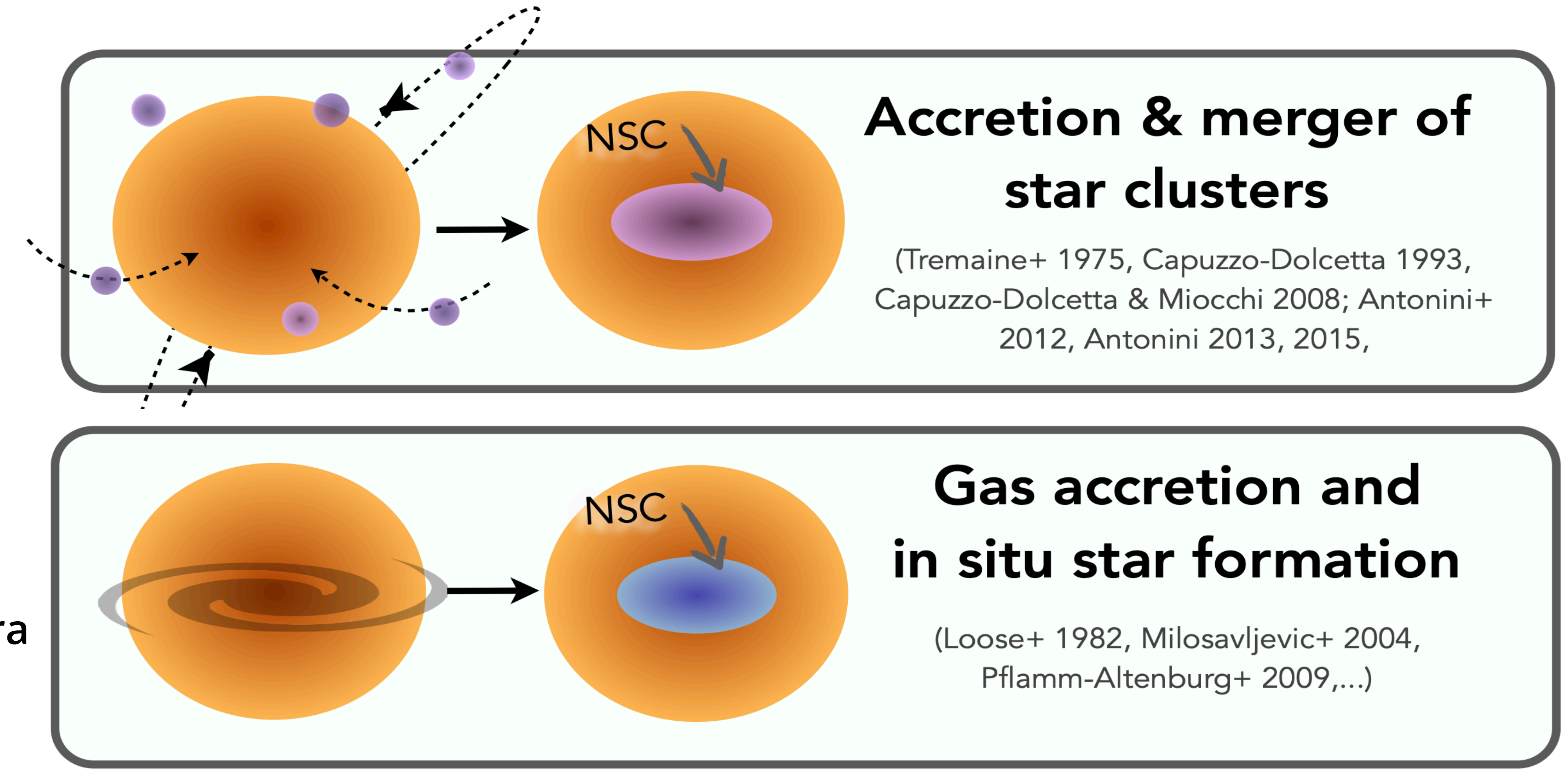
CAMK PAN

BH GROWTH
Growing Black Holes in Star Clusters

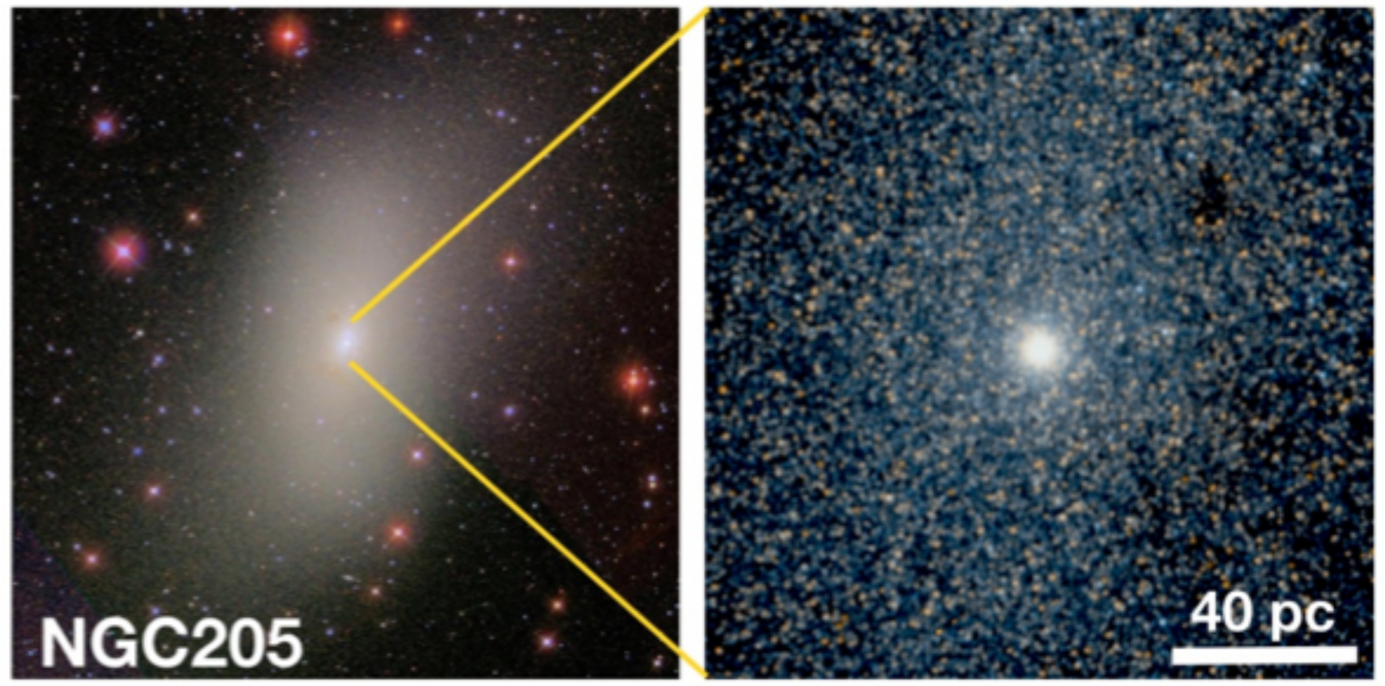
https://bhg.camk.edu.pl/

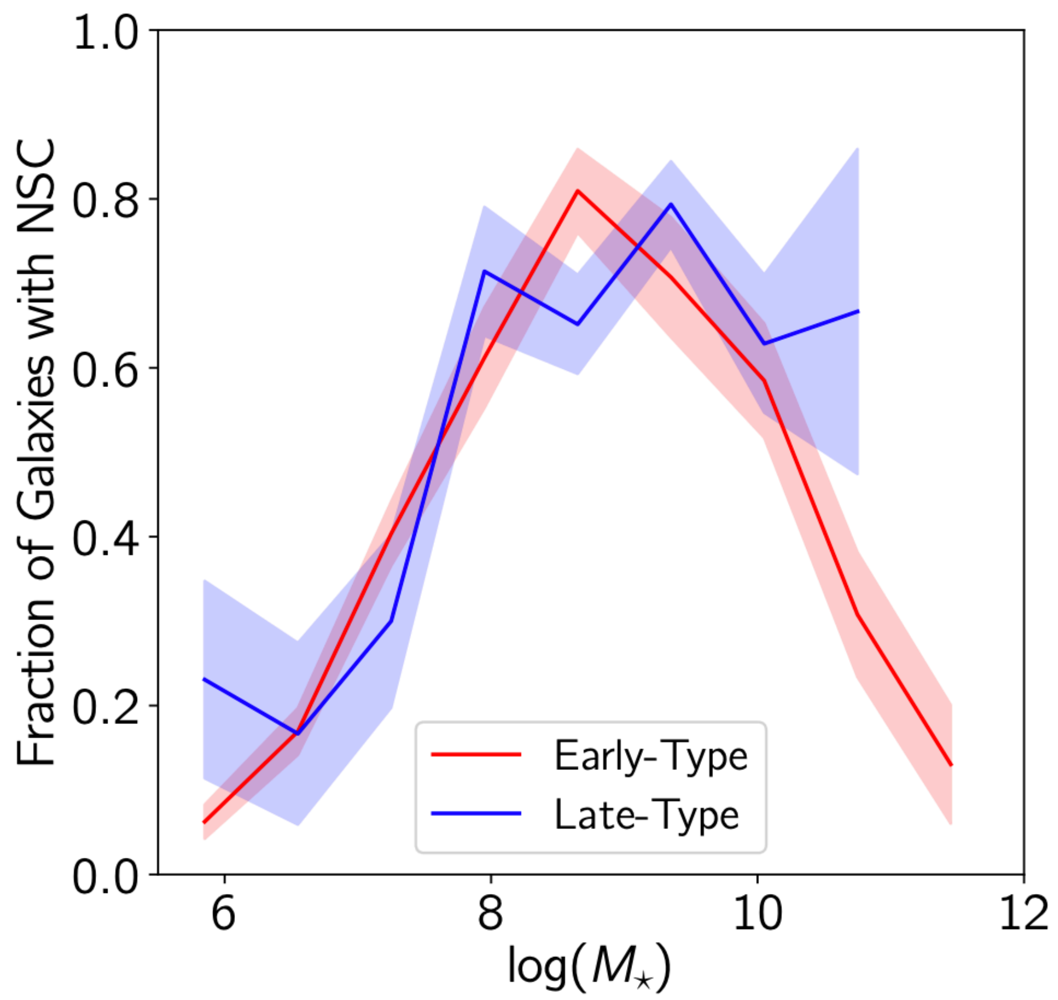
Co-existence of nuclear star clusters and massive black holes

- Nuclear Star Clusters (NSCs): Dense ($\sim 10^6 - 10^7\ \mathrm{M_\odot\ pc^{-3}}$) and massive star clusters ($\sim 10^6 - 10^9\ \mathrm{M_\odot}$) occupying the nucleus of most galaxies



Credit: Alessandra Mastrobuono-Battisti





Neumayer, Seth & Böker (2020)

- NSCs and Supermassive Black Holes (SMBH) $\sim 10^6 - 10^{10}\ \mathrm{M_\odot}$ are found to co-exist
  - **Milky Way:** NSC Mass: $2.5 \times 10^7\ \mathrm{M_\odot}$ SMBH Mass: $4.16 \times 10^6\ \mathrm{M_\odot}$
  - **M31:** NSC Mass: $4.9 \times 10^7\ \mathrm{M_\odot}$ SMBH Mass: $\sim 1.4 \times 10^8\ \mathrm{M_\odot}$

M33 and the absence of an SMBH

- **M33** has an **NSC** but **no SMBH!**
  - NSC Mass: $2 \times 10^6\ \mathrm{M}_\odot$ (Kormendy et al. 2010, McConnachie 2012)
  - Upper limit on central black hole mass: $1500\ \mathrm{M}_\odot$ (Merritt et al. 2001; Gebhardt et al. 2001)

M33 by Adam Block/Mount Lemmon SkyCenter/ University of Arizona

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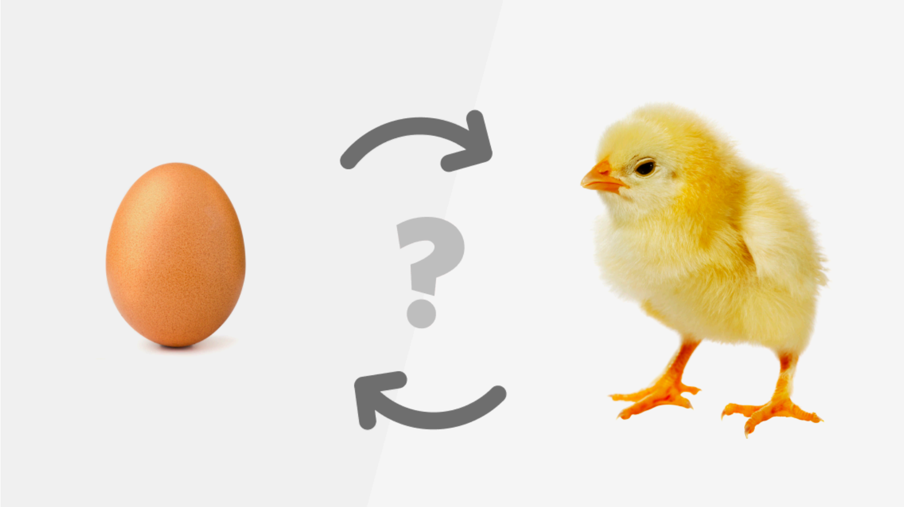
- What comes first: an NSC or an SMBH?



Can an SMBH form after an NSC?

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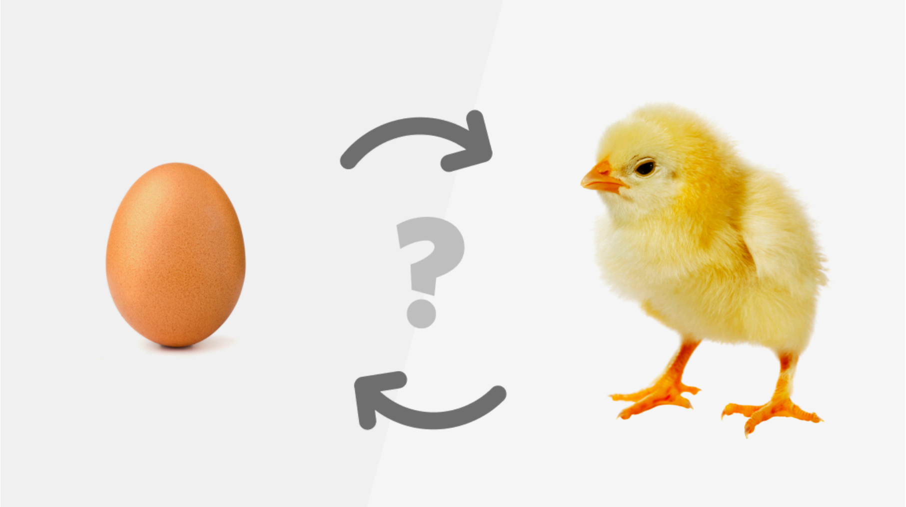


Can an SMBH form after an NSC?

- P1: Askar, Davies & Church (2021) - MNRAS.502.2682A
- P2: Askar, Davies & Church (2022) - MNRAS.511.2631A
- P3: Askar (in prep)

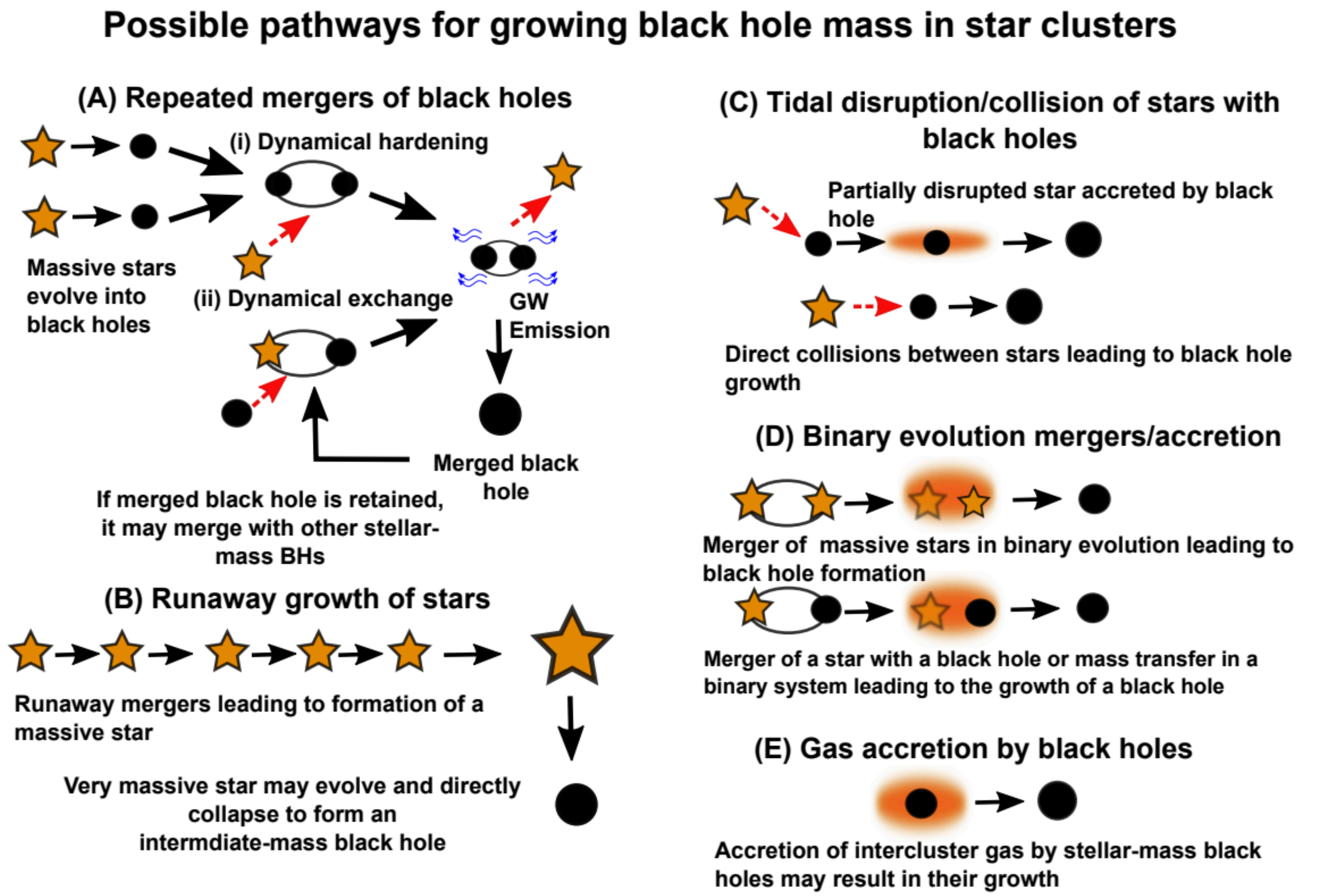
Central Idea: Building up an NSC by merging stellar clusters

- Make an NSC by merging star clusters

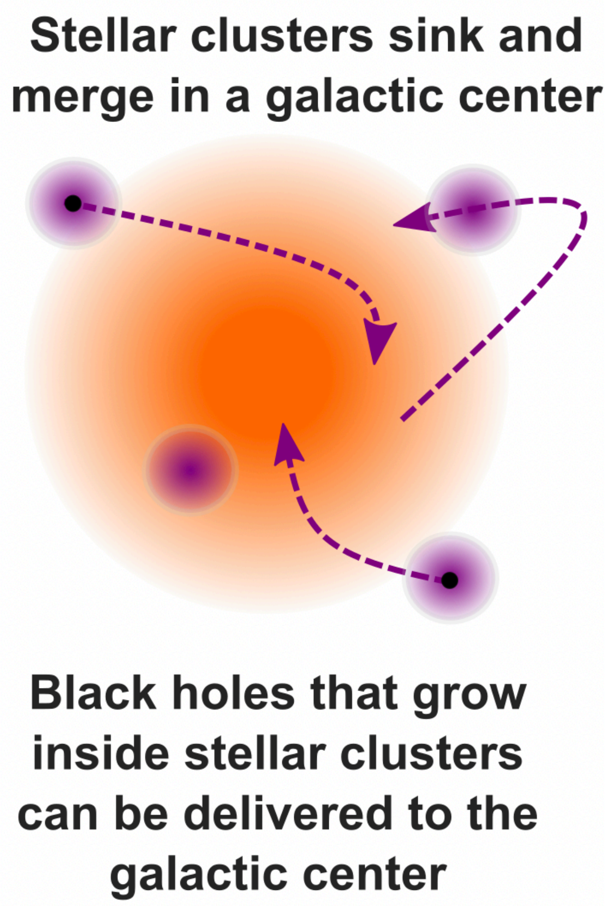
  (e.g., Hartmann et al. 2011; Antonini et al. 2012; Mastrobuono-Battisti et al. 2014)

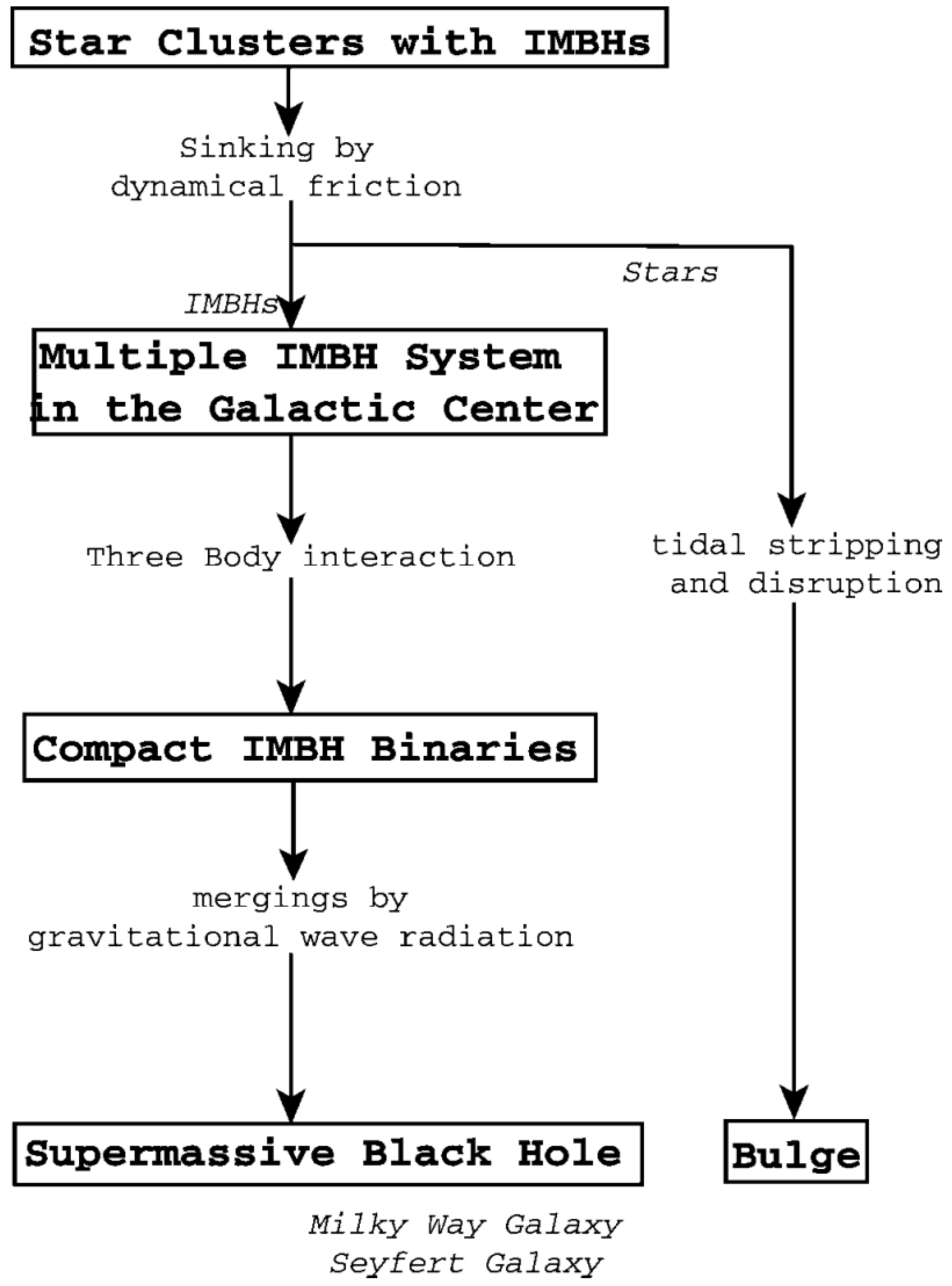
- Some of those star clusters form and retain an IMBH

  (talks and posters by *Natalia Lahén, Antti Rantala, Michiko Fujii, Benedetta Mestichelli, Maximilian Häberle, Lavinia Paiella, Konstantinos Kritos, Ambreesh Khurana*)



Askar, Baldassare & Mezcua (2024); https://arxiv.org/abs/2311.12118





Ebisuzaki et al. (2001)

What happens to the IMBHs?

- Can we keep them?
- How much must they grow to form SMBHs?

P1: Building up an NSC by merging stellar

- Carried out *N*-body simulations of the final stages of an idealised merger between 3 star clusters

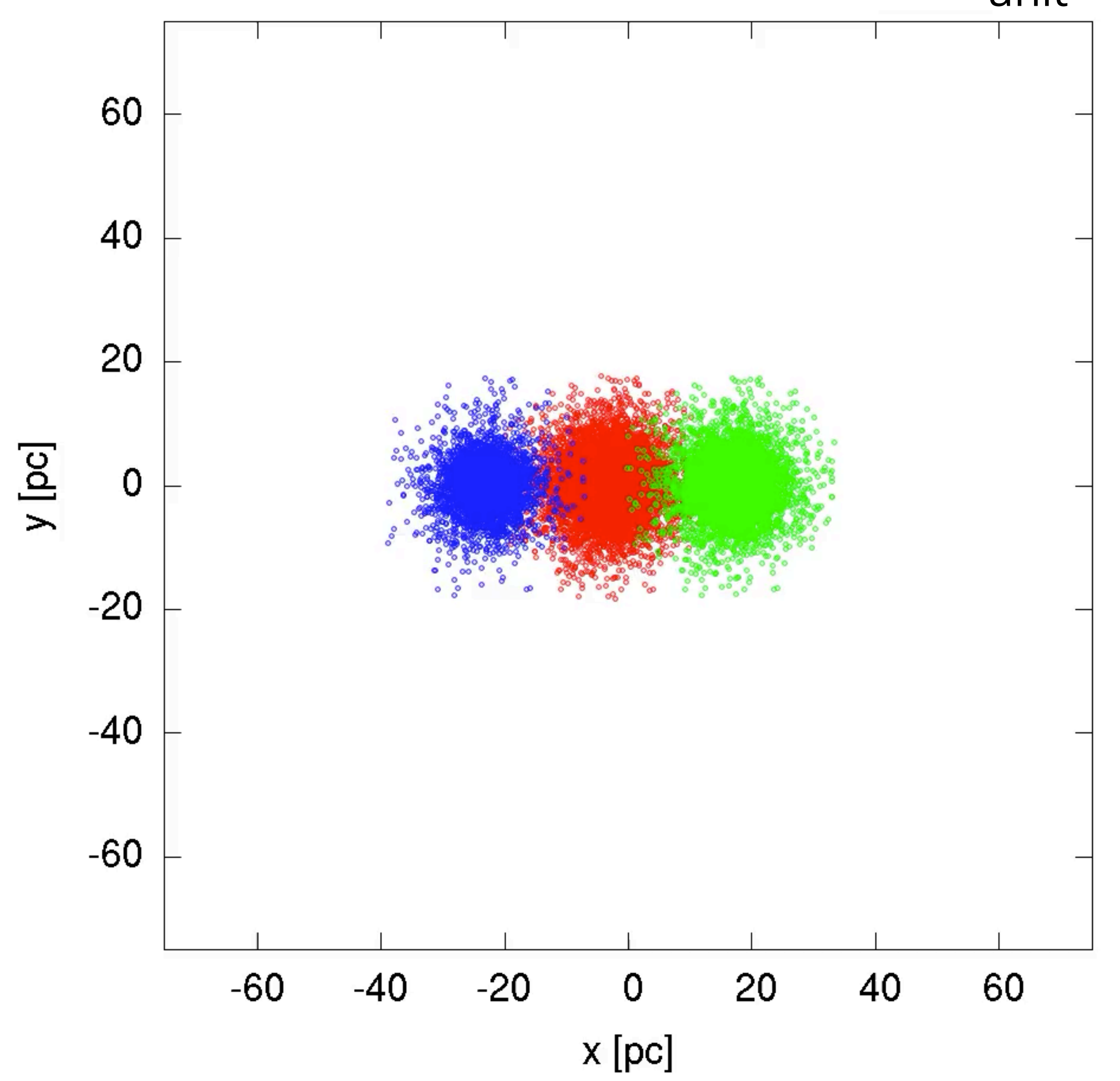
  - NBODY6++GPU - (Wang, Spurzem et al. 2015)

- Merging clusters contains stars and up to 3 central IMBHs in different configurations
  - 50 000, 30 000 and 15 000 single stars ($0.5\ M_\odot < M < 2\ M_\odot$)
  - Total Mass: $\sim 8.4 \times 10^4\ M_\odot$
- Follow growth of NSC and determine fate of one, or many, IMBHs

cf. Ebisuzaki et al. (2001); Kim, Figer & Morris (2004); Portegies Zwart et al. (2006), Miocchi et al (2006); Hartmann et al. (2011); Antonini et al. (2012); Mastrobuono-Battisti et al. (2014); Arca Sedda et al. (2015; 2019); Petts & Gualandris (2017); Arca-Sedda & Gualandris (2018); Wirth & Bekki (2020); Chassonnery & Capuzzo-Dolcetta (2021); Khan & Holley-Bockelmann (2021); Fragione (2022)

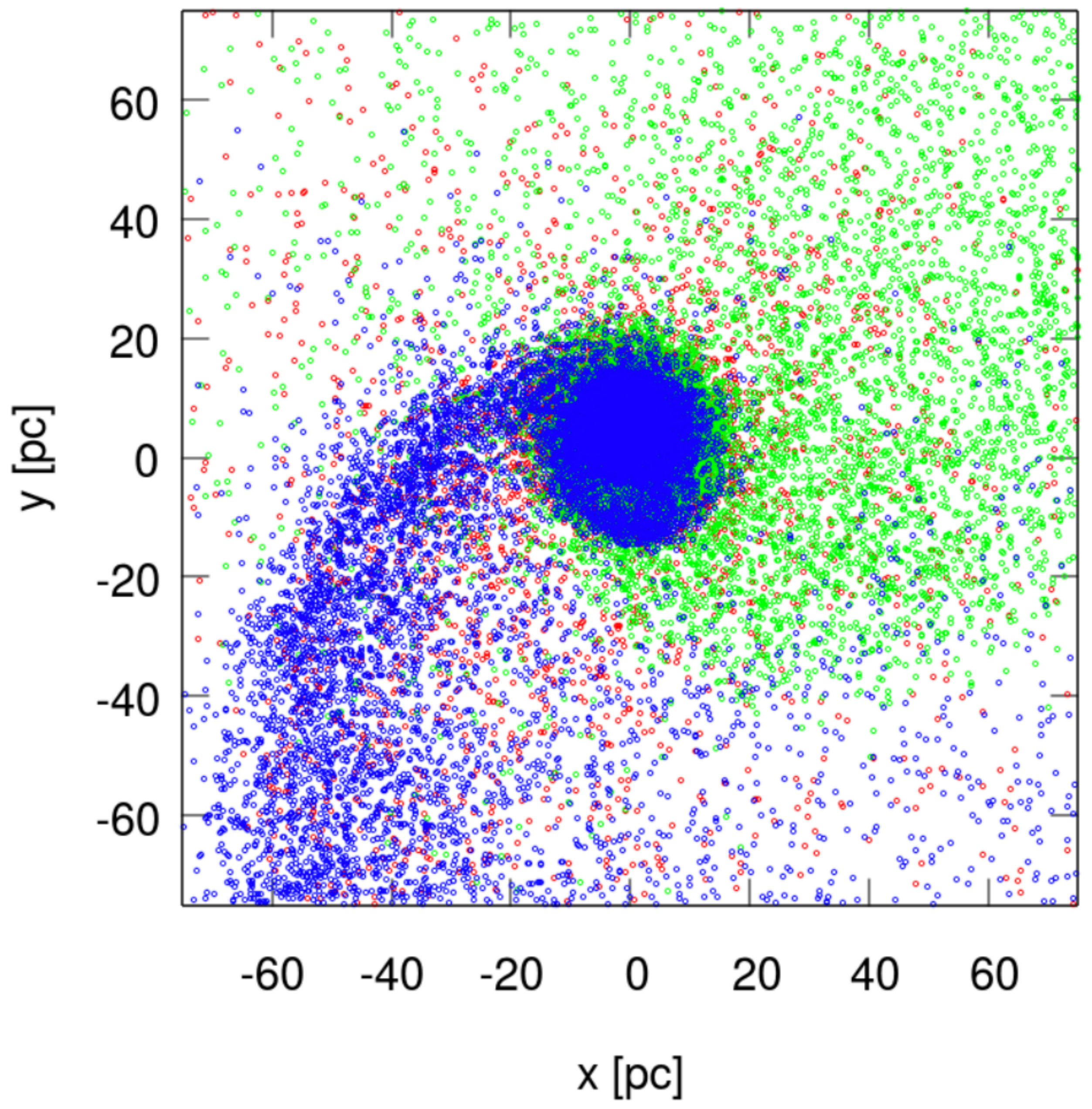
- No pre-existing SMBH
  - Assume that individual star clusters had evolved for ~ 100 Myr before they merged with each other.
  - Presence of young clusters with masses larger than $10^5\ M_\odot$ in the innermost 150 pc of a few dwarf starburst galaxies (Nguyen et al. 2014)

- 1 NB output time unit ~ 0.7 Myr

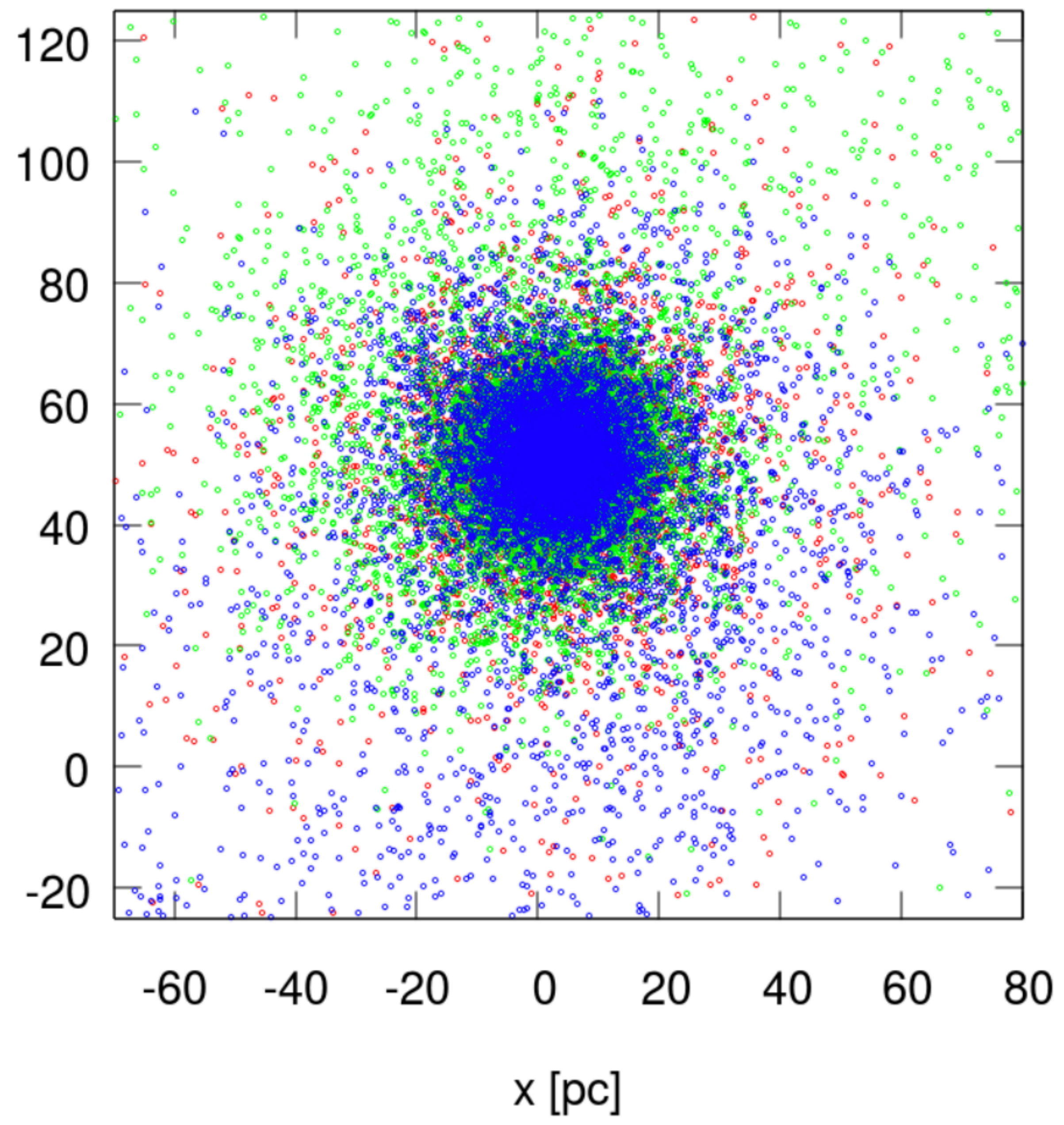


	Run	M_1 ($M_\odot$)	M_2 ($M_\odot$)	M_3 ($M_\odot$)
No IMBH	0.1	0	0	0
1 IMBH	1.1	1000	0	0
	1.2	0	500	0
	1.3	0	0	200
2 IMBHs	2.1	1000	500	0
	2.2	1000	100	0
	2.3	1000	200	0
	2.4	0	500	200
3 IMBHs	3.1	1000	500	200
	3.2	500	1000	200
	3.3	200	500	1000

P1: Merged cluster properties with no IMBH

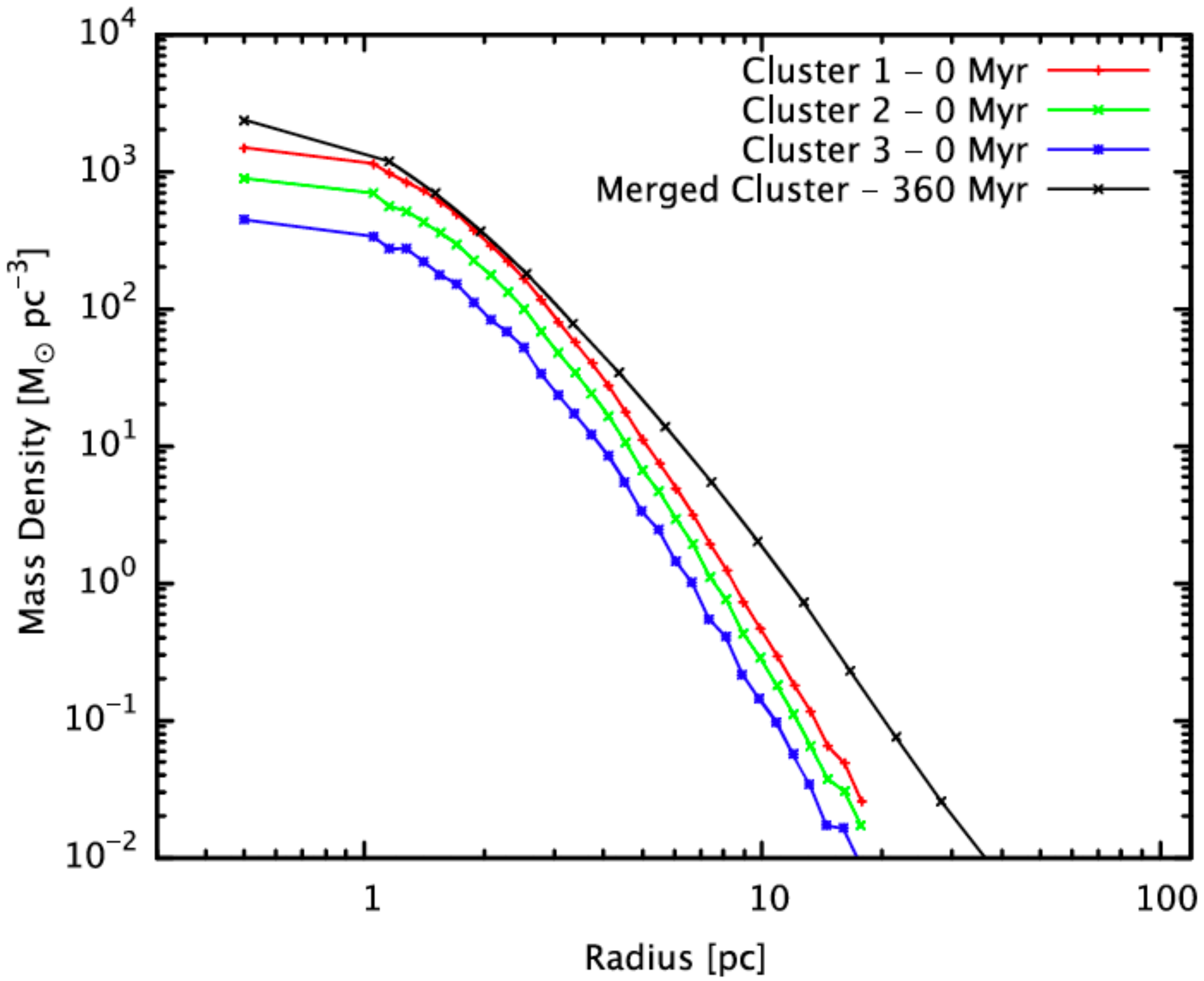


28.8 Myr



360 Myr

Density profile of the merged cluster



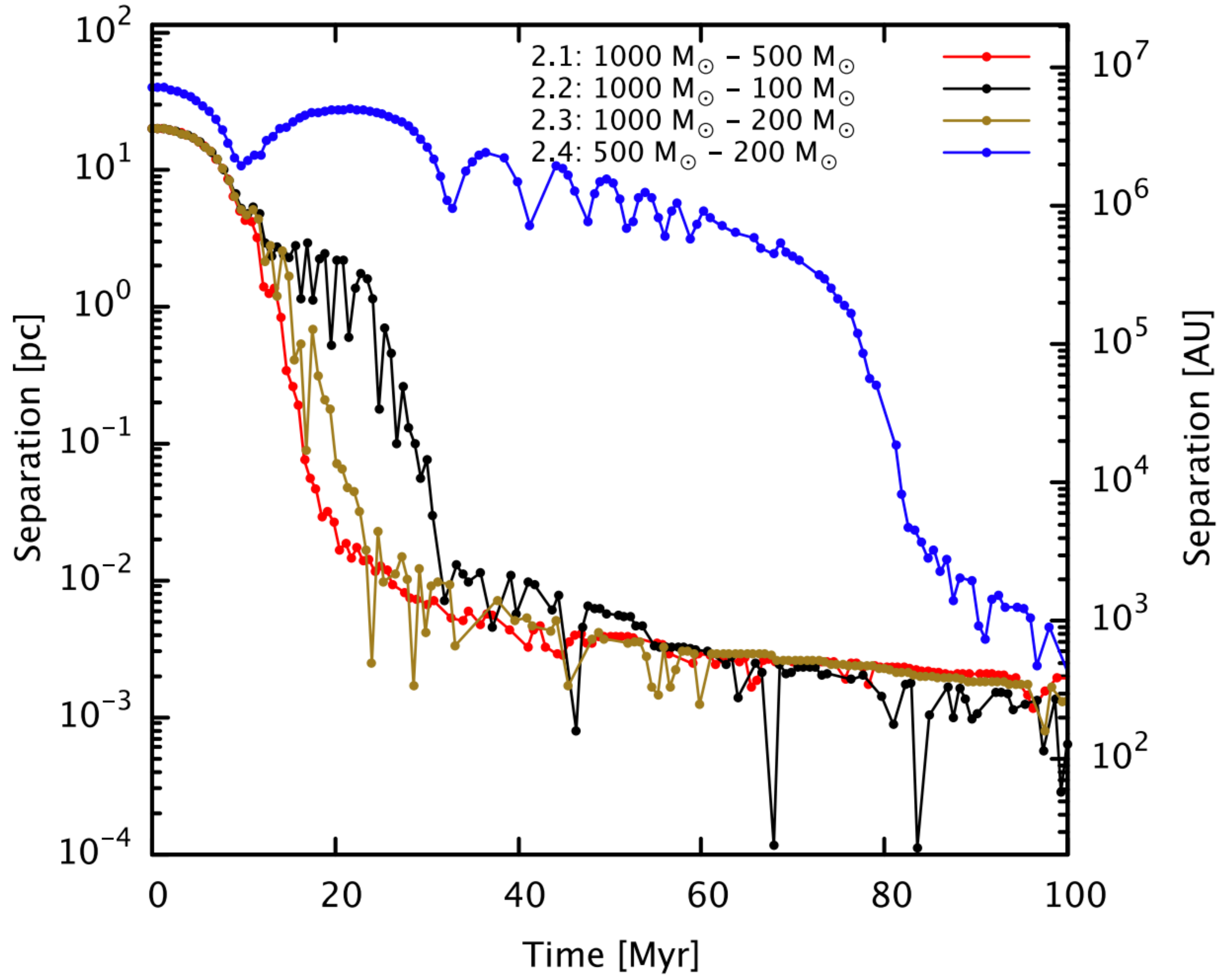
The merged cluster at 360 Myr is more radially extended and has a denser core than the 3 initial merging clusters.

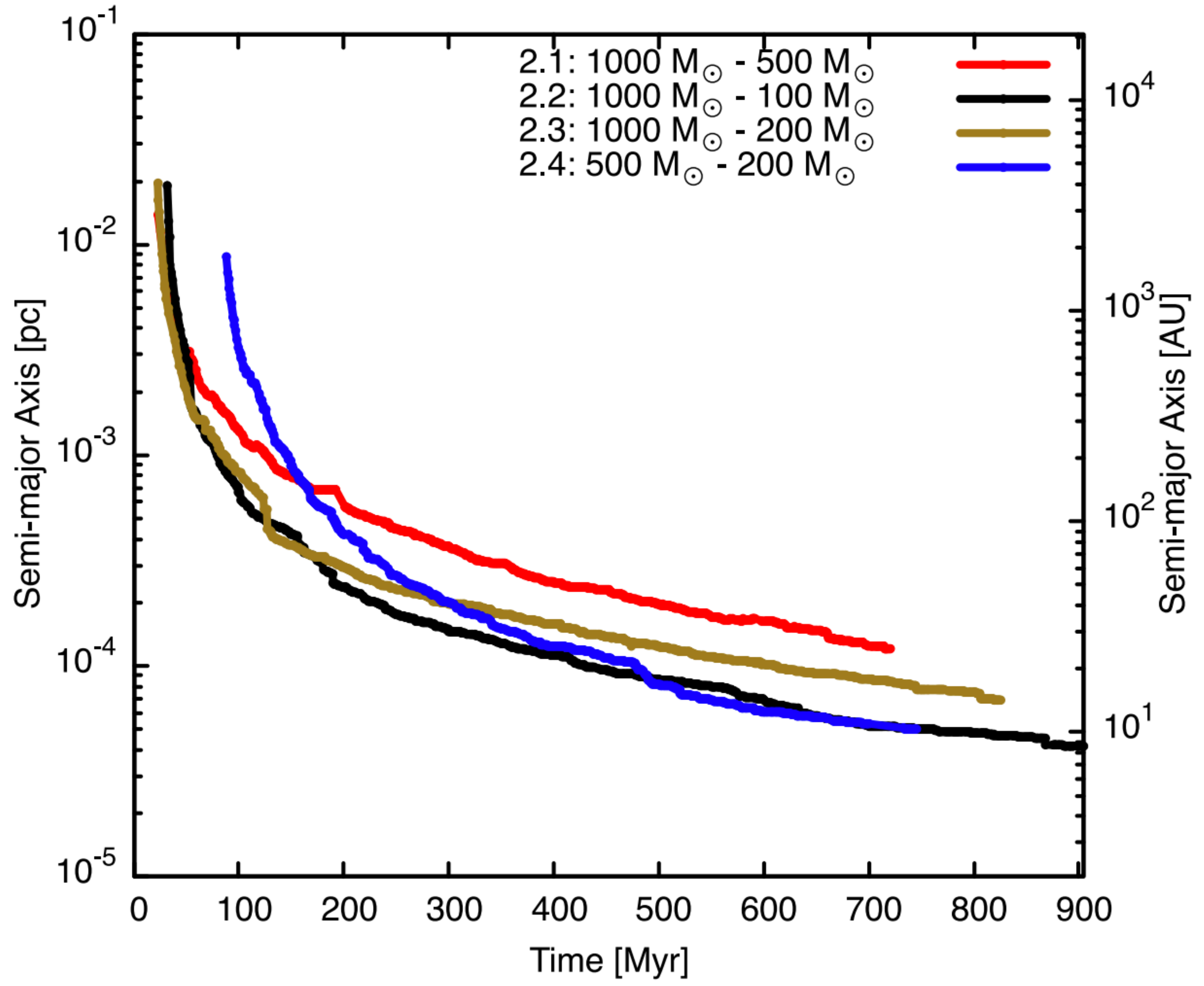
Figures from Askar, Davies & Church (2021)

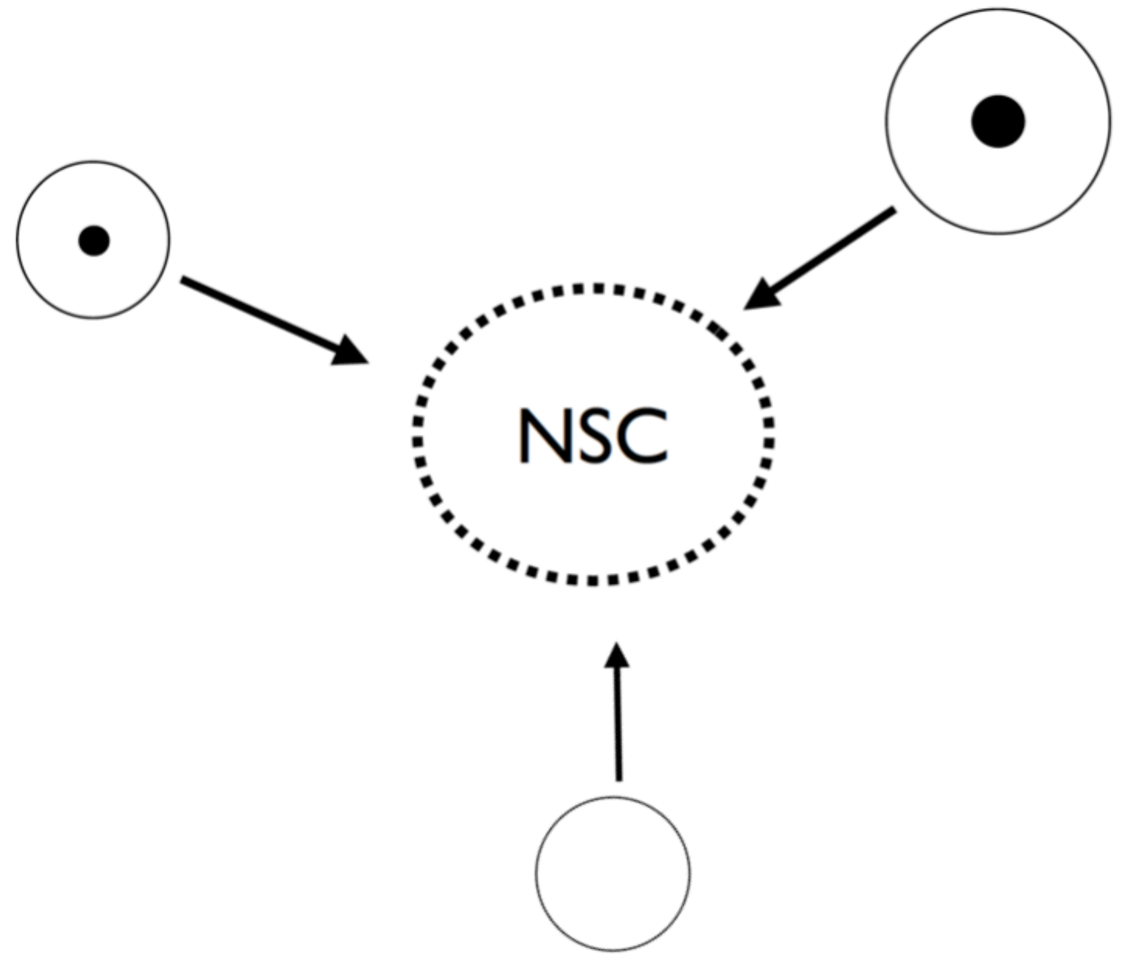
P1: Merging stellar clusters that contain 2 IMBHs

- $M_\star \ll M_{\rm imbh} \ll M_{\rm cluster}$
- IMBHs segregate to the center of the merged cluster and form a binary IMBH (talk by *Konstantinos Kritos*)
- IMBH binary hardens as it interacts with surrounding stars (talk by *Lazaros Souvaitzis*)

Run	Time (Myr)	Total mass ($M_\odot$)	$IMBH_1$ ($M_\odot$)	$IMBH_2$ ($M_\odot$)	$IMBH_3$ ($M_\odot$)
2.1 ●	716	8.55×10^4	1000	500	0
2.2 ●	914	8.50×10^4	1000	100	0
2.3 ●	825	8.52×10^4	1000	200	0
2.4 ●	745	8.47×10^4	0	500	200







Figures from Askar, Davies & Church (2021)

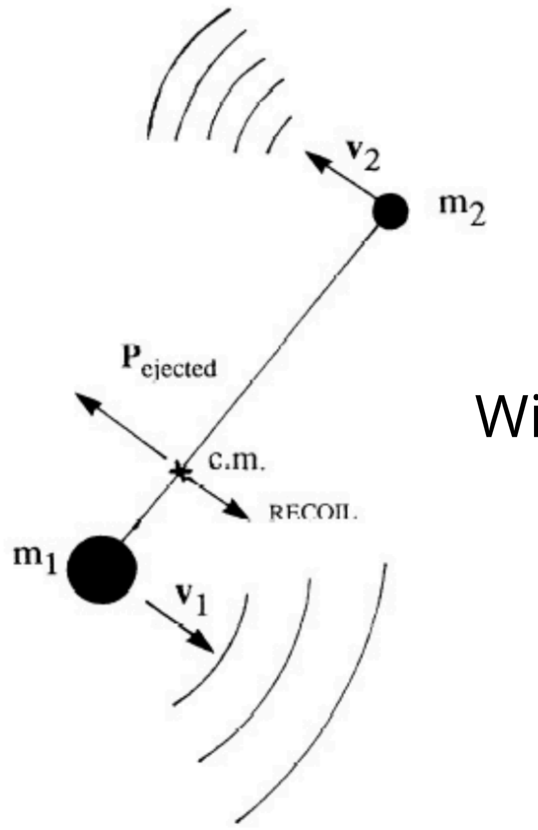
P1: IMBH binary merger and recoil kicks

- Encounters between stars and an IMBH (at apocenter) ➝ decreases semi-major axis $r_{\text{apo}} = a(1+e)$ ➝ drives up eccentricity
- Increasing eccentricity leads to efficient merger due to gravitational wave (GW) radiation emission ➝ ~ few hundred Myr to Gyr

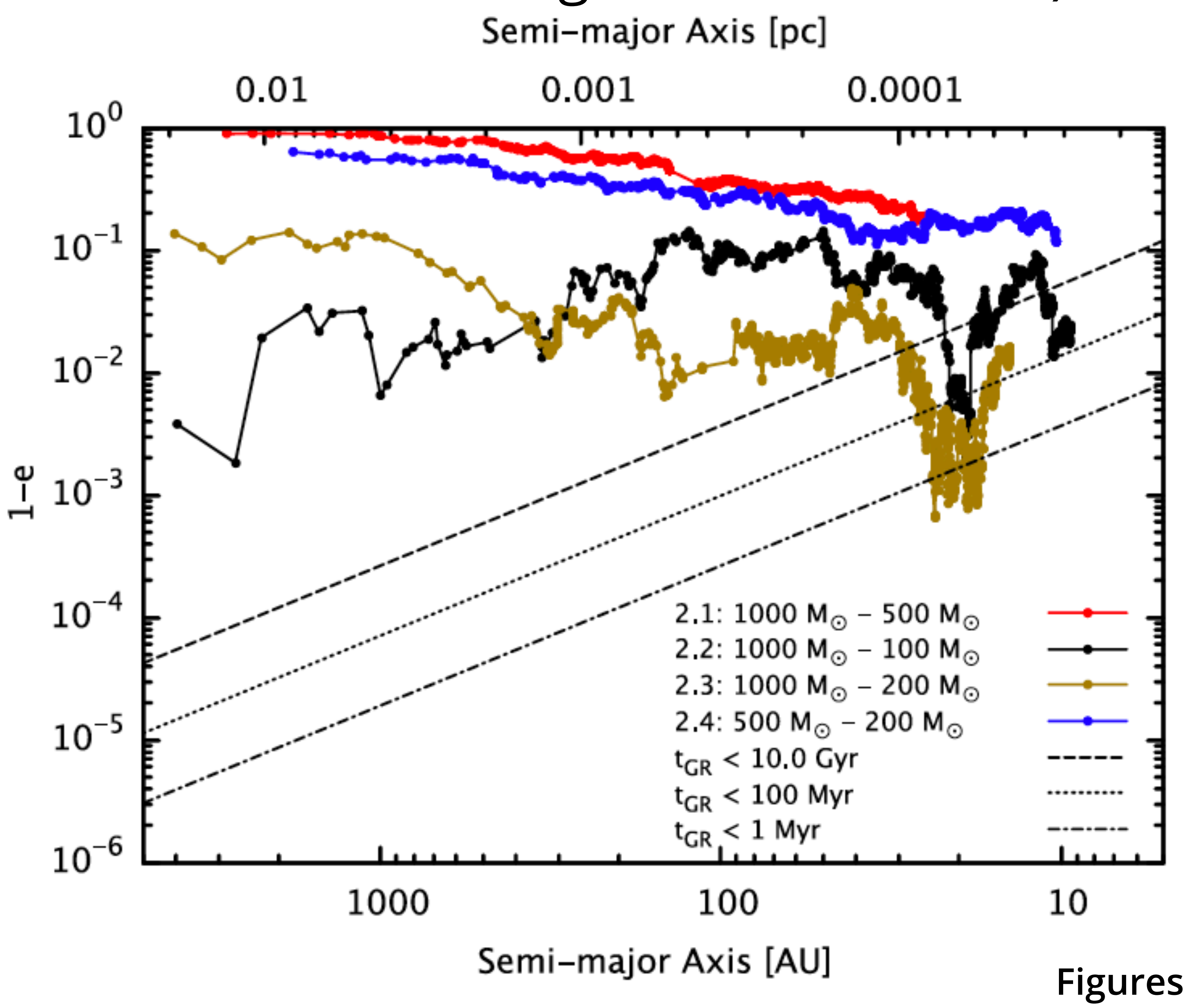
$$\tau_{gr} \simeq 10^{10} yr \left(\frac{a_{bin}}{3.3 R_\odot}\right)^4 \frac{1}{(m_1+m_2)m_1 m_2} \cdot \left(1-e^2\right)^{7/2}$$

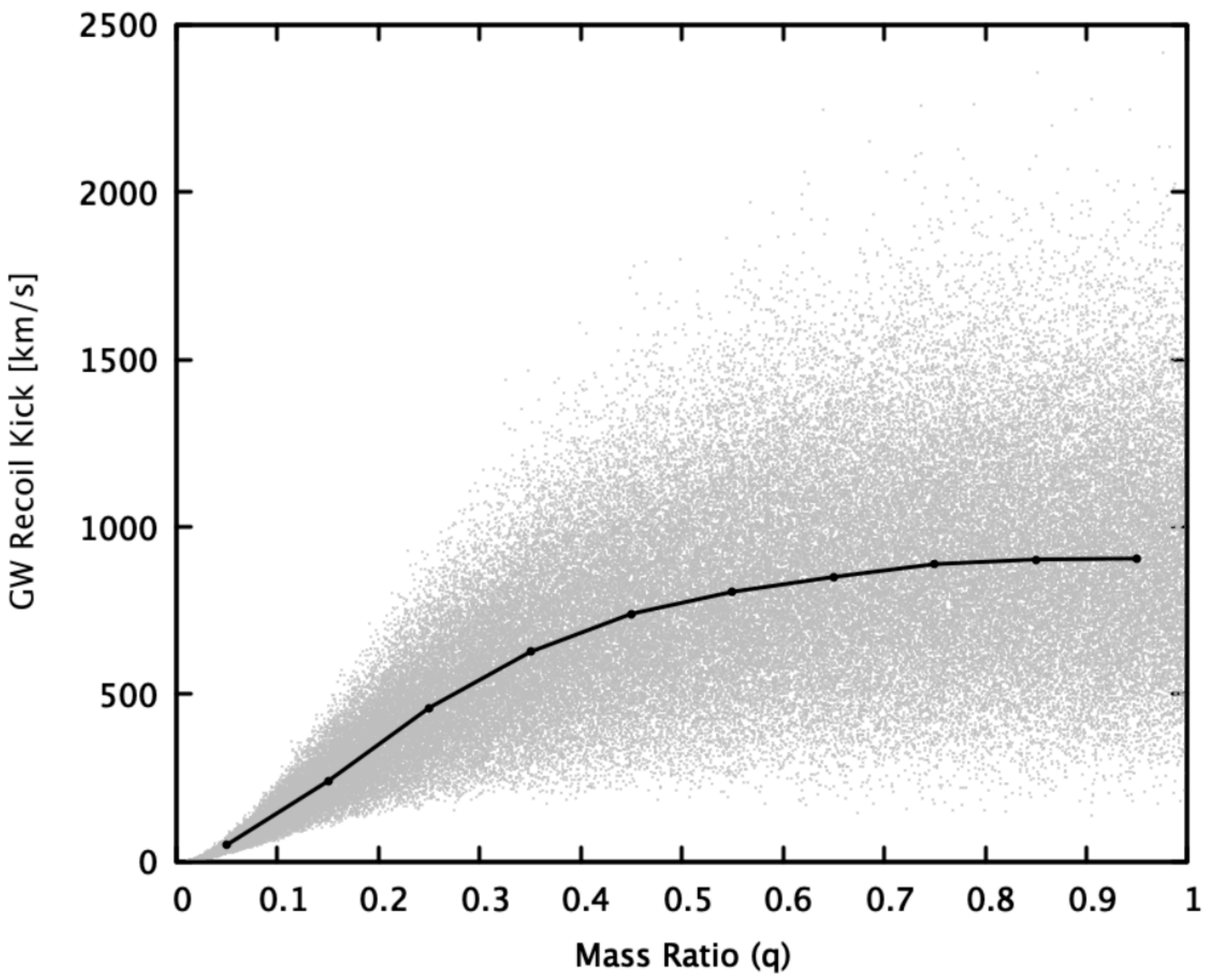
(Peters 1964)

- Merging black holes receive a GW recoil kick when they merge ➝ up to 1000 km/s
  - BH spin distributions taken from Lousto et al. (2012); peak value of about 0.7 (takes into account the accretion-driven growth of the BHs)



Wiseman (1992)





Figures from Askar, Davies & Church (2021)

Merged black hole is ejected from the cluster:

1+1 = 0

If mass ratio is less than around 0.15, merged black holes may be kept in clusters (as GW recoil kick is low):

1+ small = 1

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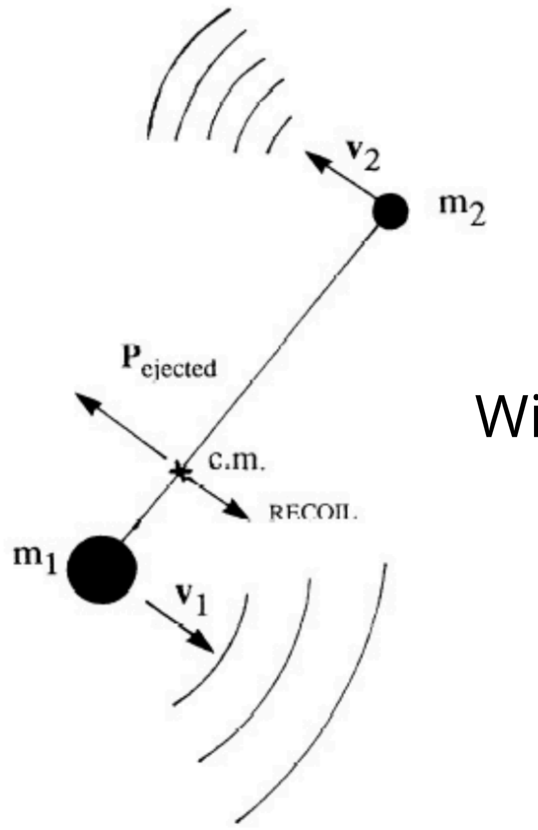

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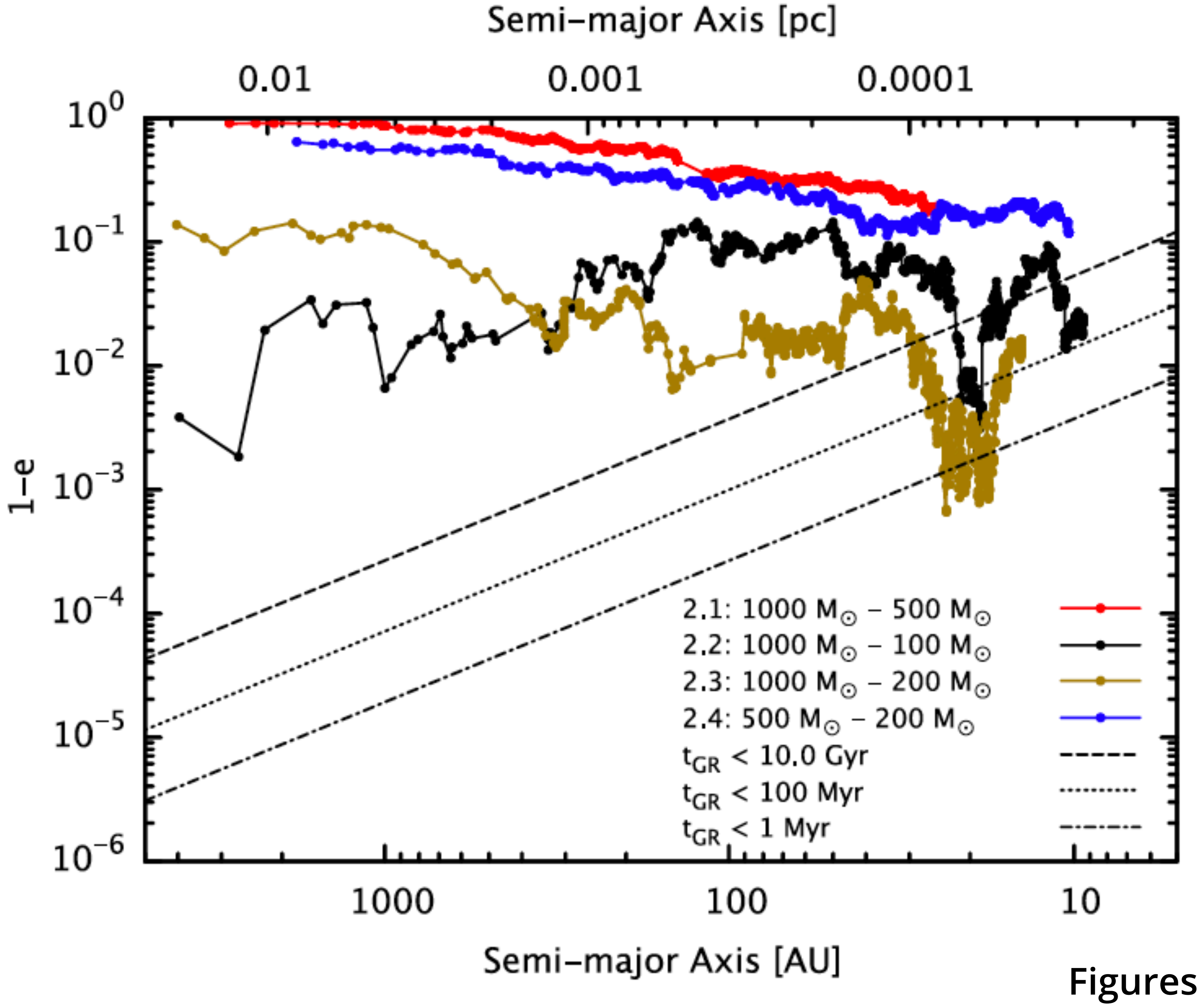

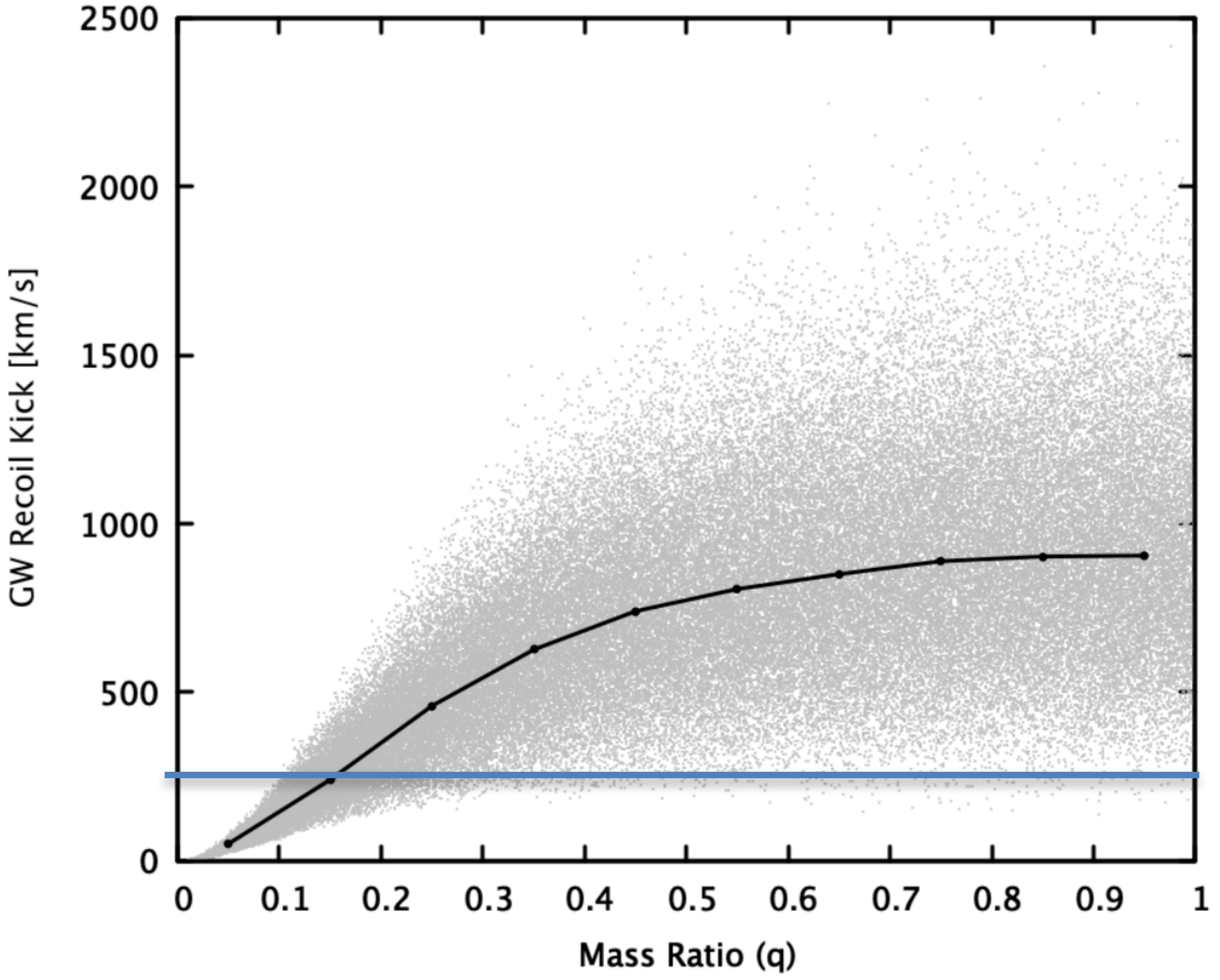

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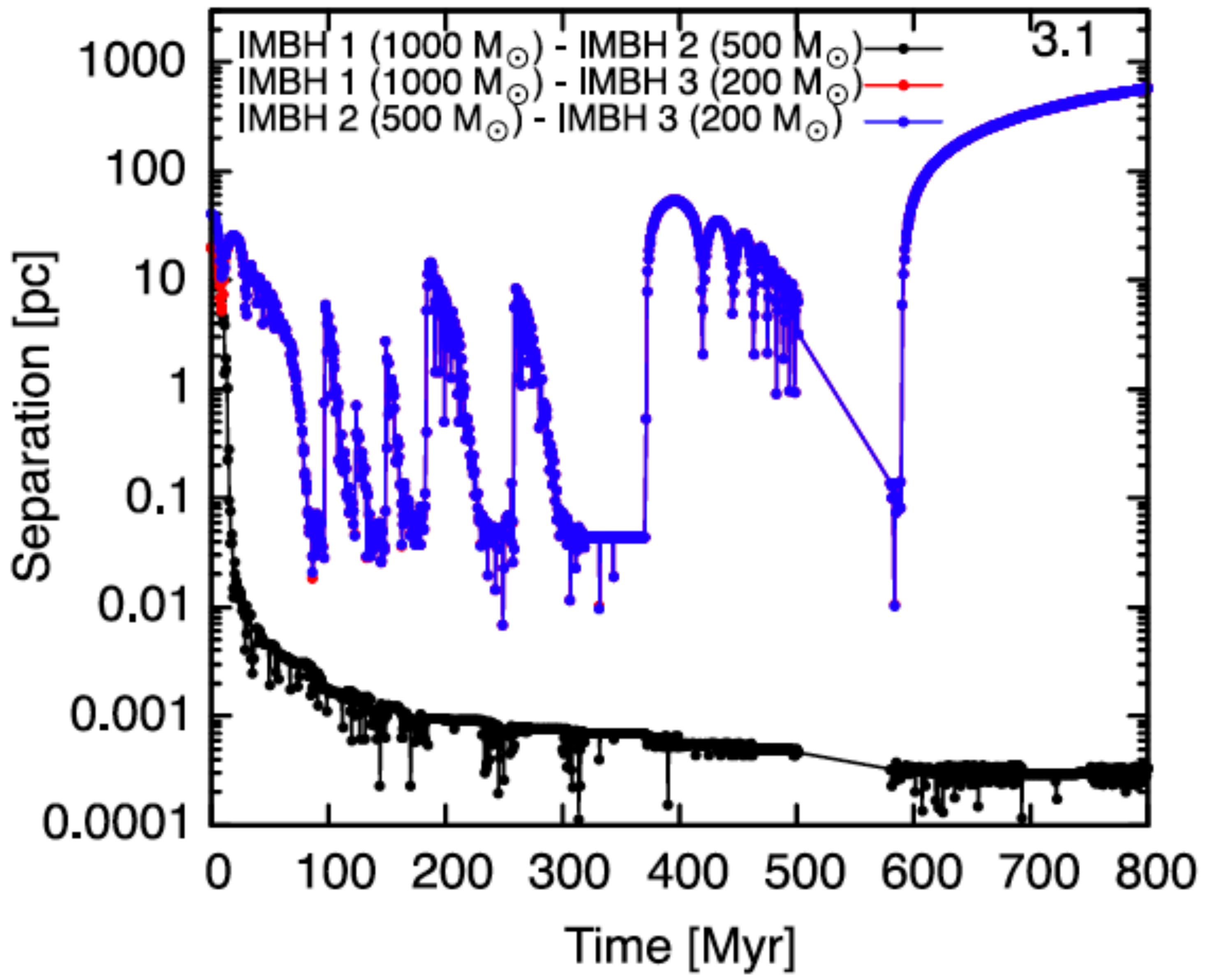
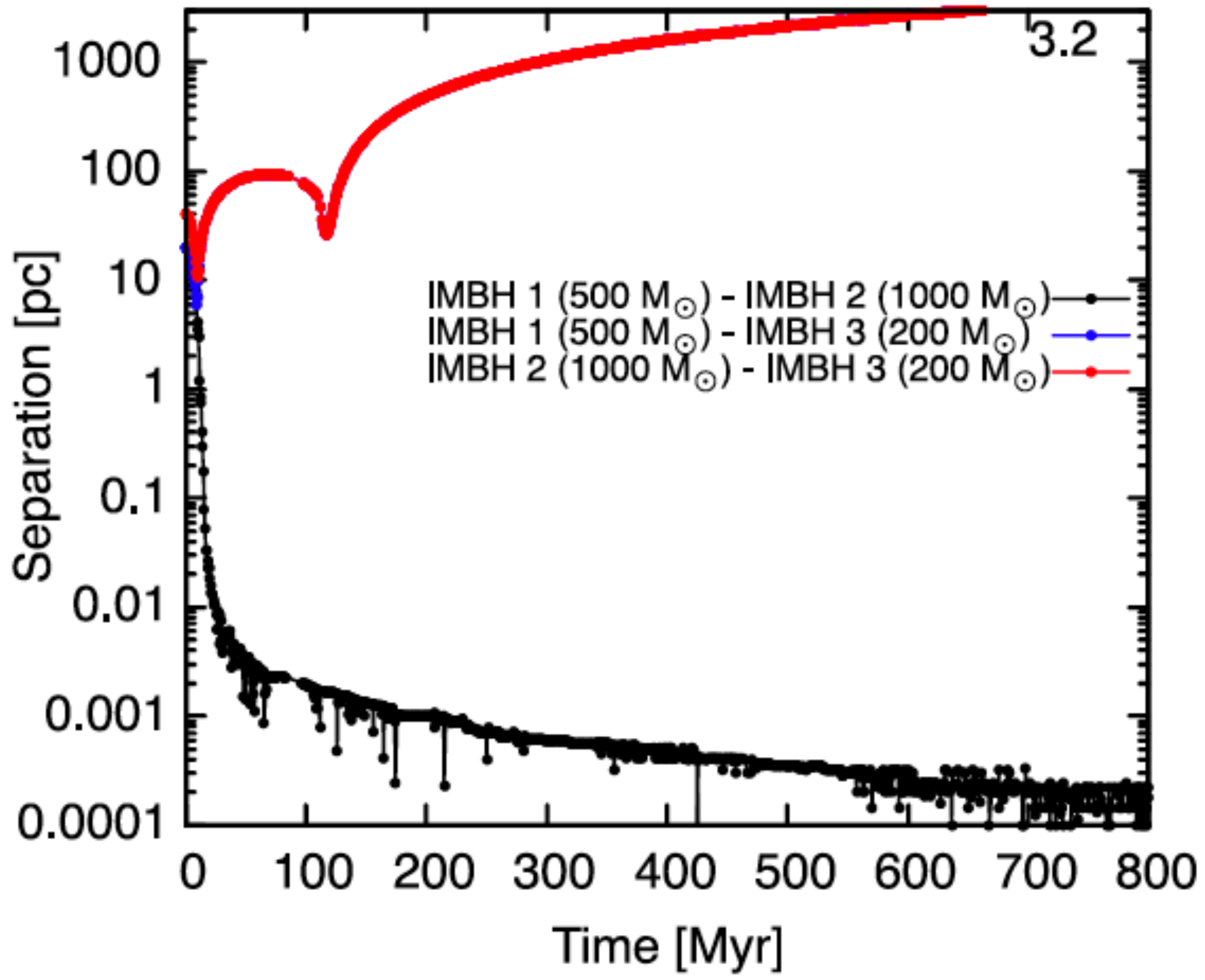
P1: Runs with 3 IMBHs: multiplicity of outcomes

- 2 most massive IMBHs form a binary
- Less massive IMBH gets scattered away due to binary - single interaction or tidally stripped away during cluster merger

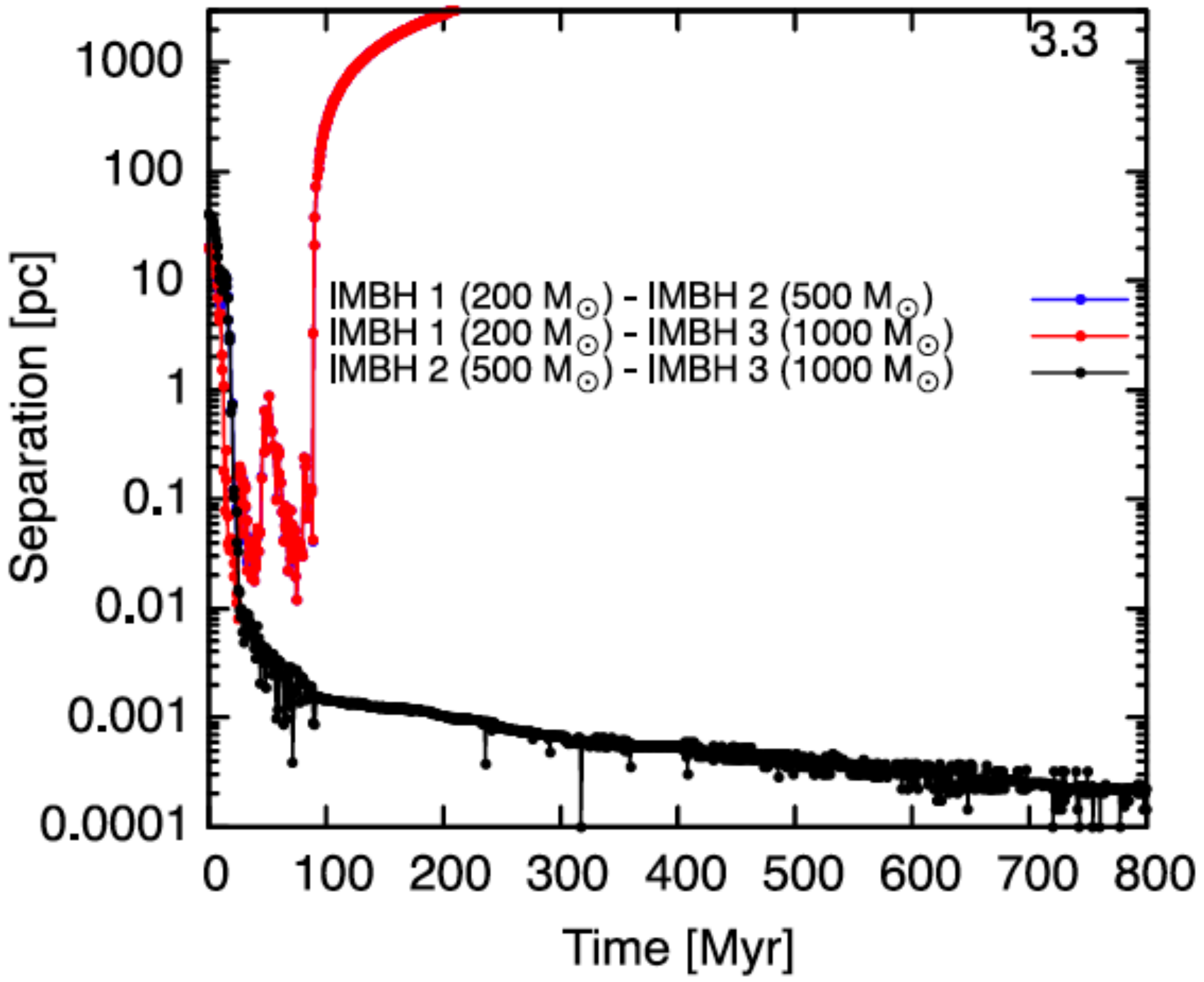
Run	Time (Myr)	Total Mass ($M_\odot$)	$IMBH_1$ ($M_\odot$)	$IMBH_2$ ($M_\odot$)	$IMBH_3$ ($M_\odot$)
3.1 ●	1511	8.57×10^4	1000	500	200
3.2 ●	832	8.57×10^4	500	1000	200
3.3 ●	939	8.57×10^4	200	500	1000



3.1: multiple binary-single IMBH scatterings



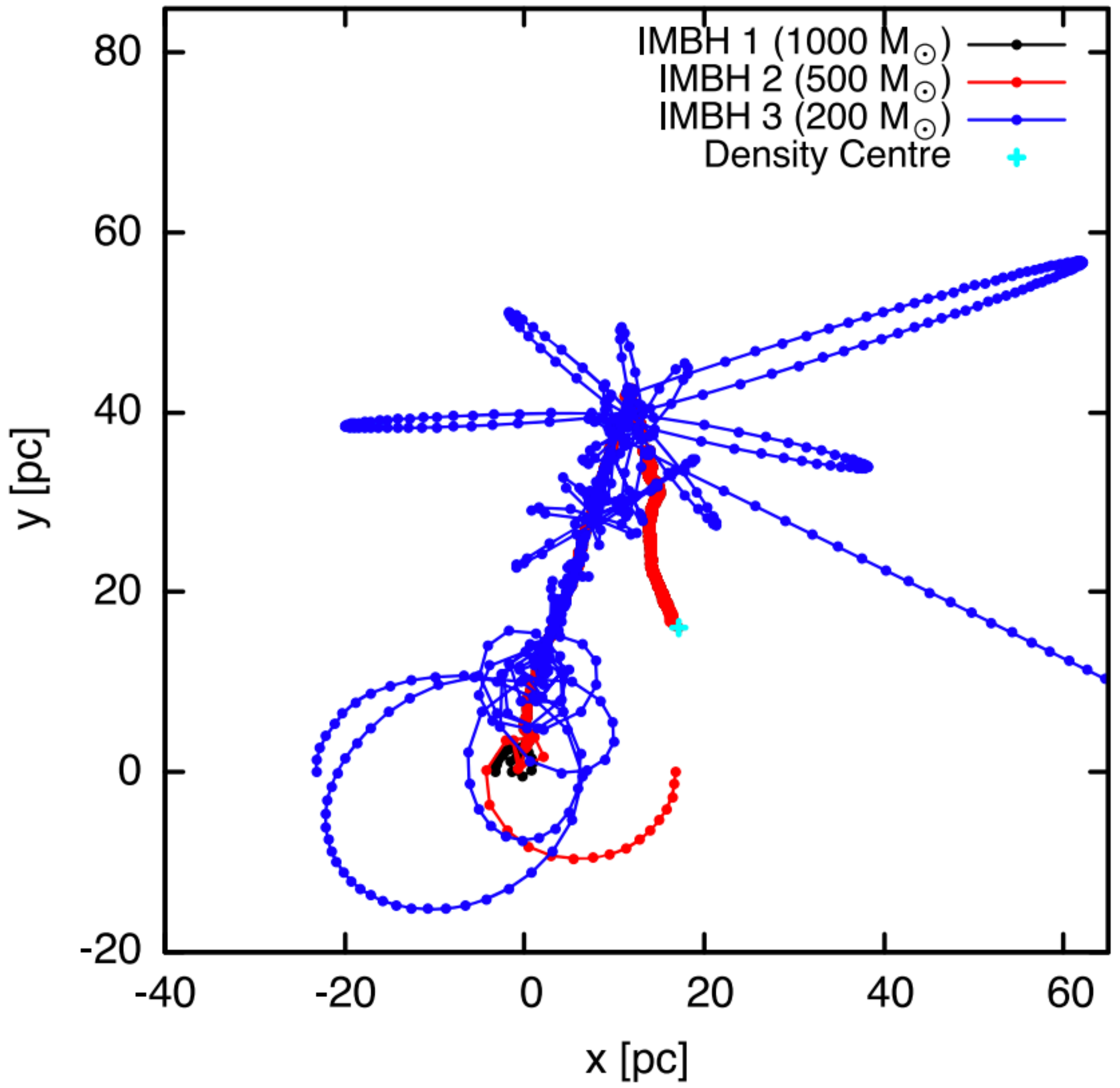
3.2: tidal stripping of third IMBH prevents triple formation



3.3: early ejection of the $200\ M_\odot$ IMBH

P1: Multiple strong binary-single IMBH scatterings

- Interactions of an IMBH triple influence the eccentricity evolution of the inner binary IMBH
- These interactions also influence the density of stars around in the vicinity of the IMBH binary
- Binary hardening is strongest for runs where stellar density around IMBH binary is highest



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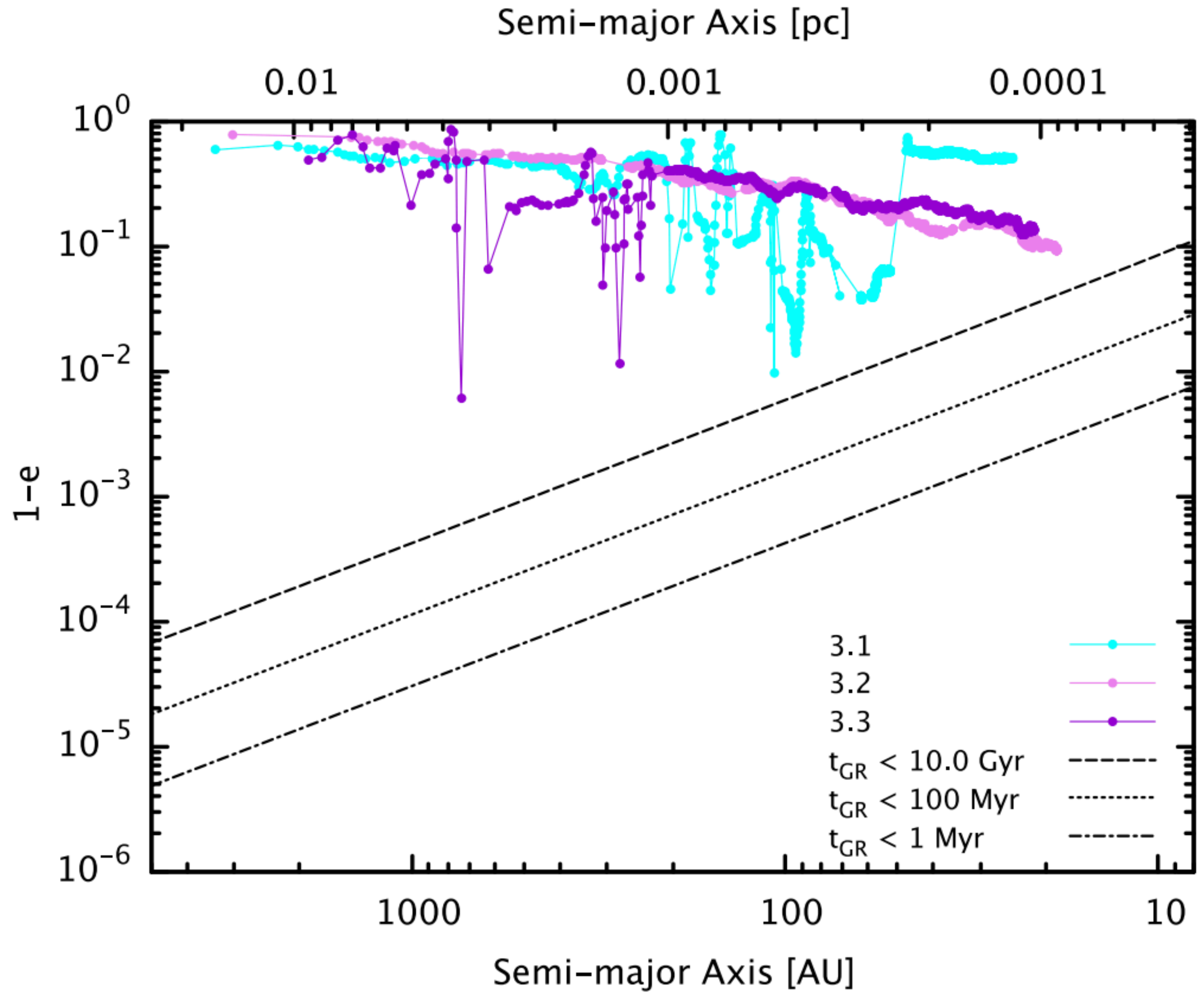
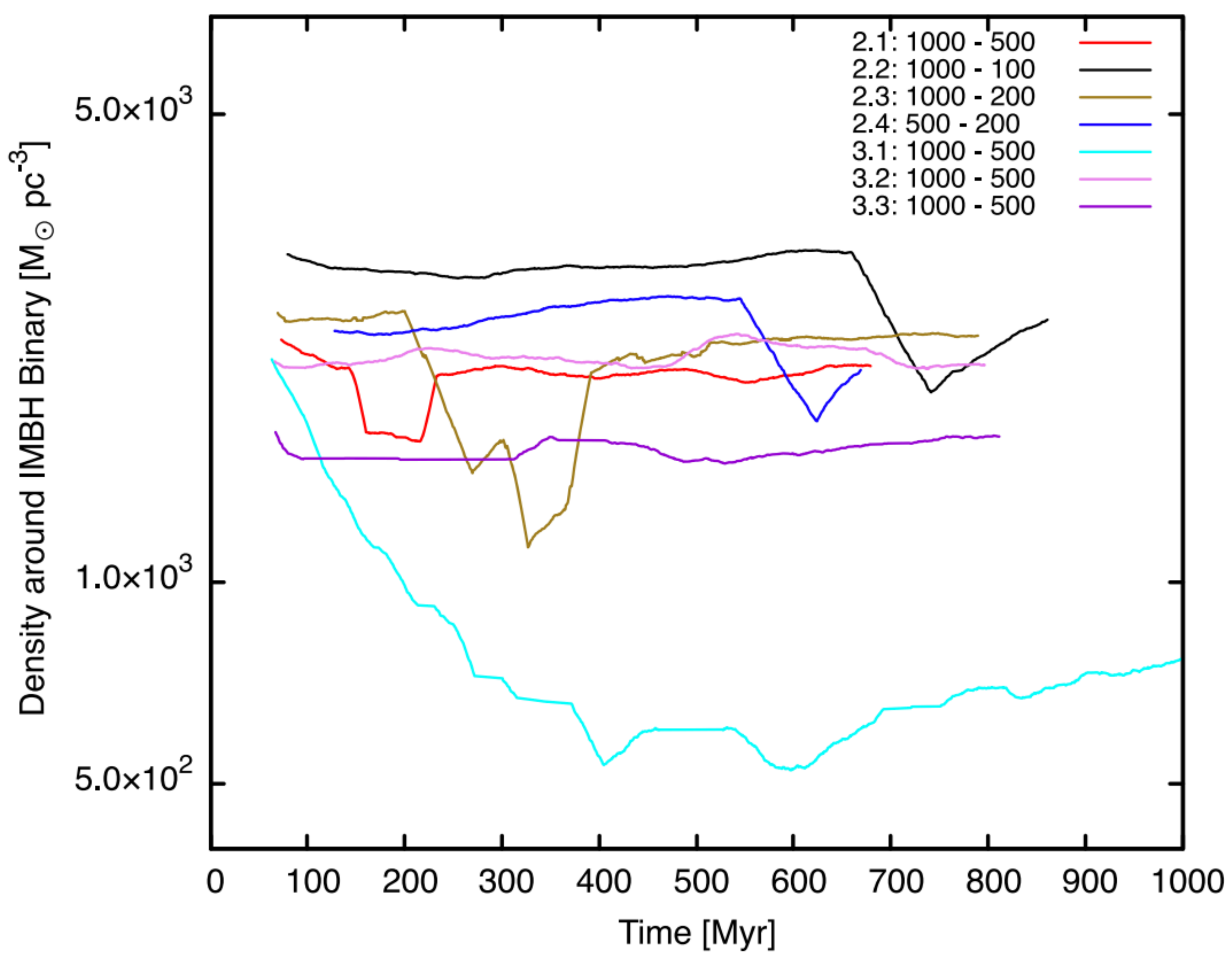
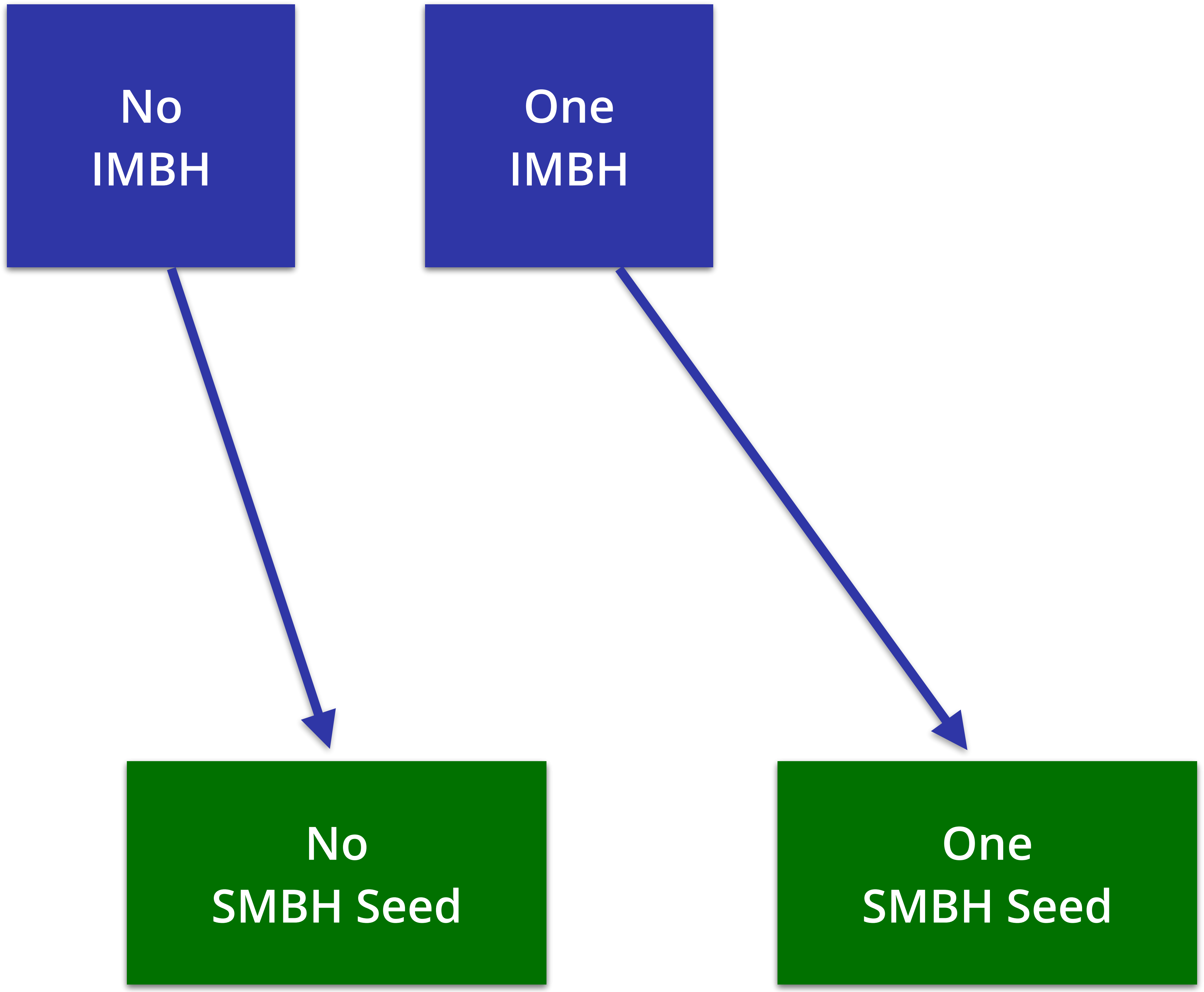




Askar, Davies & Church (2021)

P1: Flowchart of possible outcomes

- Infalling stellar clusters bring (in total):



Goes on to grow by tidal disruption of stars and/or gas accretion (i.e. wet growth with gas inflow)

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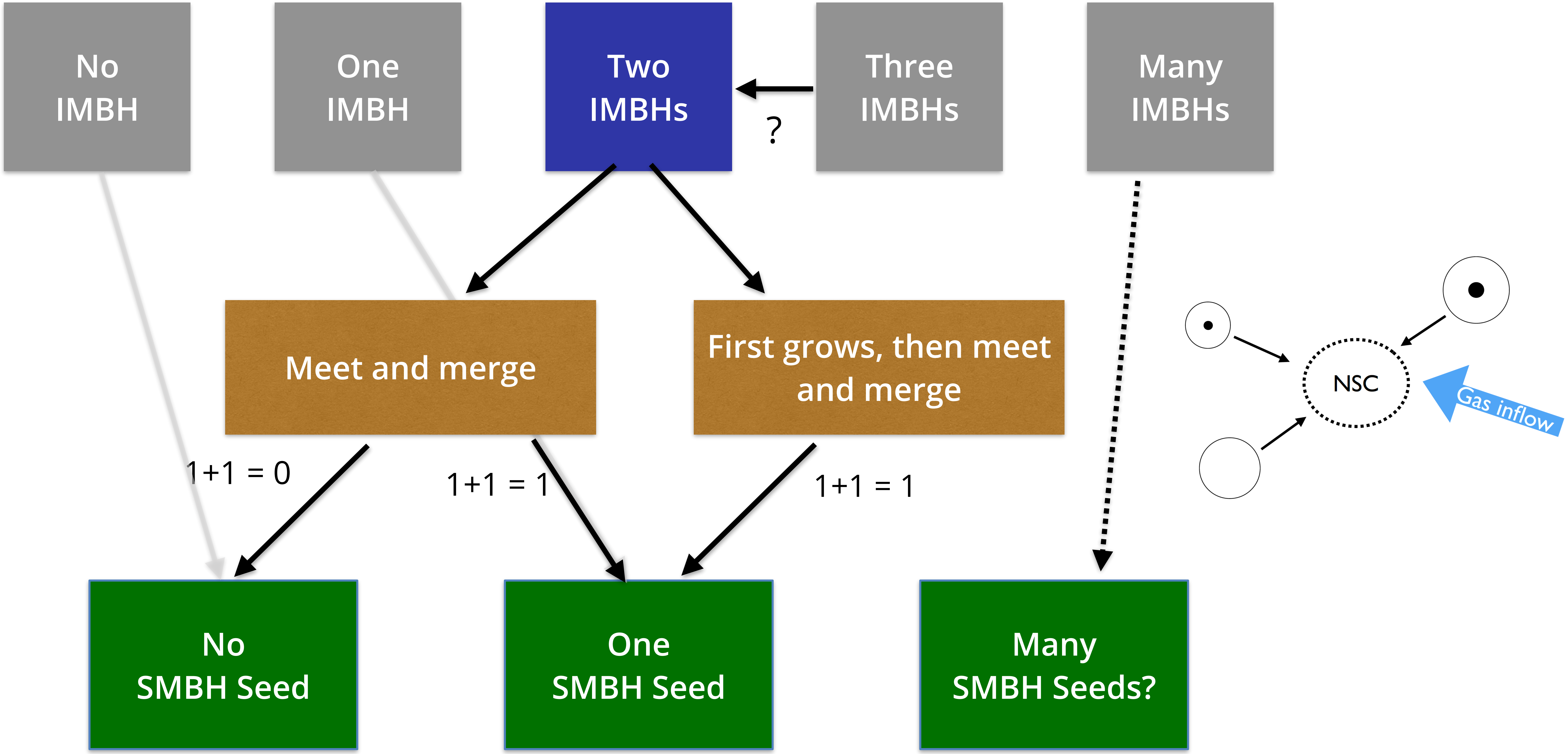
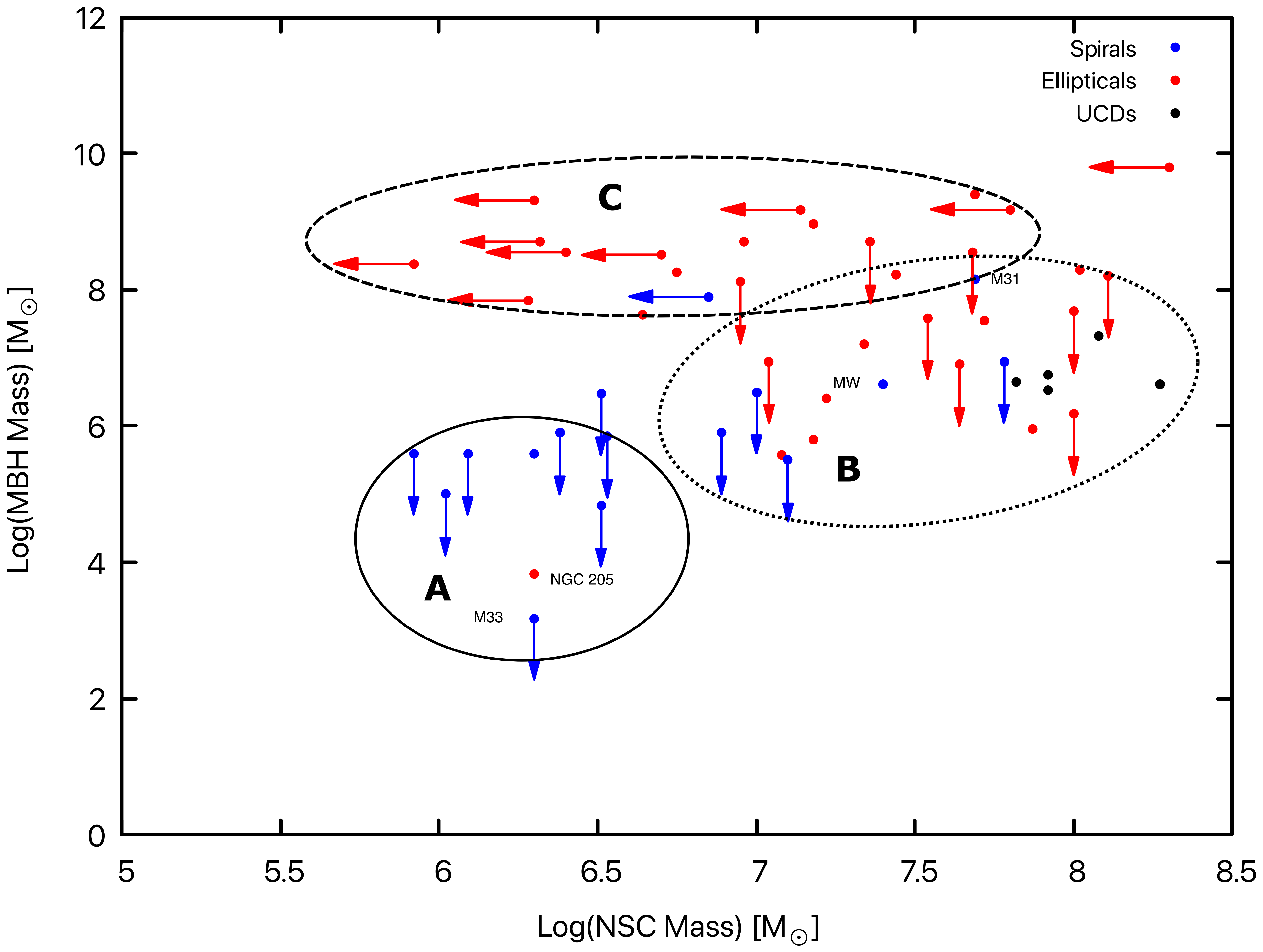


Go on to grow by tidal disruption of stars and/or gas accretion (i.e. wet growth with gas inflow)

P2: Observational consequences of this SMBH seeding mechanism



Data from Table 3 in Neumayer et al. 2022

Askar, Davies & Church (2022)

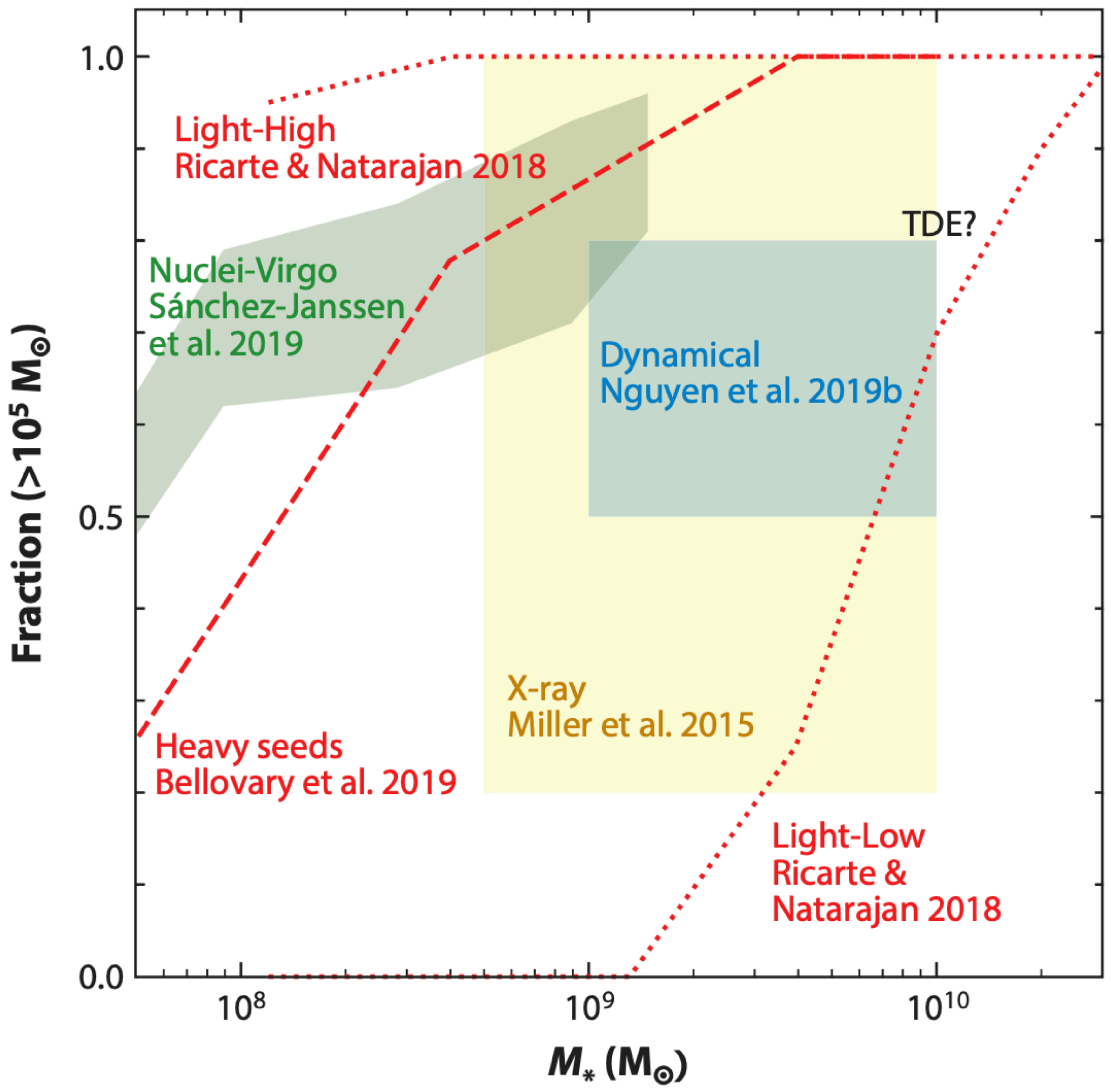
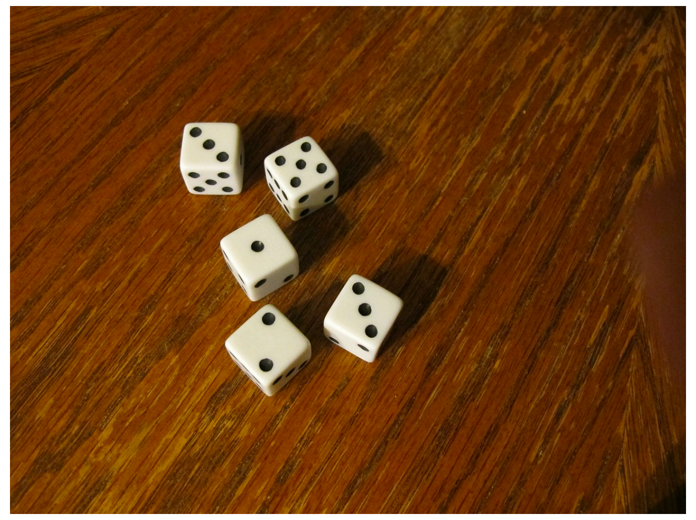
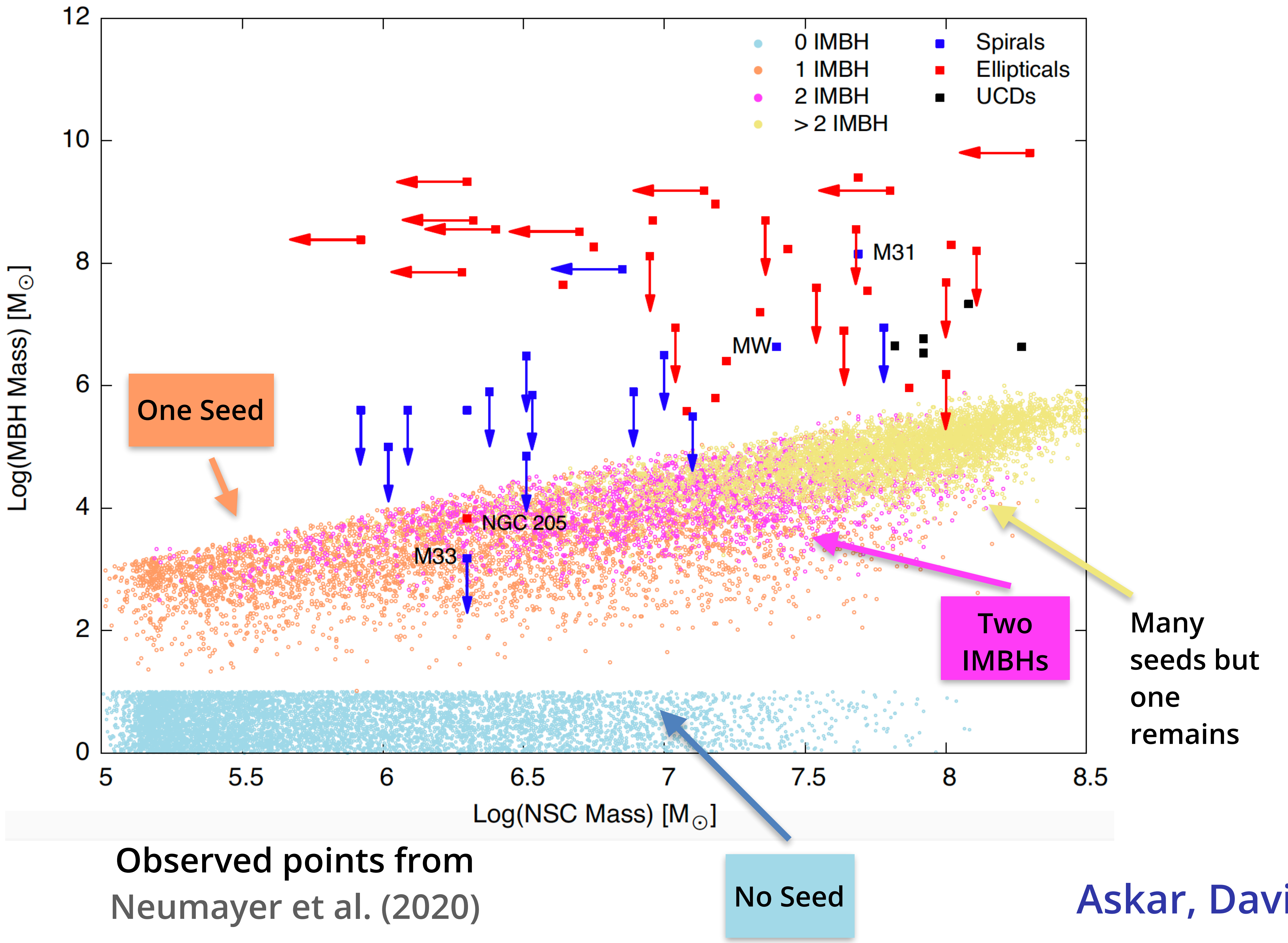


Fig 5 from Greene, Strader & Ho (2019)

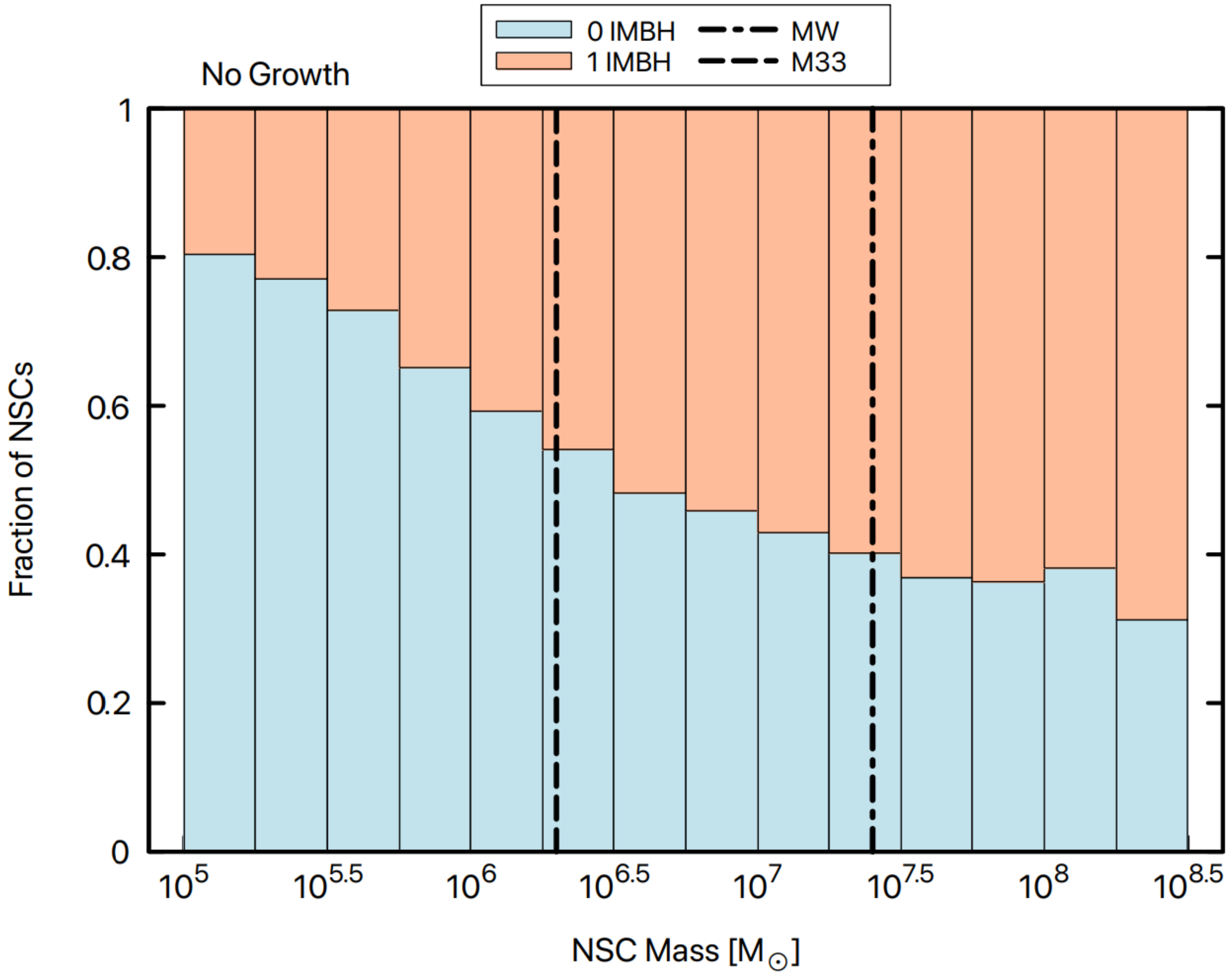
P2: SMBH seed population synthesis results

- Create mock population of galaxies containing a NSC → form NSC by merging clusters → merging clusters can bring along IMBHs
- For multiple IMBHs we assume that a binary IMBH will form and promptly merge (Askar et al. 2021)
- Many pathways but all lead to one or zero SMBHs (merge and retain OR merge and eject)





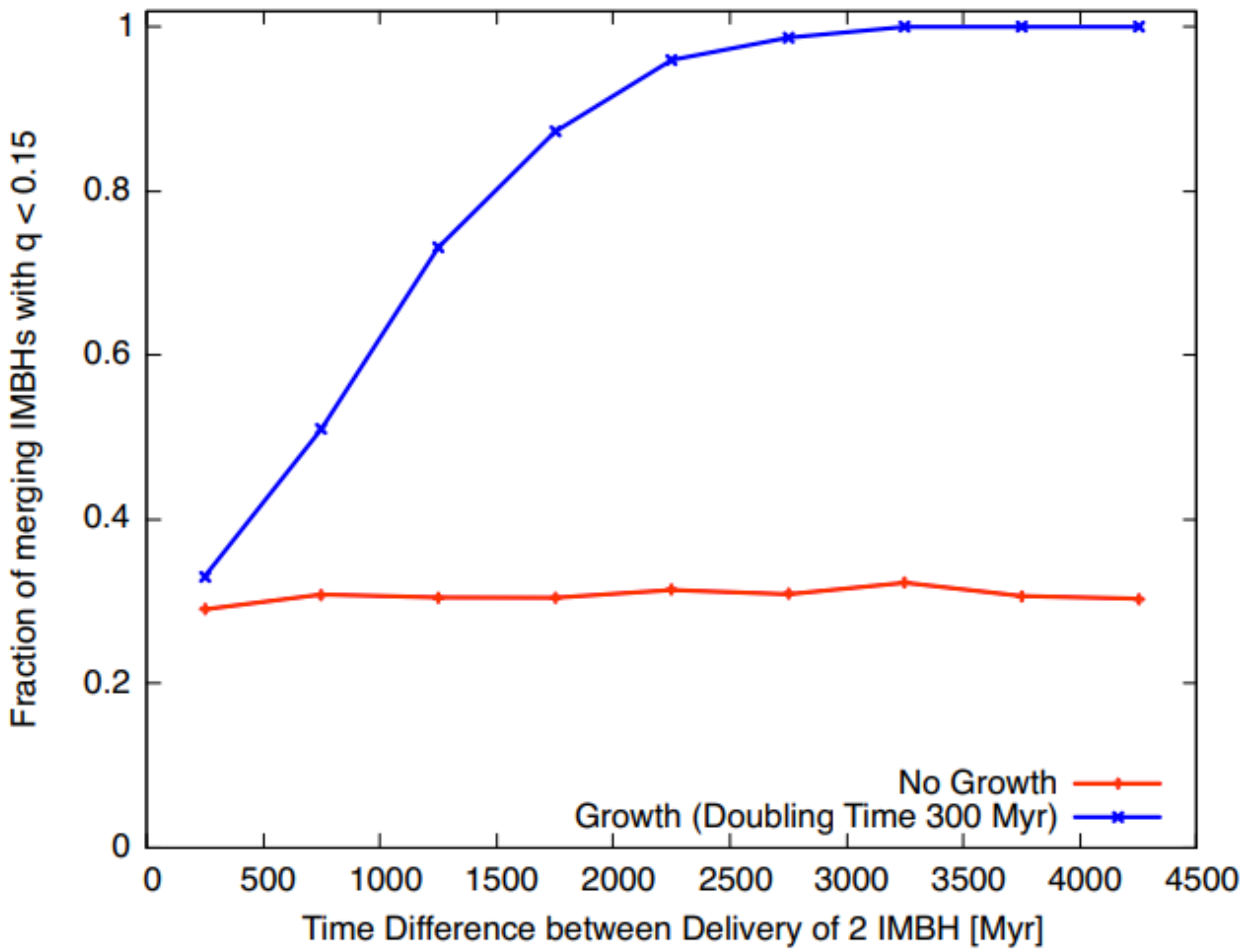
Observed points from Neumayer et al. (2020)

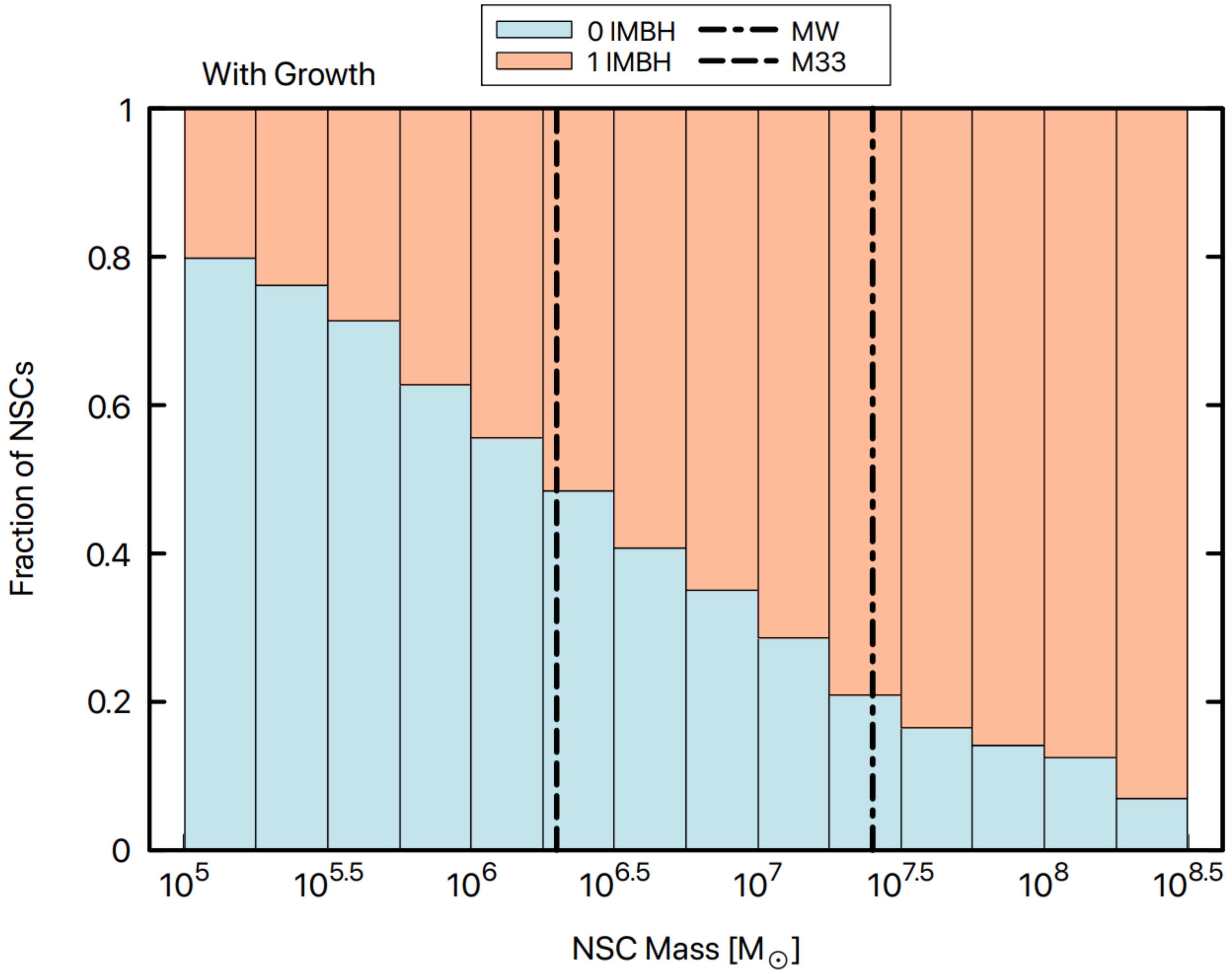


Askar, Davies & Church (2022)

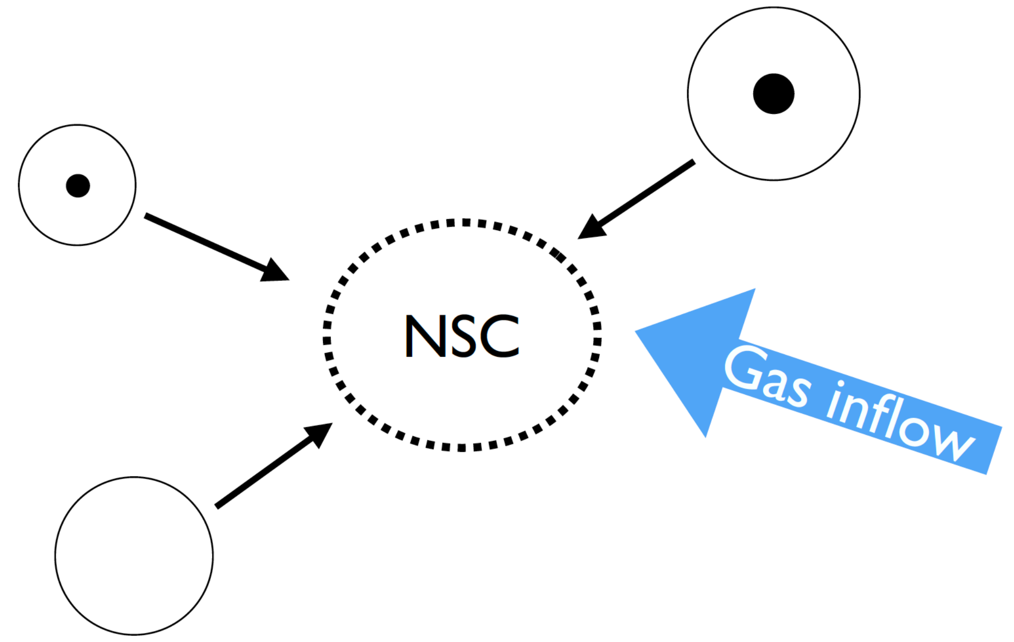
P2: SMBH seed population synthesis results

- Many pathways but all lead to one or zero SMBH seeds (merge and retain or merge and eject)
- Number, order and timing of IMBH injection matter
- Allowing for growth (at ~10% of Eddington) allows us to reproduce observed SMBH masses





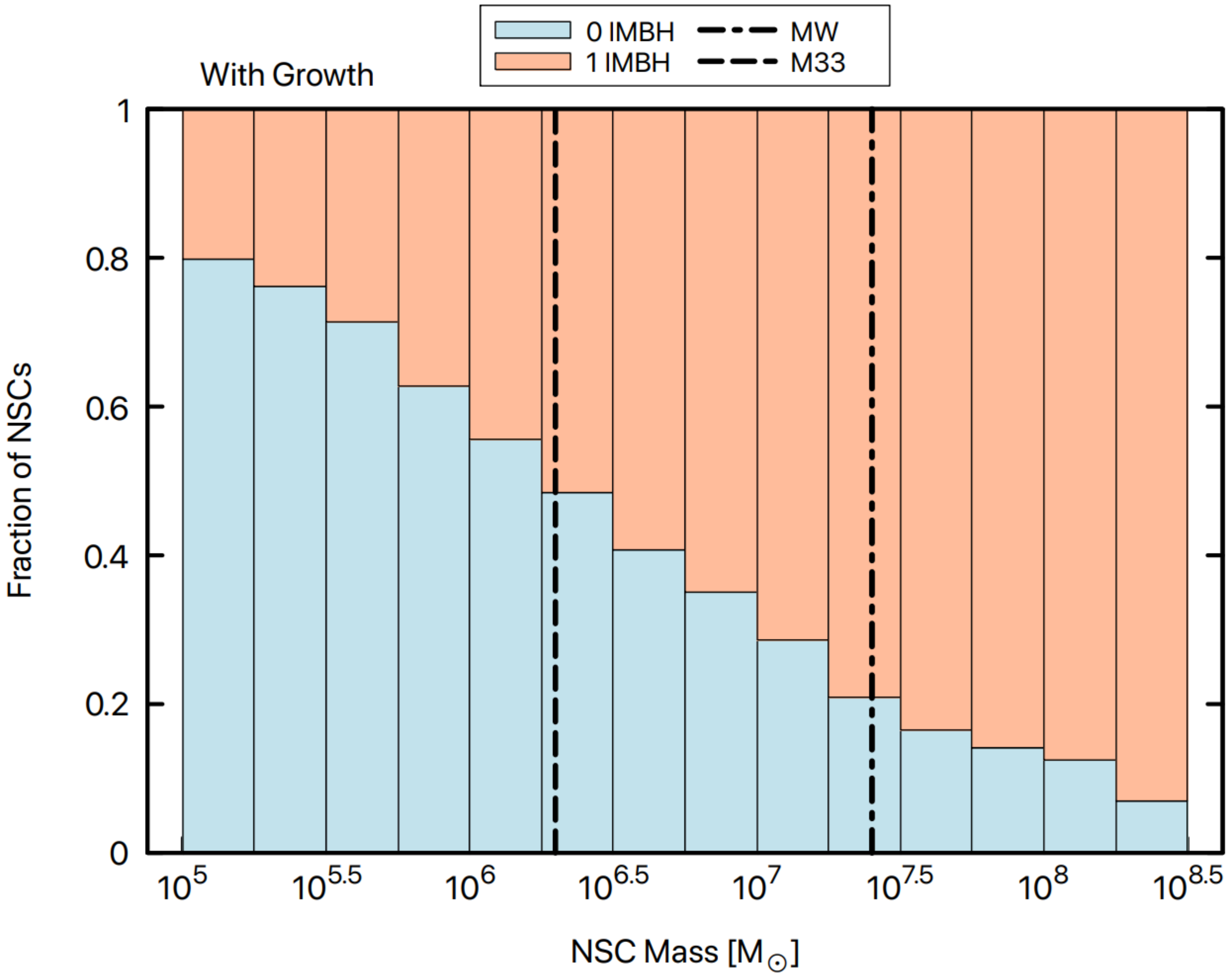
Allow BHs to grow with a doubling time of 300 Myr over 4.5 Gyr

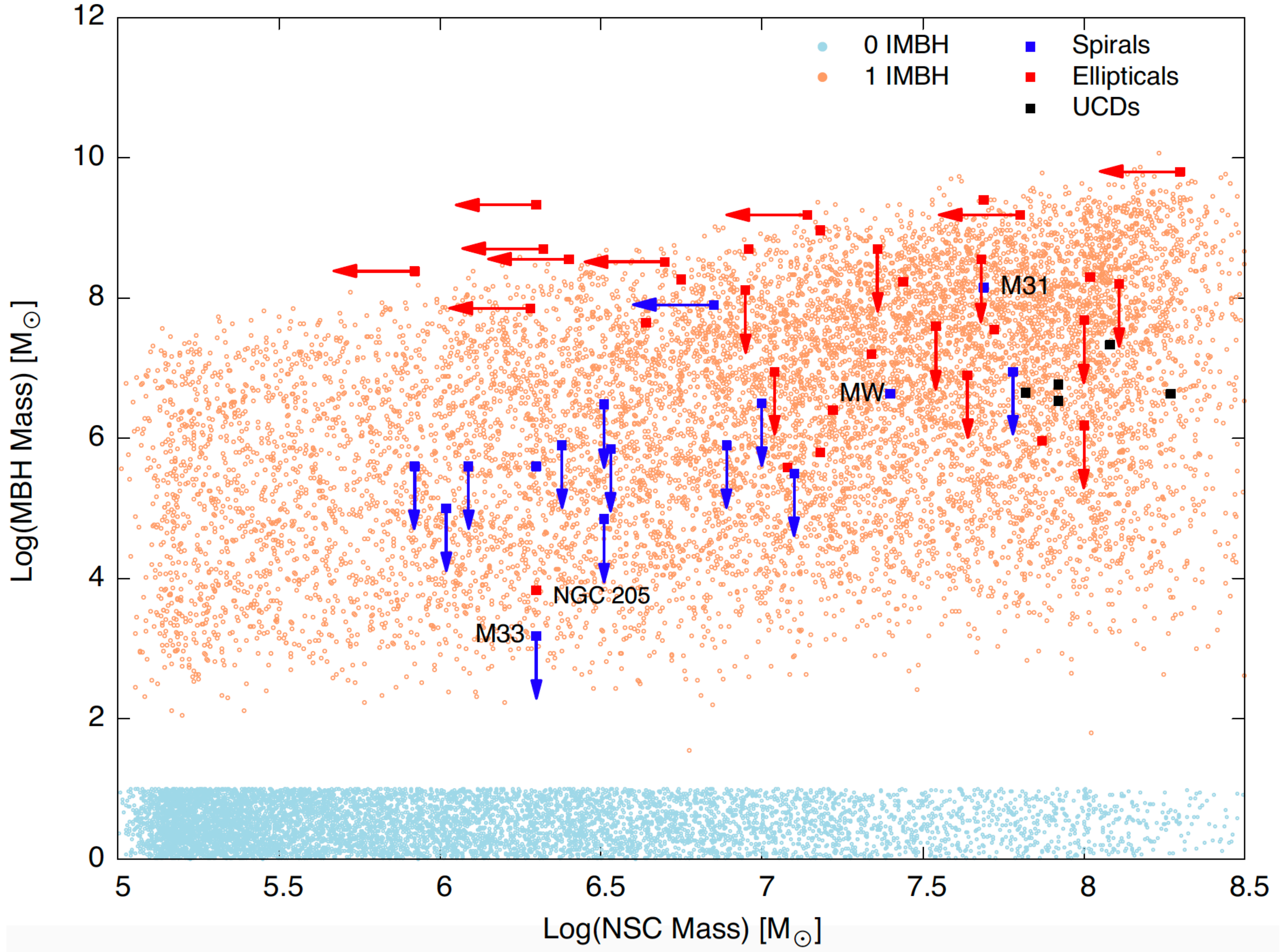


Growth of seeds by tidal disruption of stars and gas accretion (i.e. wet growth with gas inflow)

Askar, Davies & Church (2022)

- Sample 1.8×10^5 galaxies with stellar masses between $10^7 - 10^{12}\ M_\odot$
- Many pathways but all lead to one or zero SMBH seeds (merge and retain or merge and eject)
- Allowing for growth (at ~10% of Eddington) allows us to reproduce observed SMBH masses
- Number, order and timing of IMBH injection matter





Observed points from Neumayer et al. (2020)

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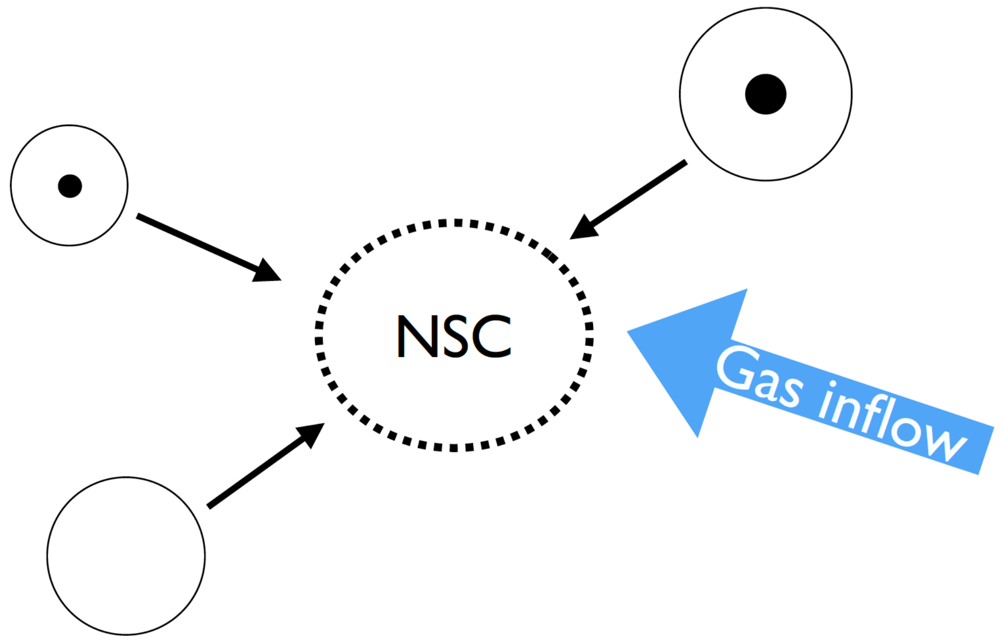

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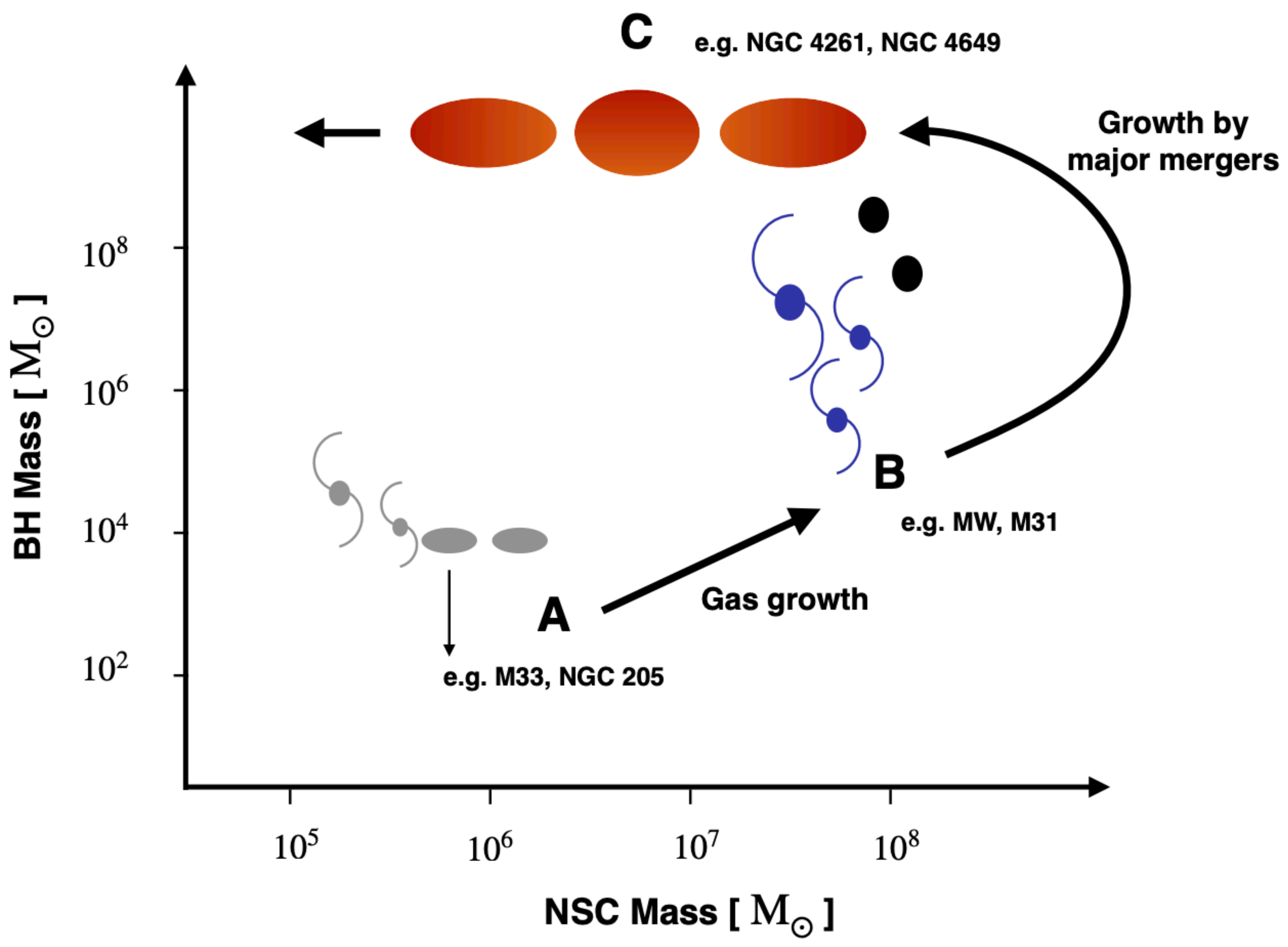
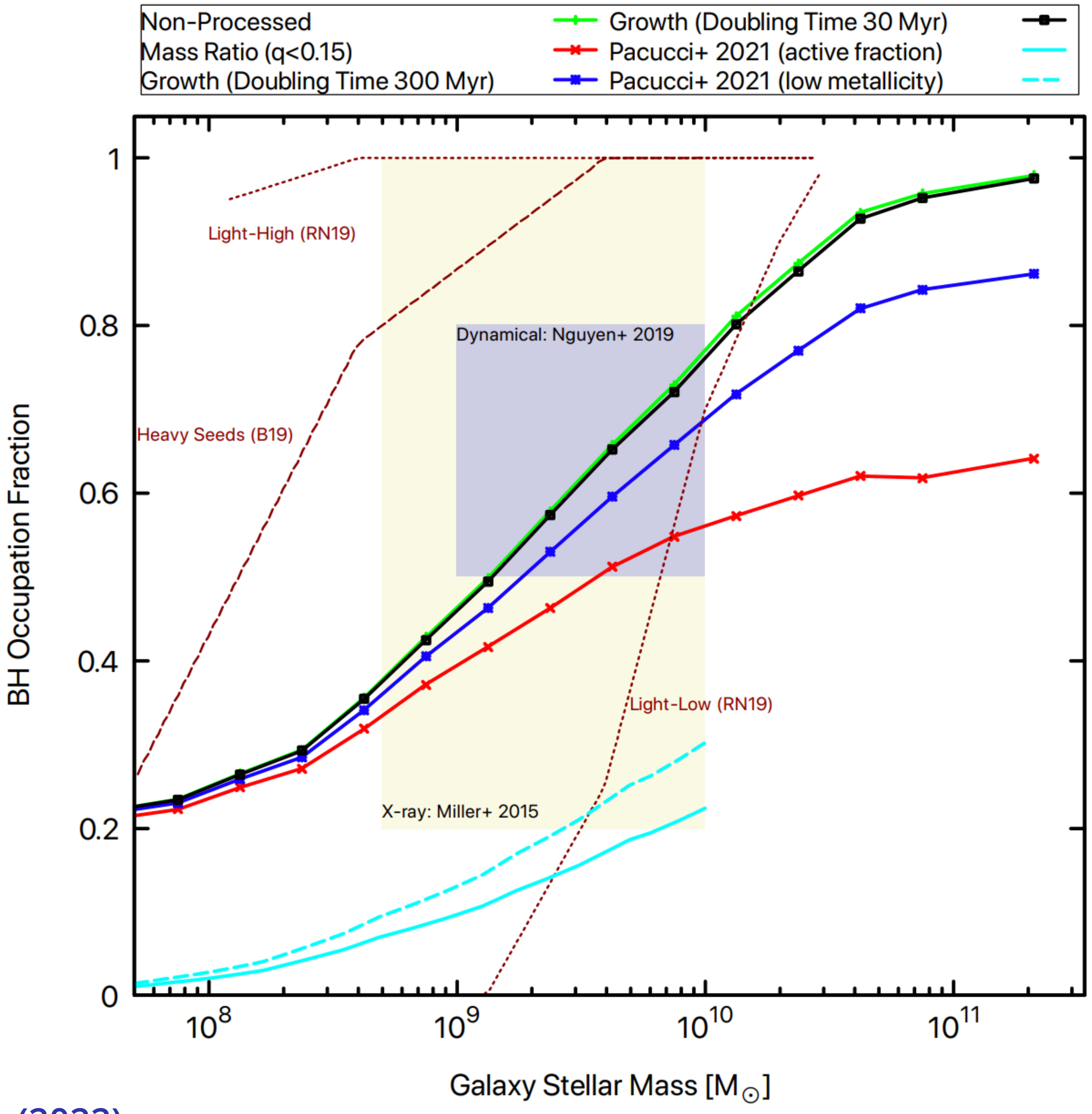
Askar, Davies & Church (2022)

P2: Possible co-evolution of galaxy, NSC and massive BH?



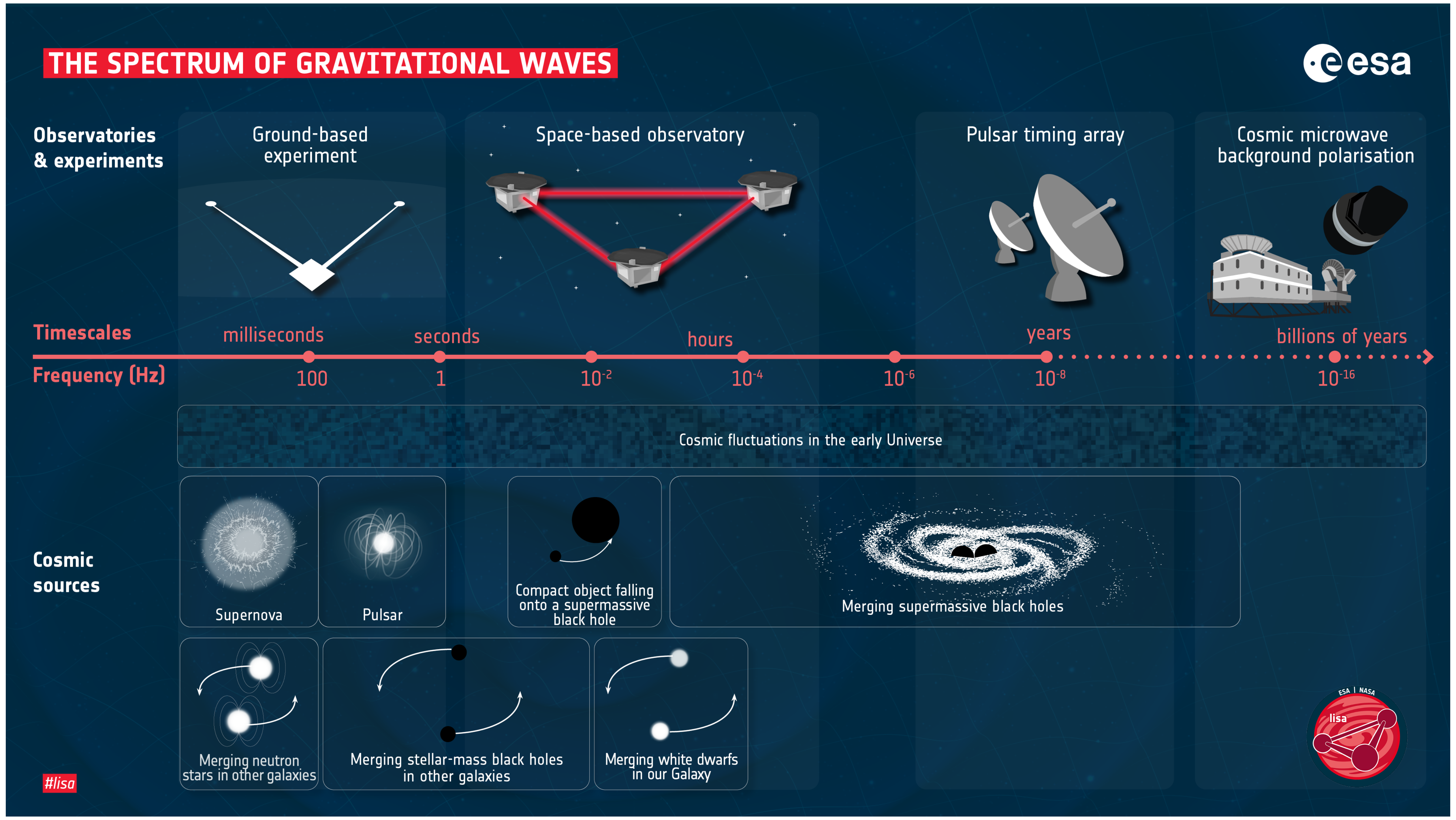
Presence of central gas could play an important role in growing both the NSC mass and BH Mass



Askar, Davies & Church (2022)

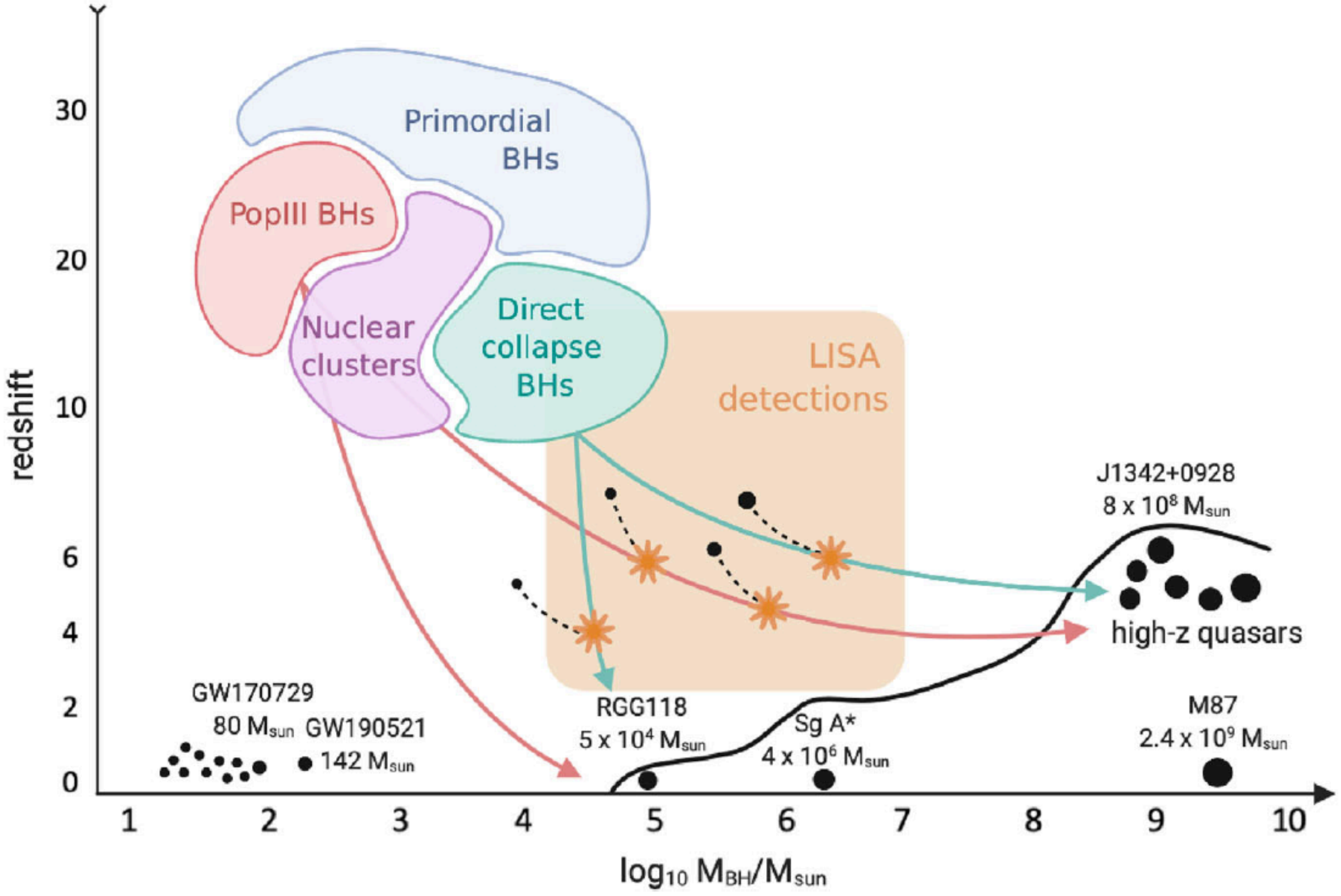
P3: Constraining the seeding mechanism with LISA

- Aim: Check whether the IMBH binary mergers we are predicting will be detectable with LISA



- **LISA**: **L**aser **I**nterferometer **S**pace **A**ntenna
- To be launched in ~2037
- 2.5 million km long arms
- Sensitive to low-frequency gravitational waves

Credit: ESA/LISA



Amaro-Seoane, Andrews, Arca Sedda, *Askar* et al. 2023 (2023LRR....26....2A)

P3: NSCs with 2 IMBHs - Merging binaries and their detectability with LISA

- Few 10^4 galaxies with NSCs in which 2 IMBHs were delivered
- Determine properties of merging binary black holes in the NSC:

Askar (in prep)

  - Use masses and the delivery time of the second black hole in the NSC
    - We assume that the assembly and growth of NSCs occurs between redshift $z = 4$ (~1.5 Gyr) and $z = 1$ (~6 Gyr)
  - Estimate the redshift corresponding to the cosmic time of merger

$$t \approx \frac{28}{1 + (1 + z)^2} \mathrm{Gyr}$$

Carmeli et al. (2006)

  - Obtain luminosity distance and comoving distance from redshift (Adachi & Kasai 2012)
  - Estimate the gravitational wave frequency at the time of binary merger using black hole radii as separation

$$f_{\rm GW} = 2f_{\rm dyn} \sim 2\left(\frac{GM}{16\pi R^3}\right)^{1/2}$$

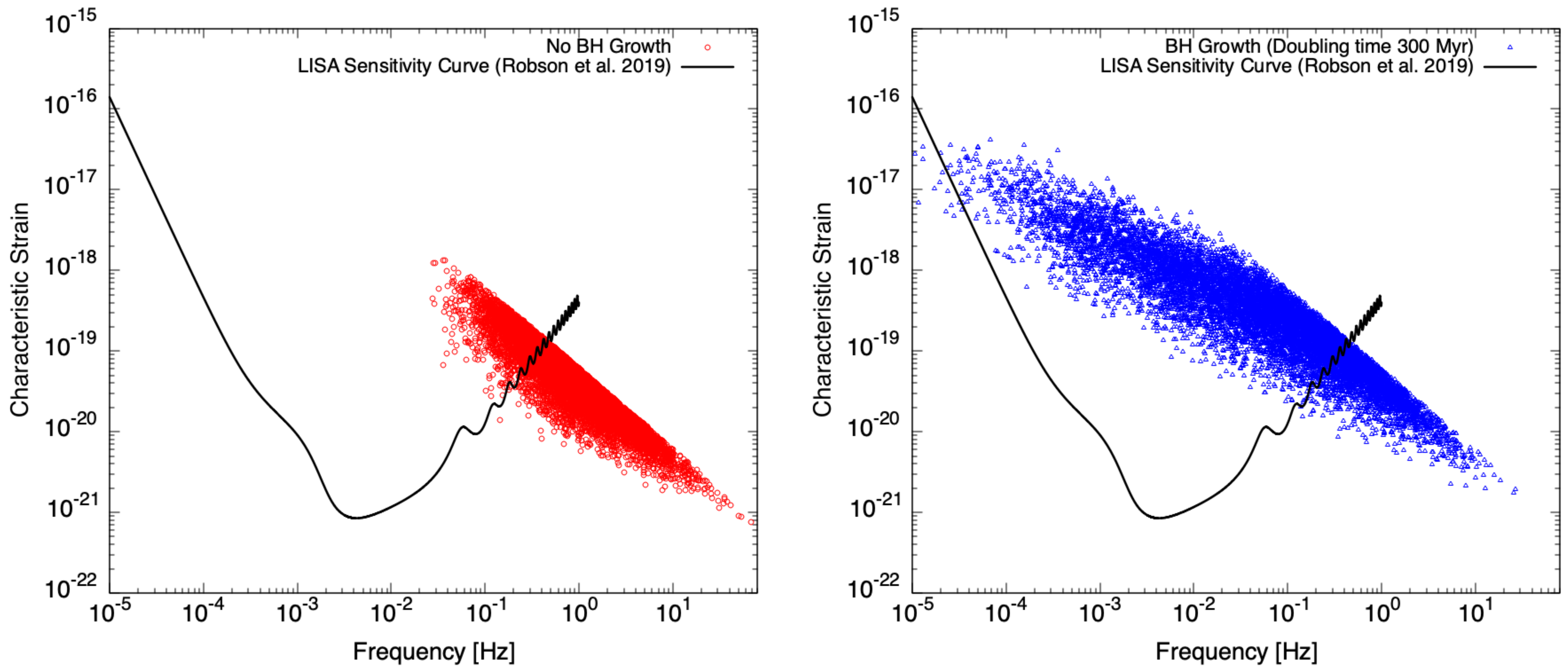
  - Obtain the strain and the characteristic strain in the observer frame at merger time

Camp & Cornish (2004)
Schutz (1997)

$$h_c \equiv h\sqrt{n} \qquad h = \frac{8\pi^{2/3}}{10^{1/2}} \frac{G^{5/3}\mathcal{M}^{5/3}}{c^4 r(z)} f_r^{2/3} \qquad n \simeq f_r^2/\dot{f}_r = \frac{5}{96\pi^{8/3}} \frac{c^5}{G^{5/3}\mathcal{M}^{5/3}} f_r^{-5/3}$$

From Sesana et al. (2005)

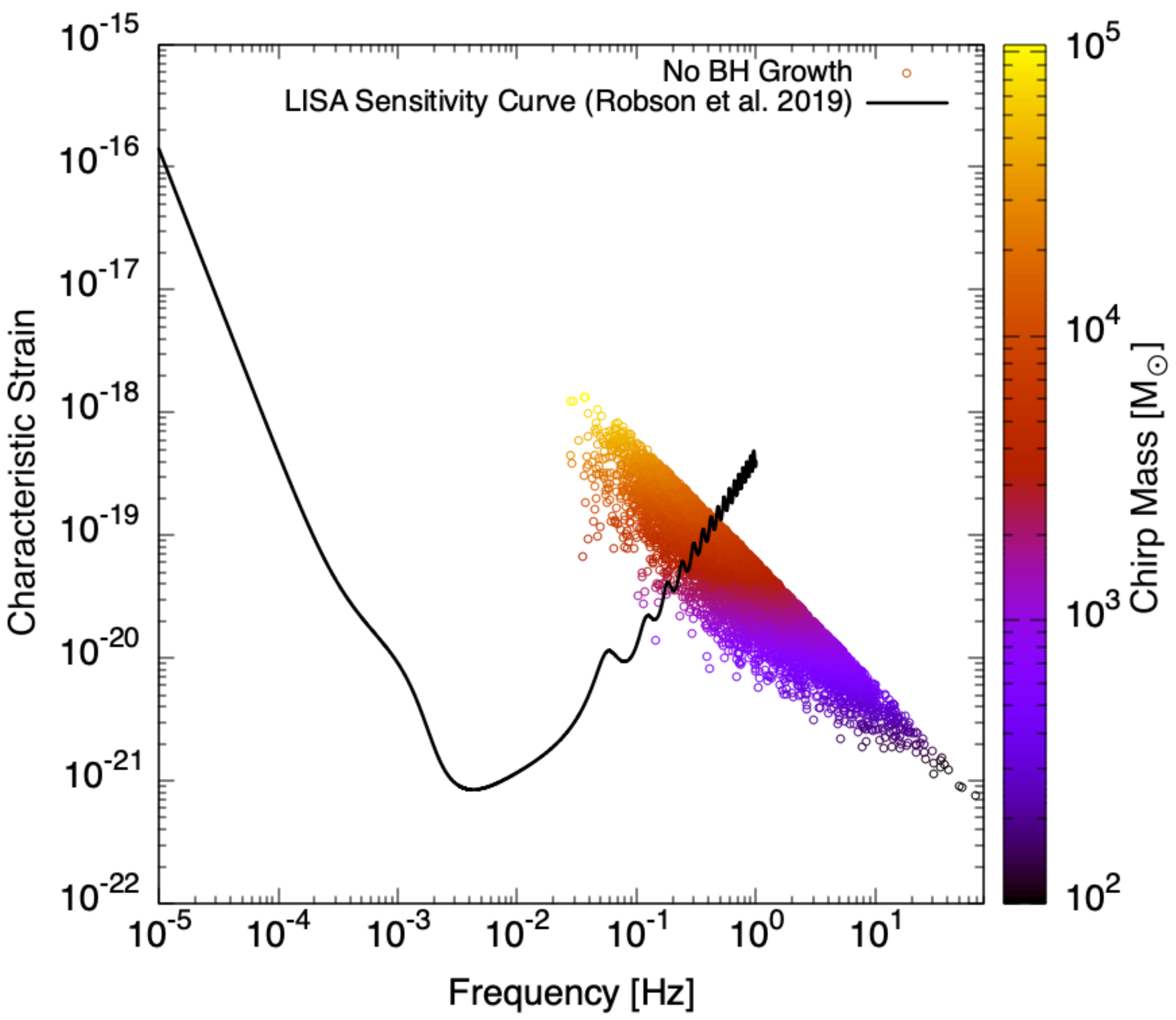
P3: NSCs with 2 IMBHs - Merging binaries and their detectability with LISA

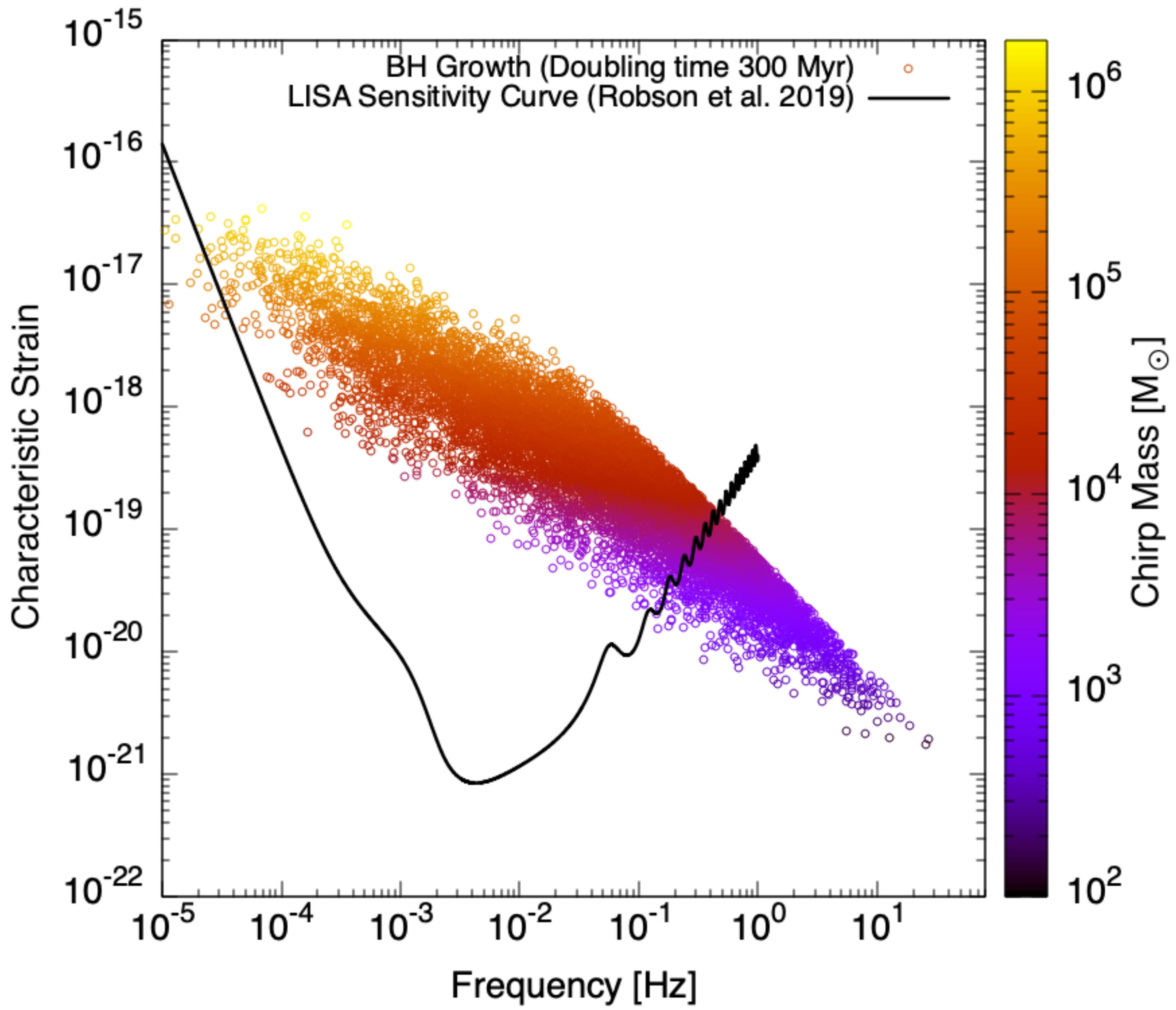


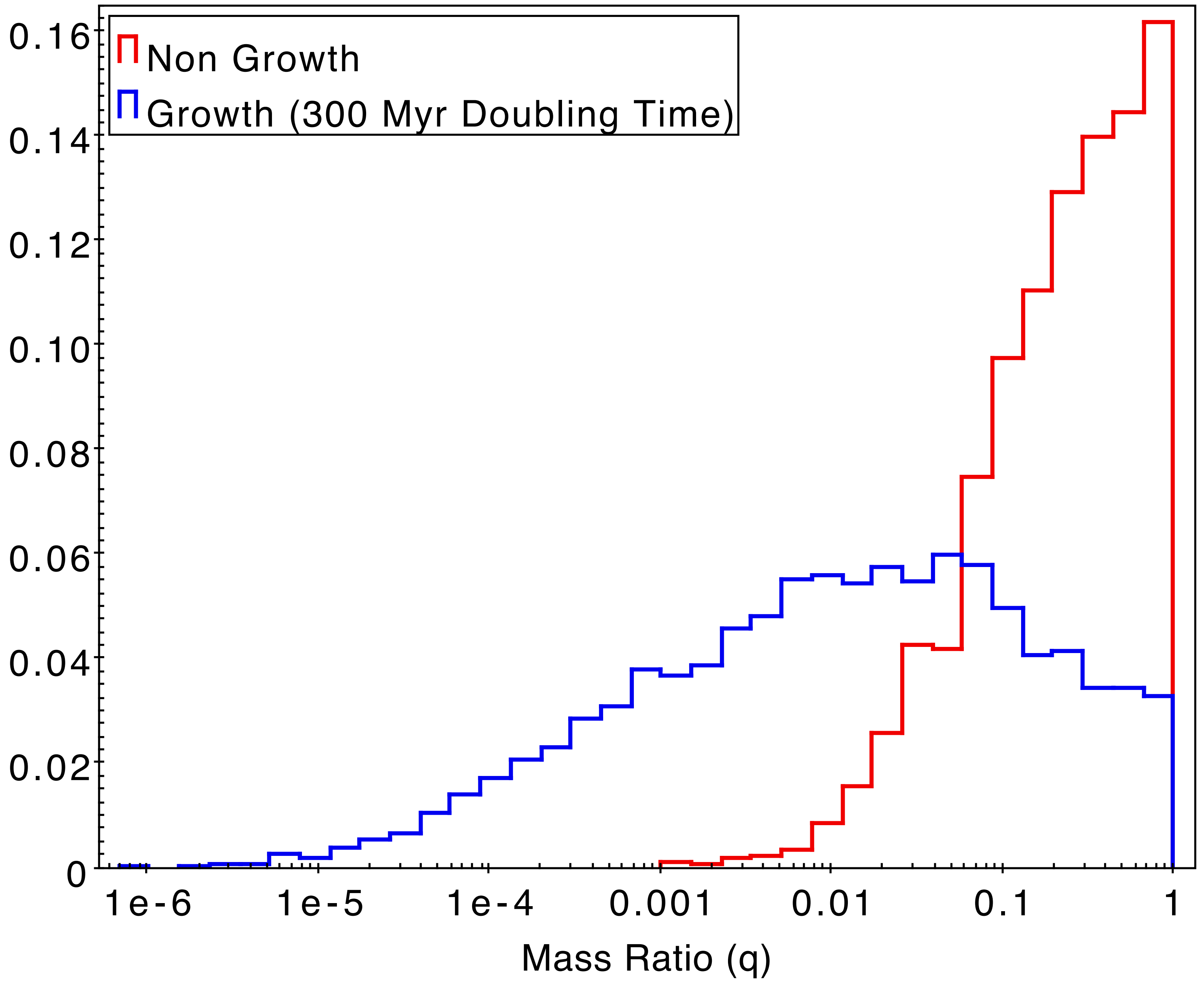
Askar (in prep)

- Considerable number of these merging black holes in the galactic nuclei will be detectable with LISA: 15% in the case where we do not allow for BH growth
- Allowing for the first black hole to grow (doubling time of 300 Myr, assuming accretion at ~10% Eddington rate) will significantly increase the number of detectable mergers (65%)
    - More massive black hole decreases the gravitational frequency and increases the characteristic strain leading to better signal-to-noise ratio for LISA

P3: NSCs with 2 IMBHs - Merging binaries and their detectability with LISA







- Low frequency, high amplitude sources with significant SNR associated with larger chirp mass
- Allowing for growth increases the chirp mass of the detected system and also contributes to a larger spread in the mass ratio resulting in a higher number of intermediate-mass ratio inspirals (Arca Sedda, Amaro-Seoane & Chen 2020)

Askar (in prep)

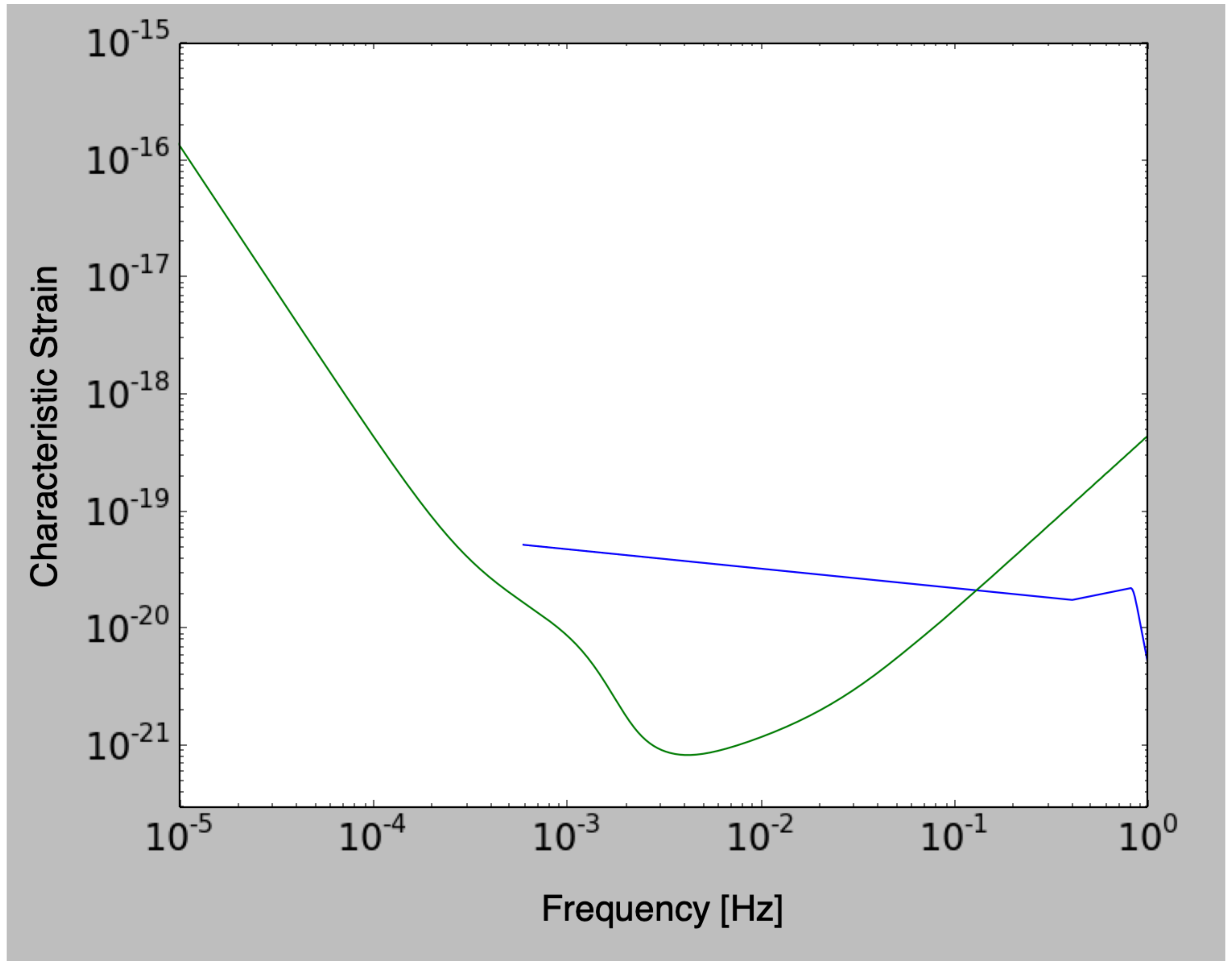
P3: NSCs with 2 IMBHs - Merging binaries and their detectability with LISA

- Most mergers taking place between redshifts 1 and 2
  - Depends on assumptions about NSC assembly and delivery time of stellar clusters with IMBH

Askar (in prep)

P3: Next Steps

- Better treatment for determination of the observable properties of the merging systems
  - Frequency and characteristic strain calculations
  - Evolution of frequency and strain with time
- Explore how do our initial assumptions affect the results?
  - IMBH masses and formation/growth in stellar clusters
  - NSC assembly time and cluster infall time
  - Growth rate for IMBH or seed SMBHs in NSCs
- Check merger properties in NSCs in which more than 2 IMBH are delivered
  - Possible hierarchal mergers of intermediate-mass/ massive black holes
- Estimate potential merger rates for the case with and without growth



$M_1 = 5203\ M_\odot$ $M_2 = 1387\ M_\odot$ $z = 1.67$ $\mathrm{SNR} = 53.7$

Using: https://github.com/eXtremeGravityInstitute/LISA_Sensitivity by Neil Cornish

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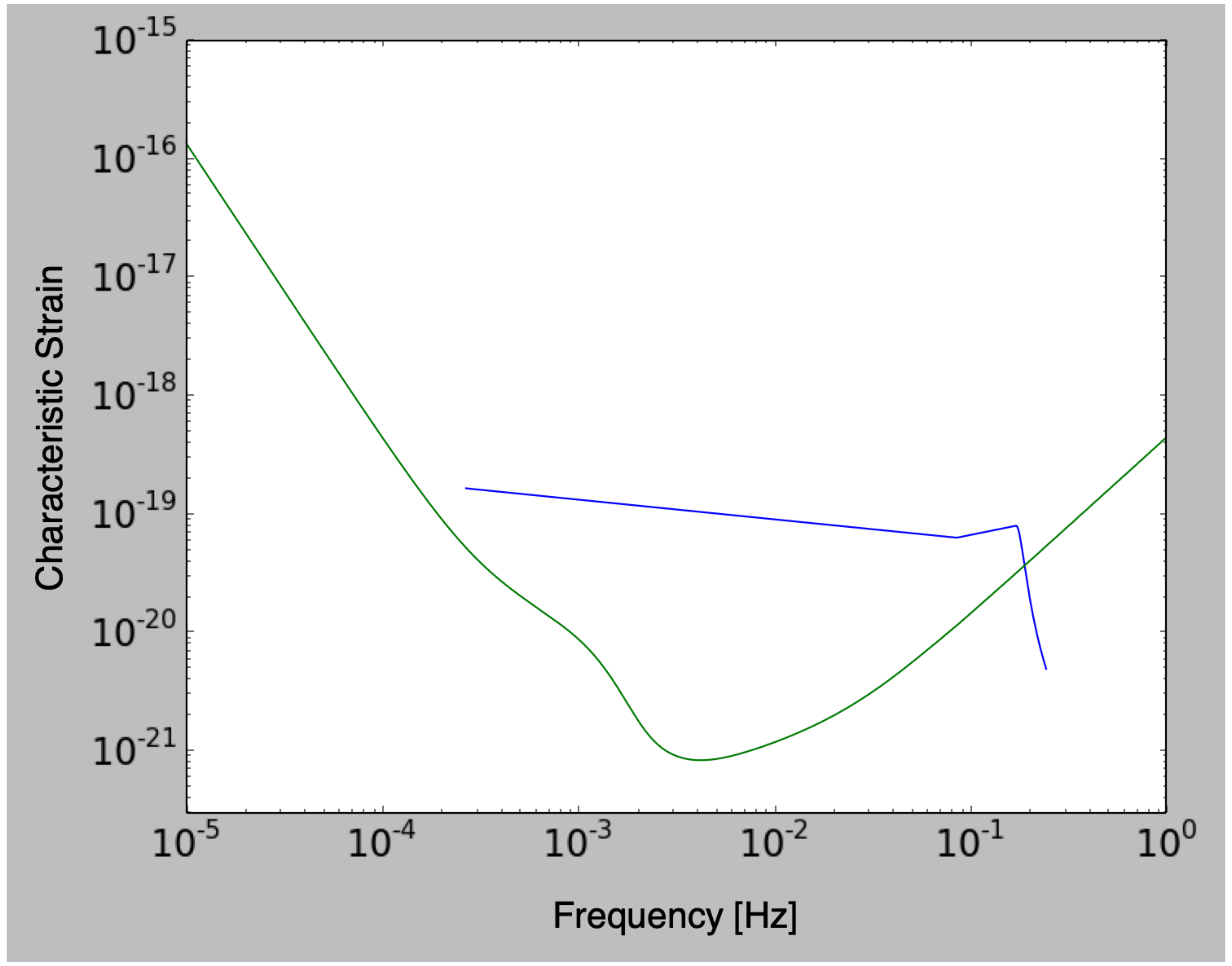

$M_1 = 1.7 \times 10^5\ M_\odot \quad M_2 = 1387\ M_\odot \quad z = 1.67 \quad SNR = 178.3$

$M(t) = M_0 \times 2^{t/300}$ where t is time difference in Myr

Using: https://github.com/eXtremeGravityInstitute/LISA_Sensitivity by Neil Cornish

Summary: LISA Binaries & intermediate-mass ratio inspirals

- Central Idea: NSC may form before an SMBH through the merger of stellar clusters
- **Stellar cluster could potentially form and deliver IMBHs to the galactic nuclei: SMBH seeds**
- **IMBH binary formation: merger due to gravitational wave radiation**
- **About 15% of such merging binary IMBH are detectable with LISA**
- **Increases to 65% if we allow one of the black holes to grow by gas accretion/tidal disruption of stars before the delivery of the second IMBH**
  - **Increased number of intermediate-mass ratio inspirals**
- **The detection (or non-detection) of these predicted merging binary black holes in the galactic nuclei with LISA can help constrain the formation/growth mechanism of supermassive black holes!**