What happened here?

13.8 Billion Years

10^{28} \text{ cm}

Big Bang

Today

John Ellis
Some Big Questions

• Why is the Universe so big and old?
• Why is it (almost) homogeneous on large scales?
• Why is its geometry (almost) Euclidean?
• What is the origin of structures in the Universe?

A possible answer:

Cosmological inflation

• What do the Planck and BICEP2 data tell us?
• Models of inflation
General Relativity & Cosmology

• Einstein’s equations:

\[ R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu} \]

• G = Newton constant, energy scale \( \sim 10^{19} \text{GeV} \),
  Distance \( \sim 10^{-32} \text{cm} \), time \( \sim 10^{-43} \text{s} \)

• Our Universe is a special solution of equations
  Size \( >> 10^{-32} \text{cm} \), age \( \sim 10^{-43} \text{s} \)

• Due to a “cosmological constant” \( \Lambda \)?
  – Due to a scalar “inflaton” field \( \phi \): \( \Lambda \sim V(\phi) \neq 0 \)?
Cosmological Inflation

- Expansion driven by cosmological constant:
  \[ H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{\Lambda}{3} \]

- Exponential expansion
- All the visible Universe was once very small
- In close contact: (almost) homogeneous
- Geometry ~ flat
Primordial Perturbations

• “Cosmological constant” due to vacuum energy in “inflaton” field $\phi$: $\Lambda \sim V(\phi) \neq 0$

• Quantum fluctuations in $\phi$ cause perturbations in energy density (scalar) and metric (tensor)

• (Almost) independent of scale size

• Visible in cosmic microwave background (CMB)
Perturbations Generate Structures

Planck

Primordial quantum perturbations as seen in the Cosmic Microwave Background

Dark matter distribution today (simulated)

You!
Inflationary Perturbations in a Nutshell

• Universe expanding like de Sitter
• Horizon $\rightarrow$ information loss $\rightarrow$ mixed state
• Effective ‘Hawking temperature’ $H/2\pi$
• Expect quantum fluctuations:
  $\langle \phi \phi \rangle, \quad \langle hh \rangle \sim H^2$

(inflaton, gravitational field: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$)
Scalar (density), tensor perturbations
• Should have thermal spectrum
• Scalars enhanced by evolution of $\phi \rightarrow r \sim \varepsilon$
Slow-Roll Inflation

• Expansion driven by cosmological constant:

\[ H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{\Lambda}{3} \]

• Getting small density perturbations requires a “small” potential:

\[ \left( \frac{V}{\epsilon} \right)^{1/4} = 0.0275 \times M_{Pl} \]

• That is almost flat:

\[ \epsilon = \frac{1}{2} M_{Pl}^2 \left( \frac{V'}{V} \right)^2, \quad \eta = M_{Pl}^2 \left( \frac{V''}{V} \right) \]

so as to get sufficient e-folds of expansion:

\[ N = \frac{v^2}{M_{Pl}^2} \int_{x_i}^{x_e} \left( \frac{V}{V'} \right) dx \]

• Main observables of scalar and tensor pert’ns:

• Scalar tilt: \[ n_s = 1 - 6\epsilon + 2\eta, \]

• tensor/scalar ratio: \[ r = 16\epsilon \]

• Perturbations \sim Gaussian: look for deviation \( f_{NL} \)
Cosmological Inflation in Light of Planck

A scalar in the sky?

Supersymmetry / supergravity?
The Spectrum of Fluctuations in the Cosmic Microwave Background

The position of the first peak \( \Rightarrow \) total density \( \Omega_{\text{Tot}} \)

The other peaks depend on density of ordinary matter \( \Omega_{\text{atoms}} \) & dark matter \( \Omega_{\text{Dark}} \)
Cosmological Inflation in Light of BICEP2

Quantum gravity radiation in the sky?
Cosmological Inflation in Light of BICEP2

- **QUANTUM GRAVITY RADIATION!**
- BICEP2 observations support for inflation
- “Large” tensor-to-scalar ratio: $r = 0.20^{+0.07}_{-0.05}$
The BICEP2 Result is a Big Deal

- Gravitational waves! Probably quantum origin
- Need to maintain proper scientific scepticism

Could draw straight line through data

Expected some dust here

Estimated background from gravitational lensing

Data too high?
Questions/Issues with BICEP2

EE data too high?

BICEP2 has only one frequency

Jack-knife test too good?

Estimates of dust background

$r = 0.16^{+0.06}_{-0.05}$
Pollution by Loops?

- Radio-emitting loops from supernova bubbles
- Leave imprint on CMB temperature maps
- Associated with magnetized dust?
- May polarize CMB
- BICEP2 towards a loop

Inflationary Landscape

Monomial Single-field potentials

BICEP2

Starobinsky

R + R^2 model
Reconciling Planck and BICEP2?

- Possible if scalar spectral index runs (fast)

\[
\frac{dn_s}{d\ln k} = \frac{2}{3} \left[(n_s - 1)^2 - 4\eta^2\right] + 2\xi
\]

where \( \xi = M_{Pl}^4 \left(\frac{V'/V'''}{V^2}\right) \)

- Bracketed terms \( O(10^{-4}) \), need \( \xi = O(10^{-2}) \)

- In slow-roll approximation, expect \( \xi \ll O(10^{-2}) \)

- Such a large value of \( \xi \) is problematic for consistency of slow-roll approximation:

\begin{align*}
\varepsilon &= O(10^{-2}) \implies V'/V = O(10^{-1}) \\
\xi &= O(10^{-2}) \text{ then requires } V'''' = O(10^{-1}) \\
\text{Change } \Delta V'' &= O(1) \text{ for } \Delta \phi = O(10)
\end{align*}
Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum (rolling down): $n_s = 0.9585 \pm 0.070$
- **BUT** strengthen upper limit on tensor perturbations: $r < 0.10$
- Challenge for simple inflationary models
  - Starobinsky $R^2$ to rescue?
  - Higgs/Supersymmetry/supergravity to rescue?
Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):
  \[ S = \frac{1}{2} \int d^4 x \sqrt{-g} (R + R^2 / 6M^2) \]
  (Starobinsky, 1980)

- No scalar!? (Mukhanov & Chibisov, 1981)

- Inflationary interpretation, calculation of perturbations:
  \[
  \delta S_b = \frac{1}{2} \int d^4 x \left[ \phi'^2 - \nabla_\alpha \phi \nabla^\alpha \phi + \left( \frac{a''}{a} + M^2 a^2 \right) \phi^2 \right]
  \]

- Conformally equivalent to scalar field model:
  \[ S = \frac{1}{2} \int d^4 x \sqrt{-\tilde{g}} \left[ \tilde{R} + (\partial_\mu \phi')^2 - \frac{3}{2} M^2 (1 - e^{-\sqrt{2/3} \phi'})^2 \right] \]
  (Stelle; Whitt, 1984)
Higgs Inflation: a Single Scalar?

- Standard Model with non-minimal coupling to gravity:

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M^2 + \xi h^2}{2} R 
\quad + \frac{\partial \mu h \partial \mu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}$$

- Consider case $1 \ll \sqrt{\xi} \ll 10^{17}$: in Einstein frame

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_P^2}{2} \hat{R} + \frac{\partial \mu \chi \partial \mu \chi}{2} - U(\chi) \right\}$$

- With potential:

$$U(\chi) = \frac{\lambda M_P^4}{4 \xi^2} \left( 1 + \exp \left( -\frac{2\chi}{\sqrt{6}M_P} \right) \right)^{-2}$$

Similar to Starobinsky, but not identical

- Successful inflationary potential at $\chi \gg M_P$
Higgs Inflation: a Single Scalar?

• Successful inflation for

\[ \xi \sim \sqrt{\frac{\lambda}{3} \frac{N_{\text{COBE}}}{0.027^2}} \sim 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2v}} \]

• BUT:
  - Requires \( \lambda > 0 \) beyond \( M_P \): need \( M_H > 127 \) GeV?
  - How natural is such a large value of \( \xi \)?

Bezrukov & Shaposhnikov, arXiv:0710.3755
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at low energy scale $\Lambda$ due to renormalization

\[
\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}
\]

- Small: renormalization due to $t$ quark drives quartic coupling $< 0$ at some scale $\Lambda \rightarrow$ vacuum unstable

- Vacuum could be stabilized by Supersymmetry

Instability @ $10^{11.1 \pm 1.1}$ GeV

Vacuum Instability in the Standard Model

- Very sensitive to $m_t$ as well as $M_H$

- Instability scale:

$$\log_{10} \left( \frac{\Lambda}{\text{GeV}} \right) = 11.3 + 1.0 \left( \frac{M_h}{\text{GeV}} - 125.66 \right) - 1.2 \left( \frac{M_t}{\text{GeV}} - 173.10 \right) + 0.4 \frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

- New measurement of $m_t = 173.34 \pm 0.76 \text{ GeV}$
Inflationary Models in Light of BICEP2

• Back to basics: monomial power-law inflationary potential?
  \[ V = \mu^{4-n} \phi^n \]

• Slow-roll parameters:
  \[ \epsilon = \frac{n^2 M_{Pl}^2}{2 \phi^2}; \eta = n(n-1) \frac{M_{Pl}^2}{\phi^2} \]

• Inflationary observables:
  \[ r = 8 n^2 \frac{M_{Pl}^2}{\phi^2}; n_s = 1 - n(n+2) \frac{M_{Pl}^2}{\phi^2} \]

• Number of e-folds:
  \[ N = \frac{1}{2n} \frac{\phi^2}{M_{Pl}^2} \]

• Consistency condition:
  \[ r = 8 \left( 1 - n_s - \frac{1}{N} \right) \]

• Comfortably satisfied by the measurements
  \[ r = 0.16_{-0.05}^{+0.06}, n_s = 0.960 \pm 0.008, N = 50 \pm 10 \]

JE, García, Nanopoulos & Olive, arXiv:1403.7518
Inflationary Models in Light of BICEP2

• What is the power in the monomial inflationary potential?

\[ V = \mu^{4-n}\phi^n \]

• Two expressions for \( n \):

\[ n = \frac{rN}{4}; \quad n = 2[N(1-n_s)-1] \]

• Numerical values from measurements:

\[ n = 2.0^{+0.9}_{-0.8}; \quad n = 2.0 \pm 1.1 \]

• \( n = 2 \) perfectly OK, \( n = 1, 3 \) potentials unbounded below, \( n = 4 \) has \( \Delta \chi^2 > 8 \)

• Looks like quadratic inflationary potential

\[ V = \mu^2\phi^2 \simeq (2 \times 10^{16} \text{ GeV})^4 \]

\[ m = \sqrt{2\mu} = 1.8 \times 10^{13} \text{ GeV} \]

\[ \phi = \sqrt{200M_{Pl}} \]

JE, García, Nanopoulos & Olive, arXiv:1403.7518
Destabilization of Electroweak Vacuum during Inflation

- Transition out of unstable electroweak vacuum if $H > 10^{10}$ to $10^{12}$ GeV
- BICEP2 measurements corresponds to
  $$V \sim (2 \times 10^{16} \text{ GeV})^4$$
- Corresponding to
  $$H \sim 10^{14} \text{ GeV}$$
- Strengthens case for new physics beyond the Standard Model, scale $< 10^{11}$ GeV

Kobakhidze & Spencer-Smith: arXiv:1301.2846
Inflation Cries out for Supersymmetry

- Want “elementary” scalar field
  (at least looks elementary at energies $<< M_P$)
- To get right magnitude of perturbations
- Prefer mass $<< M_P$
  ($\sim 10^{13}$ GeV in simple $\varphi^2$ models)
- And/or prefer small self-coupling $\lambda << 1$
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive, & Tamvakis: 1983
Sneutrino Inflation?

- See-saw model of neutrino masses requires massive singlet (right-handed) neutrinos.
- In supersymmetric models would be accompanied by massive sneutrinos, with $m^2\phi^2$ potential.
- Decay of sneutrino inflaton gives efficient leptogenesis.
- **BUT**: disfavoured by Planck data.

JE, Raidal & Yanagida: hep-ph/0303242
Multiple Sneutrino Inflation?

- Expect 3 massive singlet (right-handed) neutrinos
- Consistency with Planck data?
- Marginal improvement with 2 sneutrinos
- Significant improvement with 3 sneutrinos
Multiple Sneutrino Inflation?

• Sneutrino inflation model compatible with all the neutrino and Planck data

• Neutrino masses and mixing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$m_\phi$</td>
<td>$2.6 \times 10^{12}$ GeV</td>
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<td>$\Gamma_\phi$</td>
<td>$2.2 \times 10^8$ GeV</td>
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<td>$\phi_*$</td>
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<tr>
<td>$m_\chi$</td>
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<tr>
<td>$\Gamma_\chi$</td>
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<tr>
<td>$\chi_*$</td>
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<td>$m_{\nu_2}$</td>
<td>$4.92 \times 10^{-2}$ eV</td>
</tr>
<tr>
<td>$m_{\nu_3}$</td>
<td>$3.1 \times 10^{-7}$ eV</td>
</tr>
</tbody>
</table>

• Full set of model parameters
More General Polynomial Potential

- Consider single real field with double-well potential: 
  \[ V = A\phi^2(v - \phi)^2 \]
- Shallower than \( \phi^2 \) for 
  \( 0 < \phi < v \)
- Better tensor-to-scalar ratio \( r \) for \( 0 < \phi < v \)
- Steeper than \( \phi^2 \) for 
  \( \phi < 0 \) or \( > v \): worse \( r \)

Croon, JE & Mavromatos: arXiv:1303.6253
Effective Potential in Wess-Zumino Model

• First (and minimal) supersymmetric field theory:
  \[ W = \frac{\mu}{2} \Phi^2 - \frac{\lambda}{3} \Phi^3 \]

• Effective potential:
  \[ V = \left| \frac{\partial W}{\partial \phi} \right|^2 = A v^4 (x^4 - 2 \cos \theta x^3 + x^2) \]

• Equivalent to single-field model for \( \theta = 0 \) (good)
• Combination of \( \varphi^2 + \varphi^4 \) for \( \theta = \pi/2 \) (no good)
• Good inflation possible
  – Inflaton could be sneutrino

Croon, JE & Mavromatos: arXiv:1303.6253
Supersymmetric Inflation in Light of Planck

- Supersymmetric Wess-Zumino (WZ) model consistent with Planck data

Croon, JE, Mavromatos: arXiv:1303.6253

\[ \phi^4 \]

\[ \phi^2 \]

\[ \phi^{2/3} \]
Exploring Wess-Zumino Inflation

- Generic SUSY models have 2 scalars: $\Phi = \psi + i \sigma$
- Explore 2-field parameter space of WZ model
- Different trajectories for different $\nu$

Exploring Wess-Zumino Inflation

- Explore 2-field parameter space of WZ model
- Improved compatibility with Planck data
- Enhanced non-Gaussianity

Exploring Wess-Zumino Inflation

- Statistical distribution of possible predictions assuming rotationally-invariant distribution of initial conditions


- Planck-compatibility not implausible
From Supersymmetry to Supergravity

- The only good symmetry is a local symmetry (cf., gauge symmetry in Standard Model)
- **Local supersymmetry = supergravity**
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = supergravity**
- Superpartner of graviton is gravitino fermion
- Gravitino condensation? (cf., quarks in QCD)
- **Mechanism for inflation?** [JE & Mavromatos, arXiv:1308.1906]
No-Scale Supergravity Inflation

- **Supersymmetry + gravity = Supergravity**
- Include conventional matter?
- Potentials in generic supergravity models have ‘holes’ with depths $\sim - M_P^4$
- Exception: no-scale supergravity
- Appears in compactifications of string
- Flat directions, scalar potential $\sim$ global model + controlled corrections

No-Scale Supergravity Inflation

- Simplest SU(2,1)/U(1) example:
  \[ K = -3 \ln(T + T^* - |\phi|^2/3) \]
  \[ W = \frac{\mu}{2} \Phi^2 - \frac{\lambda}{3} \Phi^3 \]

- Kähler potential:

- Wess-Zumino superpotential:

- Assume modulus \( T = c/2 \) fixed by ‘string dynamics’

- Effective Lagrangian for inflaton:
  \[ \mathcal{L}_{\text{eff}} = \frac{c}{(c - |\phi|^2/3)^2} |\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2} \]
  \[ \hat{V} \equiv \left| \frac{\partial W}{\partial \phi} \right|^2 \]

- Modifications to globally supersymmetric case

- Good inflation possible …

No-Scale Supergravity Inflation

- Inflationary potential for $\lambda \simeq \mu/3$

Similar to global case

Special case

Is there more profound connection?

- Starobinsky model:
  \[ S = \frac{1}{2} \int d^4 x \sqrt{-g} (R + \frac{R^2}{6M^2}) \]

- After conformal transformation:
  \[ S = \frac{1}{2} \int d^4 x \sqrt{-\tilde{g}} \left[ \tilde{R} + (\partial_\mu \varphi')^2 - \frac{3}{2} M^2 (1 - e^{-\sqrt{2/3} \varphi'})^2 \right] \]

- Effective potential:
  \[ V = \frac{3}{4} M^2 (1 - e^{-\sqrt{2/3} \varphi'})^2 \]

- Identical with the no-scale Wess-Zumino model for the case \( \lambda = \frac{\mu}{3} \)

[... it actually IS Starobinsky]

<table>
<thead>
<tr>
<th>See also …</th>
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<tbody>
<tr>
<td>• Nakayama, Takahashi &amp; Yanagida – arXiv:1305.5099</td>
</tr>
<tr>
<td>• Kallosh &amp; Linde – arXiv:1306:3214</td>
</tr>
<tr>
<td>• Buchmuller, Domcke &amp; Kamada – arXiv:1306.3471</td>
</tr>
<tr>
<td>• Kallosh &amp; Linde – arXiv:1306.5220</td>
</tr>
<tr>
<td>• Farakos, Kehagias and Riotto – arXiv:1307.1137</td>
</tr>
<tr>
<td>• Roest, Scalisi &amp; Zavala – arXiv:1307.4343</td>
</tr>
<tr>
<td>• Kiritsis – arXiv:1307.5873</td>
</tr>
<tr>
<td>• …</td>
</tr>
</tbody>
</table>
No-Scale Supergravity Inflation in Light of BICEP2

• Possible to accommodate quadratic potential

\[
K = -3 \ln (T + T^*) + |\phi|^2 \\
W = e^{-\frac{\phi^2}{2}} \left( \mu - \frac{m}{2} \phi^2 \right)
\]

• Can stabilize T, Im \( \phi \) while Re \( \phi \) inflates

JE, García, Nanopoulos & Olive, arXiv:1403.7518
No-Scale Supergravity Inflation in Light of BICEP2

- Re $\phi$ evolves, Im $\phi$ small
- Re $T$ and Im $T$ also well-behaved
- Sufficient inflation
- BICEP2-compatible

JE, García, Nanopoulos & Olive, arXiv:1403.7518
Supersymmetric Starobinsky Inflation in Light of BICEP2

- Im $\phi$ has $m^2\phi^2$ potential when Re $\phi = 0$
- But Im $\phi$ does not inflate
- Inflation driven by Re $\phi$
- Looks like Starobinsky
- BICEP2-incompatible

JE, García, Nanopoulos & Olive, arXiv:1403.7518
Supersymmetric Starobinsky Inflation in Light of BICEP2

- Modify Kähler potential?
  \[
  K = -3 \ln \left( T + T^* - \frac{\phi \phi^*}{3} - \frac{(T + T^*)^n}{\Lambda^2} \right)
  \]

- Unstable potential!

- Can stabilize
  \[
  K = -3 \ln \left( T + T^* - \frac{\phi \phi^*}{3} - \frac{(T + T^*)^n}{\Lambda^2} + \frac{(\phi \phi^*)^2}{\Lambda_\phi^2} \right)
  \]

- Alternative realization of quadratic inflation in no-scale supergravity

JE, García, Nanopoulos & Olive, arXiv:1403.7518
Summary

• Inflation may solve some of the biggest problems in cosmology: age, size, homogeneity, flatness, …
• Structures originated from quantum effects in the early Universe
• Another scalar field (inflaton) in the sky?
• Quantum gravitational radiation detected?
• Tension between Planck and BICEP2
• Inflation also cries out for supersymmetry
• Open season for building inflationary models
• Inflaton = superpartner of neutrino?
Time for China to get involved in CMB Experiments?
Crossing the Scalar Rubicon: Once or Twice?
No-Scale Supergravity Inflation

- Good inflation for $\lambda \simeq \mu/3$

Looks like $R^2$ model

Accessible to future Experiment?

No-Scale Framework for Particle Physics & Dark Matter

- Incorporating Starobinsky-like inflation, leptogenesis, neutrino masses, LHC constraints, supersymmetric dark matter,
- Stringy origin…?

Inflationary Models in Light of BICEP2

- Consistency condition for simple power-laws:
  \[ \mu^{4-n\phi n} \]

- They require \( r = 8 \left( 1 - n_s - \frac{1}{N} \right) \) OK with BICEP2

- \( n = 2 \) OK
Stabilization of Modulus Field

• With modified geometrical (Kähler) structure:

\[
K = -3 \ln \left( T + T^* - \frac{|\phi|^2}{3} + \frac{(T + T^* - 1)^4 + d(T - T^*)^4}{\Lambda^2} \right)
\]

• Effective inflaton potential \( \sim \) Starobinsky

• Other field directions stabilized:

Generalizations

• Common no-scale geometrical (Kähler) structure many superpotentials:

\[
K = -3 \ln \left( T + T^* - \frac{|\phi|^2}{3} \right), \\
W = M \left( \frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}} \right)
\]

\[
W = \frac{M}{4}(T - 1/2)^2(1 + 10T + 2\sqrt{3}\phi), \\
W = \frac{M}{4}(T - 1/2)^2(5 + 2T + 2\sqrt{3}\phi)
\]

\[
W = \sqrt{3}M\phi(T - 1/2), \\
W = 2\sqrt{3}M\phi T(T - 1/2)
\]

\[
\Delta W = \left[ \frac{(T - 1/2)^n 2^{(n-3)}}{(2T + 1)^{(n-3)}} \right] \\
\Delta W = \left[ \frac{(T - 1/2)^n 2^{(n-2)} \phi}{(2T + 1)^{(n-2)}} \right]
\]

also yield Starobinsky-like inflationary models

Beyond Starobinsky

- Exponential approach to constant potential:

\[ V = A \left( 1 - \delta e^{-Bx} + O(e^{-2Bx}) \right) \]

- Relations between observables:

\[ n_s = 1 - 2B^2\delta e^{-Bx}, \quad r = 8B^2\delta^2 e^{-2Bx}, \quad N_* = \frac{1}{B^2\delta} e^{+Bx}. \]

\[ n_s = 1 - \frac{2}{N_*}, \quad r = \frac{8}{B^2N_*^2} \]

- E.g., multiple no-scale moduli:

\[ K \equiv -\sum_i N_i \ln(T_i + T_i^*) : \quad N_i > 0, \quad \sum_i N_i = 3 \]

- Characteristic of generic string compactifications

- Tensor/scalar ratio may be < prediction of Starobinsky model:

\[ B = \sqrt{\left( \frac{2}{N_i} \right)} \]

\[ r = \frac{4N_i}{N_*^2} \]

- String phenomenology via the CMB?

Completing the Holy Trinity

- Scale hierarchy possible only in theory that can be calculated over many magnitudes of energy
  
  **Renormalizable**

- Theorem: (1) vectors (2) fermions (3) scalars

- Need to specify:
  
  (1) group (2) representations (3) symmetry breaking

  \[
  (1) = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \text{ [so far]} 
  \]

  \[
  (2) = \text{Singlets + doublets + triplets}
  \]

- Finally:

  (3) A scalar, mechanism of symmetry breaking

Cornwall, Levin & Tiktopoulos; Bell: Llewellyn-Smith
Measurements of CMB Fluctuations with Planck Satellite

Angular scale

$D_\ell [\mu K^2]$

Multipole moment, $\ell$

90° 18° 1° 0.2° 0.1° 0.07°

6000 5000 4000 3000 2000 1000 0

2 10 50 500 1000 1500 2000 2500
Wess-Zumino Inflation in Light of Planck

- Consistent with Planck for $x_i = 0.3, 0.4$

<table>
<thead>
<tr>
<th>Value of $x_i$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
</tr>
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<tbody>
<tr>
<td>Derived quantity</td>
<td></td>
<td></td>
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<tr>
<td>$\frac{v^2}{M_{Pl}^2}$</td>
<td>18000</td>
<td>4200</td>
<td>1600</td>
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<tr>
<td>$\epsilon$</td>
<td>0.0085</td>
<td>0.0067</td>
<td>0.0045</td>
<td>0.0020</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.0062</td>
<td>0.0074</td>
<td>-0.0073</td>
<td>-0.022</td>
</tr>
<tr>
<td>$\xi$</td>
<td>-0.000053</td>
<td>-0.000077</td>
<td>-0.000079</td>
<td>-0.000050</td>
</tr>
<tr>
<td>$r$</td>
<td>0.14</td>
<td>0.11</td>
<td>0.072</td>
<td>0.031</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.961</td>
<td>0.961</td>
<td>0.958</td>
<td>0.945</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>$-1.4 \times 10^{-6}$</td>
<td>$-1.3 \times 10^{-6}$</td>
<td>$-1.4 \times 10^{-6}$</td>
<td>$-1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$4.3 \times 10^{-8}$</td>
<td>$1.0 \times 10^{-7}$</td>
<td>$2.1 \times 10^{-7}$</td>
<td>$4.1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

- Numbers calculated for $N = 50$ e-folds

Good inflation

Croon, JE & Mavromatos: arXiv:1303.6253
July 4th 2012

The discovery of a new particle
Unofficial Combination of Higgs Data

Is this the Higgs Boson?

No Higgs here!

No Higgs here!
Inflationary Models in Light of BICEP2

- QUANTUM GRAVITY RADIATION!
- BICEP2 observations support for inflation
- “Large” tensor-to-scalar ratio: $r = 0.20^{+0.07}_{-0.05}$
- Starobinsky $R^2$ dead, quadratic inflation OK?
It Walks and Quacks like a Higgs

So far, it looks like a (bog) Standard Model Higgs Boson

JE & Tevong You, arXiv:1303.3879
Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]


Gravitino Inflation

• Inflation driven by condensate of gravitinos?
• Possible with suitable non-perturbative parameters

\[ e^{-1} V_{\text{eff infl}} = \tilde{\kappa}^{-4} \left[ 0.4878 \sigma^4 \ln \sigma^2 - 0.2549 \sigma^4 - 0.0022 \sigma^2 + 0.2574 \right] \]

• Potential can yield good \((n_s, r)\):

• Need hypothesis on dynamics

JE & Mavromatos, arXiv:1308.1906
Scalars Come of Age

• A new boson discovered at the LHC
  – A scalar, beyond any reasonable doubt
  – Consistent with the Higgs of the Standard Model

• Circumstantial evidence for scalar inflaton
  – $\Omega \sim 1$, tilt in spectrum of scalar perturbations, …
  – No sign of non-Gaussianity, strings, defects, …

• Data compatible with Starobinsky ($R + R^2$) model

• Similar predictions in Higgs inflation: **BUT** $M_H$?