Can dark energy have a color?

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• Puzzles raised by the recent observational data:
  • Dark Matter (missing mass)
  • Dark Energy (acceleration)
  • Dark matter can NOT carry gauge charges!
  • Can Dark Energy carry gauge charges?

Proposal: acceleration is driven by the phase transition is which SU(3)c symmetry is breaking
Big Bang
Three pillars of the Big Bang

Big Bang

Cosmic Expansion

CMBR

Light elements abundance
Very difficult to imagine a model that explains all this and yet is different from the Big Bang!
The bad news!

Puzzles raised by the recent observational data:

96% of the content of the Universe seems to be missing
The dark matter puzzle
Recently, studying Supernovae type Ia, astronomers stumbled upon an interesting discovery:

Our Universe is accelerating!
Supernova

Astronomical object whose physics is very well known
We can use **supernovae** to study expansion history

- Supernovae = **standard candles**
- **Their intrinsic luminosity is known**
- **Their apparent luminosity can be measured**
- The ratio of the two can provide the **luminosity-distance** \( (d_L) \) of the supernova
- The red shift \( z \) can be measured independently from spectroscopy
- **Finally, one can obtain** \( d_L(z) \) **or equivalently the magnitude** \( (z) \) **and draw a Hubble diagram**
Supernovae of a given redshift appear to be further away (dimmer) than we thought \( \Rightarrow \) Universe is accelerating

Get the best fit if we assume that beside ordinary matter there is a new component with \( \Omega_\Lambda \)
Expansion History of the Universe

Expected: Decelerated Expansion due to Gravity

Observed: Accelerated Expansion
Dark Energy Comprises 73% of Universe

- Dark Energy: 73%
- Dark Matter: 23%
- "Normal Matter": 4%
The cosmological constant

Einstein (1915) G.R.: \[ G_{\mu\nu} = \kappa T_{\mu\nu} \]

\[ G_{\mu\nu} = \kappa T_{\mu\nu} + \Lambda g_{\mu\nu} \]

Cosmological Constant

Cosmic Repulsion
Cosmological Constant: Physical Meaning

**Constant energy per unit volume** $\Delta V > 0 \Rightarrow \Delta U = \rho_A \Delta V > 0$

Energy conservation: $\Delta U = -p_A \Delta V$

$(\Delta V > 0, \Delta U > 0) \Rightarrow (p_A < 0)$

- Positive pressure *pushes against* the piston
- Negative pressure *pulls in* the piston (spring force)
What is cosmological constant?

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

Tommy Gold – astronomer and thinker 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

\[
\begin{align*}
\Lambda_{\text{pred}} &= (10^{19}\text{ GeV})^4 \\
\Lambda_{\text{obs}} &= (10^{-3}\text{ eV})^4
\end{align*}
\]

\[
\frac{\Lambda_{\text{pred}}}{\Lambda_{\text{obs}}} = 10^{124}
\]

• Coincidence problem: why is it NOW that \( \Omega_\Lambda \approx \Omega_M \)
Guess #2: Scalar field vacuum energy density

aka quintessence

- The simplest potential: $V(\phi) = \frac{1}{2} m^2 \phi^2$
- Ultra light particle $m=10^{-33}$ eV → very difficult to keep it light
- Extremely weakly coupled to ordinary matter (not to be seen by now)
- Can not be tested in accelerators!
A mechanism that can explain cosmological acceleration

- And yet can be tested in future collider experiments

- Does not require new symmetries and new fields almost of completely decoupled from the rest of the Universe
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 $M_{\text{GUT}} \sim 10^{15}$ 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 decoupled from the rest of the Universe

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

False Vacuum
unbroken symmetry

True Vacuum
broken symmetry

$$V(\phi) = \lambda \phi^2 (\phi - \phi_0)^2 - \epsilon \phi_0^2 \phi^2$$

Massive colored scalar field

$$m_\phi \approx 1\,\text{TeV}$$

Non-zero vacuum energy density

Cosmological constant

$\epsilon$ is small \quad \Rightarrow \quad \text{we are stuck in an unbroken phase for very long time}
BONUS: Model can be tested in colliders

Massive colored scalar field \rightarrow \text{Very interesting accelerator phenomenology}

New massive color singlet states:
1. Bound states of $\Phi$'s
2. Bound states of $\Phi$'s with quarks \rightarrow \text{Fractionally charged hadrons!}

Production of fractionally charged hadrons at the LHC would be a strong indication that our model is correct.
The potential barrier between the vacua is only $\sim \text{TeV}$

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

...and watch them decay

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

Can reconstruct the scalar field potential in future accelerators!
• 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

YES!

Dark Energy CAN have a color!
THANK YOU
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