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The Carnegie Astrophysics Summer Student Internship Program

Formation of Black Hole–White Dwarf X-ray Binaries in Globular Clusters

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Credit: ESA/Hubble & NASA, F. Ferraro

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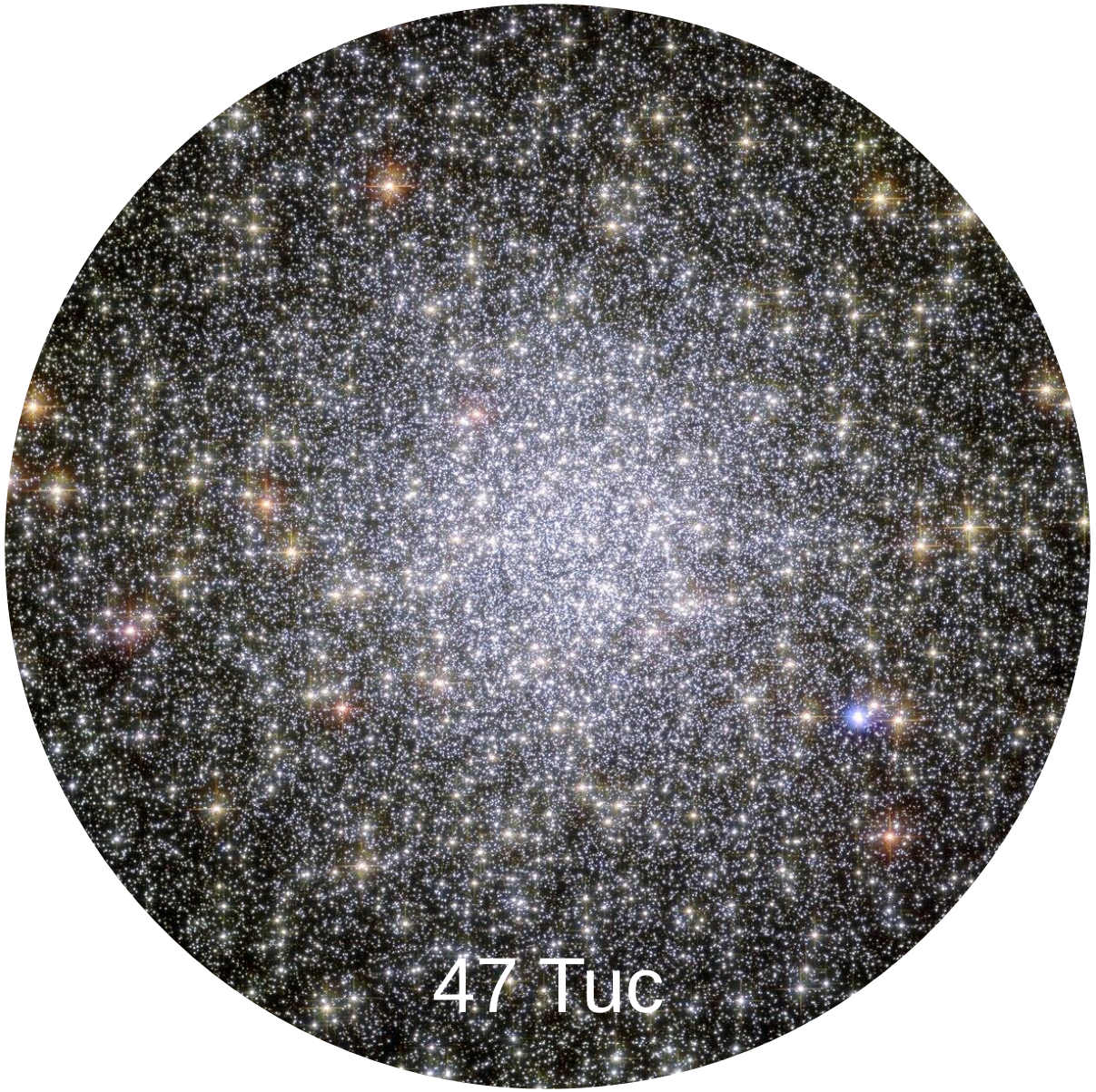
Globular Clusters

What are they?

- **Very massive**
  - 10^5 – 10^6 stars.
- **Very dense**
  - Central density of 10^4 – 10^6 stars/pc^3.
- **Very old**
  - 9 – 14 Gyr.



Credit: X-ray: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration Acknowledgment: J. Mack (STScI) and G. Piotto (University of Padova, Italy)

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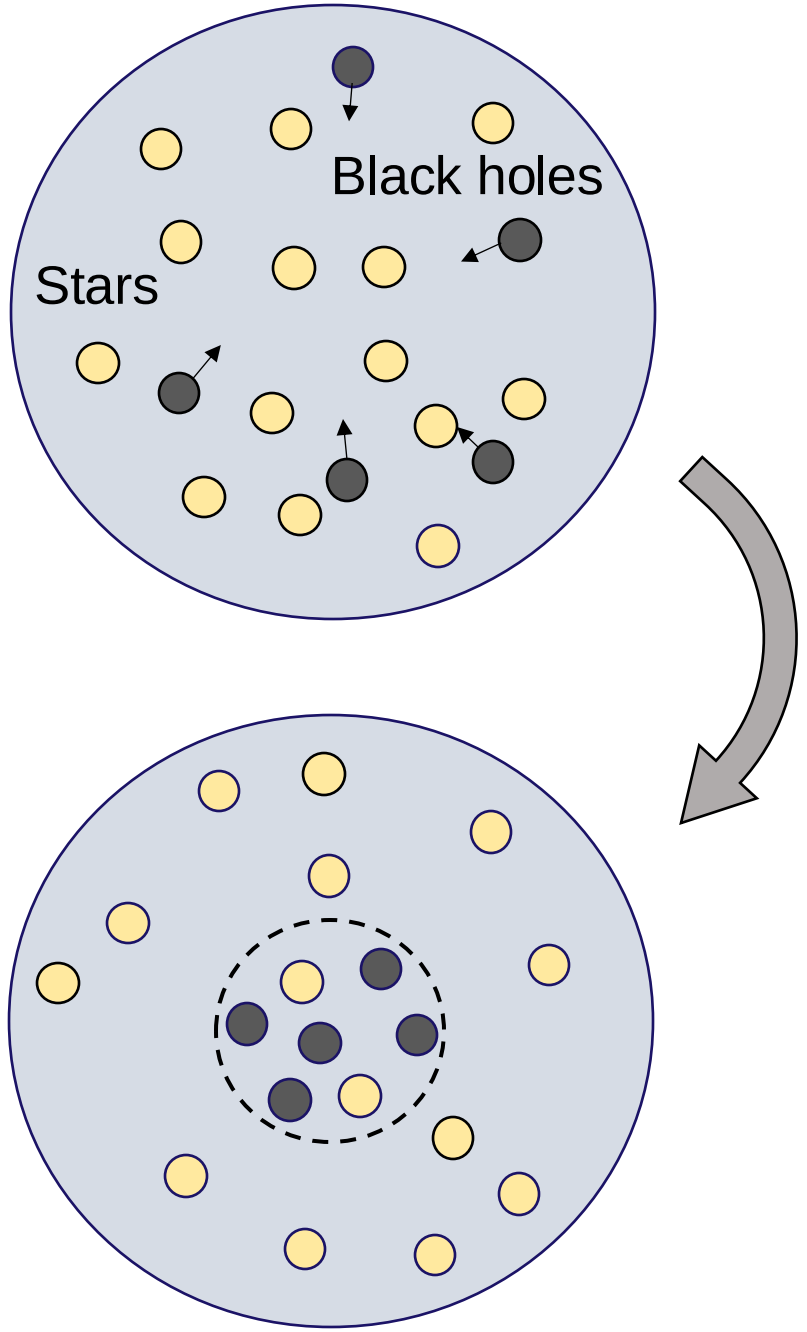
Globular Clusters

Structure and Dynamics

- **Stellar mass black holes**
  - 100s of black holes in each globular cluster.

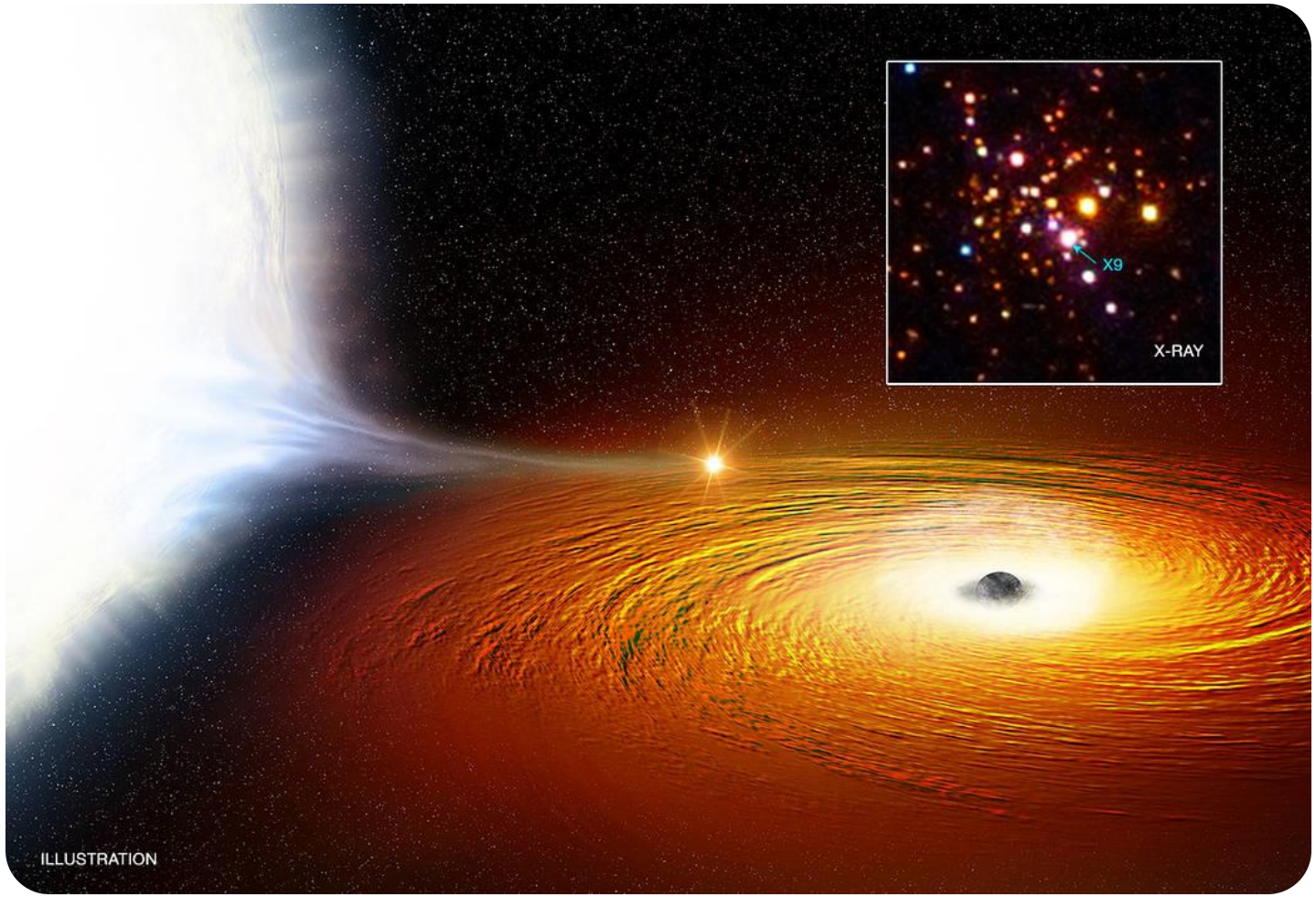
- **Mass segregation**
  - Black holes sink towards centre (Kremer et al. 2020).



Black Hole–White Dwarf X-ray Binaries

Observed Systems

- **Recent observations of black hole–white dwarf (BHWD) binaries motivate this project** (Miller-Jones et al. 2015; Dage et al. 2021; Dage et al. 2024)
- For example,
  - Galactic: 47 Tuc X9
  - Extragalactic: e.g. in Virgo cluster

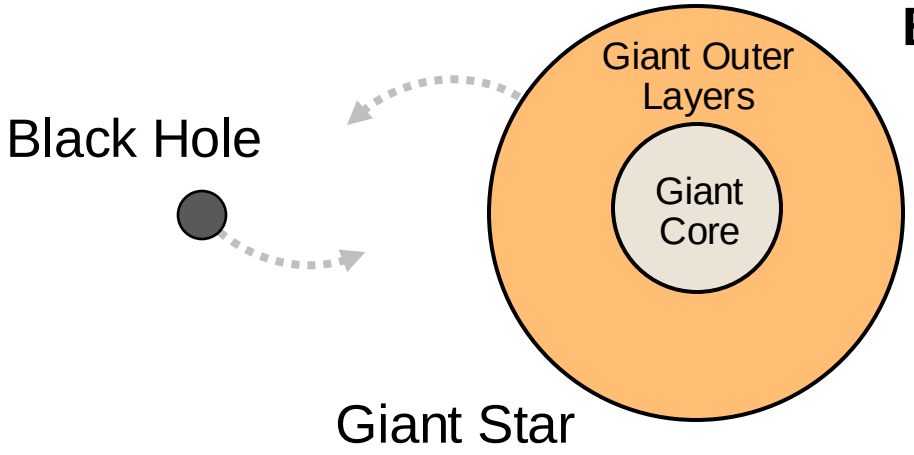


Credit: X-ray: NASA/CXC/University of Alberta/A.Bahramian et al.; Illustration: NASA/CXC/M.Weiss

Black Hole–White Dwarf X-ray Binaries

Formation Dynamics

Black hole–Giant collision



Black Hole–White Dwarf X-ray Binaries

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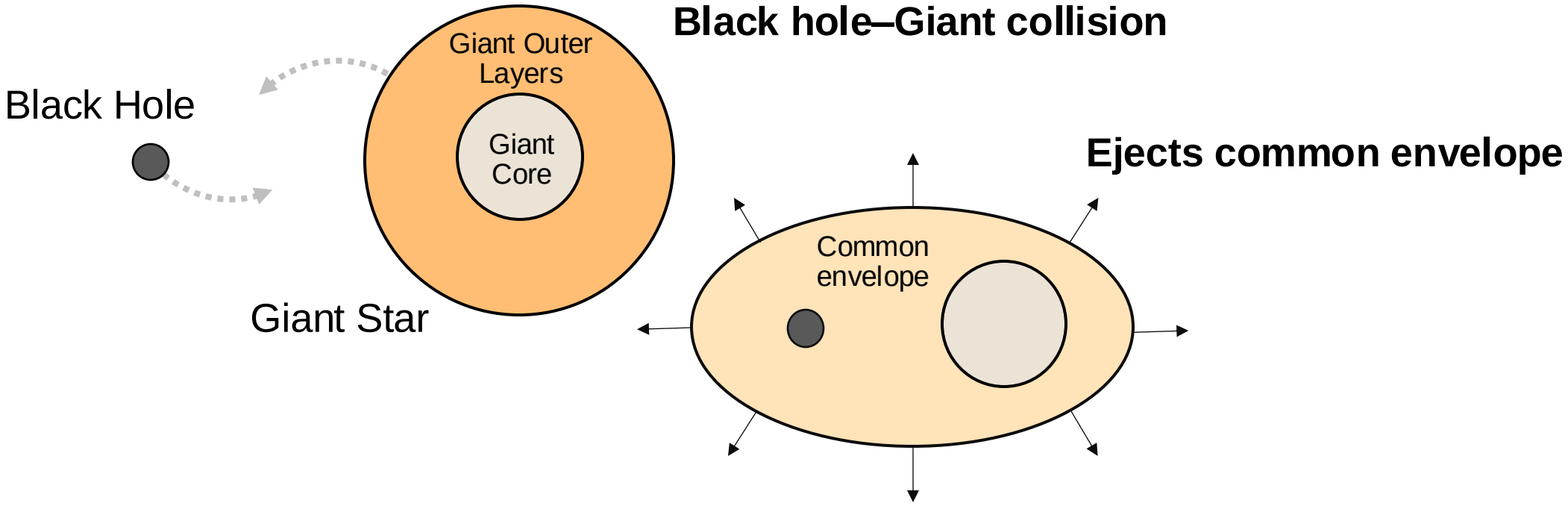

Black Hole–White Dwarf X-ray Binaries

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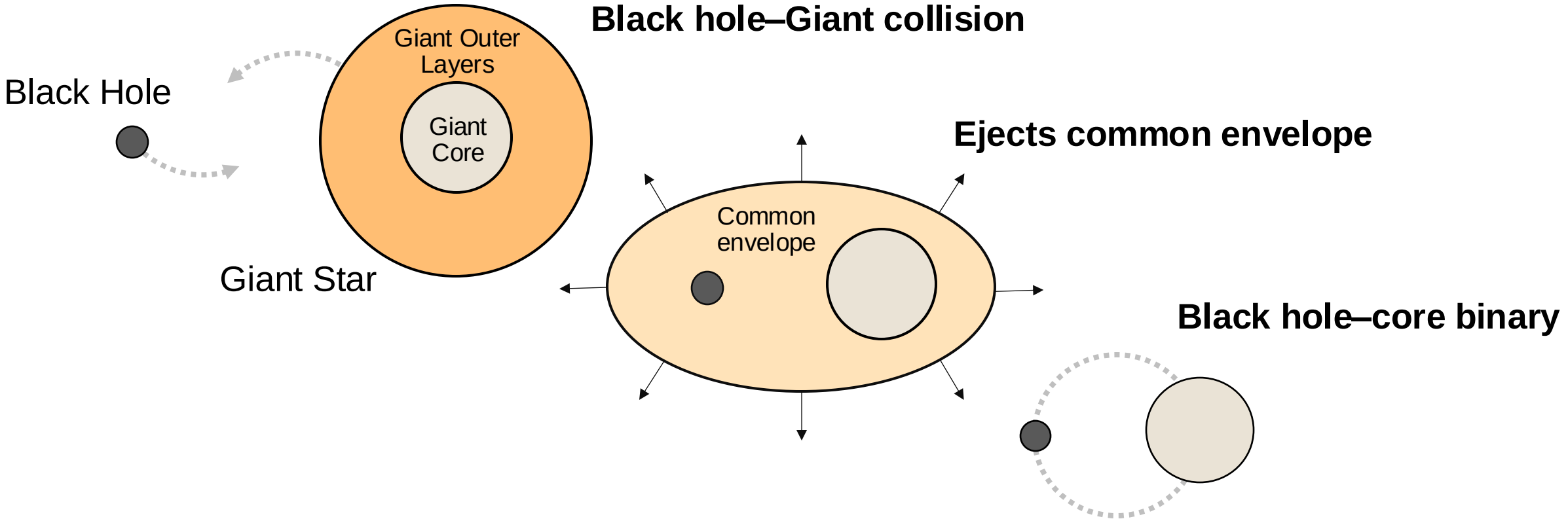
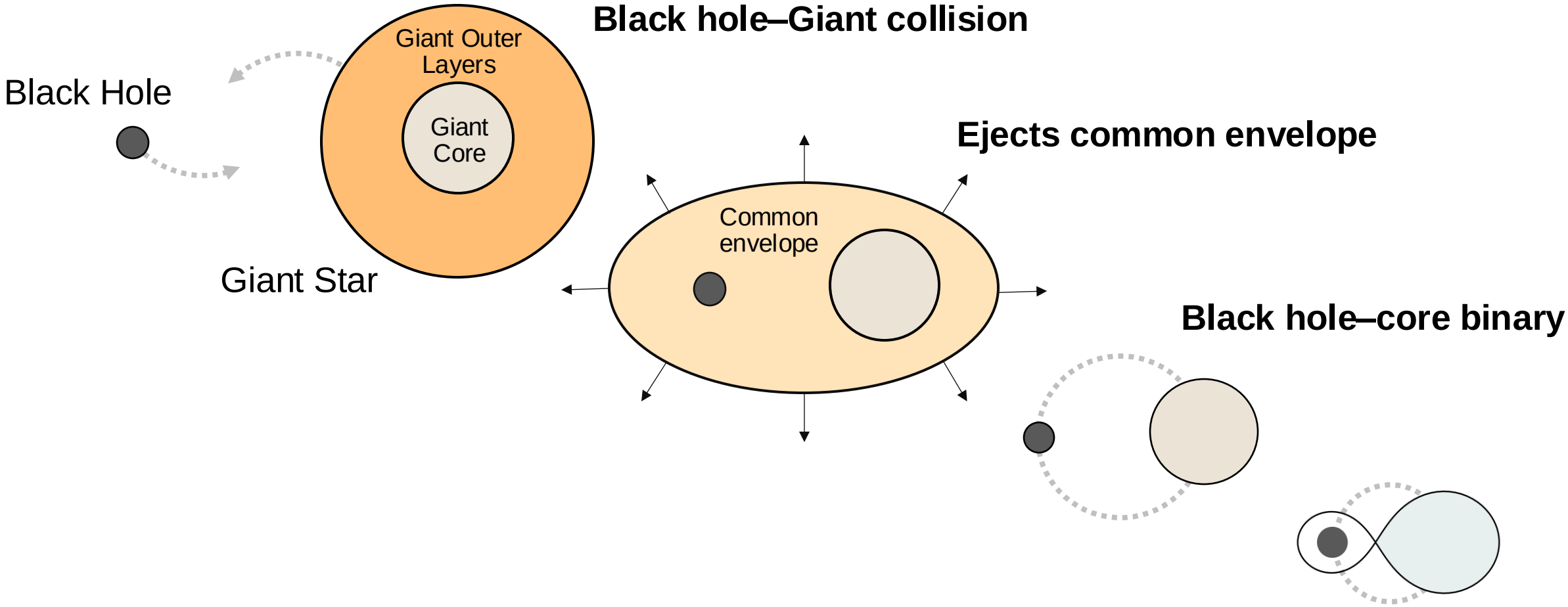


Black Hole–White Dwarf X-ray Binaries

Formation Dynamics



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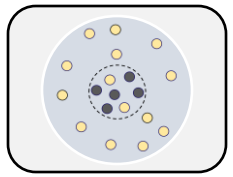
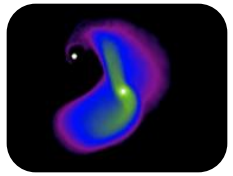
Modelling Key Evolutionary Phases



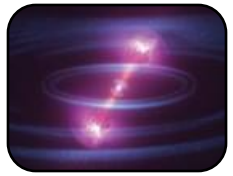
1. **N-body Simulations of Globular Clusters: Rates of Formation**



2. **Hydrodynamics Simulations of Collisions**

3. **Gravitational Wave Inspiral**

4. **Mass Transfer & Accretion**



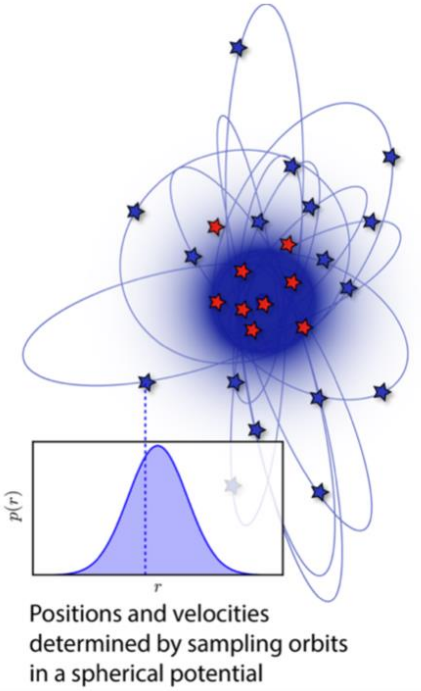
5. **Multimessenger Observational Predictions**

CMC Code N-body Simulations

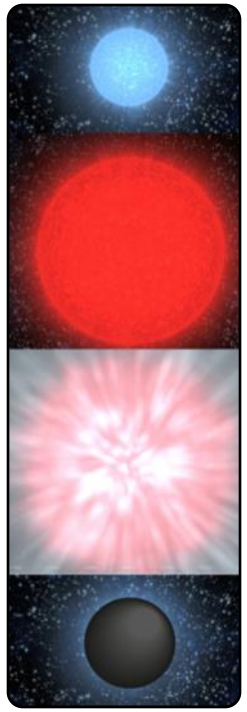
Orbits modeled for cluster evolution

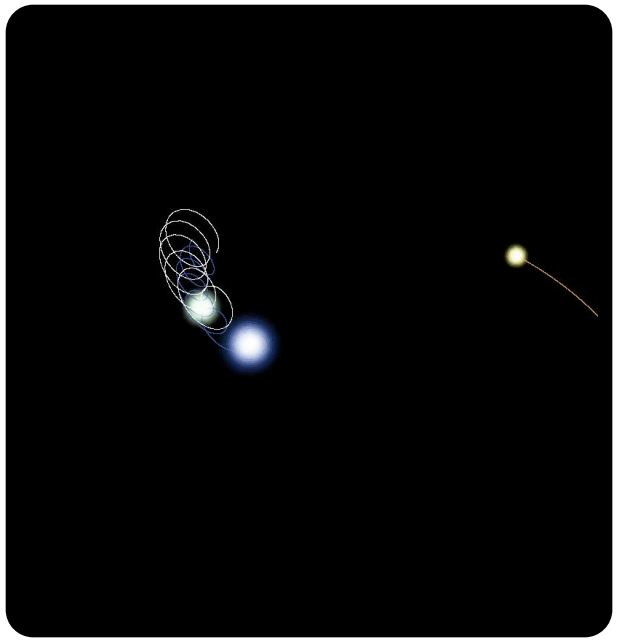
Stars modeled for stellar evolution

Direct integration of few body encounters



Positions and velocities determined by sampling orbits in a spherical potential



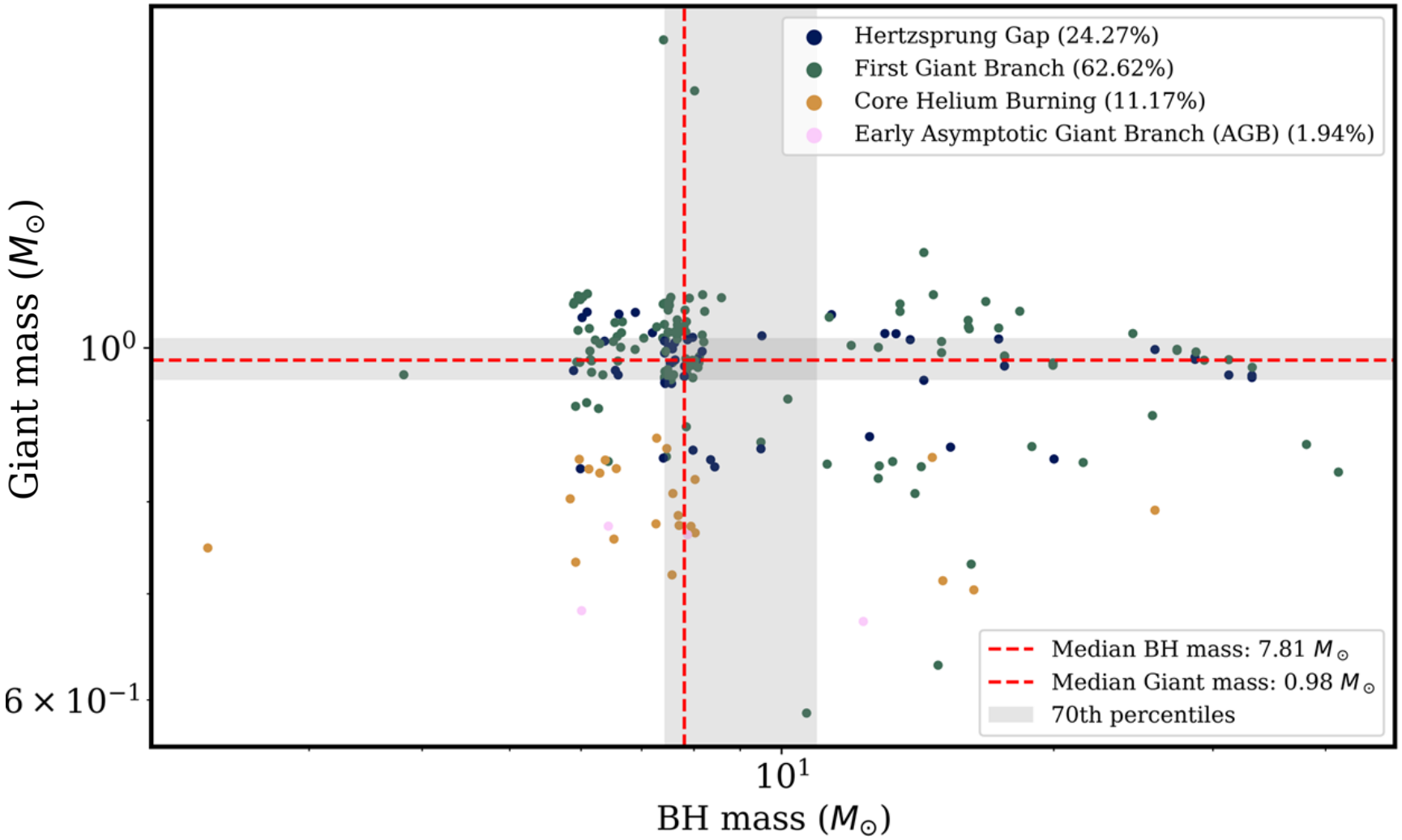


(Rodriguez et al. 2022)

Black Hole–Giant Collisions from N-body

- We track **~300 collisions** between black holes and giants.

Collision rate of ~1 Gyr^{-1} in each cluster.



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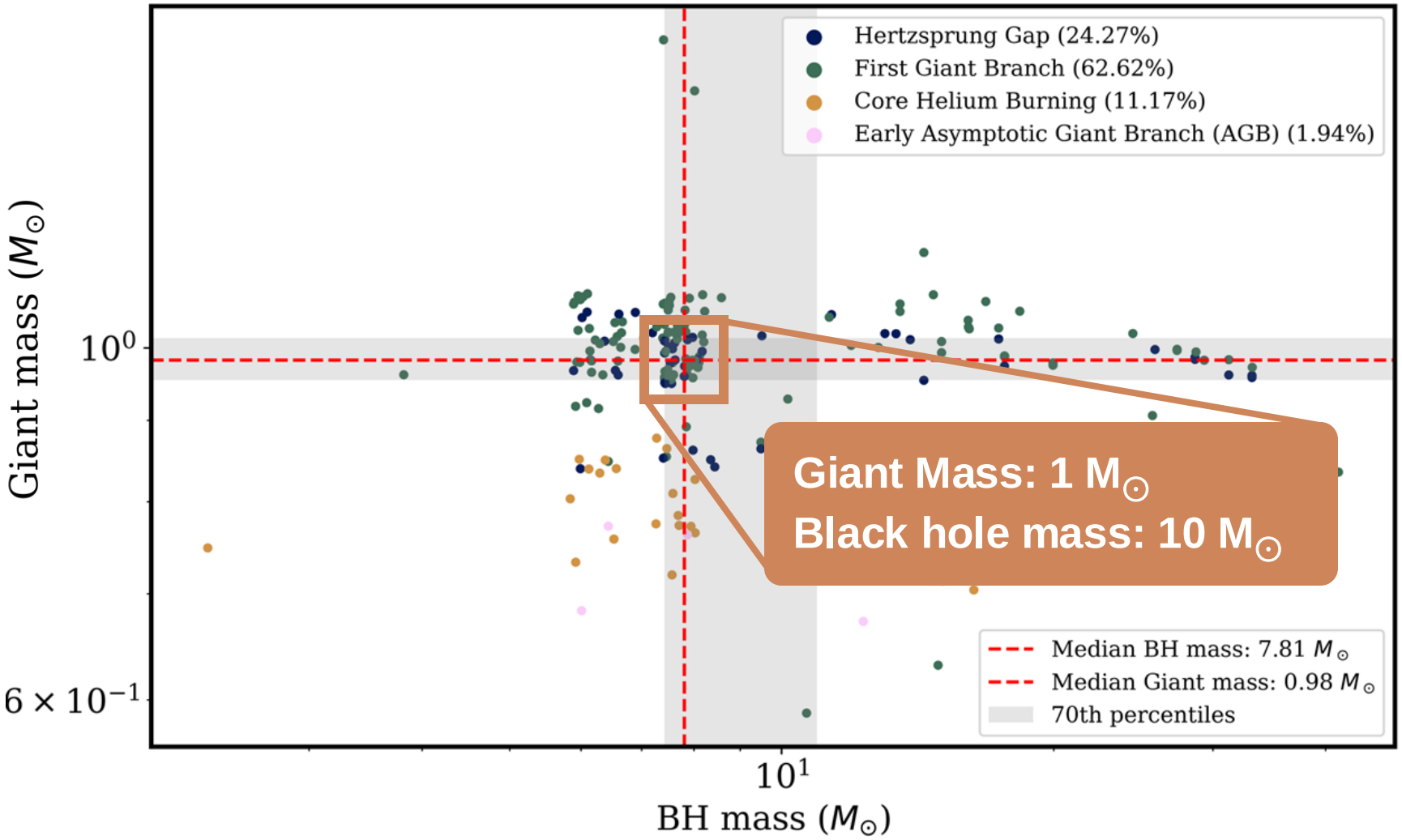
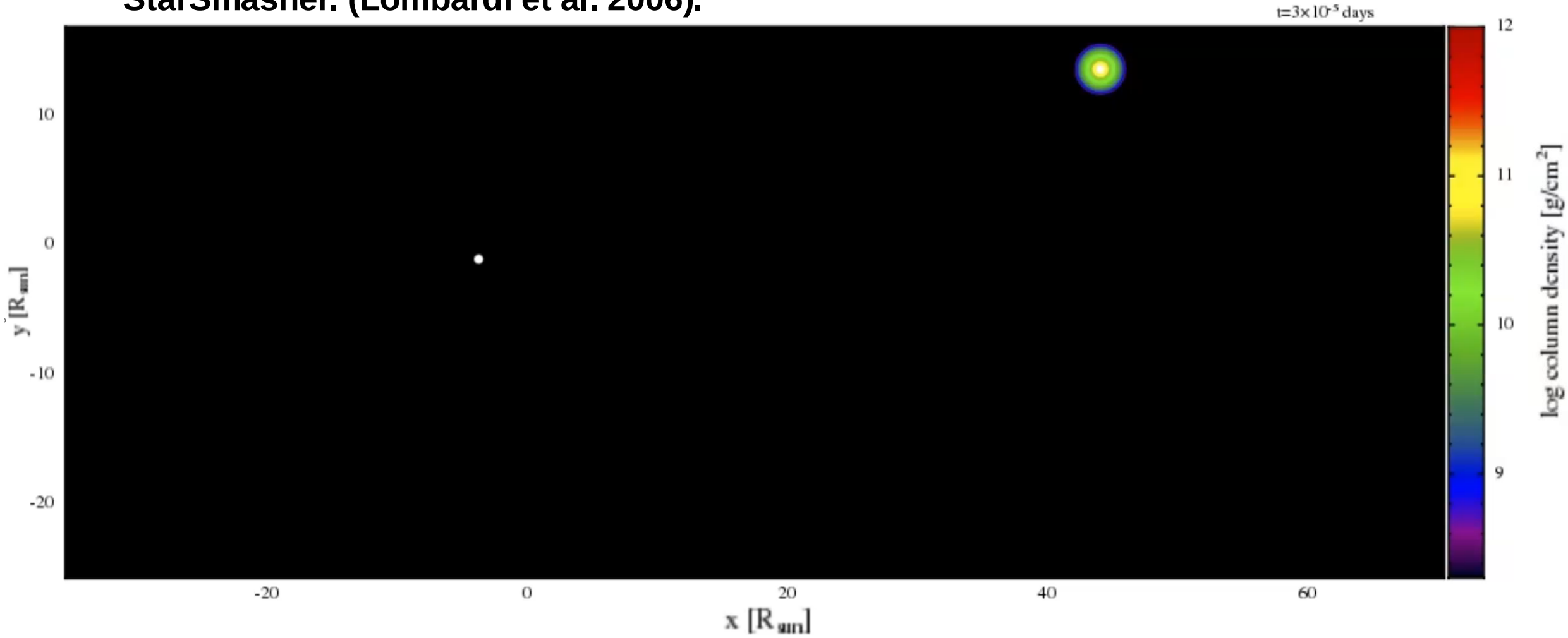


Post-Collision Binary Properties

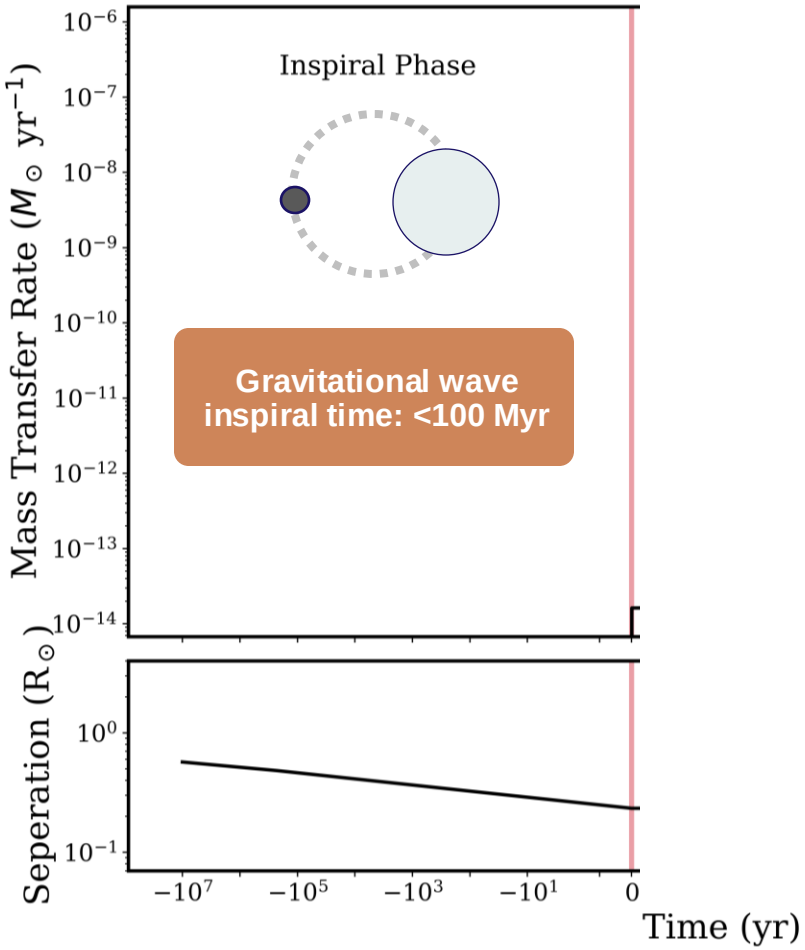
Hydrodynamics simulations using the Smoothed Particle Hydrodynamics code, StarSmasher. (Lombardi et al. 2006).



Evolution of Black Hole–White Dwarf Binary

We use the COSMIC binary evolution code to model **orbital properties** and the **mass transfer rate** in the binary system.

(Breivik et al. 2020)



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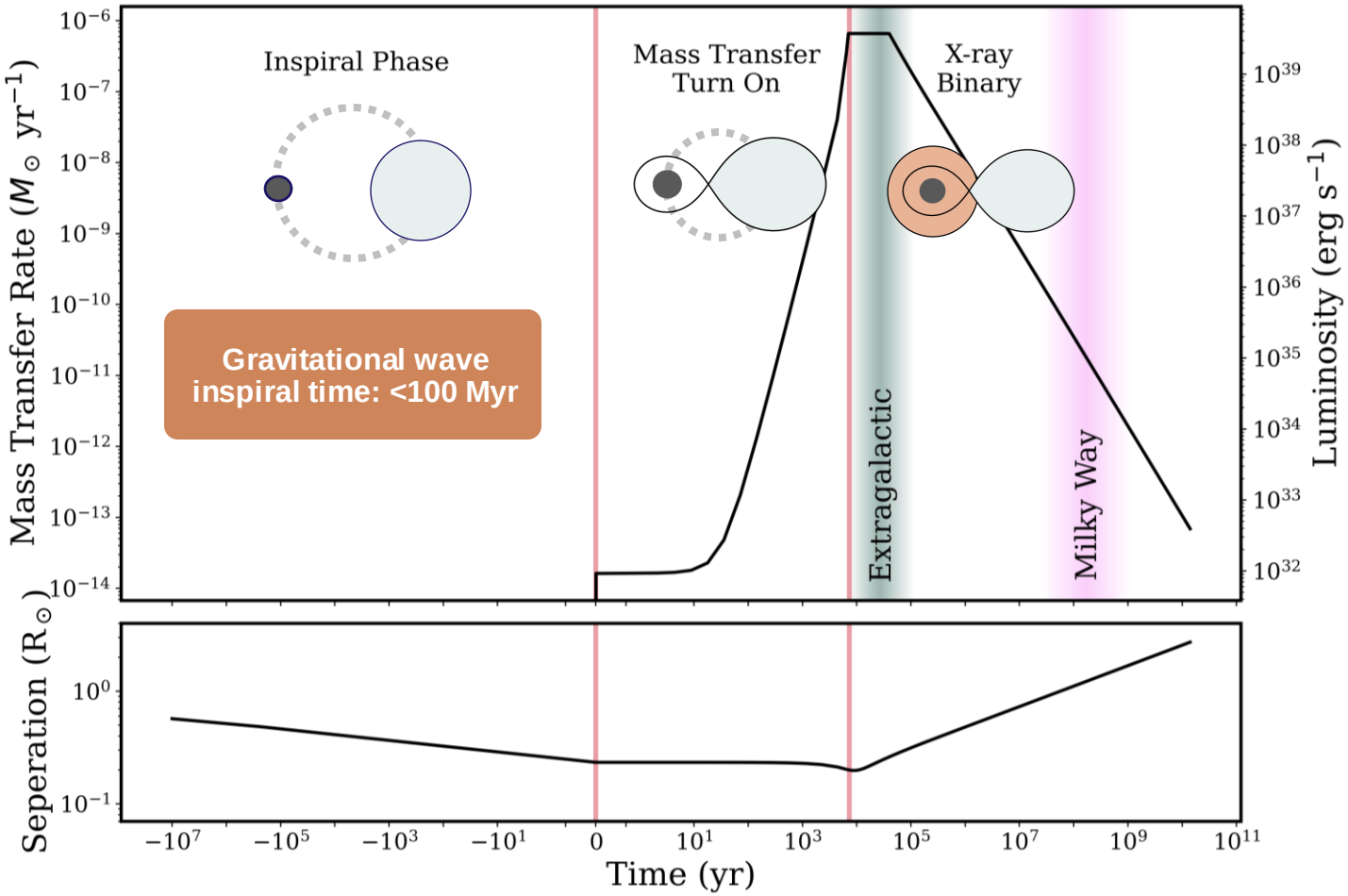


The luminosity is calculated using:

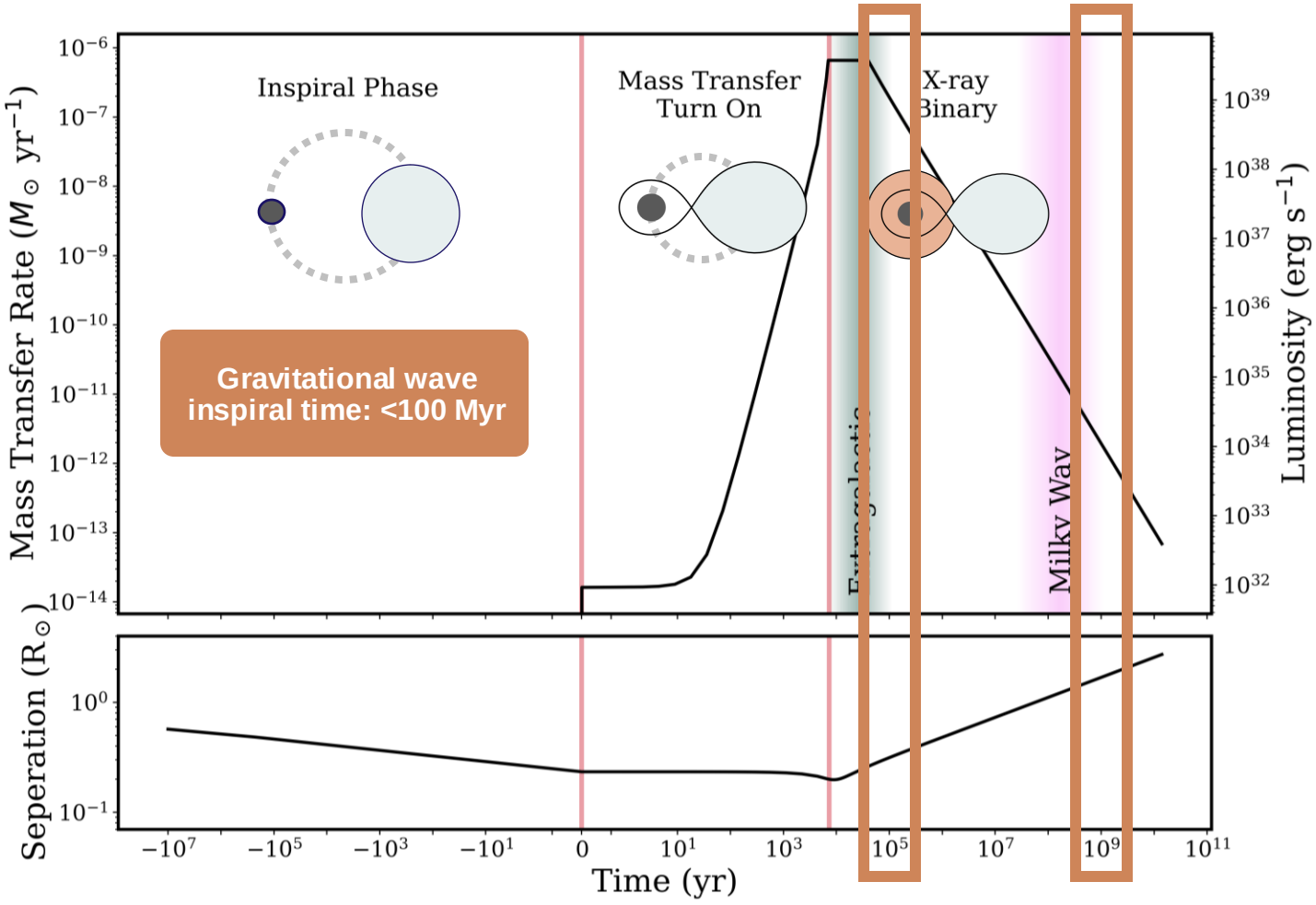
$$L = \varepsilon \dot{m} c^2$$

where ε is an efficiency factor.

ε is a free parameter; we have used a value of $\varepsilon = 0.1$.

Evolution of X-ray Binary

Using the luminosity bounds, we can obtain a rough observable lifetime, τ, for these X-ray binaries



We calculate:

$$N = \Gamma\tau$$

- Γ is the rate (from N-body),
- τ is the expected observable lifetime (from COSMIC).

Evolution of X-ray Binary

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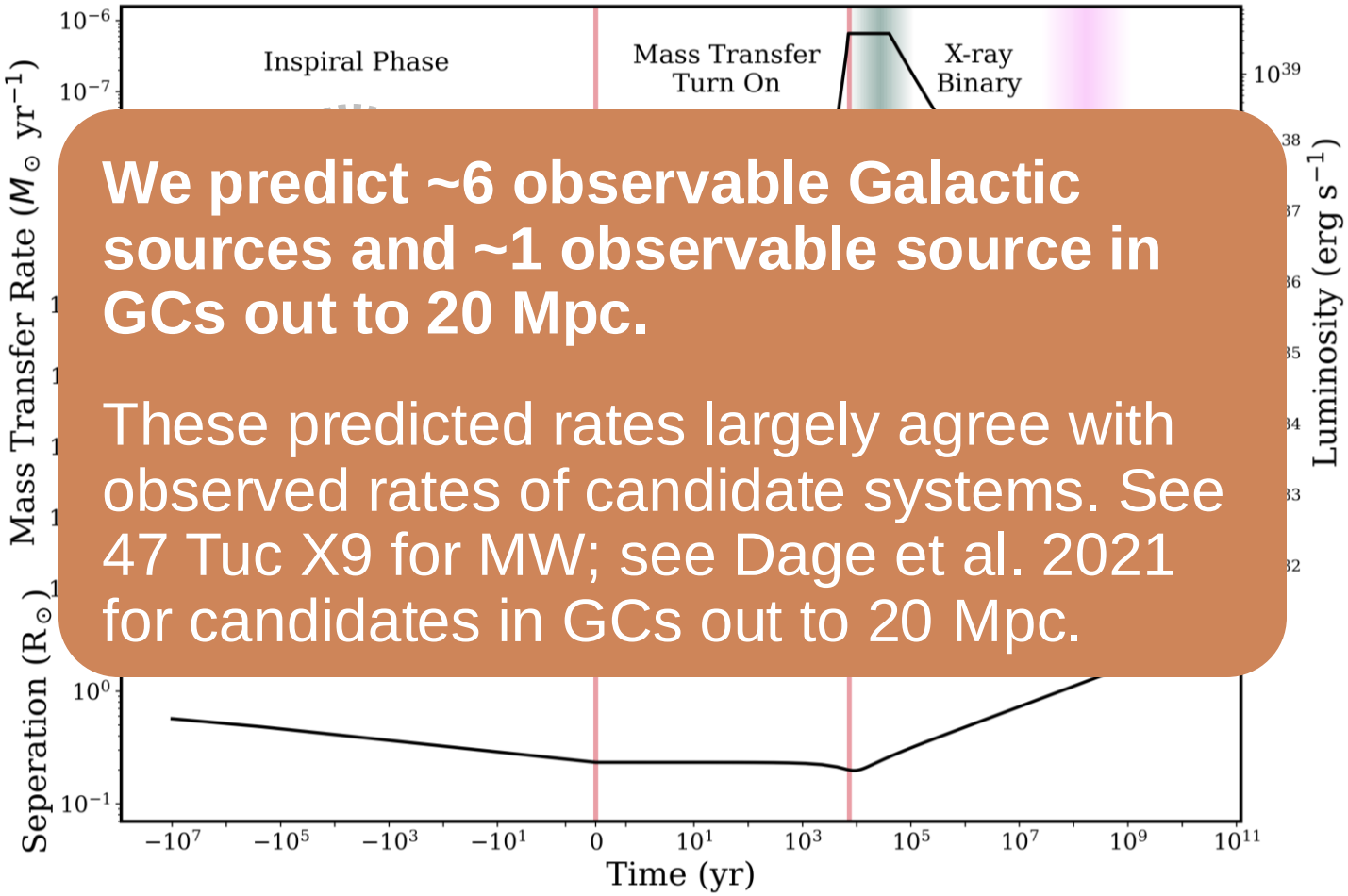


We predict ~6 observable Galactic sources and ~1 observable source in GCs out to 20 Mpc.

These predicted rates largely agree with observed rates of candidate systems. See 47 Tuc X9 for MW; see Dage et al. 2021 for candidates in GCs out to 20 Mpc.

We calculate:

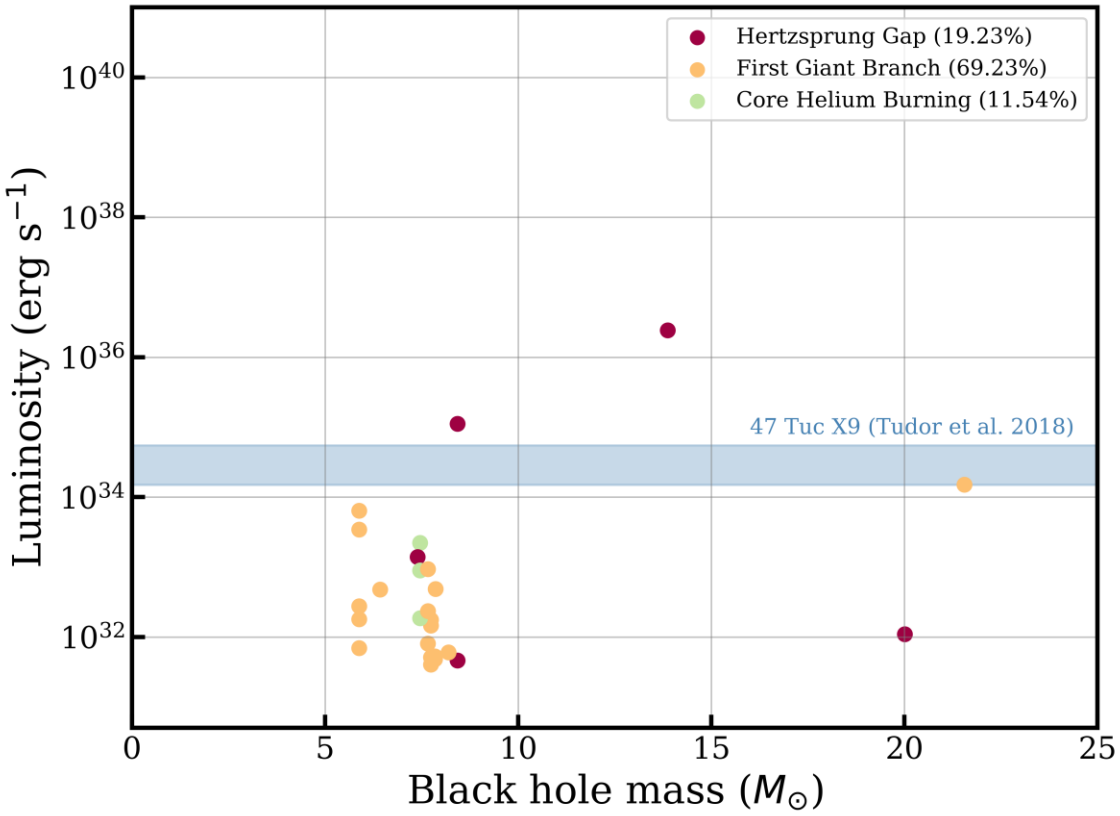
$$N = \Gamma\tau$$

- Γ is the rate (from N-body),
- τ is the expected observable lifetime (from COSMIC).

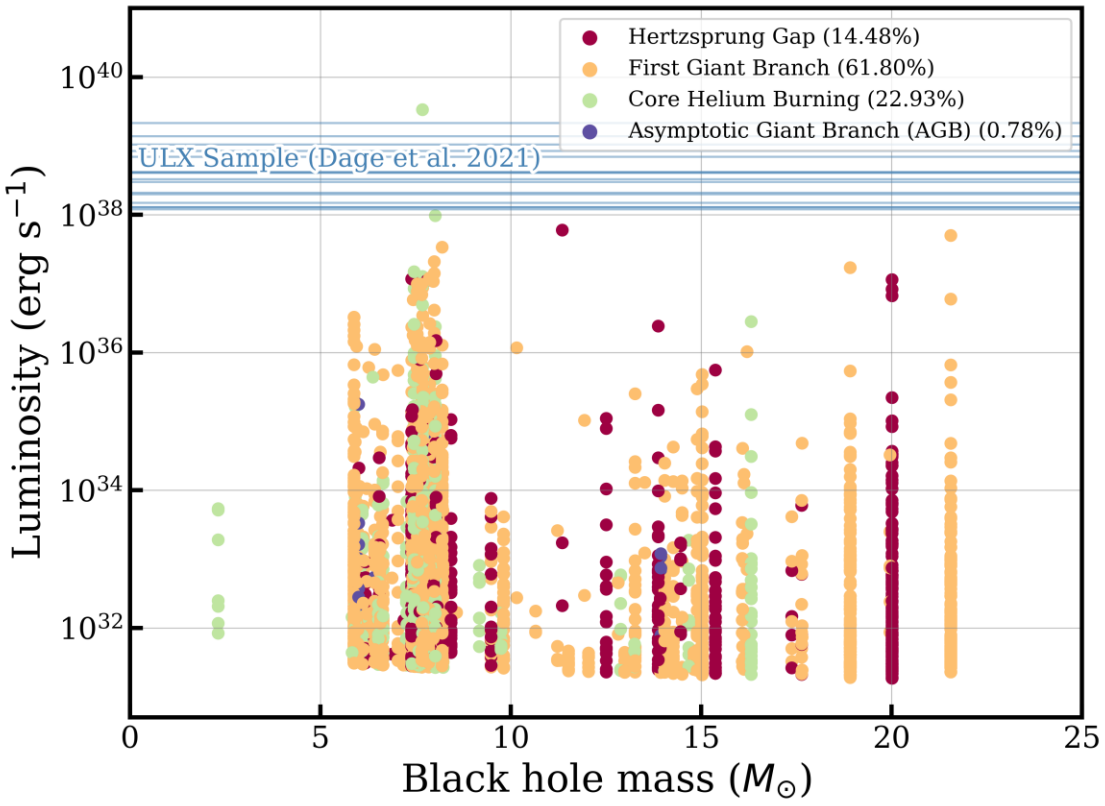
Predicted Sample Population

A more robust prediction: an artificial example population of systems from sampling simulations.

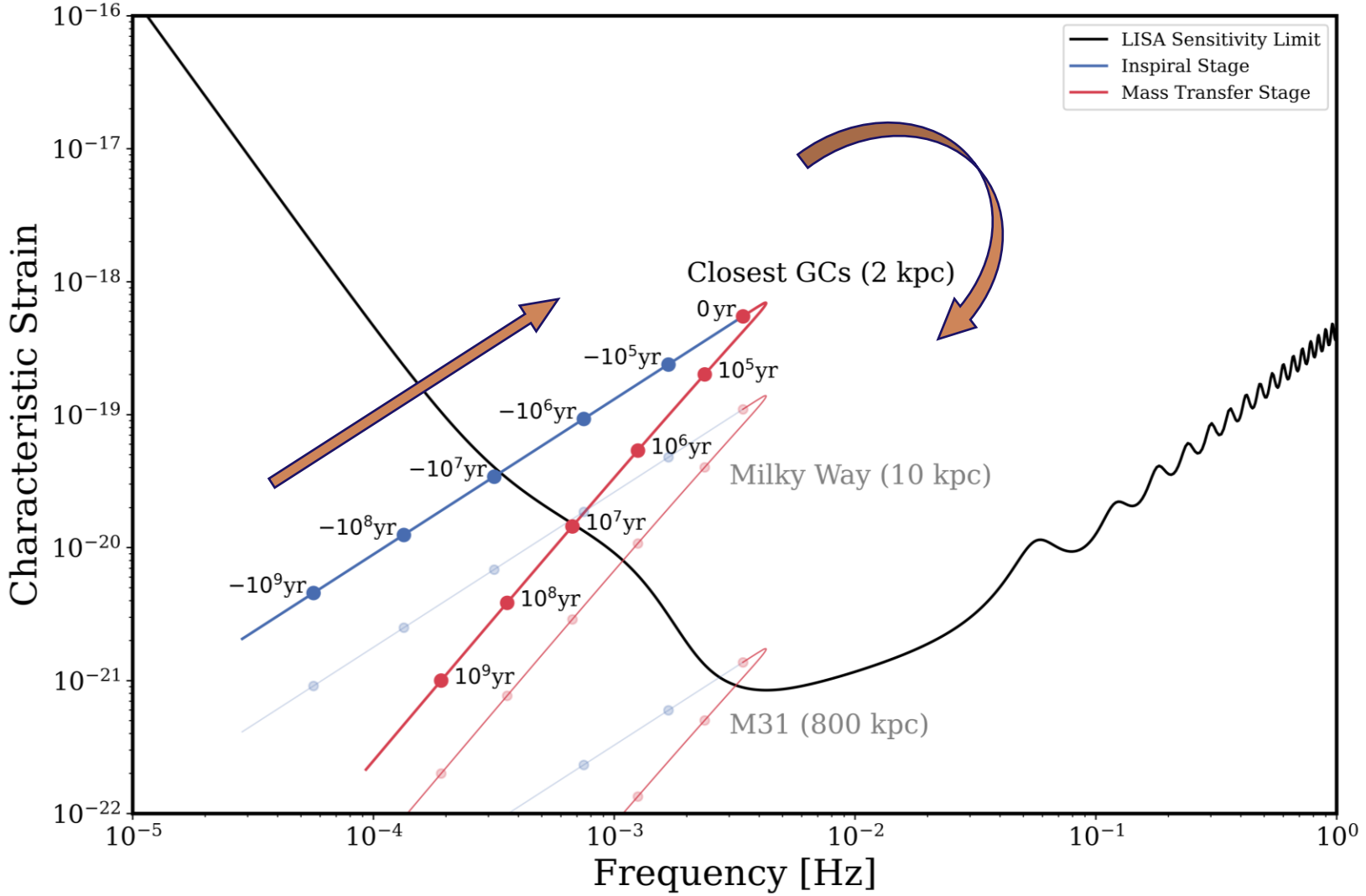
Milky Way



Virgo Cluster



Gravitational Wave Strain

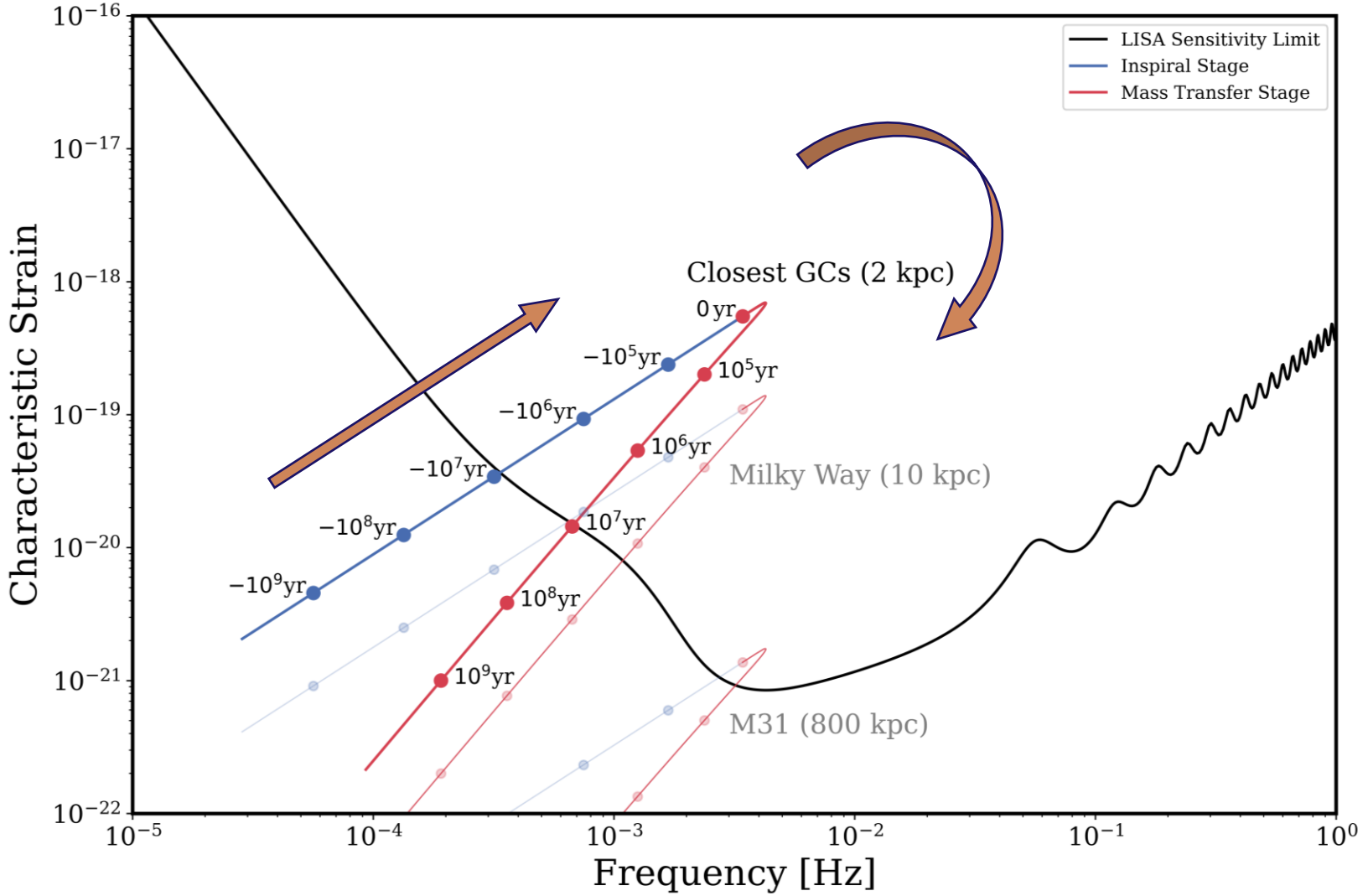


The characteristic strain is given by:

$$h \propto f_{\mathrm{GW}}^{\frac{2}{3}} \mathcal{M}^{\frac{5}{3}} d_L^{-1}$$

(Tauris 2018)

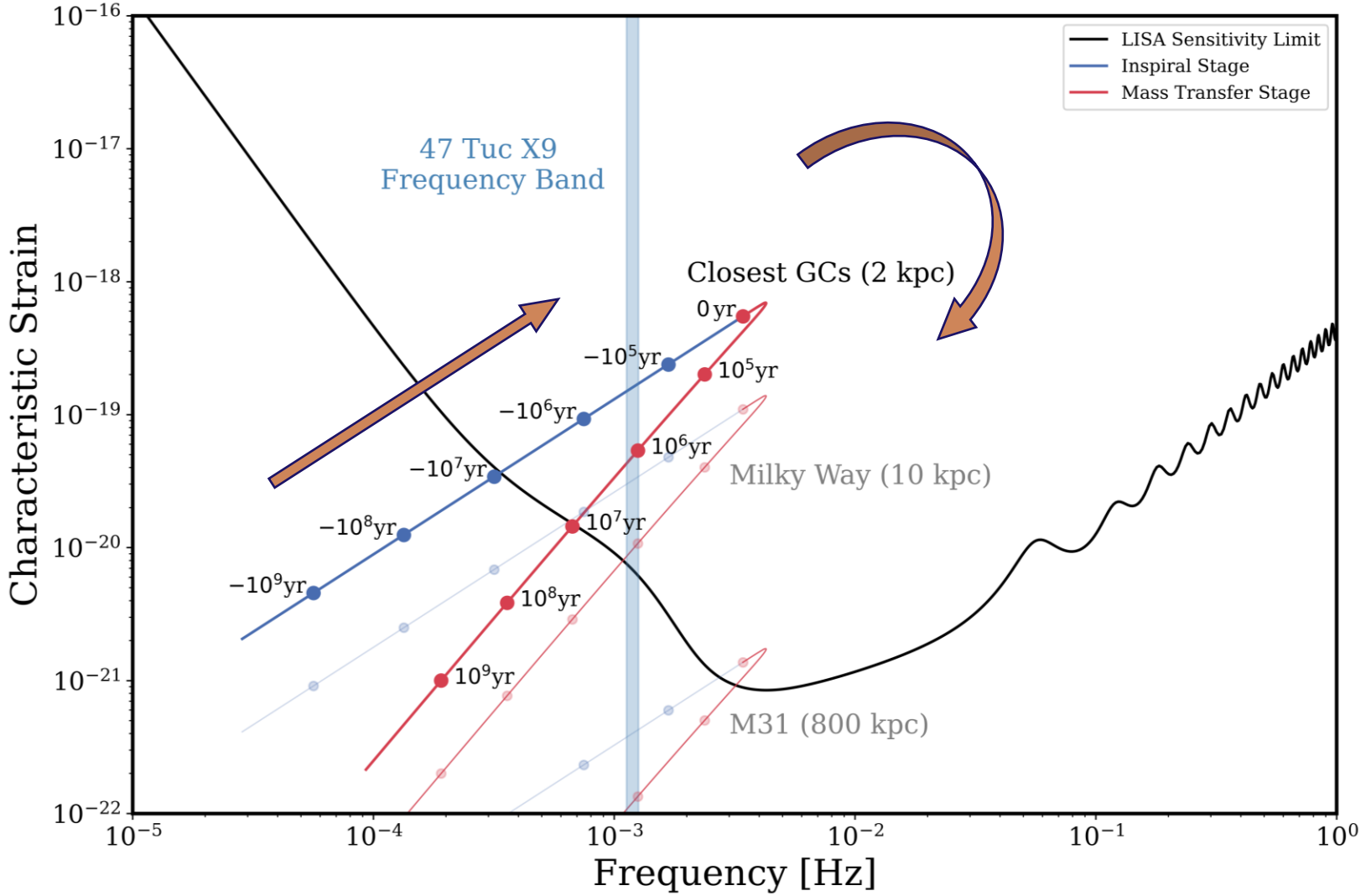
Gravitational Wave Strain



Unique GW sources from **inspiral** *and* **outspiral**.

Extremely high LISA SNRs when mass transfer initiates.

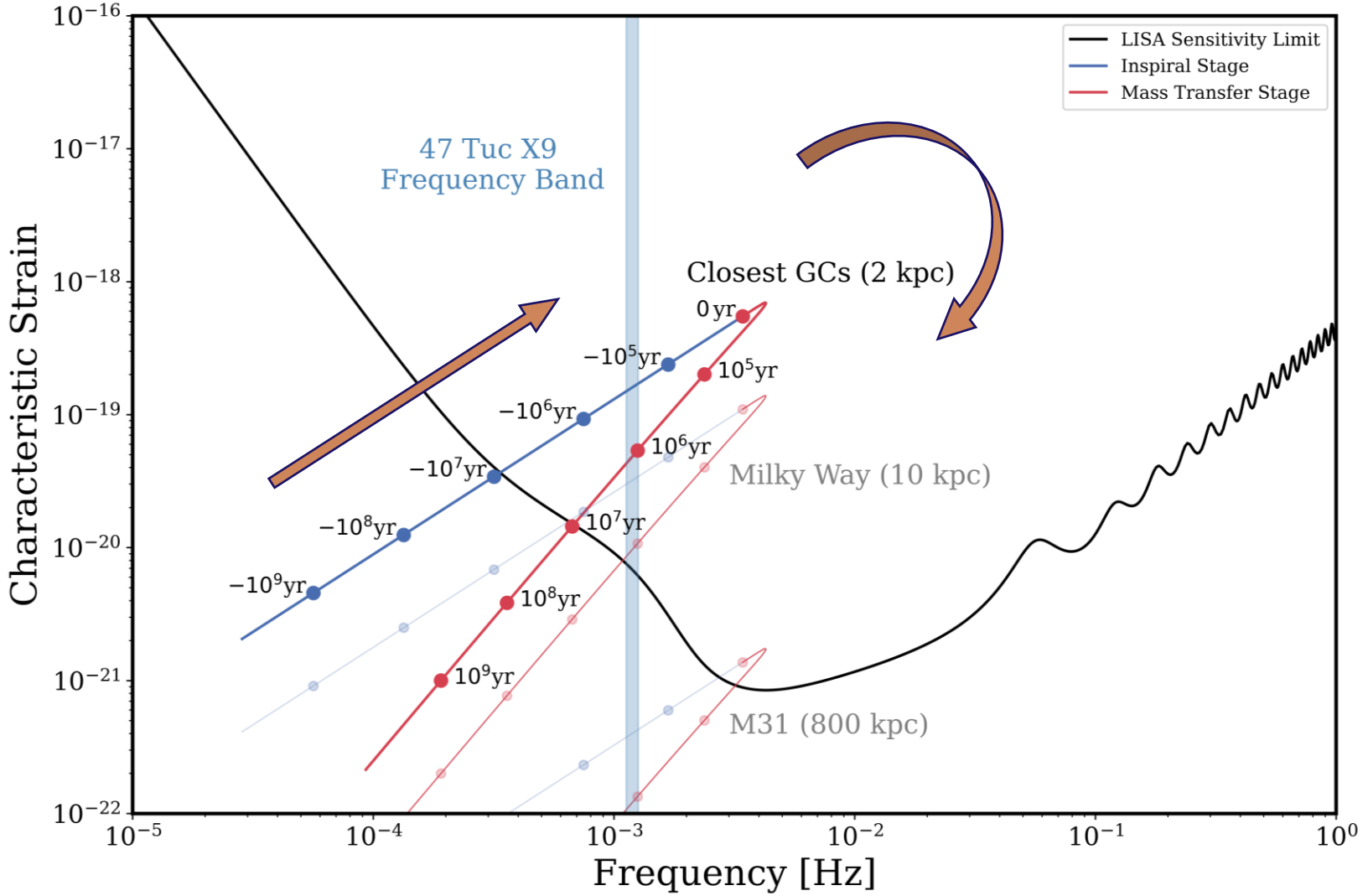
Gravitational Wave Strain



47 Tuc X9's orbital frequency is well known from EM signal modulations.

This formation channel suggests a promising SNR for LISA observation.

Gravitational Wave Strain



EM measurements **only** provide a mass ratio.

LISA will be **crucial** in **characterising individual masses**.

Conclusions

- **Black hole–Giant collisions are a key formation channel for black hole–white dwarf X-ray binaries.**
- **~6 Galactic sources and ~1 source in GCs out to 20 Mpc observable with X-rays.**
- **Galactic sources will be resolvable by LISA with gravitational waves.**
- **LISA will play a vital multimessenger role in identifying the masses of these unique binaries.**

Acknowledgements

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Electromagnetic Comparisons

Weighting follows procedure by Kremer et al. (2023).