Title: Assessing the impact of transient orbital resonances

Speakers: Lorenzo Speri

Collection: The 24th Capra meeting on Radiation Reaction in General Relativity

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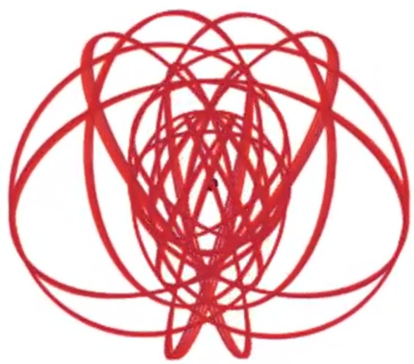
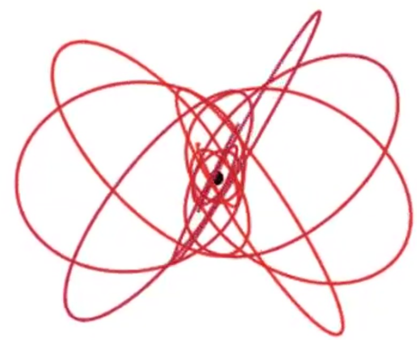
Abstract: "One of the primary sources for the future space-based gravitational wave detector, the Laser Interferometer Space Antenna, are the inspirals of small compact objects into massive black holes in the centres of galaxies.
The gravitational waveforms from such Extreme Mass Ratio Inspiral (EMRI) systems will provide measurements of their parameters with unprecedented precision, but only if the waveforms are accurately modeled.
Here we explore the impact of transient orbital resonances which occur when the ratio of radial and polar frequencies is a rational number. We introduce a new Effective Resonance Model, which is an extension of the numerical kludge EMRI waveform approximation to include the effect of resonances, and use it to explore the impact of resonances on EMRI parameter estimation.
For one-year inspirals, we find that the few cycle dephasings induced by 3:2 resonances can lead to systematic errors in parameter estimates, that are up to several times the typical measurement precision of the parameters. The bias is greatest for 3:2 resonances that occur closer to the central black hole. By regarding them as unknown model parameters, we further show that observations will be able to constrain the size of the changes in the orbital parameters across the resonance to a relative precision of 10% for a typical one-year EMRI observation with signal-to-noise ratio of 20. Such measurements can be regarded as tests of fundamental physics, by comparing the measured changes to those predicted in general relativity."

Assessing the impact of transient orbital resonances

24th Capra meeting





MAX-PLANCK-GESELLSCHAFT

Lorenzo Speri

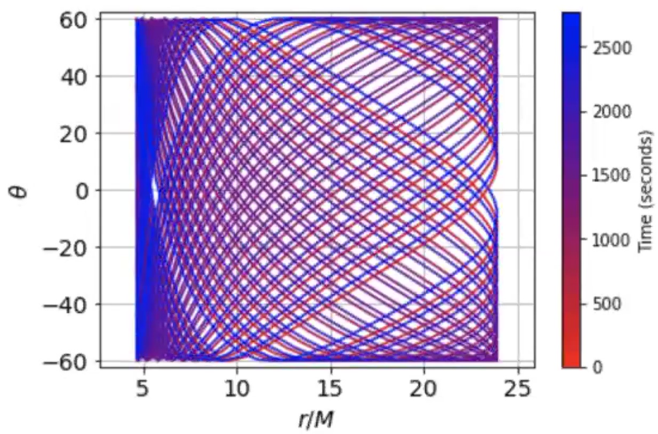
and Jonathan Gair

Max-Planck-Institut für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

based on arXiv:2103.06306

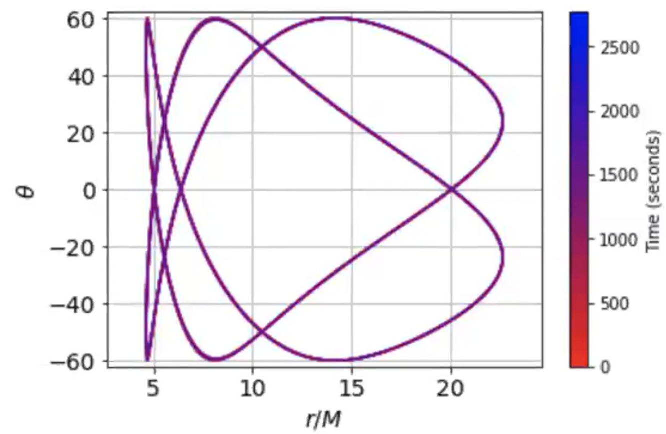
Generic Kerr Trajectory

Ergodic Trajectory



Resonant Trajectory

$$n_\theta \omega_\theta + n_r \omega_r = 0$$



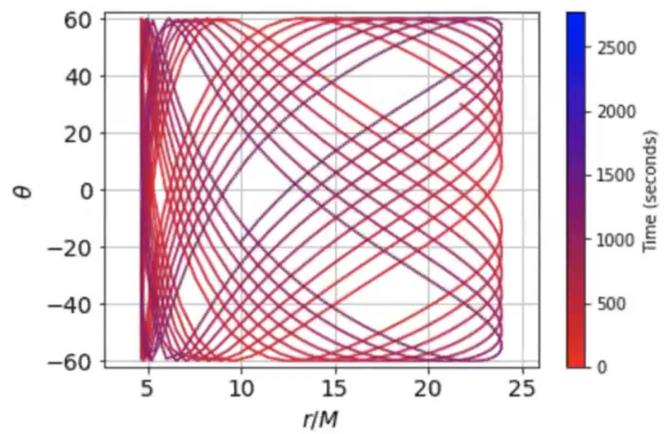
Adiabatic
Approximation

Resonances already studied in

C. P. L. **Berry**, et al. 2016. arXiv:1608.08951
E. E. **Flanagan** and T. **Hinderer,** 2012. arXiv:1009.4923

Generic Kerr Trajectory

Ergodic Trajectory



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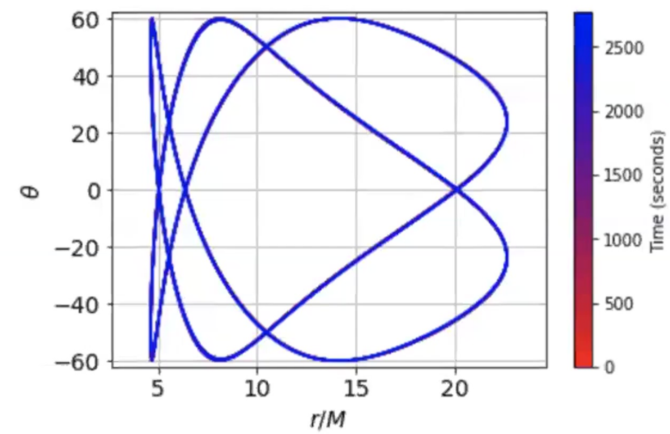

Adiabatic Approximation

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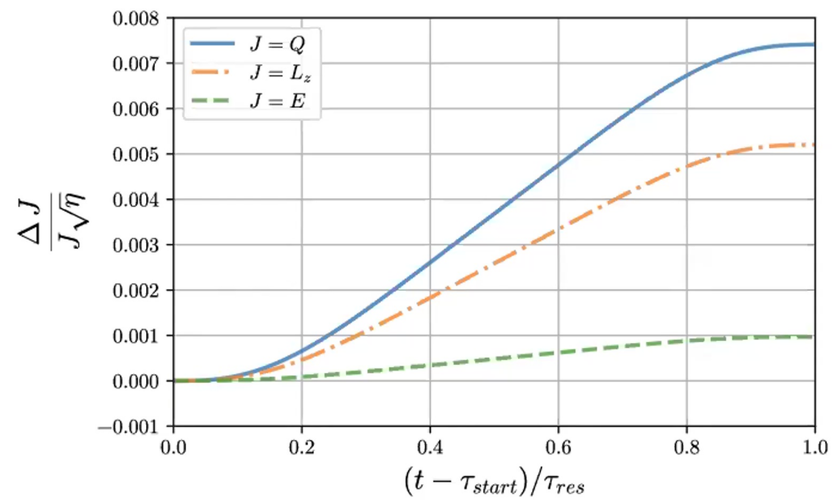
Effects of Resonances

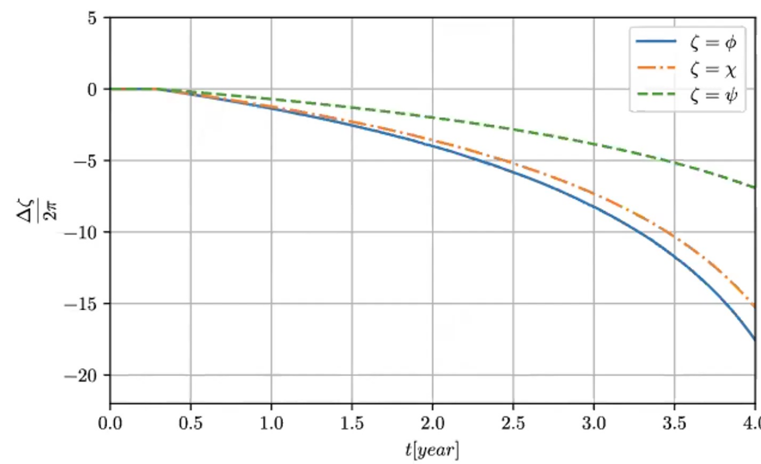
jump in the constants

$$\Delta J \sim \sqrt{\eta}$$
$$\Delta \omega \sim \sqrt{\eta}$$



Dephasing orbital phases

$$\Delta \phi \sim \frac{1}{\sqrt{\eta}}$$



Do we need to worry about modeling resonances?

If we ignore resonances…

- can we detect EMRIs?

C. P. L. **Berry et al.** arXiv:1608.08951

a loss of 4% detectable signals

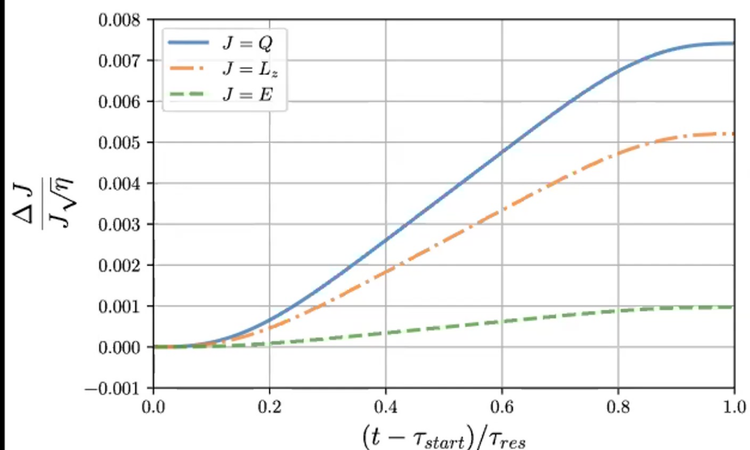
- will our measurements be biased?

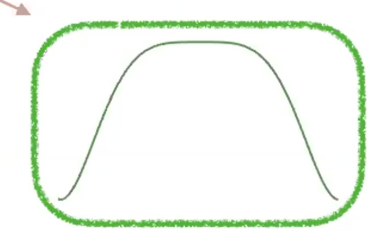
Can we detect resonances?

Parameters $\overrightarrow{\lambda} = (p, \eta, M, e, \iota, a, \mathscr{E}, \mathscr{L}_z, \mathscr{Q})$ only 3:2 resonances

Effective Resonance Model

$$\frac{dJ}{d\tau} = \eta G(J)\left[1 + \boxed{\mathscr{C}}\,\boxed{w(\tau, \tau_{res})}\right]$$

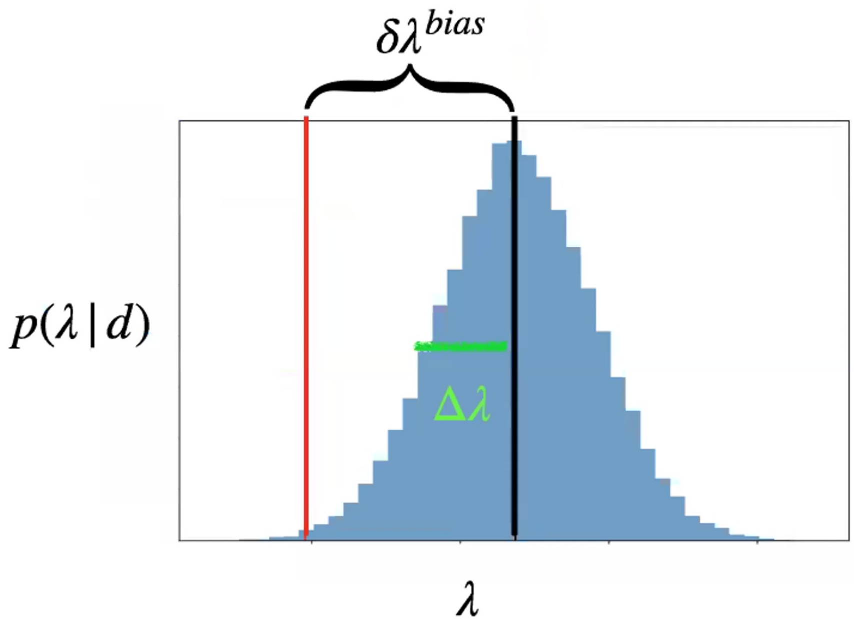




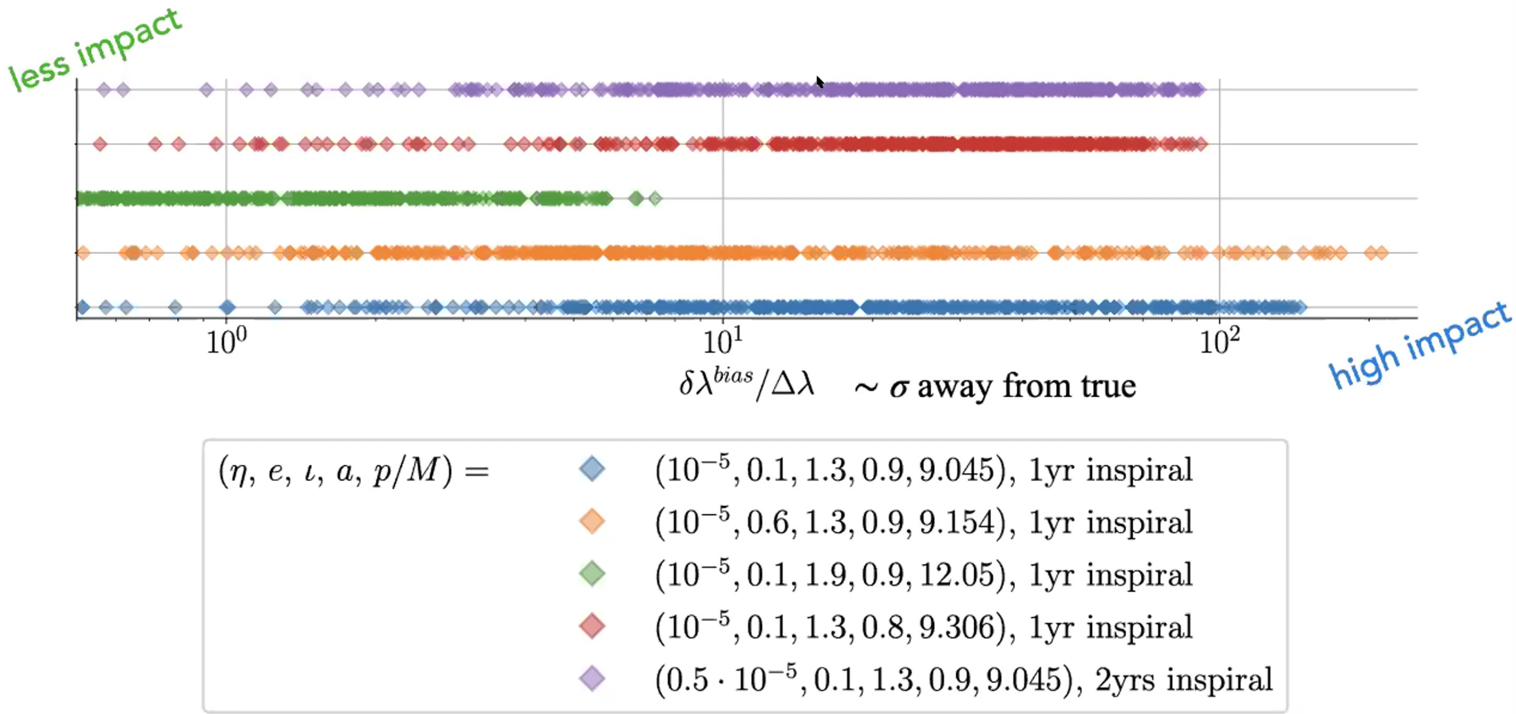
arXiv:1208.3906v2 Flanagan et al. 2014

Systematic Errors

1. draw resonance coefficients $\boxed{\mathscr{C} = (\mathscr{E}, \mathscr{L}_z, \mathscr{Q})} \sim \mathrm{U}[-0.01, +0.01]$
2. waveform
3. estimate $\delta\lambda^{bias}/\Delta\lambda \sim \sigma$ sigma away from true parameter
4. repeat



Systematic Errors $\lambda = a$

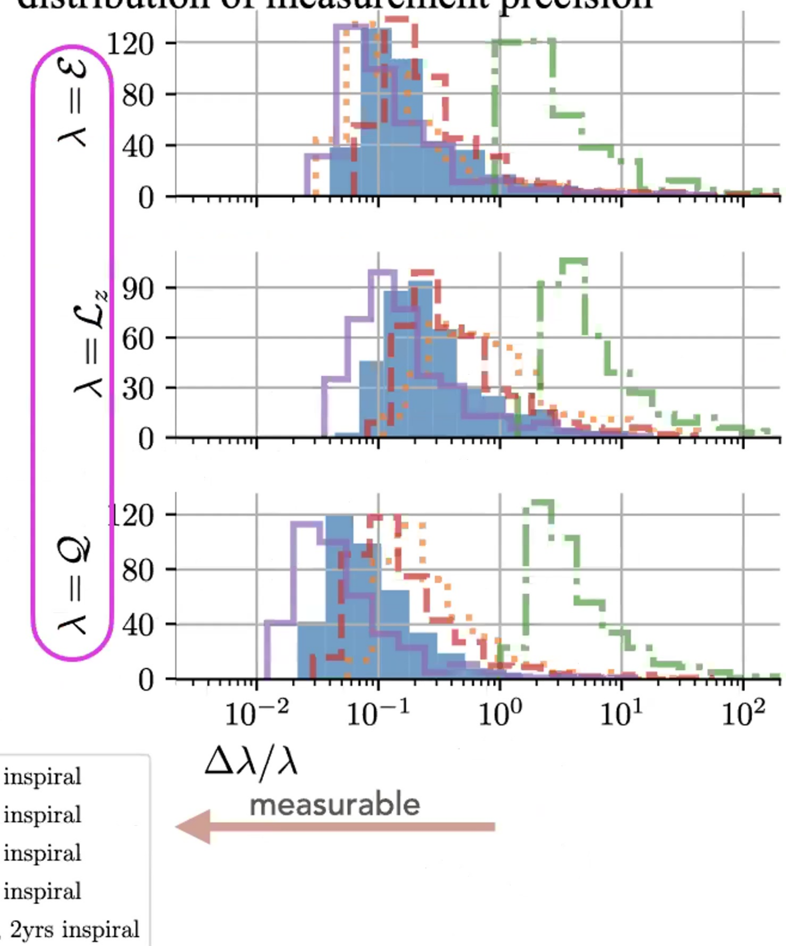


Detection of resonances

- Relative precision $\Delta\lambda/\lambda$ estimated with Fisher Matrix
- Detect resonance with $\mathscr{C}$
- Prediction of $\mathscr{C}$ → test GR
- Resonance coefficients **do not degrade** the measurement precision of other parameters

$SNR = \sqrt{(h|h)} = 20$ $\quad M = 10^6\, M_\odot$

distribution of measurement precision



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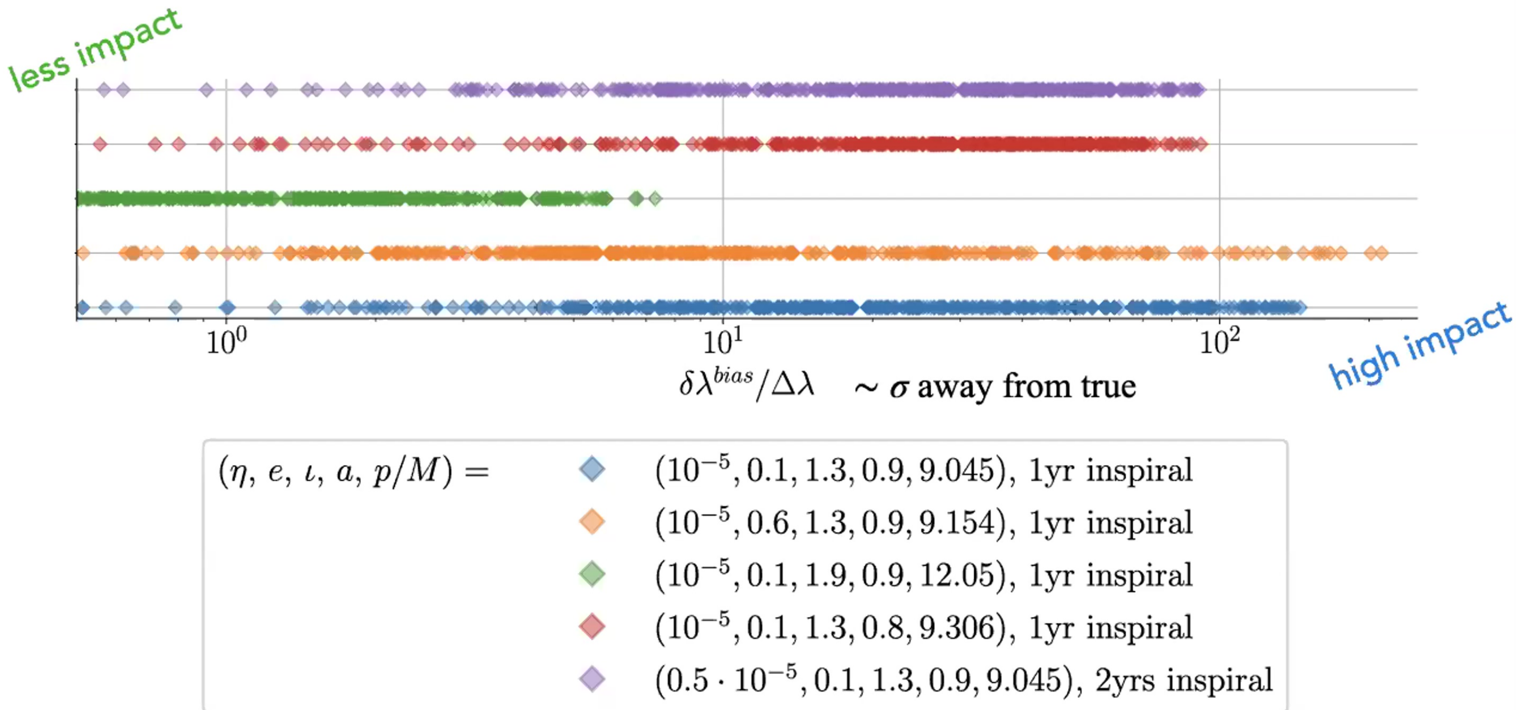

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$$\delta\lambda^{bias}/\lambda \sim 10^{-3}$$

Summary and future outlook

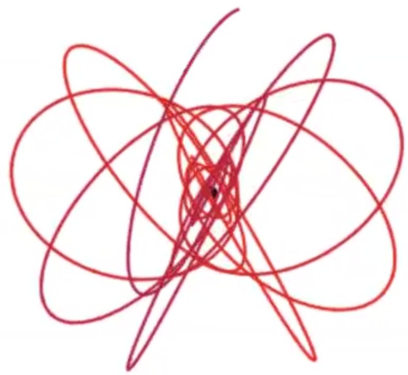
- Resonances induce large biases
- The Effective Resonance Model could be used to
  - detect resonances
  - test self-force
  - study the impact of other resonances Gupta et al. 2021
- Improve the resonance model
- FEW models and full PE

M. Katz et al. 2021, A. J. K. Chua et al. 2020

Take home

A small step for the constants of motion,

a giant leap for biases in EMRI parameter estimation



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