Constraining Axions with Quantum Technology

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IP3

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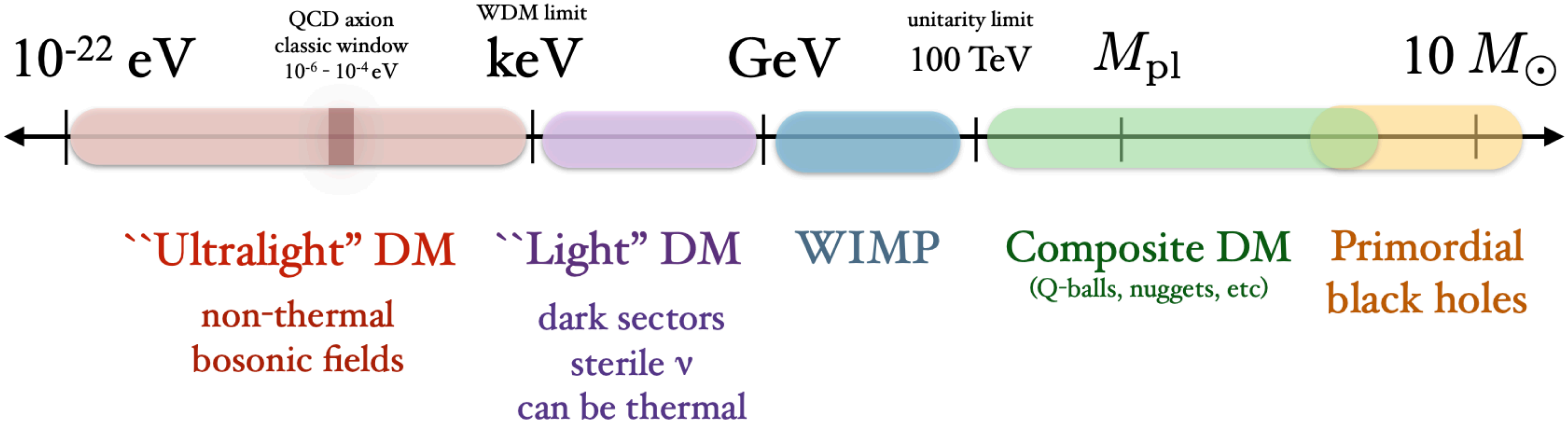
20th PATRAS Workshop on Axions WIMPs & WISPs

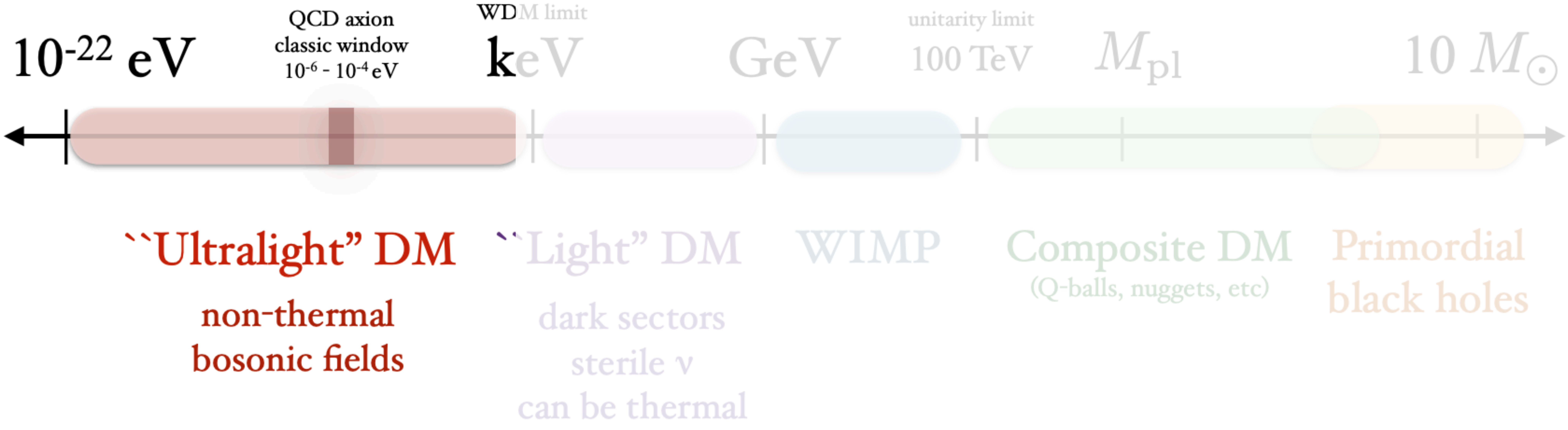
Tenerife. September 22-26. 2025

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, $n_\phi \left(\lambda_{\text{coh}}/2\pi\right)^3 >> 1$

- Spin-0 dark matter in the mass range $\approx 10^{-22}$ **eV** $\lesssim m_\phi \lesssim 1$ **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.

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

$|\vec{\beta}| \approx 10^{-3}$ - 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 : $\omega \sim m_\phi$

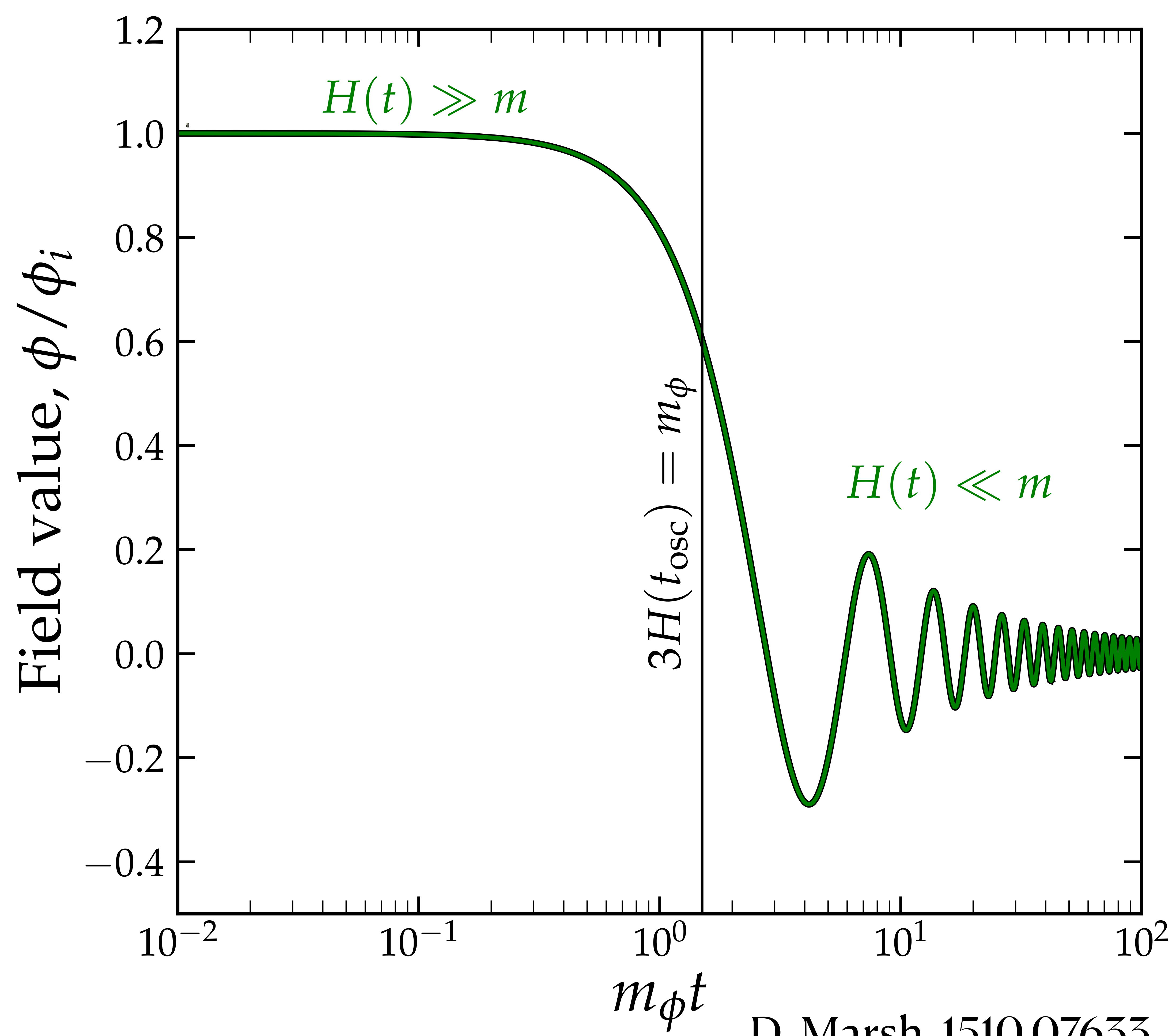
✓Small corrections from the kinetic energy : $\frac{\Delta\omega}{\omega} \sim \frac{\langle v_\phi^2 \rangle}{c^2} \sim 10^{-6}$

✓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, $H < < m_\phi$ 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

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

✓RG running

✓Threshold matching

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

✓Chiral Lagrangian

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

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

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

✓**Pion mass** →

$$m_{\pi,\mathrm{eff}}^2(a) = m_\pi^2\big(1 + \delta_\pi(a)\big) \longrightarrow \delta_\pi(a) = -\frac{c_{GG}^2}{2}\frac{a^2}{f^2}\left(1 - \frac{\Delta_m^2}{\hat{m}^2}\right) + \mathcal{O}(\tau_a^2)$$

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

✓**Nucleon mass** →

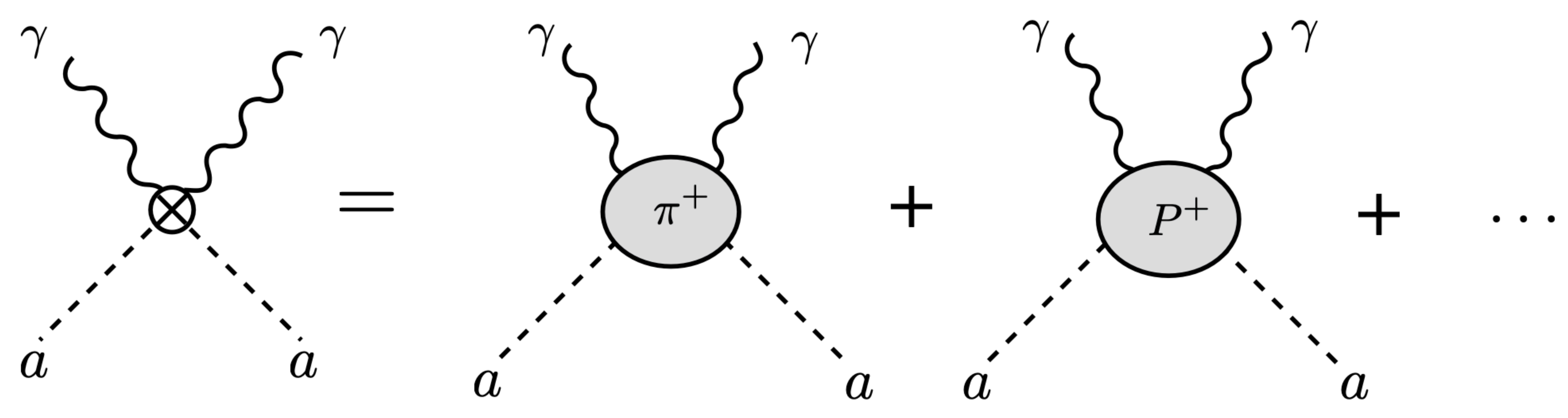
$$\mathcal{L}_{\chi\mathrm{PT}}^{(2)} = c_1 \mathrm{tr}[\chi_+]\bar{N}N + \ldots \longrightarrow \mathcal{L} \ni 4c_1 m_\pi^2\, \delta_\pi(a)\bar{N}N + \ldots$$

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

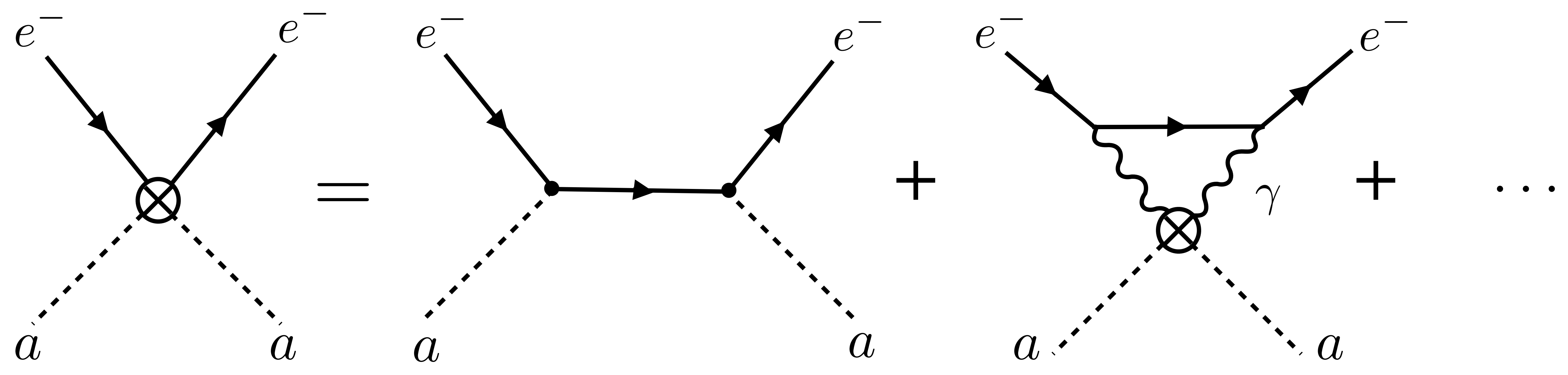
$$\mathcal{L}_{\mathrm{eff}}^{D=6}(\mu \lesssim \Lambda_{\mathrm{QCD}}) = \bar{N}\left(C_N(\mu)\mathbb{I} + C_\delta(\mu)\tau\right) N\frac{a^2}{f^2} + C_E(\mu)\frac{a^2}{f^2}\bar{e}e + C_\gamma(\mu)\frac{a^2}{4f^2}F_{\mu\nu}F^{\mu\nu}$$

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

Quadratic interactions



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



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

Shifts in fundamental constants

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

✓ $\alpha^{\mathbf{eff}}(a) = \Big(1 + \delta_\alpha(a)\Big)\alpha$ **with** $\delta_\alpha(a) = \dfrac{1}{12\pi}\left(1 - 32c_1\dfrac{m_\pi^2}{M_N}\right)\delta_\pi(a)$

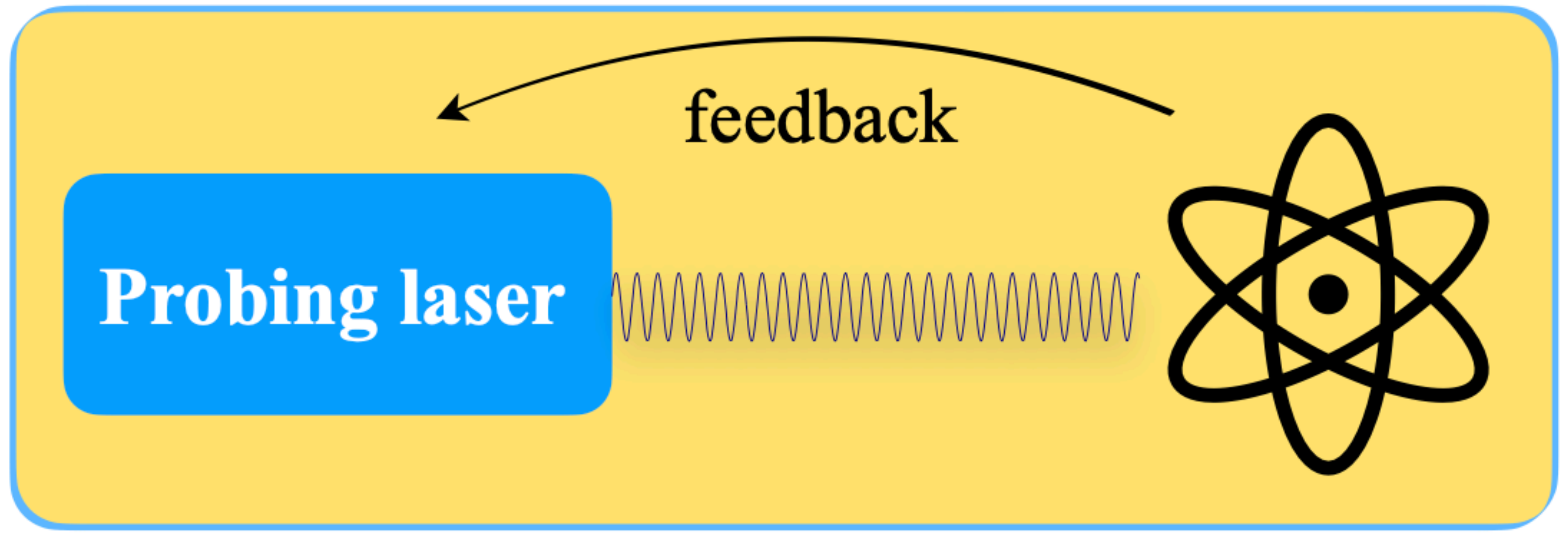
✓ $m_e^{\mathbf{eff}}(a) = m_e\big(1 + \delta_e(a)\big)$ **with** $\delta_e(a) = \dfrac{3\alpha}{4\pi}C_\gamma\dfrac{a^2}{f^2}\ln\dfrac{m_\pi^2}{m_e^2}$

✓ $M_N(a) = M_N\Big(1 + \delta_N(a)\Big)$ **with** $\delta_N(a) = -4c_1\dfrac{m_\pi^2}{M_N}\delta_\pi(a)$

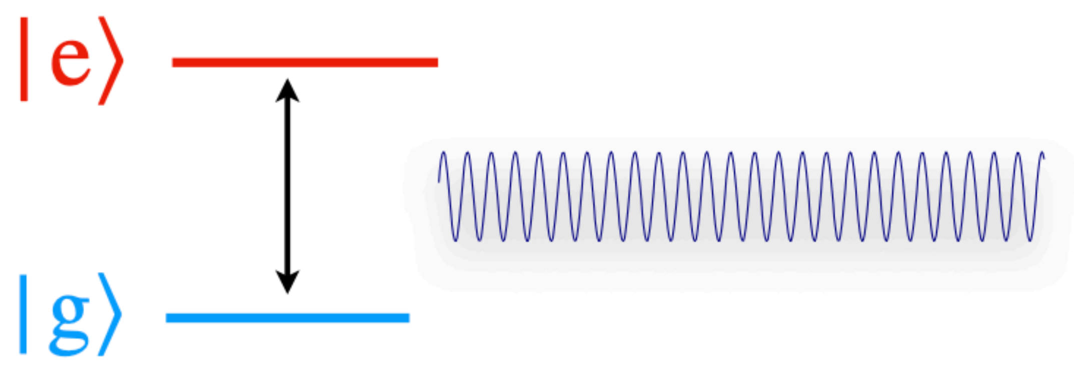
Atomic Clocks

laser/microwave is tuned in resonance with the transition

Basic components

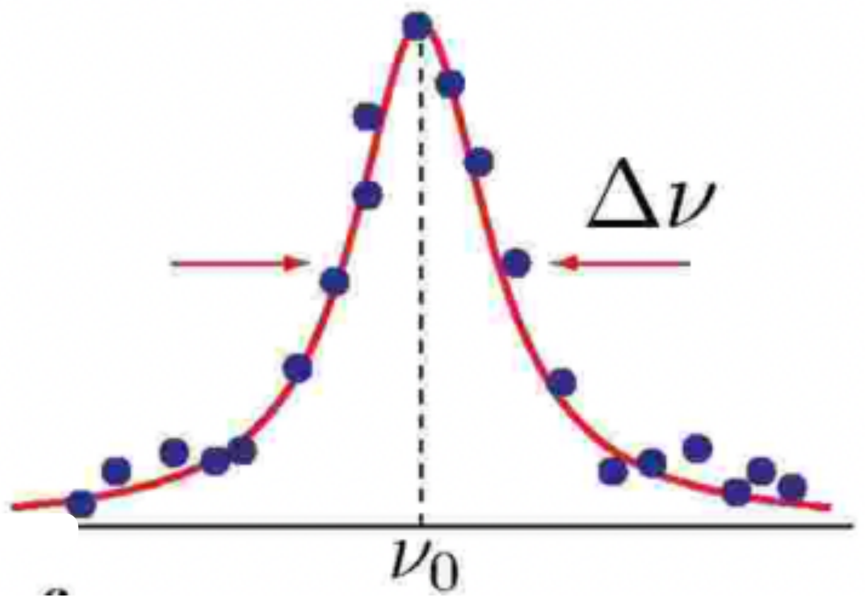


Clock transition



Measured* radiation

$= h\nu_{\text{output}}$



***Cannot measure absolute energies**

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

Different transitions of same system or distinct systems

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

Optical frequencies : $\nu \propto \alpha^2 m_e F_{\text{o}}(\alpha)$

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

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

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

Clock-ULDM connection

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

$$\approx k_\alpha\,\delta_\alpha(a) + k_e\,\delta_e(a) - \left(k_e + 2\,k_q\right)\delta_p(a) + k_q\,\delta_\pi(a)$$

In the oscillating ALP dark matter background,

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

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

Microwave clocks

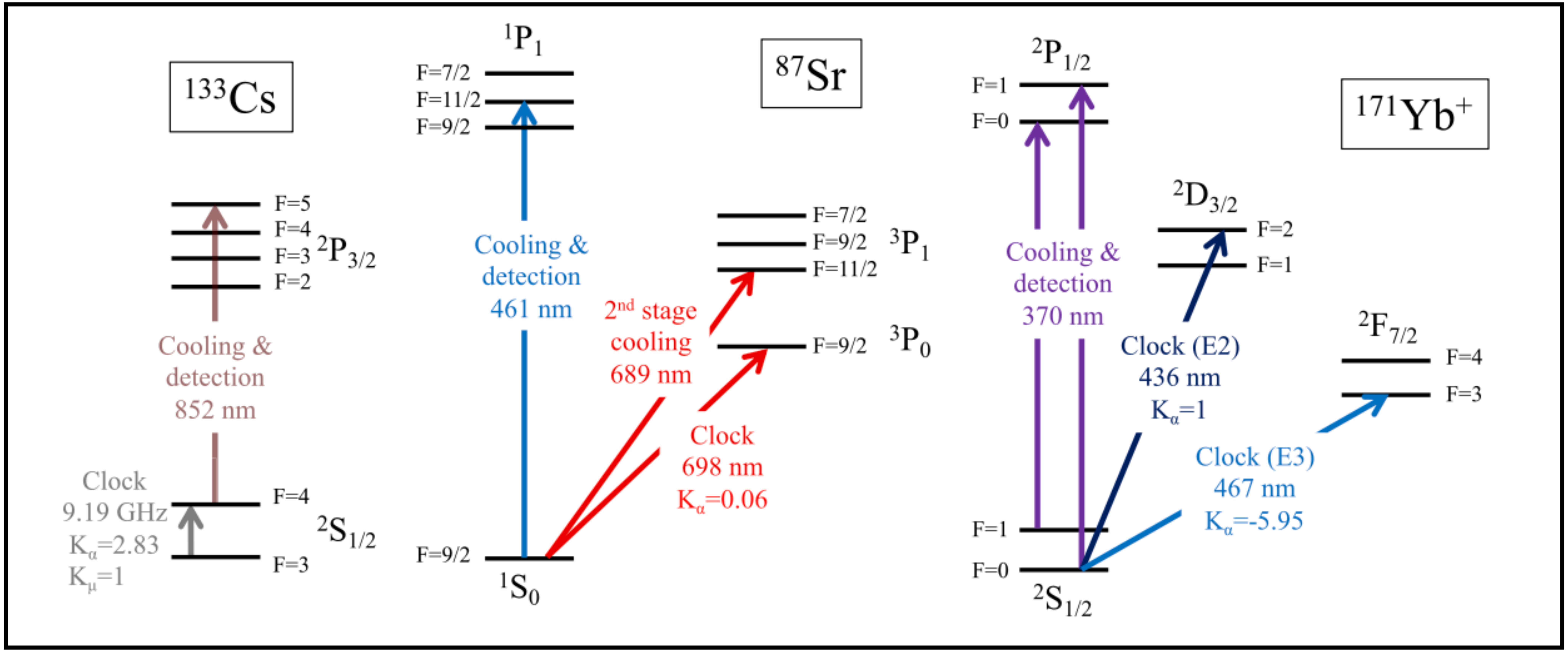
$\sim$ GHz frequencies.
Longer integration time.
Fractional uncertainty ~ 10^{-15}
Rb/Cs

clock stability $\propto \nu_0/\Delta\nu$

narrow linewidth gives higher stability

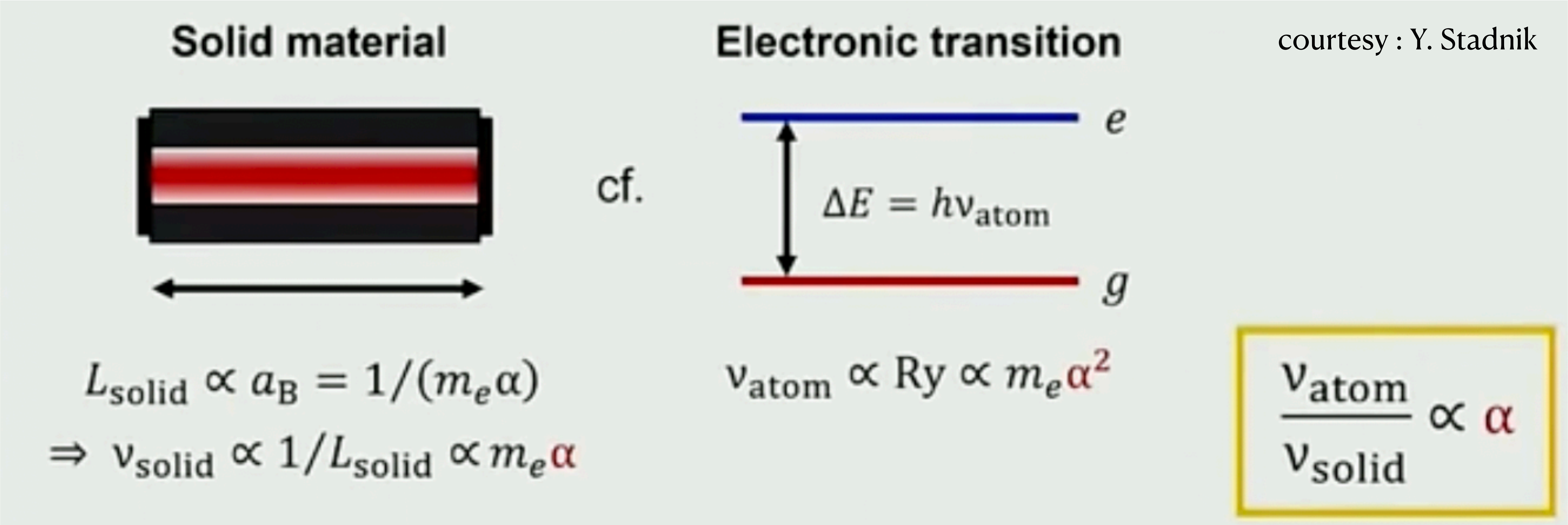
Optical clocks

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



Barontini et al. EPJ QuantumTechnology

Clock-cavity comparison



Sr/Si : $\nu_{Sr} \propto \alpha^{2.06} m_e$

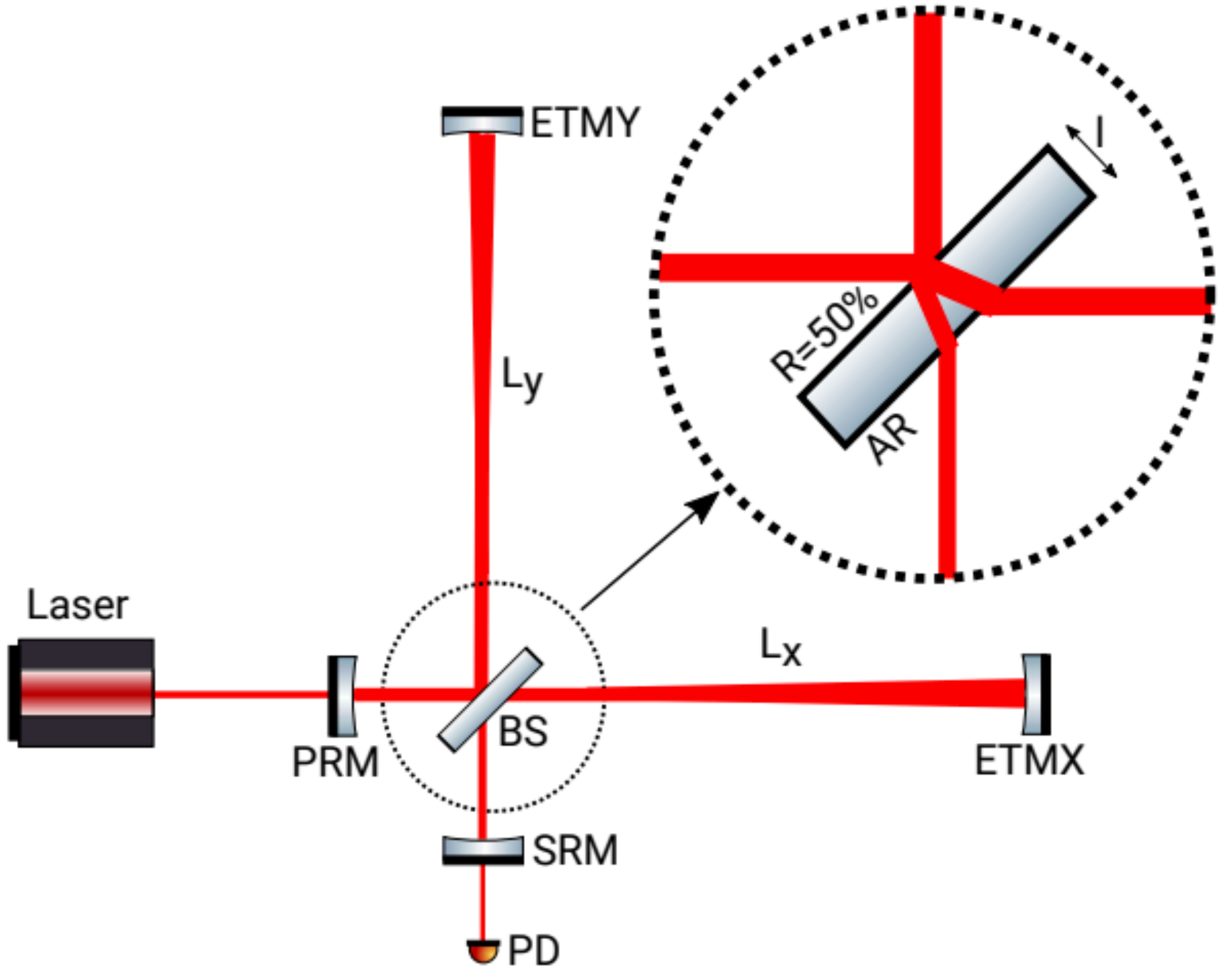
H/Si : $\nu_H \propto \alpha^4 m_e^2$

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.

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

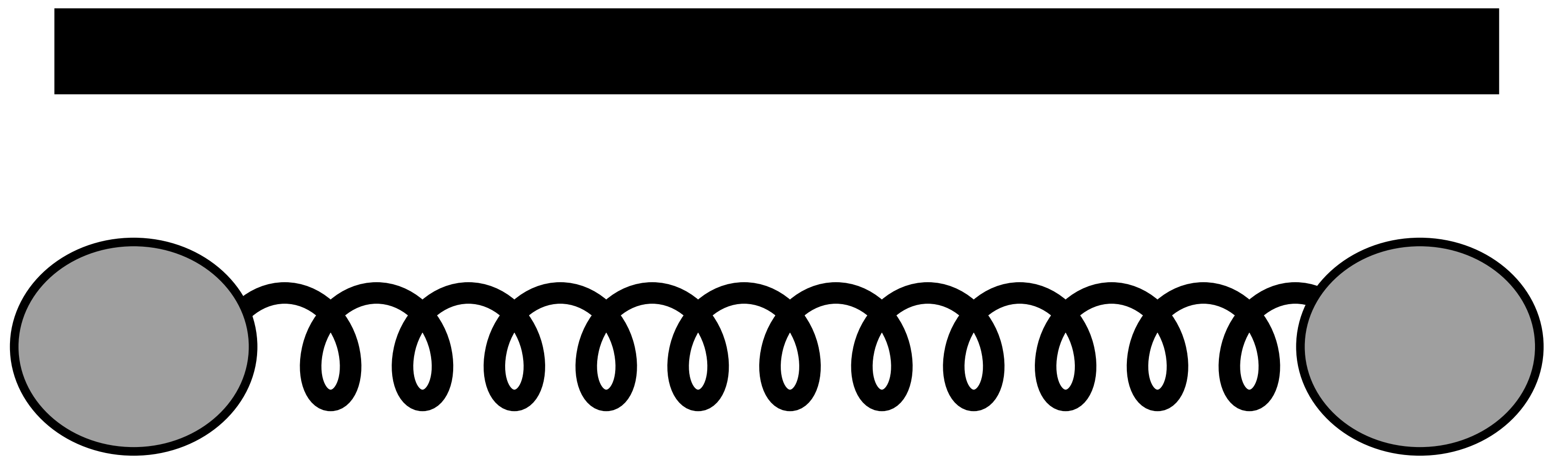


H. Grote1 *et. al*, [arXiv: 1906.06193]

- GEO-600
- LIGO

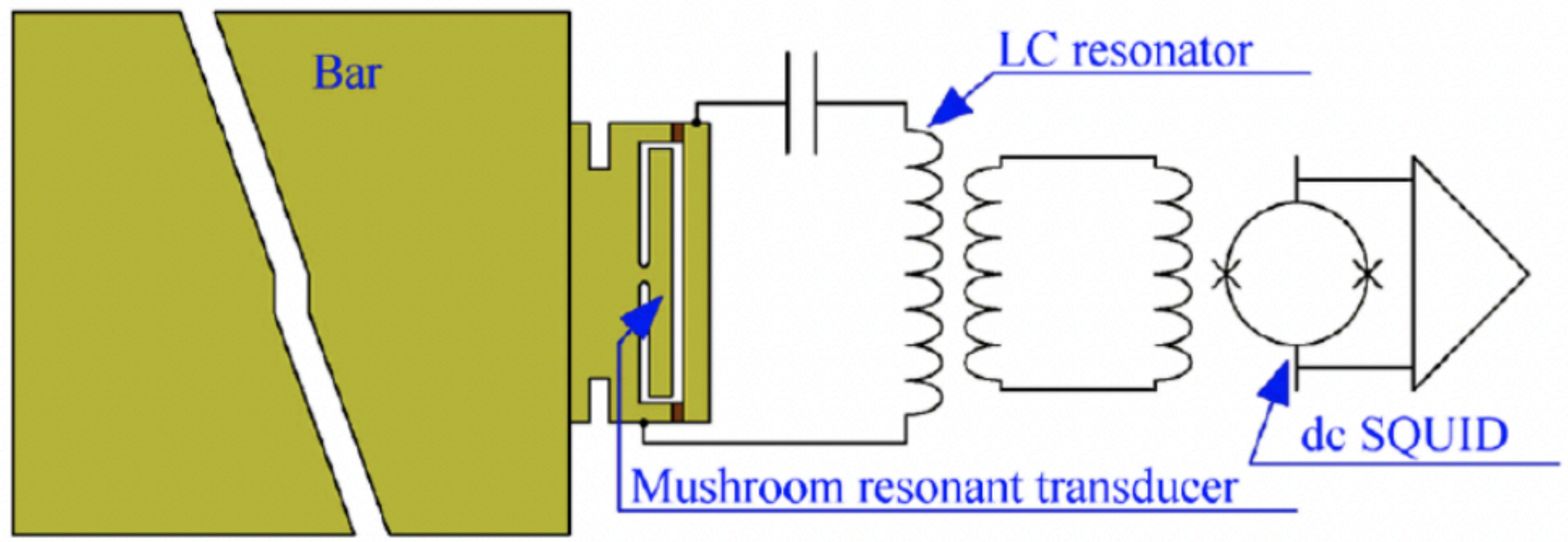
Gravitational wave detectors can be used as laser interferometers with opearating frequency $\sim \mathcal{O}$ (kHz)

Mechanical resonators



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

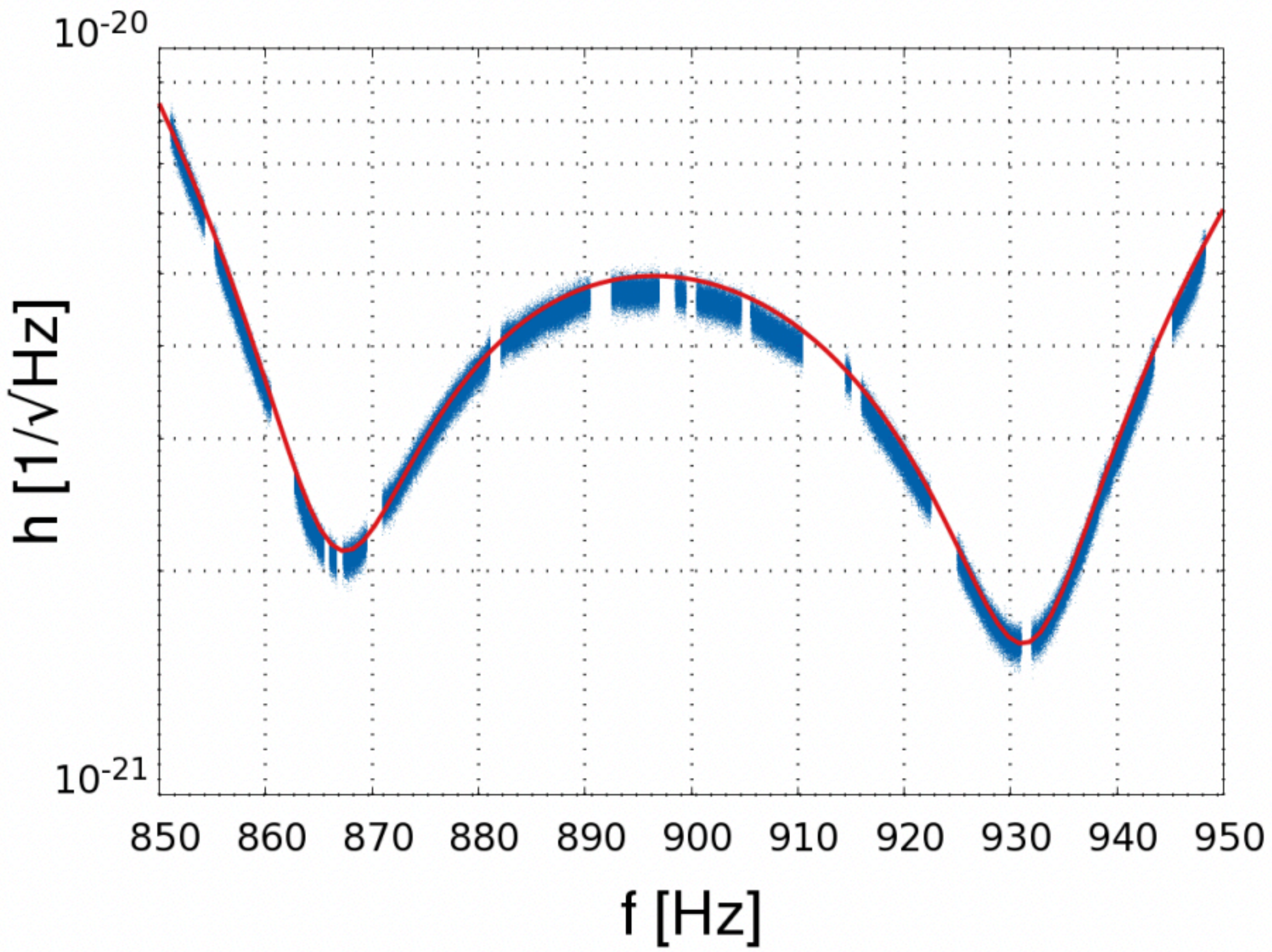
mechanical strain



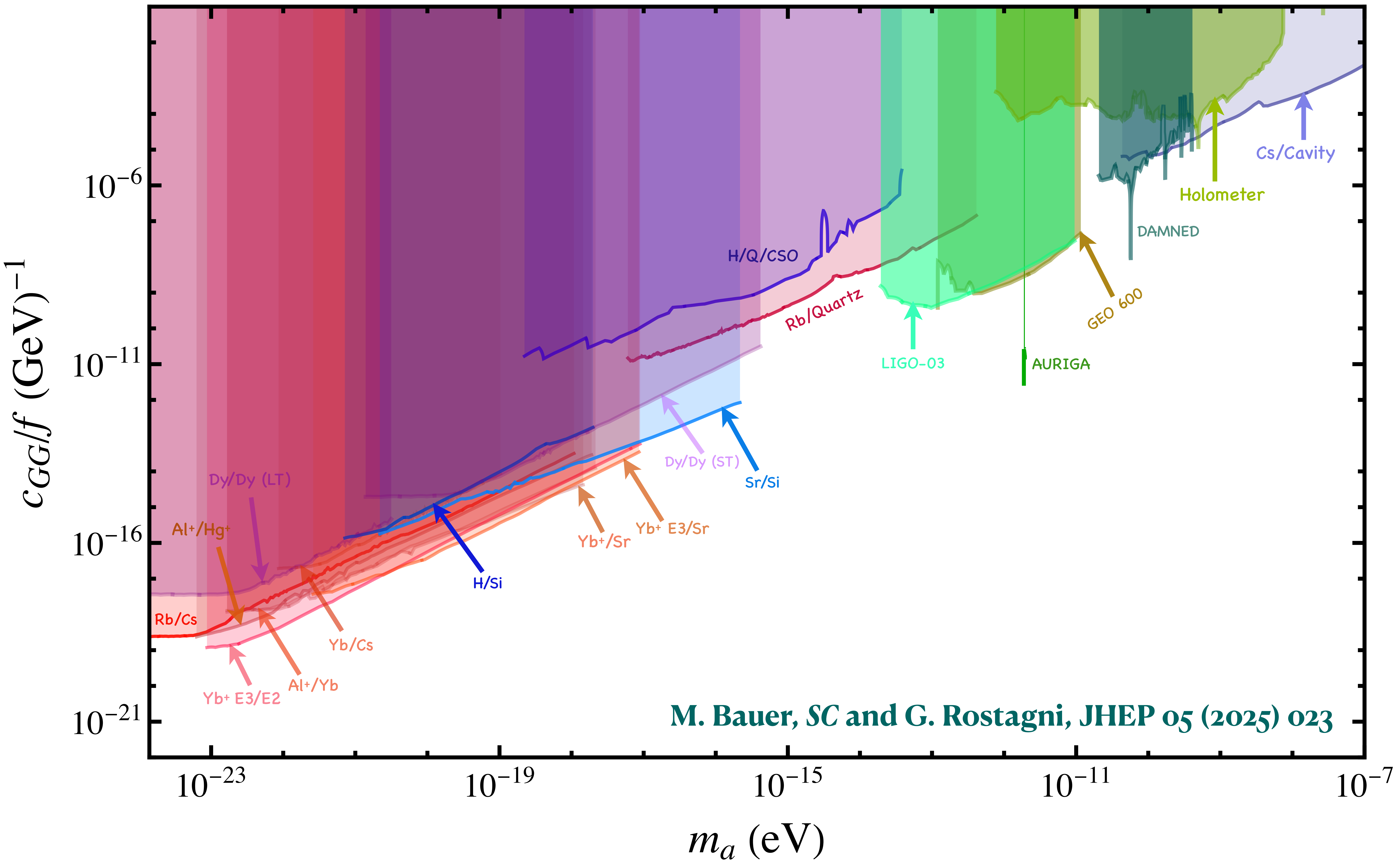
AURIGA

✓A cryogenic resonant-mass detector of bar length $\sim \mathcal{O}(\mathrm{m})$.

✓ Sensitivity over a narrow bandwidth 850-950 Hz, corresponding to ALP mass window 1.88 - 1.94 peV.



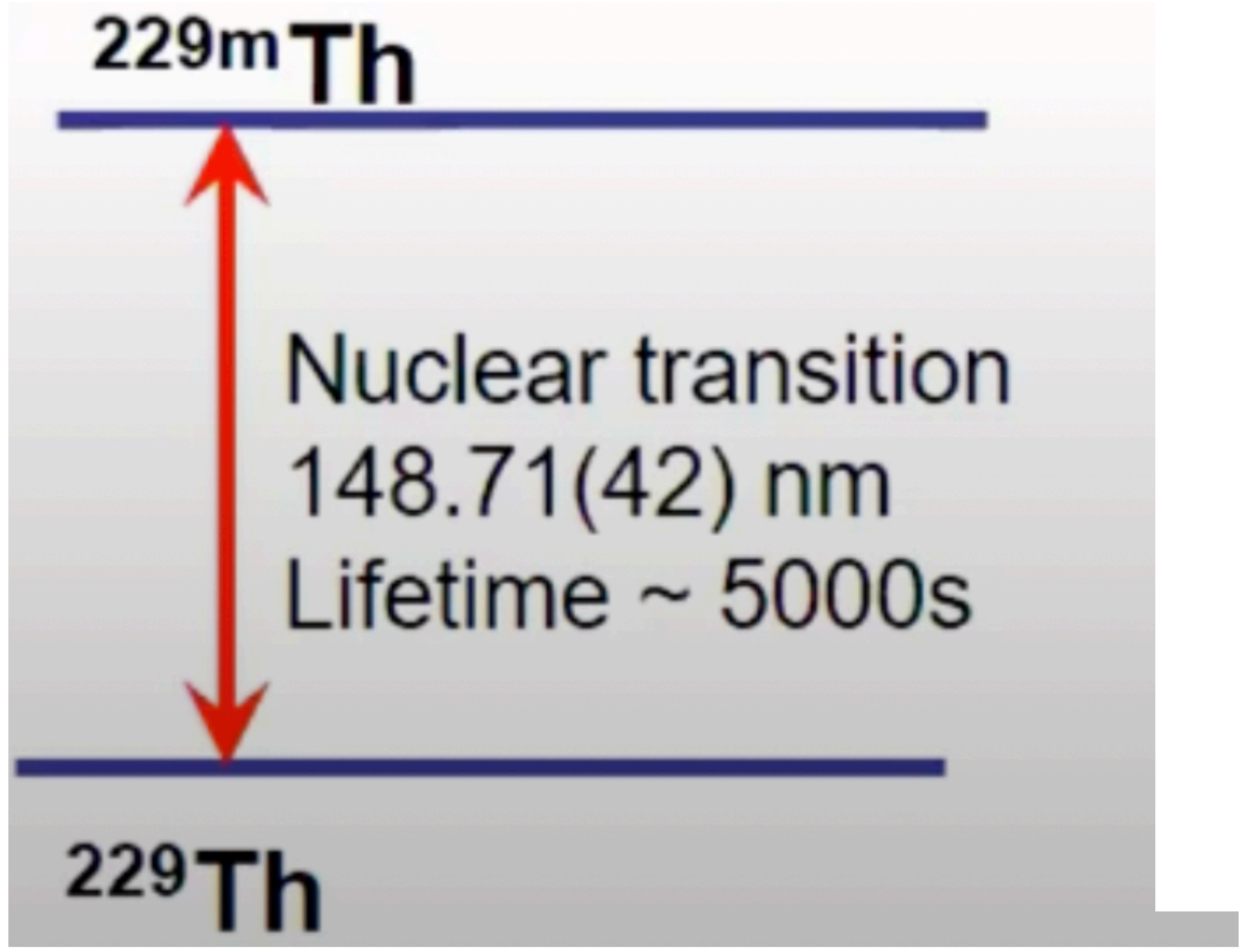
Current constraints

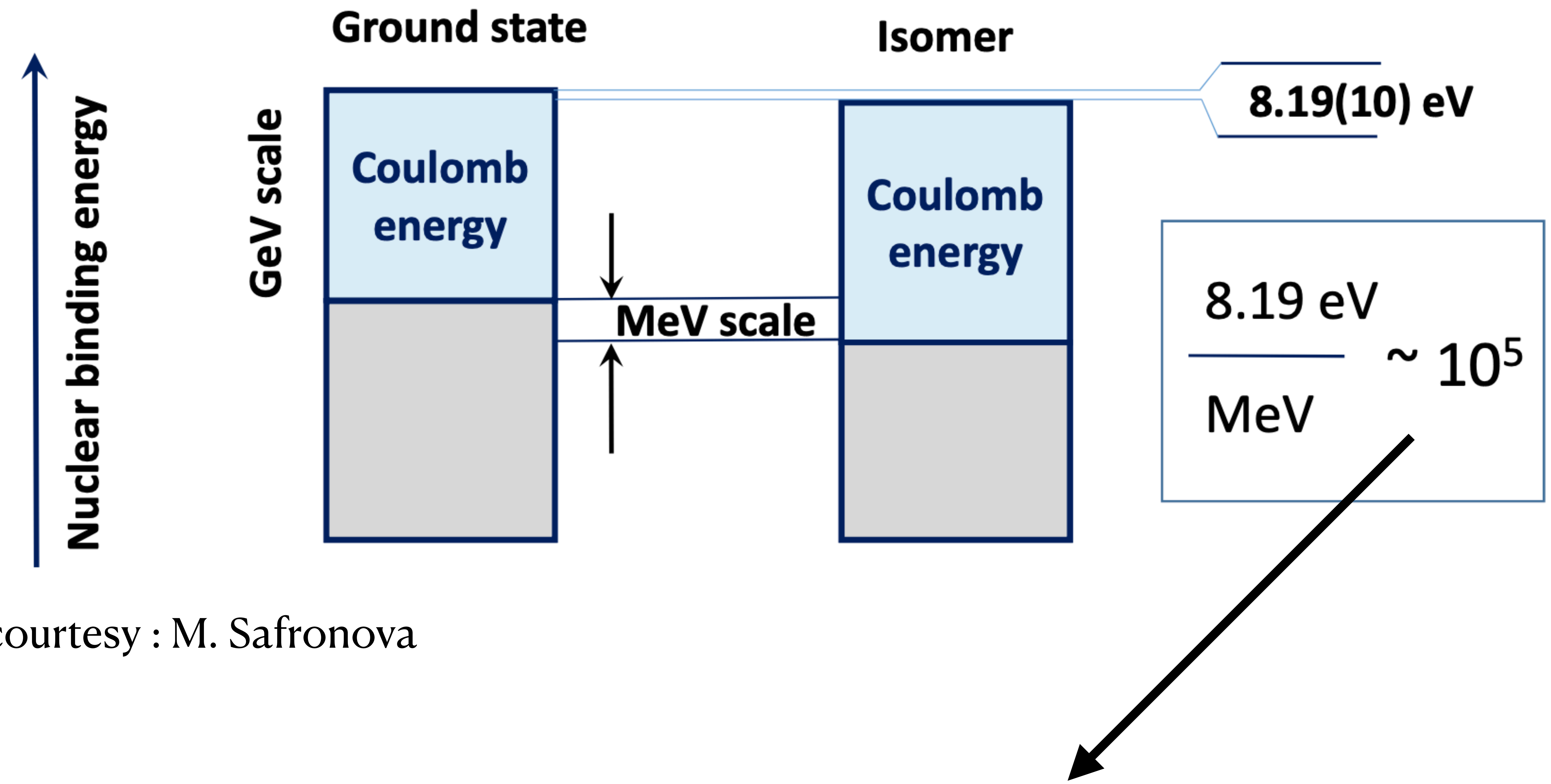


Upcoming facilities

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





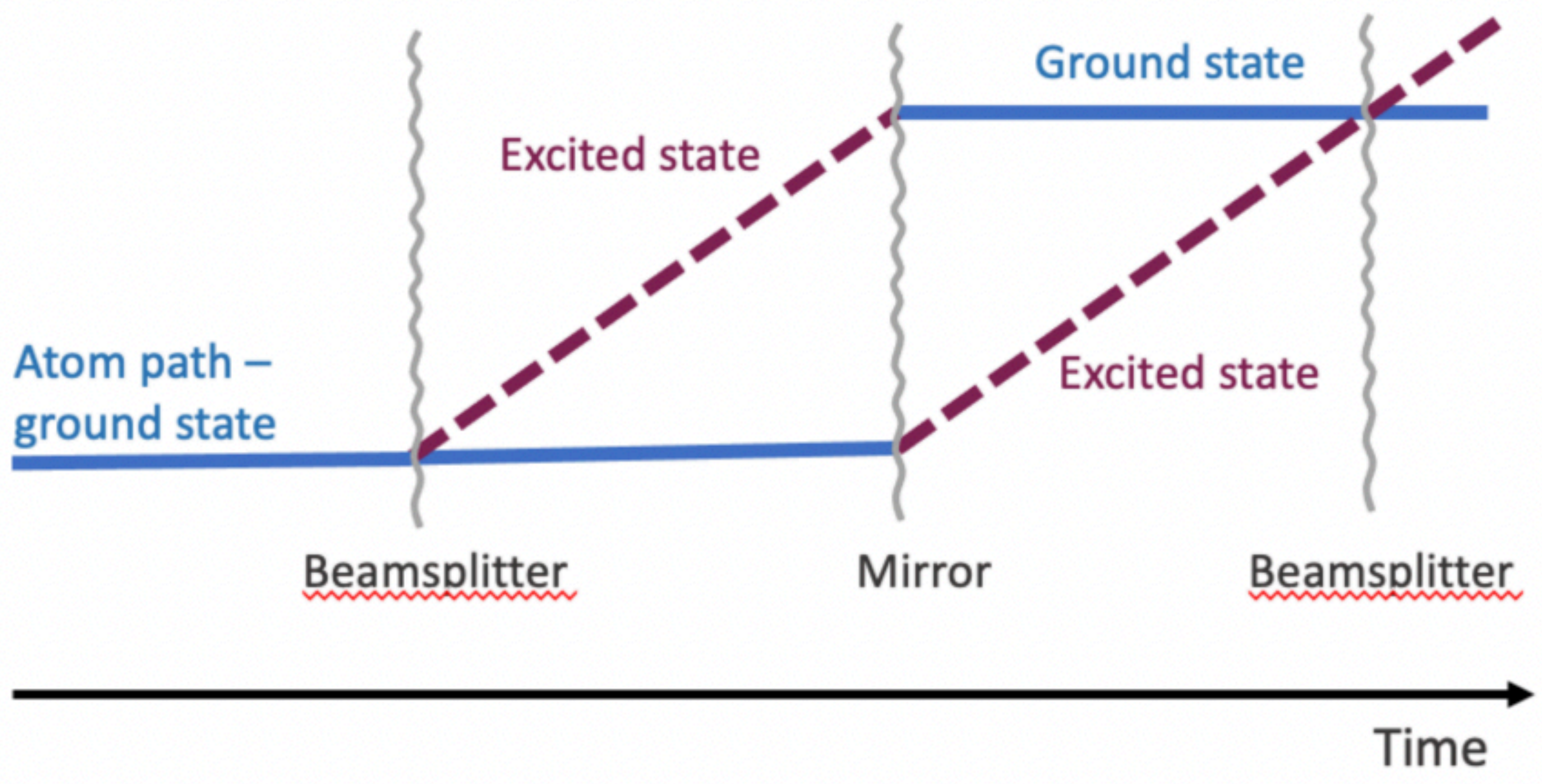
courtesy : M. Safronova

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 $\omega_A \propto m_e \alpha^{2+\xi}$.

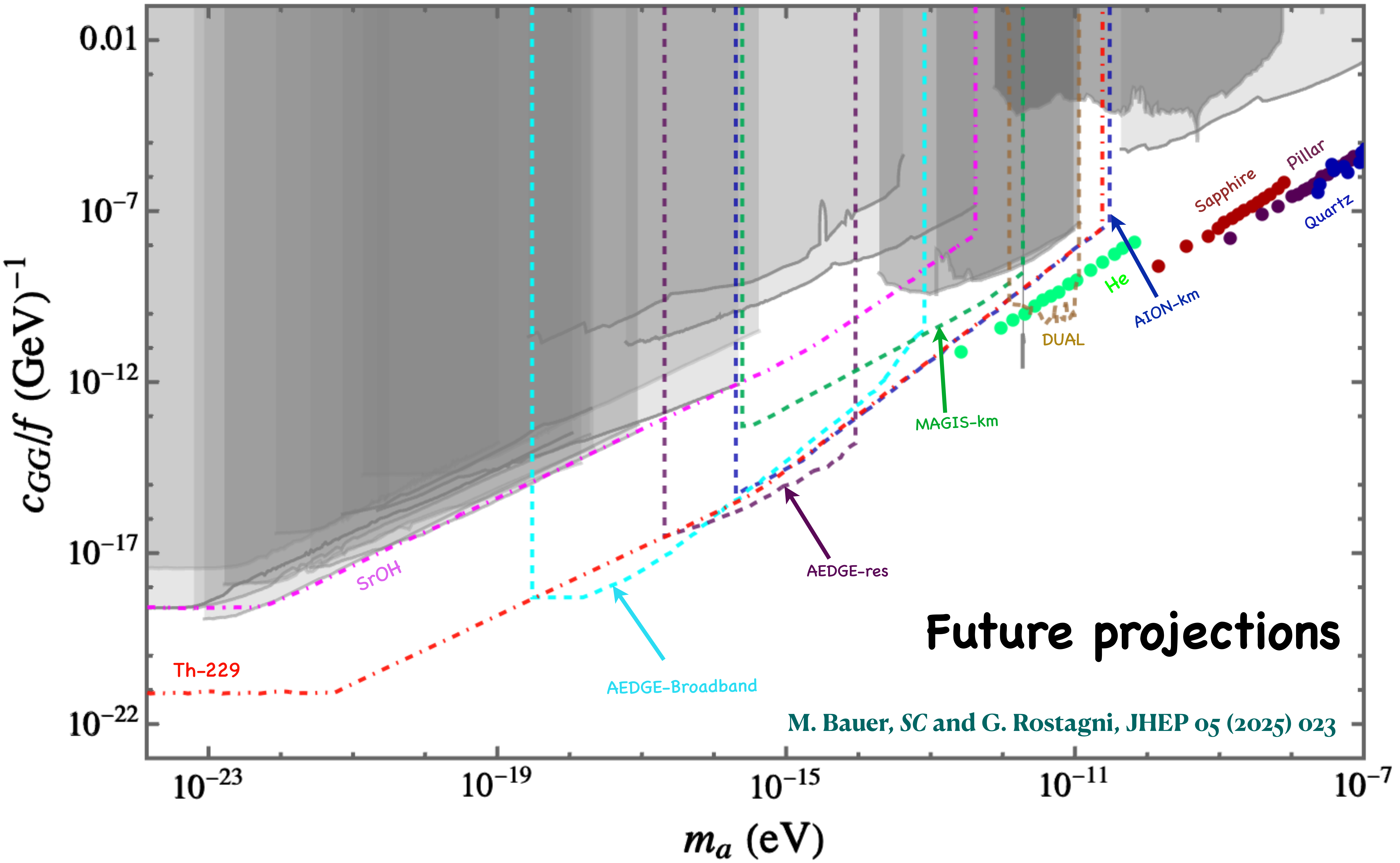


$$\omega_A(t,x) = \omega_A + \delta\omega_A(a)$$

$$\frac{\delta\omega_A(a)}{\omega_A} = \delta_e(a) + (2+\xi)\,\delta_\alpha(a)$$
$$\approx (\delta_e + (2+\xi)\delta_\alpha)\,\frac{\rho_{\rm DM}}{m_a^2 f^2}\cos(2\omega_a t) \equiv \overline{\omega}_A \cos(2\omega_a t)$$

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

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

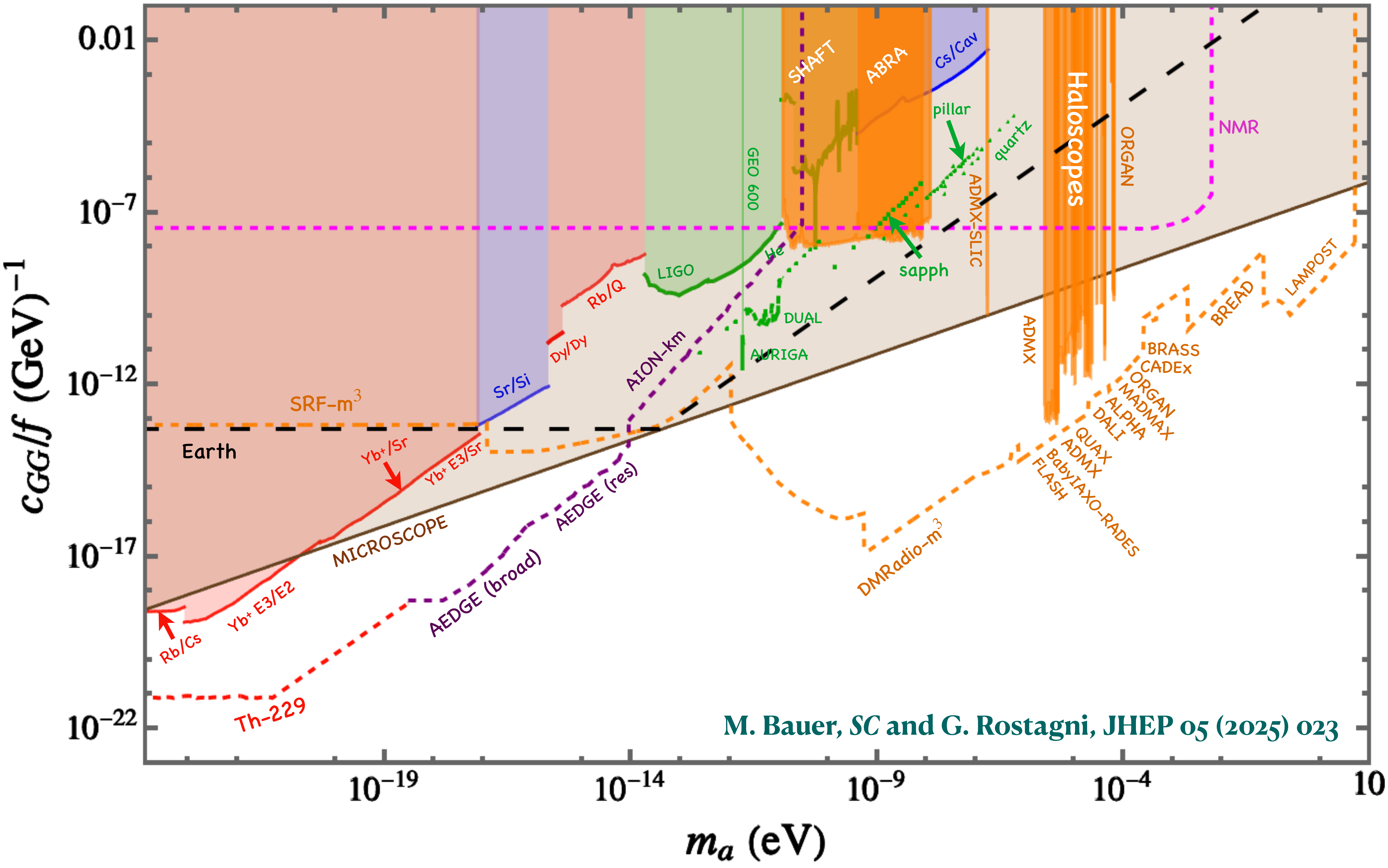


0.01
10^{-7}
10^{-12}
10^{-17}
10^{-22}
$c_{GG}/f\ (\mathrm{GeV})^{-1}$
10^{-23}
10^{-19}
10^{-15}
10^{-11}
10^{-7}
m_a (eV)
Sapphire
Pillar
Quartz
He
AION-km
DUAL
MAGIS-km
SrOH
AEDGE-res
Th-229
AEDGE-Broadband
Future projections
M. Bauer, SC and G. Rostagni, JHEP 05 (2025) 023

Take home

- ✓ Ultralight dark matter manifests through quadratic scalar 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!!



0.01
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-19}
10^{-14}
10^{-9}
10^{-4}
10
c_{GG}/f (GeV)$^{-1}$
m_a (eV)
SHAFT
ABRA
Cs/Cav
pillar
quartz
Haloscopes
ORGAN
NMR
GEO 600
ADMX-SLIC
sapph
LIGO
He
Rb/Q
DUAL
AURIGA
Dy/Dy
AION-km
Sr/Si
SRF-m^3
Earth
Yb+/Sr
Yb+ E3/Sr
MICROSCOPE
AEDGE (res)
AEDGE (broad)
Yb+ E3/E2
Rb/Cs
Th-229
DMRadio-m^3
ADMX
BRASS
CADEx
BREAD
LAMPOST
ORGAN
MADMAX
ALPHA
DALI
QUAX
ADMX
BabyIAXO-RADES
FLASH
M. Bauer, *SC* and G. Rostagni, JHEP 05 (2025) 023

ALP linear interactions

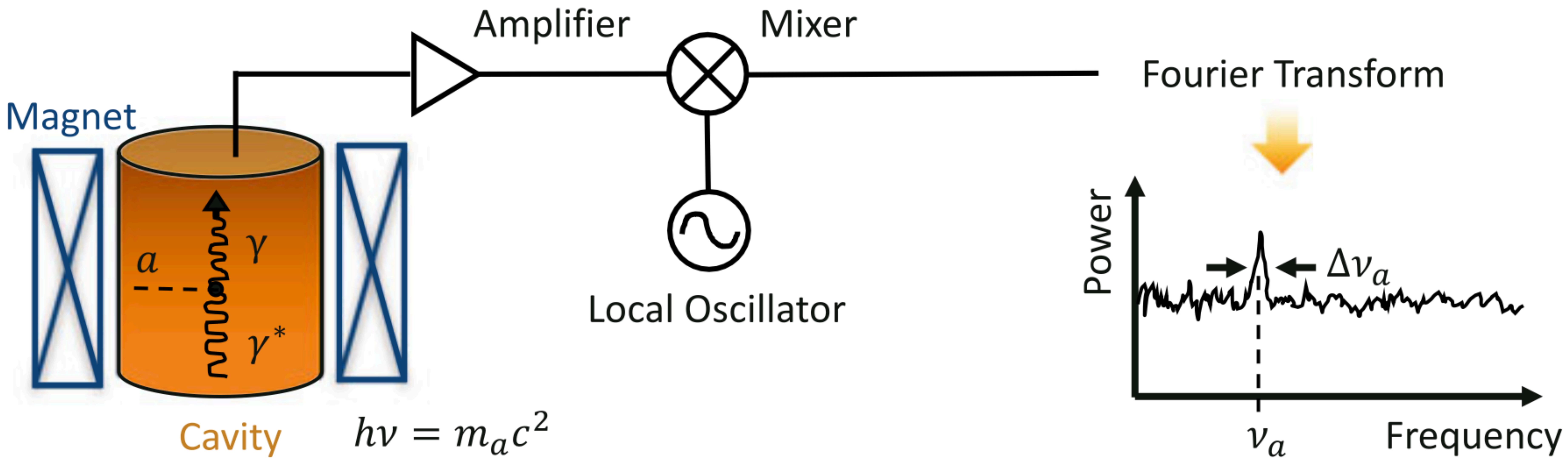
At energy scales below $\Lambda_{\rm QCD}$, the relevant ALP couplings to photons, nucleons and electrons are written in the leading order of the expansion of the decay constant *f* as

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

N → (p, n)

Cavity Haloscopes

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



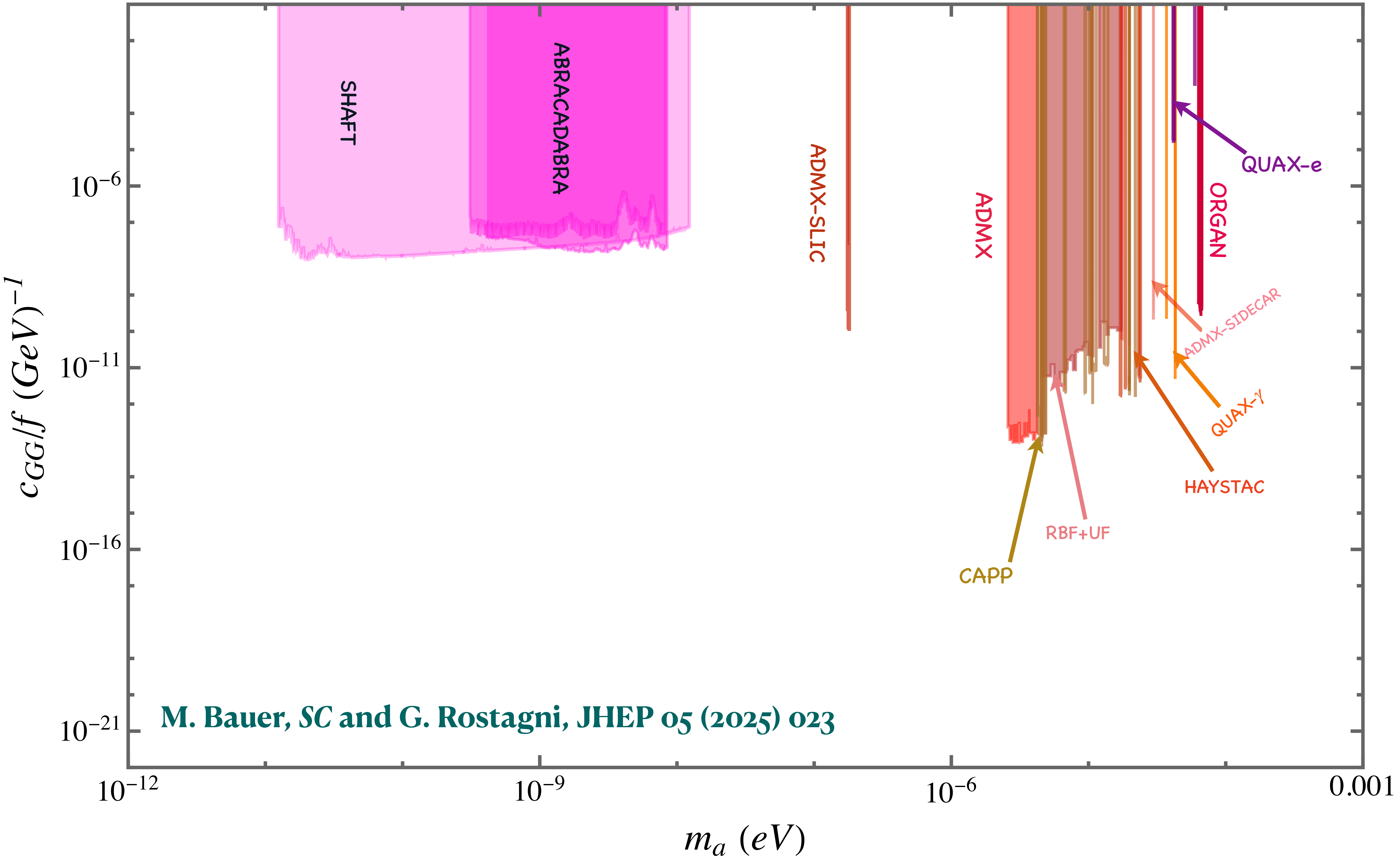
Kimball *et. al,* The Search for Ultralight Bosonic Dark Matter

Frequency dependent signal power extracted on resonance

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

Haloscope reach

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



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

Nucleons

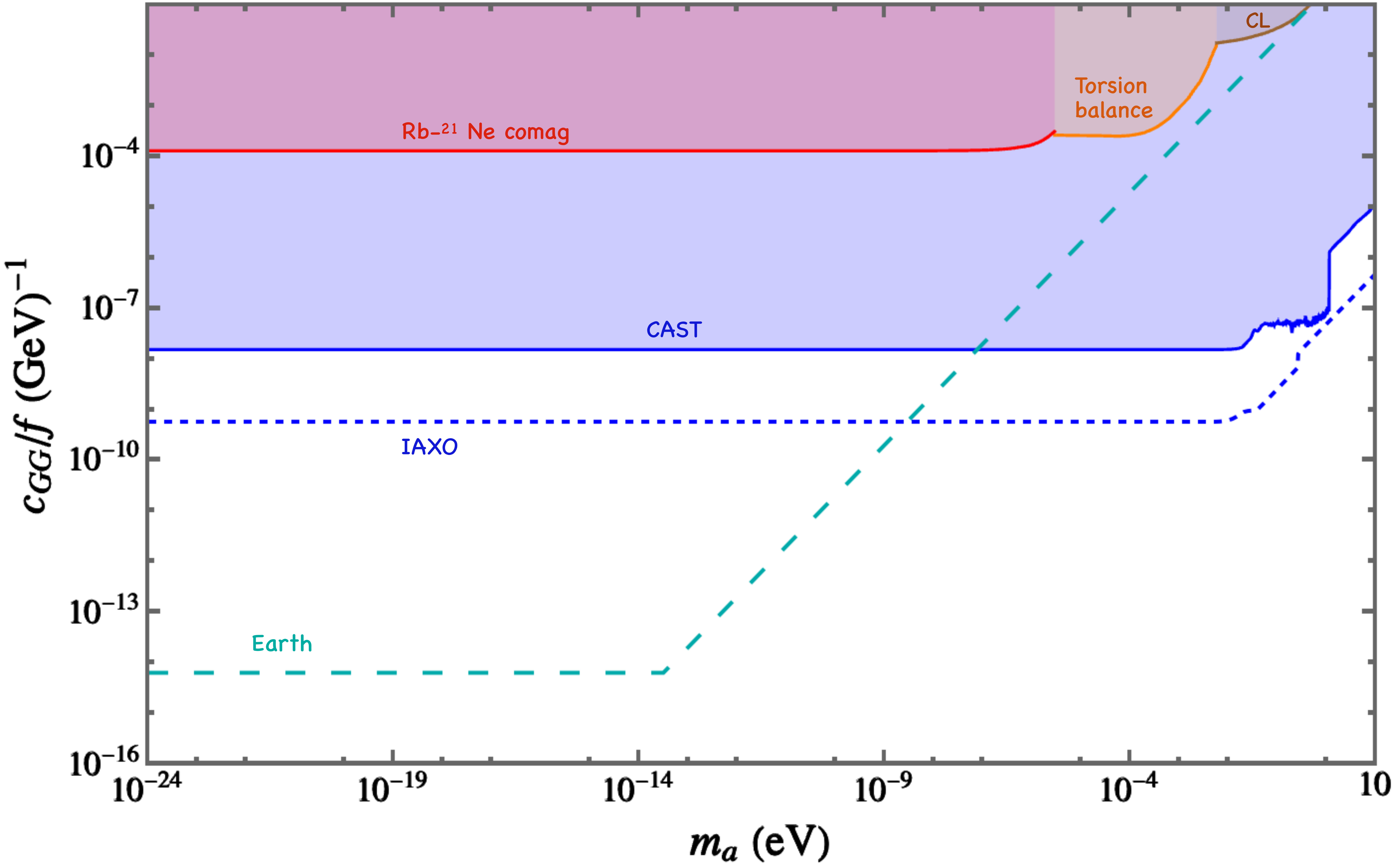
$$\mathcal{L}^{(2)}_{\chi\mathrm{PT}} = c_1 \mathrm{tr}[\chi_+]\bar{N}N + \ldots\ ,$$

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

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

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

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.

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

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

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

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

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

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

axion field at infinity takes the oscillating galactic background field

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

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

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

$$Q_{\hat m} = \left[9.3 - \frac{3.6}{A^{1/3}} - 2\frac{(A-2Z)^2}{A^2} - 0.014\frac{Z(Z-1)}{A^{4/3}}\right]\times 10^{-2};$$
$$Q_{\Delta M} = 1.7\times 10^{-3}\frac{A-2Z}{A}\,,$$
$$Q_\alpha = \left[-1.4 + 8.2\frac{Z}{A} + 7.7\frac{Z(Z-1)}{A^{4/3}}\right]\times 10^{-4}\,,$$
$$Q_e = 5.5\times 10^{-4}\frac{Z}{A}\,,$$

Damour, Donoghue, et. al

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

$$\delta_N = -4c_1\frac{m_\pi^2}{M_N}\delta_\pi,$$
$$\delta_{\Delta M} = \delta_\pi\,,$$
$$\delta_\alpha = \frac{1}{12\pi}\left(1 - 32c_1\frac{m_\pi^2}{M_N}\right)\delta_\pi\,,$$
$$\delta_e = \frac{\alpha}{16\pi^2}\ln\frac{m_e^2}{m_\pi^2}\left(1 - 32c_1\frac{m_\pi^2}{M_N}\right)\delta_\pi$$

Q_i's are positive, δ_i's are negative

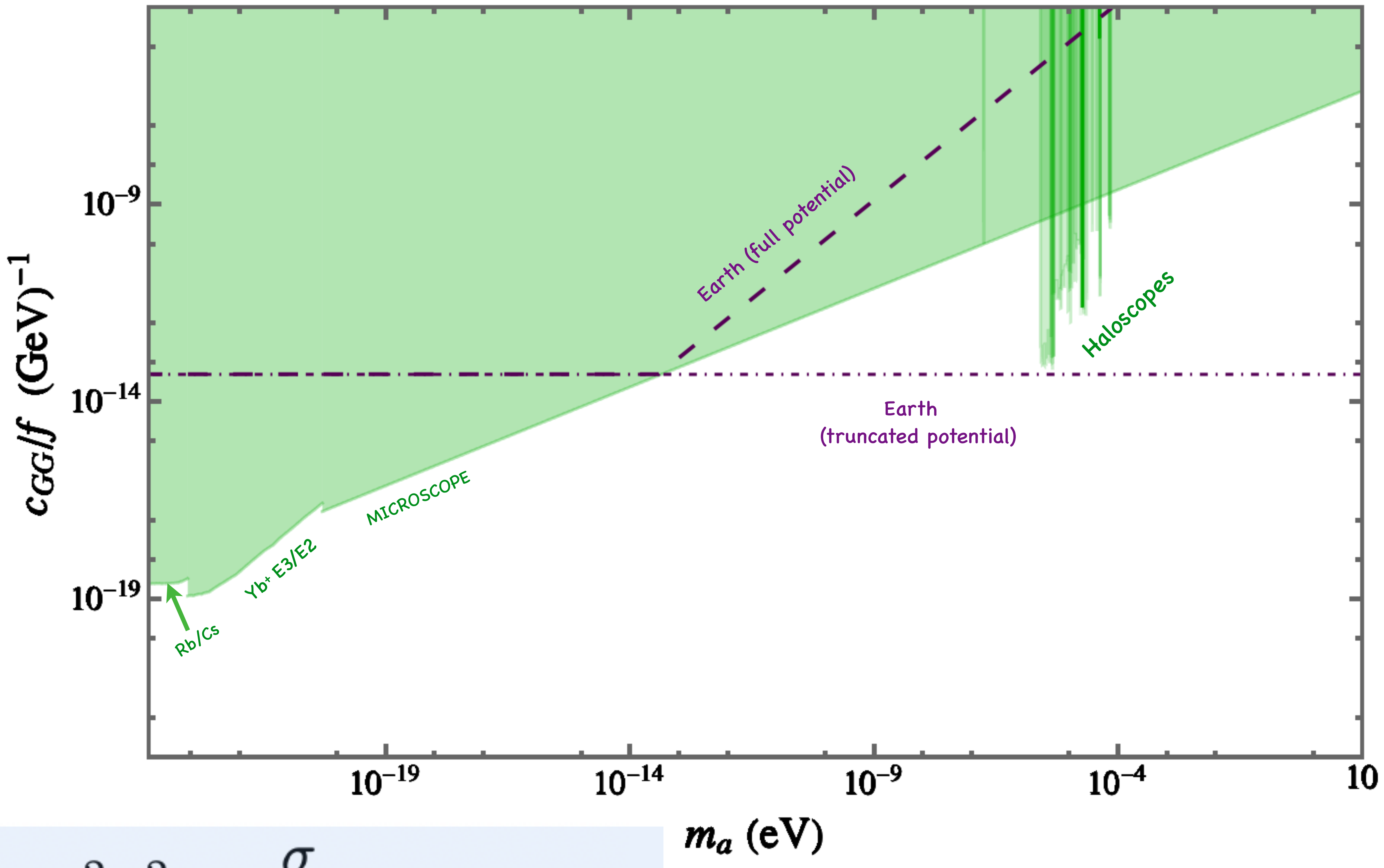
$J\_(x)$ diverges for $x \to \pi/2$

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

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

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

- 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 $r \to \infty$ 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**



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

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

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