All in the Family: the quintessential kinship between Inflation and Dark Energy

P. Q. Hung

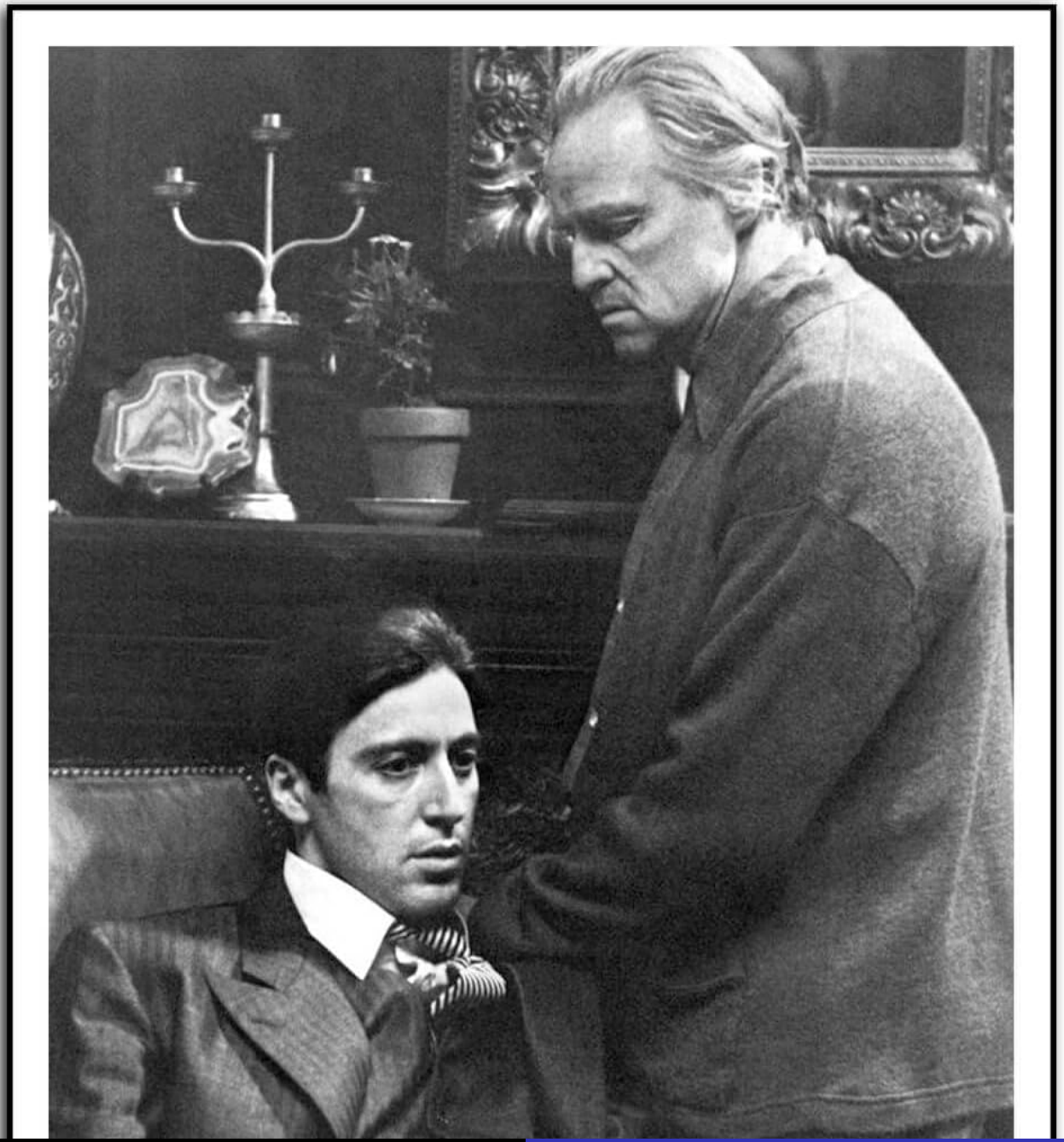
UNIVERSITY OF VIRGINIA

PASCOS 2023, UC IRVINE
June 30, 2023

ALL IN THE FAMILY

Archie Bunker (Inflation) shouting at his son-in-law Mike (Dark Energy): Are you as strong as I am? Actually, this is only for fun. Family: Genetically Related

Perhaps this is the correct picture?



What is all this family about?

For two "siblings", there are certain traits that are common to both. Here, the dominance of vacuum energies.

INFLATION

When the universe was dominated by a vacuum energy density ρ_0, the equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho_0}{3m_{pl}^2}$$

has a solution ($H = (8\pi\rho_0/3m_{pl}^2)^{1/2}$)

$$a(t) = e^{Ht}$$

$\Rightarrow$ Inflation

DARK ENERGY

For a flat universe ($\Omega_i = \rho_i/\rho_c$)

$$\Omega_m + \Omega_X = 1$$

In an expanding universe, the deceleration parameter is defined as

$$q = -\frac{\ddot{a}}{aH^2} = \frac{1+3w_X\Omega_X}{2}$$

X=Dark energy $\Rightarrow w = -1$ ($p_X = -\rho_X$) and $\Omega_X \approx 0.73 \Rightarrow q \approx -0.6 \Rightarrow$

$$\ddot{a} > 0$$

ACCELERATING UNIVERSE

Inflation and Dark Energy seem to be driven by some form of vacuum energies.Does this reflect similar dynamics? What are the driving agents?

Inflation: Lots of models.
Dark Energy: Lots of models

Most of the times there are no links between the two, despite the fact that the dynamics seem very similar.

There is a class of models where the driving agents are "axion" pseudo-Nambu-Goldstone bosons of a Peccei-Quinn $U(1)_A$ global symmetry whose potentials are induced by instantons of confining gauge groups.

Inflation (Freese, Liu, Spolyar, 9/2005)

Confining gauge group: $SU(3)_c$

Confinement scale: $\Lambda_{QCD} \sim 230 MeV$

Driving agent: Axion a of $\sigma = \frac{1}{\sqrt{2}}(v+\rho)\exp(\imath\frac{a}{v})$

Potential: $V = \Lambda_{QCD}(1-\cos(N\frac{a}{v}))$

Vacua: N degenerate vacua for N flavors

Soft breaking term to lift degeneracy: $\eta(a/v+\gamma)$

Dark Energy (PQH, 5/2006)

Confining gauge group: $SU(2)_Z$. Z: Greek Zophos=darkness

Confinement scale: $\Lambda_Z \sim 10^{-3} eV$

Driving agent: Axion-like a_Z of $\sigma_Z = v_Z \exp(\imath a_Z/v_Z) + \tilde{\sigma}_Z$

Potential: $V = \Lambda_Z^4(1 - \cos\frac{n\,a_Z}{v_Z}))$

Vacua: n degenerate vacua for n flavors

Soft breaking term to lift degeneracy: $\kappa\frac{a_Z}{2\pi v_Z}$

Could the two "siblings" be unified under the same roof?

Ischyrós Unification Theory

(IUT) (Ischyrós=Strong in Greek) arXiv:2306.13703

Simplest embedding of $SU(3)_c \times SU(2)_Z$: $SU(5)_Z$

$$SU(5)_Z \xrightarrow{M_S} SU(3)_c \times SU(2)_Z \times U(1)_X \xrightarrow{M_X} SU(3)_c \times SU(2)_Z$$

with Φ_{24} and Φ_{10} respectively

SM quarks q and dark quarks Q_Z are grouped in a $\mathbf{5} = (3,1)_{-2} + (1,2)_3$ as (q, Q_Z)

Unification

$$\alpha_3(M_S) = \alpha_Z(M_S)$$

We know $\alpha_3(M_Z) = 0.1179 \pm 0.0010 \Rightarrow \alpha_Z(M_Z)$. What should $\alpha_Z(M_Z)$ be such that $\alpha_Z(\Lambda_{DE}) \sim O(1)$?

Some RG relationships and predictions

Assumption:All new fermions have masses greater than the electroweak scale $\sim 246 GeV$.

$\frac{1}{\alpha_Z(\Lambda_Z)} = \frac{1}{\alpha_Z(M_Z)} - \frac{11}{3\pi} \ln(\frac{M_Z}{\Lambda_Z})$.

$\alpha_Z(\Lambda_Z) \sim O(1)$ and $\Lambda_Z \sim 10^{-3} eV \Rightarrow \alpha_Z(M_Z) \approx 0.026$

On the other hand

$\frac{1}{\alpha_Z(M_Z)} = \frac{1}{\alpha_3(M_Z)} + \frac{(\beta_0^{(3)} - \beta_0^{(Z)})}{2\pi} \ln(\frac{M_S}{M_Z})$.

With just **5** $\Rightarrow \alpha_Z(M_Z) \approx 0.037$ X Need extra fermions!

$\mathbf{15} = (1,3)_6 + (3,2)_1 + (6,1)_{-4}$

$\mathbf{5} + \mathbf{15} \Rightarrow \alpha_Z(M_Z) \approx 0.026$ $\surd$

Consequences?

COSMOLOGY

The Inflation part has been discussed extensively by Freese, Liu and Spolyar. We concentrate here on Dark Energy and its implications in Cosmology and in the Lab.

The global symmetries of the model are $U(1)_A^{(3)} \times U(1)_A^{(Z)}$. $U(1)_A^{(Z)}$: $\sum_{i=1}^{6} Y_i^{(Z)} \bar{Q^Z}_{L,i} \sigma_Z Q^Z_{R,i} + H.c.$. $Q^Z_{L,R} \to \exp(\mp \imath \alpha_Z)\, Q^Z_{L,R}$ and $\sigma_Z \to \exp(-2\imath\alpha_Z)$.

$$\sigma_Z = v_Z \exp(\imath a_Z / v_Z) + \tilde{\sigma}_Z,$$

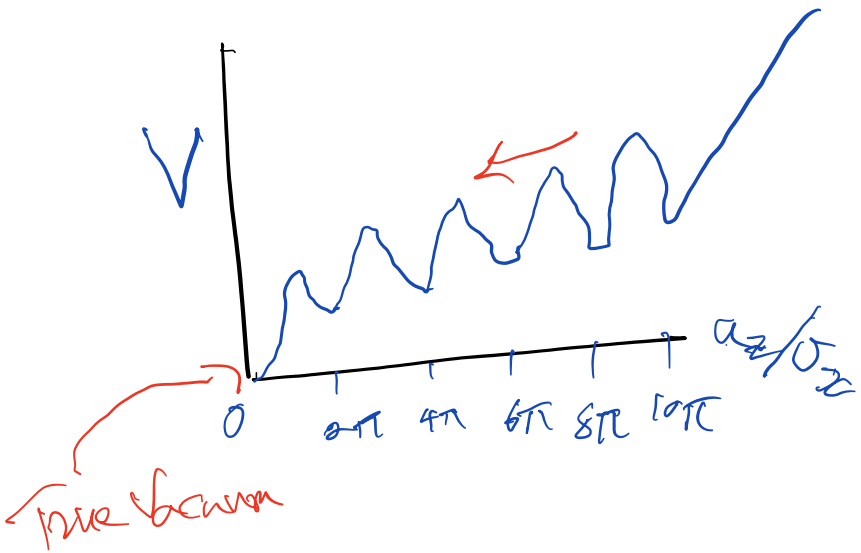
The dark Peccei-Quinn-like symmetry $U(1)_A^{(Z)}$ is broken explicitly by $SU(2)_Z$ instantons $\Rightarrow$ There remains an unbroken Z_6 symmetry (6 flavors) $\Rightarrow$ 6 degenerate vacua. a_Z, a PNG boson of mass-squared $\sim \Lambda^3 / v_Z$, becomes the quintessence field of the DE model.

COSMOLOGY

Add a soft-breaking term to lift the vacuum degeneracy, giving

$$V = \Lambda_Z^4 (1 - \cos \tfrac{n a_Z}{v_Z}) + \kappa \tfrac{a_Z}{2\pi v_Z}$$

As $T < \Lambda_Z$, the Universe got stuck in one of the false vacua. Even if it got stuck in $a_Z/v_Z = 2\pi$, the transition time is estimated to be $\tau \geq (10^{-106} s) \exp(10^{62})$



COLLIDER IMPLICATIONS

1) Q_Z $((1,2)_3)$ of **5**: $(U_Z(+2/3), D_Z(-1/3))_L$ and $U_{Z,R}(+2/3)$, $D_{Z,R}(-1/3)$ $\Rightarrow$ Anomaly! Cancellation would occur if there are dark leptons with unconventional electric charges: $(L^Z_U(1/6), L^Z_D(-5/6))_L$ and $L^Z_{U,R}(1/6)$, $L^Z_{D,R}(-5/6)$. Reason: $\sum 2\frac{Y_Q}{2} + \frac{Y_L}{2} = 0 \Rightarrow \frac{Y_L}{2} = 1/3$ with $\frac{Y_Q}{2} = 1/6$. $\Rightarrow$ Detection of these unconventional dark leptons would point toward a promising signature of DE. Dark quarks themselves would also look like SM leptons with fractional charges.

2) Anomaly cancellation can be accomplished within the mirror model of electroweak, non-sterile right-handed neutrinos.

3) **15** $= (1,3)_6 + (3,2)_1 + (6,1)_{-4}$ contains $(1,3)_{-6}$ which is SM-singlet and which could be candidates for dark matter. It interacts with SM quarks only by exchanging a massive $U(1)_X$ gauge boson since both carry $U(1)_X$ quantum numbers.

LOTS OF STUFF REMAIN TO BE DONE!

Conclusions

- A unified model of Inflation and Dark Energy within the framework of $SU(5)_Z \xrightarrow{M_S} SU(3)_c \times SU(2)_Z \times U(1)_X \xrightarrow{M_X} SU(3)_c \times SU(2)_Z$ is constructed, where $SU(3)_c \times SU(2)_Z$ are confining gauge groups.
- The accelerating universe is driven by an axion-like field a_Z whose potential is induced by instantons of the confining dark gauge group $SU(2)_Z$ and whose confining scale is $\Lambda_Z \sim 10^{-3} eV$
- Possible signatures at colliders such as the LHC
- Possible candidate of dark matter having only $SU(2)_Z$ quantum numbers.

Thank you for listening and hope to see all of you in Quy Nhon, Vietnam, July 6-12, 2024 for PASCOS 2024!