How the dynamical properties of globular clusters impact their gamma-ray and X-ray emission

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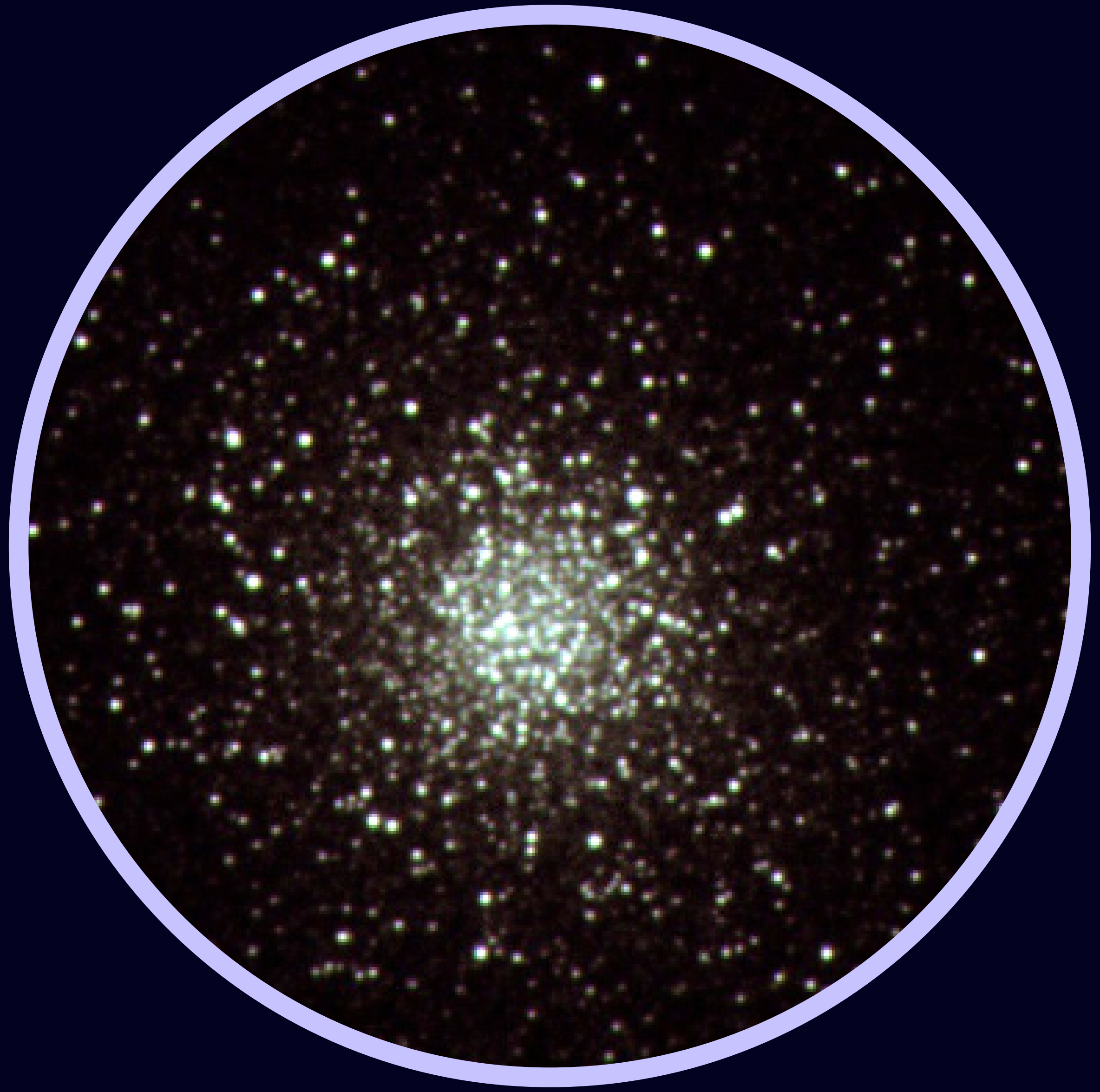
Globular clusters are evolved collections of stars

- Stars bounded by gravity.
- A high density of stars.
- >10 billion years old.
- Dynamical interactions are common.
- 47 Tuc was the first GC detected by LAT.
- 36 GCs listed in 4FGL-DR4.

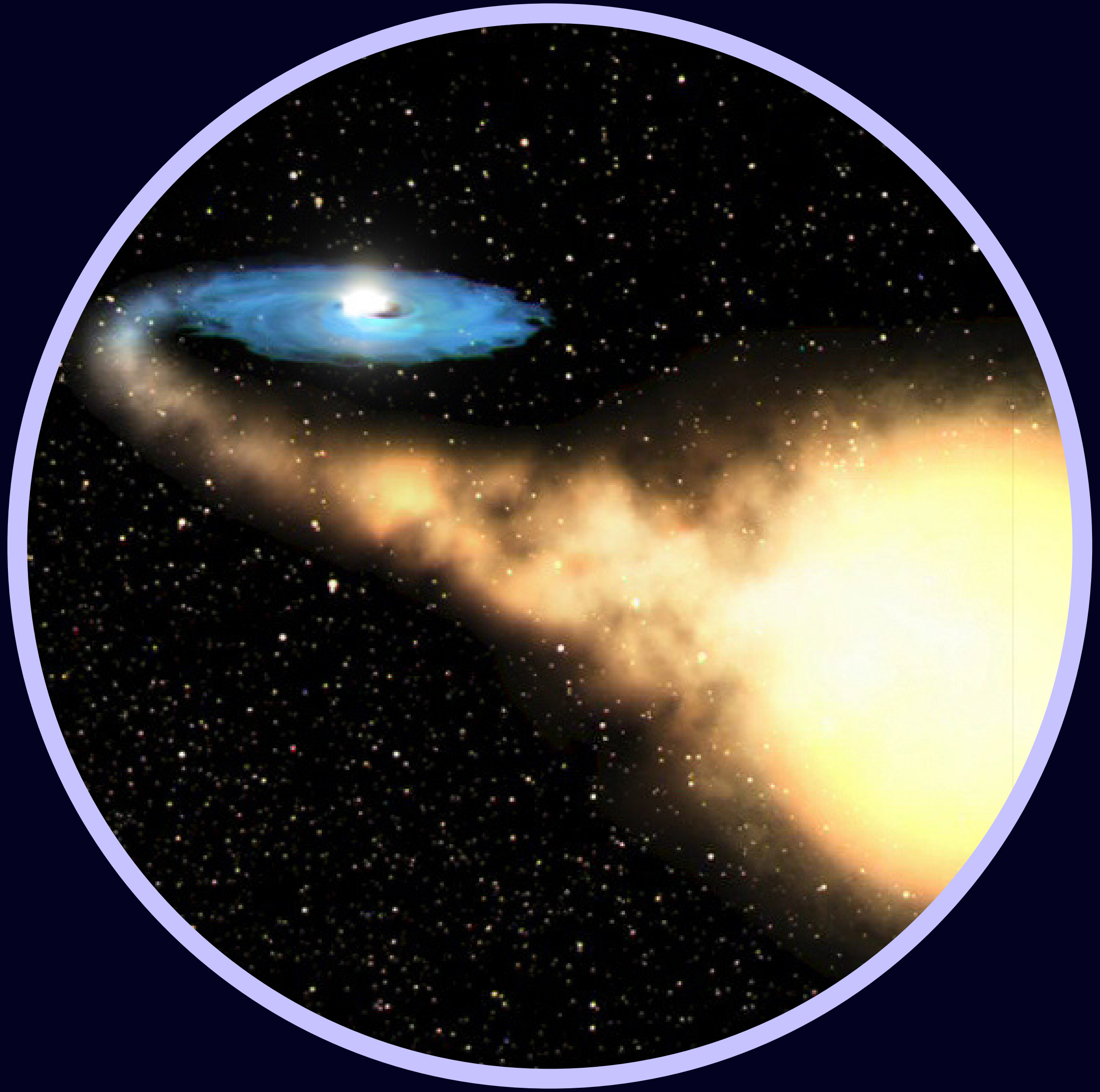


M5

IMAGE: RANIERE

Globular clusters host several compact binaries

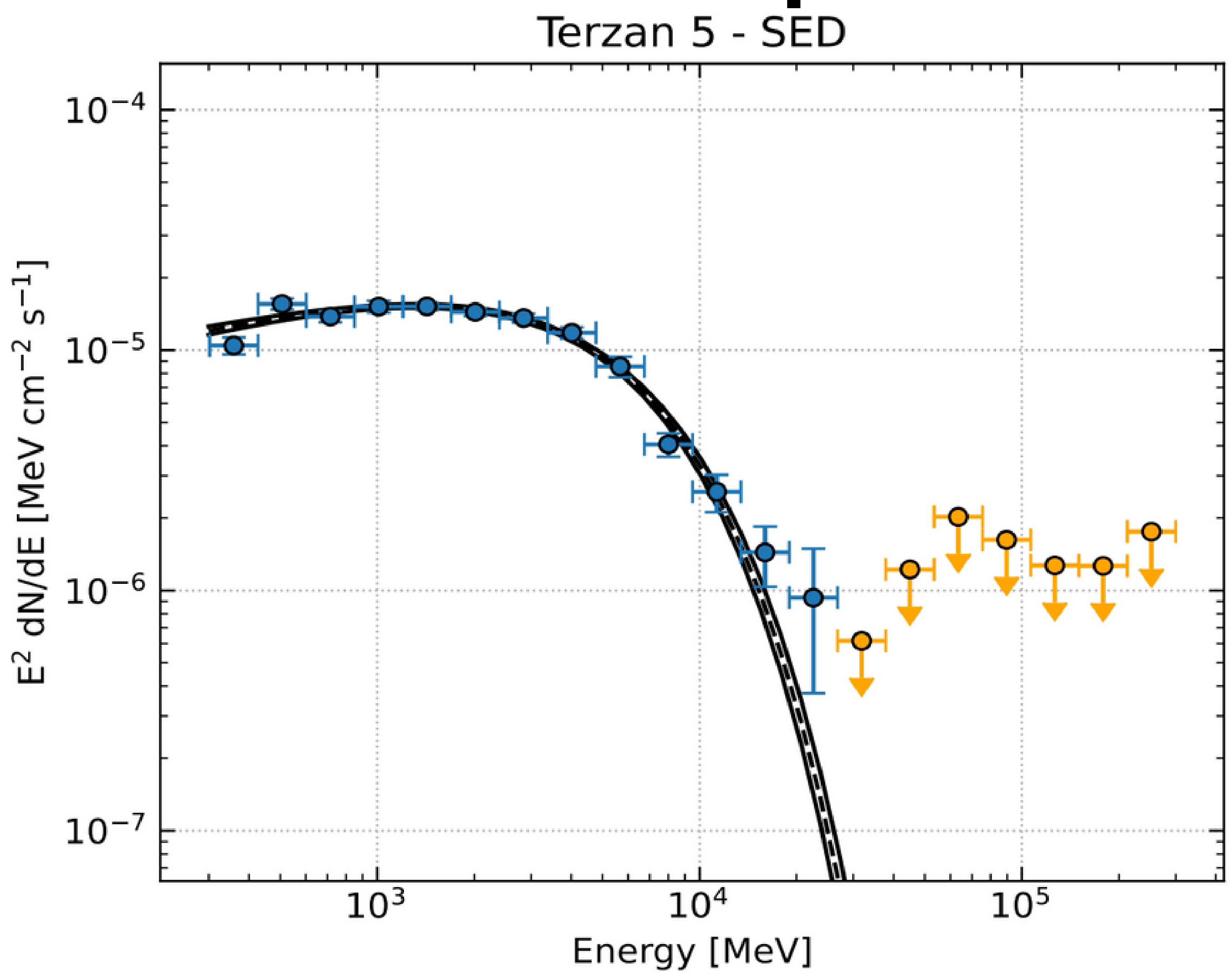
- Stellar flybys eventually produce close compact binaries in a mass-transferring regime.
- The LMXB can evolve into MSPs.
- The population of MSPs emits gamma rays.



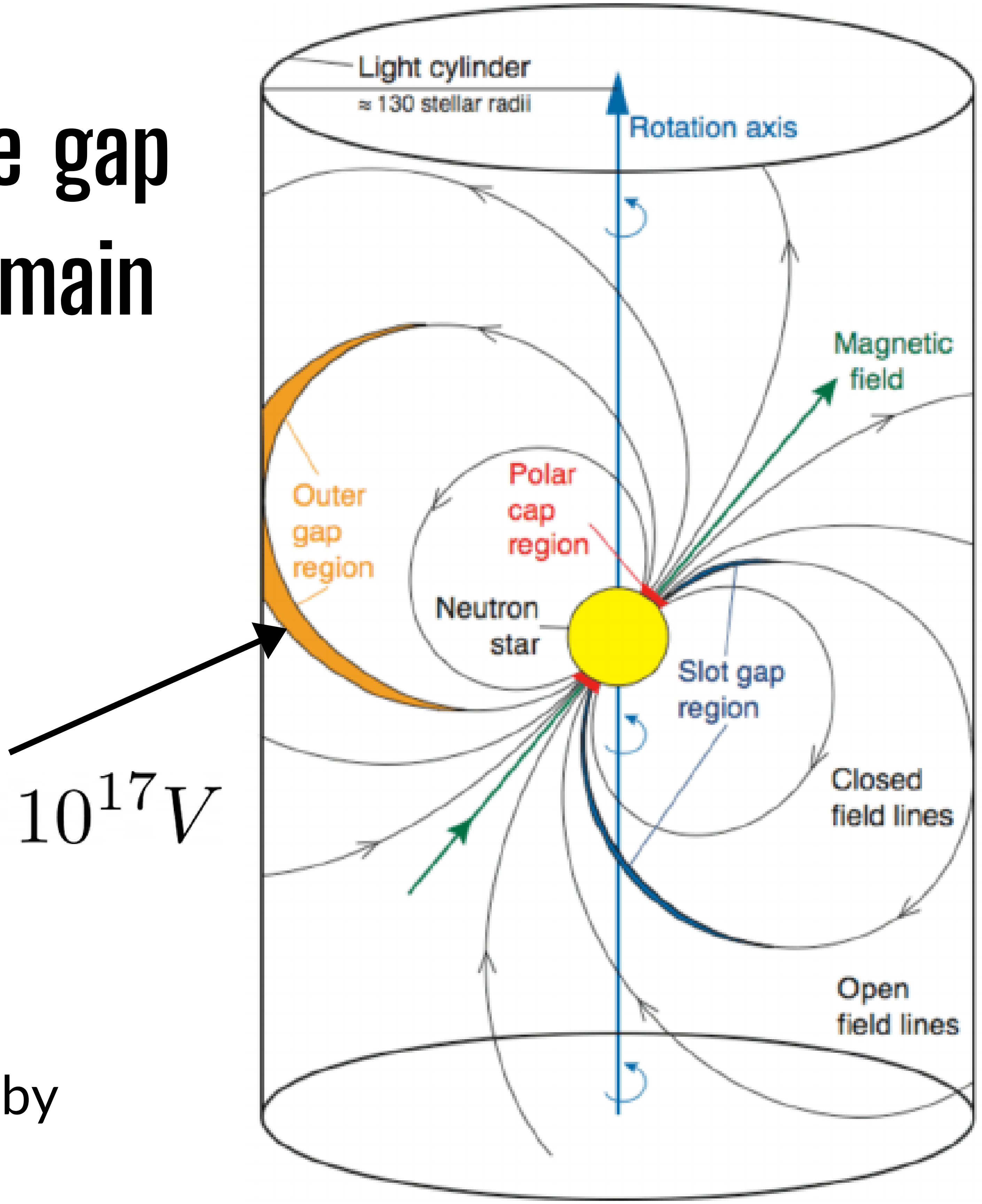
Artistic depiction of a mass-transferring binary

IMAGE: ESA, NASA, FELIX MIRABEL

The electric potential drop along the gap accelerates e-e+ up to relativistic domain



$$\Delta V \sim 10^{17} V$$



- Gamma-ray spectra of GCs are well described by the summed emission of MSPs.

LEFT FIGURE: RANIERE
RIGHT FIGURE: ALIU ET AL., (2008).

Stellar encounters dictate the formation of MSPs

- Once a binary system is formed, it may undergo subsequent encounters

Encounter rate:

$$\Gamma \propto \int (n^2/\sigma) 4\pi r^2 dr$$

Density of stars

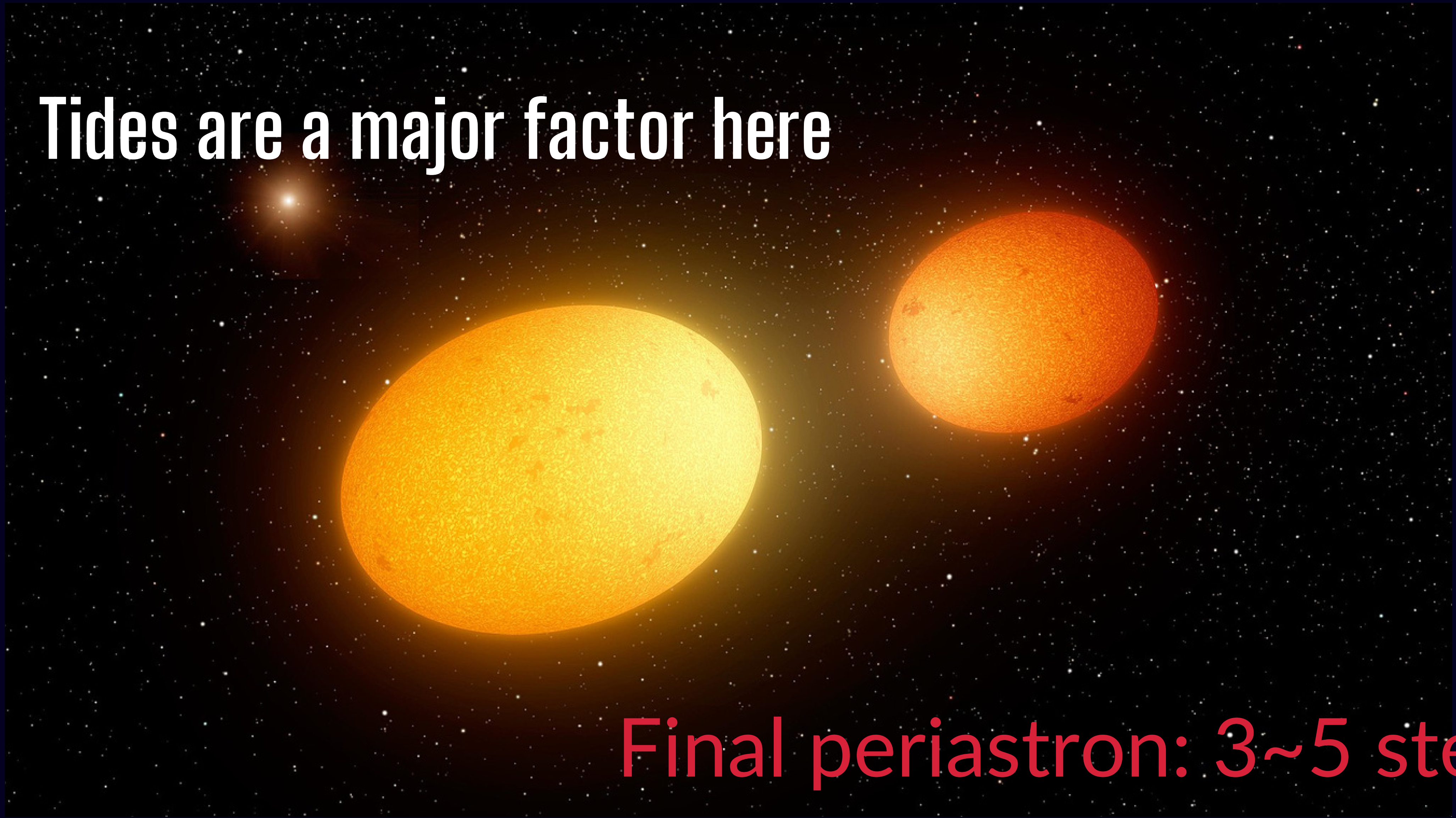
Velocity dispersion profile

Secondary encounter rate:

$$\Lambda \propto \frac{n}{\sigma} a$$

Binary orbital separation:
this should be a problem!

The two free stars must lose energy in order to become a binary, i.e. the binding energy has to be negative



Tides are a major factor here

Final periastron: 3~5 stellar radii

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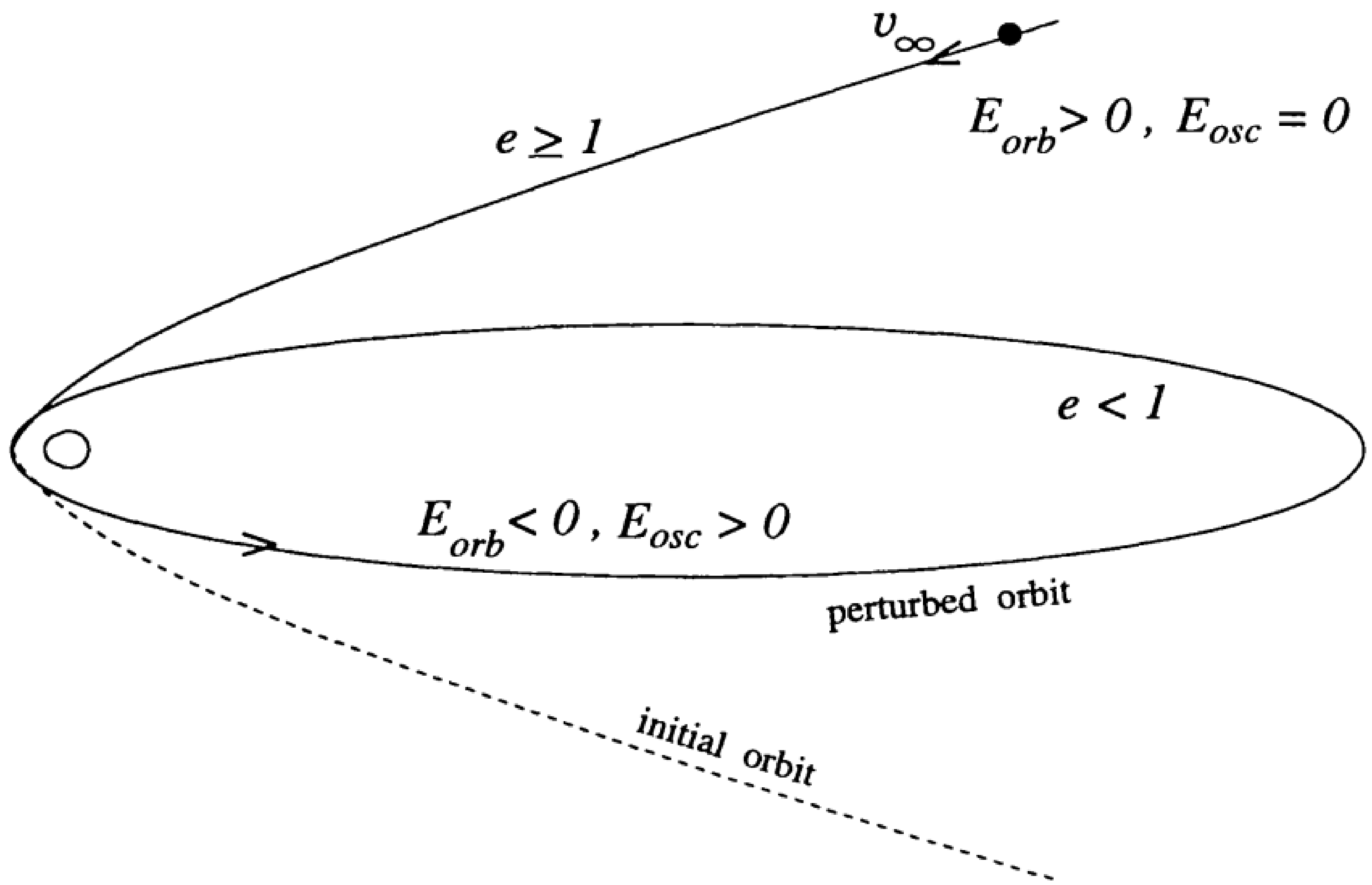
The resulting orbit is very eccentric but will circularize over time



We assume a conservative final orbital separation of 10 stellar radii.

A typical star in a GC, with half the mass of the Sun, has roughly half of the solar radius.

FIGURE: ROSEMARY MARDLING, 1996.

What are we looking for?

- We want to understand how stellar encounters affect the gamma-ray and X-ray luminosities of globular clusters. We therefore:

1. Test if stellar encounters really contribute to the formation of compact binaries in GCs.
2. Test what is the importance of secondary encounters on the evolution of these binaries in the framework of the Heggie-Hills law.

Question 1)

Are the stellar encounters really contributing to the formation of compact binary systems in GCs?

Short answer:
Yes

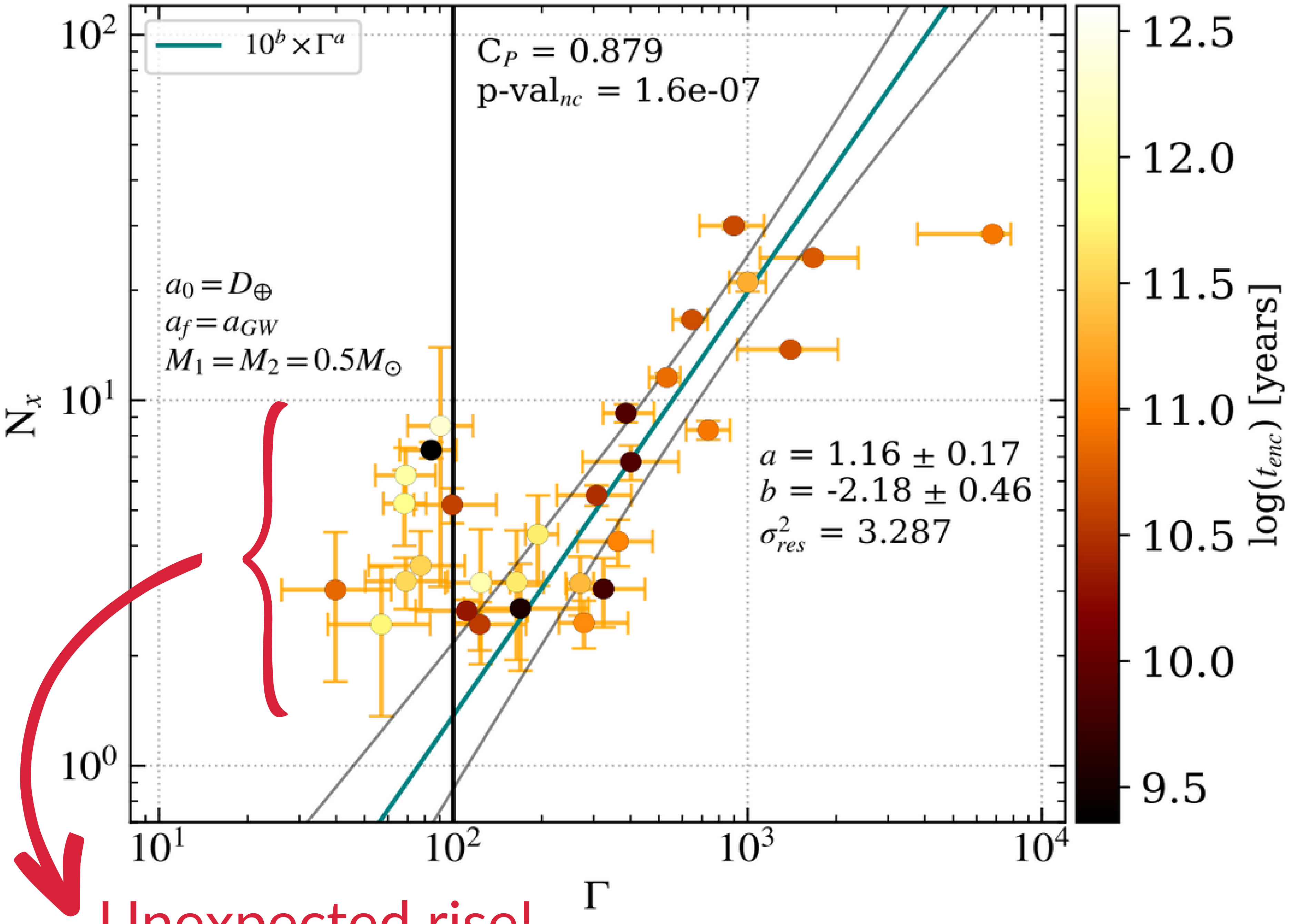
The number of X-ray sources correlates with encounter rate

The number of X-ray sources is linearly proportional to the stellar encounter rate

$$\Gamma \propto \int (n^2/\sigma) 4\pi r^2 dr$$

Shrinking time:

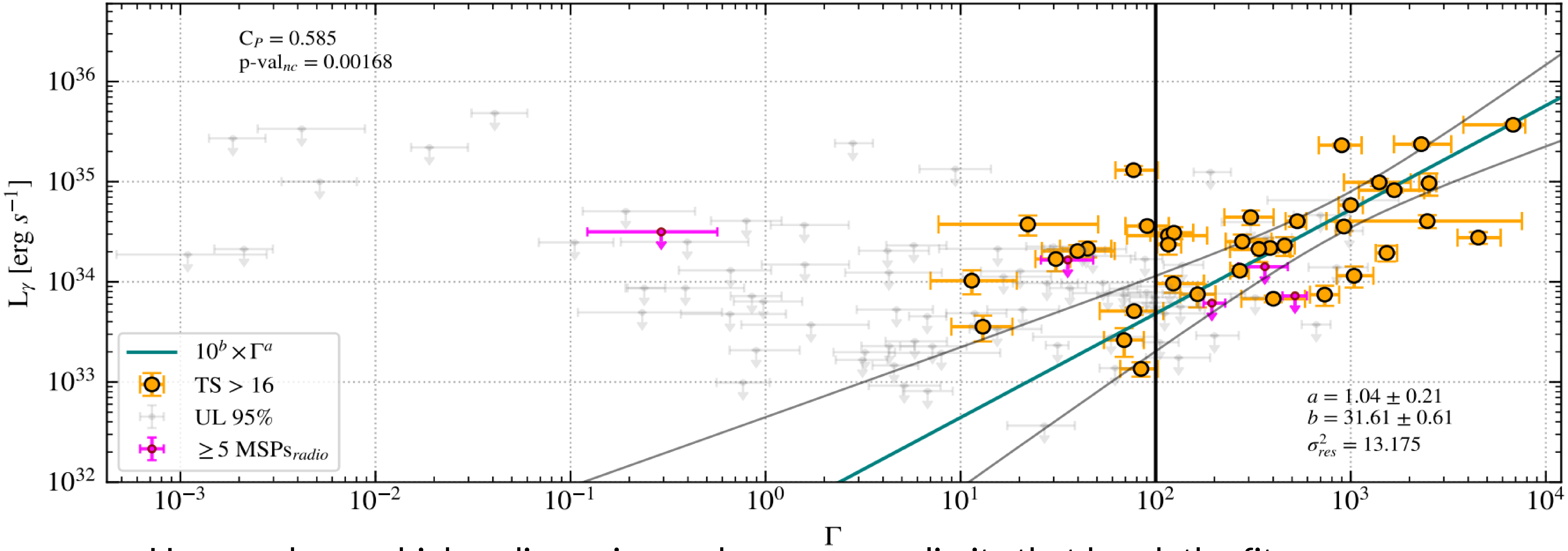
$$t_{enc} = \frac{\sigma}{2\pi G m_\star n \xi} \frac{1}{a} \Big|_{a_0}^{a_f}$$



Unexpected rise!

FIGURE: DE MENEZES ET AL. (2023).

The gamma-ray luminosity correlates with encounter rate



- Here we have a higher dispersion and some upper limits that break the fit.
- Probably because the gamma-ray emission is beamed.
- This correlation must be tighter at VHE.

FIGURE: DE MENEZES ET AL. (2023).

Question 2)

How do secondary encounters affect the evolution of compact binary systems?

Short answer:
They make the binaries harder.

The Heggie-Hills law

Hard binaries tend to get harder and soft binaries tend to get softer in face of three-body encounters

The hardness depends on the binding energy and dispersion velocity of nearby stars:

Hard	Soft
$|\epsilon| > m_\star \sigma^2$	$|\epsilon| < m_\star \sigma^2$

The Heggie-Hills law

$$|\epsilon| > m_\star \sigma^2$$

$$\frac{G m_c m_\star}{a} > m_\star \sigma^2 \longrightarrow a < \frac{G m_c}{\sigma^2}$$

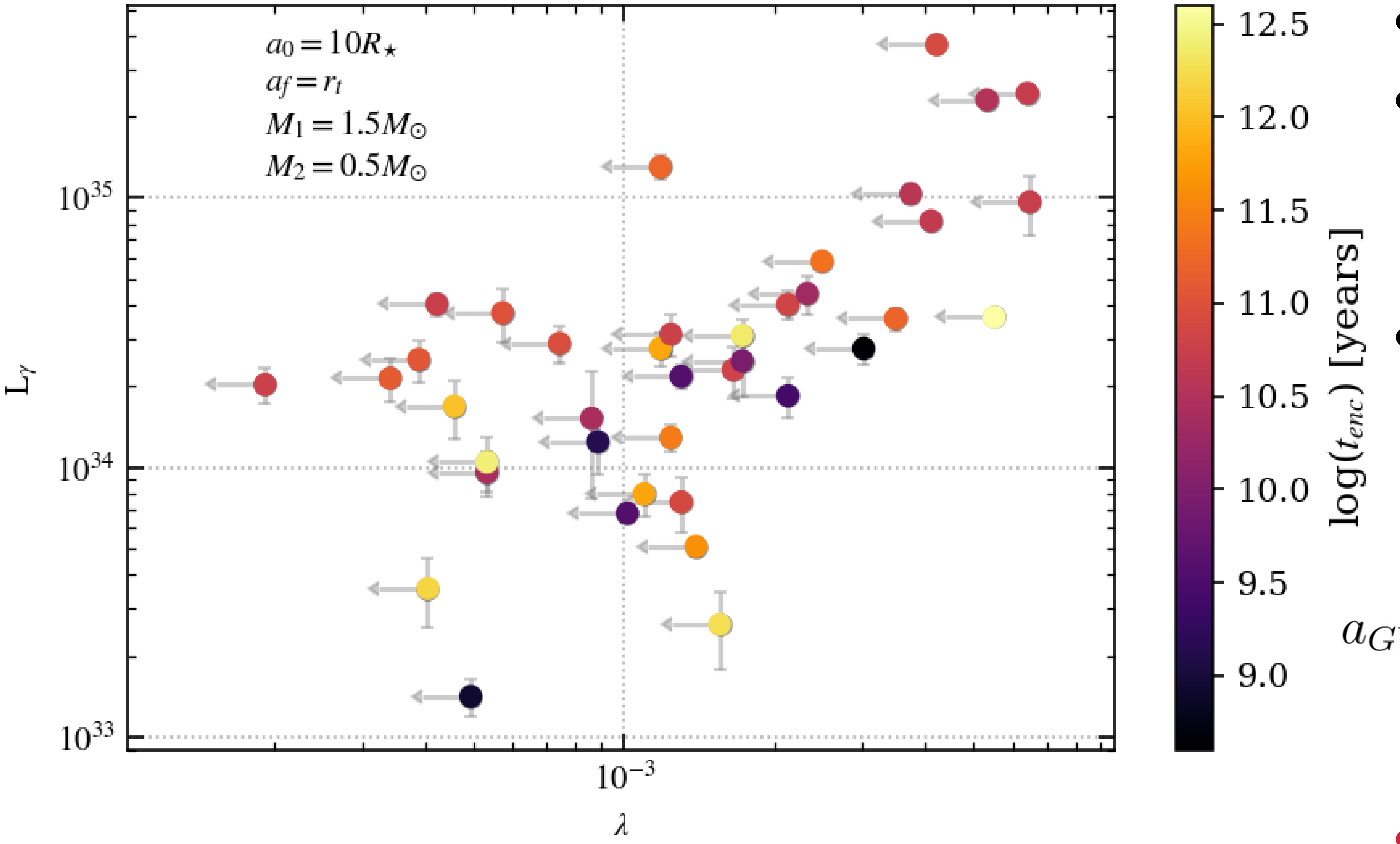
The binary will shrink if

We can rewrite it in terms of the encounter rate per formed binary:

$$\lambda = \frac{\Lambda}{\Lambda_{lim}} = \frac{Kna}{\sigma} \frac{\sigma^3}{KnGm_c} = \frac{a\sigma^2}{Gm_c}$$

If $\lambda > 1$ the binary will be ionized.

Secondary encounters make the binaries harder…



- Tidal binaries must be compact.
- We assume a = 10 stellar radii.

- For half of the clusters, the binaries are more affected by GW:

$$a_{GW} = \left[\frac{256}{5} \frac{G^2 \, m_1 \, m_2 \, (m_1 + m_2) \, \sigma}{2 \, \pi \xi \, (1 - e^2)^{7/2} \; c^5 \, \rho} \right]^{1/5}$$

- Binary ionization is unrealistic!

FIGURE: DE MENEZES ET AL. (2023).

… But not that much

The timescale for orbital decay down to the tidal radius can be larger than a Hubble time

$$t_{enc} = \frac{\sigma}{2\pi G m_\star n \xi} \frac{1}{a}\Bigg|_{a_0}^{a_f}$$

The loss of energy via GW is faster for half the sample at R = 10 stellar radii.

$$t_{GW} = \frac{5}{256} \frac{c^5 a^4 (1-e^2)^{7/2}}{G^3 m_1 m_2 (m_1 + m_2)}$$

Both timescales are quite long.
Analogous to the final parsec problem.

Summary

- Stellar close encounters dictate the formation of X-ray and gamma-ray sources for clusters with $\Gamma > 100$.
- We see an unexpected rise in the number of X-ray sources in GCs with low Γ.
- Secondary encounters help in shrinking the binaries, although not that much.
- Binary ionization is unrealistic for GCs ⟶ Requires a dispersion velocity much higher than the central escape velocity.

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Thanks!