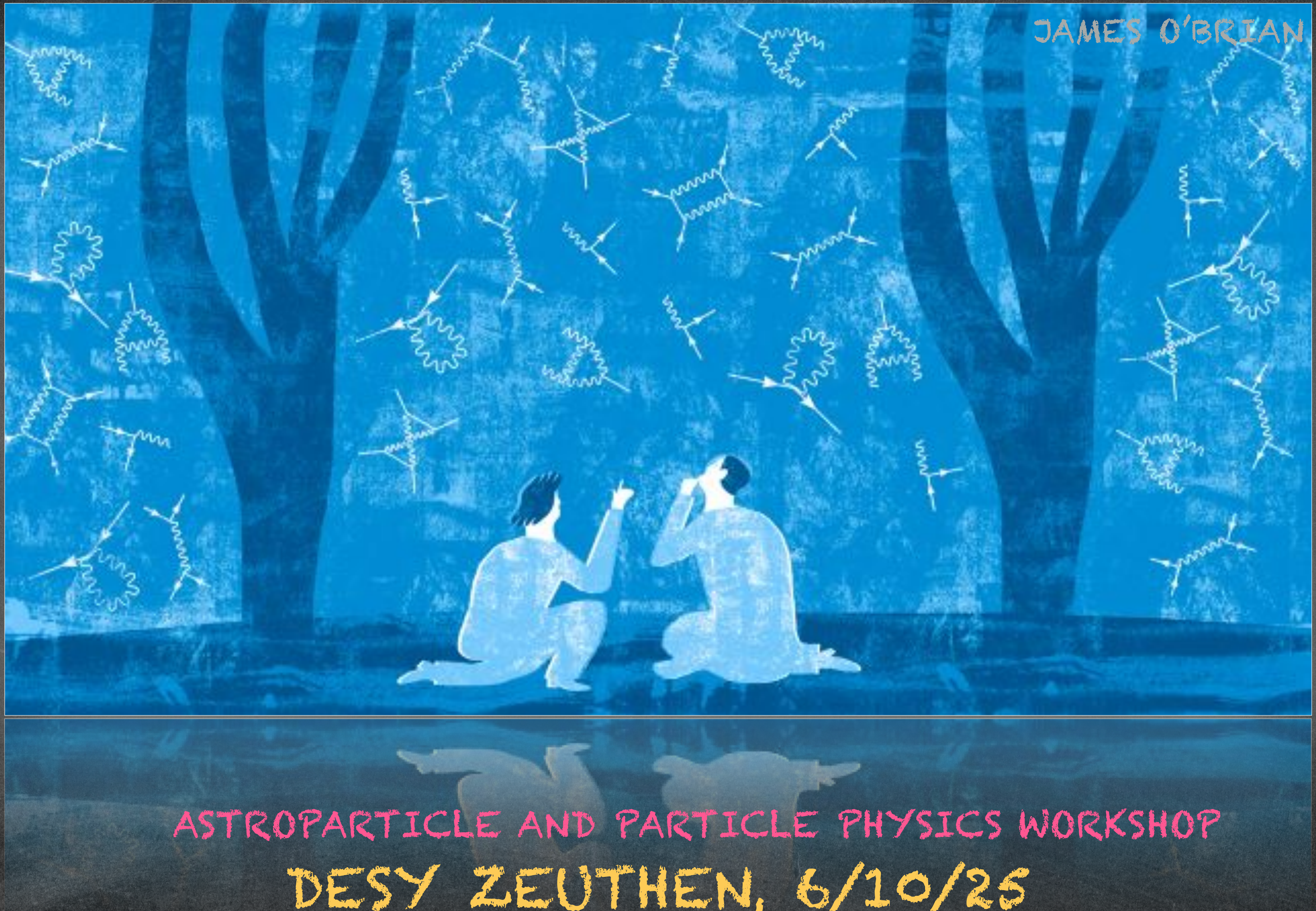
NEW-PHYSICS SEARCHES FROM QUANTUM SENSING



ASTROPARTICLE AND PARTICLE PHYSICS WORKSHOP

DESY ZEUTHEN, 6/10/25

NATHANIEL SHERRILL

Leibniz Universität Hannover

Quantum sensing

- Basics and examples
- New-physics signatures

Ultralight dark matter

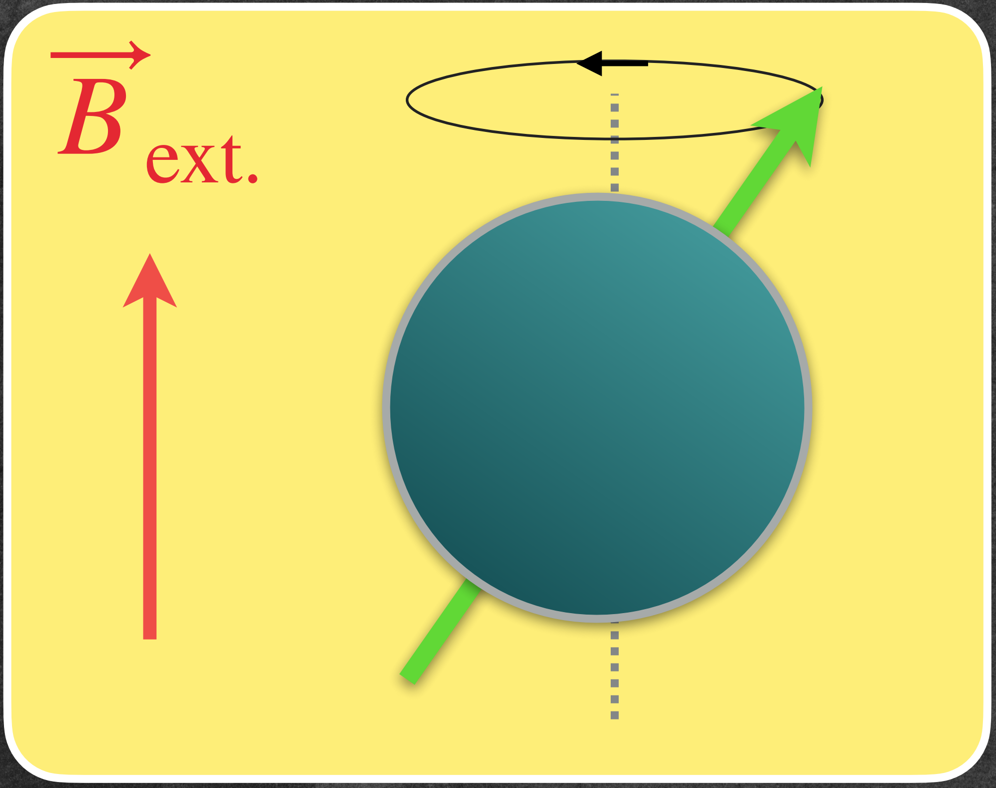
- Signals in atomic clocks
- NPL/Sussex joint study

Symmetry violations

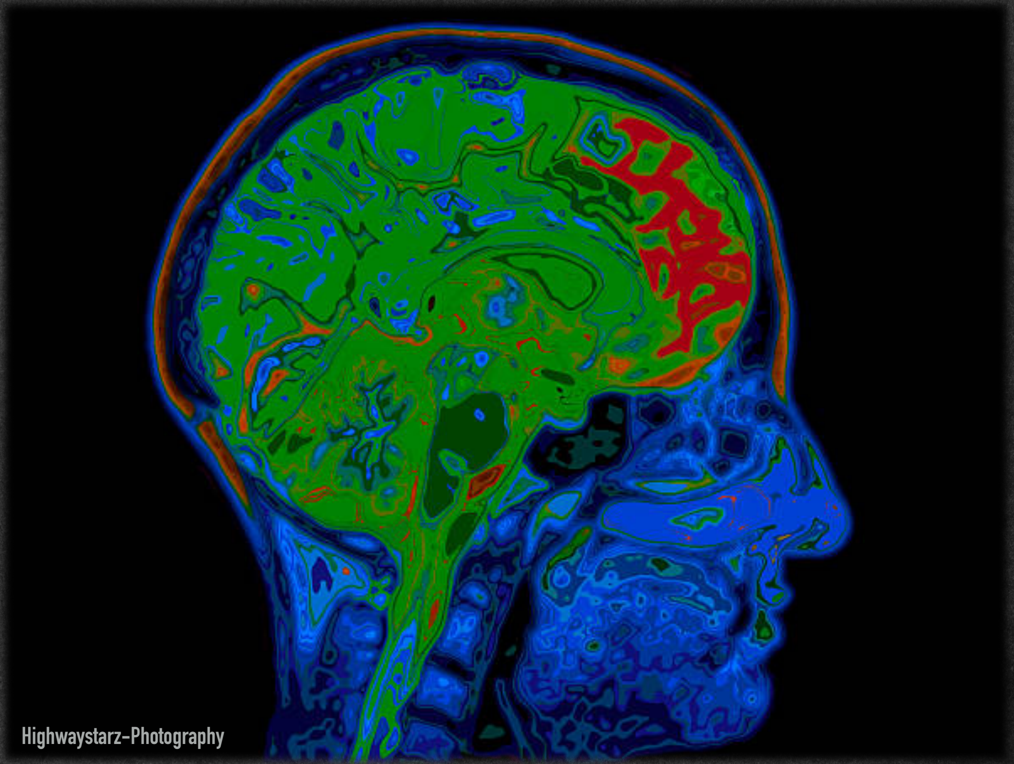
- Apparent Lorentz violation
- Modified gravity and magnetometers

QUANTUM SENSING

Leveraging intrinsic quantum properties
to perform measurements



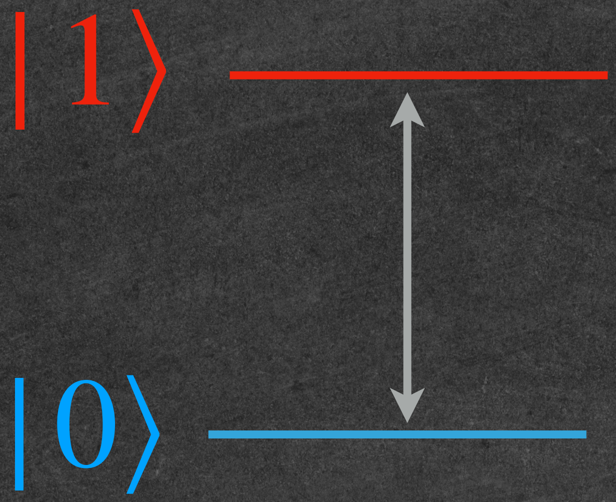
sensing magnetic fields



magnetic resonance imaging

QUANTUM SENSING

Underlying idea: 2-level system (qubit)



$$\Delta E = h\nu_0$$

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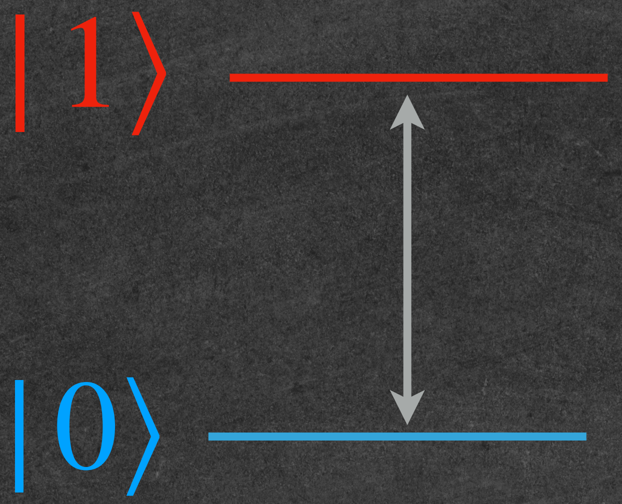
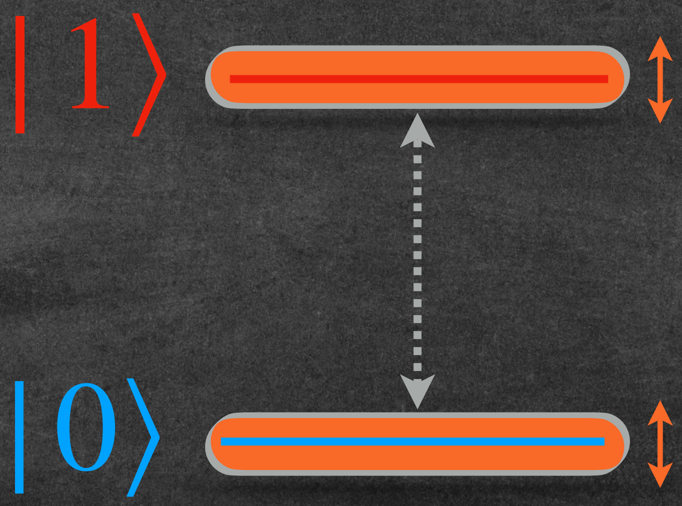


$$\Delta E = h\nu_0$$

"external field" $V(t)$ coupled to qubit



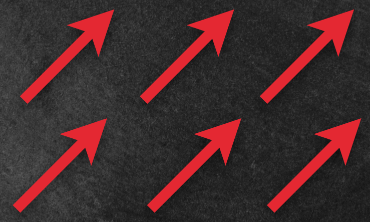
$$\Delta E = h\nu_0\,(1+V(t))$$

Q sensors ⇒ ΔE is tiny !

QUANTUM SENSING

New physics could appear as external fields

$$V(t) = \begin{cases} \text{dark matter} & \phi_{\mathrm{dm}} \sim \phi_0 \cos(mt) \\ \text{dark energy} & \phi_{\mathrm{de}} \sim t \\ \text{Lorentz violation} & b_\mu \\ \dots \end{cases}$$



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GOAL: use quantum sensing exps. to find them!

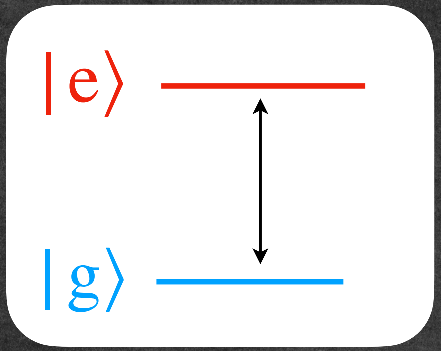
ATOMIC CLOCKS

Measure time using atomic transitions

monitored probe frequency

$= h\nu$

clock transition



$|e\rangle$

$|g\rangle$

NPL caesium fountain clock

ATOMIC CLOCKS

Sensitive to "variations" of fundamental constants

Clock observable

$$r(t) = \frac{\nu_1}{\nu_2}$$

Distinct atoms, different transitions in same atom, ...

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$$\nu_{\text{optical}} = A \cdot (cR_\infty) \cdot F_{\text{opt}}(\alpha)$$

$$\nu_{\text{microwave}} = B \cdot (cR_\infty) \cdot \alpha^2 F_{\text{MW}}(\alpha) \cdot g_N \cdot \mu$$

$$\nu_{\text{vibrational}} = C \cdot (cR_\infty) \cdot \mu^{1/2}$$

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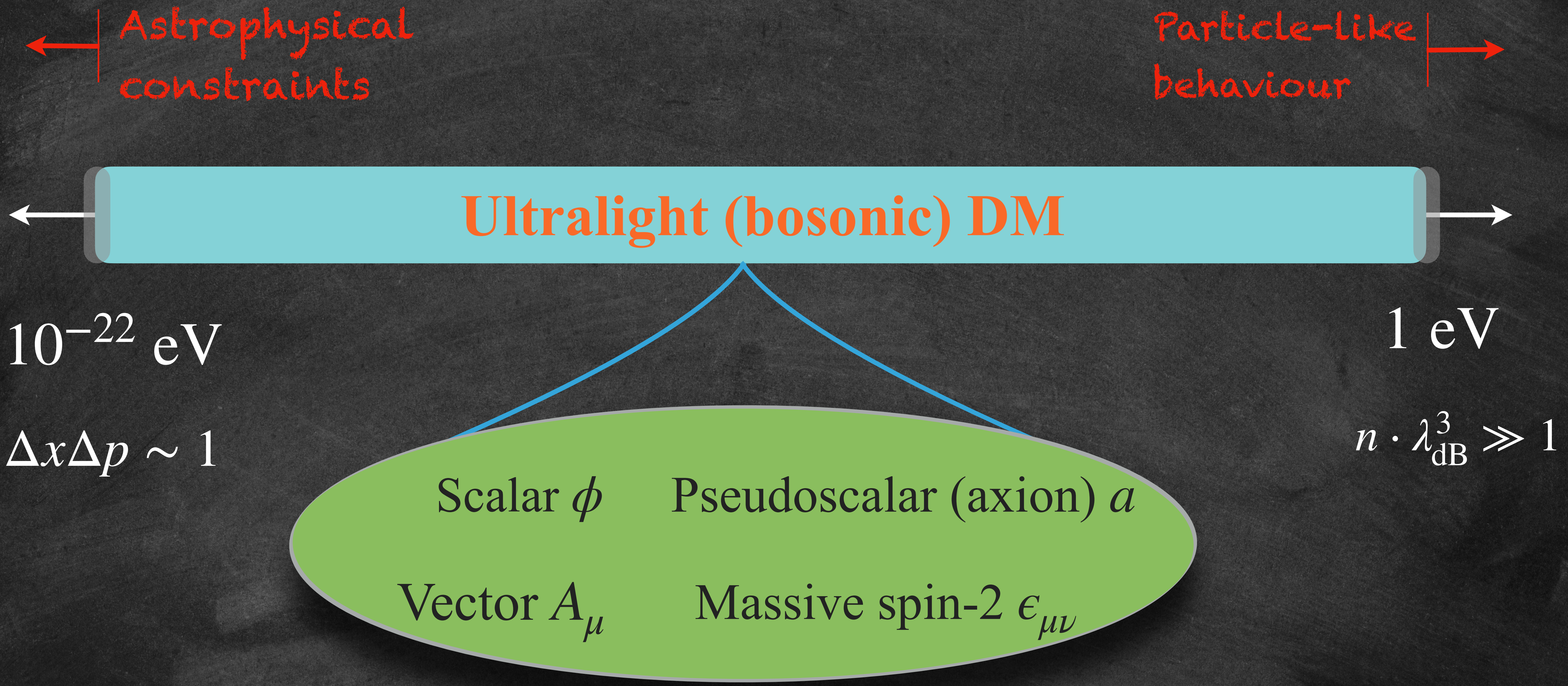
$r(t) \sim$ time-sensitive ratio of dimensionless constants

ULTRALIGHT DARK MATTER

A potential source of clock variations $r(t)$



Astrophysical constraints

Particle-like behaviour

Ultralight (bosonic) DM

10^{-22} eV

$\Delta x \Delta p \sim 1$

1 eV

$n \cdot \lambda_{\mathrm{dB}}^3 \gg 1$

Scalar ϕ

Pseudoscalar (axion) a

Vector A_μ

Massive spin-2 $\epsilon_{\mu\nu}$

ULTRALIGHT DARK MATTER

Focus on scalar ULDM

$v \ll c \Rightarrow m_\phi$ controls frequency of oscillations

$$\phi(t) \approx \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_\phi} \cos\left[m_\phi(1+\frac{1}{2}v^2+\cdots)t+\delta\right]$$

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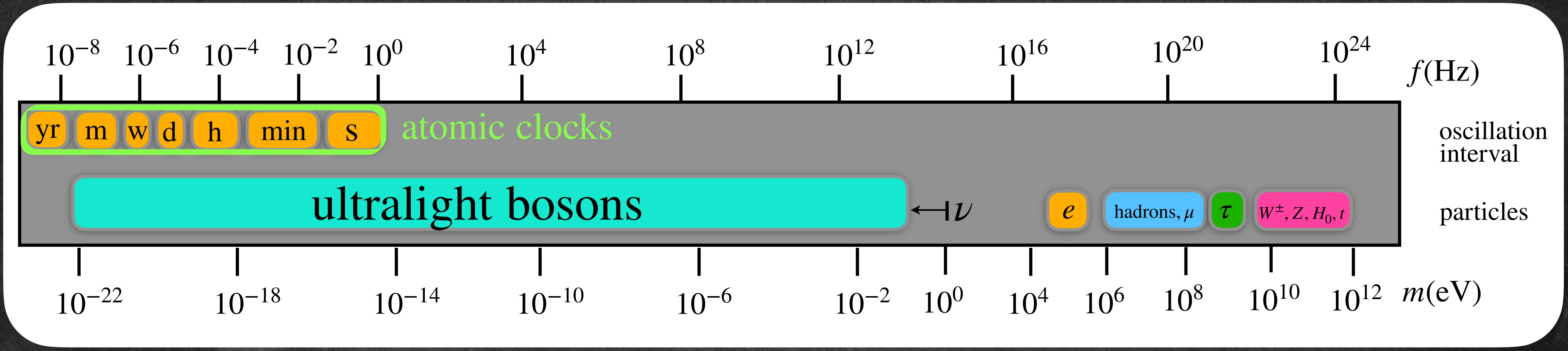

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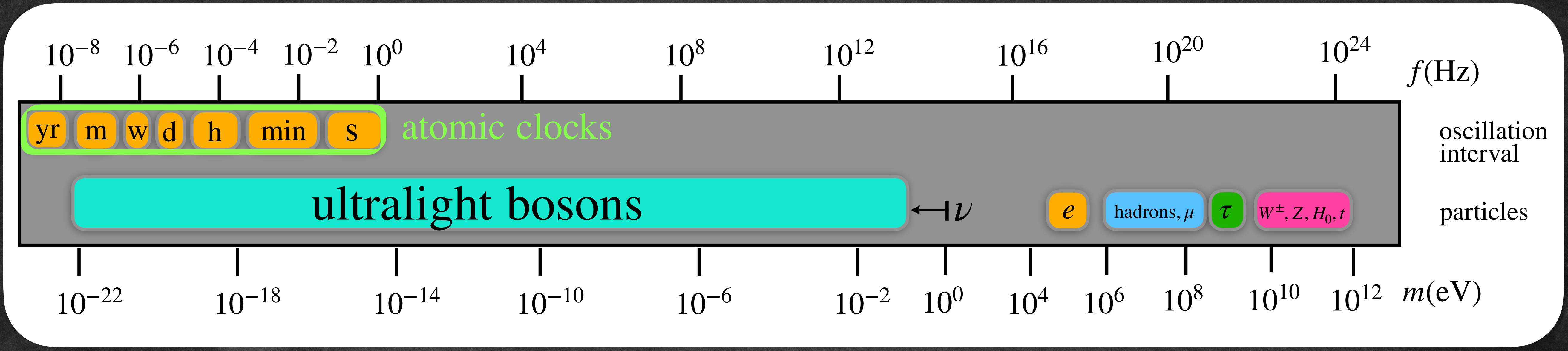

How are oscillations actually observed?

ULDM INTERACTIONS

Standard Model couplings induce signatures

$$\mathscr{L}_{\text{int},\phi} \supset -\left(\frac{\phi}{\Lambda}\right)^n \cdot \mathscr{O}_{\text{SM}}$$

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Ex: couplings in electromagnetism

$$\mathscr{L}^{\text{EM}}_{\text{int},\phi} = (\kappa\phi)^n \left(d_\gamma^{(n)} \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - d_{m_e}^{(n)} m_e \bar{\psi}_e \psi_e \right) + \cdots$$

$$\kappa = \sqrt{4\pi G} = \left(\sqrt{2} M_P\right)^{-1}$$

$$\kappa^n d_j^{(n)} \leftrightarrow 1/\Lambda^n$$

$$\alpha(\phi) = \alpha \left(1 + d_\gamma^{(n)} (\kappa\phi)^n \right) \Rightarrow \frac{\delta\alpha}{\alpha} = d_\gamma^{(n)} (\kappa\phi)^n$$

$$m_e(\phi) = m_e \left(1 + d_{m_e}^{(n)} (\kappa\phi)^n \right) \Rightarrow \frac{\delta m_e}{m_e} = d_{m_e}^{(n)} (\kappa\phi)^n$$

NPL/SUSSEX STUDY

Generic frequency parametrization

$$\nu = (\text{const.})\ (cR_\infty)\cdot\alpha^{K_\alpha}\cdot(m_e/\Lambda_{\mathrm{QCD}})^{K_\mu}\cdot(m_q/\Lambda_{\mathrm{QCD}})^{K_q}$$

$q \equiv (u+d)/2$

$m_p \approx A\cdot\Lambda_{\mathrm{QCD}} + \text{light quarks}$

quark masses + magnetic moments

$$\Rightarrow \boxed{\frac{\delta r}{r} = \Delta K_\alpha d_\gamma^{(n)}(\kappa\phi)^n + \Delta K_\mu(d_{m_e}^{(n)} - d_g^{(n)})(\kappa\phi)^n + \Delta K_q(d_{m_q}^{(n)} - d_g^{(n)})(\kappa\phi)^n}$$

New J. Phys. 25, 093012 (2023)

NPL clock comparisons

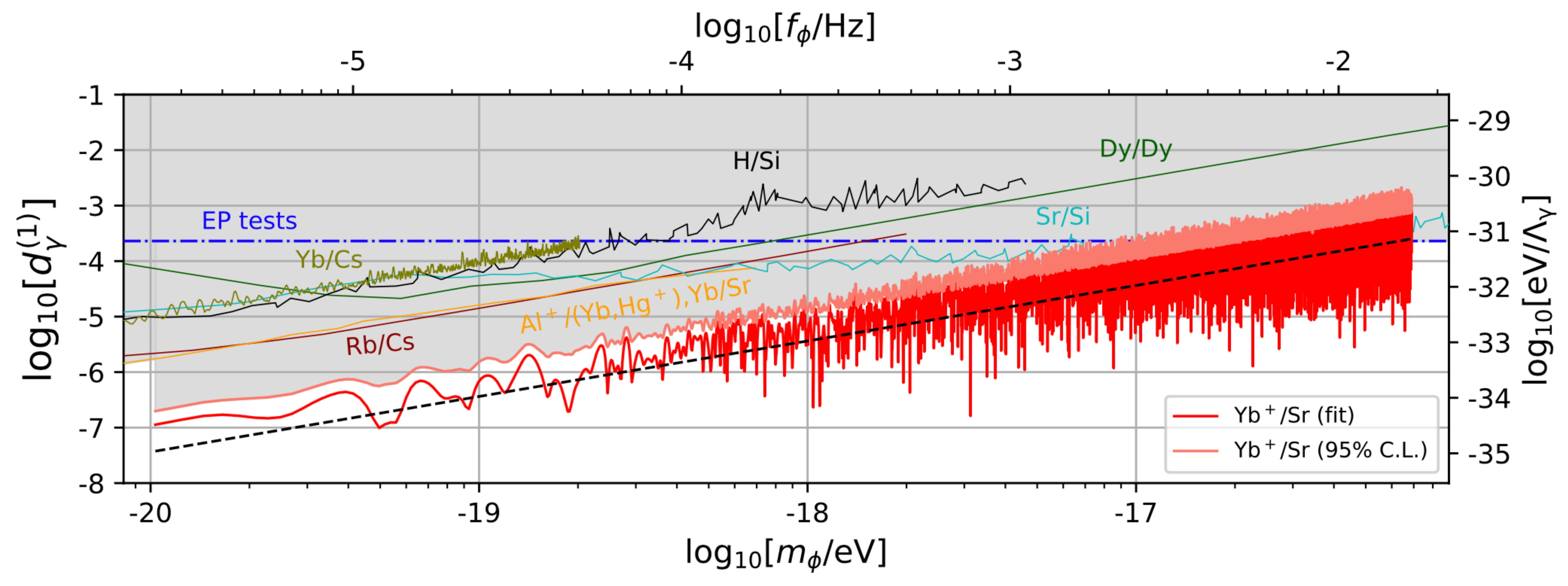
$$\left(\frac{\delta r}{r}\right)_{\mathrm{Yb^+/Sr}} = -6.01 d_\gamma^{(n)}(\kappa\phi)^n$$

$$\left(\frac{\delta r}{r}\right)_{\mathrm{Sr/Cs}} = -\left(2.77 d_\gamma^{(n)} + d_{m_e}^{(n)} - d_g^{(n)} + 0.07(d_q^{(n)} - d_g^{(n)})\right)(\kappa\phi)^n$$

NPL/SUSSEX STUDY

Example

Results for $n = 1$ electromagnetic coupling



"Old" (!) – for updated limits, see https://cajohare.github.io/AxionLimits/

SPACETIME SYMMETRY VIOLATIONS

"Apparent" effect for (some) slowly varying interactions

$$(A_\mu A_\nu)\bar{\psi}\gamma^\mu i\overleftrightarrow{\partial^\nu}\psi \qquad A_\mu = \text{vector or } \partial_\mu\phi$$

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$$m \sim 10^{-21}\ \text{eV}$$

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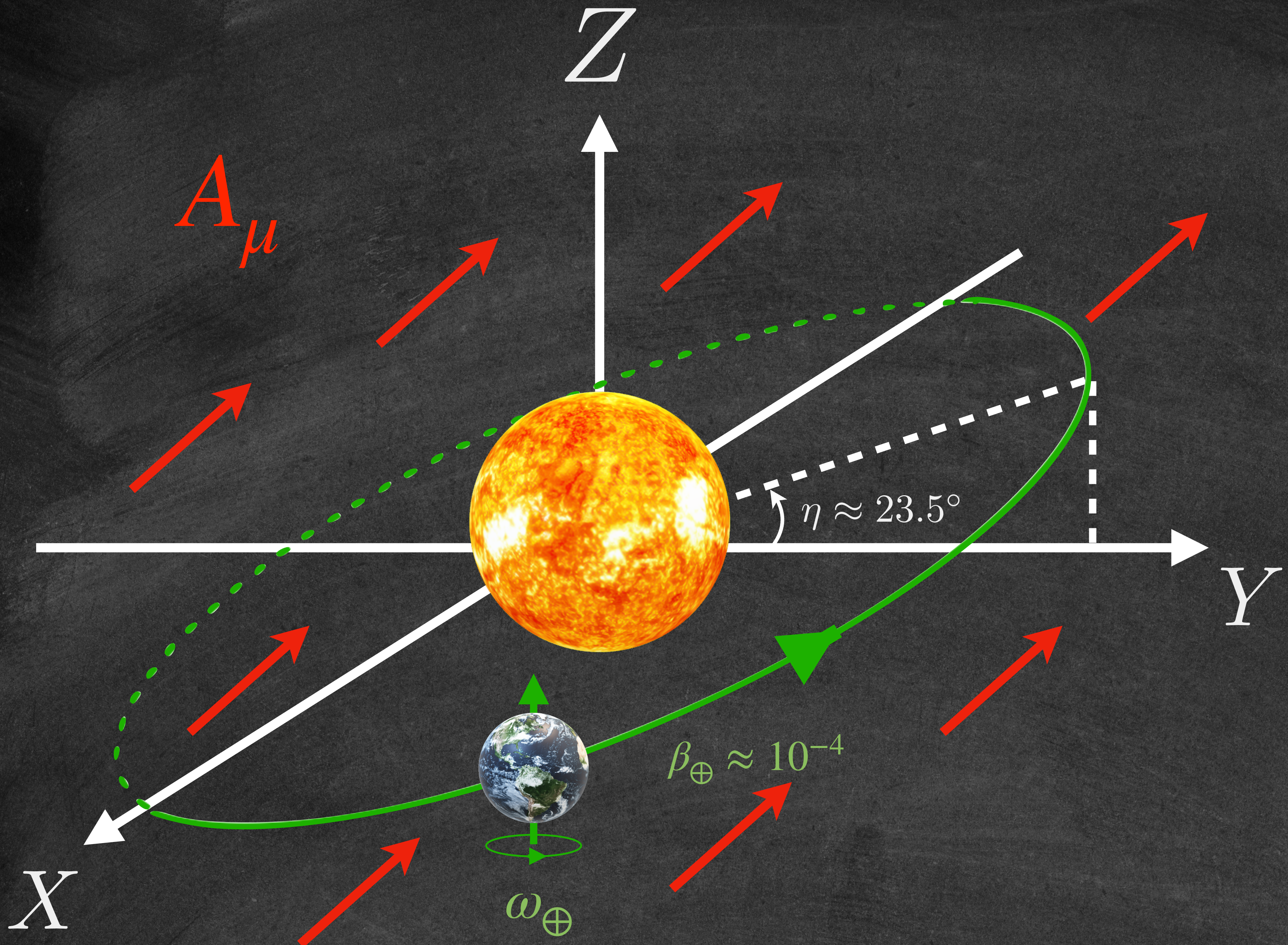
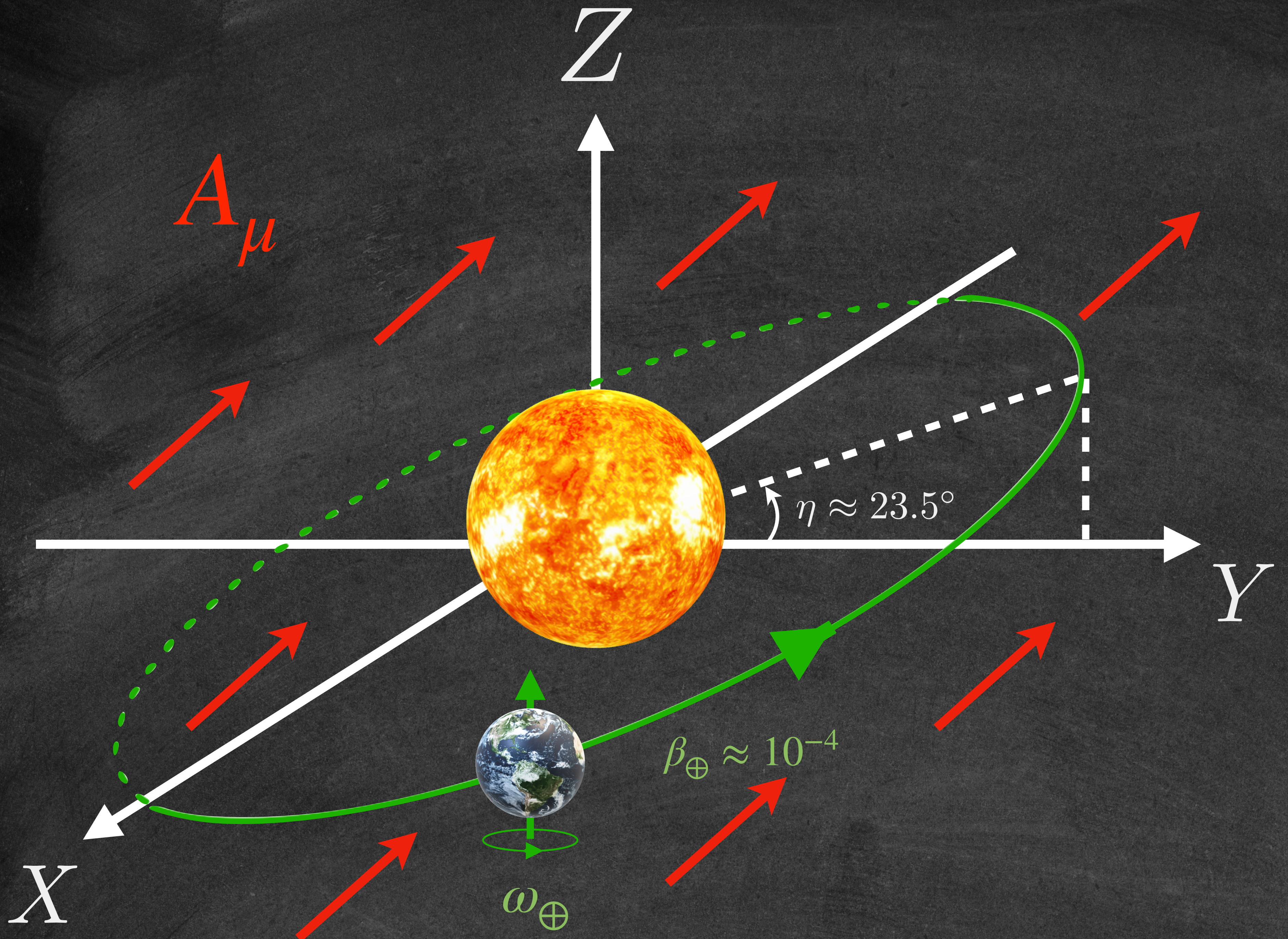
If $T_{\text{exp.}} \ll 1 \text{ month} \Rightarrow$ field appears frozen

$A_\mu \to A_\mu =$ "fixed vector background field"

LORENTZ VIOLATION


Z
A_μ
$\eta \approx 23.5°$
Y
$\beta_\oplus \approx 10^{-4}$
X
$\omega_\oplus$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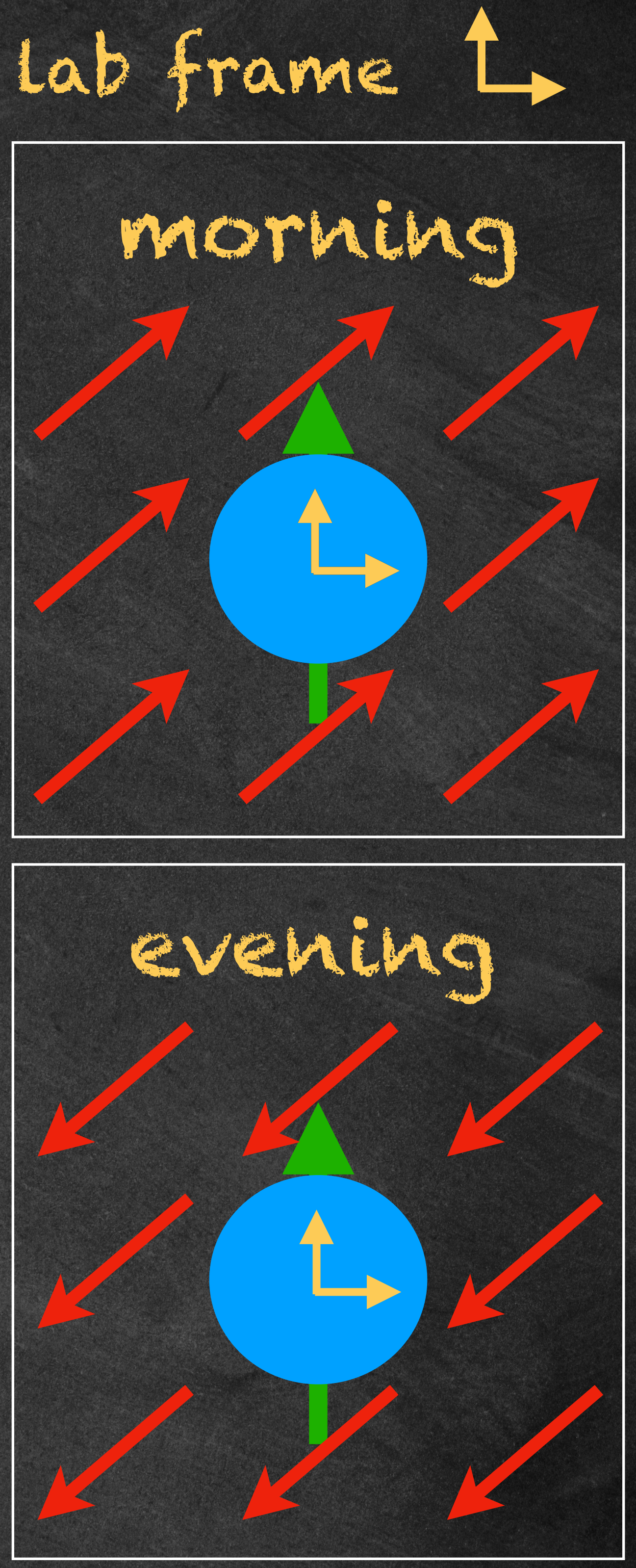
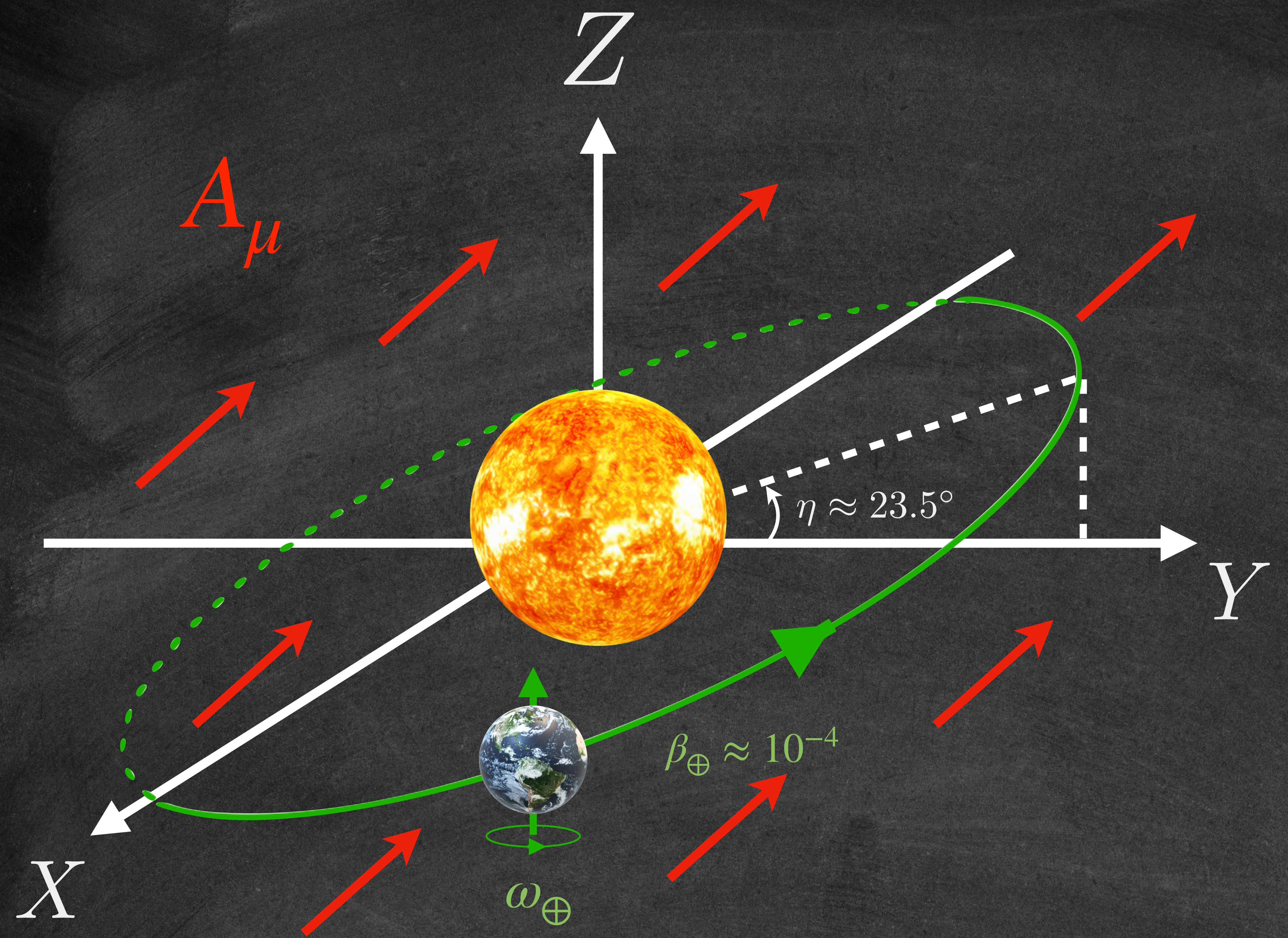
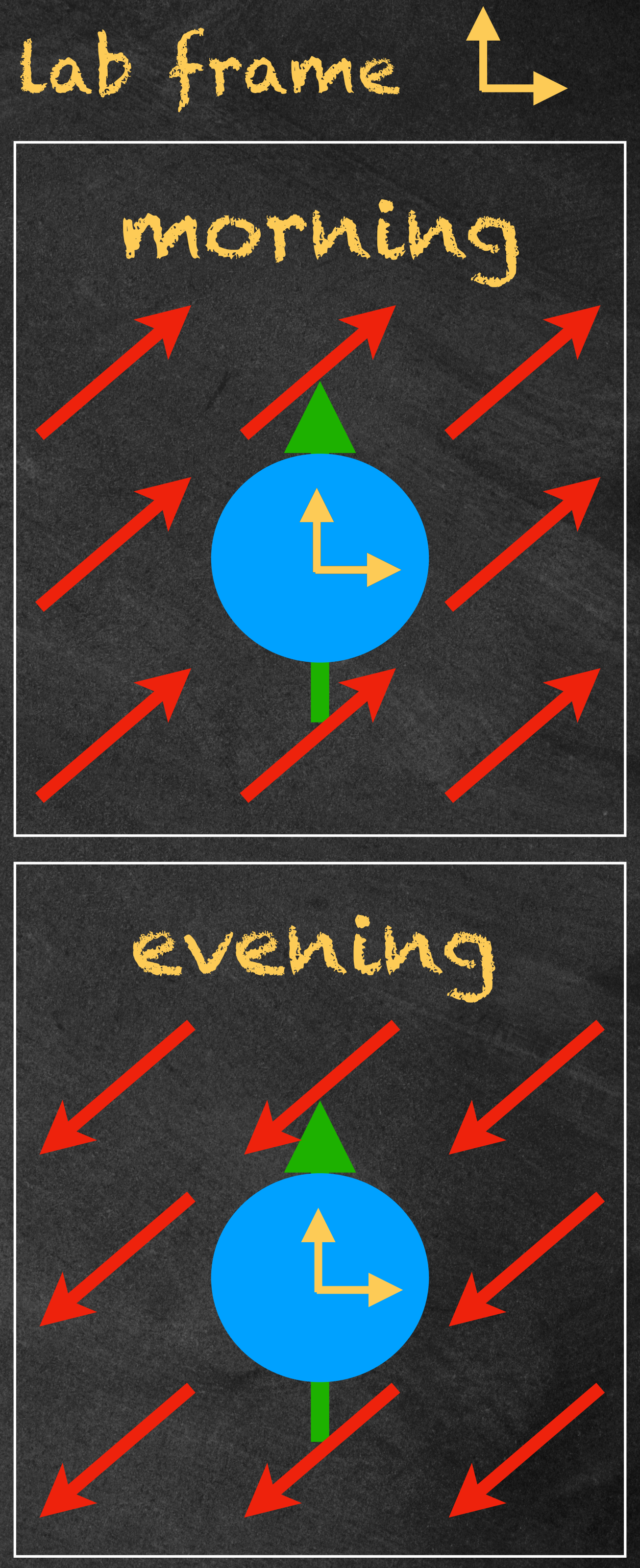

lab frame
morning
evening





measurement time

colatitude

$$\mathcal{O}_{\rm lab} = \mathcal{O}_{\rm lab}(\chi, \psi, \omega_\oplus T_\oplus)$$

lab orientation

LORENTZ VIOLATION

$$(A_\mu A_\nu)\overline{\psi}\gamma^\mu i\overset{\leftrightarrow}{\partial^\nu}\psi \to c_{\mu\nu}\overline{\psi}\gamma^\mu i\overset{\leftrightarrow}{\partial^\nu}\psi$$

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Quantum sensing exps. (magnetometers) give best constraints

M. Smiciklas, J. M. Brown, L. W. Cheuk, and M. V. Romalis
Phys. Rev. Lett. 107, 171604 (2011)

Coefficient	Constraint
$c^n_{YZ} + c^n_{ZY}$	$< (4.8 \pm 4.4) \times 10^{-29}$
$c^n_{XZ} + c^n_{ZX}$	$< (-2.8 \pm 3.4) \times 10^{-29}$
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Implications for modified gravity

G. Domenech, A. Ganz, F. Kirk,
NS, A. Tsabodimos
[in preparation]

TESTING GRAVITY

Disformal metric transformations

J. Beckenstein, Phys. Rev. D 48, 3641 (1993)

$$\tilde{g}^{\mu\nu} = \mathscr{C}^2(g^{\mu\nu} + \mathscr{D}A_\mu A_\nu)$$

$$\mathscr{D} = D(2 + DX)$$

$$X = A_\mu A^\mu$$

conformal coupling

disformal coupling

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Expand in matter action

$$S_{\text{matter}} \supset \int d^4x\sqrt{-g}\left[\left(g_{\mu\nu} - \frac{DA_\mu A_\nu}{1+DX}\right)\bar{\psi}\gamma^\nu \overleftrightarrow{D}^\mu\psi - \frac{1}{4}\frac{D^2X}{1+DX}A_\mu\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}\bar{\psi}\gamma_5\gamma_\nu\psi\right]$$

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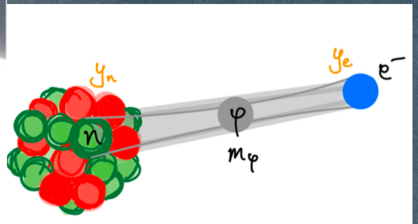
Reinterpreting magnetometer limits $\Rightarrow$

[preliminary]

$$D_\phi \lesssim 10^{19}\ \text{GeV}^{-4} \qquad D_A \lesssim 10^{-35}\ \text{GeV}^{-2}$$

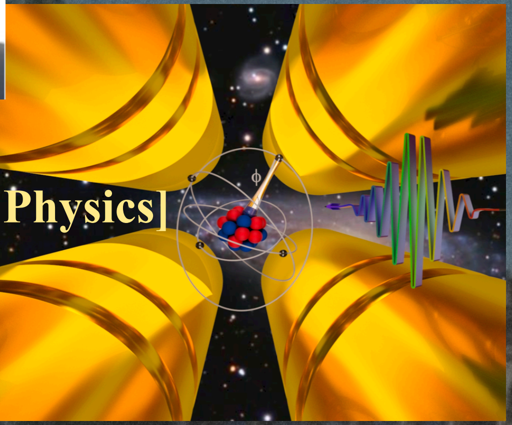
$$\Lambda_\phi \gtrsim 15\ \text{keV} \qquad \Lambda_A \gtrsim 17\ \text{GeV}$$

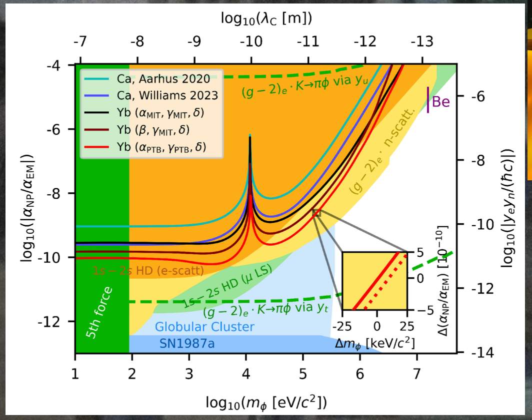
JOINT QSENSING ACTIVITIES AT LEIBNIZ



[Figure: Fiona Kirk
cf. J. Hur (MIT)/ Physics Synopsis]

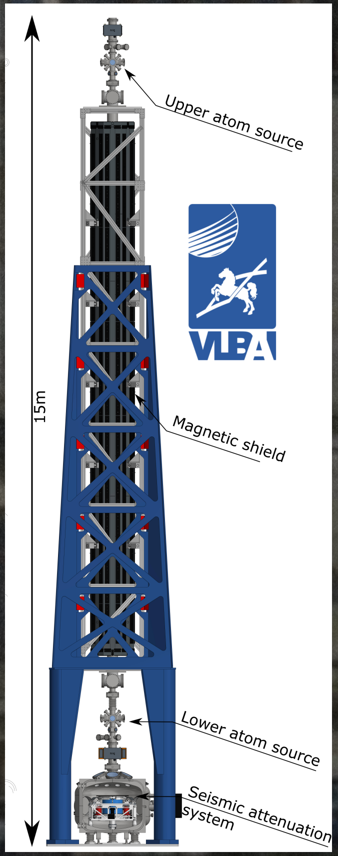
Elina Fuchs
[Institute for Theoretical Physics]





Aldo Ejlli
[Albert Einstein Institute]

ALPS II



Dark matter searches, GWs/tests of gravity, cavity/atom interferometer experiments, quantum enchancements, ...

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[Institute for Quantum Optics]

VLBAI

Interested in discussing/collaborating?
nathaniel.sherrill@itp.uni-hannover.de

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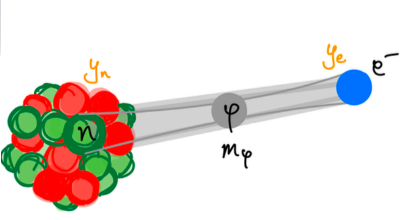

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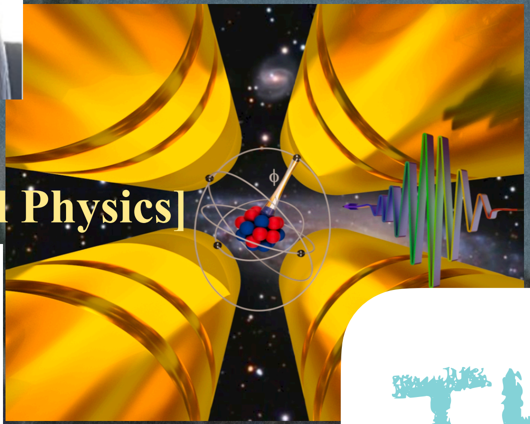

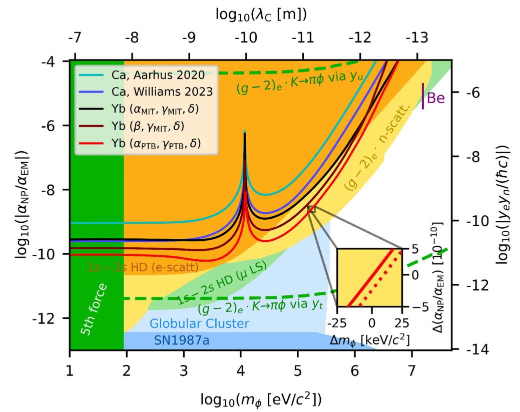

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ALPS II

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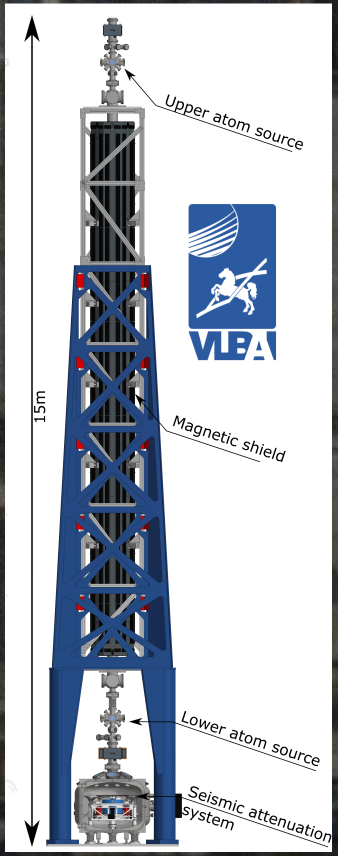

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