Probing ultralight bosons with compact eccentric binaries

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Supermassive Black Hole and Fundamental Physics
Sep 26, 2021 · ITP CAS

w/ Boye Su, Xingyu Zhang
2107.13527

Weakly coupled & light degrees are well motivated BSM physics
but are hard to probe

DM: gravity evidences only

Most searching strategies assume beyond gravity couplings

Gravity probe is considered somewhat indirect:
statistics / collective phenomena

New opportunities from GWs and (SM)BHs
Precision measurements; more informative

Ultralight bosons

- Gravitational atom
  Fast rotating BH / Superradiance
  / Quasi-stable bound state

$$(\Box - \nu^2)\sigma = 0$$

$$\sigma = 2\mathrm{Re}\frac{1}{\sqrt{2\nu}}\psi_{n\ell m}e^{-\mathrm{i}E_n t}$$

- Produced through Im E_n / Depleted through GWs

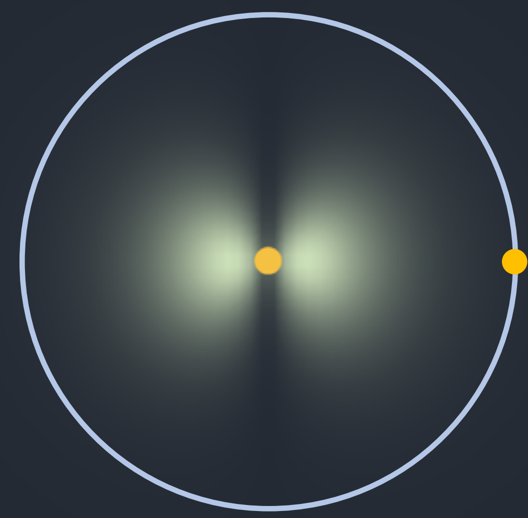
$$T_{\mathrm{prod}}(|211\rangle) \sim 10^6\mathrm{yr}(M/10M_\odot)(0.016/\alpha)^9$$

$$T_{\mathrm{depl}}(|211\rangle) \sim 10^8\mathrm{yr}(M/10M_\odot)(0.062/\alpha)^{15}$$

Arvanitaki & Dubovsky 11; Yoshino & Kodama 12; Baumann, Chia, et al 19, 20;
Tong, Wang, et al 20, 21; Chen, Shu et al. 19; Chen, Liu et al. 21

"Gravitational collider physics"

- GA-BH binary / GA-PSR binary
  Orbital induced level transition



- Energy transferred between the cloud and the orbit
  Sinking orbit / floating orbit

- Works only when orbital frequency matches energy split
  Several discrete narrow bands in orbital separation

- Many free parameters: challenging for GW observation

Baumann, Chia, et al 19, 20; Tong, Wang, et al 20, 21

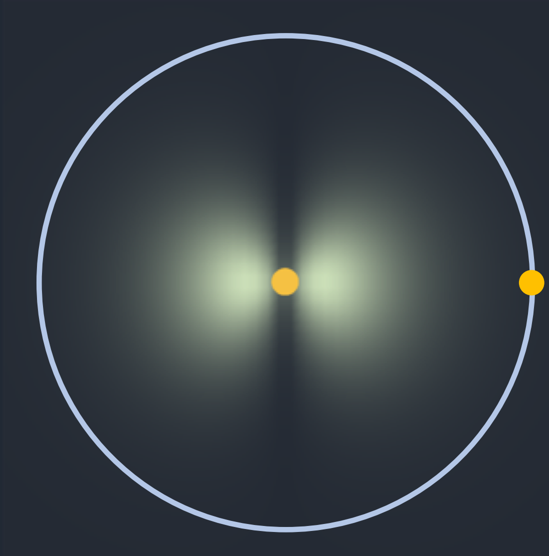
Gravitational collider goes off-shell

- Energy distribution of GA

$$\rho_{211}(\mathbf{x}) = \frac{1}{64\pi}\alpha^5\nu^5 m_{\rm C}\, r^2 e^{-\alpha\nu r}\sin^2\theta$$

$$m_{\rm C} \simeq \alpha m_{\rm Kerr}$$

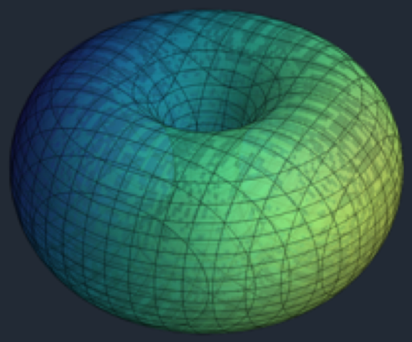
$$J_{\rm C} \simeq J_{\rm Kerr} \qquad Q_{\rm C} \simeq \alpha^{-3} Q_{\rm Kerr}$$



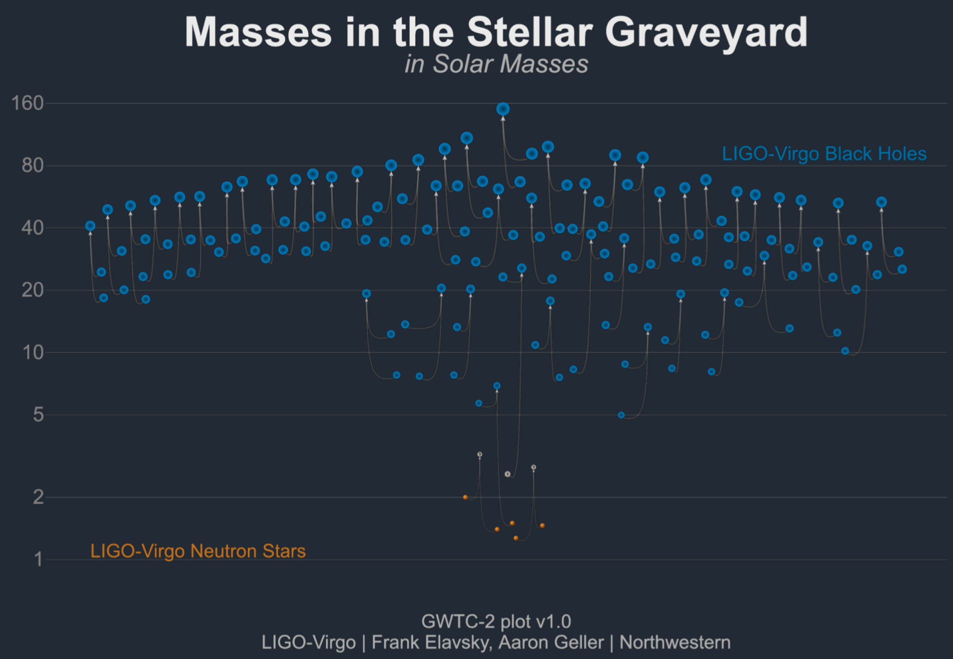
- A small fraction of mass but huge quadrupole ~ $1/\alpha^3$

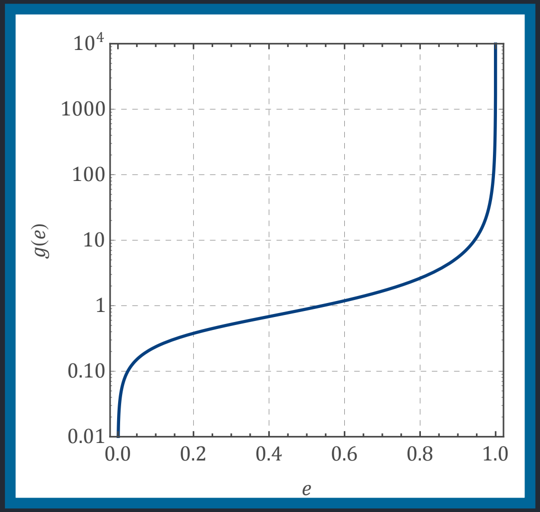
1~10 for NS, ~100 for WD

- Significant orbital precession



Compact eccentric binaries





$$\mathcal{G}(e) \equiv \frac{e^{12/19}}{1-e^2}\left(1+\frac{121}{304}e^2\right)^{870/2299}$$

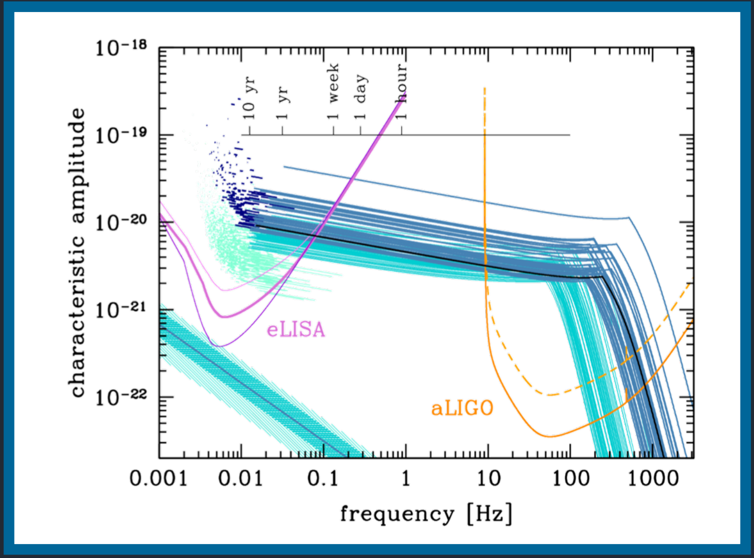
Resolving orbital precession needs observably large orbital eccentricity

No eccentric binaries confirmed in LIGO, with a good reason

Compact eccentric binaries

But LIGO-type binaries are expected to be eccentric
at lower frequencies
Important targets of space GW telescopes

PSR-BH are expected to be eccentric, too
Could be seen in the future



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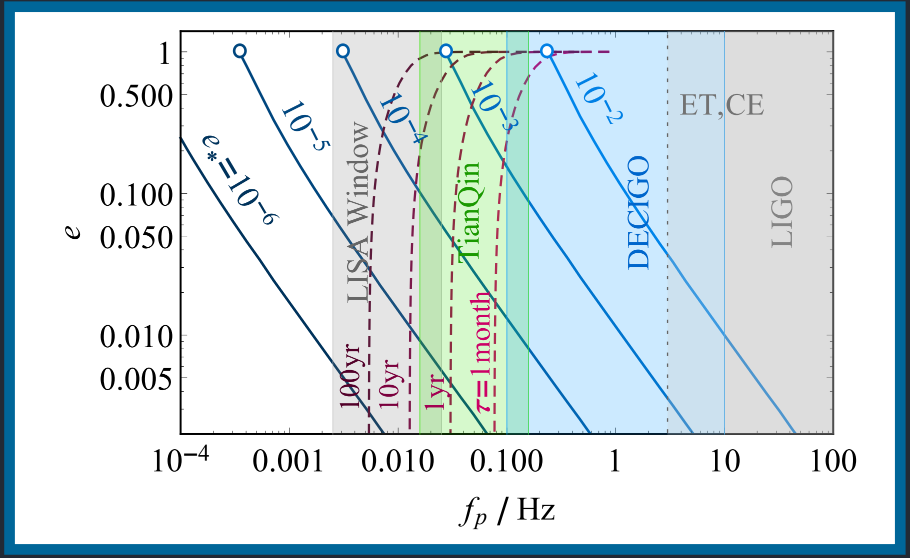
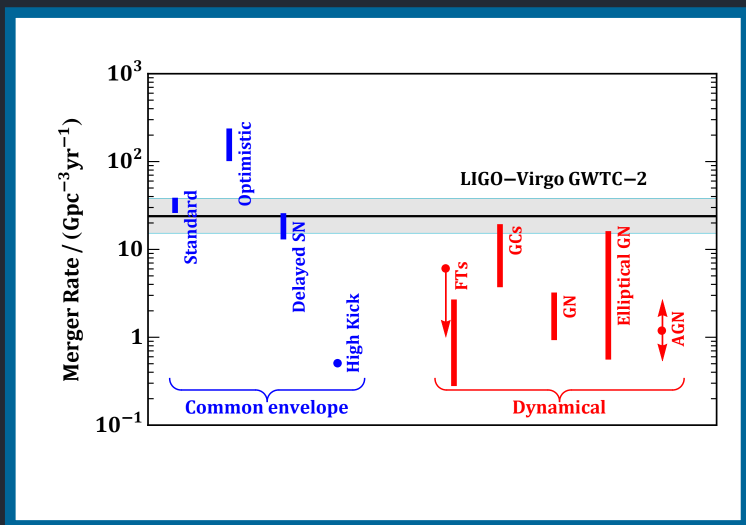
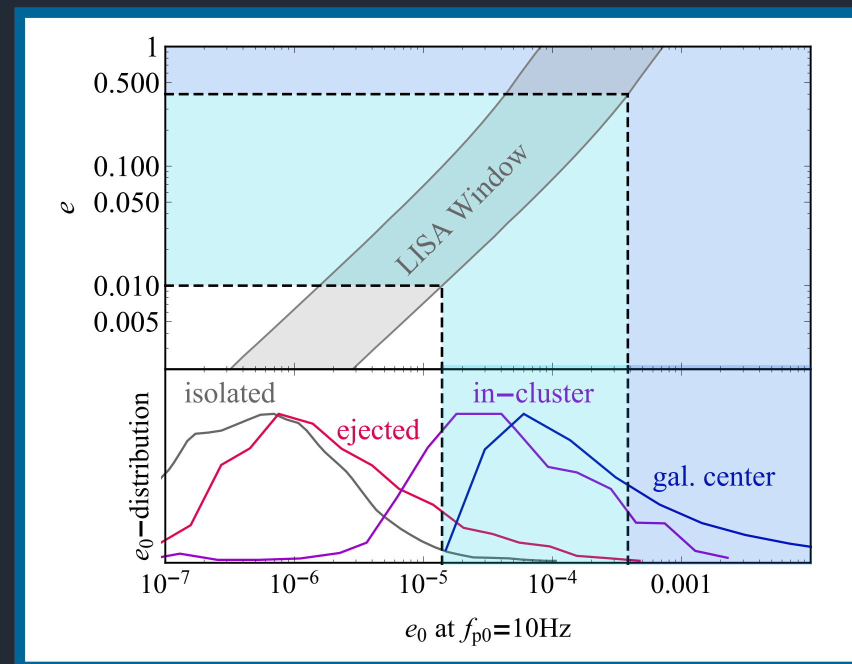
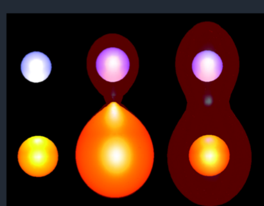


Randall & ZZX 19

Compact eccentric binaries







Randall & ZZX 17, 18

LIGO/Virgo: 2010.14533; CE: 1405.7016; Field Triples: 1608.07642, 1703.06614; GCs: 1809.01152GN: 1706.09896; Elliptical GN: 1705.05848; AGN: 1602.03831

Cloud-induced precessions

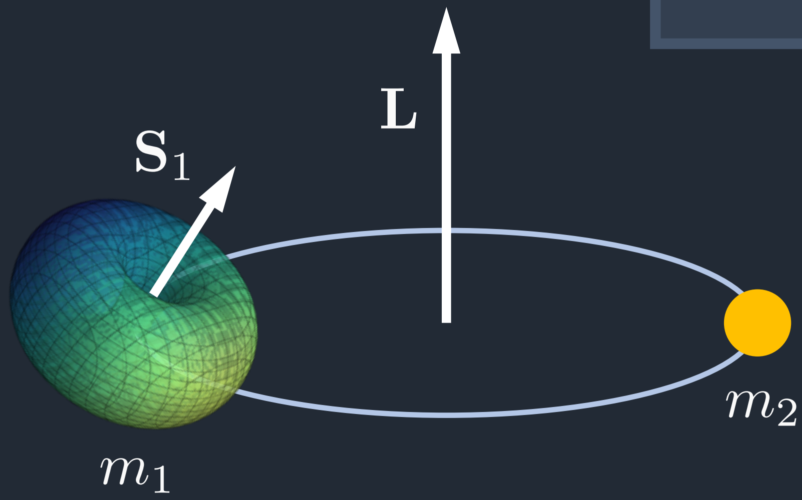
Interaction potential: orbital, quadrupole-orbit, and spin-orbit

Spin-spin always negligible

$$V_\mathrm{O} = -\frac{Gm\mu}{r} + \text{1PN terms}$$

$$V_\mathrm{Q} = \frac{Gm\mu}{2r^3} q_1 (1 - 3\cos^2 n_1)$$

$$V_\mathrm{SO} = \frac{2GL}{r^3}(m_1 + \tfrac{3}{4} m_2) s_1 \cos n_1$$



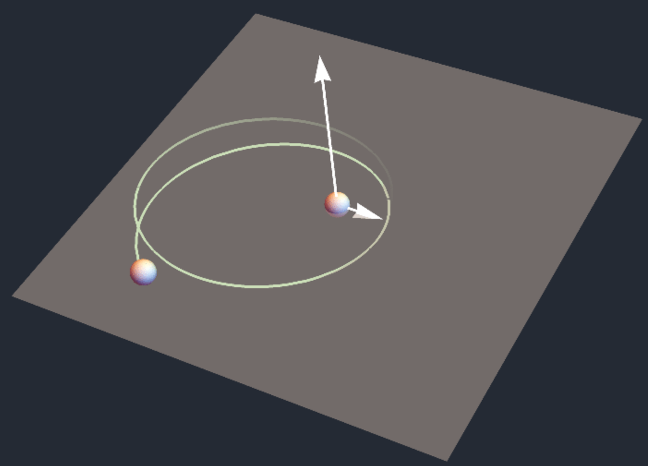
$$\cos n_1 = \mathbf{S}_1 \cdot \mathbf{L}$$

$$q_1 = Q_1/m_1$$

$$s_1 = S_1/m_1$$

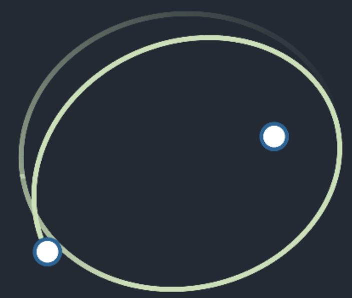
Cloud-induced precessions

Nodal precession



Confined in a small cone by
angular momentum conservation,
Unimportant for GW

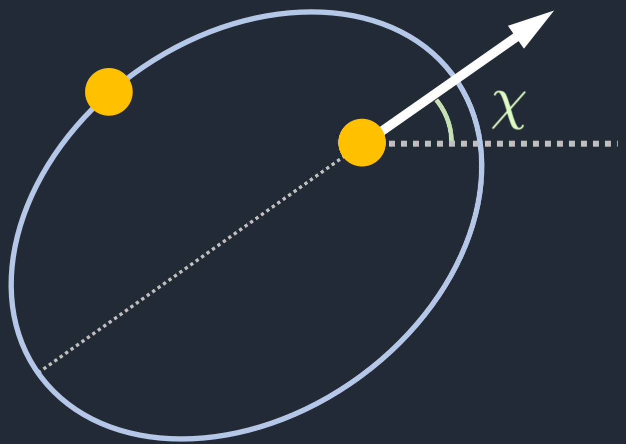
Apsidal precession



Typically very significant,
main signal

* Also spin precessions, but happen to be unobservable

Apsidal precession rate



$$\dot\chi = \dot\chi_{\rm GR} + \dot\chi_Q + \dot\chi_S$$

$$V_{\rm O} = -\frac{Gm\mu}{r} + \text{1PN terms}$$

$$V_{\rm Q} = \frac{Gm\mu}{2r^3} q_1 (1 - 3\cos^2 n_1)$$

$$V_{\rm SO} = \frac{2GL}{r^3}(m_1 + \tfrac{3}{4}m_2) s_1 \cos n_1$$

$$\dot\chi_{\rm GR} = \frac{3Gm\omega}{a(1-e^2)}$$

$$\dot\chi_{\rm Q} = \frac{3\omega}{4a^2(1-e^2)^2} q_1 (1 - 3\cos^2 n_1)$$

$$\dot\chi_S = \frac{-3\omega^2}{(1-e^2)^{3/2}} s_1 \left(1 + \tfrac{m_1}{3m}\right) \cos n_1$$

Parameter space

$$\frac{\dot{\chi}_Q}{\dot{\chi}_{GR}} \simeq \frac{3u_1}{2\alpha^3}\frac{Gm_1}{a(1-e^2)}$$

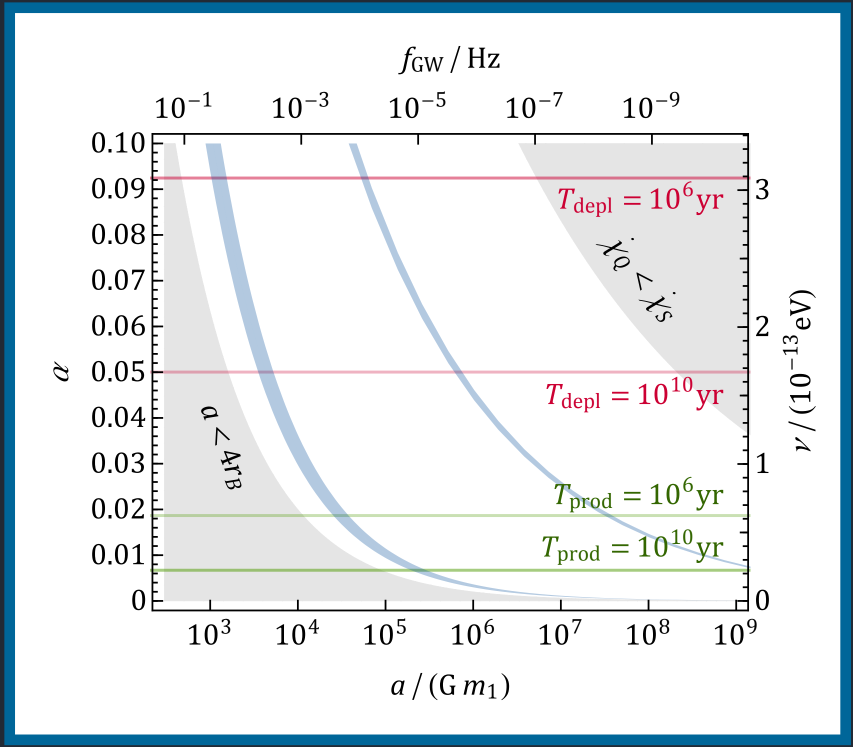
$$\frac{\dot{\chi}_Q}{\dot{\chi}_S} \simeq \frac{3u_1}{2\alpha^3(1+u_1/3)}\left[\frac{Gm_1}{a(1-e^2)}\right]^{1/2}$$

$$u_1 \equiv m_1/m$$

GR precession can be subtracted up to measurement errors

SO precession as contamination

Much widened paramter space



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GW signals

Perturbativity pushes the system to mHz ~ dHz window

$$f_2 = \frac{1}{\pi}\sqrt{\frac{Gm}{a^3}} < \frac{1}{\pi}\sqrt{\frac{Gm}{(4r_{\rm B})^3}} \sim 0.14\text{Hz}\left(\frac{\alpha}{0.05}\right)^3\left(\frac{10M_\odot}{m_1}\right)$$

GWs trace orbital motion

$$h^{ij} = \frac{2G}{d}\Lambda^{ij,k\ell}\ddot{M}^{k\ell} \qquad M^{ij} = \mu r^i r^j \qquad r_i = r(\cos\bar{\psi}, \sin\bar{\psi})$$

$$r = \frac{a(1-e^2)}{1+e\cos\psi} \qquad \bar{\psi} = \psi + \chi$$

Eccentricity: nonuniform motion (Kepler's 2nd law)
Apsidal precession: two sets of frequencies in radial and angular directions

GW signals

- Eccentricity: harmonics

$$\omega_n = n\omega$$

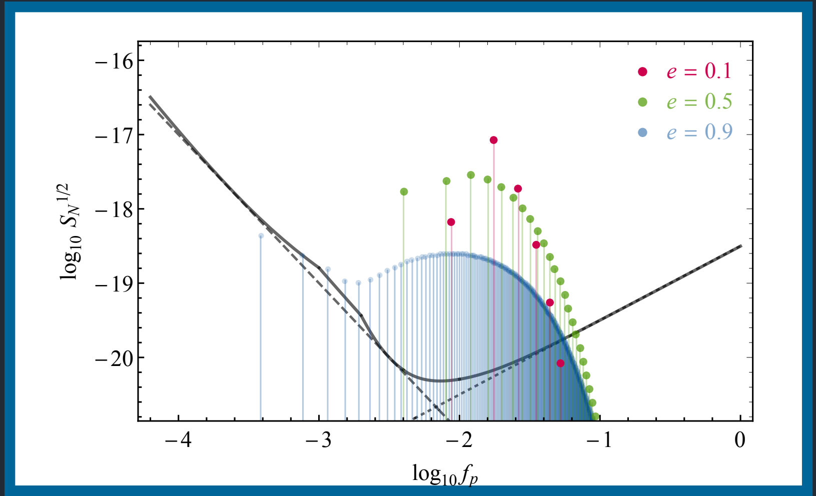
- Precession: triple split

$$(\omega_n, \omega_{n\pm}) \equiv (n\omega, n\omega \pm 2\dot{\chi})$$

The highest component almost always dominates; the other two practically unobservable

- Observable: anharmonic overtone

absent for circular orbit
at least at Newtonian level



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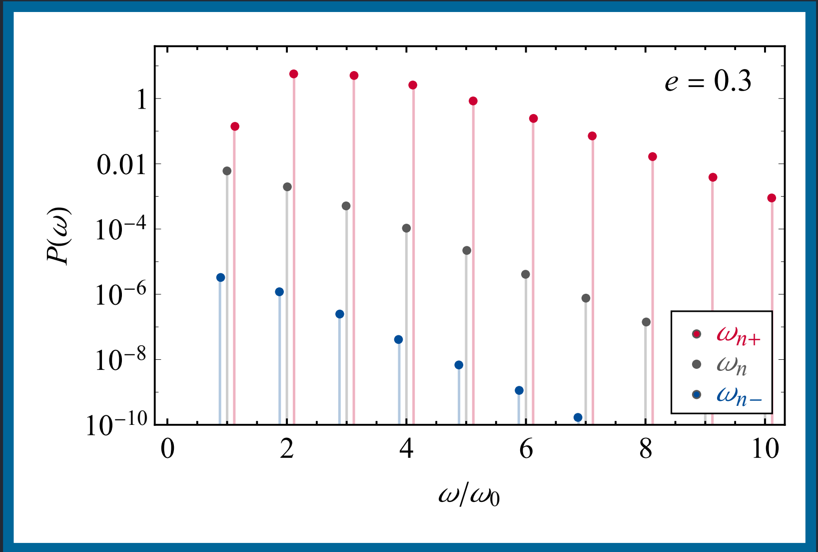

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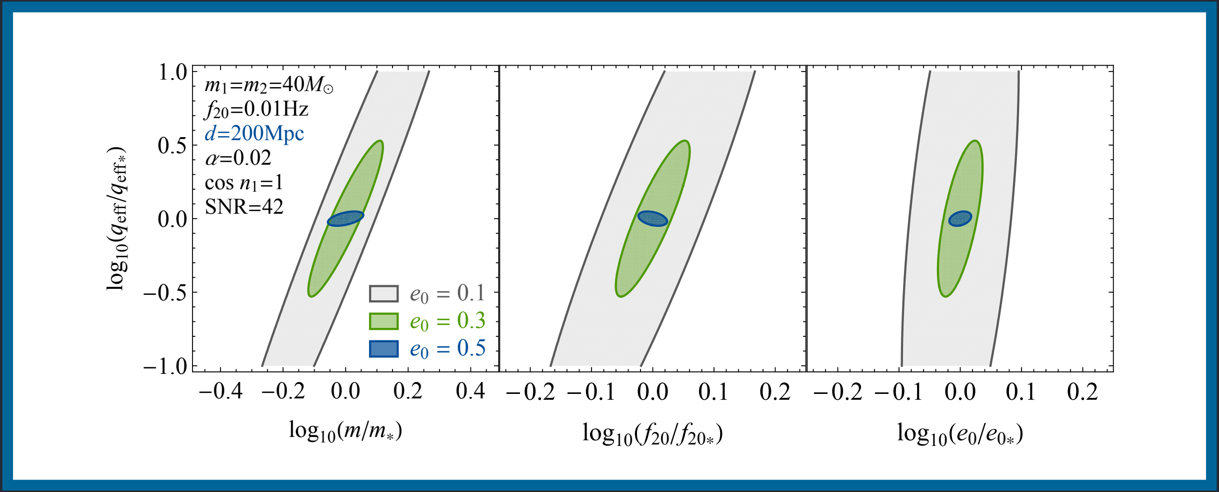
GW signals

- Observability of anharmonic overtones relies on the frequency resolution
- 1yr data @ 0.01Hz $10^{-5} < q_1/a^2 < \alpha$

A partial time-domain Fisher forecast



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Pulsar-GA binaries

- 5 Keplerian parameters:

P_b	T_0	$x = a \sin I$	e	χ_0
10^{-12}	10^{-13}	10^{-8}	10^{-7}	10^{-8}

- Post-Keplerian parameters:

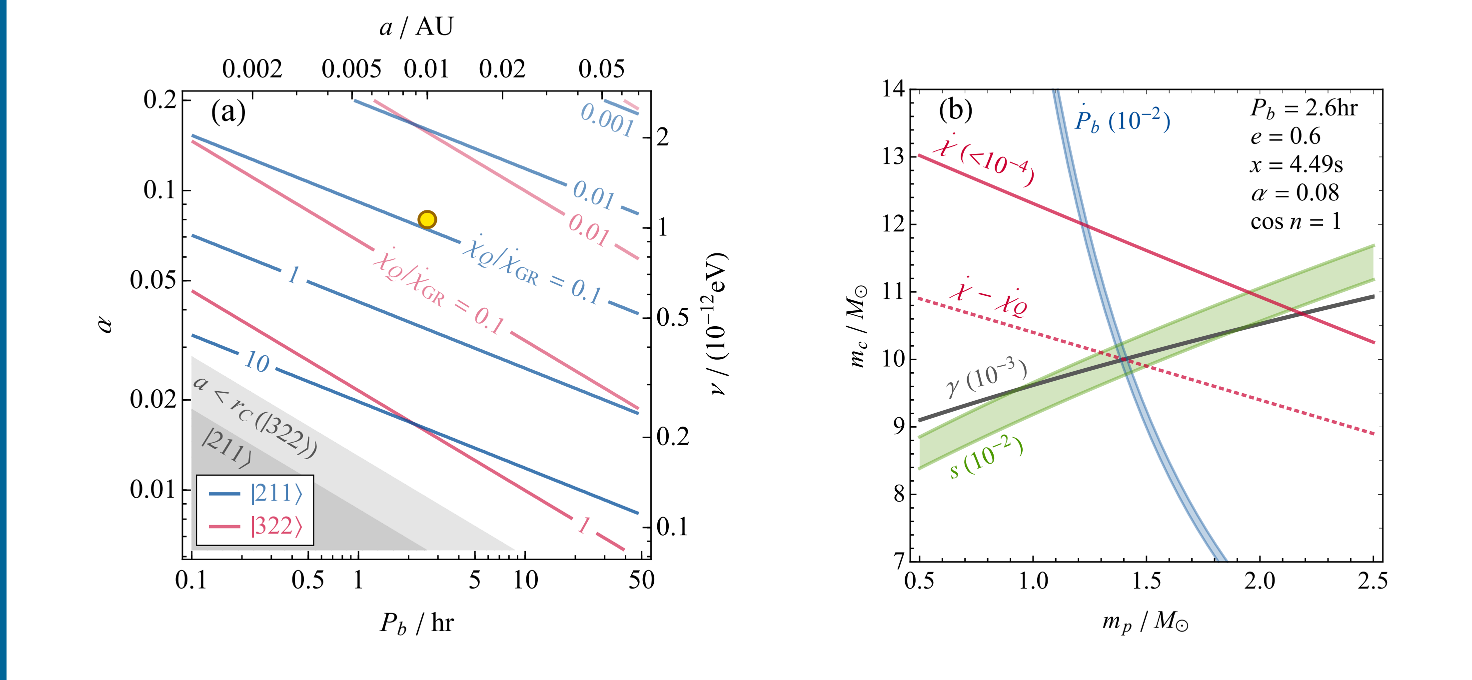
$\dot{\chi}$,	γ,	$\dot{P}_b$,	r,	s,	δ_θ,	$\dot{e}$,	$\dot{x}$
10^{-7}	10^{-5}	10^{-5}	(10^{-2})	(10^{-4})			

Strongly affected by mass quadrupole

- 2 PKs to fix the system (two masses)
- more PKs as consistency check

Pulsar-GA binaries

GA induces dramatic misfit in apsidal precession



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Summary

Astro BHs typically born with large spin

natural factories and habitat for ultralight bosons

GA-borne binaries typically exhibit large orbital precessions

much larger than other known contributions

Future GW and pulsar timing data could discover them

Also applicable to binaries with SMBHs