Title: Superradiant clouds and black hole binaries

Speakers:

Series: Strong Gravity

Date: December 13, 2023 - 3:30 PM

URL: https://pirsa.org/23120055

Abstract: Superradiant instabilities may create clouds of ultralight bosons around rotating black holes, forming so-called "gravitational atoms". The presence of a binary companion can induce transitions between bound states of the cloud ("resonances"), as well as from bound to unbound states ("ionization"). These processes backreact on the binary dynamics and leave characteristic imprints on the emitted GWs, carrying direct information about the mass of the boson and the state of the cloud. Even though some of the resonances can destroy the cloud before the system becomes observable in GWs, their backreaction forces the binary inclination towards attractors, opening up the possibility to infer the existence of the boson from a statistical analysis of a population of binary black holes. We also discuss implications for eccentric orbits and merger rates

Gravitational atoms and black hole binaries

Giovanni Maria Tomaselli

Universiteit van Amsterdam

Perimeter Institute

December 13, 2023

Earlier works by: D. Baumann, J. Stout, H.S. Chia, R. Porto

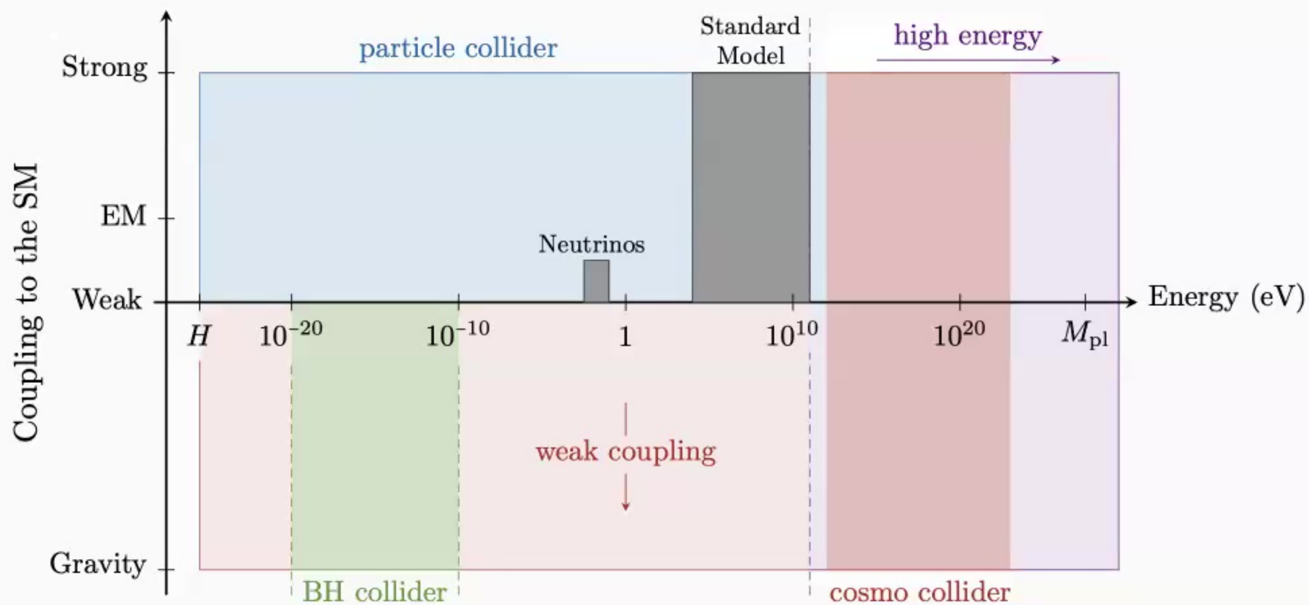
- "Probing Ultralight Bosons with Binary Black Holes", arXiv:1804.03208 PRD
- "Gravitational Collider Physics", arXiv:1912.04932, PRD

My works:

- "Ionization of Gravitational Atoms", arXiv:2112.14777, PRD
- "Sharp Signals of Boson Clouds in Black Hole Binary Inspirals", arXiv:2206.01212, PRL
- "Dynamical Friction in Gravitational Atoms", arXiv:2305.15460, JCAP
- "Resonant history of gravitational atoms in black hole binaries", **upcoming**

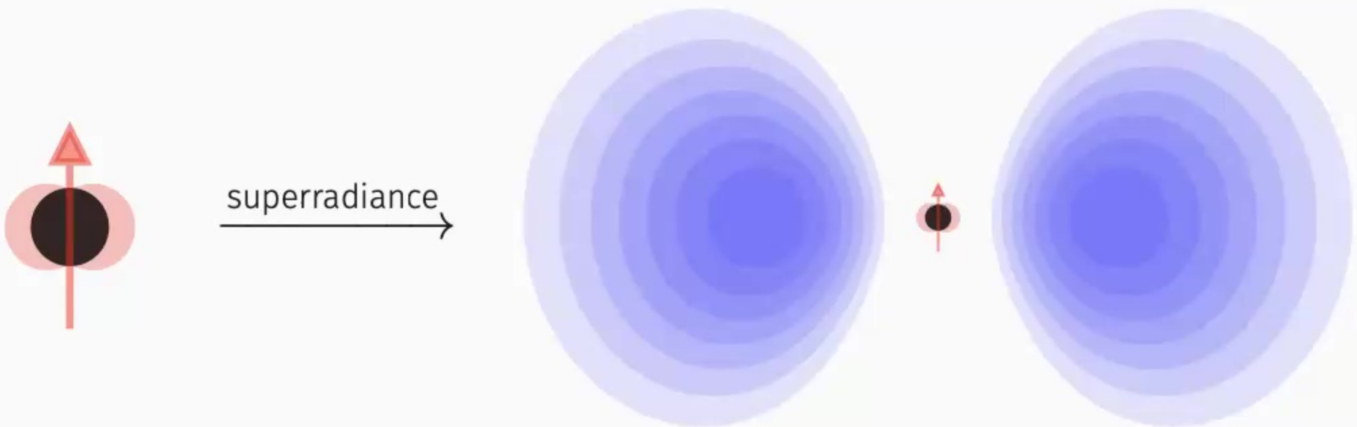
Collaborators: D. Baumann, G. Bertone, J. Stout, T. Spieksma

Motivation



Gravitational waves as probes of weakly-coupled new physics

The Gravitational Atom



$$(\Box - \mu^2)\Phi = 0 \quad \longrightarrow \quad i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \dots\right)\psi$$

Gravitational fine structure constant: $\alpha = \mu M \sim \mathcal{O}(0.1)$.

[Zeldovich '72; Starobinsky '73; Dolan '07; Arvanitaki et al. '09]

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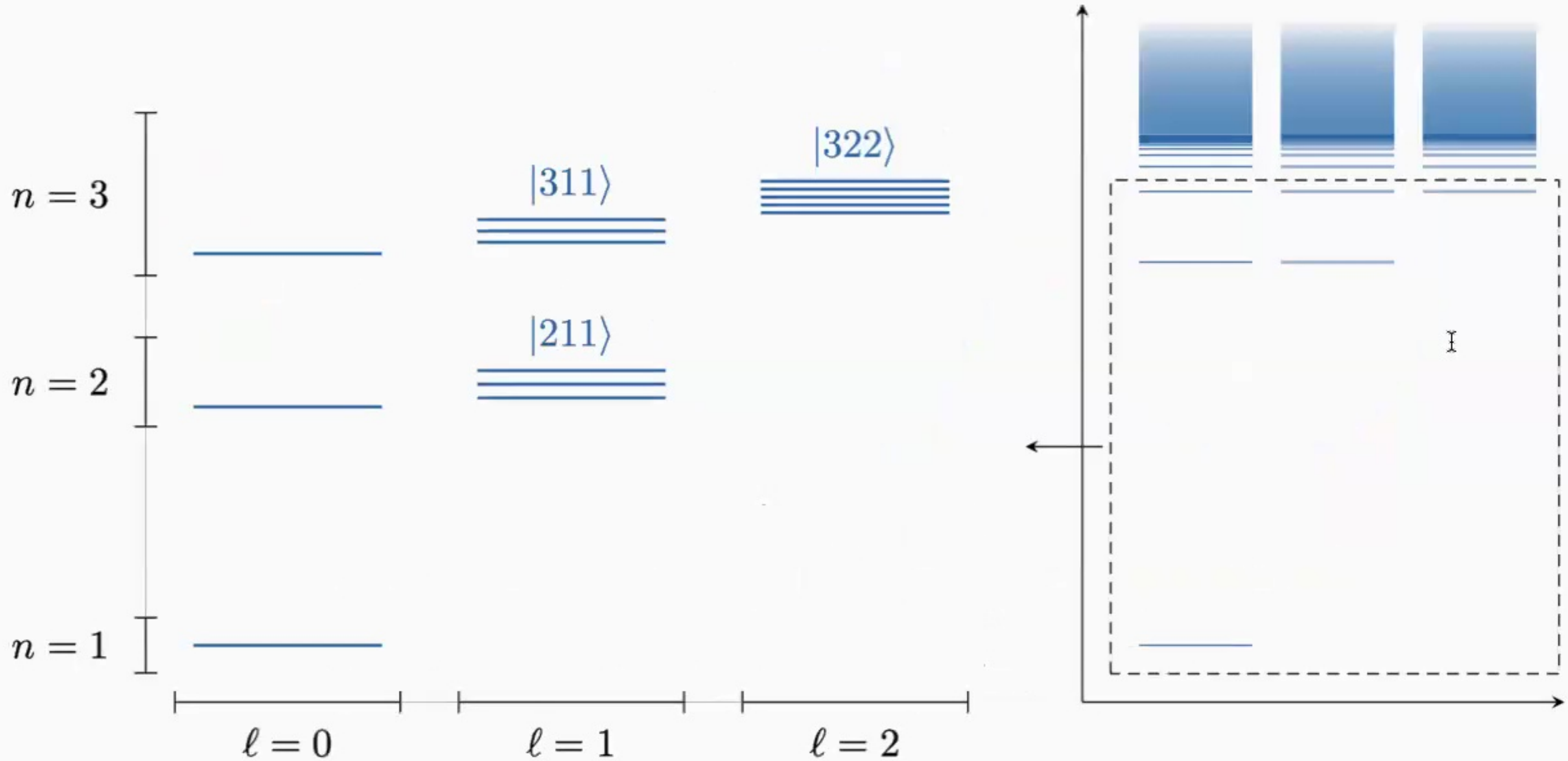
The spectrum



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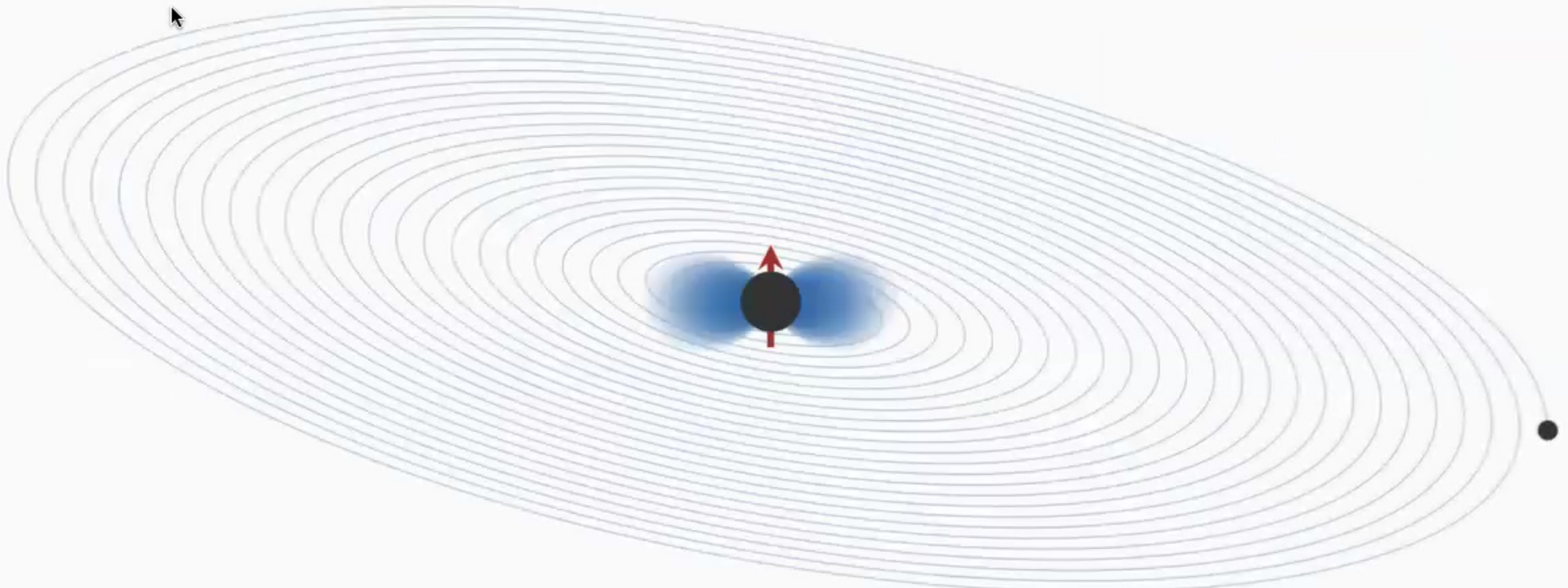
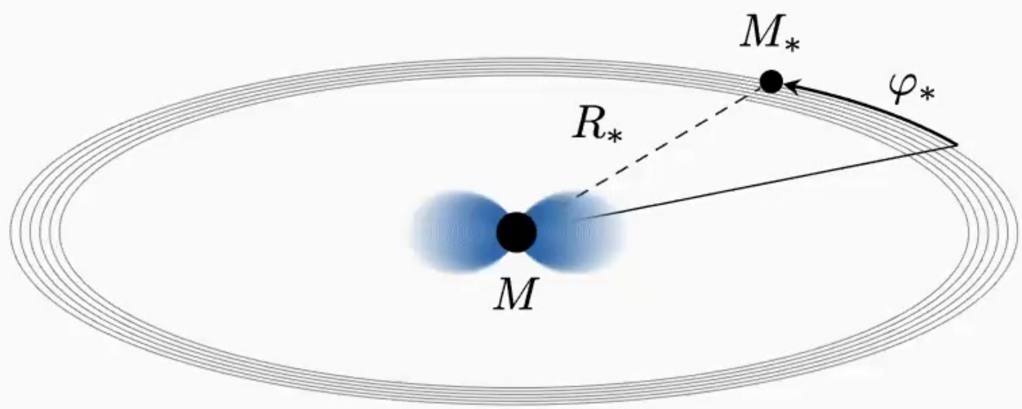
How does a cloud affect a **binary inspiral**?



The binary can induce transitions between bound states ("Rabi oscillations") and excite unbound states ("photoelectric effect")...

Perturbation with slowly increasing frequency:



$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \underbrace{V_*(R_*, \varphi_*)}_{\text{perturbation}}\right)\psi$$

Level mixing:

$$\langle a|\, V_*(t)\,|b\rangle = \sum_g \eta^{(g)}\, e^{-ig\Omega t}$$

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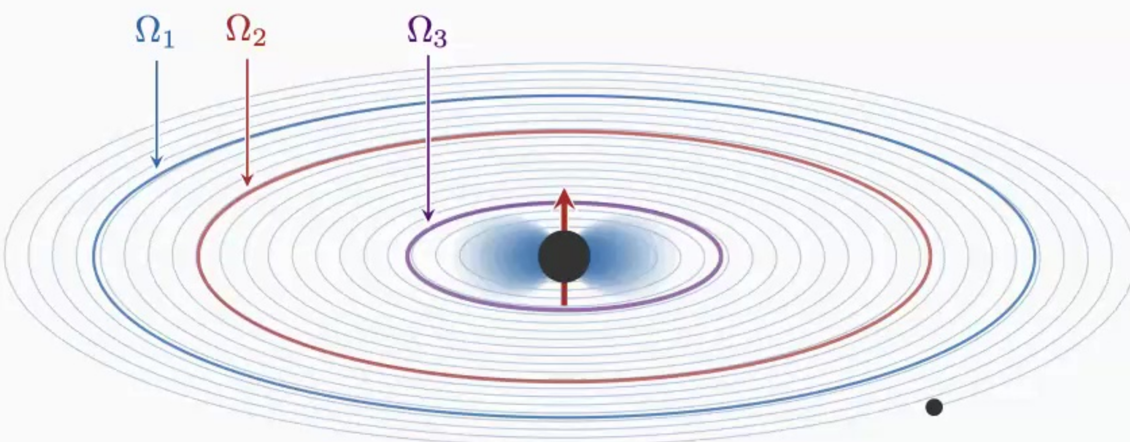
At specific frequencies, the perturbation is **resonantly enhanced**:



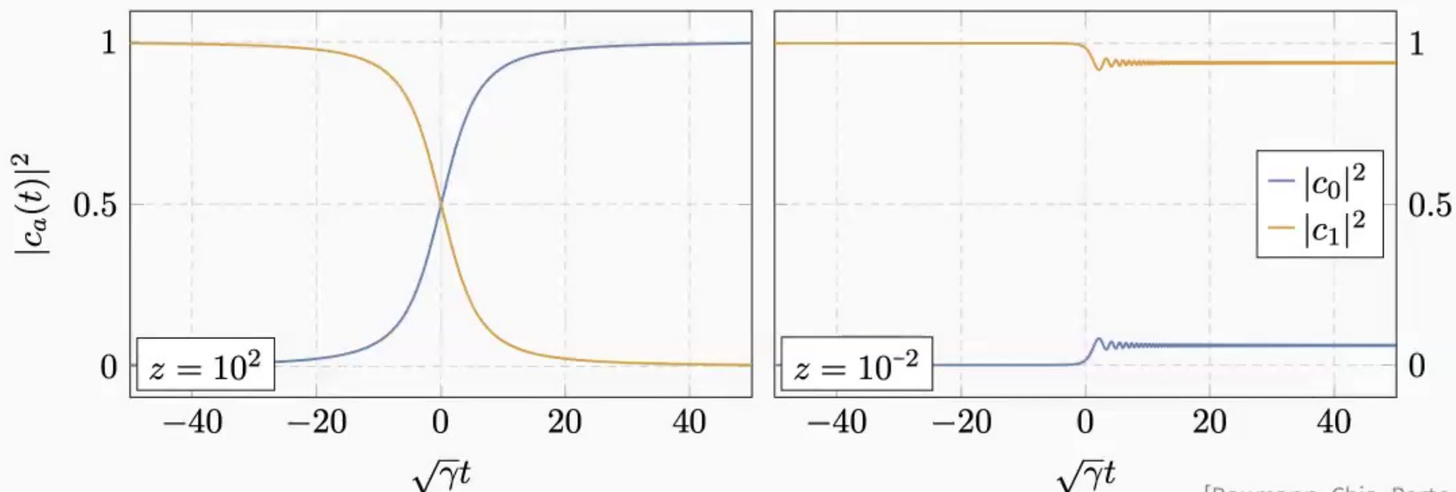
$$\Omega_r = \left|\frac{\Delta E}{\Delta m}\right| \sim 10\,\text{mHz}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3$$

[Baumann, Chia, Porto, Stout '18]

Landau-Zener transitions

$$\mathcal{H} = \begin{pmatrix} -\frac{1}{2}\Delta E & \eta^{i\varphi_*(t)} \\ \eta^{i\varphi_*(t)} & \frac{1}{2}\Delta E \end{pmatrix} \quad \longrightarrow \quad \mathcal{H}_D = \begin{pmatrix} (\Omega(t) - \Delta E)/2 & \eta \\ \eta & -(\Omega(t) - \Delta E)/2 \end{pmatrix}$$

Landau-Zener transitions with parameter $z \equiv \eta^2/\dot{\Omega}$.



[Baumann, Chia, Porto, Stout '19]

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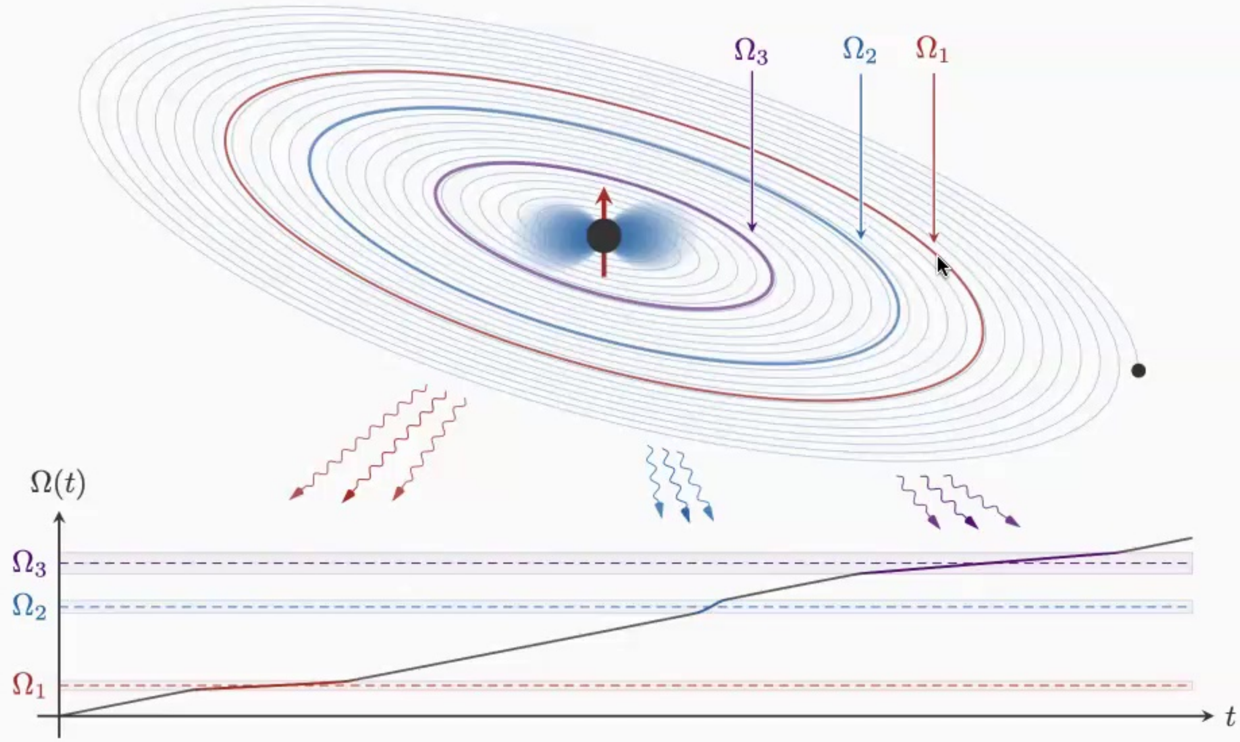
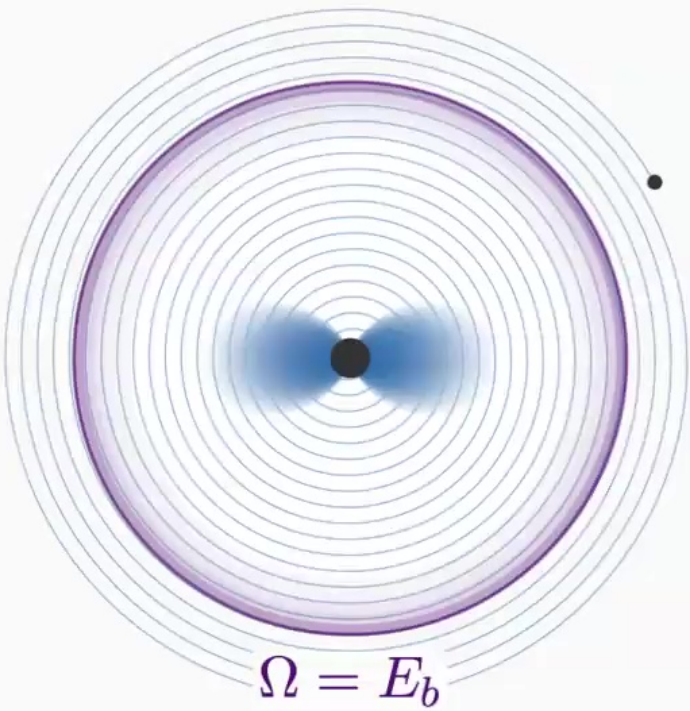
BACKREACTION ON THE ORBIT (RESONANCES)

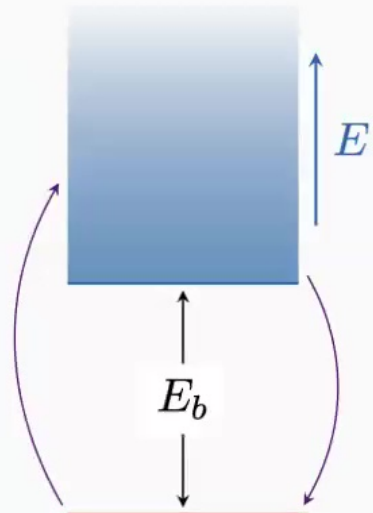


[Baumann, Chia, Porto, Stout '19]

IONIZATION

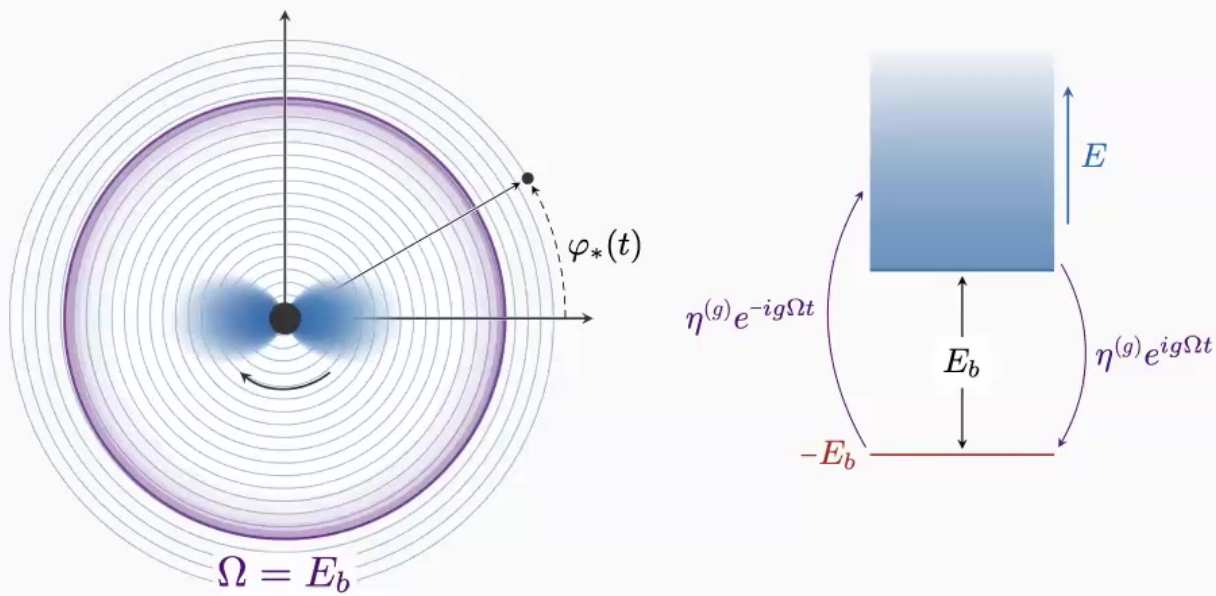
Orbital frequency above **threshold** to excite **transitions to unbound states**





[Baumann, Bertone, Stout, GMT, '21]

Fermi's Golden Rule

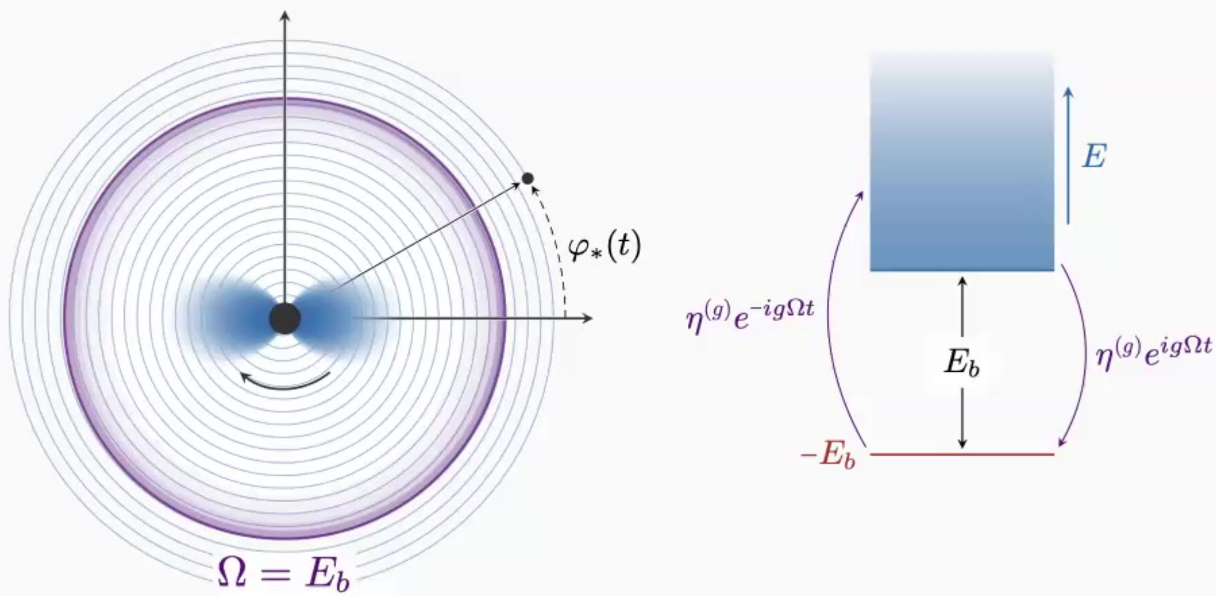


The transition rate (per unit energy) is given by Fermi's Golden Rule:

$$\mathrm{d}\Gamma = \mathrm{d}E \underbrace{|\eta^{(g)}|^2}_{\text{Level mixing}} \delta(\underbrace{E - E_b - g\Omega}_{E - E_*^{(m)}})$$

[Baumann, Bertone, Stout, GMT, '21]

Ionization Power

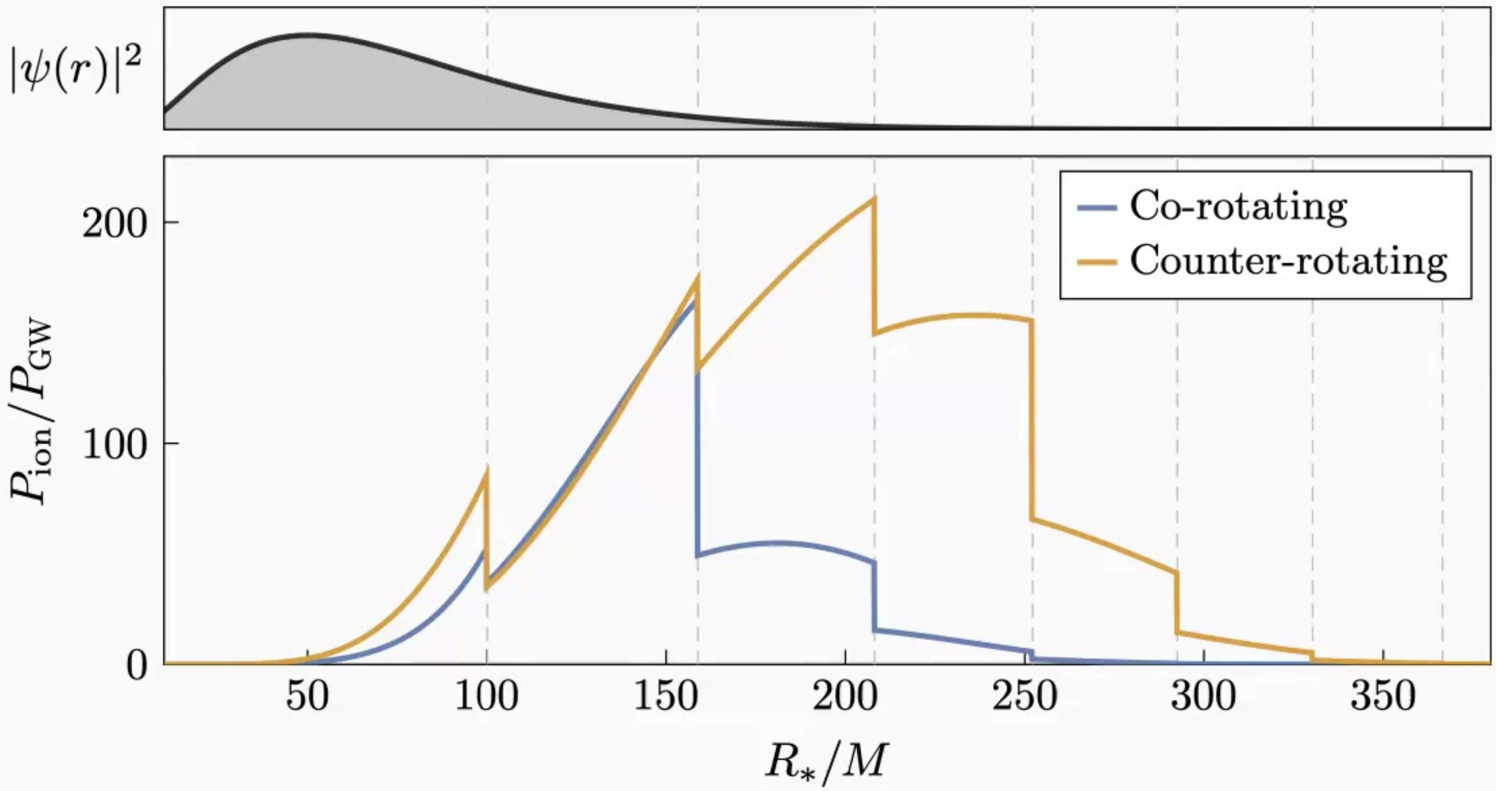


Summing over all bound states gives the total **ionization power**:

$$P_{\text{ion}} = \frac{M_c}{\mu} \sum_{\ell,m} g\Omega \, |\eta^{(g)}|^2 \, \Theta(E_*^{(m)})$$

[Baumann, Bertone, Stout, GMT, '21]

Ionization plot

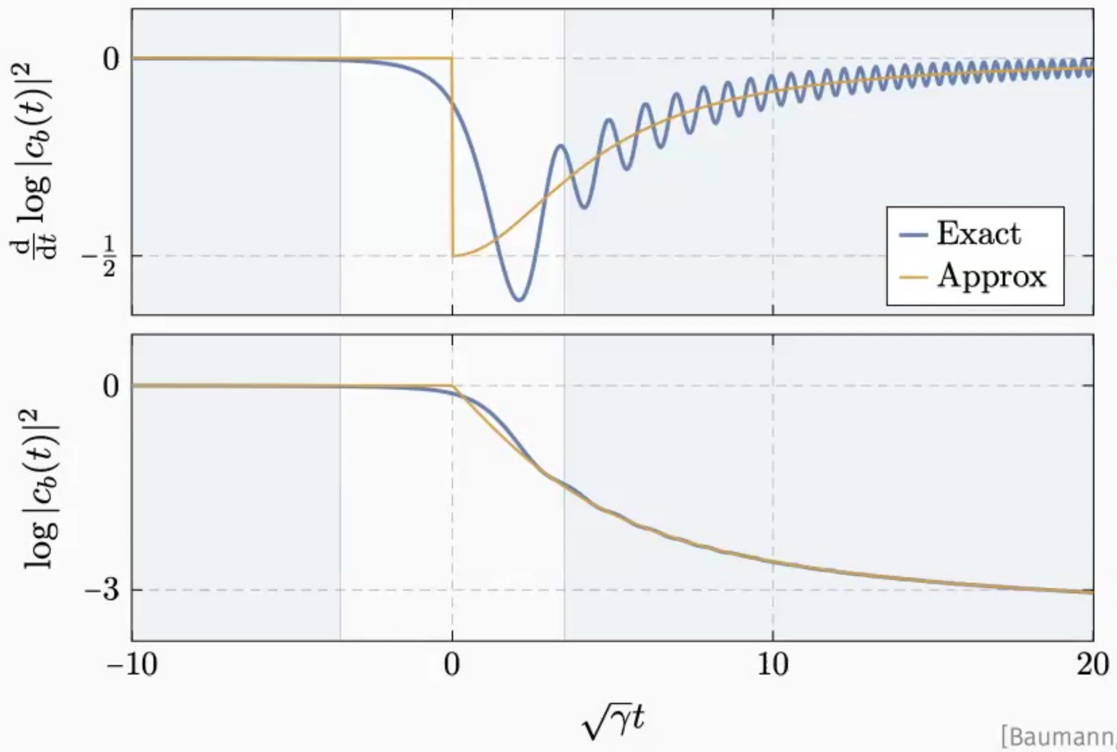


[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.01$, $q = 10^{-3}$]

[Baumann, Bertone, Stout, GMT, '21]

Discontinuities?

When $\Omega(t) \approx \Omega_0 + \gamma t$ "hits" the continuum, the deoccupation starts.



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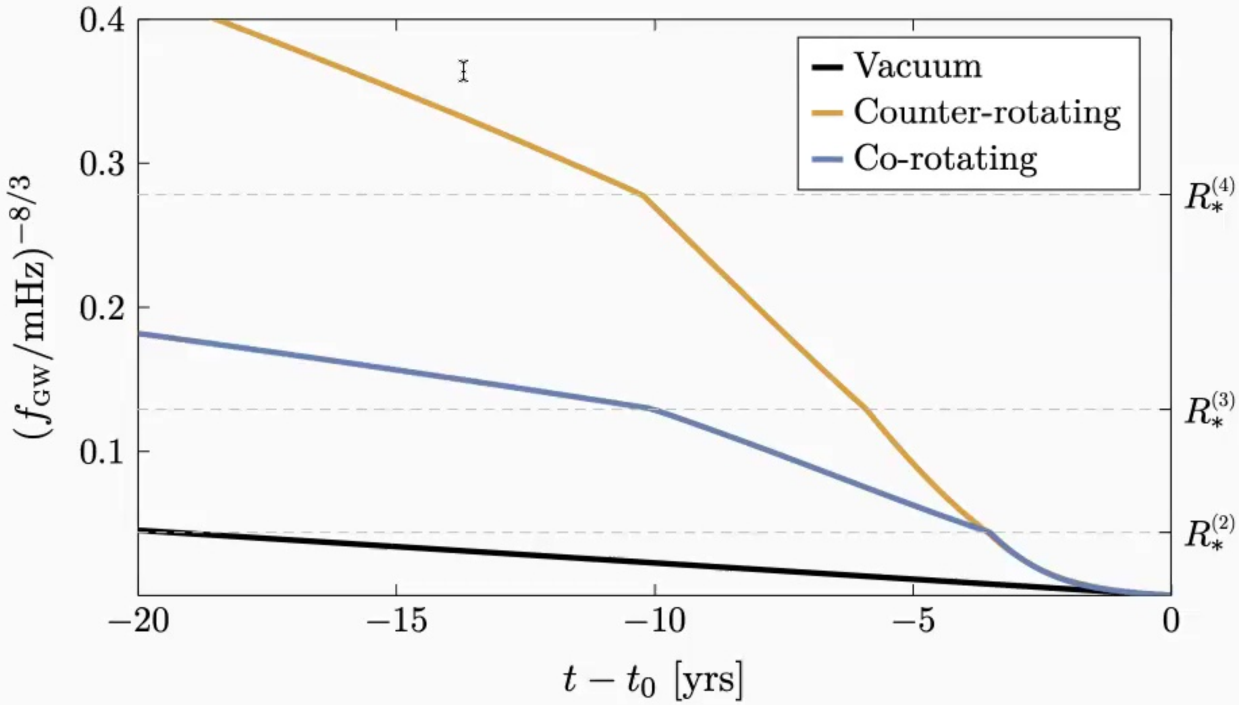
[Baumann, Bertone, Stout, GMT, '21]

Frequency evolution

Kinks in the frequency evolution: **signature** of the cloud!

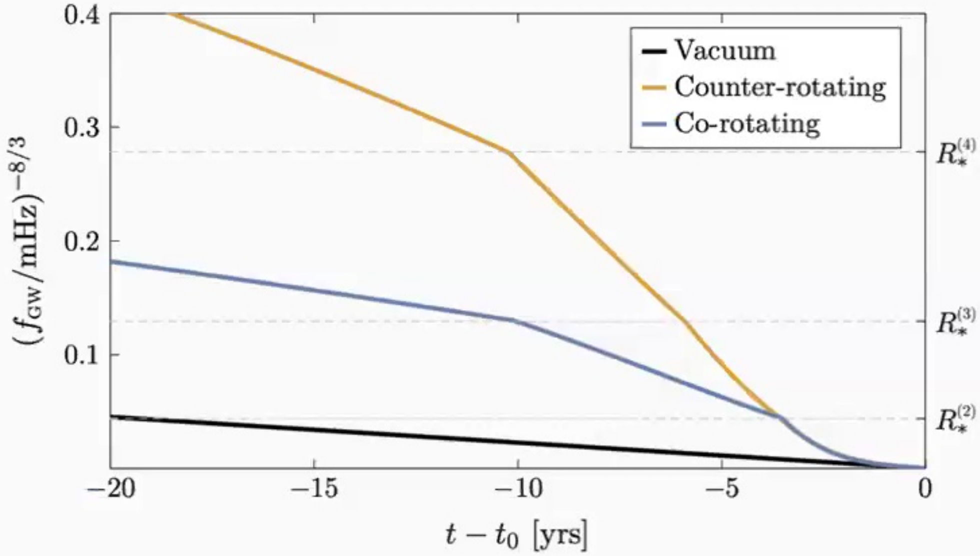


$[M = 10^4 M_\odot$, $|211\rangle$, initial: $R_* = 400M$, $M_*/M = 10^{-3}$, $M_c/M = 10^{-2}]$

[Baumann, Bertone, Stout, GMT, '22]

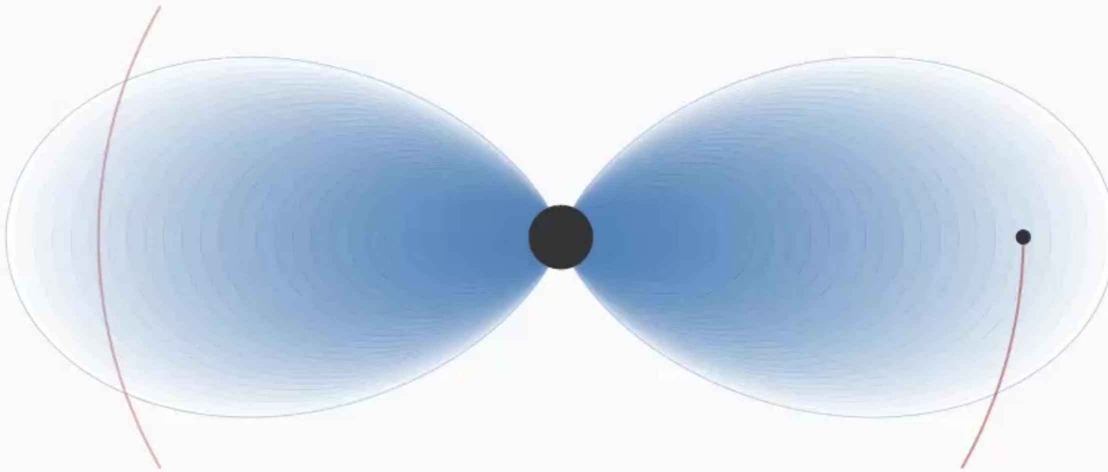
Kinks in the frequency

Kinks in the frequency evolution: **signature** of the cloud!



$$f_{\rm GW}^{(g)} = \frac{6.45\,\text{mHz}}{g}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{2}{n}\right)^2$$

[Baumann, Bertone, Stout, GMT, '22]

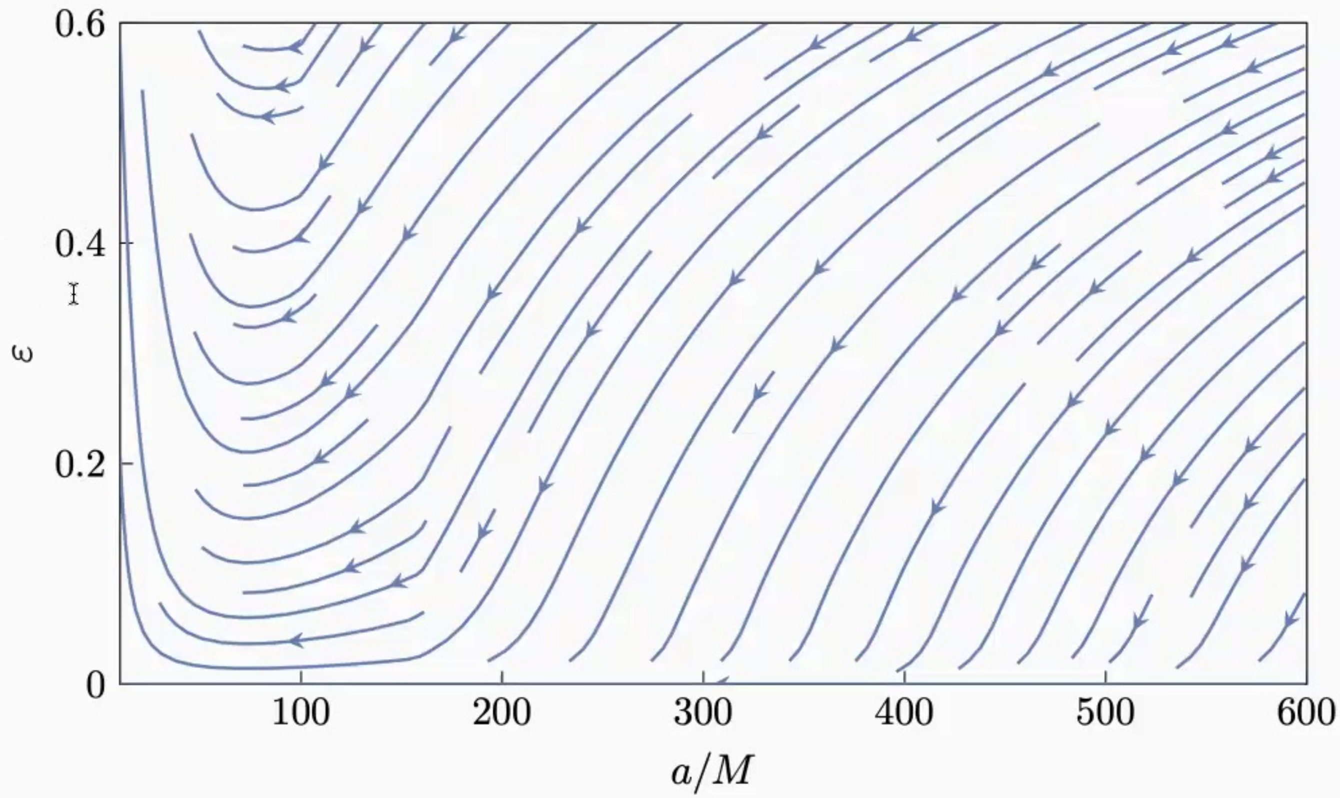


Ionization or **dynamical friction**?

$$P_{\mathrm{DF}} = \frac{4\pi M_*^2 \rho}{v} \log(v \mu b_{\mathrm{max}})$$

[GMT, Bertone, Spieksma '23]

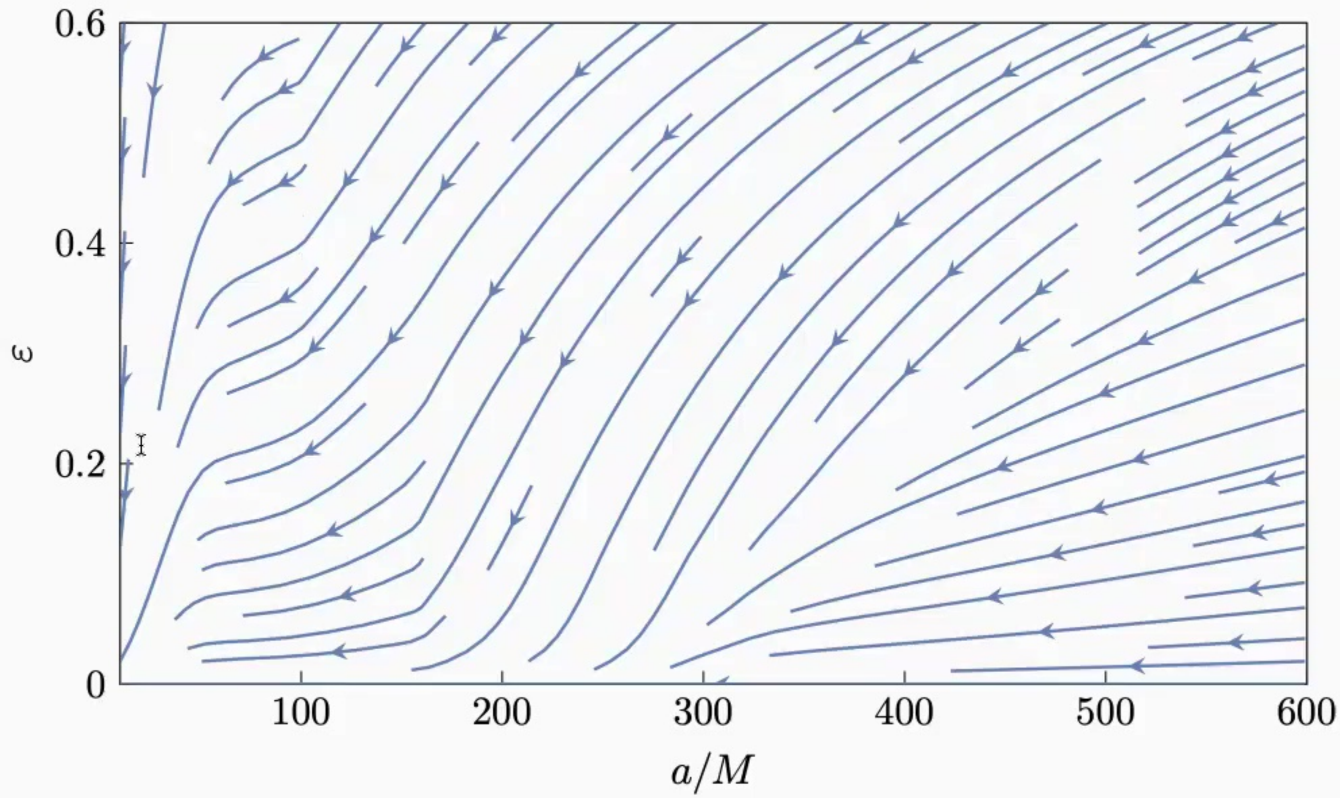
Evolution of eccentricity (no GWs)



[$|211\rangle$, $\alpha = 0.2$, $q = 10^{-3}$, equatorial co-rotating]

[GMT, Bertone, Spieksma '23]

Evolution of eccentricity



[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.01$, $q = 10^{-3}$, equatorial co-rotating]

[GMT, Bertone, Spieksma '23]

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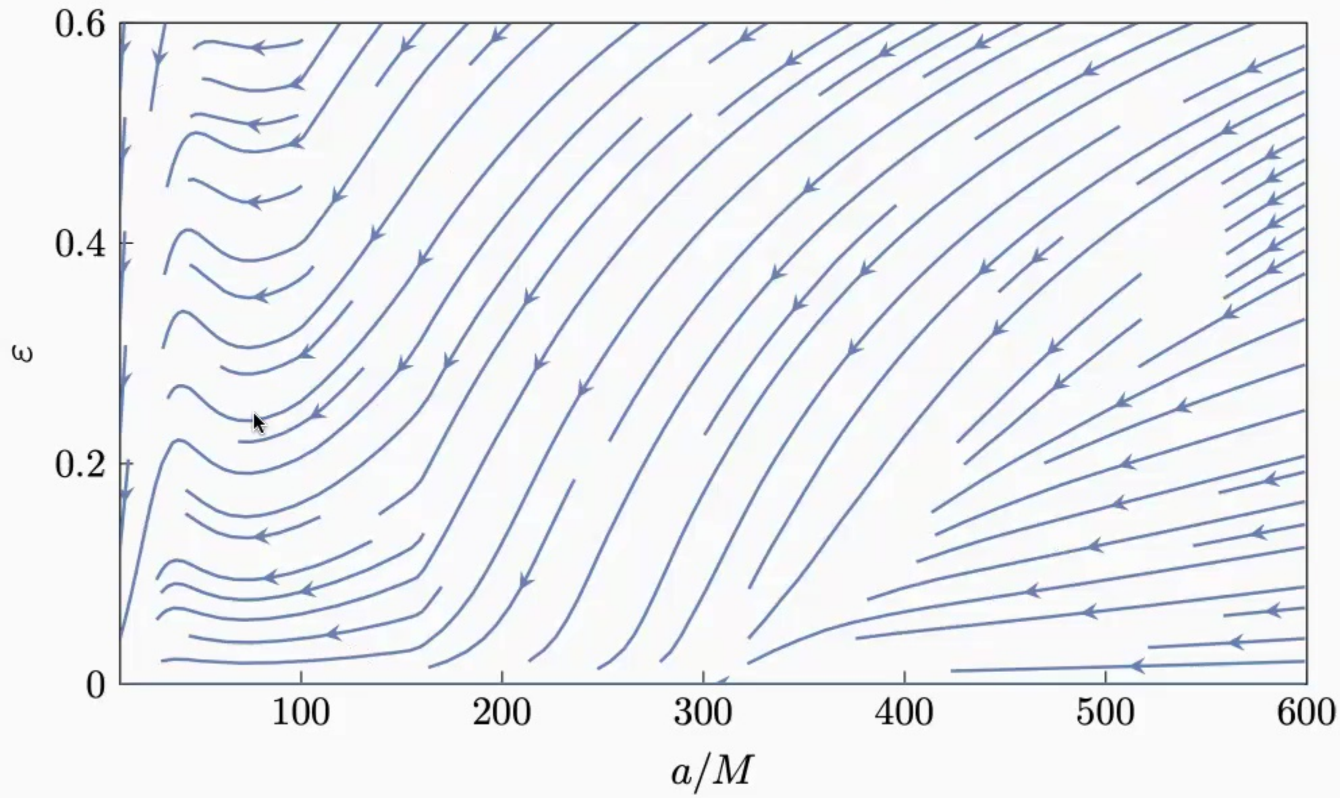
Evolution of eccentricity (higher mass)



[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.1$, $q = 10^{-3}$, equatorial co-rotating]

[GMT, Bertone, Spieksma '23]

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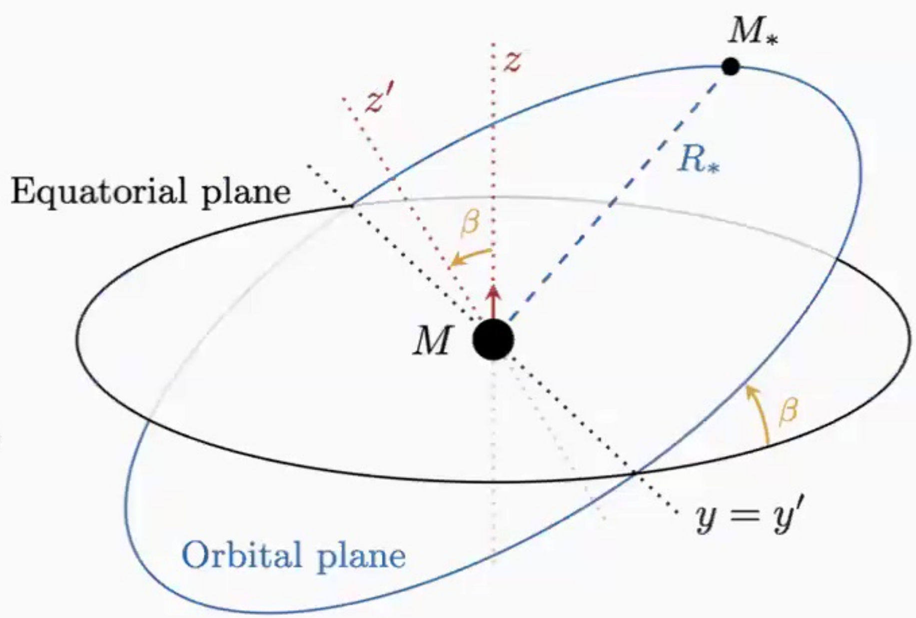
Ionization on inclined orbits

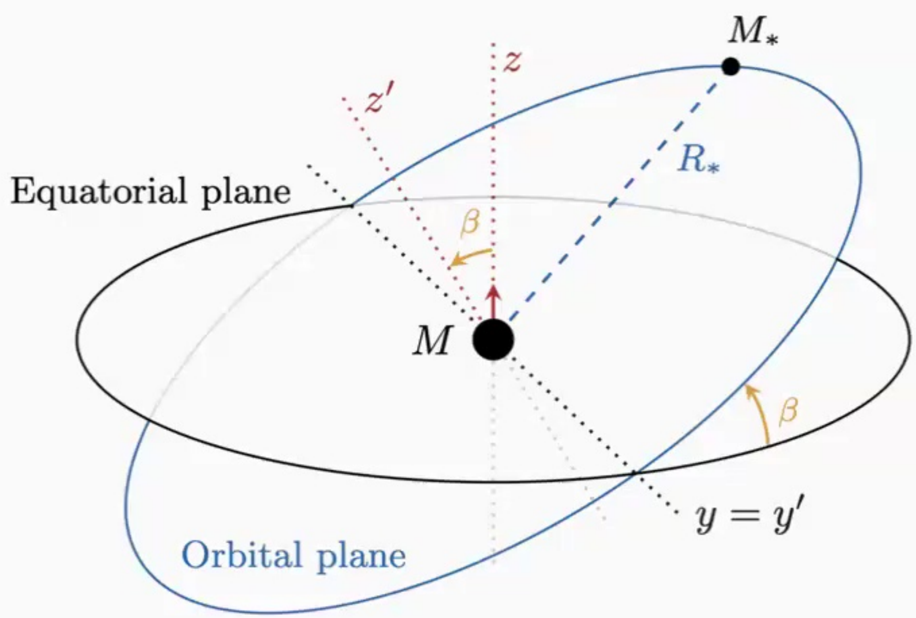


Precession? Evolution of β?

[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.1$, $q = 10^{-3}$, equatorial co-rotating]

[GMT, Bertone, Spieksma '23]

Ionization on inclined orbits

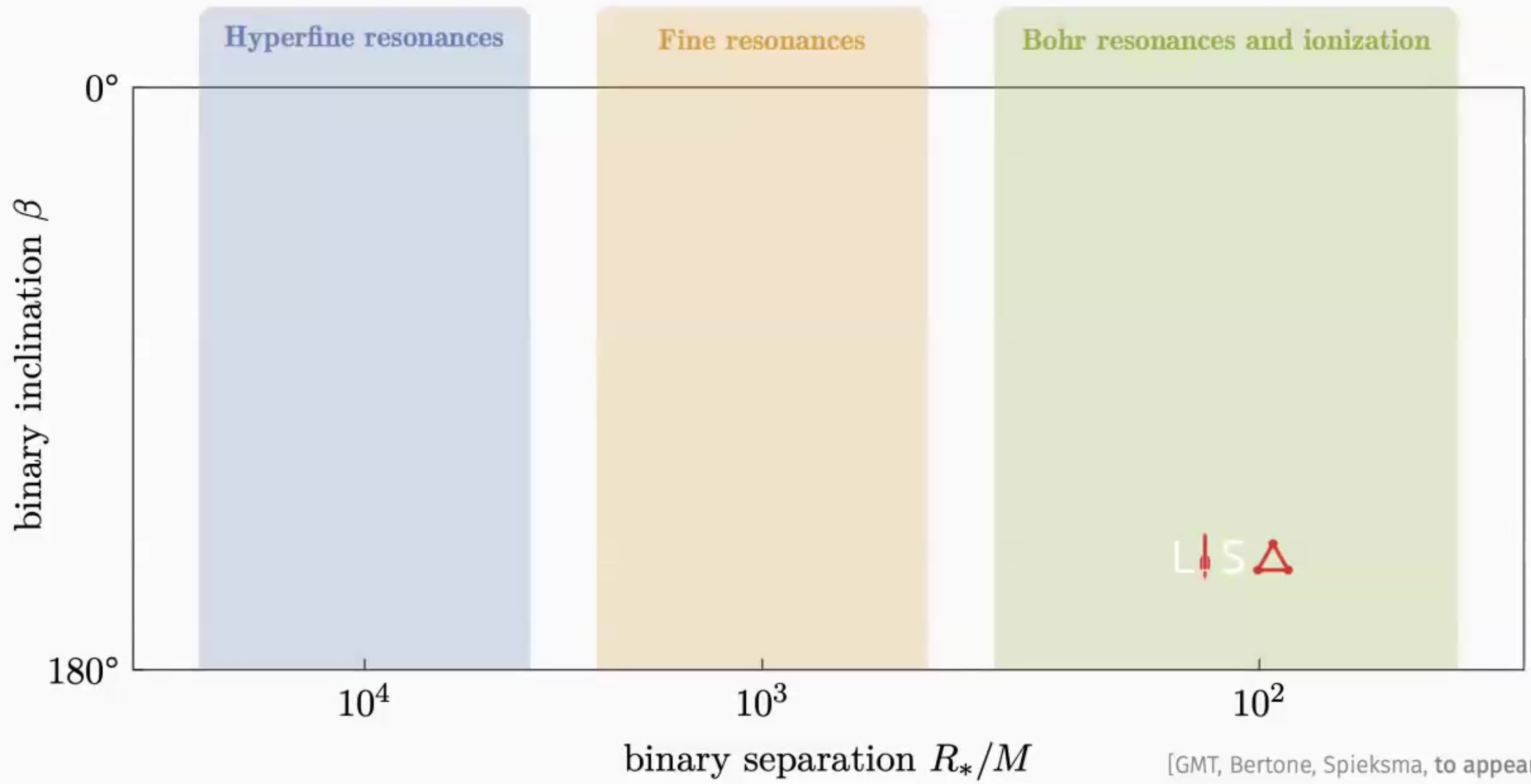


Precession? **No.** Evolution of β? **Yes (mild).**

[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.1$, $q = 10^{-3}$, equatorial co-rotating]

[GMT, Bertone, Spieksma '23]

Resonant history



[GMT, Bertone, Spieksma, to appear]

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Realistic cloud-binary configuration

Crucial to study early (**hyperfine**) resonances, like $|211\rangle \to |210\rangle$:

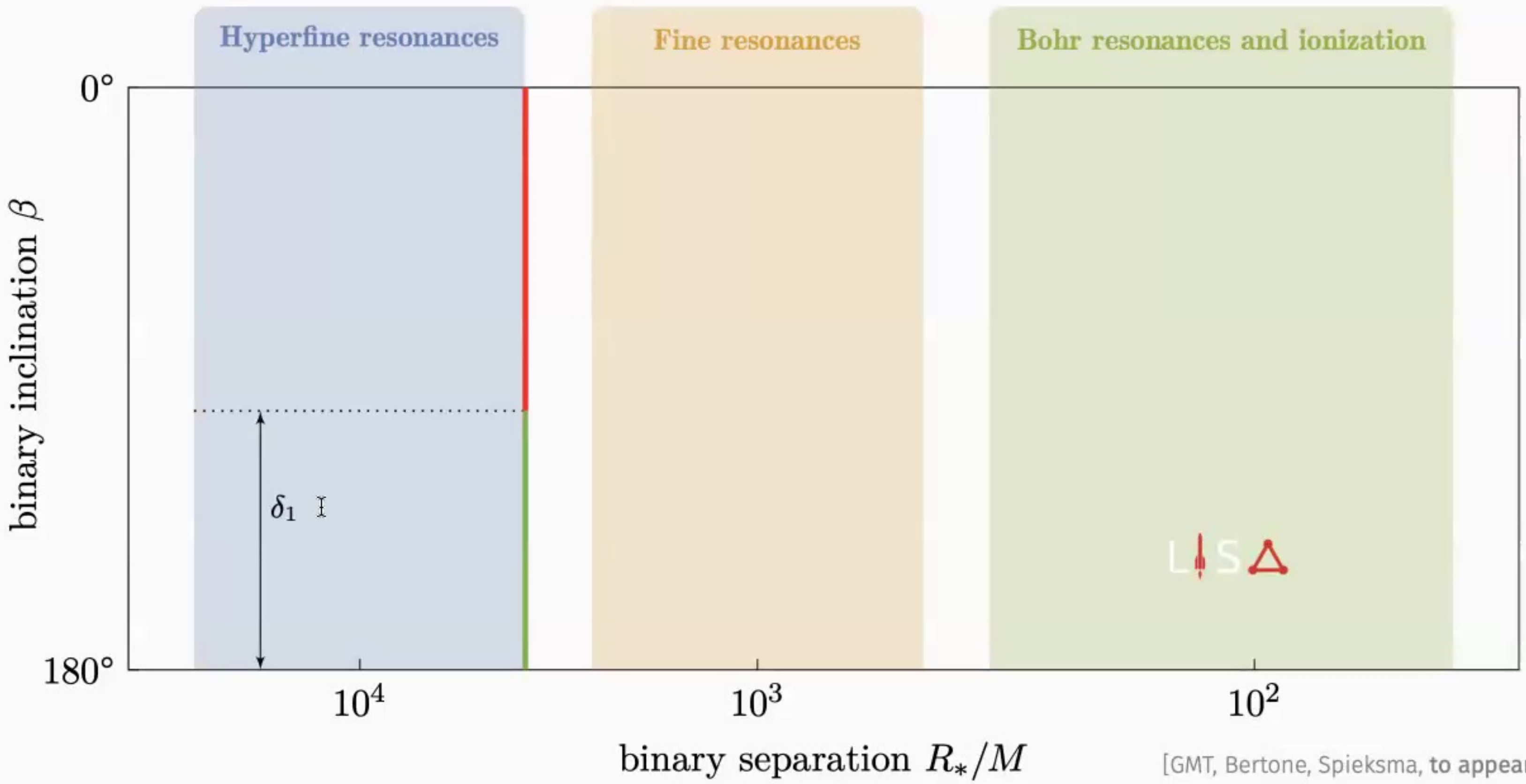
- they are all **floating**, towards **decaying** states
- $T_{\rm float} \gg T_{\rm decay}$
- strong on co-rotating ($\beta = 0°$)
- vanishing on counter-rotating ($\beta = 180°$)

$\Longrightarrow$ angular interval $180° - \delta_1 < \beta < 180°$
where the resonance is weak and the **cloud survives**

$\Omega(t)$ highly nonlinear $\Longrightarrow$ more complicated than just $z \ll 1$

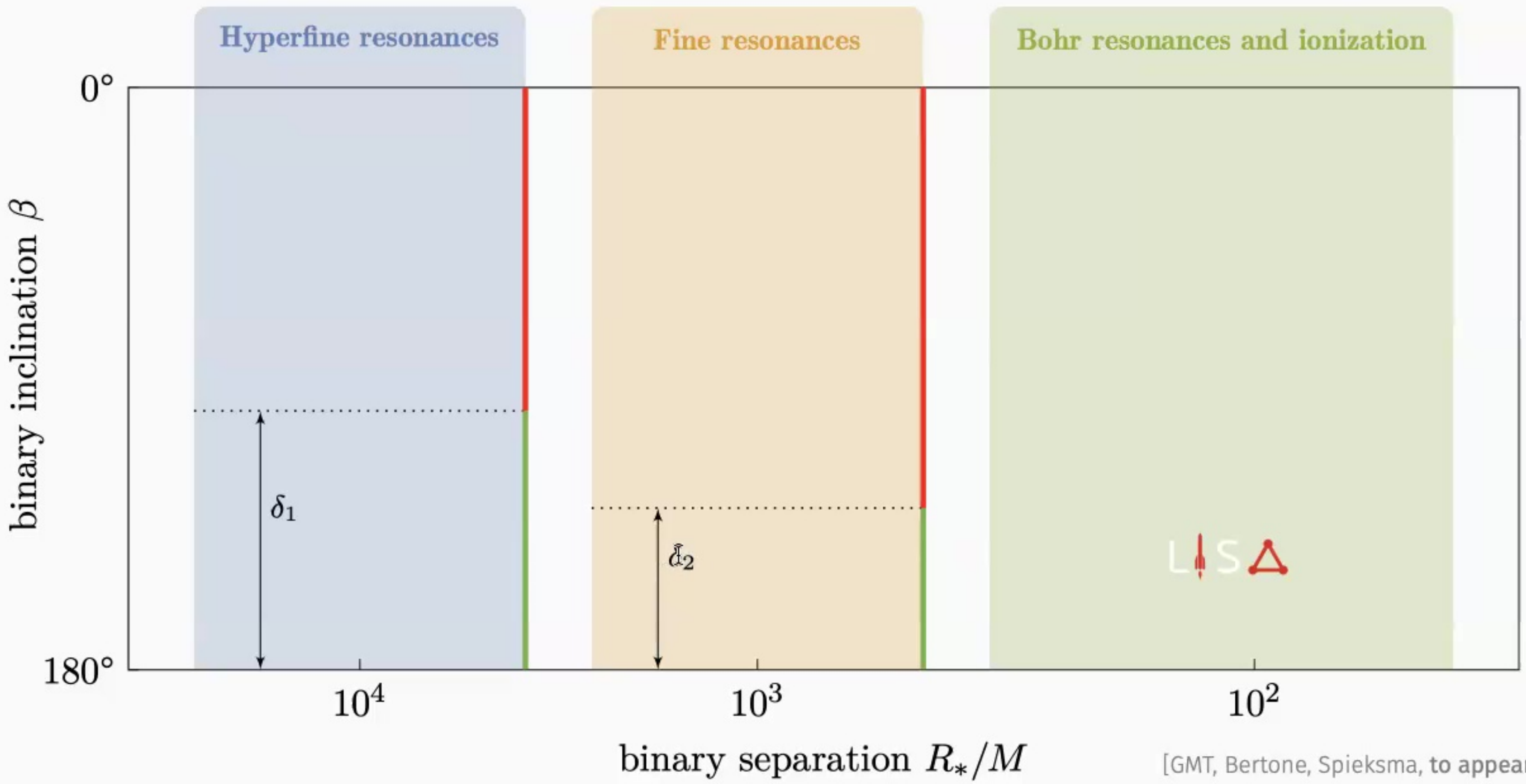
[GMT, Bertone, Spieksma, **to appear**]

Resonant history



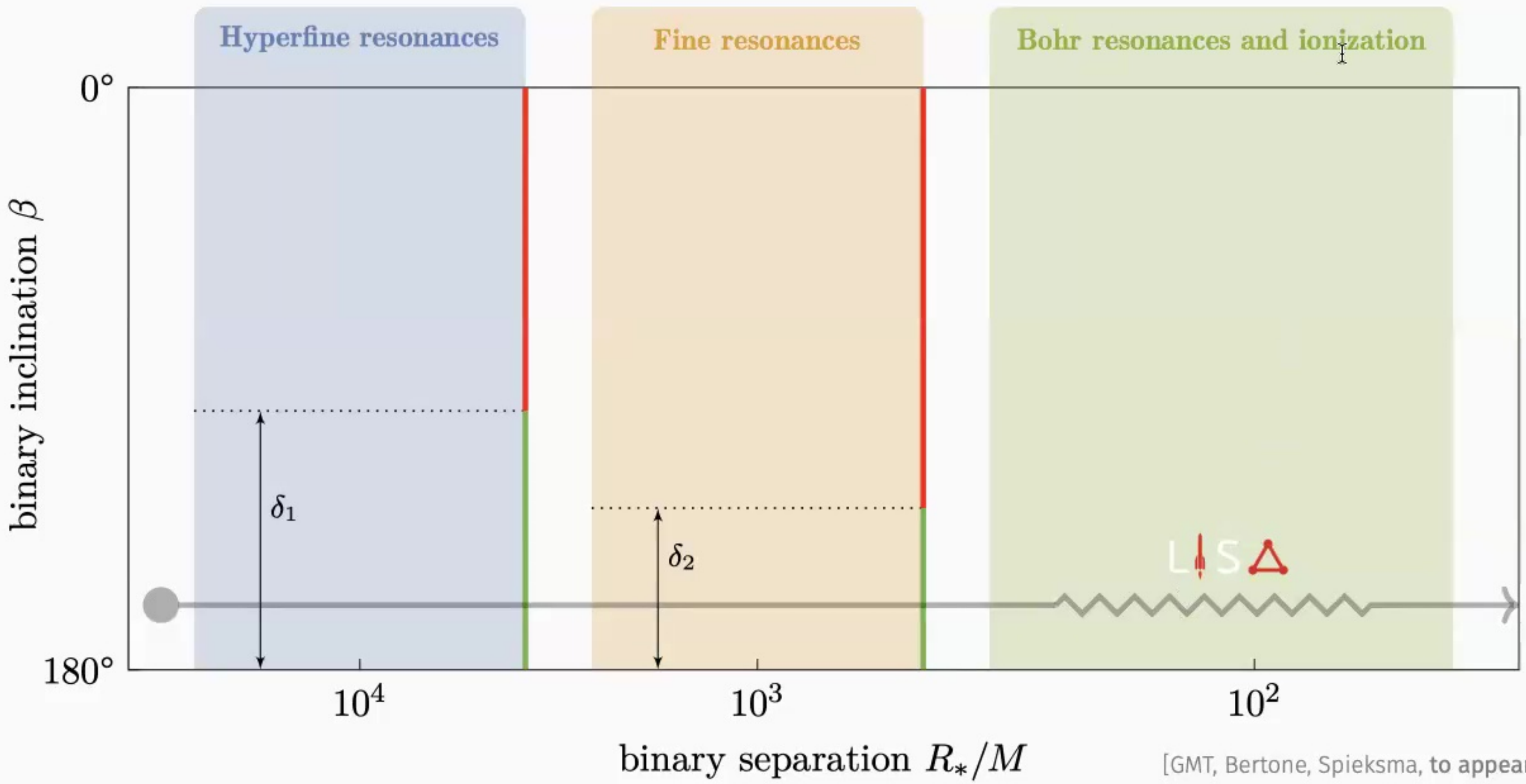
[GMT, Bertone, Spieksma, **to appear**]

Resonant history



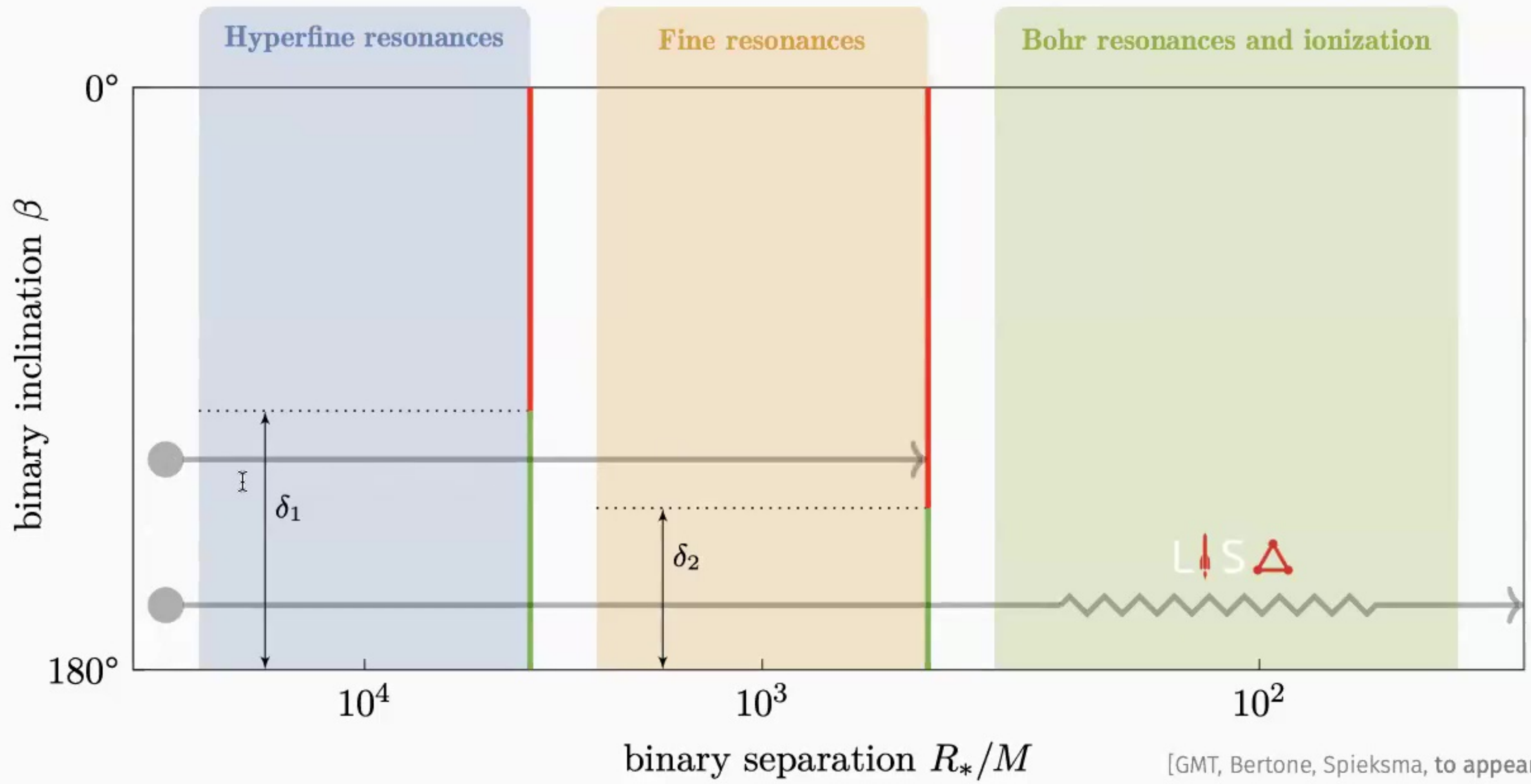
[GMT, Bertone, Spieksma, **to appear**]

Resonant history



[GMT, Bertone, Spieksma, to appear]

Resonant history



[GMT, Bertone, Spieksma, to appear]

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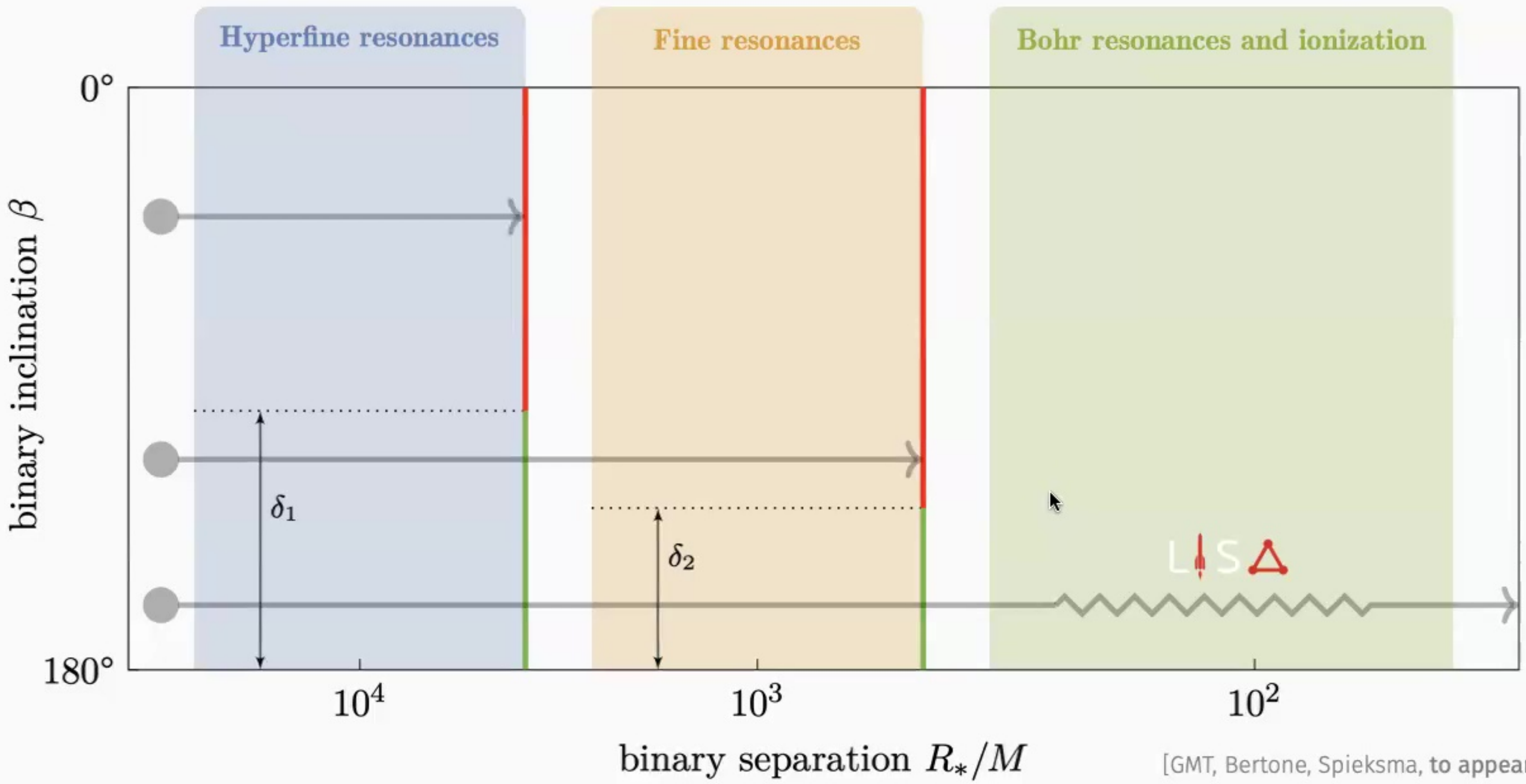
Resonant history



[GMT, Bertone, Spieksma, to appear]

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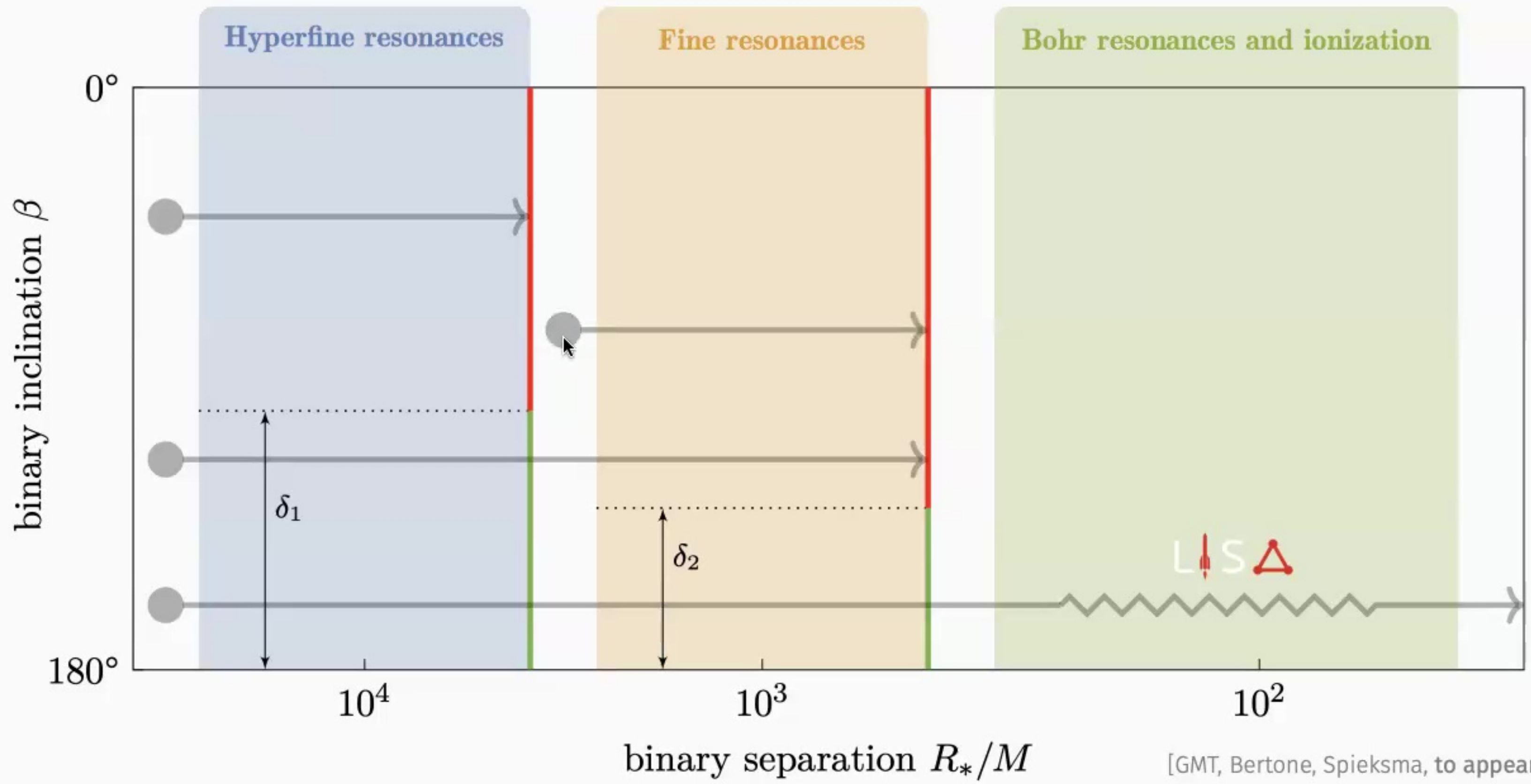
Resonant history



[GMT, Bertone, Spieksma, **to appear**]

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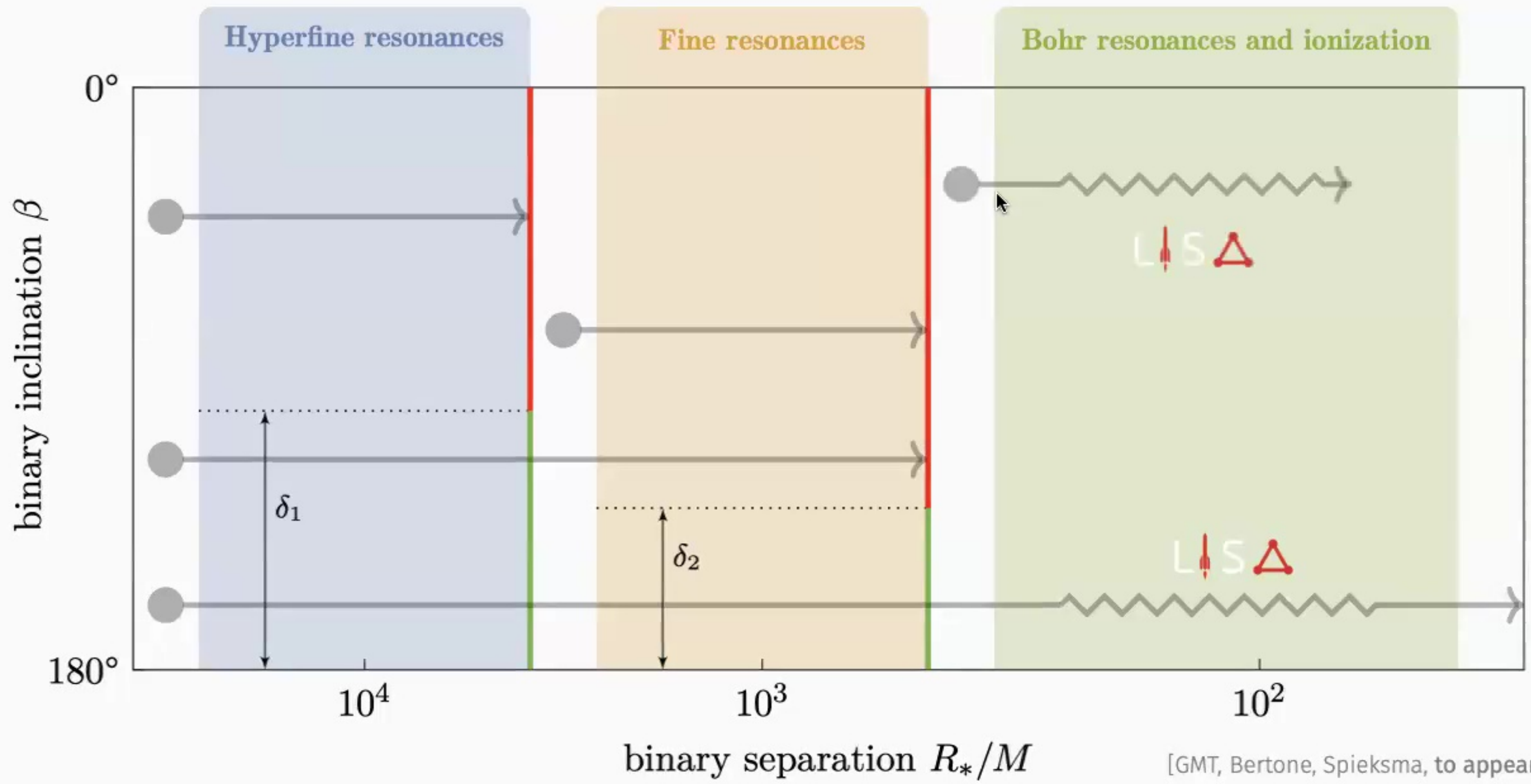
Resonant history



[GMT, Bertone, Spieksma, to appear]

Observables

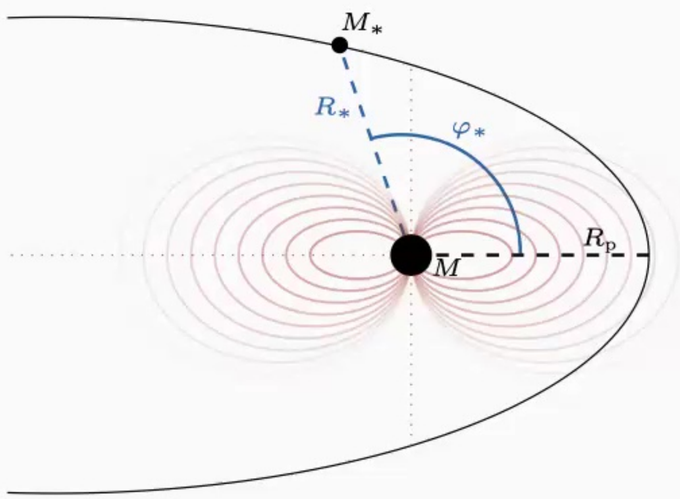
The cloud survives for $\beta \approx 180°$:

- Observe **Ionization** and many (Bohr) **sinking resonances**

The cloud is destroyed $\beta < 180°$:

- The resonance changes the binary parameters
- Observe nearly **circular** and **co-rotating** inspiral
- Can infer the existence of the boson from a **statistical analysis** of a population of BBHs

Dynamical Capture



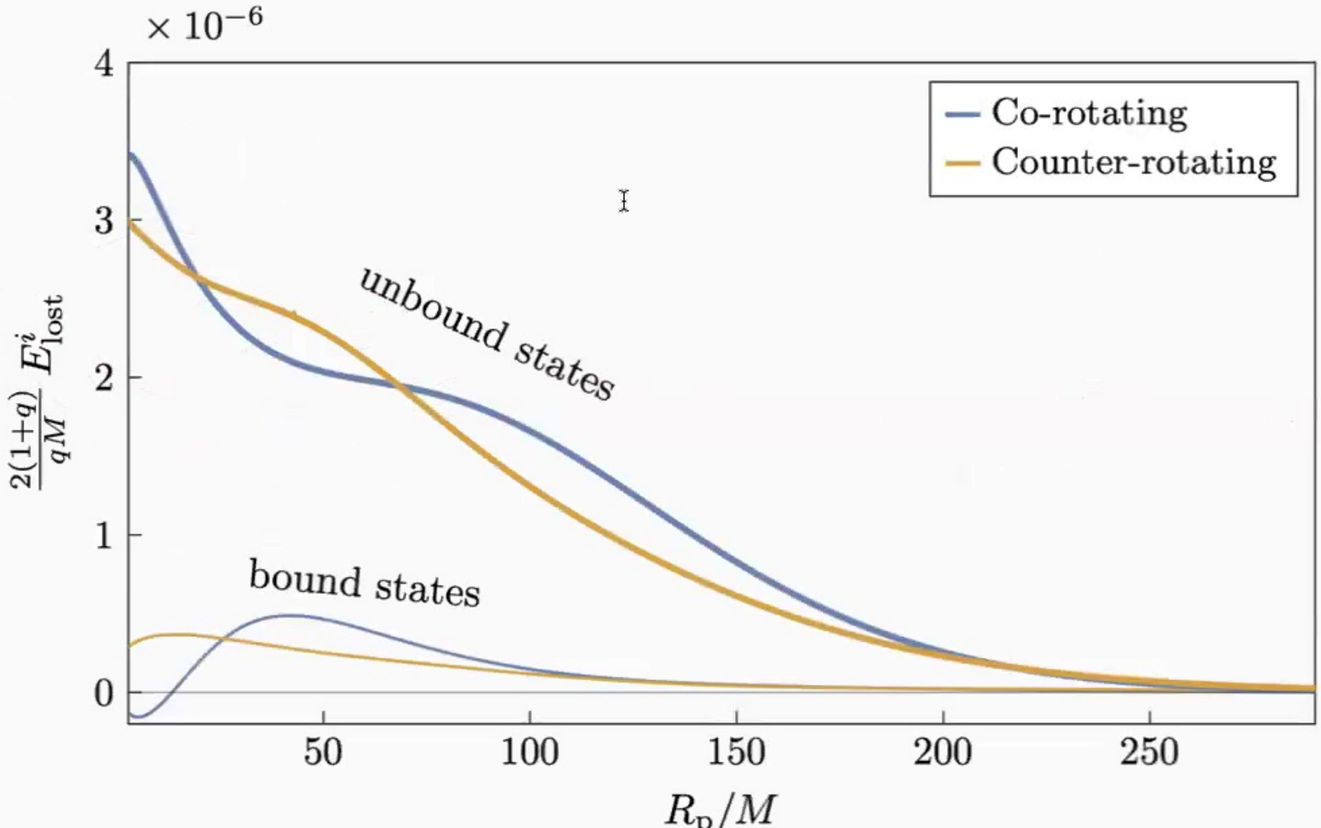
Eccentricity → 1

$$\sigma_{\mathrm{GW}} = 2\pi M^2 \left(\frac{85\pi}{6\sqrt{2}}\right)^{2/7} q^{2/7}(1+q)^{10/7} v^{-18/7}$$

The cloud opens up a new channel for **energy loss**!

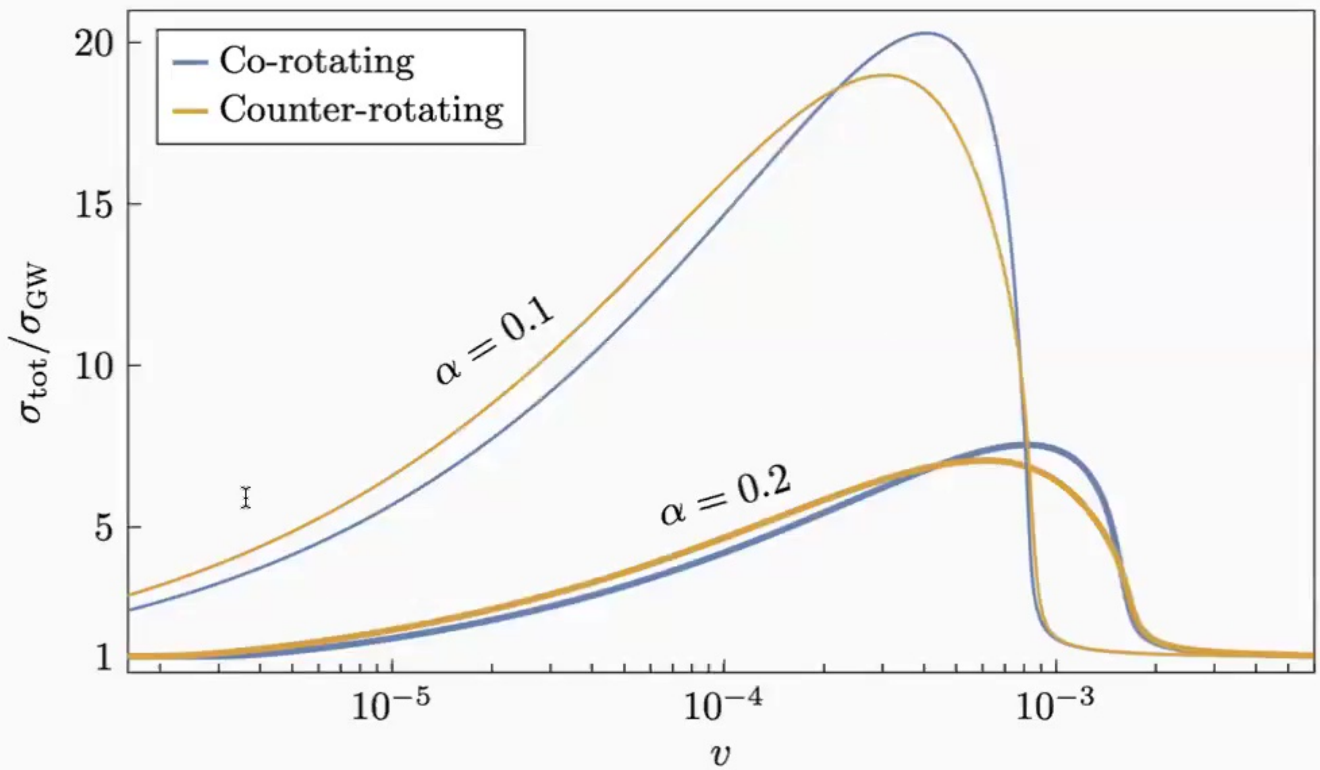
[GMT, Bertone, Spieksma '23]

Energy lost



[GMT, Bertone, Spieksma '23]

DYNAMICAL CAPTURE CROSS SECTION



[GMT, Bertone, Spieksma '23]

SUMMARY

- **Resonances** give peculiar GWs features and set the cloud's state.
- **Ionization** dominates dynamics and has sharp GWs features.
- **Resonant history** determines the observed configuration.

- Accretion on the companion ✓
- Eccentric orbits ✓
- Inclined orbits ✓
- Enhanced dynamical capture cross section ✓
- Relativistic dynamics ✗ but recent numerical work by: [Brito, Shah 2307.16093]