INSPIRALING SYSTEMS IN DENSE STELLAR ENVIRONMENTS: FORMATION, DYNAMICS, AND DETECTION CHALLENGES

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GWsky | March 23, 2026

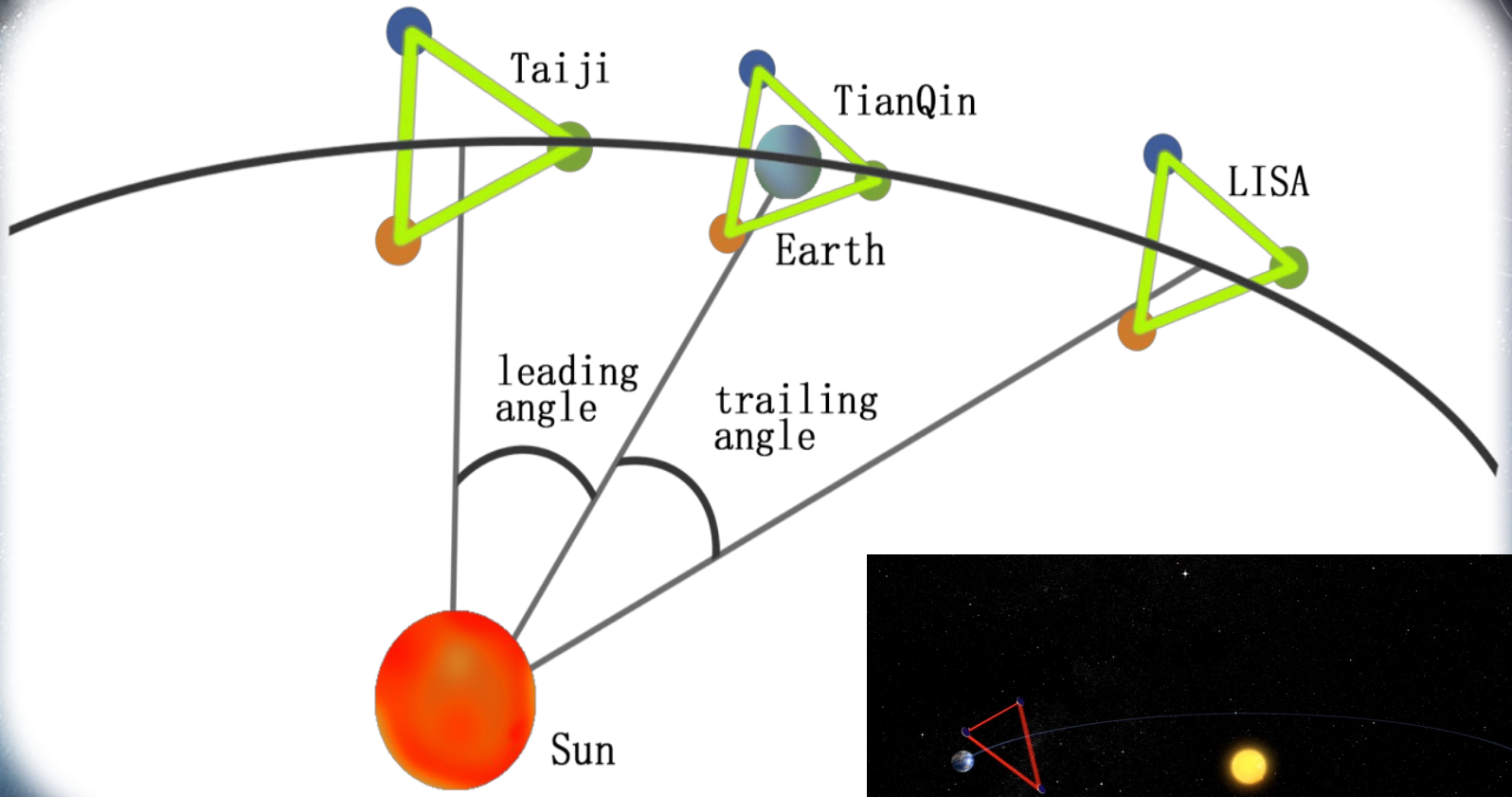
The Milky Way from the Himalayas.
Photo by @prashant3052

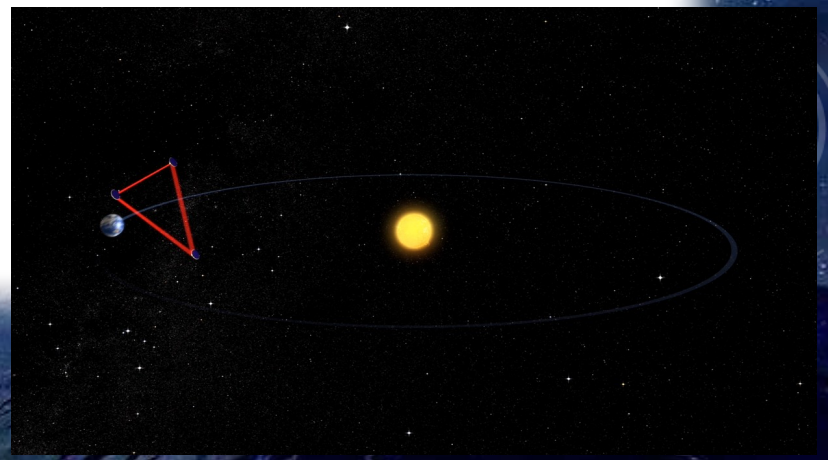
~10 years from now we will have 2 space-based GW detectors

- LISA (Laser Interferometer Space Antenna)
- TIANQIN

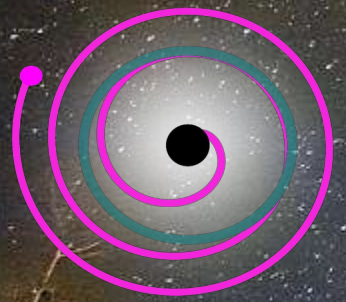
  or

  TAIJI





What is an inspiraling system?



A binary system that evolves **only** due to the emission of gravitational waves

EMRIs = SMBH + CO

e.g. Rubbo+2006; Amaro-Seoane+2007; Berry+2019

$10^6 M_{Sun}$ or more

BH, NS, WD
(a few Solar Masses)

$q \sim 10^5 - 10^6$

XMRIS = SMBH + BD

Amaro-Seoane,2019

$q \sim 10^8$

$\sim 10^{-2} M_{Sun}$

IMRIs

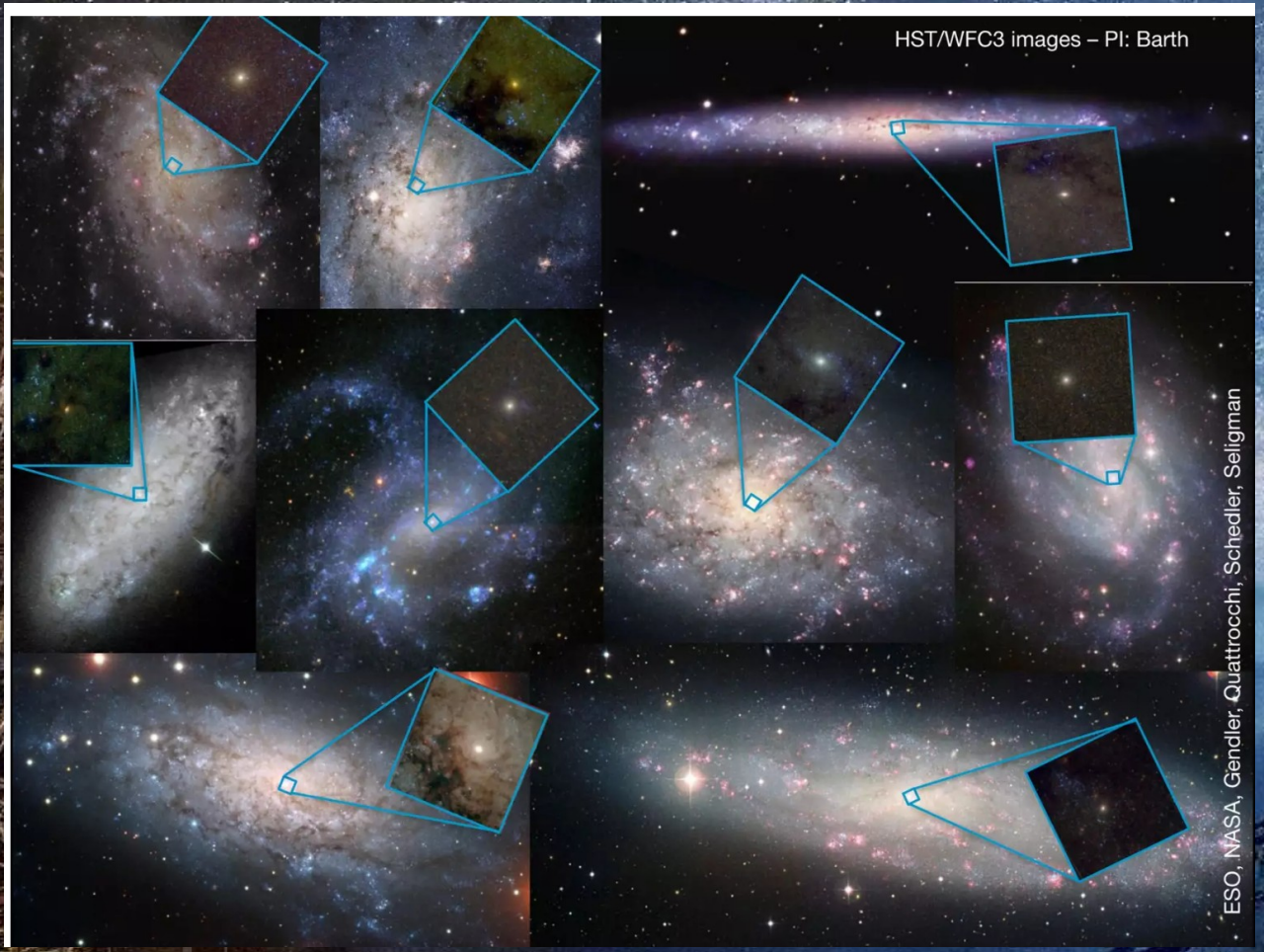
- **IMBH + SMBH**
- **IMBH + IMBH**
- **IMBH + BH**

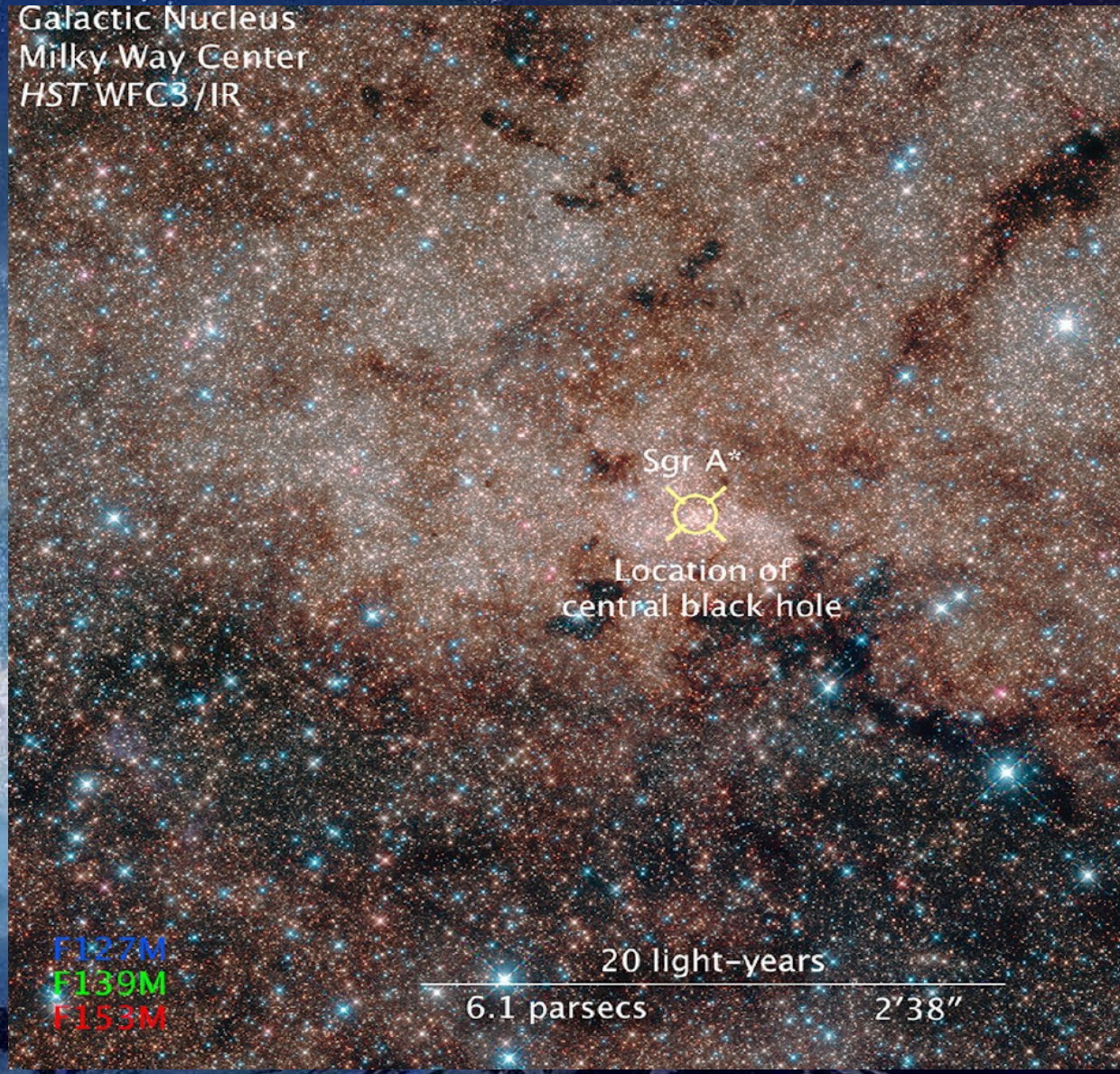
$$q = M_\bullet / m_{BH} \in (10, 10^4)$$

e.g. Coleman+2002,Gair+2011; Konstantinidis+ 2013; Haster+2016; Amaro-Seoane+2018

Where are they formed?

They form in dense stellar system like nuclear clusters where densities can exceed $10^6 M_\odot/pc^3$.





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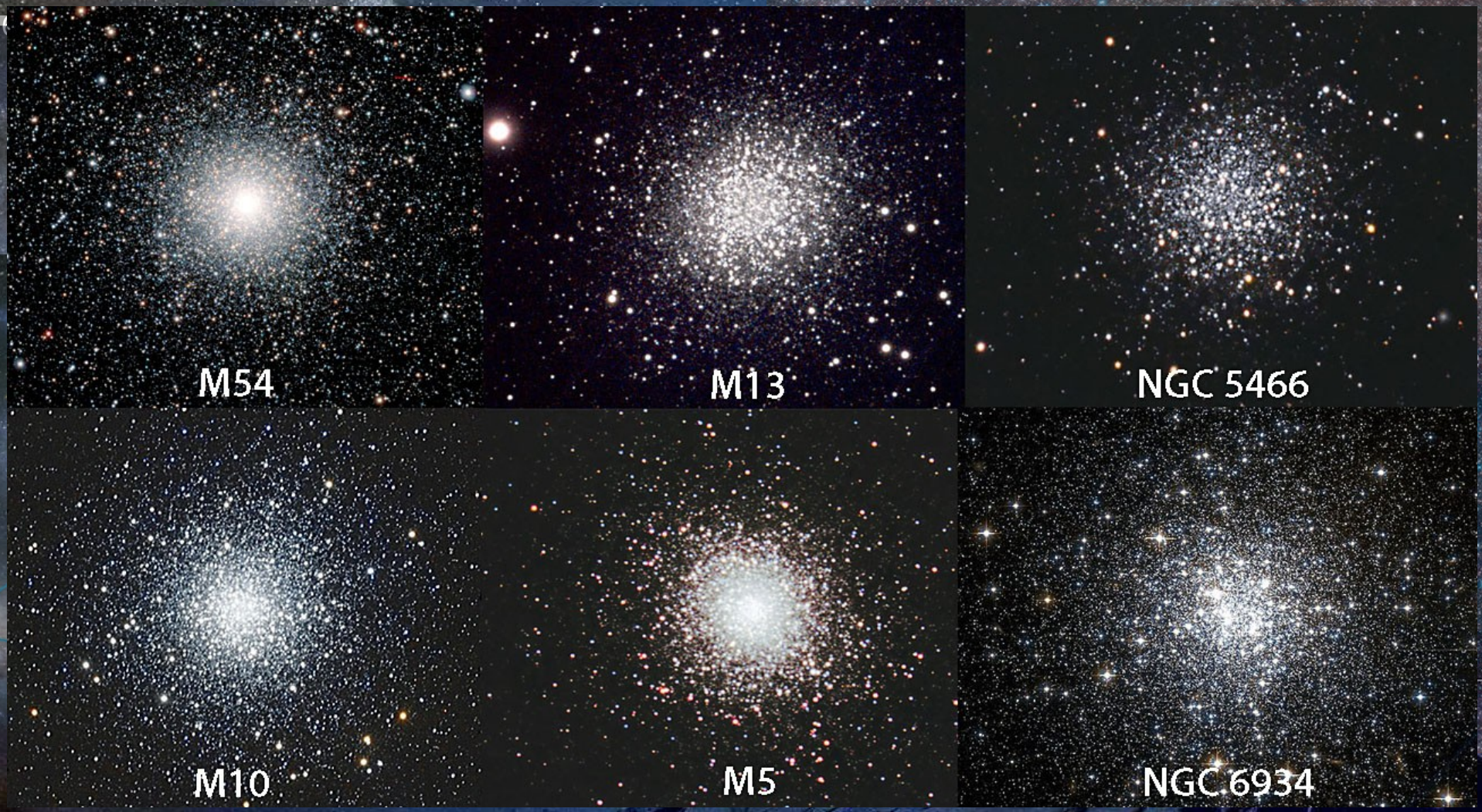
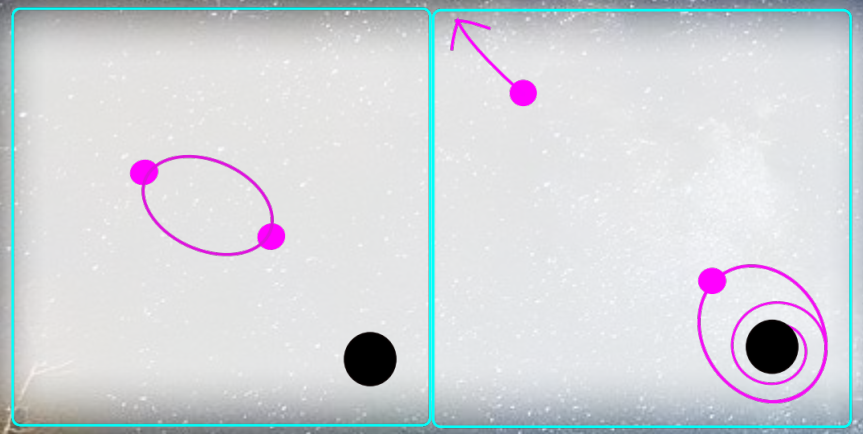


How are they formed?

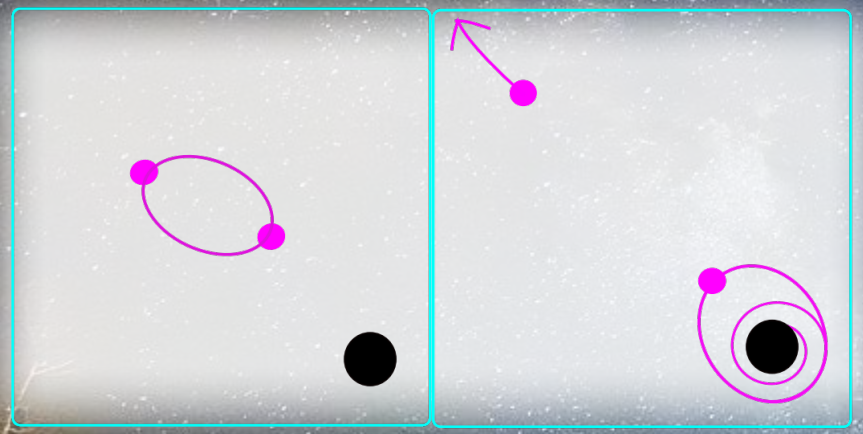
Different environments
=
Diverse formation mechanisms



Disruption of binaries deposits
stars/ BHs on tightly bound orbits
[Hills 1998]

then GWs take over [Miller+05]
Eccentricity:
Could be nearly circular? [Miller+05]
Or maybe just mildly eccentric? [Raveh &Perets 21]

How are they formed?



Disruption of binaries

[Hills 1998]

Different environments

=

Diverse formation mechanisms

Highly eccentric

No preferred inclination

Captures by GW emission

[eg. Portegies Zwart & McMillan (2002, *ApJ*)]

Galaxy mergers

[e.g. Nate Bode & Wegg 2013; Naoz et al. 2022; Vázquez-Aceves et al, 2022].

Can boost formation rates

How are they formed?

Disruption of binaries [Hills 1998]

Captures by GW emission

[eg. Portegies Zwart & McMillan (2002, *ApJ*)]

Galaxy mergers

[e.g. Nate Bode & Wegg 2013; Naoz et al. 2022; Vázquez-Aceves et al, 2022].

Different environments

=

Diverse formation mechanisms

- EMRIs Aligned with disk
- Likely circular when entering detection band

Wet EMRI

Pan, Zhen et al.,2021

AGN-embedded BHs migrate inwards [Levin et al. 2007]

In situ formation [Stone et al. 2017]

After that:

Migration [McKernan et al. 2011]

Growth through mergers [Bellovary et al. 2016] and accretion [Gilbaum & Stone 2022]

- Environment can be very important

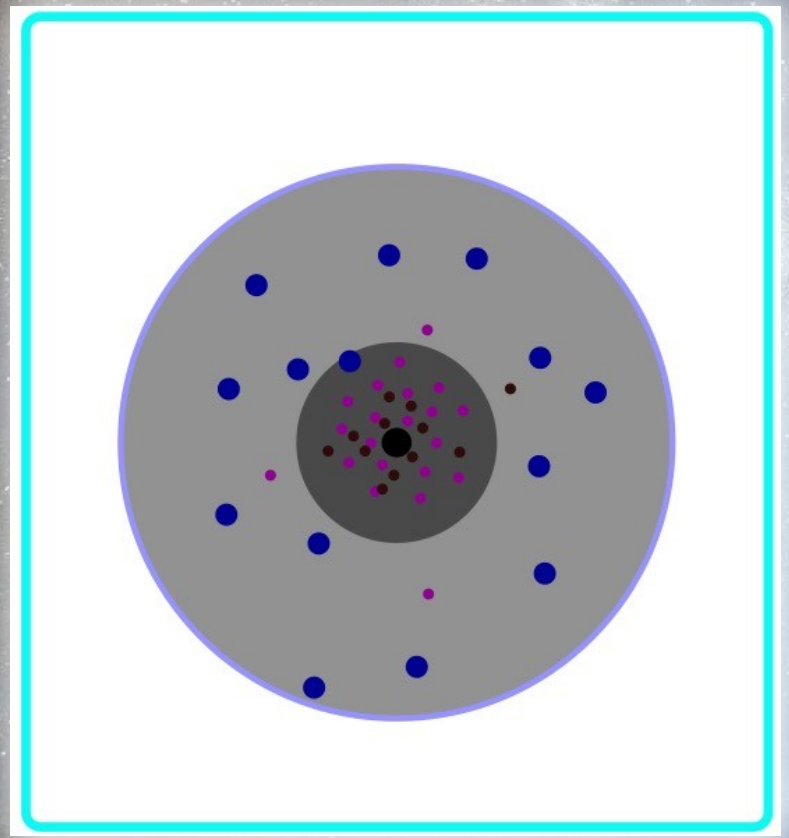
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimeter); NASA/CXC/CfA/R.Kraft et al. (X-ray)

How are they formed?

Different environments

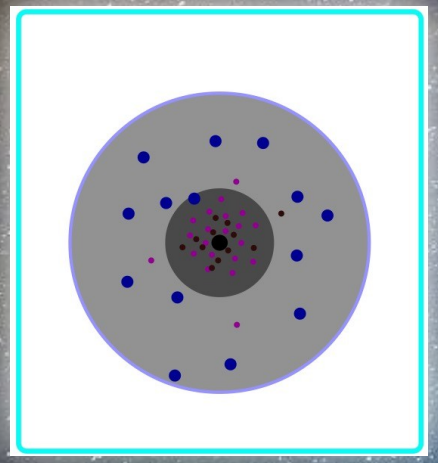
=

Diverse formation mechanisms



[Peebles (1972), Bahcall & Wolf (1976)]

How are they formed?

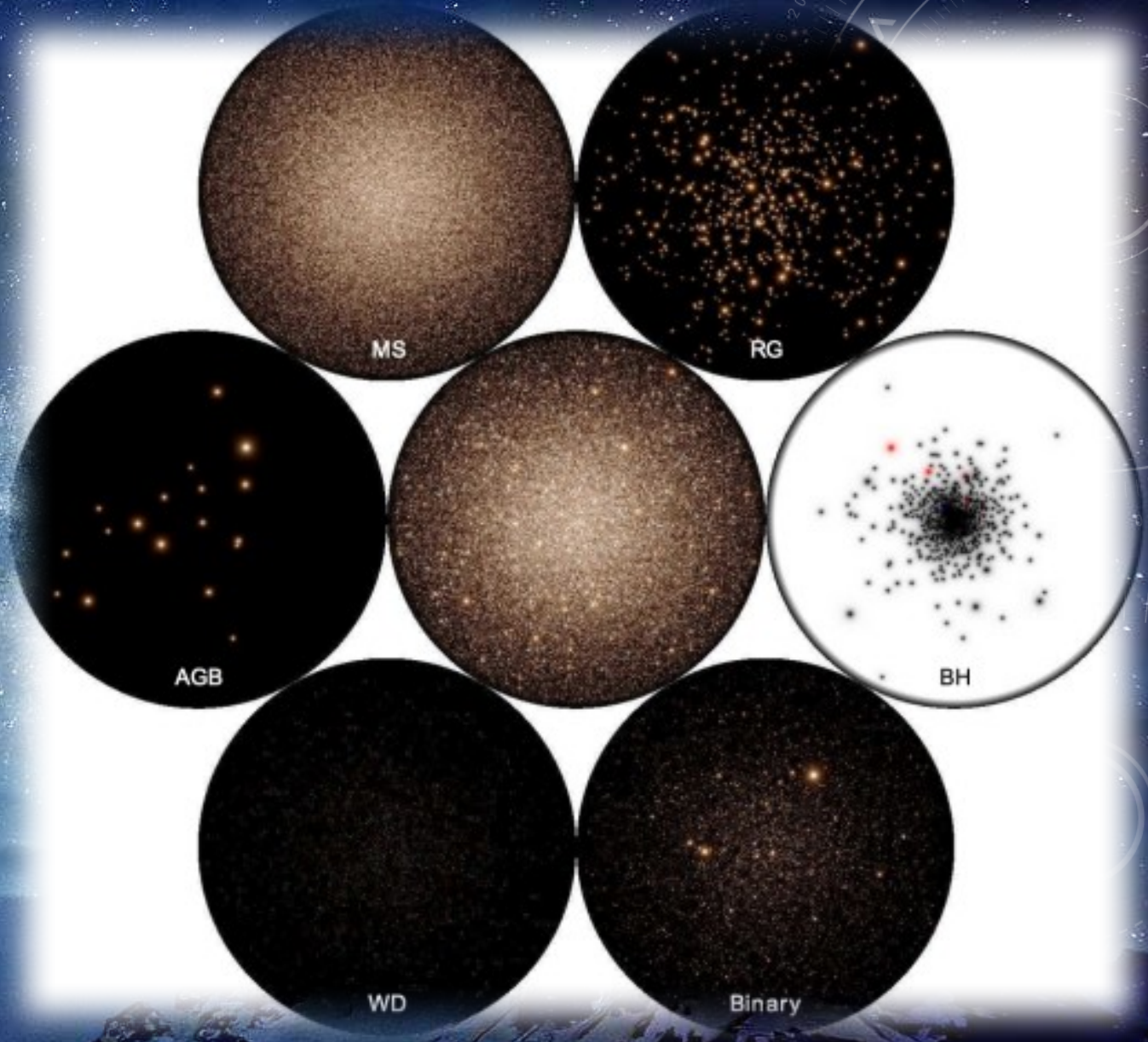


Mass segregation

Observations and N-body simulations of the innermost structure of the Milky Way's nuclear star indicate the existence of a power-law density cusp around Sgr A*

$$\rho(r) \sim r^{-\gamma}$$

[Peebles (1972), Bahcall & Wolf (1976)]



[The Dragon simulations, Wang et al. (2016)]

Formation Mechanism

Key process in a dense system:

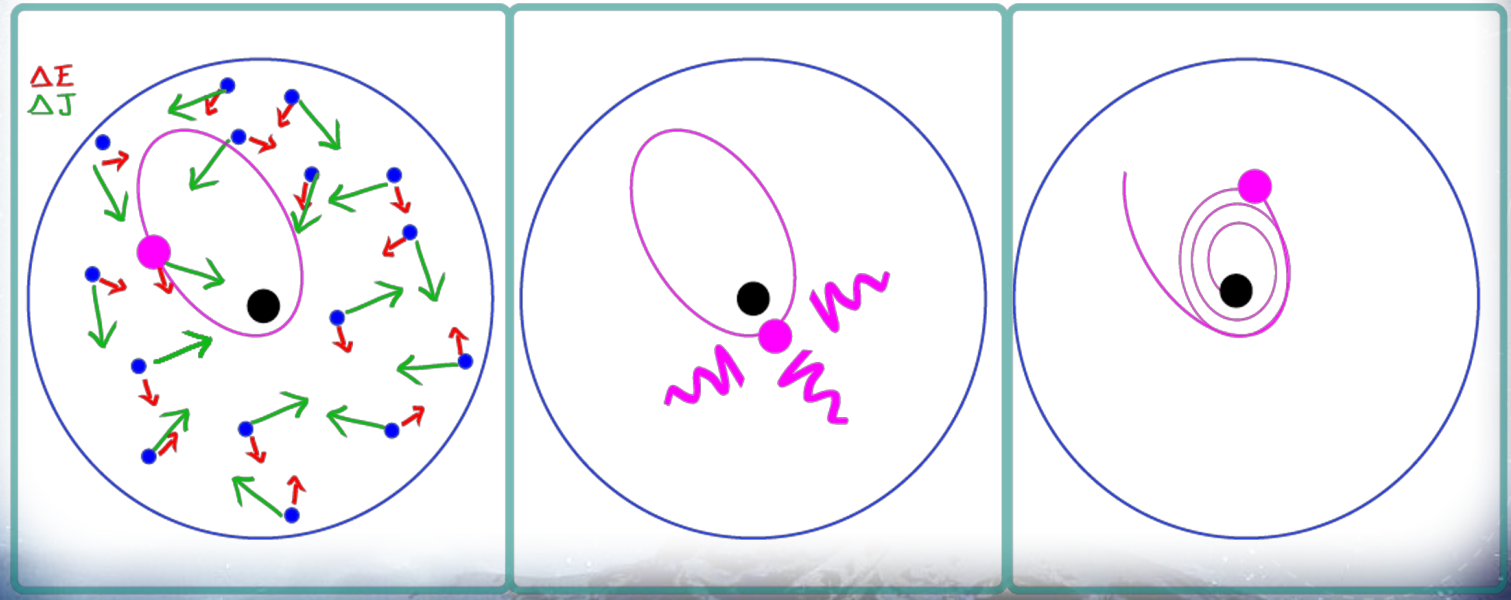
Two-body relaxation

Increases the eccentricity of an orbiting object

At pericenter, the energy loss by GW emission becomes significant.

The orbit reaches a critical semimajor axis a_{crit} such that

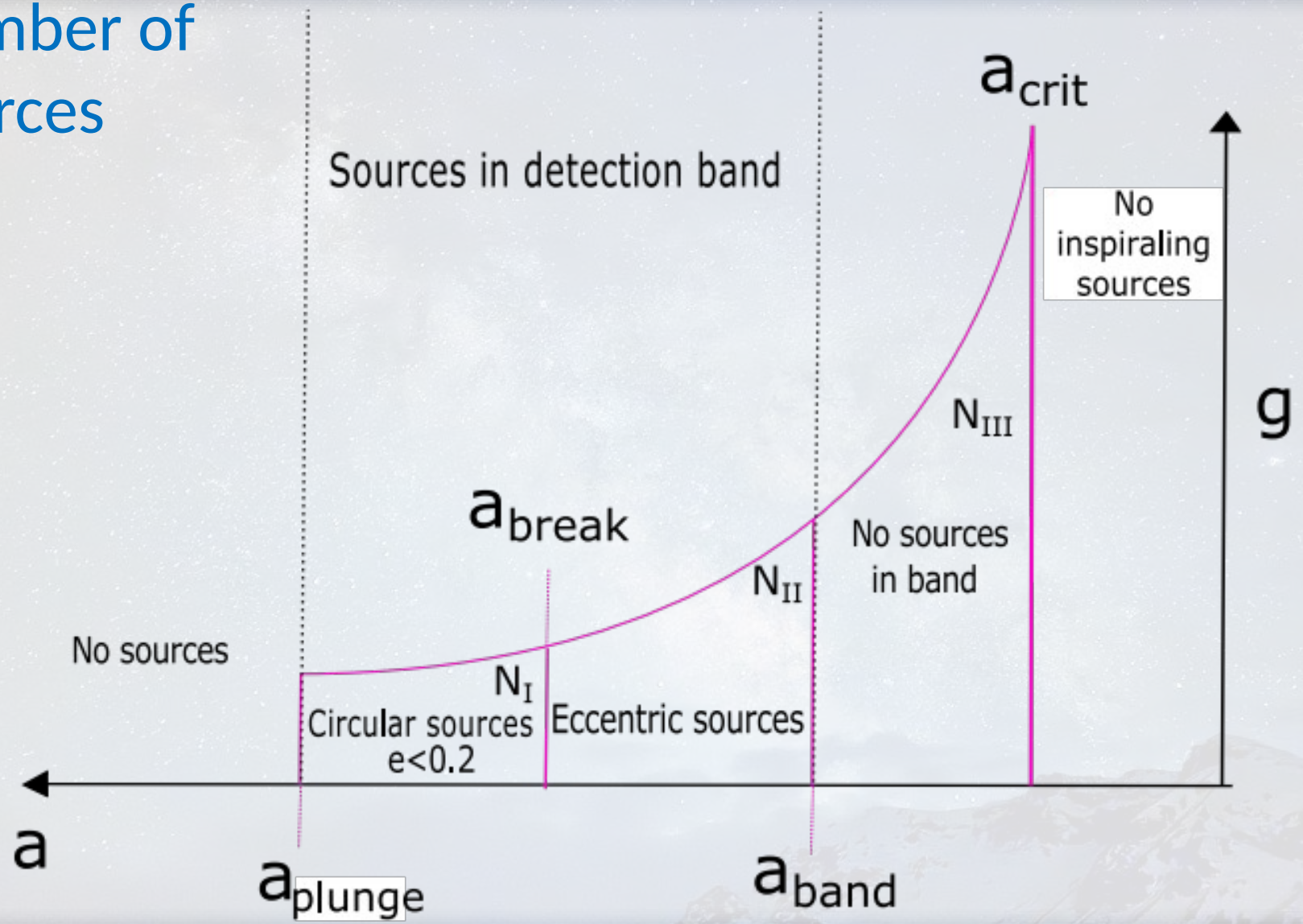
$$T_{GW} \lesssim T_{rlx}(a_0) \times (1 - e_0^2).$$



Two-body relaxation

[Hopman & Alexander (2005), Amaro-Seoane et al. (2007)]

Number of sources



Amaro-Seoane (2018)]

Why do we care about channels?

We need to know

- What's the detection rate?
- What are their typical orbital parameters?
- How do the waveform looks like?
- Which effects can modify the waveform?
- What information can be extracted?

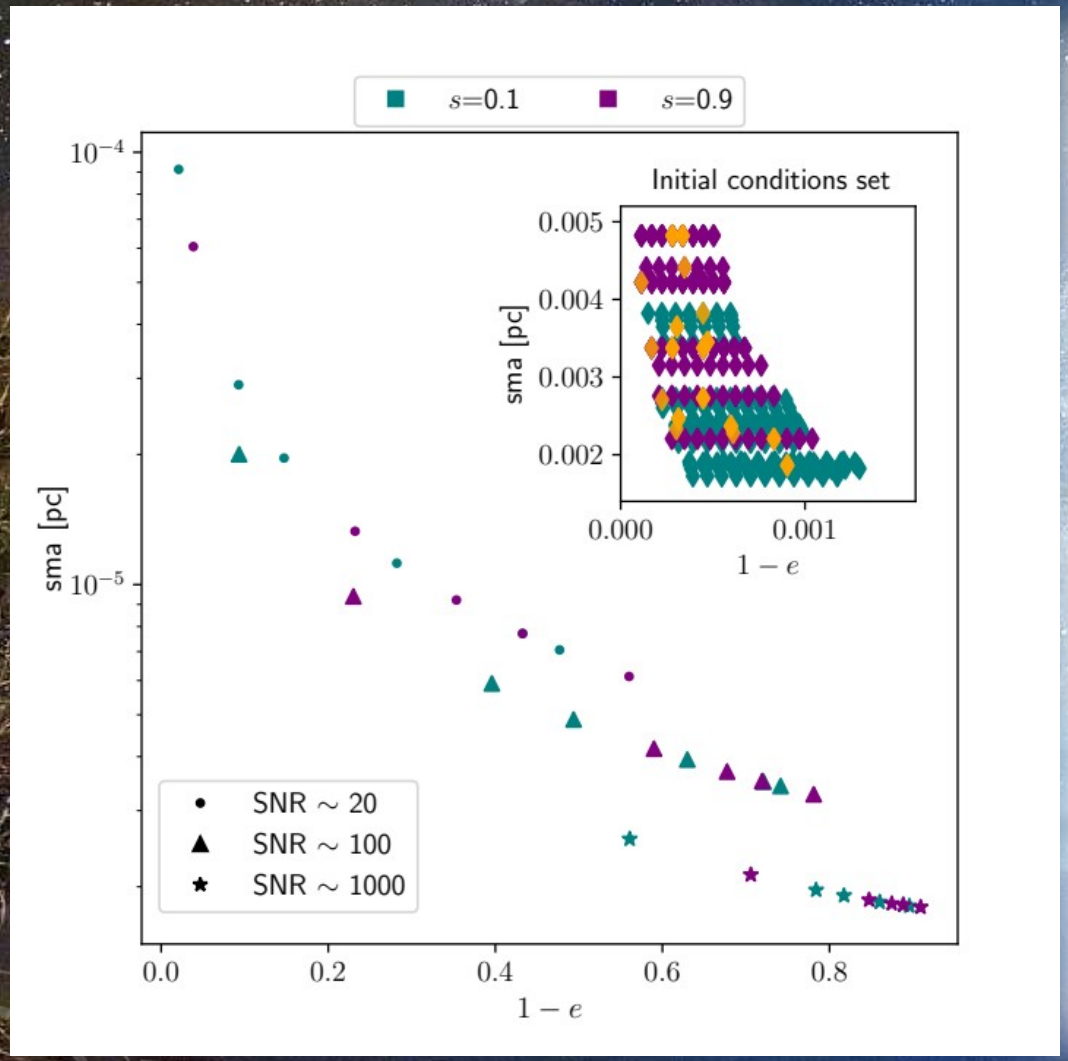
Let’s talk a bit about

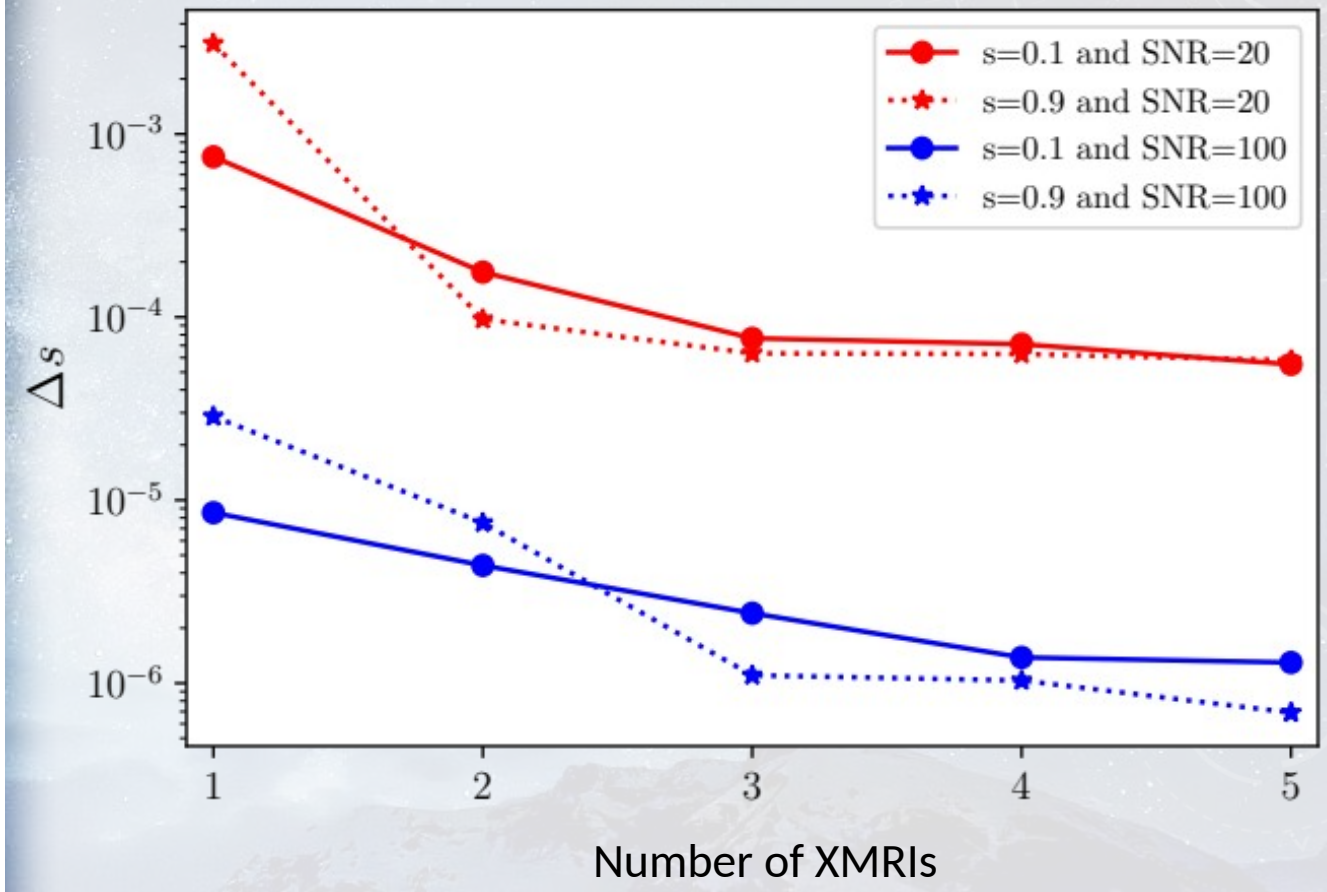
XMRIs : Extremely large mass ratio insprials

IMRIs : Intermediate mass ratio inspirals

EMRIs : Extreme mass ratio inspirals

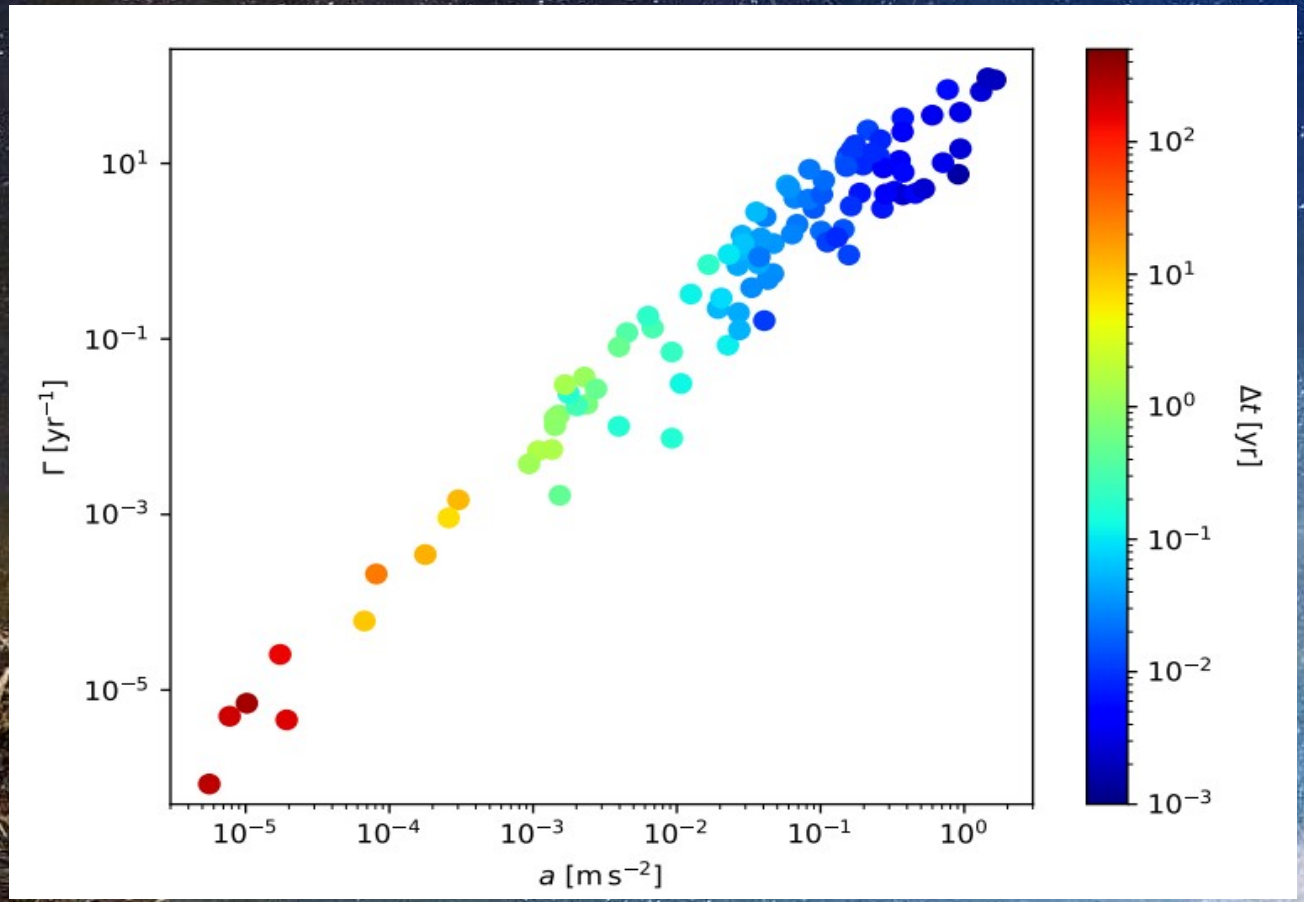
XMRIs in the Galactic Center





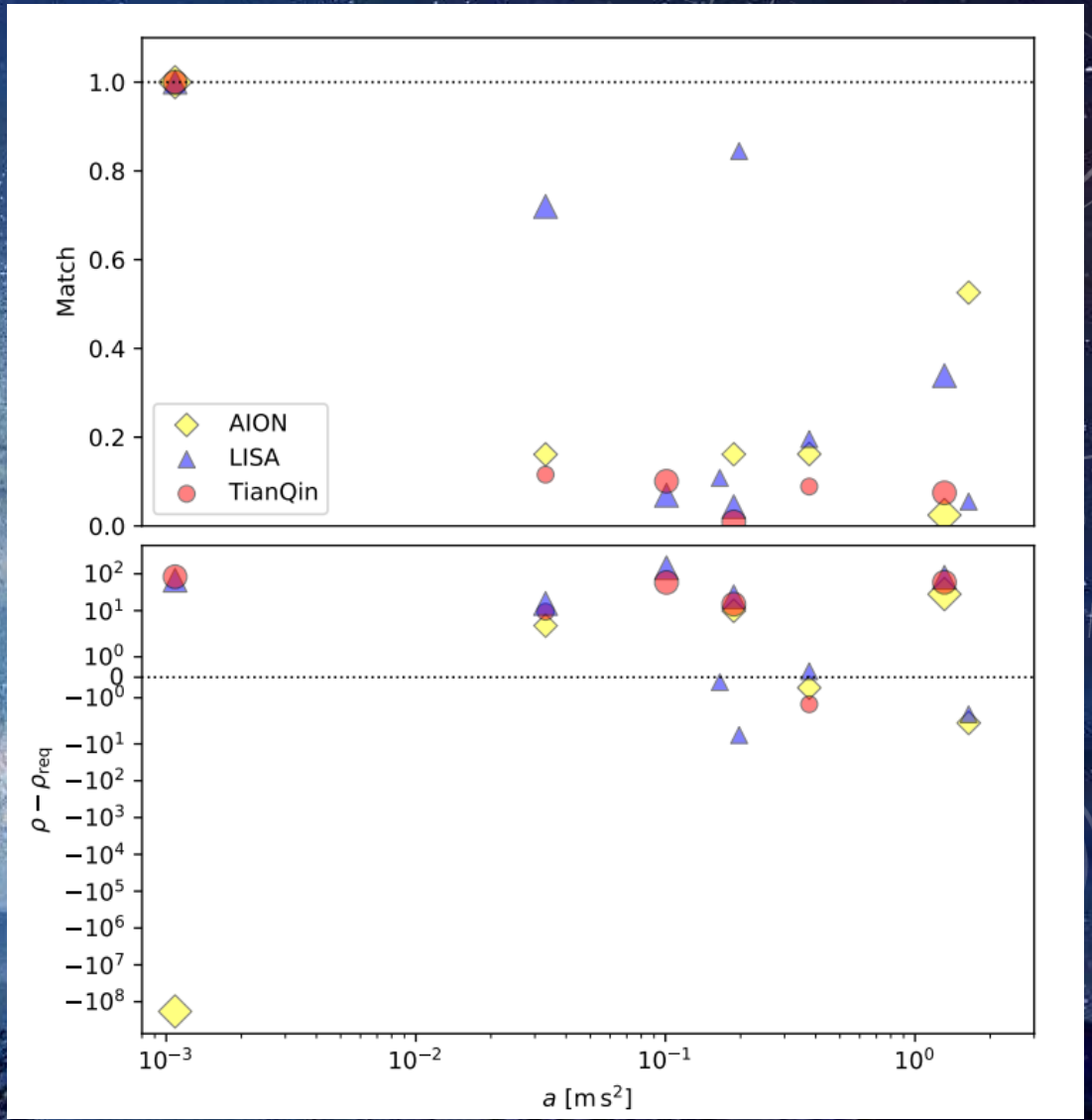
[Vázquez-Aceves et al., 2025]

IMRIs in Globular Clusters



Brownian Motion: Frequent weak encounters

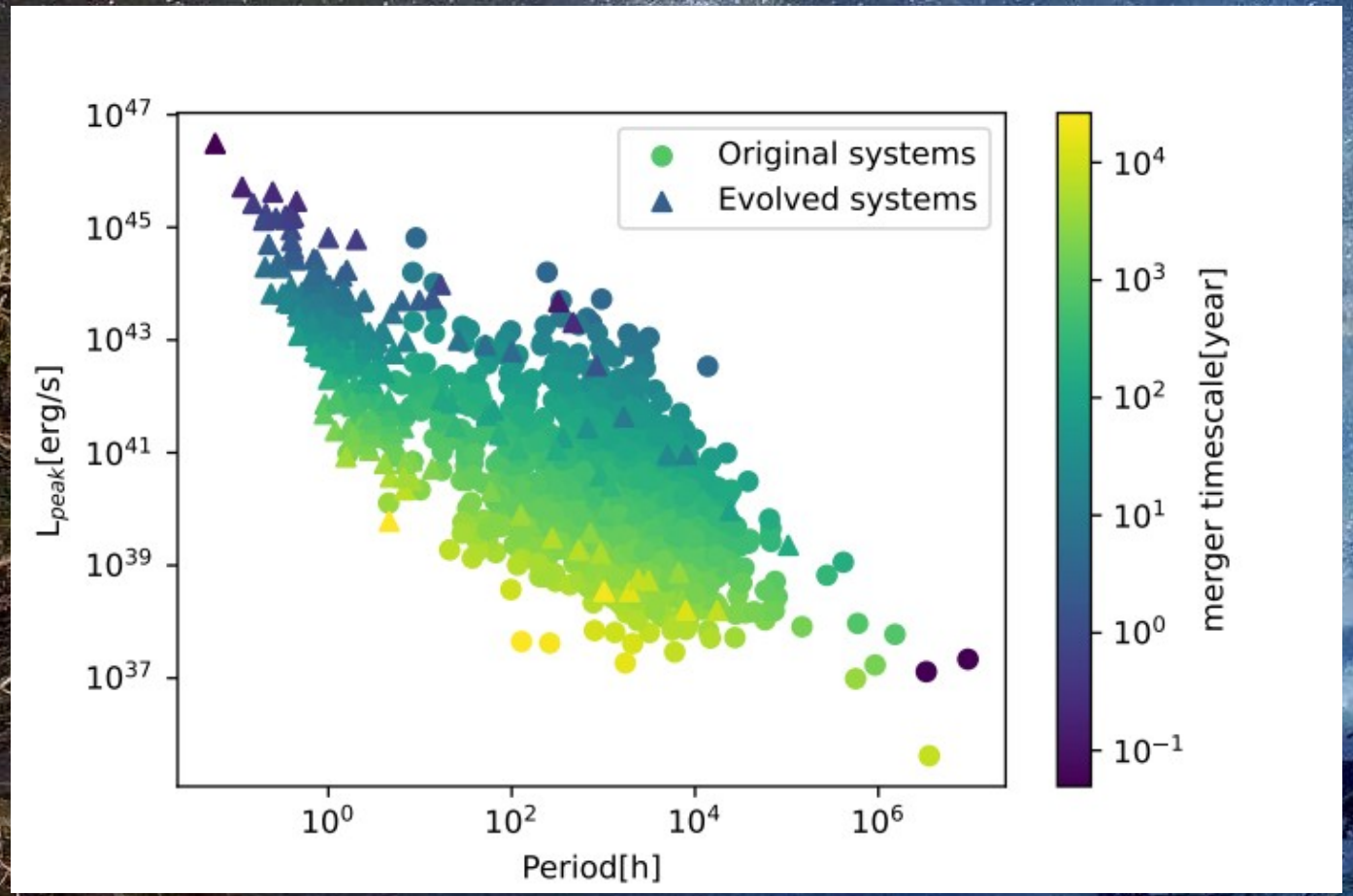
Acceleration induces phase shift leading to significant mismatch

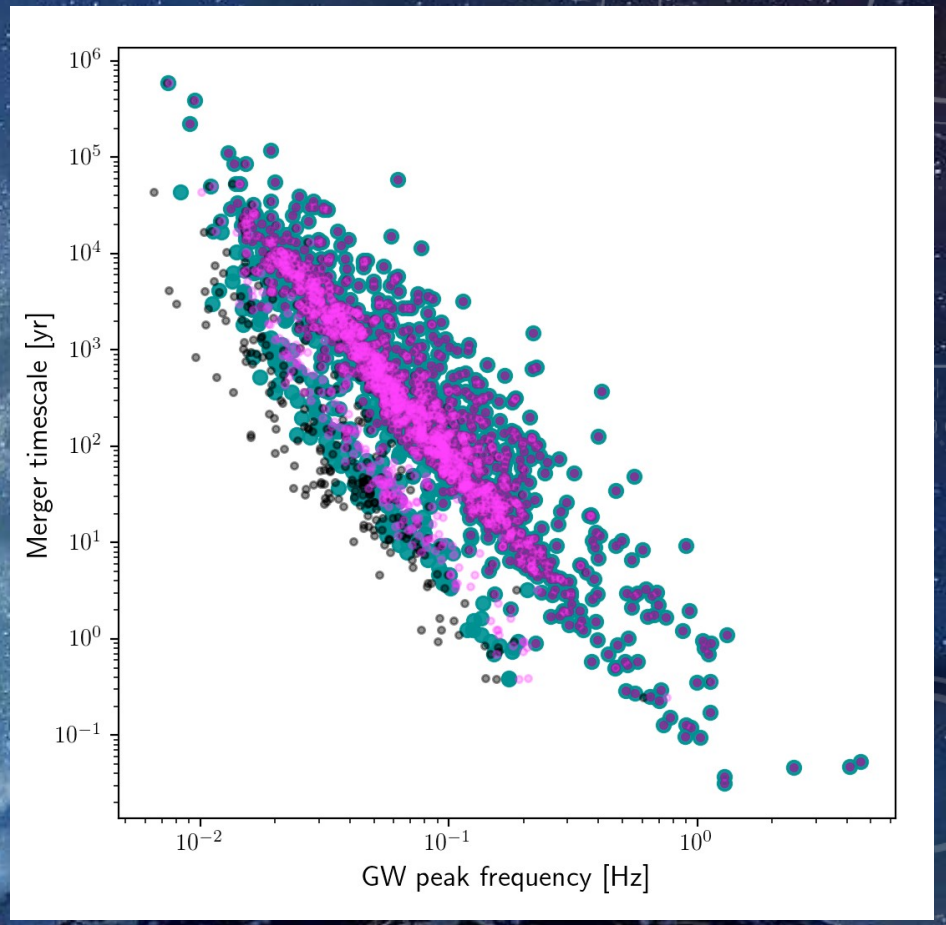


[Torres-Orjuela et al, 2025]

Multimessenger signals!

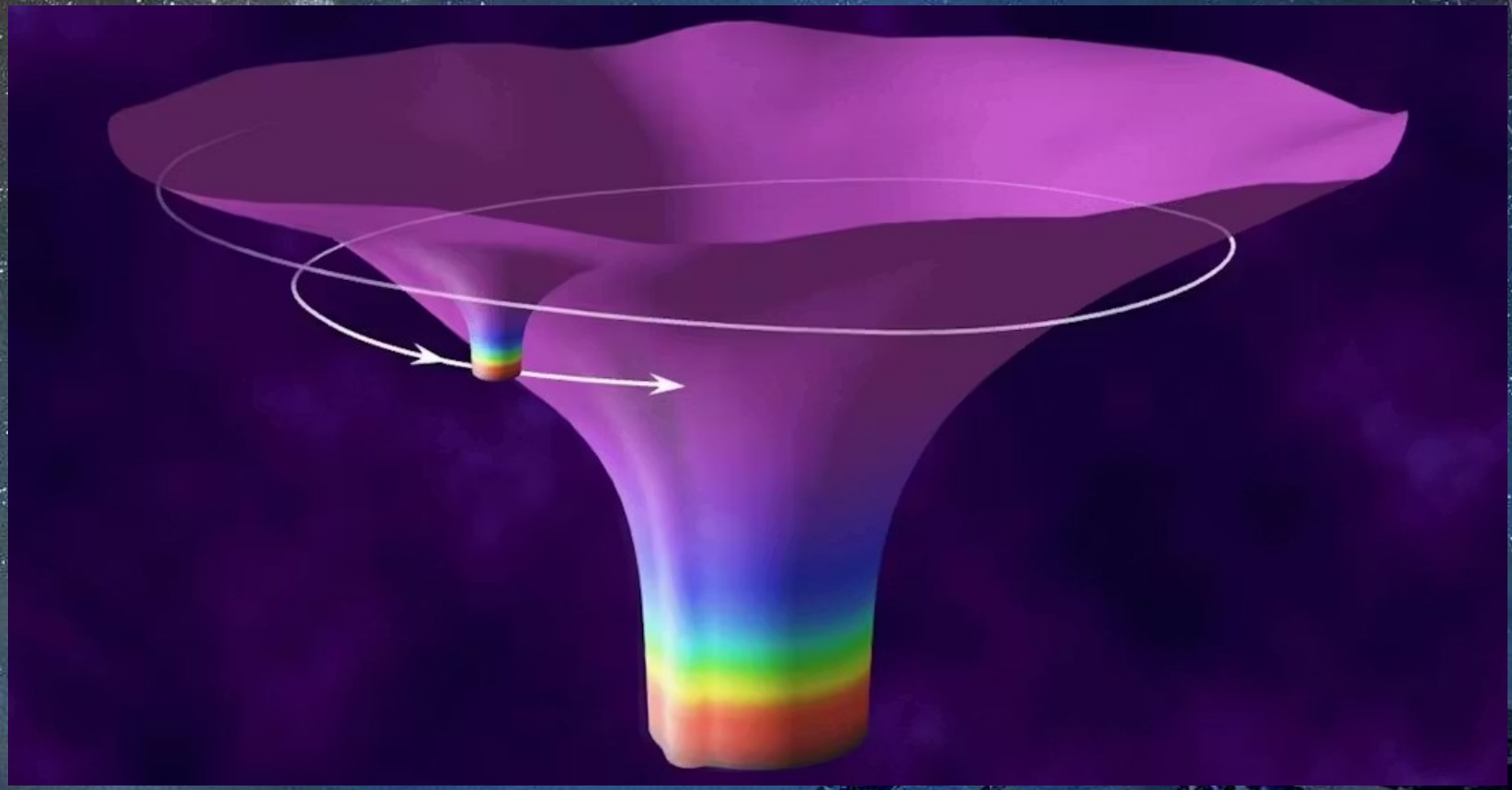
Tidal Stripping of WD by light-IMBH in Globular Clusters





Vázquez-Aceves et al., in prep

Now EMRIs



EMRIs

Usually we think:

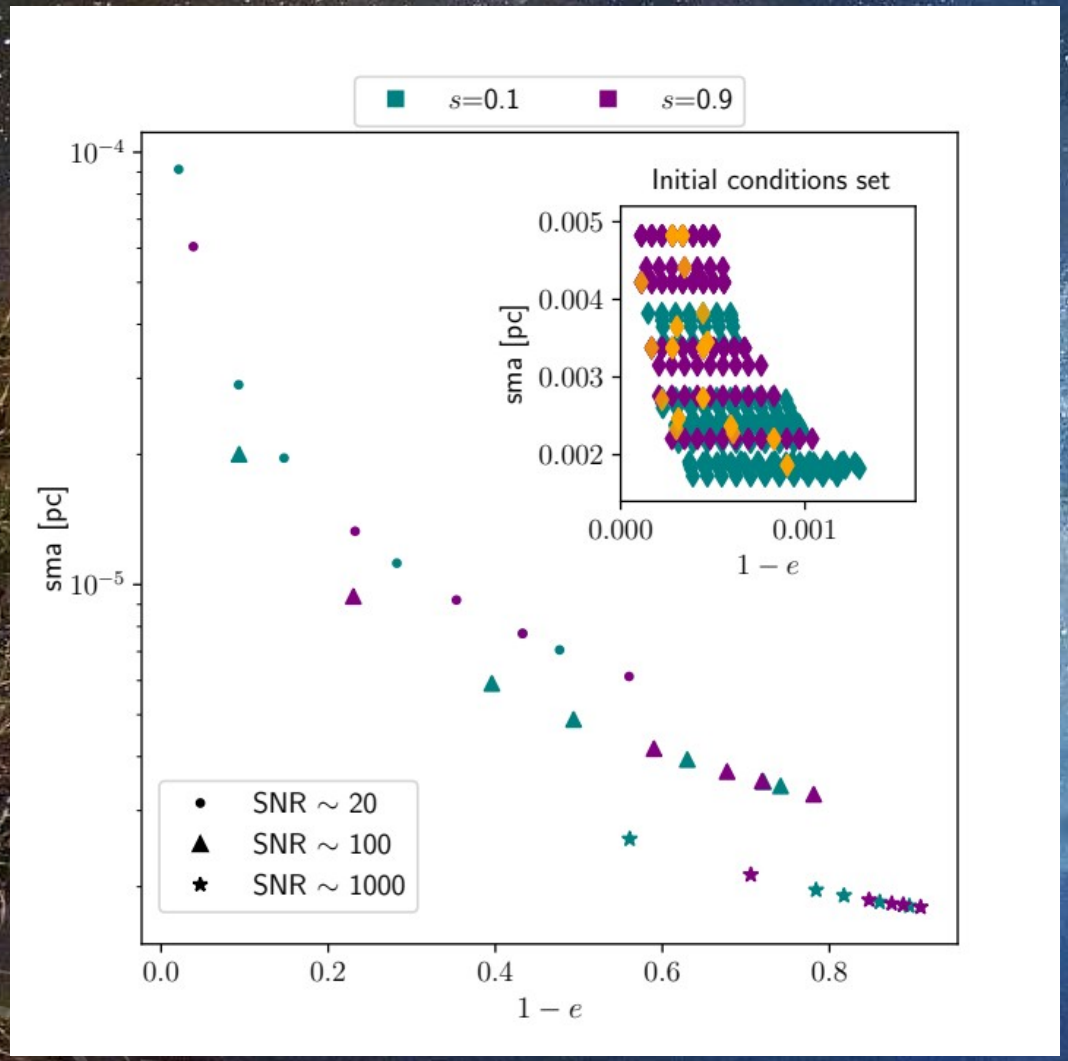
EMRIs evolve in isolation

Why?

- Event rates are low ~10^{-6} per year, they do not accumulate
  LISA may detect between 1 to 4000 per year
  [Babak et al. 2017, Bonetti & Sesana 2020, Rom et al. 2024]

- They are located very deep in galactic nuclei
- Environment will not affect the waveforms significantly … ?

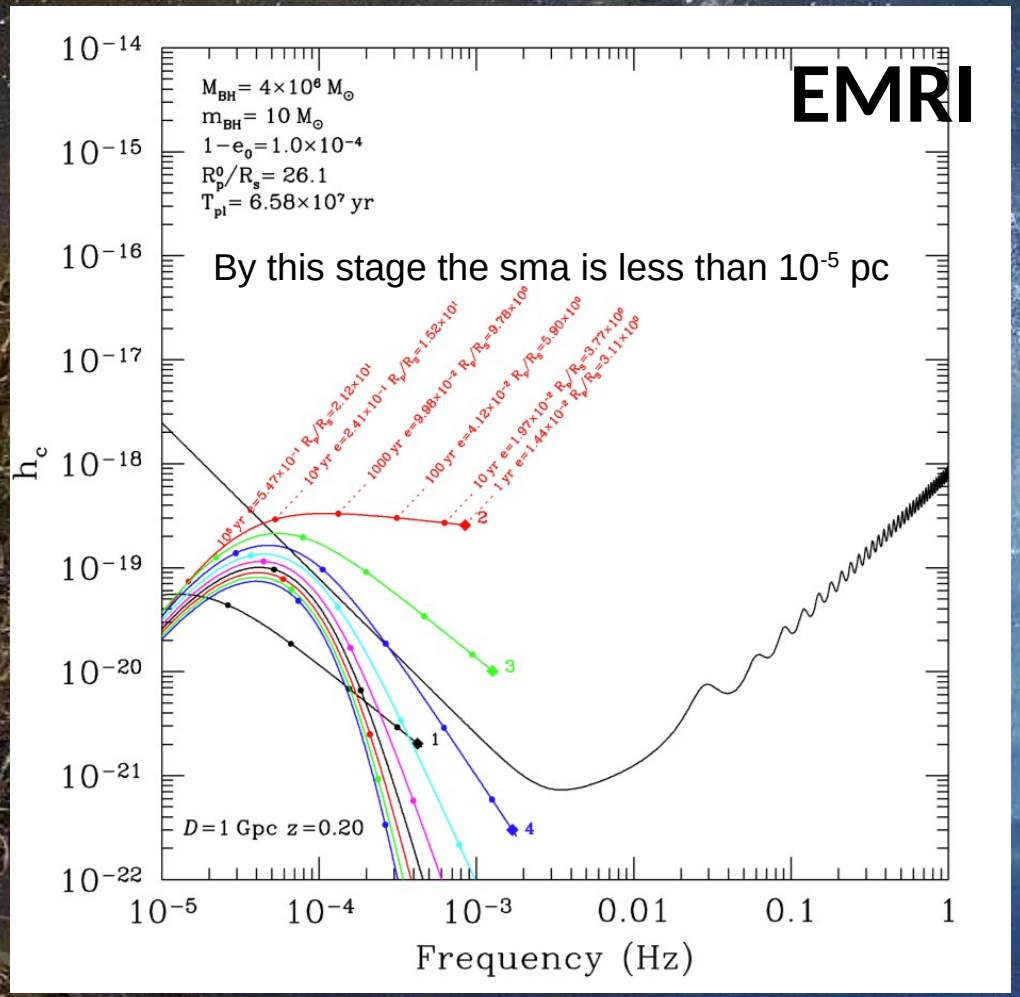
XMRIs in the Galactic Center



A population of ~ 10 XMRIs is expected to reside in our Galactic Center

We could expect the same for similar galaxies...

But what happens if we have



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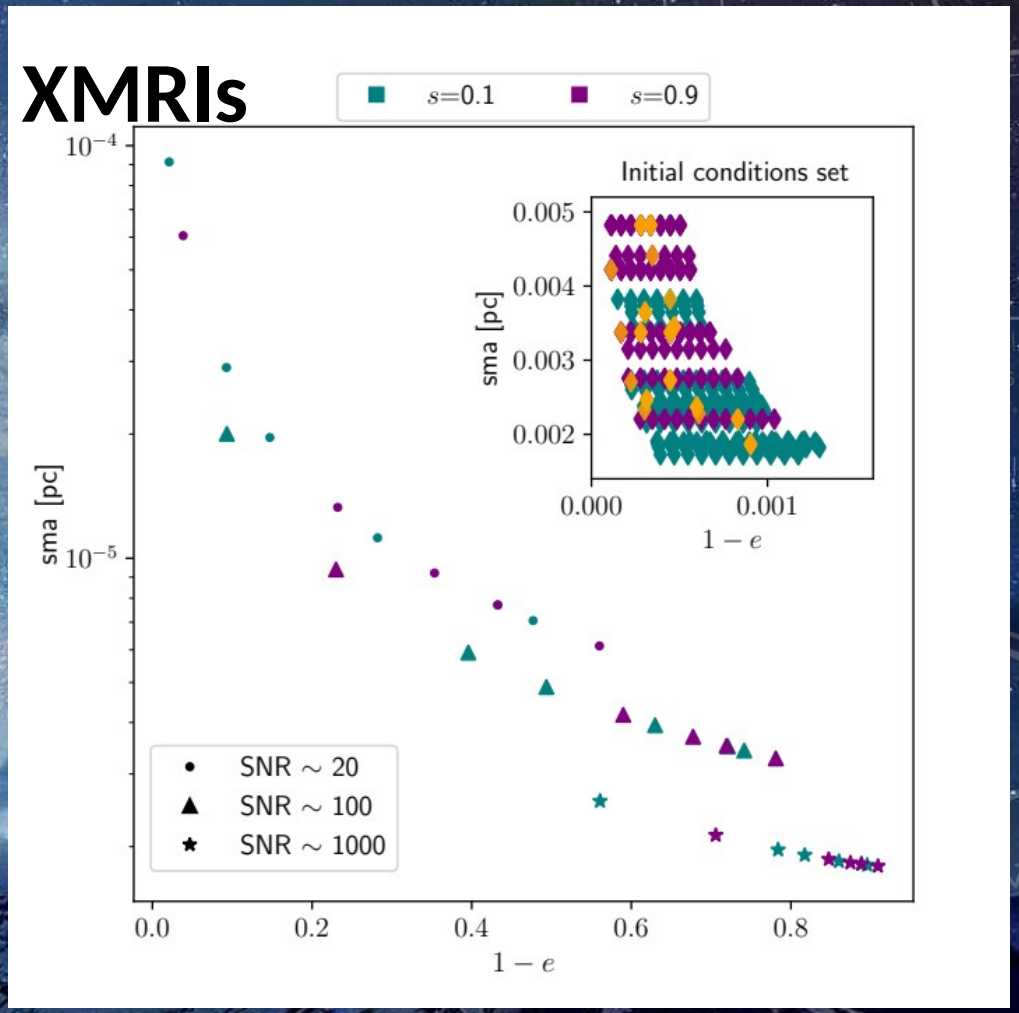

[Amaro Seoane 2020]

But what happens if we have EMRI + XMRIs

Evolved a system with 1 EMRI
(we still expect to have just 1 EMRI per galaxy)

And added a few XMRIs (10)

- Few body regime, evolved with ARWV code
- Evolution of orbits with 2.5PN corrections

[Mikkola & Tanikawa 1999,Chassonnery et al 2019]

We evolved the system and checked the GW emission

XMRIS: 4 XMRIs with SNR below 10, loudest system SNR~ 400

System	sma [pc]	ecc
E	1.019×10^{-3}	0.9970
X_1	5.7323×10^{-6}	0.4978
X_2	2.917×10^{-4}	0.98765
X_3	1.507×10^{-4}	0.9839
X_4	1.999×10^{-4}	0.9014
X_5	8.954×10^{-5}	0.8655
X_6	4.107×10^{-5}	0.7956
X_7	6.001×10^{-5}	0.6954
X_8	1.096×10^{-5}	0.2044
X_9	7.739×10^{-6}	0.36583
X_{10}	3.512×10^{-6}	0.2529

Vázquez-Aceves et al., in prep

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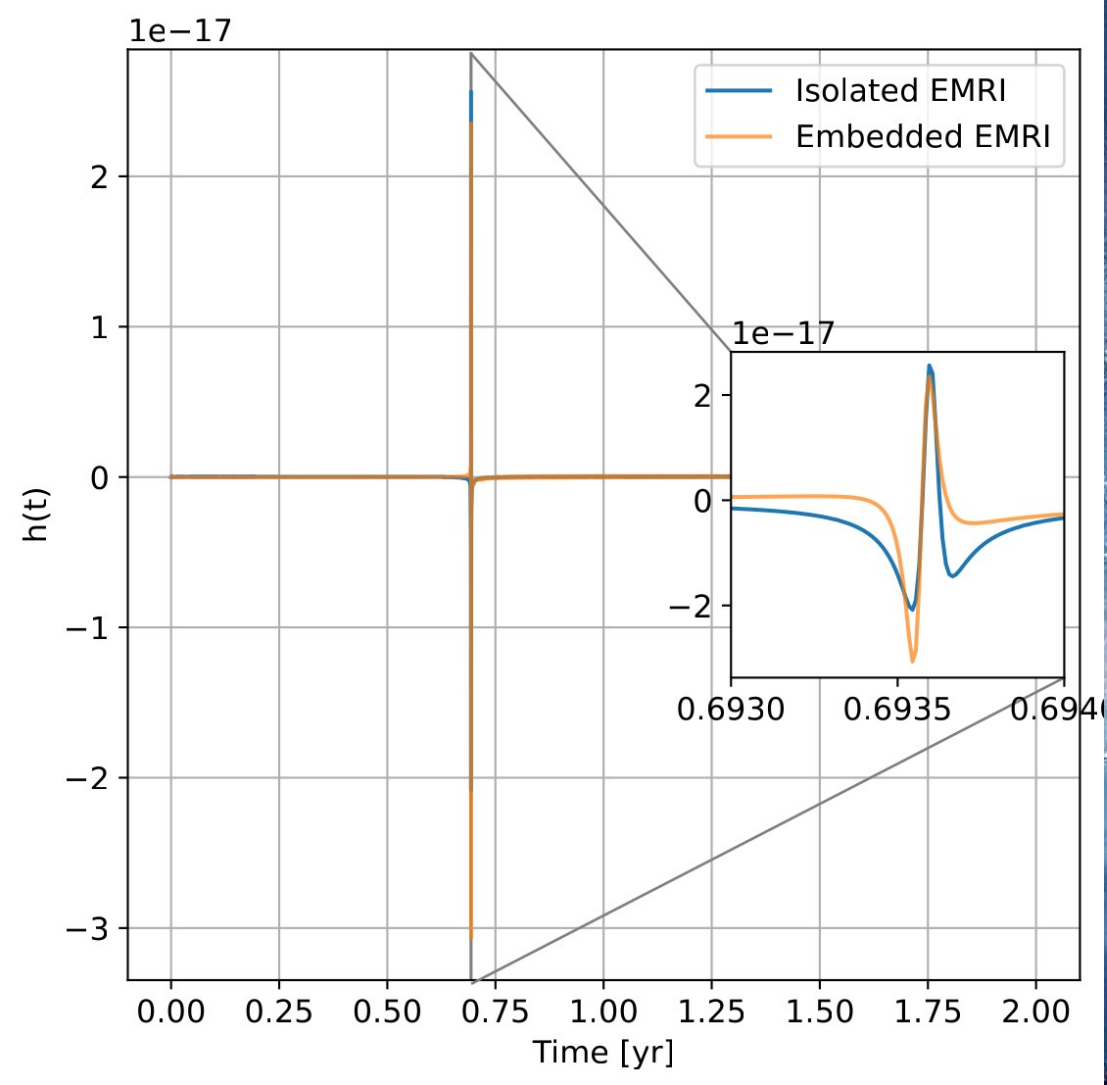


$$FF = \frac{(h(\Theta) \mid h'(\Theta))}{\sqrt{(h(\Theta) \mid h(\Theta))(h'(\Theta) \mid h'(\Theta))}}$$

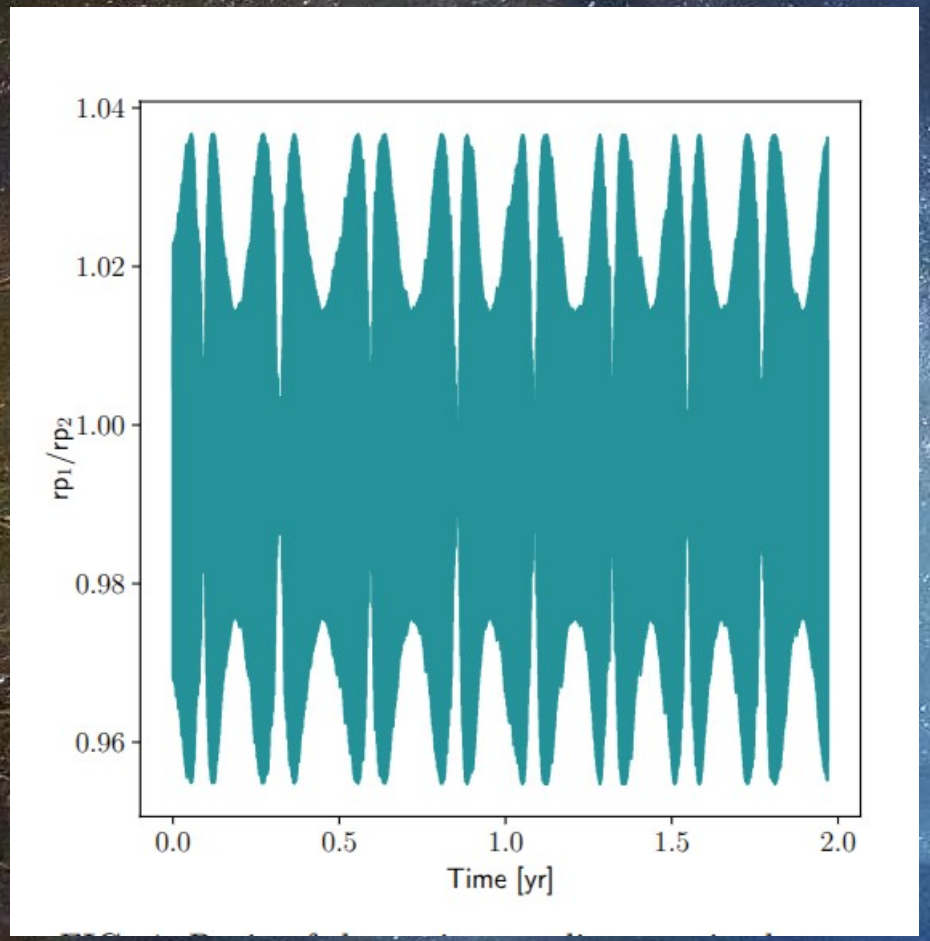
System	Fitting Factor
$E + X_1$	0.8125
$E + X_2$	0.8126
$E + X_3$	0.8110
$E + X_4$	0.8066
$E + X_5$	0.8122
$E + X_6$	0.8123
$E + X_7$	0.8109
$E + X_8$	0.8116
$E + X_9$	0.8122
$E + X_{10}$	0.8068
$E + X_{1-10}$	0.8002

TABLE II. Fitting factor of after two years of observation

EMRI GW signal: 2 years

Vázquez-Aceves et al., in prep

Only XMRIs



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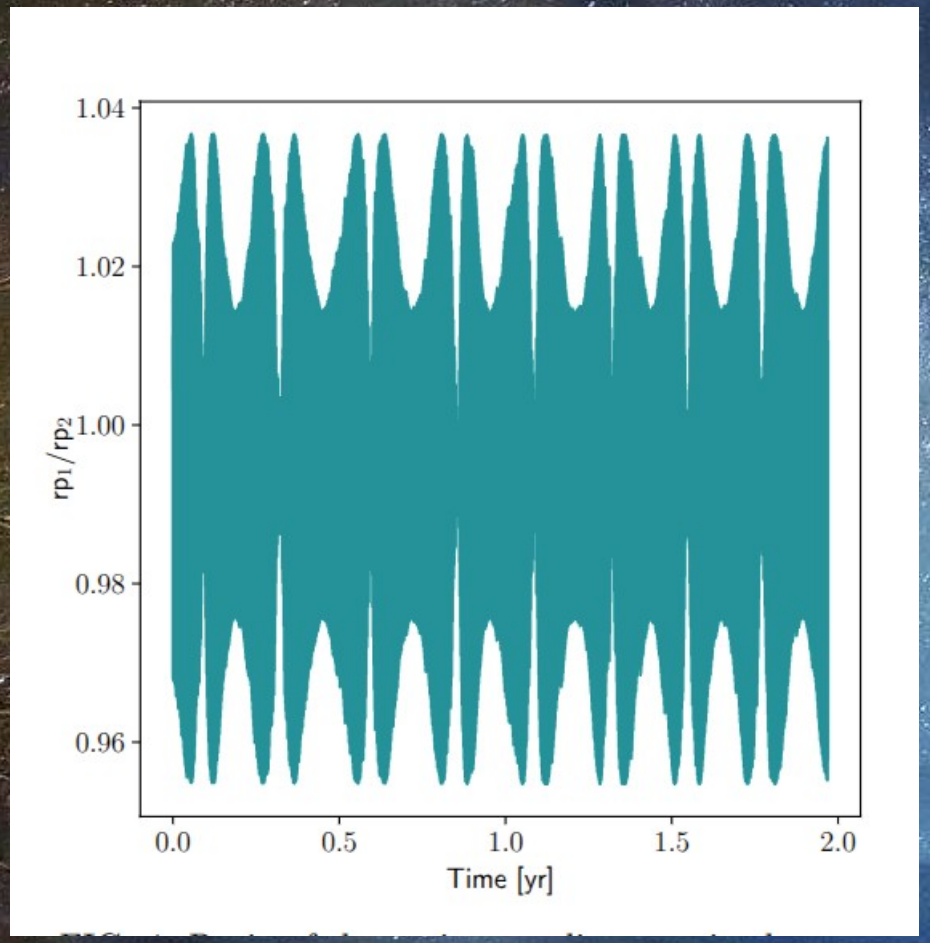
Pericenter comparison X_1 isolated vs $XMRI_{2\text{-}10}$

Vázquez-Aceves et al., in prep

XMRIs



Pericenter comparison XMRI-1 isolated vs XMRI 1-10

In this case, the fitting factor is always less than 0.5

- Need to consider multi-inspiral environments when developing future GW search pipelines and waveform models.

- Can these modulations be used to infer the presence of other inspiraling systems?

- More simulations are needed

Vázquez-Aceves et al., in prep

To conclude…

Inspiraling systems everywhere

(Probably more than what we have calculated)

We need to consider few-body influence (EMRI + XMRIs)

Detection can :

Help us with our dynamical models, galactic evolution, BH growth.

Test of fundamental physics and physics of black holes

(you know better)

Equation of state for degenerate matter from multimessenger signals.

Detecting IMBHs (without doubts about it)

We need:

Event rates, number of detectable systems

Good techniques to identify signals

and extract parameters.

THANKS!

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