Composite Ultralight Scalars, Fifth Forces and Atomic Clocks

Shourya Mukherjee - University of Maryland

Phenomenology Symposium - 11th May, 2026

Abhishek Banerjee, Zackaria Chacko, Shourya Mukherjee [2605.xxxxx]

Outline

A. Ultralight Scalars

- Basic Properties
- Direct Probes
- Indirect Probes

B. Why Compositeness?

- Compositeness Phenomenology
- Explicit Models

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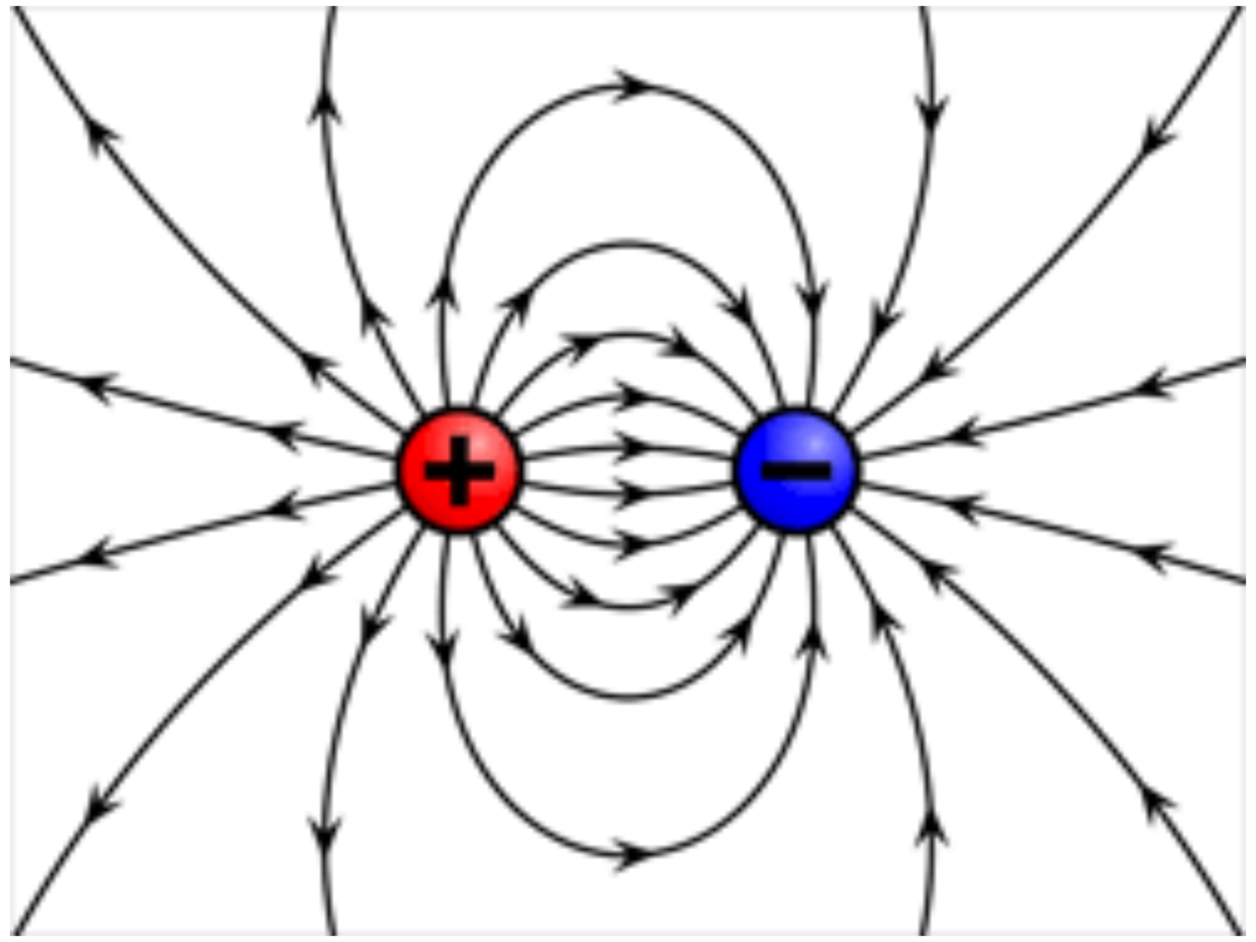
- Direct Probes
- Indirect Probes

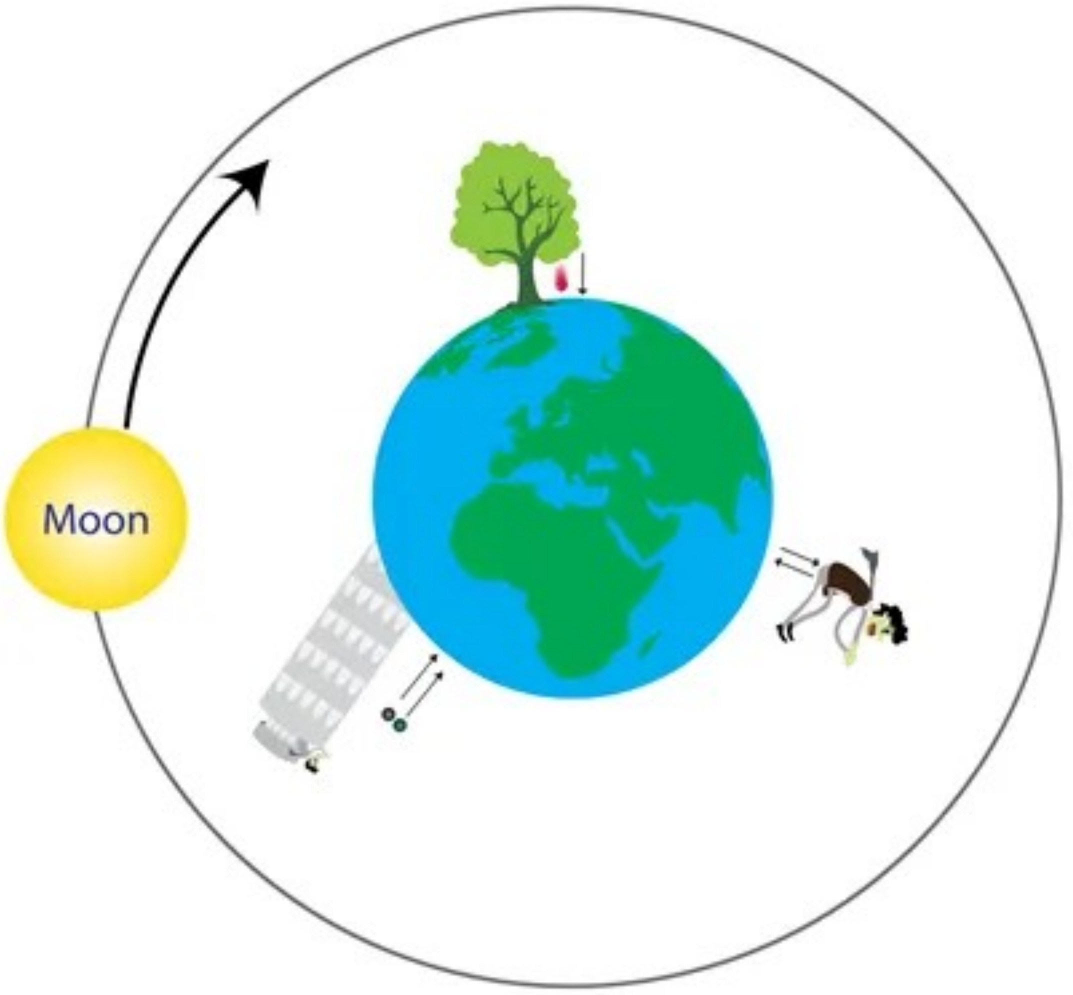
B. Why Compositeness?

- Compositeness Phenomenology — In this talk
- Explicit Models

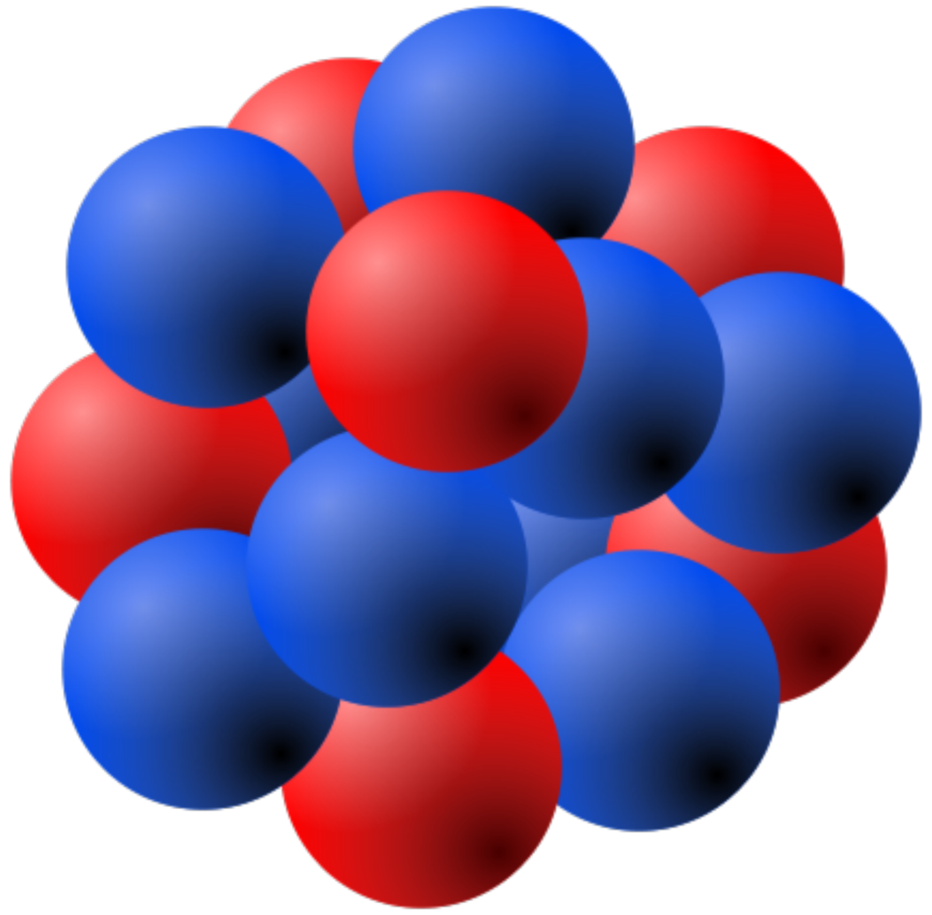
Forces



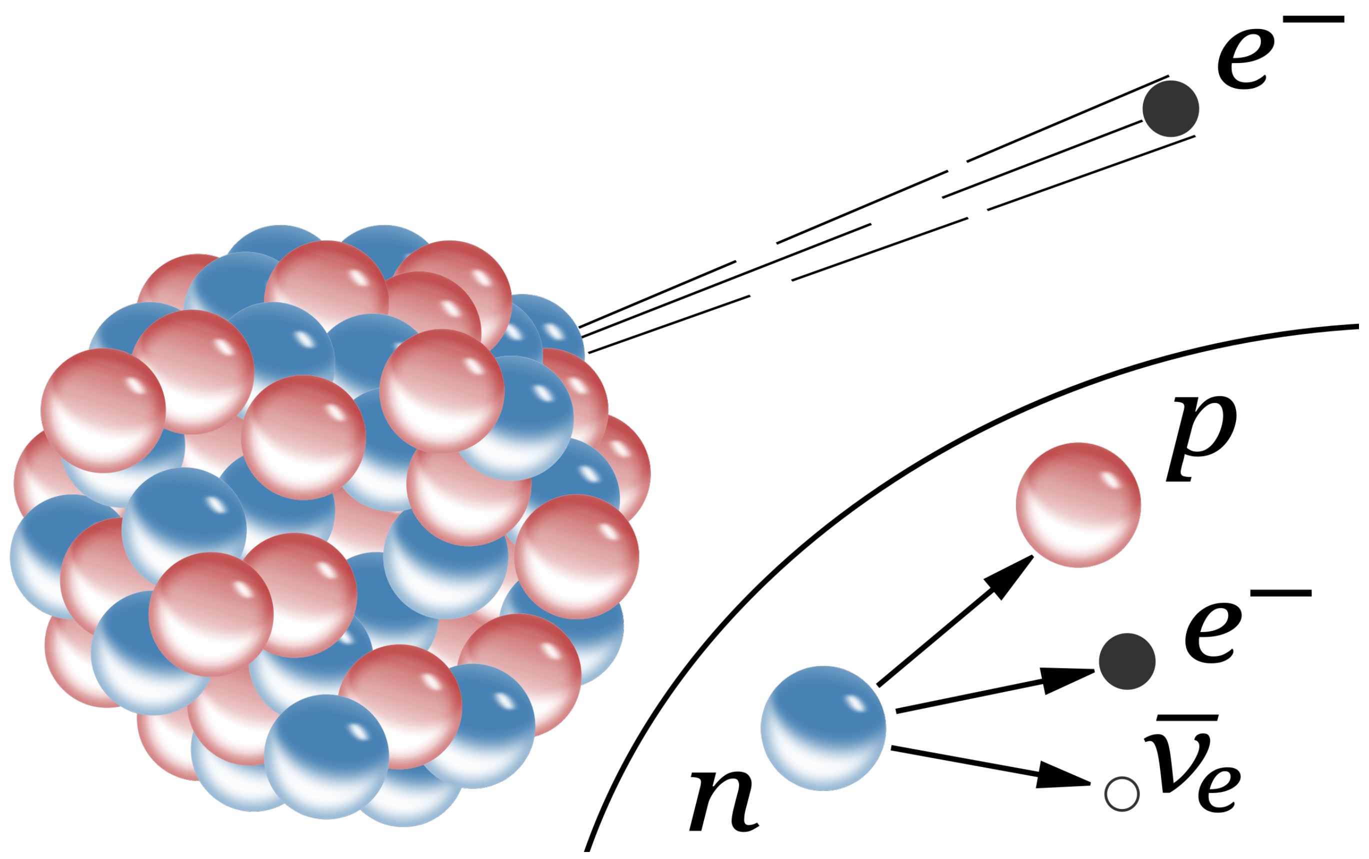
Electromagnetism



Gravity

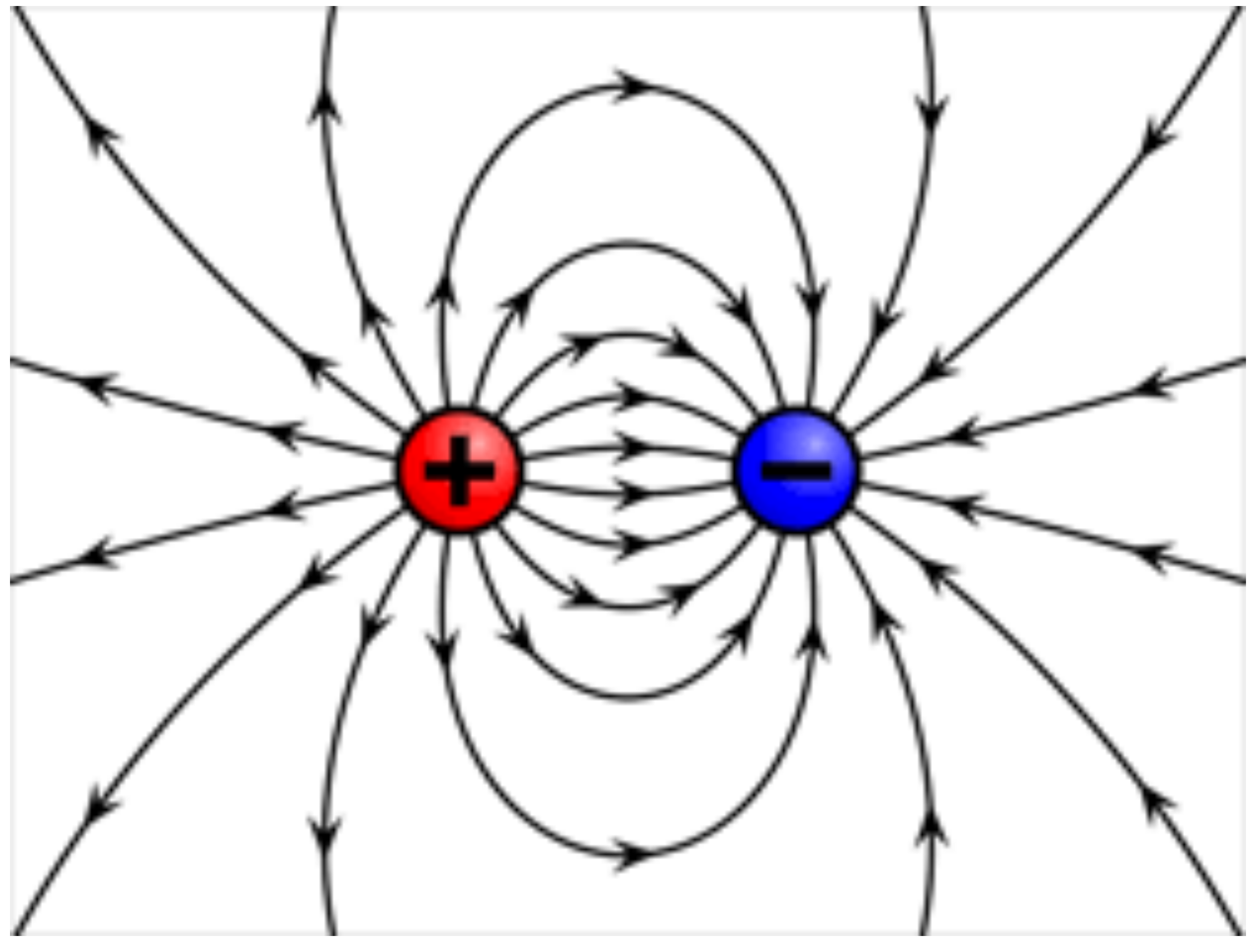


Strong Force



Weak force

Forces



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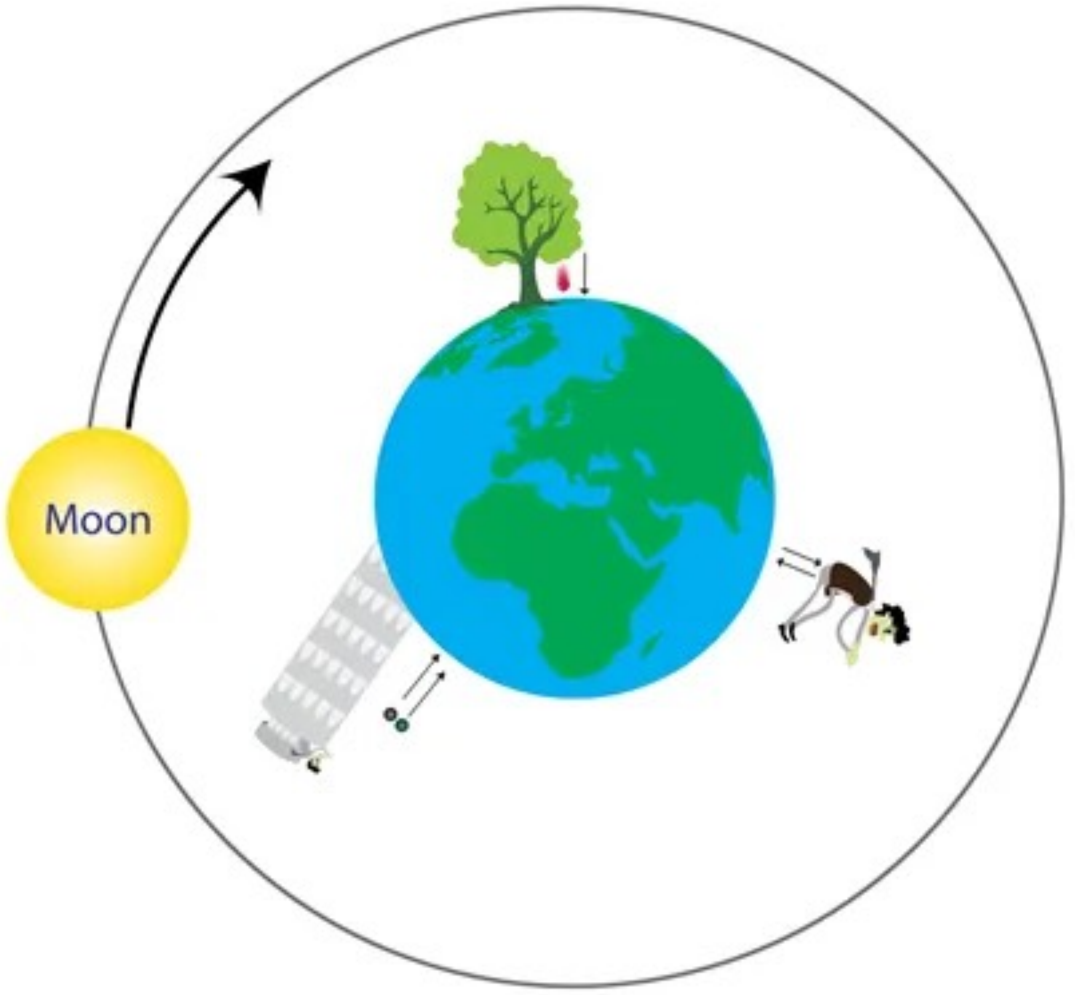

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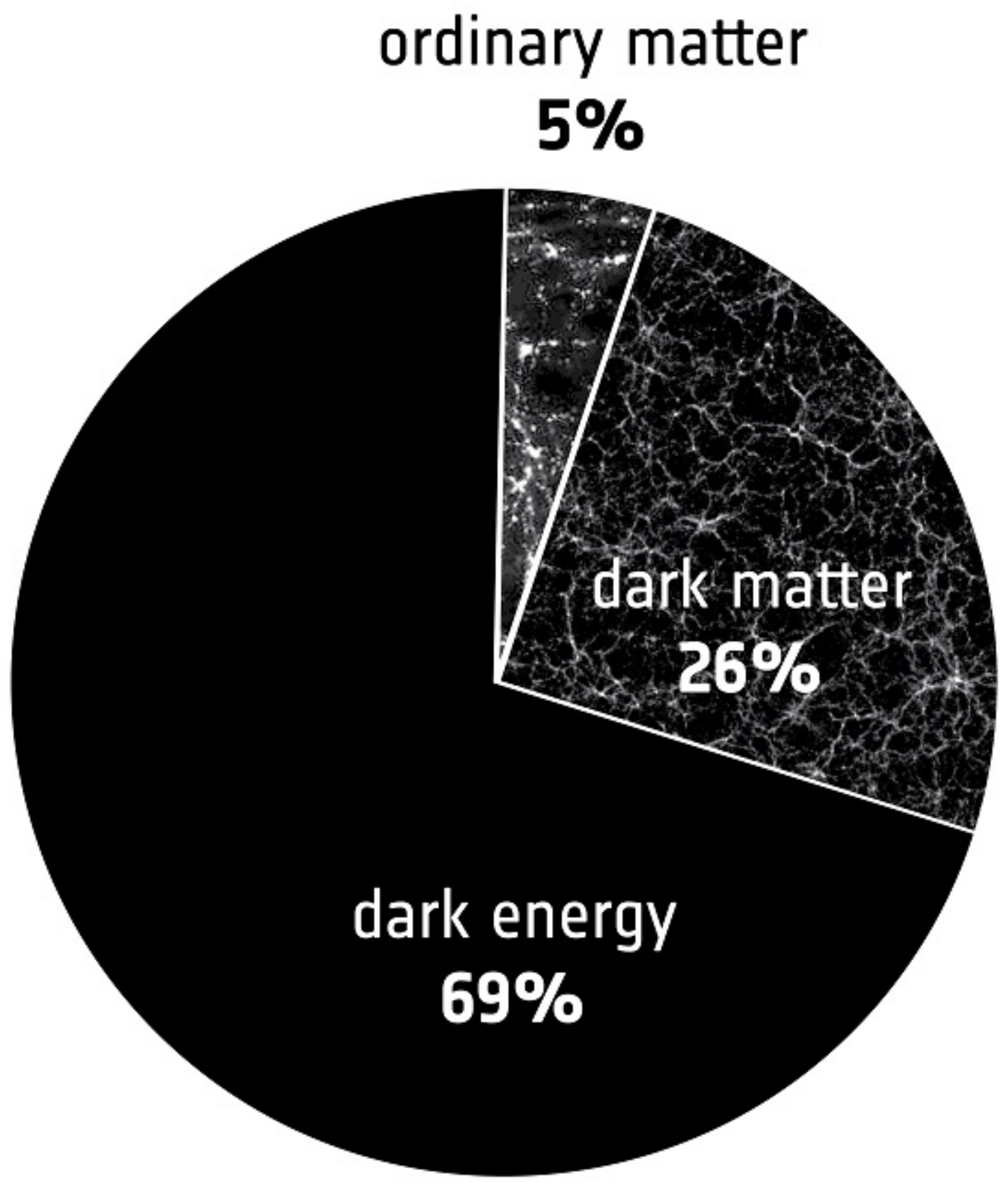
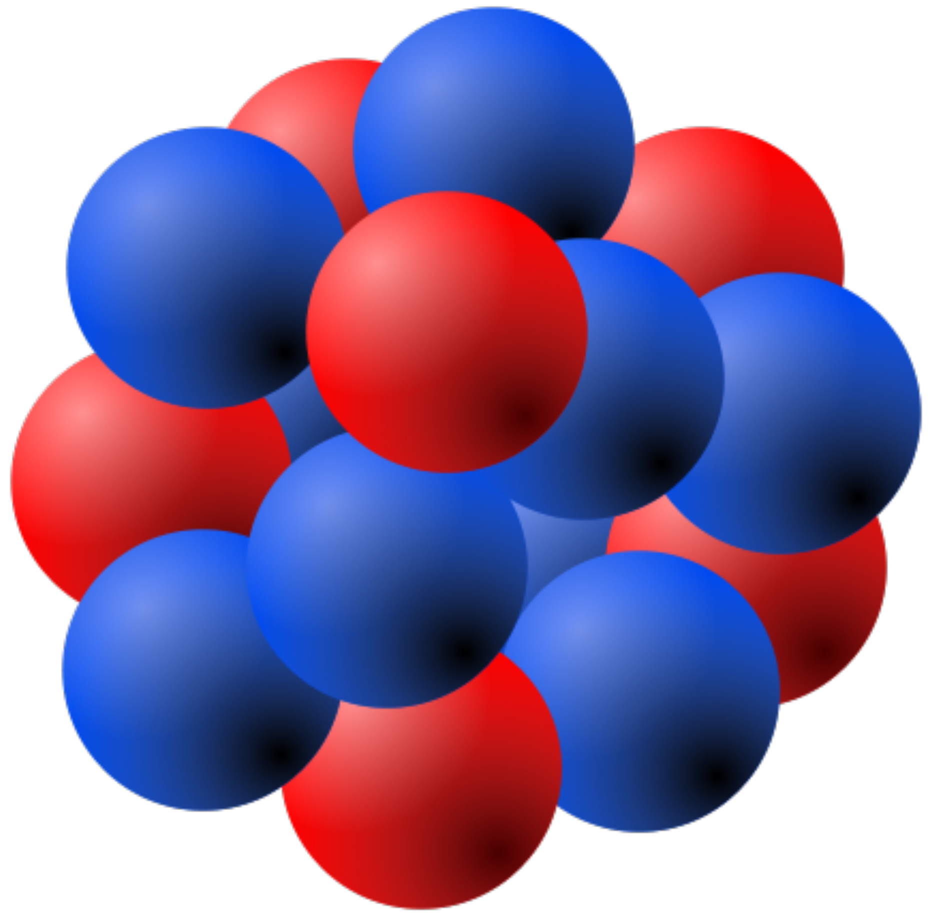


Dark Sectors



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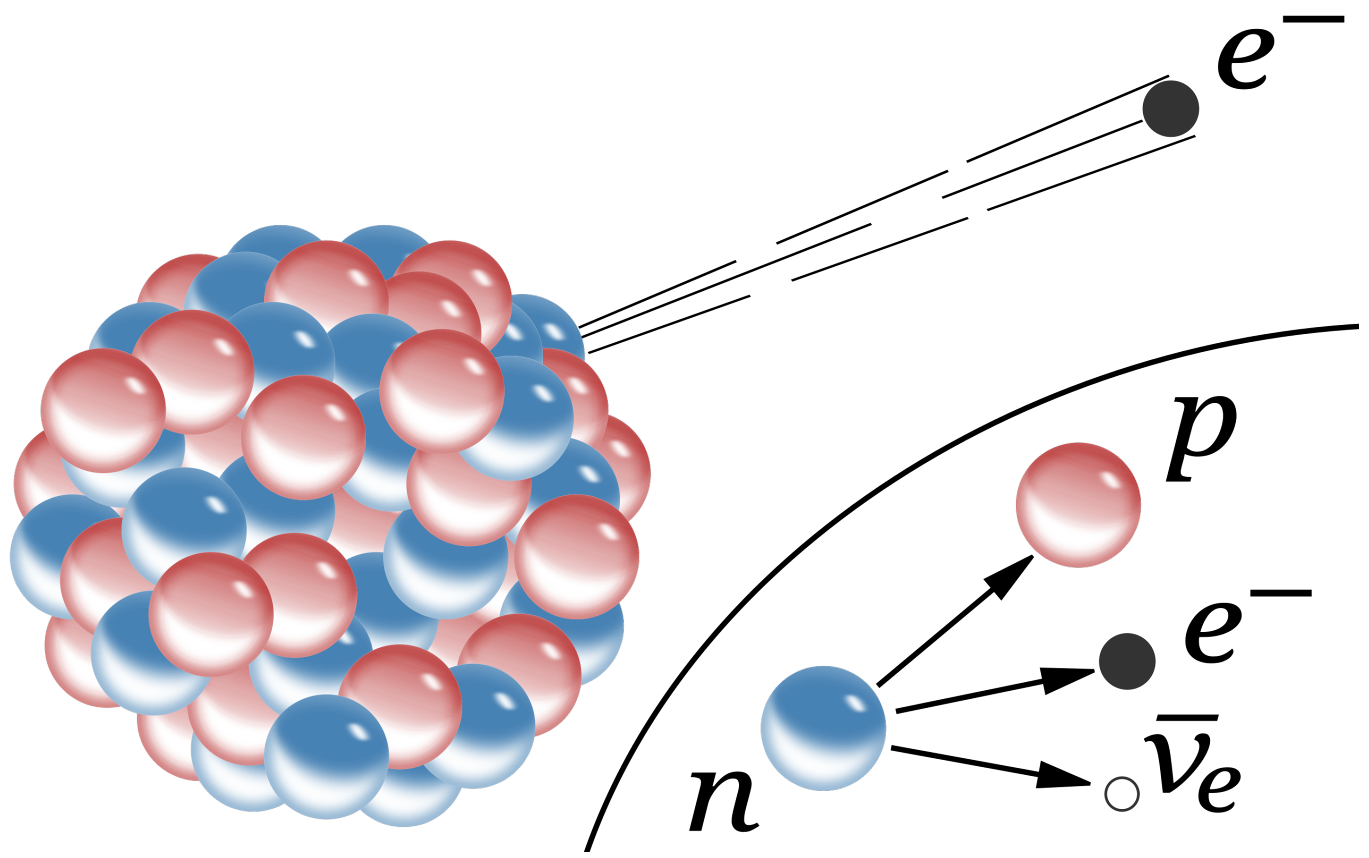

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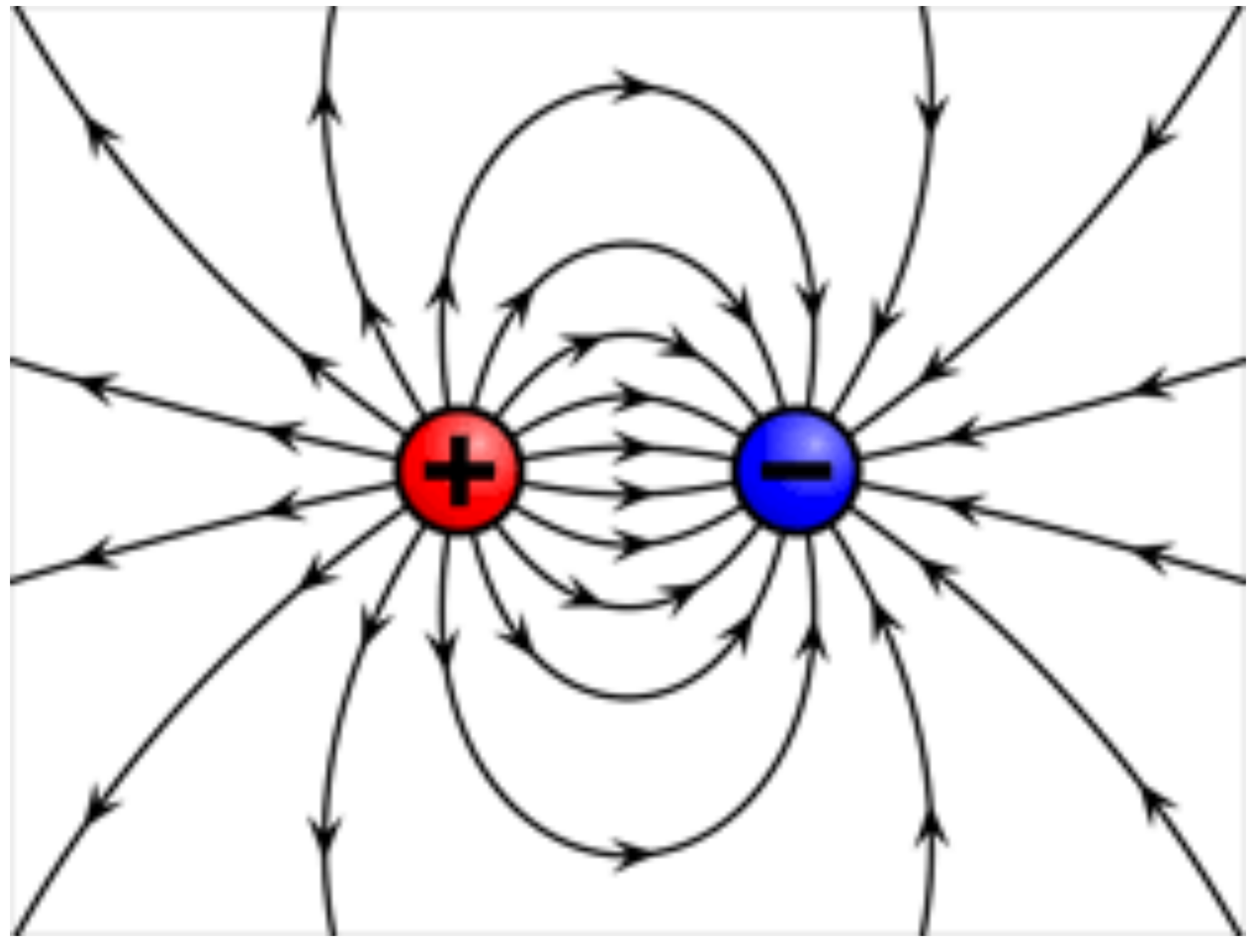

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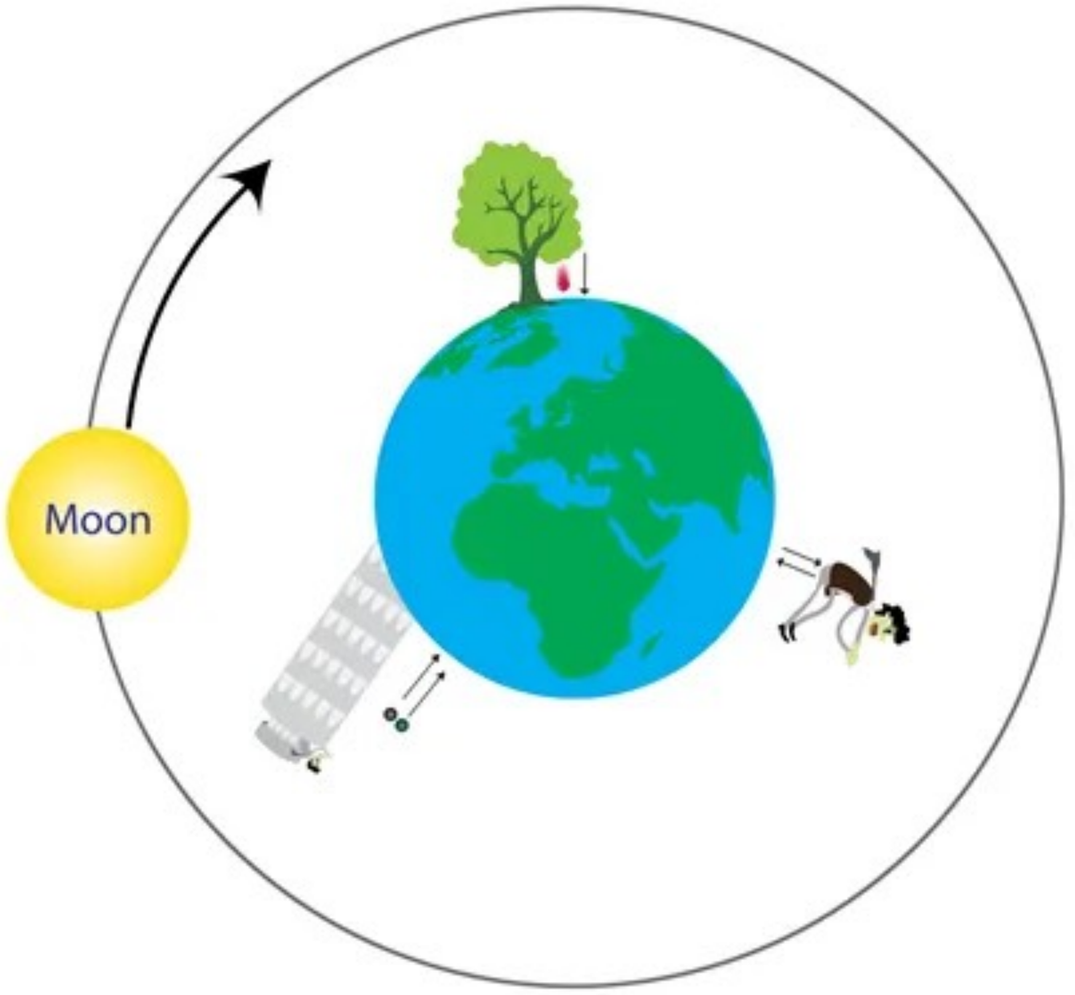

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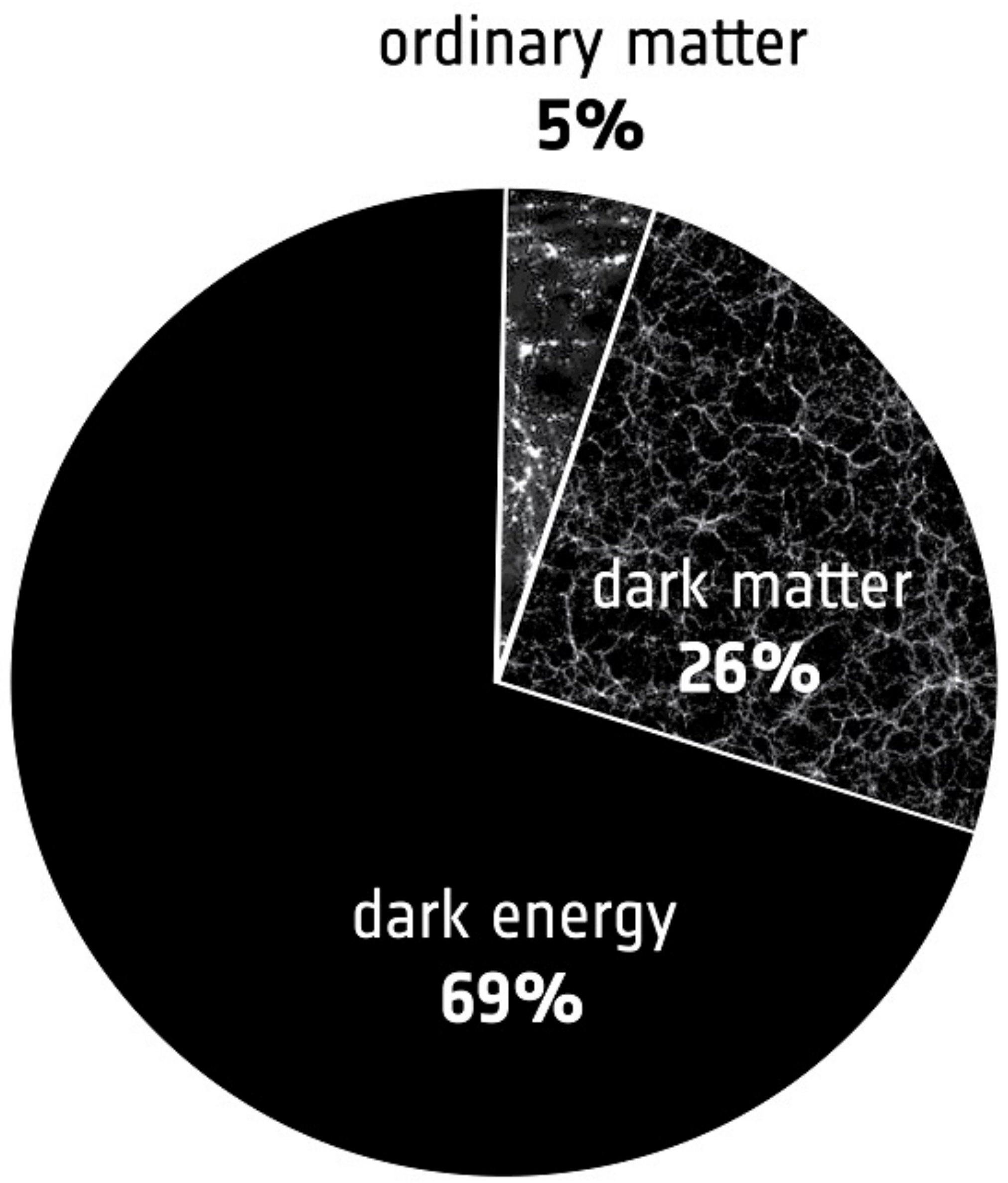
New forces!



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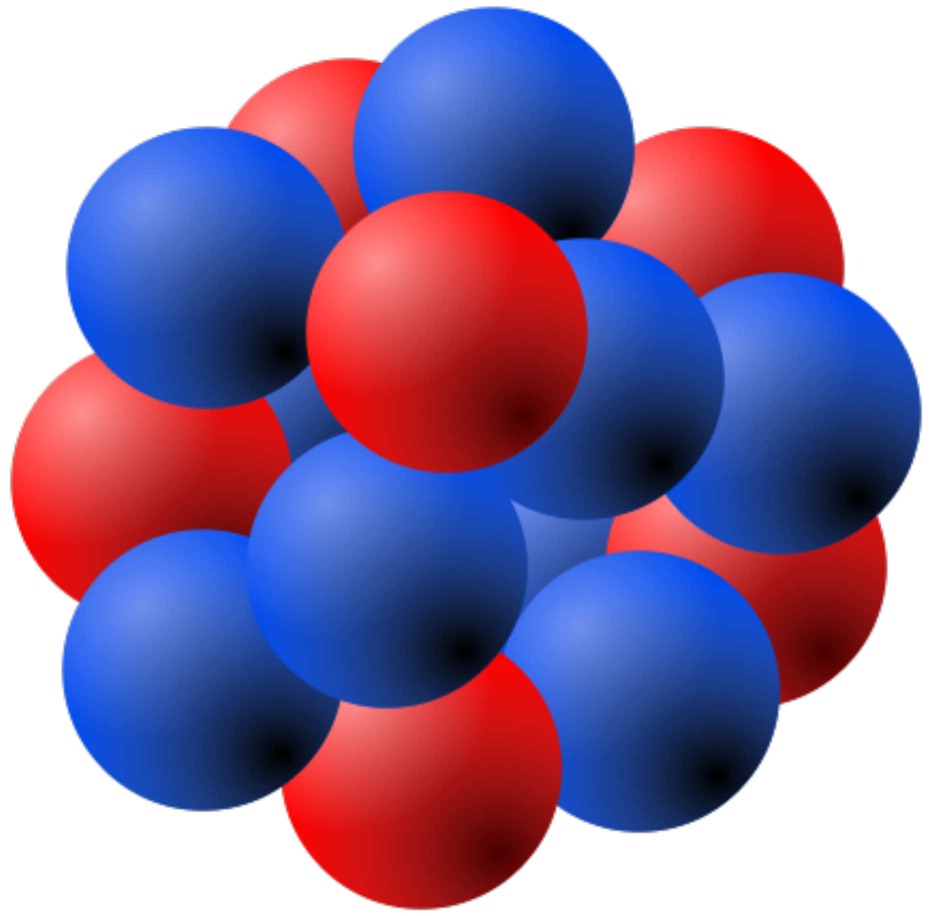

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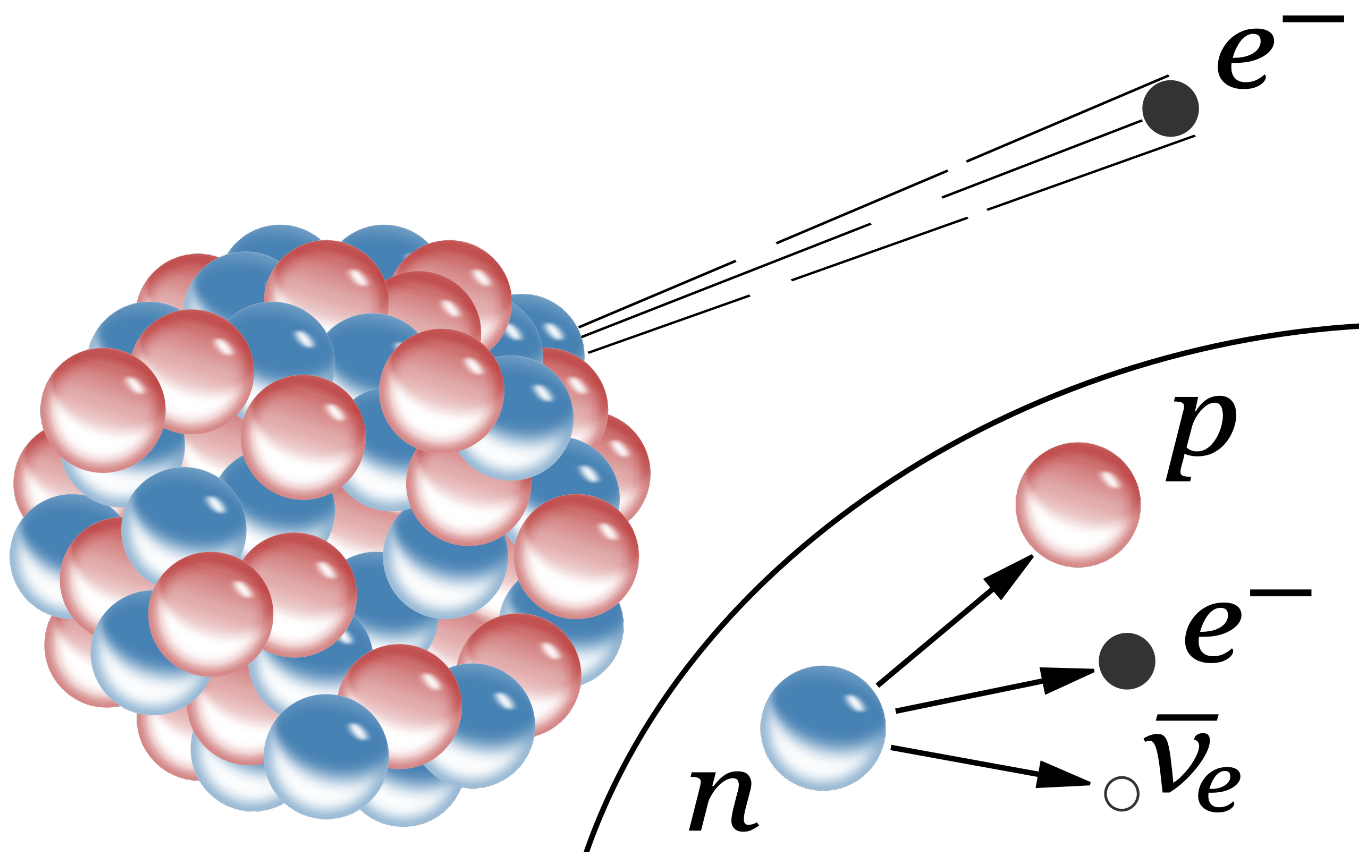
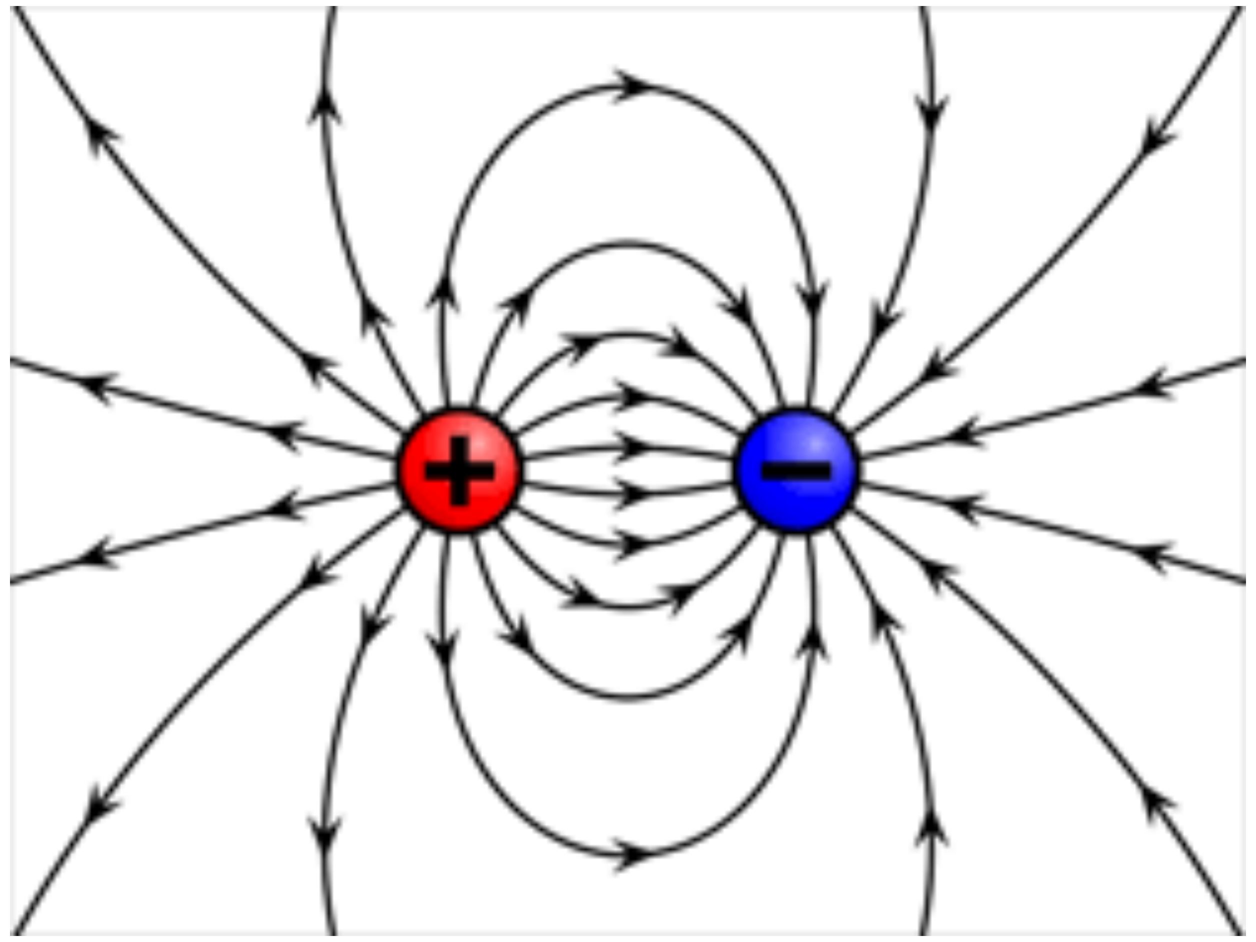


Weak force

Forces - Scalar Mediated Forces



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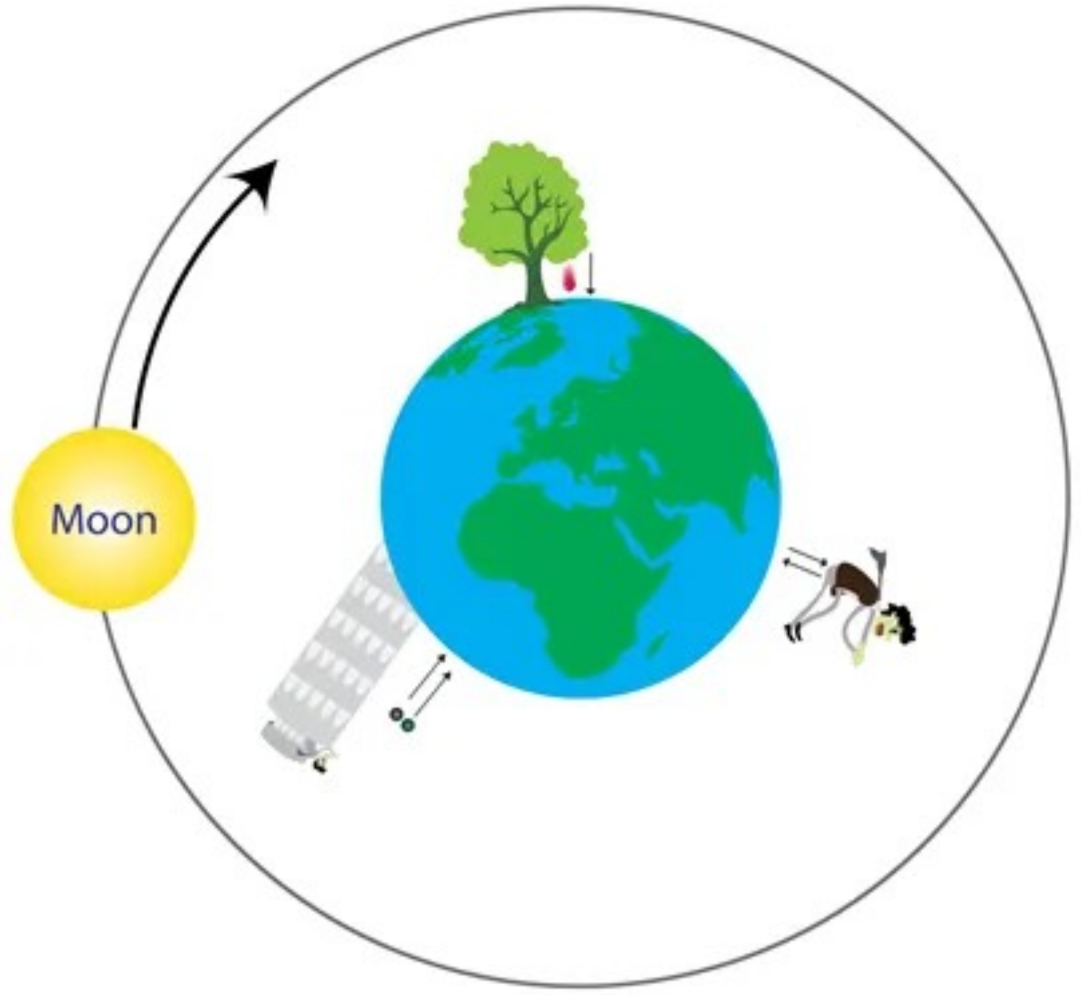

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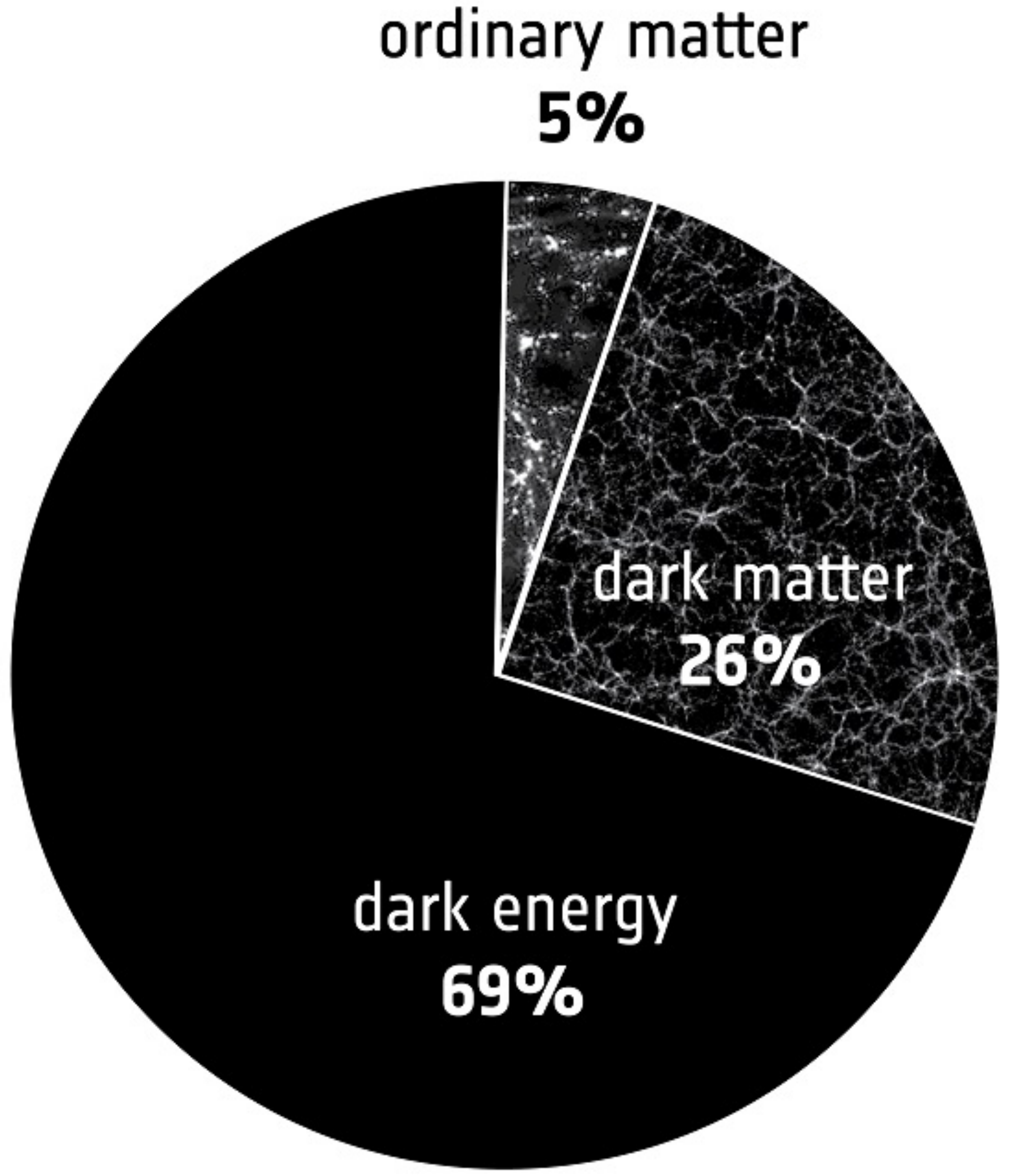

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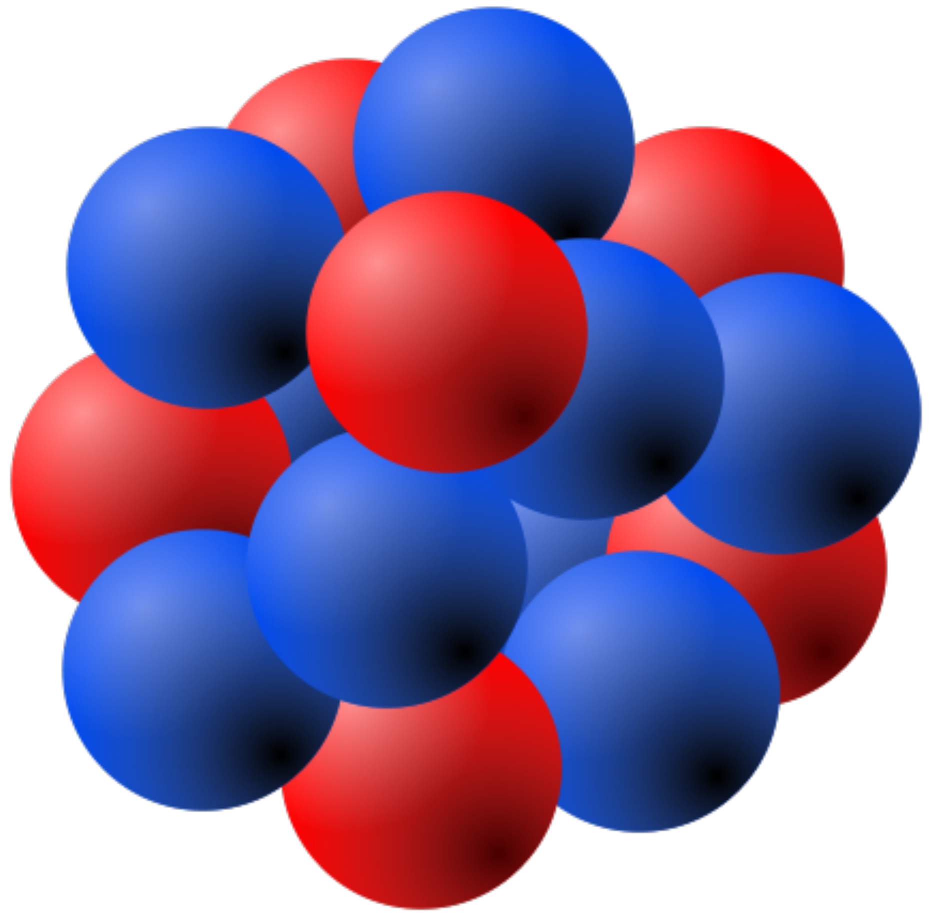

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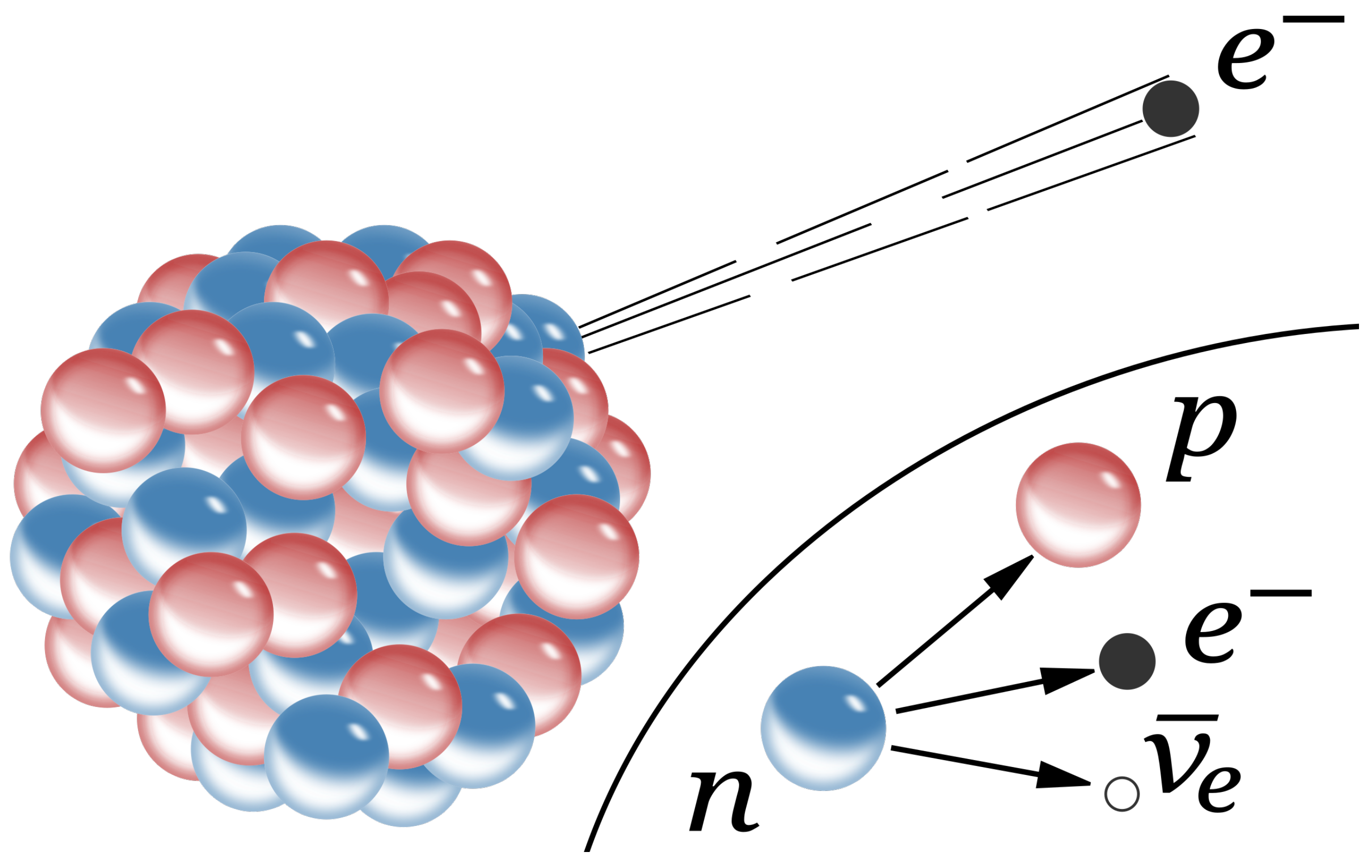
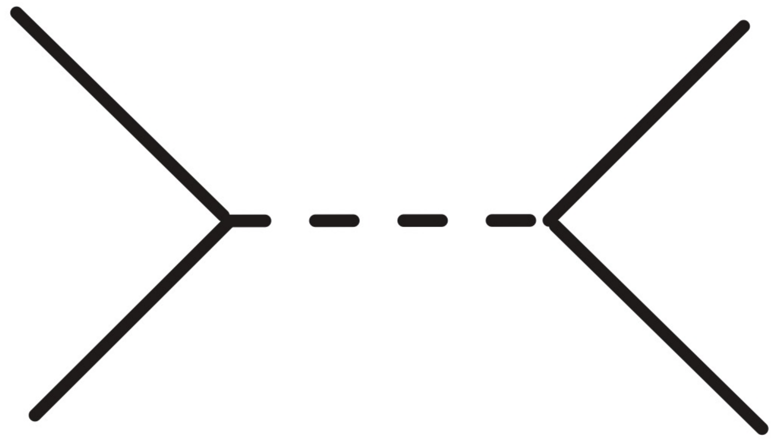


Weak force

$$\underline{\varphi \mathcal{O}_{\rm SM}}$$



$$V(r) = -\frac{\alpha_5}{r} e^{-m_\varphi r}$$

Coupling to Photons*

$$\mathscr{L} \supset \frac{d_e}{M_{\rm Pl}} \varphi F^{\mu\nu} F_{\mu\nu}$$

d_e : dimensionless interaction strength

* For the purpose of this talk, I do not distinguish between the hypercharge boson and photon.

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This interaction leads to

1) Variation of fine structure constant

$$\alpha(\varphi) = \alpha(0)\left(1 + \frac{d_e}{M_{\rm Pl}}\varphi\right)$$

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2) Weak Equivalence Principle (WEP) violating, long-range, fifth forces

Consider the EM contribution to the mass of the nucleon: $m_N(\alpha)$

Thus m_N now has φ dependence: $m_N(\varphi) \equiv m_N(\alpha(\varphi))$

Coupling to Photons

At leading order,

$$m_N(\varphi) = m_N(0) + \left.\frac{\partial m_N}{\partial \varphi}\right|_0 \varphi = m_N(0) + \left.\frac{\partial m_N}{\partial \ln \alpha}\frac{\partial \ln \alpha}{\partial \varphi}\right|_0 \varphi = m_N(0) + \frac{\partial m_N}{\partial \ln \alpha}\frac{d_e}{M_{\mathrm{Pl}}}\varphi$$

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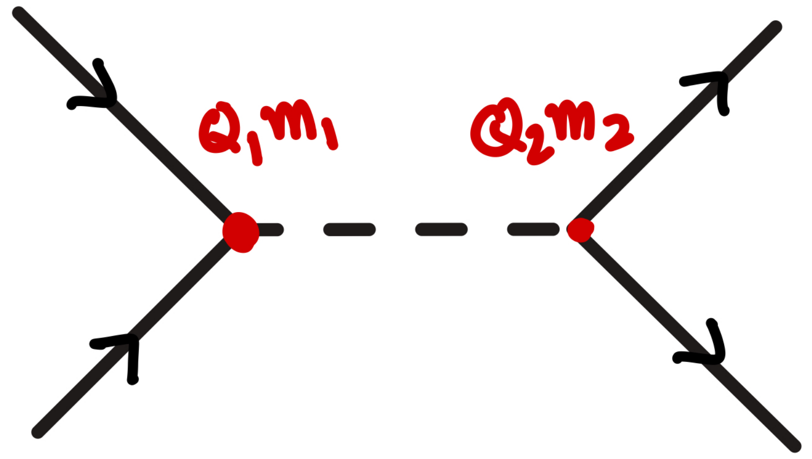
This translates into a Yukawa force coupling between nucleons and φ

$$\mathscr{L} \supset m_N(\varphi)\bar{N}N \to \frac{d_e}{M_{\rm Pl}}\left[\frac{\partial \ln m_N}{\partial \ln \alpha} m_N\right]\varphi \bar{N}N$$

composition dependent



We define the "dilatonic charge" of a test source as,

$$Q_A = \frac{\partial \ln m_A}{\partial \ln \alpha}$$

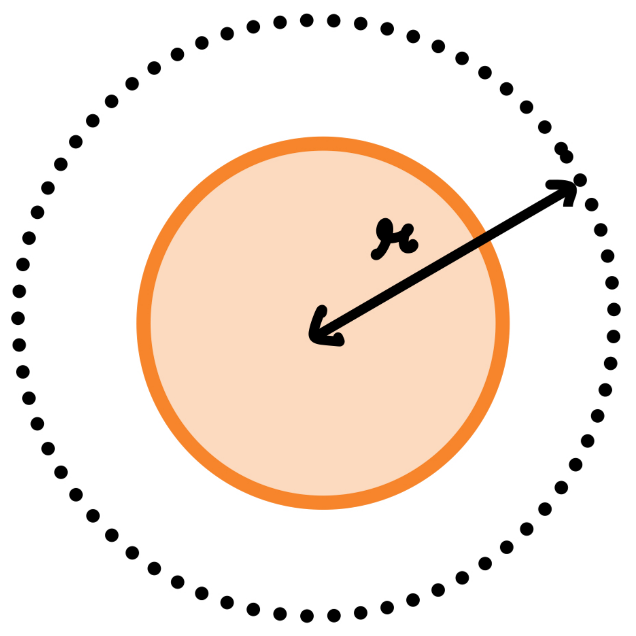
Sourcing of ULS Field

Any object generates a nonzero φ field. The field is being generated by the "charge" QM.

Delaunay, Lee, Ozeri, Perez, Ratzinger, Yu

Outside a homogenous spherical source of radius R and mass M, the field is,

$$\varphi\,(r > R) \quad \xrightarrow{m_\varphi R \ll 1} \quad -\,QM\,\frac{d_e}{M_{\rm Pl}}\frac{e^{-m_\varphi r}}{4\pi r}$$



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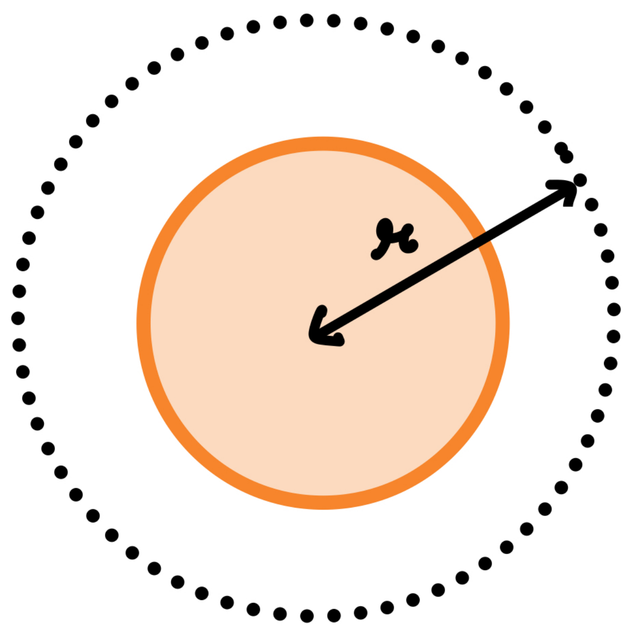
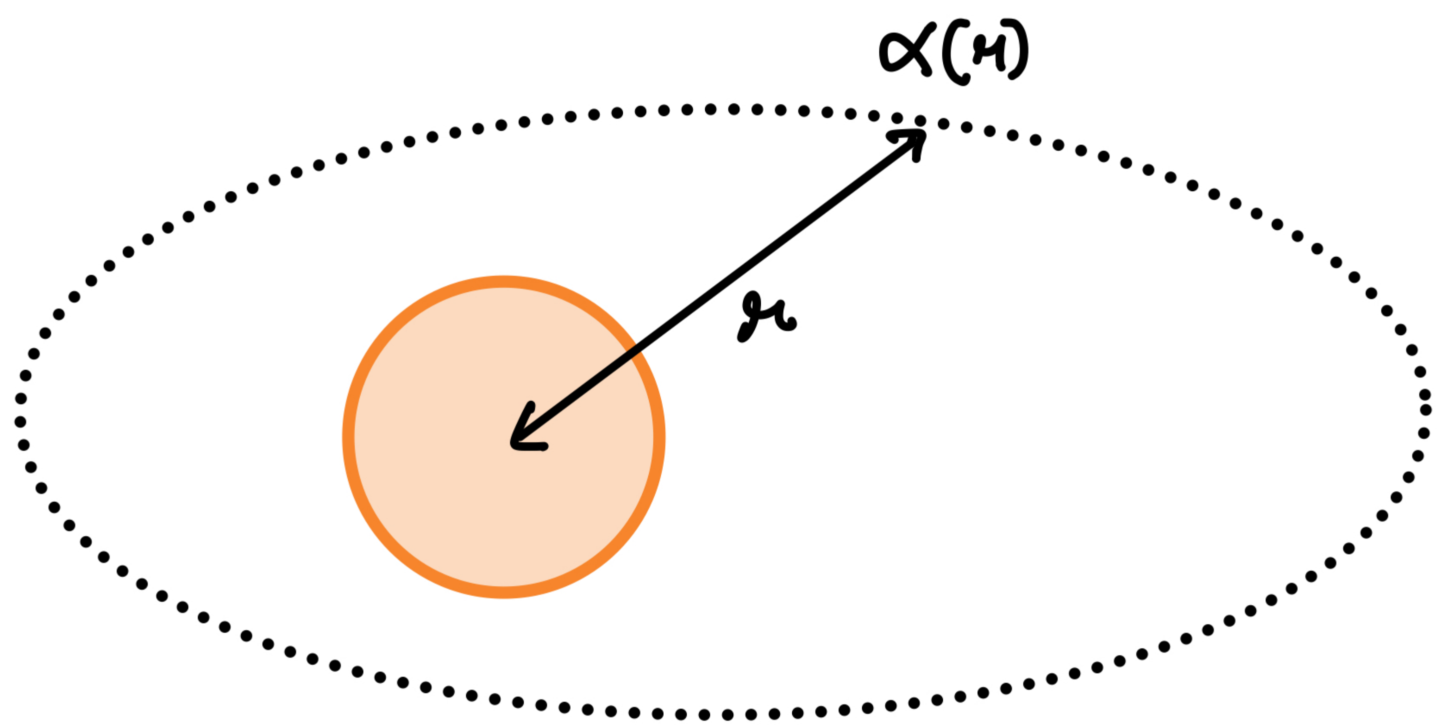


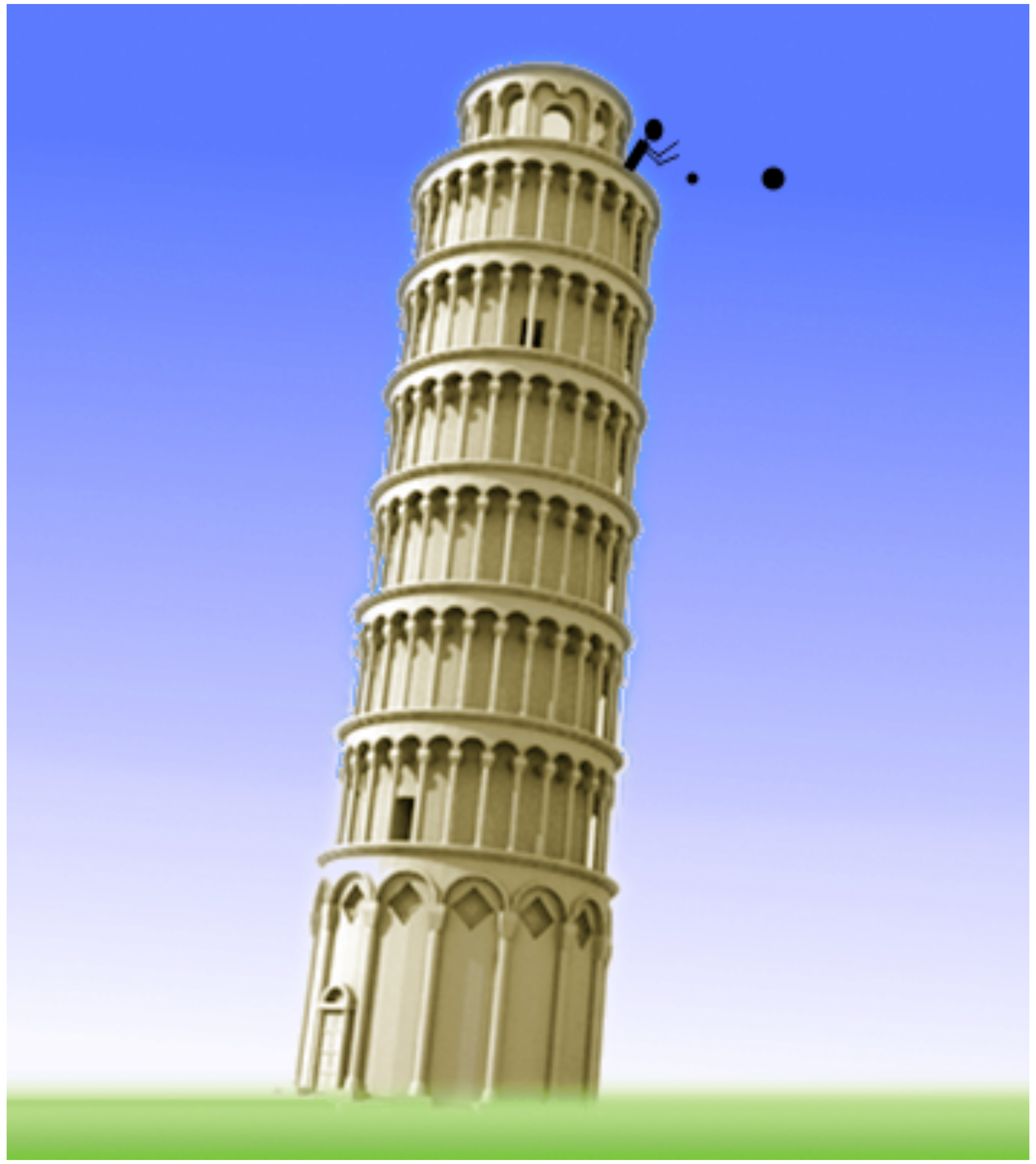
1) Massive objects such as Earth and Sun behave as coherent static sources for φ.

2) $\alpha(\varphi(r))$ is dependent on its position from the source.



Direct Probes - Test of WEP Violation

More and more sophisticated versions of dropping objects.



Leaning Tower of Pisa experiment

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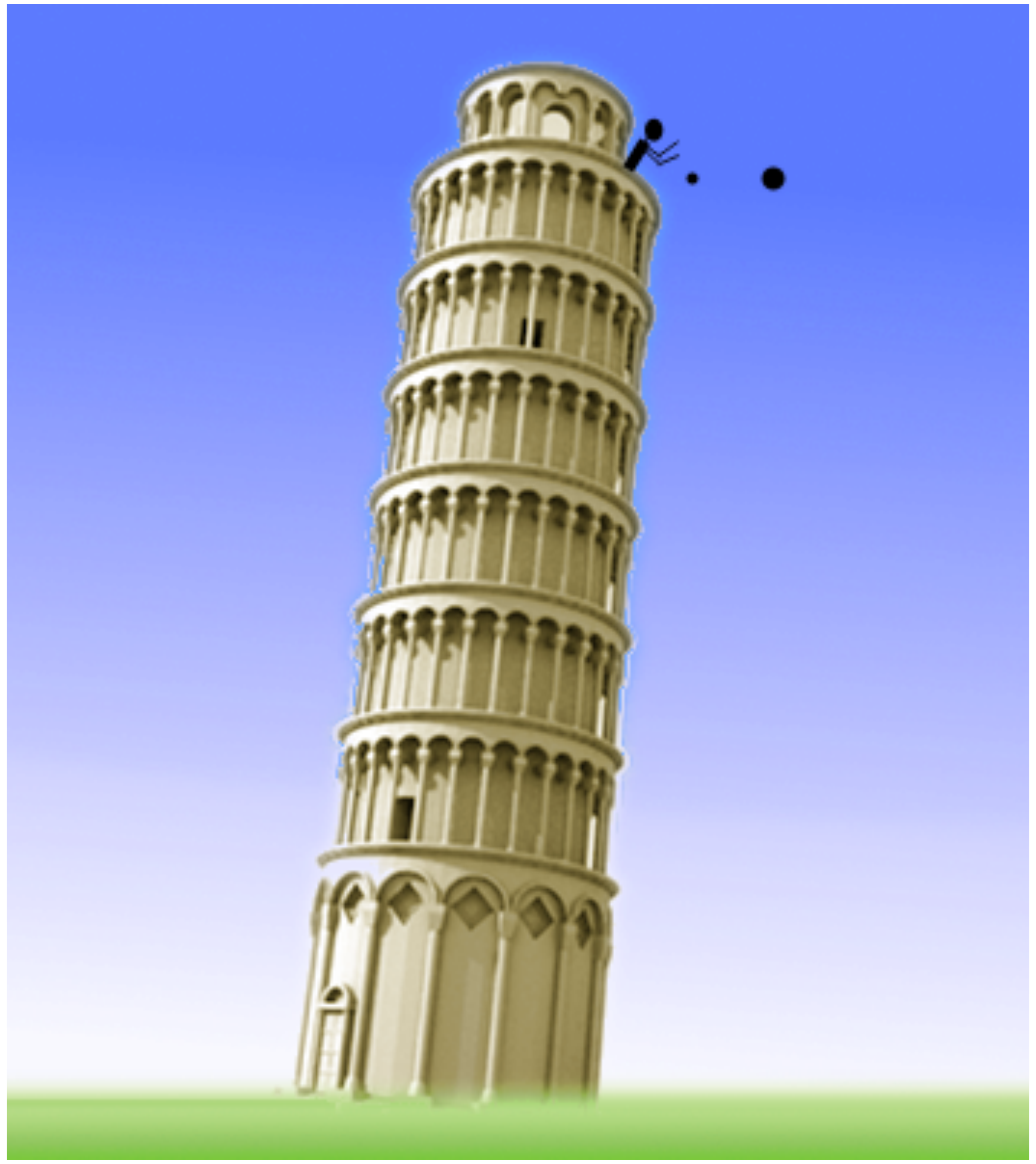

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MICROSCOPE
Satellite based experiment in low orbit

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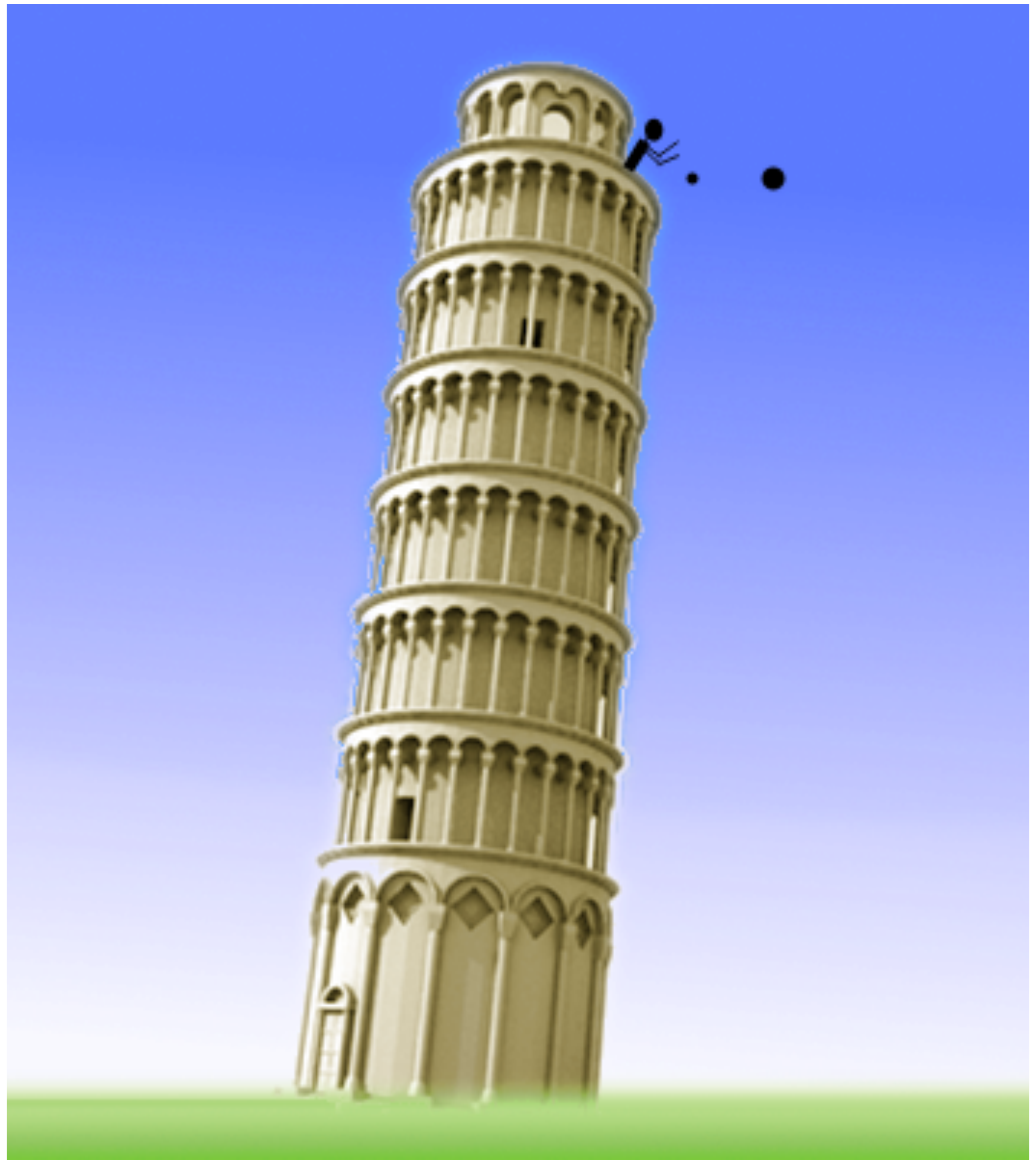

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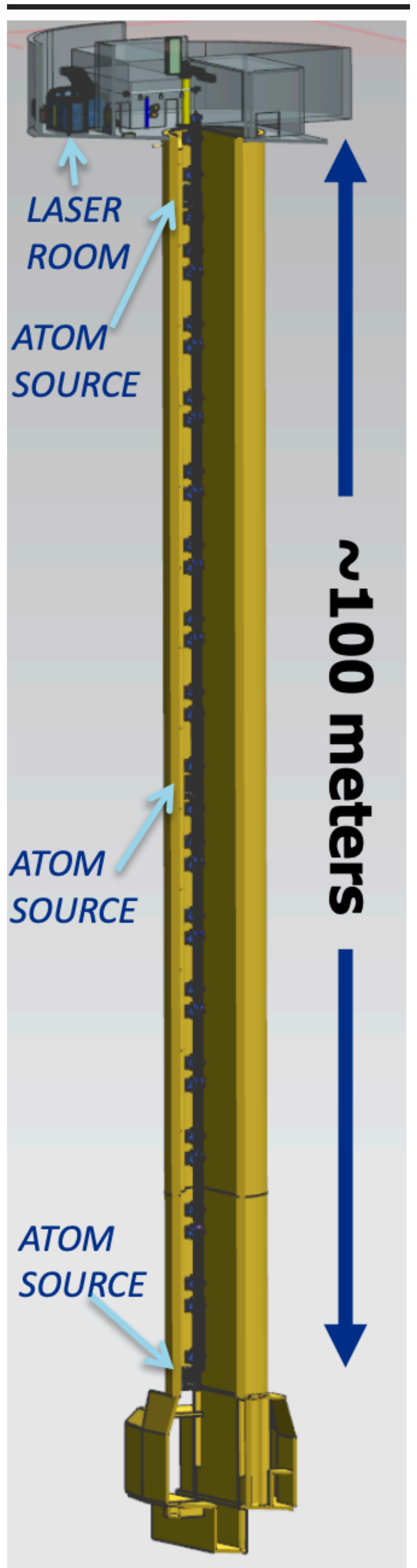

Cold atom interferometry

MAGIS-100

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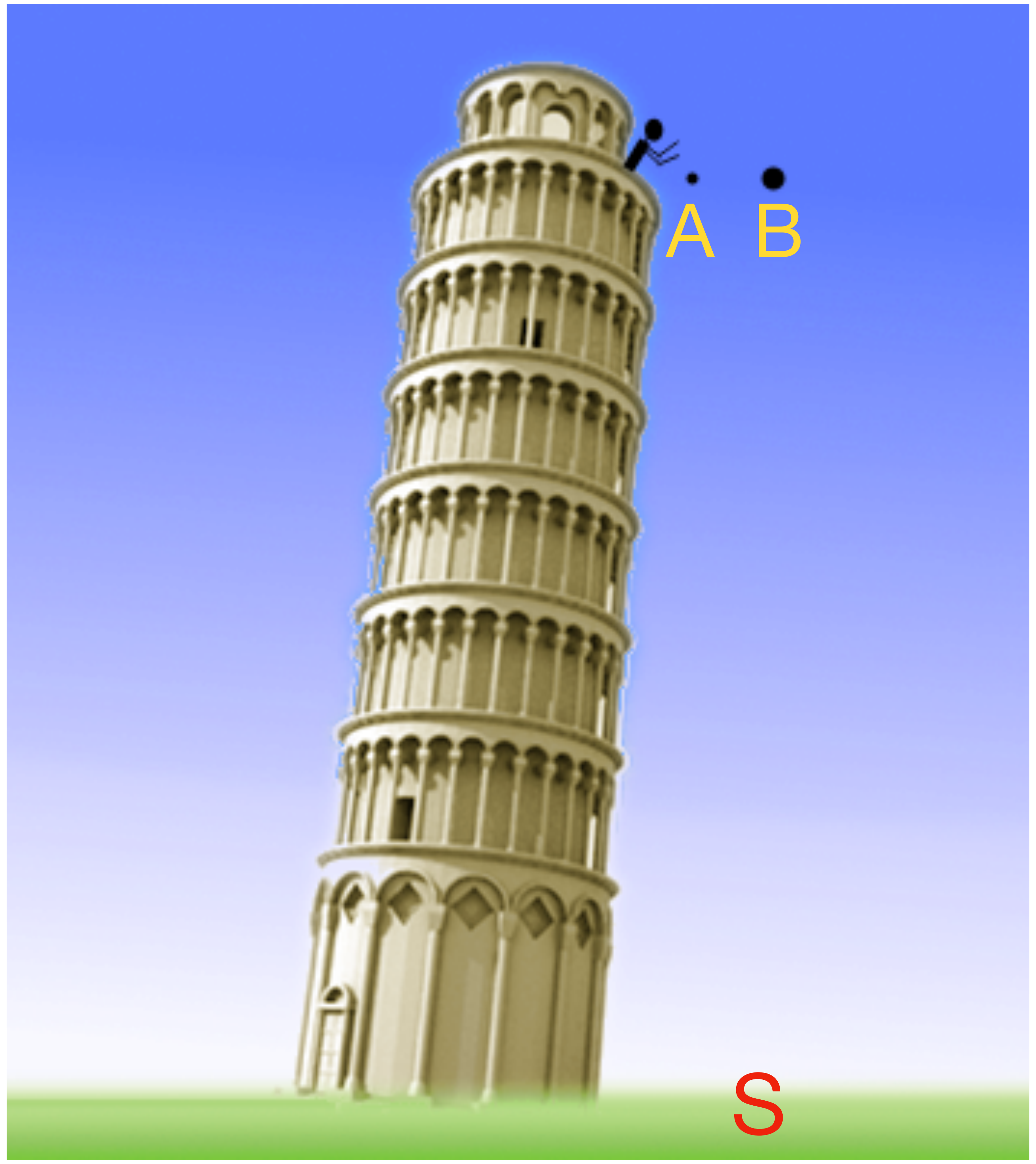

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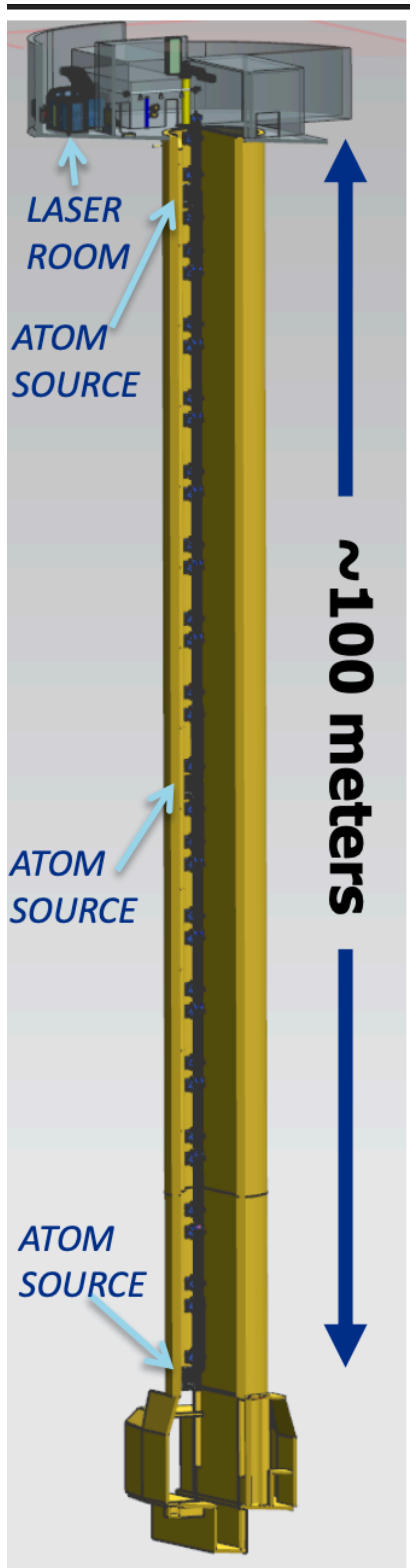
Satellite based experiment in low orbit

$$\eta_{EP} = 2\frac{|\vec{a}_{A,S} - \vec{a}_{B,S}|}{|\vec{a}_{A,S} + \vec{a}_{B,S}|} \simeq d_e^2\, \Delta Q_{AB}\, Q_s$$



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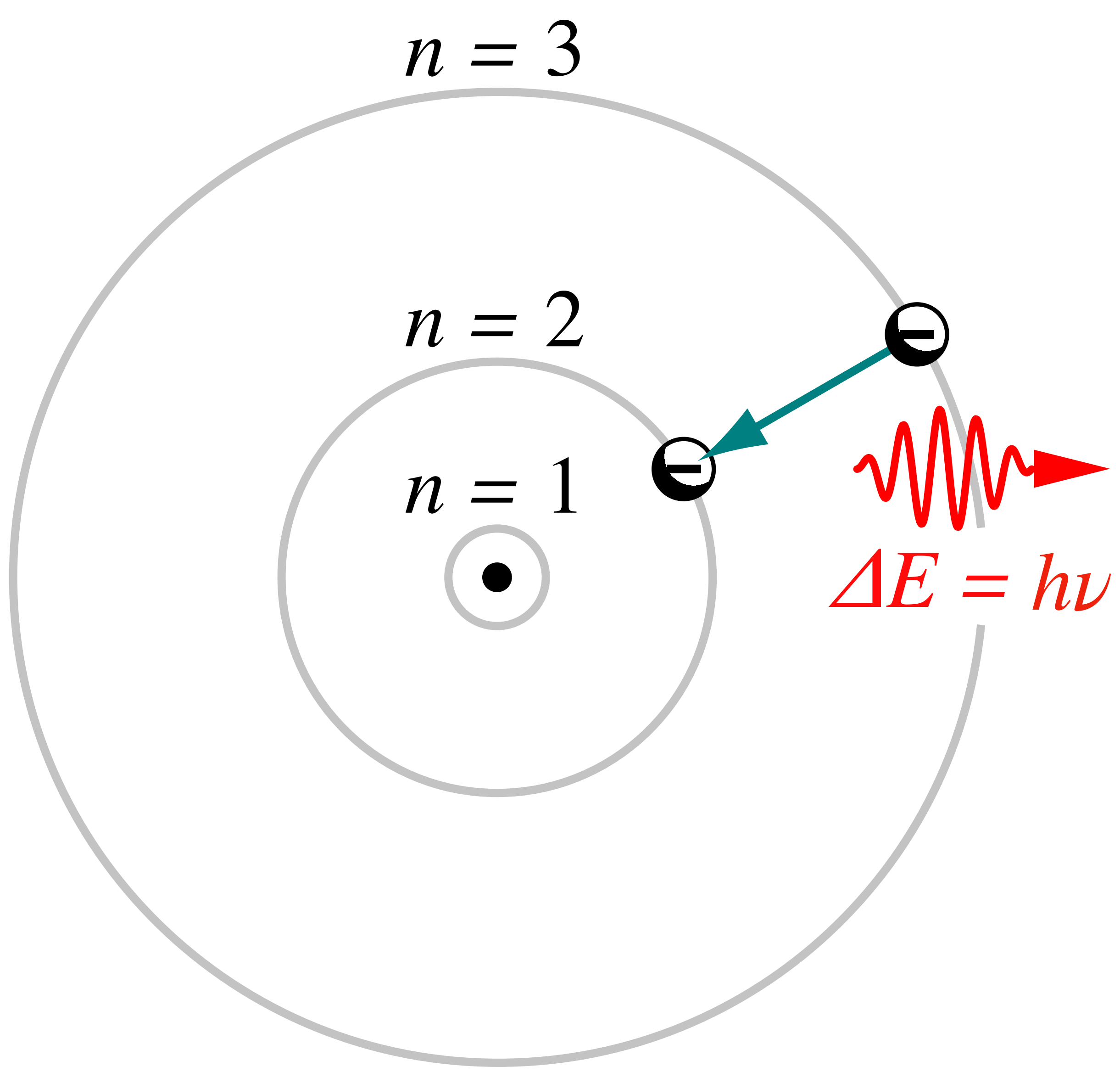
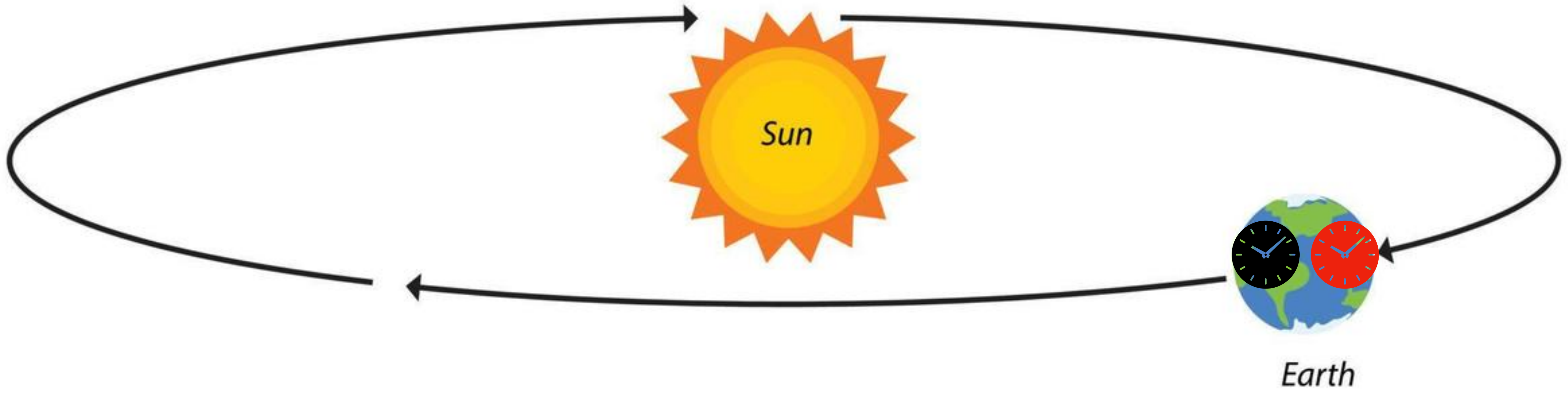
Indirect Probes - Clocks

Atomic/nuclear transitions are very sensitive to variations in $\alpha(\varphi(r))$. This can be used to indirectly test for EP violations.





Two different clocks on Earth

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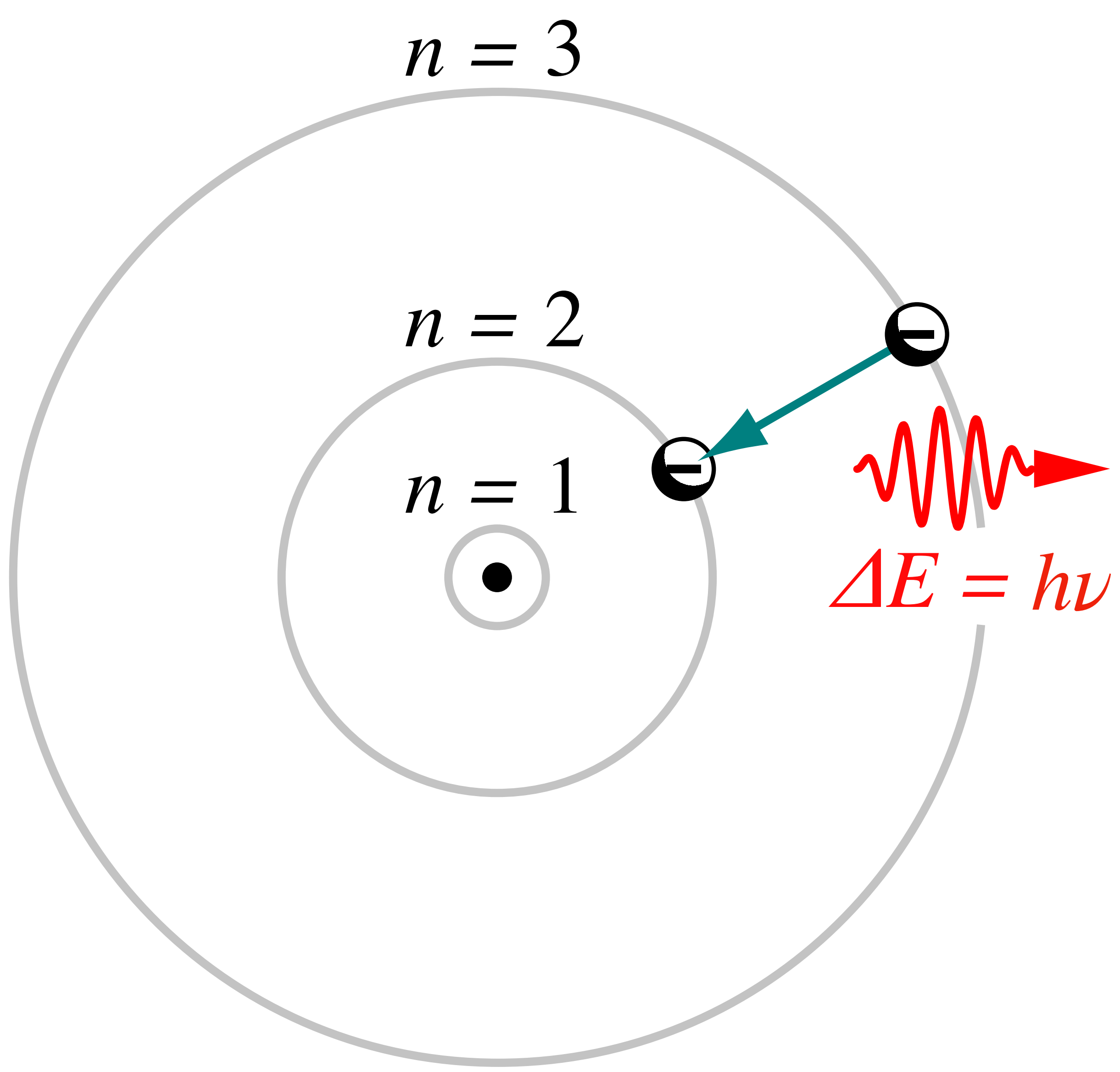
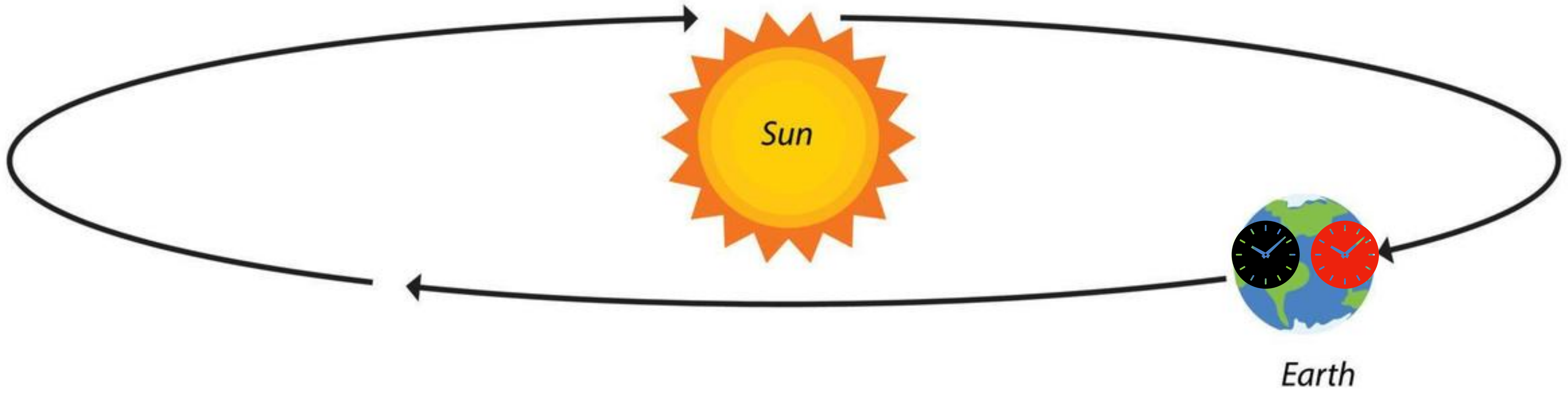




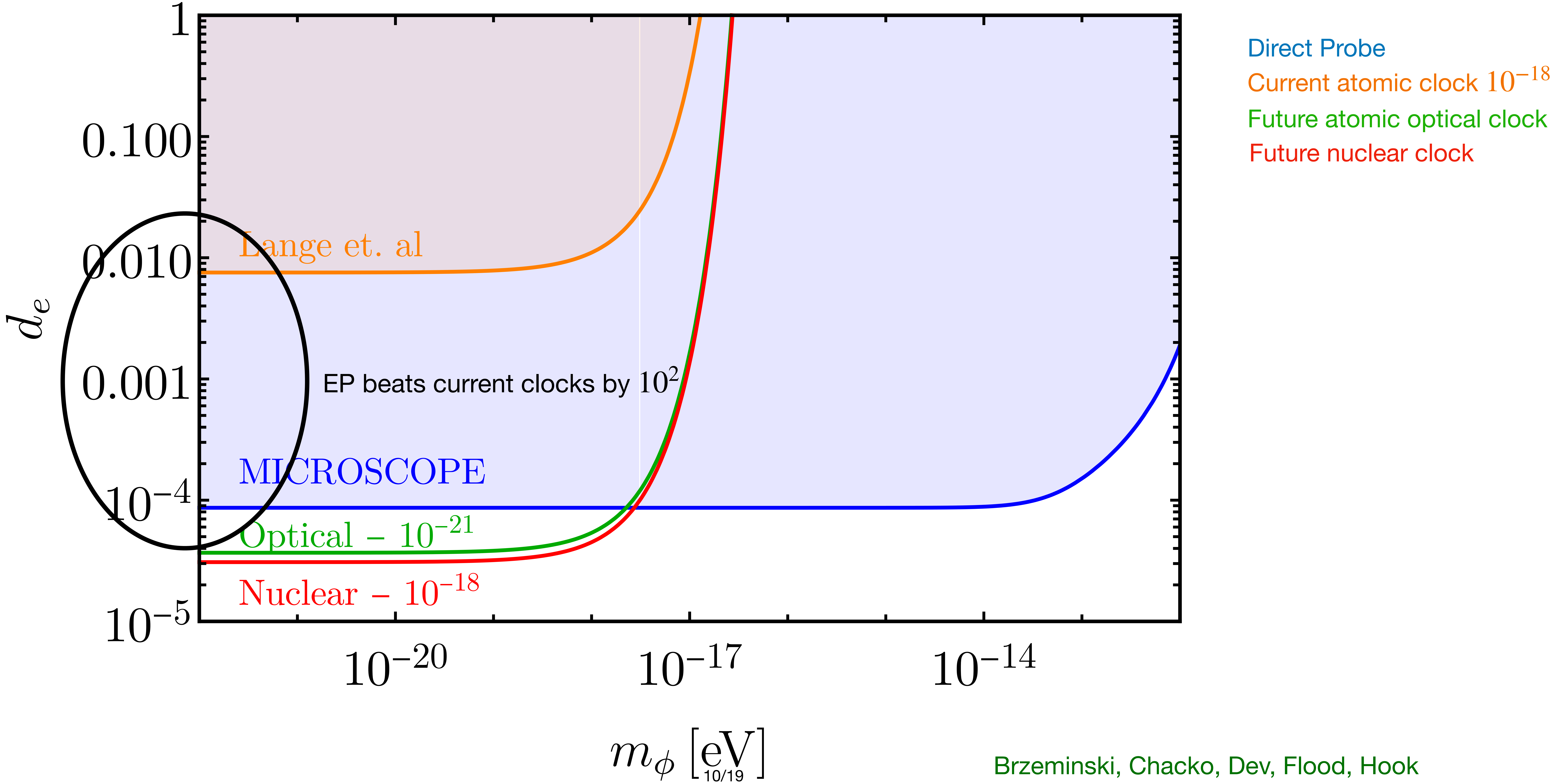
Two different clocks on Earth

$$\frac{\partial \ln \nu}{\partial \ln \varphi} = \frac{\partial \ln \nu}{\partial \ln \alpha}\frac{\partial \ln \alpha}{\partial \ln \varphi} \equiv k_\alpha \frac{d_e}{M_{\rm Pl}}\varphi \propto k_\alpha Q_S \frac{d_e^2}{M_{\rm Pl}^2}$$

k_α: sensitivity coefficients

Ludlow, Boyd, Ye, Peik, Schmidt
Flambaum, Dzuba
Dzuba, Flambaum, Marchenko

Summary of Constraints



Brzeminski, Chacko, Dev, Flood, Hook

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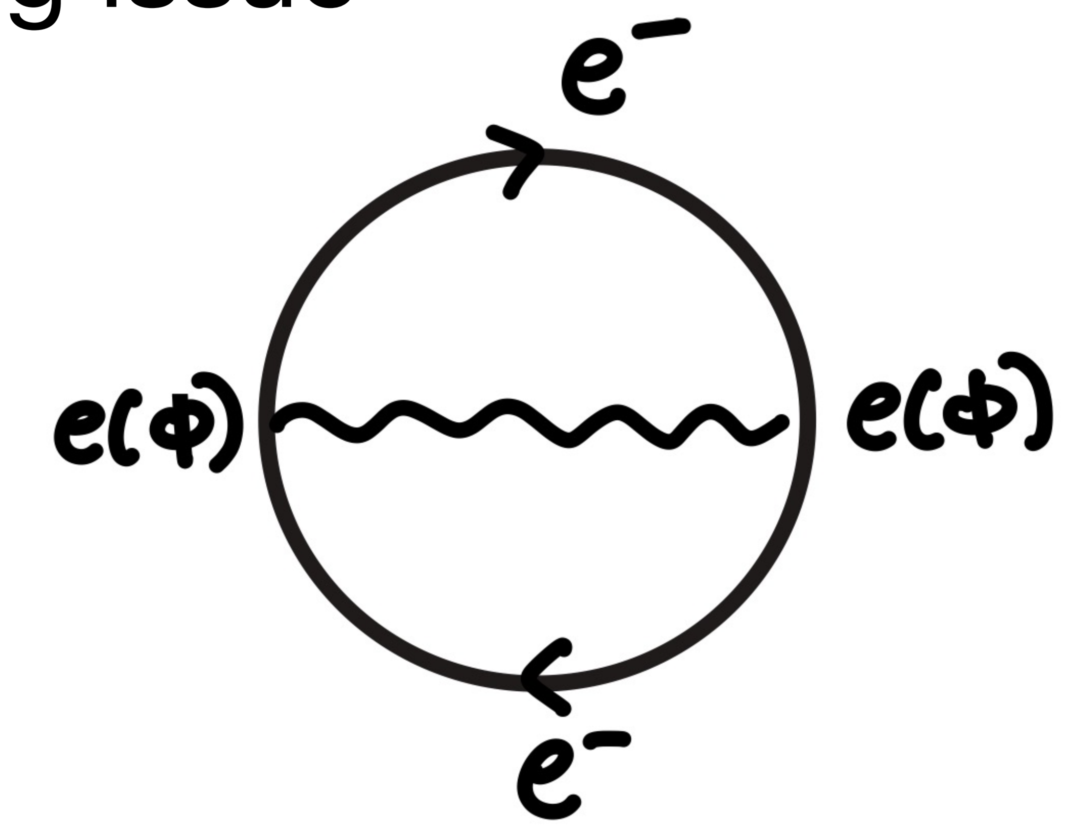
3) Fine tuning issue



$$\delta m_\varphi^2 \sim \frac{e^2}{(16\pi^2)^2}\frac{d_e^2}{M_{\rm Pl}^2}\Lambda_{\rm cut}^4$$

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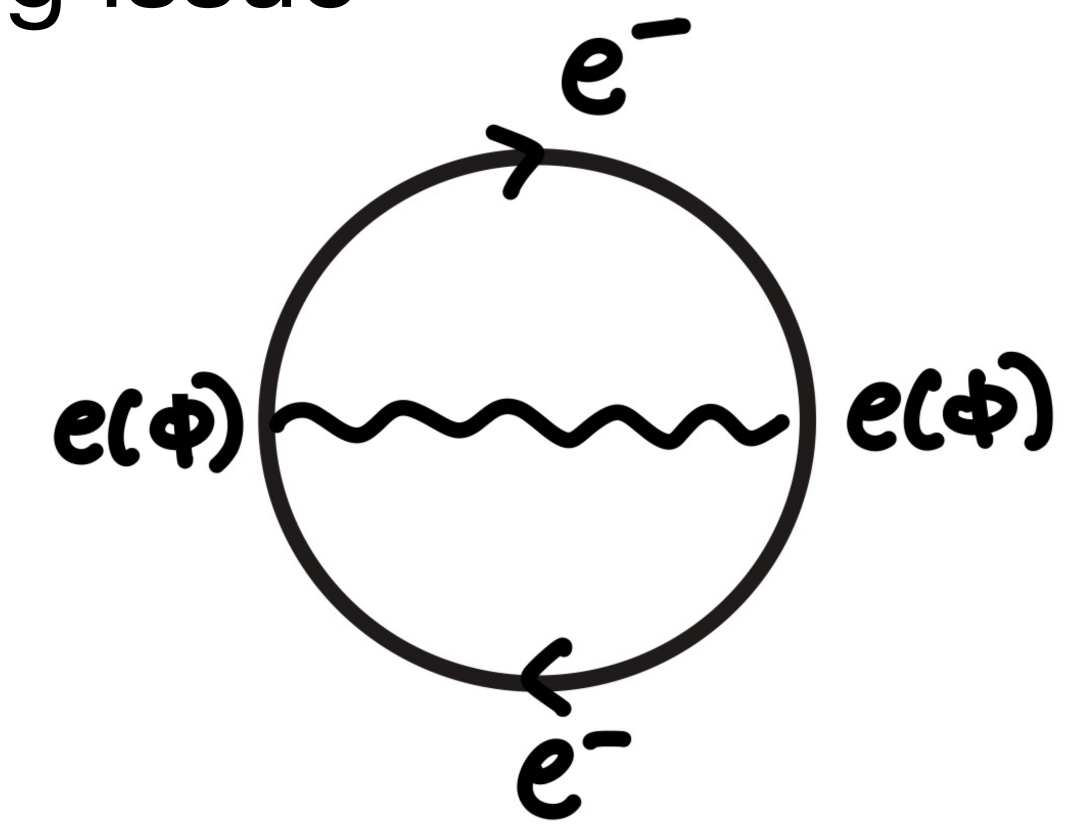
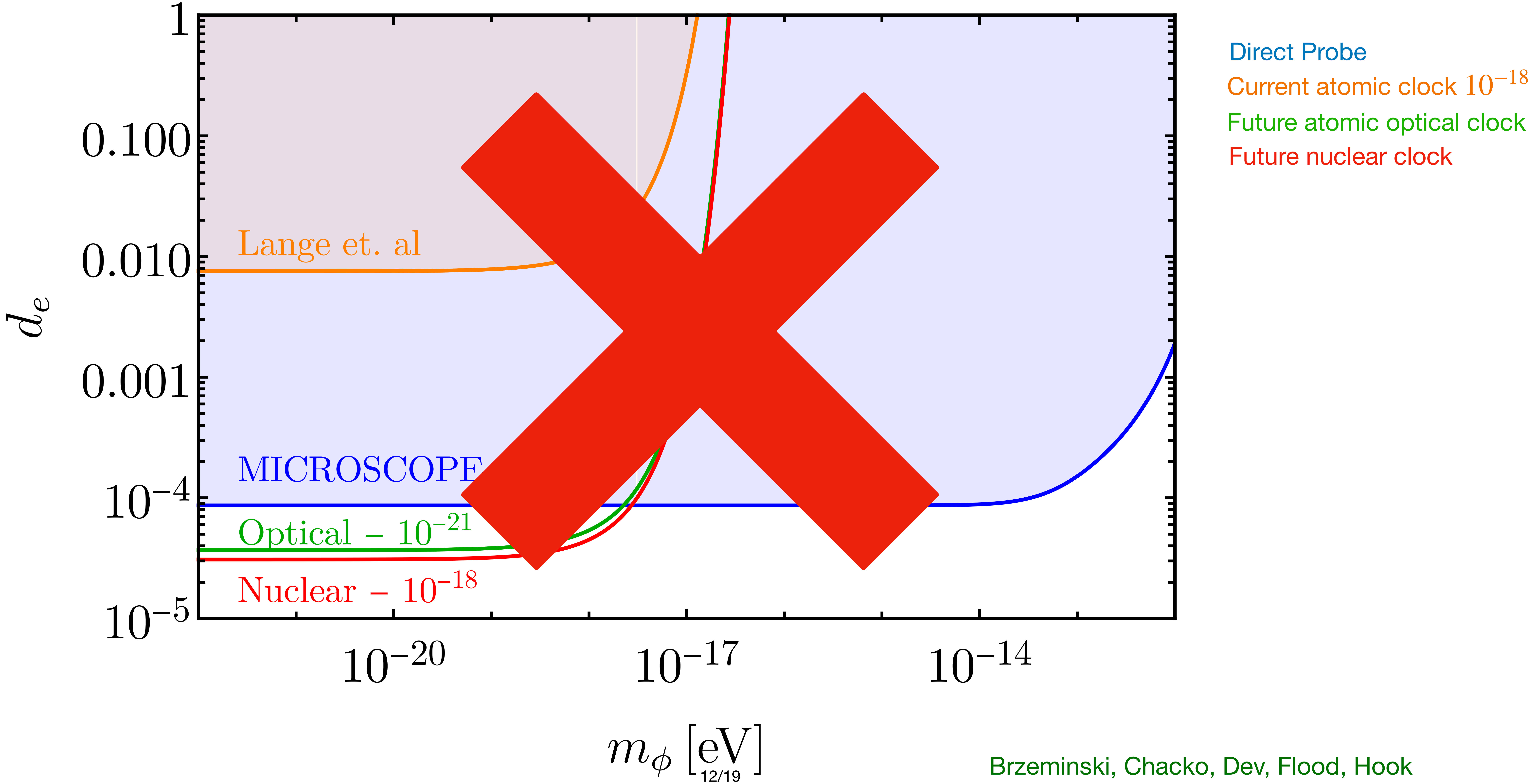


$$\delta m_\varphi^2 \sim \frac{e^2}{(16\pi^2)^2}\frac{d_e^2}{M_{\rm Pl}^2}\Lambda_{\rm cut}^4$$

Eg: For AU range force $m_\varphi \sim 10^{-18}\,\mathrm{eV}$. Currently $d_e \sim 10^{-4} \Rightarrow \Lambda_{\rm cut} \lesssim \mathrm{O}(100\,\mathrm{MeV})$

Thus NP needs to be a neutral dark sector.

Summary of Constraints



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Not a new question. In the context of the Higgs, there were a lot of ideas.

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1) Solutions based on symmetry arguments.

discrete $\mathbb{Z}_N$ symmetry - N copies of SM — Brzeminski, Chacko, Dev, Hook; Delaunay, Geller, Heller-Algazi, Perez, Springmann

dilaton based (pNGB of scale symmetry) — Banerjee, Csaki, Geller, Heller-Algazi, Ismail

2) Solutions based on compositeness.

This work: Interesting signals as we will see.

Minimal Sketch

Basic Idea: It is a composite pNGB of a hidden sector.

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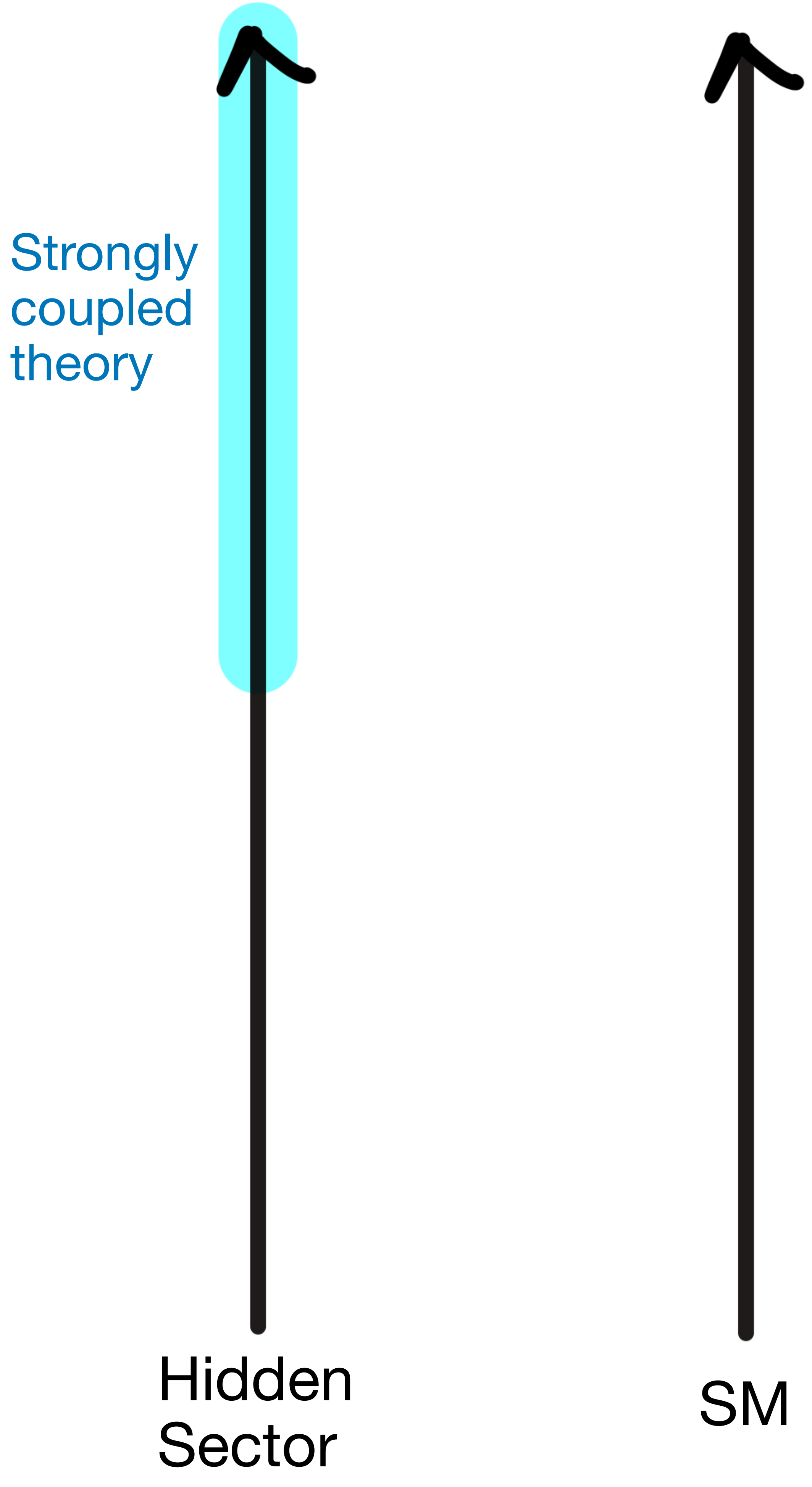

- There is a strongly-coupled theory in the UV with a global $U(1)$.

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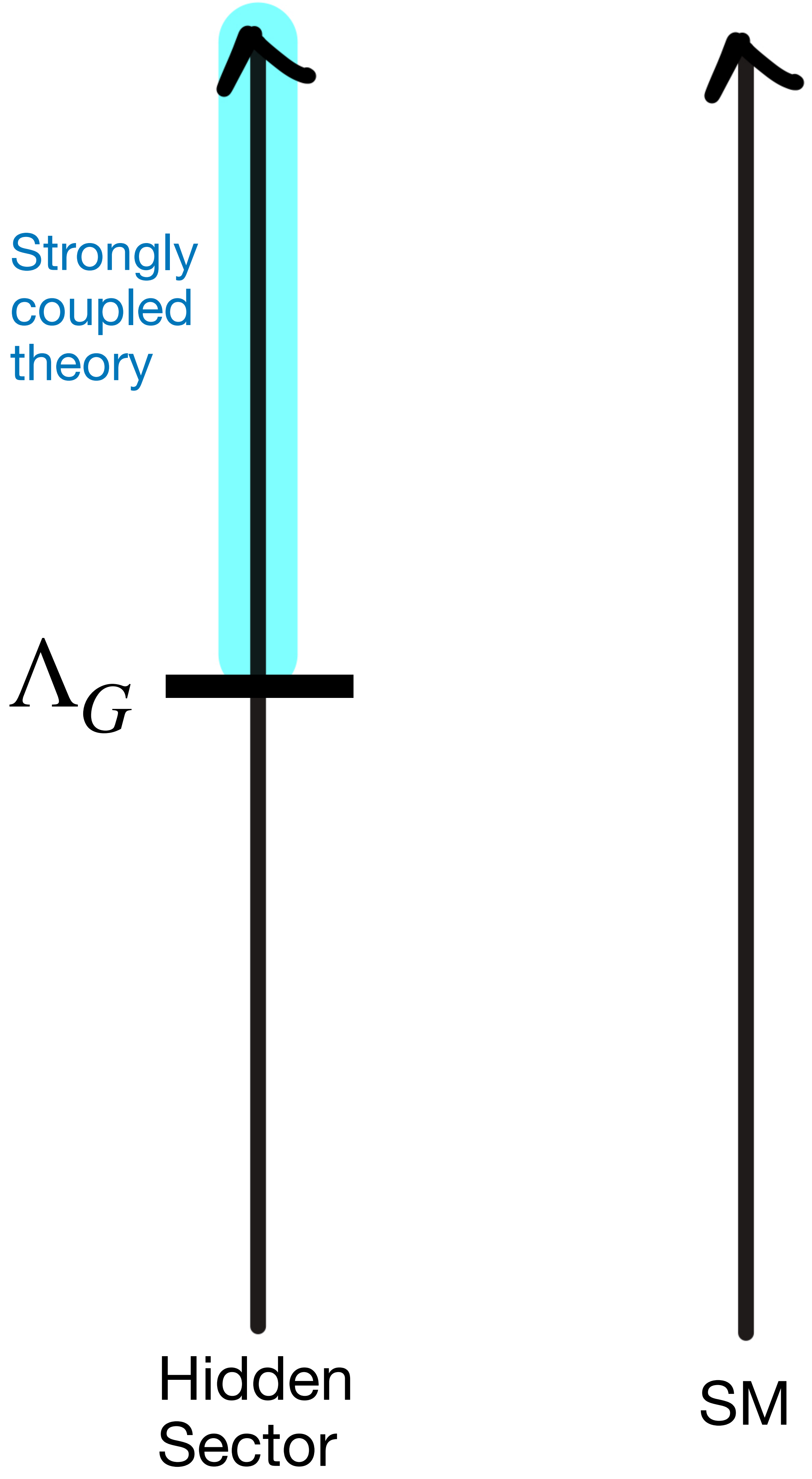

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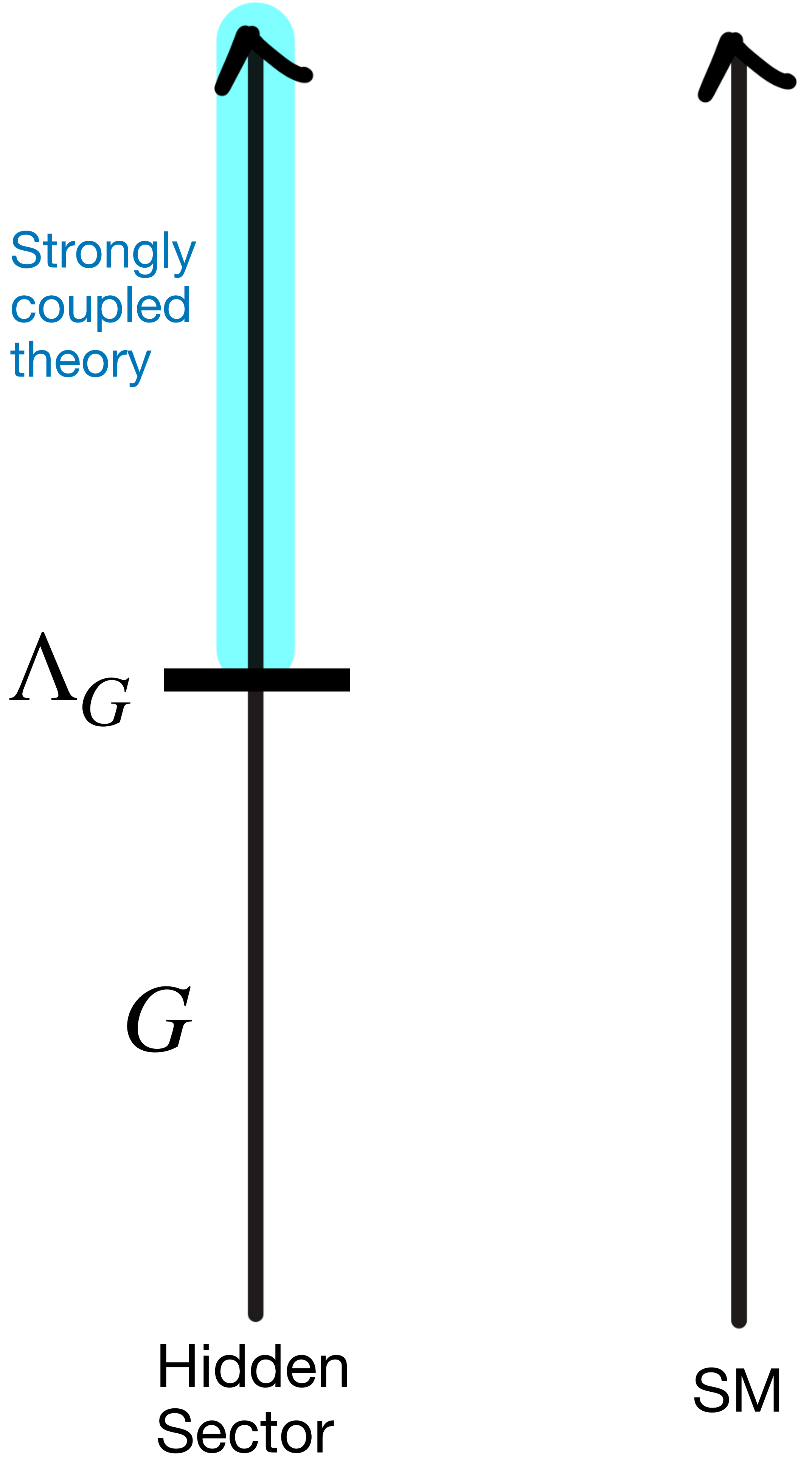

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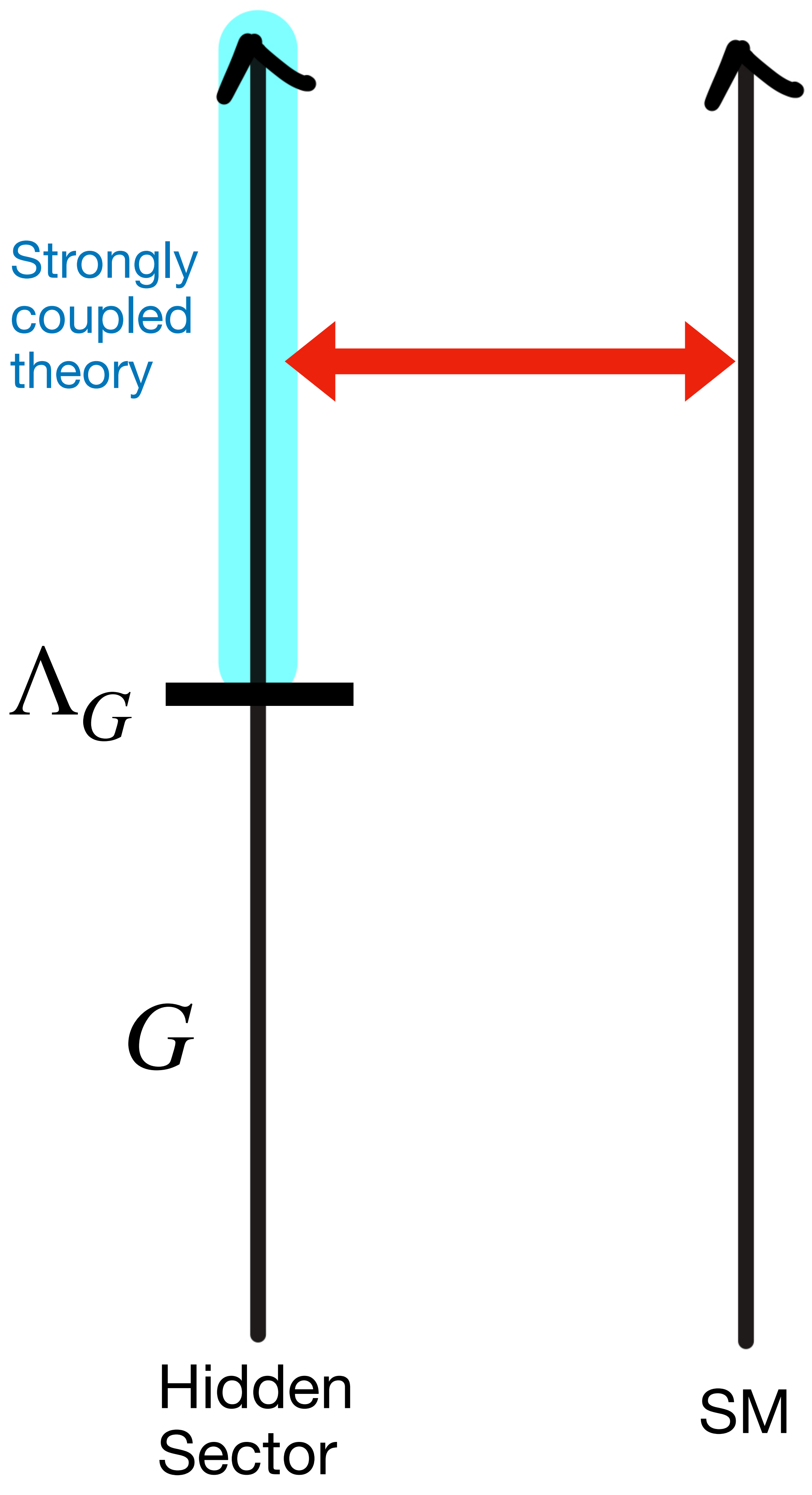

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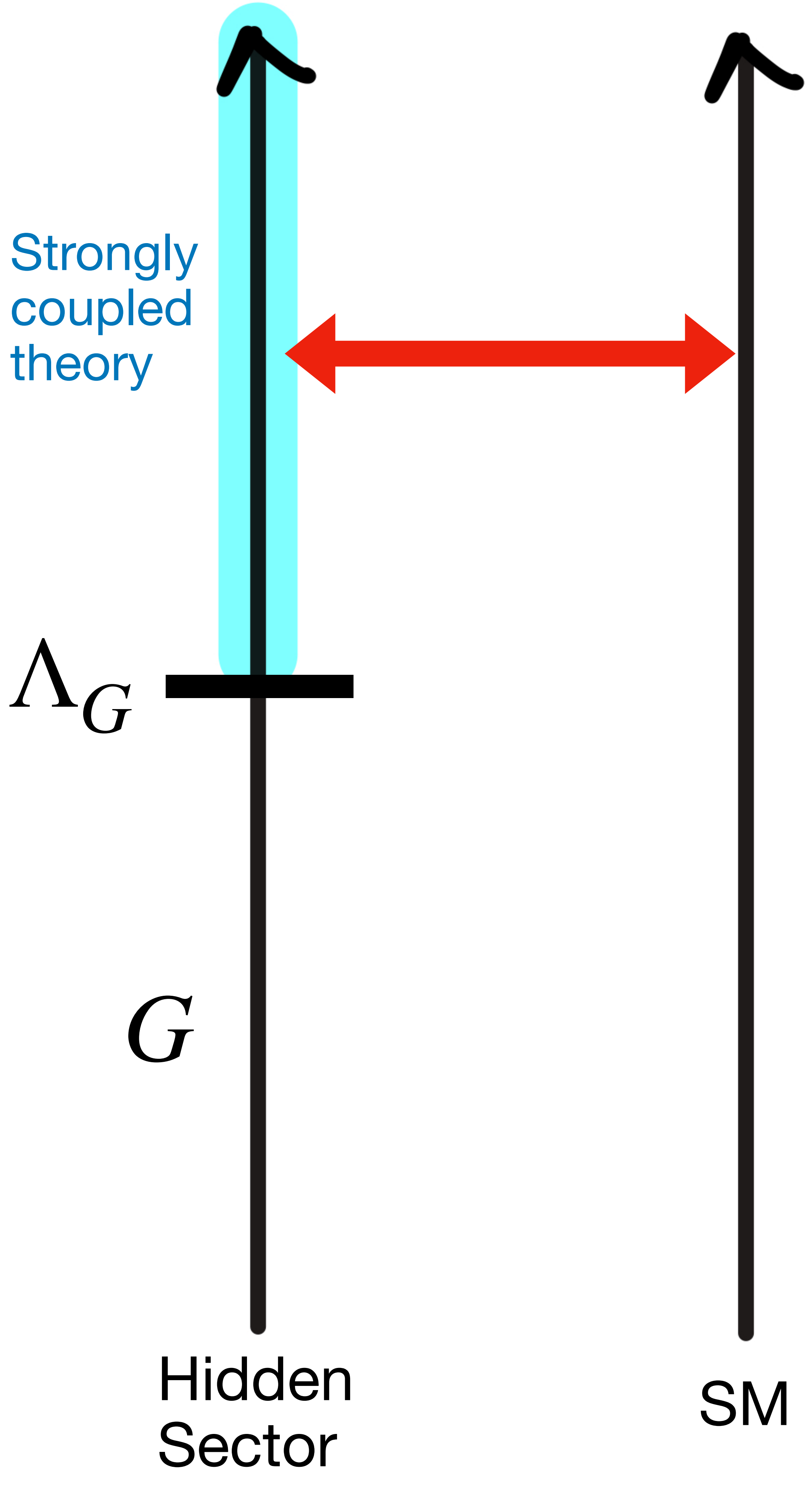

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- A relevant deformation grows in the IR and breaks the sector at a scale $\Lambda_G \sim 4\pi f_G$.
- Some scalar operator acquires a vev which breaks $U(1) \rightarrow \varnothing$. One Goldstone, G, is generated
- Interaction of the strong sector with the SM provides an explicit breaking which provides a mass i.e. pNGB.

Notation: G is the "composite" ultralight field vs φ the "elementary" field.

Effect of Compositeness

We want to see the effect of this compositeness in the interaction of G with the photons.

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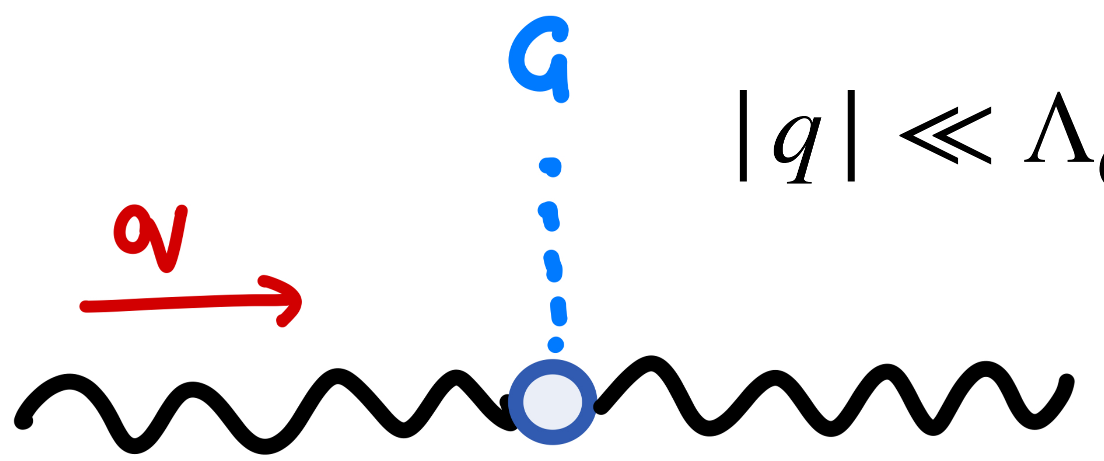

$|q| \ll \Lambda_G$

Probe cannot resolve internal dynamics

$$\Pi^G_{\rm strong}(q^2) = \frac{d_e}{M_{\rm Pl}} G$$

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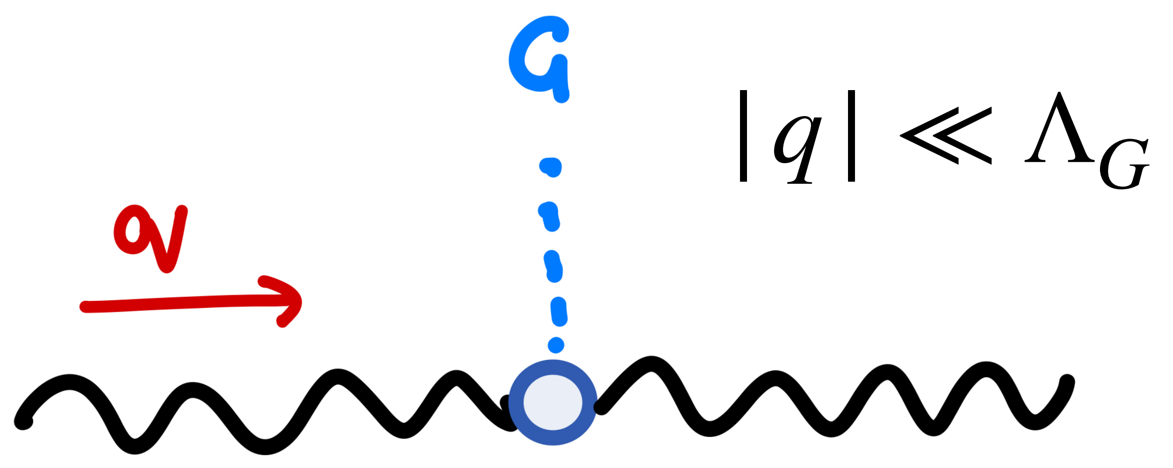
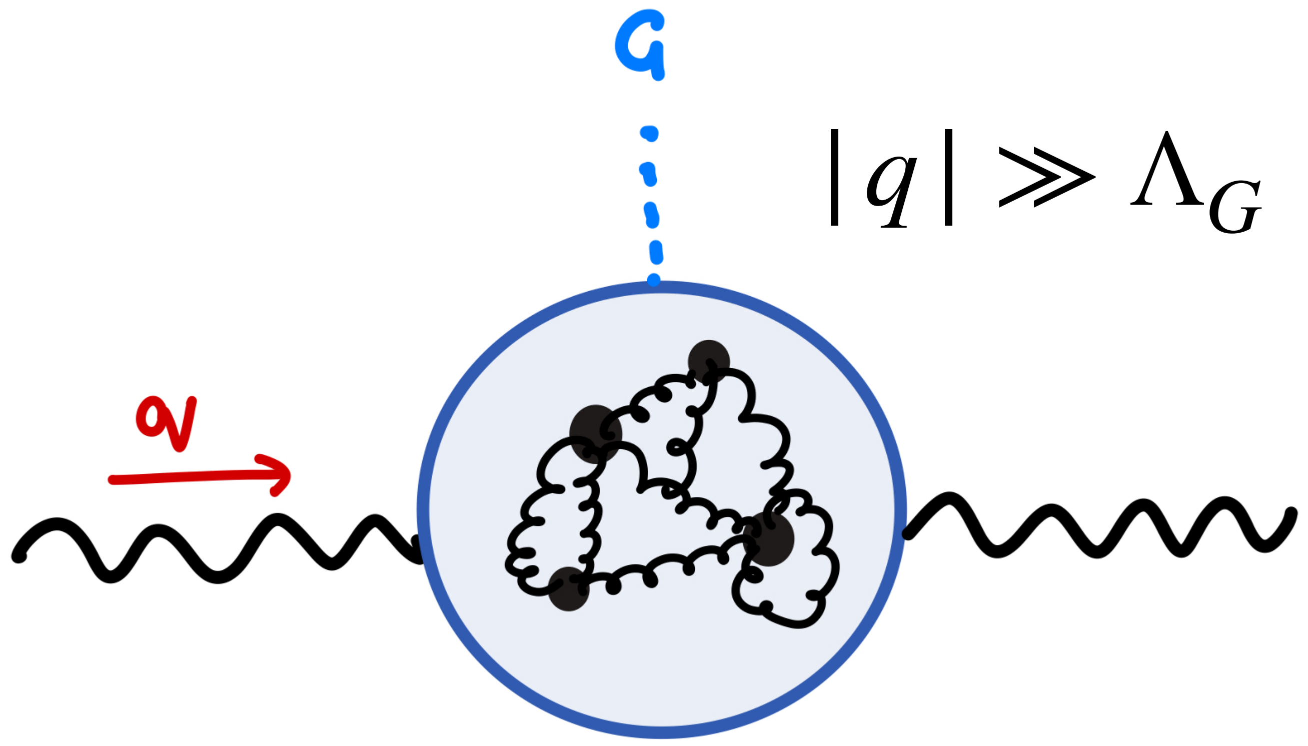


Probe cannot resolve internal dynamics



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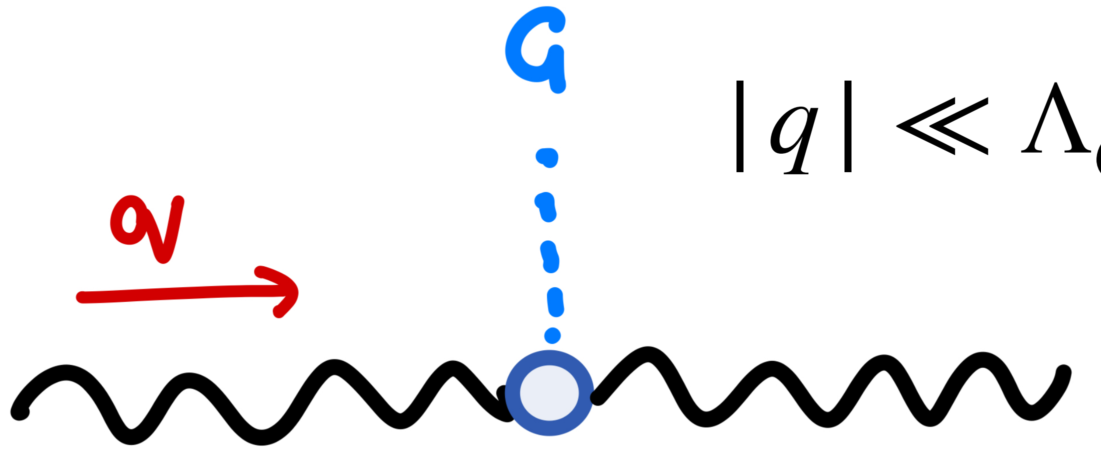

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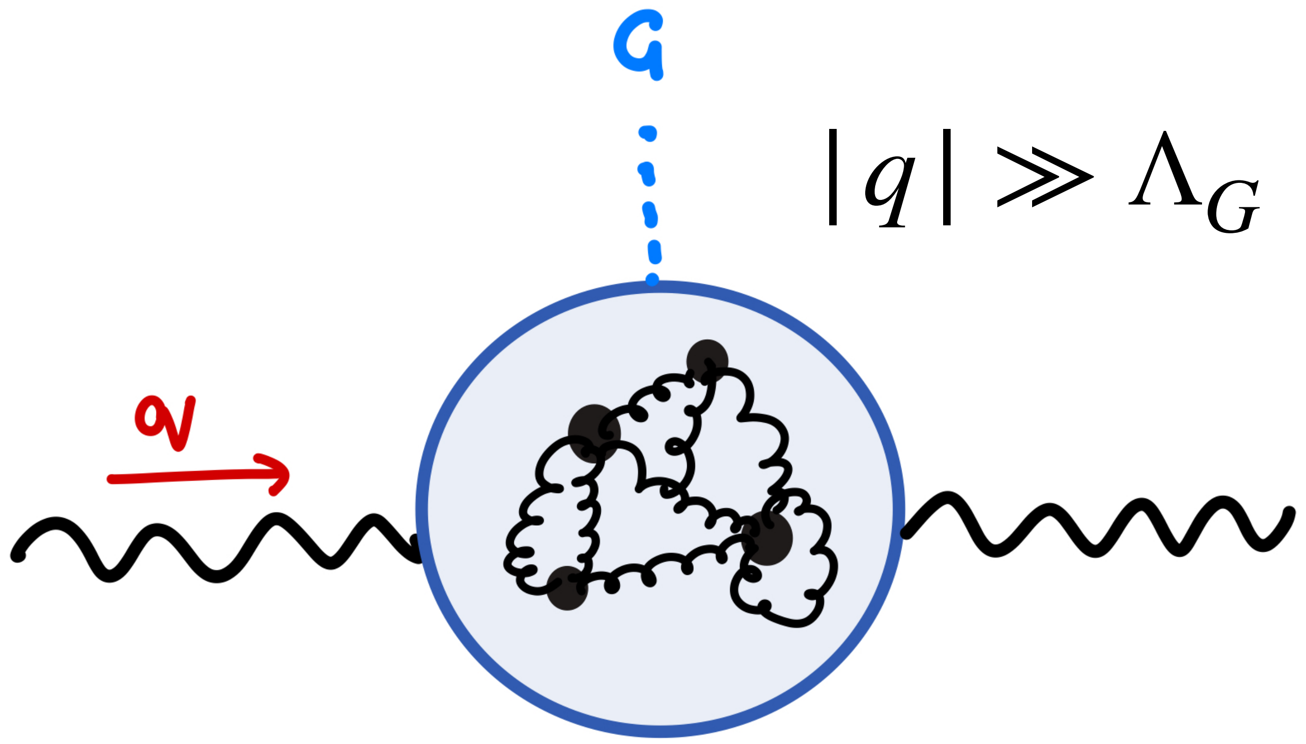

$|q| \gg \Lambda_G$

Probe resolves strong dynamic, coupling softens

$$\bar{\mathcal{F}}(q^2, \Lambda_G) = \begin{cases} 1 & |q^2| \lesssim \Lambda_G^2 \\ \left(\frac{\Lambda_G}{|q|}\right)^n & |q^2| \gtrsim \Lambda_G^2 \end{cases}$$

n is model-dependent, form factor physics is not!

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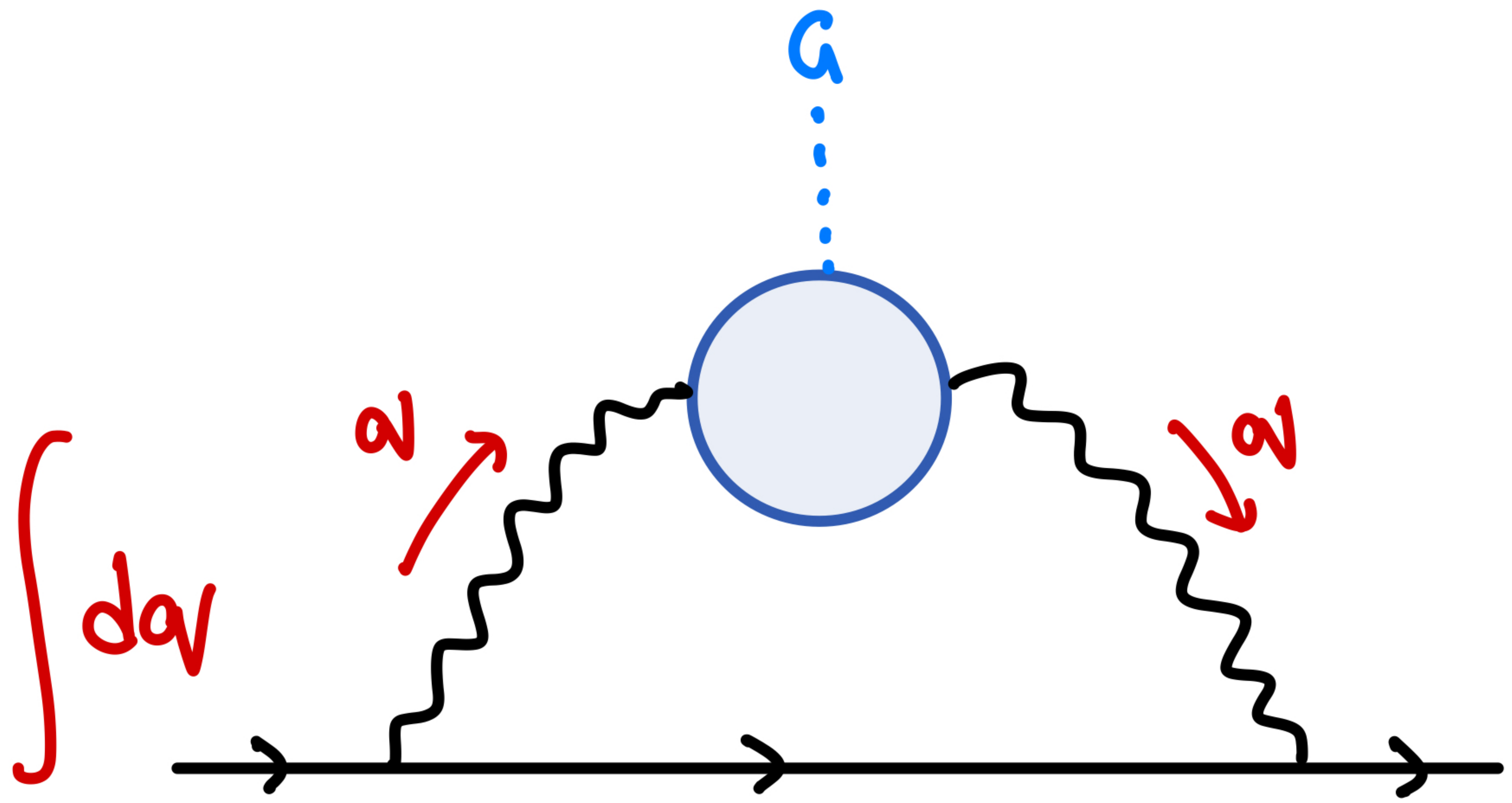

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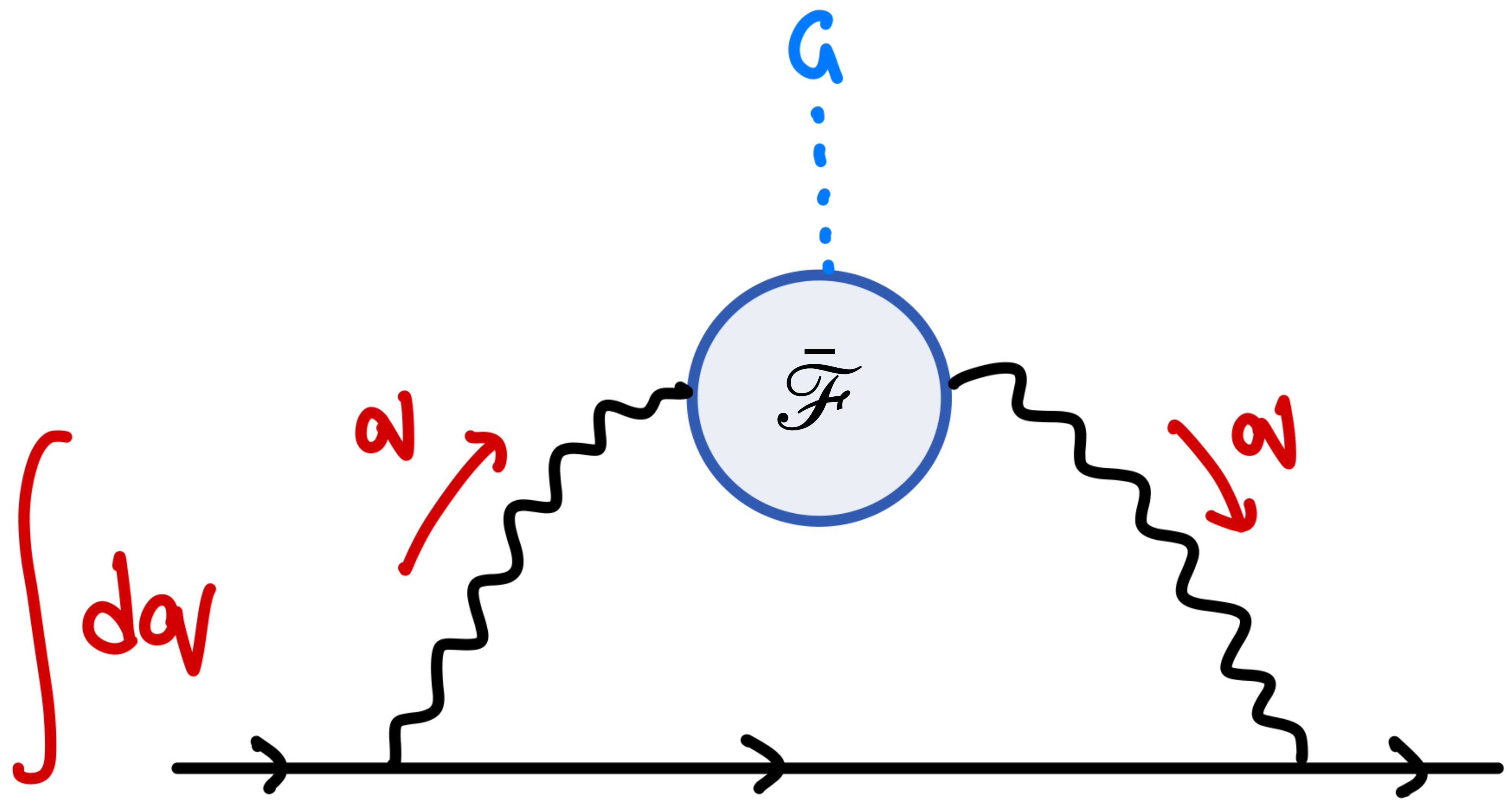

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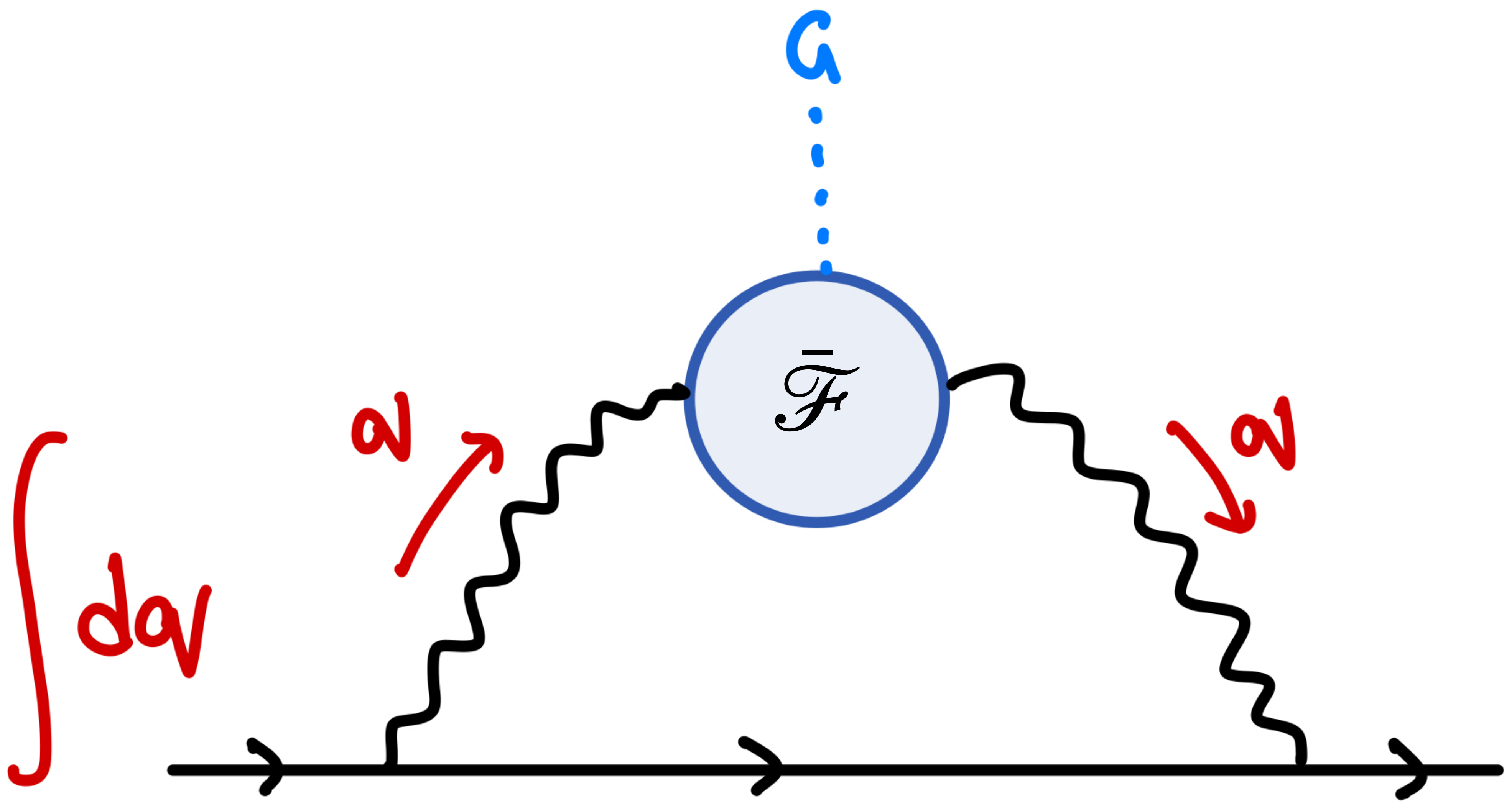

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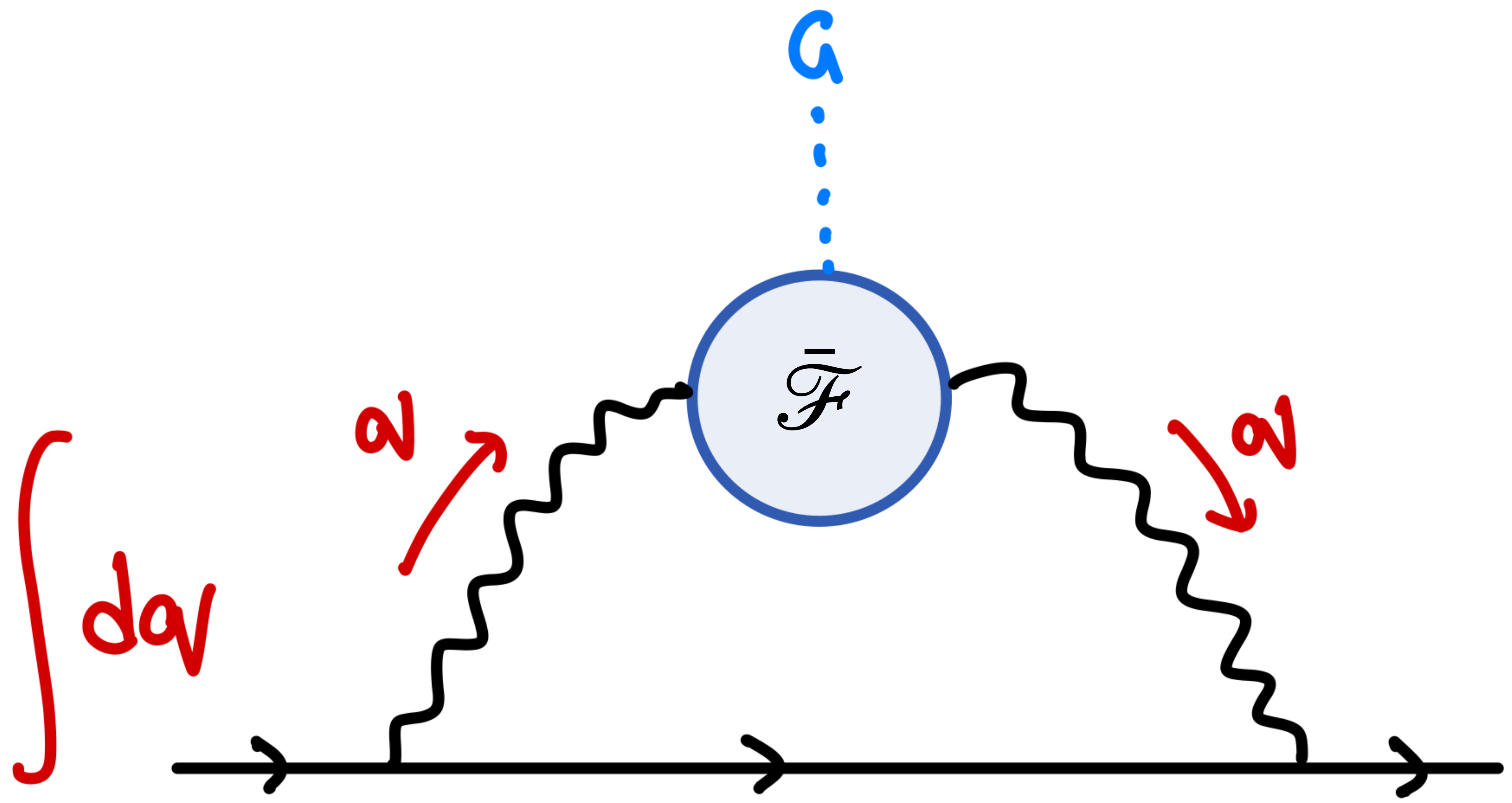

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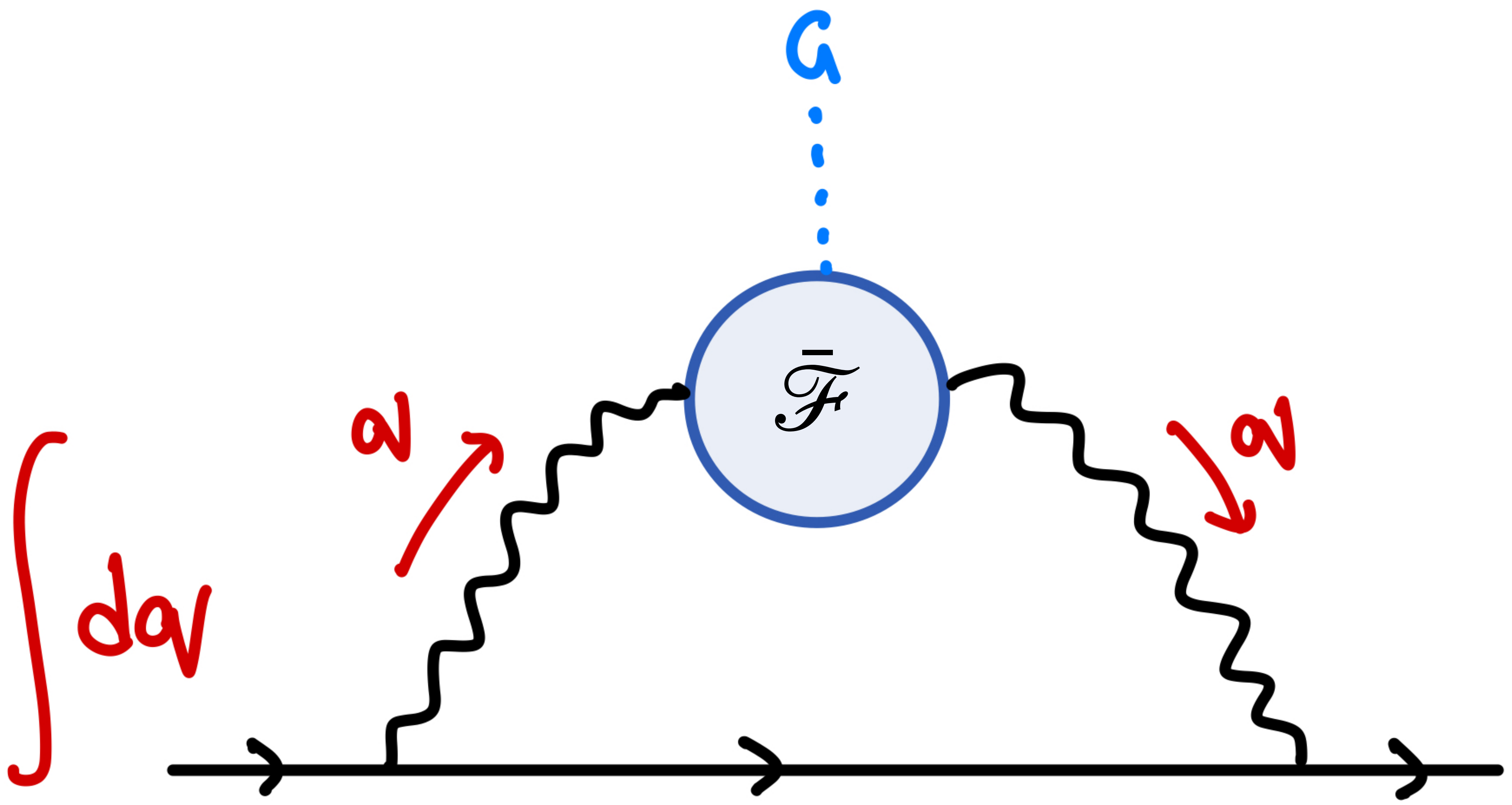

e^-

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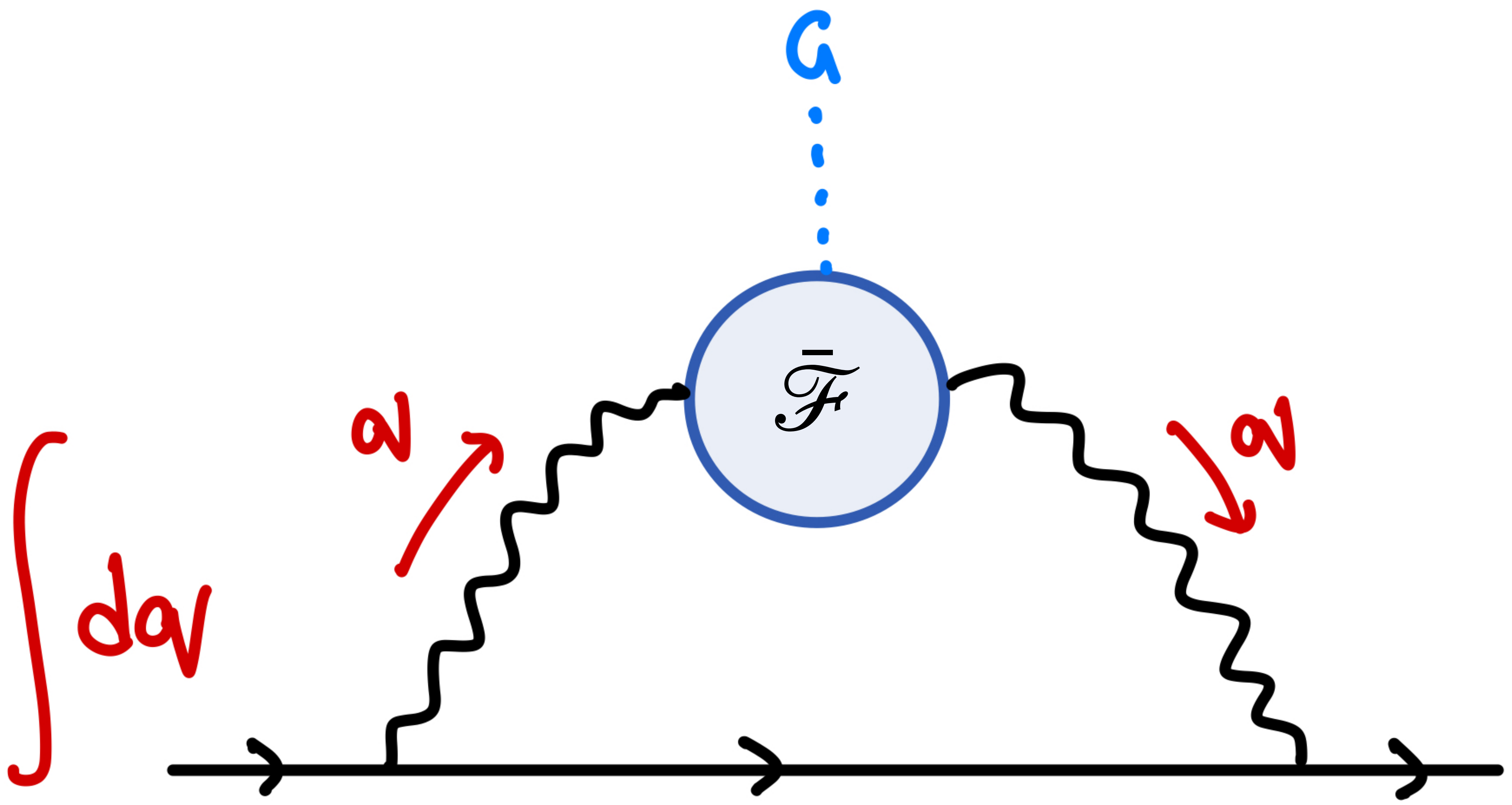

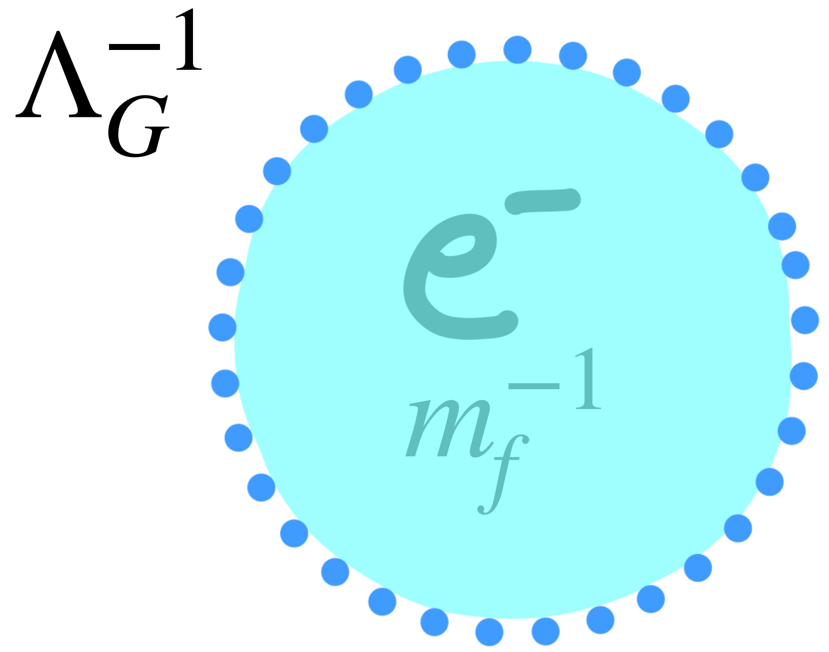

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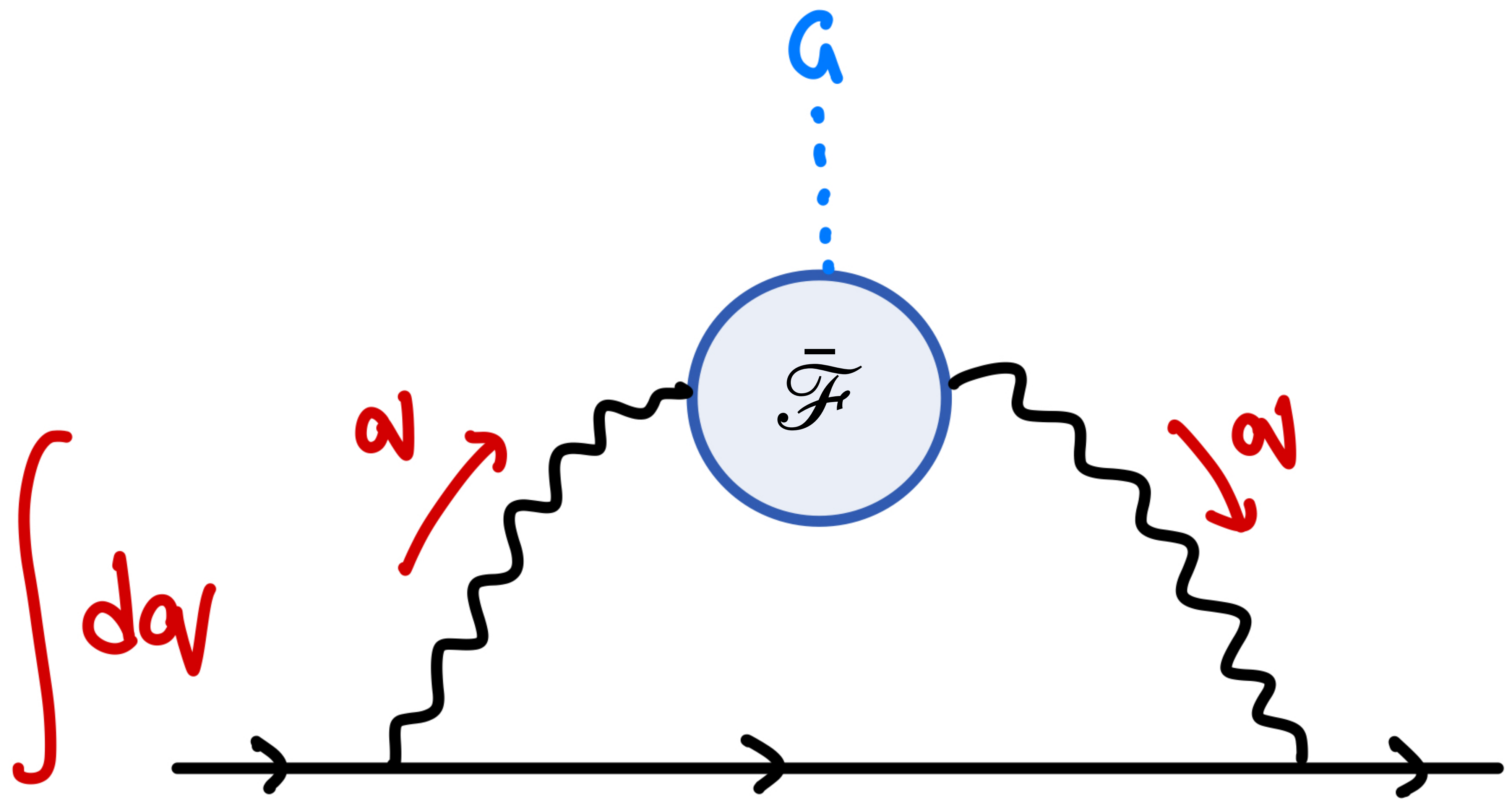

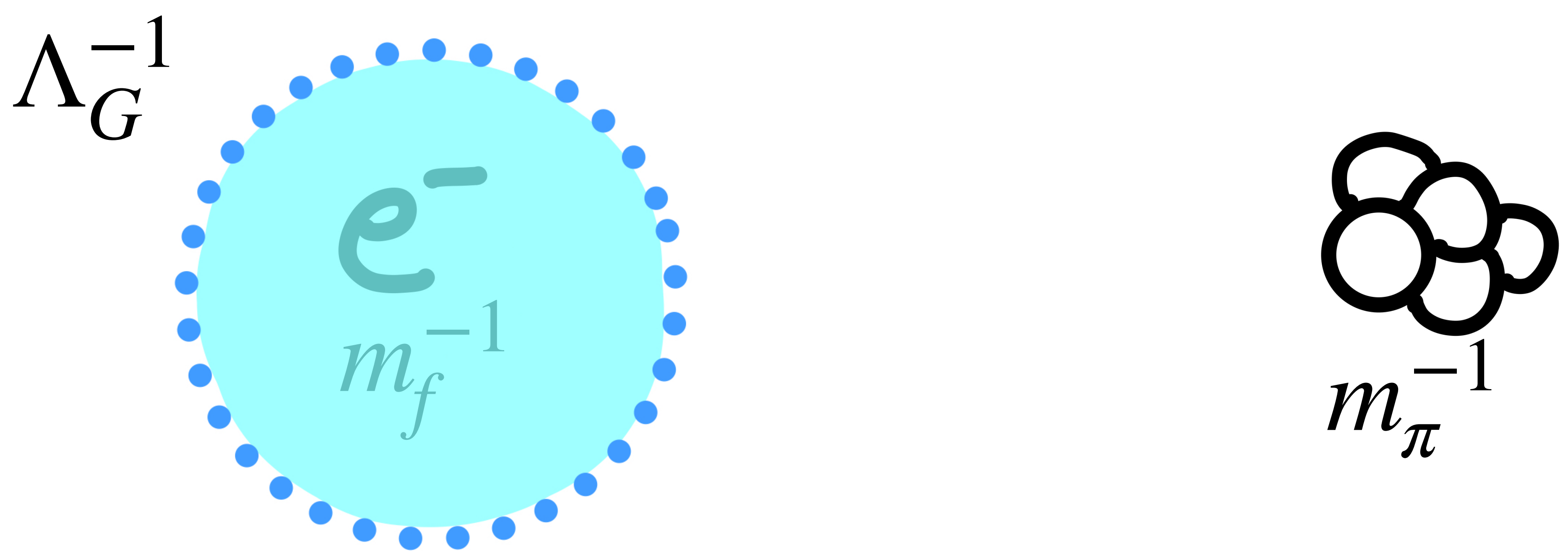

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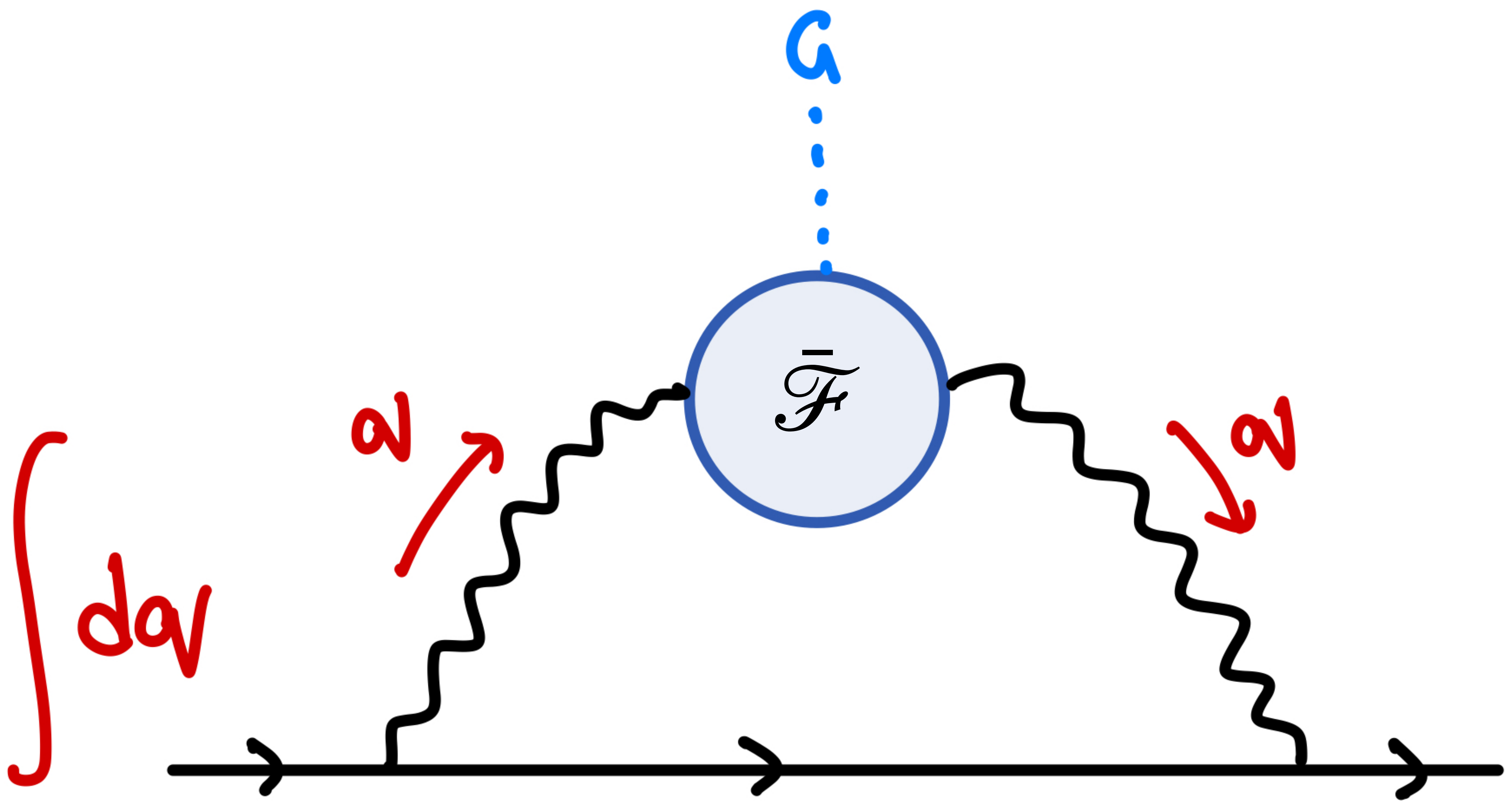

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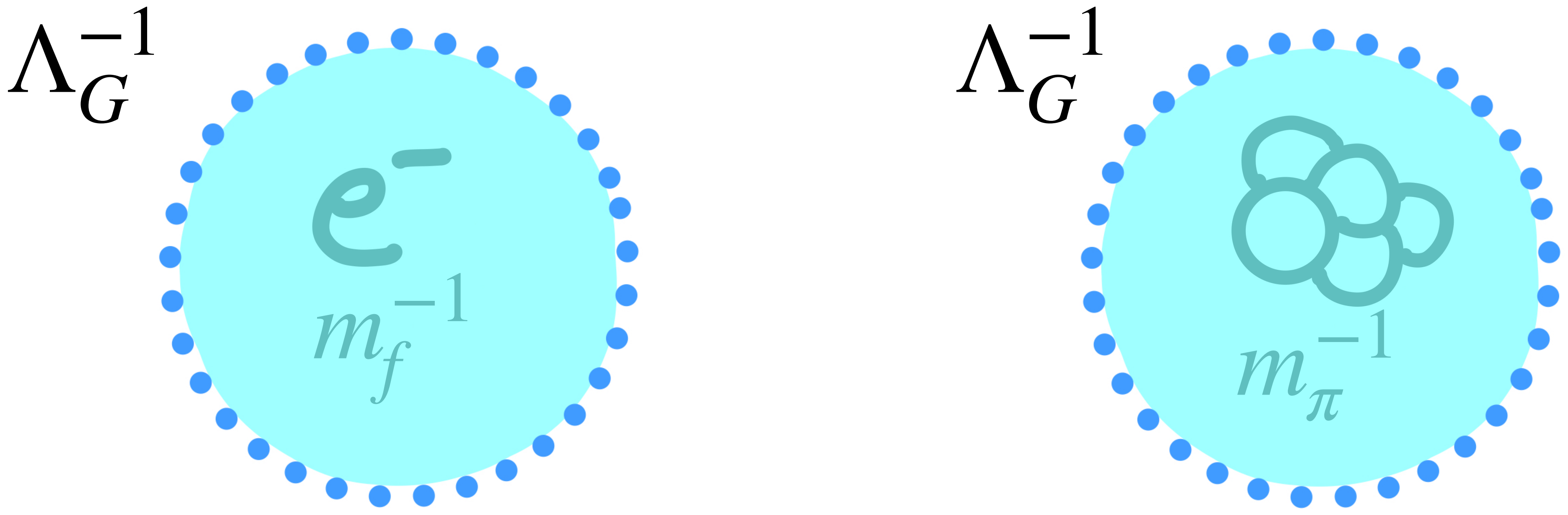

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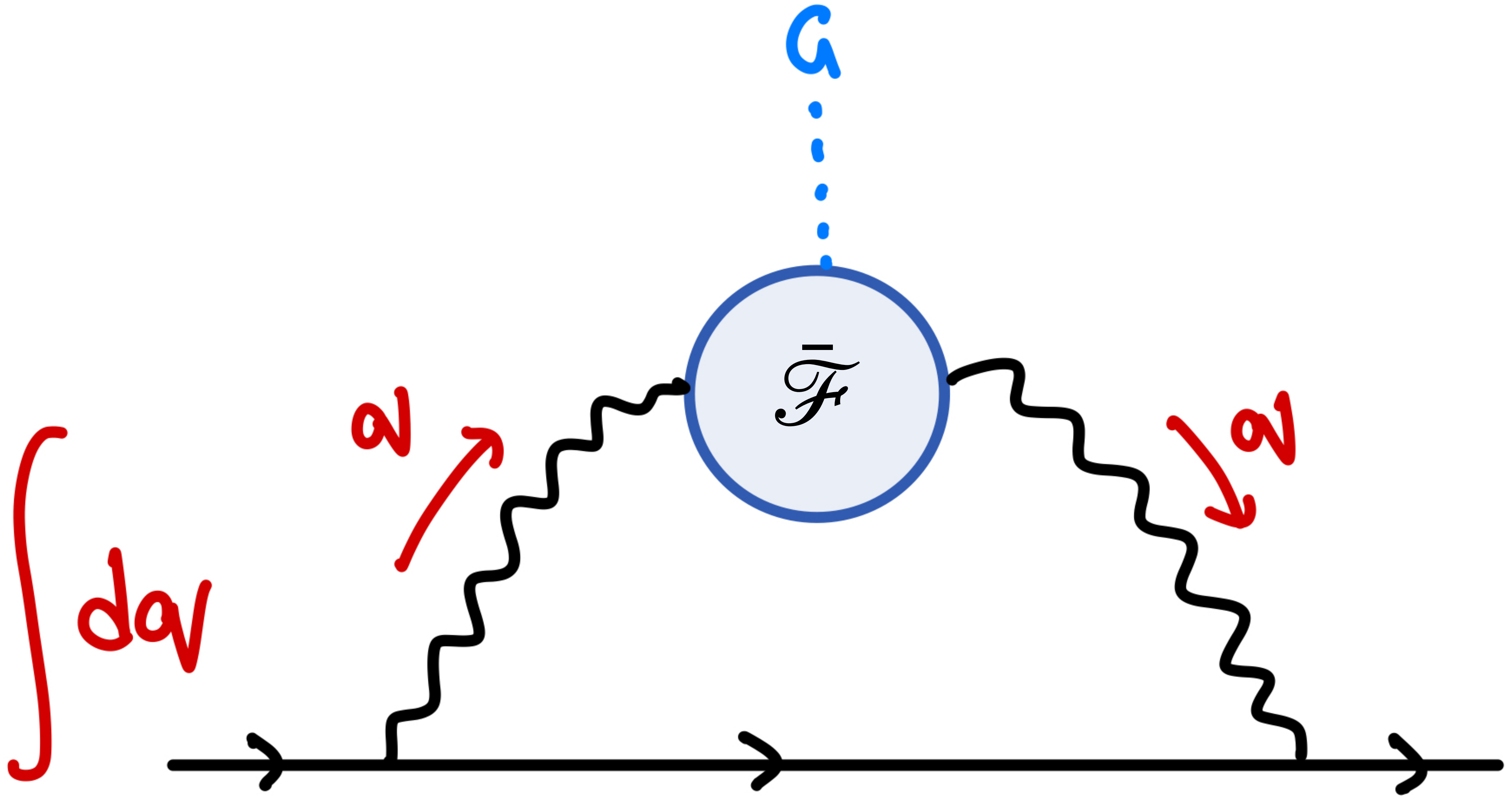
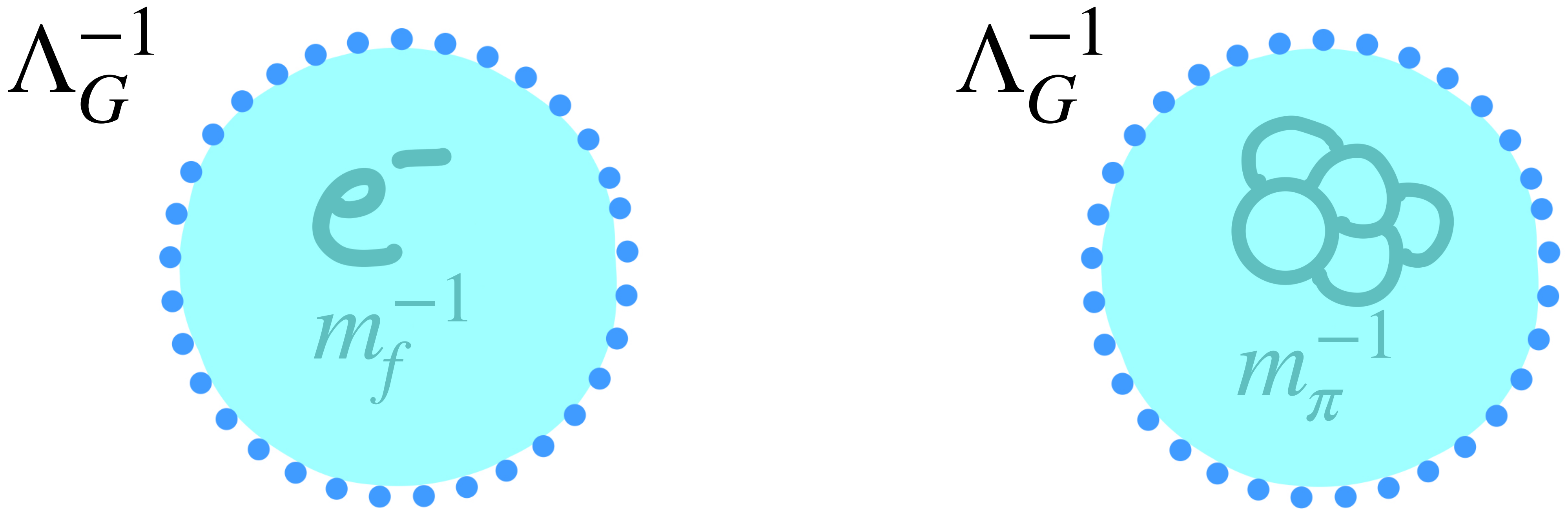


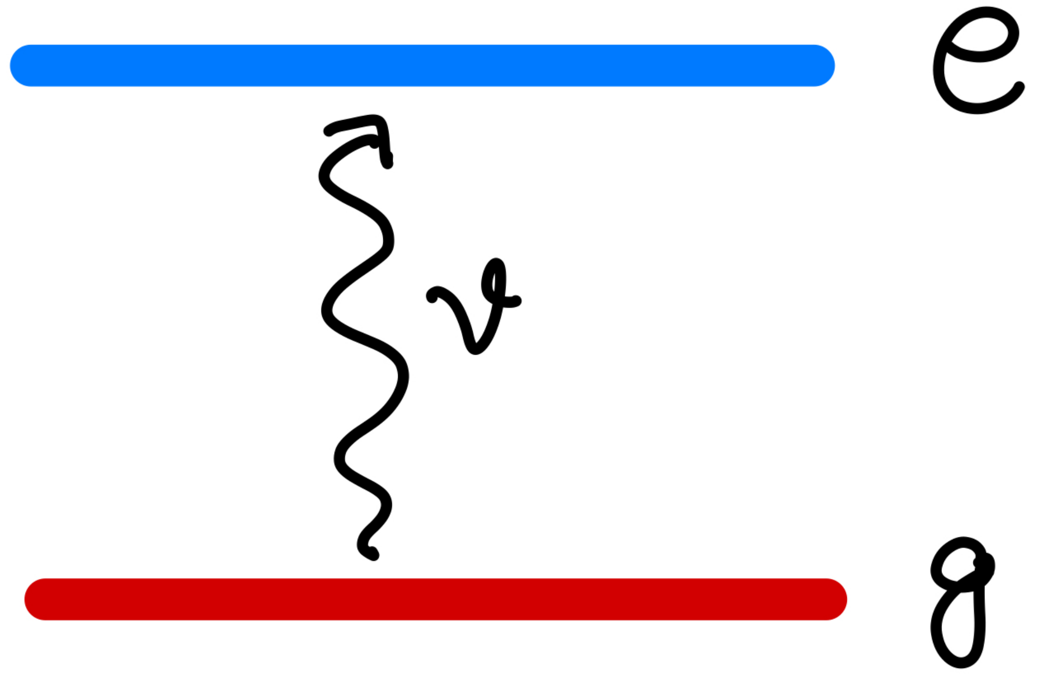


The sourcing can be weakened:

$$Q_G = Q \times \begin{cases} \frac{\Lambda_G}{m_\pi}, & \Lambda_G \lesssim m_\pi \\ 1 & \Lambda_G \gtrsim m_\pi \end{cases}$$

Effect on Indirect Probes

The effect on fine-structure variation is,



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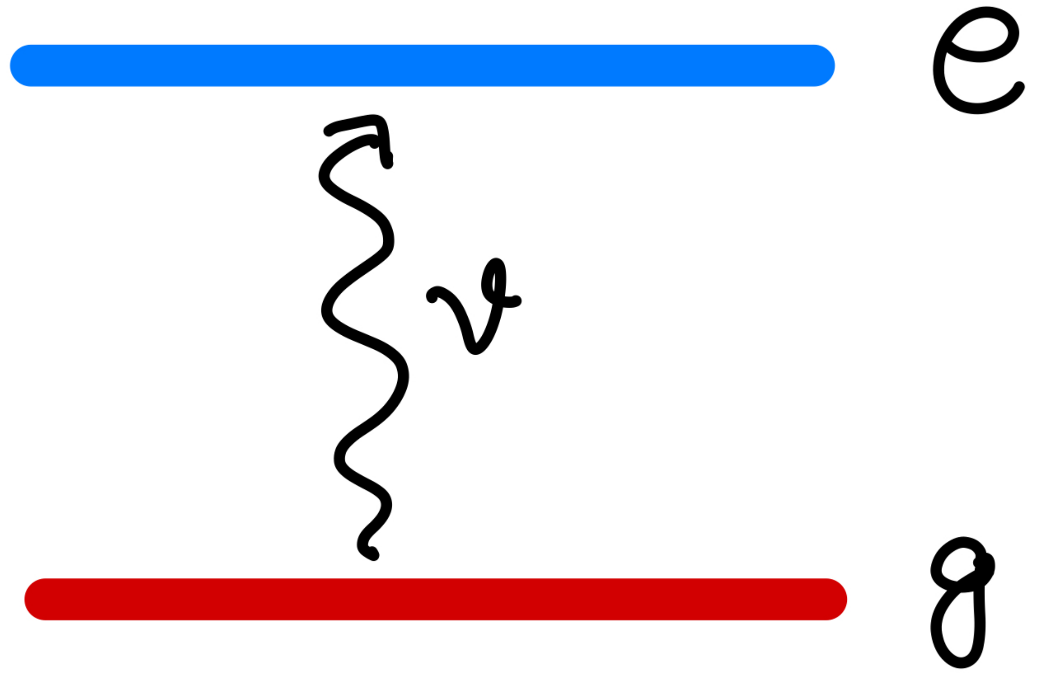

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What is the *characteristic momentum scale* involved in here?
It is the individual binding energies $\alpha(G(r))$ that must be modified.

$$\nu(G(r)) = e(G(r)) - g(G(r))$$

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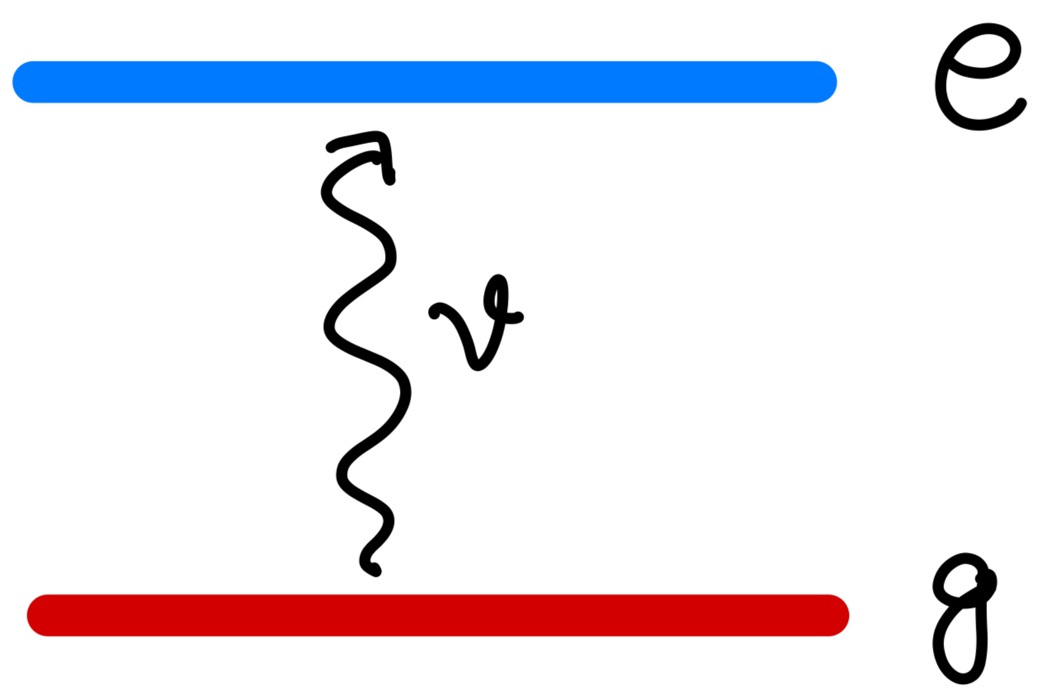

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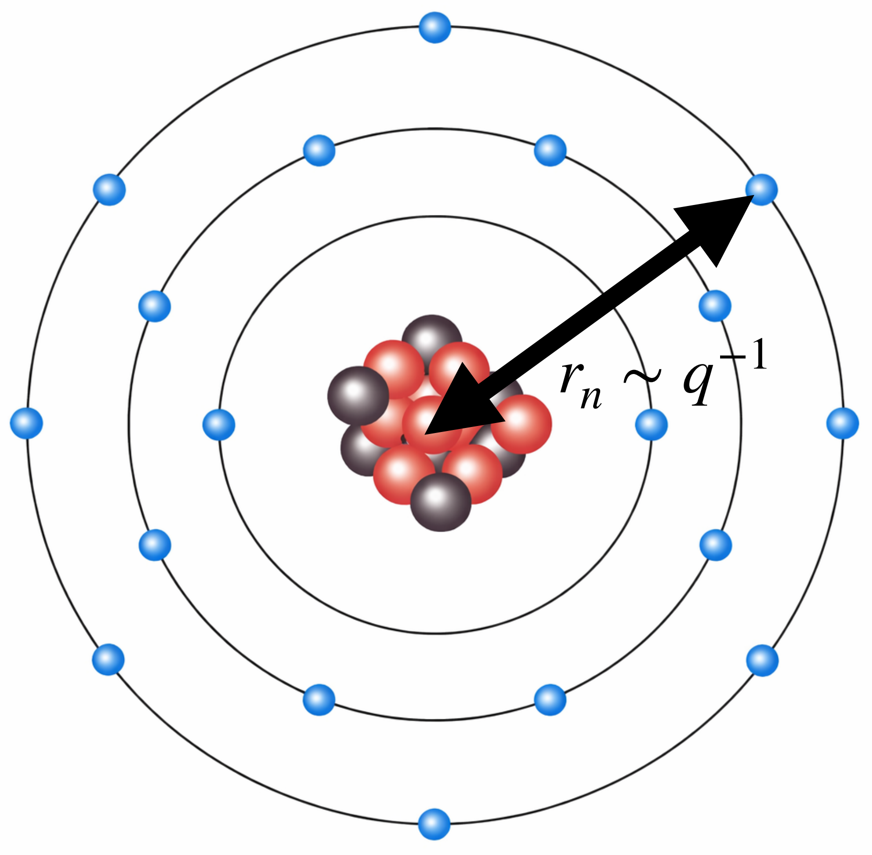

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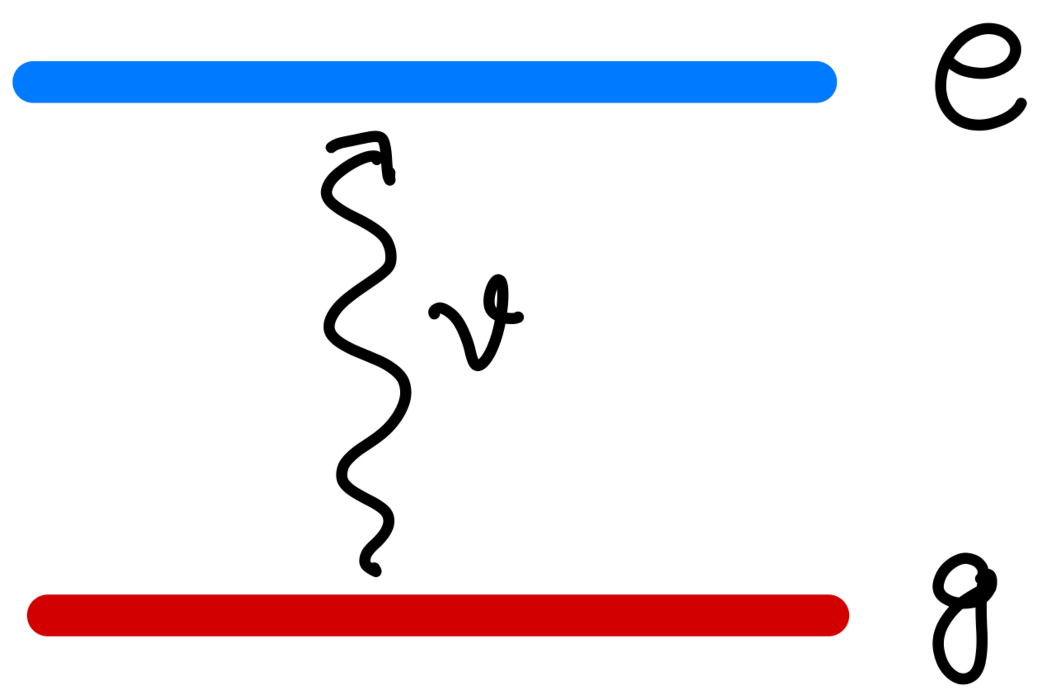

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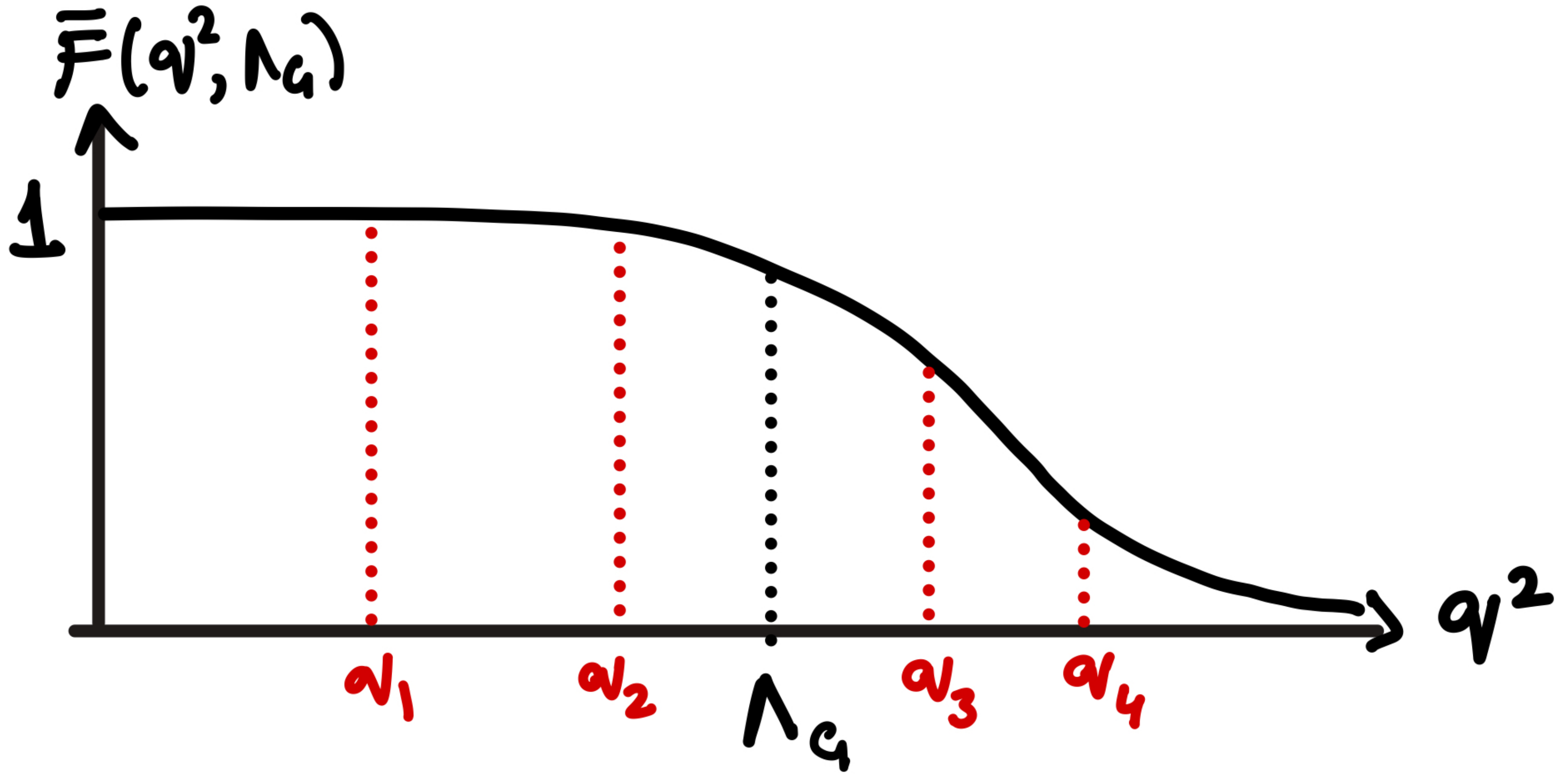
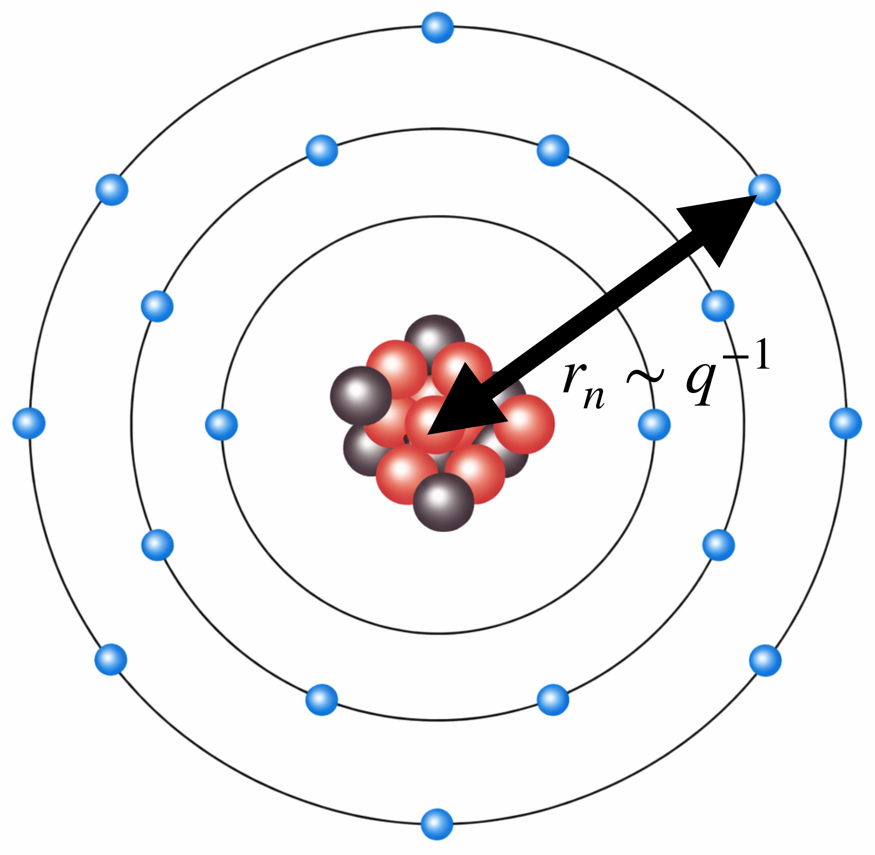


Optical clock $\sim$ O(keV)

Nuclear clock $\sim$ O(100MeV)



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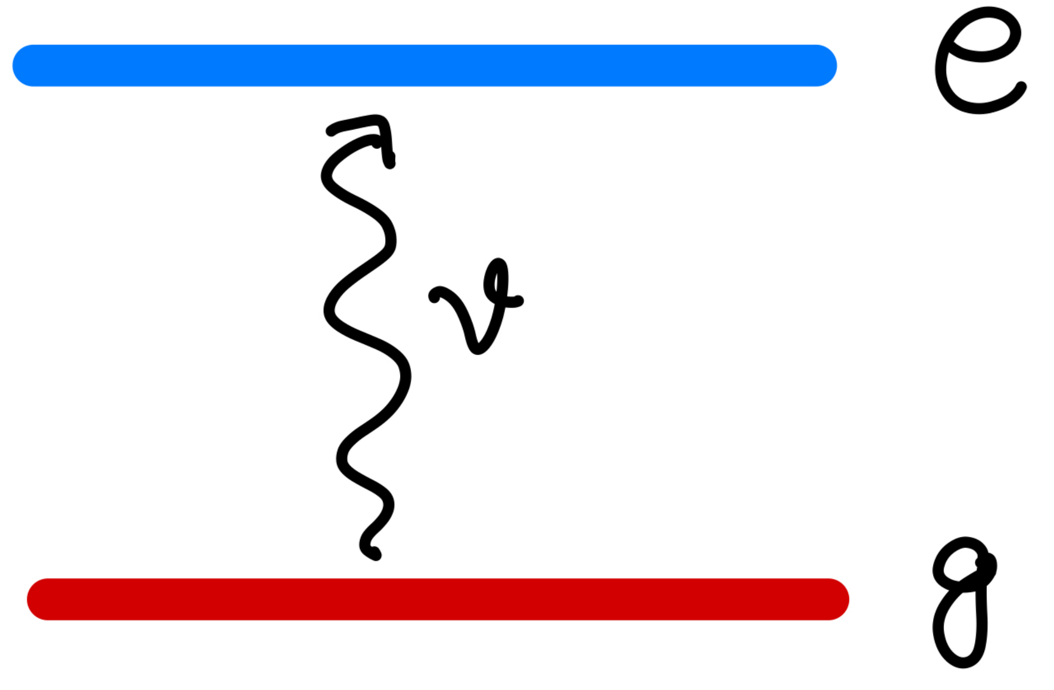

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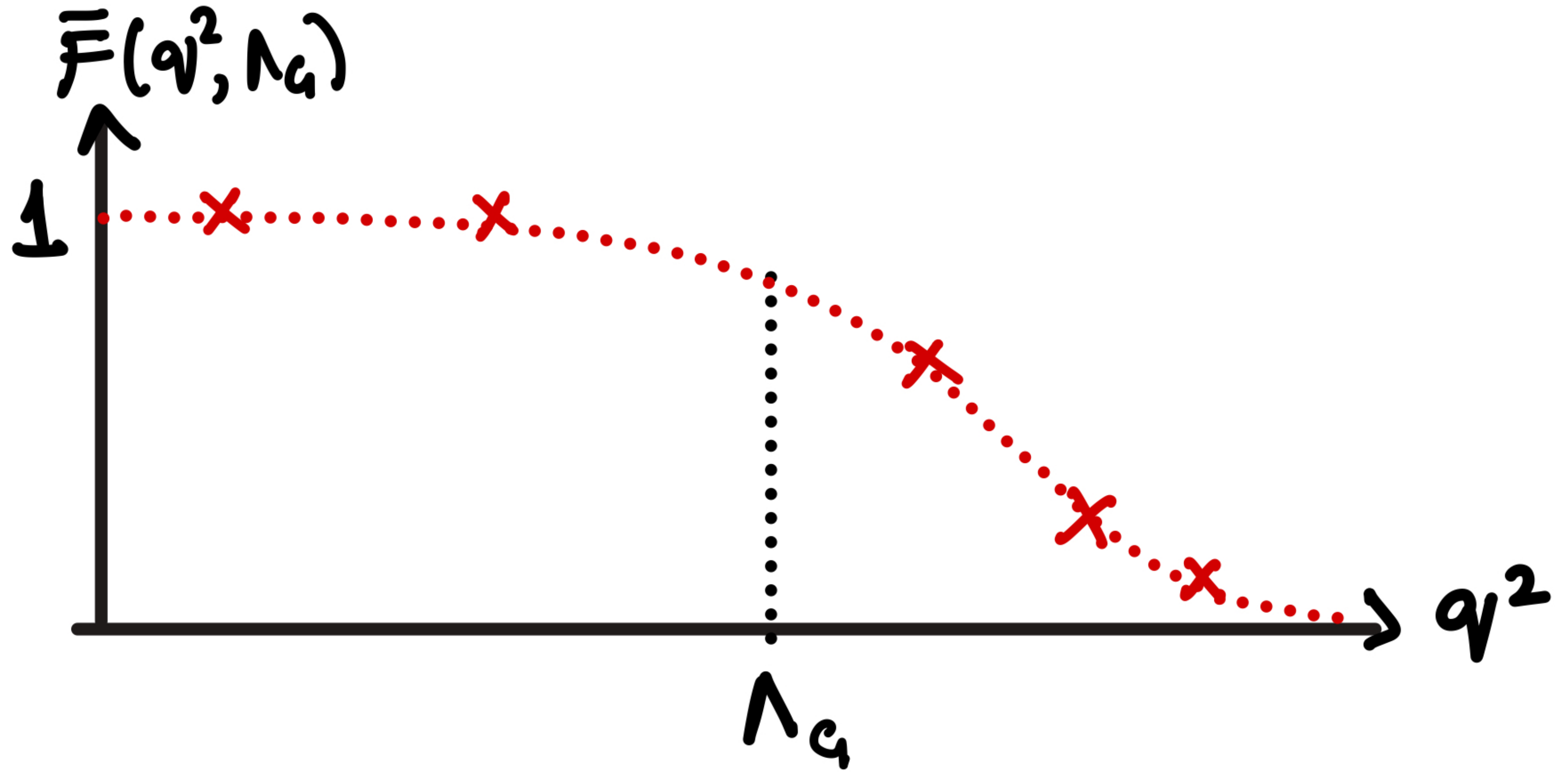

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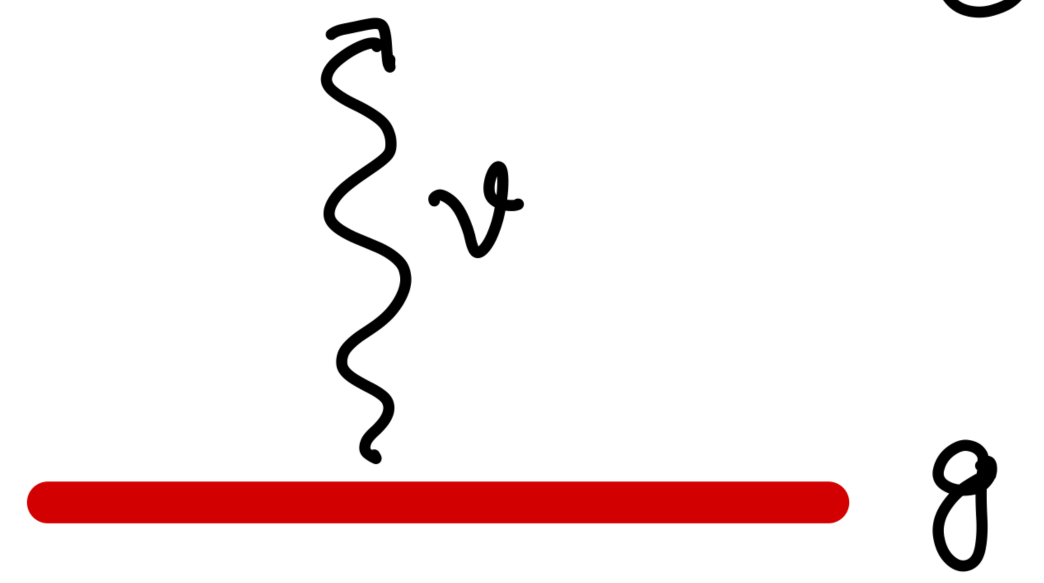

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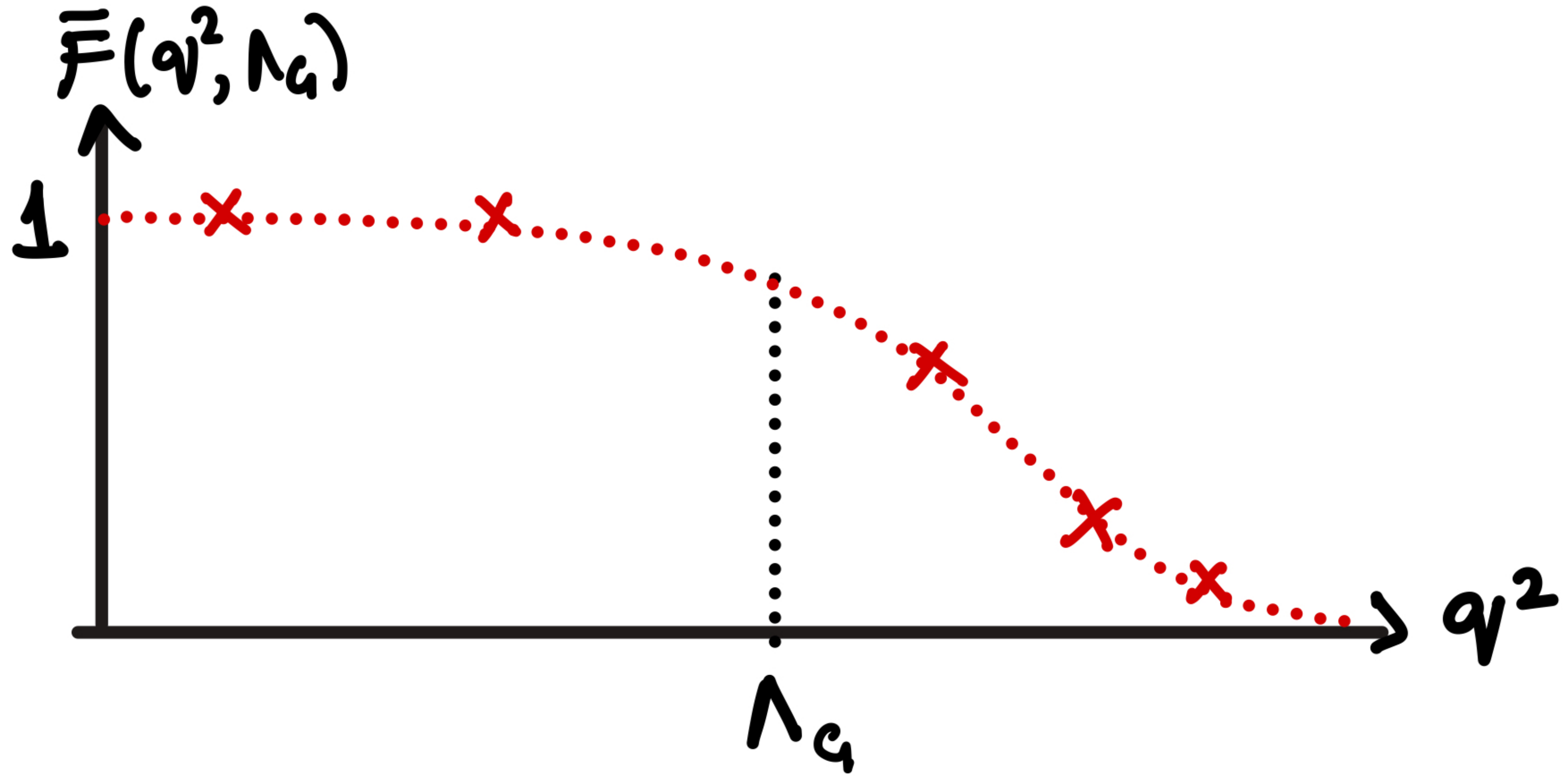
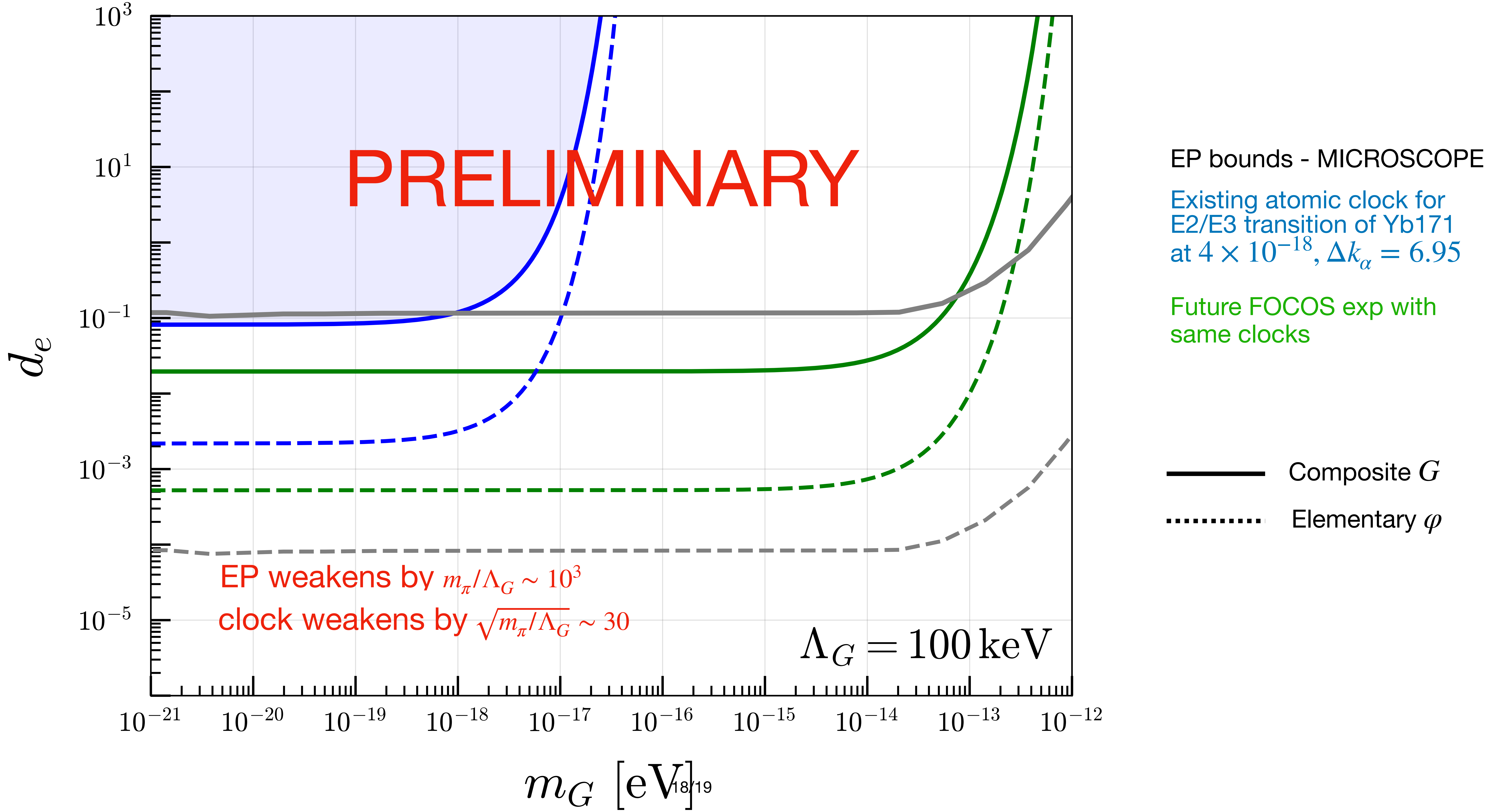


Very interesting regime is when $\Lambda_G \in (1\,\mathrm{keV}, 100\,\mathrm{MeV})$
Using different systems, one can probe different parts of the form factor of this strongly interacting hidden sector!

Composite ULS Parameter Space



Key Takeaways

- There is a large class of natural models for ultralight scalars which is a composite emerging from a hidden strongly-coupled sector. The dynamics of the theory introduces a form factor in the interactions.

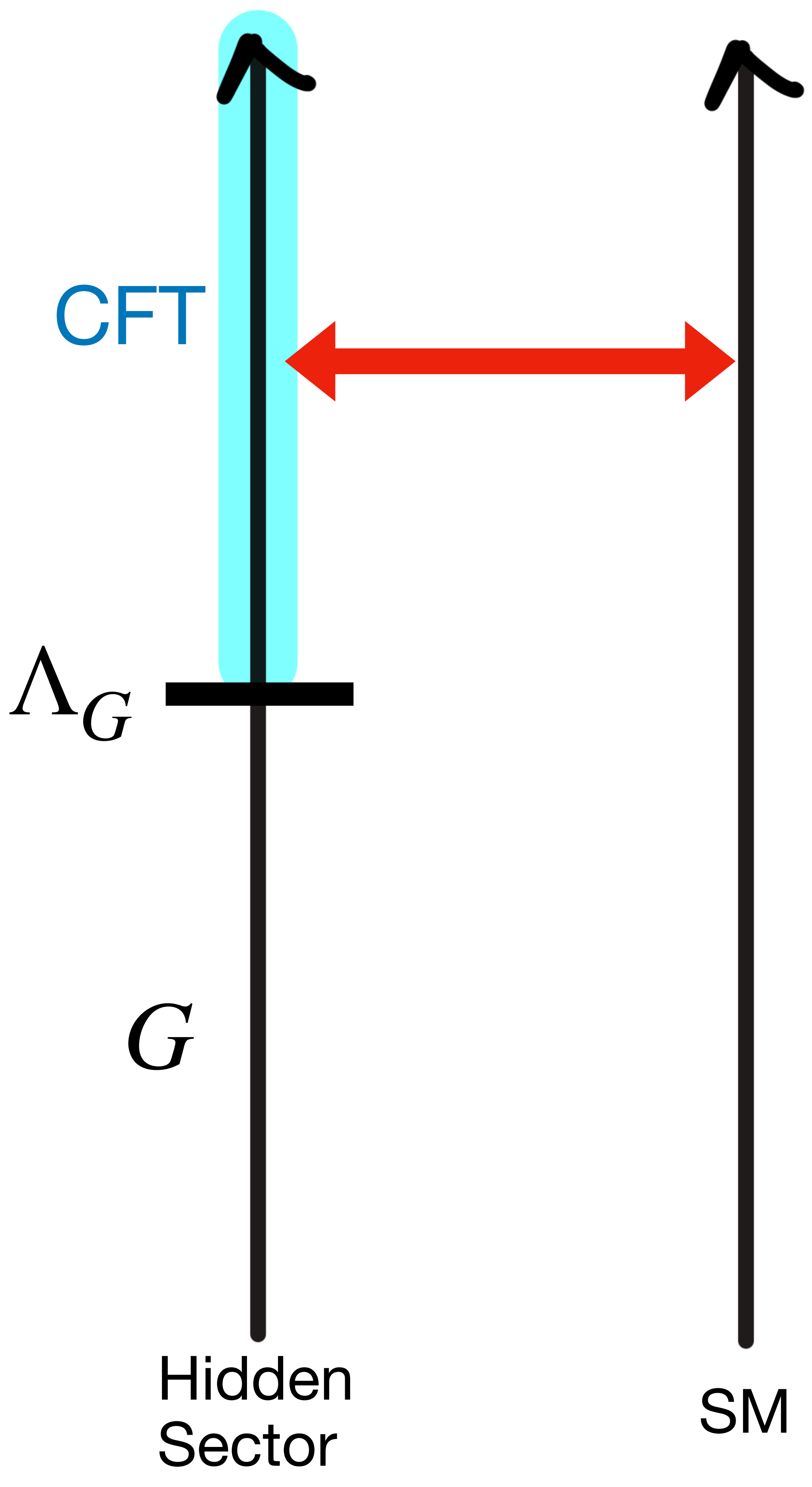
- The momentum-dependent form factor reshuffles the usual hierarchy of bounds.

- For suitable Λ_G, conventional EP tests are mitigated relative to clock-based probes, and current atomic clocks provide the leading constraints.

- Where are the explicit models? Ask me during the break!

Backup Slides

Minimal Model



The strongly-coupled theory in the UV is taken to be a “Conformal Field Theory” - a theory which can run over many decades while remaining approximately scale-invariant.

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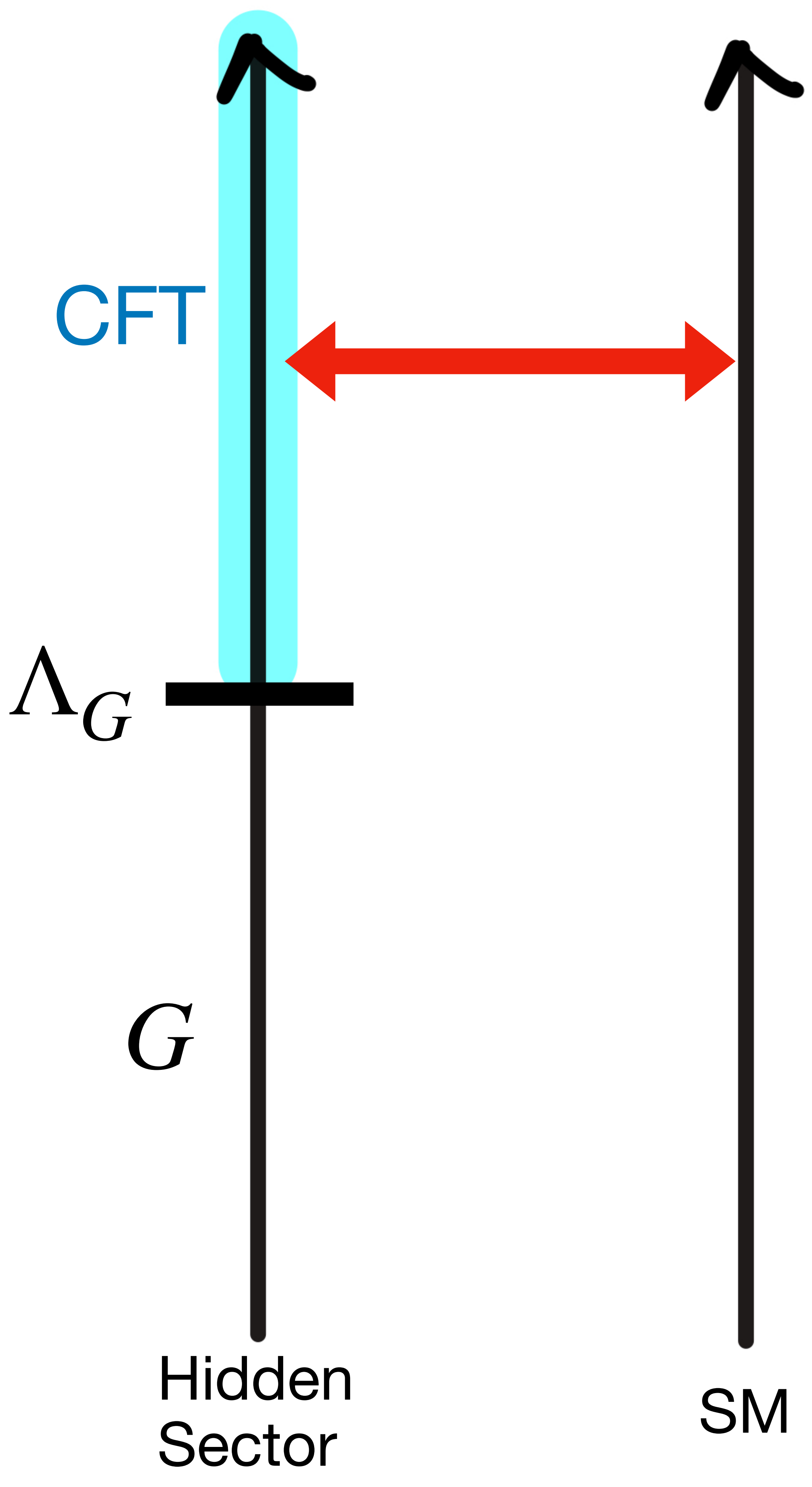

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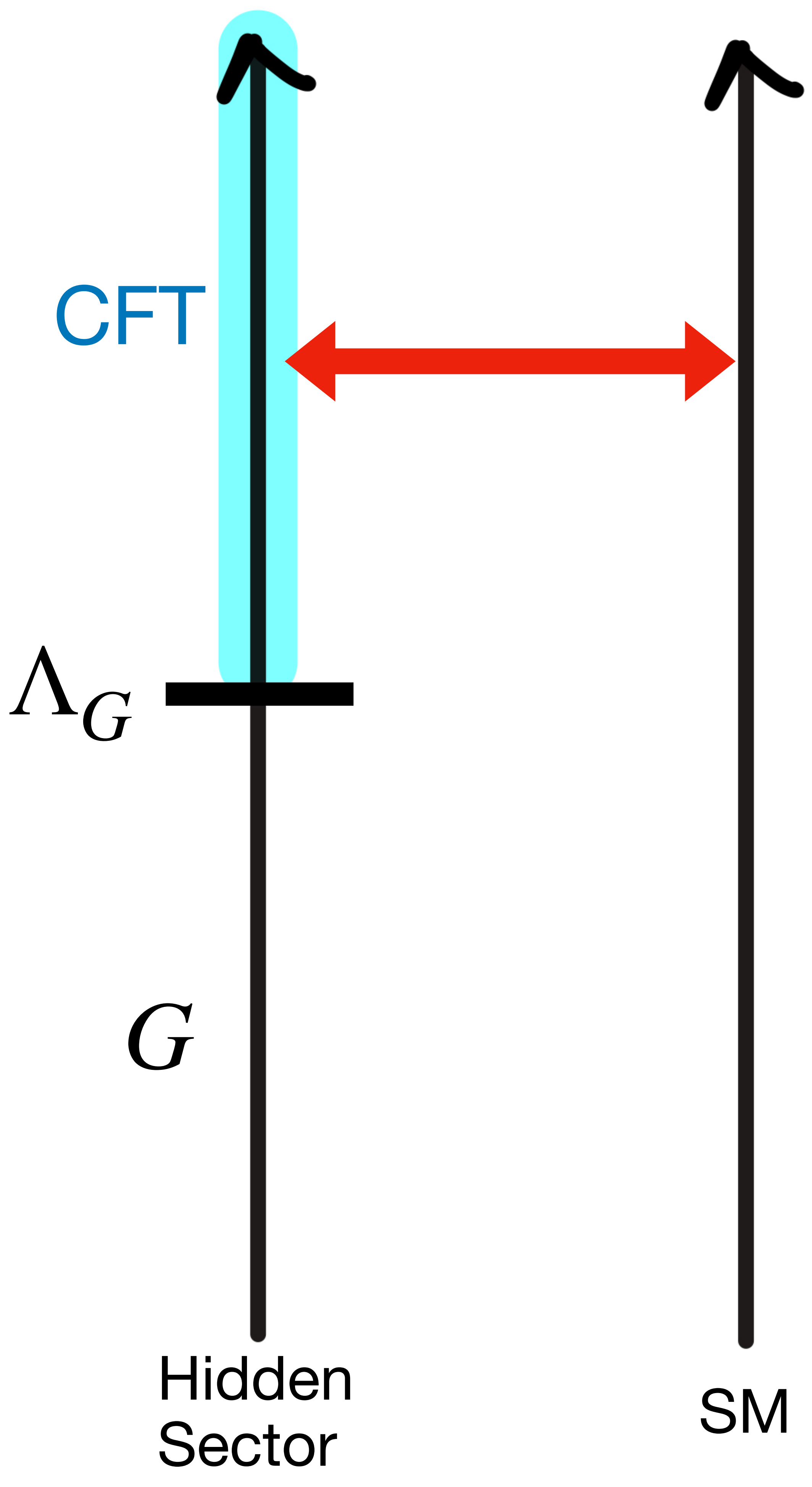

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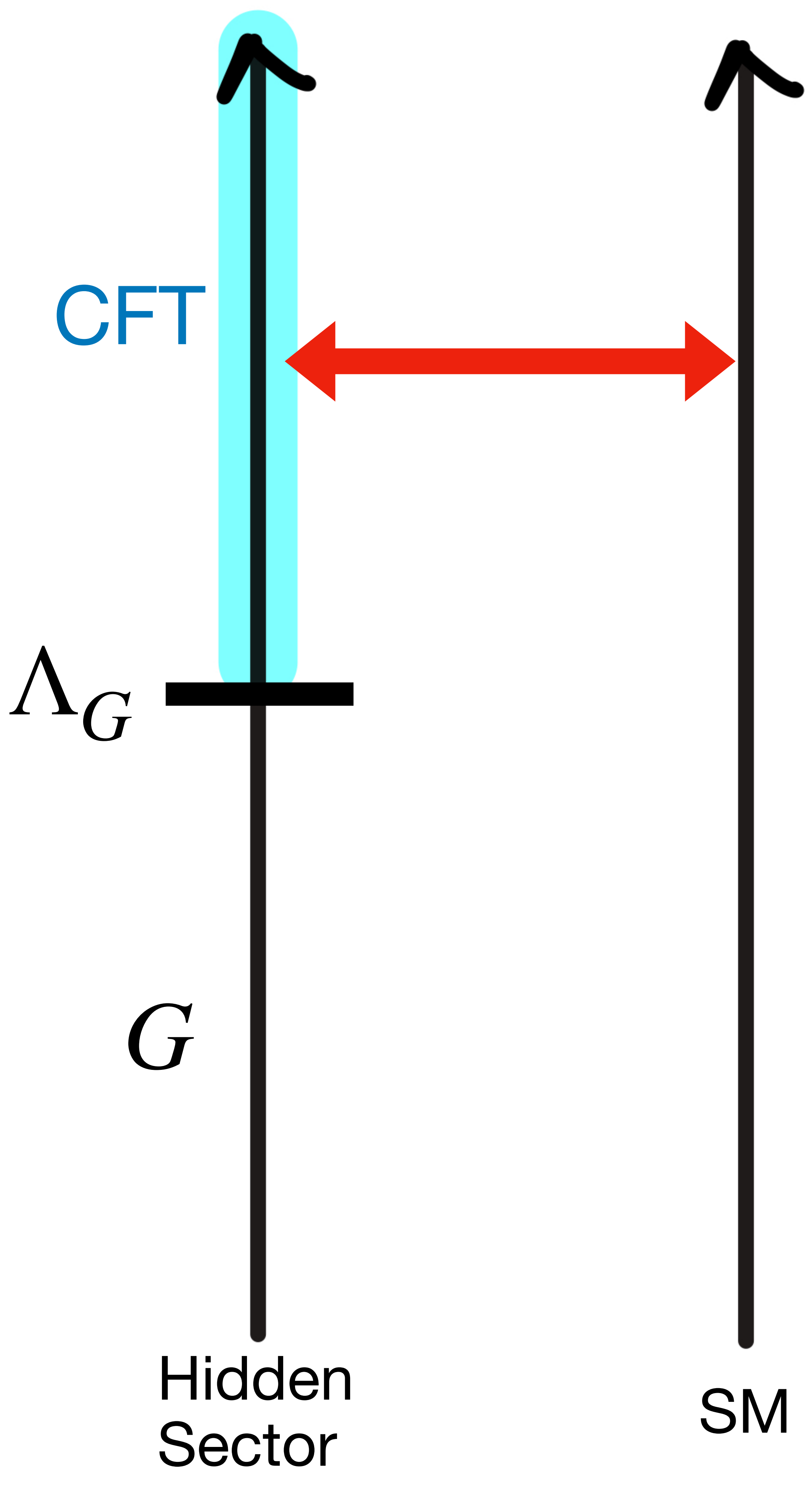

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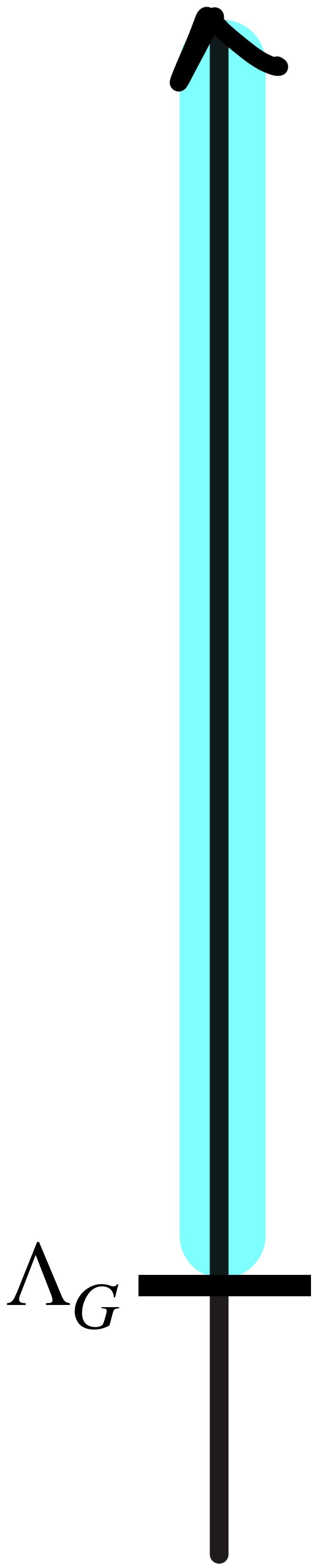
Symmetry breaking by a scalar operator getting a vev

$$\langle \mathcal{O}_G \rangle : \quad U(1)_{\rm CFT} \longrightarrow \varnothing$$

Minimal Model - Interactions



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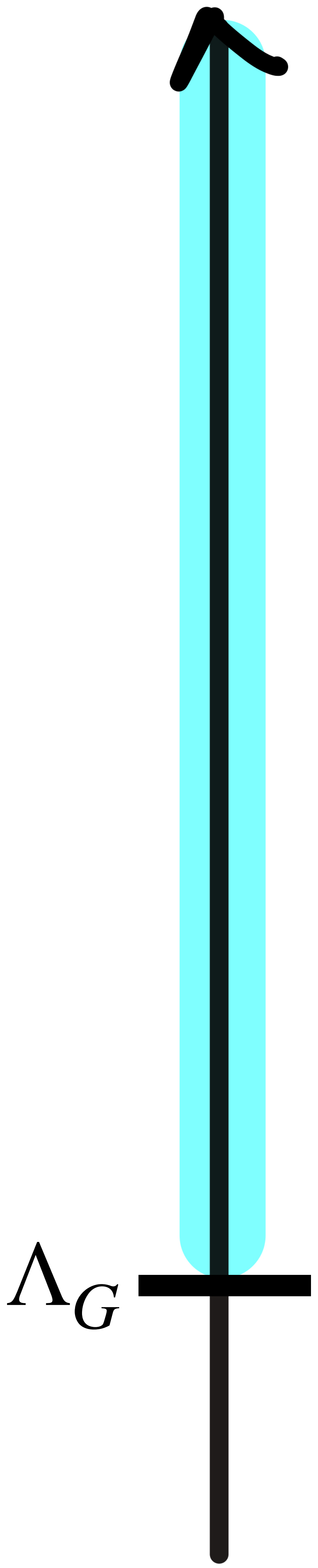

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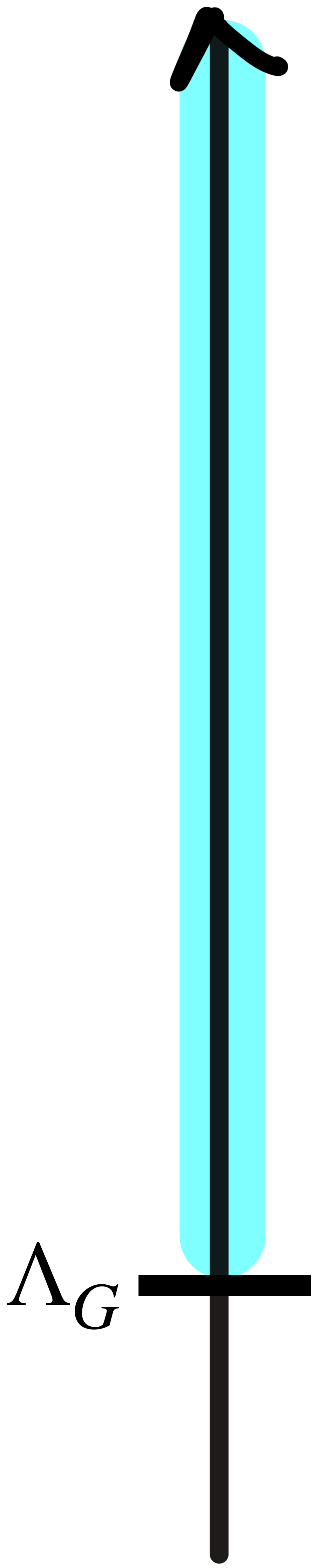

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$\mathcal{O}^{\mu\nu}$ antisymmetric tensor operator - (Δ_T , q_T) interacting via the photon portal.

$|\hat{\epsilon}| \sim {\rm O}(1)$ $\qquad$ $\Delta_T \geq 2$ (unitarity constraint)

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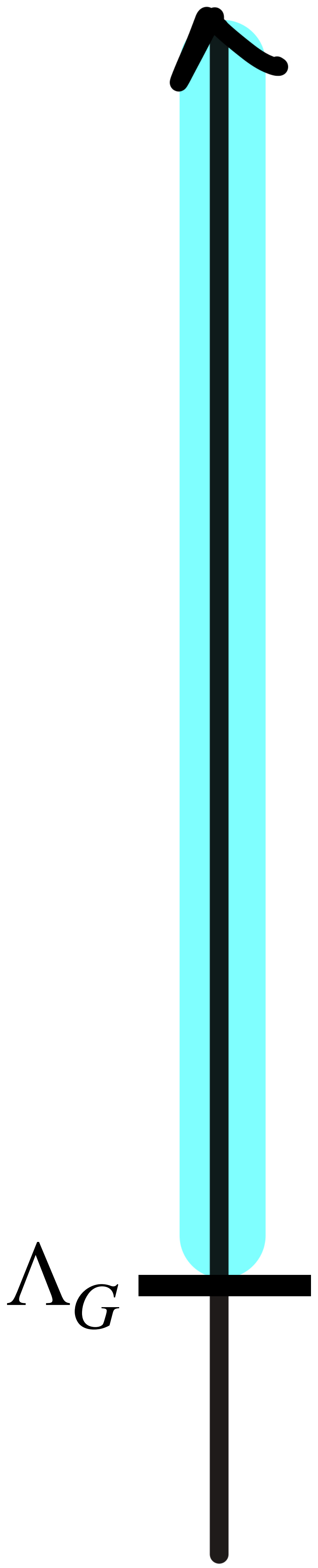

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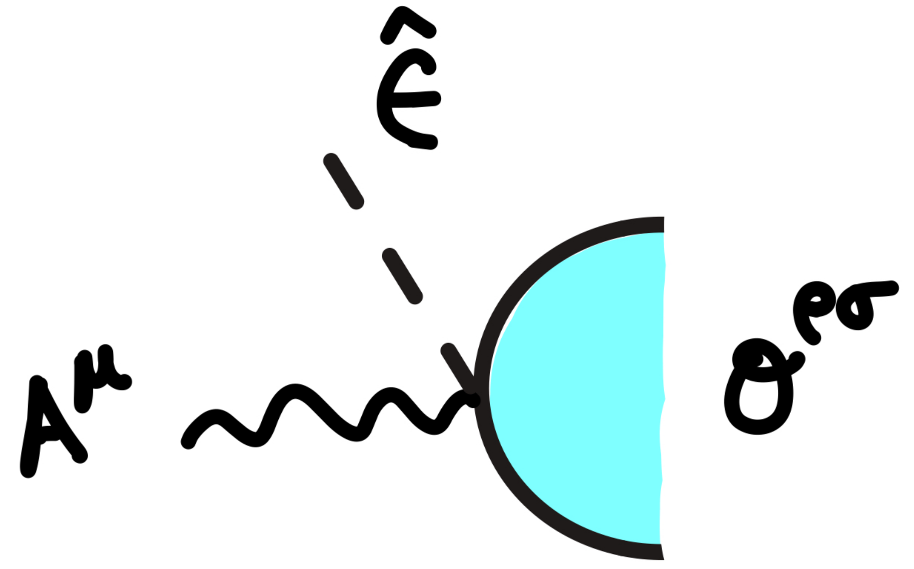

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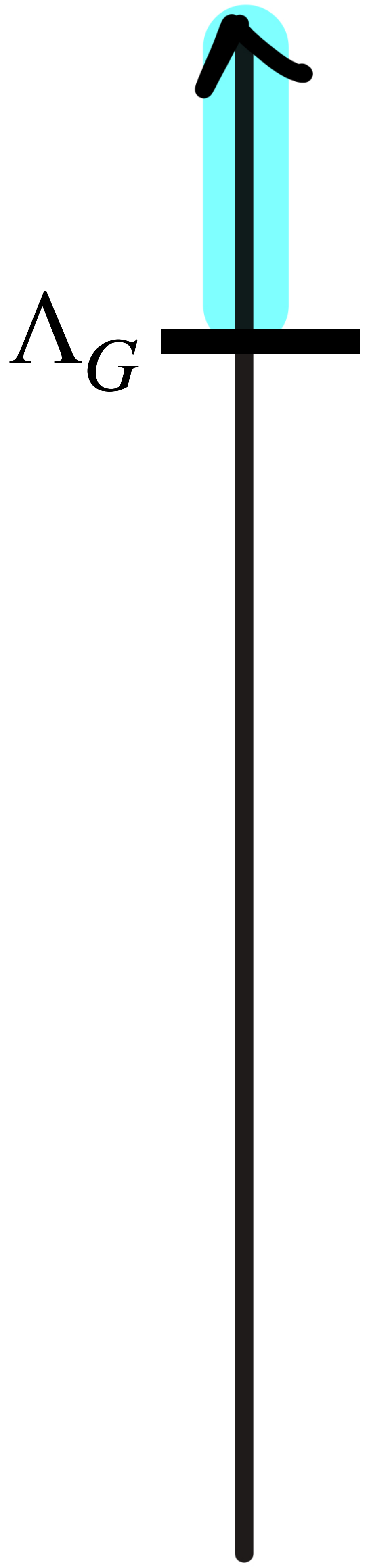

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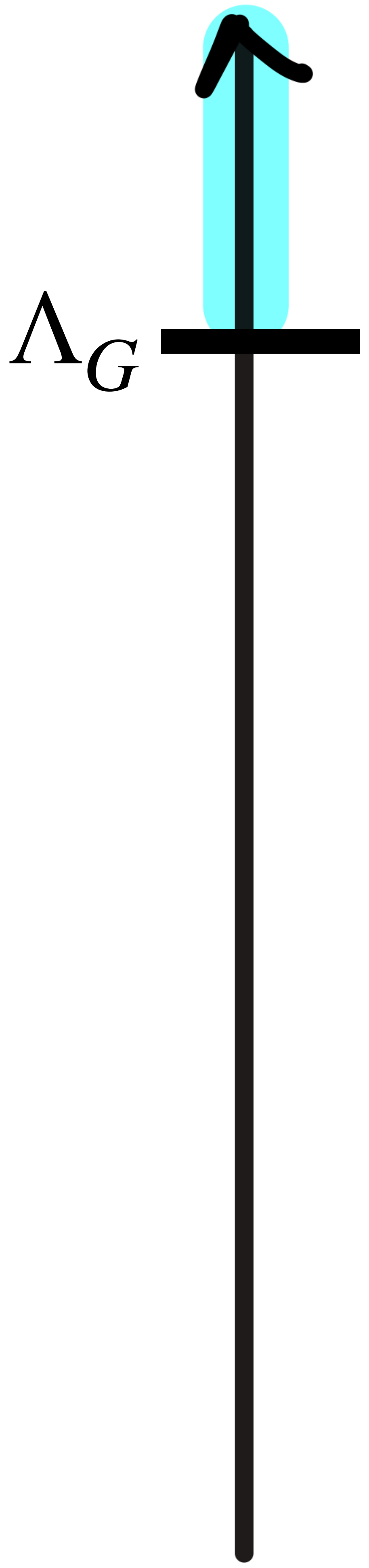
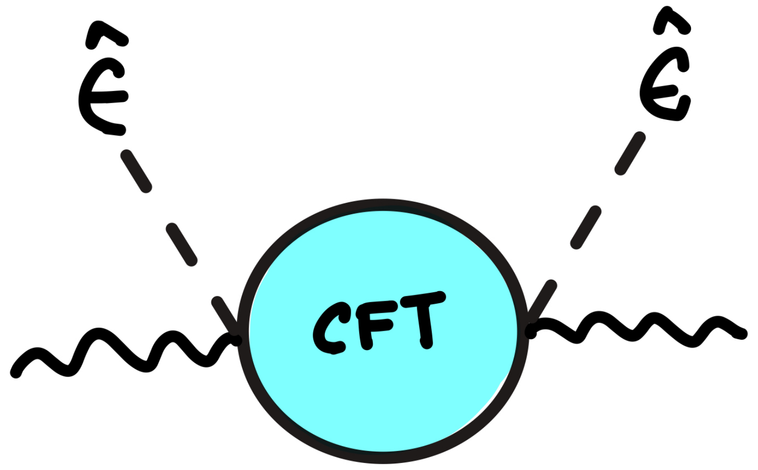
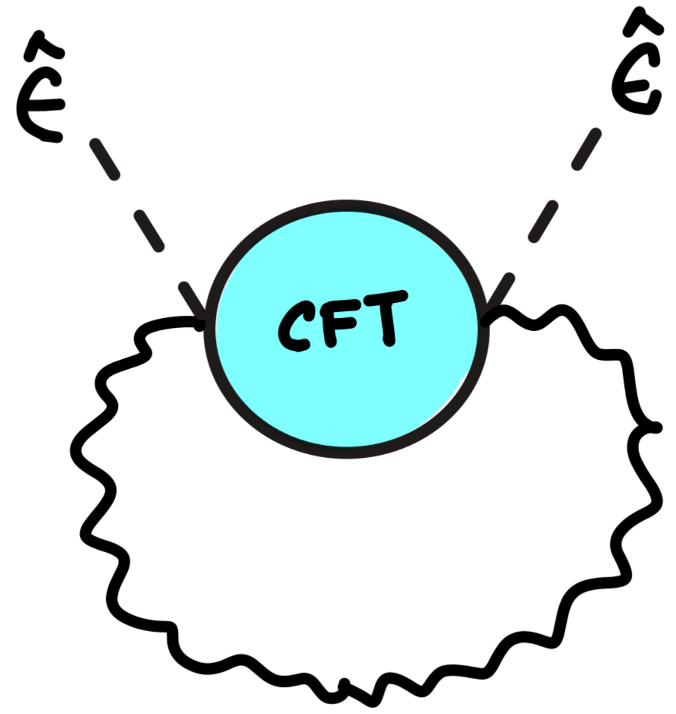


From the tensor operator



$$\mathscr{L} \supset \frac{|\hat{\epsilon}|^2}{16\pi^2}\left(\frac{\Lambda_G}{M_{\rm Pl}}\right)^{2\Delta_T-4} \cos(2q_T\hat{G} + 2\arg\hat{\epsilon})\, F^{\mu\nu}F_{\mu\nu}$$



$$V_T \simeq -\Lambda_T^4 \cos(2q_T\hat{G} + 2\arg\hat{\epsilon})$$

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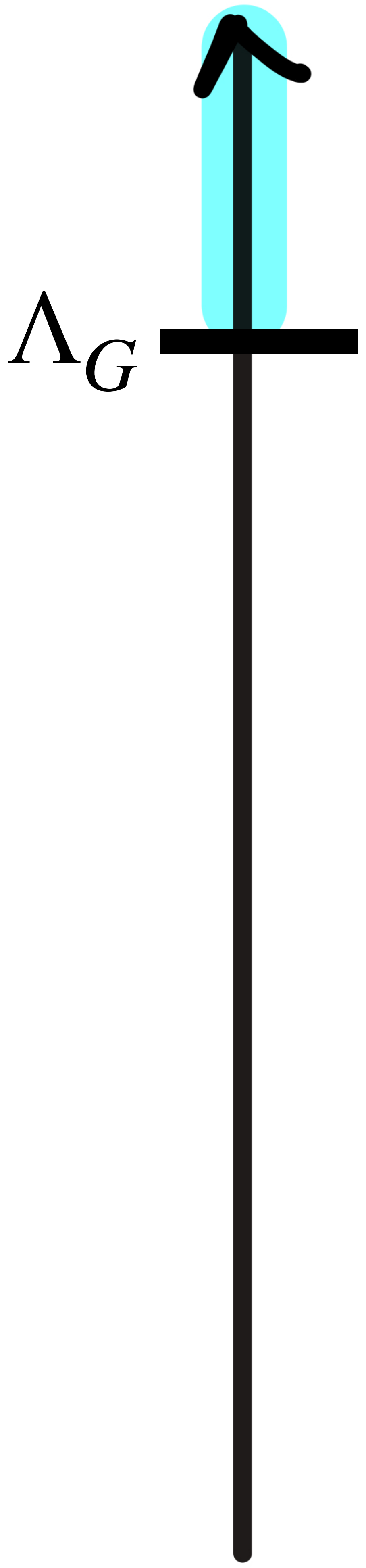

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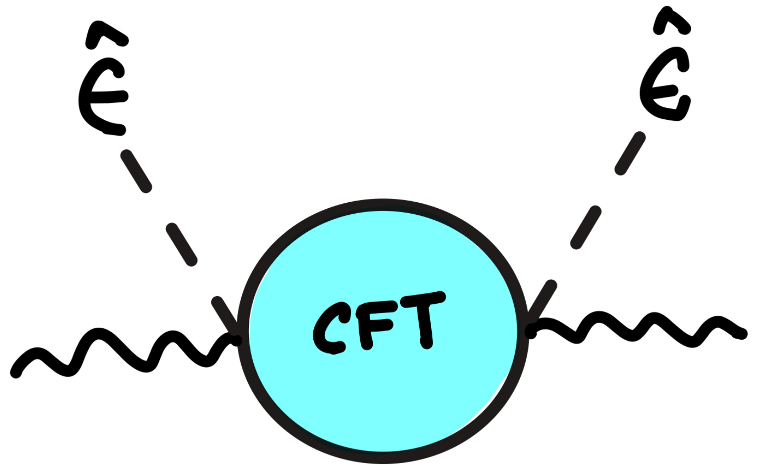
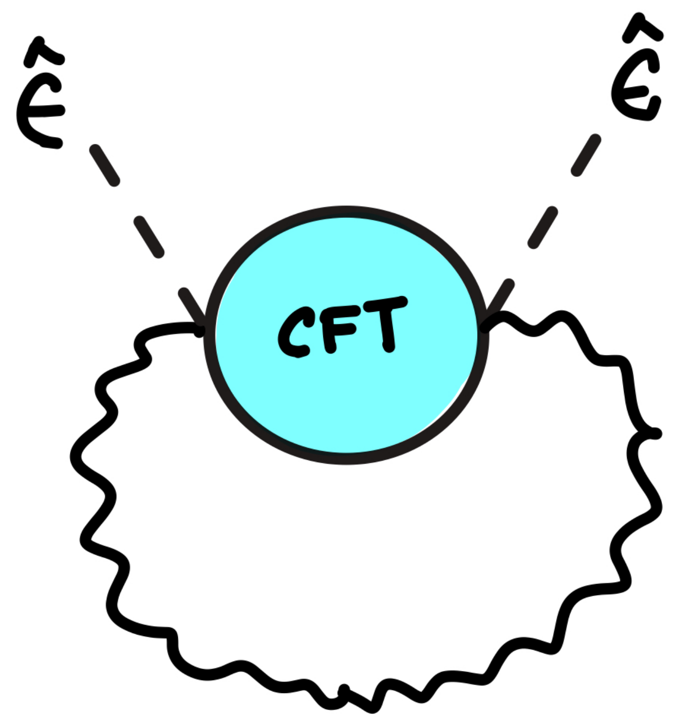
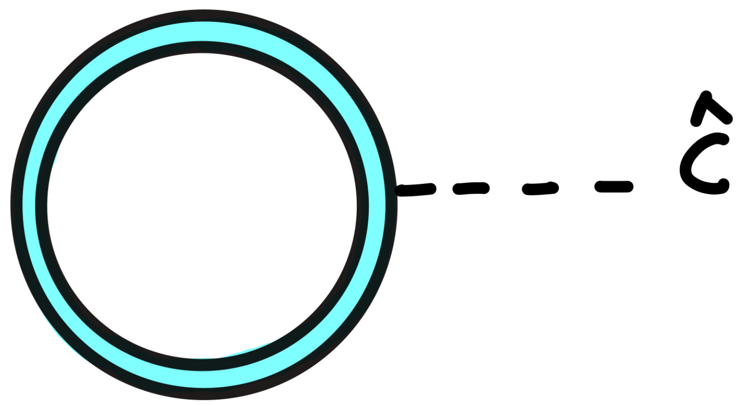


$$\mathscr{L} \supset \frac{|\hat{\epsilon}|^2}{16\pi^2}\left(\frac{\Lambda_G}{M_{\rm Pl}}\right)^{2\Delta_T-4} \cos(2q_T\hat{G} + 2\arg\hat{\epsilon})\, F^{\mu\nu}F_{\mu\nu}$$



$$V_T \simeq -\Lambda_T^4 \cos(2q_T\hat{G} + 2\arg\hat{\epsilon})$$

From the scalar operator,



$$V_S \equiv -\Lambda_S^4 \cos(q_S\hat{G} + \arg\hat{c})$$

Minimal Model - A Natural Model!

The total potential is, $$V(\hat{G}) = -\Lambda_T^4 \cos(2q_T\hat{G}) - \Lambda_S^4 \cos(q_S\hat{G} + \delta)$$

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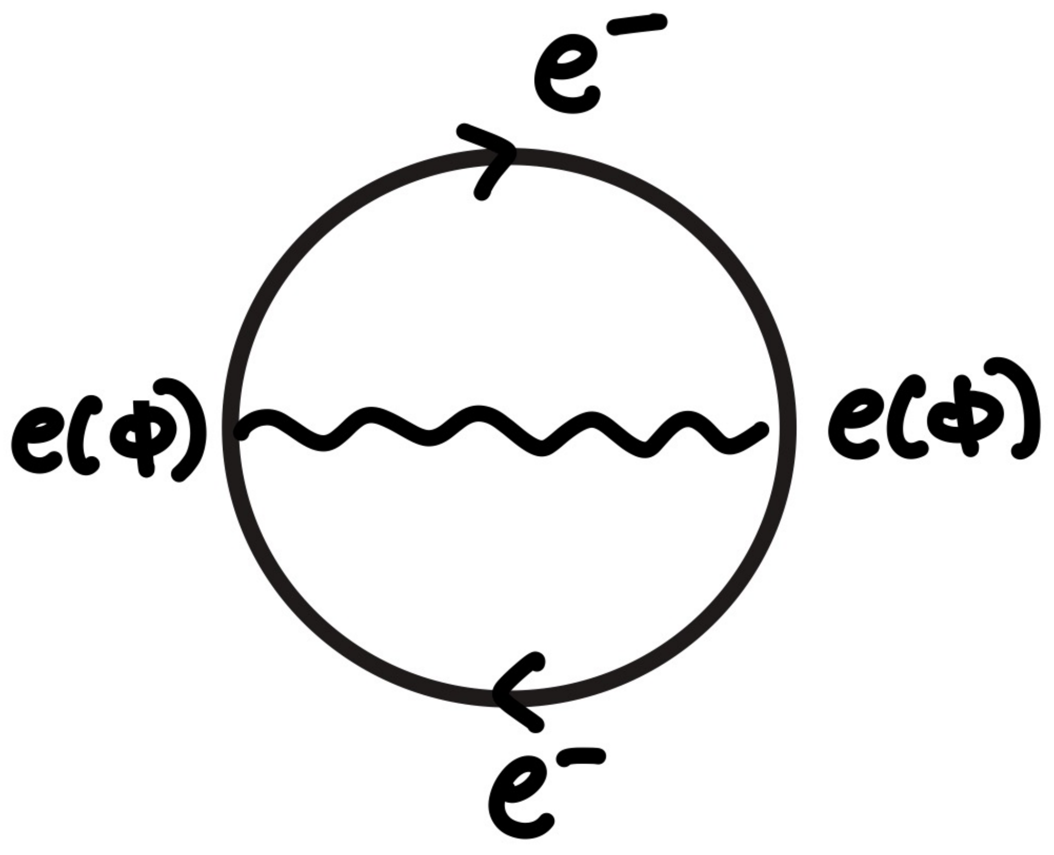

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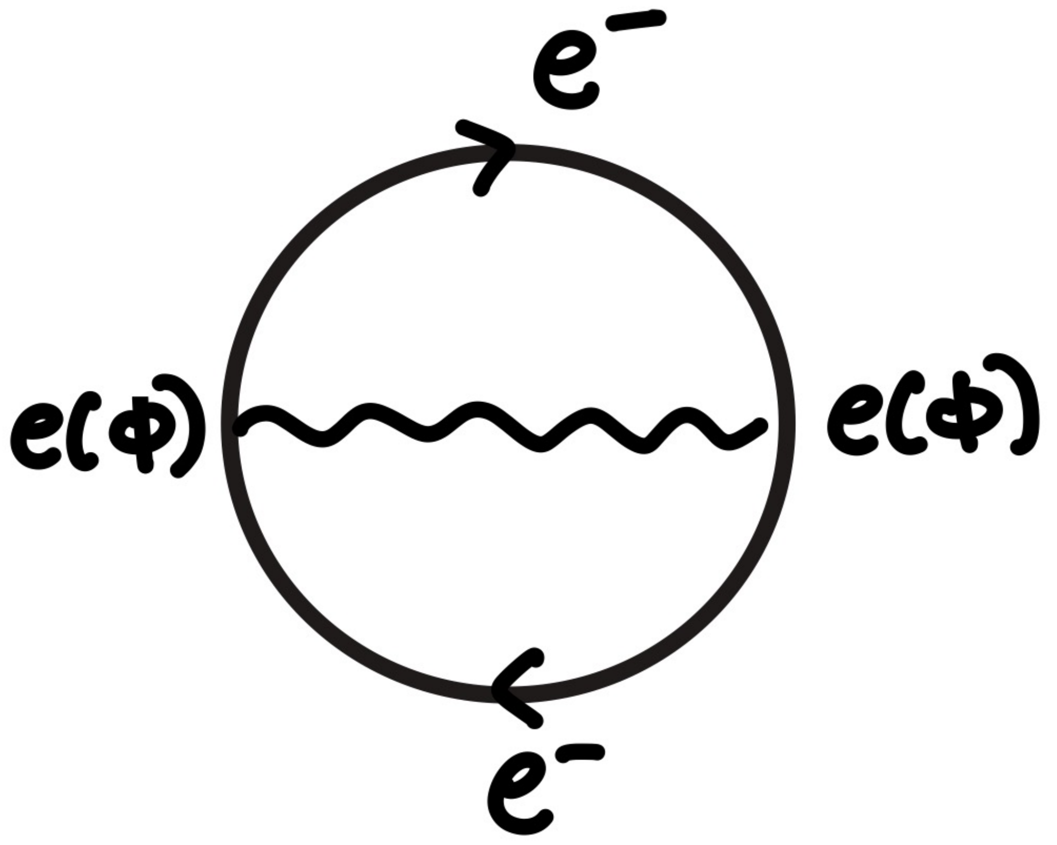

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Hence, this model does not suffer from a naturalness issue!

Derivation of Form-Factor

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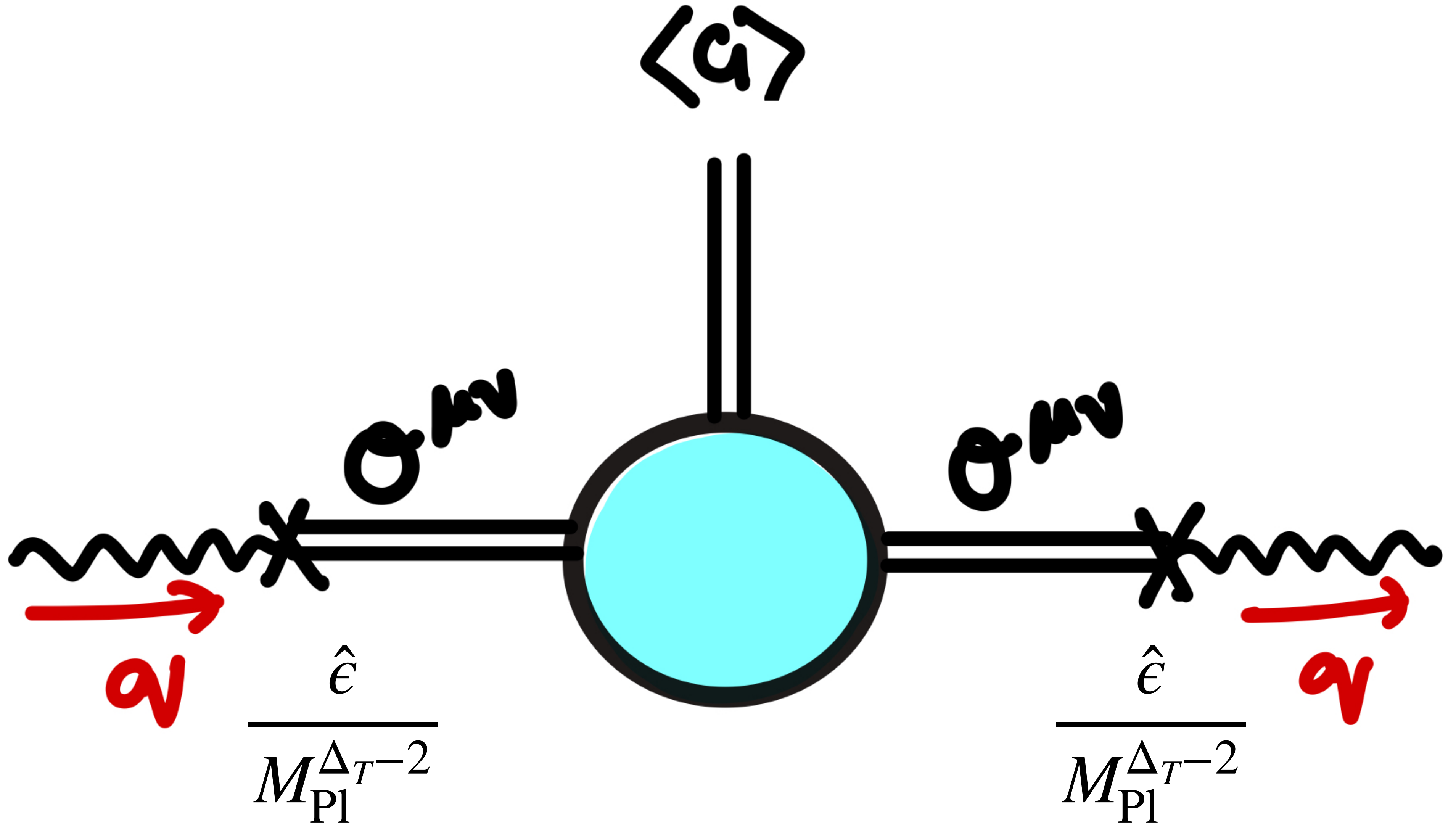

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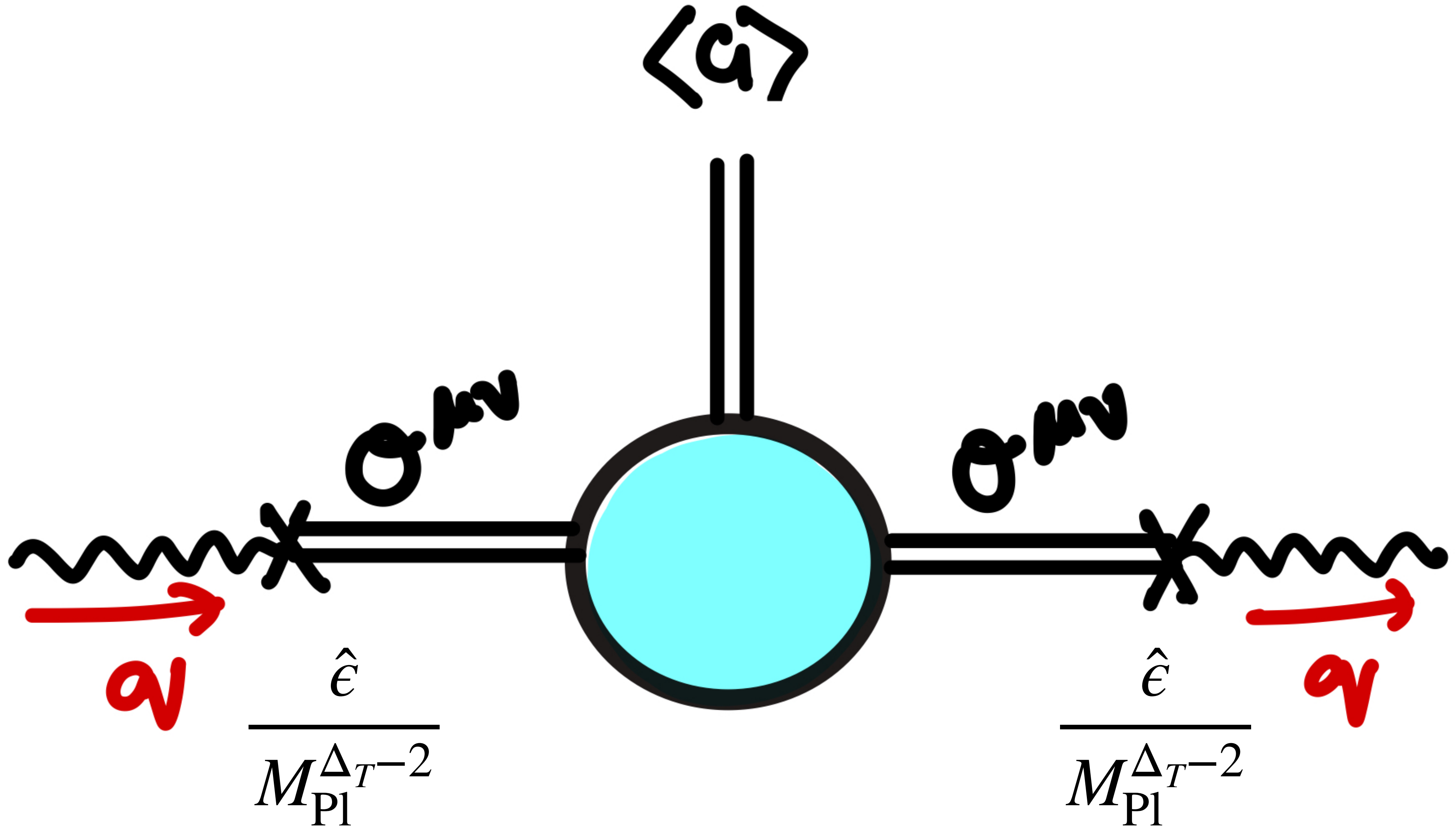

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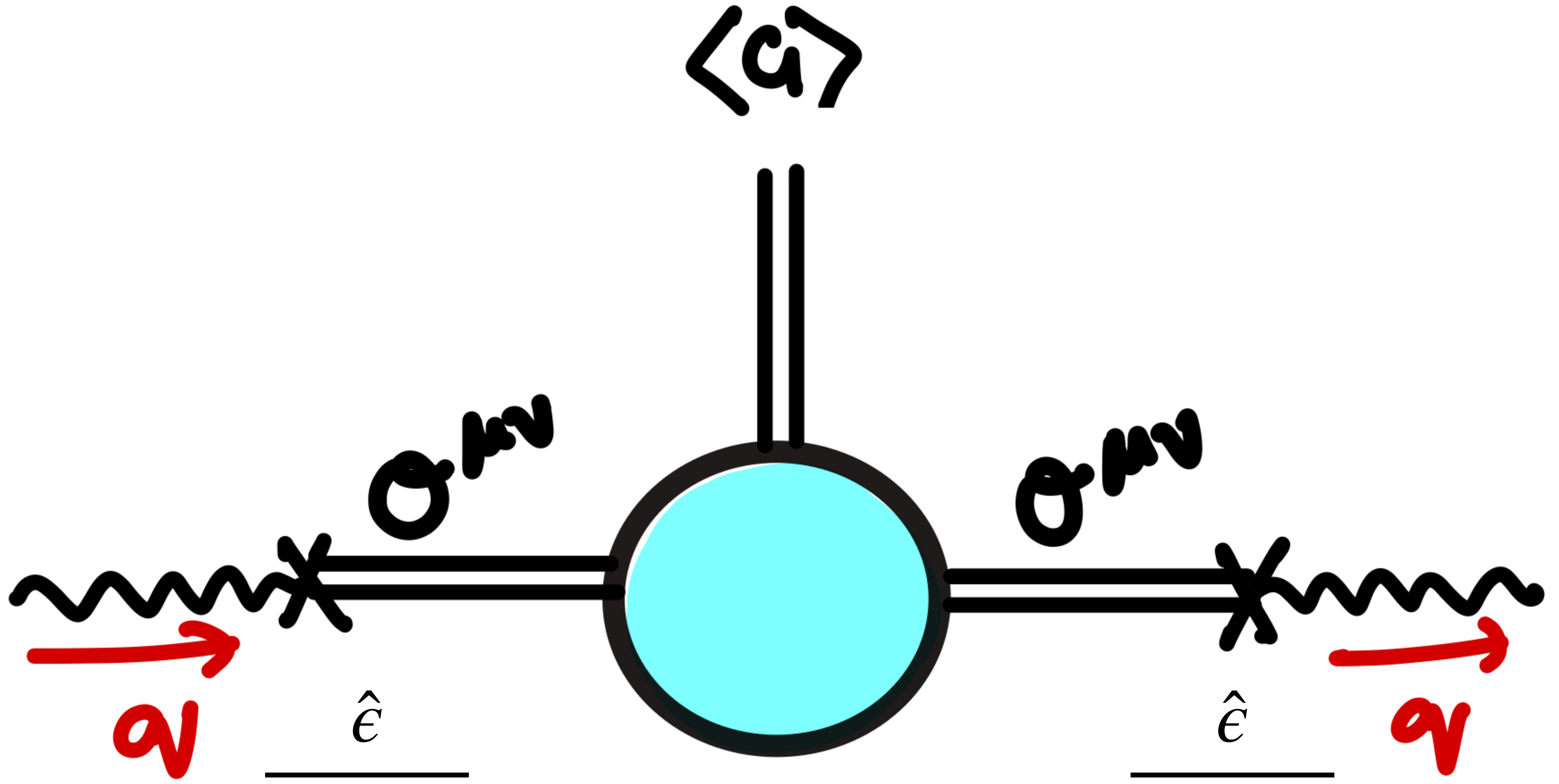

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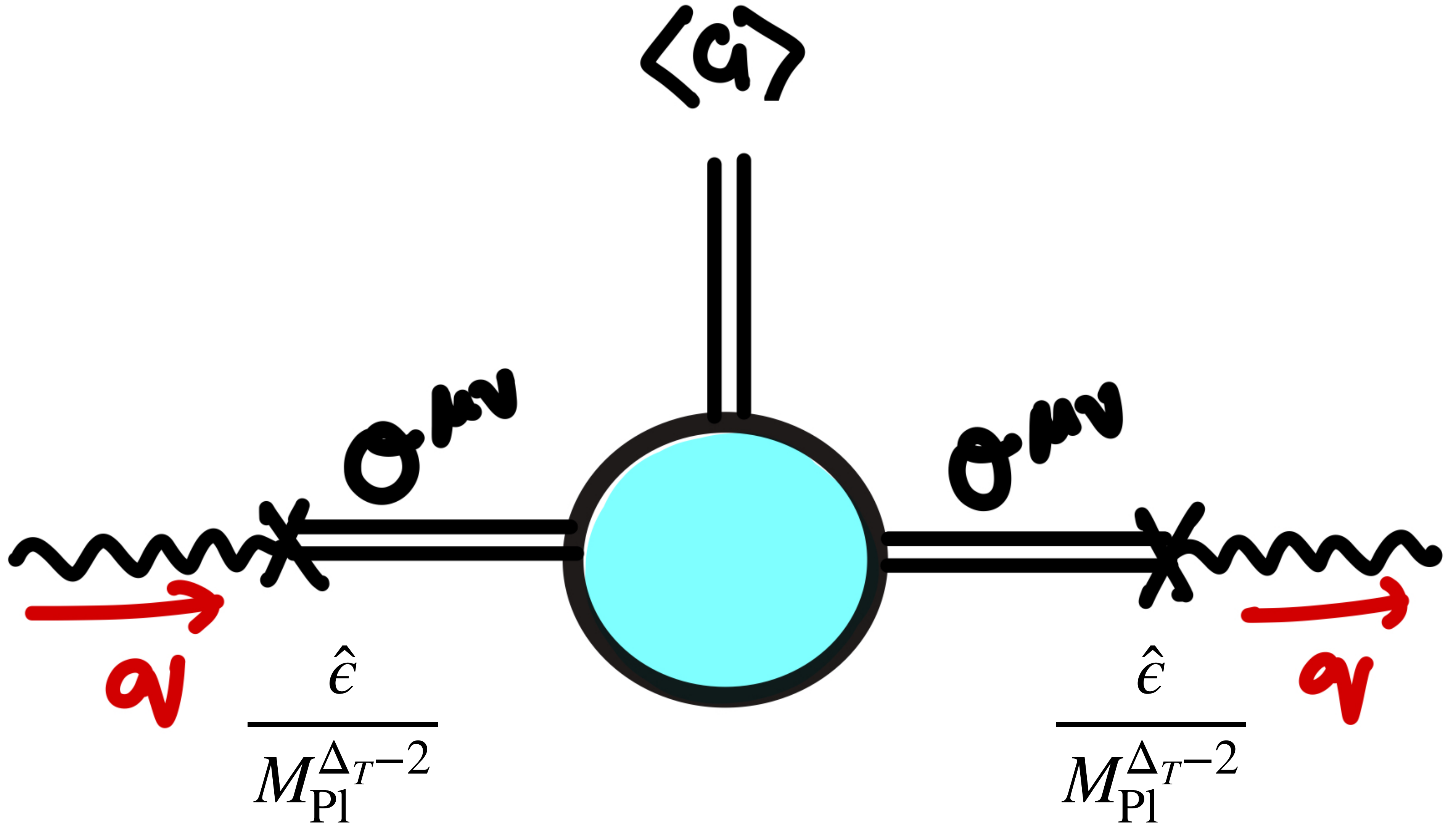
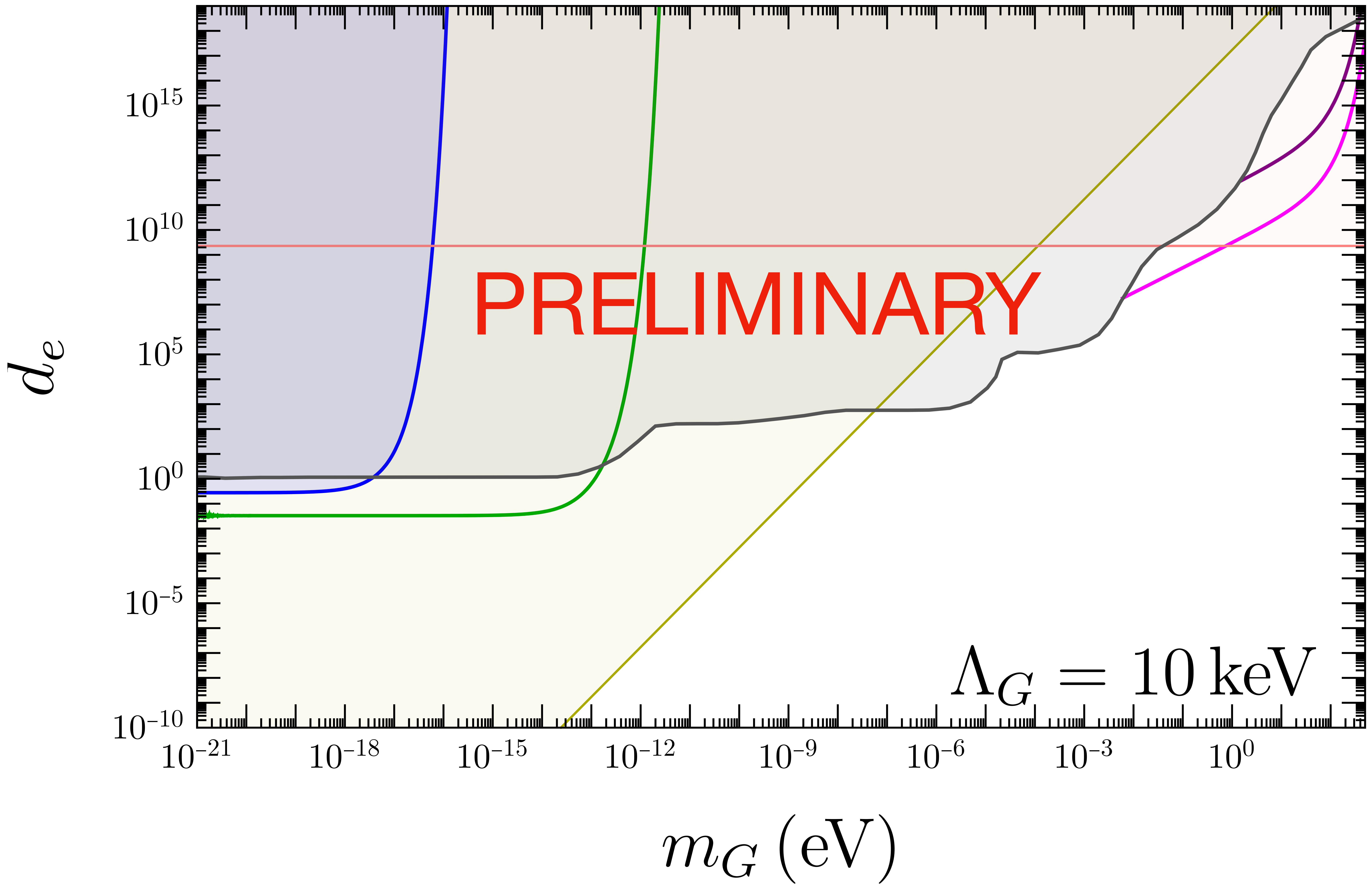


Fix the IR coefficient by matching.

$$\bar{\mathcal{F}}(q^2,\Lambda_G) = \begin{cases} 1 & |q^2| \lesssim \Lambda_G^2 \\ \left(\frac{\Lambda_G}{|q|}\right)^{\Delta_G+4-2\Delta_T} & |q^2| \gtrsim \Lambda_G^2 \end{cases}$$

Minimal Model Parameter Space



EP bounds - MICROSCOPE

Astro cooling bounds

Existing atomic clock for E2/E3 transition of Yb171 at 4×10^{-18}, $\Delta k_\alpha = 6.95$

Future FOCOS exp with same clocks

Proposed setup with atomic clock of 10^{-18}

Proposed setup with atomic clock of 10^{-22}

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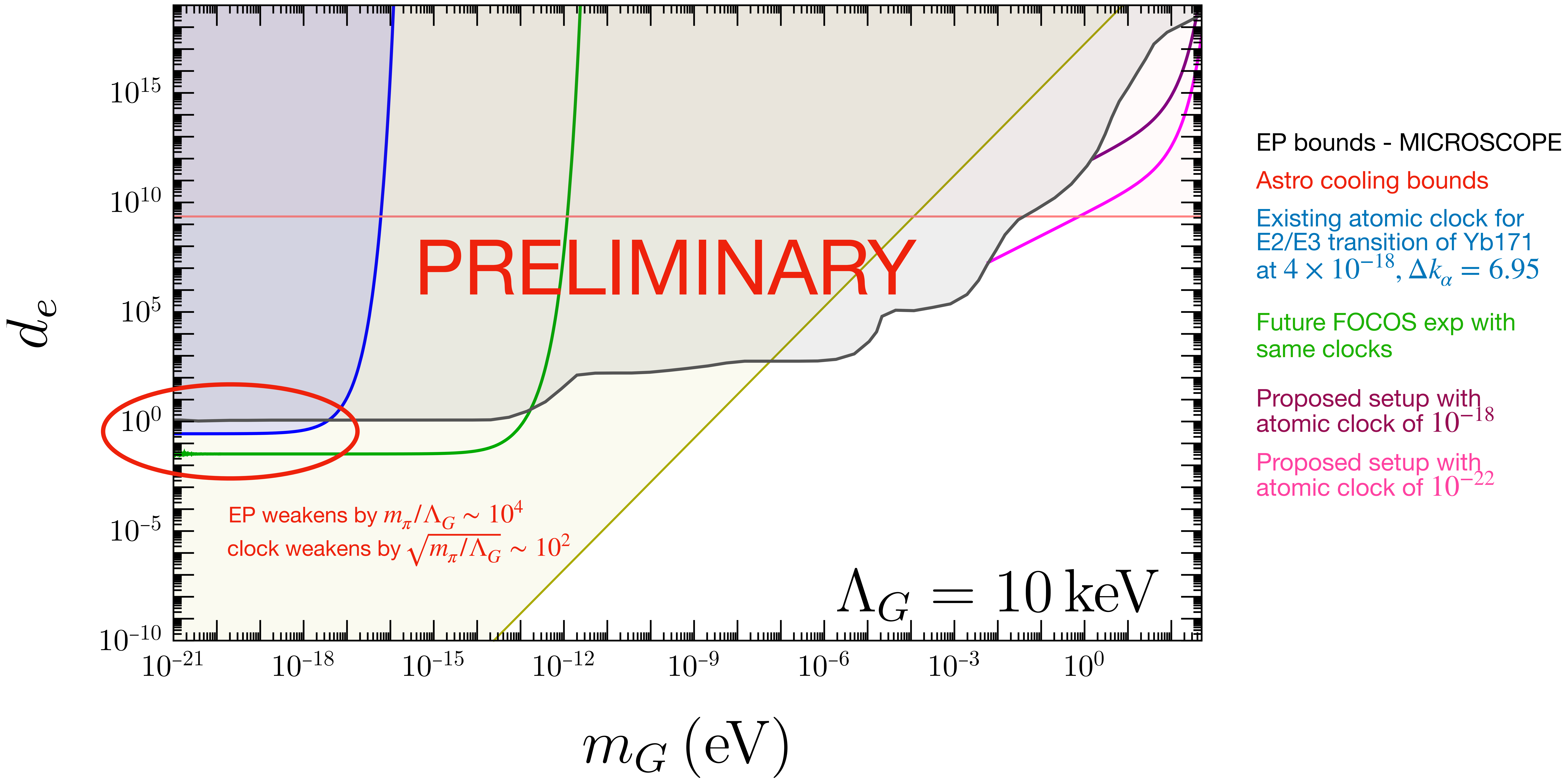

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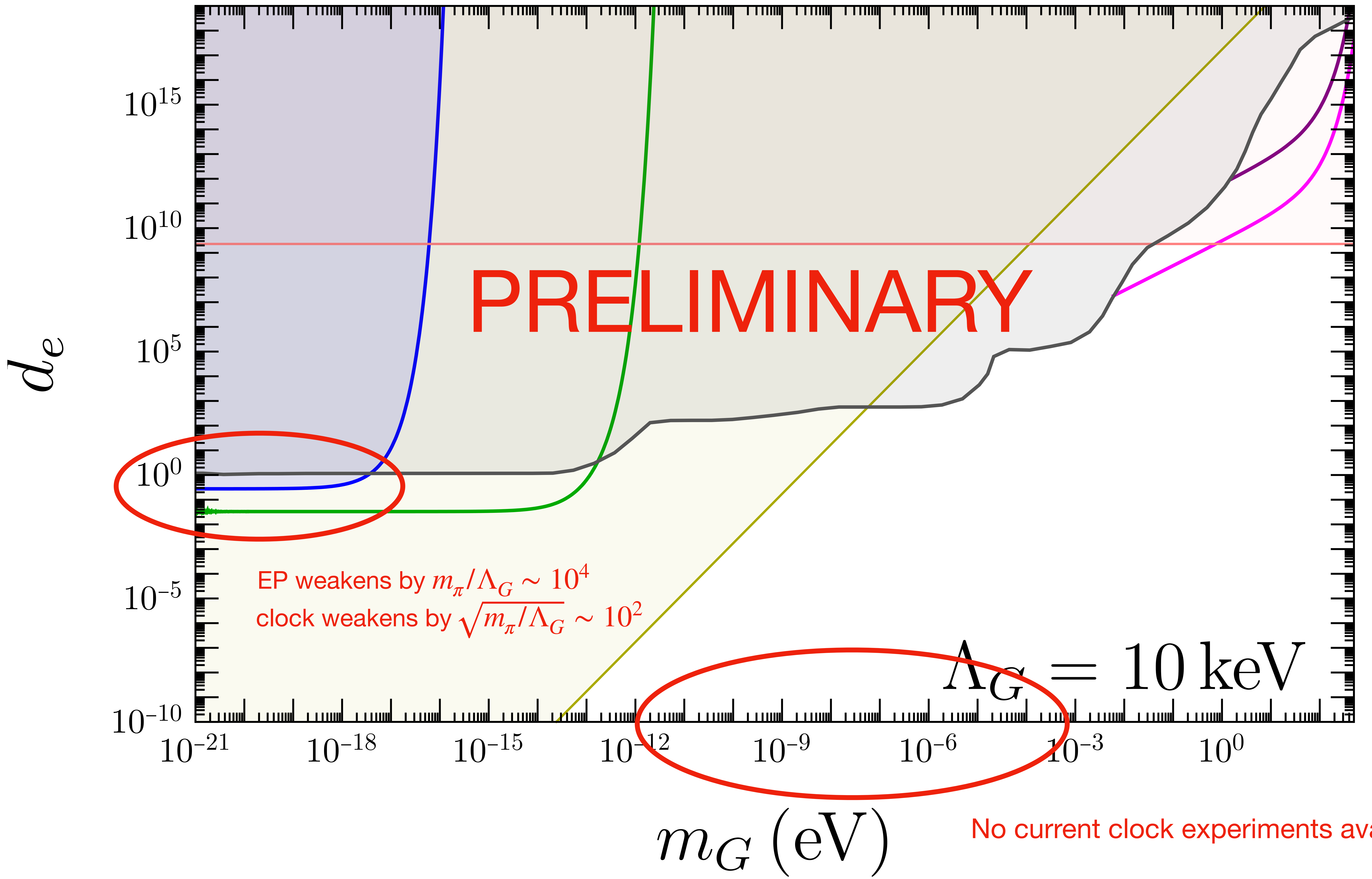

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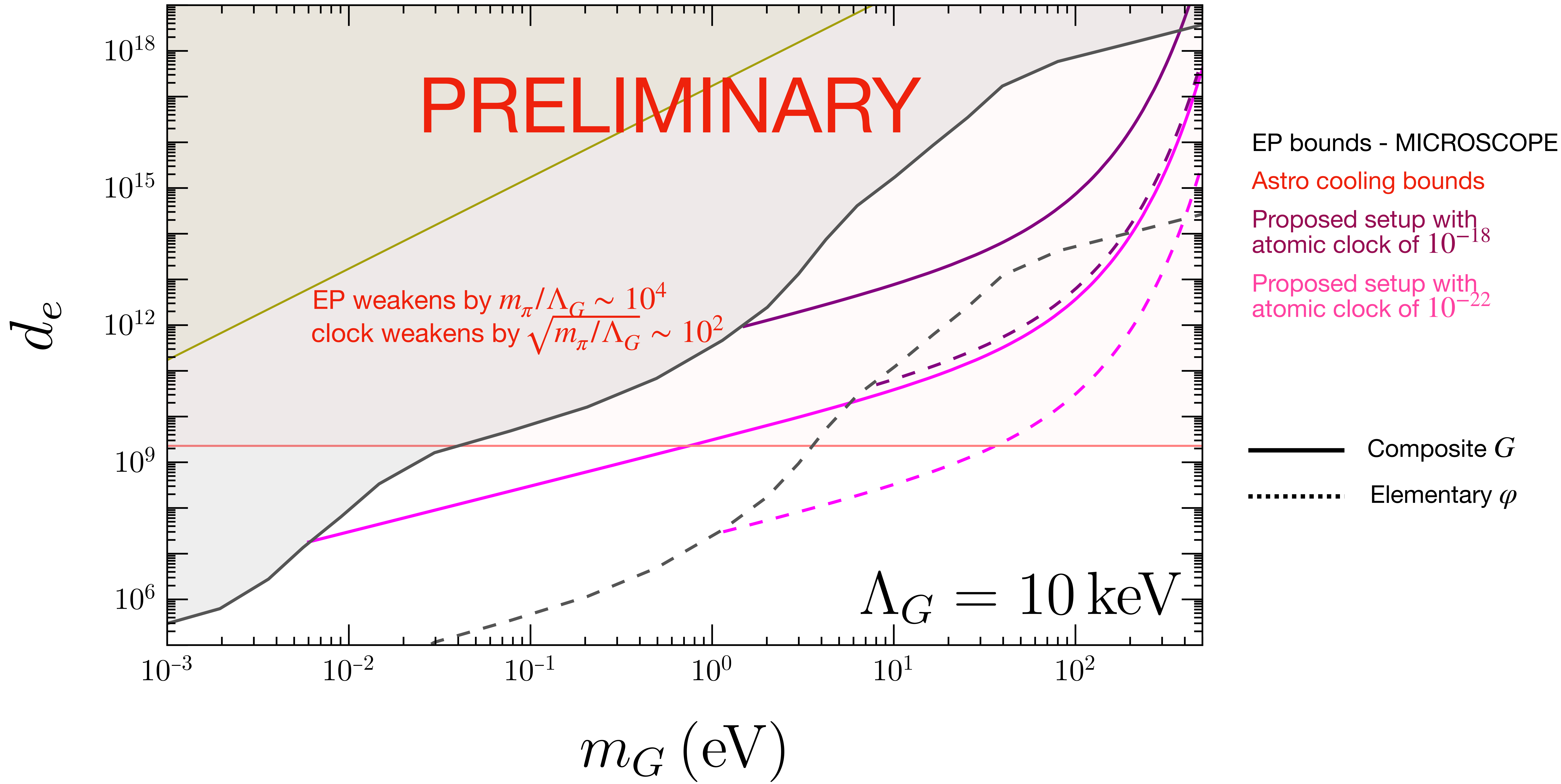

Extended Model

Basic Idea: To obtain sizable interaction strength with SM even for very small m_G, one needs to break the relationship between m_G and the interaction strength.

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CFT : $O(2)$ global symmetry

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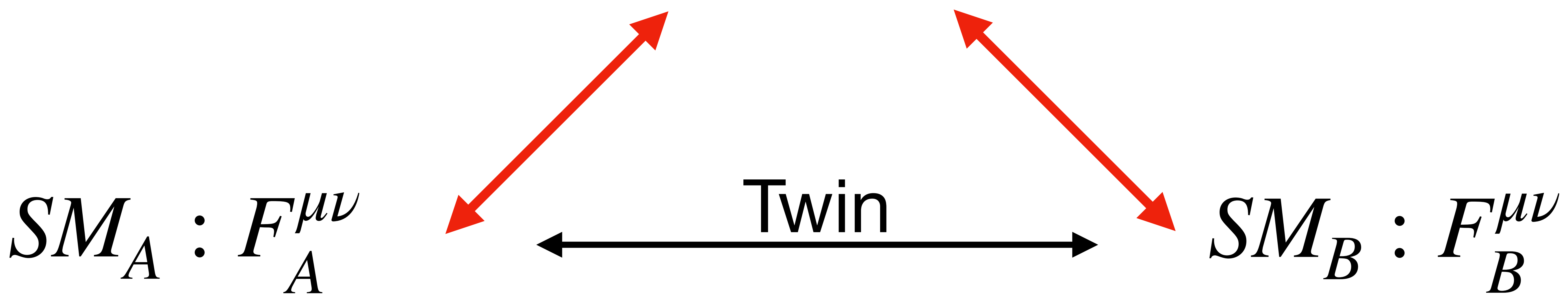

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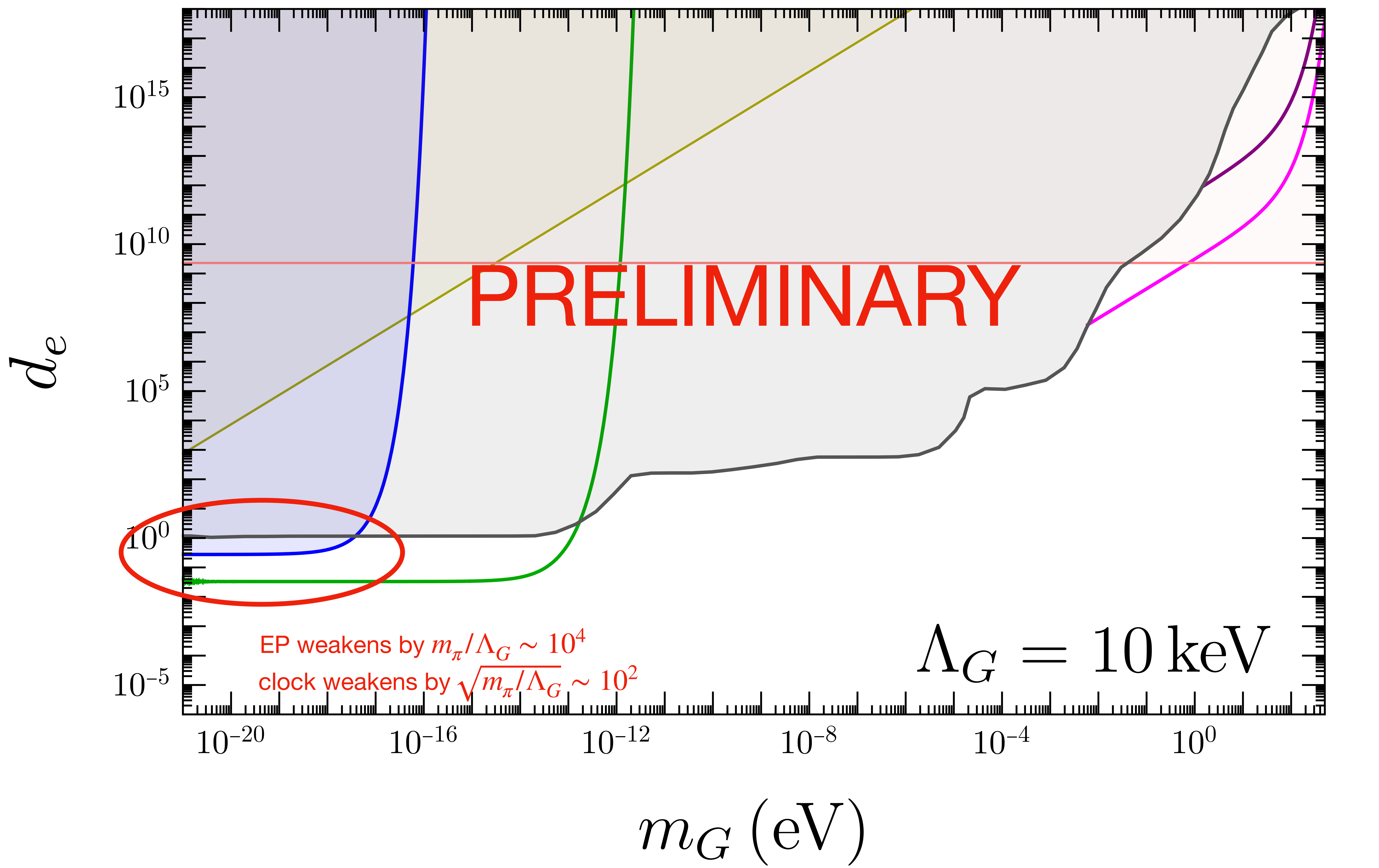

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