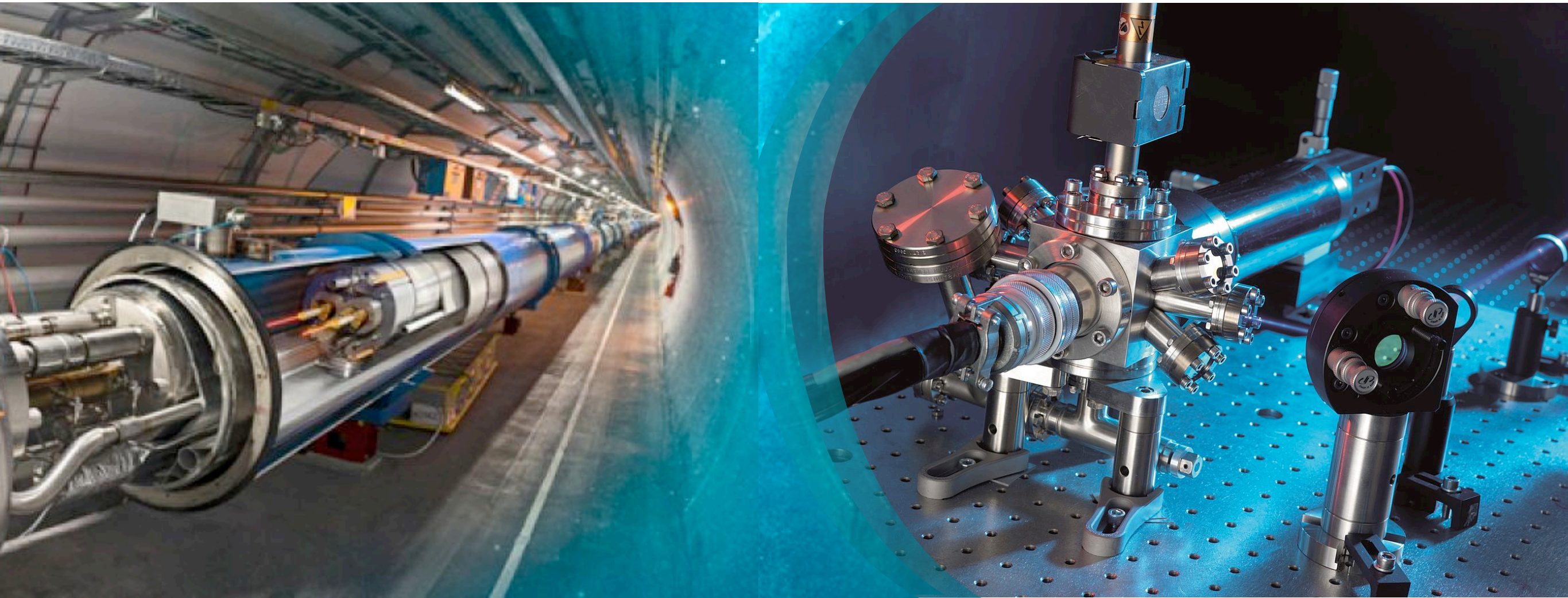


Ultralight Dark Matter

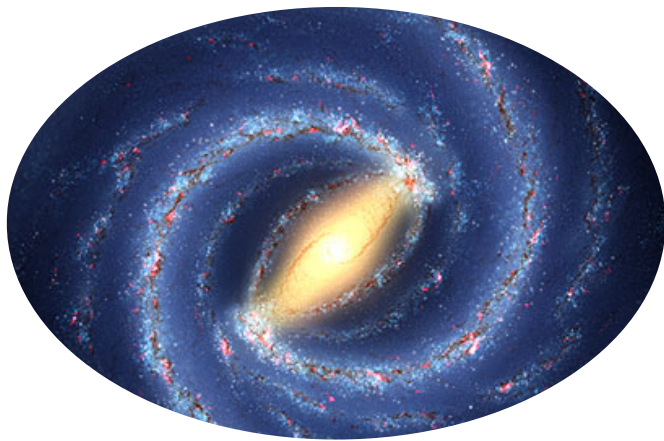


Martin Bauer, PASCOS 26, Sheffield, 25.6.2026



What is dark matter

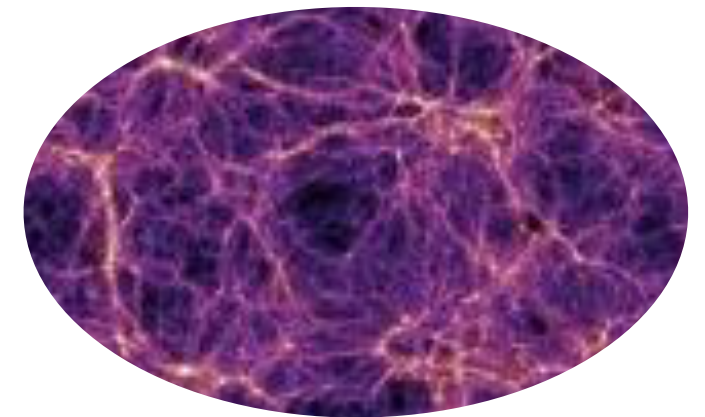
There is overwhelming evidence for the existence of dark matter at different scales



Rotation curves



gravitational lensing



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?

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

Light thermal dark matter

Heavy thermal dark matter

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

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

$$\Rightarrow m_\chi \lesssim 120 \text{ TeV}$$



What is the DM scale?

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

Light thermal dark matter

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

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

$$m_\chi > \frac{1}{\sigma M_{\text{Pl}}} \Rightarrow m_\chi > 0.1 \text{ eV}$$

Heavy thermal dark matter

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

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

$$\Rightarrow m_\chi \lesssim 120 \text{ TeV}$$

0.1 eV

ν

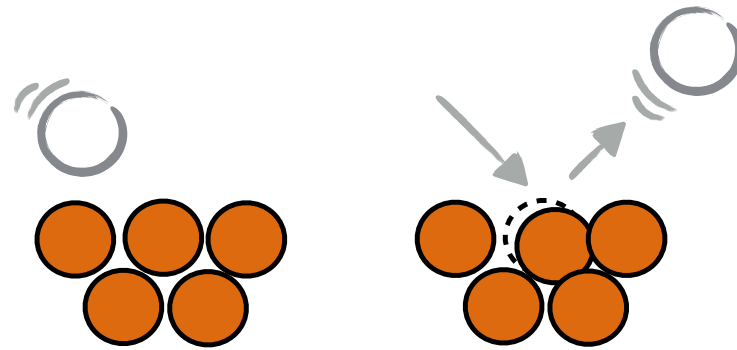
120 TeV

M_{Pl}



Extensive experimental programme

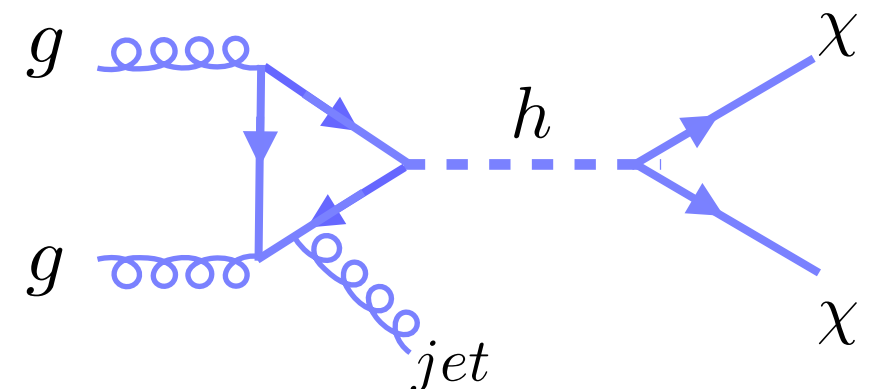
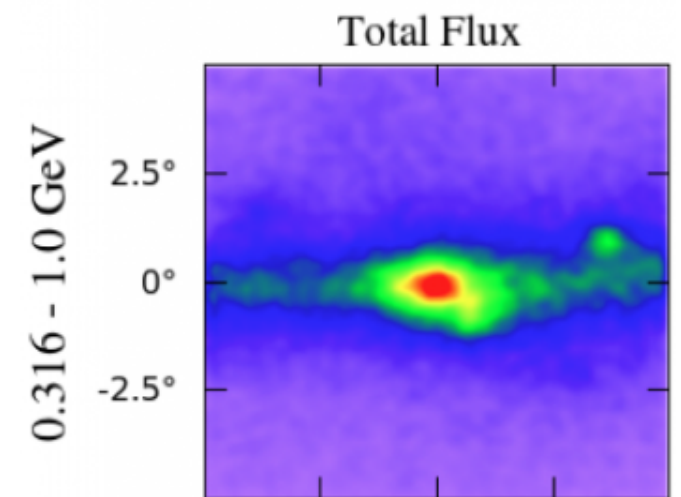
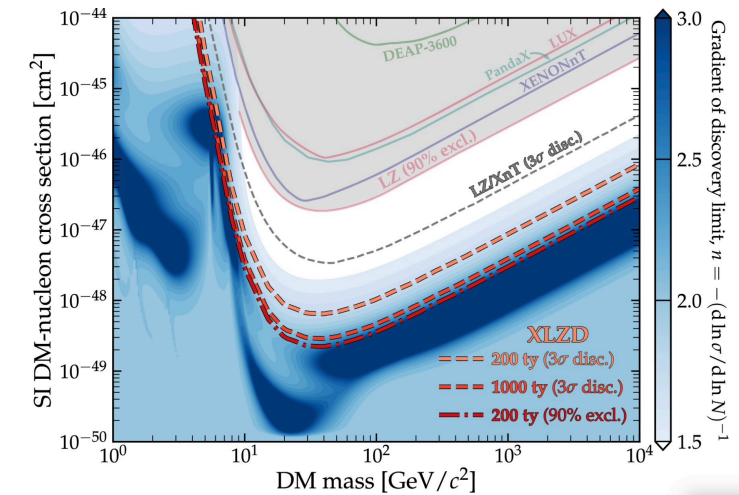
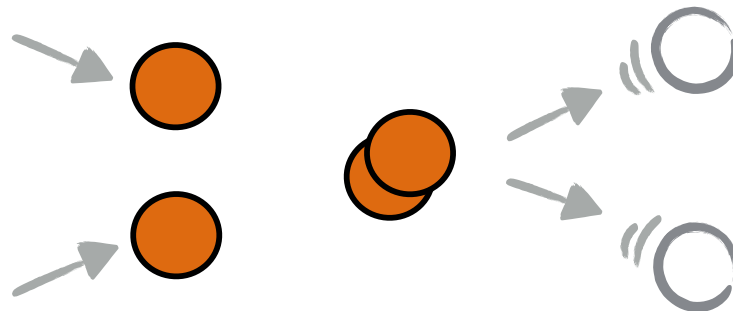
Direct
detection



Indirect
detection



Collider
searches



What is the DM scale?

What do we know about the scale of DM?



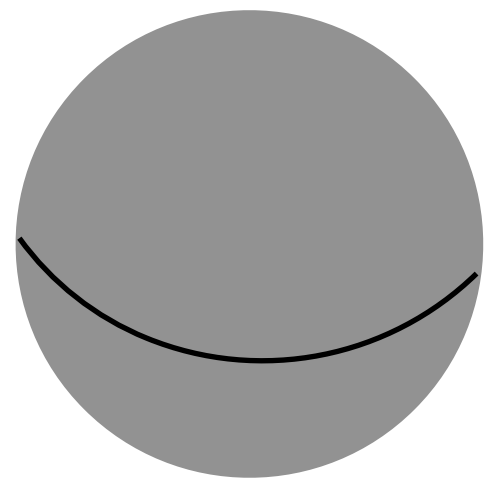
What is the DM scale?

What do we know about the scale of DM?

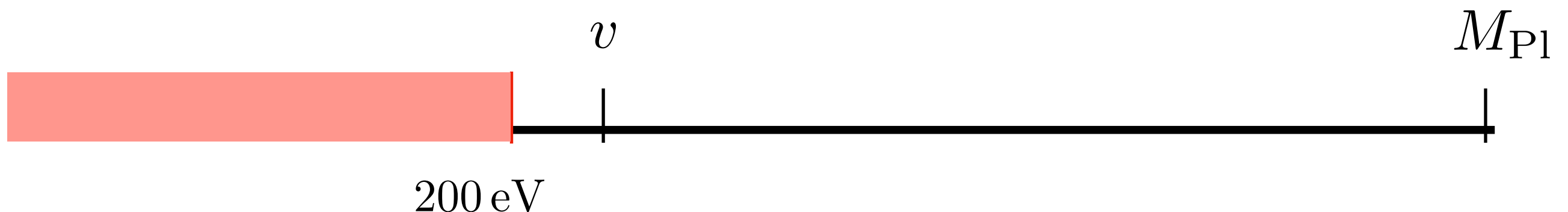
For **fermions**, the Pauli exclusion principle provides a lower limit

$$\left(\frac{9\pi M}{4m_\chi^4 R^3} \right)^{1/3} \leq \sqrt{\frac{2G_N M}{R}} \quad \Rightarrow \quad m_\chi \gtrsim 200 \text{ eV}$$

dwarf galaxies



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



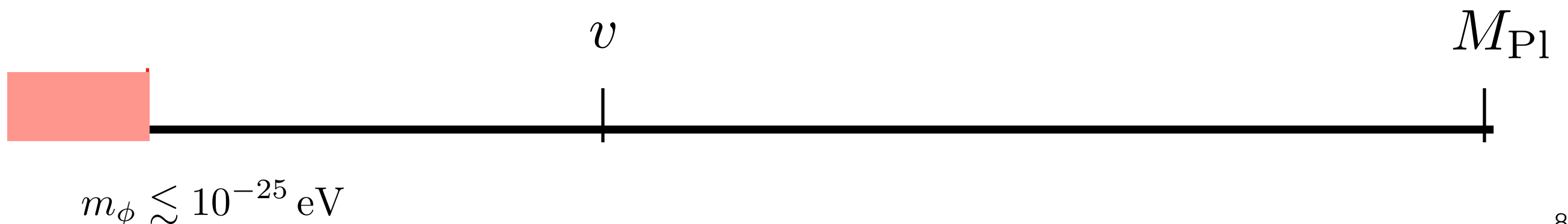
What is the DM scale?

For bosons there is no such lower limit.

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

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

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 well motivated:

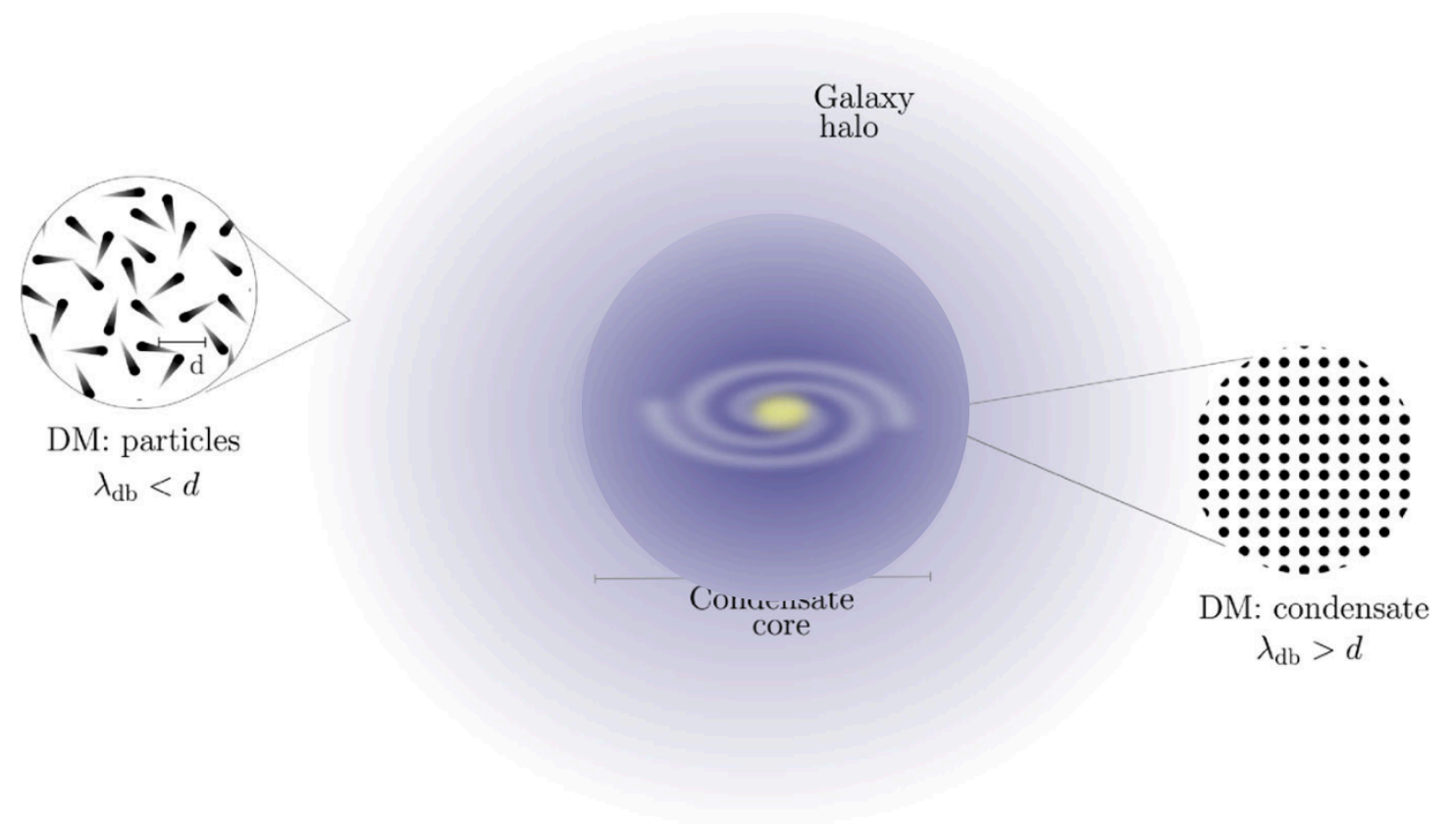
$$m_\phi \approx 10^{-22} \text{ eV} \quad \Rightarrow \quad \lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1 \text{ kpc}$$



Ultralight Dark Matter

Ultralight dark matter forms dense, stable soliton cores

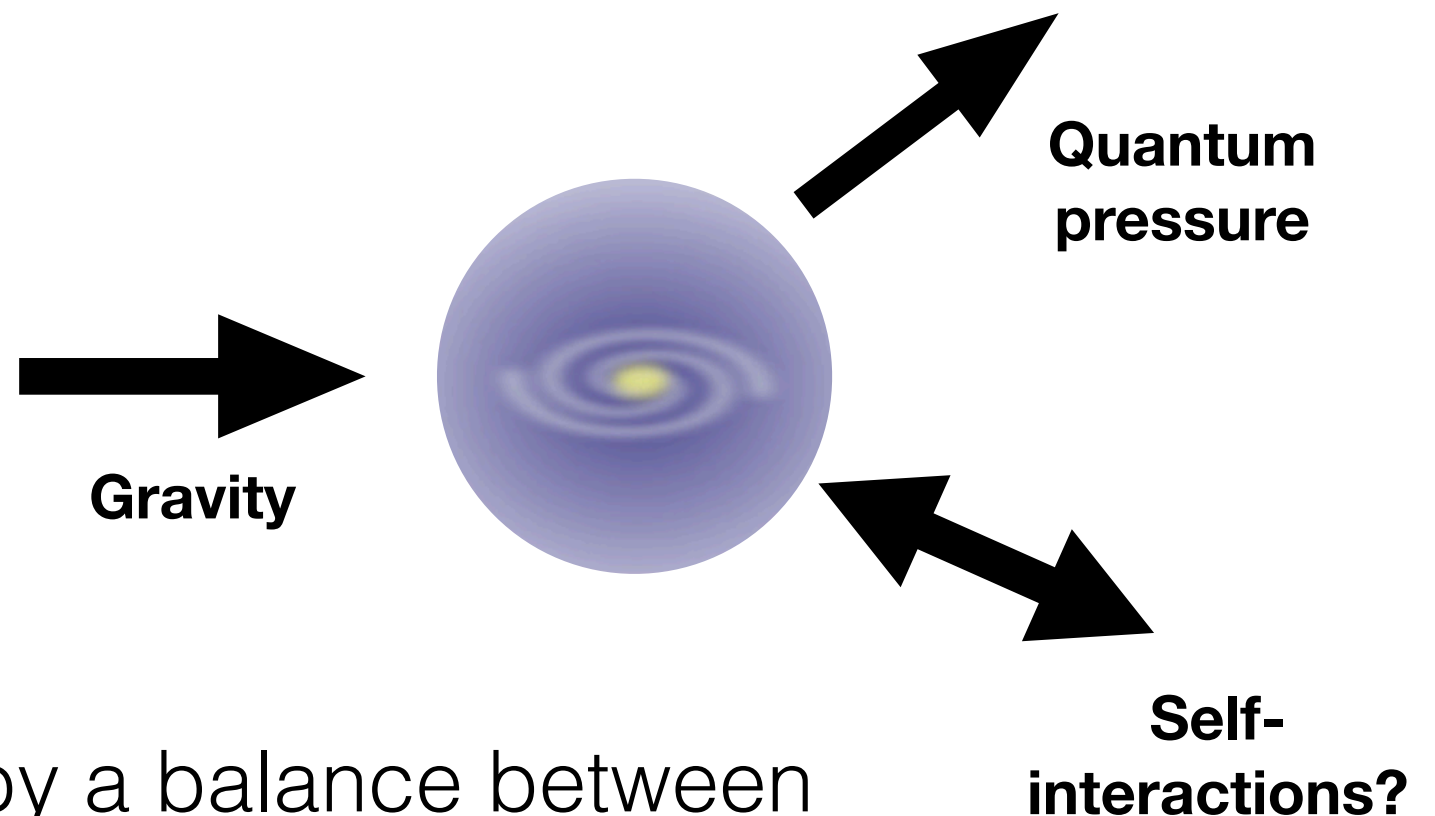
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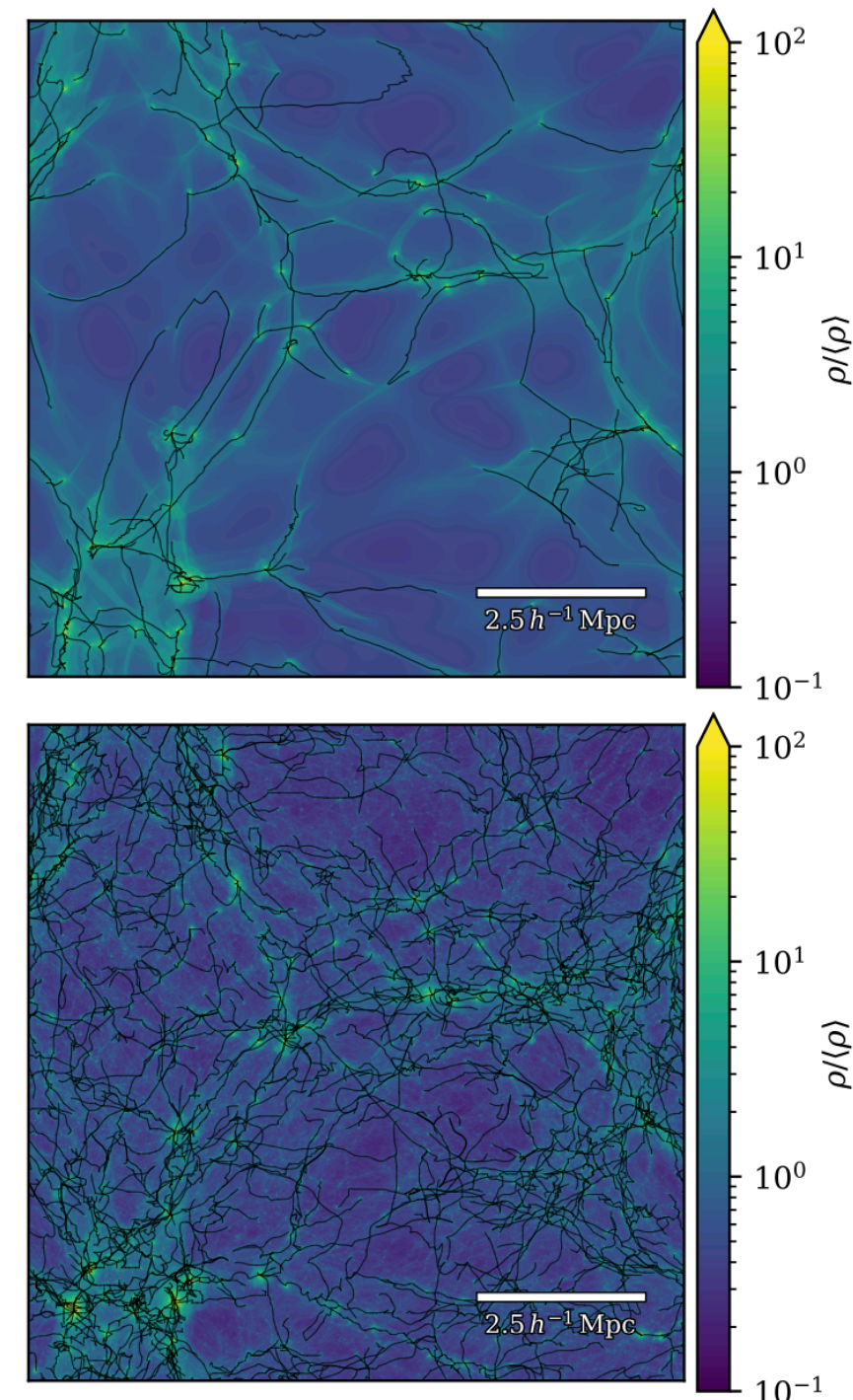
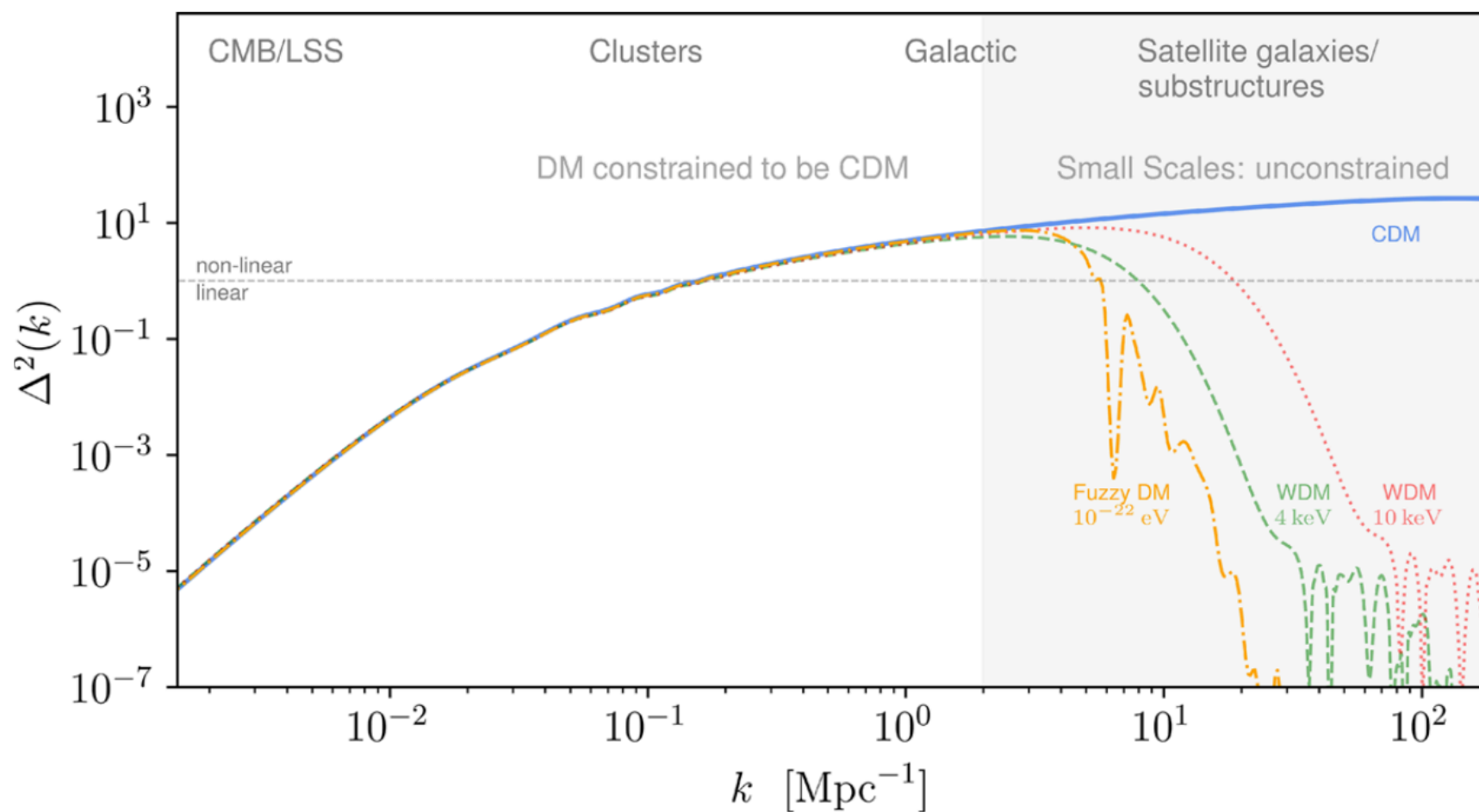


The size of the core is set by a balance between quantum pressure and gravity

Self-interactions change the equation

Ultralight Dark Matter

Fit the small scale power spectrum:

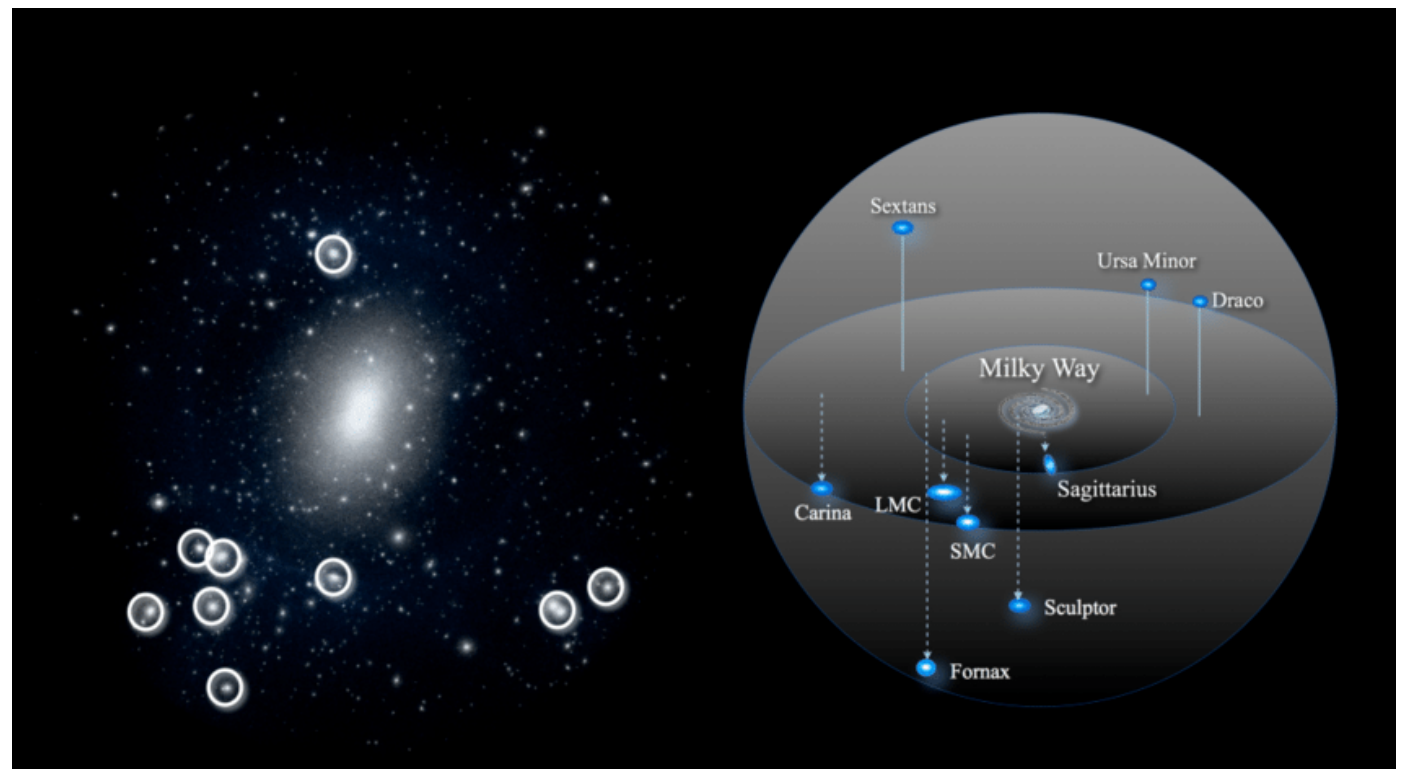
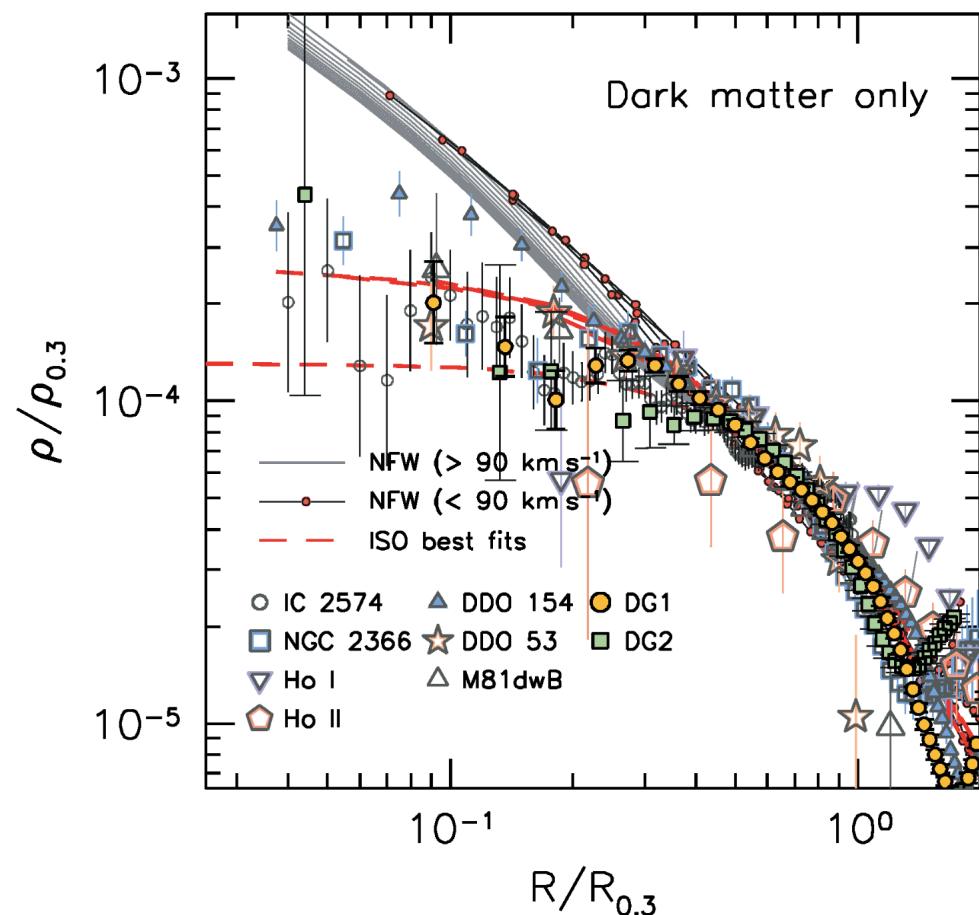


Ultralight Dark Matter

Missing satellite problem

Baryonic physics suppresses the number of luminous satellite galaxies

Jeon et al. [2506.09152]



Diversity problem

Popollo, Delliou [2209.14151]

Baryon interactions could explain cores for dwarfs (cusps form in MW-type galaxies)

Ultralight Dark Matter

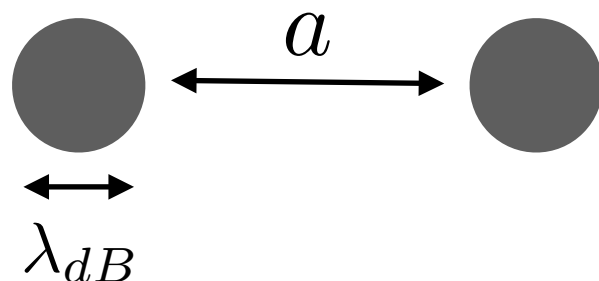
For very light scalar fields, the occupation number is very high and the field can be treated classically.

Quantum Field Theory

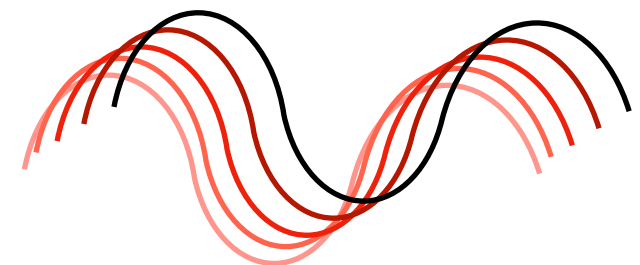
Large spacing

Large (continuous)
occupation number

Particle quantum
mechanics



Classical field theory



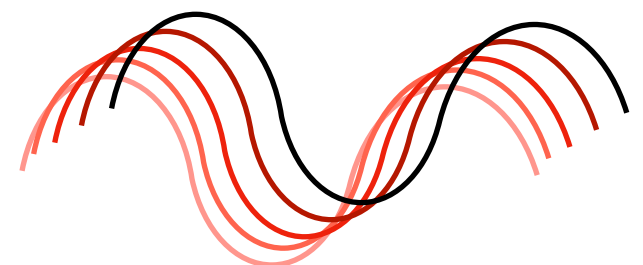
Ultralight Dark Matter

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

For $m < \text{few eV}$, dark matter is described as a classical wave

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

$$N_{\text{dB}} \approx 10^{94} \left(\frac{10^{-22} \text{ eV}}{m} \right)^4 \left(\frac{250 \text{ km/s}}{v} \right)^3$$



Ultralight Dark Matter

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

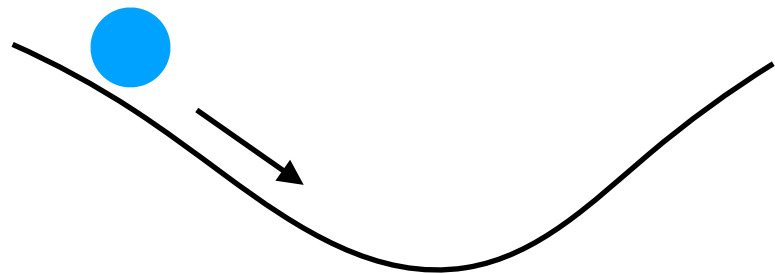
This kind of dark matter was never in thermal equilibrium

Dark Matter relic density from misalignment:

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

$$H(t) > m_a$$

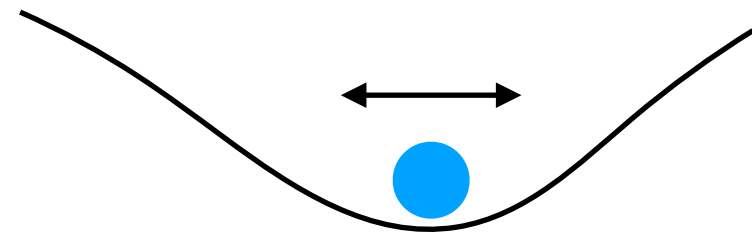
Solution $a(t) = \text{const.}$



early universe: Hubble friction

$$H(t) < m_a$$

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



late universe: oscillations

Ultralight Dark Matter

early universe: Hubble friction

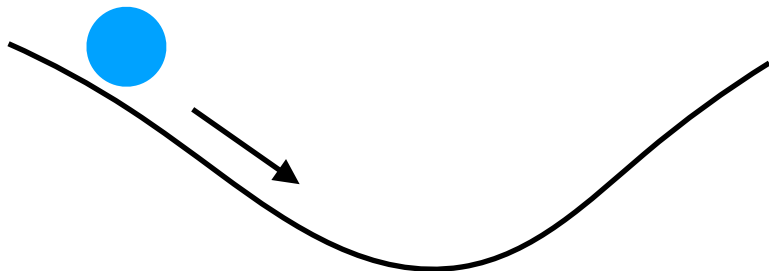
Redshifts like a cosmological constant:

$$a(x) = \text{constant} \quad \dot{a}(x) = 0$$

$$\frac{p}{\rho} = -1$$

$$H(t) > m_a$$

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



late universe: oscillations

Redshifts like cold matter:

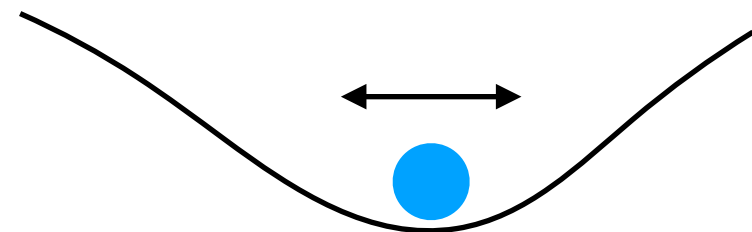
$$\dot{a}(x) = -a_0 m_a \sin(m_a t)$$

$$\langle \dot{a}^2(x) \rangle = m_a^2 \langle a^2(x) \rangle$$

$$\frac{\langle p \rangle}{\langle \rho \rangle} = 0$$

$$H(t) < m_a$$

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



Ultralight Dark Matter

Mass is fixed by halo size

$$m_a \gtrsim 10^{-22} \text{eV}$$

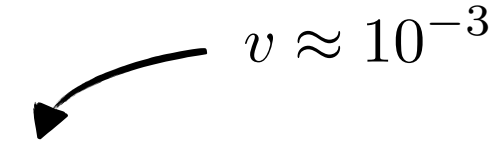
Amplitude is fixed by the dark matter energy density

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

The angular frequency is determined by the rest mass.

$$\omega \sim m_a$$

Small corrections from the kinetic energy

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


$v \approx 10^{-3}$

Coherence time is set by the frequency spread

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

Particle models

Axions or axionlike particles are excellent candidates for light dark matter, because they have a reason to be light

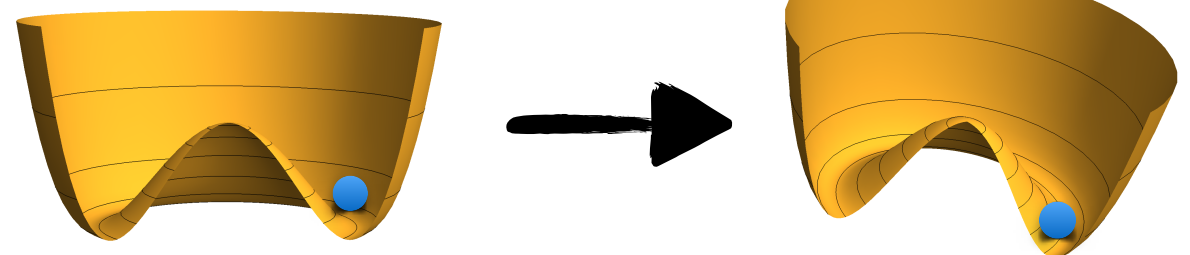
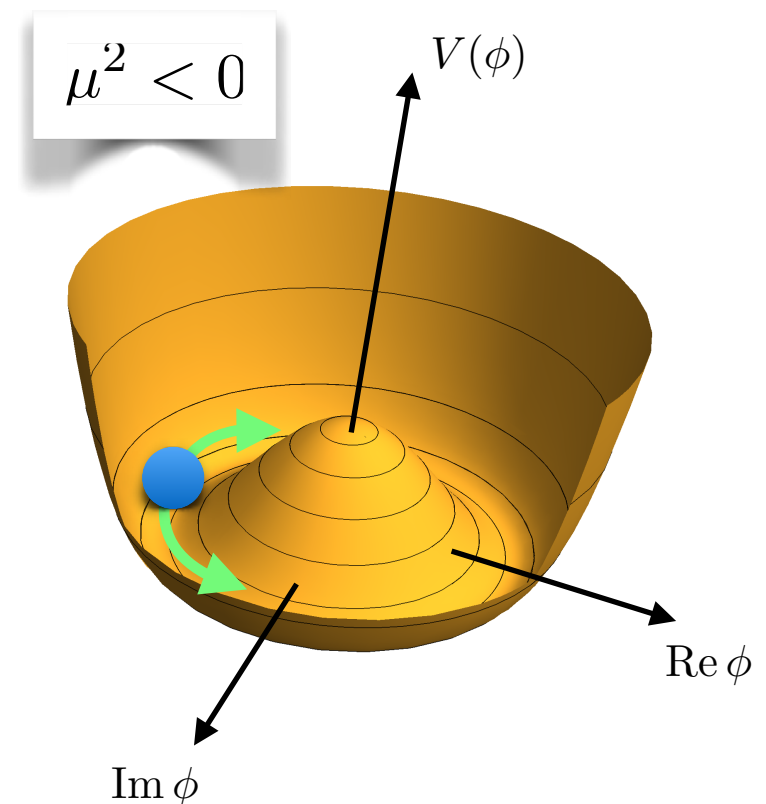
$$V(\phi) = \mu^2 \phi \phi^\dagger + \lambda (\phi \phi^\dagger)^2 \quad \phi = (f + s)e^{ia/f}$$

$$2 \text{ states} \quad m_s^2 = 4\lambda f^2 = |\mu^2| \quad m_a^2 = 0$$

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

For approximate global symmetries

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



Particle models



ρ, P, N

The most famous example is the pion

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

$$\langle \bar{q}_L q_R \rangle = \Lambda_{\text{QCD}}^3 \approx \text{GeV}^3$$

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

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda_{\text{QCD}}^3 \approx (140 \text{ MeV})^2$$

π



ALP phenomenology

At leading order ALPs/axions interact like pseudoscalars

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

Couplings are related to the UV structure

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

ALP phenomenology

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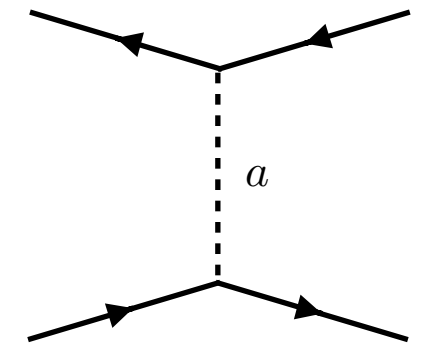
These interactions lead to spin-dependent observables in the non-relativistic limit (see also [Andreas Ringwalds talk](#))

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

ALP phenomenology

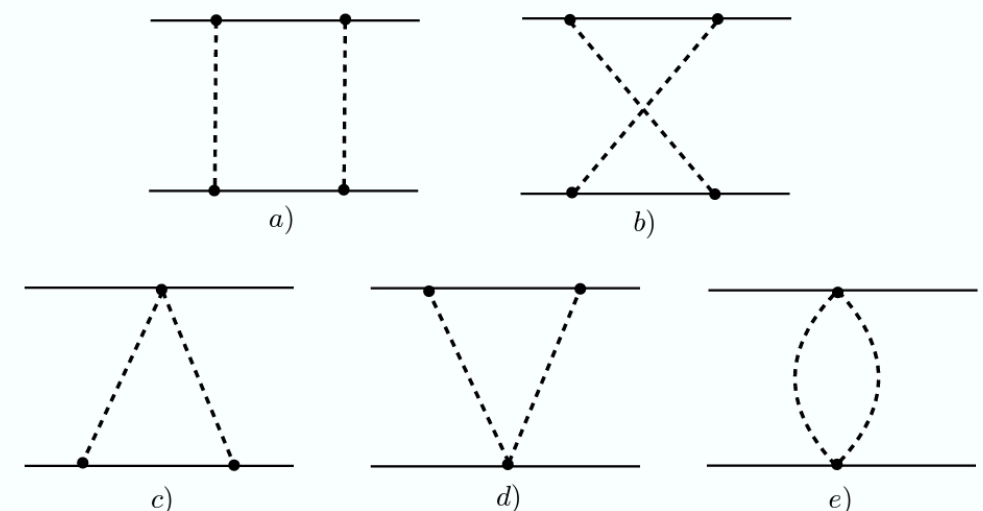
Forces induced by axion exchange are difficult to discover, because they require experiments with polarised targets

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



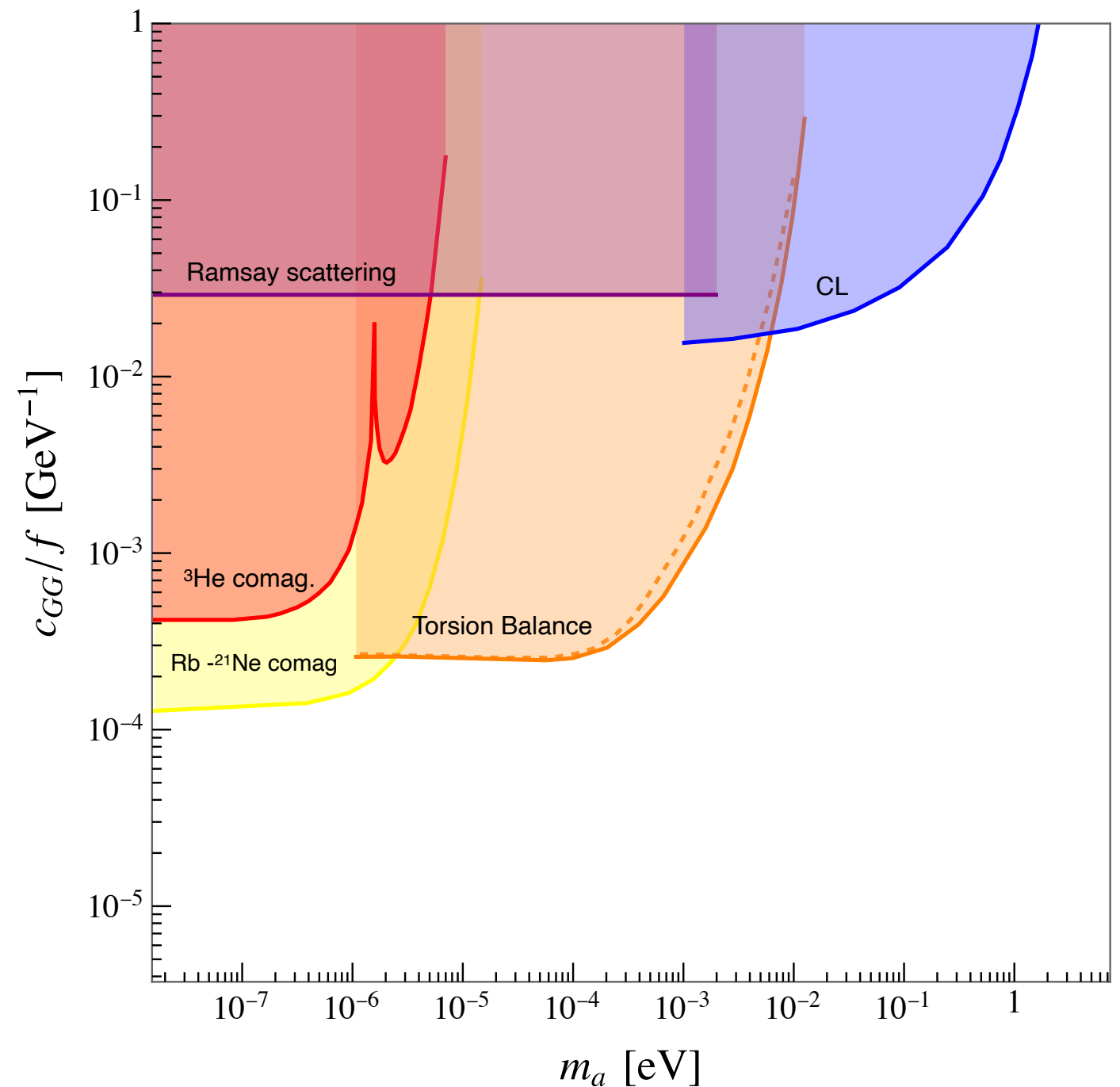
However, the exchange of two axions leads to spin-independent forces

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



ALP phenomenology

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



MB, Chakraborti, Rostagni, [2408.06412]

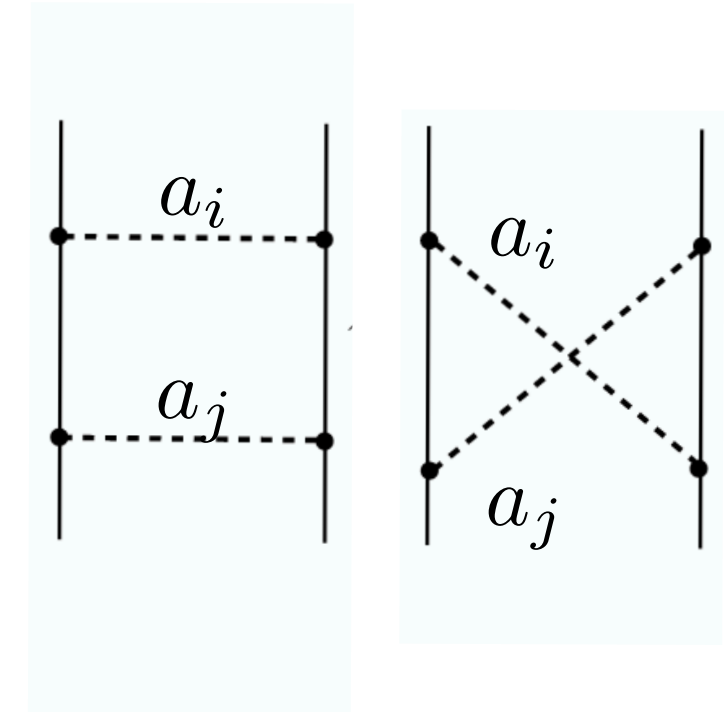
MB, Rostagni [2307.09516]

Fifth forces in the Axiverse

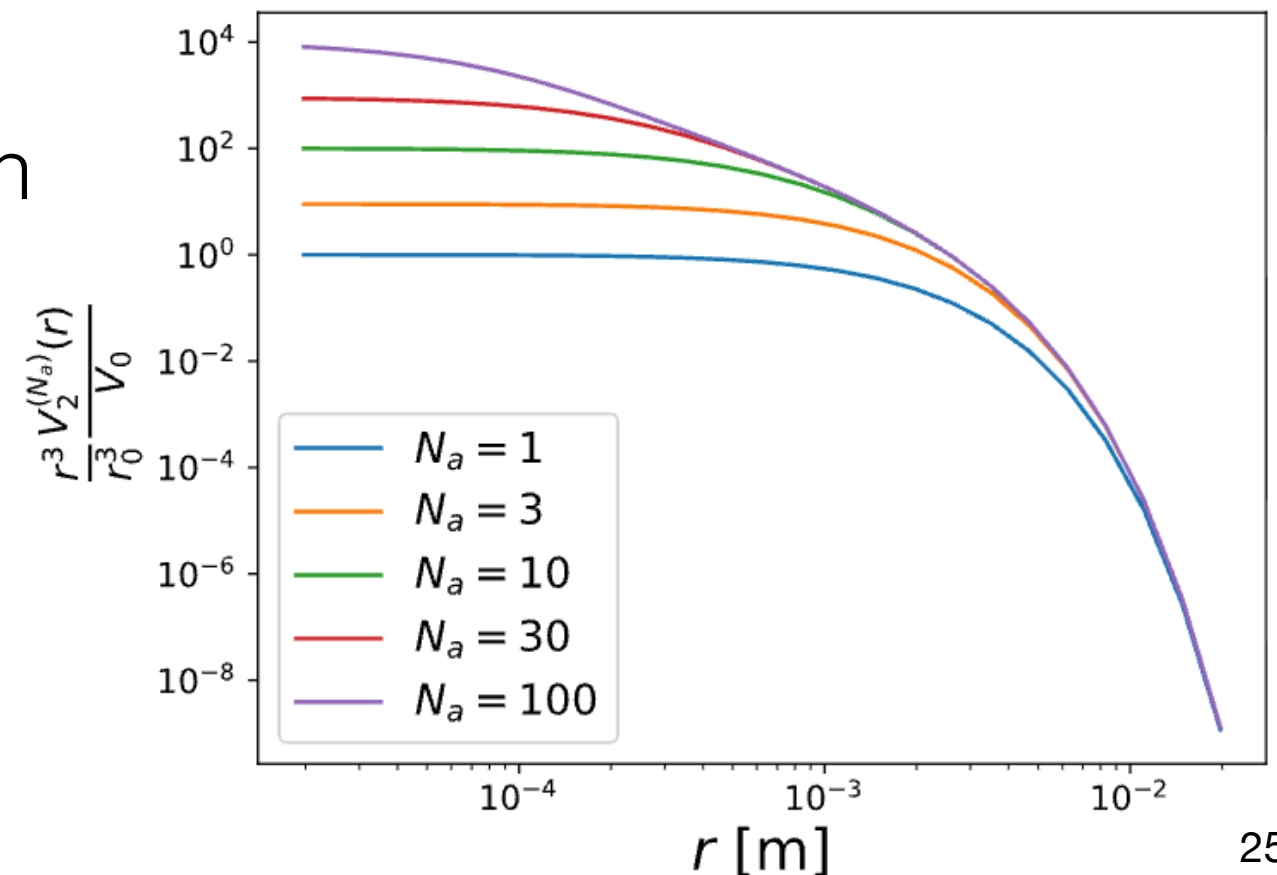
Spin-independent potential for N_a axions

$$V_2^{(N_a)}(r) = \frac{1}{128\pi^3} \sum_{i,j=1}^{N_a} \frac{1}{f_i^2 f_j^2} \left\{ \frac{3}{r^5} g_i^\alpha g_i^\beta g_j^\alpha g_j^\beta \mathcal{K}(x_a) \right. \\ + \frac{12}{r^5} \left[\frac{g_i^\alpha g_j^\alpha c_{ij}^\beta}{M_\alpha} + (\alpha \leftrightarrow \beta) \right] \left[\mathcal{K}(x_a) + \frac{x_a^4}{48} K_0(x_a) \right] \\ \left. - \frac{8}{r^3} c_{ij}^\alpha c_{ij}^\beta x_a K_1(x_a) \right\},$$

Potential can scale differently than one-particle exchange allows



Kaluza-Klein ALP



Quadratic Interactions

At leading order ALPs/axions interact like pseudoscalars

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

What about higher order terms? At dimension 6

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

Quadratic Interactions

All these couplings are related to the UV coupling structure

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

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

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

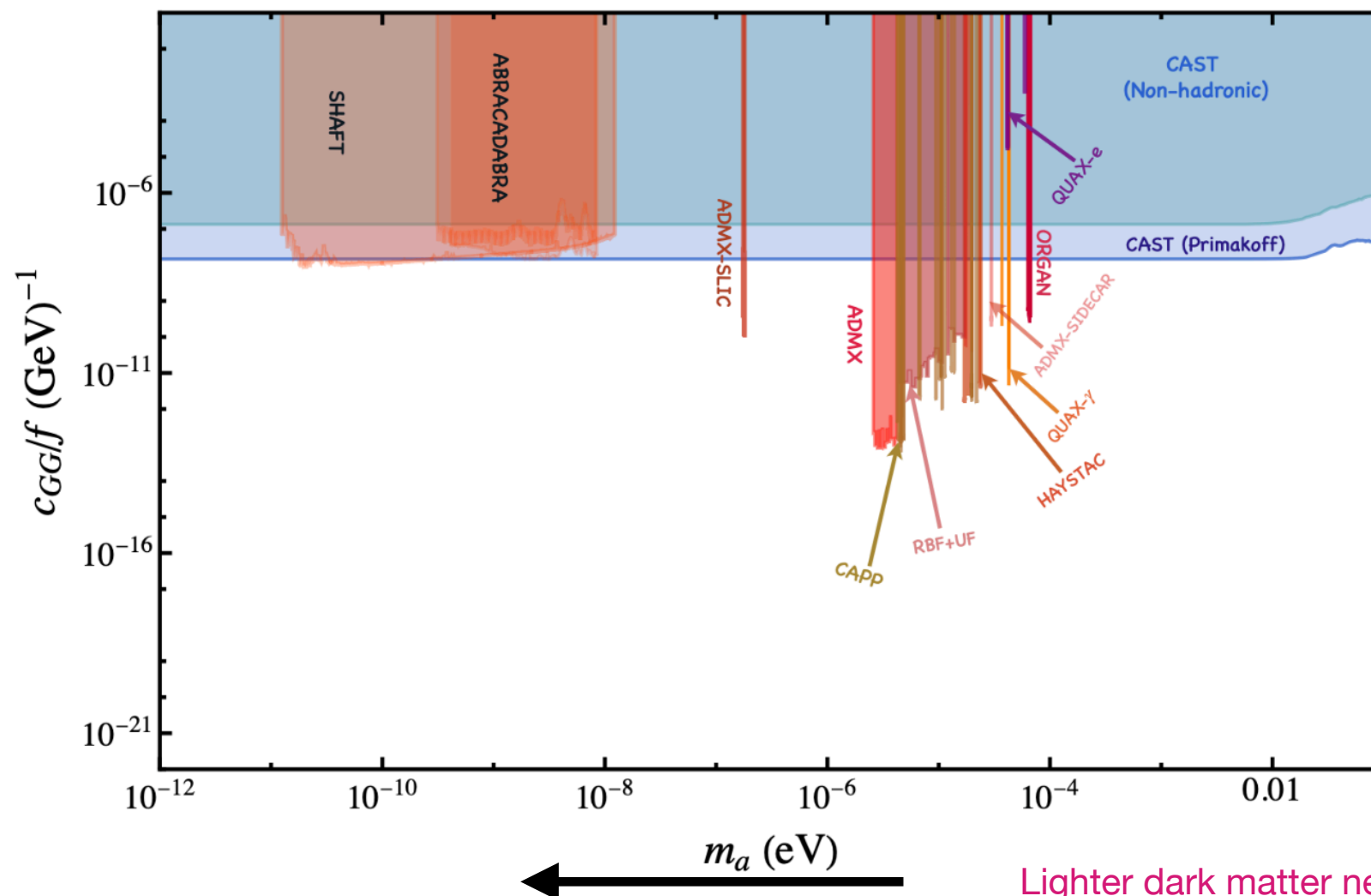
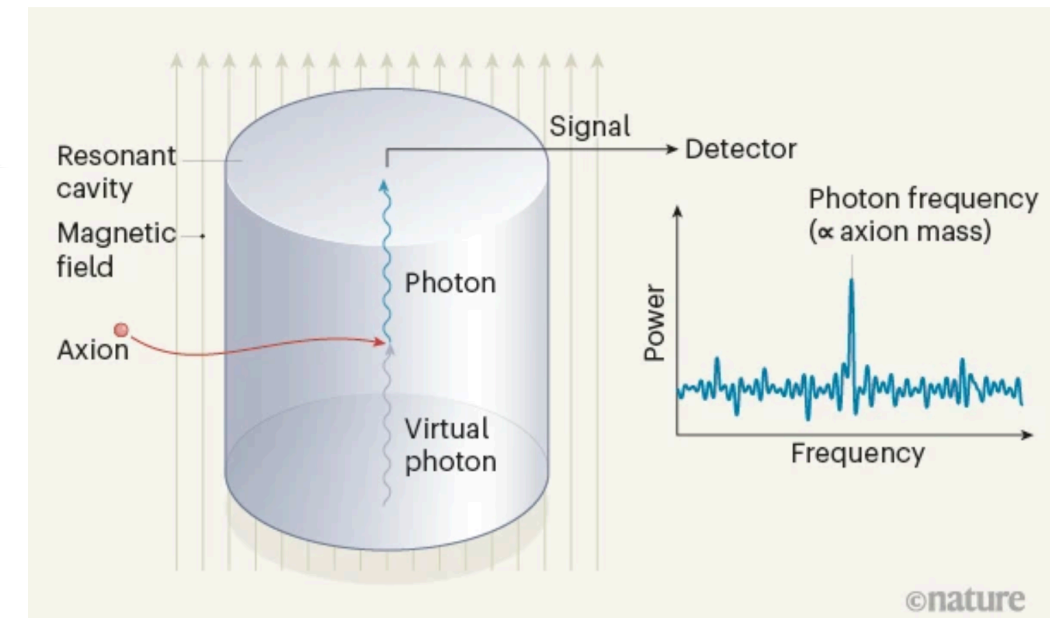
$$C_E = -m_e \frac{3\alpha}{4\pi} C_\gamma \ln \frac{m_\pi^2}{m_e^2}$$

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

ALP phenomenology

Resonant cavities

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



Probes axion interactions with photons

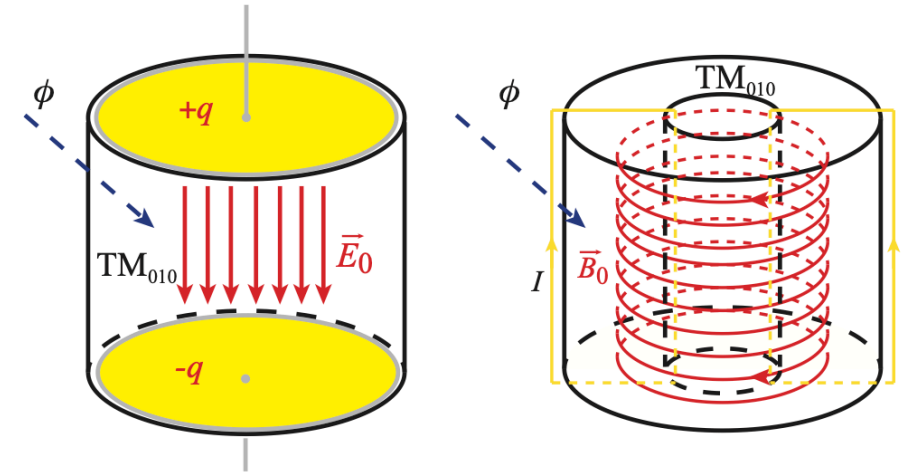
$$c_{\gamma\gamma}^{\text{eff}} \frac{\alpha}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} = c_{\gamma\gamma}^{\text{eff}} \frac{\alpha}{\pi} \frac{a}{f} \vec{E} \cdot \vec{B}$$

MB, Chakraborti, Rostagni,
[2408.06412]

Lighter dark matter needs larger cavities

ALP phenomenology

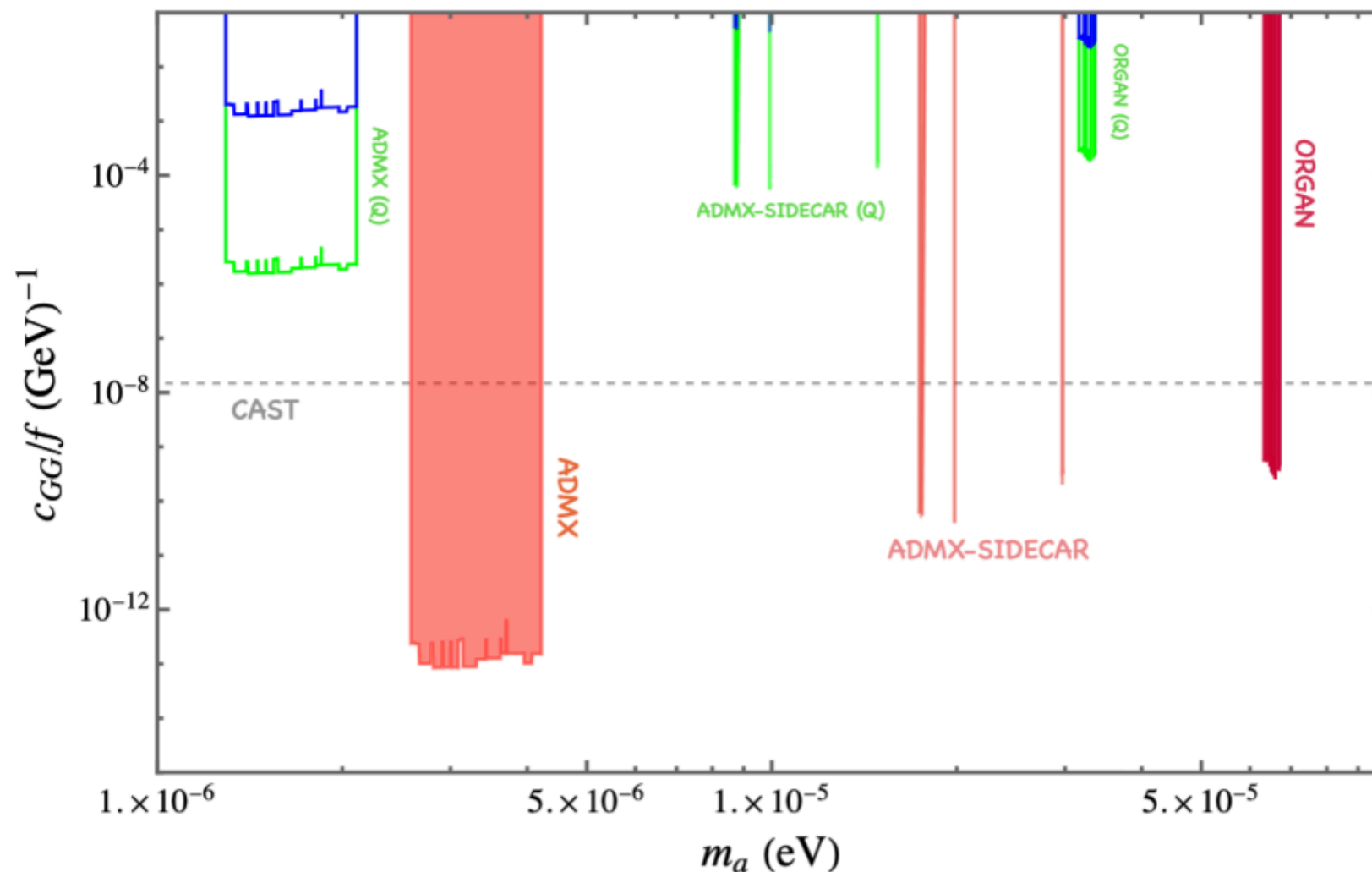
Quadratic axion interactions allow to extend the parameter space



Flambaum et al, 2207.14437

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

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



MB, Chakraborti, Rostagni,
[2408.06412]

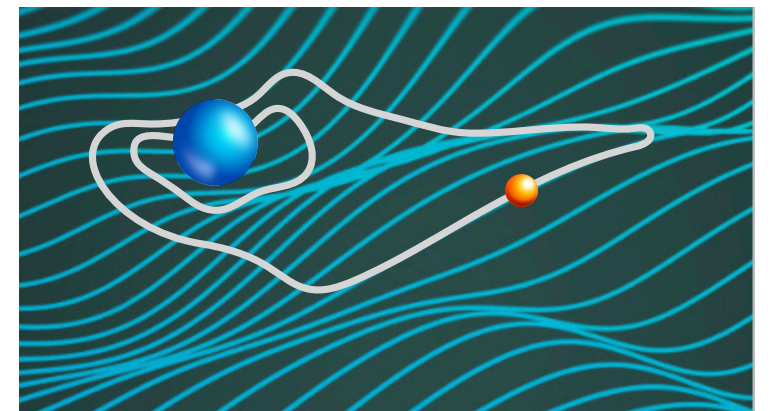
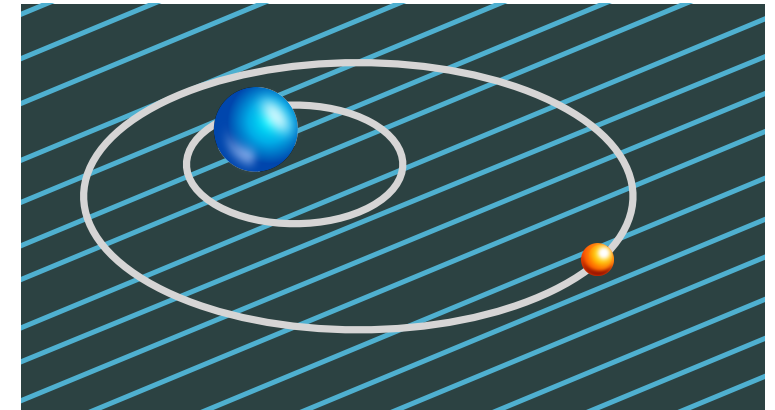
ALP phenomenology

Standard model fields in a scalar background field

$$\phi(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi} \cos \omega t$$

Can be described with time-dependent masses and coupling constants

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\phi}{\Lambda} F_{\mu\nu} F^{\mu\nu} \\ &= -\frac{1}{e^2} \frac{1}{1 + \phi/\Lambda} F_{\mu\nu} F^{\mu\nu} + \mathcal{O}(\phi^3/\Lambda^3) \end{aligned}$$



Leads to oscillating fundamental constants

$$\alpha^{\text{eff}} = \alpha(1 + \phi(t)/\Lambda)$$

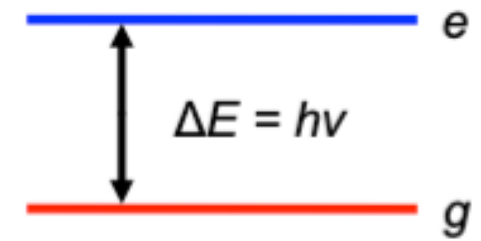
Quadratic ALP couplings are scalar

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

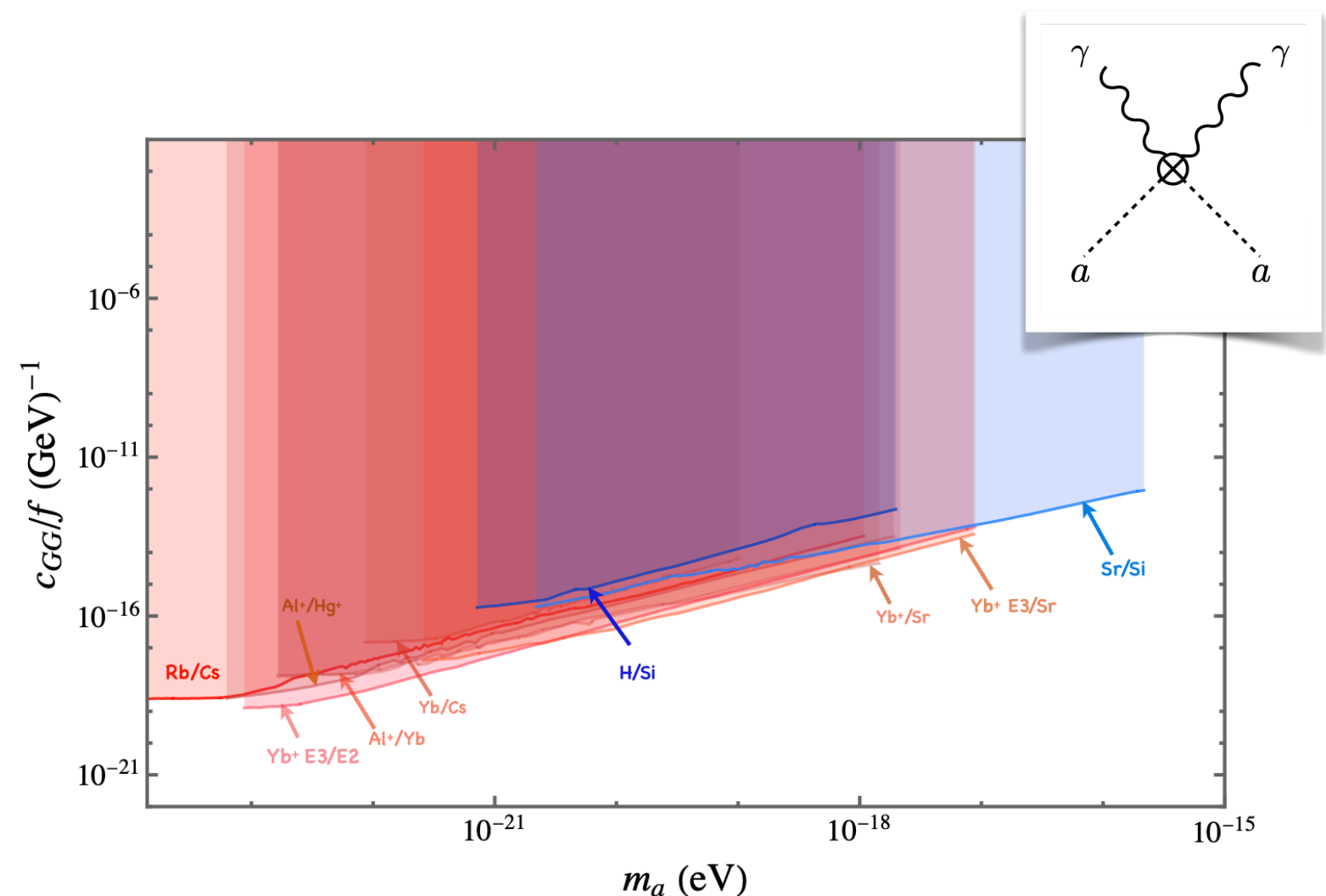
ALP phenomenology

Clocks and clock-cavity bounds

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



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



MB, Chakraborti, Rostagni,[2408.06412]

ALP phenomenology

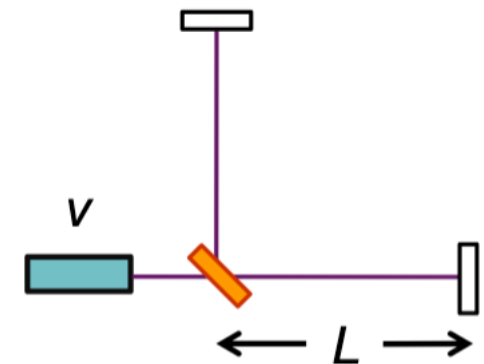
Ion clocks

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

Laser interferometers

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

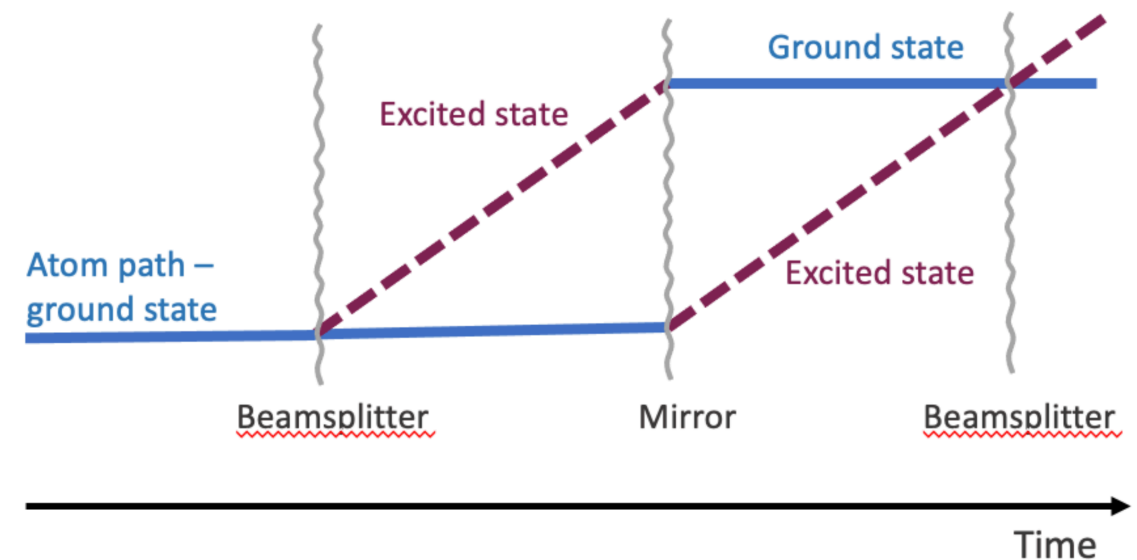
$$\frac{\delta n}{n} = -5 \times 10^{-3} \left(2 \frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e} \right)$$



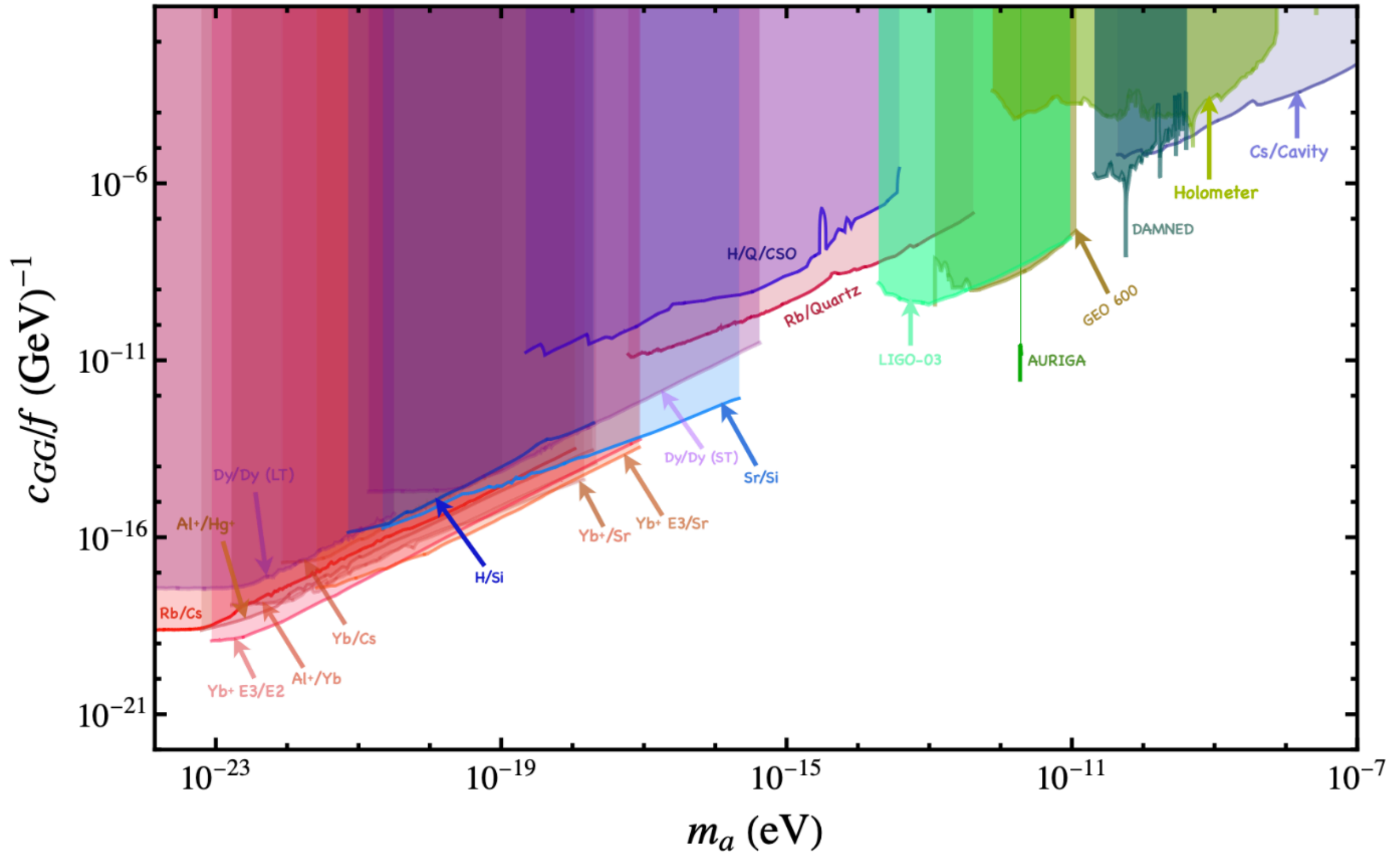
Atom interferometers

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

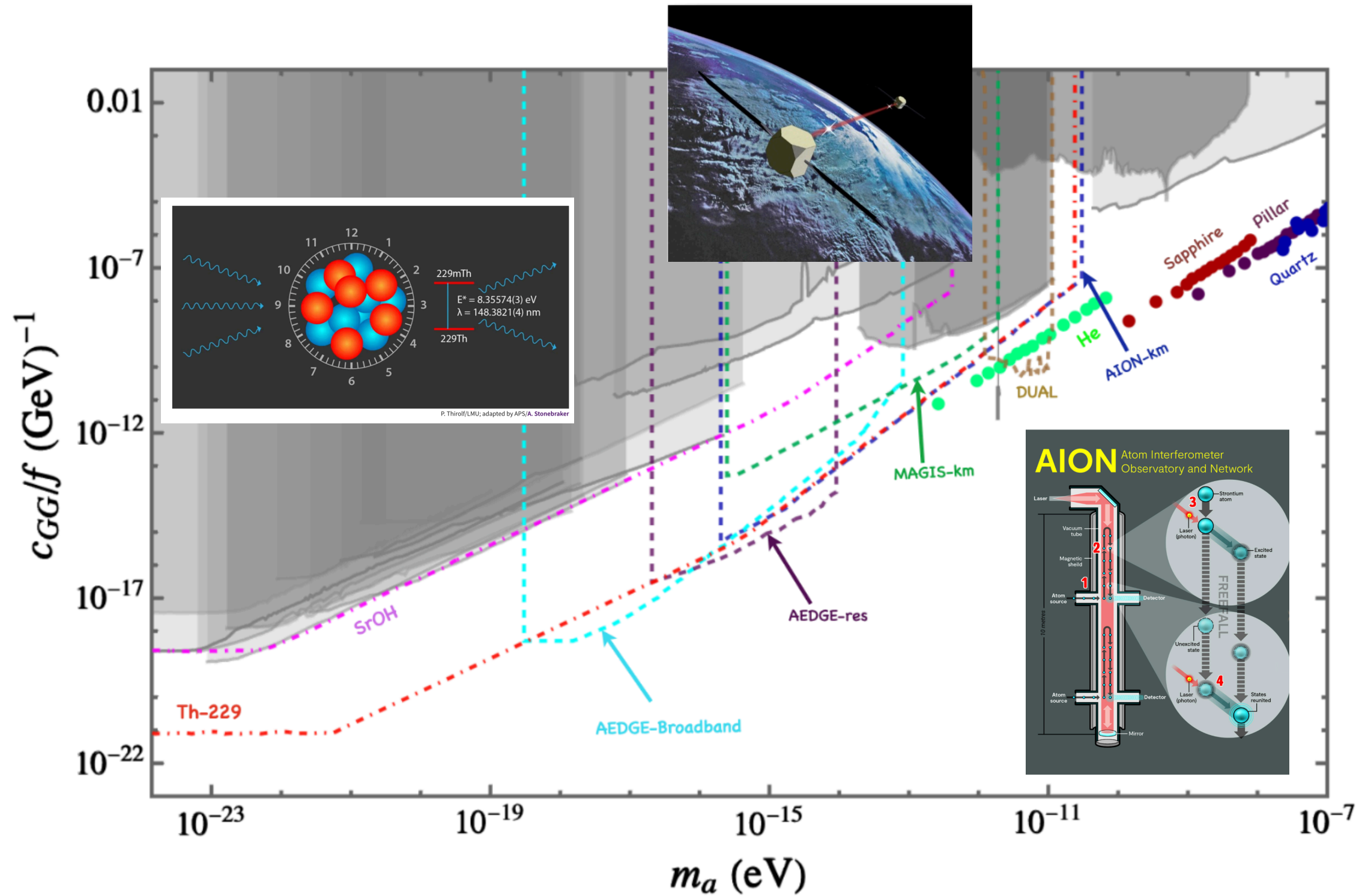
$$\Phi_s = 4 \overline{\omega_a} n \Delta r \sin^2(m_a T)$$



ALP phenomenology



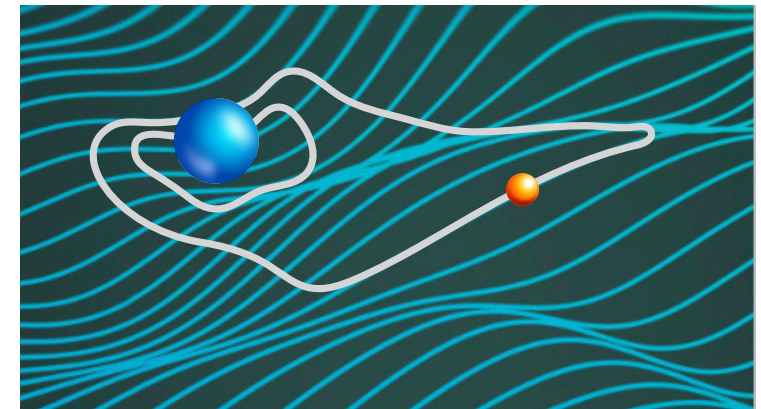
ALP phenomenology



ALP phenomenology

Couplings to the SM

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\phi}{\Lambda} F_{\mu\nu} F^{\mu\nu} \\ &= -\frac{1}{e^2} \frac{1}{1 + \phi/\Lambda} F_{\mu\nu} F^{\mu\nu} + \mathcal{O}(\phi^3/\Lambda^3)\end{aligned}$$



$$\alpha^{\text{eff}} = \alpha(1 + \phi(t)/\Lambda)$$

Where is the scale Λ coming from? A UV completion

$$\mathcal{L}_S = \partial_\mu S \partial^\mu S^\dagger - \mu_S^2 S^\dagger S - d_S \frac{\mu_S^2}{\Lambda} \phi S^\dagger S + \lambda_S (S^\dagger S)^2 + S \sum_f \kappa_f \bar{f} f$$

the mass of the mediator oscillates, too: $m_S^2(\phi) = \mu_S^2 \left(1 + \frac{d_S}{\Lambda} \phi \right)$

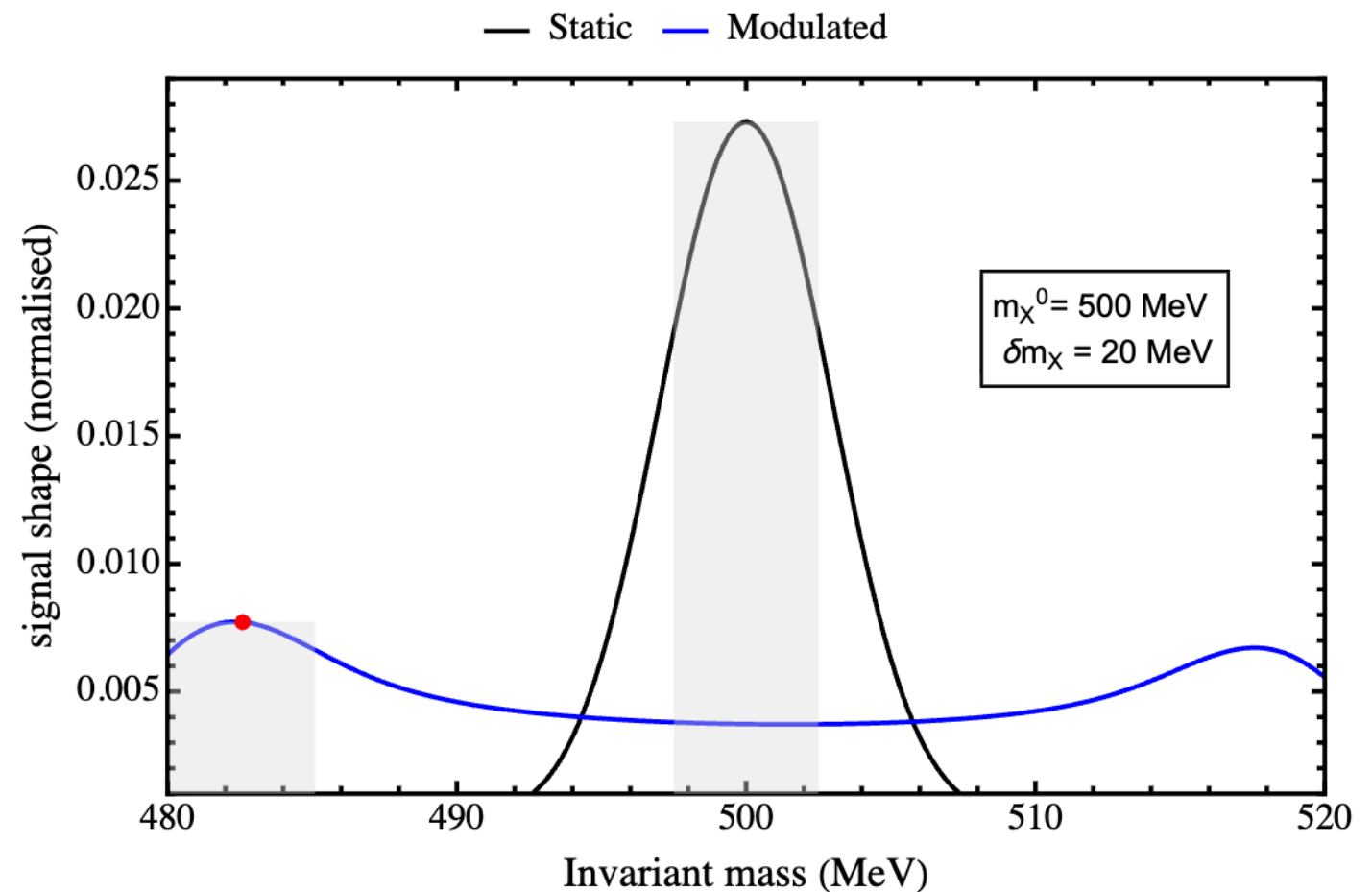
Oscillating Resonances

What happens when a resonance ‘oscillates’?

The resonance peak is modulated

$$m_S^2(\phi) = \mu_S^2 \left(1 + \frac{d_S}{\Lambda} \phi \right)$$

If this mediator is produced at a collider, the signal would be smeared out even if the unmodulated resonance is narrow



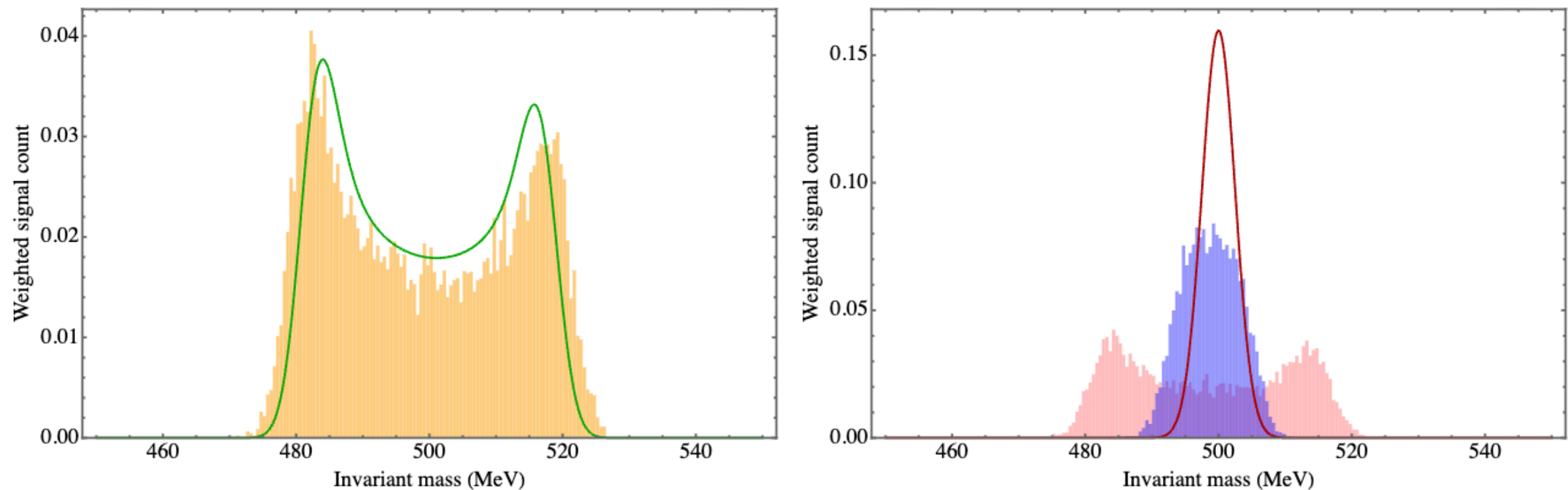
Gan, Liu. 2302.03056

MB, Chakraborti 2601.19844

Fieg, Fox, Zhang, Ghosh, Varada 2605.11071

Oscillating Resonances

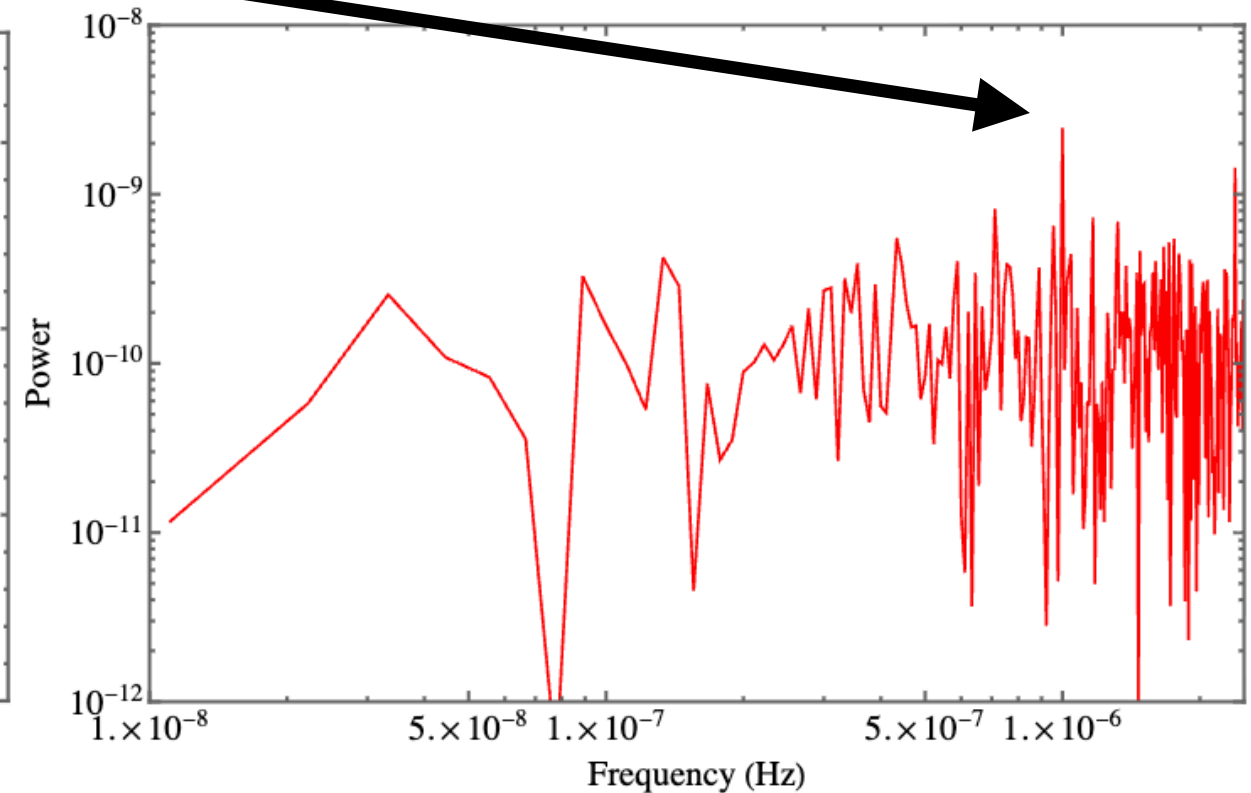
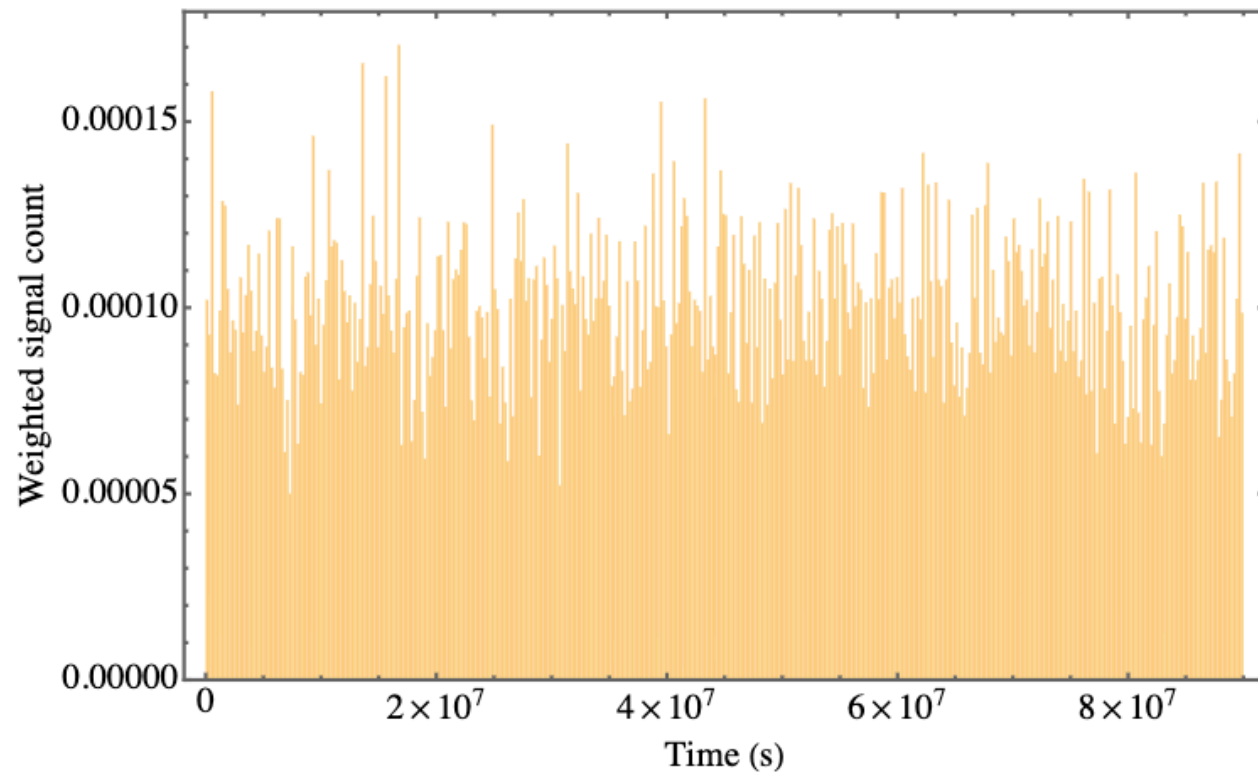
Detect both peaks and demodulate the signal



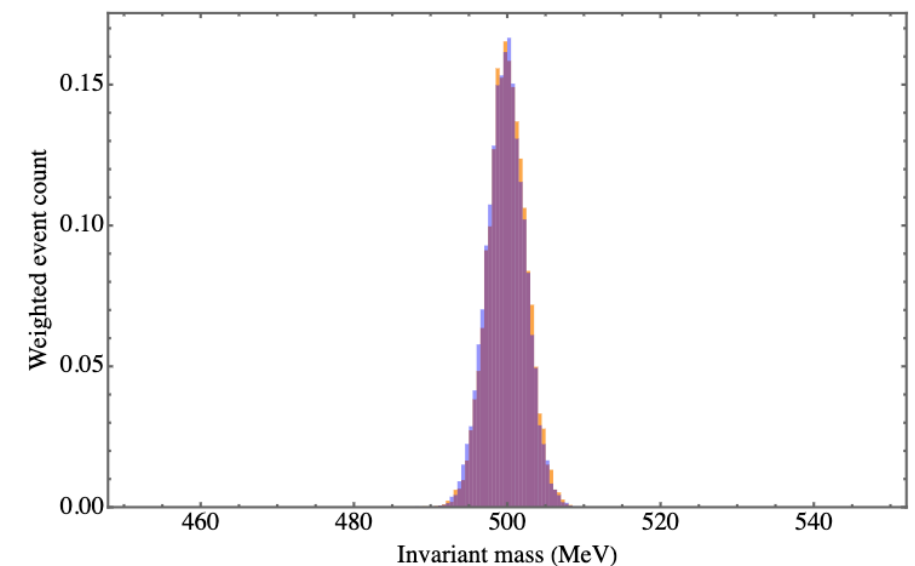
The signal peak can't be fully recovered even if this method works

Oscillating Resonances

Use time-binned data and fourier transform and look for a peak in frequency space

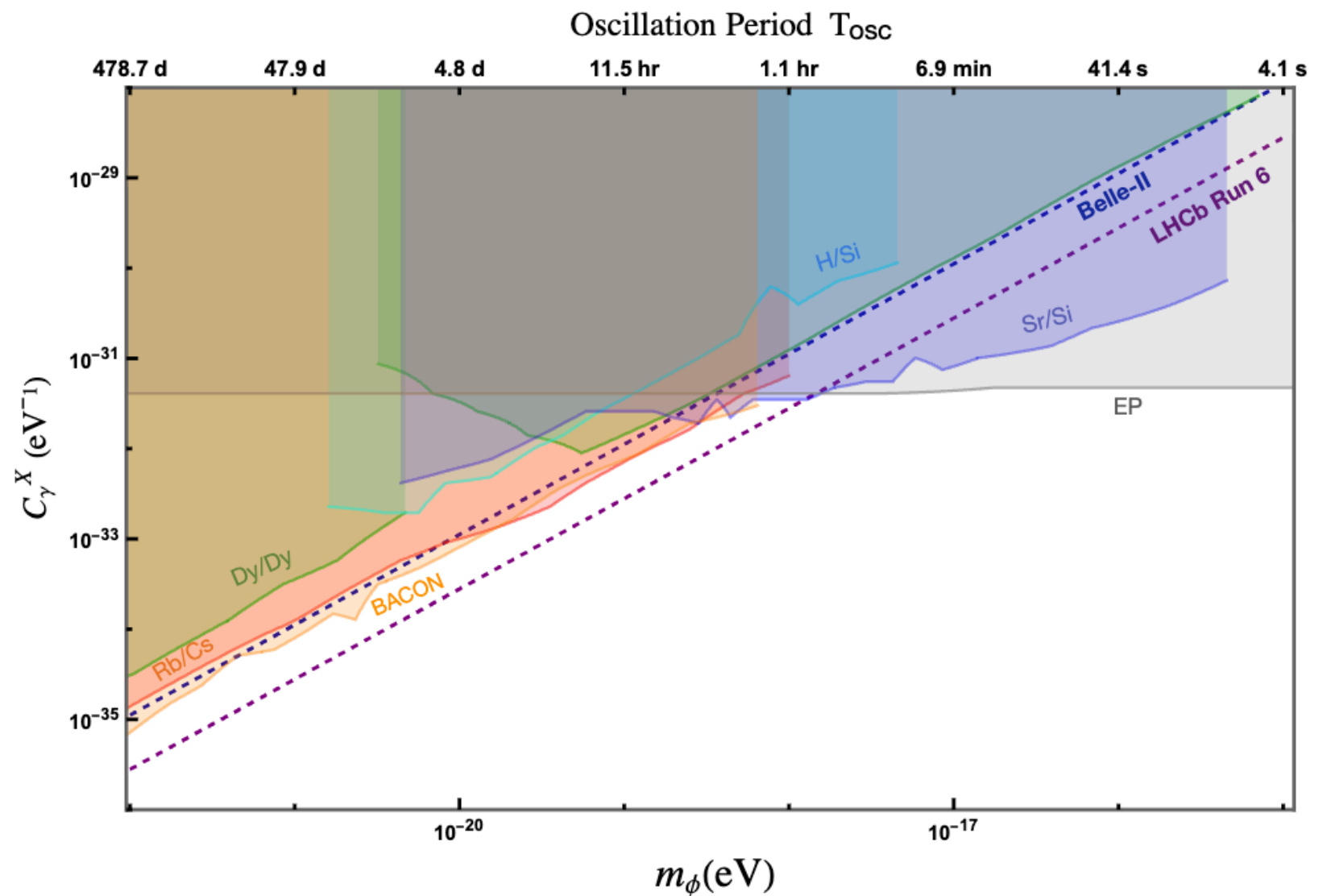
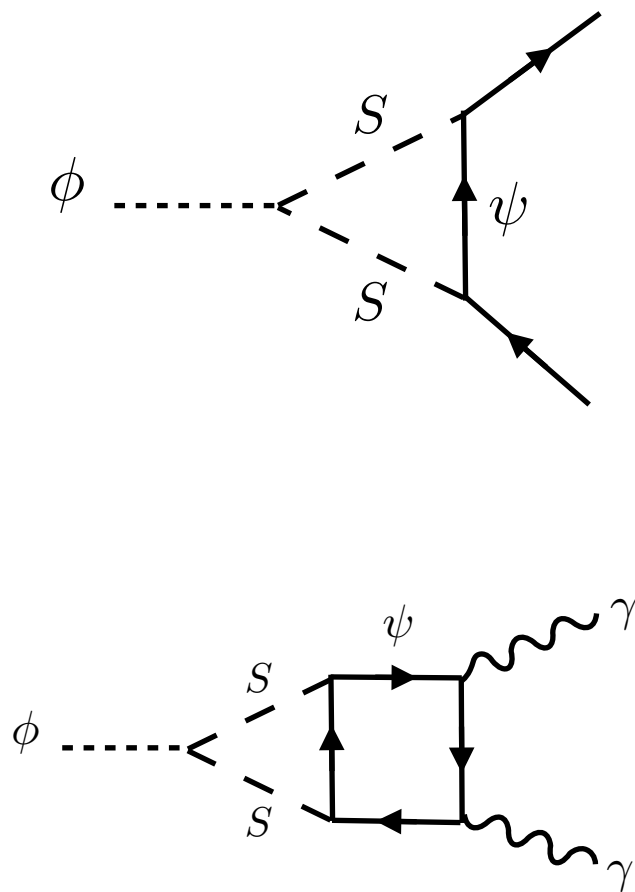


Time-binned data allows to reproduce the peak fully (in principle)



Oscillating Resonances

Quantum sensors are very sensitive to oscillating fundamental constants, but depending on the UV completion, colliders can compete



ALP phenomenology

Quadratic couplings can induce effective mass terms

$$\mathcal{L} \ni a^2 \left(-\frac{1}{2} m_a^2 + \frac{C_N}{f^2} \bar{N} N \right) \quad \Rightarrow \quad (\partial_t^2 - \Delta + \bar{m}_a^2(r)) a = J_{\text{source}}(r)$$

with

$$\bar{m}_a^2(r) = m_a^2 + \sum_i \frac{Q_i^{\text{source}} \delta_i}{f^2} \rho_{\text{source}}(r)$$

Close to a source (e.g. earth), the profile of the field changes



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

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

ALP phenomenology

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 Z is negative

$$c_{GG} \neq 0 \quad \Rightarrow \quad \sum_i Q_i^{\text{source}} \delta_i < 0 \qquad Z(\delta_i) = \frac{1}{4\pi f^2} \frac{M_{\text{source}}}{R_{\text{source}}} \sum_i Q_i^{\text{source}} \delta_i$$

Couplings are dictated by pion mixing

$$\delta_\pi = -2c_{GG}^2 \frac{m_u m_d}{(m_u + m_d)^2} \qquad \delta_N = -4c_1 \frac{m_\pi^2}{M_N} \delta_\pi$$

“Charges” are positive

$$Q_{\hat{m}} = \left[9.3 - \frac{3.6}{A^{1/3}} - 2 \frac{(A-2Z)^2}{A^2} - 0.014 \frac{Z(Z-1)}{A^{4/3}} \right] \times 10^{-2},$$

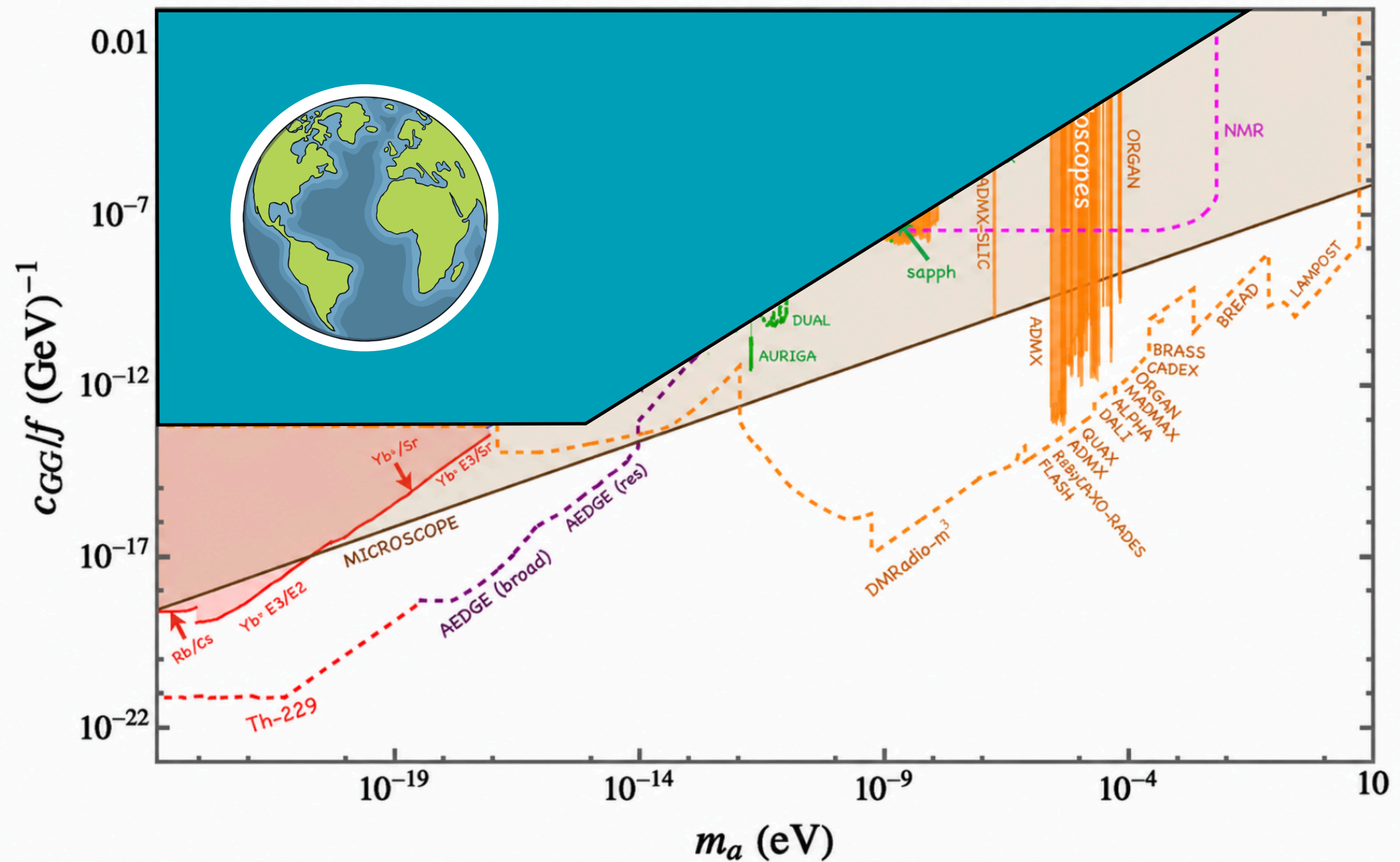
ALP phenomenology

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.

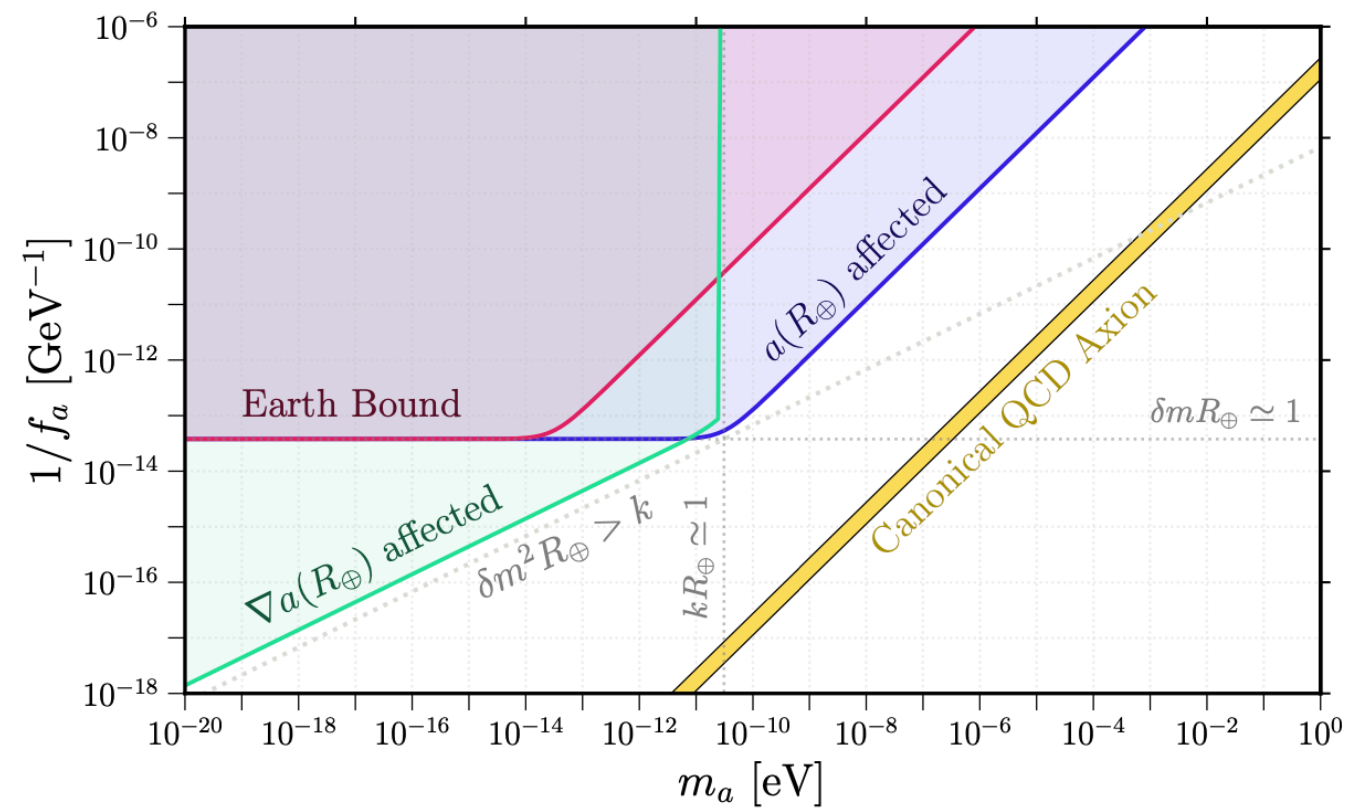
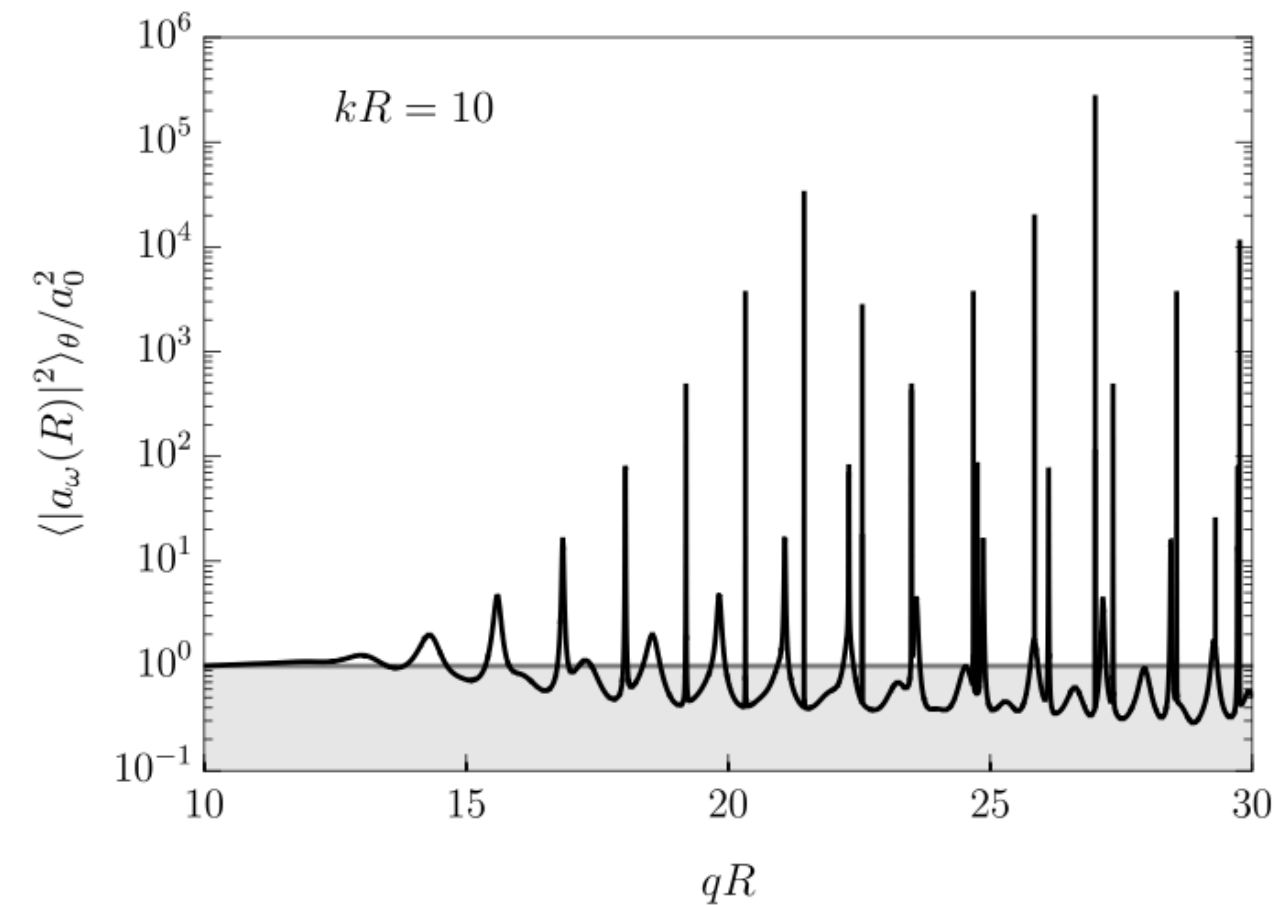
ALP phenomenology



ALP phenomenology

A solution for $\beta \neq 0$

$$a(\vec{x}, t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_a} \cos(m_a(t + \vec{\beta} \cdot \vec{x}))$$



Conclusions

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

Instead of scattering or annihilation, look for oscillating fundamental constants.

Quantum sensors are excellent probes. Colliders can probe the UV completion using time-stamped data

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

Backup

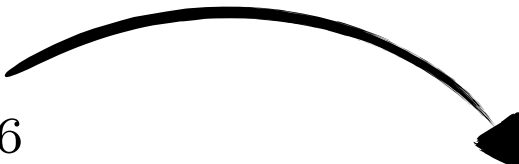
Misalignment Mechanism

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

EL-equations:

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

appr. flat
 $|g| = a(t)^6$



yields:

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