Semi-analytic prescriptions for black hole seeding in nuclear star clusters

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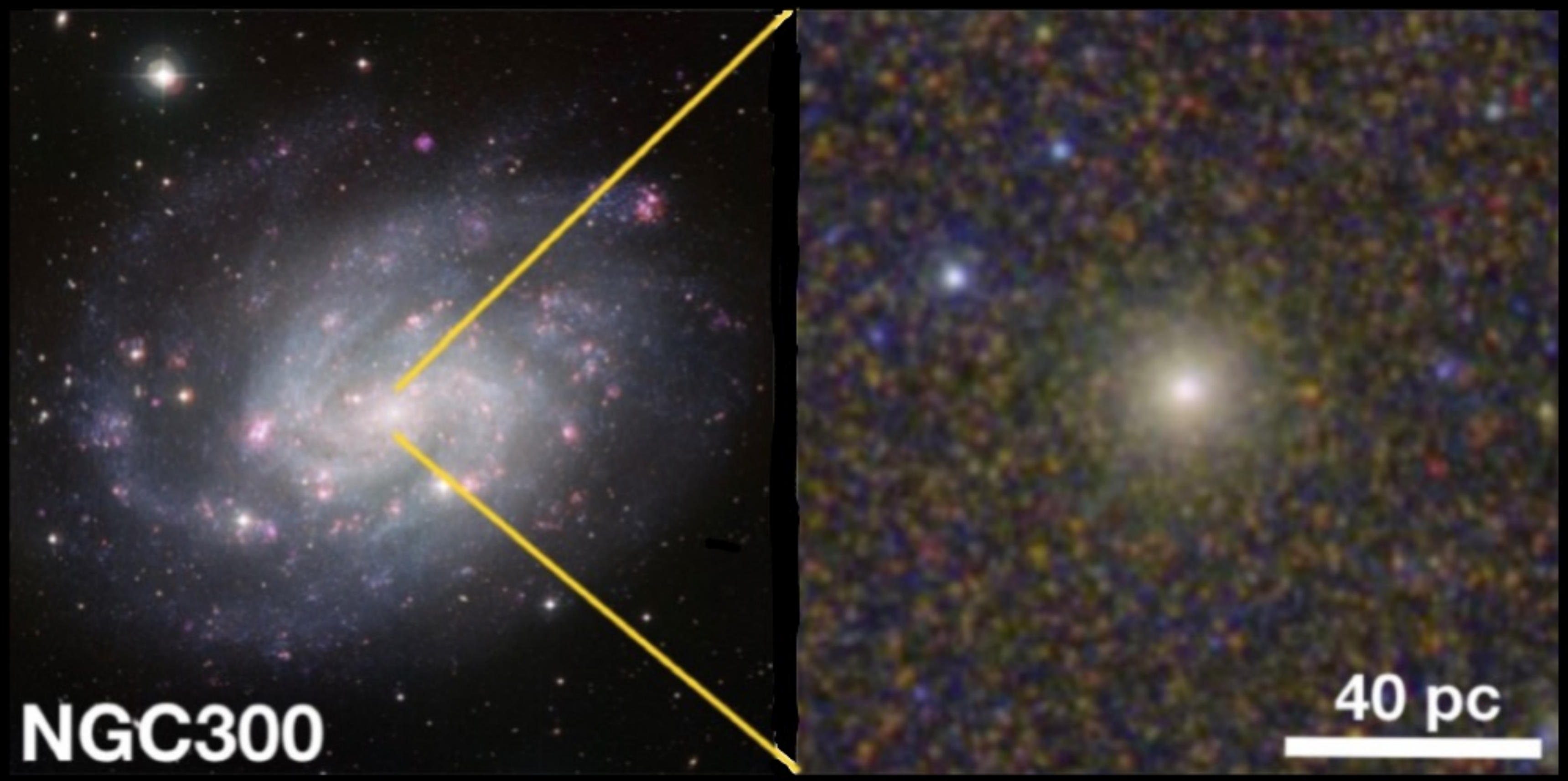
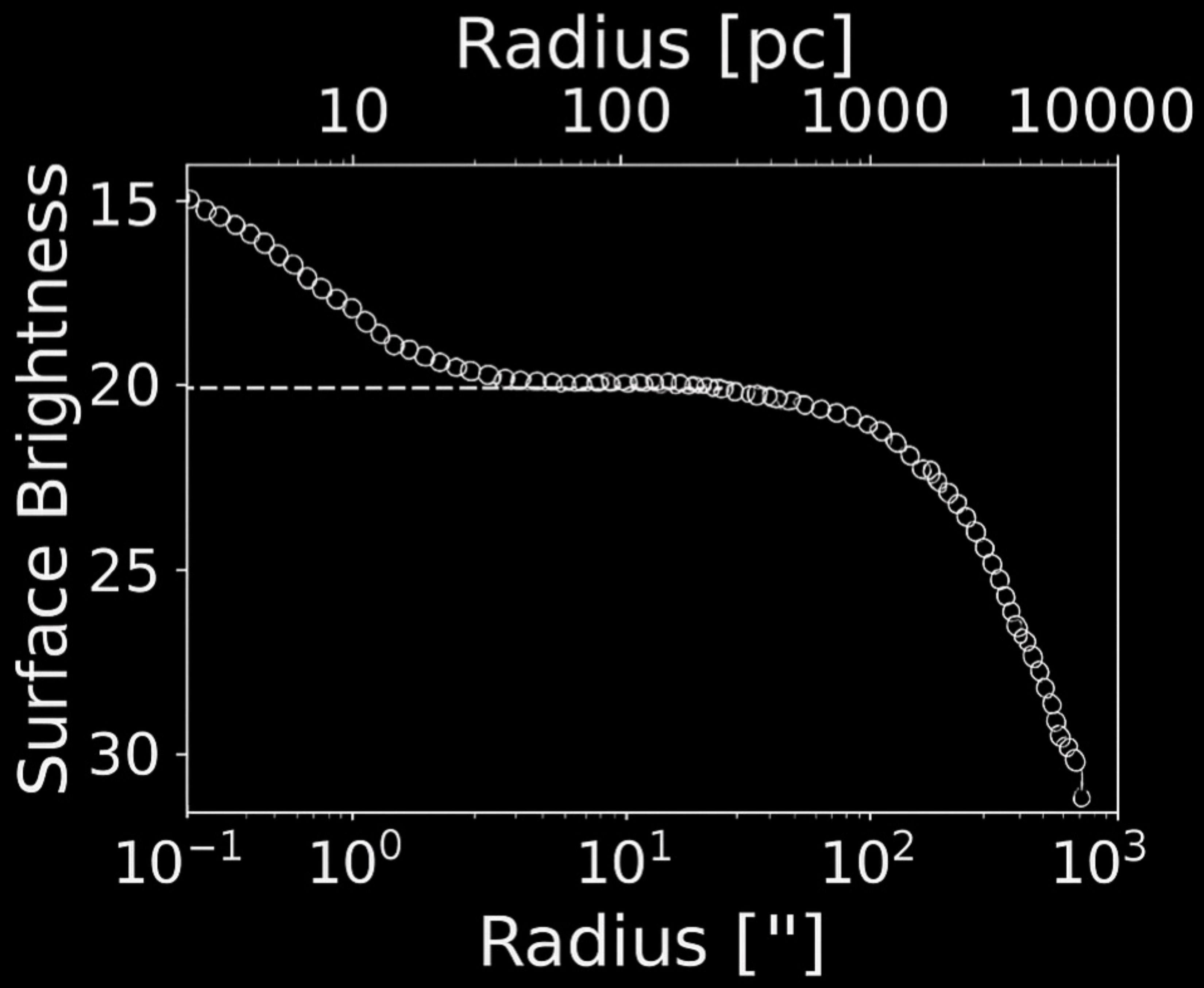
Nuclear star clusters (NSCs)





Adapted from Neumayer et al. (2020)

gravitationally bounded stellar system

observed masses ~ 10^5 - 10^9 M⊙

mean sizes ~ 3.3 pc

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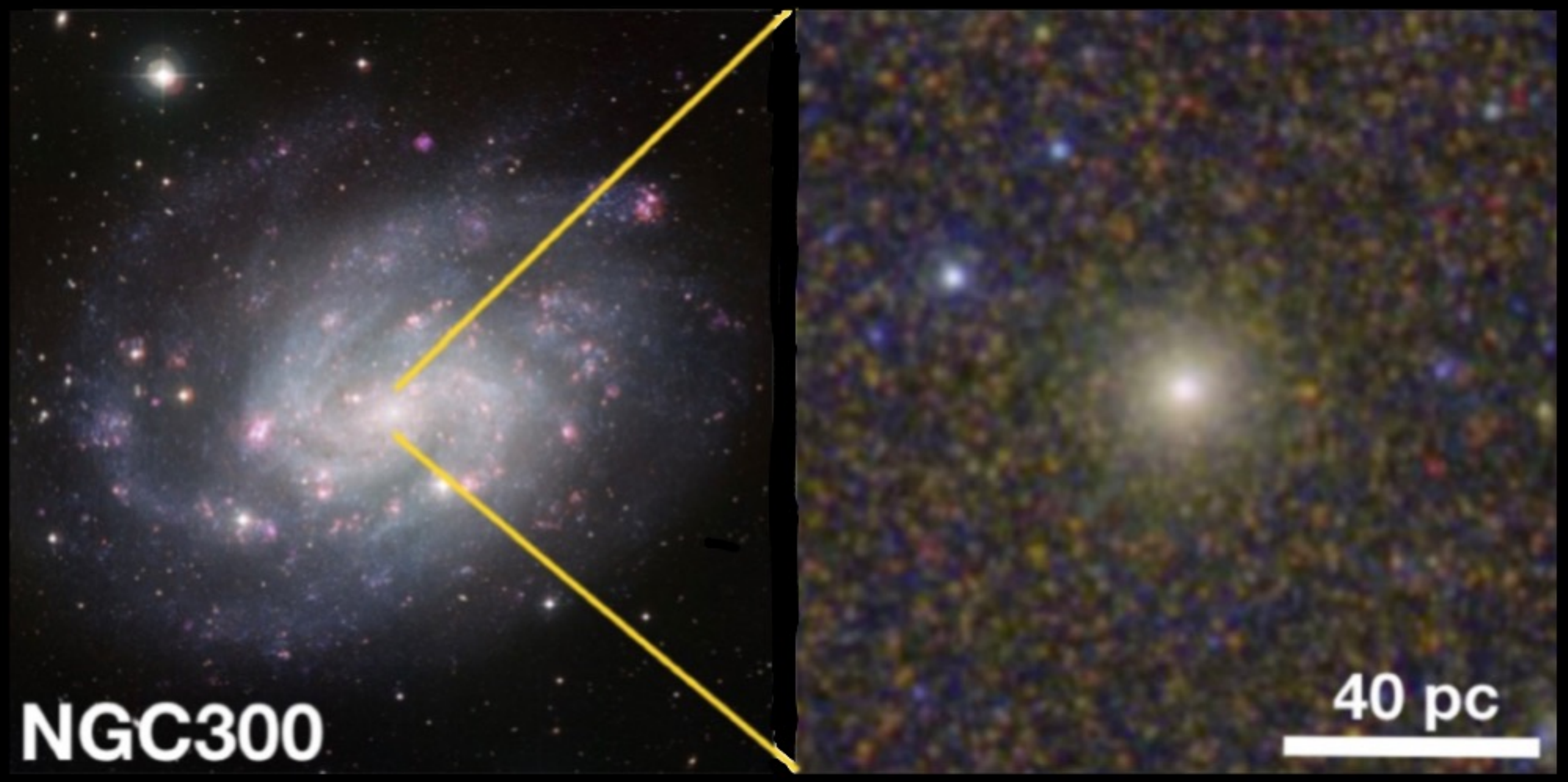

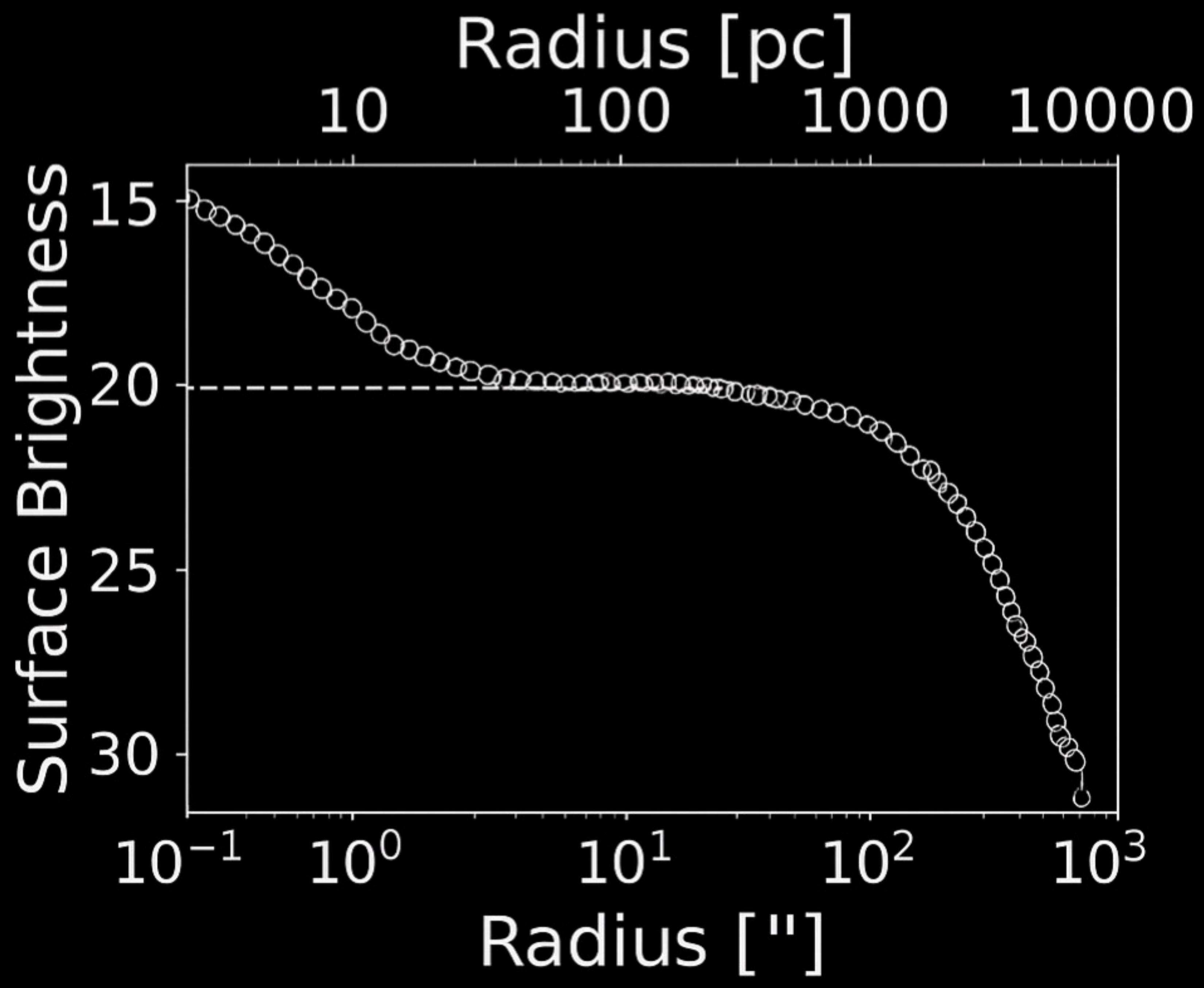

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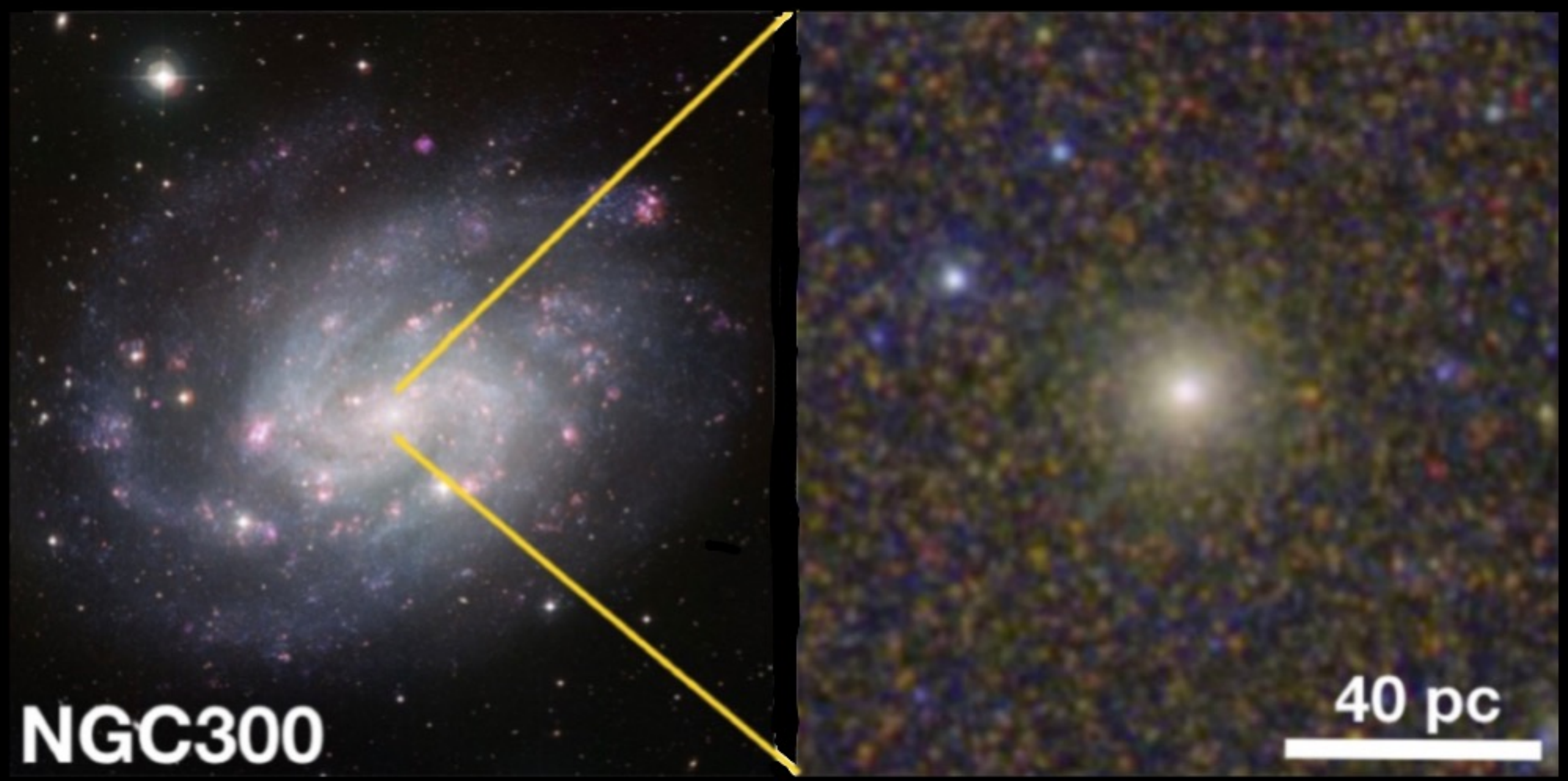

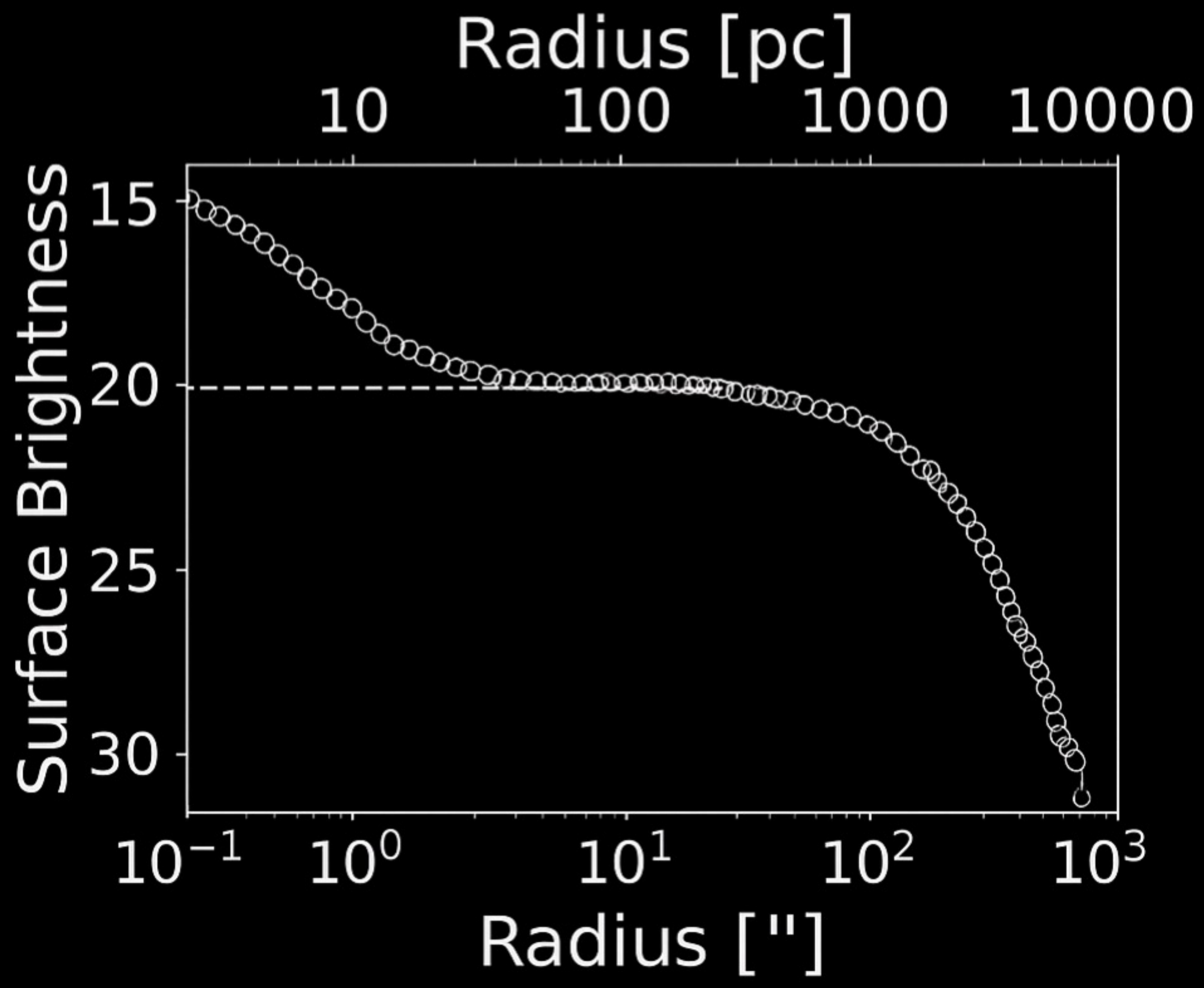

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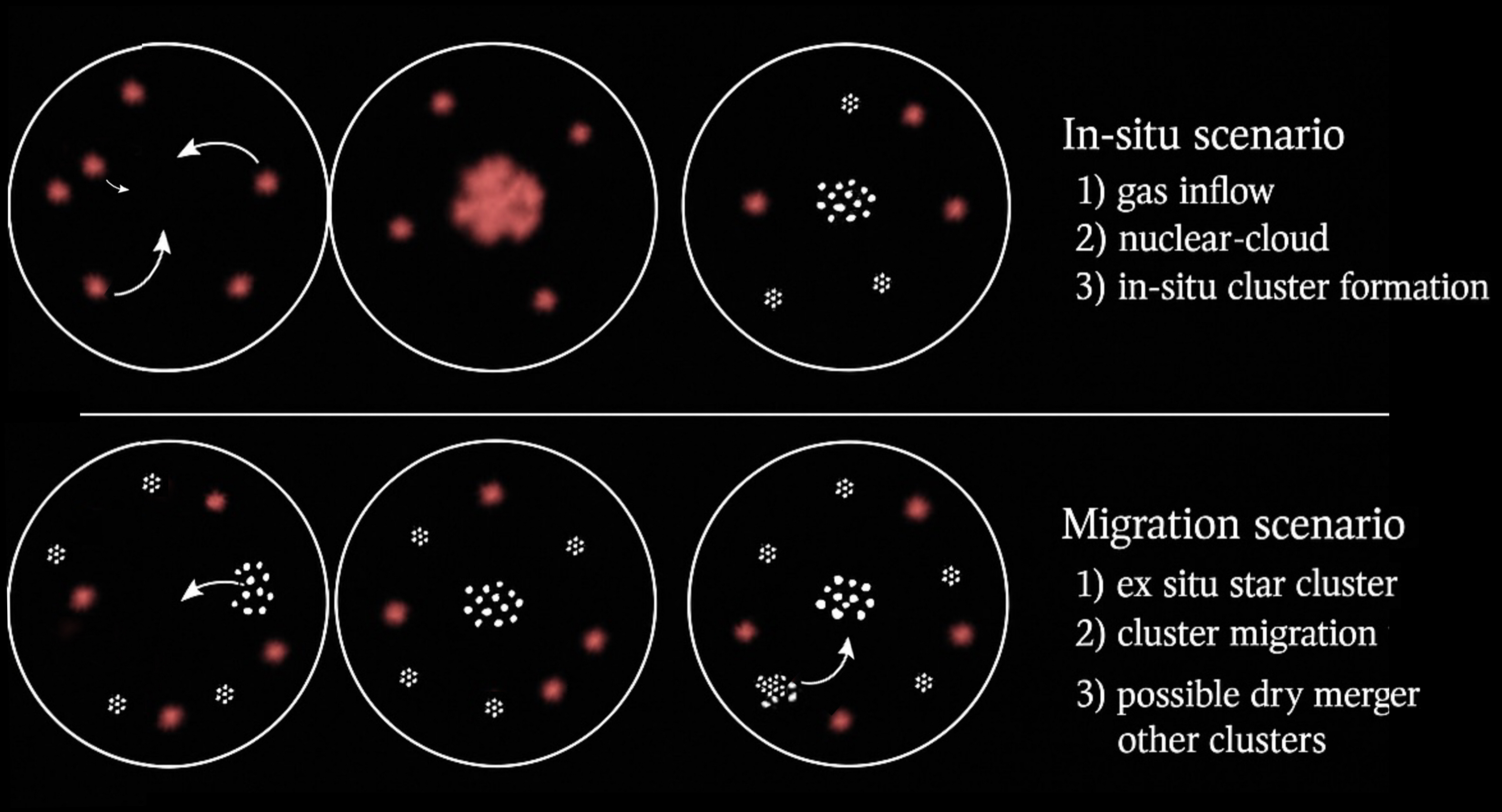
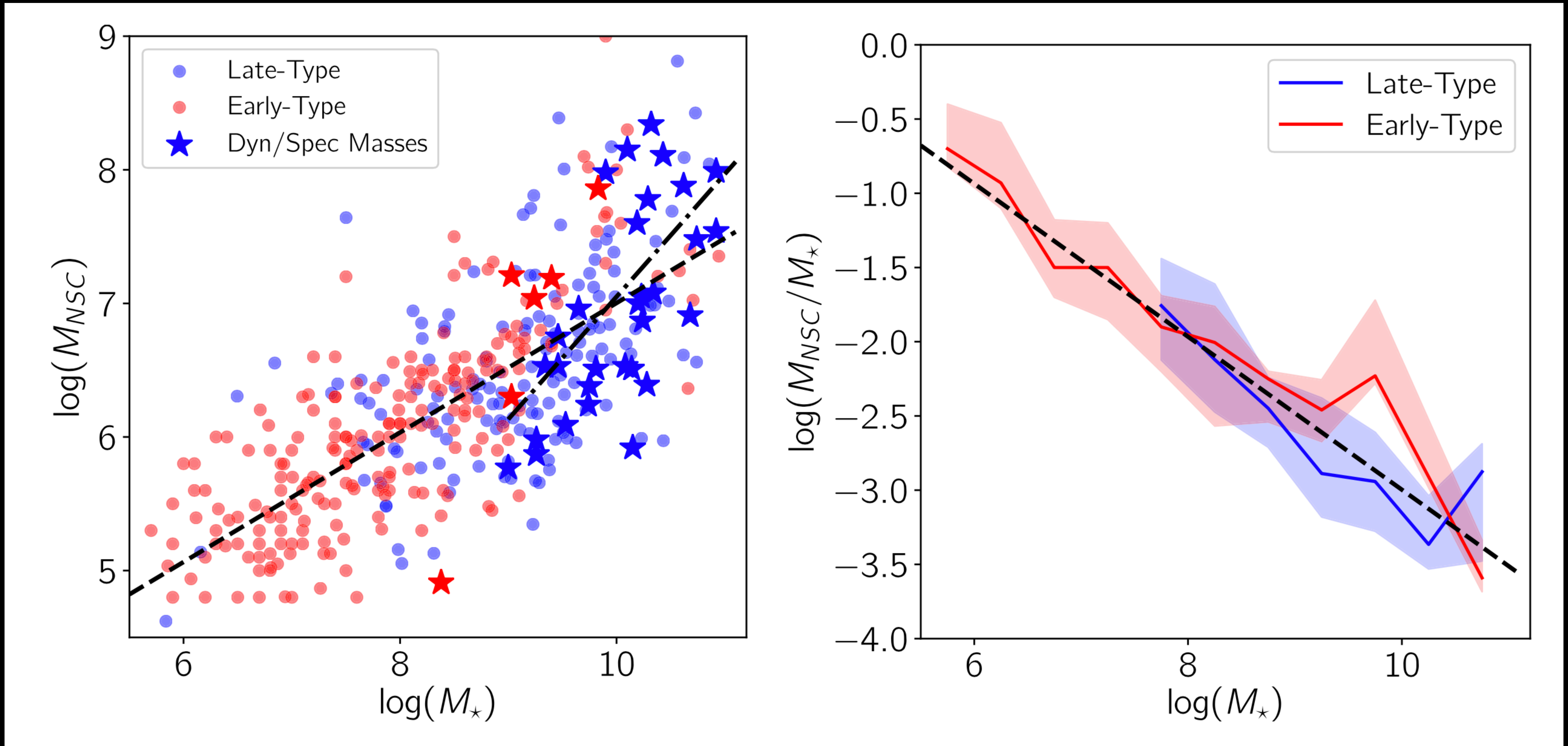
Formation of NSCs



Adaptation from Guillard et al., 2016.

NSCs & host galaxies



Neumayer et al. (2020)

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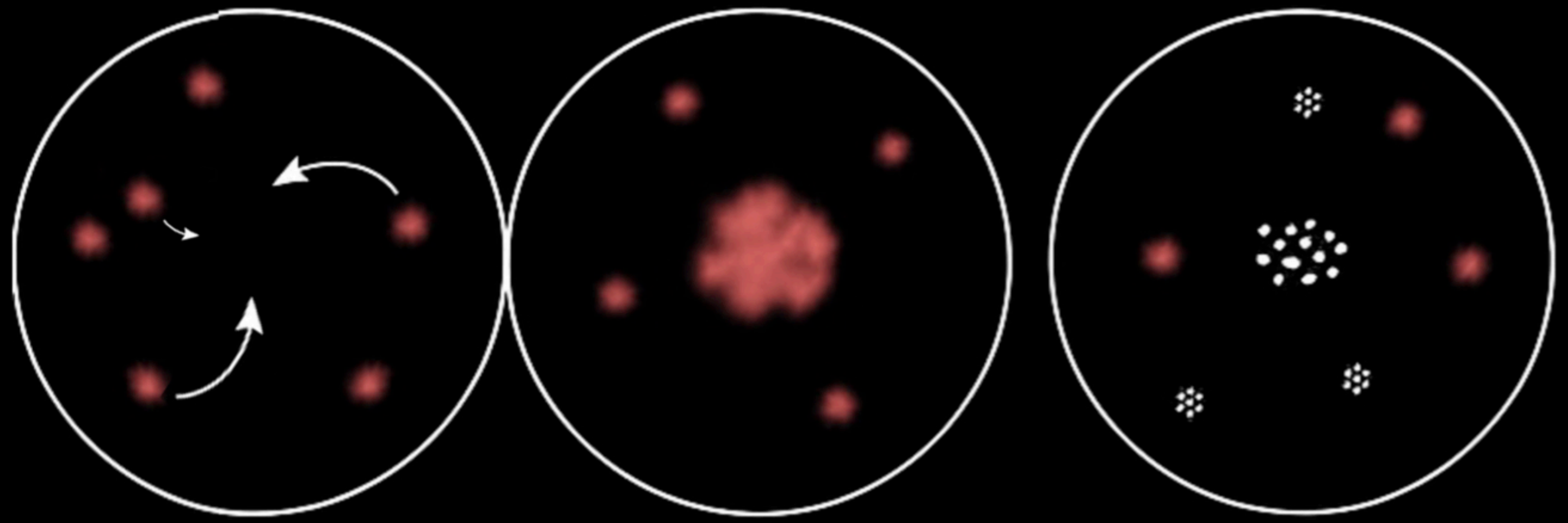
NSC model in Galacticus

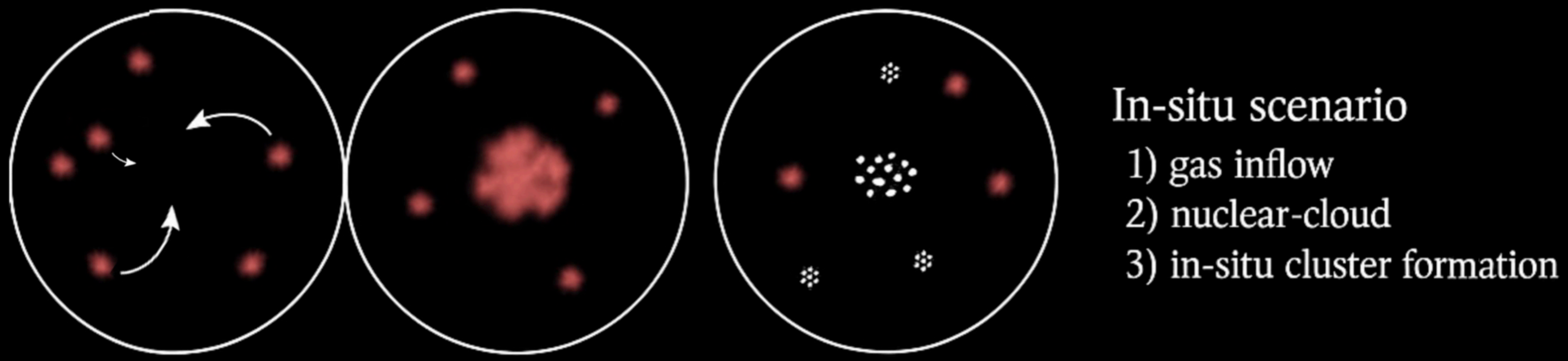


In-situ scenario
1) gas inflow
2) nuclear-cloud
3) in-situ cluster formation

$$\dot{M}^{\rm gas}_{\rm NSC} = A_{\rm reservoir}\,\dot{M}^{\rm stellar}_{\rm spheroid}$$

Antonini et al. (2015)

NSC model in Galacticus



$$\dot{M}^{\mathrm{gas}}_{\mathrm{NSC}} = A_{\mathrm{reservoir}}\, \dot{M}^{\mathrm{stellar}}_{\mathrm{spheroid}}$$

Antonini et al. (2015)

$$\dot{M}^{\mathrm{NSC}}_{\mathrm{stellar}} = f_c \frac{M^{\mathrm{NSC}}_{\mathrm{gas}}}{t_{\mathrm{SF}}}$$

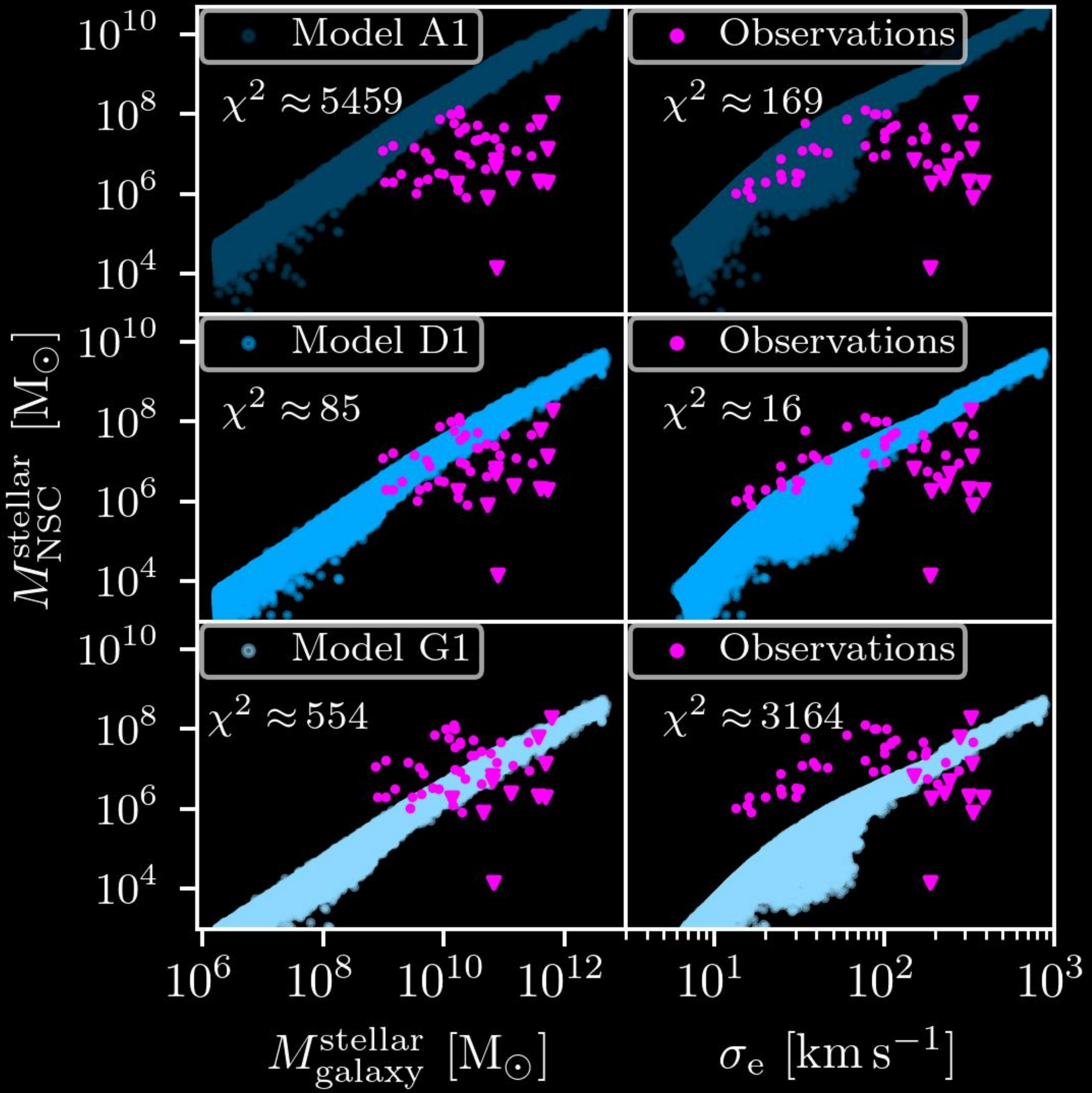
Krumholz et al. (2009)

Model	$A_{reservoir}$
A1	10^{-1}
D1	10^{-2}
G1	10^{-3}

Model D1 is closer to observations, but not good enough.

In agreement with values reported by Antonini et al. (2015)

Liempi et al. (2025)



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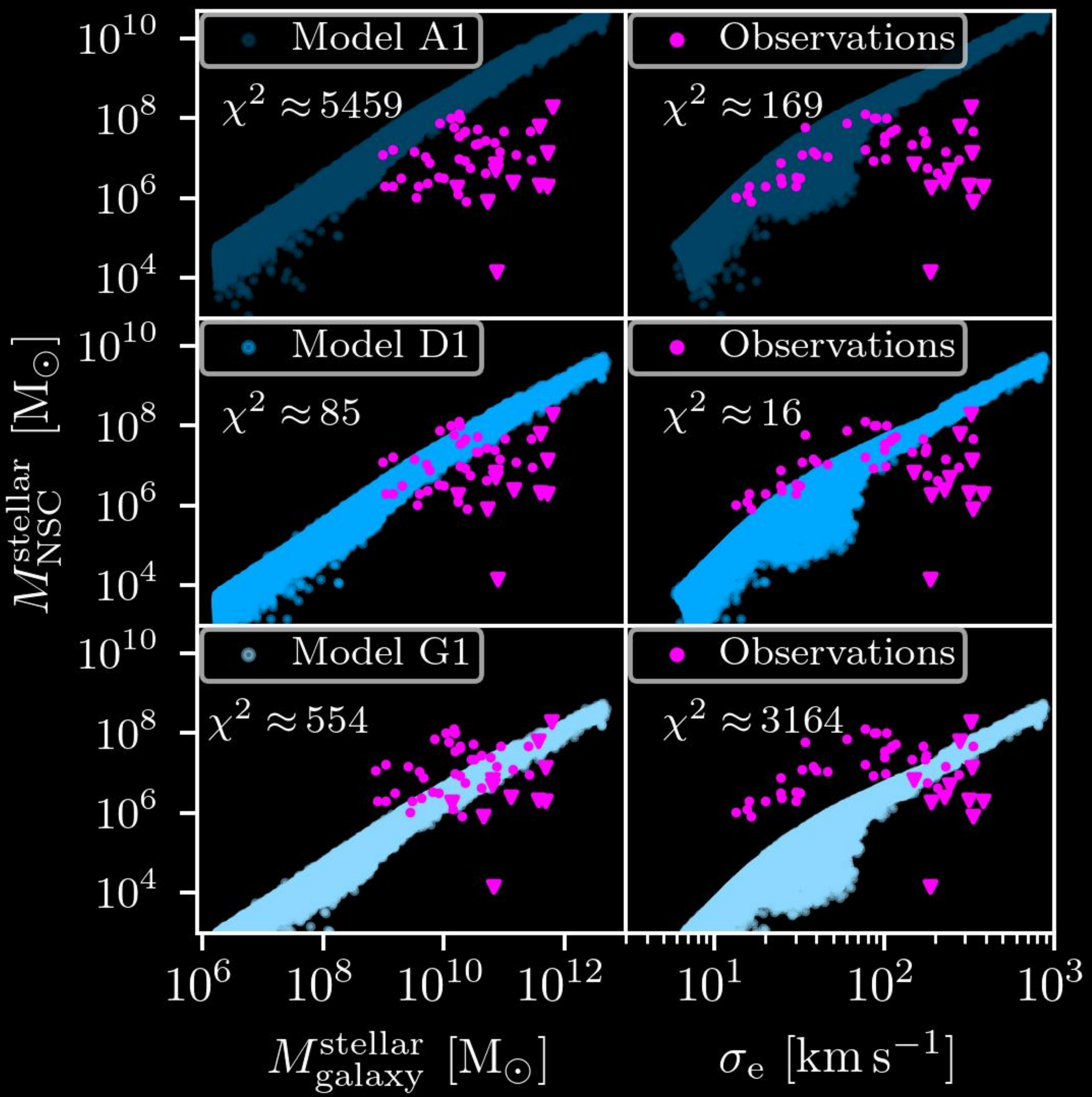

Scenario I: Runaway stellar collisions

$$M_{\rm crit}(r_{\rm NSC}) = r_{\rm NSC}^{\frac{7}{3}} \left(\frac{4\pi M_\star}{3\Sigma_0 t_H G^{\frac{1}{2}}} \right)^{\frac{2}{3}}$$

Vergara et al. (2023,2024)

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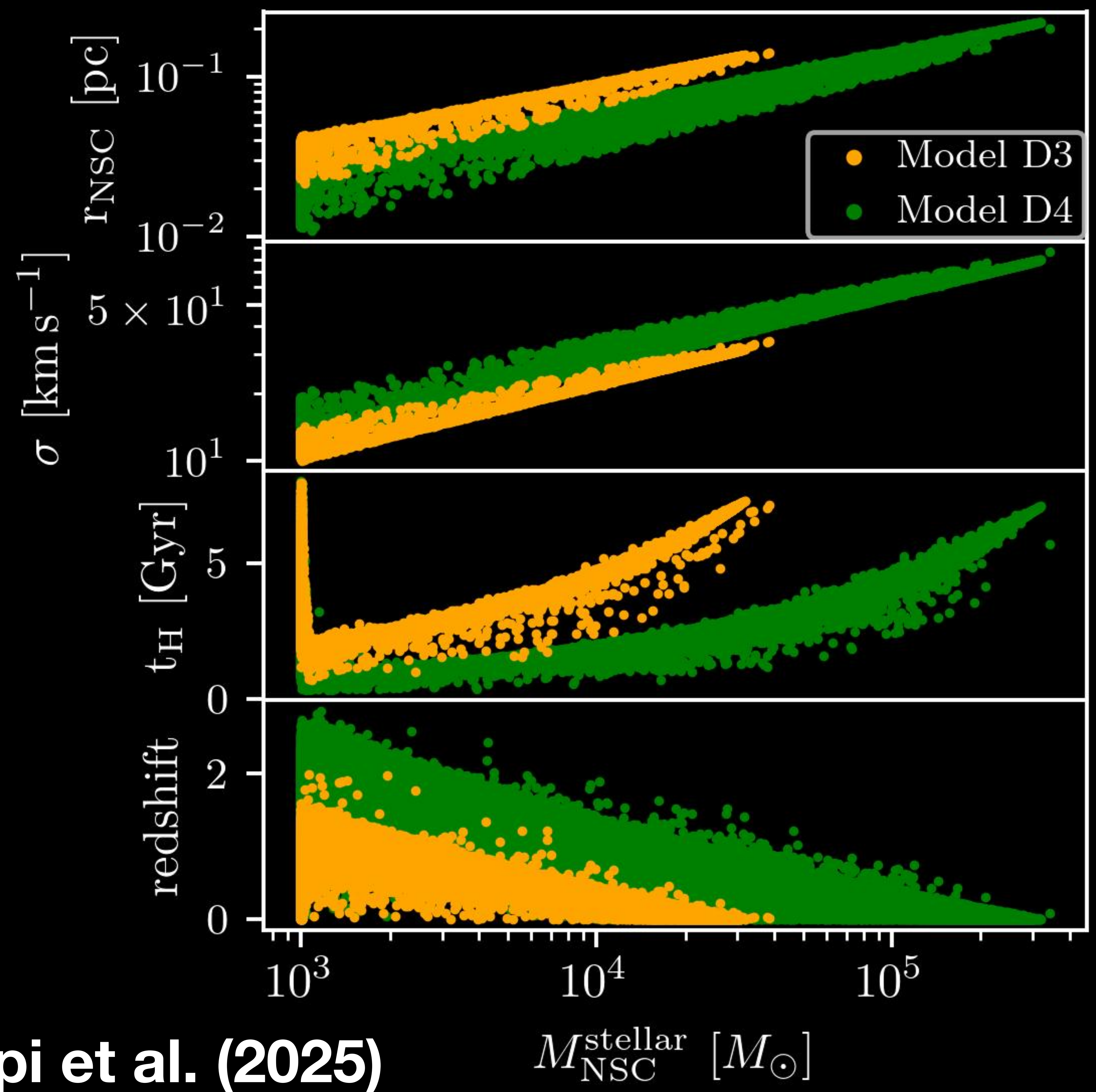
Vergara et al. (2023,2024)

$$r_{\rm NSC} = 3.3\,{\rm pc} \left(\frac{M_{\rm dyn}}{10^6\,{\rm M_\odot}} \right)^{0.5}$$

observed correlation



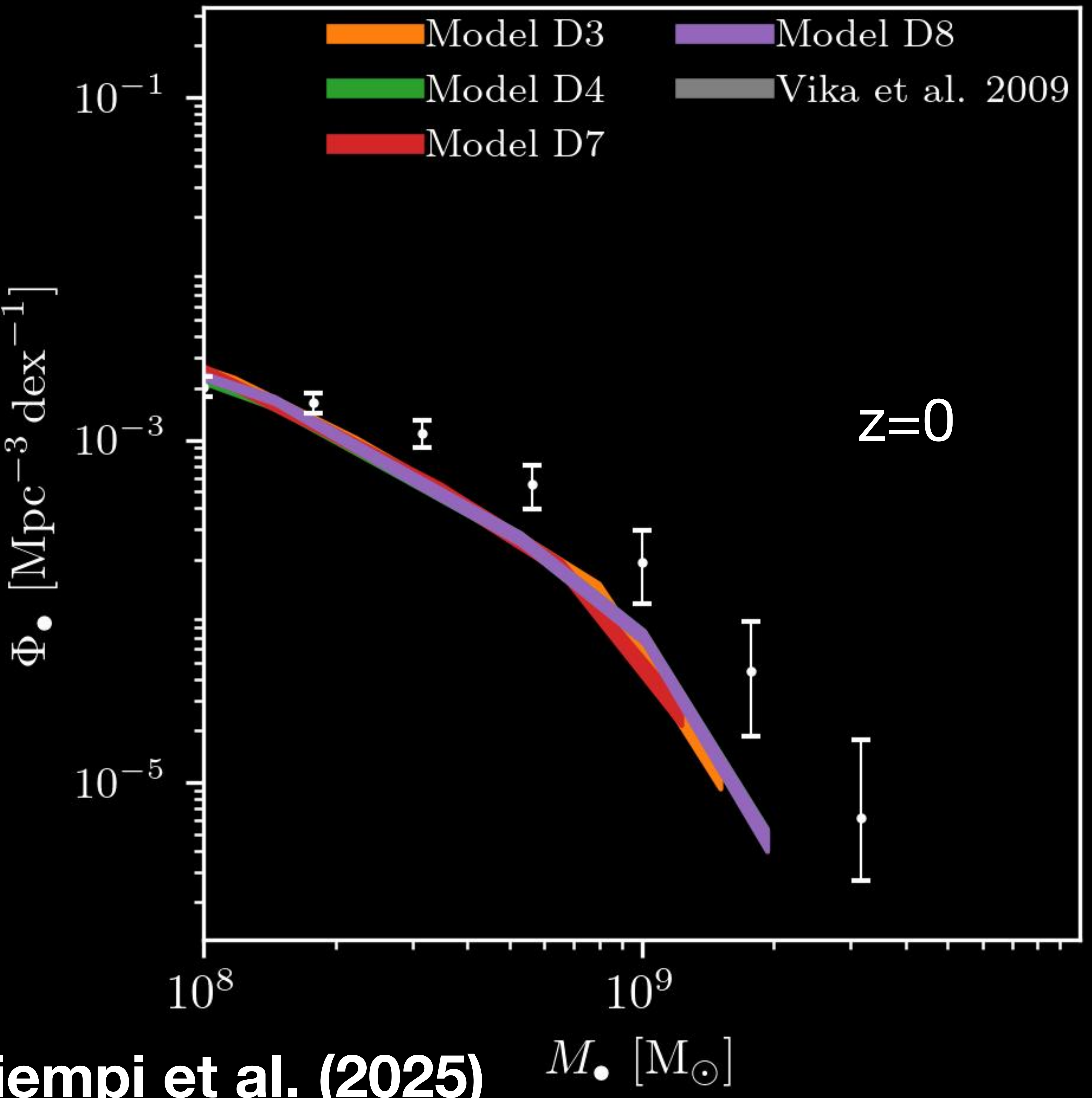
Liempi et al. (2025)

Scenario I: Runaway stellar collisions

Model D3-D7 -> r_{NSC} = 0.2 r_{NSC}
Model D4-D8 -> r_{NSC} = 0.1 r_{NSC}

Different models, more compact NSCs

$$r_{\rm NSC} = 3.3\,{\rm pc}\left(\frac{M_{\rm dyn}}{10^6\,{\rm M_\odot}}\right)^{0.5}$$



Liempi et al. (2025)

Scenario II: Very massive stars

Rapid formation of a very massive star >50000 $M_\odot$ and subsequently an IMBH from runaway collisions

Direct N-body and Monte Carlo simulations of dense star clusters

Marcelo C. Vergara[1⋆], Abbas Askar[2⋆⋆], Albrecht W. H. Kamlah[3,1], Rainer Spurzem[1,4,5], Francesco Flammini Dotti[1], Dominik R.G. Schleicher[6,7], Manuel Arca Sedda[8,9,10,11], Arkadiusz Hypki[12,2], Mirek Giersz[2], Jarrod Hurley[13,14], Peter Berczik[2,15,16], Andres Escala[17], Nils Hoyer[3,18,19], Nadine Neumayer[3], Xiaoying Pang[20,21], Ataru Tanikawa[22,23], Renyue Cen[24,25], and Thorsten Naab[26]

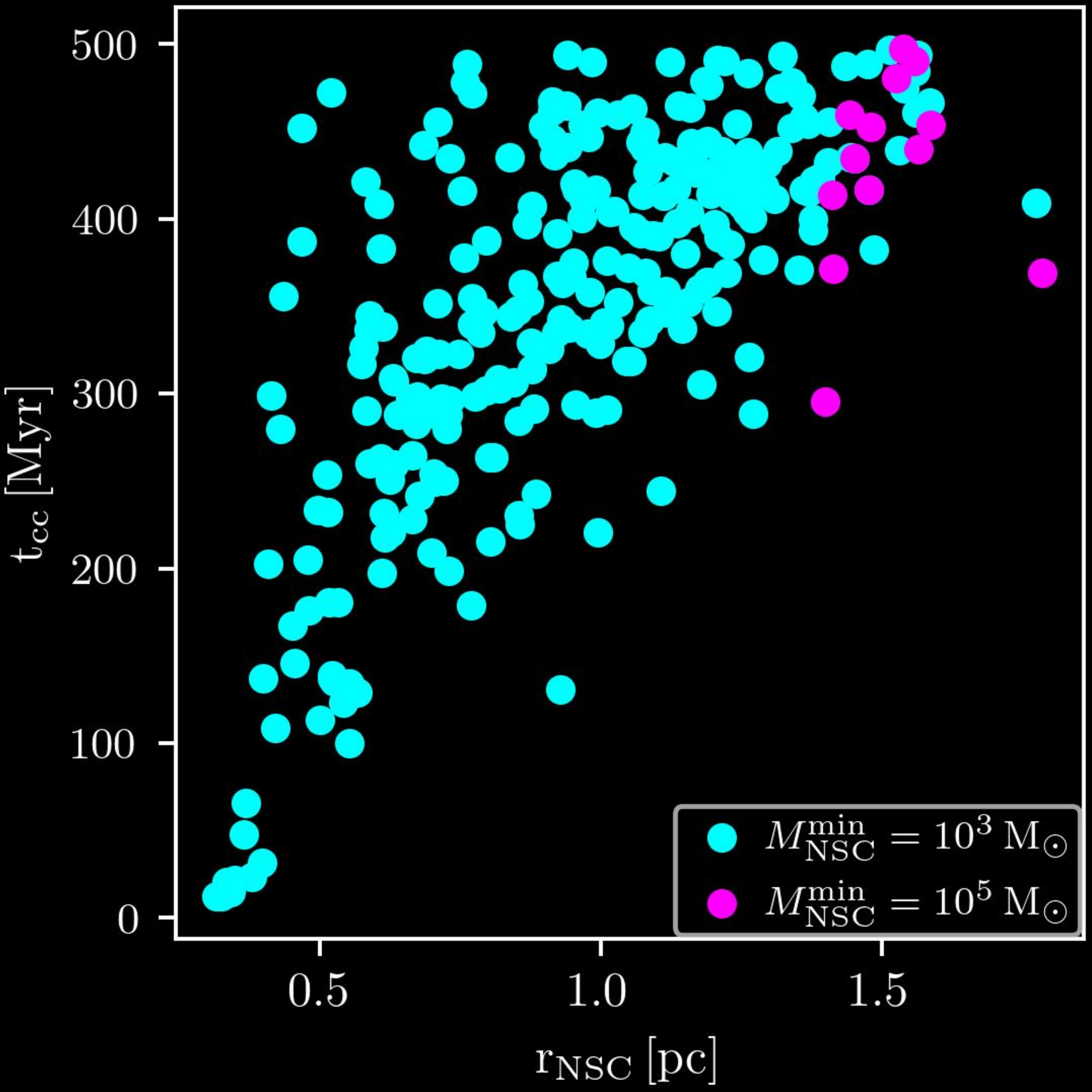
https://arxiv.org/pdf/2505.07491

Vergara et al., submited

Scenario II: Very massive stars

We seed NSCs with ages less than 500 Myr, and with core collapse timescales shorter than the age

$$t_{\rm cc} \sim 0.2\, t_{\rm relax}$$



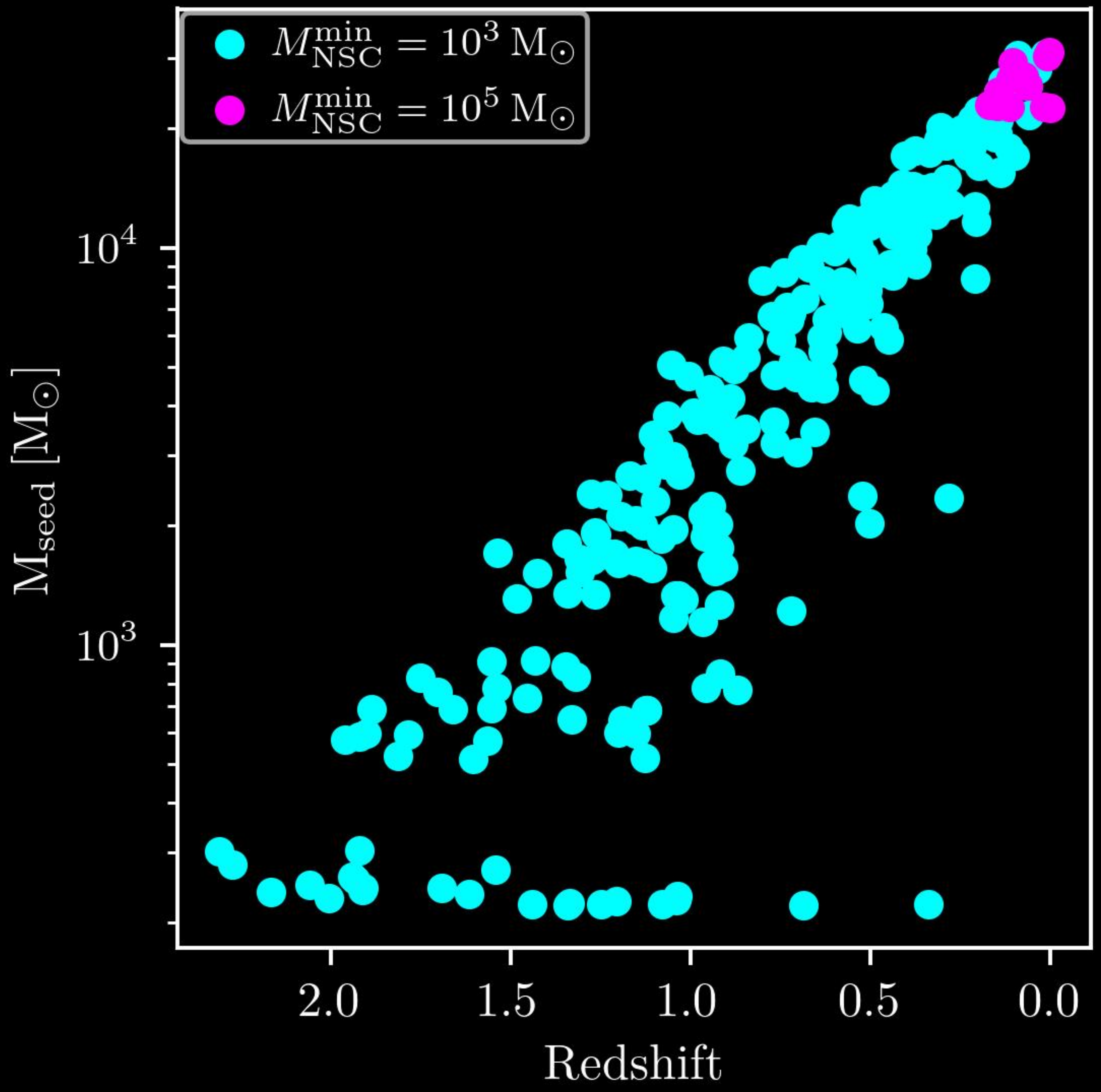
Scenario II: Very massive stars

We seed NSCs with ages less than 500 Myrs

for a Kroupa initial mass function,

$$f_{>3.5\,\mathrm{M}_\odot} = \frac{\int_{3.5\,\mathrm{M}_\odot}^{125\,\mathrm{M}_\odot} \Phi(M) M \,\mathrm{d}M}{\int_{0.01\,\mathrm{M}_\odot}^{125\,\mathrm{M}_\odot} \Phi(M) M \,\mathrm{d}M} \approx 0.22$$

$$M_{\mathrm{seed}} = f_{>3.5\,\mathrm{M}_\odot} M_{\mathrm{stellar}}^{\mathrm{NSC}}$$



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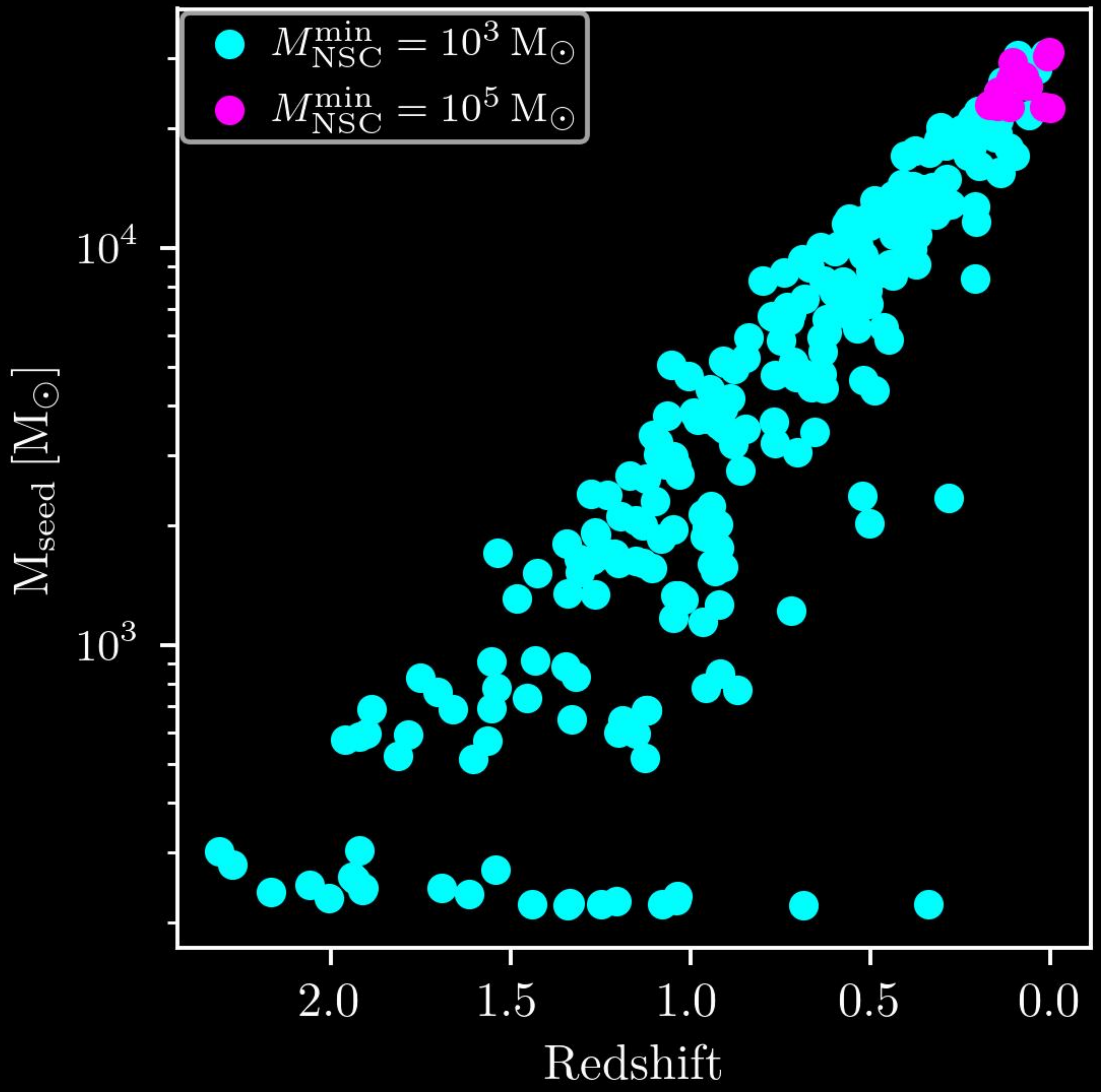
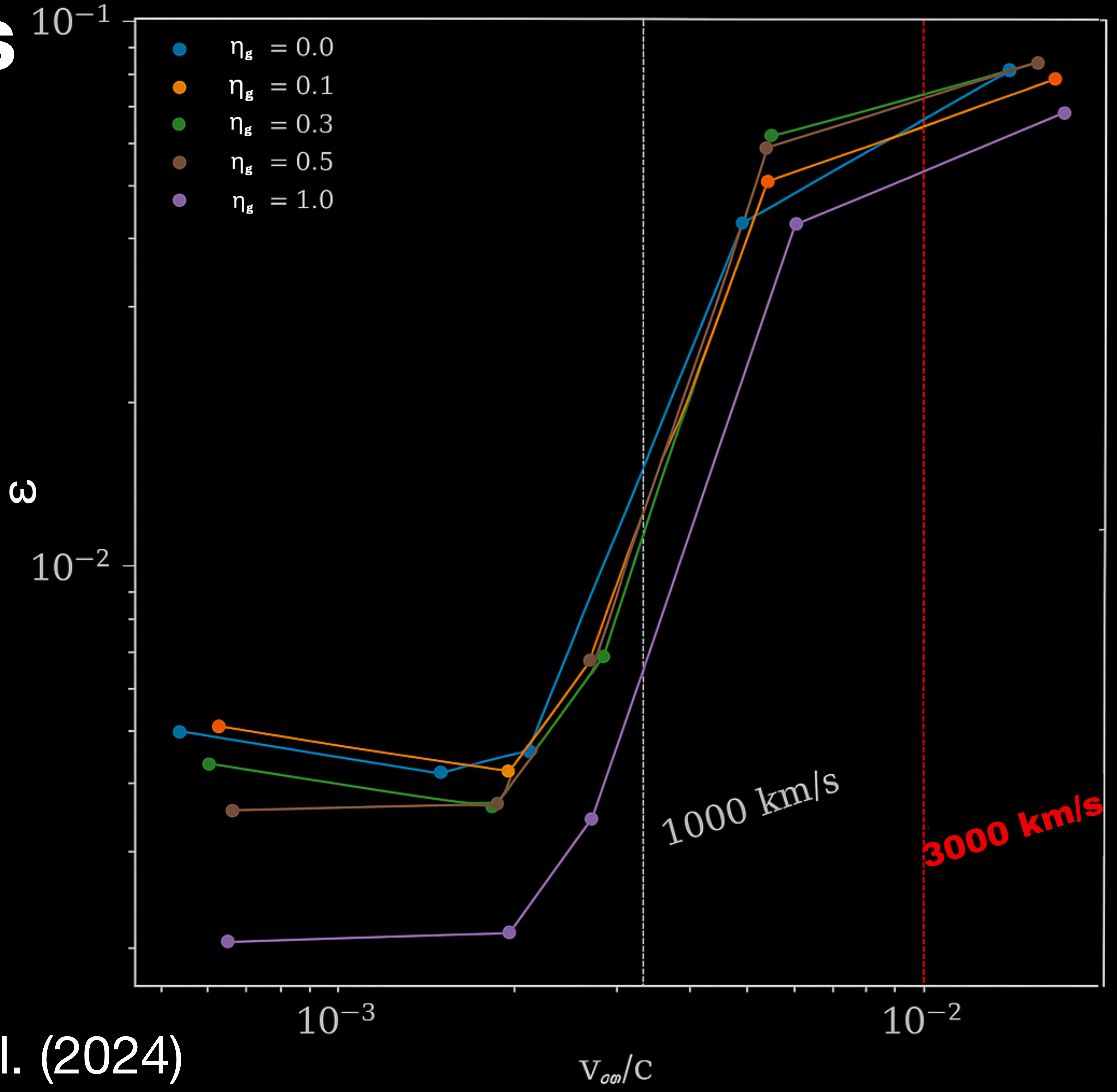


Scenario III: Dark cores

Stellar-mass black holes sub-clusters within NSC.

Formation of BH seeds of at least 10^3 $M_{\odot}$ if the cluster is relativistic, in sub-clusters with initial mass equals 10^5 $M_{\odot}$.



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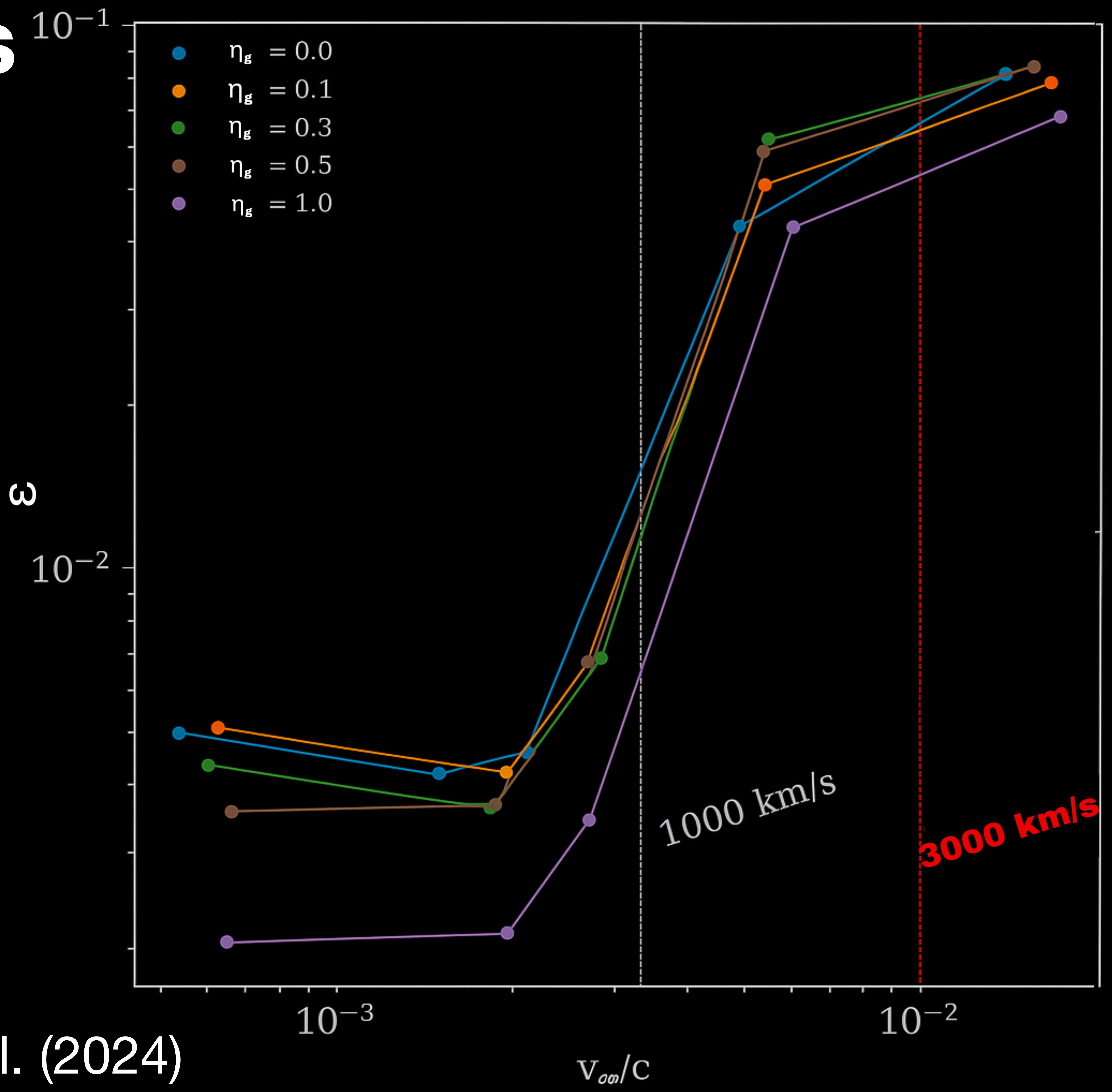

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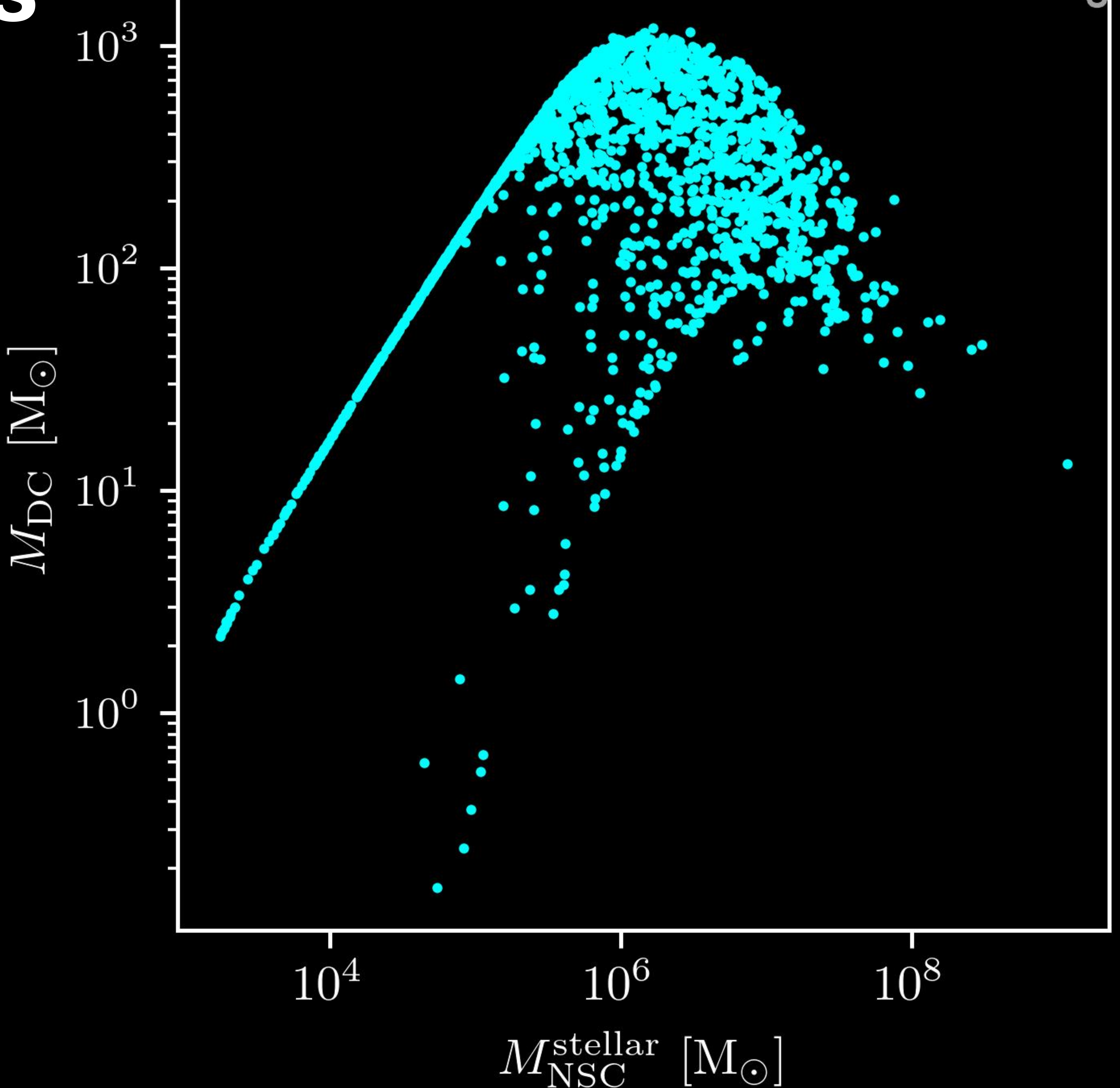
Scenario III: Dark cores

$$\dot{M}_{\rm BHs}^{\rm NSC} = \epsilon_\bullet \, \dot{M}_{\rm stellar}^{\rm NSC}$$

for a Kroupa initial mass function,

$$\epsilon_\bullet = 1.6 \times 10^{-3}$$

$$\dot{M}_{\rm DC}^{\rm NSC} = \frac{M_{BHs}^{\rm NSC}}{t_{\rm cc}}$$



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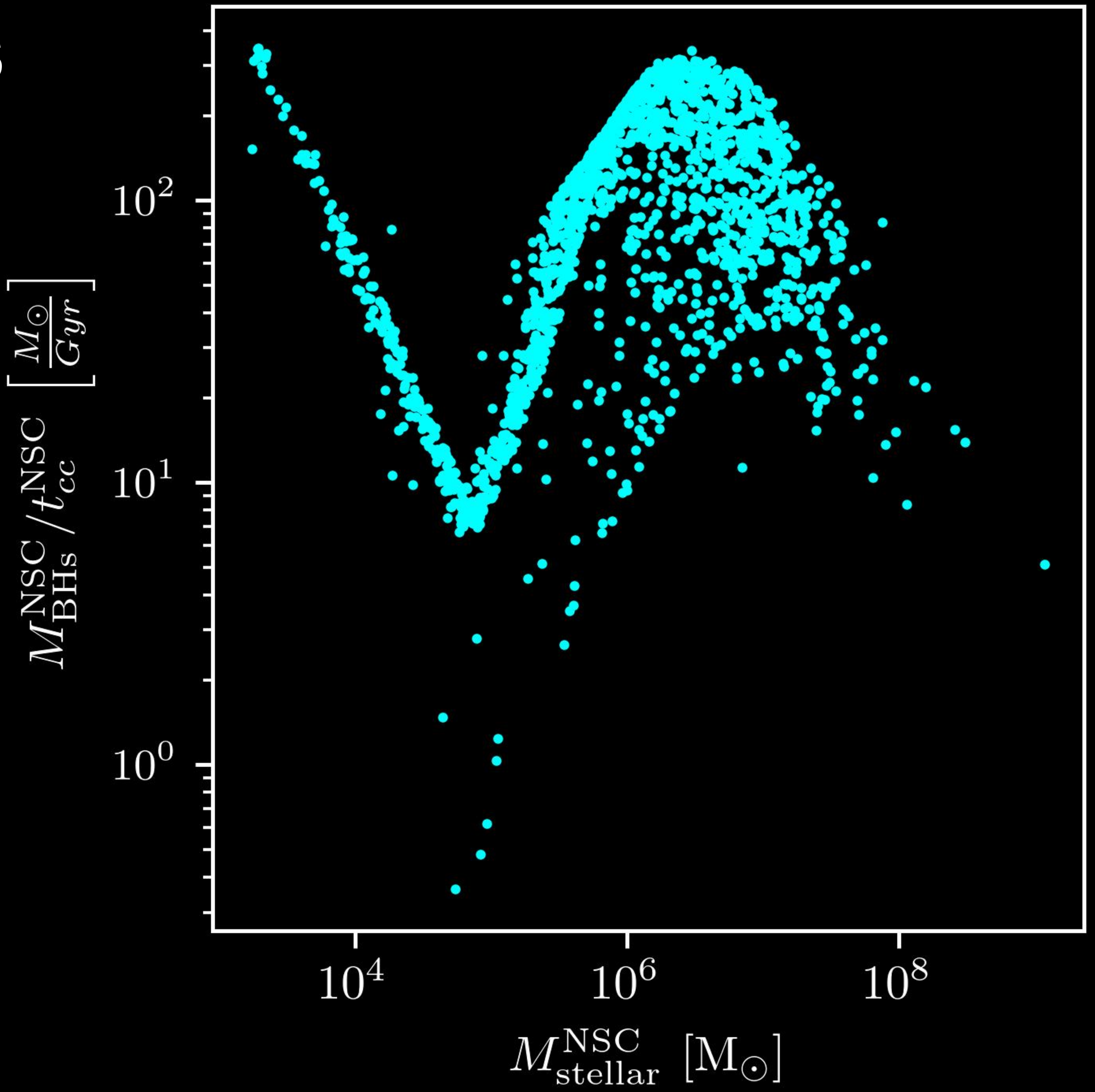

Summary

We are developing a semi-analytic nuclear star cluster model.

We are applying seeding prescriptions from N-body simulations in a galaxy evolution context. Formation of seeds above $10^3 M_\odot$ (up 10 ~$10^5 M_\odot$)

We plan to incorporate all the BH formation prescriptions in one single model!

Implementation of the Globular migration scenario under test and profiling.

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Thank you!

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