Phenomenology Beyond Colliders

Clare Burrage

University of Nottingham

University of Nottingham
UK | CHINA | MALAYSIA

The Hunt for Light Scalar Fields at the Precision Frontier

Clare Burrage

University of Nottingham

Outline:

What can we do in space?

What can we do with atoms?

What can we do with photons?

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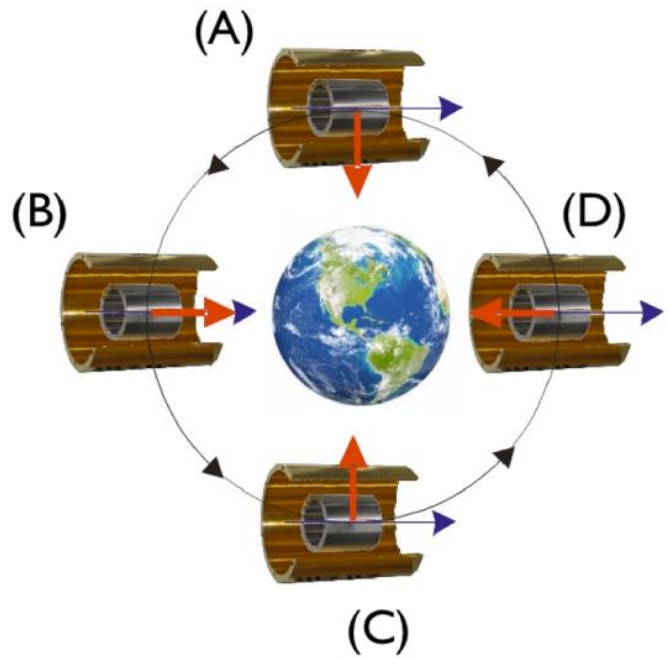
WHAT CAN WE DO IN SPACE?

MICROSCOPE

Testing the Weak Equivalence Principle
Concentric cylinders of platinum-rhodium alloy & titanium-aluminium-vanadium alloy



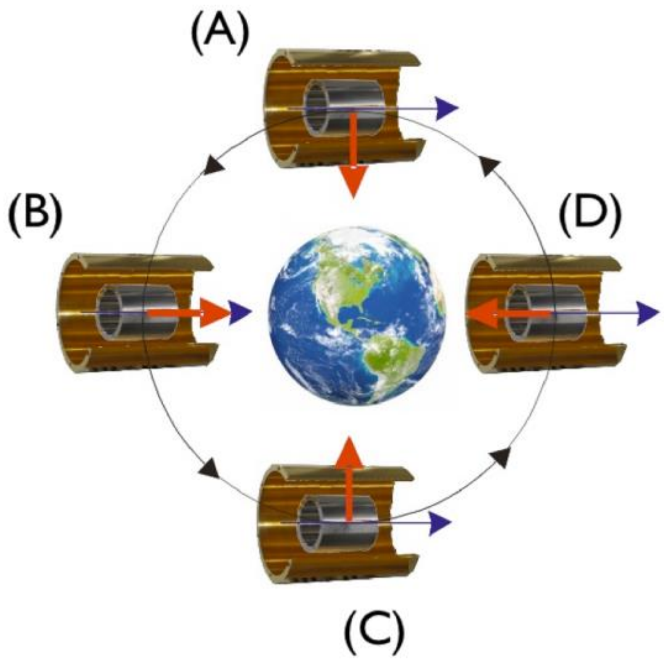
Orbited at a height of 710 km for ~135 days

Berge. Rep. Prog. Phys. 86 (2023) 066901

MICROSCOPE

Eötvös parameter

$$\eta_{\mathrm{A,B}} = 2\frac{a_{\mathrm{A}} - a_{\mathrm{B}}}{a_{\mathrm{A}} + a_{\mathrm{B}}}$$



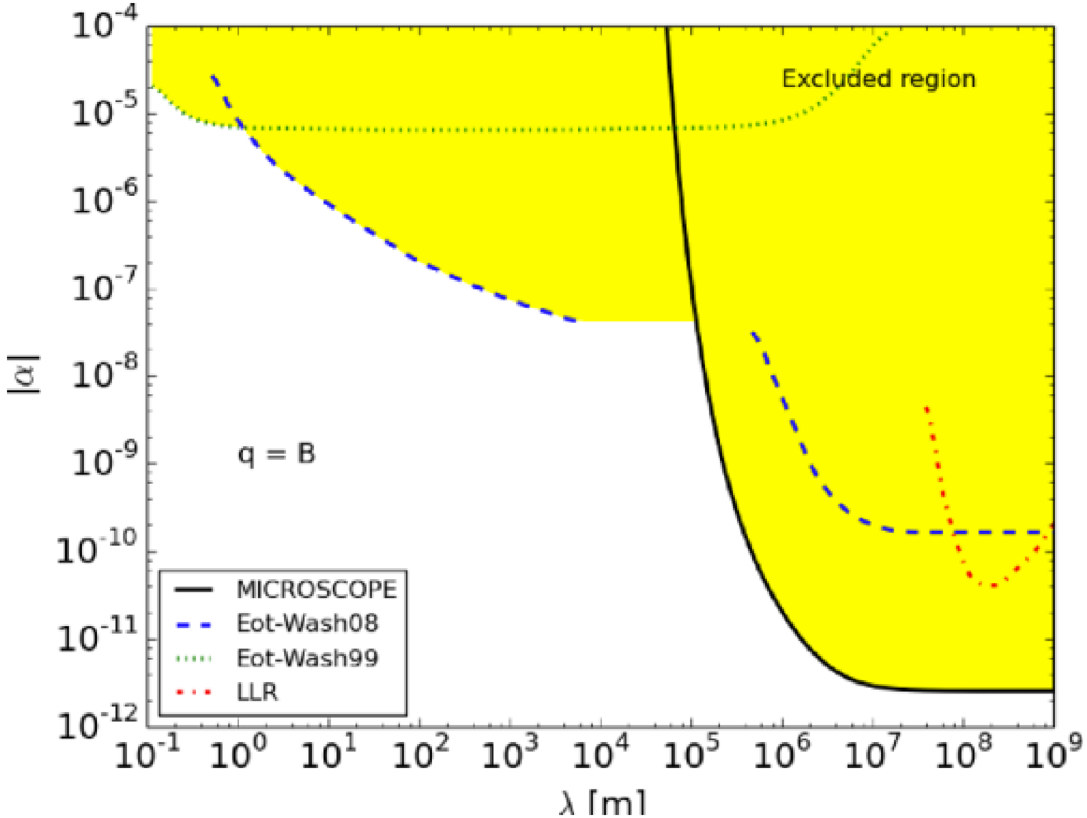
$\eta(Ti; Pt) = [-1.5 \pm 2.3 \pm 1.5] \times 10^{-15}$

Touboul et al. Phys. Rev. Lett. 129, 121102 (2022), Class. Quantum Grav. 39 204009 (2022)

Violations of WEP

New vector or scalar mediated Yukawa interactions

$$U(r) = -\frac{GM}{r}\left[1 + \alpha \exp\left(-\frac{r}{\lambda}\right)\right],$$

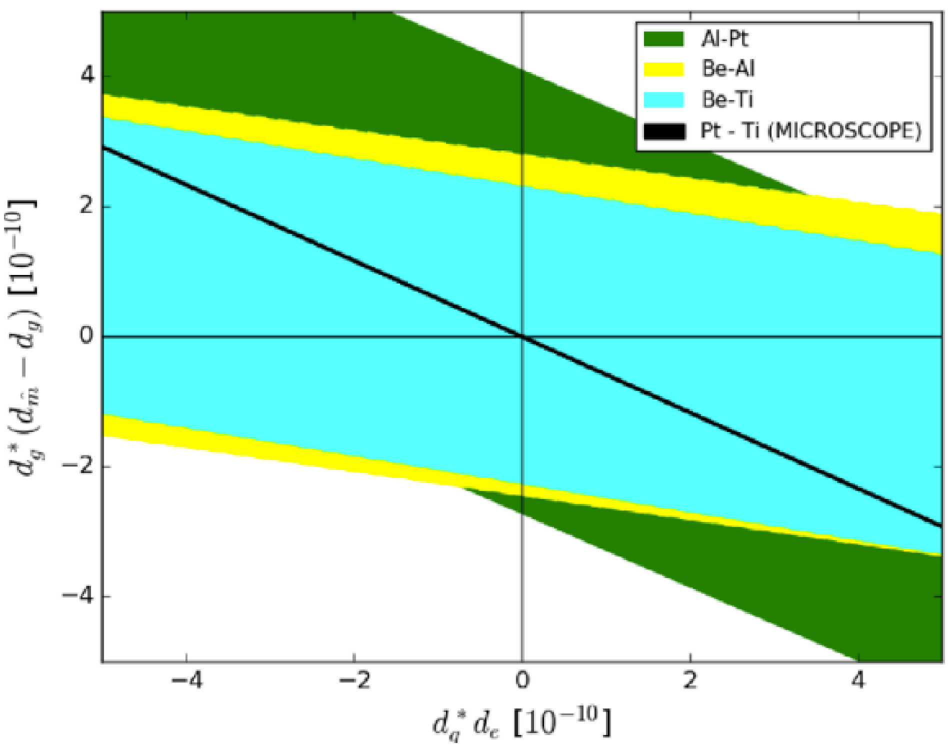


Berge. Rep. Prog. Phys. 86 (2023) 066901

Violations of WEP

Constraints on a massless ‘dilaton’

$$\mathcal{L}_{\text{int}} = \frac{\phi}{M_{\text{Pl}}^2}\left[\frac{d_{\text{e}}}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_{\text{g}}\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_{\text{g}})m_i\bar{\psi}_i\psi_i\right]$$



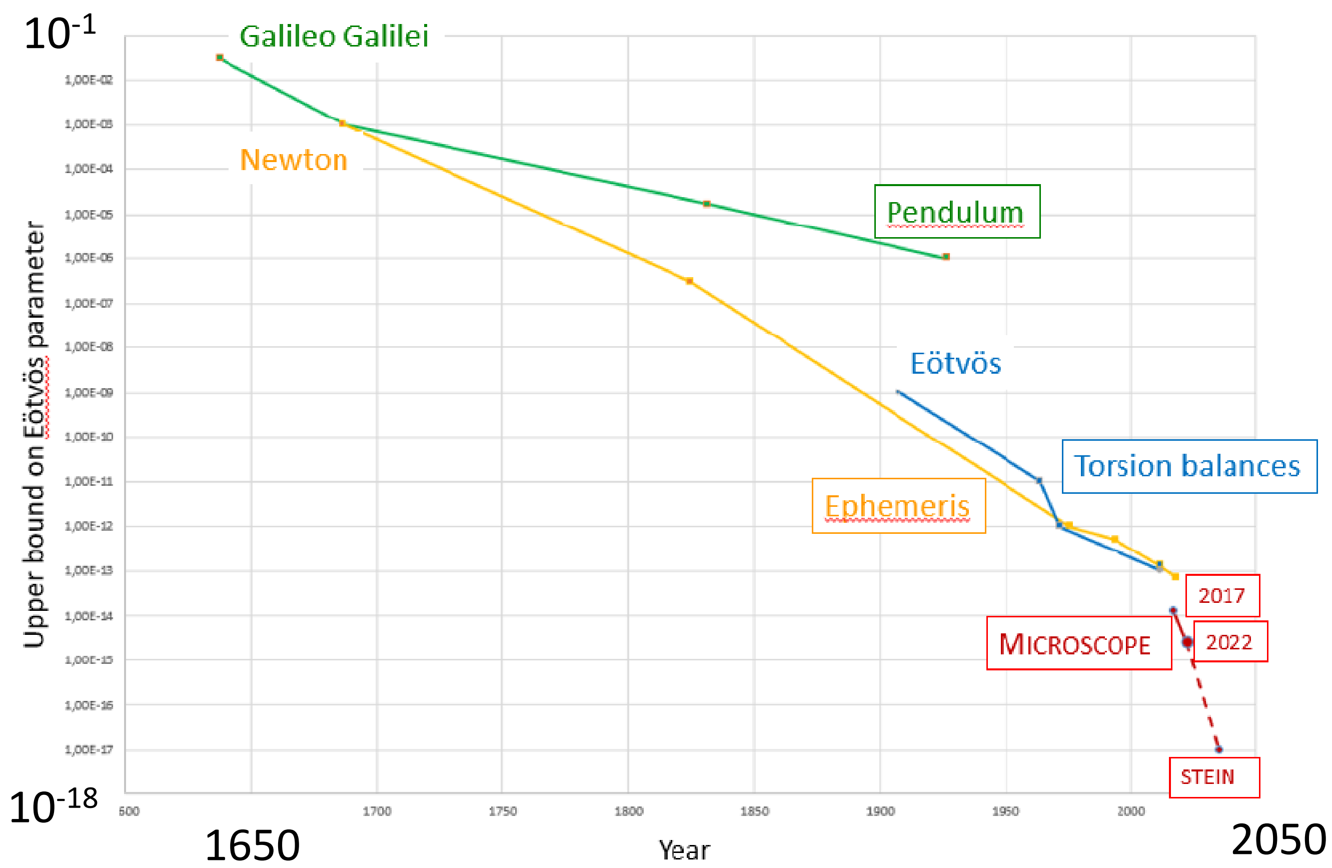
Berge. Rep. Prog. Phys. 86 (2023) 066901

Damour, Donoghue. PRD (2010) 8 084033, CQG (2010) 20 202001,

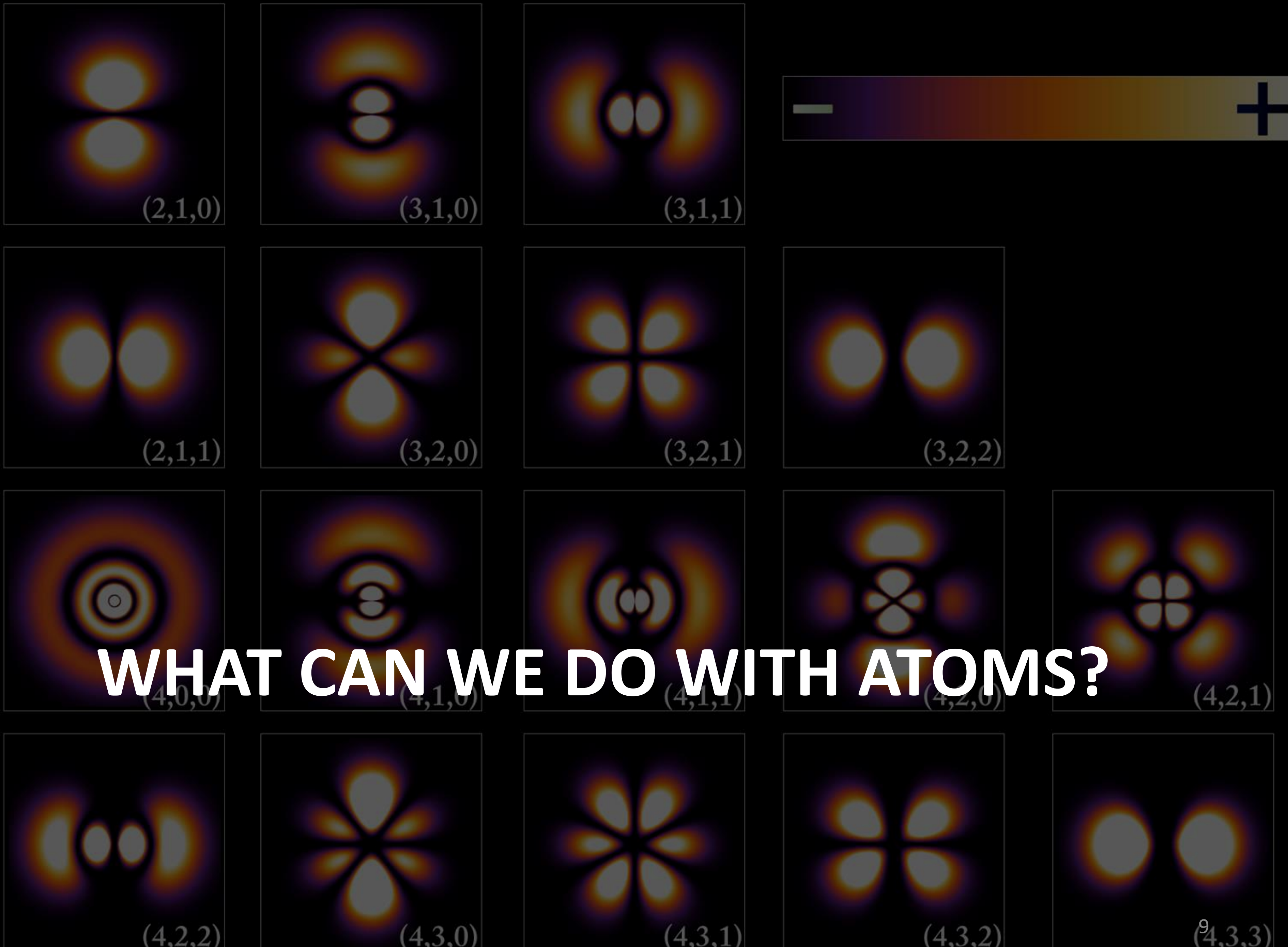
Future Searches

Satellite Test of Einstein's gravitation theory (STEIN)

Step 2 proposal for an ESA F-Class mission

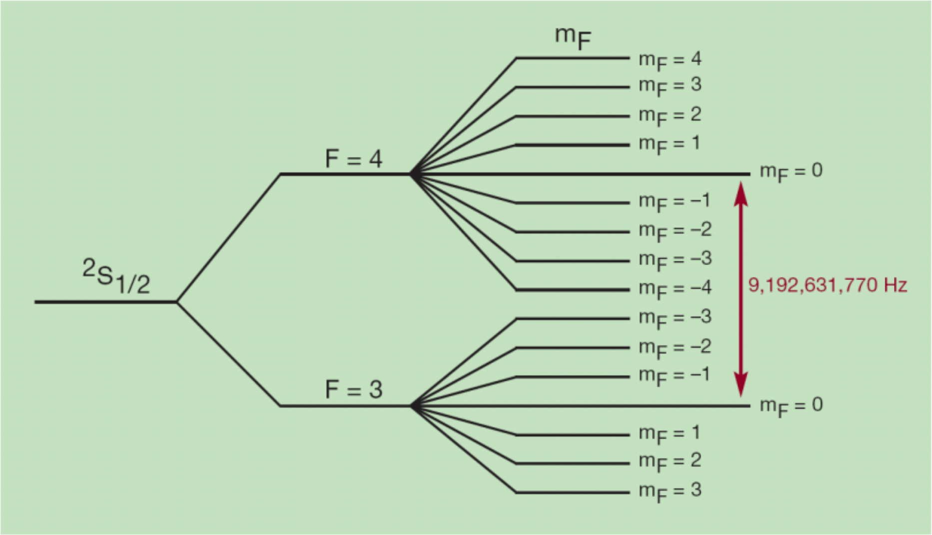


WHAT CAN WE DO WITH ATOMS?



Atomic Clocks

Driven oscillations in a ‘two state’ system



1 second = 9,192,631,770 transitions between hyperfine levels of the ground state of caesium 133 (at 0K)

Atomic Clocks

Typical accuracy Δf / f ~ 10^{-18}

Compare two different clocks:

Different transitions have different sensitivities to different fundamental constants

Ultra-Light Scalar Dark Matter

Light and feebly interacting bosons can be dark matter

A scalar field oscillating in a quadratic potential

$$\phi_{\rm homog}(t) = \phi_\infty \cos(mt + \delta)$$

Gives zero pressure and dark matter energy density

$$\rho_{\rm DM} = \frac{1}{2} m^2 \phi_\infty^2$$

Preskill, Wise, Wilczek. Phys. Lett.B 120 (1983) 127–132. Abbott, Sikivie. Phys. Lett.B 120 (1983) 133–136. Dine, Fischler, Phys. Lett. B 120 (1983)137–141.
For a review see e.g. Ferreira. Astron. Astrophys. Rev. 29 (2021) 1, 7

Ultra-Light Scalar Dark Matter

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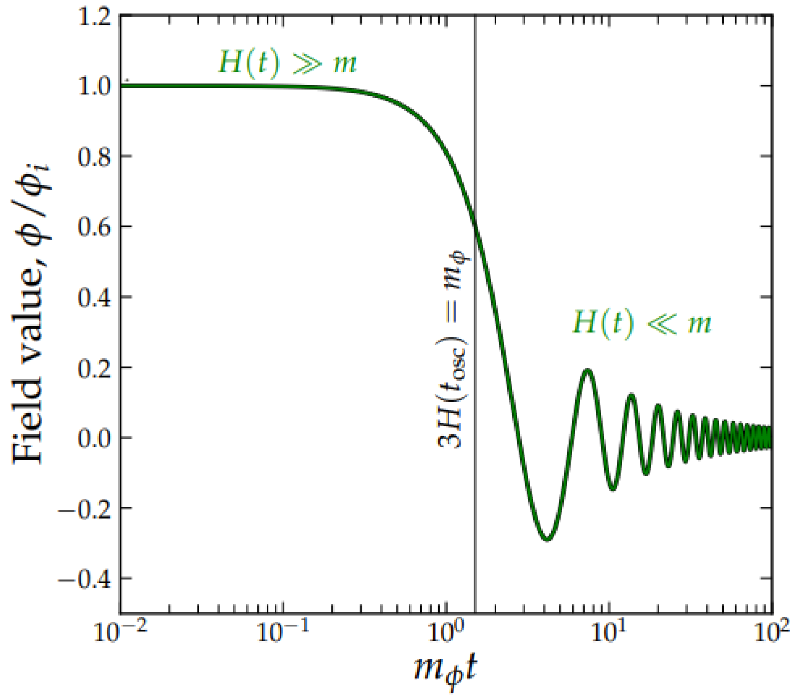


High occupation numbers mean they can be described as classical fields exhibiting a wave-like behaviour

Figure from lecture notes by O'Hare. Arxiv:2403.17697

Atomic Clocks

Interactions with matter

$$\mathcal{L} = (\kappa\phi)^n \left(d_\gamma^{(n)} \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - d_{m_e}^{(n)} m_e \bar{\psi}_e \psi_e \right)$$

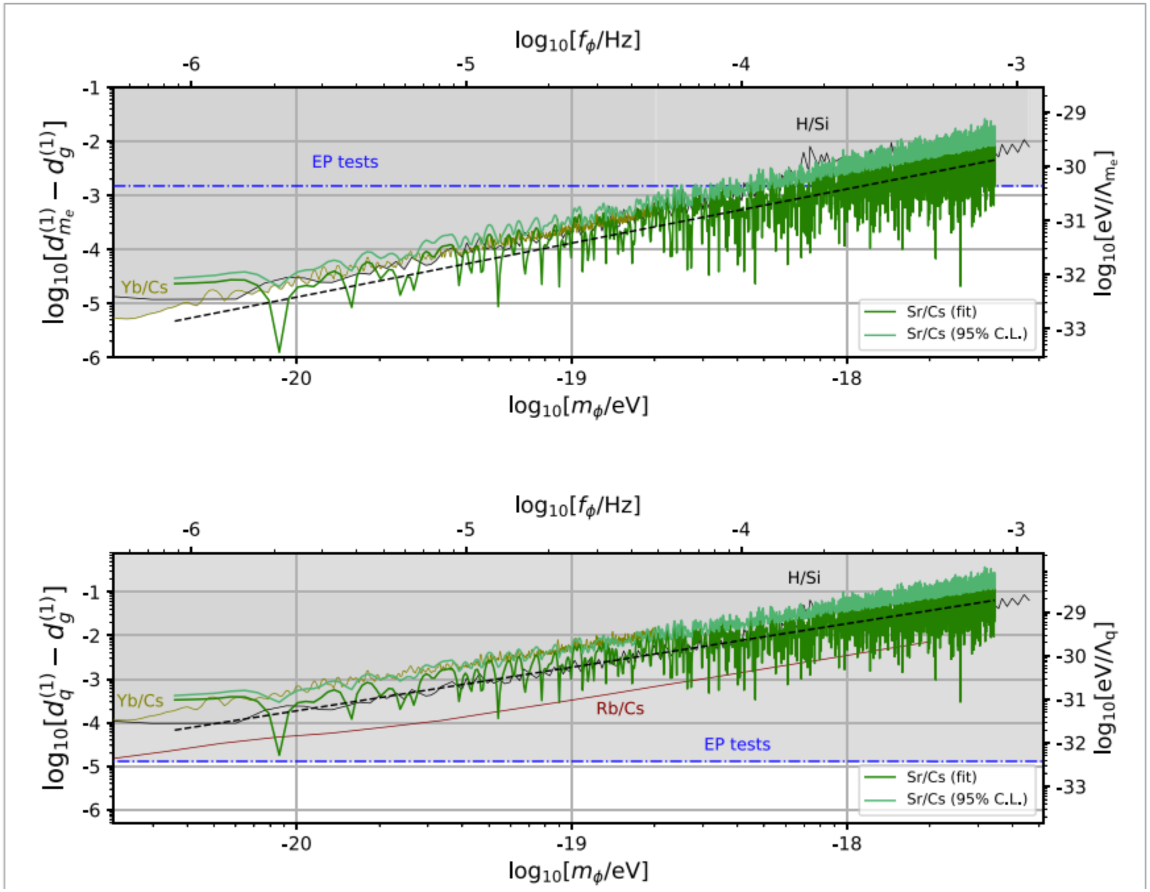
Lead to variations in fundamental constants

$$\frac{\delta\alpha}{\alpha} \equiv d_\gamma^{(n)} (\kappa\phi)^n \qquad \frac{\delta m_f}{m_f} \equiv d_{m_f}^{(n)} (\kappa\phi)^n \qquad \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} \equiv d_g^{(n)} (\kappa\phi)^n$$

Sherrill et al, New J. Phys. 25 093012 (2023)

Atomic Clocks – Constraints on ULDM

$$\phi_{\rm homog}(t) = \phi_\infty \cos(mt + \delta)$$



Sherrill et al, New J. Phys. 25 093012 (2023)

For dark energy and modified gravity constraints and forecasts see:

Elder et al. Phys.Rev.D 112 (2025) 4, 044053

Ultra-Light Scalar Dark Matter

Quadratic interactions from

e.g. symmetric Higgs portals, axion models

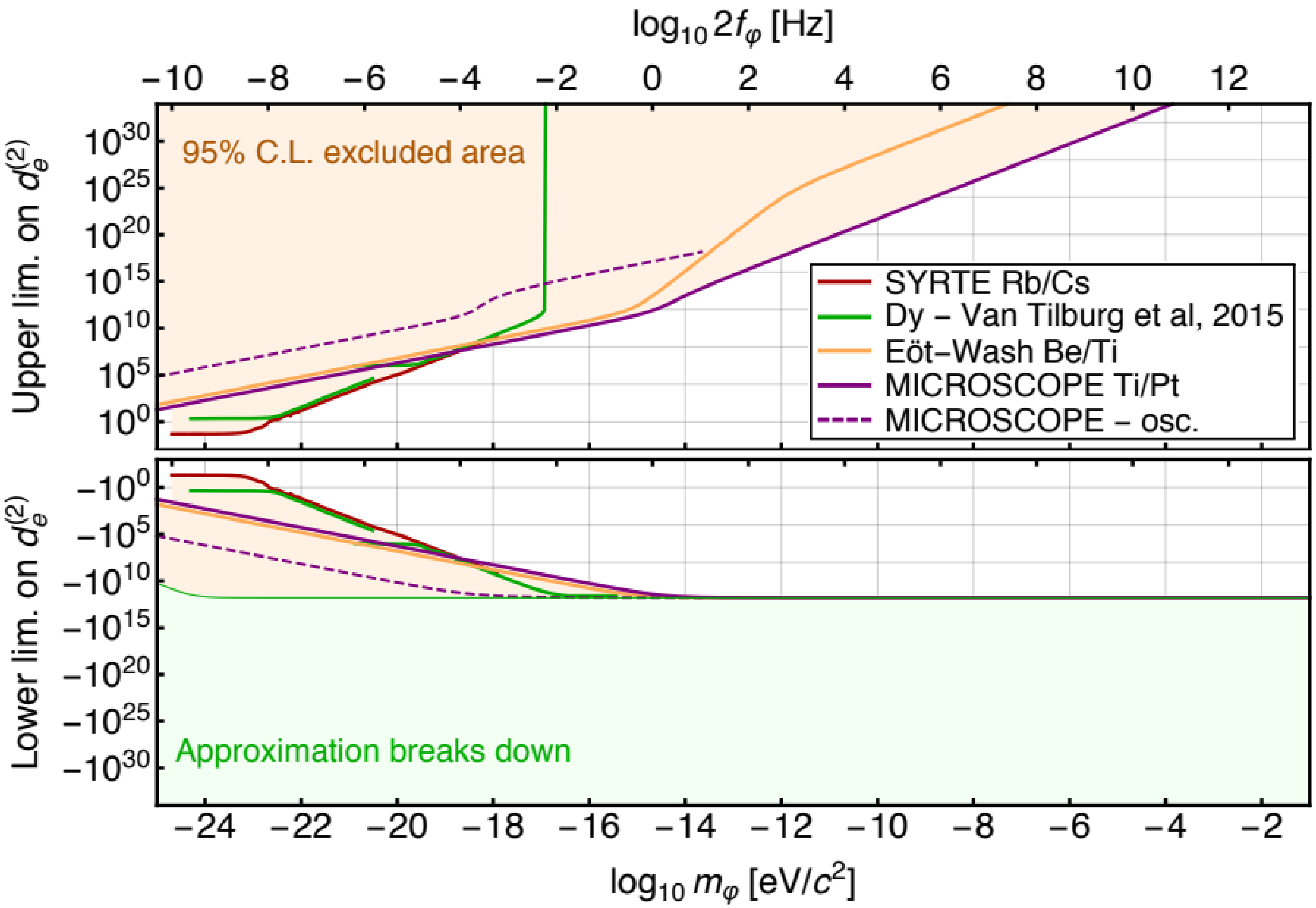
$$\mathcal{L}_{int} = \frac{(\kappa\phi)^2}{2}\left[\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\ \mu\nu} - \sum_{i=u,d,e}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

Leading to: Varying fundamental 'constants'

Macroscopic couplings to non-relativistic energy density

$$S = \int d^4x\left(\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}\rho\alpha\phi^2\right)$$

Ultra-Light Scalar Dark Matter - Constraints



Hees, Minazzoli, Savalle, Stadnik, Wolf. Phys. Rev. D 98 no. 6, (2018) 064051

See also: Banerjee, Perez, Safronova, Savoray. JHEP 10 (2023) 042

Bartnick, Springmann, Stelzl, Weiler. arxiv:2509.25305

Bauer, Chakraborti, Rostagni, JHEP 05 (2025) 023

Ultra-Light Scalar Dark Matter

$$S = \int d^4x \left(\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}\rho\alpha\phi^2 \right)$$

Density dependent effective mass, can lead to short Compton wavelengths

$$\lambda_C = \frac{h}{m_{\rm eff}c} \approx 10^{-5} \left(\frac{\rm GeV^{-2}}{\alpha} \right)^{1/2} \left(\frac{\rm g/cm^3}{\rho} \right)^{1/2} \rm cm$$

Scalar cavity can suppress the amplitude of dark matter oscillations

CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

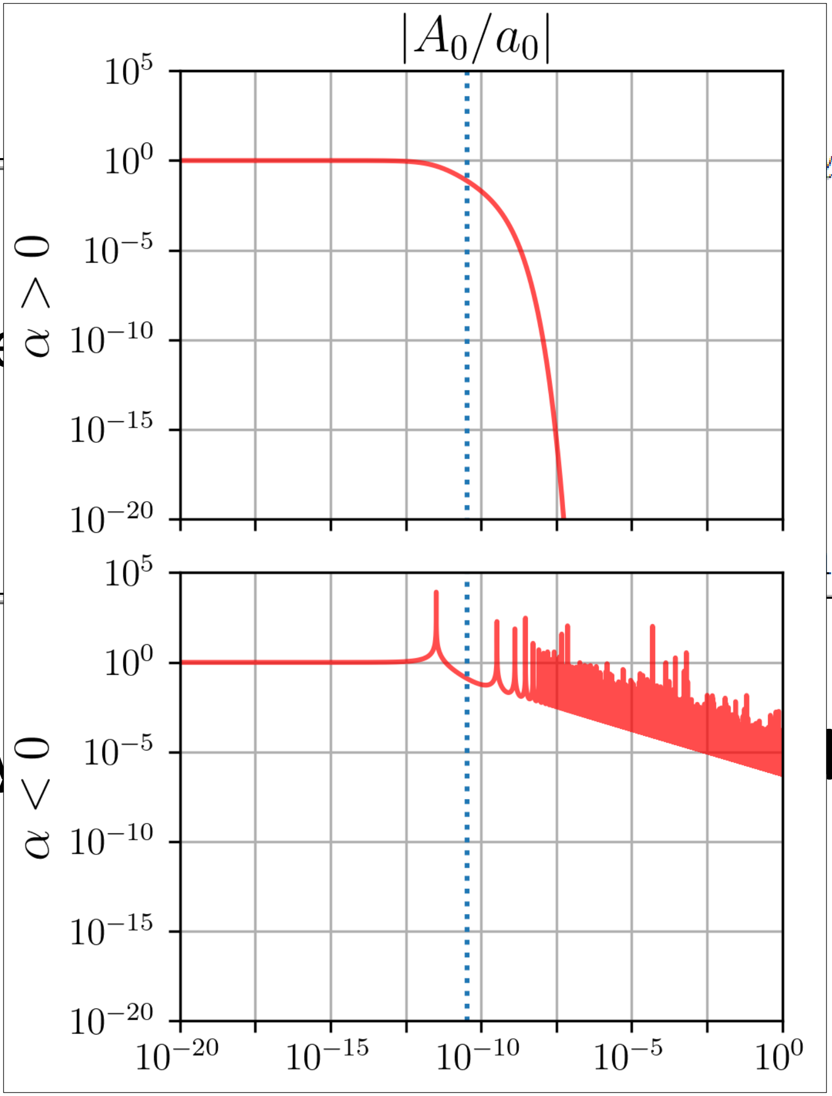
Ultra-Light Scalar Dark Matter

S = ... $\phi^2\Big)$

Density de... n lead to short

$\lambda_C =$ ... $\Big)^{1/2}$ cm

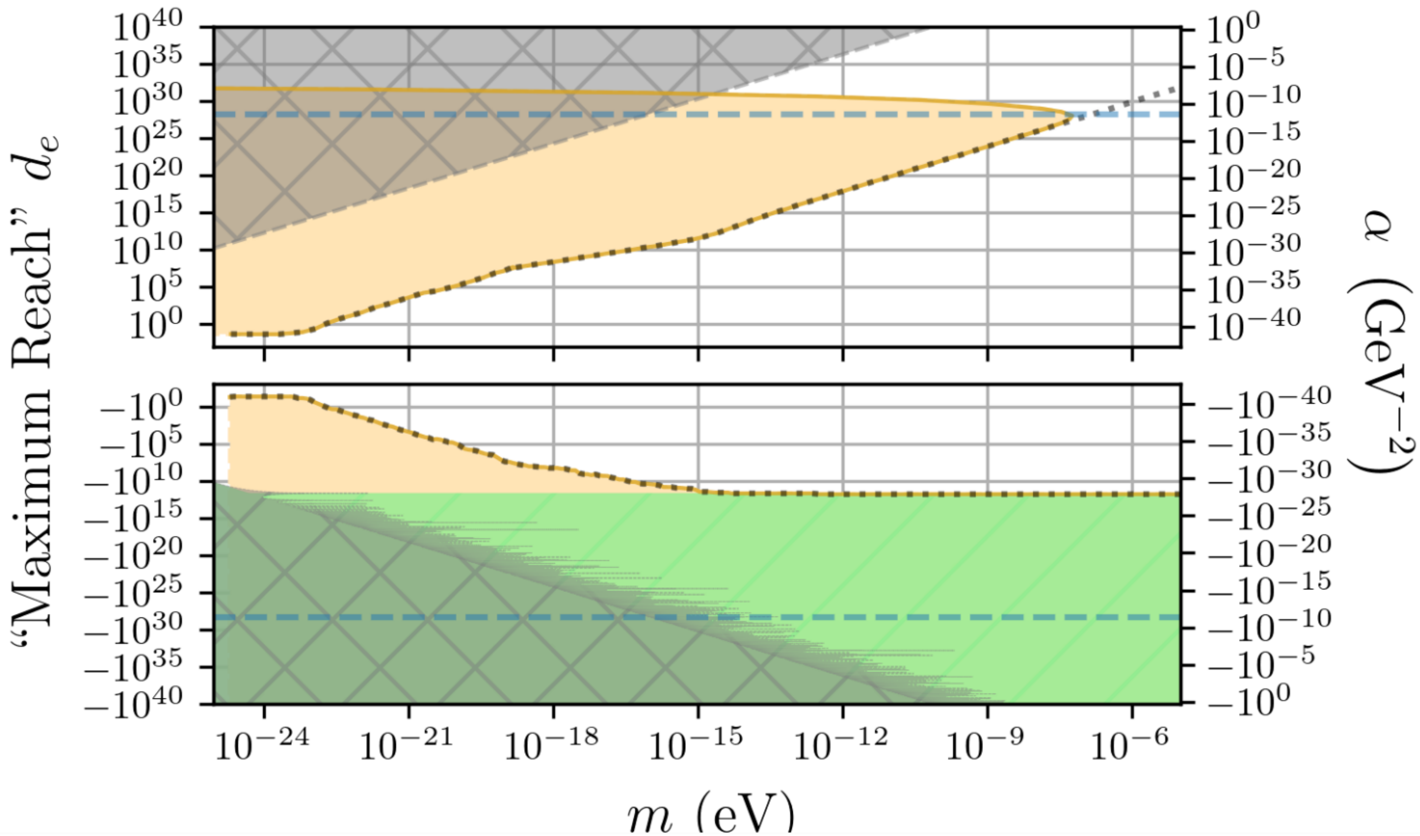
Scalar cavity ... le of dark matter



CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

Effects of a Spherical Cavity

Naive rescaling weakens constraints at strong coupling



Also new opportunities for space-based searches

CB, MacDonald, Ross, Rybka, Todarello. arXiv:2507.16526

Networks of atomic clocks

Search for spatial gradients from dark matter velocity dispersion

$$\phi(t, \boldsymbol{x}) = \phi_0 \cos\left(\omega t - \boldsymbol{k} \cdot \boldsymbol{x}\right)$$

Induced frequency shift

$$\frac{\delta(\nu^A/\nu^B)}{\nu^A/\nu^B} = \kappa\phi_0 d_{\mathrm{eff}}[\cos(\omega t) - \cos(\omega t - \delta)]$$

$$\approx \kappa\phi_0 d_{\mathrm{eff}} \sin(\omega t)\delta,$$

$$\delta = \omega \Delta t - \boldsymbol{k} \cdot \Delta \boldsymbol{x},$$

Δt the time delay due to signal propagation

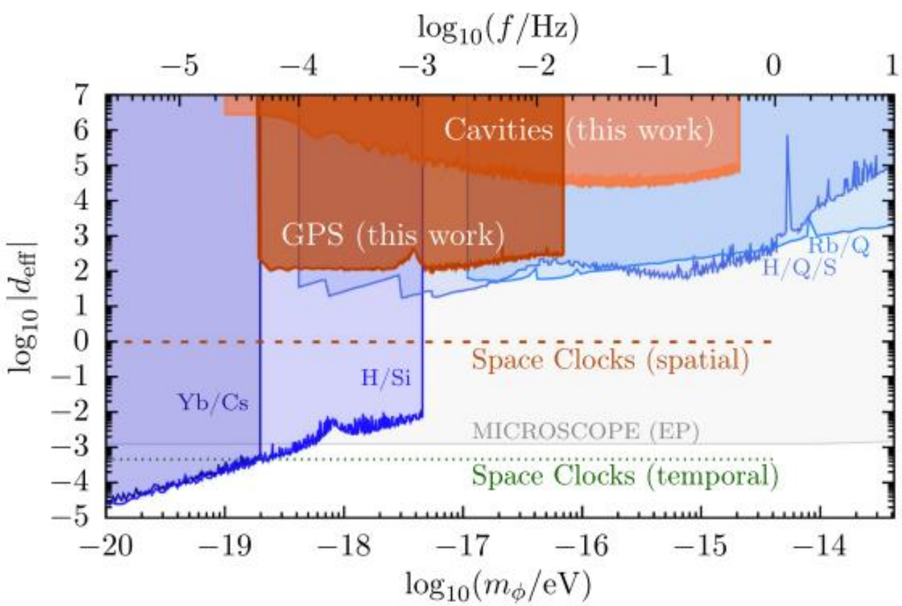
Δx the distance between the oscillators

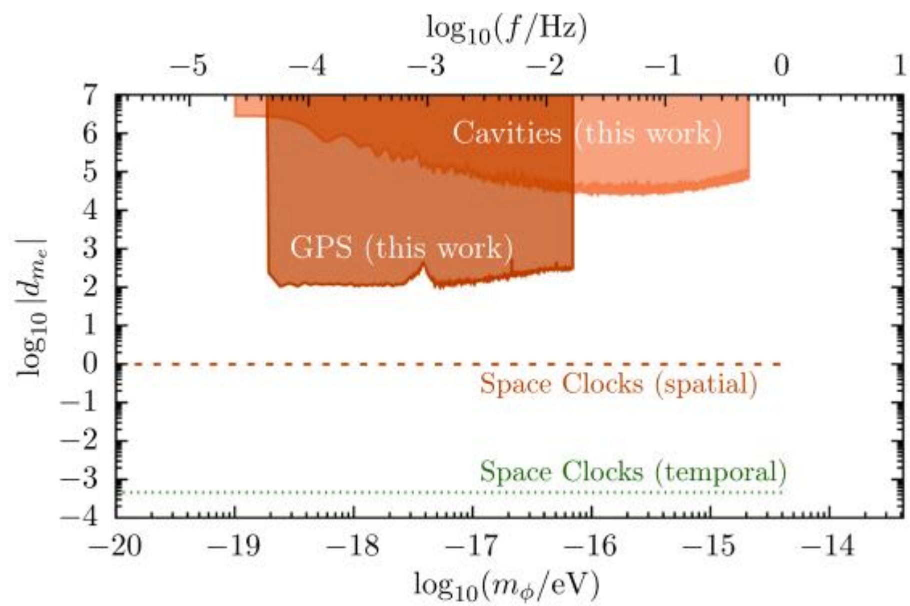
Filzinger et al. Phys Rev Lett. 134 031001 (2025)

Networks of atomic clocks

Constraints from optical cavities, 2220 km separation,

Atomic clocks on GPS satellites, 30 satellites orbiting at a radius of 26,000 km





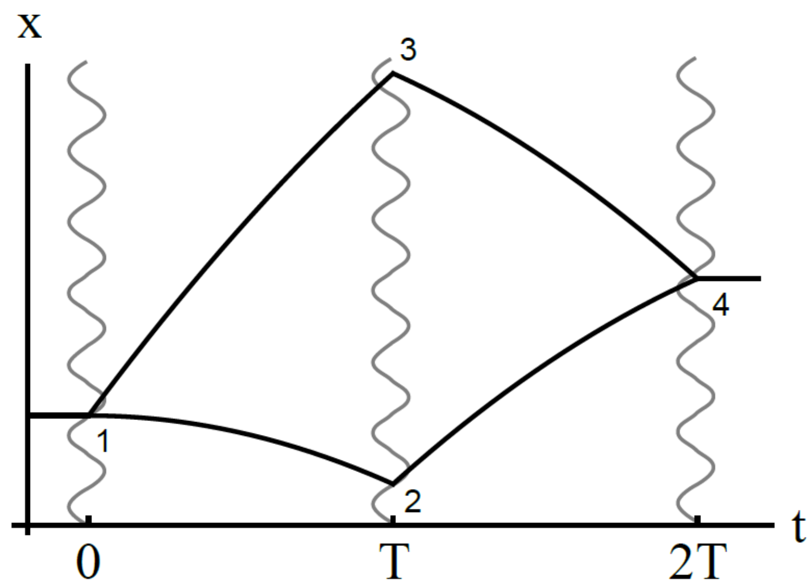
Filzinger et al. Phys Rev Lett. 134 031001 (2025)
Schioppo et al. Nat. Commun. 13, 212 (2022)

Atom Interferometry

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons

Atom interferometry

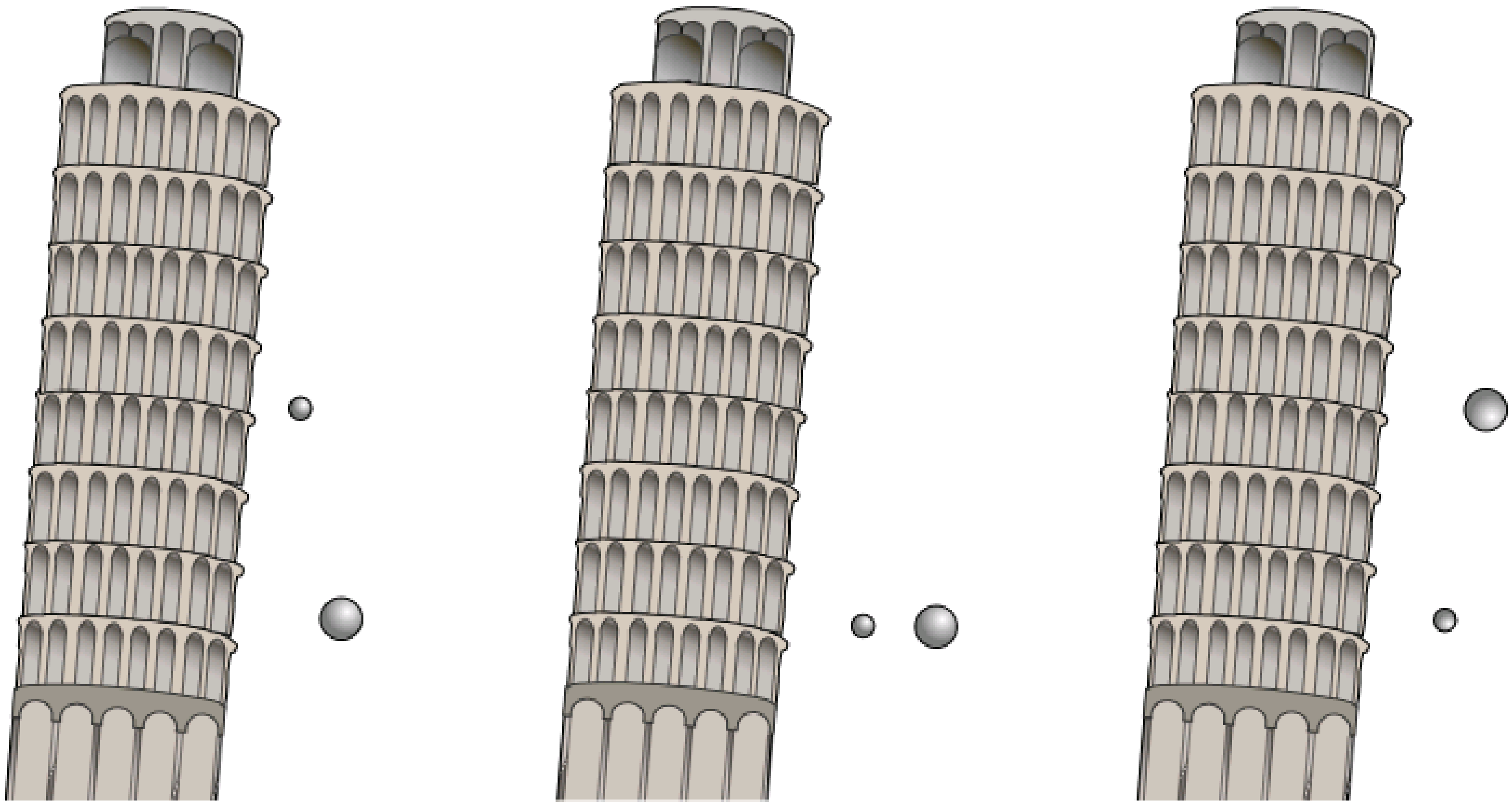


Phase difference accumulates from:
the propagation phase, the laser interaction phase, and the final wavepacket separation phase

Determines probability atoms exit in ground or excited state

As a test of the equivalence principle

Do objects with different composition fall at the same rate?



Old idea Galileo New physics?

Image credit: Theresa Knott

The Chameleon

A scalar field with canonical kinetic terms, non-linear potential, and direct coupling to matter

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)\rho_\mathrm{m}\right)$$

$$V(\phi) = \frac{\Lambda^5}{\phi}, \quad A(\phi) = \frac{\phi}{M} \ ,$$

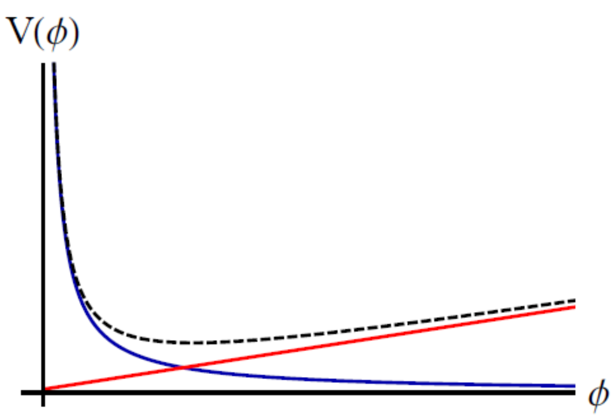
Khoury, Weltman. Phys.Rev.Lett. 93 (2004) 171104. Image credit: Nanosanchez

Varying Mass

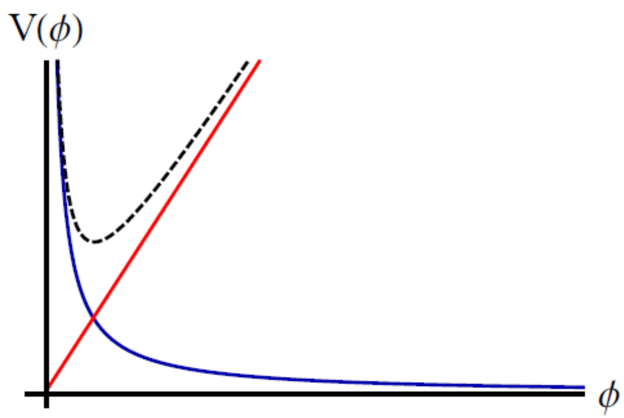
Dynamics governed by an effective potential

$$V_{\text{eff}} = \frac{\Lambda^5}{\phi} + \frac{\phi}{M}\rho$$

Non-linearities in the potential mean that the mass of the field depends on the local energy density



Low density

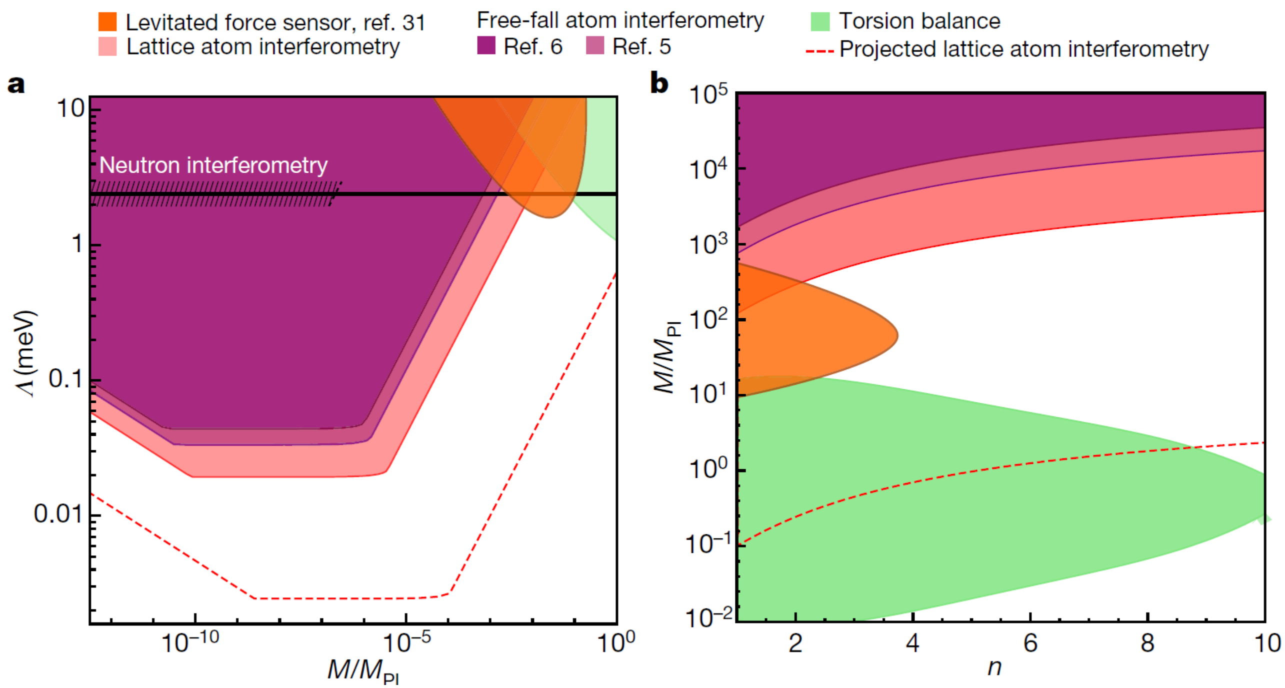


High density

Field is suppressed inside compact objects

Chameleon: Combined Constraints

Bare potential: $V(\phi) = \Lambda^{n+4}/\phi^n$
Bare matter coupling: M



Anomalous acceleration < 6.2 nm s^{-2}

Panda, Tao, Ceja, Khoury, Tino, Muller. Nature 631, 515–520 (2024)
See also: Sabulsky, Dutta, Hinds, Elder, CB, Copeland. Phys.Rev.Lett. 123 (2019) 6, 061102
Brax, Davis, Elder. Phys. Rev. D 107 (2023) 084025

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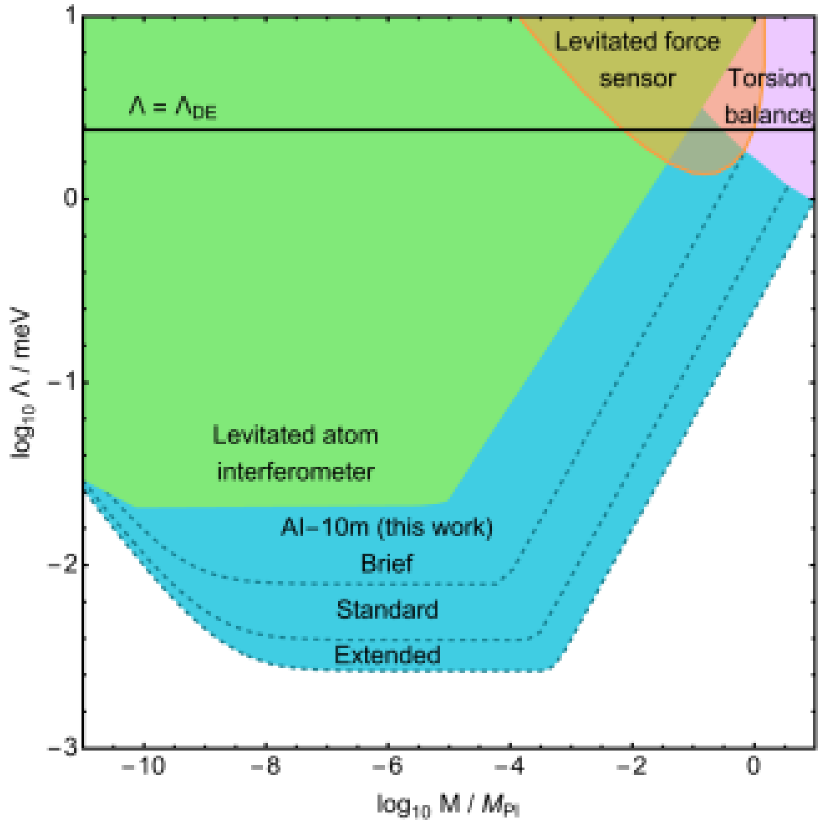
Bare potential: $V(\phi) = \Lambda^{n+4}/\phi^n$

Bare matter coupling: M

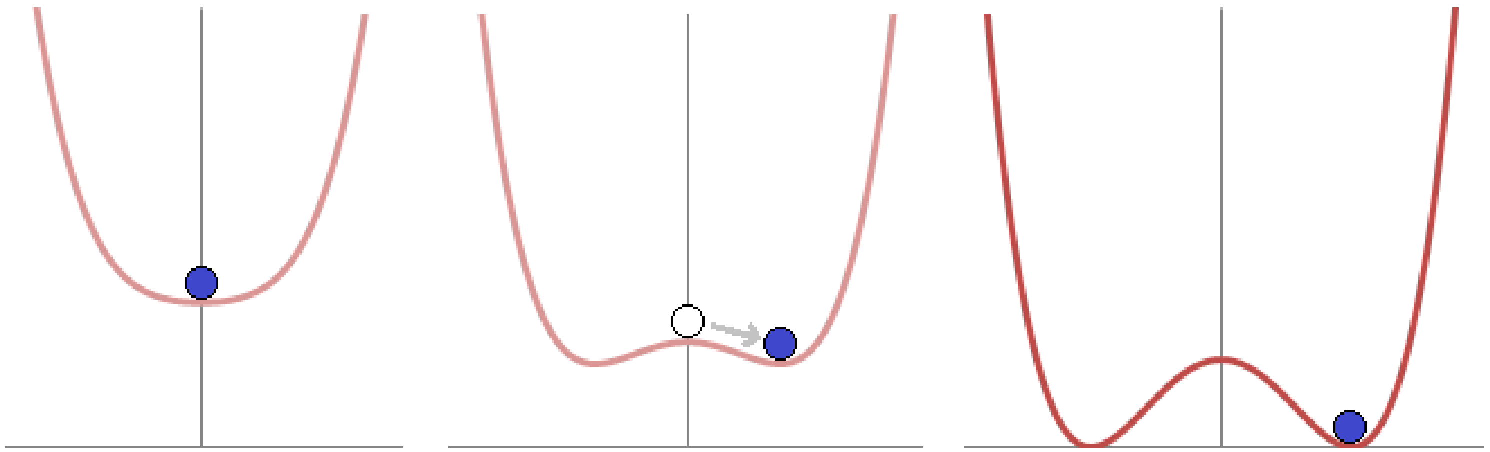


Banks, Carlton, Elder, Hird, McCabe. arXiv:2511.09750

Symmetron Screening

Effective potential

$$V_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$

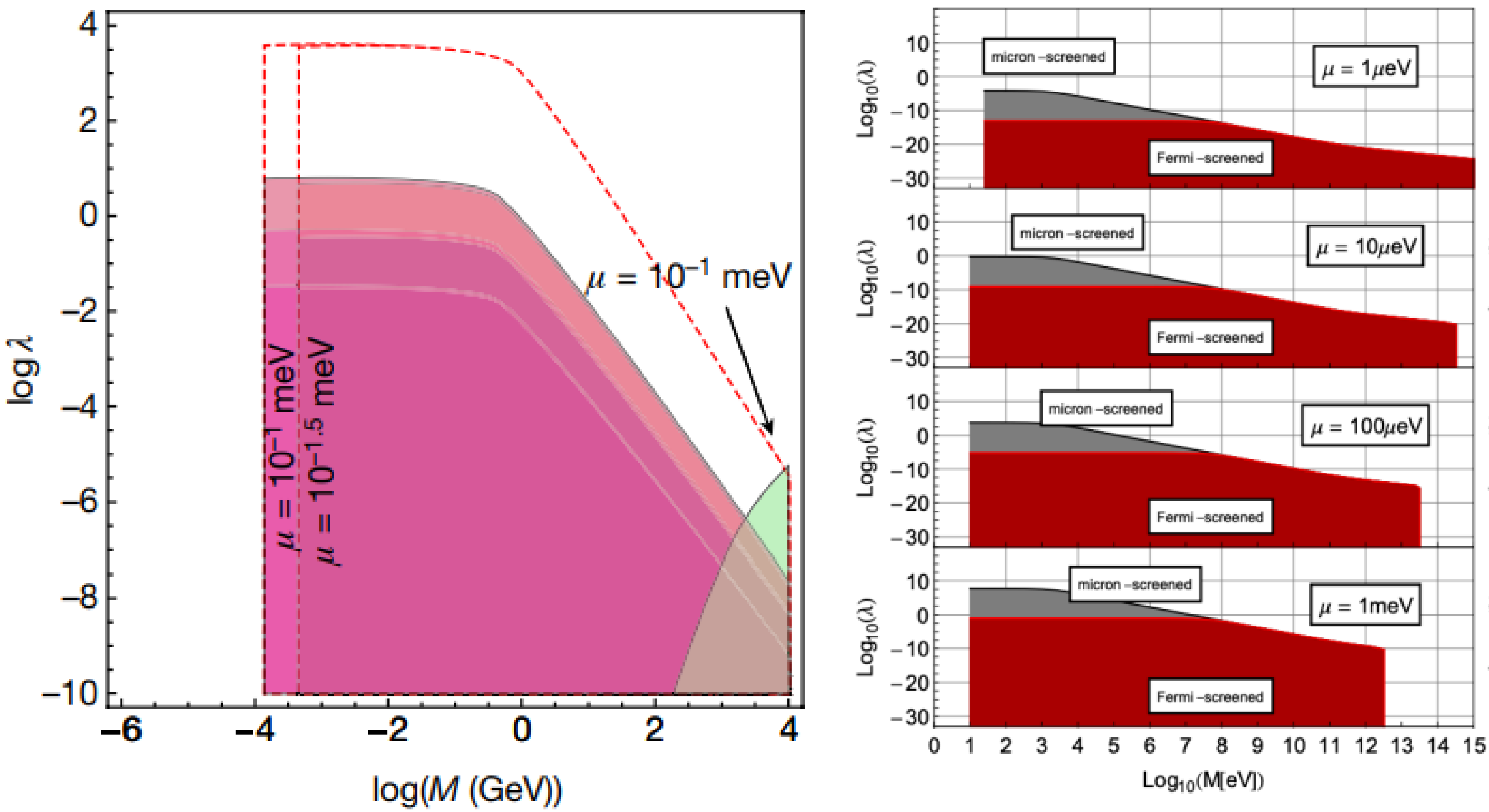


Fifth force vanishes when symmetry is restored

$$F = \phi\nabla\phi/M^2$$

Hinterbichler, Khoury. Phys.Rev.Lett. 104 (2010) 231301

Symmetron: Laboratory Constraints

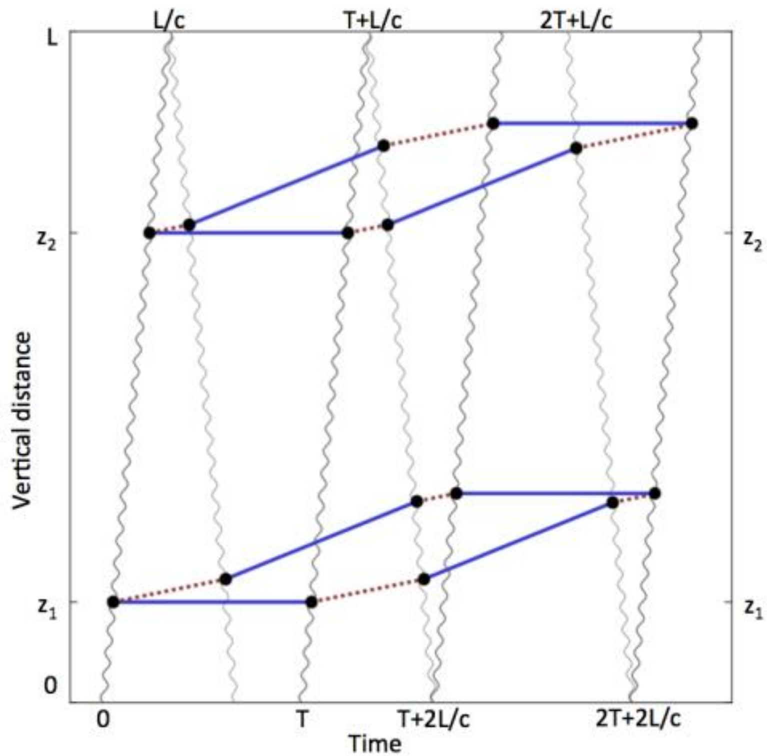


Panda, Tao, Ceja, Khoury, Tino, Muller. Nature 631, 515–520 (2024), Jenke, Bosina, Micko, Pitschmann, Sedmik, Abele, Eur. Phys. J. ST 230, 1131 (2021), 2012.07472.
Constraints do not contain corrections from Millington, Udemba. arXiv:2508.16726

Detecting Oscillations

Transition frequency may also oscillate with time

Differential interferometer, one laser interacts with (at least) two spatially separated clouds of atoms



Arvanitaki et al. Phys. Rev. D 97, 075020 (2018). Badurina et al. JCAP 05 (2020) 011

Detecting Oscillations

Over the interferometer

$$\overline{\Phi}_{\rm s} = 8\frac{\Delta\omega_A}{m_\phi} \times \left|\sin\left[\frac{m_\phi n L}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\right|$$

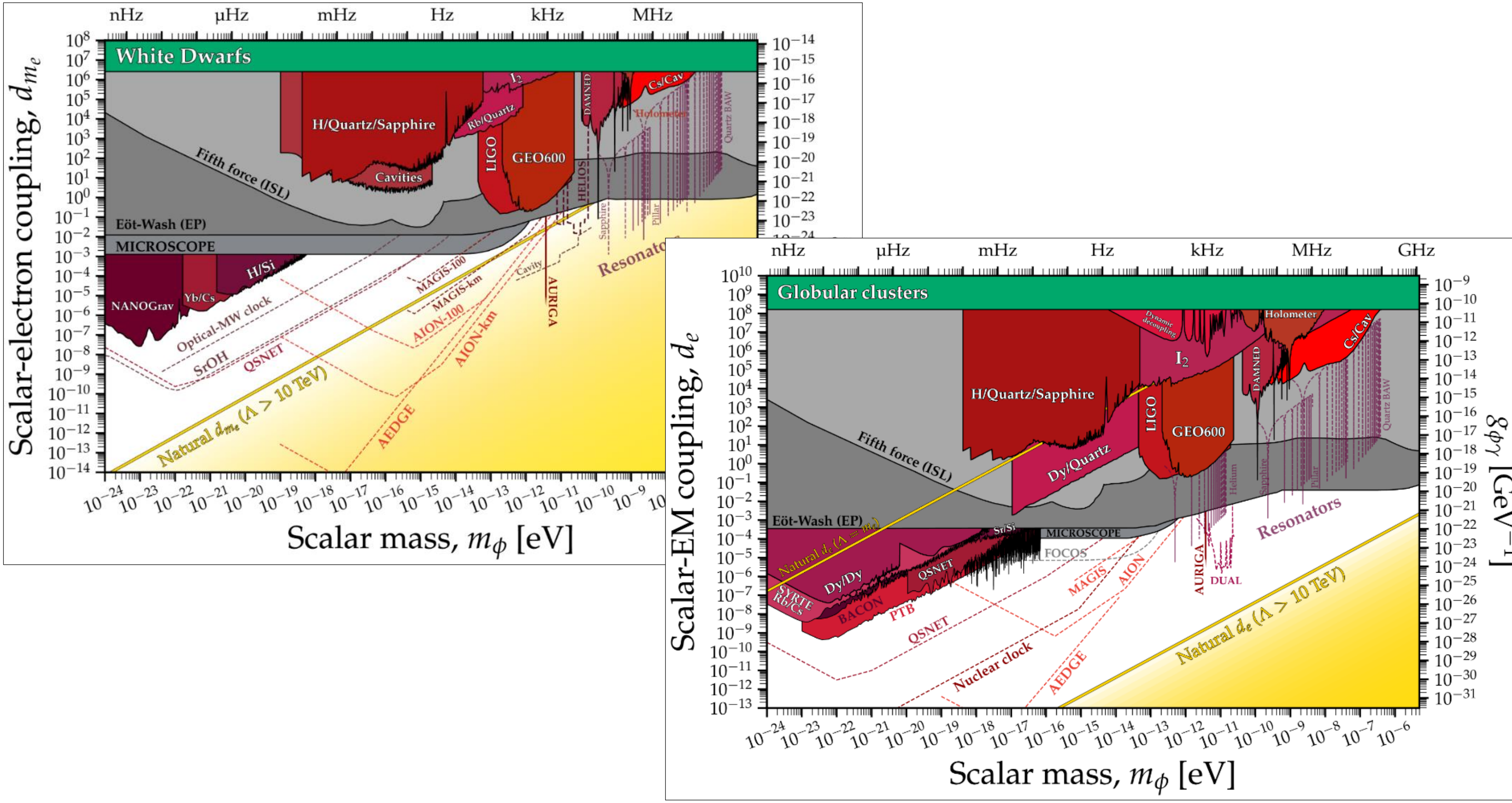
Terrestrial Very Long Baseline AI, e.g. AION, Magis, 100m and 1km baseline

Space based AEDGE,~ 10^5 km baseline

AION

Arvanitaki et al. Phys. Rev. D 97, 075020 (2018), Abdalla et al. EPJ Quant. Technol. 12 (2025) 1 42. Abou El-Neaj et al. EPJ Quant. Technol. 7 (2020) 6.

ULDM Sensitivity



https://cajohare.github.io/AxionLimits/

Also sensitive to other dark matter models e.g. spin 2.

Blas, Carlton, McCabe. Phys. Rev. D. 111 (2025) 11 11 5020

Also sensitive to dark matter gradients. Geraci, Derevianko. Phys. Rev. Lett. 117, 261301 (2016)

AI GW Detector

GW distortion of space time

$$ds^2 = c^2 dt^2 - (1 + h \sin(\omega(t-z) + \phi_0))\, dz^2 - (1 - h \sin(\omega(t-z) + \phi_0))\, dy^2 - dx^2$$

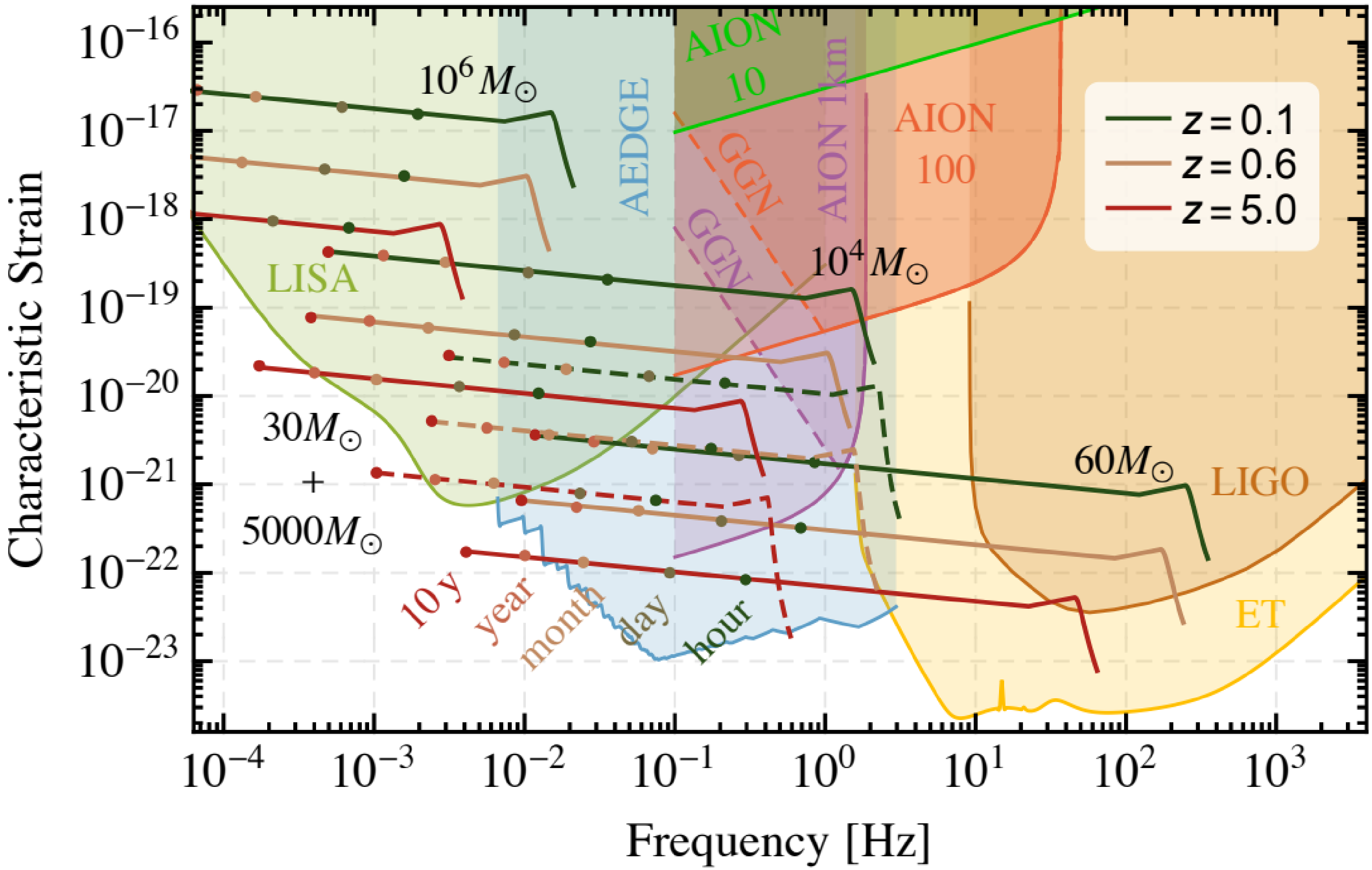
will change the space-time coordinates of the interaction points

Spatial separation of the two interferometers much larger than the separation of the wavepackets in each interferometer

Phase shift difference between interferometers

$$\Delta\phi_{\mathrm{diff}} = 4\frac{h\,\omega_A}{\omega}\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\frac{\omega\,(z_2 - z_1)}{2c}\right)\sin\left(\omega T + \frac{\omega\,(z_1 + z_2)}{2c} + \phi_0\right)$$

Sensitivity



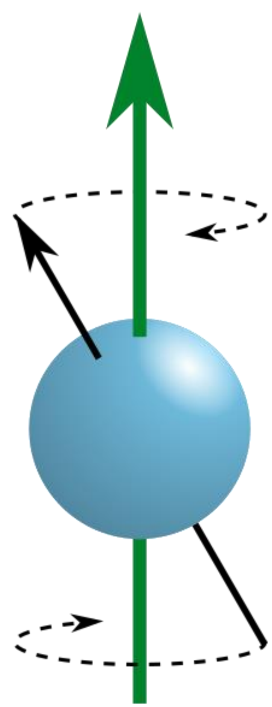
Badurina et al. JCAP 05 (2020) 011

Spin Precession

In the presence of a magnetic field the spin dipole axis precesses

- Can be detected with NMR

Can search for things that look like magnetic fields



Axions – Pseudo-scalar ULDM

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G}\text{Tr}G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l}\sum_\alpha \bar{l}_\alpha\gamma_\mu\gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q}\sum_\beta \bar{q}_\beta\gamma_\mu\gamma_5 q_\beta$$

Coupling to photons

Coupling to Gluons

Coupling to leptons

Coupling to quarks

Axion solution to the strong CP problem*

Axion-like particles – pseudo scalars with similar couplings

* But see also: Ai, Cruz, Garbrecht, Tamarit. Phys.Lett.B 822 (2021) 136616

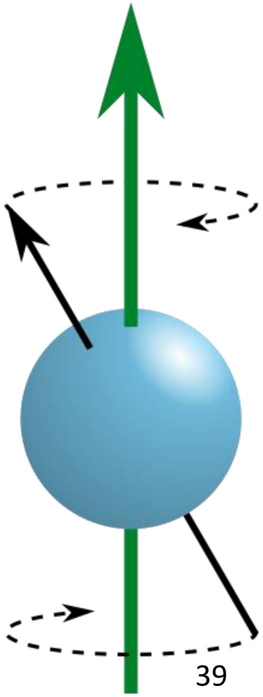
Spin Precession

Axions and ALPS couple to CP odd quantities

$$\mathcal{L}_{\rm ax} = g_{a\bar{\psi}\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$$

The axion gradient acts like a (pseudo-) magnetic field

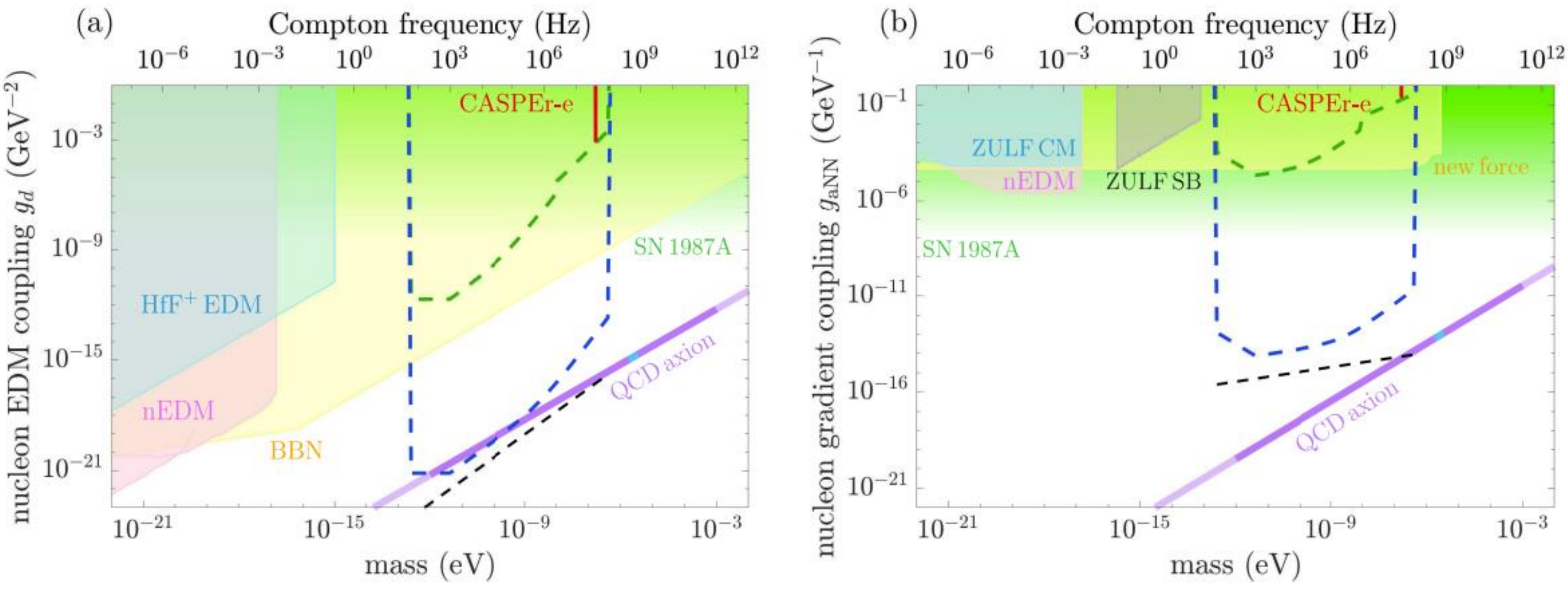
Spins will precess around the direction of the axion gradient



Jackson Kimball et al. Springer Proc.Phys. 245 (2020) 105-121

CASPEr Constraints

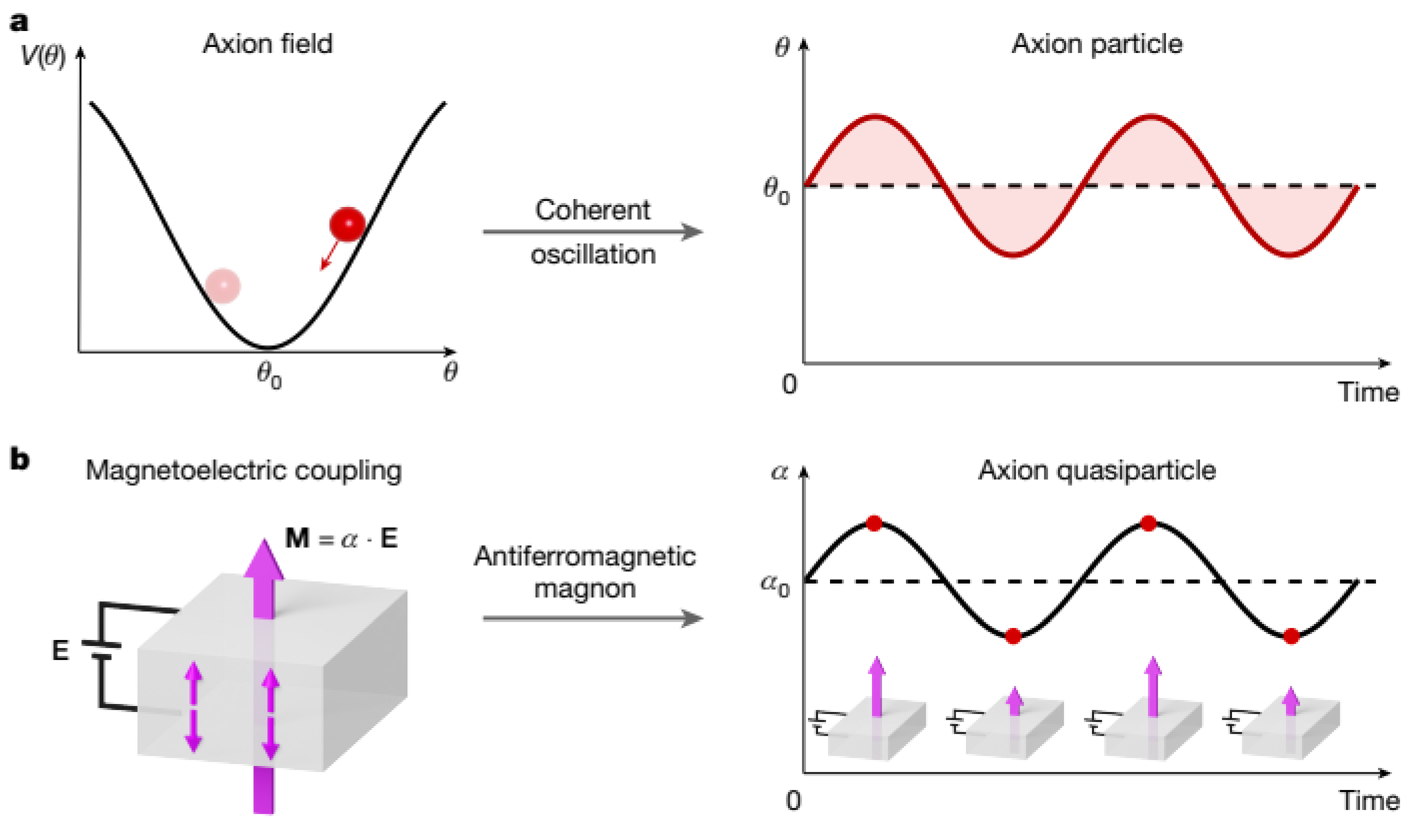
Precision measurement of ^{207}Pb solid state NMR in polarised crystal (4.6 mm) – extension to 80cm sample



Aybas et al. Phys. Rev. Lett. 126, 141802 (2021)

Quasi-particles

Axion quasi-particle observed in $MnBi_2Te_4$ (2D material) - magnons in an anti-ferromagnetic material



Qiu et al, Nature 641 62 (2025)

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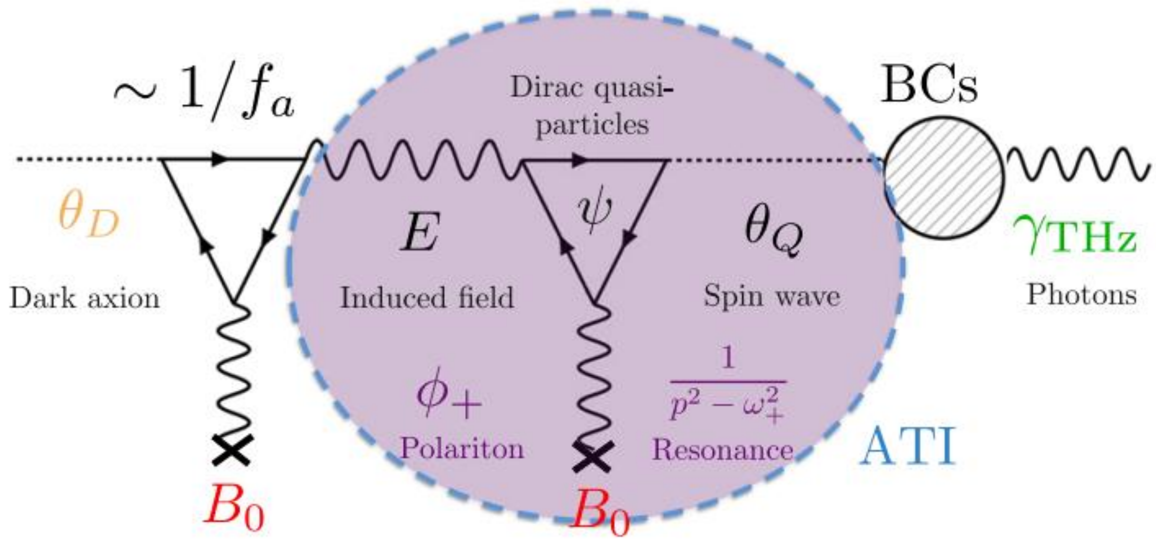
Axion quasi-particle observed in $MnBi_2Te_4$ (2D material)

Couple to a dark matter axion field

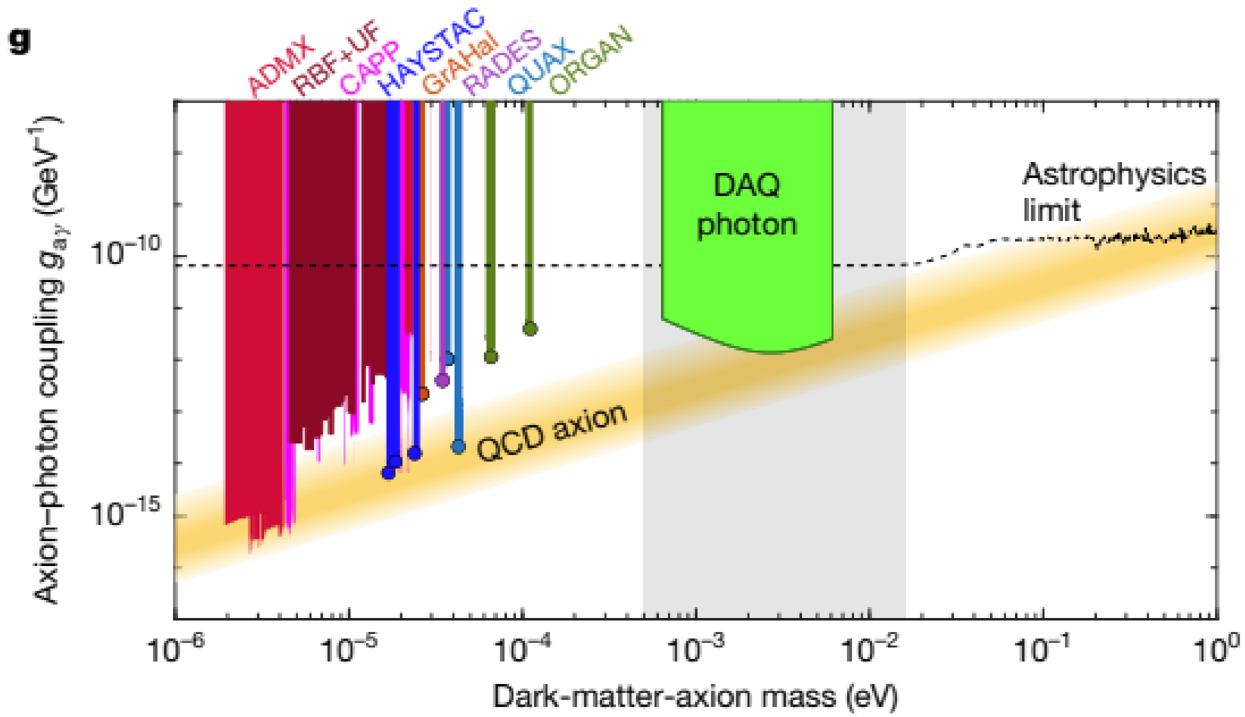


Qiu et al, Nature 641 62 (2025), Marsh et al PRL 123 121601 (2019)

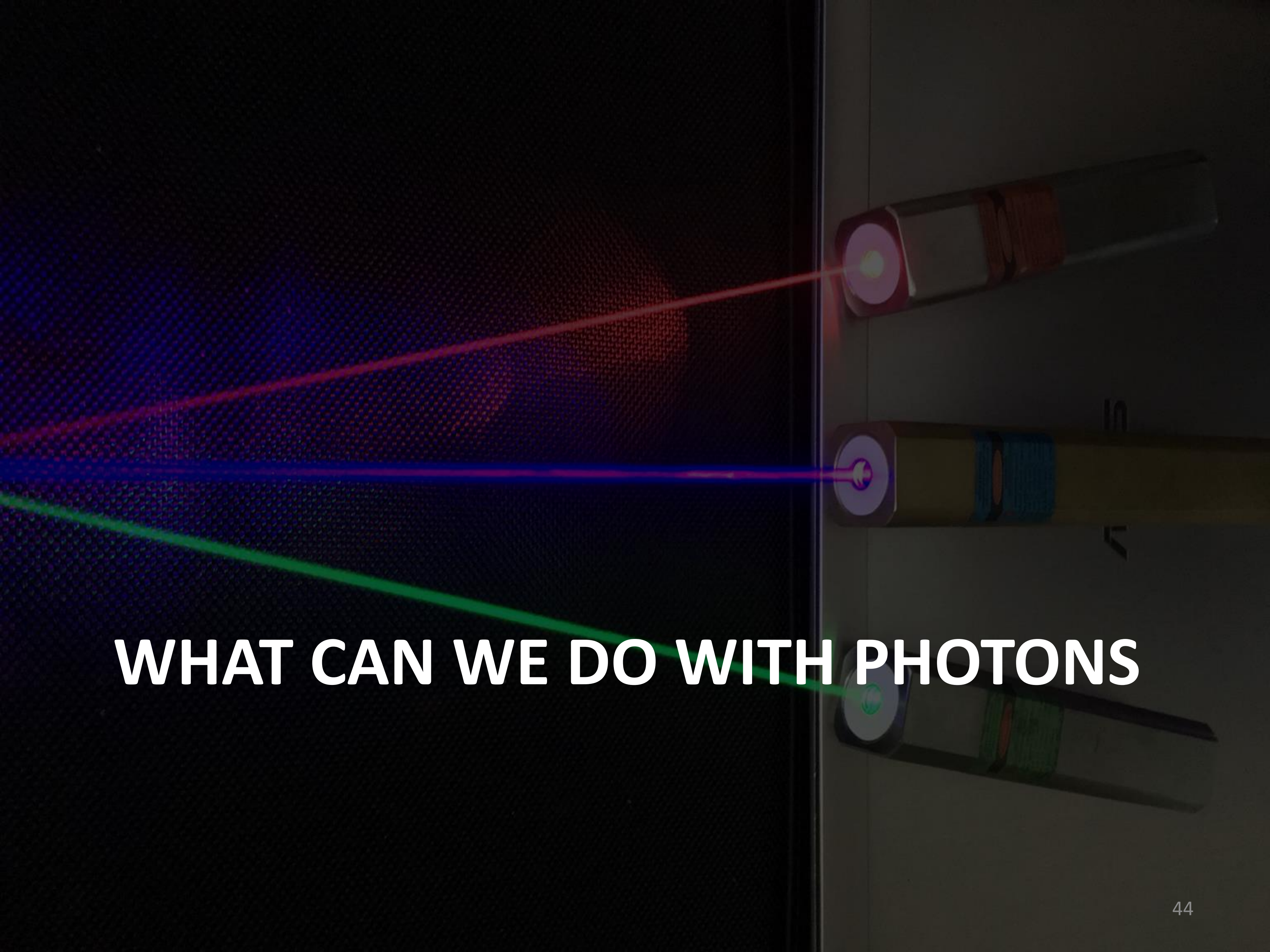
Quasi-particles

Collective excitations in $MnBi_2Te_4$ (2D material)

Couple to a dark matter axion field



Qiu et al, Nature 641 62 (2025), Marsh et al PRL 123 121601 (2019)



WHAT CAN WE DO WITH PHOTONS

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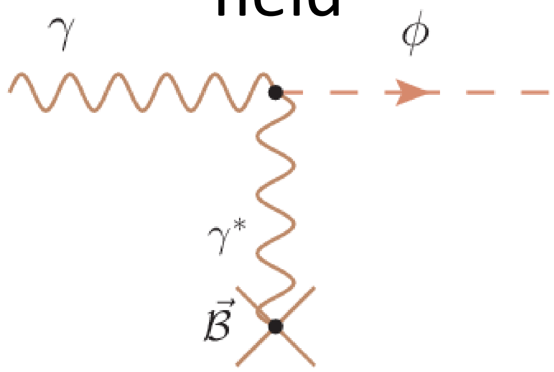
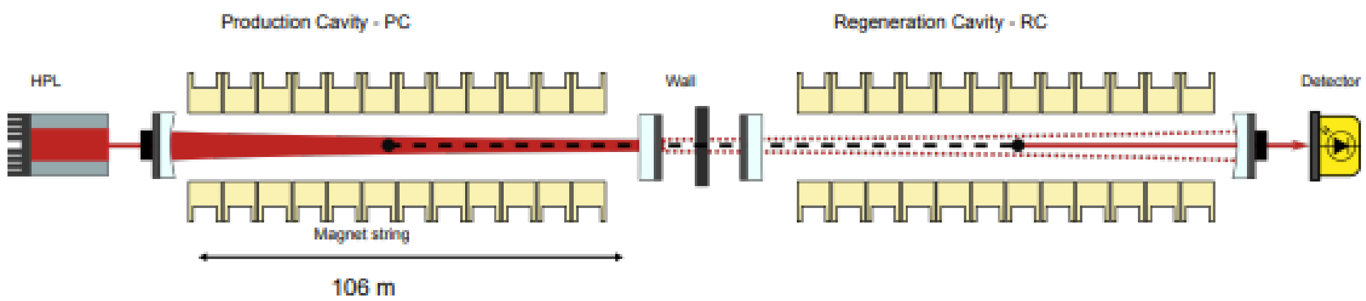
Light Shining Through Walls

Axion-photon mixing in the presence of a magnetic field



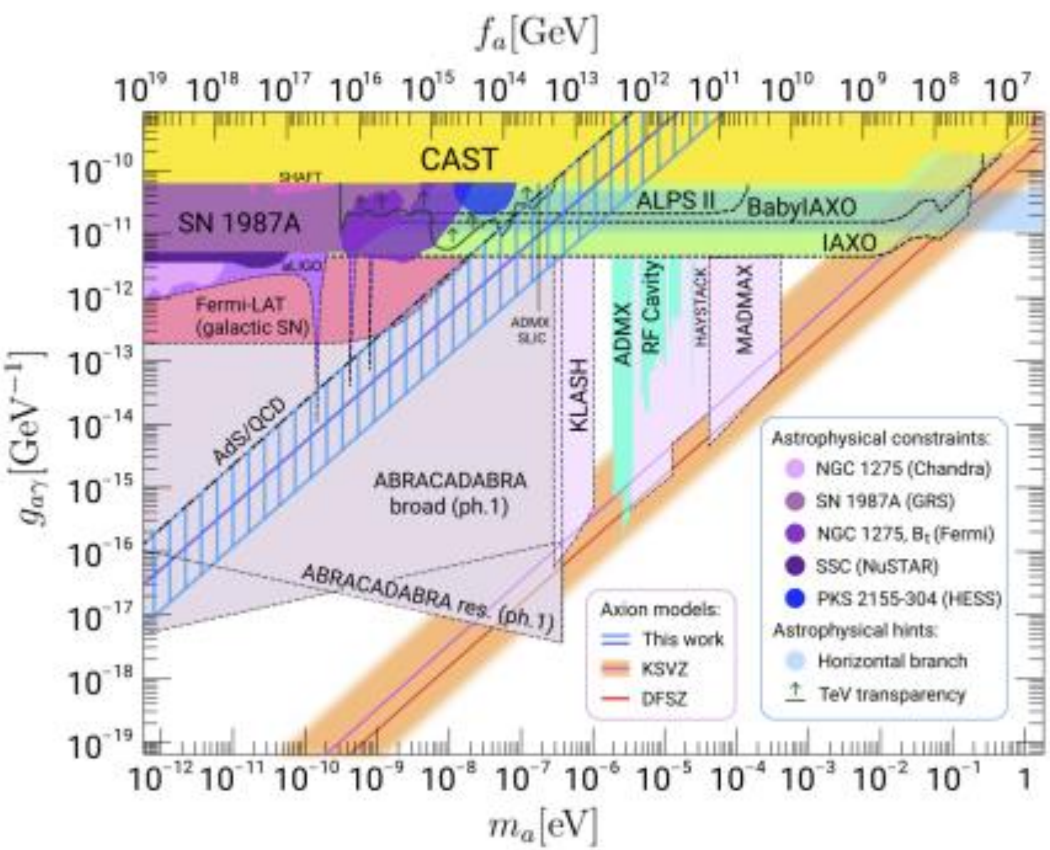
ALPS II experiment at DESY, using recycled HERA magnets



Bähre et al. JINST, 8:T09001, 2013

Light Shining Through Walls

Axion-photon mixing in the presence of a magnetic field

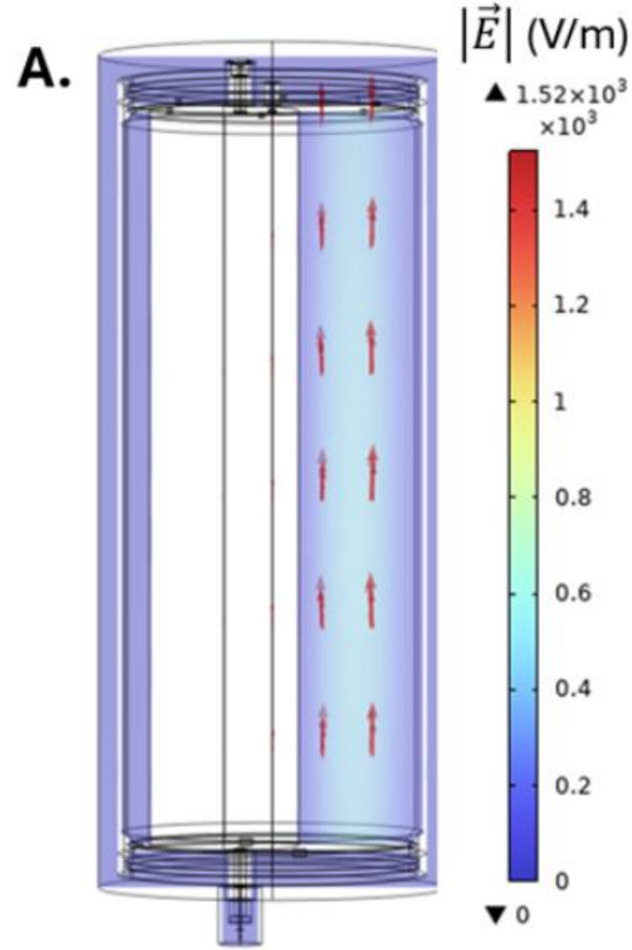


Heuchel, Lindner, Oceano. arXiv:2302.11934

Haloscope

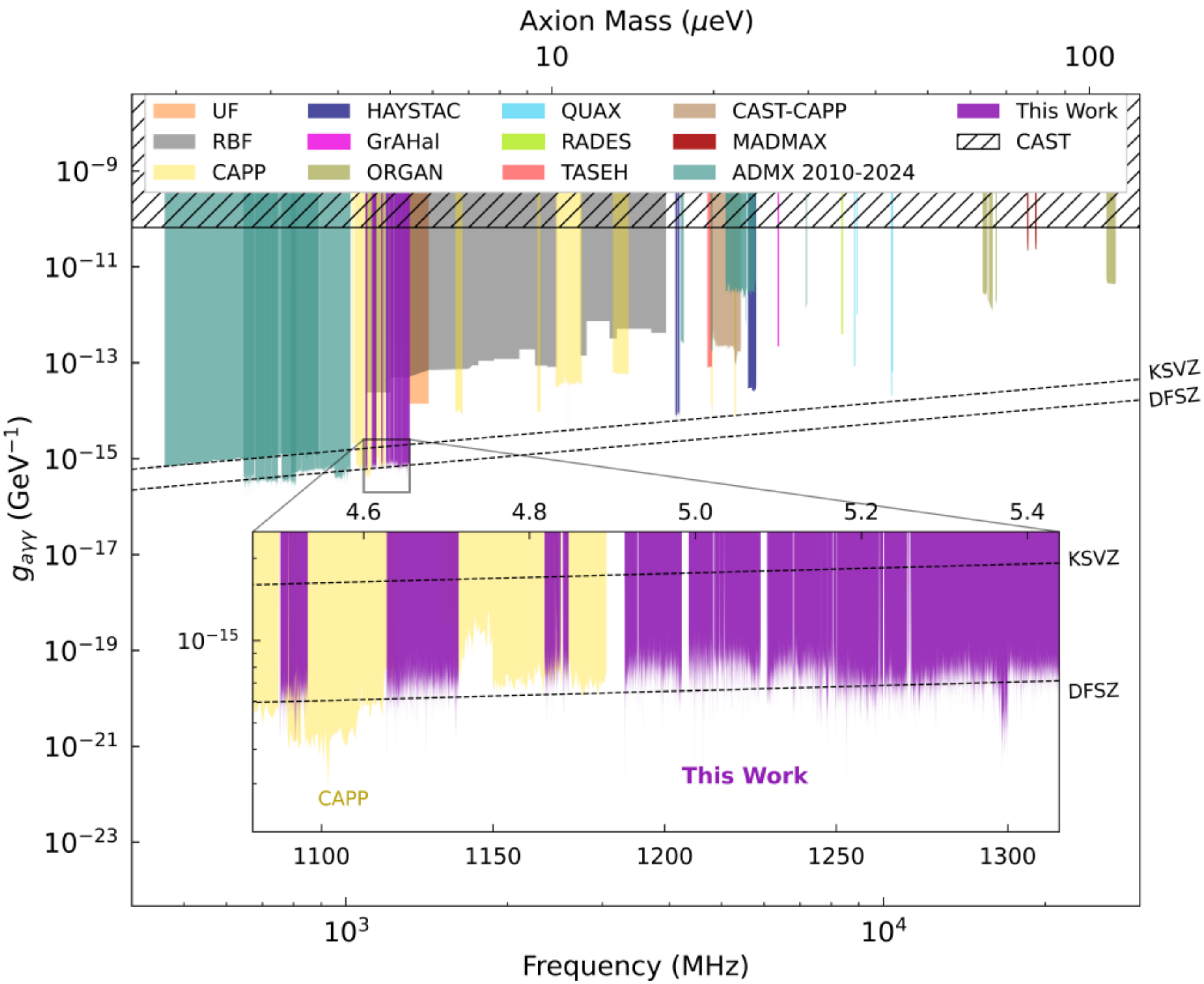
Axions in the dark matter halo, converted into photons in a magnetic field

- resonant enhancement at cavity frequency
- Signal proportional to cavity volume, magnetic field and cavity Q-factor
- Noise proportional to black body radiation, amplifier noise



Sikivie. PRL 51 16 1415 (1983)
Carosi et al. Phys. Rev. Lett. 135, 191001 (2025)

Haloscope

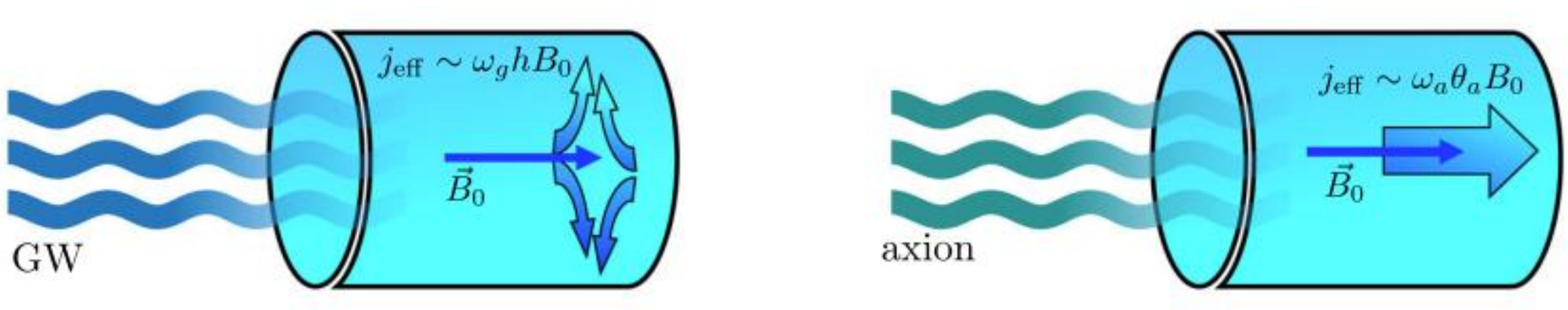


Carosi et al. Phys. Rev. Lett. 135, 191001 (2025)

Gravitational Wave Detection

Coupling of the form ~ h $B \cdot B_0$

Inverse Gertsenshtein effect induces effective currents that couple to the EM modes of a cavity

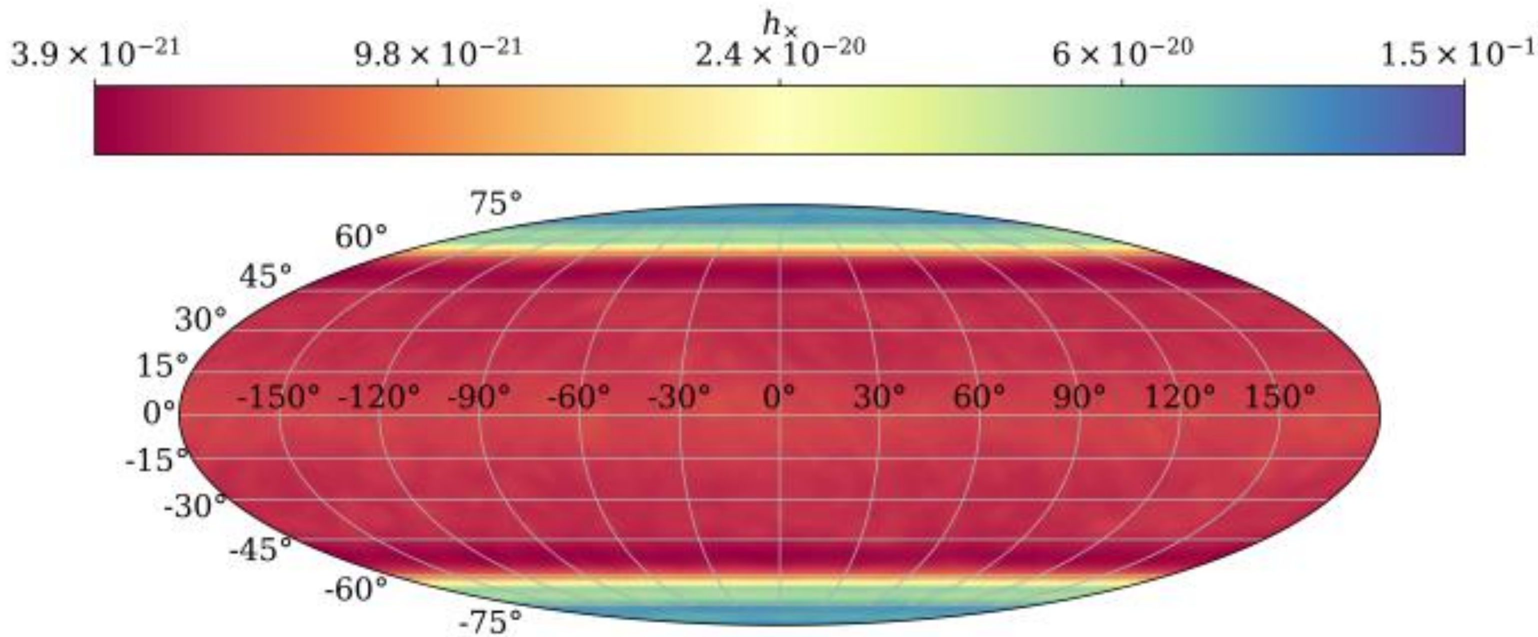


Enables narrow band high-frequency gravitational wave detection

Berlin et al. Phys. Rev. D 105 116011 (2022)
Gertsenshtein. Sov. Phys. JETP 14 84 (1962)

Gravitational Wave Detection

Reanalysis of CAPP-12T (multi-cell) data for 5.311 GHz GW

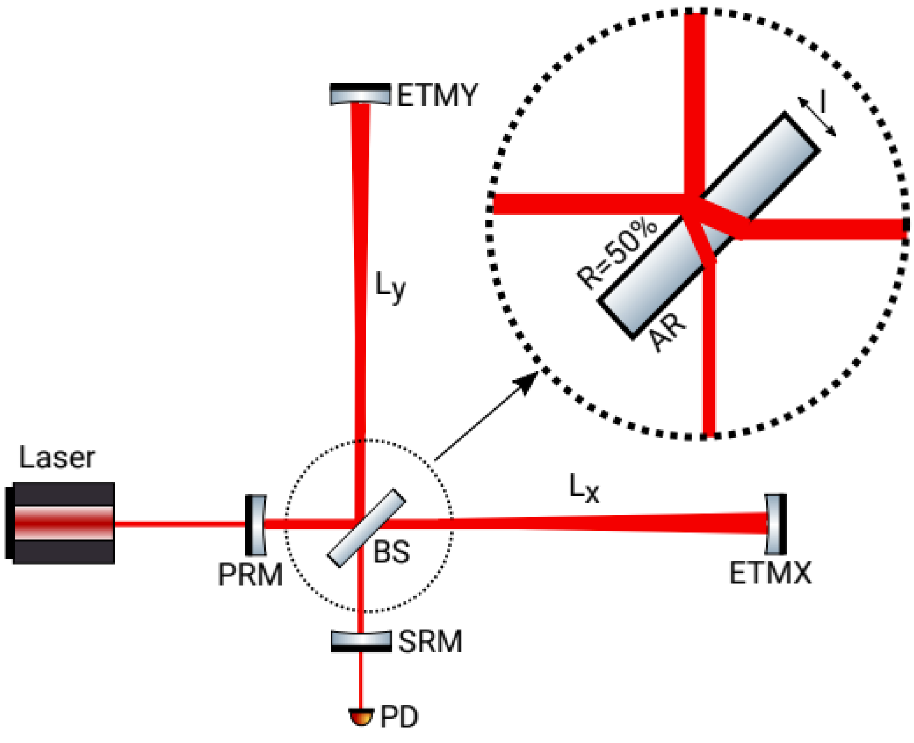


Excludes superradiance from axion clouds around black holes with mass ~ 10^{-6} $M_{\odot}$ within ~ 10^{-2} AU

Kim et al. arXiv:2511.17817

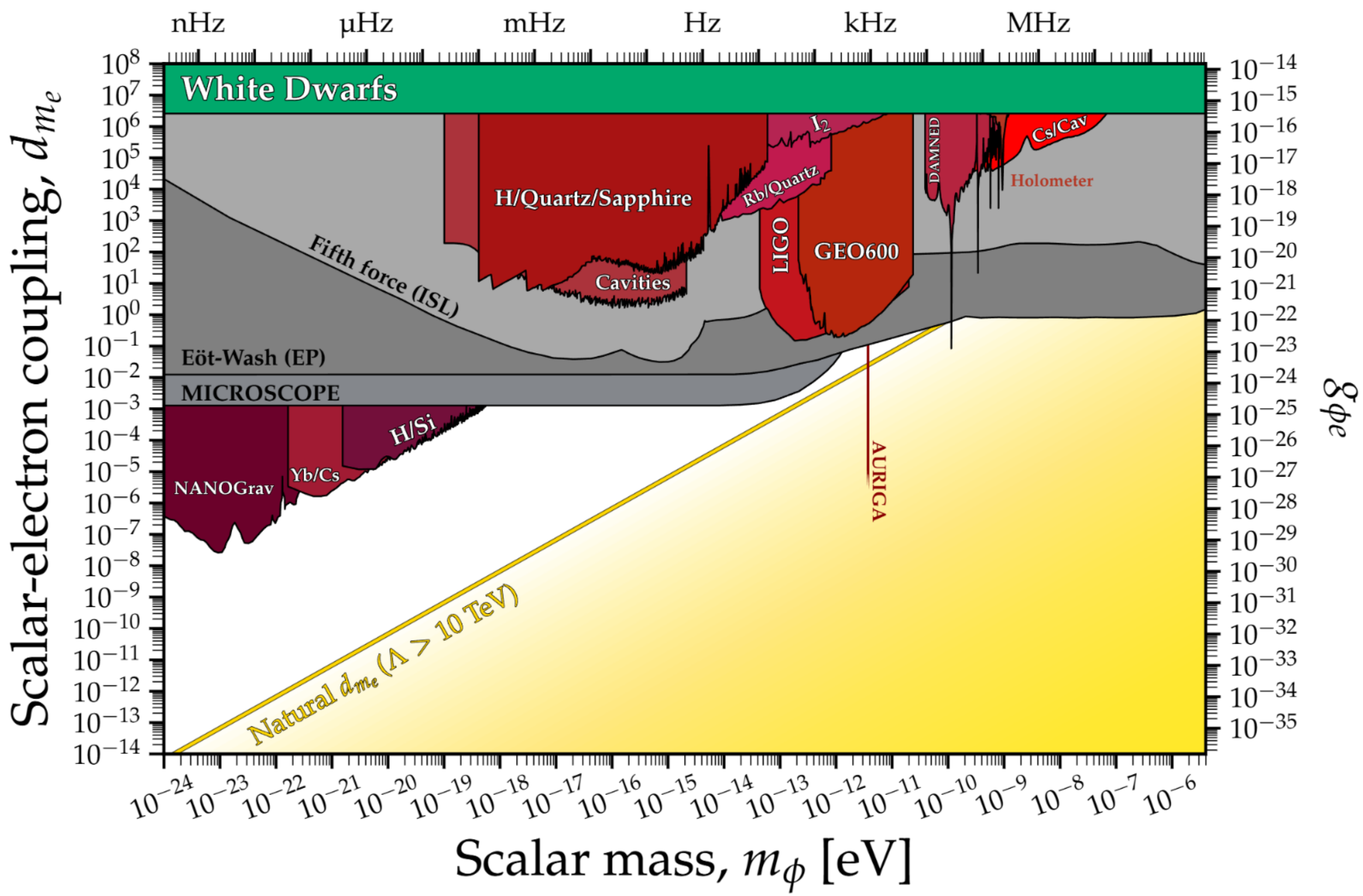
Michelson Interferometer

Beam splitter and arm mirrors (if freely suspended) produce path length changes if physical constants vary in space / time



Grote, Stadnik Phys.Rev.Res 1 (2019) 3 033187

Michelson Interferometer



Grote, Stadnik Phys.Rev.Res 1 (2019) 3 033187
https://cajohare.github.io/AxionLimits/

Summary

Many opportunities to search for light and feebly coupled new physics

Advances in precision enabled by developing quantum technologies

Careful theoretical modelling needed to match precision of observations

Huge parameter space to explore

- How to best use resources?