Black holes

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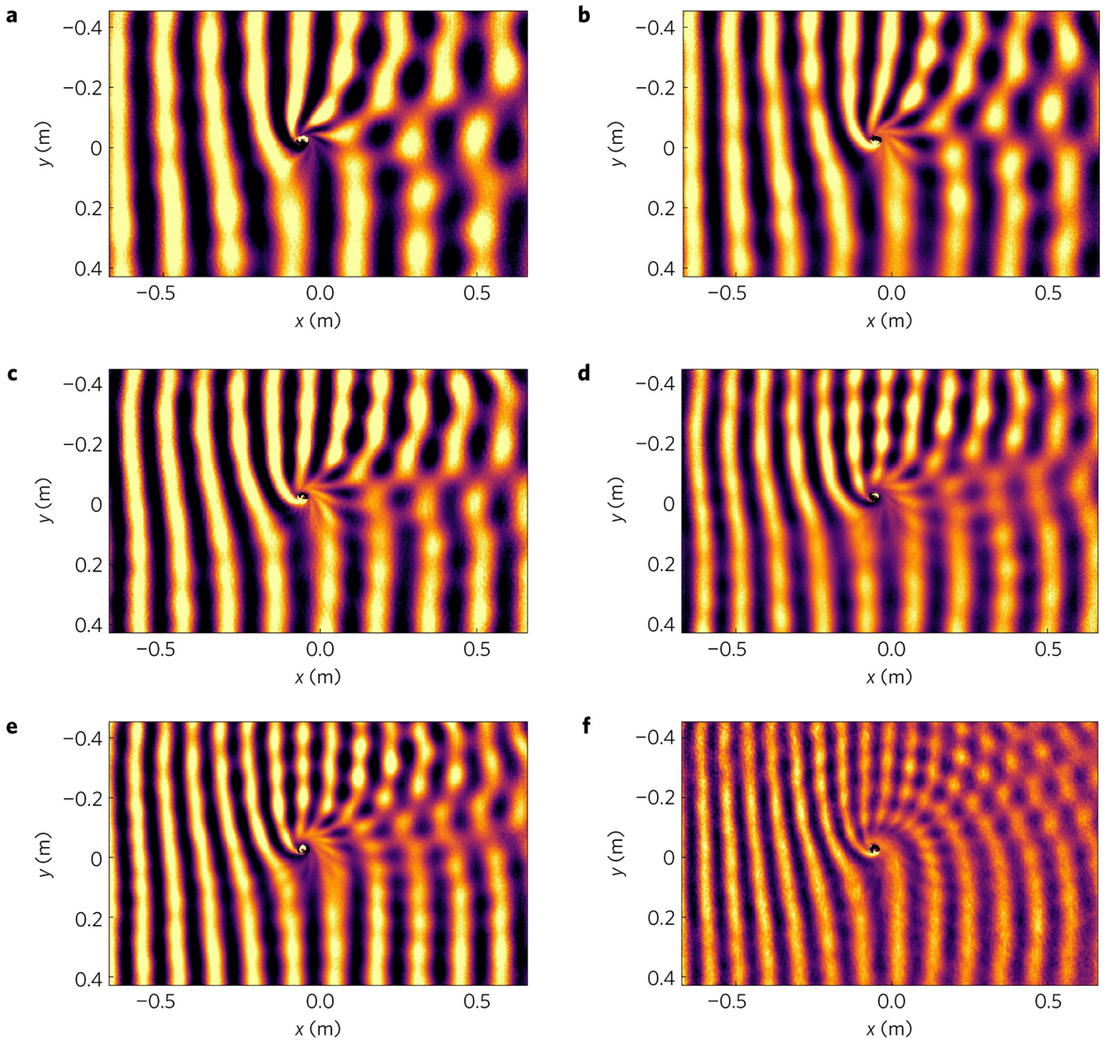
Black hole superradiance

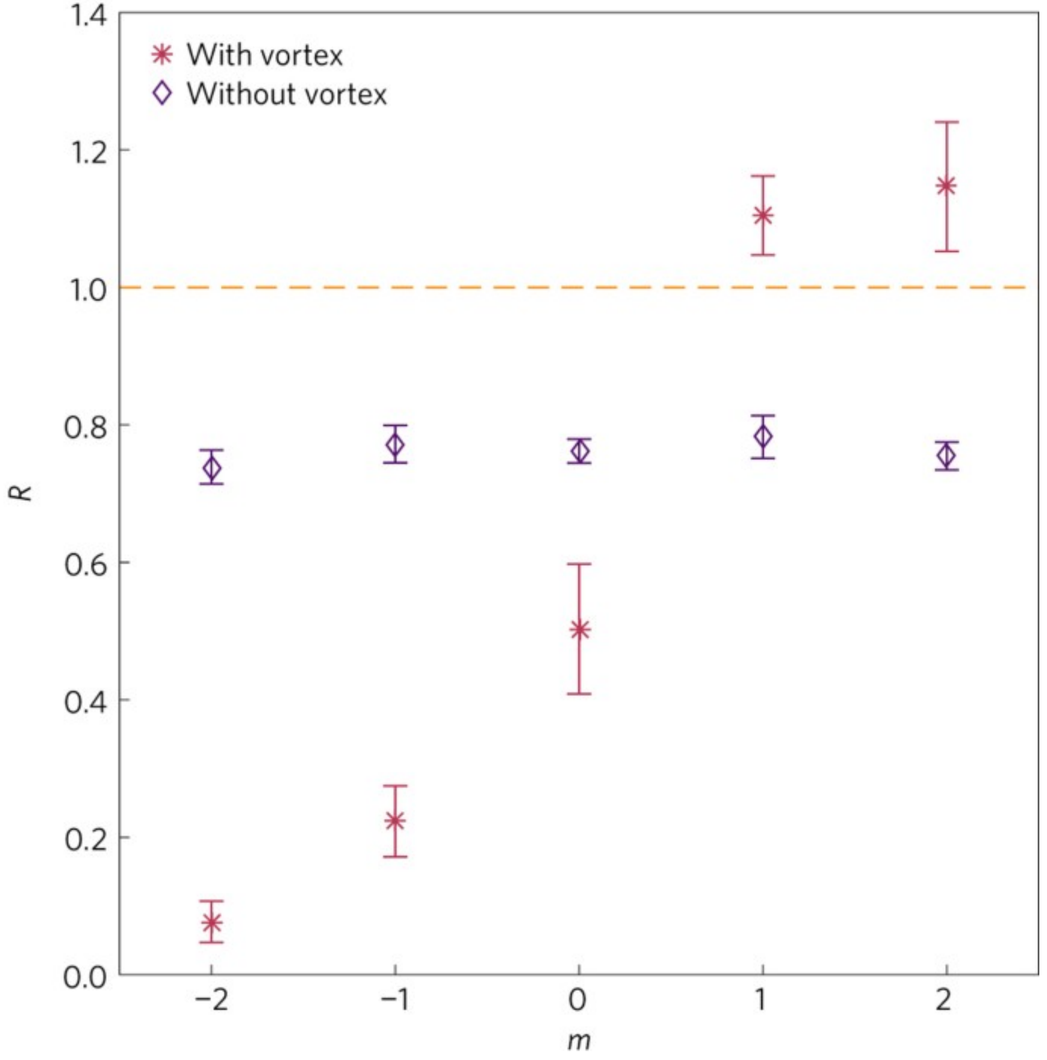
To the blackboard

Rotational Superradiance

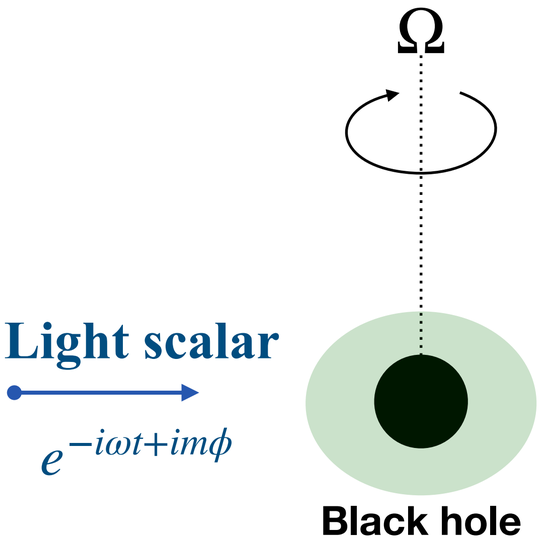
Rotational superradiance

Rotational superradiance





‘Black hole bombs’



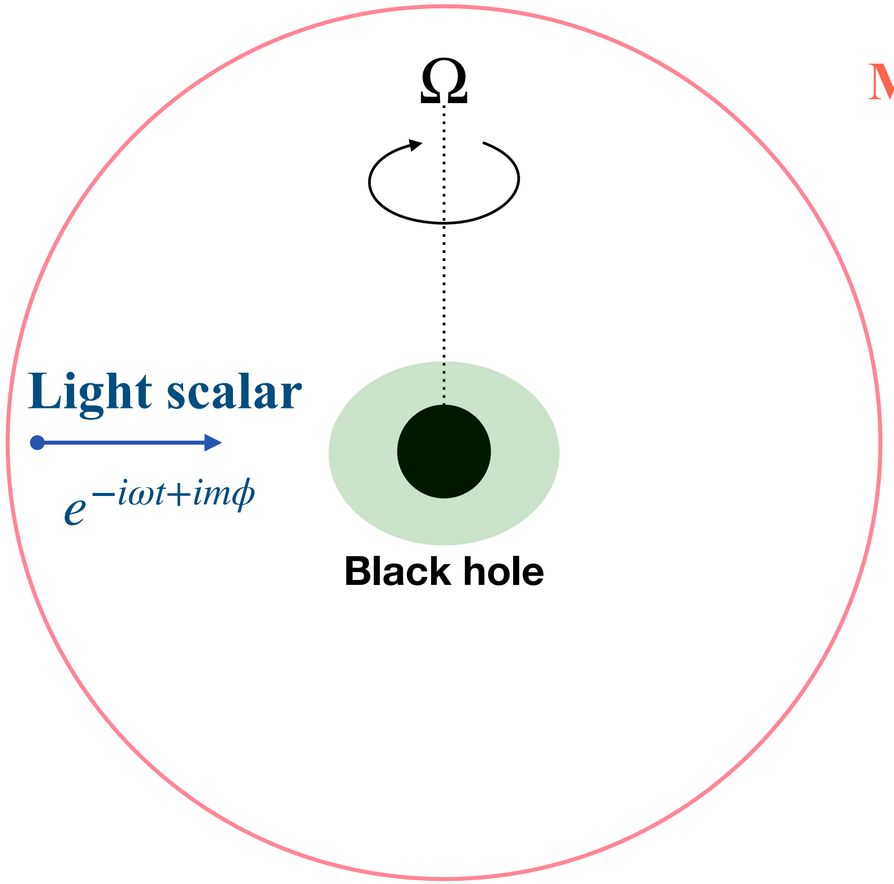
Amplification

$$\omega < m\Omega$$

Dissipation induced by ergoregion

Press & Teukolsky (1972)

‘Black hole bombs’



Mirror

Amplification

$$\omega < m\Omega$$

Dissipation induced by ergoregion

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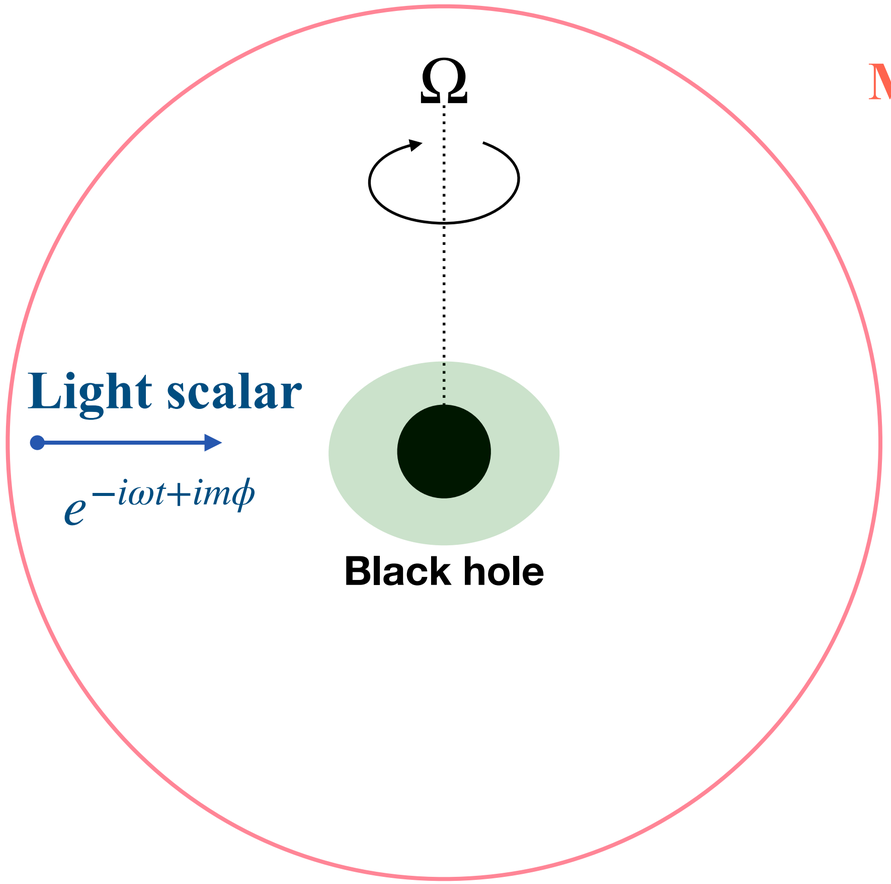

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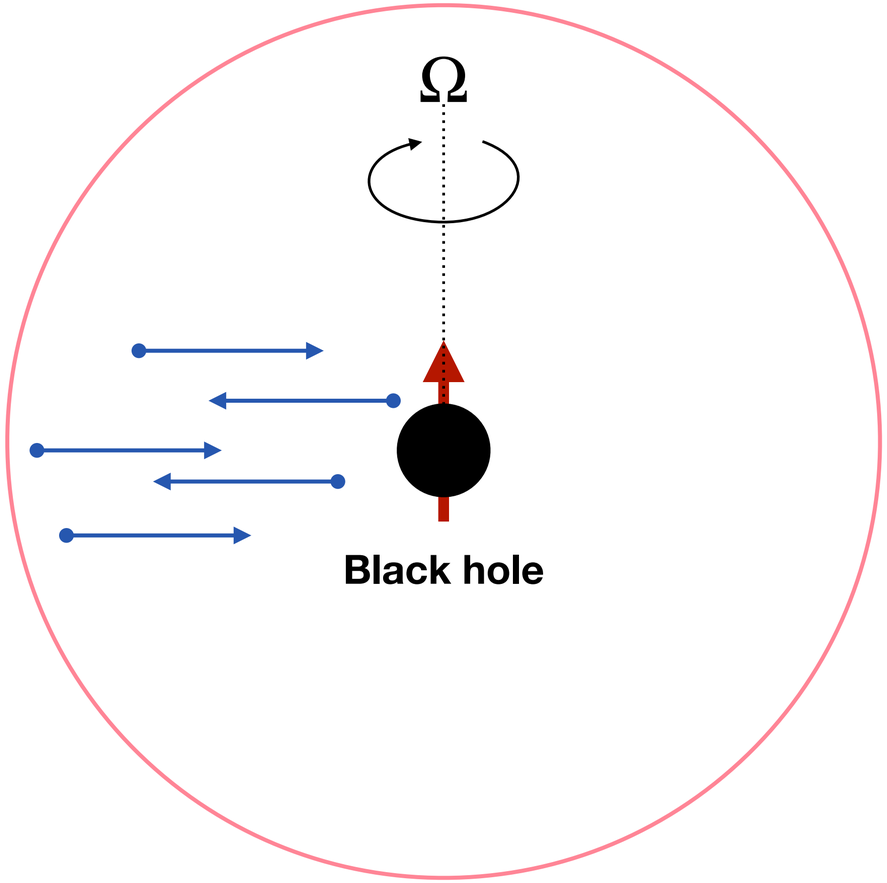

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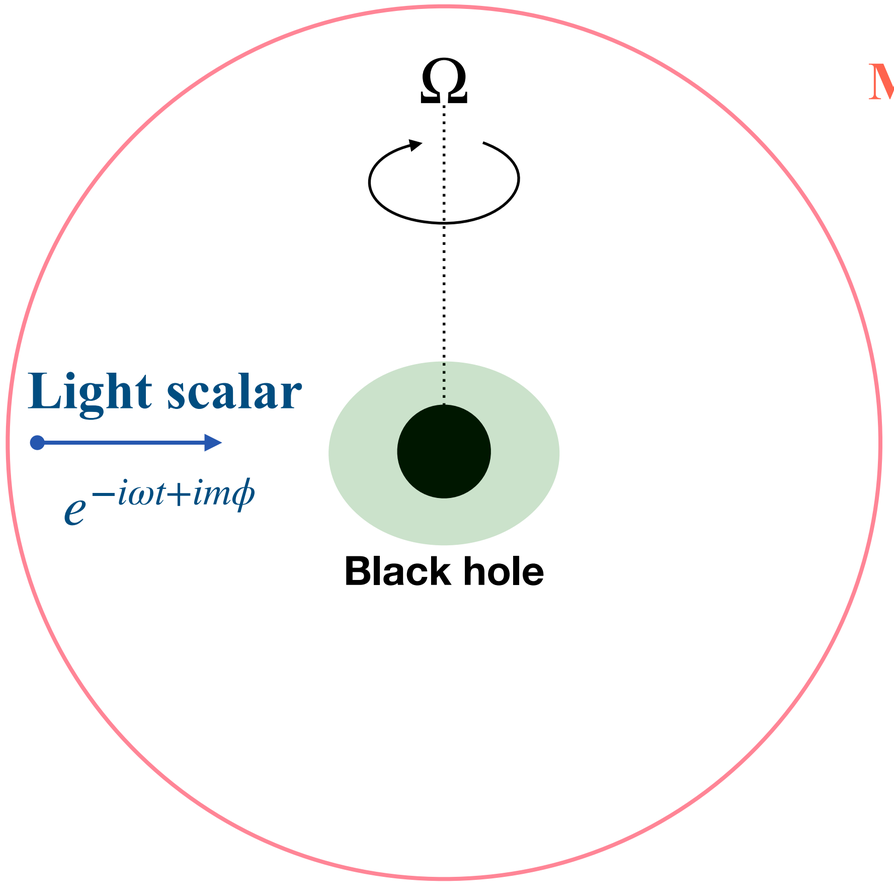
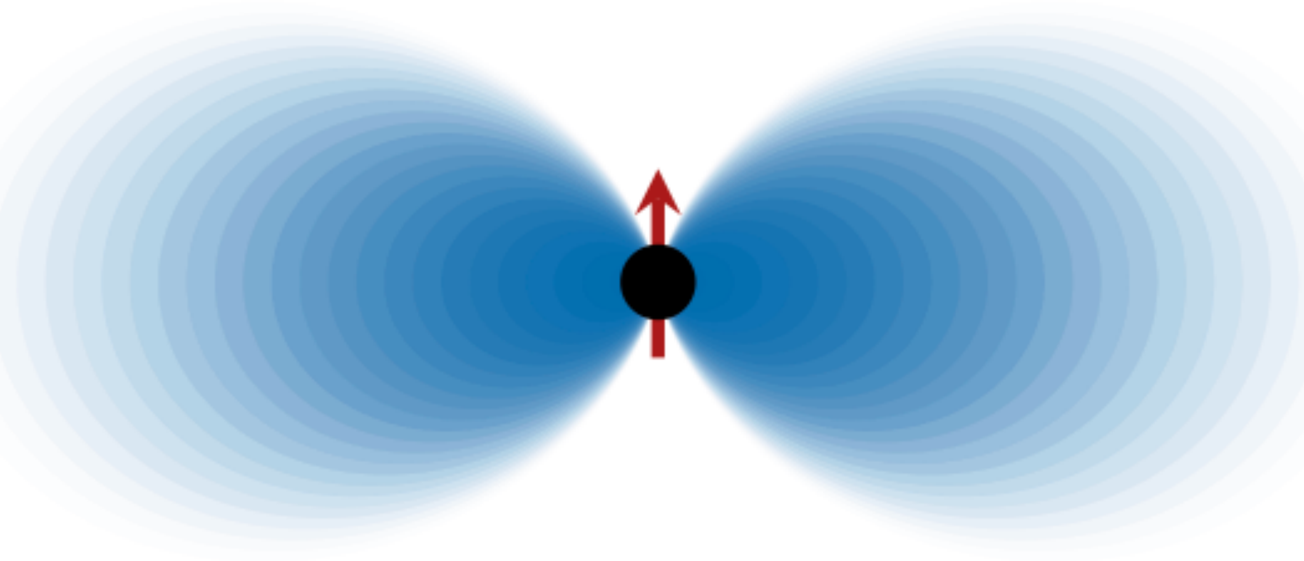


Mirror

Amplification

$\omega < m\Omega$

$\omega = m\Omega$



$\rho \sim 10^{35}\rho_{\rm DM}$

Dissipation induced by ergoregion

Press & Teukolsky (1972)

Black hole superradiance

To the blackboard

Eigenstates of a scalar field around a Kerr black hole

$$\left(\Box - \mu^2\right)\Phi = 0$$

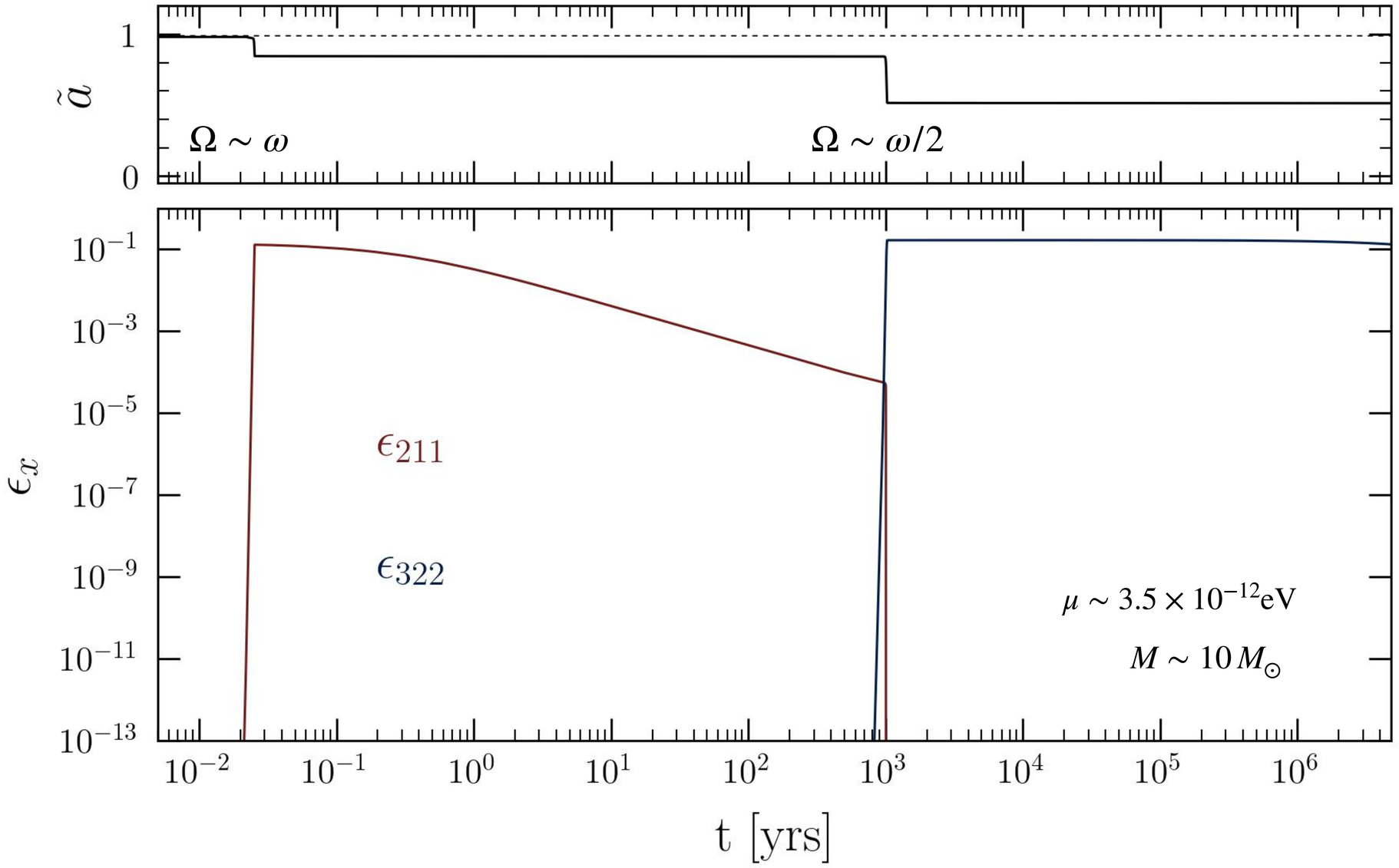
Black hole superradiance

SJW & Mummery (2024)

Dimensionless Spin

$(0 < \tilde{a} \lesssim 1)$

Normalized Bound State Density



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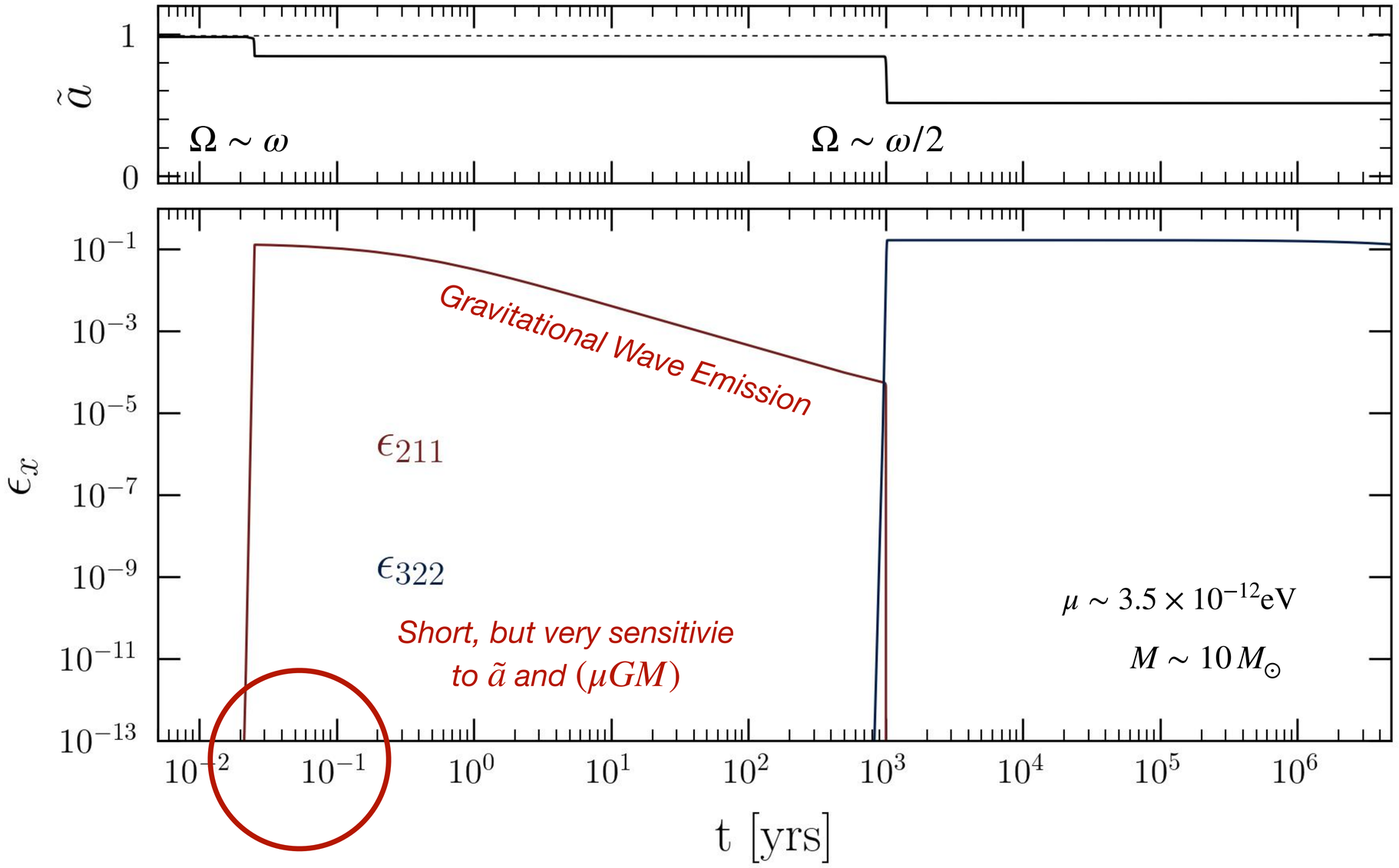
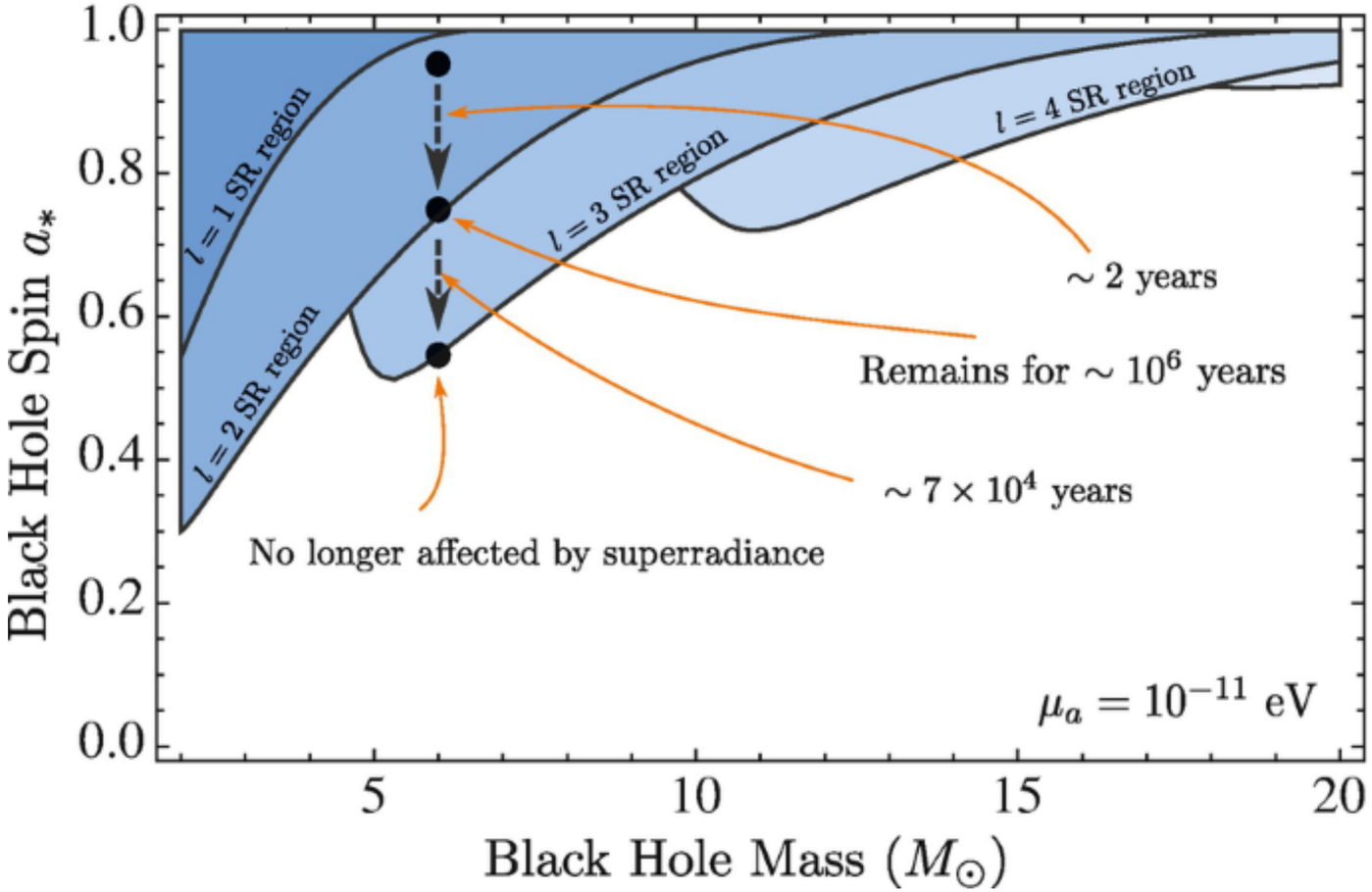


Observable Consequences

- Incompatibility of highly spinning black holes



Arvanitaki, Dimopoulos, Dubovsky. Kaloper, J. March-Russell (2010)

Observable Consequences

- Narrow Freq. Gravitational Waves

$|nlm\rangle$

$|nlm\rangle$

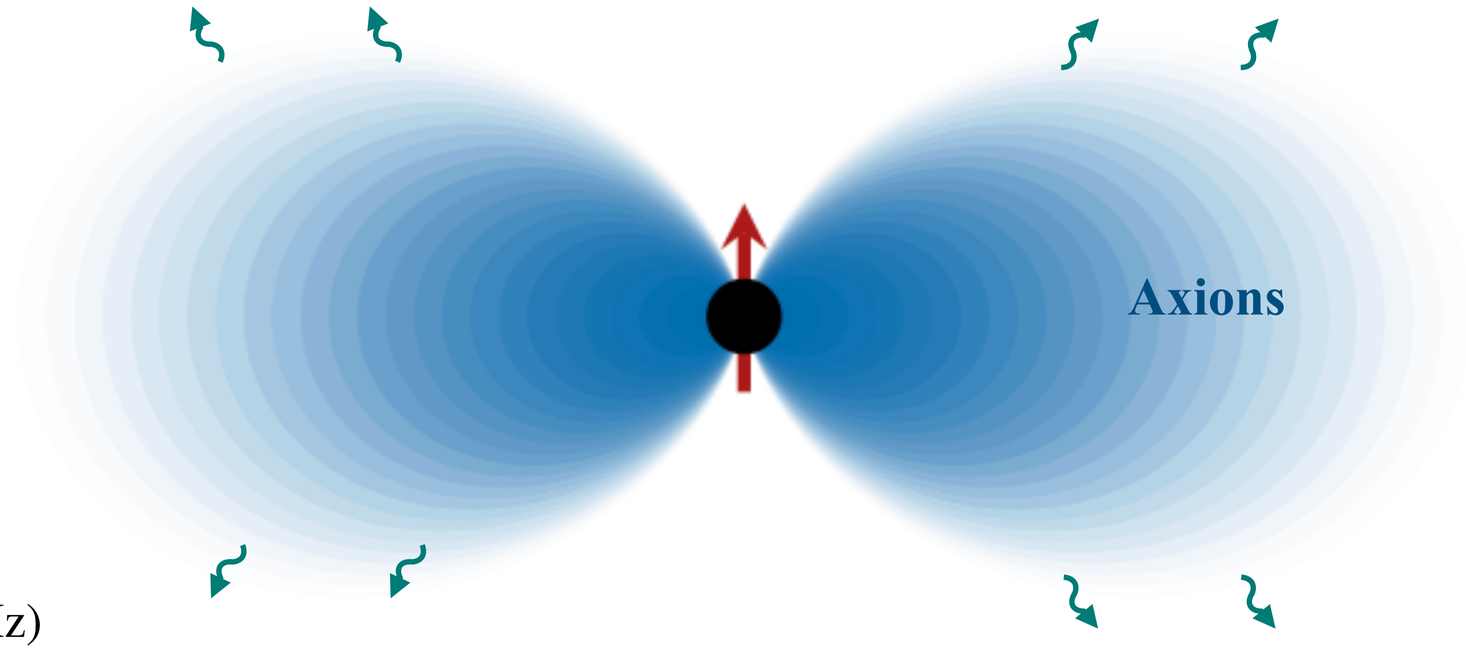
GW

$f \sim 2m_a \lesssim \mathcal{O}(\text{kHz})$

$|n'l'm'\rangle \dashrightarrow |nlm\rangle$

GW

$f \sim (E_{b'} - E_b) \lesssim \mathcal{O}(\text{Hz})$



Zeldovich (1972) Press & Teukolsky (1972), Arvanitaki, Dimopoulos, Dubovsky. Kaloper, J. March-Russell (2010), Arvanitaki & Dubovsky (2011), Brito, Cardoso, Pani (2015)

But they are not always isolated…

- Binary compansions can deplete clouds…

  but generate additional GW signatures

- Accretion / mergers can complicate long-time evolulationary history

See e.g. Baumann et al (2019, 2021, 2022), Berti et al (2019), Tomaselli et al (2024), Chia et al (2023), Bošković et al (2024), …

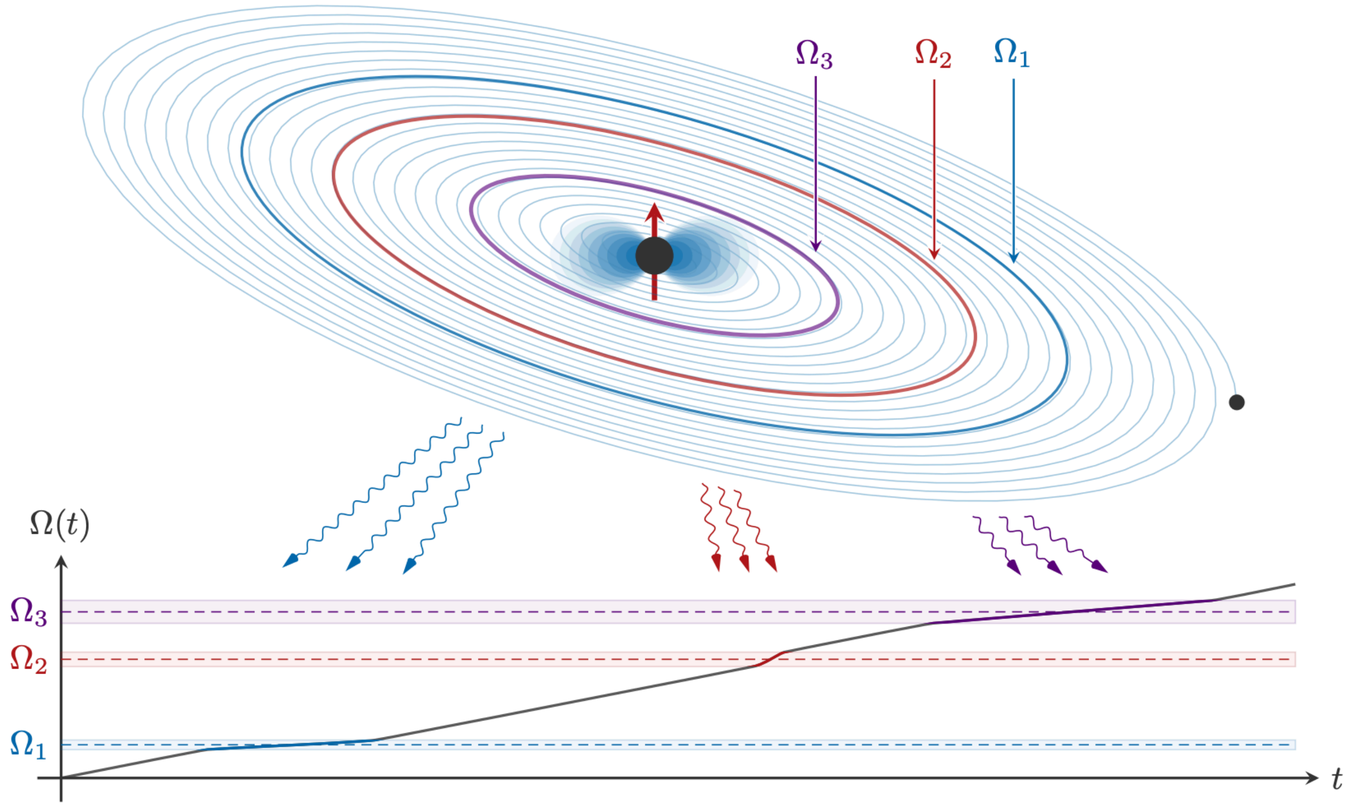


Image credit: Baumann et al (2019)

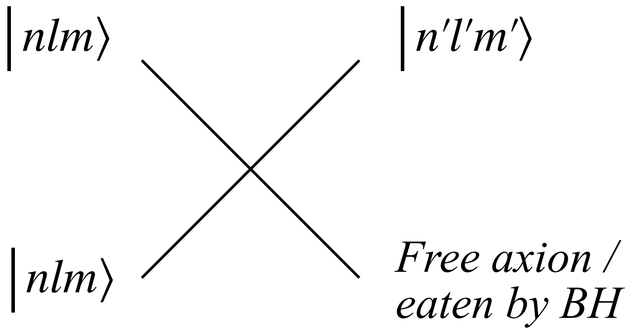
Nor are non-interacting…

To the blackboard

Derivation of self-interactions

Axions are not non-interacting...

$$\left(\Box - m^2\right)\phi = -\frac{\lambda}{6}\phi^3$$



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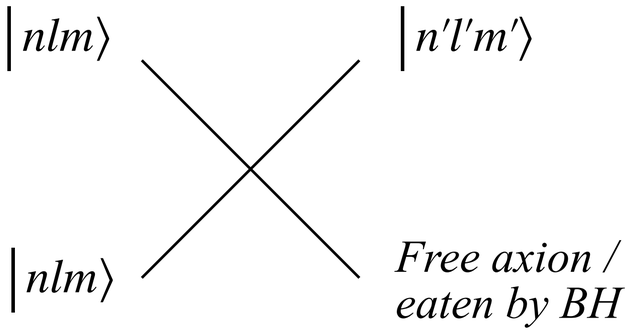


Drive system toward equilibrium density

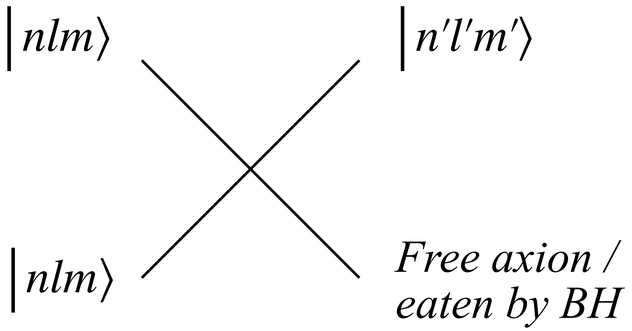
Consequences:

- *Linear spin extraction*
- *Less GWs*
- *Coupled non-linear evolution*
- *Axion background*

Axions are not non-interacting…

SJW & Mummery (2024)

$$\left(\Box - m^2\right)\phi = -\frac{\lambda}{6}\phi^3$$



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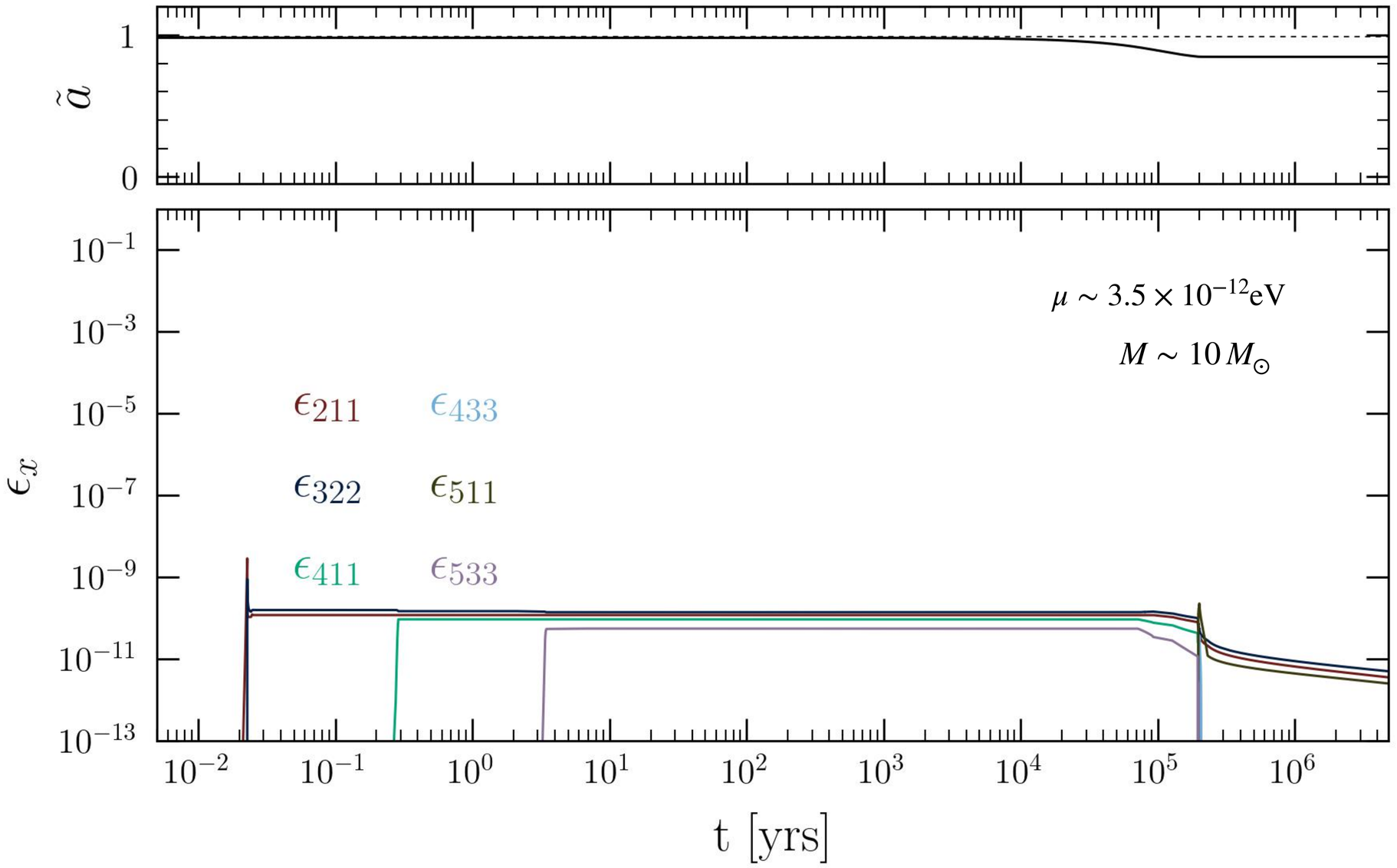

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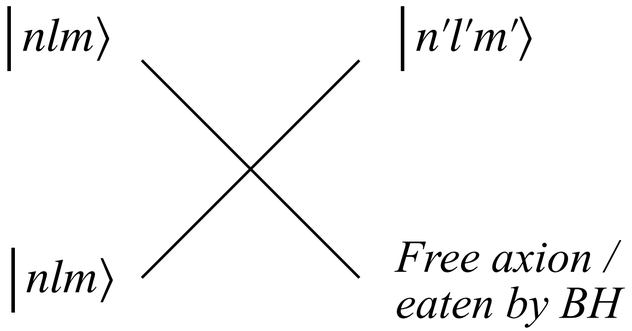

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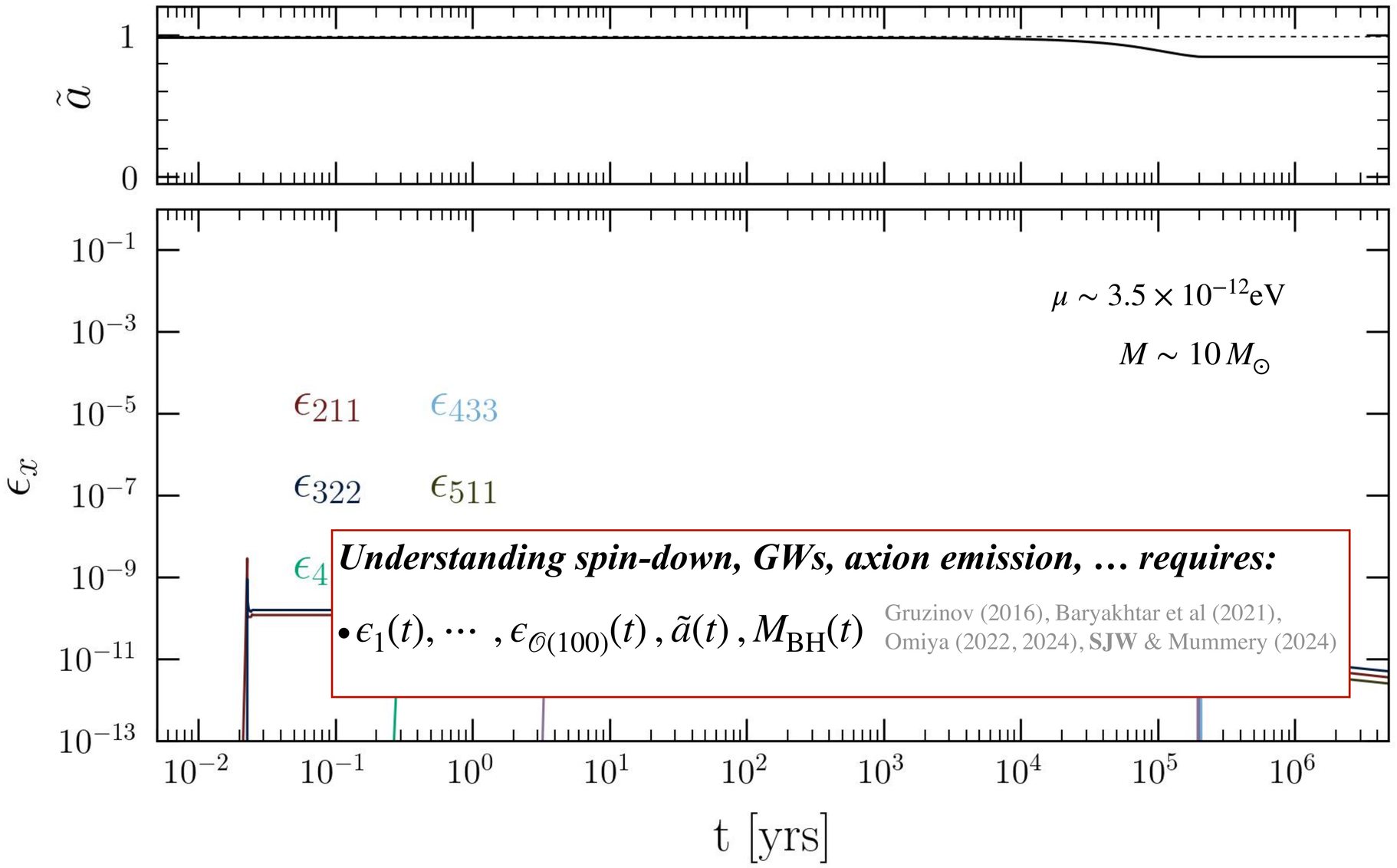


Understanding spin-down, GWs, axion emission, … requires:

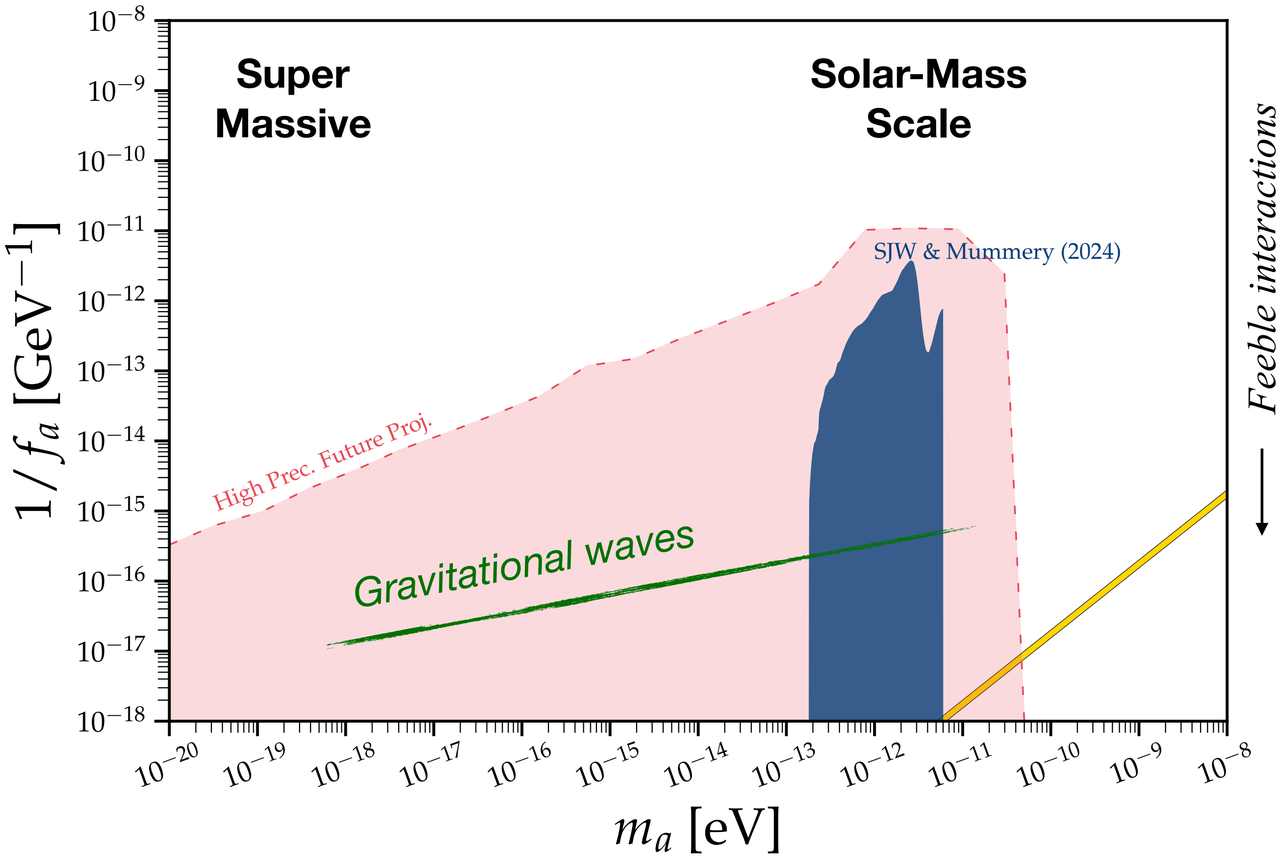
- $\epsilon_1(t), \cdots, \epsilon_{\mathcal{O}(100)}(t), \tilde{a}(t), M_{\rm BH}(t)$

Gruzinov (2016), Baryakhtar et al (2021), Omiya (2022, 2024), SJW & Mummery (2024)

Consequences:

- *Linear spin extraction*
- *Less GWs*
- *Coupled non-linear evolution*
- *Axion background*

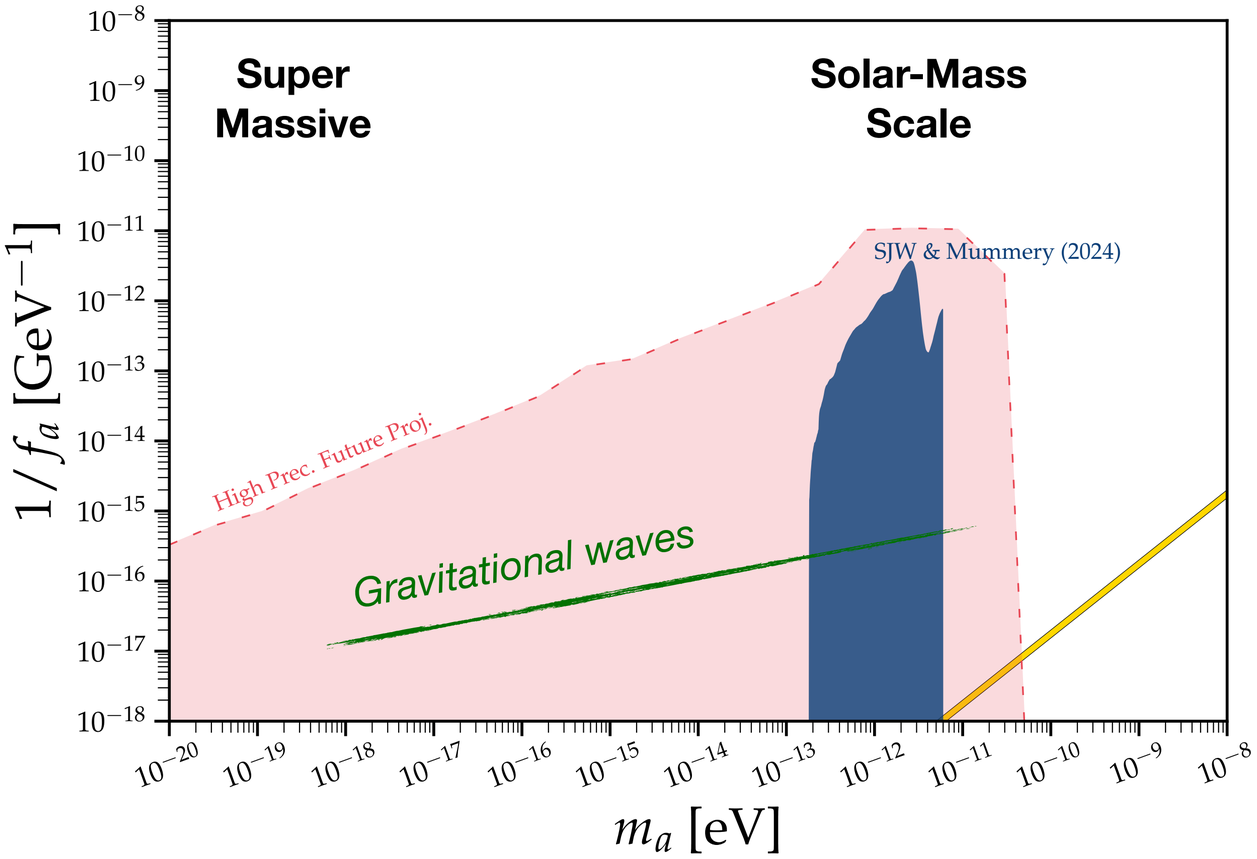
Current status and outlook



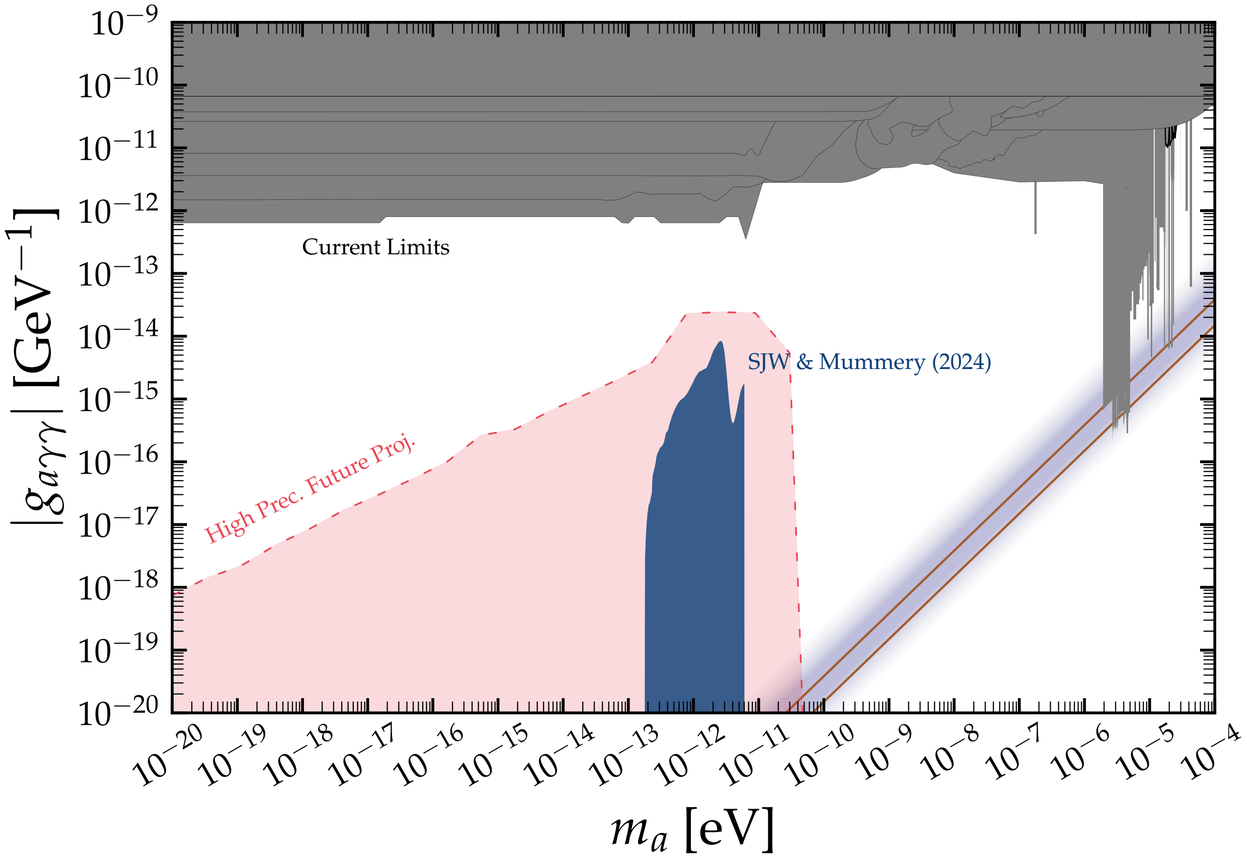
Generally applicable to light bosons (higher spin = faster rates)!

SJW & Mummery (2024)

Current status and outlook



$$g_{a\gamma} \sim \mathcal{O}(1)\frac{\alpha_{\rm em}}{2\pi f_a}$$



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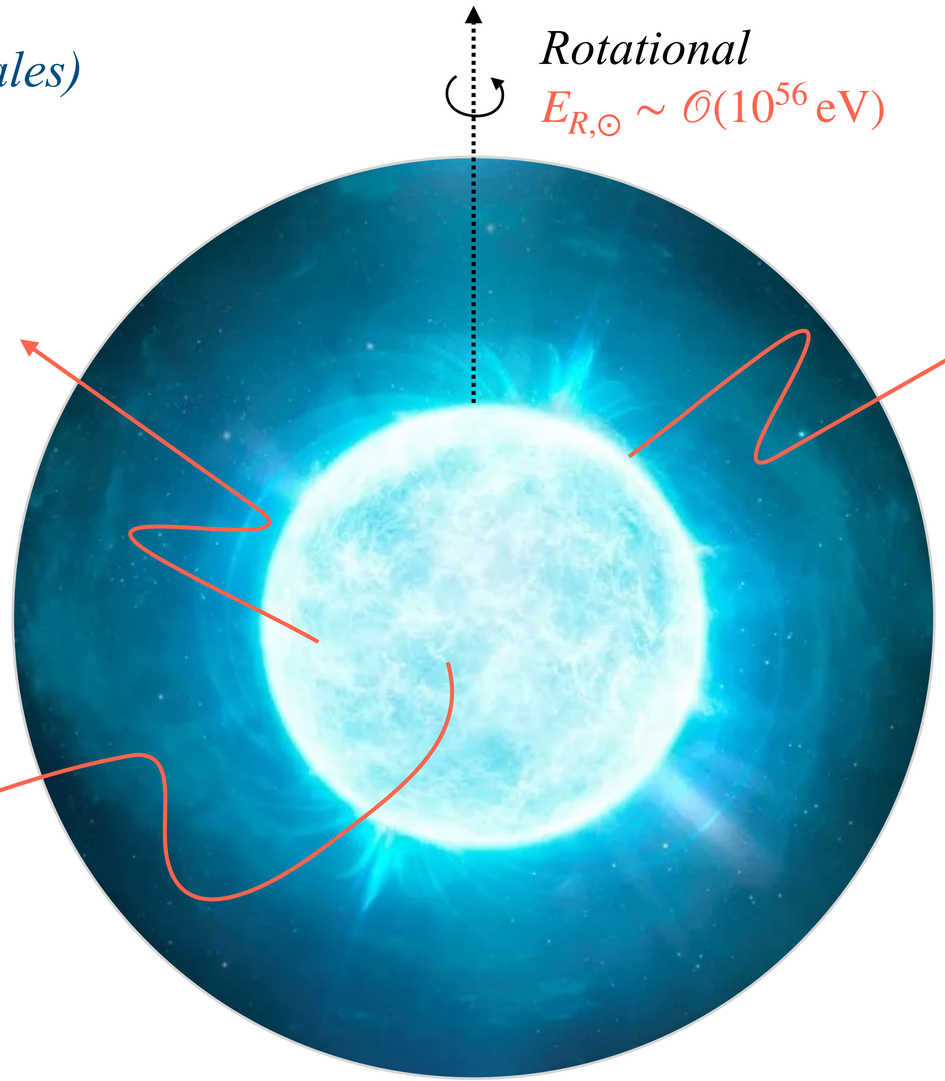
SJW & Mummery (2024)

Axions near compact objects

- *Large energy resevoirs*
- *Confinement (+ Astrophysical timescales) = large densities*



Rotational

$E_{R,\odot} \sim \mathcal{O}(10^{56}\,\mathrm{eV})$

Nuclear

$E_{N,\odot} \sim \mathcal{O}(10^{66}\,\mathrm{eV})$

Thermal

$E_{T,\odot} \sim \mathcal{O}(10^{55}\,\mathrm{eV})$

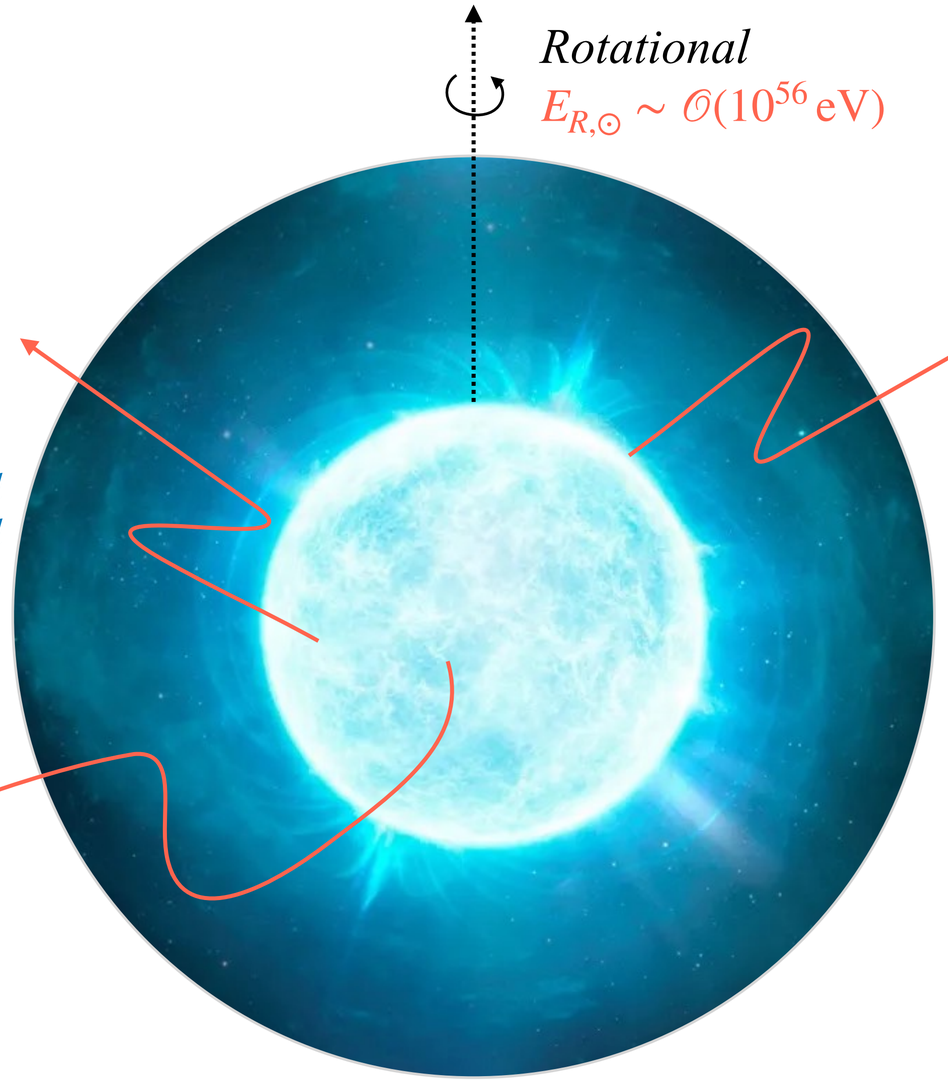
Linear Kinetic

$E_{K,\odot} \sim \mathcal{O}(10^{60}\,\mathrm{eV})$

Electromagnetic

$E_{B,\odot} \sim \mathcal{O}(10^{56}\,\mathrm{eV})$

Axions near compact objects



Rotational

$E_{R,\odot} \sim \mathcal{O}(10^{56}\,\mathrm{eV})$

Nuclear

$E_{N,\odot} \sim \mathcal{O}(10^{66}\,\mathrm{eV})$

*See e.g. Hook & Huang (2017), Balkin et al (2021,2022,2023), Gomez-Banon et al (2024), Kumaoto et al (2024), Caputo, **SJW**, et al (to appear)*

Thermal

$E_{T,\odot} \sim \mathcal{O}(10^{55}\,\mathrm{eV})$

'Stellar basins', K. Van Tillberg (2021)

Linear Kinetic

$E_{K,\odot} \sim \mathcal{O}(10^{60}\,\mathrm{eV})$

(dynamical friction, see e.g. Aurrekoetxea et al 2023, Tomaselli 2025)

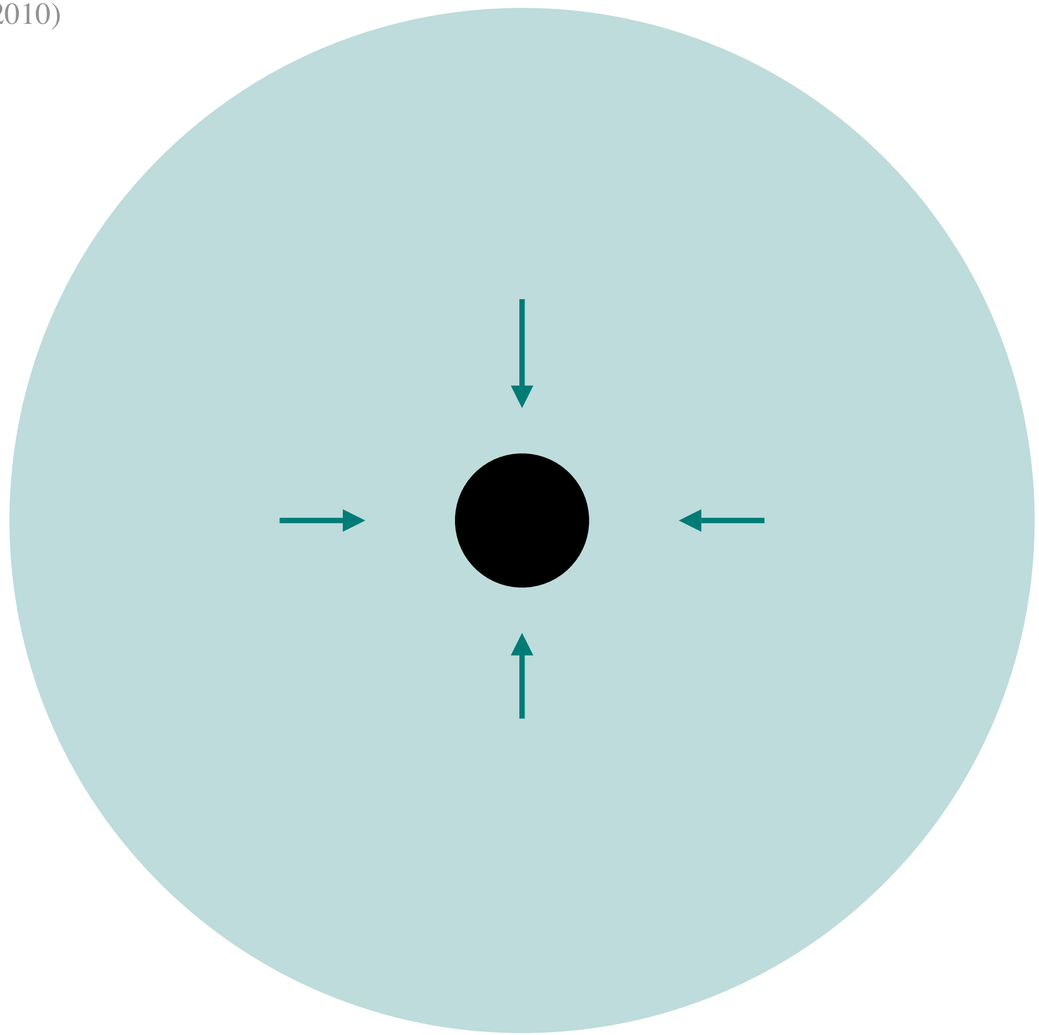
Electromagnetic

$E_{B,\odot} \sim \mathcal{O}(10^{56}\,\mathrm{eV})$

***SJW** et al (to appear)*

Dark matter spikes

Gondolo & Silk (1999), Lacki & Beacom (2010)



Dark matter is collisionless, and so contracts adibatically creating dense local spike

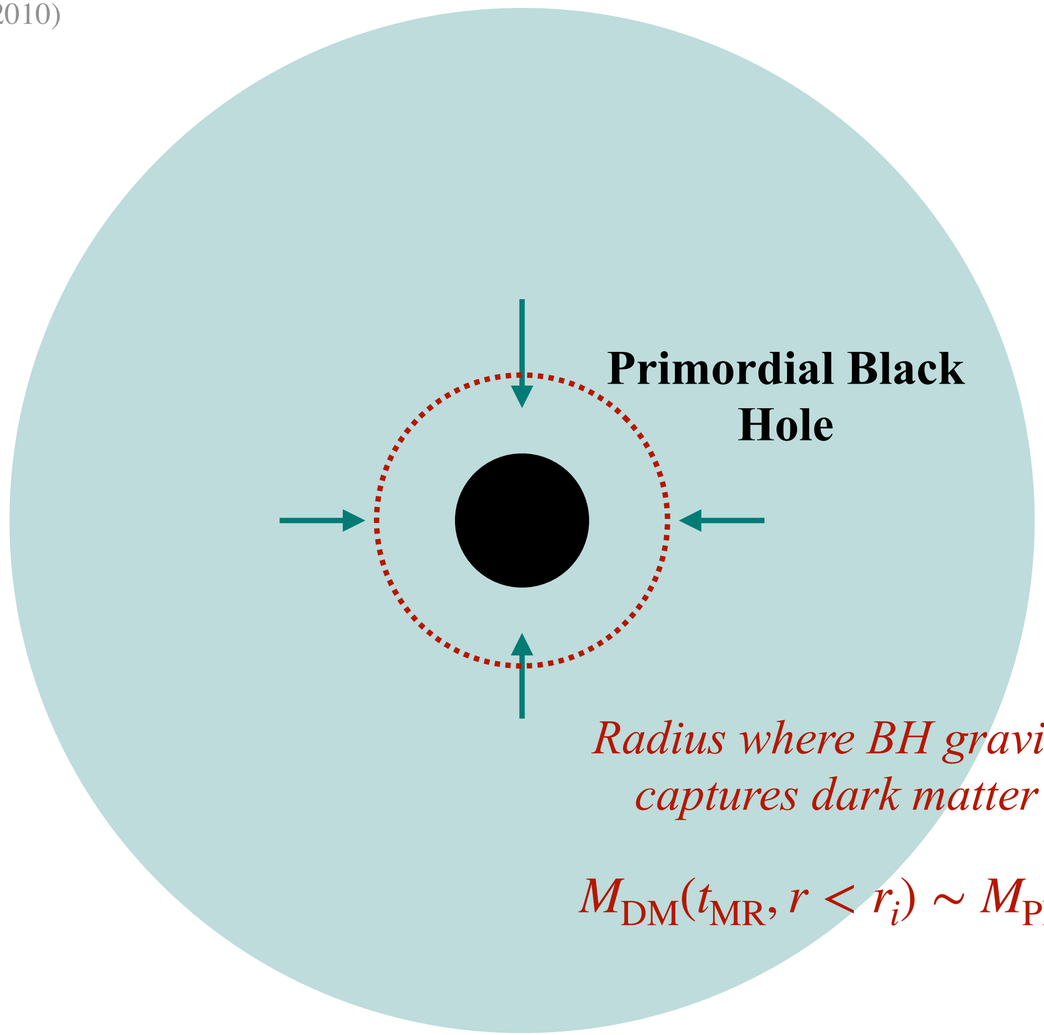
For negligible KE (and no interactions),

$$\rho \propto r^{-9/4}$$

Non-relativistic dark matter

Dark matter spikes

Gondolo & Silk (1999), Lacki & Beacom (2010)



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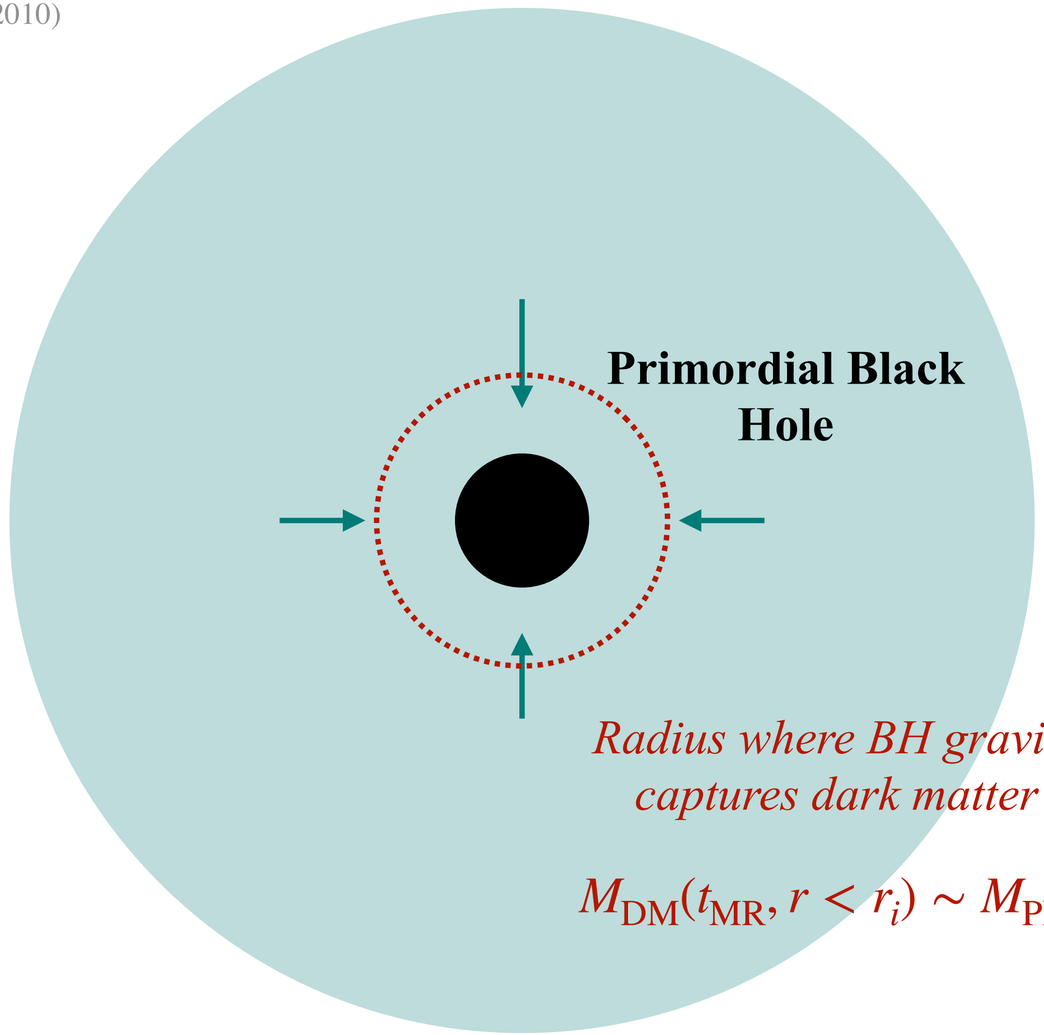

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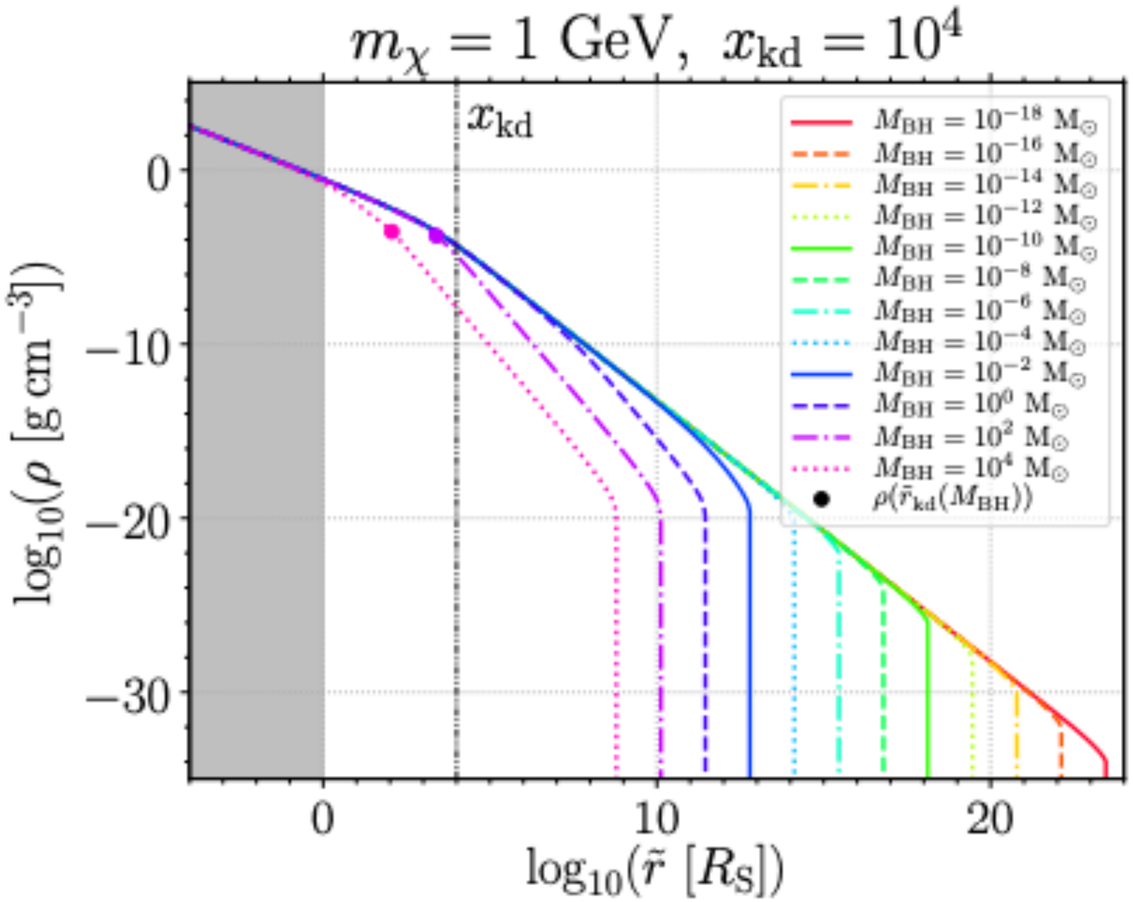
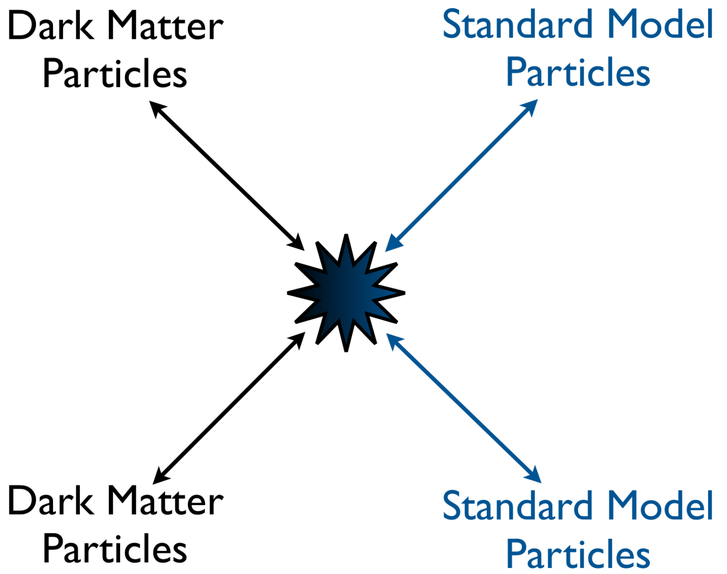
What sort of observational consequences arise from ultra-dense regions around these objects?

Non-relativistic dark matter

Dark matter spikes

(Search strategies for WIMPS + PBHs)





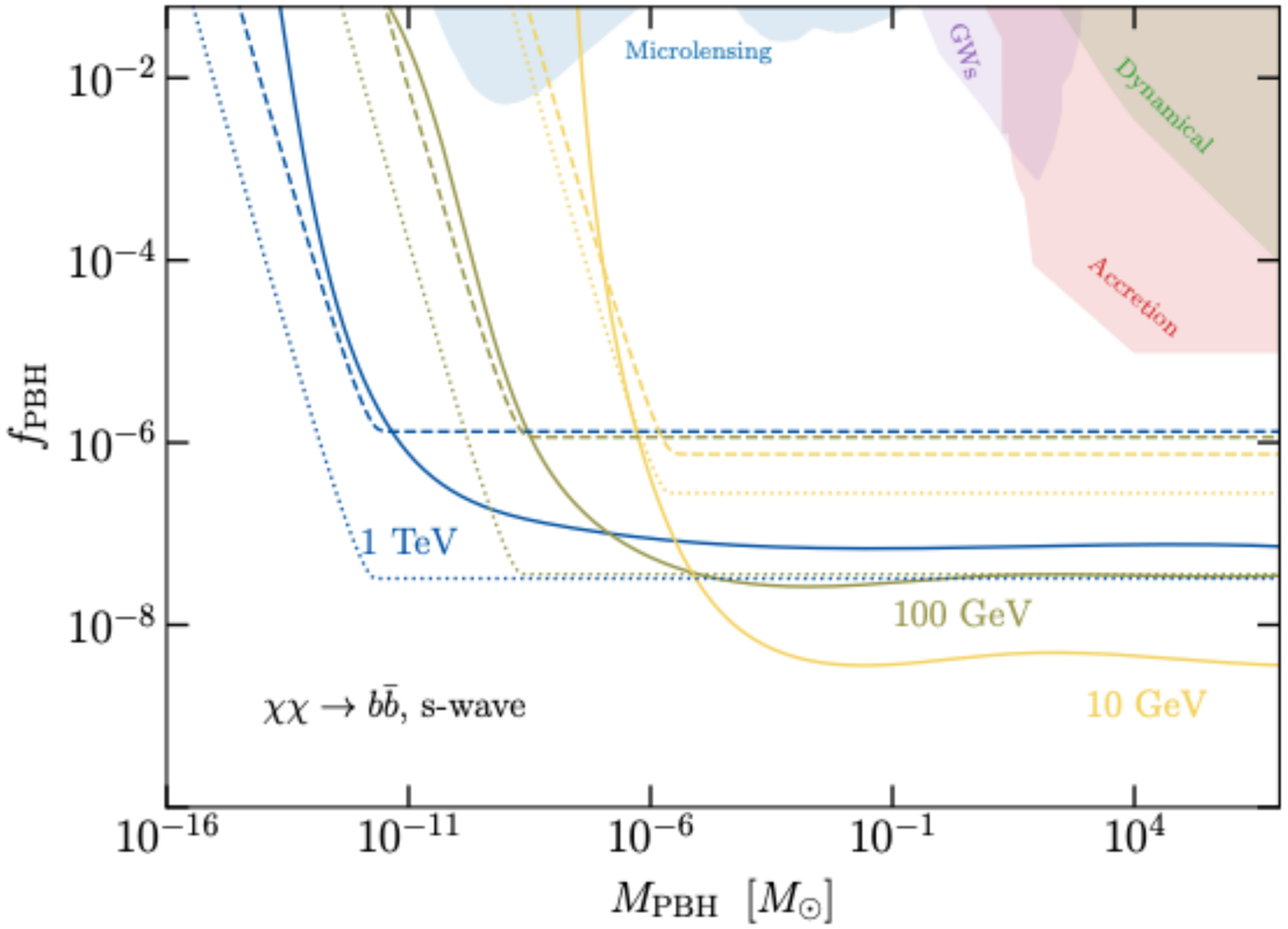
$$\frac{dE}{dt} \propto \int dV\, \rho(r)^2$$

Eroshenko (2016), Boudad et al (2021)

Profile becomes sensitive to annihlations, kinetic decoupling of WIMPs, etc…

Dark matter spikes

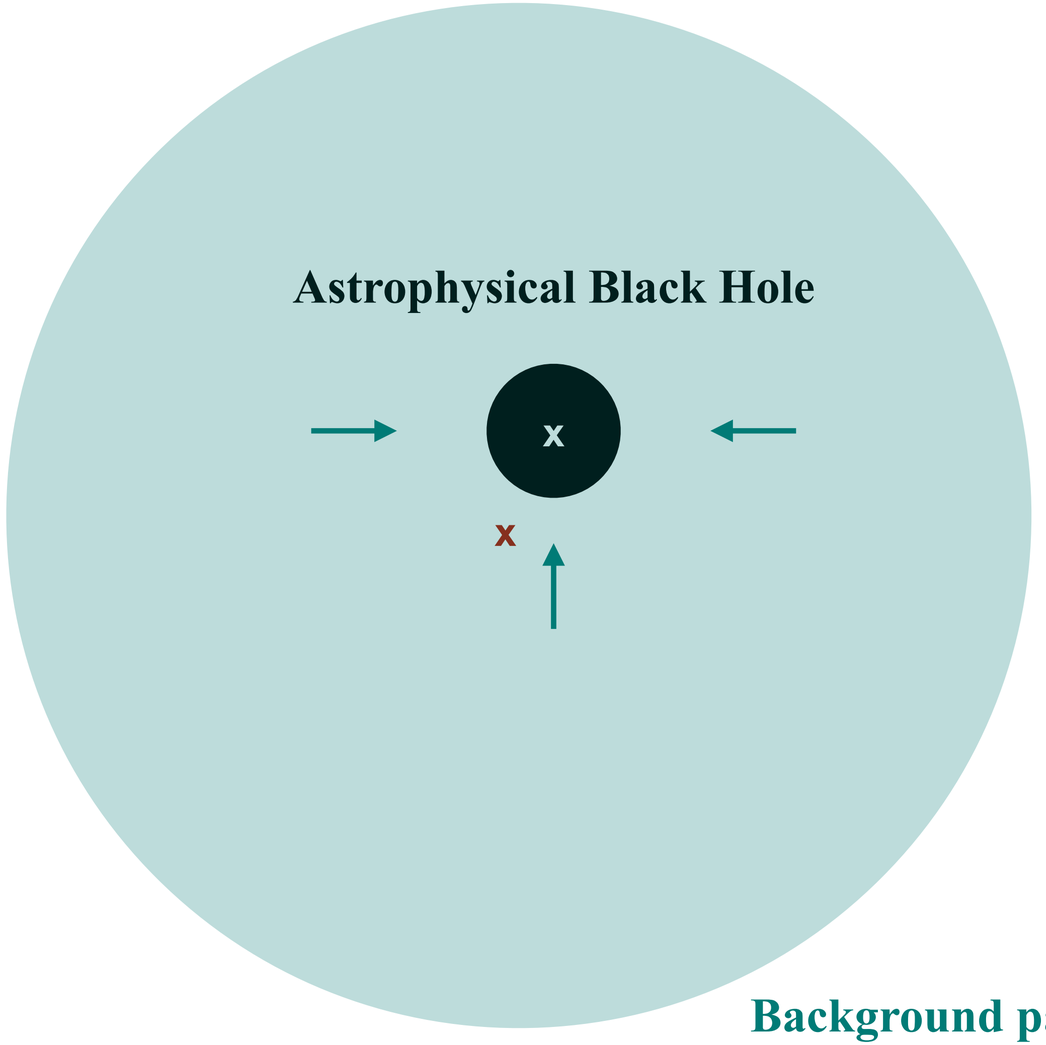
A no-go theorem for PBHs + WIMPS



p-wave suppression can also be largely overcome!

Lacki & Beacom (2010), Carr et al (2021), Utrilla Ginées et al (2022), Boudad et al (2021), …

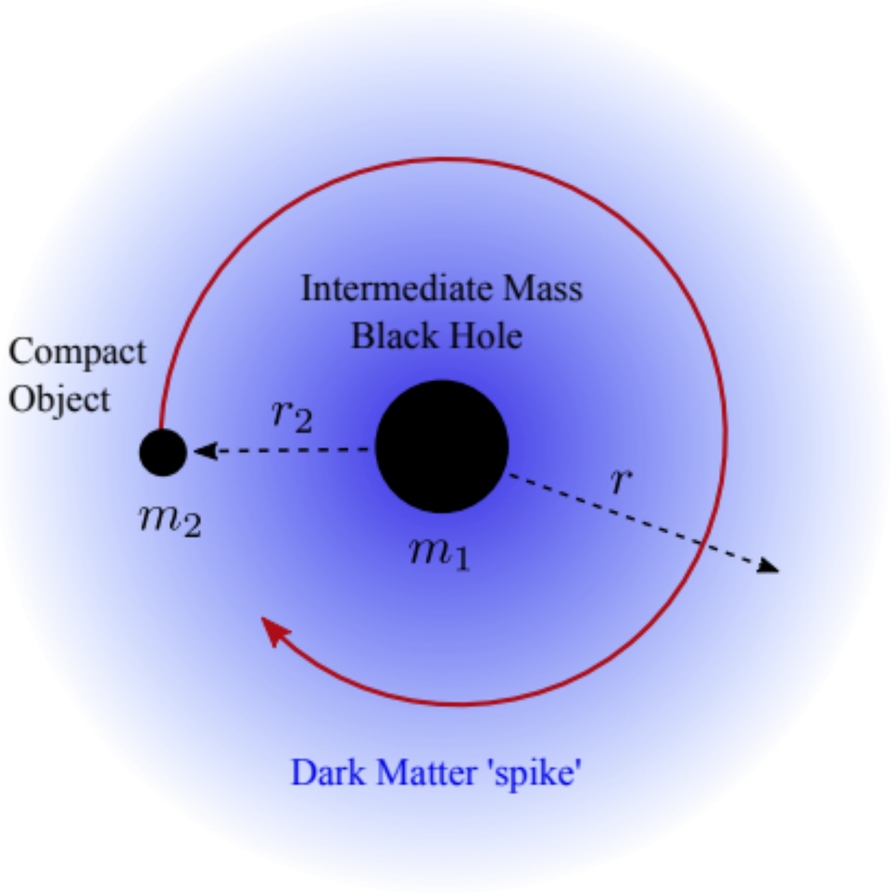
Dark matter spikes around astrophysical black holes

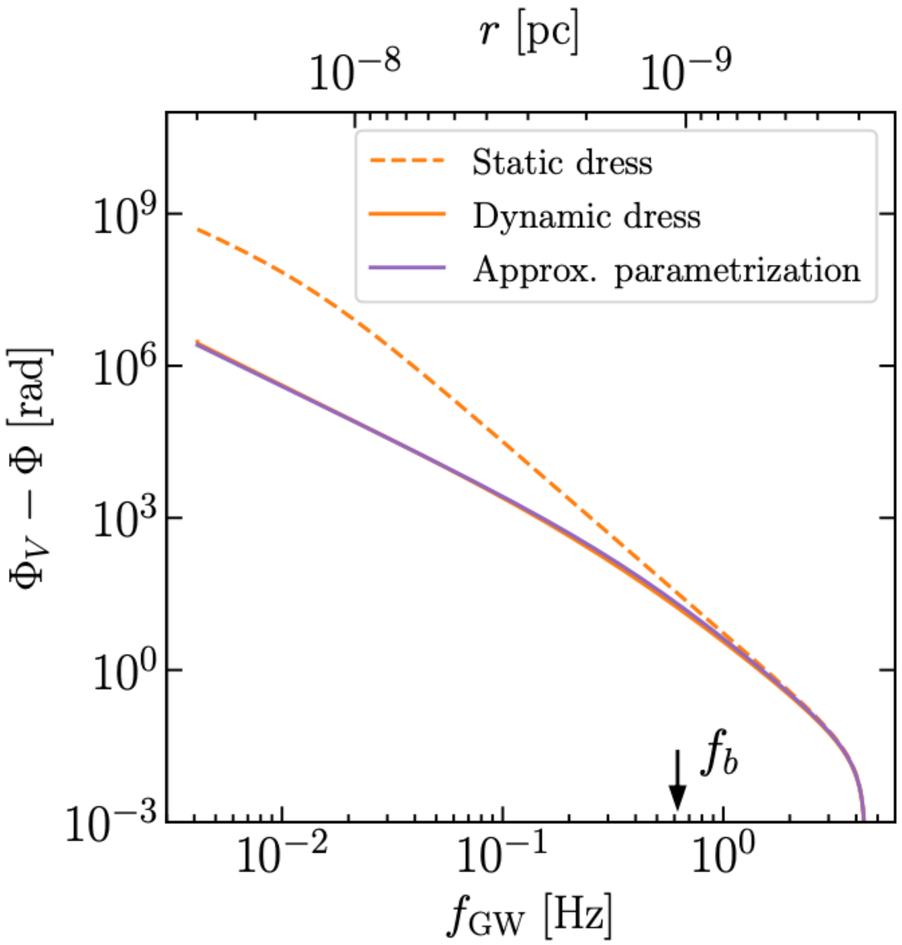


- **Non-isolated systems**
- **Aligned center of mass?**
- **Non-zero relative velocities**
- **Time evolution of ambient halo**
- **…**

Background particle dark matter

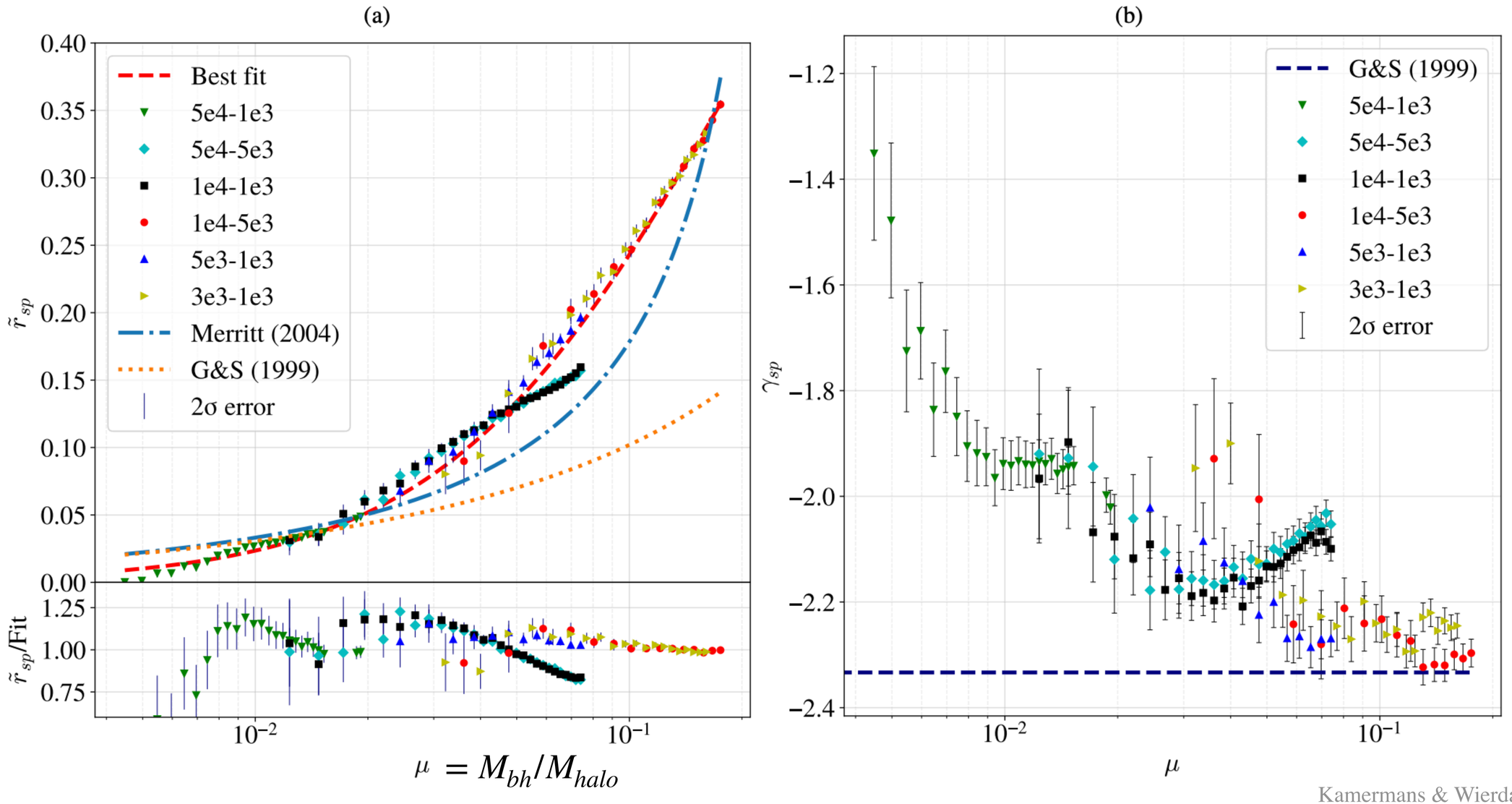
GWs from spikes?





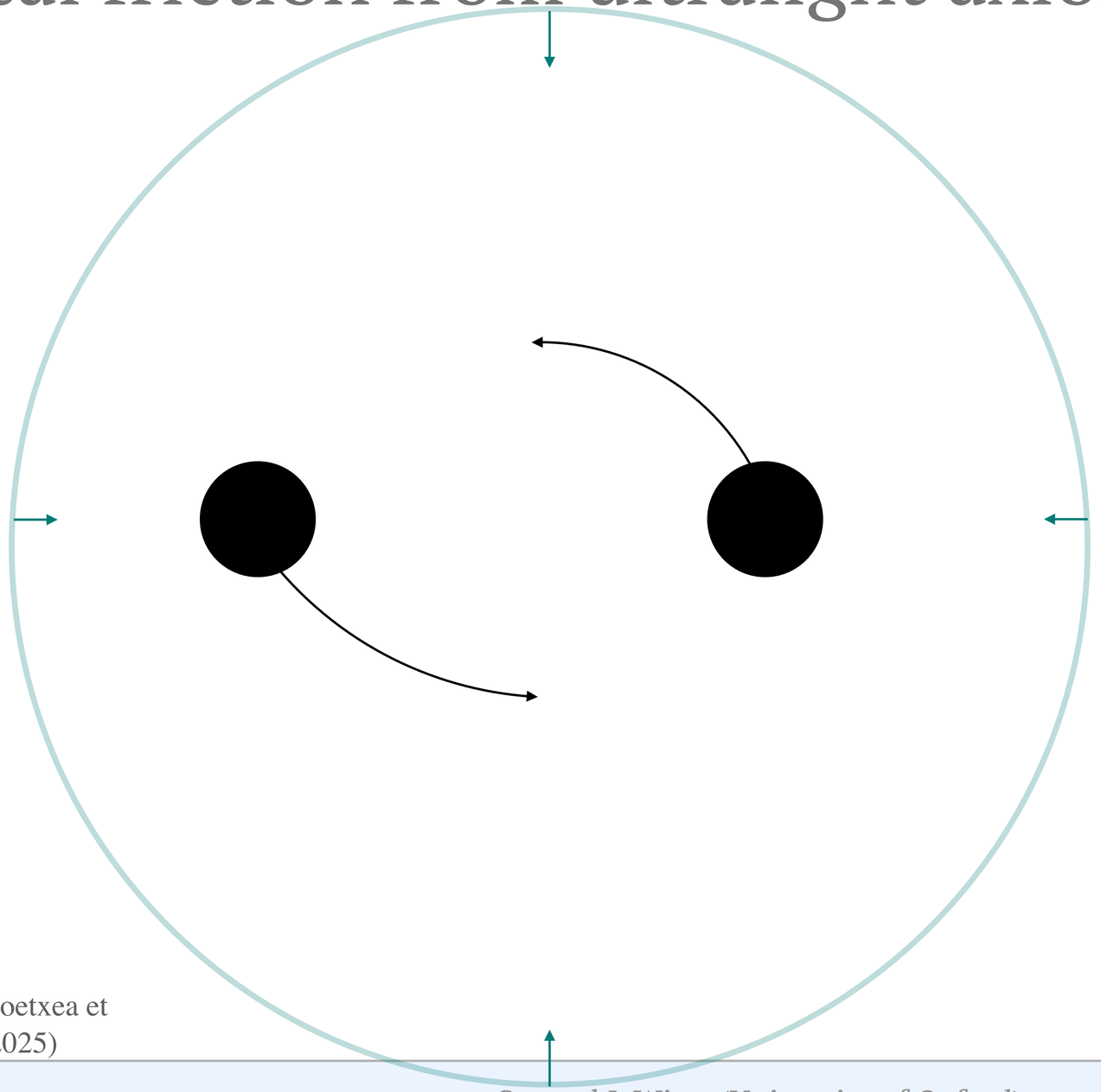
Kavanagh et ak (2022)

Dark matter spikes around astrophysical black holes



Kamermans & Wierda (2024)

Dynamical friction from ultralight axions



To the blackboard

Bamber et al (2023), Aurrekoetxea et al (2023,2024), Tomaselli (2025)