New Bounds on Macroscopic Scalar-Field Topological Defects from Non-Transient Signatures due to Environmental Dependence and Spatial Variations of the Fundamental Constants

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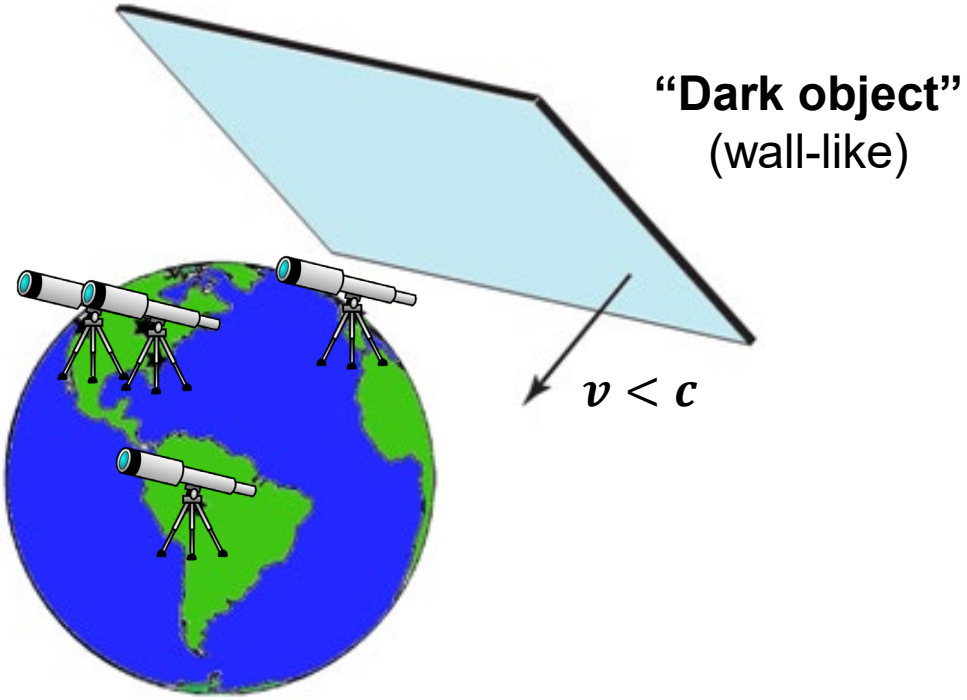
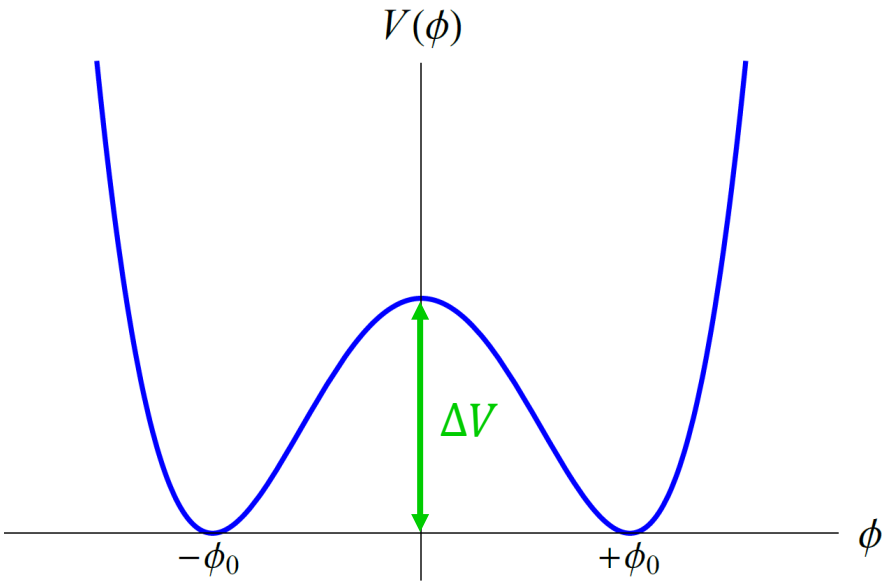
Dark Objects

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



Topological Domain Walls

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



φ^4 potential

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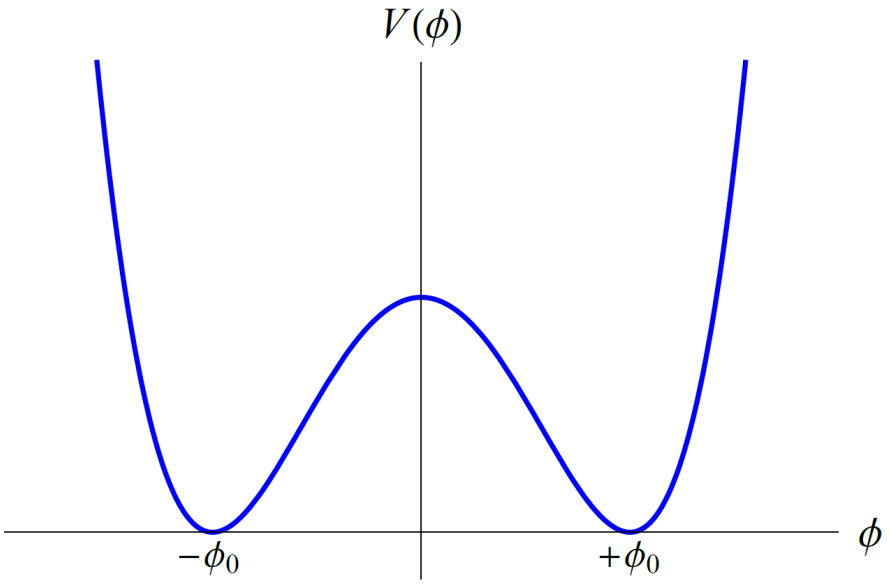
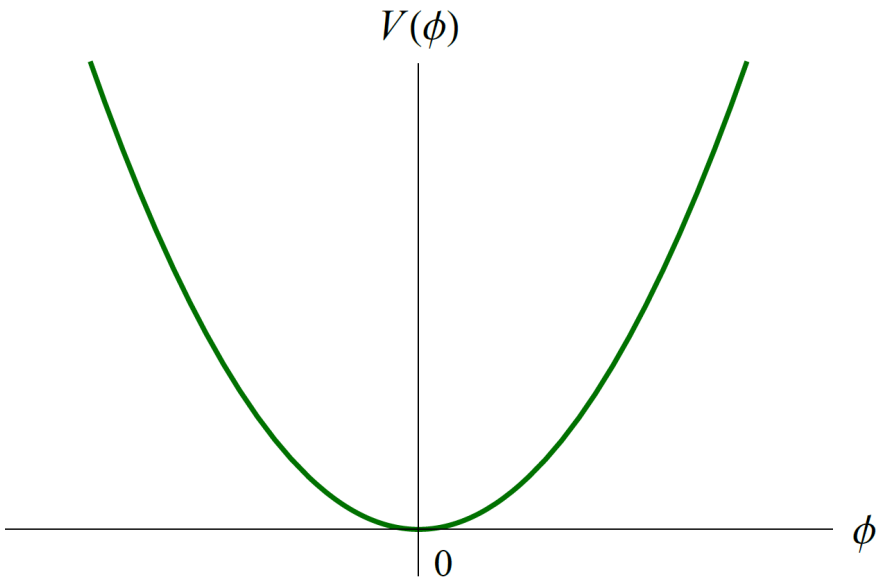


φ^4 potential
(non-trivial topology)



φ^2 potential
(trivial topology)

Topological Domain Walls

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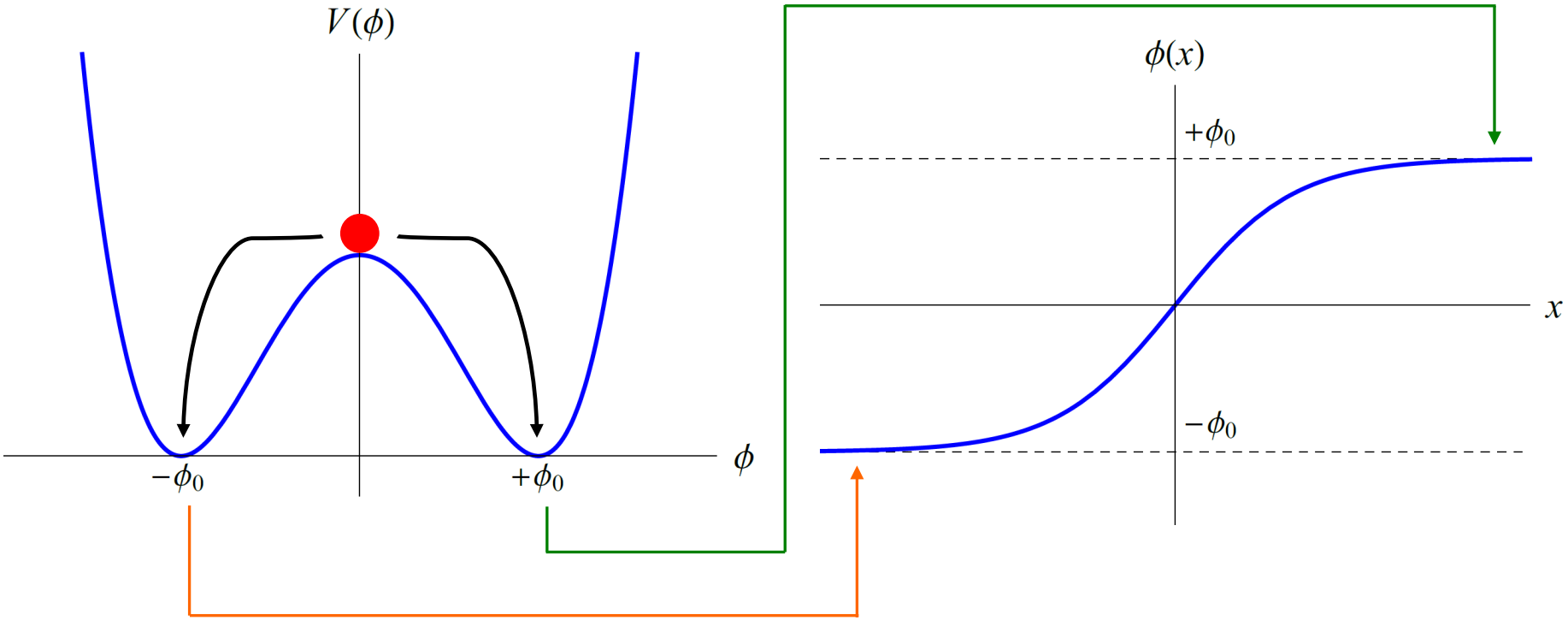
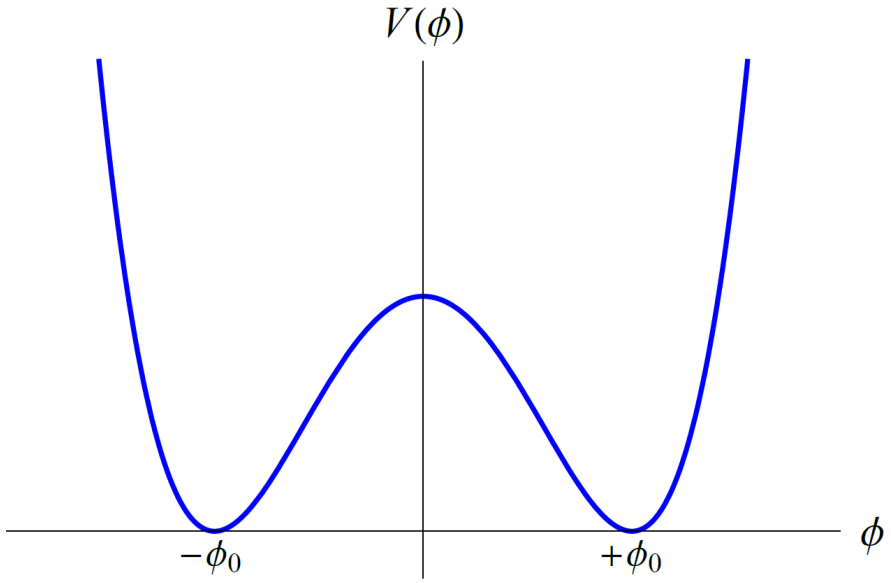
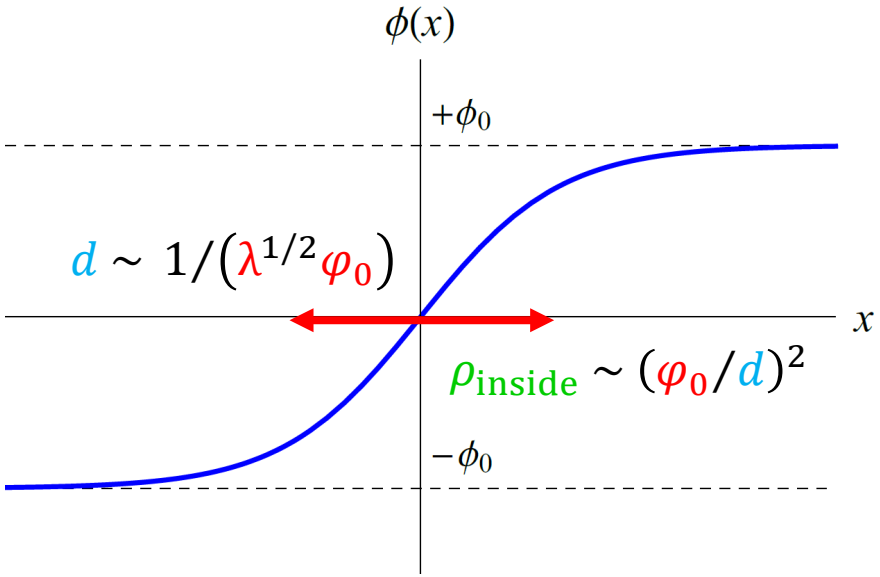
- Different regions in space may settle in different vacua/minima



Topological Domain Walls

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

Variations of Fundamental Constants

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

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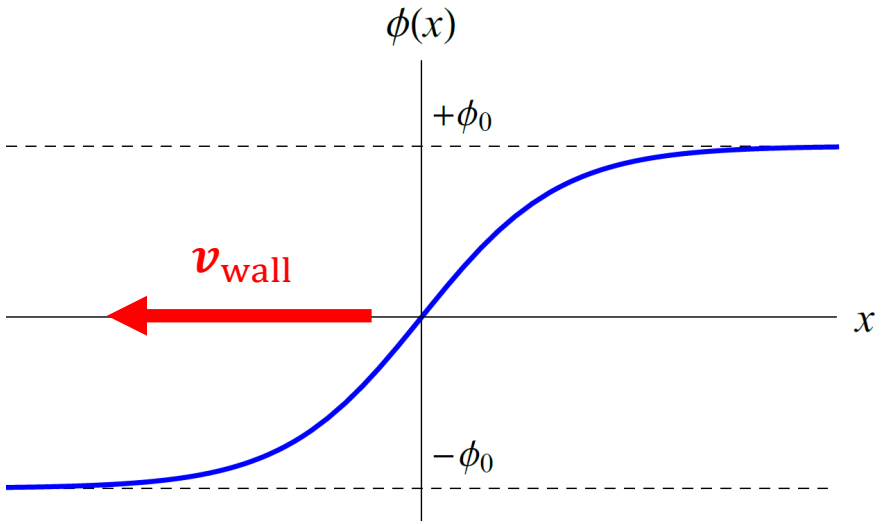
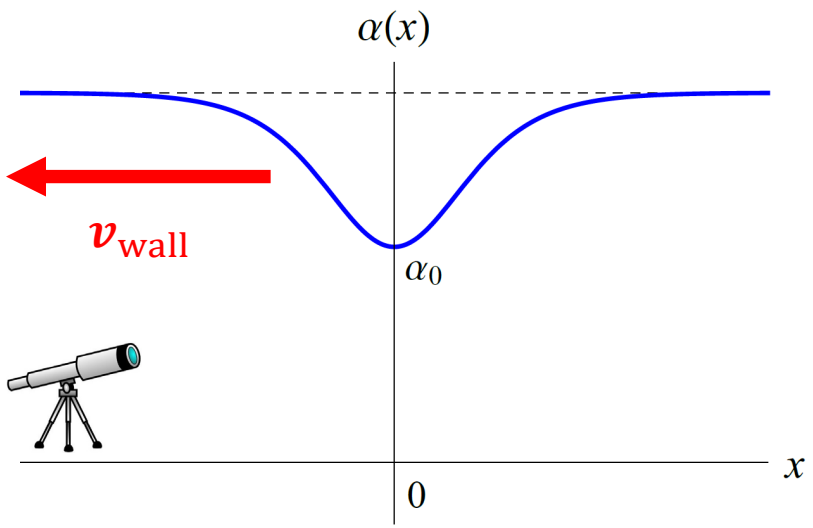
- A passing domain wall induces apparent **transient** variations of fundamental constants, due to a temporary change in φ^2





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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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- 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)]
  - Several talks outlining results at the previous MG15 meeting

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

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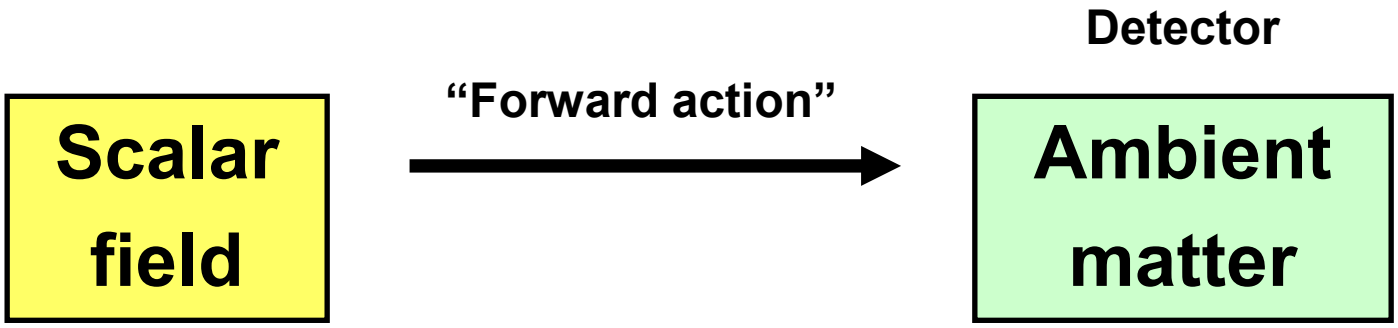

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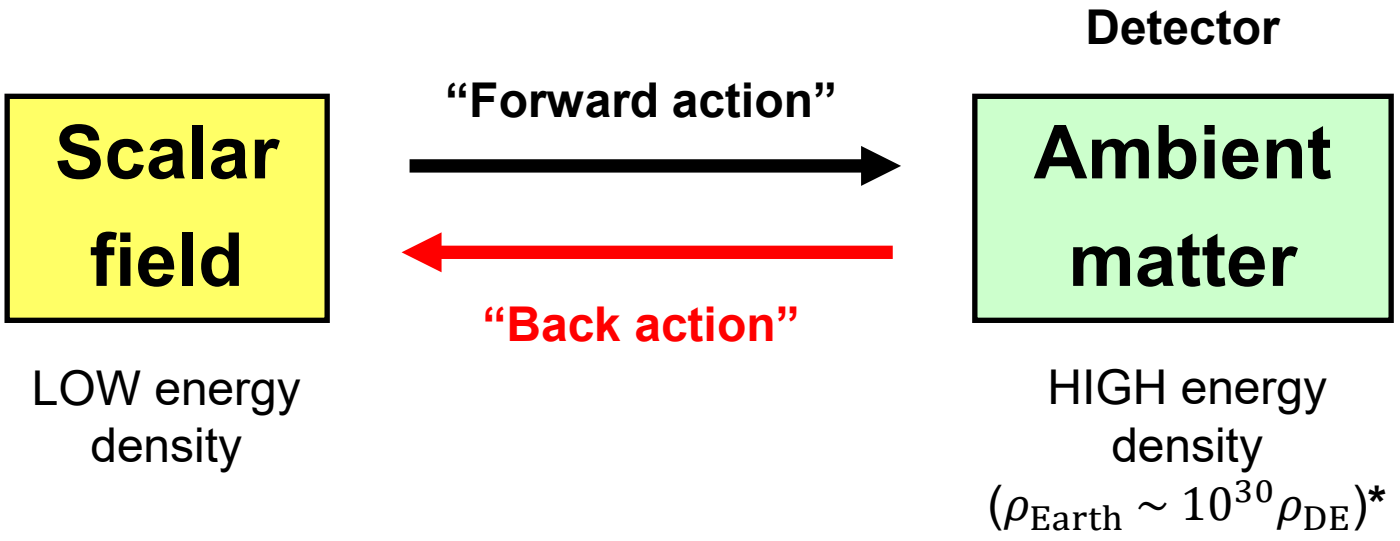

* Cannot necessarily neglect "back action" *even when the interaction strength is feeble*

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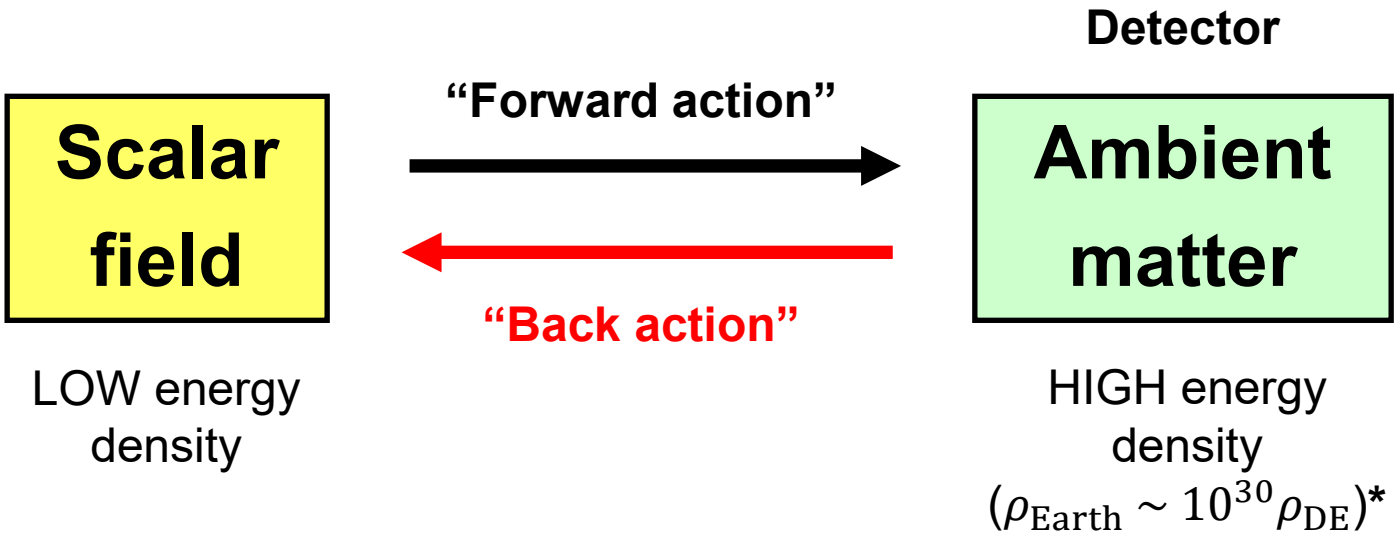
- These back-action effects lead to **quasi-non-transient** (quasi-time-independent) variations of fundamental constants



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Non-relativistic ambient matter

ρ_γ = Coulomb binding energy

ρ_e = electron mass-energy

ρ_N = nucleon mass-energy

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

Ambient matter contribution

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

Effective potential

Environmental Dependence of "Constants"

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

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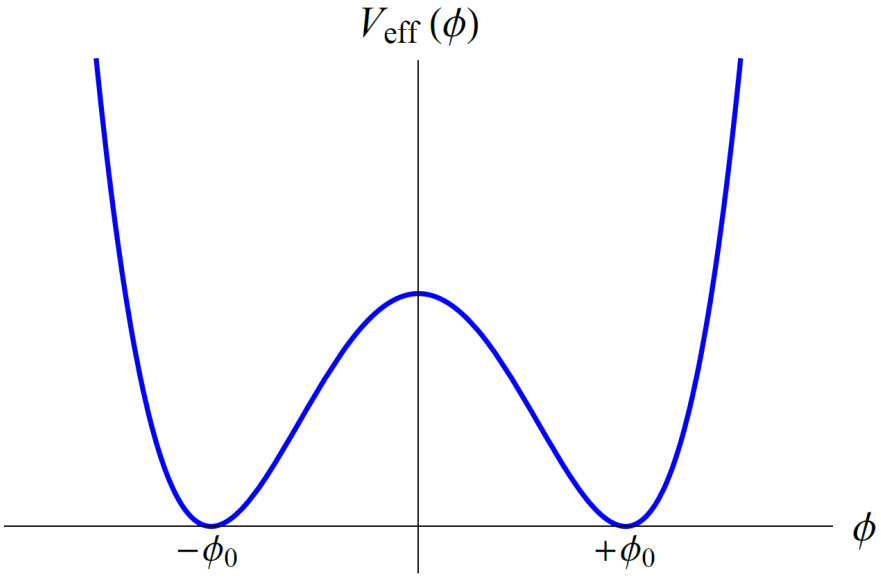

Low-density environment (non-trivial topology, *supports* domain walls)

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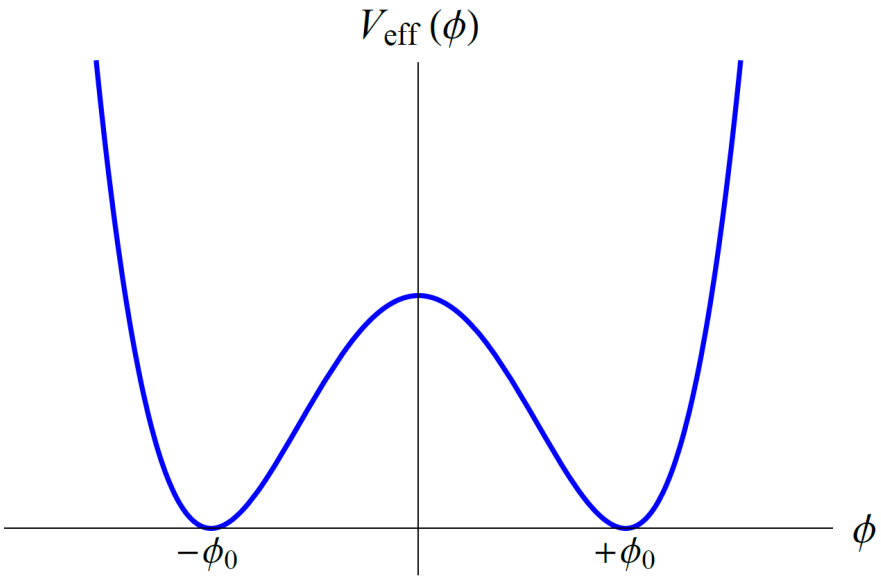

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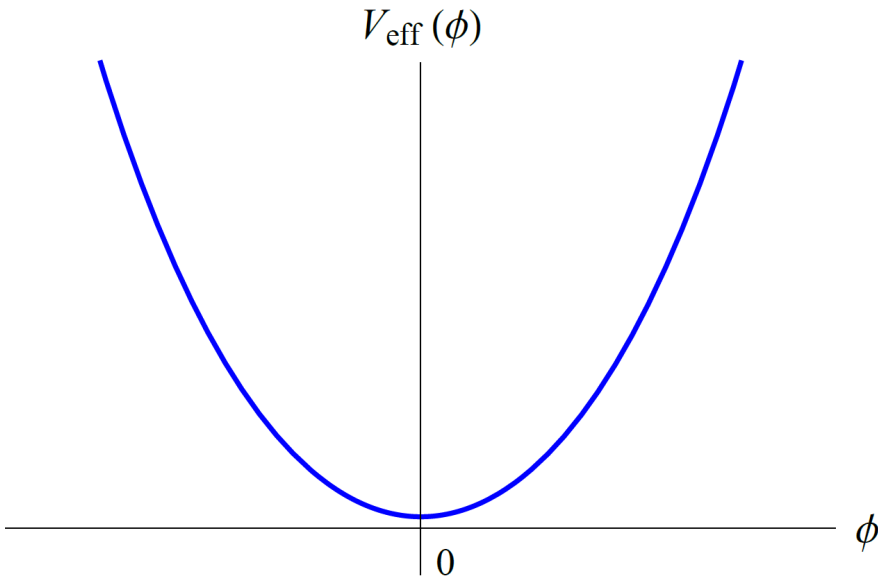

High-density environment (trivial topology, *destabilises* domain walls)

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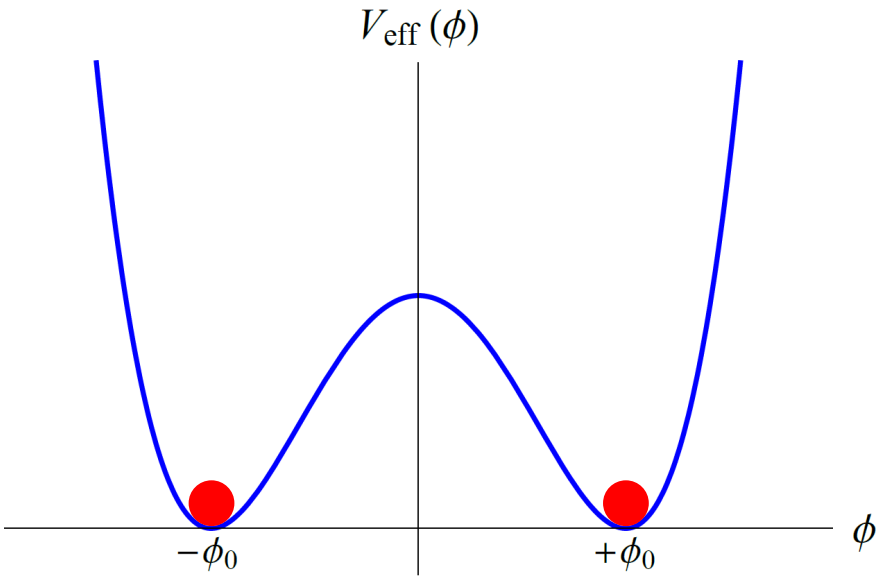

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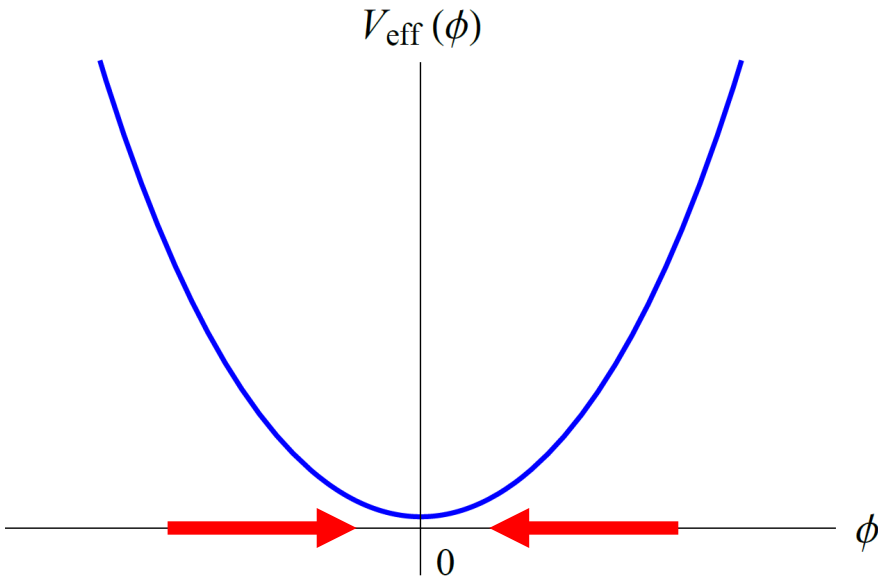

High-density environment

- Scalar field φ tends to be screened in dense environments

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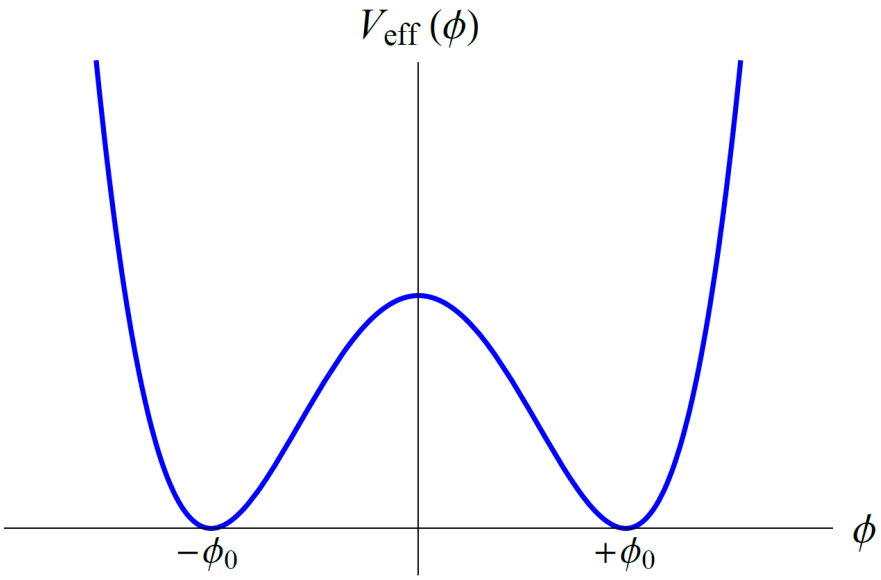

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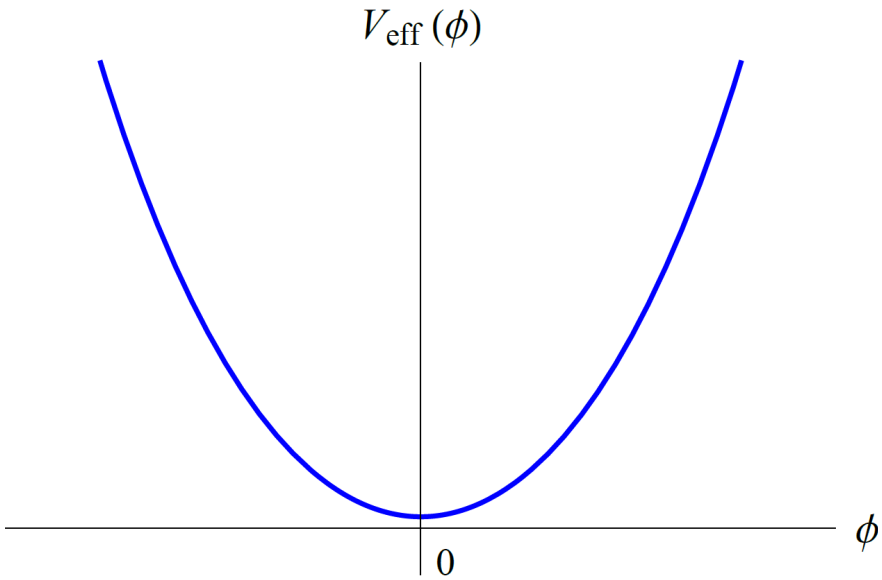
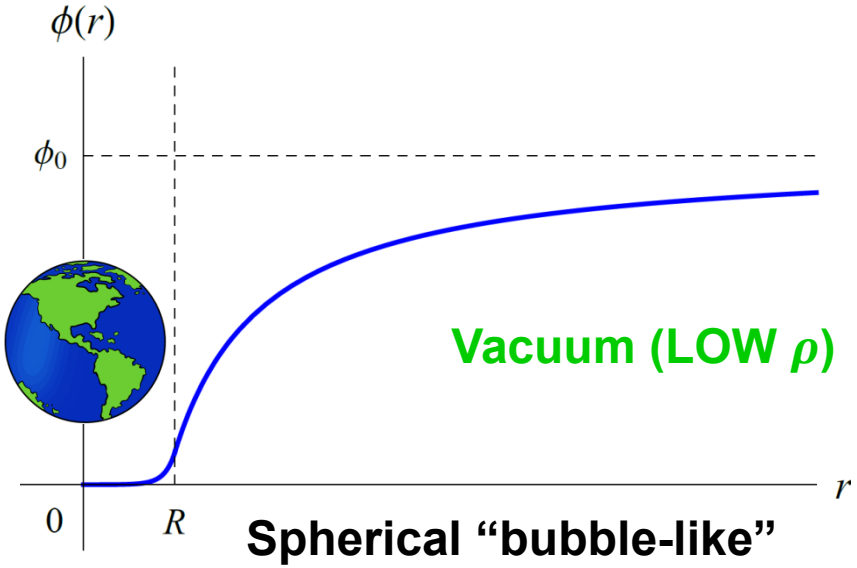


High-density environment

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

Spatial Variations of “Constants”

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



Earth (HIGH ρ)

Spherical “bubble-like” defect around Earth (fixed to Earth)

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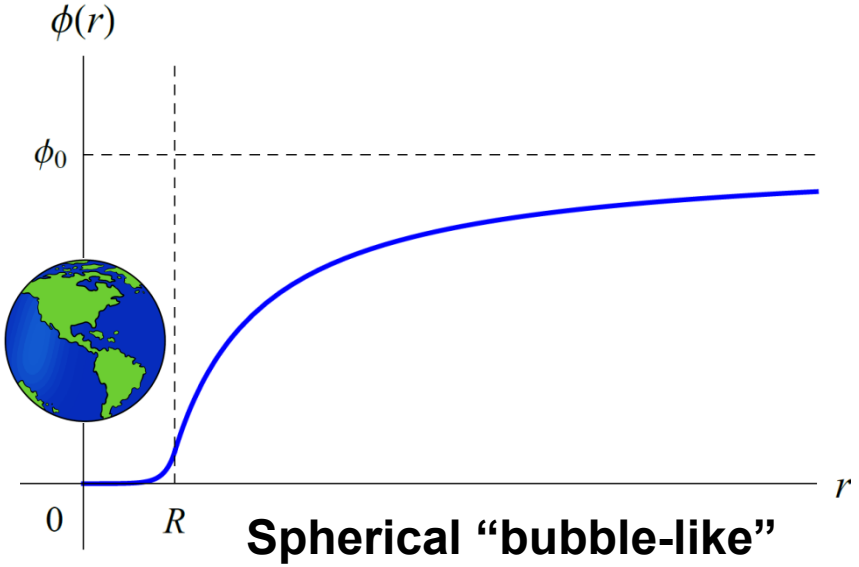

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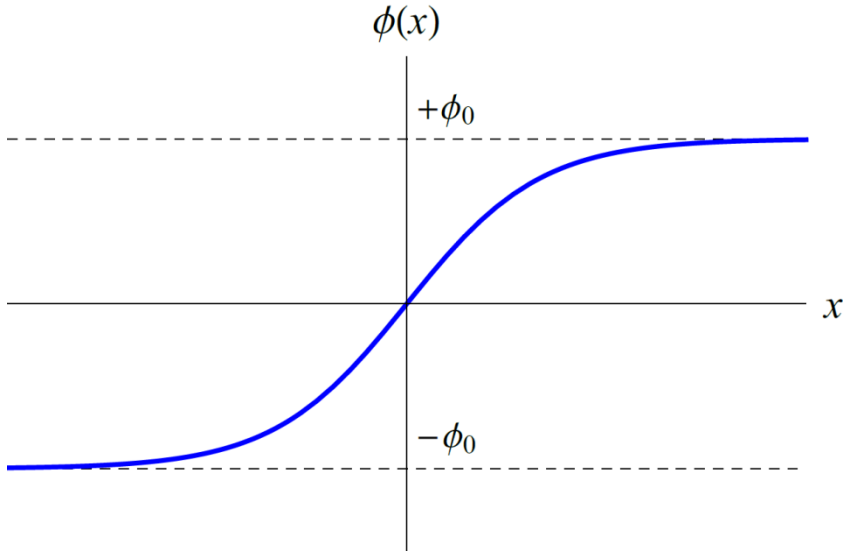

Planar defect in free space (“free” domain wall)

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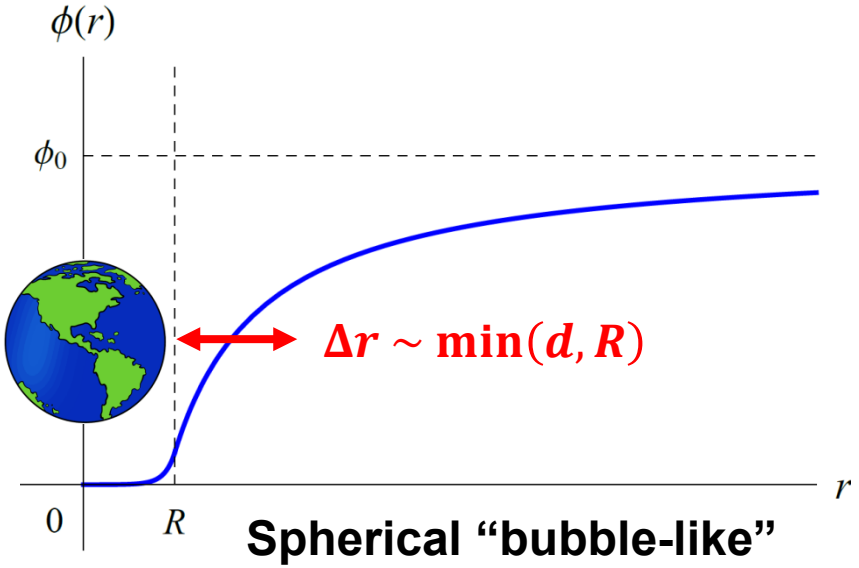

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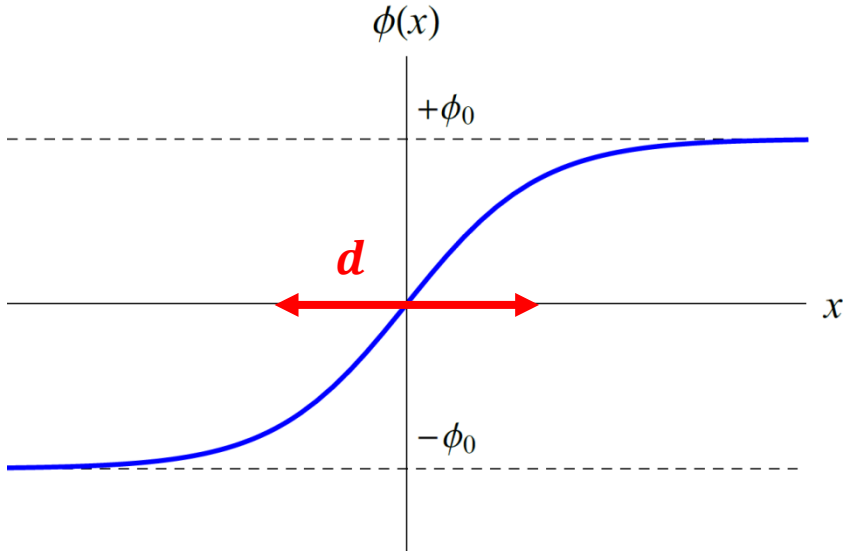

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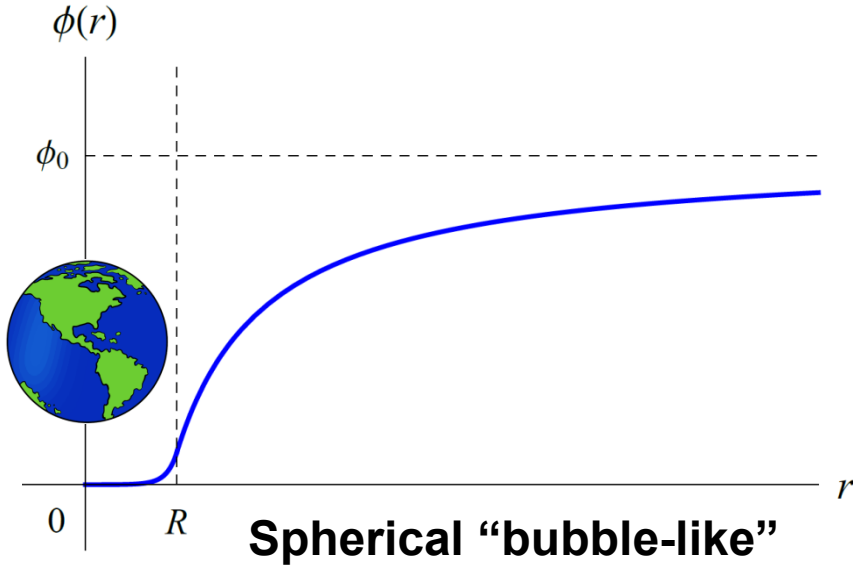

Spherical “bubble-like” defect around Earth (fixed to Earth)

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

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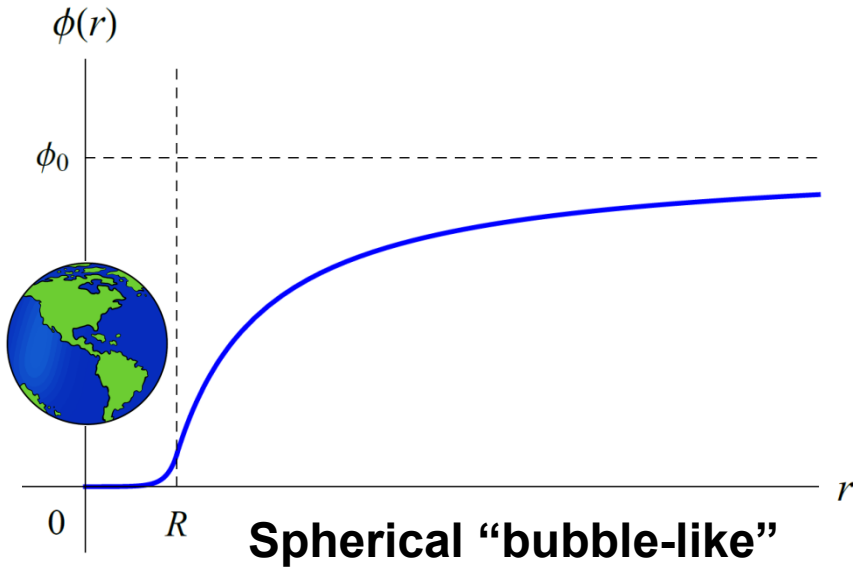

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Very generic signatures – present even if Universe consists of only a *single* domain (i.e., when *no cosmological* domain walls)

⇒ We don’t have to wait for a (possibly single or non-existent) domain wall of *cosmological origin* to pass by Earth!

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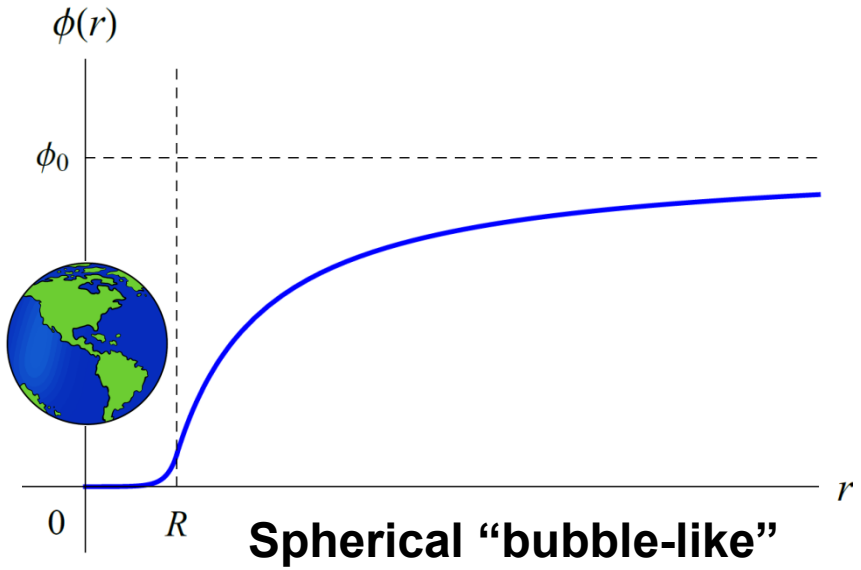

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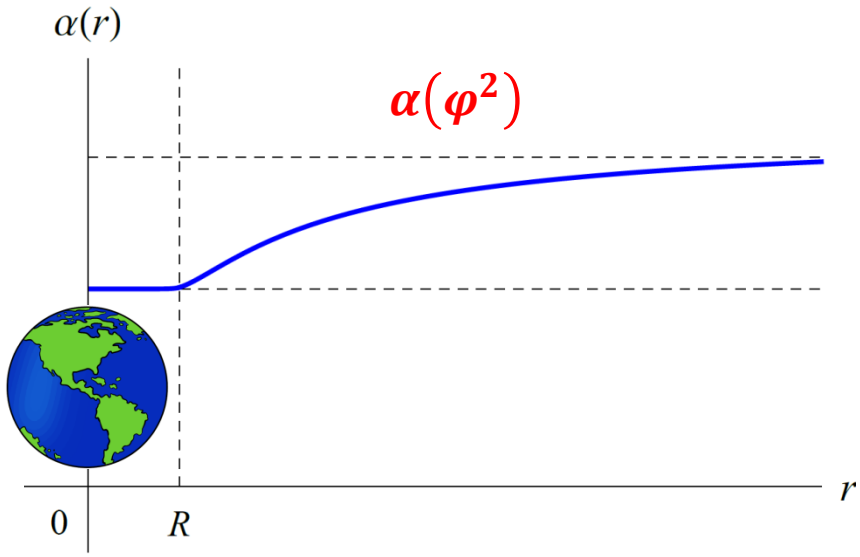

- **Spatial gradients of “constants”** arise around a dense body

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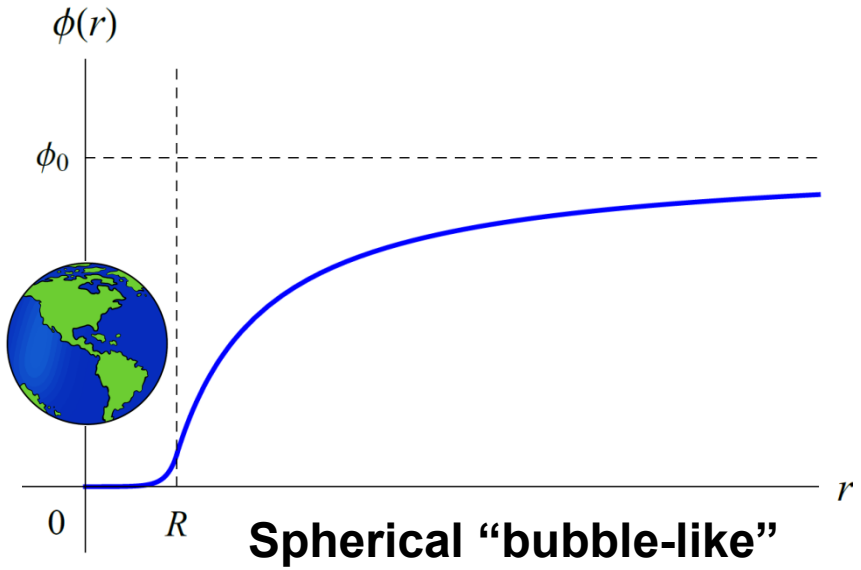

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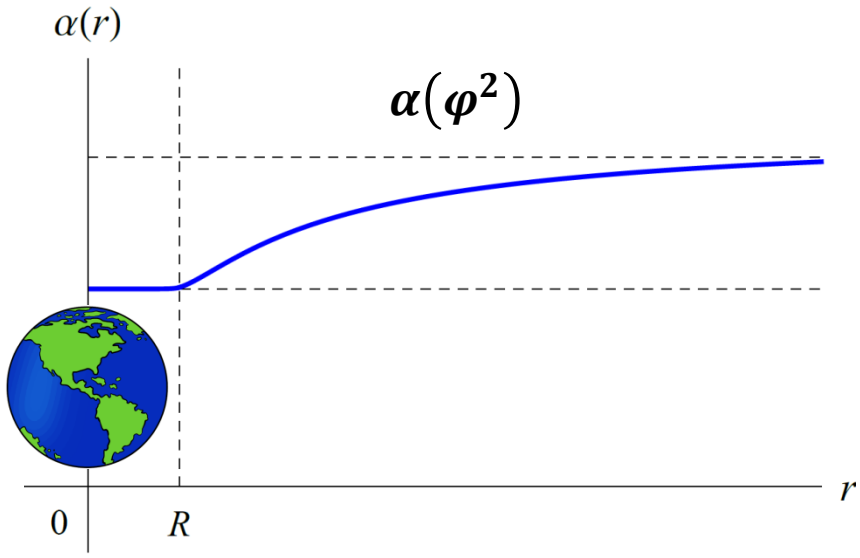

- **Spatial gradients of "constants"** arise around a dense body
- Can search for these spatial gradients (e.g., $\boldsymbol{\nabla}\,\alpha/\alpha$) with:
  1. Equivalence-principle-violating forces: $\delta\boldsymbol{a}_{\rm test} = -\boldsymbol{\nabla}\,[m_{\rm test}(\alpha)]/m_{\rm test}$
  2. 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

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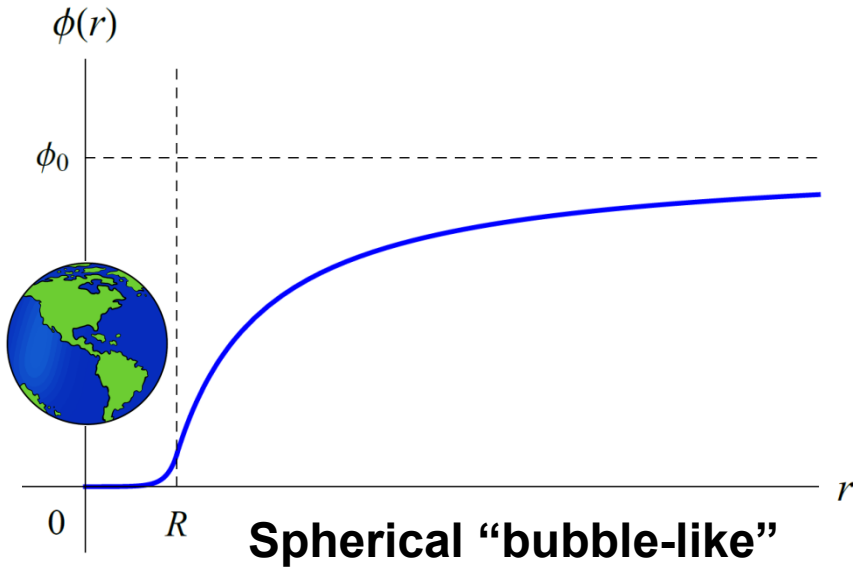
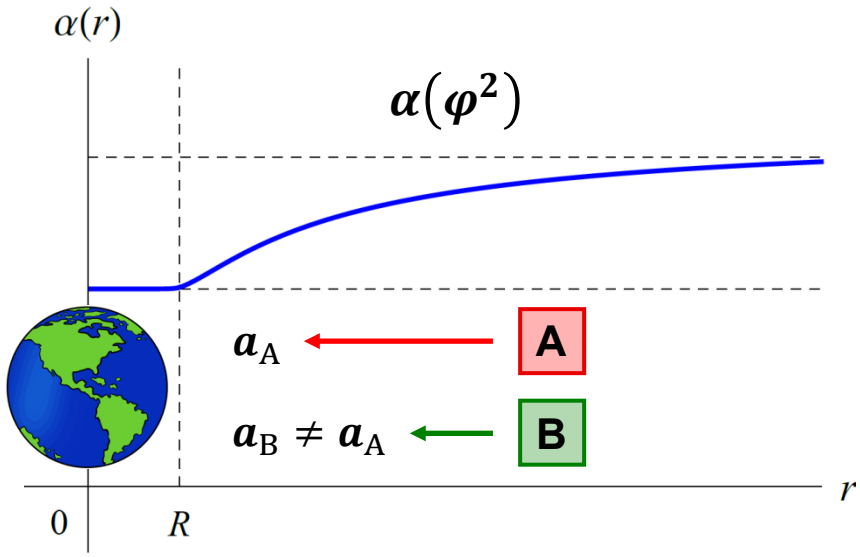


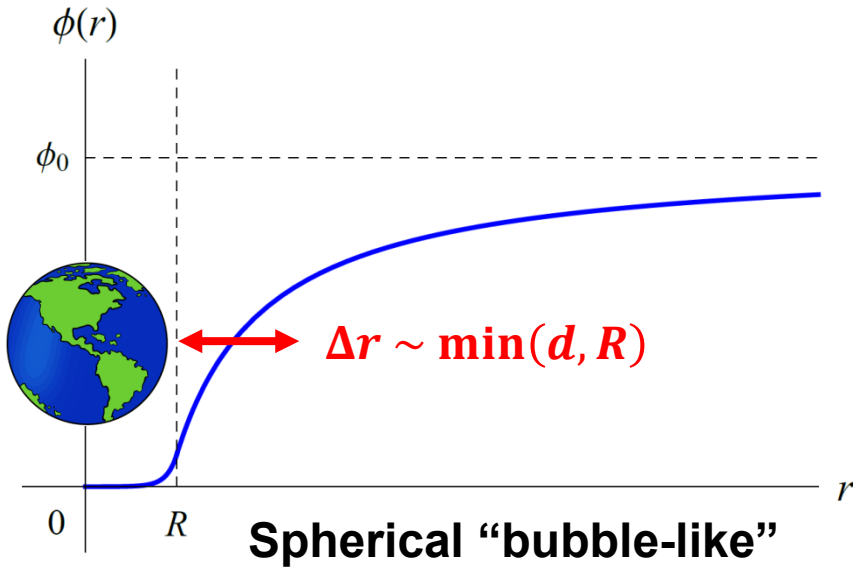
Spherical "bubble-like" defect around Earth



- **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"

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



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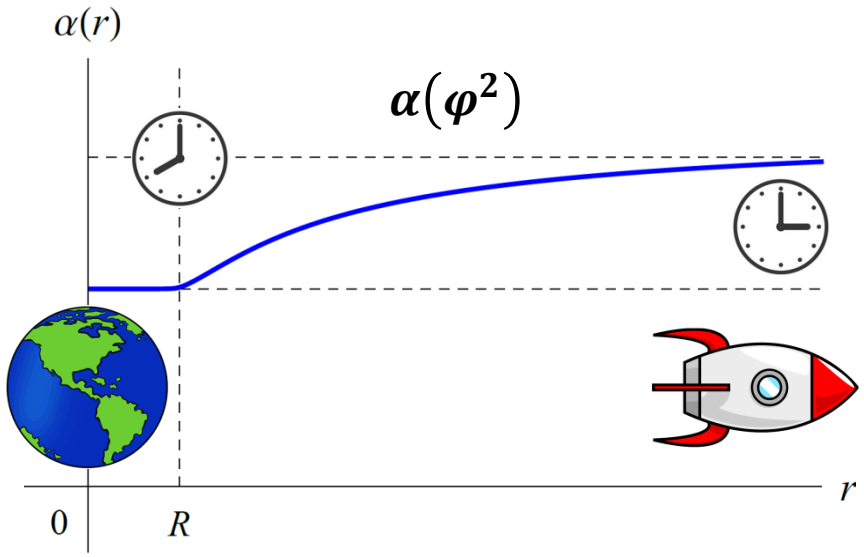

In space ($\Delta h \sim 10^4$ km)

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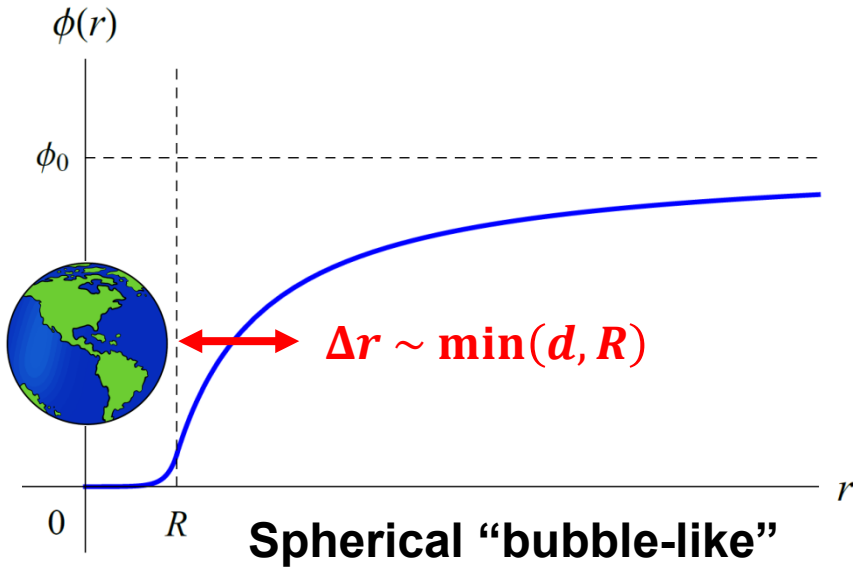

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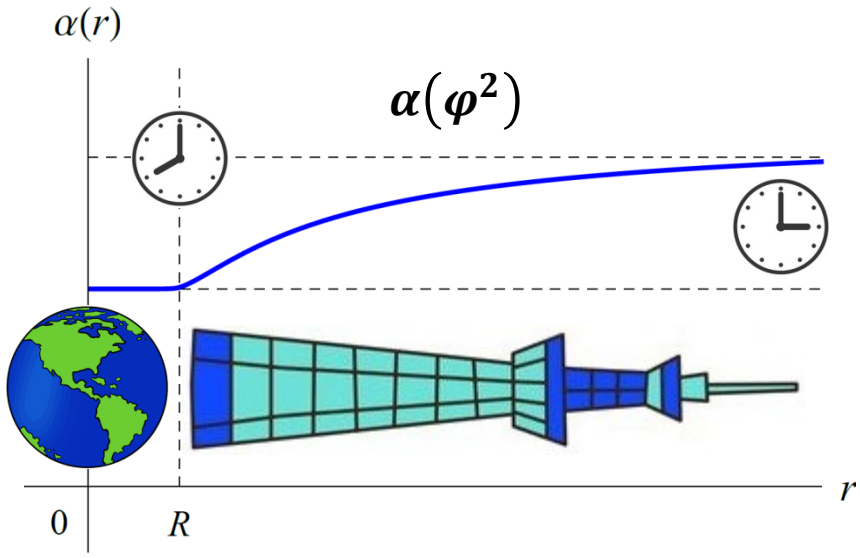

TOKYO SKYTREE ($\Delta h \sim 0.5$ km)

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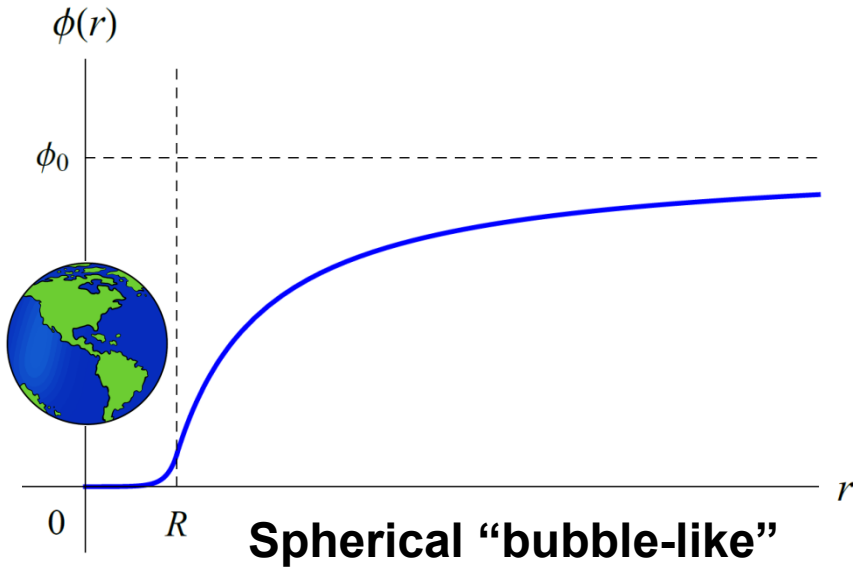

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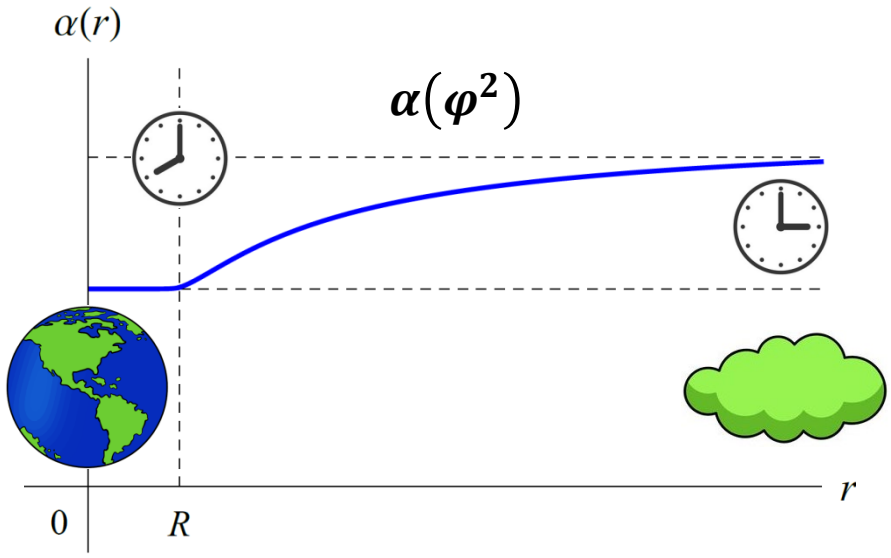

Distant gas clouds

- **Spatial gradients of "constants"** arise around a dense body
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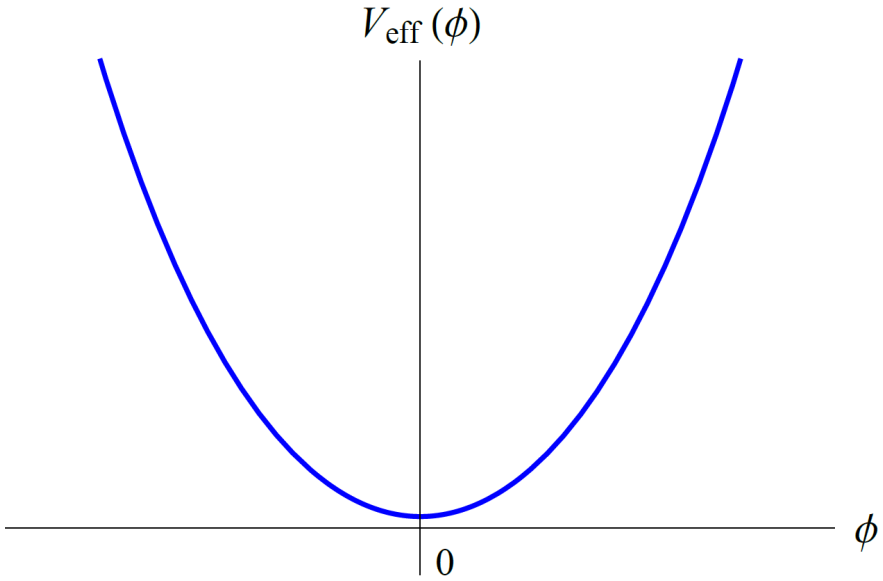
Cosmological Production of Domain Walls

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



High-density environment
("early" Universe, no walls)

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

Cosmological Production of Domain Walls

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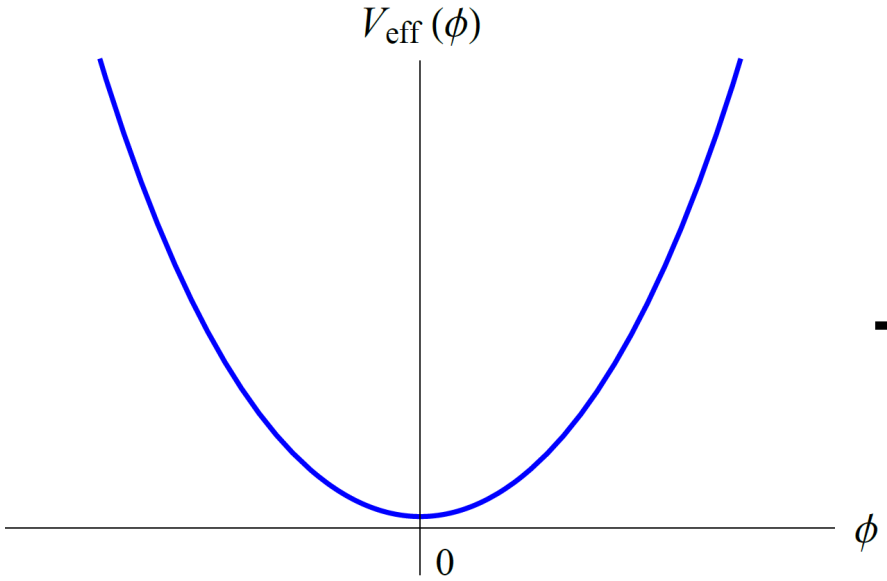

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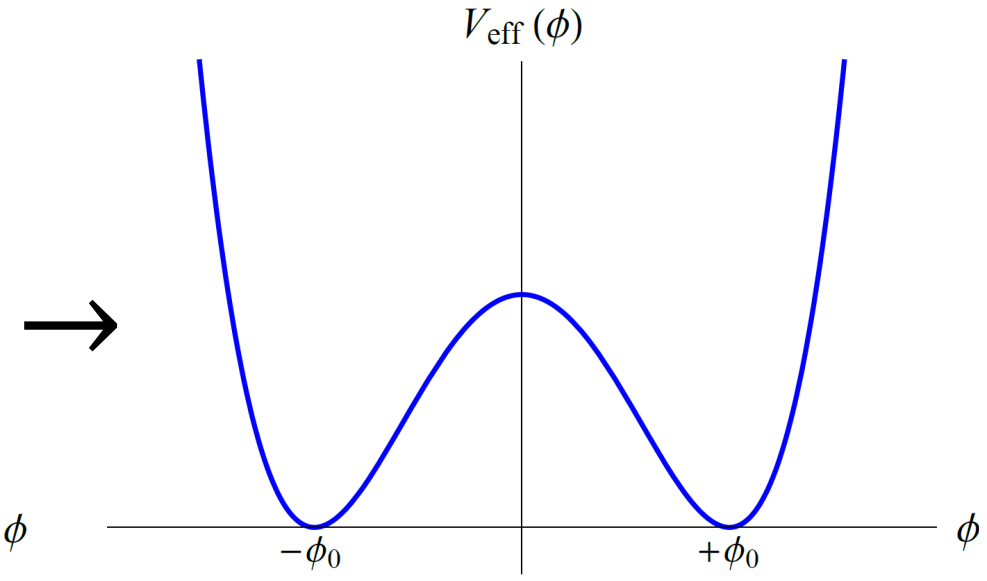

Low-density environment
("late" Universe, walls produced)

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

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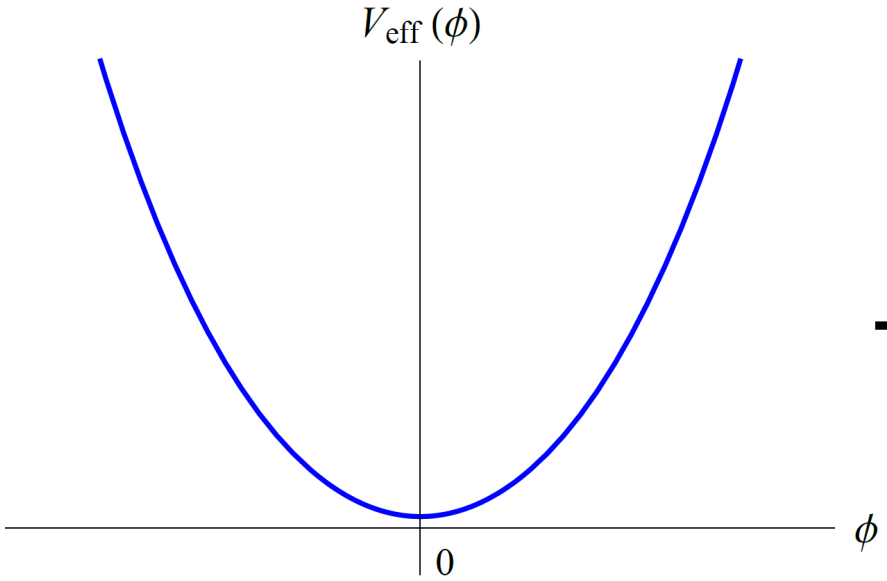

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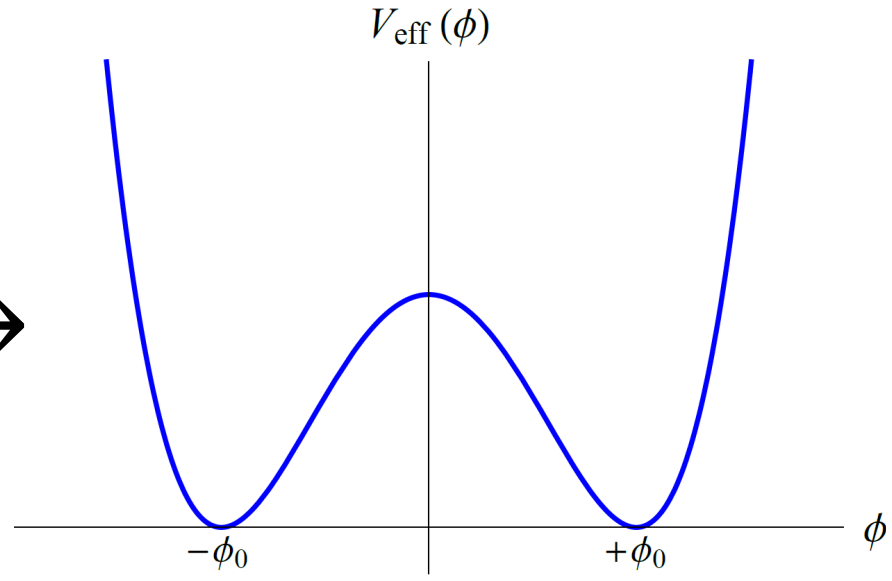


Low-density environment
("late" Universe, walls produced)

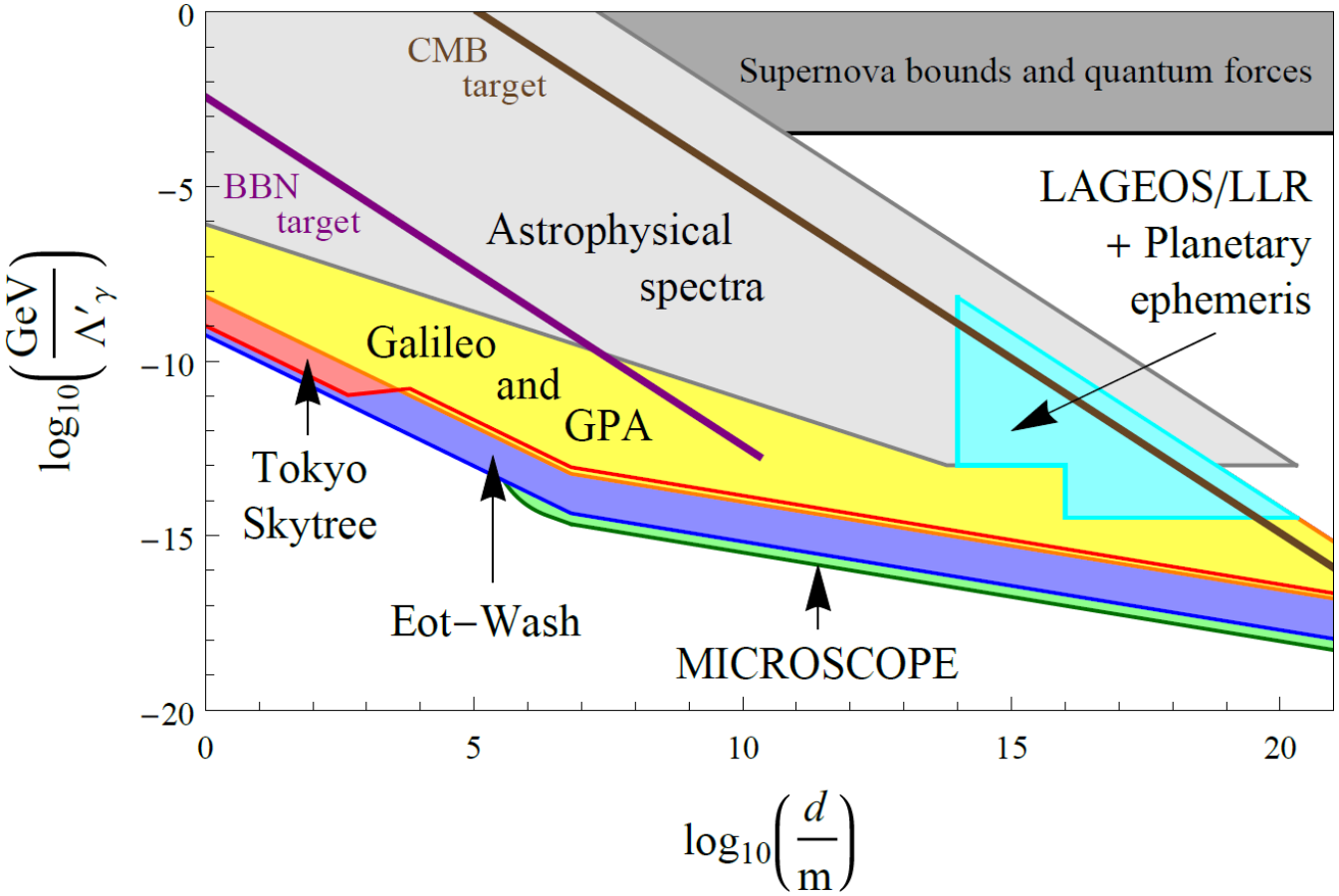
- As Universe cools, distant regions tend to settle in different vacua/minima – expect $\sim\mathcal{O}(1)$ domain wall to survive to present day
- Even if only 1 wall stretching across the Universe survives, gravitational effects of wall(s) on CMB constrain $\rho_{\rm wall(s)} < 10^{-5}\rho_{\rm total}$

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

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

Improvement over previous bounds from different non-transient signatures (by up to $\sim 10^{15}$)!

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

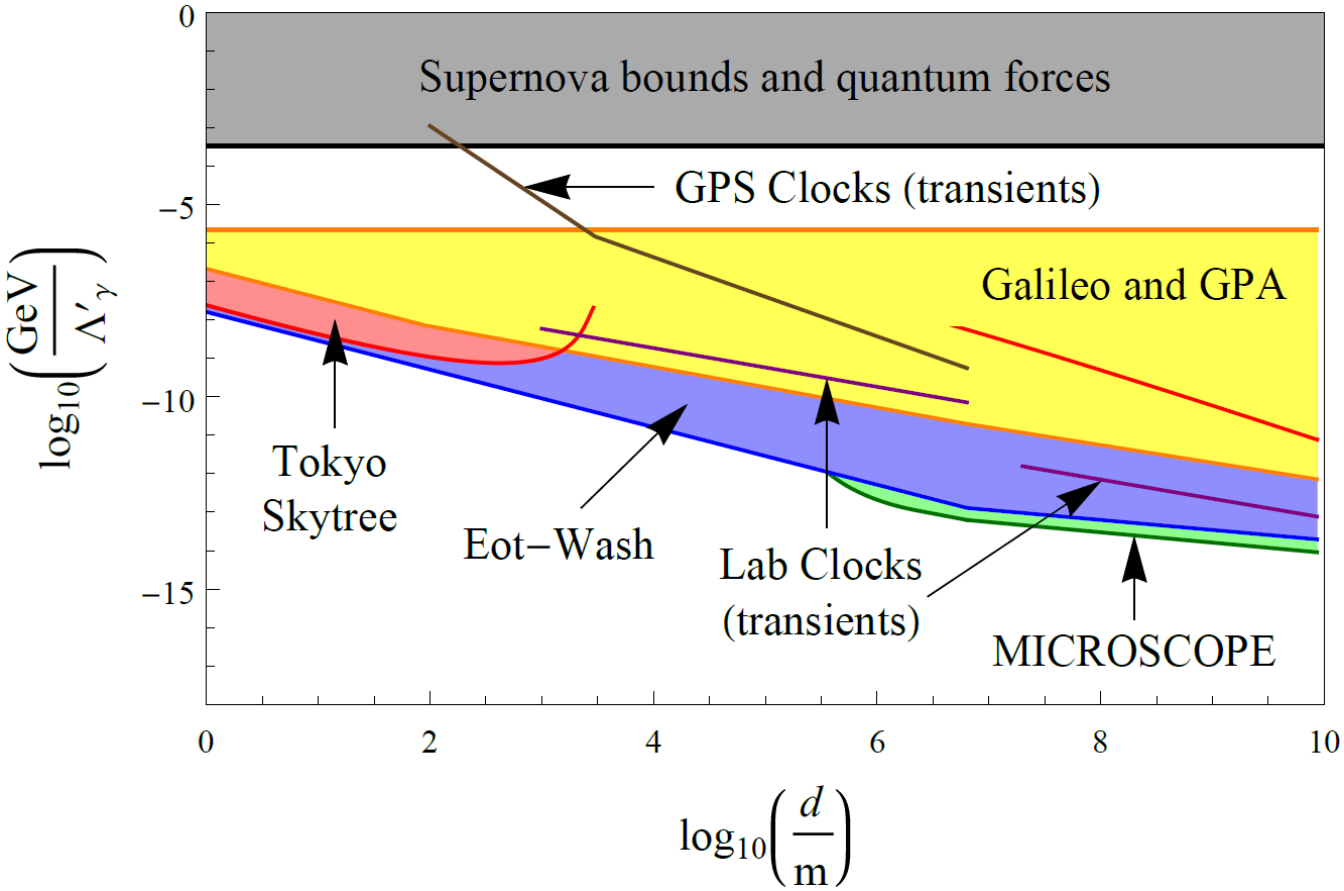


Constraints on φ^2 Interaction with the Photon

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

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

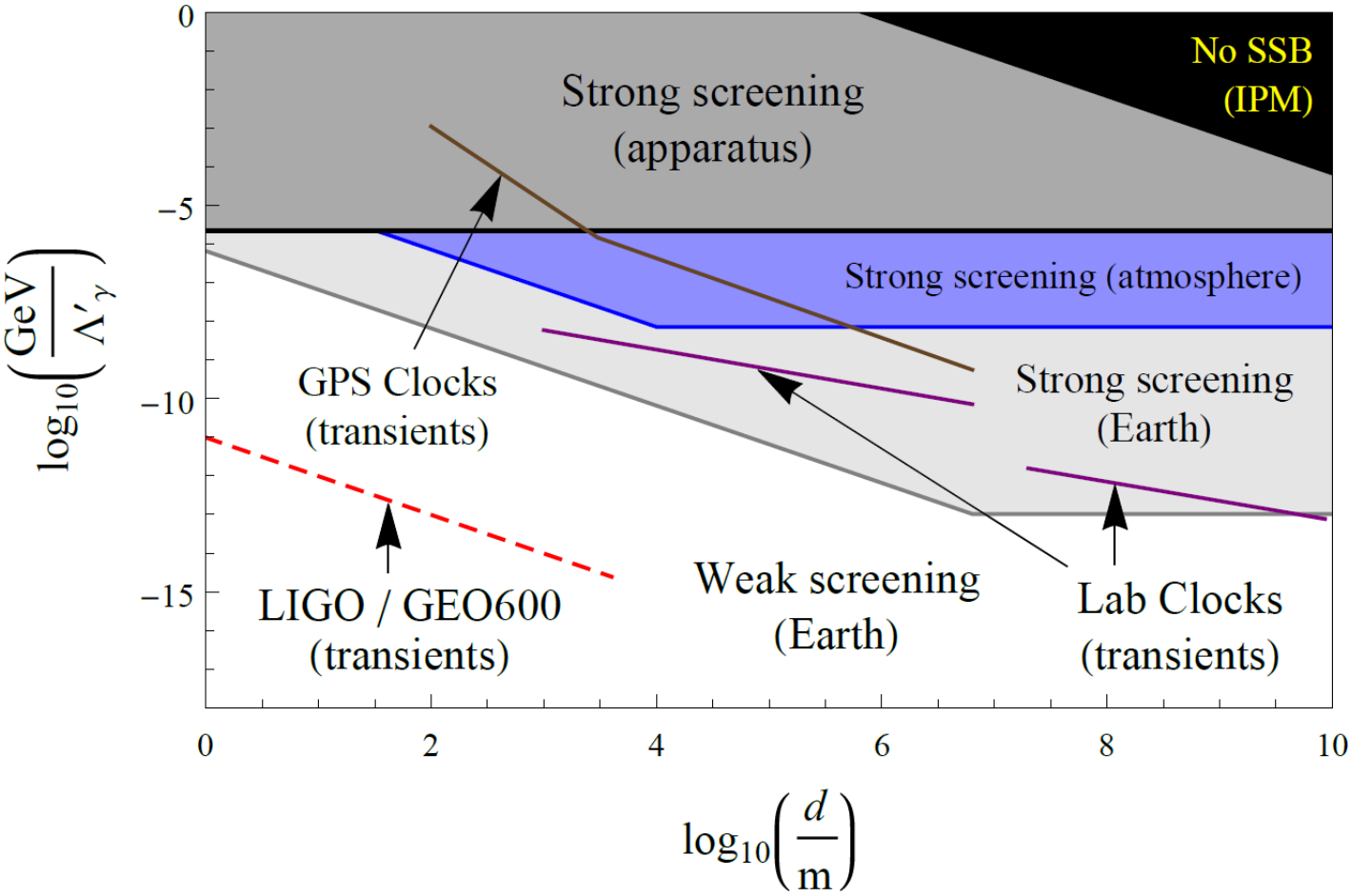
Our new limits from quasi-non-transient effects improve over transient signatures and over previous bounds from different non-transient signatures (by up to $\sim 10^{10}$)!



Scrutinising Bounds from Transient Signatures

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

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



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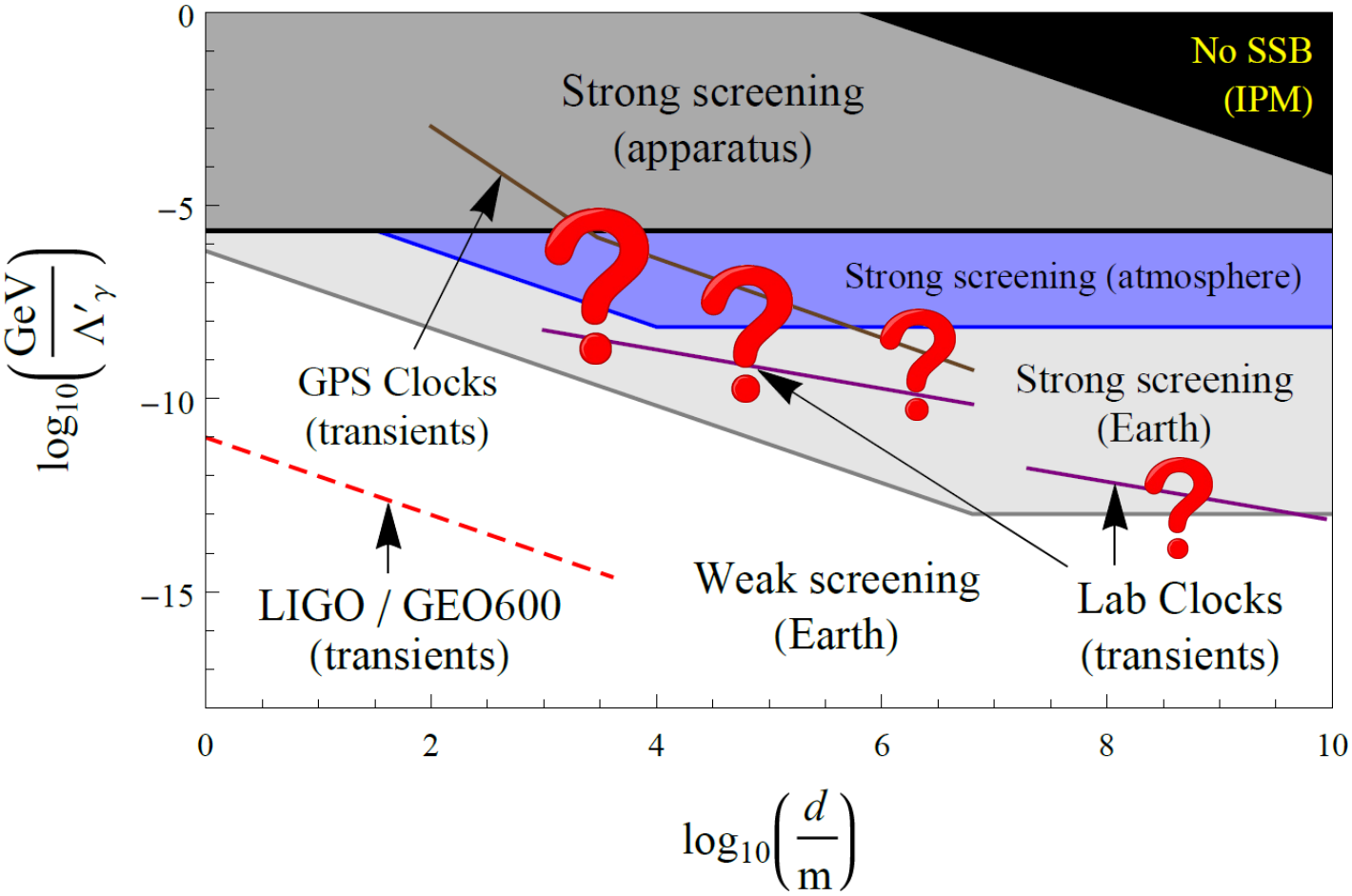

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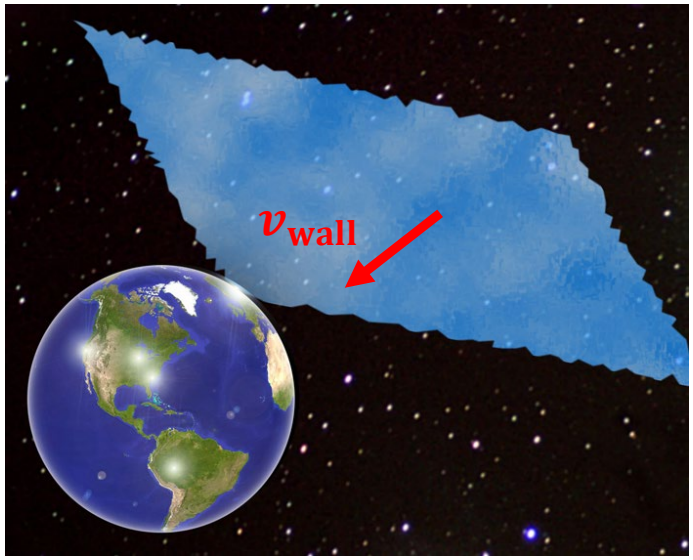

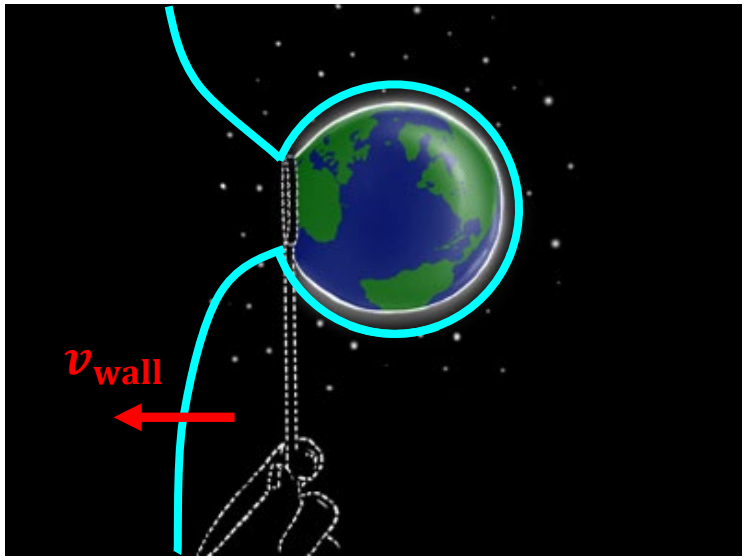

Domain wall incident on Earth

(Meta)stable bubble around Earth?

Scrutinising Bounds from Transient Signatures

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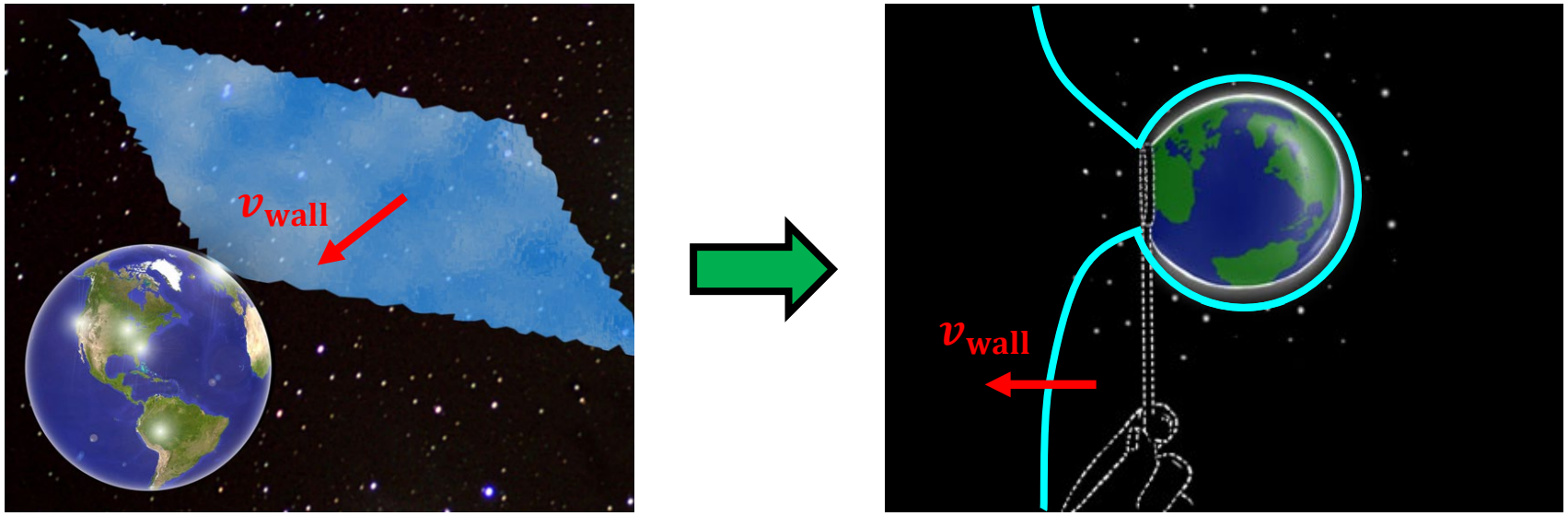


Domain wall incident on Earth

(Meta)stable bubble around Earth?

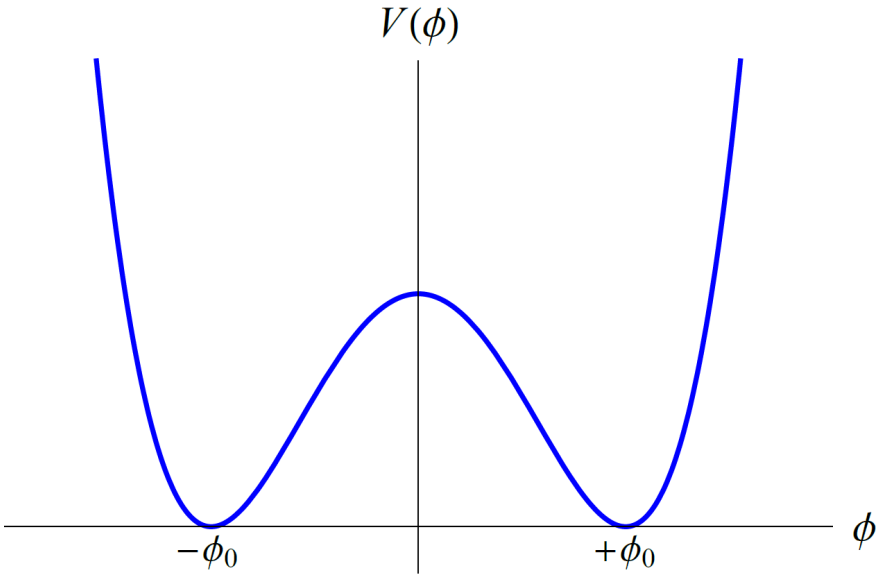
Transient signatures may be qualitatively different from those assumed previously – ongoing work

Comparison to Oscillating Scalar Field

Domain wall

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

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

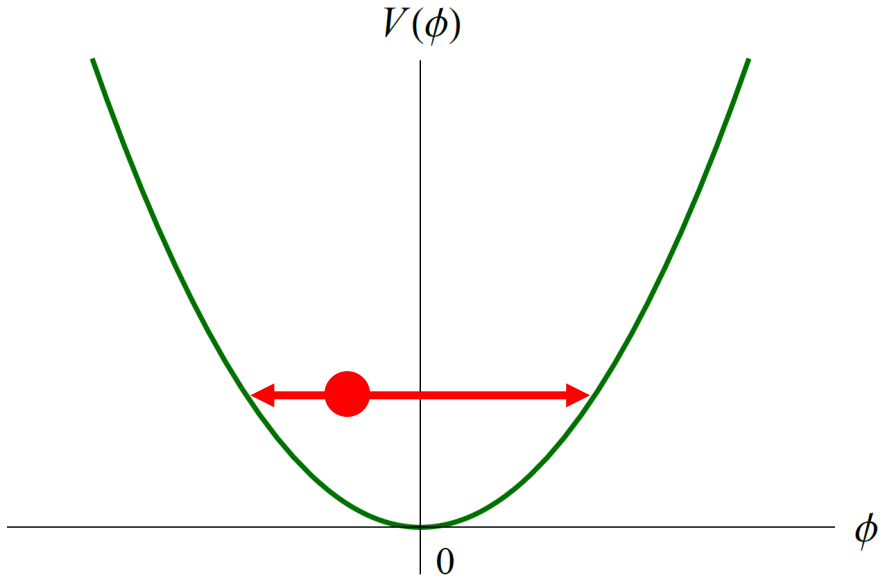


$$V(\varphi) = \frac{\lambda}{4}\left(\varphi^2 - \varphi_0^2\right)^2$$

Oscillating field
[may explain dark matter]

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

$$\varphi_0^2 \sim \rho/m_\varphi^2 \sim \rho T_{\text{osc},\varphi}^2 = \rho\lambda_{\text{Comp},\varphi}^2$$



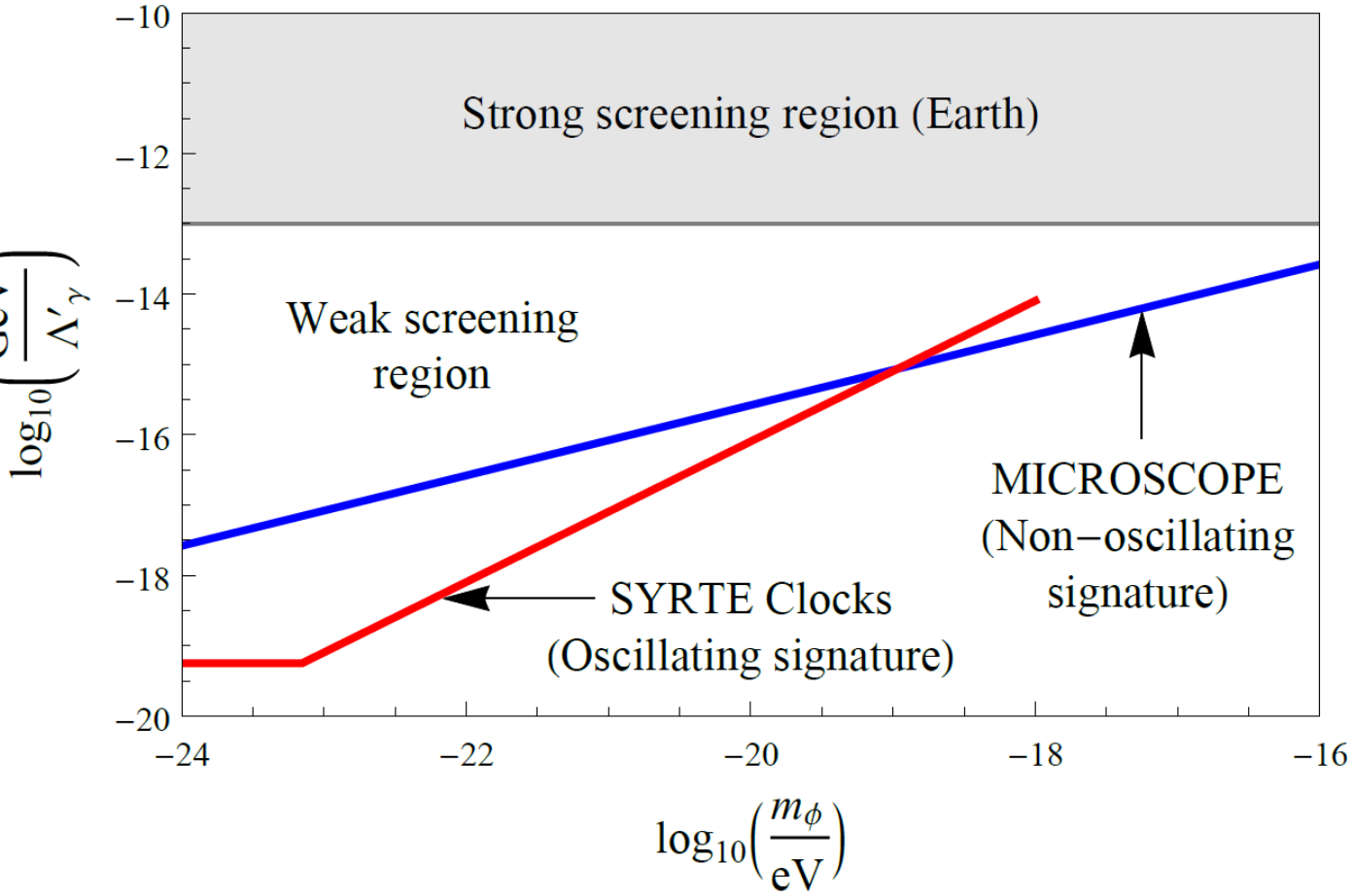
$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

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



Summary

- "Back-action" effects of ambient matter onto the scalar field in models of topological defects with φ^2 interactions induce "quasi-non-transient" variations of the fundamental constants
- Using data from accelerometers and clock-comparison experiments to search for these quasi-non-transient signatures, we've obtained more stringent limits than previous bounds from *complementary types of transient and non-transient signatures* (by up to **15 orders of magnitude**)
- Previous clock-based searches for transient signatures of passing domain walls may have assumed qualitatively incorrect signatures by neglecting "back-action" effects

Back-Up Slides

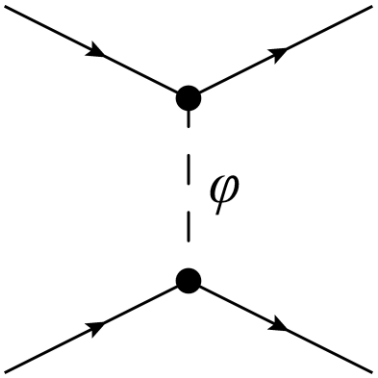
Fifth Forces: Linear vs Quadratic Couplings

[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 ($\varphi\bar{X}X$)

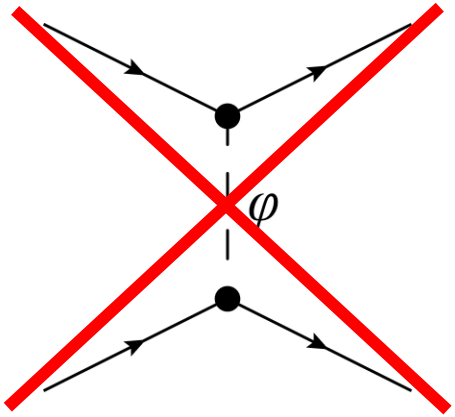
$\Box\varphi + m_\varphi^2\varphi = \pm\kappa\rho$ **Source term**



$$\varphi = \varphi_0 \cos(m_\varphi t) \pm A\frac{e^{-m_\varphi r}}{r}$$

Quadratic couplings ($\varphi^2\bar{X}X$)

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



$$\varphi = \varphi_0 \cos(m_\varphi t)\left(1 \pm \frac{B}{r}\right)$$

Gradients + amplification/screening

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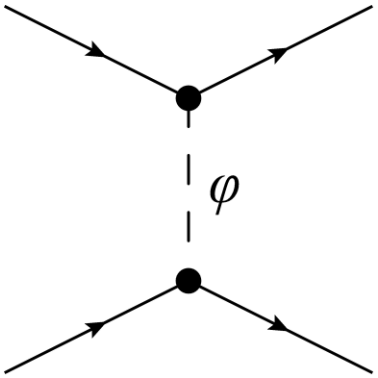

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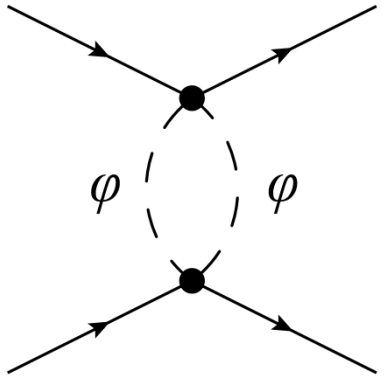


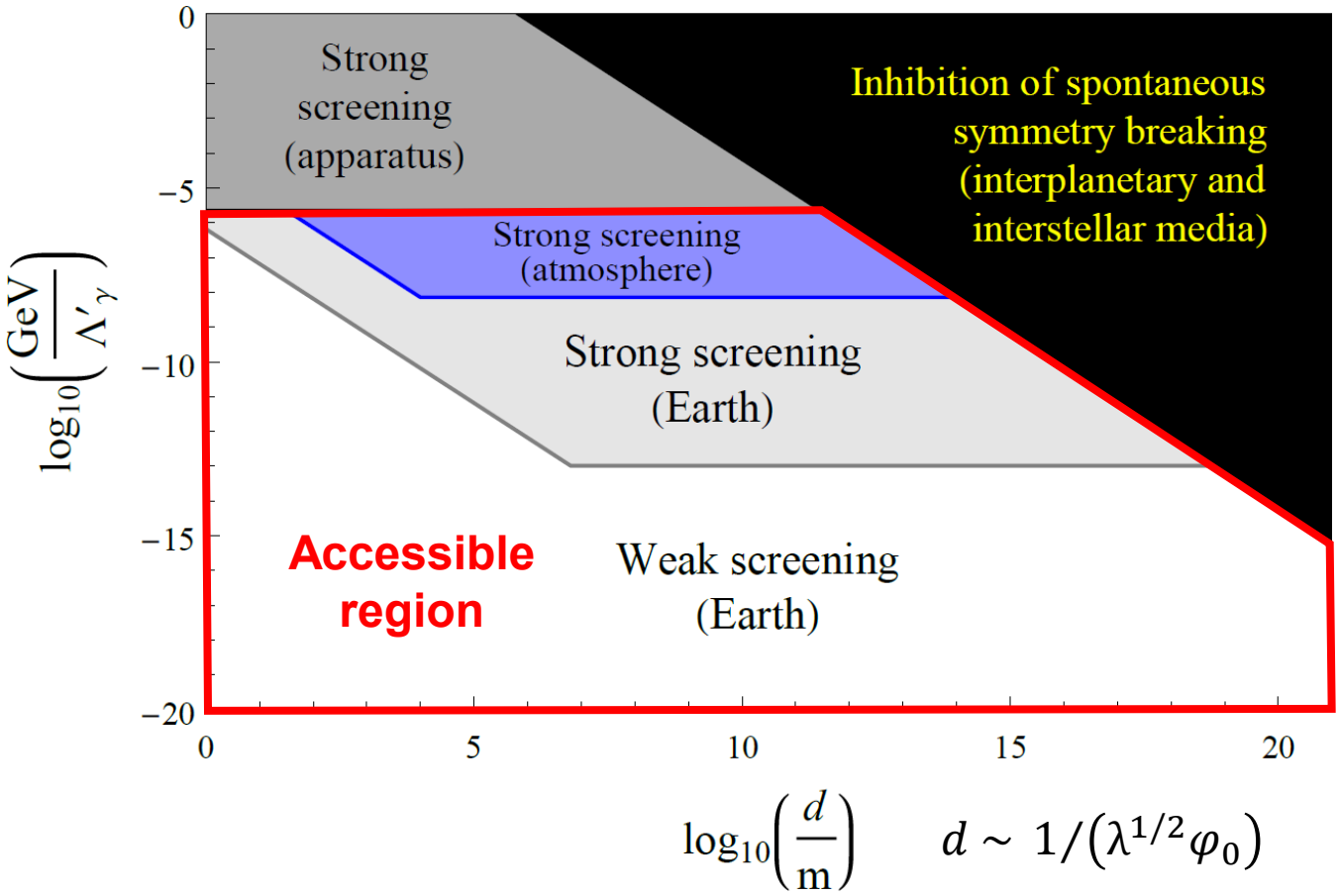
$$\varphi = \varphi_0 \cos(m_\varphi t)\left(1 \pm \frac{B}{r}\right) - C\frac{e^{-2m_\varphi r}}{r^3}$$

Gradients + amplification/screening

Screening of Scalar Field φ

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

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



Interpretation of Single-Clock-Type Experiments

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

- The Tokyo Skytree experiment measured the gravitational potential difference between a pair of Sr optical clocks separated by a height difference of $\Delta h \approx 450\,\mathrm{m}$; for details, see: [Takamoto *et al*., *Nature Photonics* **14**, 411 (2020) – talk in our Tuesday session]
- To distinguish the effects of a scalar field φ from the usual gravitational redshift effect, can "reference" a single pair of clocks against a combination of laser-ranging and gravimeter measurements (which provide an independent prediction of the clock frequency shift within the framework of relativity)

$$\left.\begin{array}{l} \Delta\nu_{\mathrm{Sr}} \propto \Delta\left(m_e\alpha^2\right) \\ \Delta\boldsymbol{a}_{\mathrm{grav}} \propto \boldsymbol{\nabla} m_N \end{array}\right\} \Rightarrow \left(\frac{\Delta\nu_{\mathrm{Sr}}}{\nu_{\mathrm{Sr}}}\right)_{\mathrm{eff}} \approx \Delta\left(\varphi^2\right)\left[\frac{2}{\left(\Lambda'_\gamma\right)^2} + \frac{1}{\left(\Lambda'_e\right)^2} - \frac{1}{\left(\Lambda'_N\right)^2}\right]$$

“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.]