Tests of general relativity from the working group perspective

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Princeton Gravity Initiative, Princeton University

PRINCETON UNIVERSITY

LISA CONSORTIUM

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What can we learn from LISA that we cannot using other instruments?

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$$\frac{c^3}{G} \sim 10^{36} J \cdot s/m^2$$

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No extra fields*

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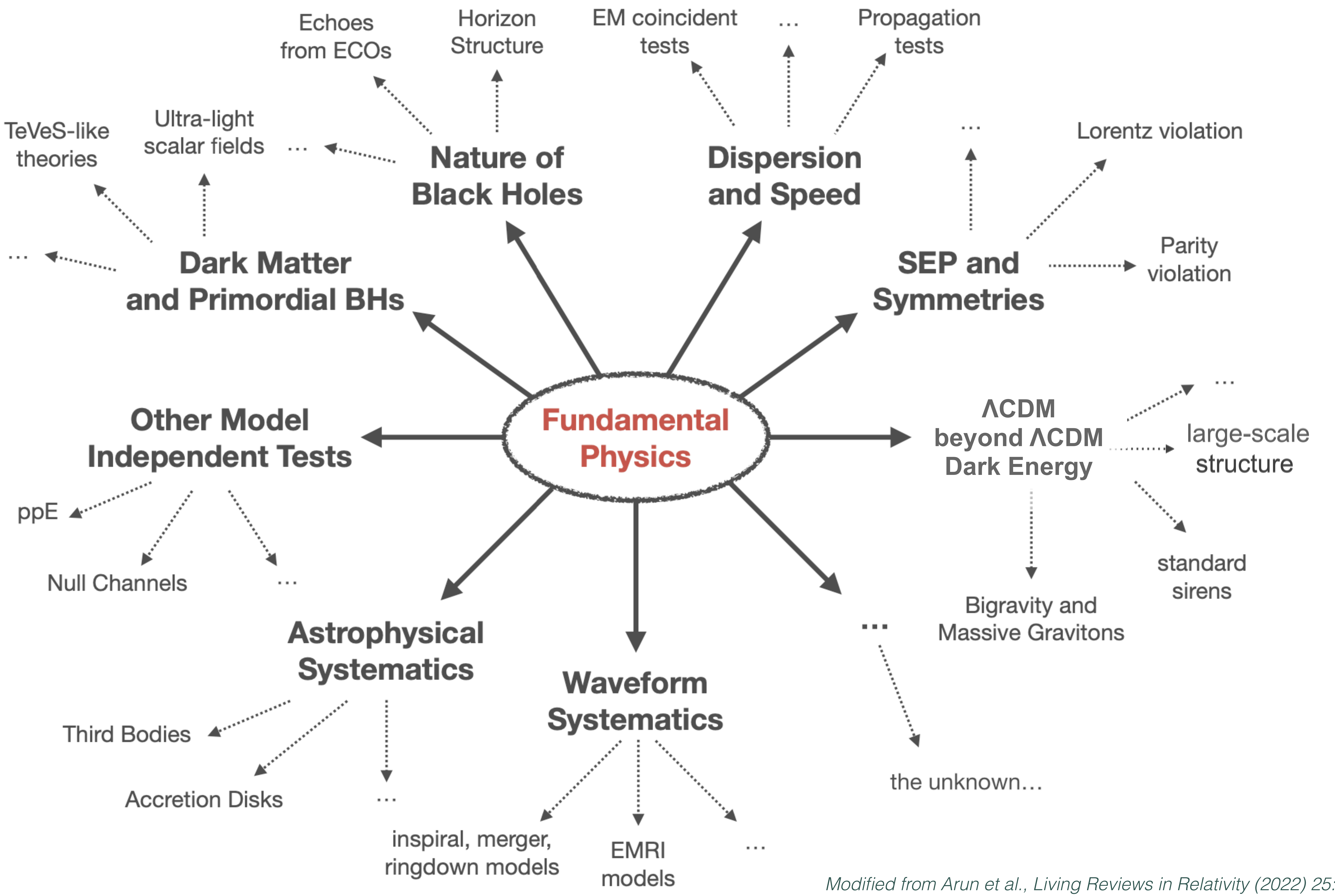
Parametrized ringdown (**BH Spectroscopy**)



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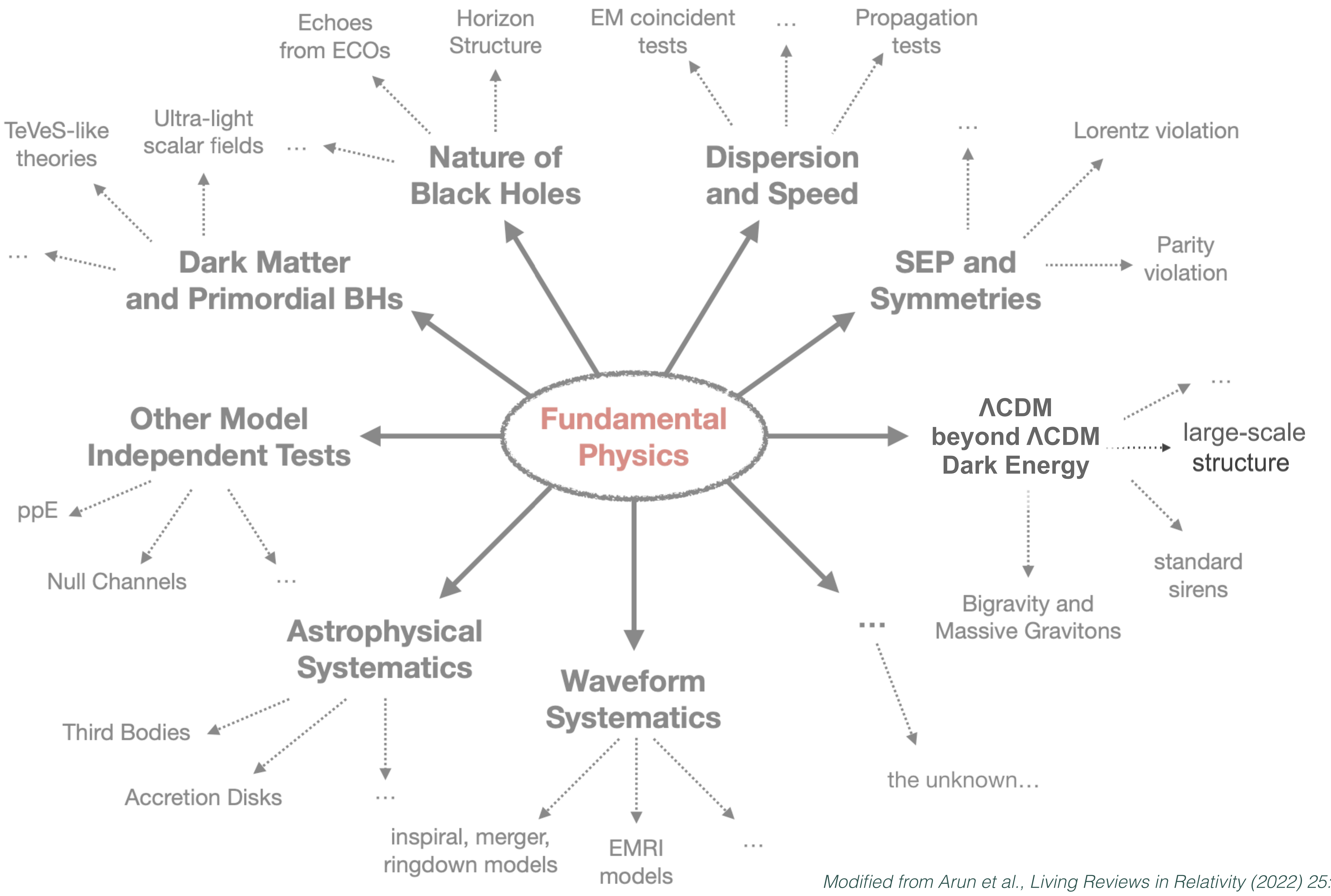

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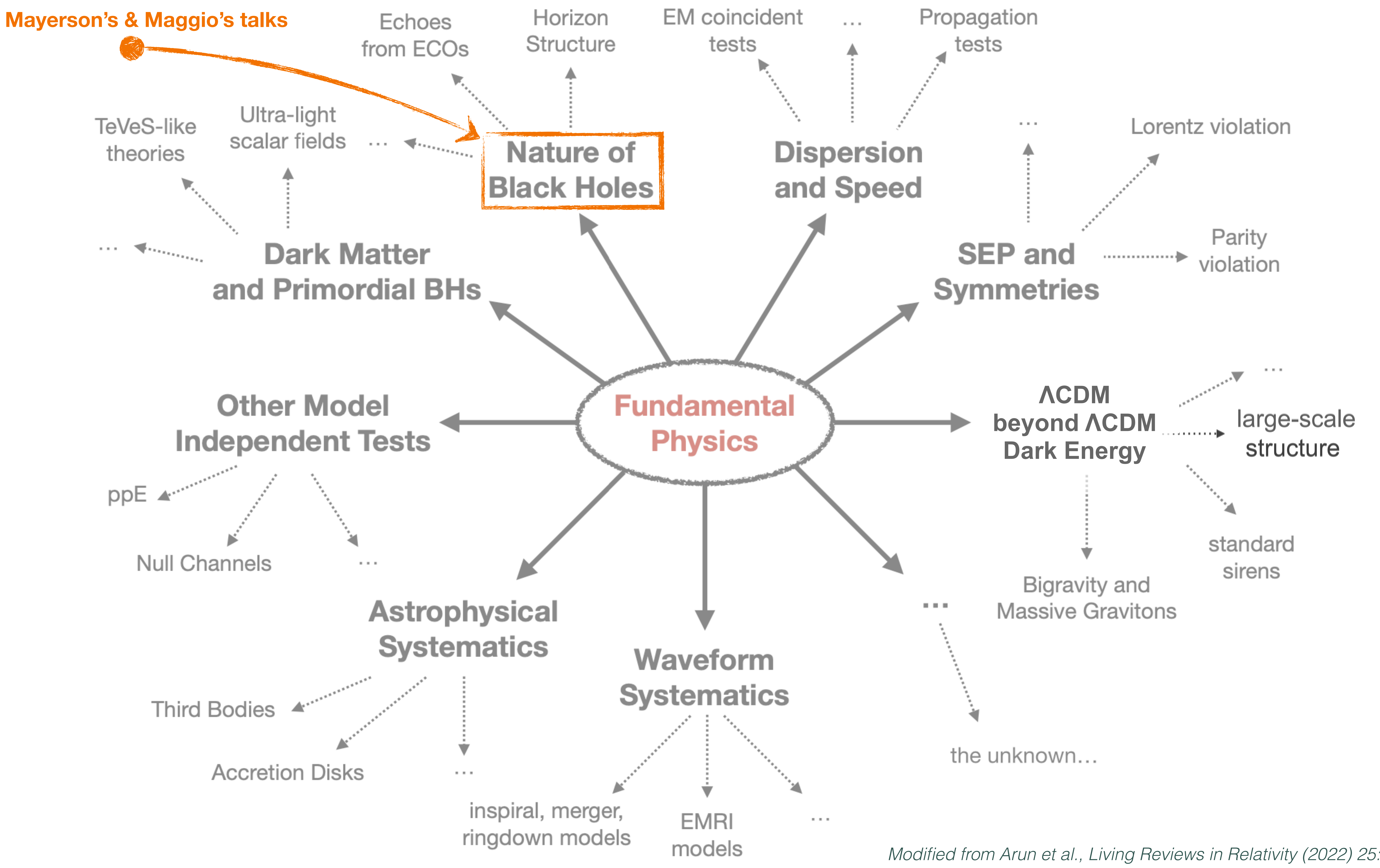

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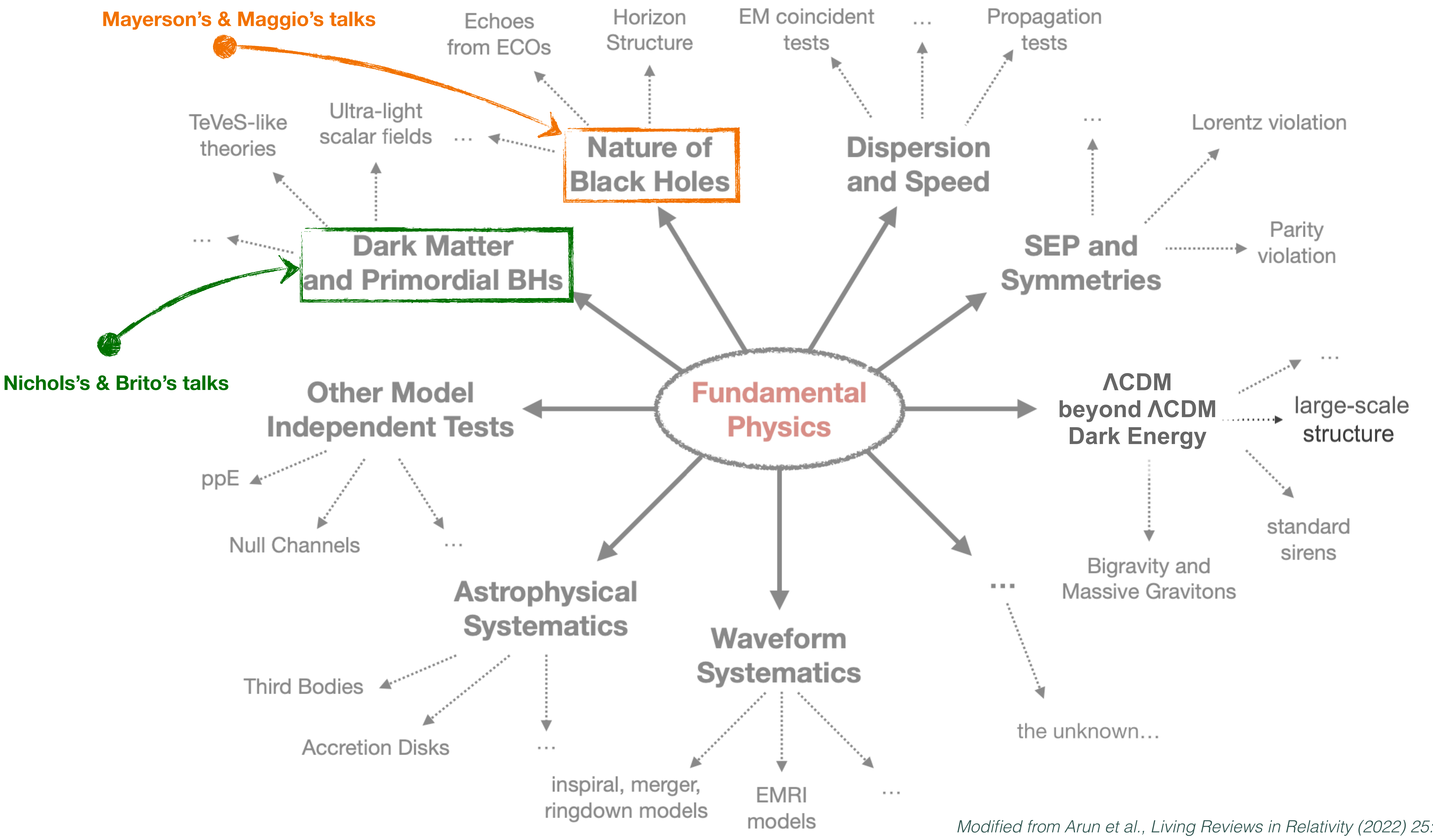

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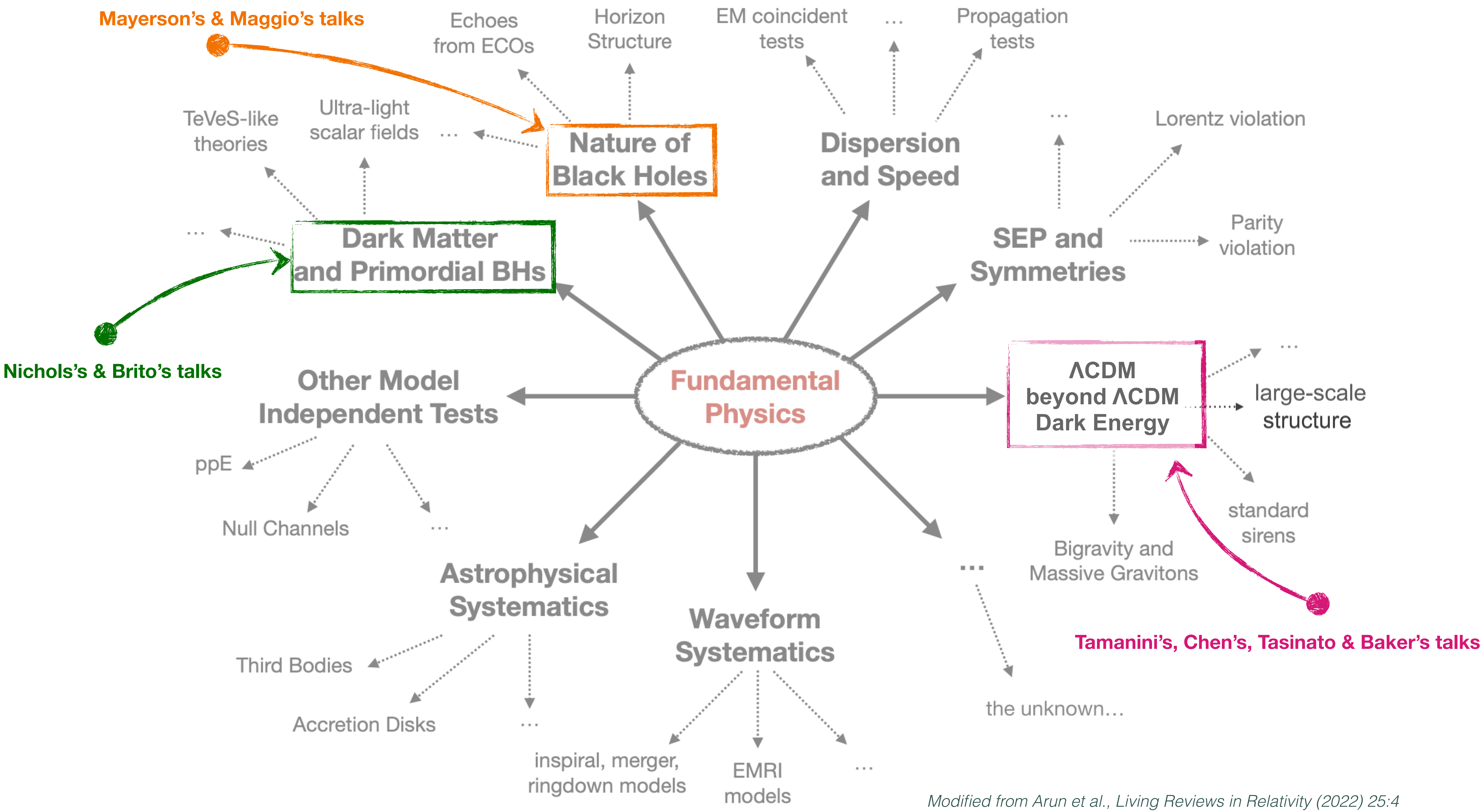

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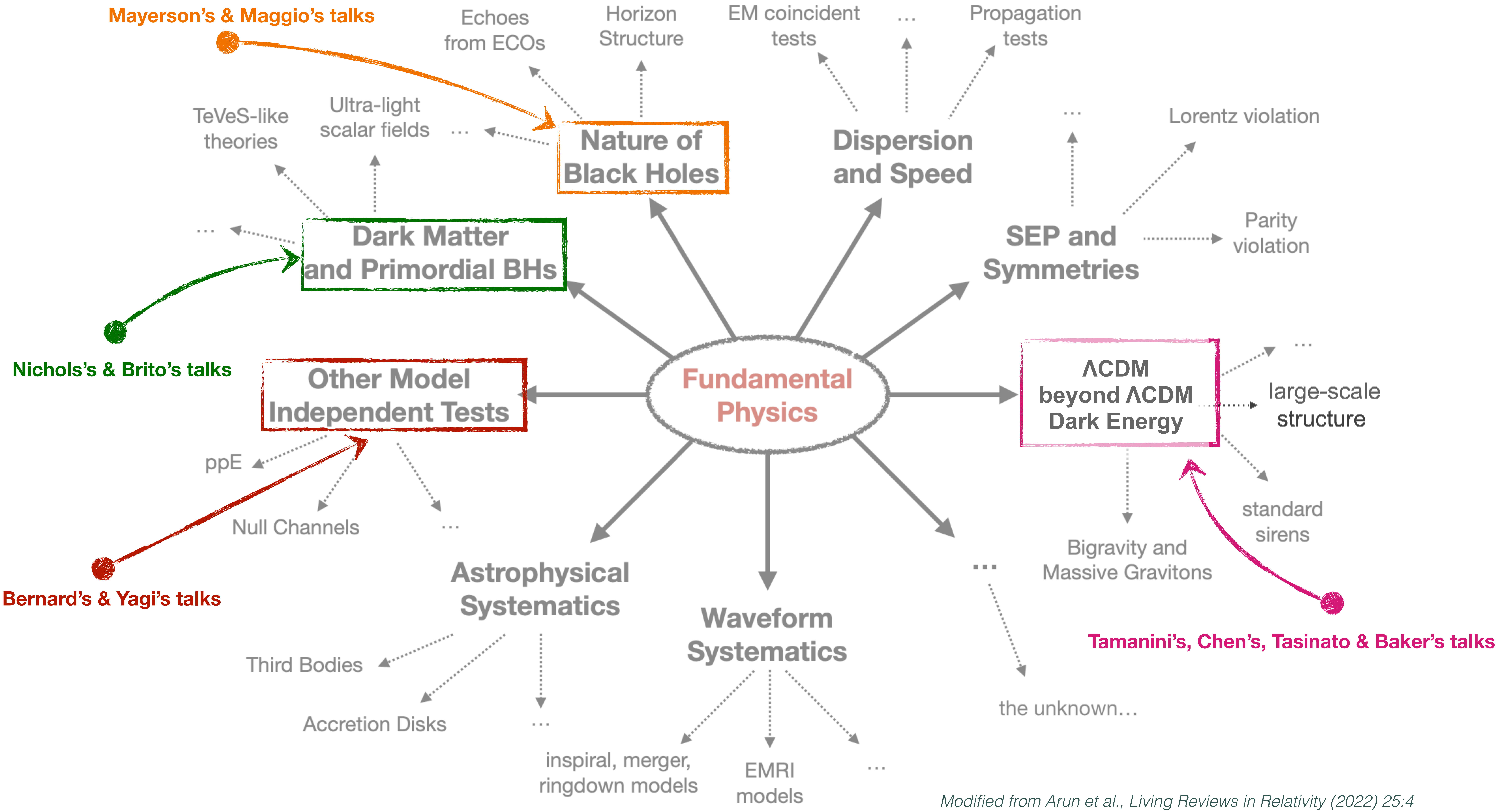

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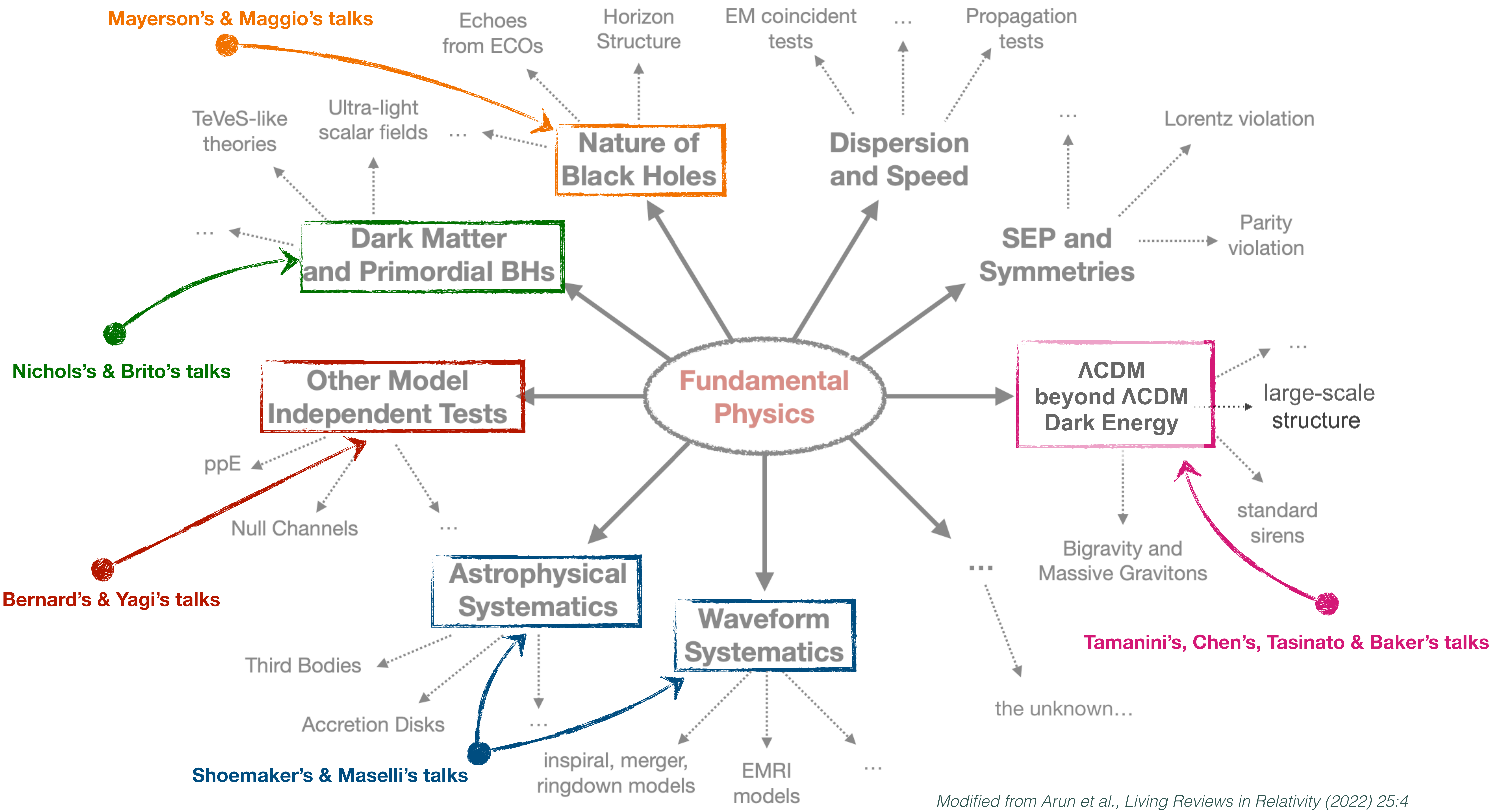

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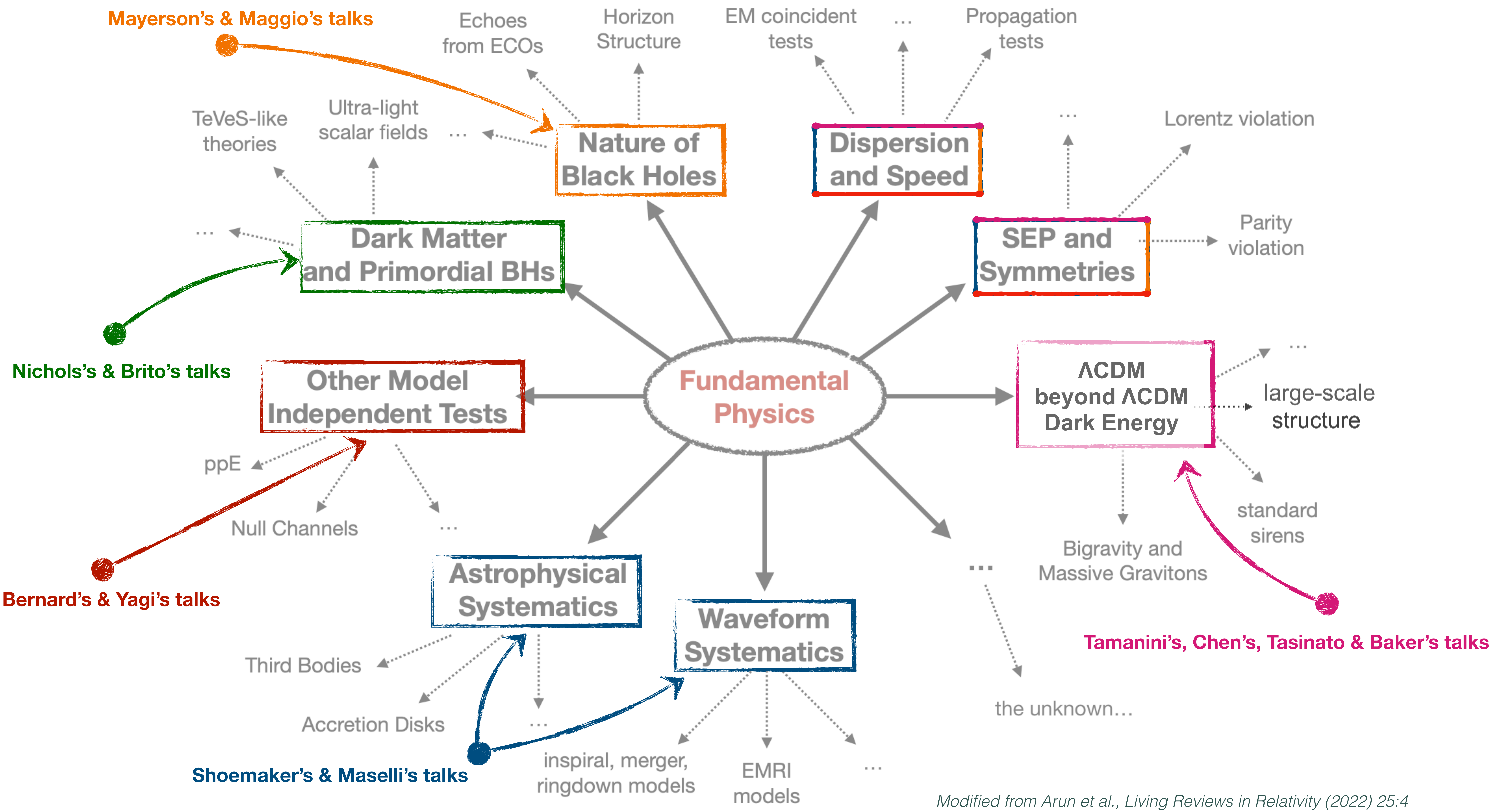

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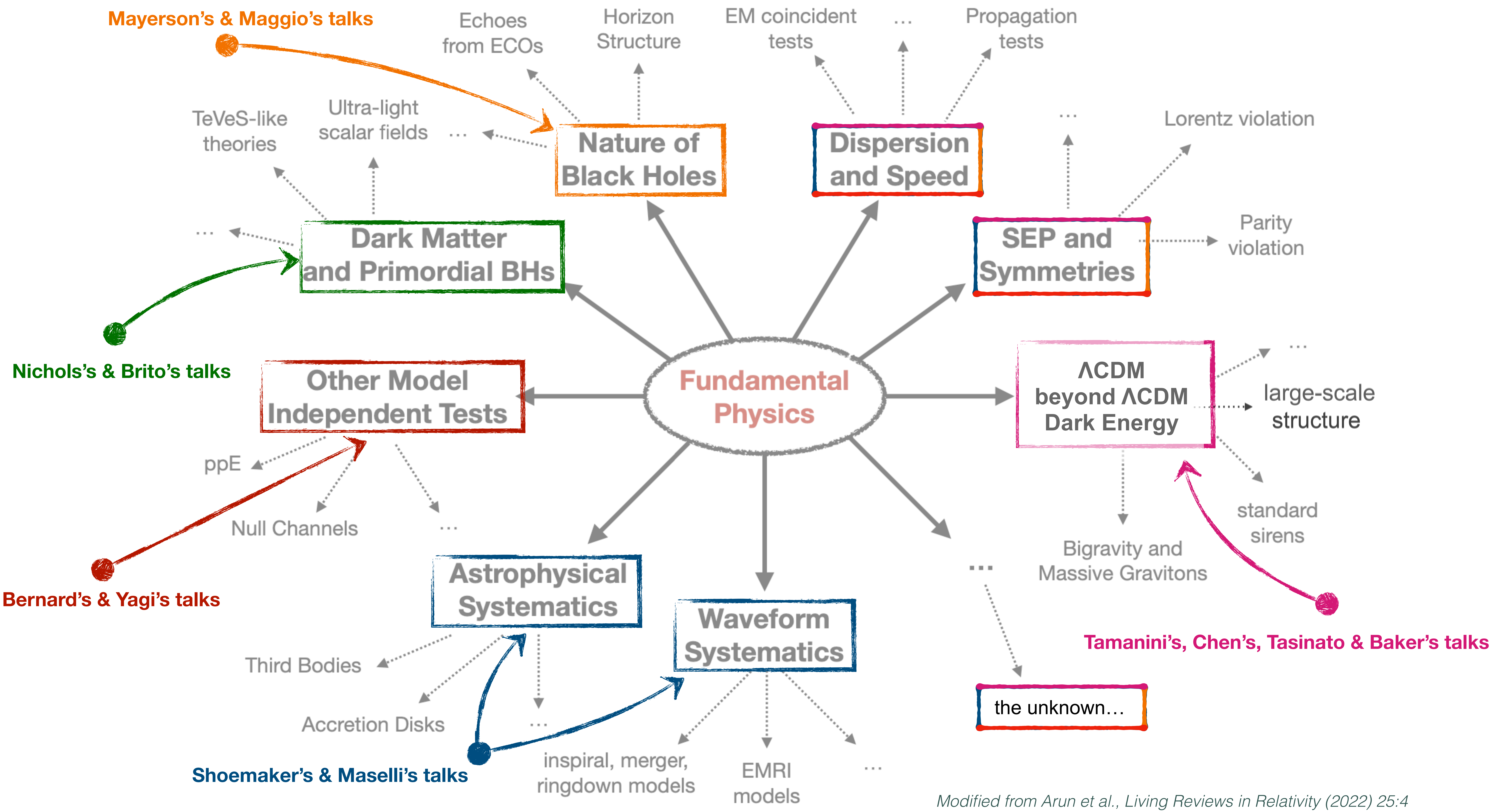

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Outline: Three short stories

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New physics → New fields: scalar fields and BHs

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Decaying radial profile:

$$\rho_{\ell m} = \gamma_\ell \delta_{m,0} \frac{M}{R^3}\left(\frac{a}{R}\right)^\ell \cos\left(\frac{\pi r}{4R}\right)$$

Black holes beyond general relativity

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e.g., Maselli, Franchini, Gualtieri & Sotiriou, (2004.11895)

$$\underbrace{}_{}\overset{\textbf{Metric tensor}}{} \quad \overset{\textbf{Matter fields}}{}$$

Metric tensor

Matter fields

$$S[\mathbf{g}, \varphi, \Psi] = S_0[\mathbf{g}, \varphi] + \alpha S_c[\mathbf{g}, \varphi] + S_{\mathrm{m}}[\mathbf{g}, \varphi, \Psi]$$

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Action Matter fields

Black holes beyond general relativity

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Thus, these **"*large*" BHs are effectively Kerr BHs.**

Difference in the GW phase evolution of EMRIs with and without scalar charge

Maselli, Franchini, Gualtieri, et al., (2106.11325)

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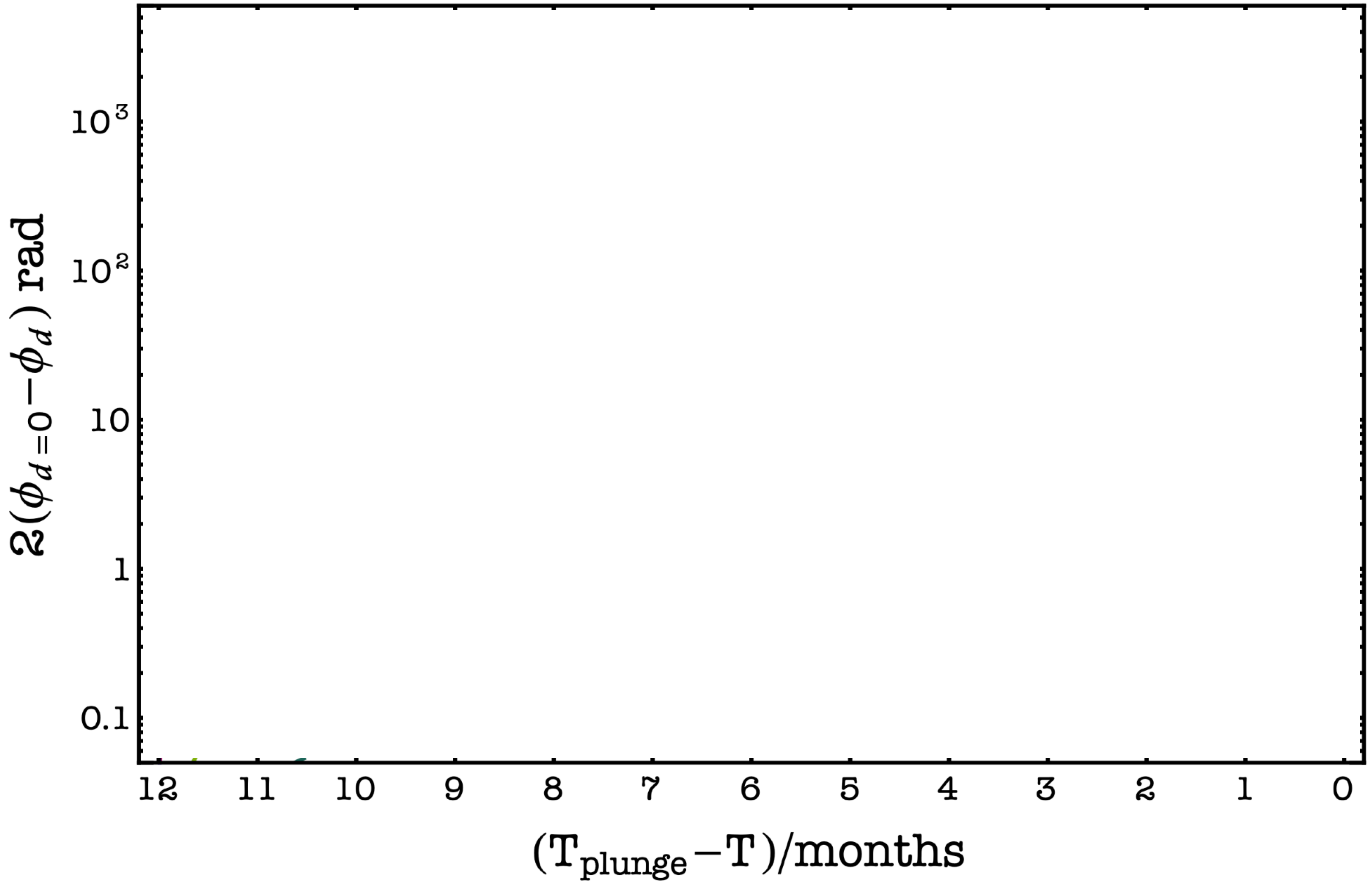

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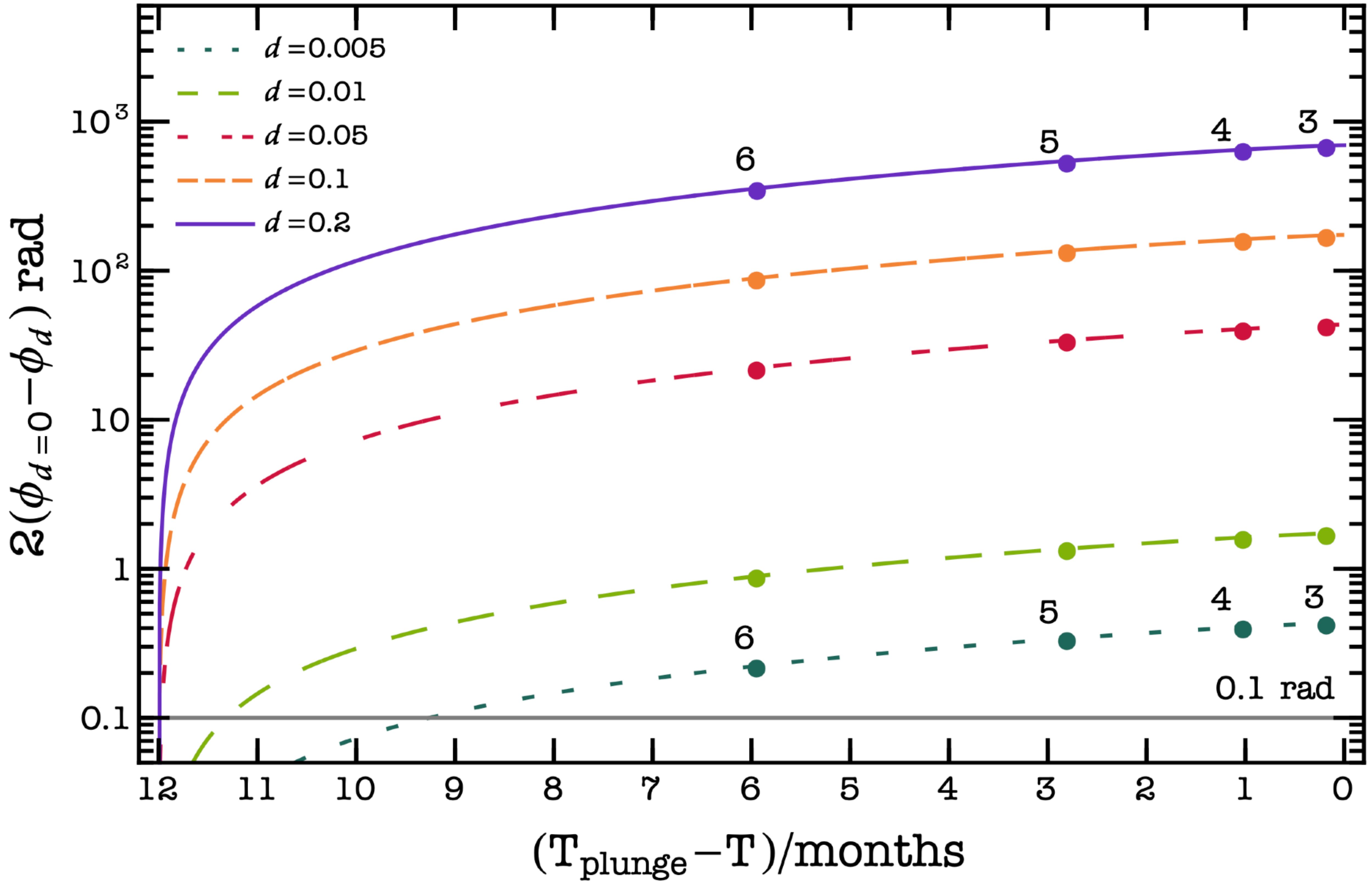

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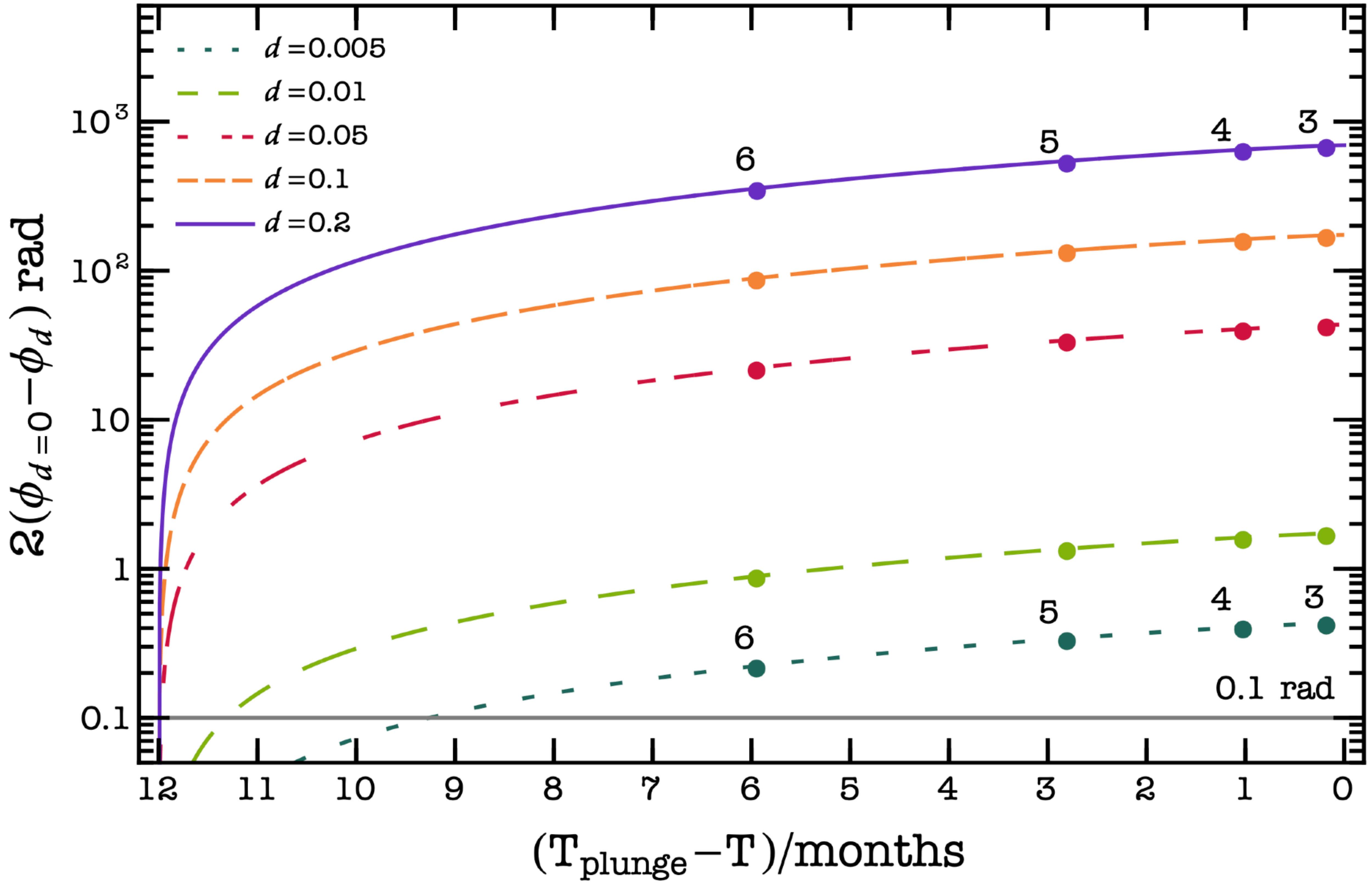

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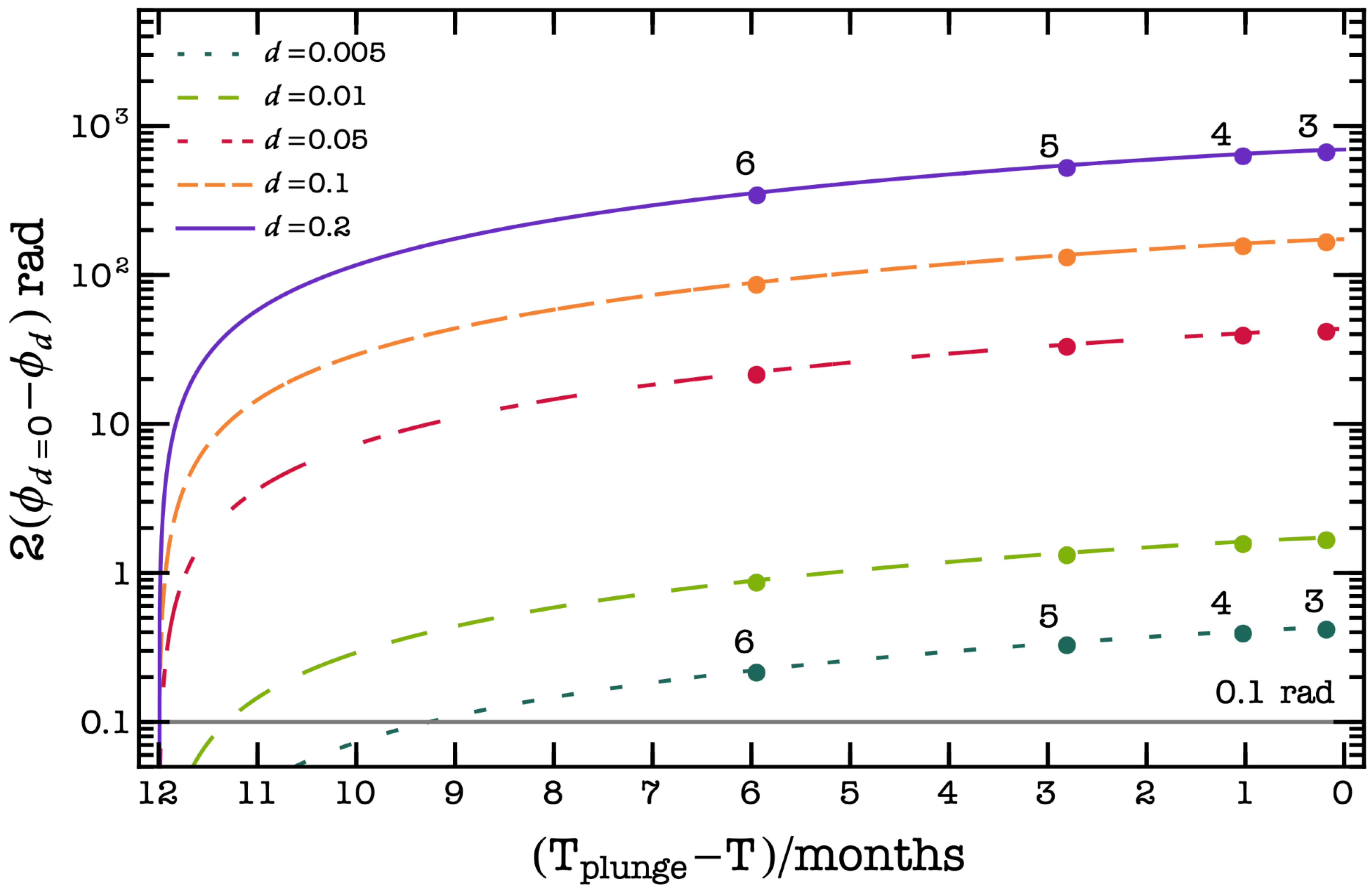

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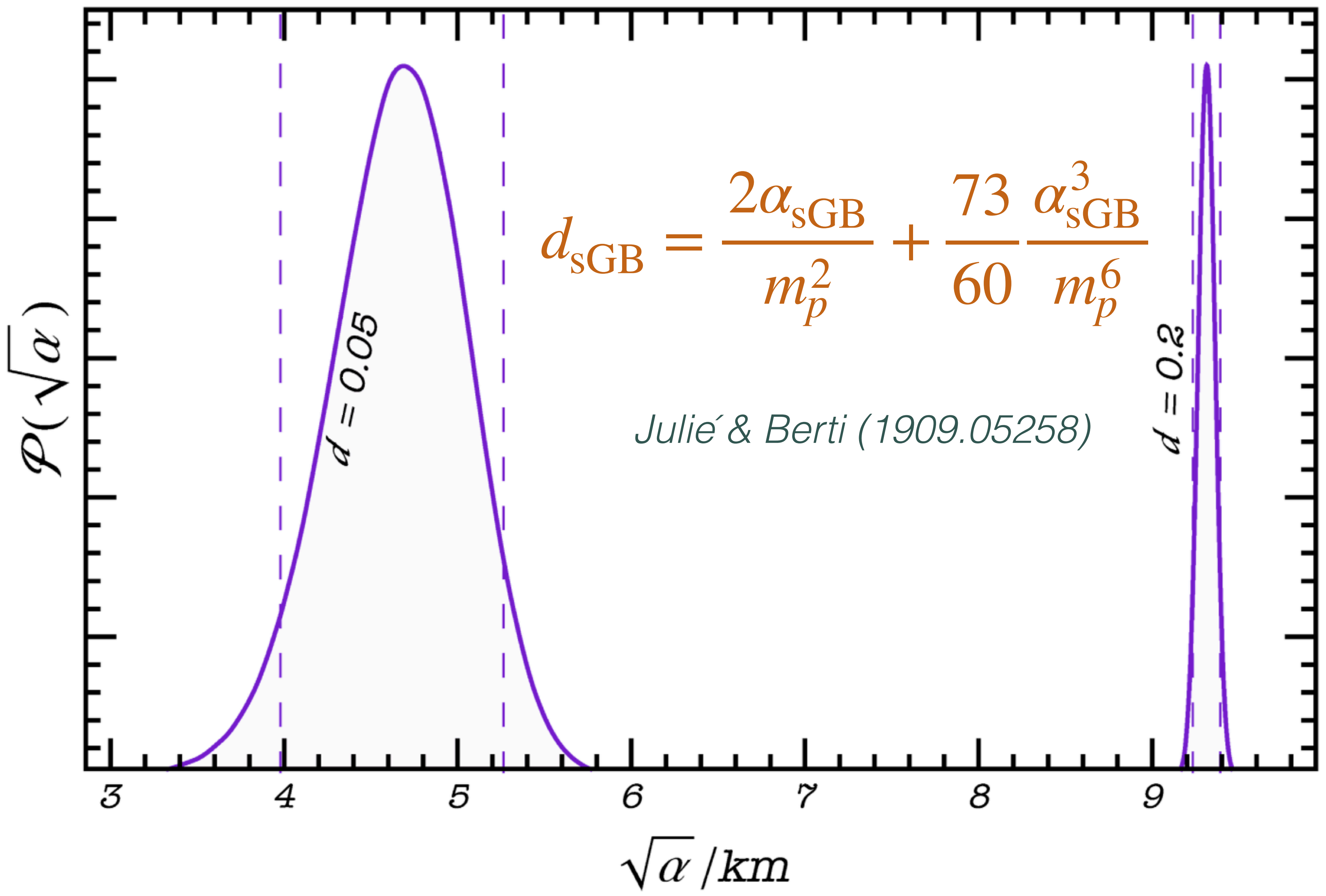

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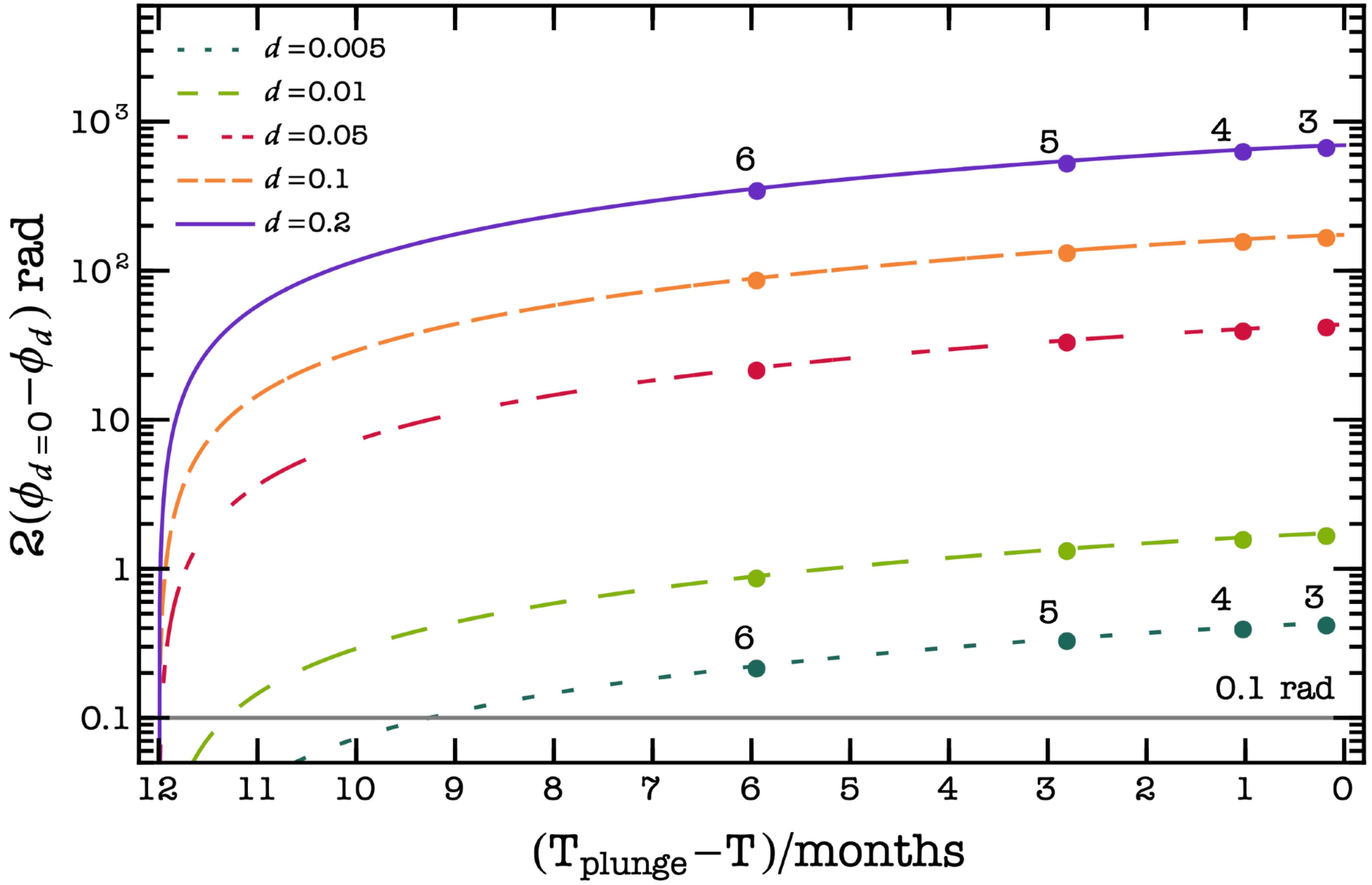

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Outline: Three short stories

New physics → New fields: scalar fields and BHs

A **scalar** (and potentially other) charge on the secondary **will affect the waveform.**

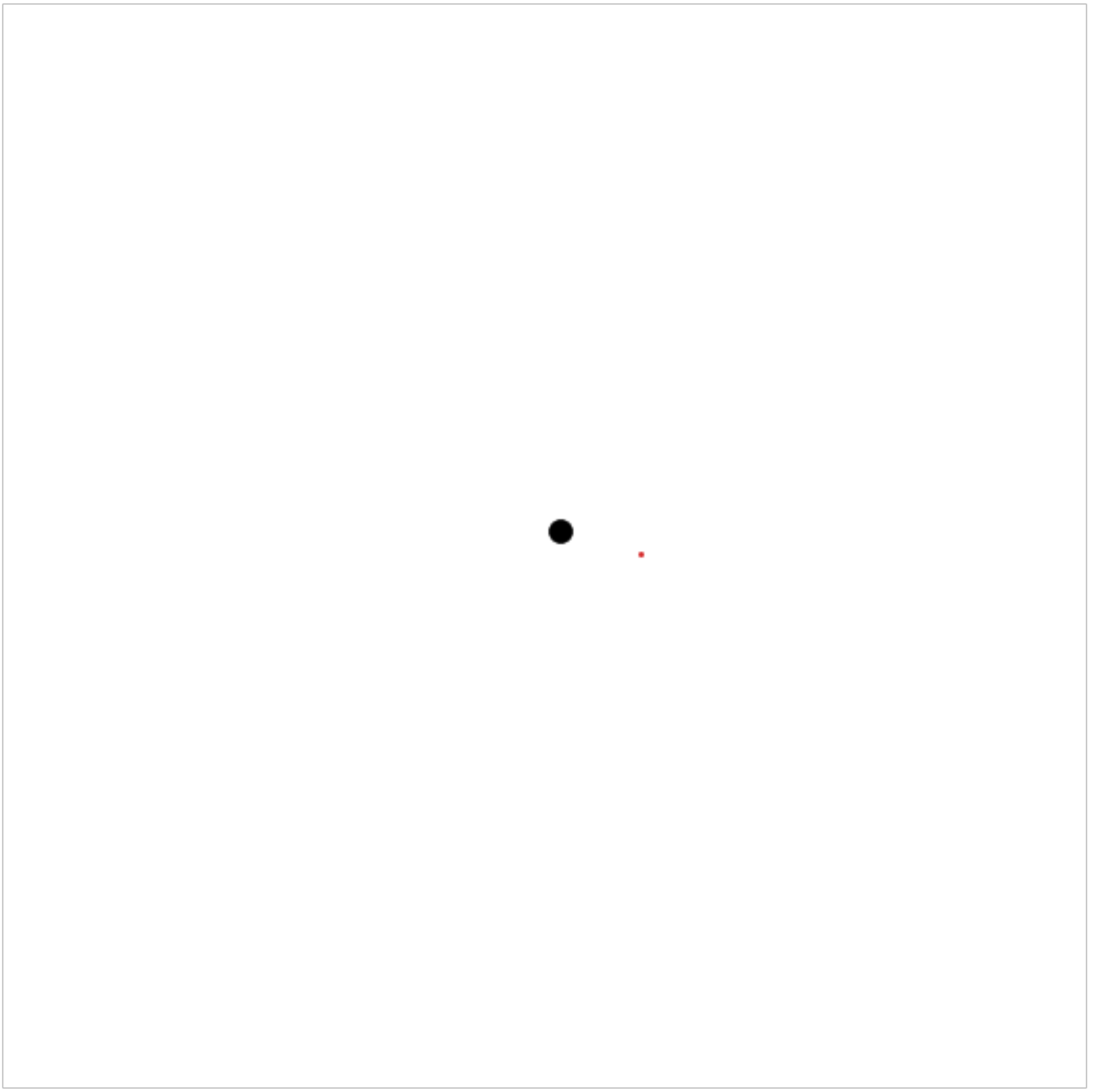
Beyond the adiabatic approximation:

Development of **full usable waveforms in beyond-GR theories or environments**

Multiband or multi-messenger prospects:

Exploit the **fundamental role played by different detectors** across the gravitational and electromagnetic spectra

EMRIs: Geodesics and Orbital Resonances



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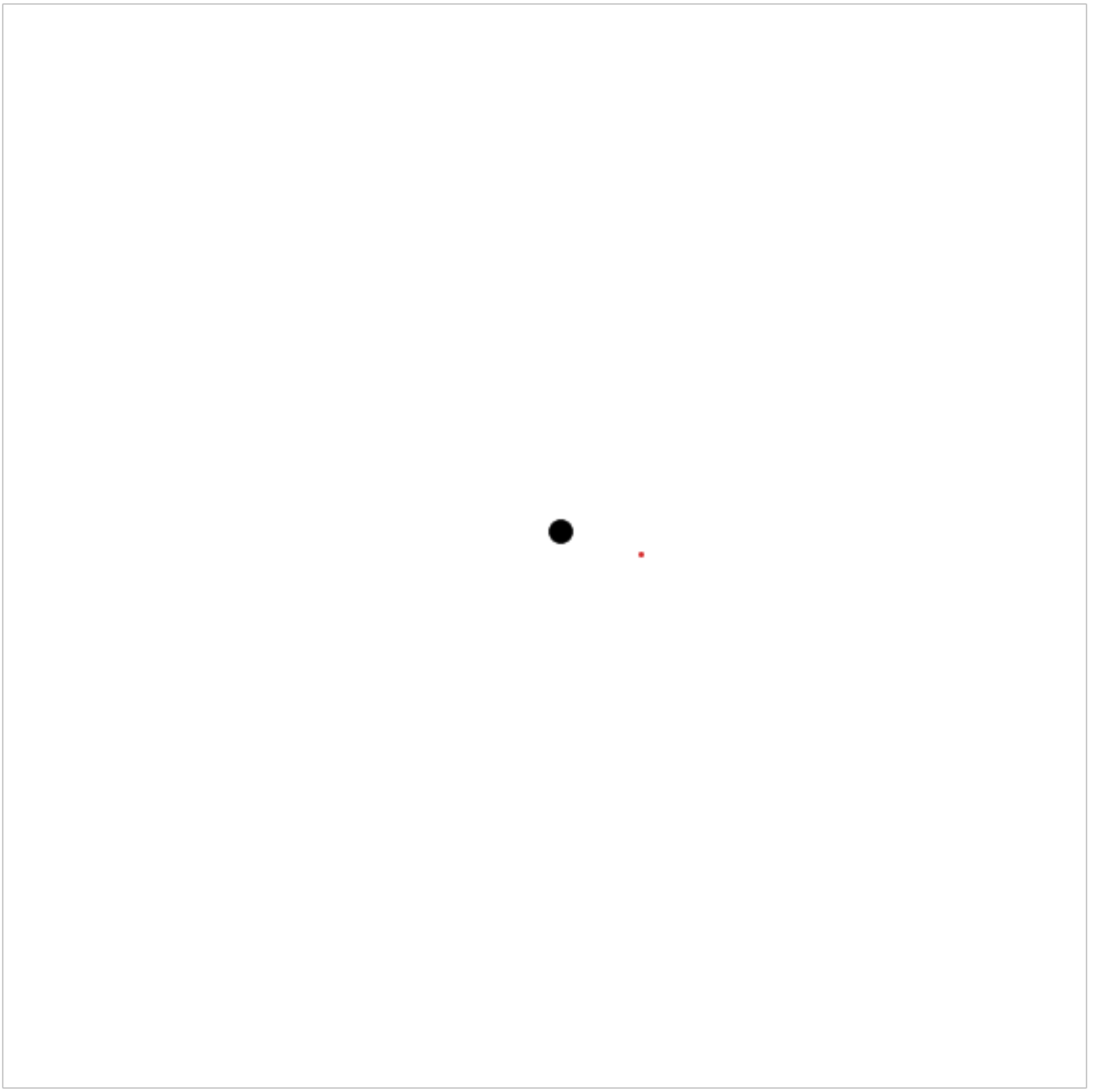

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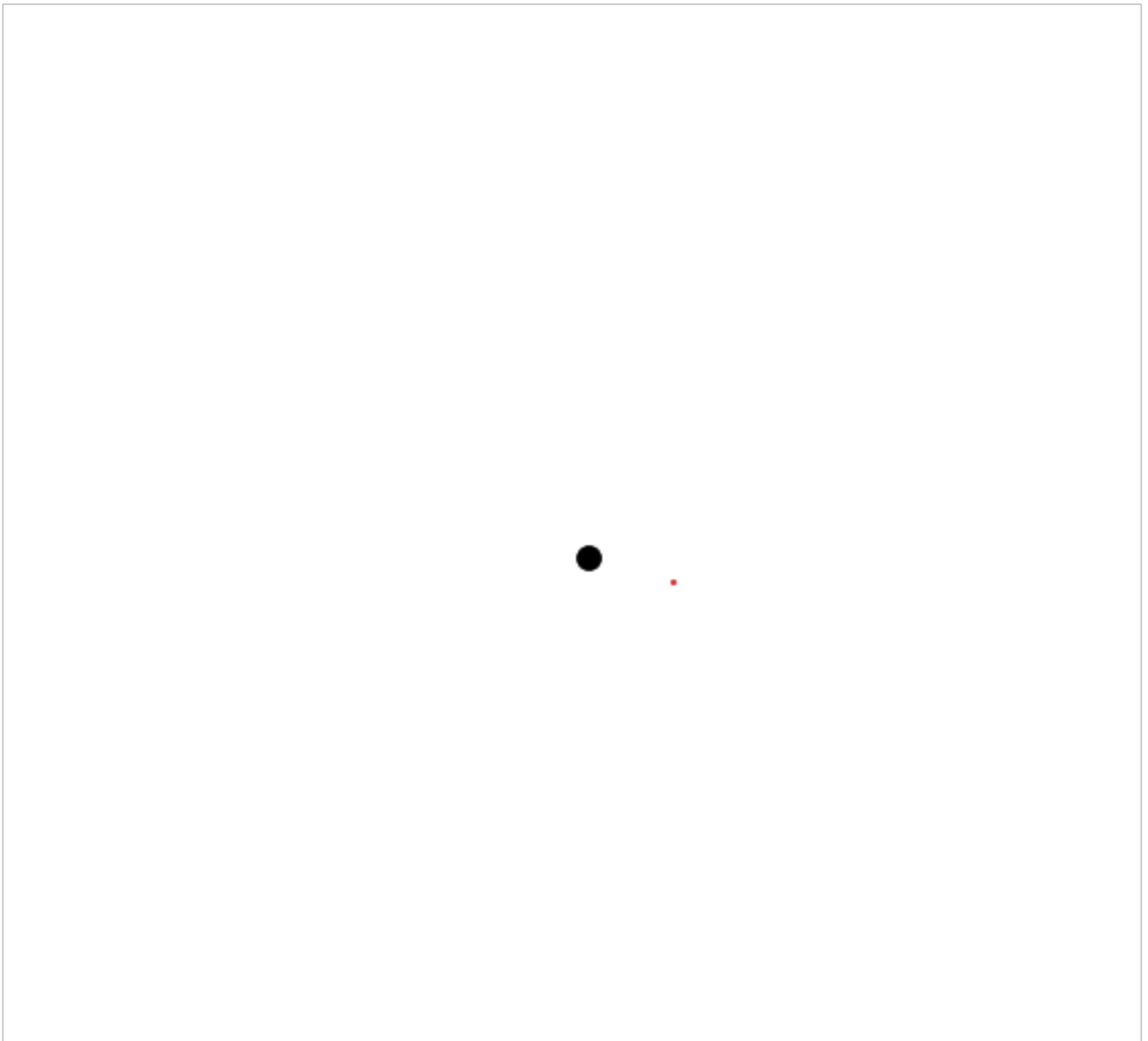

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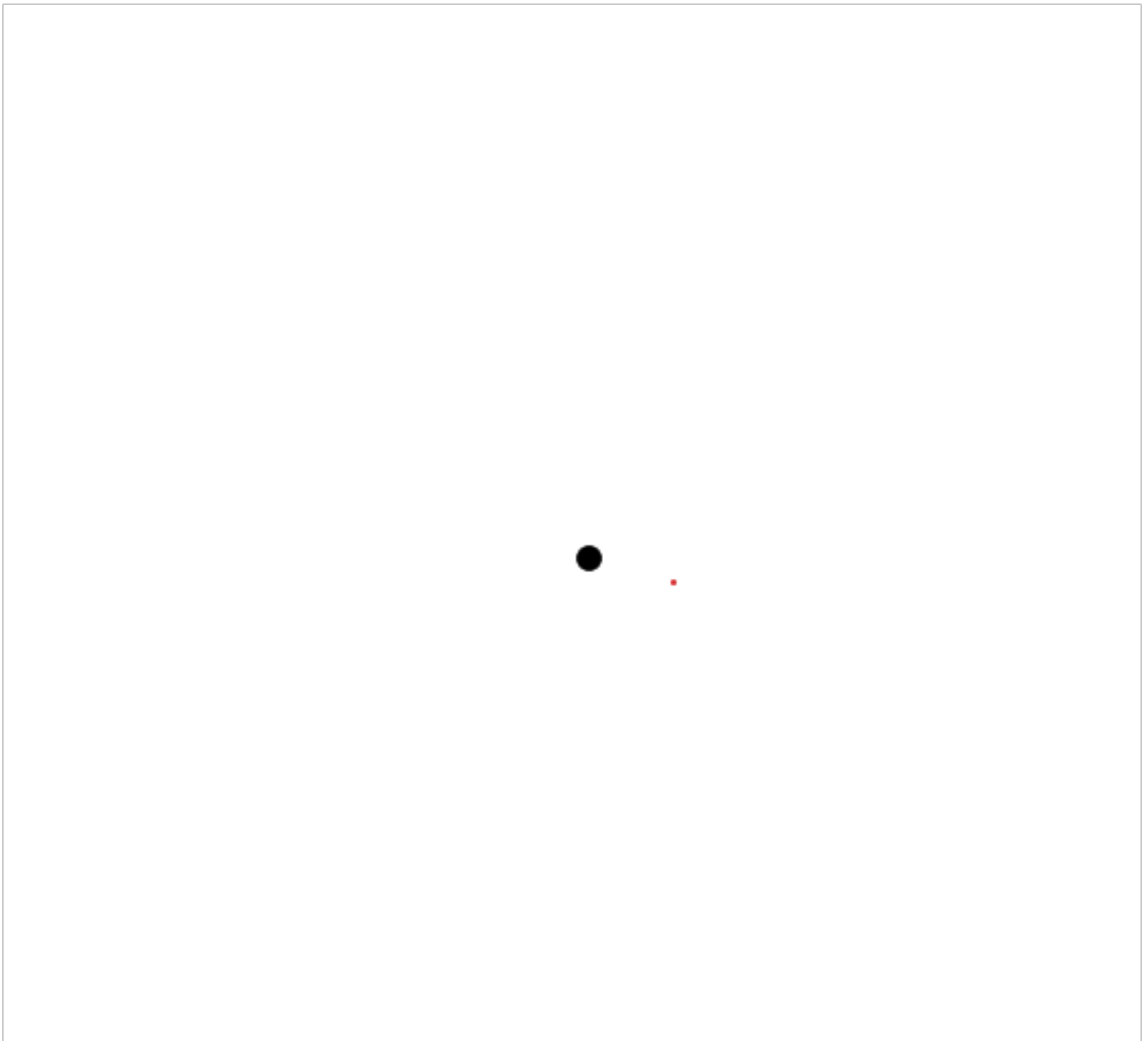

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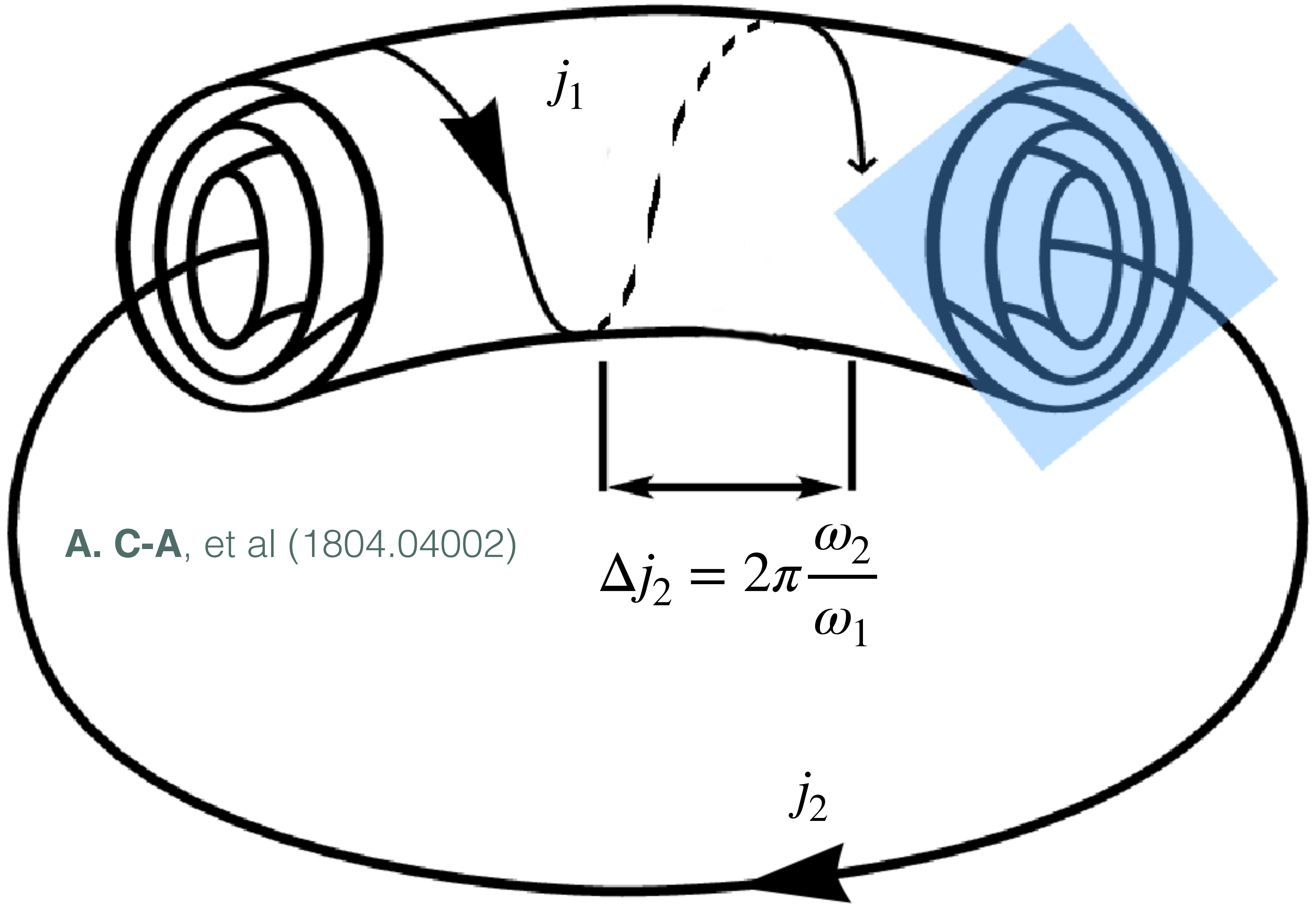

A. C-A, et al (1804.04002)

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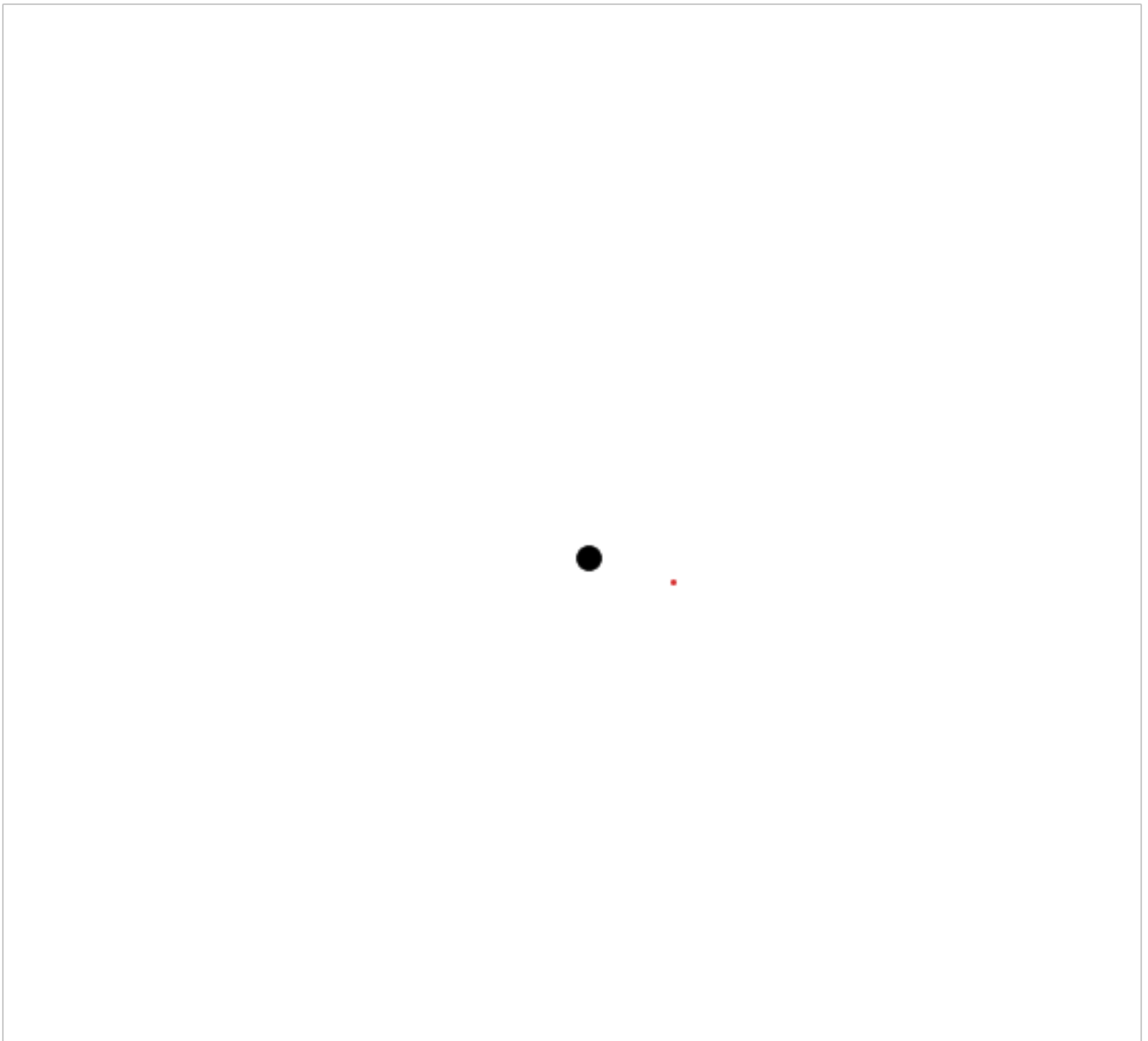

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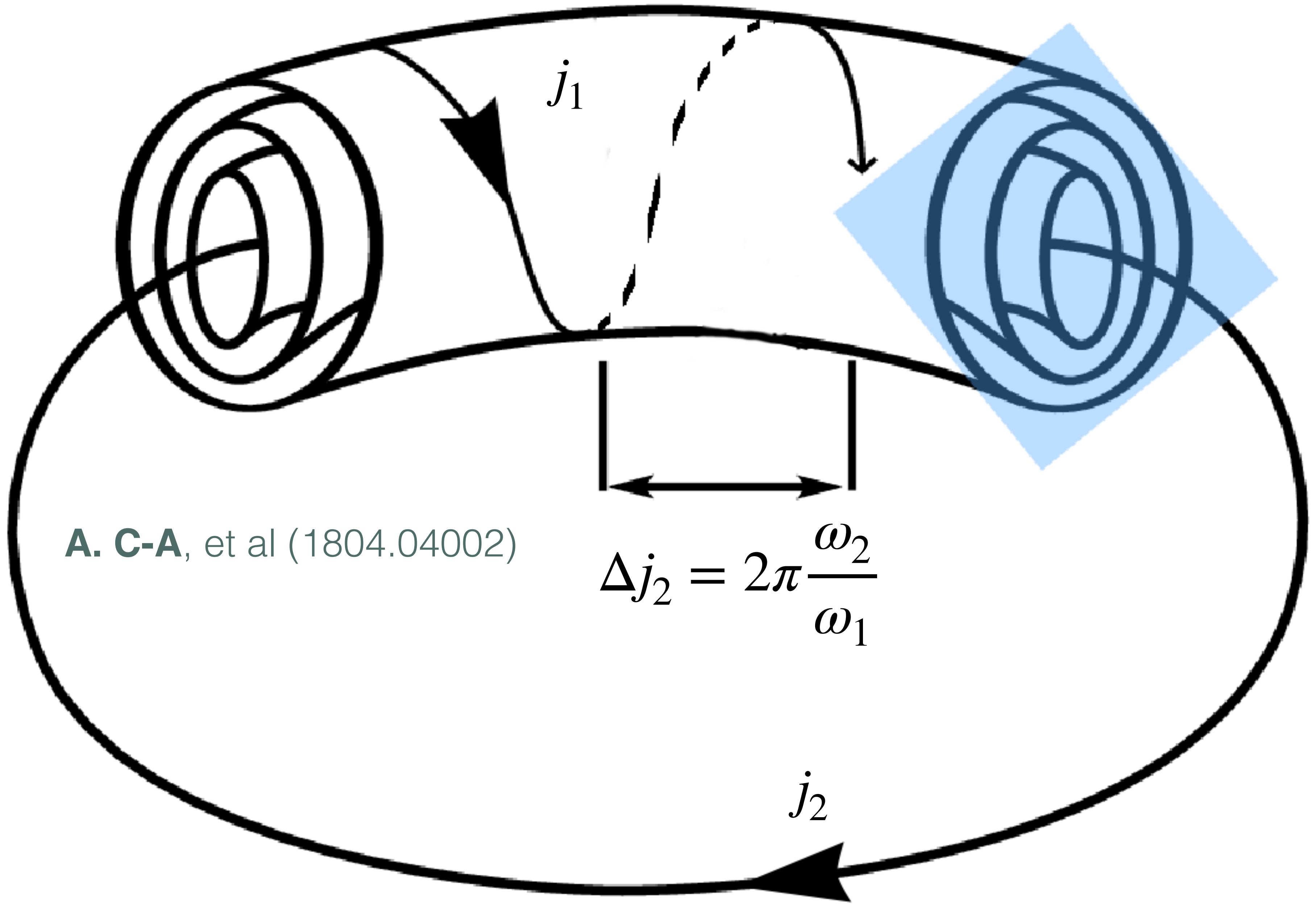

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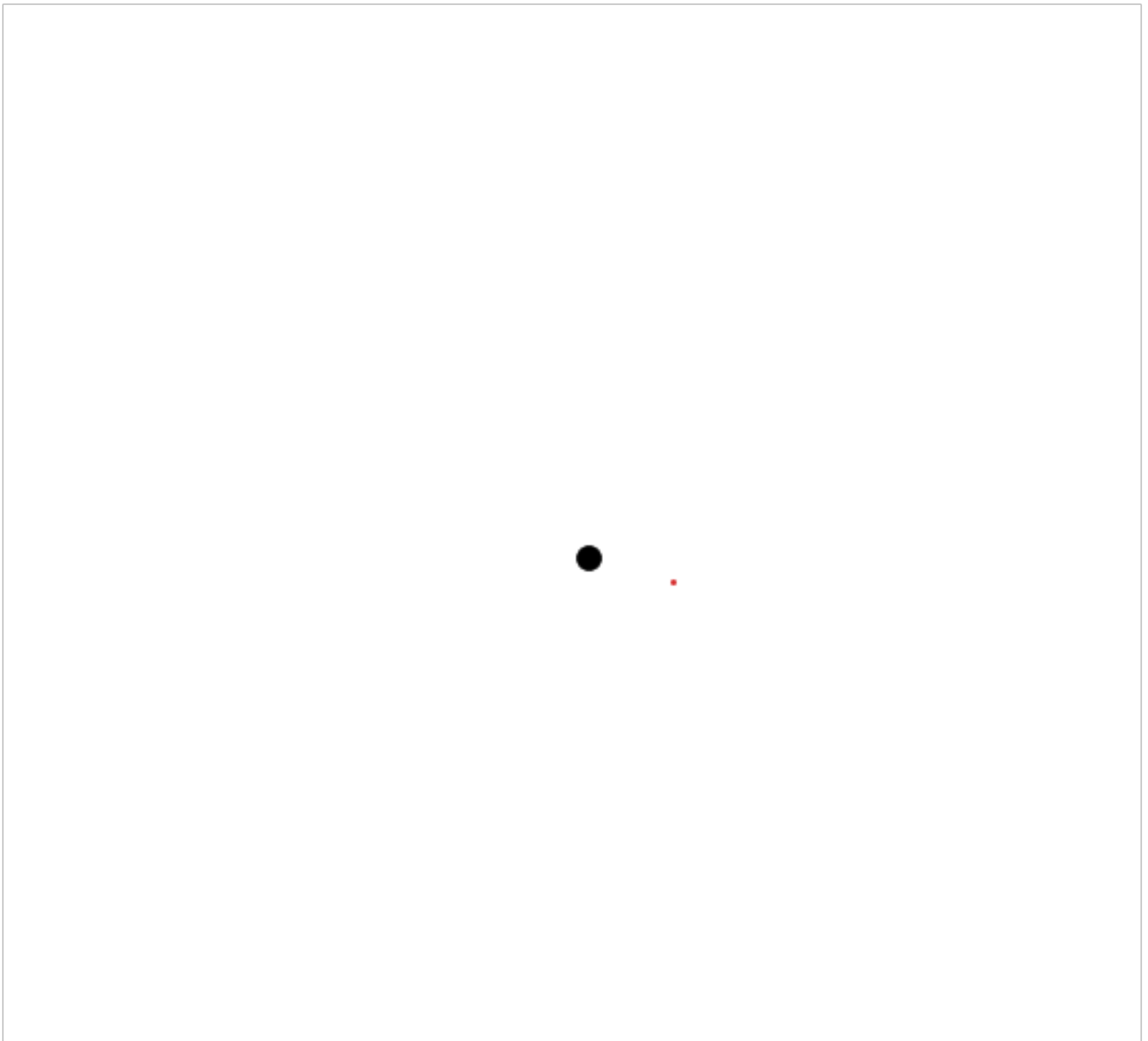

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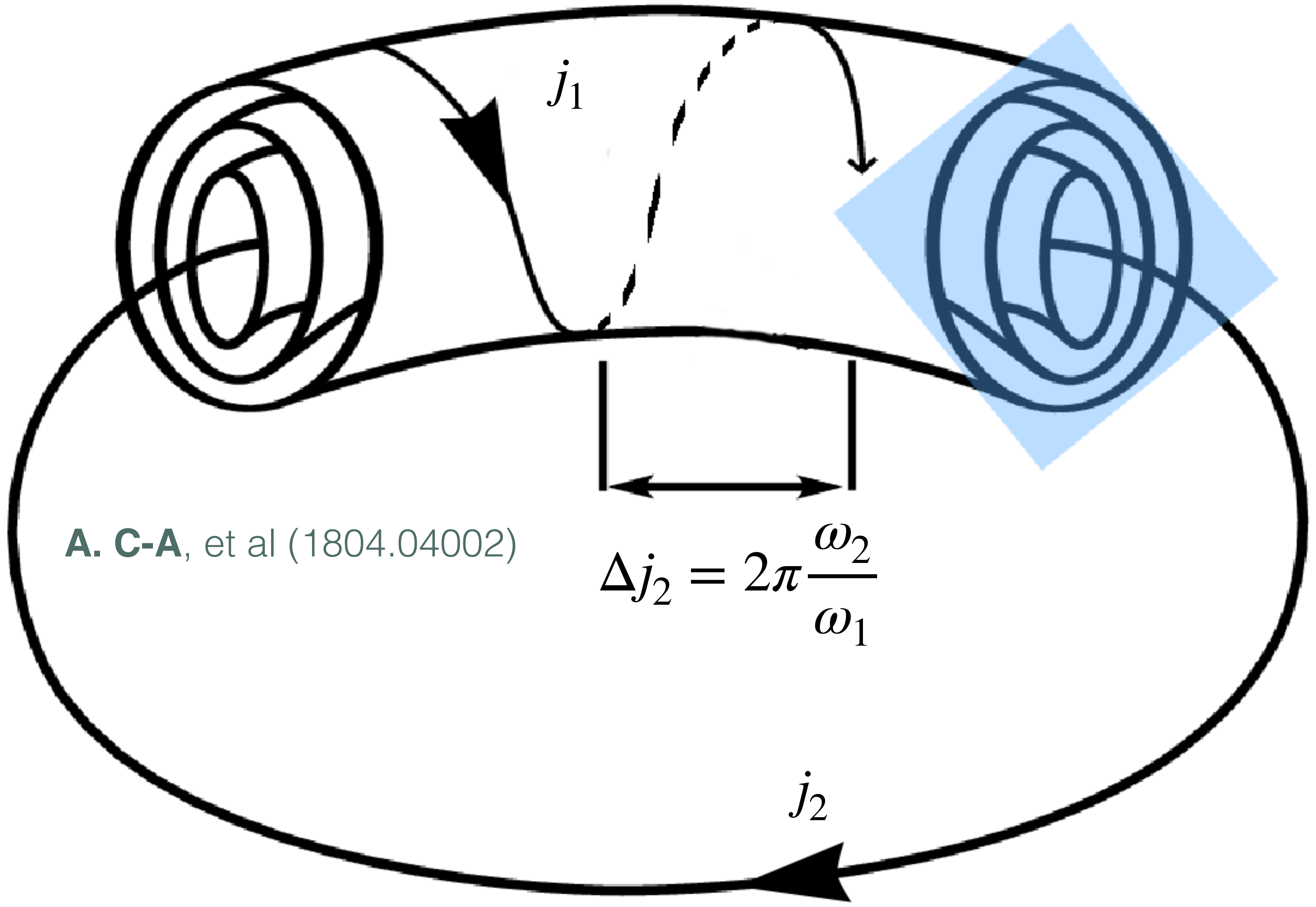

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Under a **perturbation**:

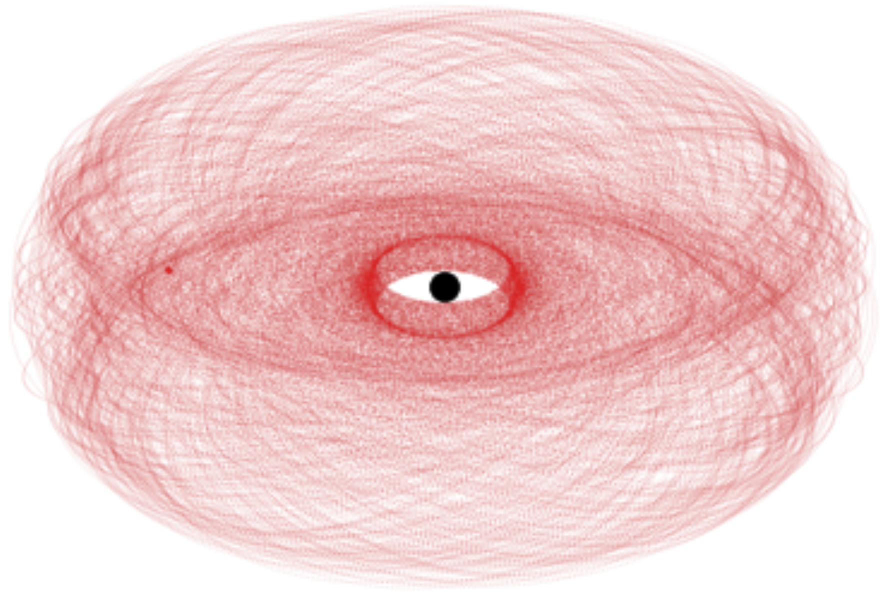
(e.g., accretion disk, third body, non-GR)

e.g., Arnold, Kozlov, & Neishtadt, *Mathematical Aspects of Classical and Celestial Mechanics* (1997)

$$\left| m\Omega_r + n\Omega_\theta \right| > \frac{K(\epsilon)}{\left(|m| + |n| \right)^3}$$

A possible observational detection of non-Kerr black holes

From the **trajectory**



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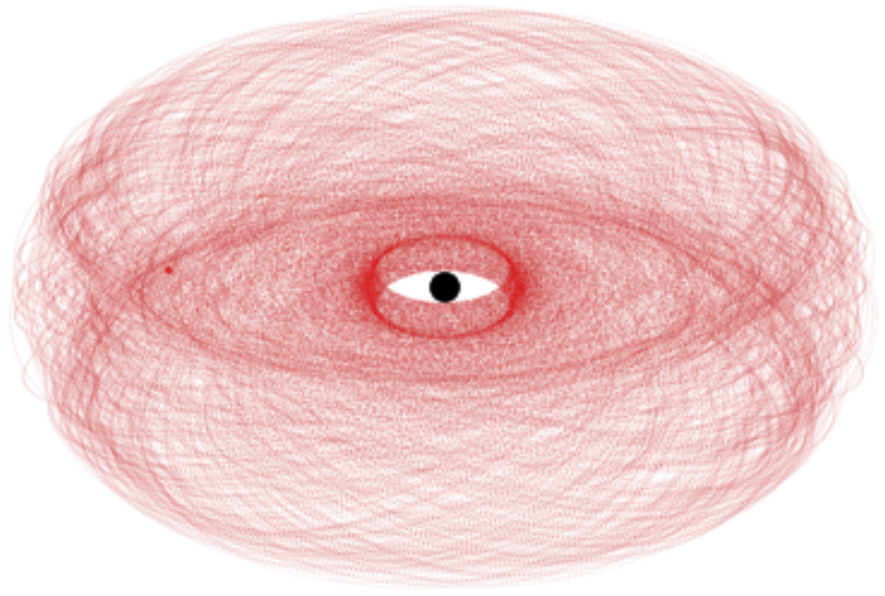

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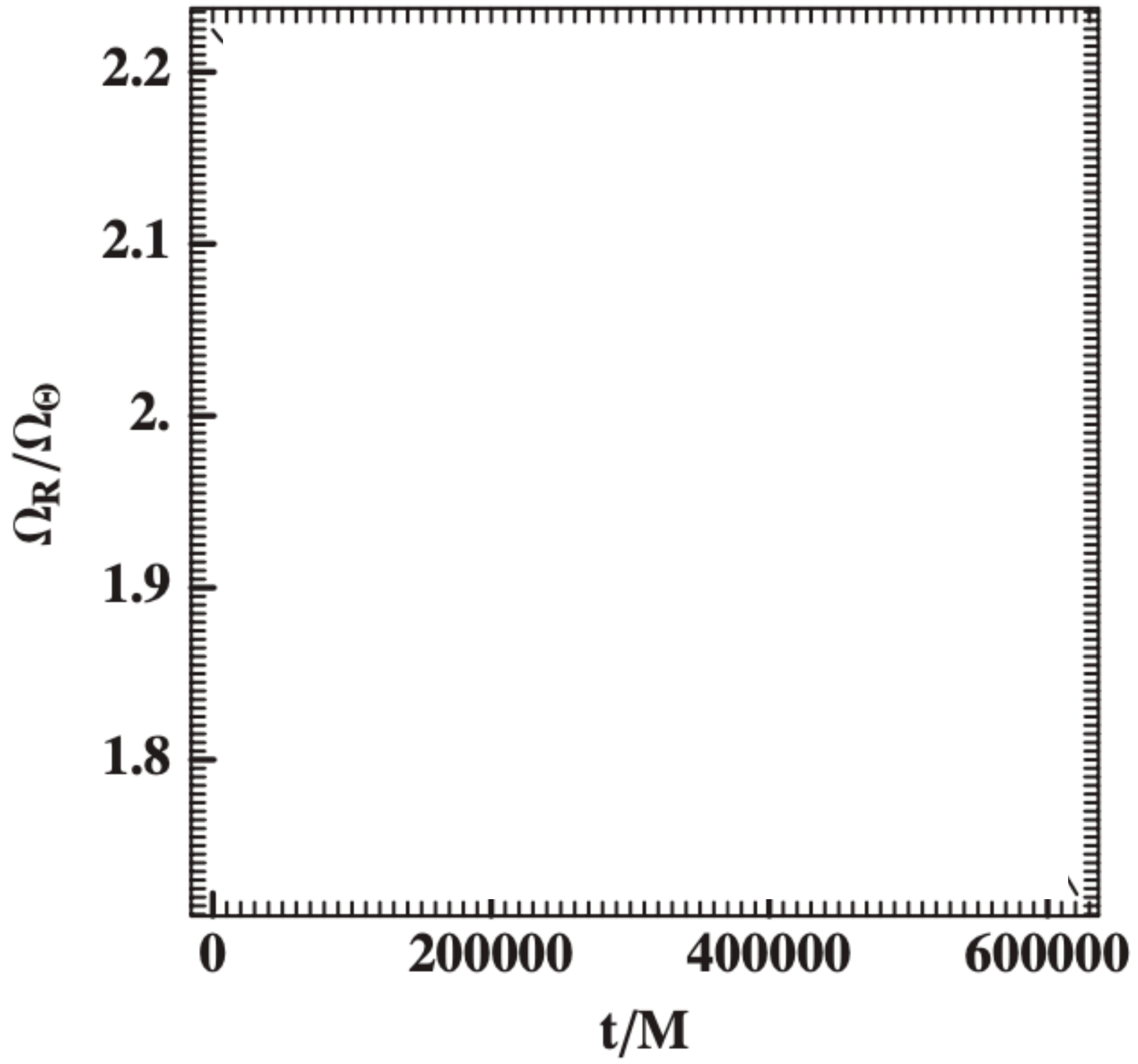

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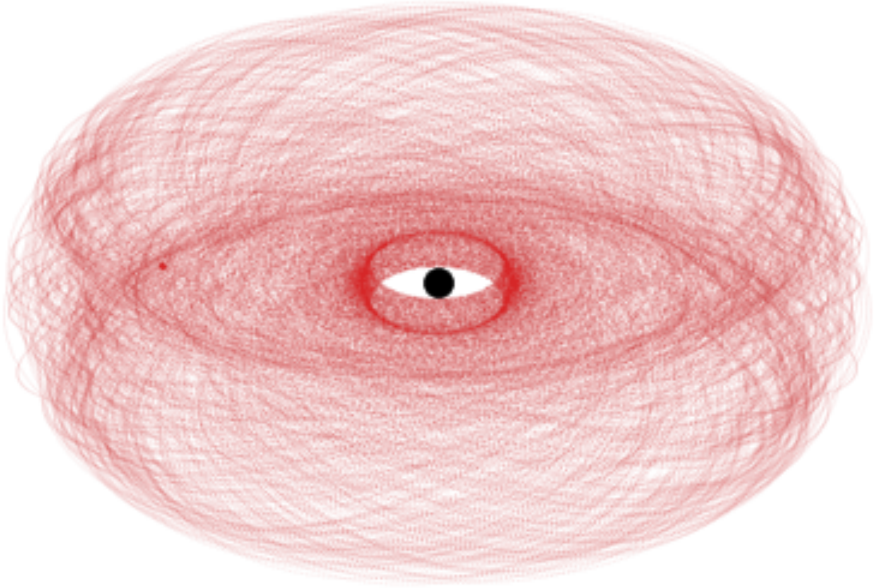

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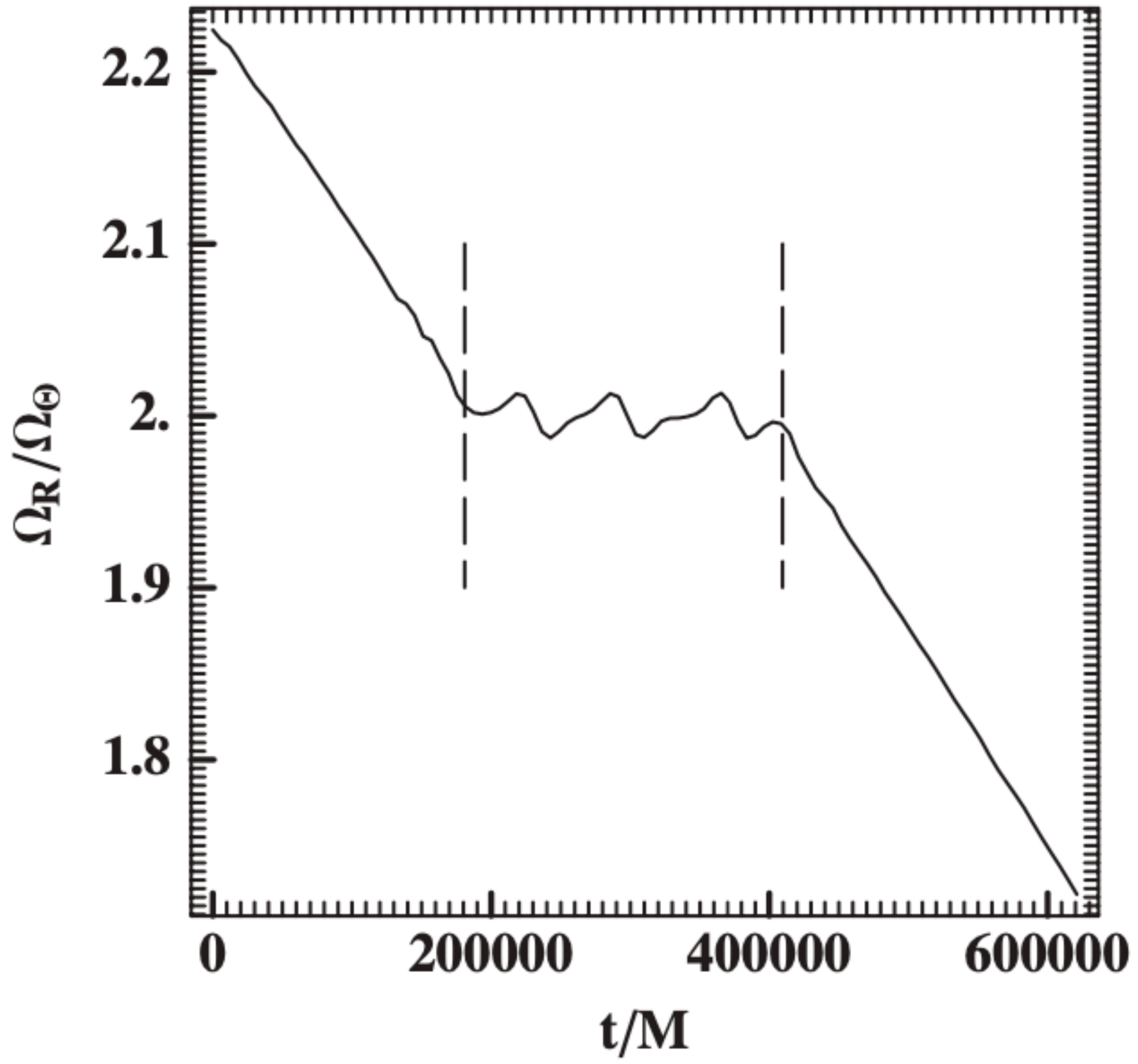

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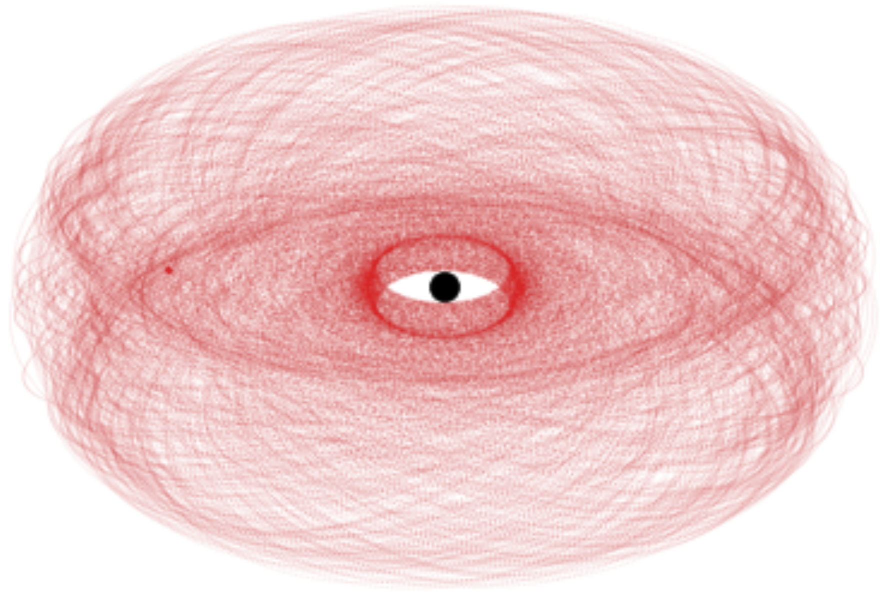

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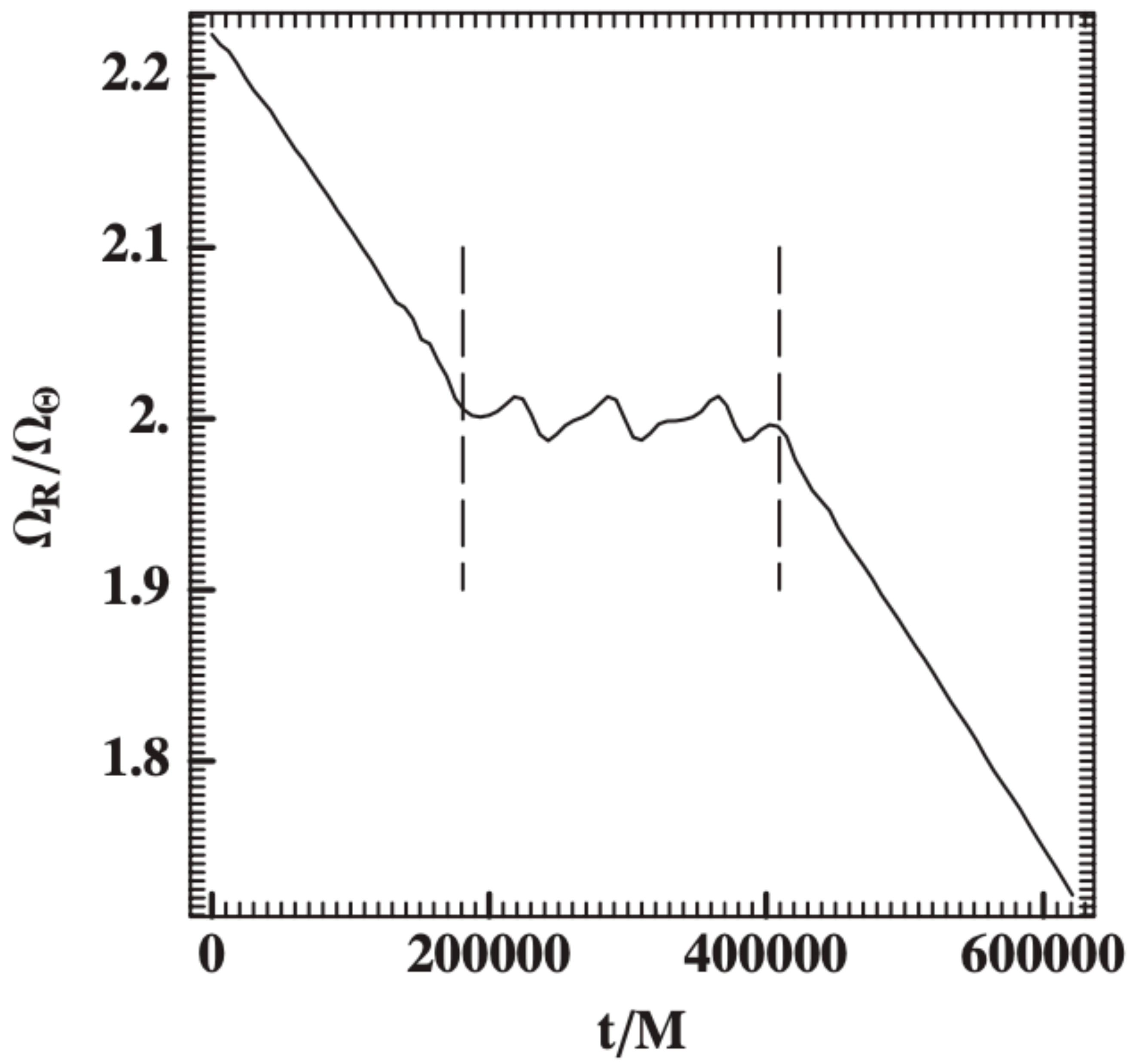

From the **gravitational waves**

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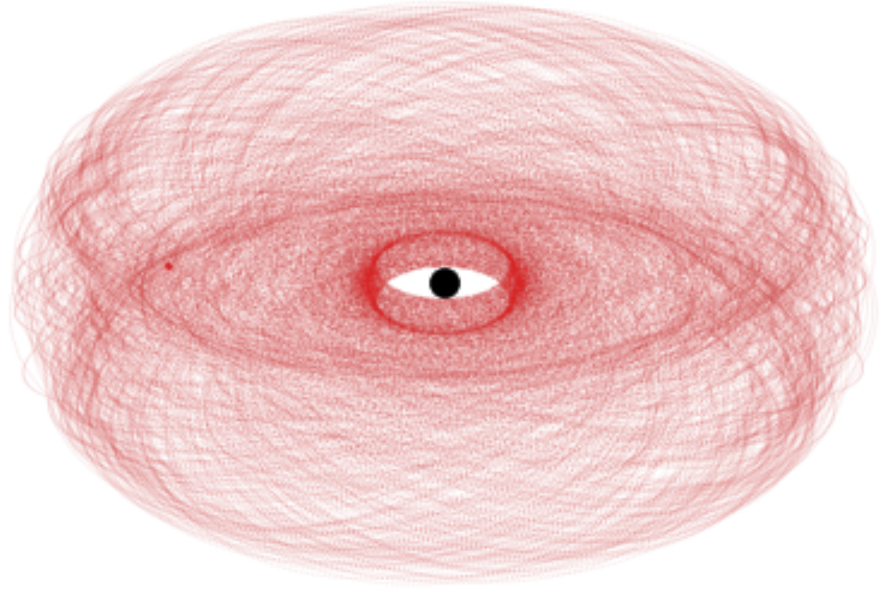

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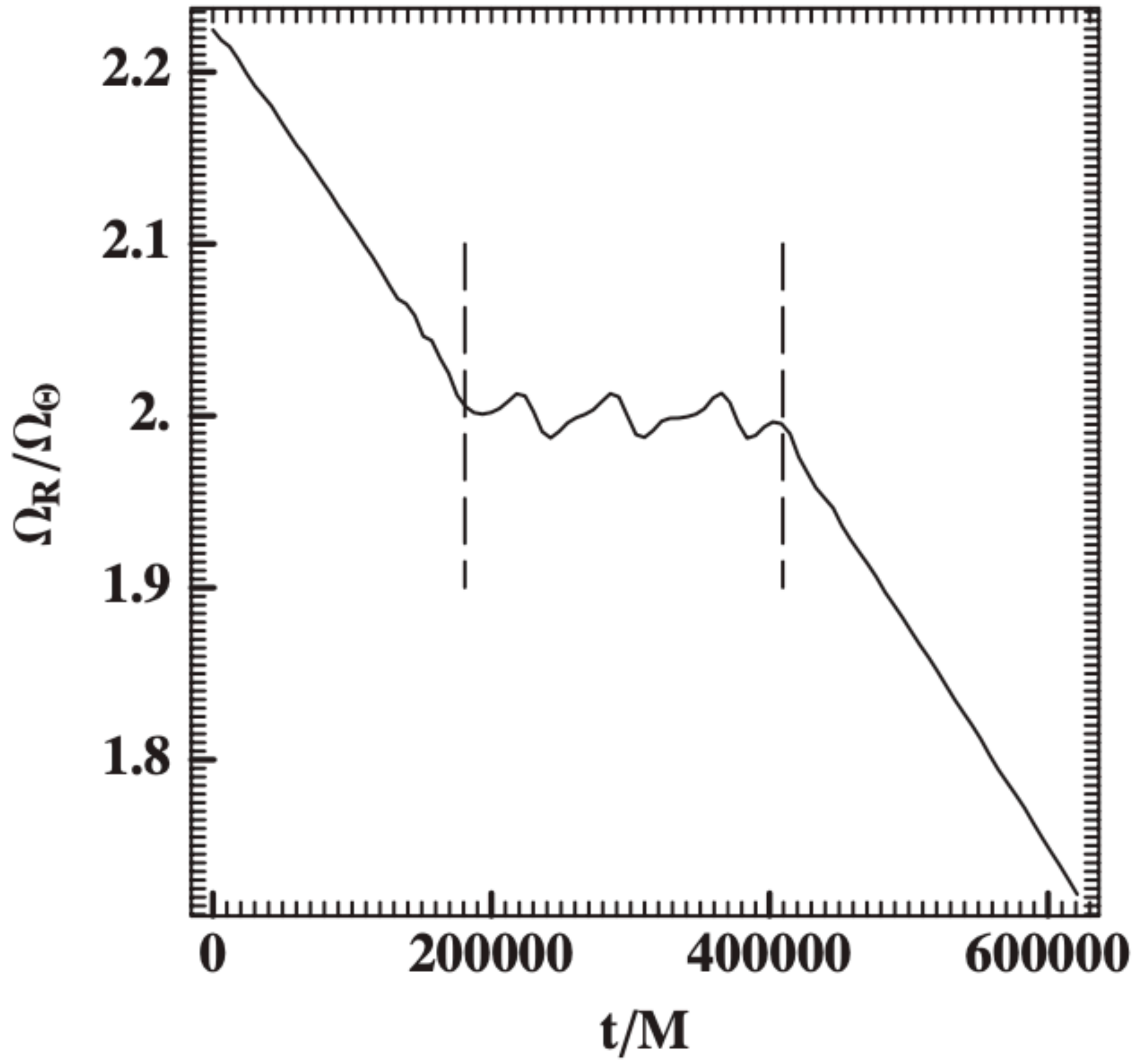

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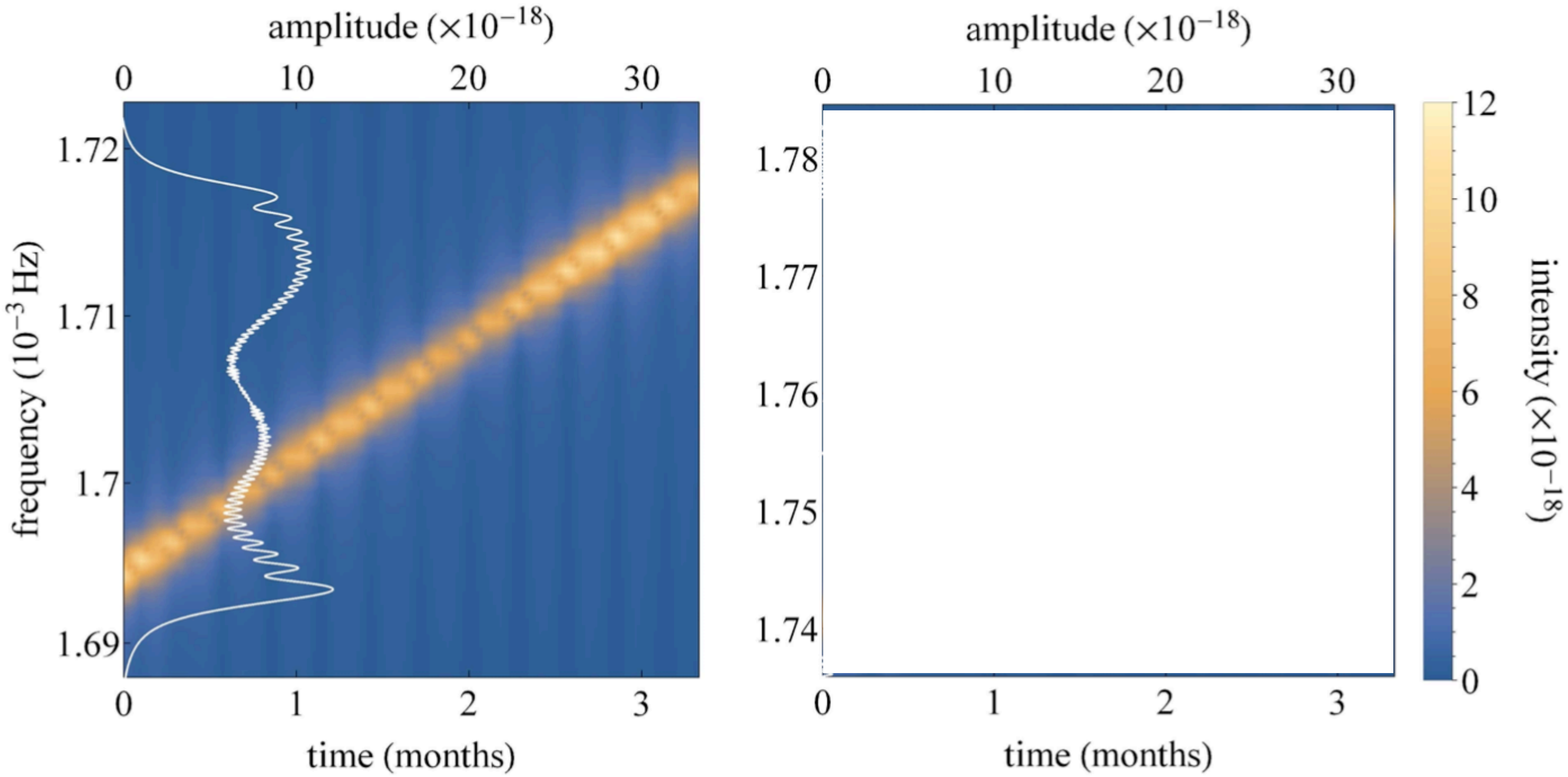

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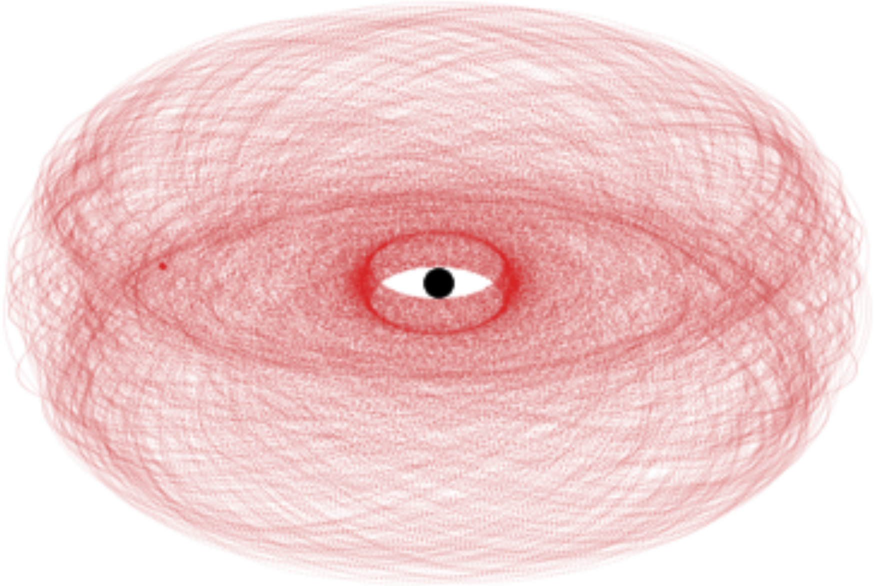

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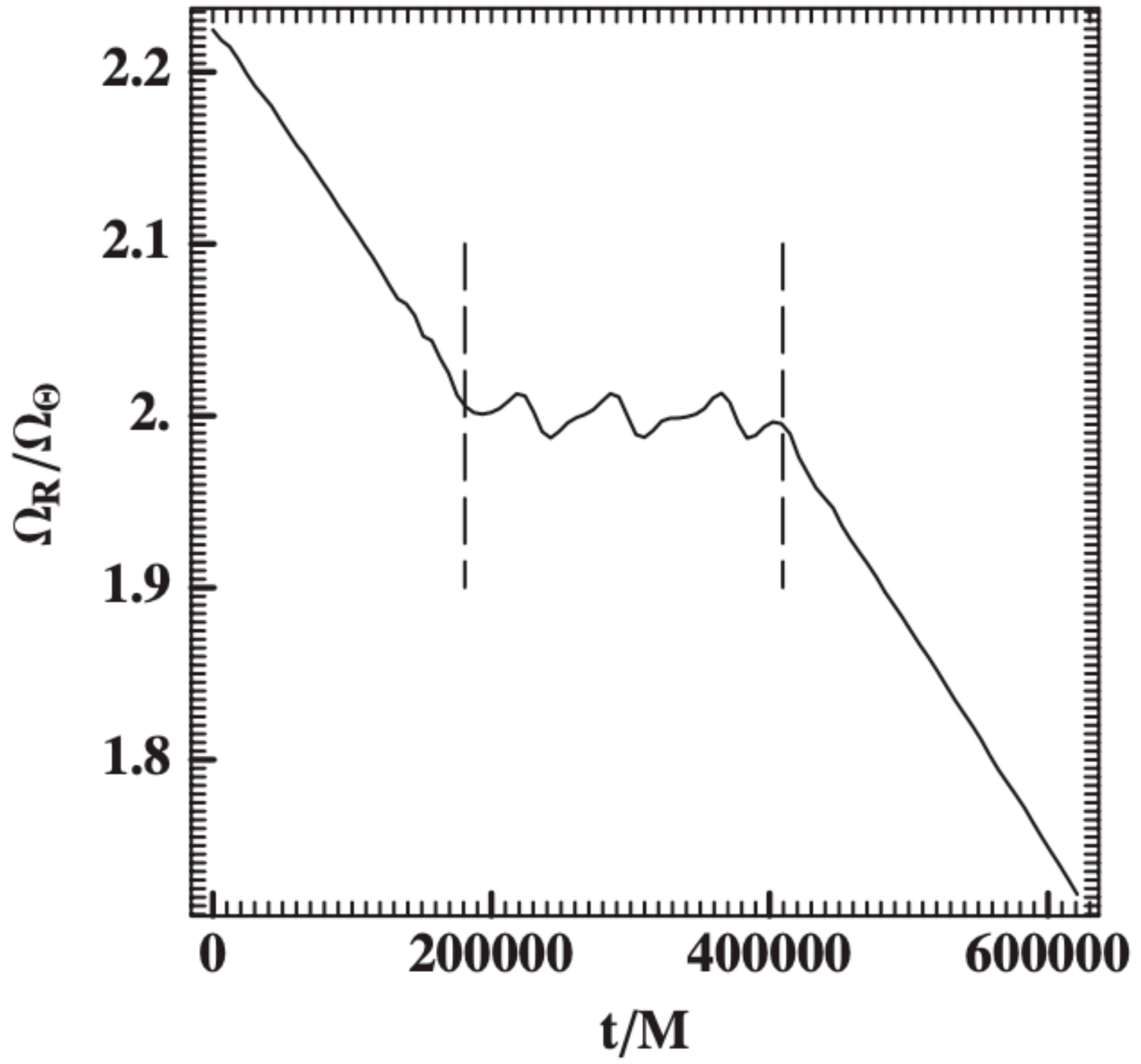

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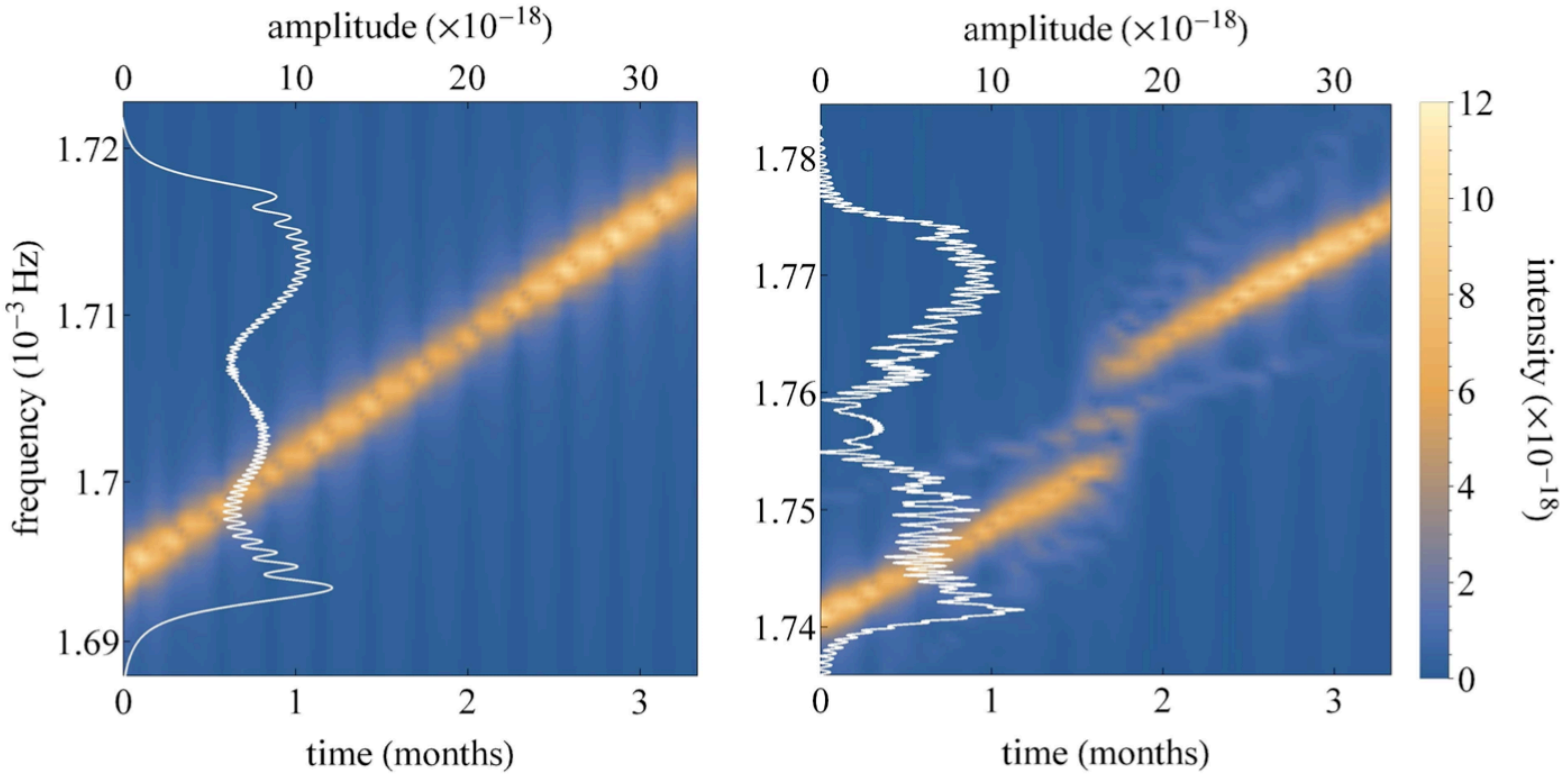

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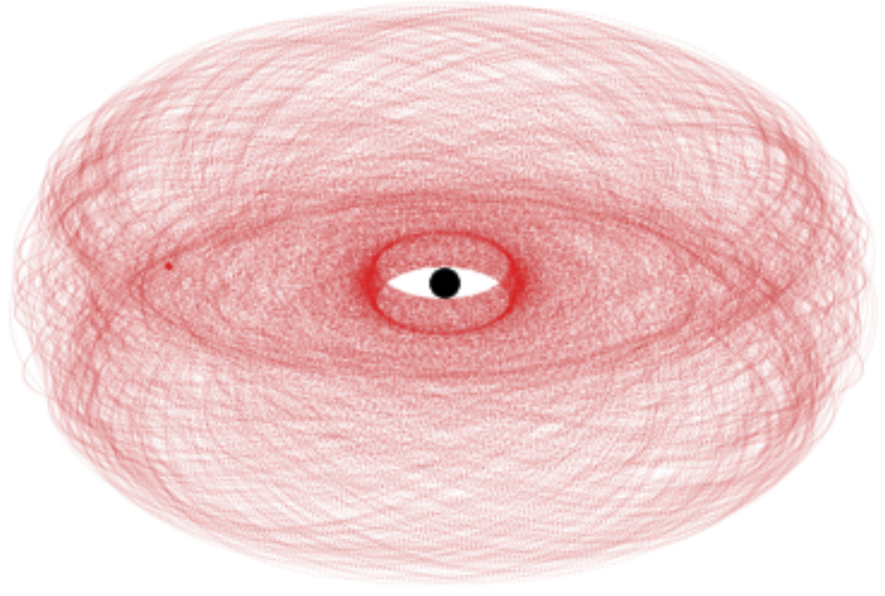

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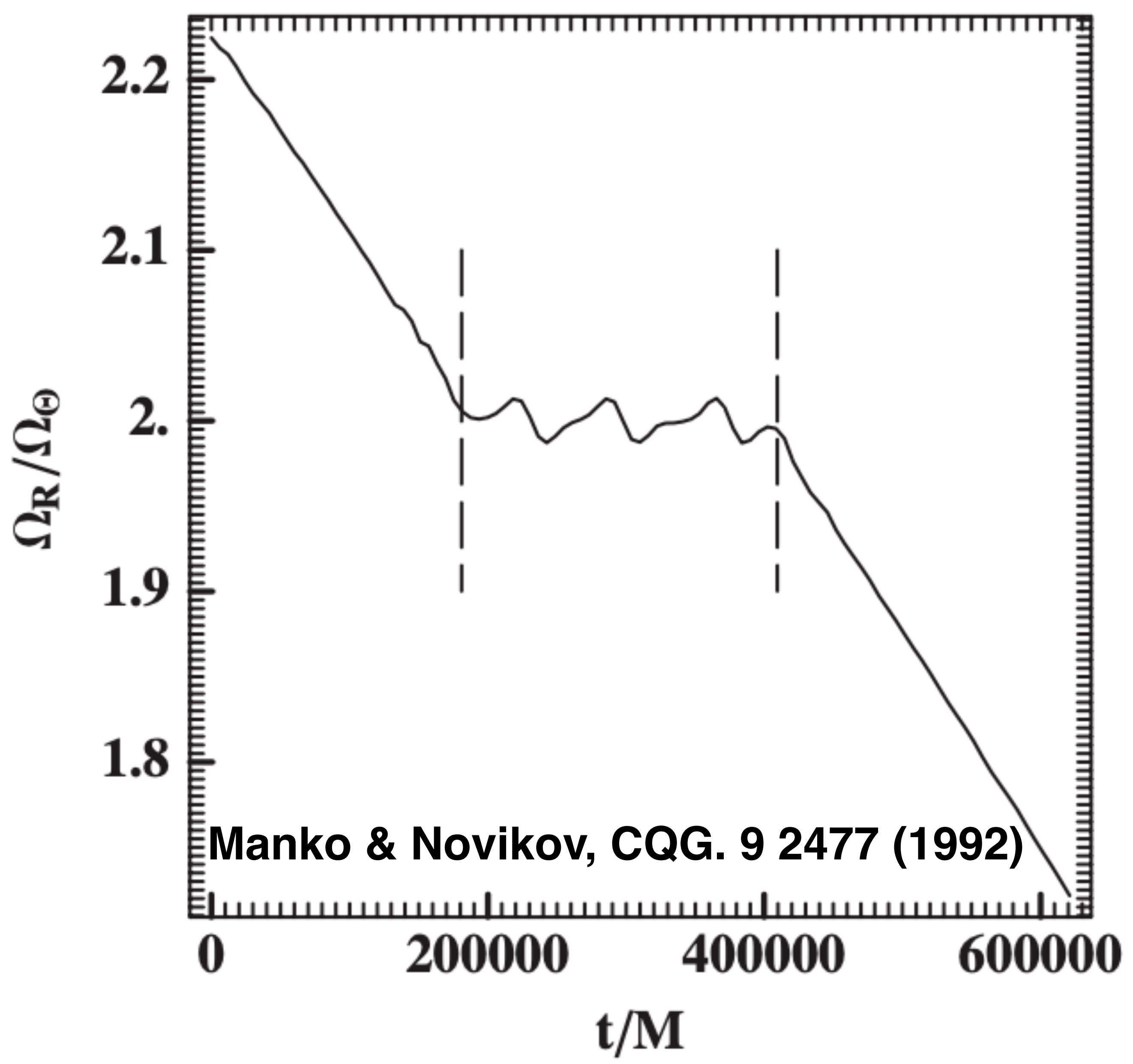

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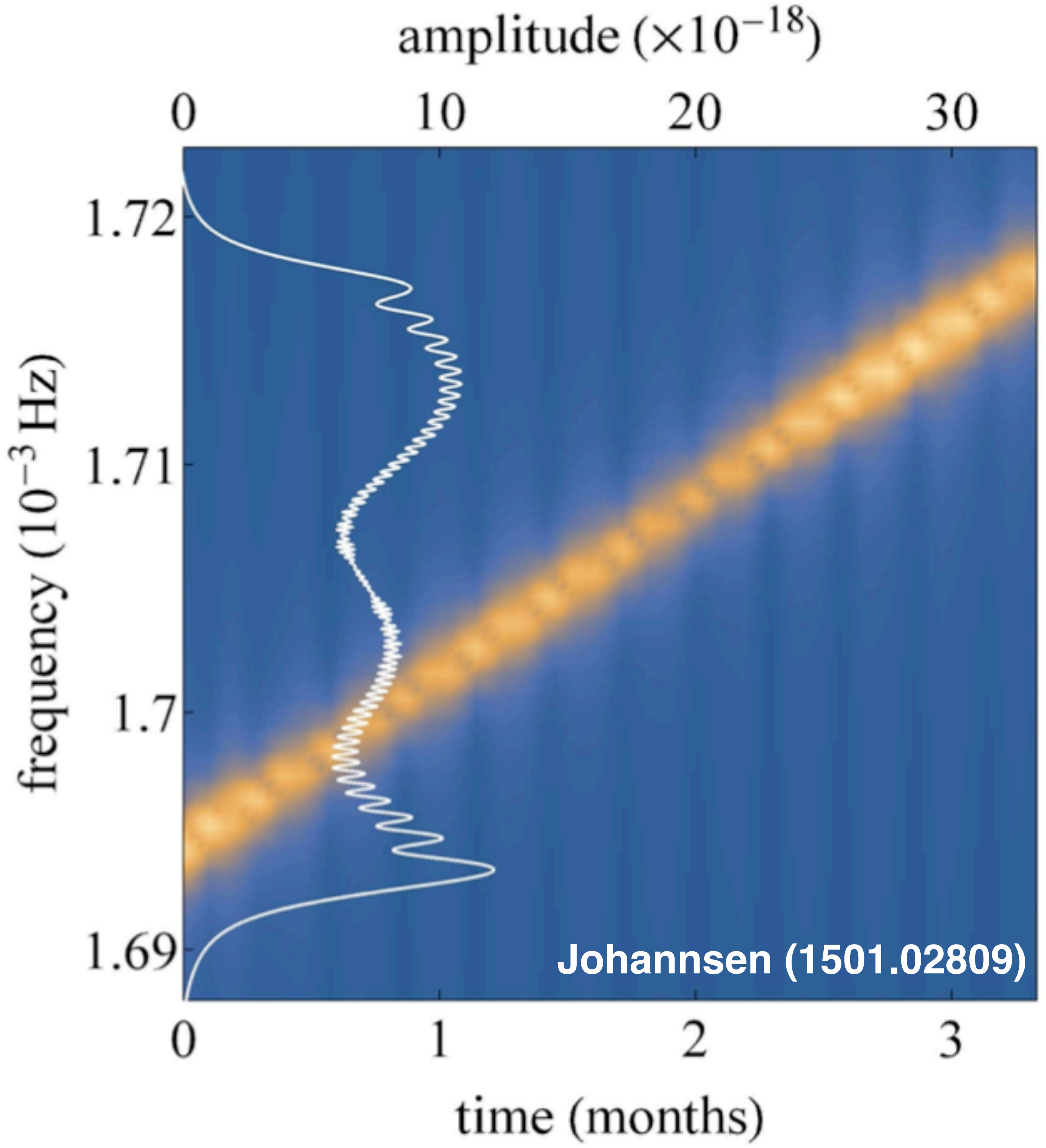

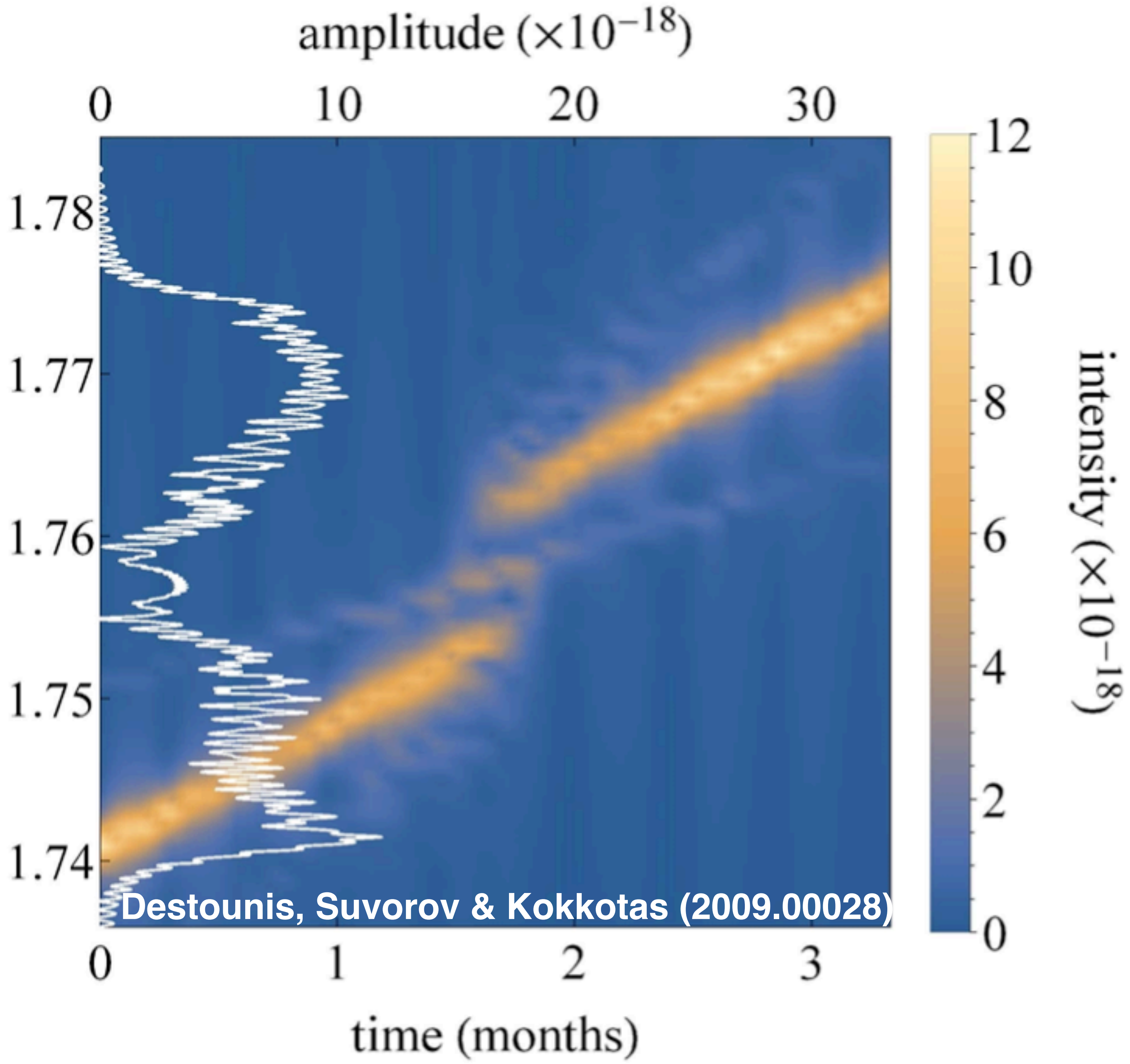

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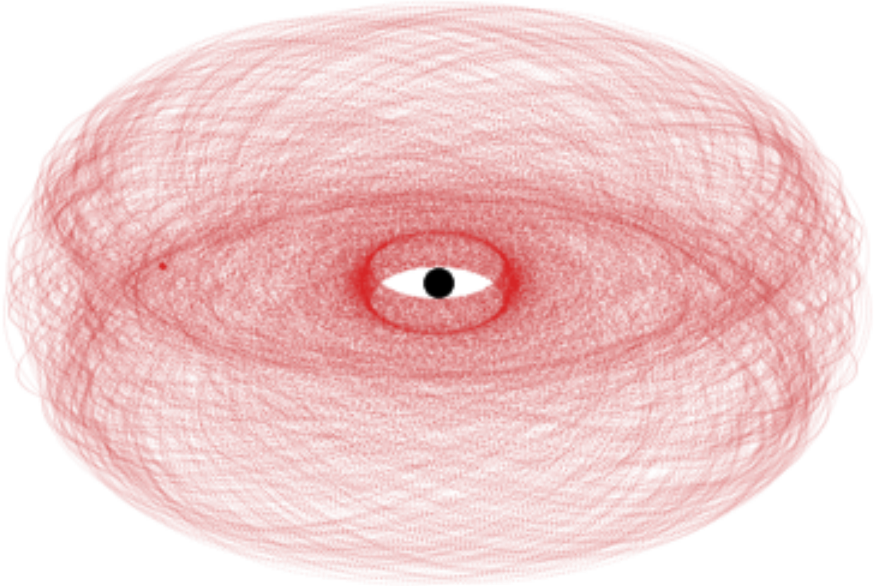
From the trajectory



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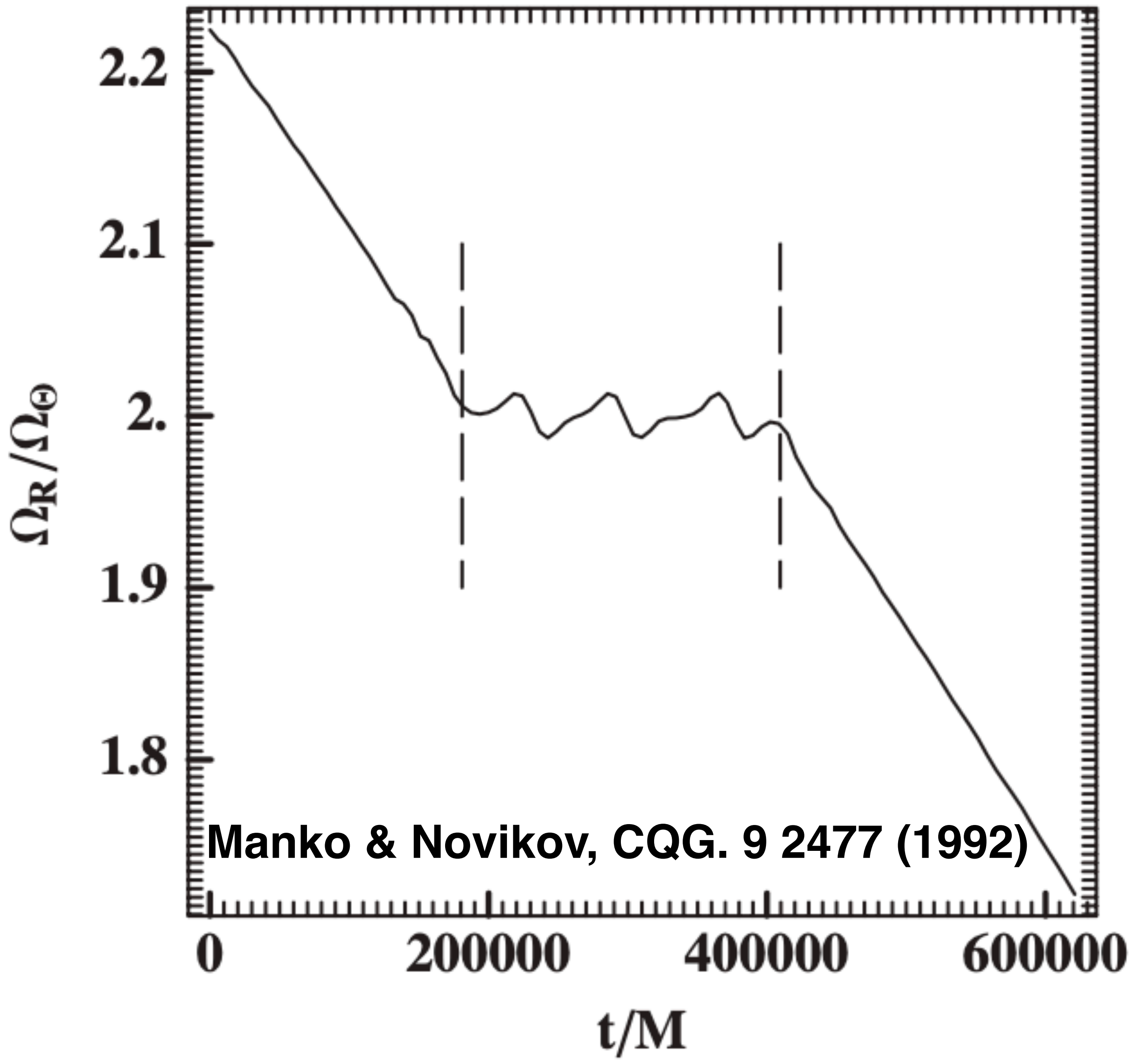

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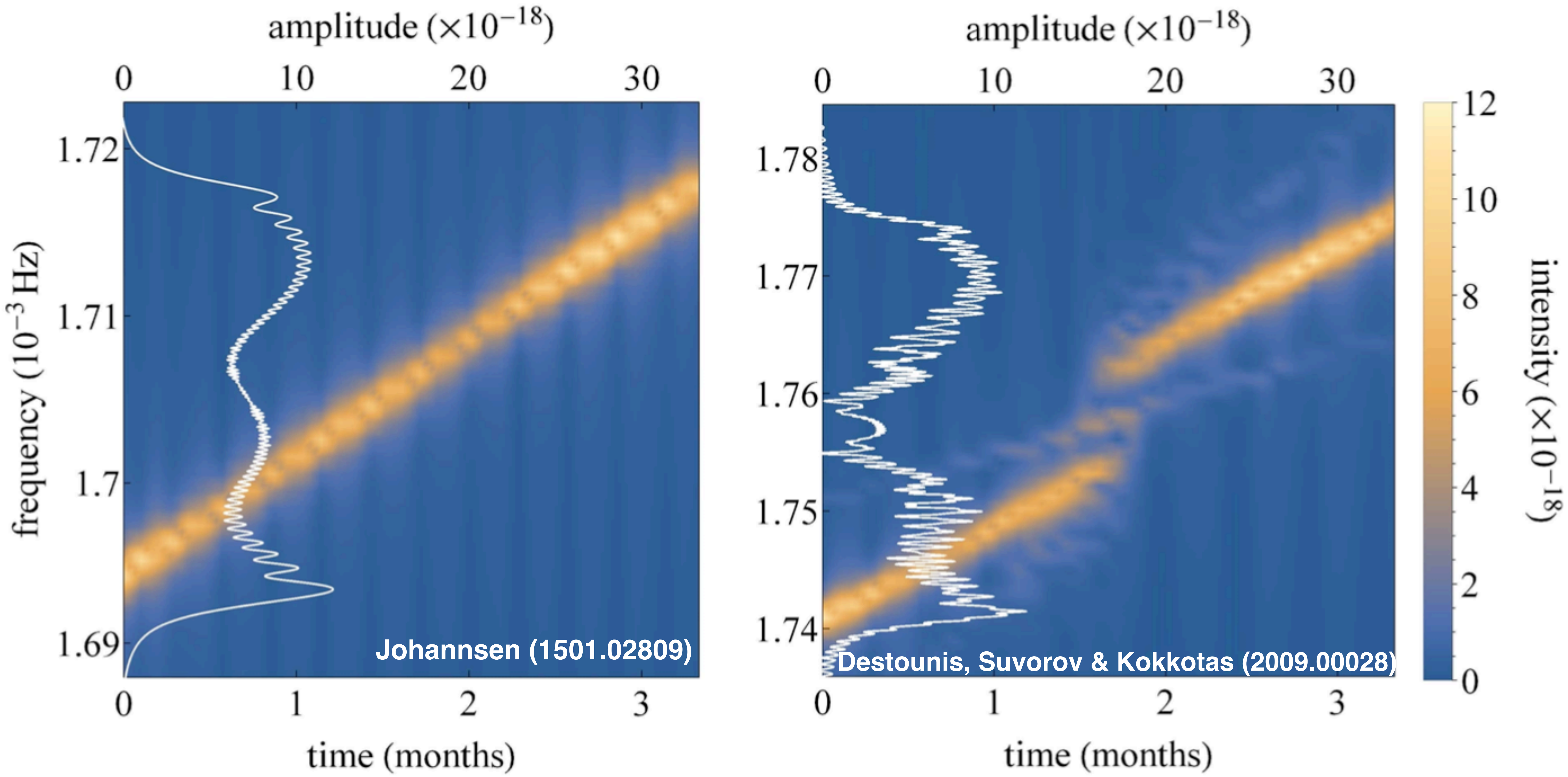

Linearized **Einsteinian** adiabatic **fluxes**:

$$E(t) = E(0) + \frac{dE}{dt}\bigg|_0^t \qquad L_z(t) = L_z(0) + \frac{dL_z}{dt}\bigg|_0^t$$

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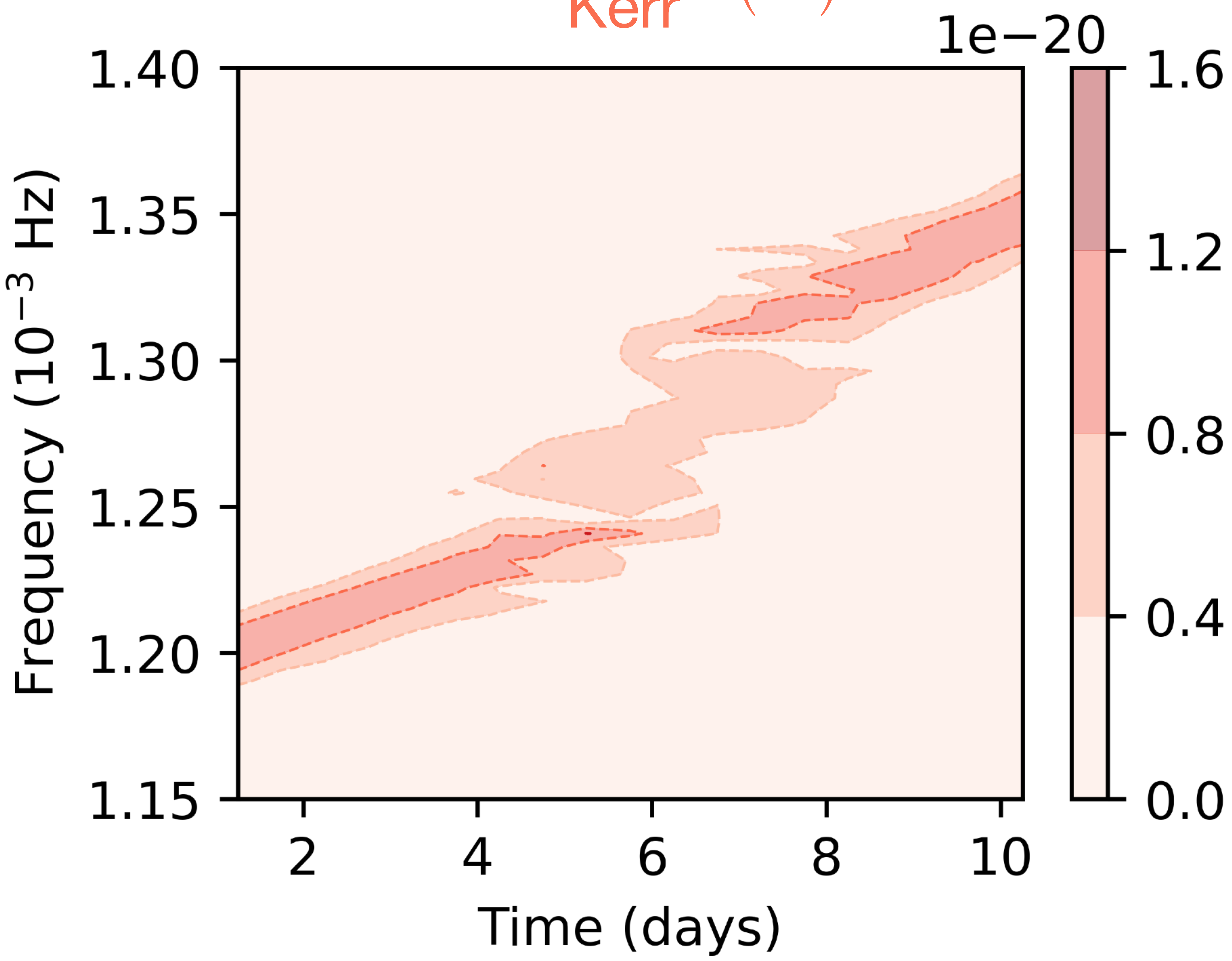

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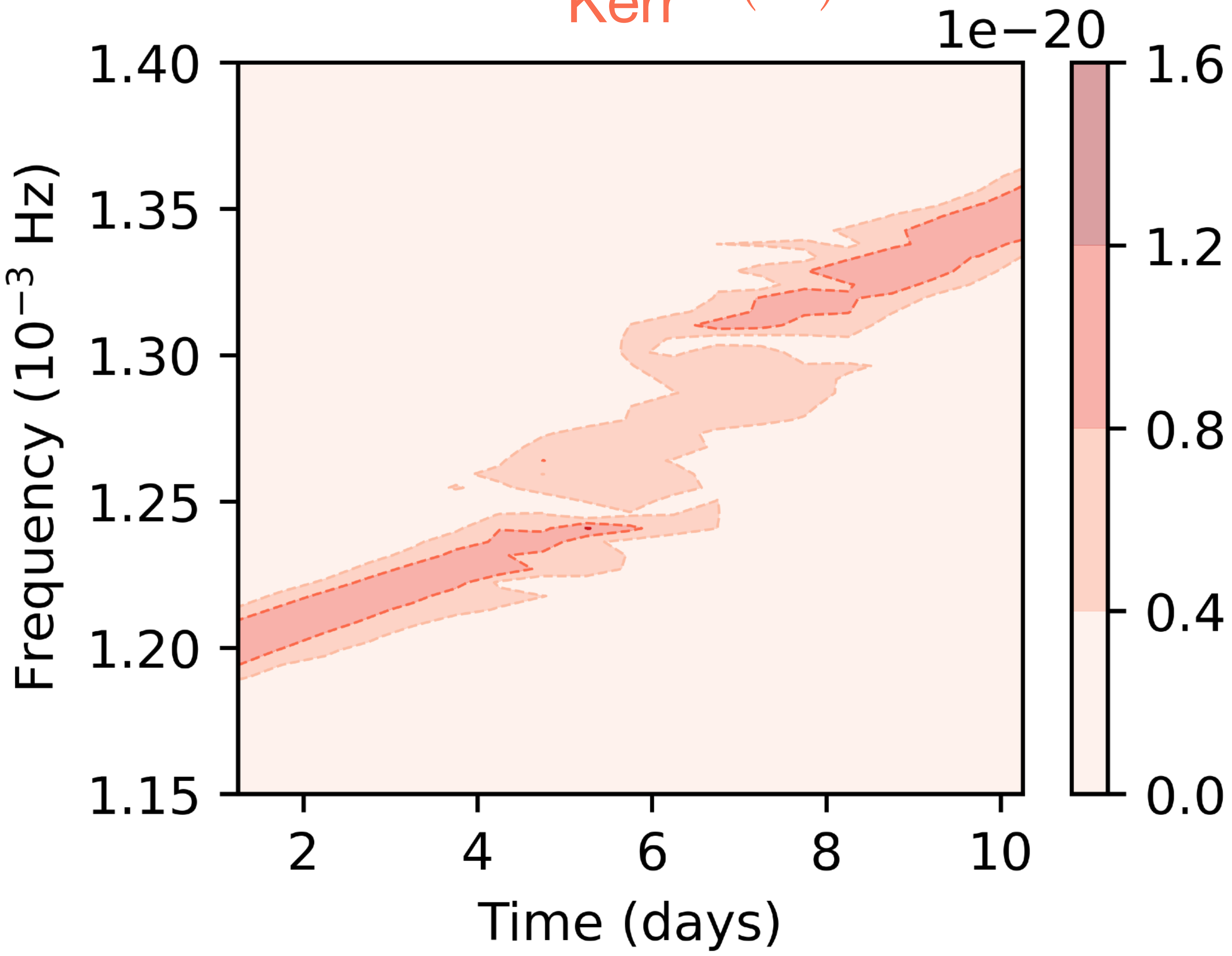

IC: a=0.8, p=4.66 e=0.7 m/M=10^{-6}

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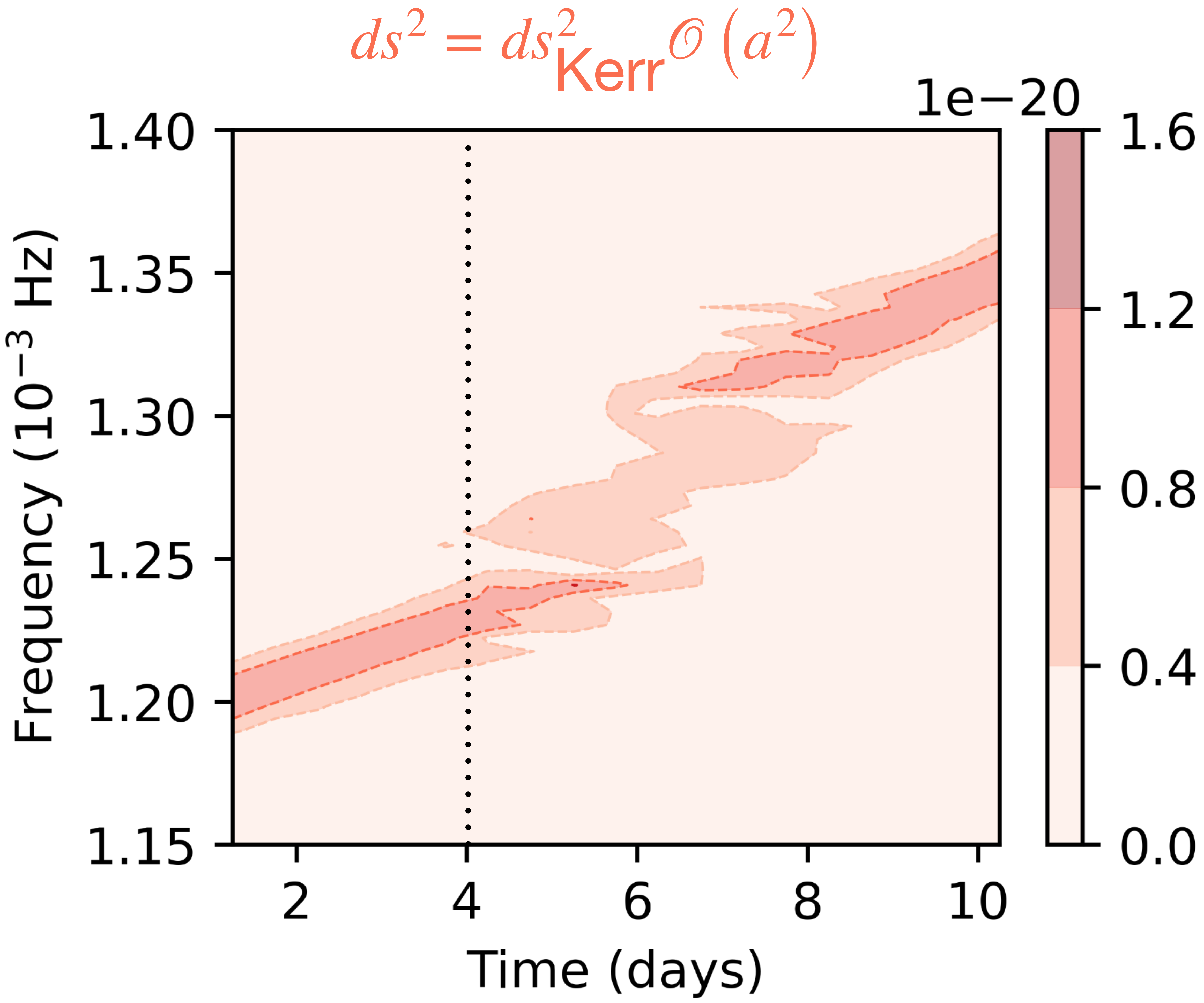

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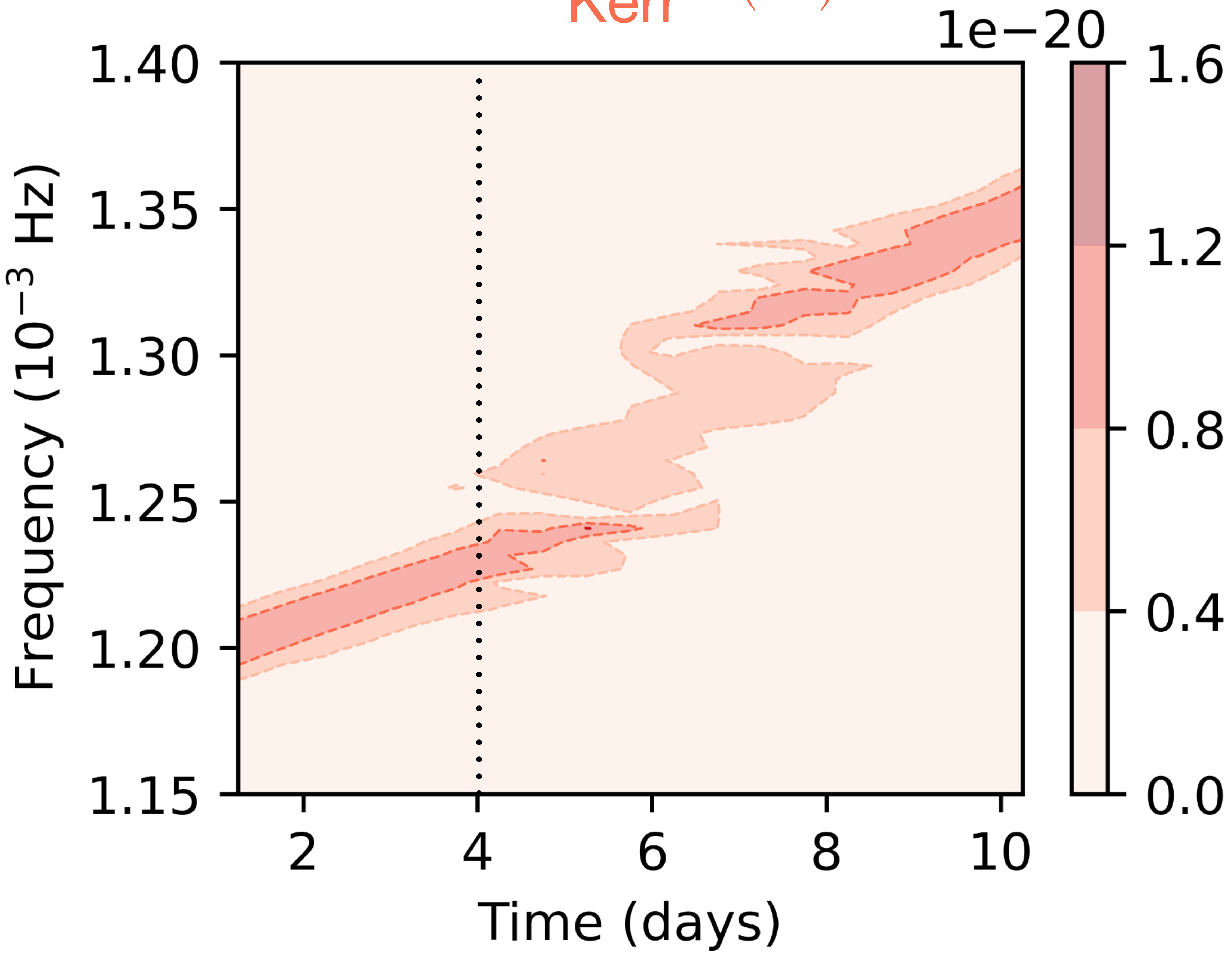

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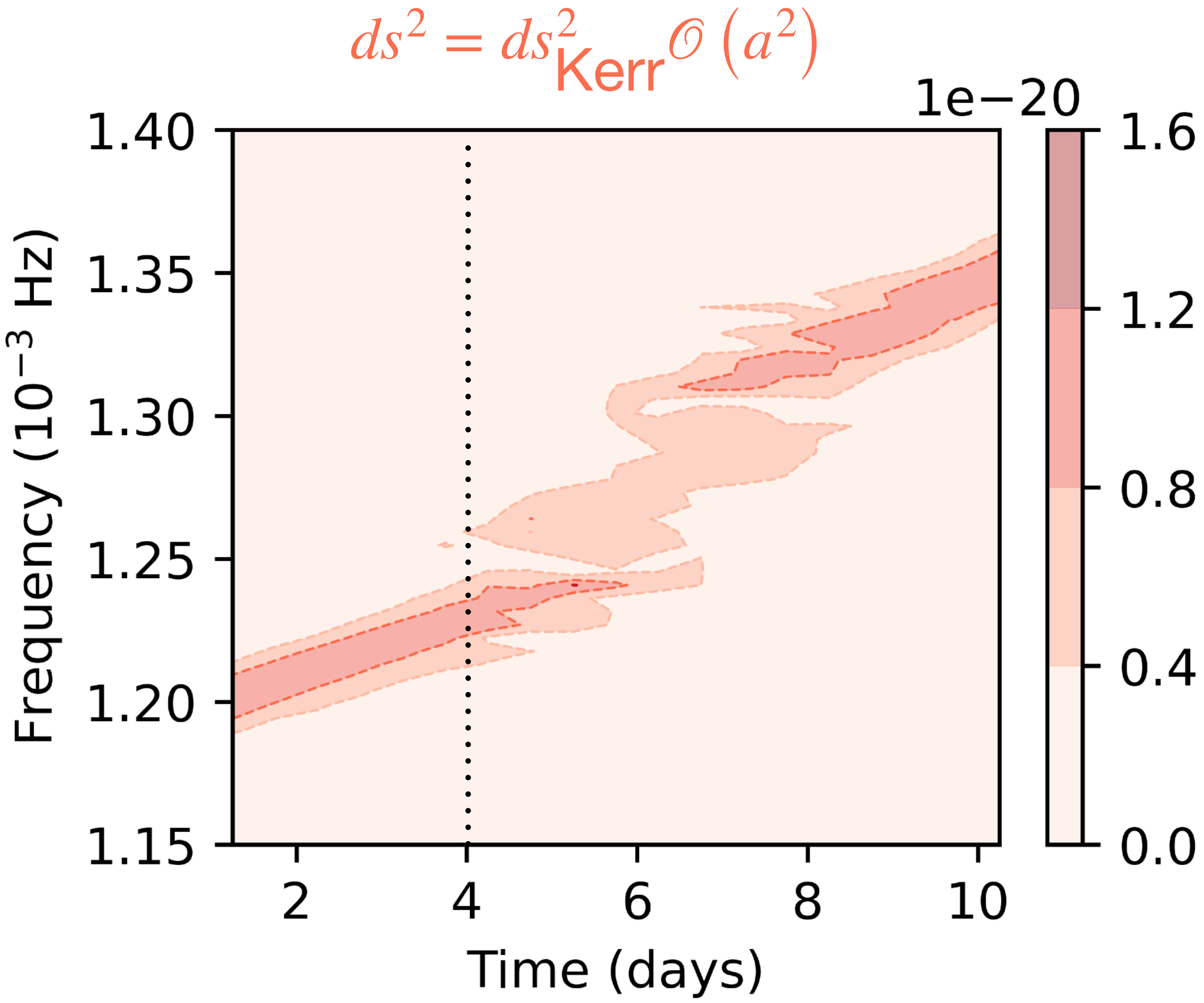

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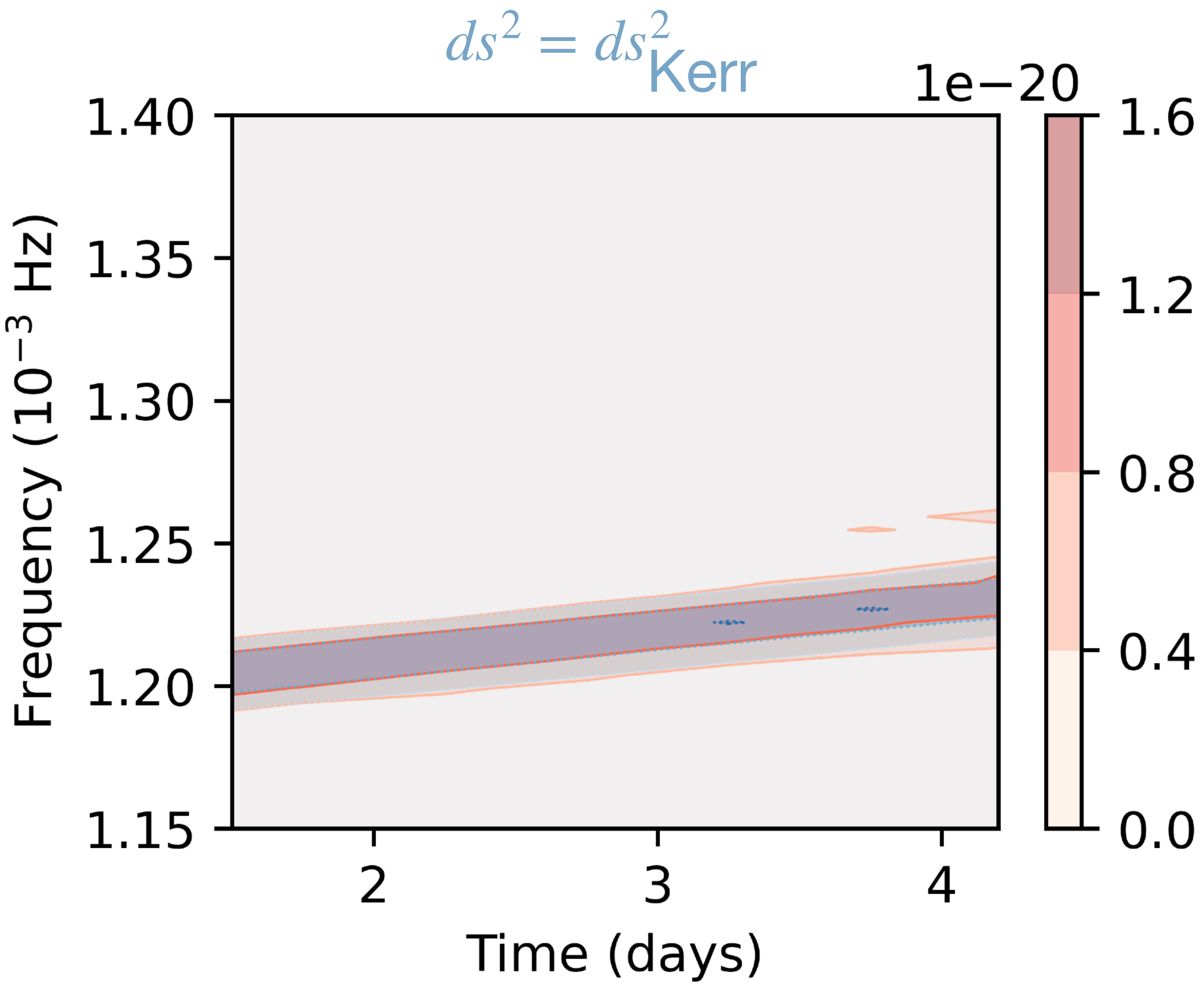

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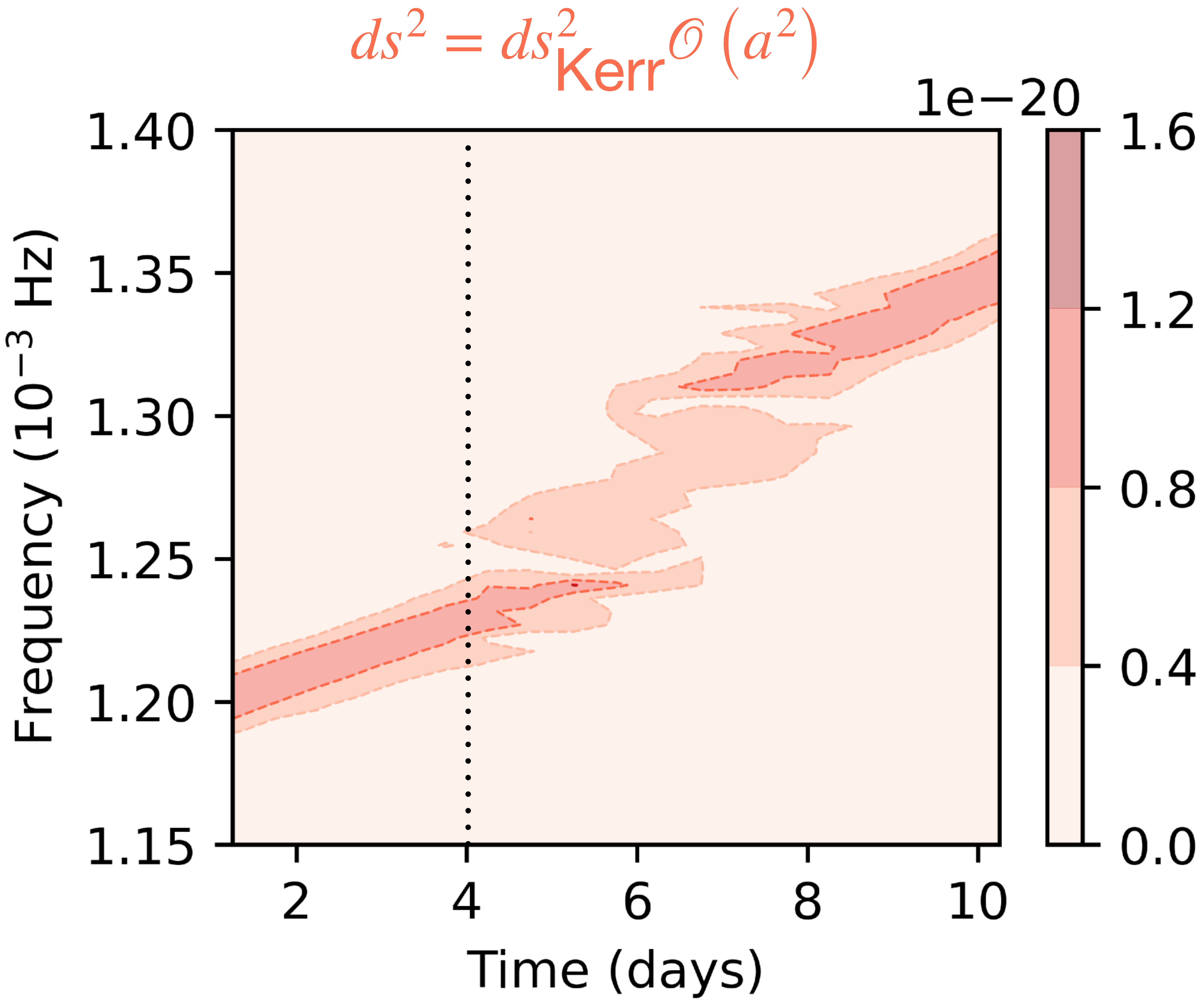

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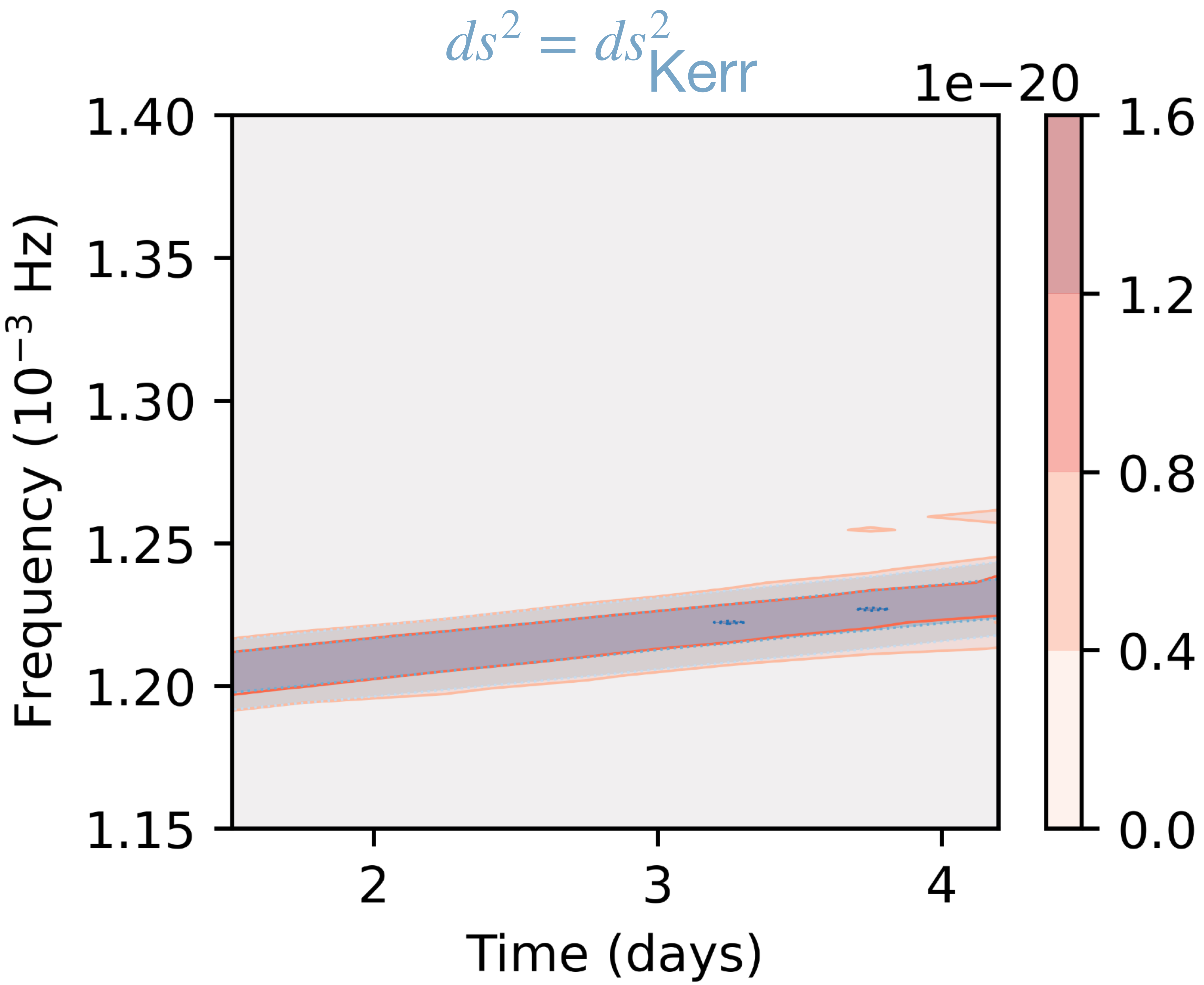

Now, let us add a "**kick**" to the flux!

e.g., see Speri & Gair (2103.06306) for a study and model within GR around resonances
see Pan, Yang, Bernard, et al., (2306.06576) for an introduction of a resonance effective Hamiltonian

The impact of resonances (very brief description)

e.g., Flanagan & Hinderer (0805.3337)

The (simplified) GR two body problem in the EMRI case in terms of **action-angle variables** $\mathbf{J} = \left(J_r, J_\theta, J_\phi\right)$

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For a slowly evolving system, each component of the ***self force*** can be written as:

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Why a kick? Resonant effects within GR

Self-force resonances

Flanagan & Hinderer (1009.4923)

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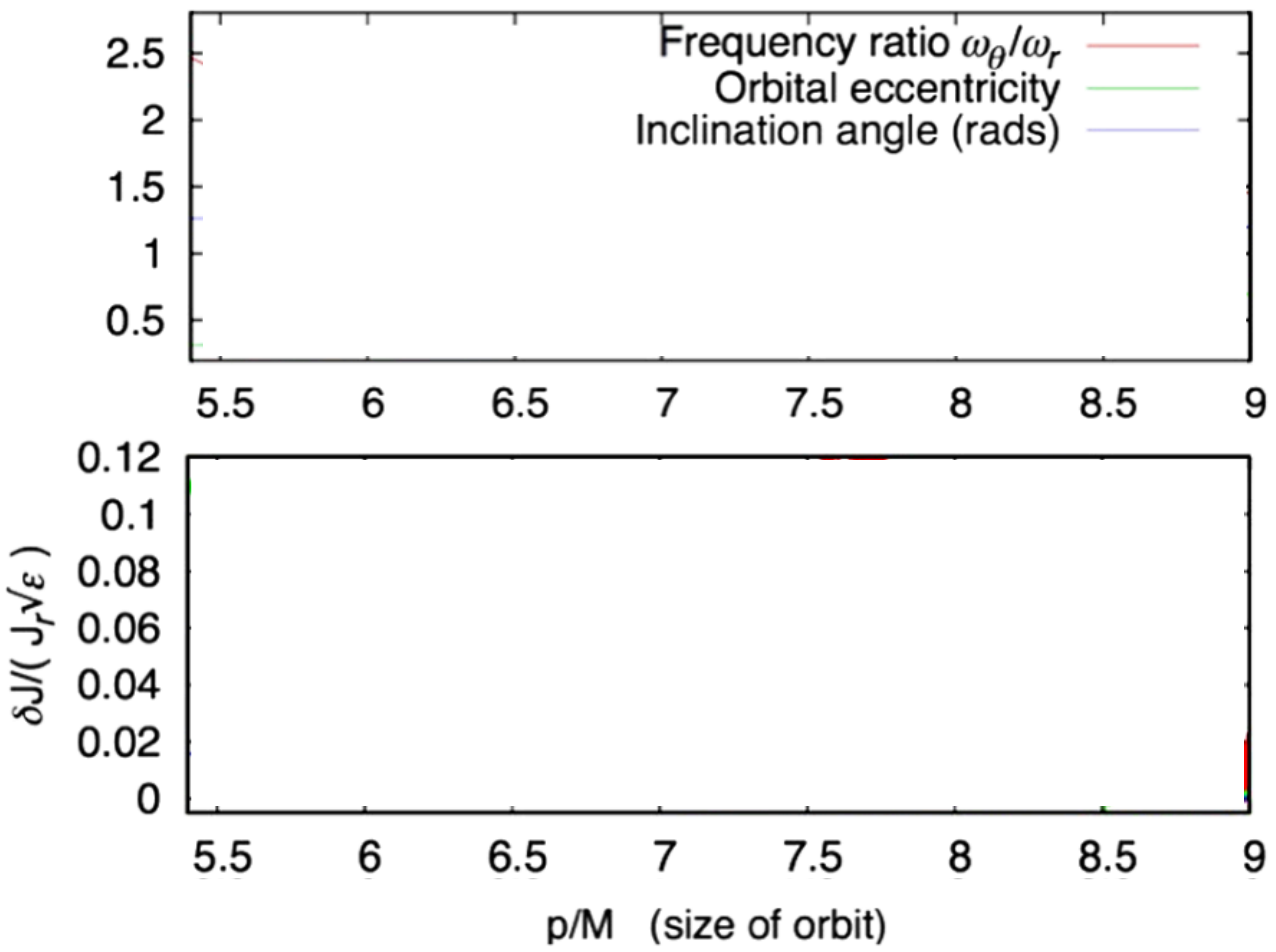

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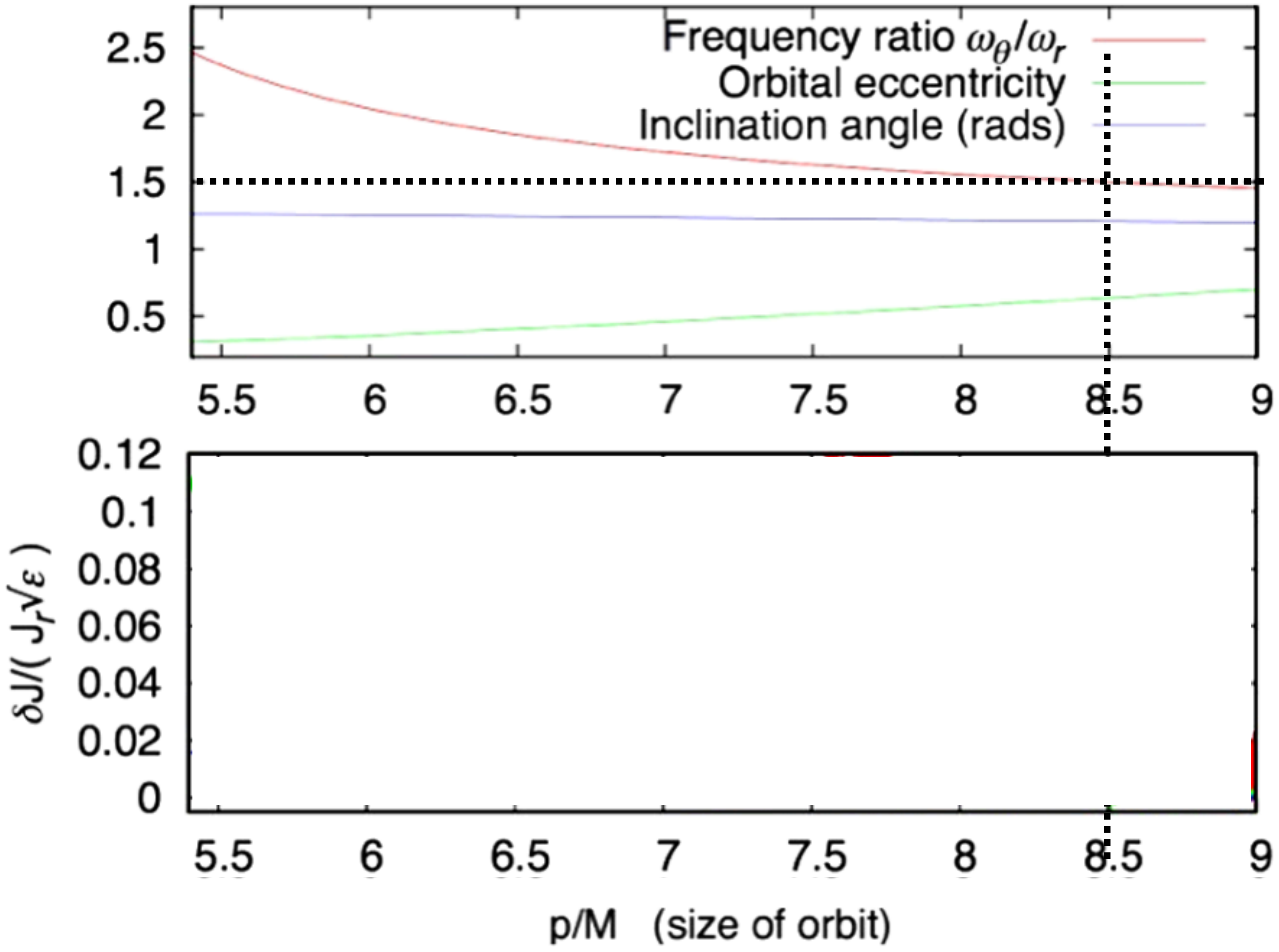

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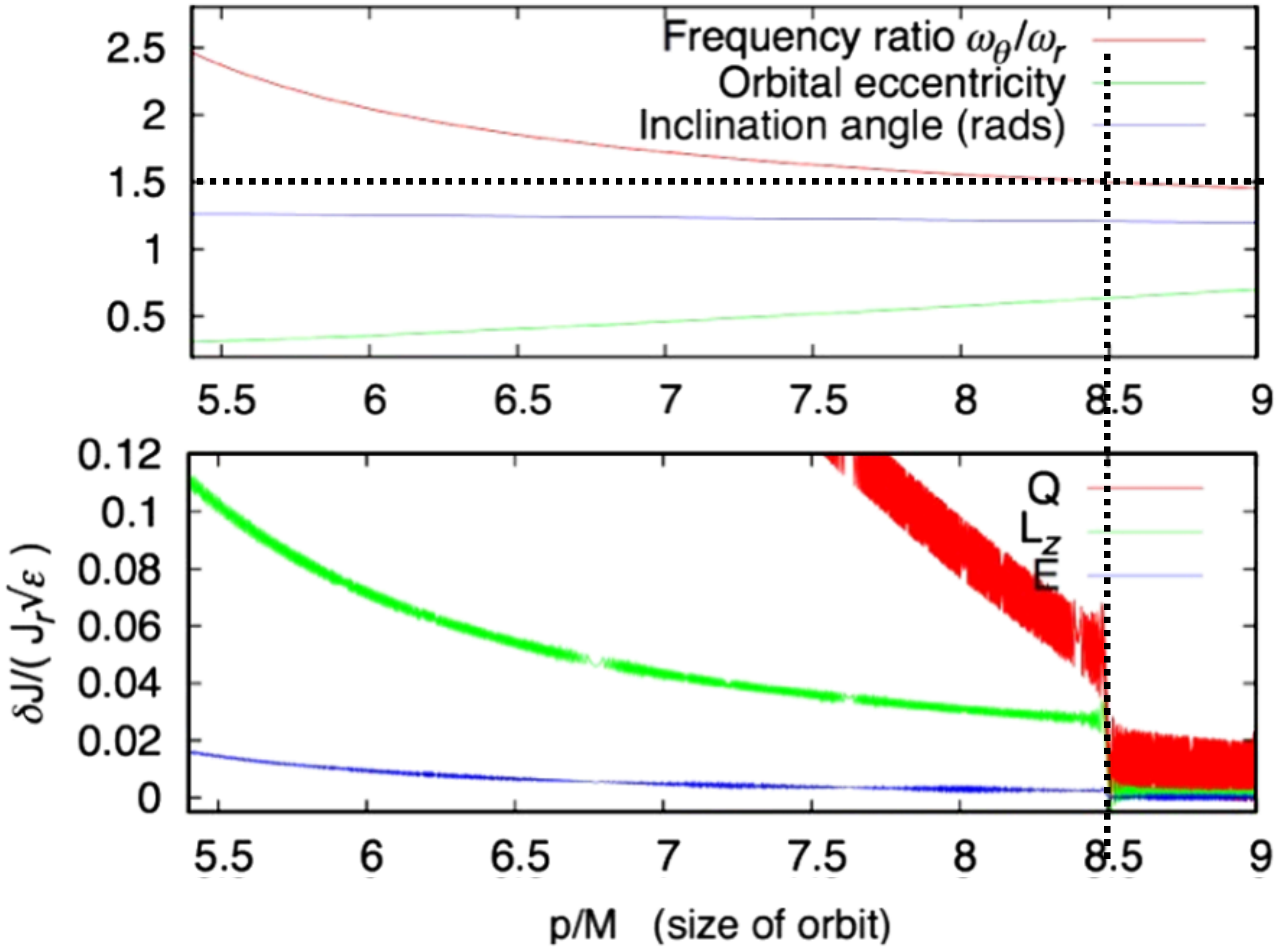

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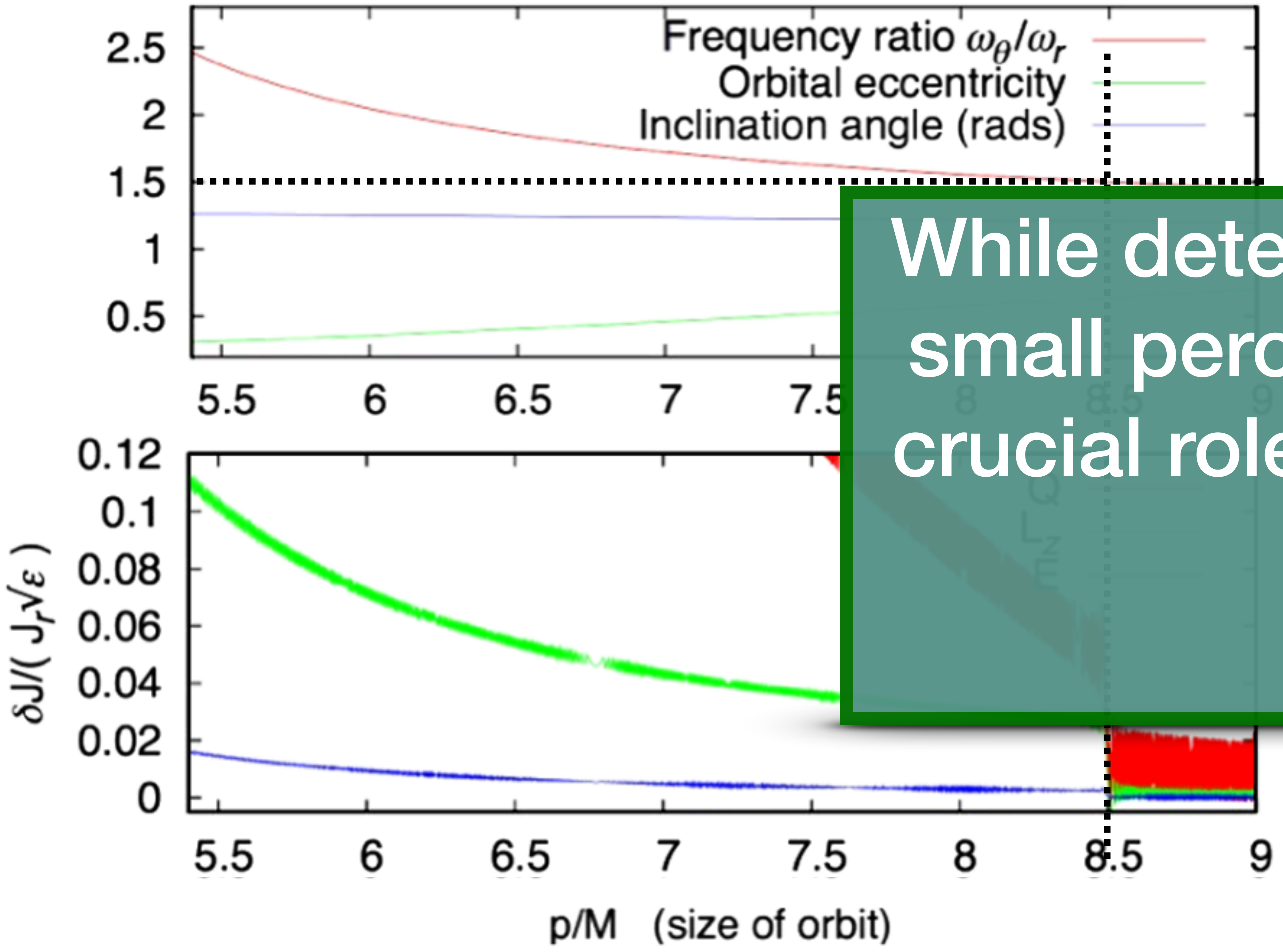

While detection may only result in a small percentage of loss, it plays a crucial role in accurately estimating parameters!

Berry, Cole, Cañizares, et al., (1608.08951)

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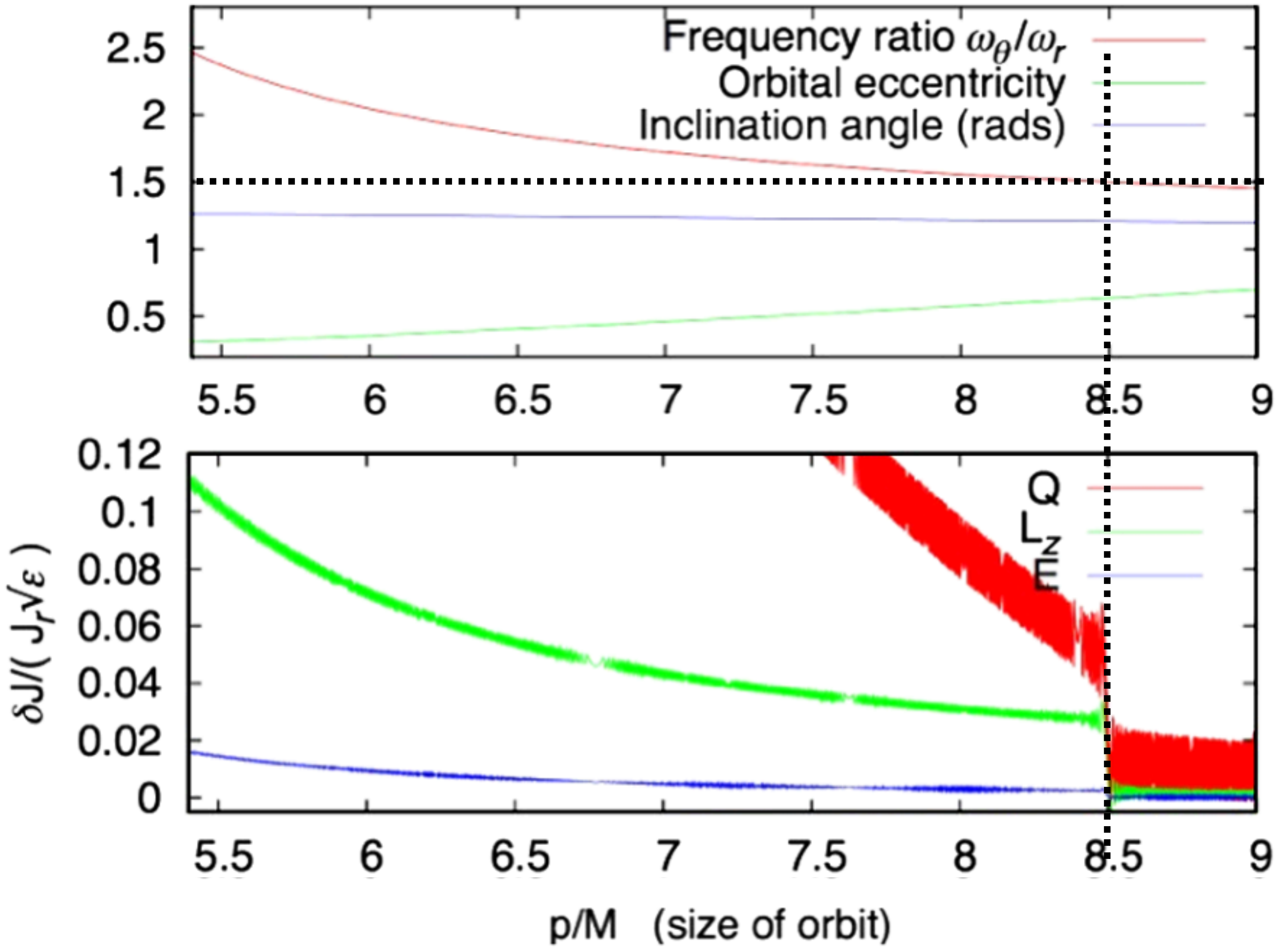

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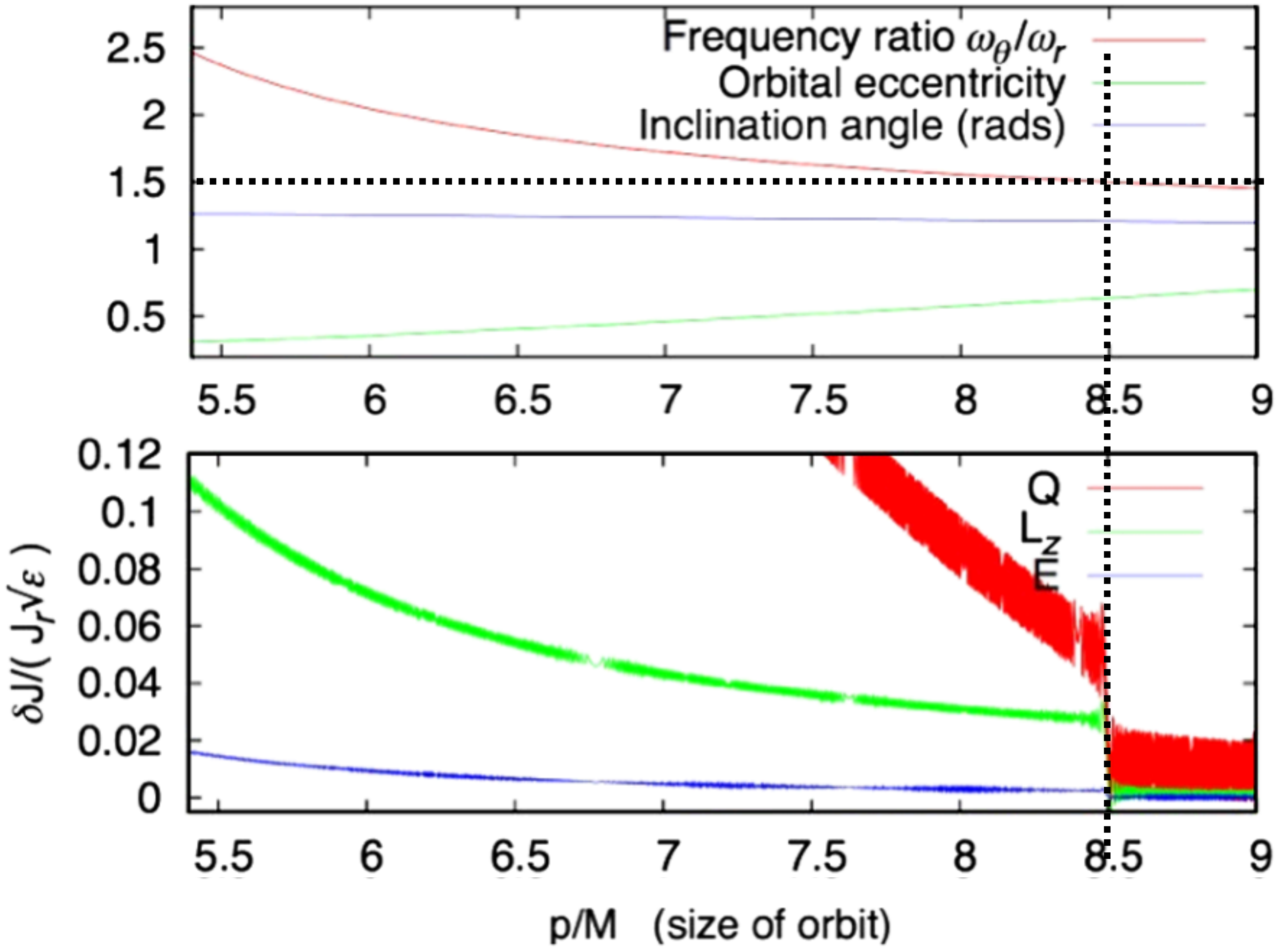

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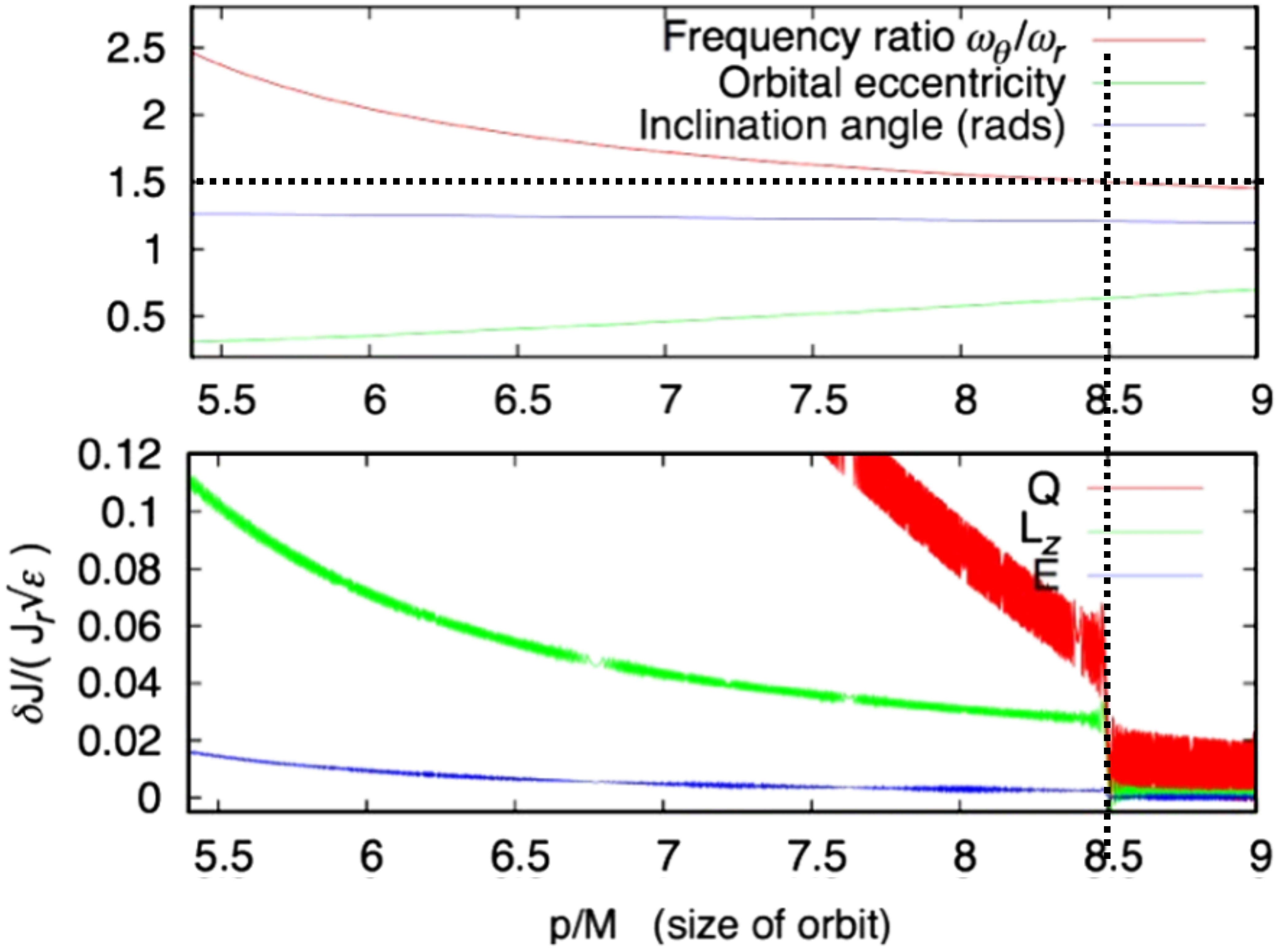

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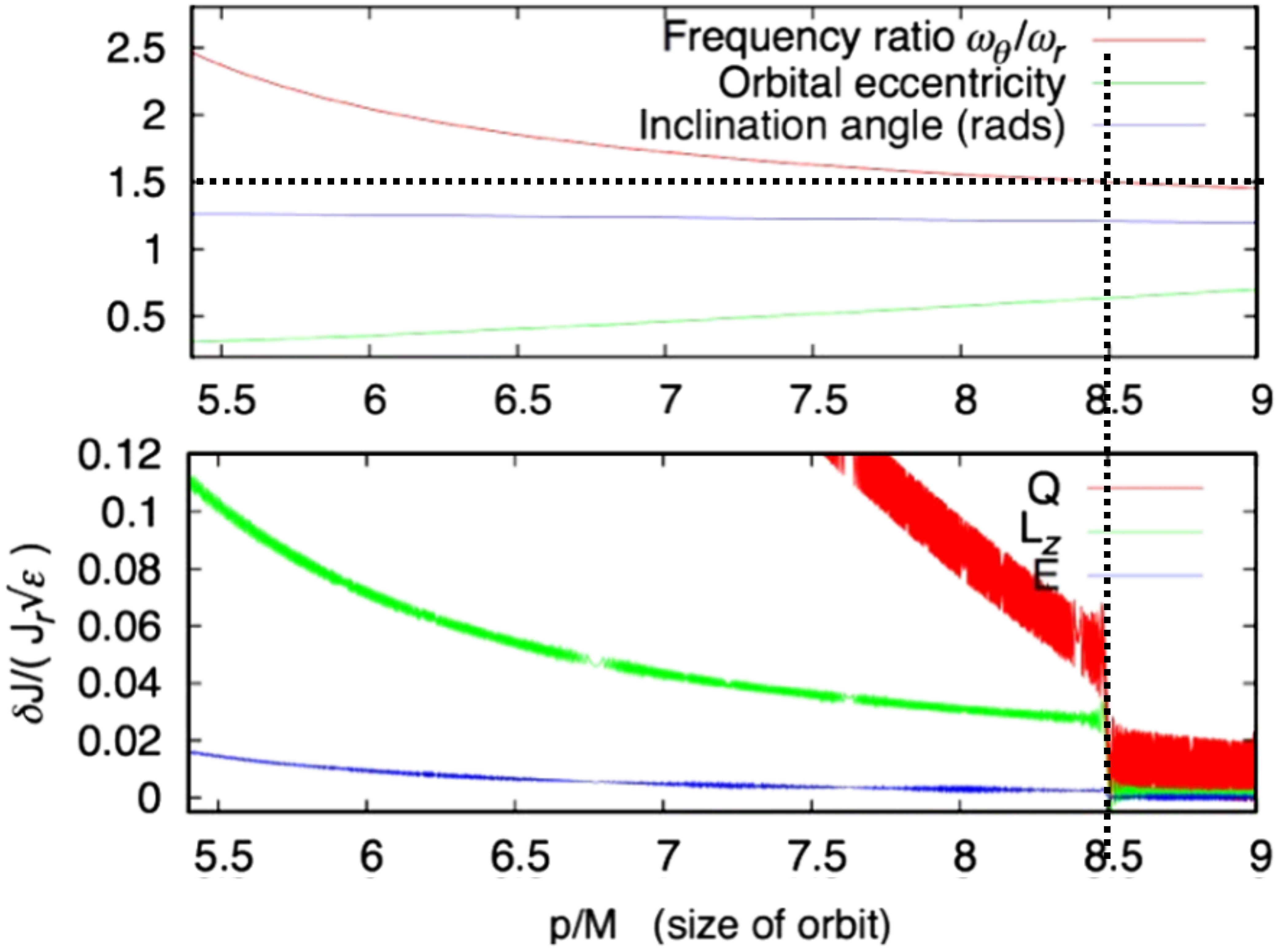

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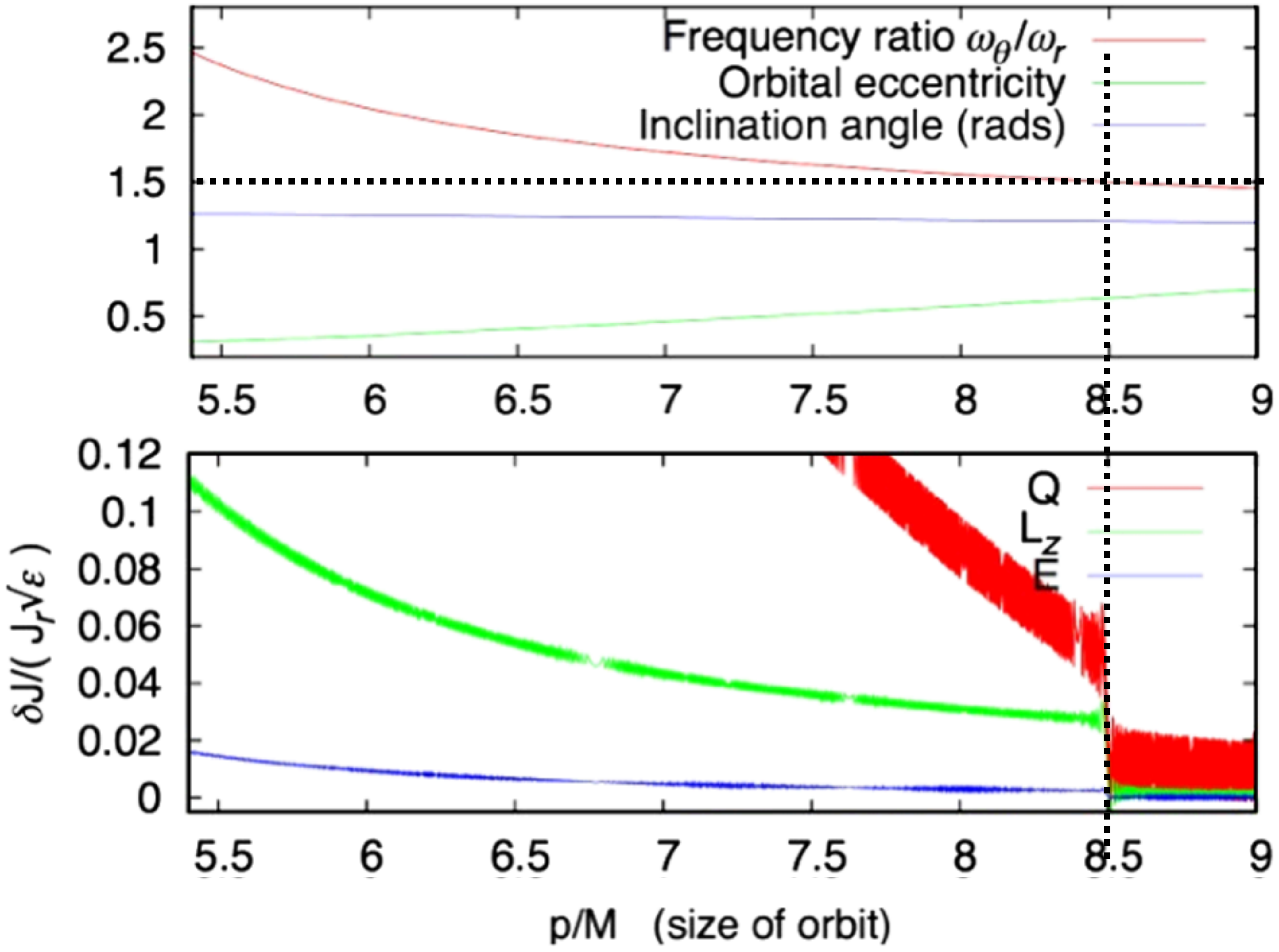
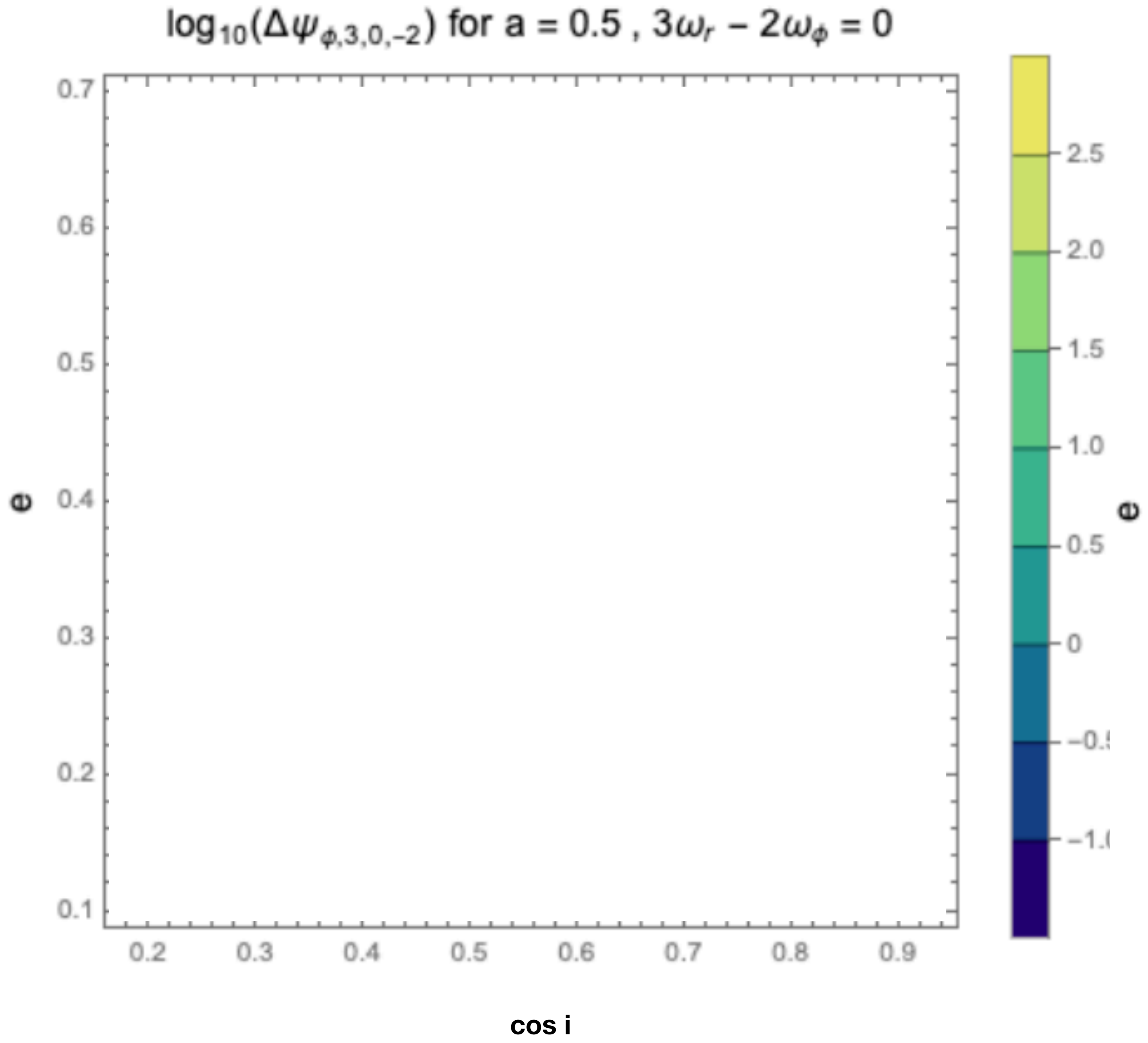
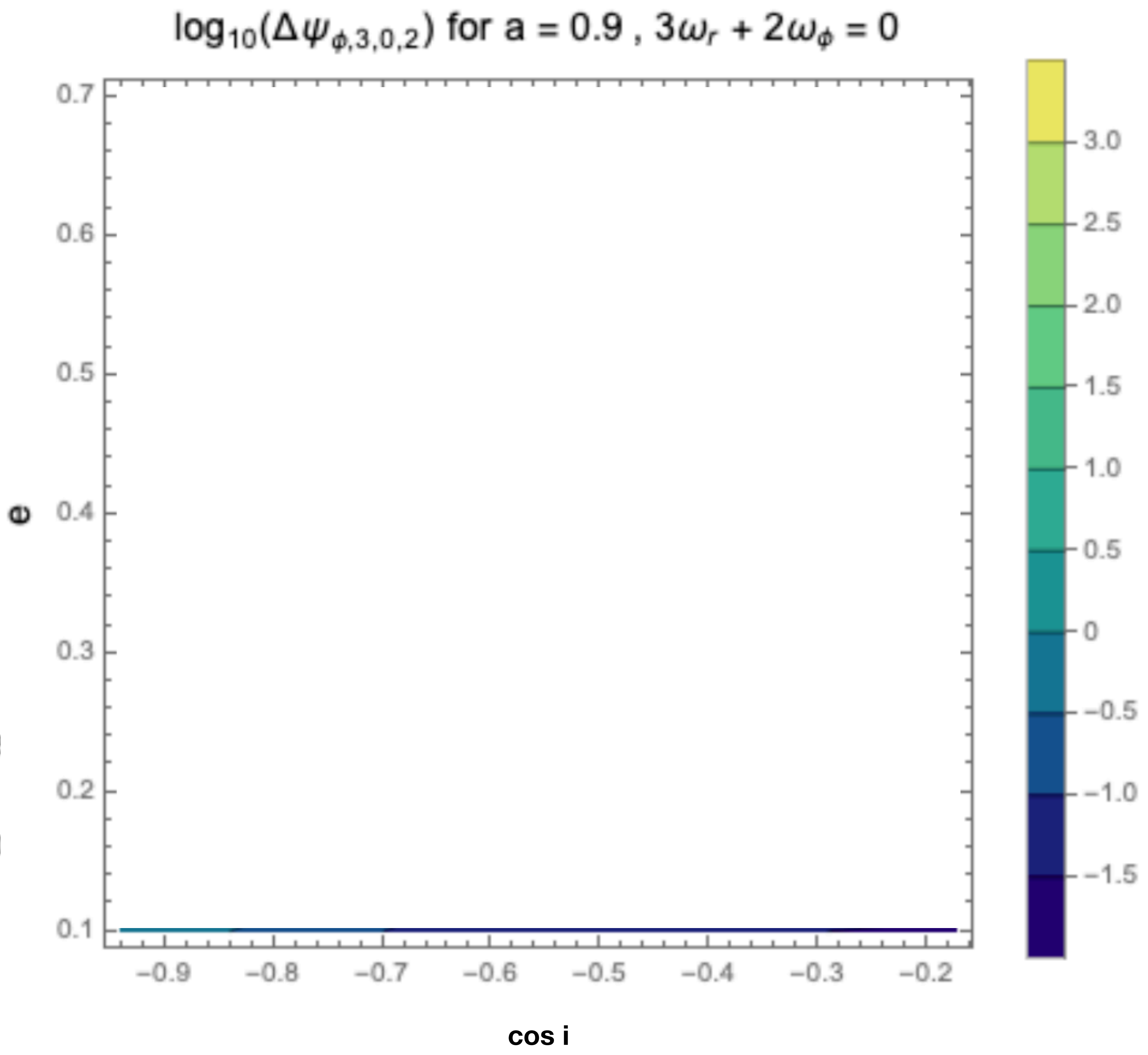


Tidal resonances

e.g., Gupta, Bonga, Chua, et al., (2104.03422); Gupta, Speri, Bonga, et al., (2205.04808)





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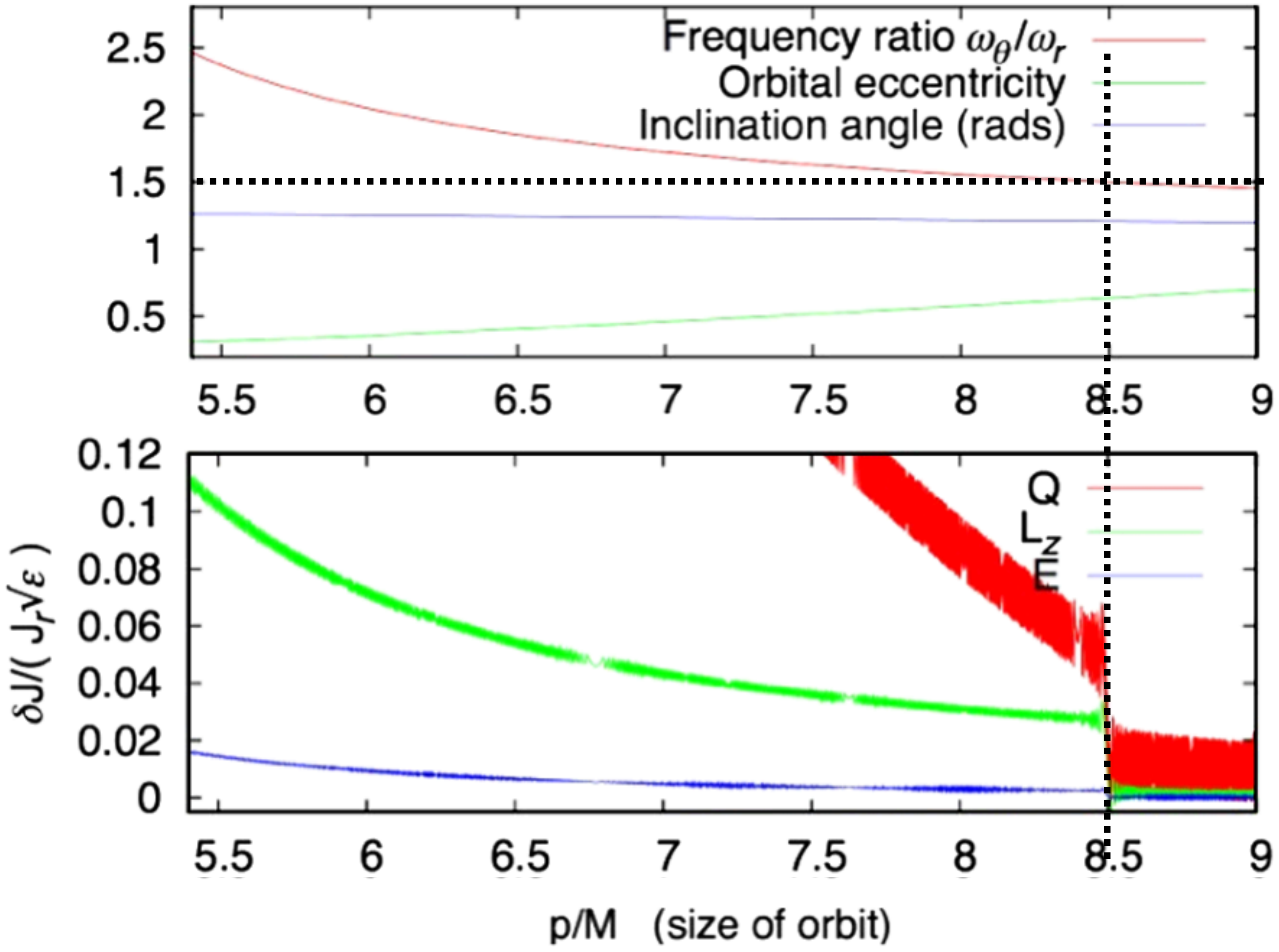

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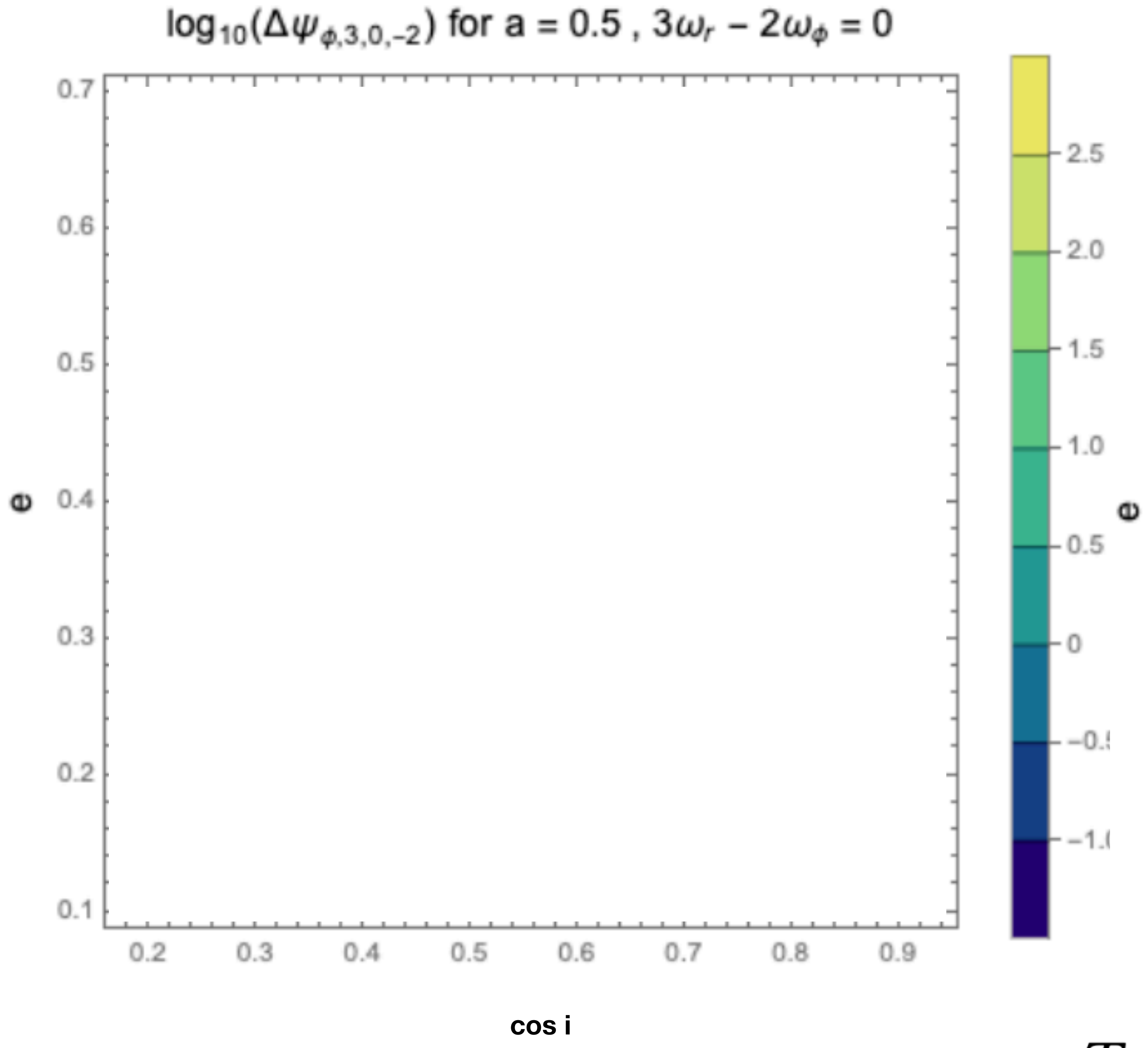

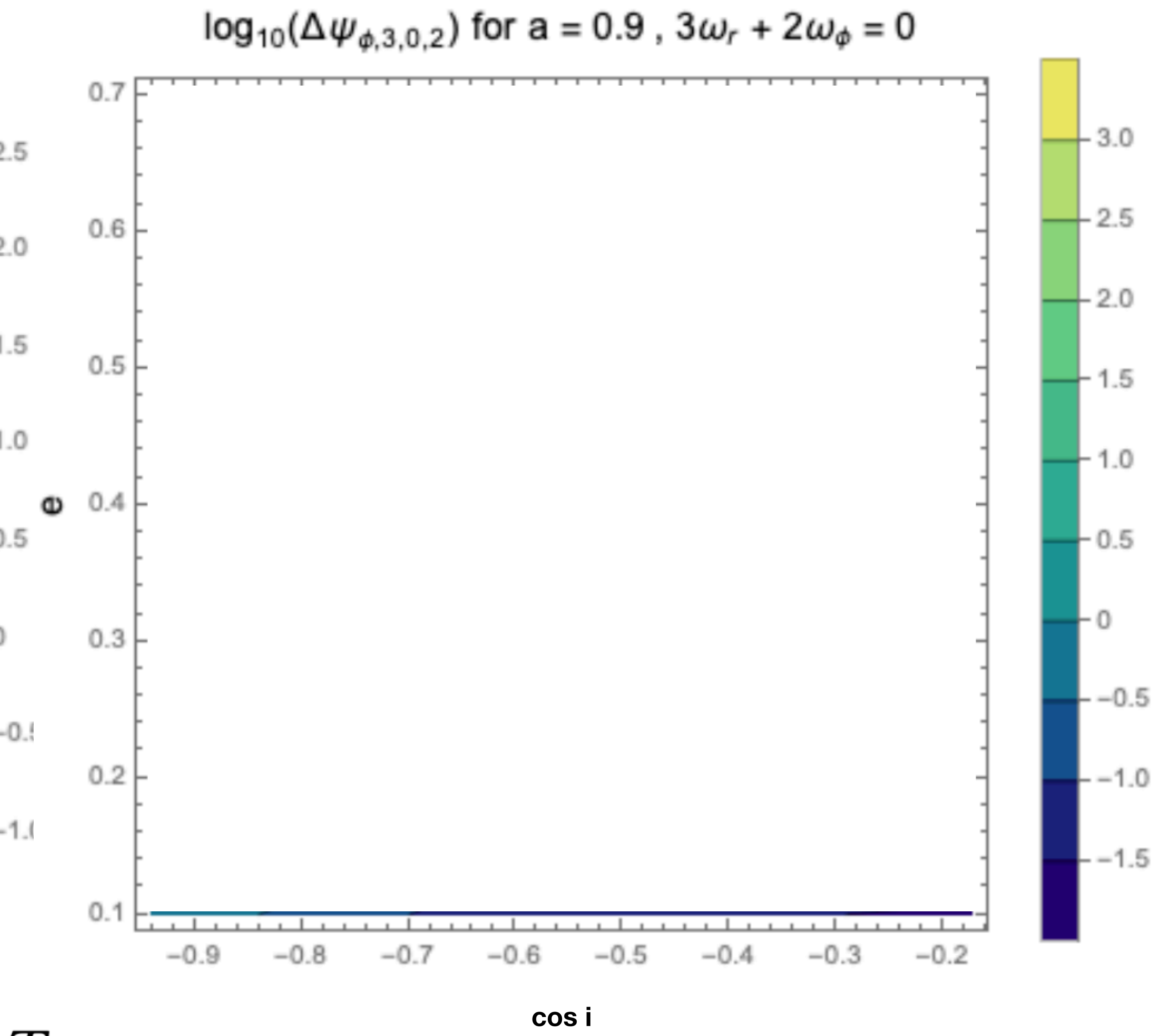

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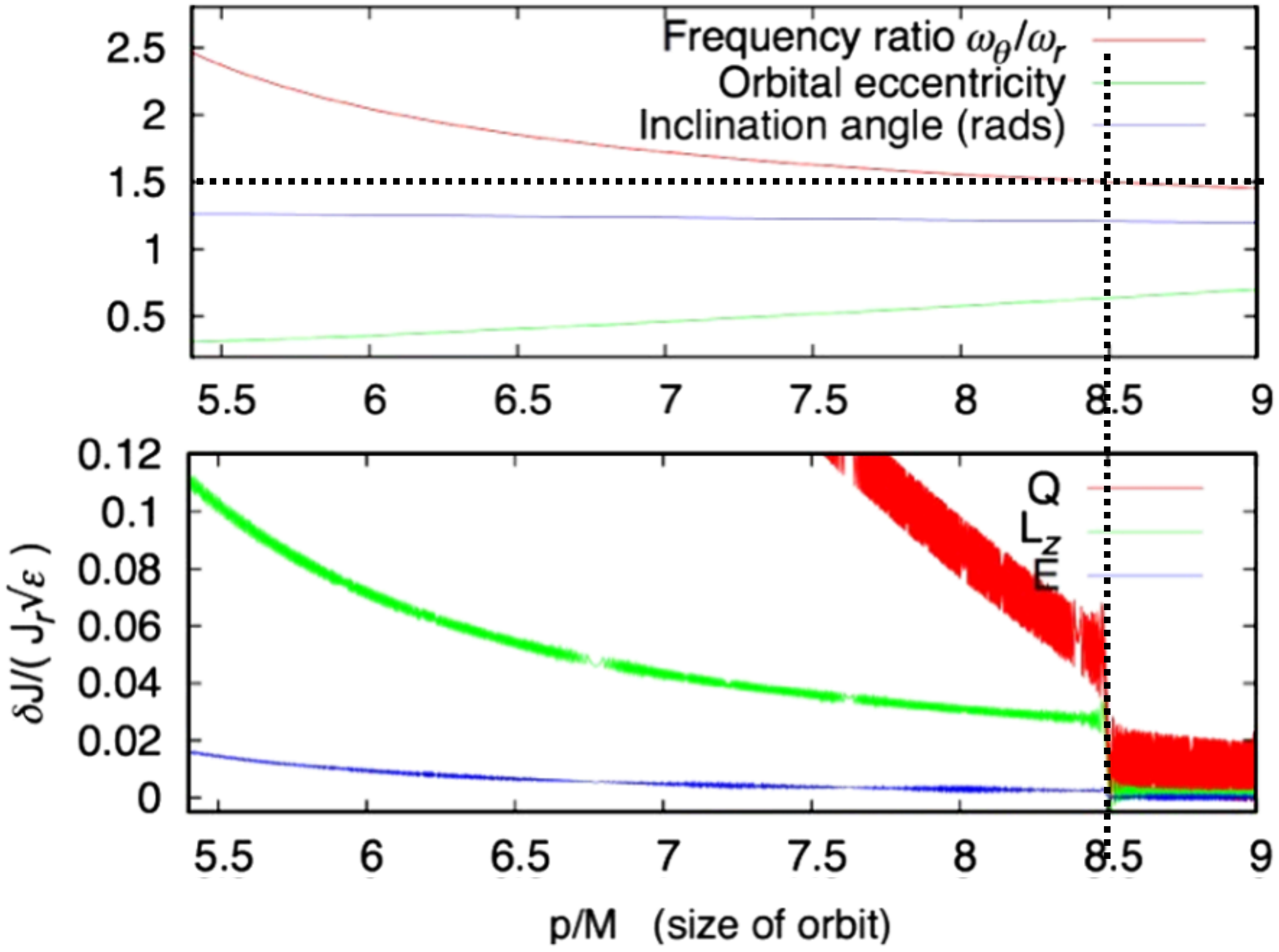

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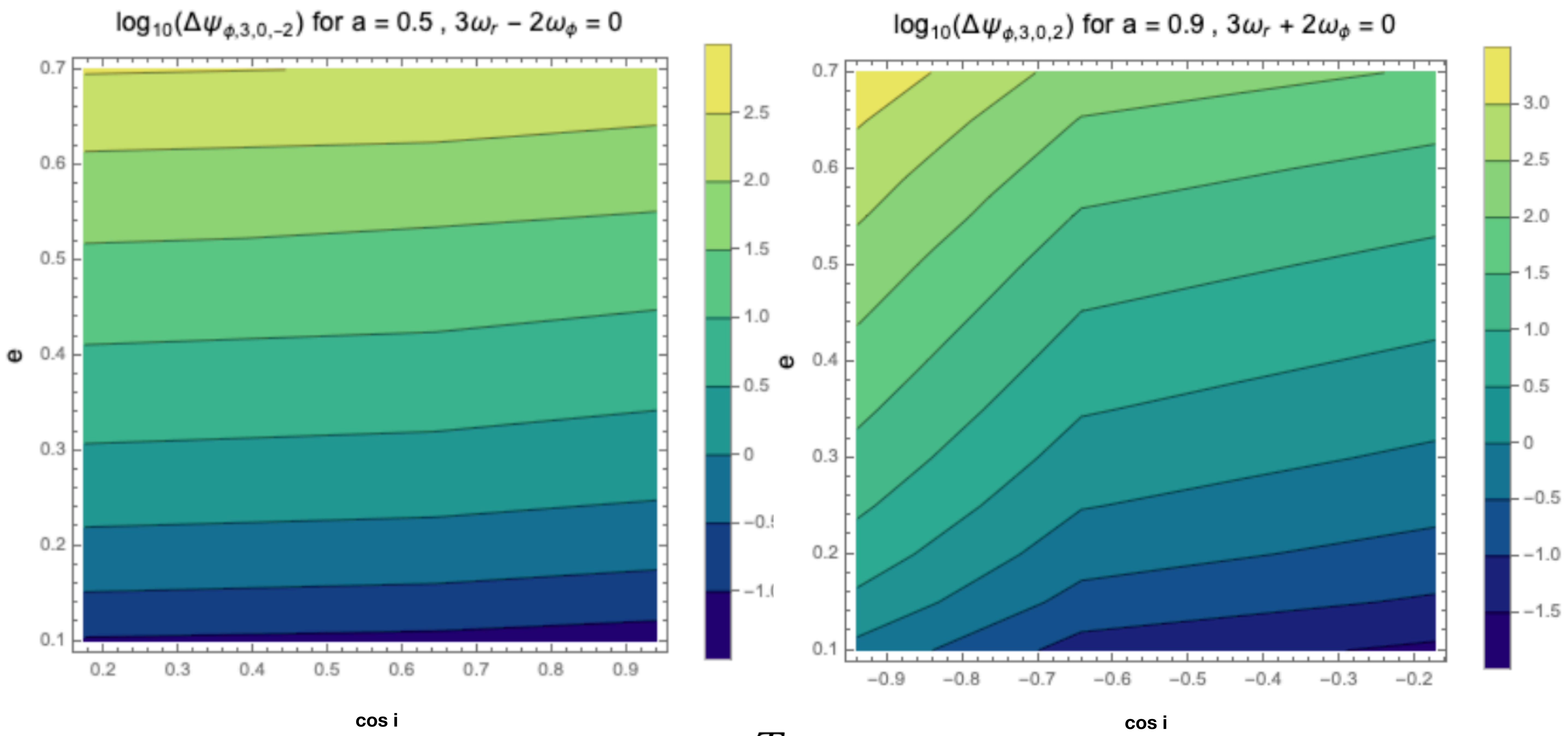

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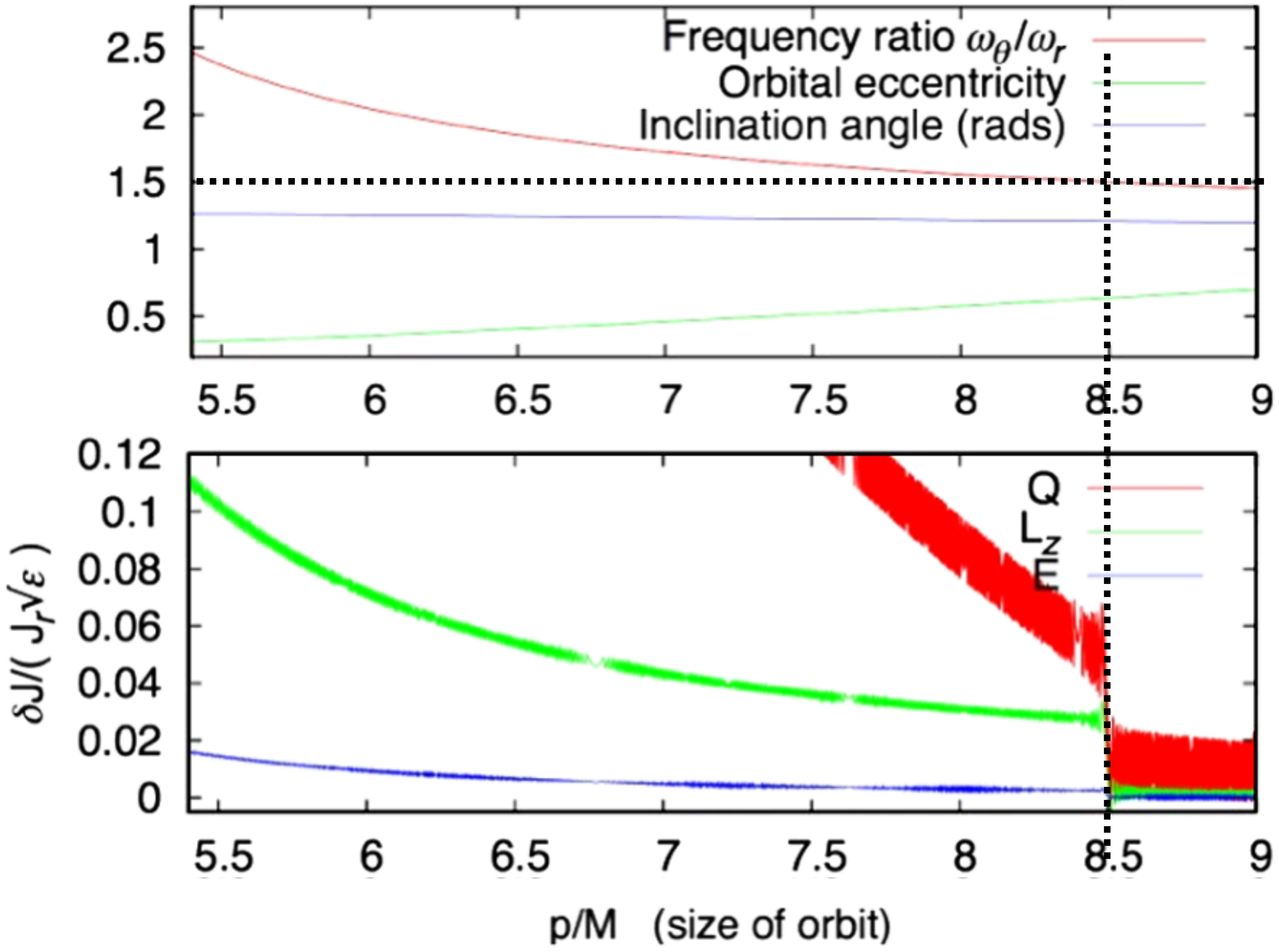

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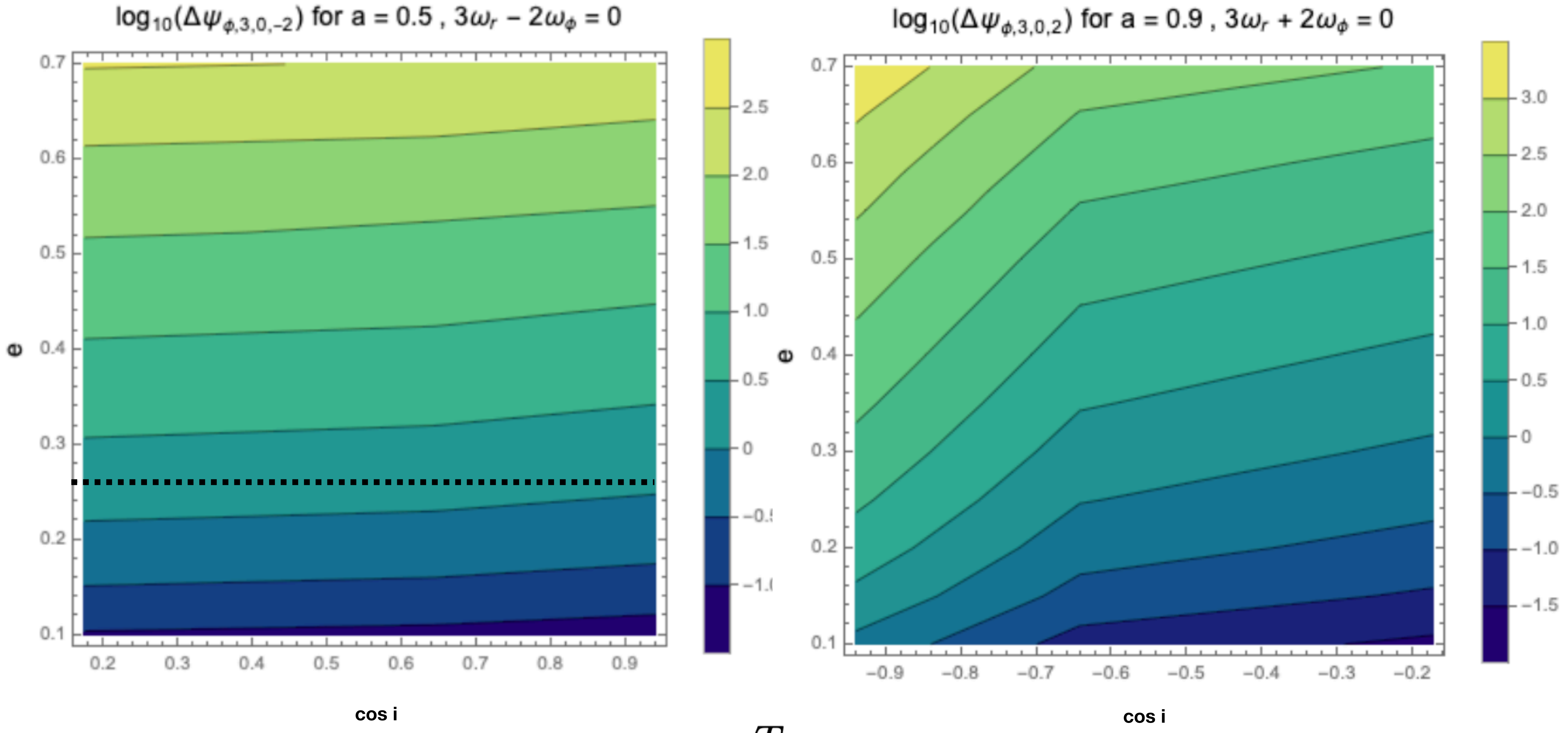

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Outline: Three short stories

New physics → New fields: scalar fields and BHs

A **scalar** (and potentially other) charge on the secondary **will affect the waveform.**

Beyond the adiabatic approximation:

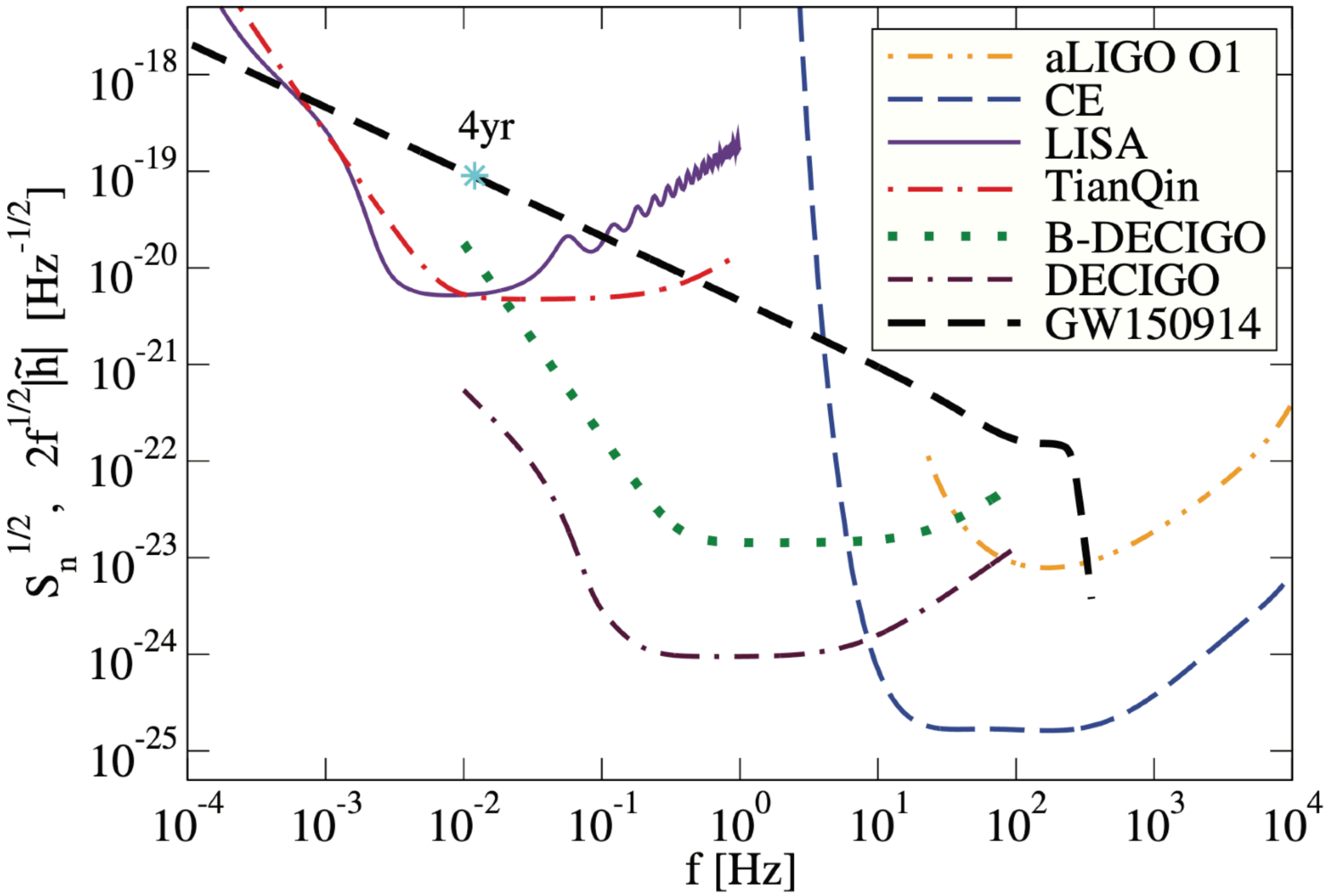
Development of **full usable waveforms in beyond-GR theories or environments**

Multiband or multi-messenger prospects:

Exploit the **fundamental role played by different detectors** across the gravitational and electromagnetic spectra

Multi-band gravitational wave tests of general relativity

Carson & Yagi (1905.13155)



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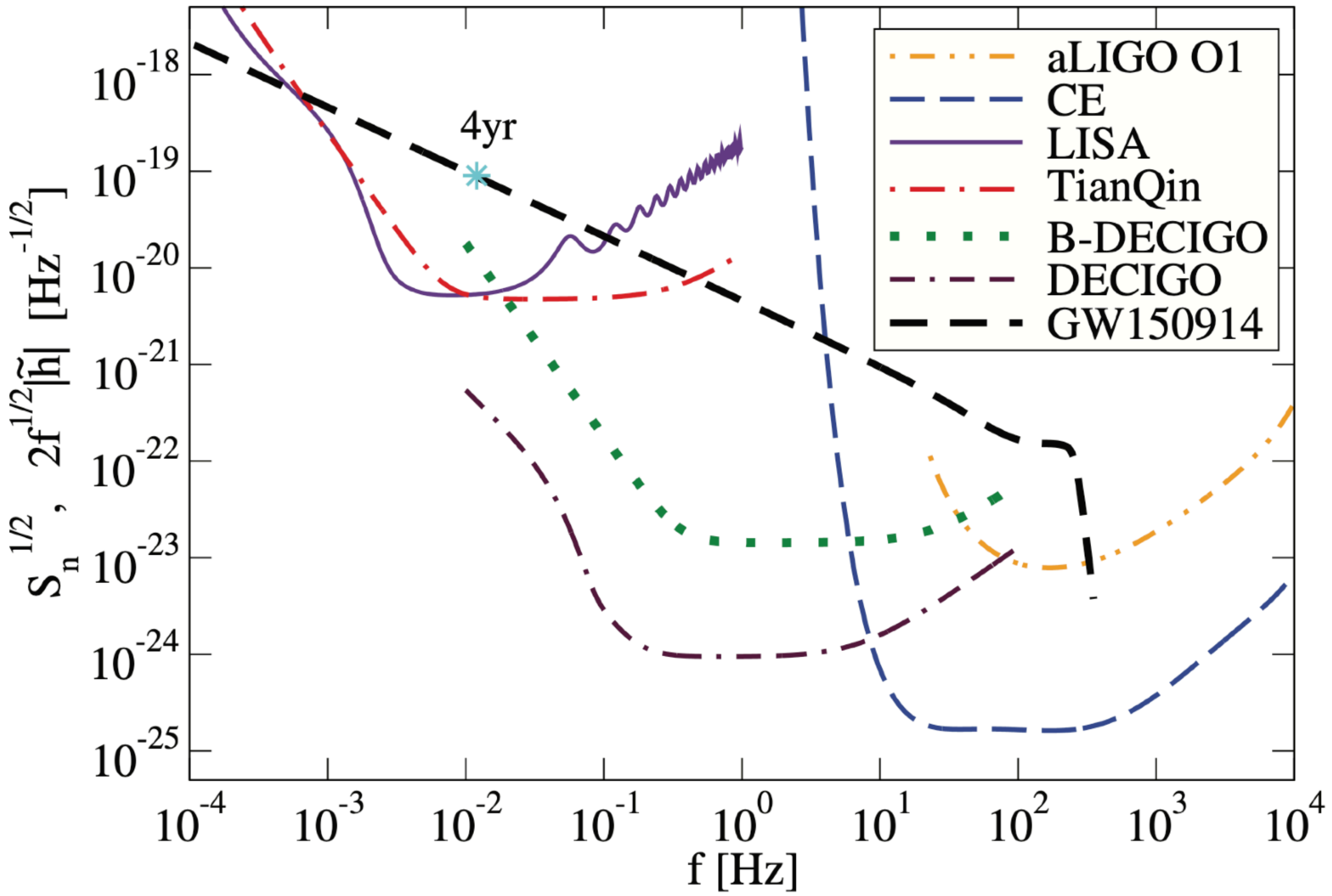

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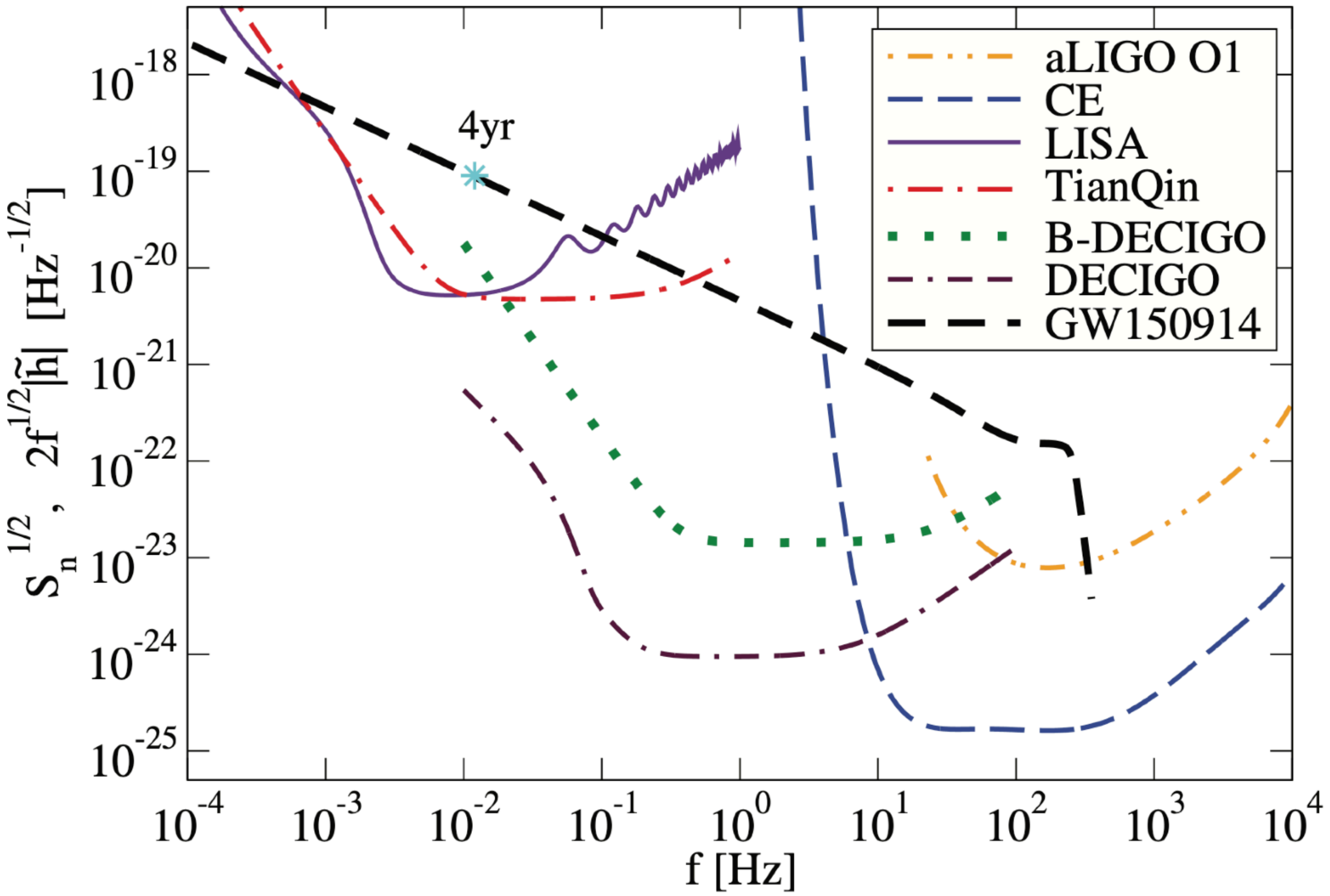

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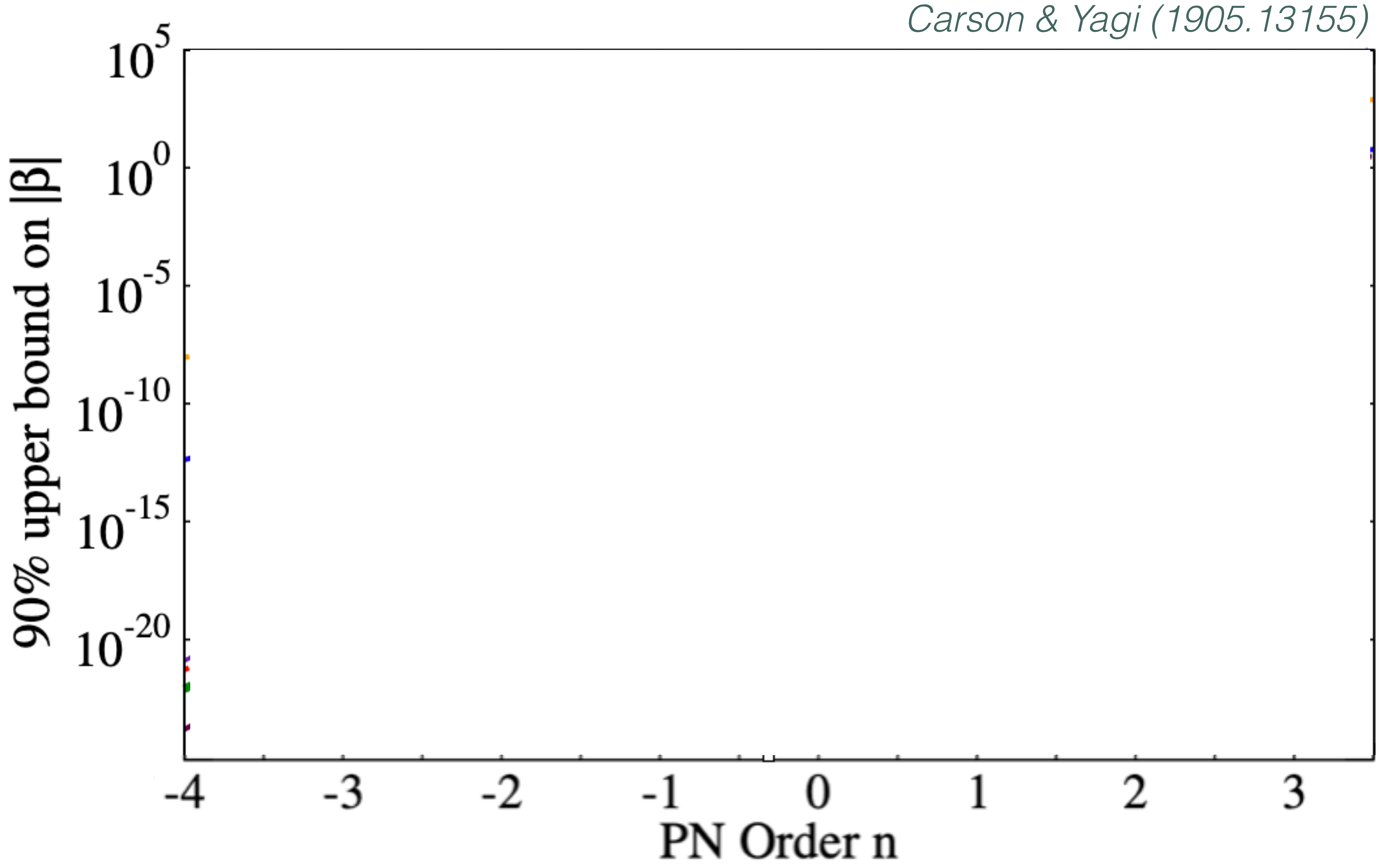

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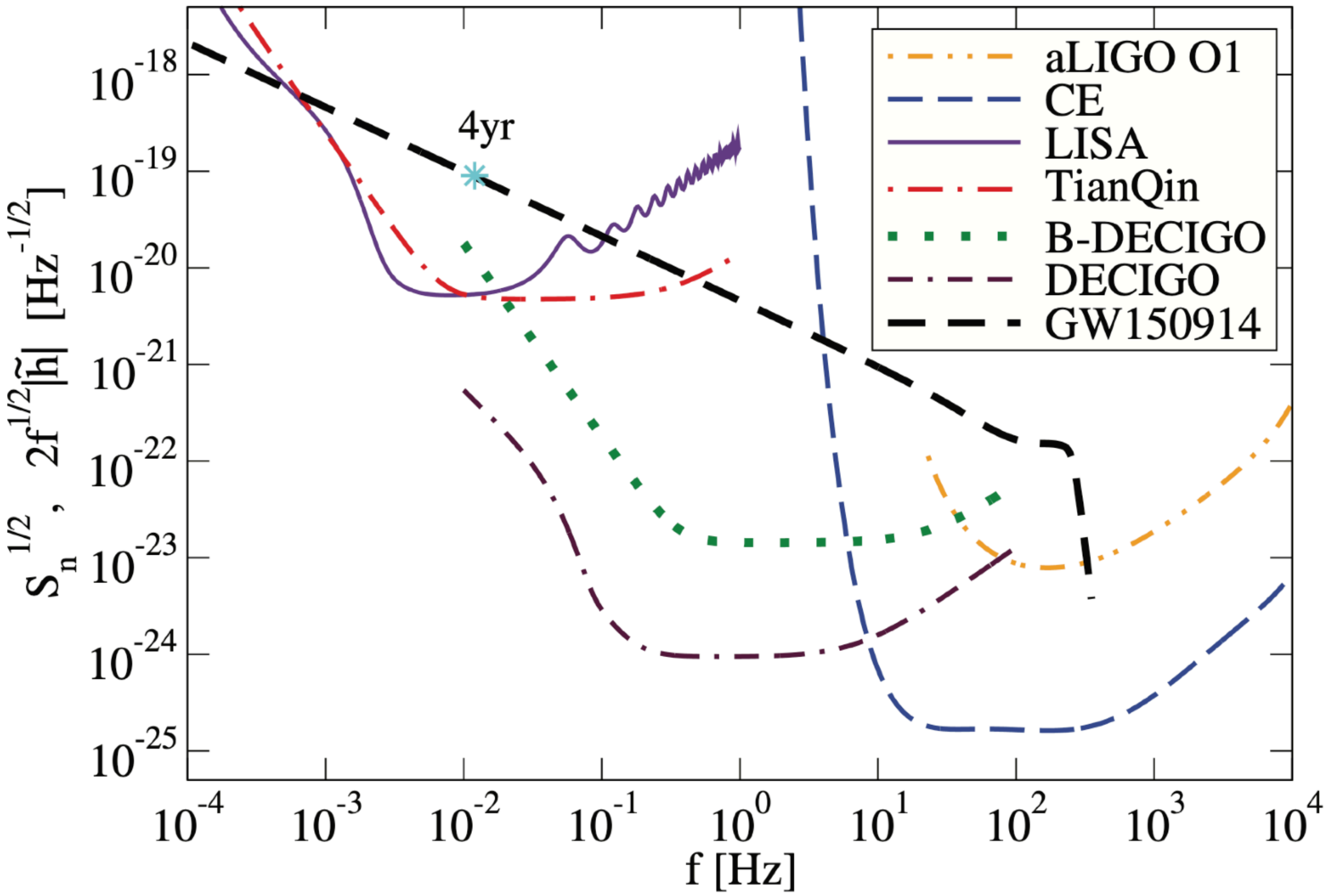
Multi-band gravitational wave tests of general relativity

Carson & Yagi (1905.13155)



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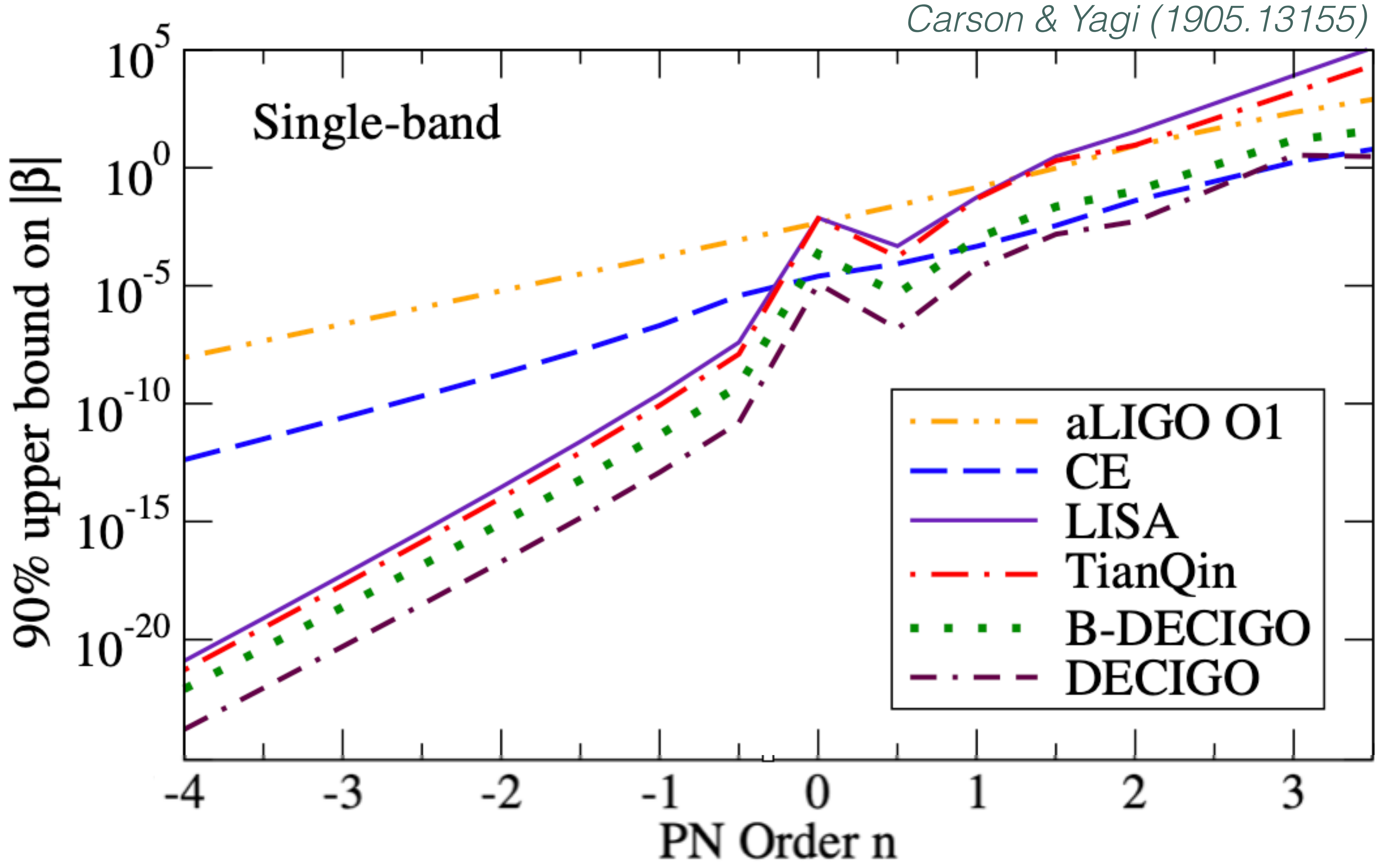

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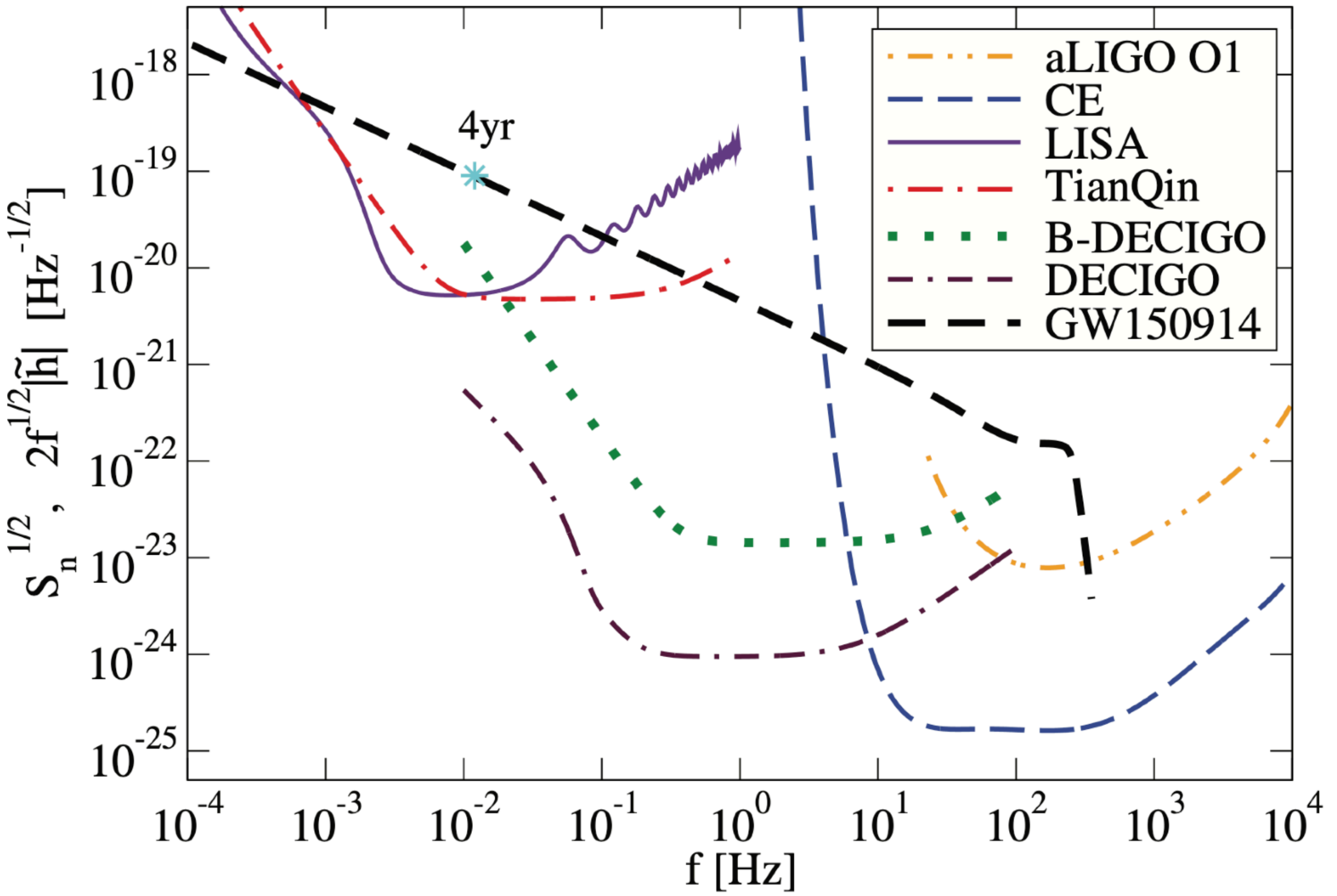

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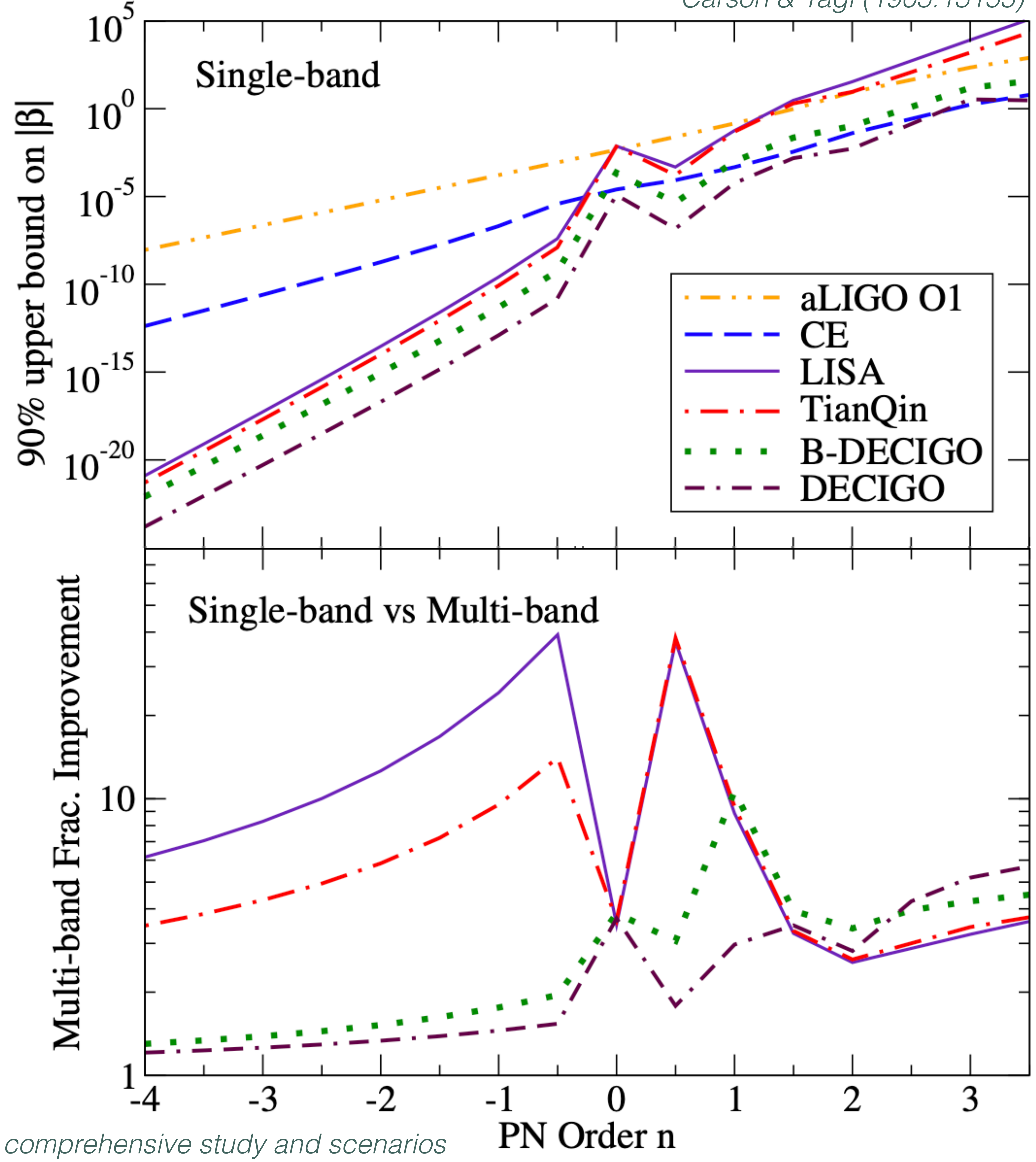

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see, also, Perkins, Yunes & Berti (2010.09010) for a comprehensive study and scenarios

Multi-band gravitational wave tests of general relativity: dCS as an example

Analytical solutions valid only in the **small coupling approximation**

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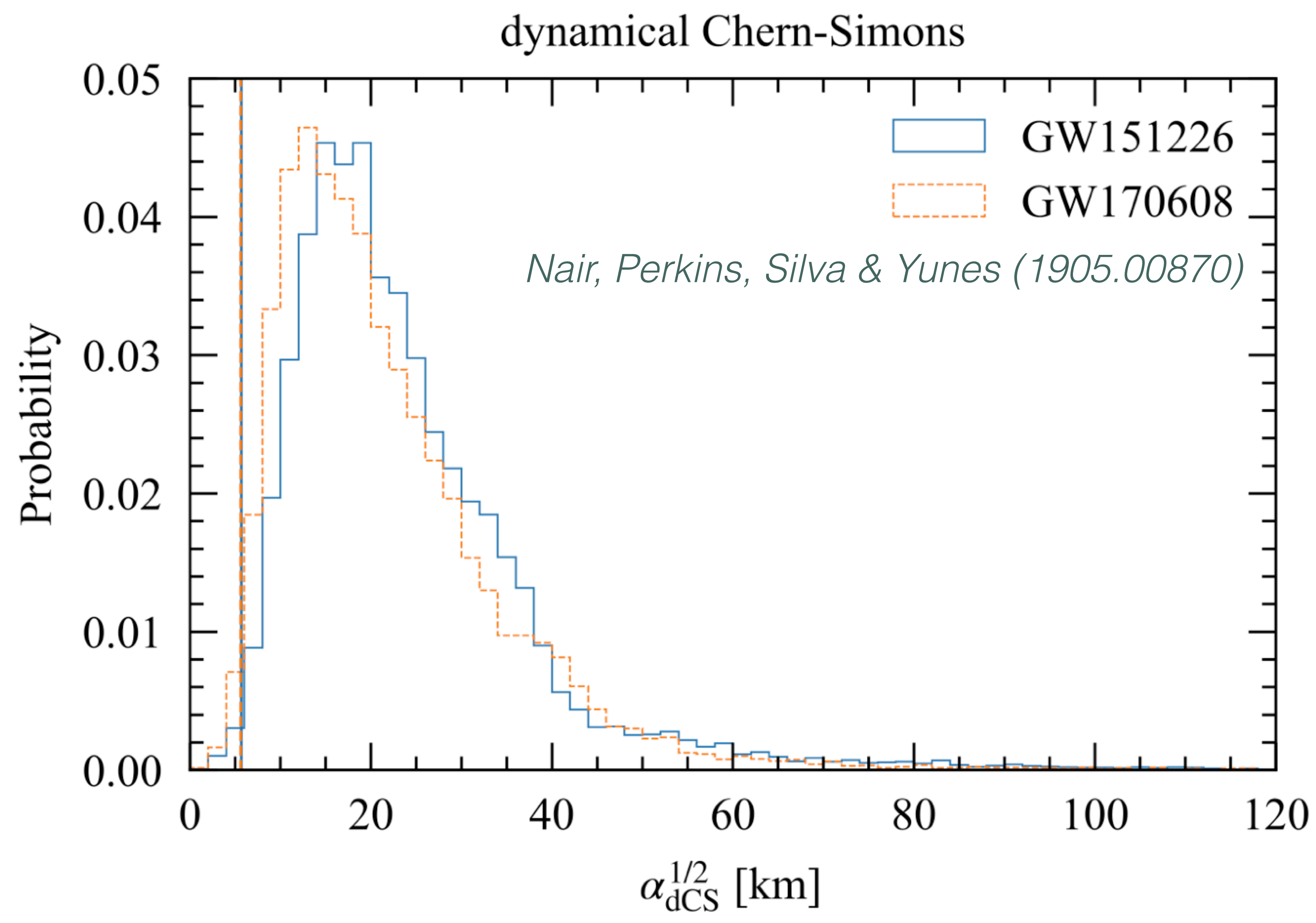

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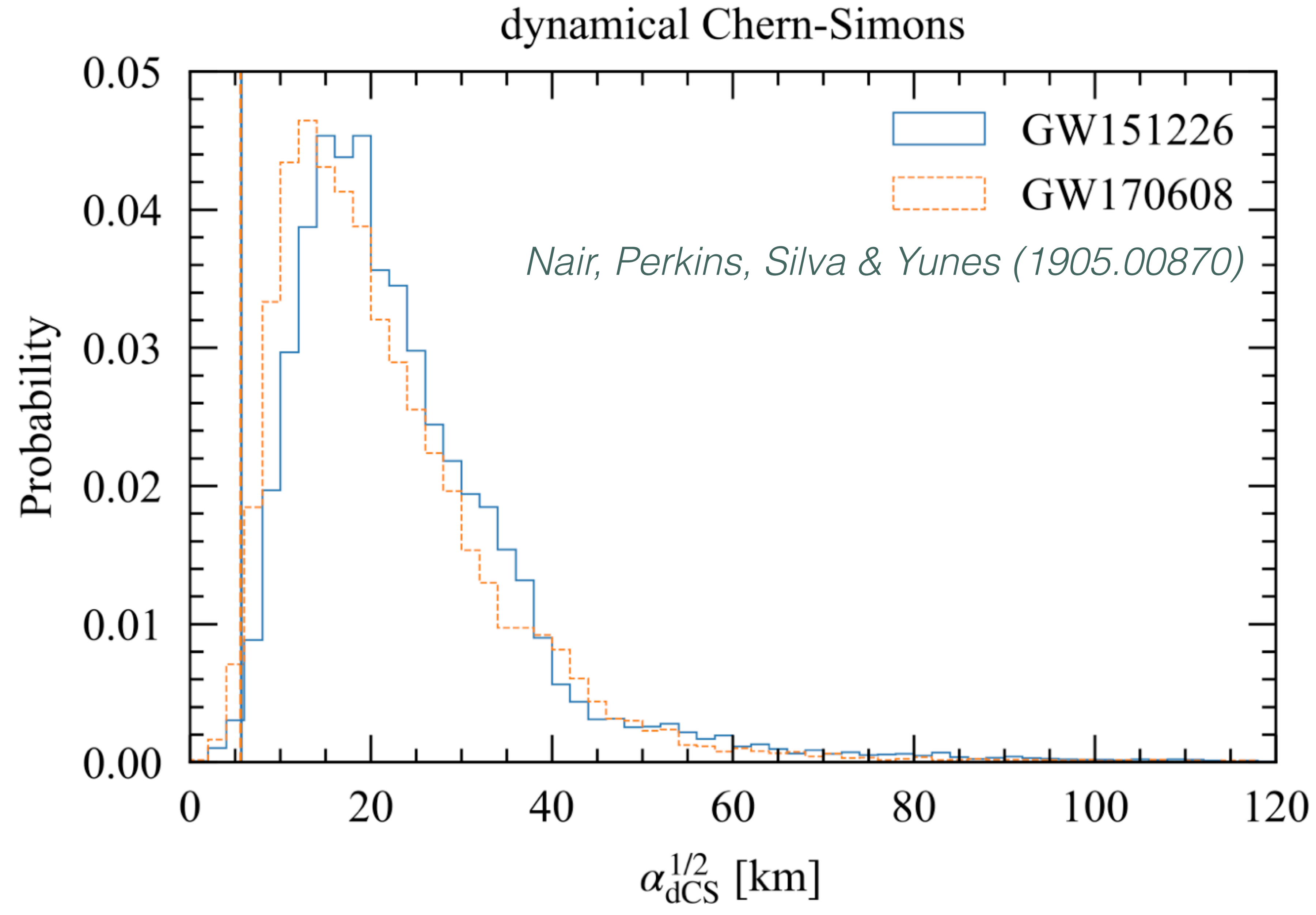

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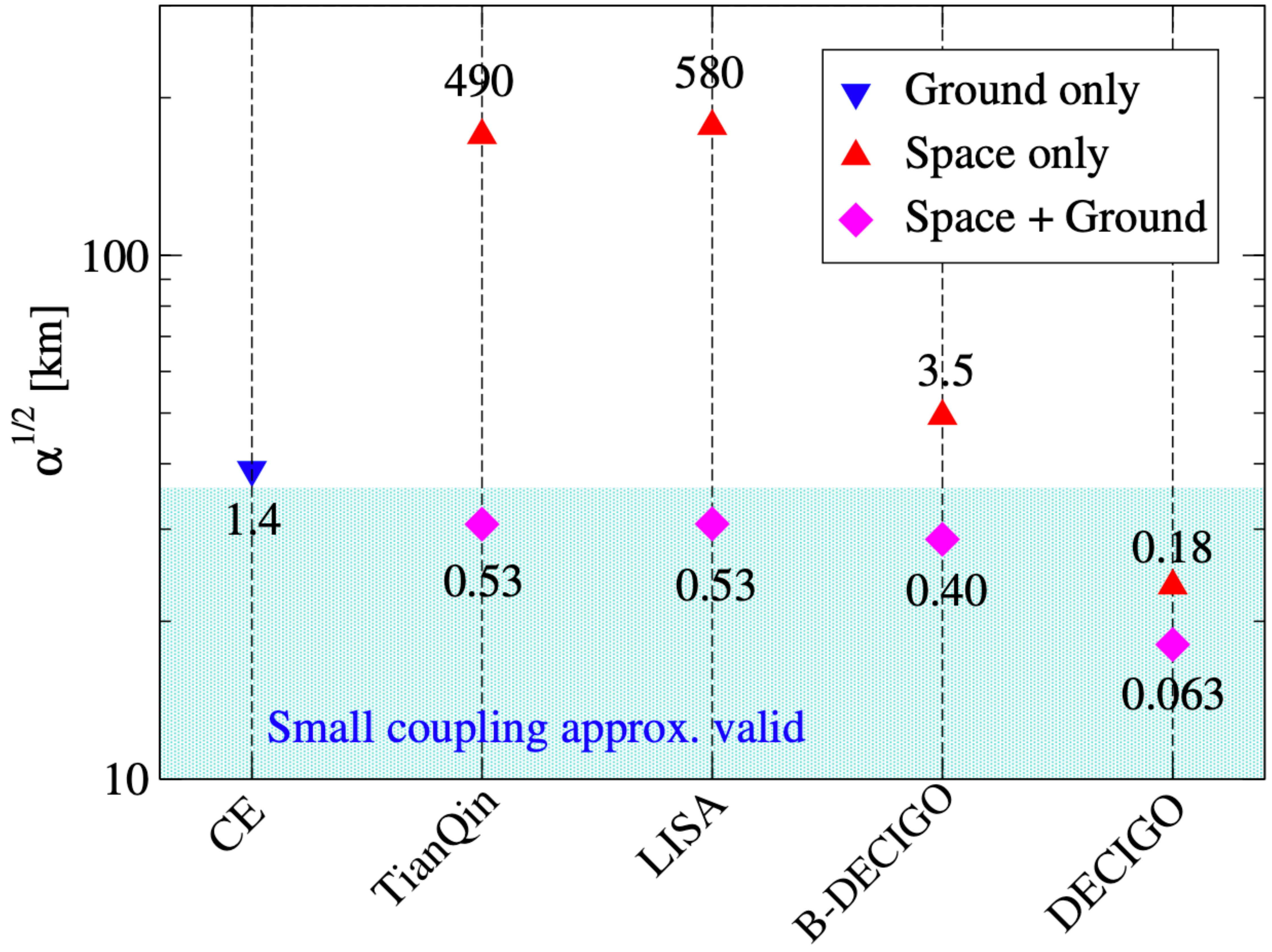

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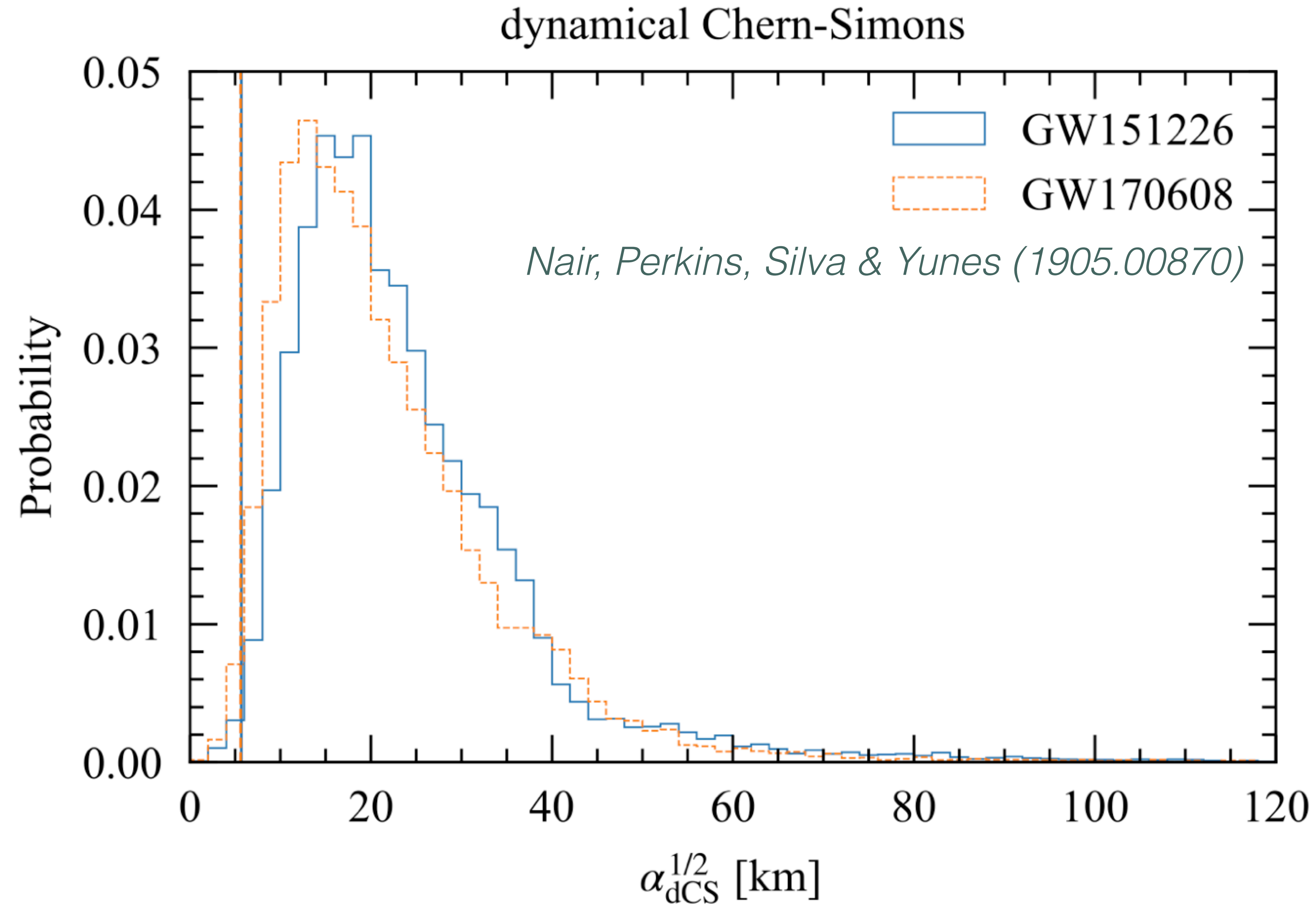

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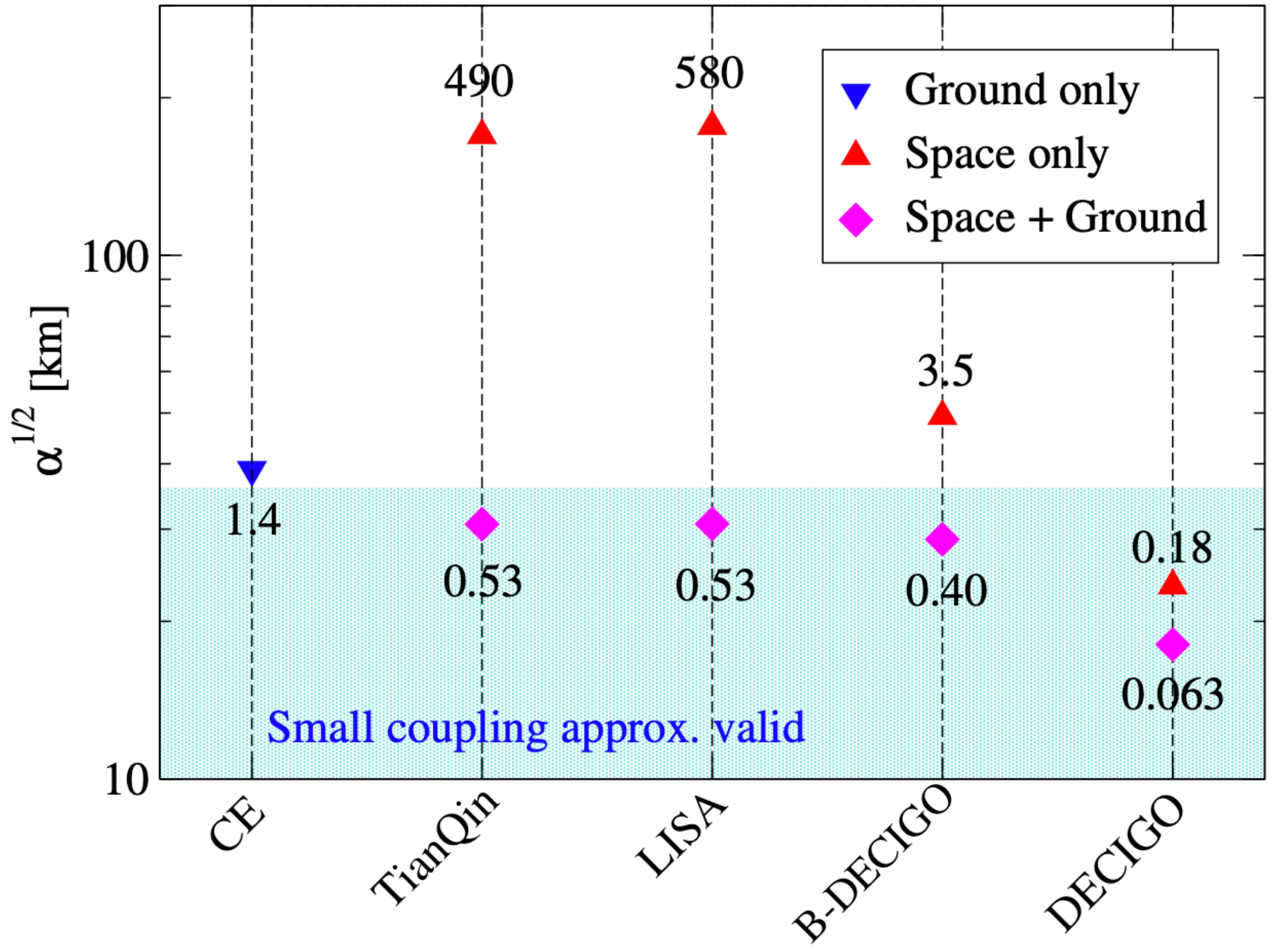

Silva, Holgado, ***ACA*** & Yunes (2004.01253)

I+Love+Q with NICER & LVC data: $\alpha_{\rm dCS}^{1/2} \leq 8.5$ km

Multi-band EM signature in massive black hole binaries: strong thermal X-ray emission until 1-2 days prior to the merger

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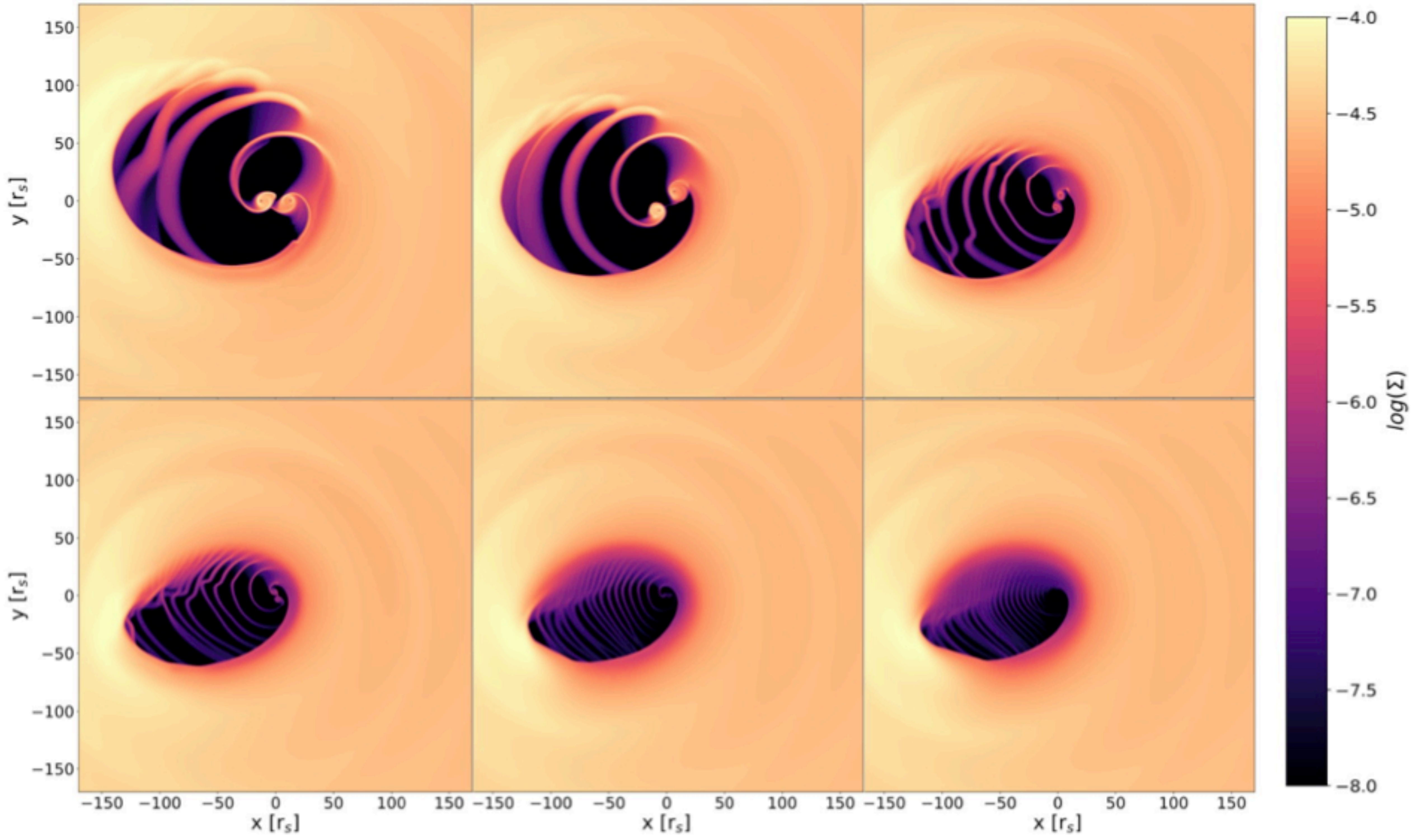

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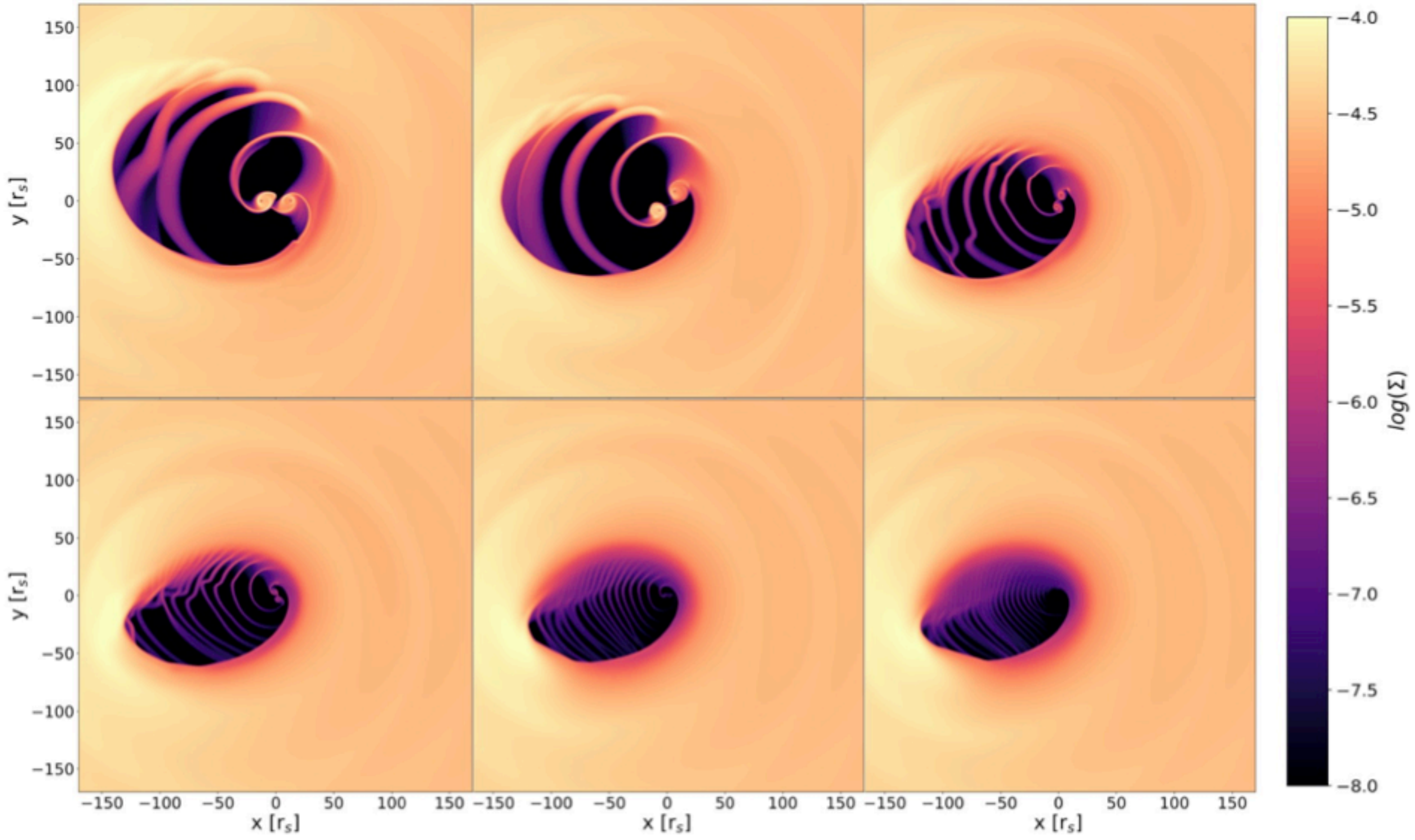

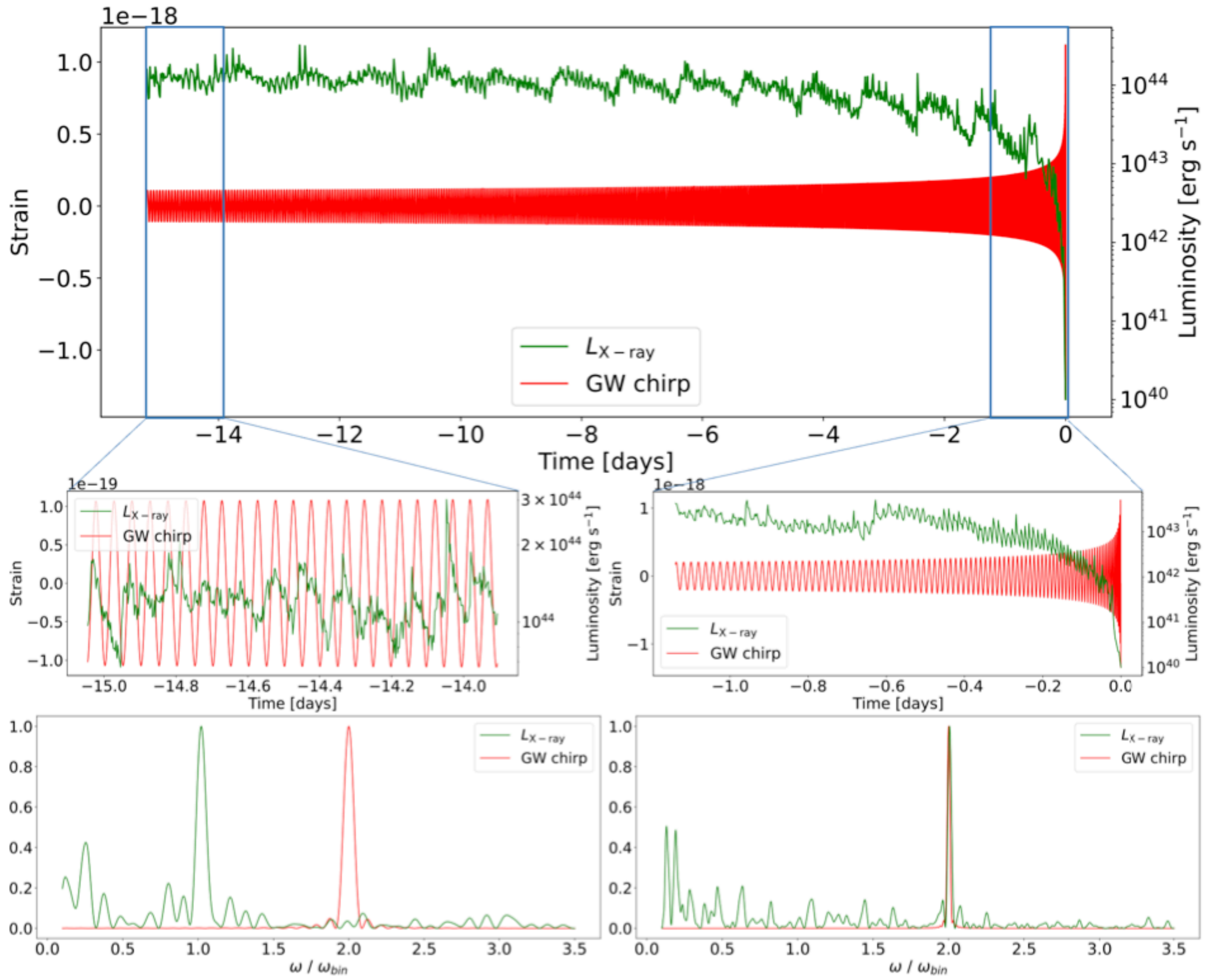

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Discussion

We cannot make a list of the truly unexpected. However, there are sources that the community have speculated about that would be quite interesting and revolutionary, if discovered.

Breaking degeneracies with astrophysics, environmental effects, etc., also requires precise modeling. We can also think about synergies for multi band and multi-messenger observations

It is crucial to **match the increased level of modeling** precision **with the expected level of observation precision**.

LISA design is changing. Most predictions and tests might be revisited once we know the configuration LISA will fly with.

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*I particularly thank T. **Baker**, E. **Berti**, R. **Brito**, V. **Cardoso**, P. **Pani**, C. **Sopuerta** & T. **Sotiriou** for their input to write this talk.*

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Thank you!

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