Probing Ultra-Low-Mass Dark Matter and Macroscopic Topological Defects via Varying Fundamental “Constants”

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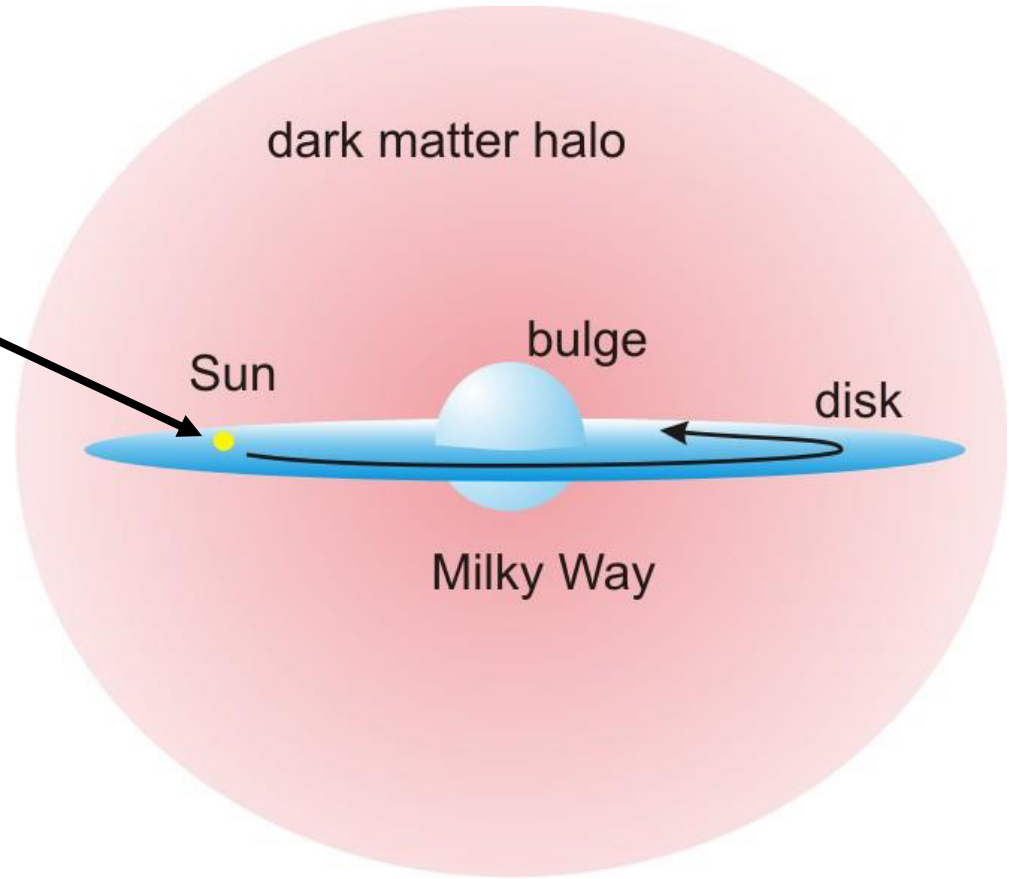
Dark Matter

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

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

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



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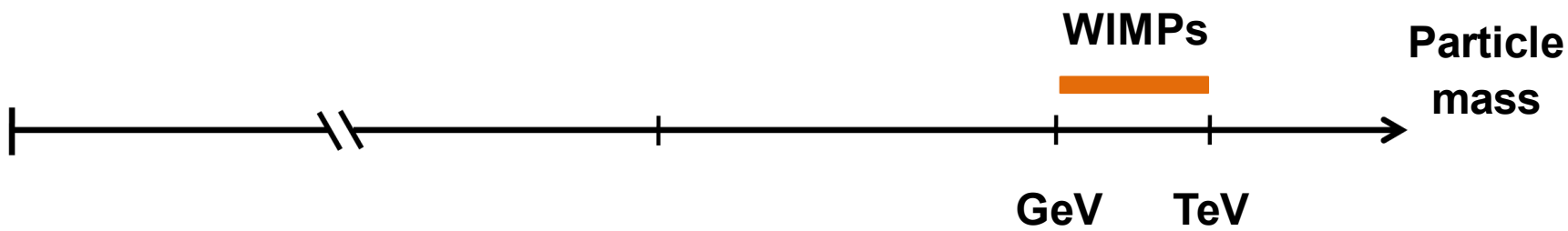

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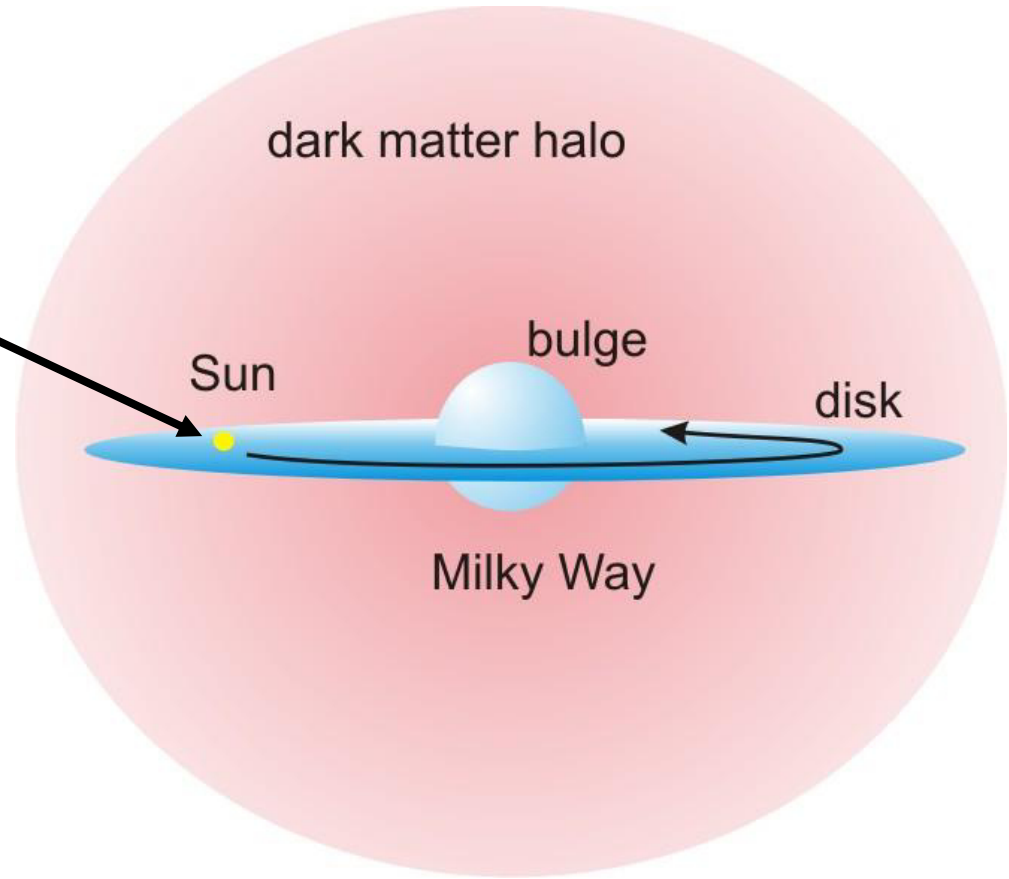

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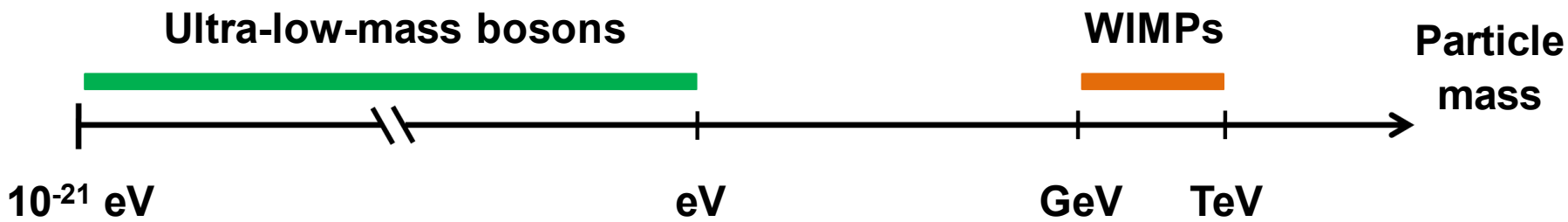

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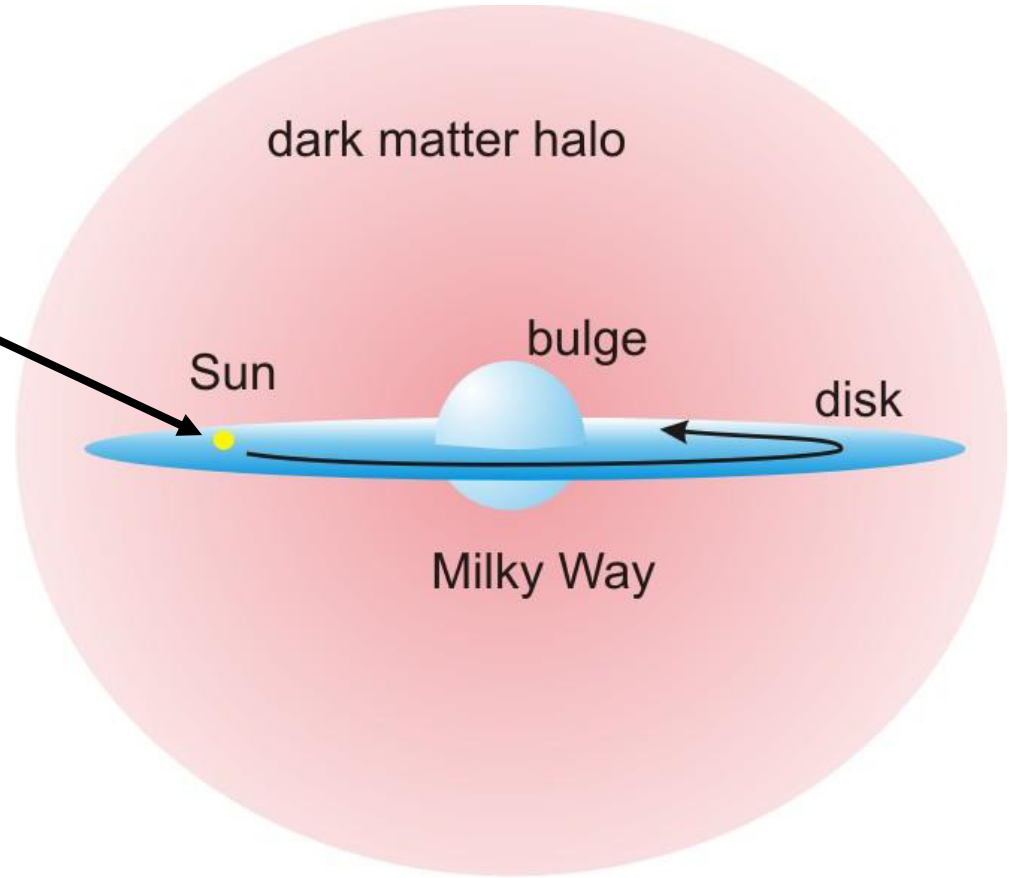
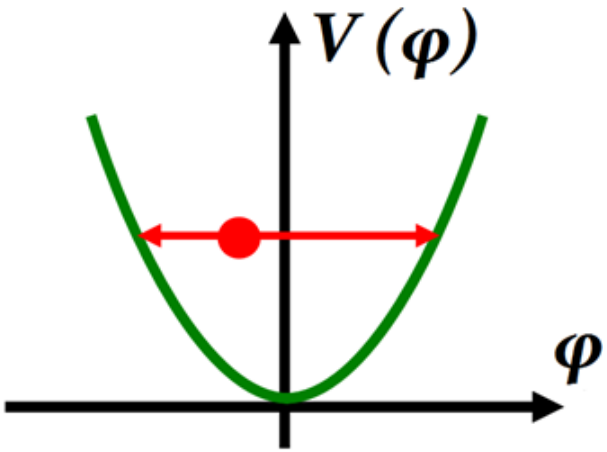


Low-mass Spin-0 Dark Matter

- 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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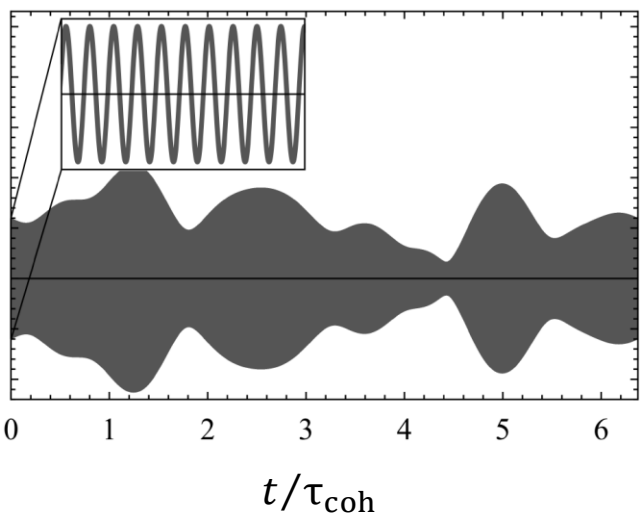
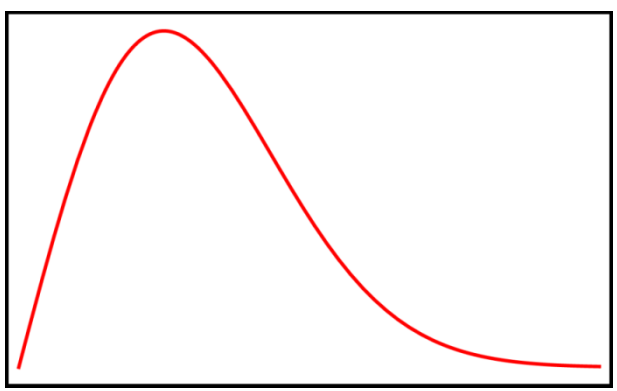
Evolution of φ_0 with time



Probability distribution function of φ_0 (e.g., Rayleigh distribution)



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

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

IR frequencies

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

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

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- *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)]

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

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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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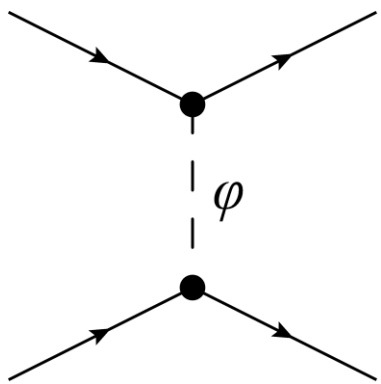
Fifth Forces: Linear vs Quadratic Couplings

[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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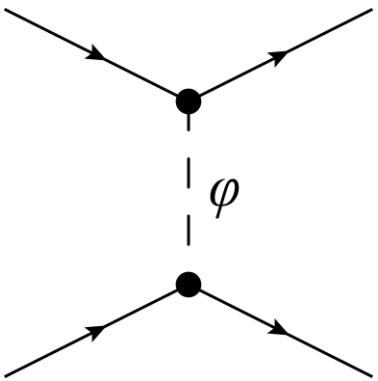

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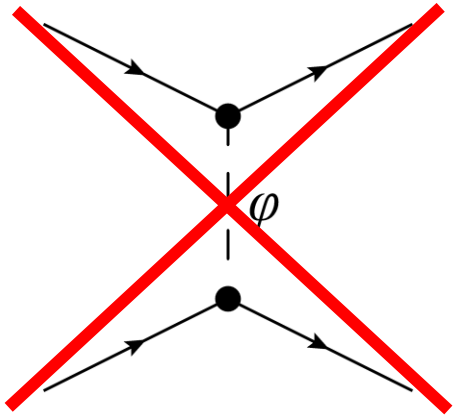

$$m_{\mathrm{eff}}^2(\rho) = m_\varphi^2 \mp \kappa'\rho$$

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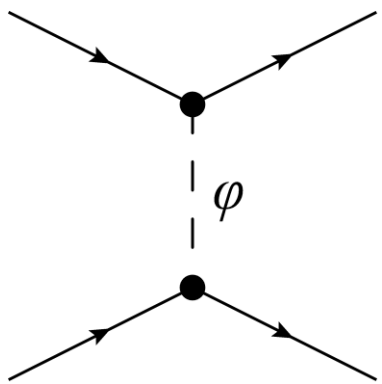

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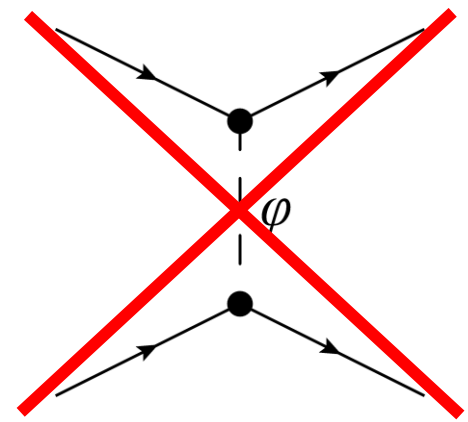

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Gradients + amplification/screening

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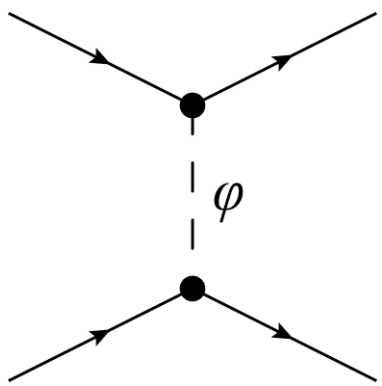

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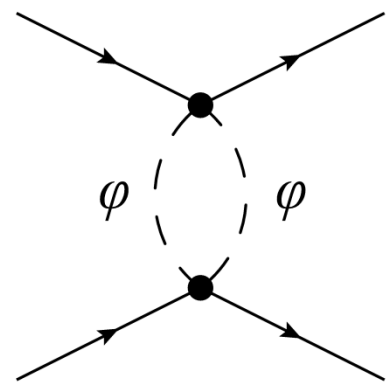

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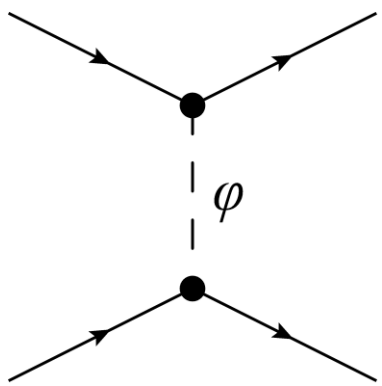

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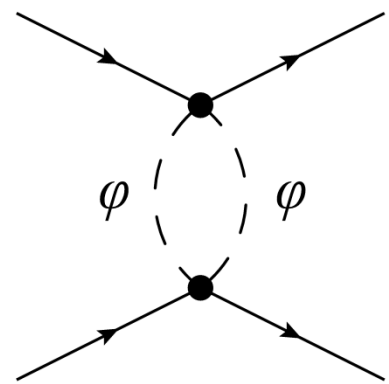

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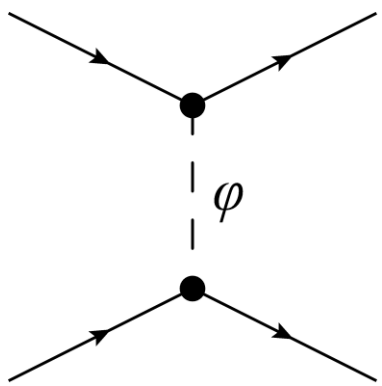

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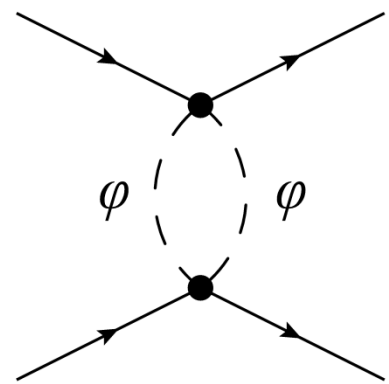

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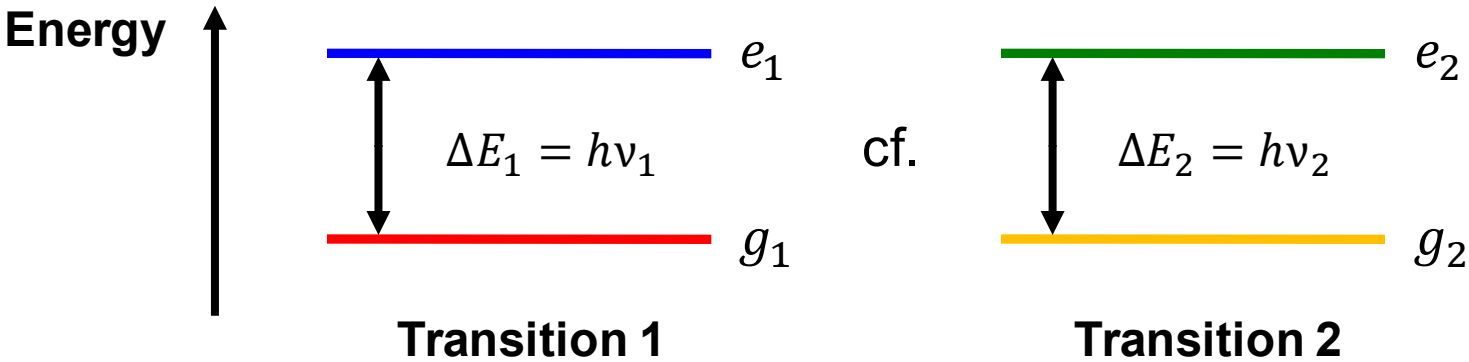
"Fifth-force" experiments: torsion pendula, atom interferometry

Gradients + amplification/screening

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



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

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)]

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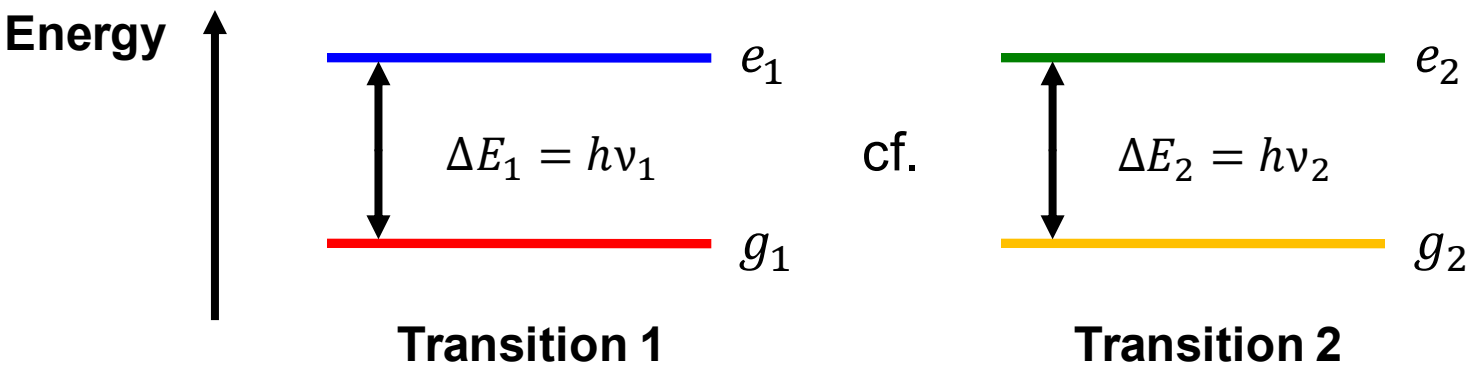
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015)], [Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)]



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

- **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)]
- **Yb^+(E3)/Sr [PTB]:** [Huntemann, Peik *et al.*, Ongoing]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ [NIST + JILA]:** [Hume, Leibrandt *et al.*, Ongoing]

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)

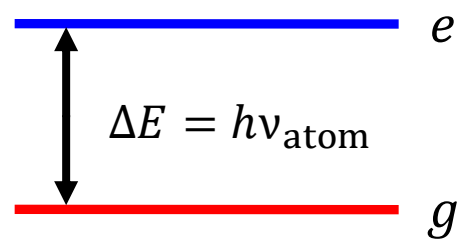
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

cf.

Electronic transition



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

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

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

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

- **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)]
  - **Sr^+ vs Glass cavity [Weizmann]:** [Aharony *et al.*, arXiv:1902.02788]
- **Sr/H vs Silicon cavity [JILA + PTB]:** [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]
  - **H vs Sapphire/Quartz cavities [UWA]:** [Campbell *et al.*, arXiv:2010.08107]

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

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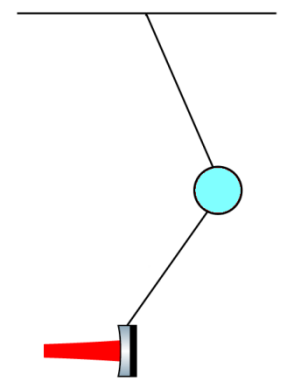
Solid material

cf.

Freely-suspended mirrors

Double-pendulum suspensions



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

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

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

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

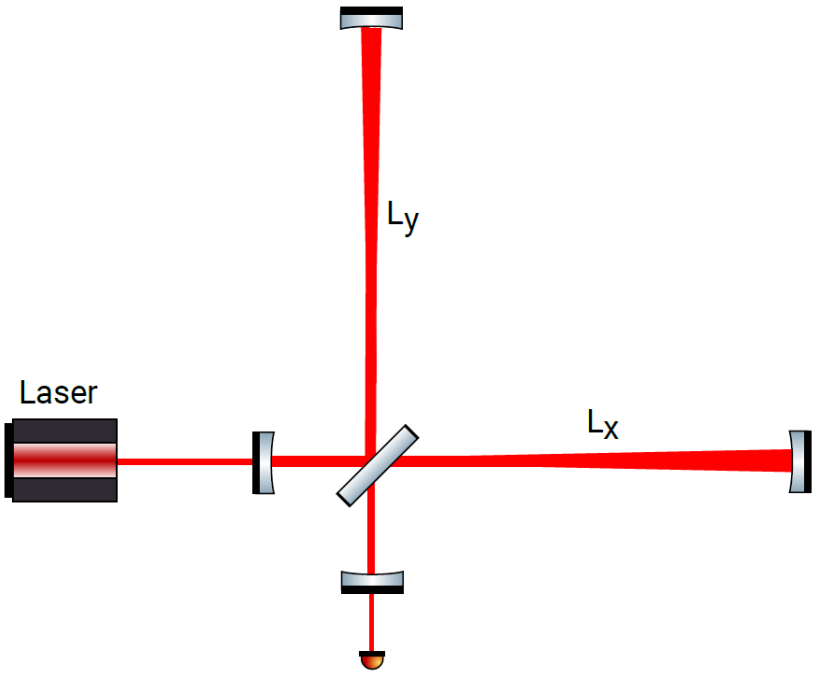
$$\boxed{\frac{\nu_{\text{solid}}}{\nu_{\text{free}}} \propto m_e \alpha}$$

cf. $\dfrac{\nu_{\text{atom}}}{\nu_{\text{solid}}} \propto \alpha$

Small-scale experiment currently under development at Northwestern University

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

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



Michelson interferometer (GEO600)

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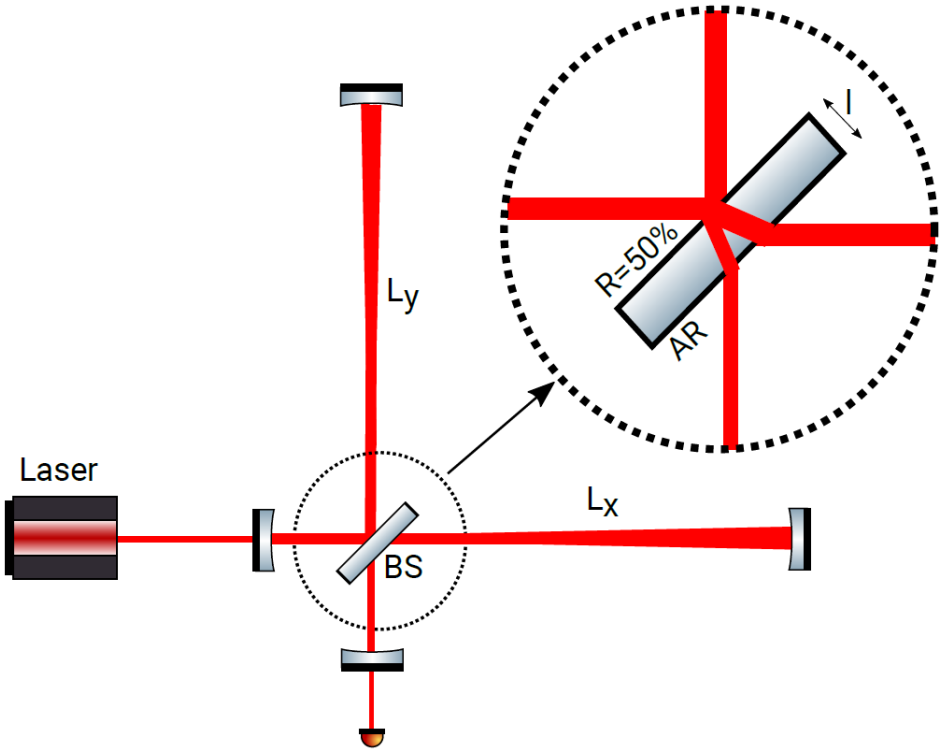

- Geometric asymmetry from beam-splitter

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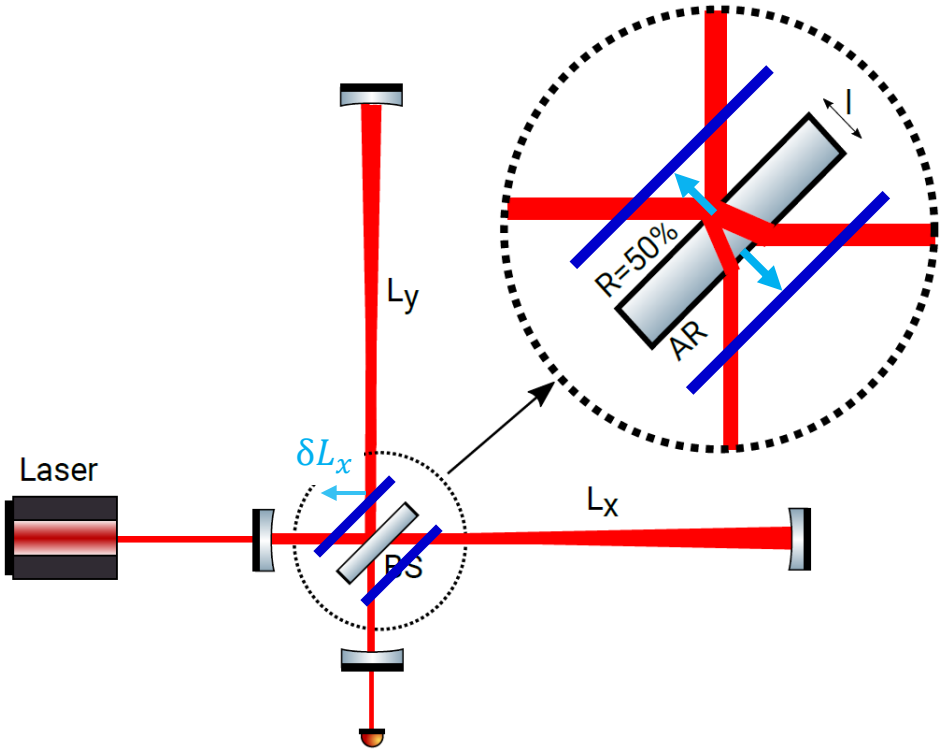

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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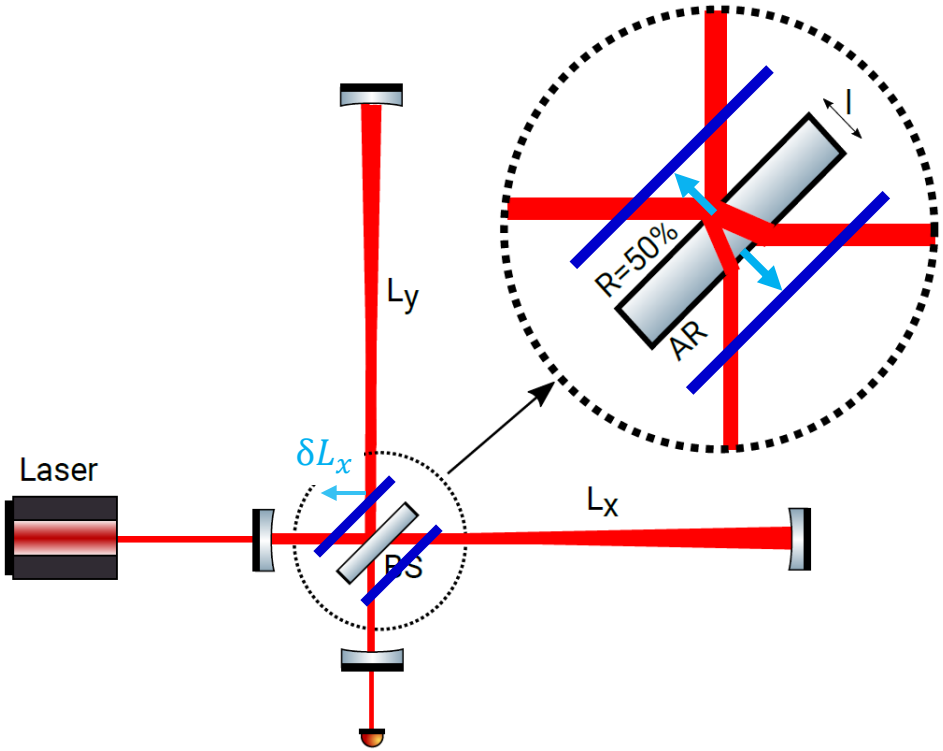

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

First preliminary results using old GEO600 data were recently reported:

[Vermeulen, talk at *Kashiwa Dark Matter Symposium*, 2020]

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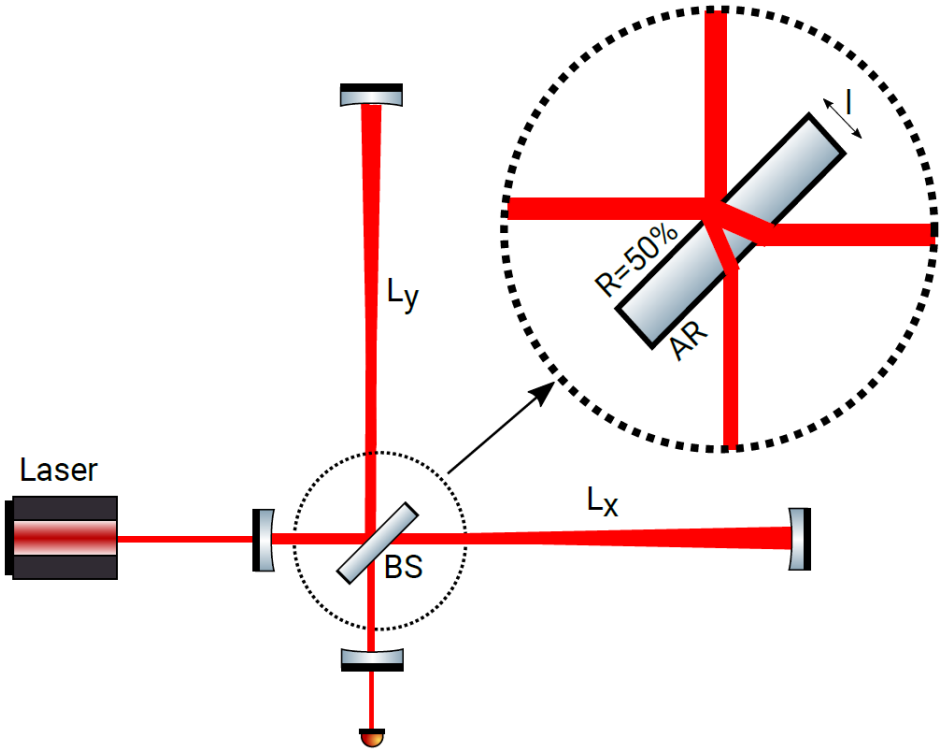


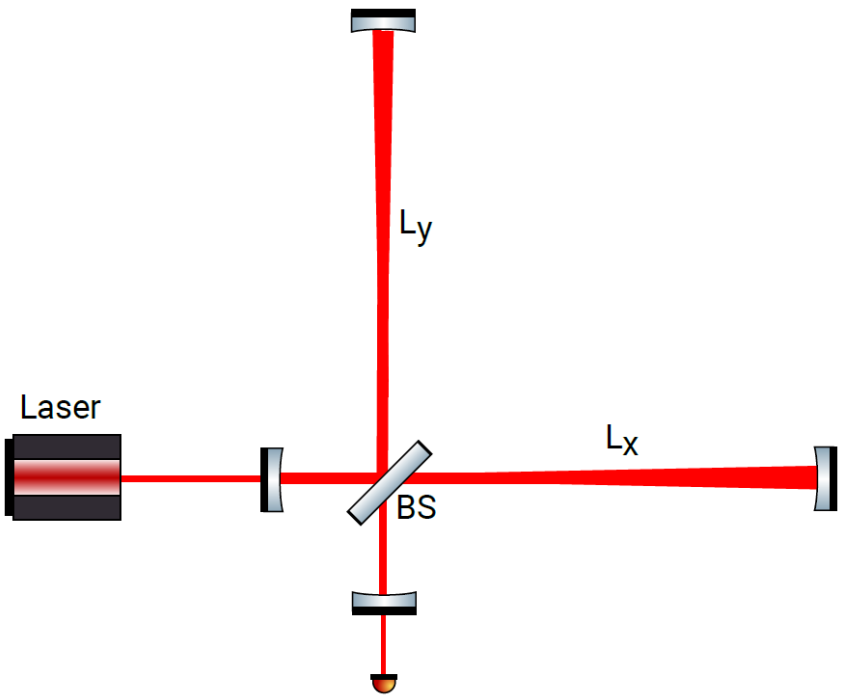
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

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

Michelson vs Fabry-Perot-Michelson Interferometers

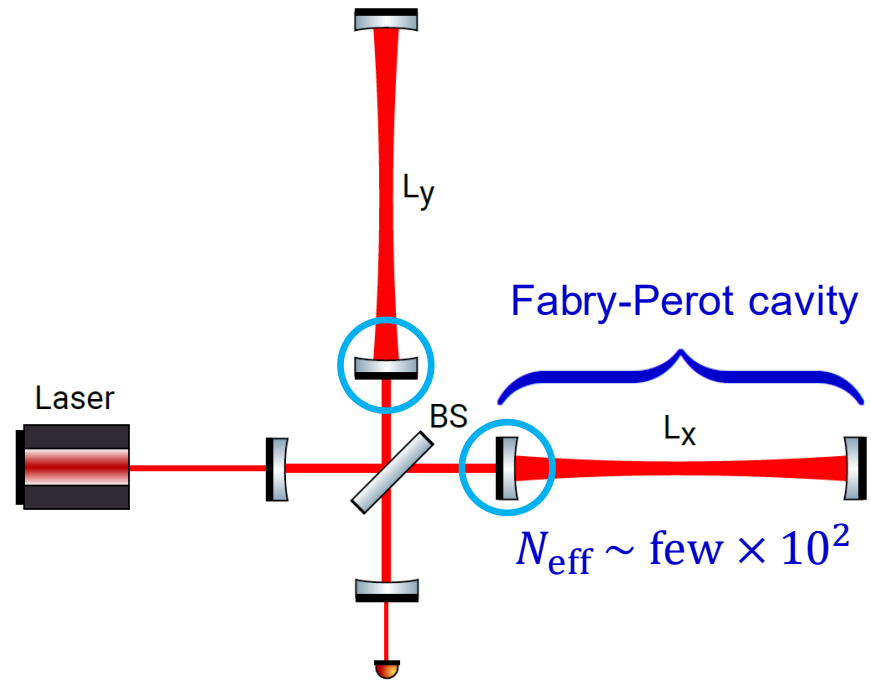
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)



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

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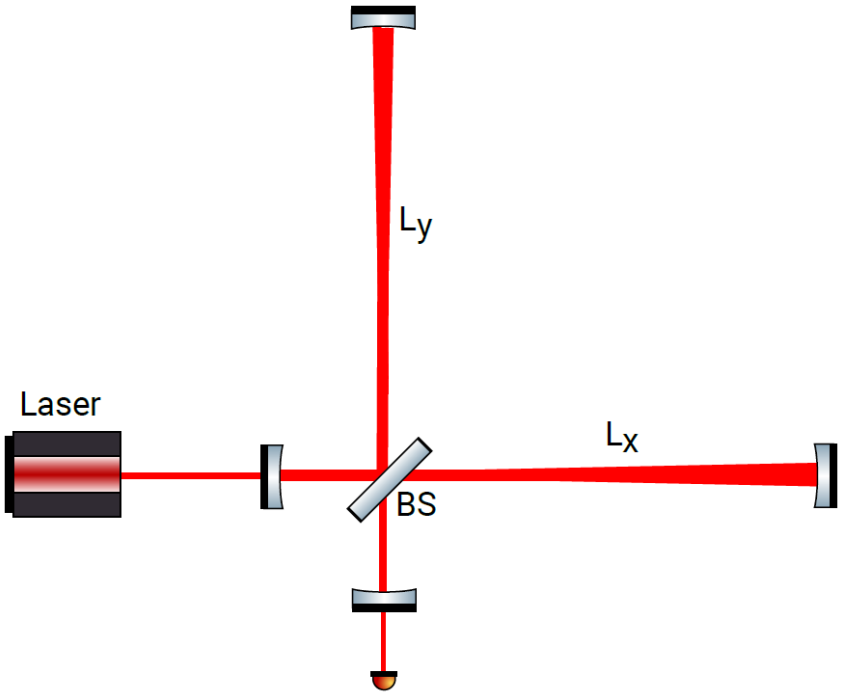

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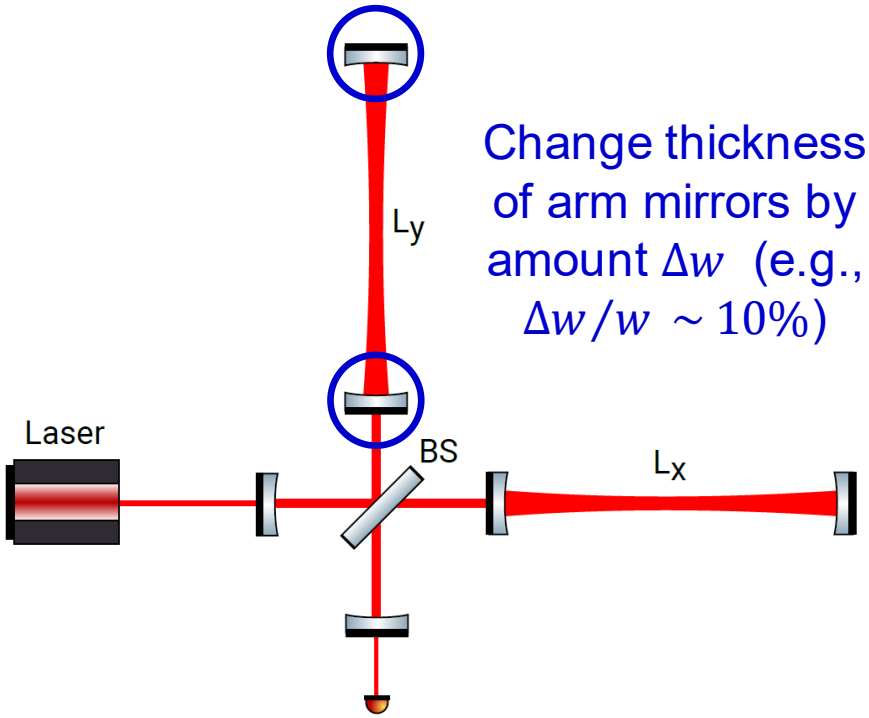


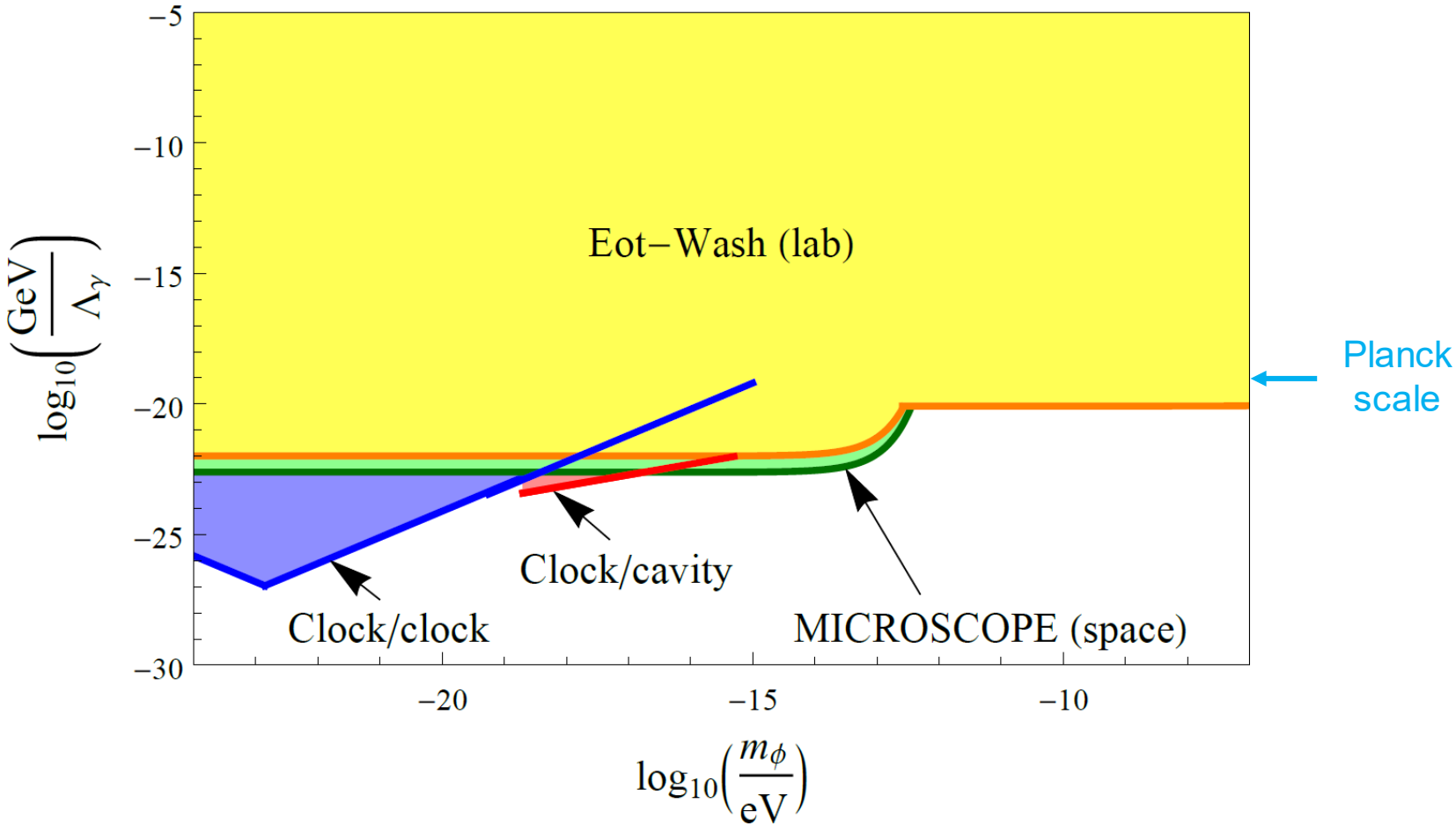
Change thickness of arm mirrors by amount Δw (e.g., $\Delta w / w \sim 10\%$)

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

Constraints on Linear Interaction of Scalar Dark Matter with the Photon

Clock/clock constraints: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Hees *et al.*, *PRL* **117**, 061301 (2016)]; **Clock/cavity constraints:** [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]

4 orders of magnitude improvement!



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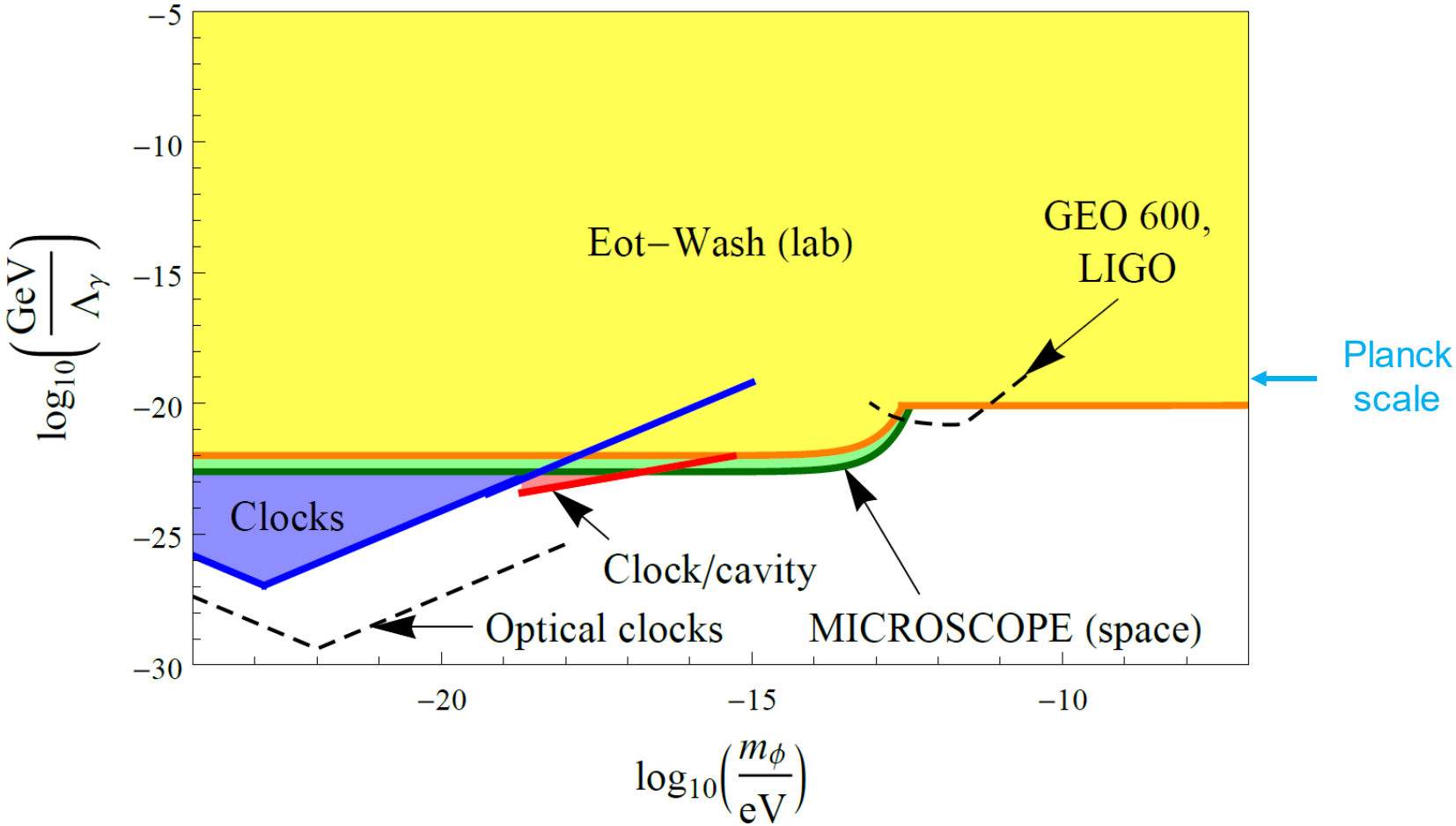

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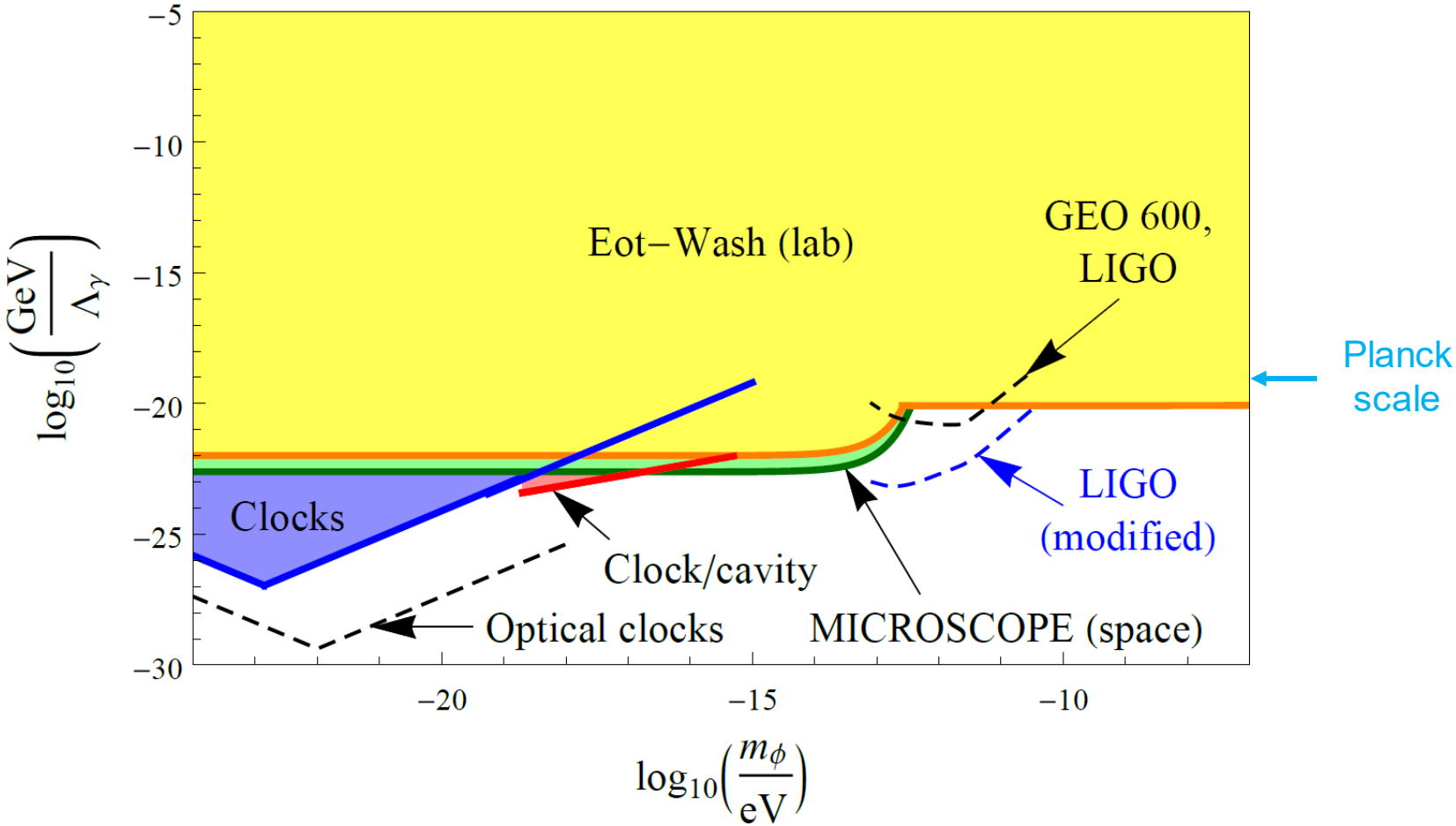

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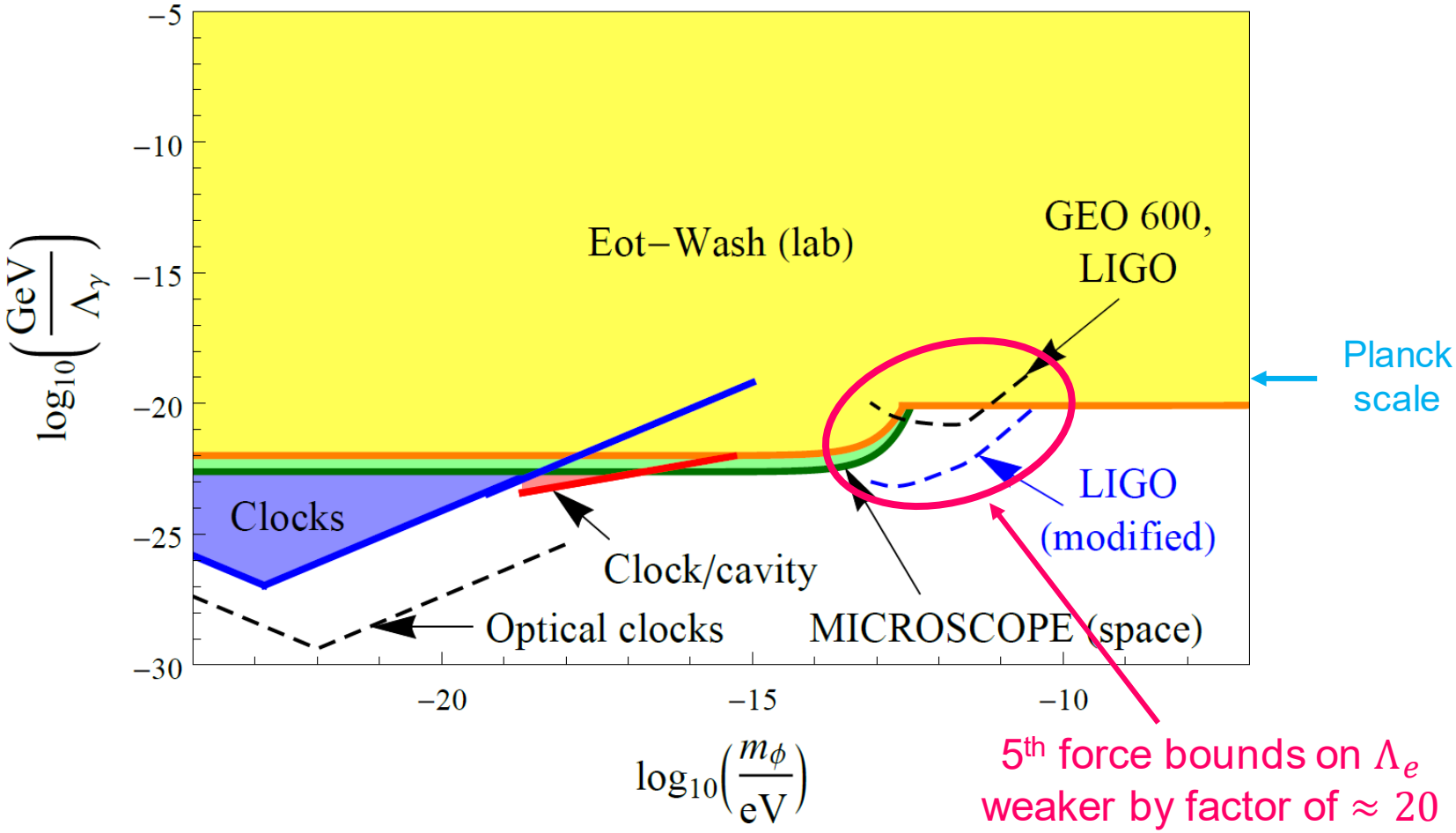
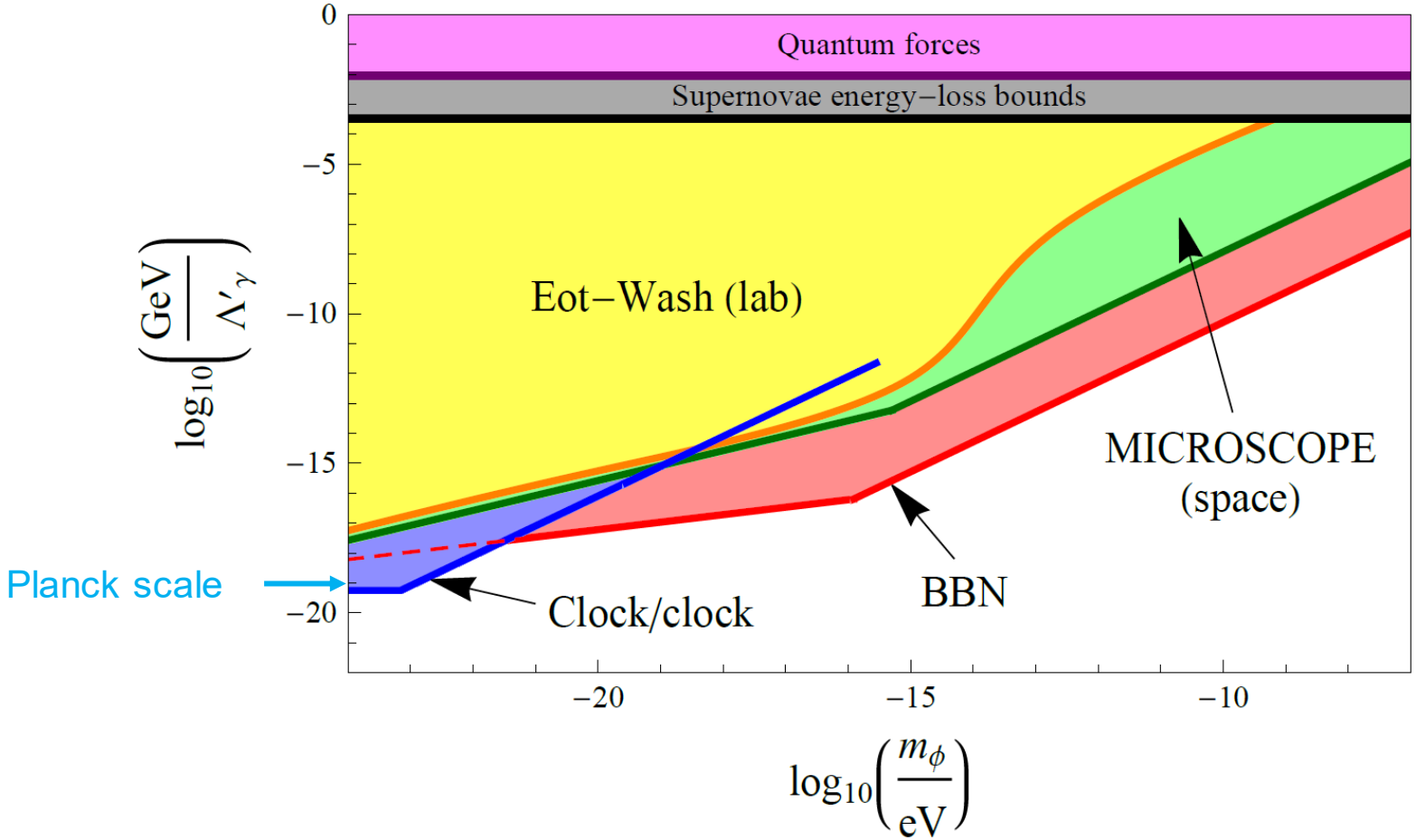


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

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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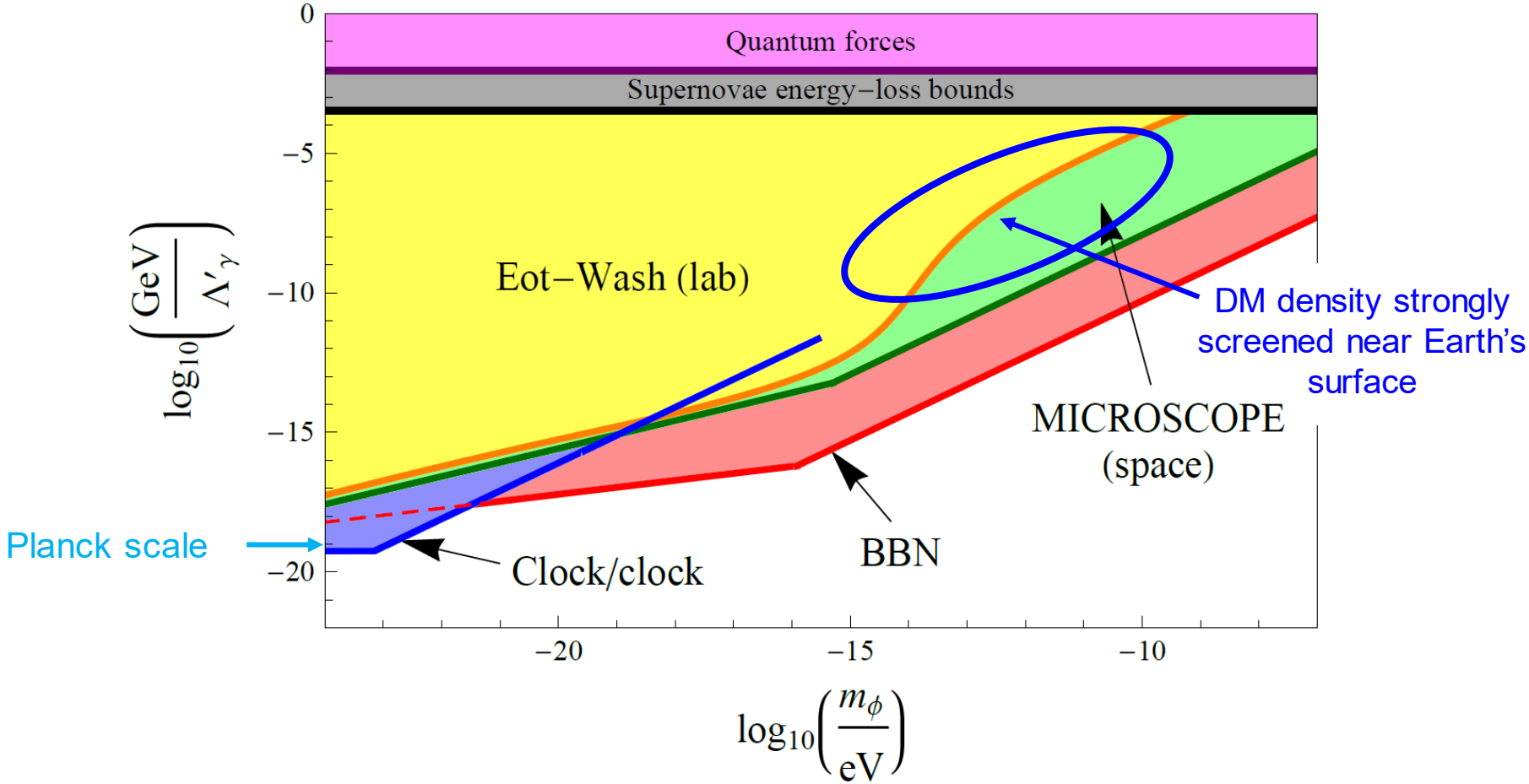
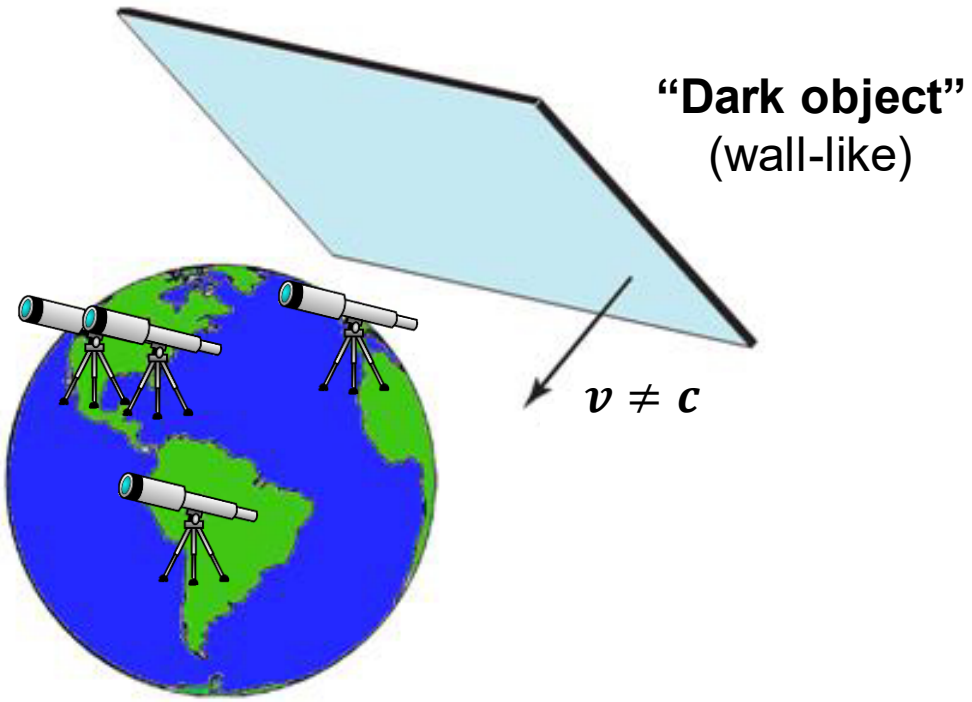


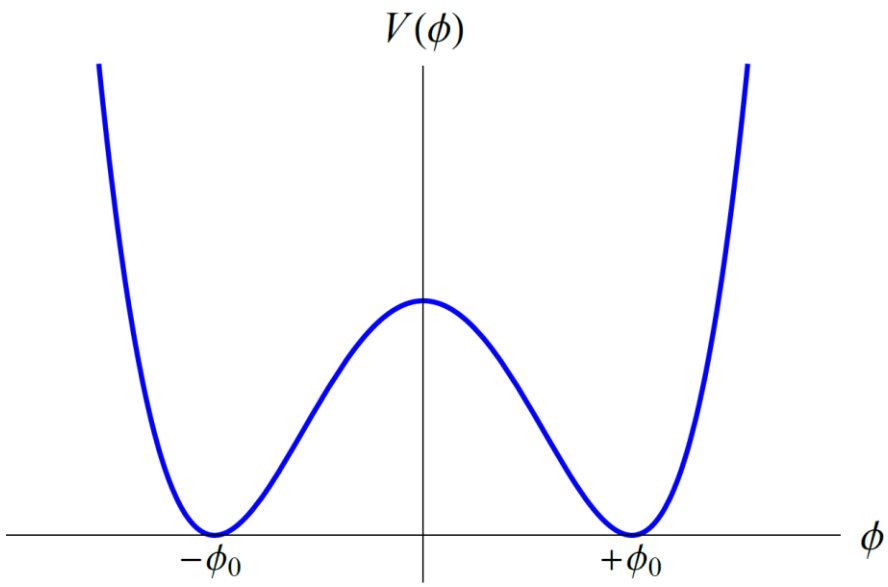
Dark Objects

- Recent interest to search for possible transient signatures of macroscopic **"dark objects"** that might pass through Earth
- <u>Basic idea</u>: use *terrestrial networks* of detectors to search for *correlated signatures* of passing objects (similarly to GW searches)



Topological Domain Walls

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



φ^4 potential

Topological Domain Walls

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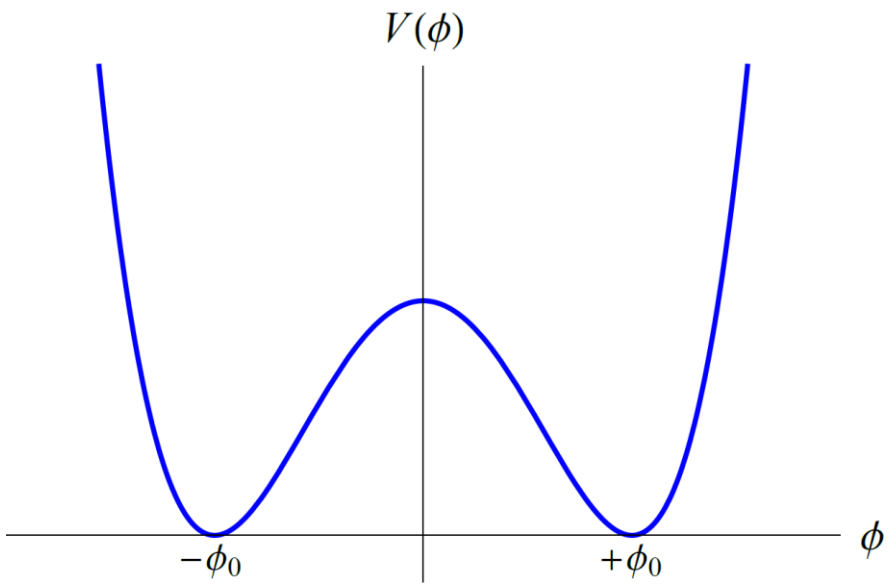
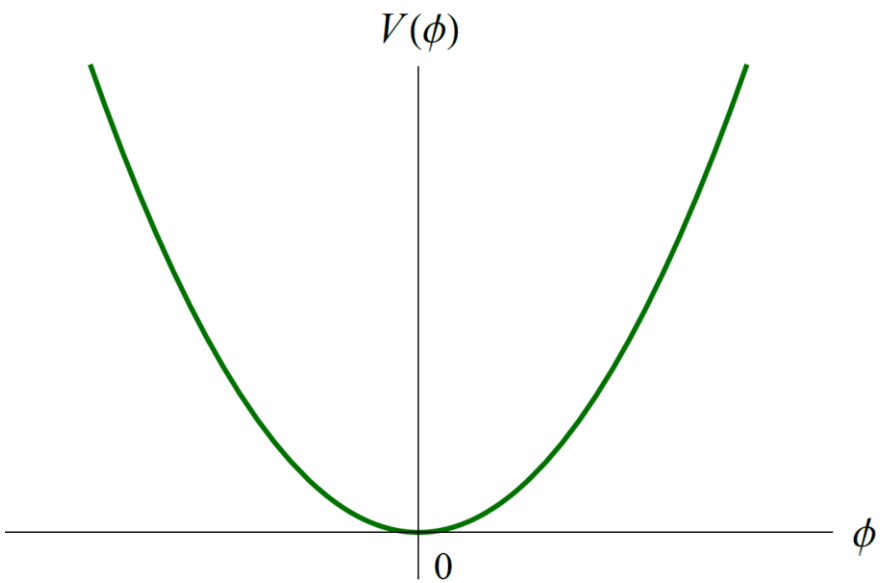


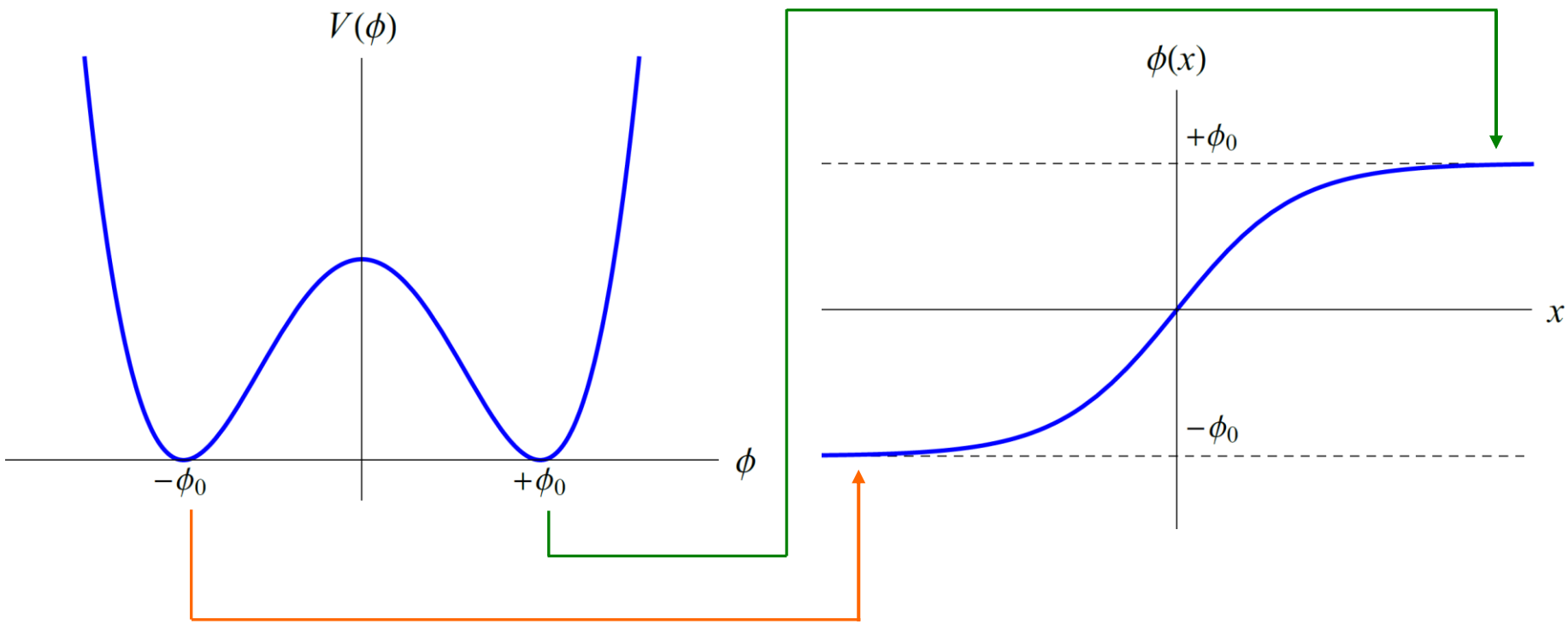
φ^4 potential
(non-trivial topology)



φ^2 potential
(trivial topology)

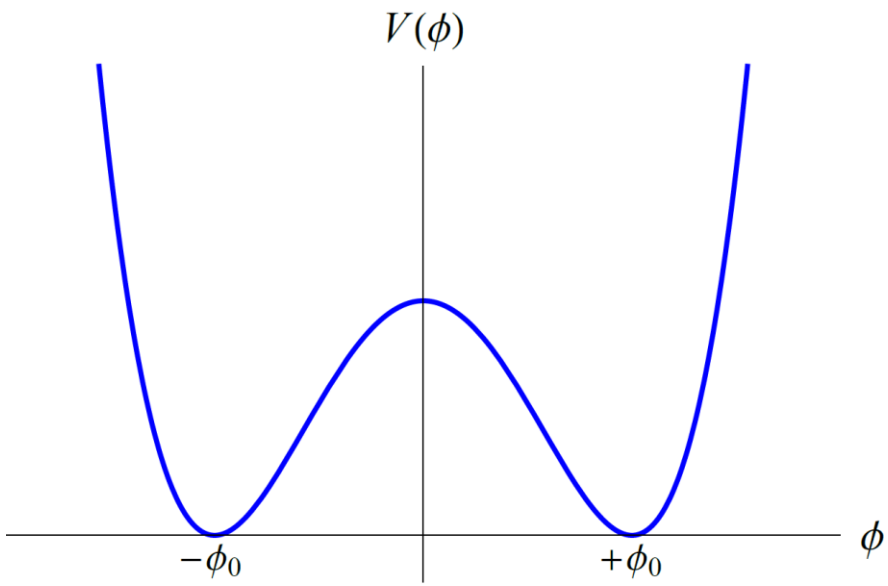
Topological Domain Walls

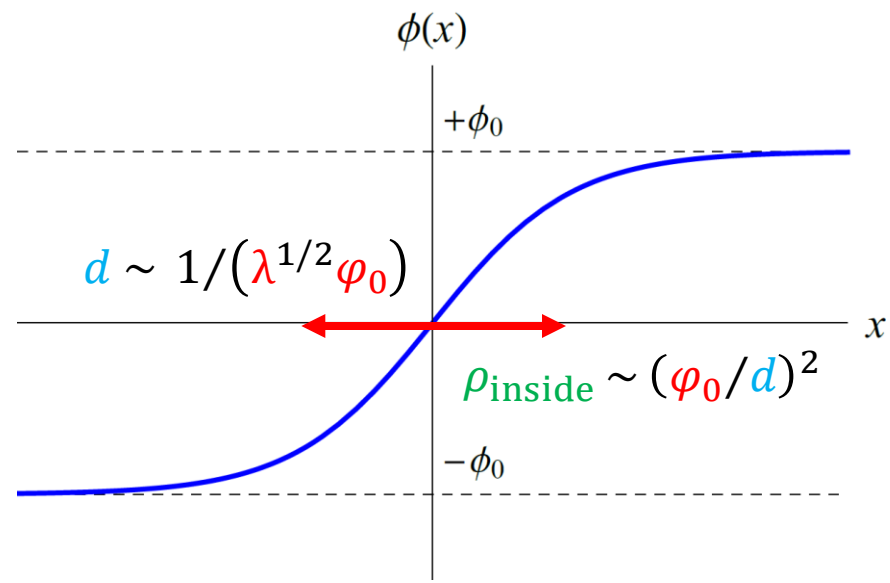
- Consider a real scalar field φ with potential $V(\varphi) = \lambda(\varphi^2 - \varphi_0^2)^2/4$
- Different regions in space may settle in different vacua/minima



Topological Domain Walls

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





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

Variations of Fundamental Constants

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

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

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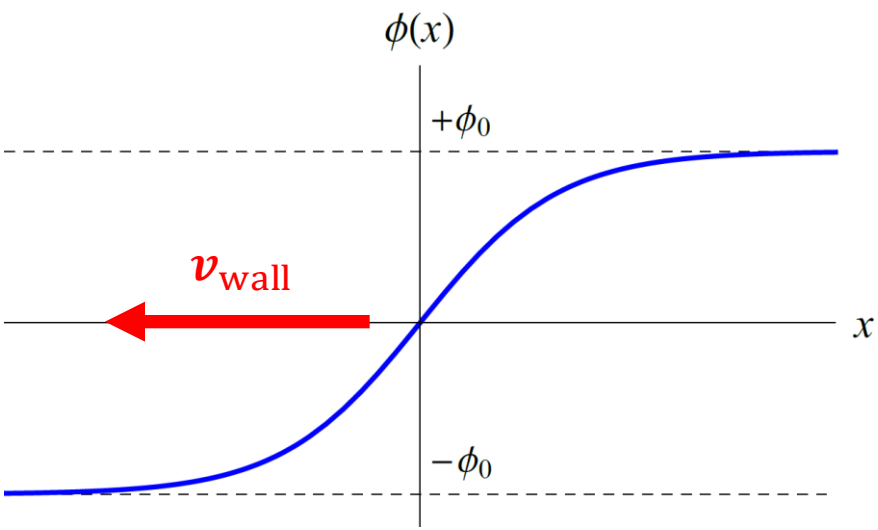
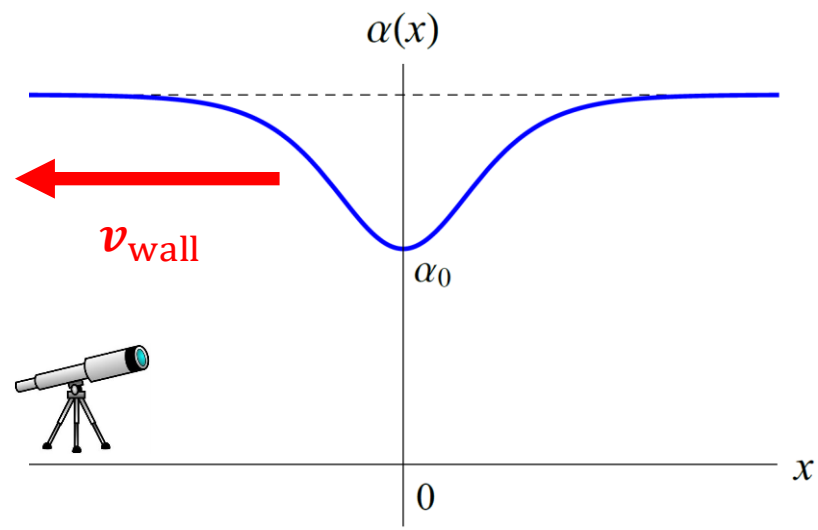
- A passing domain wall induces apparent **transient** variations of fundamental constants, due to a temporary change in φ^2





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- 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)]

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- 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 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)]

Variations of Fundamental Constants

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

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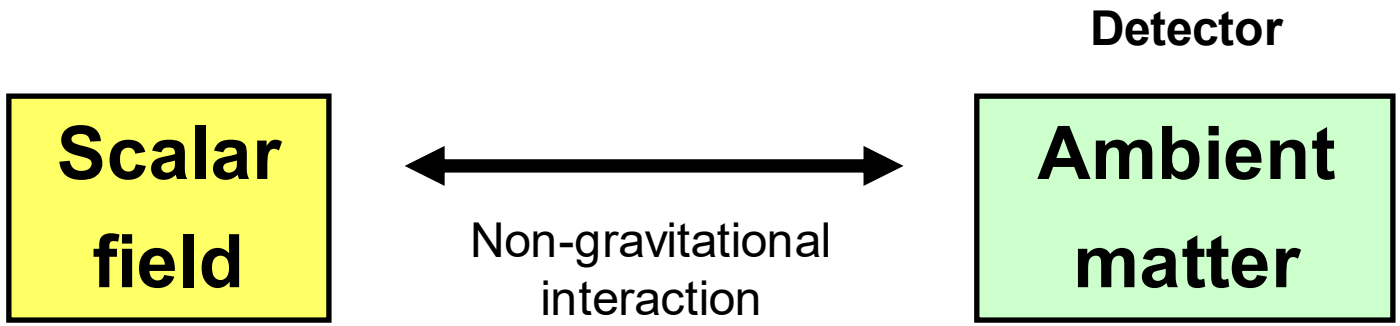

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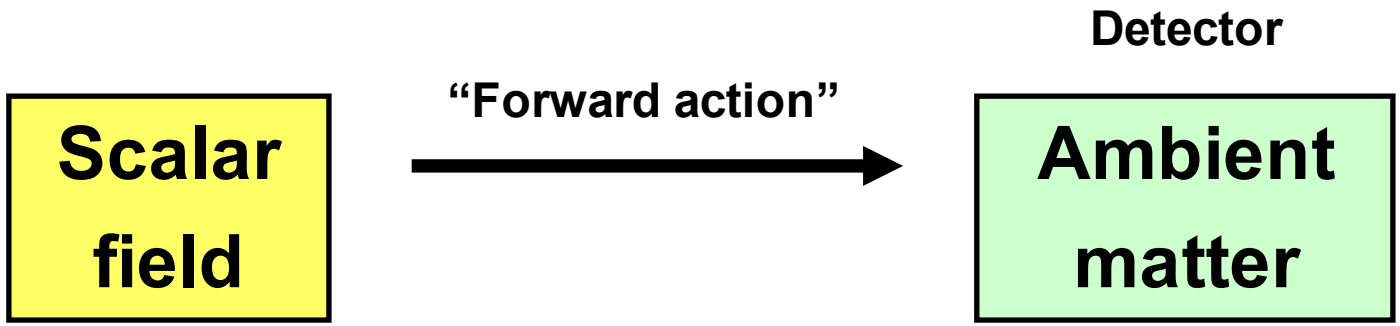

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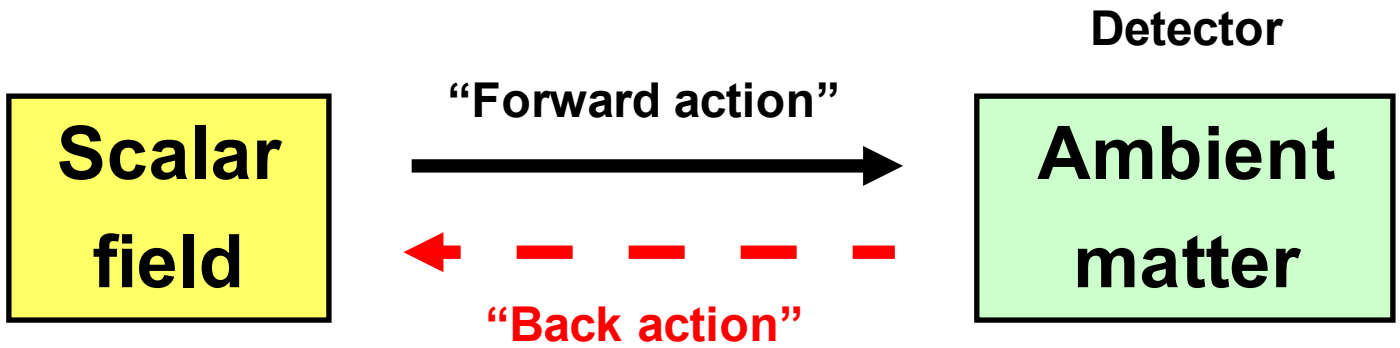

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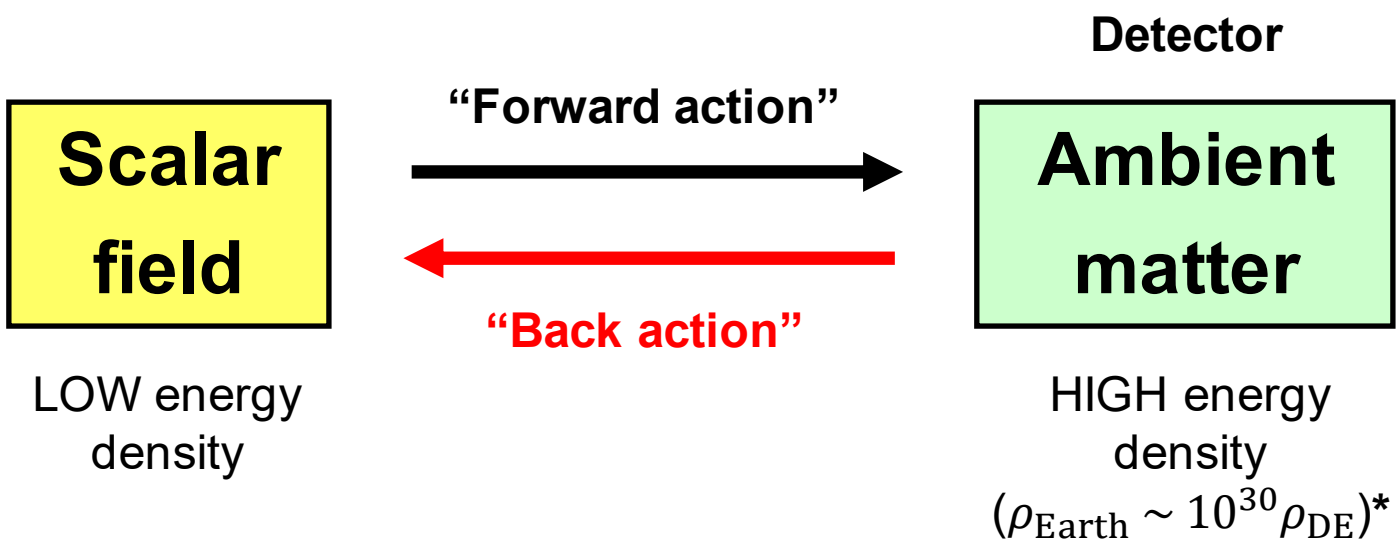
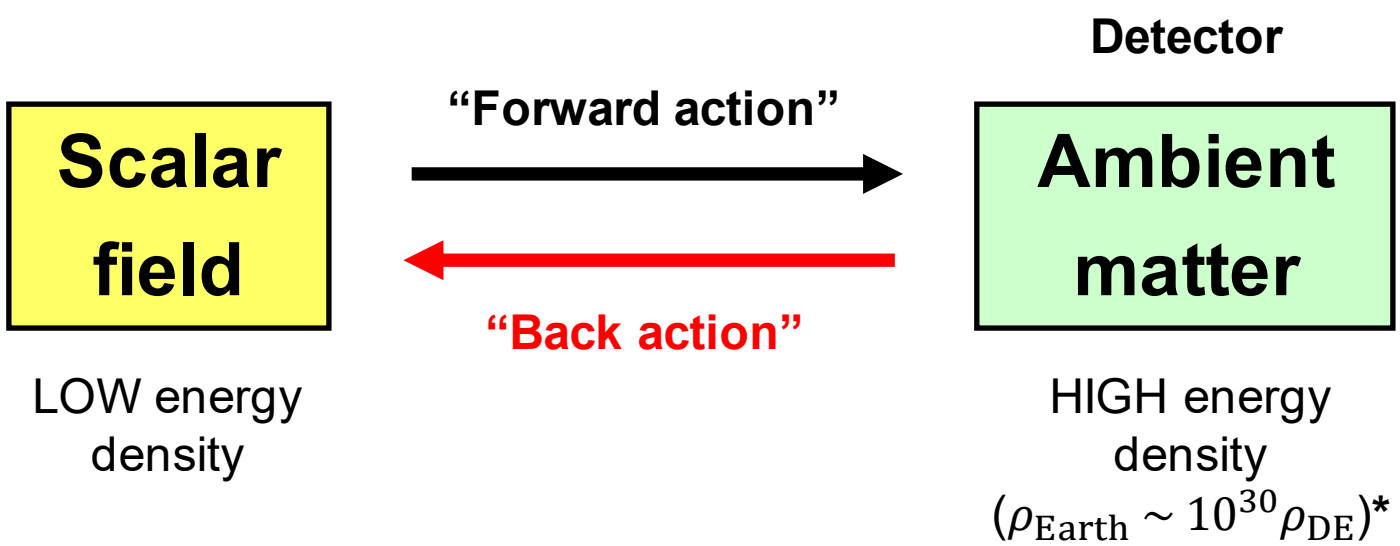


* Cannot necessarily neglect "back action" *even when the interaction strength is feeble*

Variations of Fundamental Constants

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

- Previous work overlooked **"back-action" effects** of ambient matter on the domain-wall scalar field with φ^2 interactions
- These back-action effects lead to **non-transient** (time-independent) variations of fundamental constants



* Cannot necessarily neglect "back action" *even when the interaction strength is feeble*

Variations of Fundamental Constants

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

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Non-relativistic ambient matter

ρ_γ = Coulomb binding energy

ρ_e = electron mass-energy

ρ_N = nucleon mass-energy

Variations of Fundamental Constants

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

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$$\Rightarrow \quad V_{\text{eff}}(\varphi) = V(\varphi) + \sum_{X=\gamma,e,N} \frac{\rho_X \varphi^2}{(\Lambda'_X)^2}$$

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

Environmental Dependence of "Constants"

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

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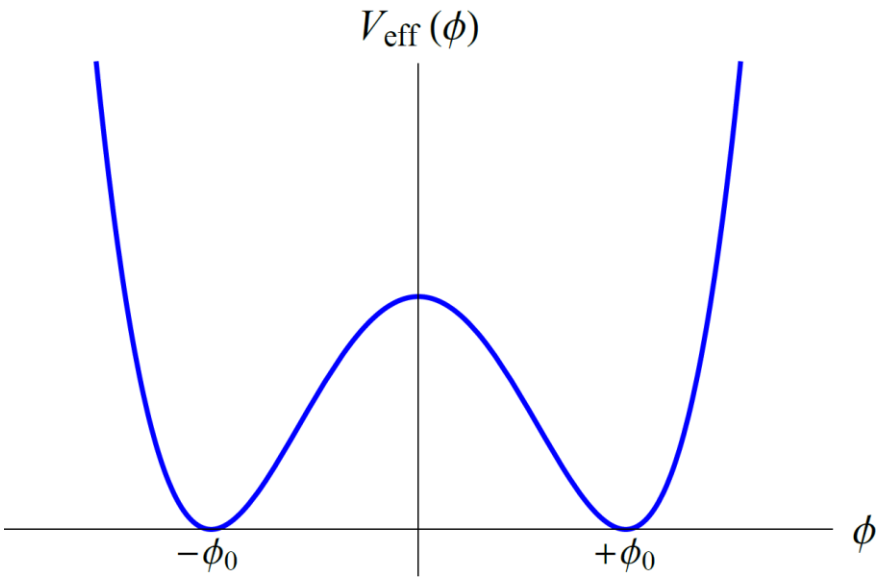

Low-density environment (non-trivial topology, *supports* domain walls)

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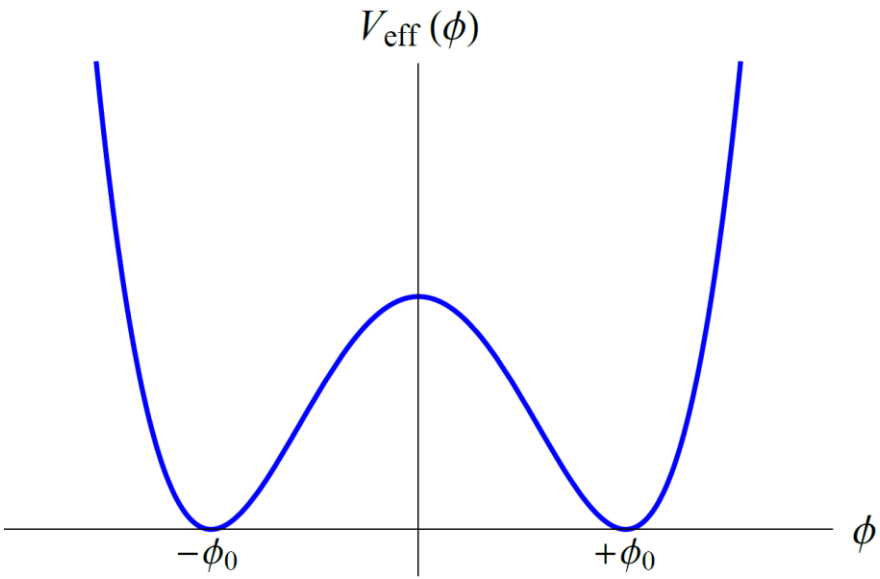

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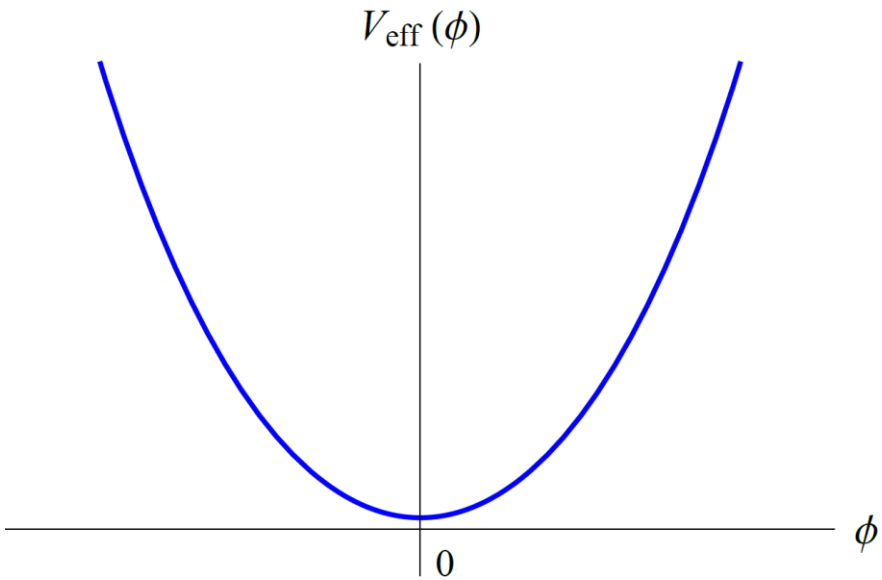

High-density environment (trivial topology, *destabilises* domain walls)

Environmental Dependence of "Constants"

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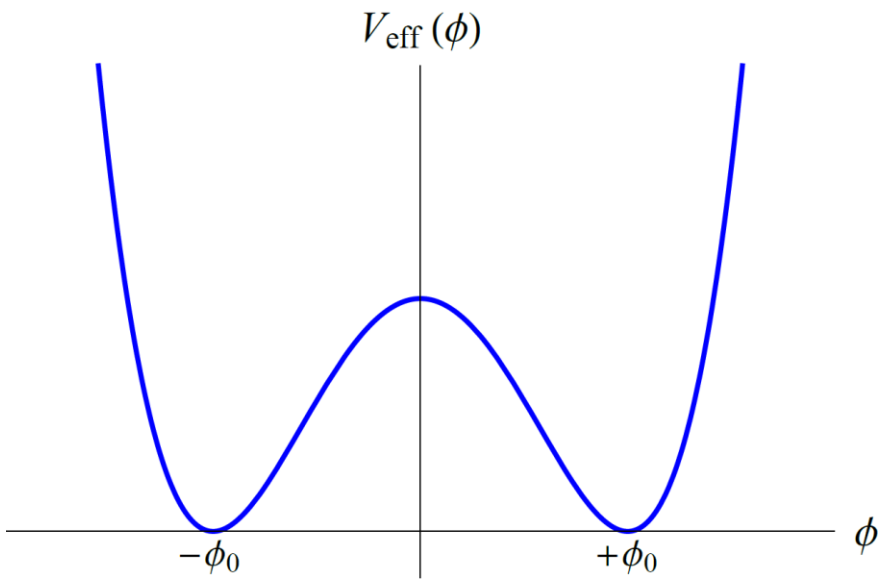

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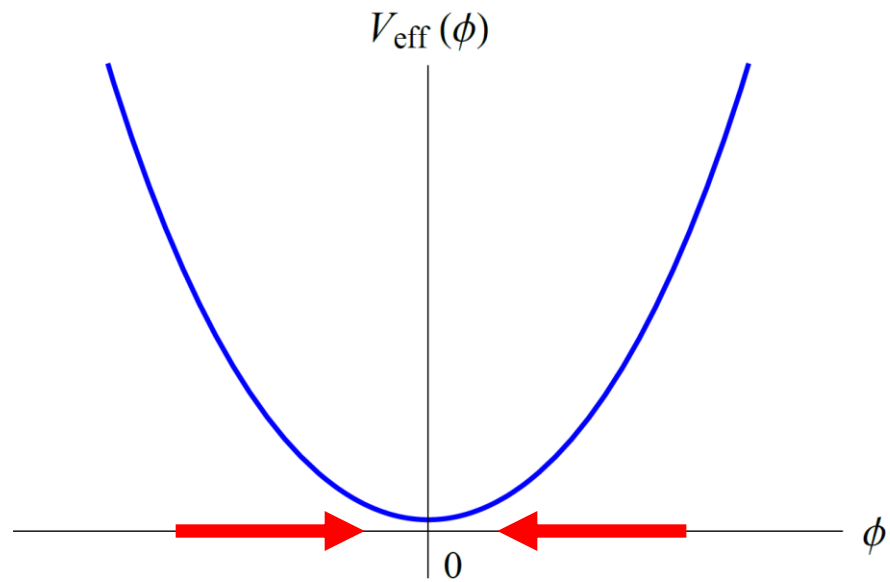

High-density environment

- Scalar field φ tends to be screened in dense environments

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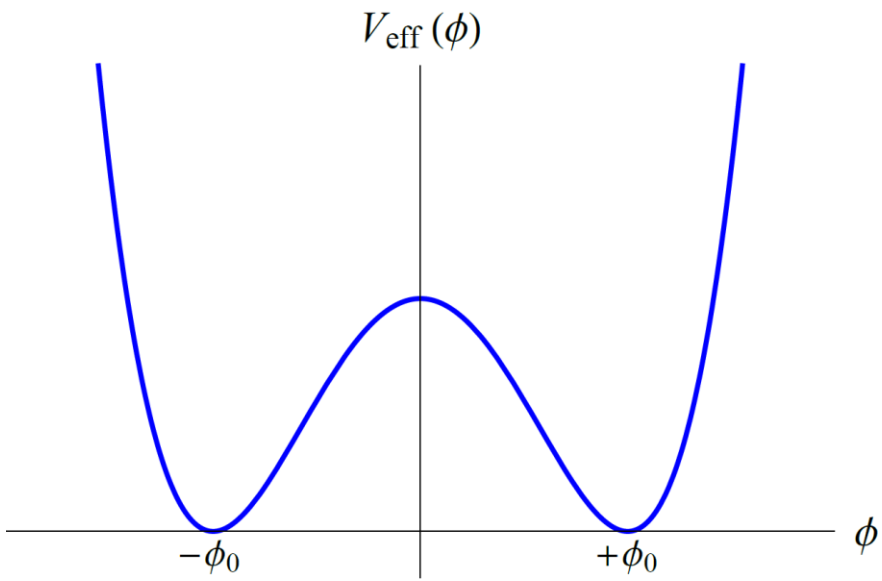

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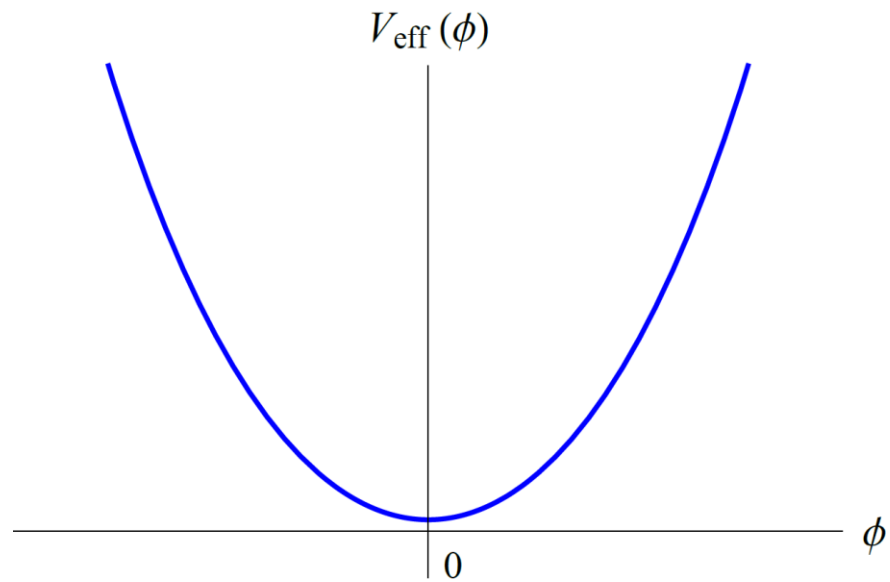
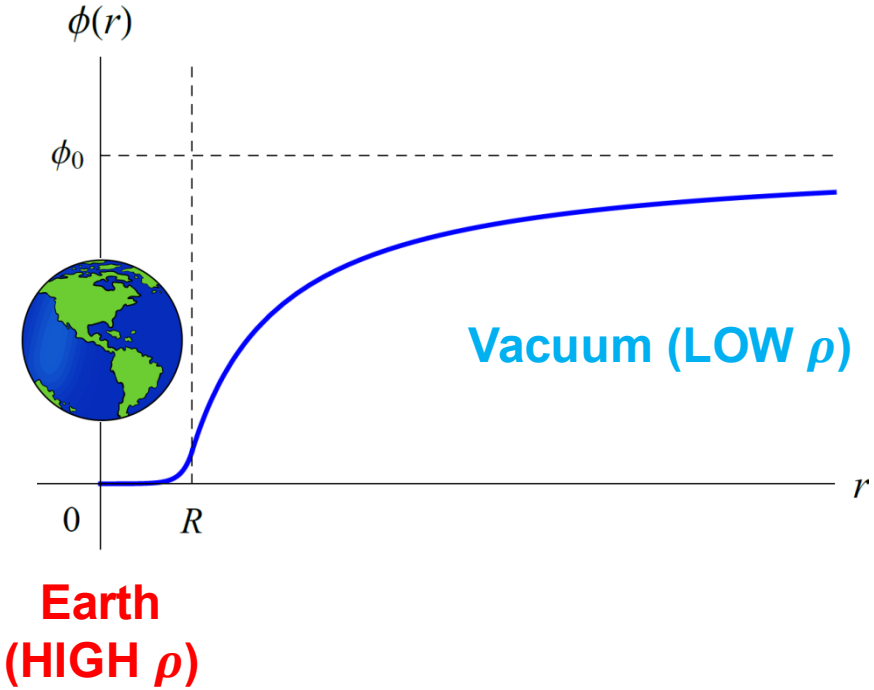


High-density environment

- Scalar field φ tends to be screened in dense environments
- $\alpha(\rho), m_f(\rho)$ $\Rightarrow$ **Environmental dependence of "constants"**

Spatial Variations of "Constants"

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



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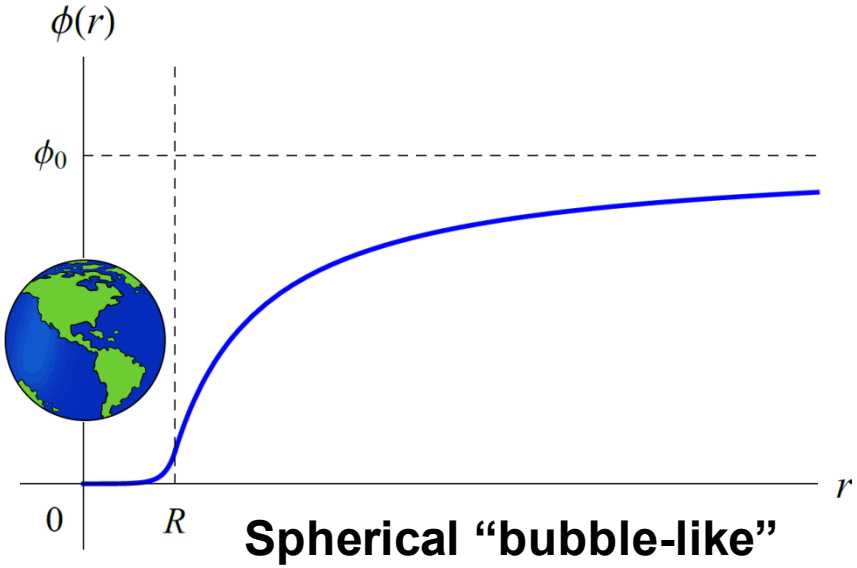
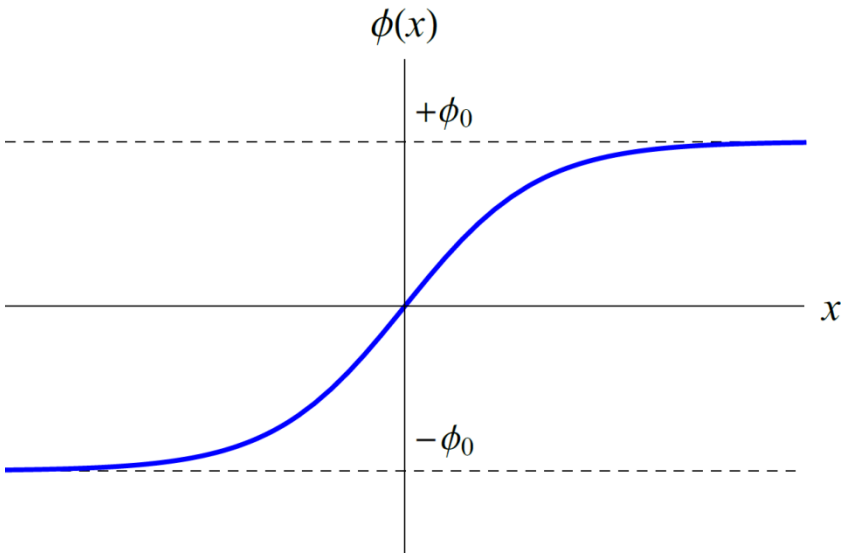


Spherical "bubble-like" defect around Earth



Planar defect in free space ("free" domain wall)

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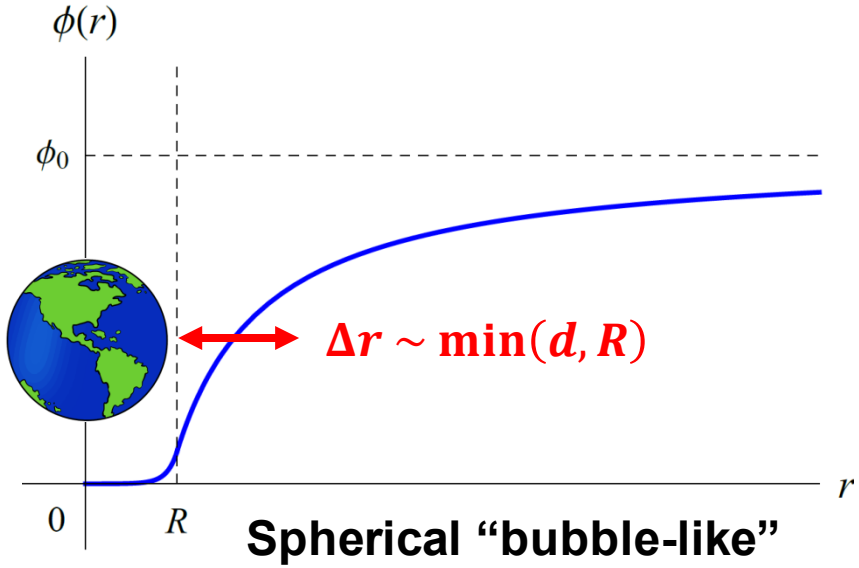

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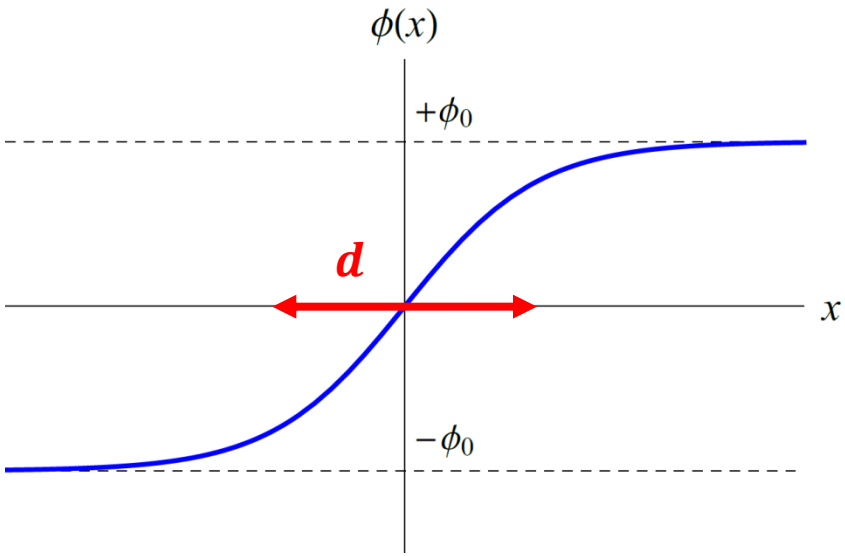

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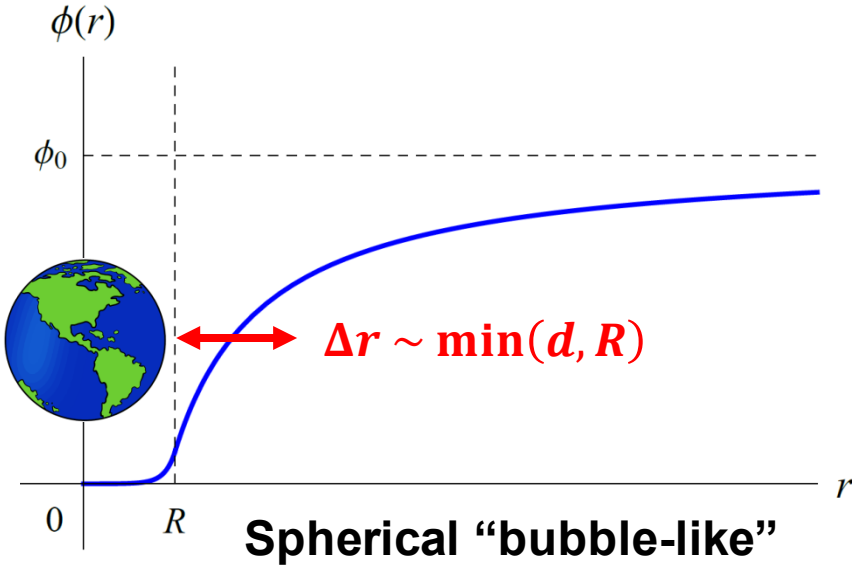

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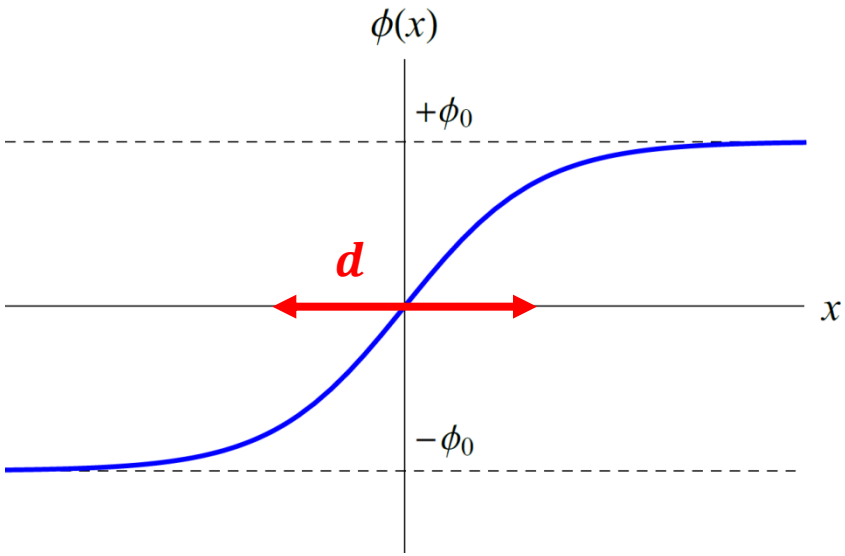

Planar defect in free space ("free" domain wall)

Very generic signatures – present even if Universe consists of only a *single* domain (i.e., when *no* domain walls at all)

Spatial Variations of "Constants"

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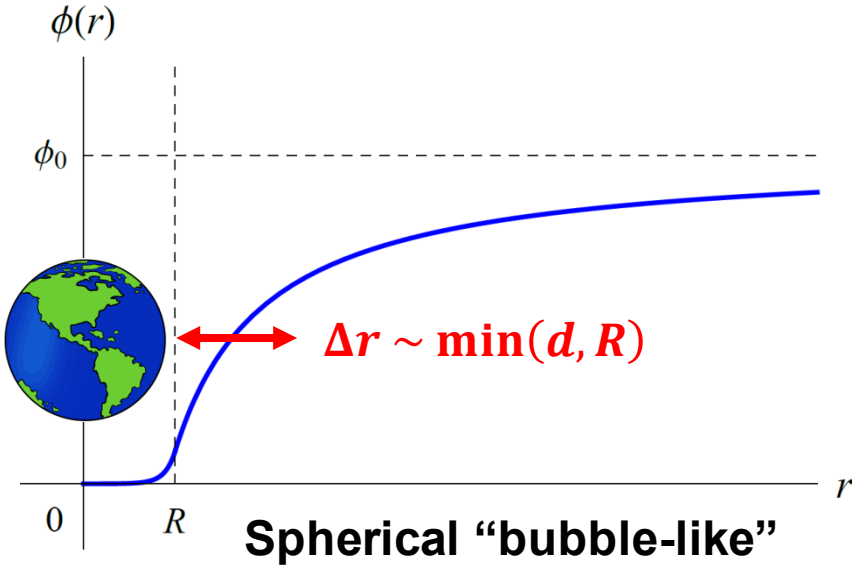

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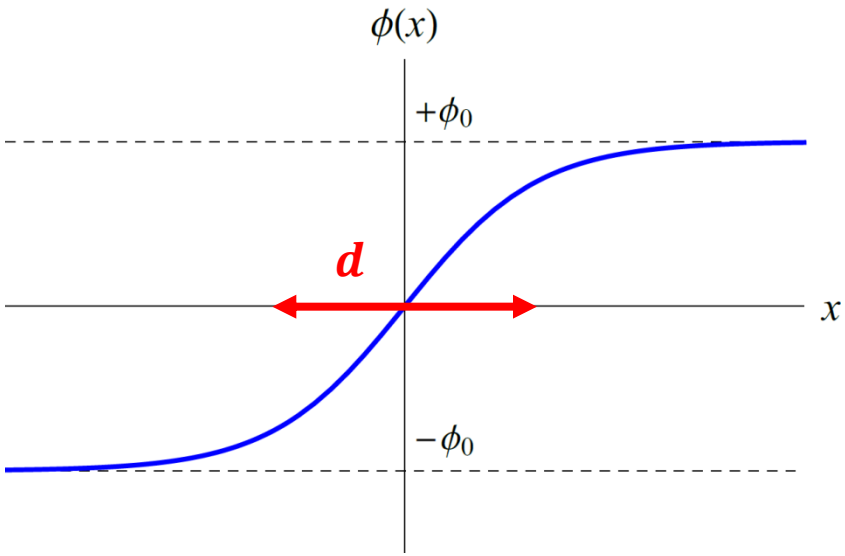

Planar defect in free space ("free" domain wall)

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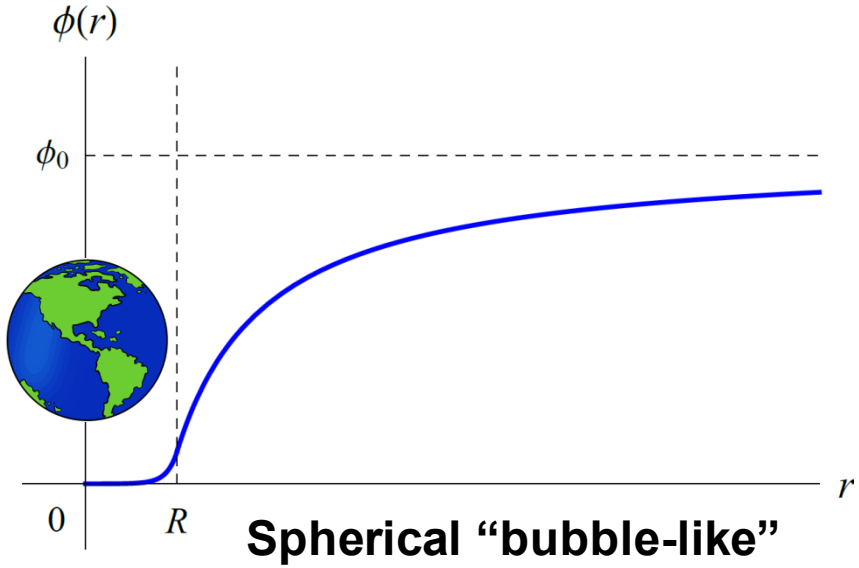
⇒ We don't have to wait for a (possibly single or non-existent) domain wall to pass by Earth!

Spatial Variations of "Constants"

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



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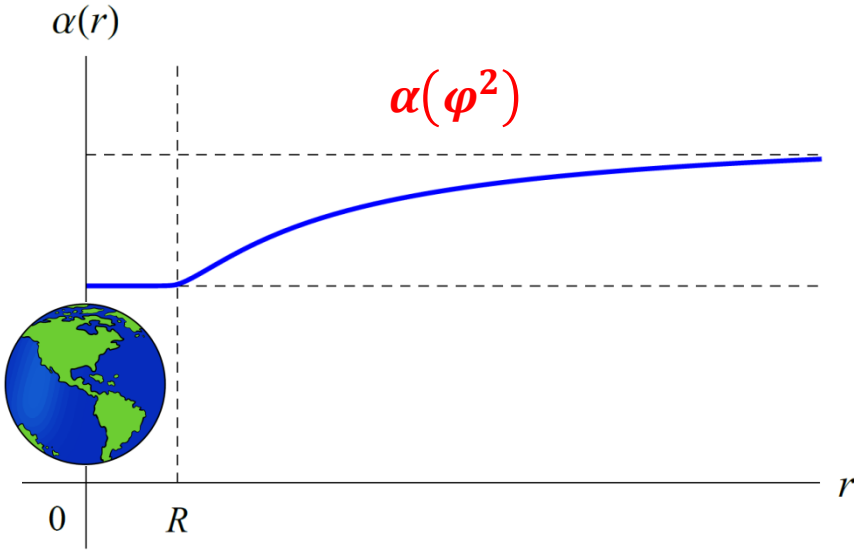

- **Spatial gradients of "constants"** arise around a dense body

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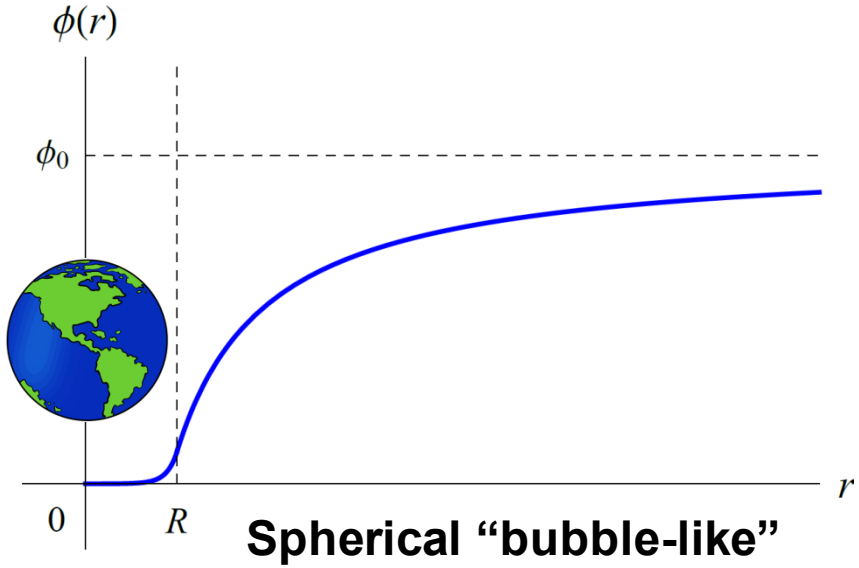

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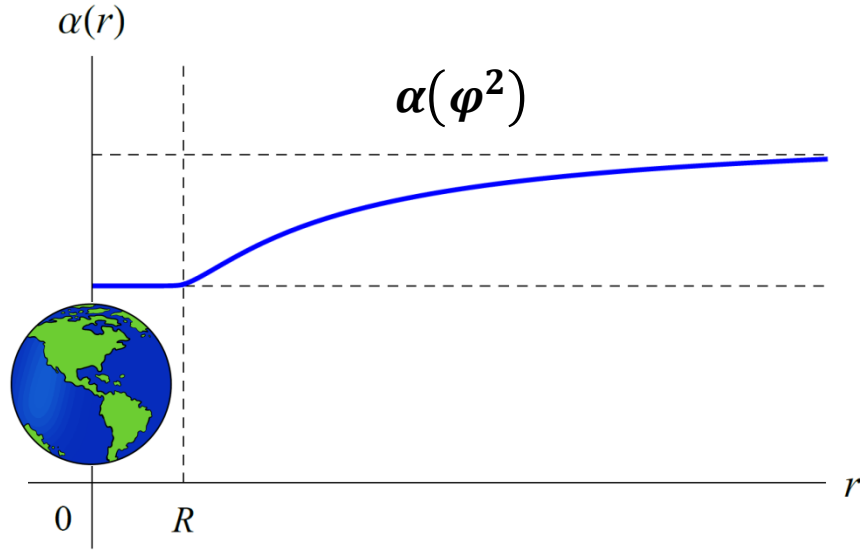

- **Spatial gradients of "constants"** arise around a dense body
- Can search for these spatial gradients (e.g., $\boldsymbol{\nabla}\,\alpha/\alpha$) with:
  1. Equivalence-principle-violating forces: $\delta\boldsymbol{a}_{\rm test} = -\boldsymbol{\nabla}\,[m_{\rm test}(\alpha)]/m_{\rm test}$
  2.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

Spatial Variations of "Constants"

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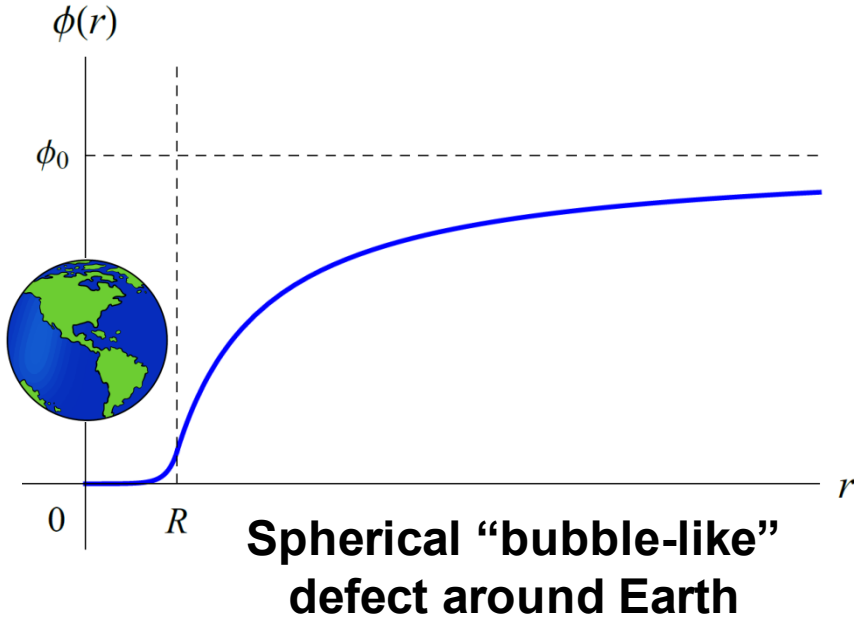

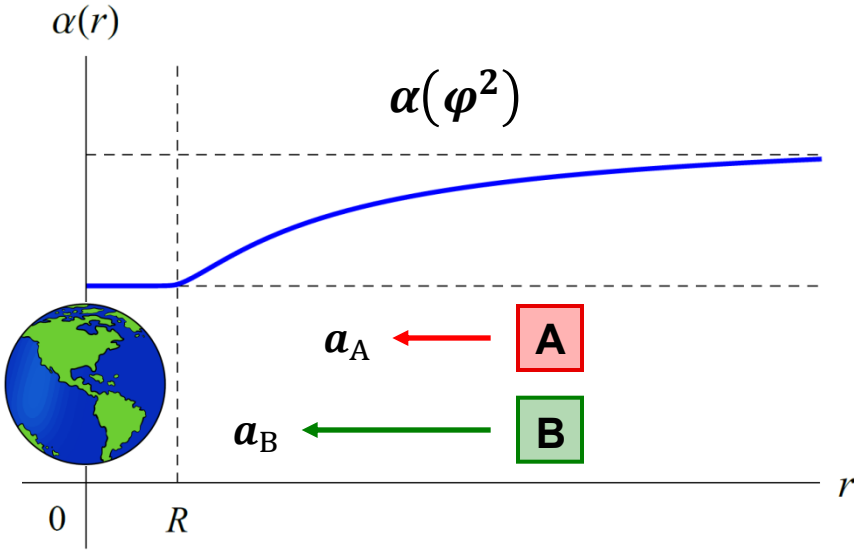

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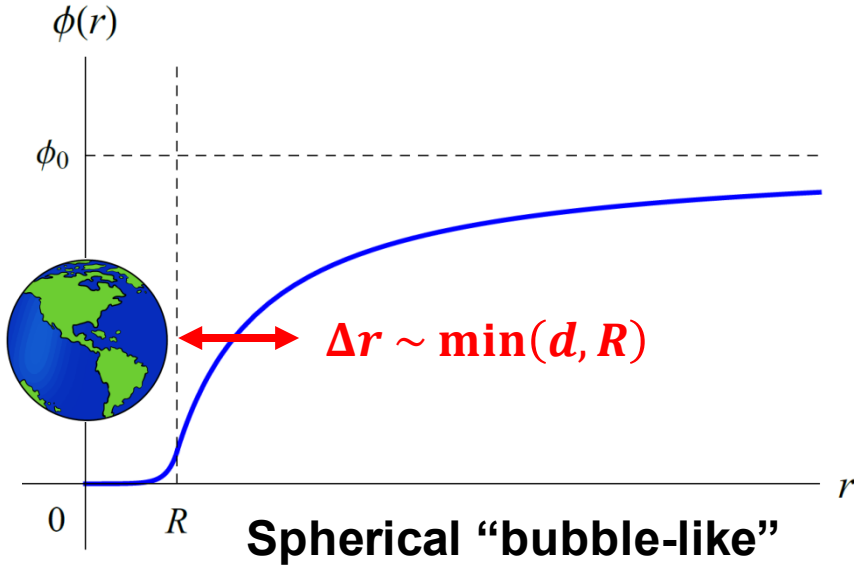

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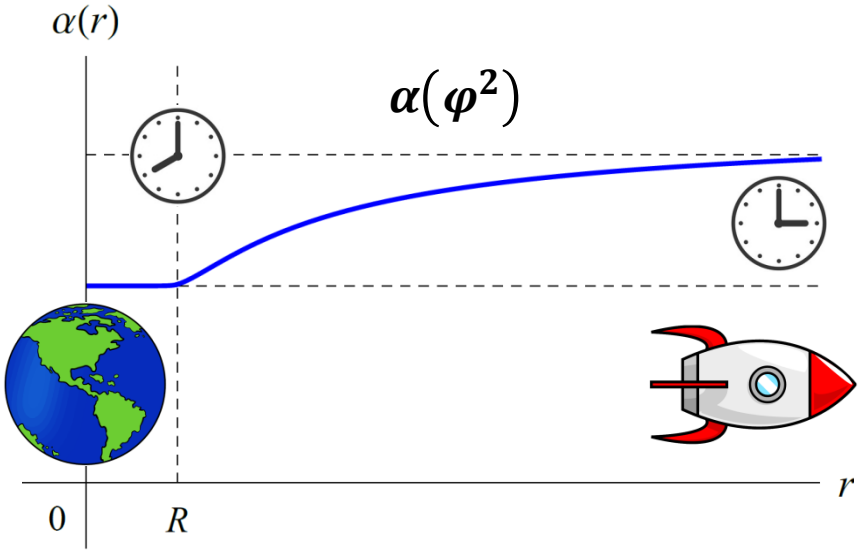

In space $(\Delta h \sim 10^4\ \mathrm{km})$

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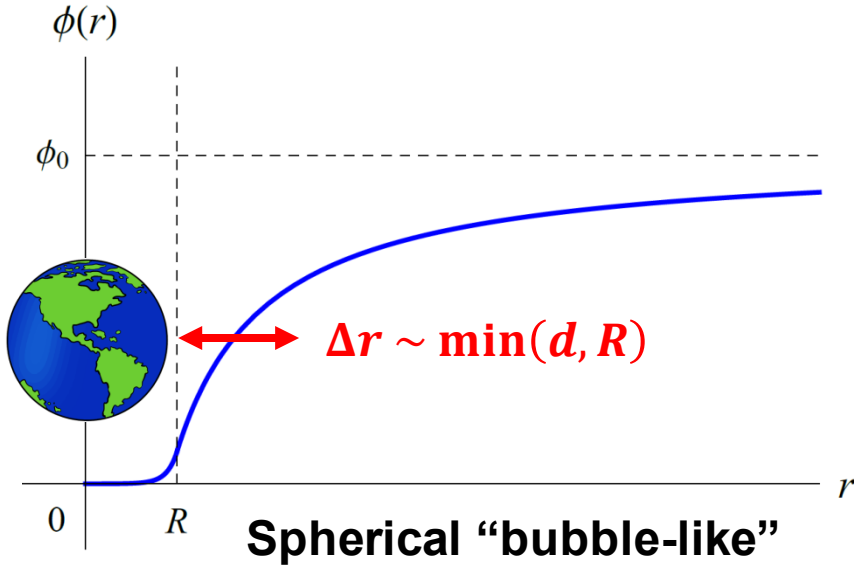

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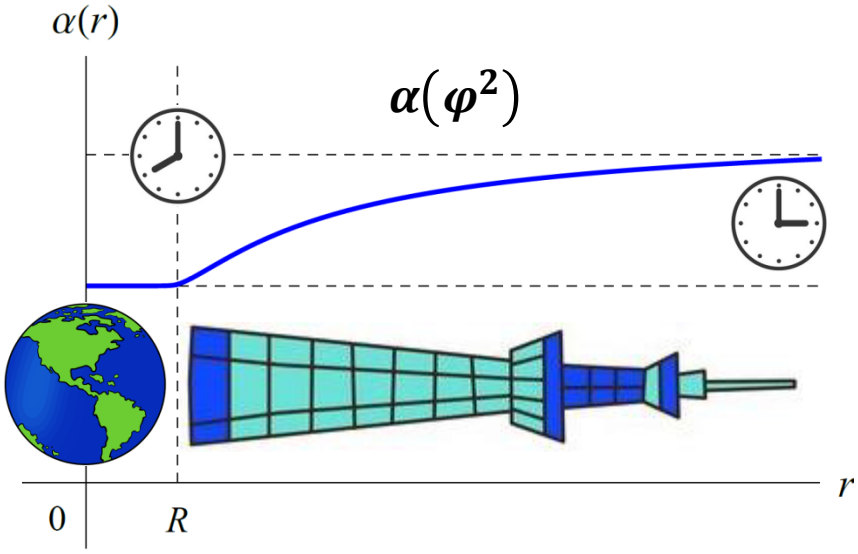

TOKYO SKYTREE ($\Delta h \sim 0.5\,\mathrm{km}$)

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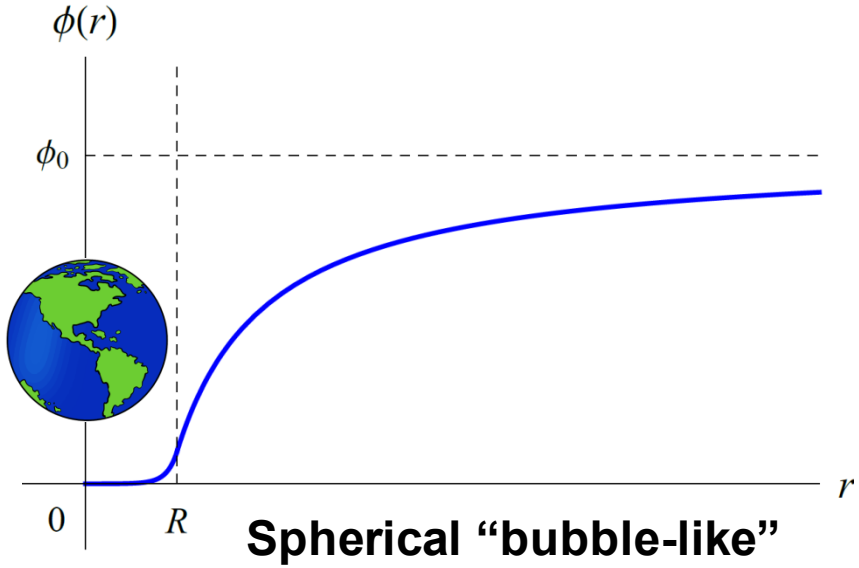

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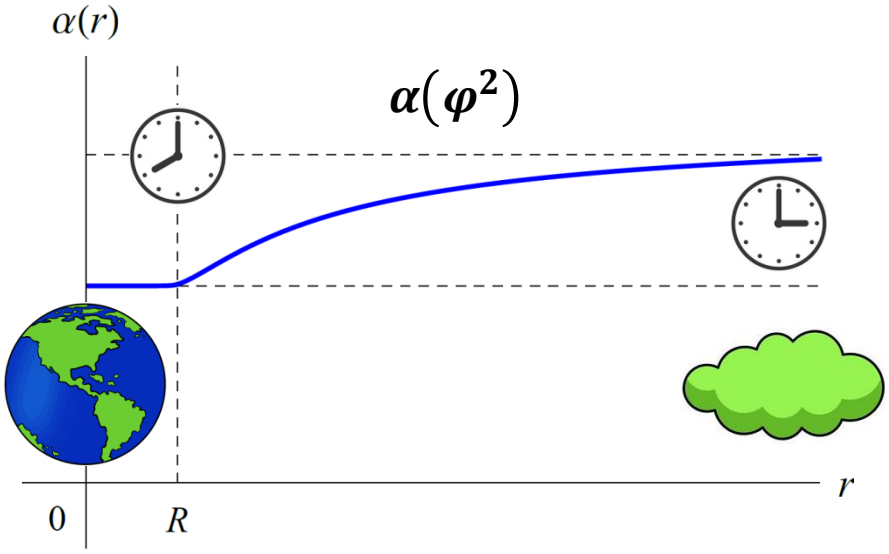

Distant gas clouds

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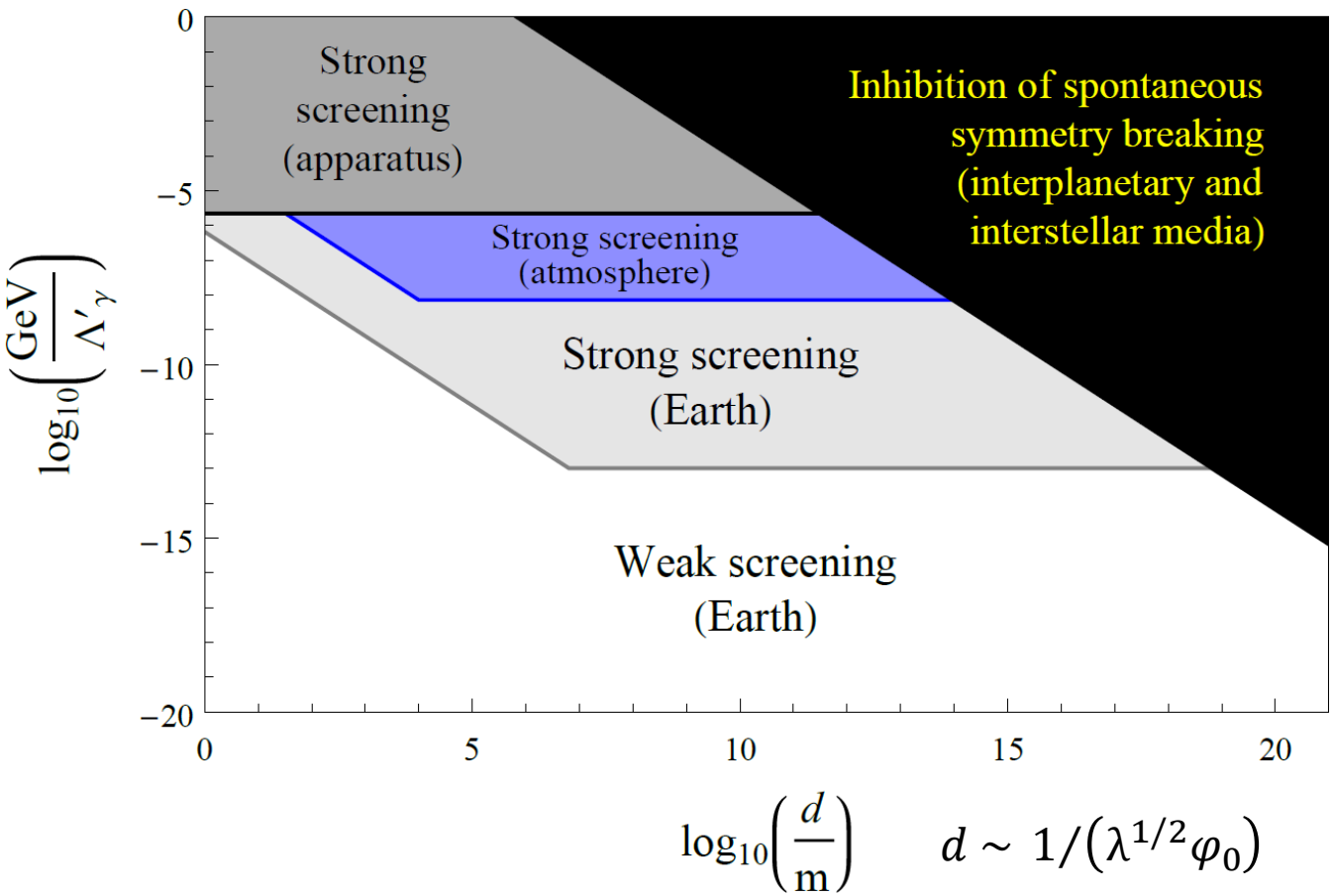
Screening of Scalar Field φ

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

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



$d \sim 1/(\lambda^{1/2}\varphi_0)$

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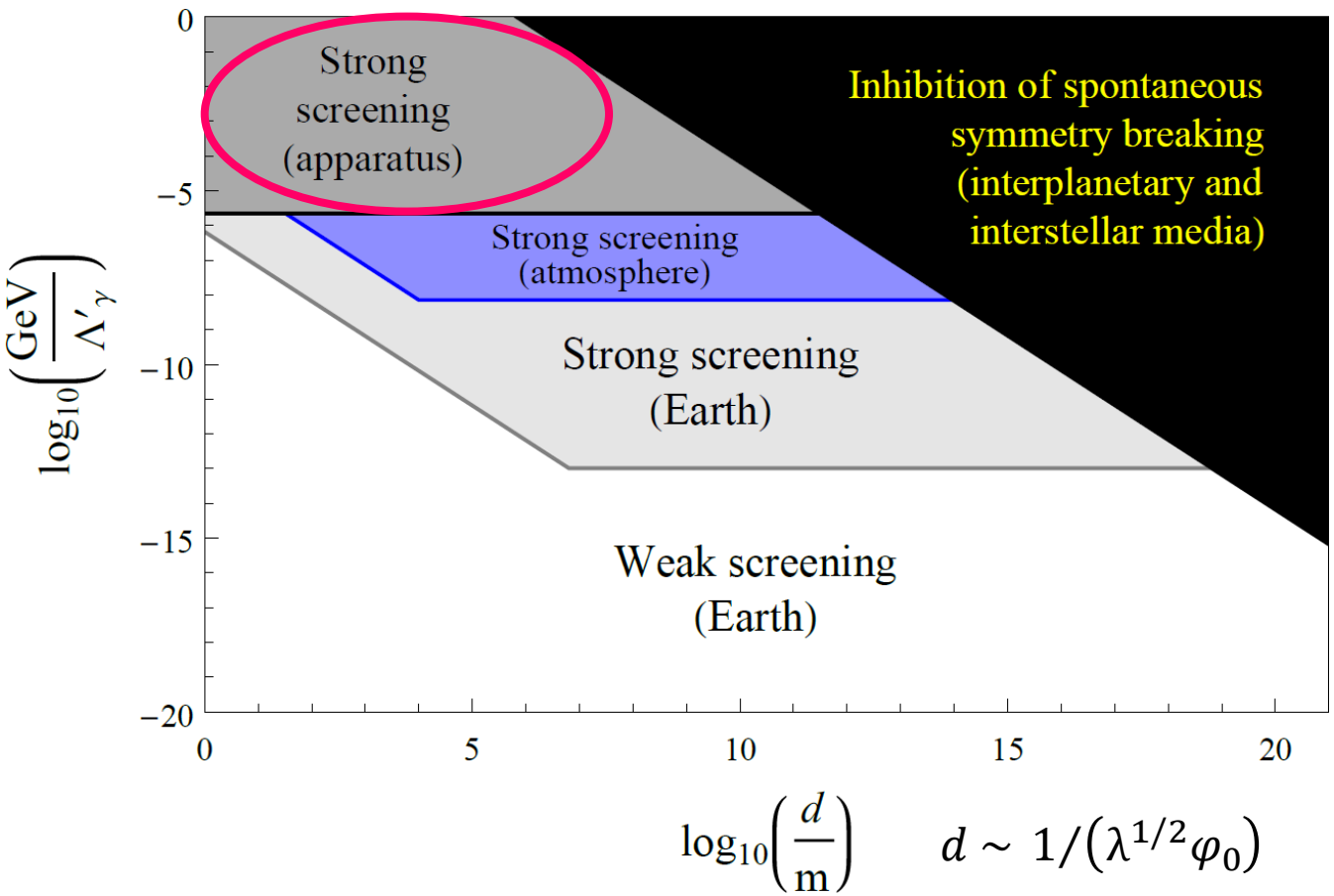

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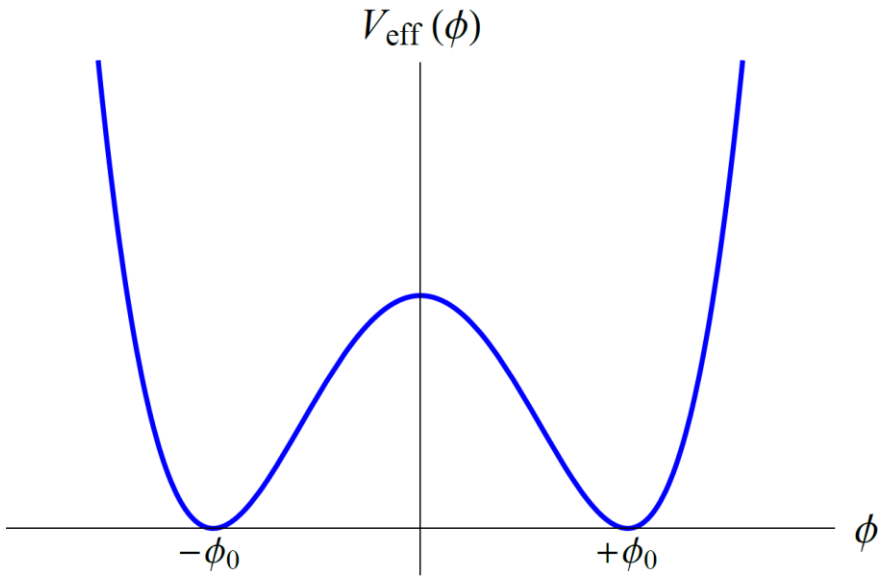
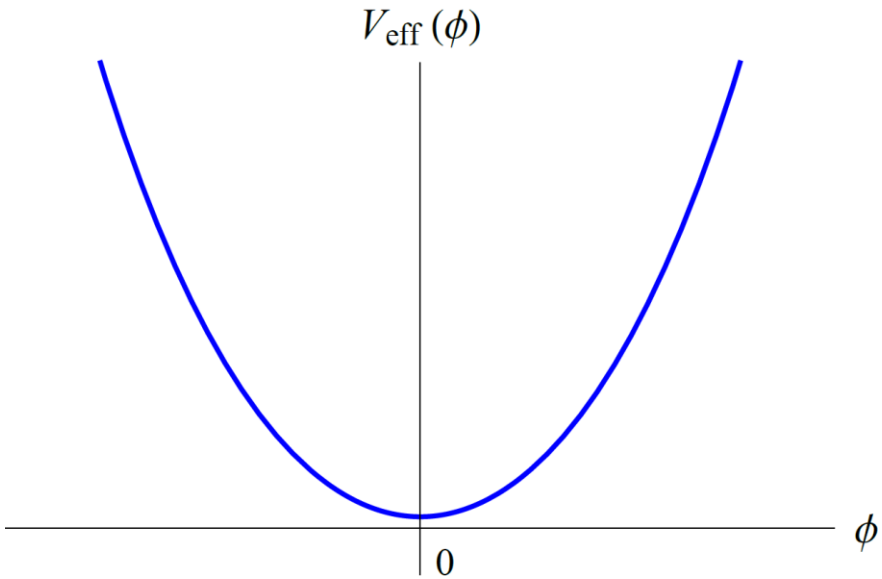
Cosmological Production of Domain Walls

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



Low-density environment
("late" Universe)



High-density environment
("early" Universe)

- As Universe cools, distant regions tend to settle in different vacua/minima – expect $\sim\mathcal{O}(1)$ domain wall to survive to present day

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

Cosmological Production of Domain Walls

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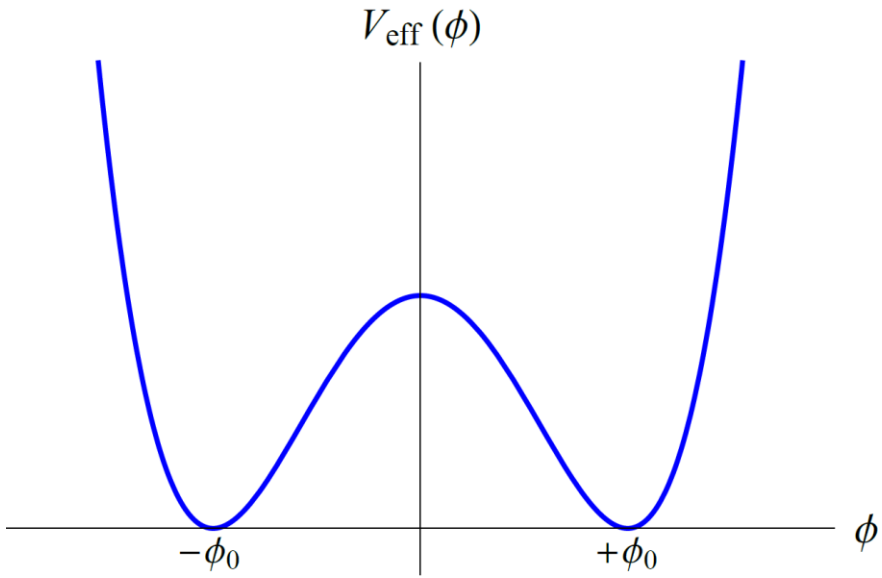

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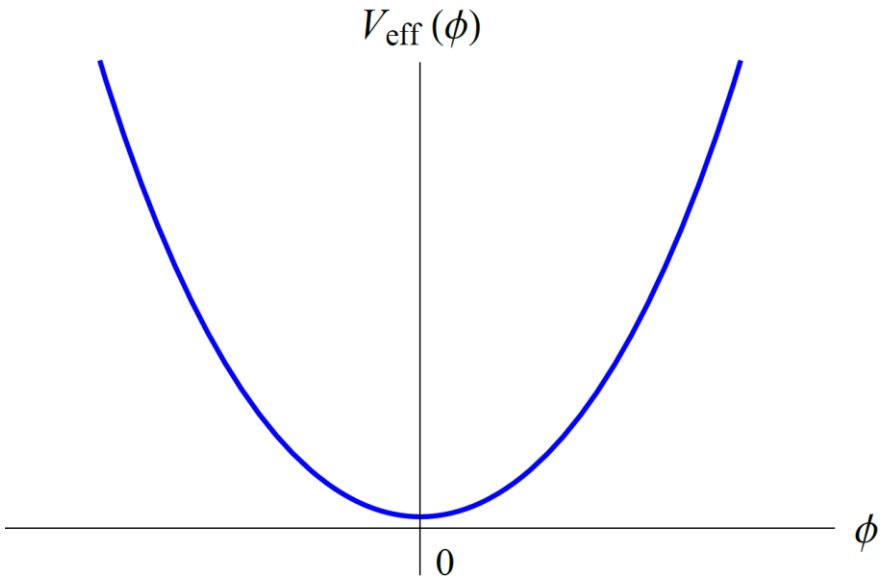


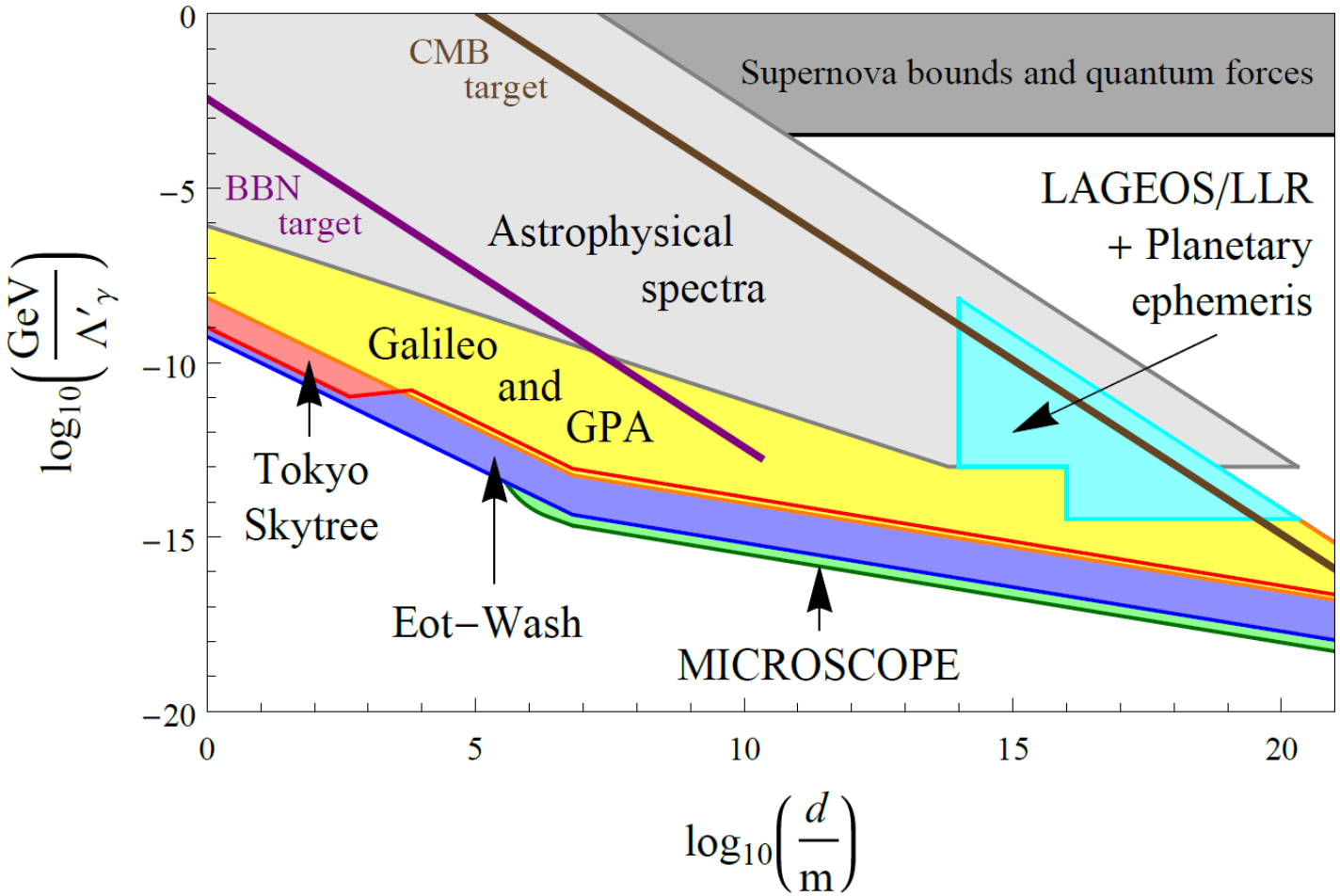
High-density environment
("early" Universe)

- As Universe cools, distant regions tend to settle in different vacua/minima – expect $\sim\mathcal{O}(1)$ domain wall to survive to present day
- Even if only 1 wall stretching across the Universe survives, gravitational effects of wall(s) on CMB constrain $\rho_{\rm wall(s)} < 10^{-5}\rho_{\rm total}$

Constraints on φ^2 Interaction with the Photon [Single wall, $\rho_{\text{wall}} \sim 10^{-5}\rho_{\text{total}}$]

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

Leading new limits scale as $\propto \rho_{\text{wall}}^{1/4}$ $\Rightarrow$ Constrain $\rho_{\text{wall}} \ll 10^{-10}\rho_{\text{total}}$!

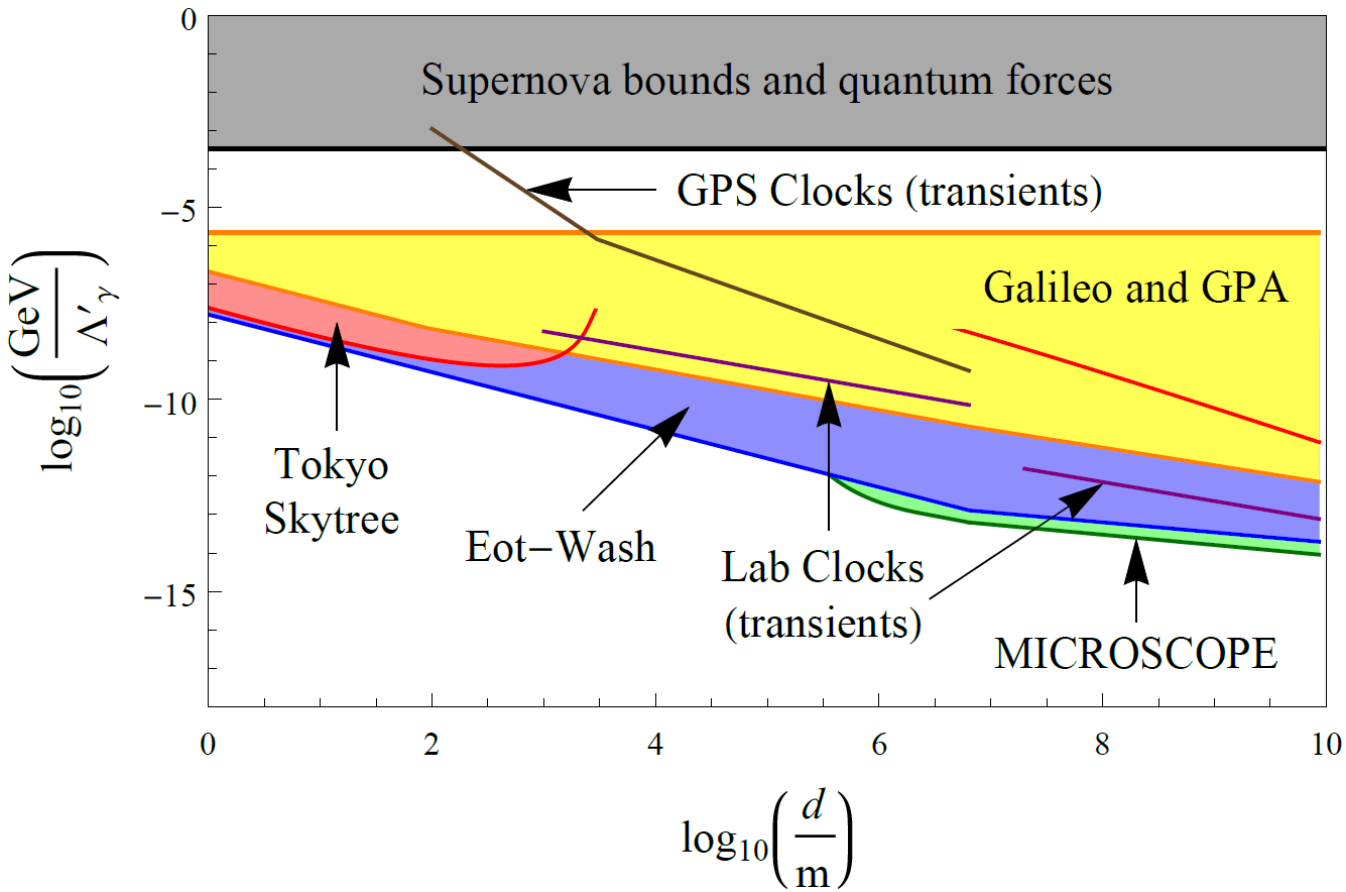


Constraints on φ^2 Interaction with the Photon

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

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

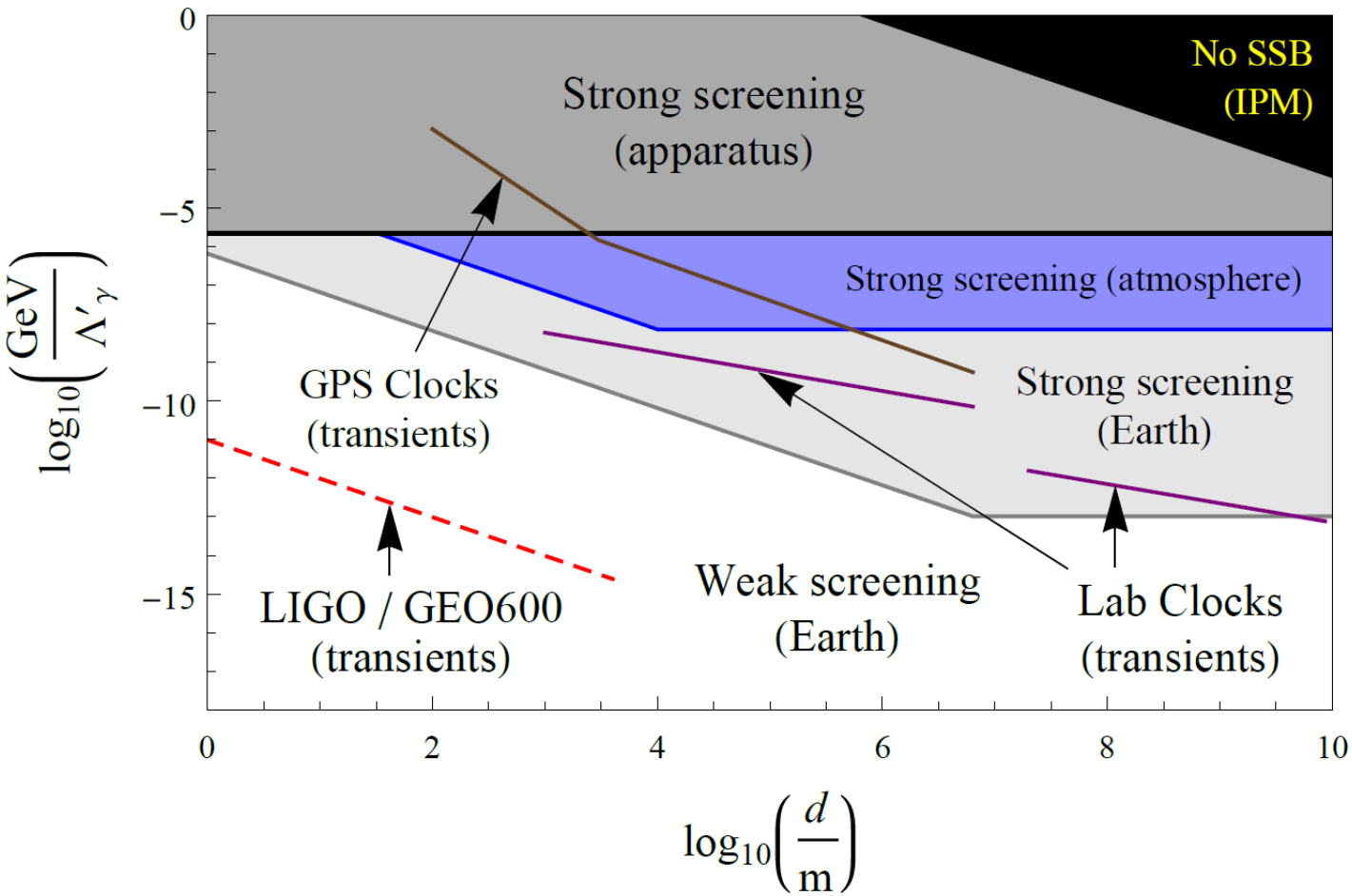
Our new limits from quasi-non-transient effects improve over transient signatures and over previous bounds from different non-transient signatures (by up to $\sim 10^{10}$)!



Scrutinising Bounds from Transient Signatures

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

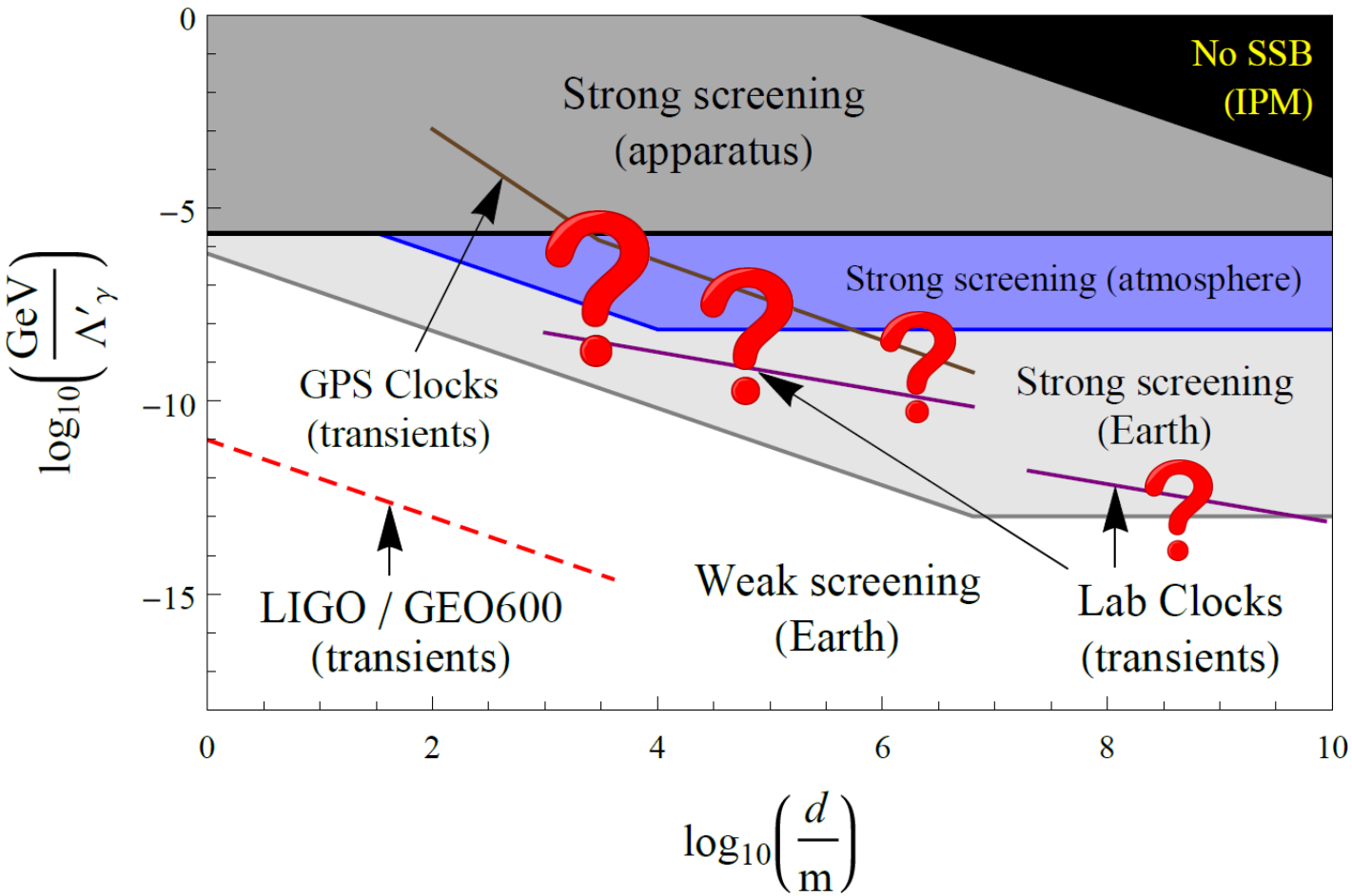
Strongly repulsive potential generated by Earth likely **prevents the unperturbed passage of a domain wall through Earth** – contrary to earlier assumptions



Scrutinising Bounds from Transient Signatures

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

Strongly repulsive potential generated by Earth likely **prevents the unperturbed passage of a domain wall through Earth** – contrary to earlier assumptions



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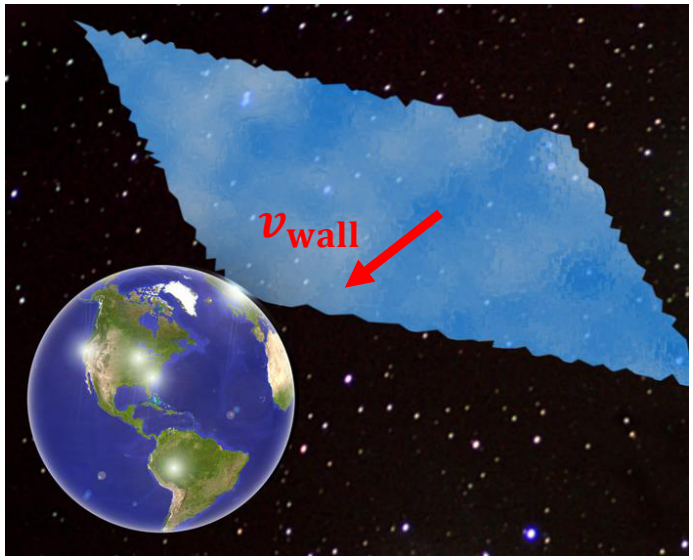

Domain wall incident on Earth

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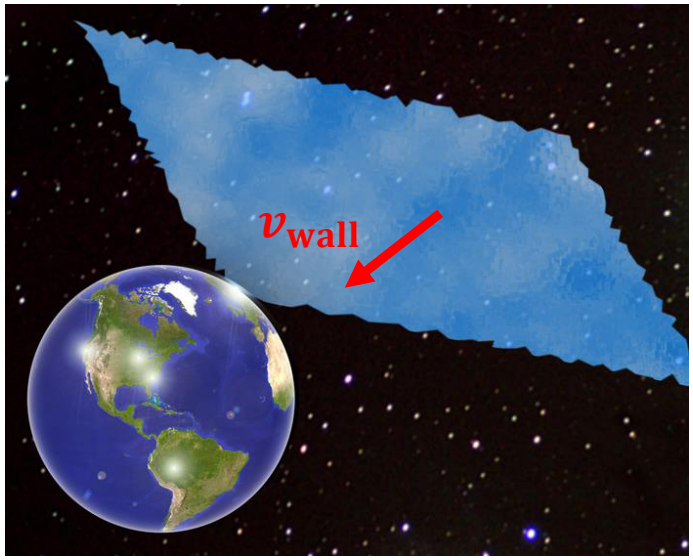
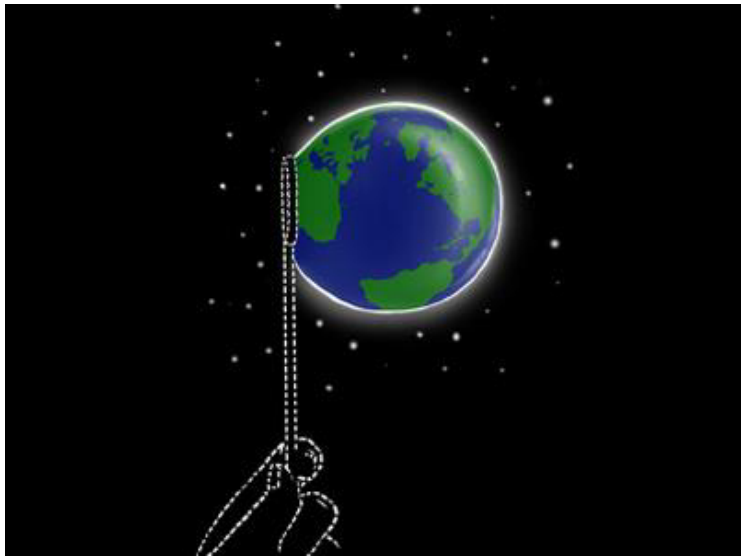


Domain wall incident on Earth



(Meta)stable bubble around Earth?

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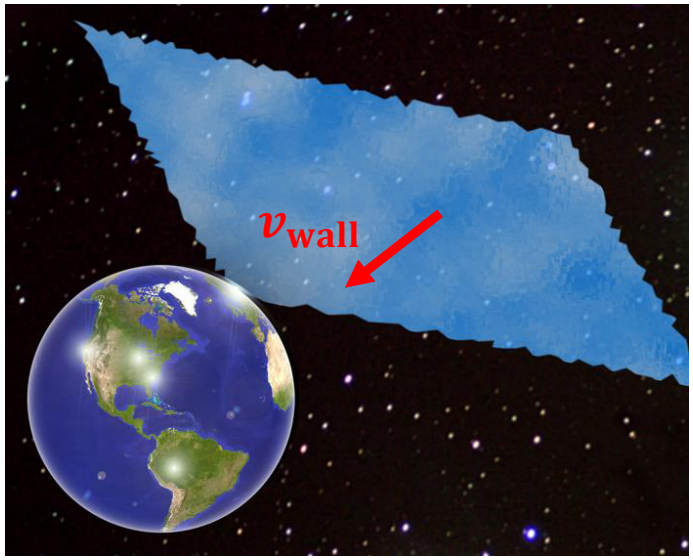

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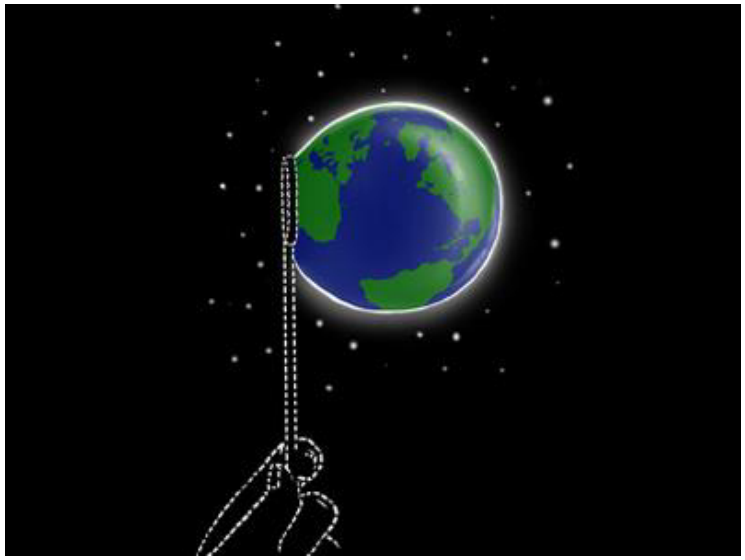

(Meta)stable bubble around Earth?

Transient signatures may be qualitatively different from those assumed previously – ongoing work

Summary

- Varying fundamental “constants” arise in models of scalar-field ultra-low-mass dark matter and scalar-field macroscopic topological defects
- Using existing datasets, we have improved limits on dark matter and domain walls by up to **15 orders of magnitude** compared with previous bounds
- Utilised novel approaches based on precision low-energy experiments (often table-top scale), including: spectroscopy (clocks), torsion pendula, optical cavities and interferometry

Back-Up Slides

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)]

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

$$\mathcal{L}_f = -\frac{\varphi}{\Lambda_f}m_f\bar{f}f \approx -\frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}m_f\bar{f}f \quad \Rightarrow \quad \frac{\delta m_f}{m_f} \approx \frac{\varphi_0\cos(m_\varphi t)}{\Lambda_f}$$

$$\varphi = \varphi_0\cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x}) \quad \Rightarrow \quad \boldsymbol{F} \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$$

$$\left.\begin{aligned} \mathcal{L}'_\gamma &= \frac{\varphi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \\ \mathcal{L}'_f &= -\frac{\varphi^2}{(\Lambda'_f)^2}m_f\bar{f}f \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} &\frac{\delta\alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \Delta\rho_\varphi \\ &\boldsymbol{F} \propto \boldsymbol{\nabla}\rho_\varphi \end{aligned}\right.$$

Dark-Matter-Induced Cosmological Evolution of the Fundamental Constants

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

Consider *quadratic couplings* of an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad \text{c.f.} \quad \mathcal{L}_f^{\rm SM} = -m_f \bar{f} f \quad => \quad m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2}\right]$$

$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

$$\rho_\phi = \frac{m_\phi^2 \phi_0^2}{2} \quad => \quad \phi_0^2 \propto \rho_\phi$$

Dark-Matter-Induced Cosmological Evolution of the Fundamental Constants

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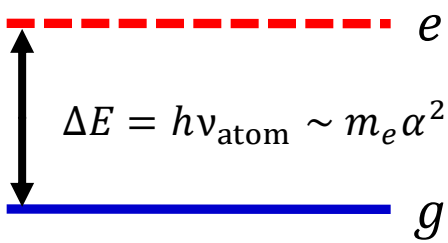
'Slow' drifts [Astrophysics (high $\rho_{\rm DM}$): BBN, CMB]
+ Gradients [Fifth forces]

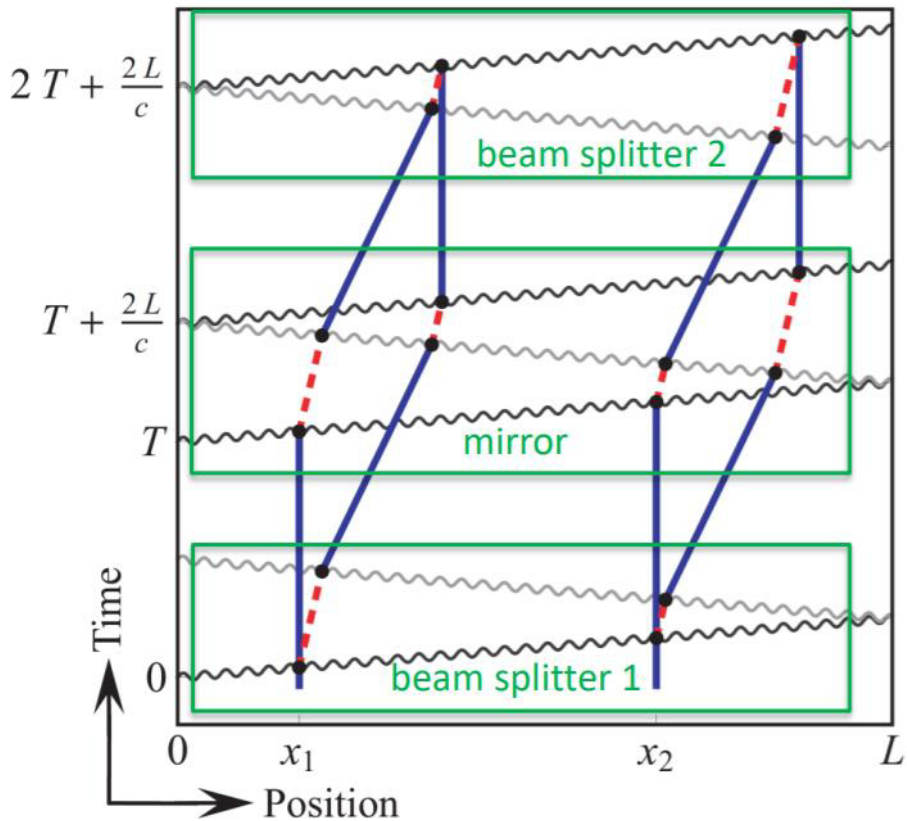
Oscillating variations
[Laboratory (high precision)]

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

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

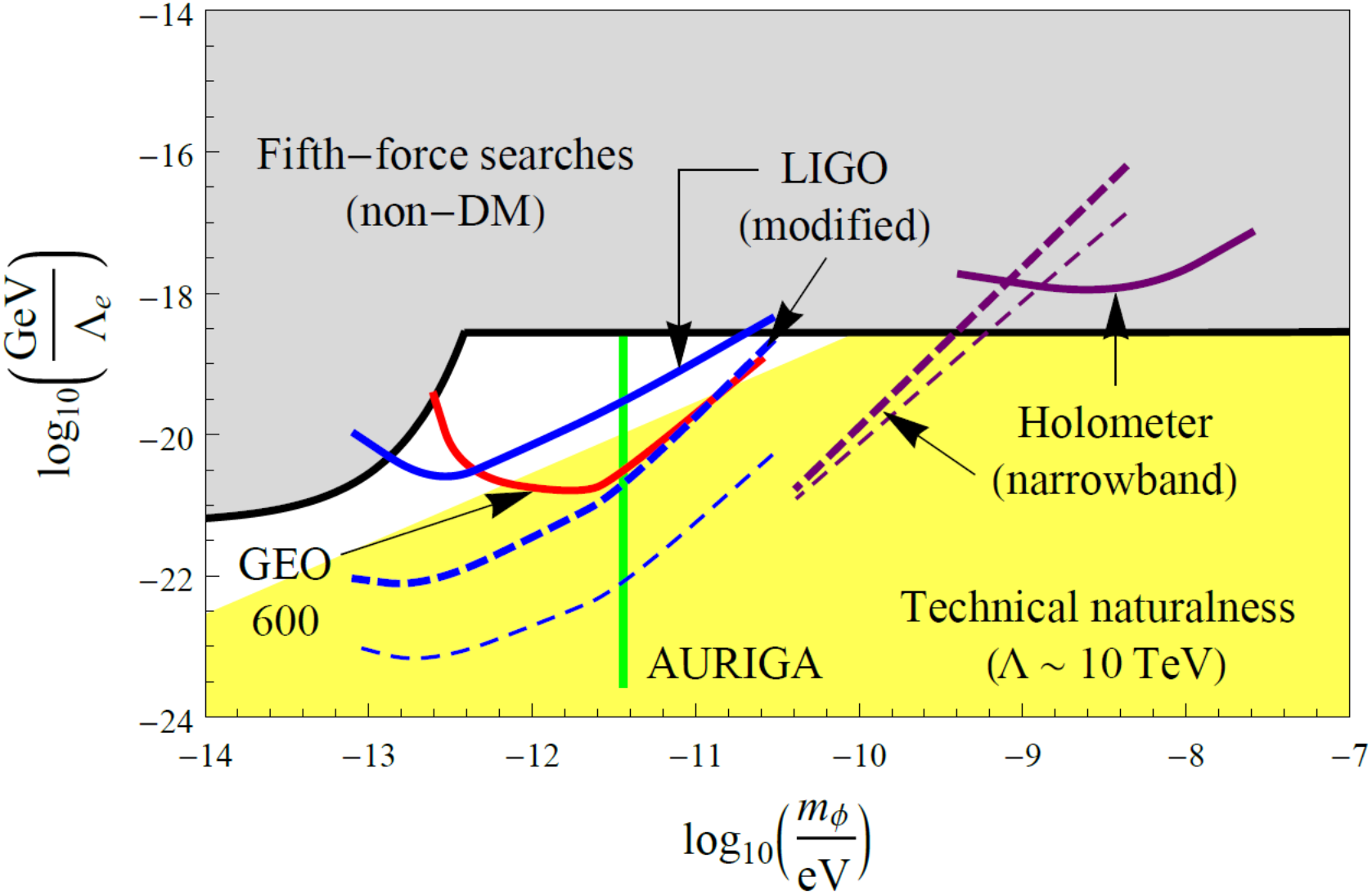
Electronic transition





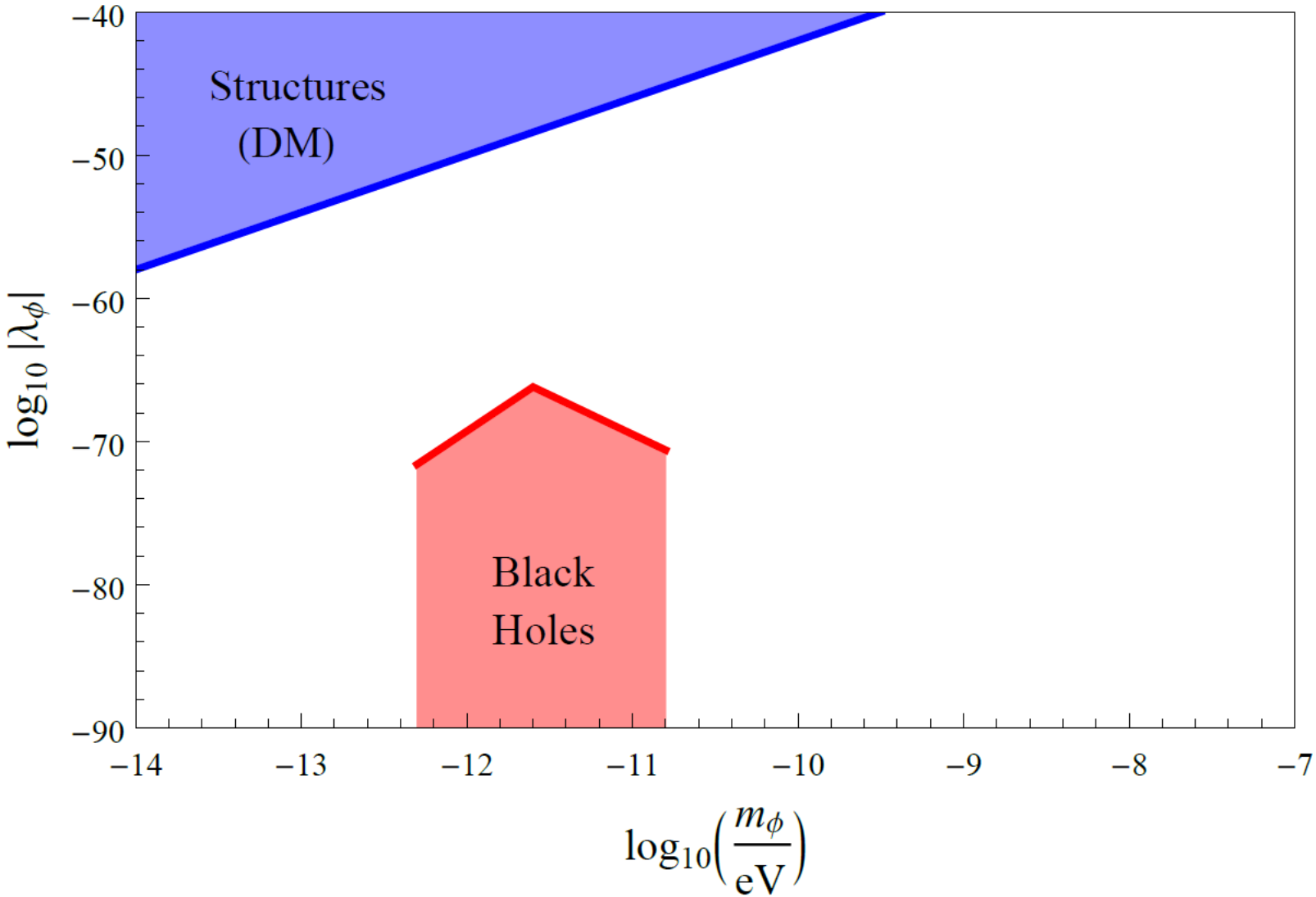
Phase shift between the two separated atom interferometers is maximised when $T_{\text{osc}} \sim 2T$: $\boxed{\delta(\Delta\Phi)_{\text{max}} \sim \delta\nu_{\text{atom}} \cdot T_{\text{osc}}}$

Linear Interaction of Scalar Dark Matter with the Electron



Quartic Self-Interaction of Scalar

[Li, Rindler-Daller, Shapiro, *PRD* **89**, 083536 (2014)], [Arvanitaki, Baryakhtar, Huang, *PRD* **91**, 084011 (2015)]

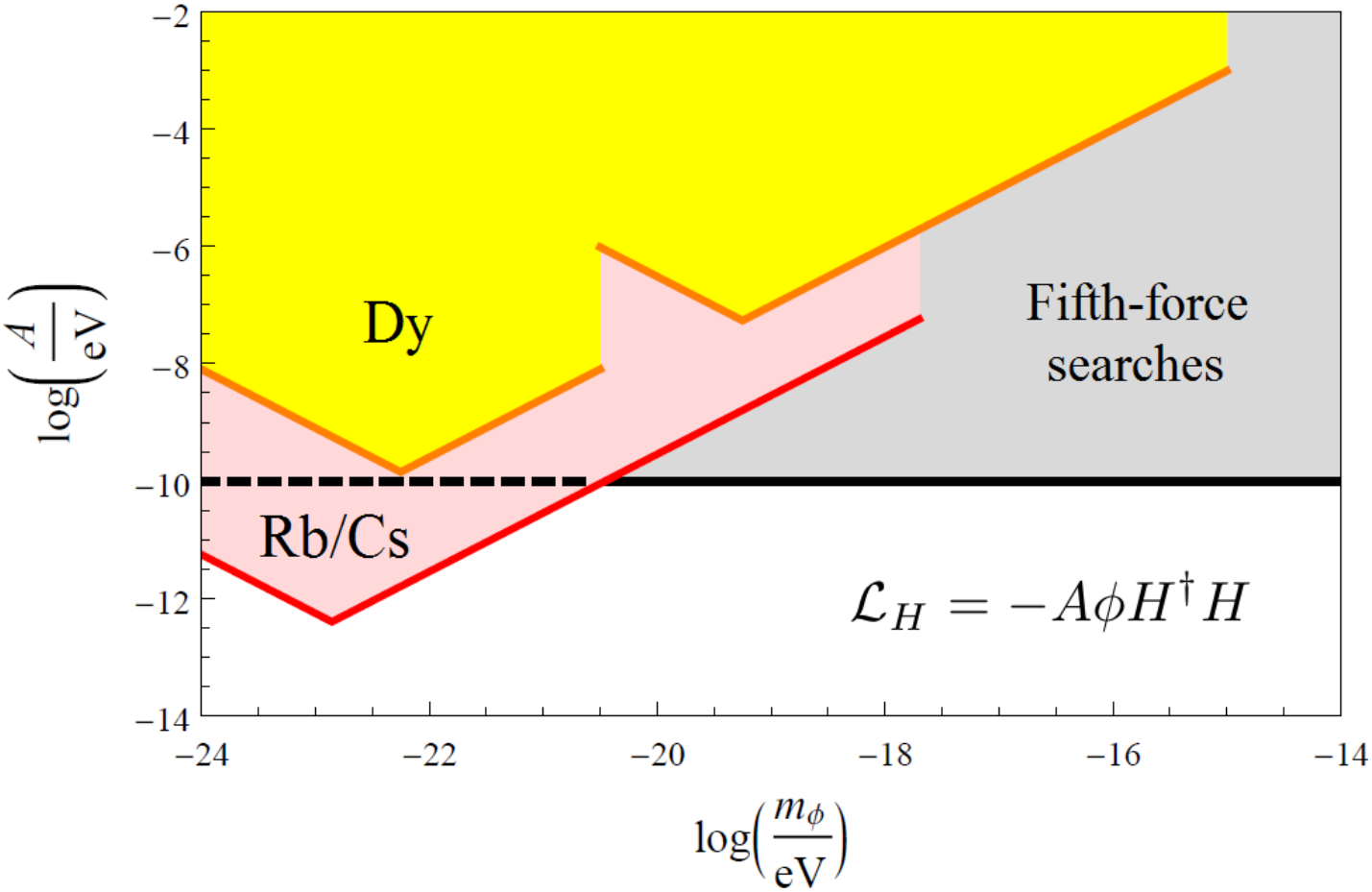


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

[Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!



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)

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

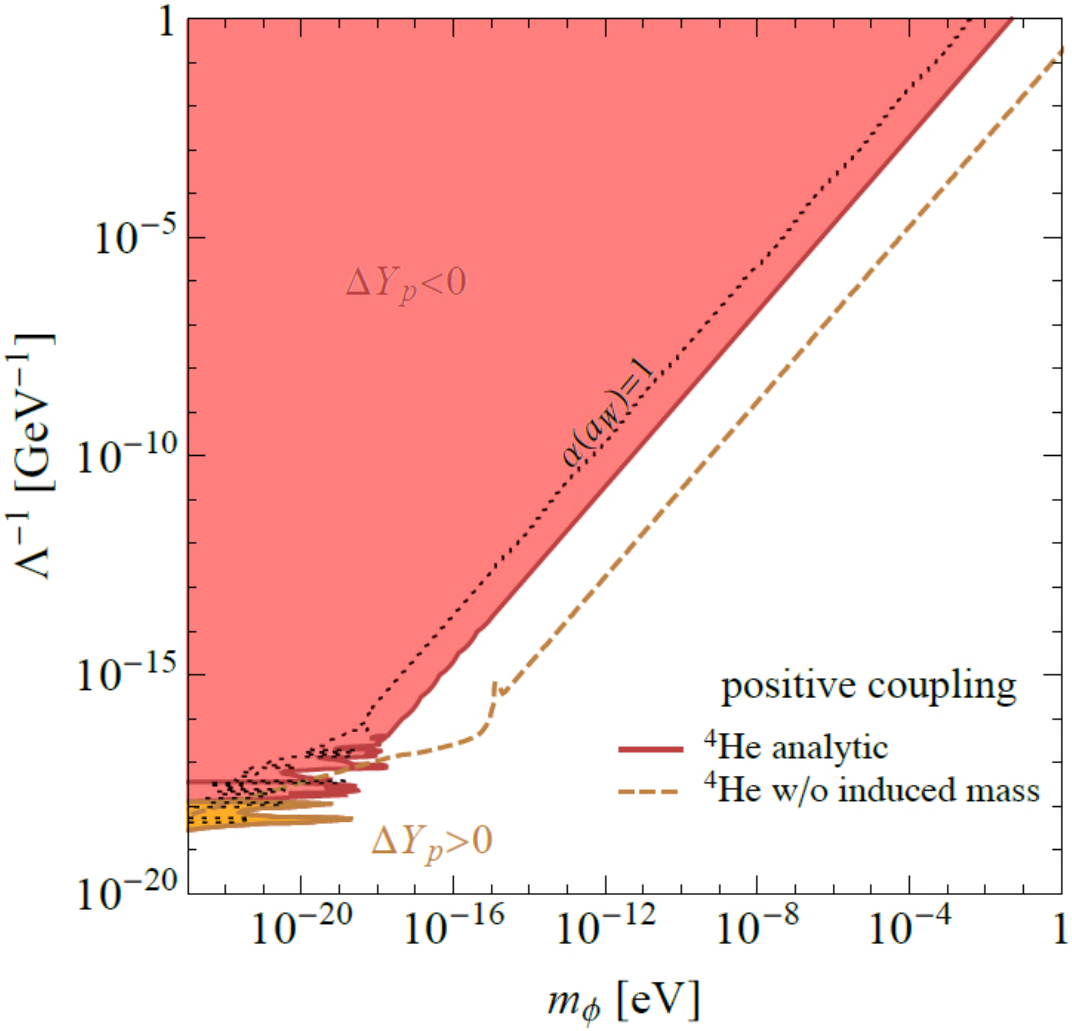
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN (Universal φ^2 Coupling)

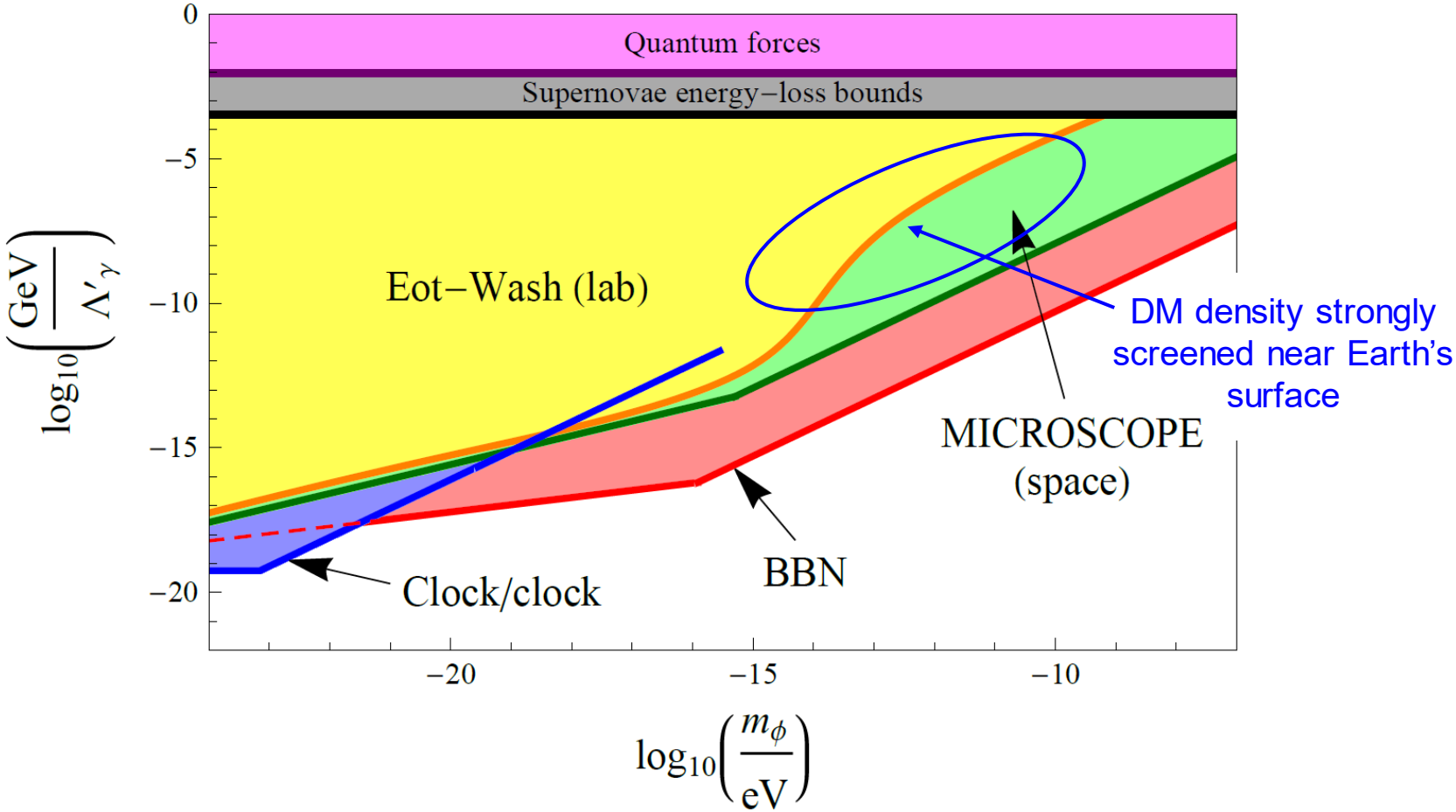
[Sibiryakov, Sörensen, Yu, *JHEP* **2020**, 75 (2020)]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

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!



“Dark Matter” Network of Domain Walls?

- **Many open questions and unsubstantiated assumptions!**
- How to increase ρ_{walls} inside a galaxy by at least $\sim 10^5$ times, compared to the density outside of the galaxy?

  [Expect wall network to be “stiff”.]
- How to form networks of domain walls that pass through Earth on a “convenient” average timescale, T_{avg}, of hours to years?

  [Numerical simulations indicate that walls tend to efficiently annihilate over time, leaving only $\sim \mathcal{O}(1)$ wall at present day.]
- How to form “simple” domain-wall networks with non-relativistic wall speeds in galaxies ($\sim 300\ \text{km/s}$ locally)?

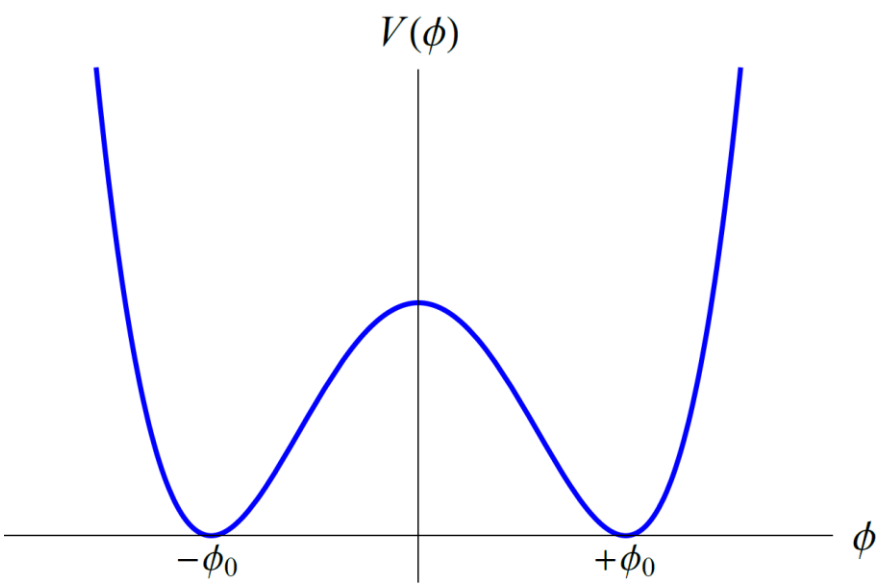
  [Numerical simulations indicate that domain walls travel at semi-relativistic speeds.]

Comparison to Oscillating Scalar Field

Domain wall

$$\varphi(x) = \varphi_0 \tanh(x/d)$$

$$\varphi_0^2 \sim \rho v d T_{\text{avg}} \ll \rho \left(v T_{\text{avg}}\right)^2$$



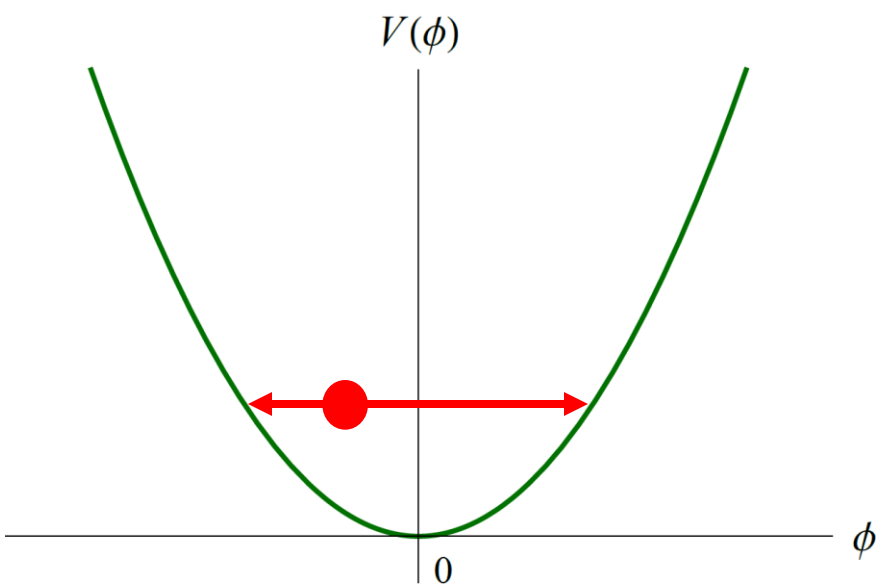
$$V(\varphi) = \frac{\lambda}{4}(\varphi^2 - \varphi_0^2)^2$$

Oscillating field

[may explain dark matter]

$$\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right)$$

$$\varphi_0^2 \sim \rho/m_\varphi^2 \sim \rho T_{\text{osc}}^2$$

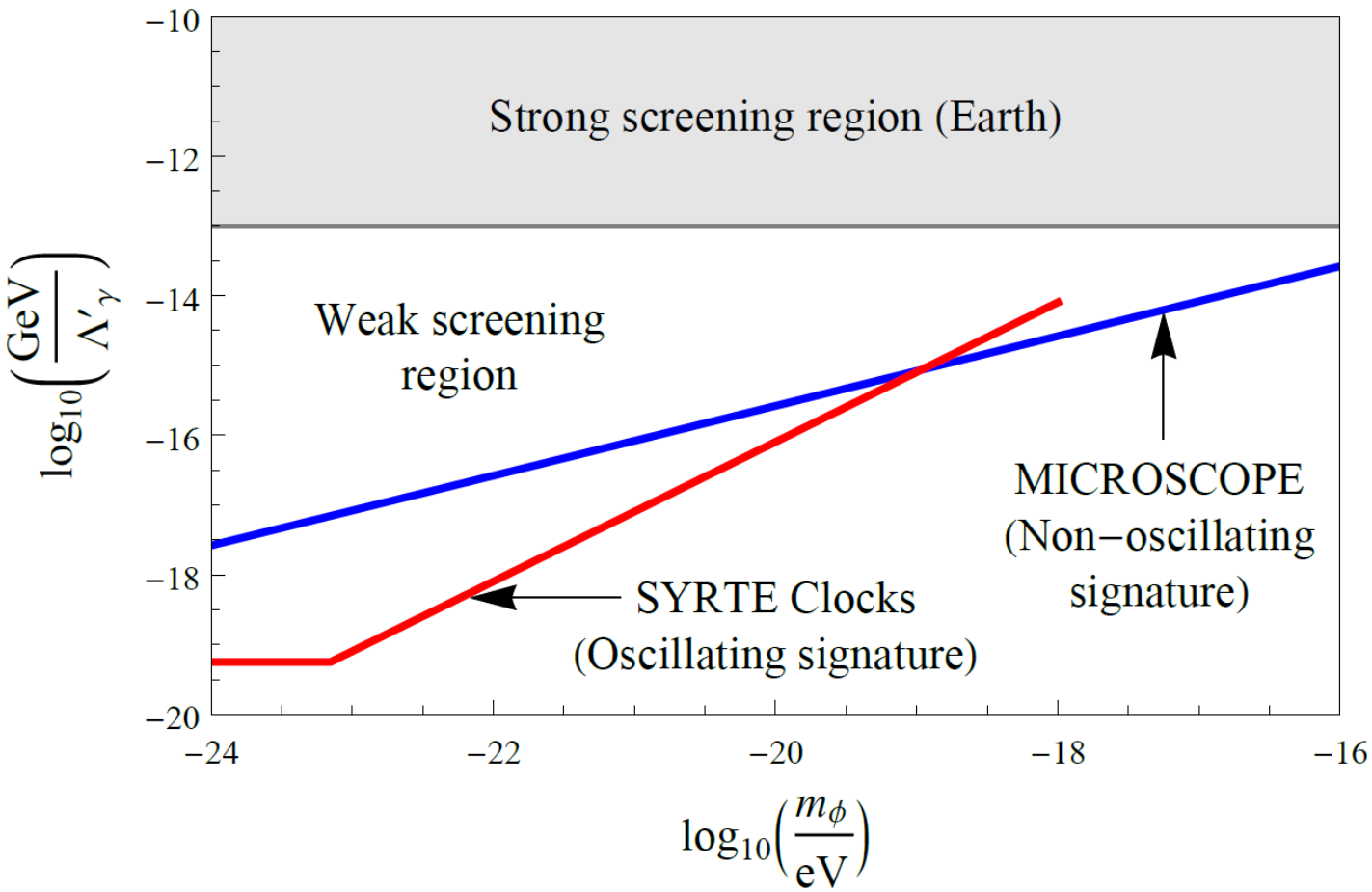


$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

φ^2 Interaction of Oscillating Scalar Dark Matter Field with the Photon

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

When screening is sufficiently weak, oscillating signatures tend to dominate



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Further improvement possible with current state-of-the-art optical clocks