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Testing strong-field gravity with quasi periodic oscillations

A.M., P. Pani, L. Gualtieri, V. Ferrari, L. Stella +
ApJ 801 115 (2015), PRD 92 083014 (2015), arXiv:1612.00038 +

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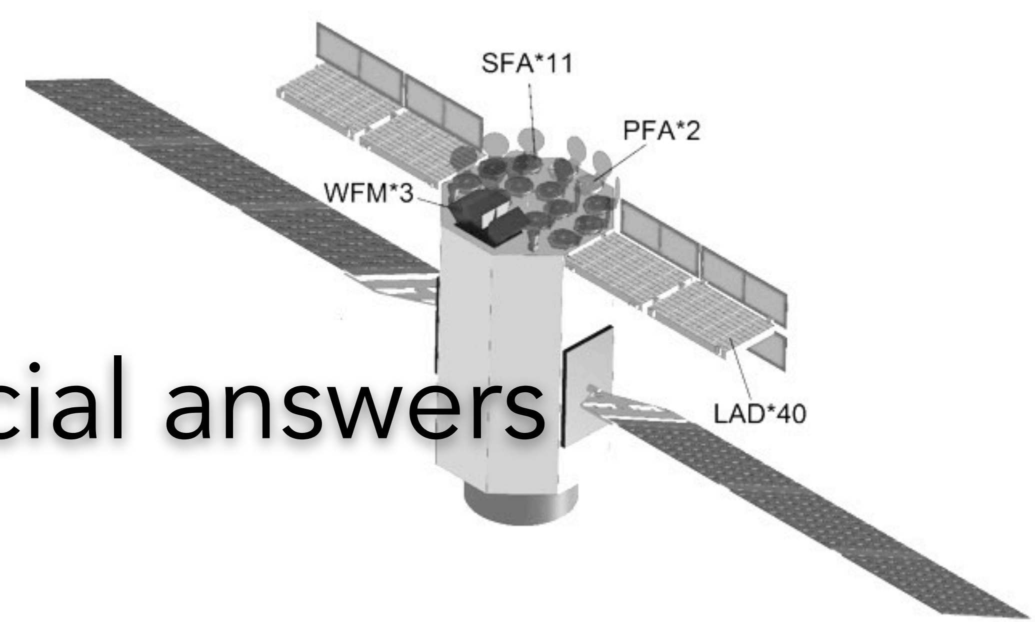
High-throughput X-Ray Astronomy in the eXTP era Feb 7th, 2017

The strong gravity regime

- How does gravity behave in the strong field regime?
- Does General Relativity accurately describe gravity in the strong field regime?
  - Singularities, dark energy/matter, quantum connection +
- Can other forms of matter/fields form ultra dense objects?

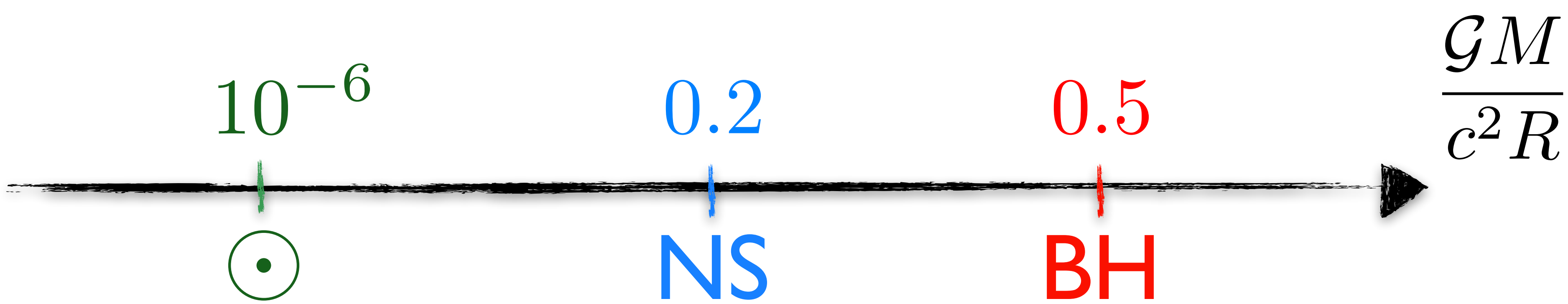


eXTP may provide crucial answers

102 years of General Relativity

GR represents the best description of gravity we have, and has passed all observational and experimental tests

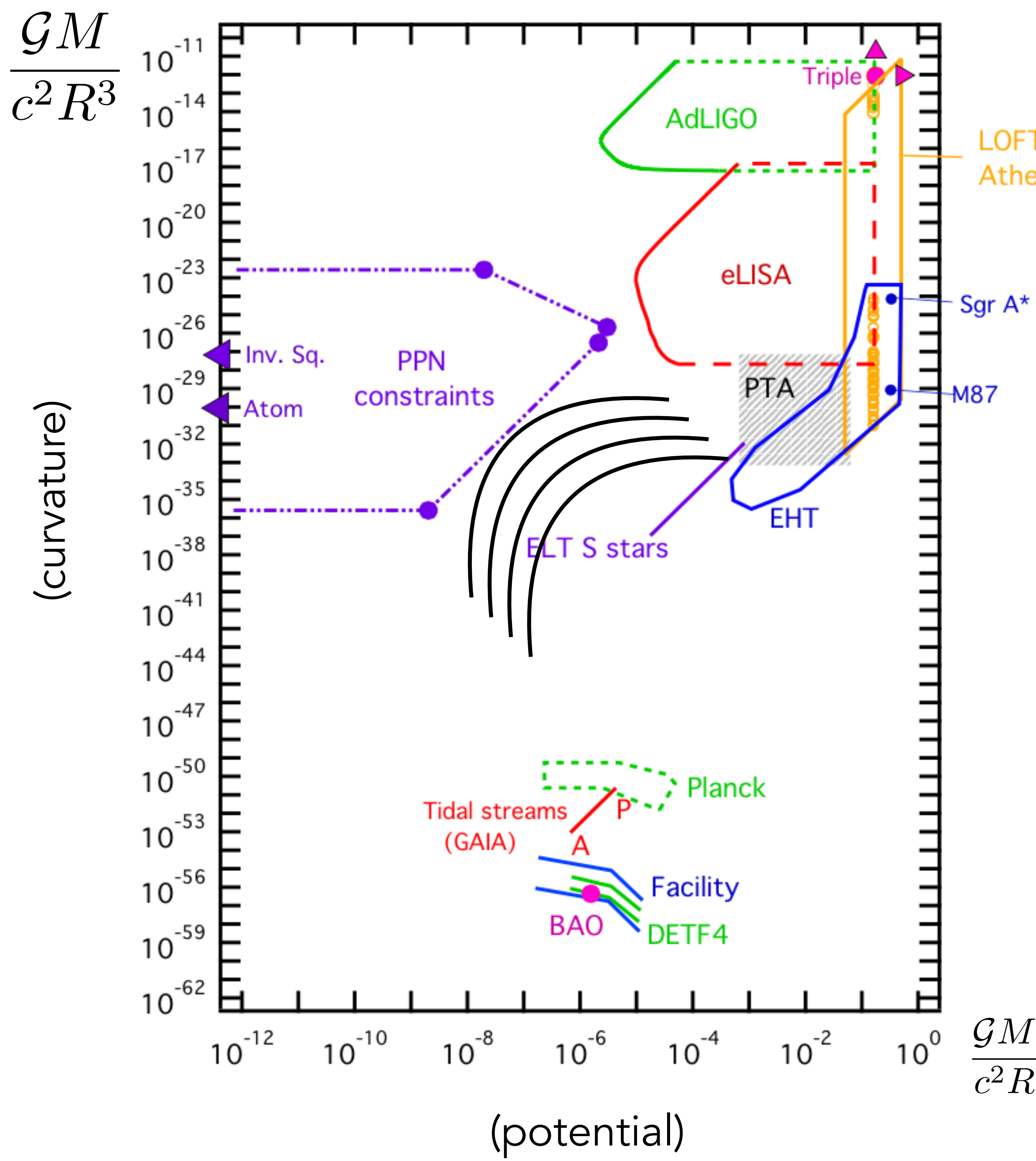
- weak - field has been probed extensively, what about the strong - gravity regime?



✓ PPN parameters from Cassini spacecraft $\gamma - 1 \sim 10^{-5}$

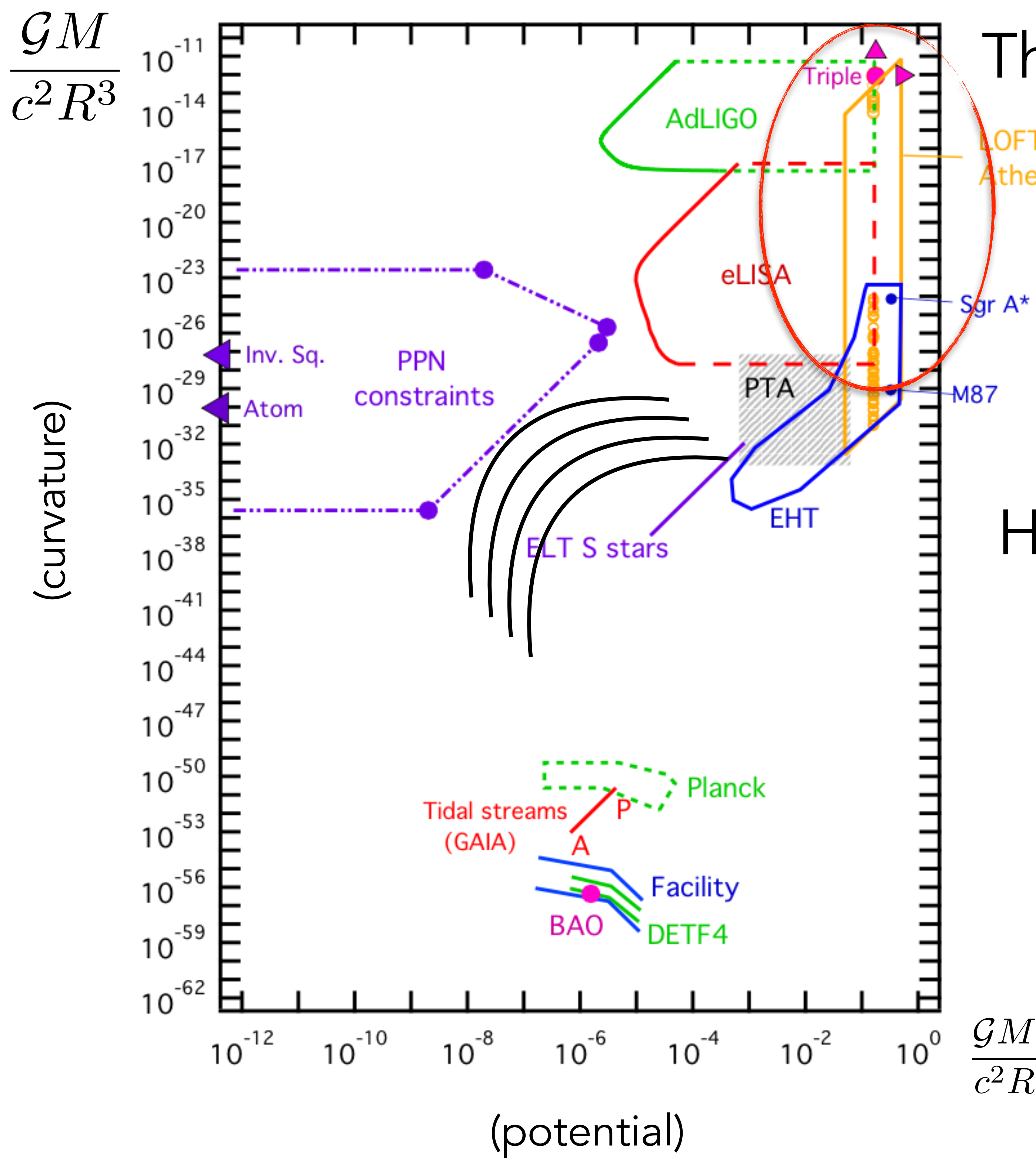
✓ Eventually Gravitational Waves come to the game

The strong gravity regime



Baker et al., ApJ 802:63, (2015)

The strong gravity regime



The strong gravity corner

Horizon of stellar mass BHs

Baker et al., ApJ 802:63, (2015)

Alternative theories: EDGB

A natural way to modify the strong field regime is to include quadratic curvature invariant in the action

$$S = \frac{1}{2}\int d^4x\sqrt{g}\ R$$

General Relativity

Alternative theories: EDGB

A natural way to modify the strong field regime is to include quadratic curvature invariant in the action

$$S = \frac{1}{2}\int d^4x\sqrt{g}\left[R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\alpha e^\phi}{4}\mathcal{R}^2_{\mathrm{GB}}\right]$$

General Relativity

Einstein-Dilaton-Gauss-Bonnet

ϕ is the Dilaton field

α enters as coupling dimensionful parameter ~ $\left[\ell^2\right]$

QPOs and black holes

Quasi Periodic Oscillations in the flux emitted from accreting LMXBs are though to originate in the innermost region of the accretion flow

- ✓ The Relativistic Precession Model associates 3 types of QPOs to a combination of the epicyclic frequencies

Stella and Vietri, Phys. Rev. Lett. 82, 17 (1999)

- ✓ In GR particles on circular-equatorial orbits, will oscillate under small perturbations δr and $\delta\theta$

- ✓ X-ray emission modulated by the azimuthal ν_ϕ, periastron $\nu_{\rm per}$ and nodal $\nu_{\rm per}$ precession frequencies

$$\nu_{\rm nod} = \nu_\phi - \nu_\theta \qquad\qquad \nu_{\rm per} = \nu_\phi - \nu_r$$

RPM

System of 3 equations in there unknown variables

$$\nu_\phi^{\mathrm{GR}} = \frac{1}{2\pi}\frac{M^{1/2}}{r^{3/2} + a^\star M^{3/2}}$$

$$\nu_r^{\mathrm{GR}} = \nu_\varphi^{\mathrm{GR}}\left(1 - \frac{6M}{r} + 8a^\star\frac{M^{3/2}}{r^{3/2}} - 3a^{\star 2}\frac{M^2}{r^2}\right)^{1/2}$$

$$\nu_\theta^{\mathrm{GR}} = \nu_\varphi^{\mathrm{GR}}\left(1 - 4a^\star\frac{M^{3/2}}{r^{3/2}} + 3a^{\star 2}\frac{M^2}{r^2}\right)^{1/2}$$

✔ Complete application of RPM: J1665-40 discovery by RXTE

Motta et al., MNRAS 437, 2554-2565 (2014)

$$M = (5.31 \pm 0.07)M_\odot$$

$$a^\star = (0.290 \pm 0.003)$$

$$r = (5.68 \pm 0.04)r_g$$

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$$\sim 10\%\ r_{\rm ISCO}$$

produced near the horizon,
probe of the strong field

Why eXTP? quality and quantity

eXTP is expected to measure QPOs frequencies with very high precision

- ~5 times better than RXTE

eXTP is expected to measure multiple QPOs triplets from the same black hole $(\nu_\phi, \nu_{\rm nod}, \nu_{\rm per})_{i=1,\dots n}$

- 3n quantities equations for 2+n variables $(M, a^\star, r_i)$

- ✓ For n>1 redundancy would test GR

Testing gravity with eXTP

We compute two set of frequencies within EDGB theory for two emission radii $r_{1,2} = (1.1, 1.4) r_{\rm ISCO}$

$$(\nu_\phi, \nu_{\rm nod}, \nu_{\rm per})_1 \qquad (\nu_\phi, \nu_{\rm nod}, \nu_{\rm per})_2$$

- True signals measured by eXTP with $(\sigma_{\nu_\phi}, \sigma_{\nu_{\rm nod}}, \sigma_{\nu_{\rm per}})$

- Try to interpret the signals with GR and to measure the BH parameters

$$(M_1, a_1^\star, r_1) \qquad (M_2, a_2^\star, r_2)$$

For General Relativity ($\alpha = 0$) $M_1 = M_2$ and $a_1^\star = a_2^\star$

Testing gravity with eXTP

Rules of the game

$$\Delta M = M_1 - M_2 \qquad \Delta a^\star = a_1^\star - a_2^\star \qquad \Delta r = r_1 - r_2$$

- Verify that the distribution of the variables $\vec{\mu} = (\Delta M, \Delta a^\star, \Delta r)$ is consistent with a Gaussian distribution with zero mean

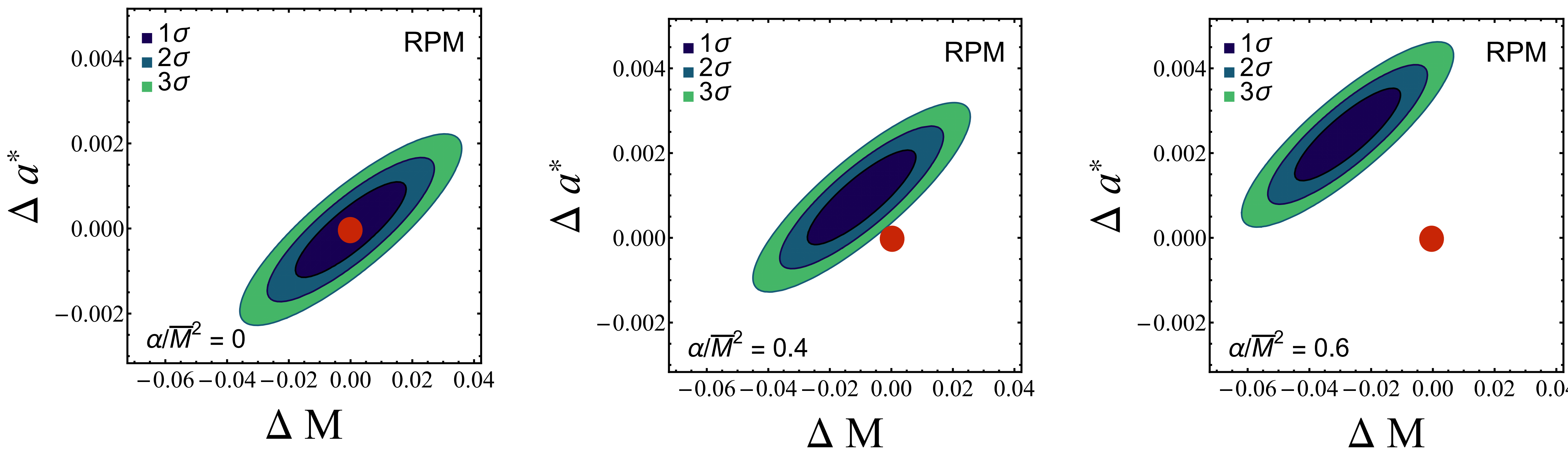
$$\mathcal{P} \sim \mathcal{N}(\vec{\mu}, \Sigma = \Sigma_1 + \Sigma_2)$$

- Define $\chi^2 = (\vec{x} - \vec{\mu})^{\mathrm{T}} \Sigma^{-1} (\vec{x} - \vec{\mu})$

$\chi^2 = c$ → 1σ, 2σ, 3σ → Probability of 32%, 5%, 0.3% to be consistent

Confidence intervals

BH parameters: $M = 5.3 M_\odot \;\; a^\star = 0.5$



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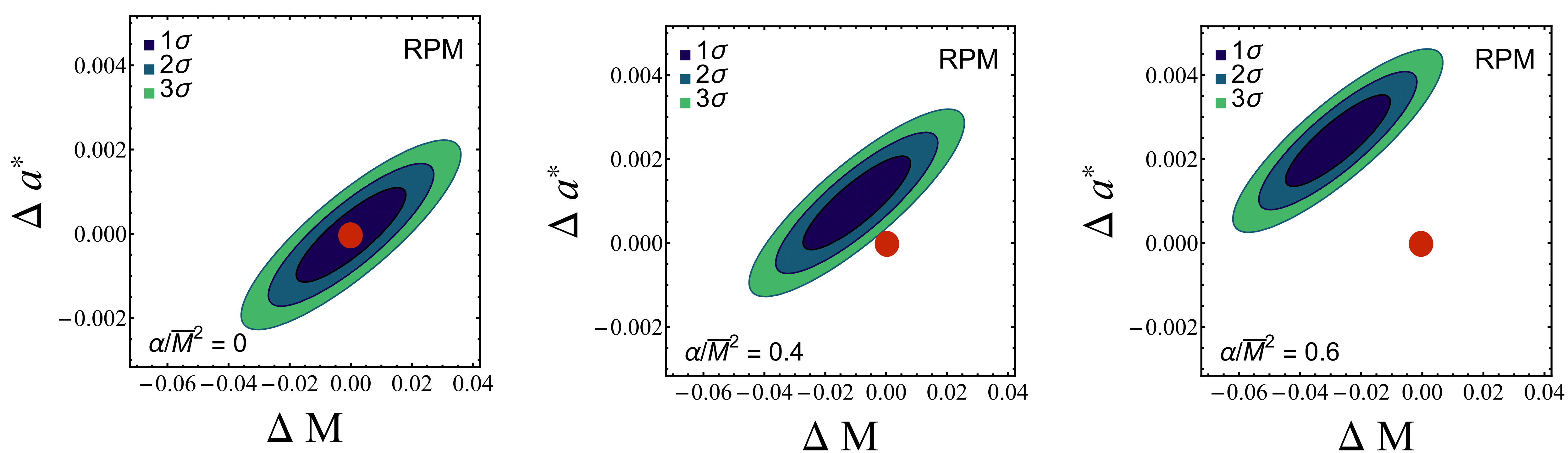

Consistent with GR

Confidence intervals

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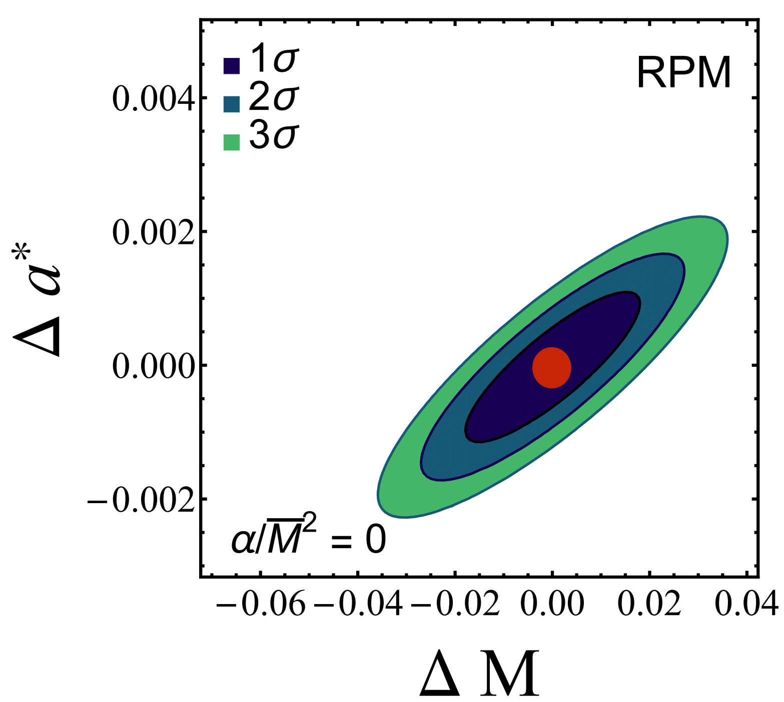
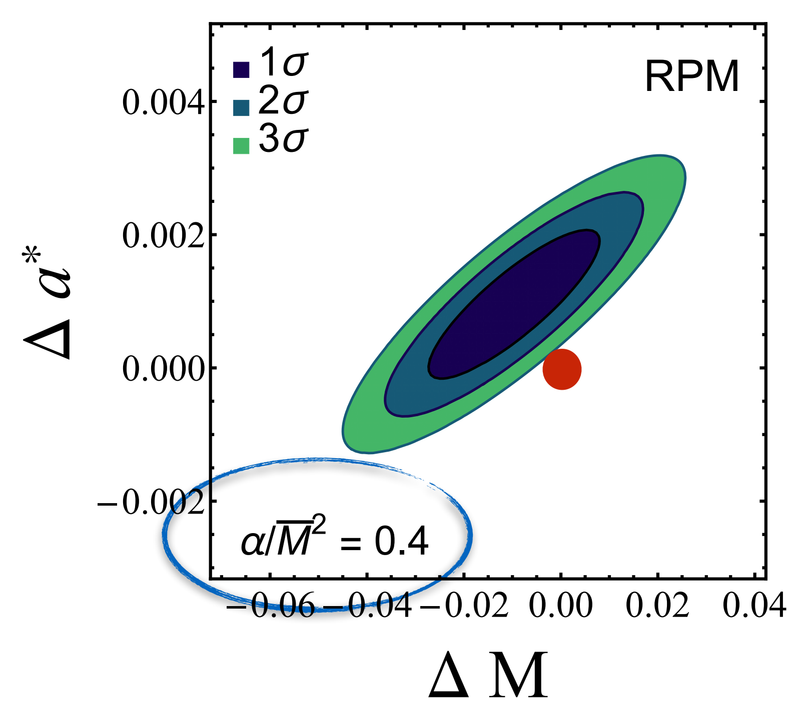
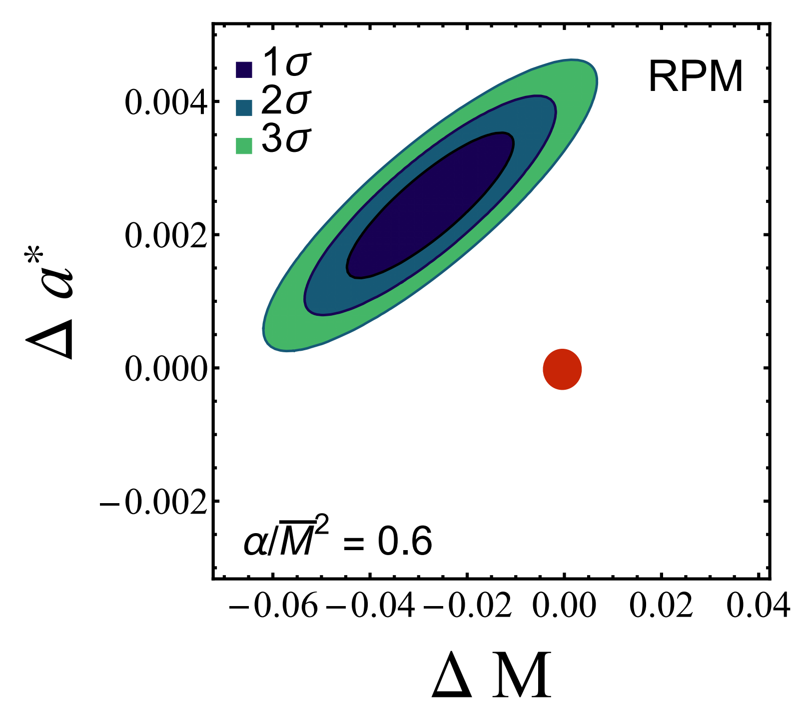




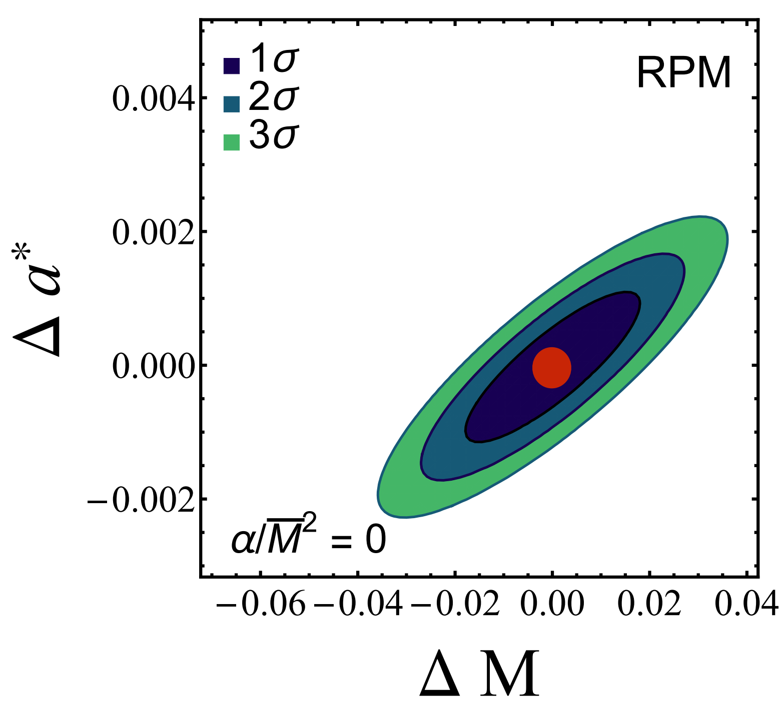


Consistent with GR

3σ threshold

Confidence intervals

BH parameters: $M = 5.3 M_{\odot}$ $a^{\star} = 0.5$



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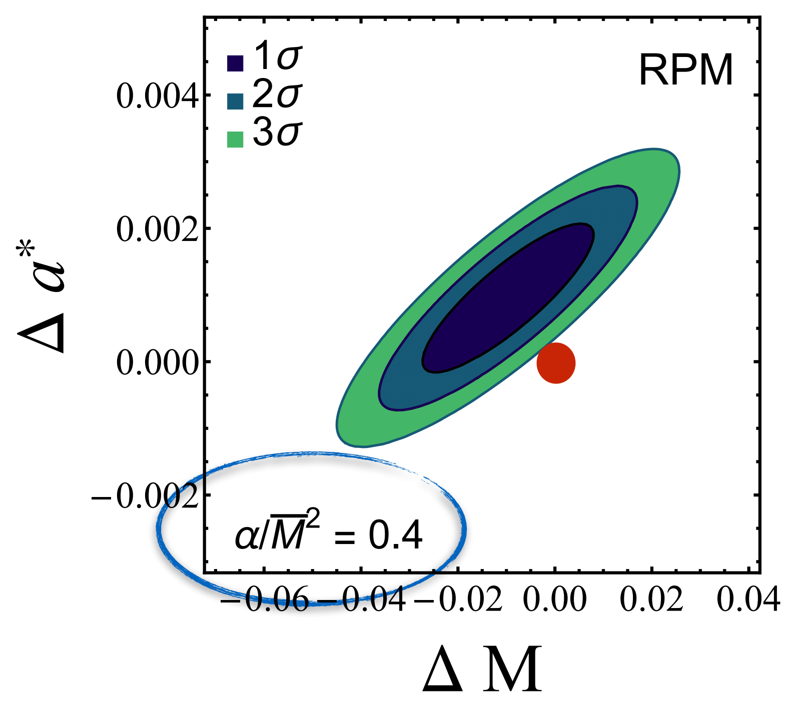

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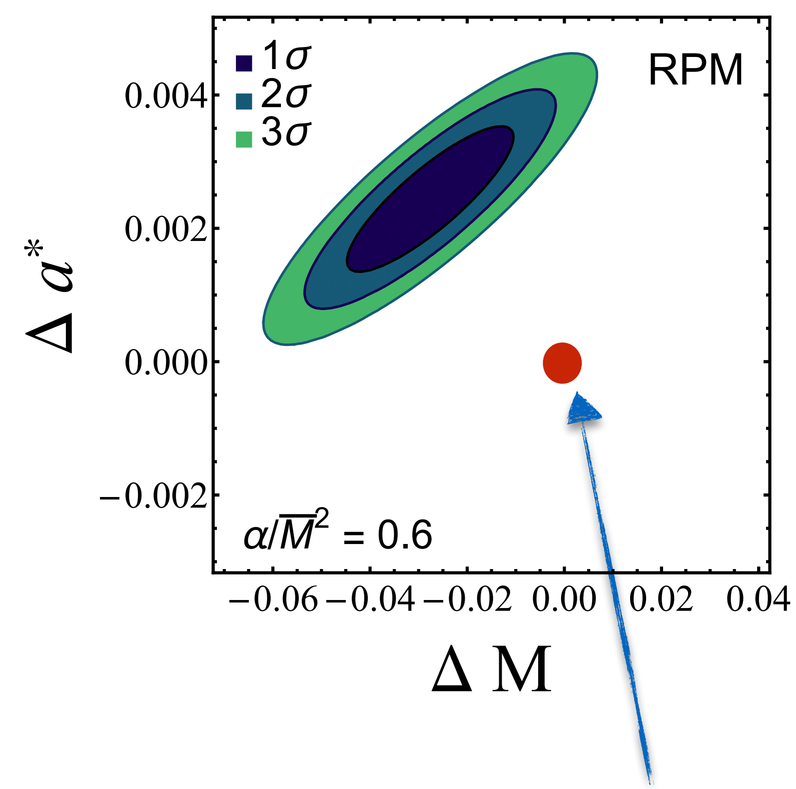
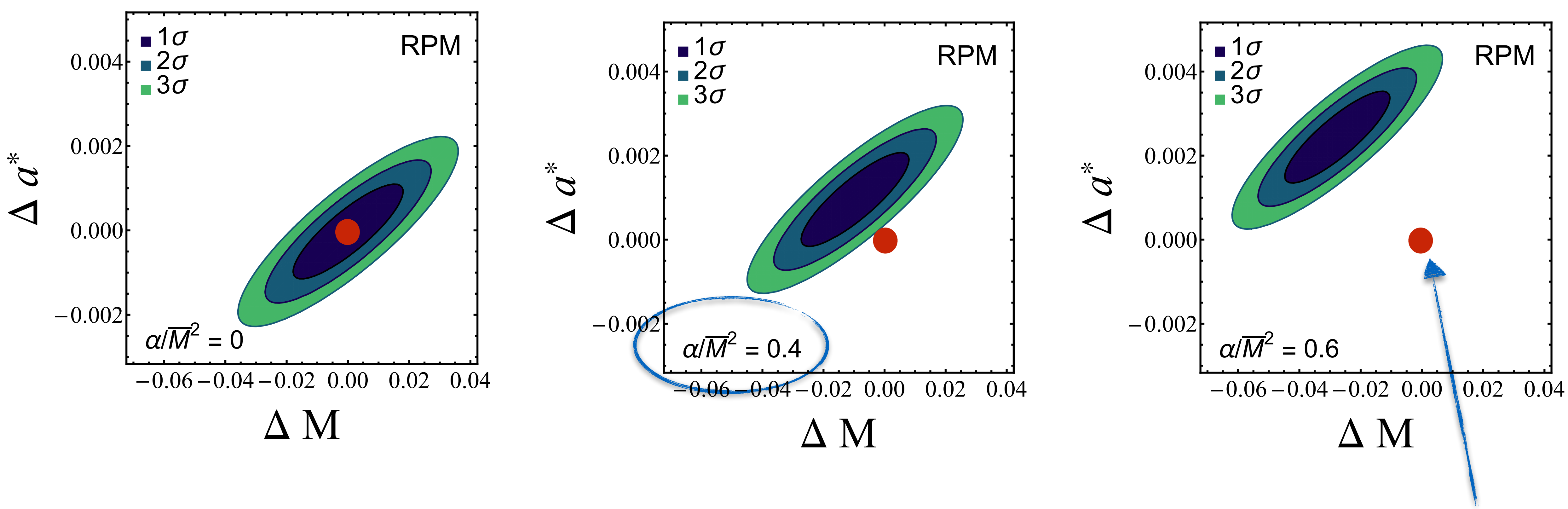


Datasets inconsistent >> 3σ

Confidence intervals

BH parameters: $M = 5.3 M_\odot \;\; a^\star = 0.5$



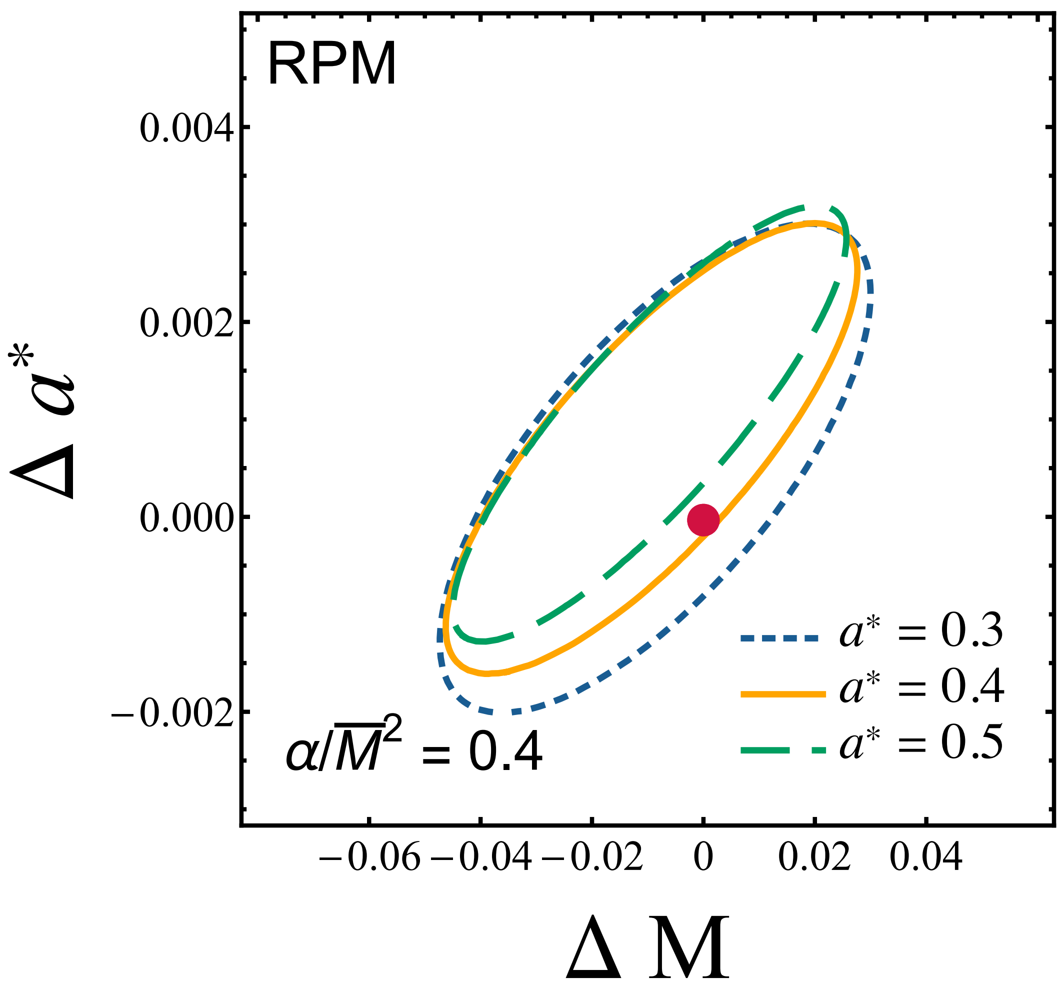
Consistent with GR

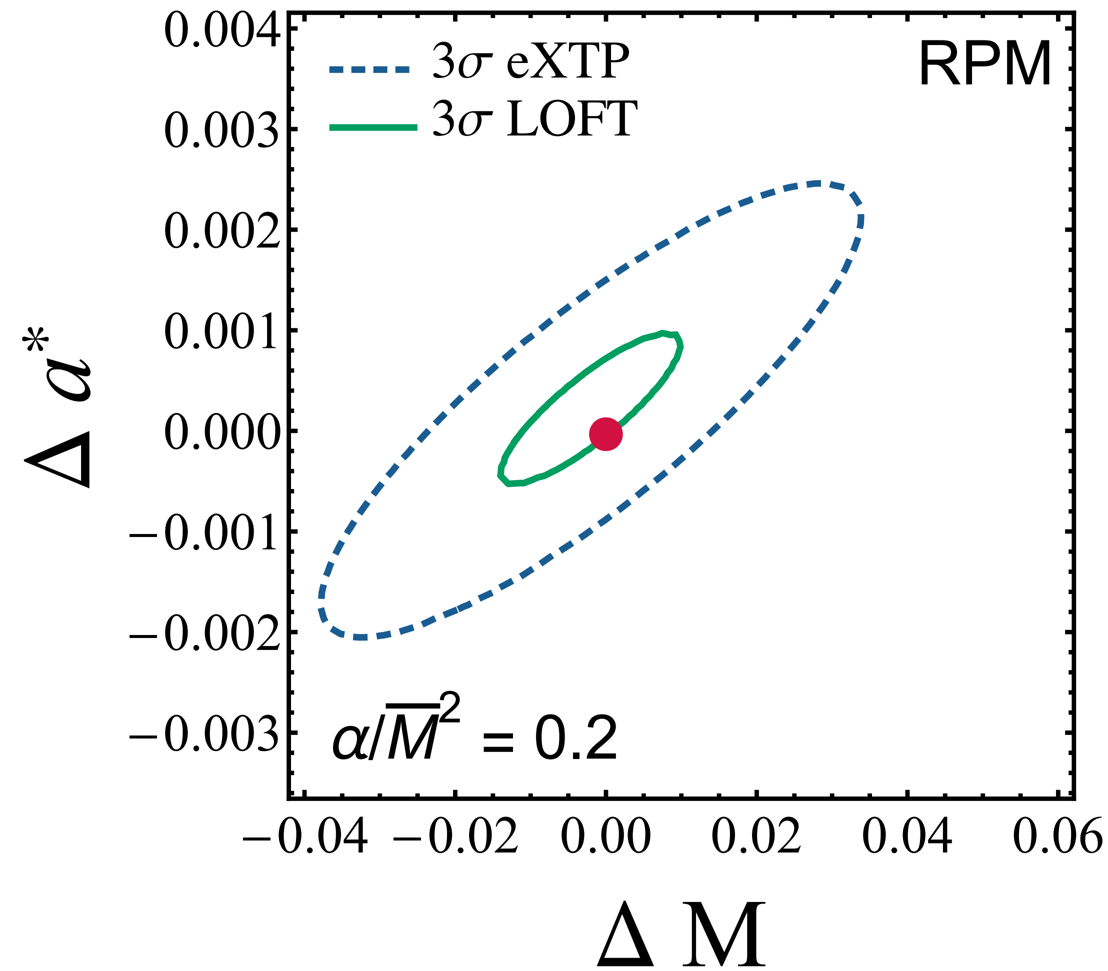
3σ threshold

Datasets inconsistent >> 3σ

In this case $0.4 \lesssim \alpha/M^2 \lesssim 0.6$ would be excluded

Confidence intervals





✓ Our ability to distinguish the theory increases with the BH spin

✓ Money in the box: more area more gain

Back up

Epicyclic frequencies