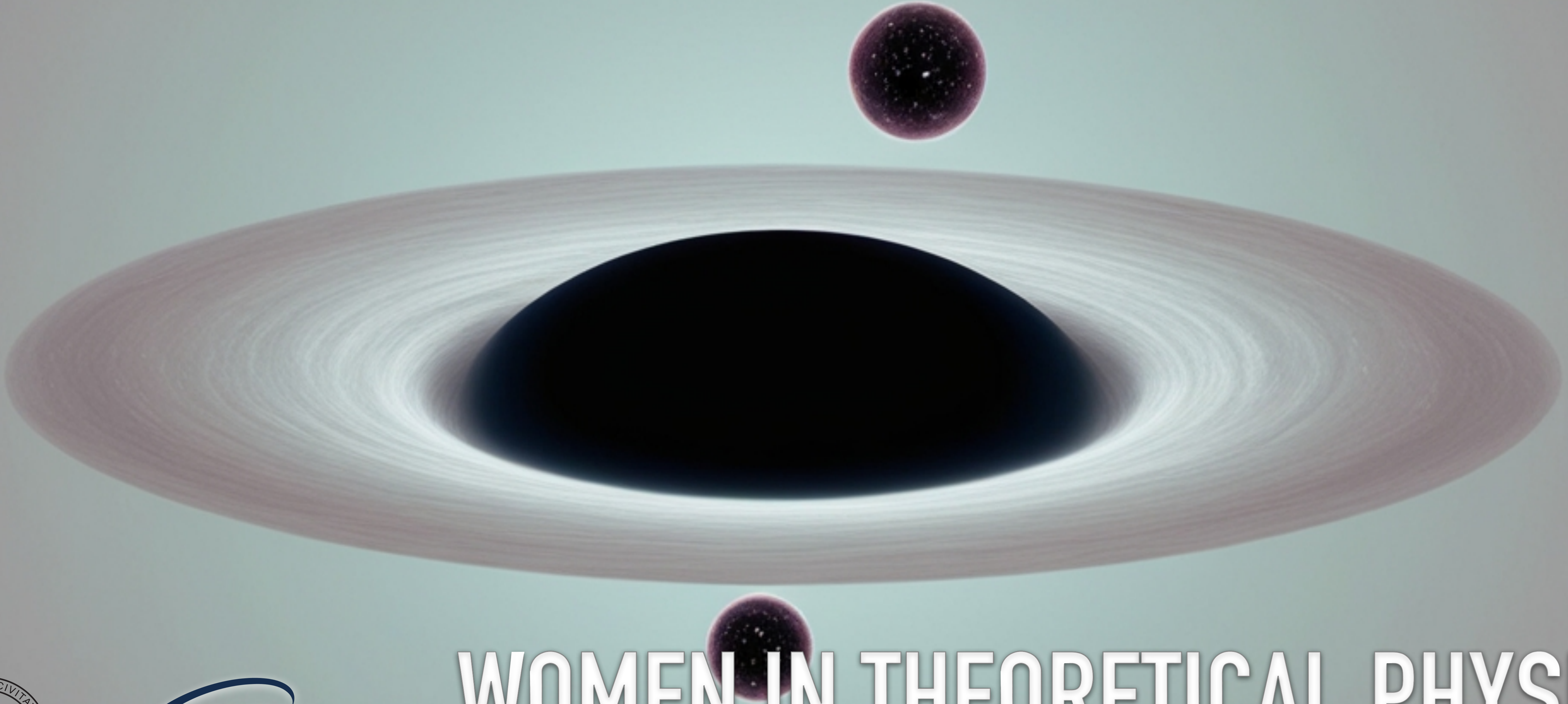

WOMEN IN THEORETICAL PHYSICS

"MILLA BALDO CEOLIN" NATIONAL PRIZE 2023

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October 8, 2024

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DI PERUGIA

Università degli Studi di Perugia

DIPARTIMENTO DI FISICA E GEOLOGIA
Corso di Laurea Magistrale in Fisica

TESI DI LAUREA:

Tidal deformations of a slowly spinning binary system

Candidato:
Marta Cocco

Relatore:
Prof.ssa Marta Orselli

Anno Accademico 2022/2023

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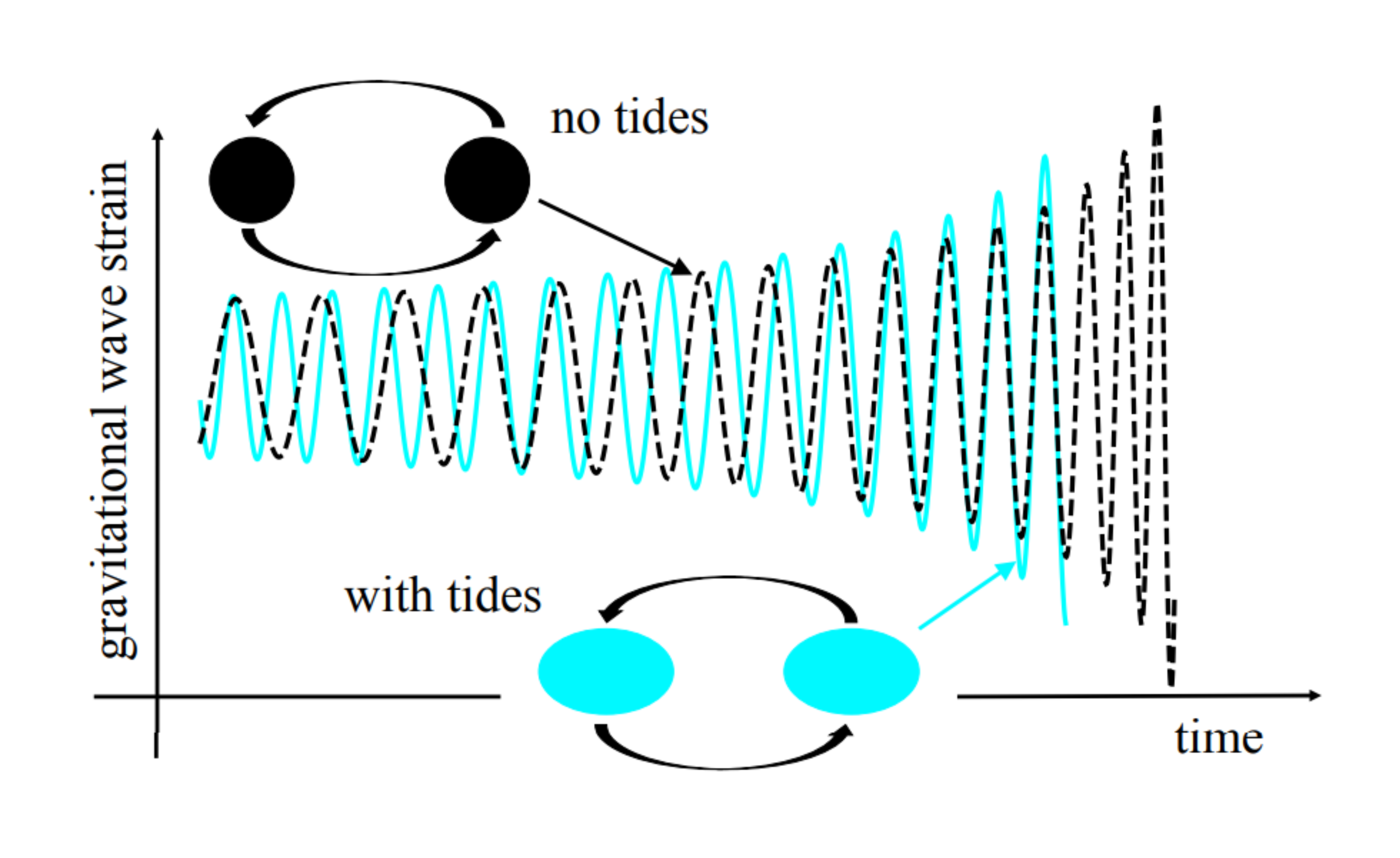
Tidal forces

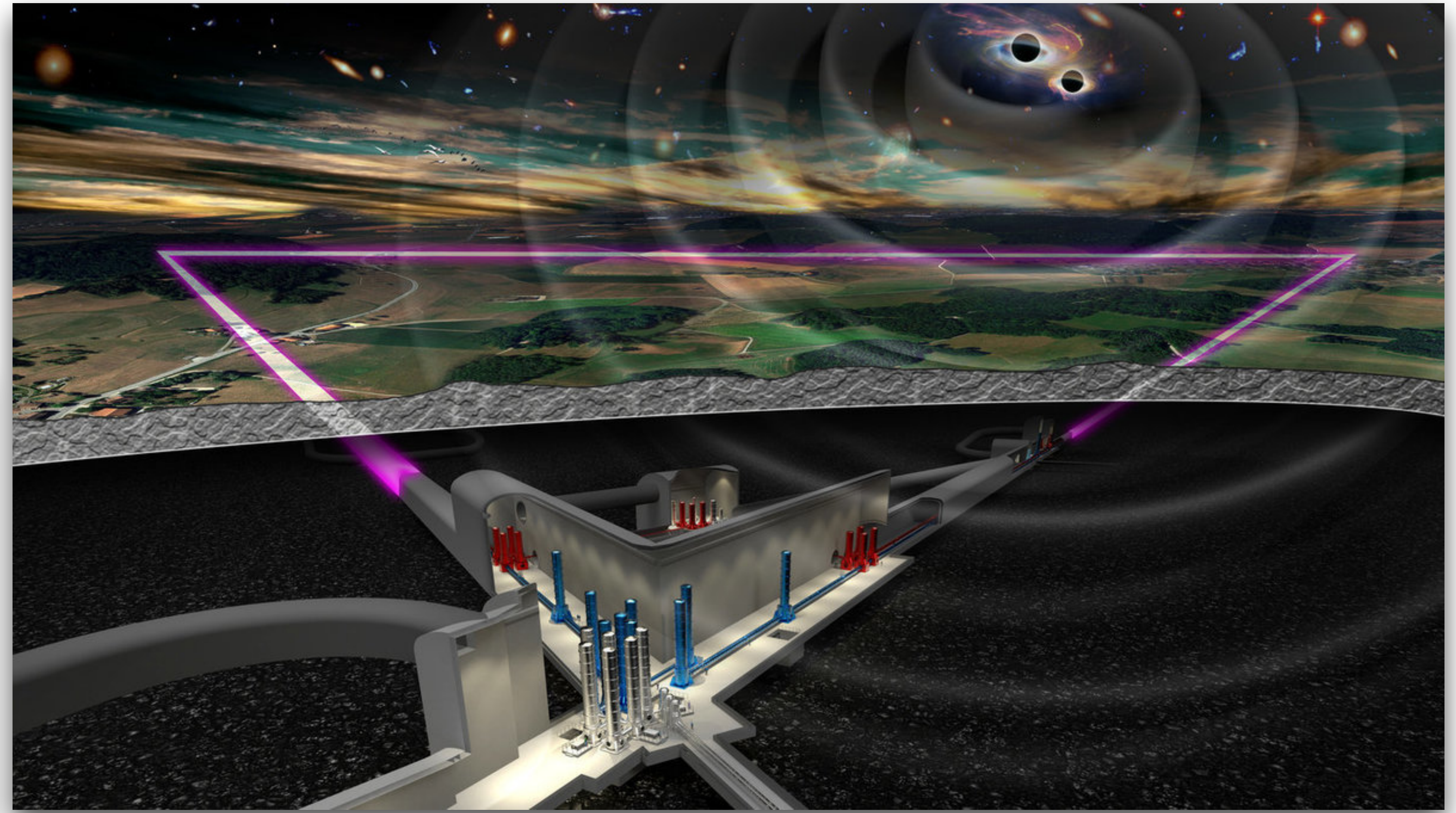
Tidal effects can have an impact on **gravitational waves emitted by binary systems**

[T. Hinderer (2008); E. E. Flanagan and T. Hinderer (2008)]

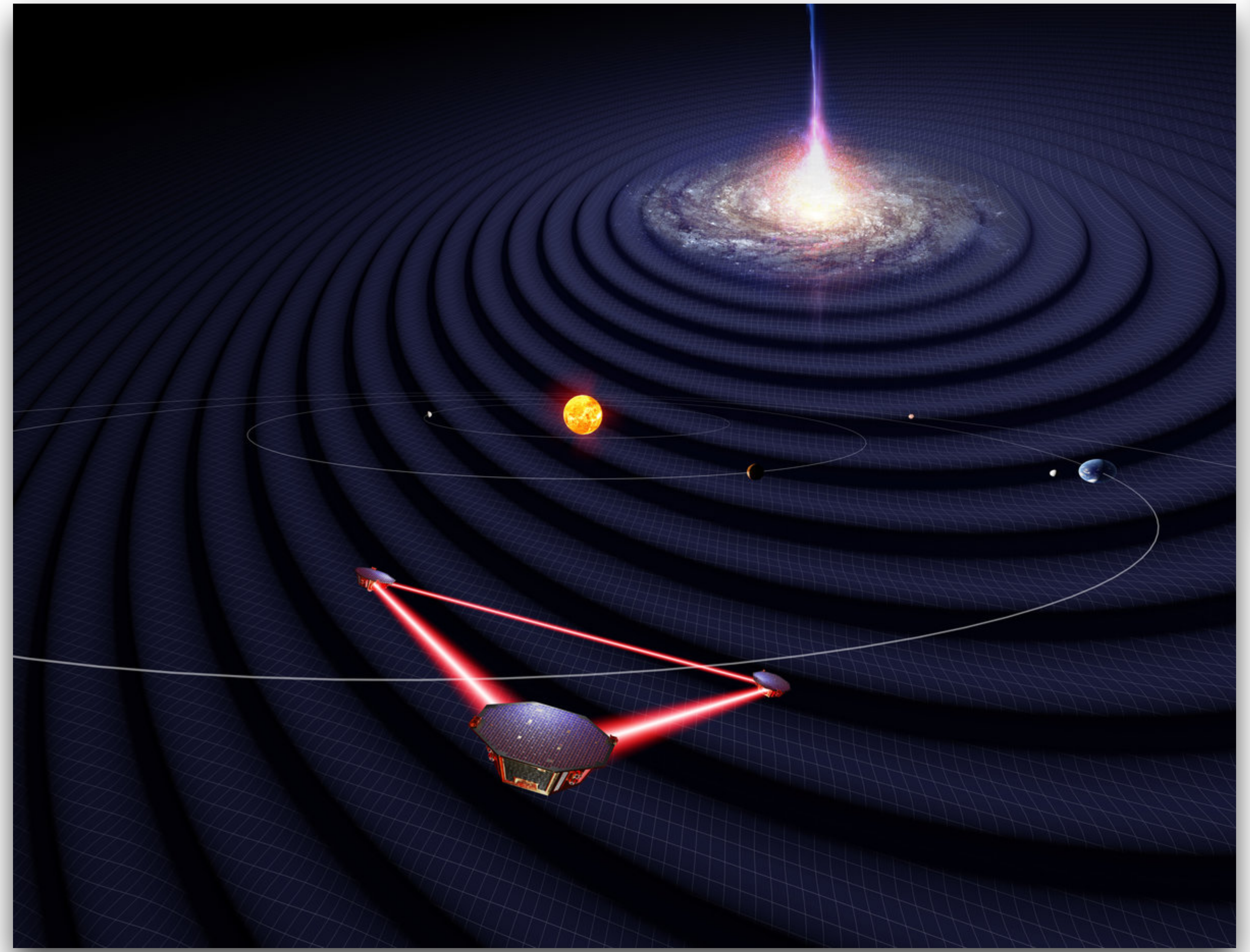


[N. Yunes, M. Coleman Miller, K. Yagi (2022)]

Tidal forces



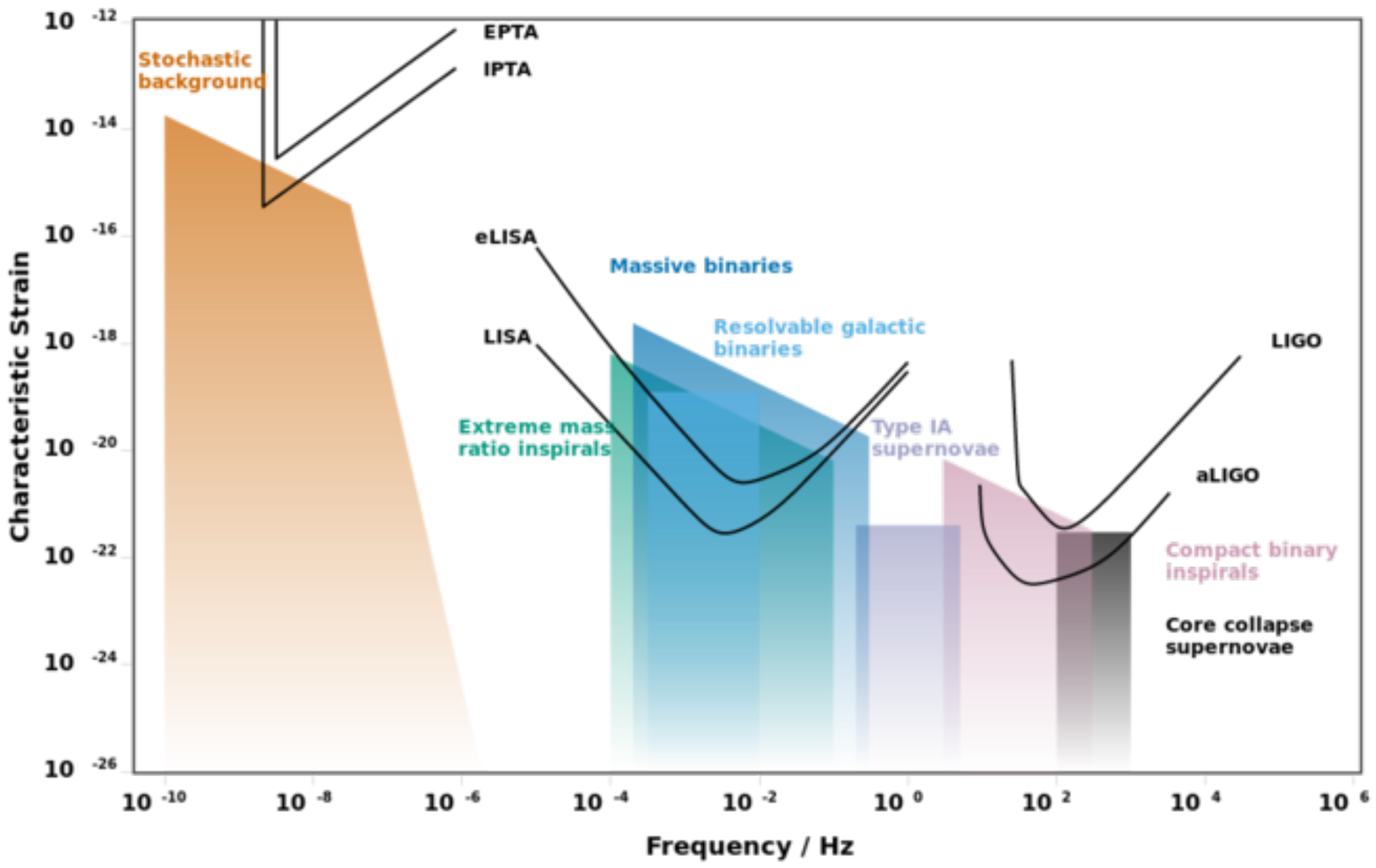
Einstein Telescope [Max Planck Institute]



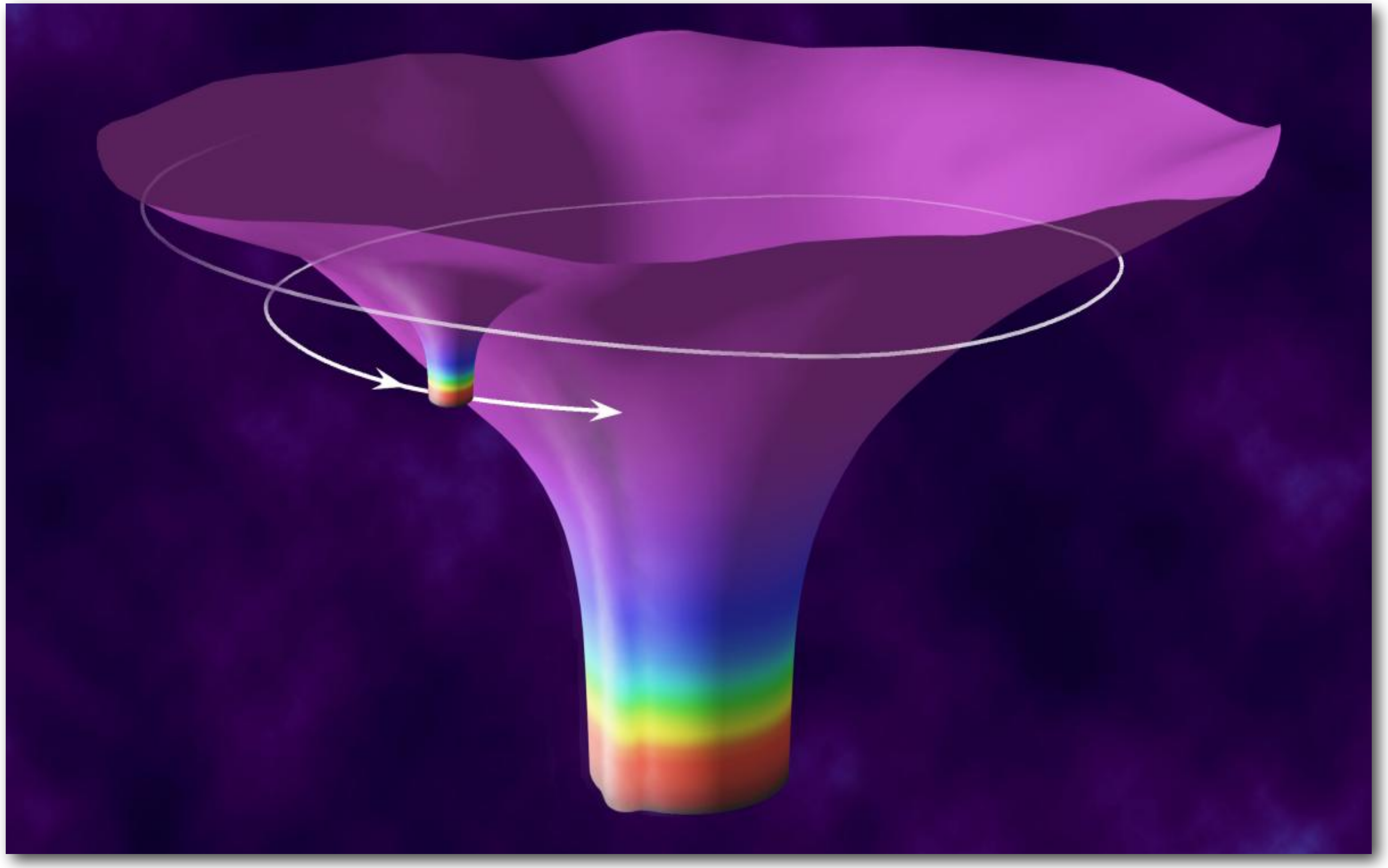
LISA [Max Planck Institute]

The **upcoming generation** of gravitational waves detectors (e.g. LISA, ET) will provide an **improved sensitivity** and a **wider frequency range**

Tidal forces



[C. Moore, R. Cole, C. Berry (2013)]



Extreme mass ratio inspiral [Wikipedia]

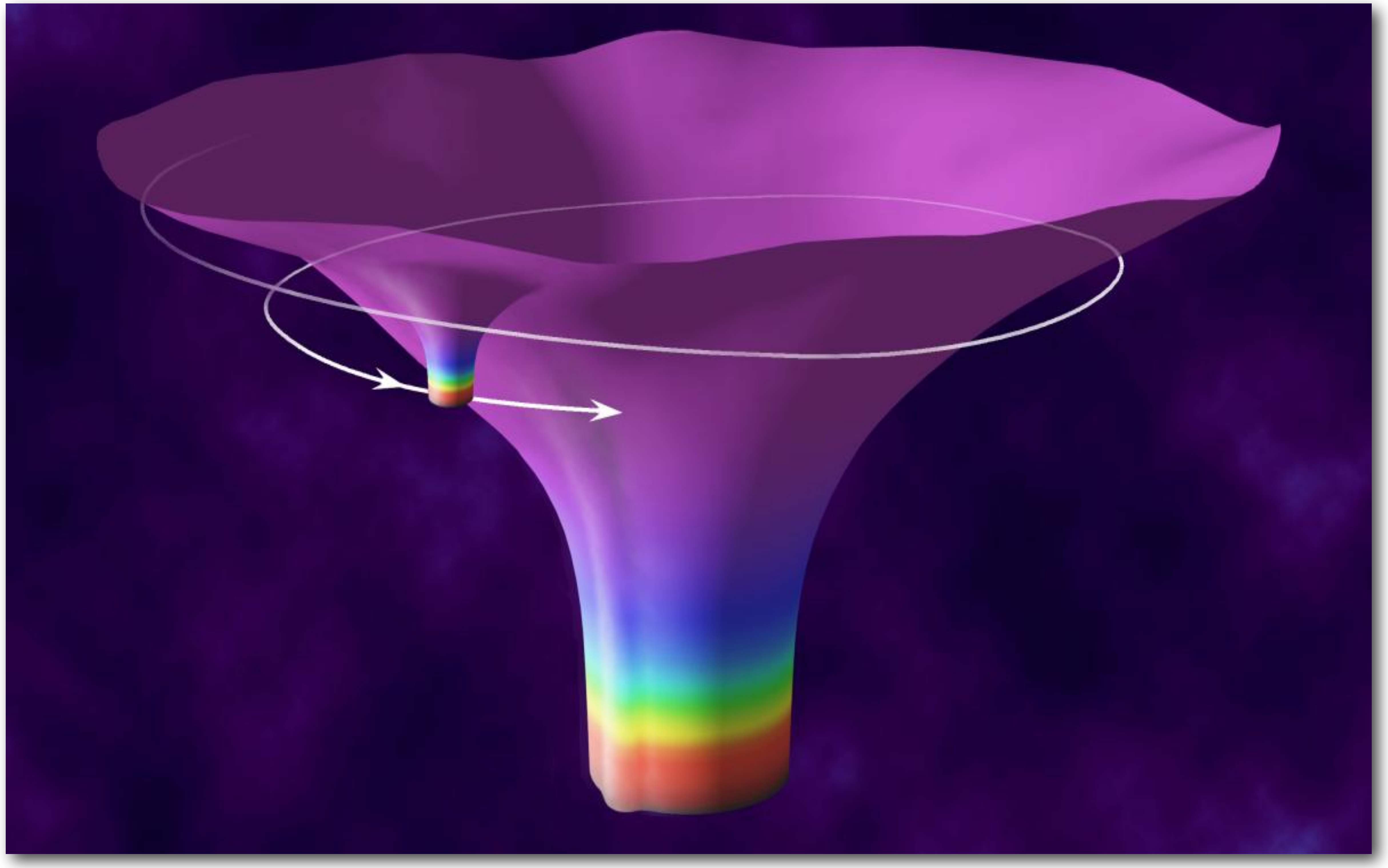
LISA will detect **EMRIs**

EMRIs are a **probe** of the **surrounding environment**: accretion disks, dark matter, **supermassive black hole**

Tidal forces

In my Master's thesis, I studied:

- the effects of **tidal forces**
- exerted by a third supermassive black hole
- on the **EMR binary system's dynamics**



Extreme mass ratio inspiral [Wikipedia]

LISA will detect **EMRIs**

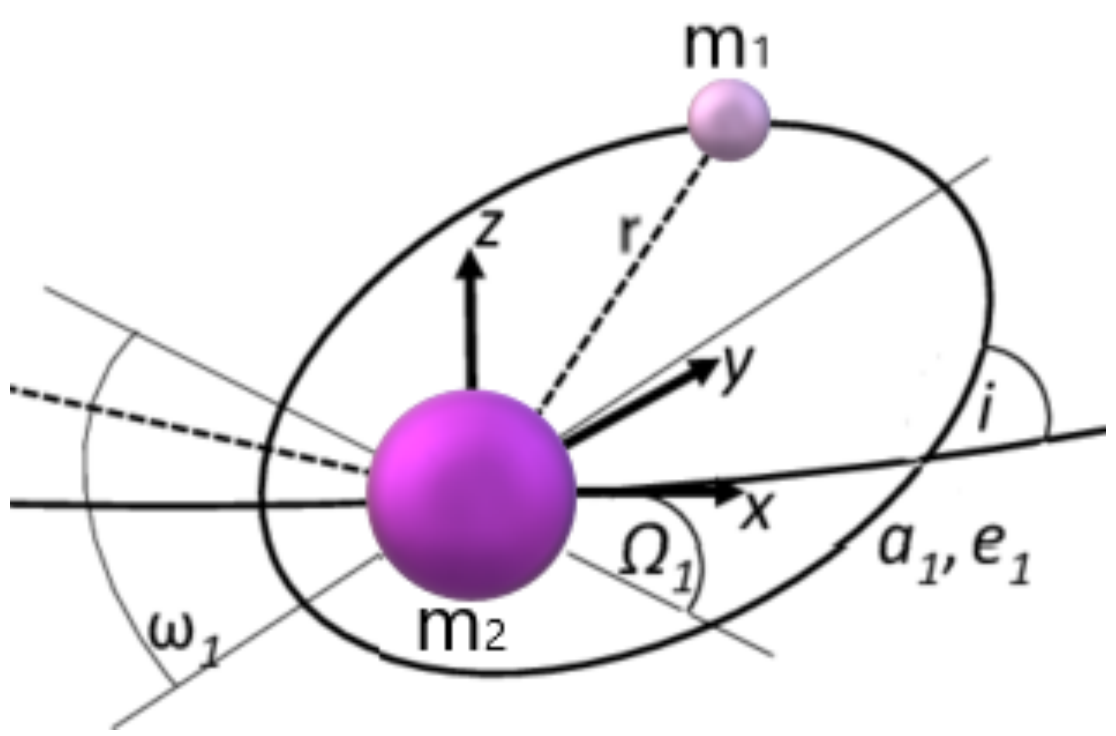
EMRIs are a **probe** of the **surrounding environment**: accretion disks, dark matter, **supermassive black hole**

But how can we study all of this, analytically?

Tidal effects on an EMR system

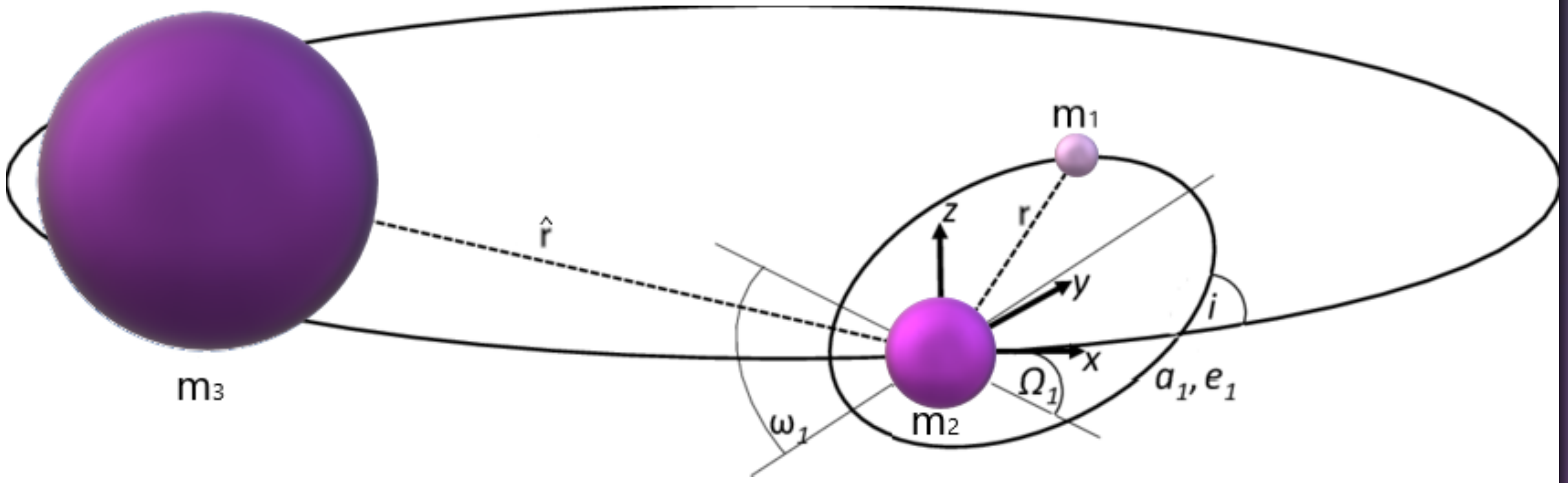
Hierarchical condition

$$\underbrace{m_1 \ll m_2}_{\text{EMR}}$$



[B. Deme (2021)]

Tidal effects on an EMR system



[B. Deme (2021)]

Hierarchical condition

$$\underbrace{m_1 \ll m_2}_{\text{EMR}} \ll m_3$$

↓

Small-tide approximation

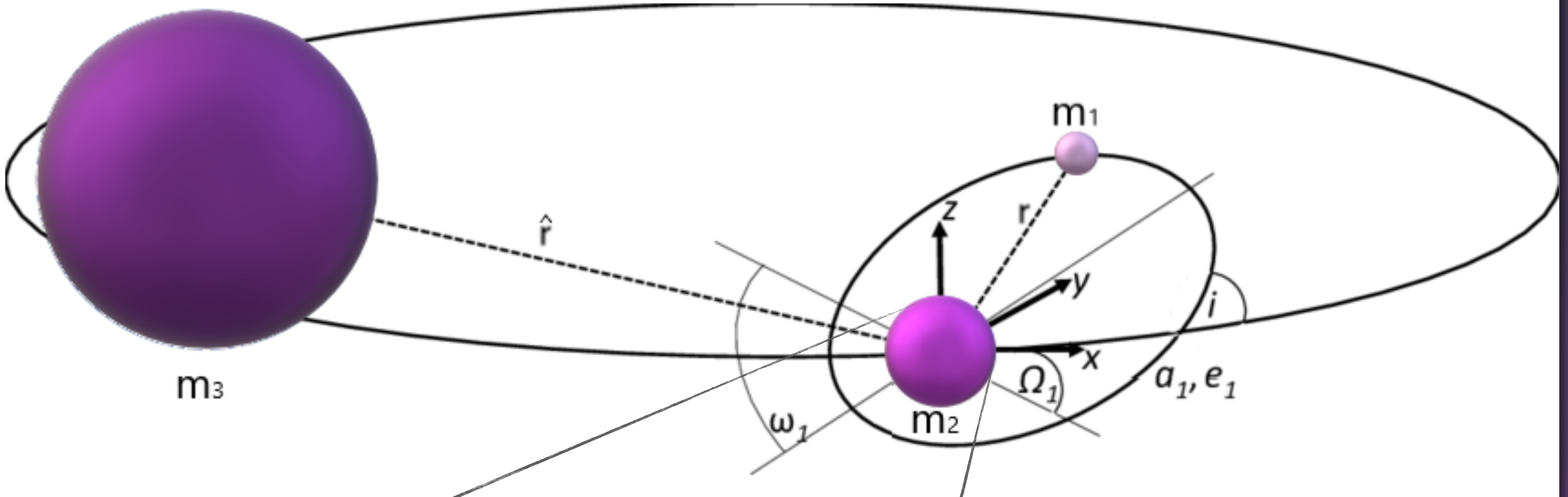
- The presence of the external black hole is written through **tidal forces**, small corrections to spacetime of the inner binary
- Quadrupole tidal moments $\sim \mathcal{O}\left(\frac{m_2}{\mathcal{R}}\right)^2$

Tidal effects on an EMR system

- Previous analysis: m_2 was non-rotating black hole
  [F. Camilloni, G. Grignani, T. Harmark, R. Oliveri, M. Orselli and D. Pica (2023)]

- Now: m_2 is **slowly rotating**

- **Coupling terms** between the black hole's spin χ_2 and the quadrupole tidal moments



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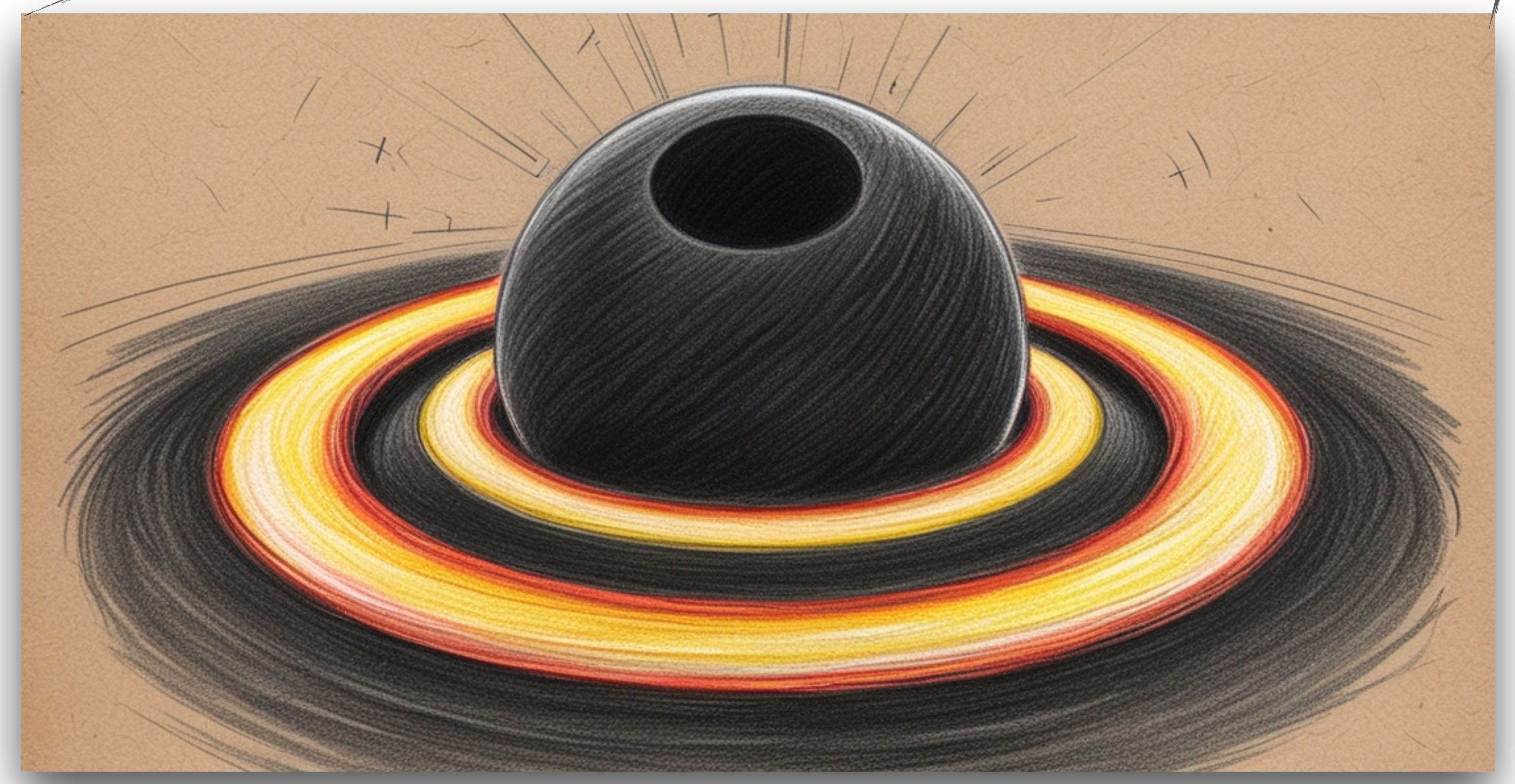
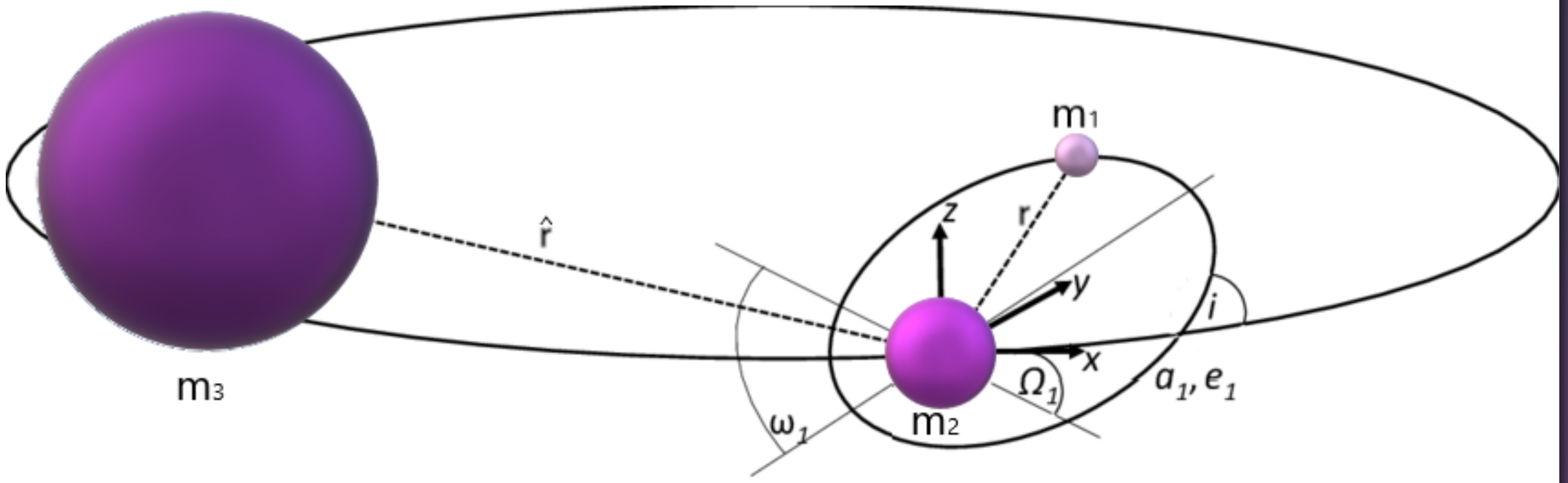


Tidal effects on an EMR system

The particle m_1 moves in a metric $g_{\mu\nu}$
[E. Poisson (2015)] :



[B. Deme (2021)]

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

non-rotating black hole

→ black hole's (m_2) slow rotation $\propto \chi_2 \ll 1$

→ presence of the external black hole $m_3 \propto \mathscr{E}_{ab}, \mathscr{B}_{ab}$

→ coupling between the spin and tidal moments $\propto \chi_2\mathscr{E}_{ab}, \chi_2\mathscr{B}_{ab}$

Tidal effects on an EMR system

➤ We can study the dynamics of the test particle m_1 in the EMR system, in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu}$$

$$\mathscr{A} = \mathscr{A}_0$$

Radius r

Energy E

Angular momentum L

➤ the **ISCO**, which stands for the Innermost Stable Circular Orbit (massive particles)

➤ the **photon sphere** (massless particles)

Tidal effects on an EMR system

➤ We can study the dynamics of the test particle m_1 in the EMR system, in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h^{(rot)}_{\mu\nu}$$

Radius r

Energy E

Angular momentum L

$$\mathscr{A} = \mathscr{A}_0 + \chi_2 \, \mathscr{A}_{rot}$$

- ➤ the **ISCO**, which stands for the Innermost Stable Circular Orbit (massive particles)
- ➤ the **photon sphere** (massless particles)

Tidal effects on an EMR system

- We can study the dynamics of the test particle m_1 in the EMR system, in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h^{(rot)}_{\mu\nu} + h^{(tidal)}_{\mu\nu}$$

Radius r

Energy E

Angular momentum L

$$\mathscr{A} = \mathscr{A}_0 + \chi_2 \, \mathscr{A}_{rot} + \eta \, \mathscr{A}_{tidal}$$

- the **ISCO**, which stands for the Innermost Stable Circular Orbit (massive particles)
- the **photon sphere** (massless particles)

Tidal effects on an EMR system

➤ We can study the dynamics of the test particle m_1 in the EMR system, in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}^{(rot)} + h_{\mu\nu}^{(tidal)} + h_{\mu\nu}^{(coupling)}$$

$$\mathscr{A} = \mathscr{A}_0 + \chi_2 \mathscr{A}_{rot} + \eta \mathscr{A}_{tidal} + (\chi_2 \eta + \eta_1)\mathscr{A}_{coupling}$$

Radius r

Energy E

Angular momentum L

➤ the **ISCO**, which stands for the Innermost Stable Circular Orbit (massive particles)

➤ the **photon sphere** (massless particles)

Tidal effects on an EMR system

$$r_{ISCO} = 6m_2 - 4\chi_2\sqrt{\frac{2}{3}}\, m_2 \cos\beta + \eta\left(3072 m_2 - \chi_2 \frac{27320}{3}\sqrt{\frac{2}{3}} m_2 \cos\beta\right) + \eta_1(\chi_2)\,\frac{16}{3}\sqrt{\frac{2}{3}} m_2$$

If we place the inner binary in an ISCO around a Kerr BH of mass m_3:

$$\eta = \frac{m_2^2\, m_3}{2\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\left[1 - \frac{1}{2}(1 + 4\sin^2\gamma)\sin^2\beta\right]$$

$$\eta_1 = \chi_2 \frac{m_2^2\, m_3}{\left(\hat{r}^{\sigma}_{ISCO}\right)^3} \cos\beta$$

Tidal effects on an EMR system

$$r_{ISCO} = 6m_2 - 4\chi_2\sqrt{\frac{2}{3}}\,m_2\cos\beta + \eta\left(3072m_2 - \chi_2\frac{27320}{3}\sqrt{\frac{2}{3}}m_2\cos\beta\right) + \eta_1(\chi_2)\frac{16}{3}\sqrt{\frac{2}{3}}m_2$$

0 0

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$$\eta_1 = \chi_2\frac{m_2^2\,m_3}{\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\cos\beta$$

0

In the non-rotating case,

Tidal effects on an EMR system

$$r_{ISCO} = 6m_2 - 4\chi_2\sqrt{\frac{2}{3}}\, m_2 \cos\beta + \eta\left(3072m_2 - \chi_2\frac{27320}{3}\sqrt{\frac{2}{3}}m_2\cos\beta\right) + \eta_1(\chi_2)\frac{16}{3}\sqrt{\frac{2}{3}}m_2$$

→ 0 0 → 0

If we place the inner binary in an ISCO around a Kerr BH of mass m_3:

$$\eta = \frac{m_2^2\, m_3}{2\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\left[1 - \frac{1}{2}(1 + 4\sin^2\gamma)\sin^2\beta\right] = 0 \rightarrow \boxed{\sin^2\beta^*(\gamma) = \frac{2}{1 + 4\sin^2\gamma}}$$

$$\eta_1 = \chi_2 \frac{m_2^2\, m_3}{\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\cos\beta \rightarrow 0$$

In the non-rotating case, there exist orbital configurations in which the tidal effects vanish

Tidal effects on an EMR system

$$r_{ISCO} = 6m_2 - 4\chi_2\sqrt{\frac{2}{3}}\, m_2 \cos\beta + \eta\left(3072 m_2 - \chi_2 \frac{27320}{3}\sqrt{\frac{2}{3}} m_2 \cos\beta\right) + \eta_1(\chi_2)\,\frac{16}{3}\sqrt{\frac{2}{3}} m_2$$

→ 0 !!!

If we place the inner binary in an ISCO around a Kerr BH of mass m_3:

$$\eta = \frac{m_2^2\, m_3}{2\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\left[1 - \frac{1}{2}(1 + 4\sin^2\gamma)\sin^2\beta\right] = 0 \;\rightarrow\; \sin^2\beta^*(\gamma) = \frac{2}{1 + 4\sin^2\gamma}$$

$$\eta_1 = \chi_2 \frac{m_2^2\, m_3}{\left(\hat{r}^{\sigma}_{ISCO}\right)^3}\cos\beta$$

!!!

In the rotating case, there exist orbital configurations in which the tidal effects vanish, but we have a residual tidal effect thanks to the spin coupling!

Does this project have a future?

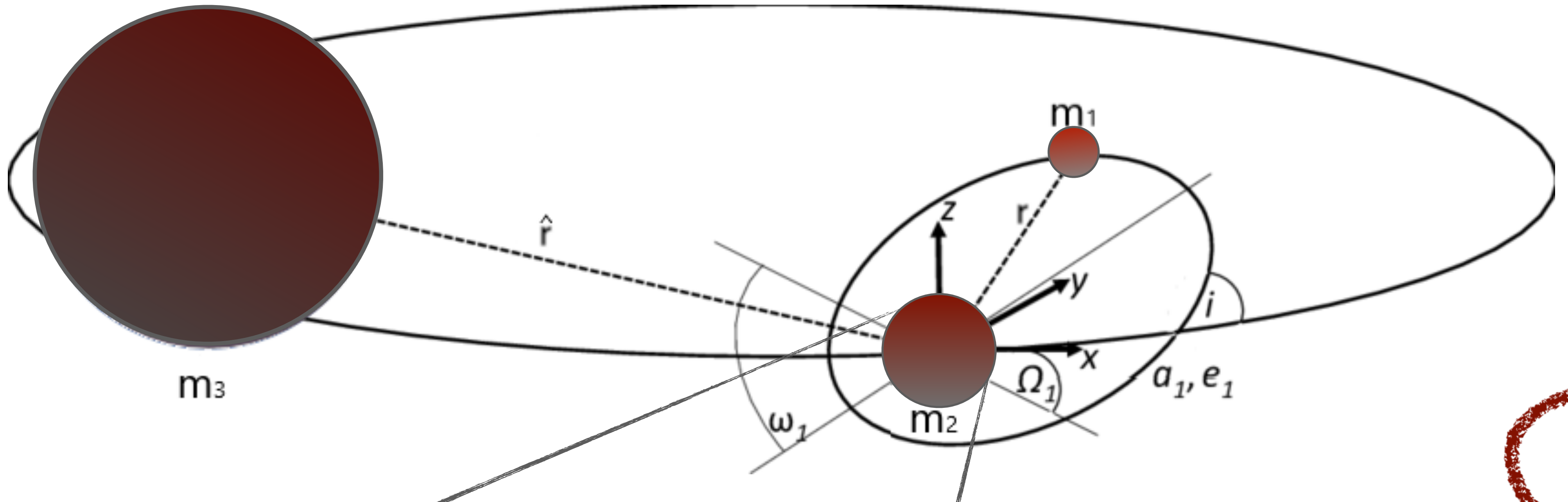
My academic life, now

PhD Program:

START:
1/11/2023 (UNIPG)
1/12/2023 (NBI)

END (planned):
11/2026

Tidal deformations in hierarchical 3-body systems



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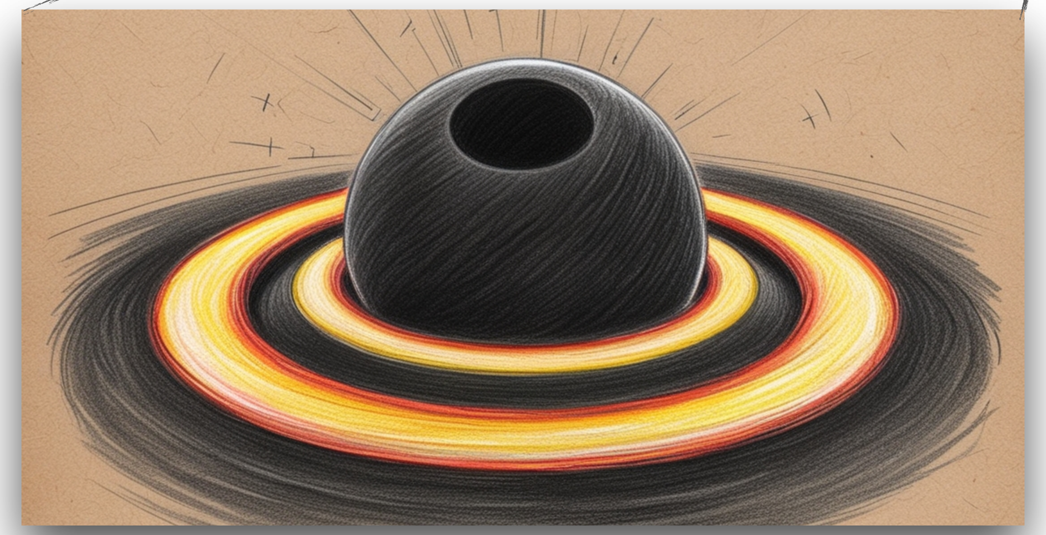

Strong field spin couplings in hierarchical triples*

Same scenario of my Master's thesis, but now the perturbed black hole m_2 is ~~slowly~~ **ROTATING**!

→ Linear perturbations to the Kerr metric:

Teukolsky equation + metric reconstruction techniques

*work in progress |M. Cocco, G. Grignani, T. Harmark, M. van de Meent, M. Orselli, D. Pereñiguez

PhD Program:

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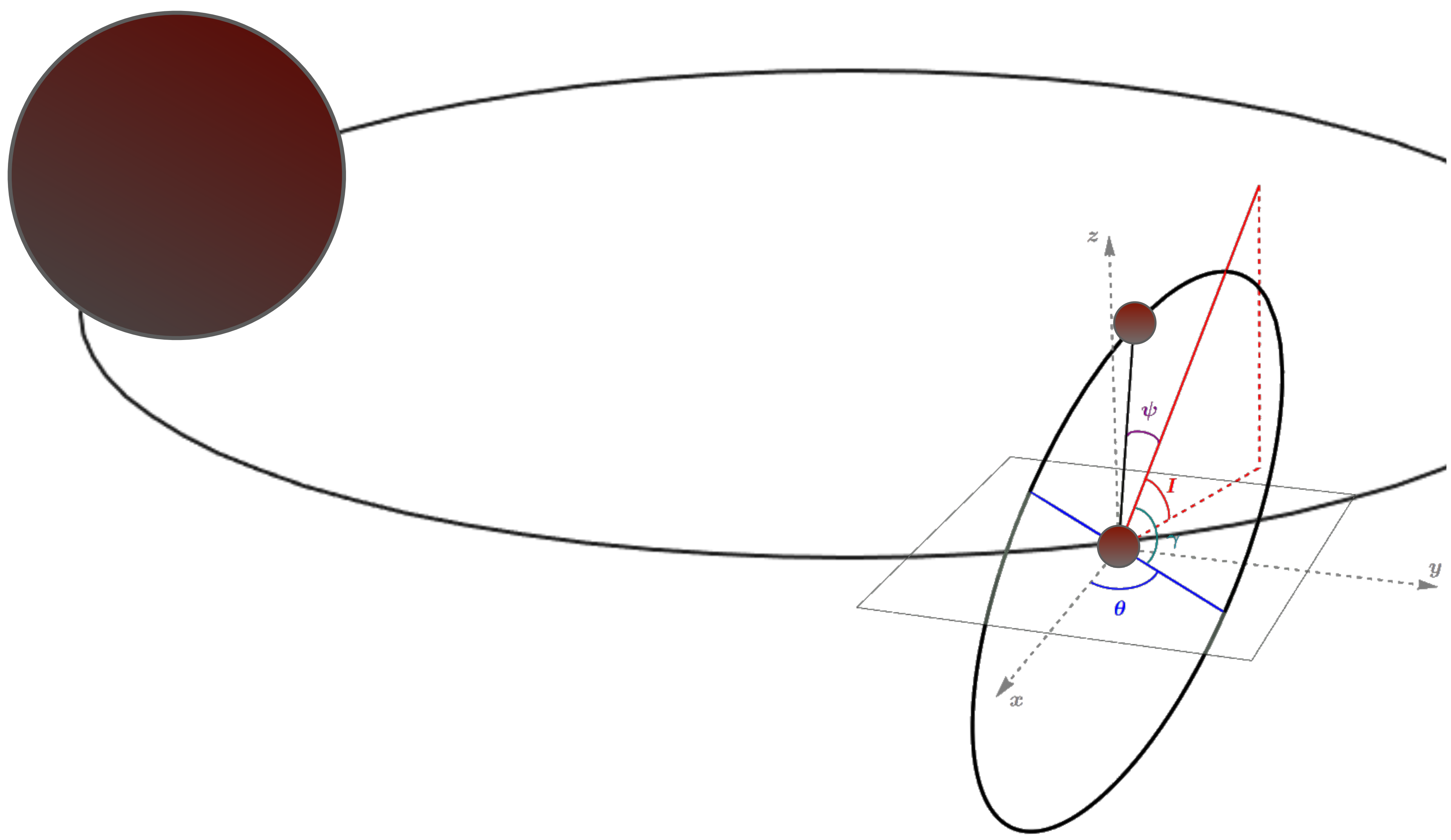
Tidal deformations in hierarchical 3-body systems

Precession resonance in a 3-body system in a Strong Gravity regime*

A BHB with COMPARABLE masses perturbed by a black hole



*in preparation |M. Cocco, G. Grignani, T. Harmark, M. Orselli, D. Pica

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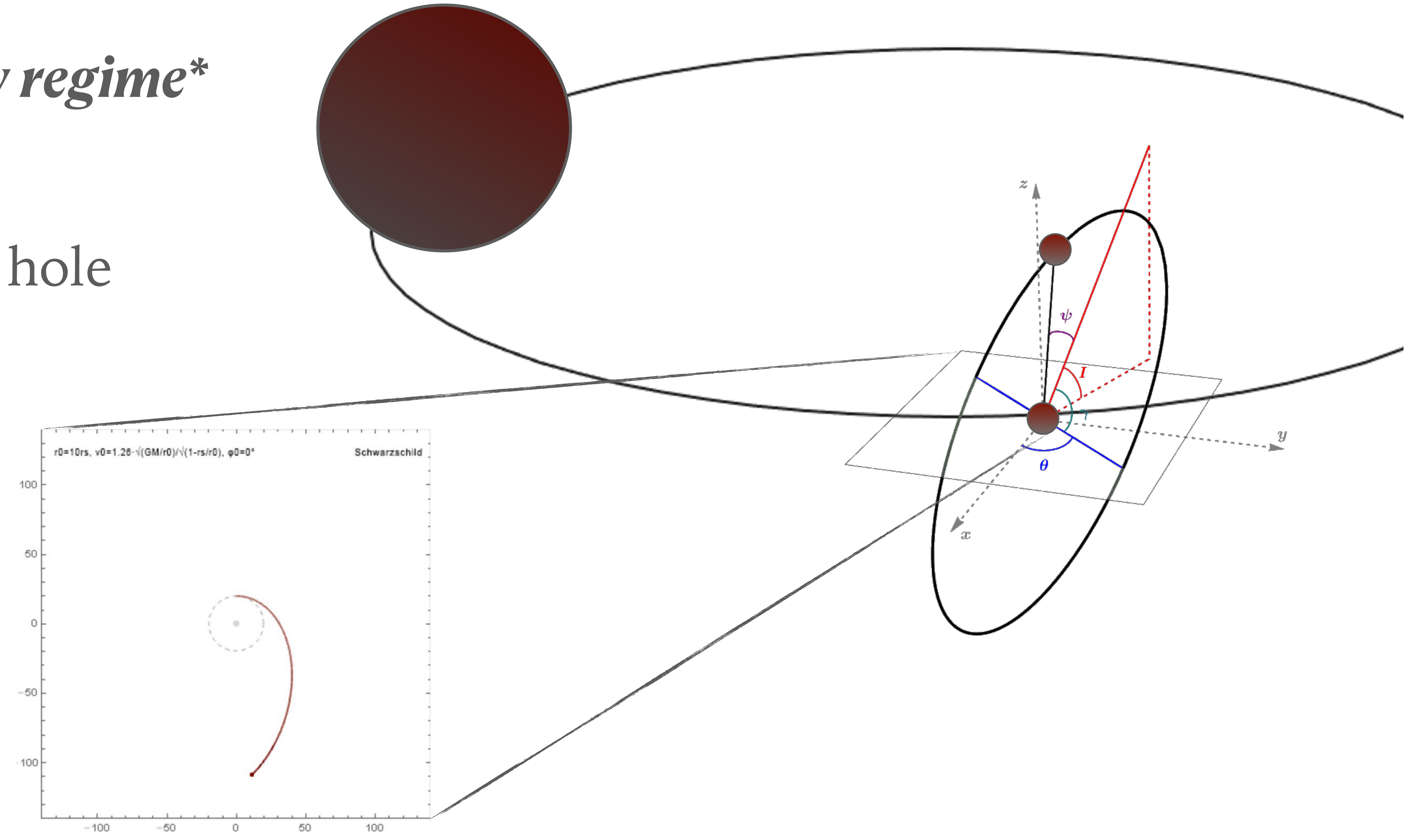

Precession resonance:

excitation in the inner eccentricity

*in preparation |M. Cocco, G. Grignani, T. Harmark, M. Orselli, D. Pica

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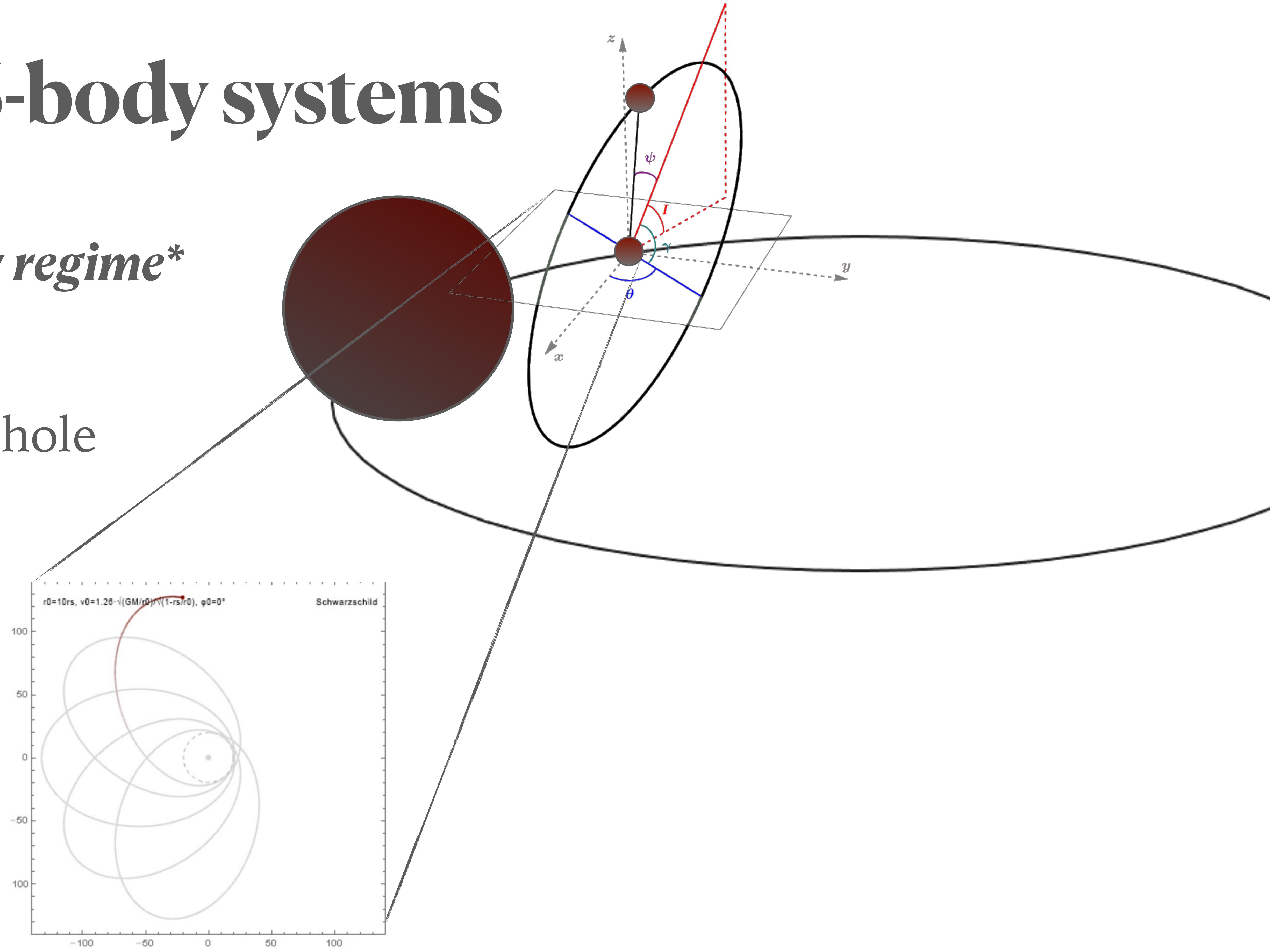

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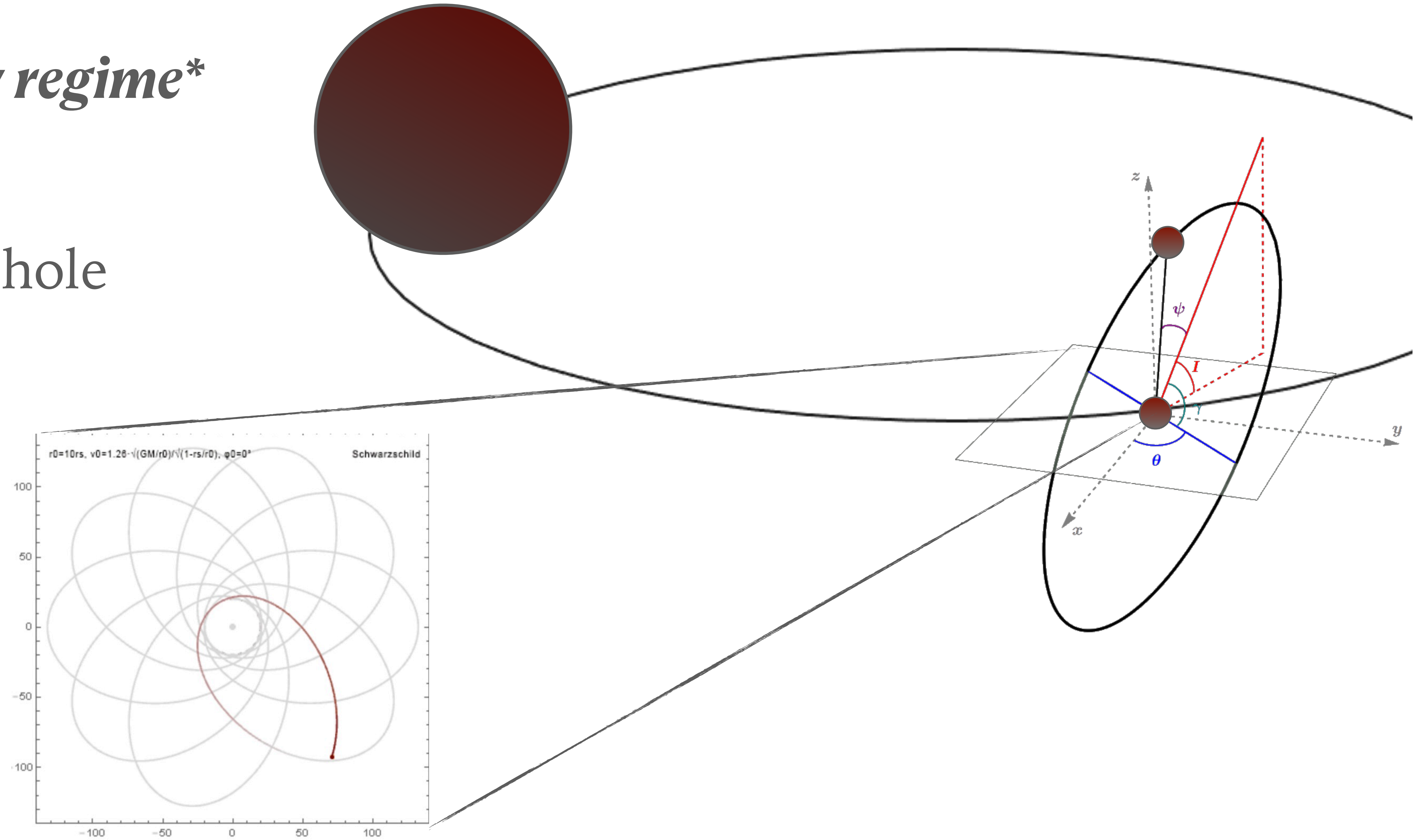

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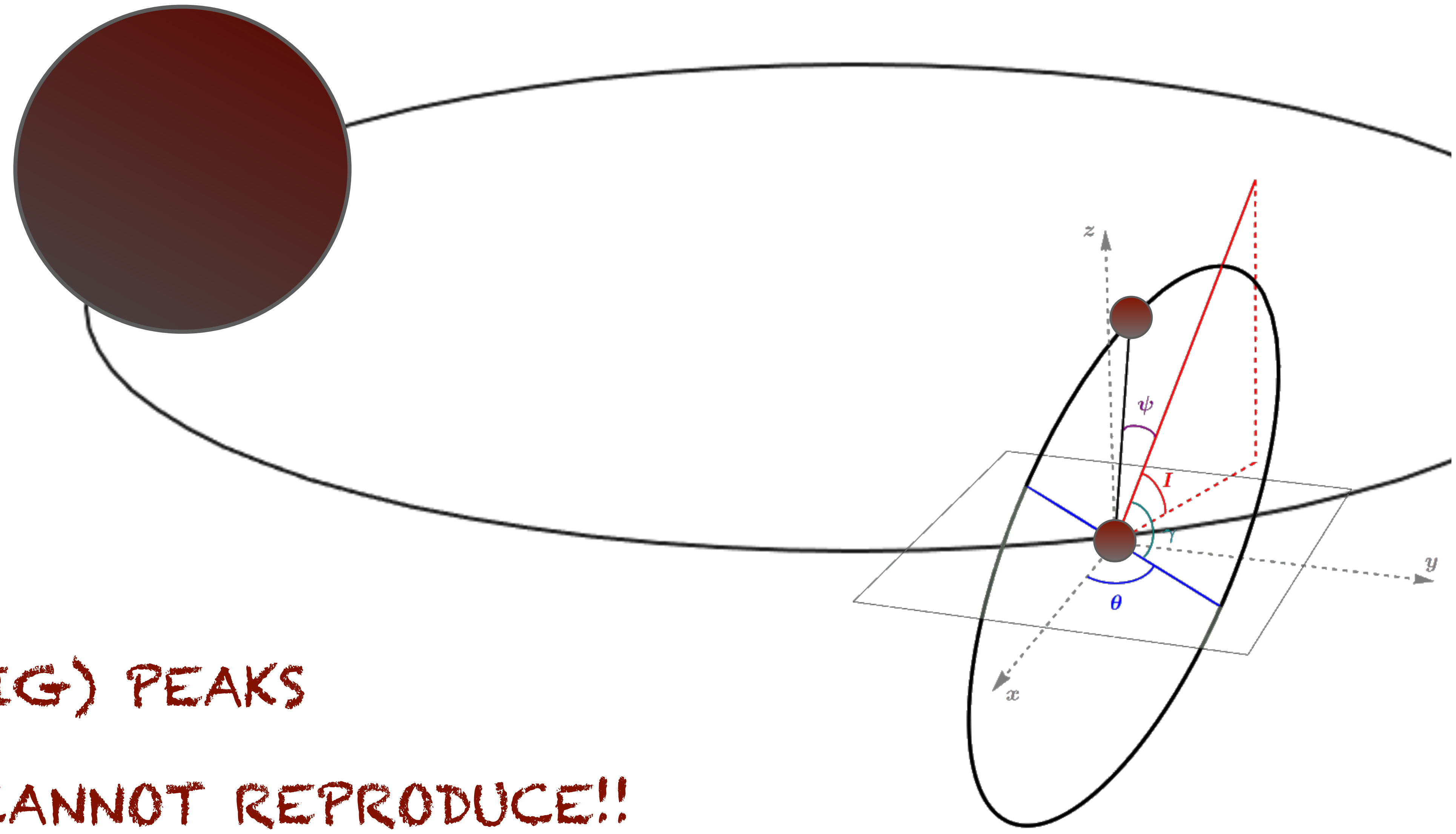


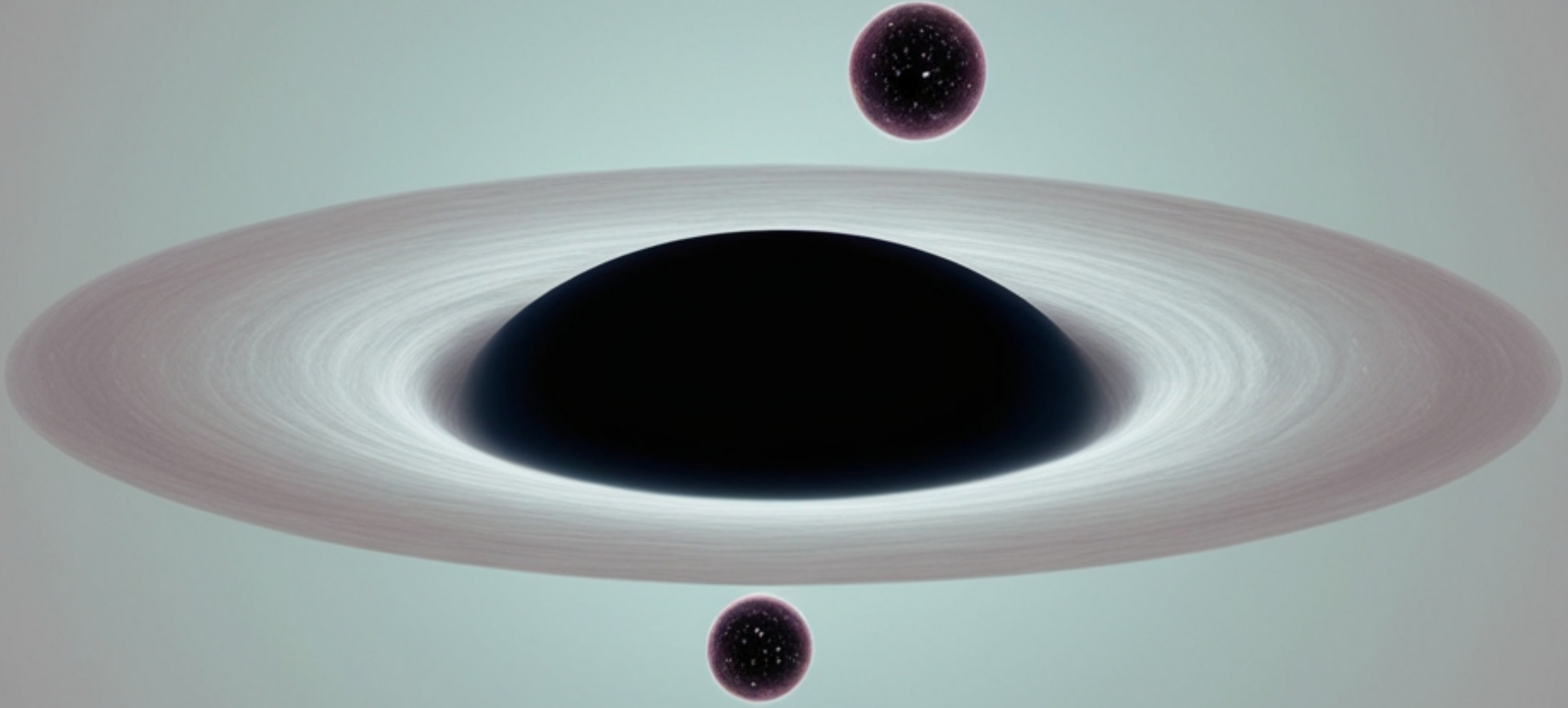
A BHB with COMPARABLE masses perturbed by a black hole

Precession resonance:

excitation in the inner eccentricity

WITH GR WE SEE (BIG) PEAKS
THAT A CLASSICAL APPROACH CANNOT REPRODUCE!!

*in preparation |M. Cocco, G. Grignani, T. Harmark, M. Orselli, D. Pica



THANK YOU!