

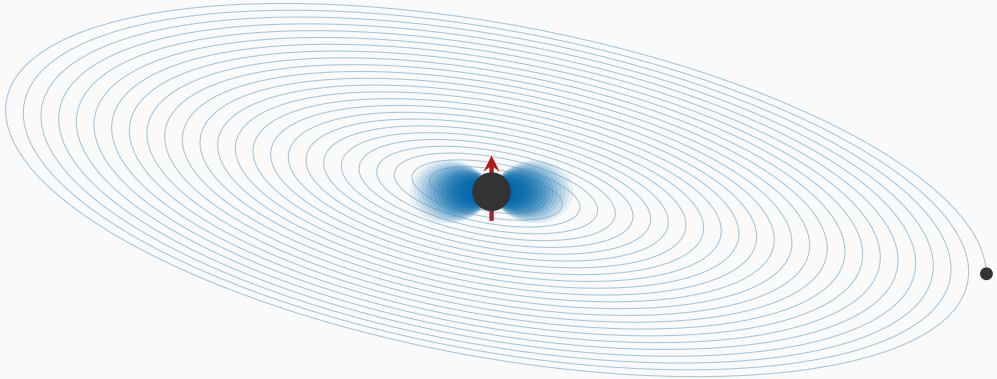
DISCOVERING GRAVITATIONAL ATOMS WITH BINARY SYSTEMS

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ADVANCED STUDY

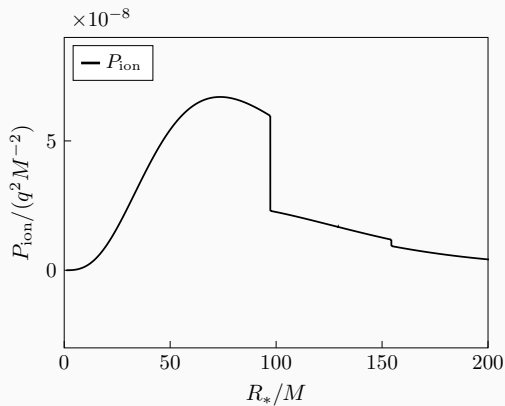
2nd New Horizons for Psi
Beijing, August 24, 2026

Binary inspiral + superradiant cloud

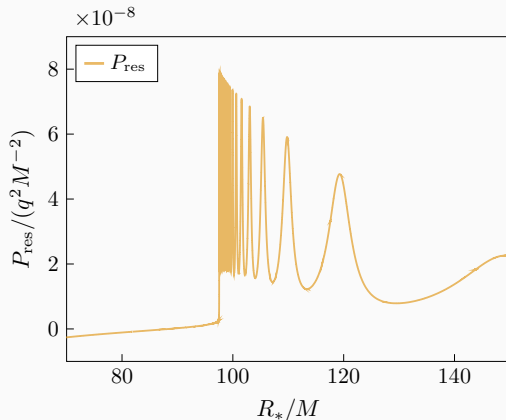


TWO FLUXES

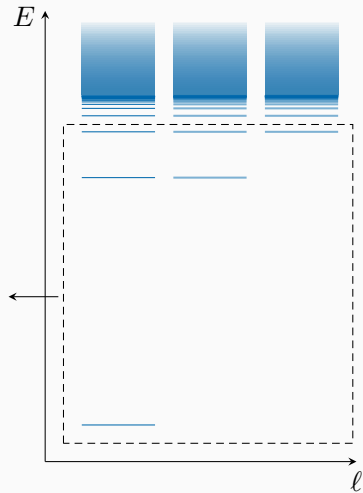
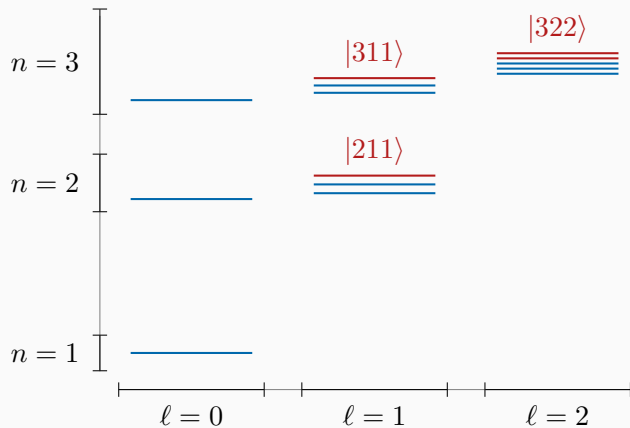
Ionization
(Infinity flux)



Resonances
(Horizon flux)

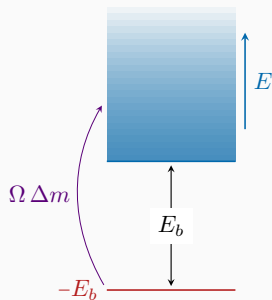


SPECTRUM



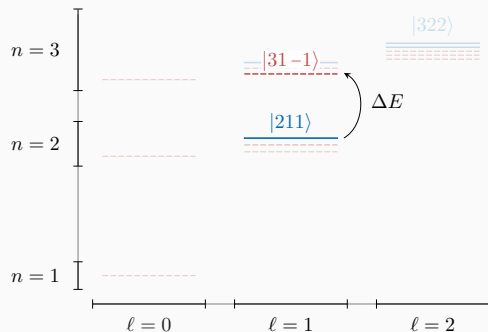
RESONANCES

Ionization
(Infinity flux)



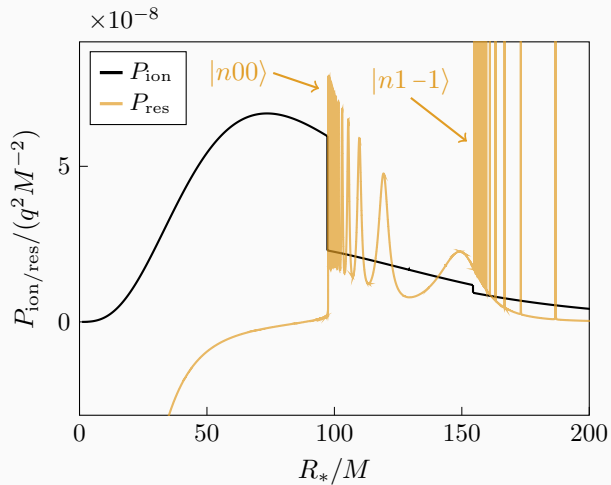
$$E_b \leq \Omega \Delta m$$

Resonances
(Horizon flux)



$$\Delta E = \Omega \Delta m, \quad \Delta \Omega \sim |\Gamma|$$

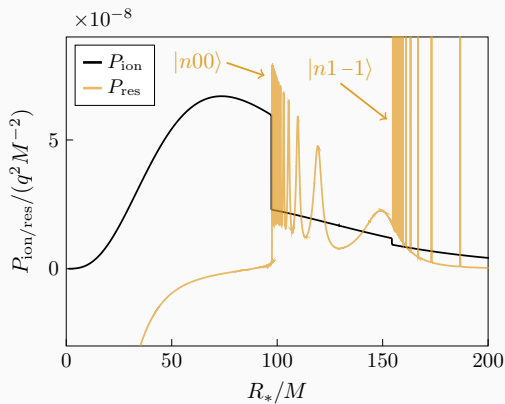
ACCUMULATION OF RESONANCES



Resonances accumulate at

$$R_*^{(\text{disc})}$$

ACCUMULATION OF RESONANCES: BINARY EVOLUTION



(schematically)

$$\dot{\mathcal{E}} = -P_{\text{ion}} - P_{\text{res}} - P_{\text{gw}}$$

What happens around the the discontinuities/accumulations?

Fixed $\Omega \implies$ infinitely many ($n \rightarrow \infty$),
infinitely narrow ($\Delta\Omega \sim \Gamma$),
infinitely weak ($e^{-2\pi Z} \rightarrow 1$) resonances.

AVERAGED P_{res}

Fixed $\Omega \implies$ infinitely many ($n \rightarrow \infty$),
infinitely narrow ($\Delta\Omega \sim \Gamma$),
infinitely weak ($e^{-2\pi Z} \rightarrow 1$) resonances.

Idea: take small interval $[R_* - \delta, R_* + \delta]$.

Define $\langle P_{\text{res}} \rangle = \frac{1}{2\delta} \int_{R_* - \delta}^{R_* + \delta} P_{\text{res}} \, dR'_*$

For small δ , $\langle P_{\text{res}} \rangle$ also acquires a discontinuity ΔP_{res} at $R_*^{(\text{disc})}$.

ZERO-ENERGY WAVEFUNCTION

Bound and unbound states converge to the **same** zero-energy mode:

Unbound:
$$\psi(\mathbf{r}) \xrightarrow{k \rightarrow 0} \sqrt{\frac{4\pi k}{r}} J_{2\ell+1}(2\sqrt{2\mu\alpha}r) Y_{\ell m}(\hat{\mathbf{r}})$$

Bound:
$$\psi(\mathbf{r}) \xrightarrow{n \rightarrow \infty} \frac{2(\mu\alpha)^{3/2}}{n^{3/2}\sqrt{2\mu\alpha}r} J_{2\ell+1}(2\sqrt{2\mu\alpha}r) Y_{\ell m}(\hat{\mathbf{r}})$$

Different prefactor due to **discrete** vs **continuum** normalization.

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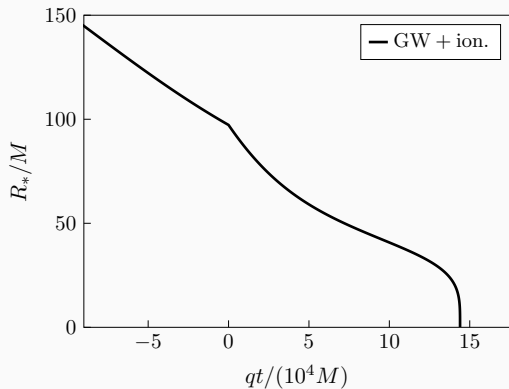
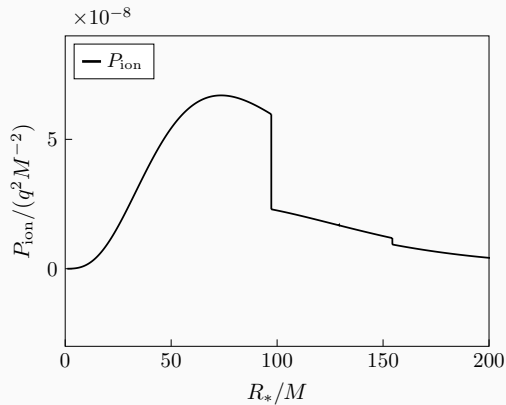
Bound: $\psi(\mathbf{r}) \xrightarrow{n \rightarrow \infty} \frac{2(\mu\alpha)^{3/2}}{n^{3/2}\sqrt{2\mu\alpha}r} J_{2\ell+1}(2\sqrt{2\mu\alpha}r) Y_{\ell m}(\hat{\mathbf{r}})$

Different prefactor due to **discrete** vs **continuum** normalization.

$$\implies \boxed{\Delta P_{\text{res}} = -\Delta P_{\text{ion}}}$$

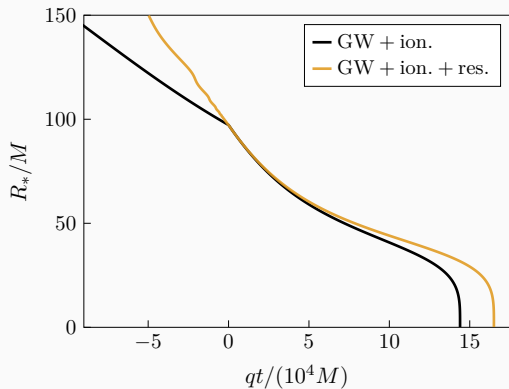
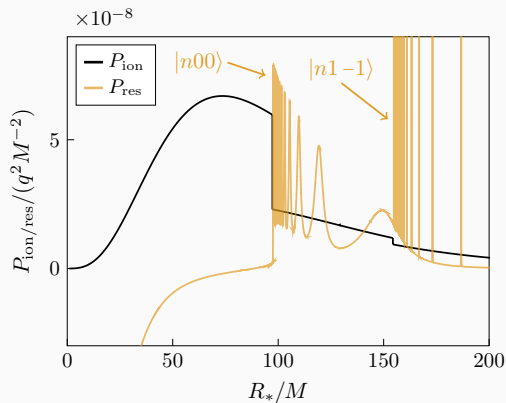
(but $\Delta P_{\text{res}} = \Delta P_{\text{ion}}$ when $\Gamma > 0$)

SHARP FEATURES IN THE FREQUENCY EVOLUTION?



[Baumann, Bertone, Stout, GMT '21]

NO SHARP FEATURES IN THE FREQUENCY EVOLUTION



[GMT '25]

CHIRPING FREQUENCY

What if $\dot{\Omega} \neq 0$?

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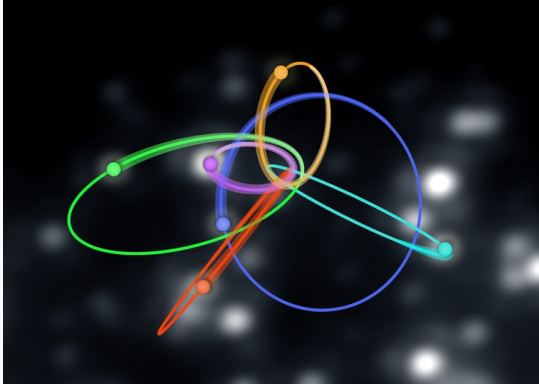
- ΔP_{ion} gets **blurred** over $\Delta\Omega \sim \sqrt{\dot{\Omega}}$
- Each resonance widens, from $\Delta\Omega \sim \Gamma$ to $\Delta\Omega \sim \sqrt{\dot{\Omega}}$
 - **But** $|\int P_{\text{res}}|$ **does not change!**
 - Goodbye infinitely narrow resonances
 - Different resonances now overlap

Same (stronger) conclusion: **smooth** evolution.

TRICKY MODELING

- Always need to keep **both** P_{ion} and P_{res} close to $R_*^{(\text{disc})}$
- $\dot{\mathcal{E}} = -P_{\text{ion}} - P_{\text{res}} - P_{\text{gw}}$
Numerically tricky: discontinuities + infinitely narrow resonances
 - high resolution?
 - artificial blurring/average?
- Relevant at both **large** and **small** separations! (see Richard's talk)

Open problem, please solve!



How about **Sgr A***?

What do S-stars say about clouds
(and other environments)?

Two options:

- **measure precession**
- **cluster evolution**

PER-ORBIT PRECESSION

Simplest approach (no orbit fit): consider per-orbit precession $\Delta\varpi$:

$$\underbrace{\Delta\varpi_{\text{tot}}}_{\text{measured}} = \underbrace{\Delta\varpi_{\text{GR}}}_{\text{predicted}} + \Delta\varpi_{\text{env}}$$

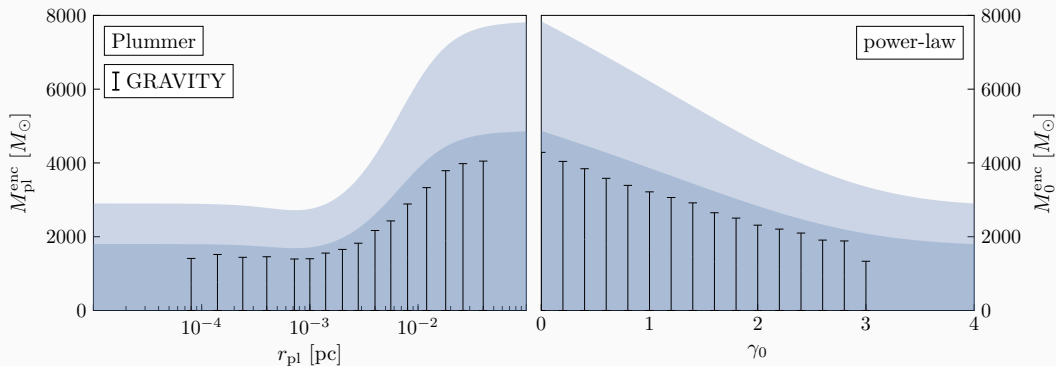
$$\text{S2 : } \Delta\varpi_{\text{tot}} = 11.1' \pm 1.5', \quad \Delta\varpi_{\text{tot}} = 12.1'$$

Can calculate environmental part analytically:

$$\dot{\varpi}_{\text{env}} = -\frac{\sqrt{1-e^2}}{\sqrt{Ma} e} \frac{\partial \langle V \rangle}{\partial e}$$

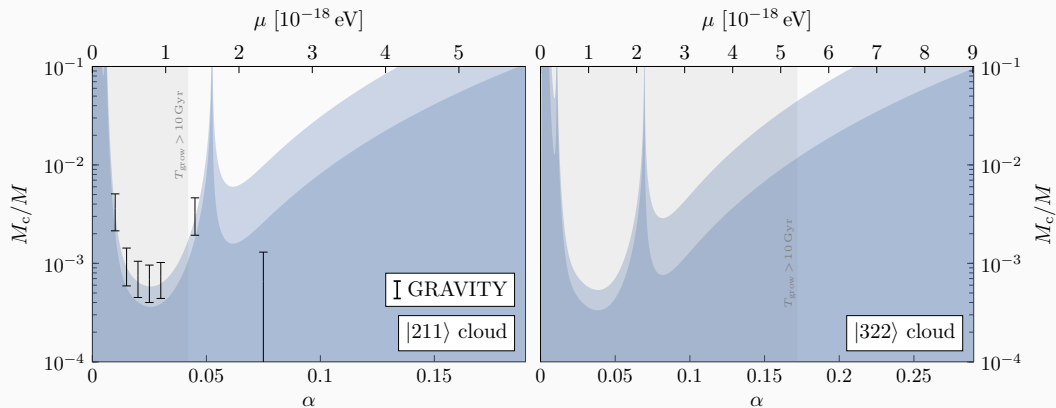
BOUNDS ON PLUMMER AND POWER-LAW PROFILES

Most of the (single-star) constraining power comes from the per-orbit precession, e.g.:



BOUNDS ON SUPERRADIANT CLOUD'S MASS

Assuming equatorial orbit:



CLOUD'S POTENTIAL AND PRECESSION

$$V_c = \underbrace{-\frac{M_c}{r} \left(1 - e^{-r/r_c} \left(1 + \frac{3r}{4r_c} + \frac{r^2}{4r_c^2} + \frac{r^3}{24r_c^3} \right) \right)}_{\text{monopole}} + \underbrace{+ 3 \frac{M_c r_c^2}{r^3} (3 \cos^2 \theta - 1) \left(1 - e^{-r/r_c} \left(1 + \frac{r}{r_c} + \frac{r^2}{2r_c^2} + \frac{r^3}{6r_c^3} + \frac{r^4}{24r_c^4} + \frac{r^5}{144r_c^5} \right) \right)}_{\text{quadrupole}}$$

- **Inside** the cloud: **retrograde** precession.
- **Outside** the cloud: **prograde** precession.

DYNAMICAL FRICTION: BOUNDS WITHOUT PRECISE ASTRONOMY?

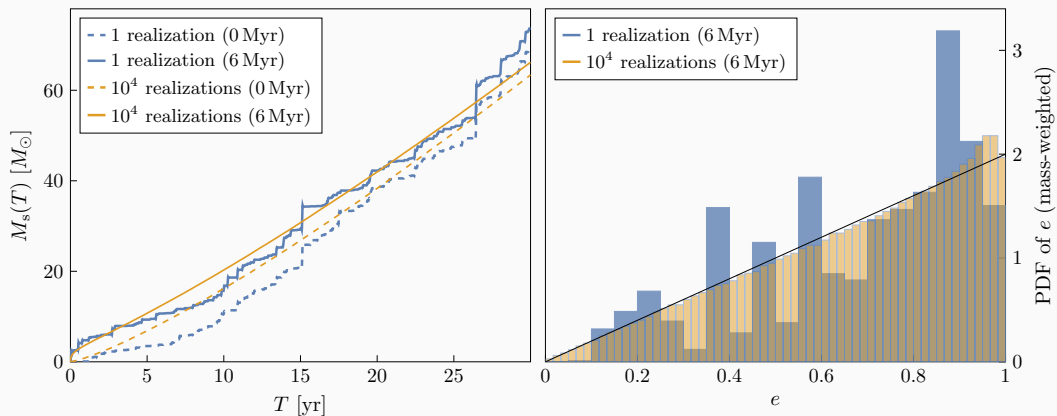
Decay of stellar orbits under dynamical friction:

$$T_{\text{DF}} \sim \frac{1-e}{6} \frac{M}{M_c} \frac{M}{M_*} T \sim \frac{0.01}{M_c/M} \times 10 \text{ Myr}$$

A star plunging into the cloud would “quickly” decay into the BH.

Can we place bounds without precise astrometry?

DYNAMICAL FRICTION: THE CLUSTER REPLENISHES



[GMT, Caputo, '25]

SUMMARY

EMRIs

- Smooth evolution due to **ionization** + **resonances** (infinity + horizon)
- Need a clever/careful way to integrate the binary evolution

Sgr A*

- Bounds from S2 precession
- Stars **decay**! But cluster gets replenished. Other ideas?

Thank you!

Backup

BOUNDS ON SUPERRADIANT VECTOR CLOUD'S MASS

