Probing dark matter with gravitational waves

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Universiteit van Amsterdam

CDM Annual Workshop

Adelaide – November 29, 2023


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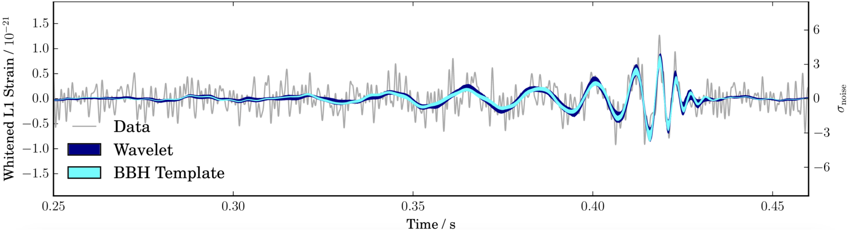
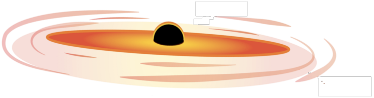
Vacuum waveforms



- LIGO/Virgo finds binary mergers assuming they happened in vacuum.
- OK for short duration & low mass. What about **future interferometers**?
- Environmental effects can build up over **long duration signals**.

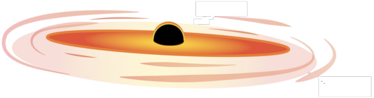
What environments?

Accretion disk

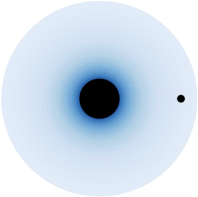


What environments?

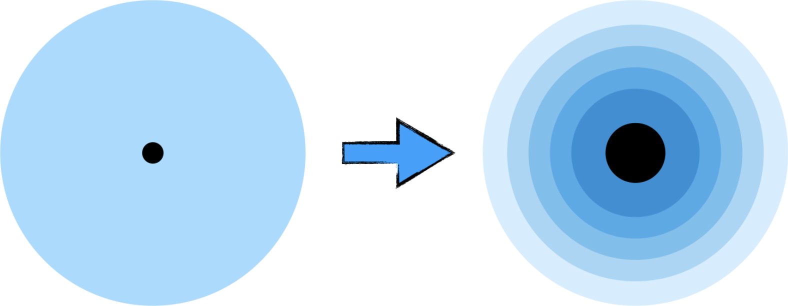
Accretion disk



Dark matter 'spike'



Dark matter 'spike'



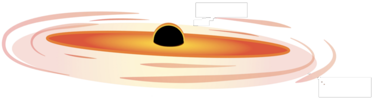
$$\rho \approx \rho_0 \frac{R_{\rm s}}{r} \quad \longrightarrow \quad \rho = \rho_{\rm s} \left(\frac{r_{\rm s}}{r} \right)^{\gamma_{\rm s}}$$

Black hole growth adiabatically contracts DM halo.

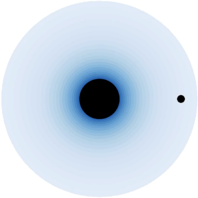
[Gondolo & Silk '99]

What environments?

Accretion disk



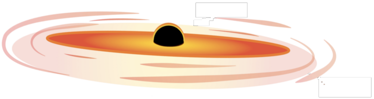
Dark matter
'spike'



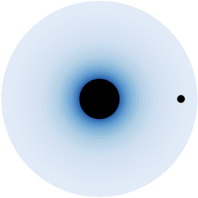
$$\rho = \rho_{\rm s} \left(\frac{r_{\rm s}}{r} \right)^{\gamma_{\rm s}}$$

What environments?

Accretion disk

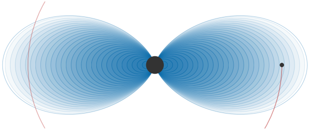


Dark matter 'spike'

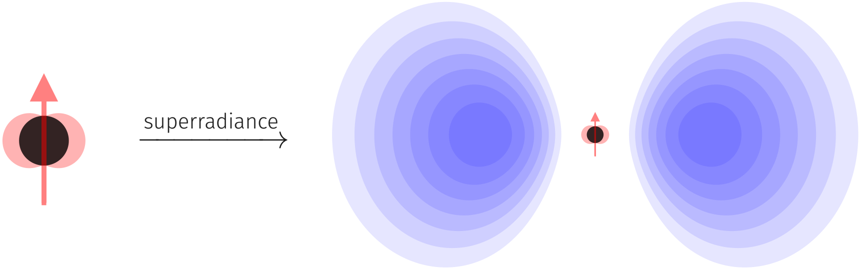


$$\rho = \rho_s \left(\frac{r_s}{r}\right)^{\gamma_s}$$

Gravitational 'atom'



Gravitational Atom

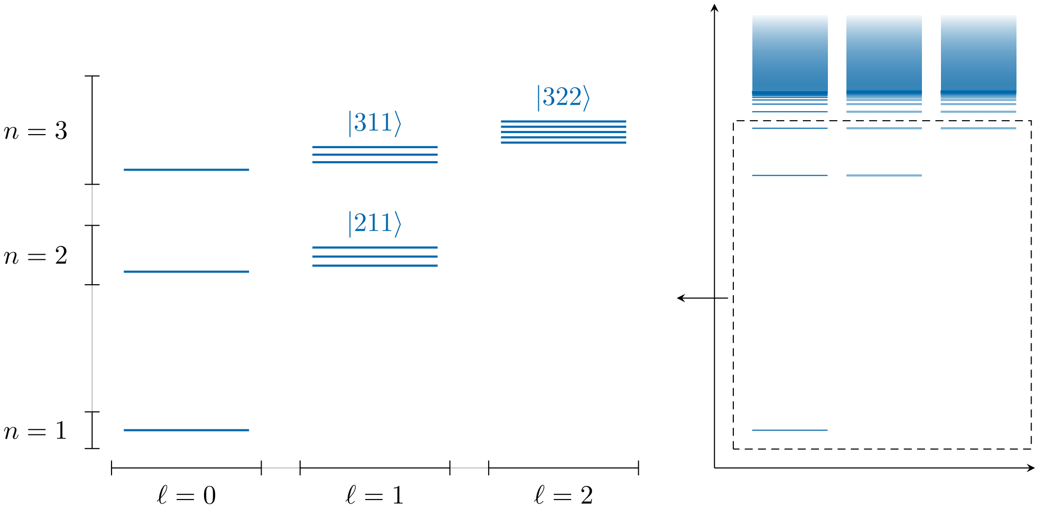


$$(\Box - \mu^2)\Phi = 0 \quad \longrightarrow \quad i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \dots\right)\psi$$

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

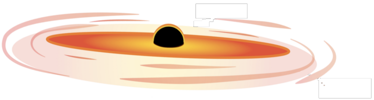
[Zeldovich '72; Starobinsky '73; Dolan '07; Arvanitaki et al. '09]

The spectrum

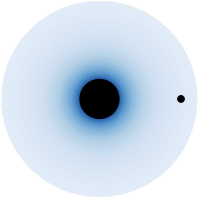


What environments?

Accretion disk

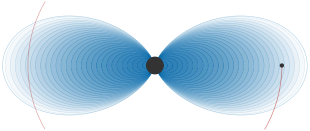


Dark matter 'spike'



$$\rho = \rho_s \left(\frac{r_s}{r}\right)^{\gamma_s}$$

Gravitational 'atom'



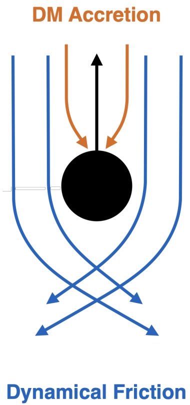
$$i\dot{\psi} = \left(-\frac{\nabla^2}{2\mu} - \frac{\alpha}{r}\right)\psi$$

Environmental effects

vacuum GR

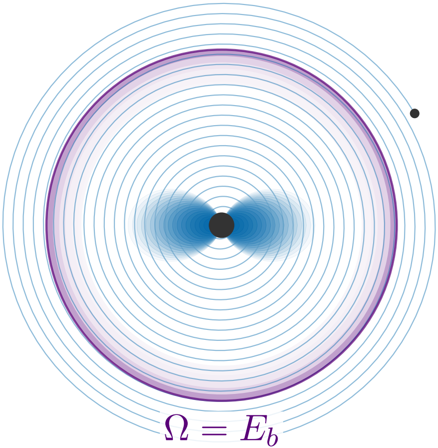
$$\boxed{\dot{E}_{\rm binary} = \dot{E}_{\rm GW}} + \dot{E}_{\rm envir}$$

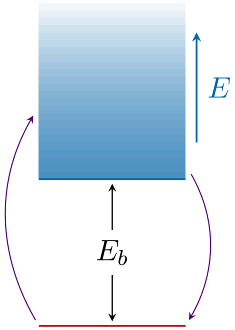
- **Dynamical friction**
- Accretion
- Gas torques
- Orbital resonances



Dynamical friction is ionization ("photoelectric effect")

Physical mechanism behind dynamical friction in **gravitational atoms**:





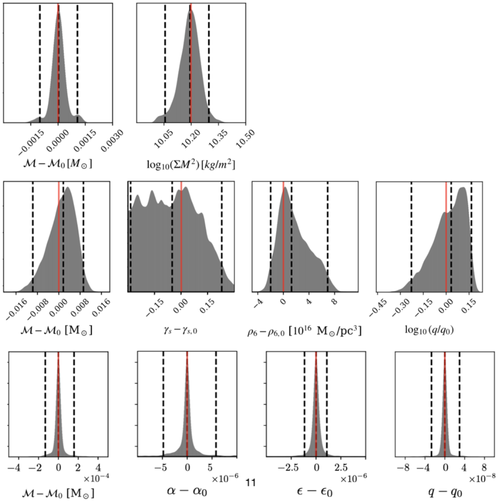
[Baumann, Bertone, Stout, GMT 2112.14777, 2206.01212 PRL]

Estimate environment parameters from waveform

Accretion disk

Dark matter ‘spike’

Gravitational atom



[Cole, Bertone, Coogan, Gaggero, Karydas, Kavanagh, Spieksma, GMT 2211.01362 Nature Astronomy]

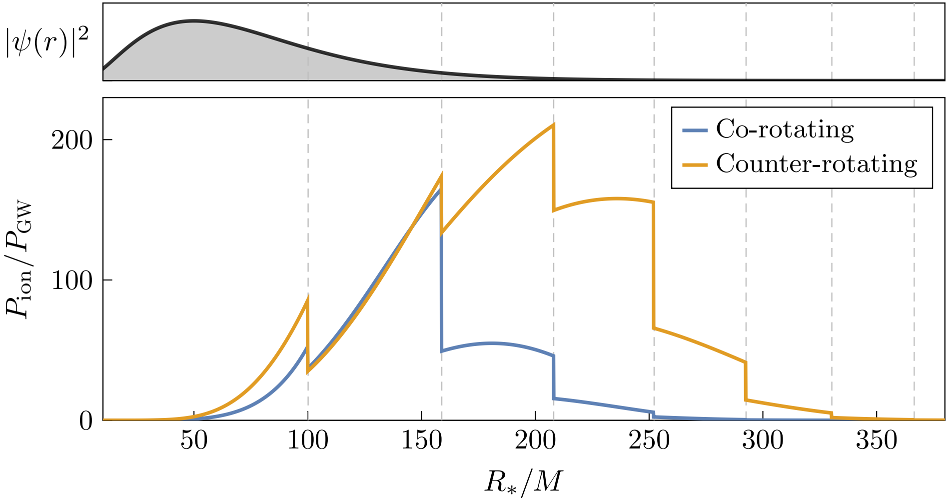
Summary

- GW astronomy can give information about **black hole environments**.
- Interesting scenarios are **dark matter spikes** and **gravitational atoms**.

- Environments can be **measured** and **distinguished**.
- Peculiar signatures in gravitational atoms.

Backup

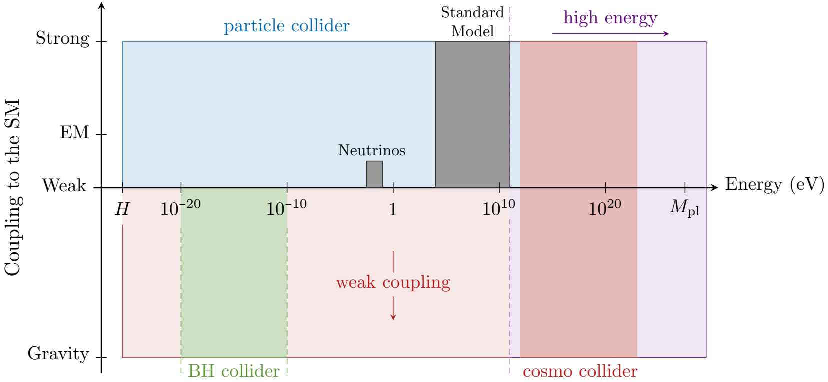
Ionization plot



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

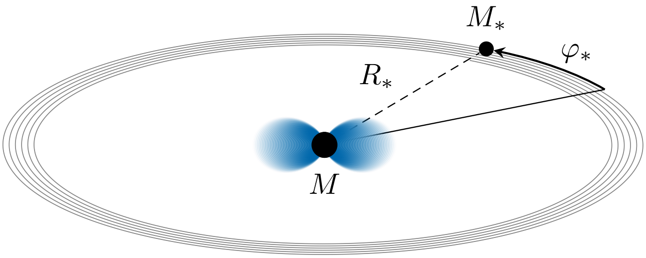
[Baumann, Bertone, Stout, GMT 2112.14777 PRD, 2206.01212 PRL]

Motivation



Gravitational waves as probes of weakly-coupled new physics

Gravitational perturbation with slowly increasing frequency:



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

Rich phenomenology: “Rabi oscillations”, “photoelectric effect”, …

Gravitational Atoms @ University of Amsterdam & GRAPPA:

H.S. Chia, R. Porto, D. Baumann, G. Bertone, J. Stout, G.M.T., T. Spieksma

"Probing Ultralight Bosons with Binary Black Holes"
1804.03208, PRD

"The Spectra of Gravitational Atoms"
1908.10370, JCAP

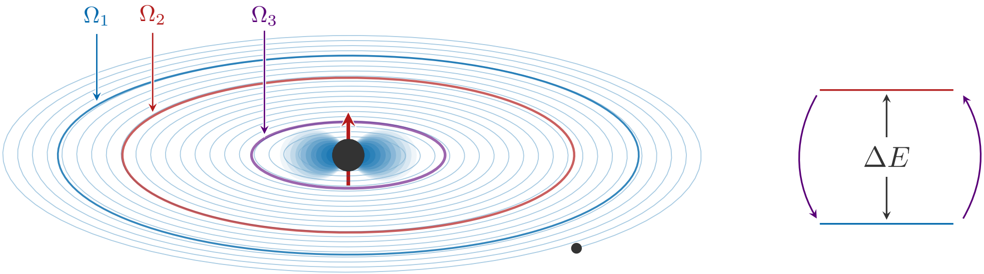
"Gravitational Collider Physics"
1912.04932, PRD

"Ionization of Gravitational Atoms"
2112.14777, PRD

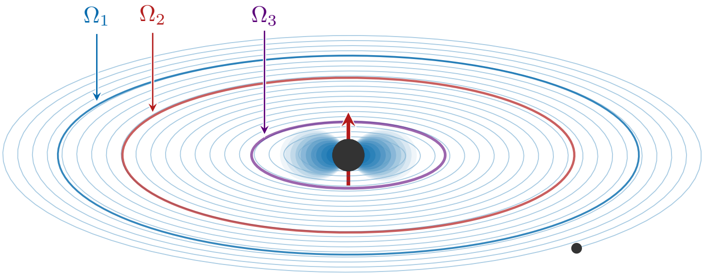
"Sharp Signals of Boson Clouds in Black Hole Binary Inspirals"
2206.01212, PRL

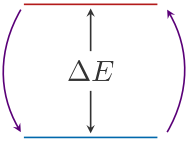
"Dynamical Friction in Gravitational Atoms"
2305.15460, JCAP

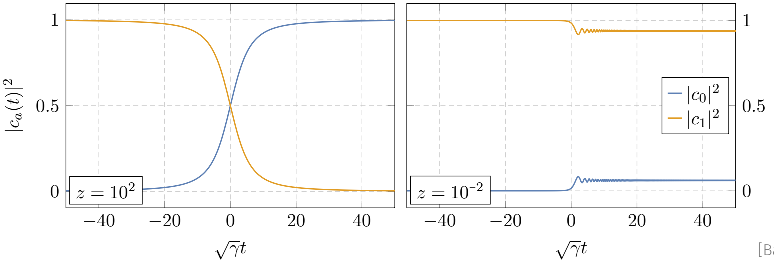
Resonances ("Landau-Zener transitions")



Resonances ("Landau-Zener transitions")

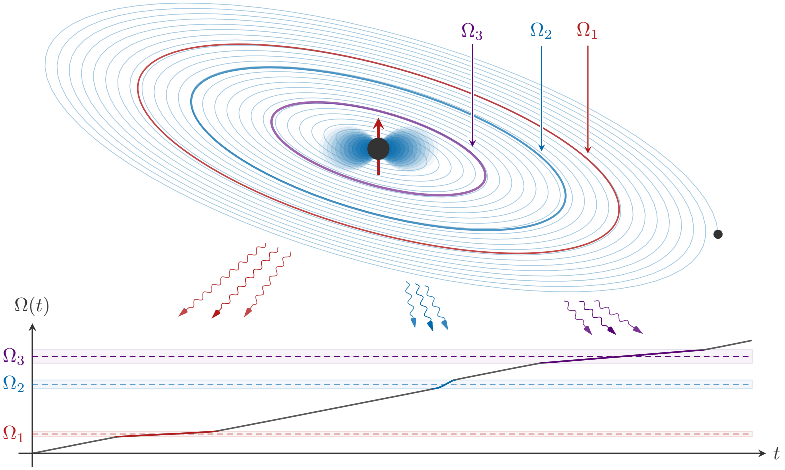






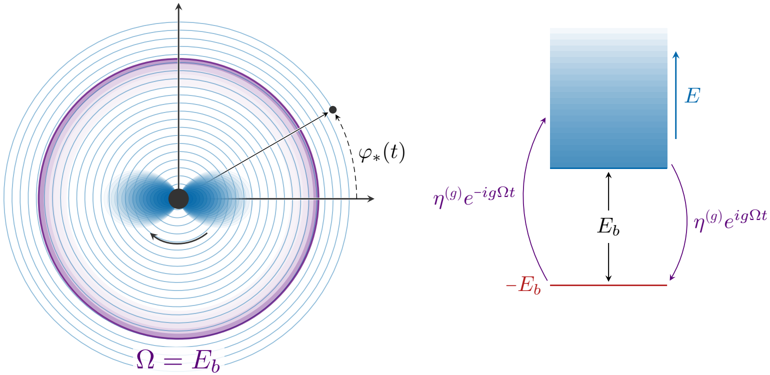
[Baumann, Chia, Porto, Stout 1912.04932]

Backreaction on the orbit



[Baumann, Chia, Porto, Stout 1912.04932]

Ionization Power

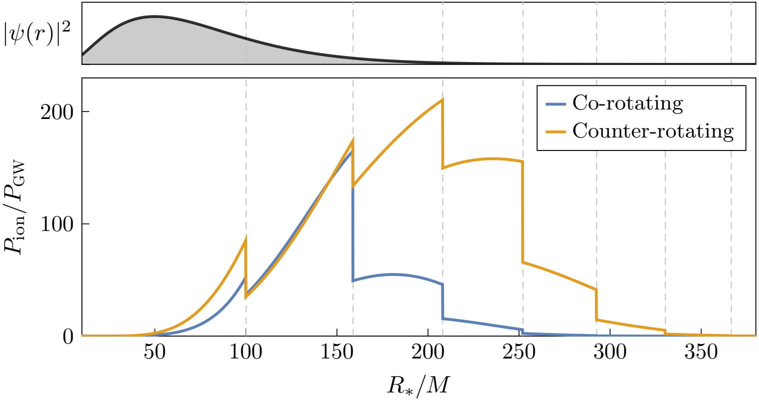


With Fermi's Golden Rule we can compute the **ionization power**:

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

[Baumann, Bertone, Stout, GMT 2112.14777]

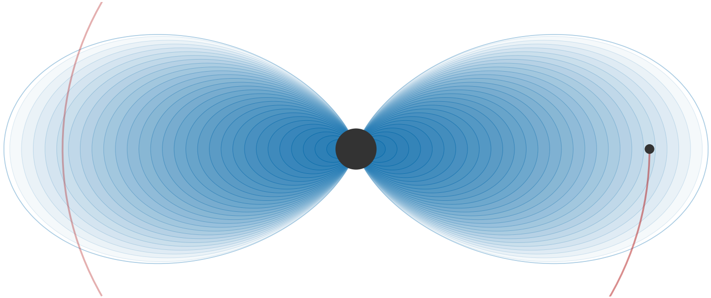
Sharp features



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

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

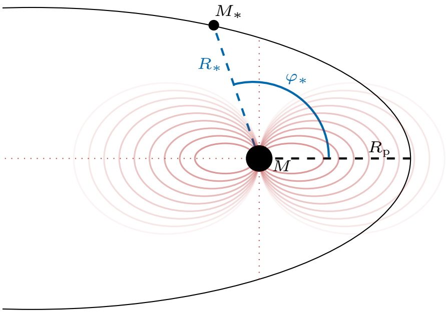
[Baumann, Bertone, Stout, GMT 2112.14777]



Backreaction of ionization = **dynamical friction**

[GMT, Spieksma, Bertone 2305.15460]

Dynamical Capture



Soft burst of GWs:

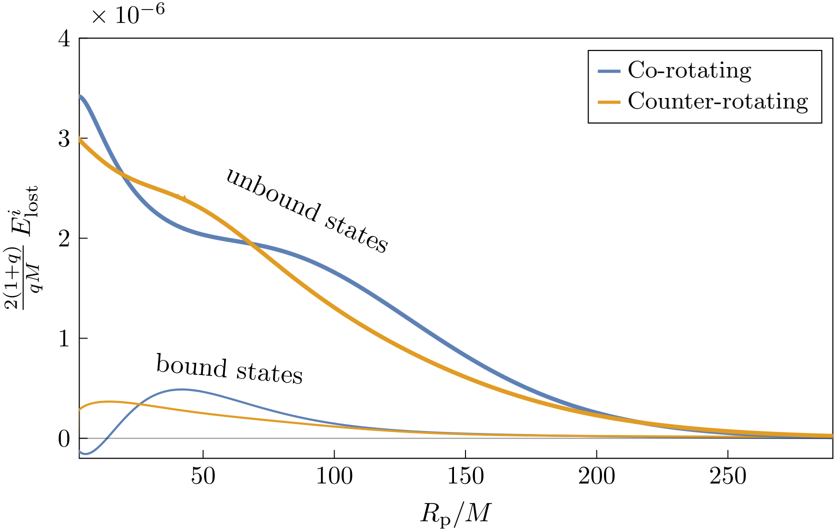
$$\sigma_{\mathsf{GW}} = 2\pi M^2 \left(\frac{85\pi}{6\sqrt{2}}\right)^{2/7} q^{2/7}(1+q)^{10/7} v^{-18/7}$$

$$\sigma_{\mathrm{tot}} = \sigma_{\mathsf{GW}} + \sigma_{\mathrm{cloud}}$$

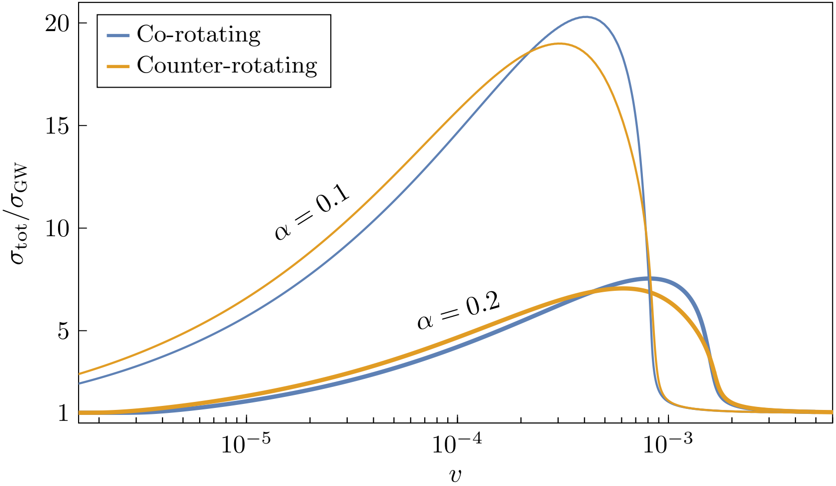
The cloud opens up a new channel for **energy loss**!

[GMT, Spieksma, Bertone 2305.15460]

Energy lost



[GMT, Spieksma, Bertone 2305.15460]



[GMT, Spieksma, Bertone 2305.15460]

Ionization on eccentric orbits

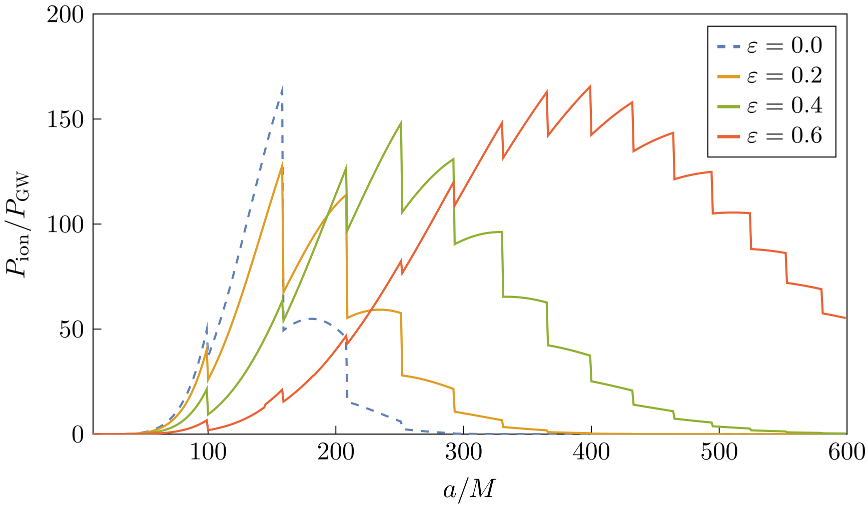
$$\langle E;\ell m|V_*(t,\vec{r})|n_b\ell_b m_b\rangle = \sum_{\ell_*,m_*} \frac{4\pi\alpha q}{2\ell_*+1} \overbrace{Y_{\ell_* m_*}(\theta_*,\varphi_*)\times I_r(R_*)}^{\text{not monochromatic}} \times I_\Omega$$

$$= \sum_g \eta^{(g)} e^{-ig\varphi_*(t)}$$

- g is now independent of m;
- no (simple) formula for $\eta^{(g)}$.

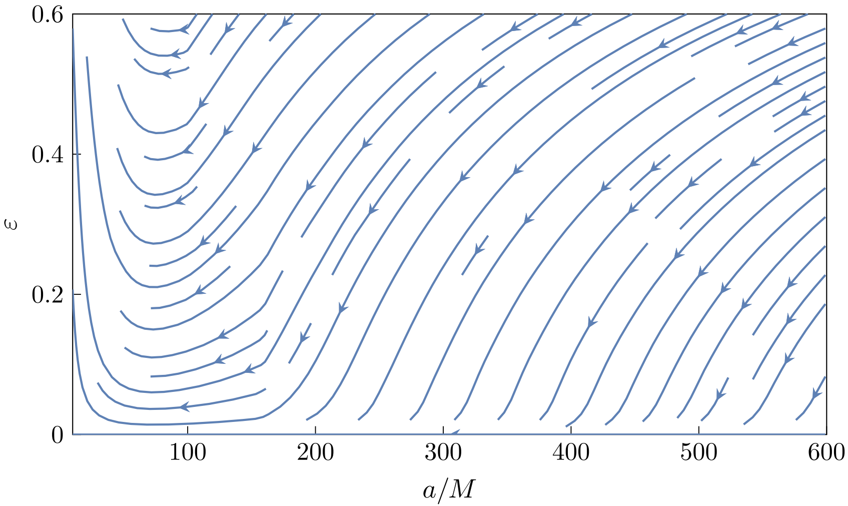
$$P_{\text{ion}} = \frac{M_{\text{c}}}{\mu} \sum_{\ell,m,g} g\Omega\, |\eta^{(g)}|^2\, \Theta(E_*^{(m)})$$

Ionization plot on eccentric orbits



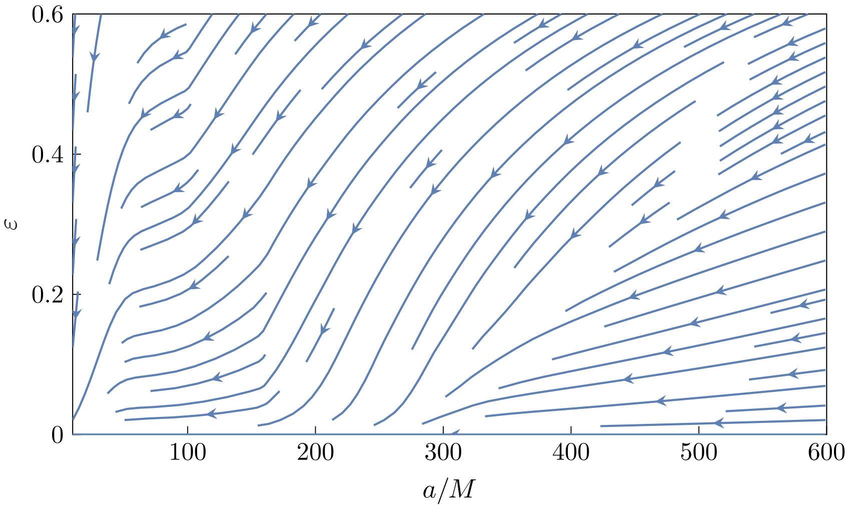
[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.01$, $q = 10^{-3}$, equatorial co-rotating]

Evolution of eccentricity (no GWs)



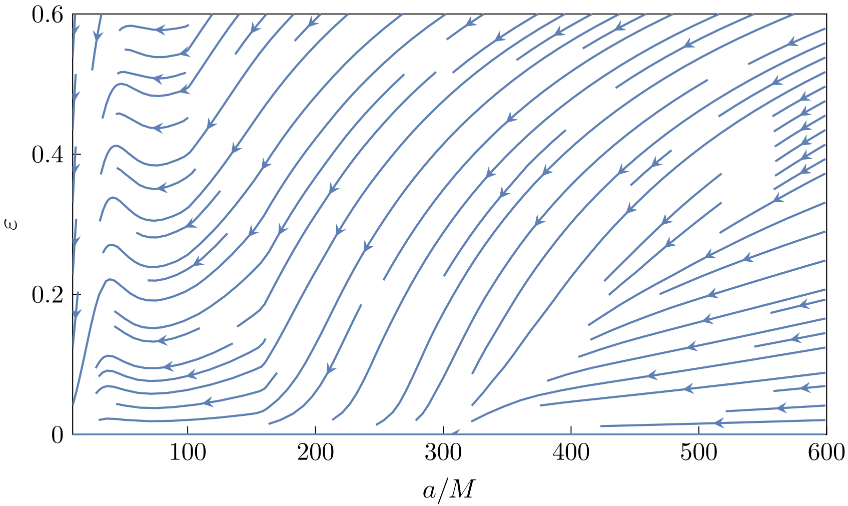
[$|211\rangle$, $\alpha = 0.2$, $q = 10^{-3}$, equatorial co-rotating]

Evolution of eccentricity



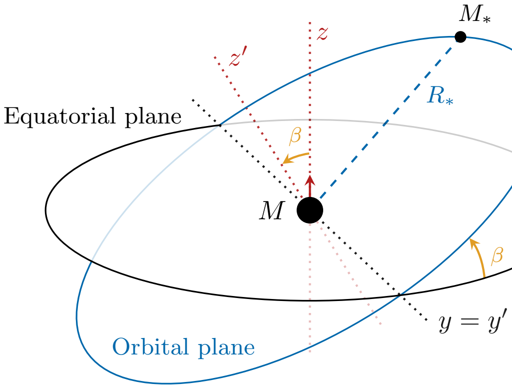
[$|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.01$, $q = 10^{-3}$, equatorial co-rotating]

Evolution of eccentricity (higher mass)



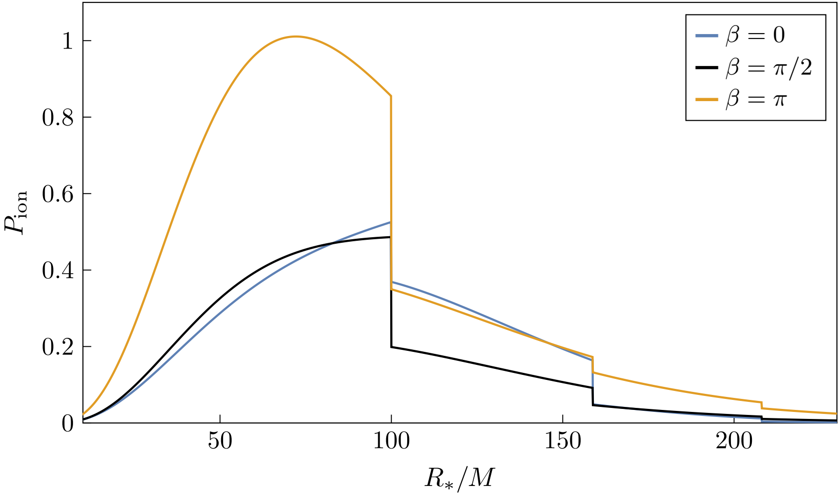
$[|211\rangle$, $\alpha = 0.2$, $M_c/M = 0.1$, $q = 10^{-3}$, equatorial co-rotating]

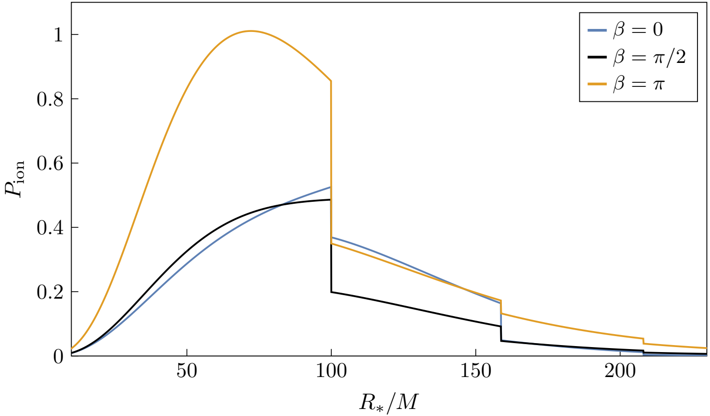
Ionization on inclined orbits



Precession? Evolution of β?

Ionization plot on inclined orbits





No precession! Negligible variation of β.

Level mixing

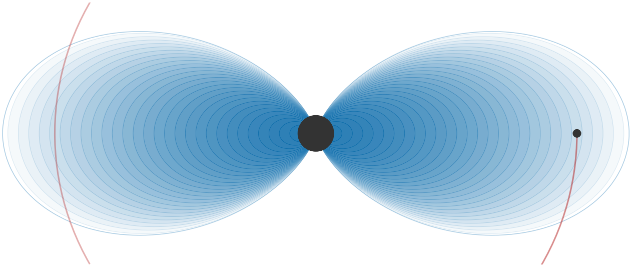
$$\mathrm{d}\Gamma_{\ell m} = \mathrm{d}E \underbrace{|\eta^{(g)}|^2}_{\text{Level mixing}} \delta(\underbrace{E - E_b - g\Omega(t)}_{E - E_*^{(m)}})$$

Multipole expansion:

$$\langle E; \ell m | V_*(t, \vec{r}) | n_b \ell_b m_b \rangle = \sum_{\ell_*, m_*} \frac{4\pi\alpha q}{2\ell_* + 1} Y_{\ell_* m_*}(\theta_*, \varphi_*) \times I_r(R_*) \times I_\Omega$$
$$= \sum_g \eta^{(g)} e^{-ig\Omega t}$$

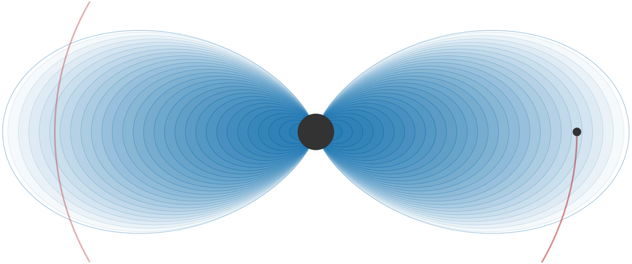
On **equatorial quasi-circular** orbits, $g = \pm(m - m_b)$.

Adapting P_{DF}



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

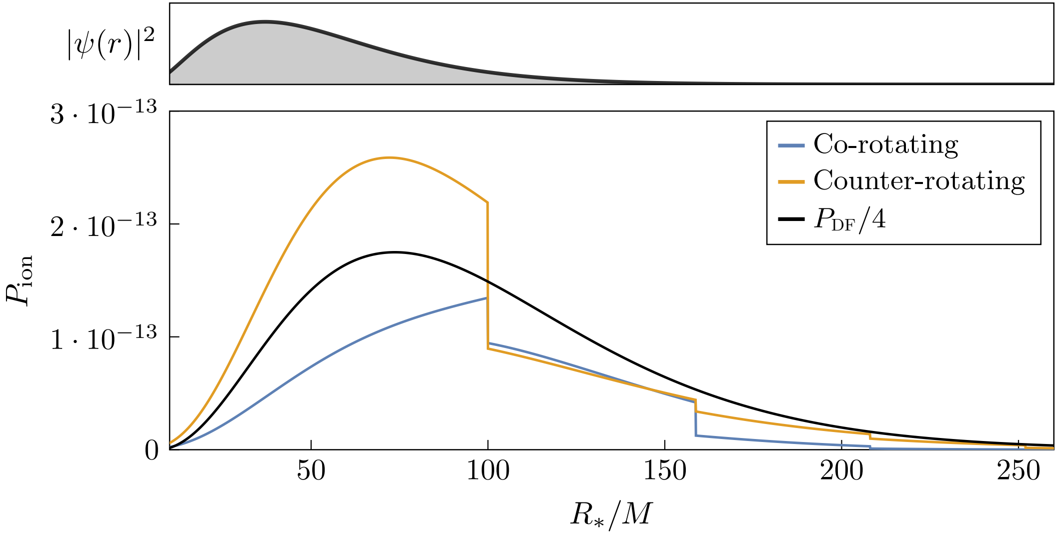
Adapting P_{DF}



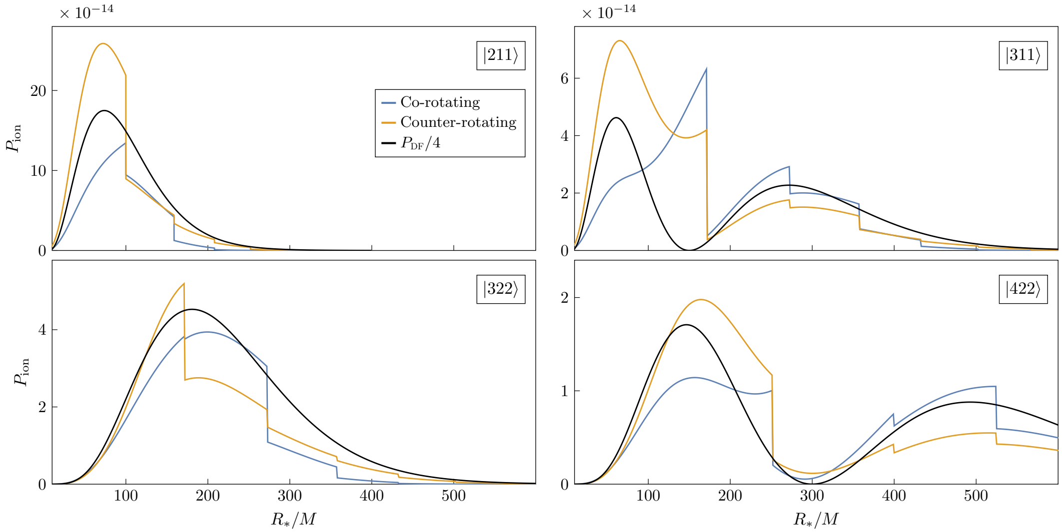
$$P_{\text{DF}} = \frac{4\pi M_*^2 \rho}{v} \log(v\mu b_{\max})$$

Need to fix: ρ, v, $b_{\max}$.

P_{ion} VS P_{DF}: NUMERICAL



P_{ion} VS P_{DF}: NUMERICAL



P_{ion} VS P_{DF}: PHYSICAL ARGUMENTS

- $P_{\text{ion}}/P_{\text{DF}}$ roughly independent of the state;
- $P_{\text{ion}}/P_{\text{DF}}$ independent of the parameters:

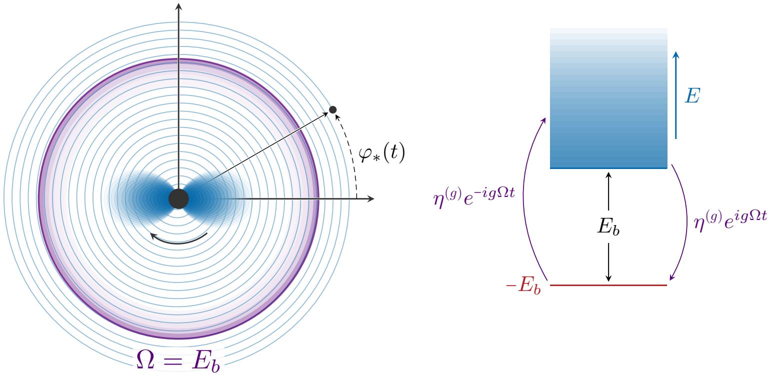
$$P_{\text{DF}} \sim P_{\text{ion}} = \alpha^5 q^2 \frac{M_{\text{c}}}{M} \mathcal{P}(\alpha^2 R_*/M)$$

- Same physical interpretation:

$$P_{\text{DF}} \sim P_{\text{ion}} = \int_{\partial V} T^{0i} \, \mathrm{d}S$$

- What does P_{DF} fail to describe?

Fermi's Golden Rule



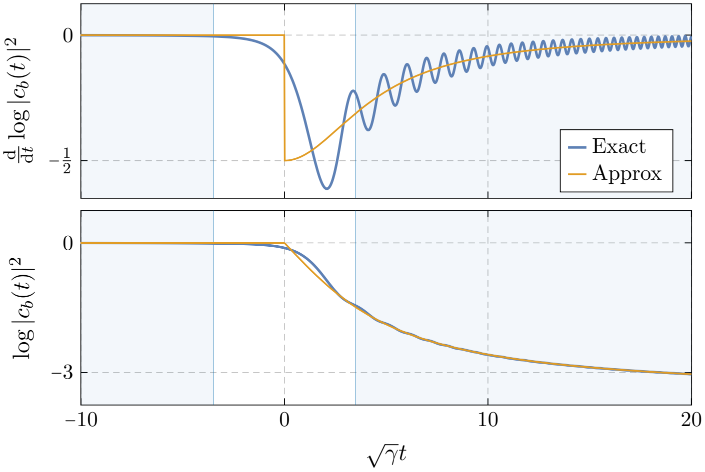
The transition rate (per unit energy) is given by Fermi's Golden Rule:

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

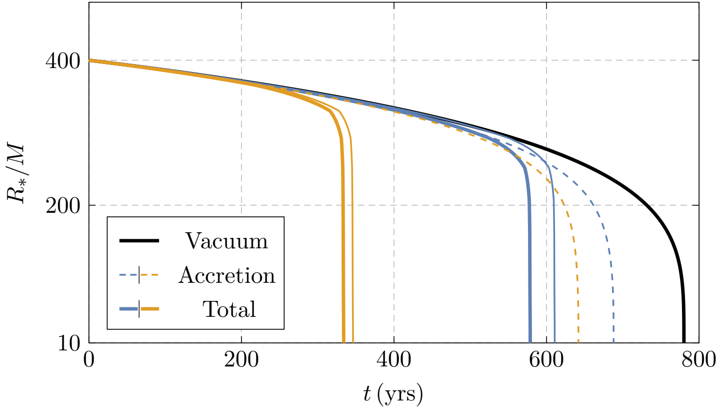
[Baumann, Bertone, Stout, GMT 2112.14777]

Discontinuities?

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



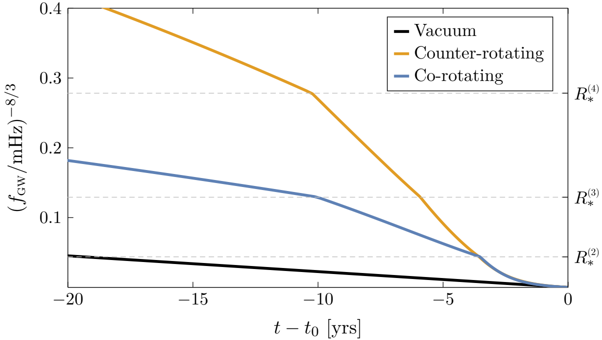
Large impact on IMRI, for both co-rotating and counter-rotating orbits.



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

KINKS IN THE FREQUENCY

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



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

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[Baumann, Bertone, Stout, GMT 2206.01212]

Ionization plot on inclined orbits