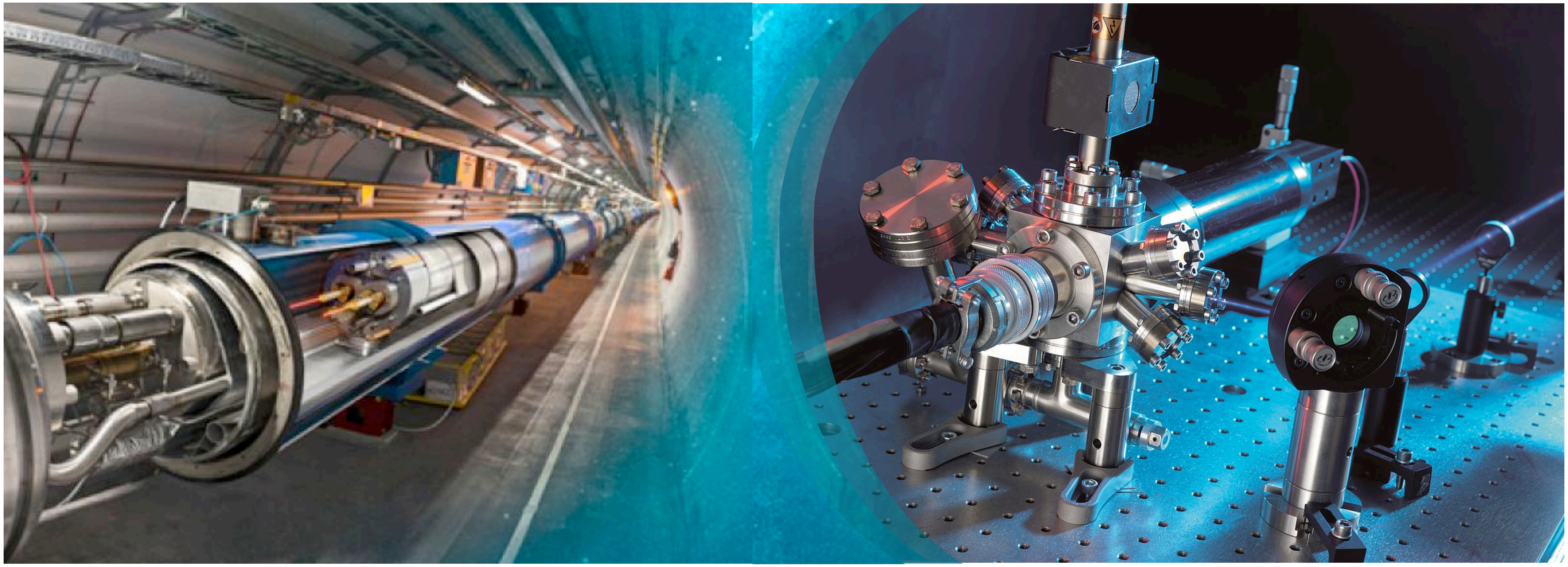
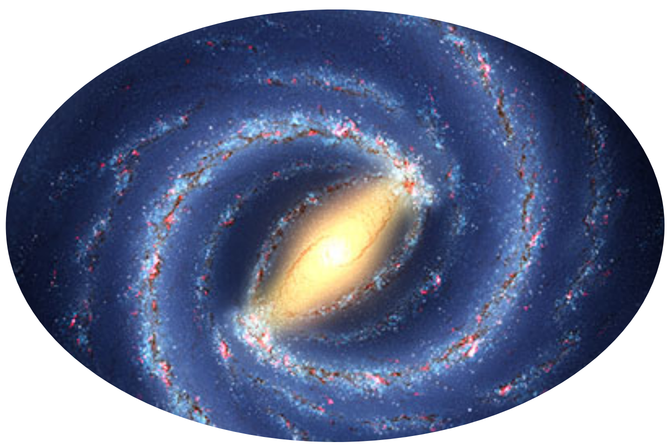


Axion Dark Matter

Martin Bauer, UK HEP forum, 21.10.2025

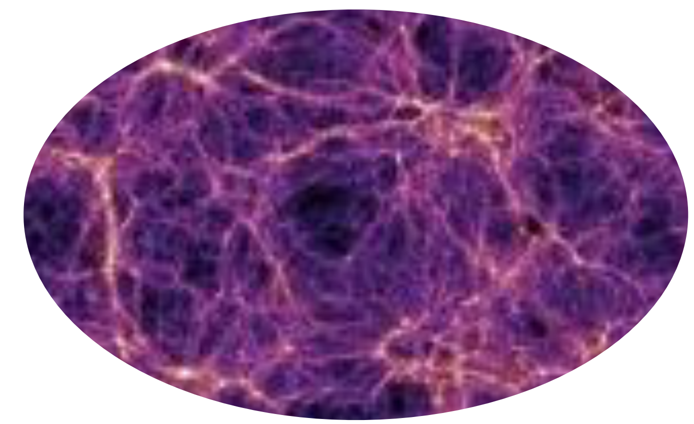
What is dark matter ?

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



Rotation curves

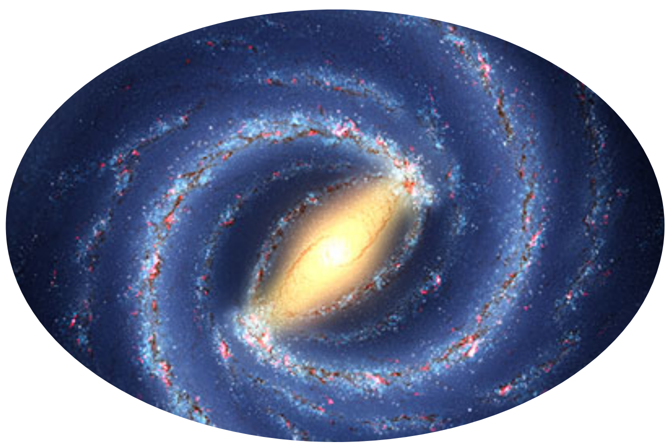
gravitational lensing



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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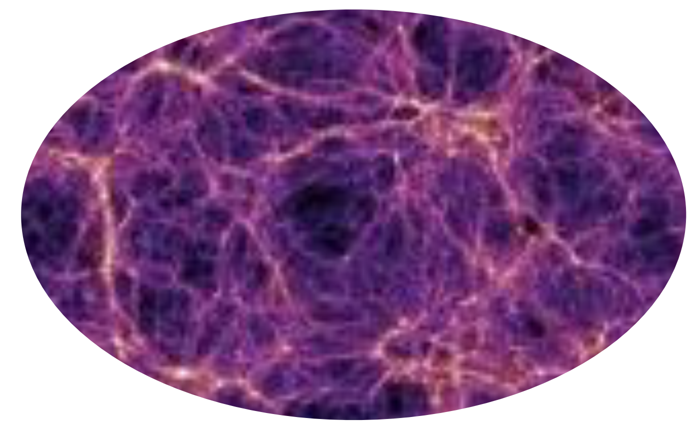


Structure formation

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?

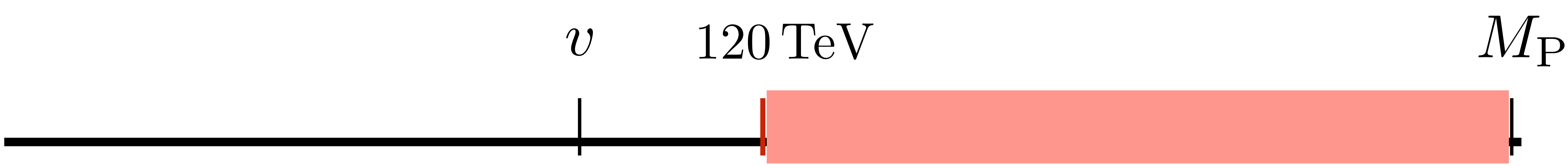
What is the DM scale?

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

$$\sigma \sim \frac{g^4}{m_\chi^2}$$

$$g^2 \lesssim 4\,\pi$$

$$\Rightarrow \quad m_\chi \lesssim 120\,\mathrm{TeV}$$



What is the DM scale?

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

$$\Gamma = n \cdot \sigma = H$$

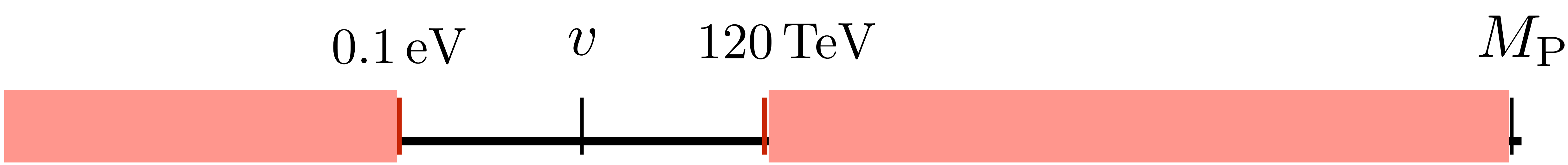
$$(m_\chi T)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}} \cdot \sigma = \frac{T^2}{M_{\mathrm{Pl}}}$$

$$m_\chi > \frac{1}{\sigma M_{\mathrm{Pl}}} \qquad \Rightarrow m_\chi > 0.1\,\mathrm{eV}$$

$$\sigma \sim \frac{g^4}{m_\chi^2}$$

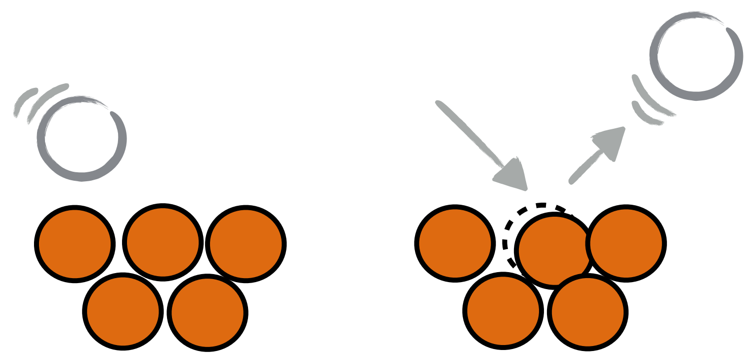
$$g^2 \lesssim 4\,\pi$$

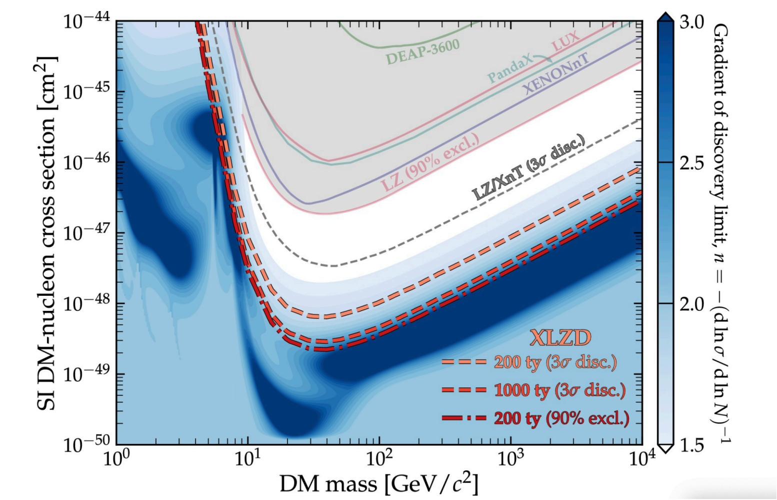
$$\Rightarrow \qquad m_\chi \lesssim 120\,\mathrm{TeV}$$



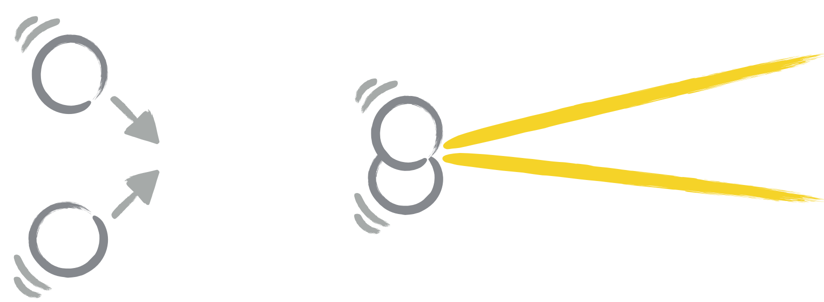
Extensive Programme

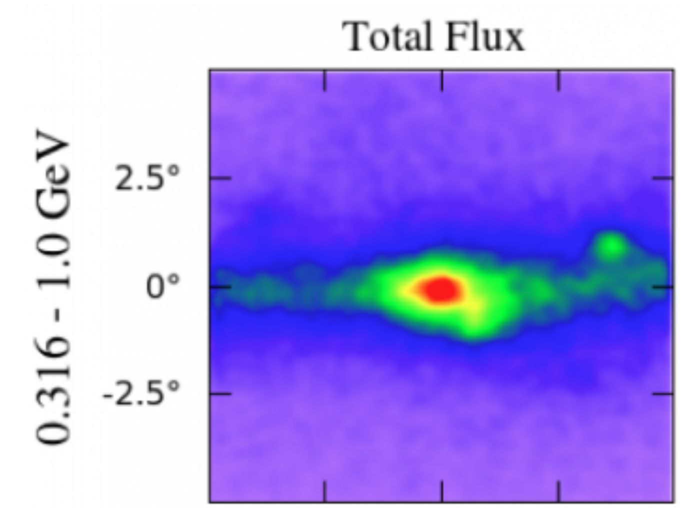
Direct detection



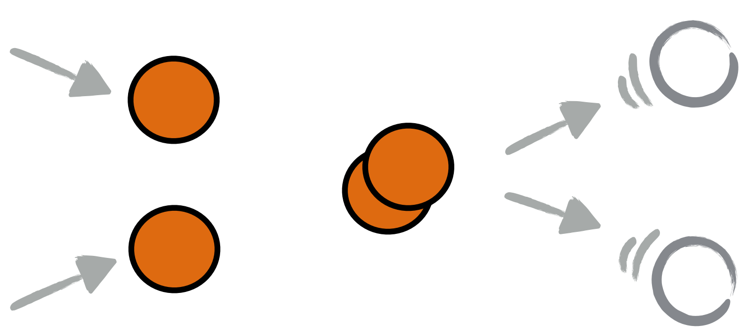


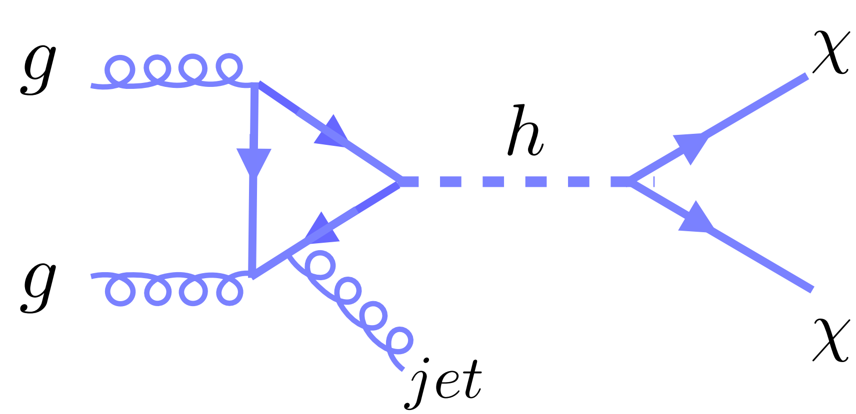
Indirect detection





Collider searches





What is the DM scale?

What do we know about the scale of DM?

7

What is the DM scale?

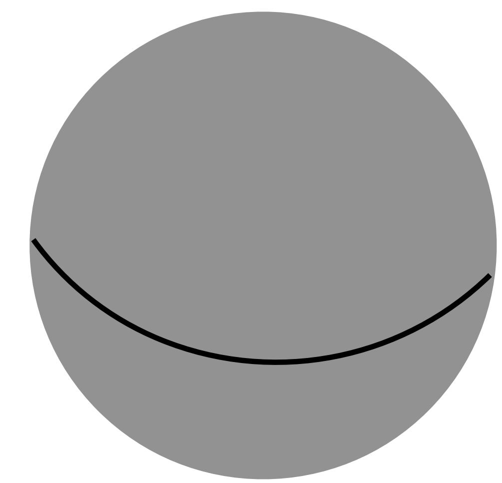
What do we know about the scale of DM?

For **Fermions**, the Pauli exclusion principle provides a lower limit

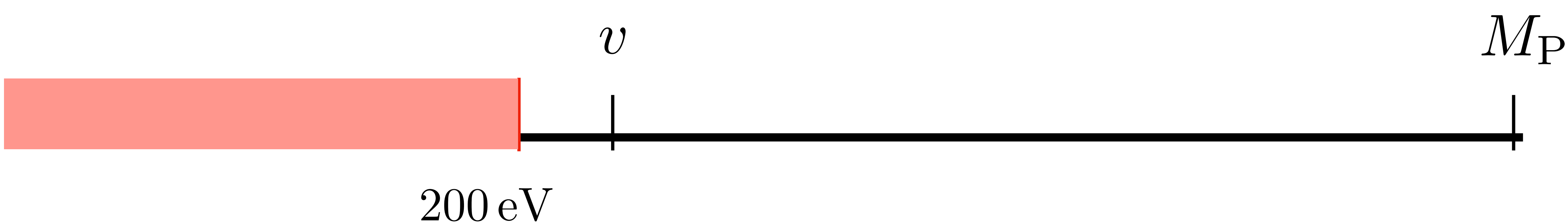
$$\left(\frac{9\pi M}{4 m_\chi^4 R^3}\right)^{1/3} \leq \sqrt{\frac{2 G_N M}{R}}$$

$$\Rightarrow \quad m_\chi \gtrsim 200\,\mathrm{eV}$$

dwarf galaxies



$$M \approx 10^7 M_\odot$$
$$R \approx 500\,\mathrm{pc}$$



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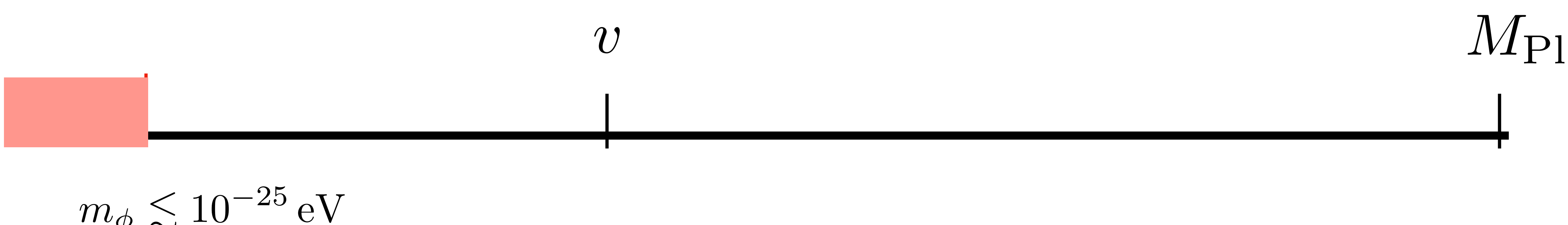
What is the DM scale?

For bosons there is no such lower limit.

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.



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What is the DM scale?

For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

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

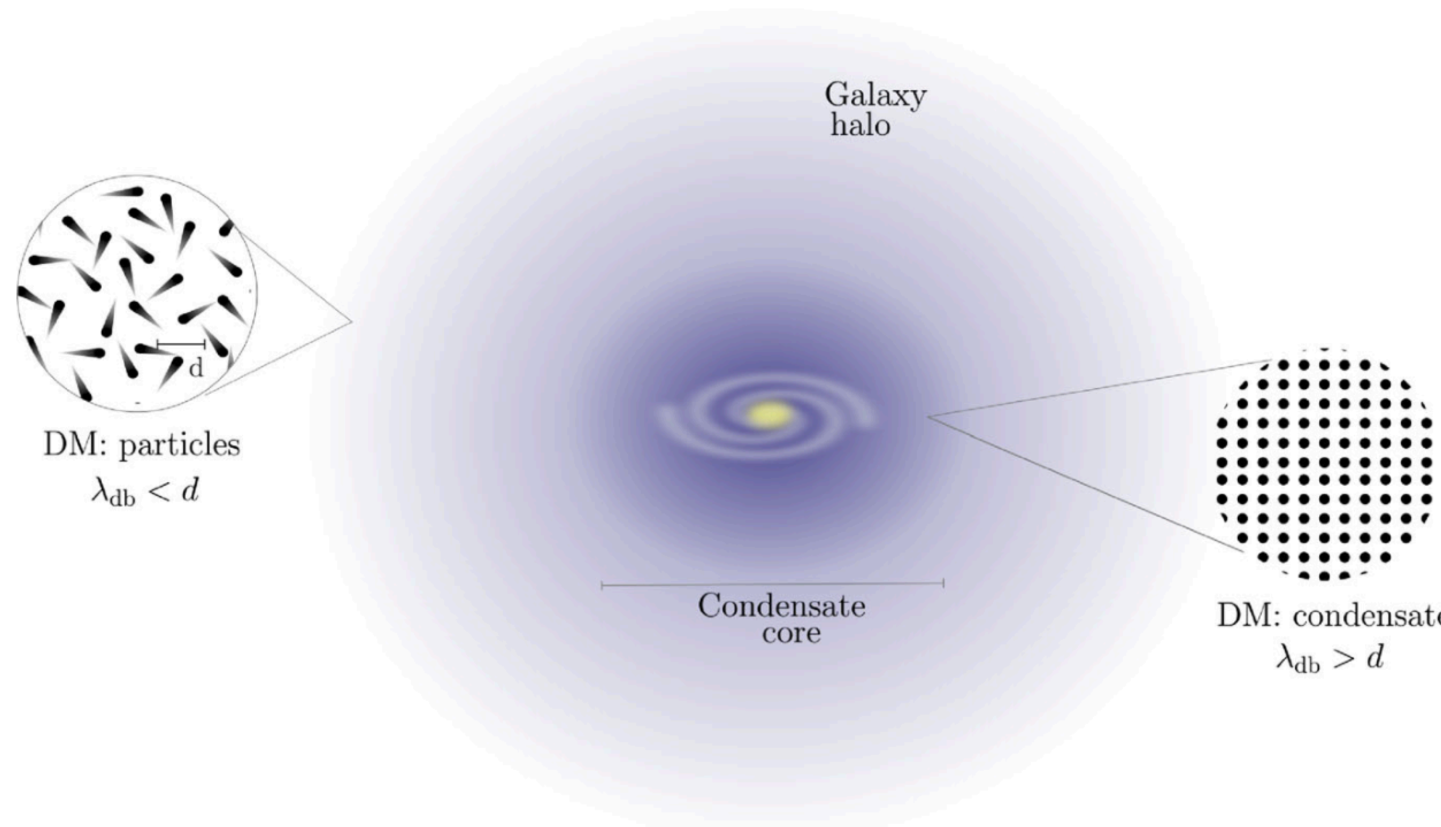
10

Ultralight Dark Matter

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

$$m_\phi \approx 10^{-22}\,\mathrm{eV} \qquad \Rightarrow$$

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



Ultralight Dark Matter

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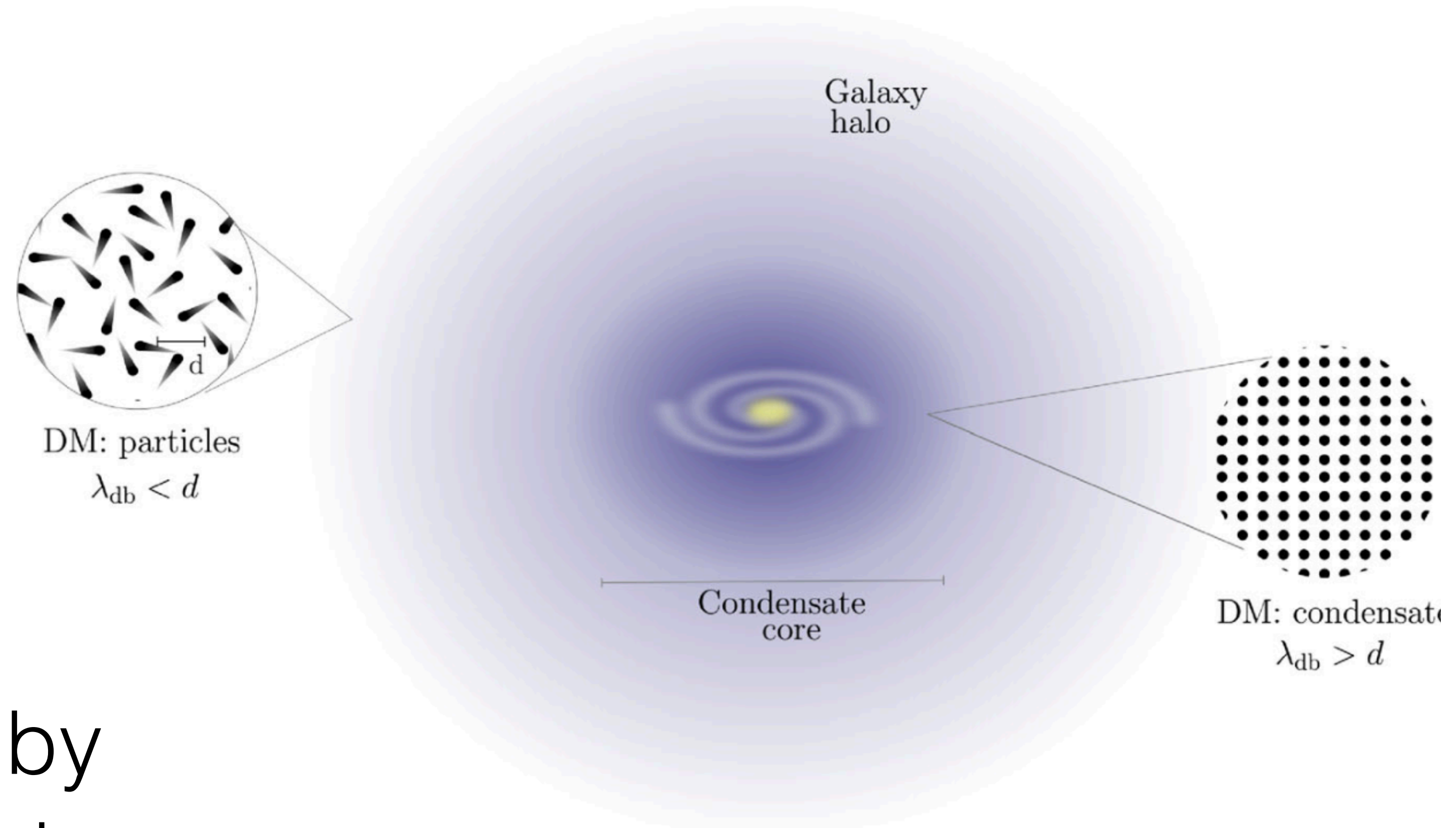
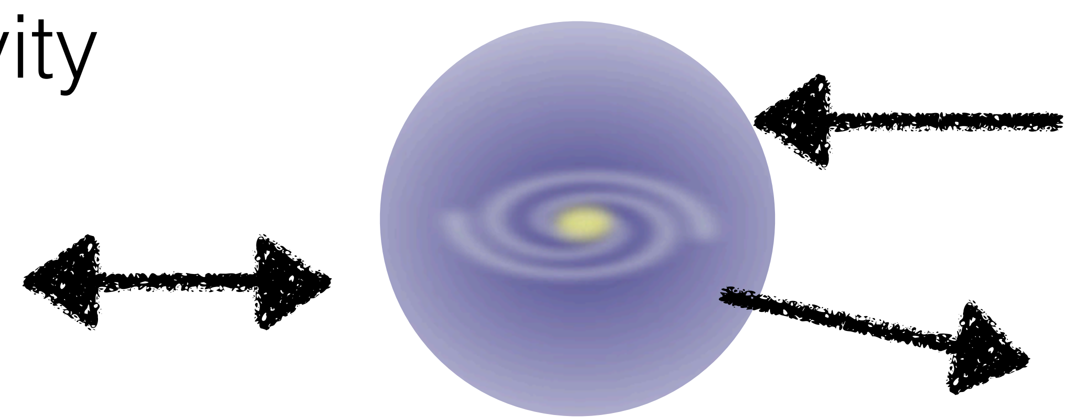


The size of the core is set by the balance between quantum pressure and gravity



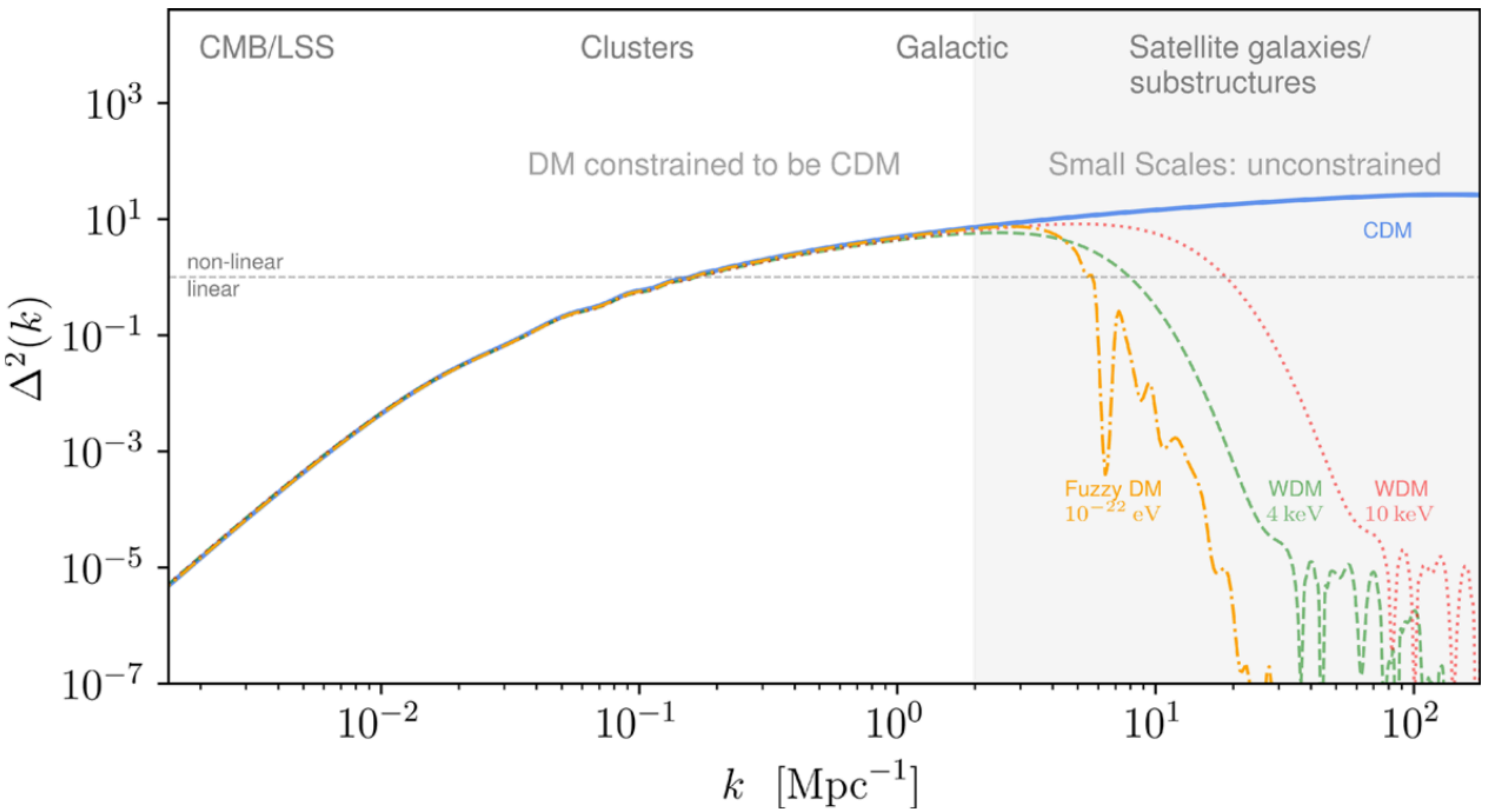
Gravity

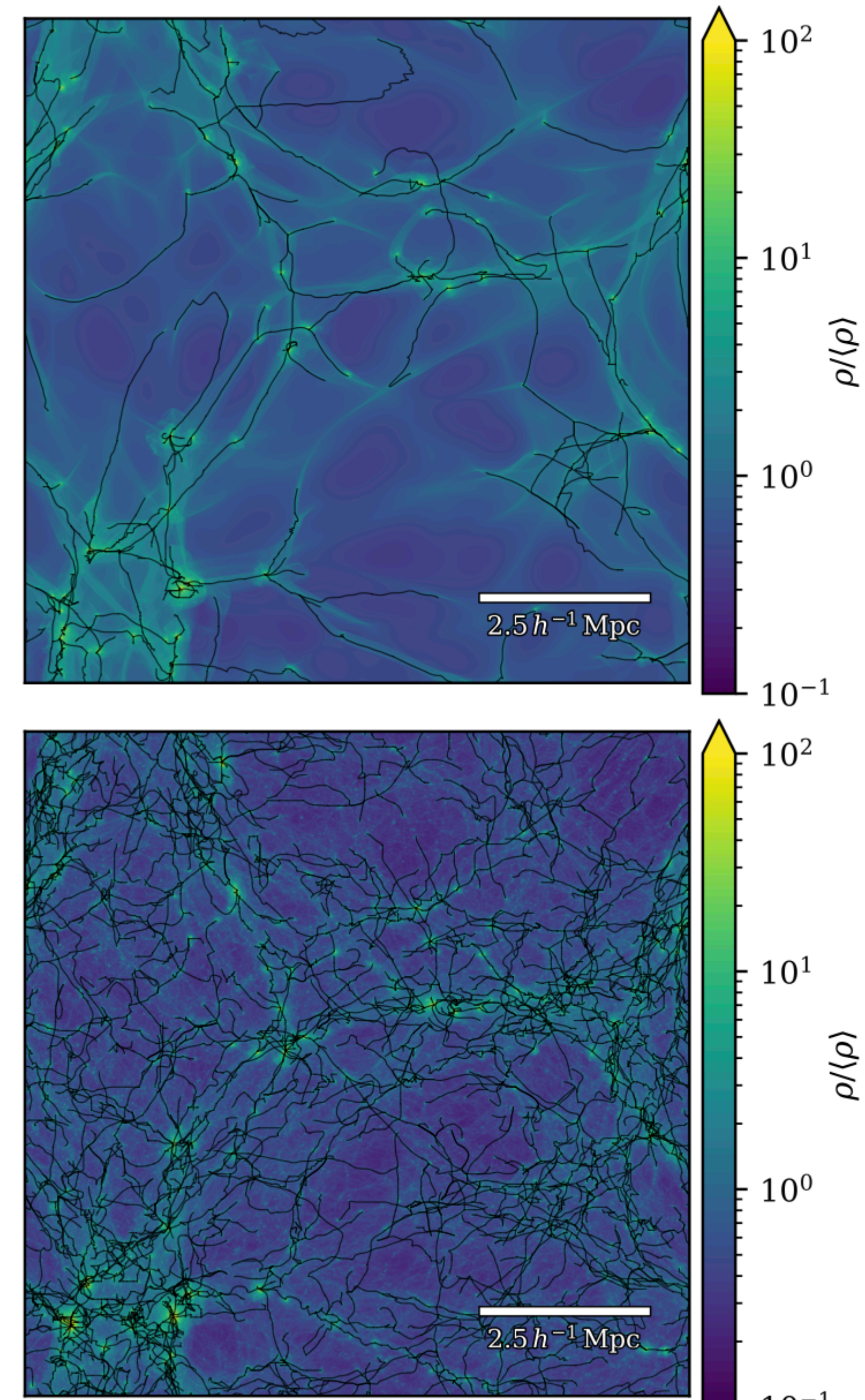
Self-interactions

Quantum pressure

Ultralight Dark Matter

Fit the small scale power spectrum:

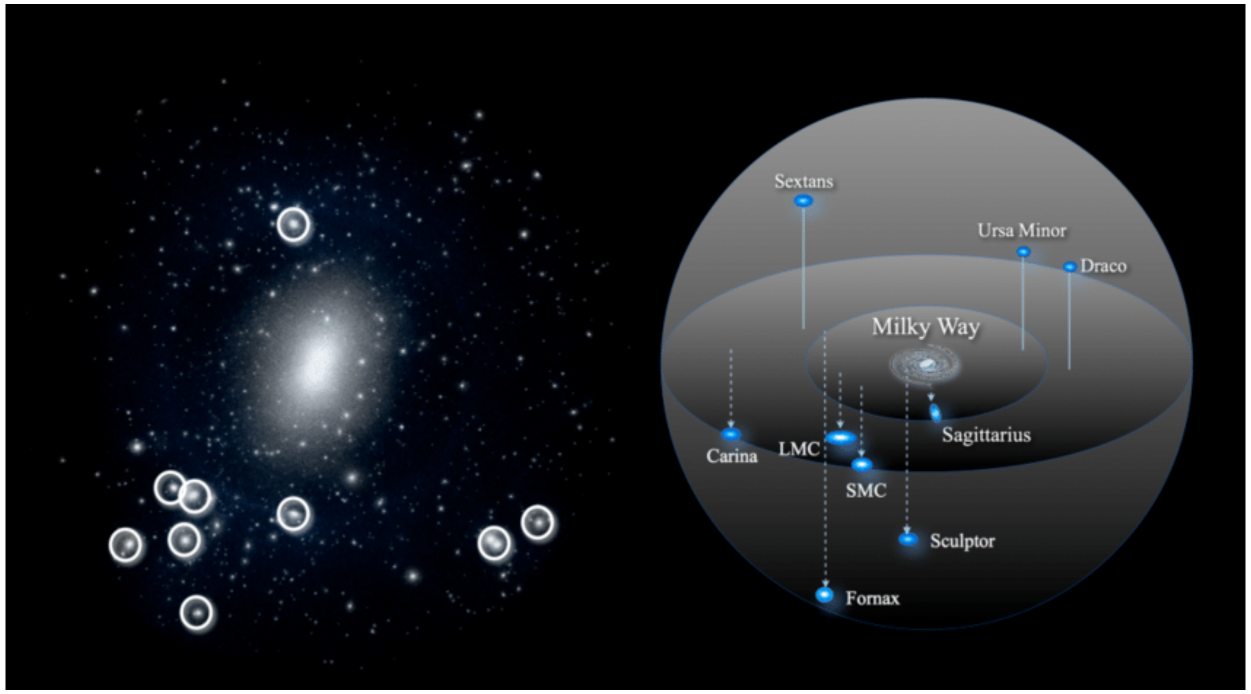


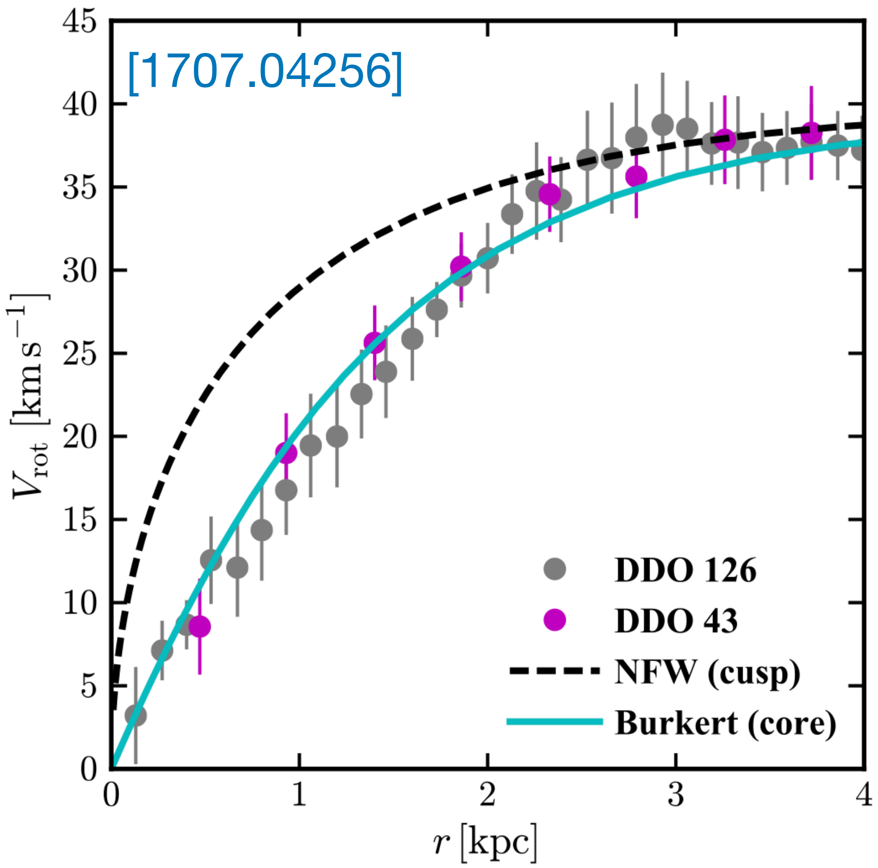


May et al. 2021

Ultralight Dark Matter

Missing satellite problem





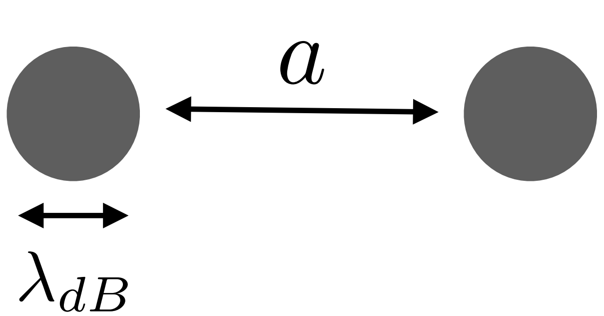
Core cusp problem

What is the DM scale?

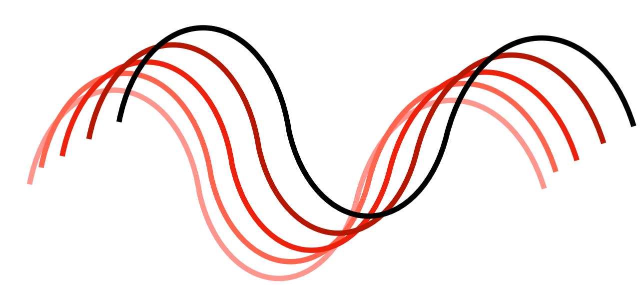
For very light scalar fields, the occupation number is very high and the field can be treated classically.

QFT

Large spacing.
Particle mechanics



Large (continuous) occupation number.
Classical field theory



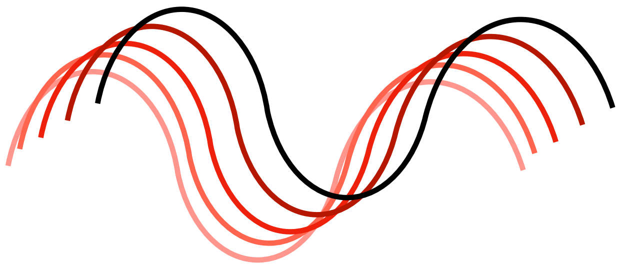
Ultralight Dark Matter

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

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

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

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



Ultralight Dark Matter

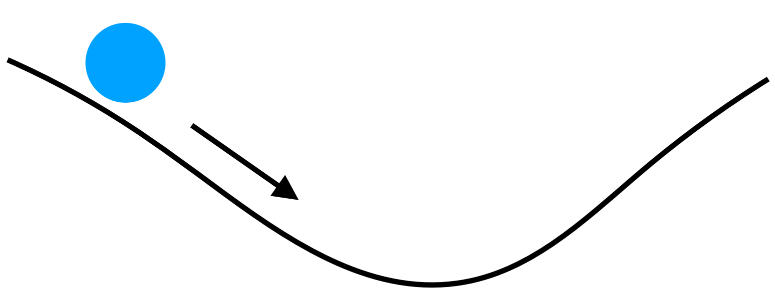
For very light scalar fields, the occupation number is very high and the field can be treated classically.

Dark Matter relic density from misalignment:

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

$$H(t) > m_a$$

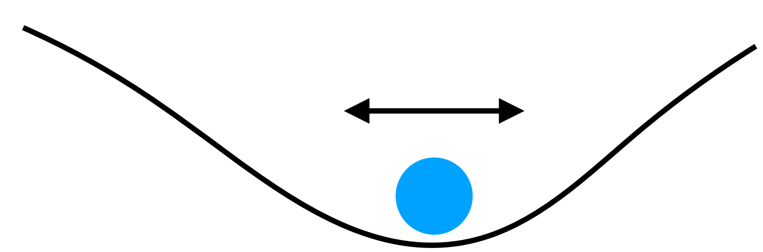
Solution $a(t) = \text{const.}$



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

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

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

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

Particle models

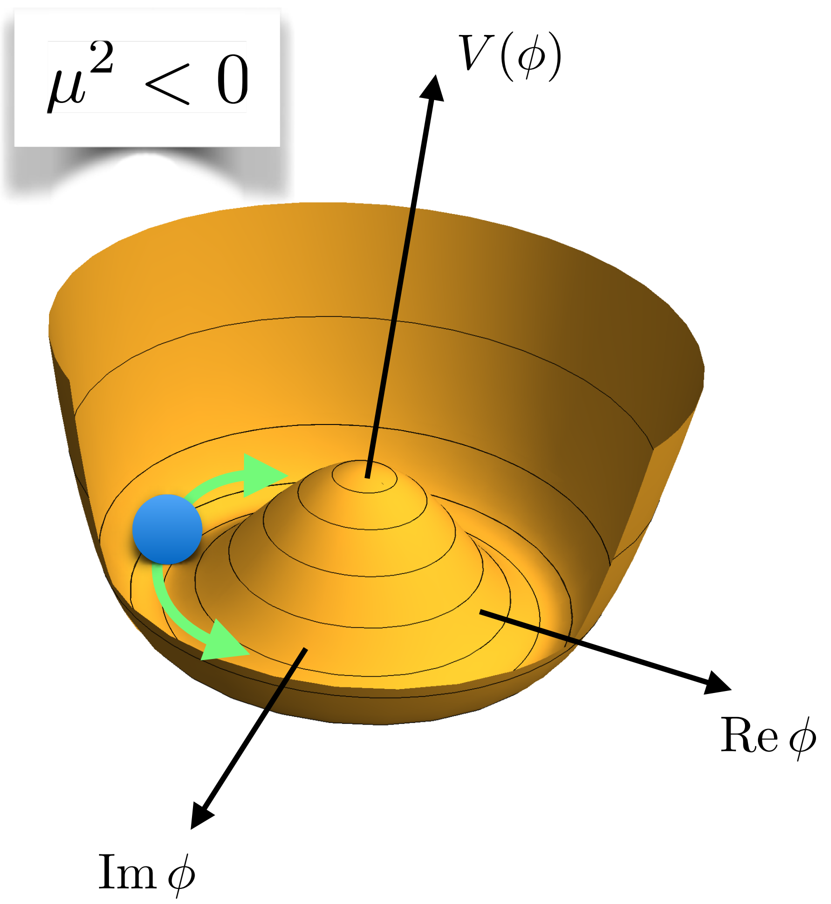
Axions or axionlike particles are excellent candidates for light dark matter

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

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

2 states

$$m_s^2 = 4\lambda f^2 = |\mu^2| \qquad\qquad m_a^2 = 0$$



Particle models

ρ, P, N

The most famous example is the pion

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

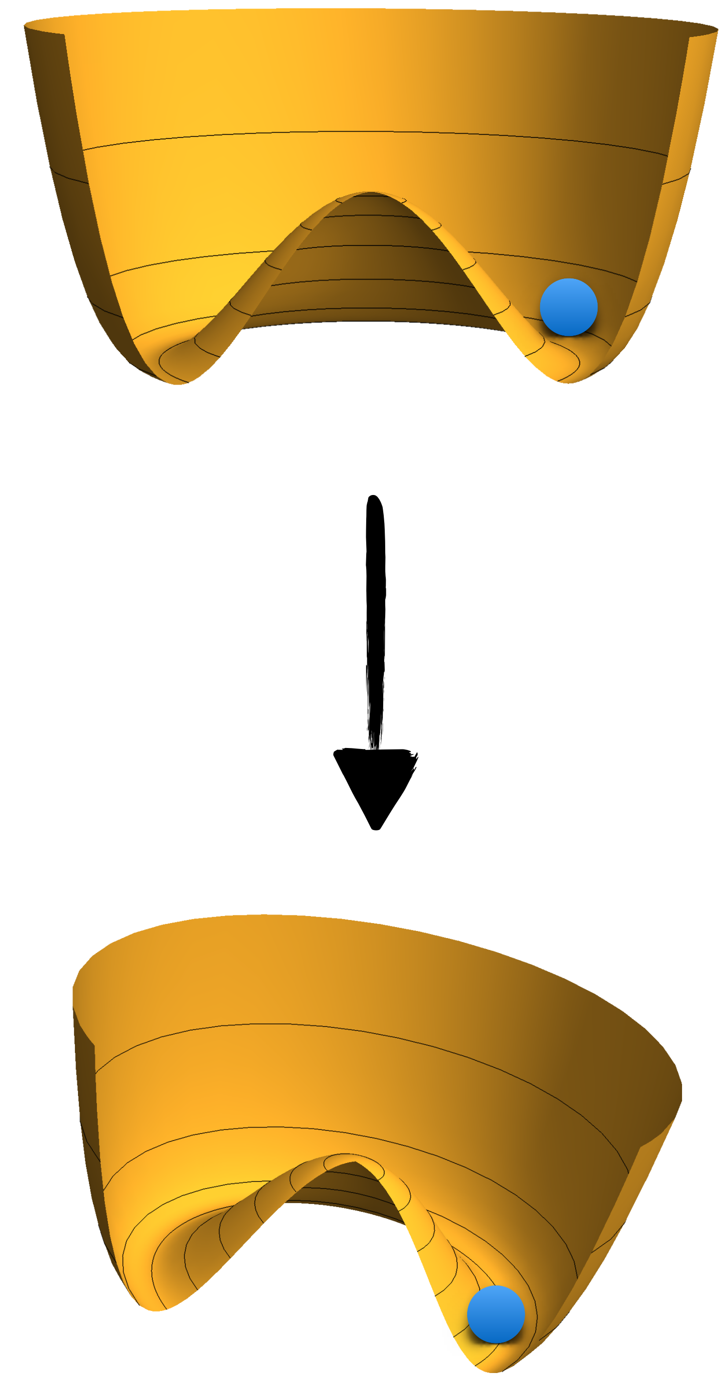
$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

π

Particle models

An exactly massless boson is very problematic.

The global symmetry can be broken by explicit masses or anomalous effects



$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots + \frac{1}{2} m_a^2 a^2$$

$$m_a = \frac{\mu^2}{f}$$

Small masses $\longleftrightarrow$ Small couplings

ALP phenomenology

At leading order ALPs/axions interact like pseudoscalars

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

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

At leading order ALPs/axions interact like pseudoscalars

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

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

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

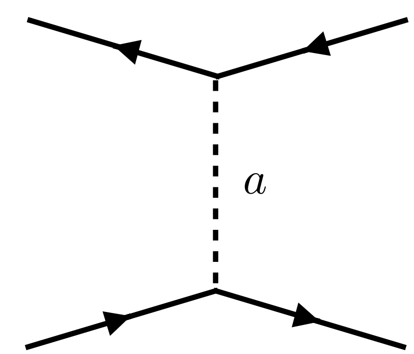
$$g_P\frac{a}{f}\bar{N}i\gamma_5 N \longrightarrow V_{pp}(r) \approx -\frac{g_P g_P}{4\pi f^2 r^3}\left[S_1 \cdot S_2 - 3S_1 \cdot \hat{r}\right]$$

ALP phenomenology

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

$$g_P \frac{a}{f} \bar{N} i \gamma_5 N$$

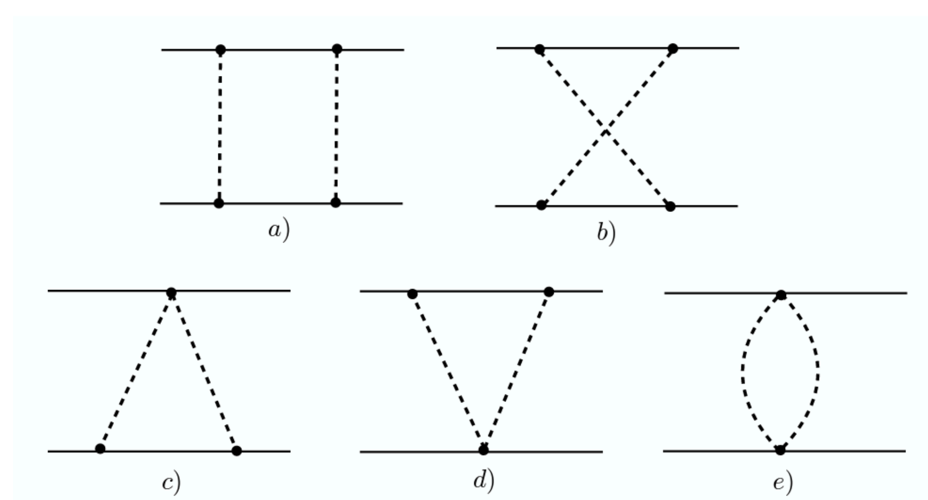
$$V_{pp}(r) \approx -\frac{g_P g_P}{4\pi f^2 r^3}\left[S_1 \cdot S_2 - 3 S_1 \cdot \hat{r}\right]$$



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

$$M_N \, \delta_N \bar{N} N \frac{a^2}{f^2}$$

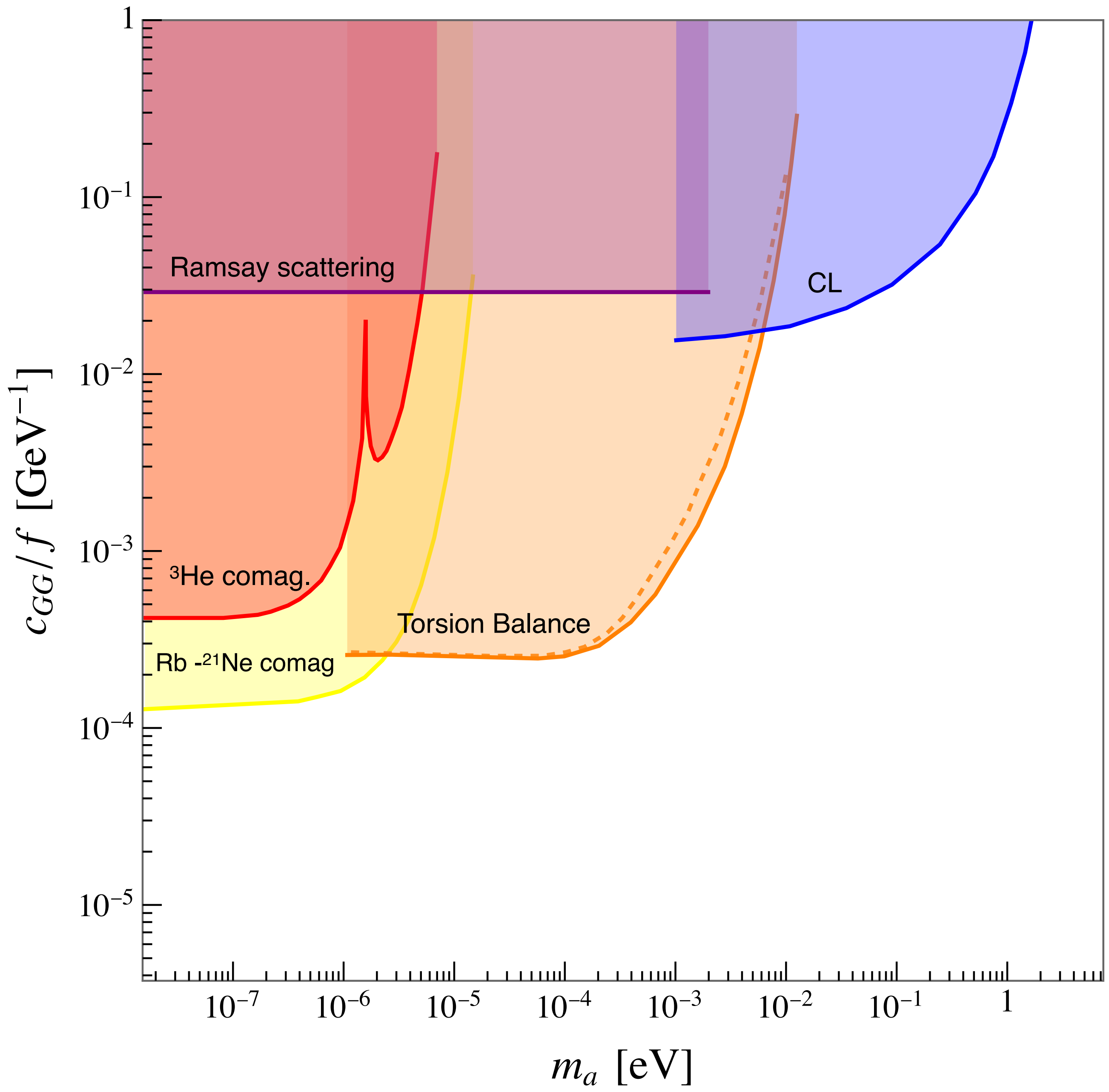
$$V_2(r) \approx -\frac{\delta_N^2 M_N^2}{64\pi^3 f^4 r^3}$$



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, *JHEP* 05 (2025) 023

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

ALP phenomenology

At leading order ALPs/axions interact like pseudoscalars

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What about higher order terms? At dimension 6

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

ALP phenomenology

All these couplings are related to the UV coupling structure

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

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

$$\boxed{C_N = -2c_1 c_{GG}^2 m_\pi^2\left[1 - \left(\frac{m_u - m_d}{m_u + m_d}\right)^2\right]}$$

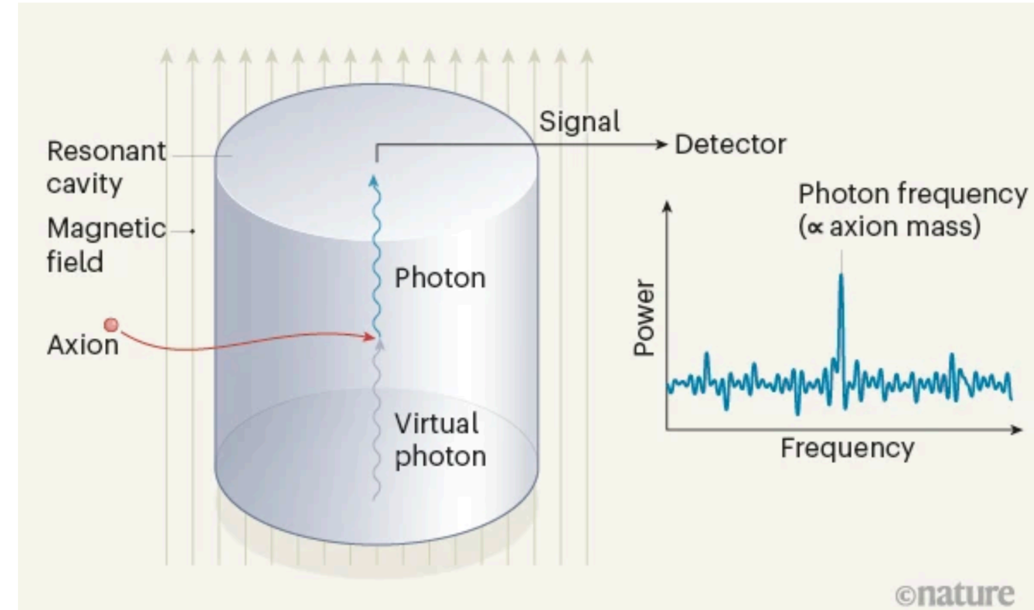
$$\boxed{C_E = -m_e\frac{3\alpha}{4\pi}C_\gamma \ln\frac{m_\pi^2}{m_e^2}}$$

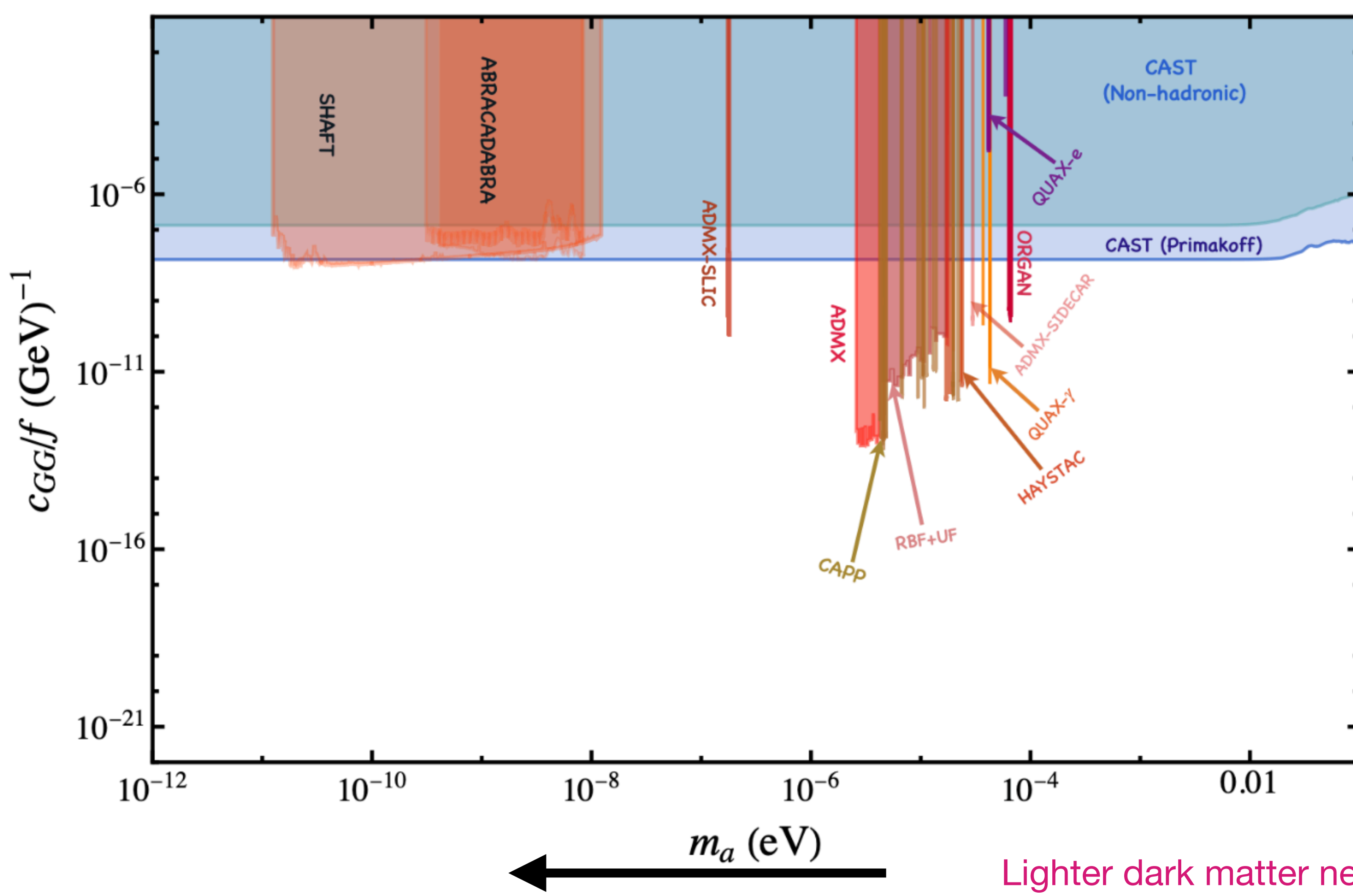
$$\boxed{C_\gamma(\mu) = \frac{\alpha}{24\pi}c_{GG}^2\left(-1 + 32c_1\frac{m_\pi^2}{M_N}\right)\left(1 - \frac{\Delta_m^2}{\hat{m}^2}\right)}$$

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

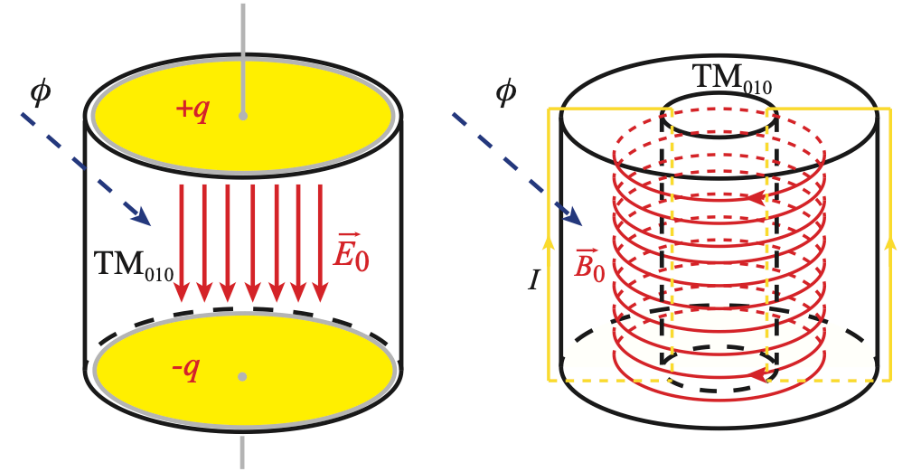
$$c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} = c_{\gamma\gamma}^{\rm eff}\,\frac{\alpha}{\pi}\,\frac{a}{f}\,\vec{E}\cdot\vec{B}$$

MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,’, *JHEP* 05 (2025) 023

Lighter dark matter needs larger cavities

Flambaum et al, 2207.14437

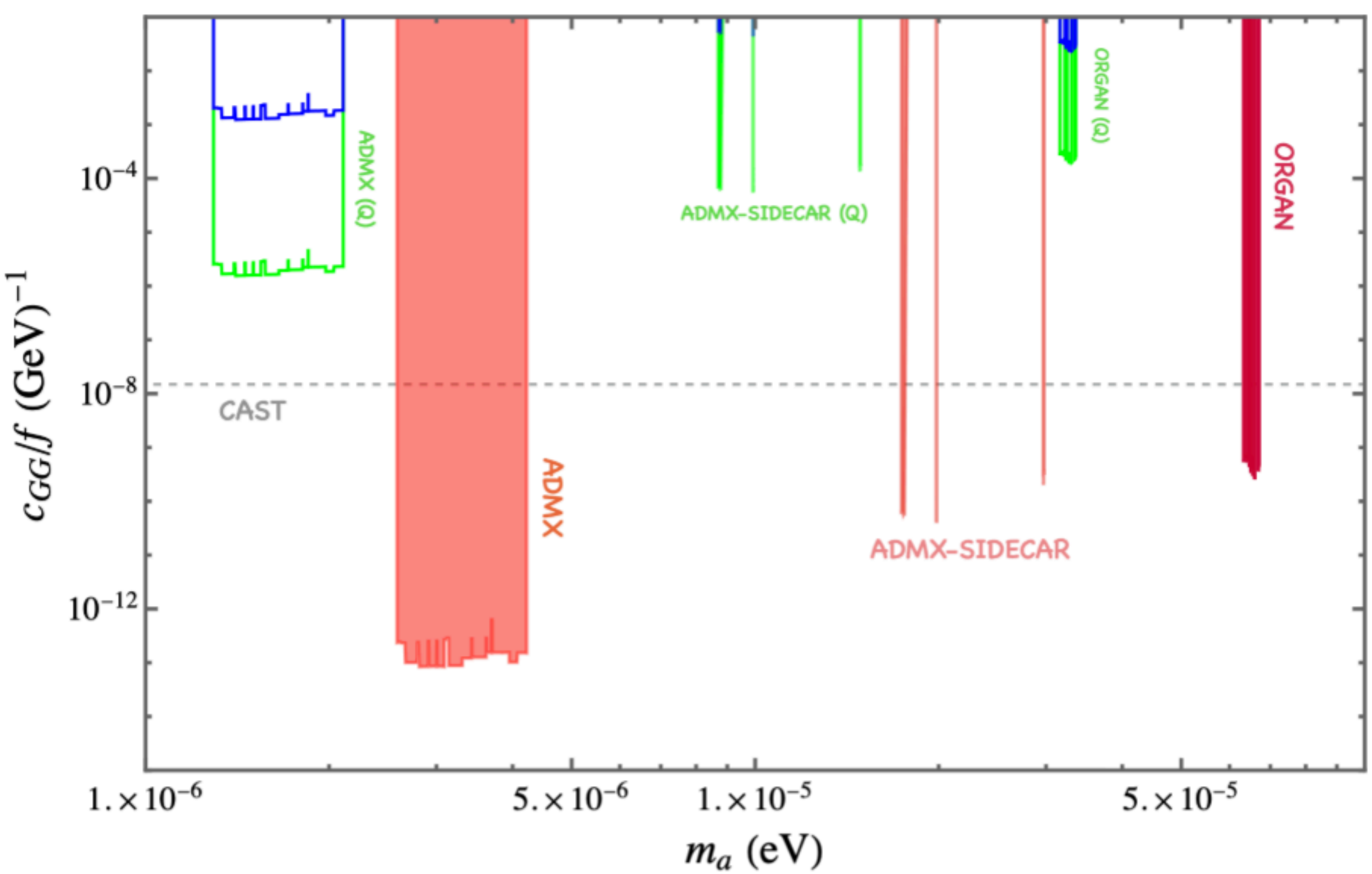
ALP phenomenology



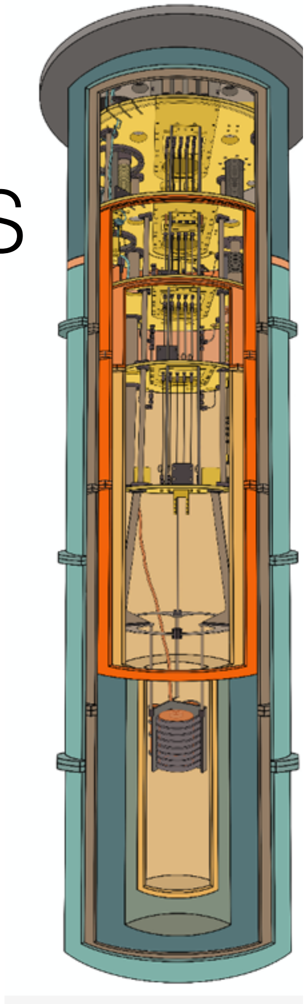
Quadratic axion interactions allow to extend the parameter space

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

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



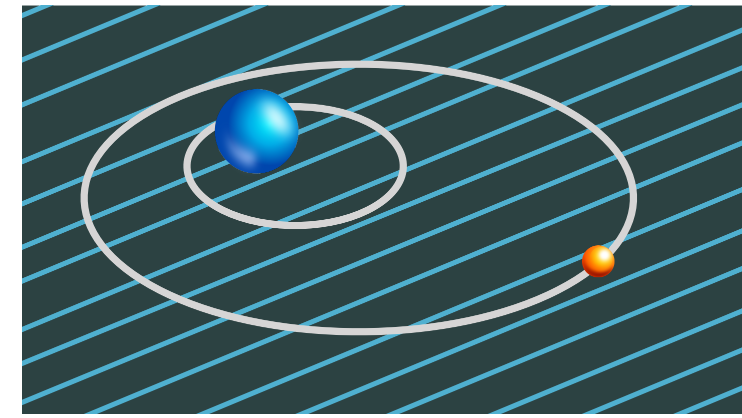
QSHS



MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,', *JHEP* 05 (2025) 023

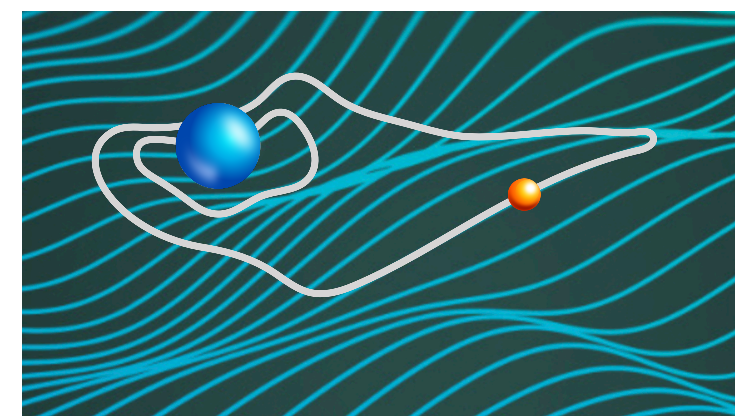
ALP phenomenology

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

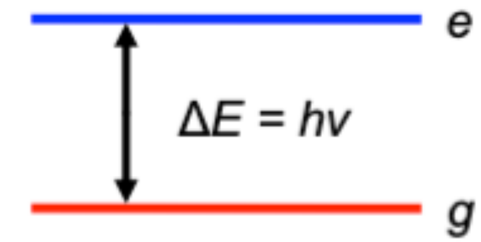


$$\mathcal{L} = m_e \bar{e}e + C_E \frac{a^2}{f^2}\bar{e}e$$

Leads to oscillating fundamental constants

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

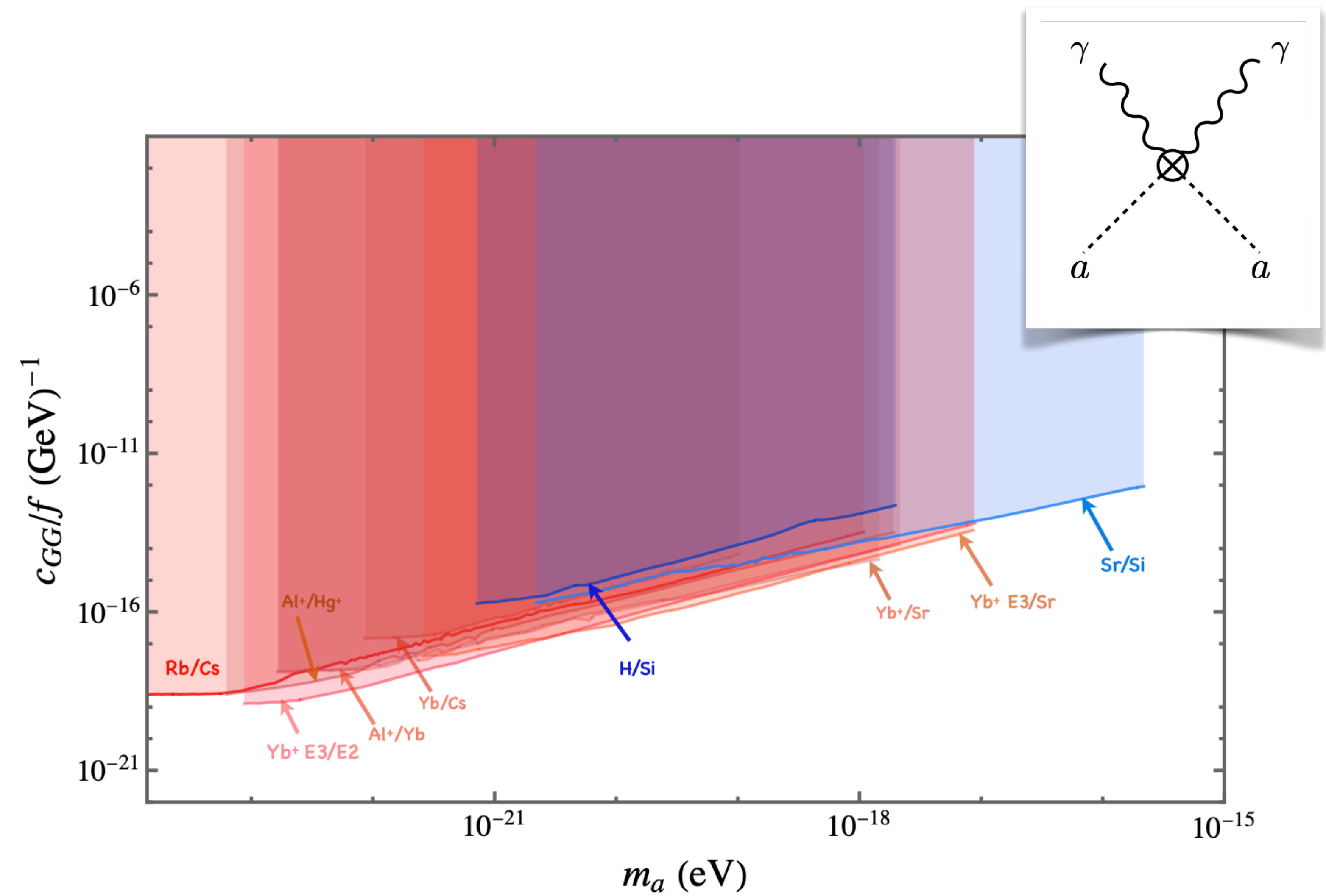
ALP phenomenology



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,', *JHEP* 05 (2025) 023

ALP phenomenology

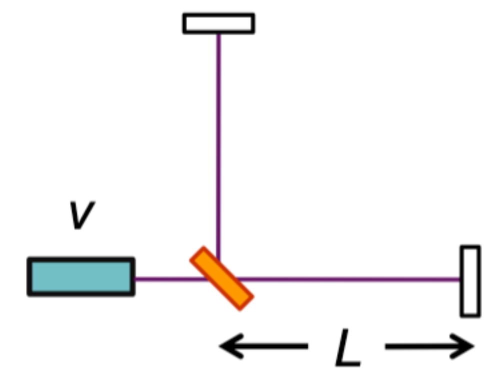
Ion clocks

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

Laser interferometers

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

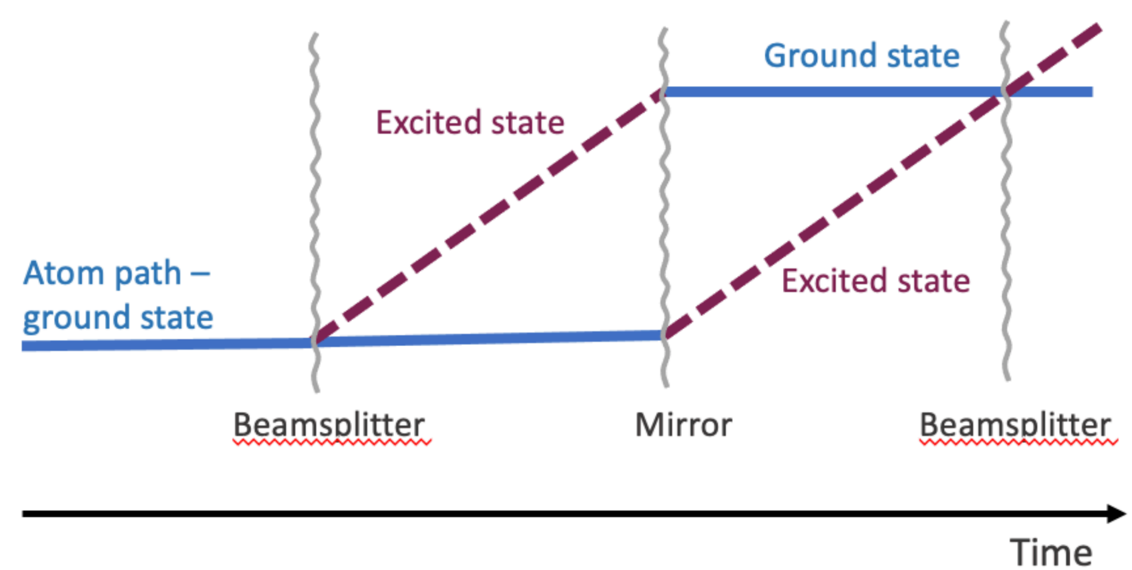
$$\frac{\delta n}{n} = -5 \times 10^{-3} \left(2\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right)$$



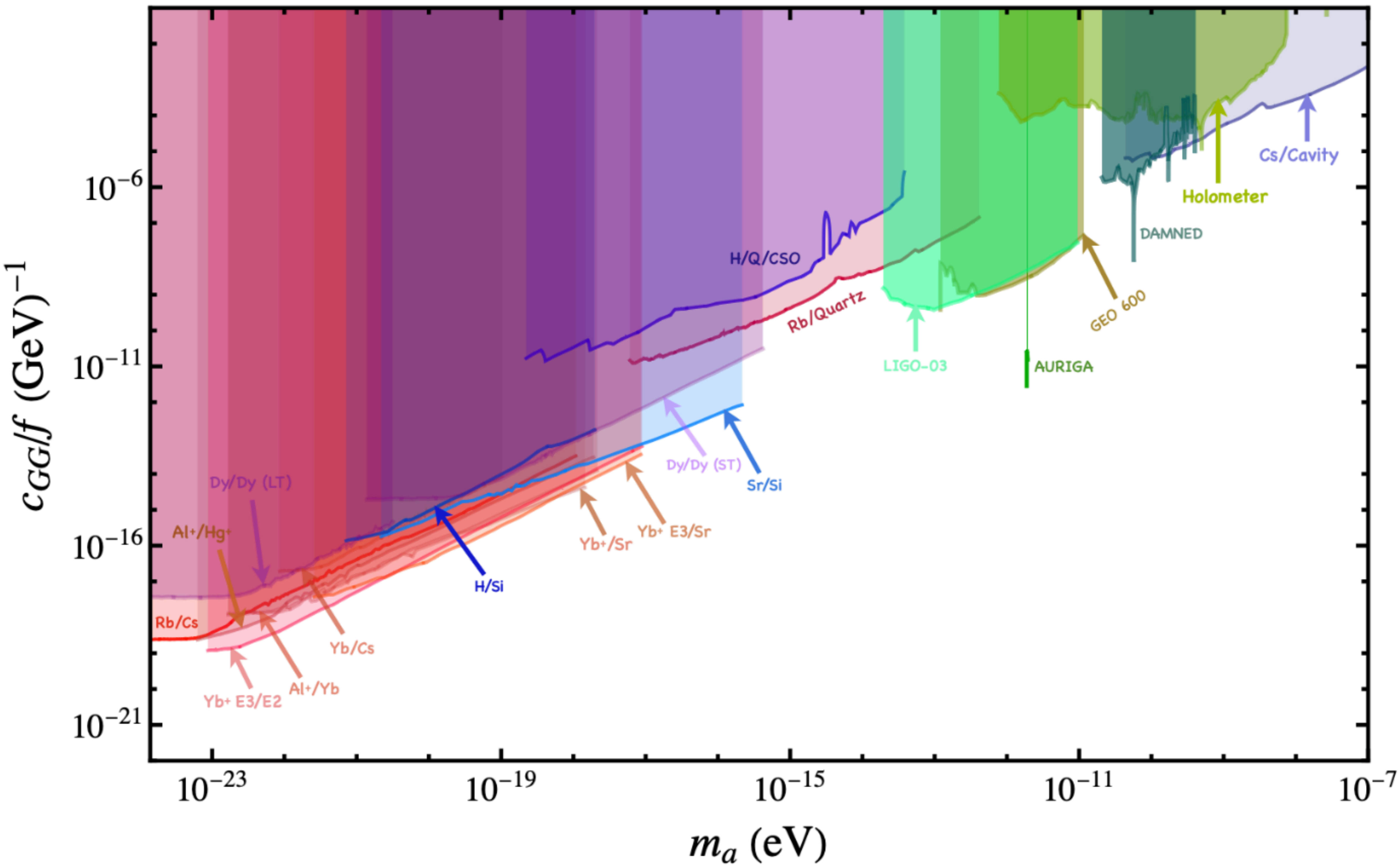
Atom interferometers

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

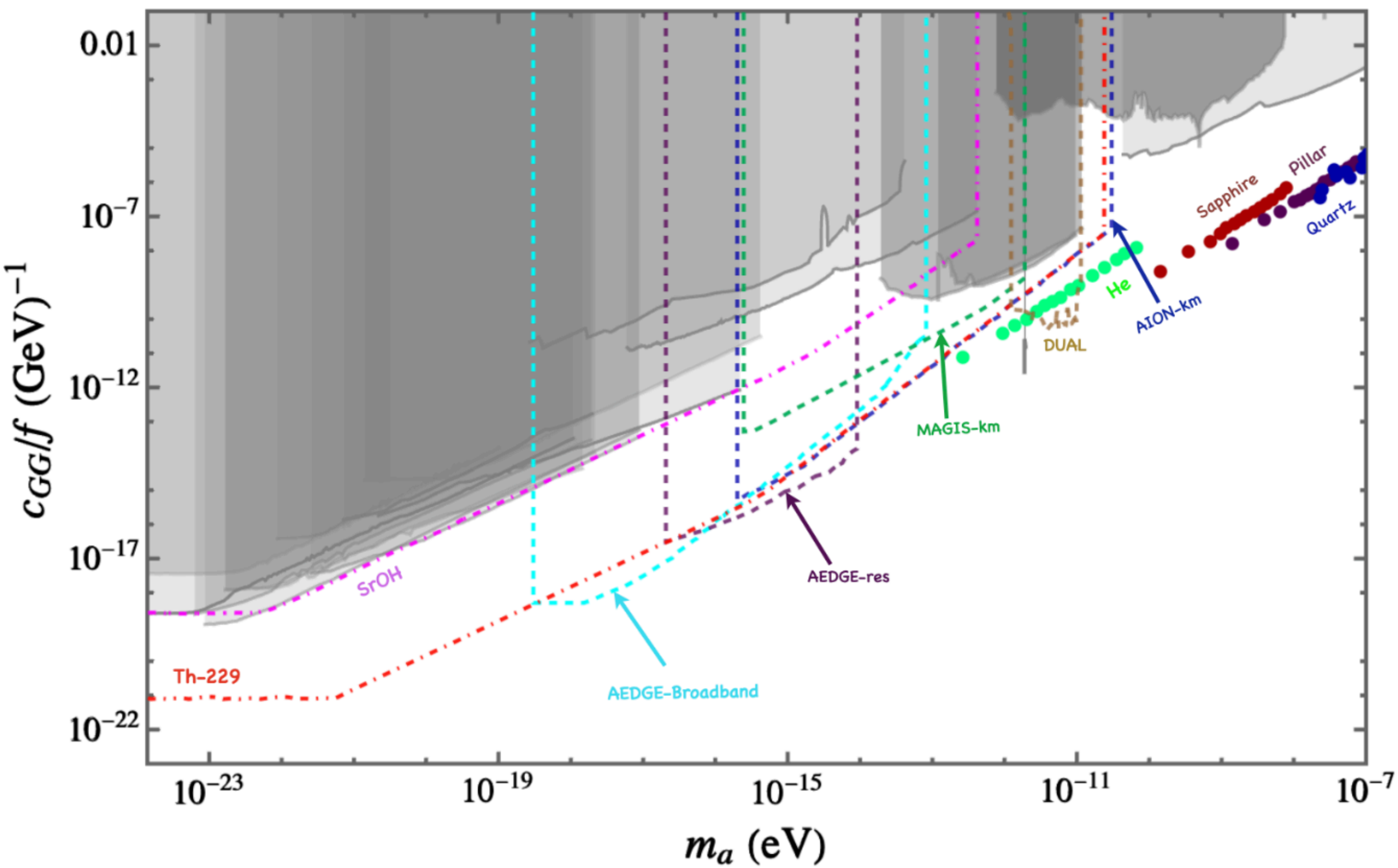
$$\Phi_s = 4\,\overline{\omega_a} n \Delta r \sin^2(m_a T)$$



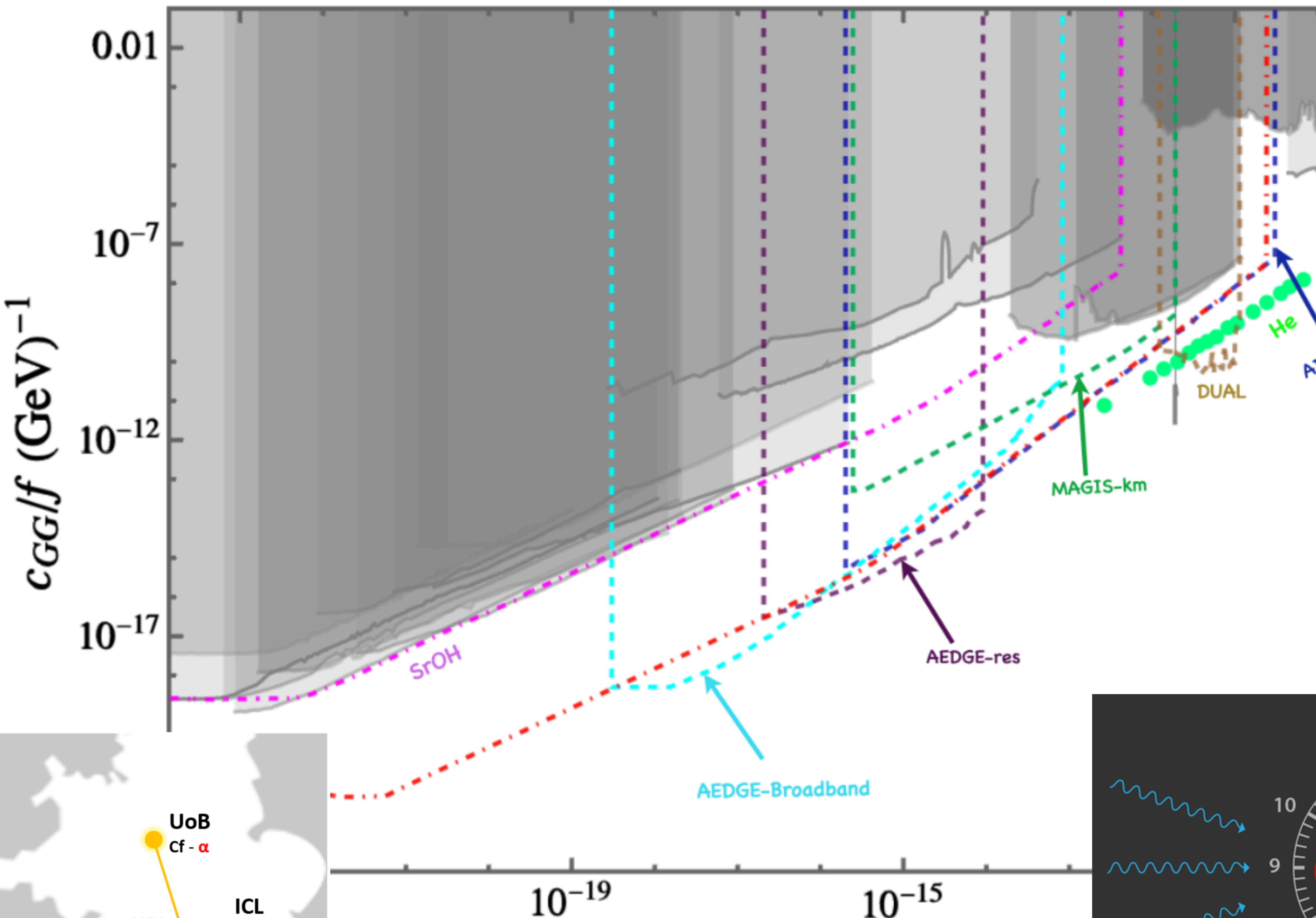
ALP phenomenology

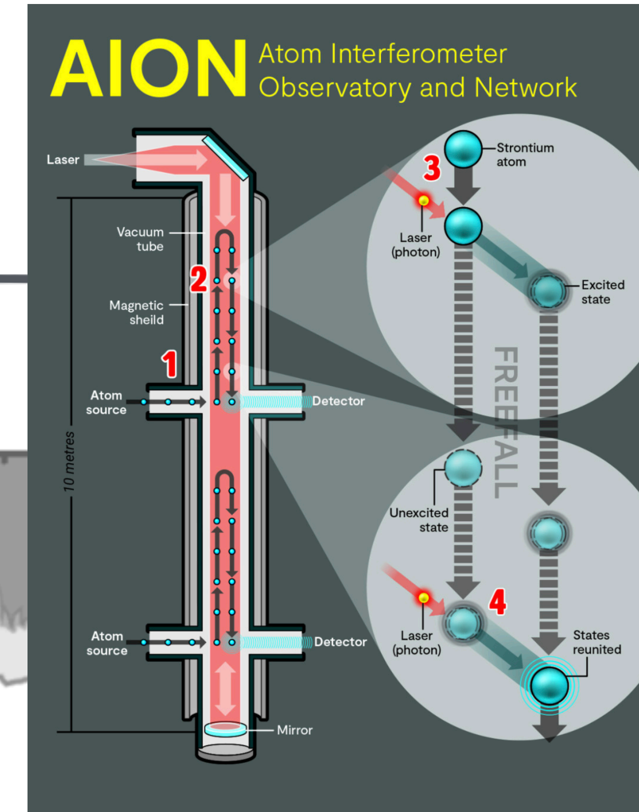


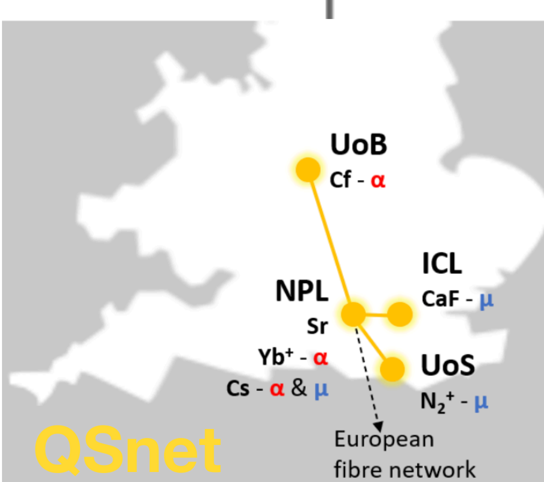
ALP phenomenology

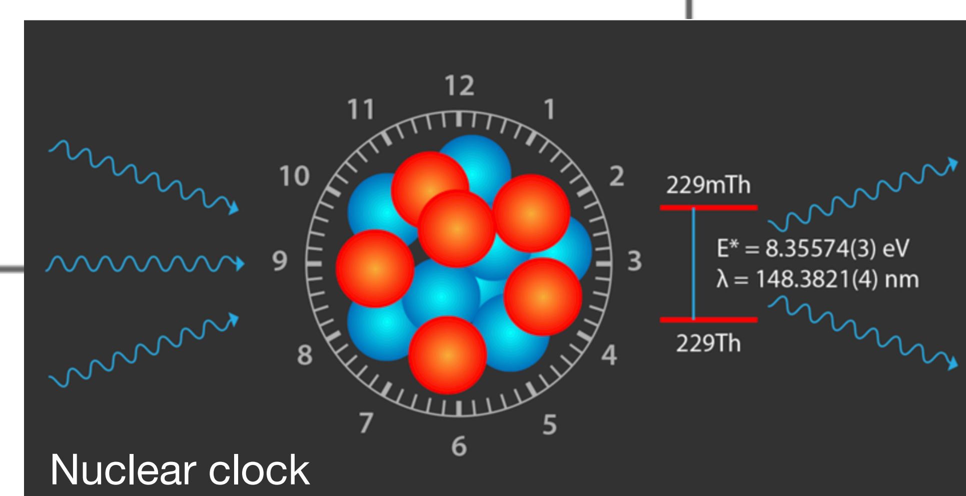


ALP phenomenology









P. Thirolf/LMU; adapted by APS/A. Stonebraker

ALP phenomenology

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

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

With the boundary condition $a(\vec{x},t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos\left(m_a(t+\vec{\beta}\cdot\vec{x})\right)$

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

$$a(r,t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos\left(m_a t\right)\left[1 - Z(\delta_i) J_\pm\left(\sqrt{3|Z(\delta_i)|}\right)\frac{R_{\rm source}}{r}\right] \qquad \text{for} \quad \beta = 0$$

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

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

ALP phenomenology

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

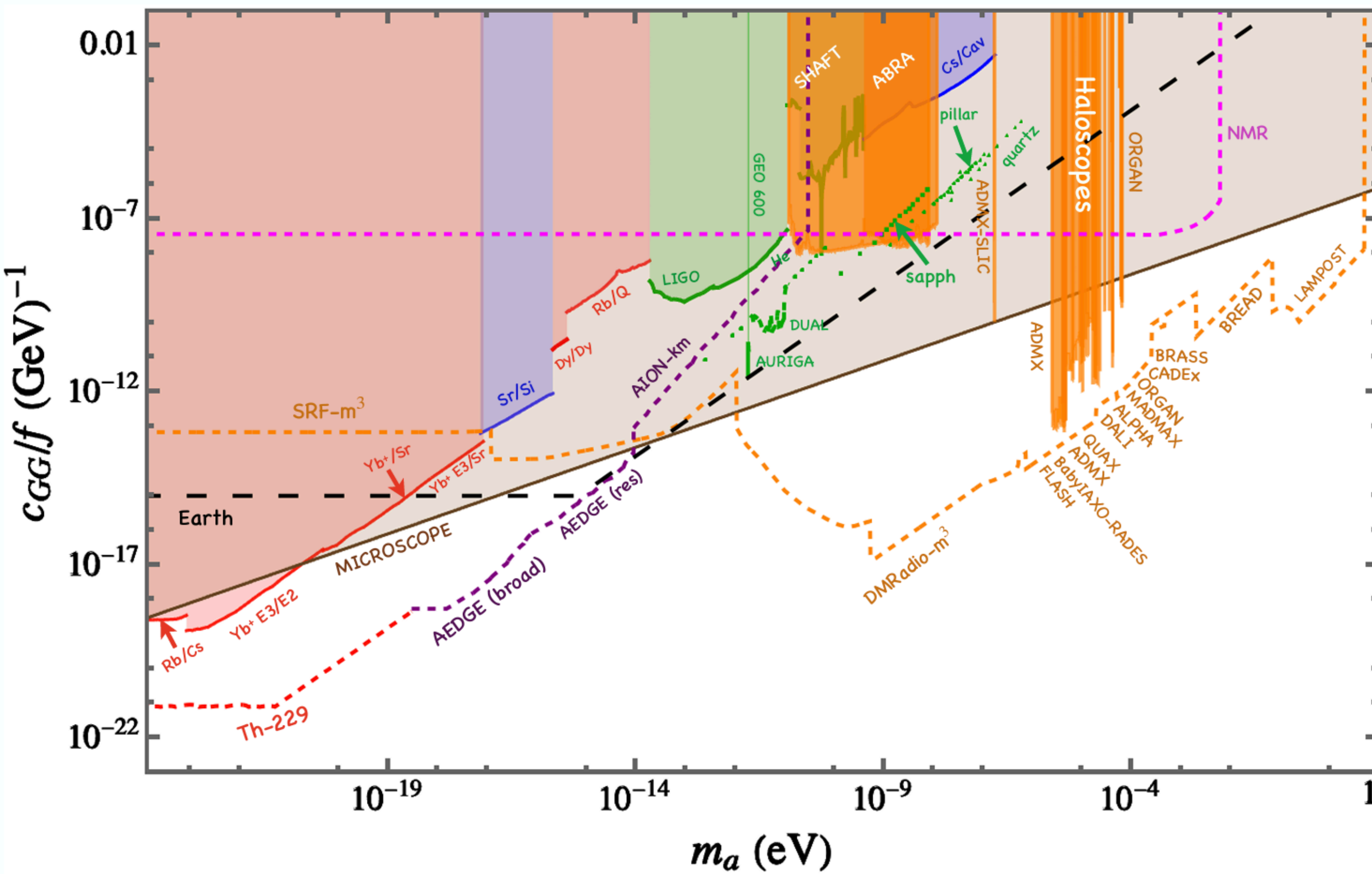
However for axions it is strictly negative

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

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.

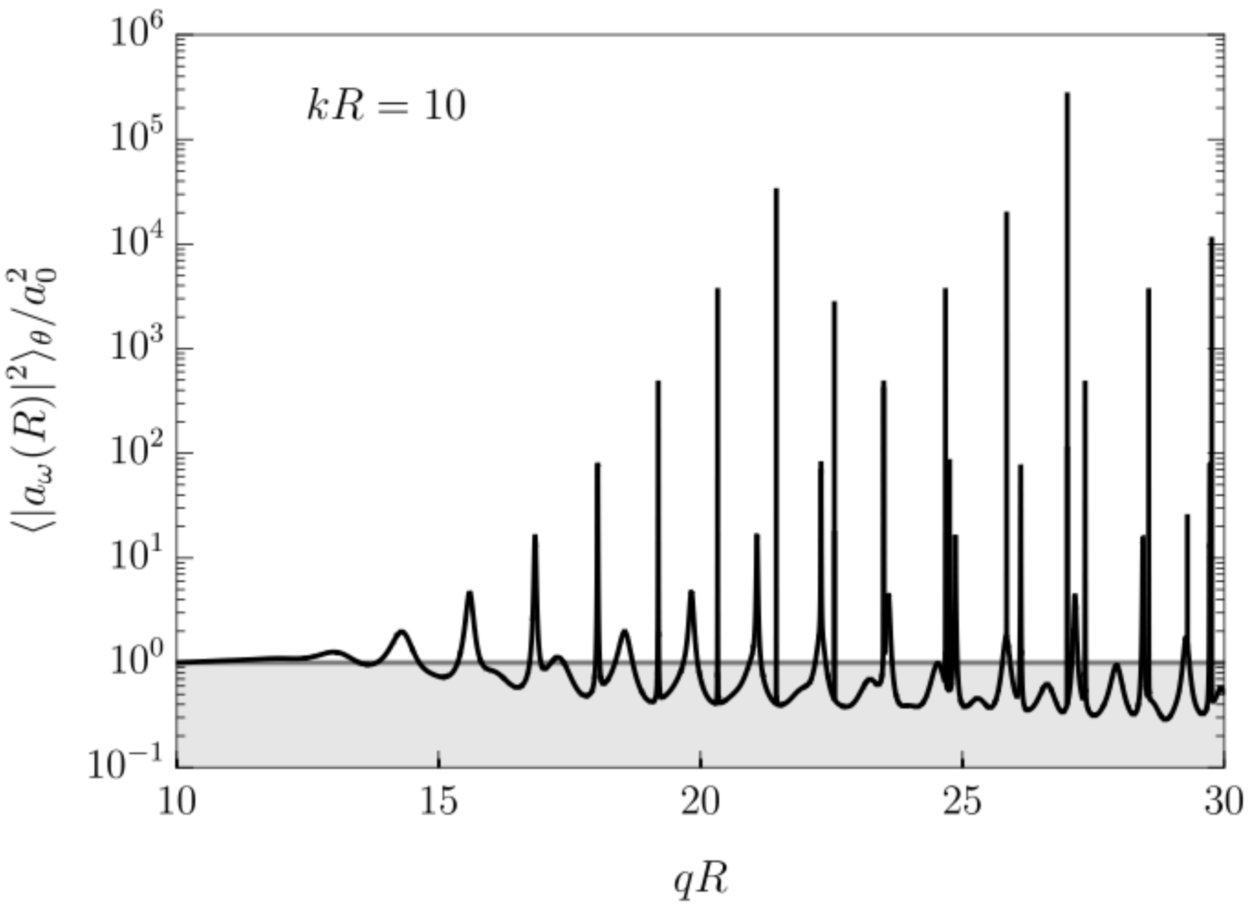
Hook, Huang, JHEP 06 (2018) 036, [1708.08464].

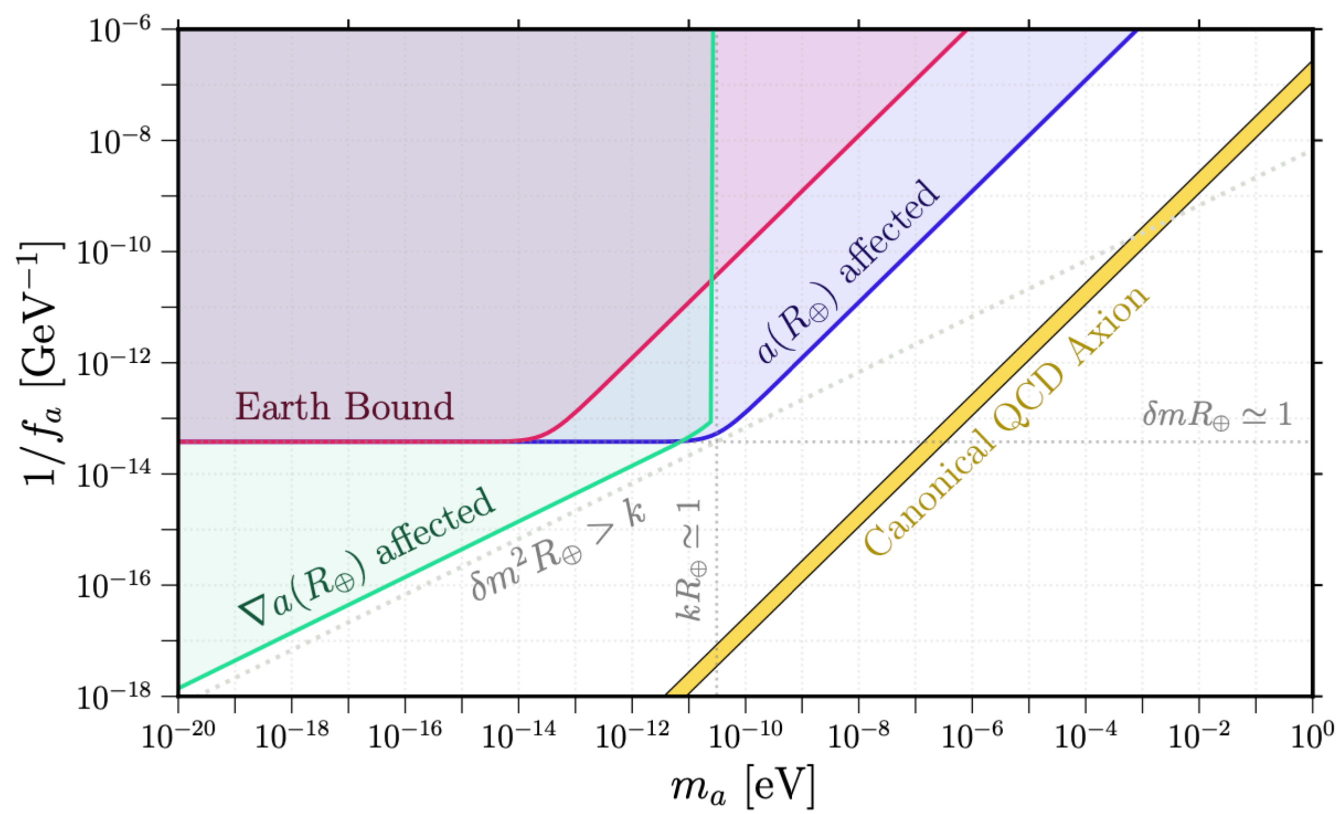
ALP phenomenology



ALP phenomenology

A solution for $\beta \neq 0$





Garcia del Castillo, Hammett, Jaeckel, [2502.04456]

Banerjee, Bloch, Bonnefoy, Ellis, Perez, Savoray, Springmann, Stadnik, [2502.04455]

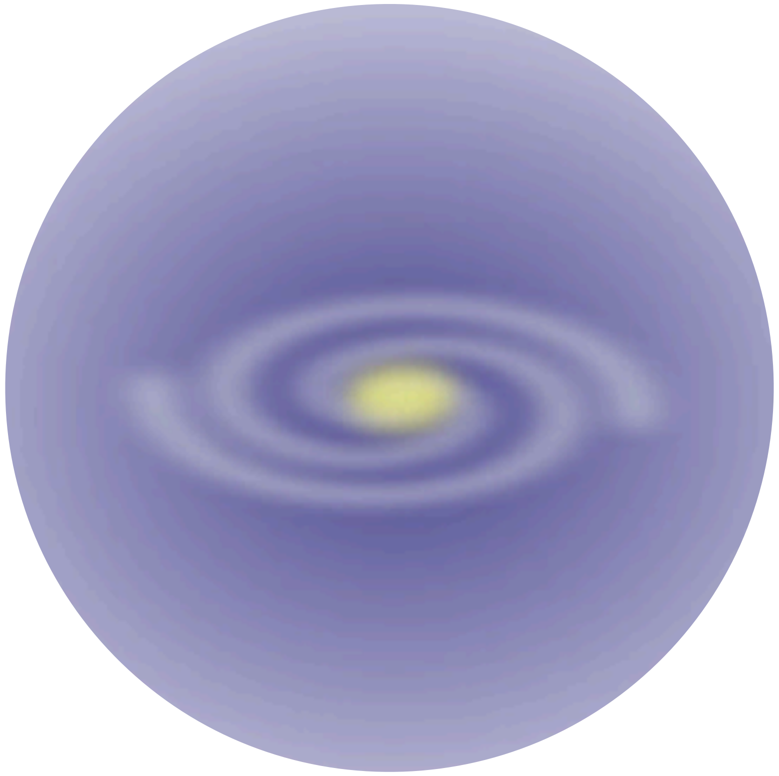
ALP phenomenology

The axion potential that fixes the sign of the a^2 interaction

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

Also fixes the sign of the a^4 self-interaction, which implies *attractive* self-interactions

$$V(a) = -\frac{m^2}{24 f^2} a^4 + \ldots$$



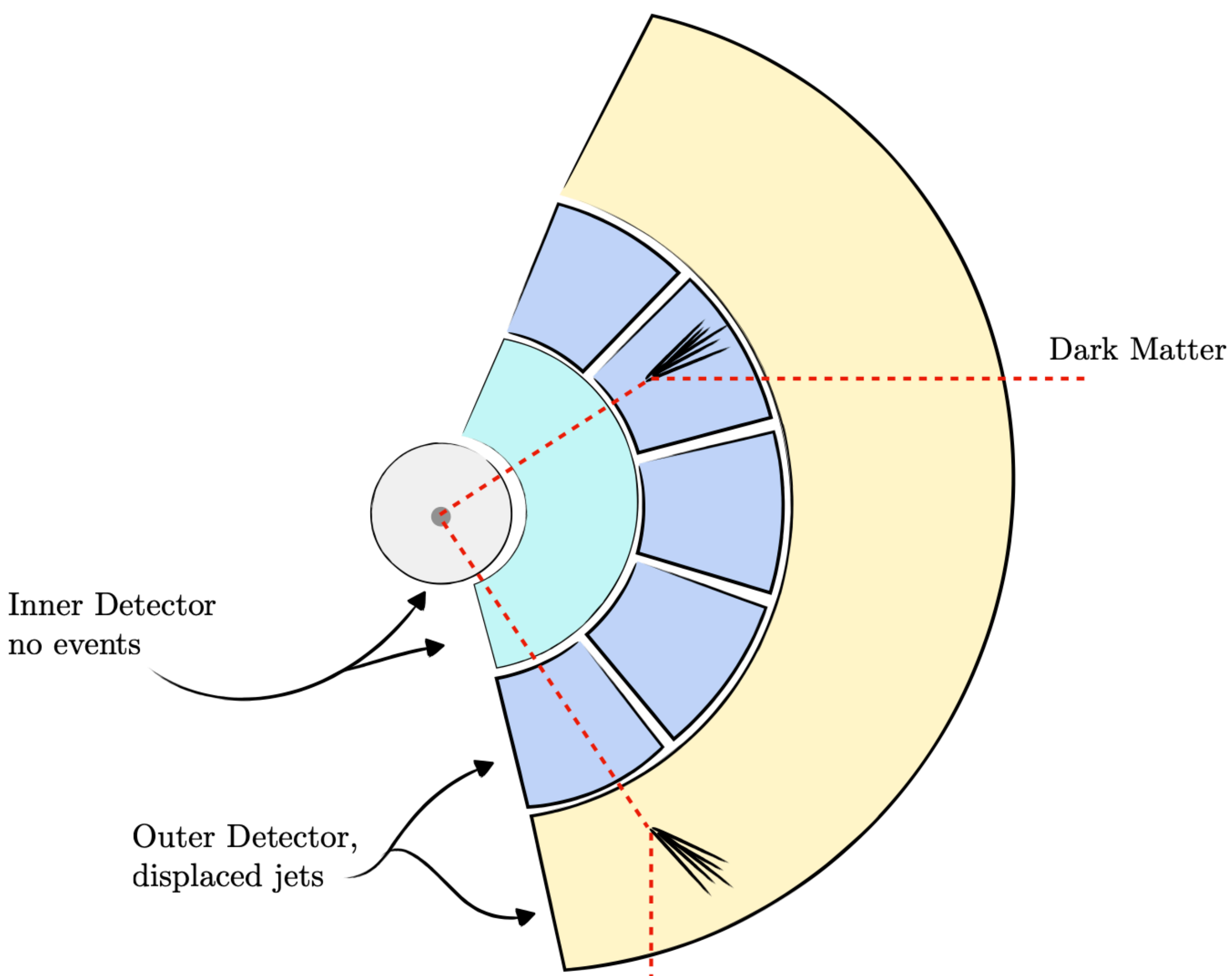
This leads to instabilities
(clumps, axion stars)

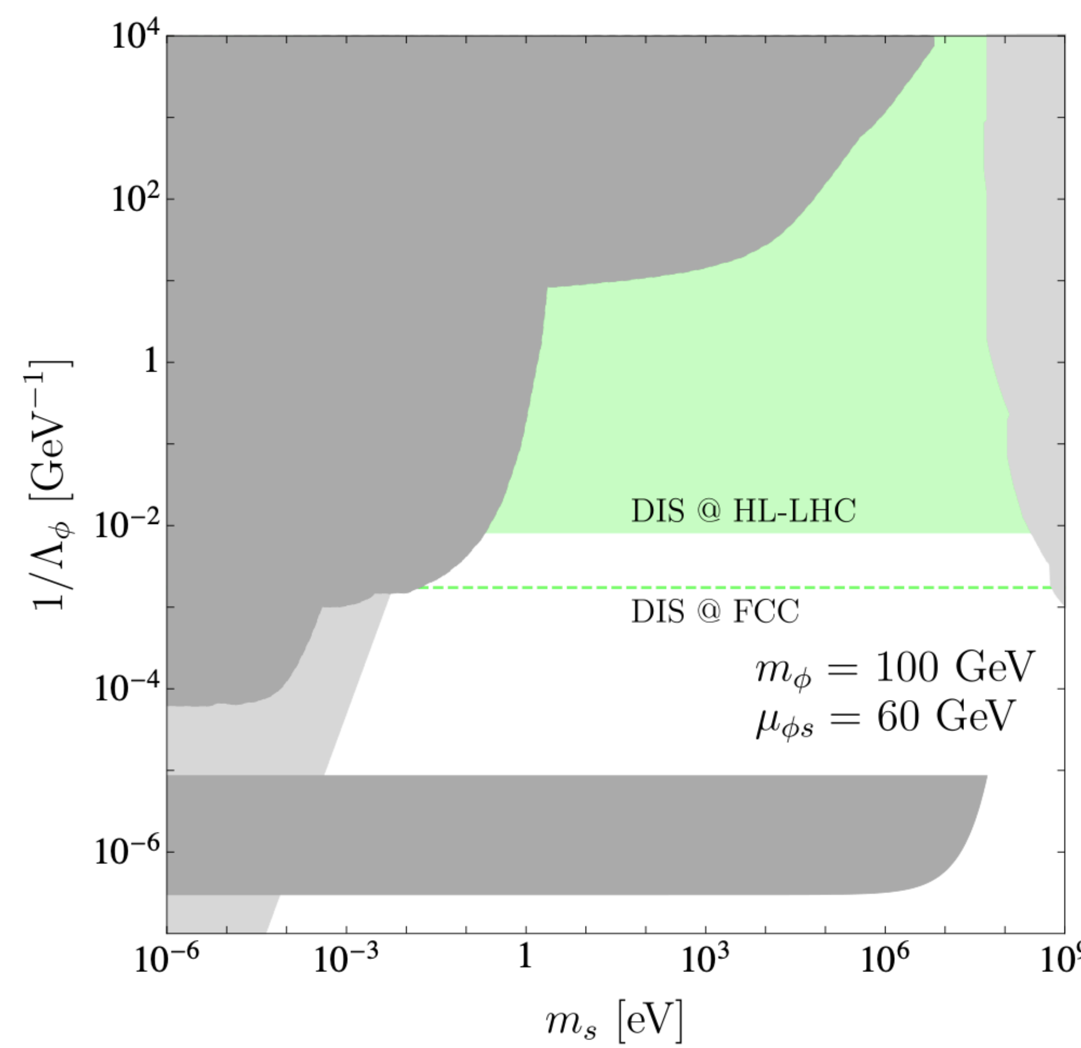
J. Fan, *Phys.Dark Univ.* 14 (2016) 84-94 [1603.06580].

Collider Observables

At colliders, dark matter can be produced with a boost and scatter off solid detector components even if its light

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{\mu_{\phi s}}{2}\phi s^2 - \frac{\alpha_s}{\Lambda_\phi}\,\phi\,\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu}$$





SciPost Phys. **10** (2021) no.2, 030

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

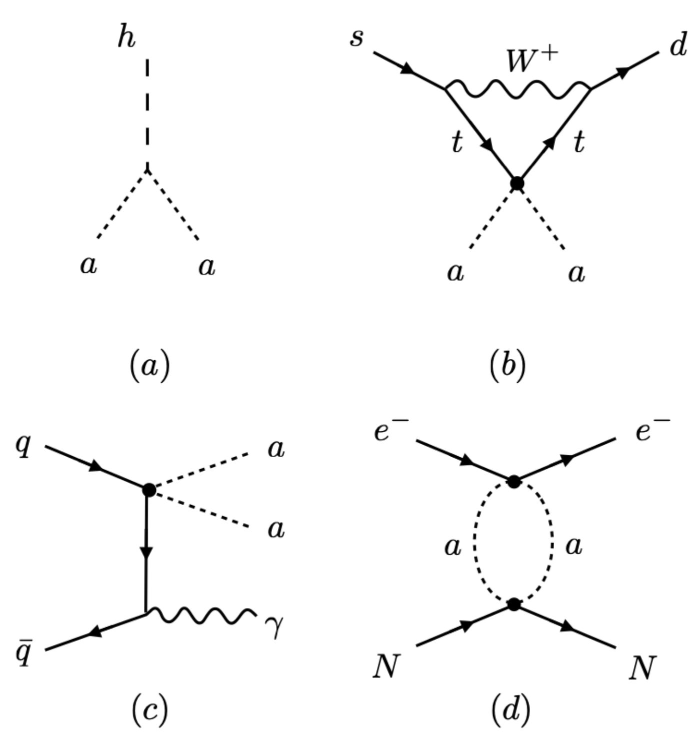
Collider searches can probe light dark matter where quantum sensors can't

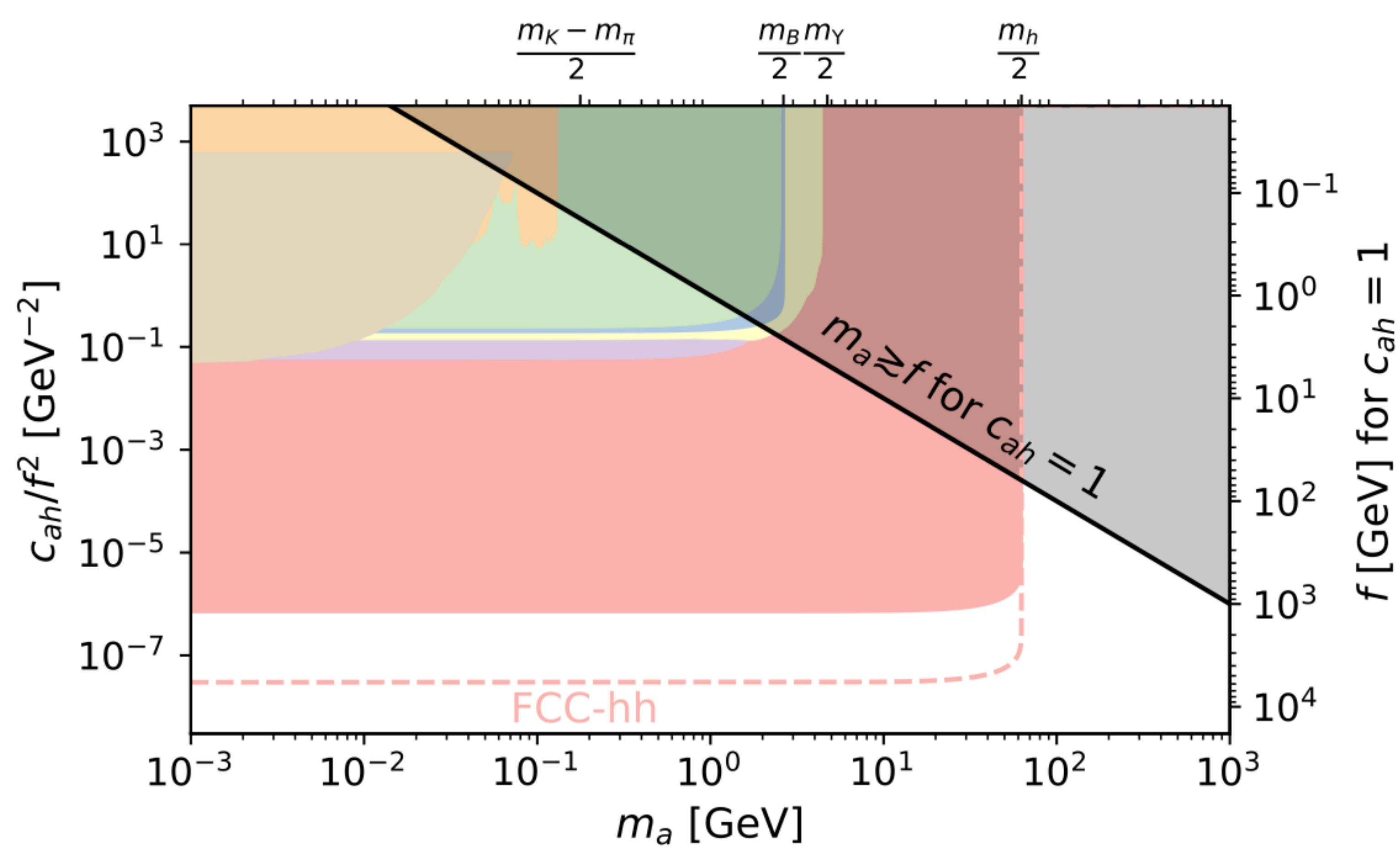
Backup

The Higgs portal

Axion couplings through the Higgs portal

$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi\,.$$





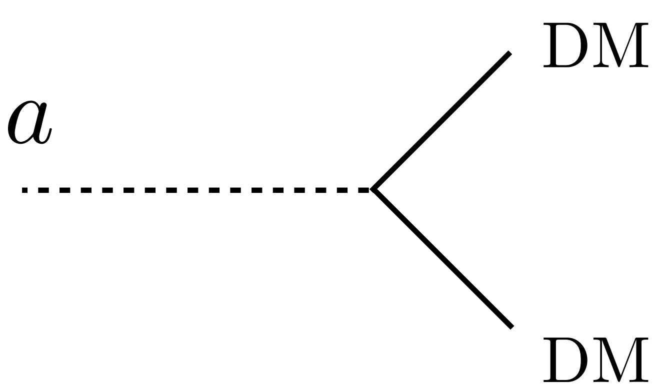
Spectroscopy is hopeless

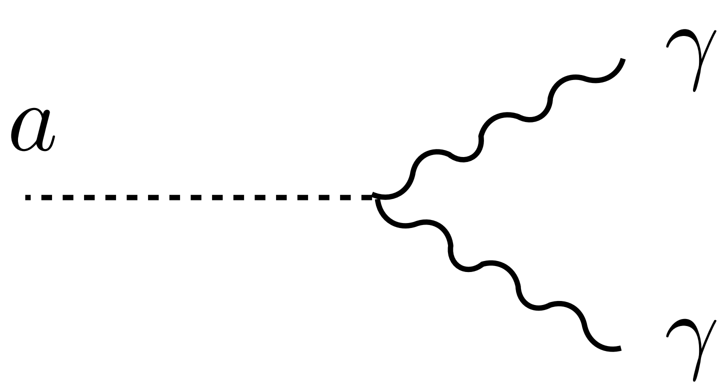
$$\frac{c_{ah}}{f^2} < 5 \times 10^6 \left(\frac{r_C}{\mathrm{fm}}\right)^2\ \mathrm{GeV}^{-2}$$

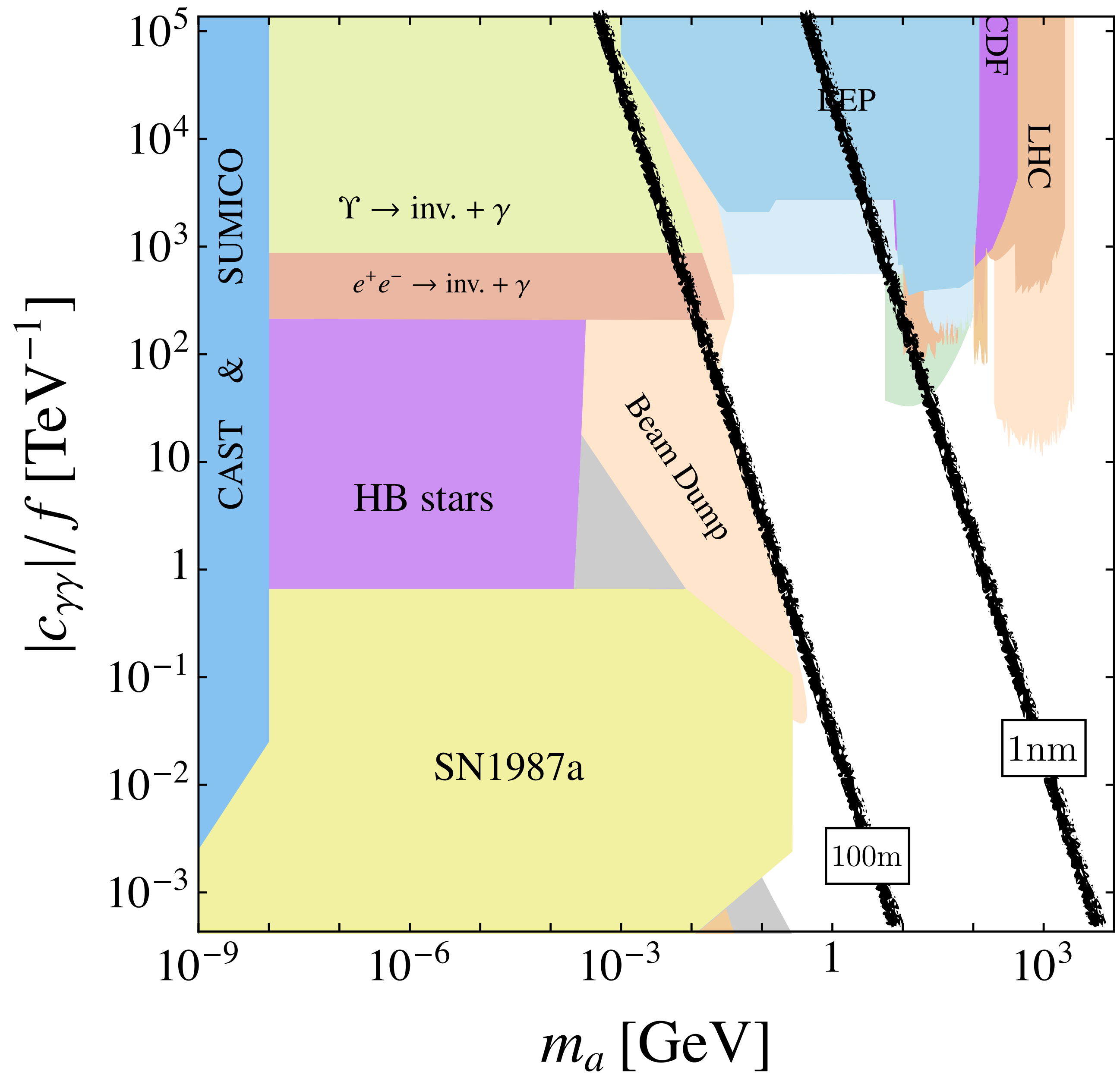
ALP phenomenology

What if the axions decay?

Axions could be mediators to a dark sector



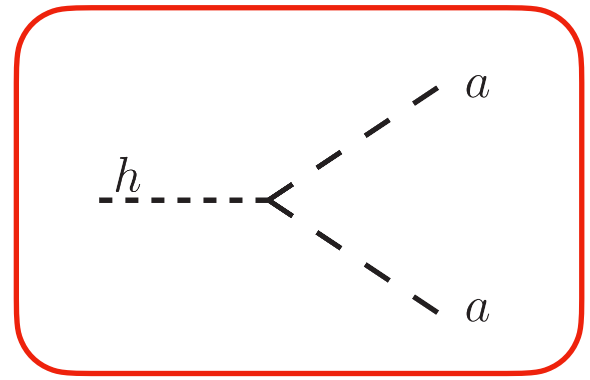


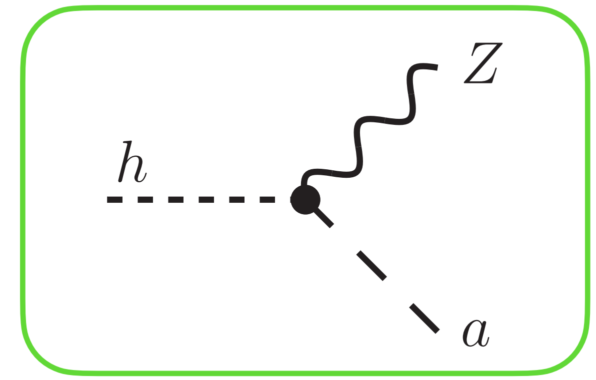


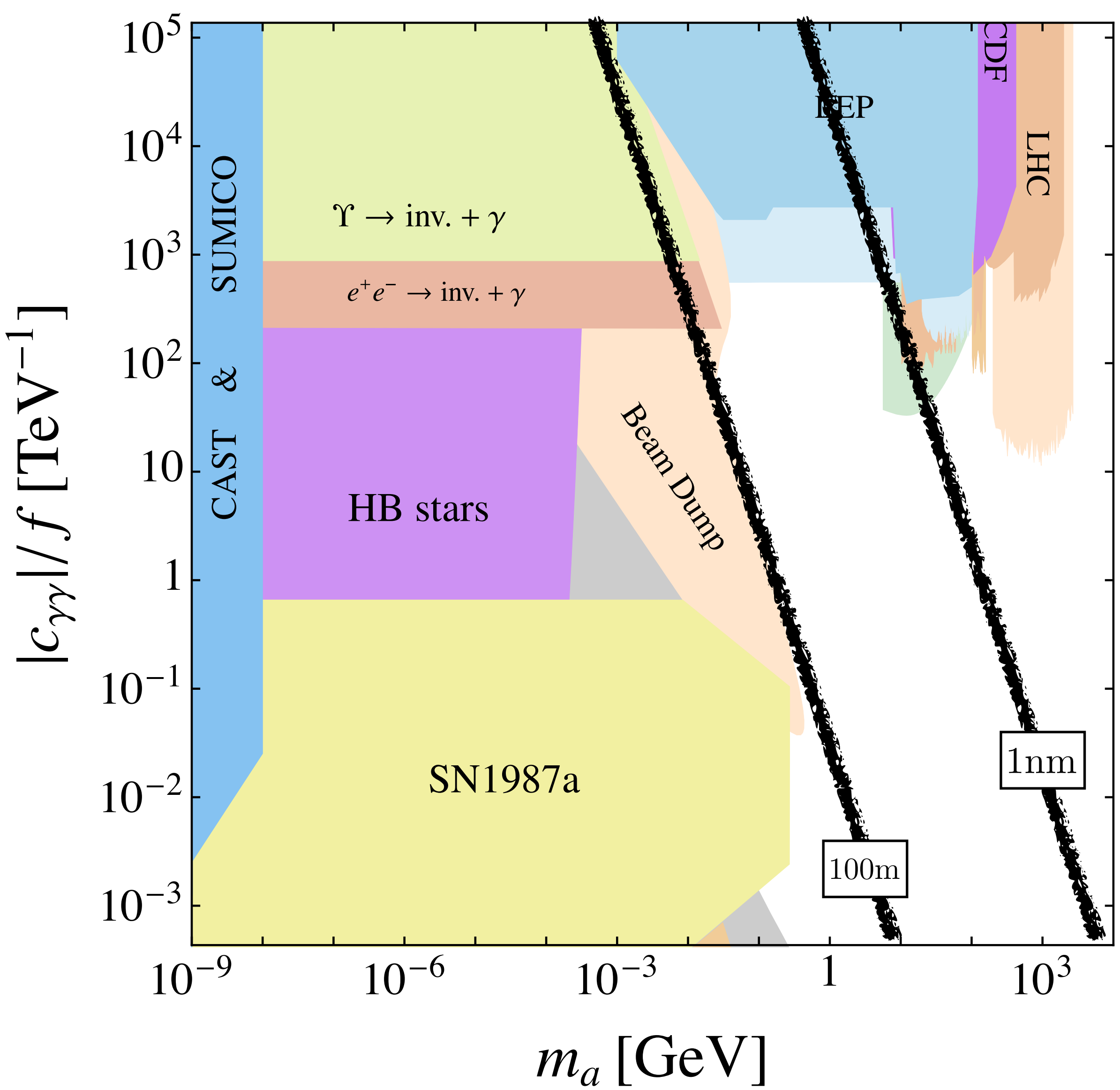
ALP phenomenology

Big Advantage of the LHC:

The only place that produces Higgs!







$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi + \frac{c^5_{Zh}}{f}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \mathrm{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2} + \frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \mathrm{h.c.}\right)\phi^\dagger\phi$$

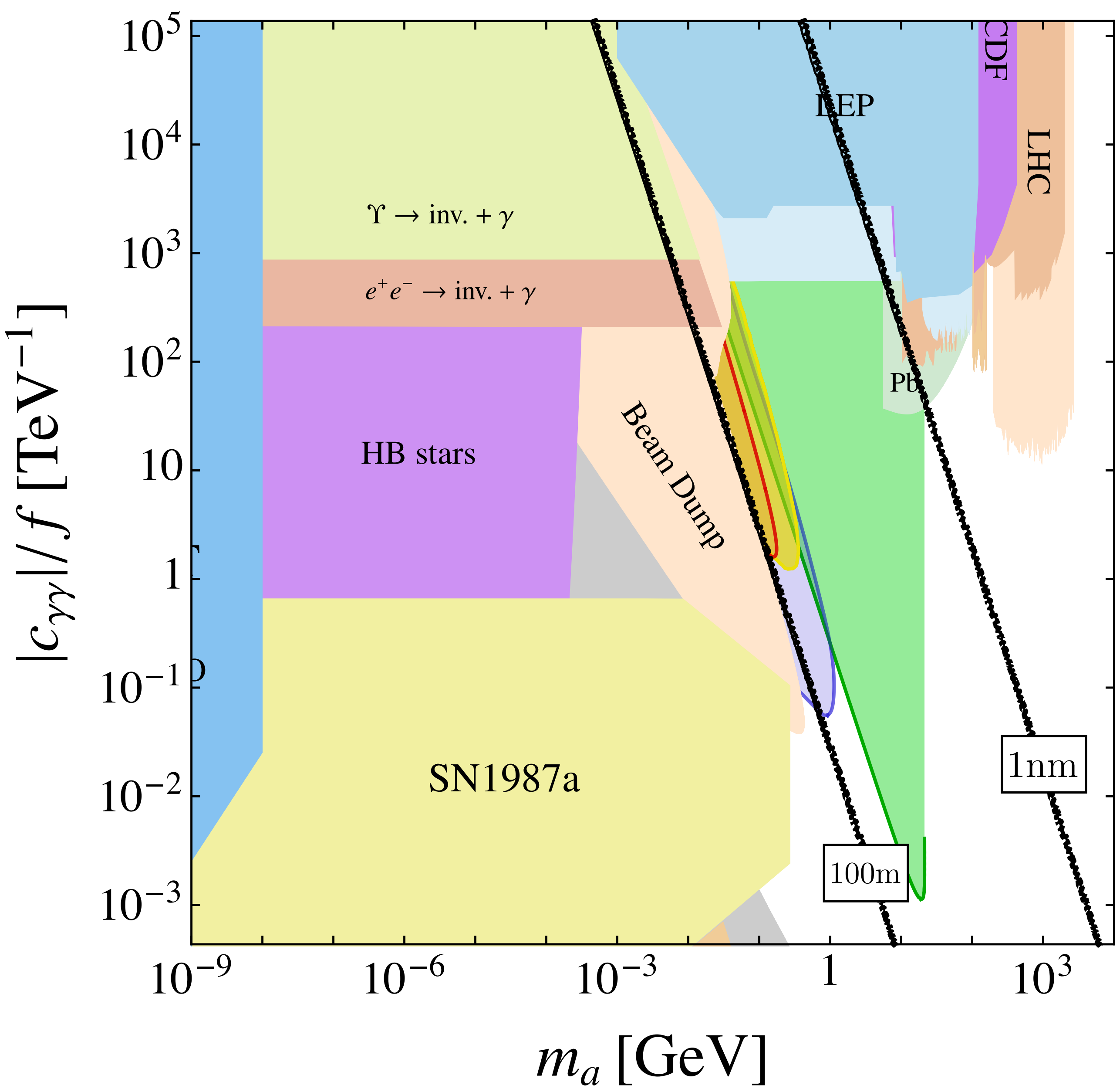
MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

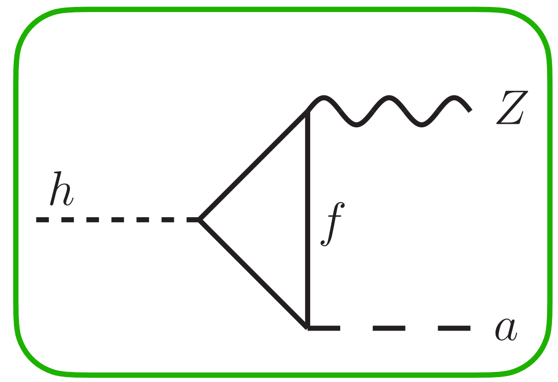
How to close the gap?

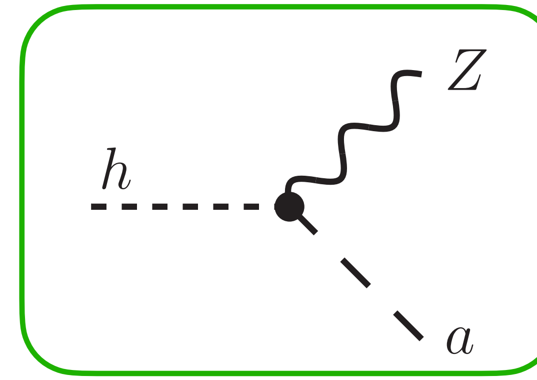
Big Advantage of the LHC:

The only place that produces Higgs!



Theoretically interesting:





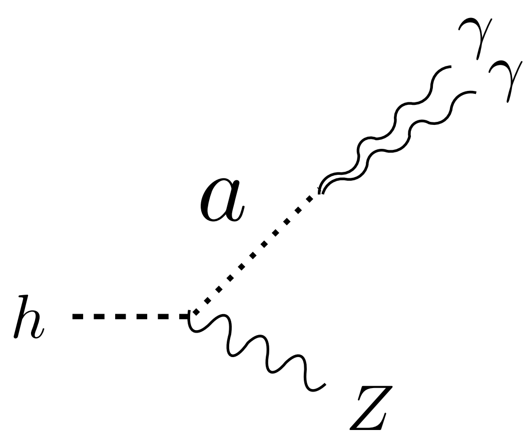
$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi + \frac{c_{Zh}^5}{f}\left(\partial^\mu a\right)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2} + \frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\phi^\dagger\phi$$

$\mathrm{Br}(h \to Za) < 1\,‰$ $\quad c_{Zh}^{\text{eff}} = 0.015$

How to close the gap?

Many experimental signatures:

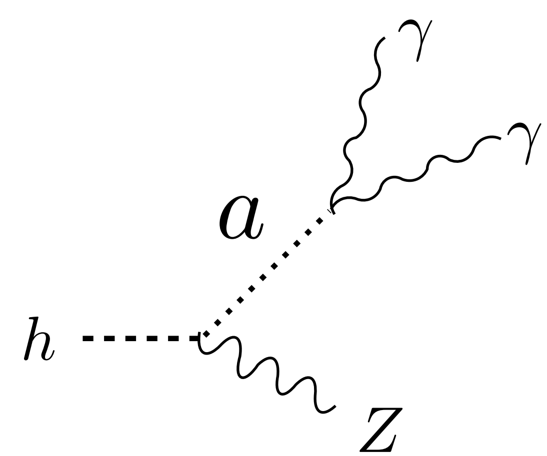
Low mass,
small coupling



$\mathrm{Br}(h \to Z\gamma) > \mathrm{Br}_{\mathrm{SM}}(h \to Z\gamma)$

Always enhanced!

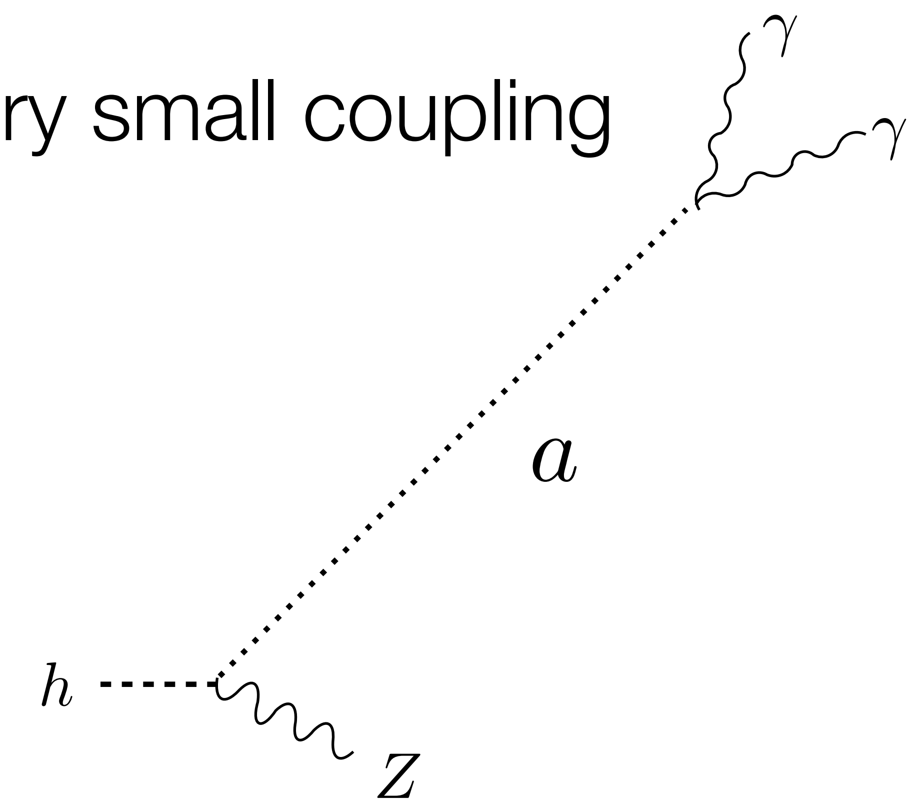
medium mass,
small coupling



Exotic signatures

$$h \to Z\gamma\gamma$$

very small coupling



Very challenging
exotic signatures

$$h \to Z + E_{T,\,\mathrm{miss}}$$

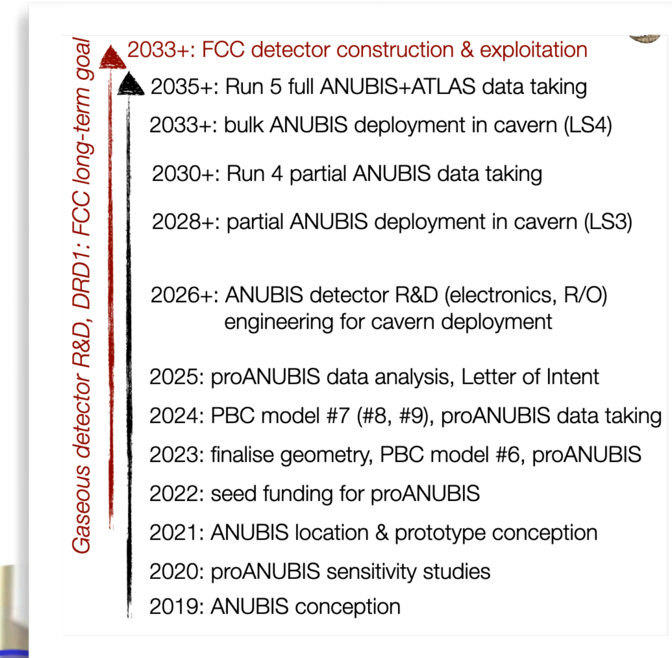
$$a \to \gamma\gamma$$

How to close the gap?

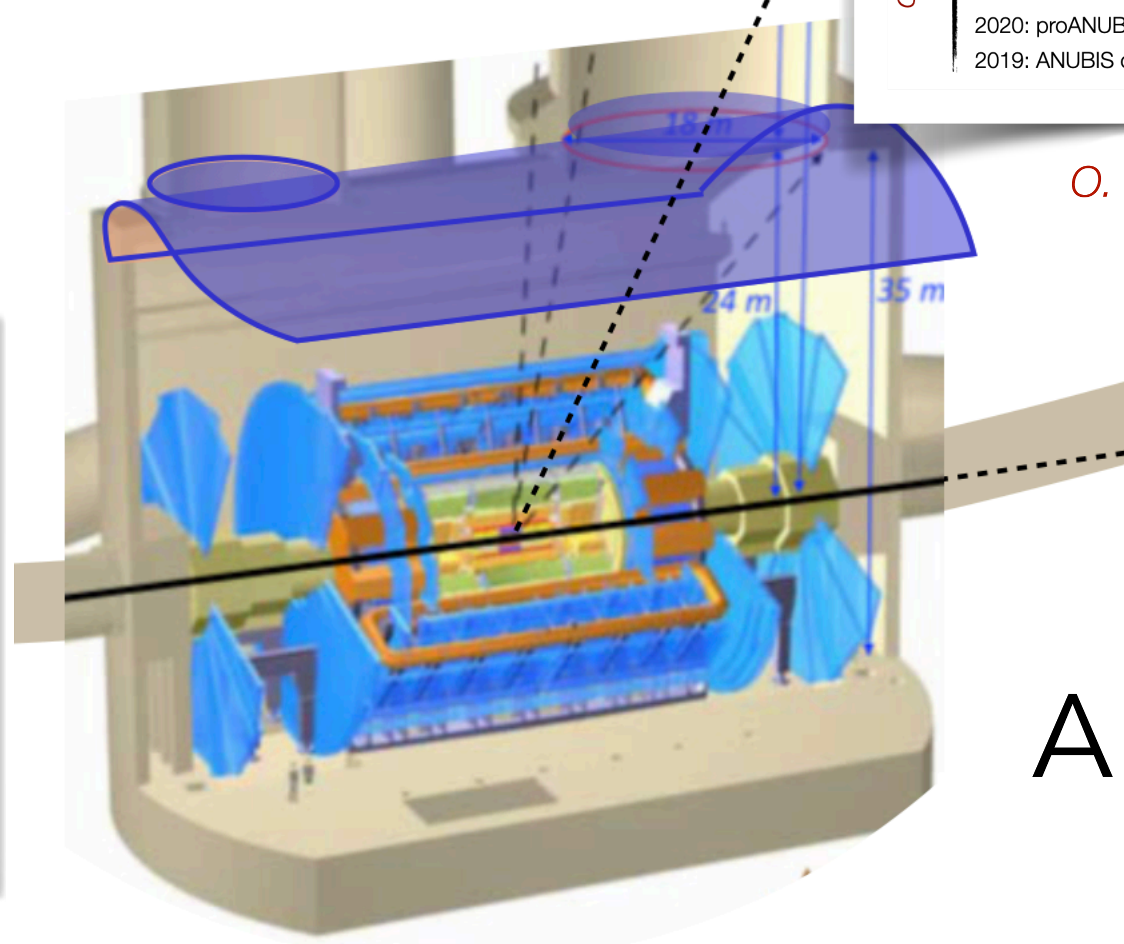
A dedicated detector for long-lived particles at ATLAS

ANUBIS: Instrument the cavern ceiling, significantly increase fiducial volume

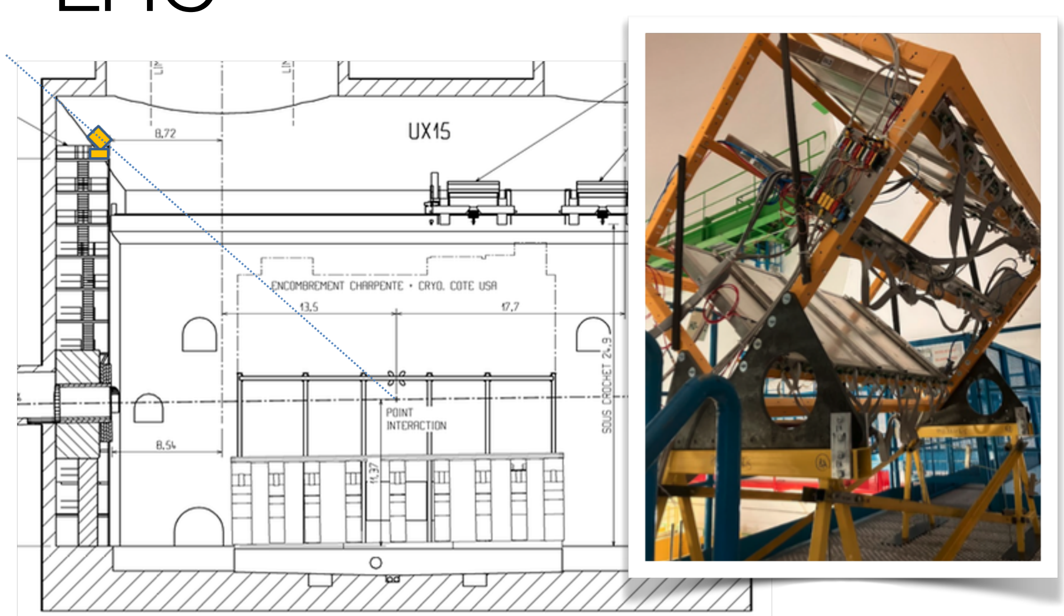
- Complementary to ‘forward physics’
- Active veto from ATLAS
- Full exploitation of the LHC



O. Brandt, UK-ECFA,24



ANUBIS



Demonstrator in the cavern

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:

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