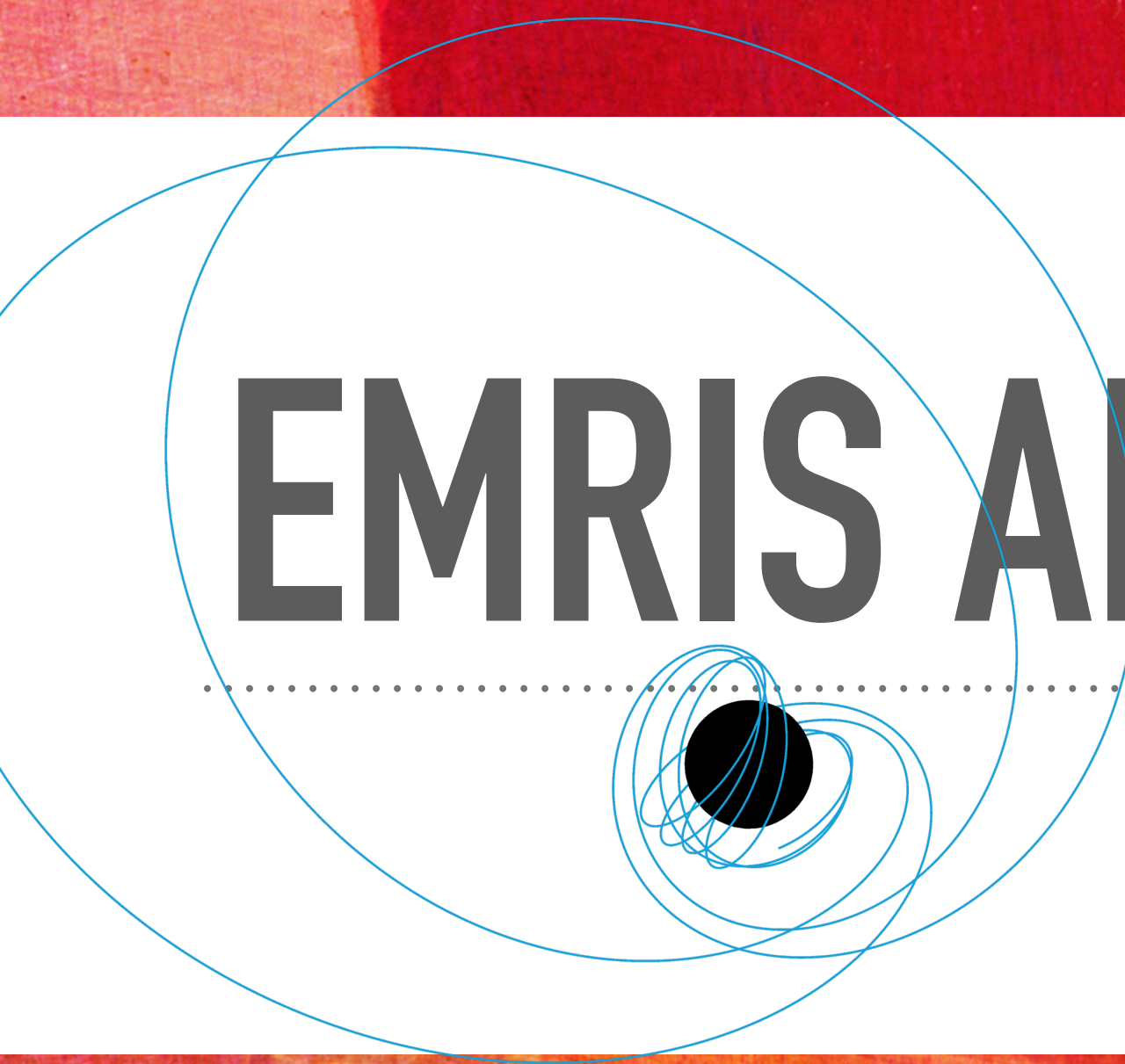




EMRIS AND THEIR ROLE IN GW SCIENCE

Amin Boumerdassi | 24/04/25

CONTENTS

- What are EMRIs?
- Why are they a topic of interest?
- What can EMRIs do for us?
- Applications in astrophysics & cosmology

A RECIPE TO MAKE EMRIS AT HOME

.....

Ingredients:

- One massive object e.g. supermassive black hole
- One compact object e.g. neutron star, white dwarf, black hole
- Ensure the objects have mass ratio $< 10^{-4}$

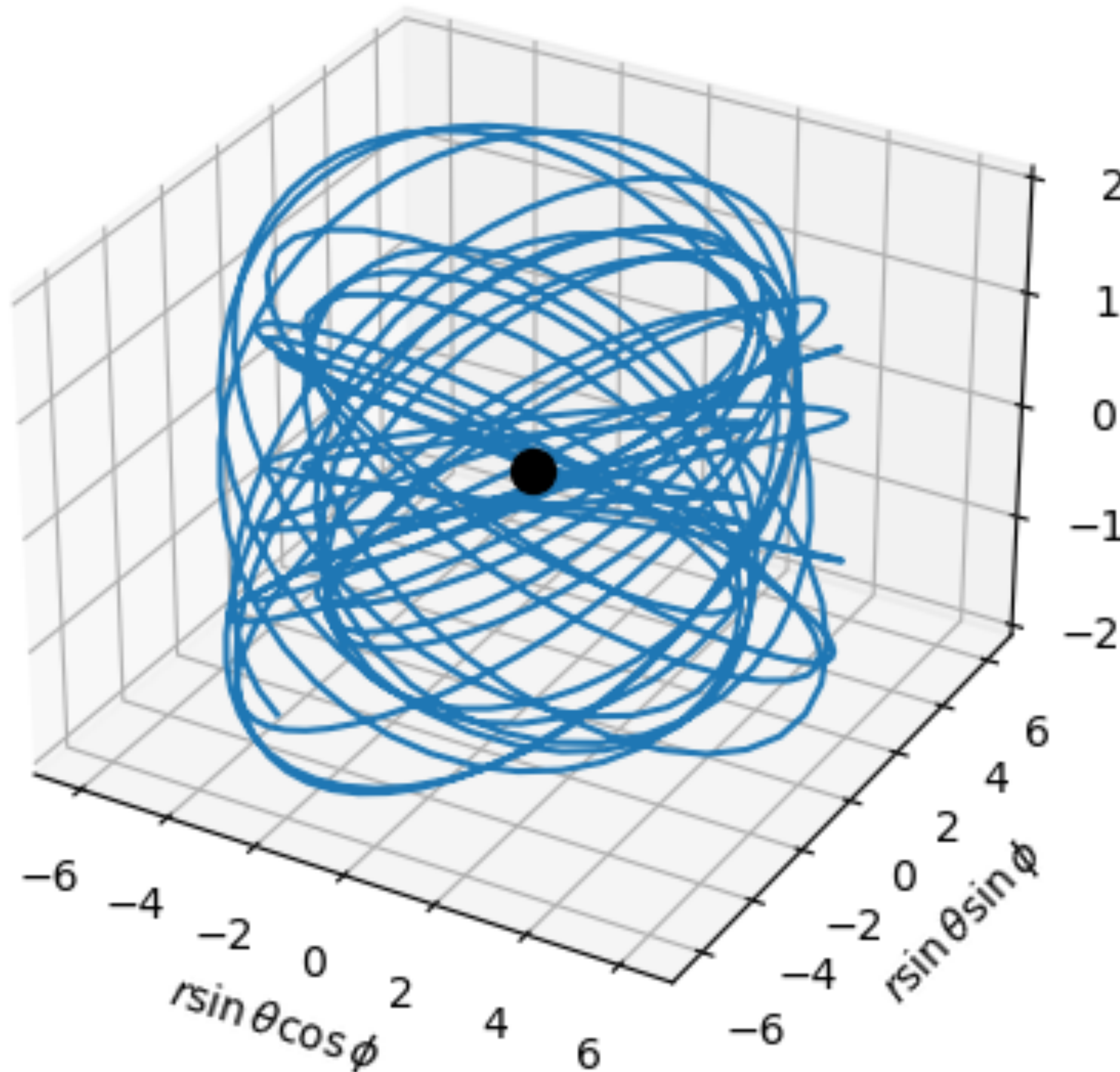
Steps:

- Place the massive object somewhere in the universe
- Let the compact object get captured by the massive object (not too close, not too far, not too slow, not too fast)

The result:

A years-long, highly eccentric and relativistic inspiral of the CO into the MO. It also produces unique GW emissions.

- There are many proposed formation mechanisms for EMRIs!



Credits: Ollie Burke

LOOKING AT EMRI WAVEFORMS

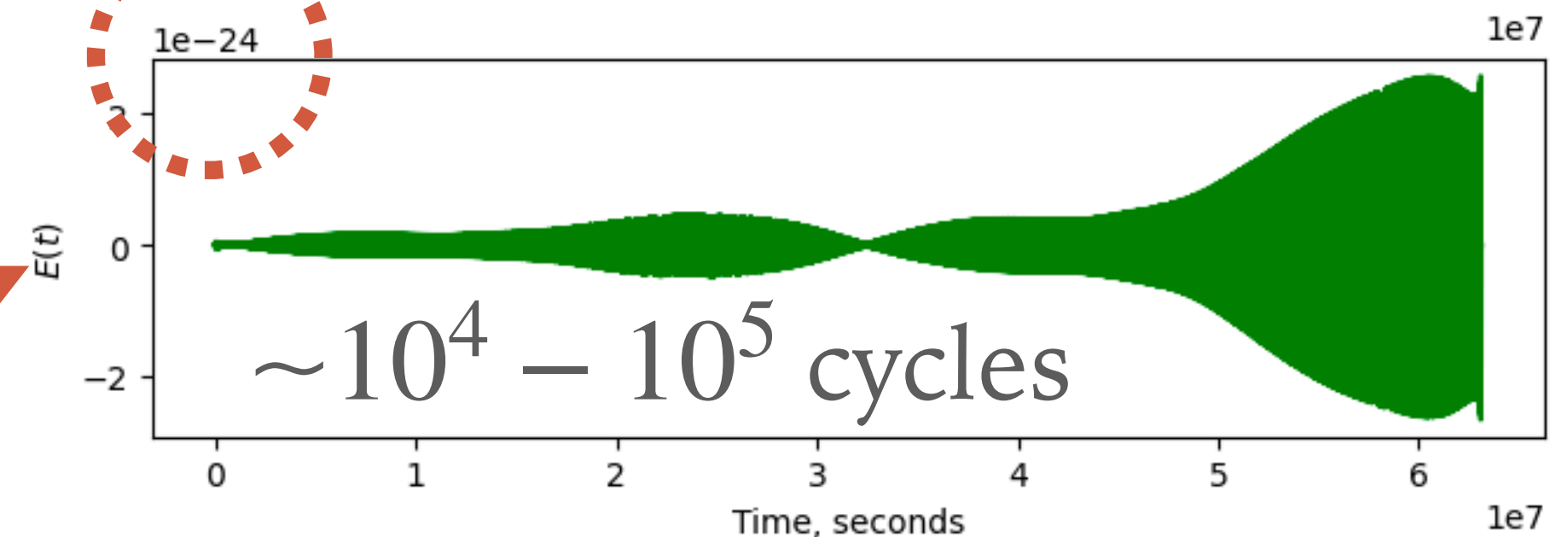
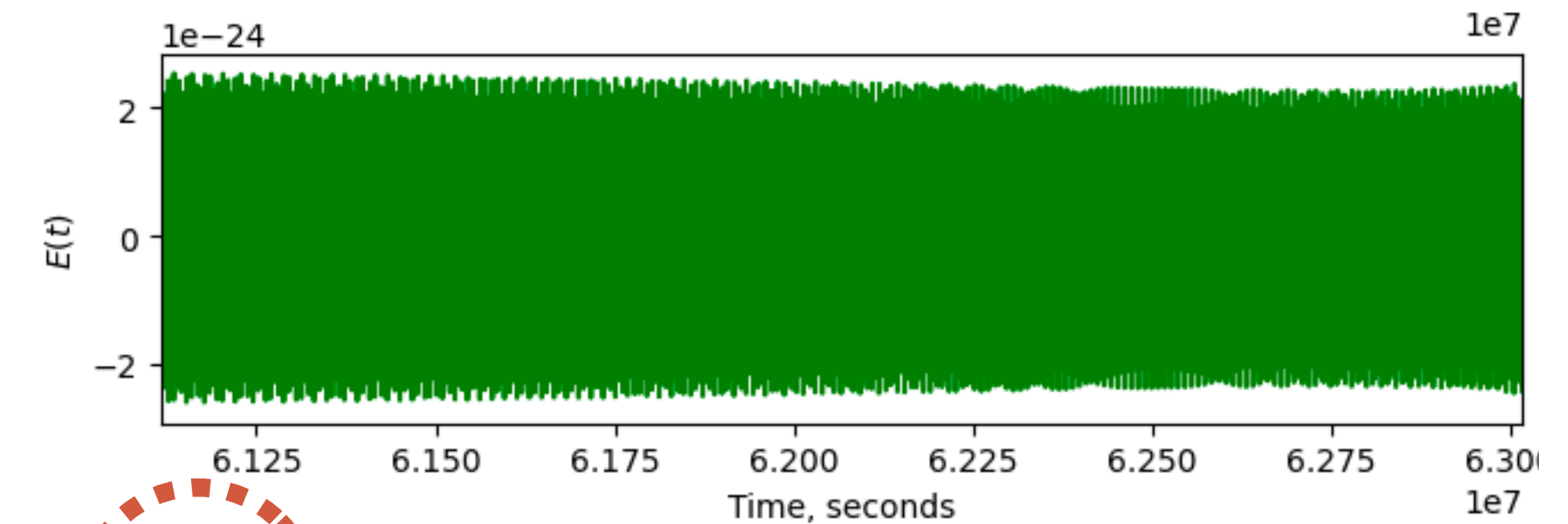
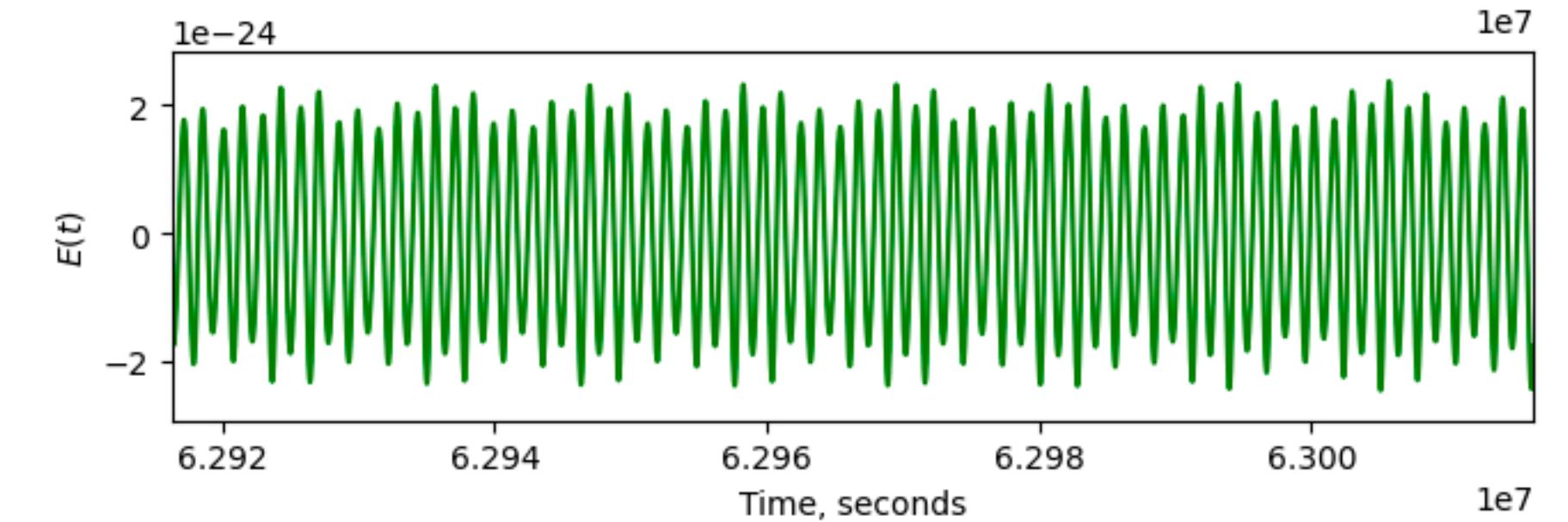
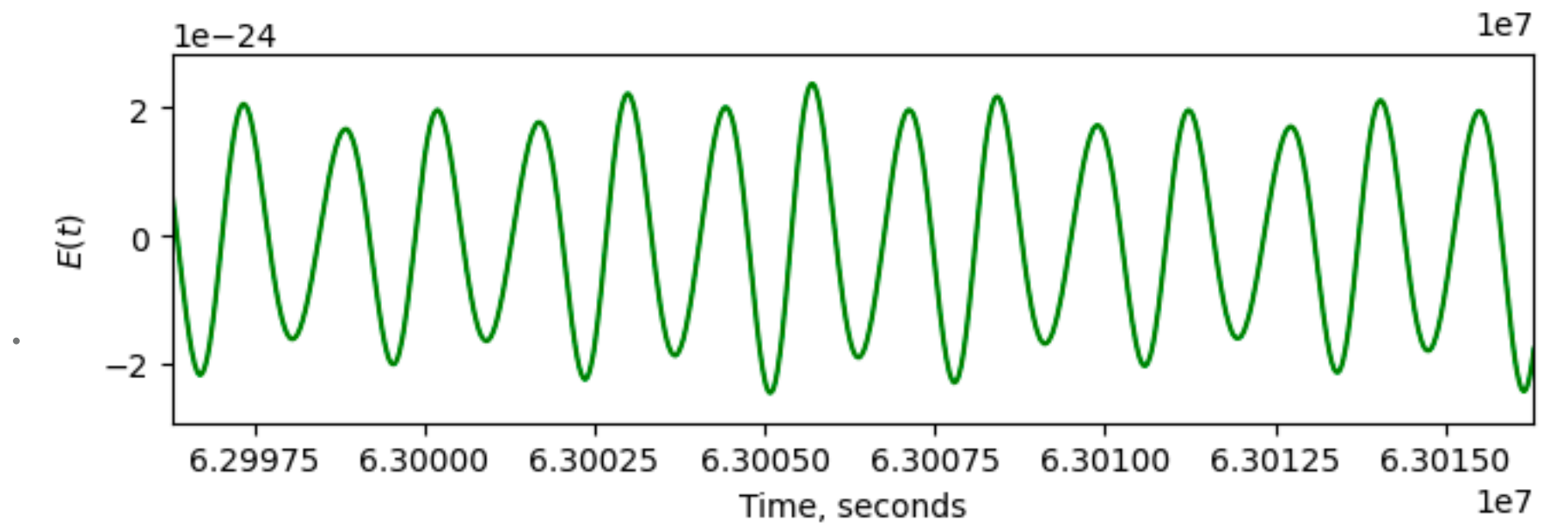
Short-term

- EMRI waveforms contain many time-varying, anisotropic harmonic modes.
- Most accurately modelled with black hole perturbation theory but very time-consuming
- Most quickly modelled with machine learning methods e.g. FastEMRIWaveforms

Long-term

“EMRIs are funky/hard/etc.”

Anonymous



WHY DO EMRIS MATTER?

- A unique, yet to be detected GW source
- Challenging test of current and developing data analysis techniques
- Allows very high precision parameter estimation
- Novel avenue for doing astrophysics and cosmology

Example accuracies:

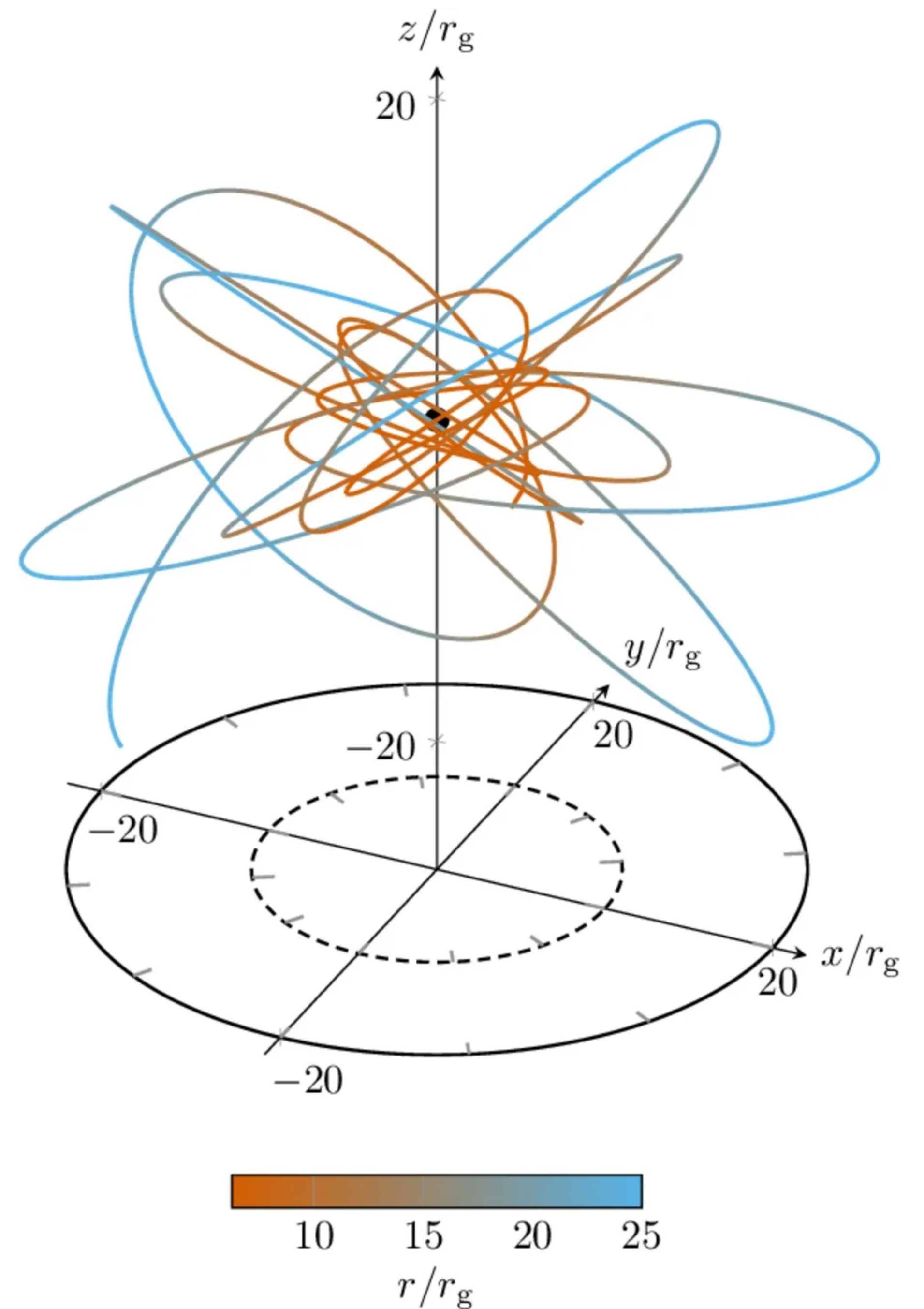
$$\left(\frac{\Delta M}{M}, \frac{\Delta \mu}{\mu}, \frac{\Delta a}{a}, \frac{\Delta e_0}{e_0} \right) = (10^{-4}, 10^{-4}, 10^{-4}, 10^{-4})$$

“

SO3: Probe the properties and immediate environments of Black Holes in the local Universe using EMRIs and IMRIs

LISA Definition Study Report ([arXiv:2402.07571](https://arxiv.org/abs/2402.07571))

EMRIS FOR ASTROPHYSICS



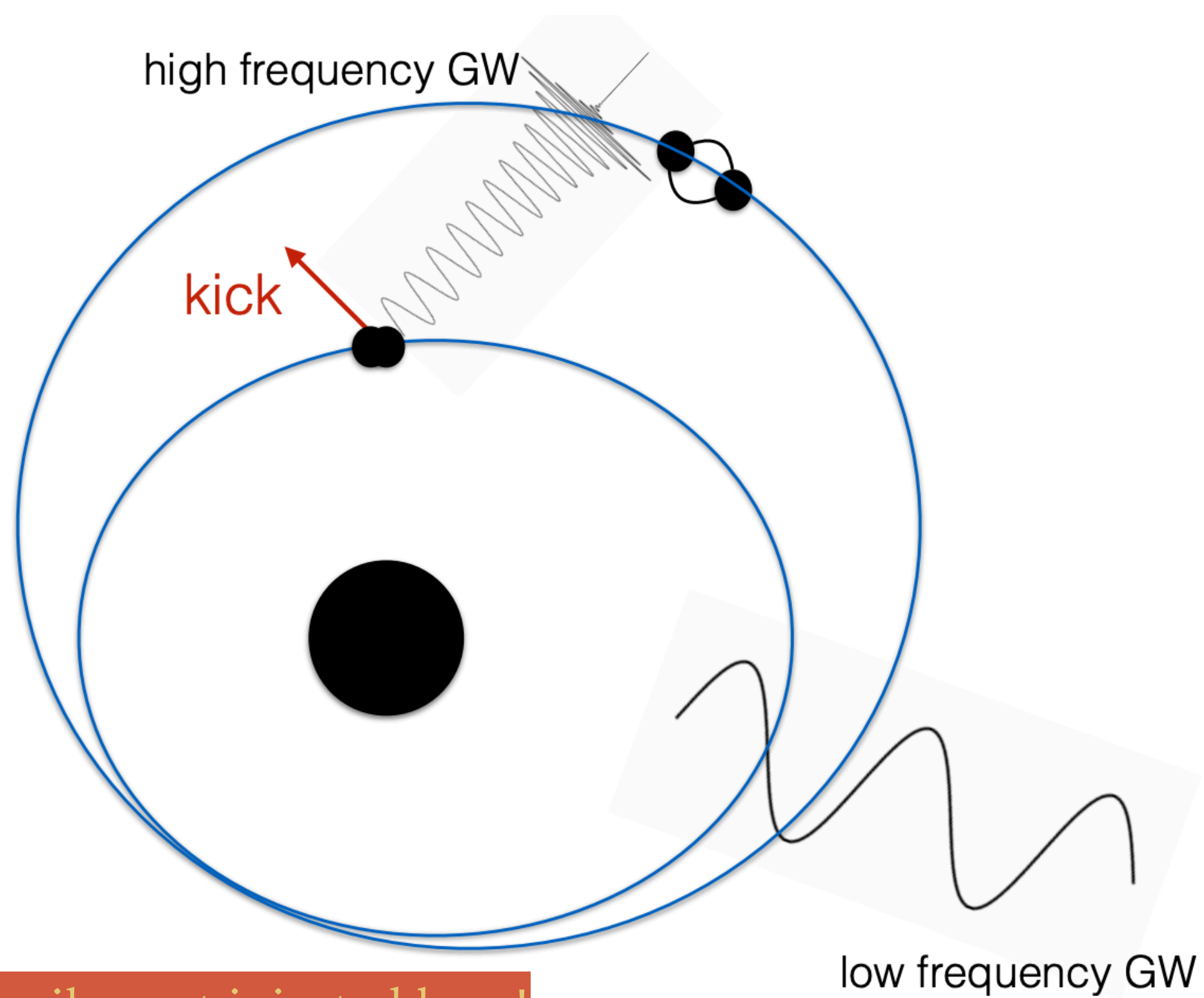
ASTROPHYSICS APPLICATIONS

For example:

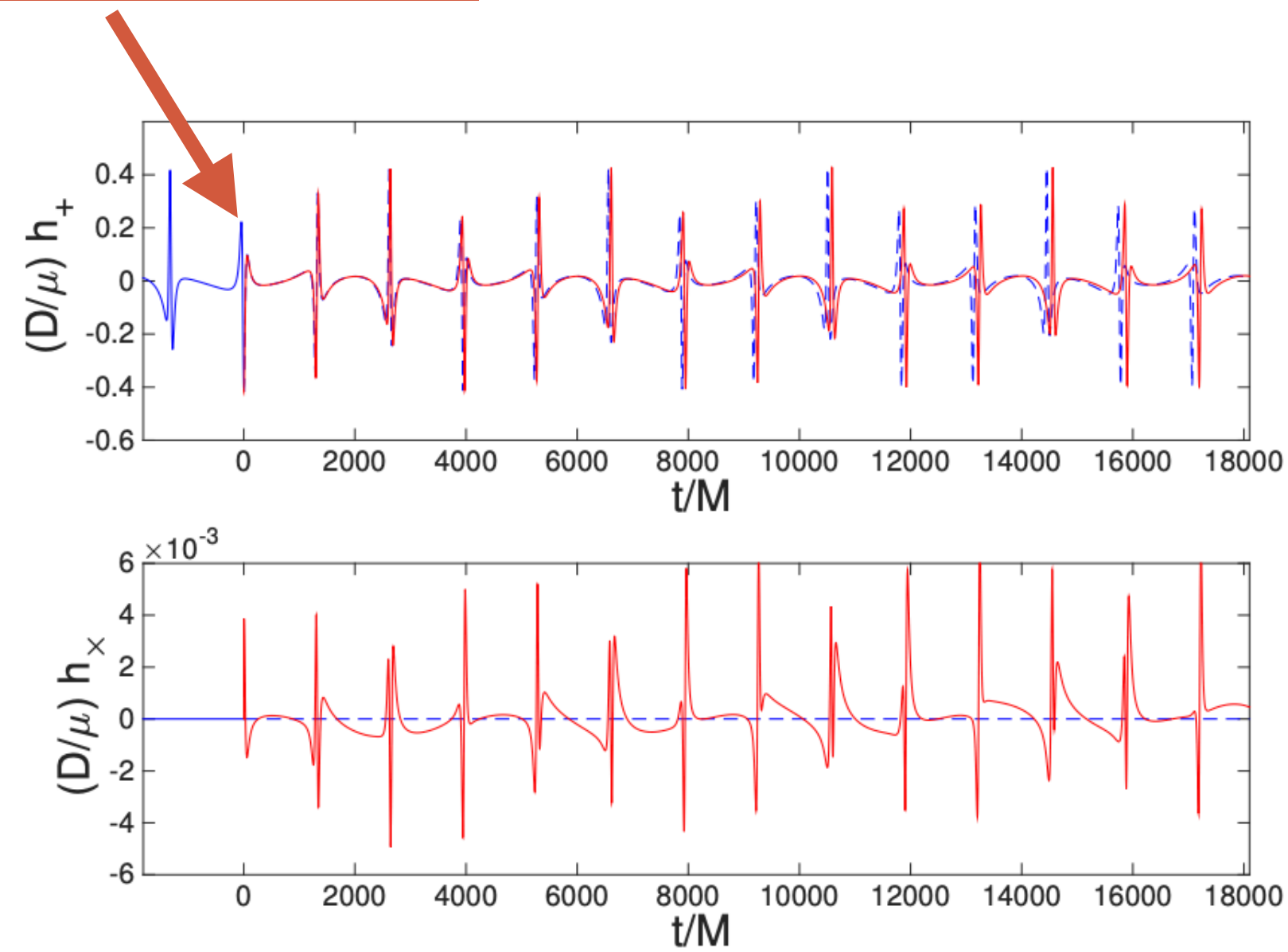
- Testing accretion disk and jet models of AGNs associated with EMRIs ([arXiv:2501.03252](#))
- Finding the distribution of MBH masses and spins (Marta Volonteri *et al* 2005 *ApJ* **620** 69)
- Constraining the rate of accretion in AGNs ([arXiv:2207.10086](#))
- Observing the effect of third bodies on EMRIs ([arXiv:1108.5174](#))

We'll look at:

- Testing GR with b-EMRIs ([arXiv:1801.07060](#))
- Testing the no-hair theorem with EMRIs ([arXiv:gr-qc/0612029](#))



Recoil event injected here!



TESTING GR WITH B-EMRIS ([ARXIV:1801.07060](https://arxiv.org/abs/1801.07060))

- A more exotic type of EMRI where the CO is a BBH

Pre-CO merger:

- We observe a very short EMRI signal $h_1(t)$

Post-CO merger:

- The BBH merges and recoils
- We observe a **different** and longer EMRI signal $h_2(t)$

In effect, a truncated EMRI that precedes a longer-lived one.

TESTING GR WITH B-EMRIS (ARXIV:1801.07060)

We have two tests of GR.

Test 1:

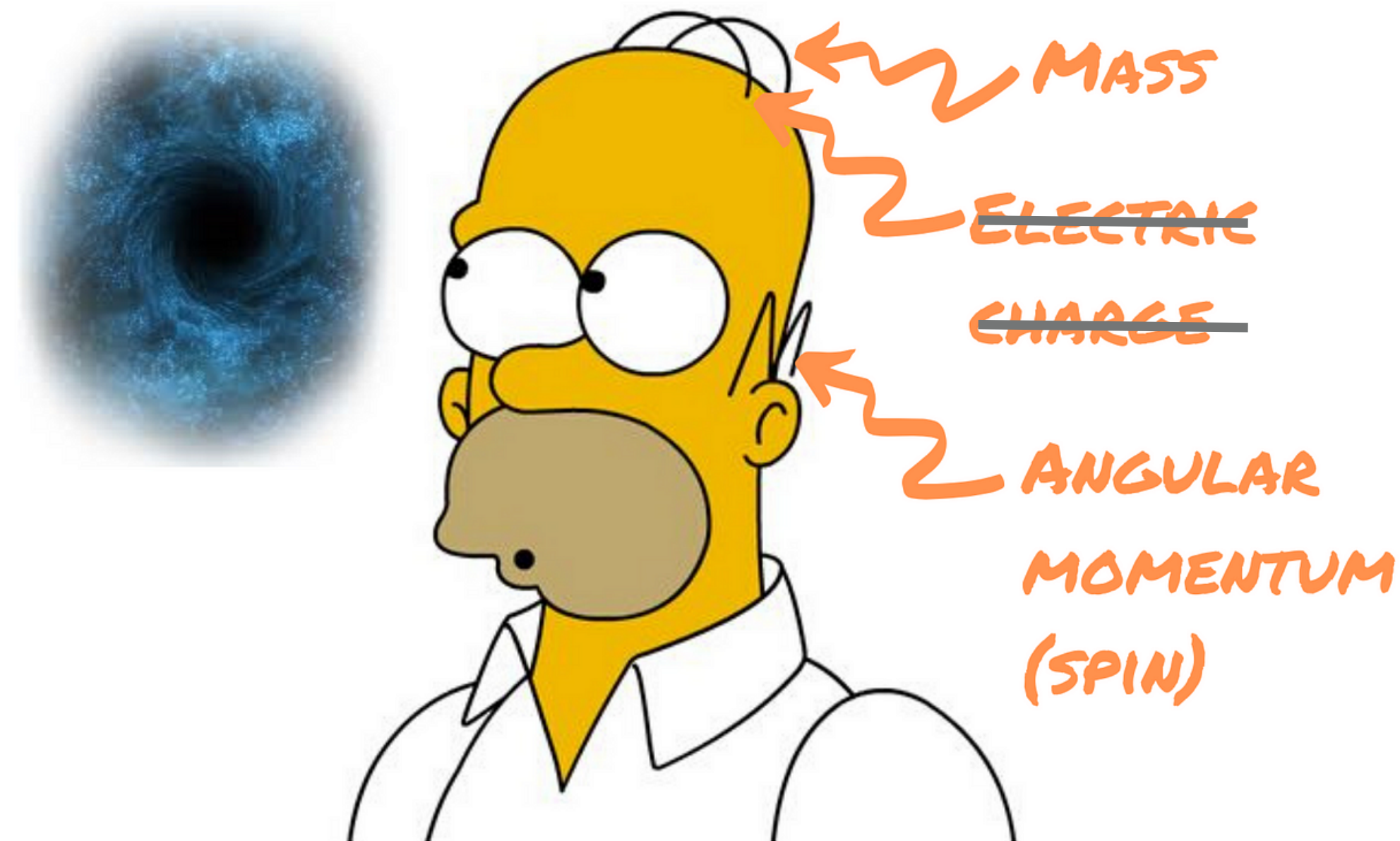
Compare predictions and observations of b-EMRI GWs.

$$h_{true} \neq h_{model} \implies \text{GR fails to model b-EMRI GWs}$$

Test 2:

Compare predictions and observations of the merged BBH's recoil velocity ν and lost mass Δm .

$$(\nu_{true}, \Delta m_{true}) \neq (\nu_{model}, \Delta m_{model}) \implies \text{GR fails to model b-EMRI astrophysics}$$



To understand the no-hair theorem:

- Define a mass quadrupole moment Q , and spin angular momentum S
- In GR, $Q = -\frac{S^2}{M}$
- (M, S) completely characterise Kerr spacetime geometry

The idea:

- Multiple EMRI parameters $(e, \iota, \Phi, \dots)$ have a dependence on Q
- Do a Fisher matrix analysis of parameters $(M, \mu, \dots, Q)$ using $h(\theta)$
- Are there EMRIs with non-GR values for Q ?

EMRIS FOR COSMOLOGY



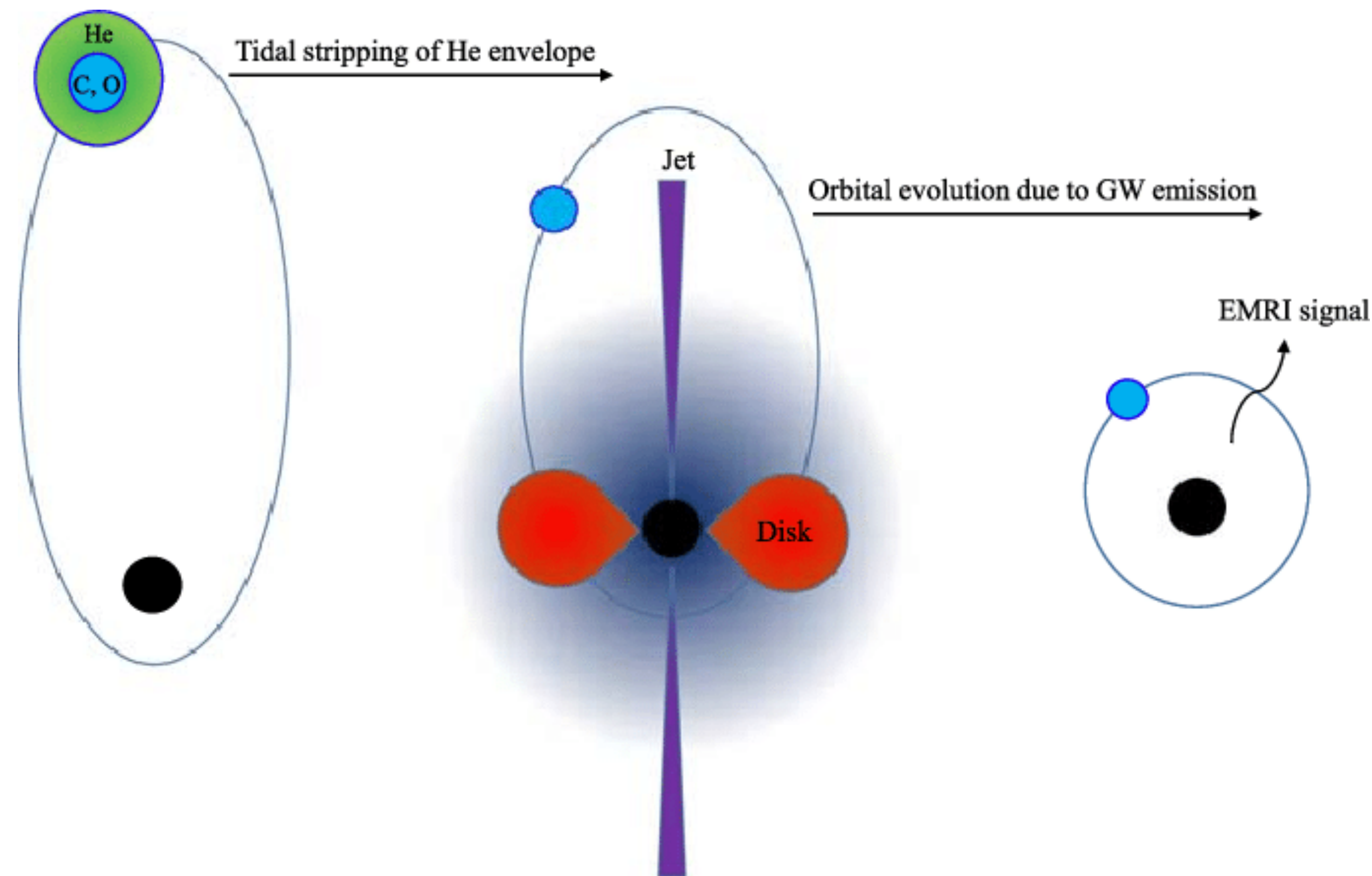
COSMOLOGY APPLICATIONS

For example:

- Improving constraints on cosmological parameters by estimating the fraction of EMRIs from AGNs ([arXiv:2403.04950](#))
- Understanding the impact (or lack of impact) of EMRI SGWs on LISA detections ([arXiv:2007.14403](#))

We'll look at:

- Estimating the Hubble constant with wet EMRIs ([arXiv:2501.03252](#))



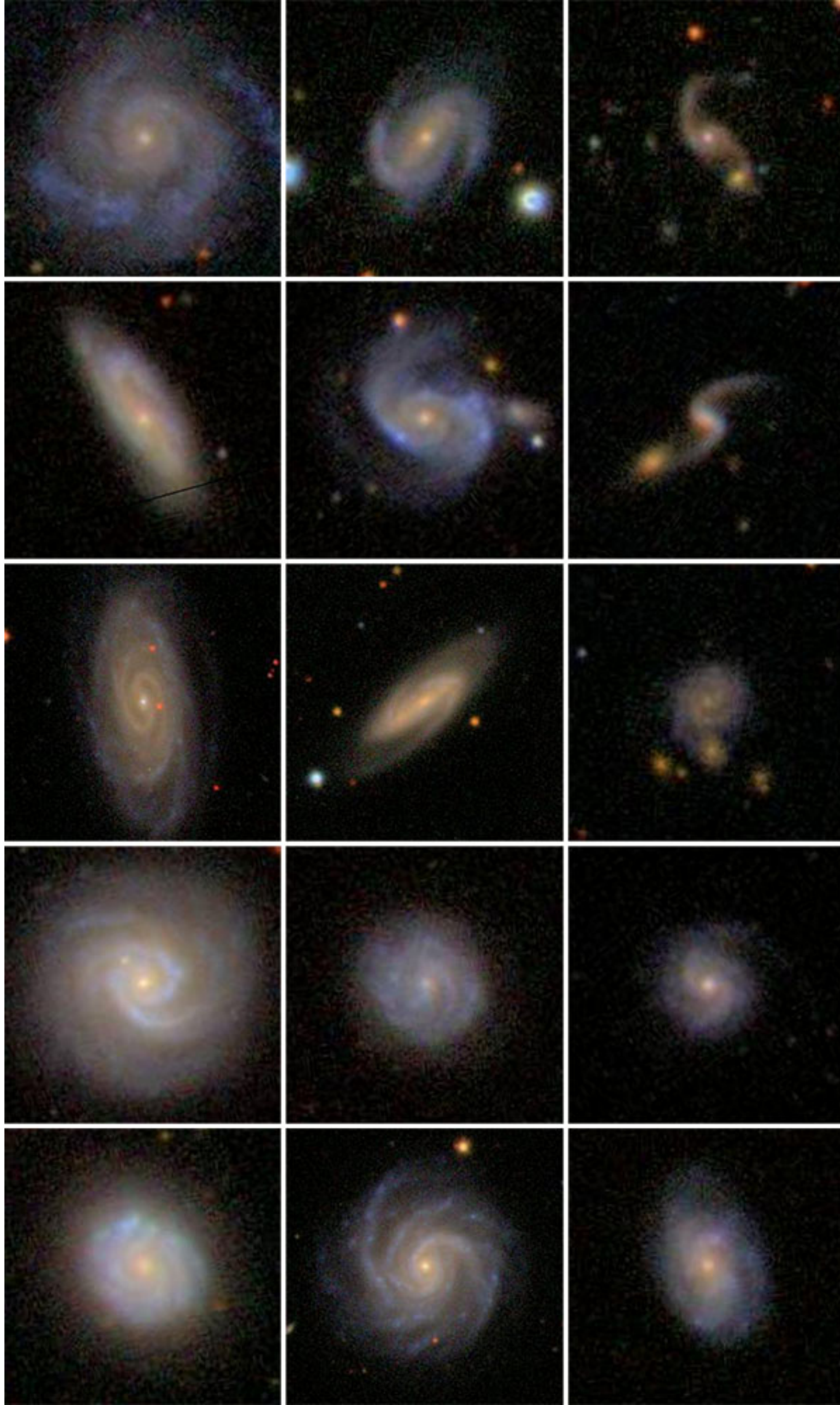
Some formation mechanisms:

- Capture of BH onto accretion disk
- Formation of BH *inside* accretion disk

Example:

- wet EMRI formation through tidal stripping of an MBH and coincident X-ray flare ([arXiv:1911.04117](#))

Can we locate the host galaxy?



How precisely can we localise the host galaxy of a wet EMRI?

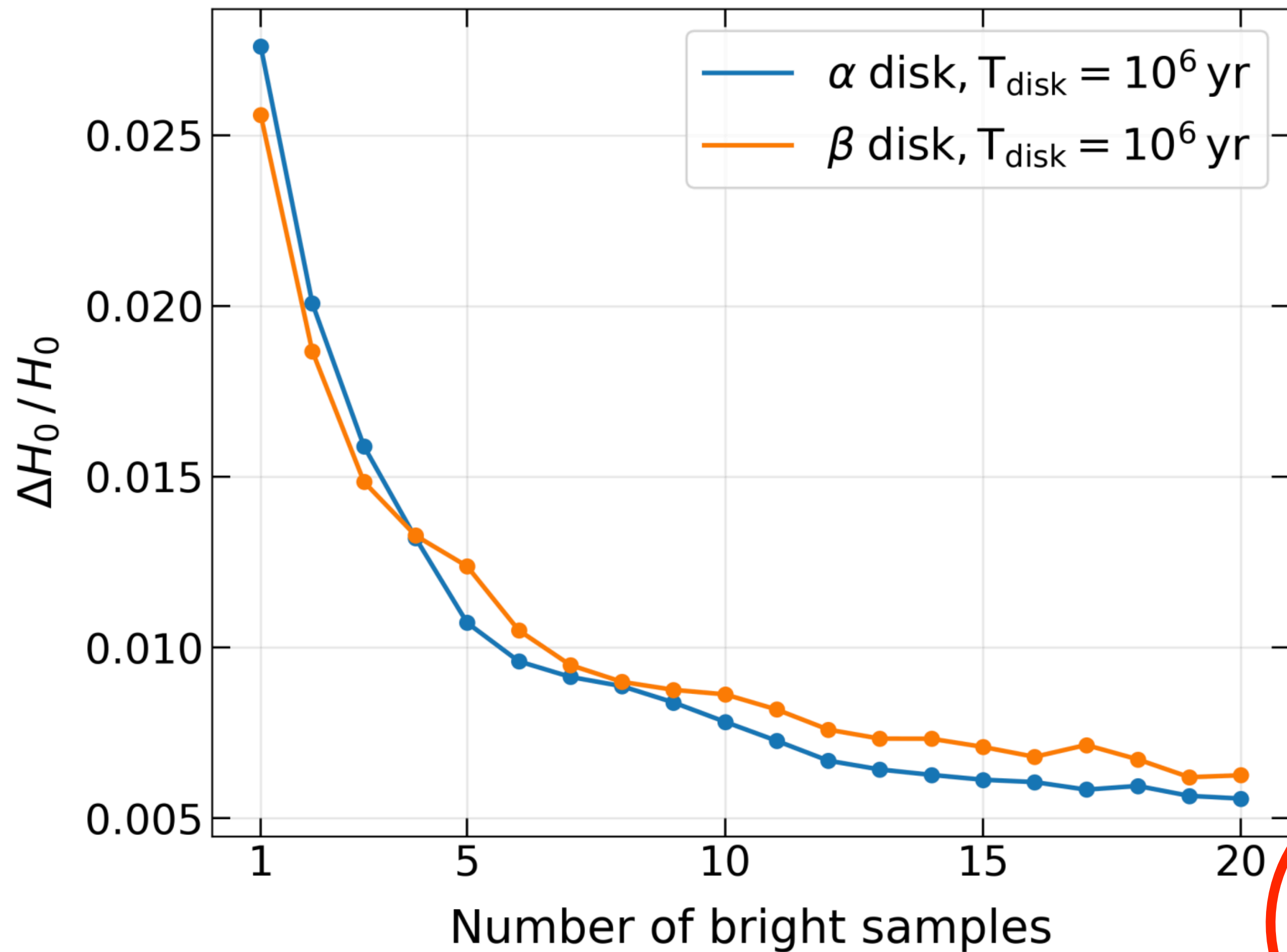
1. Use Fisher matrix formalism to get covariances of sky coordinates Σ_{ij}
2. Calculate a solid angle uncertainty $\Delta\Omega_s$

$$\Delta\Omega_s = 2\pi \sin \theta_s \sqrt{\Sigma_{\theta_s \theta_s} \Sigma_{\phi_s \phi_s} - (\Sigma_{\theta_s \phi_s})^2}$$

How many potential host galaxies N are contained within the sky volume corresponding to $\Delta\Omega_s$?

$N < 1.1$ host galaxies $\implies$ bright siren

$N > 1.1$ host galaxies $\implies$ dark siren



Ingredients:

- One estimated luminosity distance d_L
- One estimated redshift z
- One Λ CDM cosmology model, $\Omega_{m,0}$ & $\Omega_{\Lambda,0}$

Steps:

Define equations for Hubble parameter, and luminosity distance; solve for H_0

$$H(z) = H_0 \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

$$d_L(z) = c(1+z) \int_0^z \frac{dz'}{H(z')}$$

Caveat: we want more than a point estimate!

USING DARK SIREN EMRIS TO ESTIMATE H_0 (ARXIV:2501.03252)

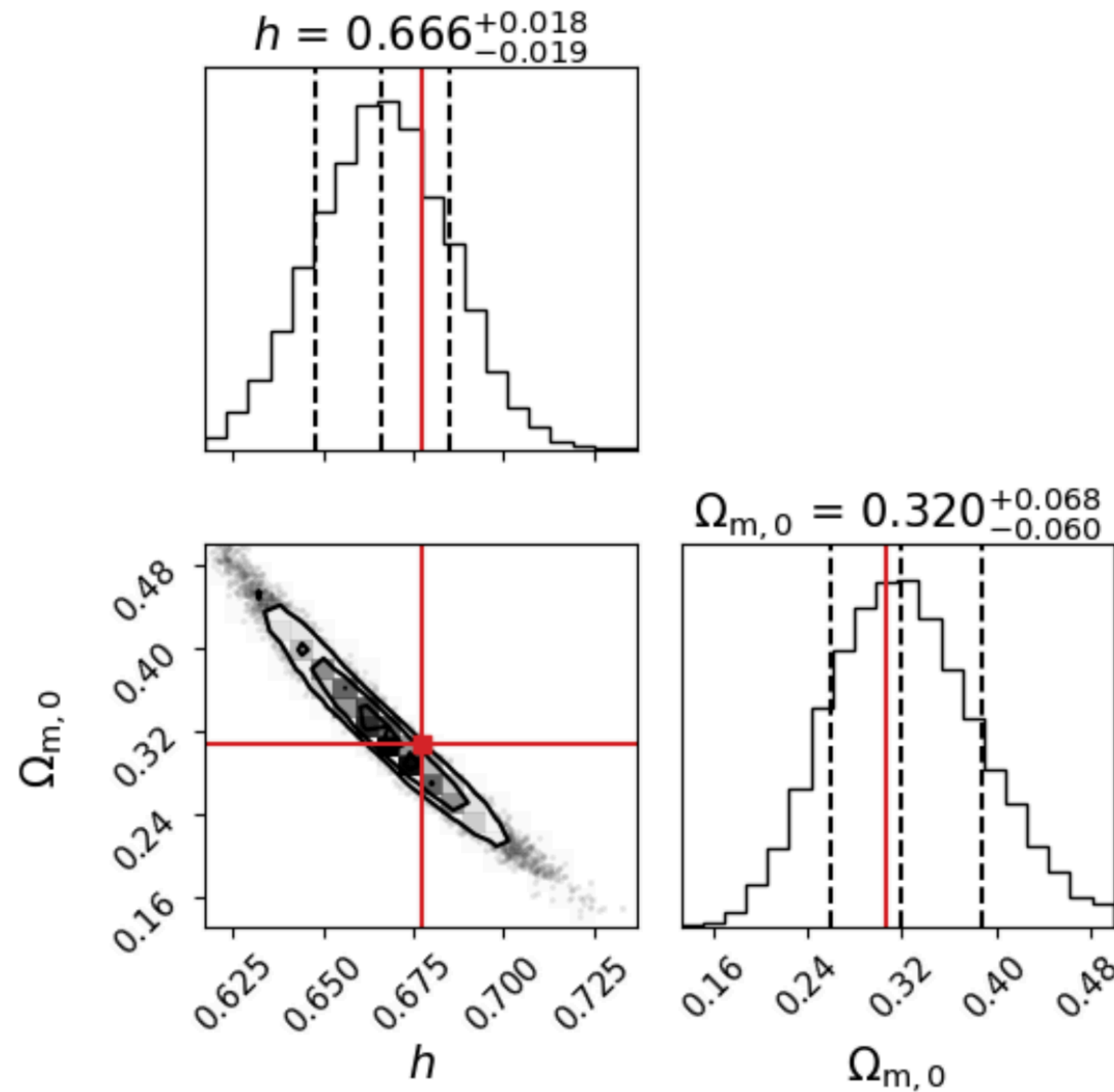
.....

Ingredients:

- Wet EMRI events $\mathbf{D} = (D_1, D_2, D_3, \dots)$
- Parameters $\Theta = (H_0, \Omega_{m,0}, \dots)$
- A Bayesian mentality

Steps:

1. Perform inference of $\Theta | D$ e.g. with MCMC, nested sampling etc.
2. Marginal posteriors reveal the distribution of H_0



IN CONCLUSION

EMRI waveforms are:

- challenging to analyse
- a unique avenue for doing astrophysics and cosmology

EMRI detections will:

- stress-test GR $\implies$ help formulate a more accurate description of gravity
- provide novel estimates of the Hubble constant $\implies$ help in resolving the conflicting estimates in cosmology
- answer many other science questions!