Title: Can Dark Energy Have a Color?

Date: Jun 06, 2008 10:00 AM

URL: http://pirsa.org/08060145

Abstract: About 20-30 years ago, scientific community was interested in knowing whether dark matter can carry gauge charges. The answer was found to be no. Today, we can ask a similar question: Can dark energy carry gauge charges? The answer this time seems to be yes. We study the possibility that the current accelerated expansion of the universe is driven by the vacuum energy density of a colored scalar field which is responsible for a phase transition in which the gauge SU(3)_c symmetry breaks. If we are stuck in a SU(3)_c - preserving false vacuum, then SU(3)_c symmetry breaking can be accommodated without violating any experimental QCD bounds or bounds from cosmological observations. As a bonus, the model can likely be tested at the LHC. A possible consequence of the model is the existence of fractionally charged massive hadrons. The model can be embedded in supersymmetric theories where massive colored scalar fields appear naturally.

Motivation

- Puzzles raised by the recent observational data:
  - Dark Matter Problem
  - Dark Energy Problem

Concentrate on the Dark Energy Problem

- Many explanations proposed
- Still far from the satisfactory solution

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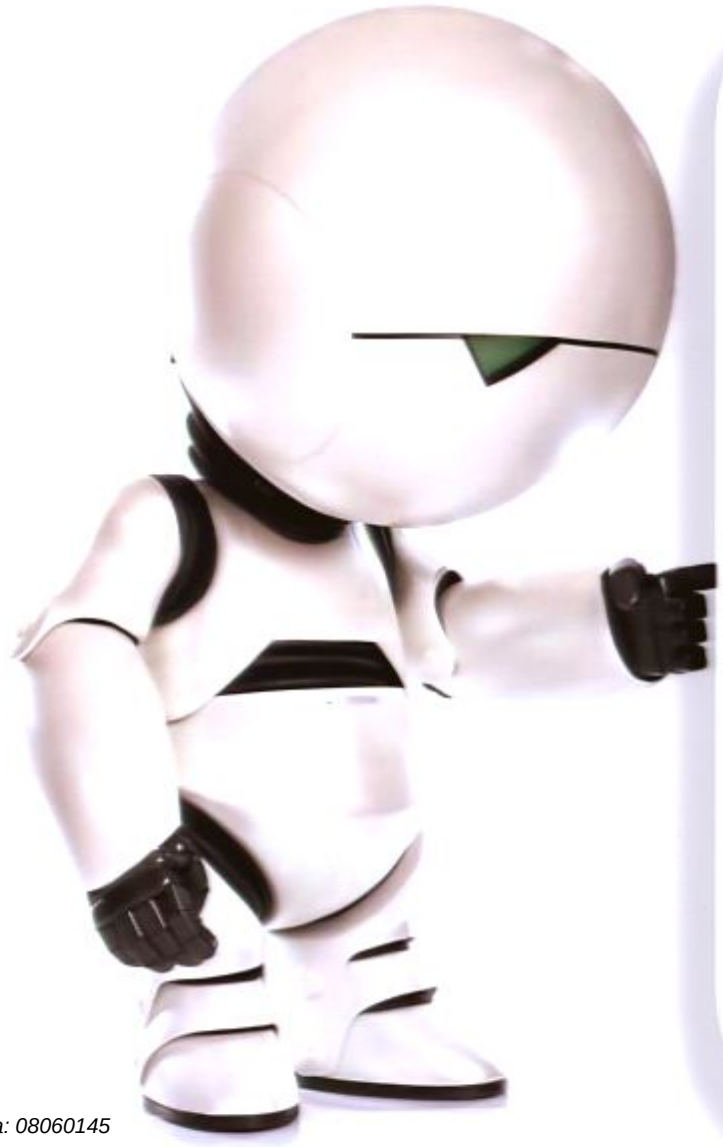
Outline



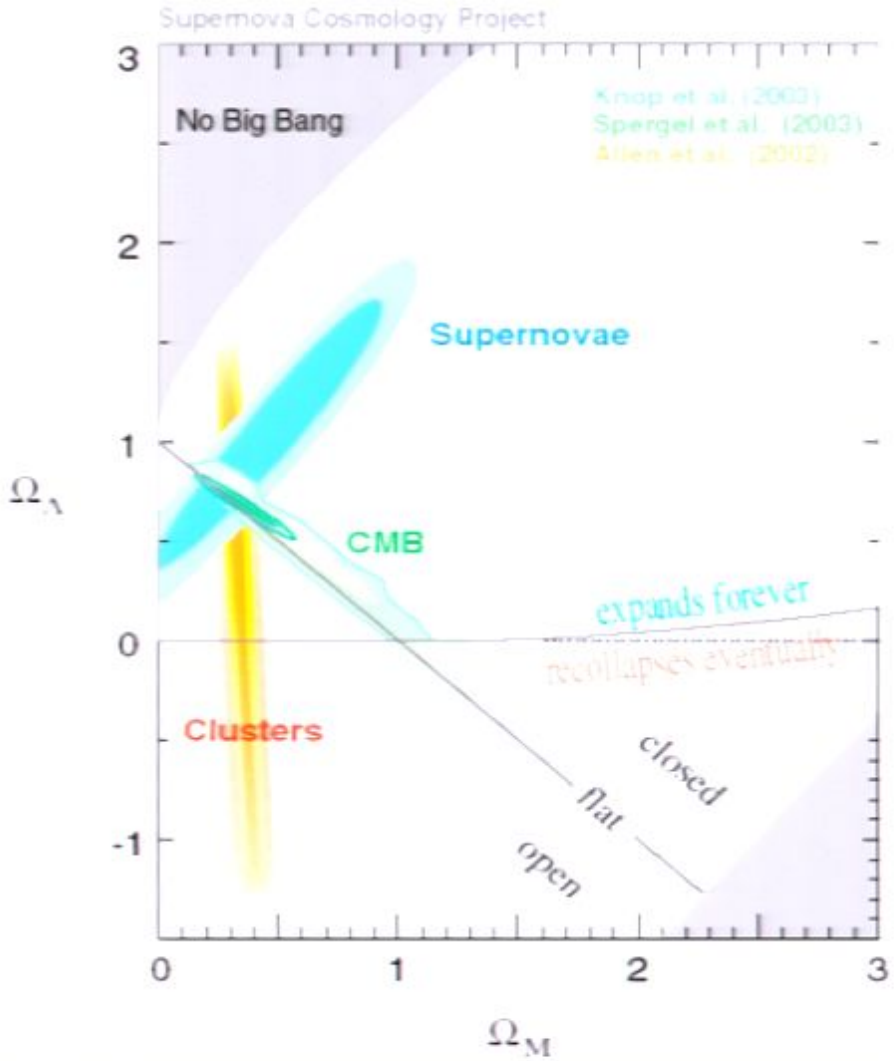
- **Introduction**
- **Question:**

Can Dark Energy carry gauge charges?

- **Dark matter can NOT carry gauge charges!**
- **Dark Energy can!**

- **Proposal: acceleration is driven by the phase transition is which $SU(3)_c$ symmetry is breaking**

The standard model of cosmology



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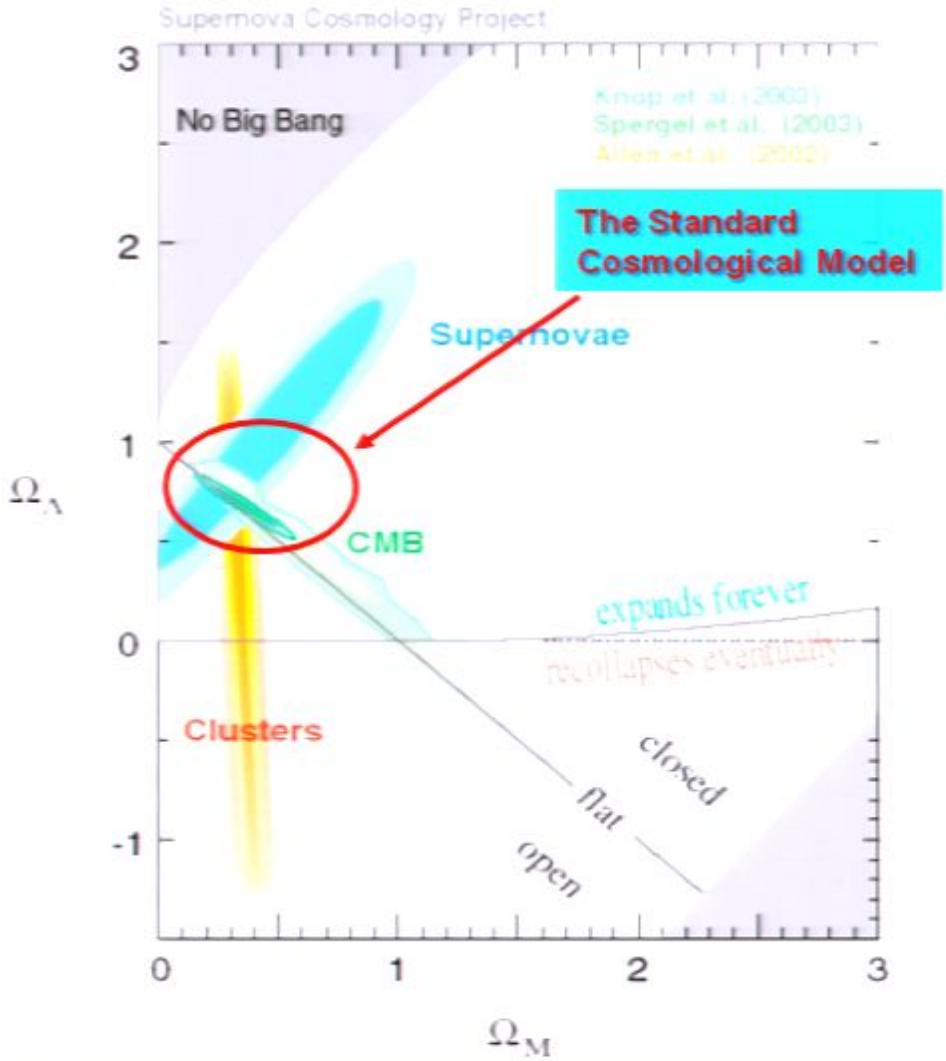

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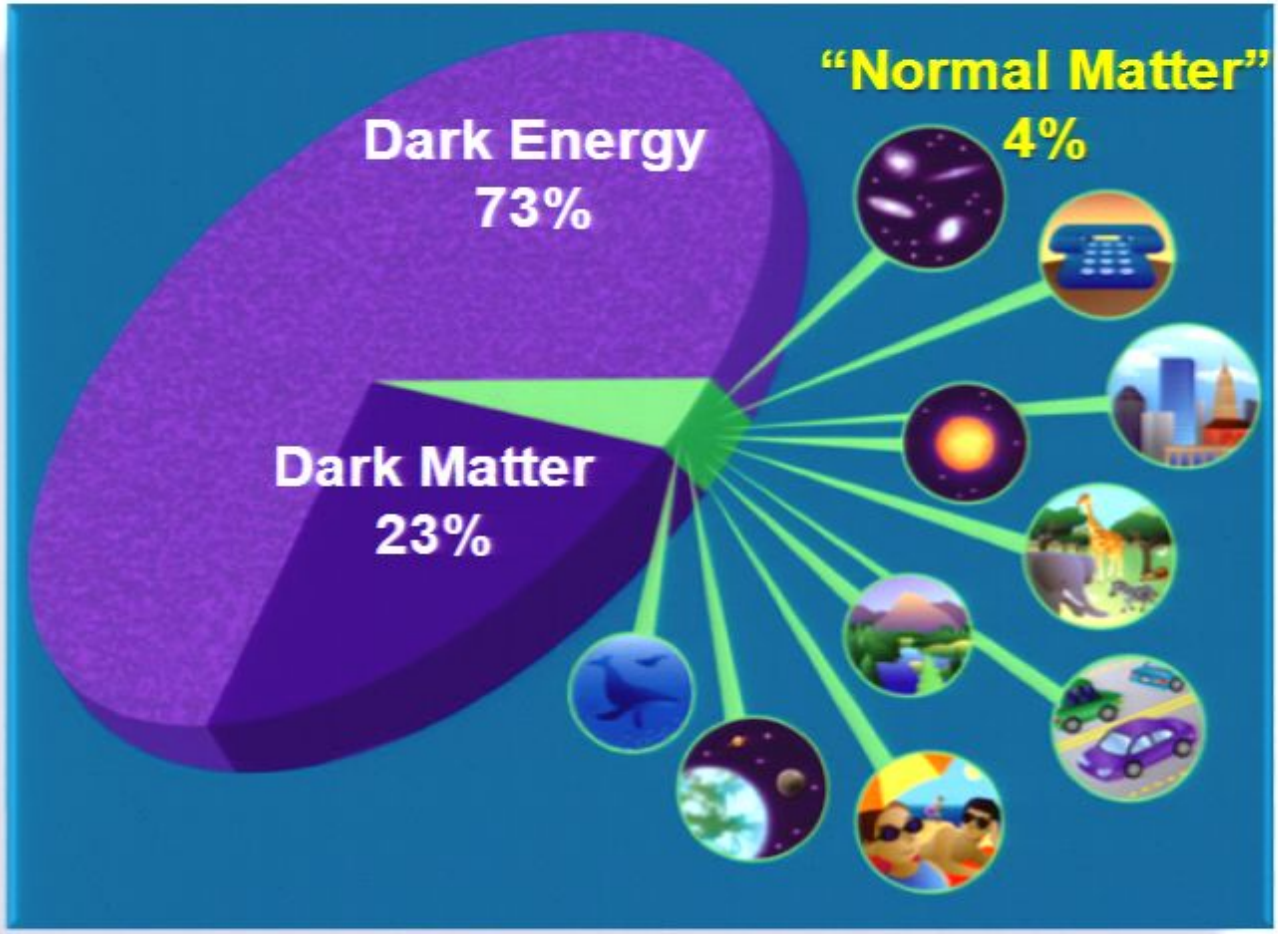

The bad news!

96% of the content of the Universe seems to be missing

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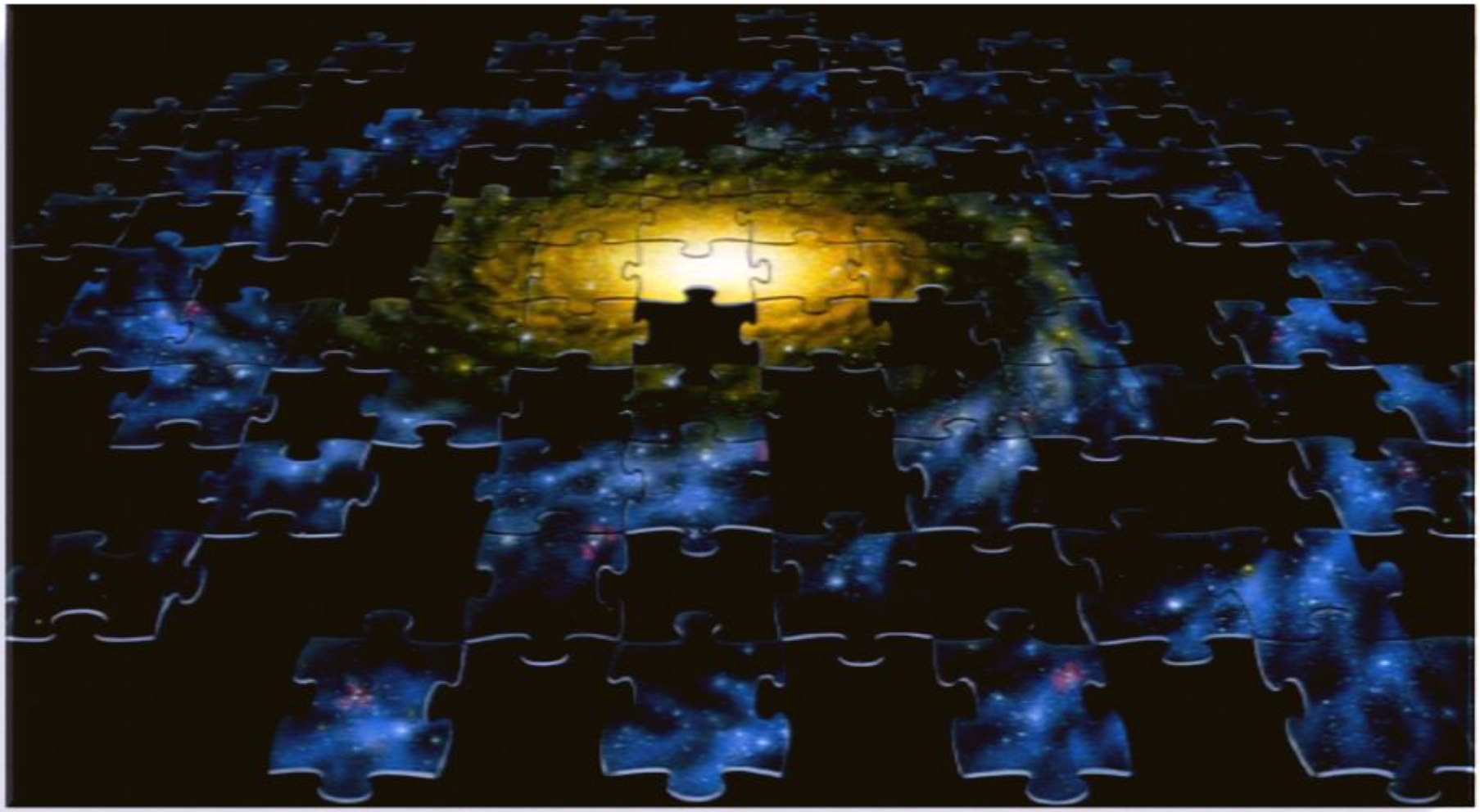
The dark matter puzzle



Dark Energy Puzzle

Studying Supernovae type Ia,
astronomers stumbled upon an interesting discovery

Our Universe is accelerating!

Dark energy - Cosmological constant?

- Something else with the constant energy density Ω_Λ
- Minimal solution: vacuum energy density
- This energy drives an accelerated expansion

What is cosmological constant?

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."

Tommy Gold – astronomer from Cornell

What is cosmological constant?

Guess #1: Gravitational vacuum energy density

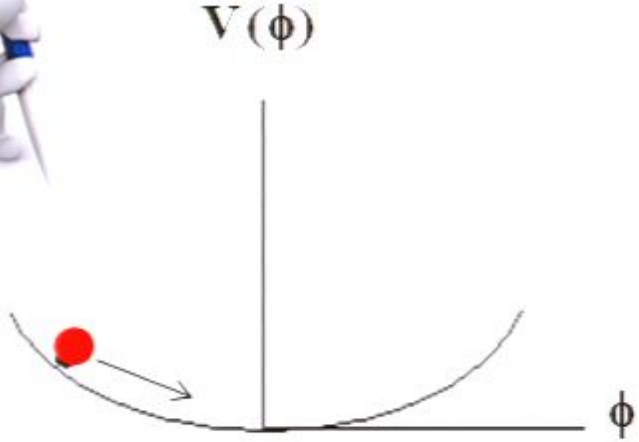
- **Problems:**

1. Quantum gravity effects not fully understood
2. Huge discrepancy between the prediction and observation

$$\left.\begin{aligned}\Lambda_{\text{pred}} &= (10^{19}\,\text{GeV})^4 \\ \Lambda_{\text{obs}} &= (10^{-3}\,\text{eV})^4\end{aligned}\right\} \quad \frac{\Lambda_{\text{pred}}}{\Lambda_{\text{obs}}} = 10^{124}$$

Guess #2: Scalar field vacuum energy density

aka quintessence



Guess #3: Modified Gravity Models

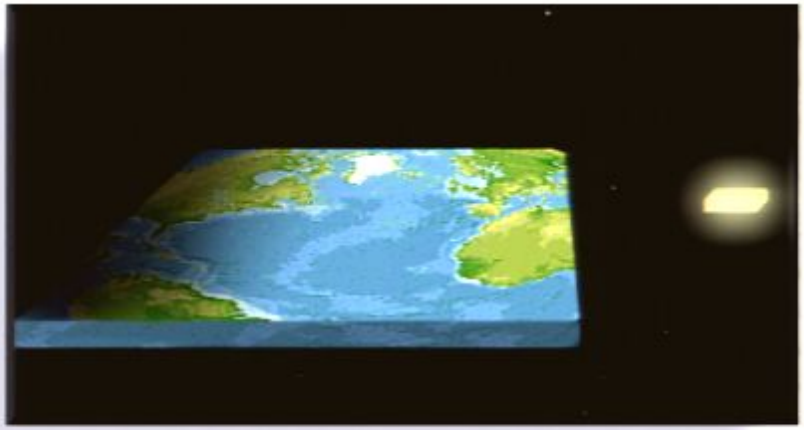
aka f(R) models

$$S = \frac{1}{G}\int dx^4 \sqrt{-g}\, f(R)$$

Guess #4: K-essence

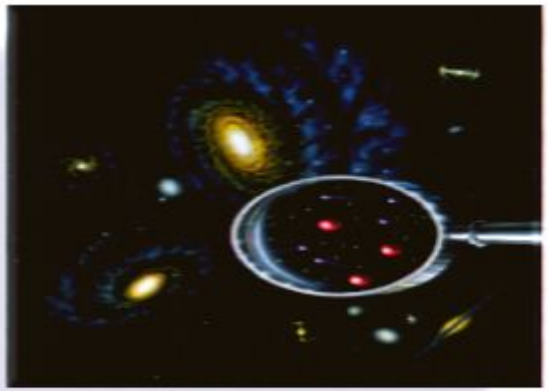
$$S = \int dx^4 \sqrt{-g}\left[-\frac{R}{G} + f(\nabla_\mu \phi \nabla^\mu \phi)\right]$$

Guess #5: Brane World Models



Our proposal

D.S., G. Starkman, R. Matsuo, PRD (2008)



A mechanism that can explain cosmological acceleration

- And yet can be tested in future collider experiments
- Does not require symmetries and fields decoupled from the rest of the Universe

Analogy with primordial Inflation

•In its history, our Universe already had a period of acceleration:

Primordial Inflation !

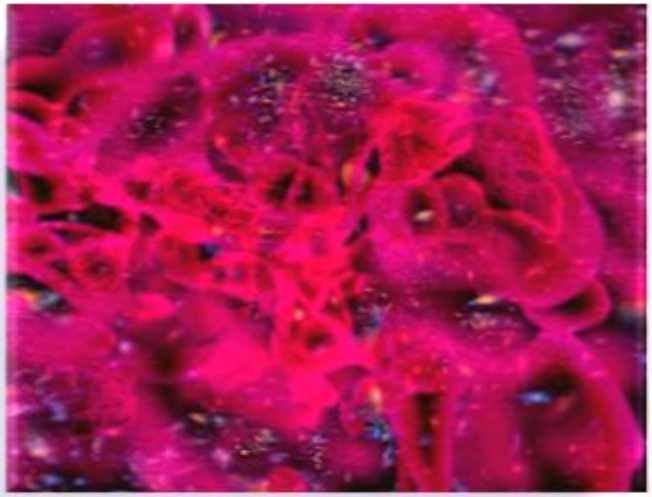
- Imagine you were living ~ 1 Hubble time after the onset of primordial inflation, at $t \sim 10^{-35}$ sec
- If you were very smart to figure out that $M_{GUT} \sim 10^{15}$ GeV
- You would conclude that there is a phase transition going on right now that is driving accelerated expansion of the Universe

It is likely that something similar is happening NOW!

- **Interesting question:** what symmetry is being broken right now

- Obviously, one can always invent a new symmetry decupled from the rest of the Universe

- Instead, the most interesting possibility is that one of the only two remaining gauge symmetries $\boxed{SU(3)_c \text{ or } U(1)_{EM}}$ is breaking

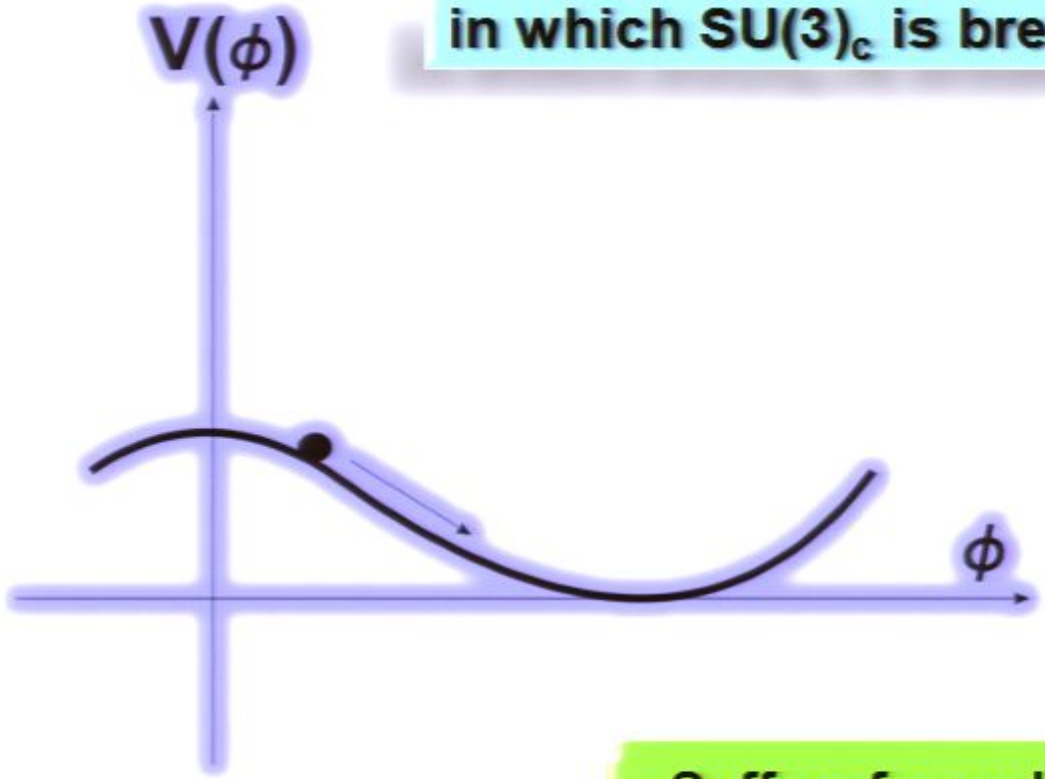


Artistic view of a universe filled by a turbulent sea of dark energy

Dark energy has a color!

Second order phase transition

in which $SU(3)_c$ is breaking



- Very light colored scalar field
- Rolling down its potential

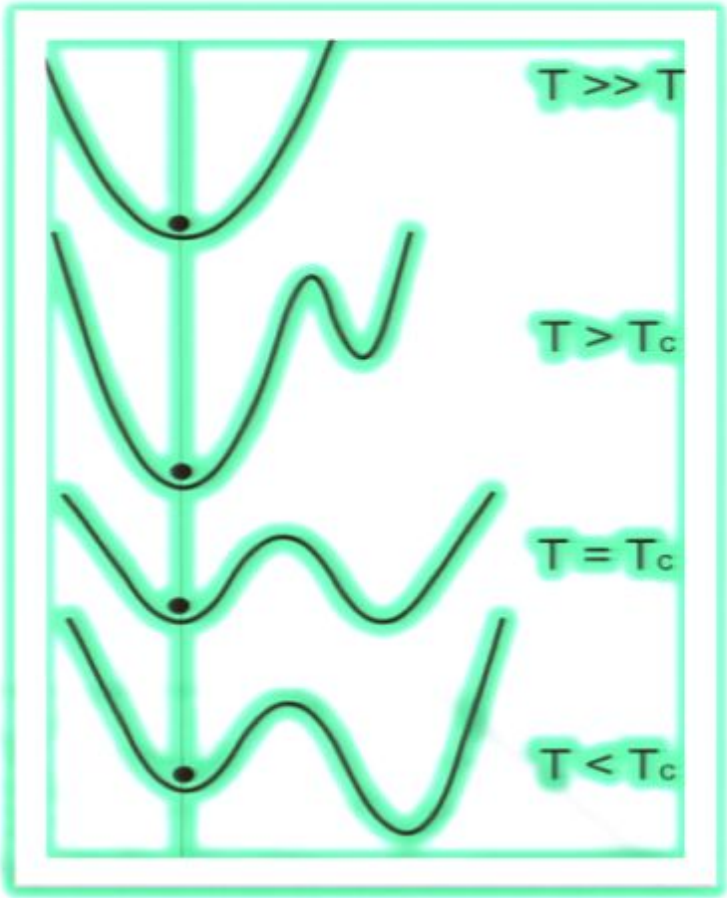
→

- Suffers form all shortcomings of quintessence models

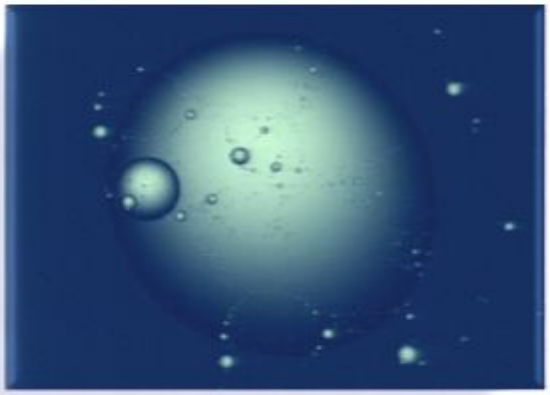
+

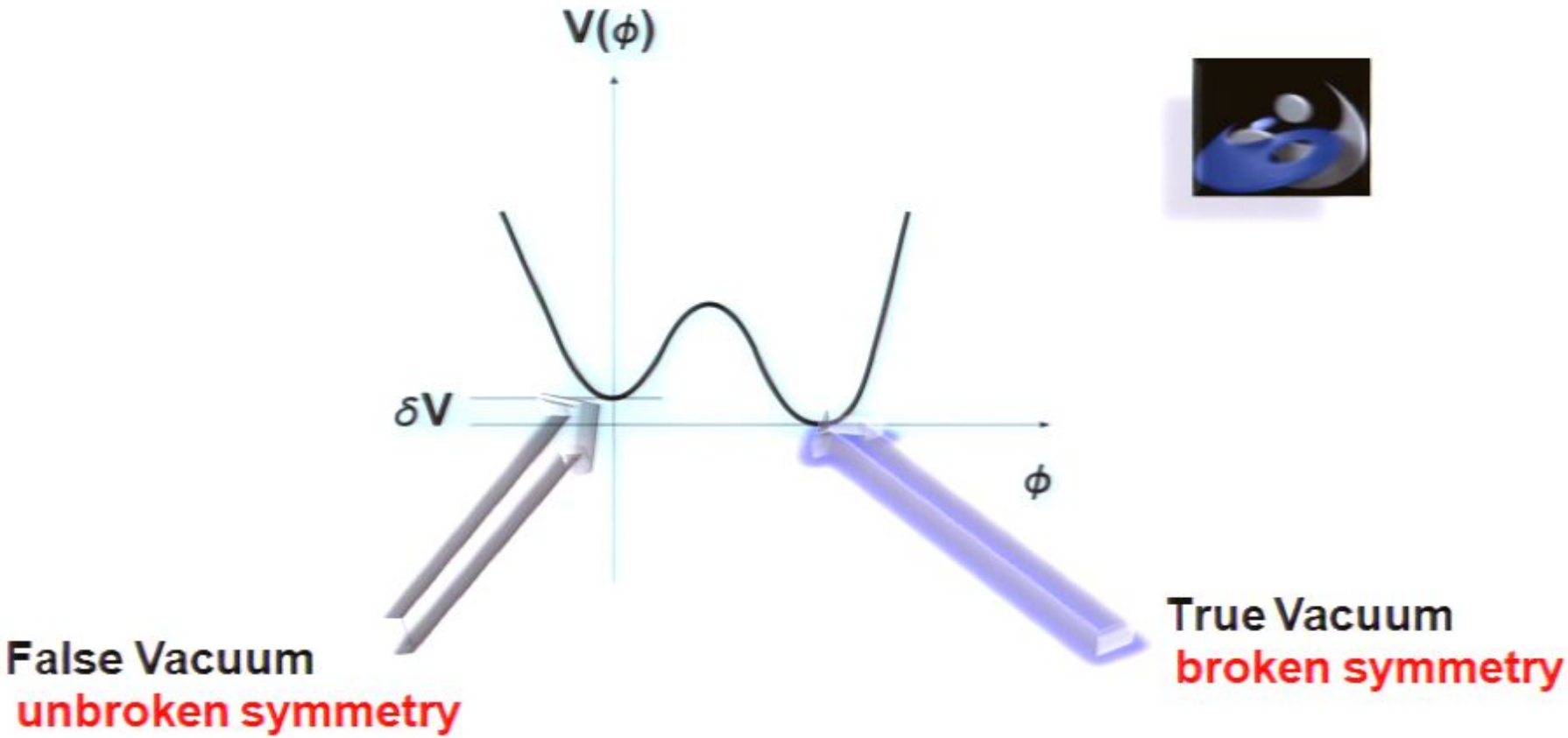
- Very difficult to hide the light colored scalar field

First order phase transition



- Much more convenient

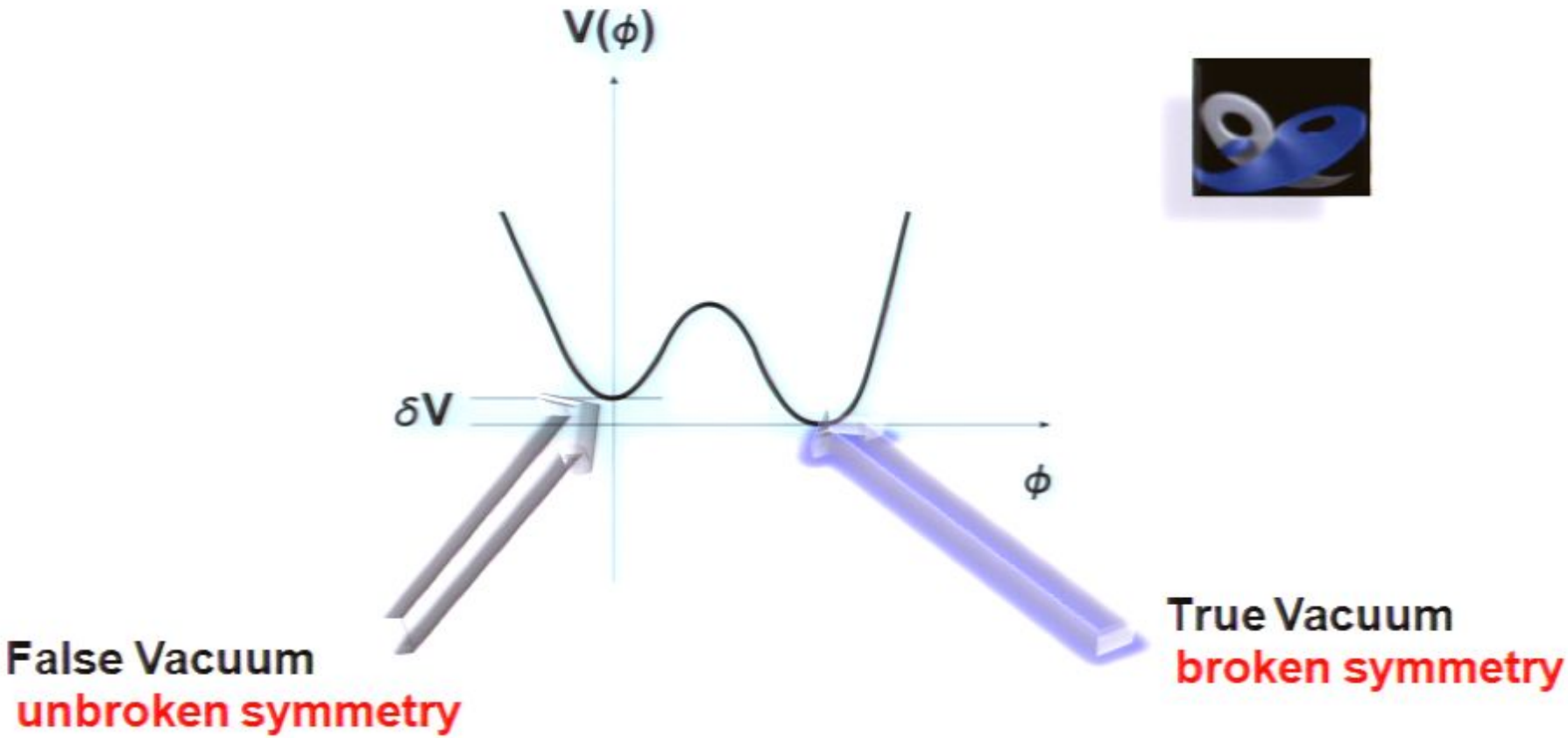




Non-zero vacuum energy density ⟷ Cosmological constant

Non-zero scalar field VEV ⟷

- Massive gluons
- Quark confinement broken
- Protons do not exist



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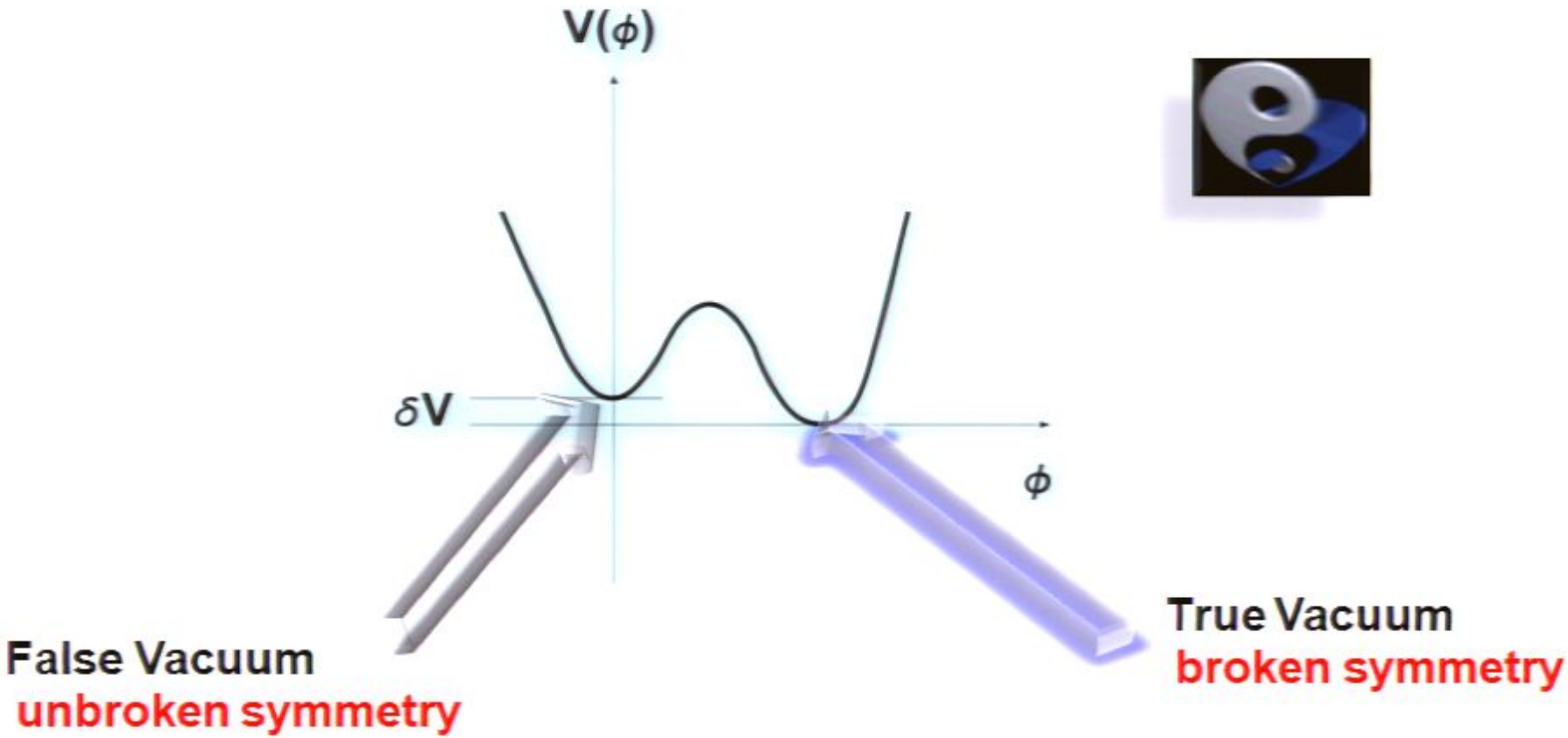

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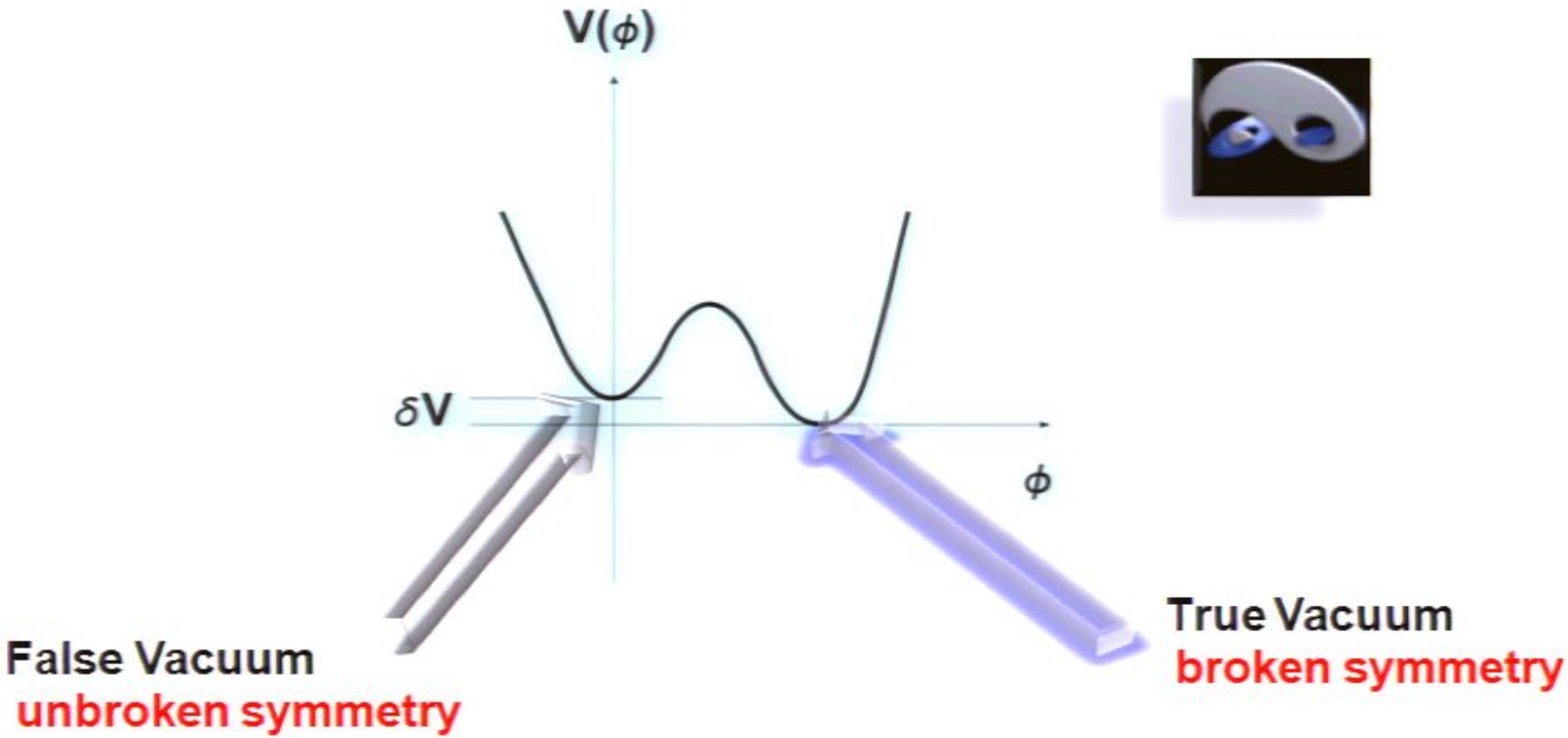

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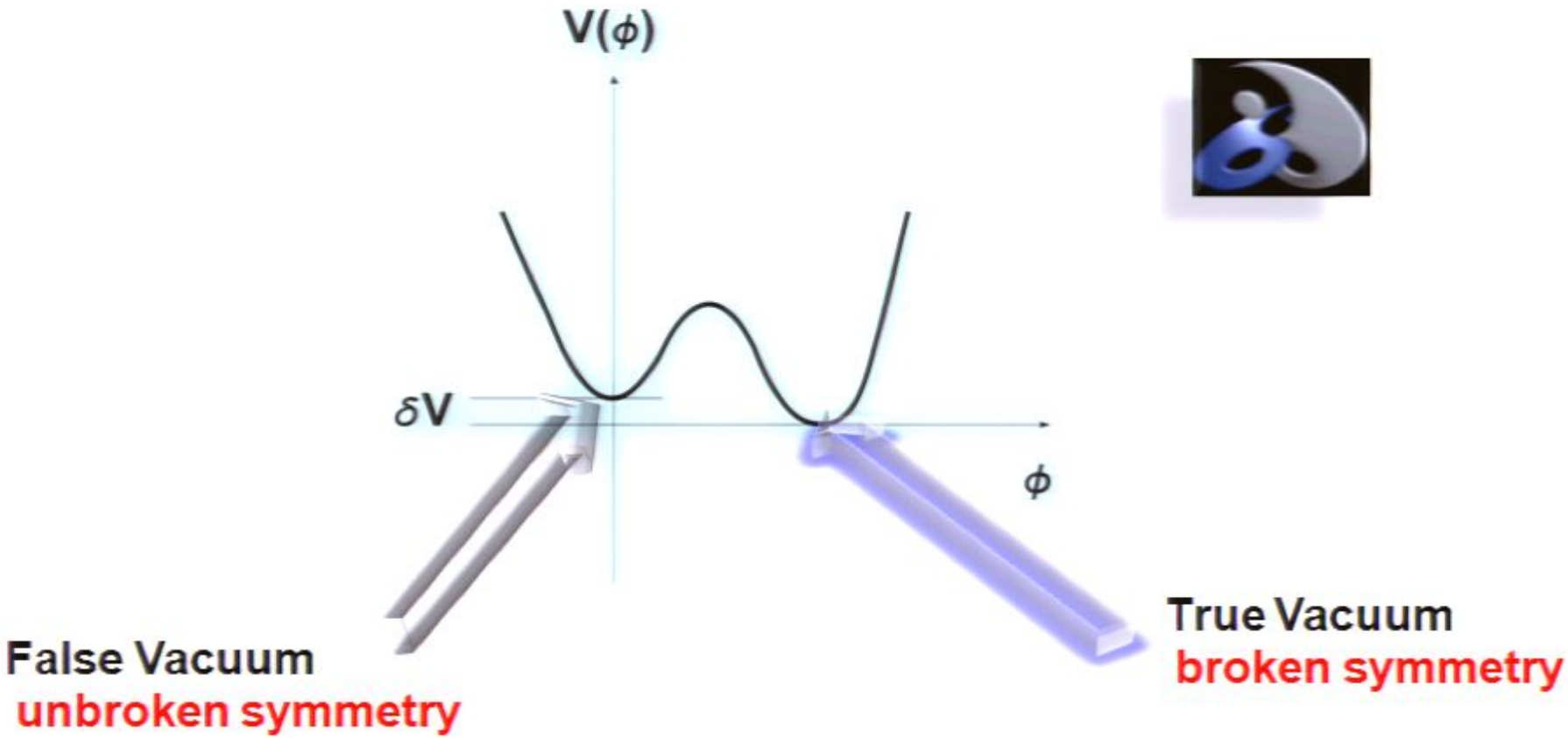

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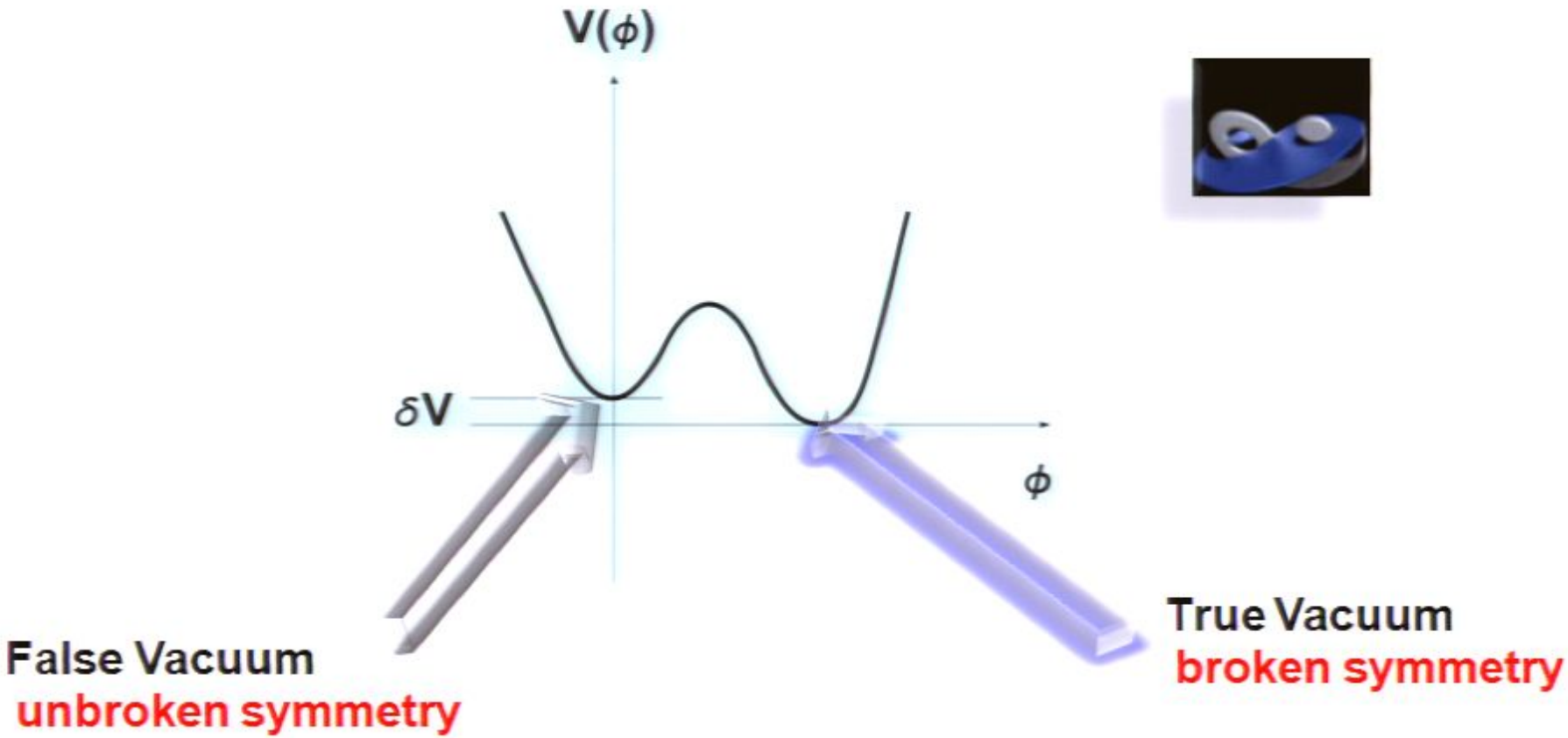

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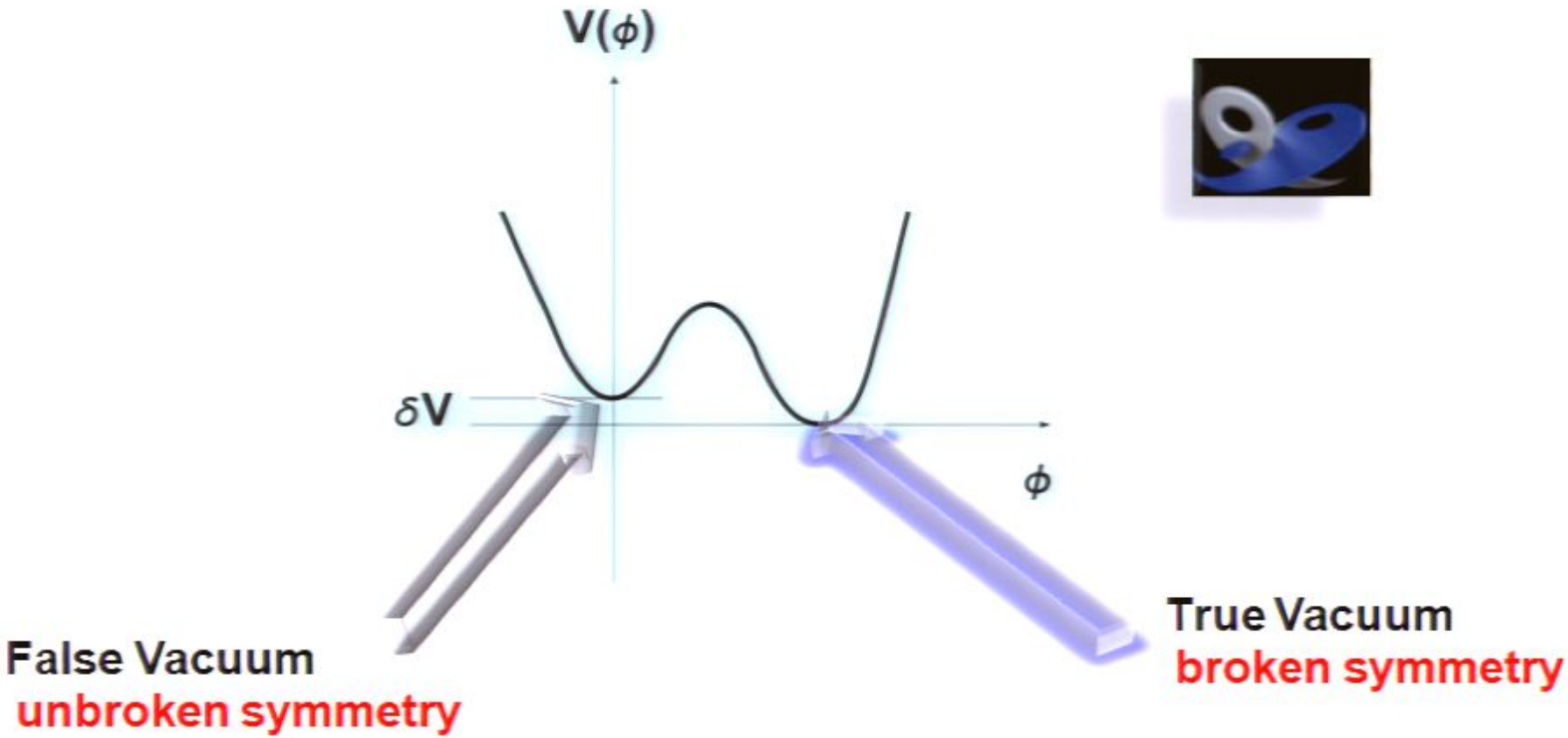

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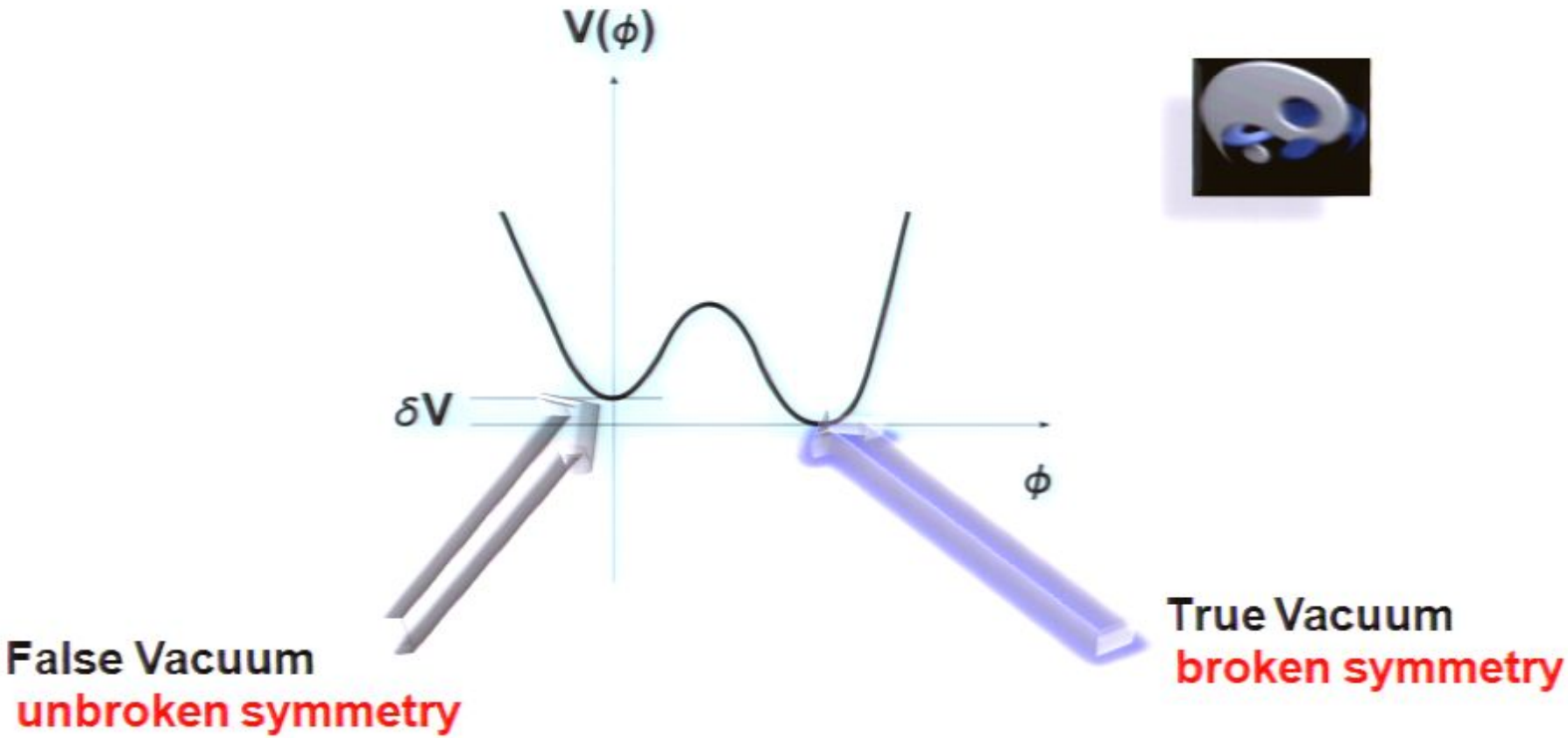

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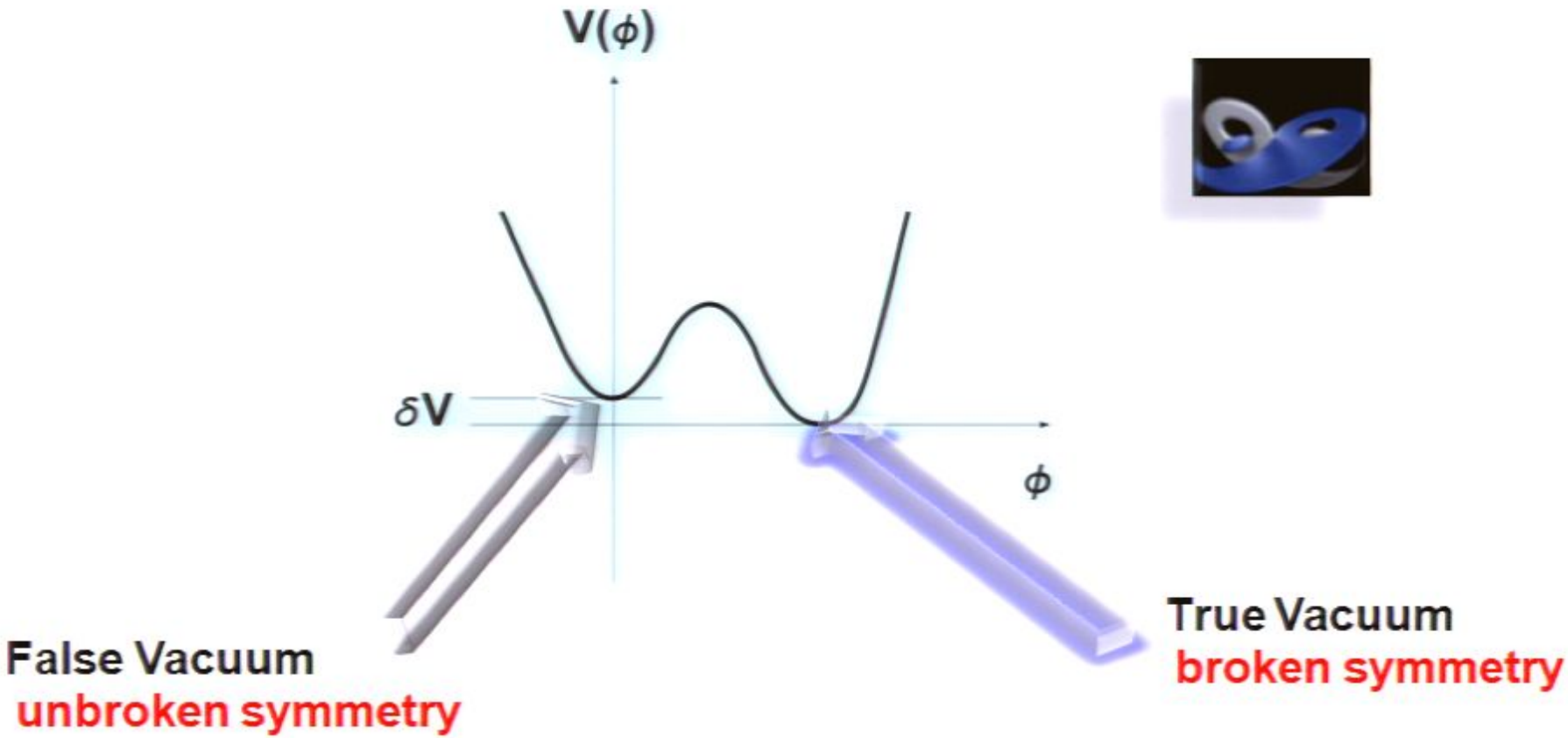

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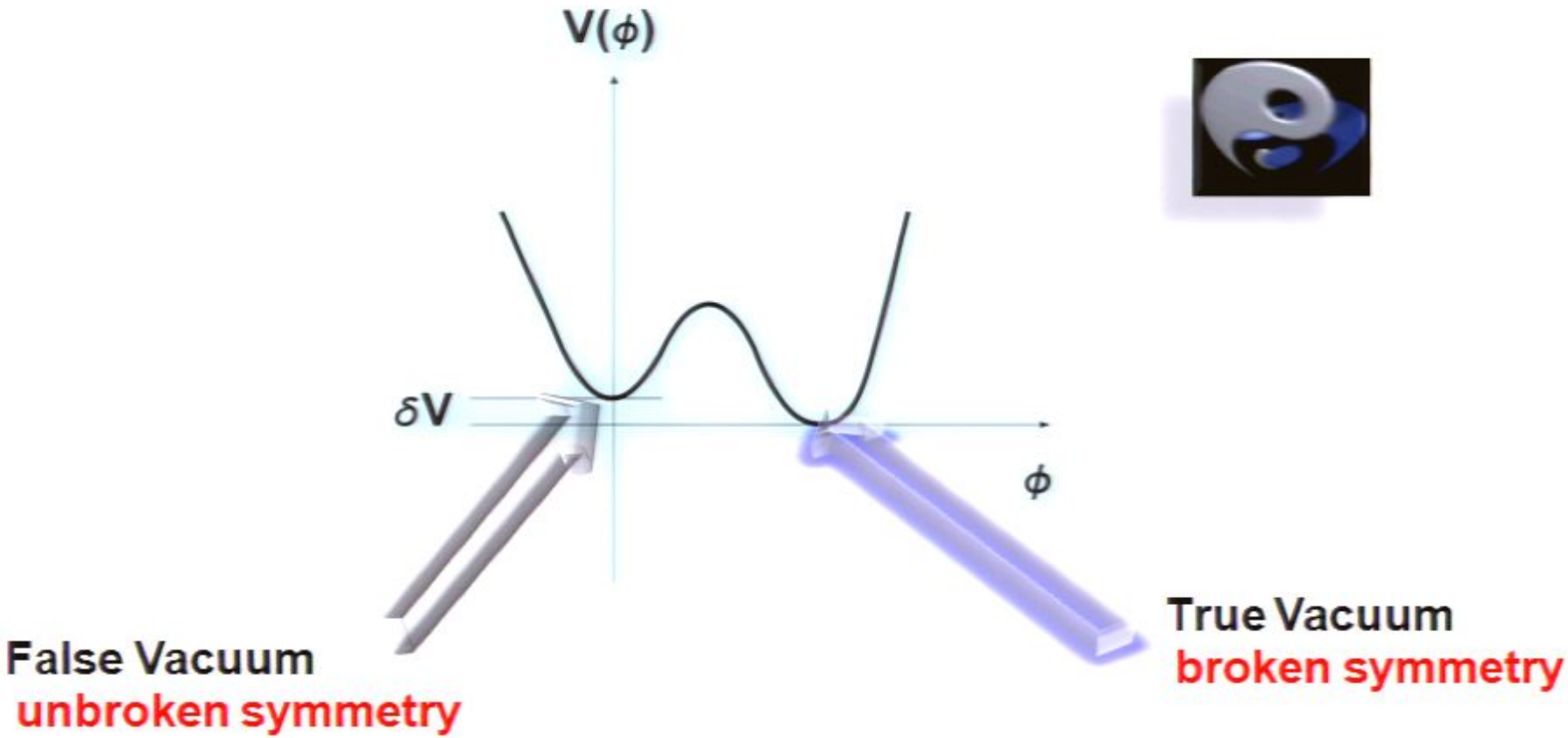

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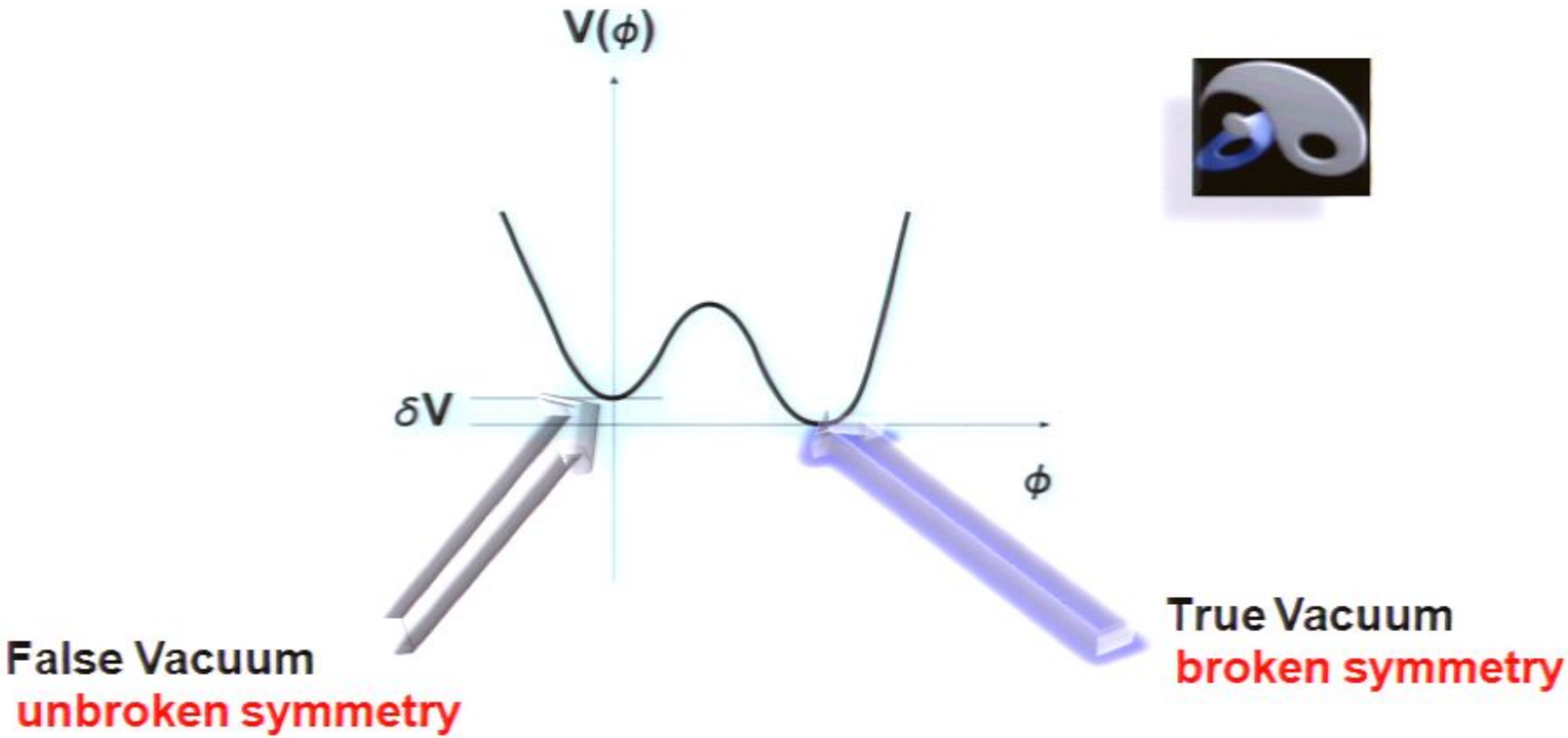

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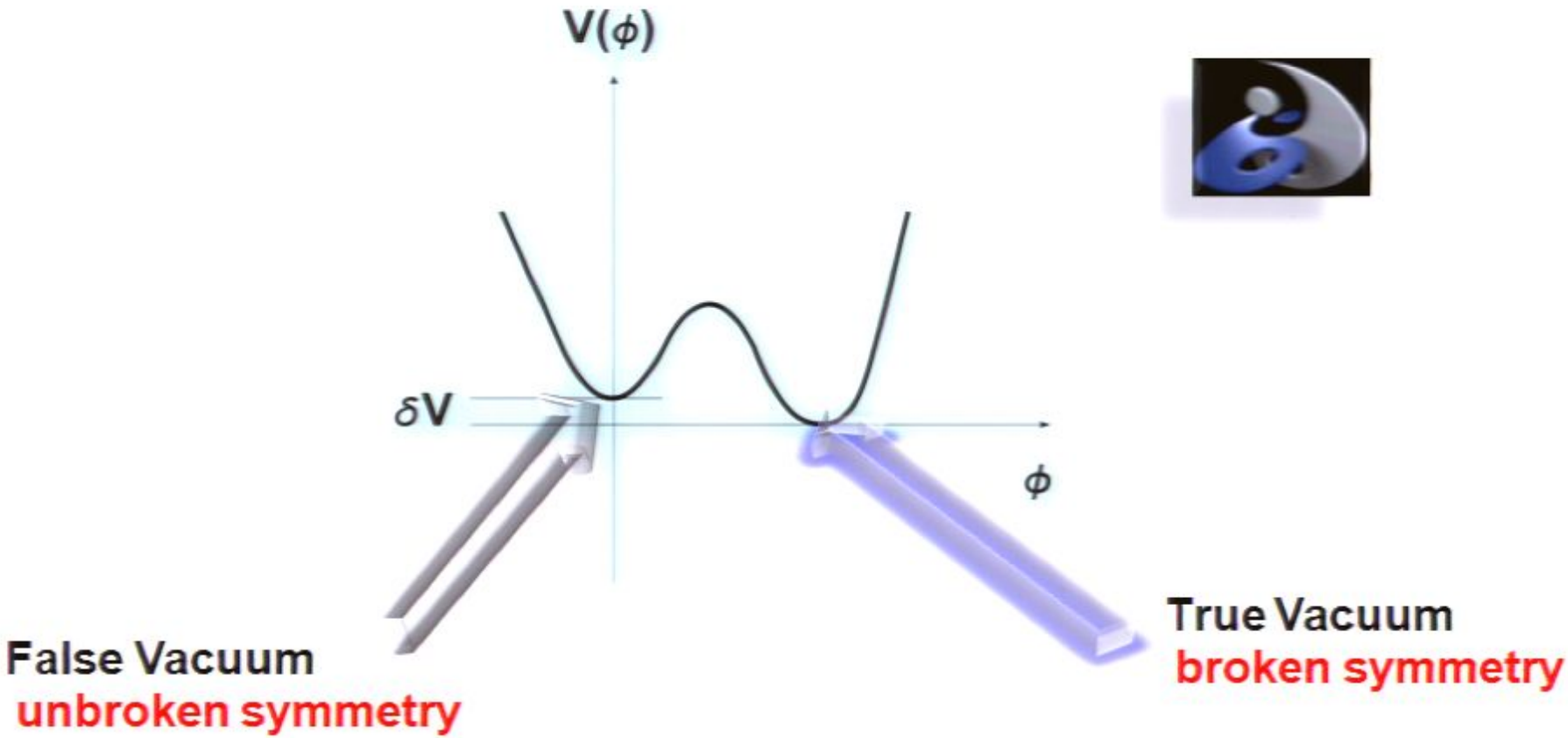

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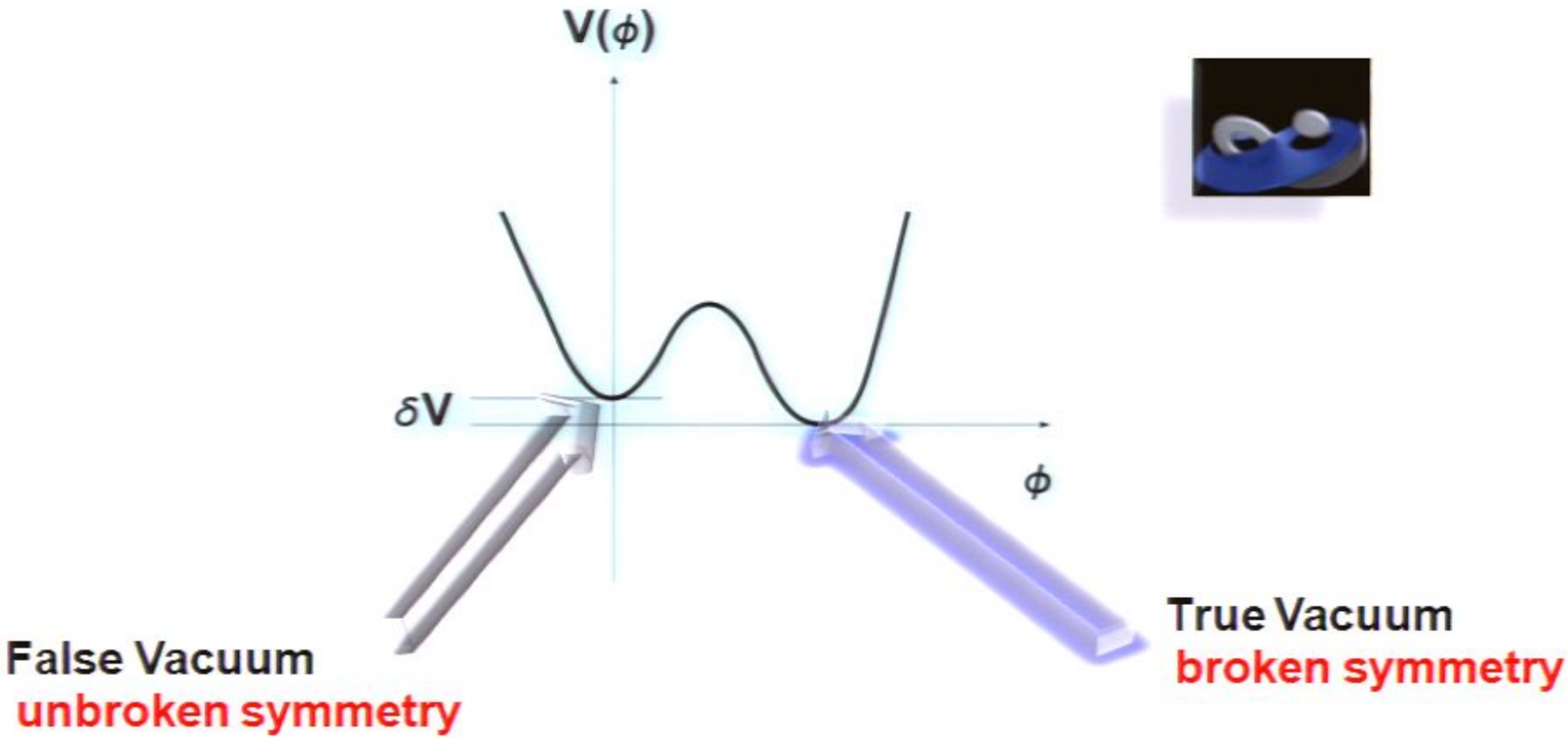

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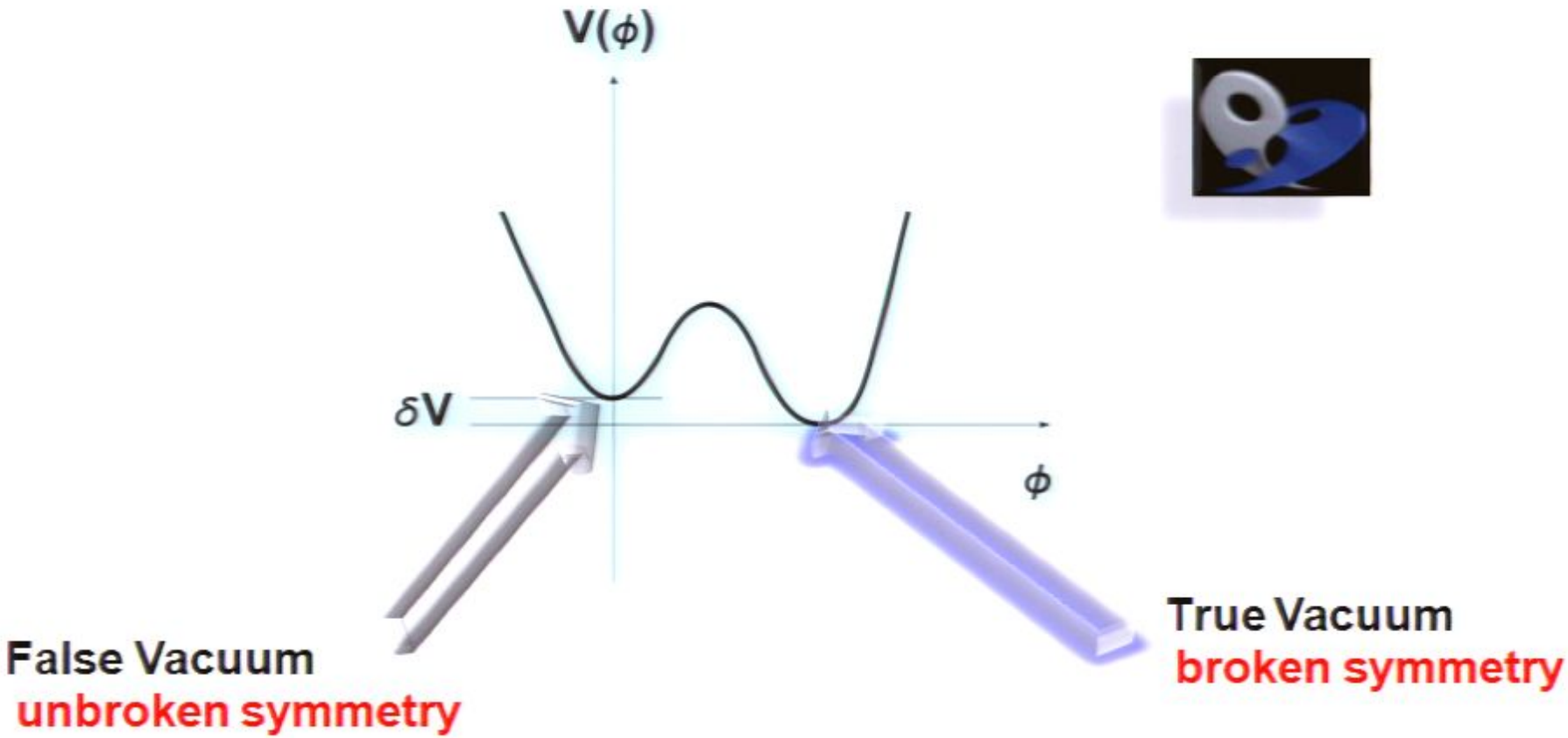

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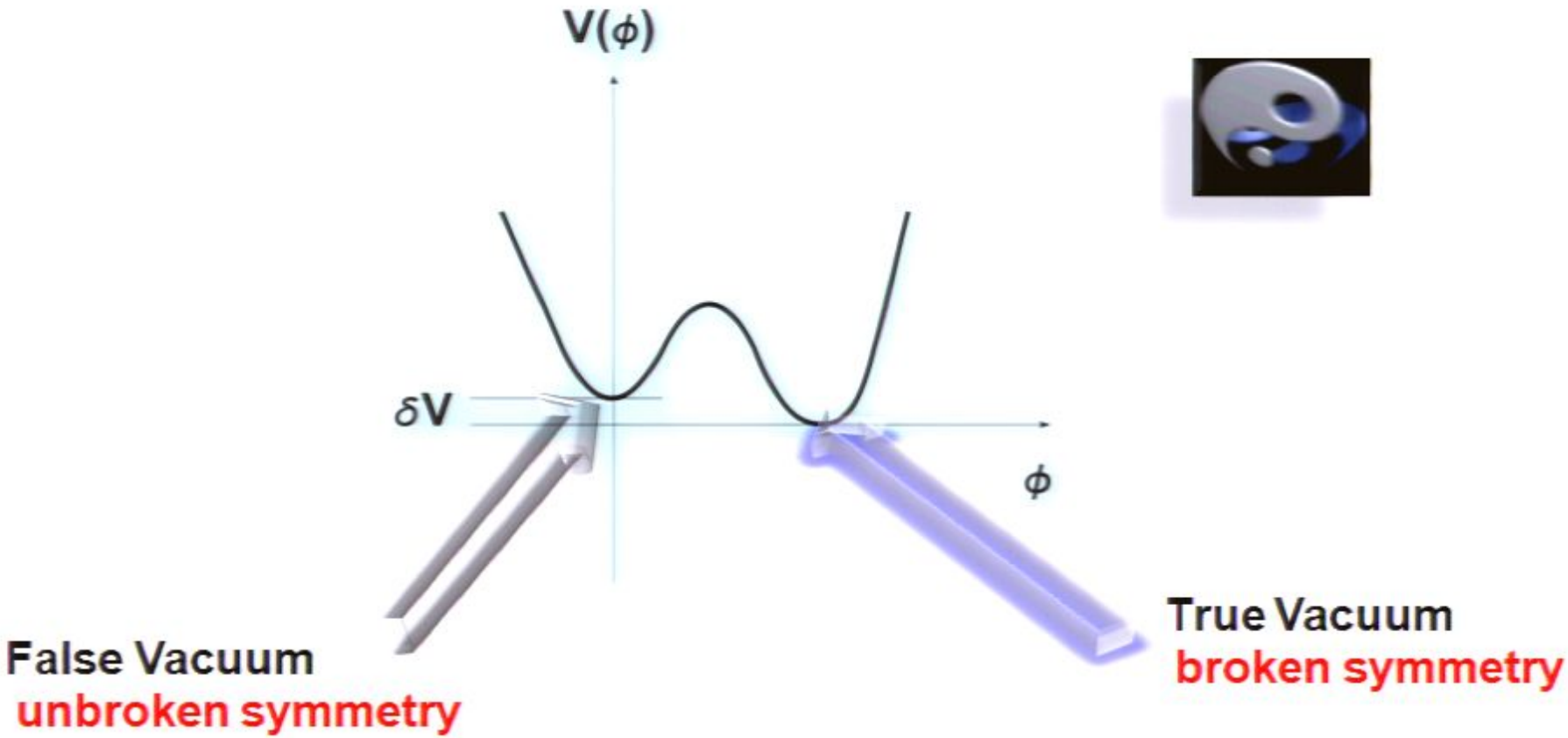

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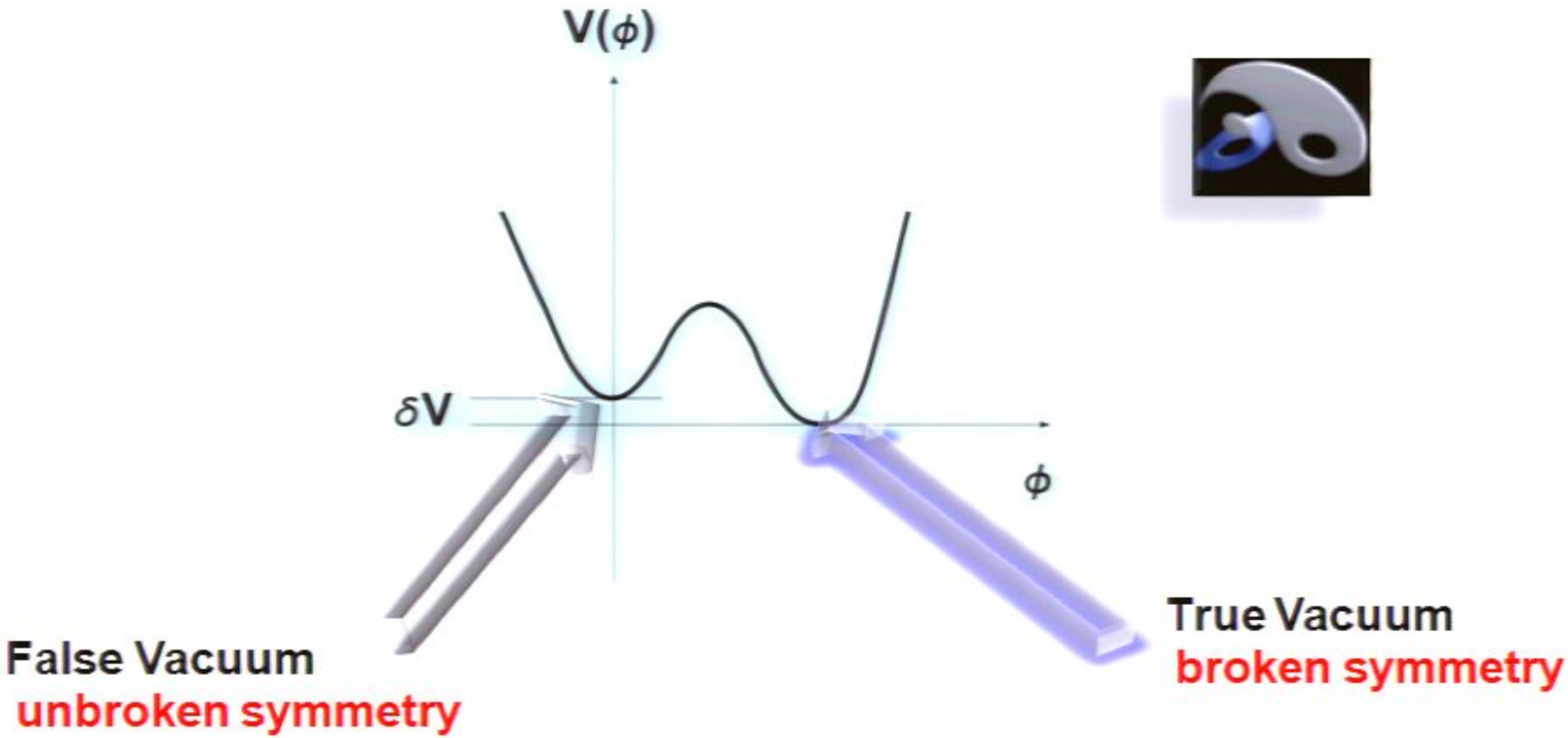

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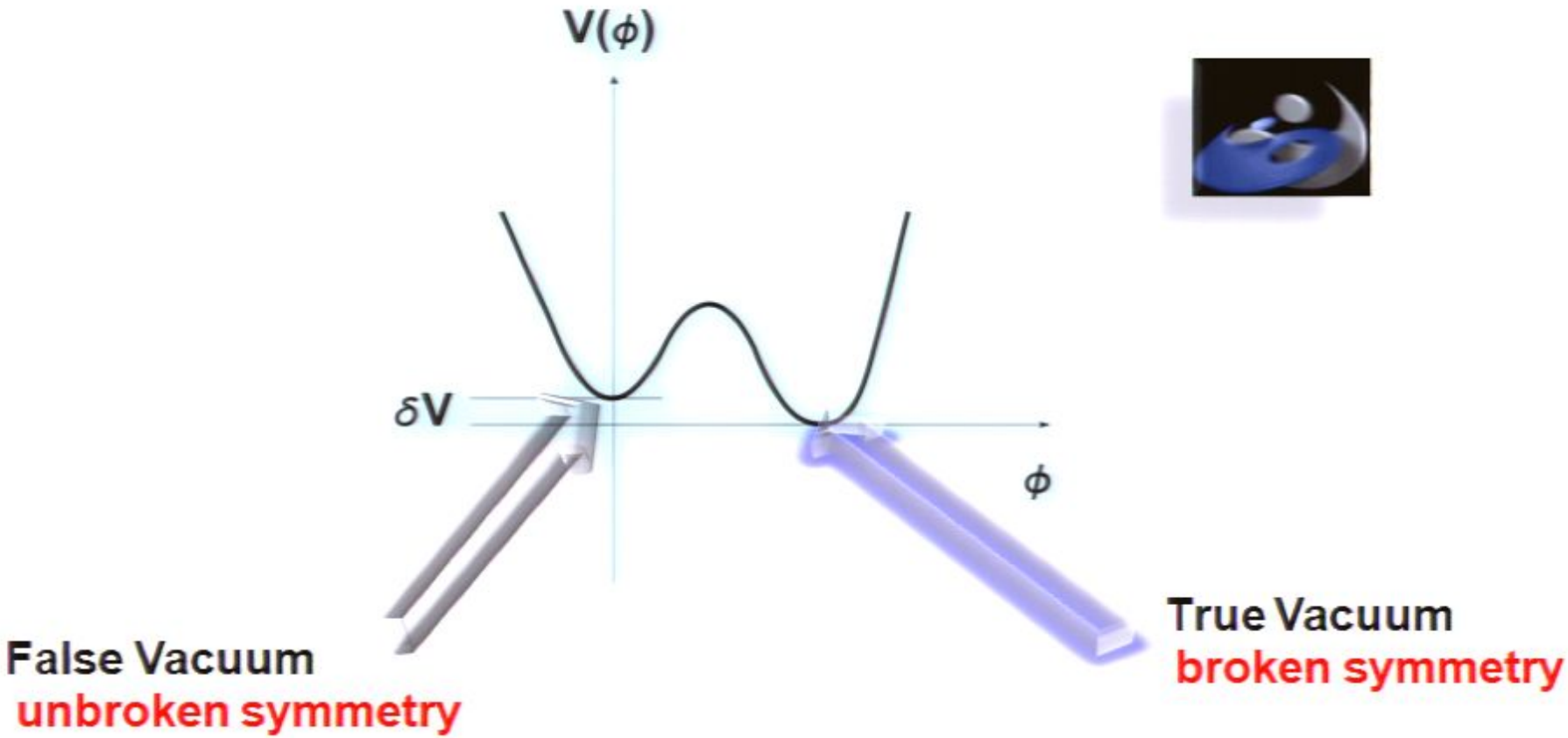

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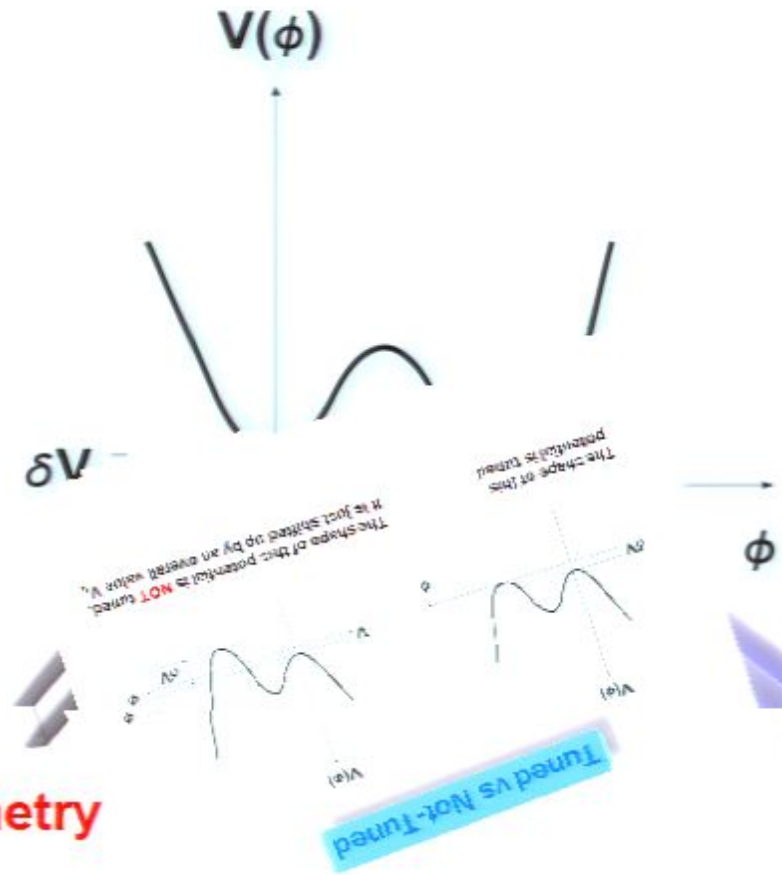

False Vacuum
unbroken symmetry

True Vacuum
broken symmetry

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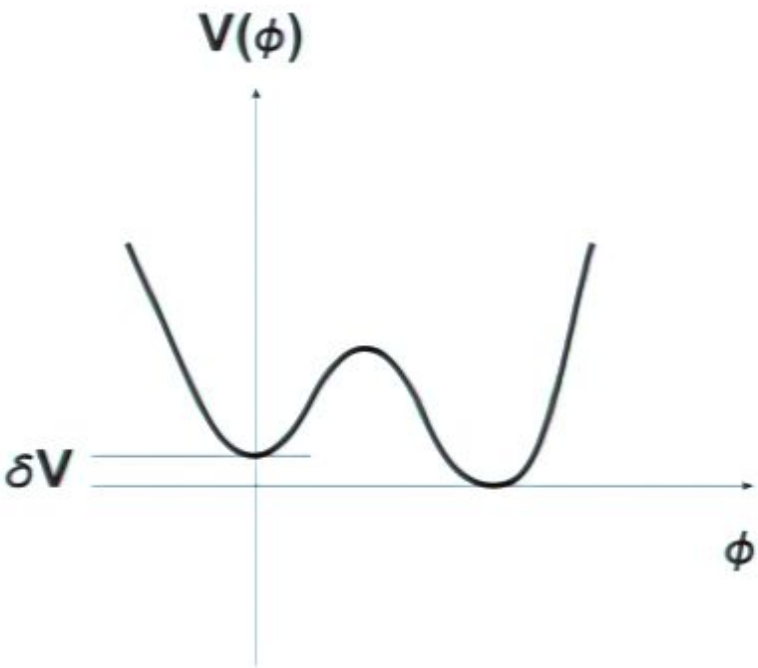
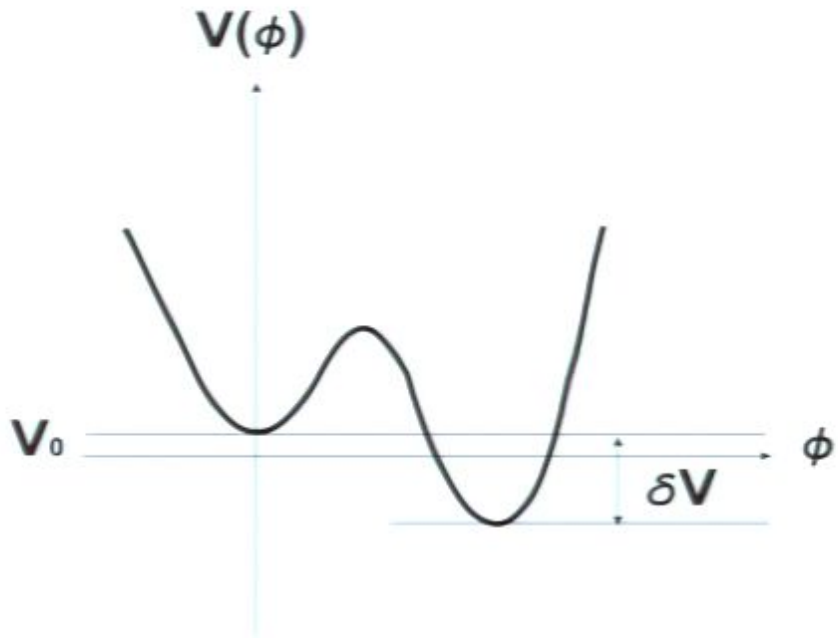
Tuned vs Not-Tuned

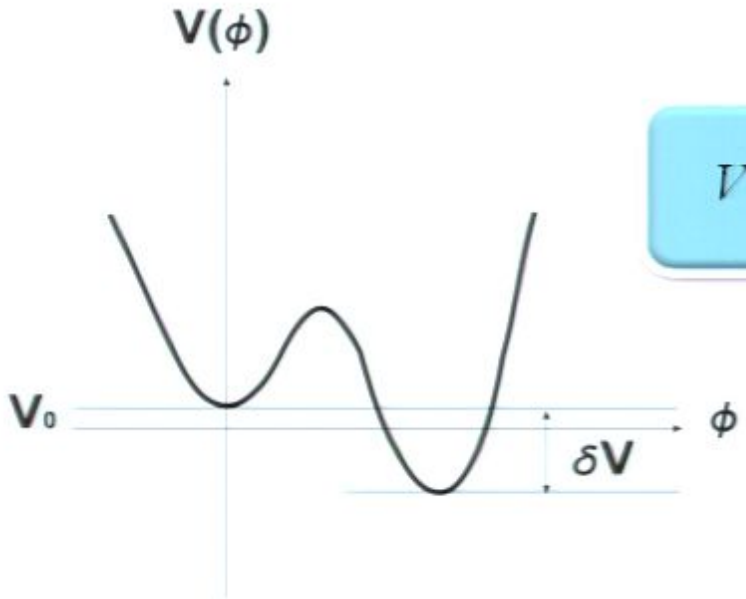




The shape of this potential is tuned

The shape of this potential is **NOT** tuned. It is just shifted up by an overall value V_0.

MODEL for SU(3)c breaking



$$V(\varphi) = \frac{\mu^2}{4}(Tr\,\varphi^2) + \frac{\lambda_1}{16}(Tr\,\varphi^2)^2 + \frac{\lambda_2}{6}(Tr\,\varphi^3)$$

- Massive colored scalar field φ
- Adjoint representation of $SU(3)_c$

- In a diagonal traceless representation

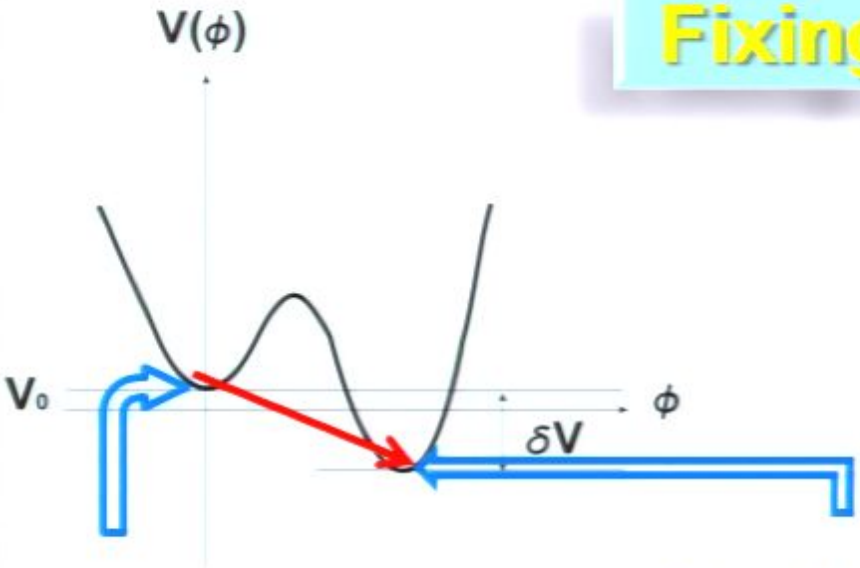
$$V(\phi) = \frac{9}{4}\lambda_1\phi^2(\phi - \phi_0)^2 - \frac{9}{4}\varepsilon\phi_0^2\phi^2 + V_0$$

V_0 is an overall shift of the potentia

$$\phi_0 = \frac{2}{9}\frac{\lambda_2}{\lambda_1} \qquad \delta V = \frac{9}{4}\varepsilon\phi_0^4 \qquad \varepsilon = \lambda_1 - \frac{2\mu^2}{3\phi_0^2}$$

ε is the measure of the fine tunin
of the shape of the potential

Fixing the parameters



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True Vacuum
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V_0 : vacuum energy density

Cosmological constant
Input from observations

$$V_0 \approx (10^{-3}\, eV)^4$$

Mass of the colored scalar field:

$$m_\phi \approx \mu \approx TeV$$

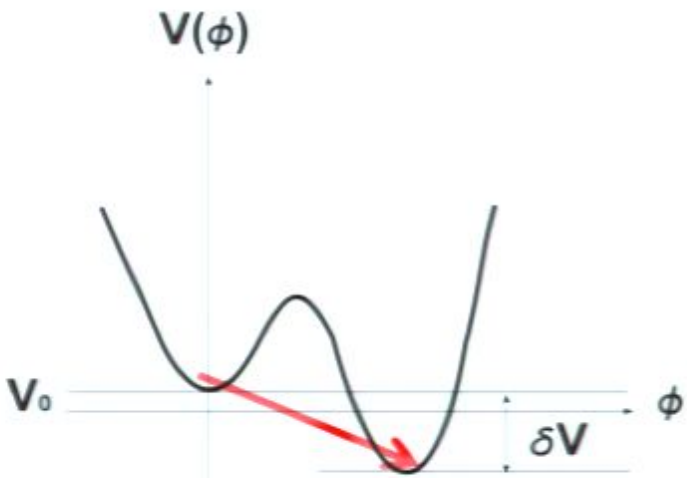
Difference in energy between the vacua:

$$\delta V \approx \varepsilon \times TeV$$

Interesting numerology :

$$V_0 = \left(\frac{TeV}{M} TeV \right)^4 = (10^{-3}\, eV)^4$$

Transition Rate



$$\delta V \approx \varepsilon \cdot TeV$$

Transition Rate: $\Gamma = Be^{-S_E}$

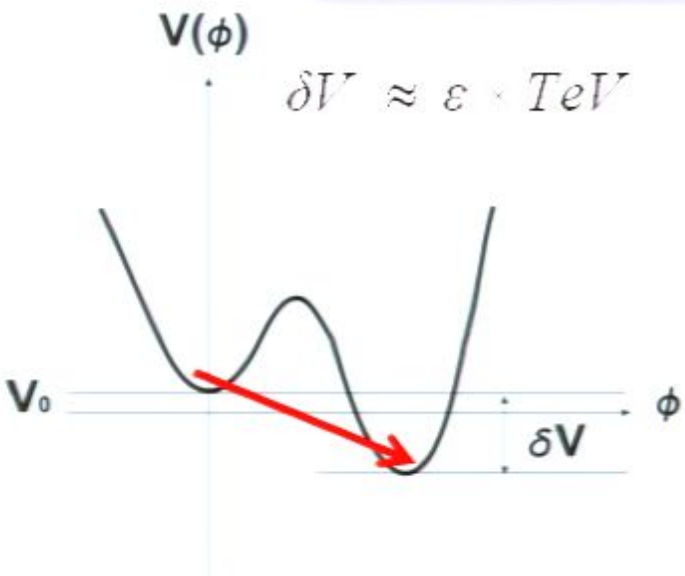
Euclidean Action: $S_E = \frac{\pi^2 \lambda_1^2}{54} \frac{1}{\varepsilon^3}$

Transition time is greater than the life-time of the universe if $S_E \geq 400$ → $\varepsilon \leq 0.1$

Mild fine tuning of the shape of the potential satisfies all of the cosmological constraints! →

1. Accelerated expansion
2. Equation of state w=-1
3. We still exist

Future of our Universe



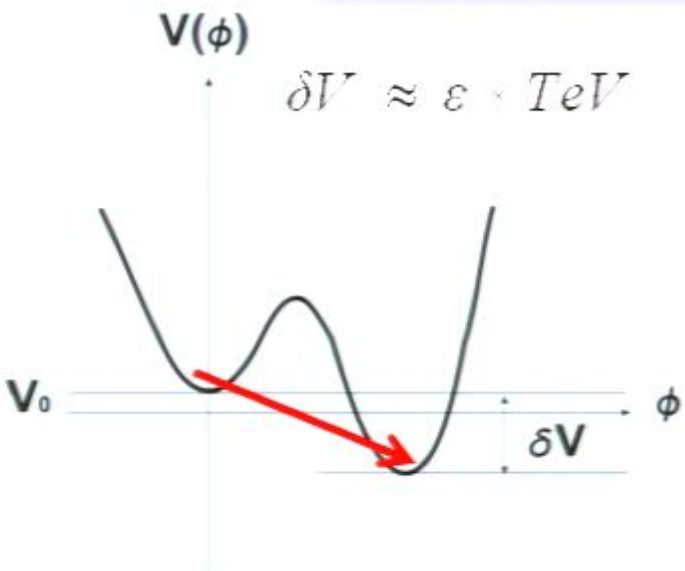
- First order phase transition proceeds with nucleation of bubbles of true vacuum
- If $\varepsilon = 0$, the transition time is infinite
- If $\varepsilon \approx 0.1$, we are just about to tunnel to the true vacuum (doomsday!?)

- True vacuum is not necessarily an absolute doomsday
- e.g. $SU(3)_c \rightarrow SU(2)_c$ some gluons remain massless, quark confinement survives (protons survive)
- However, if the true vacuum is AdS, after the tunneling the whole universe collapses into a black hole (Coleman-De Luccia) →

TRUE DOOMSDAY!

I'm Sorry!

Future of our Universe



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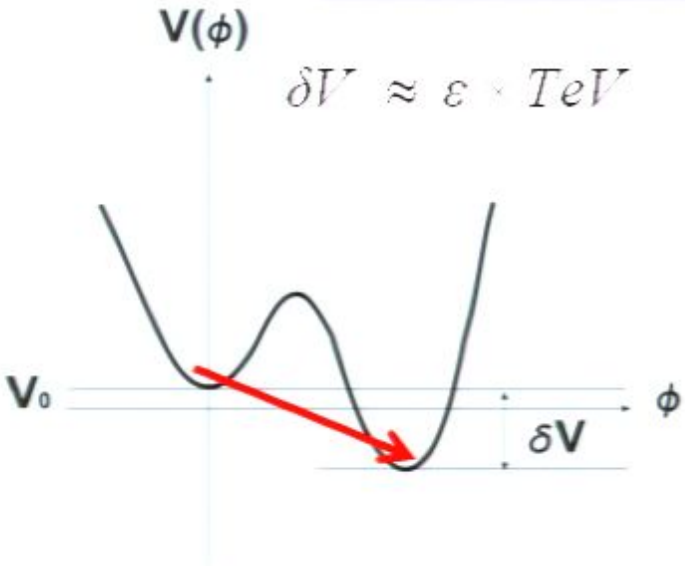

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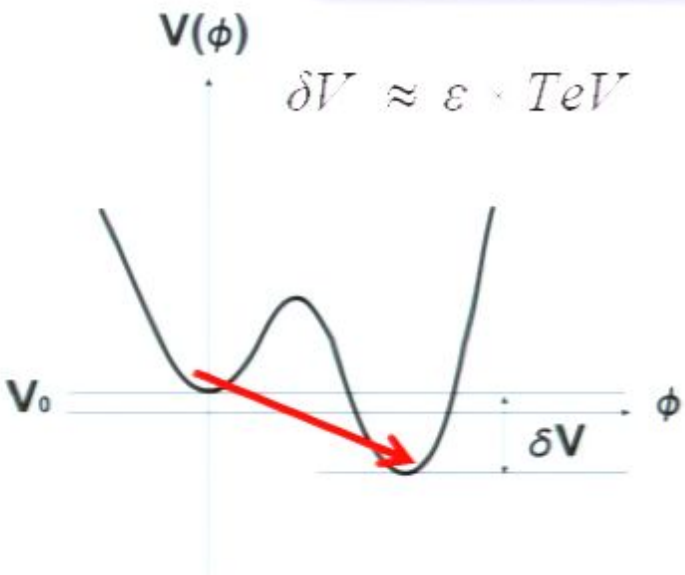

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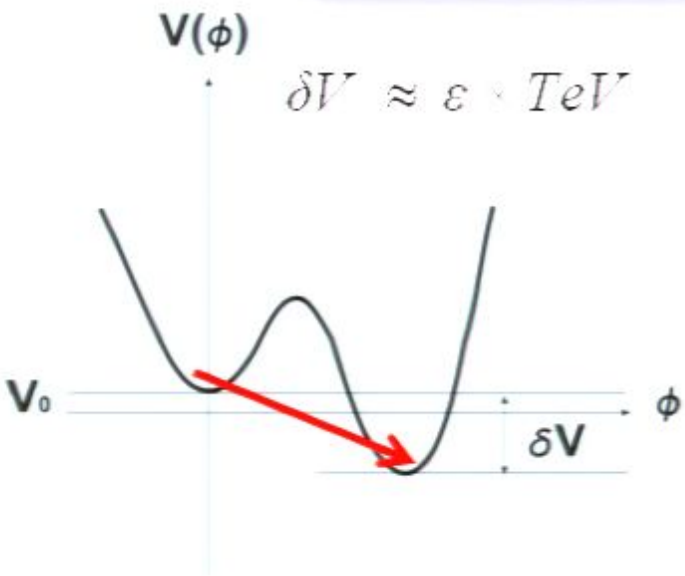

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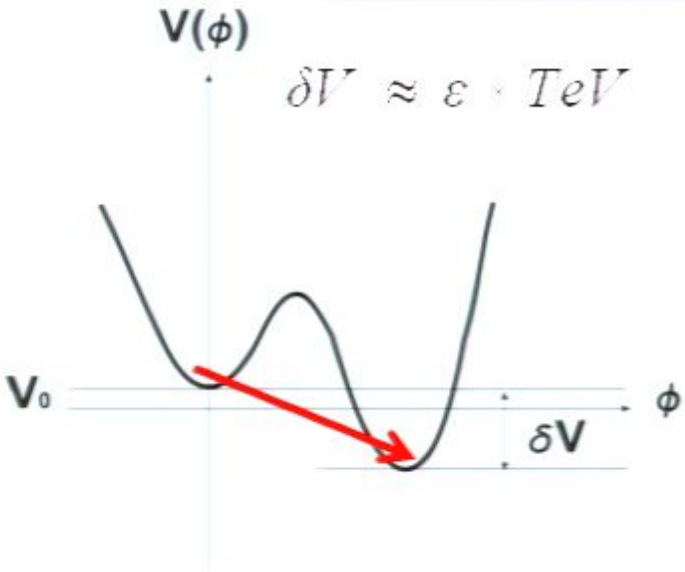

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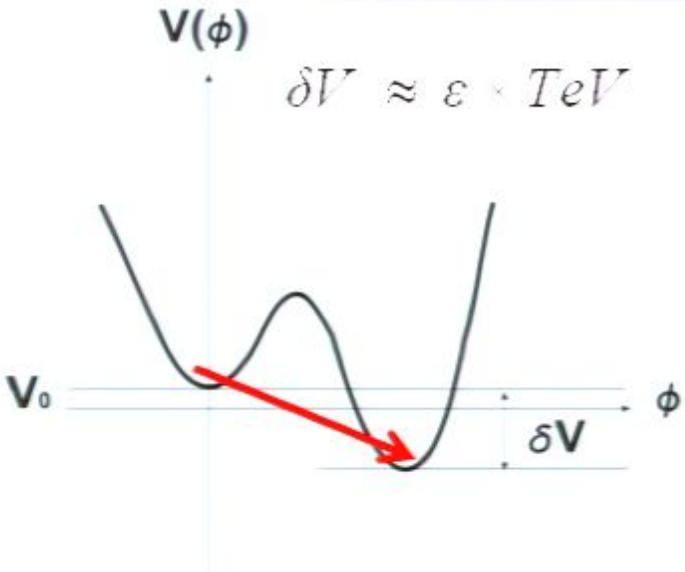

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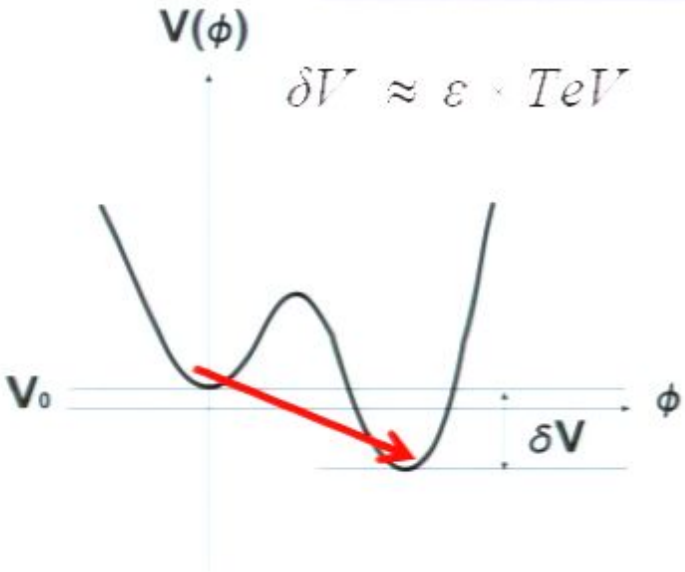

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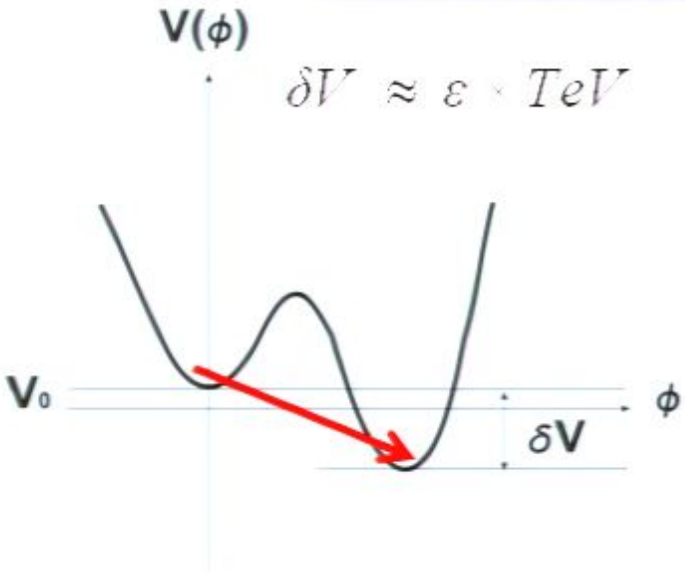

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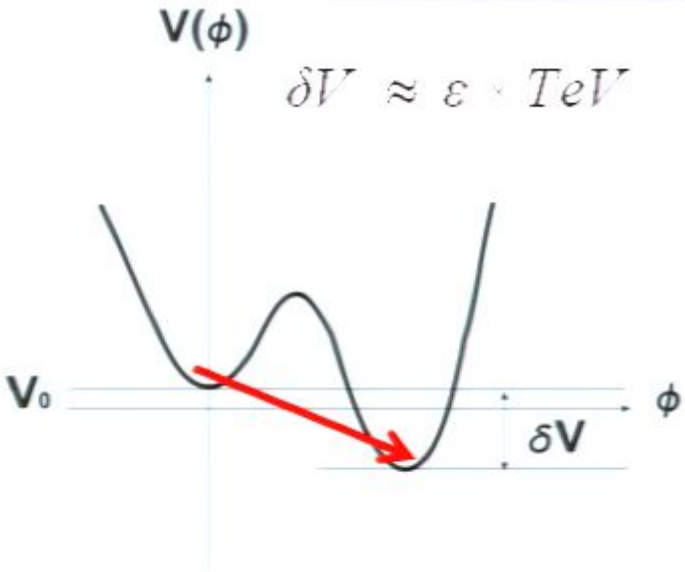

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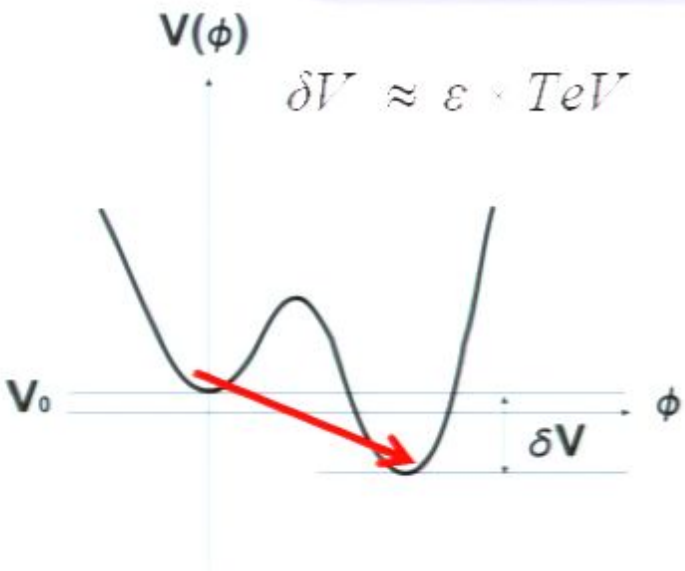

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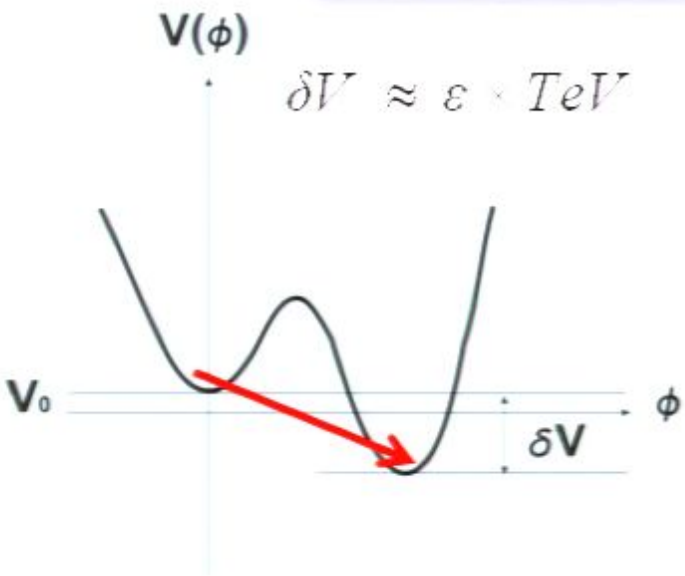

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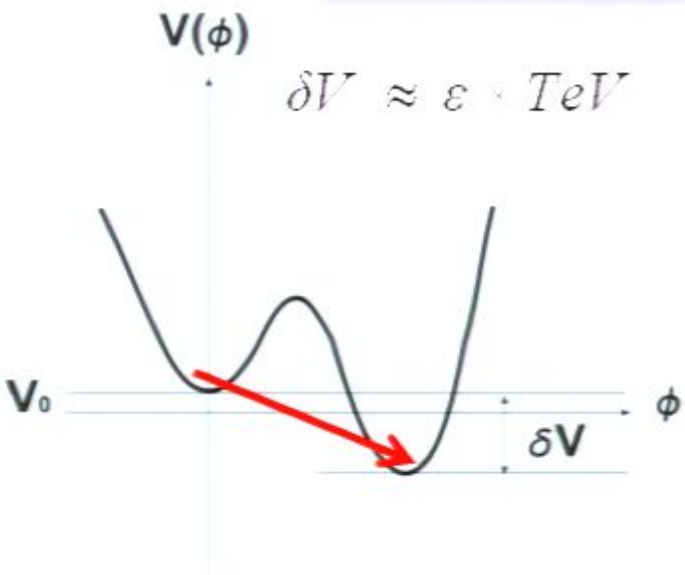

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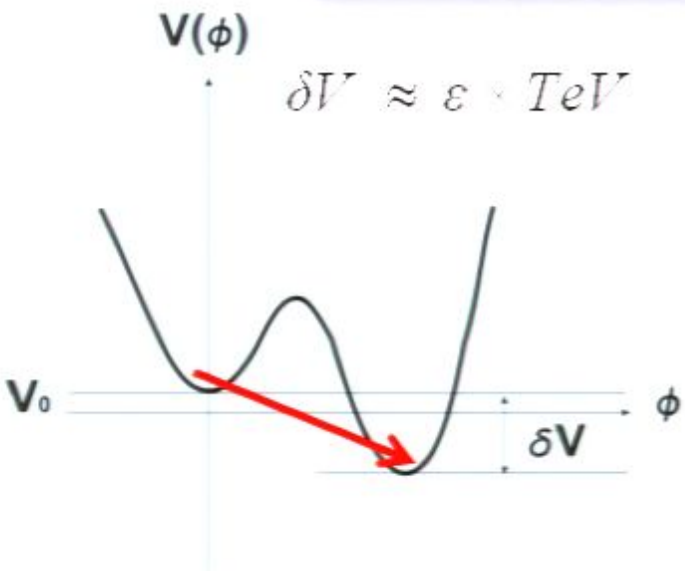

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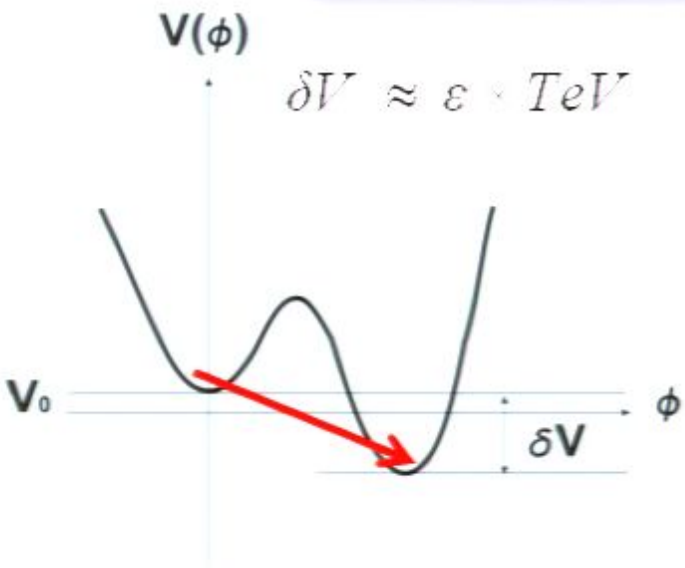

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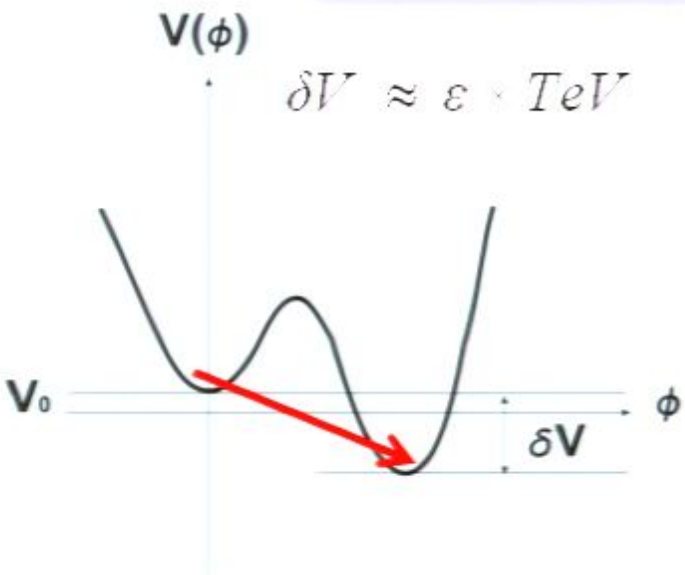

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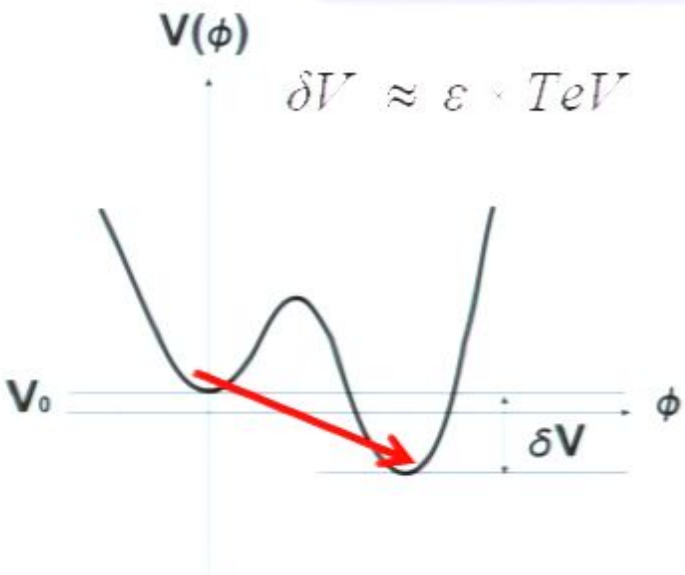

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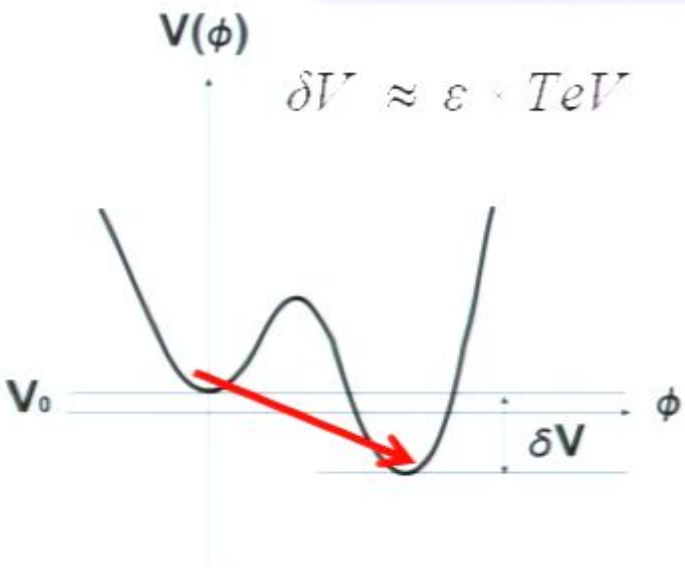

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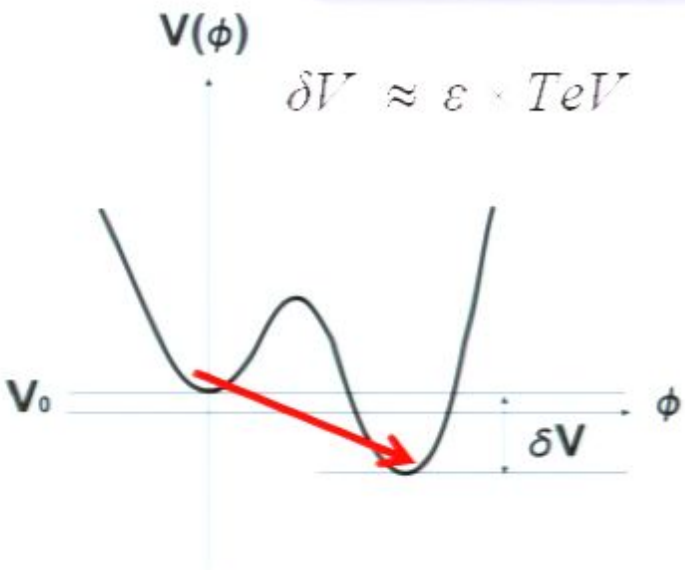

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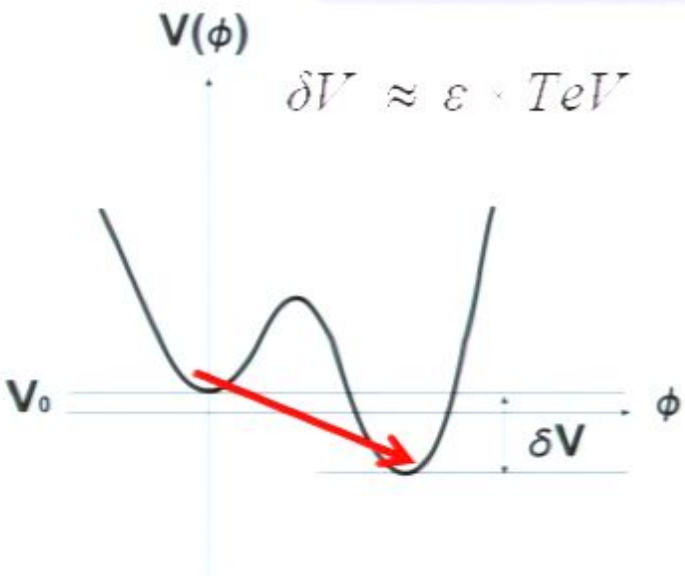

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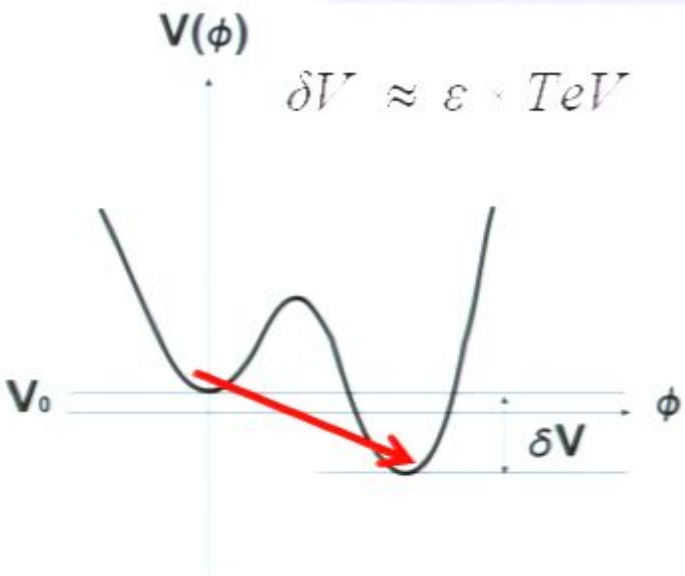

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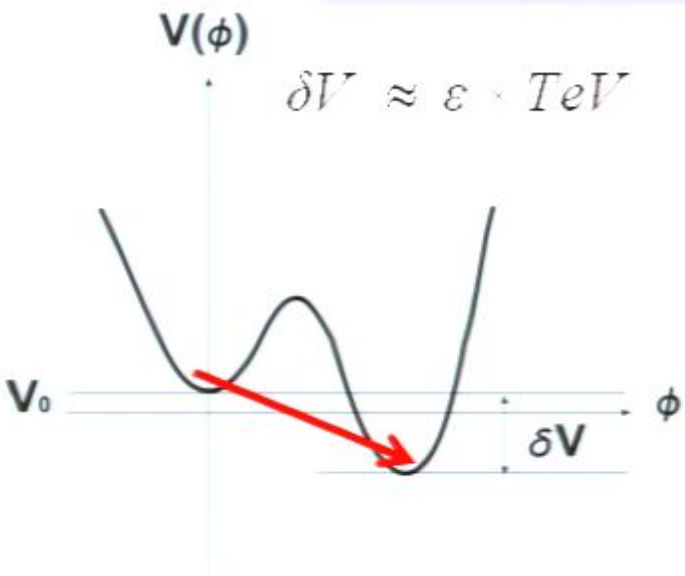

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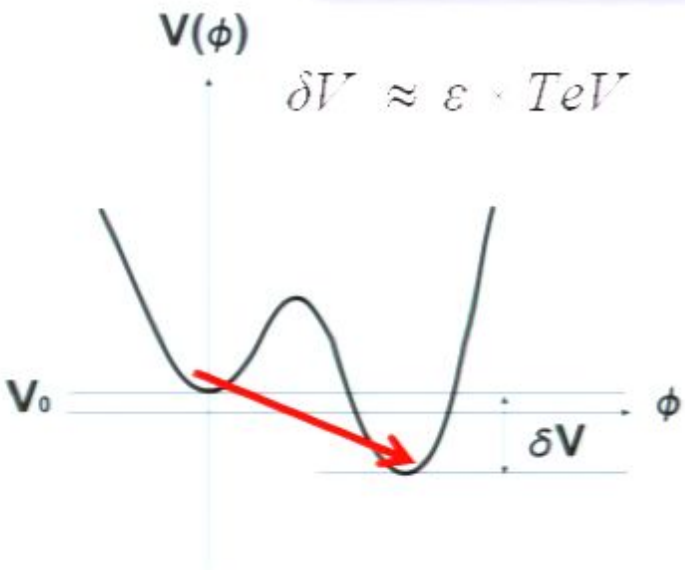

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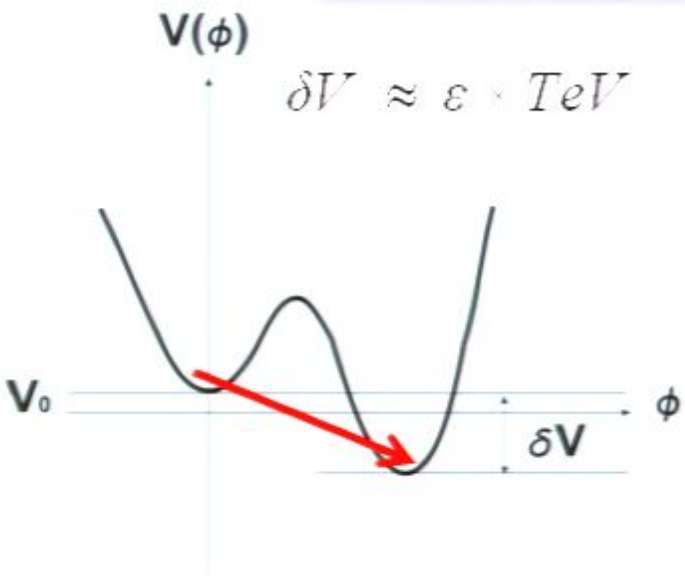

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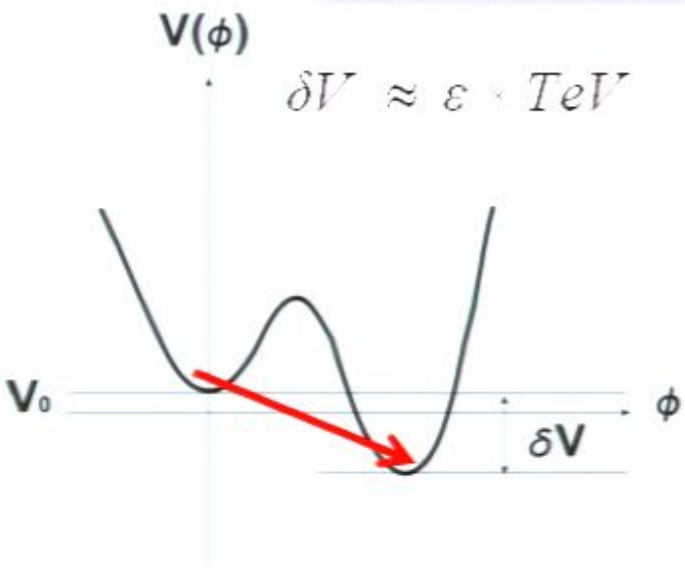

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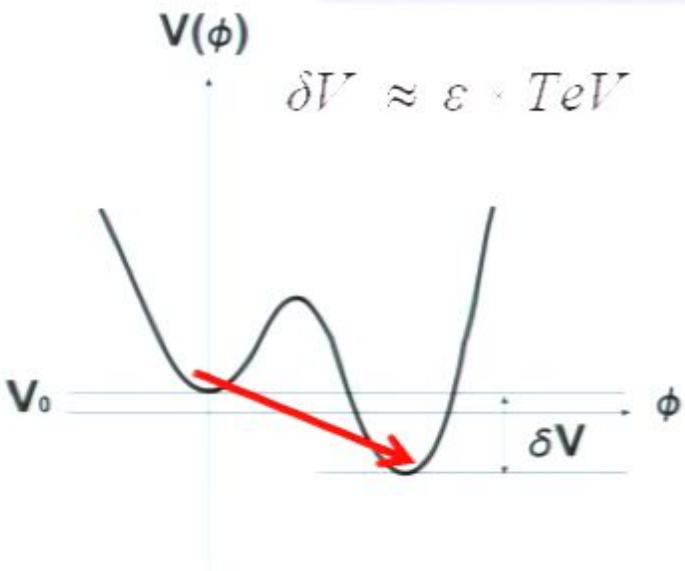

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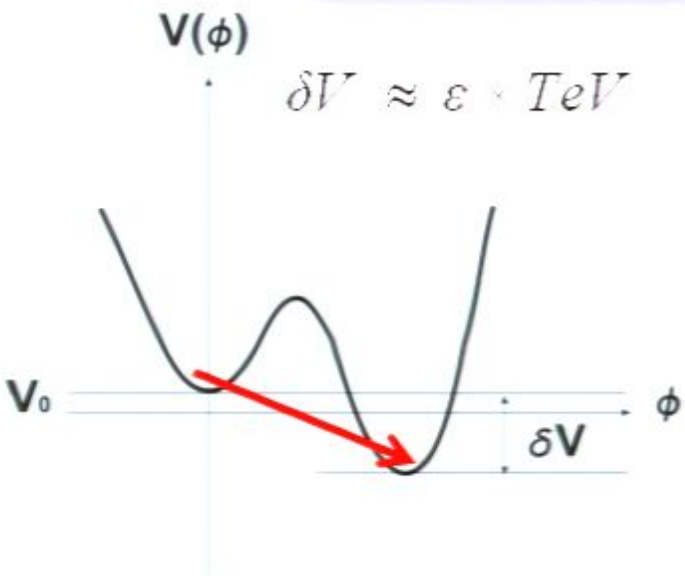

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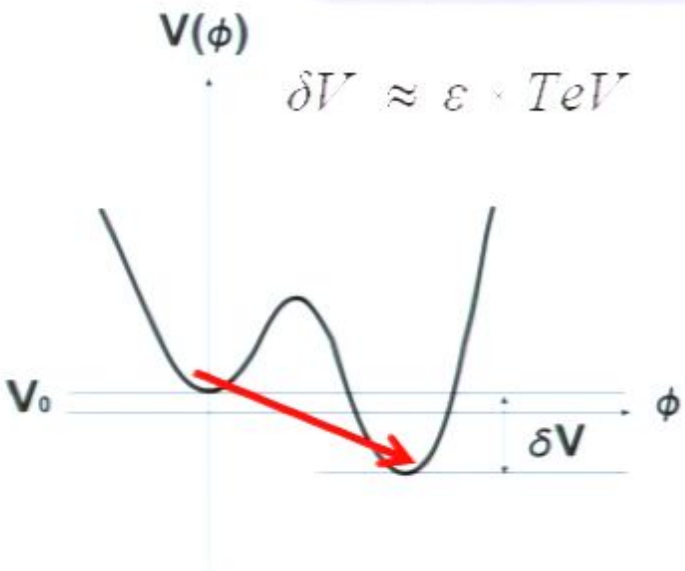

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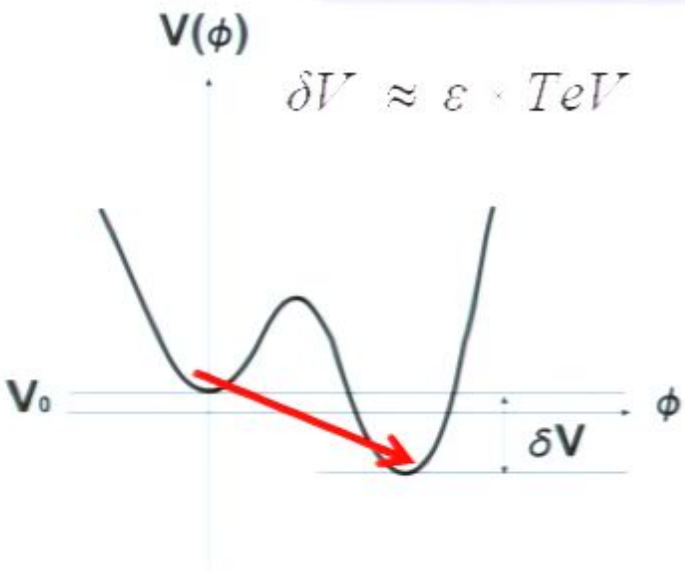

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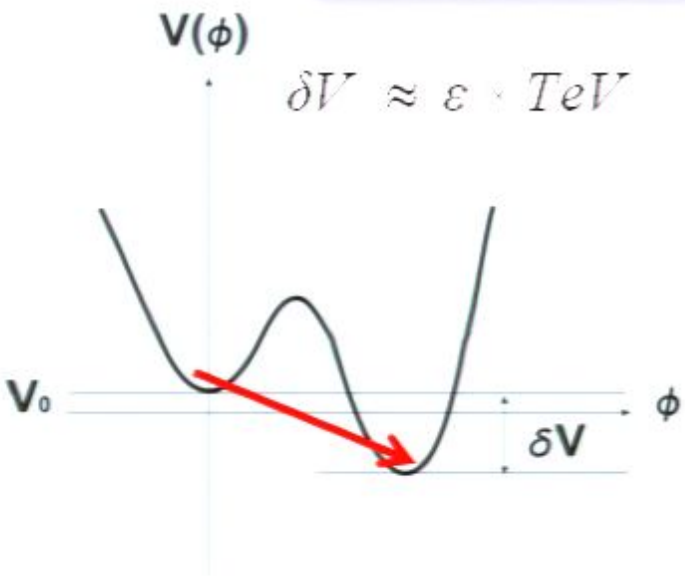

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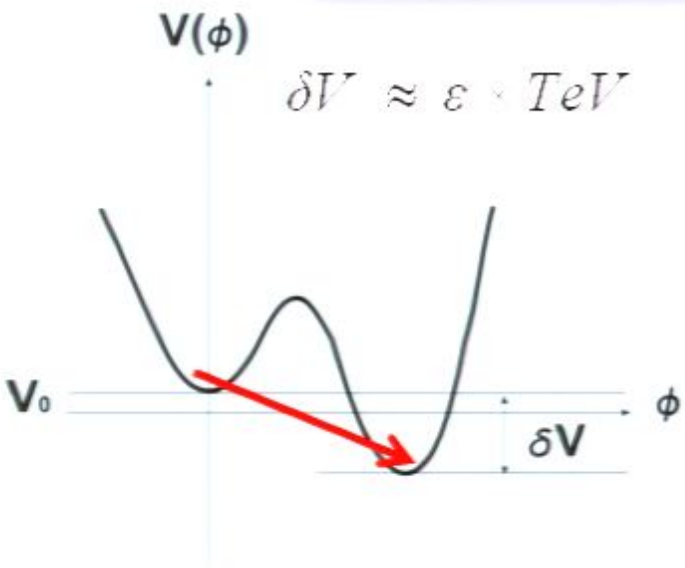

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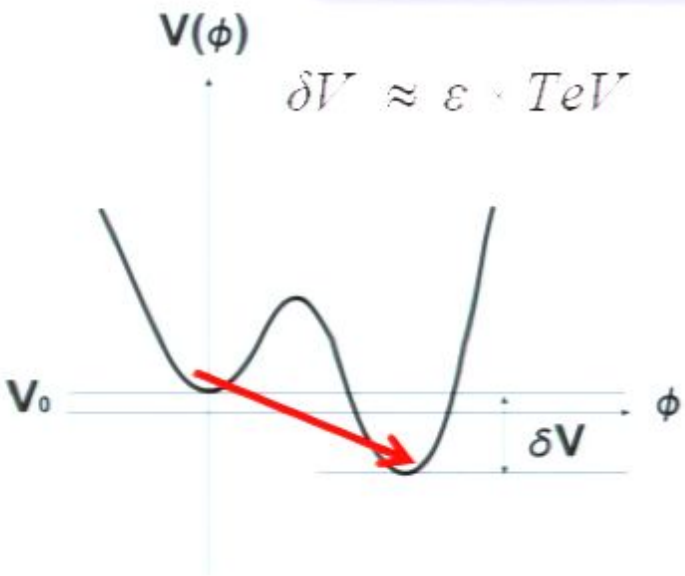

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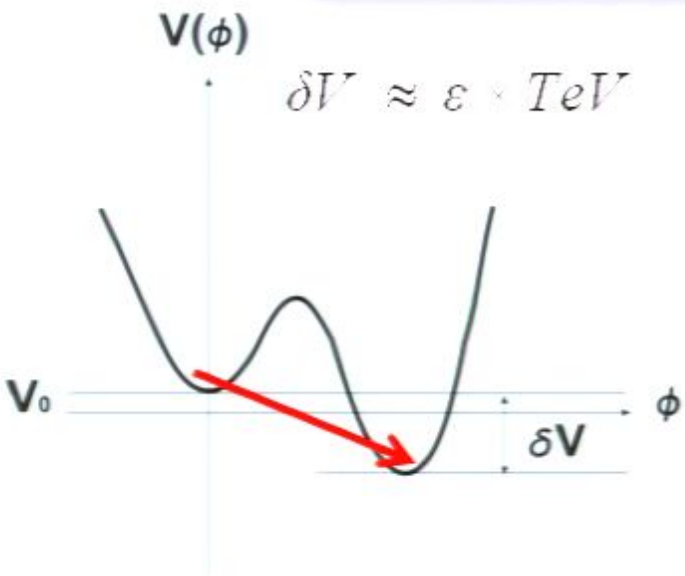
Future of our Universe



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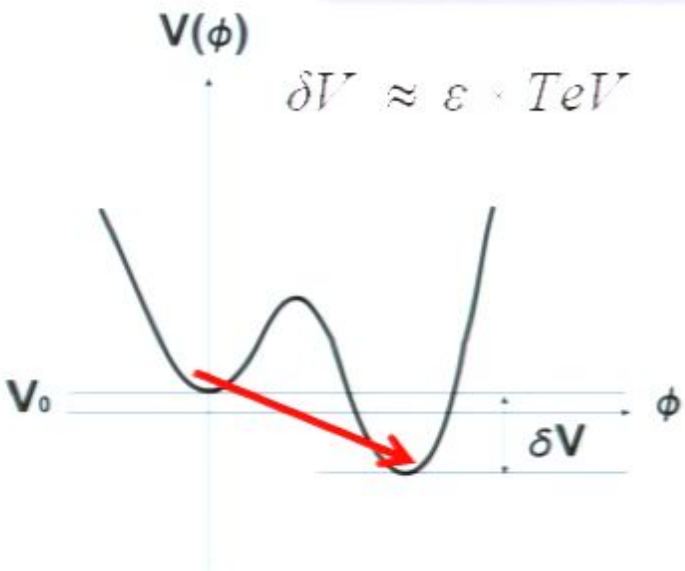

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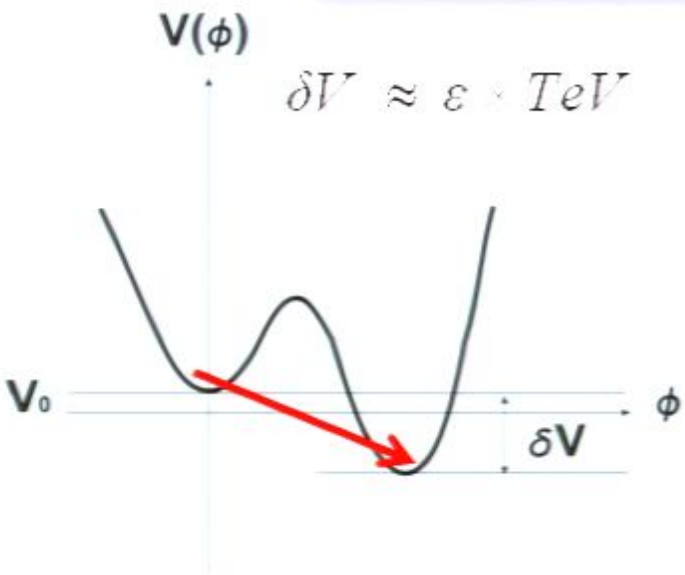

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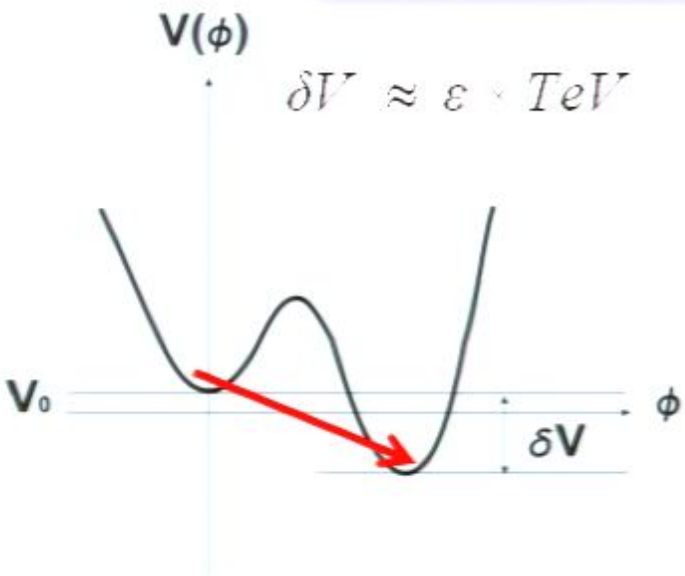

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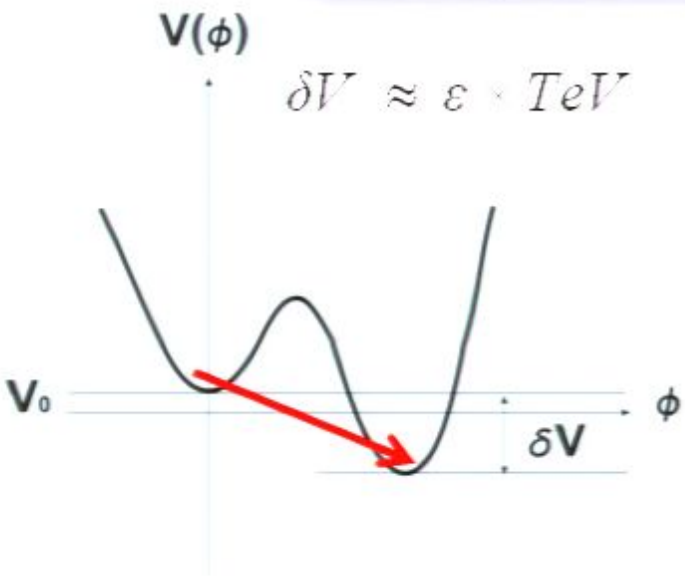

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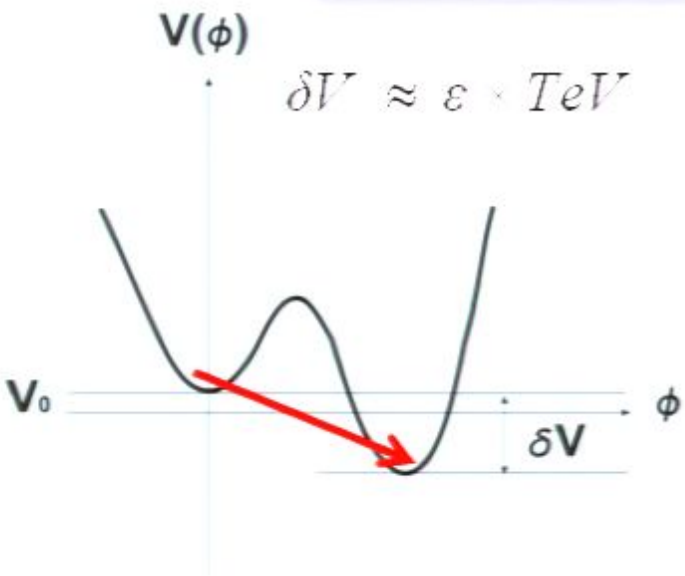

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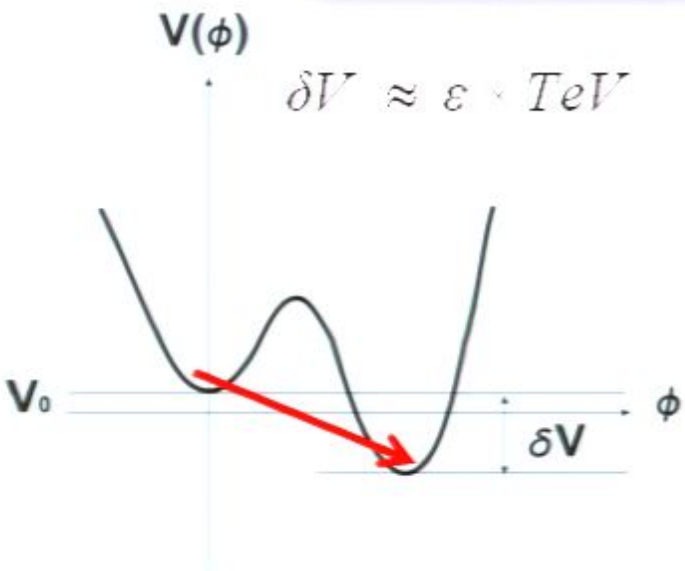

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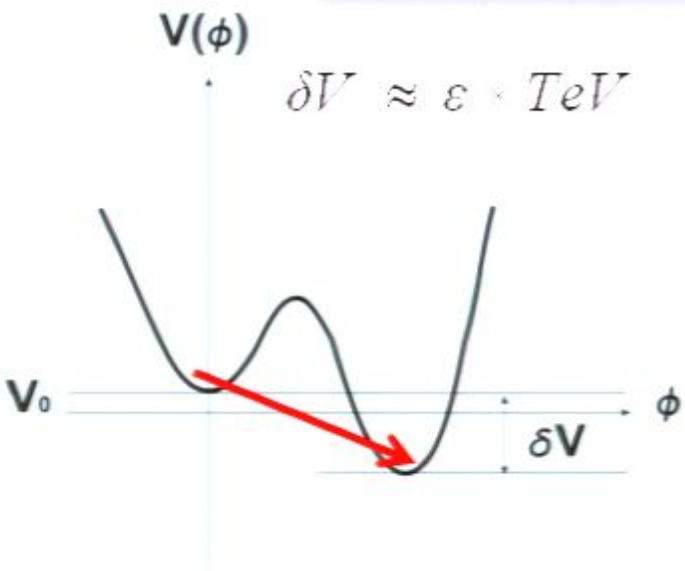

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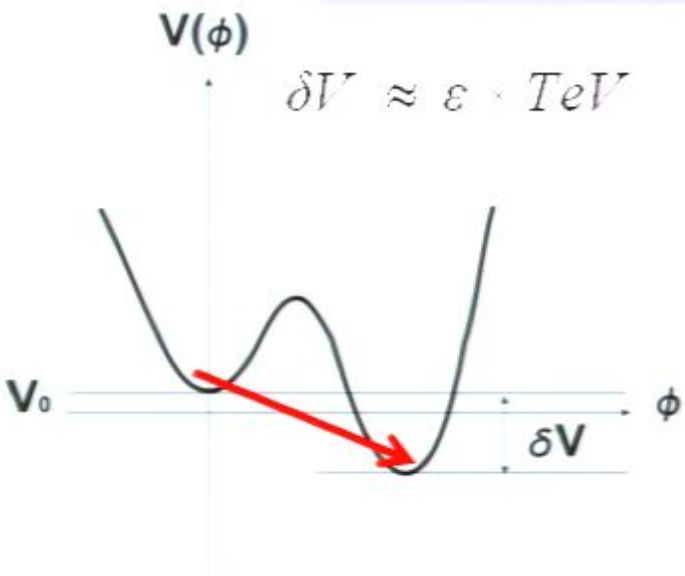

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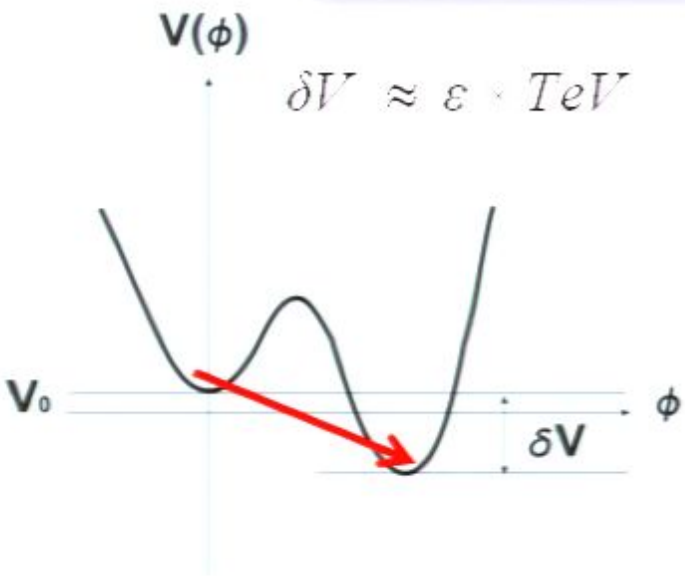

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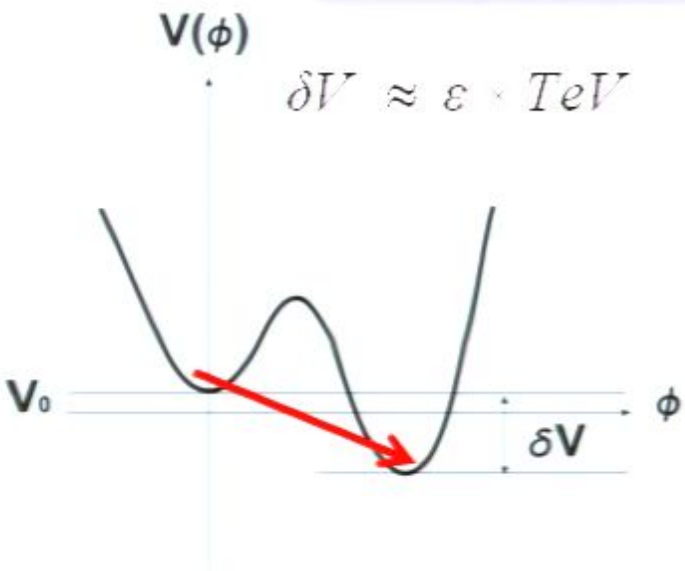

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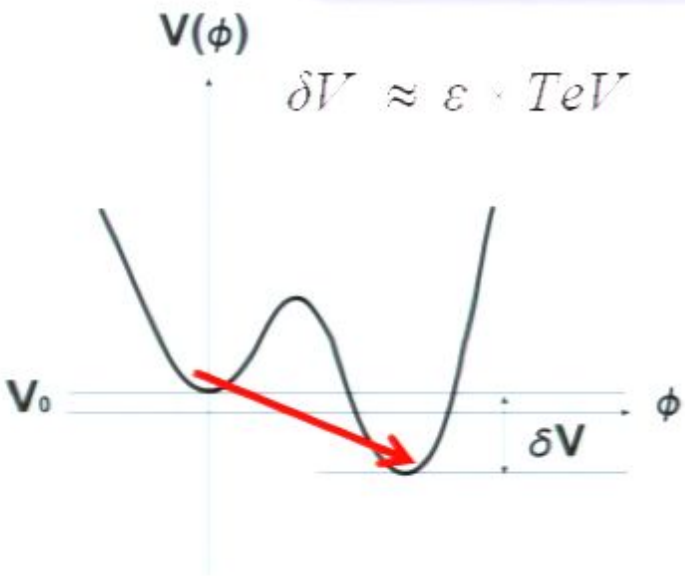

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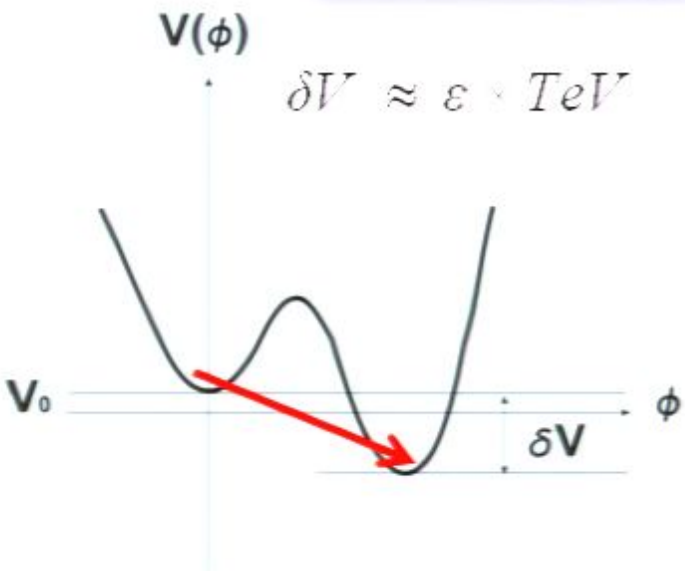

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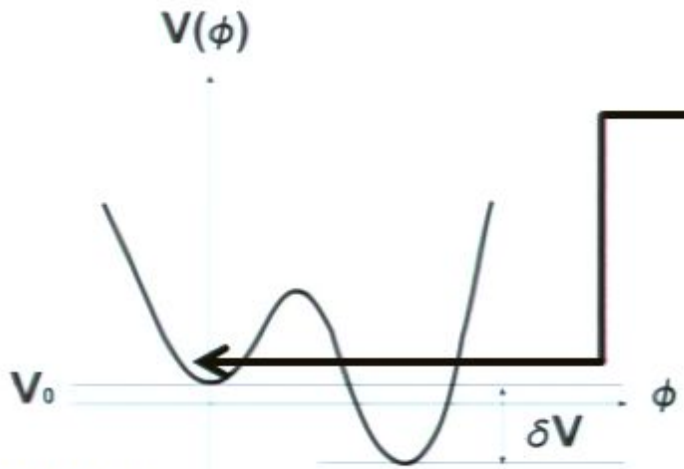
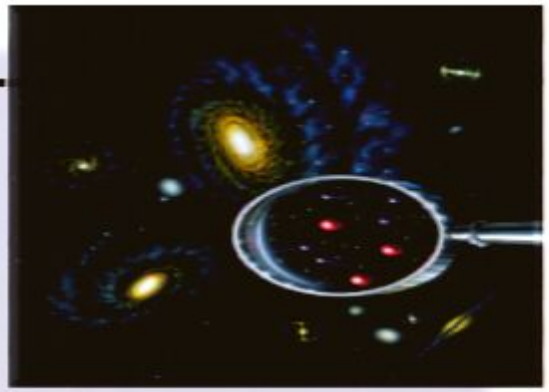
Particle Physics Phenomenology





We live in the False Vacuum
with unbroken symmetry!

Scalar field has zero VEV ⟷

- Massless gluons
- Quarks confined
- Protons do exist

Mass of the colored scalar field ~ TeV: ⟷ Low energy QCD phenomenology unchanged!

BONUS:

Model can be tested in colliders

Massive colored scalar field ➡ Very interesting near future accelerator phenomenology

New massive color singlet states:

1. Bound states of Φ's
2. Bound states of Φ's with quarks ➡ Fractionally charged hadrons $(\phi q q)$

Adjoint representation is 8-dim in SU(3) classification scheme

$8 \times 8 \quad (\phi\phi)$ and $8 \times 3 \times \bar{3} \quad (\phi q \bar{q})$ contain singlets (color free states)

3,6,10,15,21 support color singlets which are fractionally charged, i.e. FRACTIONALLY CHARGED HADRONS (FCH)!

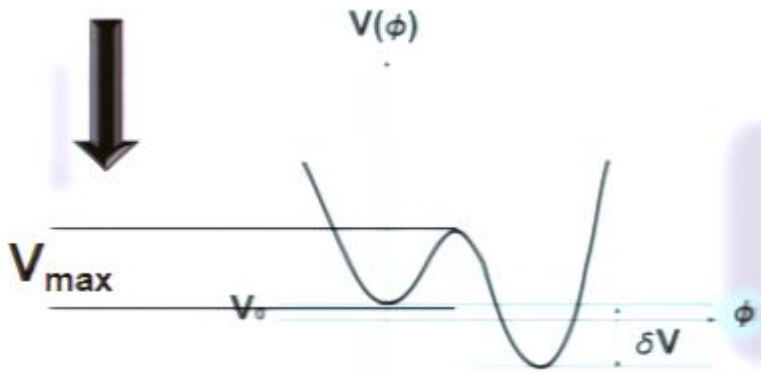
Experimental Signature

- ϕ can decay into gluons and quarks
- lifetime depends on the couplings and specific representation of $SU(3)_c$
- Fast decay ➡ main signature will be gluon and quark jets in excess of SM prediction

- To produce FCH, lifetime of ϕ should be longer than the characteristic hadronization time $\sim (100\text{MeV})^{-1}$
- e.g. if ϕ is protected by some symmetry

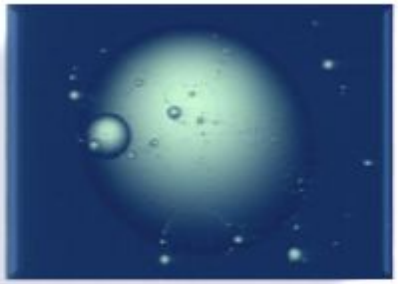
Production of fractionally charged hadrons is a very interesting prediction of this model!

The potential barrier between the vacua is only ~ TeV

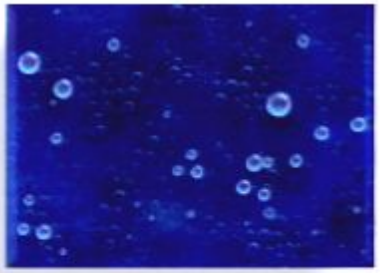


$$V_{\max} = \frac{9}{64}\lambda_1 \phi_0^4 \approx TeV^4$$

Can produce small bubbles of true vacuum (of TeV $^{-1}$ size)…



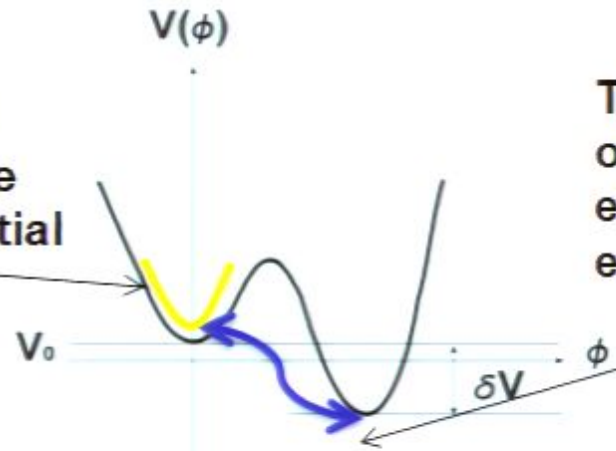
…and watch them decay



Production of a critical bubble (able to expand) is suppressed (otherwise we could destroy the Universe!)

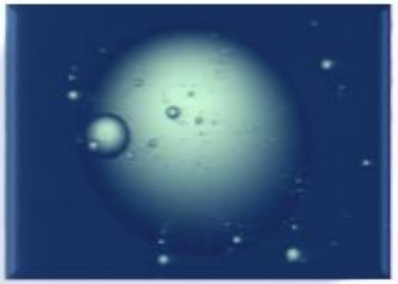
Vachaspati, PRD, 04: How to reconstruct field theory by studying field excitations if "kink" solutions are present

If we excite the field locally we can learn only about the local structure of the potential



To learn about the global shape of the potential we need to excite the solution that extrapolates between the vacua

Need to excite a kink solution, (closed domain wall) i.e. a small bubble of true vacuum



Can reconstruct the scalar field potential in future accelerators!

Reconstructing the field theory by studying kink excitations
Inverse Scattering method

Theory given by: ⟹ $$L = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$$

Equation of motion: ⟹ $$\left[-\frac{d^2}{dx^2} + V''(\phi_0(x))\right]\psi_n = \omega_n \psi_n$$

Φ_0 → kink solution

Zero mode (ω = 0): ⟹ $$\psi_0 = \frac{d\phi_0}{dx} = \pm\sqrt{2V(\phi_0)}$$

Bogomolnyi equation

$$-z''_n + U_{n+1} z_n = \omega_n^2 z_n$$ **where** $$U_n = \left(-\frac{z'_n}{z_n}\right)^2 + \left(-\frac{z'_n}{z_n}\right)' + \omega_n^2$$

Solve for Z_0 and find

$$V(\phi_0) = \left.\frac{\alpha^2}{2z_0^2}\right|_{x(\phi_0)}$$

SUSY

- Model can be embedded in super-symmetric theories where massive colored scalar fields appear naturally

- It has been known for a while that many of the true vacua in the landscape of super-symmetric vacua are color breaking

- A vast part of the parameter space has been excluded as non-physical

- We see that some of these vacua can drive accelerated expansion!

Conclusions

- First order phase transition in which $SU(3)_c$ breaks can explain accelerated expansion of the universe
- Low energy QCD phenomenology remains the same
- New signature for the future collider experiments
- Can reconstruct the potential in colliders!

YES!

Dark Energy CAN have a color!

THANK YOU