

AstroParticle Symposium

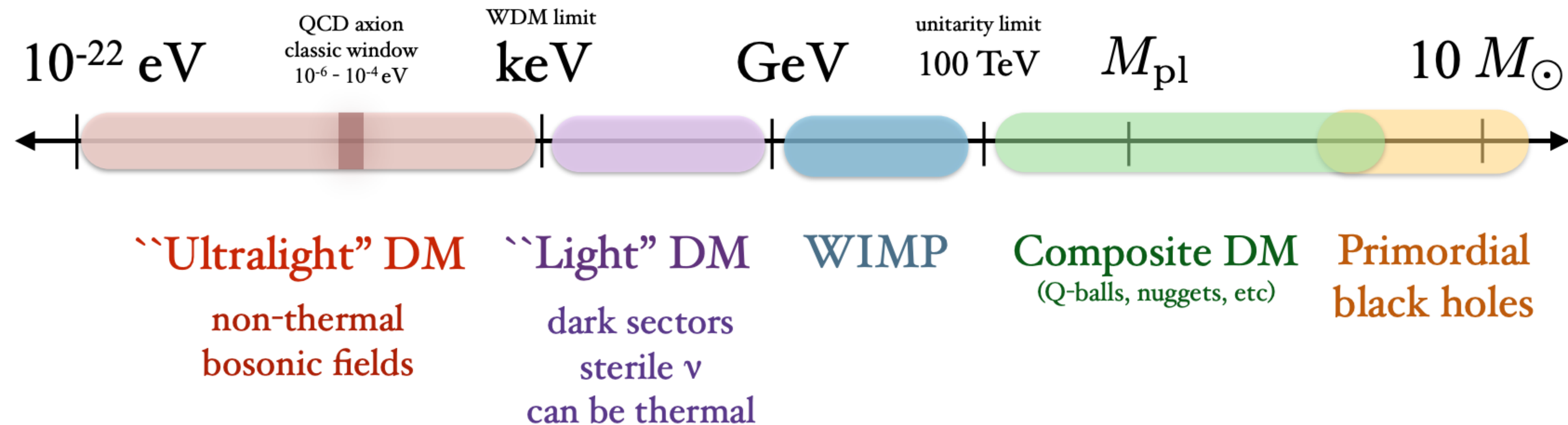
Université Paris-Saclay

Quantum Sensors in the Search for Ultralight Axion-like Dark Matter

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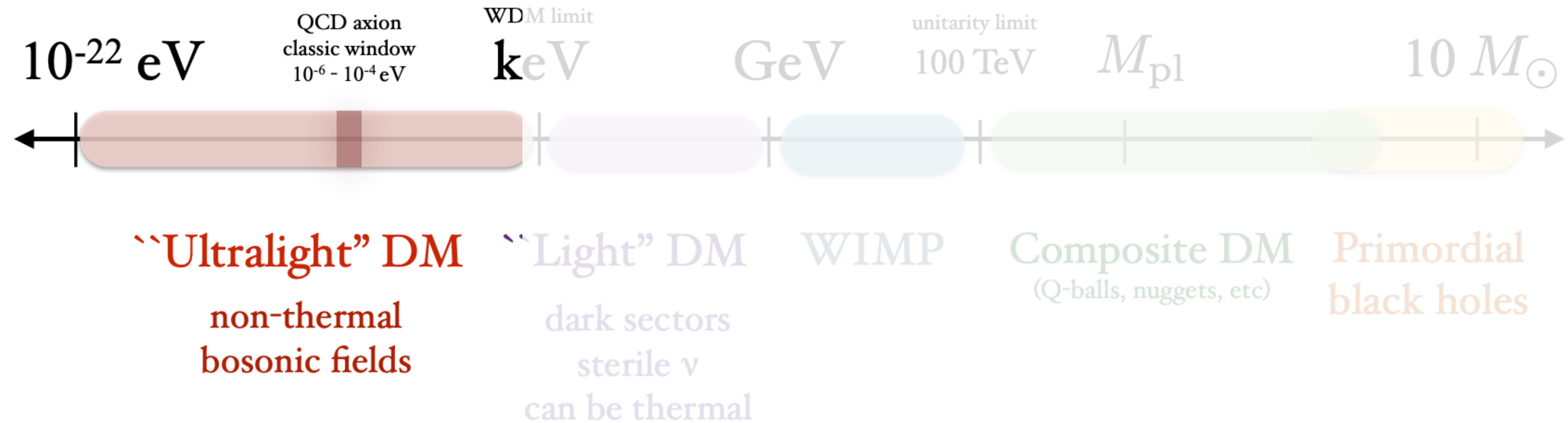


Dark matter on the mass scale



Slide courtesy : James Beacham, Snowmass 2019

Dark matter on the mass scale



Wave-like dark matter

fixed by the halo size, $\lambda \sim \mathcal{O}(\text{kpc})$

classical prescription,
 $n_\phi (\lambda_{\text{coh}}/2\pi)^3 \gg 1$

- Spin-0 dark matter in the mass range $\approx 10^{-22} \text{ eV} \lesssim m_\phi \lesssim 1 \text{ eV}$
- When light bosons make up most of dark matter, their number density in galactic halos is high, giving the field a large occupation number — effectively behaving like a classical “wave-like” field.

$$\phi(\vec{x}, t) \approx \underbrace{\frac{\sqrt{2\rho_{\text{DM,local}}}}{m_\phi}}_{\phi_0} \cos(m_\phi(t + \vec{\beta} \cdot \vec{x}))$$

$|\vec{\beta}| \approx 10^{-3}$ - dark matter velocity

$\vec{x}$ dependent term amounts to a random phase

We ignore the velocity dispersion term $\propto |\beta|^2$

Ultralight dark matter

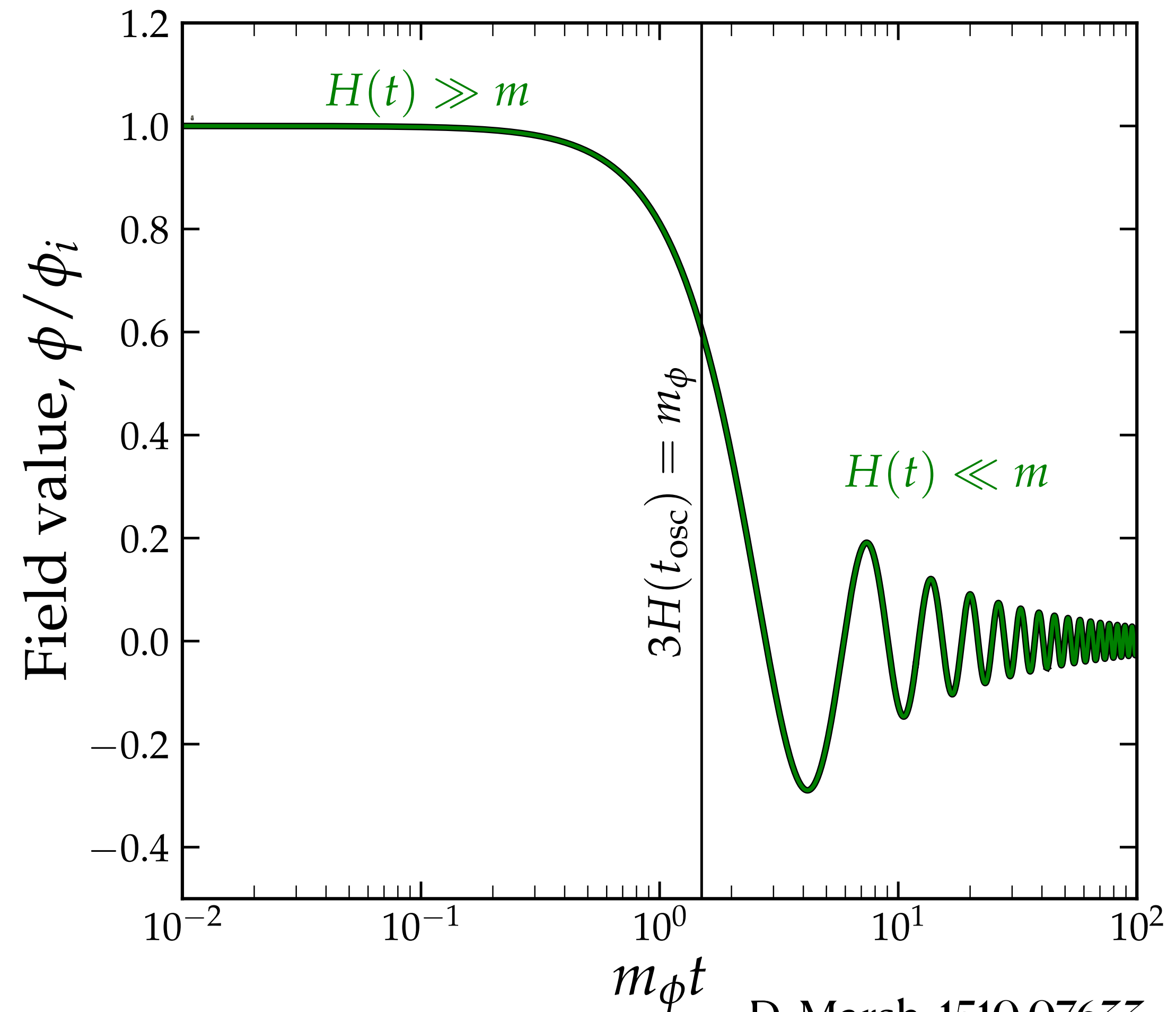
Low-mass bosonic particles form a coherently oscillating classical field described by :

- ✓ Amplitude fixed by dark matter energy density : $\rho_\phi = \frac{1}{2}m_\phi^2\phi_0^2$ ($\rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3$)
- ✓ The angular frequency determined by the rest mass : $\omega \sim m_\phi$
- ✓ Small corrections from the kinetic energy : $\frac{\Delta\omega}{\omega} \sim \frac{\langle v_\phi^2 \rangle}{c^2} \sim 10^{-6}$
- ✓ Coherence time is set by the frequency spread : $\tau_{\text{coh}} \sim \frac{2\pi}{\Delta\omega} \sim 10^6 T_{\text{osc}}$

ULDM genesis

- In the early universe, a generic classical field evolves as $\ddot{\phi} + 3H(t)\dot{\phi} + m_\phi^2\phi = 0$.
- When $3H > m_\phi$, the system behaves like an overdamped oscillator - the field remains static.
- Oscillations start when $3H \sim m_\phi$ and the field slowly starts rolling towards its potential minimum.
- As the Universe expands, $H \ll m_\phi$ and the field oscillates and its energy density scales as $\rho \propto a^{-3}$, like cold DM.

Misalignment mechanism



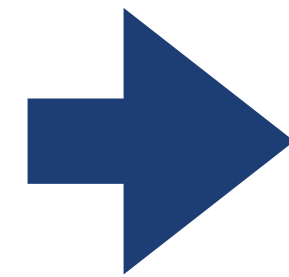
D. Marsh, 1510.07633

C. O'Hare, 2403.17697

ALPs interactions at different scales

M. Bauer, SC and G. Rostagni, JHEP 05 (2025) 023

✓ ALPs at the UV scale

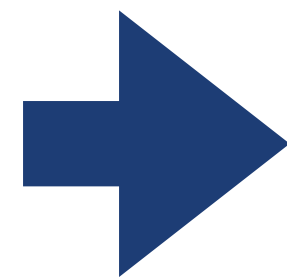


$$\mathcal{L}_{\text{eff}}^{D \leq 5}(\mu > \Lambda_{\text{QCD}}) \ni \frac{\partial^\mu a}{2f} c_{uu} \bar{u} \gamma_\mu \gamma_5 u + \frac{\partial^\mu a}{2f} c_{dd} \bar{d} \gamma_\mu \gamma_5 d + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \dots$$

✓ RG running

✓ Threshold matching

✓ Chiral Lagrangian



$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{4} \text{tr}[\Sigma m_q(a)^+ + m_q(a) \Sigma^+]$$

$$\Sigma = \exp(i\sqrt{2}\Pi/f_\pi)$$

Quark mass matrix is
ALP-field dependent !!

$$m_q(a) = e^{-i\kappa_q \frac{a}{f} c_{GG}} m_q e^{-i\kappa_q \frac{a}{f} c_{GG}}$$

ALP quadratic interactions

$$m_q(a) = e^{-i\kappa_q \frac{a}{f} c_{GG}} m_q e^{-i\kappa_q \frac{a}{f} c_{GG}} \rightarrow m_\pi^2(a) \propto \text{Tr}[m_q(a)] \approx \text{Tr}[m_q] - \frac{a^2}{2f^2} \text{Tr}[\{\kappa_q^2, m_q\}]$$

✓ **Pion mass** $\rightarrow m_{\pi,\text{eff}}^2(a) = m_\pi^2(1 + \delta_\pi(a)) \rightarrow \delta_\pi(a) = -\frac{c_{GG}^2}{2} \frac{a^2}{f^2} \left(1 - \frac{\Delta_m^2}{\hat{m}^2}\right) + \mathcal{O}(\tau_a^2)$

$\hat{m} = (m_u + m_d)/2, \Delta_m = (m_u - m_d)/2, \tau_a = m_a^2/m_\pi^2$

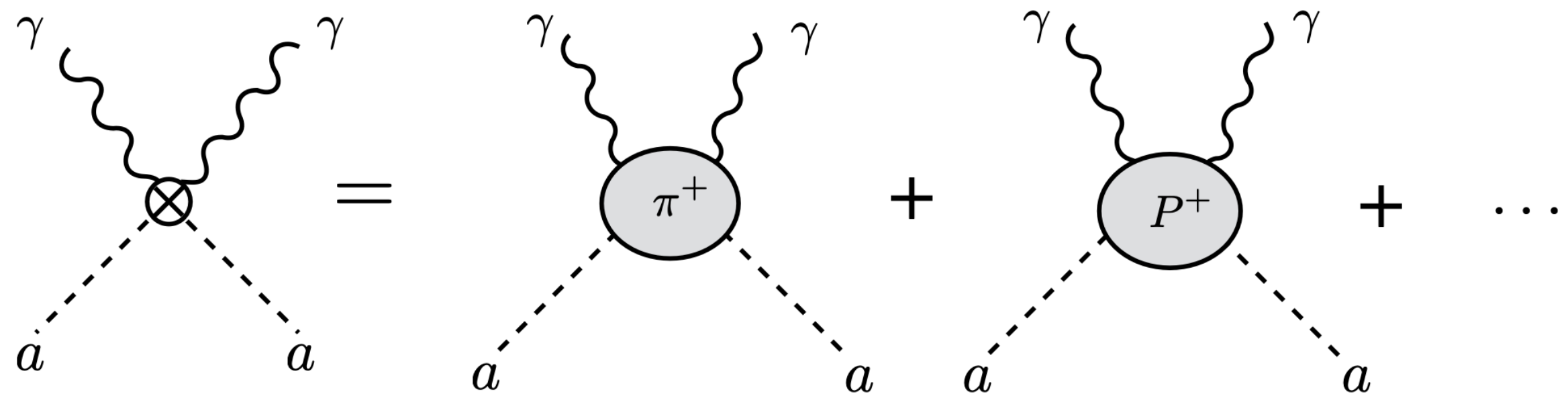
✓ **Nucleon mass** $\rightarrow \mathcal{L}_{\chi\text{PT}}^{(2)} = c_1 \text{tr}[\chi_+] \bar{N}N + \dots \rightarrow \mathcal{L} \ni 4c_1 m_\pi^2 \delta_\pi(a) \bar{N}N + \dots$

$c_1 = -1.26 \text{ GeV}^{-2}$ (Alarcon *et.al*, 1210.4450)

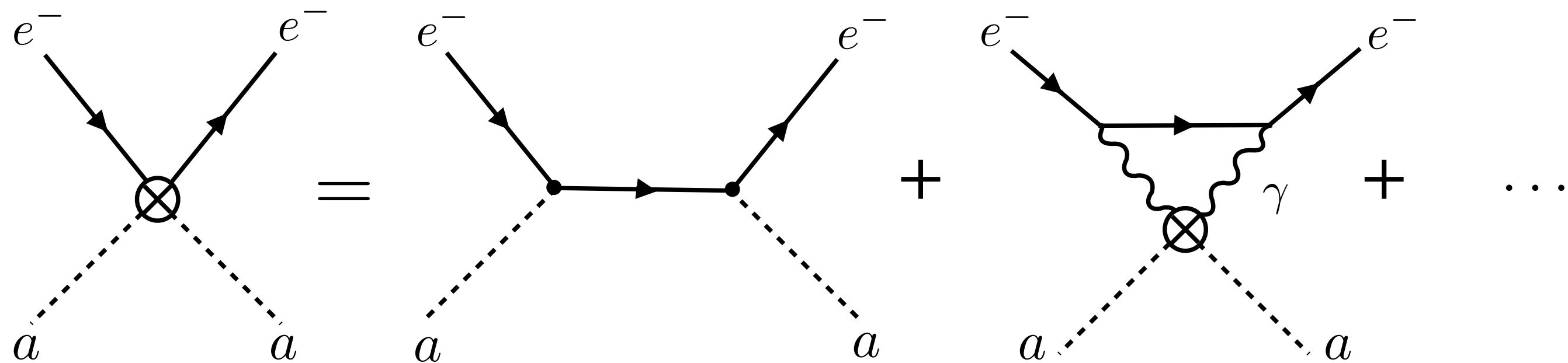
$$\mathcal{L}_{\text{eff}}^{D=6}(\mu \lesssim \Lambda_{\text{QCD}}) = \bar{N} \left(C_N(\mu) \mathbb{1} + C_\delta(\mu) \tau \right) N \frac{a^2}{f^2} + C_E(\mu) \frac{a^2}{f^2} \bar{e}e + C_\gamma(\mu) \frac{a^2}{4f^2} F_{\mu\nu} F^{\mu\nu}$$

At quadratic order in f , ALPs have scalar interactions described by the dim-6 operators

Quadratic interactions



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



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

Shifts in fundamental constants

In the oscillating dark matter background, the low-energy quadratic lagrangian induces a time-dependent component in the following fundamental constants :

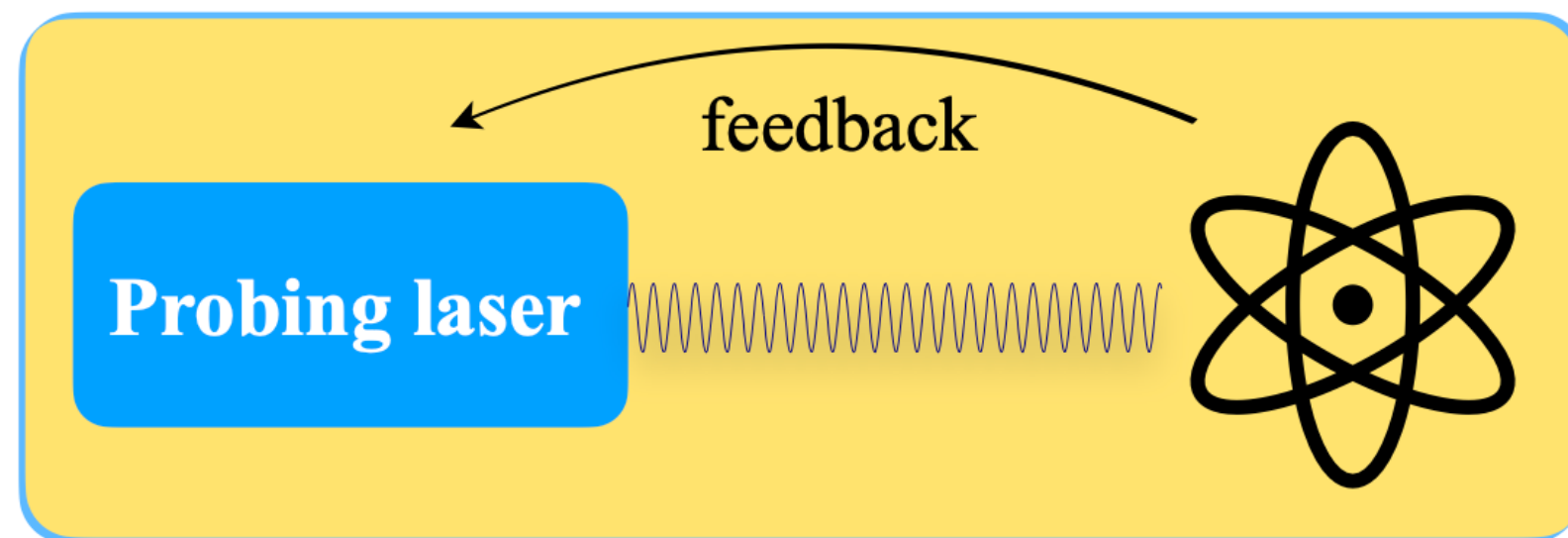
$$\checkmark \alpha^{\text{eff}}(a) = \left(1 + \delta_\alpha(a)\right) \alpha \quad \text{with} \quad \delta_\alpha(a) = \frac{1}{12\pi} \left(1 - 32c_1 \frac{m_\pi^2}{M_N}\right) \delta_\pi(a)$$

$$\checkmark m_e^{\text{eff}}(a) = m_e \left(1 + \delta_e(a)\right) \quad \text{with} \quad \delta_e(a) = \frac{3\alpha}{4\pi} C_\gamma \frac{a^2}{f^2} \ln \frac{m_\pi^2}{m_e^2}$$

$$\checkmark M_N(a) = M_N \left(1 + \delta_N(a)\right) \quad \text{with} \quad \delta_N(a) = -4c_1 \frac{m_\pi^2}{M_N} \delta_\pi(a)$$

Atomic Clocks

Basic components

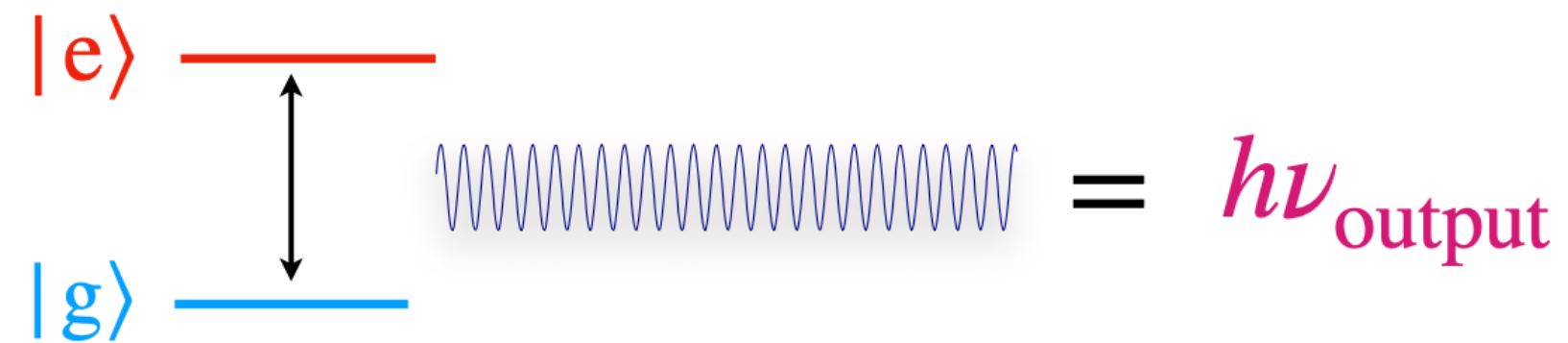


***Cannot measure absolute energies**

$$r_{\text{observable}} = \frac{\nu_1}{\nu_2}$$

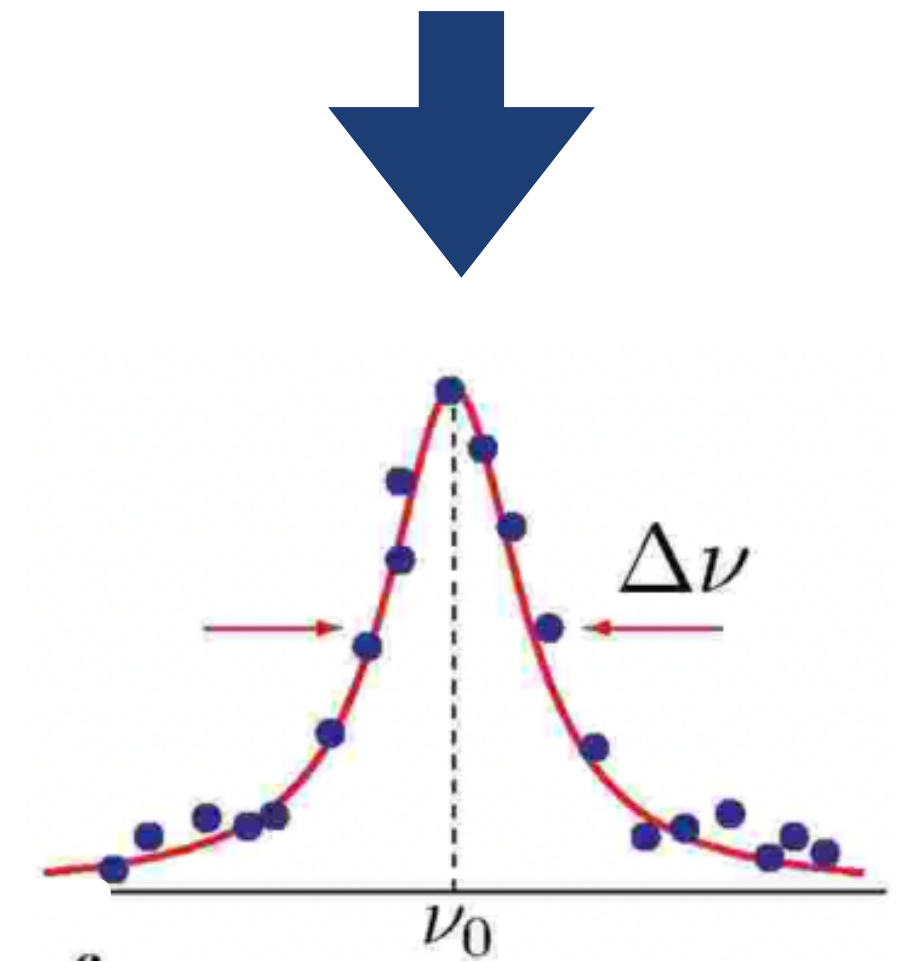
**Different transitions of same system
or distinct systems**

Clock transition



Measured* radiation

laser/microwave is
tuned in resonance
with the transition



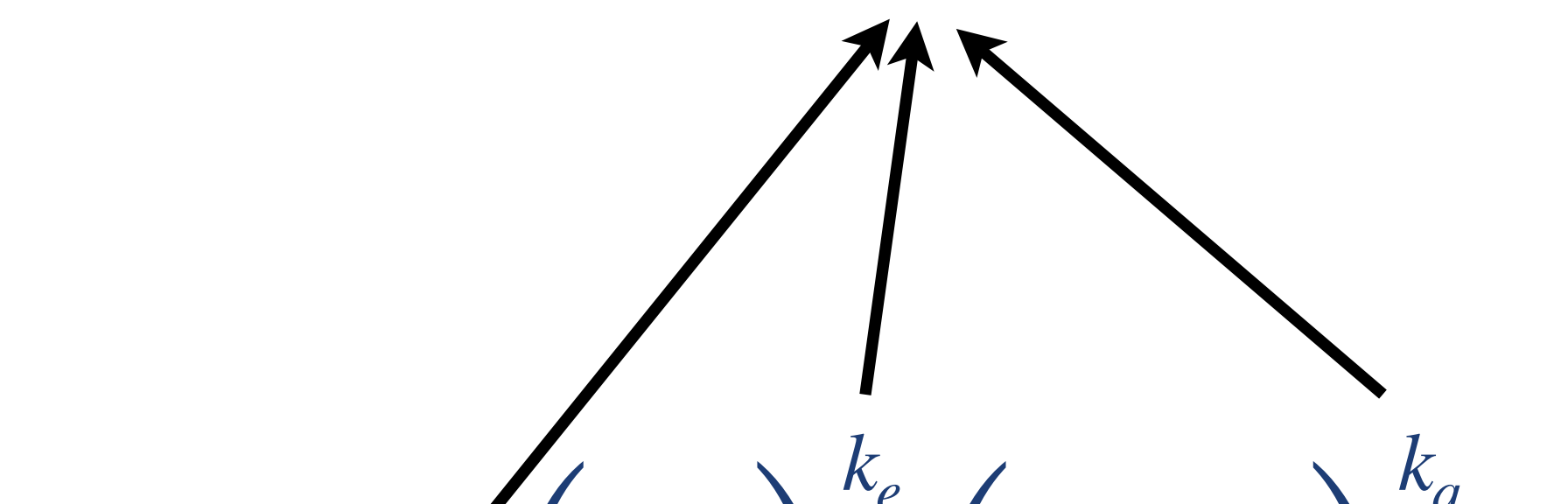
Hyperfine frequencies : $\nu \propto \alpha^4 m_e^2 / m_p F_{\text{MW}}(\alpha)$

Optical frequencies : $\nu \propto \alpha^2 m_e F_o(\alpha)$

A generic clock prescription

- ✓ The frequency ratio of atomic transitions in two different atomic clocks A and B is parametrised as:

Difference in the sensitivity coefficients


$$\nu_{A/B} \propto \alpha^{k_\alpha} \left(\frac{m_e}{m_p} \right)^{k_e} \left(\frac{m_q}{\Lambda_{\text{QCD}}} \right)^{k_q}$$

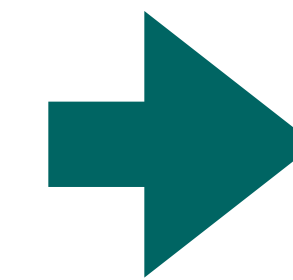
- ✓ To obtain a signal in the clock comparison, the sensitivity coefficients of the two systems must be different.

Clock-ULDM connection

$$\begin{aligned}\frac{\delta\nu_{A/B}}{\nu_{A/B}} &= k_\alpha \frac{\delta\alpha}{\alpha} + k_e \left(\frac{\delta m_e}{m_e} - \frac{\delta m_p}{m_p} \right) + k_q \left(\frac{\delta m_q}{m_q} - \frac{\delta\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}} \right) \\ &\approx k_\alpha \delta_\alpha(a) + k_e \delta_e(a) - (k_e + 2k_q) \delta_p(a) + k_q \delta_\pi(a)\end{aligned}$$

In the oscillating ALP dark matter background,

$$\frac{\delta\nu_{A/B}}{\nu_{A/B}} \propto a^2 = \frac{2\rho_{\text{DM}}}{m_a^2} \cos^2 m_a t = \frac{\rho_{\text{DM}}}{m_a^2} (1 + \cos 2m_a t)$$



Signal is obtained when
clock frequency $\omega \simeq 2m_a$

Microwave clocks

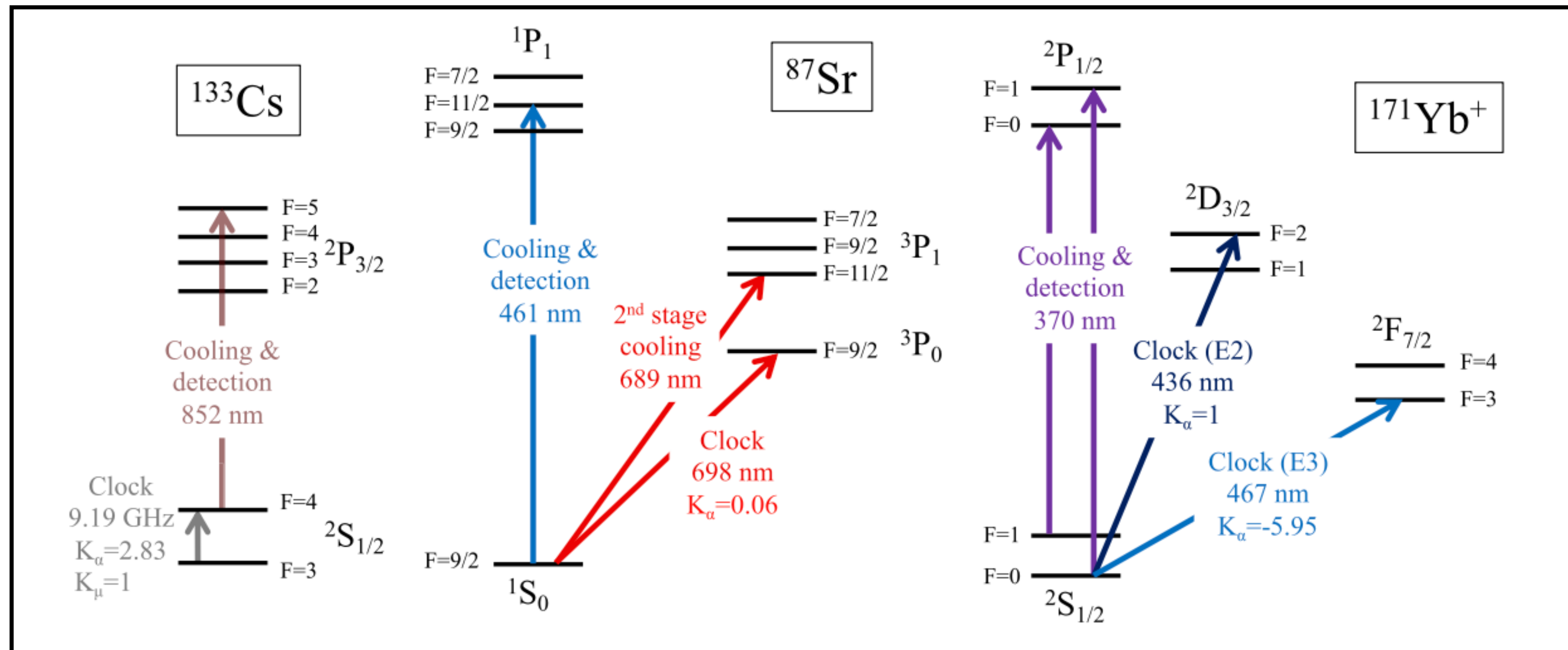
~ GHz frequencies.
Longer integration time.
Fractional uncertainty $\sim 10^{-15}$
Rb/Cs

$$\text{clock stability} \propto \nu_0 / \Delta\nu$$

narrow linewidth gives higher stability

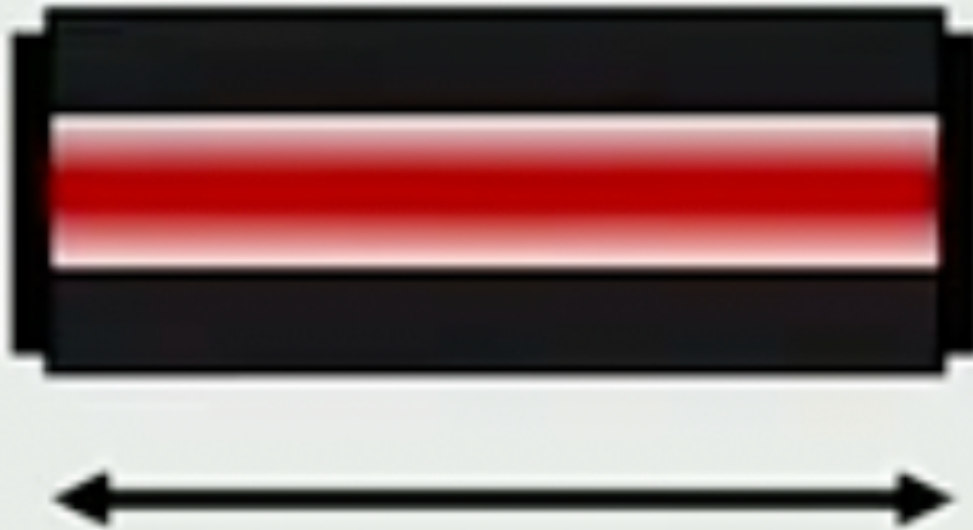
Optical clocks

~ THz frequencies.
Fractional uncertainty $\sim 10^{-17}$
Yb, Al, Hg, Sr ion clocks



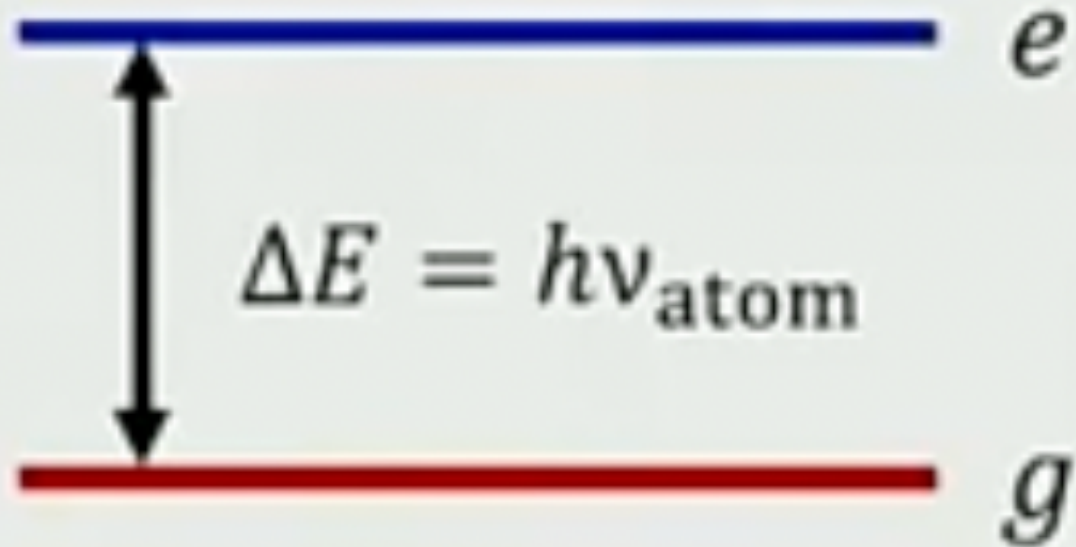
Clock-cavity comparison

Solid material



$L_{\text{solid}} \propto a_B = 1/(m_e \alpha)$
 $\Rightarrow \nu_{\text{solid}} \propto 1/L_{\text{solid}} \propto m_e \alpha$

cf.



$\nu_{\text{atom}} \propto Ry \propto m_e \alpha^2$

courtesy : Y. Stadnik

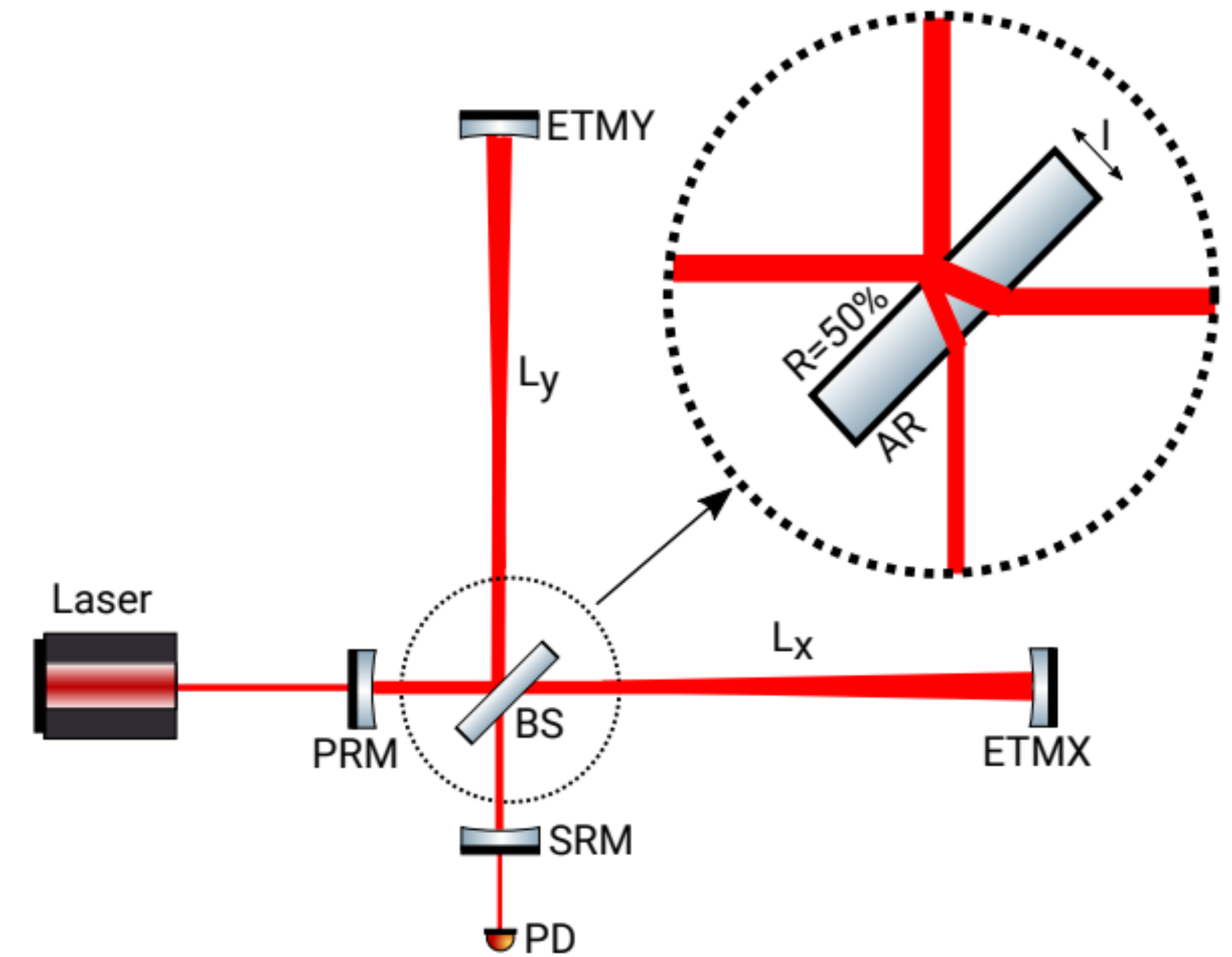
$$\frac{\nu_{\text{atom}}}{\nu_{\text{solid}}} \propto \alpha$$

$\text{Sr/Si} : \nu_{\text{Sr}} \propto \alpha^{2.06} m_e$
 $\text{H/Si} : \nu_{\text{H}} \propto \alpha^4 m_e^2$

Optical interferometers

- ✓ A two-arm laser interferometer detects tiny differences in optical path lengths; even with equal arms, geometric asymmetries from the beam splitter can induce phase shifts.
- ✓ If freely suspended, the beam splitter and mirrors can respond to time-varying fundamental constants, causing oscillations in the optical path and generating a detectable signal.

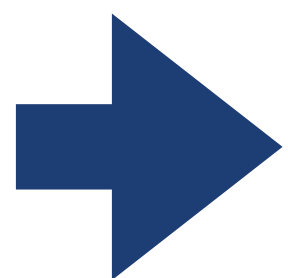
$$\delta(L_x - L_y) = \sqrt{2} \left[\left(n - \frac{1}{2} \right) \delta l + l \delta n \right] \approx n l [\delta_\alpha(a) + \delta_e(a)]$$



H. Grote *et. al*, [arXiv: 1906.06193]

- GEO-600

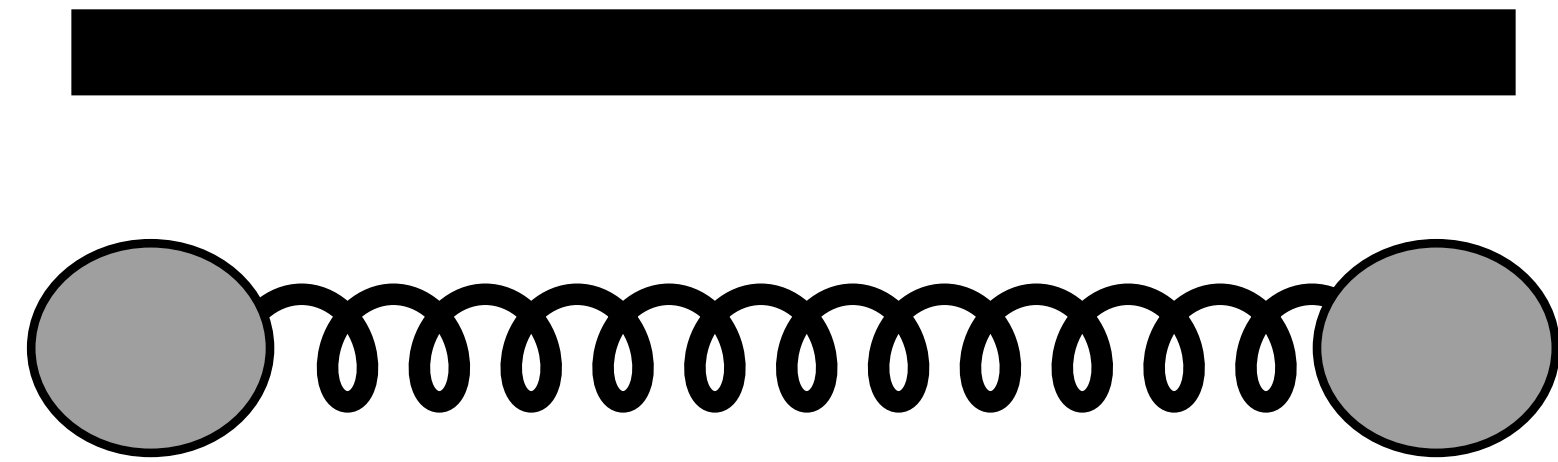
- LIGO



Gravitational wave detectors can be used as laser interferometers

with operating frequency $\sim \mathcal{O}$ (kHz)

Mechanical resonators

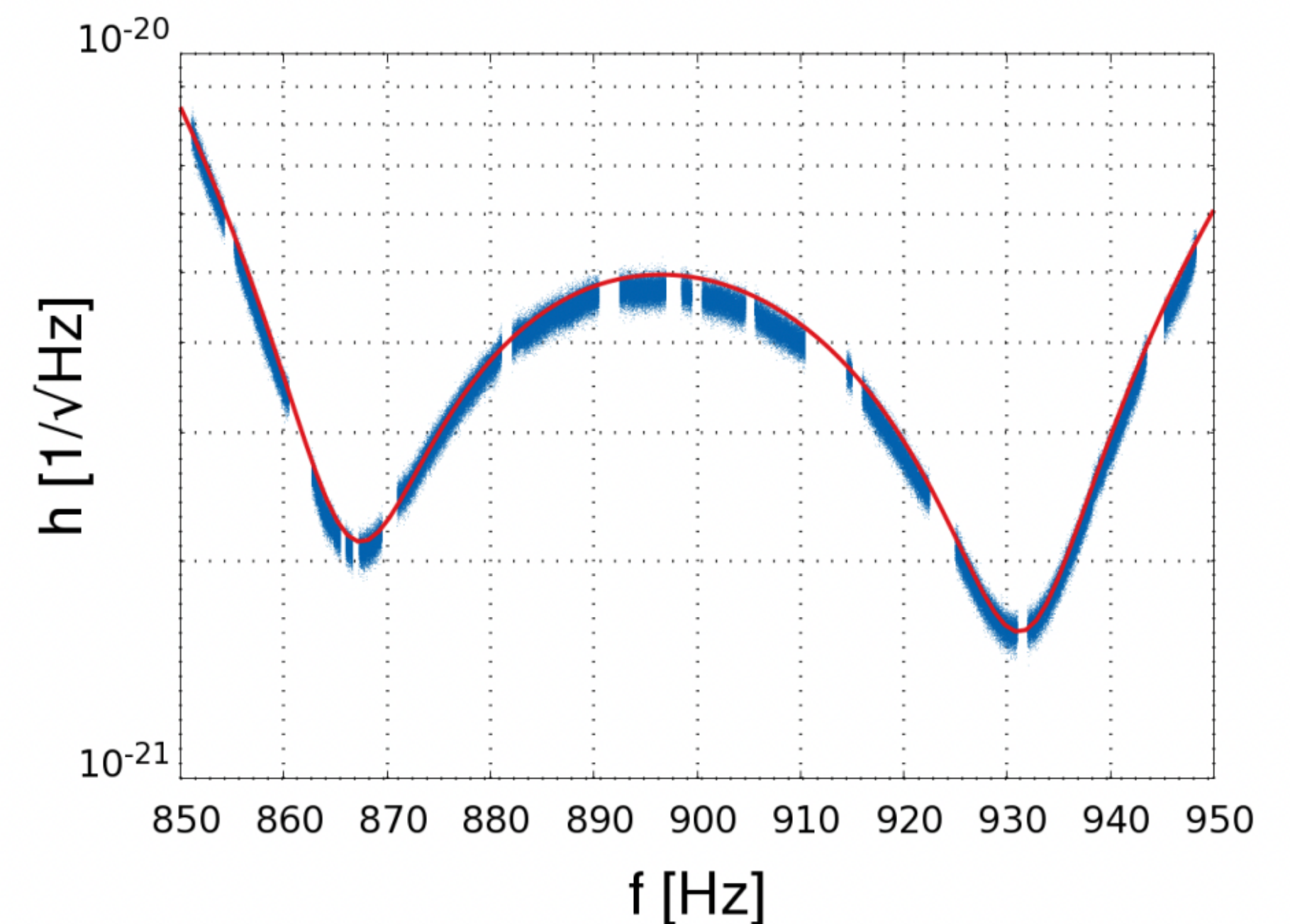
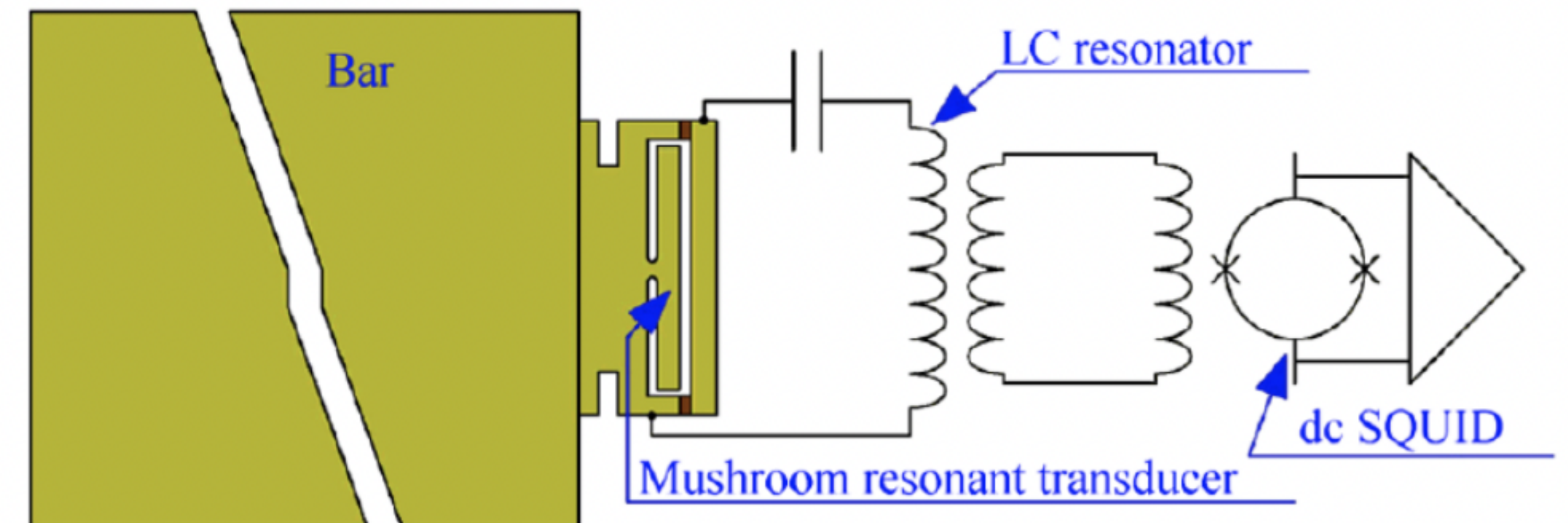


$$h(t) = -(\delta_\alpha(a) + \delta_e(a))$$

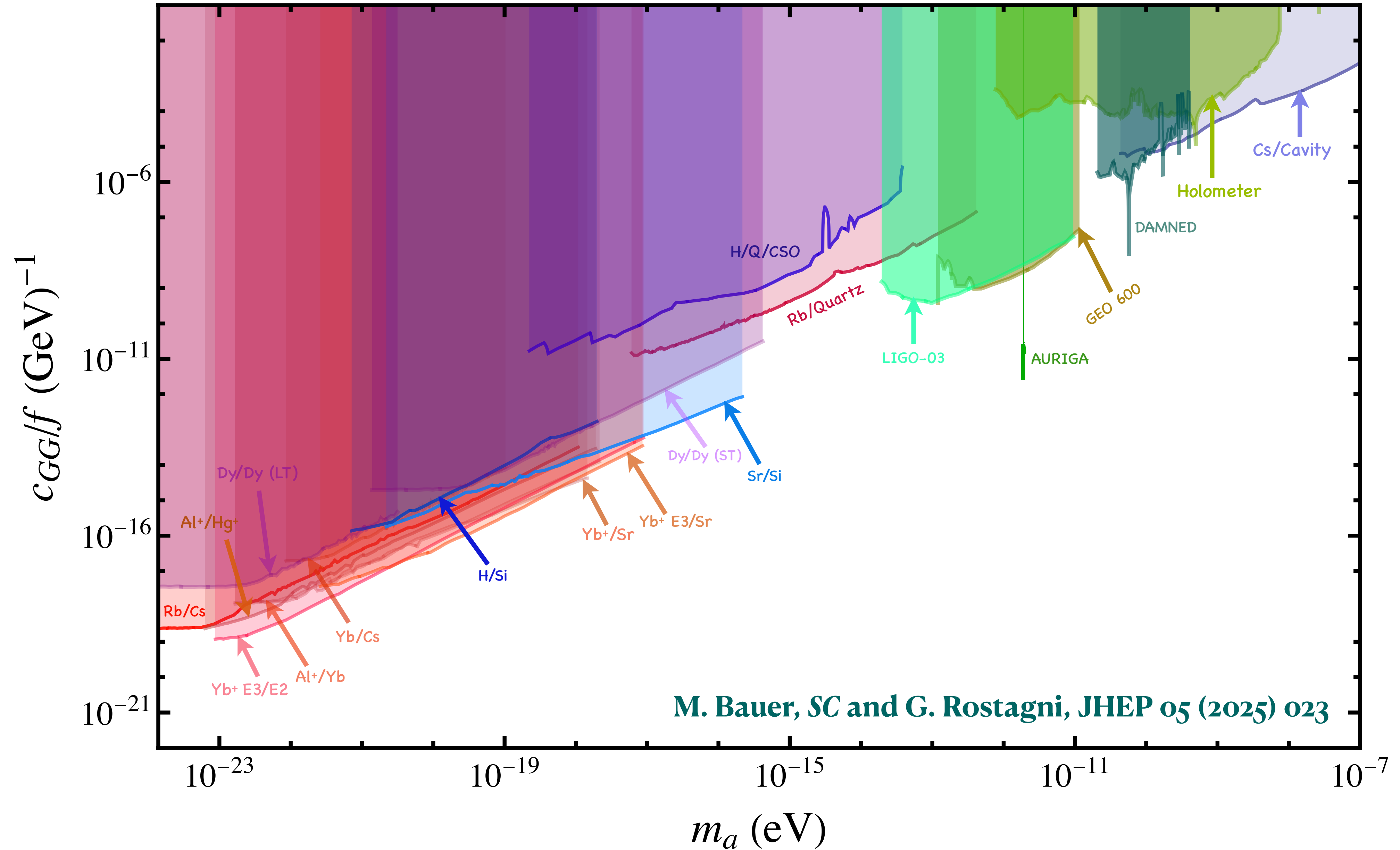
mechanical strain

AURIGA

- ✓ A cryogenic resonant-mass detector of bar length $\sim \mathcal{O}(\text{m})$.
- ✓ Sensitivity over a narrow bandwidth 850-950 Hz, corresponding to ALP mass window 1.88 - 1.94 peV.



Current constraints



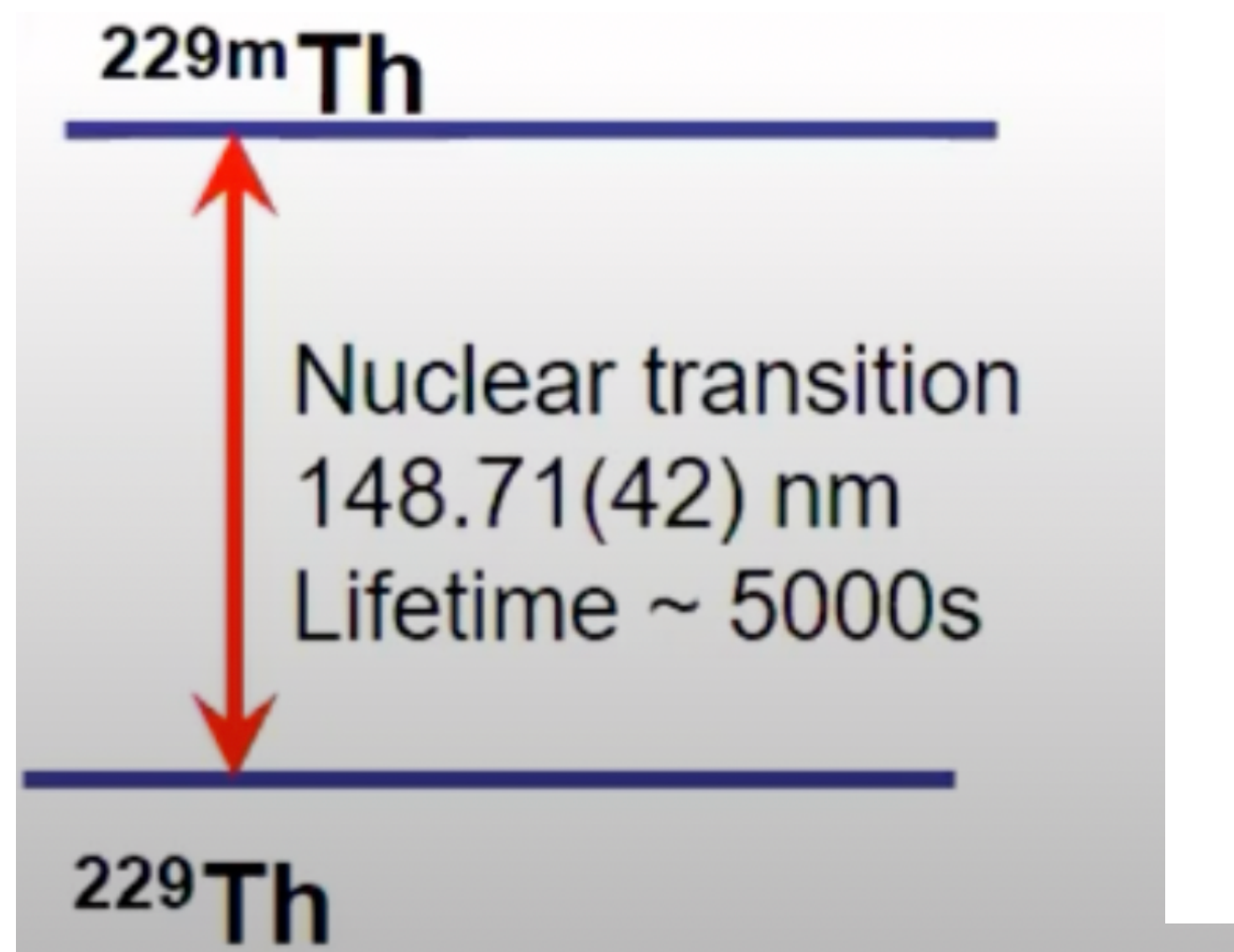
Upcoming facilities

Nuclear clock – ^{229}Th

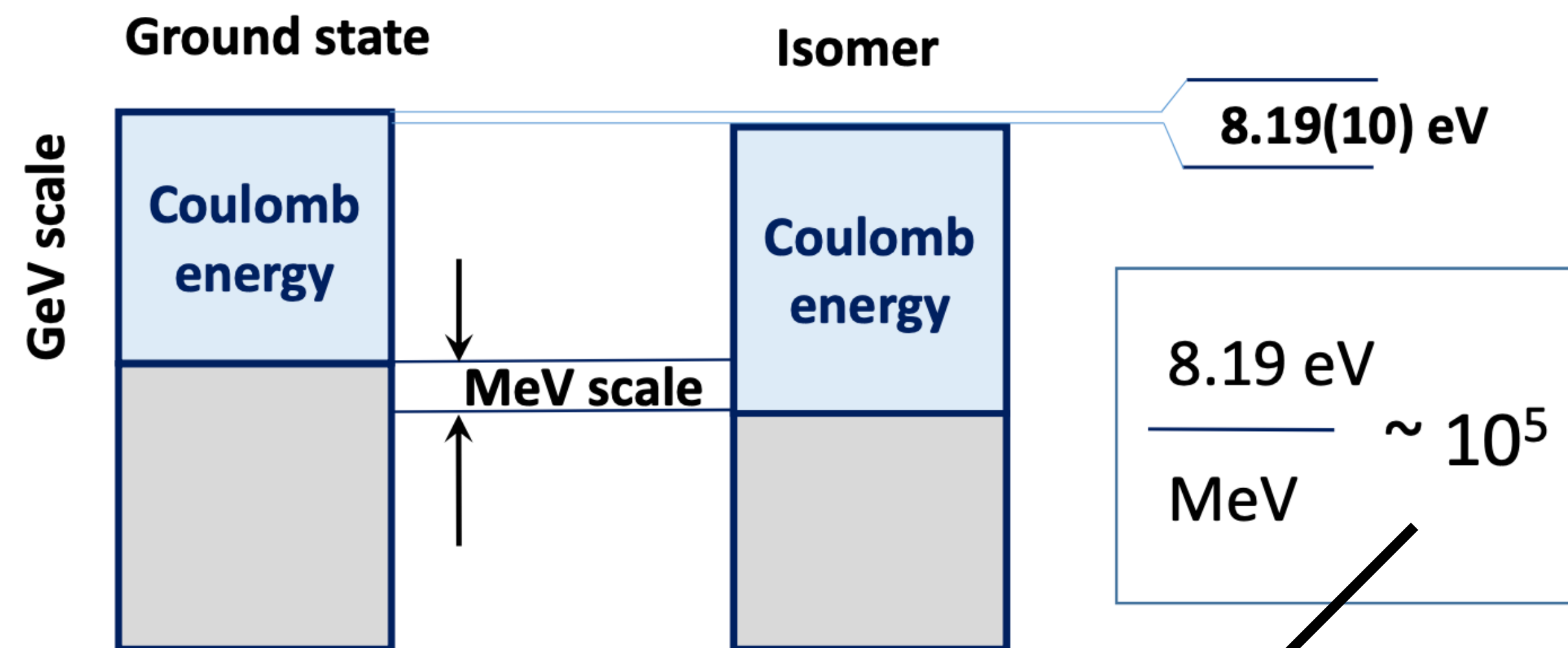
Seiferle et al., Nature 573, 243 (2019)

T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020)

Caputo et. al, arXiv 2407.17526



Nuclear binding energy

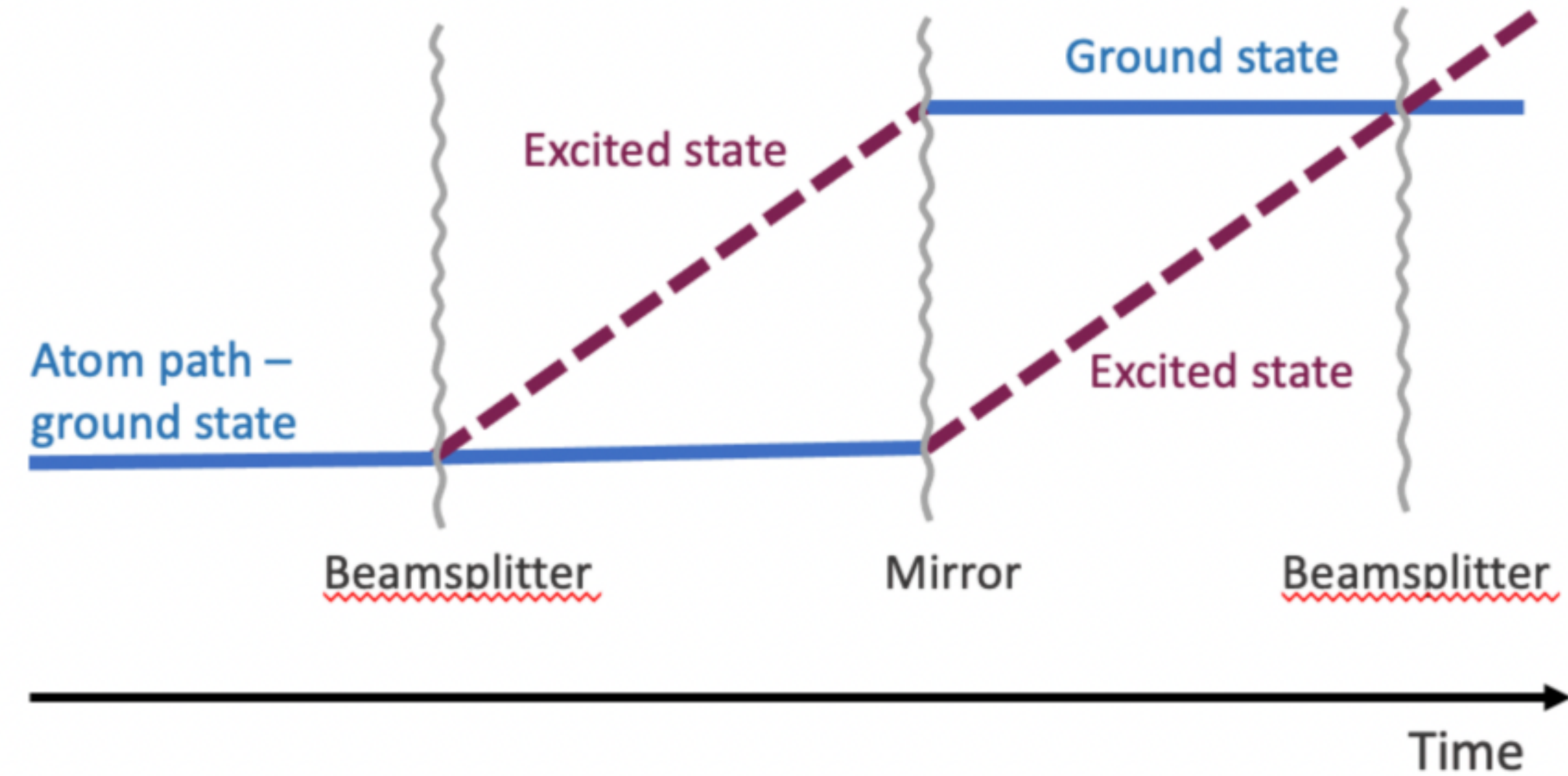


courtesy : M. Safronova

Unprecedented sensitivity – Corresponds to sensitivity coefficients $k_\alpha, k_q \sim \mathcal{O}(10^4 - 10^5)$

Atom interferometers

- ✓ Atomic interferometers detect DM-induced phase shifts by measuring the phase difference between split atomic wave packets, with signals appearing when the atomic transition period matches the interferometer duration.
- ✓ The FC oscillations generate an oscillatory component in the electronic transition frequency, which is $\omega_A \propto m_e \alpha^{2+\xi}$.

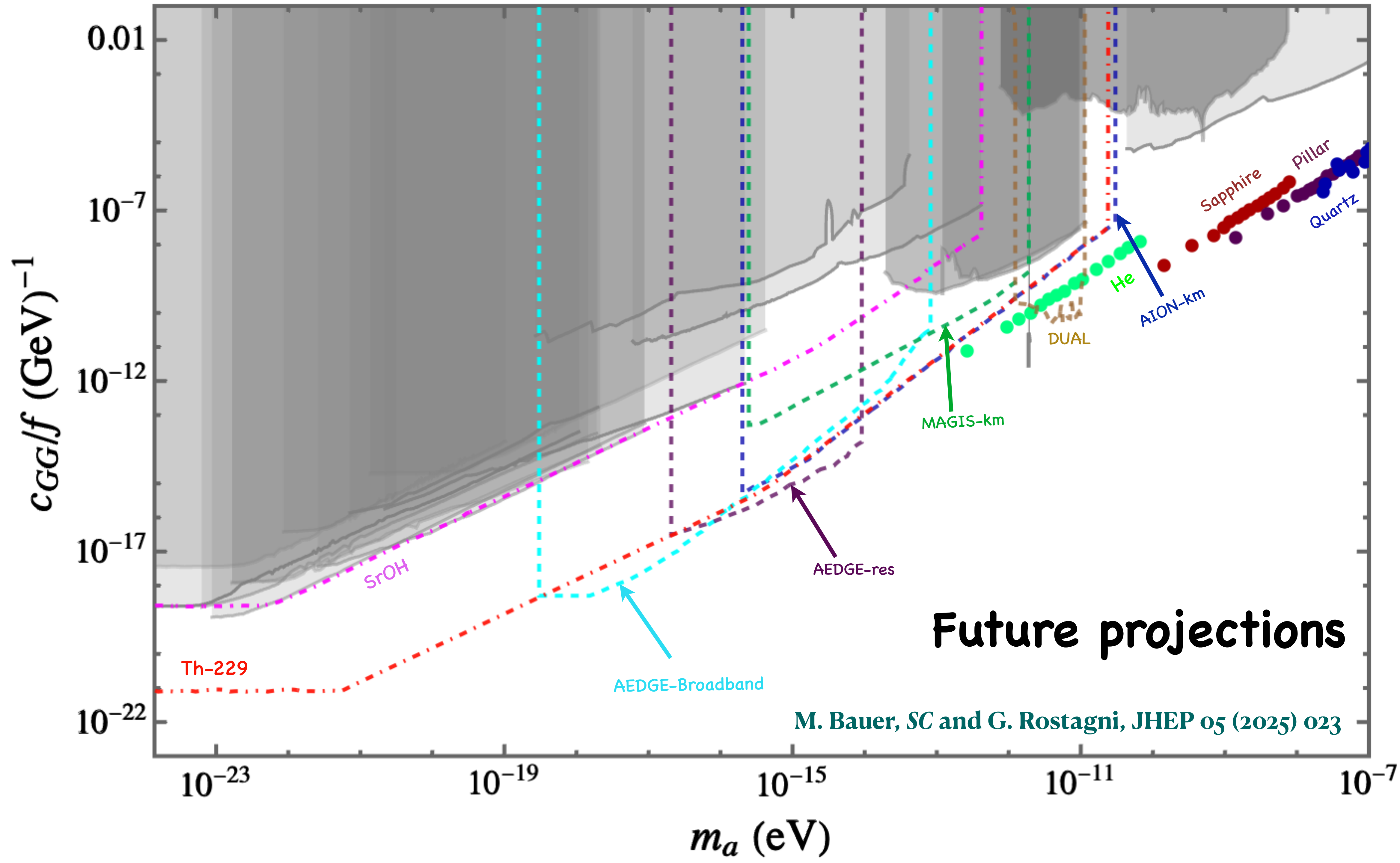


$$\omega_A(t, x) = \omega_A + \delta\omega_A(a) \quad \frac{\delta\omega_A(a)}{\omega_A} = \delta_e(a) + (2 + \xi) \delta_\alpha(a)$$

$$\approx (\delta_e + (2 + \xi)\delta_\alpha) \frac{\rho_{\text{DM}}}{m_a^2 f^2} \cos(2\omega_a t) \equiv \bar{\omega}_A \cos(2\omega_a t)$$

$$\Phi_s = 4 \bar{\omega}_a n \Delta r \sin^2(m_a T)$$

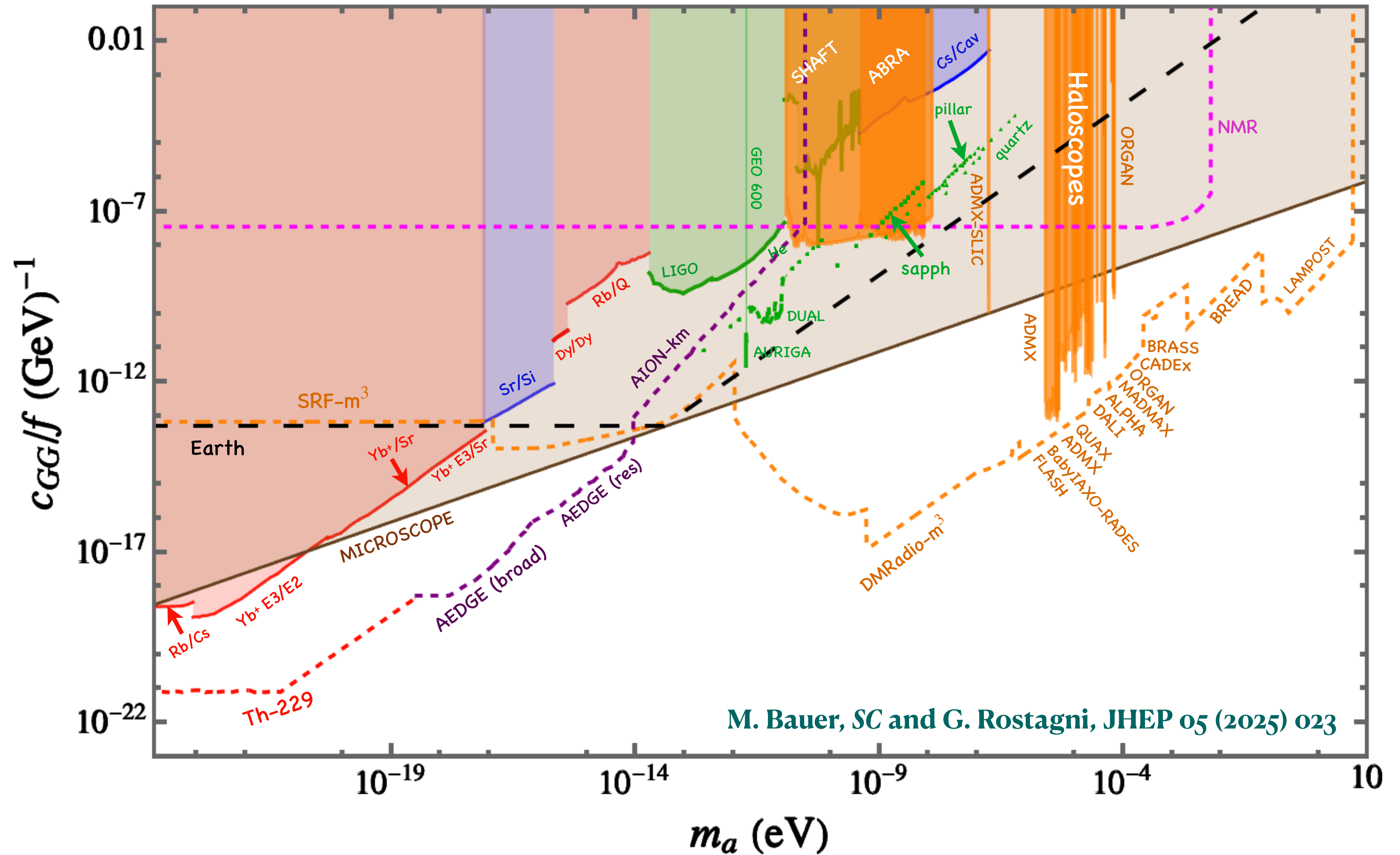
- Longer baseline corresponds to higher sensitivity
- Low frequencies prone to gravity gradient noise



Take home

- ✓ Ultralight axion-like dark matter manifests through quadratic couplings, leading to oscillations of fundamental constants.
- ✓ Quantum sensors — from clocks to interferometers — already probe these effects, with future advances promising substantial gains in sensitivity.

Thank you!!



ALP Linear interactions

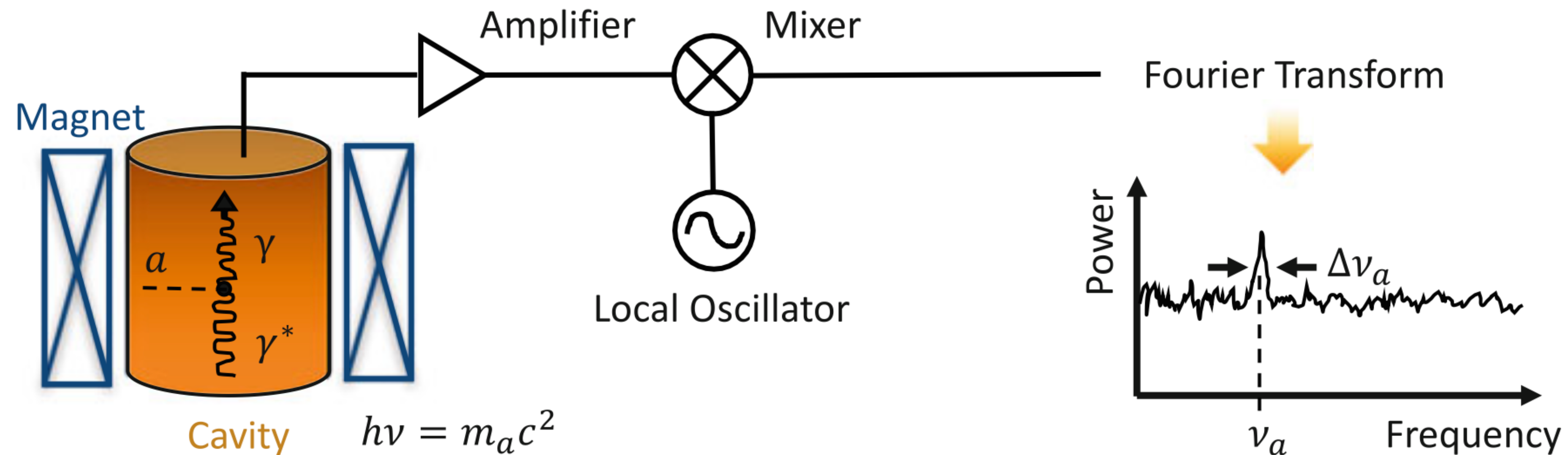
At energy scales below Λ_{QCD} , the relevant ALP couplings to photons, nucleons and electrons are written in the leading order of the expansion of the decay constant f as

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


(p, n)

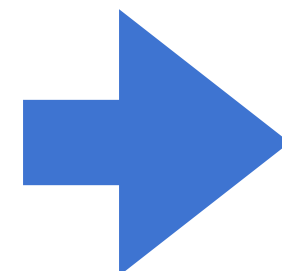
Cavity Haloscopes

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



Kimball *et. al*, The Search for Ultralight Bosonic Dark Matter

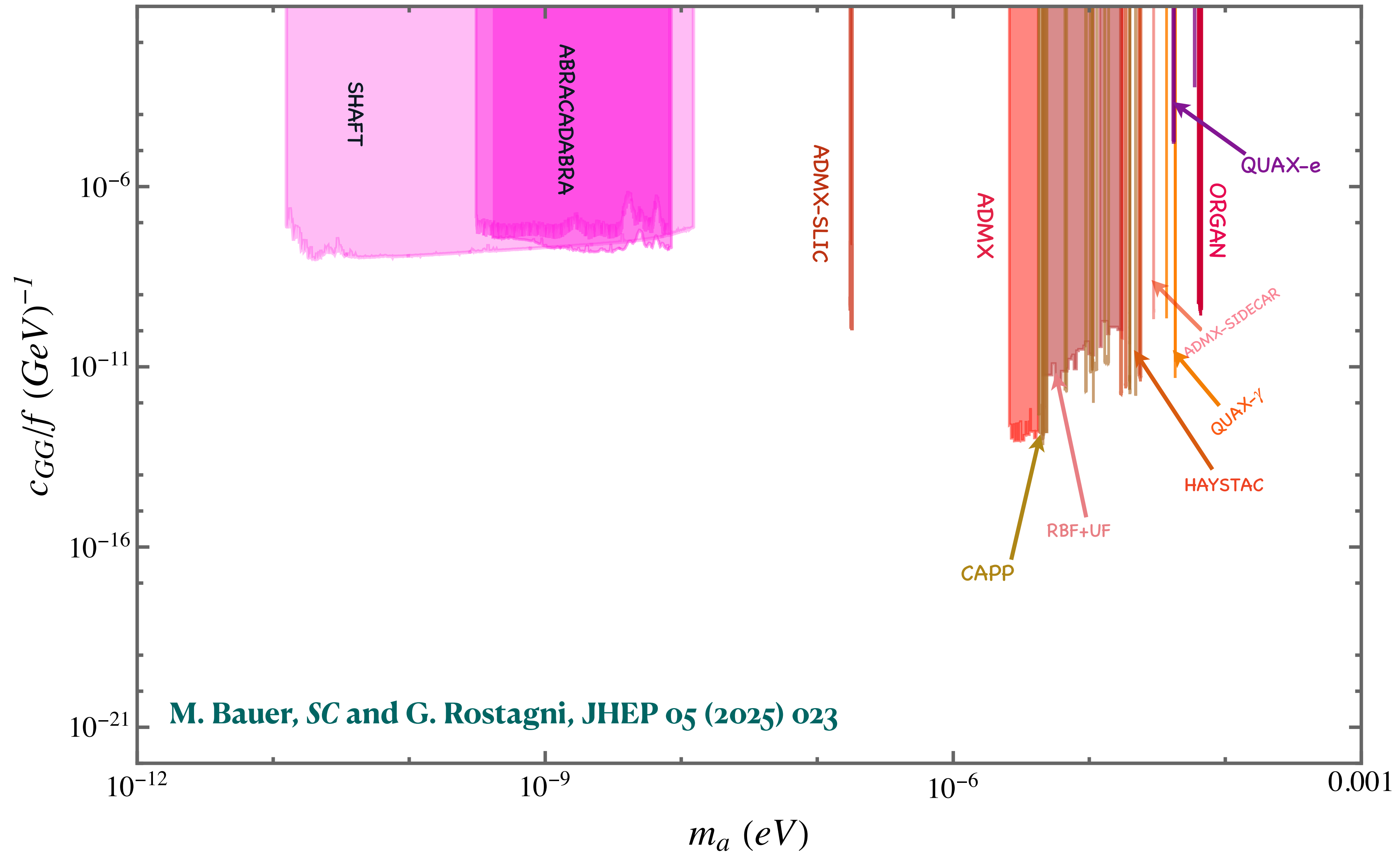
Frequency dependent signal power
extracted on resonance



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

Haloscope reach

$$c_{\gamma\gamma}^{\text{eff}}(\mu_0) = c_{\gamma\gamma}(\Lambda) - 1.92 c_{GG}(\Lambda)$$



Nucleons

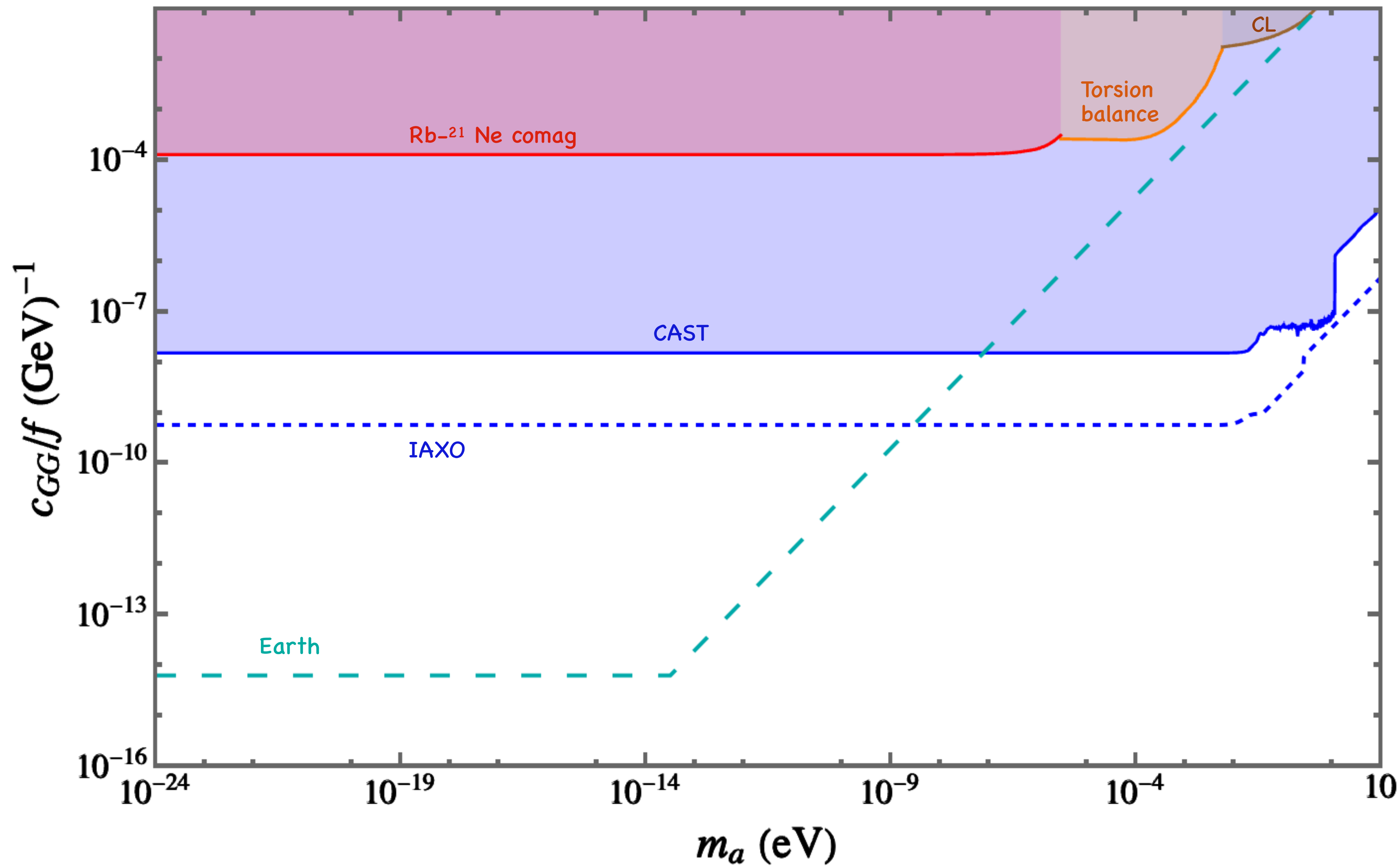
$$\mathcal{L}_{\chi\text{PT}}^{(2)} = c_1 \text{tr}[\chi_+] \bar{N} N + \dots ,$$

$$\chi_+ = 2B_0 (\xi^\dagger m_q(a) \xi^\dagger + \xi m_q^\dagger(a) \xi)$$

$$M_N = M_0 - 4c_1 m_\pi^2$$

$$c_1 \text{tr}[\chi_+] \bar{N} N = C_N \frac{a^2}{f^2} \bar{N} N + \dots = 4c_1 m_\pi^2 \delta_\pi(a) \bar{N} N + \dots$$

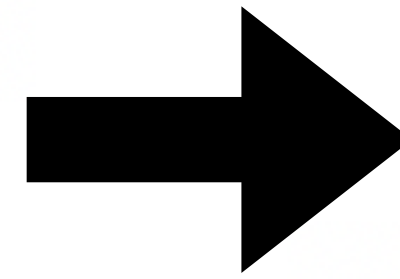
Non-DM ALP landscape



Finite density effects

Axion-field value is different in the vicinity of a massive object (such as the earth) than in the vacuum.

$$(\partial_t^2 - \Delta + m_a^2)a = -\sin\left(\frac{a}{f}\right) \sum_i \frac{Q_i^{\text{source}} \delta_i}{f} \rho_{\text{source}}(r)$$

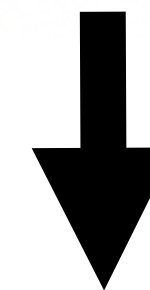


$$= -\frac{a}{f} \sum_i \frac{Q_i^{\text{source}} \delta_i}{f} \rho_{\text{source}}(r) + \mathcal{O}\left(\frac{a^3}{f^3}\right)$$

The source term up to quadratic axion interactions can be absorbed in the effective mass term

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

$$(\partial_t^2 - \Delta + \bar{m}_a^2(r))a = 0.$$



axion field at infinity takes the oscillating galactic background field

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

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

$$Z_\delta = \frac{1}{4\pi f^2} \frac{M_{\text{source}}}{R_{\text{source}}} \sum_i Q_i^{\text{source}} \delta_i$$

$$J_+(x) = \frac{3}{x^3} (x - \tanh x),$$

$$J_-(x) = \frac{3}{x^3} (\tan x - x).$$

Q_i 's are positive, δ_i 's are negative

$J_-(x)$ diverges for $x \rightarrow \pi/2$

$$\frac{c_{GG}}{f} \gtrsim \left(\frac{6}{\pi^3} \frac{m_u m_d}{(m_u + m_d)^2} \frac{M_\oplus}{R_\oplus} |Q_{\hat{m}}| \right)^{-1/2} \approx \frac{1}{10^{15}} \text{ GeV}^{-1}$$

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

$$Q_{\Delta M} = 1.7 \times 10^{-3} \frac{A-2Z}{A},$$

$$Q_\alpha = \left[-1.4 + 8.2 \frac{Z}{A} + 7.7 \frac{Z(Z-1)}{A^{4/3}} \right] \times 10^{-4},$$

$$Q_e = 5.5 \times 10^{-4} \frac{Z}{A},$$

Damour, Donoghue, et. al

$$\delta_\pi = -2c_{GG}^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

$$\delta_N = -4c_1 \frac{m_\pi^2}{M_N} \delta_\pi,$$

$$\delta_{\Delta M} = \delta_\pi,$$

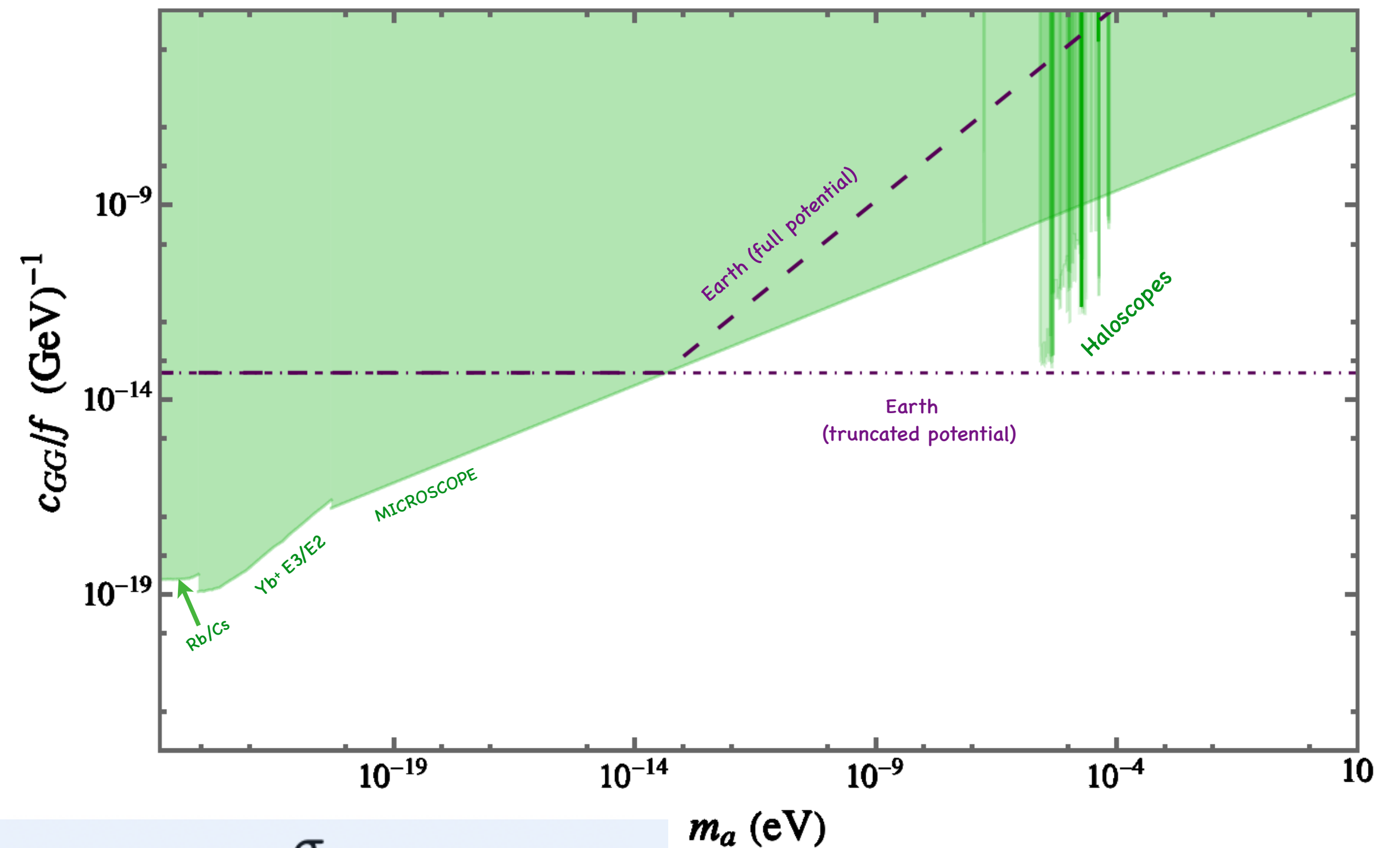
$$\delta_\alpha = \frac{1}{12\pi} \left(1 - 32c_1 \frac{m_\pi^2}{M_N} \right) \delta_\pi,$$

$$\delta_e = \frac{\alpha}{16\pi^2} \ln \frac{m_e^2}{m_\pi^2} \left(1 - 32c_1 \frac{m_\pi^2}{M_N} \right) \delta_\pi$$

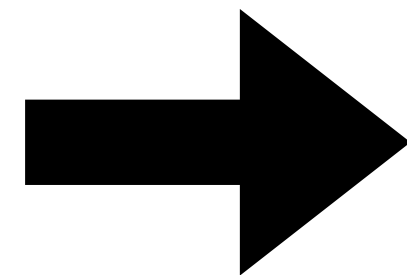
critical value of the axion-gluon
coupling under the small-coupling
approximation

- Axion potential is periodic, resulting in a cutoff for the field value $a \sim \pi/f$, implying that the higher order operators in the expansion regulates the divergence in the field.
- For non-DM axion, the boundary condition at $r \rightarrow \infty$ is a vanishing field value, so the full solution can be obtained. In the case of axion dark matter it should be finite as the free oscillating field - **Needs proper treatment**

$$V = -m_\pi^2 f_\pi^2 \epsilon \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2 \left(\frac{a}{2f_a} \right)}.$$



For the axion field value to deviate from the vacuum solution, the potential energy induced by the source needs to be **sufficiently large** to turn the axion mass tachyonic



$$m_a^2 f^2 + \frac{\sigma}{M_N} \rho_N \delta_\pi < 0,$$

$$m_a^2 f^2 < 5 \times 10^{17} c_{GG}^2 \text{ eV}^4.$$