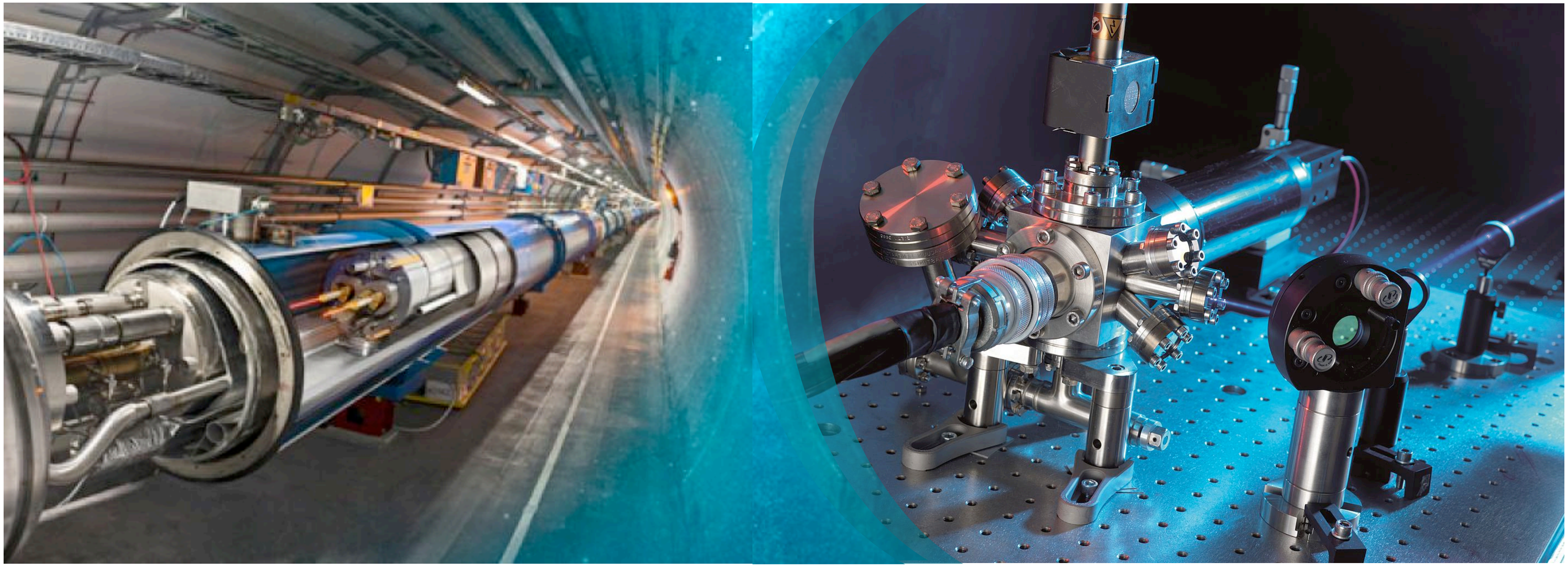


Axion Dark Matter

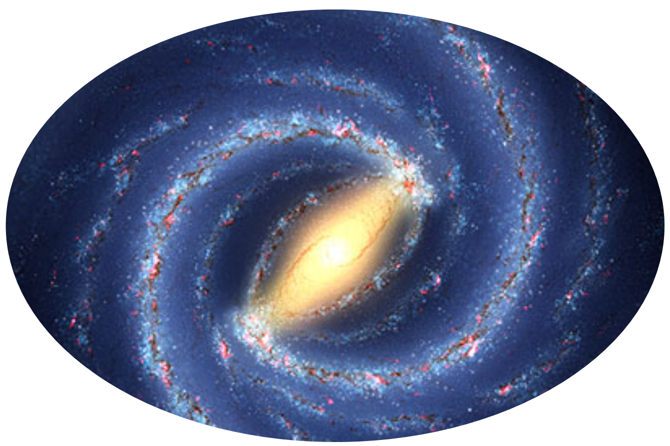
The good, the bad and new ways to detect it

Martin Bauer, 21.1.2025

QTFP Community Meeting 2025

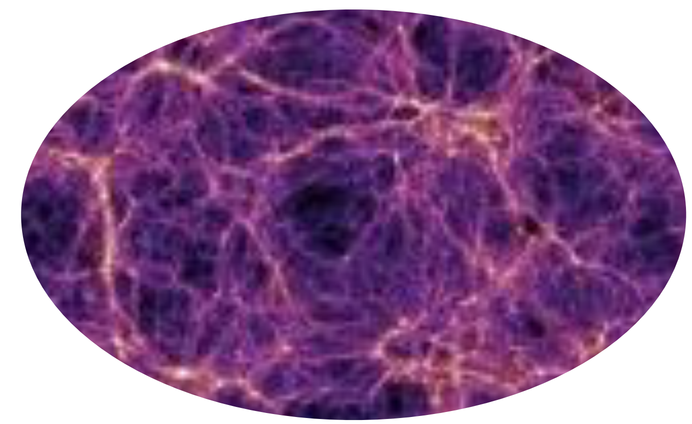
What is dark matter ?

There is overwhelming evidence for the existence of dark matter at different scales



Rotation curves

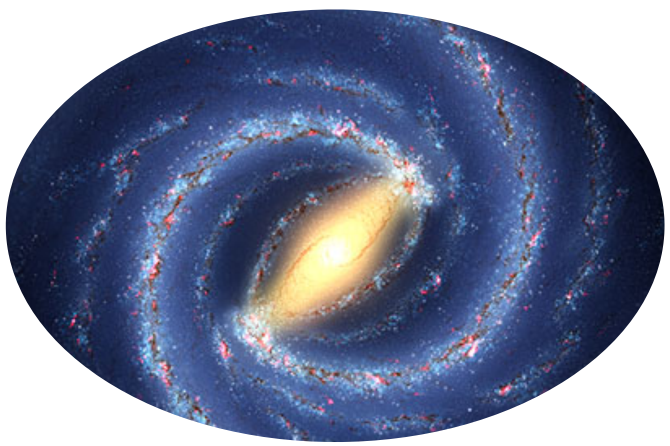
gravitational lensing



Structure formation

What is dark matter

There is overwhelming evidence for the existence of dark matter at different scales



Rotation curves

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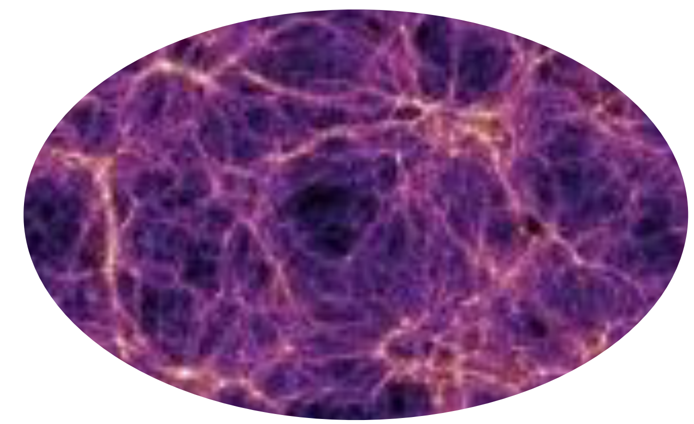


Structure formation

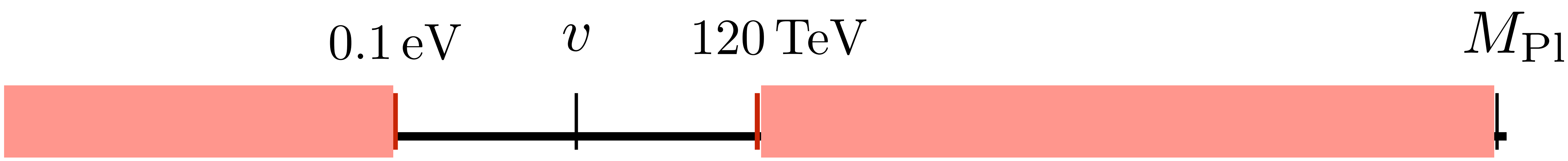
We have currently no strong argument to prefer a specific fundamental model to describe dark matter

What can we say? How universal are our detection strategies? Are we missing something?

What is the DM scale?

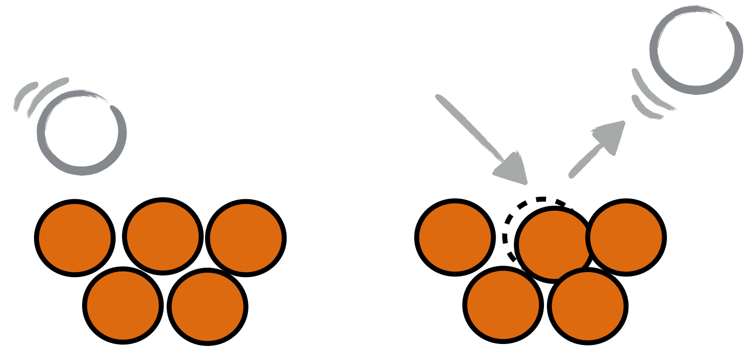
If Dark Matter is a thermal relic, it's mass is constrained from perturbativity and demanding non-relativistic dark matter today

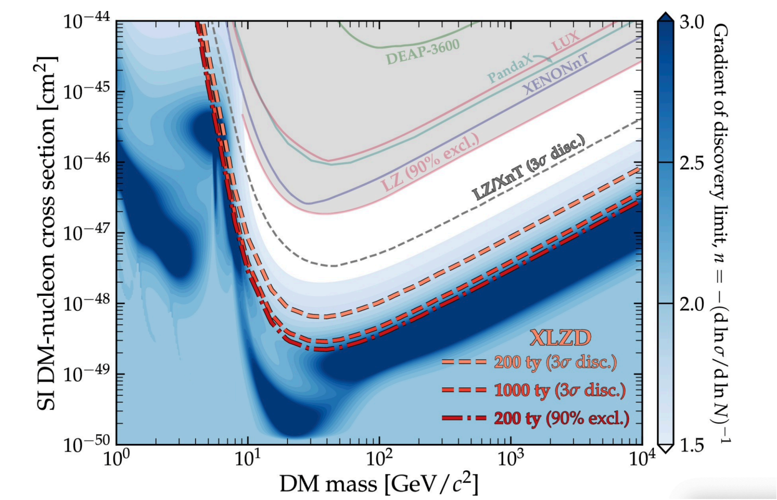
$$\left(\frac{\Omega_X}{0.2}\right) \approx \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma}$$



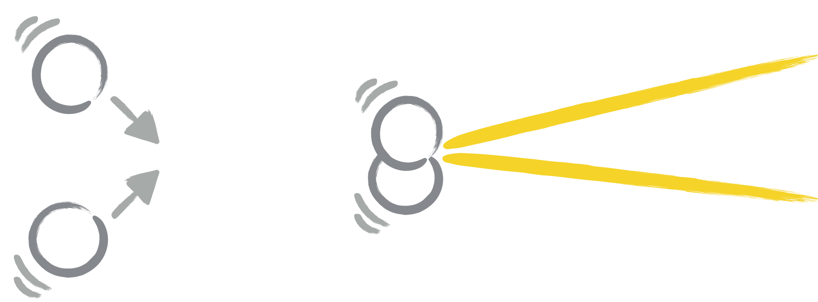
Extensive Programme

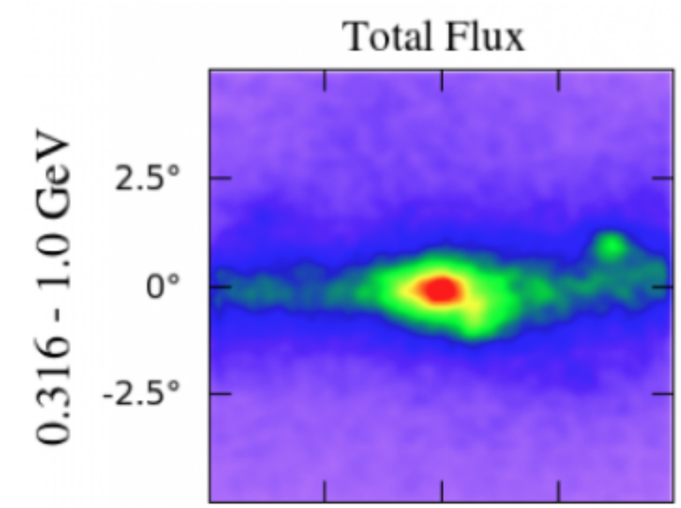
Direct detection



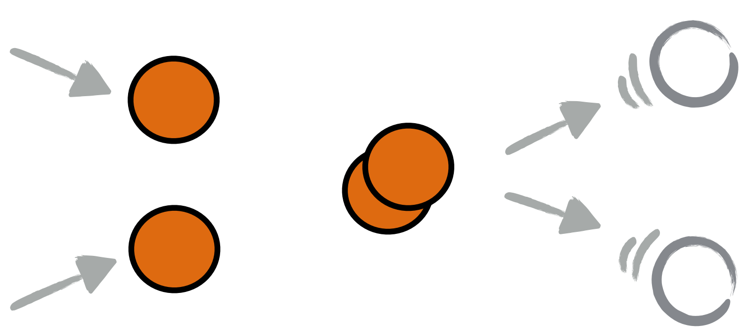


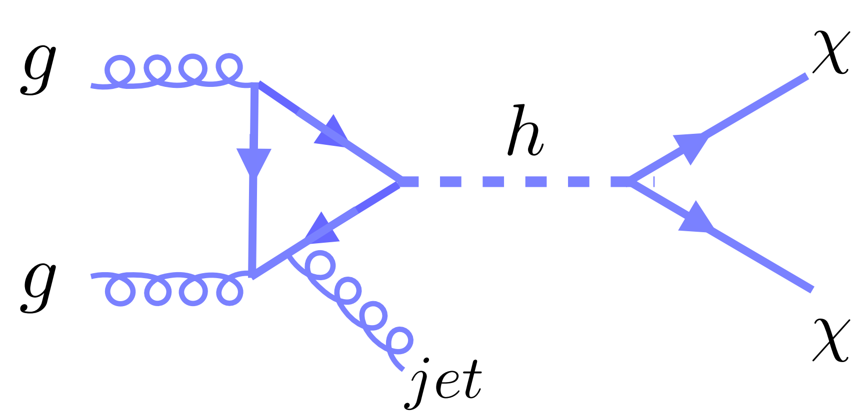
Indirect detection





Collider searches





What is the DM scale?

What do we know about the scale of DM?

What is the DM scale?

For **Fermions**, the Pauli exclusion principle provides a lower limit $m_\chi \gtrsim 200\,\mathrm{eV}$

Dark **bosons** can be arbitrary light, but for a mass of

$$m_\phi \lesssim 10^{-25}\,\mathrm{eV}$$

the de Broglie wavelength is larger than a few hundred kpc and galaxy-size structures don't form.

What is the DM scale?

For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

$$m_\phi \approx 10^{-22}\,\mathrm{eV} \qquad \Rightarrow \qquad \lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1\,\mathrm{kpc}$$

Ultralight Dark Matter

For bosons there is no such lower limit. There is however a scale that is particularly motivated:

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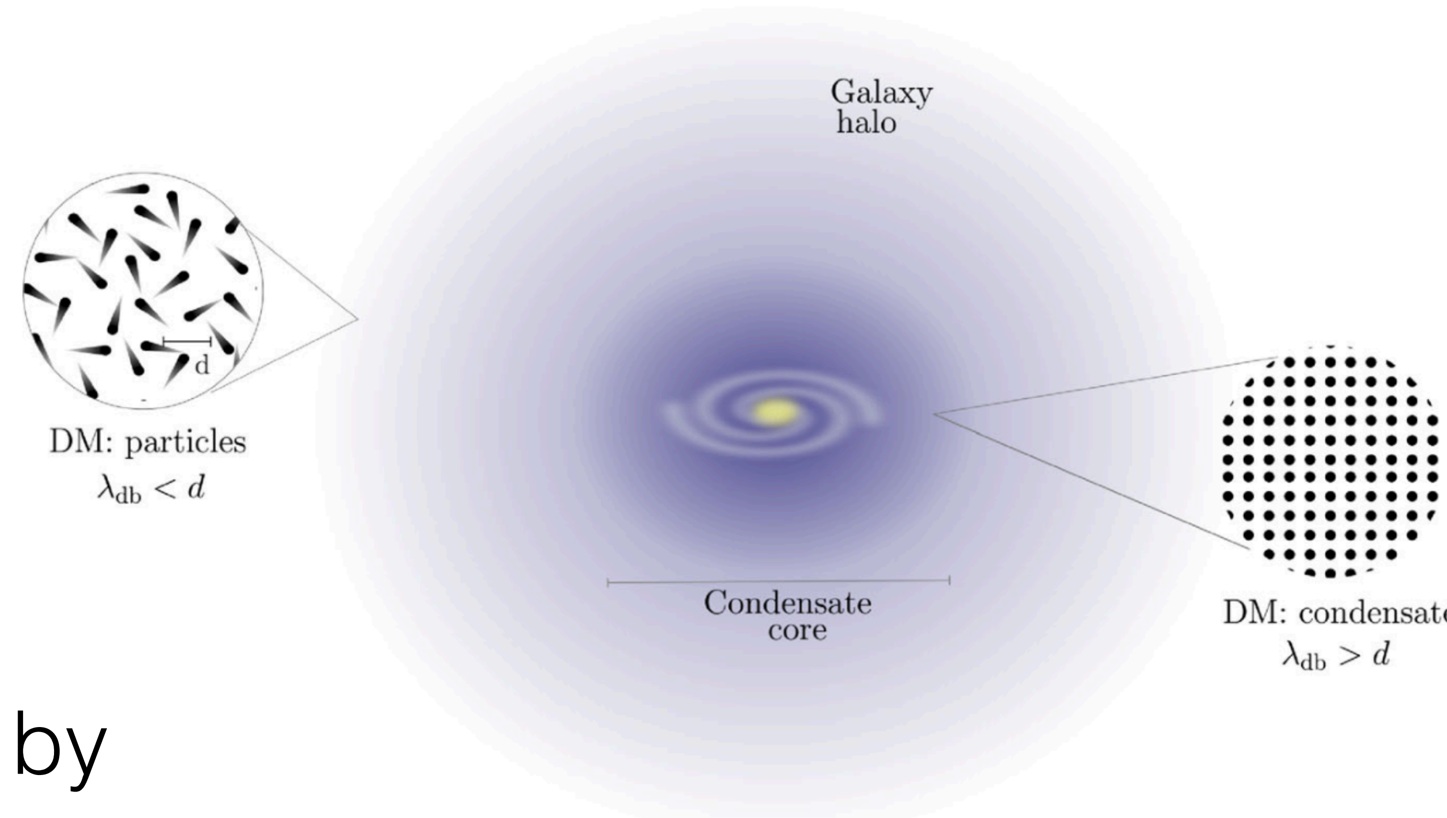
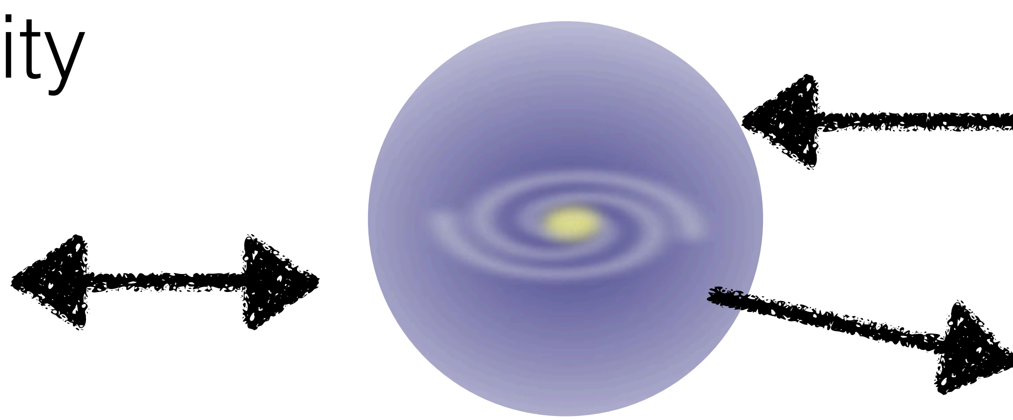
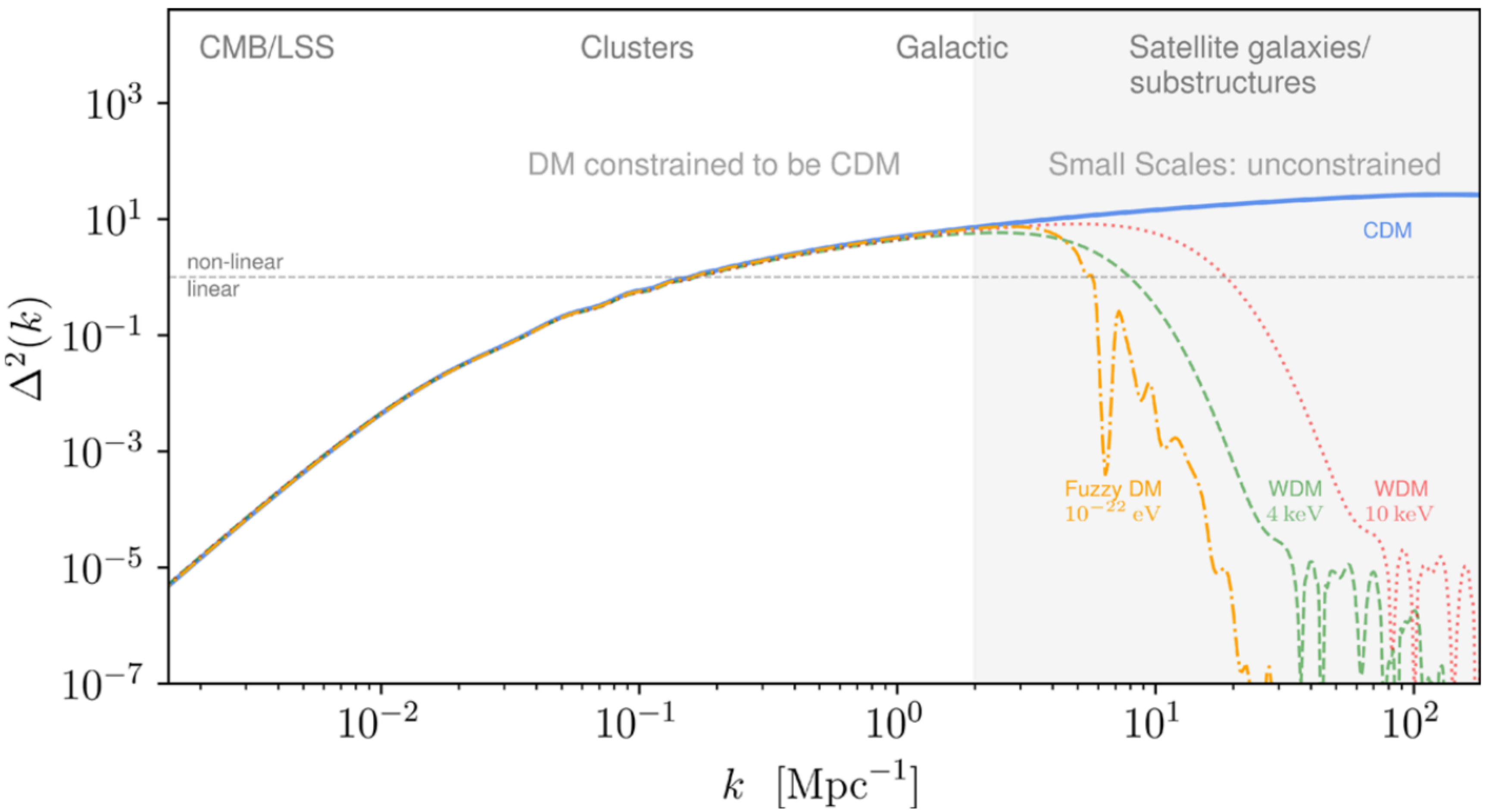


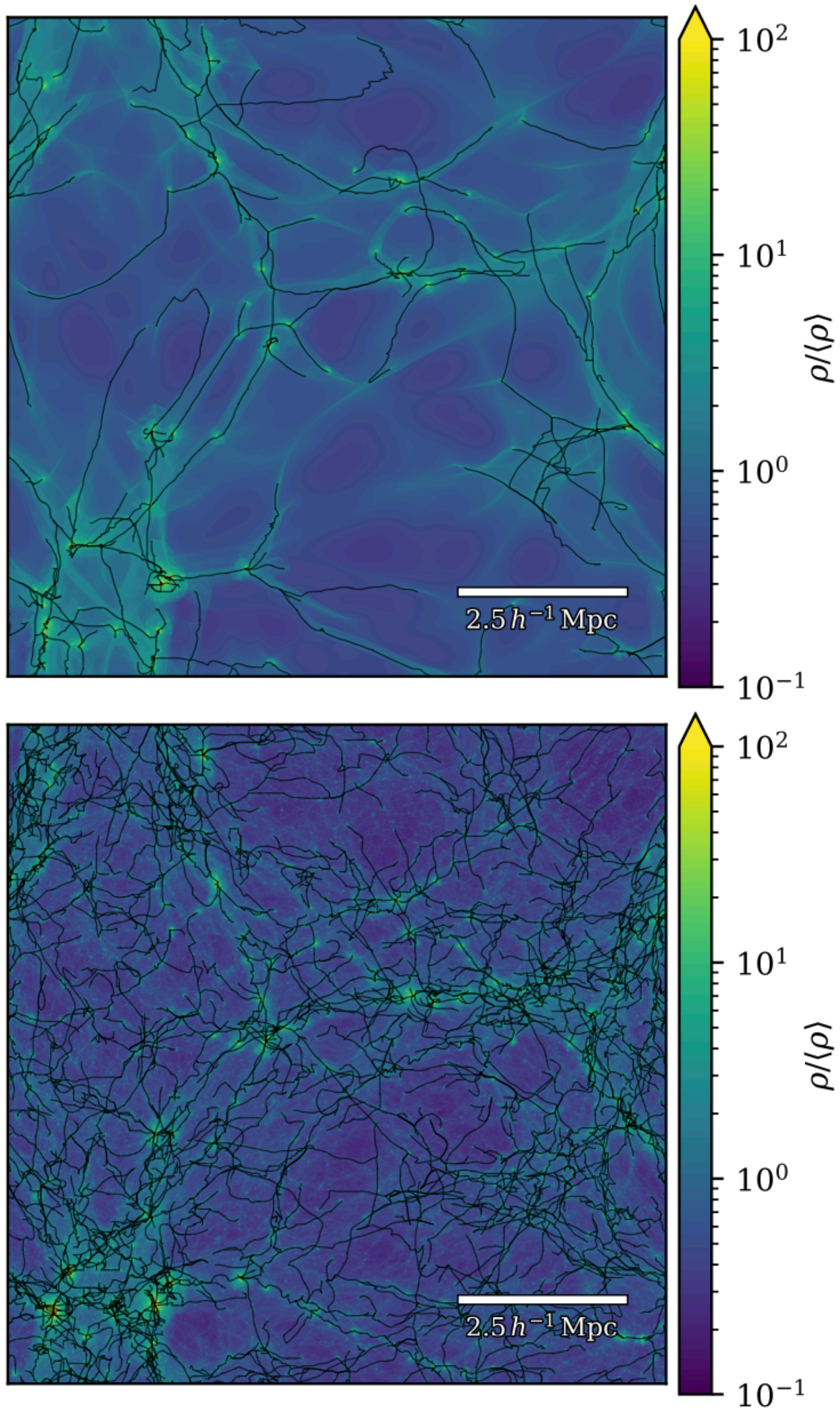
The size of the core is set by the balance between quantum pressure and gravity



Ultralight Dark Matter

Fit the small scale power spectrum:

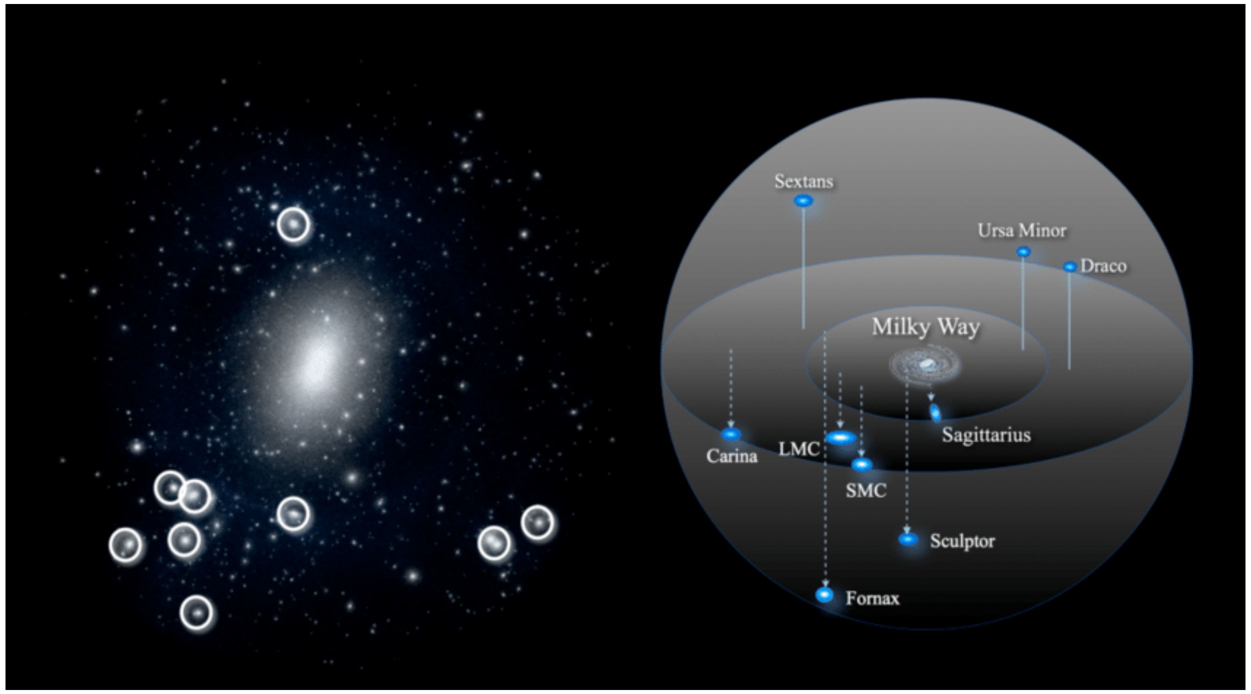


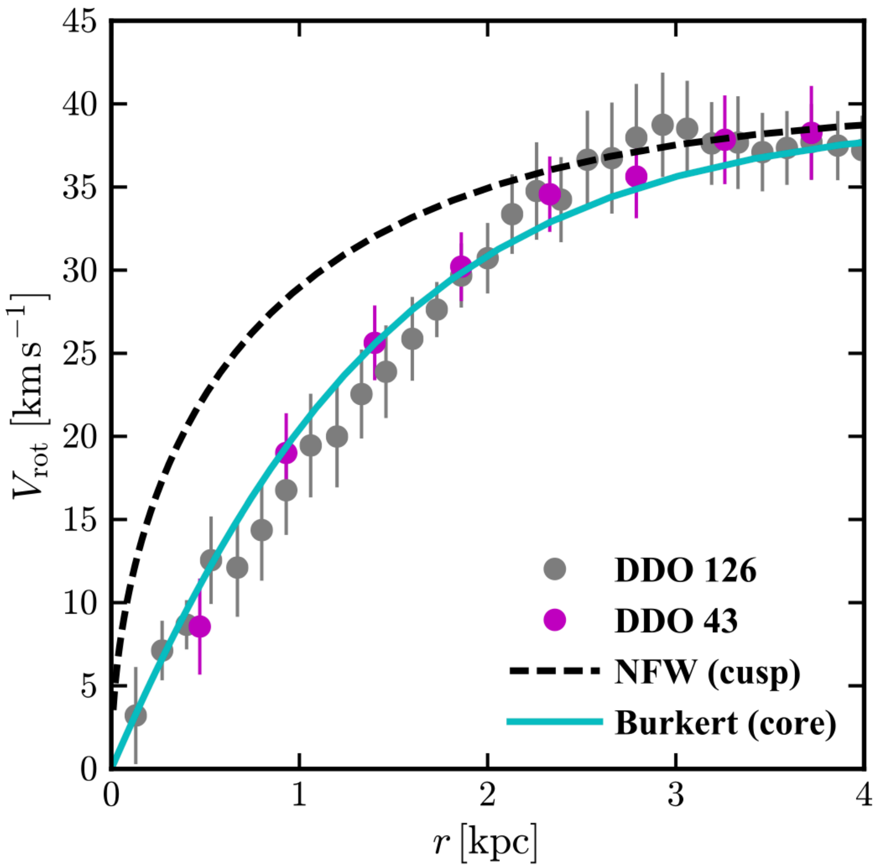


May et al. 2021

Ultralight Dark Matter

Missing satellite problem





Core cusp problem

[1707.04256]

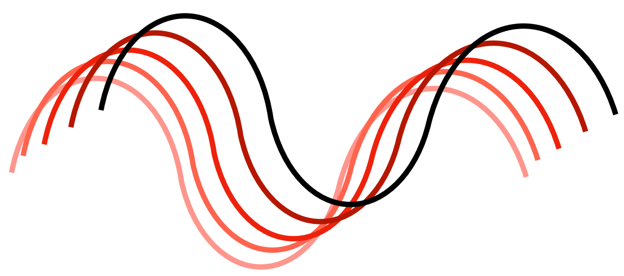
Ultralight Dark Matter

The de Broglie wavelength is large, but the occupation number is high.

For m < 30 eV, dark matter is described as a classical wave

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right) = 1.49\,{\rm km}\left(\frac{10^{-6}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

$$N_{\rm dB} \sim \left(\frac{34\,{\rm eV}}{m}\right)^4 \left(\frac{250\,{\rm km/s}}{v}\right)^3$$



Ultralight Dark Matter

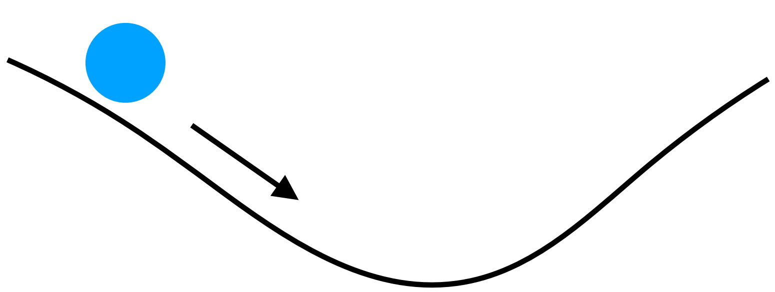
For very light scalar fields, the occupation number is very high and the field can be treated classically.

Dark Matter relic density from misalignment:

$$\ddot{a} + 3H(t)\dot{a} + m_a^2 a = 0$$

$H(t) > m_a$

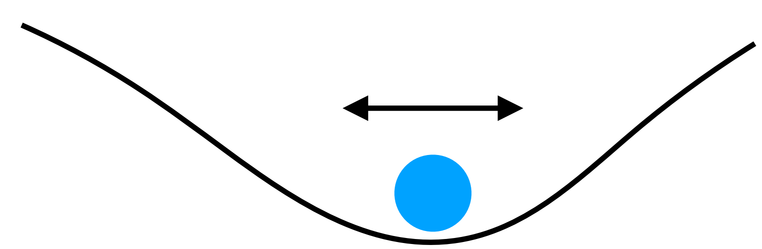
Solution $a(t) = \mathrm{const.}$



early universe: Hubble friction

$H(t) < m_a$

harm. oscillator: $a(t) = a_0 \cos(m_a t)$



late universe: oscillations

Cosmological implications

Mass is fixed by halo size $m_a \gtrsim 10^{-22}\mathrm{eV}$

Amplitude is fixed by the dark matter energy density

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \overset{!}{=} \rho_{\mathrm{DM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

The angular frequency is determined by the rest mass.

$$\omega \sim m_a$$

$v \approx 10^{-3}$

Small corrections from the kinetic energy

$$\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

Coherence time is set by the frequency spread

$$\tau_c = \frac{2\pi}{\Delta\omega} = \frac{2\pi}{m_a v^2} \approx 1\mathrm{s} \left(\frac{\mathrm{MHz}}{m_a}\right)$$

ALP phenomenology

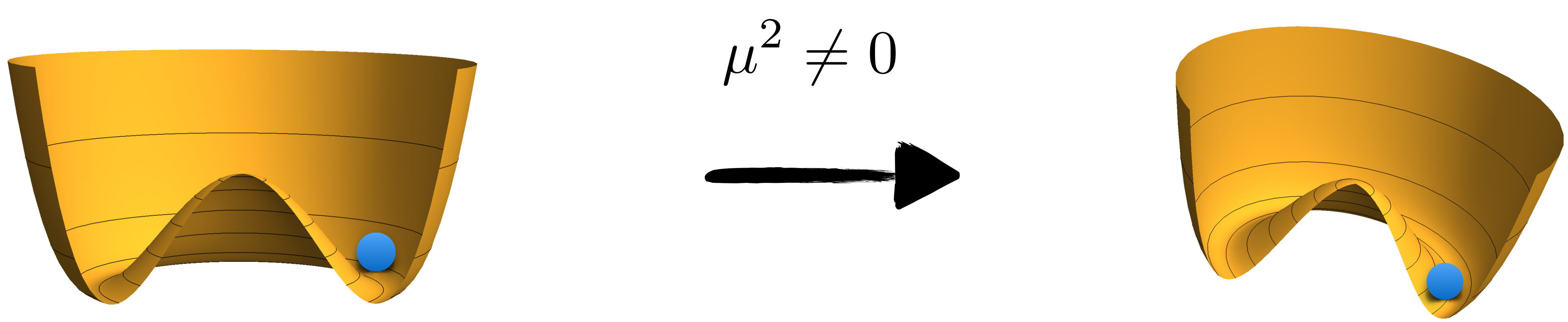
Axions or axion-like particles are excellent candidates for light dark matter

$$\phi = (f + s)e^{ia/f}$$

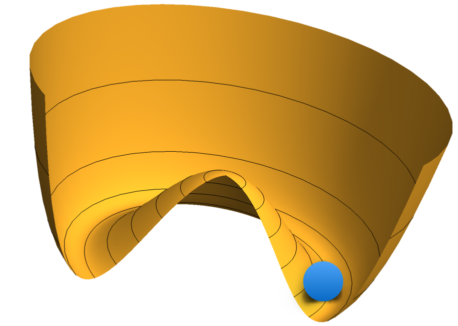
They are goldstone bosons: contributions to the axion mass are suppressed by the same scale that suppresses interactions

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{2}\left(\frac{\mu^2}{f}\right)^2 a^2 + c_{ee}\frac{\partial^\mu a}{f}\bar{e}\gamma_\mu\gamma_5 e + \dots$$

small mass = small couplings



ALP phenomenology



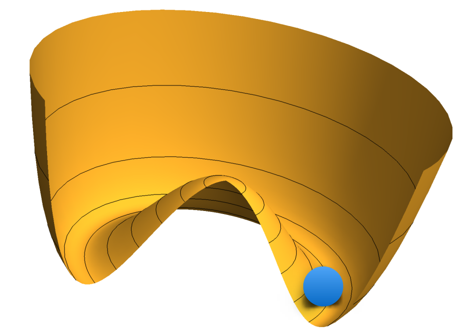
At leading order axions interact like pseudoscalars

$$\mathcal{L}_{\rm eff}^{D\leqslant 5}(\mu \lesssim \Lambda_{\rm QCD}) = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{2f}\,c_{ee}\,\bar{e}\,\gamma_\mu\gamma_5\,e + g_{Na}\,\frac{\partial^\mu a}{2f}\,\bar{N}\gamma_\mu\gamma_5 N + c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

We assume theta = 0 and take running and matching into account

$$g_{Na} = g_0(c_{uu} + c_{dd} + 2c_{GG}) \pm g_A\,\frac{m_\pi^2}{m_\pi^2 - m_a^2}\left(c_{uu} - c_{dd} + 2c_{GG}\,\frac{m_d - m_u}{m_u + m_d}\right)$$

ALP phenomenology



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These interactions lead to spin-dependent observables in the non-relativistic limit

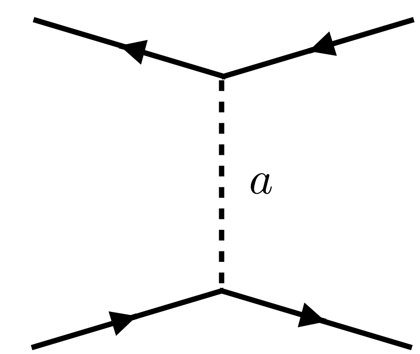
$$g_p a \bar{N} i\gamma_5 N \longrightarrow V_{pp}(r) \approx -\frac{g_p g_p}{4\pi M_N^2 r^3}\left[S_1\cdot S_2 - 3S_1\cdot\hat{r}\right]$$

ALP phenomenology

Forces induced by axion exchange are difficult to discover, because they require experiments with polarised targets

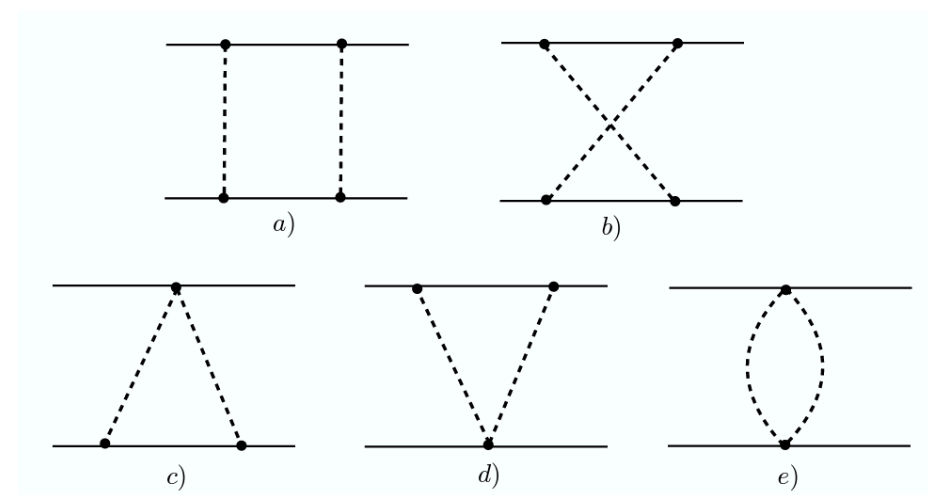
$$g_p a \bar{N} i \gamma_5 N$$

$$V_{pp}(r) \approx -\frac{g_p g_p}{4\pi M_N^2 r^3}\left[S_1 \cdot S_2 - 3 S_1 \cdot \hat{r}\right]$$



However, the exchange of two axions leads to spin-independent forces

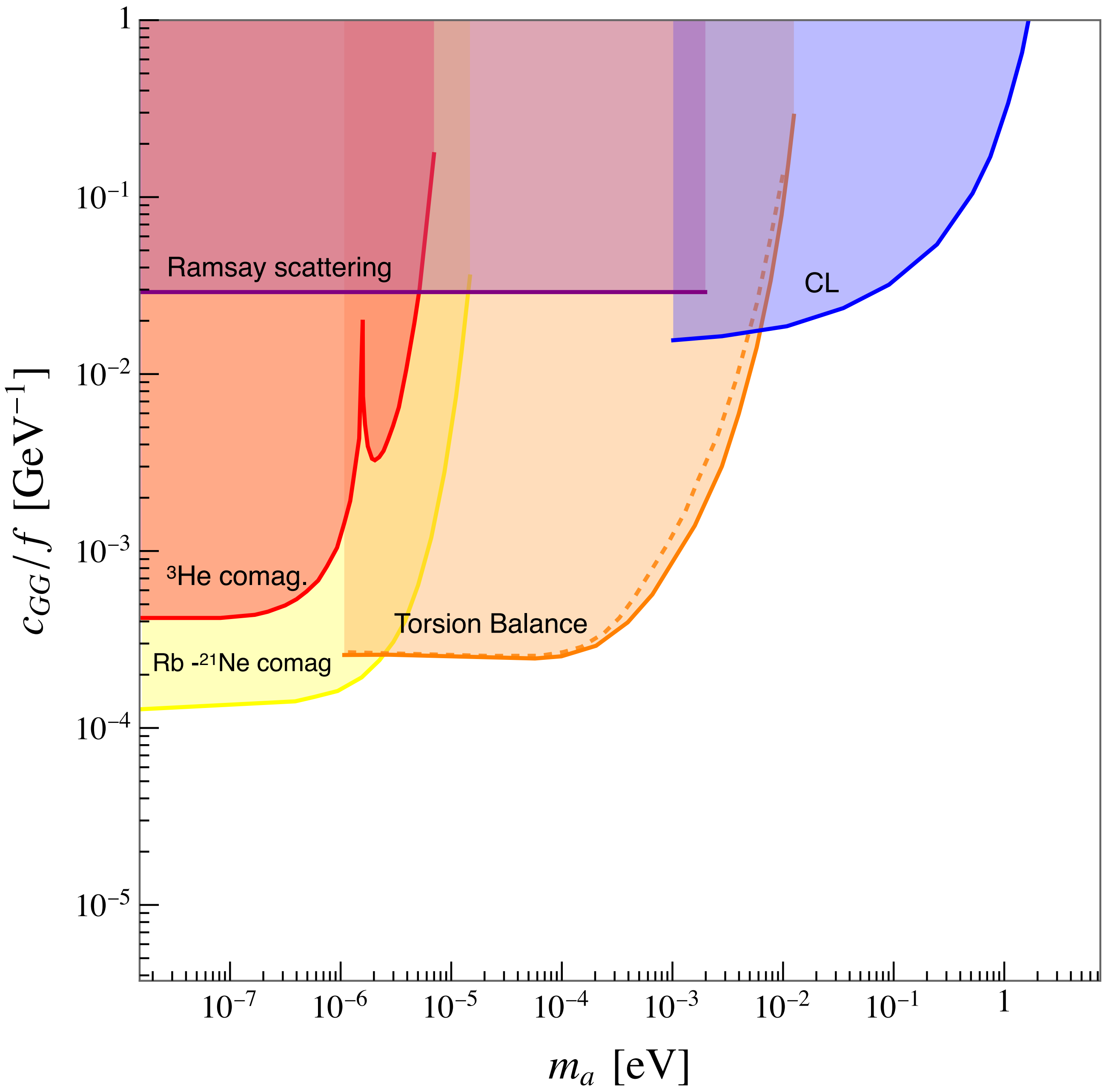
$$V_2(r) \approx -\frac{C_{N_1} C_{N_2}}{64\pi^3 f^4}\frac{1}{r^3}$$



MB, Rostagni, Phys. Rev. Lett. 132 (2024) 101802, [2307.09516].

ALP phenomenology

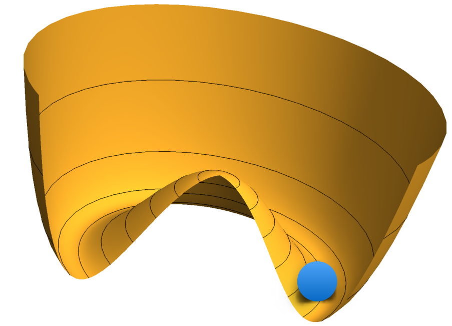
Fifth force bounds from axion-pair exchange can compete with single axion exchange because of the spin-independent potential



MB, Chakraborti, Rostagni, [arXiv:2408.06412 [hep-ph]]

MB, Rostagni, Phys. Rev. Lett. 132 (2024) 101802, [2307.09516].

ALP phenomenology



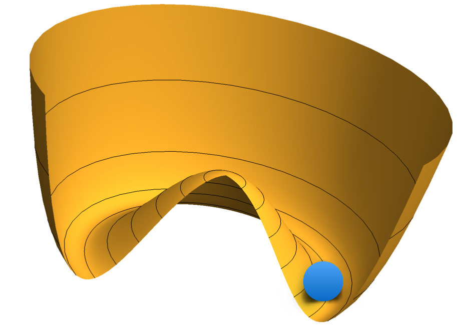
At leading order ALPs/axions interact like pseudoscalars

$$\mathcal{L}_{\rm eff}^{D\leqslant 5}(\mu \lesssim \Lambda_{\rm QCD}) = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{2f}\,c_{ee}\,\bar{e}\,\gamma_\mu\gamma_5\,e + g_{Na}\,\frac{\partial^\mu a}{2f}\,\bar{N}\gamma_\mu\gamma_5 N + c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

What about higher order terms? At dimension 6

$$\mathcal{L}_{\rm eff}^{D=6}(\mu \lesssim \Lambda_{\rm QCD}) = \bar{N}\,(C_N(\mu)\mathbb{1} + C_\delta(\mu)\tau)\,N\,\frac{a^2}{f^2} + C_E(\mu)\,\frac{a^2}{f^2}\,\bar{e}e + C_\gamma(\mu)\,\frac{a^2}{4f^2}\,F_{\mu\nu}F^{\mu\nu}$$

ALP phenomenology



All these couplings are related to the UV coupling structure

$$\mathcal{L}_{\text{eff}}^{D\leqslant 5}(\mu \lesssim \Lambda_{\text{QCD}}) = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{2f}\,c_{ee}\,\bar{e}\,\gamma_\mu\gamma_5\,e + g_{Na}\,\frac{\partial^\mu a}{2f}\,\bar{N}\gamma_\mu\gamma_5 N + c_{\gamma\gamma}^{\text{eff}}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{\text{eff}}^{D=6}(\mu \lesssim \Lambda_{\text{QCD}}) = \bar{N}\left(C_N(\mu)\mathbb{1} + C_\delta(\mu)\tau\right)N\,\frac{a^2}{f^2} + C_E(\mu)\,\frac{a^2}{f^2}\,\bar{e}e + C_\gamma(\mu)\,\frac{a^2}{4f^2}\,F_{\mu\nu}F^{\mu\nu}$$

Requires careful running and matching, e.g.

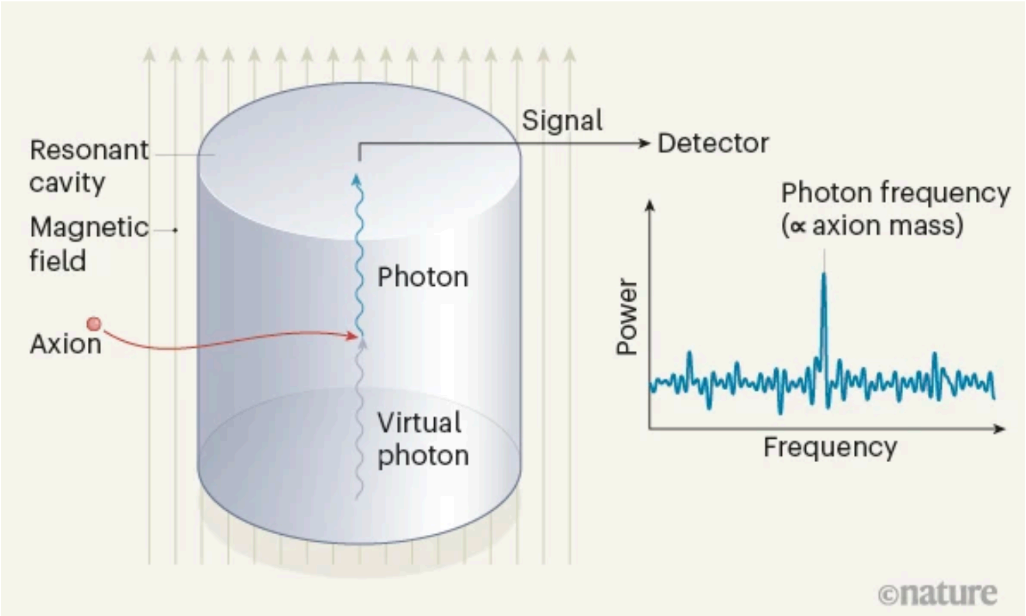
$$C_N = -2c_1 c_{GG}^2 m_\pi^2\left[1 - \left(\frac{m_u - m_d}{m_u + m_d}\right)^2\right] \qquad C_E = -m_e\,\frac{3\alpha}{4\pi}\,C_\gamma \ln\frac{m_\pi^2}{m_e^2}$$

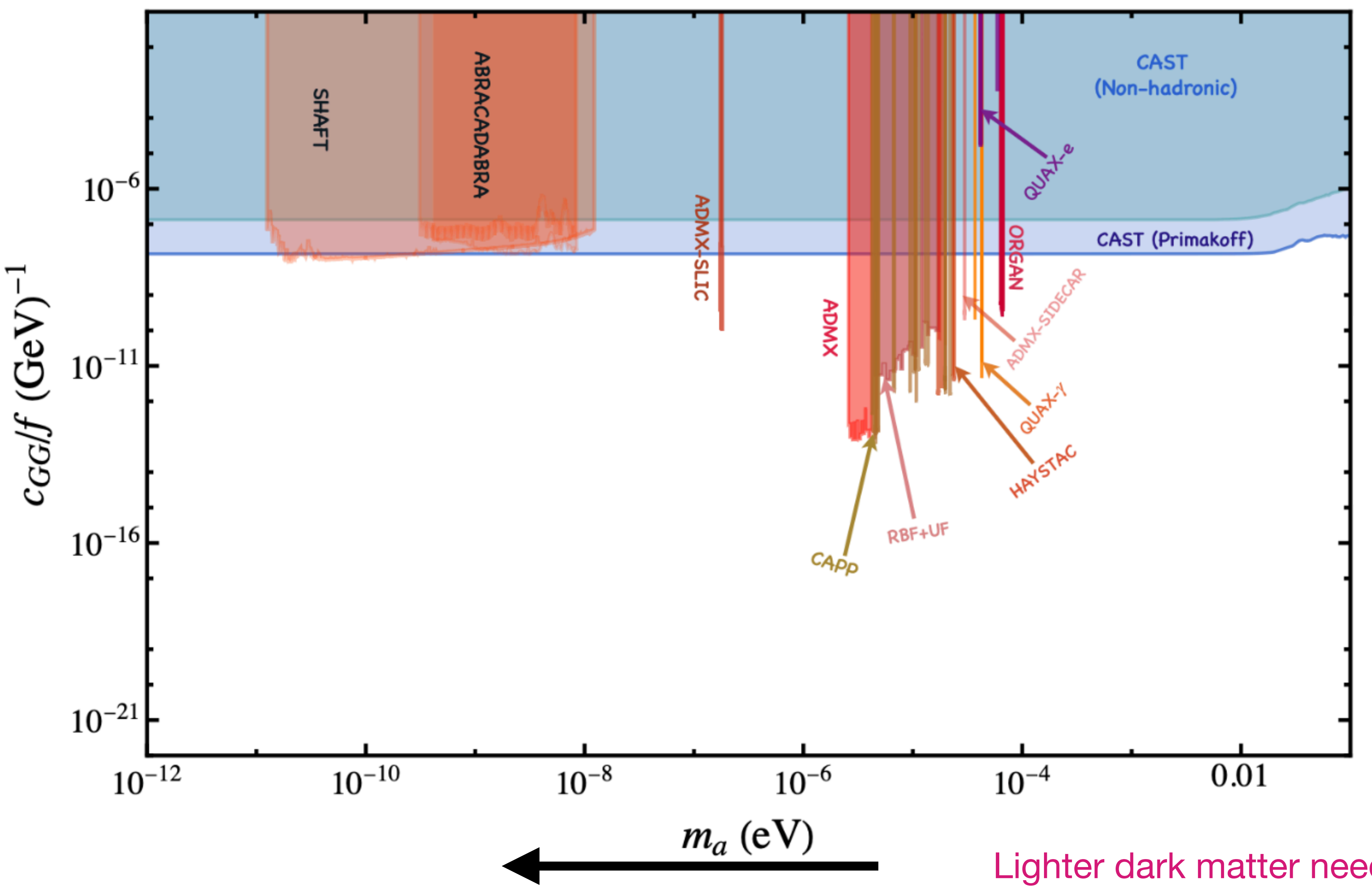
$$C_\gamma(\mu) = \frac{\alpha}{24\pi}\,c_{GG}^2\left(-1 + 32c_1\,\frac{m_\pi^2}{M_N}\right)\left(1 - \frac{\Delta_m^2}{\hat{m}^2}\right)$$

ALP phenomenology

Resonant cavities

$$P_{a\to\gamma} = \frac{\alpha^2}{\pi^2}\frac{\left(c_{\gamma\gamma}^{\rm eff}\right)^2}{f^2}\frac{\rho_{\rm DM}}{m_a}B_0^2 V C \min(Q_L, Q_a)$$





Probes axion interactions with photons

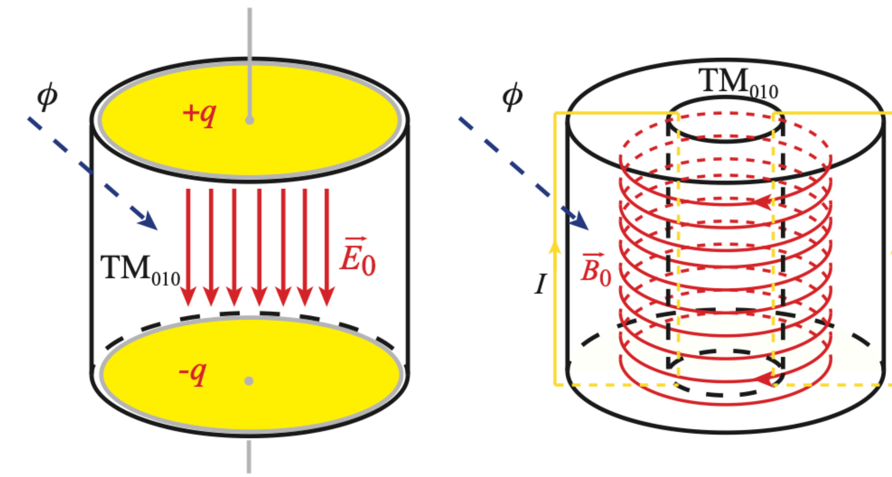
$$c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} = c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{\pi}\,\frac{a}{f}\,\vec{E}\cdot\vec{B}$$

MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,', [arXiv:2408.06412 [hep-ph]]

Lighter dark matter needs larger cavities

Flambaum et al, 2207.14437

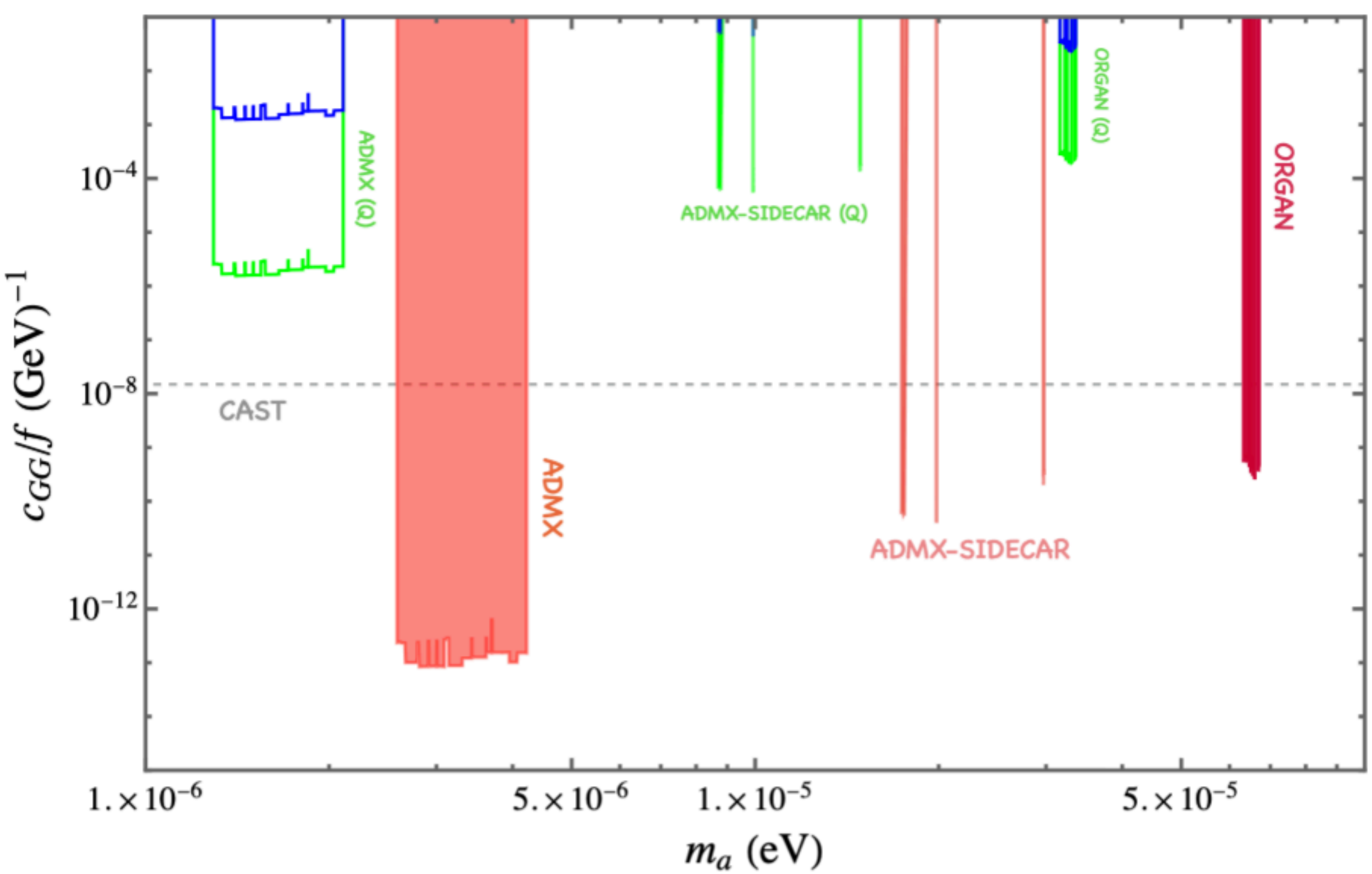
ALP phenomenology



Quadratic axion interactions allow to extend the parameter space

$$C_\gamma \frac{a^2}{4f^2} F_{\mu\nu}F^{\mu\nu} = C_\gamma \frac{a^2}{2f^2}(E^2 - B^2)$$

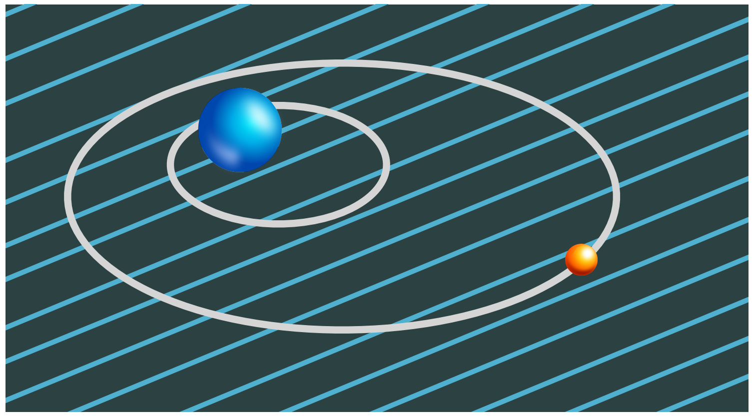
$$P_{aa\to\gamma} \propto \left(\frac{C_\gamma}{f^2}\frac{\rho_{\rm DM}}{m_a}\right)^2 (B_0^2 + E_0^2) V C_\phi \min(Q_L, Q_a)$$



MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,', [arXiv:2408.06412 [hep-ph]]

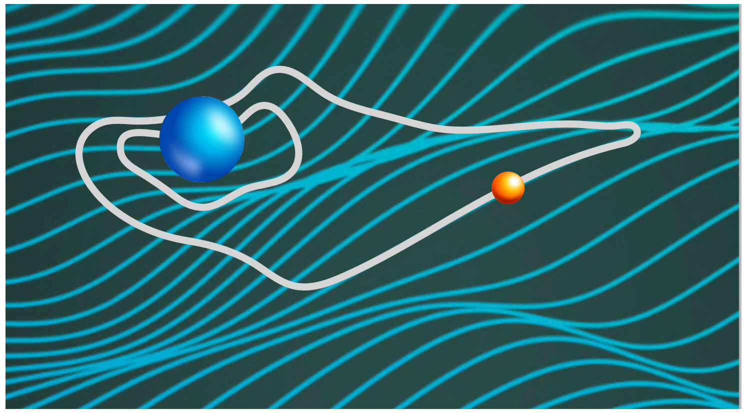
ALP phenomenology

Standard model fields in this background



$$a^2 = \frac{2\rho_{DM}}{m_a^2}\cos^2 m_a t = \frac{\rho_{DM}}{m_a^2}(1 + \cos 2m_a t)$$

Can be described with time-dependent masses and coupling constants



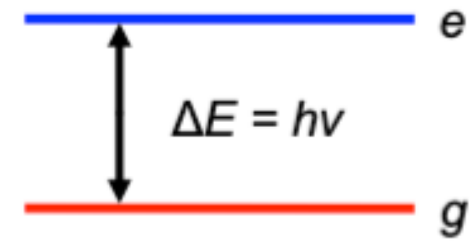
$$\mathcal{L} = m_e \bar{e}e + C_E \frac{a^2}{f^2}\bar{e}e$$

Leads to oscillating fundamental constants

$$m_{\text{eff}}(a^2) = m_e \left(1 + C_E \frac{\rho_{\text{DM}}}{f^2 m_a^2} + C_E \frac{\rho_{\text{DM}}}{f^2 m_a^2}\cos(2m_a t)\right)$$

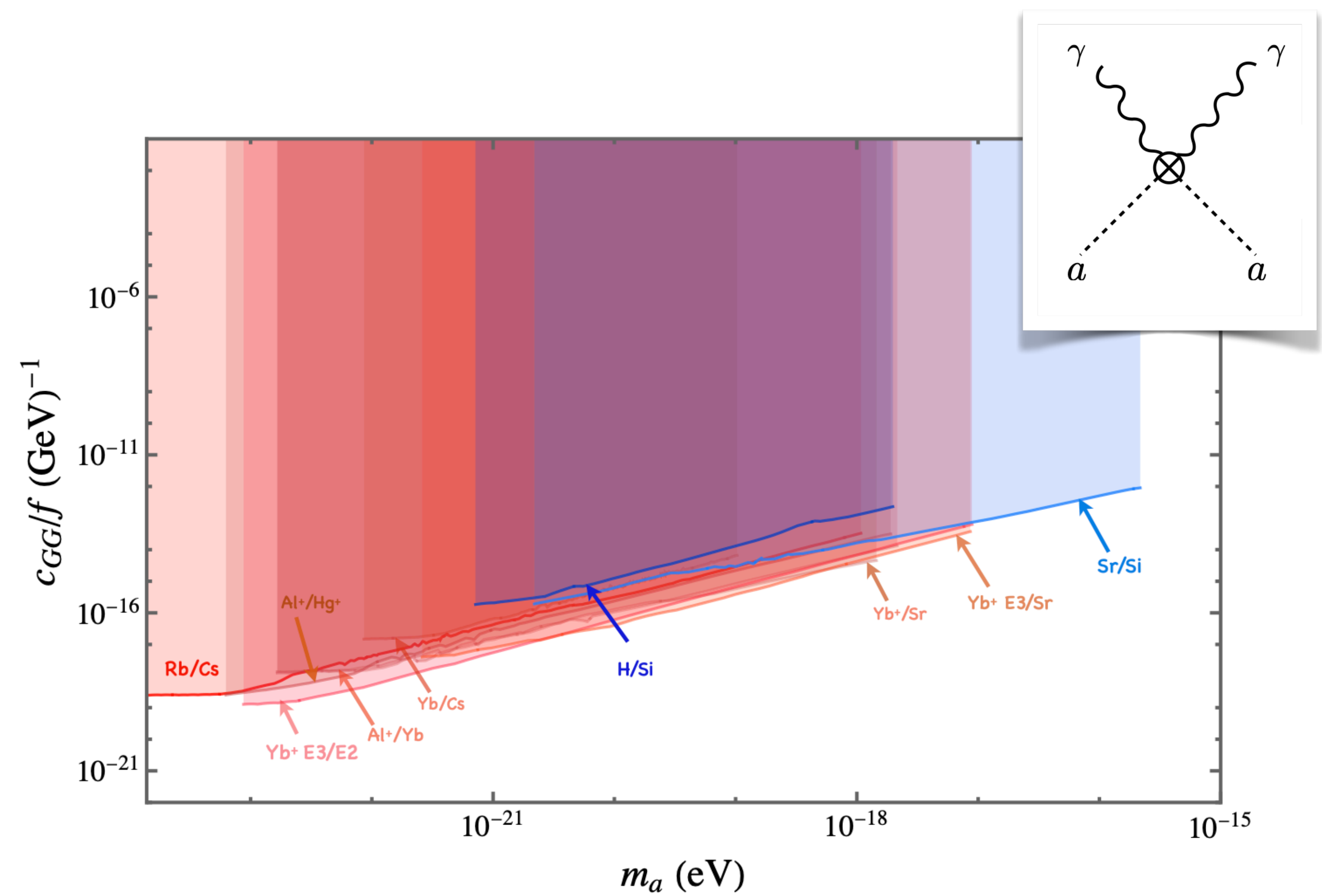
ALP phenomenology

Clocks and clock-cavity bounds



$$\frac{\delta \nu_{A/B}}{\nu_{A/B}} = k_\alpha \frac{\delta\alpha}{\alpha} + k_e \left(\frac{\delta m_e}{m_e} - \frac{\delta m_p}{m_p} \right) + k_q \left(\frac{\delta m_q}{m_q} - \frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} \right)$$

Unique sensitivity to ultra-light states via precision measurements of transition frequencies



MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,', [arXiv:2408.06412 [hep-ph]]

ALP phenomenology

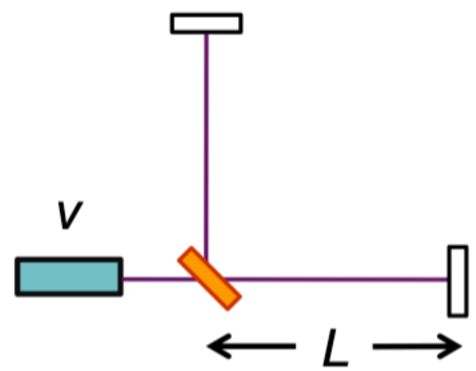
Ion clocks

$$\frac{\delta\nu_{A/B}}{\nu_{A/B}} = k_\alpha \frac{\delta\alpha}{\alpha} + k_e \left(\frac{\delta m_e}{m_e} - \frac{\delta m_p}{m_p}\right) + k_q \left(\frac{\delta m_q}{m_q} - \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}}\right)$$

Laser interferometers

$$\frac{\delta l}{l} = -\left(\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right)$$

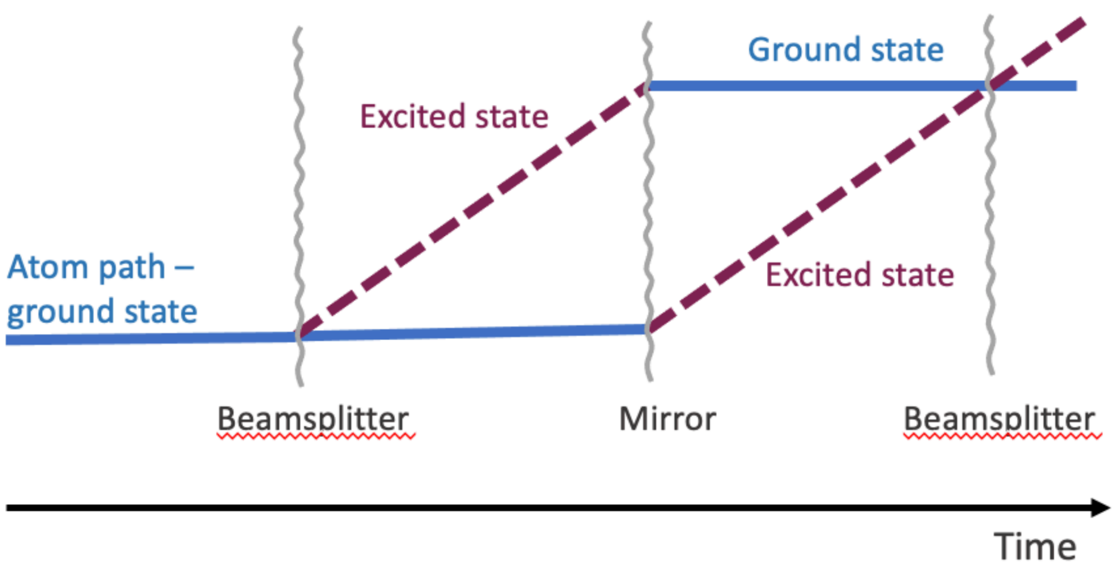
$$\frac{\delta n}{n} = -5\times 10^{-3}\left(2\,\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right)$$



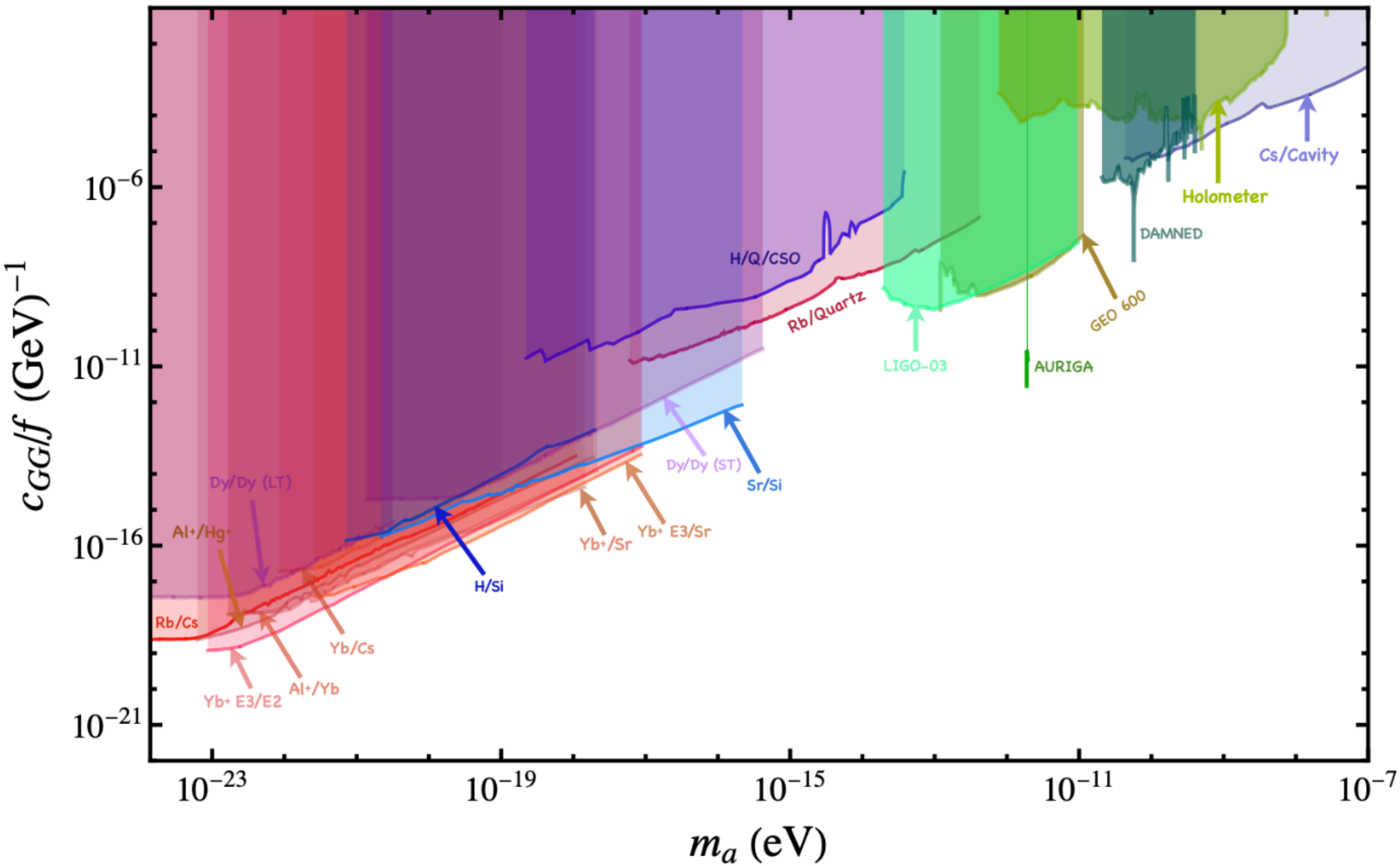
Atom interferometers

$$\frac{\delta\omega_A(a)}{\omega_A} = \delta_e(a) + (2+\xi)\,\delta_\alpha(a)$$

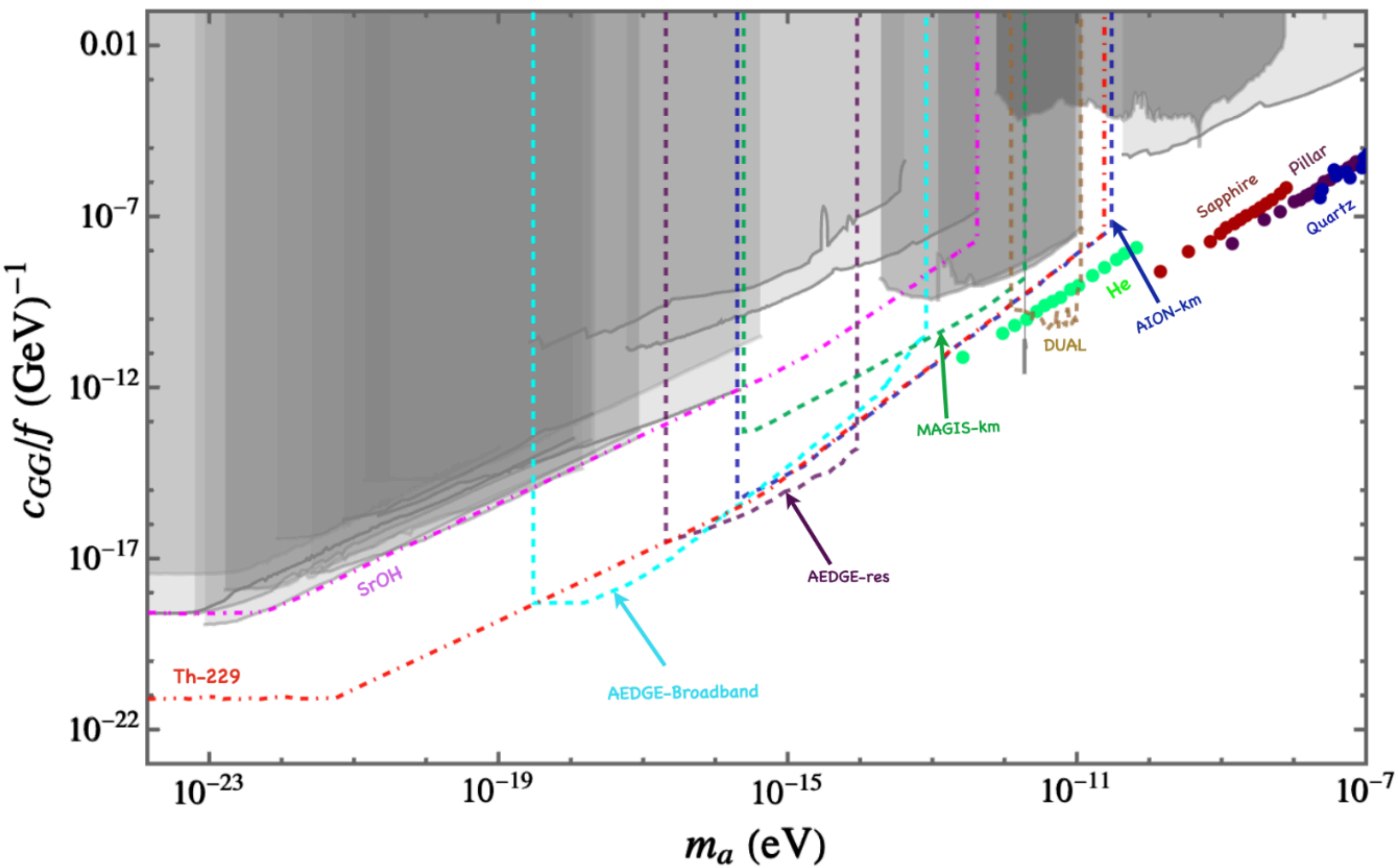
$$\Phi_s = 4\,\overline{\omega_a} n \Delta r \sin^2(m_a T)$$



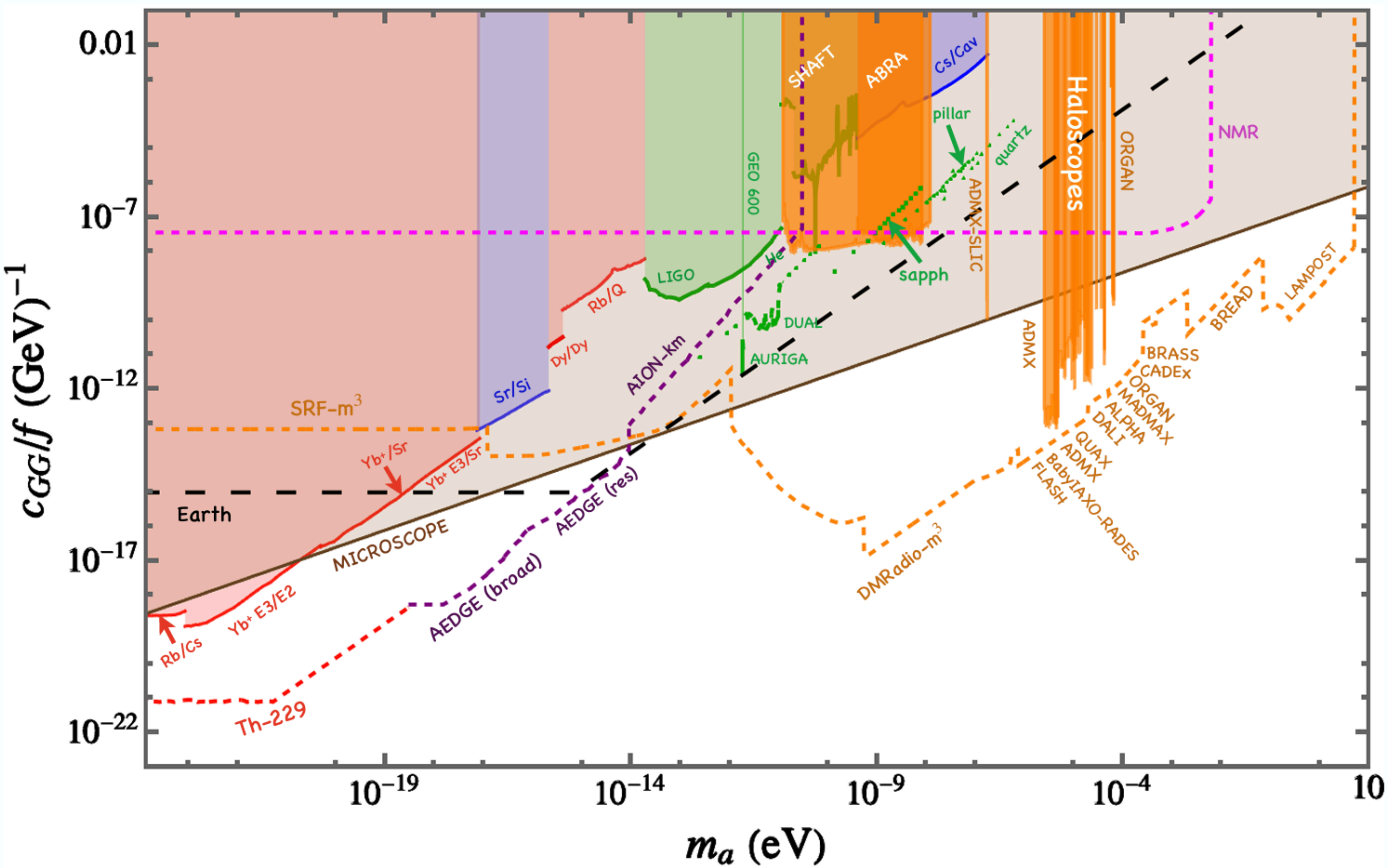
ALP phenomenology



ALP phenomenology

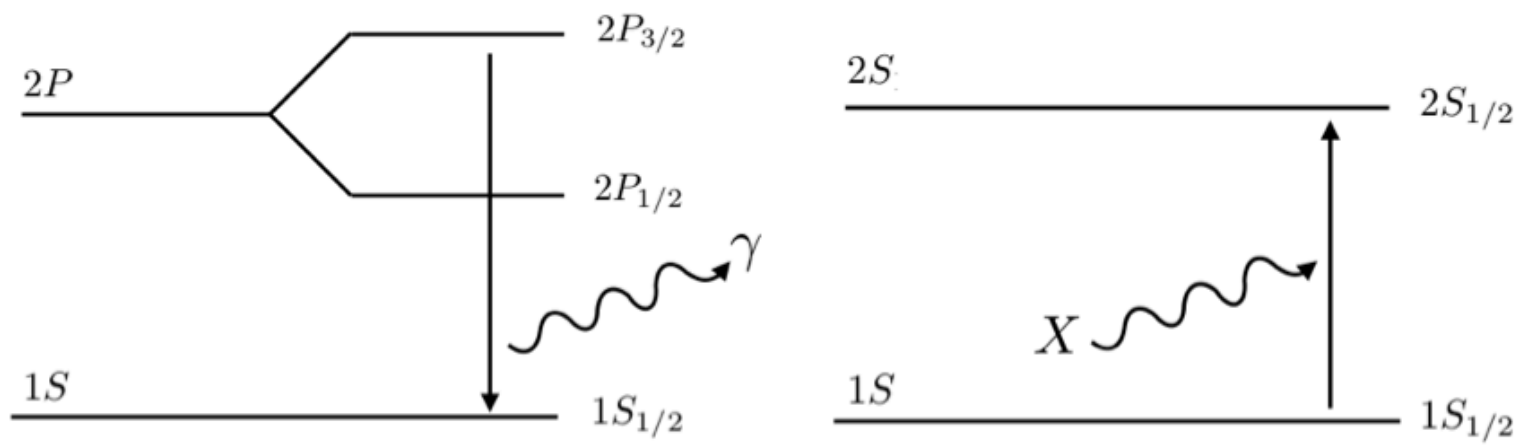


ALP phenomenology



Dark matter absorption

Another way to observe dark matter is via absorption



Depending on the quantum numbers of the dark matter states these can be forbidden transitions

Software to automate the calculation of the overlap integrals and transition rates covering all dark matter candidates is now available

MB, Perez-Soler and Shergold,``Generalised hydrogen interactions with **CINCO**: a window to new physics,''[arXiv:2407.12913 [hep-ph]].

Conclusions

Light dark matter has very different properties compared to WIMPs. Most established searches are blind on this eye.

Axions or axion-like particles are interesting candidates. They appear in many UV extensions of the Standard Model

Quadratic interactions are important and lead to the dominant constraints at low masses

It's imperative to fully utilise our experimental capabilities to search and hopefully discover light dark matter.

…the bad

Axion dark matter has many desirable properties, but quadratic couplings imply non-perturbative effects

$$\left(\partial_t^2 - \Delta + \bar{m}_a^2(r)\right) a = J_{\rm source}(r) \qquad \bar{m}_a^2(r) = m_a^2 + \sum_i \frac{Q_i^{\rm source}\delta_i}{f^2}\rho_{\rm source}(r)$$

Where the effective mass includes a contribution from the ALP-matter quadratic terms, so that close to a source (like earth)

$$a(r,t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos\left(m_a t\right)\left[1 - Z(\delta_i) J_\pm\left(\sqrt{3|Z(\delta_i)|}\right)\frac{R_{\rm source}}{r}\right]$$

With

$$Z(\delta_i) = \frac{1}{4\pi f^2}\frac{M_{\rm source}}{R_{\rm source}}\sum_i Q_i^{\rm source}\delta_i$$

Hees, Minazzoli, Savalle, Stadnik, Wolf,, Phys. Rev. D 98 (2018) 064051, [1807.04512]
Banerjee, Perez, Safronova, Savoray, Shalit, JHEP 10 (2023) 042, [2211.05174]

…the bad

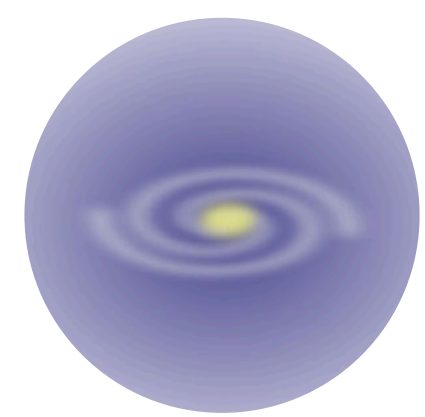
For large field values the function J diverges.
If the sign of Z is positive this leads to a suppression (screening) of the axion field close to massive bodies.

However for axions it is strictly negative

$$c_{GG} \neq 0 \quad \Rightarrow \quad \sum_i Q_i^{\text{source}} \delta_i < 0\,.$$

The axion field value is displaced from its vacuum value due to the effective mass from the high density environment, so theta=0 isn't a valid assumption anymore.

The axion potential also leads to *attractive* self-interactions

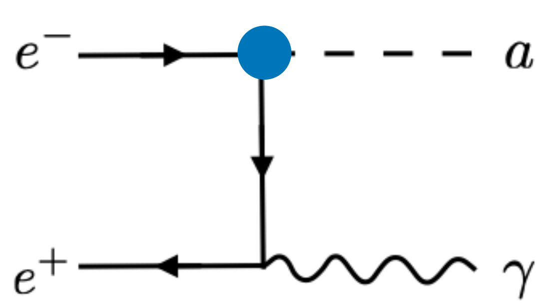


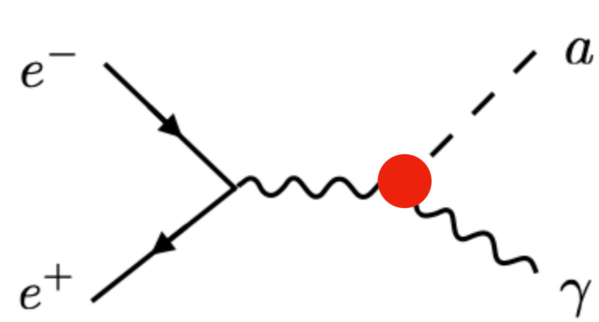
Hook, Huang, JHEP 06 (2018) 036, [1708.08464].

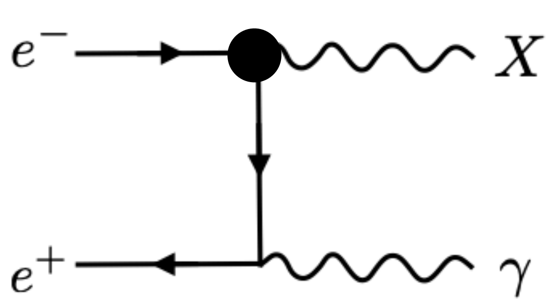
DM spin measurement

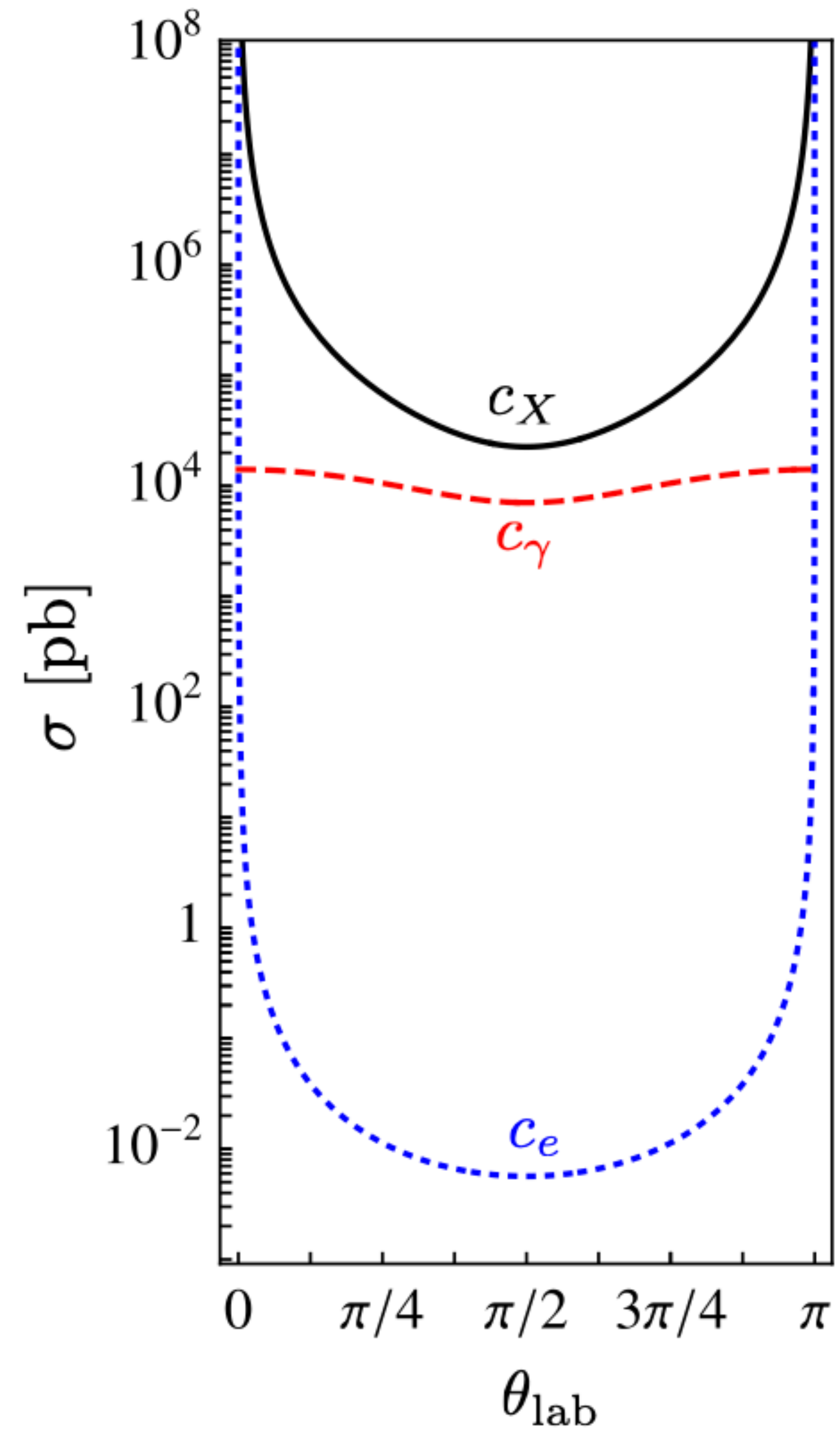
What if the ALP, dark photon is stable?

Angular distribution can distinguish t-channel from s-channel





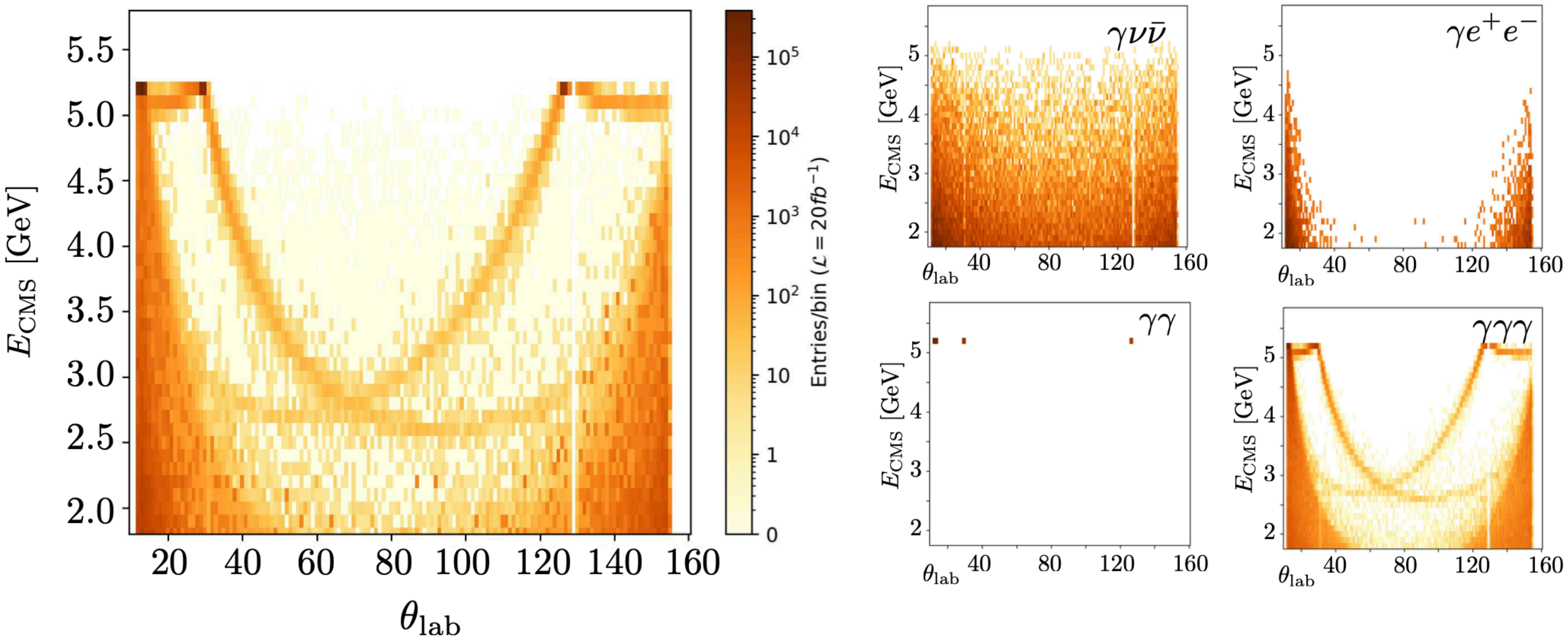




MB, Erner, *Phys.Rev.D* 108 (2023) 11

Invisible states and polarisation

Backgrounds for e+e- -> X + γ at Belle II

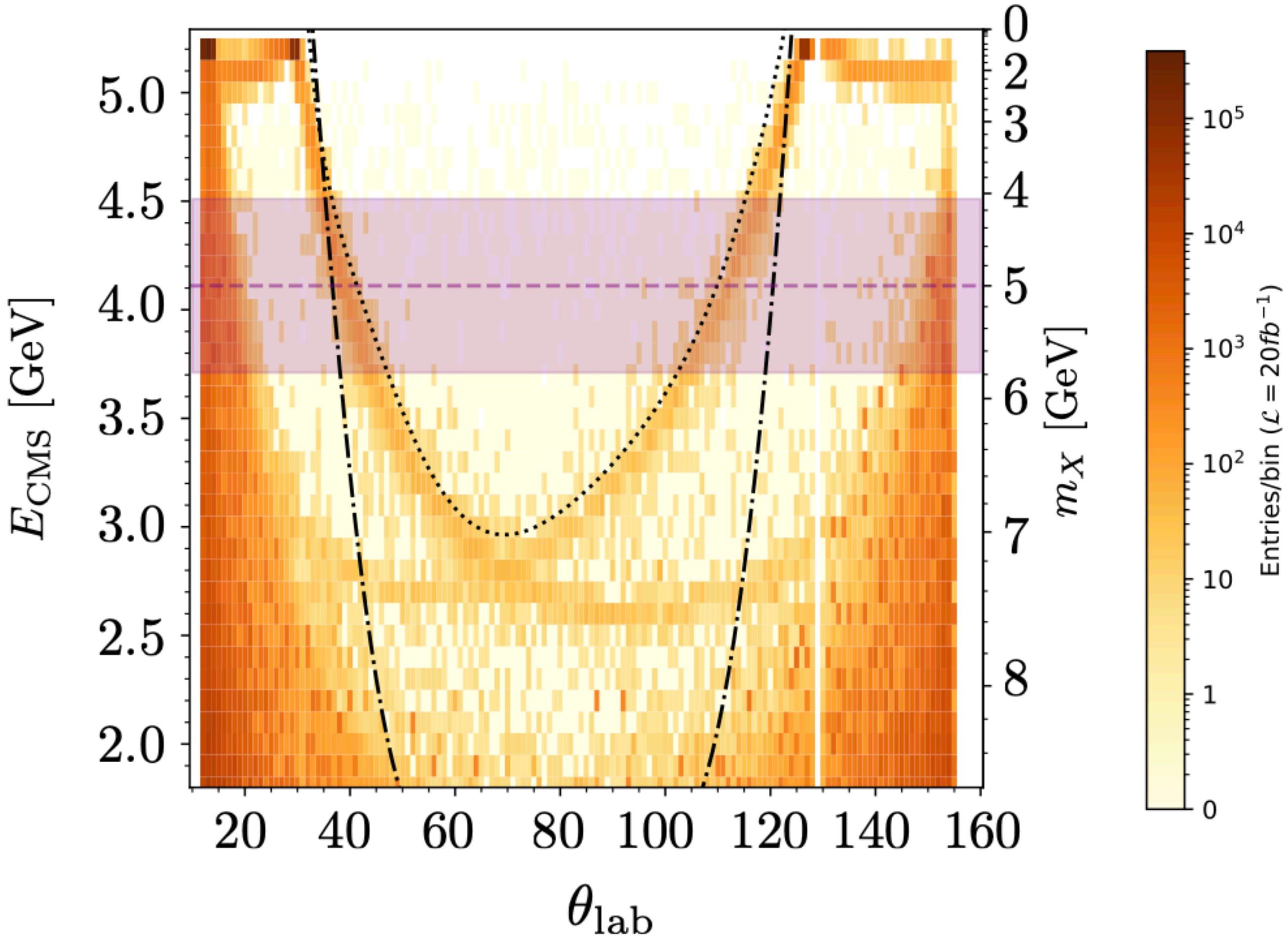


MB, Erner, *Phys.Rev.D* 108 (2023) 11

Invisible states and polarisation

Polarised beams eliminates background and distinguishes ALP-electron and photon interactions

Unpolarised



MB, Erner, *Phys.Rev.D* 108 (2023) 11

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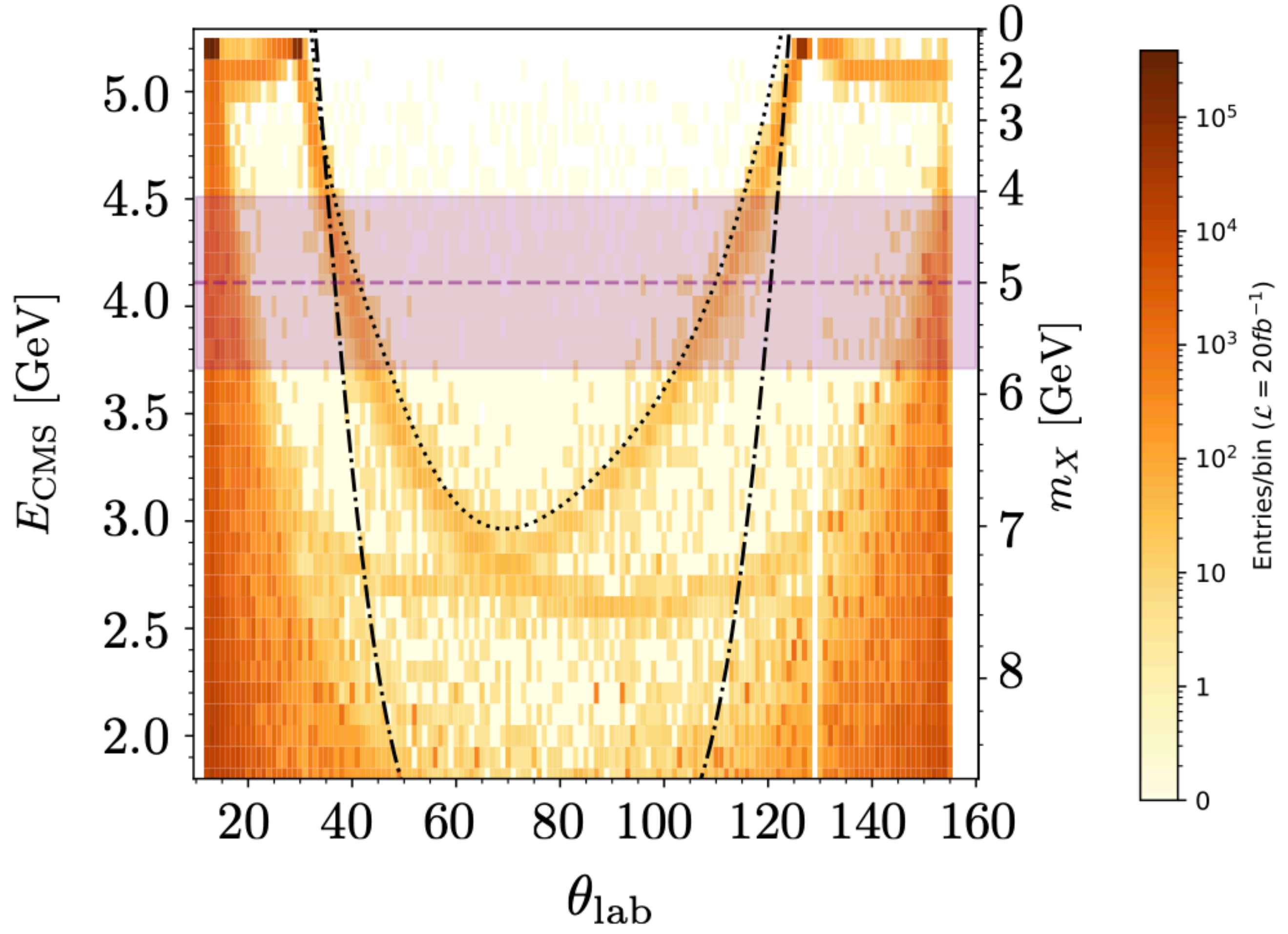
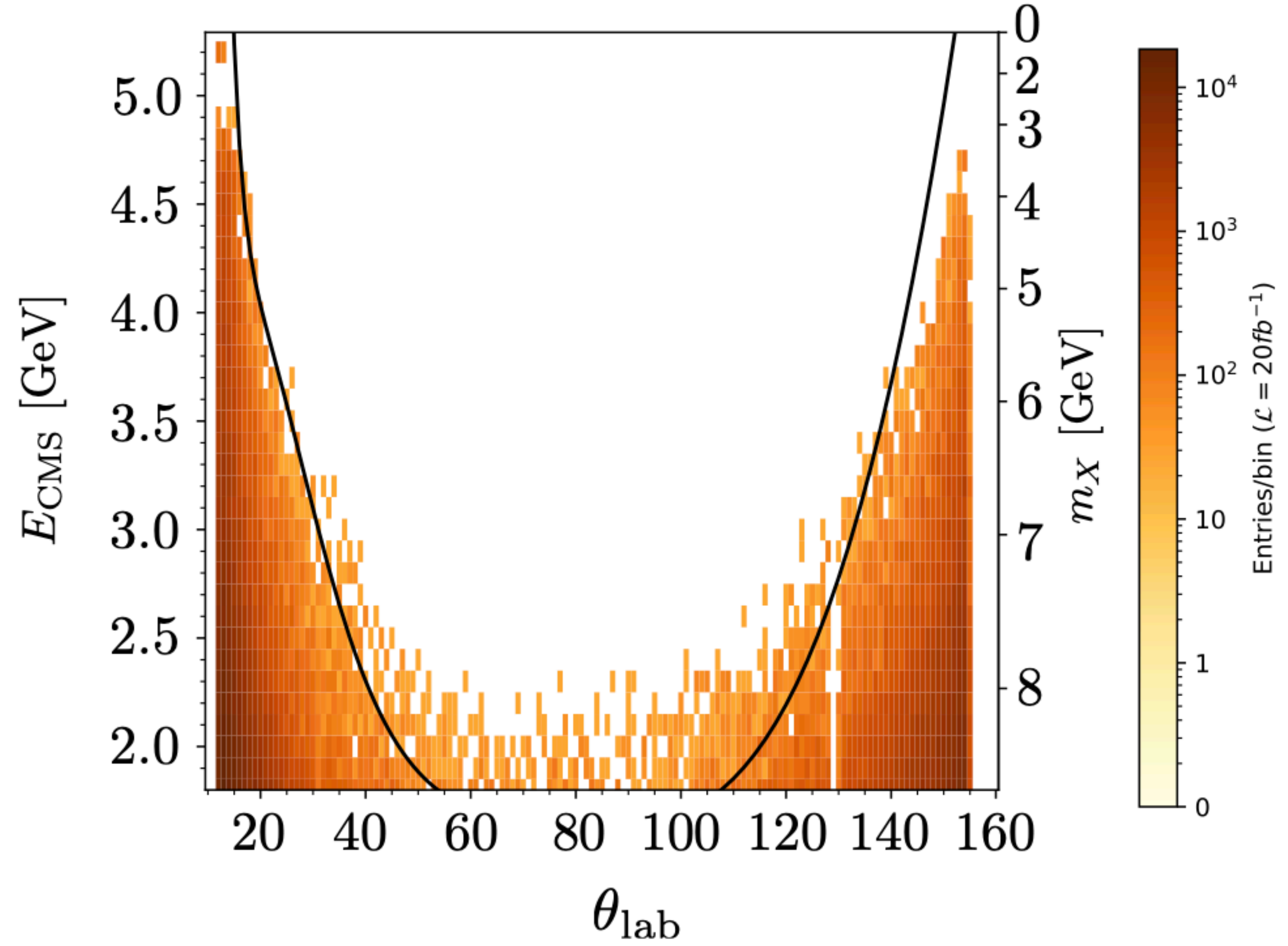


Polarised beams



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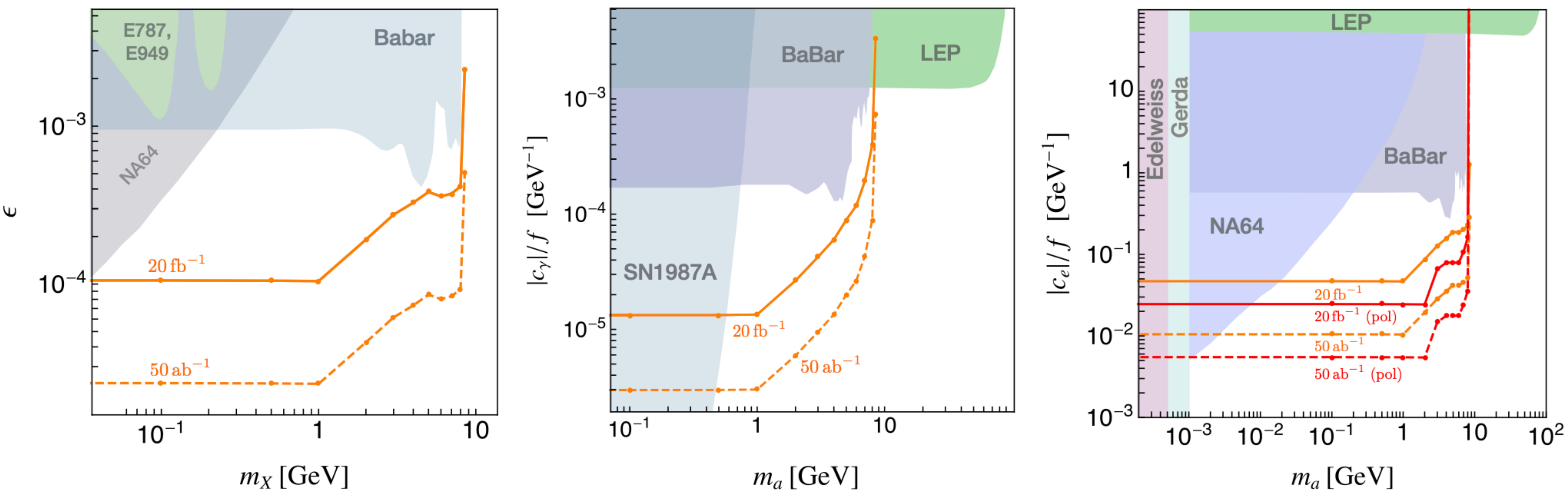

MB, Erner, *Phys.Rev.D* 108 (2023) 11

Misalignment Mechanism

Action:

$$\frac{1}{\sqrt{|g|}}\mathscr{L} = (\partial^\mu \phi^*)(\partial_\mu \phi) - V(\phi) = (\partial^\mu \phi^*)(\partial_\mu \phi) - m_\phi^2\, \phi^* \phi$$

EL-equations:

$$\begin{aligned}
0 &= \partial_t \left(\frac{\partial \mathscr{L}}{\partial(\partial_t \phi^*)} \right) - \frac{\partial \mathscr{L}}{\partial \phi^*} \\
&= \partial_t \left(\sqrt{|g|}\, \partial_t \phi \right) + \sqrt{|g|}\, m_\phi^2 \phi \\
&= (\partial_t \sqrt{|g|})\,(\partial_t \phi) + \sqrt{|g|}\, \partial_t^2 \phi + \sqrt{|g|}\, m_\phi^2 \phi \\
&= \sqrt{|g|} \left[\frac{(\partial_t \sqrt{|g|})}{\sqrt{|g|}}\, (\partial_t \phi) + \partial_t^2 \phi + m_\phi^2 \phi \right] . \\
&= \frac{(\partial_t a^3)}{a^3}\, (\partial_t \phi) + \partial_t^2 \phi + m_\phi^2 \phi = \frac{3\dot{a}}{a}\, \dot{\phi} + \ddot{\phi} + m_\phi^2 \phi
\end{aligned}$$

appr. flat

$|g| = a(t)^6$

yields:

$$\boxed{\ddot{\phi}(t) + 3H\dot{\phi}(t) + m_\phi^2 \phi(t) = 0}$$