Dynamics of black holes in dense stellar systems

Sambaran Banerjee
Helmholtz-Instituts für Strahlen- und Kernphysik (HISKP) and
Argelander-Institut für Astronomie (AIfA), University of Bonn

@ The Astronomical Institute
Charles University of Prague

Lecture 3

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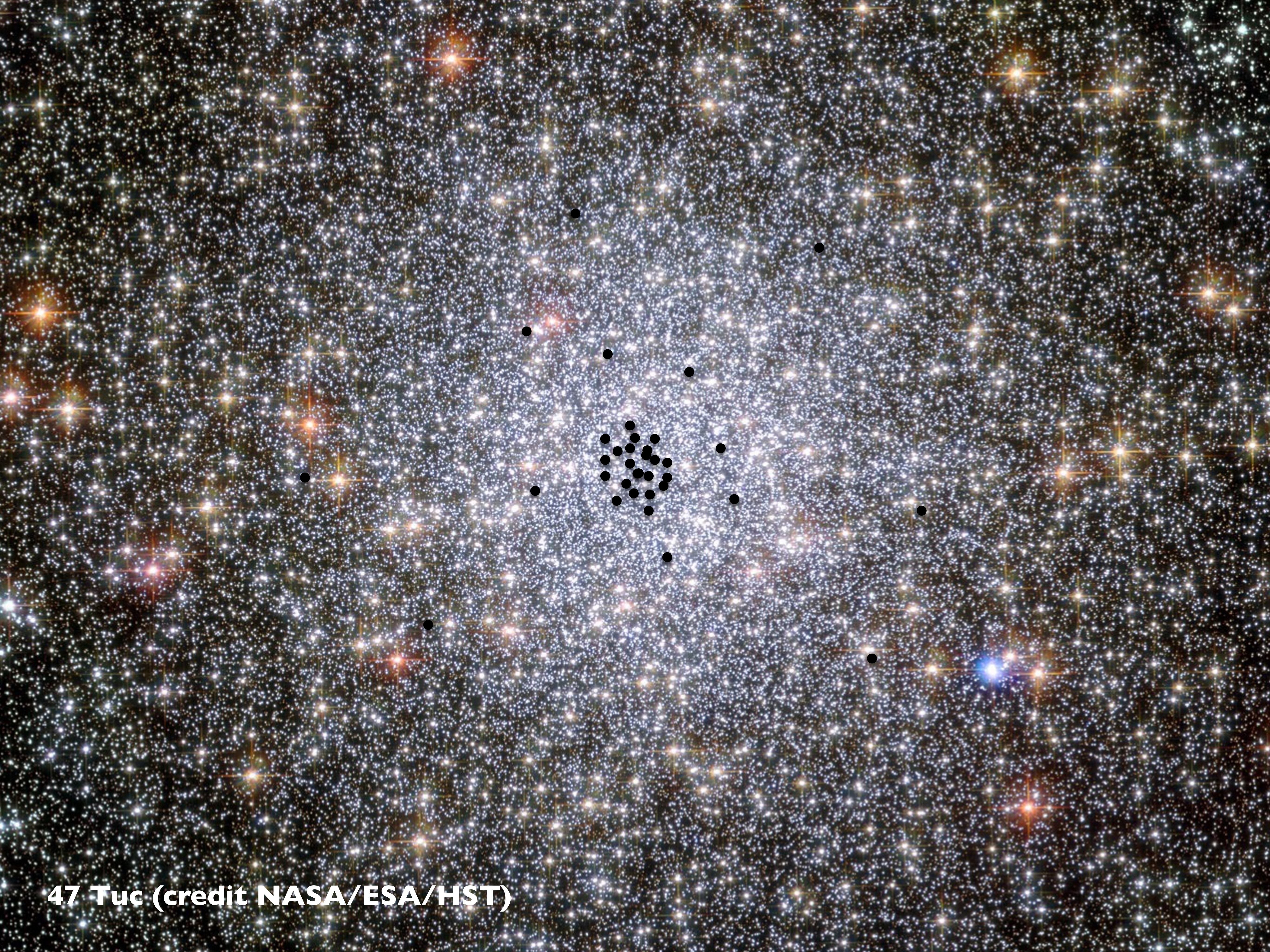
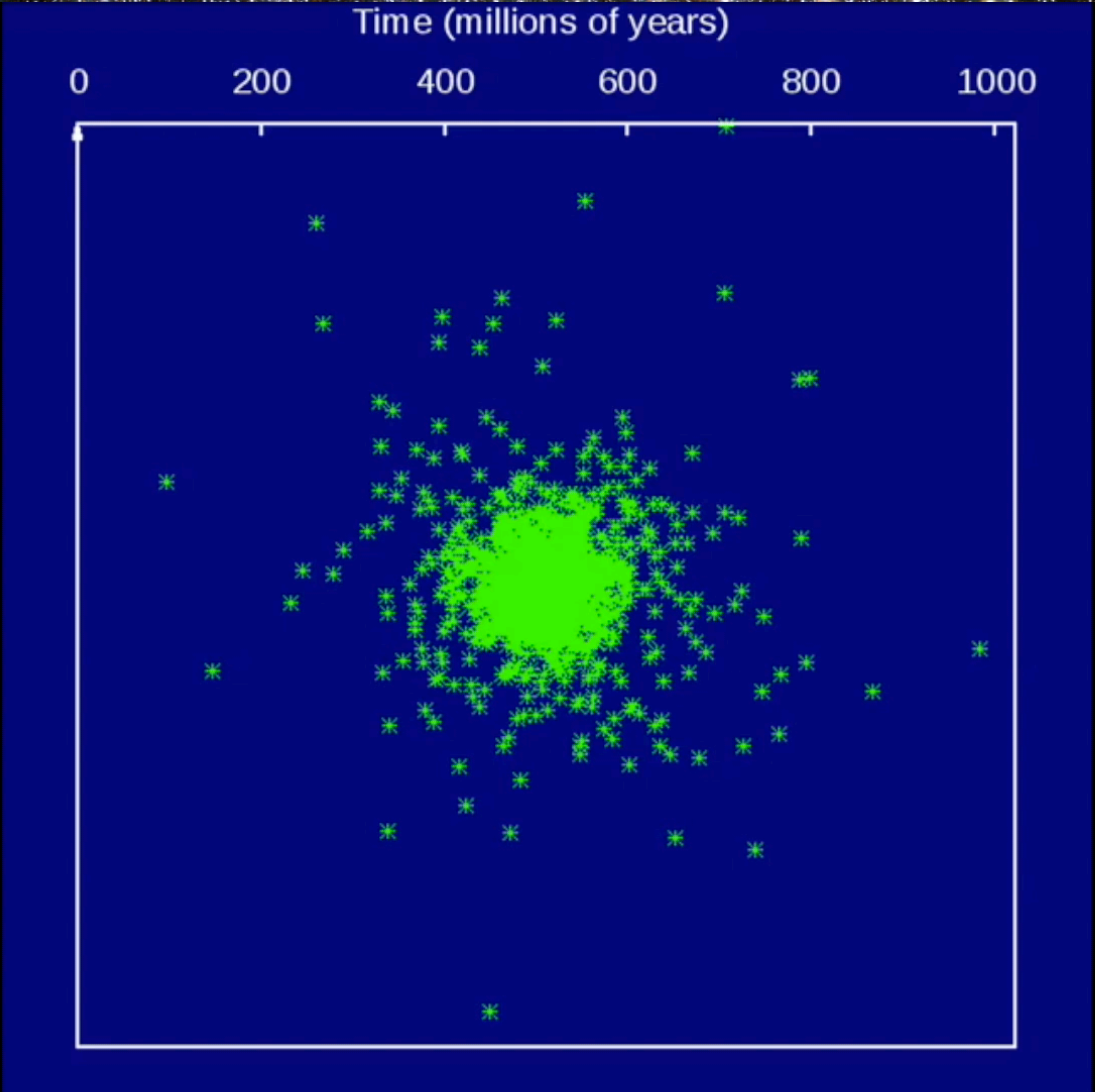
DFG Deutsche Forschungsgemeinschaft



47 Tuc (credit NASA/ESA/HST)



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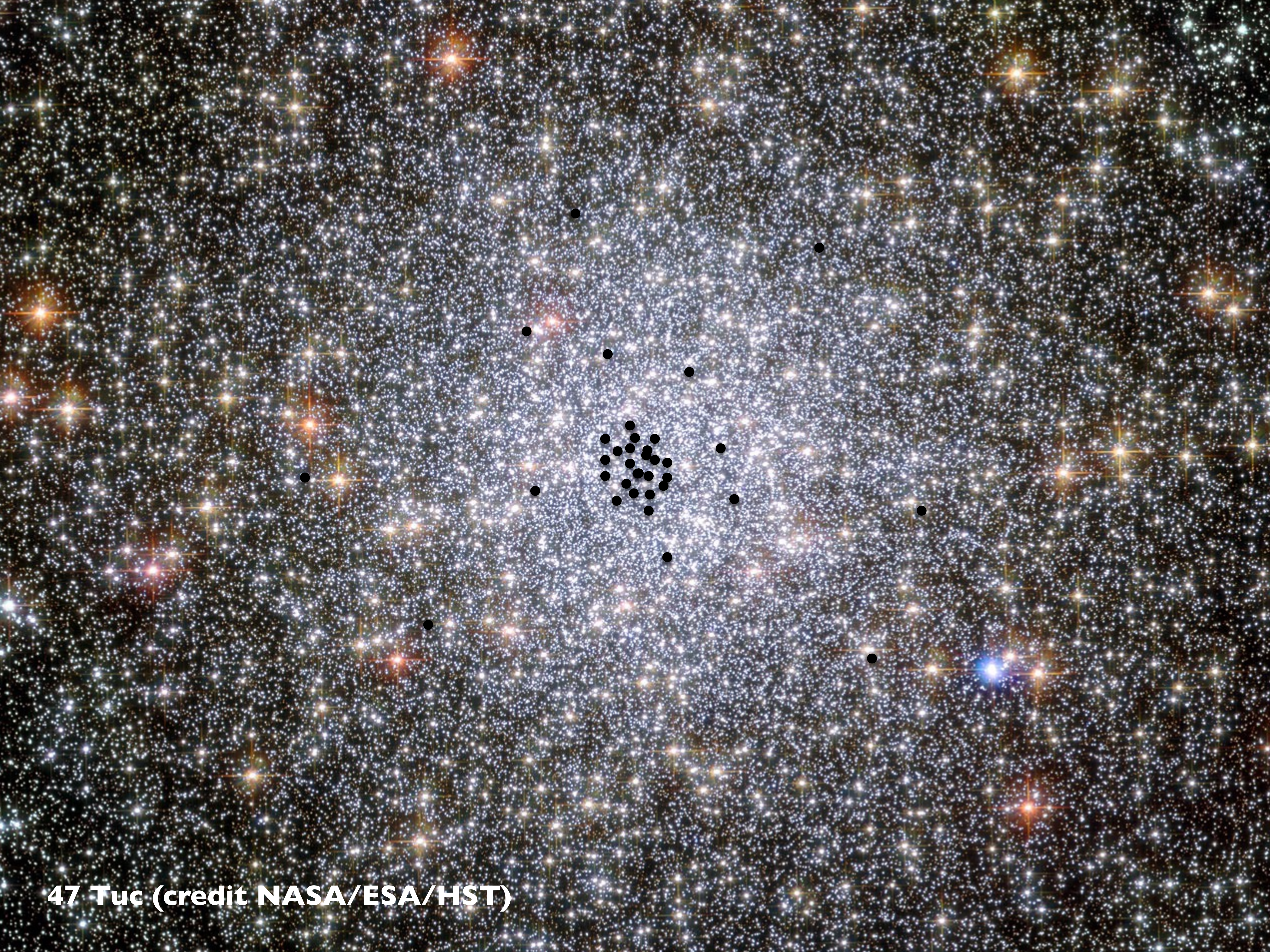

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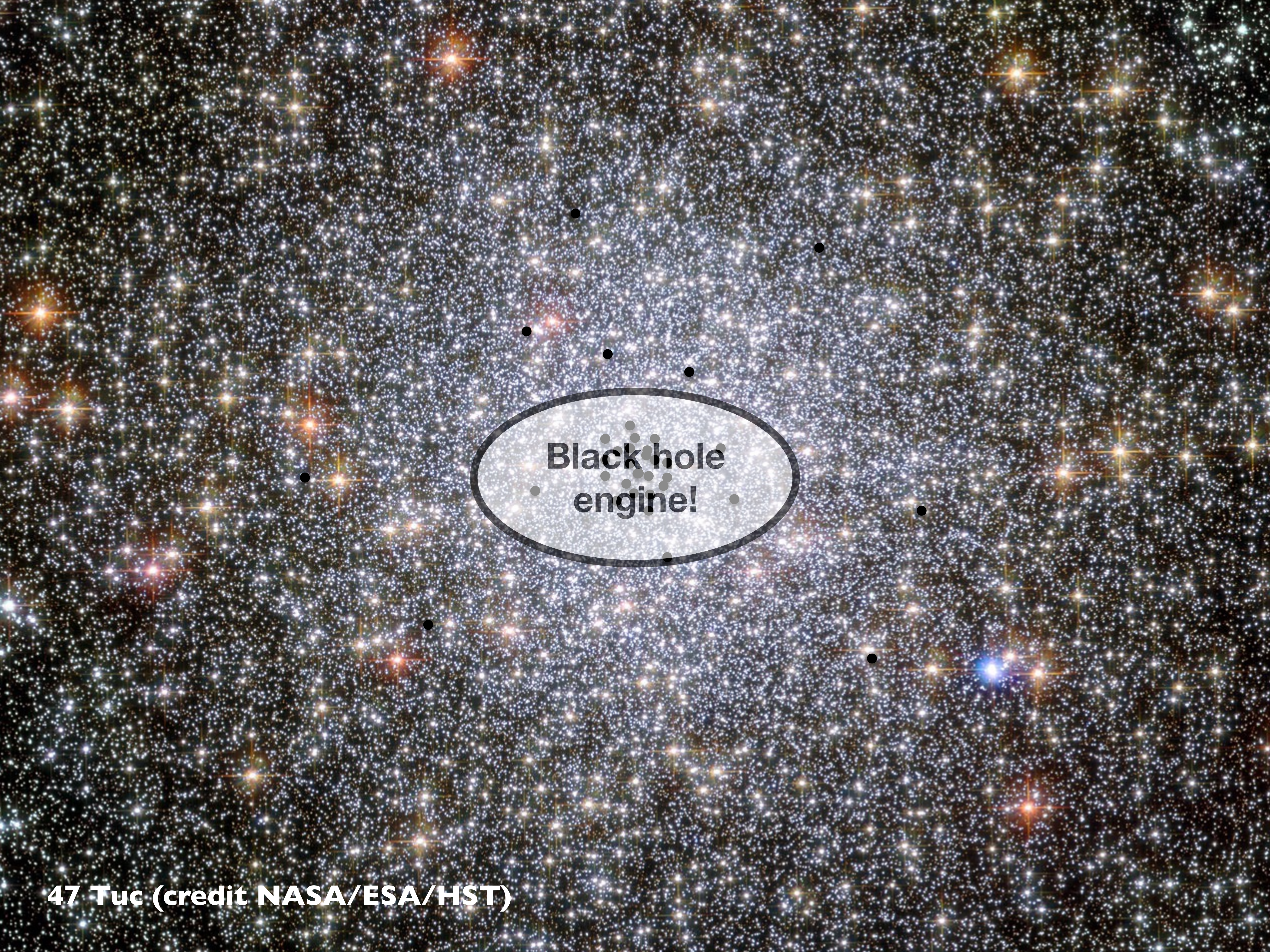
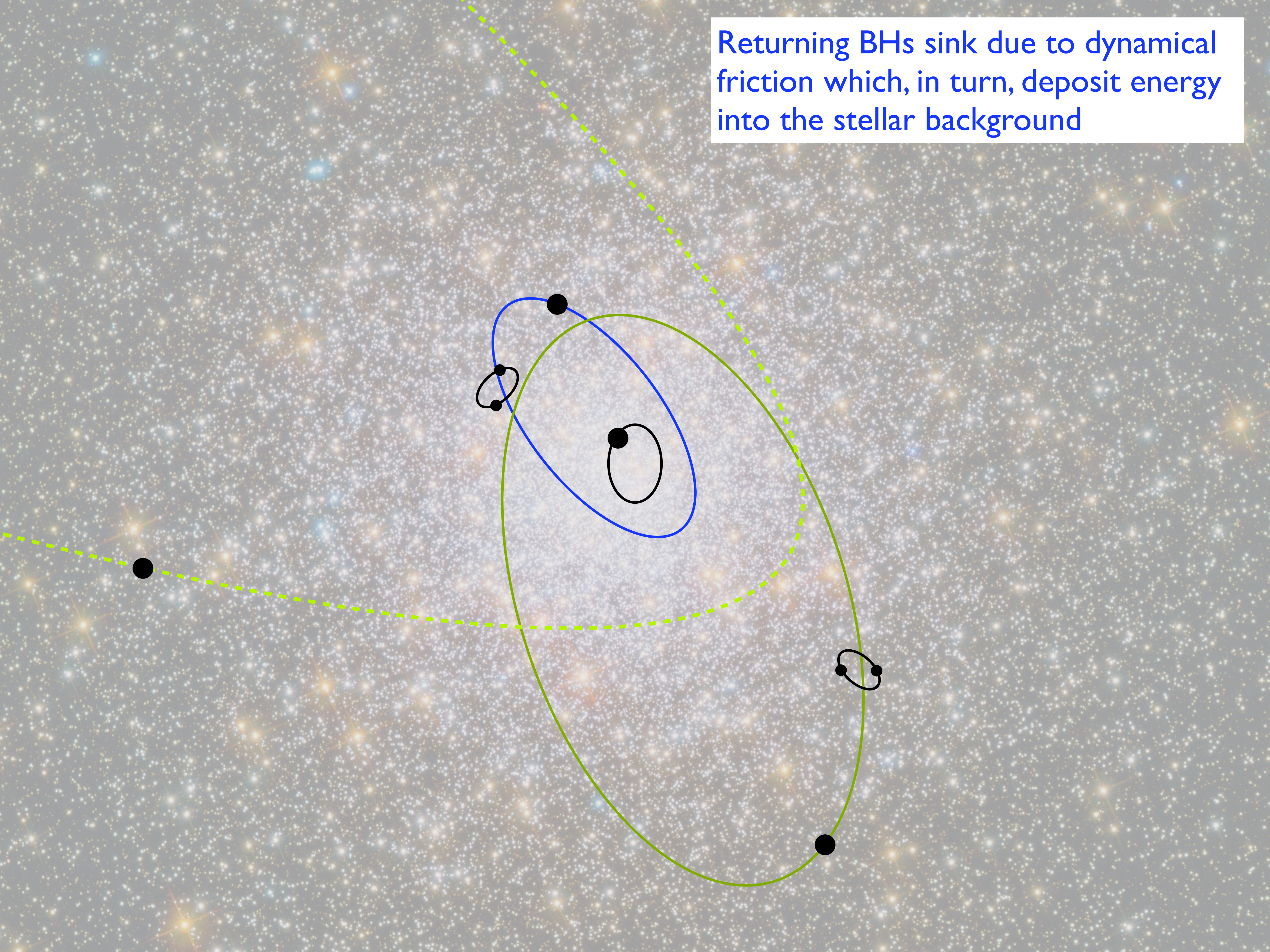


47 Tuc (credit NASA/ESA/HST)

Returning BHs sink due to dynamical friction which, in turn, deposit energy into the stellar background



Dynamical friction caused by “wake” formation behind fast-moving massive particle due to its “gravitational focussing” effect. The wake applies retarding force to the particle.
[see Chandrashekhar’s stellar dynamics book for details]

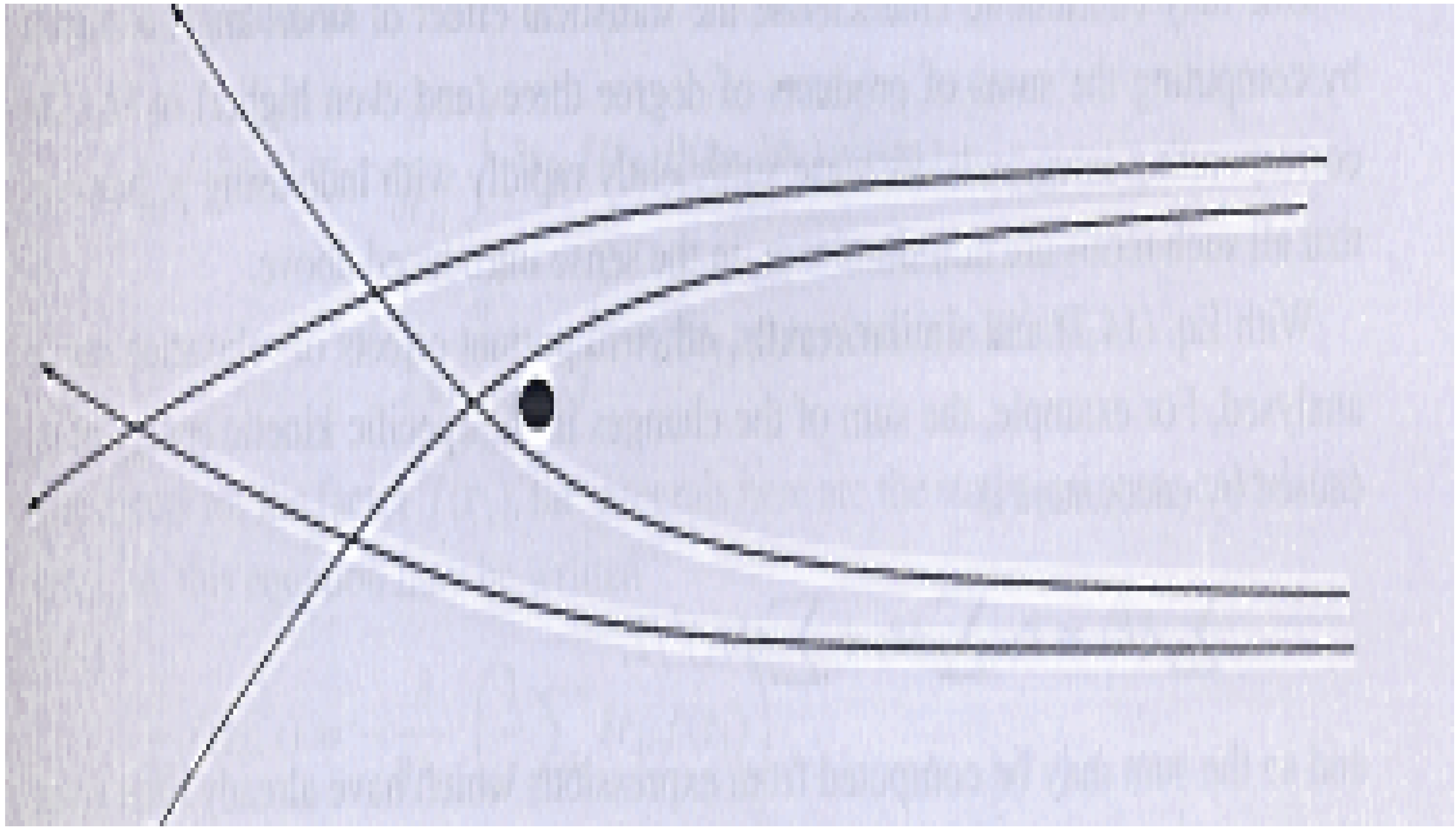


Image from Heggie & Hut’s book

Energy injection into the cluster by the “BH-engine”:

- Expands the cluster

- Delay’s secular (two-body relaxation driven) processes of the rest of the stellar system, e.g., mass segregation and core collapse

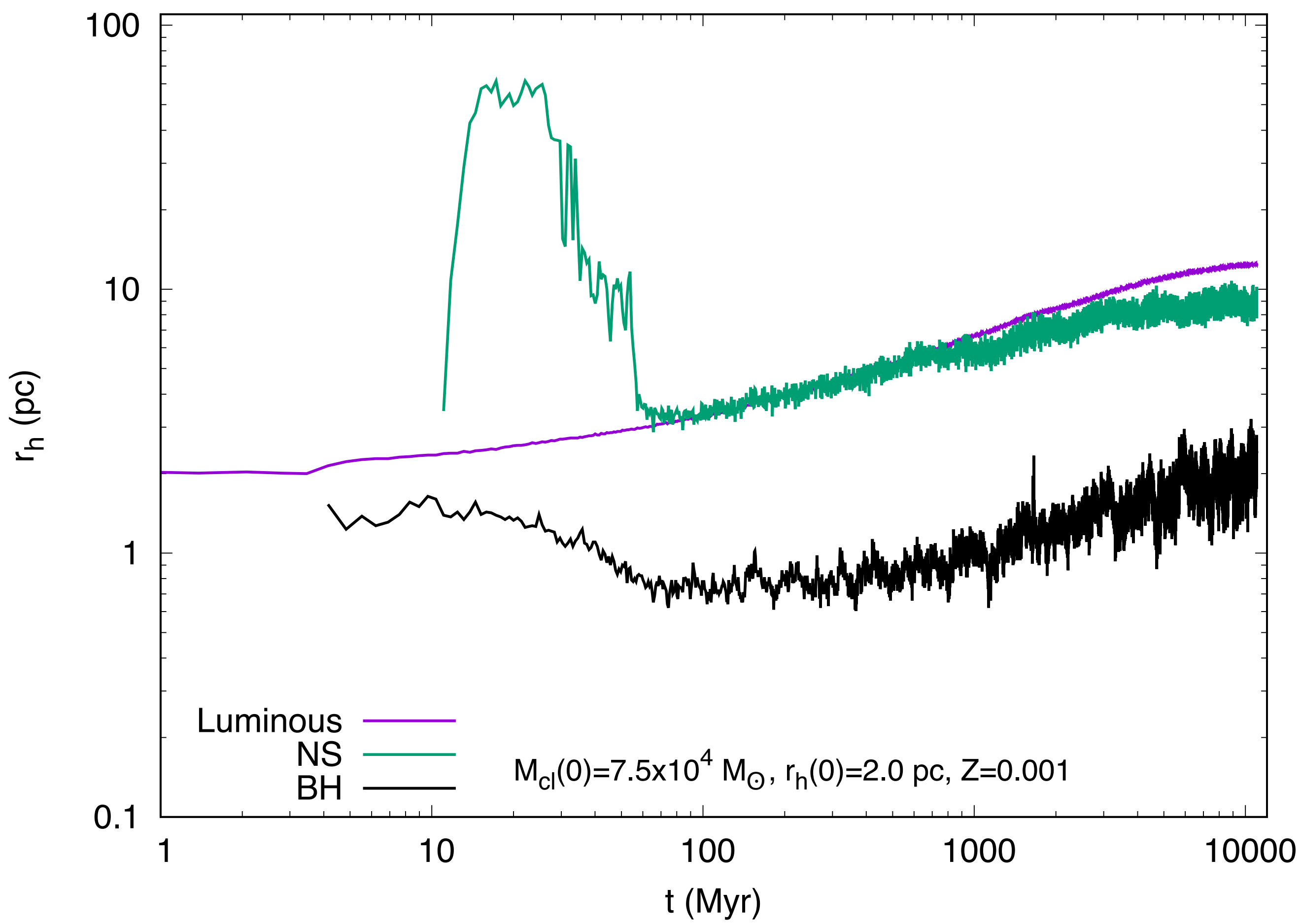
- Is essentially a manifestation of the “post-collapse expansion” due to the core-collapse of the BH sub-system

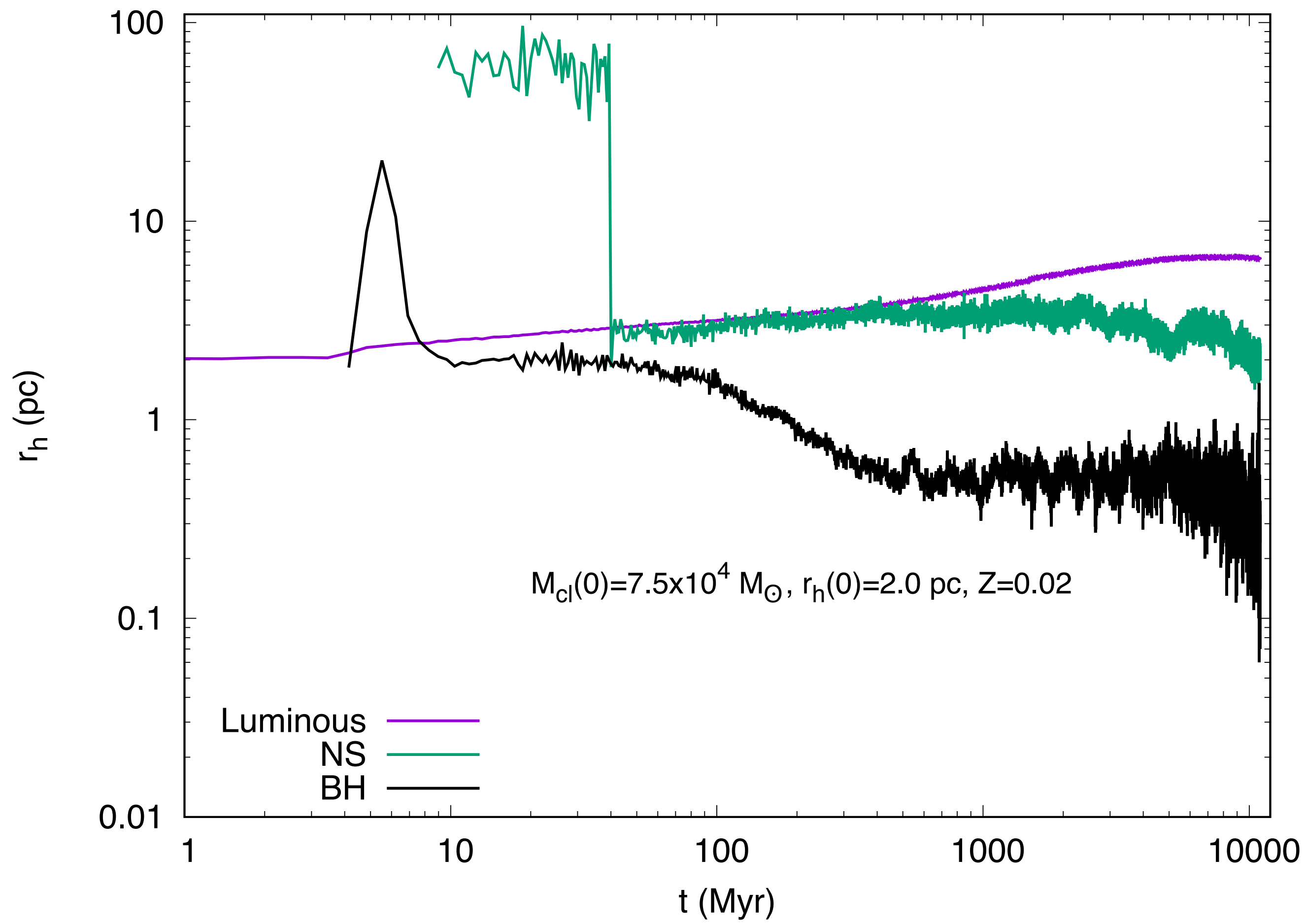
- Recall He`non’s Principle! (lecture 1)

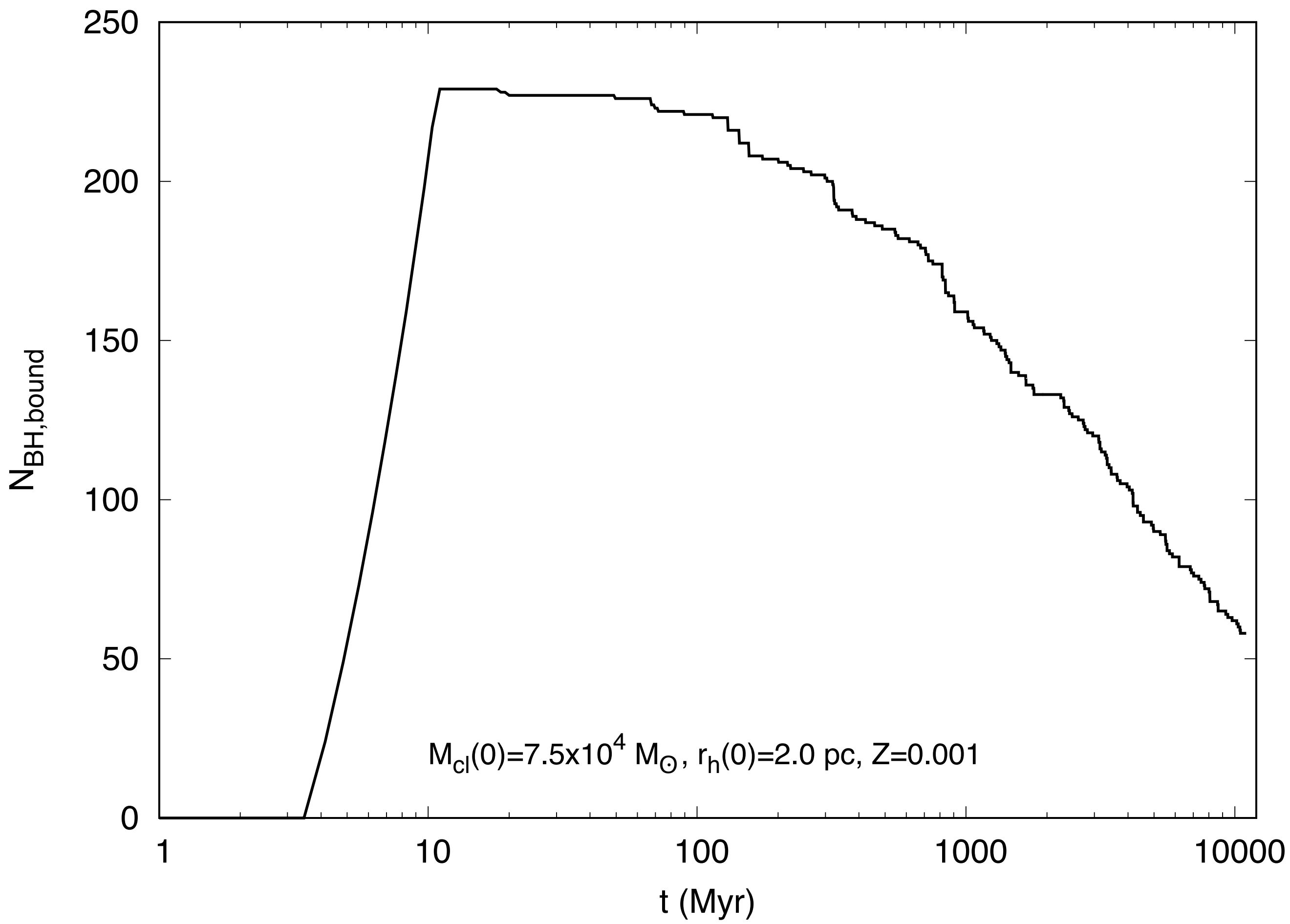
- Observational signatures?

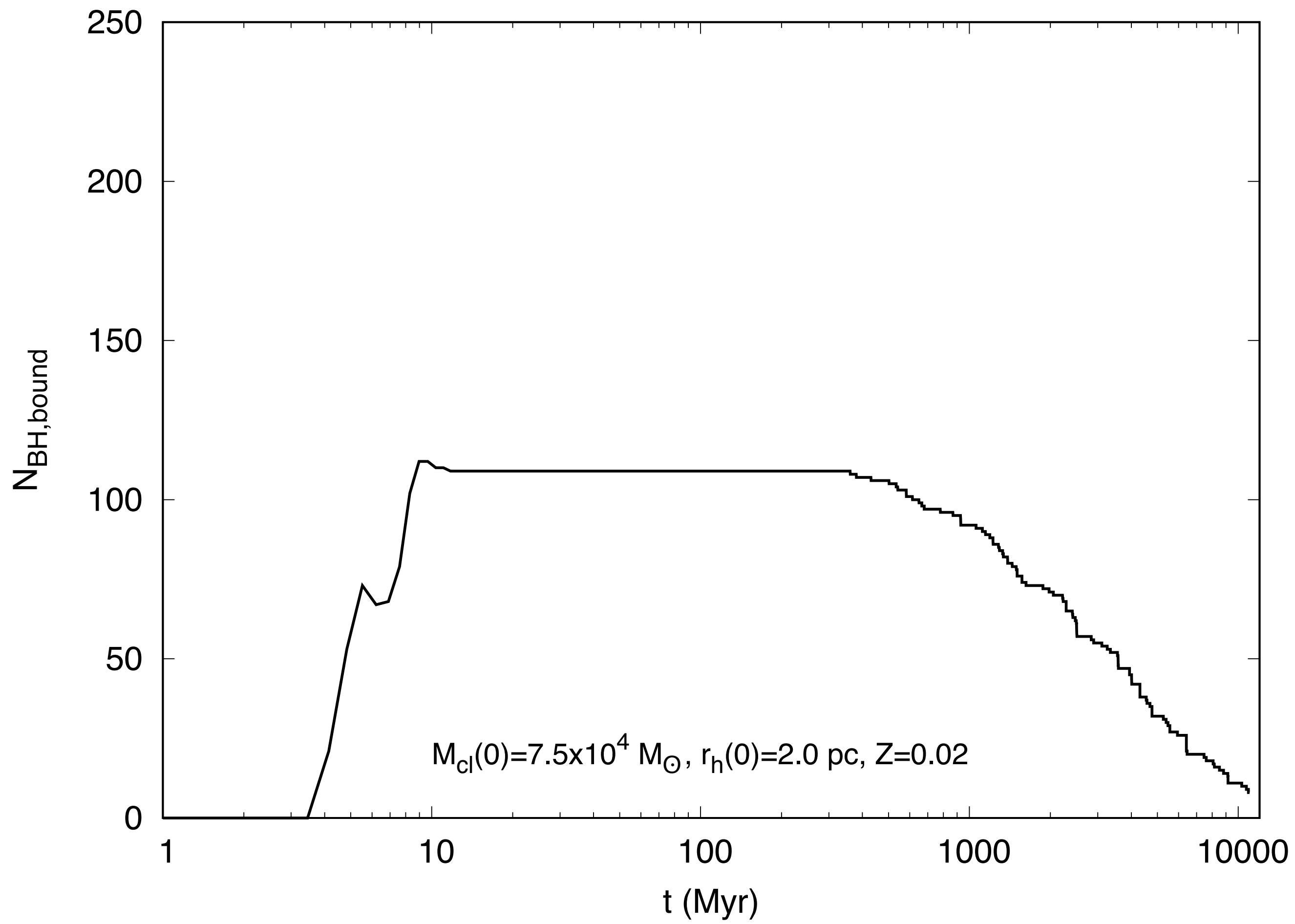
Example from N-body simulation

Banerjee, S. in prep…









Example from N-body simulation

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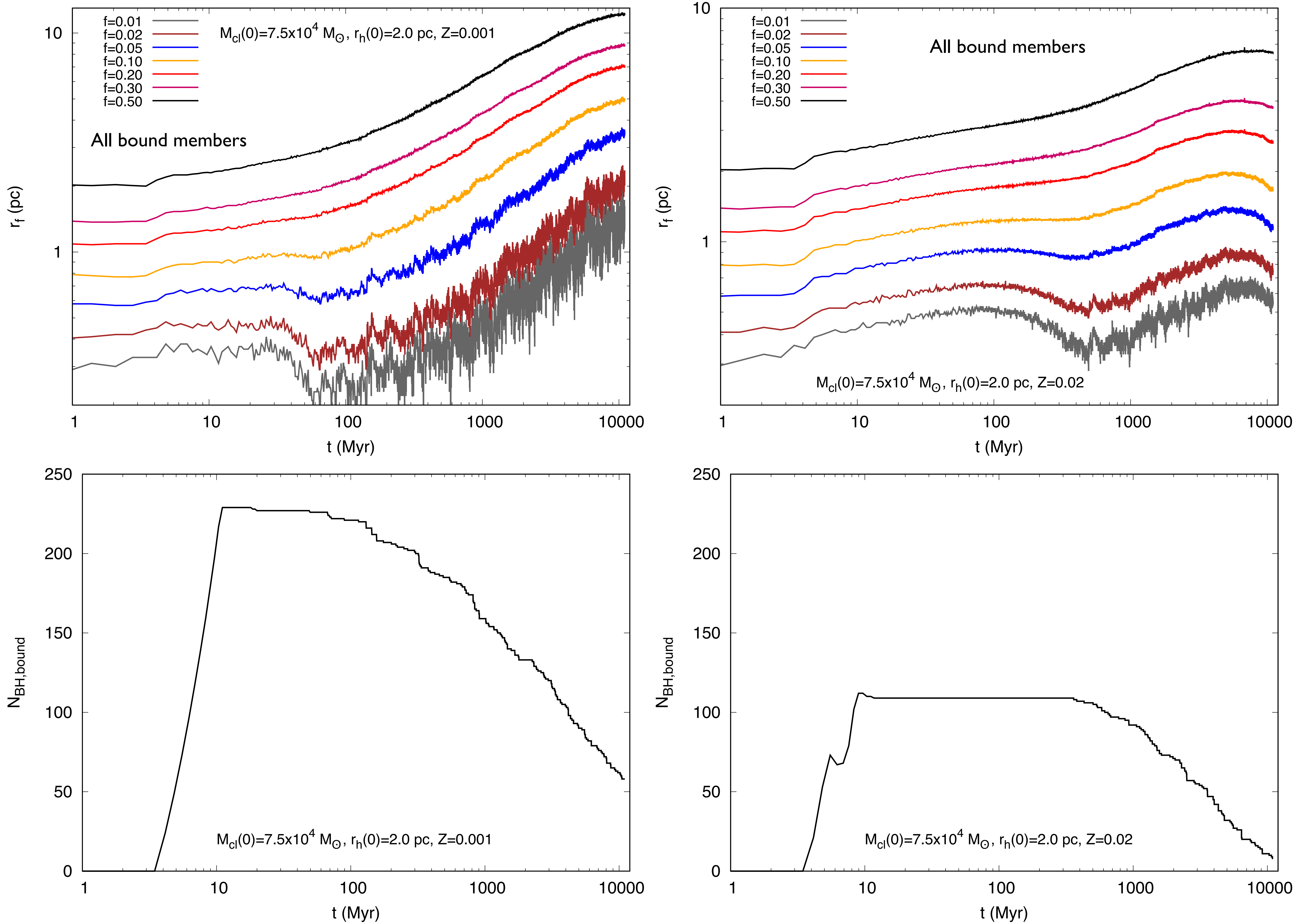

Example from N-body simulation

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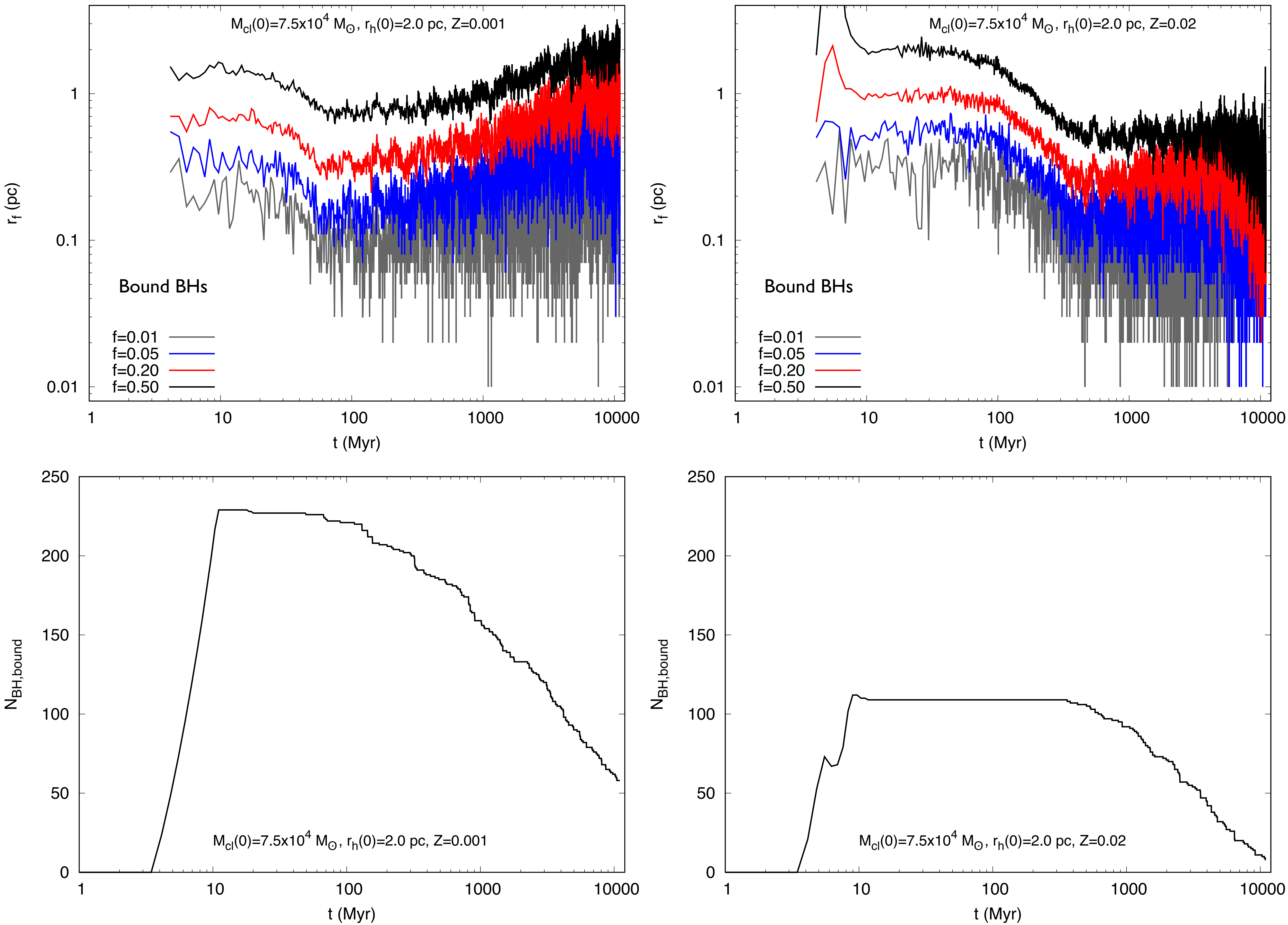
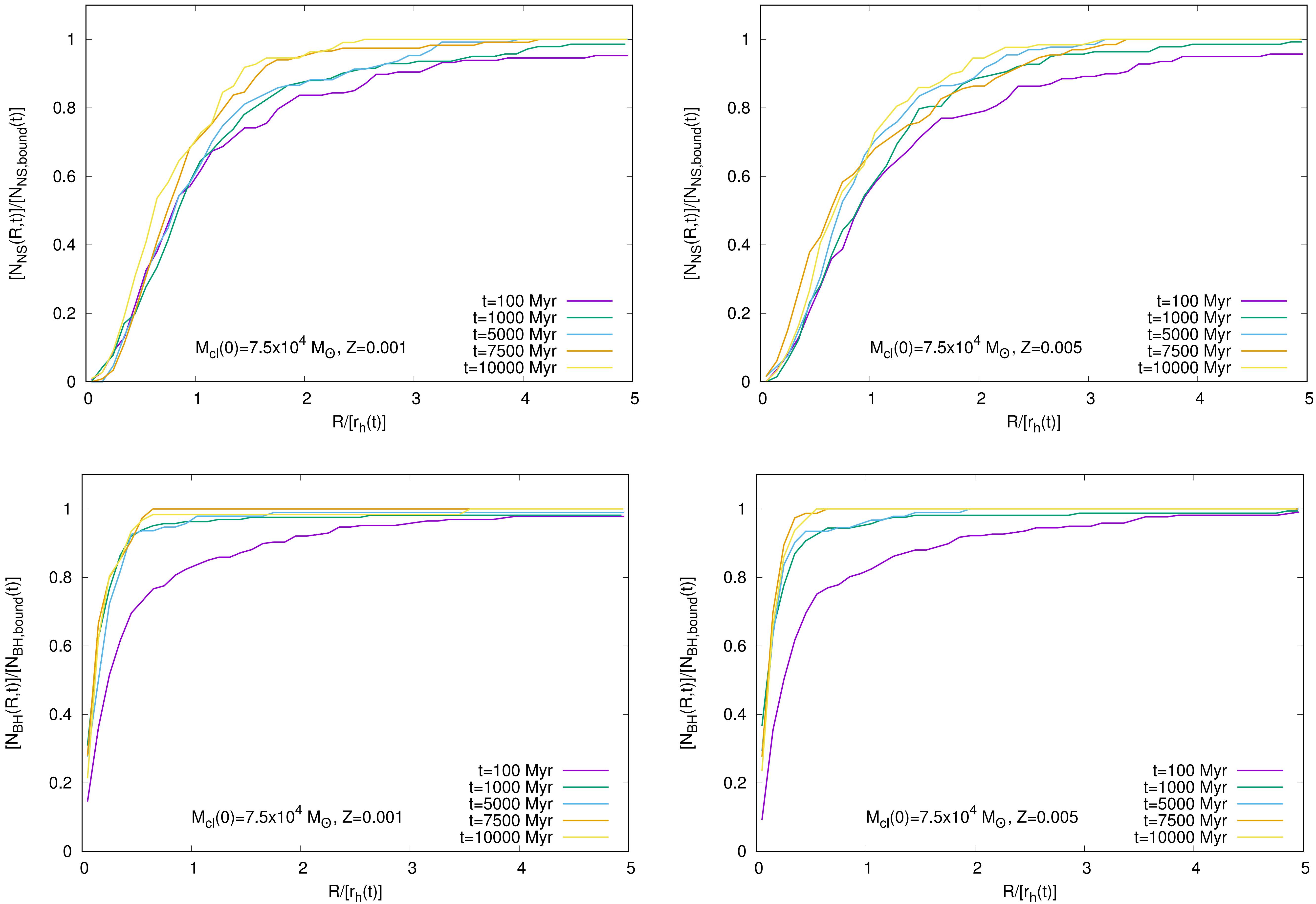


BH retention prevents mass segregation of NSs

From Banerjee, S., 2018, MNRAS, 473, 909



Non-segregation of NSs prevents them from participating in close encounters and exchange interactions with the BHs as long as a dynamically-active population of BHs remains in the cluster. This makes dynamical formation of BNS and NS-BH binaries and their mergers unlikely in stellar clusters, as confirmed in recent star-cluster simulations.

Young massive and open clusters (direct N-body):

Banerjee, S., 2018, MNRAS, 473, 909

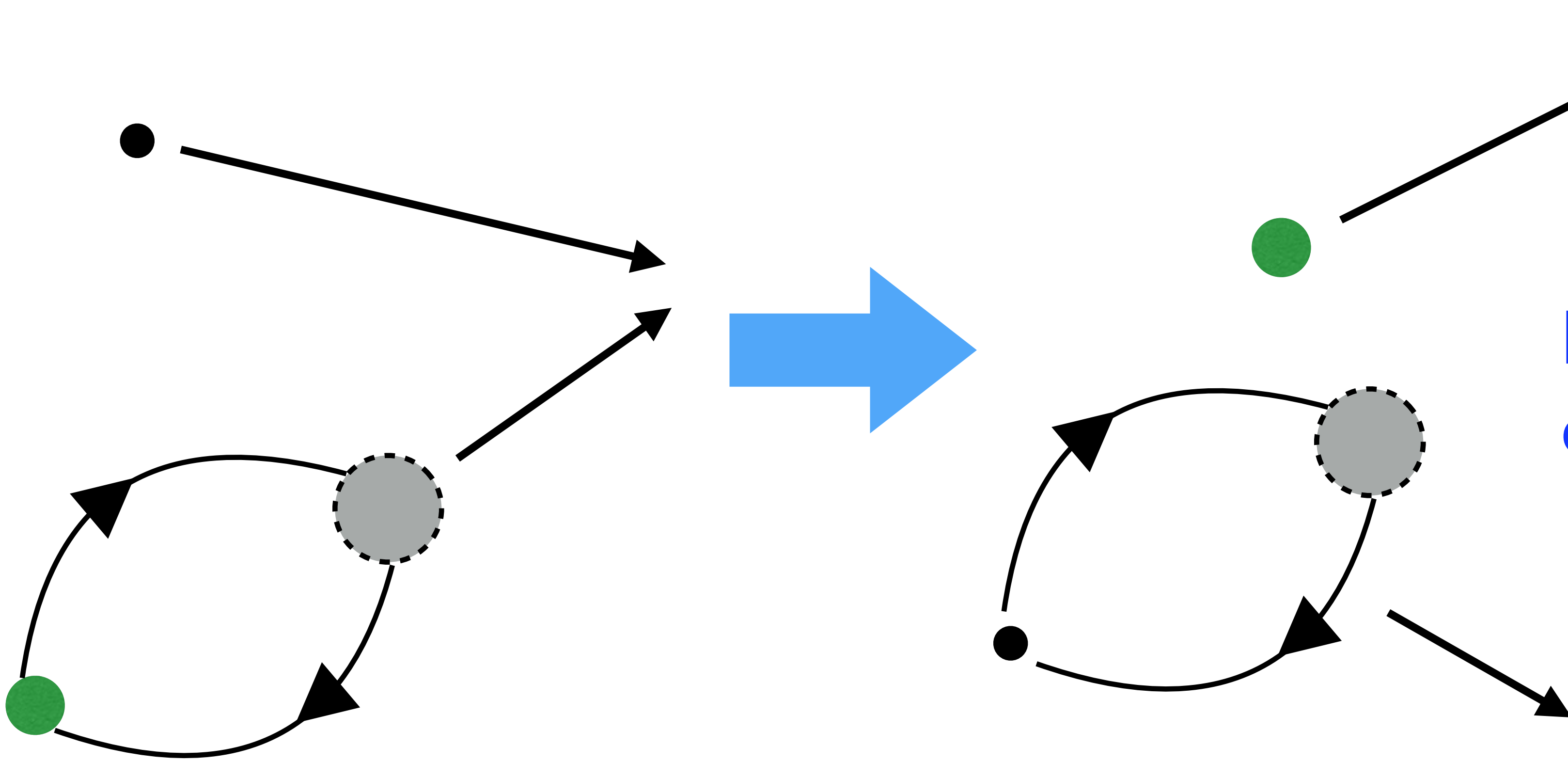
Fragione, G., Pavlík, V., Banerjee, S., 2018, MNRAS, 480, 4955 **[work initiated in Modest17 in Prague!]**

Globular clusters (Monte Carlo):

Ye, C. S., Kremer, K., Chatterjee, S., Rodriguez, C. L., Rasio, F. A., 2019, ApJ, 877, 122

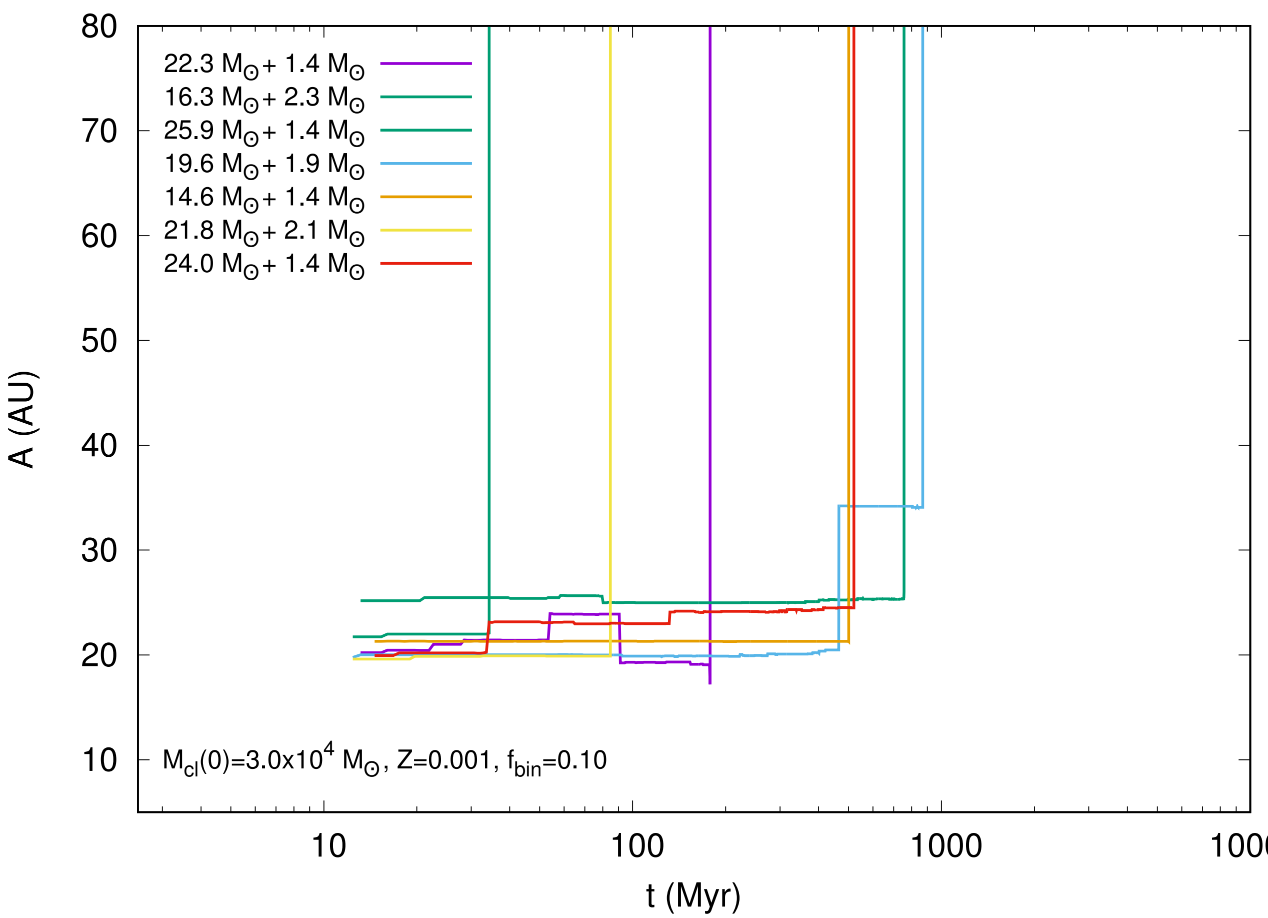
Ye, C. S., Fong, W-f., Kremer, K., Rodriguez, C. L., Fragione, G., Rasio, F. A., arXiv:1910.10740

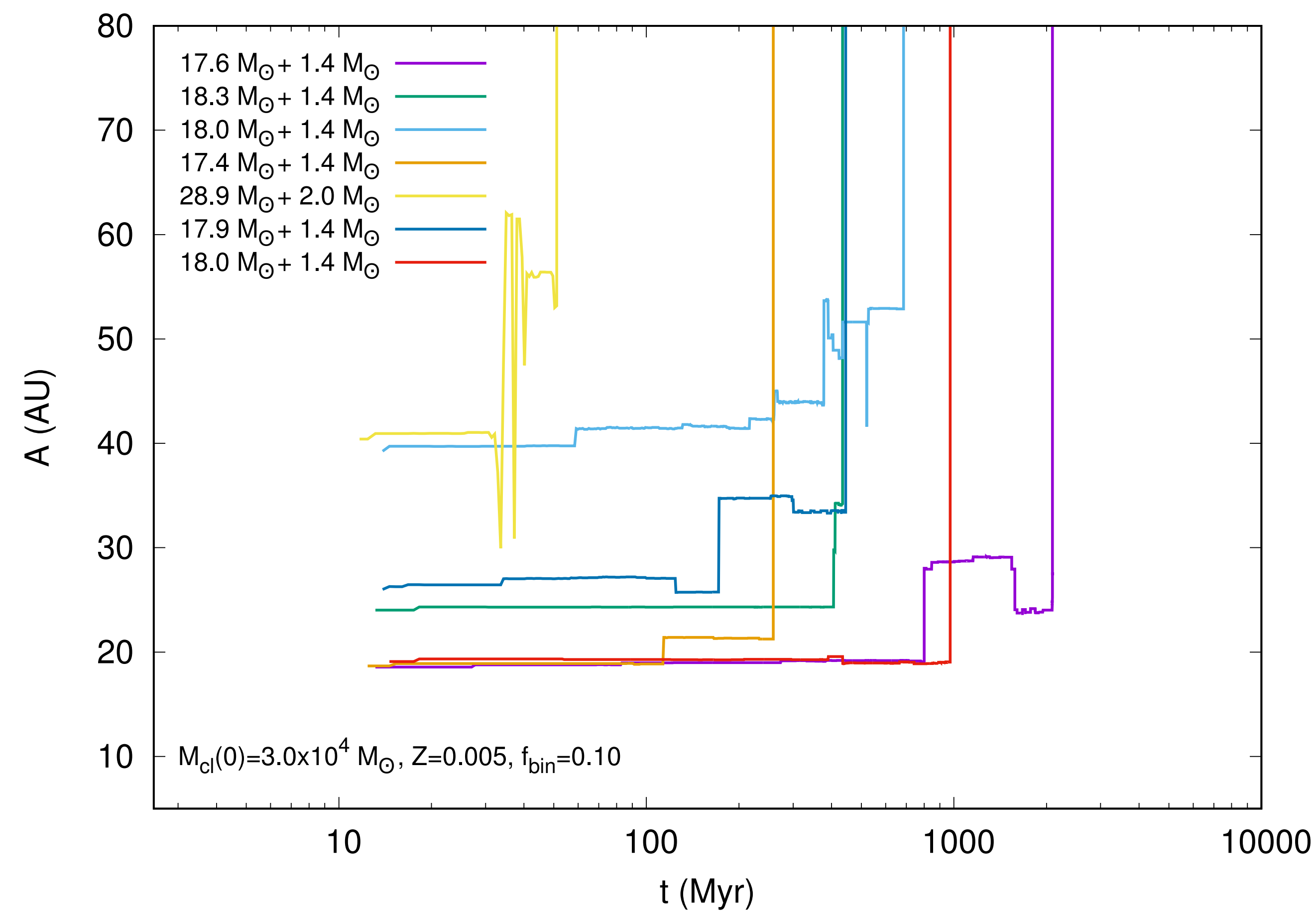
NS-BH and BNS mergers are, nevertheless, being observed by LIGO! They are then likely field binary evolution products. More studies needed.

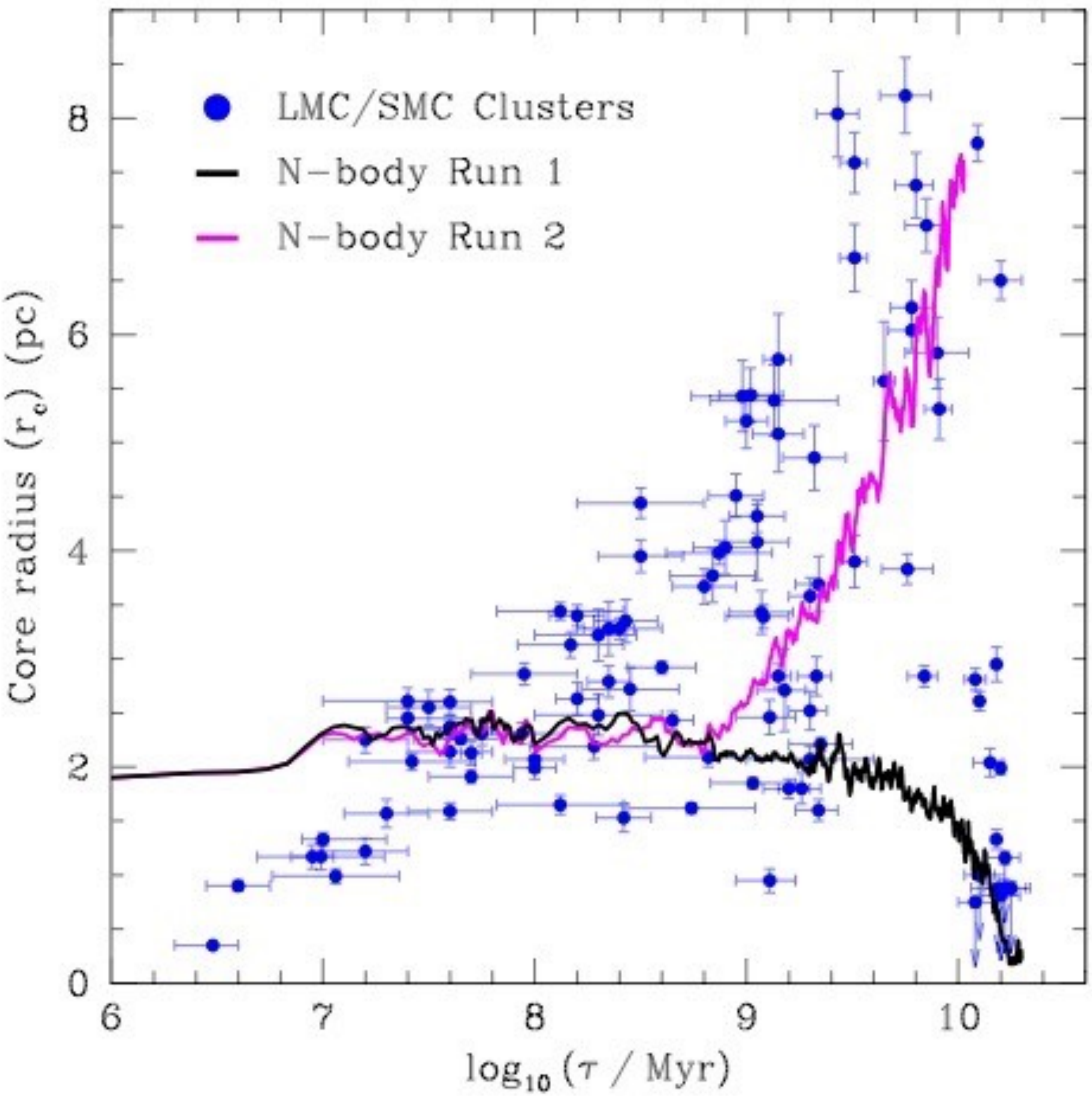


NS in a binary gets exchanged by BH in < 1 Gyr

From: Banerjee, S., 2018, MNRAS, 473, 909







Cluster core expansion in similar N-body calculations by Mackey et al., 2008, MNRAS, 386, 65 consistent with observed age-core radius relation of LMC/SMC clusters!

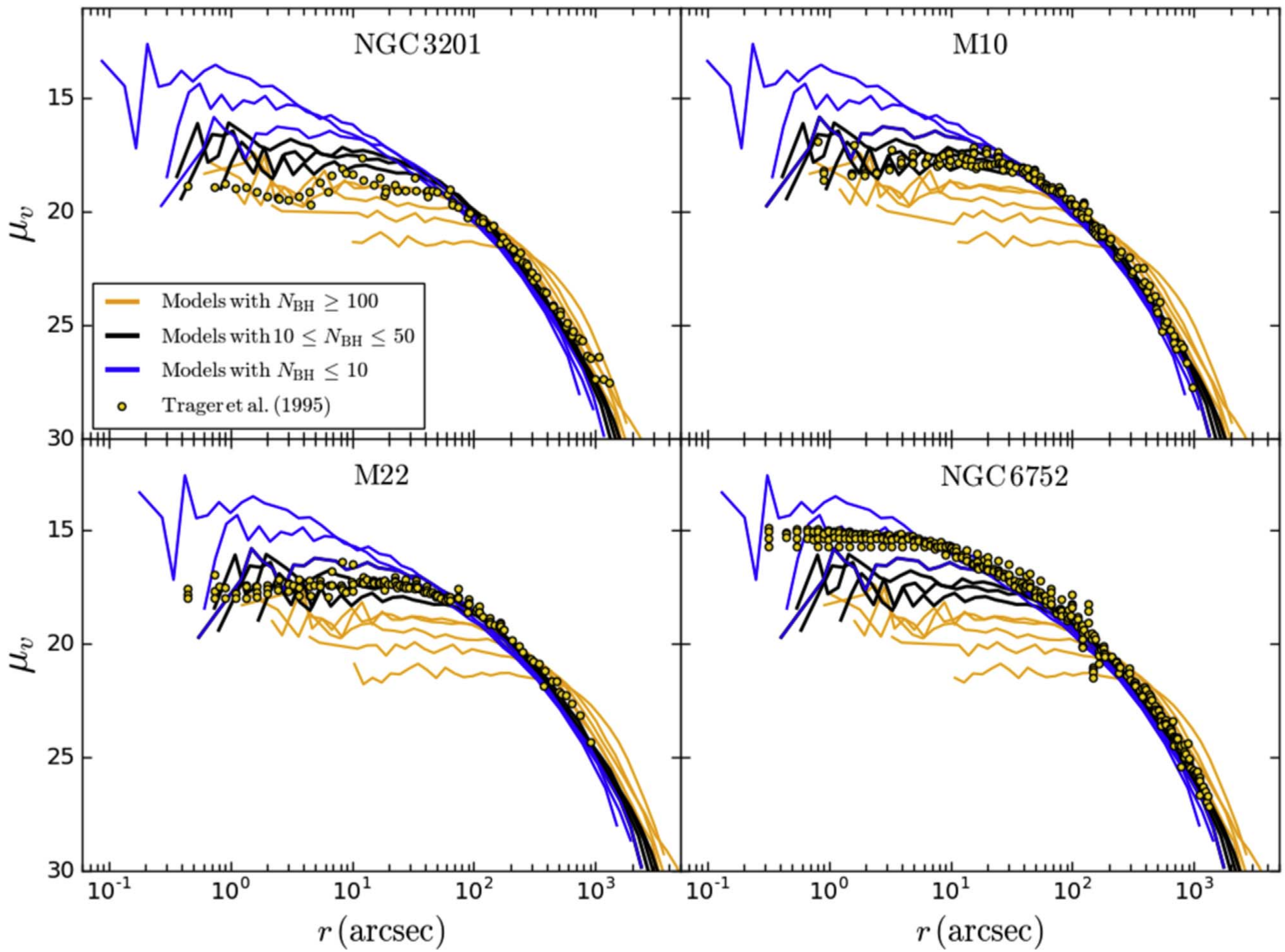
Evidence of high BH retention following supernovae collapse (low BH natal kick)?

See also:

Weatherford, N. C., et al., 2018, ApJ, 864, 13 ([non-]mass-segregation signatures of luminous stars in Galactic GCs)

Ye, C.S., et al., 2019, ApJ, 877, 122 ([non-]mass-segregation signatures of neutron stars in Galactic GCs)

Modelling individual Galactic GCs (Monte Carlo simulations)



From: Kremer, K., Chatterjee, S., Ye, C. S., Rodriguez, C. L., Rasio, F. A., 2019, ApJ, 871, 38

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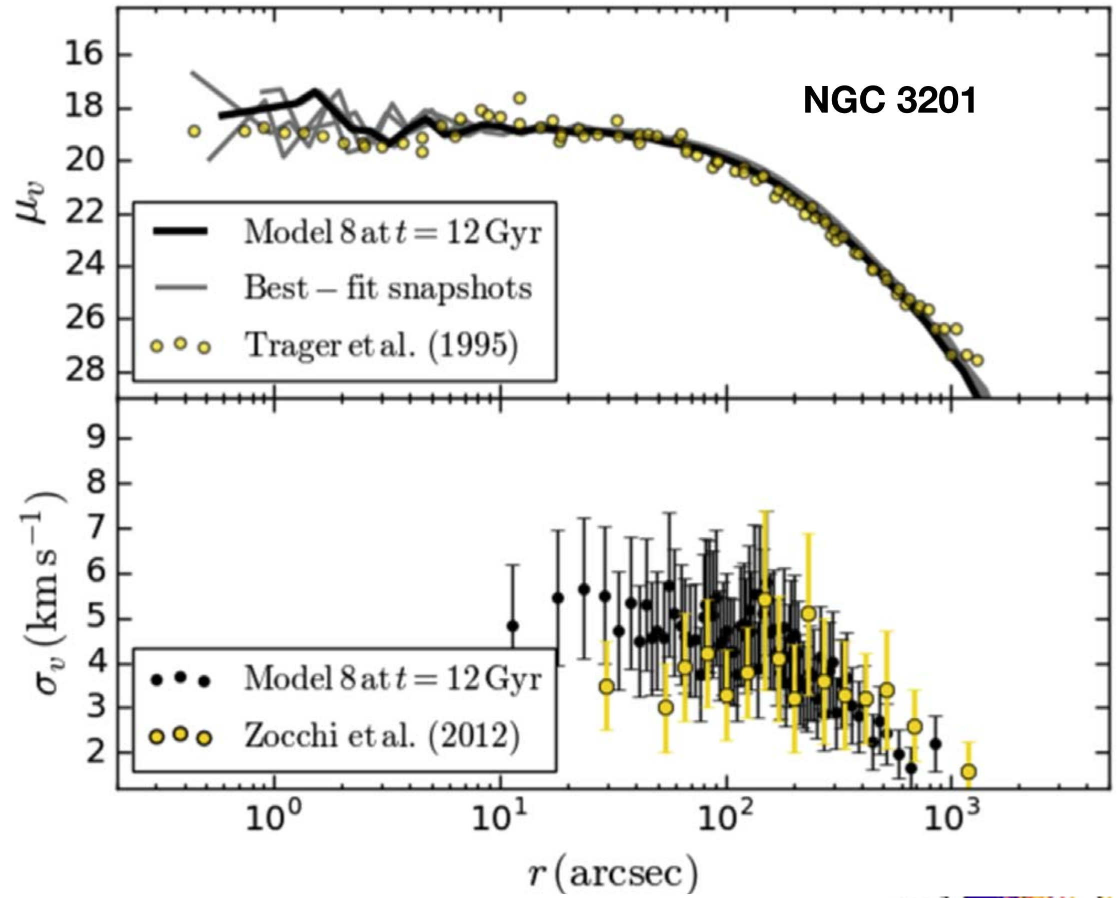
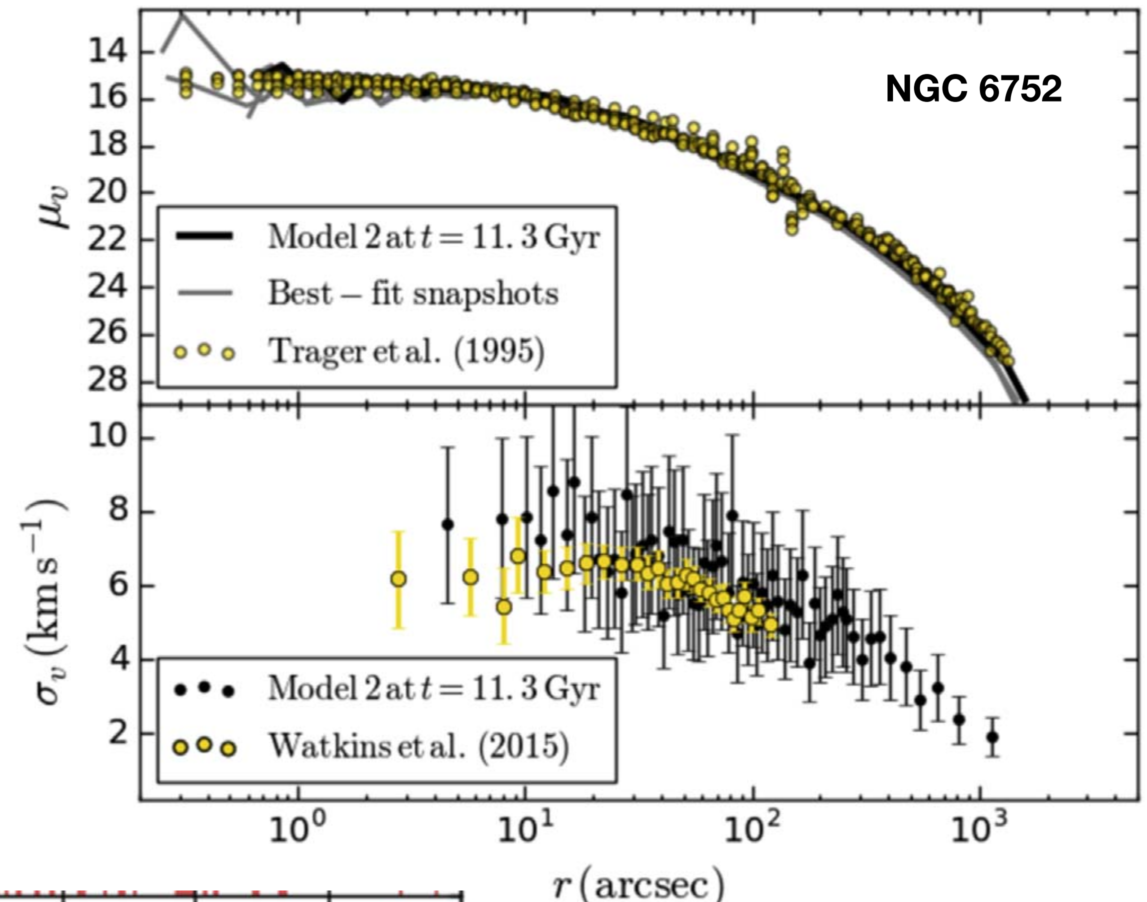
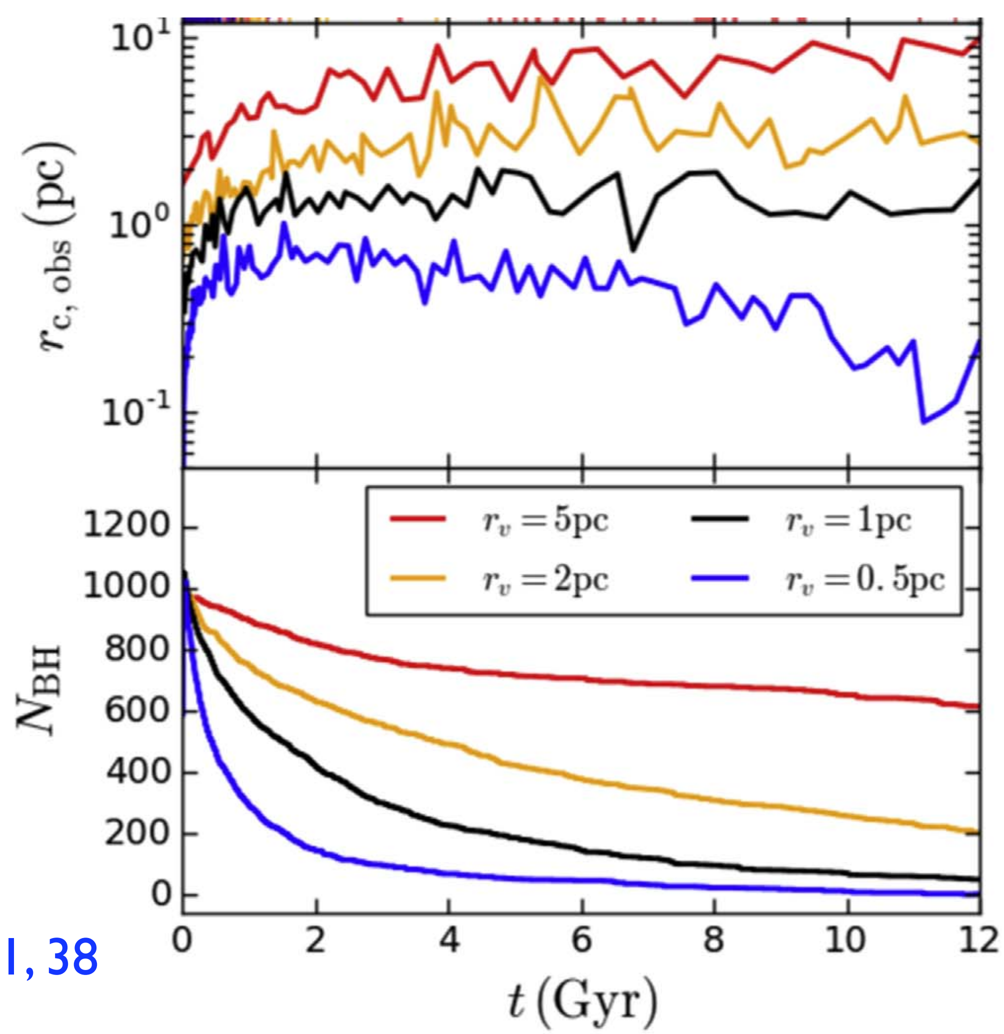
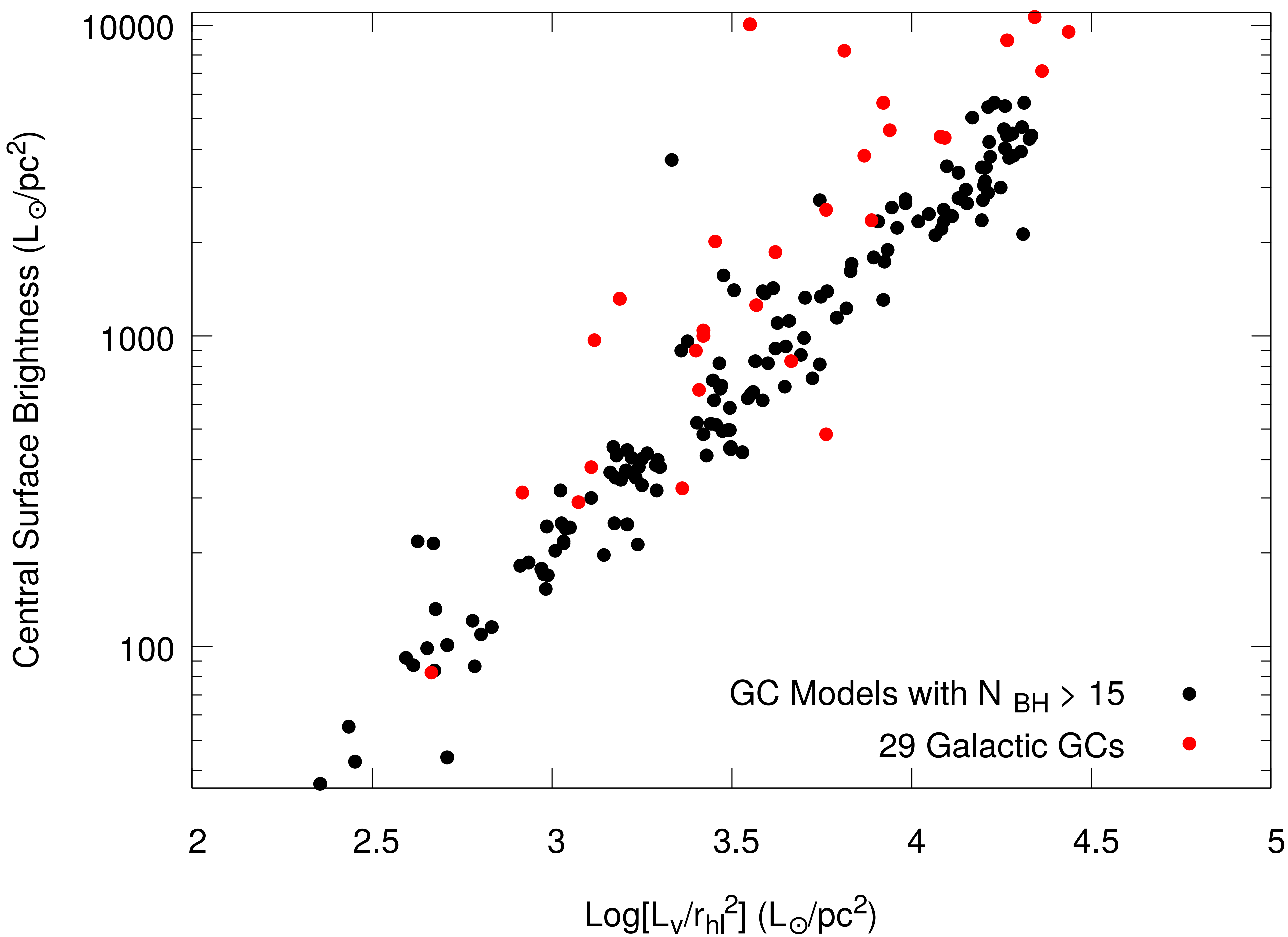






From: Kremer, K., et al., 2019, ApJ, 871, 38

Short-listing BH population-containing Galactic GCs



From:
Askar et al., 2018, MNRAS, 478, 1844

Simulate star cluster in a computer: direct N-body calculations

Solve Newtonian equation of motion for N bodies (N^2xN operation)

$$\ddot{x}_{k,i} = -G \sum_{j=1, j\neq i}^{N} \frac{m_j}{r_{ij}^3} \vec{r_{ij}} \cdot \hat{k}$$

Computationally expensive but fully self-consistent treatment of all types of dynamical interactions.

No symmetry required

Up to several 10^5 bodies doable in GPU-based/parallel architecture.

Sverre Aarseth's (IoA, Cambridge) N-body code "NOBDY6/7".

What is NBODY6/NBODY7?

- A versatile, direct, object-by-object N-body integration program initiated and still being developed by Sverre Aarseth (for at least 20 years!) [Fortran-based code]

- No assumption on initial conditions or symmetry of the N-body system (or of the problem under study)

- No approximation while dealing with internal or external forces

- Can handle (in principle!) an arbitrary population of compact subsystem (binary and above)

- Incorporates analytic (population-synthesis type) recipes of stellar and binary evolution

- Incorporates general relativity (post-Newtonian)

- Incorporates any form of static or time-varying external gravitational field (host-galactic potential, embedding gas potential)

- Publicly available!

NBODY6/NBODY7: challenges

- Time-consuming computation! (~N^3): large N becomes prohibitive
- This is dealt with a combination of algorithms (e.g., applying the neighbour scheme) and hardware assist (GPU-based force calculation, parallelization in CPU and GPU) [the GPU interface is developed mainly by Keigo Nitadori]
- Large population of binaries (e.g., high primordial-binary fraction) also results in inefficient GPU usage (also less efficient parallelization) resulting significant slow down
- Coupling with the state of the art from stellar- and binary-evolution studies
- Coupling with hydrodynamics, gas physics (currently, absent in NBODY6)
- Accessibly: skilled management required; crash recovery (often frequent) and maintenance of long-running (months!) jobs.
- Accessibly: good knowledge of the code is necessary for day-to-day work!

Other direct N-body codes (frameworks): NBODY6++, STARLAB, AMUSE

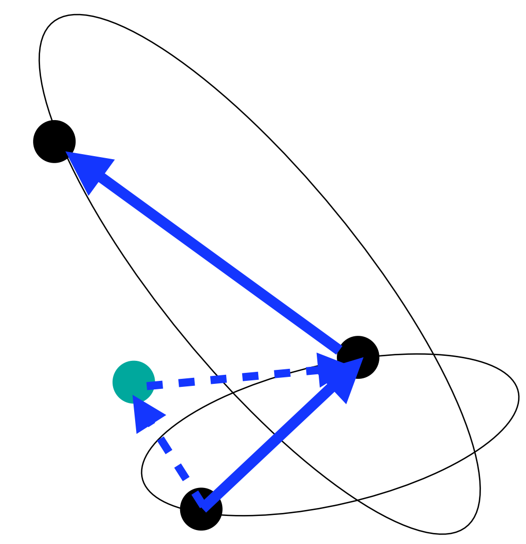
“Long-term” N-body computations with NBODY6/7
(non-exhaustive list)

$N \sim$

References	$N \sim$
Wang et al., 2016, MNRAS, 458, 1450	10^6
Heggie, D.C., 2014, MNRAS, 445, 3435	5×10^5
Sippel & Hurley, 2013, MNRASL, 430, L30 Baumgardt, H., 2017, MNRAS, 464, 2174 Banerjee, S., 2018, MNRAS, 473, 909 Aarseth, S.J., 2012, MNRAS, 422, 841 Banerjee et al., 2010, MNRAS, 402, 371	10^5
Webb & Vesperini, 2017, MNRAS, 464, 1977 Zonoozi et al., 2011, MNRAS, 411, 1989 Banerjee, S., 2017, MNRAS, 467, 524 Park et al., 2017, MNRAS, 469, 4665	5×10^4
Oh & Kroupa, 2012, MNRAS, 424, 65 Kumamoto, Fujii, & Tanikawa, 2019, MNRAS, 486, 3942 Rastello, S. et al., 2019, MNRAS, 483, 1233 Di Carlo, U.N., et al., 2019, MNRAS, 487, 2947	10^4
	10^3

NBODY 6/7 integration algorithms

Fourth-order Hermite Individual Timestep Scheme (HITS) for integration



KS regularisation (no force softening!)

KS-Chain regularization(NBODY6)/ARCHAIN(NBODY7)

Post-Newtonian treatment in ARCHAIN

[In NBODY6, GR treatment is done within a (KS-regularized) binary by applying the Peters' 1964 formula. Also applied for a hyperbolic KS pair through the tidal-dissipation formalism (KSTIDE). Retained in NBODY7 also.]

Other than the treatment of Chain subsystems and GR, NBODY6 and NBODY7 are (supposed to be!) identical.

Speed-up procedures: Ahmed-Cohen neighbour scheme, parallel processing in CPU and GPU (openMP; GPU only for regular force calculation)

Check out Aarseth's 2003 book and Nitadori & Aarseth, 2012, MNRAS, 424, 545!

Post-Newtonian treatment in NBODY7

Aarseth, 2012, MNRAS, 422, 841:

ARCHAIN (Mikkola & Merritt 2008)

PN-1, PN-2, PN-2.5, PN-3, PN-3.5

PN orders activated sequentially

BH spins (can be computationally expensive): maximal or zero spin for all BH

GR coalescence based on BBH merger timescale

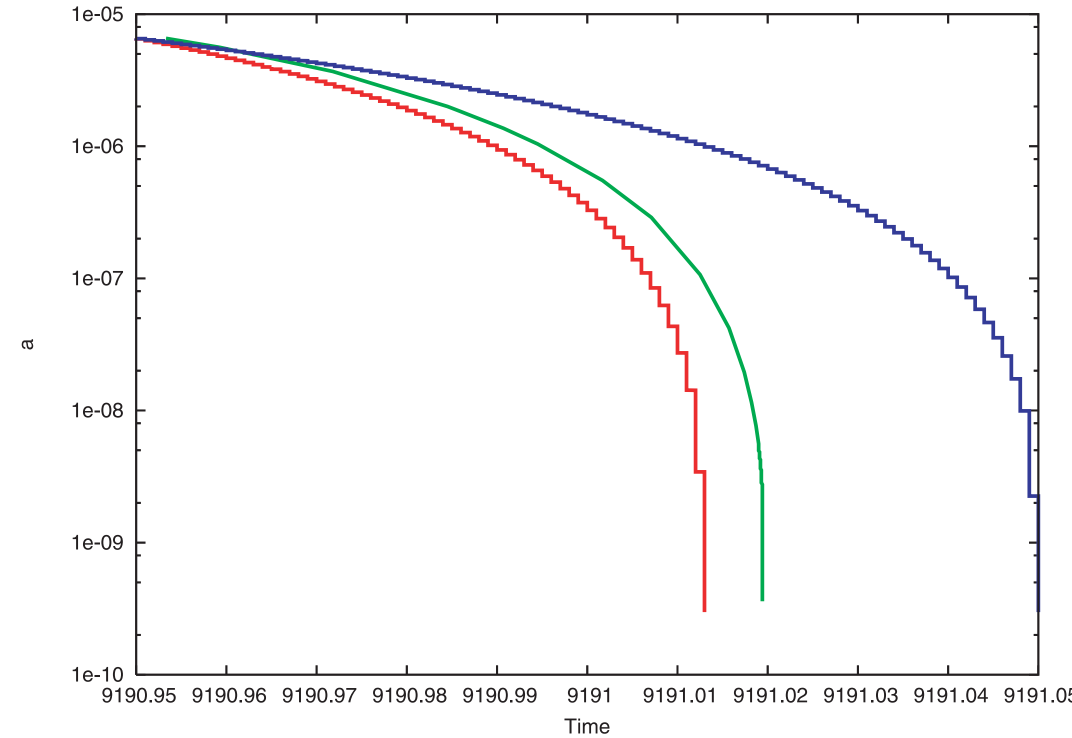


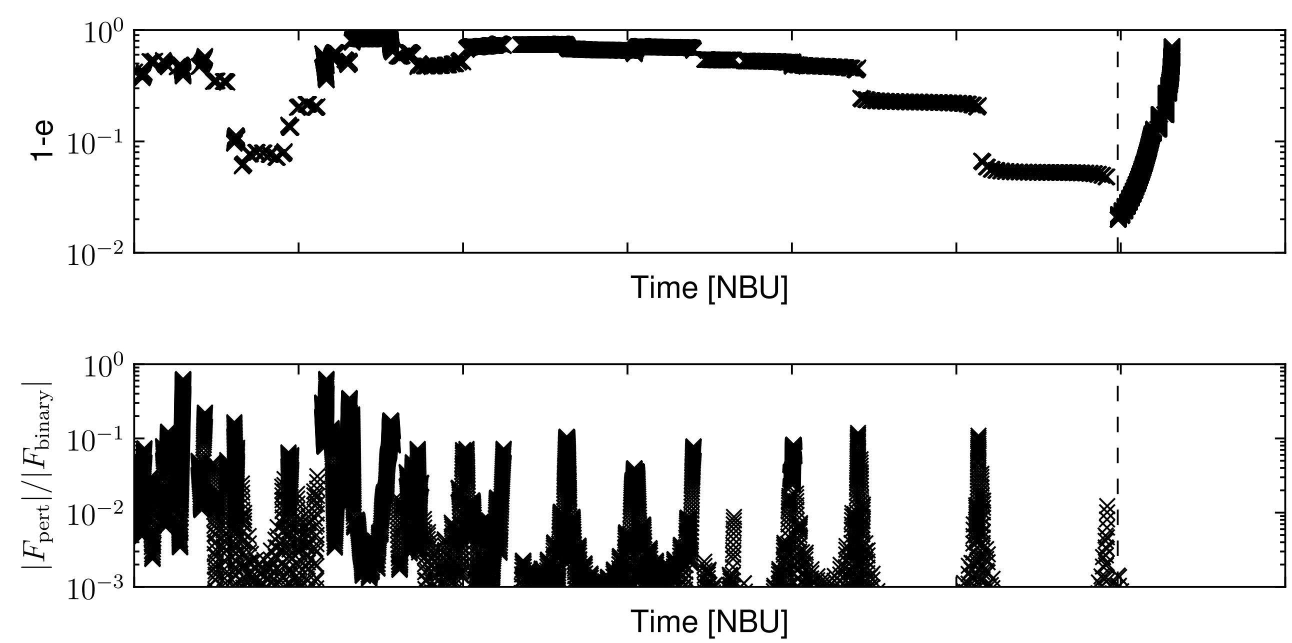
Figure 5. Semimajor axis as function of N-body time. Middle curve: actual plot from Model BH12. Upper and lower curves: orbit-averaged solution from Peters (1964) for two initial values of eccentricity, 0.9996 and 0.99965, where only the four first significant figures are available. The plot is truncated at 3×10^{-10} while the calculation extends to 1.5×10^{-11}.

Potential improvement/alternative:

Apply all PN terms at the same time

e.g.,

Brem et al., 2013, MNRAS 434, 2999



Monte Carlo simulations of stellar clusters

- Based on He´non's orbit-averaged Monte Carlo method
- Orbit-averaged but star-by-star approach
- Based on basic and reasonable assumptions: spherical symmetry and dynamical equilibrium
- NlogN operation - much faster than direct N-body summation.
- N~10^5 - 10^7 with parallel computing (~100 cores)

Currently, two semi-public versions available:

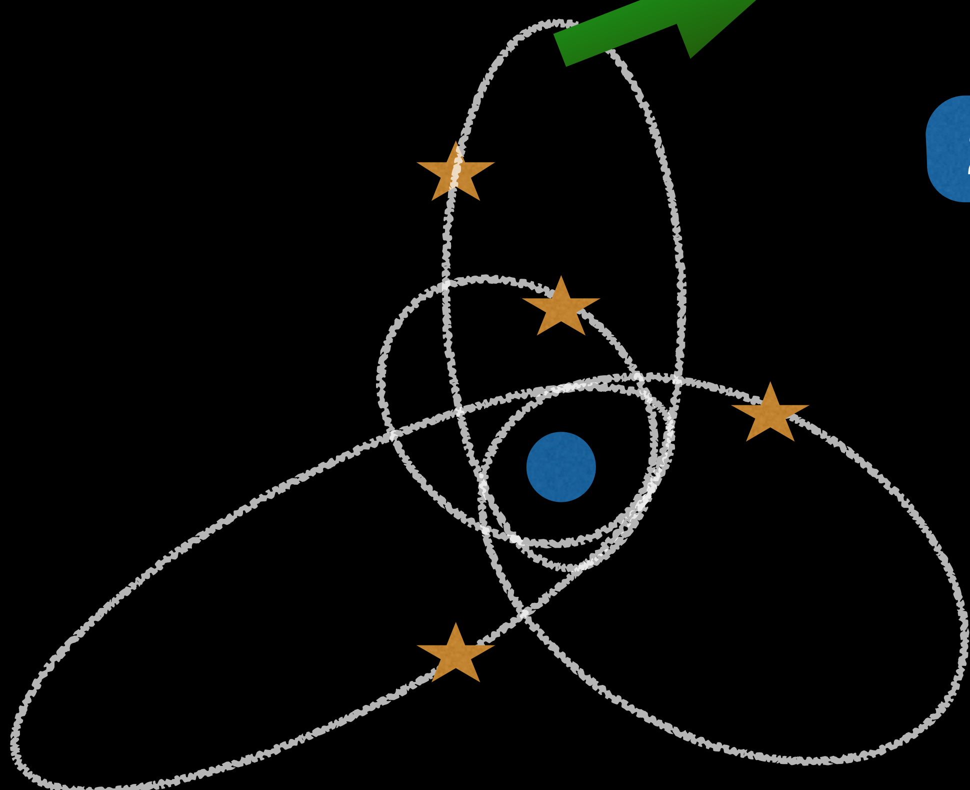
Cluster Monte Carlo (CMC): Northwestern team
[Joshi, K. J., Rasio, F. A., & Portegies Zwart, S. 2000, ApJ, 540, 969]

MOCCA: Warsaw team
[Giersz, M., Heggie, D. C., Hurley, J. R., & Hypki, A. 2013, MNRAS, 431, 2184]

Slide credit: Fred Rasio

CMC

Assume:
- 2-Body Relaxation
- Dynamical Equilibrium
- Spherical Symmetry



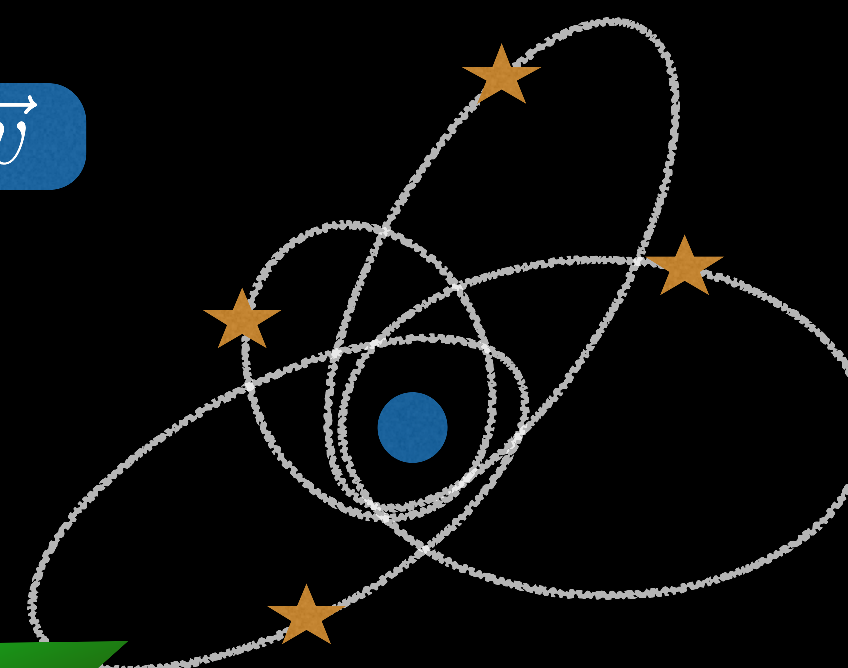
Generate **r** for each star's **E**,**J** and ϕ

2-body relaxation, get new $\vec{v}$

Calculate new **E** and **J**

Recompute ϕ

Adjust **E** and **J**



$O(N\log(N))$

Stellar evolution in NBODY: BSE

The stellar-evolution "engine" of Aarseth's NBODY6/7 is a semi-analytic stellar evolution and population synthesis program [Fortran].

SSE: fast, recipe-based, semi-analytic evolution of single stars
Hurley, J. R., Pols, O. R., & Tout, C.A. 2000, MNRAS, 315, 543

BSE: SSE + binary-interaction physics (tidal circularization, mass transfer, common envelope; also semi-analytical approach)
Hurley, J. R., Tout, C.A., & Pols, O. R. 2002, MNRAS, 329, 897

BSE is adapted to NBODY and evolves stars and binaries in tandem with their dynamical integration.

Also available as a standalone program (see Jarrod Hurley's website).

Customizable: new recipes can be added and hence into NBODY (but not so easy!)

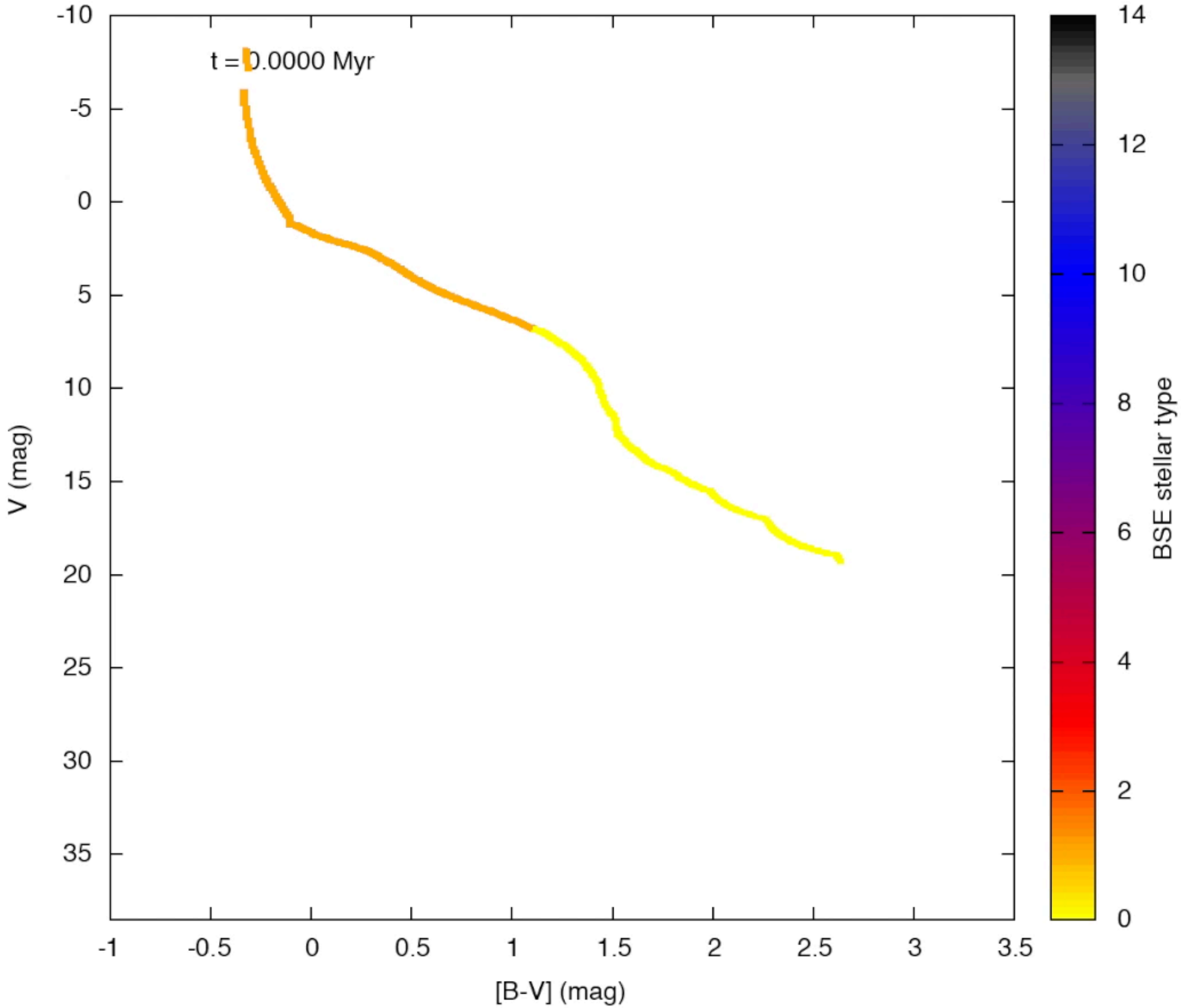
Well known variants: MOBSE (Giacobbo, N., Mapelli, M., & Spera, M. 2018, MNRAS, 474, 2959), the "new BSE" : Banerjee, S., et al, A&A, arXiv:1902.07718

A parallel implementation: StarTrack (Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223)

```
*     SSE/BSE Stellar evolution types
*     ***********************
*
*     ------------------------------------------------------------------
*    -1     Pre mainsequence.
*     0     Low main sequence (M < 0.7).
*     1     Main sequence.
*     2     Hertzsprung gap (HG).
*     3     Red giant.
*     4     Core Helium burning.
*     5     First AGB.
*     6     Second AGB.
*     7     Helium main sequence.
*     8     Helium HG.
*     9     Helium GB.
*    10     Helium white dwarf.
*    11     Carbon-Oxygen white dwarf.
*    12     Oxygen-Neon white dwarf.
*    13     Neutron star.
*    14     Black hole.
*    15     Massless supernova remnant.
*     ------------------------------------------------------------------
*
*     SSE/BSE Binary types
*     ************
*
*     ------------------------------------------------------------------
*     0     Standard case.
*    -1     Chaotic (option 27 = 2).
*    -2     Continuous circularizing (option 27 = 2).
*     9     Sequential circularization (option 27 = 1).
*    10     Circularized.
*    11     First Roche stage (option 34 = 1/2).
*    12     End of first Roche stage.
*    13     Start of second Roche stage.
*    xx     Further Roche stages.
*     ------------------------------------------------------------------
```

Long-term evolution of colour magnitude diagram (CMD) with NBODY7/BSE

$M_{\rm cl}(0) = 7.5 \times 10^4 M_\odot, r_h(0) = 2.0$ pc, $f_{\rm bin}(0) = 0.0, f_{\rm Otype}(0) = 0.0, Z = 0.005$



CMD produced with GalevNB (Banerjee, S. in prep …)
See Pang, X.-Y., et al., 2016, RAA, 16, 37

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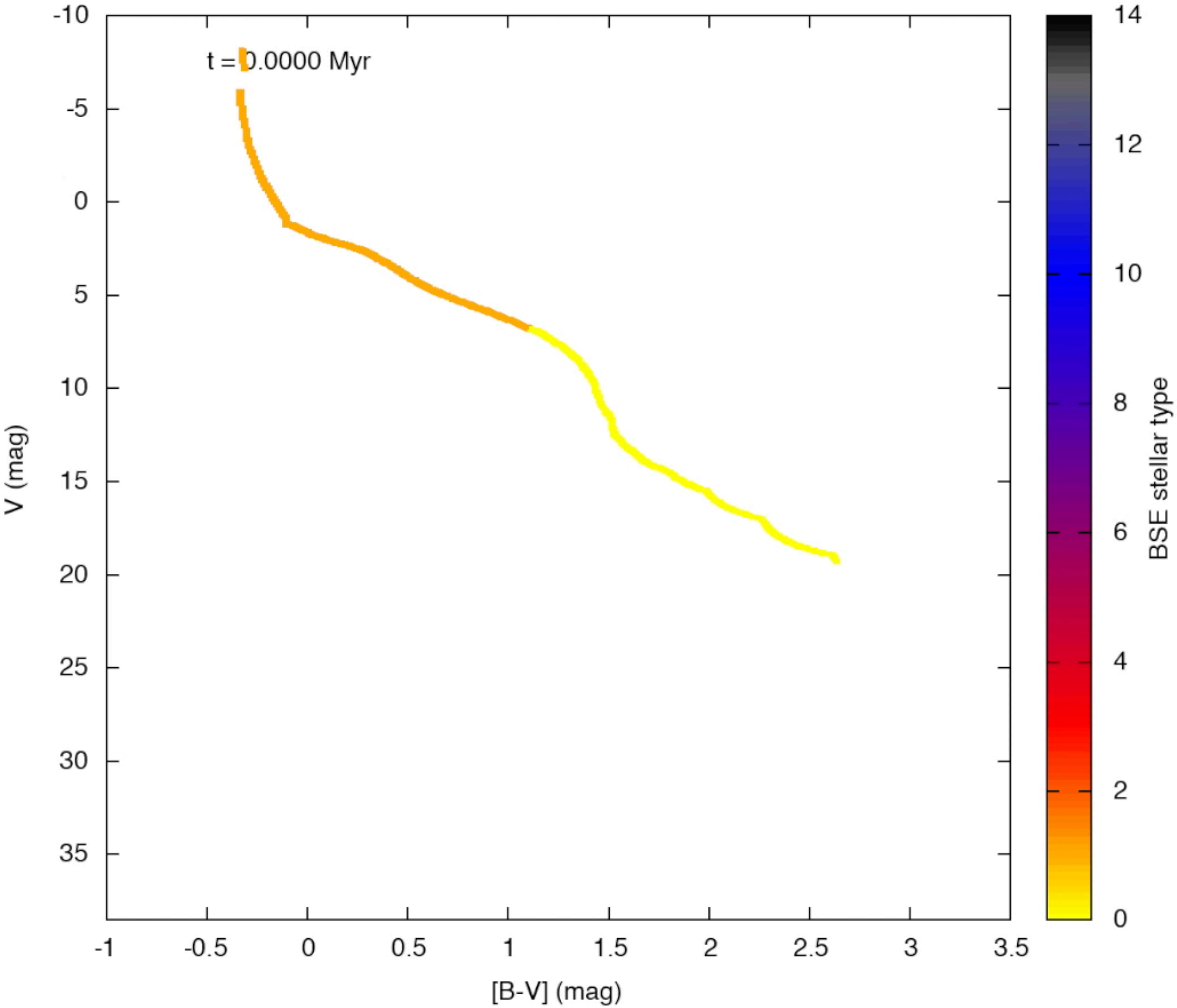
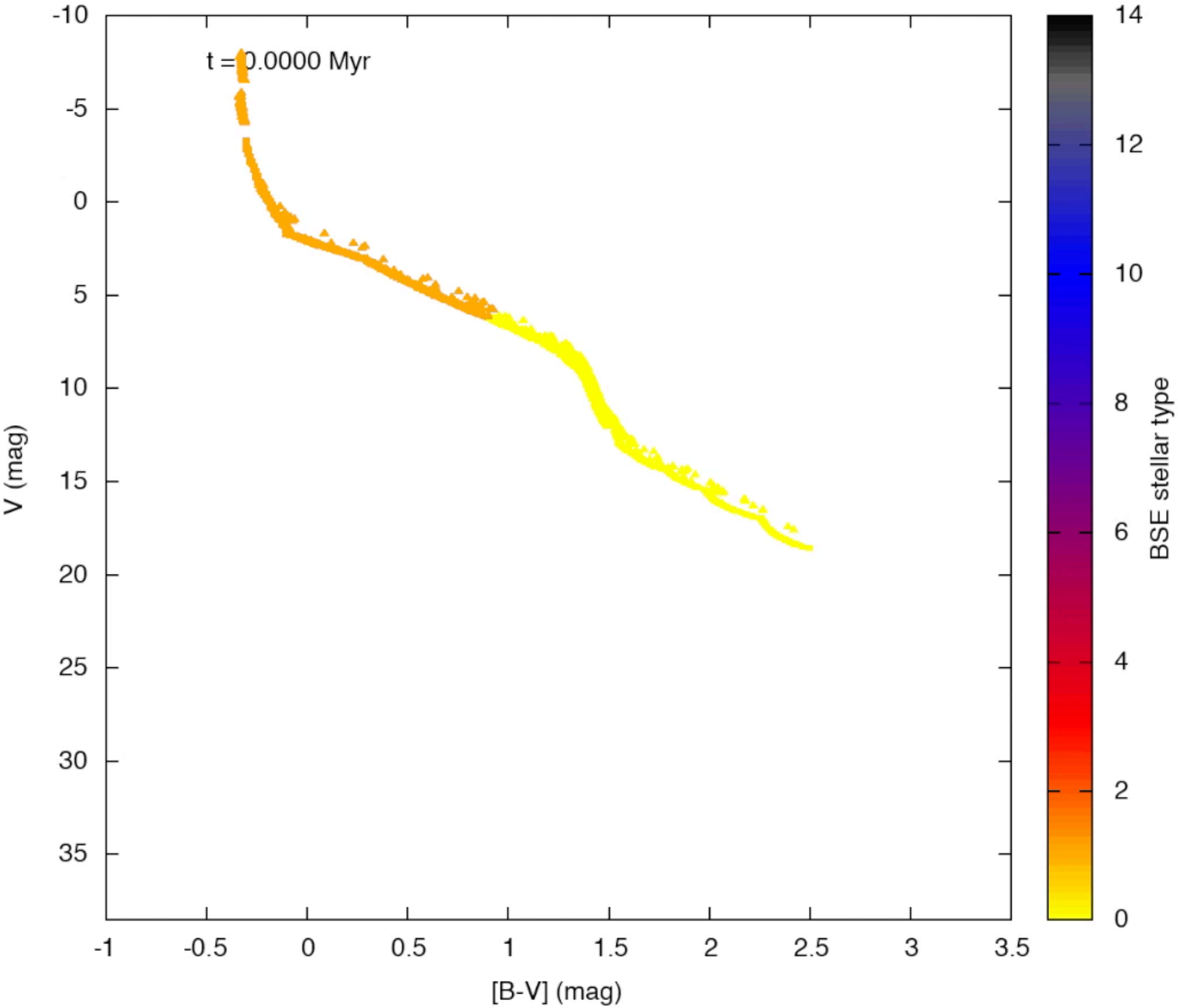


CMD produced with GalevNB (Banerjee, S. in prep ...)
See Pang, X.-Y., et al., 2016, RAA, 16, 37

Long-term evolution of colour magnitude diagram (CMD) with NBODY7/BSE

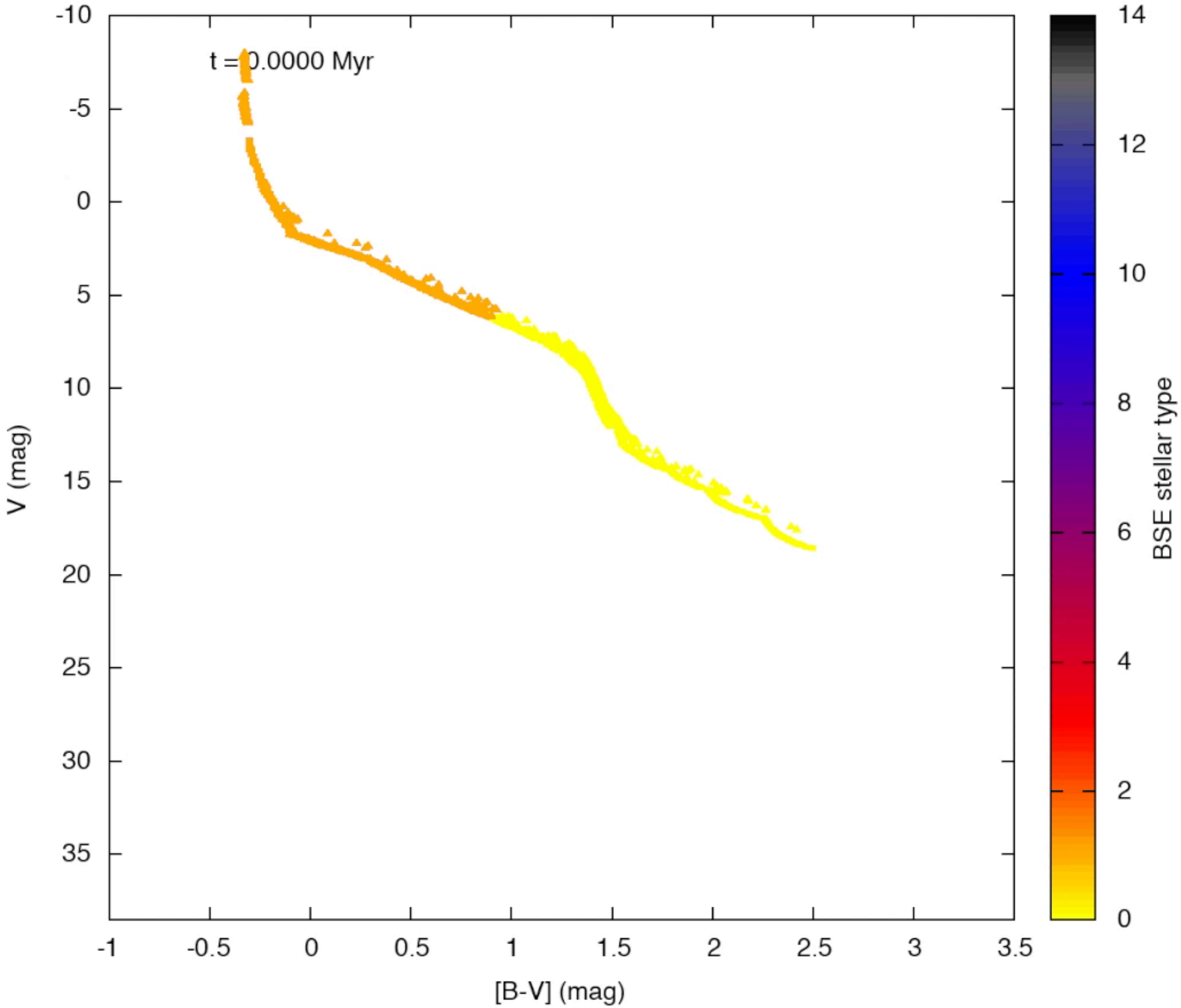
$M_{\rm cl}(0) = 5.0 \times 10^4 M_\odot, r_h(0) = 2.0~{\rm pc}, f_{\rm bin}(0) = 0.05, f_{\rm Otype}(0) = 1.0, Z = 0.001$



CMD produced with GalevNB (extended to include binaries by Banerjee, S. in prep)
See Pang, X.-Y., et al., 2016, RAA, 16, 37

Long-term evolution of colour magnitude diagram (CMD) with NBODY7/BSE

$M_{\mathrm{cl}}(0) = 5.0 \times 10^4 M_{\odot}, r_h(0) = 2.0\ \mathrm{pc}, f_{\mathrm{bin}}(0) = 0.05, f_{\mathrm{Otype}}(0) = 1.0, Z = 0.001$



CMD produced with GalevNB (extended to include binaries by Banerjee, S. in prep)
See Pang, X.-Y., et al., 2016, RAA, 16, 37

Zero-age main sequence (ZAMS) star $M_{\rm ZAMS} \gtrsim 8 M_\odot$

Recipes are necessary for wind, supernova, and fallback on the top of an underlying mass-radius relation and parametrized structural evolution of single stars, as functions of mass and metallicity.

These recipes and structural evolutions are obtained from numerical stellar-evolutionary and supernova models or (semi-)empirically (e.g., the wind recipes).

Binary interaction (BSE) can modify the evolution at any stage.

Remnant mass would depend intricately on the entire stellar-evolutionary history!

- stellar wind

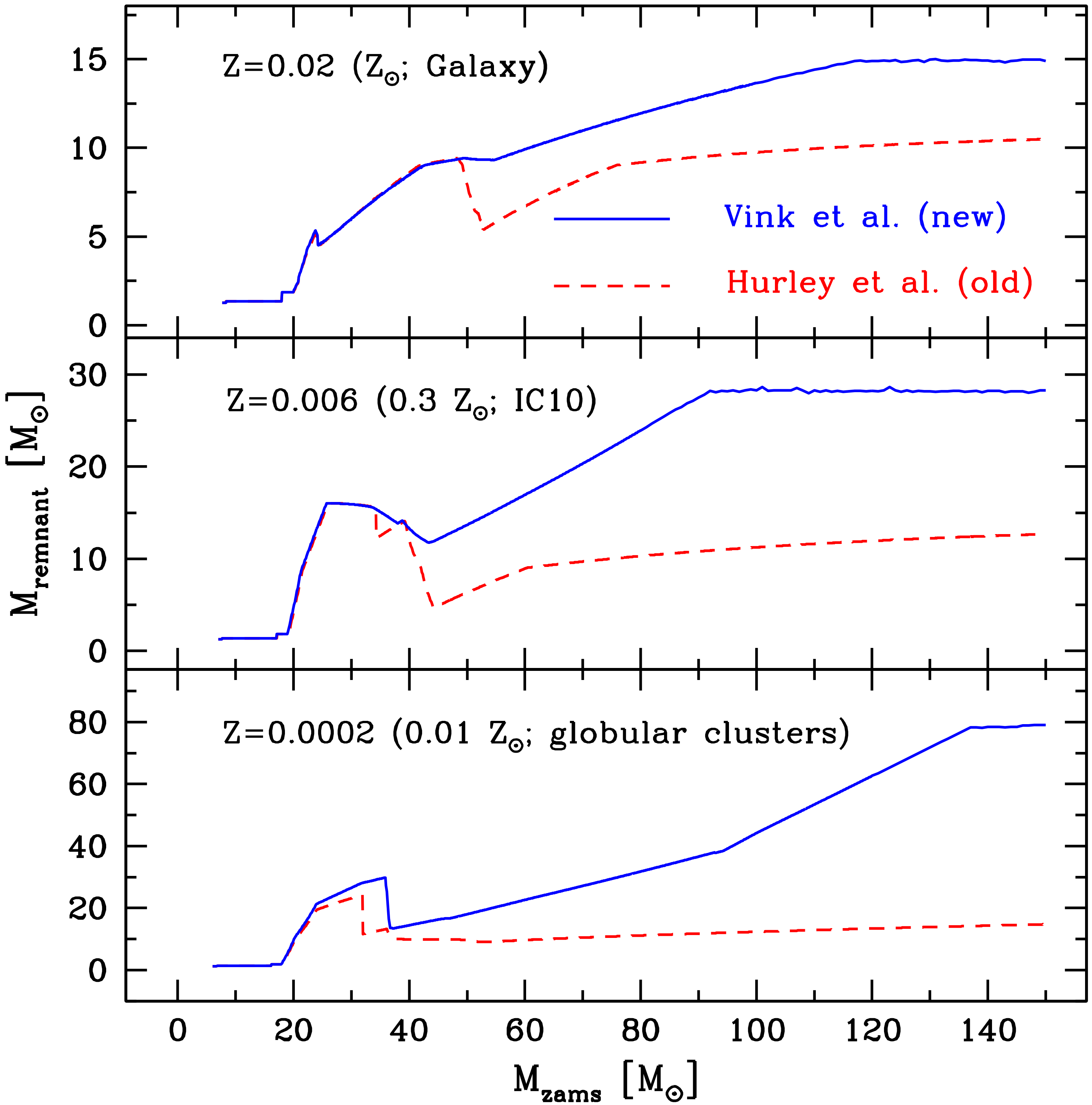
- supernova ejecta

+ supernova fallback

- neutrino emission

Remnant (NS or BH)

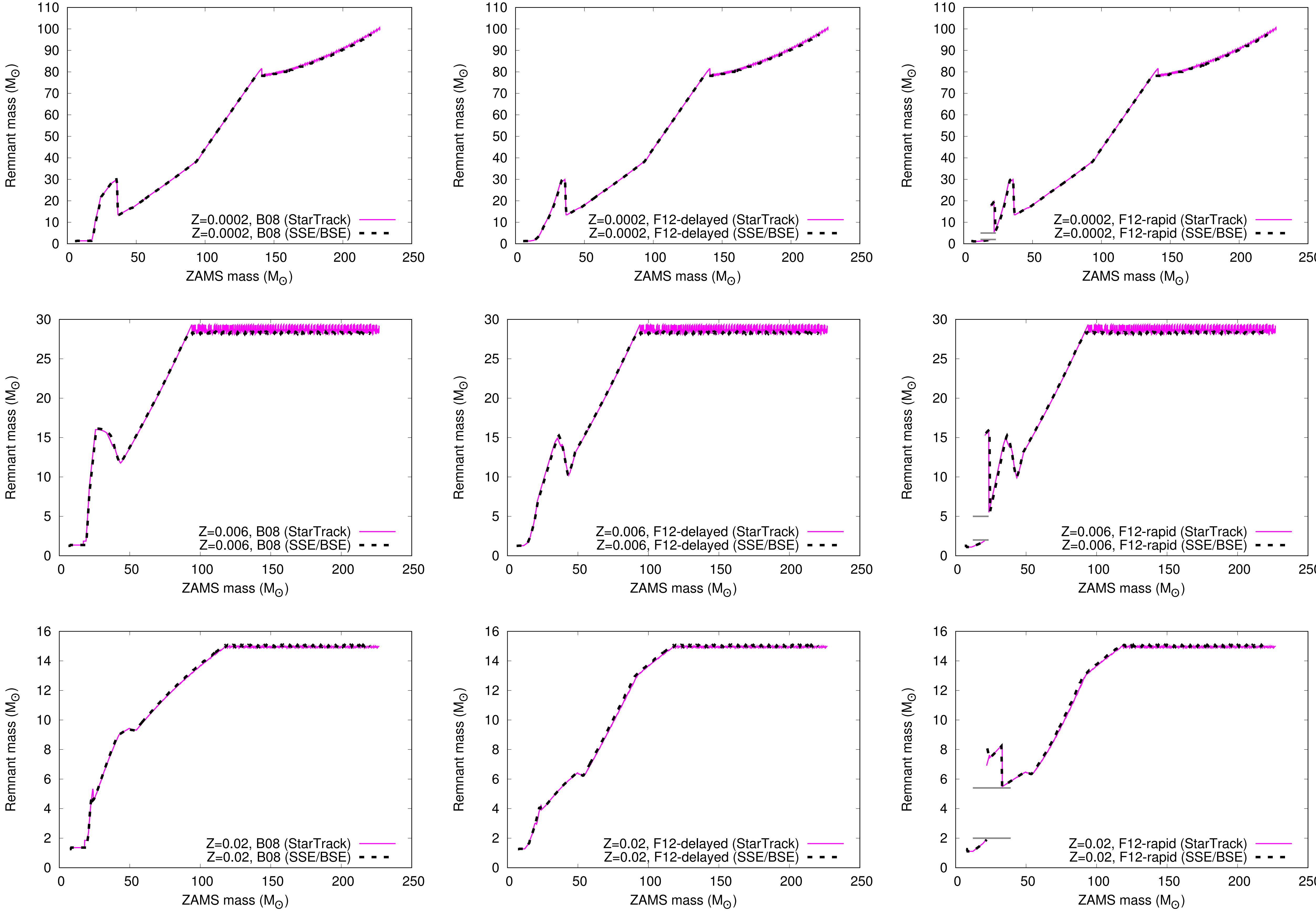
Change of wind recipes can strongly affect the remnant mass



E.g., B10 wind vs old wind:

Belczynski, K., Bulik, T., Fryer, C. L., et al. 2010, ApJ, 714, 1217 (B10)

…. the same goes for SN recipes



From Banerjee, S., Belczynski, K., Fryer, C. L., et al., A&A, arXiv:1902.07718

Remnant-formation models/recipes

B08 model: Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223 (B08)

$$\begin{cases} M_{\rm proto} = 1.50\,M_\odot & M_{\rm CO} < 4.82\,M_\odot \\ M_{\rm proto} = 2.11\,M_\odot & 4.82 \leqslant M_{\rm CO} < 6.31\,M_\odot \\ M_{\rm proto} = 0.69 M_{\rm CO} - 2.26\,M_\odot & 6.31 \leqslant M_{\rm CO} < 6.75\,M_\odot \\ M_{\rm proto} = 0.37 M_{\rm CO} - 0.07\,M_\odot & M_{\rm CO} \geqslant 6.75\,M_\odot. \end{cases}$$

$$\begin{cases} M_{\rm fb} = 0\,M_\odot & M_{\rm CO} < 5.0\,M_\odot \\ f_{\rm fb} = 0.378 M_{\rm CO} - 1.889\,M_\odot & 5.0 \leqslant M_{\rm CO} < 7.6\,M_\odot \\ f_{\rm fb} = 1.0 & M_{\rm CO} \geqslant 7.6\,M_\odot \end{cases}$$

F12-rapid model: Fryer, C. L., Belczynski, K., Wiktorowicz, G., et al. 2012, ApJ, 749, 91 (F12)

$$M_{\rm proto} = 1.0\,M_\odot,$$

$$\begin{cases} M_{\rm fb} = 0.2\,M_\odot & M_{\rm CO} < 2.5\,M_\odot \\ M_{\rm fb} = 0.286 M_{\rm CO} - 0.514\,M_\odot & 2.5\,M_\odot \leqslant M_{\rm CO} < 6.0\,M_\odot \\ f_{\rm fb} = 1.0 & 6.0\,M_\odot \leqslant M_{\rm CO} < 7.0\,M_\odot \\ f_{\rm fb} = a_1 M_{\rm CO} + b_1 & 7.0\,M_\odot \leqslant M_{\rm CO} < 11.0\,M_\odot \\ f_{\rm fb} = 1.0 & M_{\rm CO} \geqslant 11.0\,M_\odot \end{cases}$$

F12-delayed model: Fryer, C. L., Belczynski, K., Wiktorowicz, G., et al. 2012, ApJ, 749, 91 (F12)

$$\begin{cases} M_{\rm proto} = 1.2\,M_\odot & M_{\rm CO} < 3.5\,M_\odot \\ M_{\rm proto} = 1.3\,M_\odot & 3.5\,M_\odot \leqslant M_{\rm CO} < 6.0\,M_\odot \\ M_{\rm proto} = 1.4\,M_\odot & 6.0\,M_\odot \leqslant M_{\rm CO} < 11.0\,M_\odot \\ M_{\rm proto} = 1.6\,M_\odot & M_{\rm CO} \geqslant 11.0\,M_\odot. \end{cases}$$

$$\begin{cases} M_{\rm fb} = 0.2\,M_\odot & M_{\rm CO} < 2.5\,M_\odot \\ M_{\rm fb} = 0.5 M_{\rm CO} - 1.05\,M_\odot & 2.5\,M_\odot \leqslant M_{\rm CO} < 3.5\,M_\odot \\ f_{\rm fb} = a_2 M_{\rm CO} + b_2 & 3.5\,M_\odot \leqslant M_{\rm CO} < 11.0\,M_\odot \\ f_{\rm fb} = 1.0 & M_{\rm CO} \geqslant 11.0\,M_\odot \end{cases}$$

$M_{\rm rem,bar} = M_{\rm proto} + M_{\rm fb}$, $M_{\rm rem} = 0.9\ M_{\rm rem,bar}$. (BH) $M_{\rm rem,bar} - M_{\rm rem} = 0.075\ M_{\rm rem}^2$ (NS)

Adaptation of pair-instability (PSN) and pulsational pair-instability (PPSN) supernova in BSE

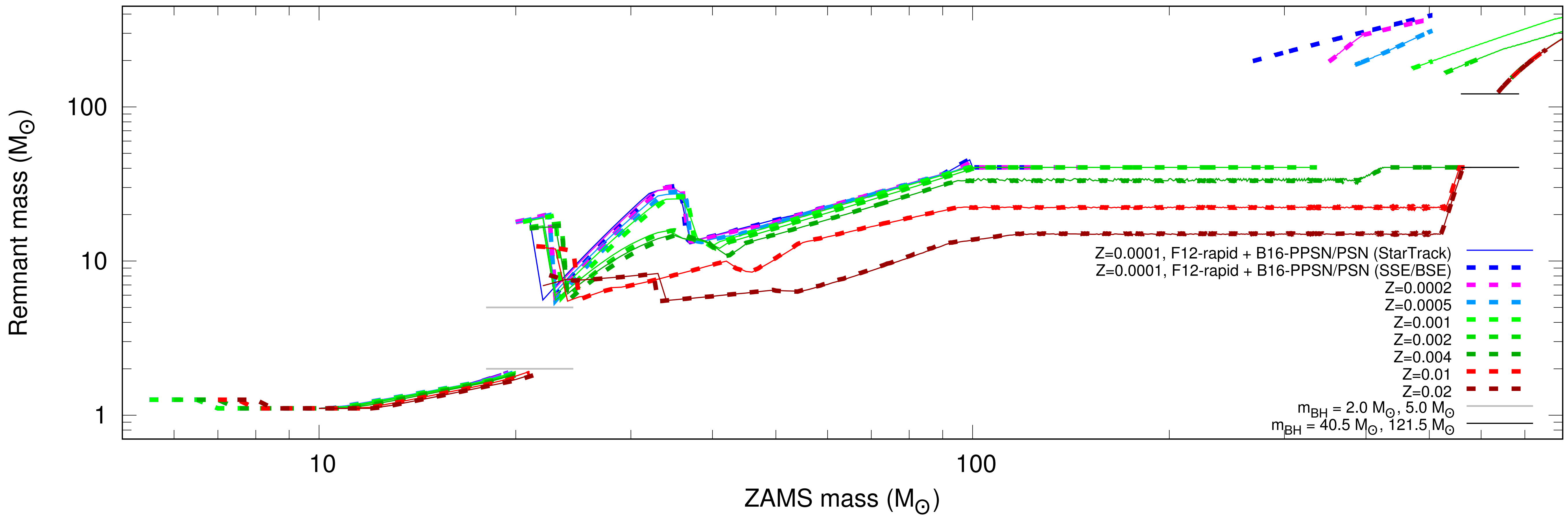


Figure from: Banerjee, S., Belczynski, K., Fryer, C. L., et al., A&A, arXiv:1902.07718

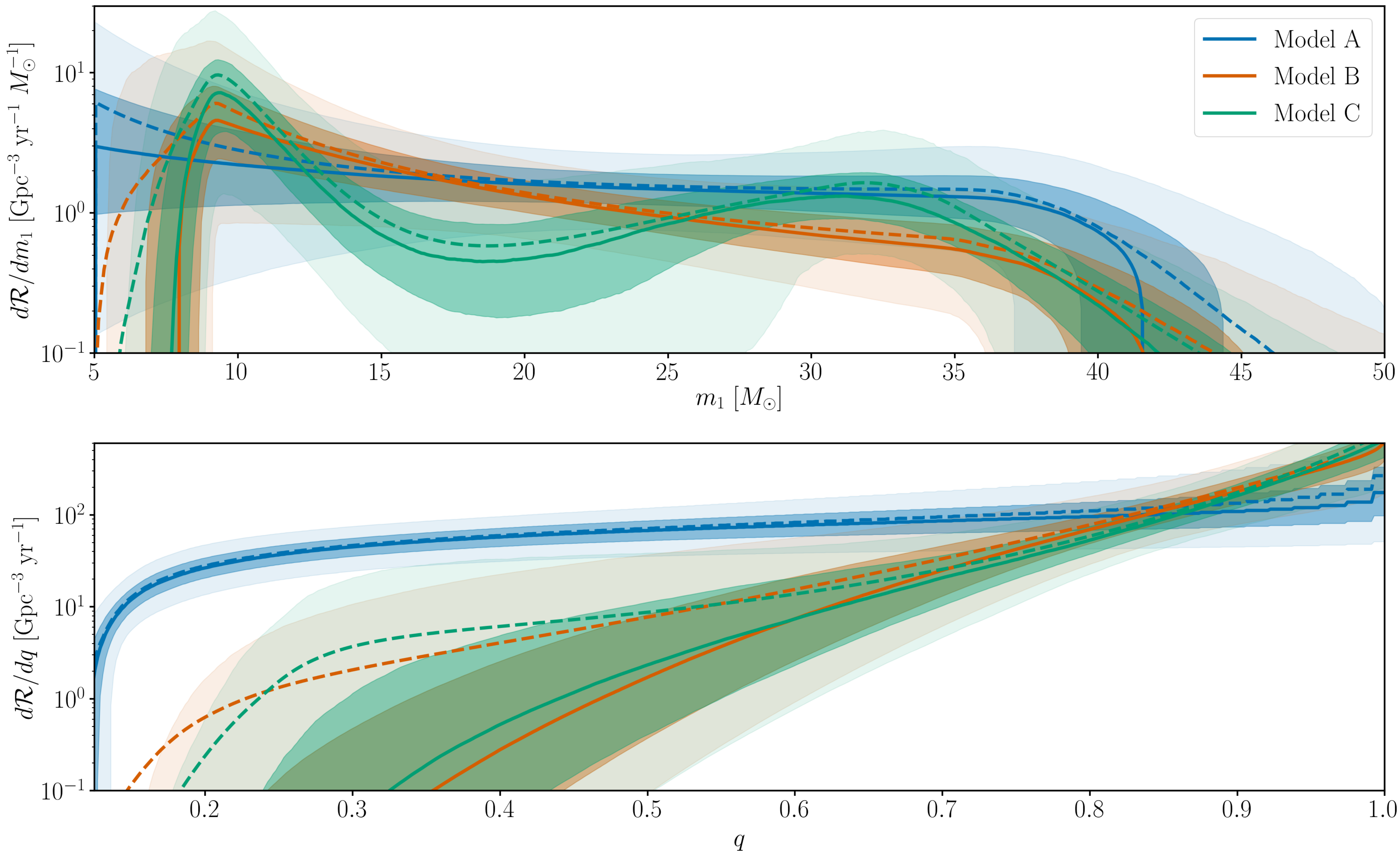
PPSN/PSN prescriptions adopted according to:

Belczynski, K., Heger, A., Gladysz, W., et al. 2016a, A&A, 594, A97 (B16)

$$M_{\rm rem,bar} = 45.0M_\odot (45.0M_\odot \leq M_{\rm He} \leq 65.0M_\odot)$$
$$= 0.0 (65.0M_\odot \leq M_{\rm He} \leq 135.0M_\odot)$$

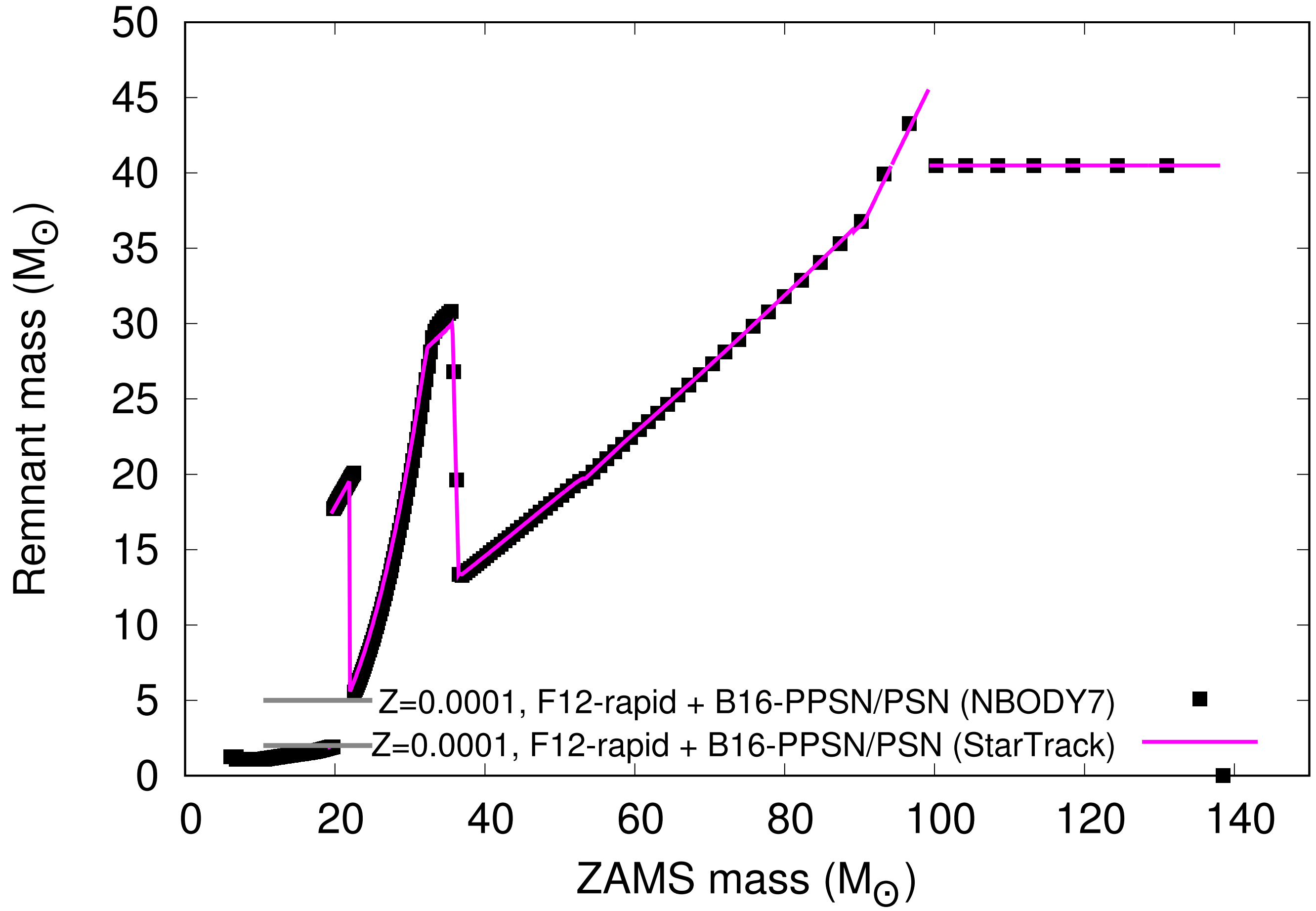
See also: Giacobbo, N., Mapelli, M., & Spera, M. 2018, MNRAS, 474, 2959

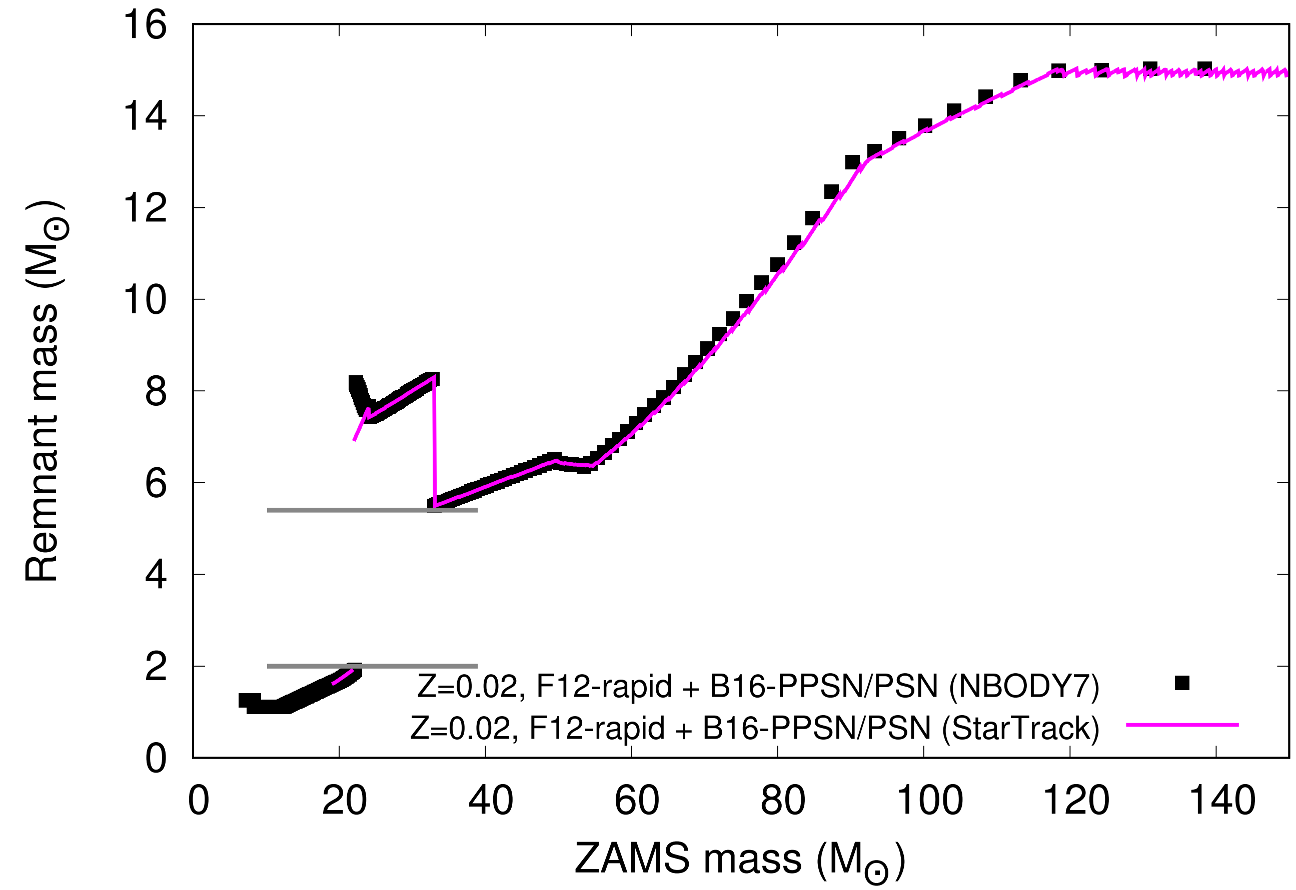
BH “upper mass limit” from LIGO O2



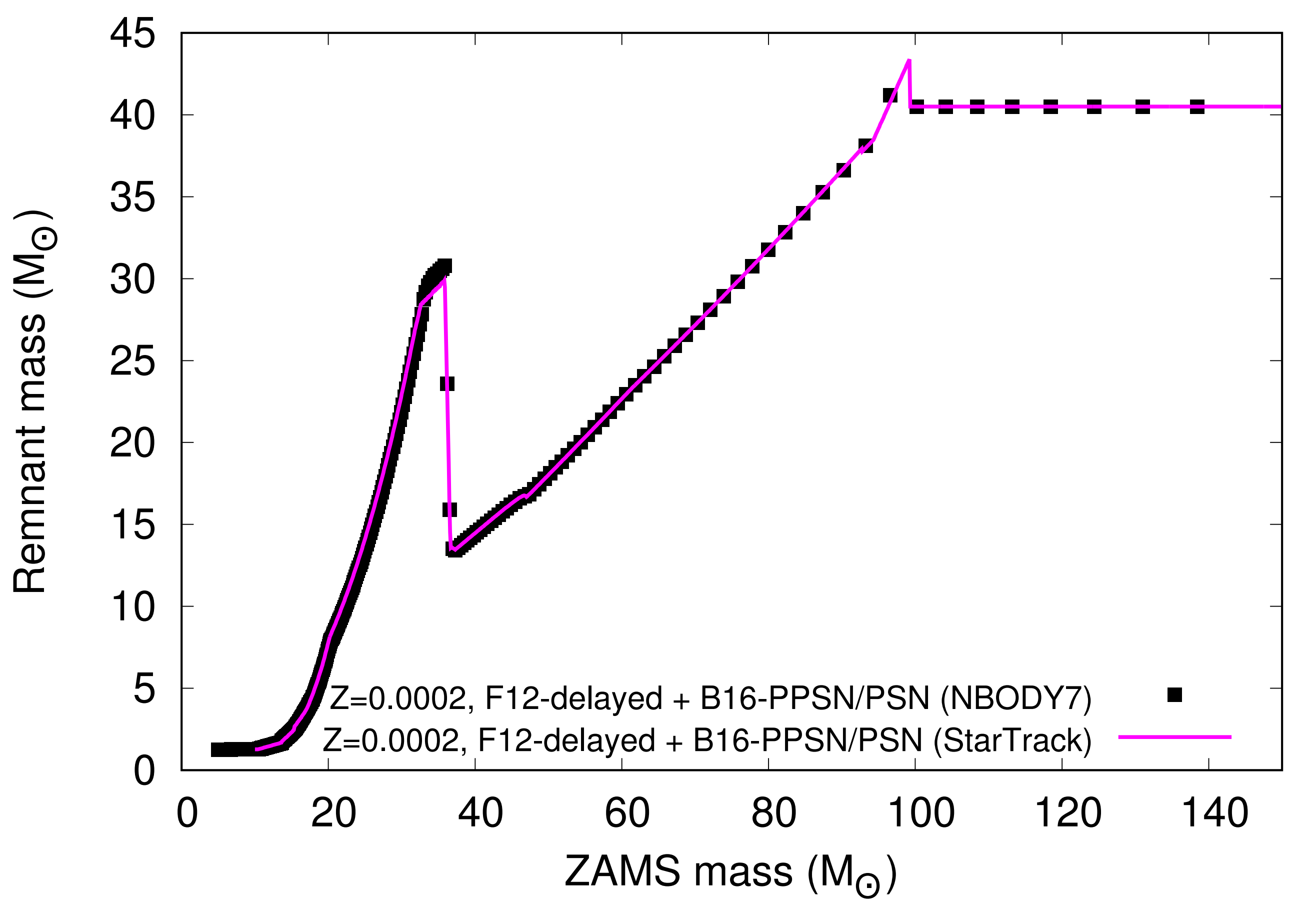
From:

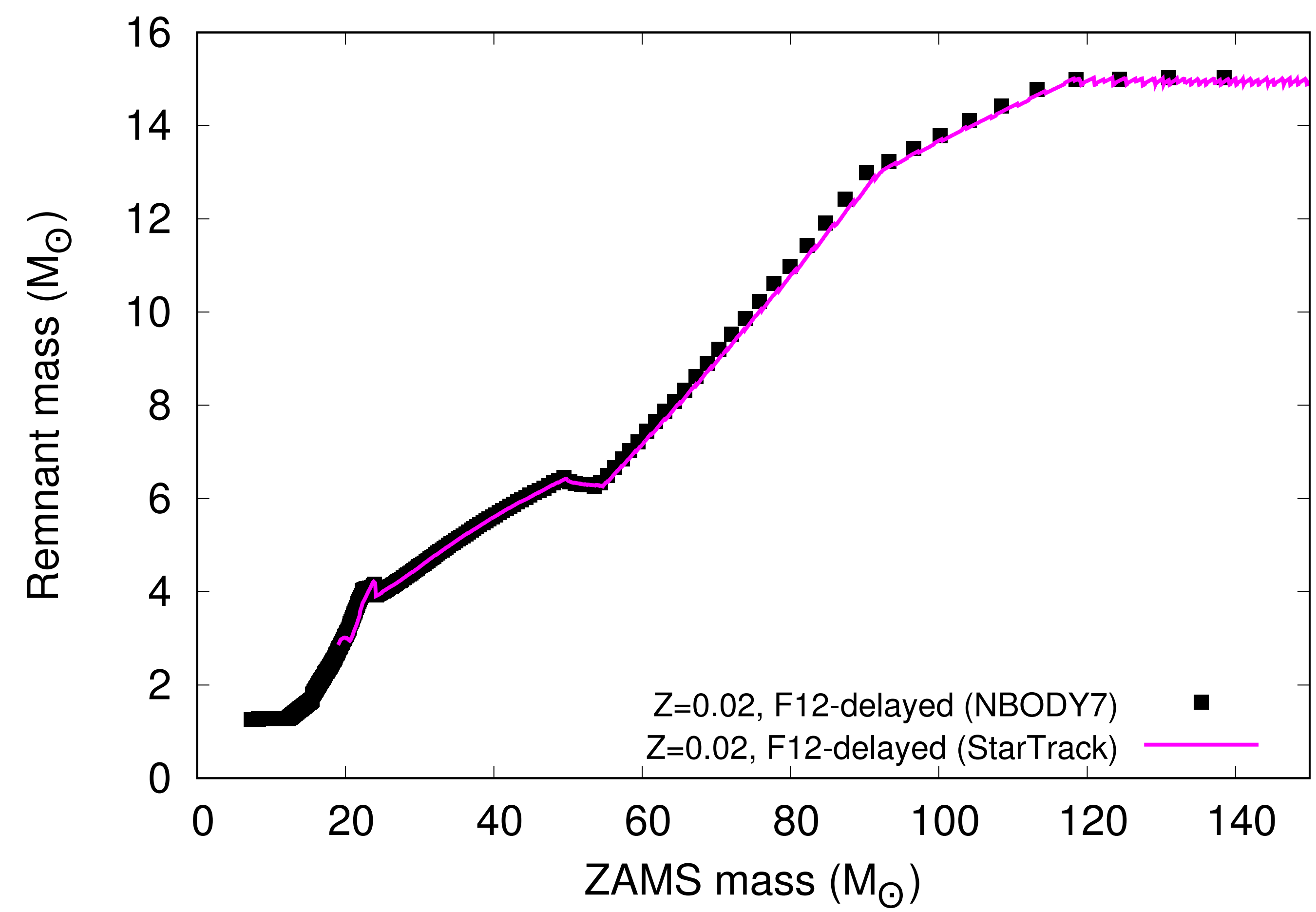
Abbott, B.P., et al., arXiv: 1811.12940



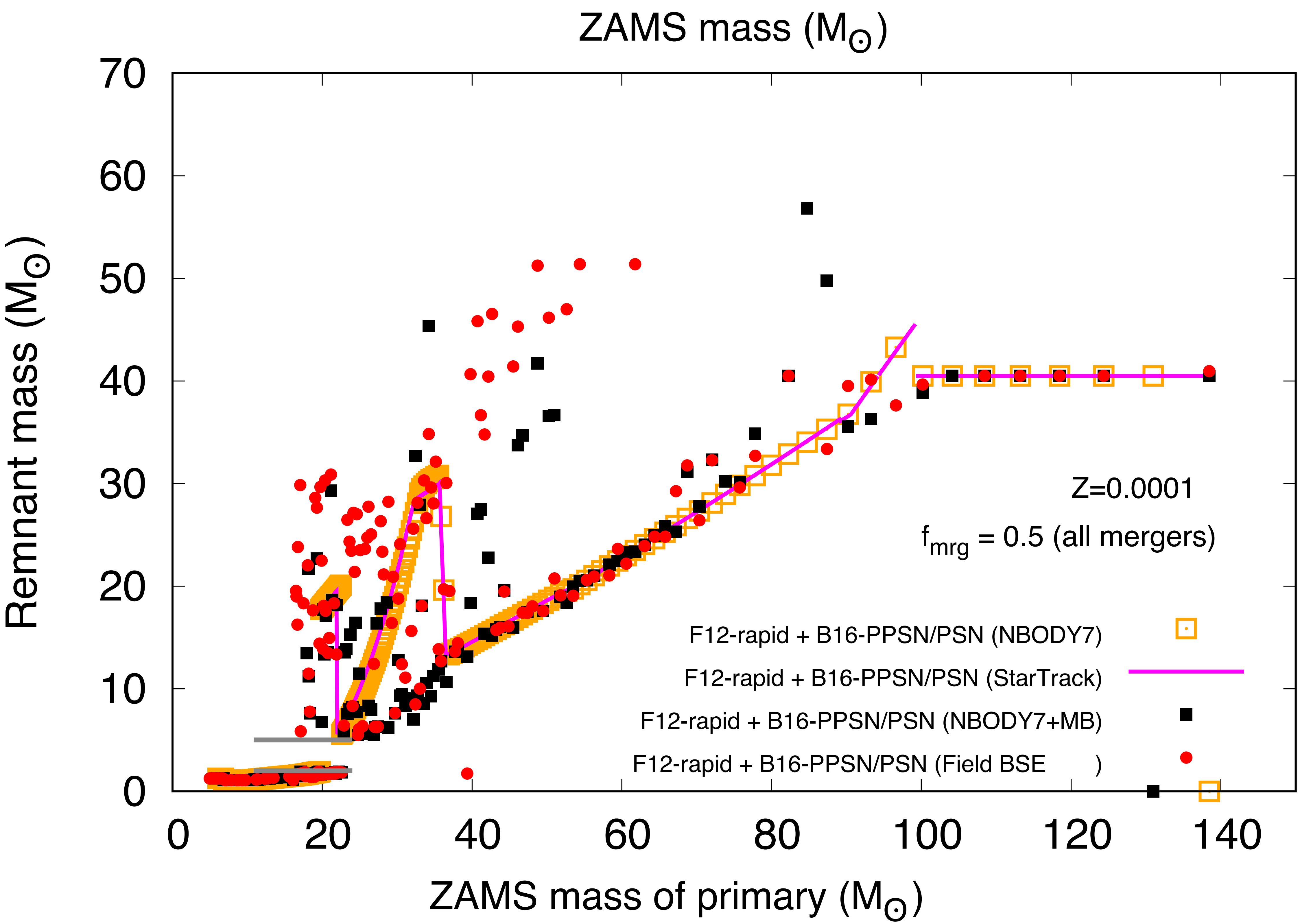


Figures from:
From Banerjee, S., Belczynski, K., Fryer, C. L., et al., A&A, arXiv:1902.07718





The effect of binary interactions (and of the dynamical environment)



Banerjee, S. in prep…

Remnant natal kick

Momentum-conserving kick (Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223):

$$v_{\rm kick} = v_{\rm kick,NS}(1 - f_{\rm fb}) \quad v_{\rm kick,NS} \approx 265 \text{ km s}^{-1}$$

Hobbs, G., et al., 2005, MNRAS, 360, 974

Typical BH retention fraction:

50%-80% depending on Z and remnant model

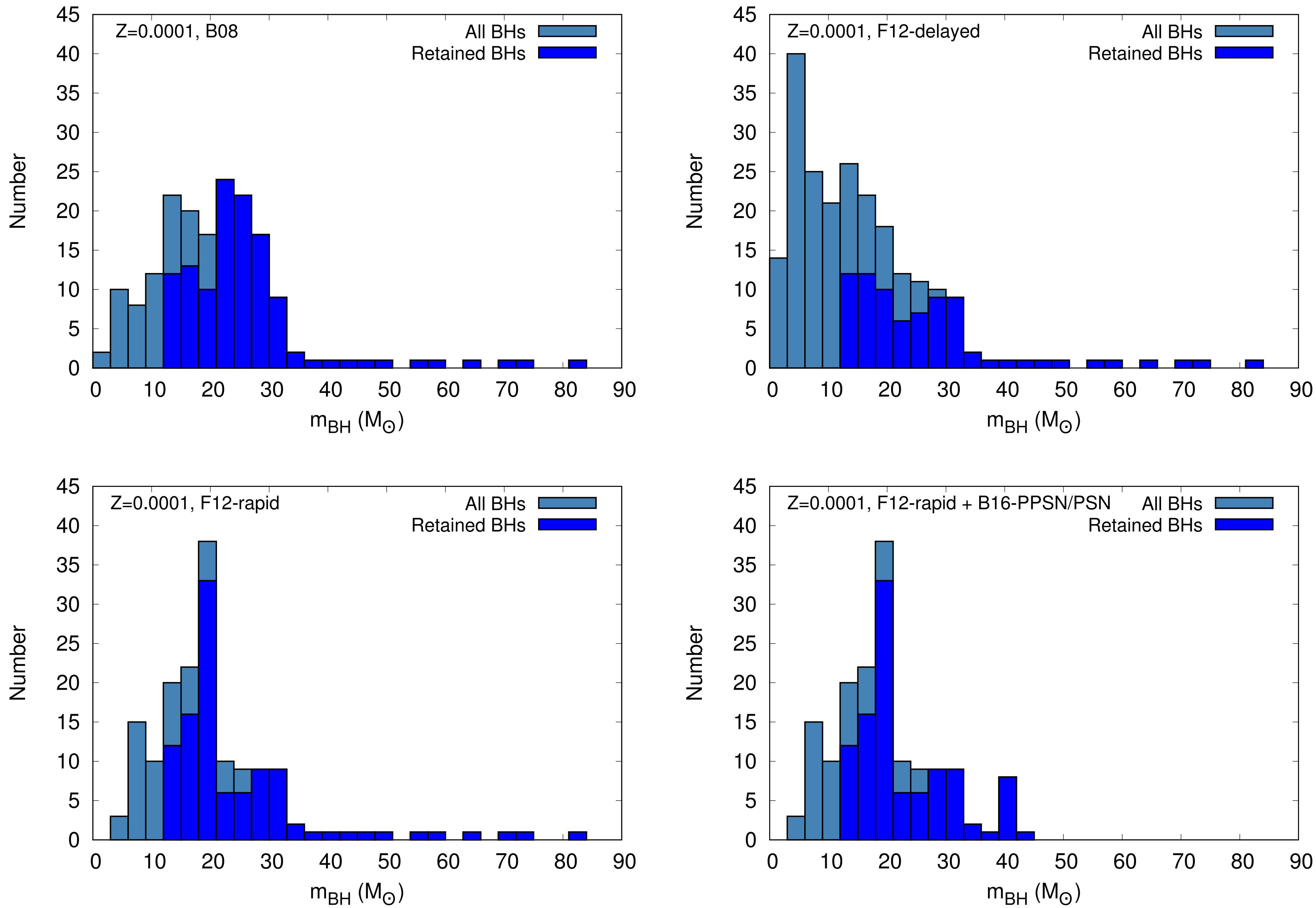
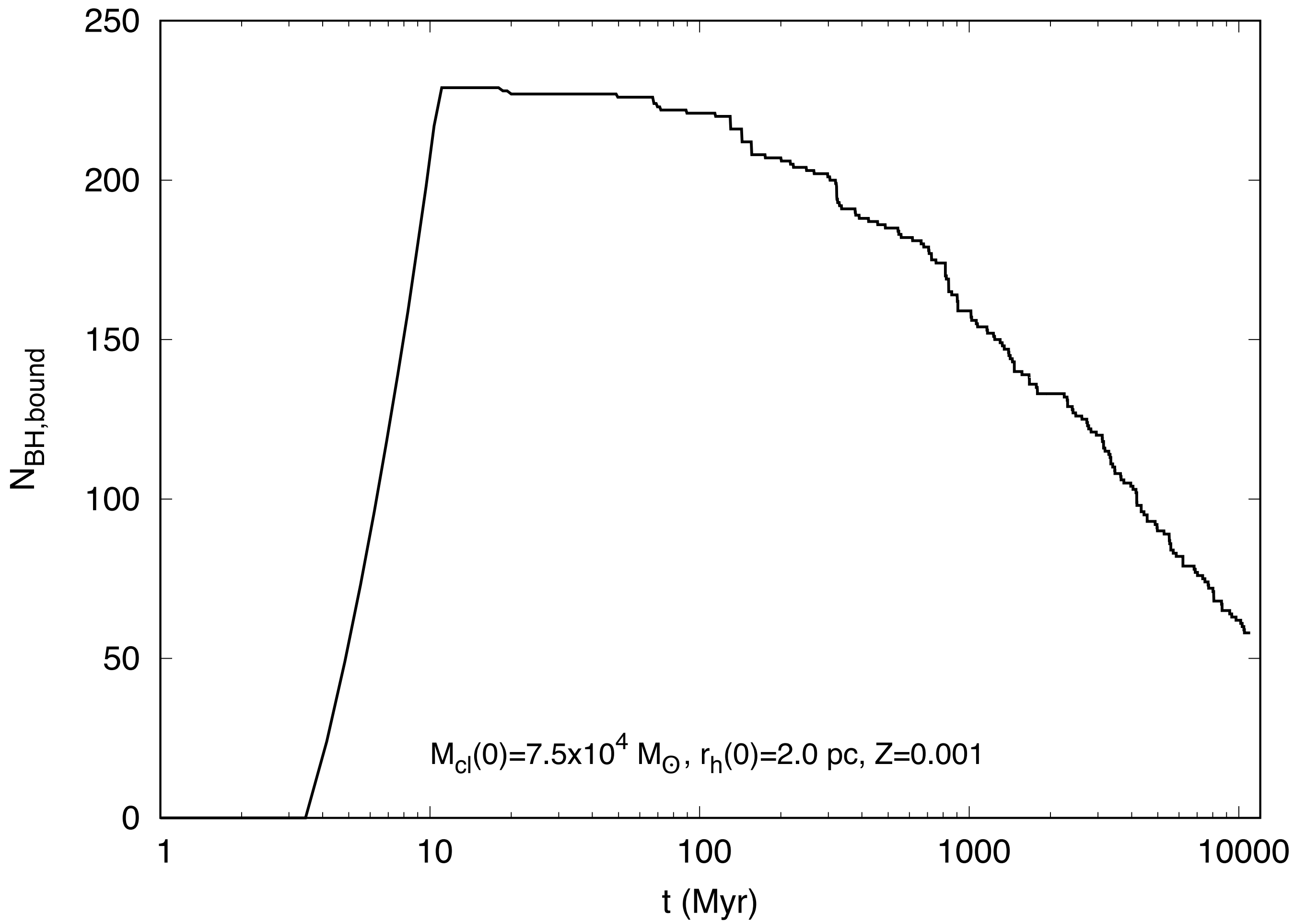
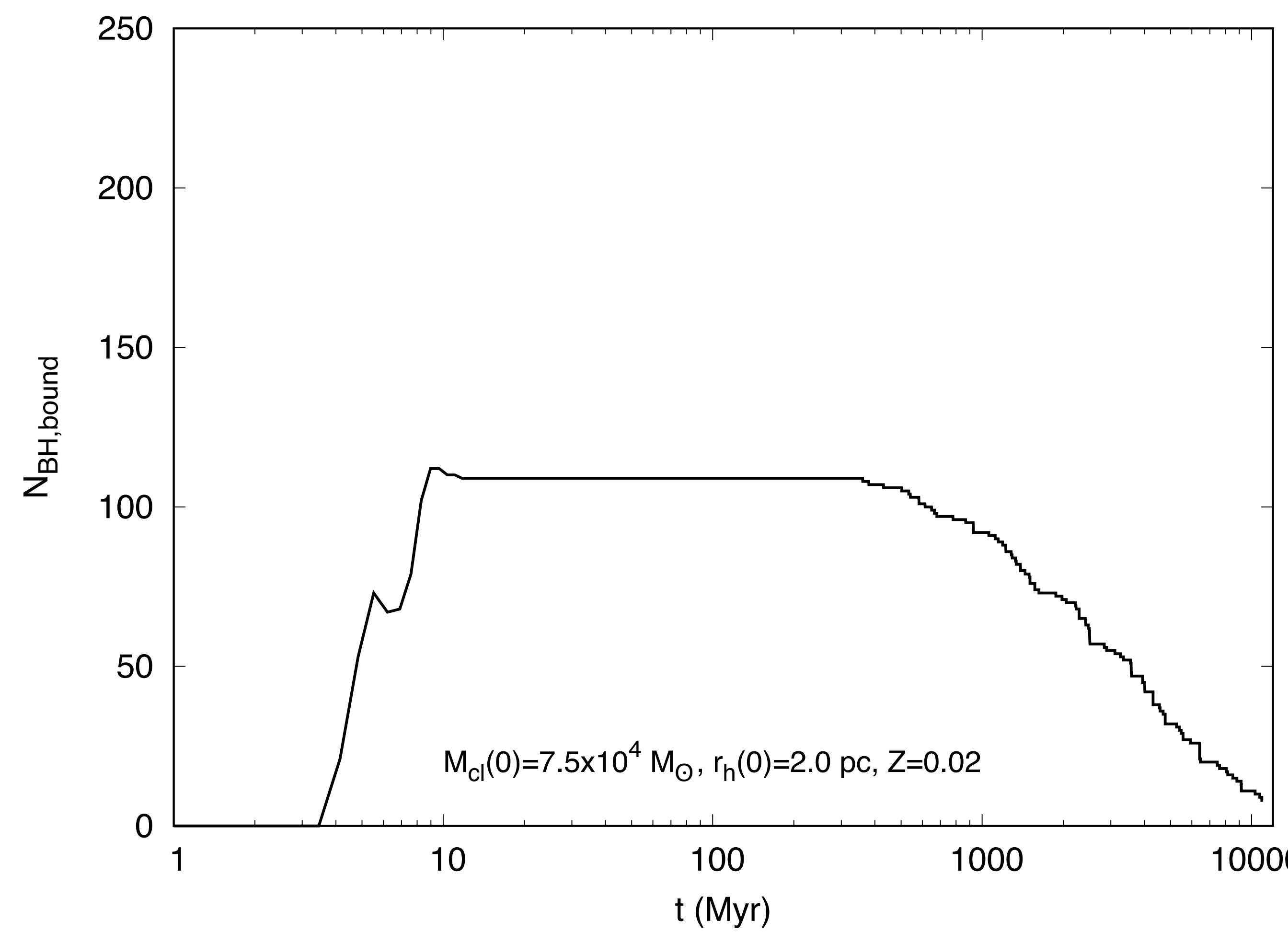


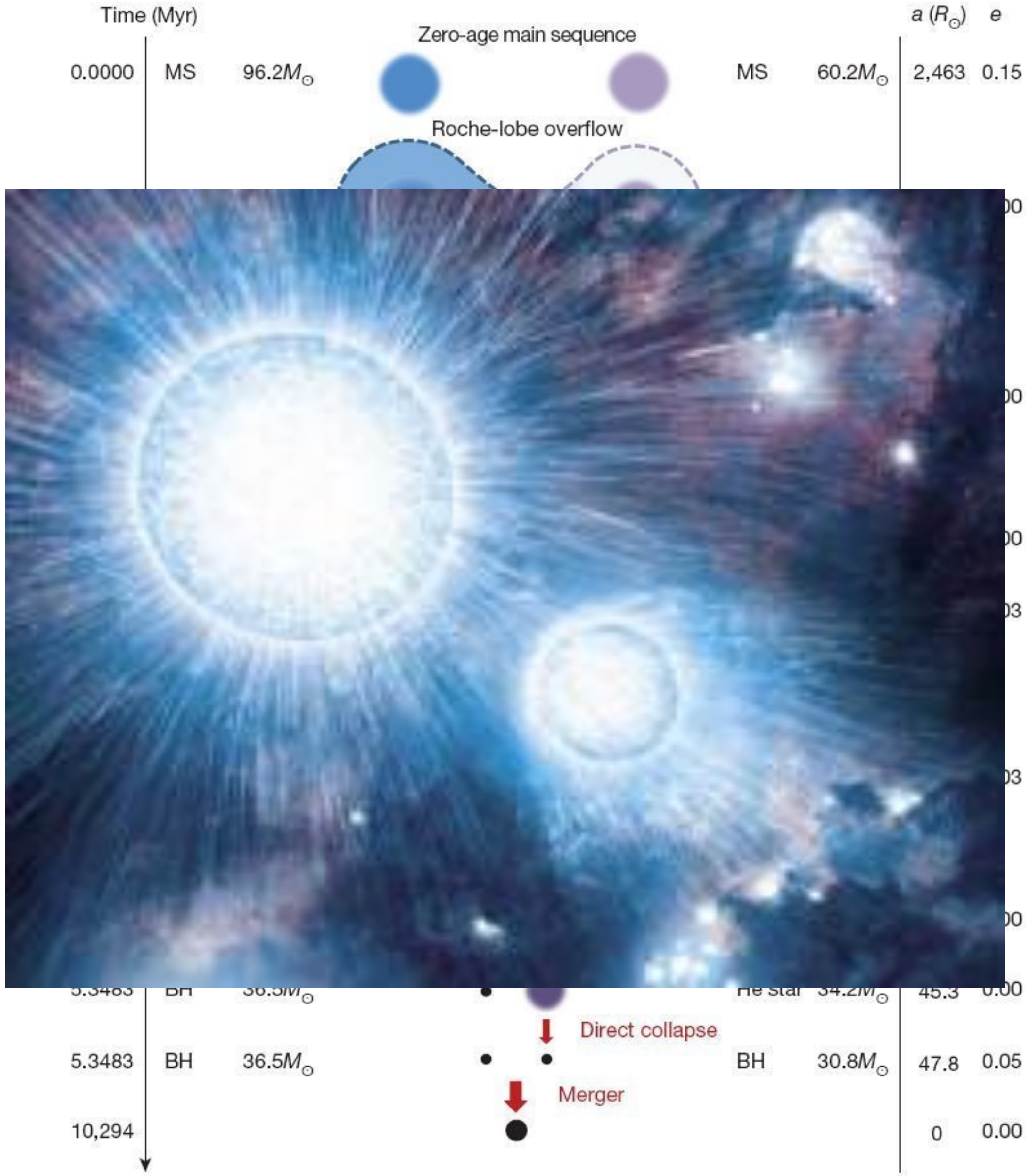
Figure from:
From Banerjee, S., Belczynski, K., Fryer, C. L., et al., A&A, arXiv:1902.07718


250
200
150
100
50
0
$N_{BH,bound}$
1
10
100
1000
10000
t (Myr)
$M_{cl}(0)=7.5x10^4\ M_{\odot}$, $r_h(0)=2.0$ pc, Z=0.001


250
200
150
100
50
0
$N_{BH,bound}$
1
10
100
1000
10000
t (Myr)
$M_{cl}(0)=7.5x10^4\ M_{\odot}$, $r_h(0)=2.0$ pc, Z=0.02

Example:

Binary black hole merger from massive binary stars

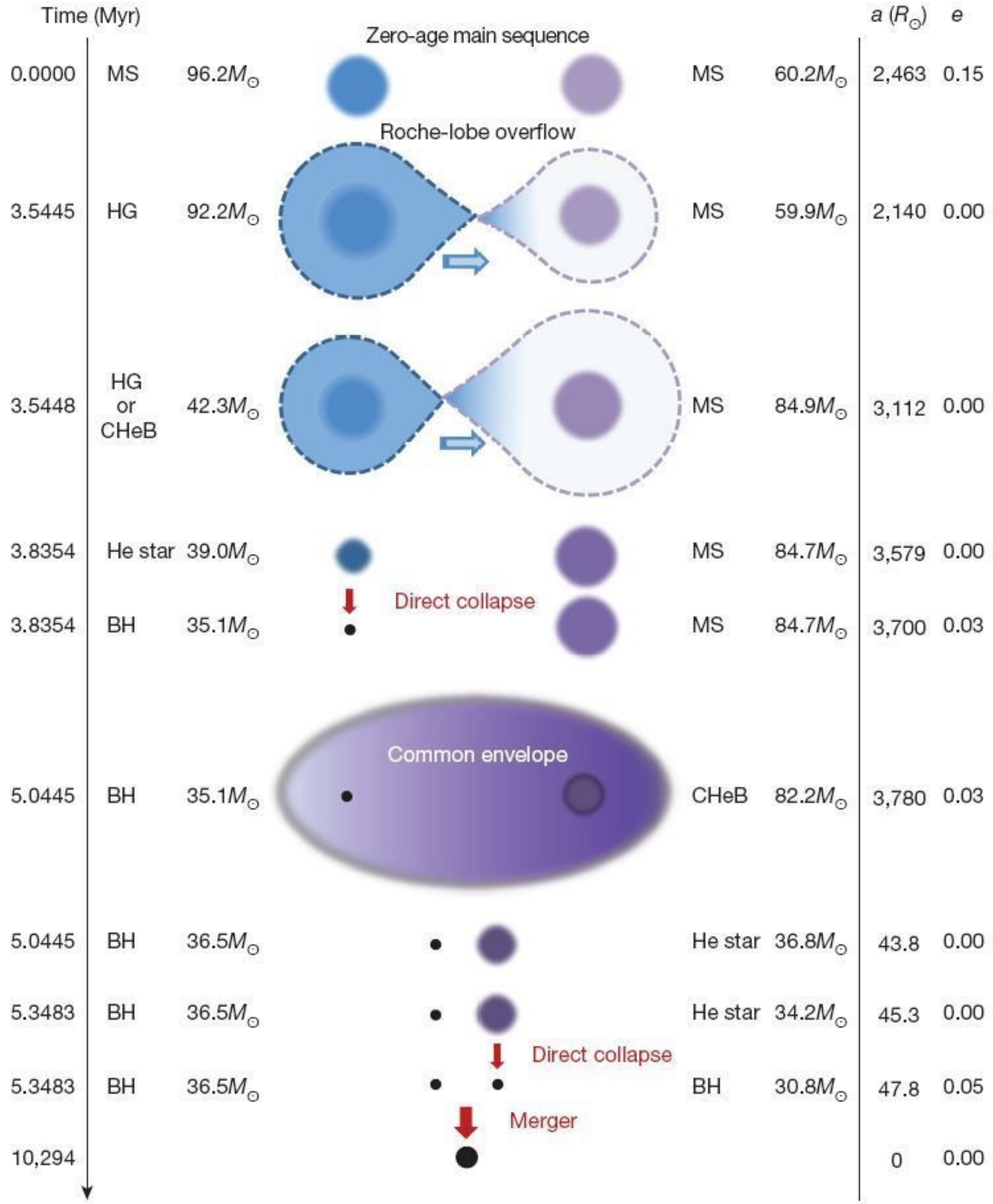


From Belczynski, K. et al. 2016, Nature, 534, 7608

See also: Marchant, P. et al. 2016, A&A, 588, A50

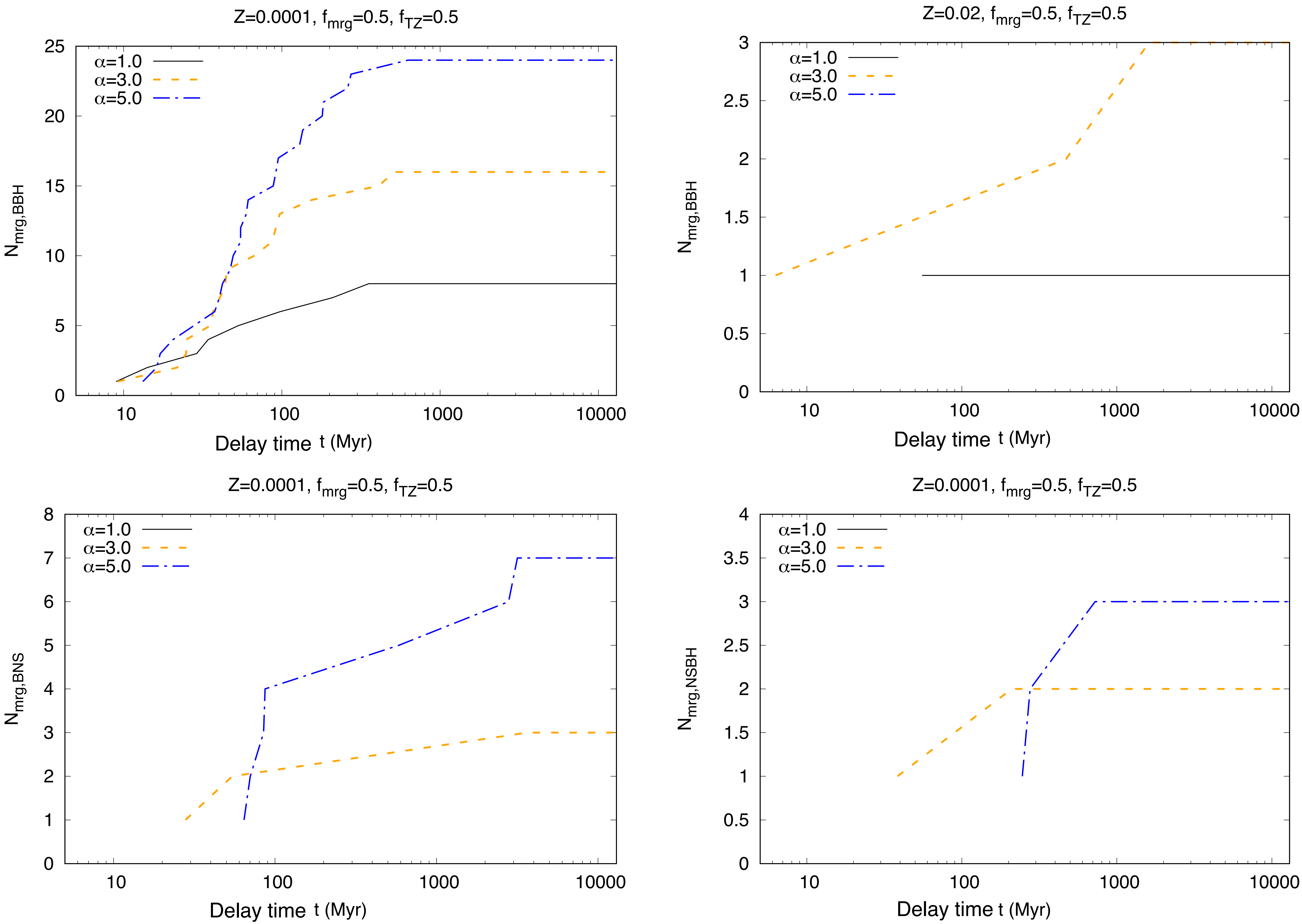
Example:

Binary black hole merger from massive binary stars



From Belczynski, K. et al. 2016, Nature, 534, 7608

See also: Marchant, P. et al. 2016, A&A, 588, A50



Compact binary mergers from massive-binary evolution in the field (~2000 massive binaries with BSE)
Binary properties according to: Sana, H. & Evans, C. J., 2011, IAUS 272, 474–485

Banerjee, S. in prep…

PC: Adam Black/University of Arizona

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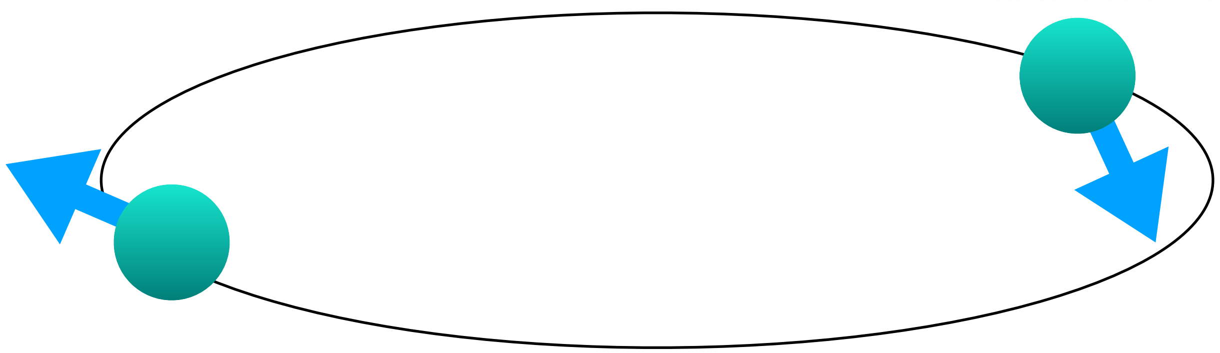
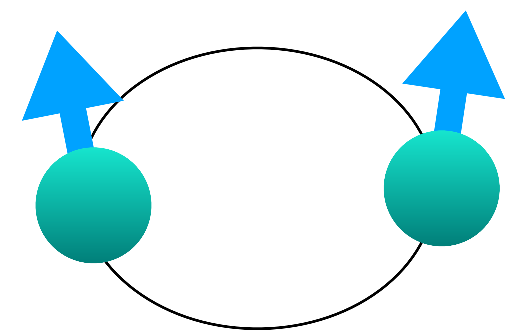


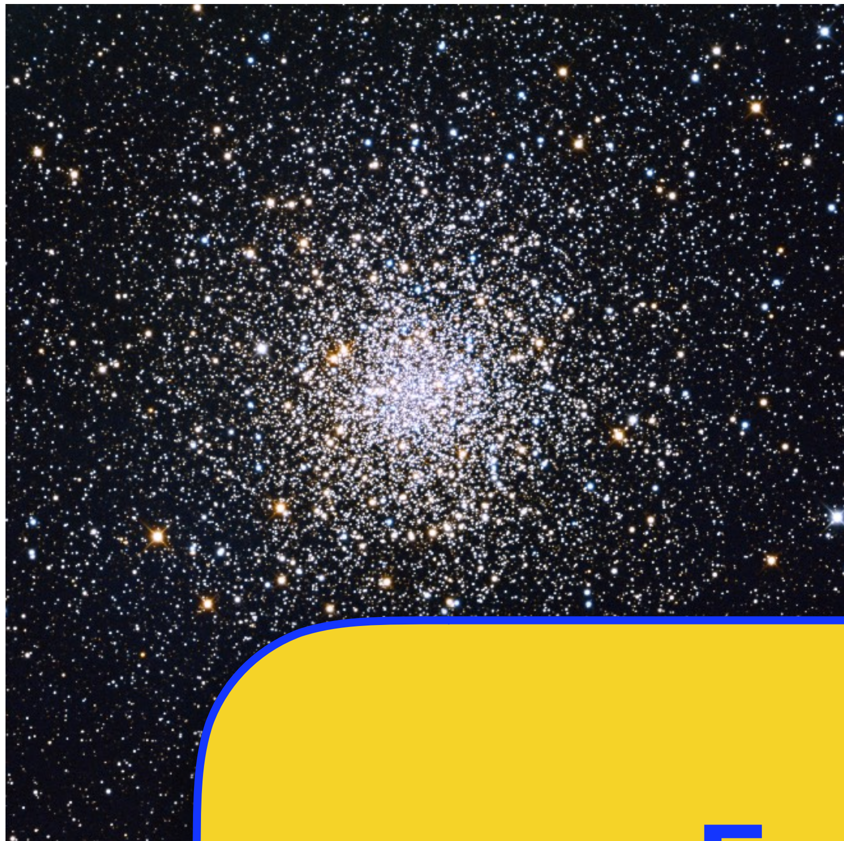


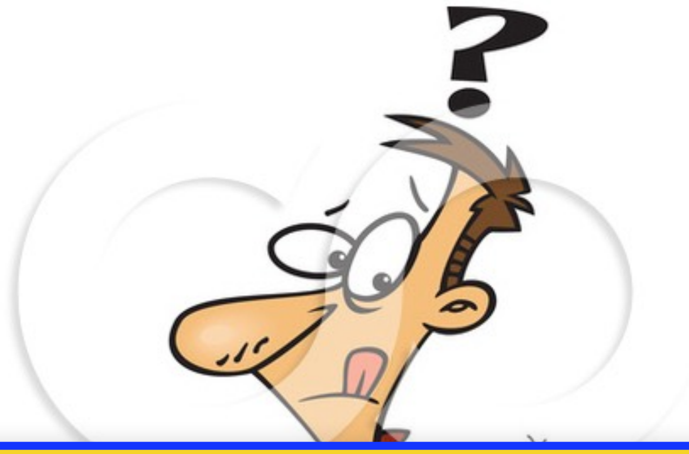
Can LIGO tell the difference in origin ??

Maybe … Maybe not (depends on how sensitive the instrument is and how far the source is)

Need LISA, DECIGO, ET, CE….. !!

! Images not to scale
! Cartoon orbits





PC:

Exciting times ahead!!!

Thank you :-)

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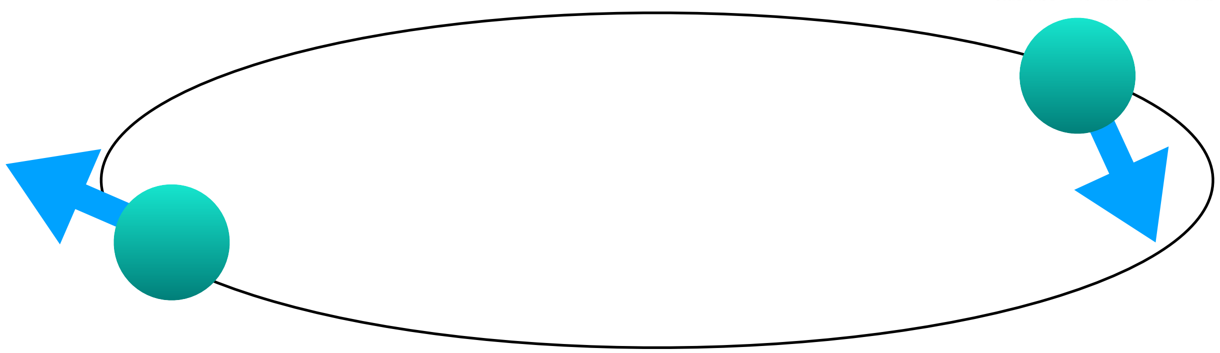
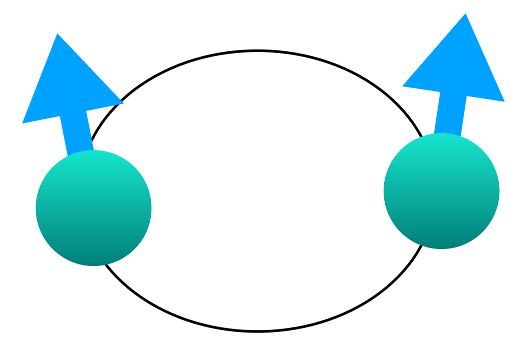
PC: Adam Black/University of Arizona





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