

Evolution of Ultralight Boson Clouds in Binary Black Hole Systems

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2nd New Horizons for Psi Workshop

ICTP-AP, Beijing, China

24–28 August 2026

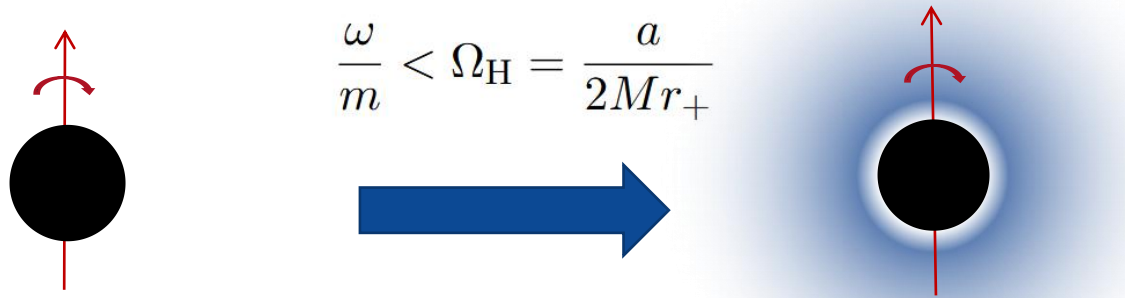


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Gravitational Atoms

- Rotating black holes can form ultralight-boson clouds through superradiant instability



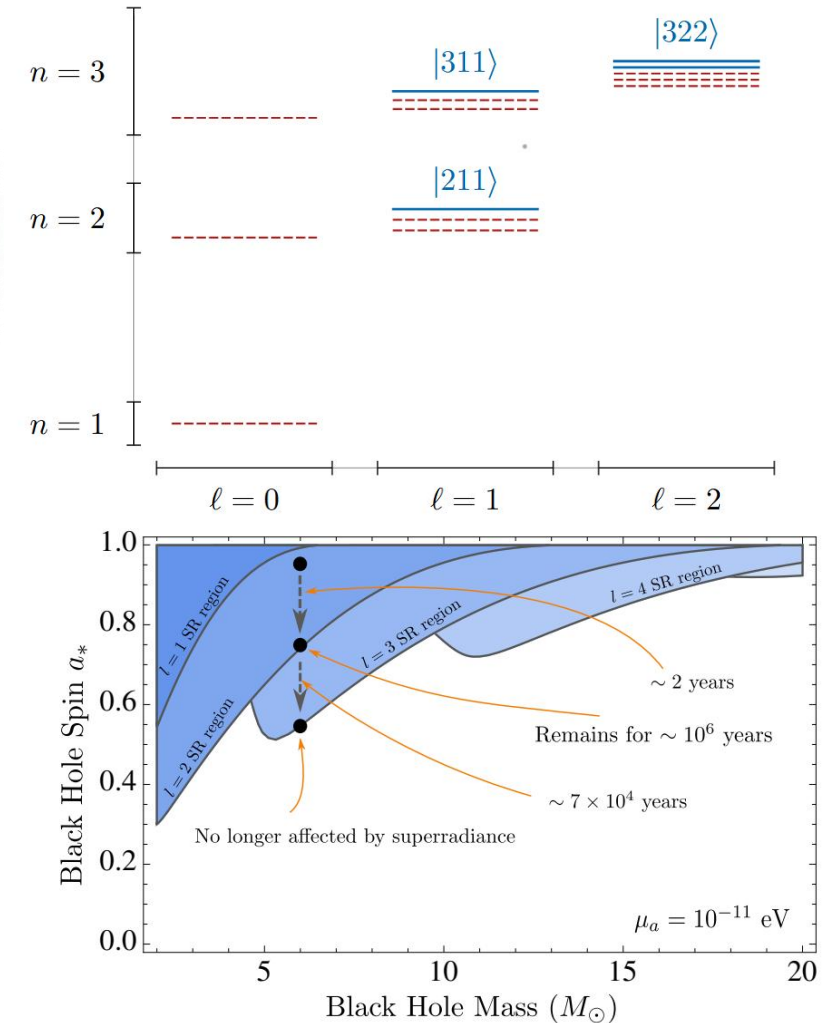
$$i\frac{\partial}{\partial t}\psi(t, \mathbf{r}) = \left[-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} \right] \psi(t, \mathbf{r})$$

- Gravitational Fine Structure constant

$$\alpha = GM\mu$$

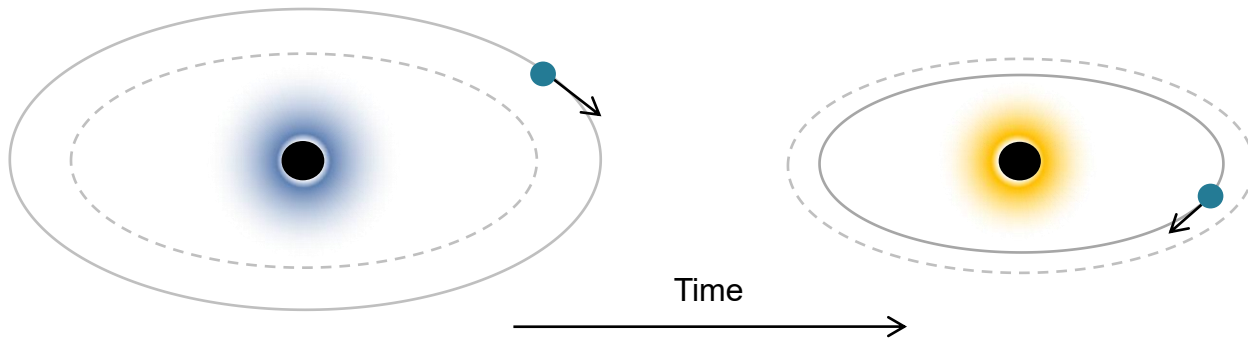
- 'Bohr radius'

$$r_{cloud} \sim \frac{1}{\alpha\mu}$$



Gravitational Atoms in Binaries

- Rotating black holes can form ultralight-boson clouds through superradiant instability

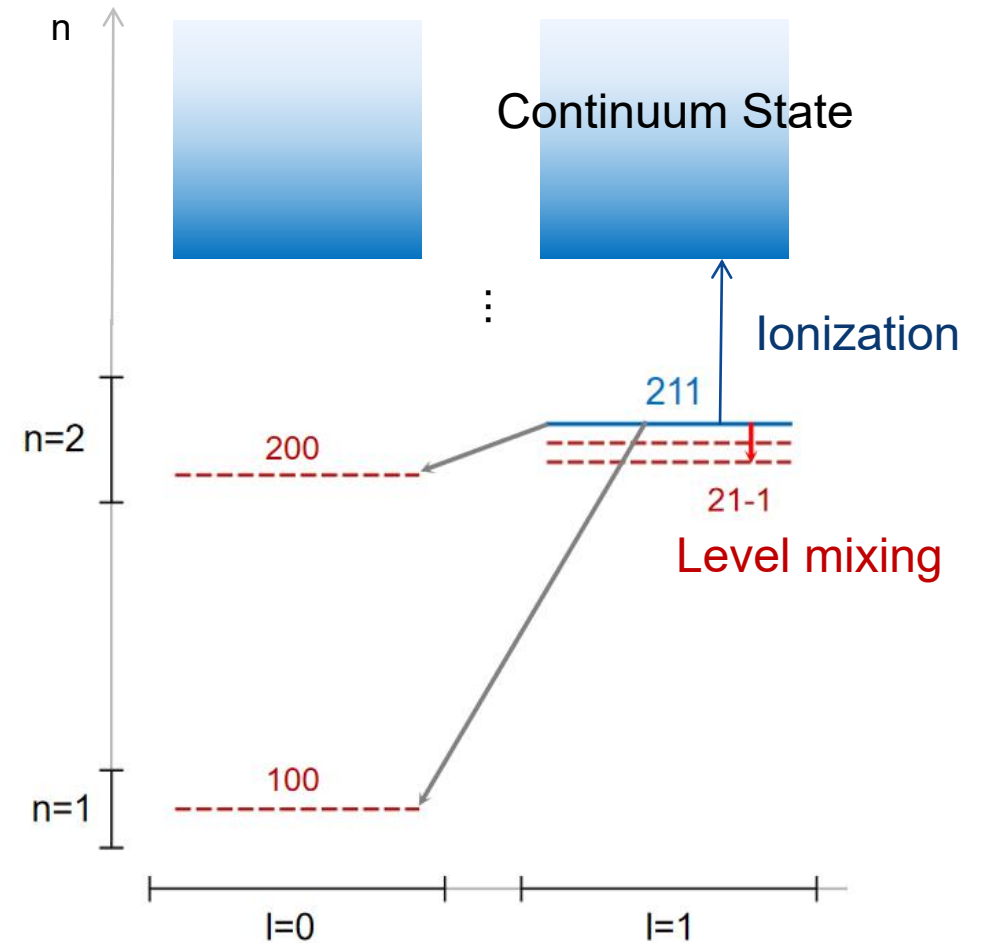


- Tidal perturbations from a companion induce level mixing and ionization

$$i\frac{\partial}{\partial t}\psi(t, \mathbf{r}) = \left[-\frac{1}{2\mu}\nabla^2 - \frac{\alpha_1}{r} \right] \psi(t, \mathbf{r}) + V_*(t, \mathbf{r})\psi(t, \mathbf{r})$$

- Landau-Zener transition

$$i\frac{d}{d\tau} \begin{pmatrix} c_a \\ c_b \end{pmatrix} = \begin{pmatrix} -\tilde{\omega}/2 & \sqrt{Z} \\ \sqrt{Z} & \tilde{\omega}/2 \end{pmatrix} \begin{pmatrix} c_a \\ c_b \end{pmatrix}$$

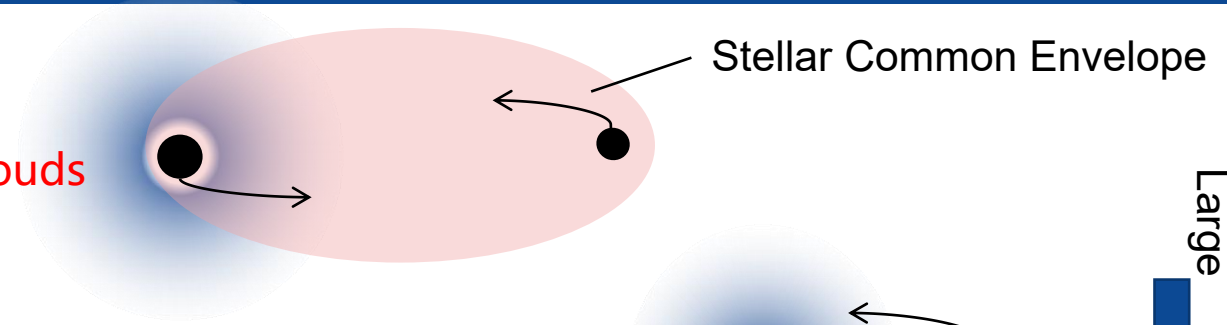


(See the talks by Tomaselli, Brito, Vicente and Xu.)

Clouds in Binaries

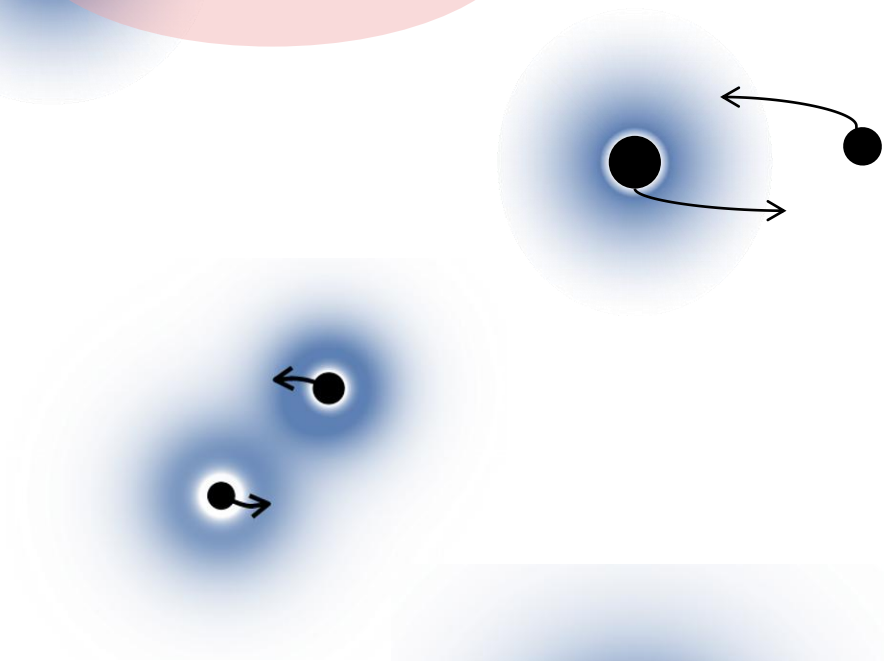
Stage 1

Common envelope contraction **protects clouds** by rapidly crossing depletion resonances



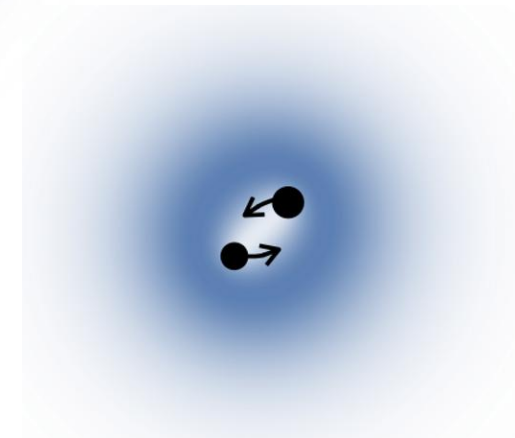
Stage 2

Cloud mass transfer redistributes cloud occupation between the two compact objects



Stage 3

Gravitational molecules/cloud common envelope can reshape orbital dynamics, especially **eccentricity**



Large
Binary Separation
Time Evolution
Small

Common-envelope Phase

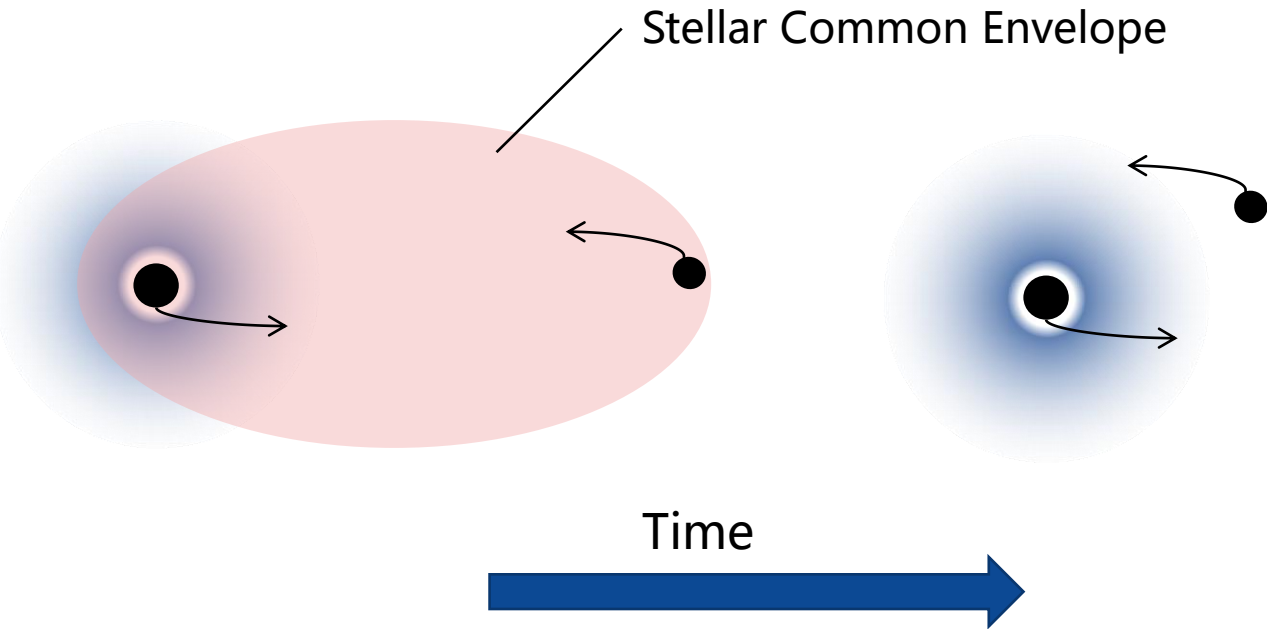
Time[Myr]	$M_1[M_{\text{sun}}]$	ST_1		ST_2	$M_2[M_{\text{sun}}]$	$a[R_{\text{sun}}]$
0.0	63.6	MS		MS	27.8	729.93
4.1	60.4	HG		MS	27.7	757.5
4.12	24.6	HeMS		MS	30.6	622.07
4.49	19.1	BH		MS	30.6	692.7
7.21	19.1	BH		CHeB	30.3	697.48
7.42	19.1	BH		CHeB	29.7	706.33
7.42	19.1	BH		HeMS	10.6	5.18
7.88	19.1	BH		BH	5.7	8.82

Stevenson, S., Vigna-Go' mez, A., et al. (2017)

Illustrative Evolution of a GW151226-like Binary

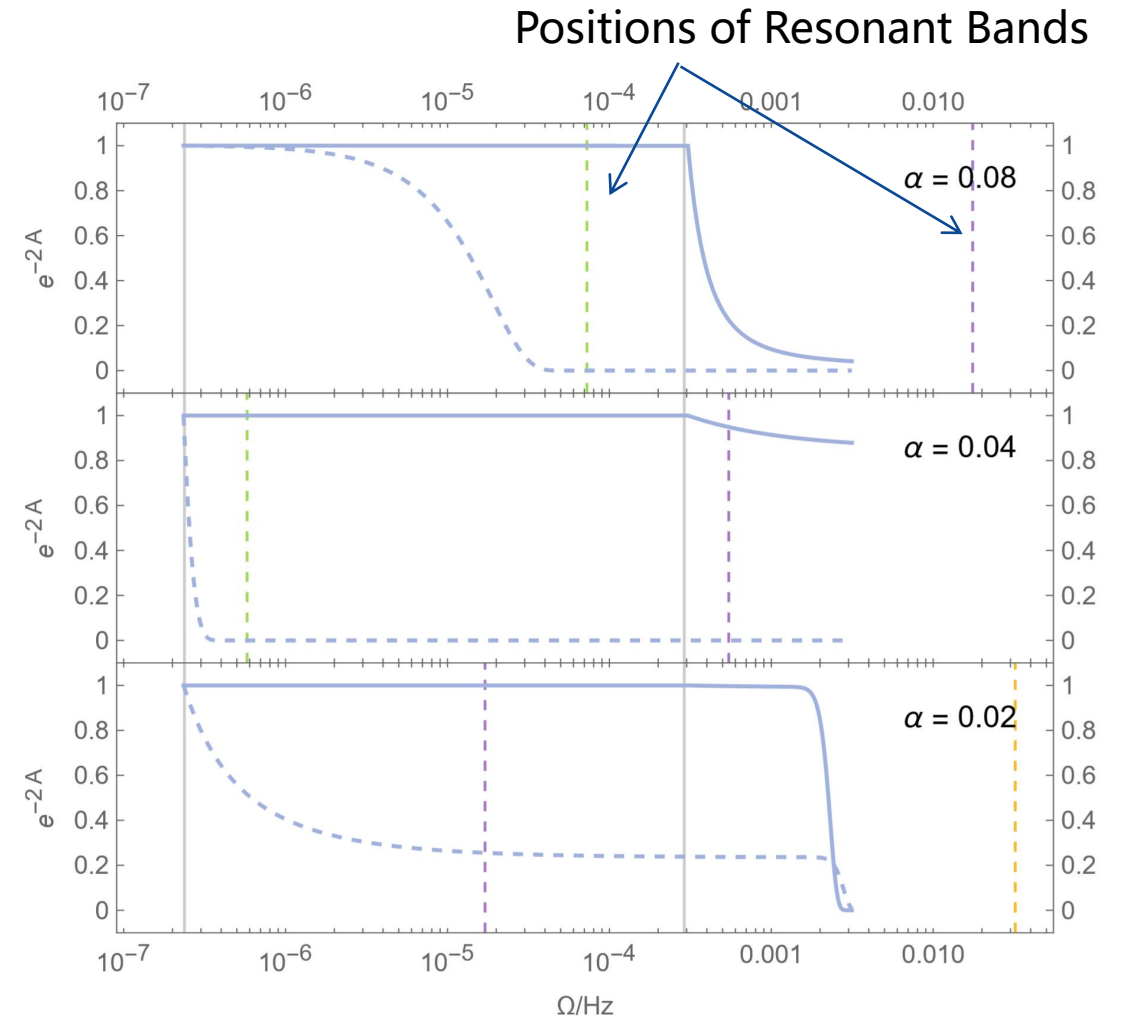
Common-envelope Phase Preserves Boson Clouds

Cloud Evolution in a GW151226-like Binary



The CE contraction lasts only $\sim 10^3$ yr

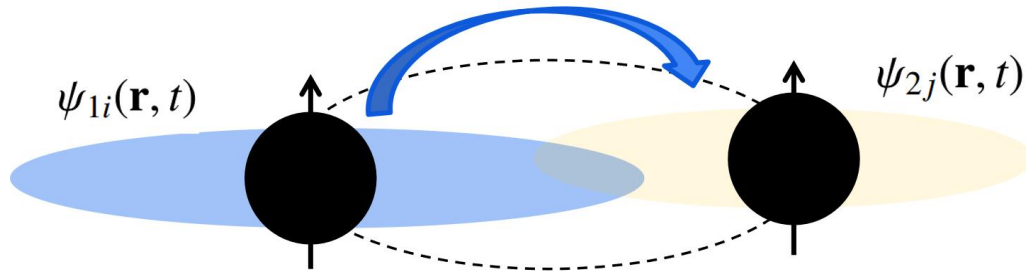
- Sweeps through mixing resonances much faster than GW-driven inspiral
- Level-mixing depletion is strongly suppressed



Ultralight bosons may survive into **mHz bands**

Cloud Mass Transfer

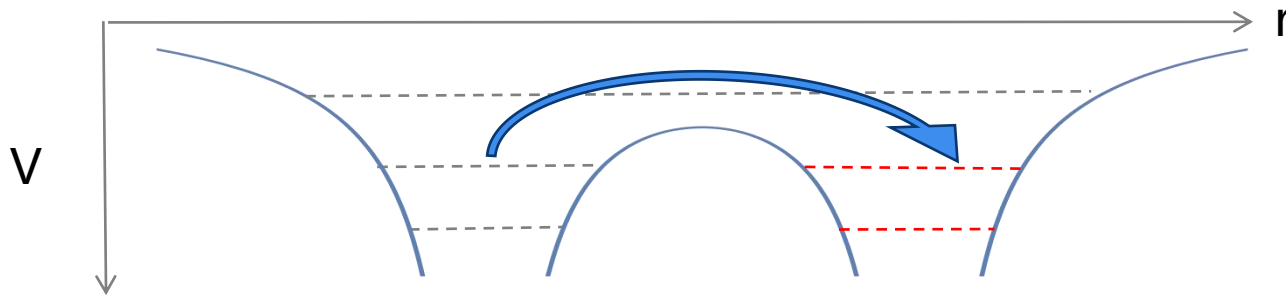
- Tidal coupling mixes cloud states localized around the two black holes.



- For a **comparable-mass** binary

$$i \frac{\partial}{\partial t} \psi(\mathbf{r}, t) = \left(-\frac{\nabla^2}{2\mu} - \frac{\alpha_1}{|\mathbf{r} - \mathbf{r}_1|} - \frac{\alpha_2}{|\mathbf{r} - \mathbf{r}_2|} \right) \psi(\mathbf{r}, t)$$

$$\psi(\mathbf{r}, t) = c_{1i}(t) \psi_{1i}(\mathbf{r}, t) + c_{2j}(t) \psi_{2j}(\mathbf{r}, t)$$



Schematic of the Double-Well Potential

Cloud Mass Transfer

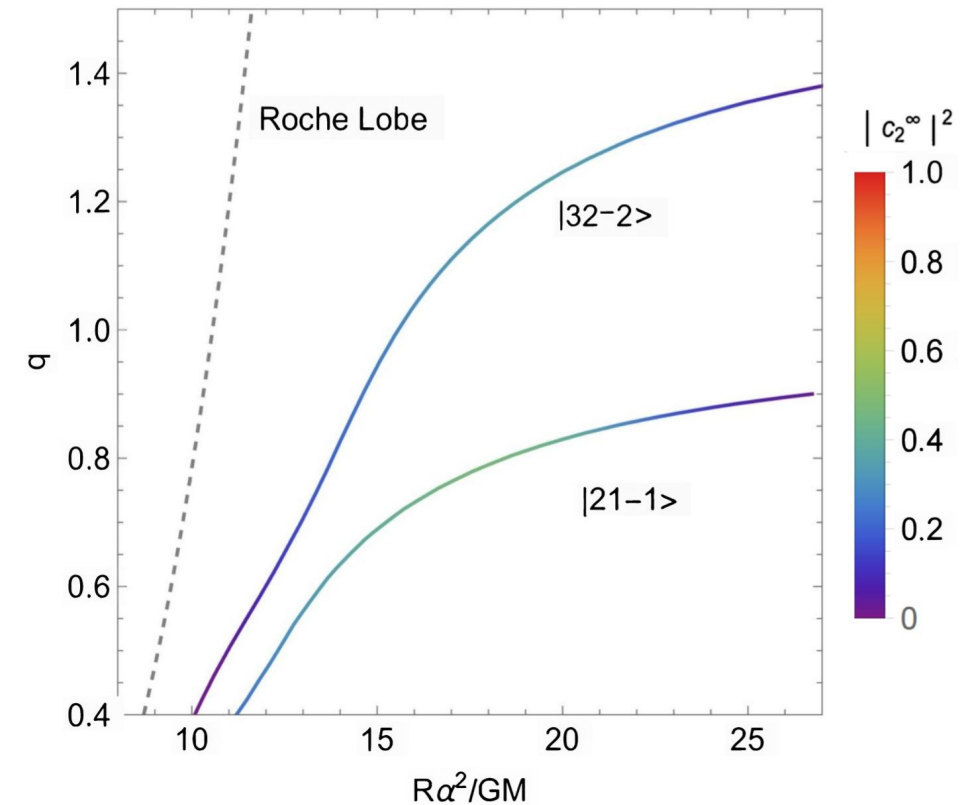
- Orbital-frequency matching drives **resonant transfer**

In a Two-level Approximation:

$$\begin{aligned} i\dot{\tilde{c}}_1 &= -\sqrt{A_{12}A_{21}} e^{i\epsilon_{21}t+i(m_2-m_1)\Phi} \tilde{c}_2, \\ i\dot{\tilde{c}}_2 &= -\sqrt{A_{12}A_{21}} e^{-i\epsilon_{21}t-i(m_2-m_1)\Phi} \tilde{c}_1, \\ \epsilon_{21} &\equiv \epsilon_2 - \epsilon_1 + (A_2 - A_1) \end{aligned}$$

Resonance Condition: $\Omega_{\text{res}} = \mp \frac{\epsilon_{21}}{m_2 - m_1}$

Transfer Efficiency: $|c_2^\infty|^2 = \frac{A_{21}}{A_{12}} (1 - e^{-\pi A^2}) \simeq \frac{\pi A_{21}^2}{(m_2 - m_1)\dot{\Omega}}$



Resonant separation and rates for mass transfer from the initial 211 mode

Cloud Mass Transfer

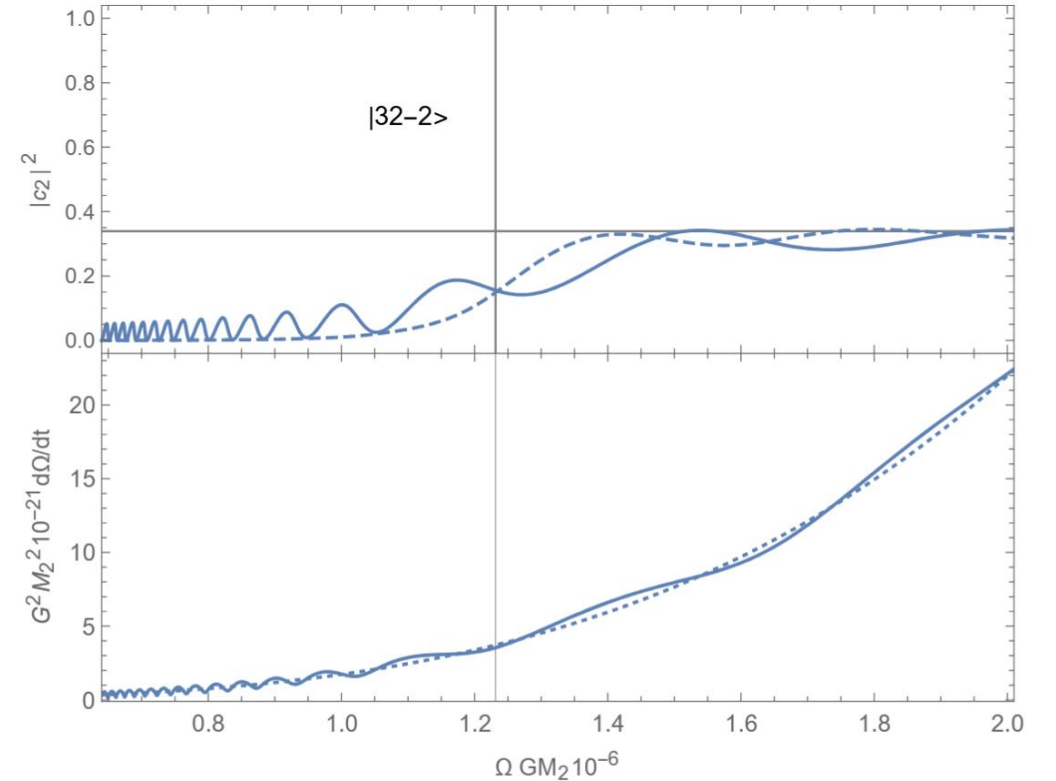
- Orbital **Backreaction** from Cloud Mass Transfer

$$\frac{dE_{\text{orb}}}{dt} = \frac{MM_*}{2R_*} \left[\frac{\dot{R}_*}{R_*} + \frac{\gamma(q-1)}{q} \right]$$

$$\gamma \sim \frac{M_c}{M} |c_2^\infty|^2 \sqrt{|m_2 - m_1| \dot{\Omega}} \simeq \frac{M_c}{M} \frac{\pi A_{21}^2}{\sqrt{|m_2 - m_1| \dot{\Omega}}}$$

The orbital-frequency evolution is

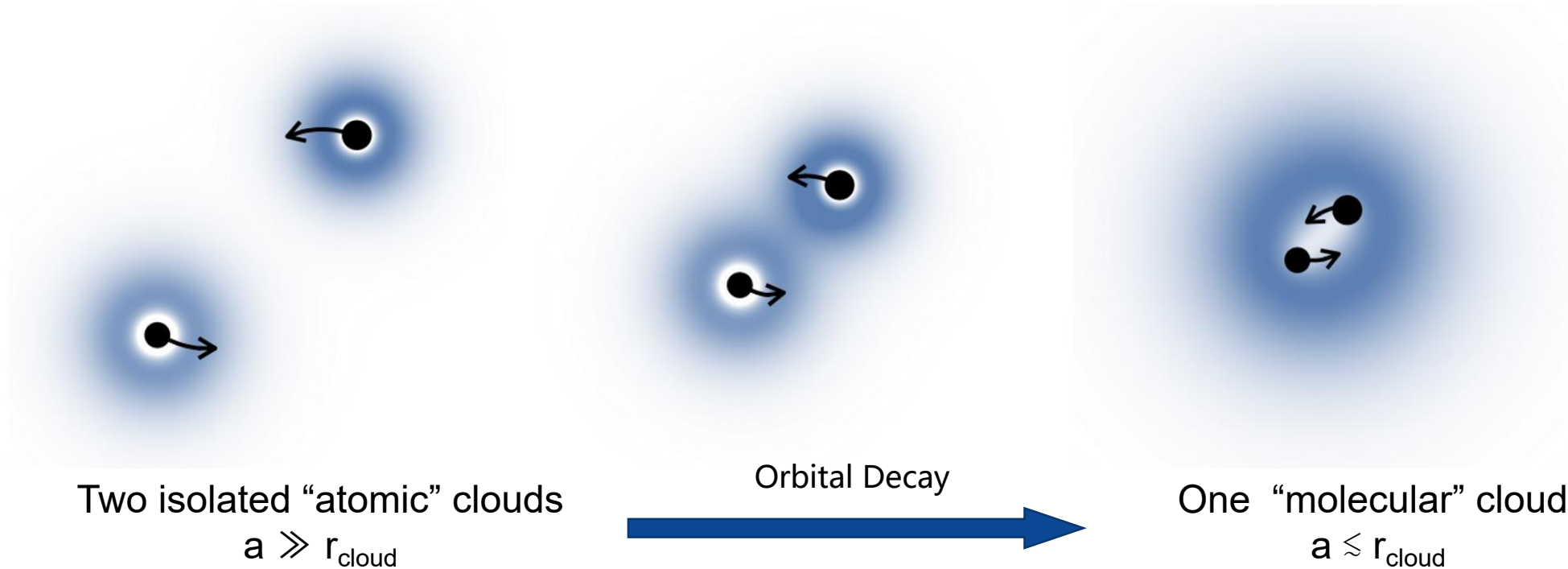
$$\dot{\Omega} = \frac{96}{5} \frac{\eta}{M_{\text{tot}}^2} (M_{\text{tot}} \Omega)^{11/3} + \frac{3\gamma(q-1)}{2q} \Omega$$



Cloud mass transfer and orbital-frequency evolution in a GW150914-like binary.

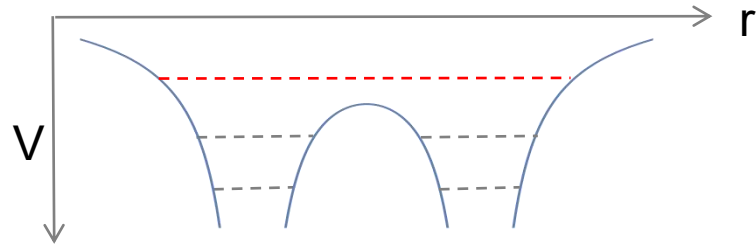
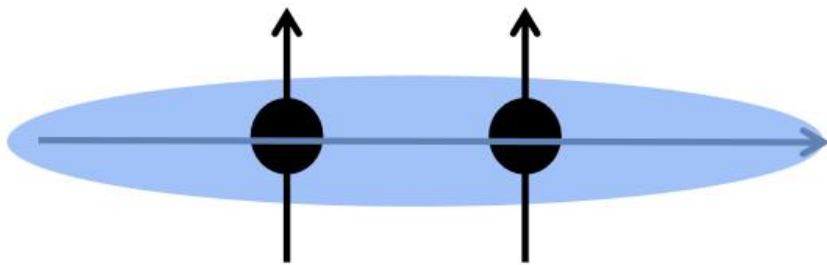
Cloud Common Envelope

- When $a \lesssim r_{\text{cloud}}$, the two localized clouds overlap.
- The system becomes a **gravitational molecule**, forming a **cloud common envelope**.



Cloud Common Envelope

- **Eigenstates** of Gravitational Molecules



Corotating Frame: $i\partial_t \Psi(t, \bar{\mathbf{r}}) = (H_0 + H') \Psi(t, \bar{\mathbf{r}})$

$$H_0 = -\frac{1}{2\mu} \bar{\nabla}^2 - \frac{GM_1\mu}{|\bar{\mathbf{r}} - \bar{\mathbf{r}}_1|} - \frac{GM_2\mu}{|\bar{\mathbf{r}} - \bar{\mathbf{r}}_2|}$$

Gravitational Molecules

$$H'$$

Perturbation

Prolate spheroidal coordinates make the molecular problem separable:

$$\Psi = e^{-i\epsilon t} e^{im\chi} R_{n\ell}(\xi) S_{\ell m}(\zeta)$$

$$\xi = \frac{r_1 + r_2}{a}, \quad \zeta = \frac{r_1 - r_2}{a}, \quad \chi = \arctan\left(\frac{y}{x}\right).$$

Conservation of the nodal numbers determines the mapping between atomic and molecular eigenstates:

$$\varphi_{1,211} + \varphi_{2,211} = \frac{e^{-i\Omega_0 t}}{\sqrt{2}} (\bar{\psi}_{211} - \bar{\psi}_{21-1} + \bar{\psi}_{310} - \bar{\psi}_{430})$$

Cloud Common Envelope

- Adiabatic and **Non-adiabatic** Evolution of Common Envelope

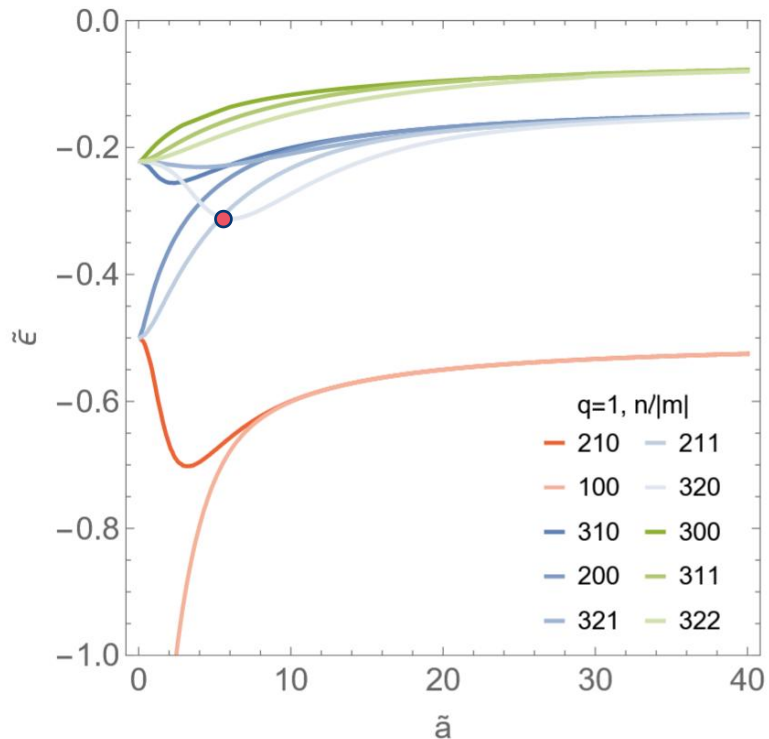
Perturbation:
$$H' = i\dot{\phi}_* \partial_{\bar{\phi}} - \left[\frac{GM_1\mu(a_1^2 - a_1\bar{r}\cos\bar{\phi})}{|\bar{\mathbf{r}} - \mathbf{a}_1|^3} + \frac{GM_2\mu(a_2^2 - a_2\bar{r}\cos\bar{\phi})}{|\bar{\mathbf{r}} - \mathbf{a}_2|^3} \right] e \cos \bar{\Omega}t + O(e^2)$$

$$\psi = c_i \bar{\psi}_i$$

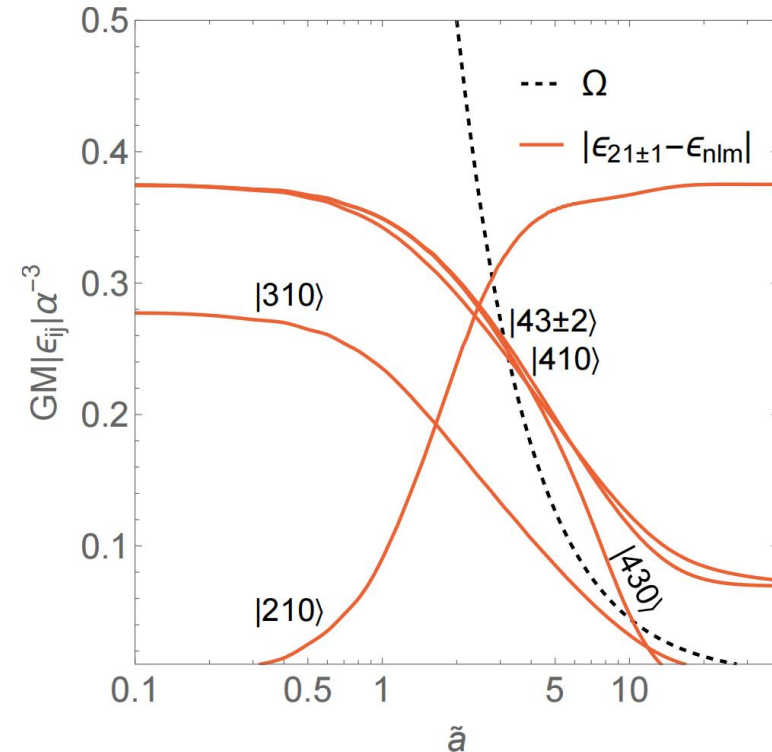
$$i\dot{c}_i = \sum_j \left[\eta_{ij} e^{i\epsilon_{ij}t} + \eta'_{ij} \left(e^{i\epsilon_{ij}t + \bar{\Omega}t} + e^{i\epsilon_{ij}t - \bar{\Omega}t} \right) \right] c_j$$

$\propto e$

Energy levels of the molecular eigenstates

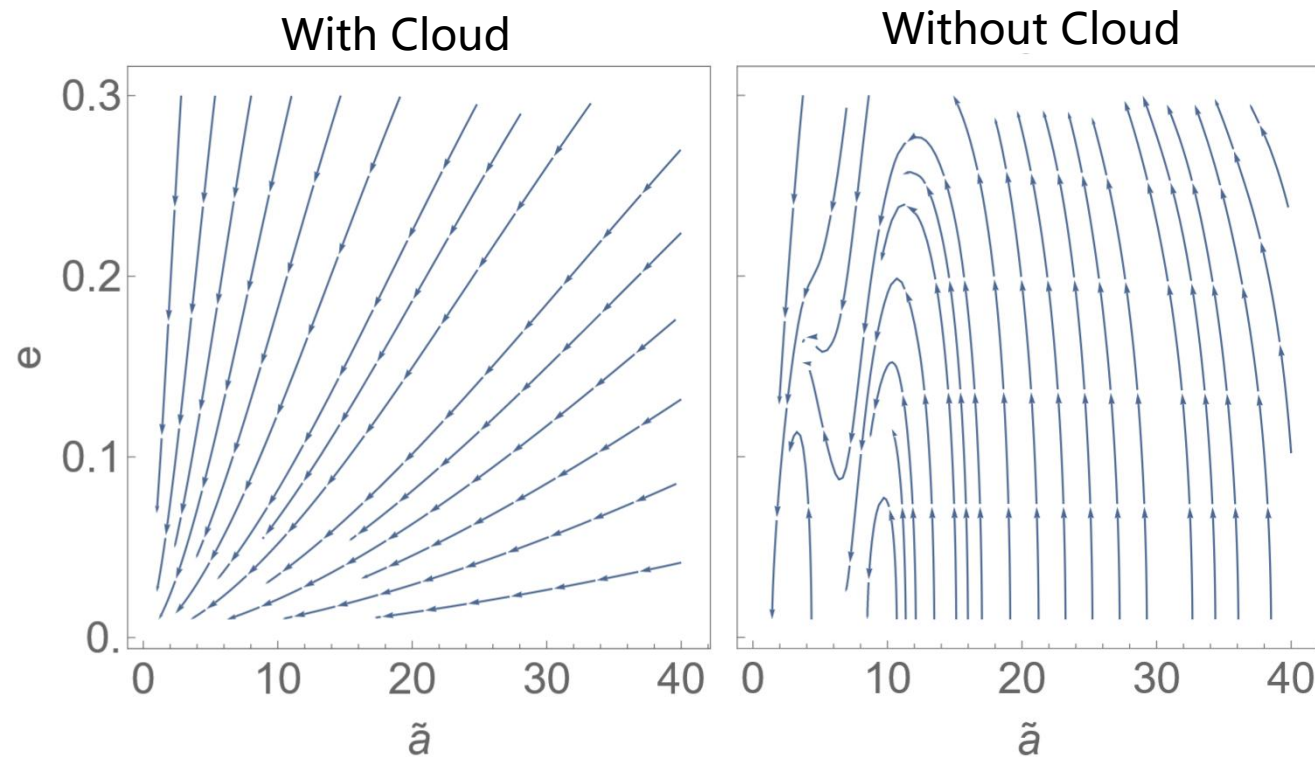


Semimajor axis at eccentricity-induced resonant transitions

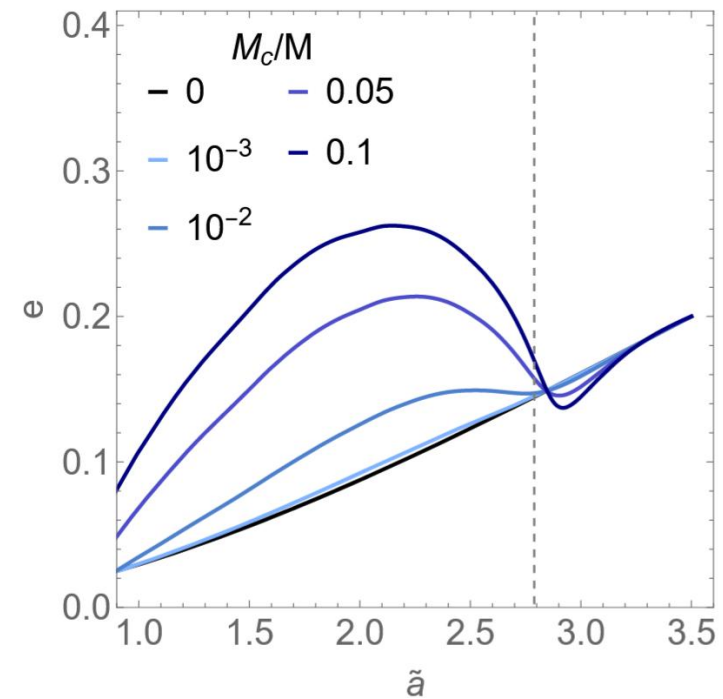


Cloud Common Envelope

- Evolution of common envelopes **backreact** on orbit and **increase eccentricity**



Evolution Trajectories of Orbital Parameters

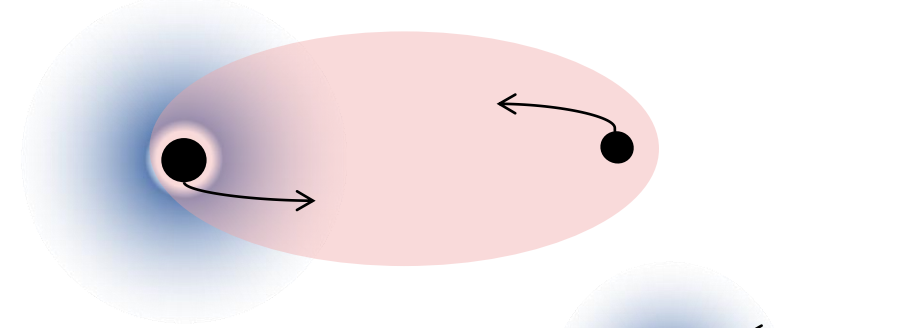


Provide a possible mechanism relevant to the inferred eccentricity of **GW200105**

Conclusion

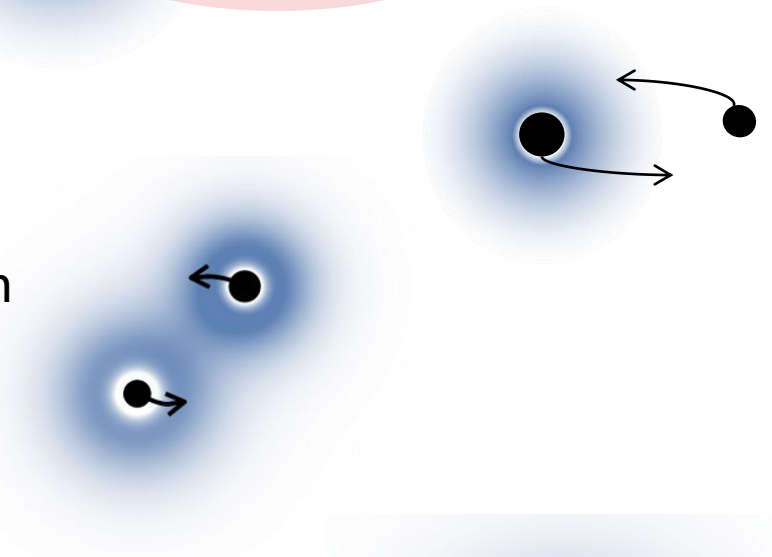
Stage 1

Common-envelope contraction can **preserve** boson clouds to **mHz band** by crossing depletion resonances rapidly.



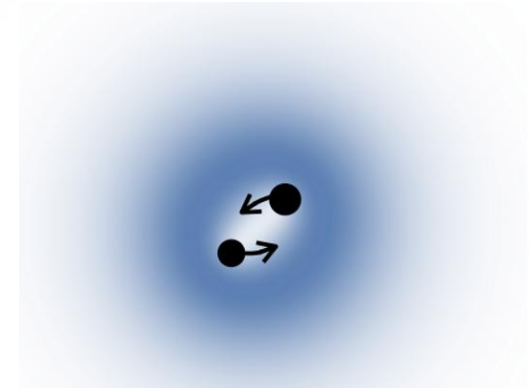
Stage 2

Tidal potential couplings of the binary enable cloud transfer from the donator black hole to the companion, even if the companion can be **non-superradiant**.



Stage 3

At small separations, evolution of cloud common envelopes can **excite orbital eccentricity** and provide a possible origin of the median orbital eccentricity of the reported GW event.



Thank you For Your Attention!

QUESTIONS?

Backup Slides

- Timescale of orbital contraction due to GW radiation

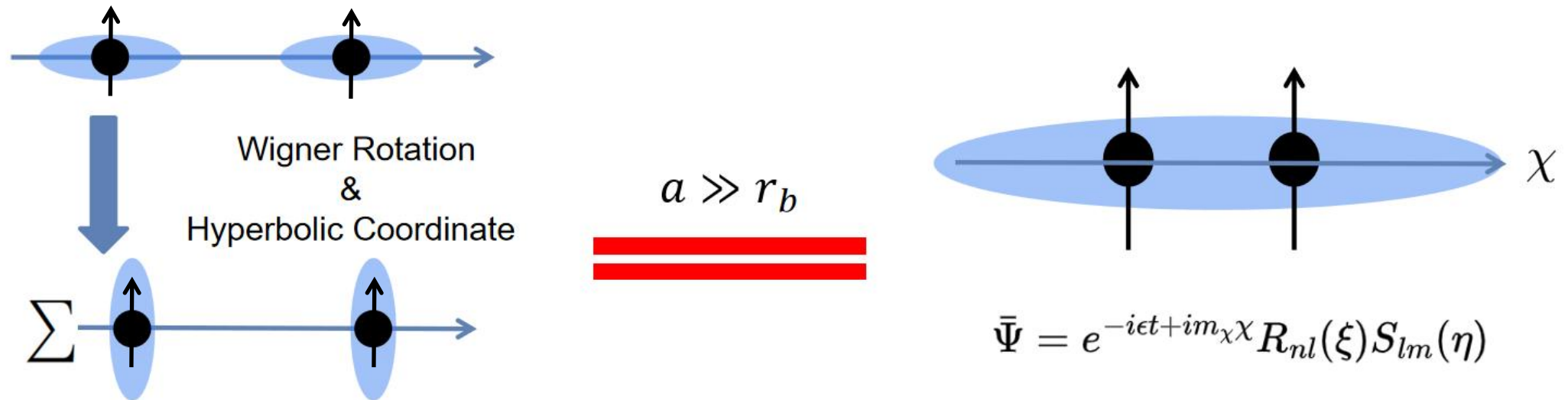
$$\tau_{\text{GW}} \equiv \frac{a}{|\dot{a}|_{\text{GW}}} = \frac{5c^5 a^4}{64 G^3 m_1 m_2 (m_1 + m_2)}$$
$$\simeq 5.4 \times 10^{15} \text{ yr} \left(\frac{a}{706 R_{\odot}} \right)^4 \left(\frac{19.1 M_{\odot}}{m_1} \right) \left(\frac{29.7 M_{\odot}}{m_2} \right) \left(\frac{48.8 M_{\odot}}{m_1 + m_2} \right).$$

$$\tau_{\text{CE}} \sim 10^3 \text{ yr} \ll \tau_{\text{GW}} \sim 5 \times 10^{15} \text{ yr}.$$

$$\xi \geq 1, \quad -1 \leq \eta \leq 1, \quad 0 \leq \phi < 2\pi$$

Backup Slides

- Initial States of the Cloud Common Envelope



Conservation of the nodal numbers determines the mapping between atomic and molecular eigenstates:

$$\varphi_{1,211} + \varphi_{2,211} = \frac{e^{-i\Omega_0 t}}{\sqrt{2}} (\bar{\psi}_{211} - \bar{\psi}_{21-1} + \bar{\psi}_{310} - \bar{\psi}_{430})$$

$$\varphi_{1,100} + \varphi_{2,100} = \sqrt{2} \bar{\psi}_{100}, \quad \varphi_{1,100} - \varphi_{2,100} = \sqrt{2} \bar{\psi}_{210}$$

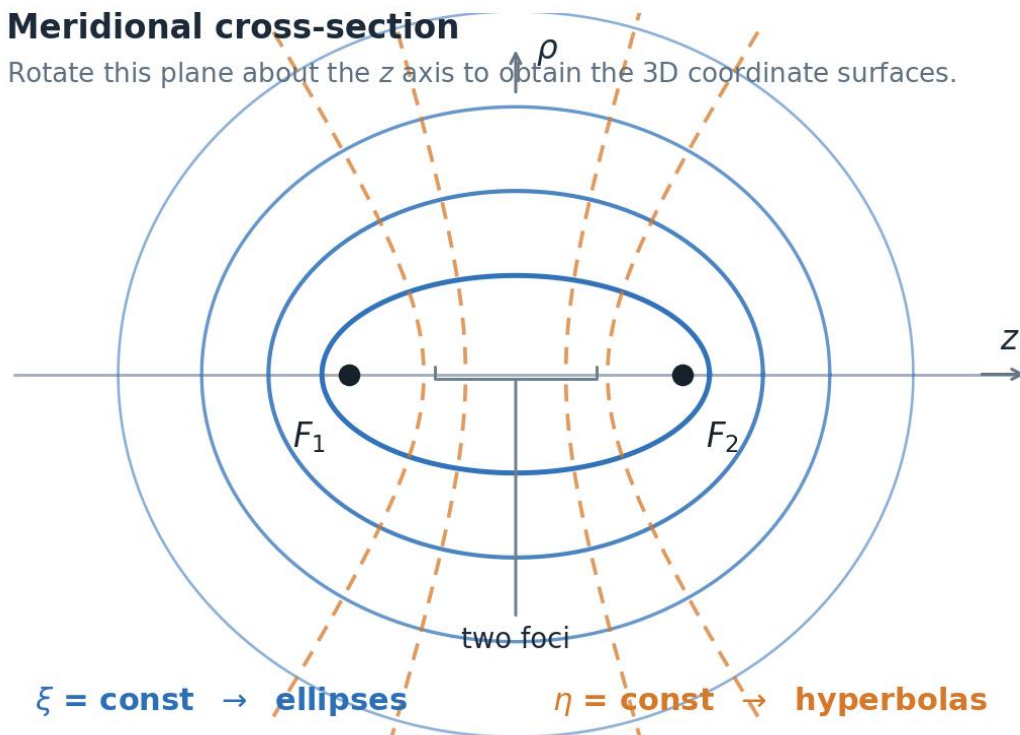
Backup Slides

Prolate Spheroidal Coordinates

A two-focus coordinate system for a binary: ellipsoids ($\xi = \text{const}$), hyperboloids ($\eta = \text{const}$), and azimuth ϕ .

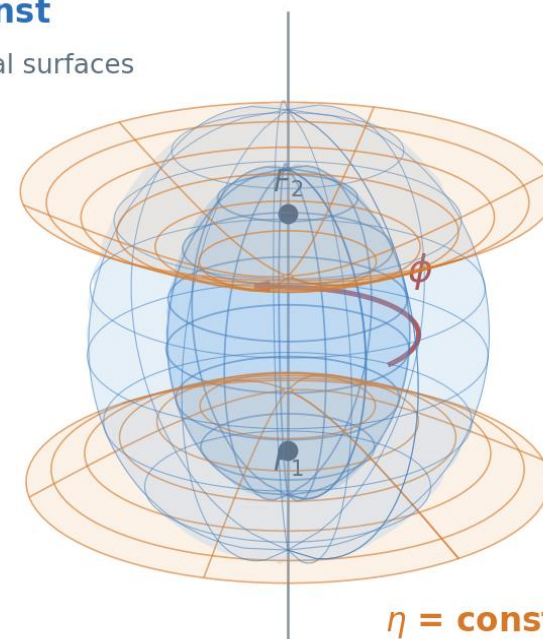
Meridional cross-section

Rotate this plane about the z axis to obtain the 3D coordinate surfaces.



$\xi = \text{const}$

ellipsoidal surfaces



$\eta = \text{const}$

hyperboloidal surfaces

Azimuthal rotation: $0 \leq \phi < 2\pi$

$$\xi \geq 1, \quad -1 \leq \eta \leq 1, \quad 0 \leq \phi < 2\pi$$

Backup Slides

- Cloud Depletion after Mass Transfer

After transfer, the cloud occupies a decaying state around companion black hole and can be depleted.

The approximate rate at which the cloud loses mass to the second black hole is $-2\Gamma_{2,21-1}|c_2|^2 M_c$

Away from resonance, the cloud evolves as

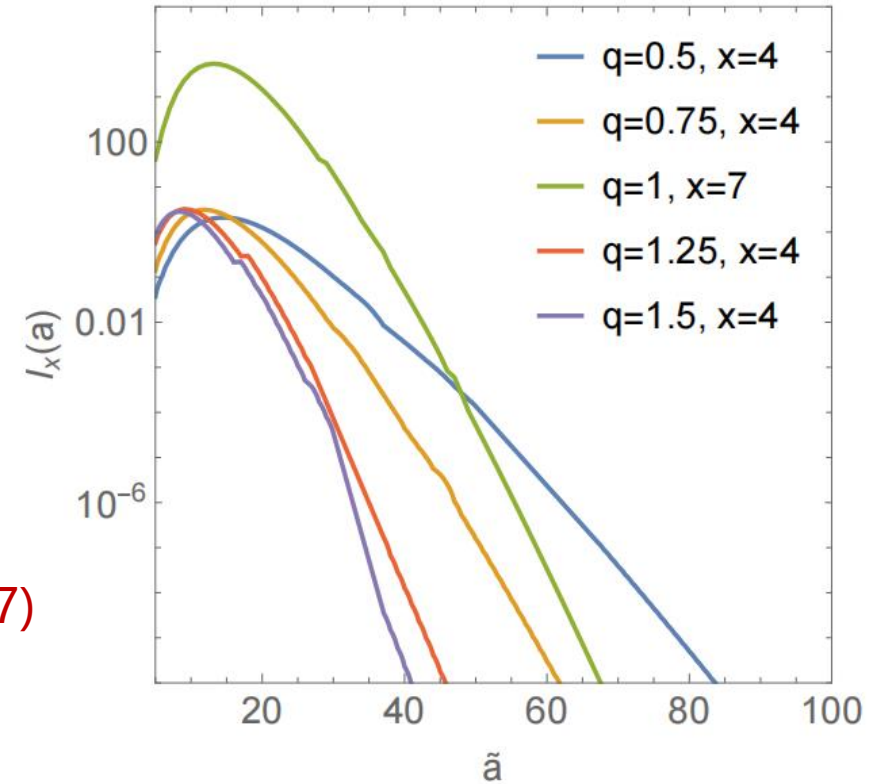
$$|c_2|^2 \approx \frac{\eta^2}{\omega^2 + \eta^2} \sin^2 \left(\int_{-\infty}^t dt' \sqrt{\omega^2 + \eta^2} \right), \quad \omega \approx \Delta\epsilon + 2\Omega$$

For $q \neq 1$

$$\Gamma_{2,21-1} \frac{\eta^2}{\omega^2} \frac{\dot{\Omega}}{\Omega} \approx \frac{40(1+q)^{1/3} q^8}{3(1-q^2)^2} \alpha^2 I_4(a) \gtrsim 1, \quad (q > 3.27)$$

For $q=1$

$$\Gamma_{2,21-1} \frac{\eta^2}{\omega^2} \frac{\dot{\Omega}}{\Omega} \approx \frac{5}{96} 2^{1/3} \alpha^2 I_7(a) \gtrsim 1,$$



$$I_4(a) = (a/r_B)^4 G^2 M^2 \eta^2 / \alpha^6$$

$$I_7(a) = (a/r_B)^7 G^2 M^2 \eta^2 / \alpha^6$$