GROSSMAN GROUP · CORNELL

Strongly Coupled Quantum Forces

Chinhsan Sieng

with Yuval Grossman, Xun-Jie Xu, and Bingrong Yu

arXiv : 2512.05968

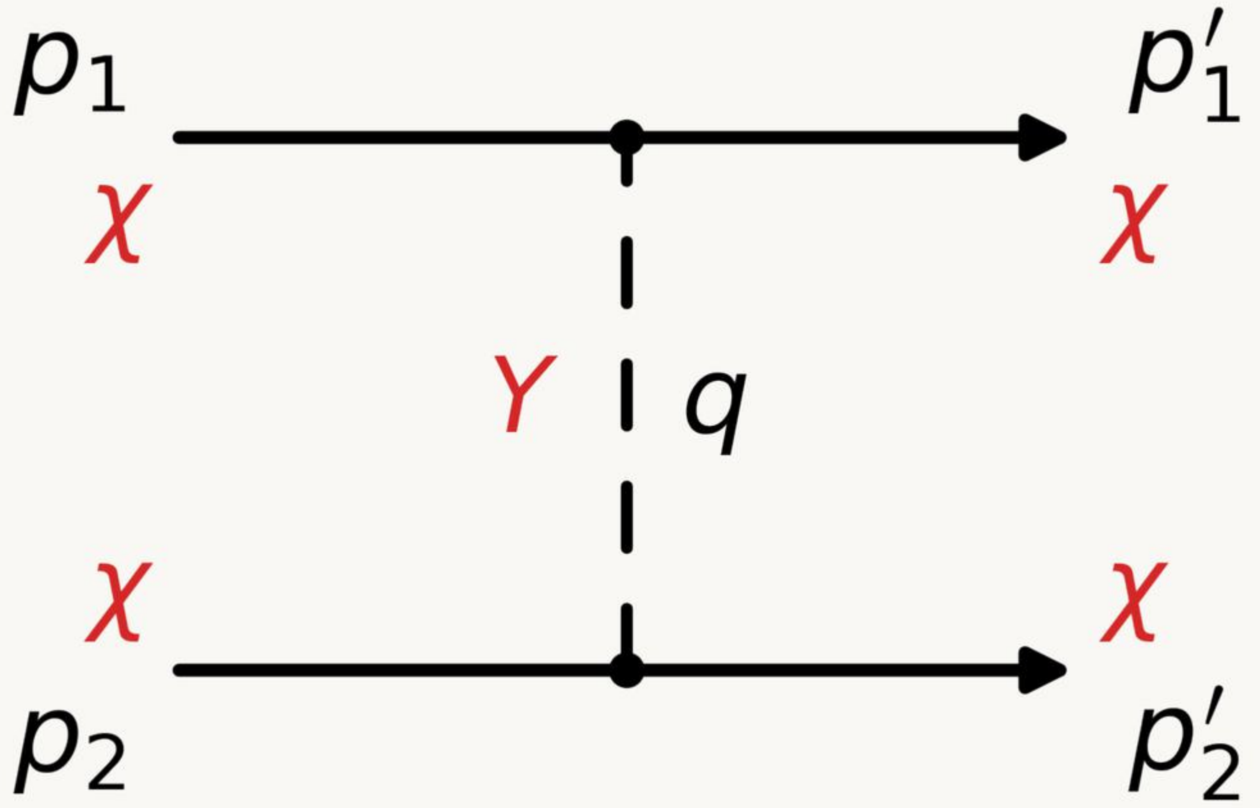
MAY 2026

Cornell University · High-Energy Theory

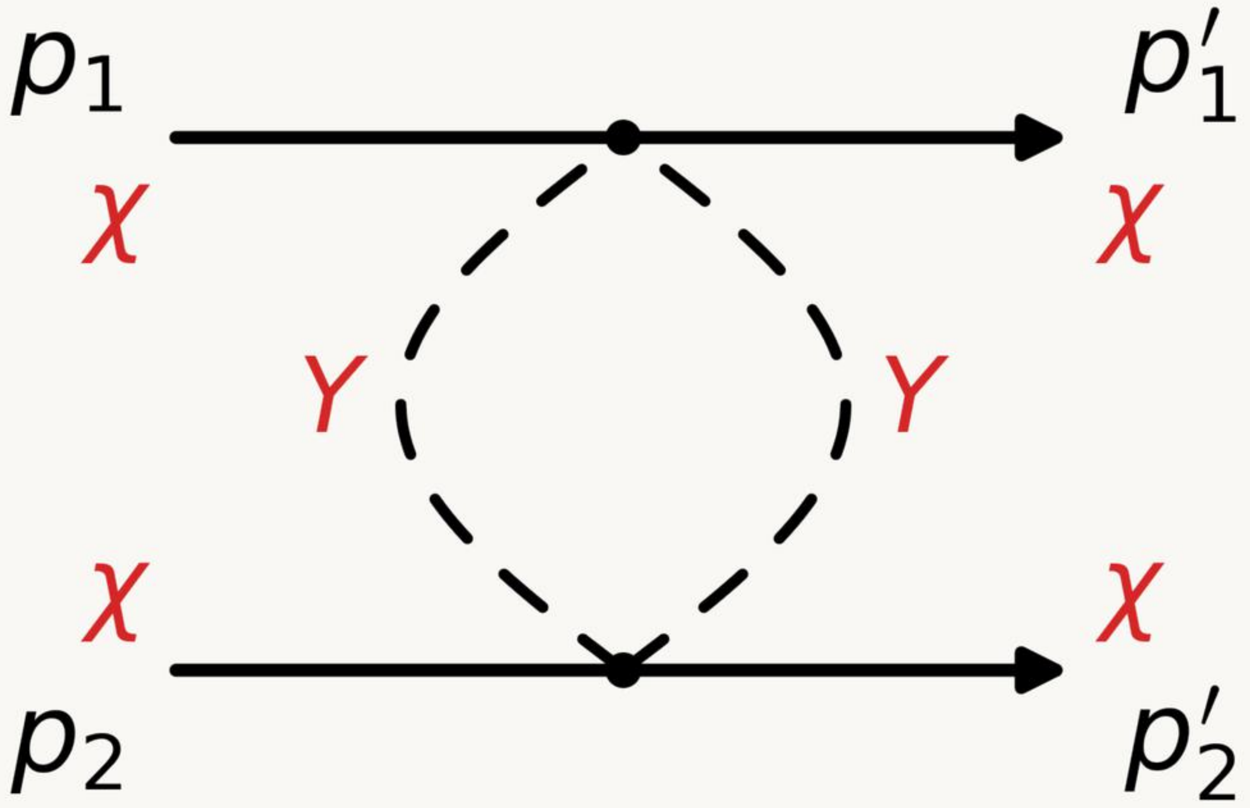
SETTING THE STAGE

Classical vs Quantum Forces

- Single mediator exchange
- Linear: $Y\bar{\chi}\chi$ $\quad Y = \gamma, \phi, Z \ldots$



- Pair mediator exchange
- Quadratic: $Y^2\bar{\chi}\chi$ $\quad Y = \phi, \gamma, \nu, \ldots$

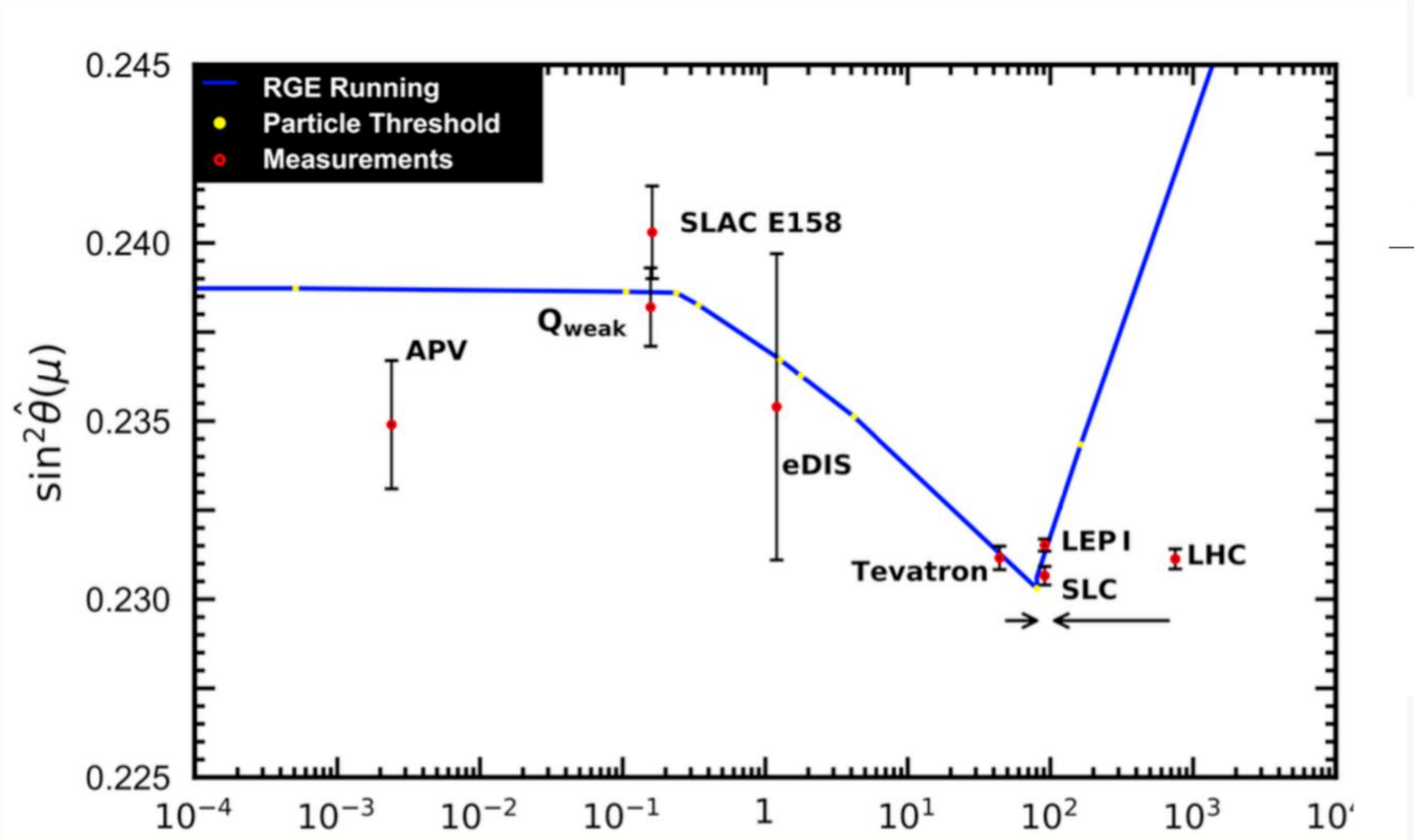


$$V(r) = -\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} \mathscr{A}(\mathbf{q}) \sim \begin{cases} r^{-1}, & Y\bar{\chi}\chi \\ \underset{\phi}{r^{-3}}, \underset{\nu}{r^{-5}}, \underset{\gamma}{r^{-7}}, & Y^2\bar{\chi}\chi \end{cases} \qquad (m_Y \to 0)$$

MOTIVATION

Why care about quantum forces?

Example: Neutrino Force - Unavoidable prediction of the SM




ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

ALL TOPICS HEALTH HUMANS LIFE EARTH PHYSICS SPACE

NEWS PARTICLE PHYSICS

A strange ‘neutrino force’ helped heal a crack in particle physics

Neutrinos and other particles can produce a subtle force, relevant for precise measurements

" it's a bigger effect than anybody had guessed, "
" the tension disappeared completely. "

Affects APV - help resolve tension in measurement of Weinberg angle

2512.07938, 2602.22466

MECHANISM

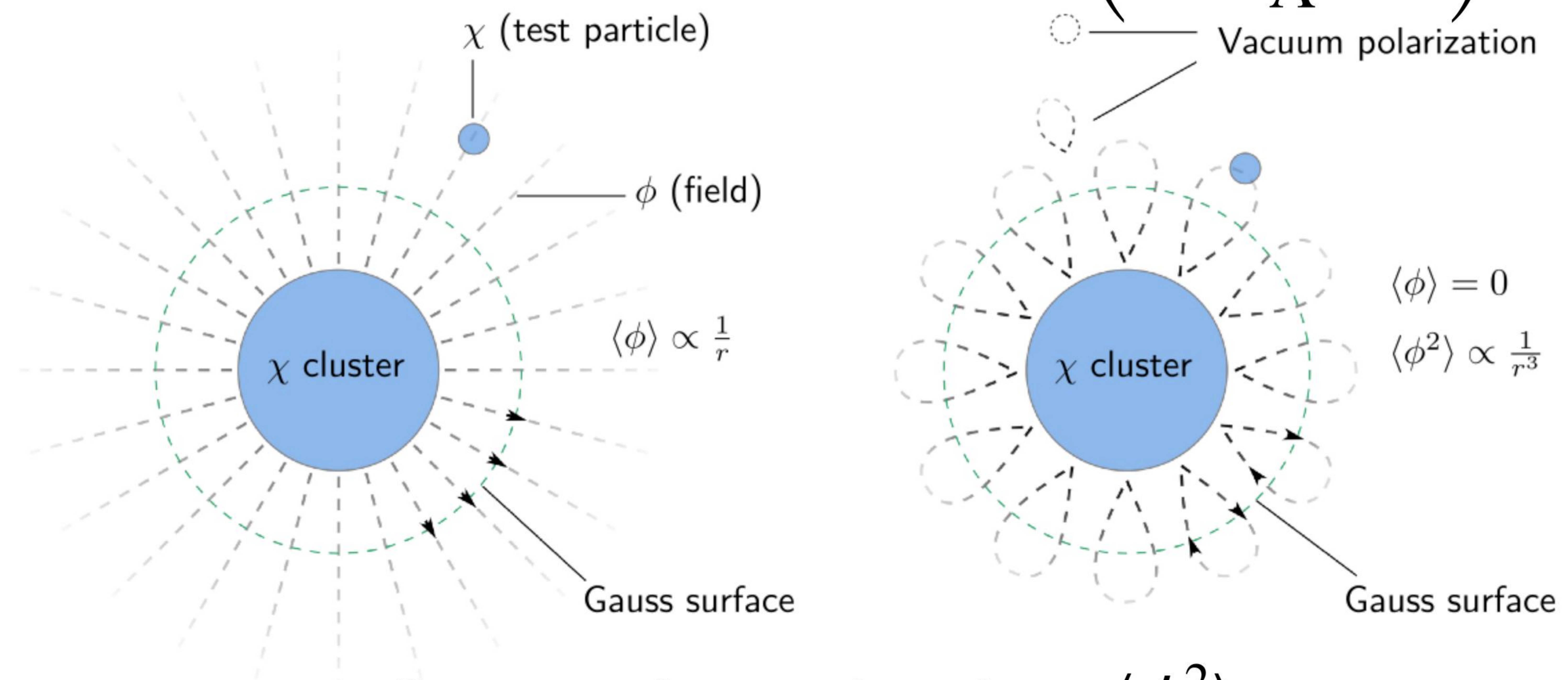
How are forces generated?

$$\mathscr{L} \supset \lambda \phi \bar{\chi}\chi$$

$$\partial^2 \phi = \lambda \langle \bar{\chi}\chi \rangle$$

$$\mathscr{L} \supset \frac{1}{2\Lambda}\phi^2 \bar{\chi}\chi$$

$$\left(\partial^2 + \frac{1}{\Lambda}\langle \bar{\chi}\chi \rangle\right)\phi = 0$$



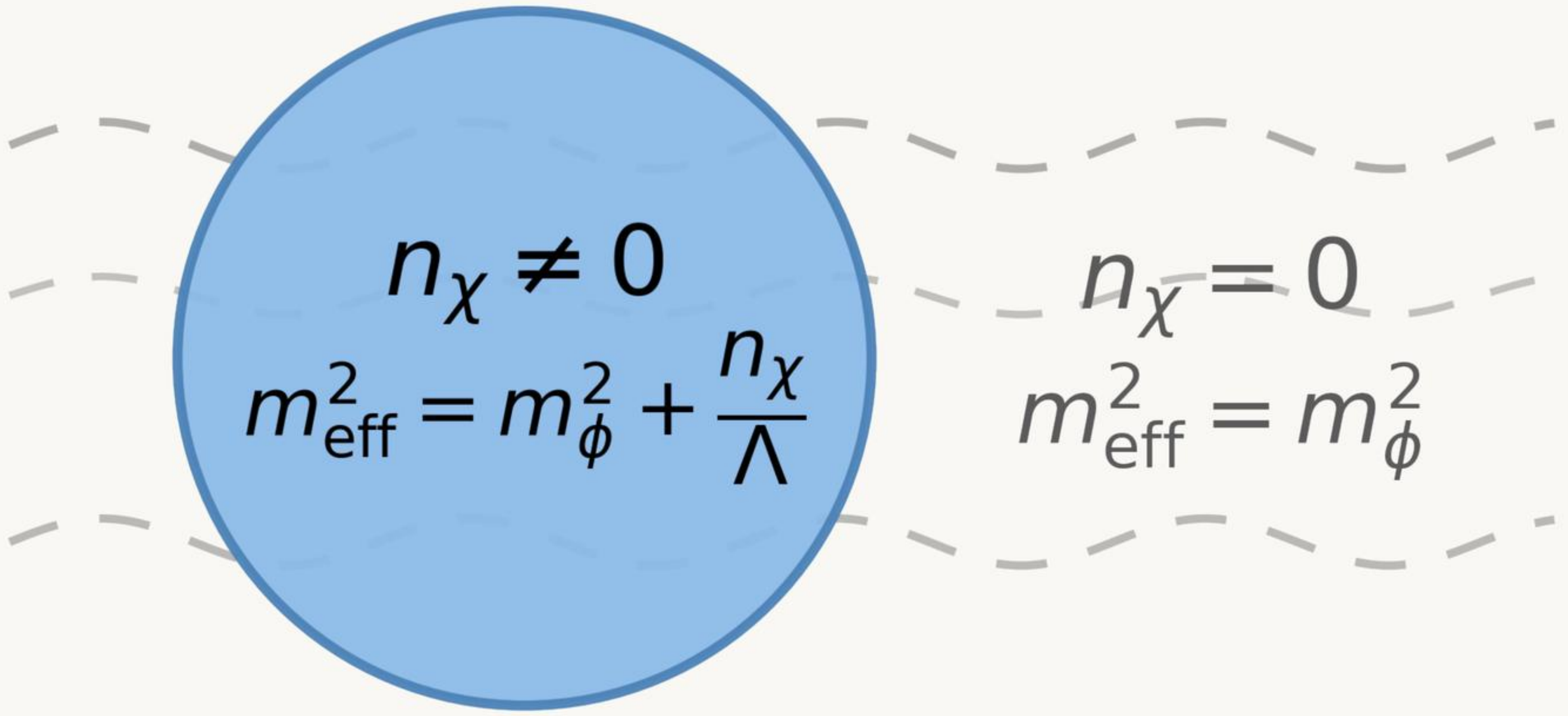
Quantum force arises from $\langle \phi^2 \rangle$

METHOD

Computing $\langle \varphi^2 \rangle$: Step 1

Solve for general ϕ classically

$$\left(\partial^2 + m_\phi^2 + \frac{1}{\Lambda}\langle \bar{\chi}\chi \rangle \right) \phi = 0$$



n_χ : source density Λ^{-1} : coupling strength

Spherical Basis:

$$\left[\partial_r^2 - \frac{\ell(\ell+1)}{r^2} + \omega^2 - m_{\text{eff}}^2(r) \right] u_{\omega\ell}(r) = 0$$

Classically $u_{\omega\ell}(r \to \infty) = 0 \implies u_{\omega\ell} = 0!$

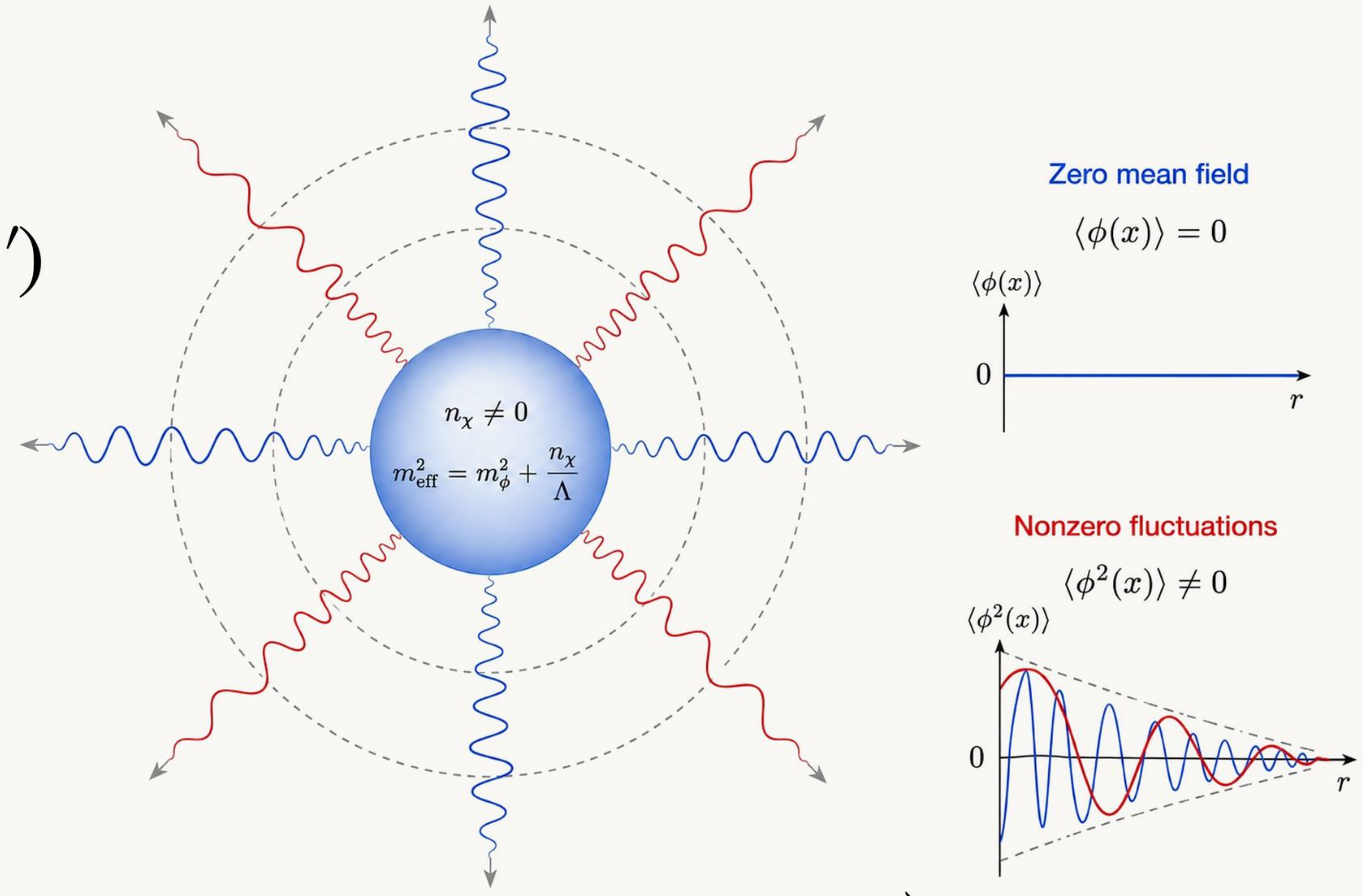
METHOD

Computing $\langle \varphi^2 \rangle$: Step 2

Quantize the mediator ϕ

Why? $\left[\hat{\phi}(\mathbf{r}), \dot{\hat{\phi}}(\mathbf{r}')\right] = i\,\delta^3(\mathbf{r} - \mathbf{r}')$

$u_{\omega\ell} \neq 0!$



$$\hat{\phi} = \sum_{\omega,\ell,m} \frac{u_{\omega\ell}(r)}{r} \left(\hat{a}_{\omega\ell m} Y_{\ell m} e^{-i\omega t} + \hat{a}^\dagger_{\omega\ell m} Y^*_{\ell m} e^{i\omega t} \right)$$

METHOD

Computing $\langle \varphi^2 \rangle$: Step 3

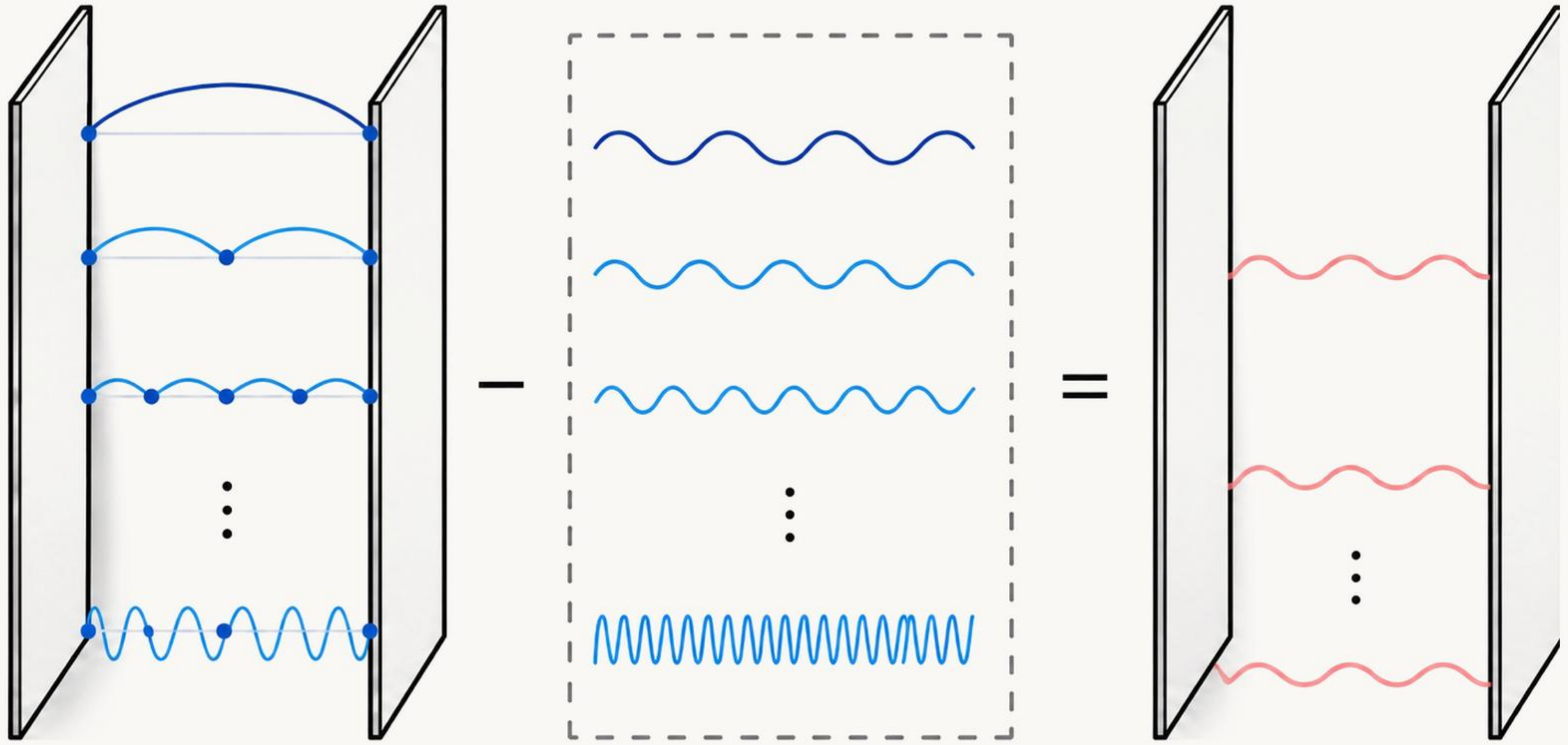
Compute $\Delta\langle\phi^2\rangle$

$$\langle\phi^2\rangle \equiv \left\langle 0 \left| \hat{\phi}^2 \right| 0 \right\rangle \sim \int \frac{d\omega}{\omega} u_\omega^2(r) \to \infty$$

$$\Delta\langle\phi^2\rangle = \langle\phi^2\rangle_{\chi \text{ source}} - \langle\phi^2\rangle_{\text{vacuum}}$$

Casimir $E_{\text{vac}}^{\text{plates}}(L) = \frac{1}{2}\sum_n \omega_n \to \infty$

$$\sum_n \omega_n - \int dn\, \omega(n) \implies \textbf{finite*}$$

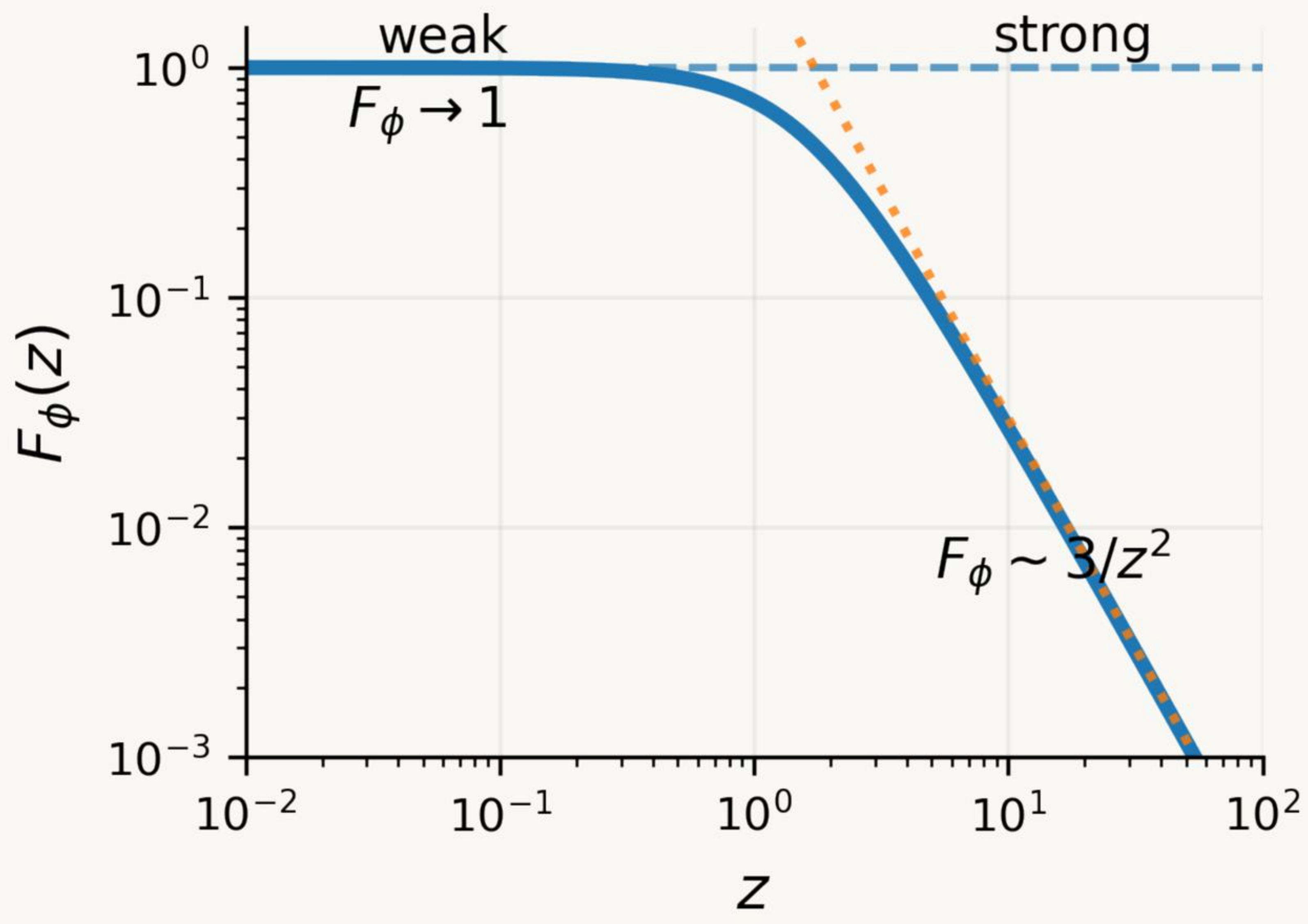


$\frac{1}{\epsilon^2} - \frac{1}{12}$ $\frac{1}{\epsilon^2}$ $-\frac{1}{12}$

FORM FACTOR

Results

$$\Delta\langle\phi^2(r)\rangle \sim \frac{1}{r^3} F_\phi(z), \quad r \gg R$$



Form Factor

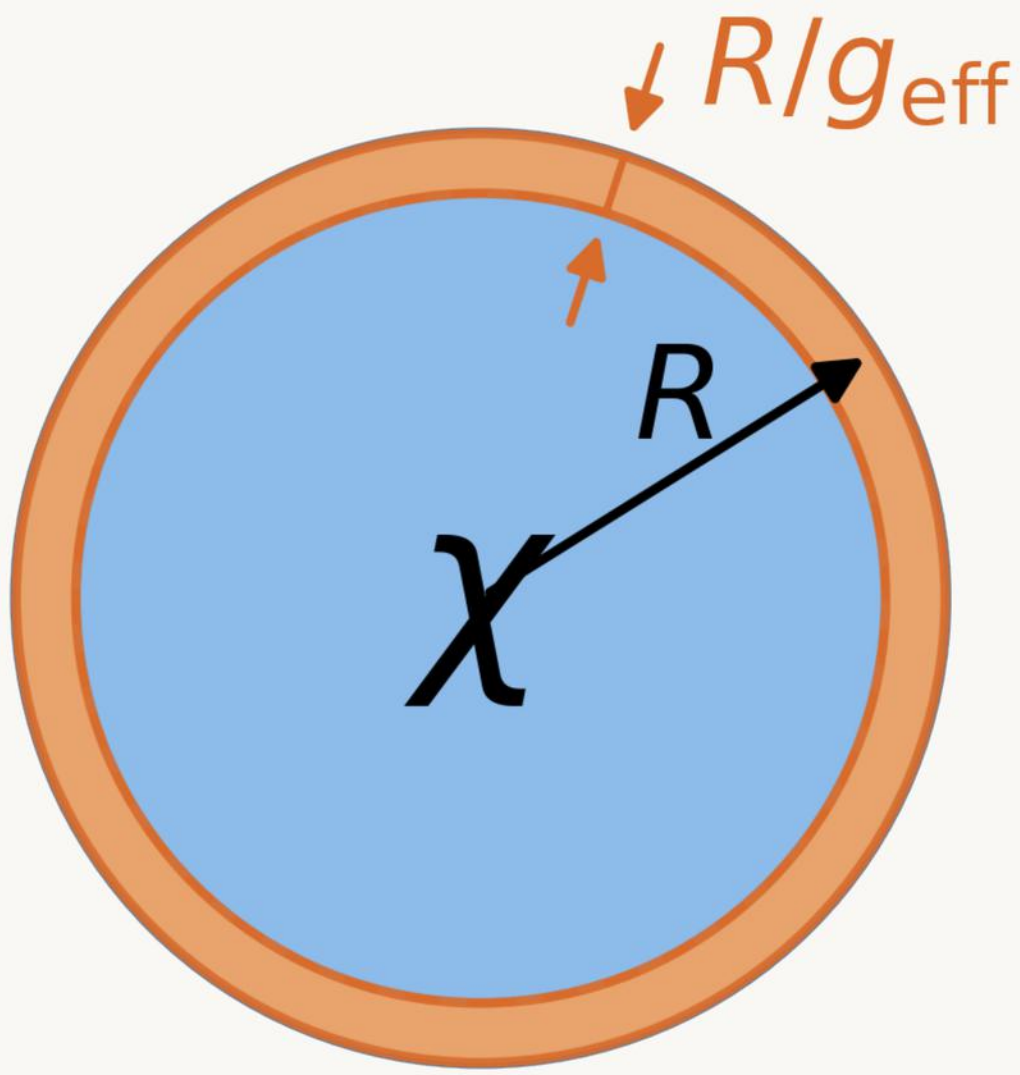
$$F_\phi(z) \equiv \frac{3}{z^2}\left(1 - \frac{\tanh z}{z}\right), \qquad z^2 \sim N_\chi/(\Lambda R) \sim N_\chi g_0 \equiv g_{\text{eff}}$$

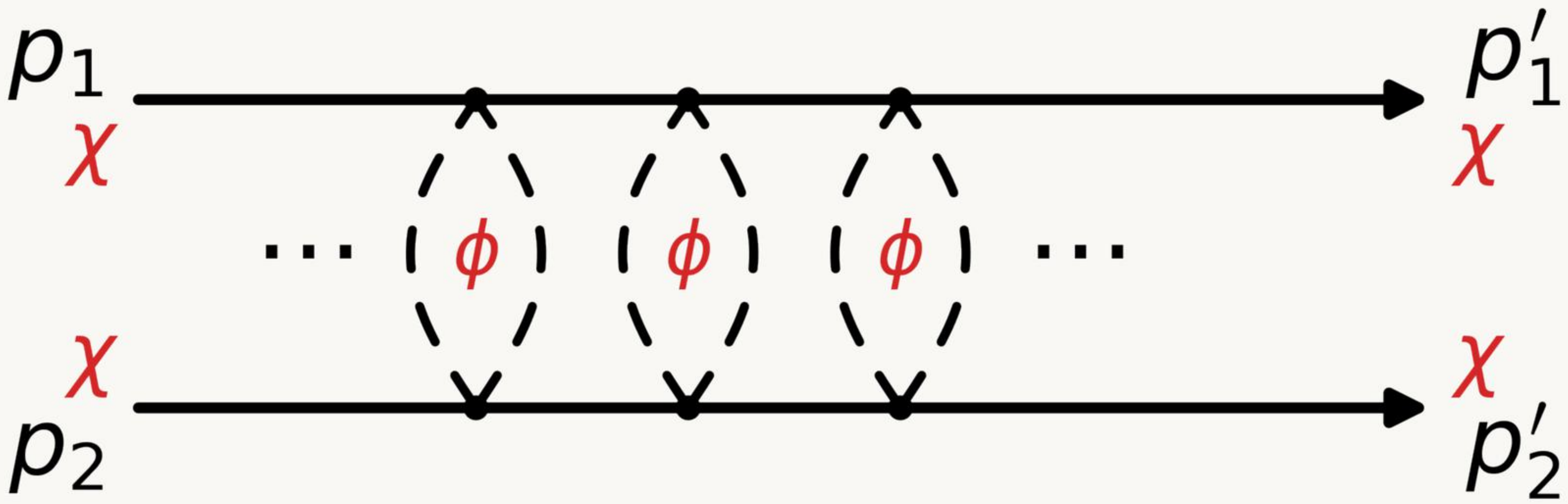
$$z \ll 1 \leftrightarrow g_{\text{eff}} \ll 1, \quad F_\phi \to 1$$ Weak-Coupling, Born Result

$$z \gg 1 \leftrightarrow g_{\text{eff}} \gg 1, \quad F_\phi \to 3/g_{\text{eff}}$$ Strong-coupling, Beyond-Born Result

PHYSICAL PICTURE

Screening — Strong Coupling





$$\frac{4\pi R^2(R/g_{\text{eff}})}{4\pi R^3/3} = 3/g_{\text{eff}}$$

Violation of superposition principle

$$V \neq N_\chi V_0, \quad V = N_\chi F(N_\chi) V_1$$

TAKEAWAYS

Conclusion

Potential = Feynman Diagram Potential $\times$ Form Factor

- Factorizable in the IR limit

Non-perturbative theory with $g_{\text{eff}} \gg 1$ in vacuum

and

Perturbative theory with $g_0 \ll 1$ in dense environments

Thank you.