Title: Emergent Conformal Violation: Does Inflation Like Fundamental Scalar Fields?

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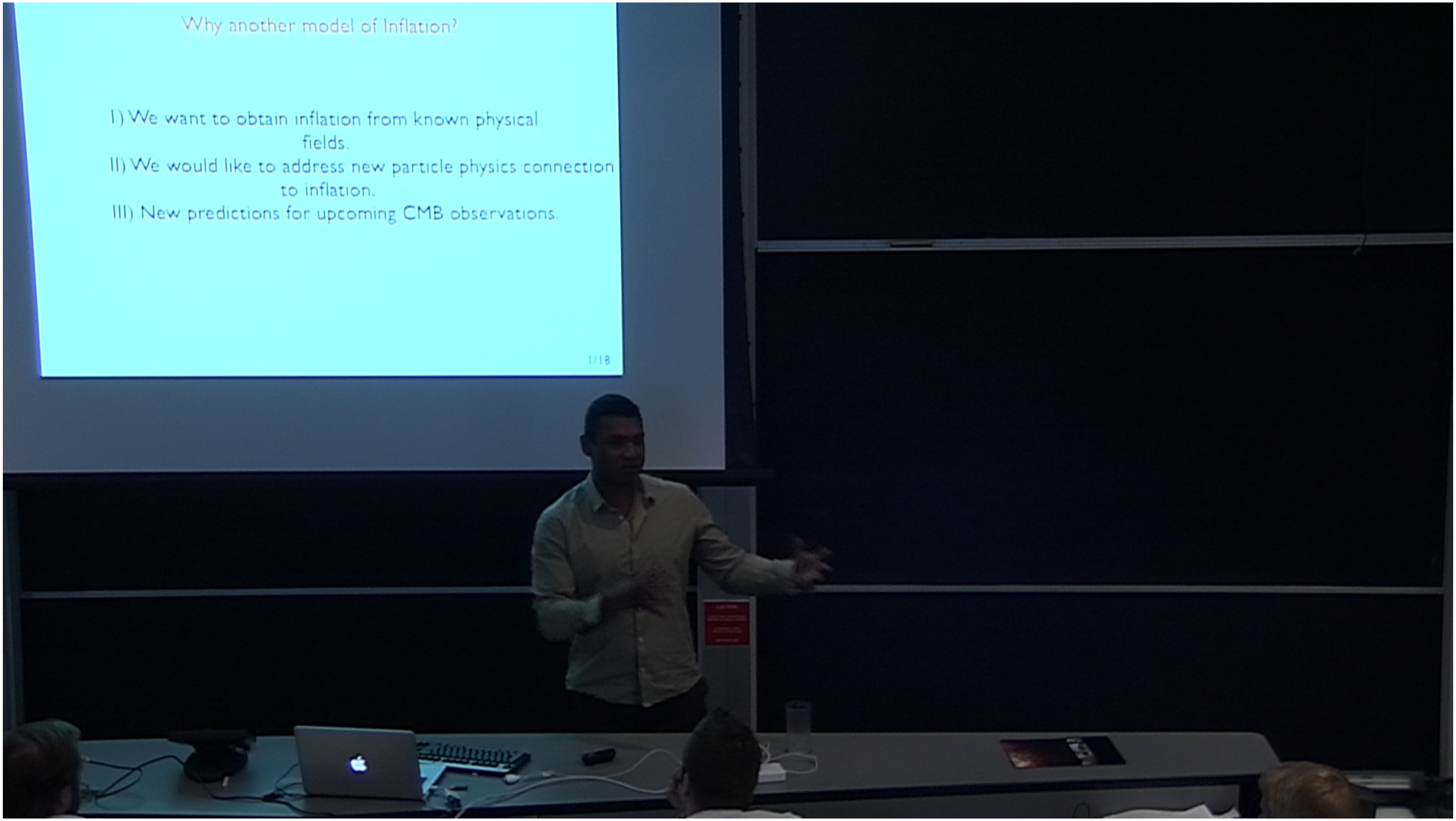
Abstract: We present a new model of inflation which does not rely on fundamental scalar fields. The theory is a conformally invariant gauge field theory minimally coupled to massless fermions. At the beginning of inflation, the conformal symmetry is dynamically broken by a BCS condensation of the fermions, leading to a spontaneously violation of conformal symmetry. A quasi de-Sitter inflationary regime is driven by the interaction between a homogenous plasma dynamo between the gauge, gravitational and condensate field. Unique observational consequences of this model are twofold : (1) The sourcing of B-mode vorticity fluctuations in upcoming CMB powerspectra. (2) A possible inflationary Baryogenesis mechanism connected to the initial conditions of inflation.


Why another model of Inflation?
I) We want to obtain inflation from known physical fields.
II) We would like to address new particle physics connection to inflation.
III) New predictions for upcoming CMB observations.
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Does Inflation Like Fundamental Scalars?

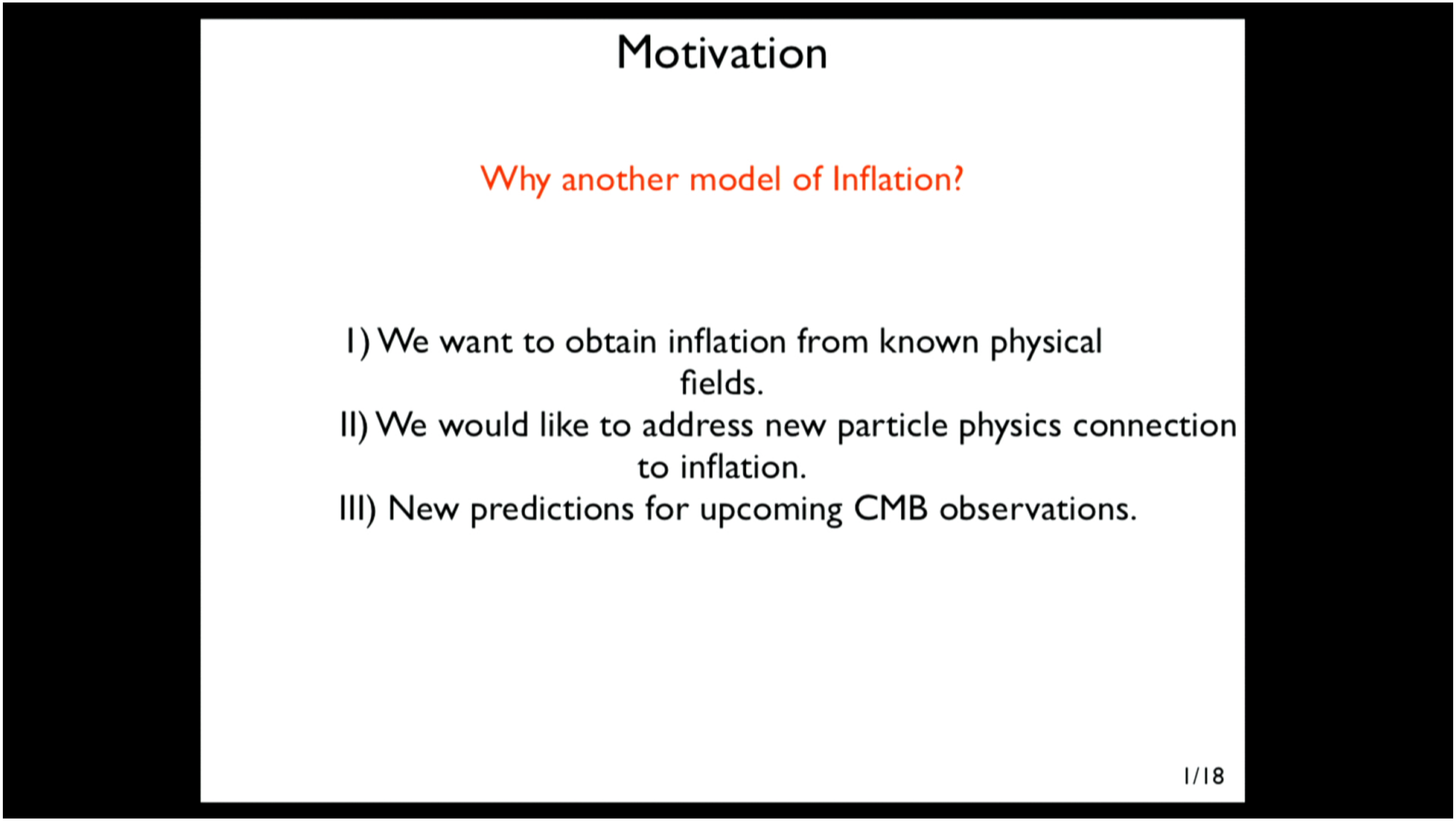
Stephon Alexander

Conformal Nature of the Universe, PI

DARTMOUTH COLLEGE

in collaboration with Antonino Marciano and David Spergel

based on **arXiv:1107.0318 [hep-th]**


Motivation
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II) We would like to address new particle physics connection to inflation.
III) New predictions for upcoming CMB observations.
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Roots of Inflation

- Guth (and others) originally proposed inflation by using ideas from:

  (1) Condensed Matter Physics: (Spontaneous symmetry breaking).

  (2) Particle Physics: SU(5) GUT. (Old Inflation)

- This idea did not work (too much anisotropy, bubble nucleation).

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Slow Roll "Chaotic

RECIPE:

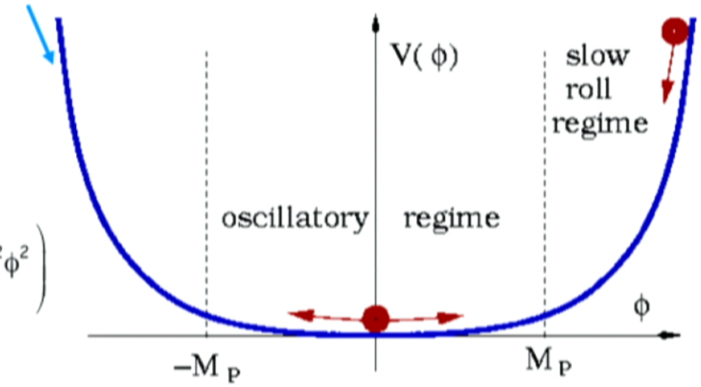
Initial conditon: Magically place scalar field at the top.

$$S[\phi] \rightarrow \int d^4x \sqrt{-g}\, \frac{1}{2}\left(-\partial_\mu \phi \partial^\mu \phi - m^2\phi^2\right)$$

Begin: $(10^{-37}\,\text{sec!})$

$$H^2 \equiv \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{1}{3M_{Pl}^2}\left(\frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + \frac{1}{2}m^2\phi^2\right)$$

$$\Rightarrow H \approx H_0 = \frac{m\ _0}{\sqrt{6}M_{Pl}},$$

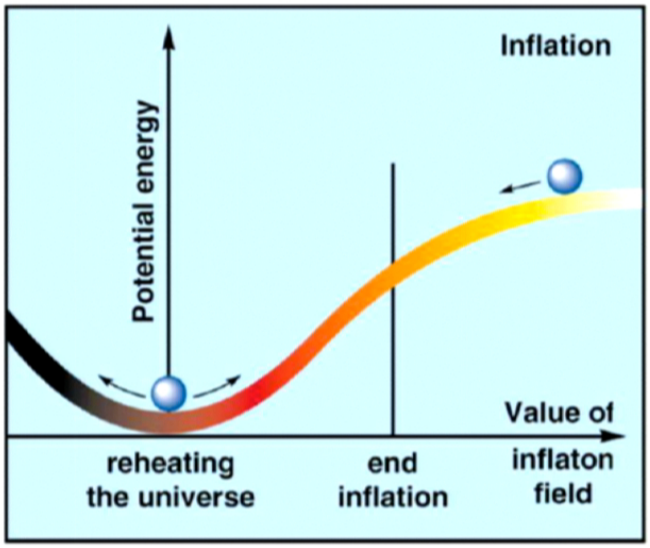


Chaotic Inflationary Model (Linde 1982)

$$\Rightarrow d^2a/dt^2 \approx H_0^2 a > 0 \rightarrow \text{acceleration!} \quad a \approx a_0 \exp(H_0 t),$$

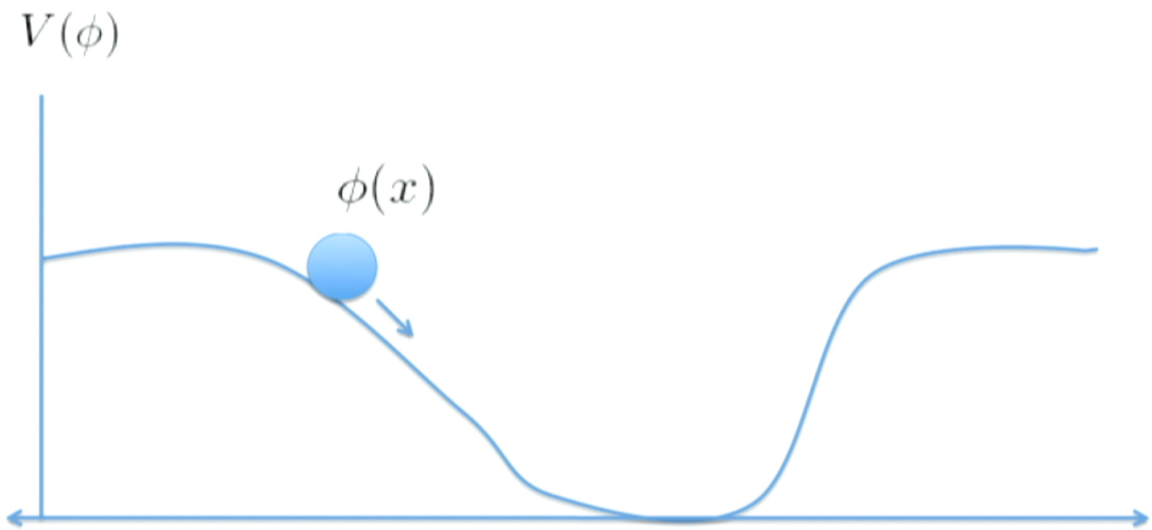
Credit: T. Prokopec

Scalar Inflation Summary

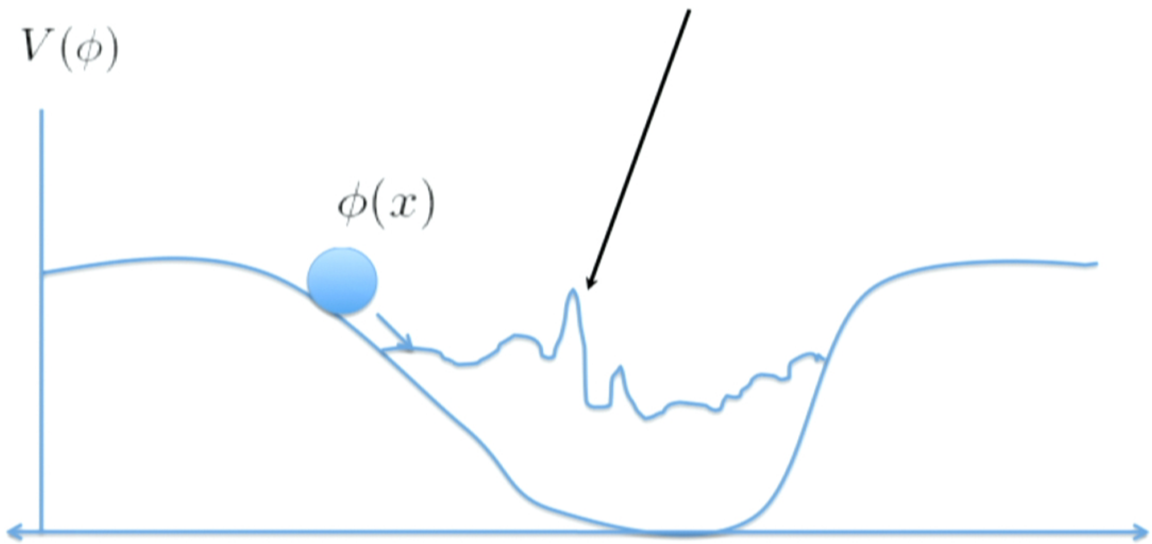


- Two phases:
  - "slow roll" down a mild slope gives inflation
  - Faster fall into lowest energy state and oscillation -> reheating
- Oscillations around minimum potential are damped by particle formation, universe gets reheated

But it is hard to get a field with these properties in our standard model of particle physics



Quantum fluctuations can destroy flatness.



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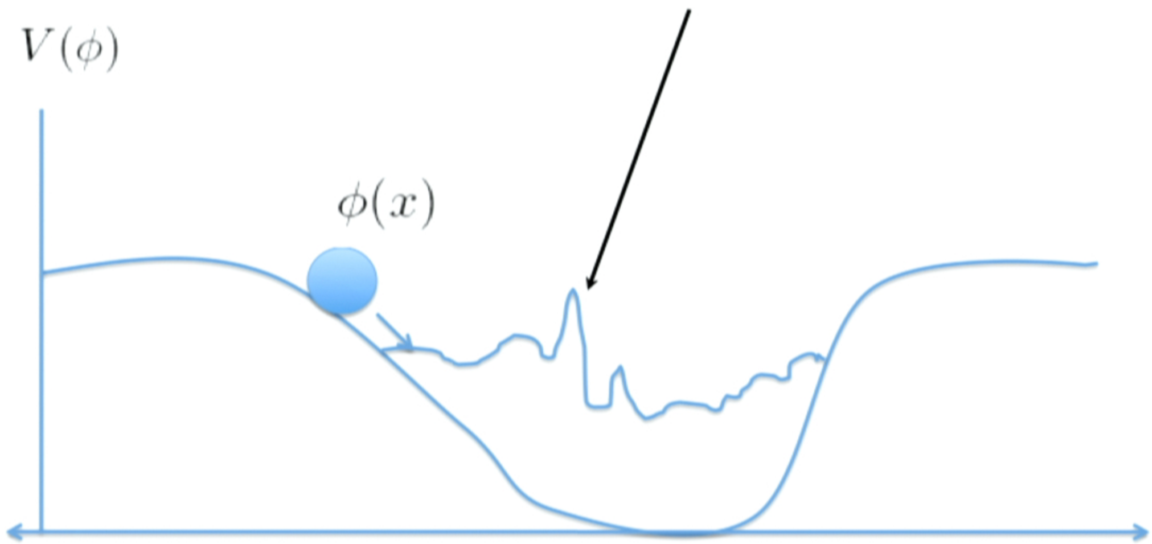

Open Questions for Inflation

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- What is the identity of the inflaton field?
- Can we find new connections between

  inflation and the standard model of particle physics, with observable consequences?

Inflation is a great idea waiting for a realistic physical model.

Can inflation return to its roots and connect to the Standard Model of Particle Physics?

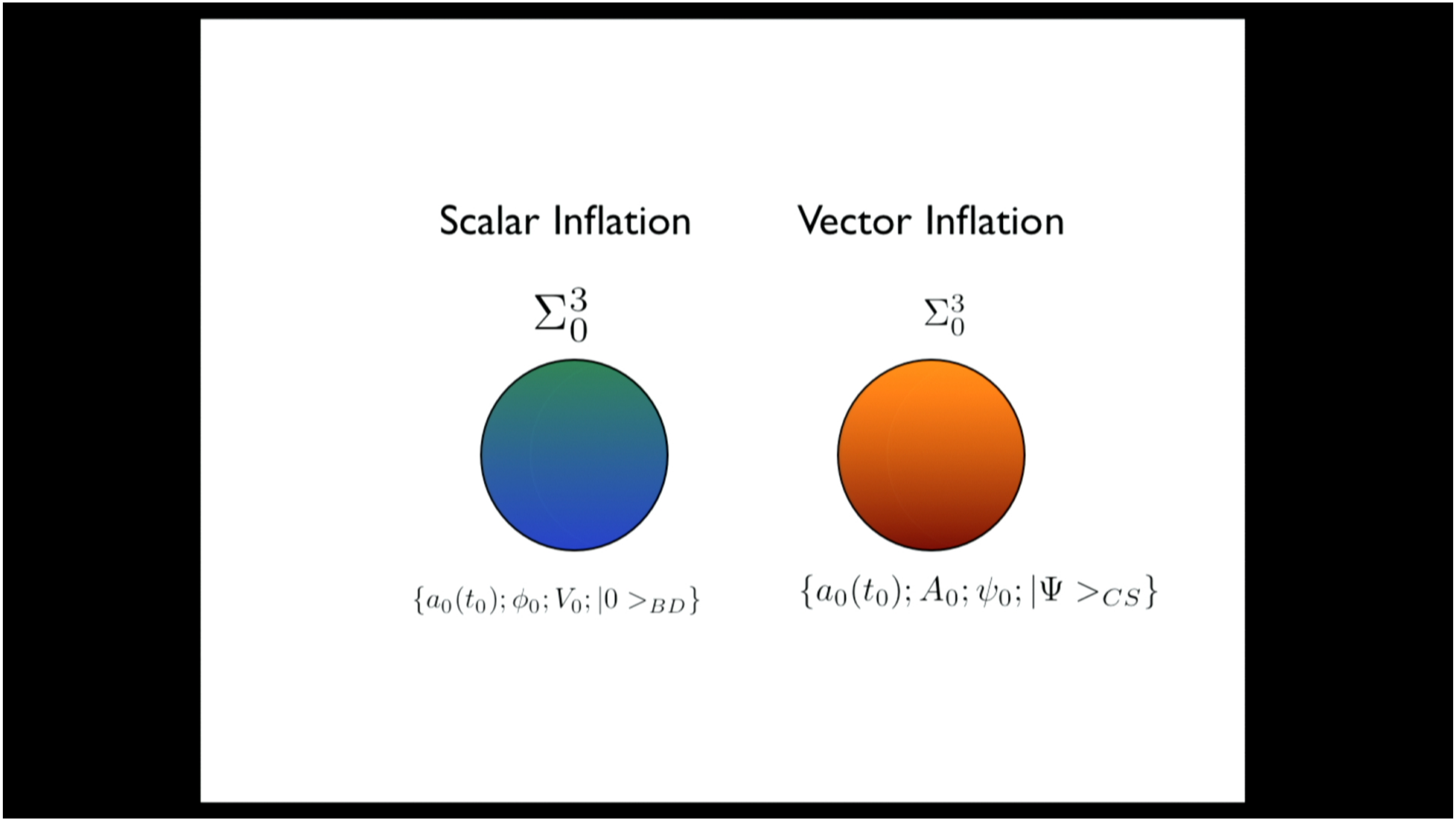
Vector Inflation

- In '89 Larry Ford proposed a vector field model of inflation. But it suffered from a few problems:

  I. Vector fields spoil isotropy.

  II. The "Slow-Roll" conditions were difficult to realize naturally.

  III. Vector model did not seem to buy anything new.


Scalar Inflation
Vector Inflation
Σ_0^3
Σ_0^3
$\{a_0(t_0); \phi_0; V_0; |0>_{BD}\}$
$\{a_0(t_0); A_0; \psi_0; |\Psi>_{CS}\}$

Theoretical framework

$$\tilde{\mathcal{L}} = \mathrm{Tr}\left[-\frac{1}{4} g_{\alpha\gamma} g_{\beta\delta} F^{\gamma\delta} F^{\alpha\beta} + \frac{1}{4}\frac{\theta}{M_*} F_{\alpha\beta}\tilde{F}^{\alpha\beta} + q\, A_\mu \mathcal{J}_5^\mu\right]$$

$$S_D = \int d^4x \sqrt{-g}\left[-i\bar{\psi}\nabla\!\!\!/\,\psi + \frac{3}{M_p^2}(\bar{\psi}\,\gamma^I\gamma_5\psi)^2 + q\,\bar{\psi}\gamma^I e_I^\mu \gamma_5 \psi A_\mu\right]$$

PARADOX

$$T^{\mu}{}_{\nu} = \begin{pmatrix} \rho(t) & & & \\ & -p(t) & & \\ & & -p(t) & \\ & & & -p(t) \end{pmatrix}$$

Massless Yang-Mills is Classically Conformally Invariant

$Tr[T^{\mu}_{\nu}] = 0 \longrightarrow$ Gauge Radiation

But for inflation $p = -\rho \longrightarrow Tr[T^{\mu}_{\nu}] \neq 0$

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We Need To Violate Conformal Symmetry To Obtain Inflation

Hint: Spontaneous Symmetry Breaking of the Vacuum State of Inflation

Given a general massless gauge theory there are three forms of anisotropies to overcome

$$T^{\mu}_{\nu} = \mathrm{Tr}\Big[-\delta^{\mu}_{\nu} A_{\rho}\mathcal{J}^{\rho}_{5} + F_{\alpha}{}^{\mu} F^{\alpha}{}_{\nu} - \frac{1}{4}\delta^{\mu}_{\nu} g^{\alpha\rho} g^{\beta\sigma} F_{\alpha\beta} F_{\rho\sigma} - A_{\nu}\mathcal{J}^{\mu}_{5}\Big]$$

Isotropic

Electromagnetic Anisotropy

Off-diagonal Anisotropy

Isotropy or Not?

Claim: The purely isotropic part of gauge field-current interaction dominates energy momentum tensor self-consistently.

$$\mathcal{J} \equiv \mathrm{Tr}[A_\mu \mathcal{J}_5^\mu]$$

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ISOTROPY: EXTENDED U(1) SYMMETRY

Large anisotropies resolved by having N copies of gauge fields randomly oriented on initial time hypersurface.

$$\Rightarrow \quad T_{ij} = \sum_{A=1}^{N} A^A_{(i}\mathcal{J}^A_{j)} \simeq \frac{N}{3} A \cdot \mathcal{J} \delta^i_j + O(1)\sqrt{N} A \cdot \mathcal{J}$$

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Gauge Field Amplification

$$\eta^{\gamma\beta}\partial^\alpha F_{\alpha\beta}+\varepsilon^{\gamma\alpha\mu\nu}\,F_{\mu\nu}\,\partial_\alpha\theta/(4M_*)+a^4\,\mathcal{J}^\gamma=0$$

$$\ddot{A}_h + k^2 A_h = -h\,k\,A_h\dot{\theta}/M_* + a^4\mathcal{J}_h$$

Chern-Simons Source

Fermion Current

$$\sqrt{2}\,\mathcal{J}_h = \mathcal{J}_1 + hi\mathcal{J}_2 = (\bar{\psi}\,(\gamma_1 + hi\gamma_2)\,\gamma_5\psi)/a$$

Einstein Equations

$$g_{\mu\nu} = a^2(\eta)\,\mathrm{diag}[-1,1,1,1] + \delta\, a^2(\eta) g^{(1)}_{\mu\nu}$$

$$3\frac{\dot{a}^2}{a^4} = \frac{8\pi G}{a^4}\left(E_+E_- + B_+B_-\right) + \\ + \ 8\pi G\left(A_+\mathcal{J}_- + A_-\mathcal{J}_+\right).$$

Key Insight: A.J ~ Constant

$$A \sim a(\eta) A_0 \qquad J \sim \frac{J_0}{a(\eta)}$$

Inflation ⇨ $a(\eta)/a_0 = (1 - H\eta)^{-1} = \exp Ht$

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Solutions for the vector fields

$$A(\eta,k)_- = A^0_- \cosh(\beta_k\eta) + \tilde{A}^0_- \sinh(\beta_k\eta) + \Xi[H,\beta,\tilde{J}_-,\eta]$$

with $\Xi[H,\beta,\tilde{J}_-,\eta] = \frac{\tilde{J}_-}{2H^2(1-H\eta)} + \frac{\beta\tilde{J}_-}{4H^3}\Psi(x)\Big|_{x=-\frac{\beta}{H}(1-H\eta)}^{x=\frac{\beta}{H}(1-H\eta)}$

$$\Psi(x) = e^x \int_\infty^x \frac{e^{-t}dt}{t}$$

the leading contribution grows as the conformal factor $\Xi \simeq \tilde{J}_0^+/[2H^2(1-H\eta)]$

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dS inflationary phase

Consistency Conditon

$$M_p^2 H^2 \simeq 2\frac{\tilde{J}_- \tilde{J}_+}{H^2}$$

Initial conditions: $A^0_- \simeq A^0_+ < 10^{-5} M_p$ $\quad \mathcal{J}_+(\eta_0) \simeq \mathcal{J}_-(\eta_0) \simeq 10^{-30} M_p^3$

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Sakharov Conditions and Inflation

(S.A, Peskin, Sheikh-Jabbari PRL 05,Lyth et. al JCAP 06)

- Baryon Violation: Global Chiral Anomaly
- CP Violation: $[CP]\vec{A}_{+} \neq \vec{A}_{-}$
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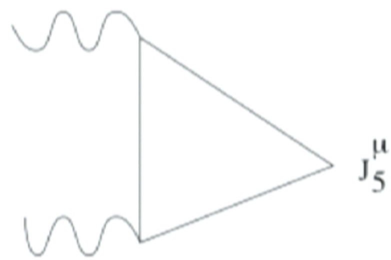
Baryon Asymmetry

- Recall the Anomaly

  Diagram:



$$\partial_\mu J^\mu = F_{\alpha\beta_k} F_{\mu\nu} \epsilon^{\alpha\beta\mu\nu} / (32\pi^2) \sim \vec{E}.\vec{B}$$

Fermion number   Chern-Simons

$$n = \int_0^{H^{-1}} d\eta \, k \, (\dot{A}_+ A_+ - \dot{A}_- A_-) \Longrightarrow$$ Condition for Inflation!

- Gauge Field gets converted into Fermions through the triangle anomaly.

$$n/s \;\sim\; 10^{-10}$$

Observations (WMAP and BBN)

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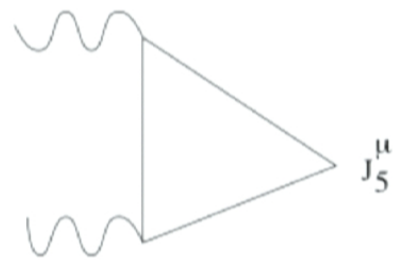

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End of inflation

$$S = S_D + \int_{\mathcal{M}_4} d^4x\sqrt{-g}\Big[\frac{M_p^2\,R}{8\pi} - \frac{1}{2}\partial_\mu\theta\,\partial^\mu\theta + m^2\,\theta^2 - \frac{1}{4}\mathrm{Tr}[F_{\alpha\beta}F^{\alpha\beta}] + \frac{\theta}{4M_*}\mathrm{Tr}[F_{\alpha\beta}\tilde{F}^{\alpha\beta}] + q\,\mathrm{Tr}[A_\mu\mathcal{J}_5^\mu]\Big]$$

The slow-roll condition is violated when the scalar reaches the minimum of the potential

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'(\theta)}{V(\theta)}\right)^2 \geq 1$$

$$\ddot{A}(\eta,k)_h + k^2 A(\eta,k)_h = -h\,k\,A(\eta,k)_h\dot{\theta}/M_* + a^3 J_h$$

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Lev Kofman, Andrei D. Linde, Alexei A. Starobinsky PRL 1994

Y. Shtanov, Jennie H. Traschen, Robert H. Brandenberger PRD 1995

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CP asymmetric parametric resonance for A in

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ABJ anomaly and decay of gauge fields into fermions

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Fermion Dynamics

$$(i\not{\partial} - e\not{A})\,\Psi(\vec{x},\eta) = 0$$

Densitize $\Psi = \sqrt[4]{-g}\,\psi\,,\qquad \overline{\Psi} = \sqrt[4]{-g}\,\overline{\psi}$

$$\psi(\vec{x},\eta) = \frac{\Psi(\vec{x},\eta)}{a^2(\eta)} = \sum_{r\,\vec{p}} \frac{1}{\sqrt{2V\omega_{\vec{p}}}}\Big[\frac{c_r(\vec{p})}{a^2(\eta)}\,u_r(\vec{p})e^{-ip\cdot x} + \\ + \frac{d^\star_r(\vec{p})}{a^2(\eta)}\,v_r(\vec{p})e^{ip\cdot x}\Big]\,,$$

$$J \sim \frac{1}{a^4}$$

Functional Schrodinger Equation

(Jackiw, Ratra, Kiefer)

$$H(\eta)\,|\Xi\rangle = -i\frac{\partial}{\partial\eta}\,|\Xi\rangle$$

$$H(\eta) = \int d^3x\sqrt{{}^{(3)}g}\;\mathcal{H}(\vec{x},\eta) =$$

$$= a^3(\eta)\sum_{r\vec{p}}\omega_{\vec{p}}\left[c_r^\dagger(\vec{p})c_r(\vec{p}) + d_r^\dagger(\vec{p})d_r(\vec{p})\right]$$

Excited Bunch-Davies Vacuum $\longrightarrow$

$$|\Xi\rangle = \prod_{\vec{p}} e^{-\frac{1}{2}[\xi_{r\vec{p}}\xi^\star_{r\vec{p}}+\eta_{r\vec{p}}\eta^\star_{r\vec{p}}]}|\xi_{\vec{p}}\,,\eta_{\vec{p}}\rangle$$

$$|\xi_{\vec{p}}\,,\eta_{\vec{p}}\rangle = e^{c_r^\dagger(\vec{p})\xi_{r\vec{p}}+d_r^\dagger(\vec{p})\eta_{r\vec{p}}}|0\rangle_{BD}$$

$${}_{BD}\langle\xi^\star_{\vec{p}}\,,\eta^\star_{\vec{p}}| = \langle 0|e^{c_r(\vec{p})\xi^\star_{r\vec{p}}+d_r(\vec{p})\eta^\star_{r\vec{p}}}$$

Coupling of fermions to geometry requires state's phase to depend on scale factor

$$\xi_{r\,\vec{p}}(\eta) = i\xi_r^{(0)} a^2(\eta)\,\frac{a_0\,\omega_{\vec{p}}}{2\,H}$$
$$\eta_{r\,\vec{p}}(\eta) = i\eta_r^{(0)} a^2(\eta)\,\frac{a_0\,\omega_{\vec{p}}}{2\,H}$$

$$\downarrow$$

$$|\Xi_a\rangle = \prod_{\vec{p}} |\xi_{\vec{p}} a^2\rangle$$

Coherent
Bunch-Davies vacuum state

$$\downarrow$$

$$\langle\Xi|\mathcal{J}^\mu|\Xi\rangle \simeq \frac{J^\mu}{a}$$

Outlooks and conclusions

1) Can Dark Matter be addressed in this model?

$SU(2) \times U(1)_Y \times U(1)'^n$

$$\mathcal{L}_{NC}^{SM} = g\,\mathcal{J}^{\mu}{}_{em} A_{\mu} + g_1\,\mathcal{J}^{\mu}{}_{1} Z^0_{1\mu}$$

$$\mathcal{L}_{\mathcal{NC}} = g\mathcal{J}^{\mu}{}_{em} A_{\mu} + \sum_{\alpha=1}^{n+1} g_{\alpha}\mathcal{J}^{\mu}{}_{\alpha} Z^0_{\alpha\mu}$$

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II) String compactification accounts for multiple copies of gauge-fields: embedding with N coincident D-branes leading to SU(N) and through pattern of symmetry breaking to N copies of U(1)

Extra U(1) anomalous: C-S term necessary for gauge-anomaly cancellation

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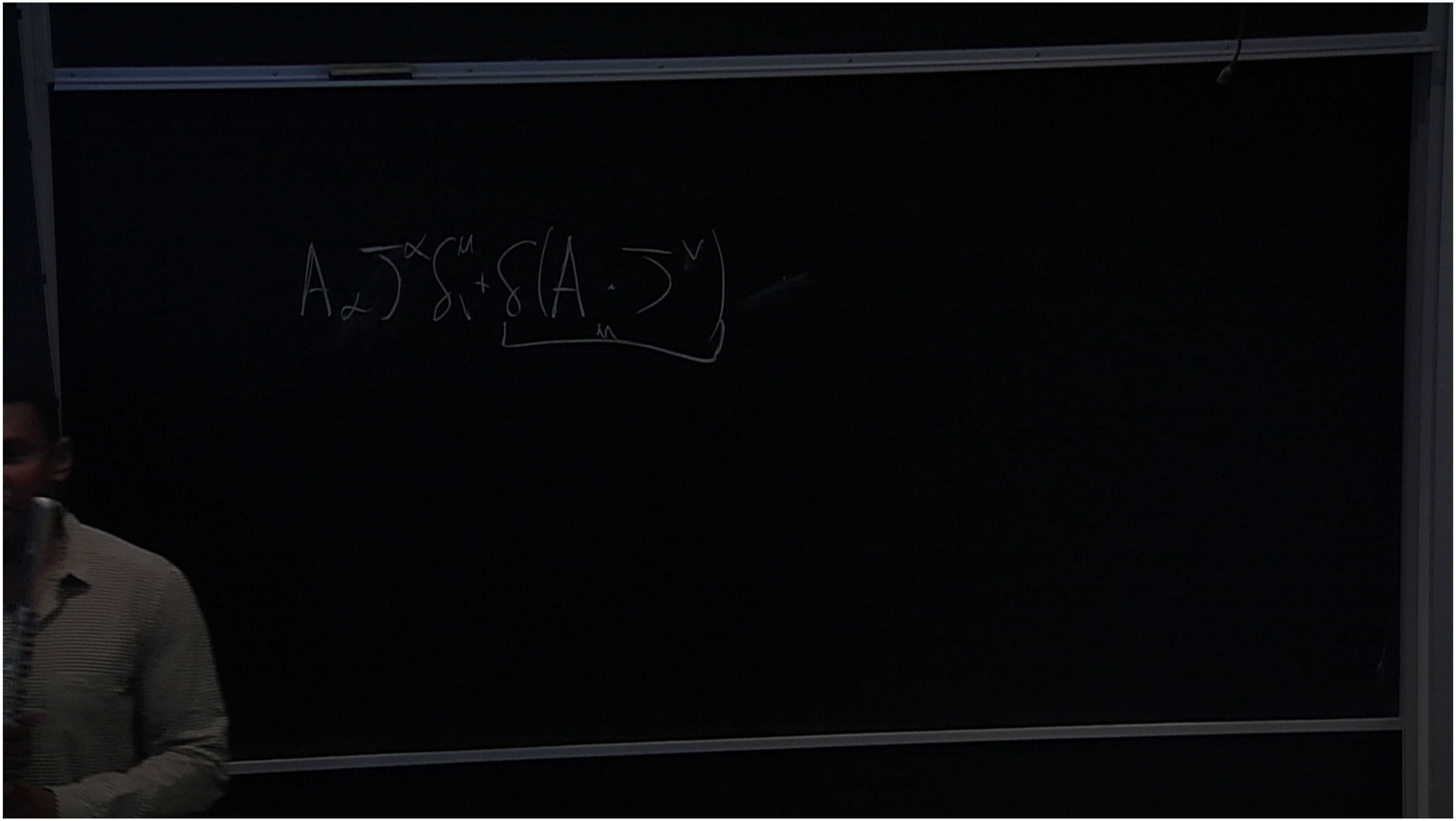
II) String compactification accounts for multiple copies of gauge-fields: embedding with N coincident D-branes leading to SU(N) and through pattern of symmetry breaking to N copies of U(1).

III) Non-vanishing vector perturbations, although red-shifting. Large scale vorticity perturbations may show.

IV) Primordial Structure formation sourced by Gauge field fluctuations
(Work in progress with J. Magueijo, A. Marciano, J. Noeller)



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