FUZZY DARK MATTER AT THE GALACTIC CENTRE

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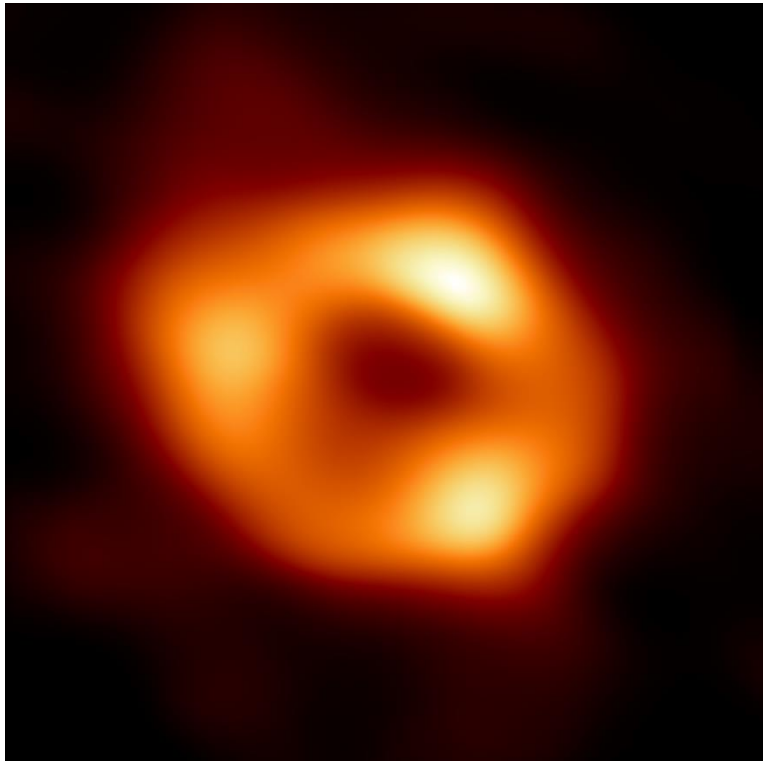
BASED ON: 2502.08709

IOP JOINT APP & HEPP ANNUAL CONFERENCE

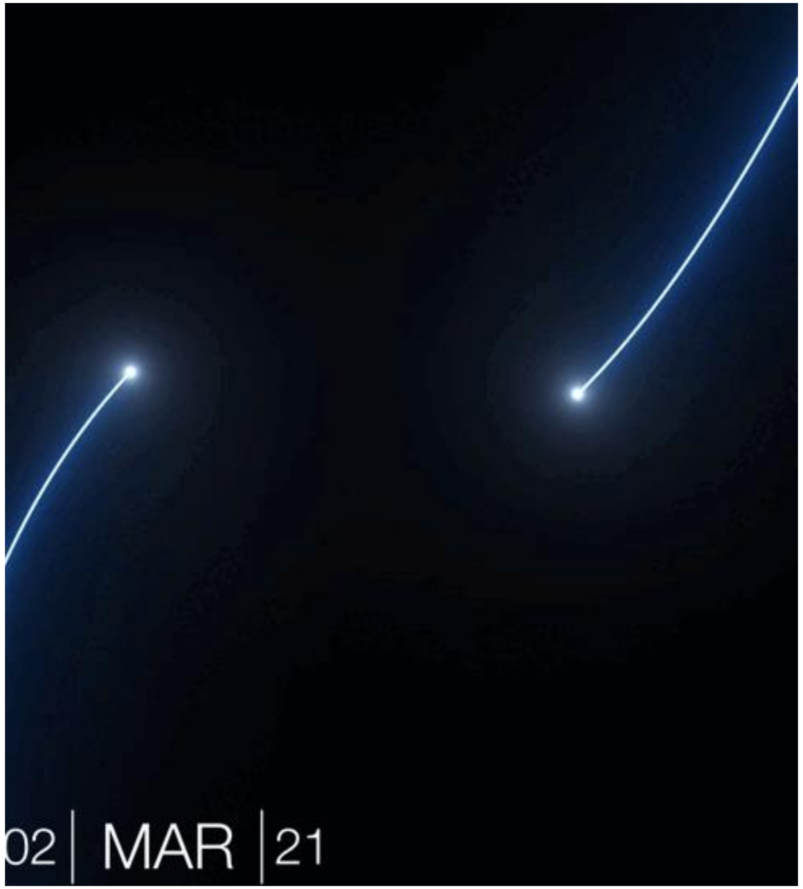
CAMBRIDGE, 7.4.2025

UNIVERSITY OF OXFORD

THERE IS A SUPER-MASSIVE BLACK-HOLE AT THE GALACTIC CENTRE



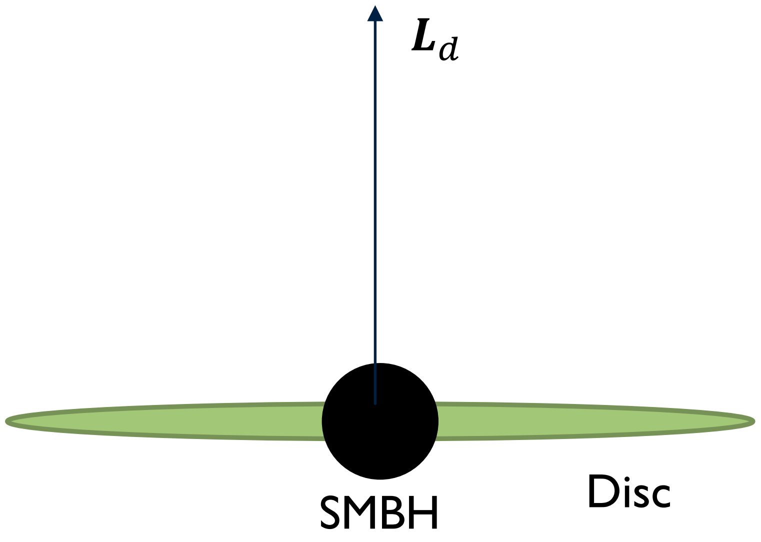
[Event Horizon Telescope, 2022]



[GRAVITY collaboration, 2021, https://www.eso.org/public/news/eso2119/]

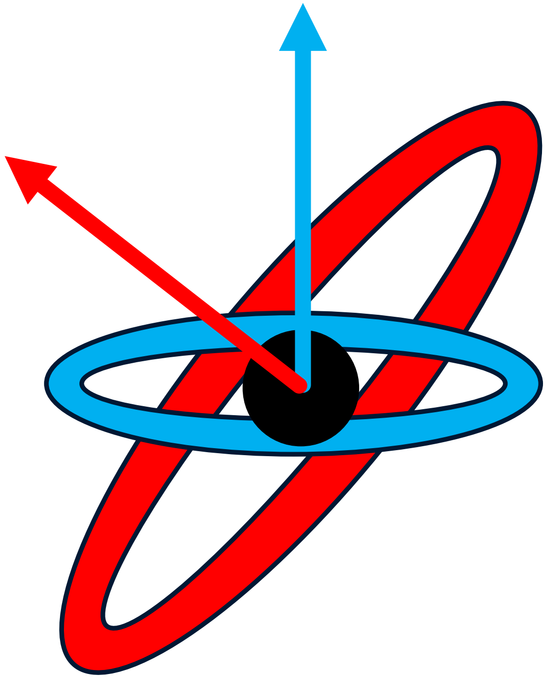
INNER PARSEC IS DOMINATED BY THE SMBH

- A disc of young, massive stars is present around the SMBH (e.g. Levin & Beloborodov 2003, Bartko et al. 2009…).
- Assume disc not too eccentric.
- What happens to the disc under the influence of a perturbation?



RESONANT RELAXATION GOVERNS THE DYNAMICS

- Evolution is slow over one orbital period.
- Average over stars' orbits to get rings.
- Rings interact gravitationally by exerting torques.
- Much faster than two-body relaxation (Rauch & Tremaine 1996).



FUZZY DARK MATTER

- Scalar field with mass m_a, which is a boson.
- Dark matter is non-relativistic → Schrödinger-Poisson system.
- Interested in 10^{-21} eV $\leq m_a \leq 10^{-19}$ eV
- Forms haloes which are Bose-Einstein condensates – all axions share the same wave-function.
- At halo centre a soliton core forms (Chavanis 2011, Schive et al. 2014; Marsh & Pop 2015).

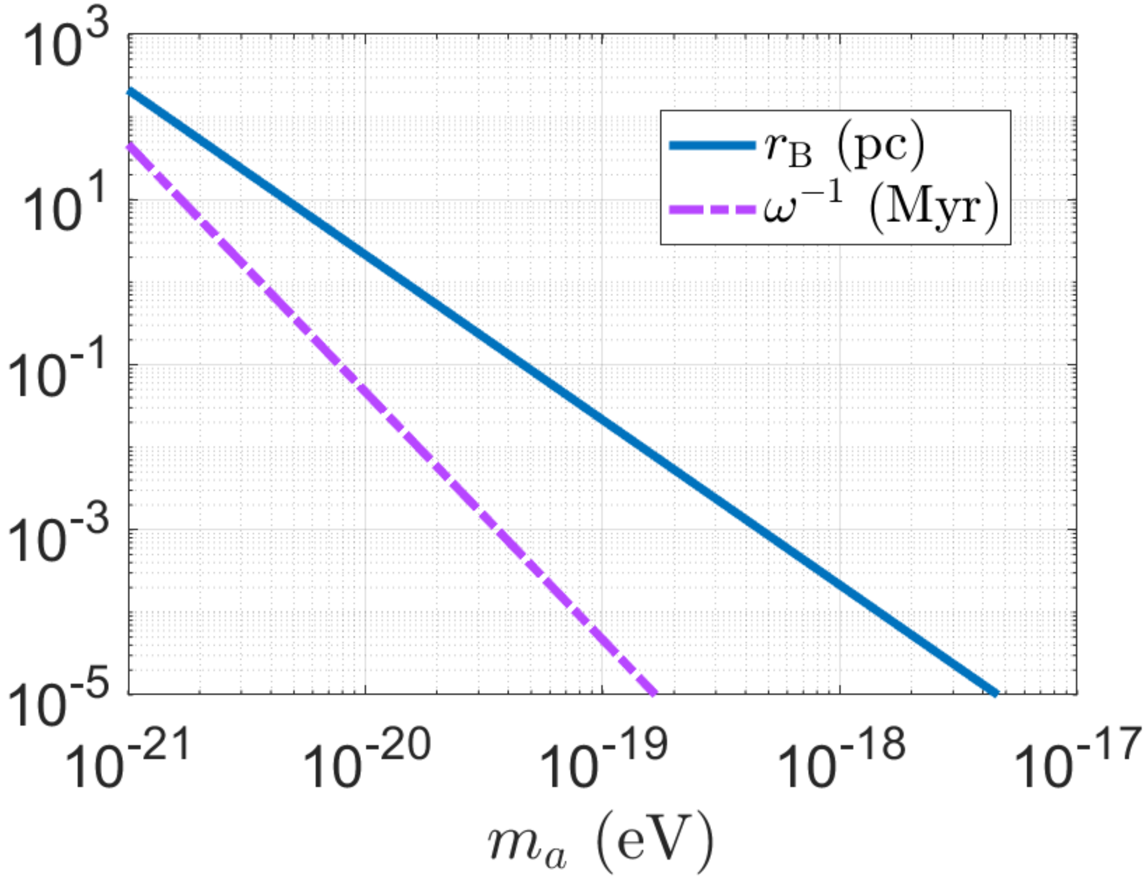
$$R_c = 100 \text{ pc} \times \left(\frac{10^9 \ M_\odot}{M_c}\right)\left(\frac{10^{-22} \text{ eV}}{m_a}\right)^2,$$

$$M_c = 6.7 \times 10^7 \ M_\odot \times \left(\frac{10^{-22} \text{ eV}}{m_a}\right)\left(\frac{M_{\text{vir}}}{10^{10} \ M_\odot}\right)^{1/3}$$

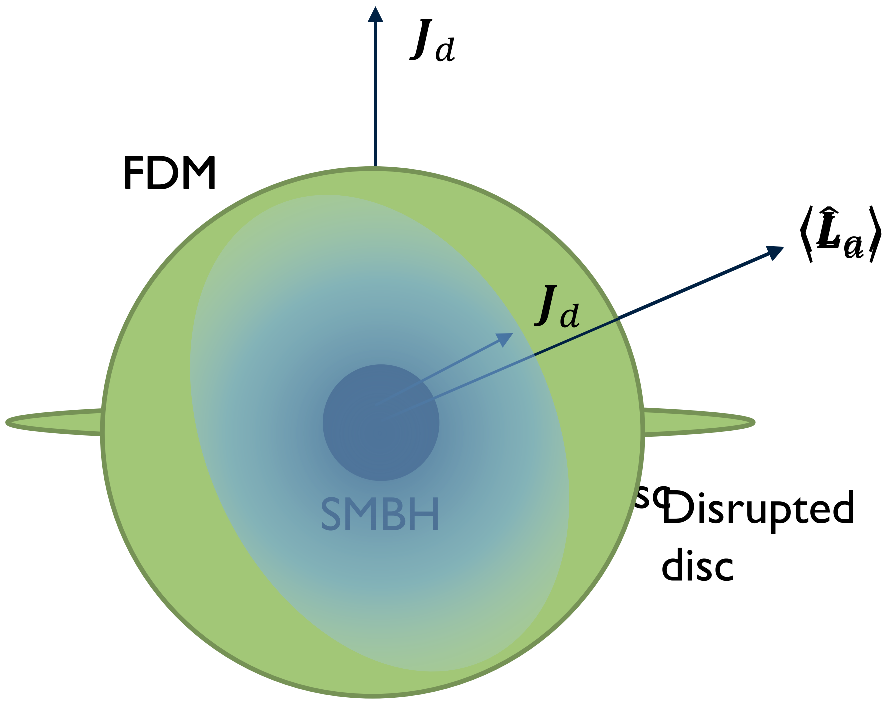
AXION CLOUD AROUND SUPER-MASSIVE BLACK HOLE

- Now insert into the core a super-massive black hole.
- Gravitational atom will form, with Hydrogen-atom-like eigenfunctions.

$$|\psi\rangle = \sum_{n,l,m} \alpha_{nlm} |nlm\rangle \quad r_{\rm B} \equiv \frac{\hbar^2}{G M_\bullet m_a^2}$$



NOW ADD A GRAVITATIONAL ATOM



$$m \ll M_d, M_a \ll M_{SMBH}$$

CALCULATE ORBIT-AVERAGED AXION POTENTIAL

- Consider a disc star: mass m, orbital elements $(a, e, i, \omega, \Omega)$.
- Potential felt by star is $\varphi(\boldsymbol{x}) = -GM_a \int d^3y \frac{|\psi(\boldsymbol{y})|^2}{|\boldsymbol{x}-\boldsymbol{y}|}$.
- Orbit average over Keplerian orbit of $\boldsymbol{x}$.
- Average over atom oscillation (frequency $\omega \gg \tau_{\mathrm{VRR}}^{-1}$).

RESONANT RELAXATION POTENTIAL

$$\langle \varphi \rangle_{\mathrm{da}} = -\sum_{l_0} \sum_{l=0}^{2l_0} J_{l,l_0} P_l \left(\hat{\mathbf{L}} \cdot \hat{\mathbf{L}}_a \right)$$

$$J_{lm} = \sum_{\substack{n_1,l_1,m_1,\\ n_2,l_2,m_2}} (-1)^{m_2} \sqrt{\frac{4\pi(2l_1+1)(2l_2+1)}{(2l+1)}} P_l(0) \begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l & l_1 & l_2 \\ m & m_1 & -m_2 \end{pmatrix}$$

$$\times\, \alpha_{n_1 l_1 m_2} \alpha^*_{n_2 l_2 m_2} \int_0^\infty \mathrm{d}y \, \frac{y^2 R_{n_1 l_1}(y) R_{n_2 l_2}(y)}{\max\{a, y\}} \left[\frac{\min\{a, y\}}{\max\{a, y\}} \right]^l s_l(a, y, e, 0).$$

TAKE SIMPLE ATOM WAVE-FUNCTION

$$|\psi\rangle \approx \alpha_{100}\,|100\rangle + \alpha_{211}\,|211\rangle$$

$$\langle\varphi\rangle_{\mathrm{da}} = \sum_{l=0}^{2} J_{l,1} P_l\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{L}}_a\right)$$

$$\boldsymbol{\Omega} = -3m_s\frac{J_{2,1}}{L}\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{L}}_a\right)\hat{\mathbf{L}}_a = -3m\frac{J_{2,1}}{L}\cos i\;\hat{\mathbf{z}}.$$

$$\omega_{\mathrm{mp}} = -m_s\frac{\sqrt{1-e^2}}{eL}\frac{\mathrm{d}J_{0,0}}{\mathrm{d}e}$$

CAN THE PERTURBER RIP THE DISC APART?

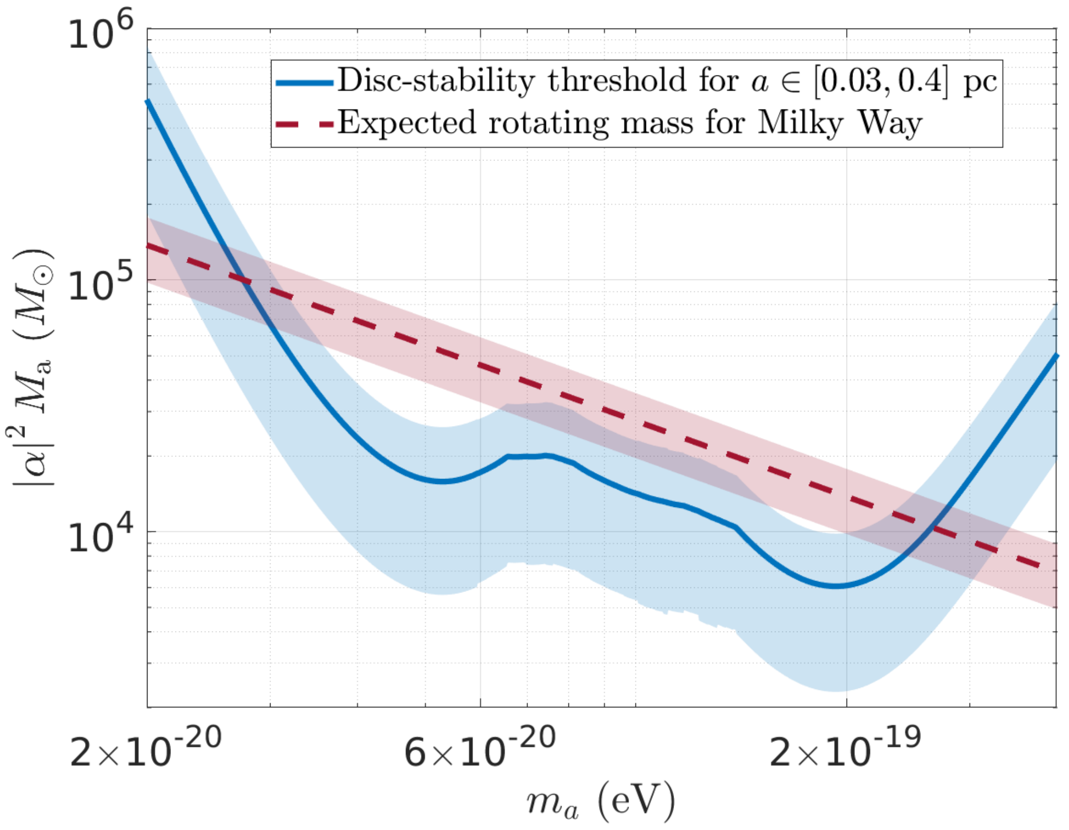
- Disc, as a whole, precesses about atom's angular-momentum vector (Kocsis & Tremaine 2015, Panamarev & Kocsis 2022).
- Stars in disc precess at a different rate – like tidal force in angular-momentum space.
- Relative torque determines stability (Panamarev, Ginat & Kocsis, 2025, forthcoming):

$$\left|\boldsymbol{\Omega}_{\mathrm{p}}(1)\times\boldsymbol{L}(1)-\boldsymbol{\Omega}_{\mathrm{p}}(2)\times\boldsymbol{L}(2)\right|\approx\left|\boldsymbol{\Omega}_{\mathrm{p}}\times\Delta\boldsymbol{L}+\Delta\boldsymbol{\Omega}_{\mathrm{p}}\ \times\boldsymbol{L}\right|\leq|\boldsymbol{\Omega}_{\mathrm{d}}\times\boldsymbol{L}|$$

DISC STABILITY

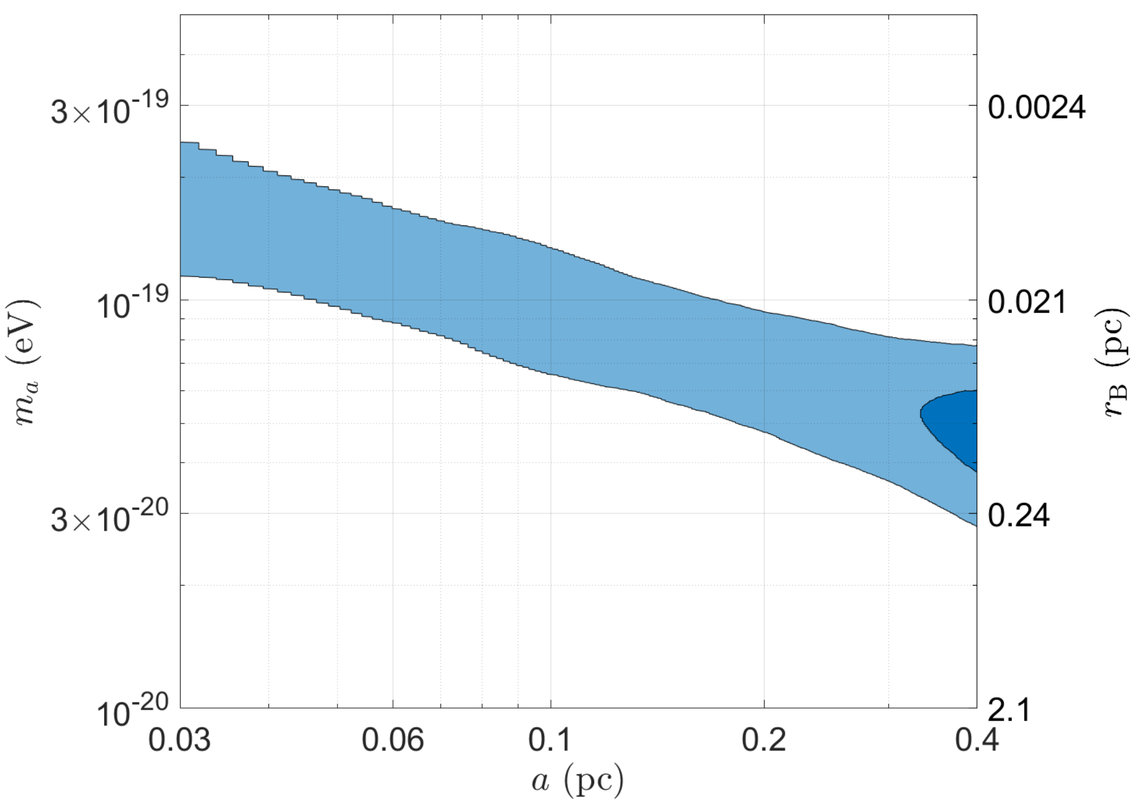
Reduces to:

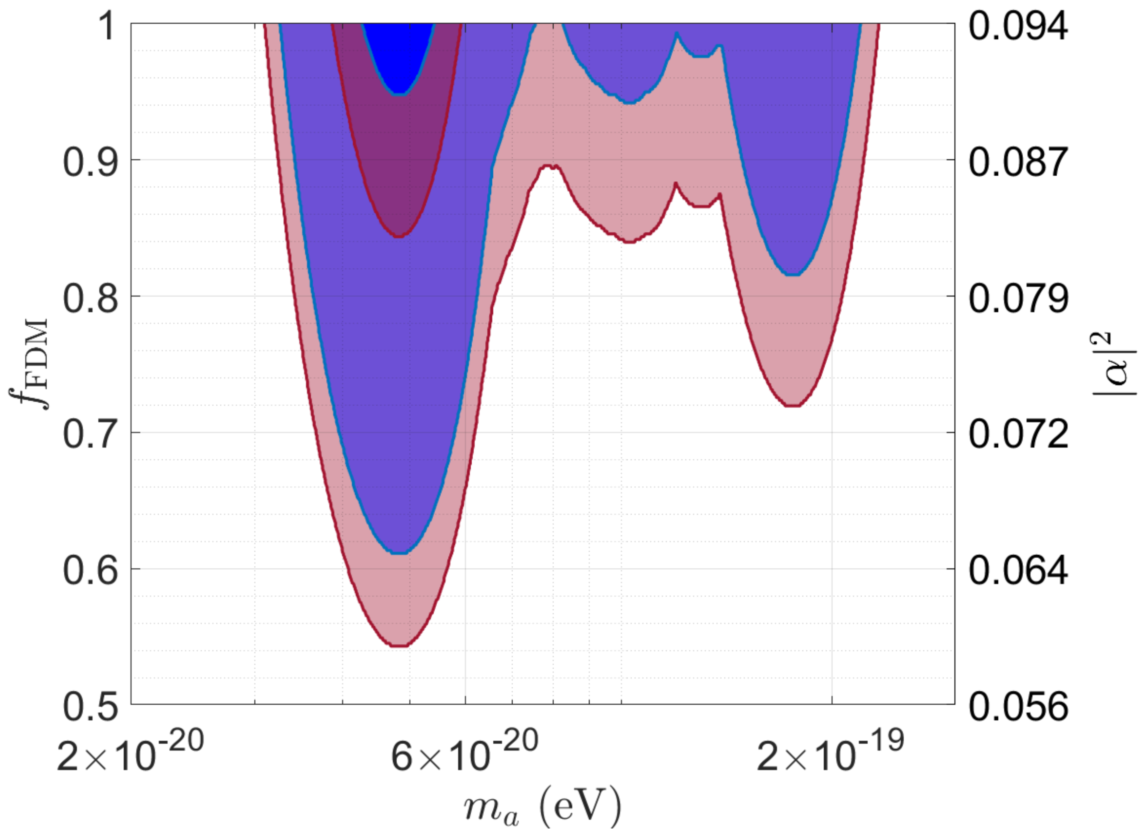
$$|\alpha_{211}|^2 M_a \leq \frac{r_B}{a_d} M_d \times \frac{f\left(\frac{a_d}{r_B}, e, \text{shape}\right)}{\cos 2\theta}$$



[Ginat & Kocsis 2025]

IS THE ATOM MASSIVE ENOUGH?





[Ginat & Kocsis 2025]

SUMMARY

- Vector resonant relaxation controls disc dynamics.
- Fuzzy dark matter produces dense concentrations in galaxy centres.
- Gravitational atom plays an important rôle in Galactic centre dynamics (if dark matter is fuzzy) via VRR.
- For plausible parameter values, disc unstable, leading to constraints on FDM masses:
  If disc is stable, then $m_a \notin [4.4, 5.3] \times 10^{-20}$ eV at 95% confidence.