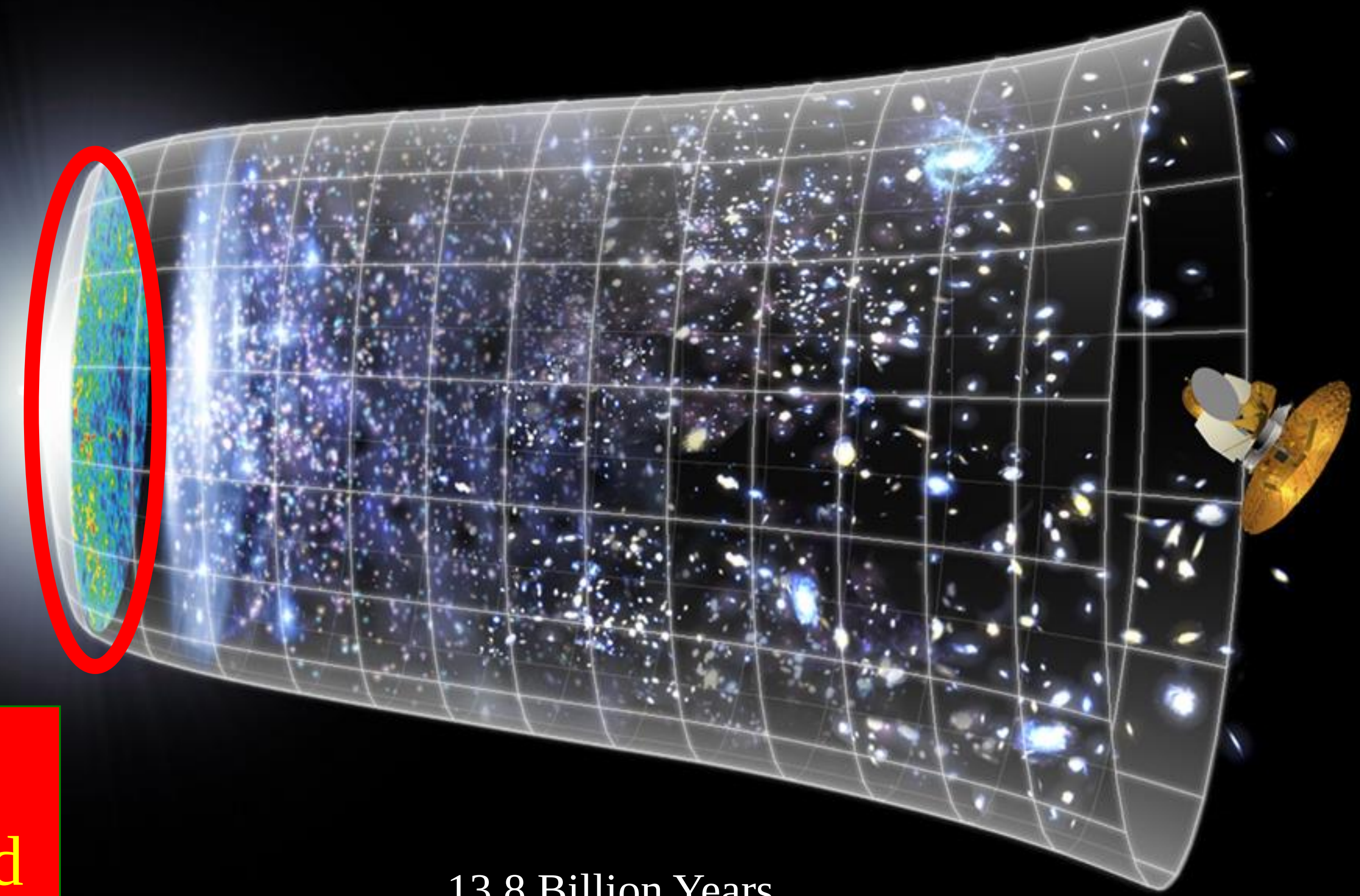
Inflation in Light of Planck & BICEP2

Big Bang



What happened here?

13.8 Billion Years

Today

10^{28} cm

John Ellis

KING'S College LONDON

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 ~ 10^{19} GeV,

  Distance ~ 10^{-32} cm, time ~ 10^{-43} s

- Our Universe is a special solution of equations

  Size >> 10^{-32} cm, age ~ 10^{-43} s

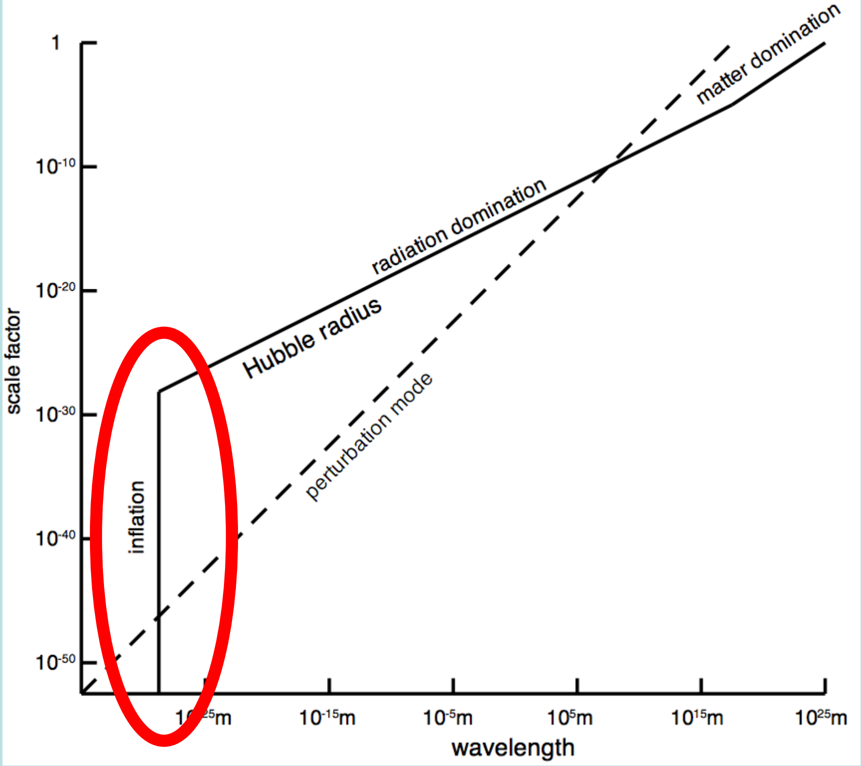
- Due to a "cosmological constant" Λ?
  - Due to a scalar "inflaton" field ϕ: $\Lambda \sim V(\phi) \neq 0$?

Cosmological Inflation

- Expansion driven by cosmological constant:

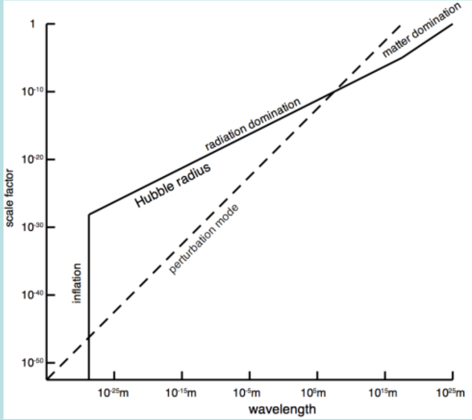
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$$ (a = scale size)

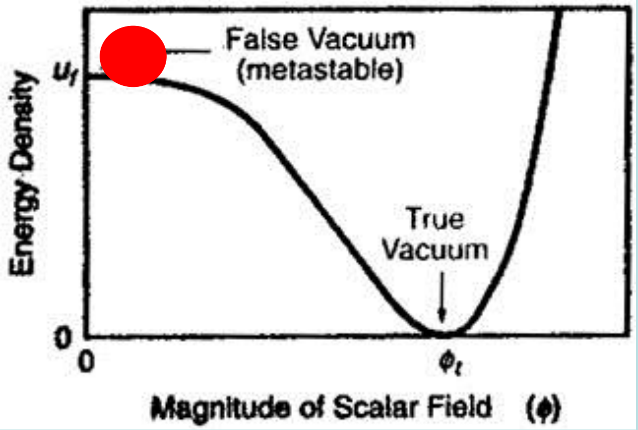
- Exponential expansion
- All the visible Universe was once very small
- In close contact: (almost) homogeneous
- Geometry ~ flat



Primordial Perturbations

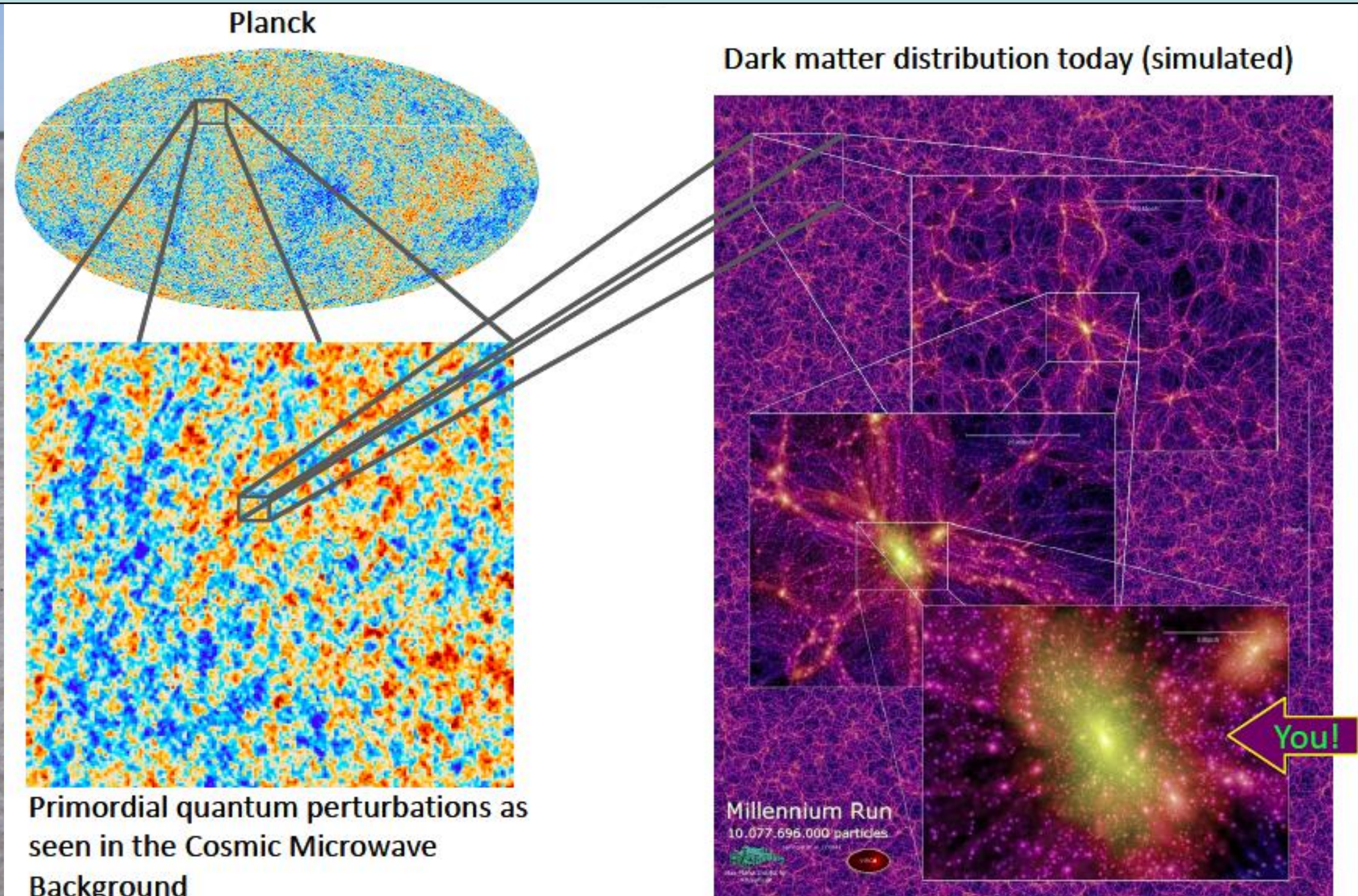
- "Cosmological constant" due to vacuum energy in "inflaton" field ϕ: $\Lambda \sim V(\phi) \neq 0$
- Quantum fluctuations in ϕ cause perturbations in energy density (scalar) and metric (tensor)
- (Almost) independent of scale size





- Visible in cosmic microwave background (CMB)

Perturbations Generate Structures



Inflationary Perturbations in a Nutshell

- Universe expanding like de Sitter
- Horizon → information loss → mixed state
- Effective ‘Hawking temperature’ $H/2\pi$
- Expect quantum fluctuations:

$$\langle\phi\phi\rangle, \qquad \langle hh\rangle \sim H^2$$

(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 ϕ → $r \sim \varepsilon$

Slow-Roll Inflation

- Expansion driven by cosmological constant:

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

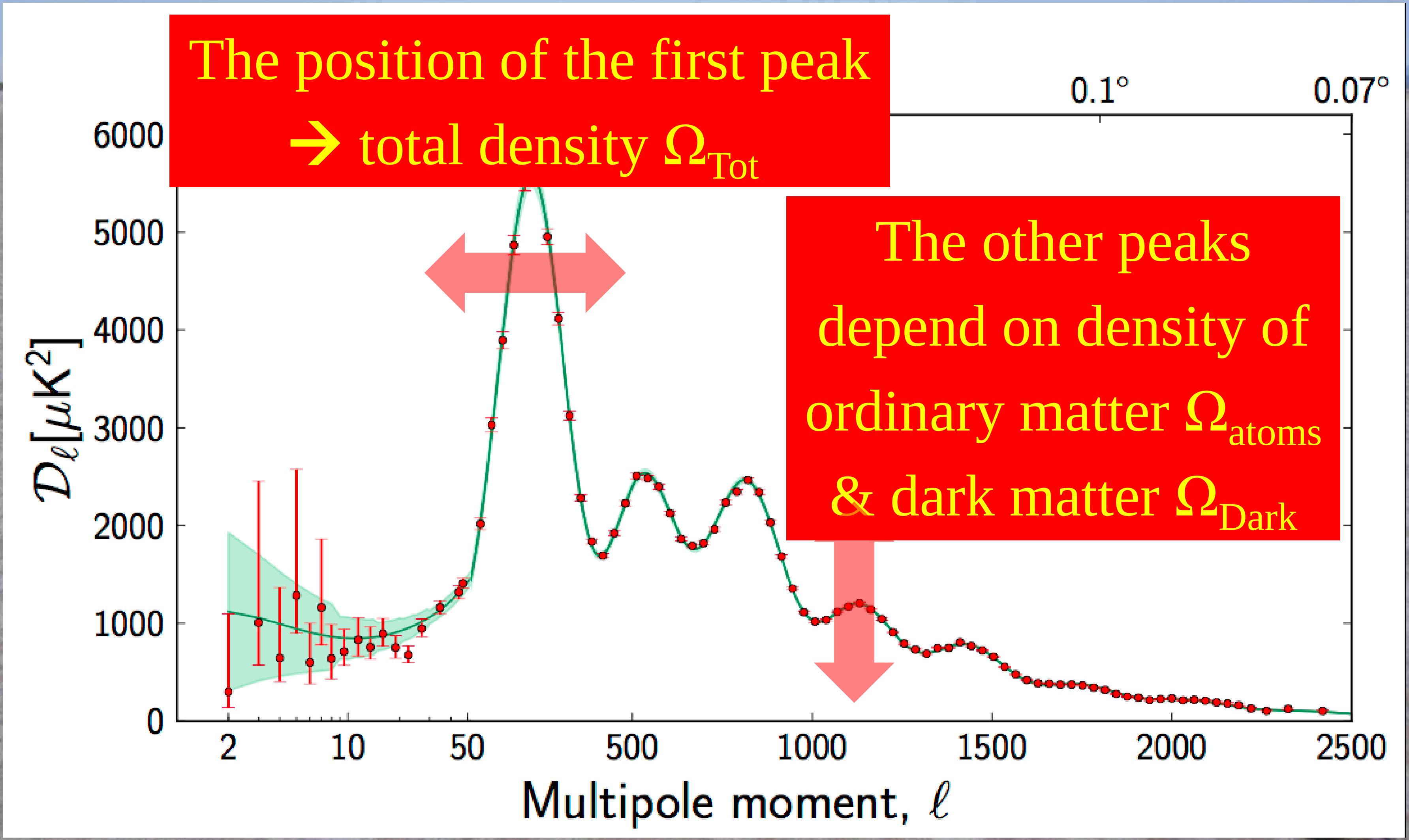
- Getting small density perturbations requires a "small" potential: $\left(\frac{V}{\epsilon}\right)^{\frac{1}{4}} = 0.0275 \times M_{Pl}$
- That is almost flat: $\epsilon = \frac{1}{2}M_{Pl}^2\left(\frac{V'}{V}\right)^2$, $\eta = M_{Pl}^2\left(\frac{V''}{V}\right)$ small

  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 ~ Gaussian: look for deviation (f_{NL})

The Spectrum of Fluctuations in the Cosmic Microwave Background

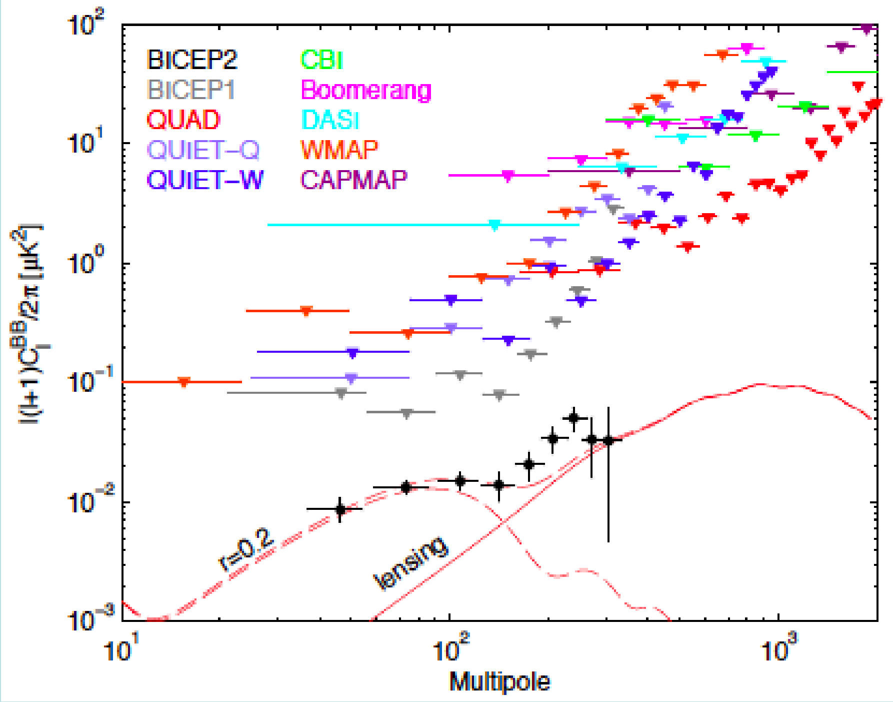


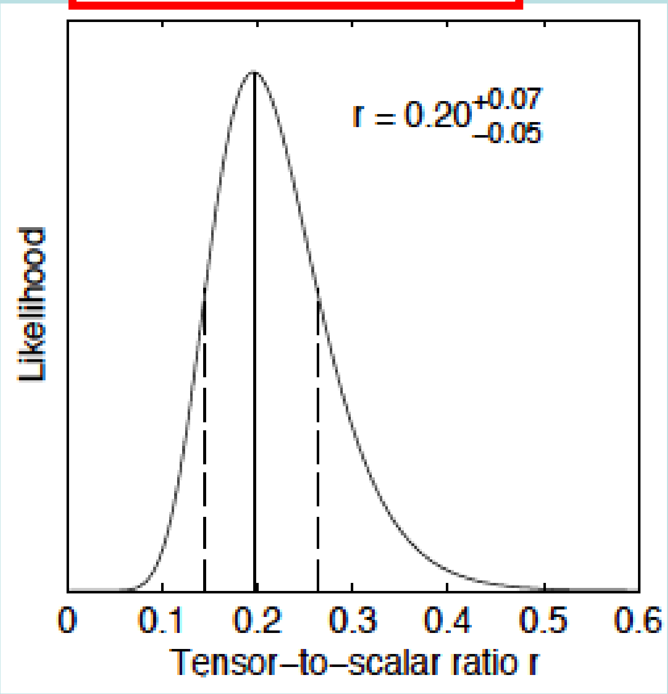
Cosmological Inflation in Light of BICEP2

Quantum gravity radiation in the sky?

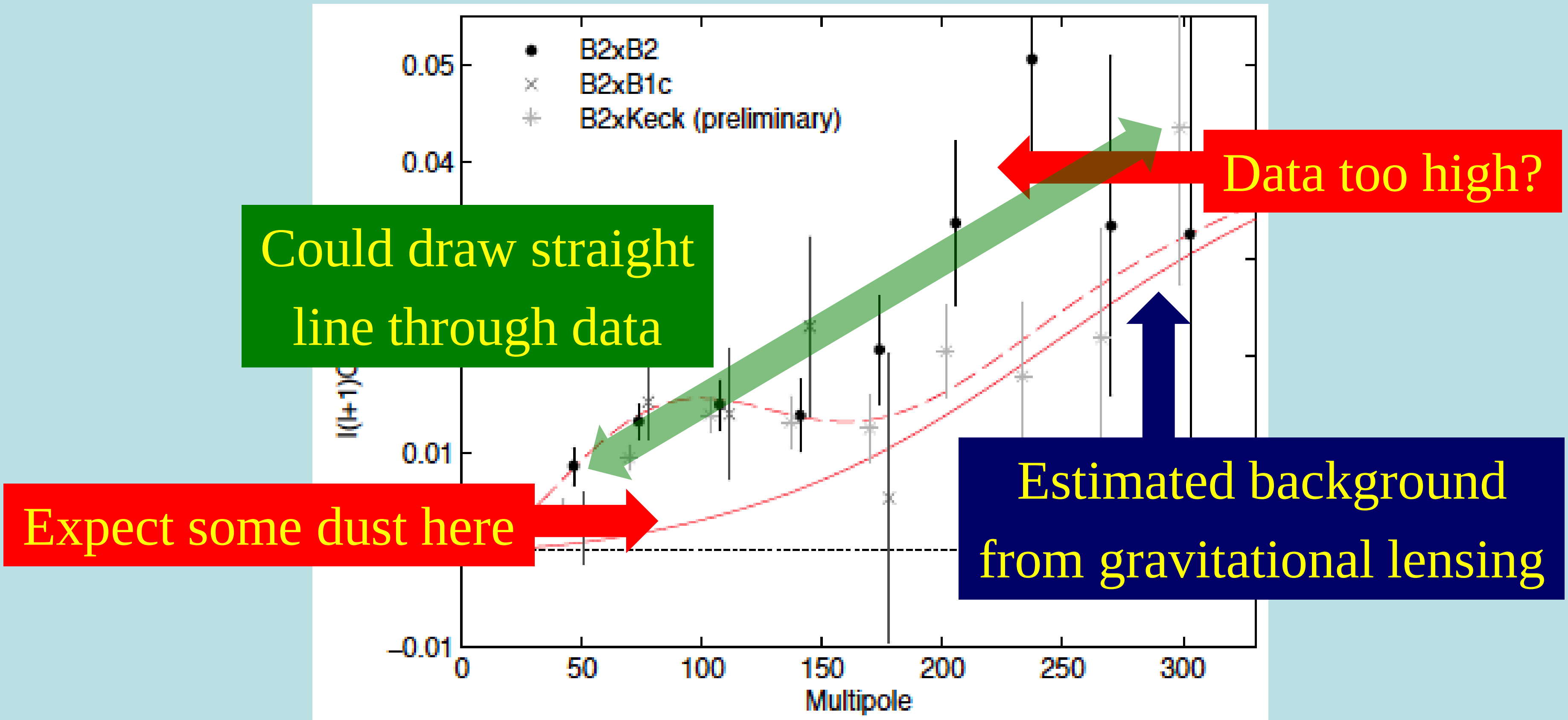
Cosmological Inflation in Light of BICEP2

- **QUANTUM GRAVITY RADIATION!**
- BICEP2 observations support for inflation
- "Large" tensor-to-scalar ratio: $\boxed{r = 0.20^{+0.07}_{-0.05}}$





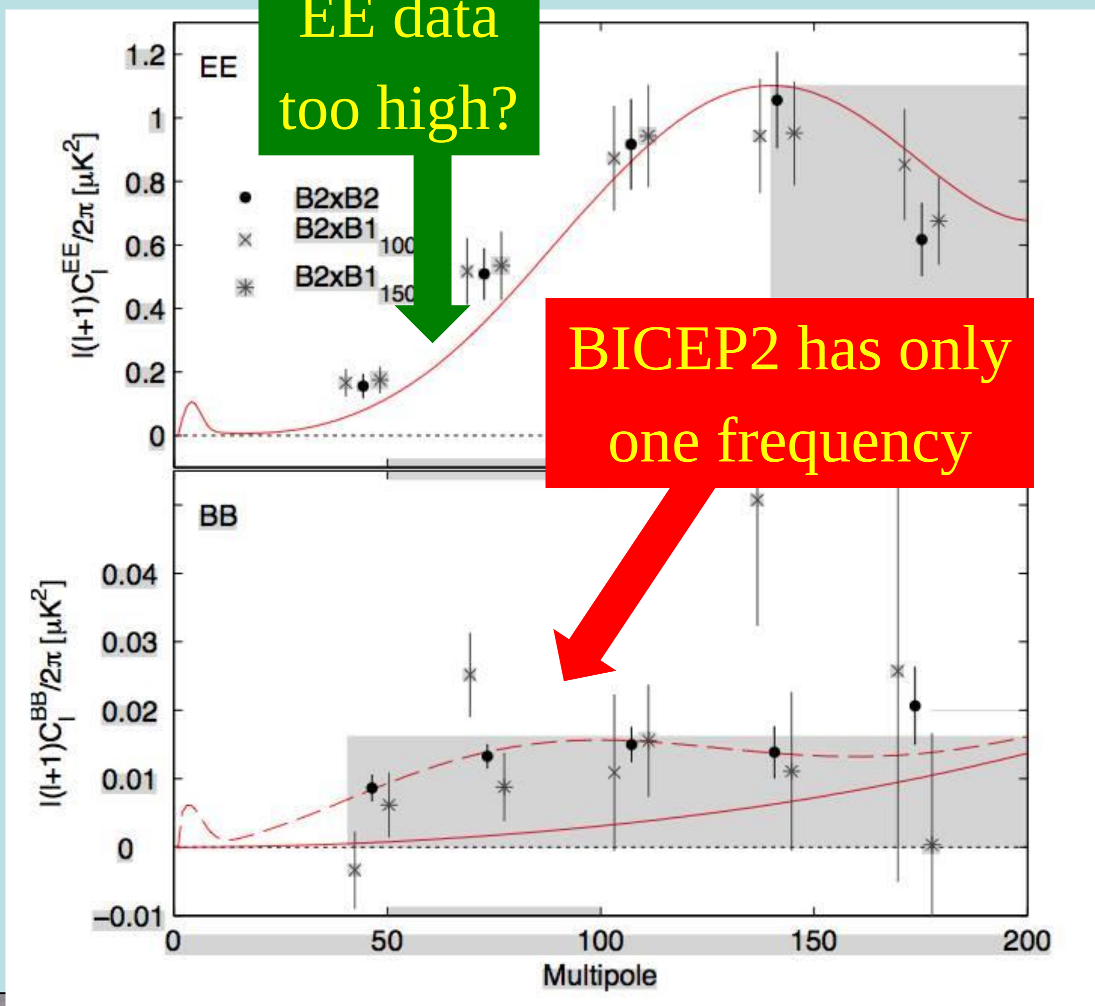
The BICEP2 Result is a Big Deal



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

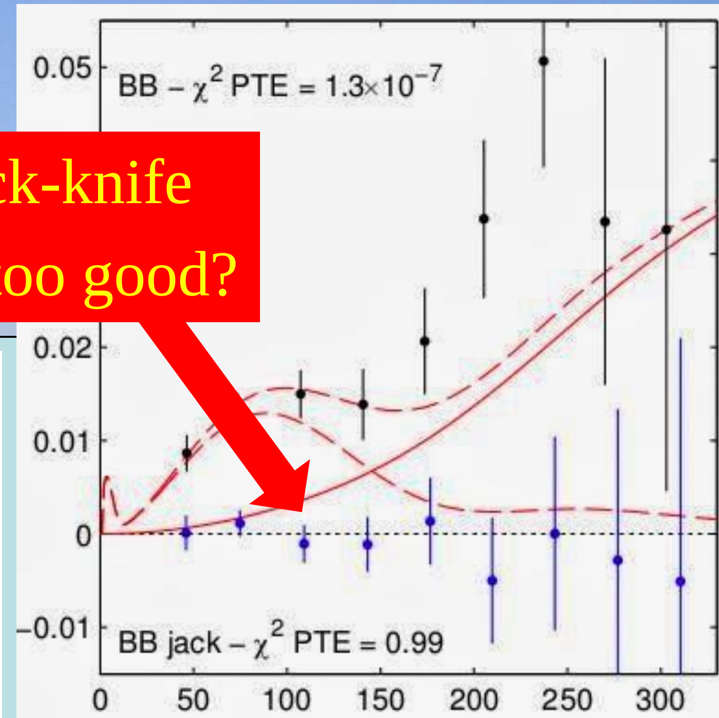
Questions/Issues with BICEP2

EE data too high?

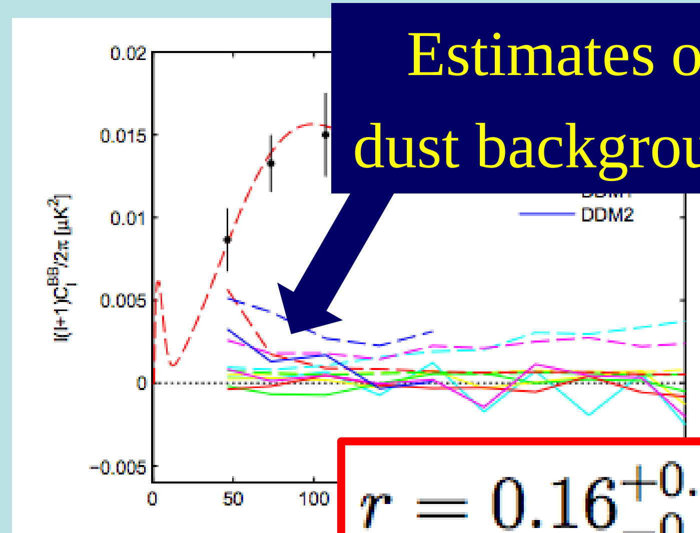


BICEP2 has only one frequency

Jack-knife test too good?

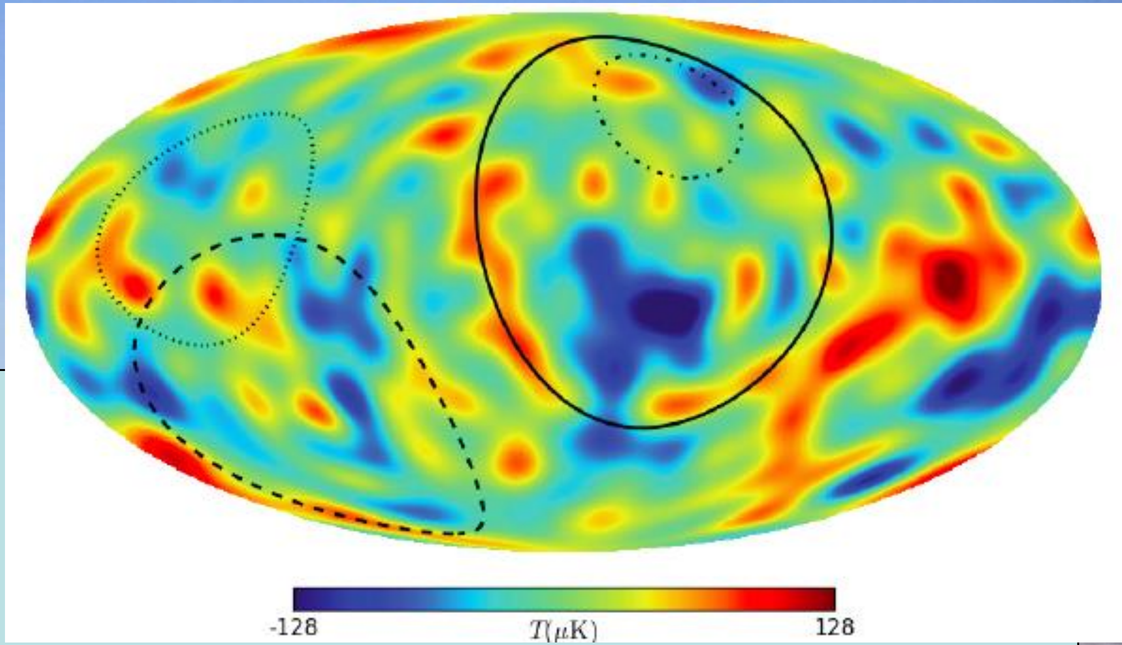


Estimates of dust background



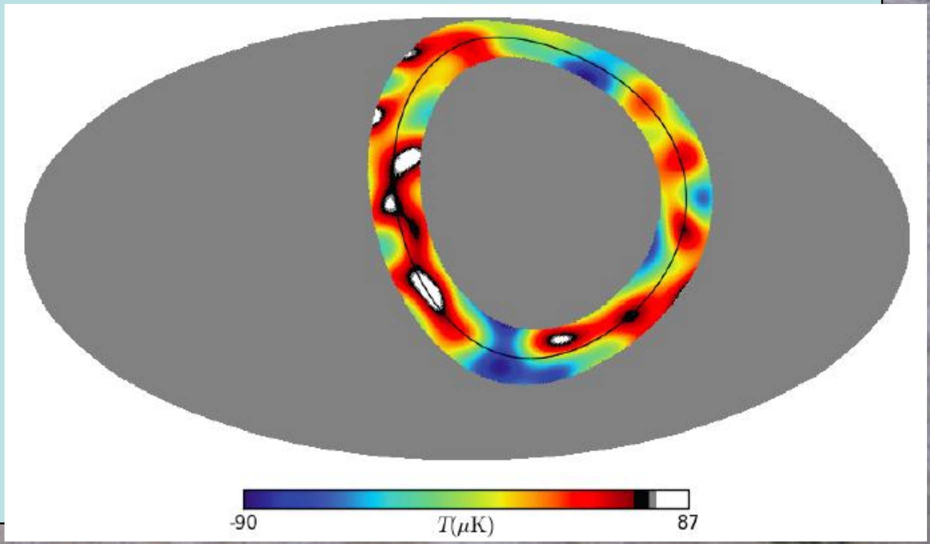
$$r = 0.16^{+0.06}_{-0.05}$$

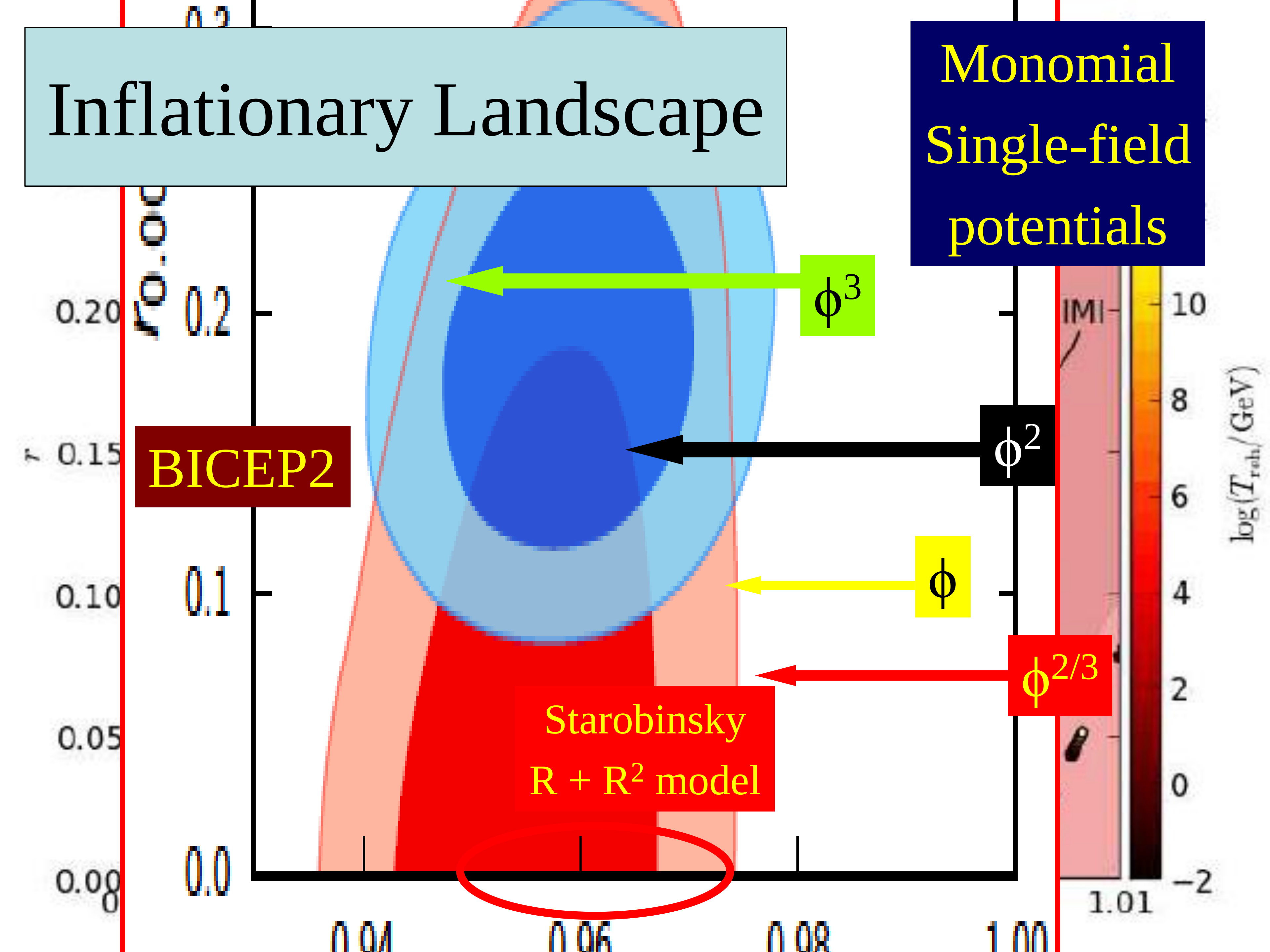
Pollution by Loops?



Liu, Mertsch & Sarkar: arXiv:1404.1899

- 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
ϕ^3
ϕ^2
ϕ
$\phi^{2/3}$
BICEP2
Starobinsky
R + R^2 model
0.2
0.1
0.0
0.20
0.15
0.10
0.05
0.00
r
0.94
0.96
0.98
1.00
1.01
10
8
6
4
2
0
−2
$\log(T_{reh}/\mathrm{GeV})$
IMI

Reconciling Planck and BICEP2?

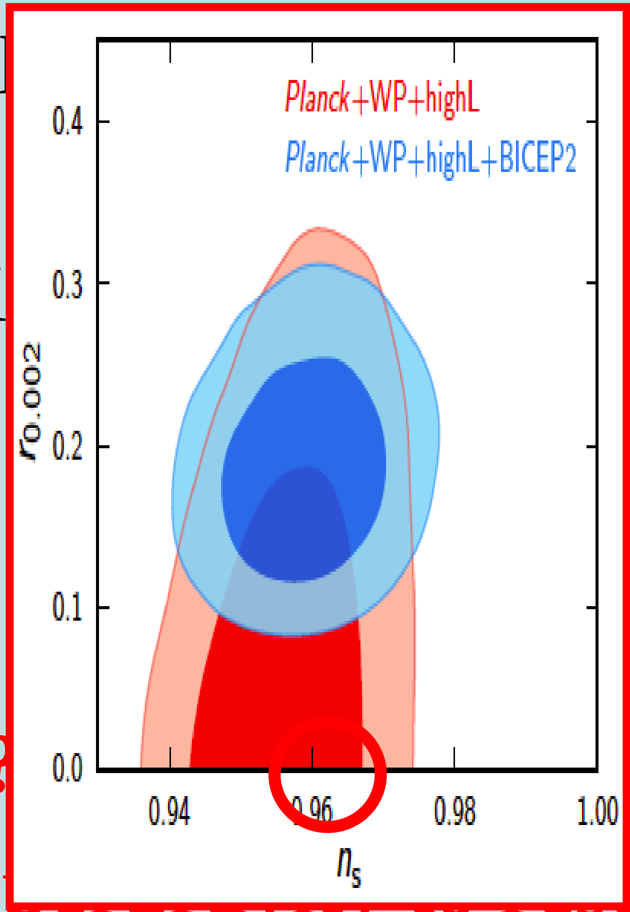
- Possible if scalar spectral index runs (fast)
- $\frac{dn_s}{d\ln k} = \frac{2}{3}\left[(n_s-1)^2 - 4\eta^2\right] + 2\xi$ where $\xi = M_{Pl}^4\left(\frac{V'V'''}{V^2}\right)$
- Bracketed terms $O(10^{-4})$, need $\xi = O(10^{-2})$
- In slow-roll approximation, expect $\xi << O(10^{-2})$
- Such a large value of ξ is problematic for consistency of slow-roll approximation:
- $\varepsilon = O(10^{-2})$ implies $V'/V = O(10^{-1})$
- $\xi = O(10^{-2})$ then requires $V''' = O(10^{-1})$
- Change $\Delta V'' = O(1)$ for $\Delta\varphi = O(10)$

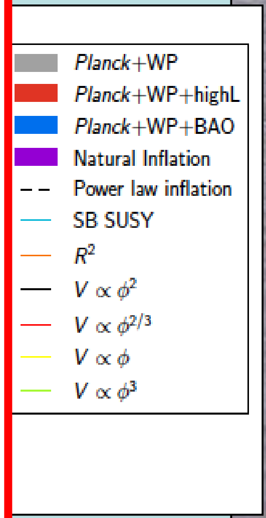
Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation s own):

  $n_s = 0.9585$

- **BUT** strengthen upper limi perturbations: $r < 0.10$
- Challenge for simple inflationary models
- **Starobinsky R^2 to rescue?**
- **Higgs/Supersymmetry/su cue?**





Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- **No scalar!?**

Starobinsky, 1980

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x\left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

- **Conformally equivalent to scalar field model:**

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

Stelle; Whitt, 1984

Higgs Inflation: a Single Scalar?

Bezrukov & Shaposhnikov, arXiv:0710.3755

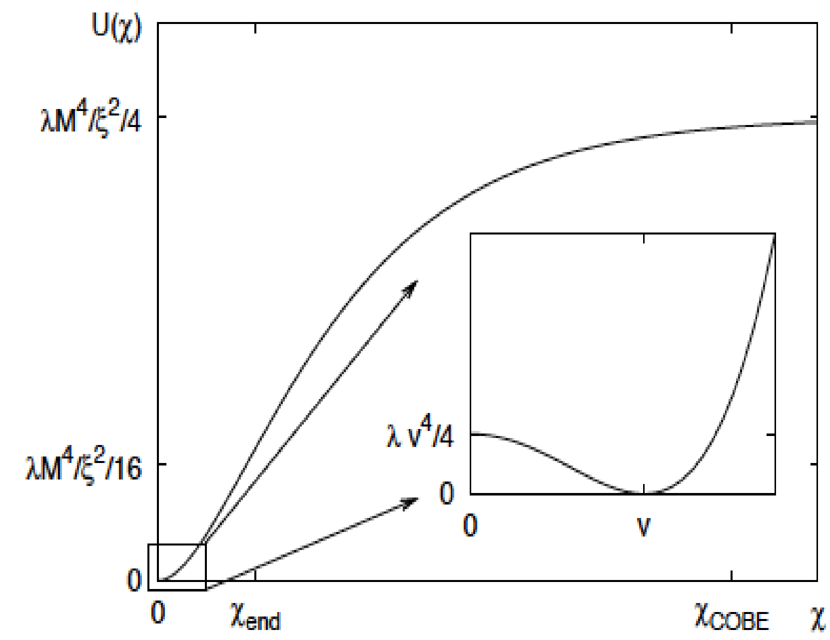
- Standard Model with non-minimal coupling to gravity:
$$S_J = \int d^4x\sqrt{-g}\left\{ -\frac{M^2+\xi h^2}{2}R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \right\}$$
- Consider case $1 \ll \sqrt{\xi} \lll 10^{17}$: in Einstein frame
$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi)\right\}$$
- With potential: $U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$

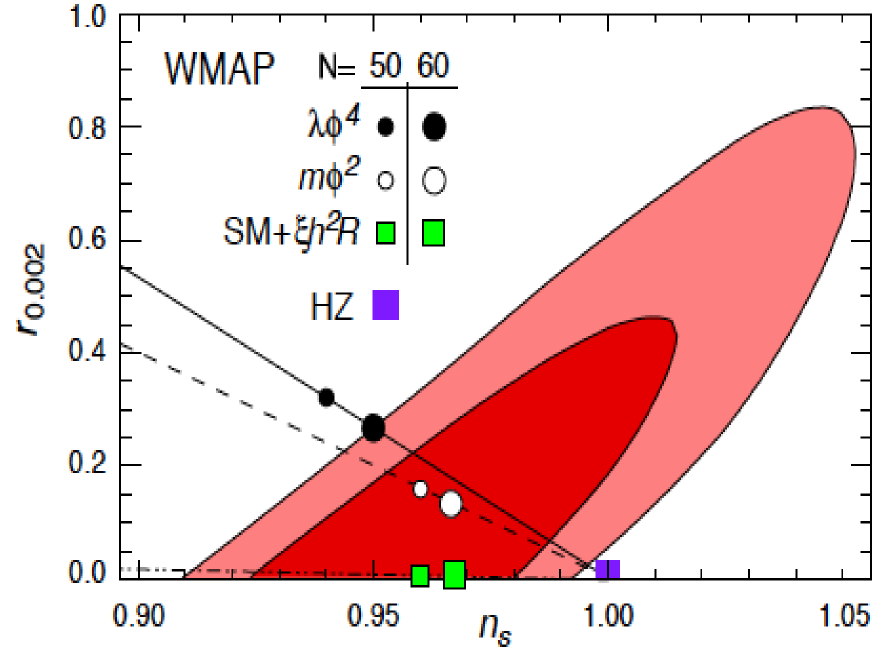
  Similar to Starobinsky, but not identical
- Successful inflationary potential at $\chi \gg M_P$

Higgs Inflation: a Single Scalar?

- Successful inflation for

$$\xi \simeq \sqrt{\frac{\lambda}{3}}\frac{N_{\rm COBE}}{0.027^2} \simeq 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2}v}$$





- **BUT:**

Bezrukov & Shaposhnikov, arXiv:0710.3755

  – Requires $\lambda > 0$ beyond M_P: need $M_H > 127$ GeV?

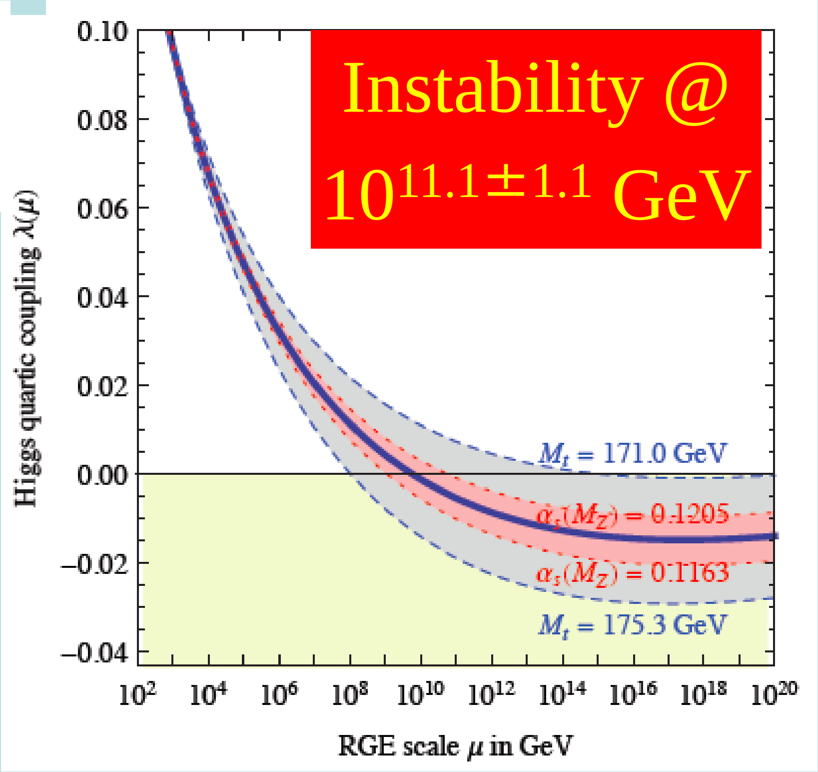
  – How natural is such a large value of ξ?

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

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

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

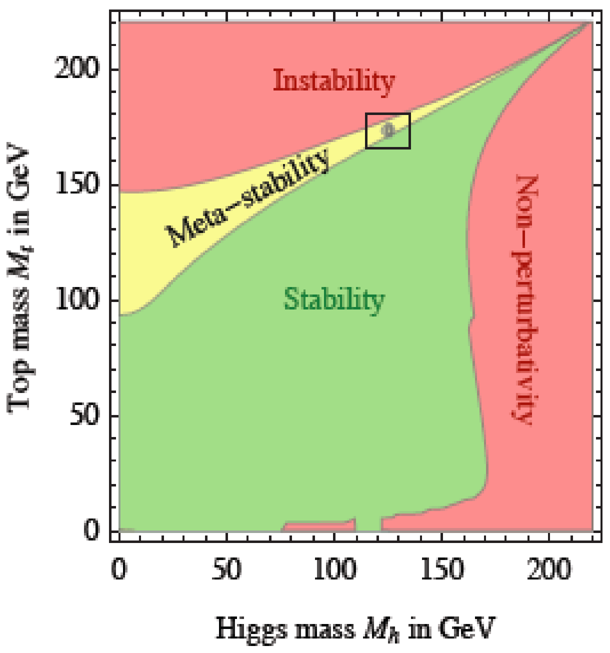


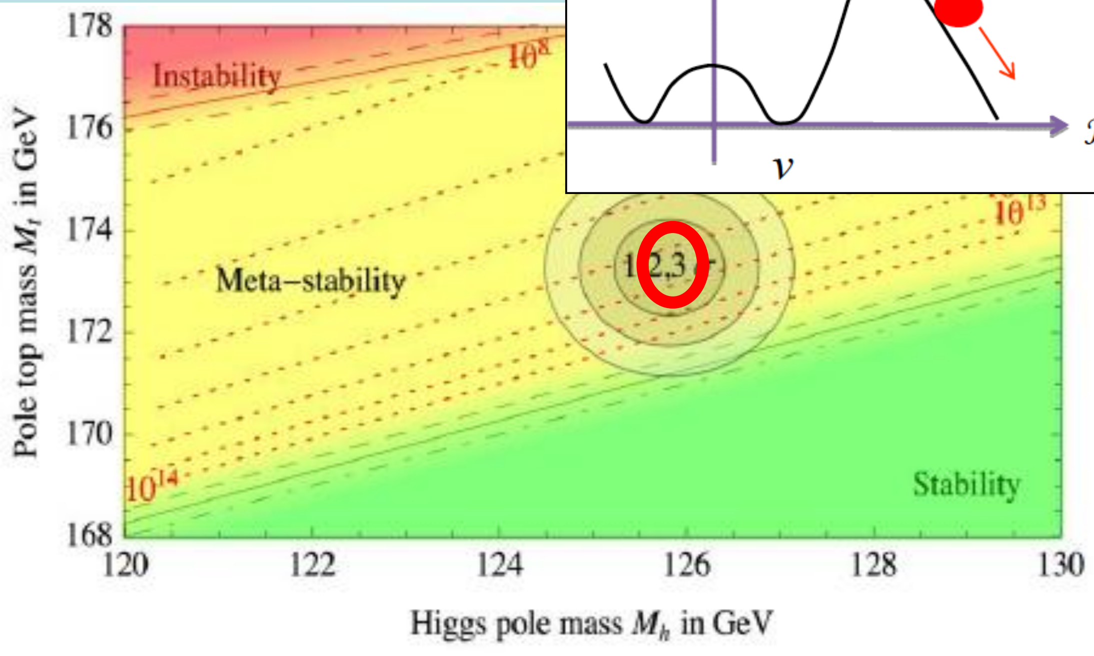
- Vacuum could be stabilized by **Supersymmetry**

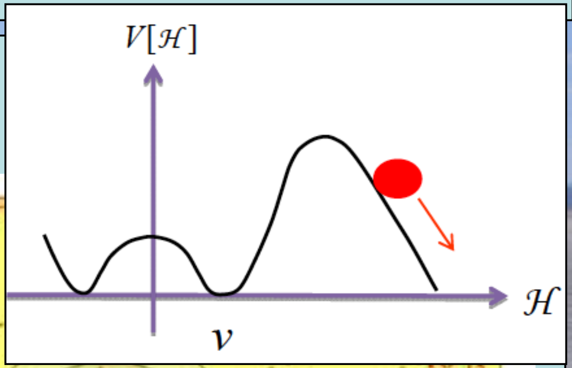
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H







- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

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

- **New measurement of m_t = 173.34 ± 0.76 GeV**

Inflationary Models in Light of BICEP2

- Back to basics: monomial power-law inflationary potential? $V = \mu^{4-n}\phi^n$
- Slow-roll parameters: $\epsilon = \frac{n^2}{2}\frac{M_{Pl}^2}{\phi^2};\ \eta = n(n-1)\frac{M_{Pl}^2}{\phi^2}$
- Inflationary observables: $r = 8n^2\frac{M_{Pl}^2}{\phi^2};\ n_s = 1 - n(n+2)\frac{M_{Pl}^2}{\phi^2}$
- Number of e-folds: $N = \frac{1}{2n}\frac{\phi^2}{M_{Pl}^2}$
- **Consistency condition:** $\boxed{r = 8\left(1 - n_s - \frac{1}{N}\right)}$
- Comfortably satisfied by the measurements

$$r = 0.16^{+0.06}_{-0.05},\ n_s = 0.960 \pm 0.008,\ N = 50 \pm 10$$

JE, Garc á, 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: $n = \frac{rN}{4}; \; n = 2\left[N(1-n_s)-1\right]$
- Numerical values from measurements:

$$\boxed{n = 2.0^{+0.9}_{-0.8}; \; n = 2.0 \pm 1.1}$$

- n = 2 perfectly OK, n = 1, 3 potentials unbounded below, n = 4 has $\Delta\chi^2 > 8$
- Looks like quadratic inflationary potential

$$\boxed{V = \mu^2\phi^2 \simeq (2 \times 10^{16}\ \mathrm{GeV})^4} \; \boxed{m = \sqrt{2}\mu = 1.8 \times 10^{13}\ \mathrm{GeV}} \; \phi = \sqrt{200} M_{Pl}$$

JE, García, Nanopoulos & Olive, arXiv:1403.7518

Destabilization of Electroweak Vacuum during Inflation

Kobakhidze & Spencer-Smith: arXiv:1301.2846

- Transition out of unstable electroweak vacuum if $H > 10^{10}$ to 10^{12} GeV
- BICEP2 measurements corresponds to

$$V \sim (2 \times 10^{16}\ \mathrm{GeV})^4$$

- Corresponding to

$$H \sim 10^{14}\ \mathrm{GeV}$$

- **Strengthens case for new physics beyond the Standard Model, scale < 10^{11} GeV**

Inflation Cries out for Supersymmetry

- Want "elementary" scalar field

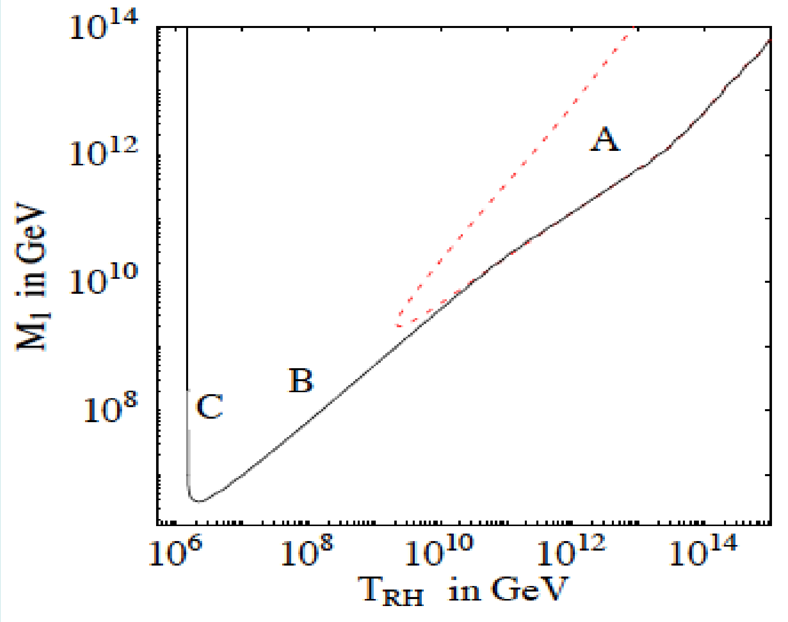
  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations
- Prefer mass << M_P

  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling λ << 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

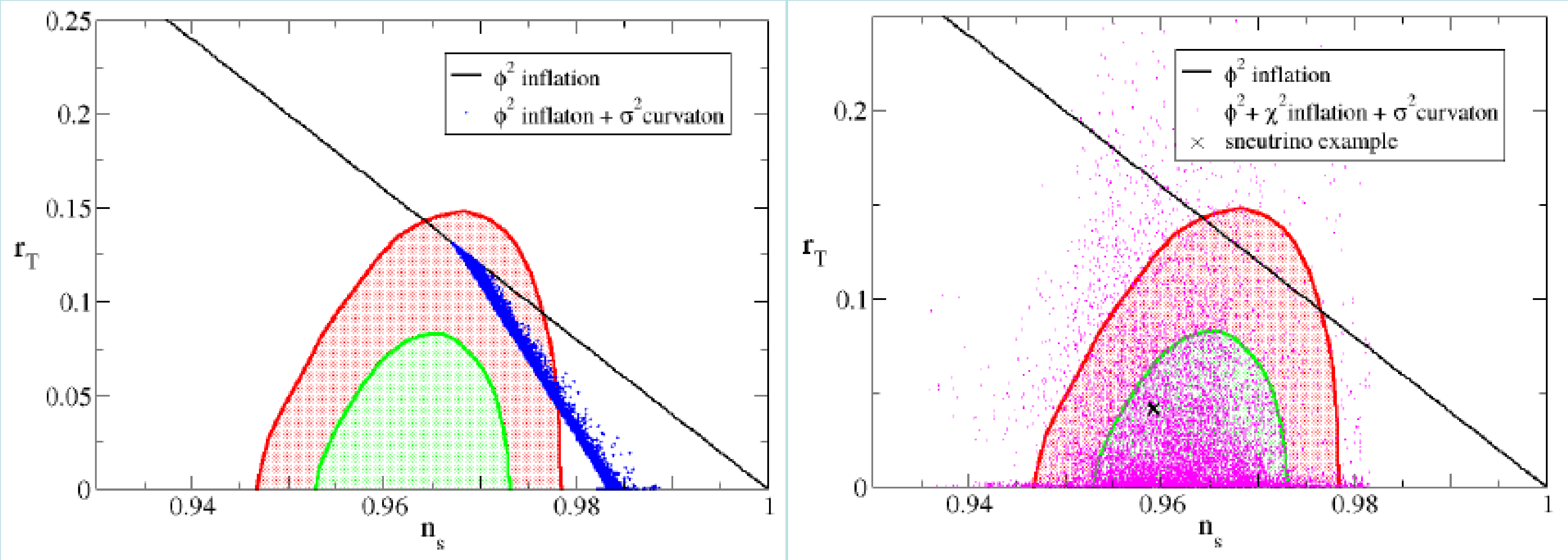


JE, Raidal & Yanagida: hep-ph/0303242

Multiple Sneutrino Inflation?

JE, Fairbairn & Sueiro: arXiv:1312.1353

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



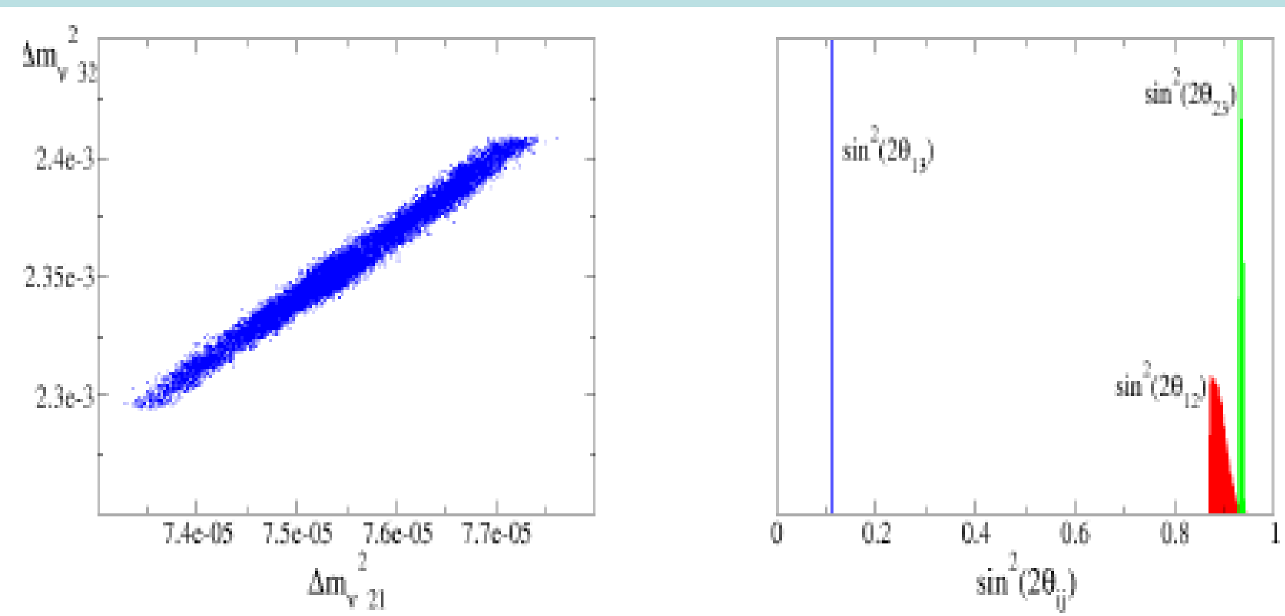
- Significant improvement with 3 sneutrinos

Multiple Sneutrino Inflation?

JE, Fairbairn & Sueiro: arXiv:1312.1353

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

- Neutrino masses and mixing



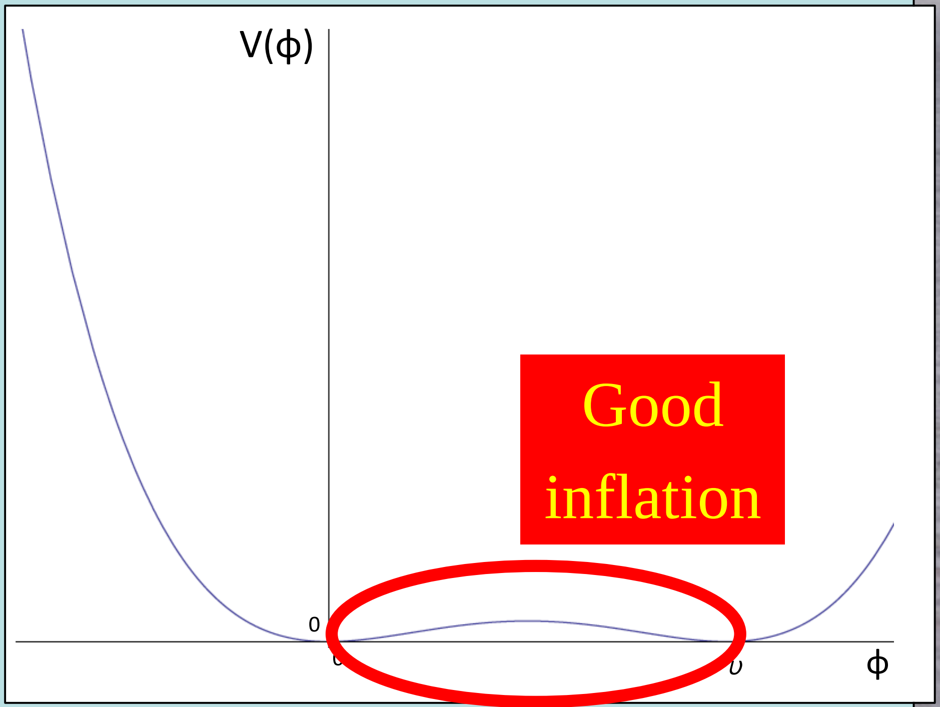
- Full set of model parameters

Parameter	Value
m_ϕ	2.6×10^{12} GeV
Γ_ϕ	2.2×10^{8} GeV
ϕ_*	2.2×10^{19} GeV
m_χ	2.2×10^{10} GeV
Γ_χ	1.5×10^{4} GeV
χ_*	2.4×10^{19} GeV
m_σ	980 GeV
Γ_σ	1.8×10^{-14} GeV
σ_*	1.2×10^{17} GeV
T_{reheat}	2.7×10^{3} GeV
δ_H	1.8×10^{-5}
n_s	0.9592
r_T	0.042
$m_{\nu1}$	4.85×10^{-2} eV
$m_{\nu2}$	4.92×10^{-2} eV
$m_{\nu3}$	3.1×10^{-7} eV

More General Polynomial Potential

- Consider single real field with double-well potential: $V = A\phi^2(v - \phi)^2$
- Shallower than φ^2 for

  $0 < \varphi < v$
- Better tensor-to-scalar ratio r for $0 < \varphi < v$
- Steeper than φ^2 for $\varphi < 0$ or $> v$: worse r



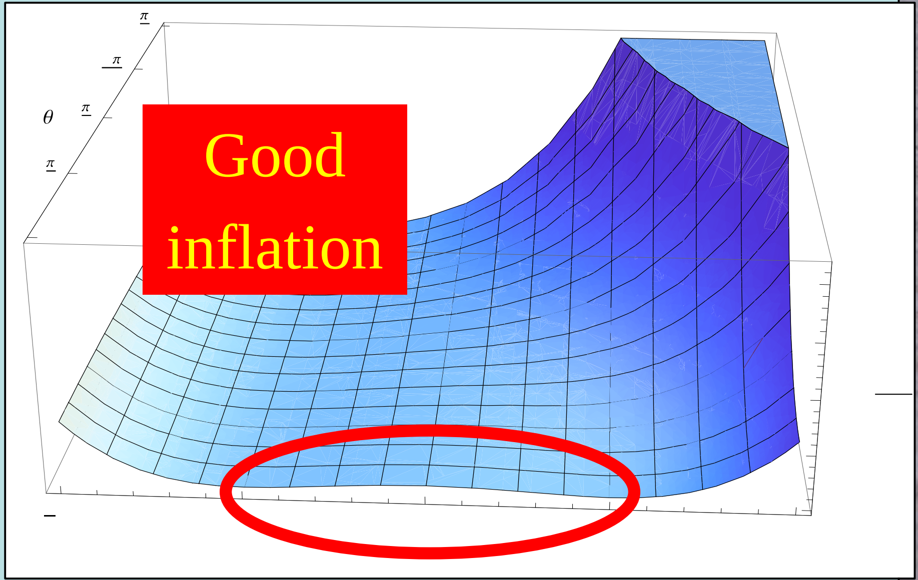
Croon, JE & Mavromatos: arXiv:1303.6253

Effective Potential in Wess-Zumino Model

- First (and minimal) supersymmetric field theory:

$$W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

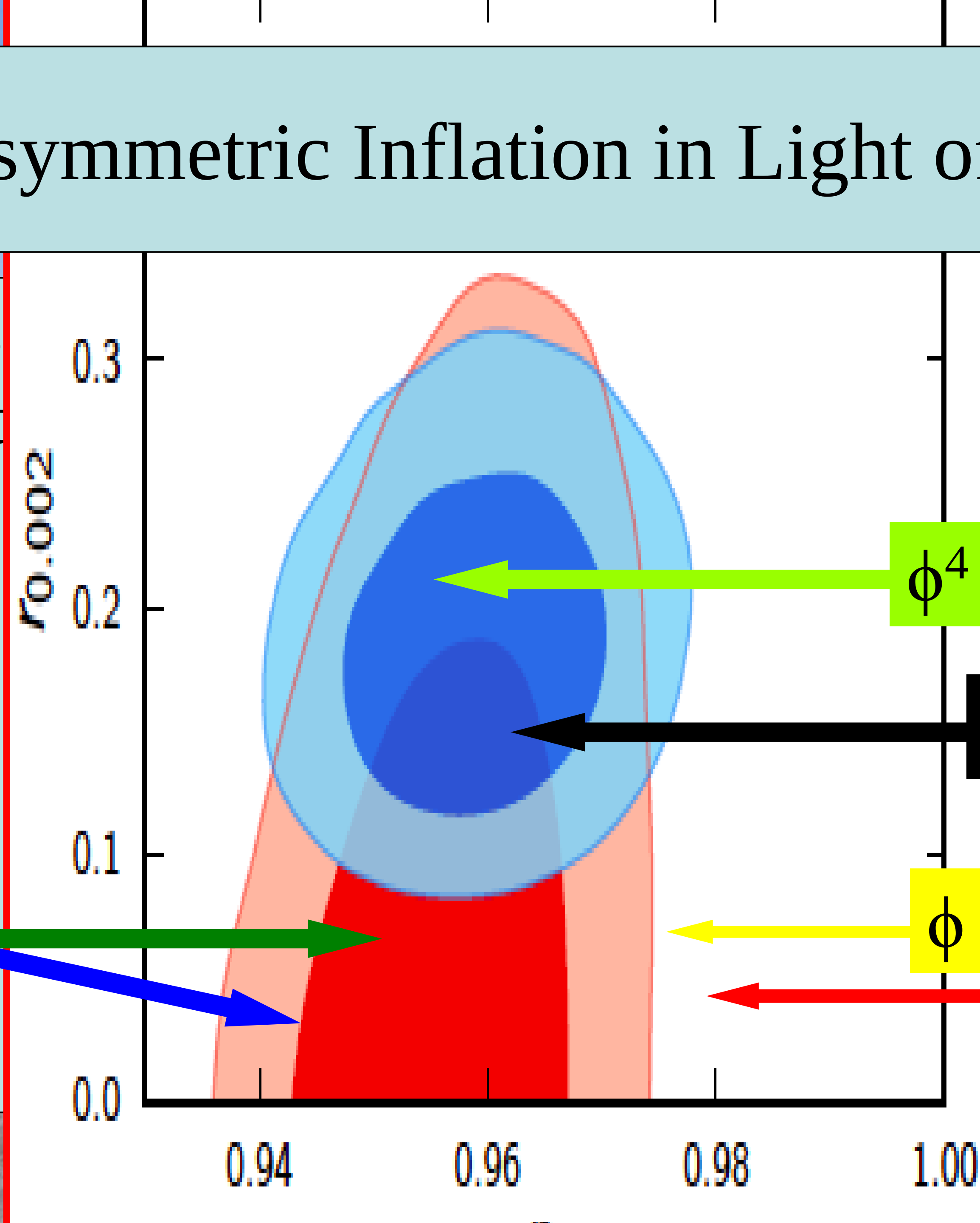
- Effective potential: $V = \left|\frac{\partial W}{\partial \phi}\right|^2 = A v^4 (x^4 - 2\cos\theta\, x^3 + x^2)$
- Equivalent to single-field model for θ = 0 (good)
- Combination of $\varphi^2 + \varphi^4$ for θ = π/2 (no good)
- **Good inflation possible**
  - **Inflaton could be sneutrino**



Croon, JE & Mavromatos: arXiv:1303.6253

Supersymmetric Inflation in Light of Planck

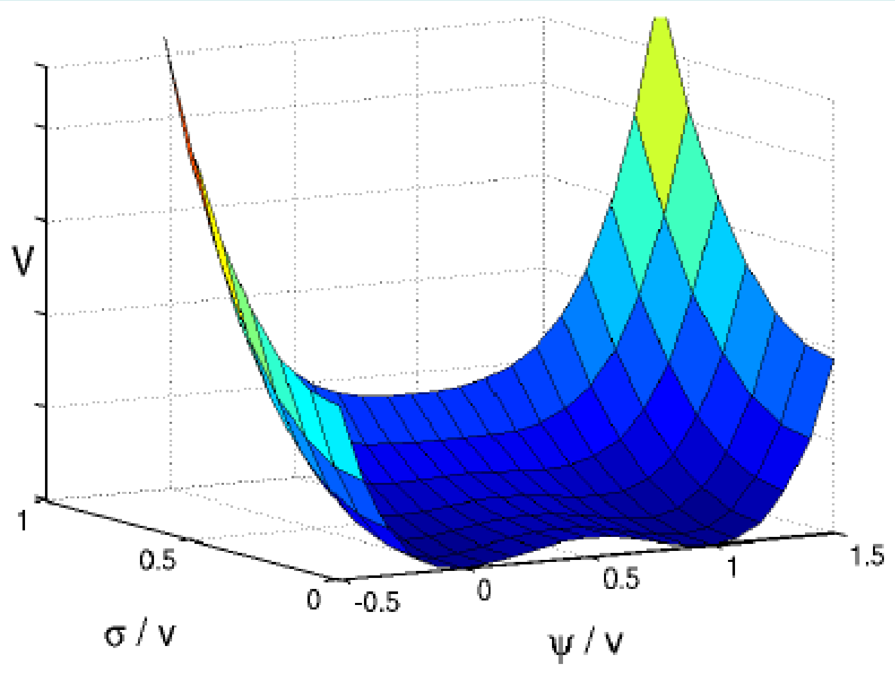
- Supers odel
  consist

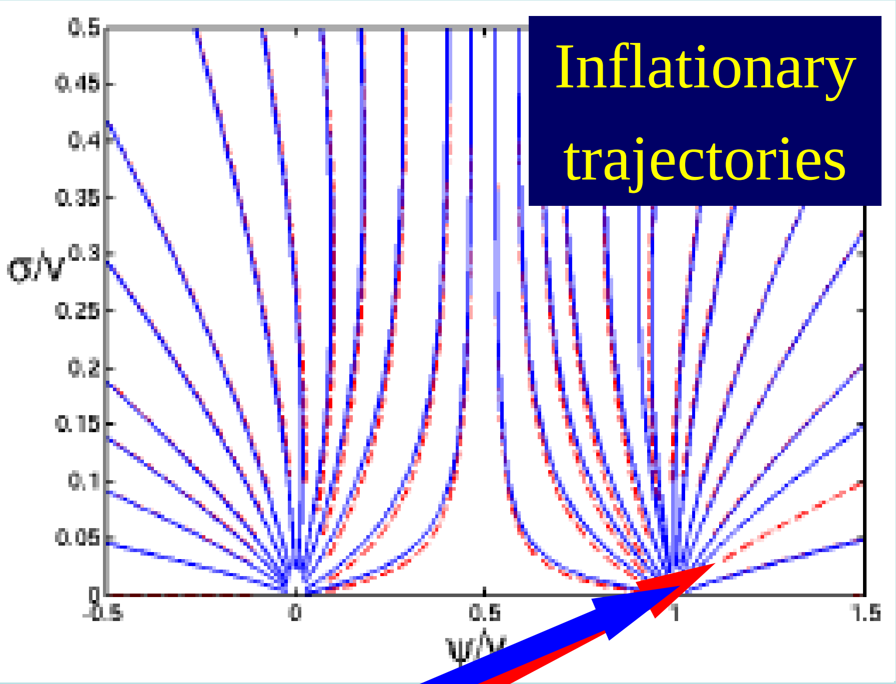


tos: arXiv:1303.6253

Exploring Wess-Zumino Inflation

- Generic SUSY models have 2 scalars: $\Phi = \psi + i\,\sigma$
- Explore 2-field parameter space of WZ model



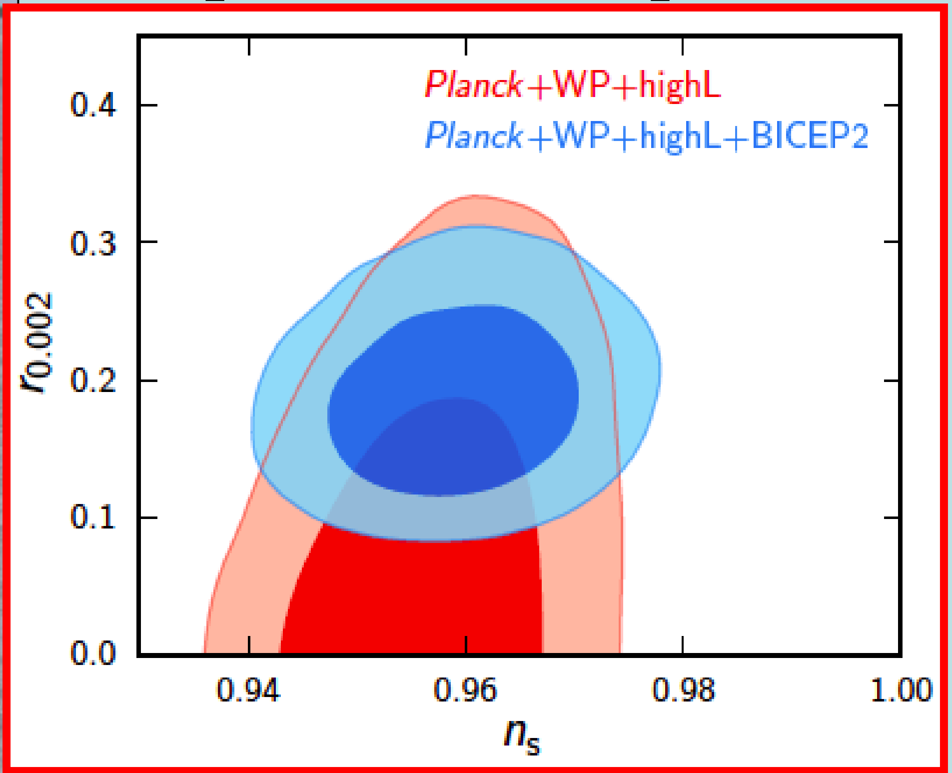


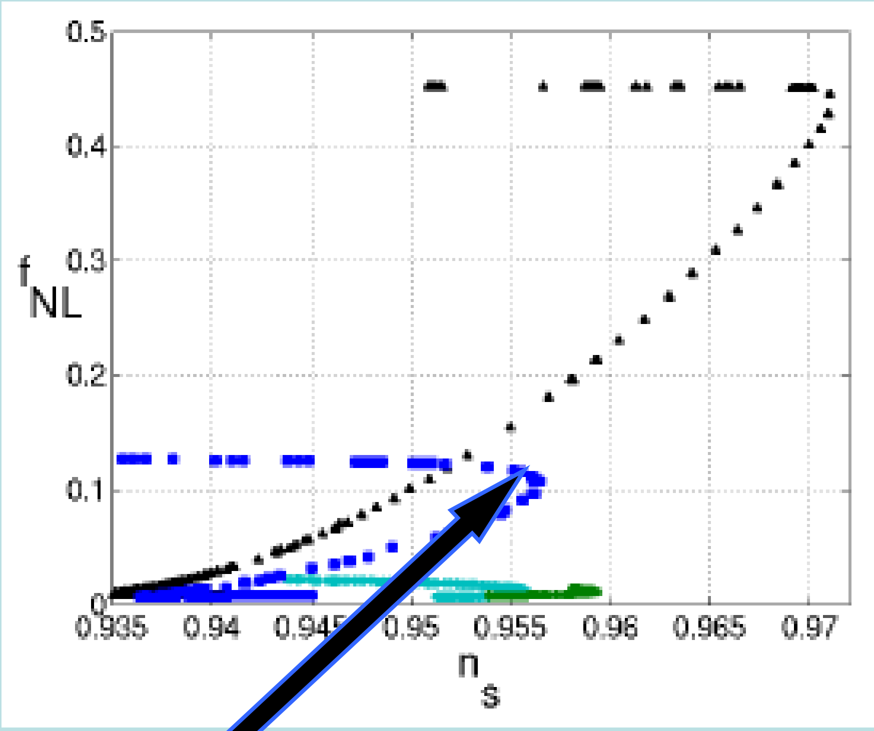
- Different trajectories for different v

JE, Mavromatos & Mulryne: arXiv:1401.6078

Exploring Wess-Zumino Inflation

- Explore 2-field parameter space of WZ model





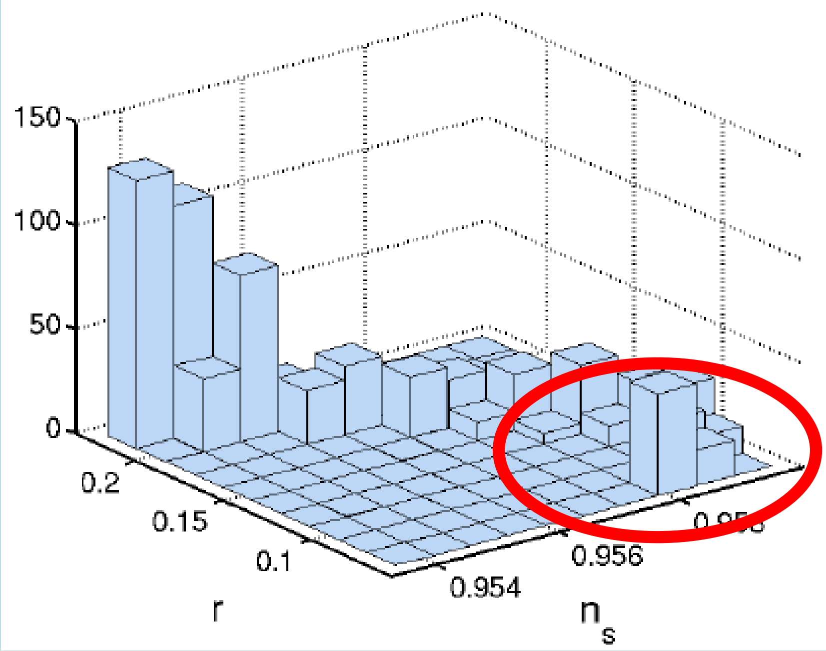
- Improved compatibility with Planck data
- Enhanced non-Gaussianity

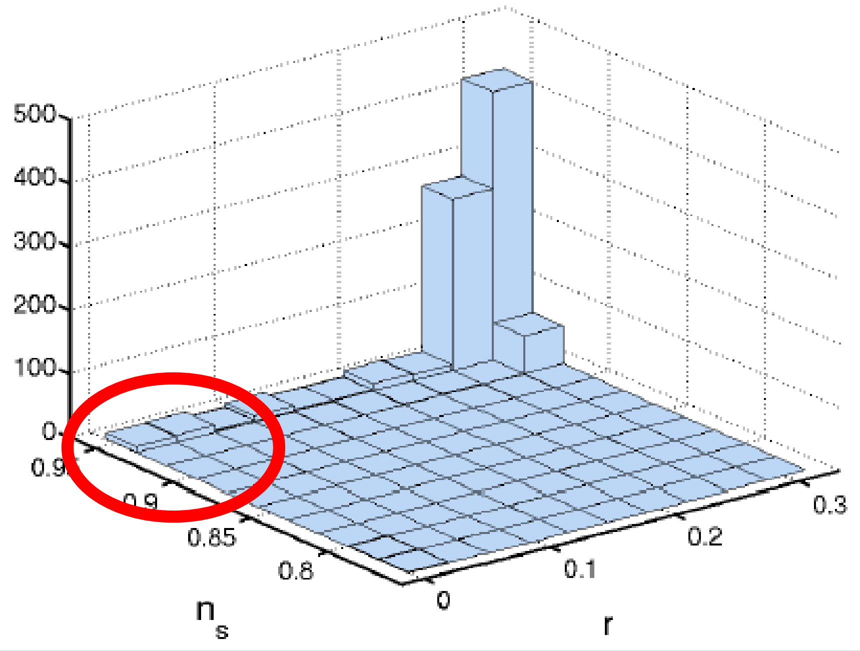
JE, Mavromatos & Mulryne: arXiv:1401.6078

Exploring Wess-Zumino Inflation

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

JE, Mavromatos & Mulryne: arXiv:1401.6078





- 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 ~ global model + controlled corrections

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537

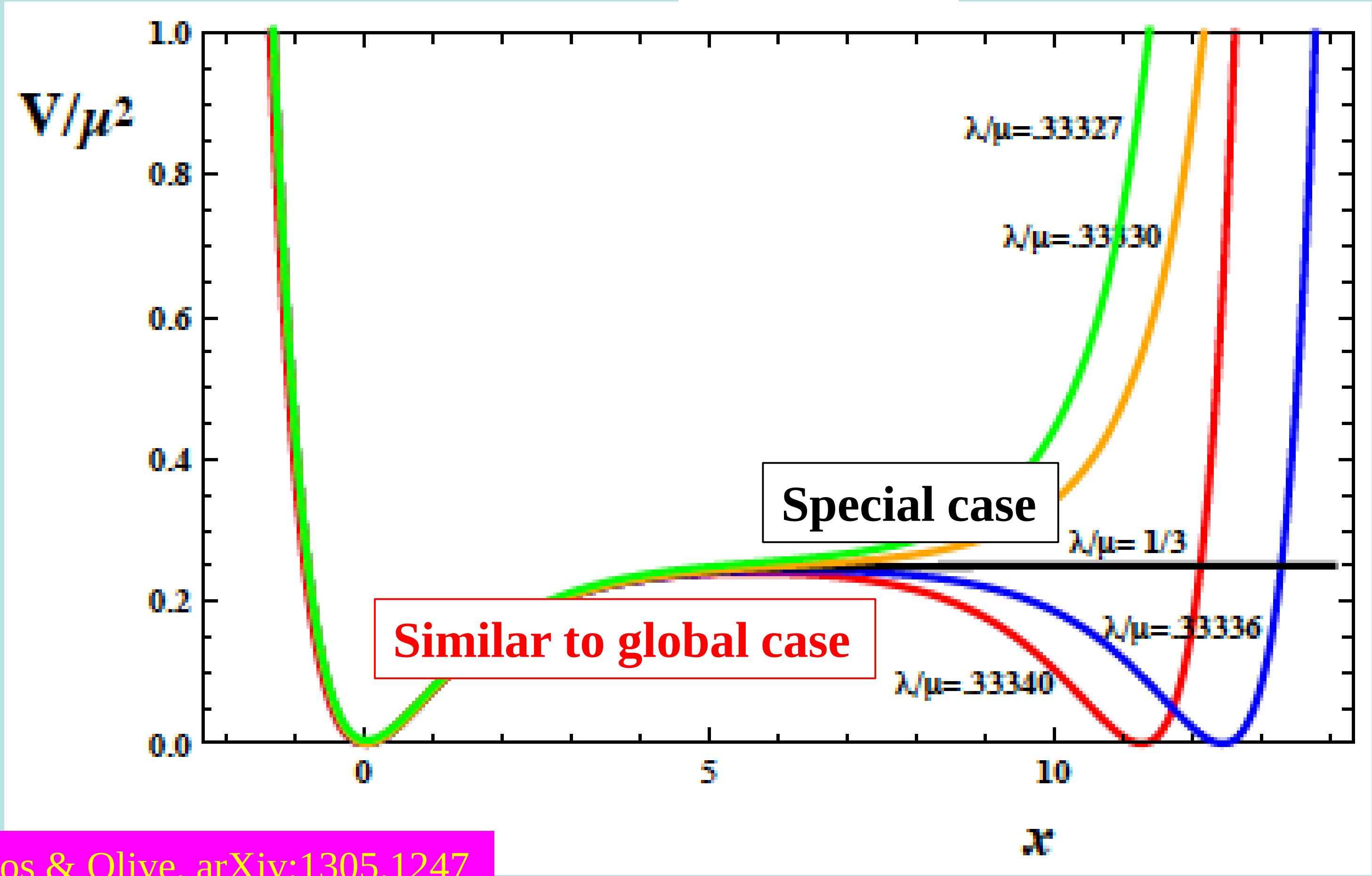
No-Scale Supergravity Inflation

- Simplest SU(2,1)/U(1) example:
- K ähler potential: $K = -3\ln(T + T^* - |\phi|^2/3)$
- Wess-Zumino superpotential: $W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$
- Assume modulus *T* = *c/2* fixed by 'string dynamics'
- Ef $\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$ $\hat{V} \equiv \left|\frac{\partial W}{\partial \phi}\right|^2$:
- Modifications to globally supersymmetric case
- Good inflation possible …

JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Supergravity Inflation

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



JE, Nanopoulos & Olive, arXiv:1305.1247

Is there more profound connection?

- Starobinsky model:

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- After conformal transformation:

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

- 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 $\lambda = \mu/3$

… it actually IS Starobinsky

JE, Nanopoulos & Olive, arXiv:1305.1247

See also …

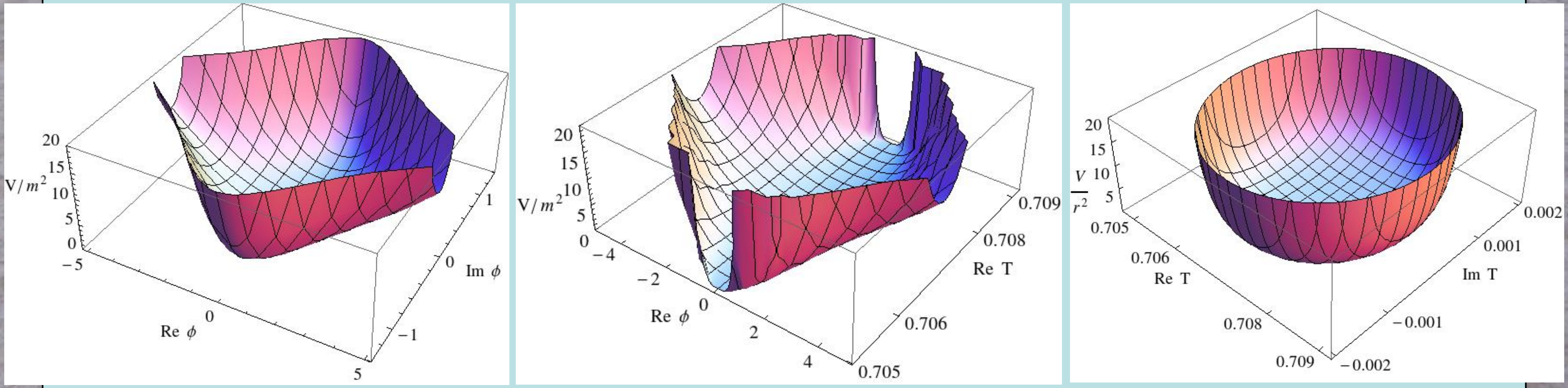
- Nakayama, Takahashi & Yanagida – arXiv:1305.5099
- Kallosh & Linde – arXiv:1306:3214
- Buchmuller, Domcke & Kamada – arXiv:1306.3471
- Kallosh & Linde – arXiv:1306.5220
- Farakos, Kehagias and Riotto – arXiv:1307.1137
- Roest, Scalisi & Zavala – arXiv:1307.4343
- Kiritsis – arXiv:1307.5873
- Ferrara, Kallosh, Linde & Porrati – arXiv:1307.7696
- …

No-Scale Supergravity Inflation in Light of BICEP2

- Possible to accommodate quadratic potential

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

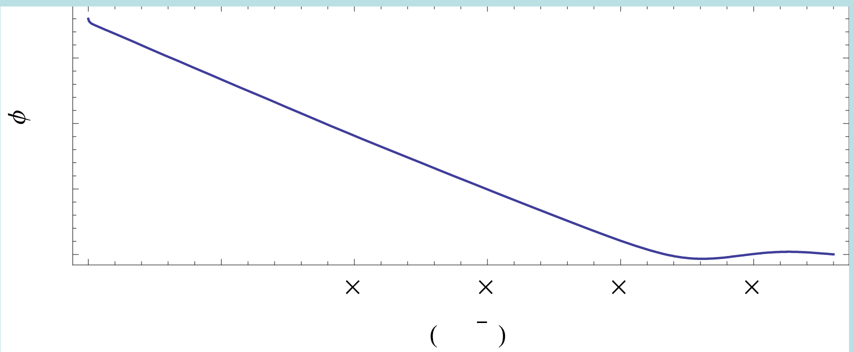
- Can stabilize T, Im ϕ while Re ϕ inflates

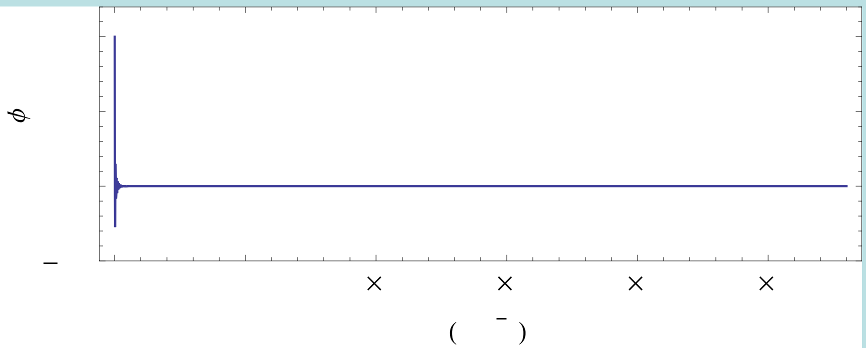


JE, García, Nanopoulos & Olive, arXiv:1403.7518

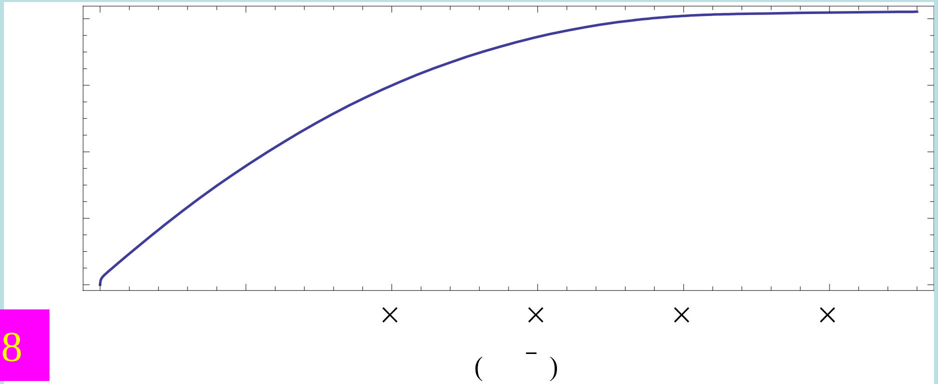
No-Scale Supergravity Inflation in Light of BICEP2

- Re ϕ evolves, Im ϕ small





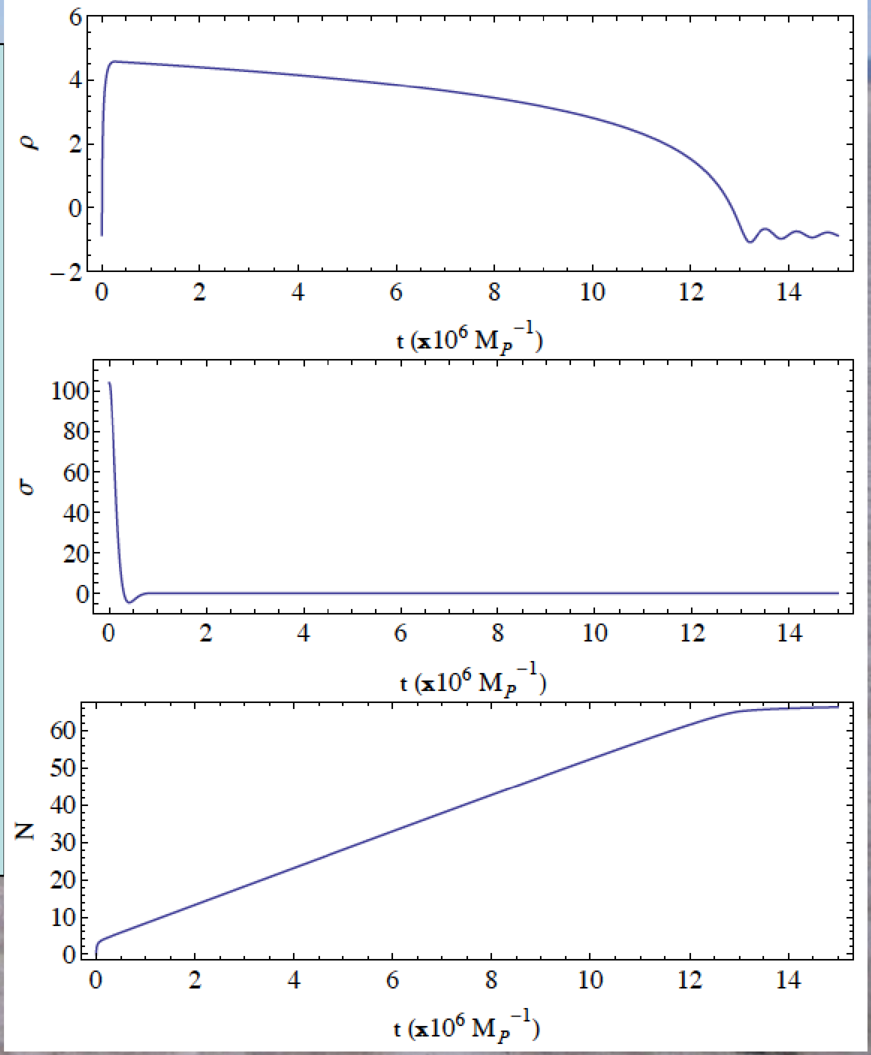
- Re T and Im T also well-behaved
- Sufficient inflation
- BICEP2-compatible



JE, García, Nanopoulos & Olive, arXiv:1403.7518

Supersymmetric Starobinsky Inflation in Light of BICEP2

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



JE, García, Nanopoulos & Olive, arXiv:1403.7518

Supersymmetric Starobinsky Inflation in Light of BICEP2

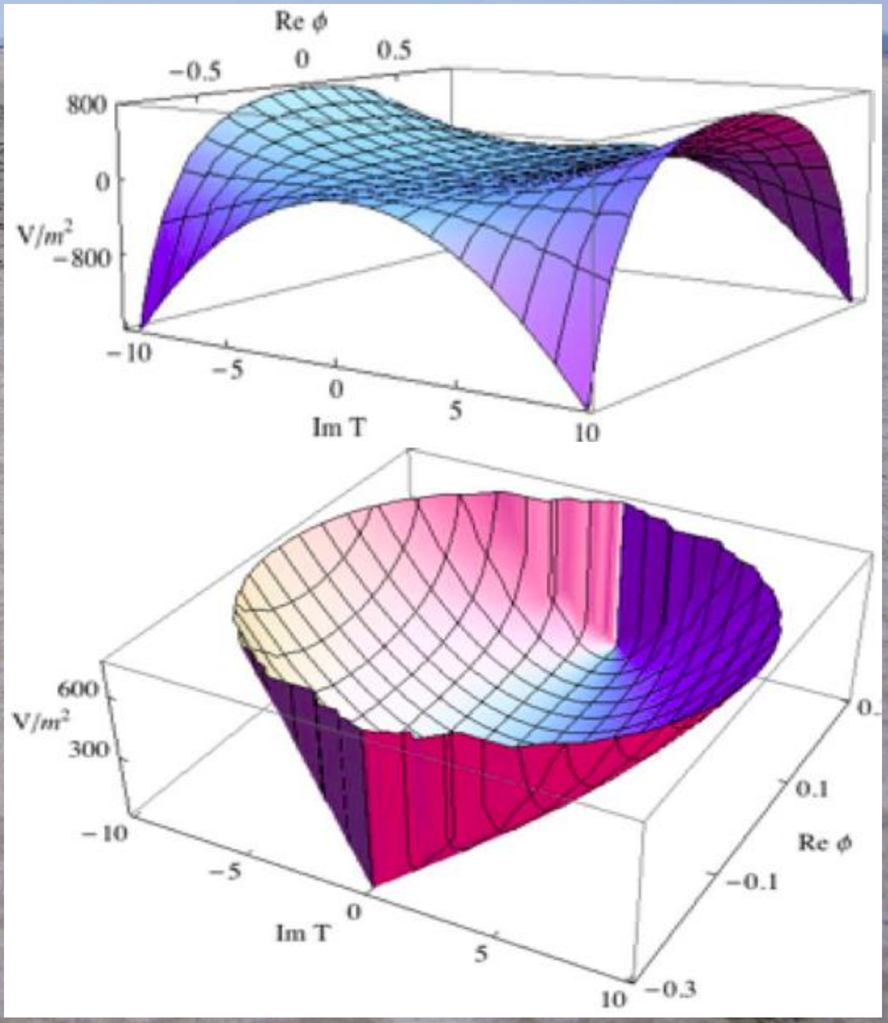
- Modify Kähler potential?

$$K = -3\ln\left(T + T^* - \frac{\phi\phi^*}{3} - \frac{(T+T*)^n}{\Lambda^2}\right)$$

- 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

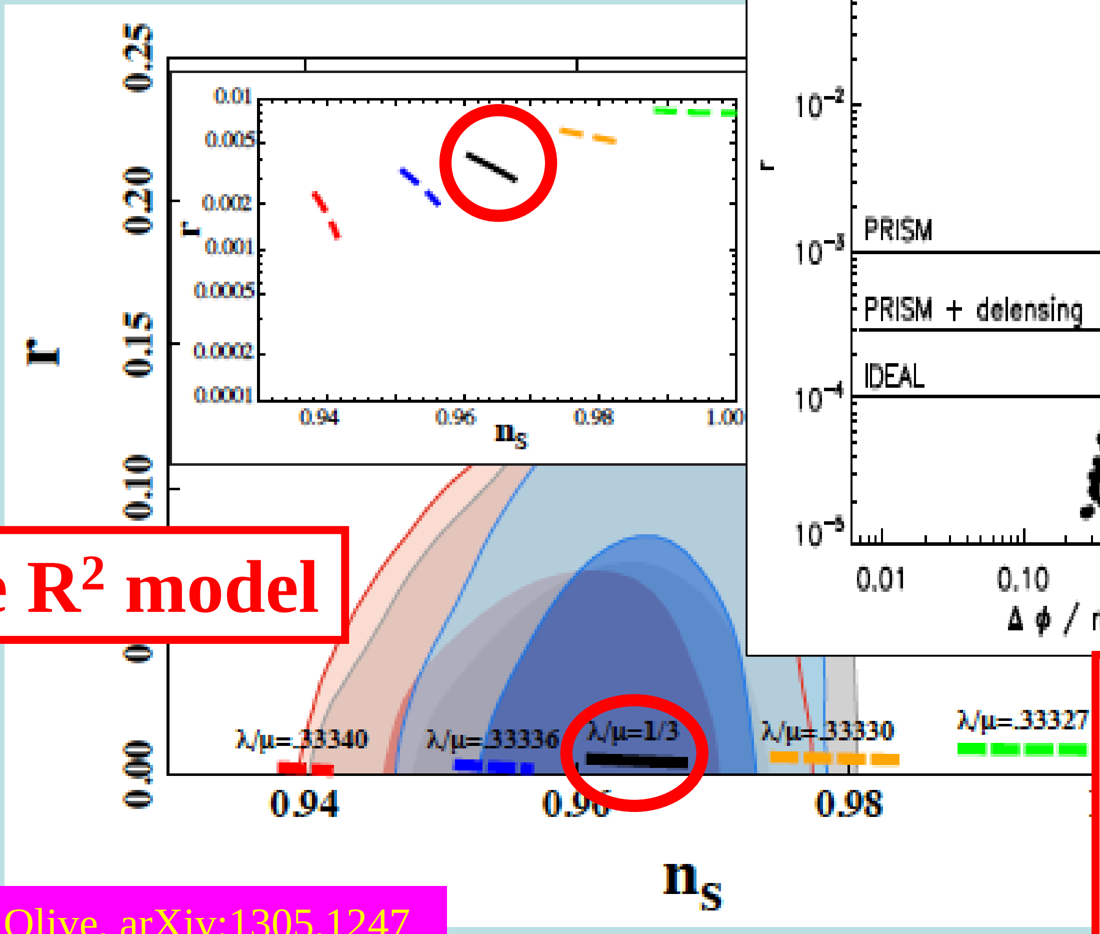
- Inflation may solve some of the biggest problems in cosmology: age, size, homogeneity, flatness, …
- Structures originated from quantum effects in the early Universe
- Another scalar field (inflaton) in the sky?
- Quantum gravitational radiation detected?
- Tension between Planck and BICEP2
- Inflation also cries out for supersymmetry
- Open season for building inflationary models
- Inflaton = superpartner of neutrino?

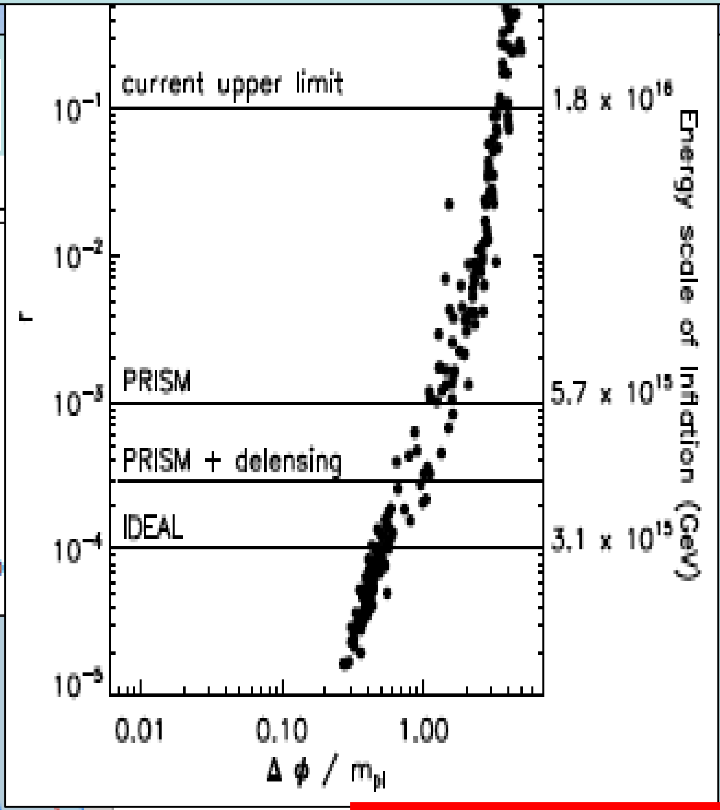
Time for China to get involved in CMB Experiments?

Crossing the Scalar Rubicon: Once or Twice?

No-Scale Supergravity Inflation

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





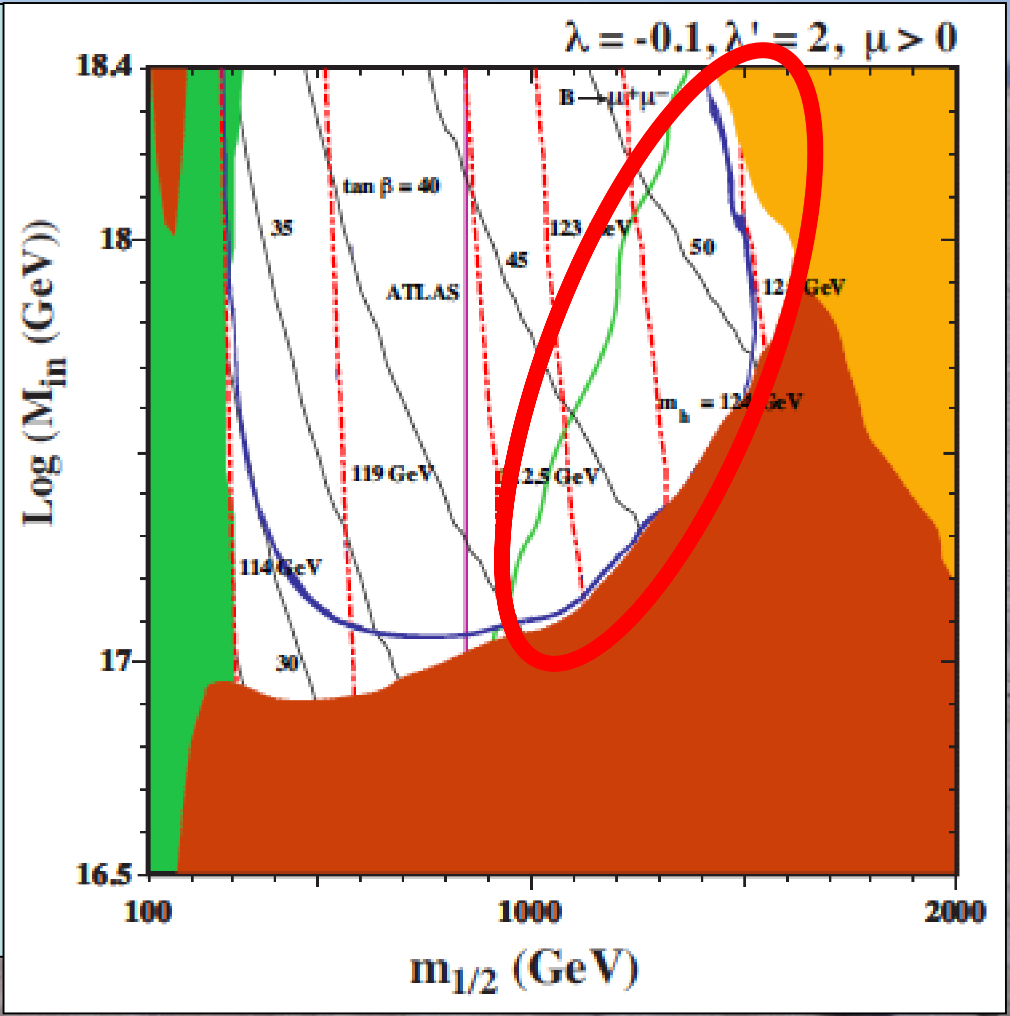
Looks like R^2 model

Accessible to future Experiment?

JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Framework for Particle Physics & Dark Matter

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



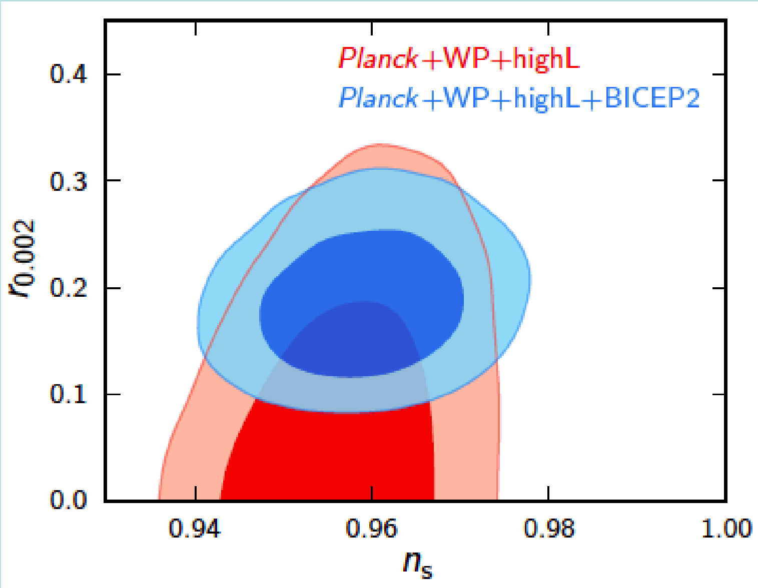
JE, Nanopoulos & Olive, arXiv:1310.4770

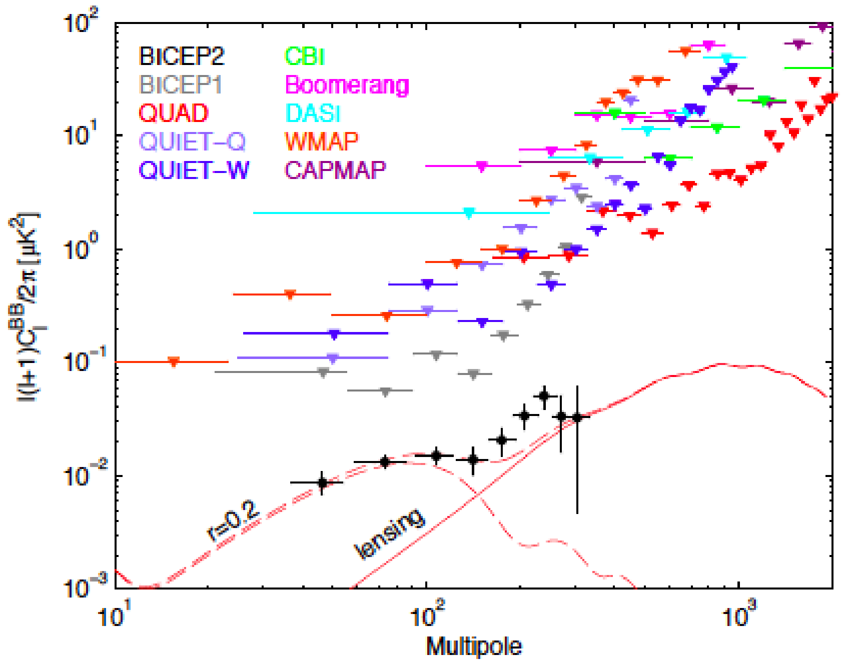
Inflationary Models in Light of BICEP2

- 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**



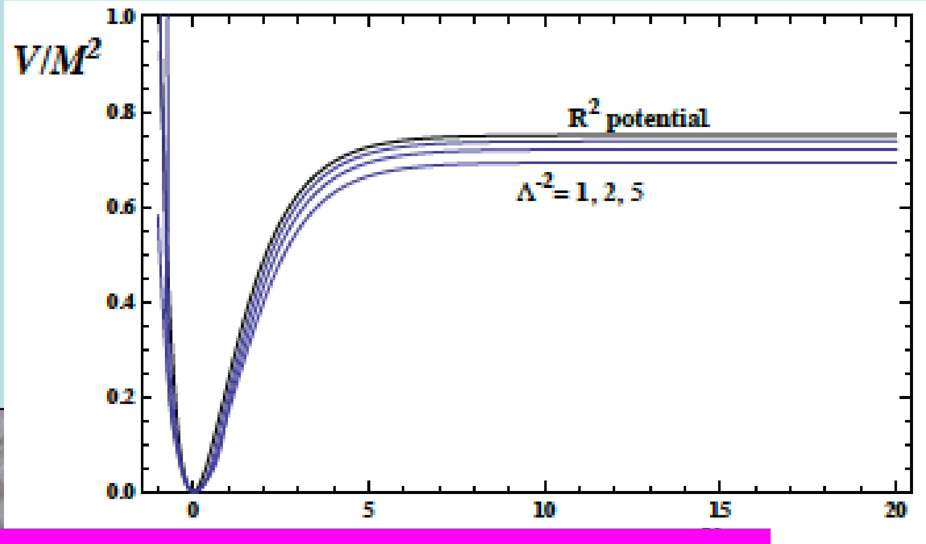


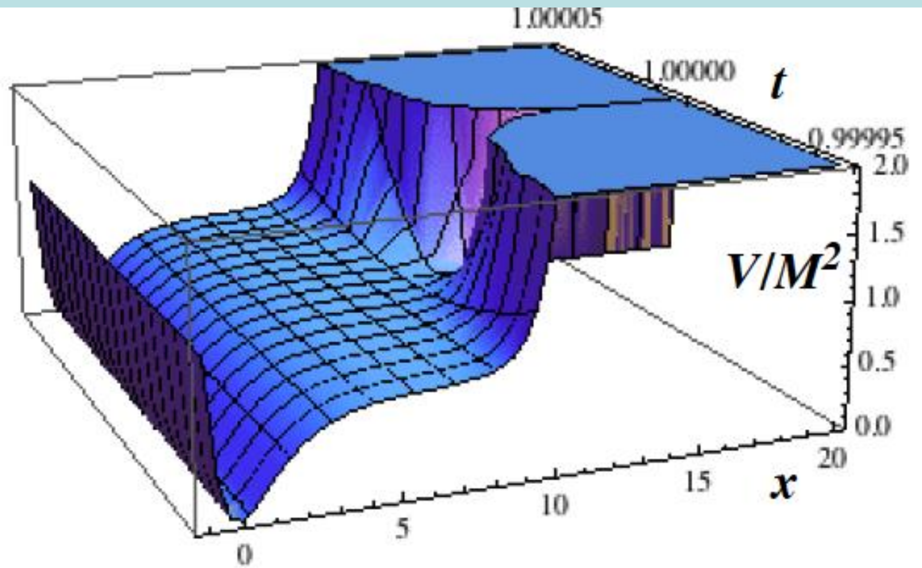
Stabilization of Modulus Field

- 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 ~ Starobinsky
- Other field directions stabilized:





JE, Nanopoulos & Olive, arXiv:1307.3537

Generalizations

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

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

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

$$W = \sqrt{3}M\phi(T-1/2) \quad W = 2\sqrt{3}M\phi T(T-1/2) \quad W = M\left[\sqrt{3}(T^2-1/4)\phi + (T-1/2)\phi^2\right]$$

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

also yield Starobinsky-like inflationary models

JE, Nanopoulos & Olive, arXiv:1307.3537

Beyond Starobinsky

- Exponential approach to constant potential:

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

- Relations between observables:

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

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

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

$$K \ni -\Sigma_i N_i \ln(T_i + T_i^*) : \quad N_i > 0, \quad \Sigma_i N_i = 3$$

- 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?**

JE, Nanopoulos & Olive, arXiv:1307.3537

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:

Cornwall, Levin & Tiktopoulos; Bell; Llewellyn-Smith

(1) group (2) representations (3) symmetry breaking

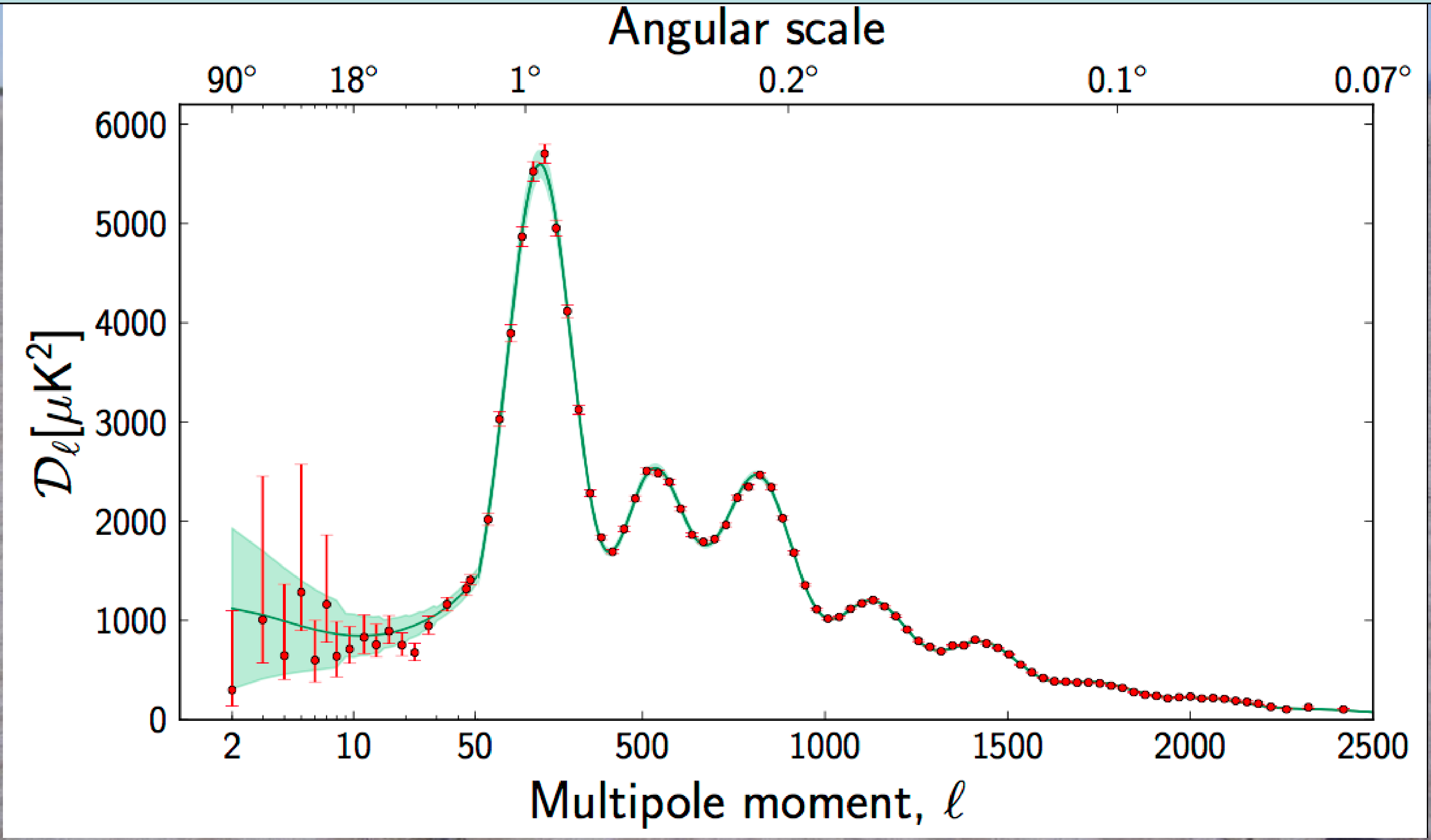
(1) = SU(3) × SU(2) × U(1) [so far]

(2) = Singlets + doublets + triplets

- Finally:

(3) A scalar, mechanism of symmetry breaking

Measurements of CMB Fluctuations with Planck Satellite



Wess-Zumino Inflation in Light of Planck

- Consistent with Planck for x_i = 0.3, 0.4

Value of x_i	0.1	0.2	0.3	0.4
Derived quantity				
$\frac{v^2}{M_{Pl}^2}$	18000	4200	1600	710
ϵ	0.0085	0.0067	0.0045	0.0020
η	0.0062	0.00074	-0.0073	-0.022
ξ	-0.000053	-0.000077	-0.000079	-0.000050
r	0.14	0.11	0.072	0.031
n_s	0.961	0.961	0.958	0.945
α_s	-1.4×10^{-6}	-1.3×10^{-6}	-1.4×10^{-6}	-1.1×10^{-6}
λ	4.3×10^{-8}	1.0×10^{-7}	2.1×10^{-7}	4.1×10^{-7}

- Numbers calculated for N = 50 e-folds

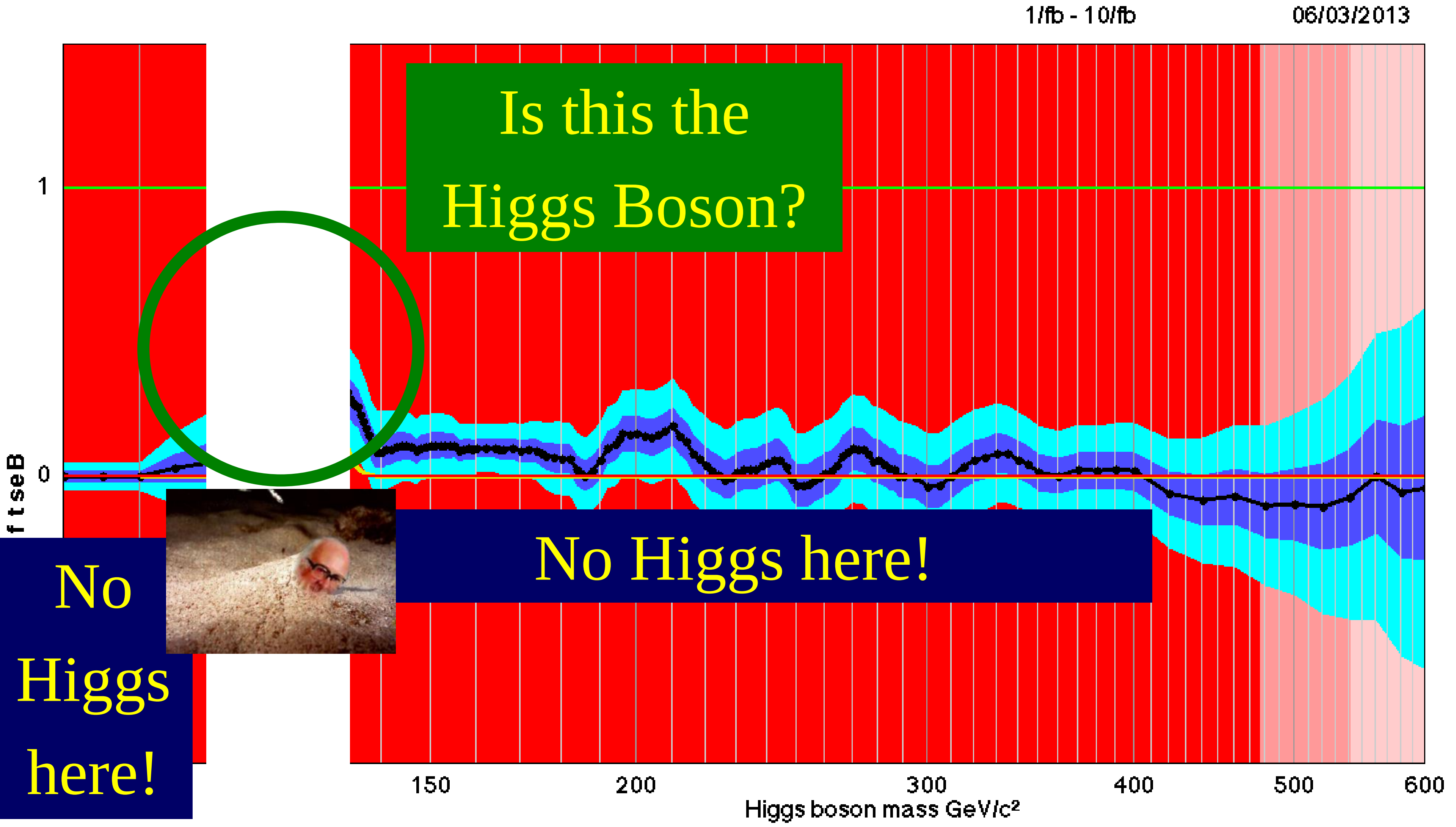
Good inflation

Croon, JE & Mavromatos: arXiv:1303.6253

July 4th 2012

The discovery of a new particle

Unofficial Combination of Higgs Data



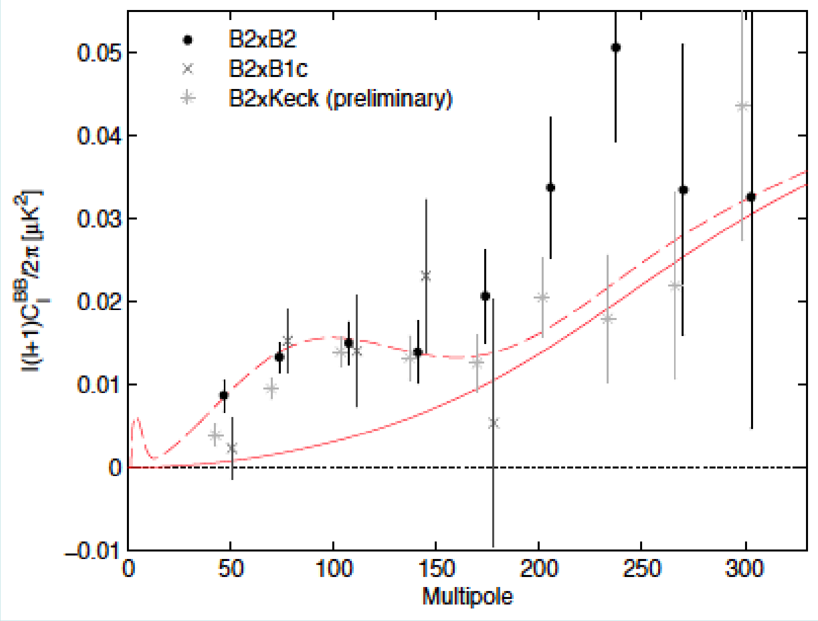
Is this the Higgs Boson?

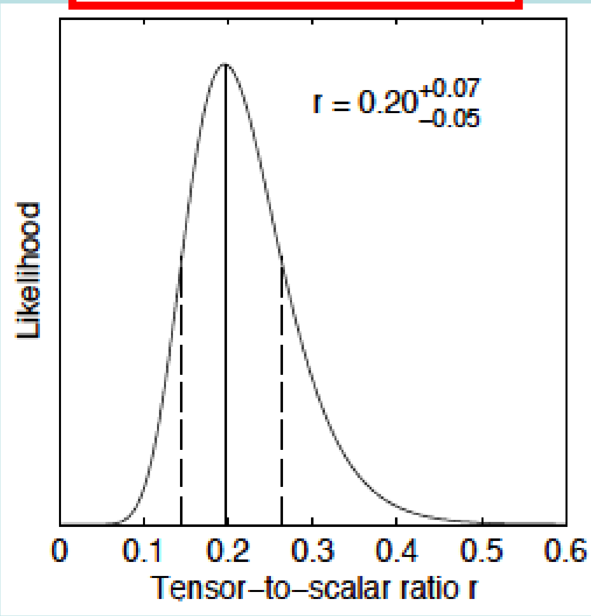
No Higgs here!

No Higgs here!

Inflationary Models in Light of BICEP2

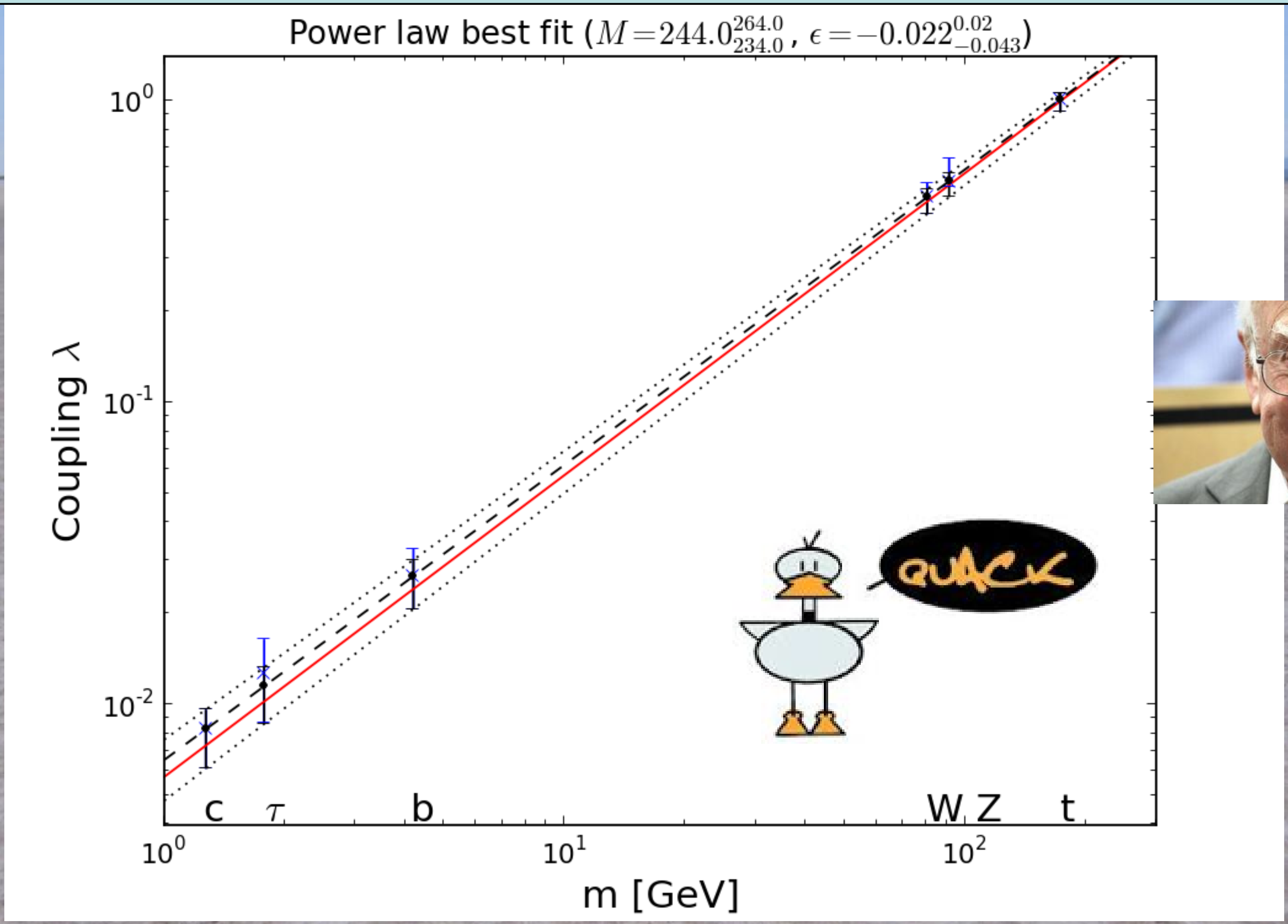
- **QUANTUM GRAVITY RADIATION!**
- BICEP2 observations support for inflation
- “Large” tensor-to-scalar ratio: $\boxed{r = 0.20^{+0.07}_{-0.05}}$





- **Starobinsky R^2 dead, quadratic inflation OK?**

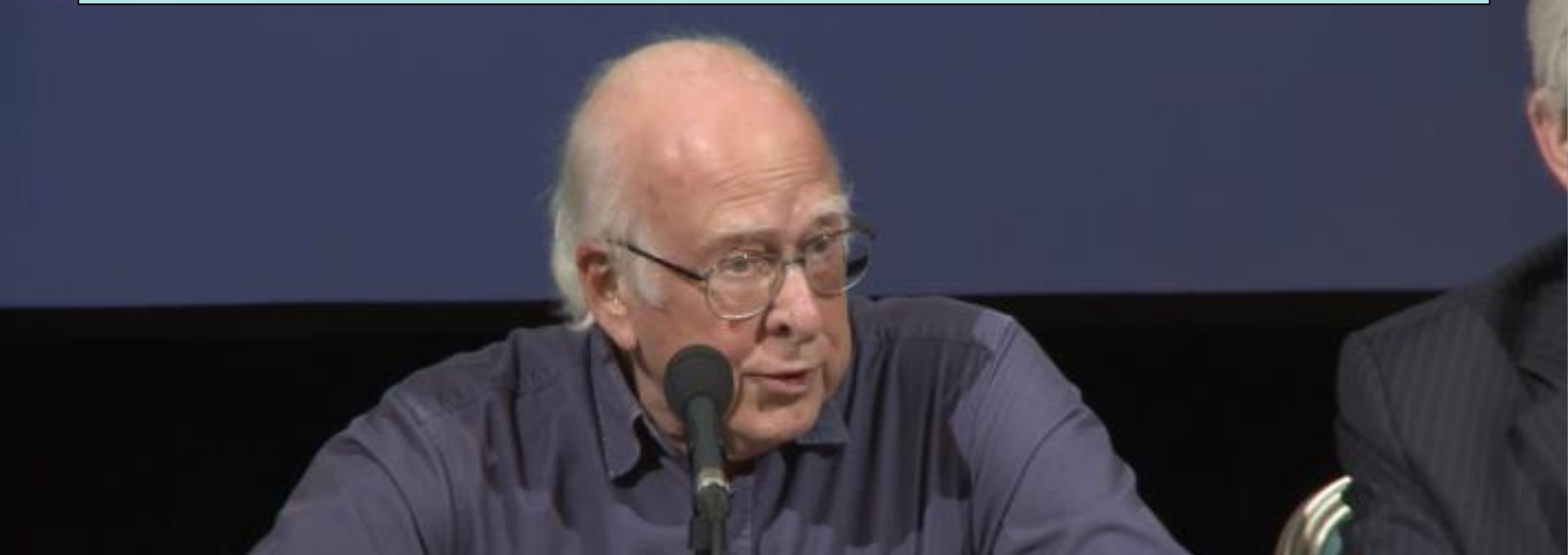
It Walks and Quacks like a Higgs



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

JE & Tevong You, arXiv:1303.3879

Dixit Swedish Academy



Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

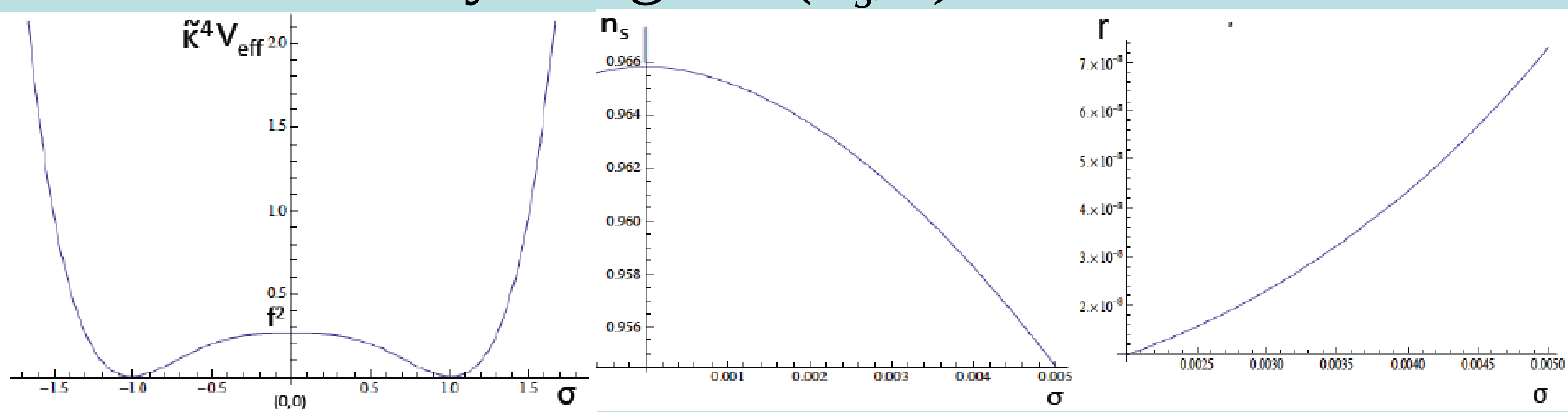
[1] = JE & Tevong You, arXiv:1303.3879

Gravitino Inflation

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

$$e^{-1}\,\mathcal{V}_{\rm eff\ infl}\ =\ \tilde{\kappa}^{-4}\left[0.4878\,\sigma^4\,\ln\sigma^2 - 0.2549\,\sigma^4 - 0.0022\,\sigma^2 + 0.2574\right]$$

- 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?