Models of Inflation:

a Bridge between String Theory and Particle Physics?

10^{28} cm

Big Bang

What happened here?

A connection with here?

13.8 Billion Years

Today

10^{28} cm
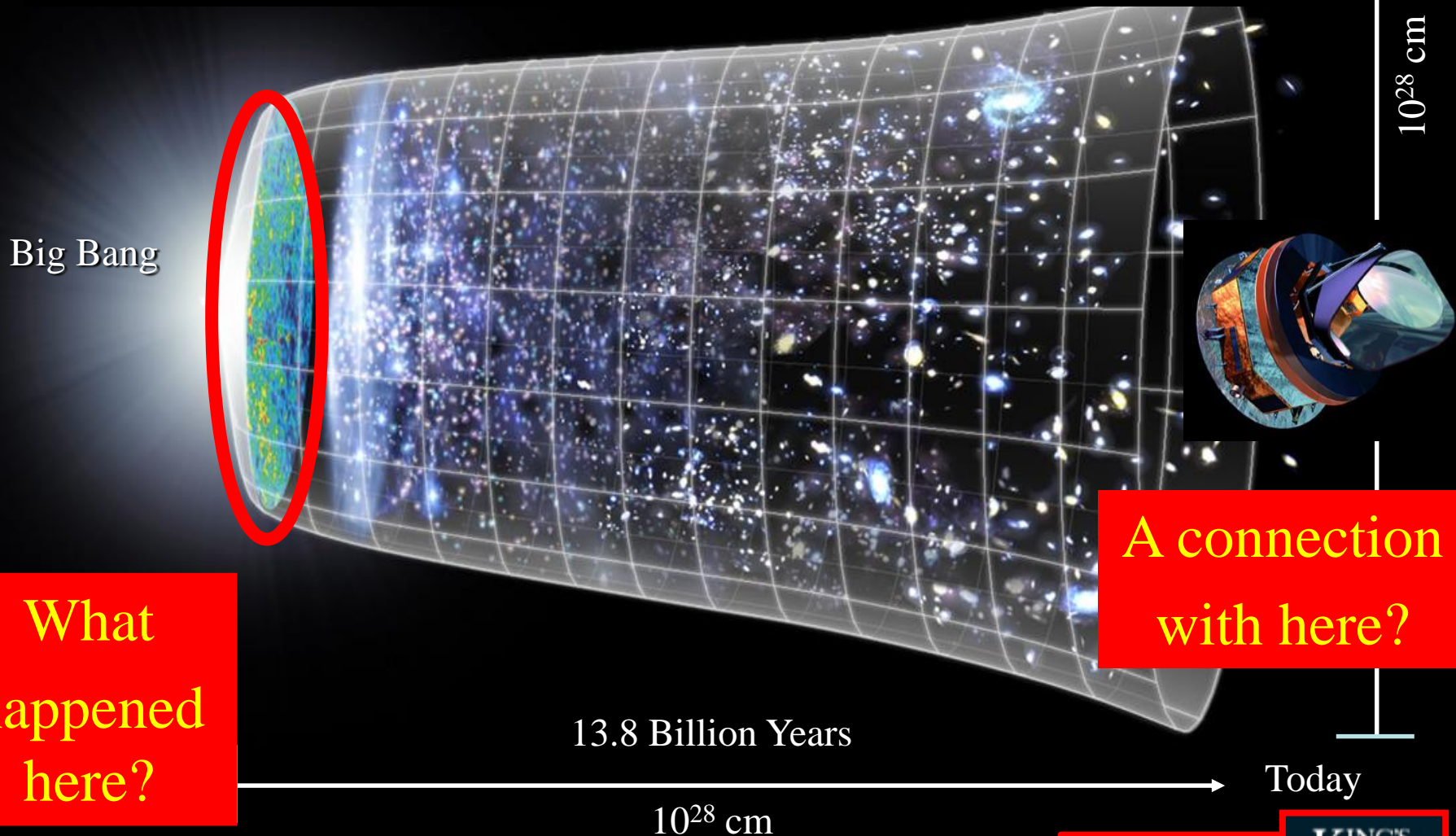
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Slow-Roll Inflation

- 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 CMB Observables

- Scalar and tensor perturbations
- Tilt in scalar spectrum (running down hill)

$$n_s = 1 - 6\epsilon + 2\eta$$

- Tensor perturbations = gravitational waves of quantum origin
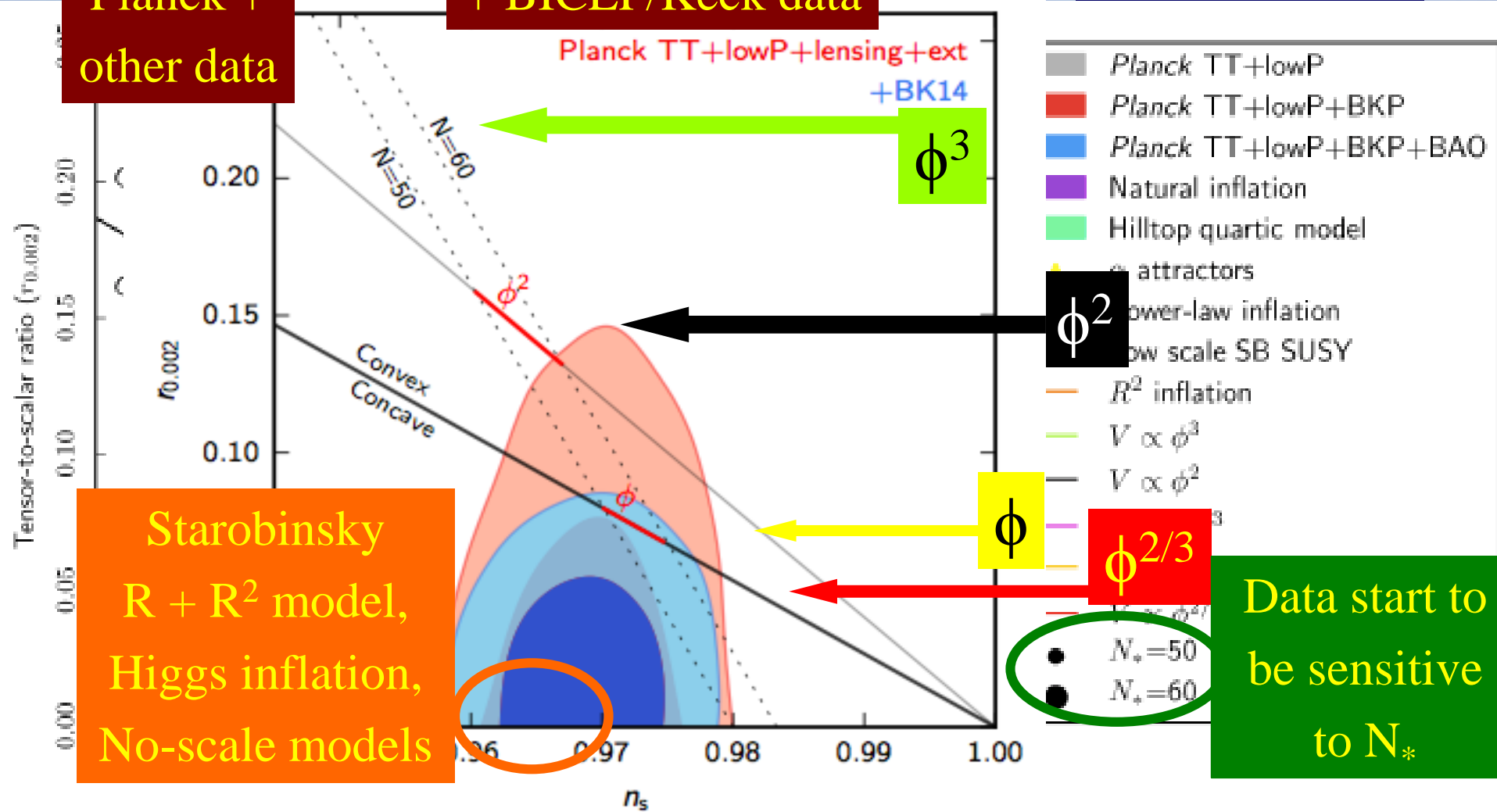- Tensor/scalar ratio:

$$r = 16\epsilon$$

- Are perturbations ~ Gaussian?
  - Look for deviations, e.g., f_{NL}
- Expected to be small in slow-roll models

Inflationary Landscape

Monomial Single-field potentials

Planck + other data

+ BICEP/Keck data

Starobinsky R + R² model, Higgs inflation, No-scale models

ϕ^3

ϕ^2

ϕ

$\phi^{2/3}$

Data start to be sensitive to N_*

Planck TT+lowP+lensing+ext

+BK14

Tensor-to-scalar ratio ($r_{0.002}$)

$r_{0.002}$

0.20

0.15

0.10

0.05

0.00

$N=60$
$N=50$

ϕ^2

Convex
Concave

ϕ

0.96   0.97   0.98   0.99   1.00

n_s

	Planck TT+lowP
	Planck TT+lowP+BKP
	Planck TT+lowP+BKP+BAO
	Natural inflation
	Hilltop quartic model
	α attractors
	Power-law inflation
	Low scale SB SUSY
	R^2 inflation
	$V \propto \phi^3$
	$V \propto \phi^2$
	$V \propto \phi^{4/3}$

$N_* = 50$
$N_* = 60$

# Challenges for Inflationary Models

- Links to low-energy physics?
  - Only SM candidate for inflaton is Higgs
    - **BUT** negative potential ....
- Link to other physics?
  - SUSY partner of RH (singlet) neutrino?
  - Some sort of axion?
- Links to Planck-scale physics?
  - Inflaton candidates in string theory?
  - Inflaton candidates in compactified string models?

Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation

- Tilted scalar perturbation spectrum (rolling down):

$$n_s = 0.968 \pm 0.006$$

- **BUT** strengthen upper limit on tensor perturbations: $r < 0.1$

- Challenge for many simple inflationary models

- **Starobinsky R^2 to rescue?**

- **Higgs/Supersymmetry/supergravity to rescue?**
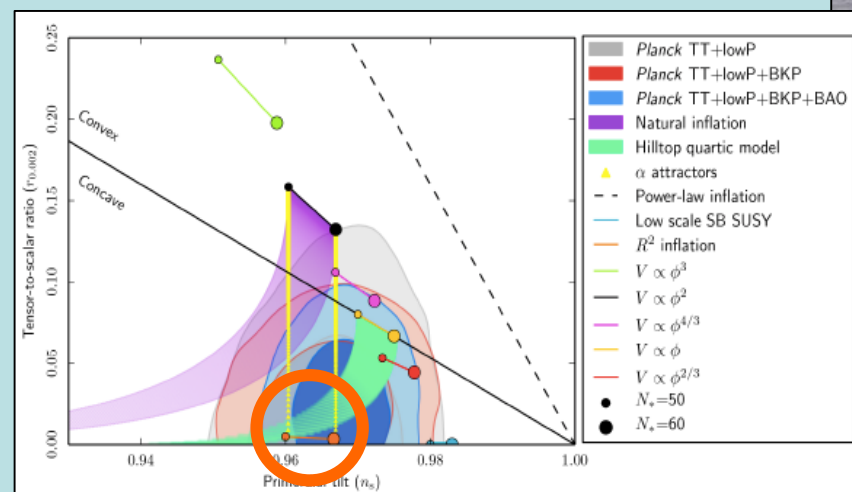
Starobinsky Model

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

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

- **No scalar!?**

- Inflationary interpretation, calculation of perturbations:

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

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

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

Higgs Inflation: a Single Scalar?

- Standard Model with non-minimal coupling to gravity:

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

- 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

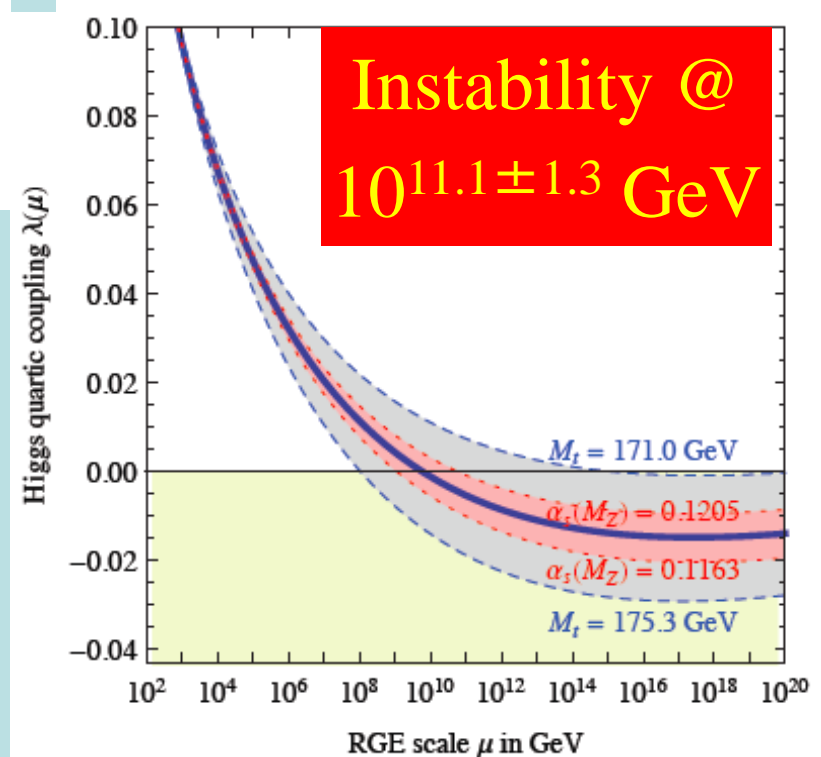- Successful inflationary potential at $\chi \gg M_P$

Problem for Higgs Inflation

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

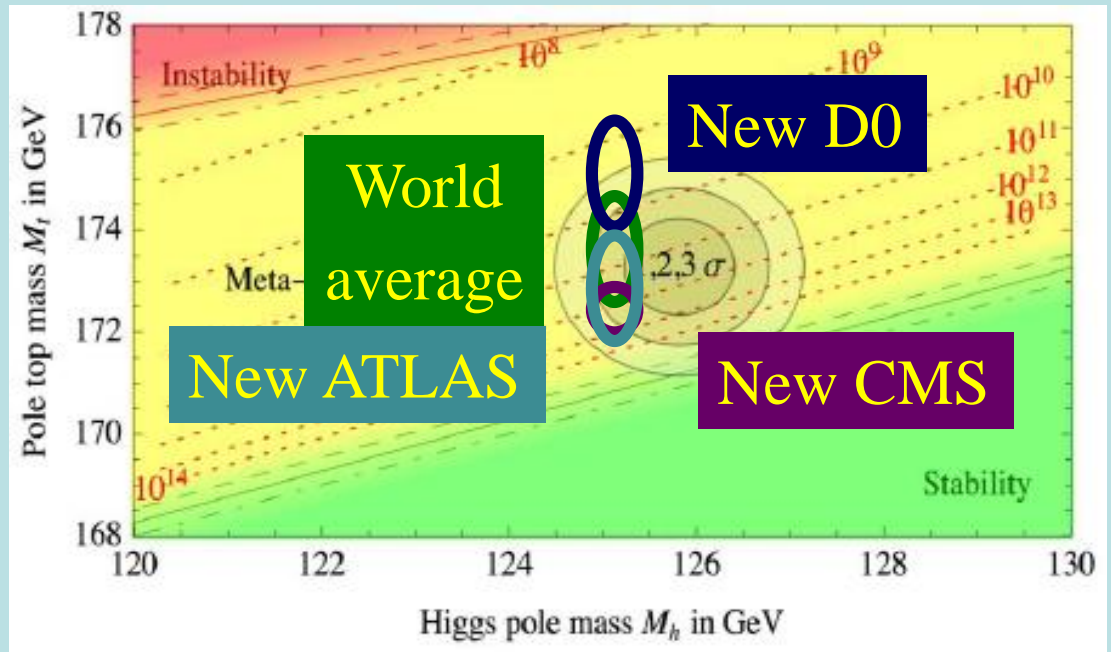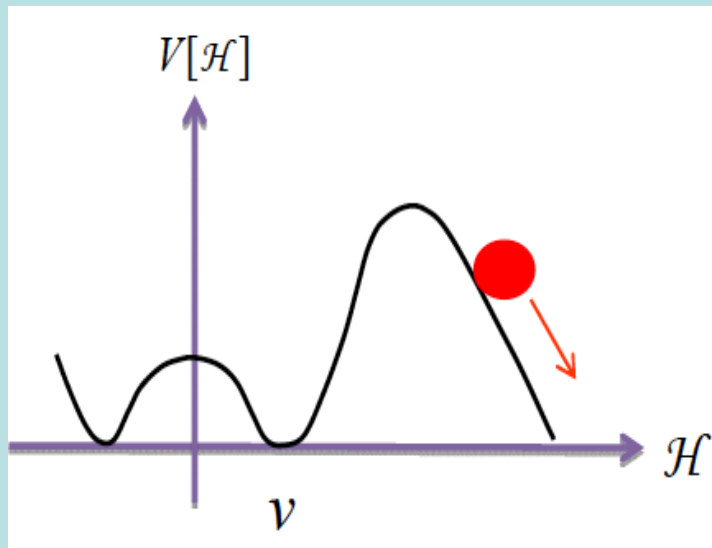$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

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

Instability @ $10^{11.1 \pm 1.3}$ GeV

- **Negative potential not suitable for inflation**
- **Problem avoided with supersymmetry**

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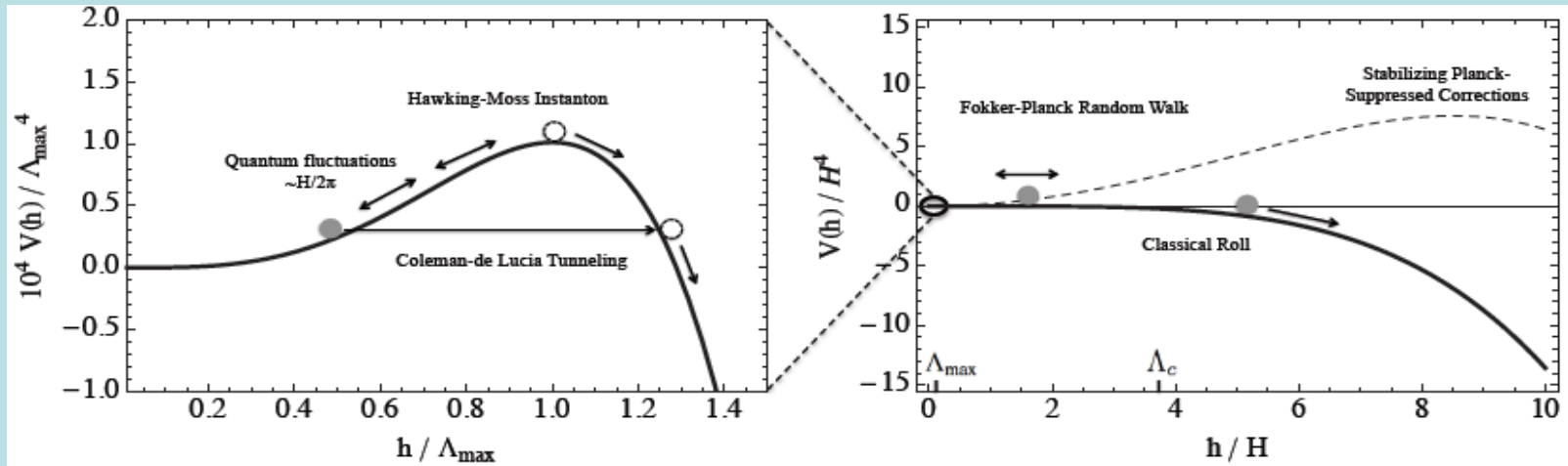
$$\log_{10} \frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0 \left(\frac{M_h}{\text{GeV}} - 125.66 \right) - 1.2 \left(\frac{M_t}{\text{GeV}} - 173.10 \right) + 0.4 \frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

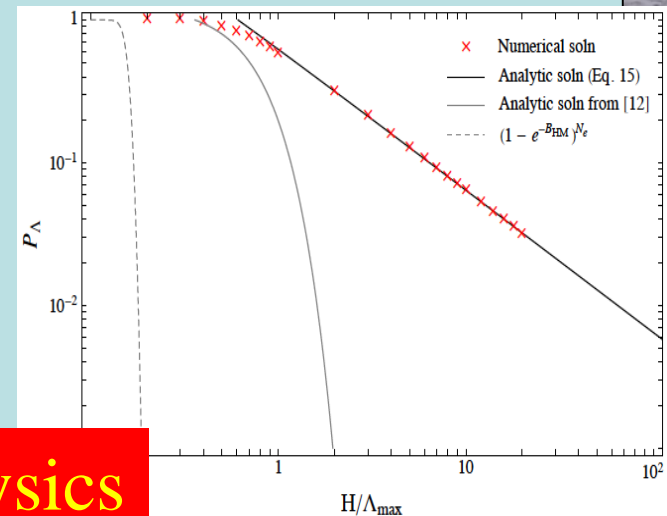$m_t = 173.3 \pm 1.0 \text{ GeV}$ ➔ $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$

Instability during Inflation?

- Do inflation fluctuations drive us over the hill?

- Then Fokker-Planck evolution

- Do AdS regions eat us?

  – Disaster if so

  – If not, OK if more inflation

Avoid with new physics

What lies beyond the Standard Model?

Supersymmetry

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

New motivations
From LHC Run 1

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 φ^2 models)

- And/or prefer small self-coupling $\lambda << 1$

- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive, & Tamvakis: 1983

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**

  Cremmer, Ferrara, Kounnas & Nanopoulos, 1983
- **Appears in compactifications of string**

  Witten, 1985
- Flat directions, scalar potential ~ global model + controlled corrections

  JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

  JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537, …

No-Scale Supergravity Inflation Revived

- Simplest SU(2,1)/U(1) example:

- Kähler potential: $K = -3\ln(T + T^* - |\phi|^2/3)$

- Wess-Zumino superpotential: $W = \dfrac{\mu}{2}\Phi^2 - \dfrac{\lambda}{3}\Phi^3$

- Assume modulus $T = c/2$ fixed by 'string dynamics'

- Eff $\mathcal{L}_{eff} = \dfrac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \dfrac{\hat{V}}{(c - |\phi|^2/3)^2}$ $\hat{V} \equiv \left|\dfrac{\partial W}{\partial \phi}\right|^2$

  :

- Modifications to globally supersymmetric case

- Good inflation possible …

No-Scale Supergravity Inflation

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

Special case = Starobinsky

$\lambda/\mu = .33327$
$\lambda/\mu = .33330$
$\lambda/\mu = 1/3$
$\lambda/\mu = .33336$
$\lambda/\mu = .33340$

JE, Nanopoulos & Olive, arXiv:1305.1247
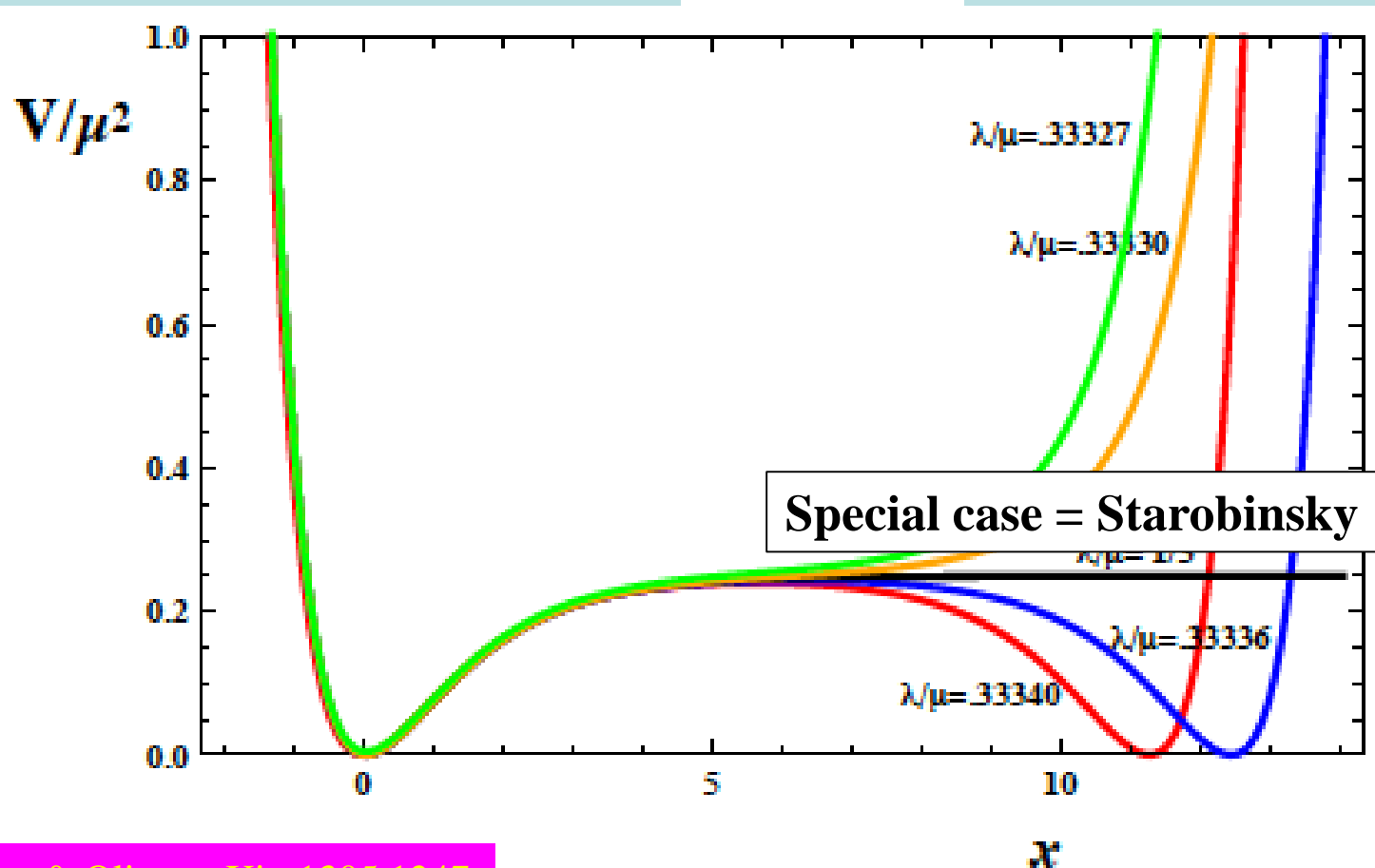
Is there more profound connection?

- 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

Cecotti, 1987

JE, Nanopoulos & Olive, arXiv:1305.1247

Beyond Starobinsky

- Exponential approach to constant potential:

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

- Relations between observables:

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

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

- 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:

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

$$r = \frac{4N_i}{N_*^2}.$$

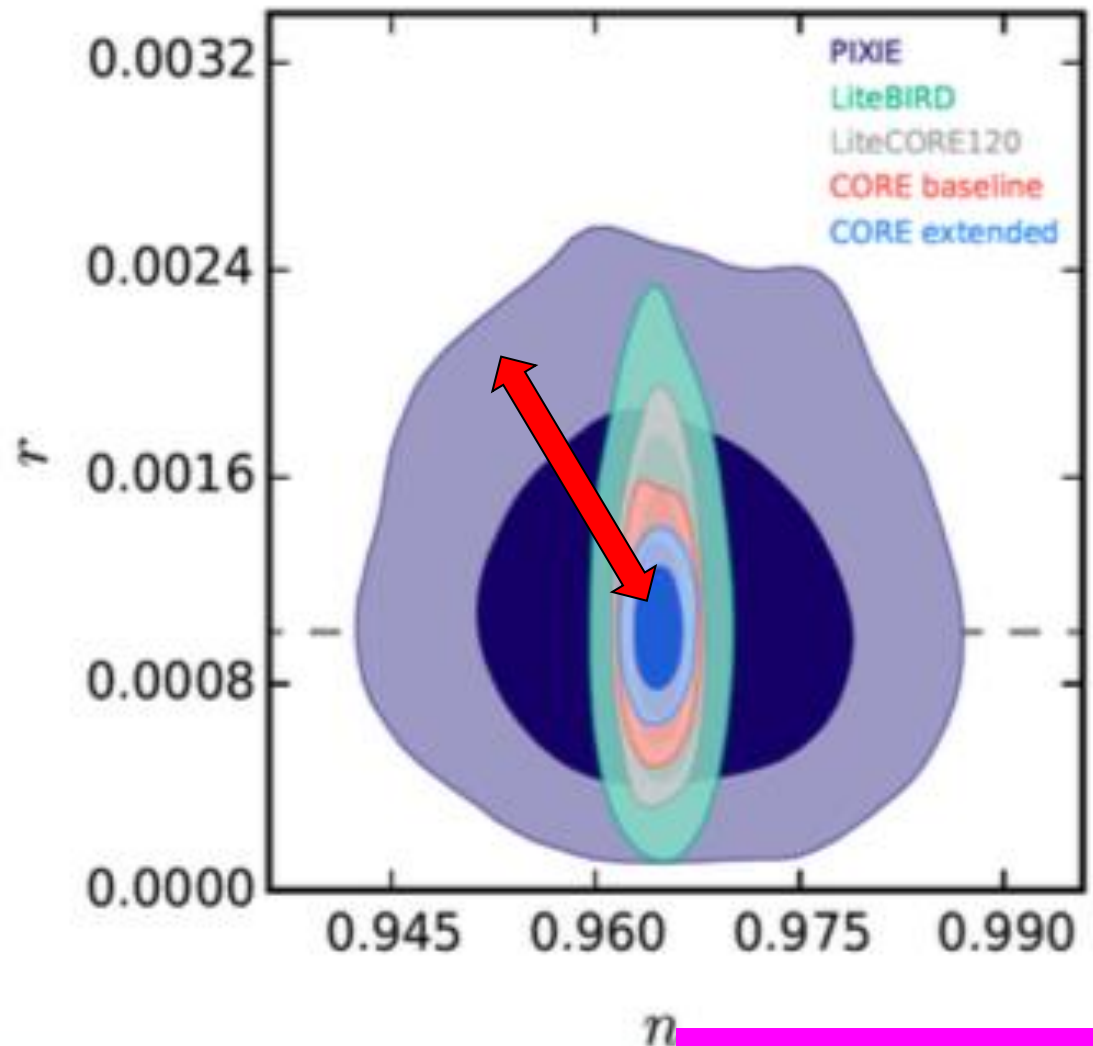- **String phenomenology via the CMB?** JE, Nanopoulos & Olive, arXiv:1307.3537

Ferrara, Kallosh, Linde & Porrati – arXiv:1307.7696

Inflationary Dream

- String-inspired inflationary model with inflation by a Kähler modulus:

$$K \ni -\Sigma_i N_i \ln(T_i + T_i^*)$$

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

- $N_i = 1$
- N_* in [44, 59]

See also …

- Nakayama, Takahashi & Ya…
- Kallosh & Linde – arXiv:13…
- Buchmuller, Domcke & Ka…
- Kallosh & Linde – arXiv:13…
- Farakos, Kehagias and Riott…
- Roest, Scalisi & Zavala – ar…
- Kiritsis – arXiv:1307.5873
- Ferrara, Kallosh, Linde & P…
- **… over 100 papers**

No-Scale Inflation

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Abstract. Supersymmetry is the most natural framework for physics above the
TeV scale, and the corresponding framework for early-Universe cosmology, including
inflation, is supergravity. No-scale supergravity emerges from generic string
compactifications and yields a non-negative potential, and is therefore a plausible
framework for constructing models of inflation. No-scale inflation yields naturally
predictions similar to those of the Starobinsky model based on $R + R^2$ gravity, with a
tilted spectrum of scalar perturbations: $n_s \sim 0.96$, and small values of the tensor-to-
scalar perturbation ratio $r < 0.1$, as favoured by Planck and other data on the cosmic
microwave background (CMB). Detailed measurements of the CMB may provide
insights into the embedding of inflation within string theory as well as its links to
collider physics.

A No-Scale Inflationary Model to Fit Them All

- A no-scale supergravity model of inflation that allows larger tensor/scalar values:

$$K = -3\ln(T + \bar{T}) + \frac{|\phi|^2}{(T + \bar{T})^3} \qquad W = \sqrt{\frac{3}{4}}\frac{m}{a}\phi(T - a) \qquad V = \frac{3m^2}{4a^2}|T - a|^2$$

Motivated by orbifold compactification

- Identify inflaton with components of modulus T:

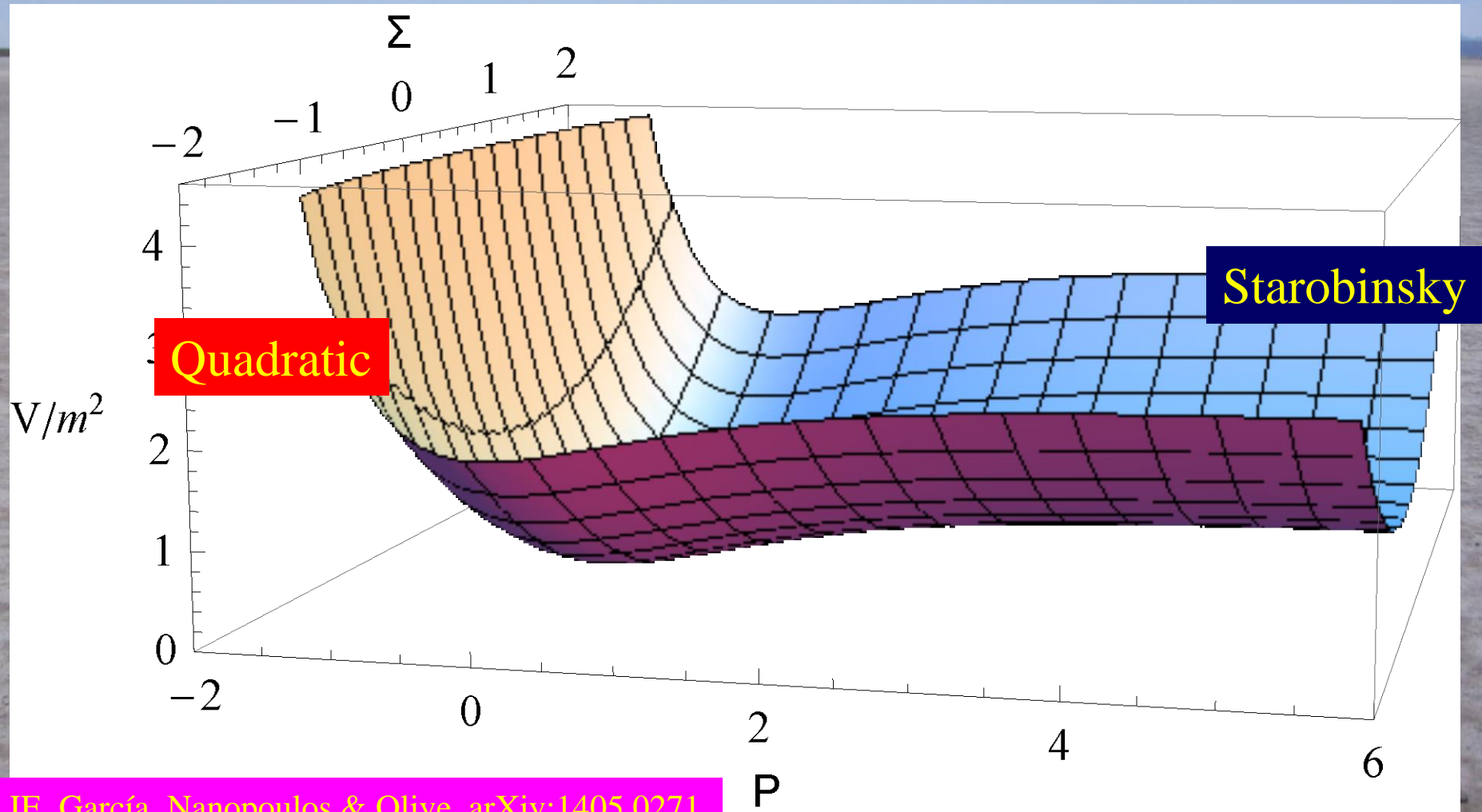$$T = a\left(e^{-\sqrt{\frac{2}{3}}\rho} + i\sqrt{\frac{2}{3}}\sigma\right)$$

- Effective Lagrangian:

Starobinsky   Quadratic

$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}e^{2\sqrt{\frac{2}{3}}\rho}\partial_\mu\sigma\partial^\mu\sigma - \frac{3}{4}m^2\left(1 - e^{-\sqrt{\frac{2}{3}}\rho}\right)^2 - \frac{1}{2}m^2\sigma^2$$
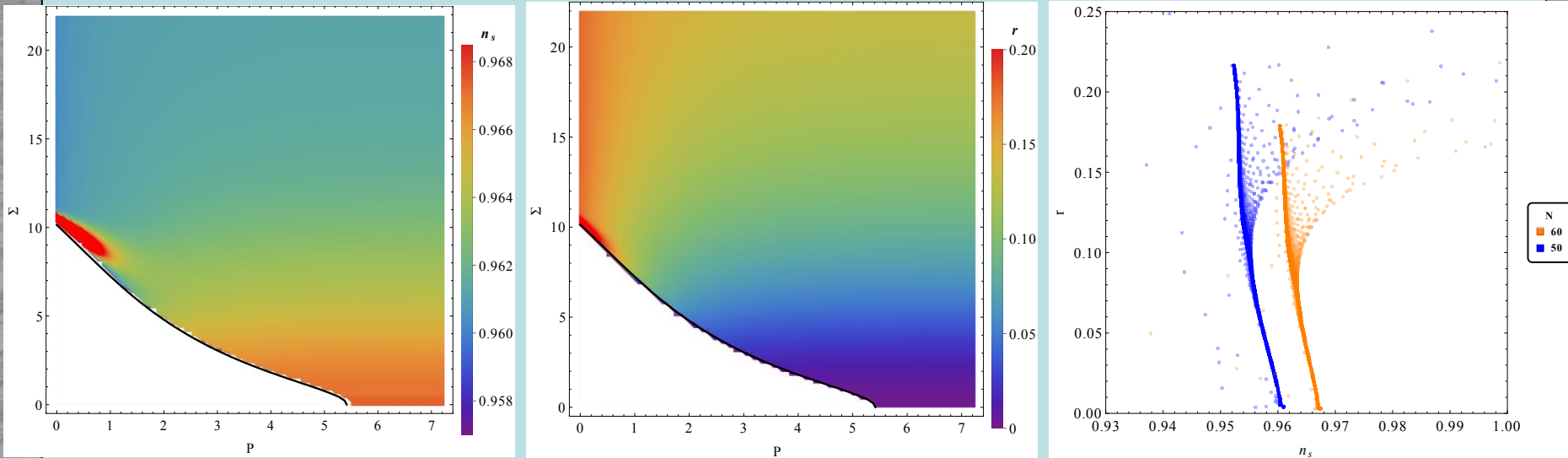
A No-Scale Inflationary Model to Fit Them All

Quadratic

Starobinsky

A No-Scale Inflationary Model to Fit Them All

- Predictions for general initial conditions

- n_s, r as functions of initial values

- Time will tell what Nature has chosen!

Two-Field Analysis of No-Scale Inflationary Model

- Isocurvature effects on curvature perturbations may suppress tensor/scalar ratio r

- n_s, r, non-Gaussianity dependences on initial values
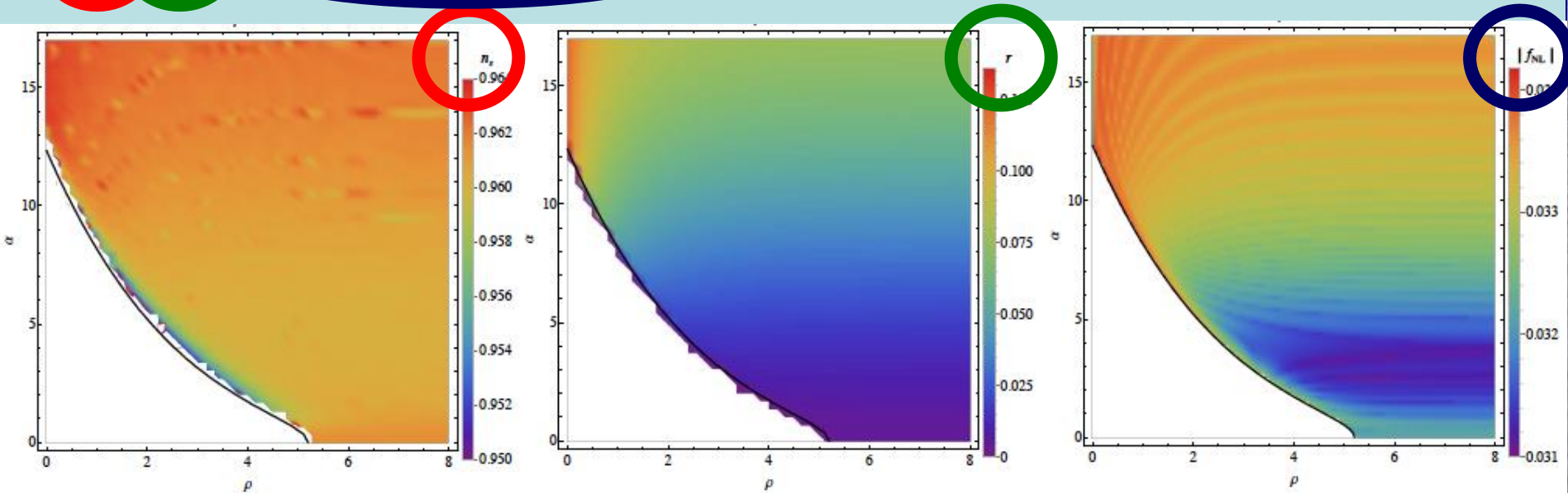
How many e-Folds of Inflation?

- General expression:

$$N_* = 67 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\mathrm{end}}}\right) + \frac{1-3w_{\mathrm{int}}}{12(1+w_{\mathrm{int}})}\ln\left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right) - \frac{1}{12}\ln g_{\mathrm{th}}$$

- In no-scale supergravity models:

$$N_* = 68.659 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(A_{S*}\right) - \frac{1}{4}\ln\left(N_* - \sqrt{\frac{3}{8}}\frac{\phi_{\mathrm{end}}}{M_P} + \frac{3}{4}e^{\sqrt{\frac{2}{3}}\frac{r_{\mathrm{end}}}{M_P}}\right)$$

$$+ \frac{1-3w_{\mathrm{int}}}{12(1+w_{\mathrm{int}})}\left(2.030 + 2\ln(\Gamma_\phi/m) - 2\ln(1+w_{\mathrm{eff}}) - 2\ln(0.81 - 1.10\ln\delta)\right)$$

$$- \frac{1}{12}\ln g_{\mathrm{th}},$$

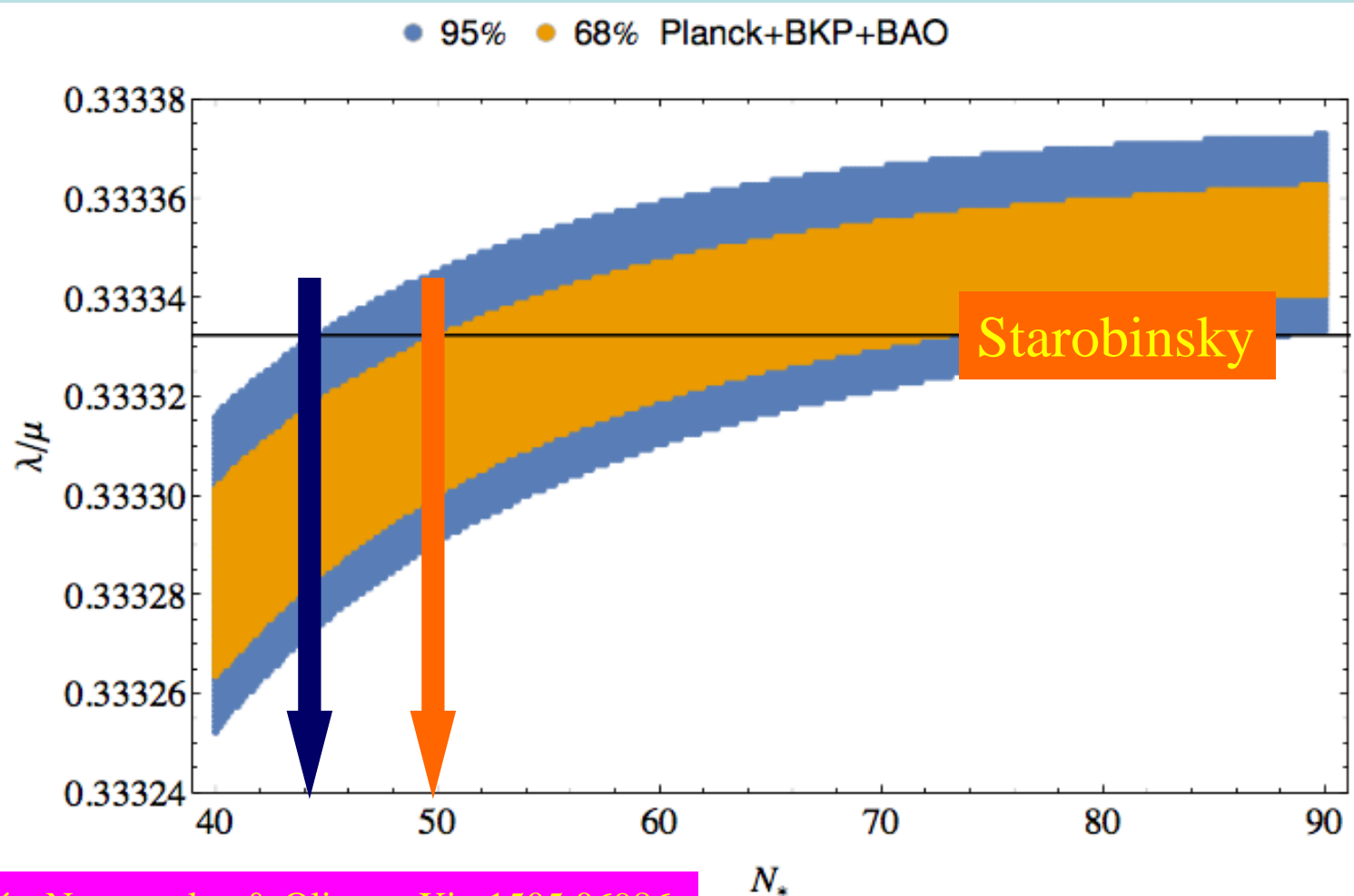**Amplitude of perturbations**

Equation of state during inflaton decay
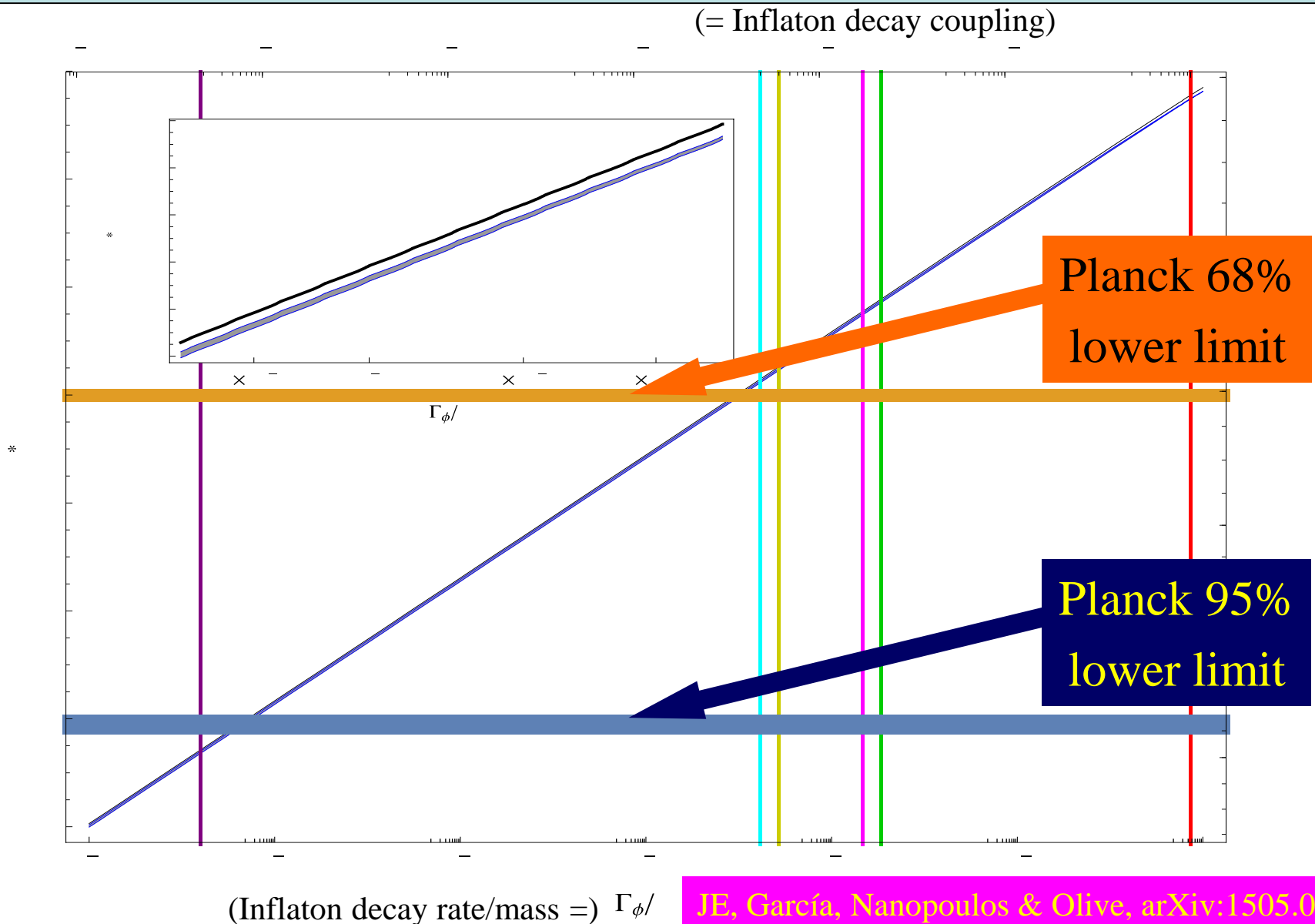
Inflaton decay rate

- **Prospective constraint on inflaton models?**

Planck Constraints on # of e-Folds

- Starobinsky-like no-scale models

Planck Constraints on # of e-Folds

(= Inflaton decay coupling)

Planck 68% lower limit

Planck 95% lower limit

$\Gamma_\phi/$

(Inflaton decay rate/mass =) $\Gamma_\phi/$ JE, García, Nanopoulos & Olive, arXiv:1505.06986

General Analysis of Reheating

- Selected models:
  1): R^2, Higgs
  2): Φ^2
  3): Φ^4
  4): $\Phi^{2/3}$
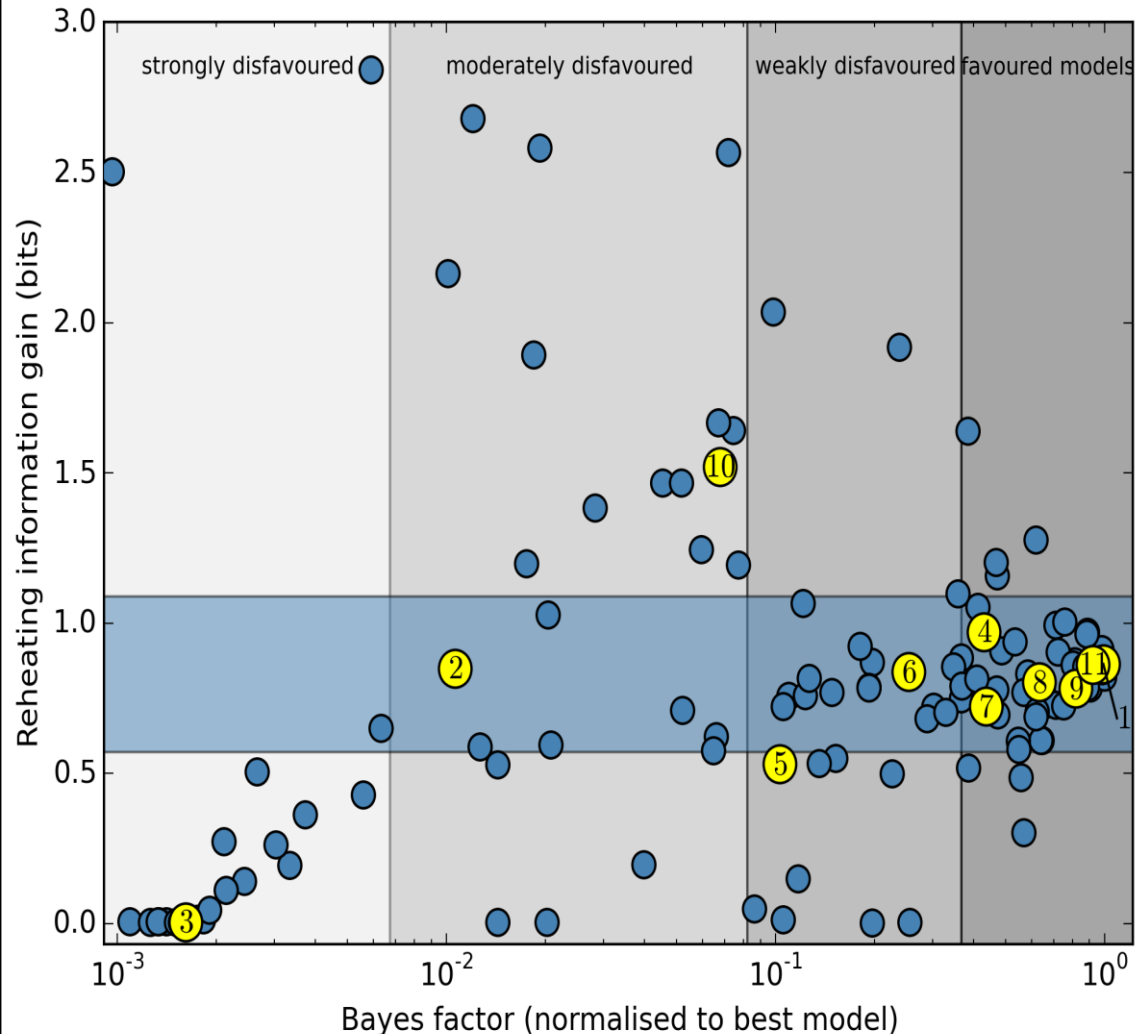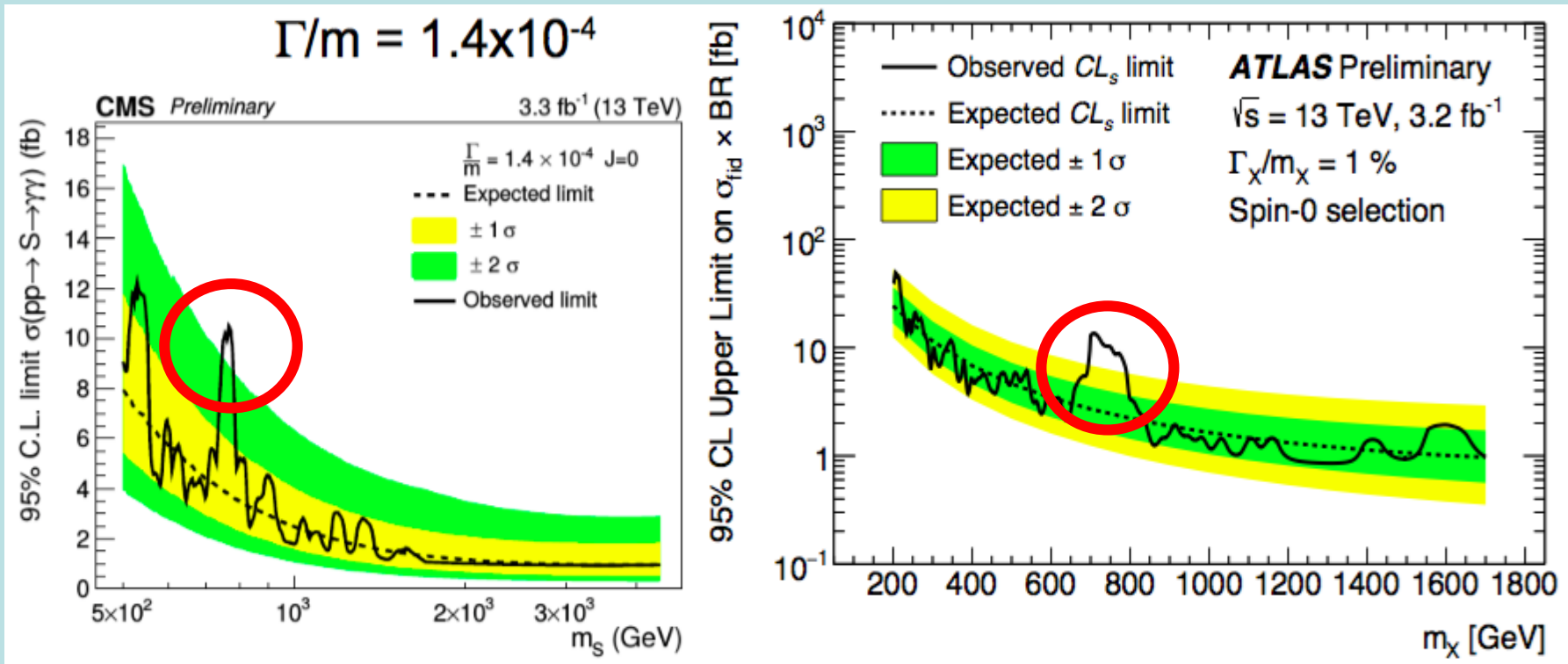 5): Φ^p, p in [0.2, 6]
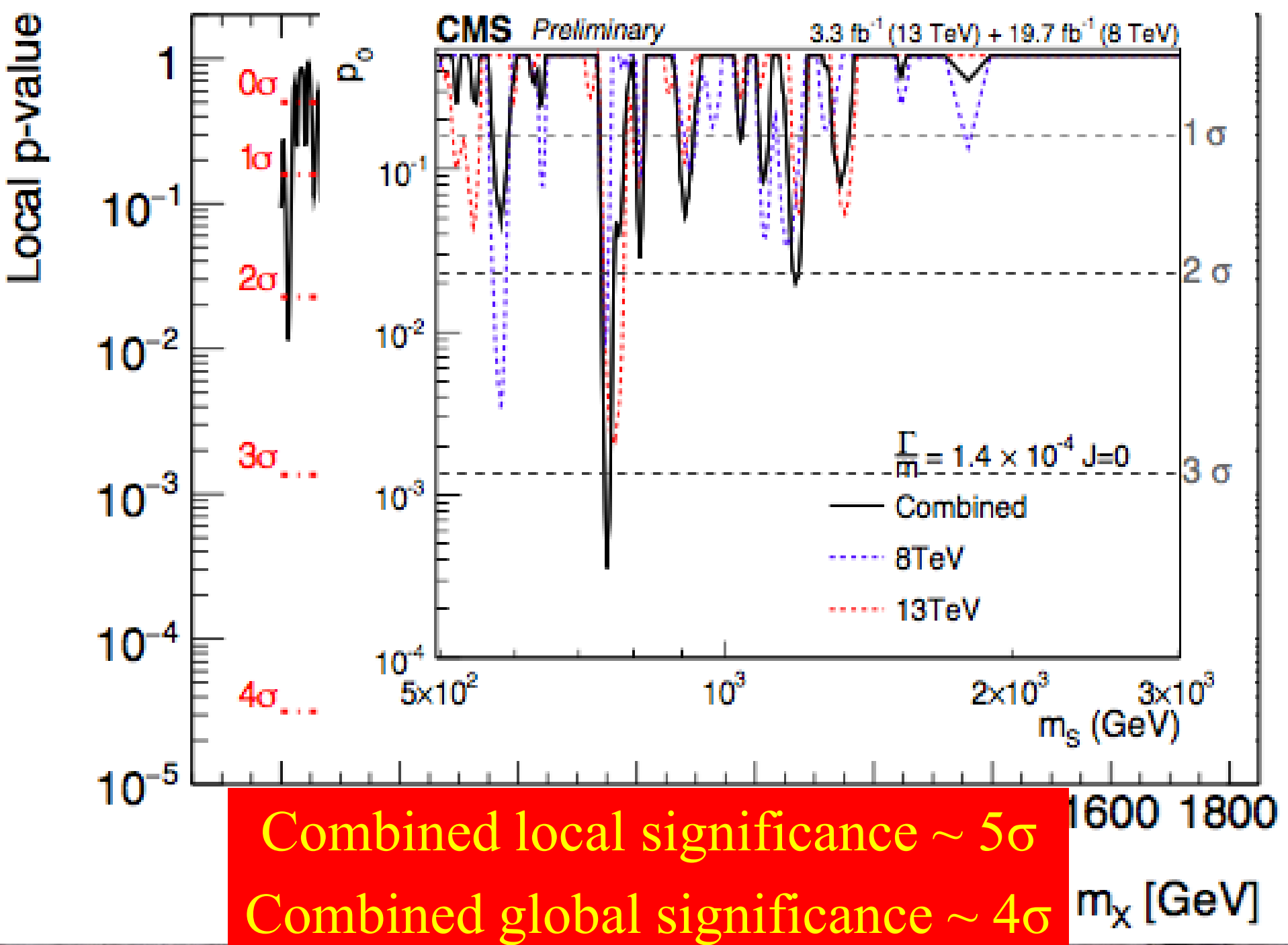 6), 7), 8): hilltop
  9): brane
  10): natural
  11): α attractors

New particle @ 750 GeV?

- **Peaks in γγ invariant mass distributions**

- Hint of new X(750) particle has not gone away
- **Wait and see!**

CMS Preliminary 3.3 fb⁻¹ (13 TeV) + 19.7 fb⁻¹ (8 TeV)

Combined local significance ~ 5σ
Combined global significance ~ 4σ

The Potential Impact of X(750)

X(750)

Standard Model

Vector-like quarks + more

X(750) and Inflation

- Another (pseudo)scalar particle?
- Extrapolation to inflation energies non-trivial
- Modifies possibility of Higgs inflation?
  - Need new study of renormalization effects
- Another candidate for the inflaton?
  - Possible with non-minimal X^2R coupling
  - Predictions similar to Higgs inflation
- Two-field inflation?
- **Wait and see! Should know in a few months**