Phenomenology of Ultralight Scalar FIPs

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Phenomenology of Ultralight Scalar FIPs

1. Motivation
2. Mediators of new forces
3. Complementary probes
4. Screening mechanisms and environmental effects
5. Dark energy
6. Dark matter
7. Solitons

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What is an Ultralight FIP?

- **FIP** = **F**eebly **I**nteracting **P**article
- **FIP** – Particle that interacts with standard-model particles via interactions that are feebler than the electroweak interactions (and possibly even feebler than gravity)
- **Ultralight** – Particle mass is much smaller than masses of standard-model particles (except possibly the neutrinos) – in these lectures, I take this to mean sub-eV or sub-keV

What is a Scalar Particle?

- Spinless boson ($S = 0$) with only 1 spin degree of freedom, regardless of whether massive or massless
- Wavefunction obeys the Klein-Gordon equation; e.g., for a free particle-wave:*

$$\left(\partial^2/\partial t^2 - \boldsymbol{\nabla}^2 + m_\varphi^2\right)\varphi(t,\boldsymbol{x}) = \left(\partial_\mu \partial^\mu + m_\varphi^2\right)\varphi(t,\boldsymbol{x}) = 0$$

- Spinless particles may be further distinguished according to their parity (P) assignment:

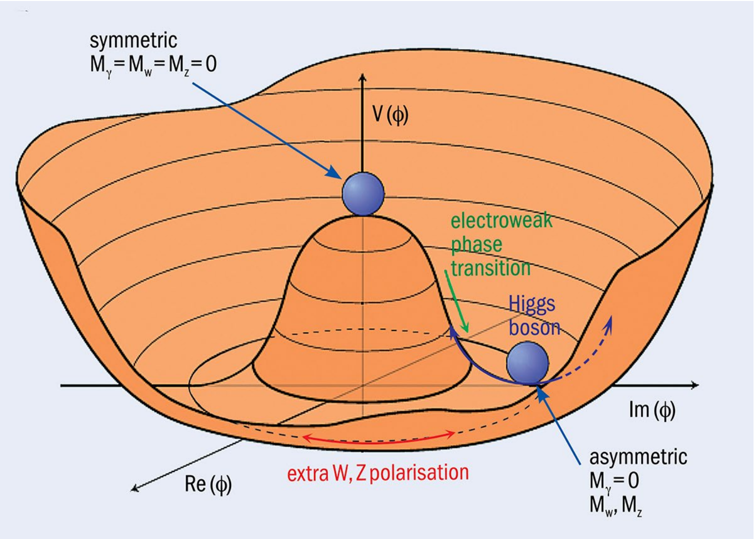
  (True) Scalar has $P = +1$: $\varphi(t,-\boldsymbol{x}) = +\varphi(t,\boldsymbol{x})$

  Pseudoscalar has $P = -1$: $\varphi(t,-\boldsymbol{x}) = -\varphi(t,\boldsymbol{x})$

* Unless explicitly stated otherwise, we assume $\hbar = c = 1$ in these lectures

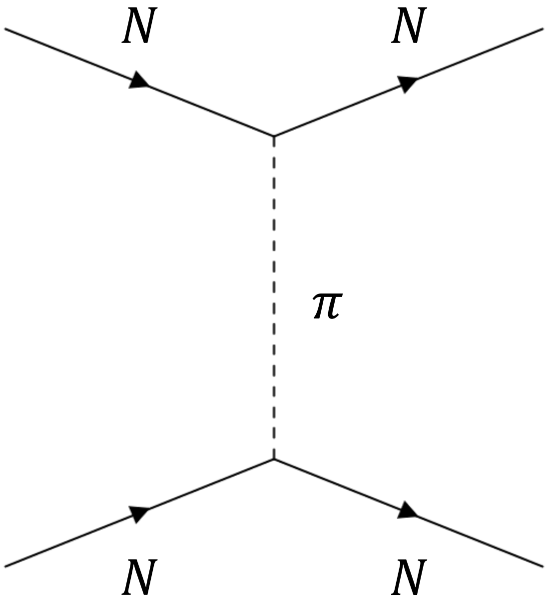
Spinless Bosons in the Standard Model

Elementary boson



Higgs boson – generator of particle masses in the SM via spontaneous symmetry breaking

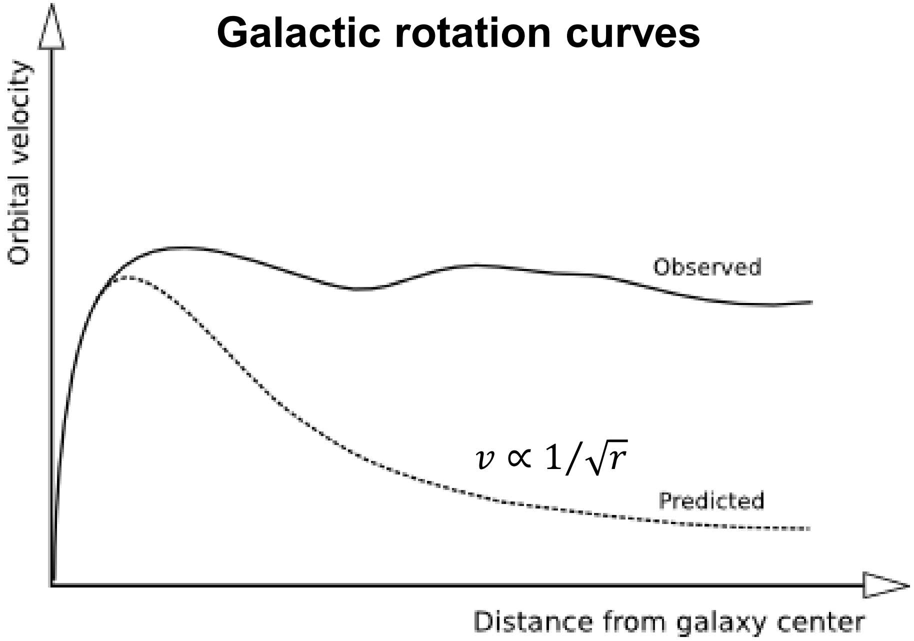
Composite bosons



Pions $(\pi^0, \pi^\pm)$ – mediators of internucleon forces at low energies

Need for New Particles (Astrophysics, Cosmology)

The Standard Model successfully explains most observed physical phenomena (and has high predictivity), but some physical phenomena remain unexplained



Anomalous galactic rotation curves interpreted as an extra matter component in galaxies: non-luminous, non-baryonic and cold matter – **dark matter** – new feebly-interacting particles provide a good candidate

Indirect evidence from observed structure formation in the Universe – need **dark matter** to provide early “seeds” for structure formation

Need for New Particles (Astrophysics, Cosmology)

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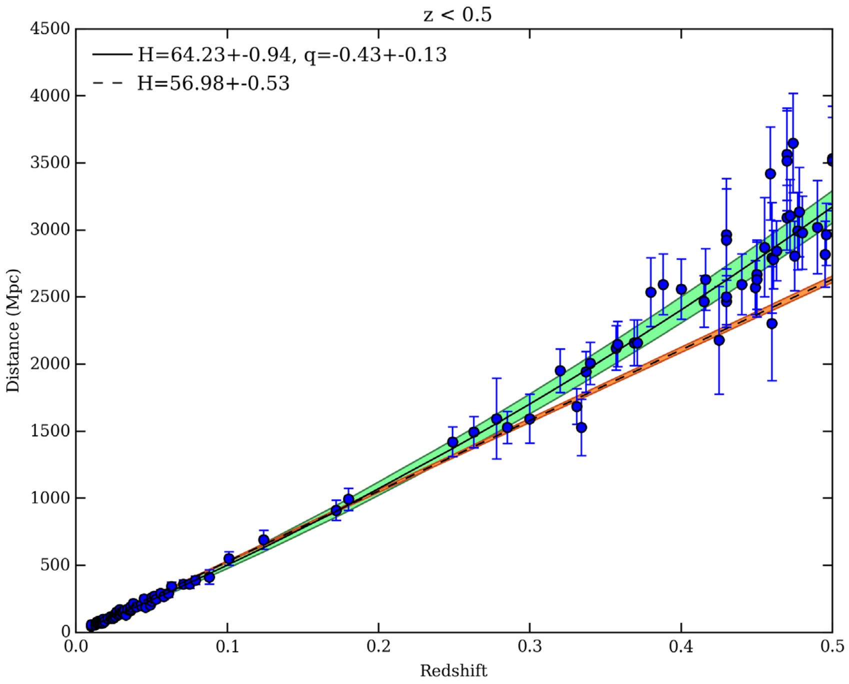
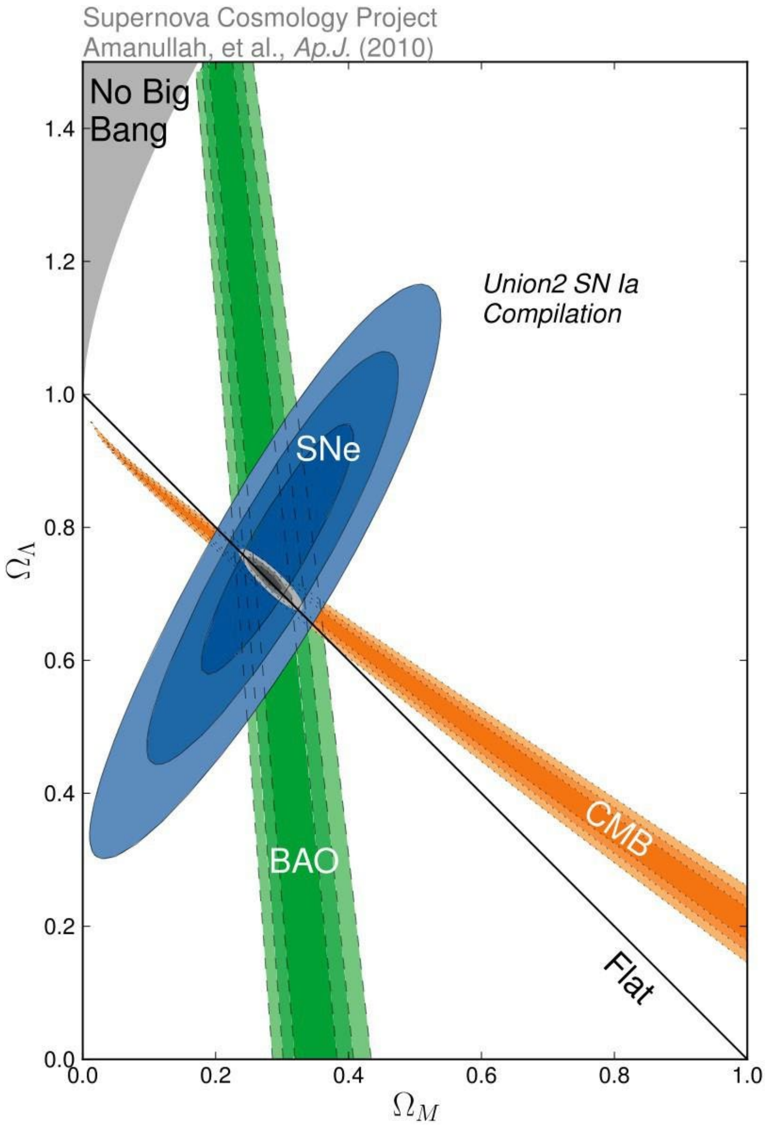
Supernova-based measurements of redshift-distance relation for galaxies



Apparent accelerating expansion of the Universe in recent times

⇒ Possible explanation in terms of a cosmological constant Λ in GR – a homogeneous energy component with negative pressure – **dark energy**

Need for New Particles (Astrophysics, Cosmology)



Precision cosmological measurements give the present-day energy budget of the Universe as:

$$\Omega_\Lambda \approx 0.7, \Omega_{\text{matter}} \approx 0.3$$

$$(\Omega_{\text{DM}} \approx 0.25)$$

Need for New Particles (Theoretical)

- **Strong CP problem** – apparently unnaturally small amount of CP violation in strong interactions – naively expect $\theta_{\mathrm{CP}} \sim \mathcal{O}(1)$, but experimentally observe $\theta_{\mathrm{CP}} \lesssim 10^{-10}$
  - Leading proposed solution is the **axion** – an ultralight feebly-interacting pseudoscalar particle
- **Hierarchy problem** – Why is $m_{\mathrm{Higgs}} \ll M_{\mathrm{Planck}}$?
  - Proposed solutions include:
    - Supersymmetry
    - Composite Higgs models
    - Models with large extra dimensions
    - **Relaxion** – an ultralight feebly-interacting scalar particle

Relation to other lectures this week

- These lectures – general phenomenological aspects of ultralight scalar FIPs
- M/Tu – Maxim Pospelov, “FIPs in the early universe”
- Th – Joerg Jaeckel, “ALPs in the FIPs” – theoretical motivation, dark matter phenomenology
- Fr – Felix Kahlhoefer, “Astronomical constraints on FIPs”

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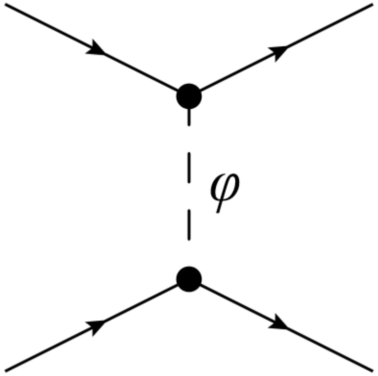
Universal Couplings (EP-Conserving)



Classical particle exchange in vacuum

$$\mathcal{L}_{\text{int}} = -\frac{\varphi T^{\mu}_{\mu}}{\Lambda} \underset{\text{NRL}}{\approx} -\frac{\varphi \rho}{\Lambda}$$

$$\Rightarrow \ V_{\varphi}(r) \approx -\frac{M_1 M_2}{\Lambda^2}\frac{e^{-m_{\varphi} r}}{4\pi r}$$

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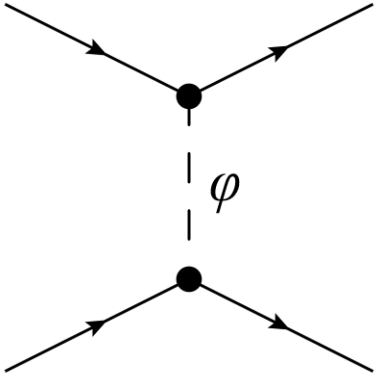

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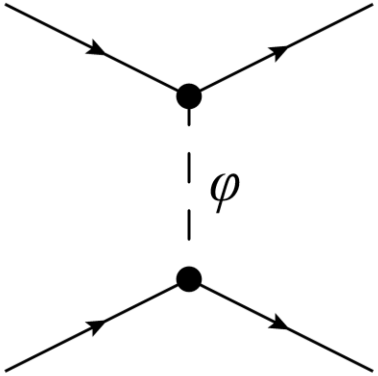

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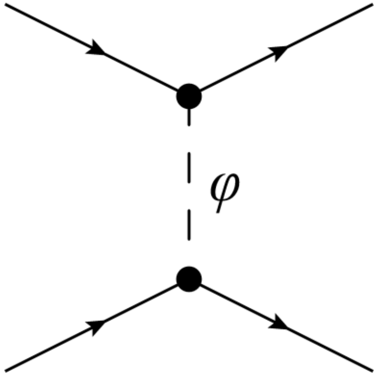

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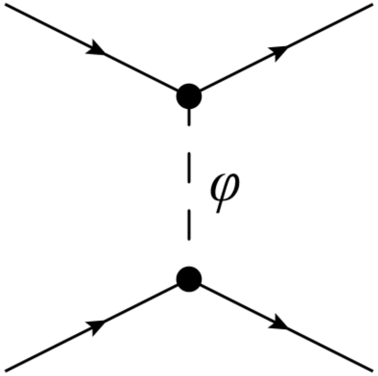
- Non-renormalisable low-energy effective field theory

cf. $\mathcal{L}_{\text{grav}} = -\frac{h_{\mu\nu} T^{\mu\nu}}{M_{\text{Pl}}} \Rightarrow V_{\text{grav}}(r) \approx -\frac{M_1 M_2}{4\pi M_{\text{Pl}}^2 r}$

Graviton field (spin-2)

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\text{Pl}}}$$

Non-Universal Couplings (EP-Violating)



$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

$$\Rightarrow \; V_\varphi(r) = -\frac{m_1}{\Lambda_1}\frac{m_2}{\Lambda_2}\frac{e^{-m_\varphi r}}{4\pi r}$$

- Different mass-energy components of an atom generally scale differently with proton number Z and atomic number $A = Z + N$:

$$M_{\text{atom}} \approx (A - Z)m_n + Zm_p + Zm_e + 100Z(Z-1)\alpha/A^{1/3} \text{ MeV} + \cdots$$

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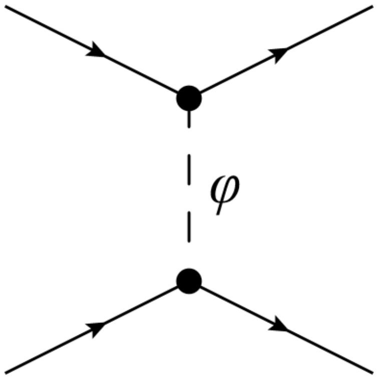

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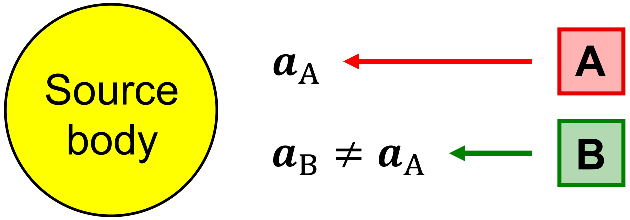
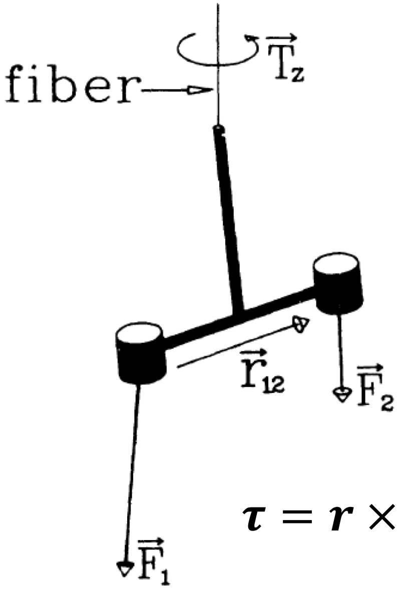
- Different atoms and isotopes would generally experience different accelerations, implying violation of the equivalence principle



Eötvös ratio: $\eta_{\text{AB}} = 2\frac{|\boldsymbol{a}_{\text{A}} - \boldsymbol{a}_{\text{B}}|}{|\boldsymbol{a}_{\text{A}} + \boldsymbol{a}_{\text{B}}|}$

Experimental Probes of EP-Violating Forces

Torsion pendula: [Wagner et al., *Class. Quantum Grav.* **29**, 184002 (2012); MICROSCOPE Collaboration, *PRL* **129**, 121102 (2022)]



$$\boldsymbol{\tau} = \boldsymbol{r} \times (\boldsymbol{F}_1 - \boldsymbol{F}_2)$$

Torsion pendulum

$$\eta^{\mathrm{Be-Al,Be-Ti}}_{\oplus,\mathrm{E\ddot{o}t-Wash}} \sim 10^{-13},$$

$$\eta^{\mathrm{Ti-Pt}}_{\oplus,\mathrm{MICROSCOPE}} \sim 10^{-15}$$

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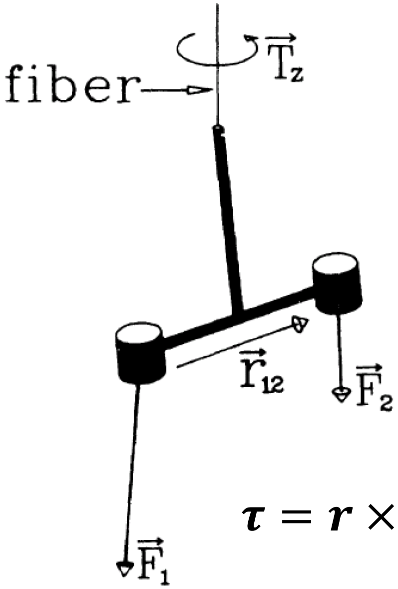
Atom interferometry: [Asenbaum *et al.*, *PRL* **125**, 191101 (2020)]



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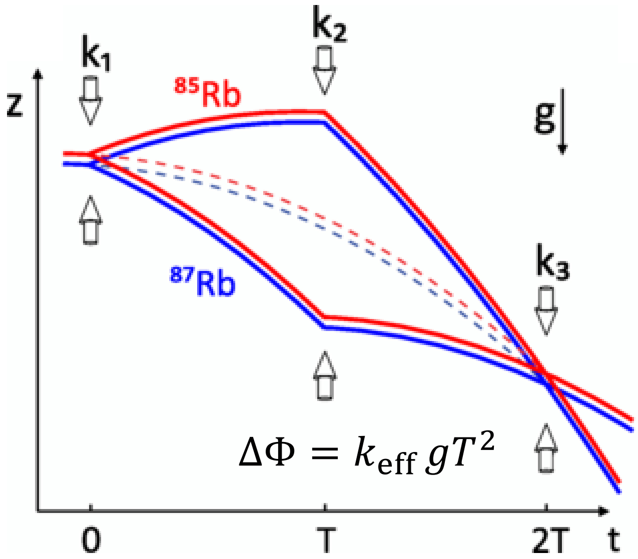


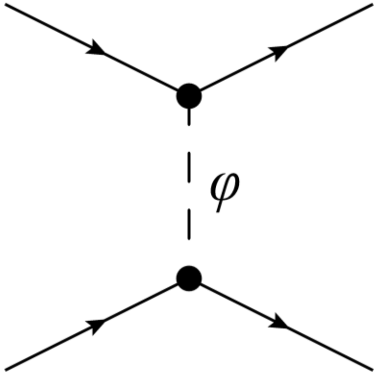
Dual-species atom interferometry

$$\delta\boldsymbol{a} = \boldsymbol{a}_{\mathrm{A}} - \boldsymbol{a}_{\mathrm{B}} \; (= \delta\boldsymbol{g}_{\mathrm{eff}})$$

$$\eta_{\oplus}^{^{85}\mathrm{Rb}-^{87}\mathrm{Rb}} \sim 10^{-12}$$

More on Non-Universal Couplings

[Ellis *et al.*, *PLB* **228**, 264 (1989)], [Leefer *et al.*, *PRL* **117**, 271601 (2016)]



$$\mathcal{L}_{\text{int}} = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

$$\varphi(r) \approx -\left[\frac{(A-Z)m_n}{\Lambda_n} + \frac{Zm_p}{\Lambda_p} + \frac{Zm_e}{\Lambda_e} + \frac{100Z(Z-1)\alpha\ \text{MeV}}{A^{1/3}\Lambda_\gamma} + \cdots\right]\frac{e^{-m_\varphi r}}{4\pi r}$$

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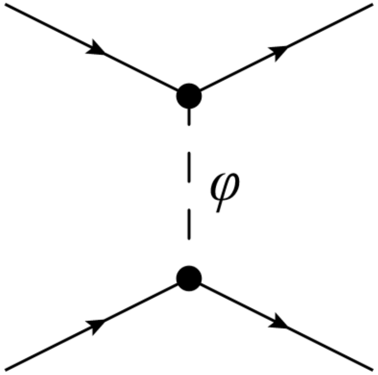

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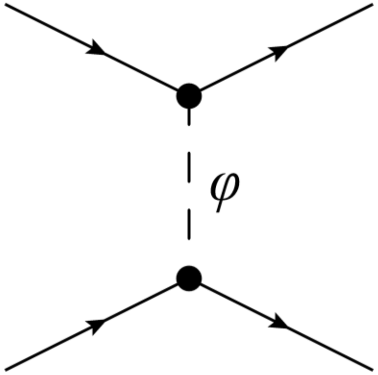
⇒ Variations in the apparent values of the fundamental constants of Nature:

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f \ \text{ cf. } \ \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \ \Rightarrow \ m_f \rightarrow m_f\left(1 + \frac{\varphi}{\Lambda_f}\right)$$

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \ \text{ cf. } \ \mathcal{L}_\gamma^{\text{SM}} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} - eJ_\mu A^\mu \ \Rightarrow \ \alpha \rightarrow \frac{\alpha}{1-\varphi/\Lambda_\gamma} \approx \alpha\left(1 + \frac{\varphi}{\Lambda_\gamma}\right)$$

Experimental Probes of Varying Fundamental Constants

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



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$$\Rightarrow \frac{\delta\alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \varphi(r) \propto \frac{e^{-m_\varphi r}}{r}$$

Can search for variations in $\alpha, m_e, \ldots$ due to changes in distance away from a source body by searching for correlated perturbations of atomic transition frequencies ($\nu \propto m_e \alpha^2 + \cdots$):

1. Sun
2. Moon
3. Massive objects in the lab

Best current clocks reach $\delta\nu/\nu \sim 10^{-18}$

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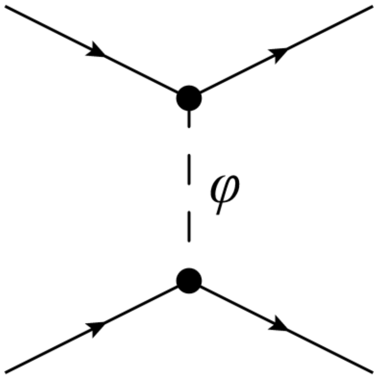

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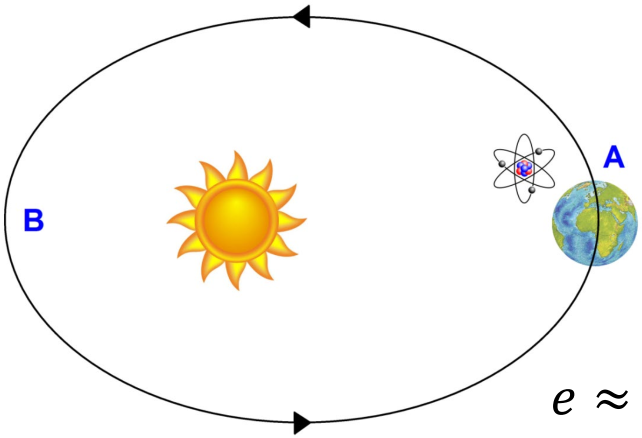

$e \approx 0.017$

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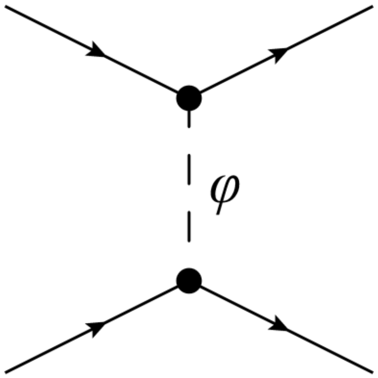

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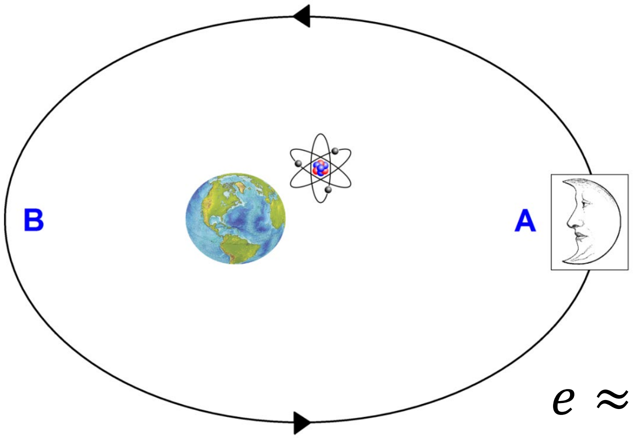

$e \approx 0.05$

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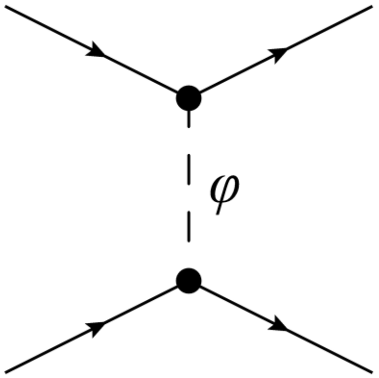

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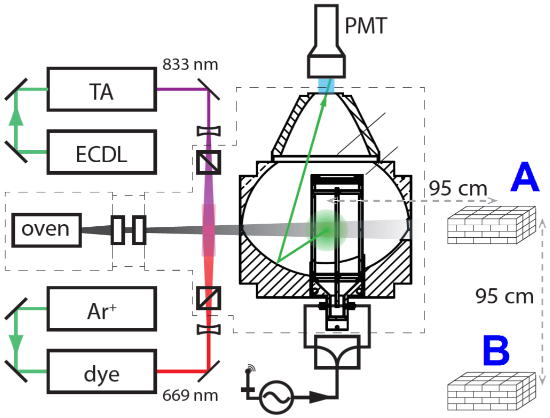

Movable
300kg
mass

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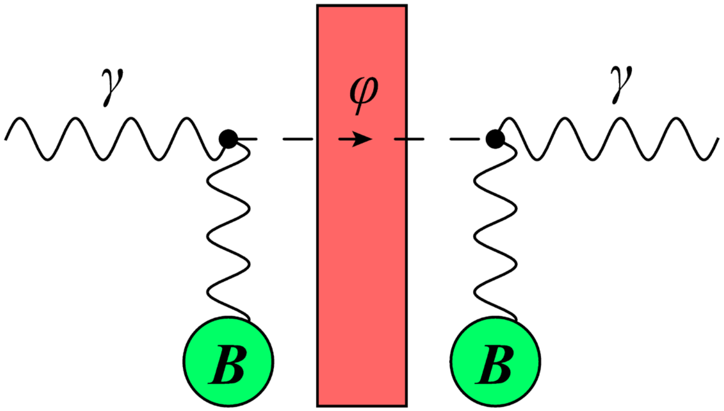
Light-shining-through-a-wall Experiments

[ALPS Collaboration, *PLB* **689**, 149 (2010)], [OSQAR Collaboration, *PRD* **92**, 092002 (2015)]



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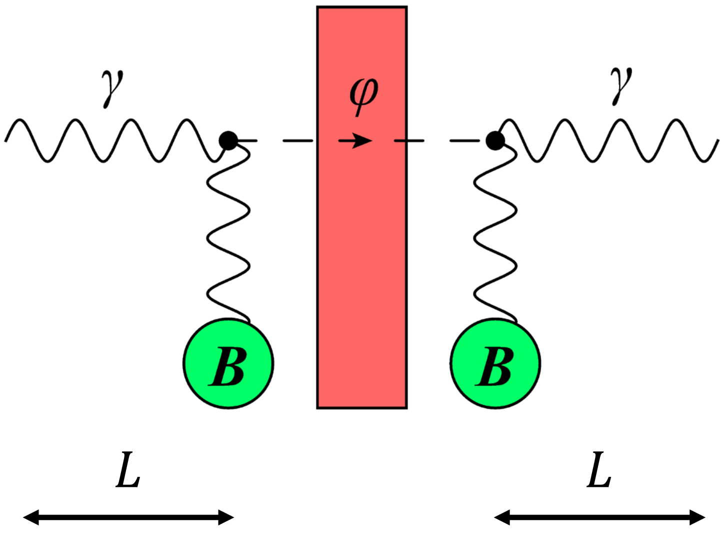

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$$\Rightarrow\ p_{\gamma\to\varphi\to\gamma} = \left(\frac{B}{\Lambda_\gamma}\right)^4\left[\frac{1}{q}\sin\left(\frac{qL}{2}\right)\right]^4$$

$q = \left|\boldsymbol{k}_\gamma - \boldsymbol{k}_\varphi\right|$ is the momentum transfer during interconversion

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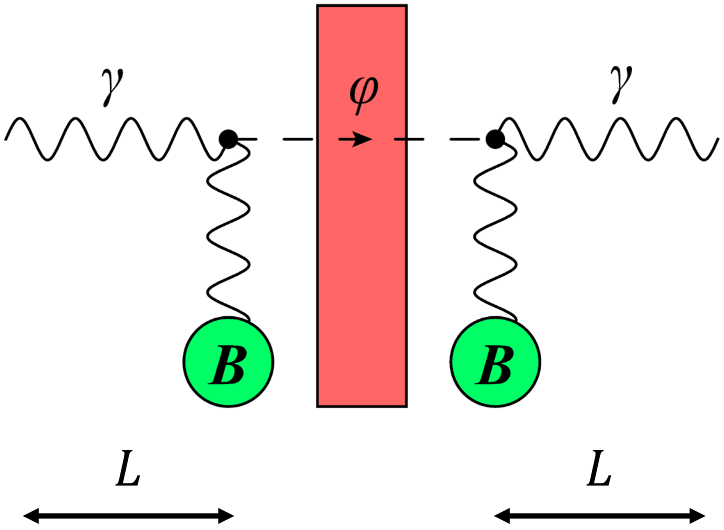

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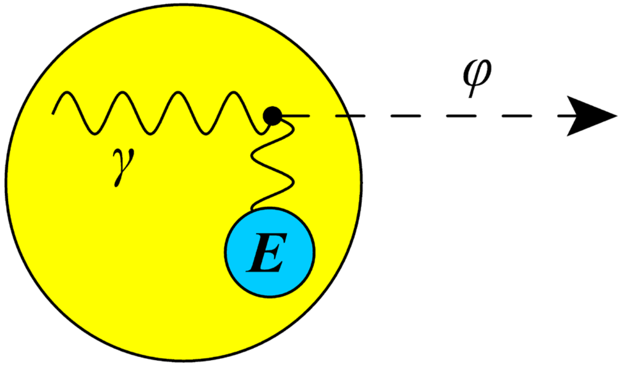
$\mathcal{L}_{\text{scalar}} \propto \varphi F_{\mu\nu}F^{\mu\nu} \propto \varphi\left(\boldsymbol{B}^2 - \boldsymbol{E}^2\right) \Rightarrow$ Need $\boldsymbol{E}_\gamma^{\text{lin}} \perp \boldsymbol{B}$

$\mathcal{L}_{\text{pseudoscalar}} \propto \varphi F_{\mu\nu}\tilde{F}^{\mu\nu} \propto \varphi \boldsymbol{E}\cdot\boldsymbol{B} \Rightarrow$ Need $\boldsymbol{E}_\gamma^{\text{lin}} \parallel \boldsymbol{B}$

Astrophysical Emission (Hot Media)

[Raffelt, *Phys. Rept.* **198**, 1 (1990)]



$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad \Rightarrow \quad \varepsilon_{\gamma\gamma\to\varphi} \sim \frac{T^7}{\Lambda_\gamma^2}$$

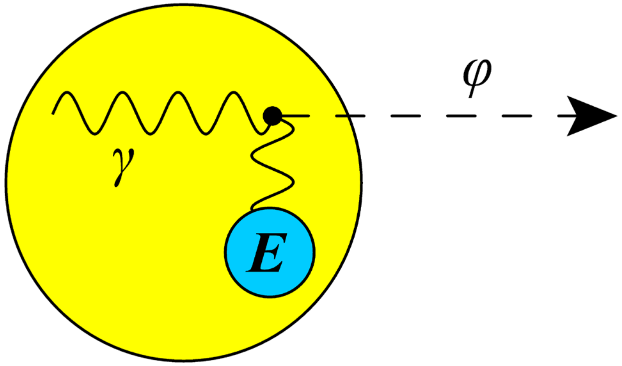
Emission possible for $m_\varphi \lesssim \mathcal{O}(T)$

Primakoff-type conversion

Excessive energy loss via additional channels would contradict stellar models and observations

Astrophysical Emission (Hot Media)

[Raffelt, *Phys. Rept.* **198**, 1 (1990)]

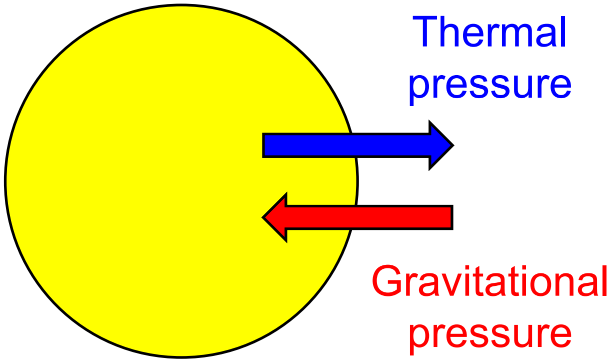


$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \;\Rightarrow\; \varepsilon_{\gamma\gamma\to\varphi} \sim \frac{T^7}{\Lambda_\gamma^2}$$

Emission possible for $m_\varphi \lesssim \mathcal{O}(T)$

Primakoff-type conversion

Excessive energy loss via additional channels would contradict stellar models and observations



Increased heating in active stars (e.g., Sun and main sequence stars, HB stars, red giants)

$$\langle E_{\rm mech}\rangle = \langle E_{\rm kin}\rangle + \langle E_{\rm grav}\rangle = \langle E_{\rm grav}\rangle/2 < 0$$

$$\langle E_{\rm mech}\rangle\downarrow \;\Rightarrow\; -\langle E_{\rm grav}\rangle/2 = \langle E_{\rm kin}\rangle\uparrow$$

Astrophysical Emission (Hot Media)

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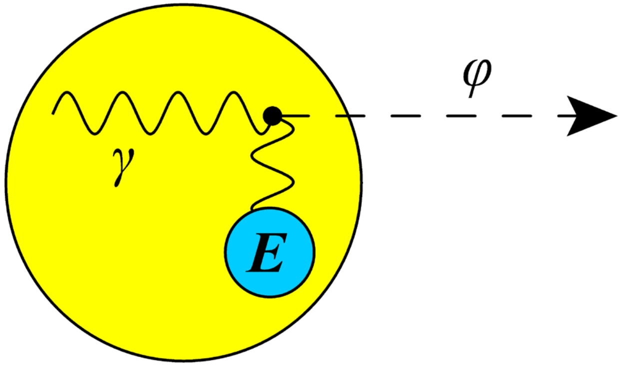

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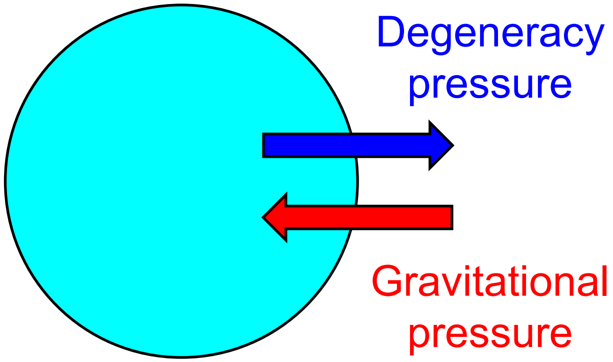
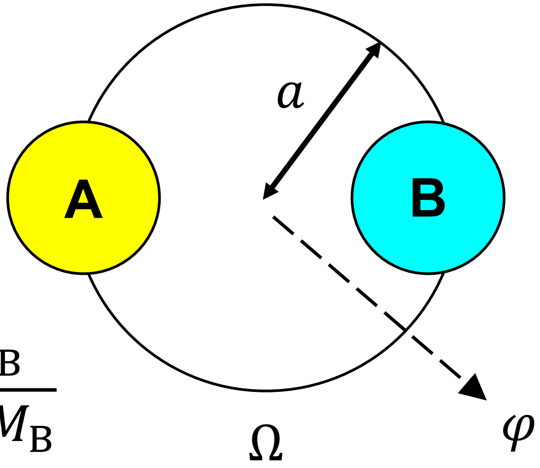


Increased cooling in dead stars (e.g., white dwarves, neutron stars)

Astrophysical Emission (Compact Binaries)

[Kumar Poddar *et al.*, *PRD* **100**, 123923 (2019)], [Dror *et al.*, *PRD* **102**, 023005 (2020)]



$$M = \frac{M_\mathrm{A} M_\mathrm{B}}{M_\mathrm{A} + M_\mathrm{B}}$$

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f$$

- Scalar Larmor radiation possible if $m_\varphi < \Omega$ (higher-order modes also possible for an elliptical orbit if $m_\varphi < n\Omega$, $n = 2, 3, \ldots$)

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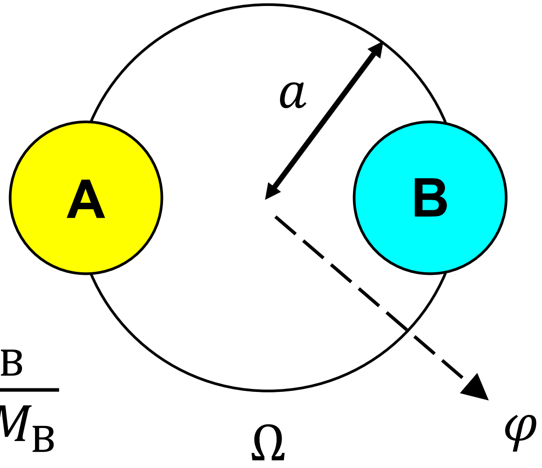

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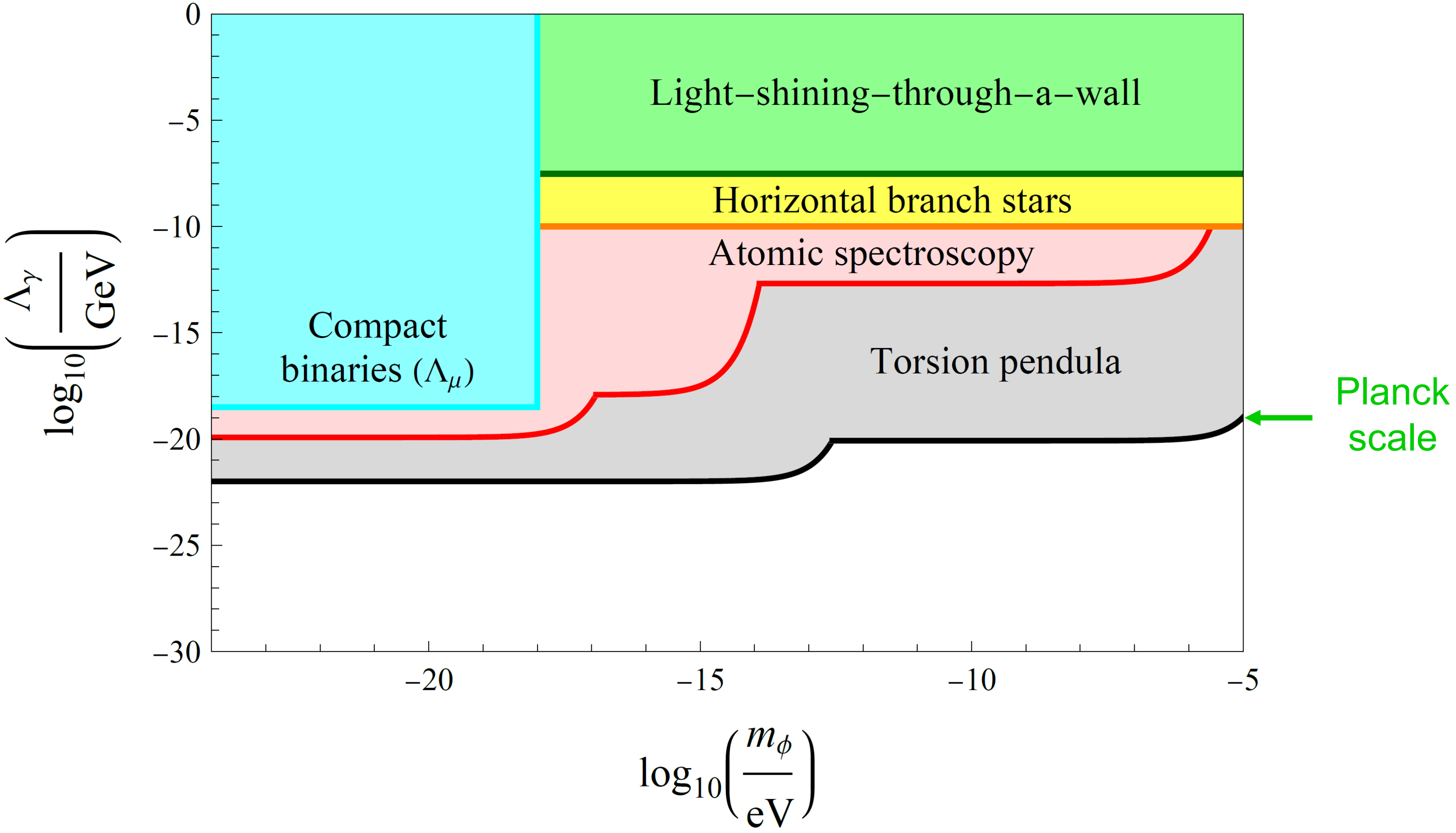
$$\frac{dE_\varphi}{dt} \sim \left(\frac{m_f}{\Lambda_f}\right)^2 (aM)^2 \Omega^4 \left(\frac{Q_\mathrm{A}}{M_\mathrm{A}} - \frac{Q_\mathrm{B}}{M_\mathrm{B}}\right)^2, \text{for } \Omega a \ll 1$$

- Dipole nature requires $Q_\mathrm{A}/M_\mathrm{A} \neq Q_\mathrm{B}/M_\mathrm{B}$, which is readily satisfied, e.g., for neutron-star/white-dwarf binary systems in the case of $f = n, e, \mu$

Landscape of $\varphi F_{\mu\nu}F^{\mu\nu}/4\Lambda_\gamma$ Coupling



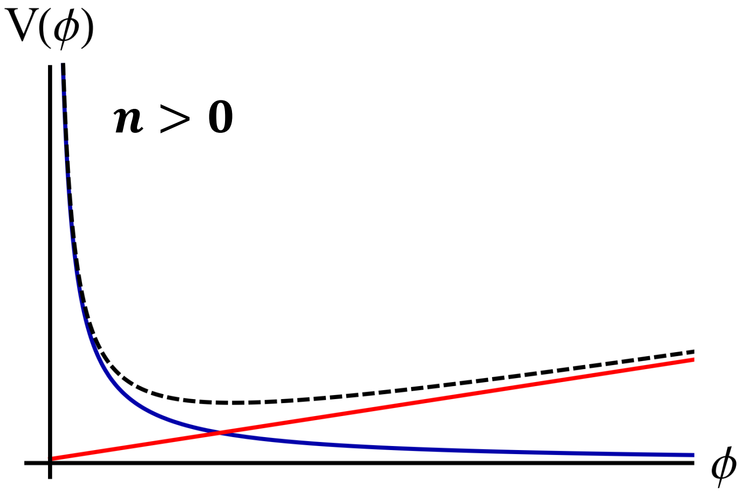
Phenomenology of Ultralight Scalar FIPs

1. Motivation
2. Mediators of new forces
3. Complementary probes
4. Screening mechanisms and environmental effects
5. Dark energy
6. Dark matter
7. Solitons

Chameleon Mechanism

[Khoury, Weltmann, *PRL* **93**, 171104 (2004); *PRD* **69**, 044026 (2004)]

$$V_{\mathrm{eff}}(\varphi) = \frac{\Lambda^{n+4}}{\varphi^n} + \frac{\rho\varphi}{M_*}$$



low ρ ⇒ low $m_{\mathrm{eff},\varphi}$

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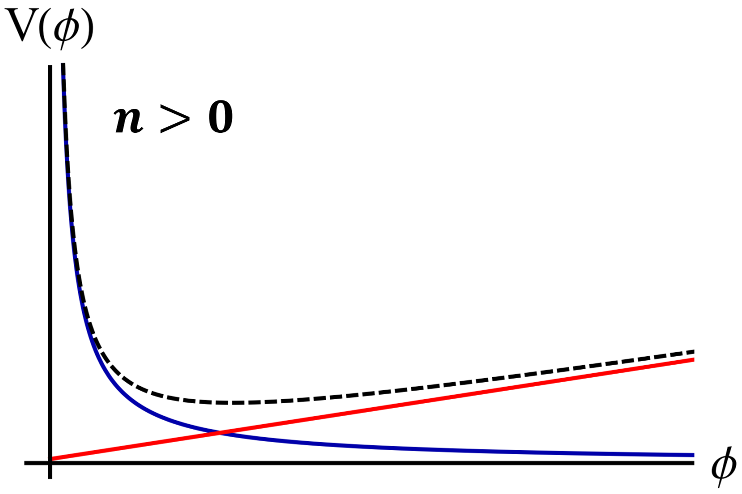

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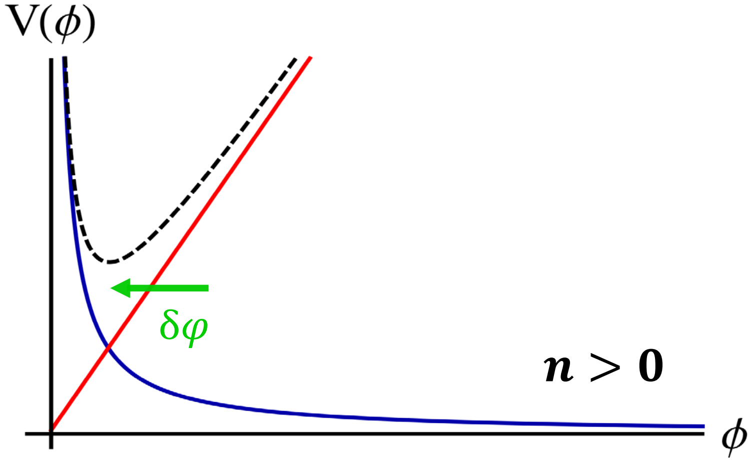


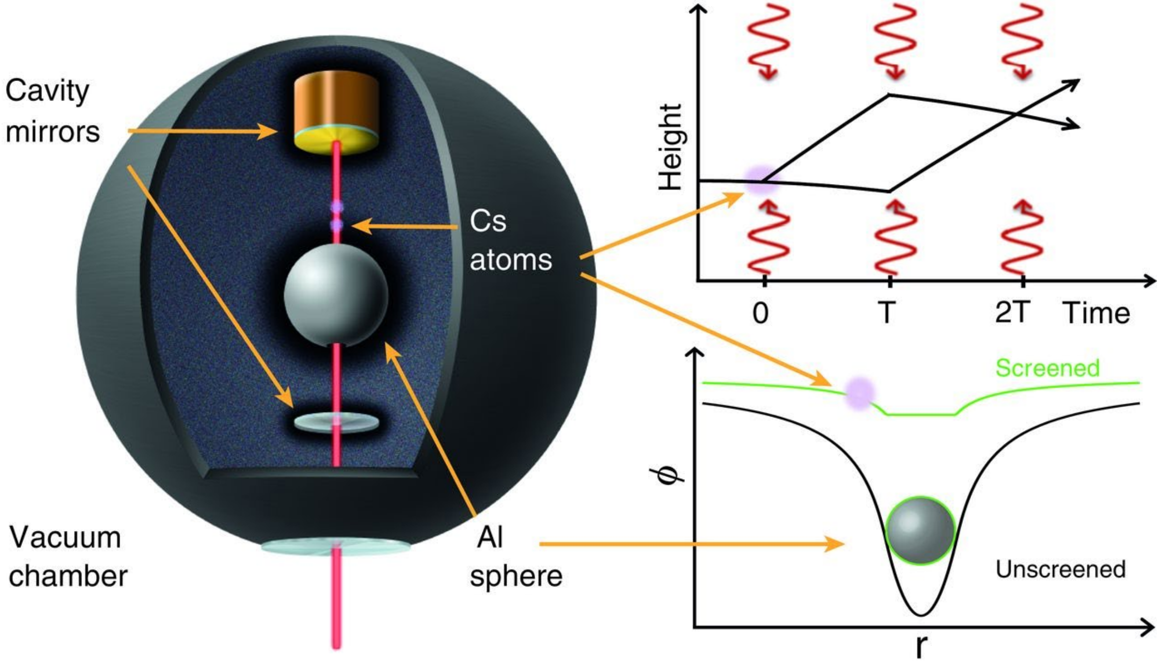
high ρ $\Rightarrow$ high $m_{\mathrm{eff},\varphi}$

- Going from a low-density environment (e.g., vacuum) to a high-density environment (e.g., terrestrial), the effective scalar mass increases, effectively reducing the interaction range $\lambda_{\mathrm{eff}} \sim 1/m_{\mathrm{eff},\varphi}$, and the value of φ diminishes
- Scalar field φ tends to be screened inside of dense bodies

Atom Interferometry Probes of Chameleons

[Burrage *et al.*, *JCAP* **03** (2015) 042], [Hamilton *et al.*, *Science* **349**, 849 (2015)], [Jaffe *et al.*, *Nat. Phys.* **13**, 938 (2017)], [Sabulsky *et al.*, *PRL* **123**, 061102 (2019)]

- Need $\lambda_{\text{eff}} \lesssim R_{\text{body}}$ inside a dense body for strong screening to occur
- Small test bodies (e.g., atoms) can evade strong screening



$$V_{\text{eff}}(\varphi) = \frac{\Lambda^{n+4}}{\varphi^n} + \frac{\rho\varphi}{M_*}$$

$$\Rightarrow \ \delta\boldsymbol{a} = \frac{\boldsymbol{\nabla}\varphi}{M_*}$$

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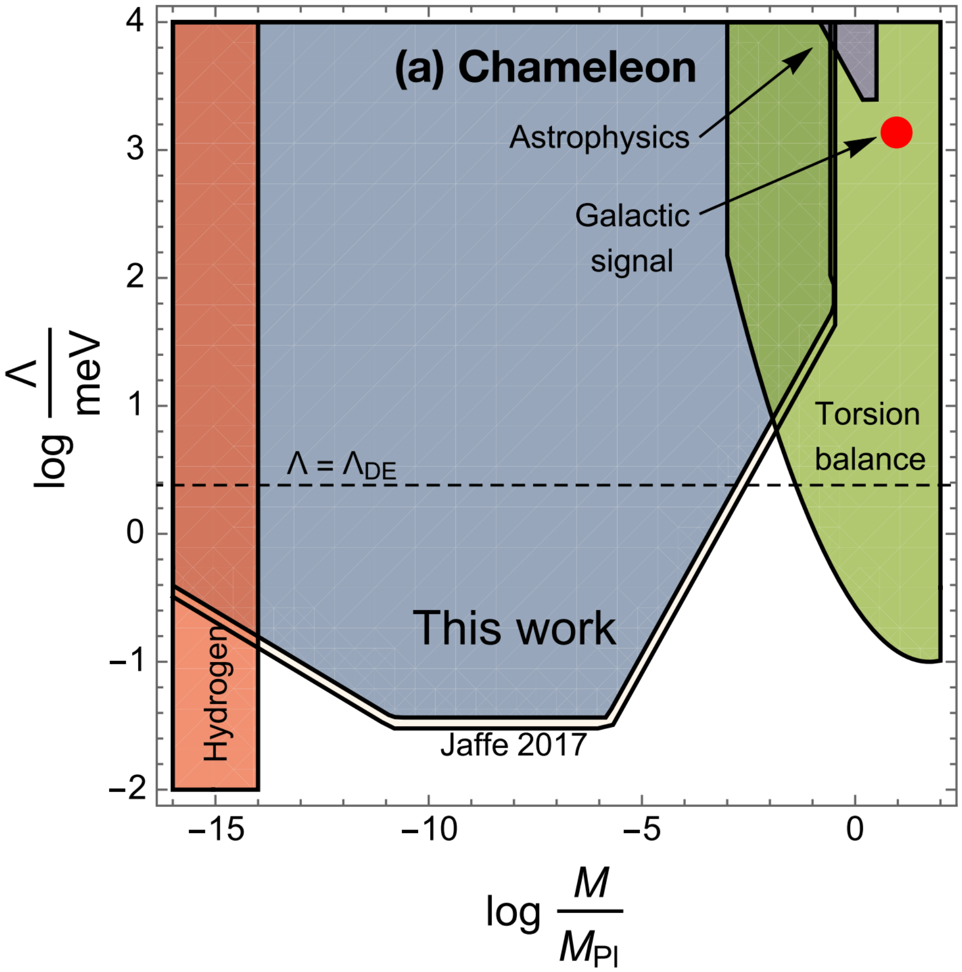

$$V_{\text{eff}}(\varphi) = \frac{\Lambda^5}{\varphi} + \frac{\rho\varphi}{M}$$

Symmetron Mechanism

[Olive, Pospelov, *PRD* **77**, 043524 (2008)], [Stadnik, *PRD* **102**, 115016 (2020)]

$$V_{\mathrm{eff}}(\varphi) = \frac{\lambda}{4}\left(\varphi^2 - \varphi_0^2\right)^2 + \sum_{X=\gamma,e,N} \frac{\rho_X \varphi^2}{\left(\Lambda'_X\right)^2}$$

Effective potential

Bare potential

Ordinary matter (non-relativistic) contribution

$$\mathcal{L}'_\gamma = \frac{\varphi^2}{\left(\Lambda'_\gamma\right)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\varphi^2}{\left(\Lambda'_f\right)^2} m_f \bar{f} f$$

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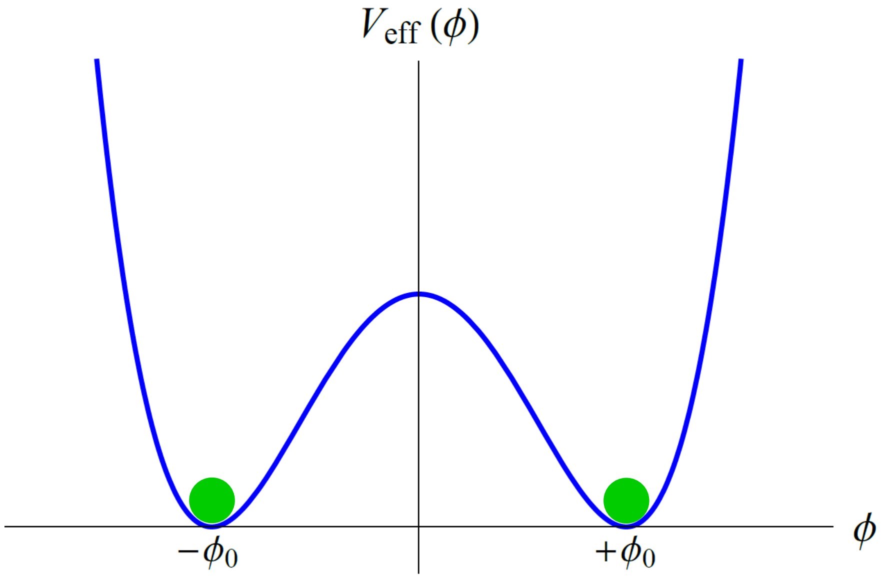
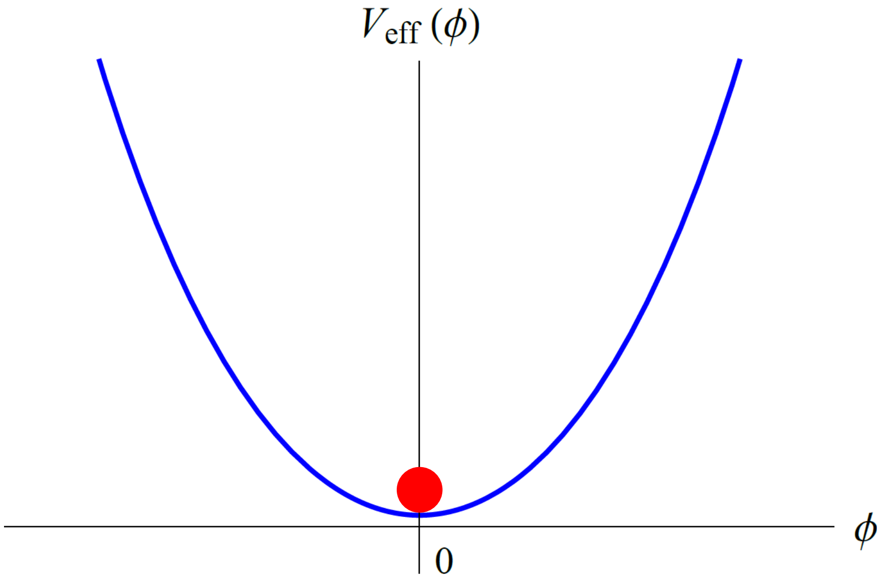


Low ρ (vacuum breaks Z_2 symmetry)



High ρ (vacuum respects Z_2 symmetry)

Z_2 symmetry: $\varphi \to -\varphi$

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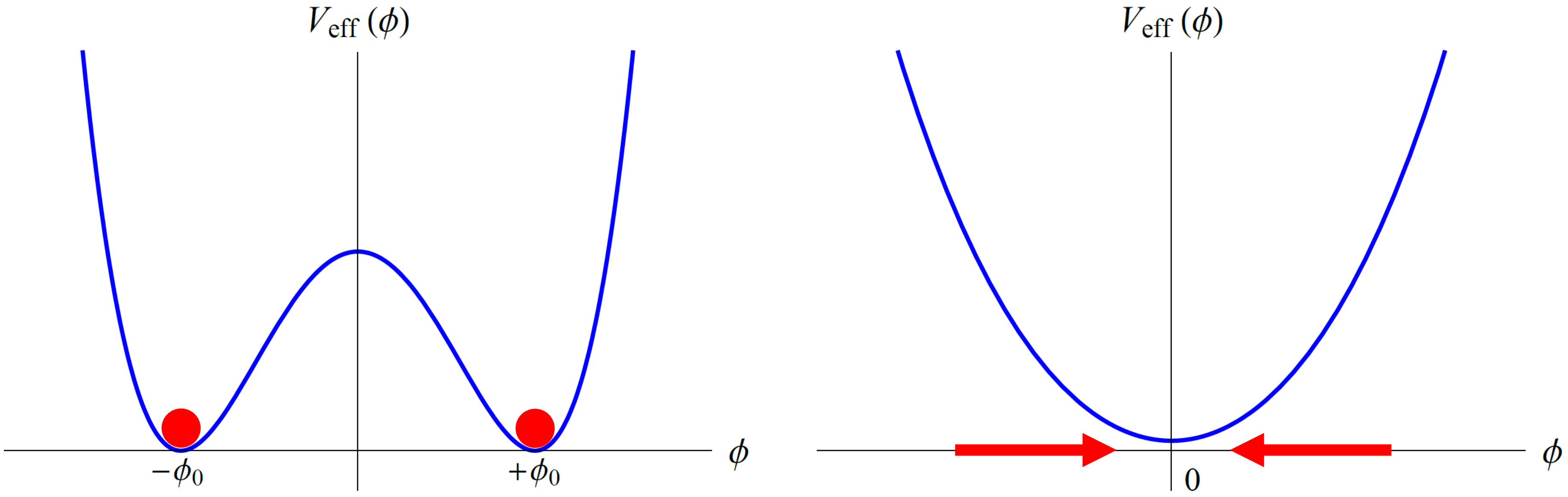

Low ρ (vacuum breaks Z_2 symmetry) **High ρ (vacuum respects Z_2 symmetry)**

- Scalar field φ tends to be screened in dense environments

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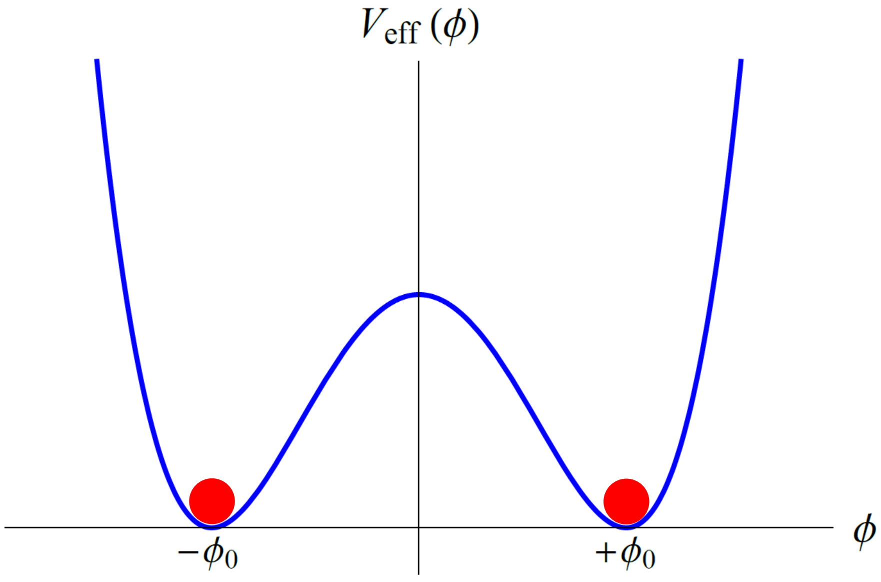

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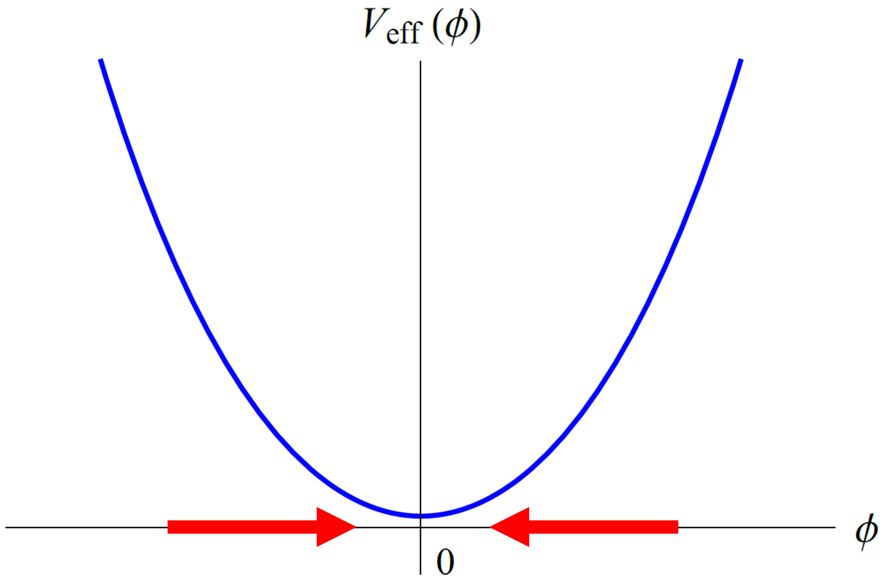
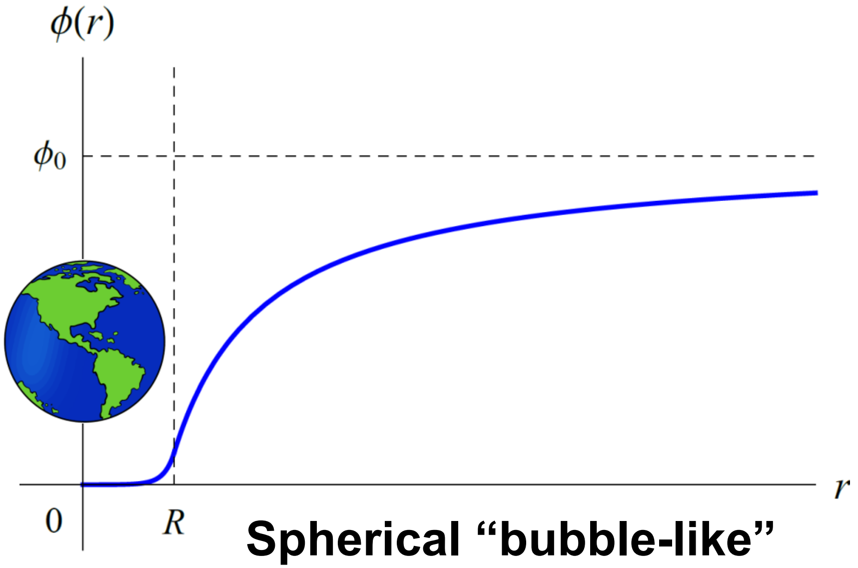


High ρ (vacuum respects Z_2 symmetry)

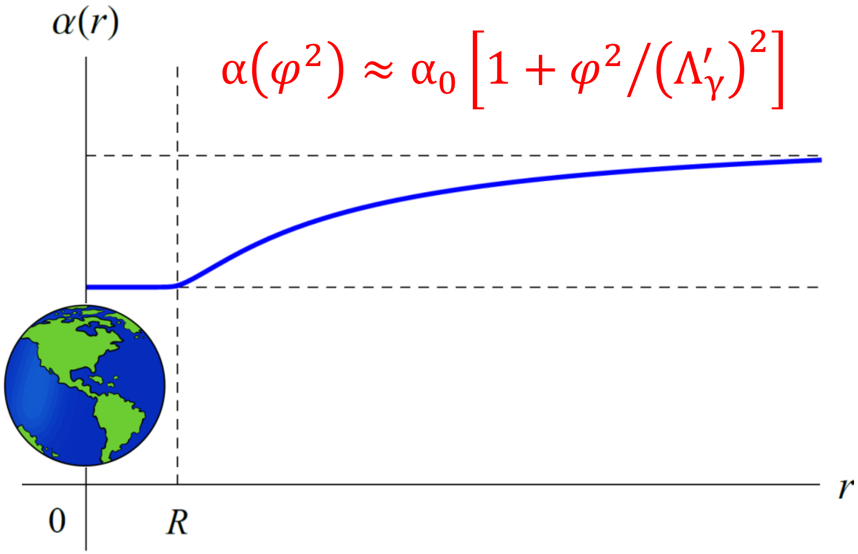
- Scalar field φ tends to be screened in dense environments
- $\alpha[\varphi^2(\rho)], m_f[\varphi^2(\rho)]$ ⇒ **Environmental dependence of "constants"**

Environmental Dependence of “Constants”

[Olive, Pospelov, *PRD* **77**, 043524 (2008)], [Stadnik, *PRD* **102**, 115016 (2020)]



Spherical “bubble-like” defect around Earth



- **Variations of “constants” with height** above a dense body

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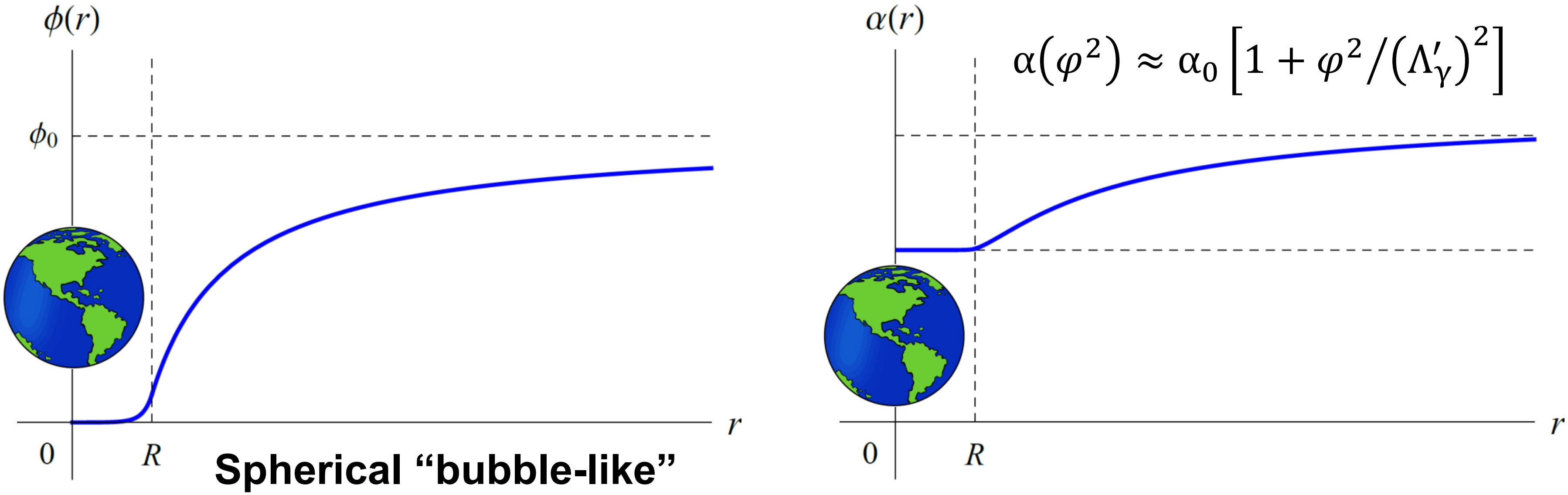

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Spherical "bubble-like" defect around Earth

- **Variations of "constants" with height** above a dense body
- Can search for these spatial variations with:
  1. Equivalence-principle-violating forces: $\delta \boldsymbol{a}_{\text{test}} = -\boldsymbol{\nabla}\,[m_{\text{test}}(\alpha)]/m_{\text{test}}$
  2. Compare clocks at different heights: $\Delta\nu/\nu \propto \Delta\alpha/\alpha$
  3. Compare laboratory and low-density ($\sim 10^{-3}\,\text{cm}^{-3}$) astrophysical spectra

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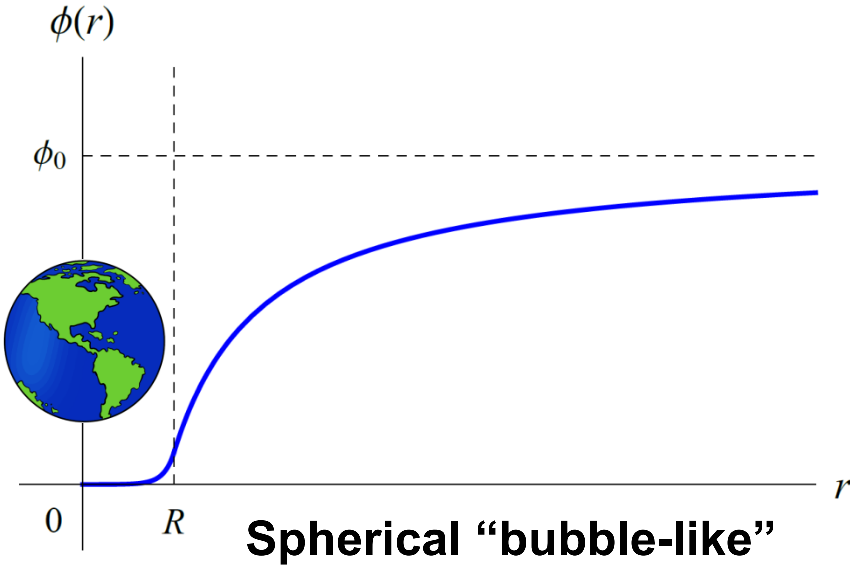

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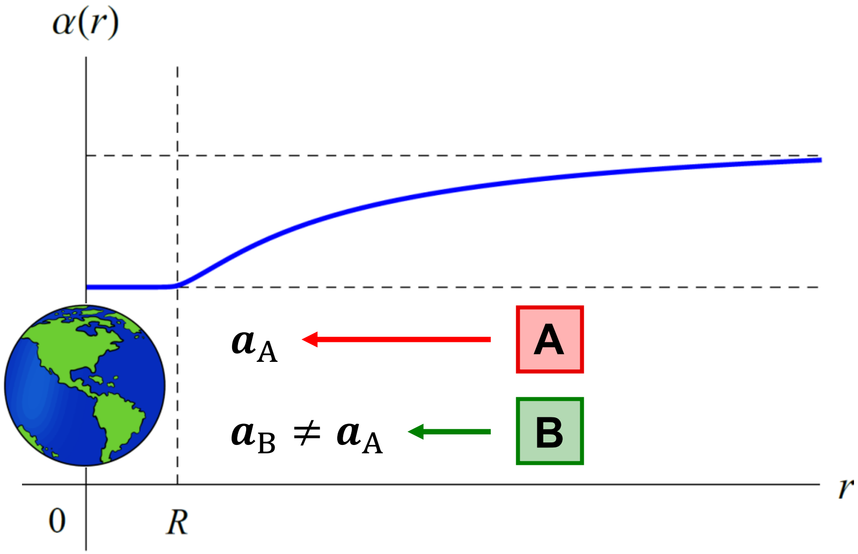

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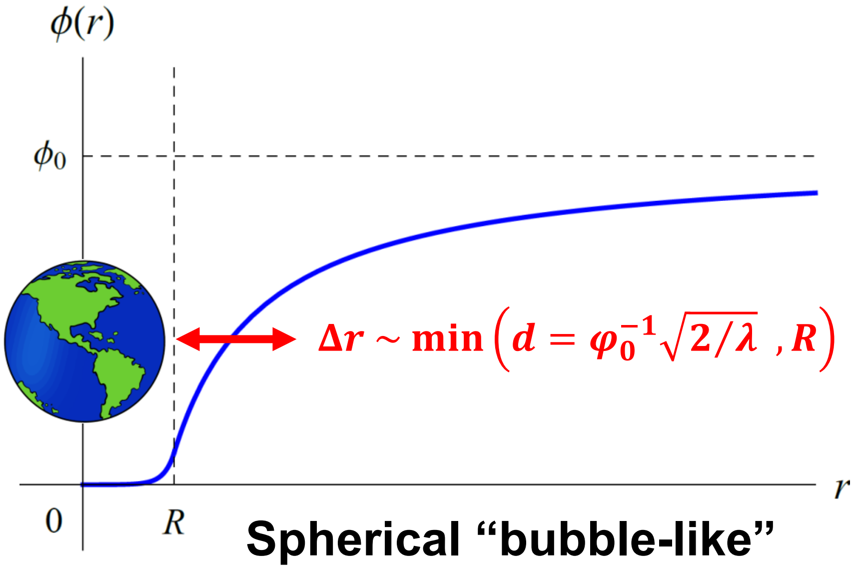

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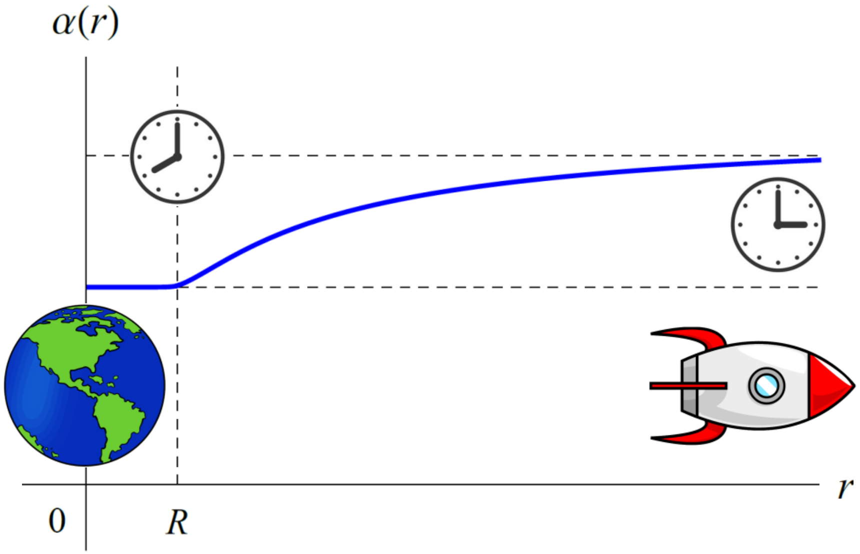

In space $(\Delta h \sim 10^4\ \mathrm{km})$

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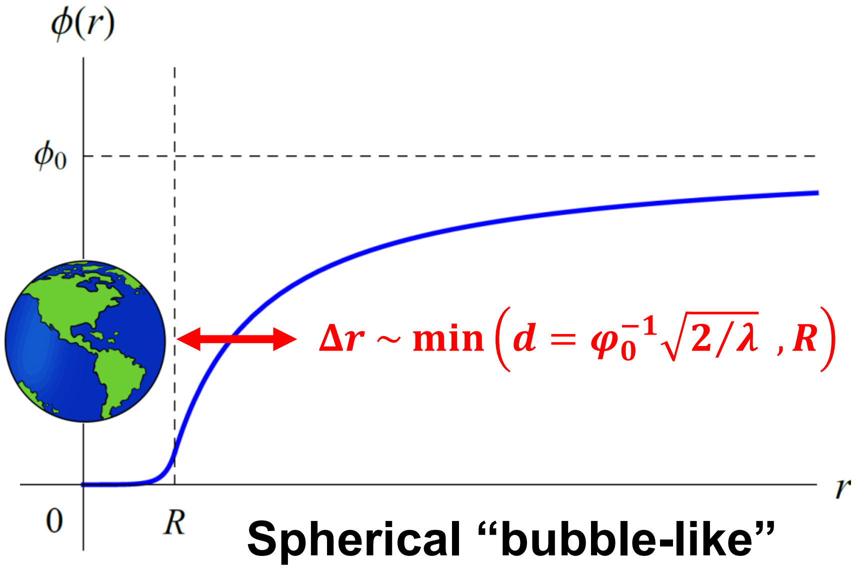

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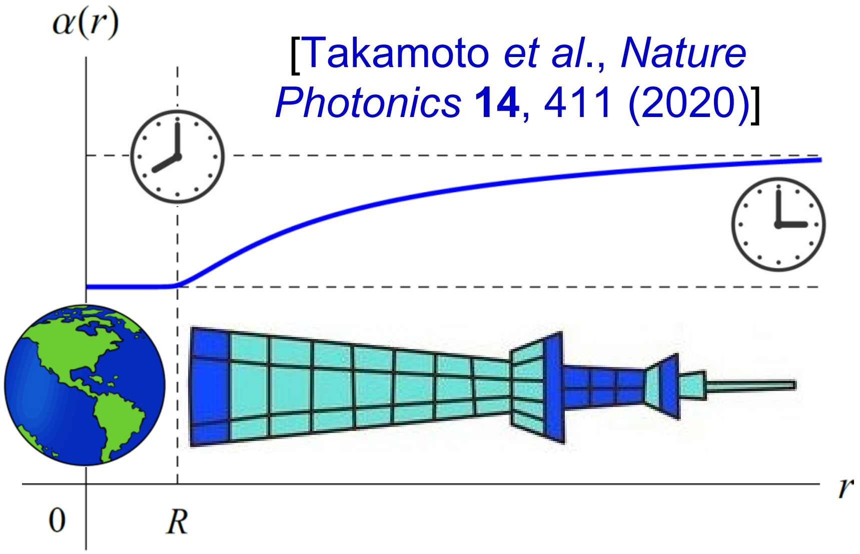

[Takamoto *et al.*, *Nature Photonics* **14**, 411 (2020)]

TOKYO SKYTREE $(\Delta h \approx 0.5\ \mathrm{km})$

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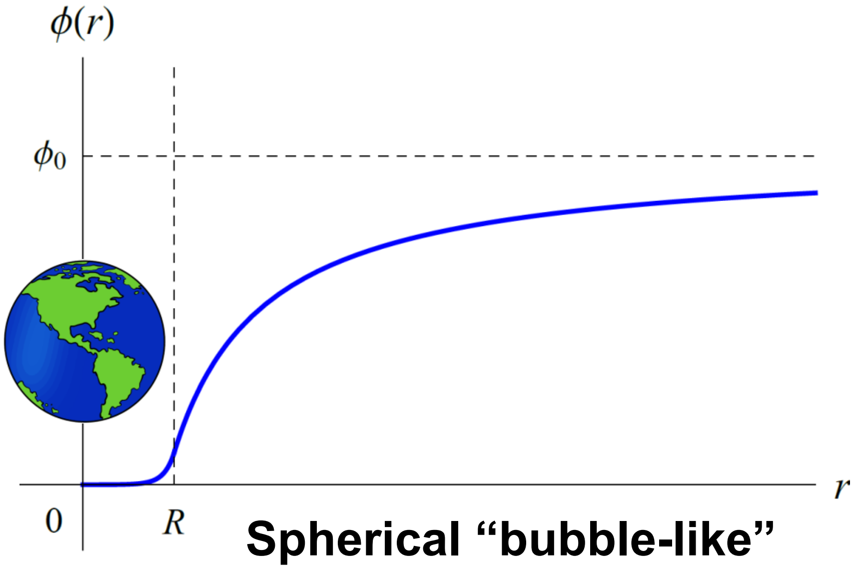

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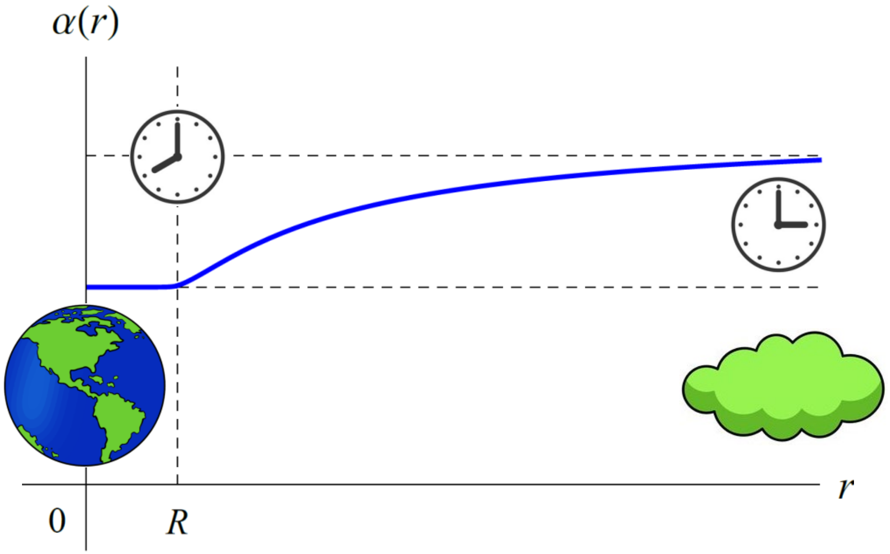

Distant gas clouds

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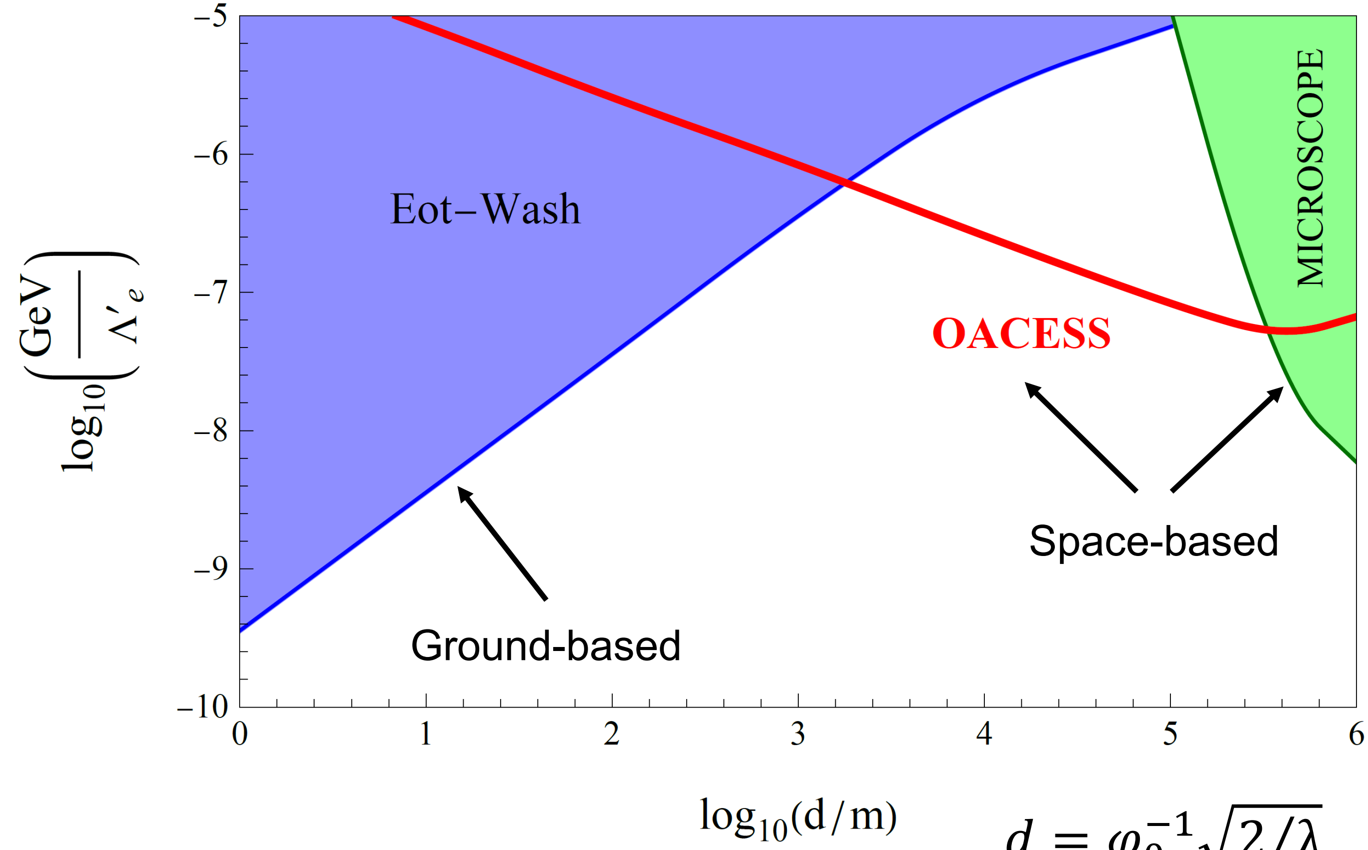
Opportunities for Space-Based Experiments

[Stadnik, *PRD* **102**, 115016 (2020)], [Schkolnik *et al.*, *Quantum Sci. Technol.* **8**, 014003 (2023)]

$$V_{\mathrm{eff}}(\varphi) = \frac{\lambda}{4}\left(\varphi^2 - \varphi_0^2\right)^2 + \frac{\rho_e \varphi^2}{(\Lambda'_e)^2}$$



$$d = \varphi_0^{-1}\sqrt{2/\lambda}$$

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Scalar-Field Dark Energy

- ΛCDM model is in principle fully consistent with the presence of a (time-independent) cosmological constant $\Lambda \sim 10^{-3}\ \mathrm{eV}$ within GR
- Nevertheless, observational data permit small deviations from the equation of state $w = p/\rho = -1$ (e.g., starting in recent times)
- Motivates class of scalar-field models known as **quintessence**, where Λ is replaced by a dynamical scalar field φ:
  - Gravity still described by GR:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

  - $\Lambda = 0$
  - $T_{\mu\nu}$ receives contributions from the quintessence field φ, as well as visible matter, radiation, dark matter, …

Quintessence

- Classical equation of motion for a scalar field φ with potential $V(\varphi)$ in an expanding Universe reads [$H(t)$ is the Hubble parameter]:

$$\frac{\partial^2\varphi}{\partial t^2} + 3H(t)\frac{\partial\varphi}{\partial t} + \frac{\partial V}{\partial\varphi} = 0, \qquad H(t) = \dot{a}(t)/a(t)$$

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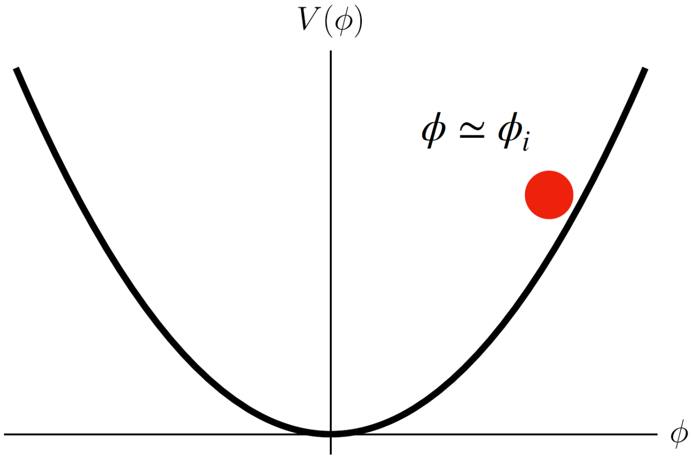

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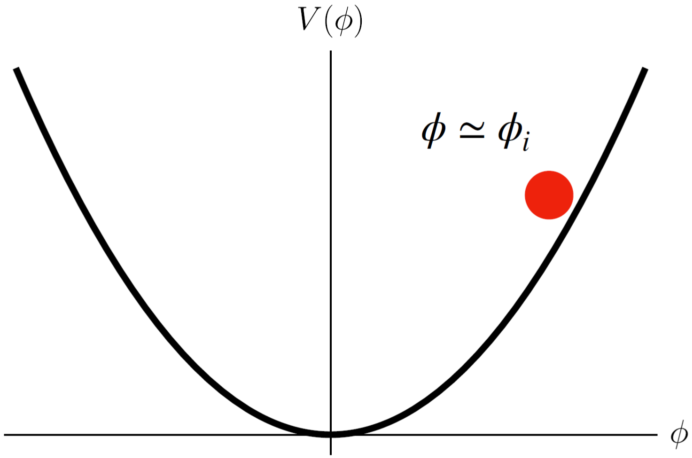

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- For the harmonic potential $V(\varphi) = m_\varphi^2\varphi^2/2$, slow-roll conditions are satisfied in the present-day Universe for $m_\varphi \sim 10^{-33}\ \mathrm{eV}$

Linear-in-time Drifts of Fundamental "Constants"

[Bekenstein, *PRD* **25**, 1527 (1982)], [Uzan, *Living Rev. Relativ.* **14**, 2 (2011)]

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad \text{cf.} \quad \mathcal{L}_\gamma^{\text{SM}} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} - eJ_\mu A^\mu \quad \Rightarrow \quad \alpha \rightarrow \frac{\alpha}{1-\varphi/\Lambda_\gamma} \approx \alpha\left(1+\frac{\varphi}{\Lambda_\gamma}\right)$$

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f} m_f \bar{f} f \quad \text{cf.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad \Rightarrow \quad m_f \rightarrow m_f\left(1+\frac{\varphi}{\Lambda_f}\right)$$

$$\frac{d\varphi}{dt} \approx \text{constant} \;\Rightarrow\; \frac{dX}{dt} \approx \text{constant}$$

Linear-in-time Drifts of Fundamental "Constants"

[Bekenstein, *PRD* **25**, 1527 (1982)], [Uzan, *Living Rev. Relativ.* **14**, 2 (2011)]

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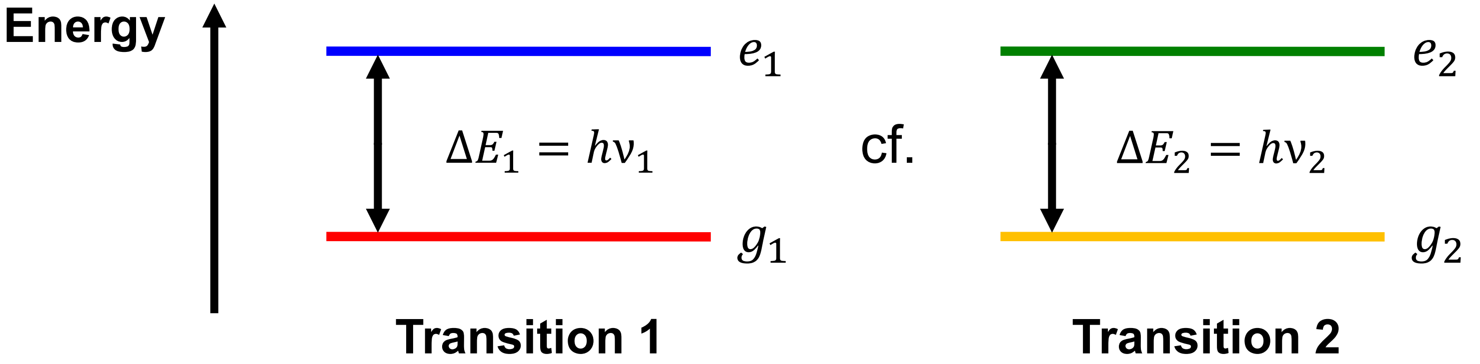
$$\frac{d\varphi}{dt} \approx \text{constant} \;\Rightarrow\; \frac{dX}{dt} \approx \text{constant}$$

Can search for linear-in-time drifts of fundamental constants using a range of laboratory, terrestrial and astronomical methods:

1. Atomic spectroscopy (clocks)
2. Quasar absorption spectra
3. Oklo phenomenon
4. Meteorite dating

Atomic Spectroscopy



$$\boxed{\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} = \left(K_{X,1} - K_{X,2}\right)\frac{\delta X}{X} \;;\; X = \alpha, m_e/m_N\,, \ldots}$$

Atomic spectroscopy (including clocks) has been used for decades to search for "slow drifts" in fundamental constants

Recent overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

"Sensitivity coefficients" K_X required for the interpretation of experimental data have been calculated extensively by Flambaum group

Reviews: [Flambaum, Dzuba, *Can. J. Phys.* **87**, 25 (2009); *Hyperfine Interac.* **236**, 79 (2015)]

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999);
Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum,
PRA **70**, 014102 (2004); Dzuba, Flambaum, *PRA* **77**, 012515 (2008)]

- Atomic optical transitions:

$$\nu_{\text{opt}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) F_{\text{rel}}^{\text{opt}}(Z\alpha)$$

Non-relativistic atomic unit of frequency

Relativistic factor

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$$K_\alpha(\mathrm{Sr}) = 0.06, K_\alpha(\mathrm{Yb}) = 0.3, K_\alpha(\mathrm{Hg}) = 0.8$$

Increasing *Z*

$$|\boldsymbol{p}_e|_{\text{near nucleus}} \sim Z\alpha m_e c$$

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Increasing *Z*

For transitions between closely spaced energy levels that arise due to the near cancellation of contributions of different nature, the K_α sensitivity coefficients can be greatly enhanced, e.g.:

- $\left|K_\alpha\left(\mathrm{Cf}^{15+}\right)\right| \approx 50$ [Dzuba *et al.*, *PRA* **92**, 060502 (2015)]

- $\left|K_\alpha\left({}^{229}\mathrm{Th}\right)\right| \sim 10^4$ [Flambaum, *PRL* **97**, 092502 (2006)]

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- Atomic hyperfine transitions:

$$\nu_{\mathrm{hf}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) \left[\alpha^2 F_{\mathrm{rel}}^{\mathrm{hf}}(Z\alpha)\right] \left(\frac{m_e}{m_N}\right) \mu$$

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Increasing *Z*

- Atomic hyperfine transitions:

$$K_{m_e/m_N} = 1$$

$$\nu_{\text{hf}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) \left[\alpha^2 F_{\text{rel}}^{\text{hf}}(Z\alpha)\right] \left(\frac{m_e}{m_N}\right) \mu$$

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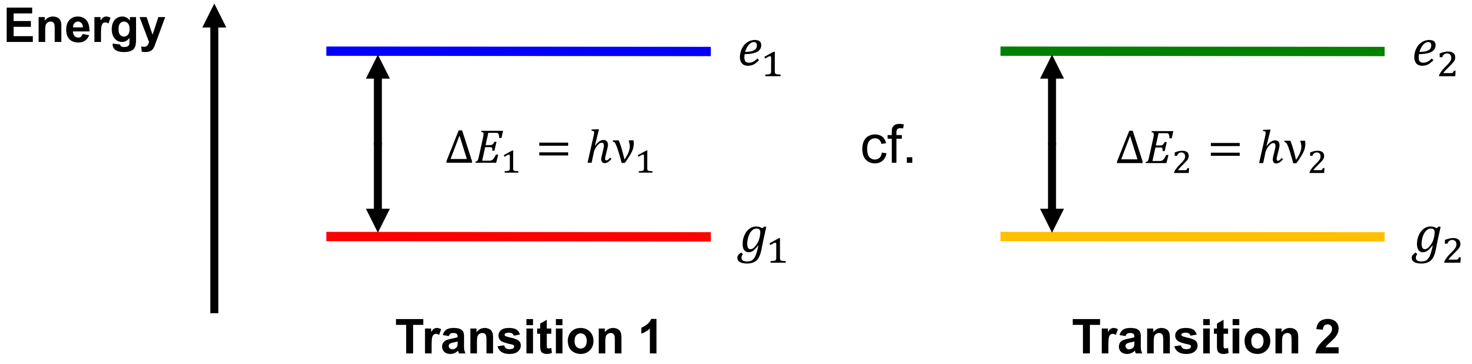
Increasing *Z*

Atomic Spectroscopy



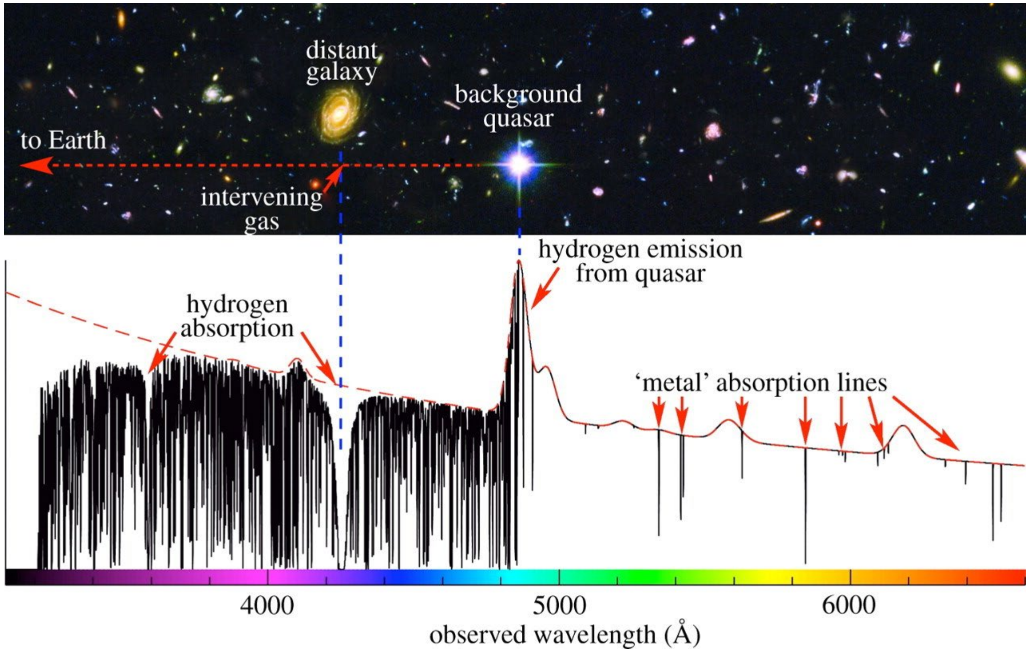
$$\boxed{\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} = \left(K_{X,1} - K_{X,2}\right)\frac{\delta X}{X}\;;\;\; X = \alpha\,,\, \mu = m_e/m_p\,, \ldots}$$

$|\delta\dot{\alpha}/\alpha|_{\mathrm{Yb}^+(E2)/\mathrm{Yb}^+(E3)} \lesssim 10^{-18}\ \mathrm{yr}^{-1}$ [Lange *et al.*, *PRL* **126**, 011102 (2021)]

$|\delta\dot{\mu}/\mu|_{\mathrm{Yb}^+(E3)/\mathrm{Cs}} \lesssim 10^{-16}\ \mathrm{yr}^{-1}$ [Huntemann *et al.*, *PRL* **113**, 210802 (2014)]

$$\Delta t \sim \mathcal{O}(1-10)\ \mathrm{yrs}$$

Quasar Absorption Spectra



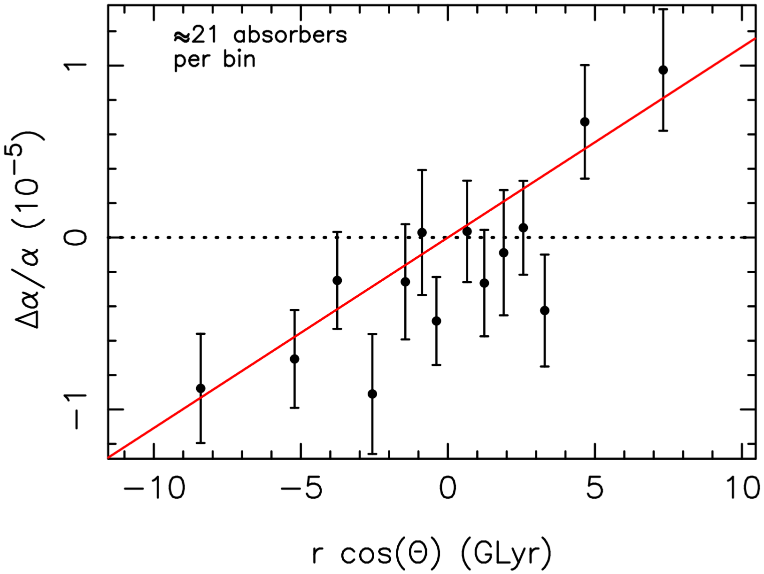
Compare frequencies of atomic absorption lines at different cosmological redshift values ($z \lesssim 7$) with reference values in the laboratory ($z = 0$)

$$|\Delta\alpha/\alpha|\big|_{z\approx 5.5-7} \lesssim 10^{-4}$$ [Wilczynska *et al.*, *Sci. Adv.* **6**, 011102 (2021)]

$$\Delta t \approx 13 \times 10^{9}\,\mathrm{yr} \;\;\Rightarrow\;\; |\dot{\alpha}/\alpha| \lesssim 10^{-14}\,\mathrm{yr}^{-1}$$

Quasar Absorption Spectra

[Webb *et al.*, *PRL* **107**, 191101 (2011)]



- $\sim 4\sigma$ hint of a spatial variation of α on cosmological length scales from $z \lesssim 4$ quasar measurements, with $|\boldsymbol{\nabla}\alpha/\alpha| \approx 10^{-6}\ (\mathrm{Glyr})^{-1}$

Quasar Absorption Spectra

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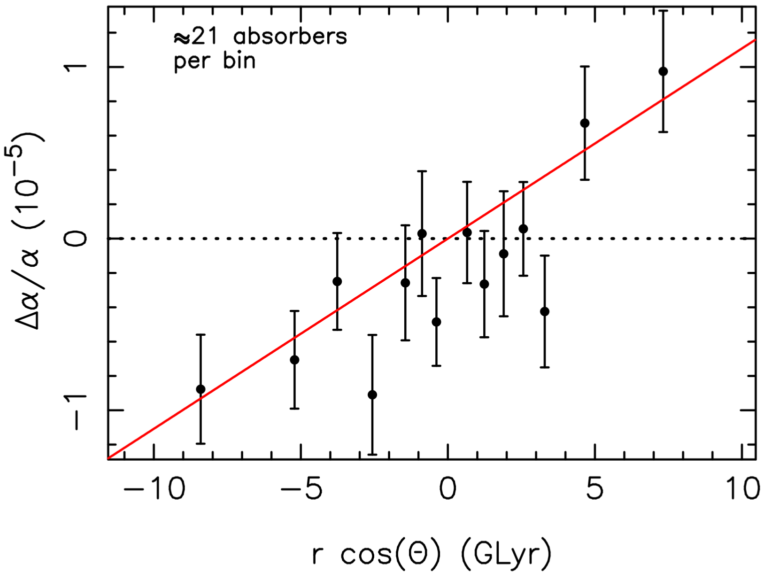

- $\sim 4\sigma$ hint of a spatial variation of α on cosmological length scales from $z \lesssim 4$ quasar measurements, with $|\boldsymbol{\nabla}\alpha/\alpha| \approx 10^{-6}\ (\mathrm{Glyr})^{-1}$
- Current laboratory measurements not sufficiently precise to corroborate these astronomical hints (for a uniform $\boldsymbol{\nabla}\alpha$):
  - $\delta(\boldsymbol{a}_1 - \boldsymbol{a}_2) \propto \boldsymbol{\nabla}\alpha/\alpha \ \Rightarrow \ |\boldsymbol{\nabla}\alpha/\alpha| \approx 6.6 \times 10^{-4}\ (\mathrm{Glyr})^{-1}$ [Stadnik, *PRA* **103**, 062807 (2021)]
  - $\Delta\alpha = \boldsymbol{\nabla}\alpha \cdot \Delta\boldsymbol{x} \ \Rightarrow$ Comparable sensitivity with latest atomic clock data

Oklo Phenomenon

[Shlyakhter, *Nature* **264**, 340 (1976)],
[Damour, Dyson, *Nucl. Phys. B* **480**, 37 (1996)], [Petrov *et al*., *PRC* **74**, 064610 (2006)]

- A natural nuclear fission reactor became operational in Oklo about $\Delta t \approx 2 \times 10^9\ \mathrm{yr}$ ago ($z \sim 0.1$), lasting for $\sim 10^5 - 10^6\ \mathrm{yr}$

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- Thermal neutron capture process $n + {}^{149}\mathrm{Sm} \rightarrow {}^{150}\mathrm{Sm} + \gamma$ is dominated by the resonant capture of a neutron with $E \approx 0.1\ \mathrm{eV}$
- Small $E \approx 0.1\ \mathrm{eV}$ arises due to near cancellation between EM and strong force contributions $\Rightarrow$ Enhanced sensitivity to α variation

$$|\Delta\alpha/\alpha|\Big|_{z\sim 0.1} \lesssim 10^{-7} - 10^{-8}$$

$$\Delta t \approx 2 \times 10^9\ \mathrm{yr} \ \ \Rightarrow \ \ |\dot{\alpha}/\alpha| \lesssim 10^{-17}\ \mathrm{yr}^{-1}$$

Meteorite Dating

[Wilkinson, *Phil. Mag*. **3**, 582 (1958)], [Dyson, in “Aspects of Quantum Theory” (1972)], [Olive, Pospelov, *et al*., *PRD* **66**, 045022 (2002)]

- Nuclear decay rates are sensitive to changes in α due to the Coulomb contribution to nuclear binding energies:

$$E_{\mathrm{EM}}^{\mathrm{nucl}} \approx \frac{100Z(Z-1)\alpha}{A^{1/3}}\ \mathrm{MeV}$$

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- Example – Rhenium-187 decay rate determination via measurements of ${}^{187}\mathrm{Os}/{}^{188}\mathrm{Os}$ and ${}^{187}\mathrm{Re}/{}^{188}\mathrm{Os}$ number ratios:

$$|\Delta\alpha/\alpha|\Big|_{z\sim 1} \lesssim 8\times 10^{-9}$$

$$\Delta t \approx 4.6\times 10^{9}\ \mathrm{yr} \ \Rightarrow\ |\dot{\alpha}/\alpha| \lesssim 2\times 10^{-18}\ \mathrm{yr}^{-1}$$

Phenomenology of Ultralight Scalar FIPs

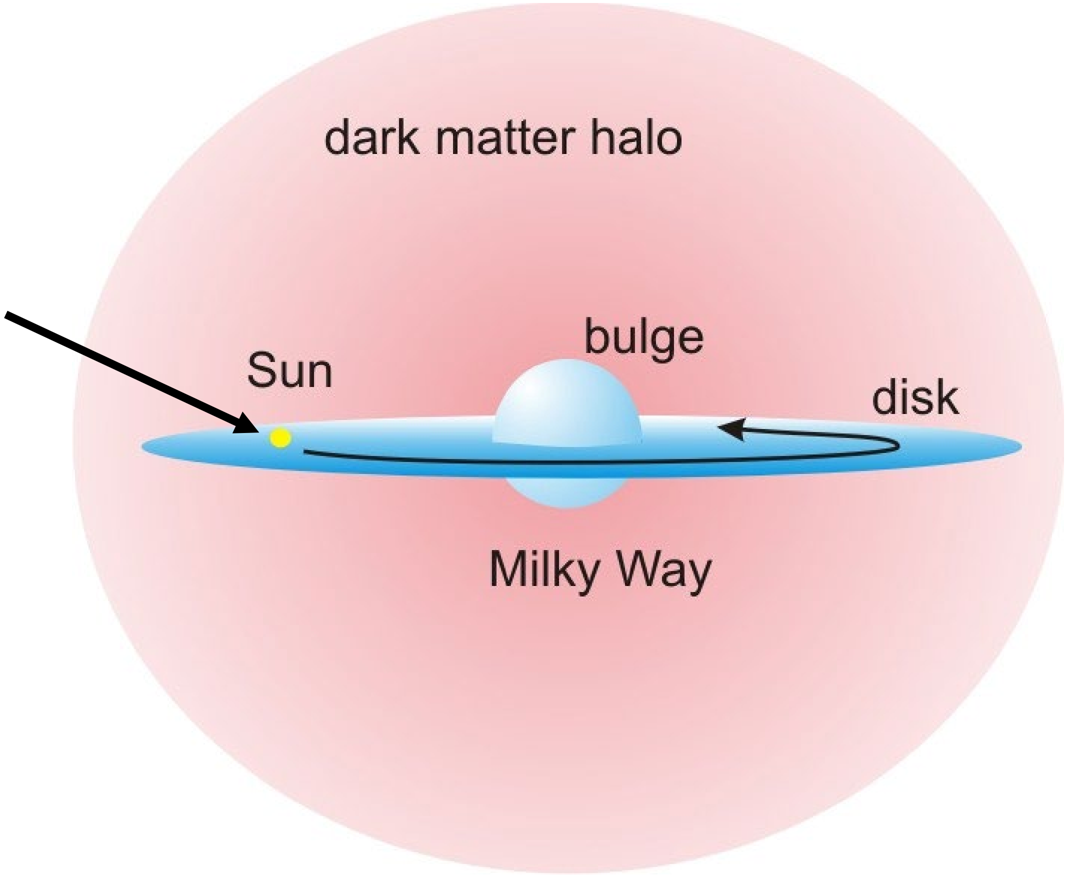
1. Motivation
2. Mediators of new forces
3. Complementary probes
4. Screening mechanisms and environmental effects
5. Dark energy
6. **Dark matter**
7. Solitons

Dark Matter

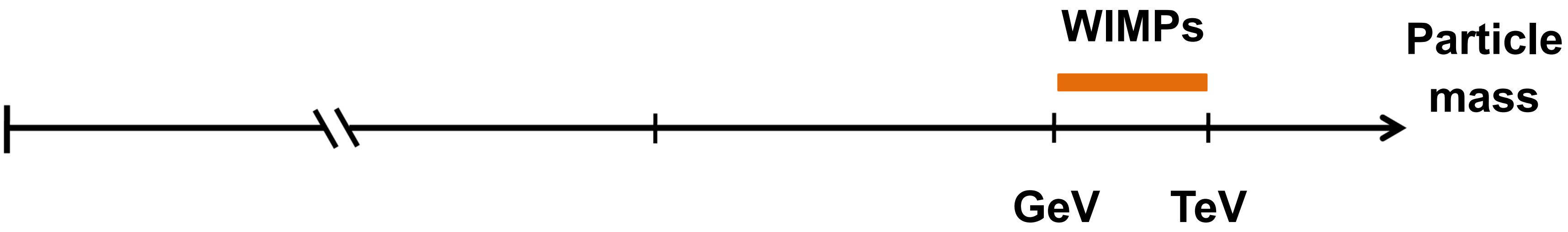
Strong astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter)

$$\rho_{\mathrm{DM}} \approx 0.4\ \mathrm{GeV/cm^3}$$

$$v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}$$



Dark Matter



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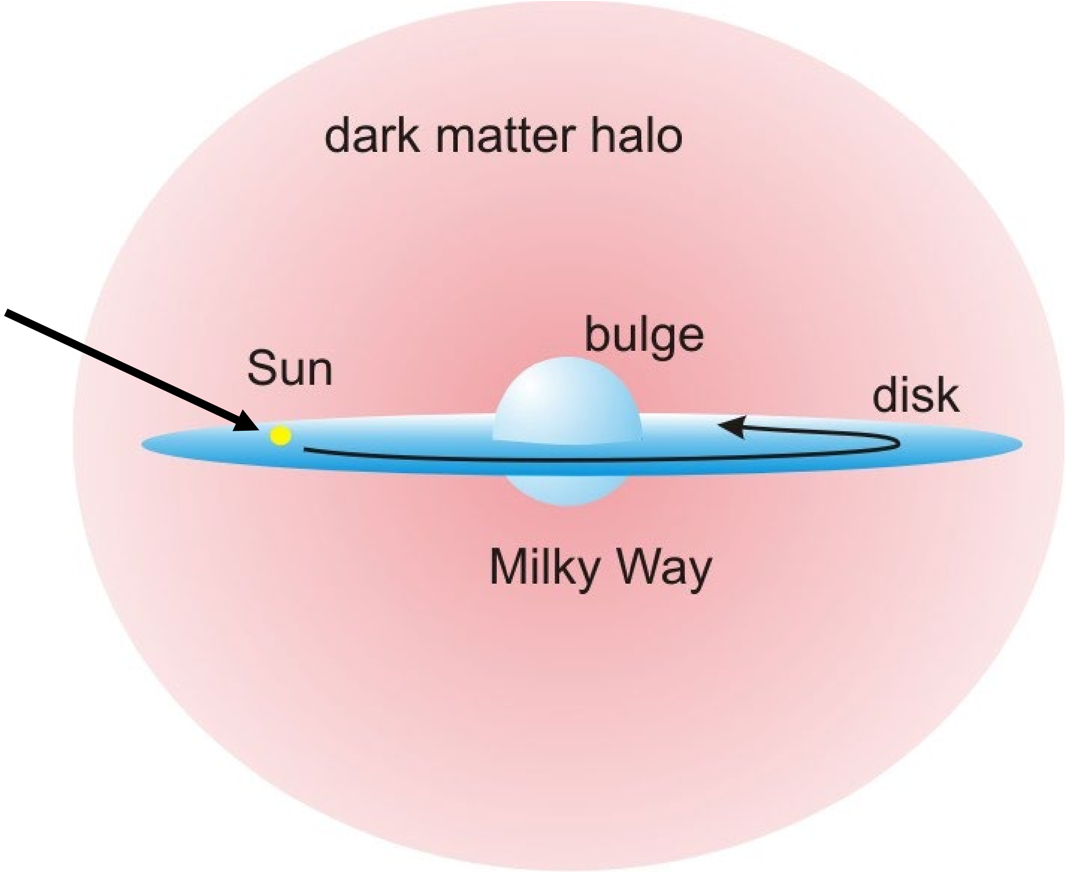

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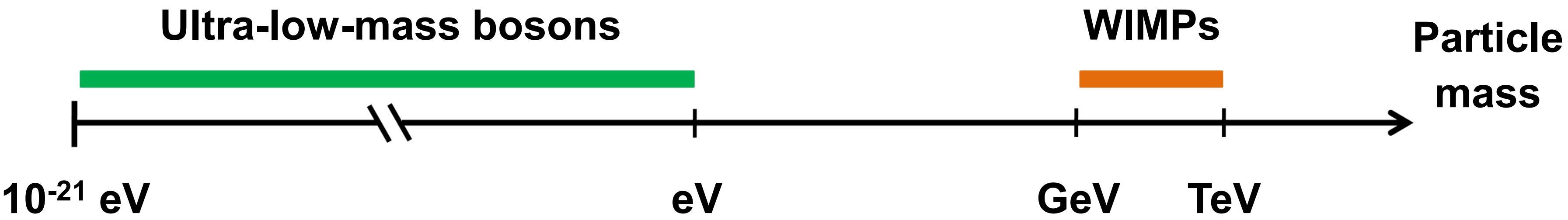

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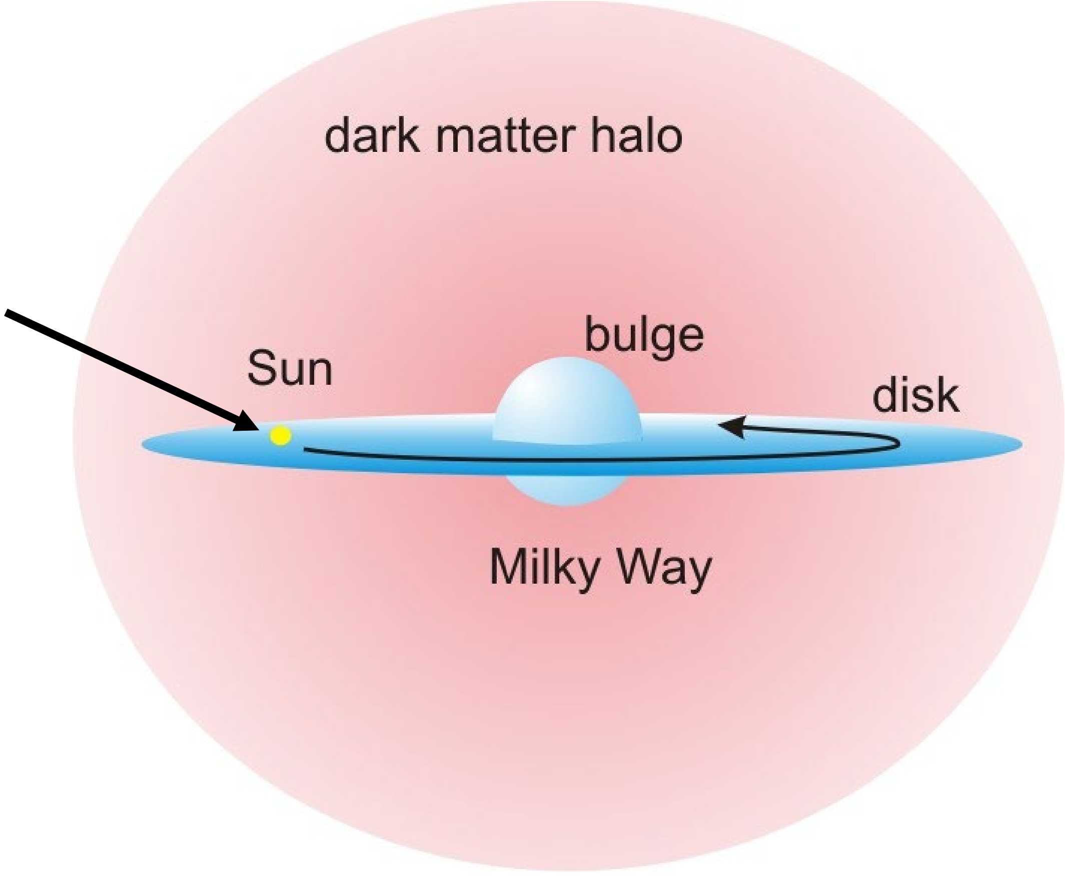
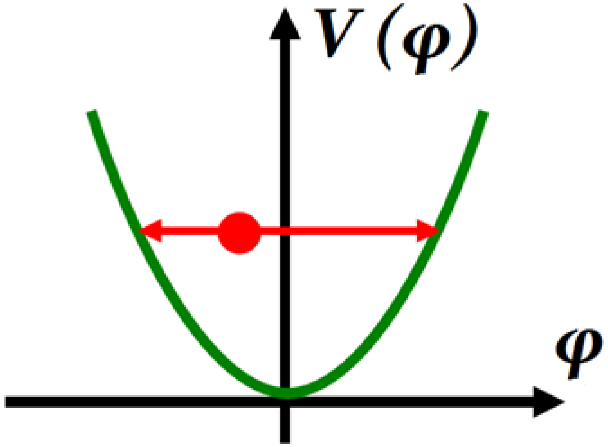


Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right)$, with energy density $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ $\left(\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}\right)$



$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

$$\ddot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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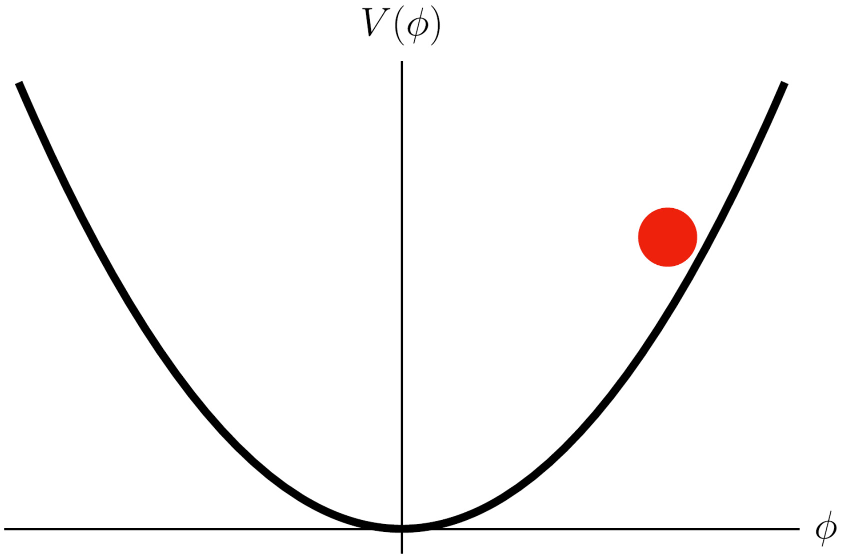

$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0 \longleftarrow$ Damped harmonic oscillator with a time-dependent frictional term

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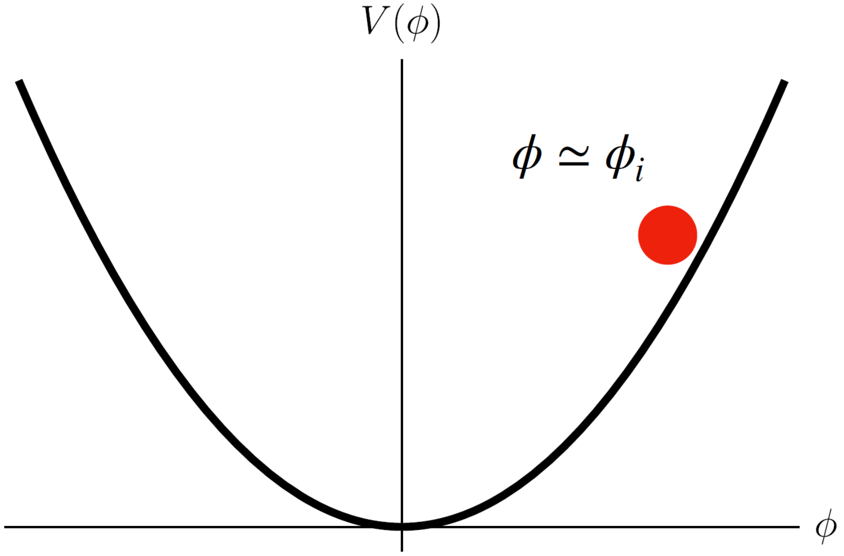

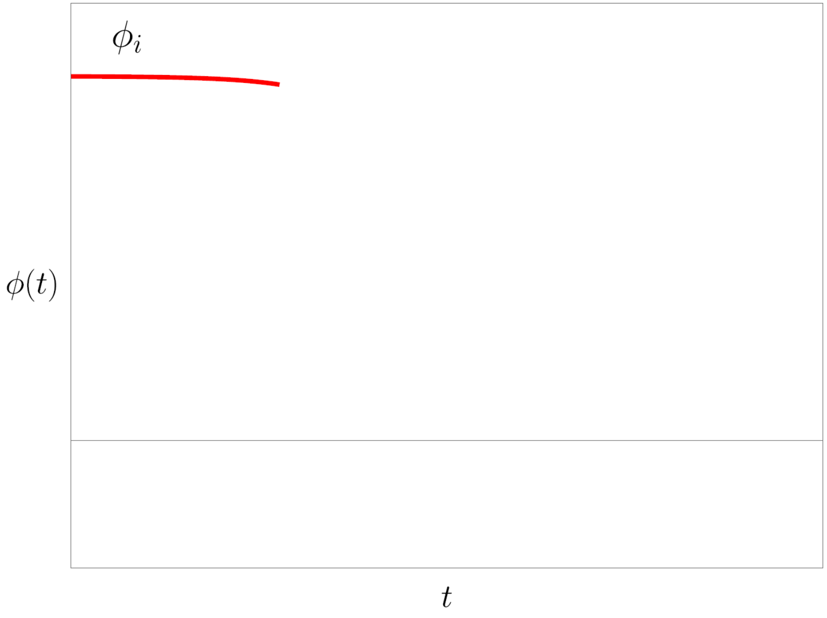

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$$m_\varphi \ll 3H(t) \sim 1/t$$

Overdamped regime

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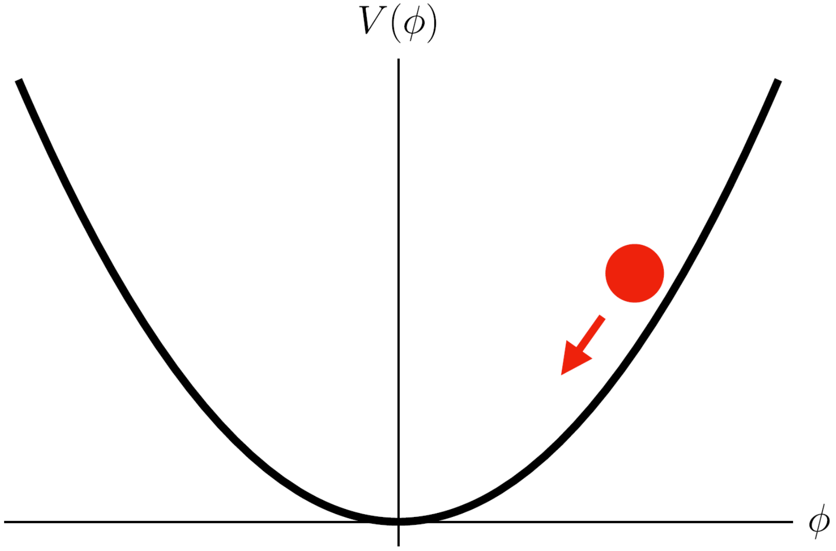
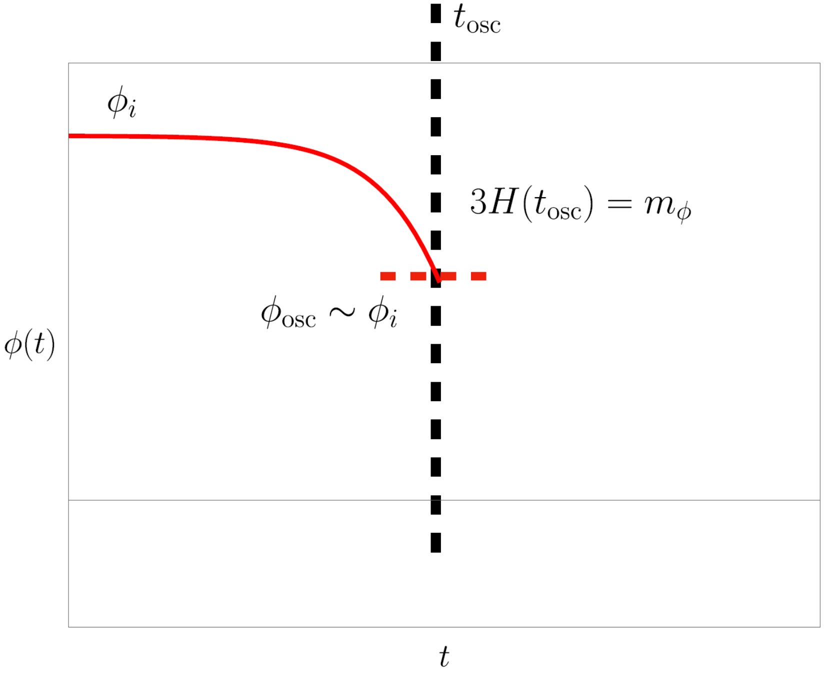




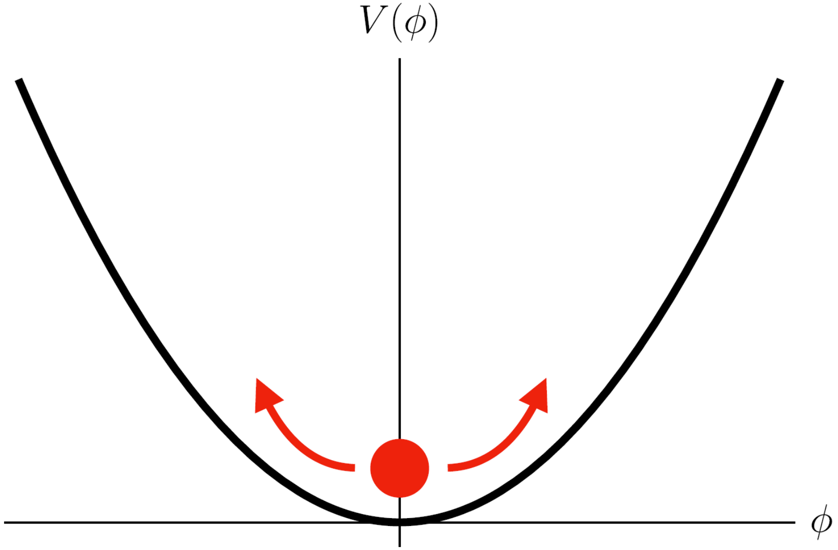
$$\ddot{\varphi} + 3H(t)\dot{\varphi} + m_\varphi^2 \varphi \approx 0$$

$$m_\varphi \sim 3H(t) \sim 1/t$$

Critically damped regime

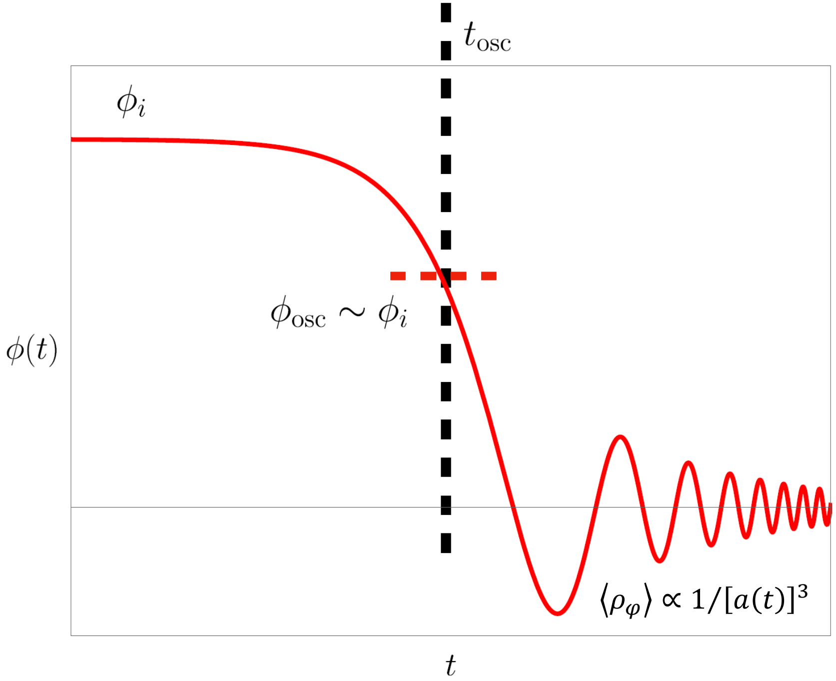
Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2/2$ $(\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3})$



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

$$m_\varphi \gg 3H(t) \sim 1/t$$



Underdamped regime

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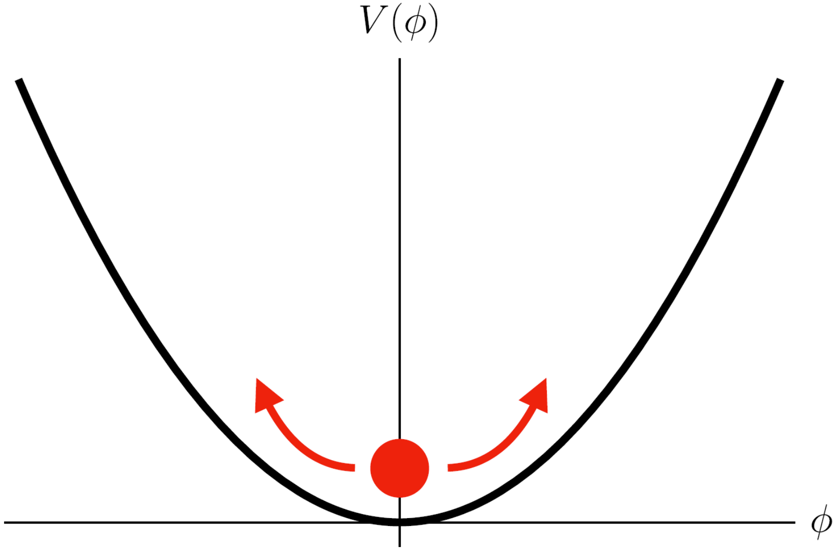

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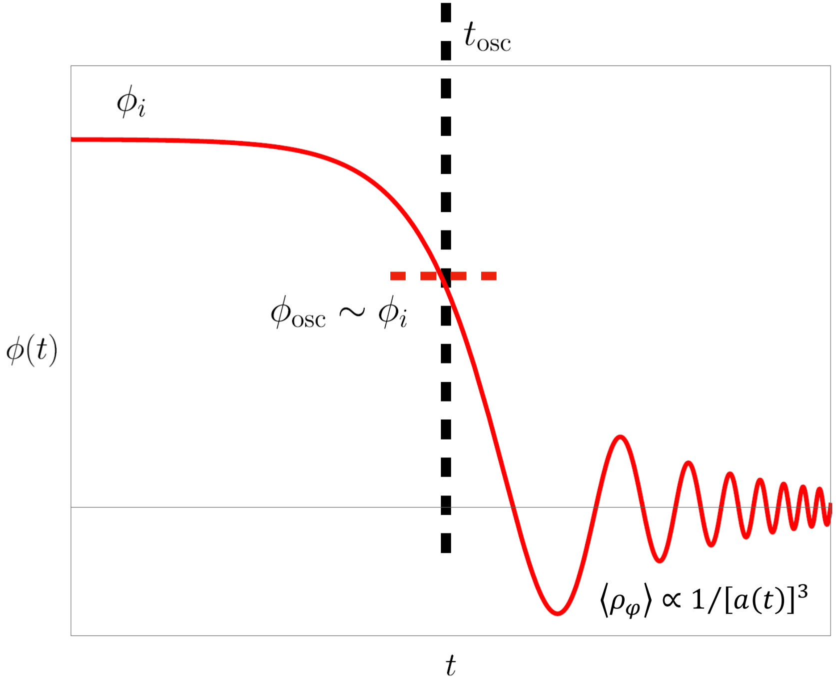

"Vacuum misalignment" mechanism – non-thermal production, $\langle\rho_\varphi\rangle$ governed by initial conditions (φ_i), redshifts as $\langle\rho_\varphi\rangle \propto 1/[a(t)]^3$, with $\langle p_\varphi\rangle \ll \langle\rho_\varphi\rangle$

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- $\Delta E_\varphi / E_\varphi \sim \langle v_\varphi^2 \rangle / c^2 \underset{\overset{\uparrow}{v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}}}{\sim} 10^{-6} \quad \Rightarrow \quad \tau_{\mathrm{coh}} \sim 2\pi / \Delta E_\varphi \underset{\overset{\downarrow}{Q_{\mathrm{DM}} \sim 10^6}}{\sim} 10^6 T_{\mathrm{osc}}$

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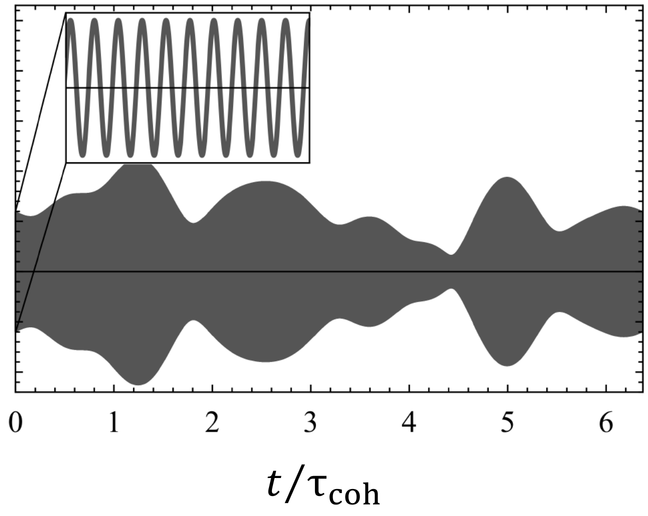
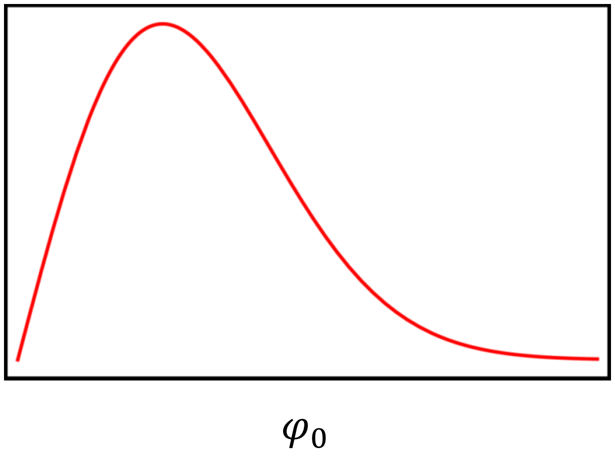
Evolution of φ_0 with time



Probability distribution function of φ_0 (Rayleigh distribution)



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* Pauli exclusion principle rules out sub-eV *fermionic* dark matter

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- $10^{-21}\ \mathrm{eV} \lesssim m_\varphi \lesssim 1\ \mathrm{eV} \quad \Leftrightarrow \quad 10^{-7}\ \mathrm{Hz} \lesssim f_{\mathrm{DM}} \lesssim 10^{14}\ \mathrm{Hz}$

$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$

IR frequencies

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

[Related figure-of-merit: $\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\mathrm{dwarf\ galaxy}} \sim 100\ \mathrm{pc} \quad \Rightarrow \quad m_\varphi \gtrsim 10^{-21}\ \mathrm{eV}$]

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Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]

Dark-Matter-Induced Variations of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad\Rightarrow\quad \frac{\delta\alpha}{\alpha} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_\gamma}$$

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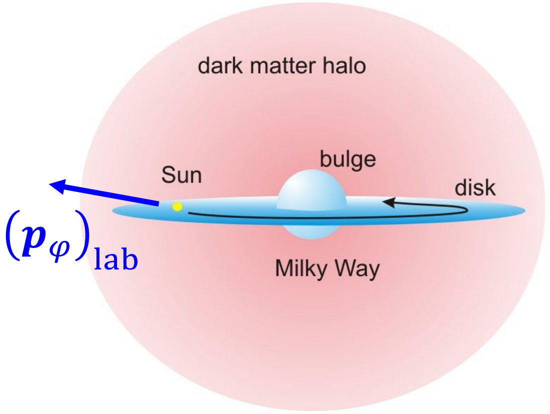
Lab frame

Solar System (and lab) move through stationary dark matter halo



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φ^2 interactions also exhibit the same oscillating-in-time signatures as above, as well as …

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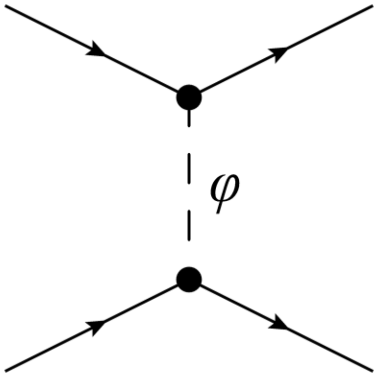
Fifth Forces: Linear vs Quadratic Couplings

[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

Consider the effect of a massive body (e.g., Earth) on the scalar DM field

Linear couplings ($\varphi \bar{X} X$)

$\Box \varphi + m_\varphi^2 \varphi = \pm \kappa \rho$ **Source term**



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Profile outside of a spherical body

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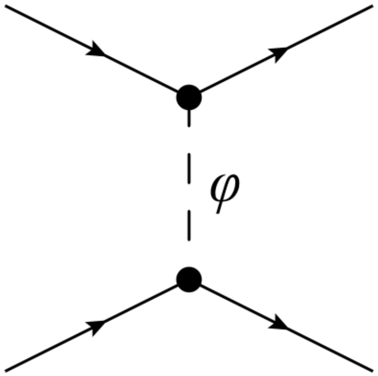

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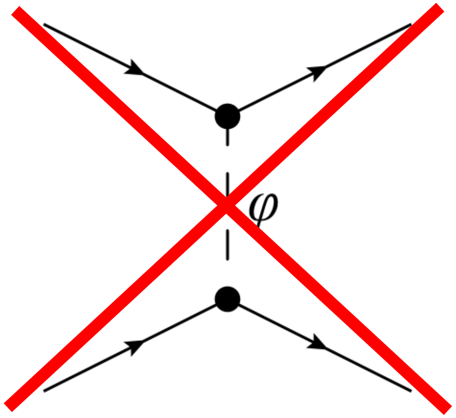

$$m_{\text{eff}}^2(\rho) = m_\varphi^2 \mp \kappa'\rho$$

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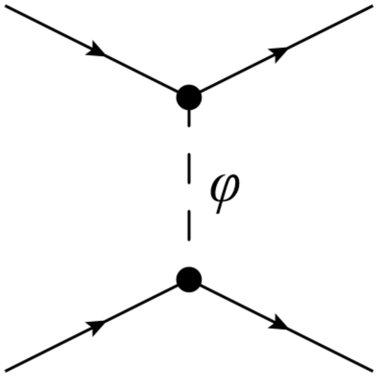

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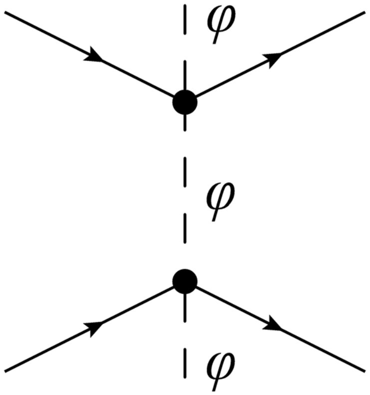

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Gradients + amplification/screening

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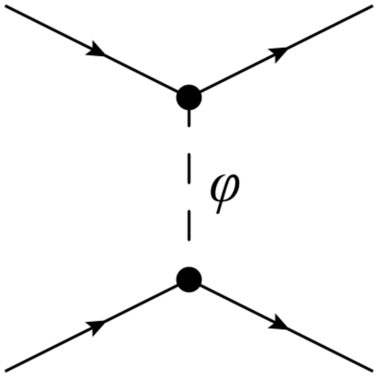

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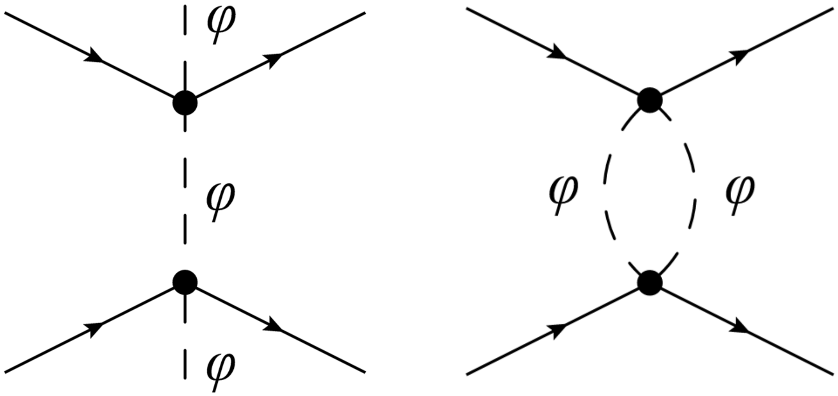

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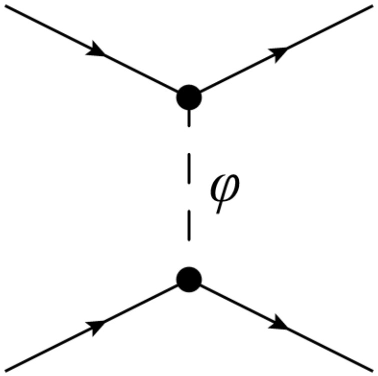

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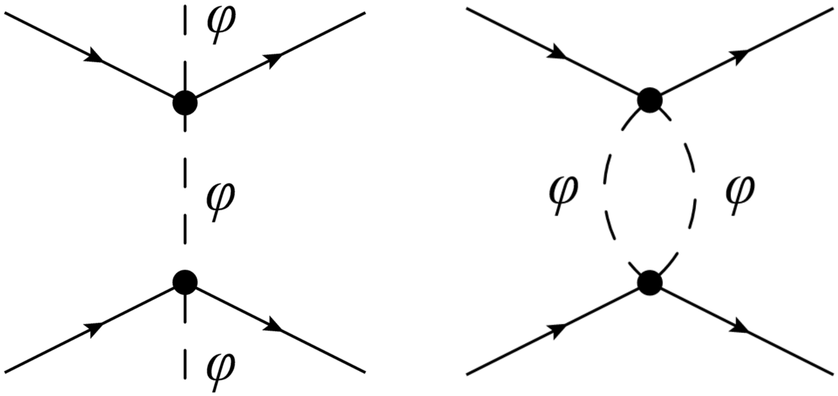

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↓

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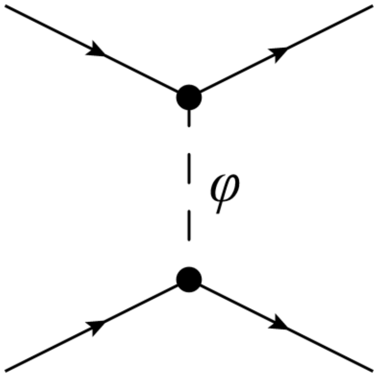

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“Fifth-force” experiments: torsion pendula, atom interferometry

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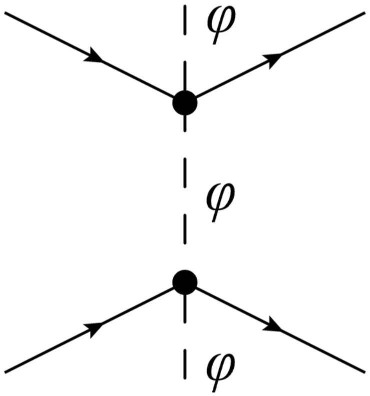

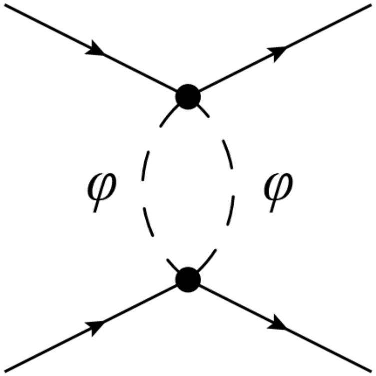

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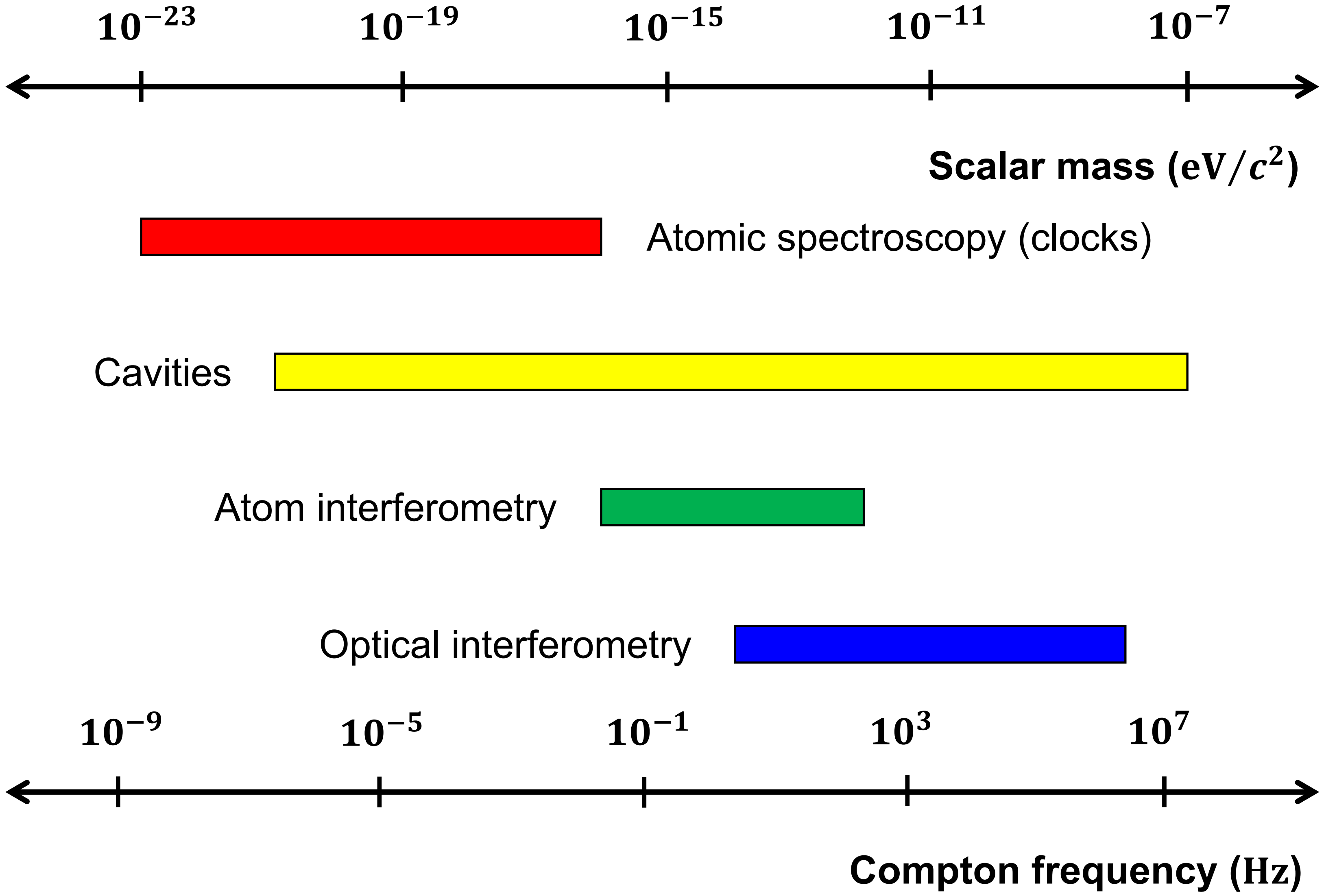
$\downarrow$

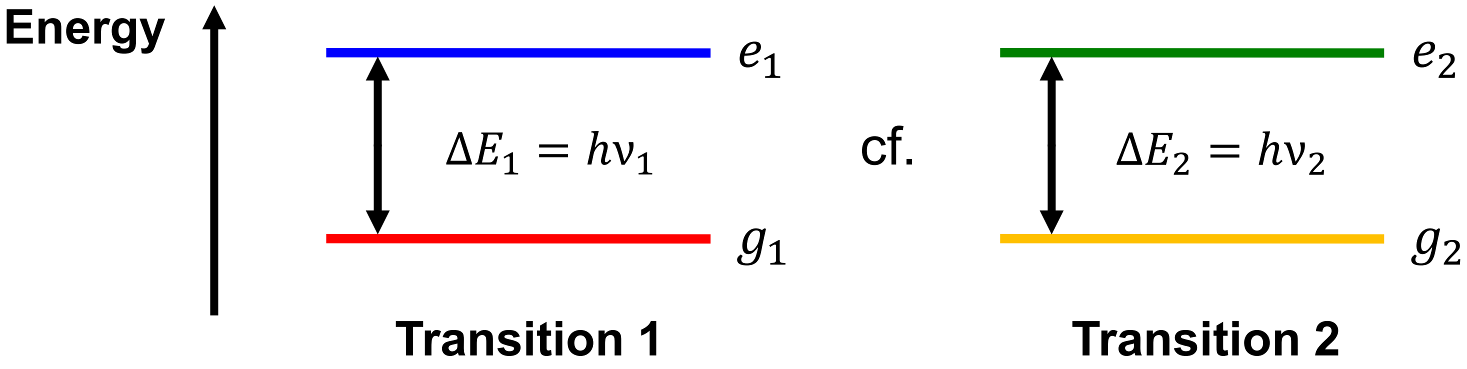
Gradients + amplification/screening

Probes of Oscillating Fundamental Constants



Atomic Spectroscopy Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik, Flambaum, *PRL* **114**, 161301 (2015)]



$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} \propto \sum_{X=\alpha, m_e/m_N, \ldots} \left(K_{X,1} - K_{X,2}\right) \cos(2\pi f_{\mathrm{DM}} t)\ ;\ 2\pi f_{\mathrm{DM}} = \underset{\text{(lin.)}}{m_\varphi} \text{ or } \underset{\text{(quad.)}}{2m_\varphi}$$

- **Dy/Cs [Mainz]:** [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]
- **Rb/Cs [SYRTE]:** [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]
- **Al$^+$/Yb, Yb/Sr, Al$^+$/Hg$^+$ [NIST + JILA]:** [BACON Collaboration, *Nature* **591**, 564 (2021)]
- **Yb/Cs [NMIJ]:** [Kobayashi *et al.*, *PRL* **129**, 241301 (2022)]
- **Yb$^+$(E3)/Sr [PTB]:** [Filzinger *et al.*, arXiv:2301.03433]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

$$L_{\text{solid}} \propto a_{\text{B}} = 1/(m_e \alpha)$$

$$\Rightarrow \ \nu_{\text{solid}} \propto 1/L_{\text{solid}} \propto m_e \alpha$$

(adiabatic regime)

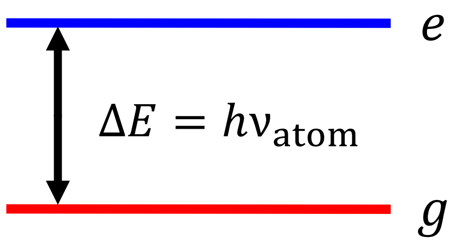
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

cf.

Electronic transition



$$L_{\text{solid}} \propto a_{\text{B}} = 1/(m_e \alpha)$$

$$\Rightarrow \nu_{\text{solid}} \propto 1/L_{\text{solid}} \propto m_e \alpha$$

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

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

- **Sr vs Glass cavity [Torun]:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Various combinations [Worldwide]:** [Wcislo *et al.*, *Science Advances* **4**, eaau4869 (2018)]
- **Cs vs Steel cavity [Mainz]:** [Antypas *et al.*, *PRL* **123**, 141102 (2019); *PRL* **129**, 031301 (2022)]
- **Sr/H vs Silicon cavity [JILA + PTB]:** [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]
- **Sr$^+$ vs Glass cavity [Weizmann]:** [Aharony *et al.*, *PRD* **103**, 075017 (2021)]
- **H vs Sapphire/Quartz cavities [UWA]:** [Campbell *et al.*, *PRL* **126**, 071301 (2021)]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

$$L_{\text{solid}} \propto a_{\text{B}} = 1/(m_e \alpha)$$

$$\Rightarrow \; \nu_{\text{solid}} \propto 1/L_{\text{solid}} \propto m_e \alpha$$

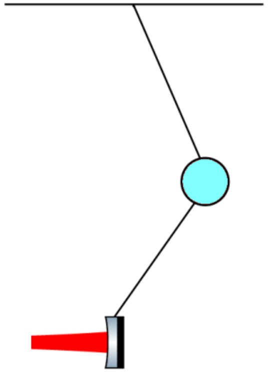
cf.

Freely-suspended mirrors

$$L_{\text{free}} \approx \text{const. for } f_{\text{DM}} > f_{\text{natural}}$$

$$\Rightarrow \; \nu_{\text{free}} \approx \text{constant}$$

Double-pendulum suspensions



$$\boxed{\frac{\nu_{\text{solid}}}{\nu_{\text{free}}} \propto m_e \alpha}$$

cf.

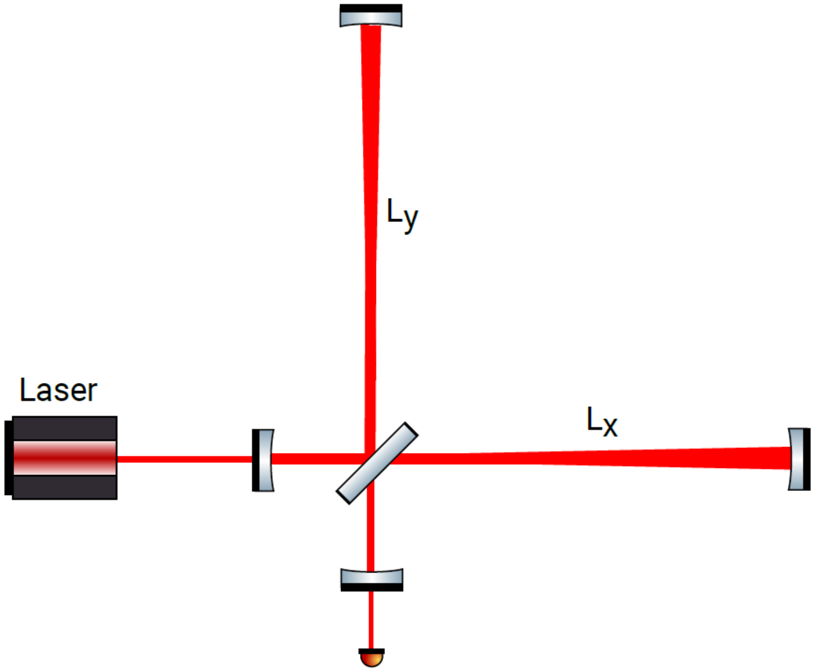
$$\frac{\nu_{\text{atom}}}{\nu_{\text{solid}}} \propto \alpha$$

Small-scale experiment currently under development at Northwestern University

[Geraci *et al.*, *PRL* **123**, 031304 (2019)]

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

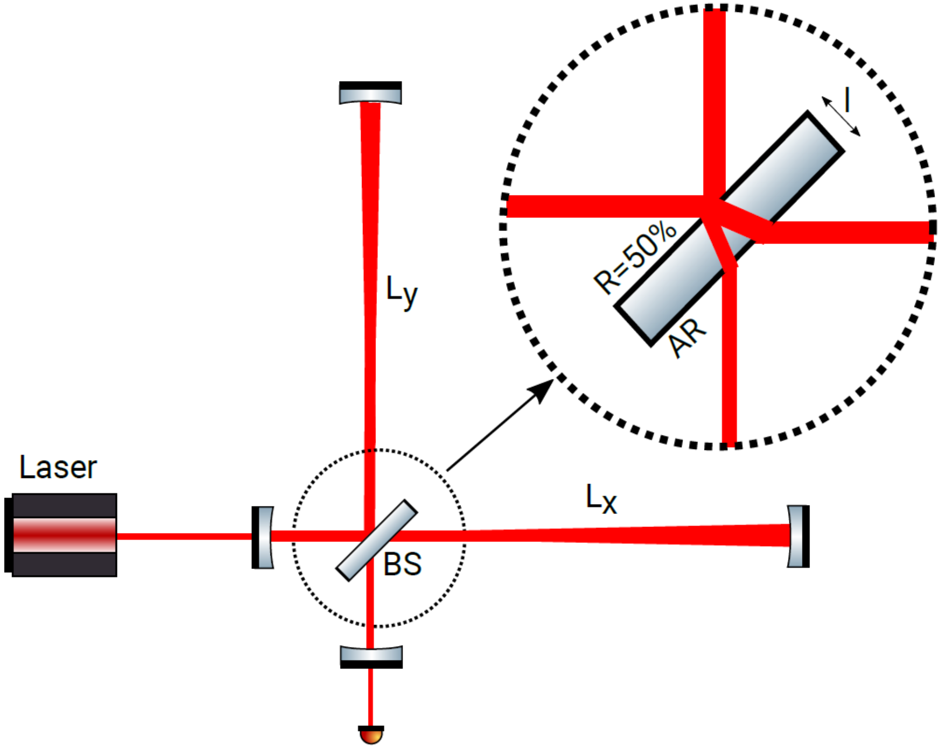
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO600)

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

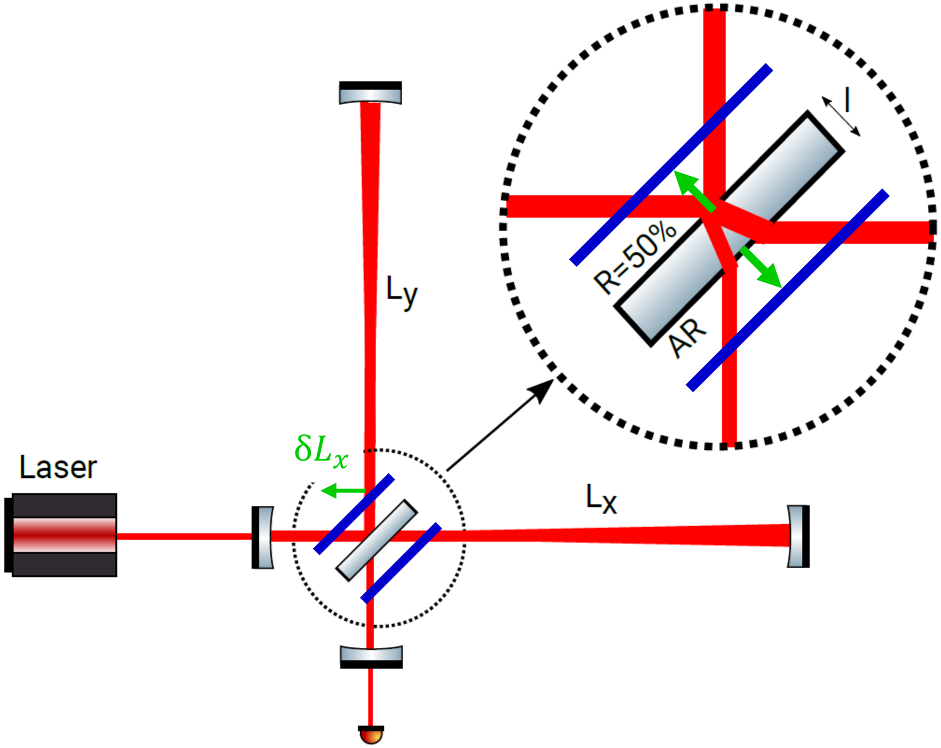
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



- Geometric asymmetry from beam-splitter

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

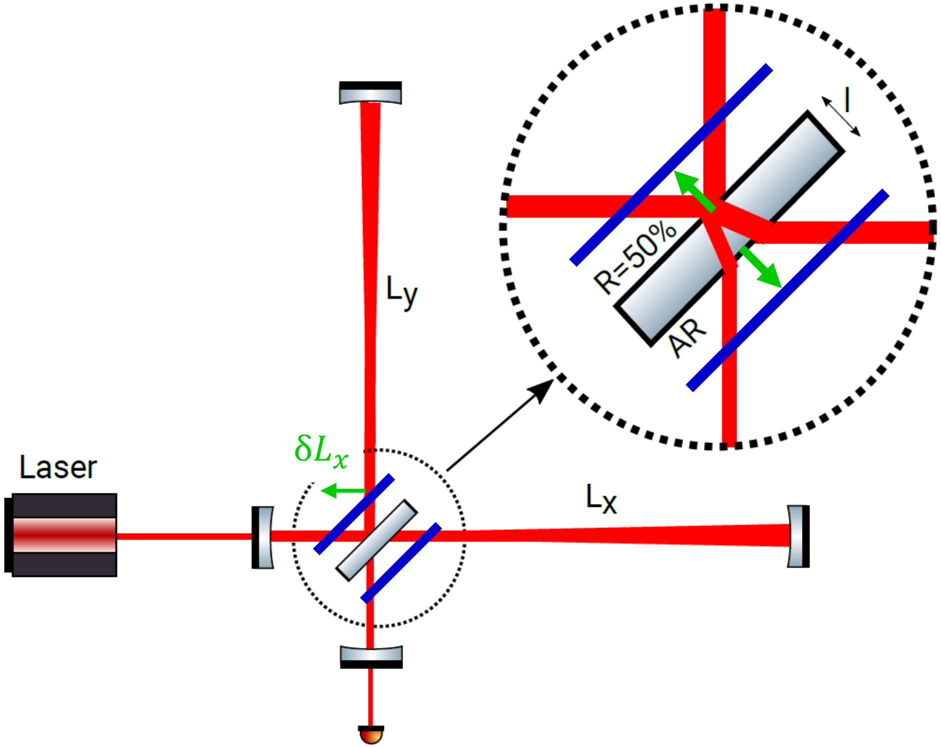
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



- Geometric asymmetry from beam-splitter: $\boxed{\delta(L_x - L_y) \sim \delta(nl)}$

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

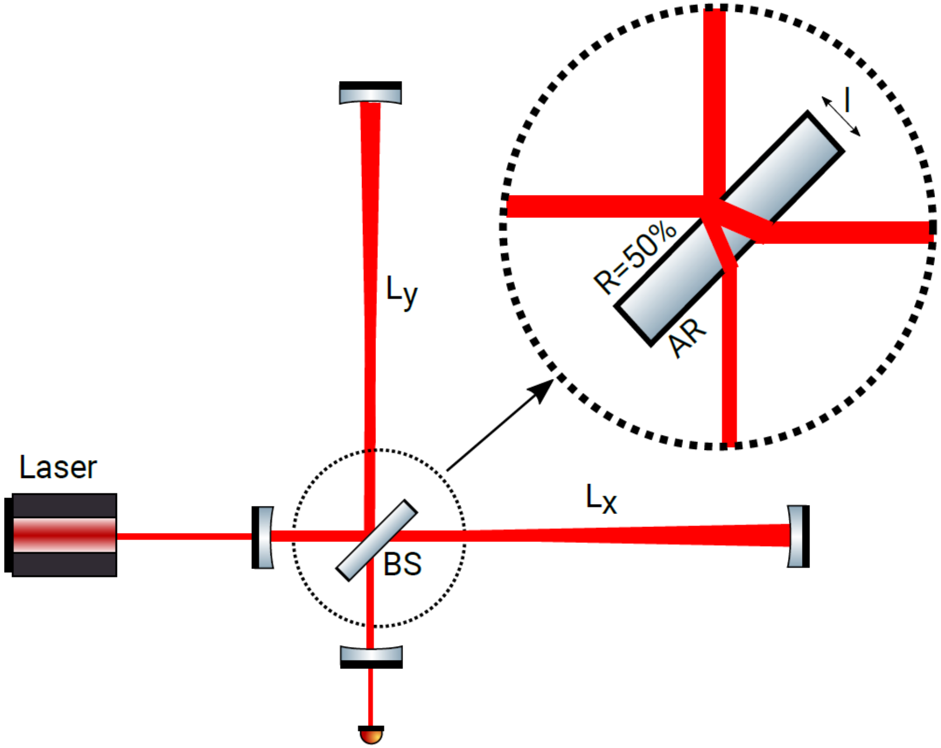


- Geometric asymmetry from beam-splitter: $\boxed{\delta(L_x - L_y) \sim \delta(nl)}$

First results recently reported using GEO600 and Fermilab holometer data:
[Vermeulen *et al.*, *Nature* **600**, 424 (2021)], [Aiello *et al.*, *PRL* **128**, 121101 (2022)]

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



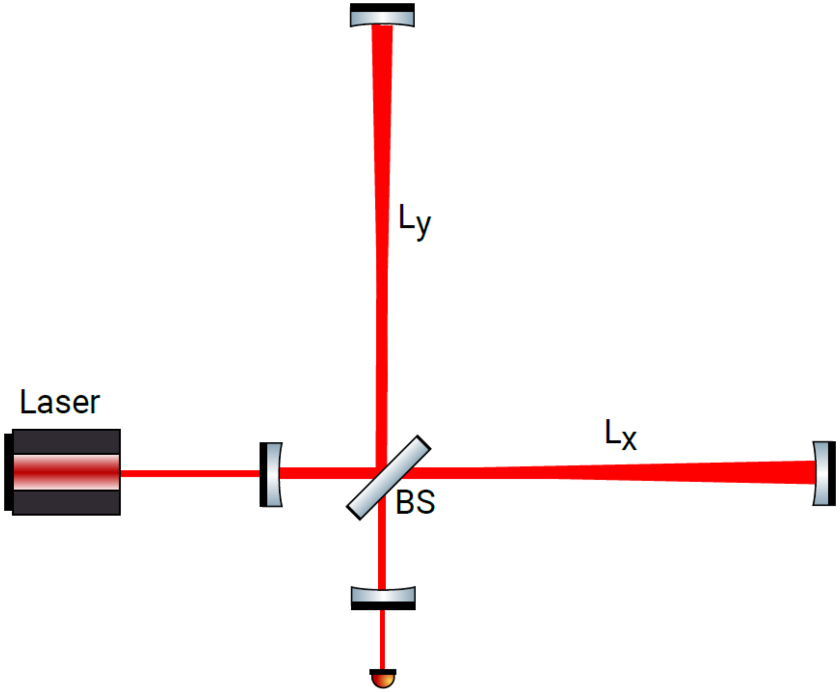
- Geometric asymmetry from beam-splitter: $\boxed{\delta\left(L_x - L_y\right) \sim \delta(nl)}$
- Both broadband and resonant narrowband searches possible:

$$f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}}(T) \sim v_{\mathrm{sound}}/l \;\;\Rightarrow\;\; Q \sim 10^6 \text{ enhancement}$$

Michelson vs Fabry-Perot-Michelson Interferometers

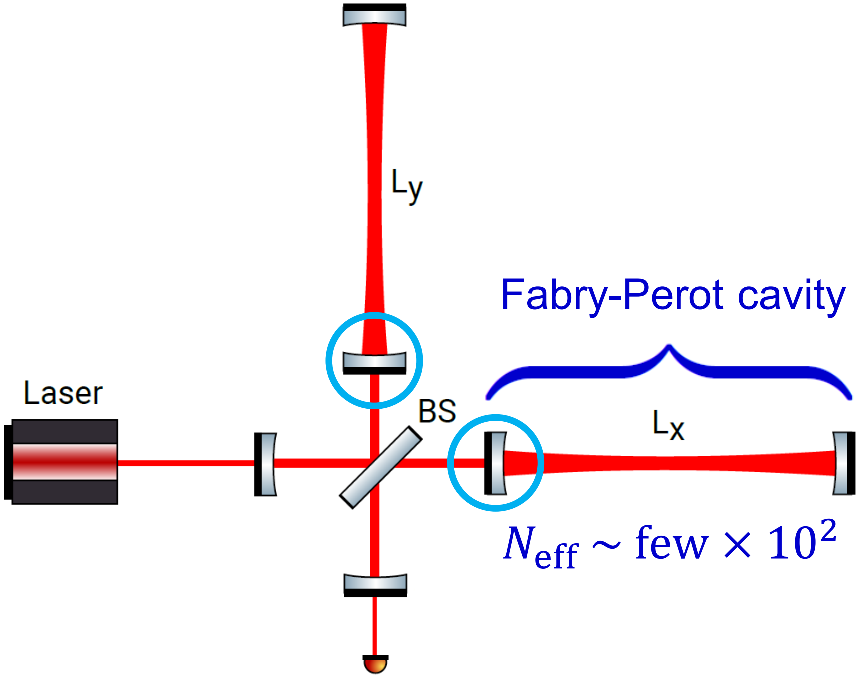
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO600)



$$\delta\left(L_x - L_y\right)_{\text{BS}} \sim \delta(nl)$$

Fabry-Perot-Michelson IFO (LIGO/VIRGO/KAGRA)

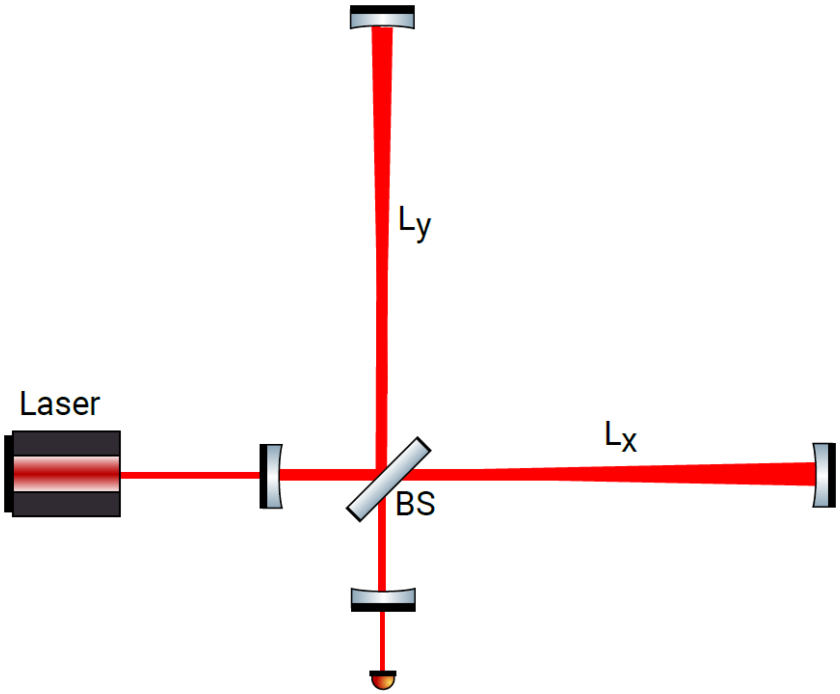


$$\delta\left(L_x - L_y\right)_{\text{BS}} \sim \delta(nl)/N_{\text{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO600)



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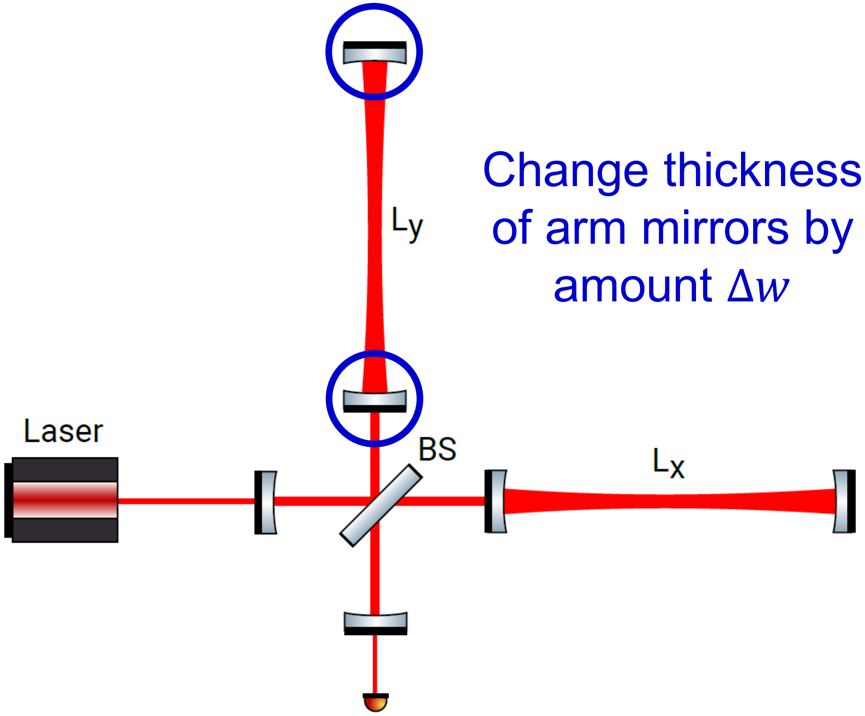
Fabry-Perot-Michelson IFO (LIGO/VIRGO/KAGRA)



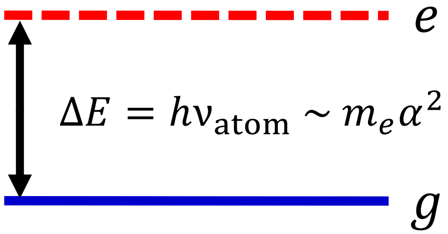
Change thickness of arm mirrors by amount Δw

$$\delta\left(L_x - L_y\right) \approx \delta(\Delta w)$$

Atom Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg, *PRD* **97**, 075020 (2018)]

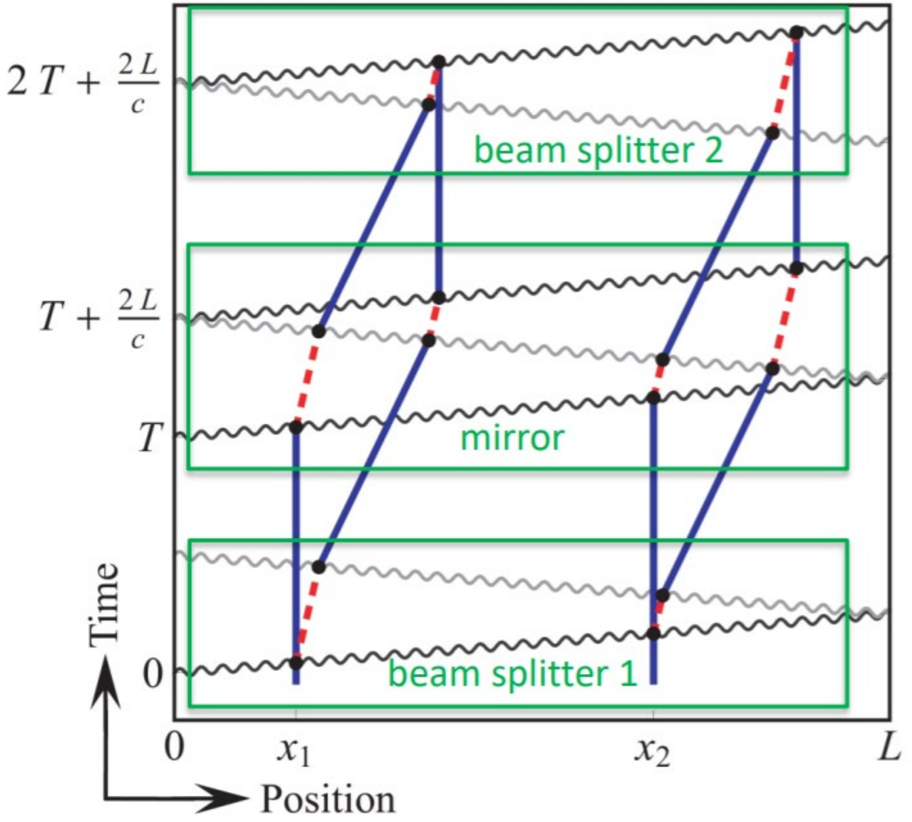
Electronic transition



$$\Delta E = h\nu_{\text{atom}} \sim m_e \alpha^2$$

When $T_{\text{osc}} \sim 2T$:

$$\delta(\Delta\Phi)_{\max} \sim T_{\text{osc}}\, \delta\nu_{\text{atom}}$$



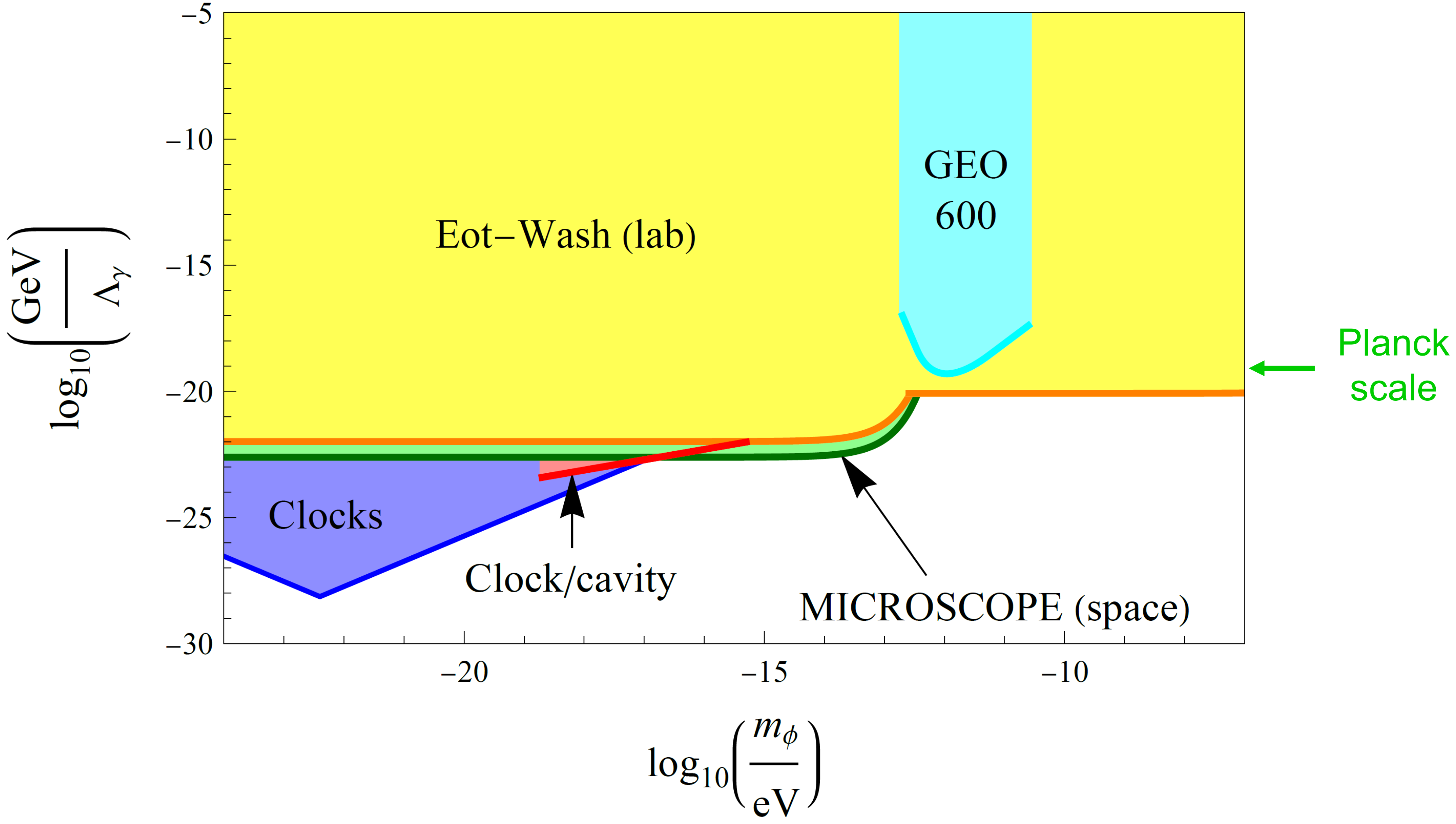
AION-10 experiment under construction at Oxford [Badurina *et al.*, *JCAP* **05** (2020) 011]

MAGIS-100 experiment under construction at Fermilab [Abe *et al.*, *QST* **6**, 044003 (2021)]

Constraints on Scalar Dark Matter with $\varphi F_{\mu\nu}F^{\mu\nu}/4\Lambda_\gamma$ Coupling

Clock/clock: [*PRL* **115**, 011802 (2015)], [*PRL* **117**, 061301 (2016)], [*Nature* **591**, 564 (2021)], [arXiv:2301.03433]; **Clock/cavity:** [*PRL* **125**, 201302 (2020)]; **GEO600:** [*Nature* **600**, 424 (2021)]

5 orders of magnitude improvement!



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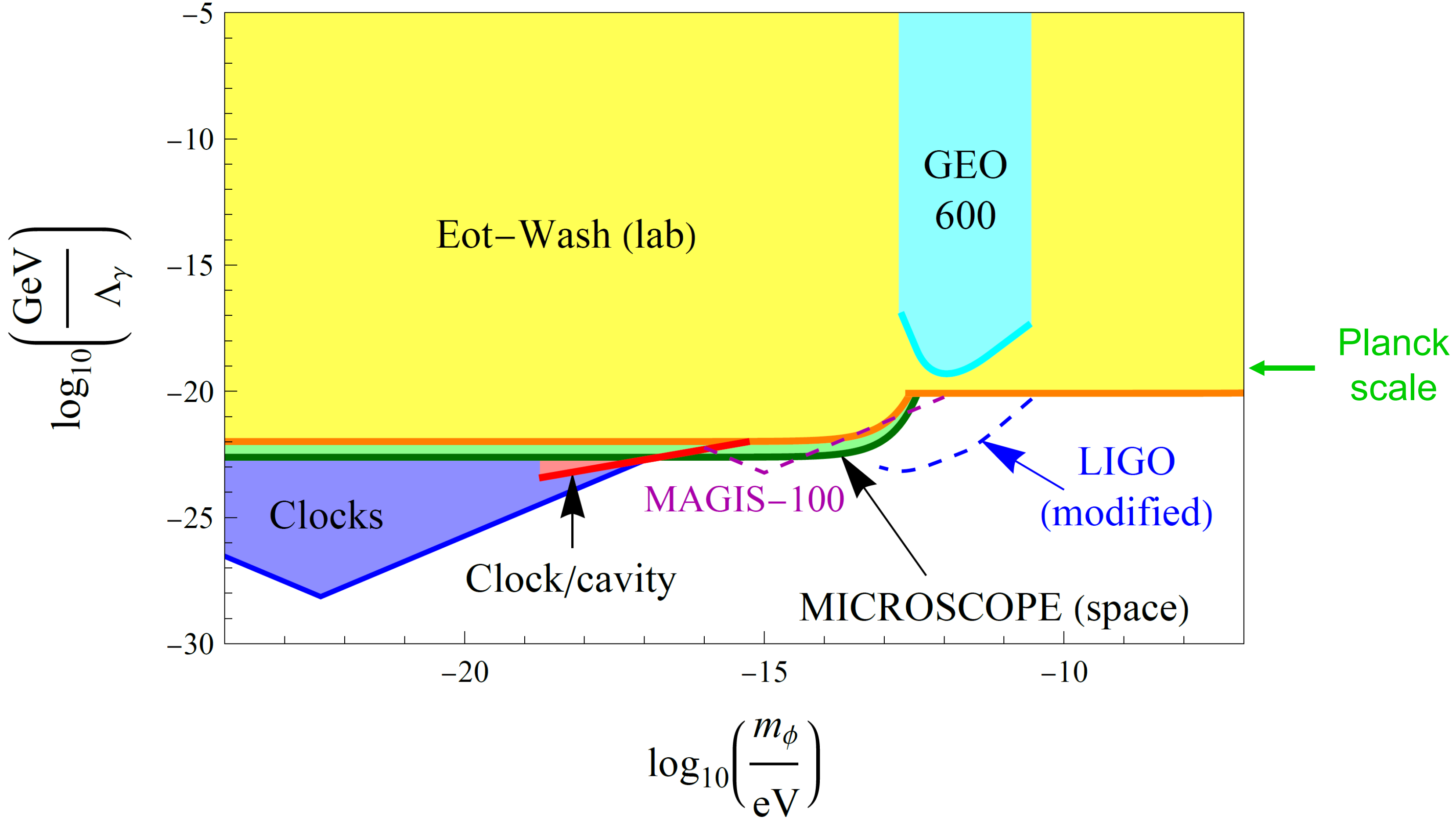

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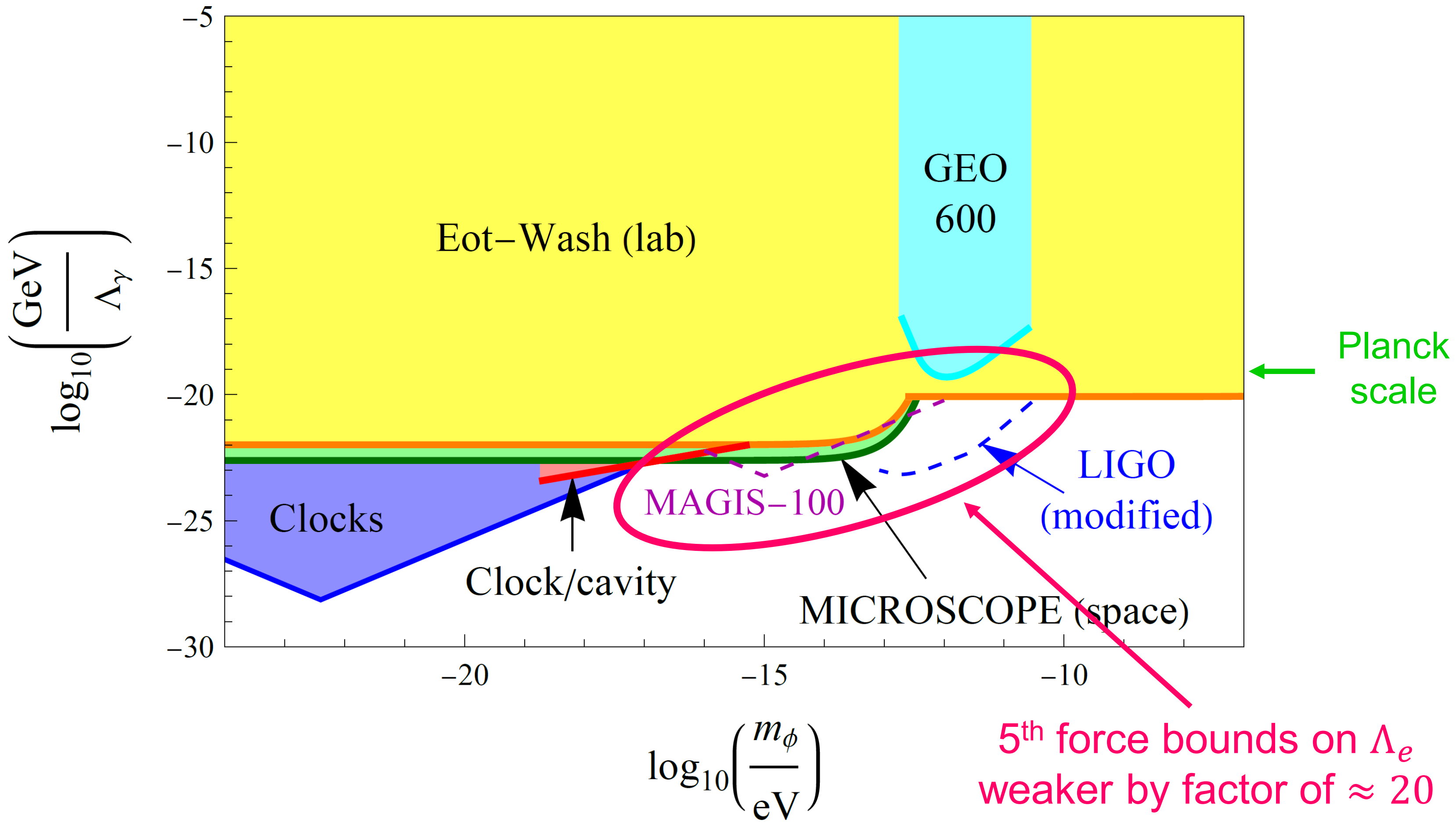
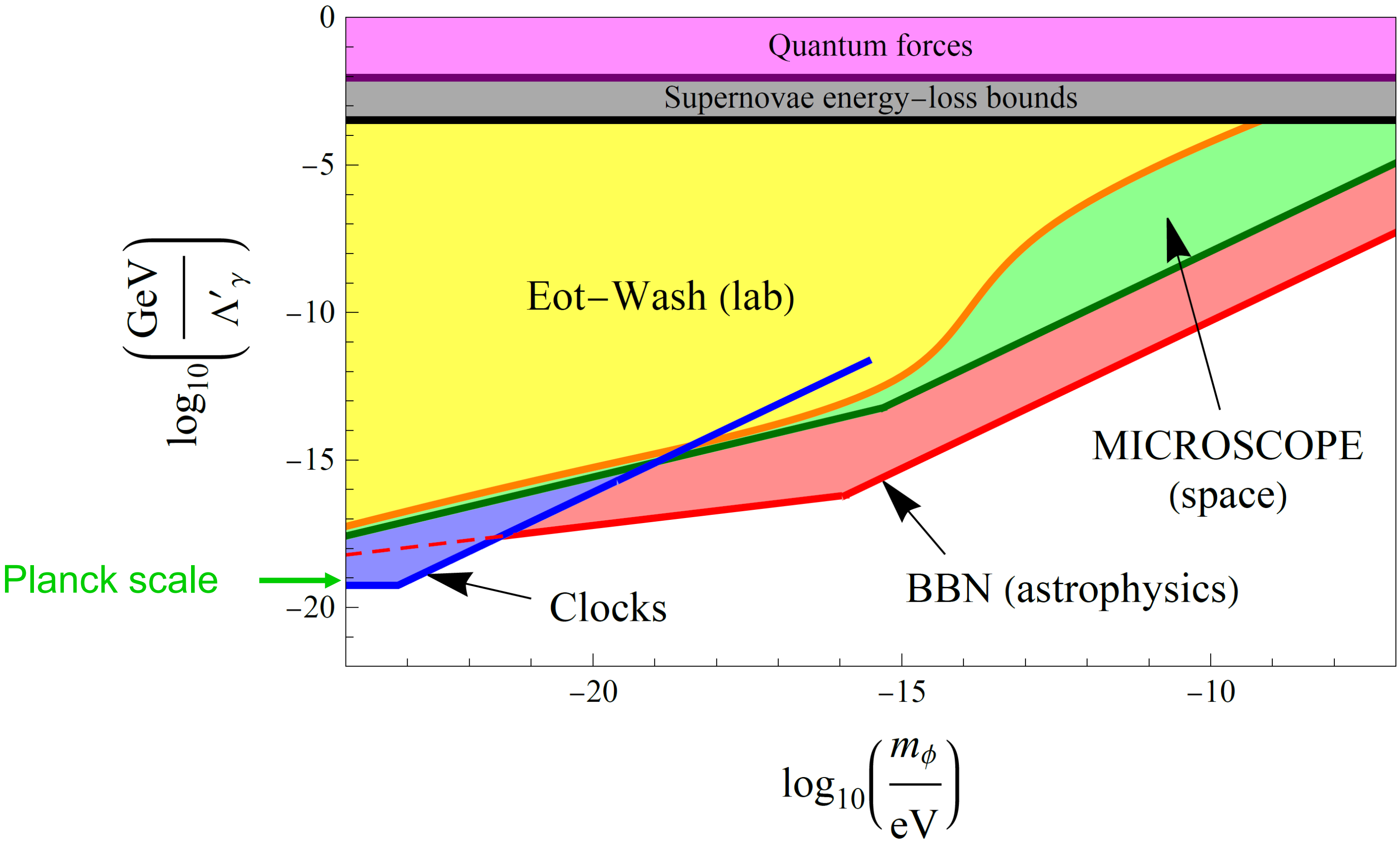


5th force bounds on Λ_e weaker by factor of ≈ 20

Constraints on Scalar Dark Matter with $\varphi^2 F_{\mu\nu}F^{\mu\nu}/4(\Lambda'_\gamma)^2$ Coupling

Clock/clock + BBN constraints: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]; **MICROSCOPE + Eöt-Wash constraints:** [Hees *et al.*, *PRD* **98**, 064051 (2018)]

15 orders of magnitude improvement!



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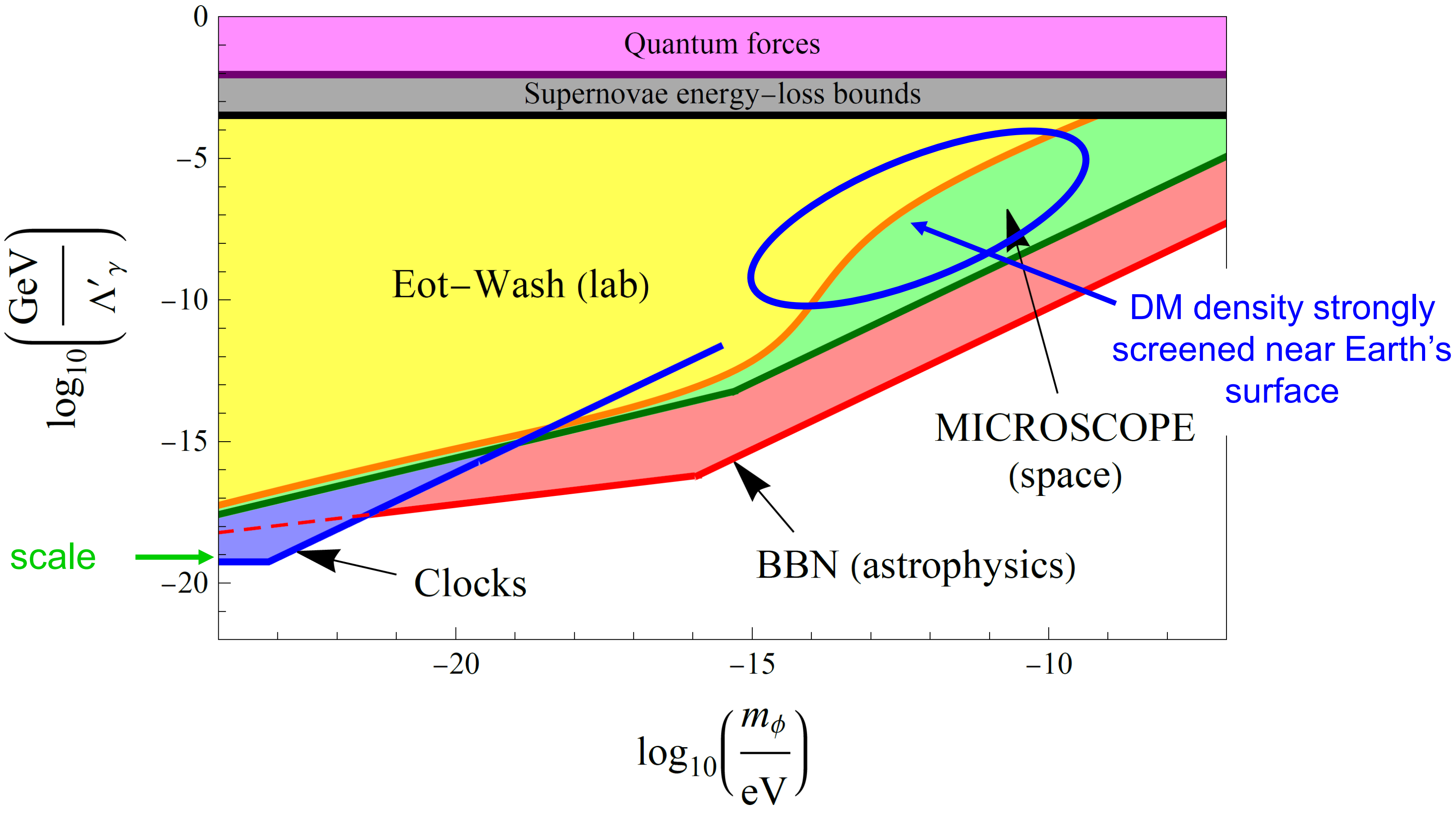


Planck scale

DM density strongly screened near Earth's surface

Phenomenology of Ultralight Scalar FIPs

1. Motivation
2. Mediators of new forces
3. Complementary probes
4. Screening mechanisms and environmental effects
5. Dark energy
6. Dark matter
7. Solitons

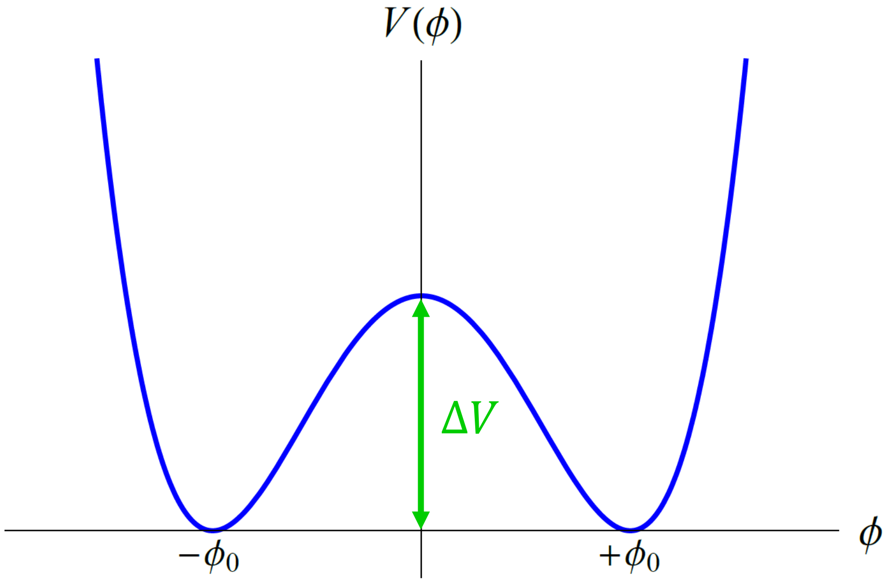
What is a Soliton?

- A soliton is a stable field configuration that doesn't spread out or dissipate
- Solitons can be topological or non-topological
- Solitons of various dimensionalities are possible within field theory:
  - 0D – Monopoles, Q-balls [$p \ll \rho \;\Rightarrow$ Good cold DM candidate]
  - 1D – Strings
  - 2D – Domain walls
- Hybrid solitonic structures also possible (e.g., monopoles connected by strings, walls connected by strings, etc.)

Topological Solitons: Domain Walls

[Zel'dovich, Kobzarev, Okun', *Sov. Phys. JETP* **40**, 1 (1975)]

- Consider a real scalar field φ with potential $V(\varphi) = \lambda\left(\varphi^2 - \varphi_0^2\right)^2/4$

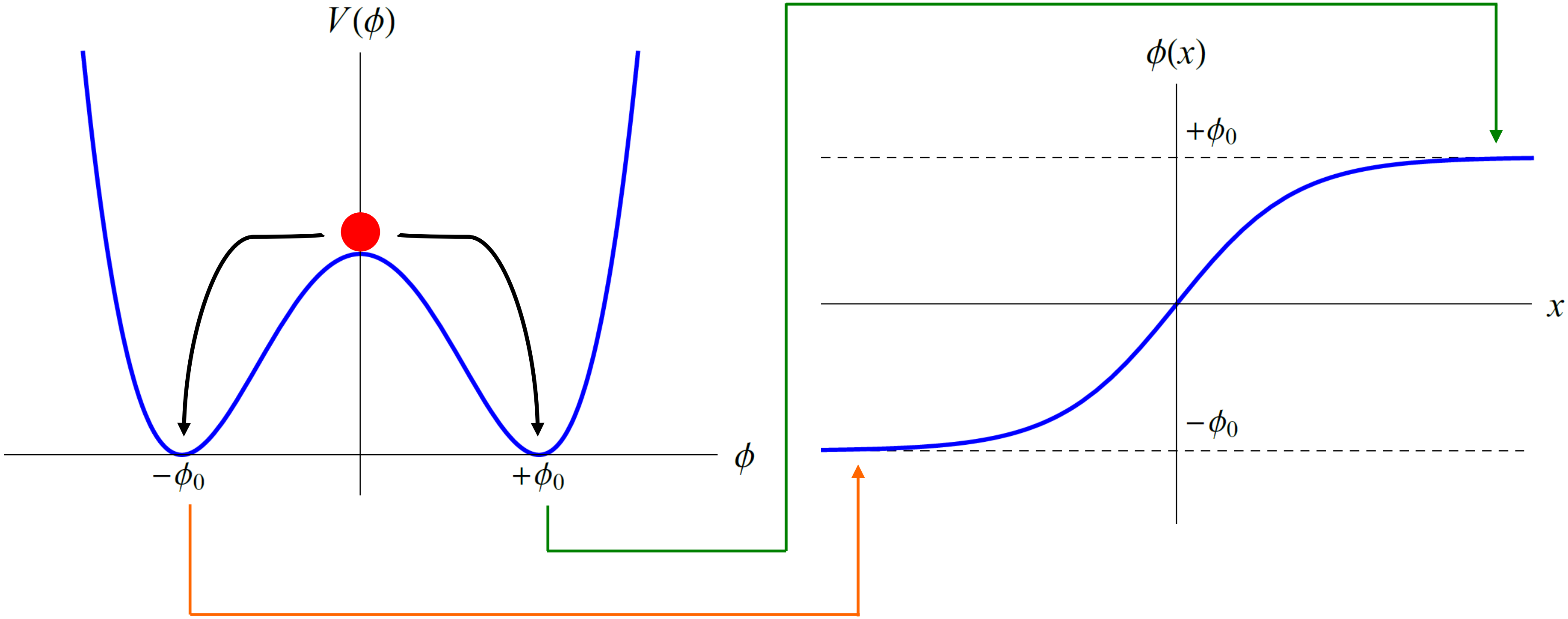


φ^4 **potential**

Topological Solitons: Domain Walls

[Zel'dovich, Kobzarev, Okun', *Sov. Phys. JETP* **40**, 1 (1975)]

- Consider a real scalar field φ with potential $V(\varphi) = \lambda\left(\varphi^2 - \varphi_0^2\right)^2/4$
- Different regions in space may settle in different vacua/minima



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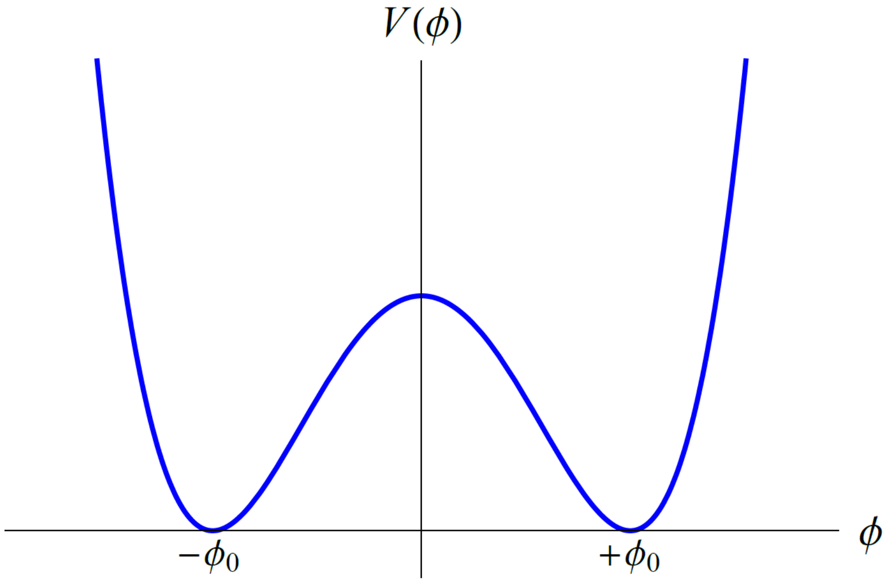
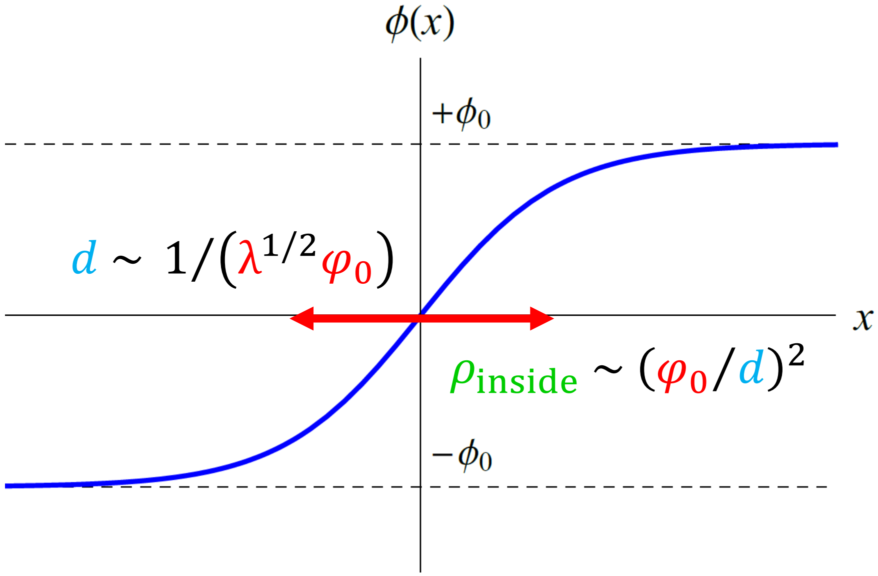
- Consider a real scalar field φ with potential $V(\varphi) = \lambda\left(\varphi^2 - \varphi_0^2\right)^2/4$
- Different regions in space may settle in different vacua/minima
- **"Domain wall"** forms – boundary between different **"domains"**





Domain wall: $\varphi(x) = \varphi_0 \tanh(x/d)$

Non-Topological Solitons: Q-balls

[Coleman, *Nucl. Phys. B* **262**, 263 (1985)]

- For a scalar field with a suitable attractive self-interaction, it is possible for $Q \gg 1$ bosons to form a stable solitonic object (Q-ball) with a total energy less than the sum of free particle energies, $E < mQ$

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- Consider a complex scalar field φ with a potential $V(\varphi)$ that satisfies $V''(0) = m^2$ and has a minimum of V/φ^2 at $\varphi = \varphi_0 \neq 0$ such that $\left(2V/\varphi^2\right)\big|_{\varphi=\varphi_0} < m^2$

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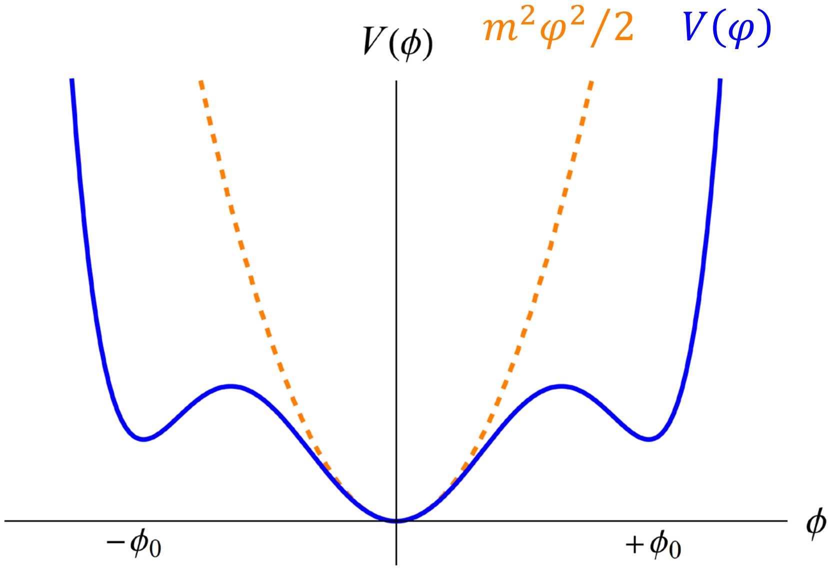
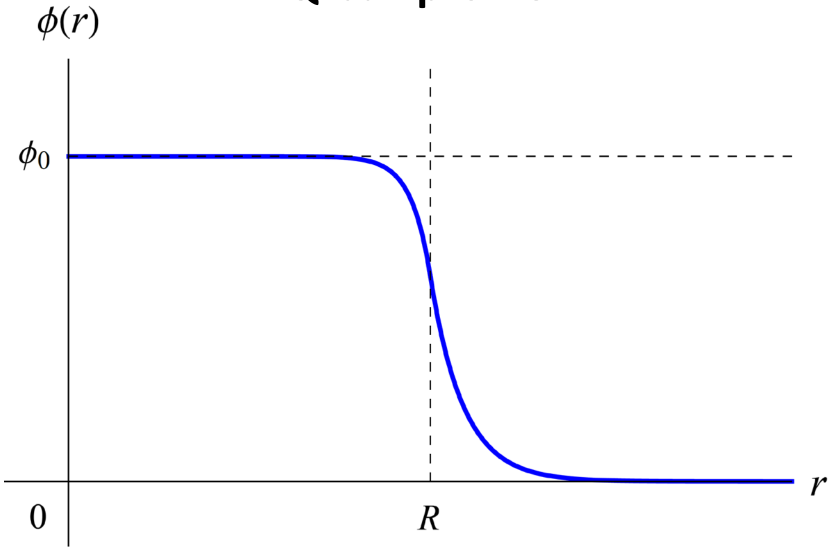
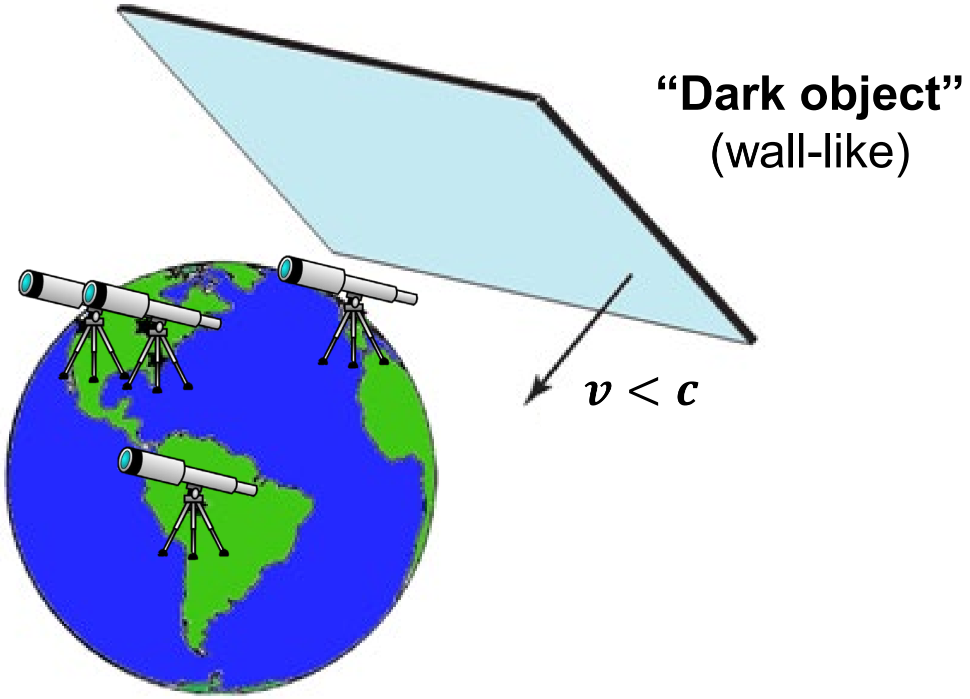


Q-ball profile



Transient Searches with Networks

- Macroscopic solitons and other “dark objects” may produce transient signatures if they pass through Earth
- Can use terrestrial networks of spatially-separated detectors to search for correlated signatures of passing macroscopic objects (similarly to GW searches)

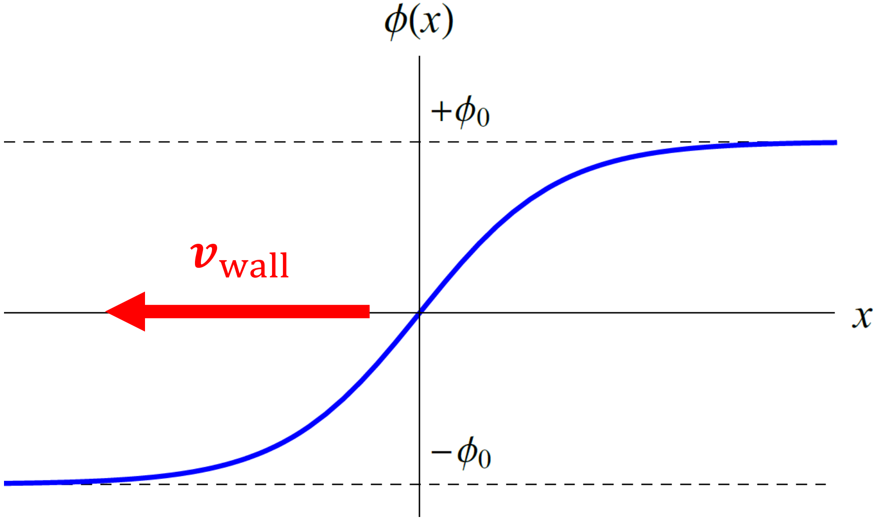


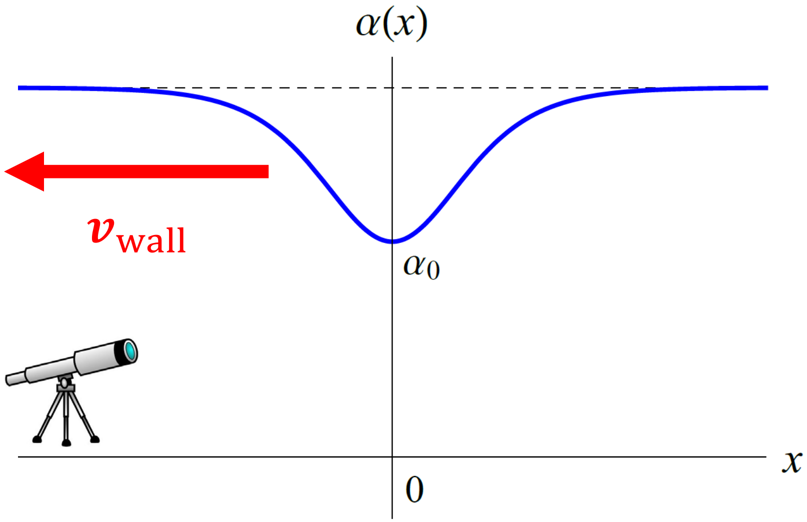
Transient Changes in “Constants”

$$\mathcal{L}_f = -\frac{\varphi^2}{\left(\Lambda'_f\right)^2} m_f \bar{f} f \quad \text{cf.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad \Rightarrow \quad m_f\left(\varphi^2\right) = m_{f,0}\left[1 + \left(\frac{\varphi}{\Lambda'_f}\right)^2\right]$$

$$\mathcal{L}_\gamma = \frac{\varphi^2}{\left(\Lambda'_\gamma\right)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad \text{cf.} \quad \mathcal{L}_\gamma^{\text{SM}} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} - eJ_\mu A^\mu \quad \Rightarrow \quad \alpha\left(\varphi^2\right) \approx \alpha_0\left[1 + \left(\frac{\varphi}{\Lambda'_\gamma}\right)^2\right]$$

- A passing domain wall induces apparent **transient** variations of fundamental constants, due to a temporary change in φ^2





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$$\mathcal{L}_\gamma = \frac{\varphi^2}{\left(\Lambda'_\gamma\right)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \ \ \text{cf.} \ \ \mathcal{L}_\gamma^{\mathrm{SM}} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} - eJ_\mu A^\mu \ \ \Rightarrow \ \ \alpha\left(\varphi^2\right) \approx \alpha_0\left[1 + \left(\frac{\varphi}{\Lambda'_\gamma}\right)^2\right]$$

- A passing domain wall induces apparent **transient** variations of fundamental constants, due to a temporary change in φ^2
- Can search for these transient variations of fundamental constants by using various networks of detectors:
  - Clocks [Derevianko, Pospelov, *Nature Physics* **10**, 933 (2014)]
  - Pulsars [Stadnik, Flambaum, *PRL* **113**, 151301 (2014)]
  - Cavities and laser interferometers [Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)], [Grote, Stadnik, *PRR* **1**, 033187 (2019)]

Transient Changes in "Constants"

$$\mathcal{L}_f = -\frac{\varphi^2}{\left(\Lambda'_f\right)^2} m_f \bar{f} f \ \text{ cf. } \ \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \ \Rightarrow \ m_f\left(\varphi^2\right) = m_{f,0}\left[1 + \left(\frac{\varphi}{\Lambda'_f}\right)^2\right]$$

$$\mathcal{L}_\gamma = \frac{\varphi^2}{\left(\Lambda'_\gamma\right)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \ \text{ cf. } \ \mathcal{L}_\gamma^{\text{SM}} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} - eJ_\mu A^\mu \ \Rightarrow \ \alpha\left(\varphi^2\right) \approx \alpha_0\left[1 + \left(\frac{\varphi}{\Lambda'_\gamma}\right)^2\right]$$

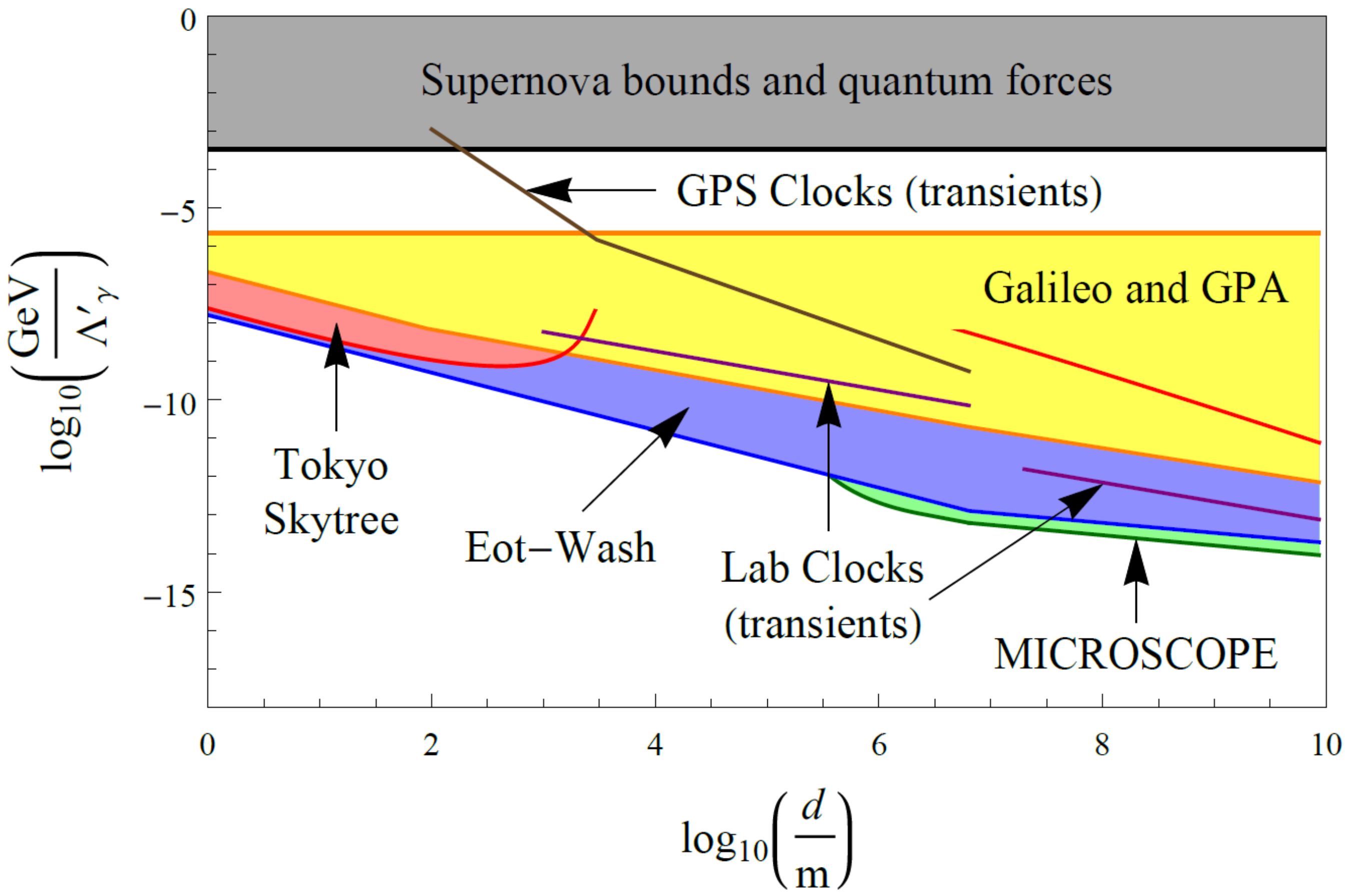
- A passing domain wall induces apparent **transient** variations of fundamental constants, due to a temporary change in φ^2
- Several clock- and cavity-based searches for domain walls with φ^2 interactions already performed:
  - [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
  - [Roberts *et al.*, *Nature Communications* **8**, 1195 (2017)]
  - [Wcislo *et al.*, *Science Advances* **4**, eaau4869 (2018)]
  - [Roberts *et al.*, *New J. Phys.* **22**, 093010 (2020)]

Constraints on Wall Model with $\varphi^2 F_{\mu\nu}F^{\mu\nu}/4(\Lambda'_\gamma)^2$ Coupling

$[\rho_{\text{walls}} \sim \rho_{\text{DM}},\ v_{\text{walls}} \sim 300\ \text{km/s},\ T_{\text{avg}} \sim 1\ \text{day} \gg \Delta t_{\text{transient}}]$

Transient bounds: [Wcislo *et al.*, *Nature Astron.* **1**, 0009 (2016)], [Roberts *et al.*, *Nature Commun.* **8**, 1195 (2017)], [Roberts *et al.*, *New J. Phys.* **22**, 093010 (2020)]

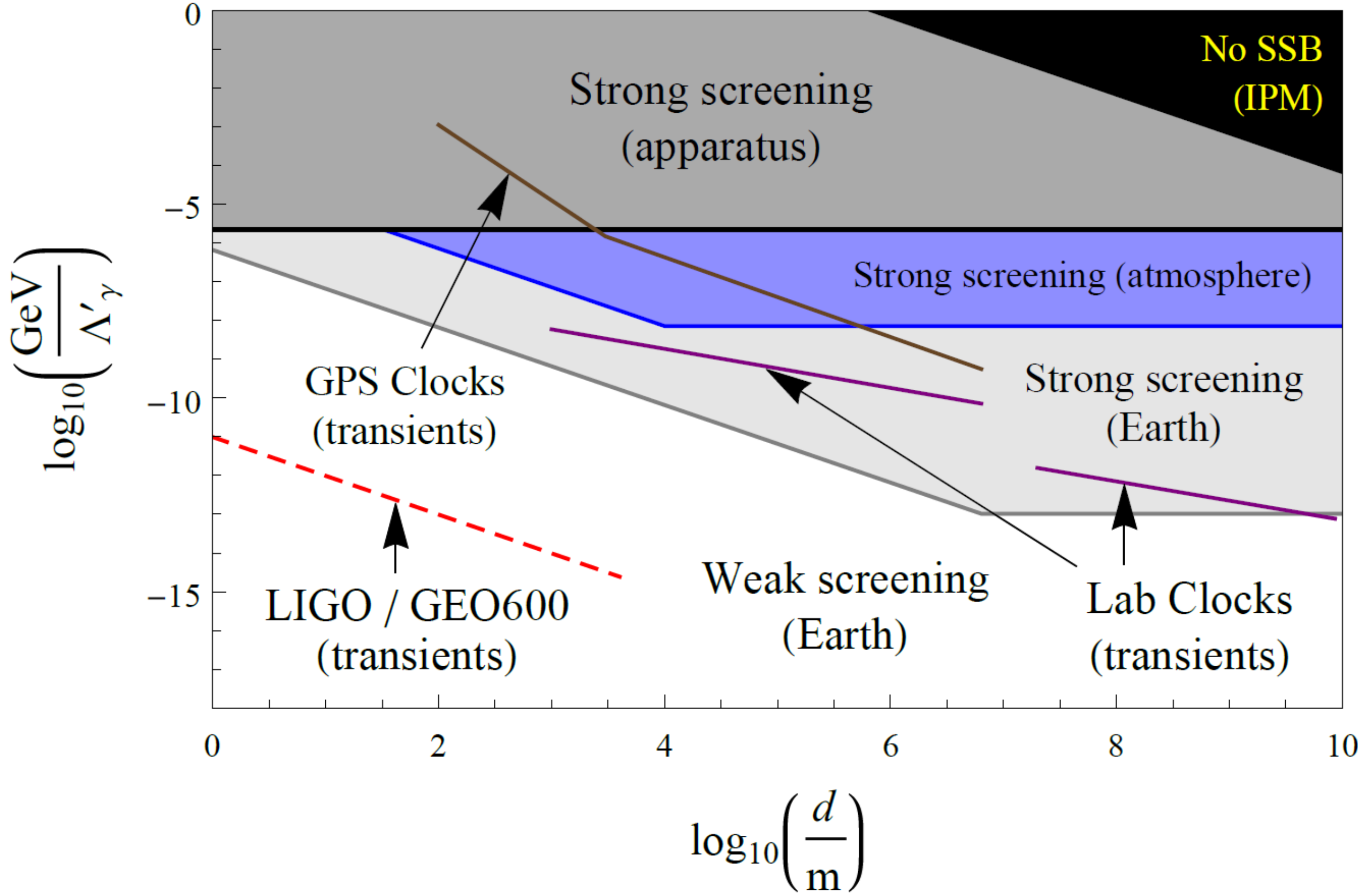
Quasi-static bounds: [Stadnik, *PRD* **102**, 115016 (2020)]



Scrutinising Bounds from Transient Signatures

[Stadnik, *PRD* **102**, 115016 (2020)]

Strongly repulsive back-action by Earth on an incoming domain wall may prevent the unperturbed passage of the wall through Earth – contrary to earlier assumptions



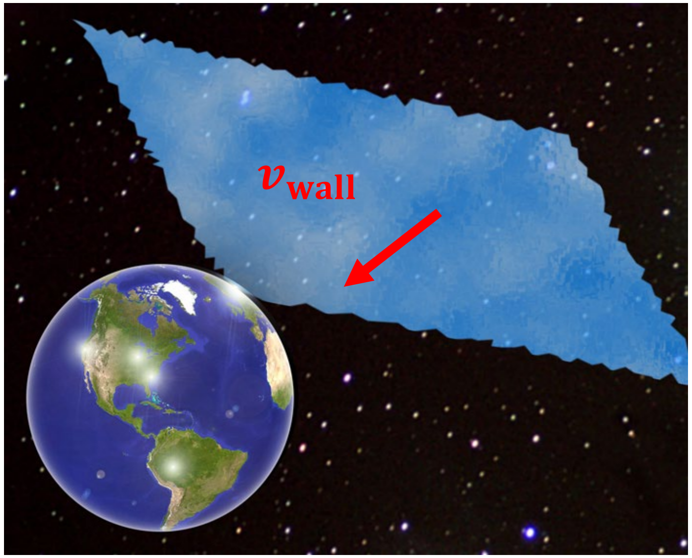
Scrutinising Bounds from Transient Signatures

[Stadnik, *PRD* **102**, 115016 (2020)]

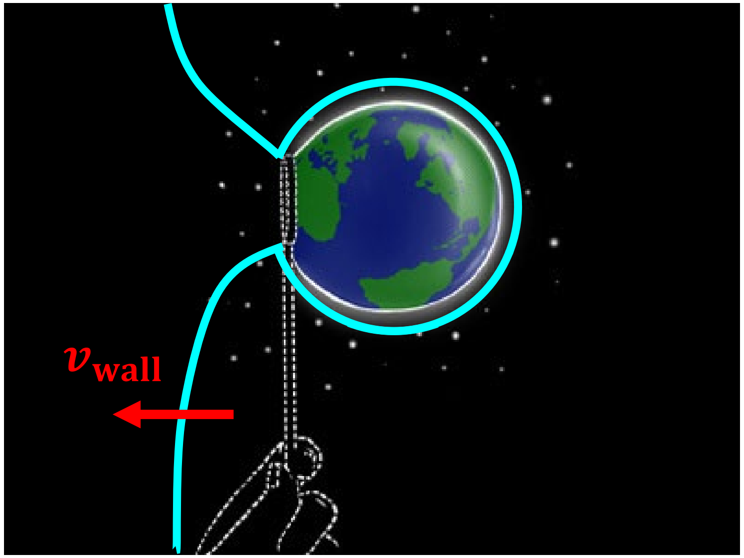
Possible outcomes of strongly repulsive back-action by Earth on an incident wall:

(i) Local part of wall may pass or “tunnel” through Earth with a temporarily diminished φ amplitude (while the rest of the wall passes around Earth)

(ii) Part of the wall may envelop Earth and “pinch off”, forming either a stable or metastable “bubble” around Earth (possible φ-radiation burst after collapse)



Domain wall incident on Earth



(Meta)stable bubble around Earth?

Phenomenology of Ultralight Scalar FIPs

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7. Solitons

Phenomenology of Ultralight Scalar FIPs

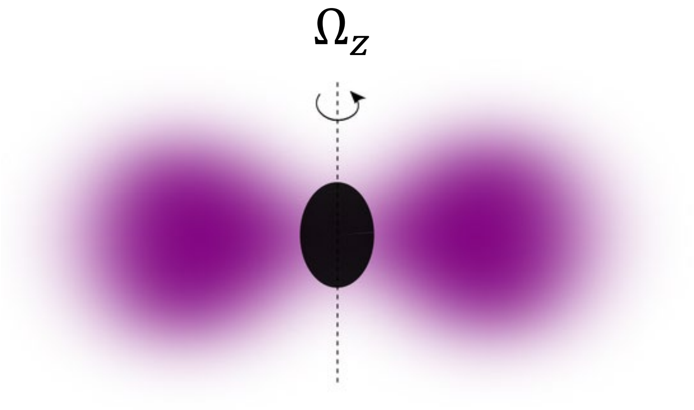
- The phenomenology of ultralight scalar FIPs (as well as other bosonic FIPs) is an extremely rich and ever-growing field of research

- Plethora of new experimental approaches and platforms have emerged in recent years, particularly in the field of precision measurements, including quantum and AMO sensors

Back-Up Slides

Black Hole Superradiance

[Arvanitaki, Dubovsky, *PRD* **83**, 044026 (2011)], [Baryakhtar *et al.*, *PRD* **103**, 095019 (2021)]



- Massive scalars can form gravitationally bound states around a spinning black hole, with energy spectrum: $E_\varphi \approx m_\varphi\left(1 - \alpha_g^2/2n^2\right)$,

$$\alpha_g = GMm_\varphi \equiv r_g m_\varphi$$

- Size of orbit: $r_c \sim n^2 r_g/\alpha_g^2$

- Can extract energy and angular momentum from the black hole into a bound state with angular momentum projection l_z if $0 < E_\varphi/\hbar < l_z\Omega_z$
- Superradiant process is efficient only if $2r_g m_\varphi \sim 1$ (i.e., when the scalar Compton wavelength is comparable to the black hole radius)
- Observations of old, fast-spinning black holes constrain scalars with masses $10^{-13}\ \mathrm{eV} \lesssim m_\varphi \lesssim 10^{-11}\ \mathrm{eV}$ (stellar-mass BHs) and $10^{-18}\ \mathrm{eV} \lesssim m_\varphi \lesssim 10^{-17}\ \mathrm{eV}$ (supermassive BH)

<u>Caveat</u>: Strong self-interactions (e.g., φ^4-type) can inhibit superradiance

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
  - Highly-charged ions
  - Molecules
  - Nuclei

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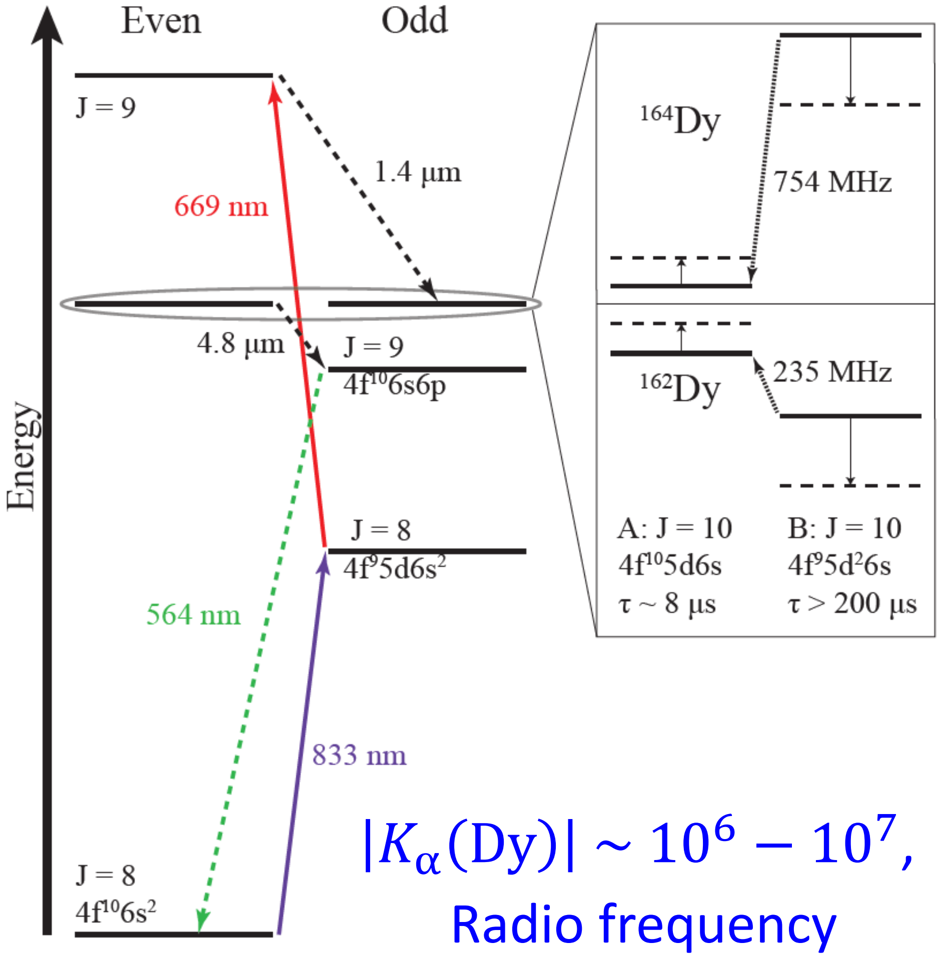

$|K_\alpha(\mathrm{Dy})| \sim 10^6 - 10^7$,

Radio frequency

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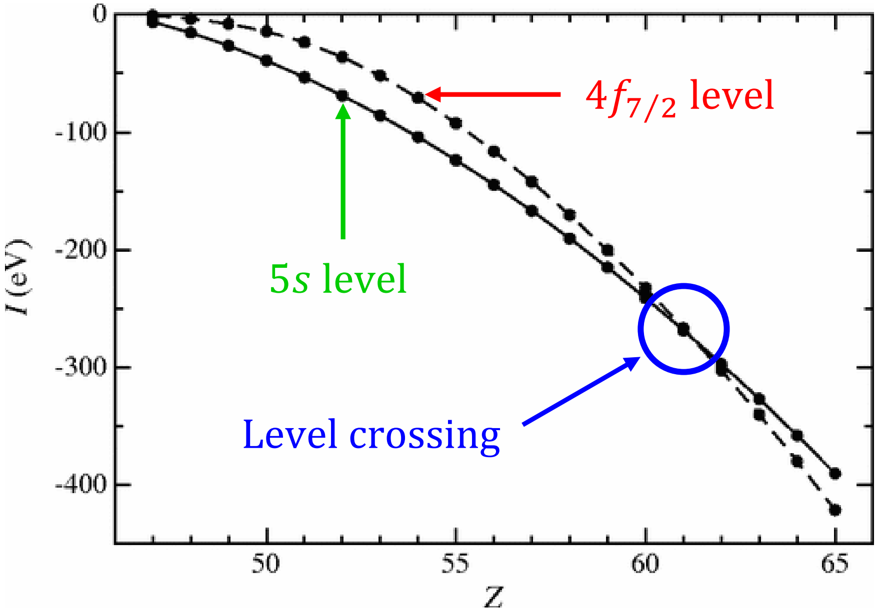
Ag isoelectronic sequence



e.g., $\left|K_\alpha\left(\mathrm{Cf}^{15+}\right)\right| \approx 50$,

Optical frequency

(Bi isoelectronic sequence)

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- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels in:
  - Atoms
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Much richer energy level structure possible in molecules than in atoms, and can include contributions from various types of energy intervals:

- Fine-structure
- Hyperfine magnetic
- Rotational
- Vibrational
- Ω-doubling

e.g., $|K_\alpha(\mathrm{HfF}^+)| \approx 2000,$

$\left|K_{m_e/m_N}(\mathrm{HfF}^+)\right| \approx 80,$

Far-infrared frequency

Enhanced Effects of Varying Fundamental Constants on Atomic and Other Transitions

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There exists a low-energy ($\approx 8\ \mathrm{eV}$) isomeric transition between the ground and first-excited states of ^{229}Th, due to fortuitous cancellation between the electromagnetic and strong force intervals

$$|K_\alpha(\mathrm{Th})| \sim 10^4,$$

Ultraviolet frequency

BBN Constraints on ‘Slow’ Drifts in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- Largest effects of DM in early Universe (highest ρ_{DM})
- Big Bang nucleosynthesis ($t_{\mathrm{weak}} \approx 1\ \mathrm{s} - t_{\mathrm{BBN}} \approx 3\ \mathrm{min}$)
- Primordial ^{4}He abundance sensitive to n/p ratio

  (almost all neutrons bound in ^{4}He after BBN)

$$\frac{\Delta Y_p(^4\mathrm{He})}{Y_p(^4\mathrm{He})} \approx \frac{\Delta(n/p)_{\mathrm{weak}}}{(n/p)_{\mathrm{weak}}} - \Delta\left[\int_{t_{\mathrm{weak}}}^{t_{\mathrm{BBN}}} \Gamma_n(t)dt\right]$$

$$p + e^- \rightleftharpoons n + \nu_e$$

$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

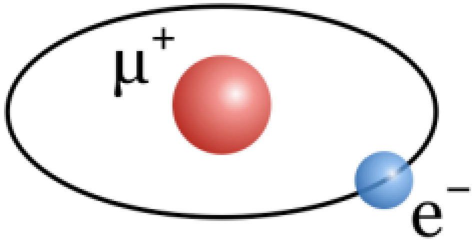
Muon Probes of Scalar DM

- Most searches for ultralight scalar DM have focused on the electromagnetic (photon) and electron couplings
- *What about searching for ultralight scalar DM via its coupling to muons?*
- Possible flavour/generational dependence of scalar couplings in the lepton sector
- Extra motivation from persistence of various anomalies in muon physics, such as:
    - Proton radius puzzle
    - $(g-2)_\mu$ puzzle
- No stable terrestrial sources of muons

Effects of Varying Fundamental Constants on Transitions in Muonic Atoms

[Stadnik, arXiv:2206.10808]

- Muonium 1S – 2S transition:



$$\nu_{1S-2S} \propto \frac{m_r e^4}{\hbar^3}$$

$$K_{m_\mu} \approx m_e / m_\mu$$

$$m_r = \frac{m_e m_\mu}{m_e + m_\mu} \approx m_e \left(1 - m_e / m_\mu\right)$$

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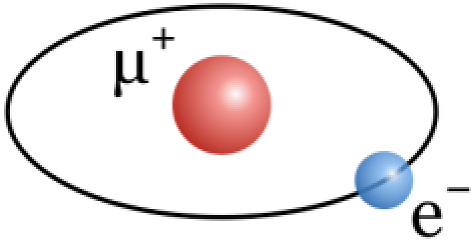

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$$m_r = \frac{m_e m_\mu}{m_e + m_\mu} \approx m_e(1 - m_e/m_\mu)$$

- Muonium ground-state hyperfine transition:

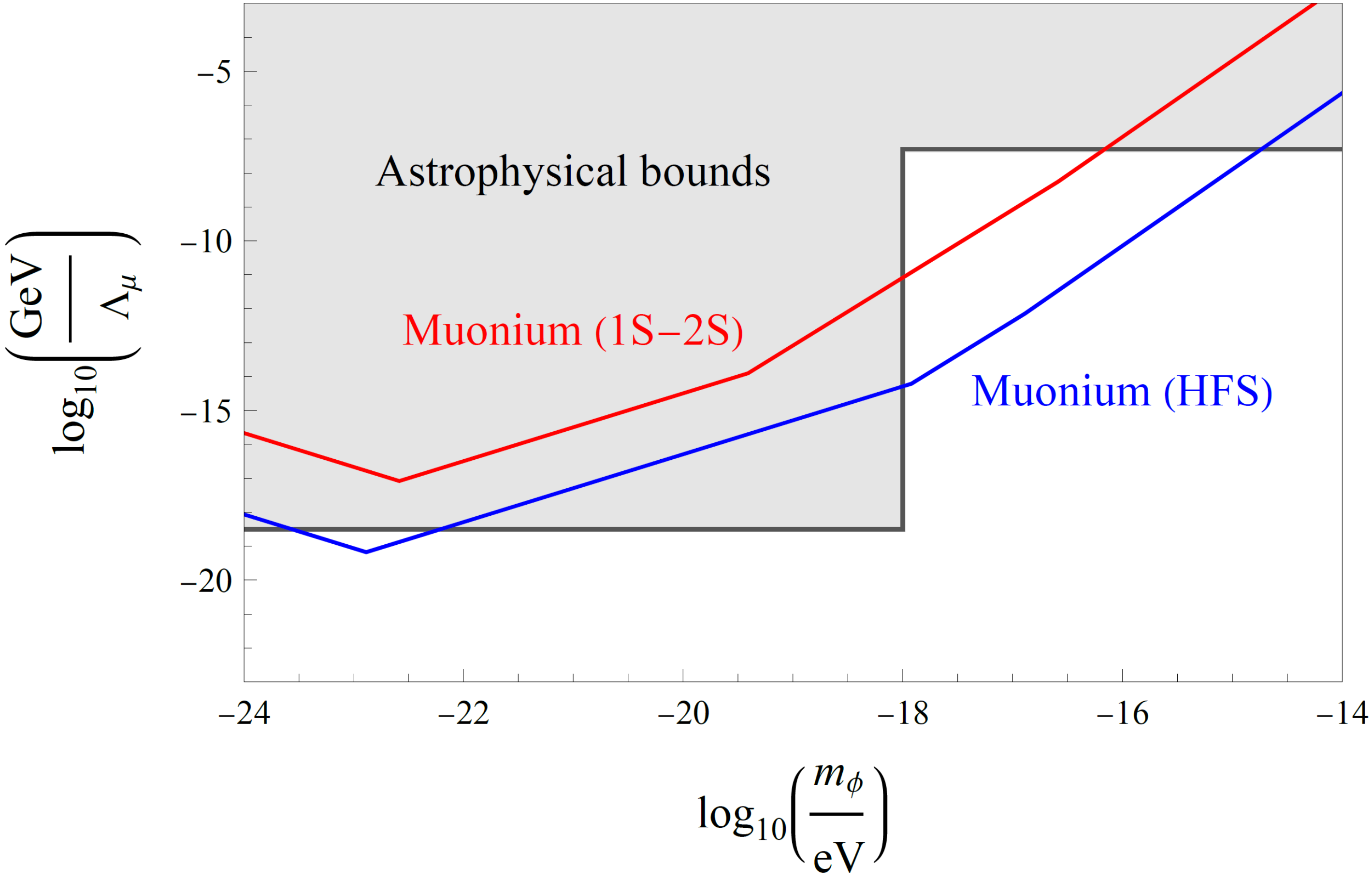
$$\nu_{\text{hf}} \propto \left(\frac{m_r e^4}{\hbar^3}\right) \frac{m_r^2 \alpha^2}{m_e m_\mu}$$

$$K_{m_\mu} \approx -1$$

Estimated Sensitivities to Scalar Dark Matter with $\varphi \bar{\mu}\mu/\Lambda_\mu$ Coupling

[Stadnik, arXiv:2206.10808]

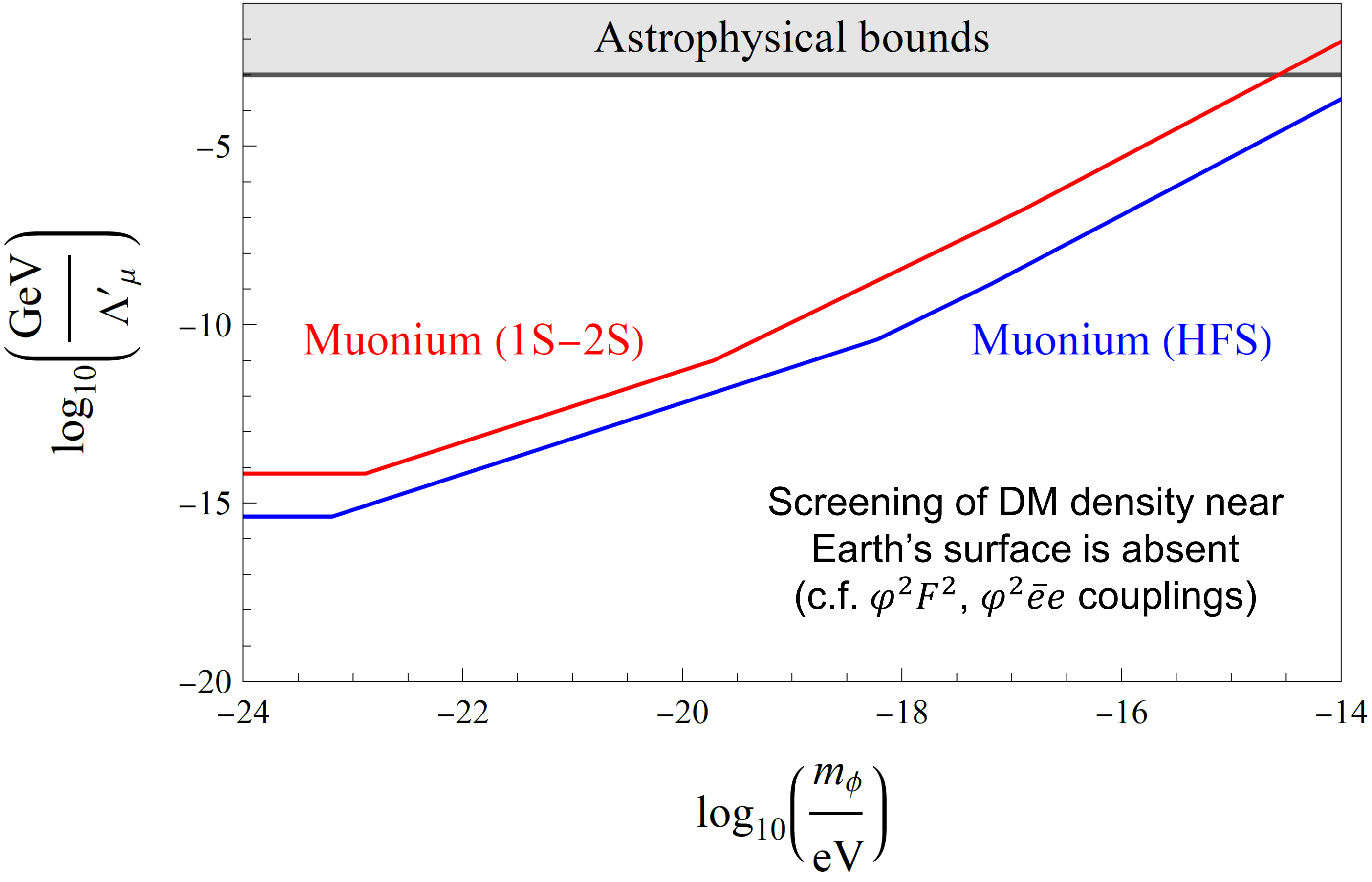
Up to 7 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)



Estimated Sensitivities to Scalar Dark Matter with $\varphi^2 \bar{\mu}\mu / (\Lambda'_\mu)^2$ Coupling

[Stadnik, arXiv:2206.10808]

Up to 12 orders of magnitude improvement possible with existing datasets!
(Best existing datasets from muonium experiments at LAMPF and RAL in 1990s)



Screening of DM density near Earth's surface is absent (c.f. $\varphi^2 F^2$, $\varphi^2 \bar{e}e$ couplings)