TESTING SUPERSYMMETRIC HIGGS INFLATION WITH NON-GAUSSIANITY

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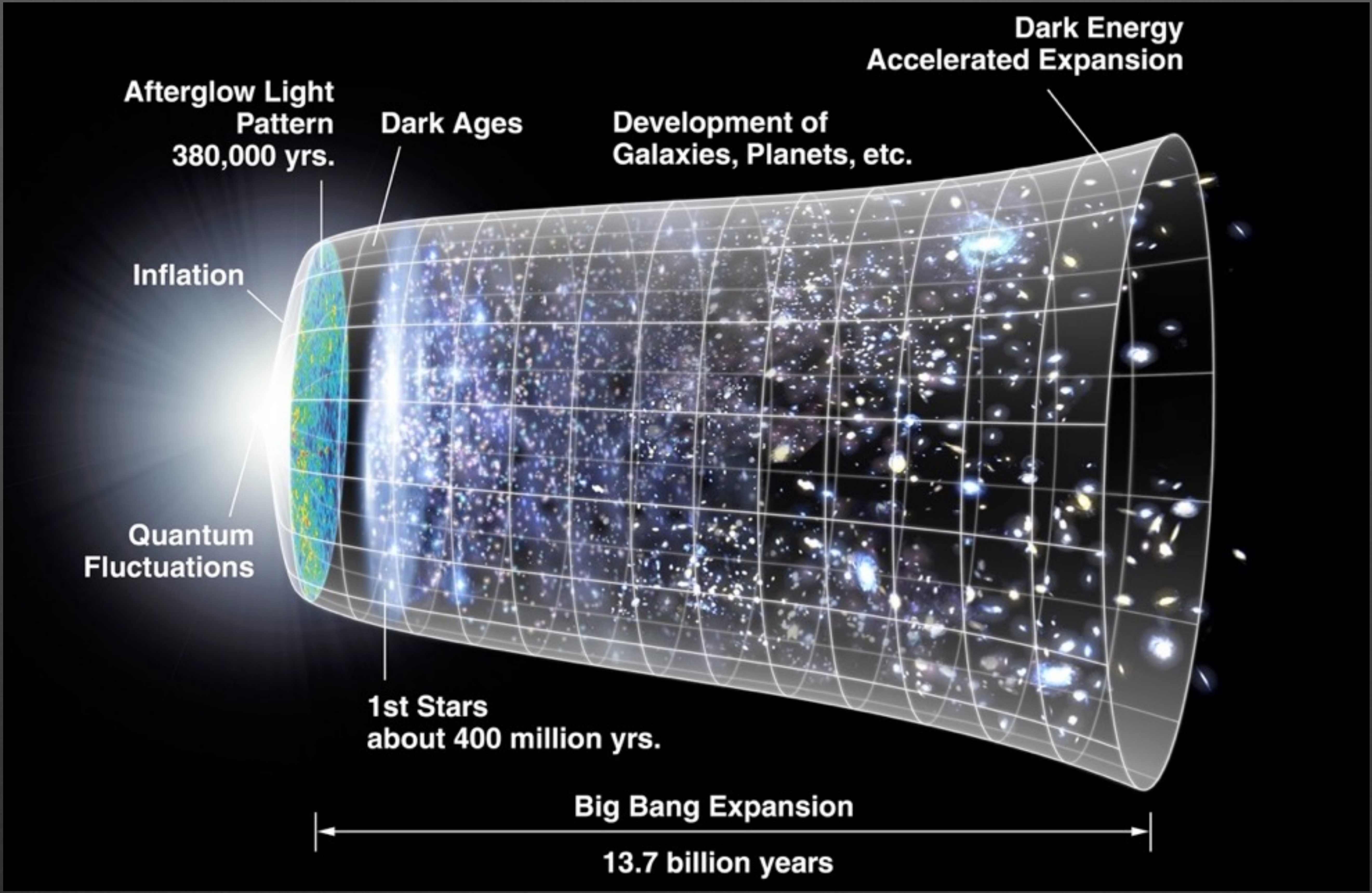
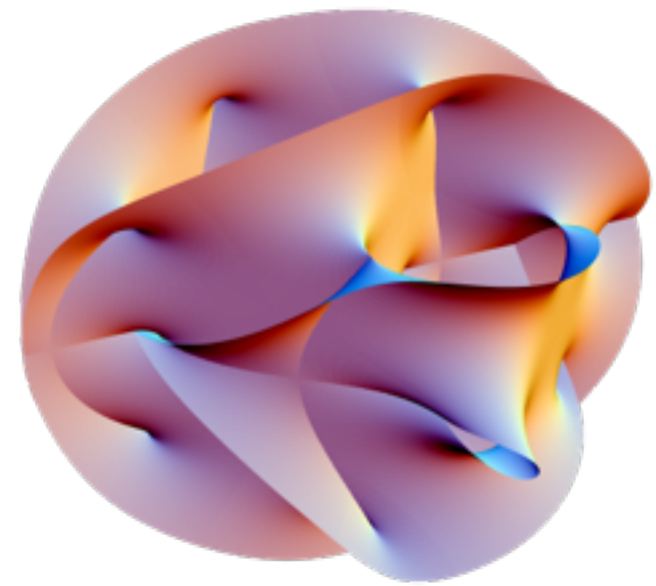
Based on arXiv:1411.5188 with Jinsu Kim



What is the particle physics behind inflation?

Two approaches in inflationary model building

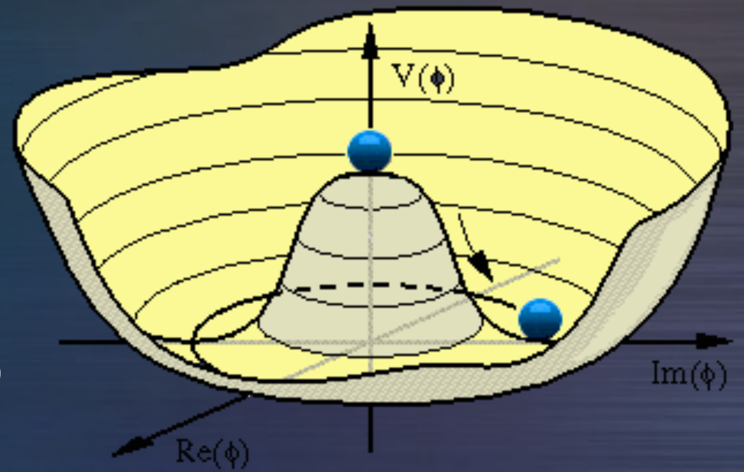
- Top-down approach
  - String-, M- and F-theory cosmology
  - D-branes, Calabi-Yau, landscape...



- Bottom-up approach
  - Low energy spectrum (SM + extension)
  - Predictability & falsifiability
  - *Higgs field can be the inflaton?*

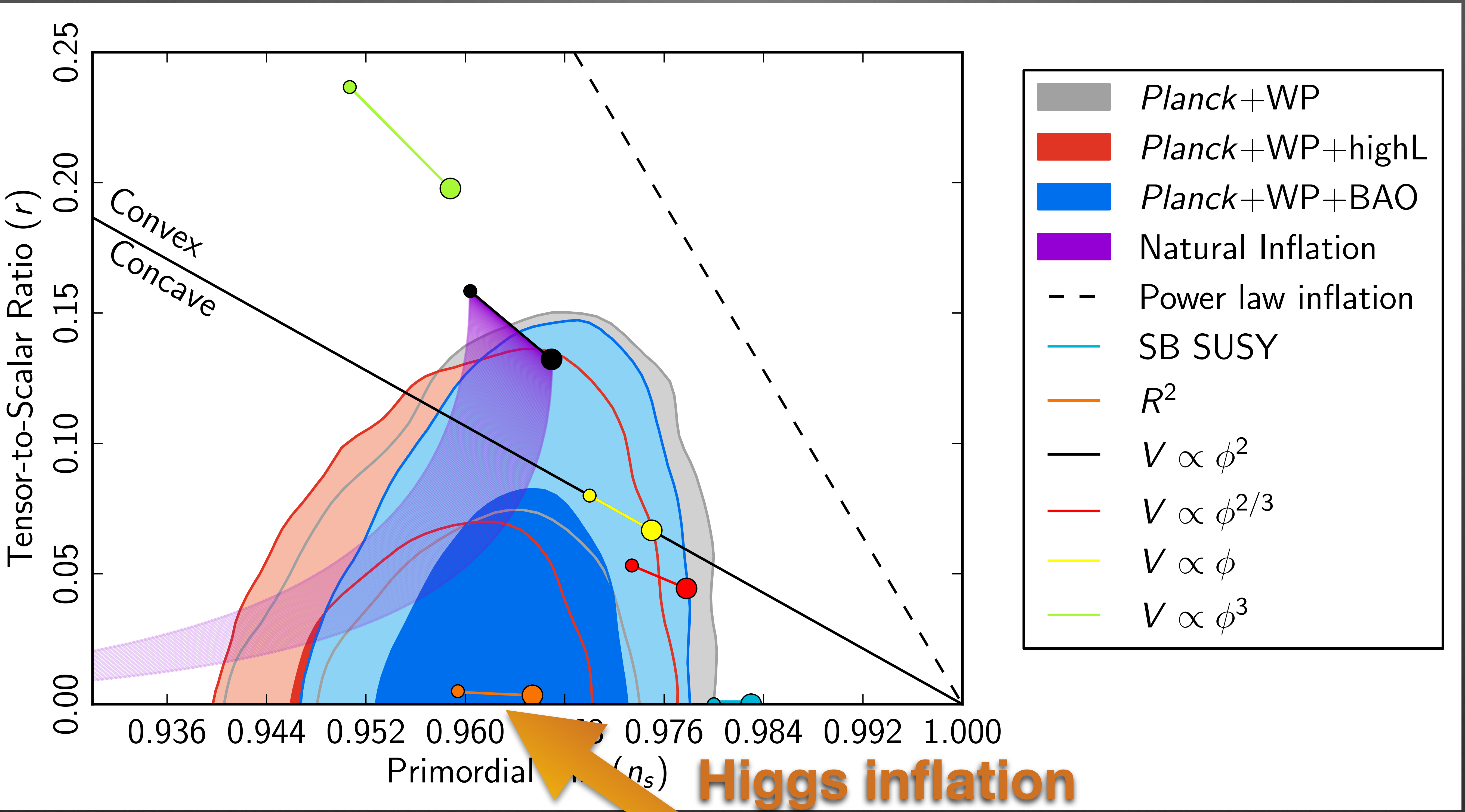
Higgs inflation

- SM Higgs boson: mass ≈ 125 GeV, $\lambda \approx O(1)$
- Chaotic inflation: $m \approx 10^{13}$ GeV or $\lambda \approx 10^{-12}$



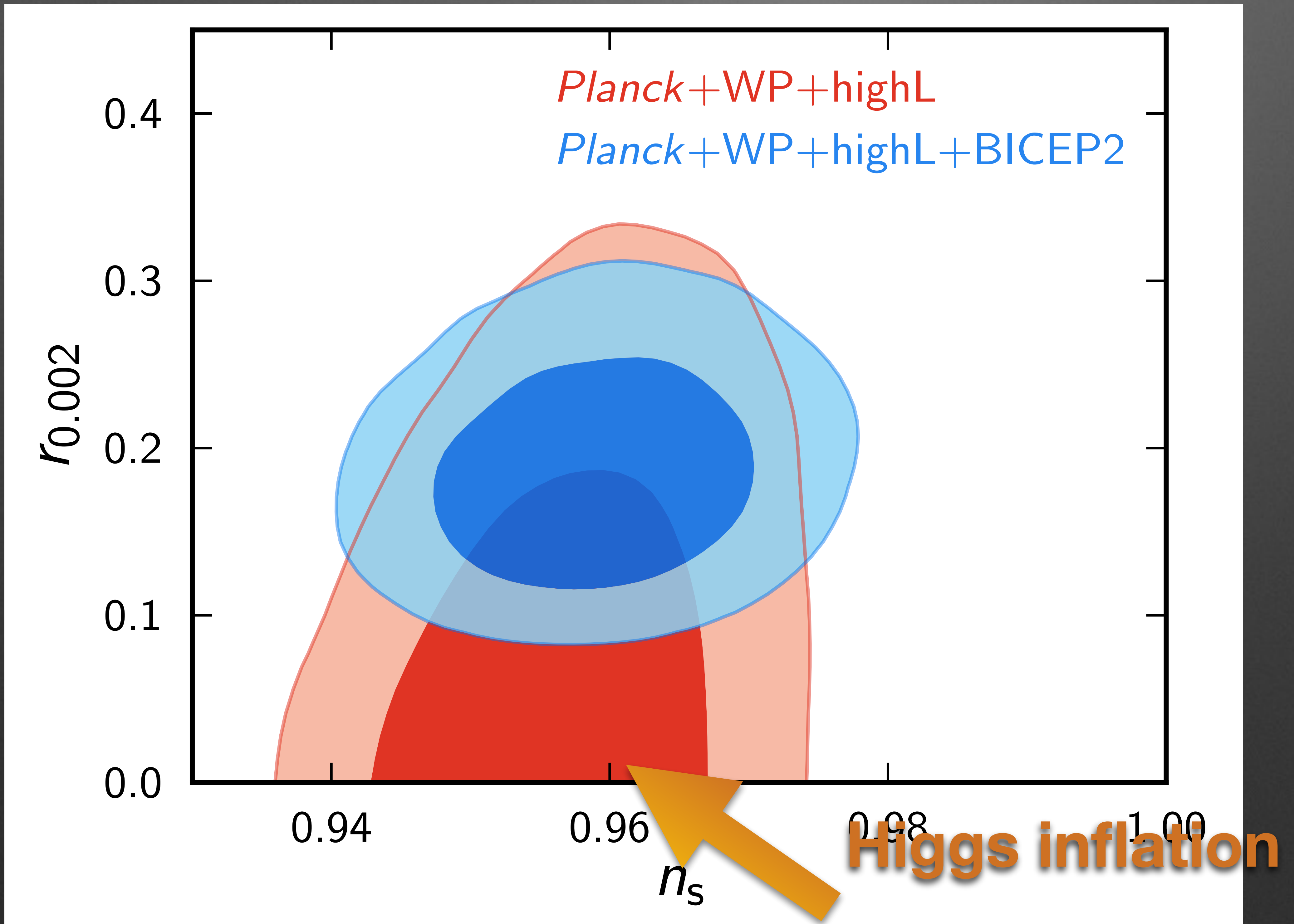
- How can ever be the same field?
  - Nonminimal coupling to gravity [Cervantes-Cota, Dehnen 1995] [Bezrukov Shaposhnikov 2008]
  - Non canonical kinetic term [Germani Kehagias] [Nakayama Takahashi] [many others]
  - Other curvature perturbation [Langlois Vernizzi] [many others]
  - Criticality of RG, ad-hoc modification beyond cutoff [Hamada et al.]

Planck (2013) [arXiv: 1303.5062]

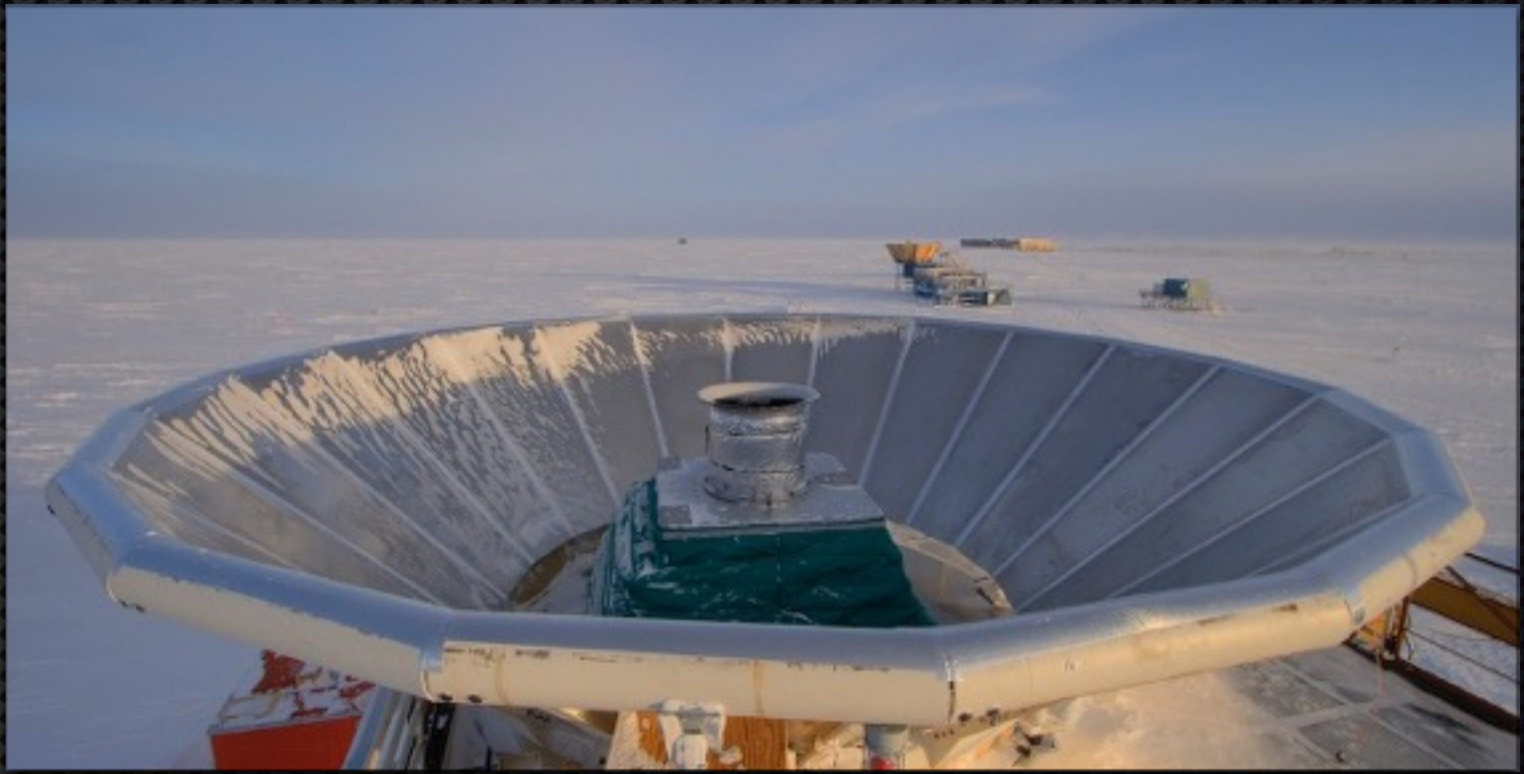


Higgs inflation

BICEP2 (2014) [arXiv: 1403.3985]



Confidence level (CL)



1σ: 68%
2σ: 95%
3σ: 99.7%
4σ: 99.994%
5σ: 99.99994%

in collider physics

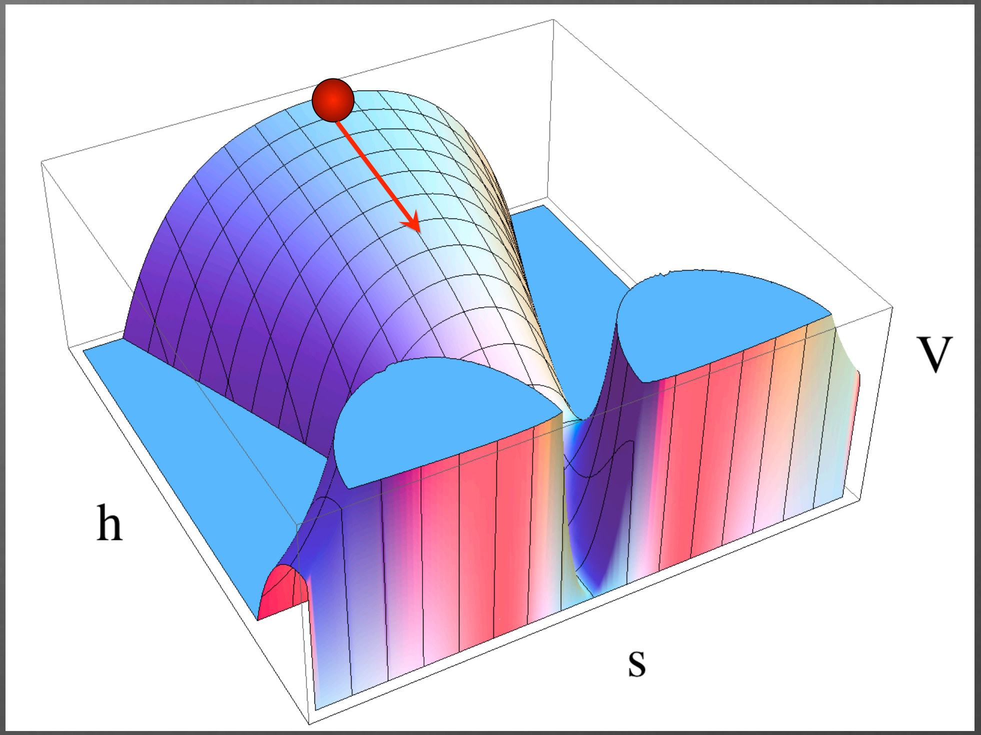
5σ ≃ 50%

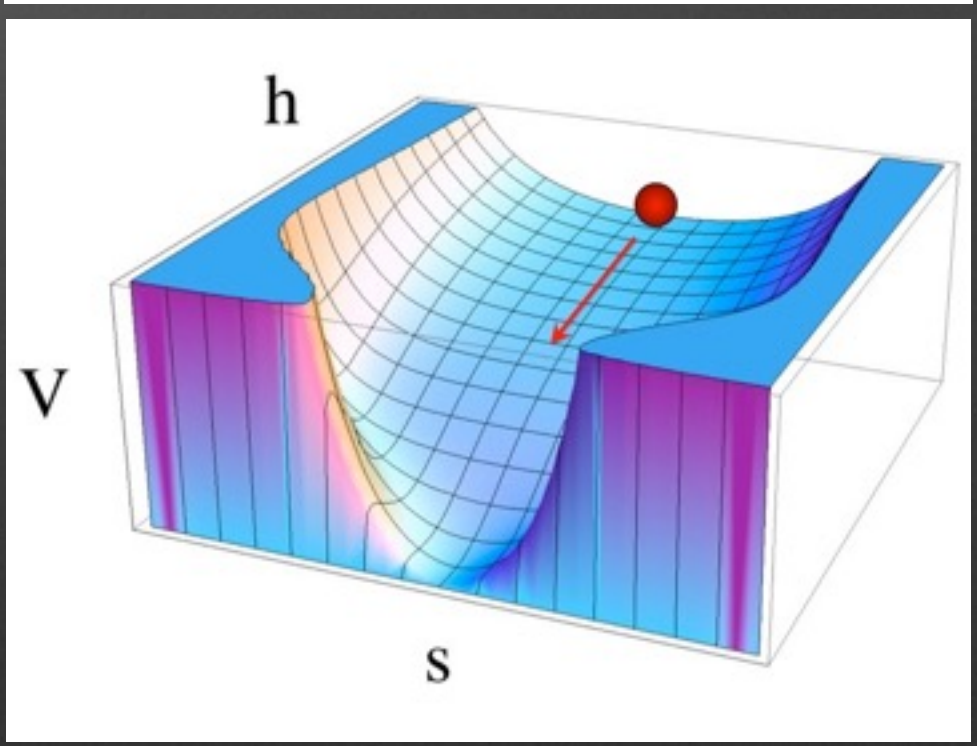
in cosmology

- The Standard Model is not a complete theory.
    - Not UV complete
    - No good dark matter candidate
    - Difficulty in baryogenesis
    - Hierarchy problem…
- Perhaps, supersymmetry is still a good guiding principle in the physics beyond the SM

SUSY Higgs inflation

- A-term MSSM inflation — not favoured by observation
- Non-minimally coupled Higgs inflation in NMSSM [Einhorn Jones 2010]
- Tachyonic instability problem [Ferrara Kallosh Linde Marrani Van Proeyen 2010]
- Tachyonic instability removed by modifying Kähler [Ferrara Kallosh Linde Marrani Van Proeyen 2011]
- Phenomenologically more natural realization of SUSY Higgs inflation [Arai, SK, Odaka 2011]





We will use this as an example of SUSY Higgs inflaiton

SUSY Higgs inflation in MSSM + N_R

[Arai, SK, Okada, arXiv:1112.2391, 1212.6828]

Right-handed neutrinos

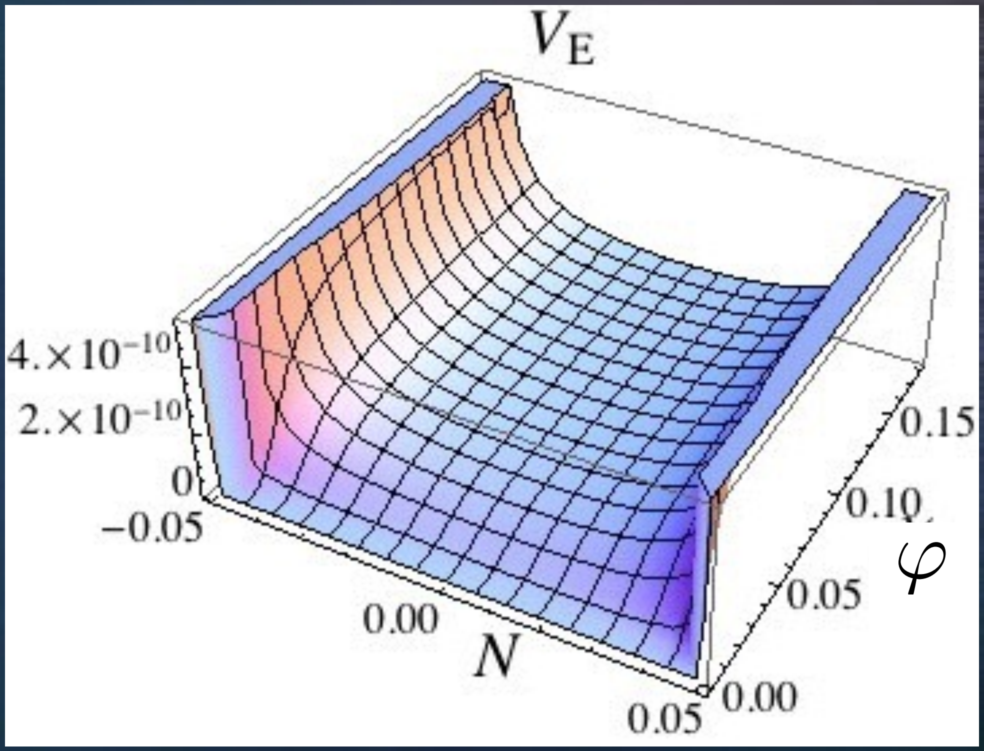
Superpotential

$$W = \mu H_u H_d + y_u u^c Q H_u + y_d d^c Q H_d + y_e e^c L H_d + \boxed{y_D N^c L H_u + M N^c N^c}$$

y_D can be naturally small

D-flat direction

$$L = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi \\ 0 \end{pmatrix}, H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}.$$



Kähler potential

$$K = -3 \ln \Phi,$$

nonminimal coupling $\xi R \varphi^2$, $\xi = \gamma/4 - 1/6$

$$\Phi = 1 - \frac{1}{3}(|N_R^c|^2 + |\varphi|^2) + \boxed{\frac{1}{4}\gamma(\varphi^2 + c.c.)} + \boxed{\frac{1}{3}\upsilon |N_R^c|^4}$$

controls tachyonic instability

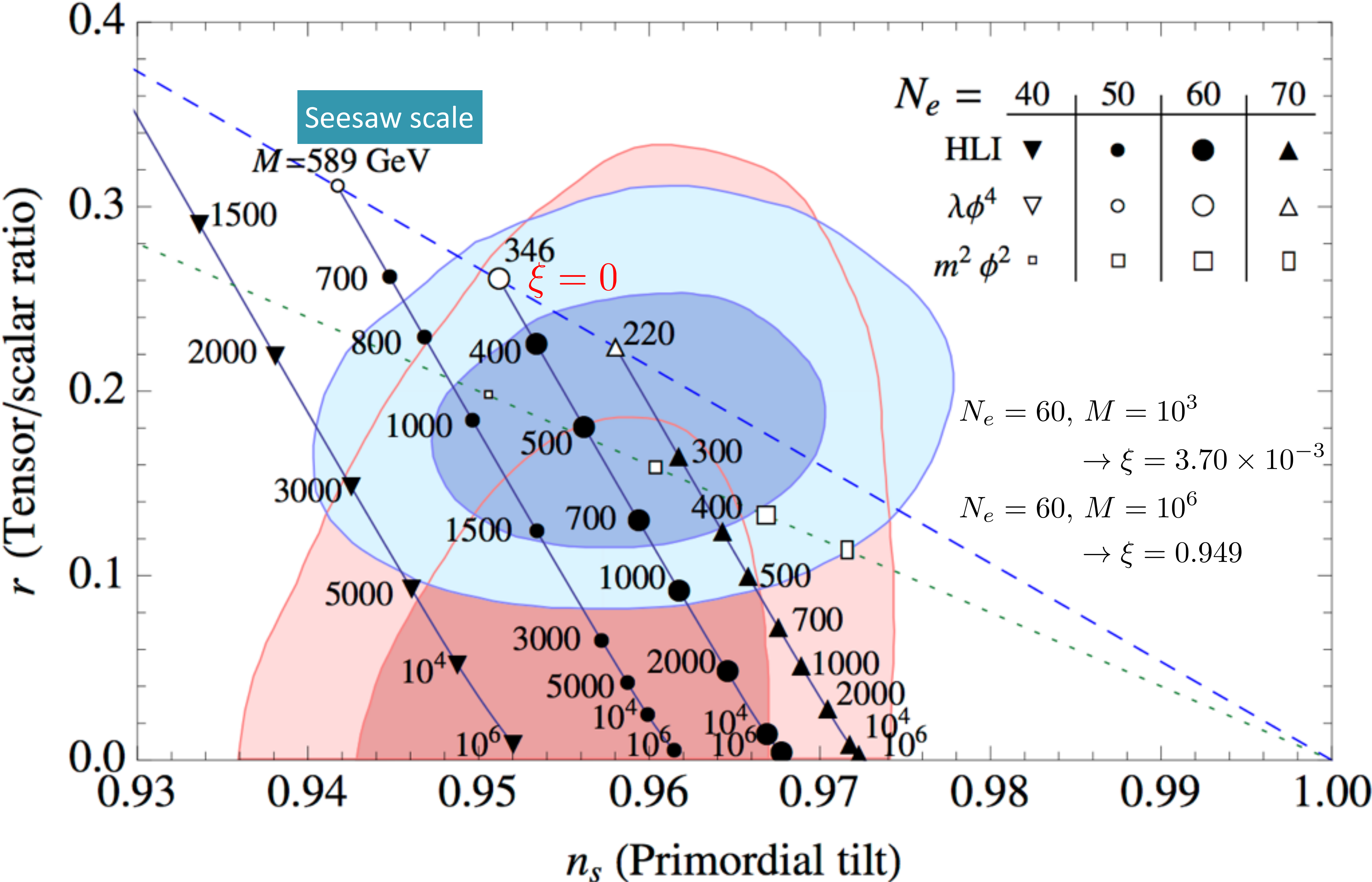
Seesaw relation

$$m_\nu = \frac{y_D^2 \langle H_u \rangle^2}{M}$$

$$m_\nu^2 \approx \Delta_{32}^2 = 2.43 \times 10^{-3} \mathrm{eV}^2 \qquad \langle H_u \rangle \approx 174 GeV$$

Large enough υ $\Longrightarrow$ single field inflation

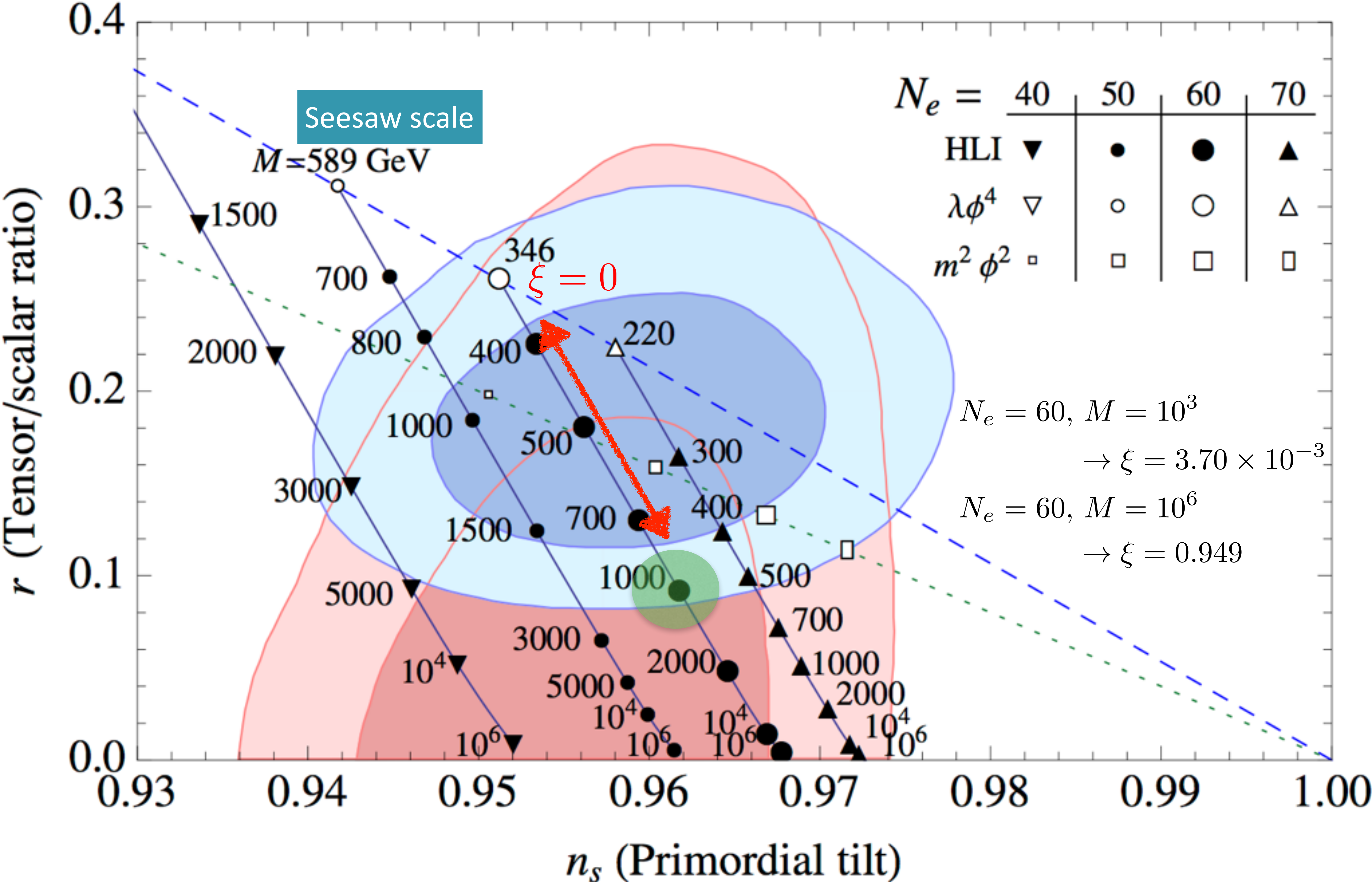
Prediction of the single-field model & BICEP2 (2014)



TeV-scale seesaw [SK, Okada 1404.1450]

- Type I seesaw: RH neutrinos production in collider negligible (singlet-doublet mixing too small)
- Type III seesaw: heavy lepton produced via EW
- M < 245 GeV already excluded (95% CL) by ATLAS
- 14 TeV run: up to 750 GeV

Prediction of the single-field model & BICEP2 (2014)



Noncanonical (quartic) term in Kähler

$\Longrightarrow$ **N_R =0**

$\Longrightarrow$ **Single-field inflation**

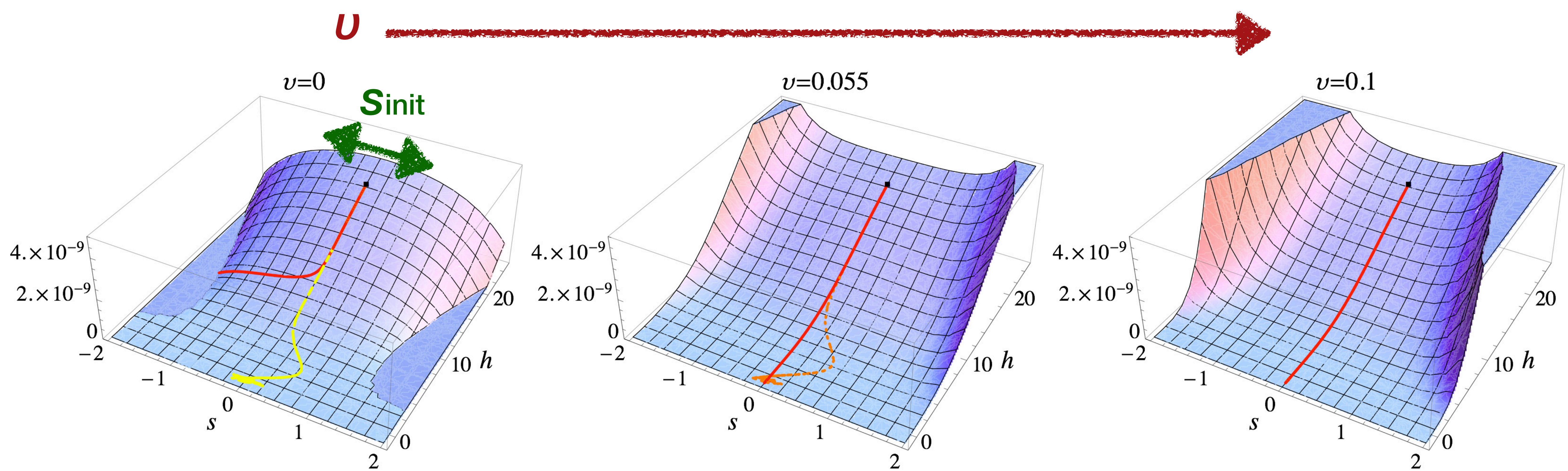
Purpose:

investigate how the multi-field effects (e.g. non-Gaussianity) restricts Kähler potential of the underlying supergravity theory

$$\Phi = 1 - \frac{1}{3}(|N_R^c|^2 + |\varphi|^2) + \frac{1}{4}\gamma(\varphi^2 + c.c.) + \frac{1}{3}\upsilon|N_R^c|^4$$

Inflaton trajectories

(2-field SUSY Higgs inflation in SUSY seesaw)



red: s_{init} =0, yellow: s_{init} = 1.617×10^{-11}, orange: s_{init} = 10^{-5}

$\dot{s}_{init}$ =0 in all cases

quantum fluctuations

$$\langle (\Delta s)^2 \rangle \approx \frac{H^2}{(2\pi)^2}$$

- Seesaw mass M =1TeV, e-folding number N =60
- h_{init} set by N =60 in the single field limit
- Trajectory dep on the parameter υ and the init cond (s_{init}, $\dot{s}_{init}$)
- Once trajectory is fixed, observables can be computed

Single field or multi field?

	SINGLE FIELD INFLATION	MULTI FIELD INFLATION
BACKGROUND EVOLUTION	Roll off simple potential	Curved trajectory in n-dimensional space
DOF OF FLUCTUATIONS	Scalar 1(=2+1-2) Vector 2 Tensor 2	Scalar n (=2+n-2) Vector 2 Tensor 2
EVOLUTION OF FLUCTUATIONS	Adiabatic, freeze outside the Hubble horizon	Adiabatic (curvature) and entropy (isocurvature)
NON-GAUSSIANITY OF SCALAR FLUCTUATIONS	Small	Can be large

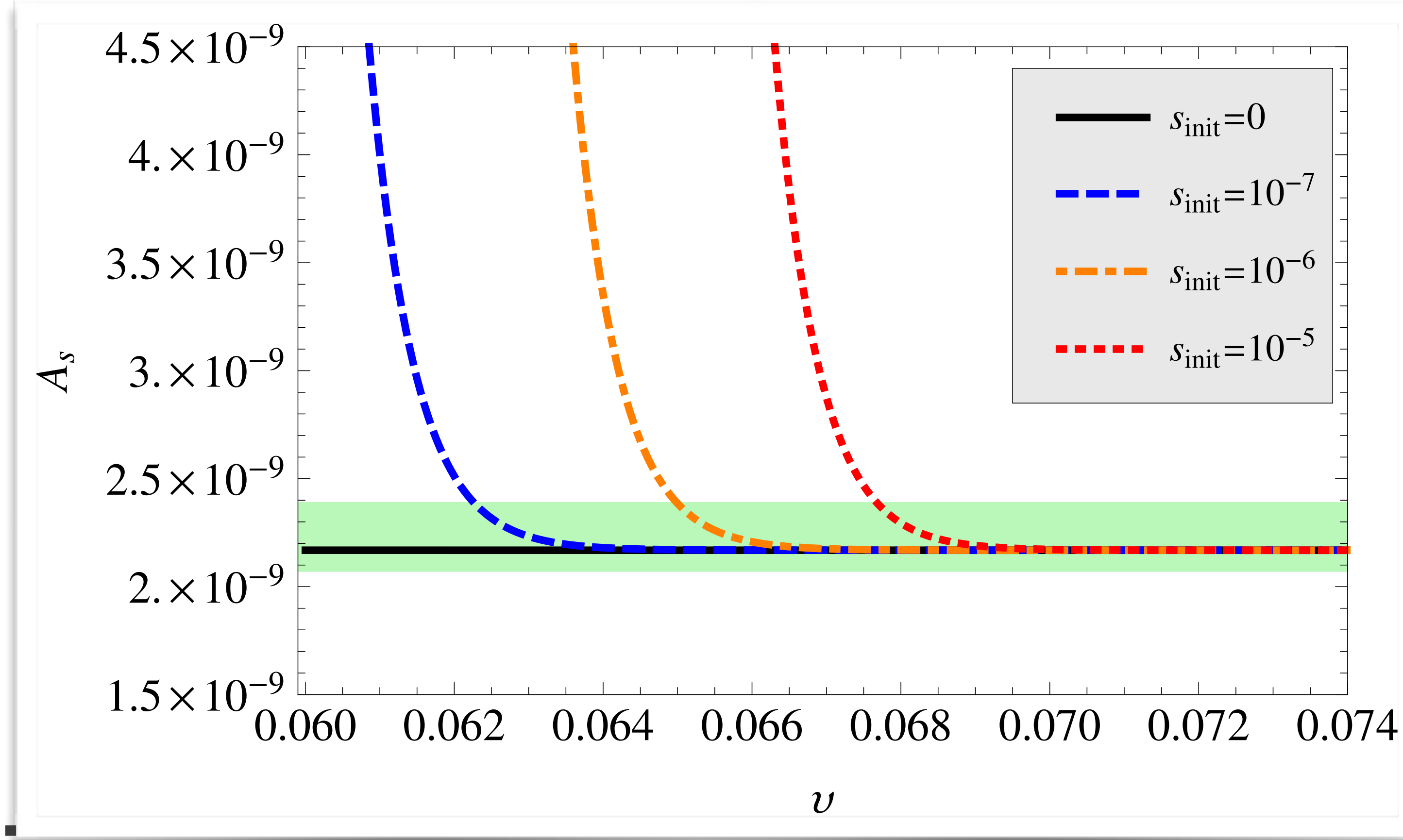
source

Scalar power spectrum A_s

$$\mathcal{P}_S = \frac{k^3}{2\pi^2} P_\zeta(k),$$

$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{k}_1 + \boldsymbol{k}_2\right) P_\zeta(k).$$

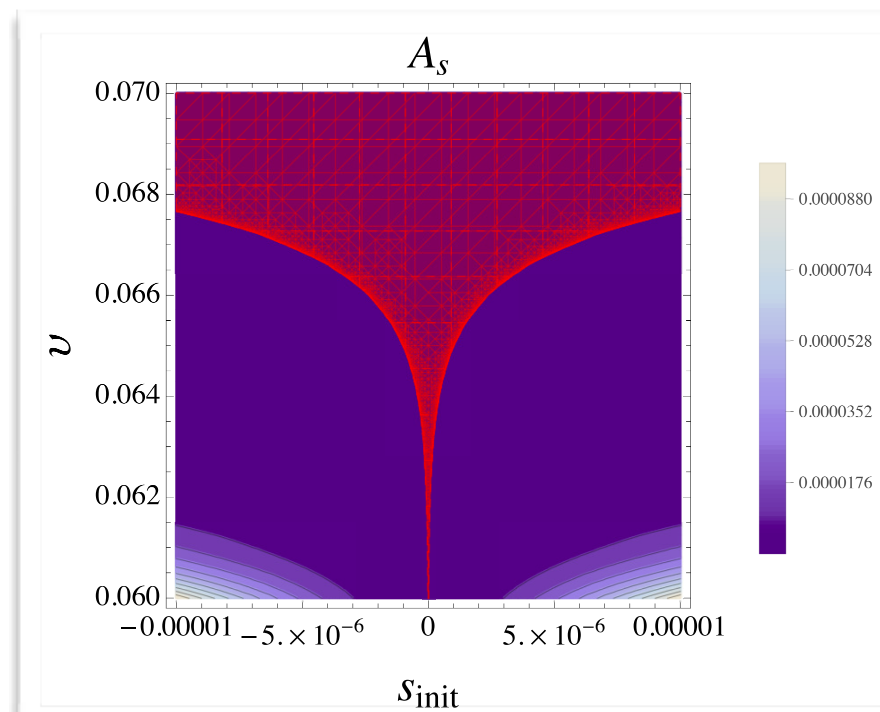
$$\mathcal{P}_S = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\frac{dn_s}{d\ln k}\ln\frac{k}{k_0} + \cdots}$$



- Observation (Planck 2013):

$$A_s \times 10^9 = 2.23 \pm 0.16 \qquad \text{(Planck)}$$

$$k_0 = 0.05\,\mathrm{Mpc}^{-1}$$



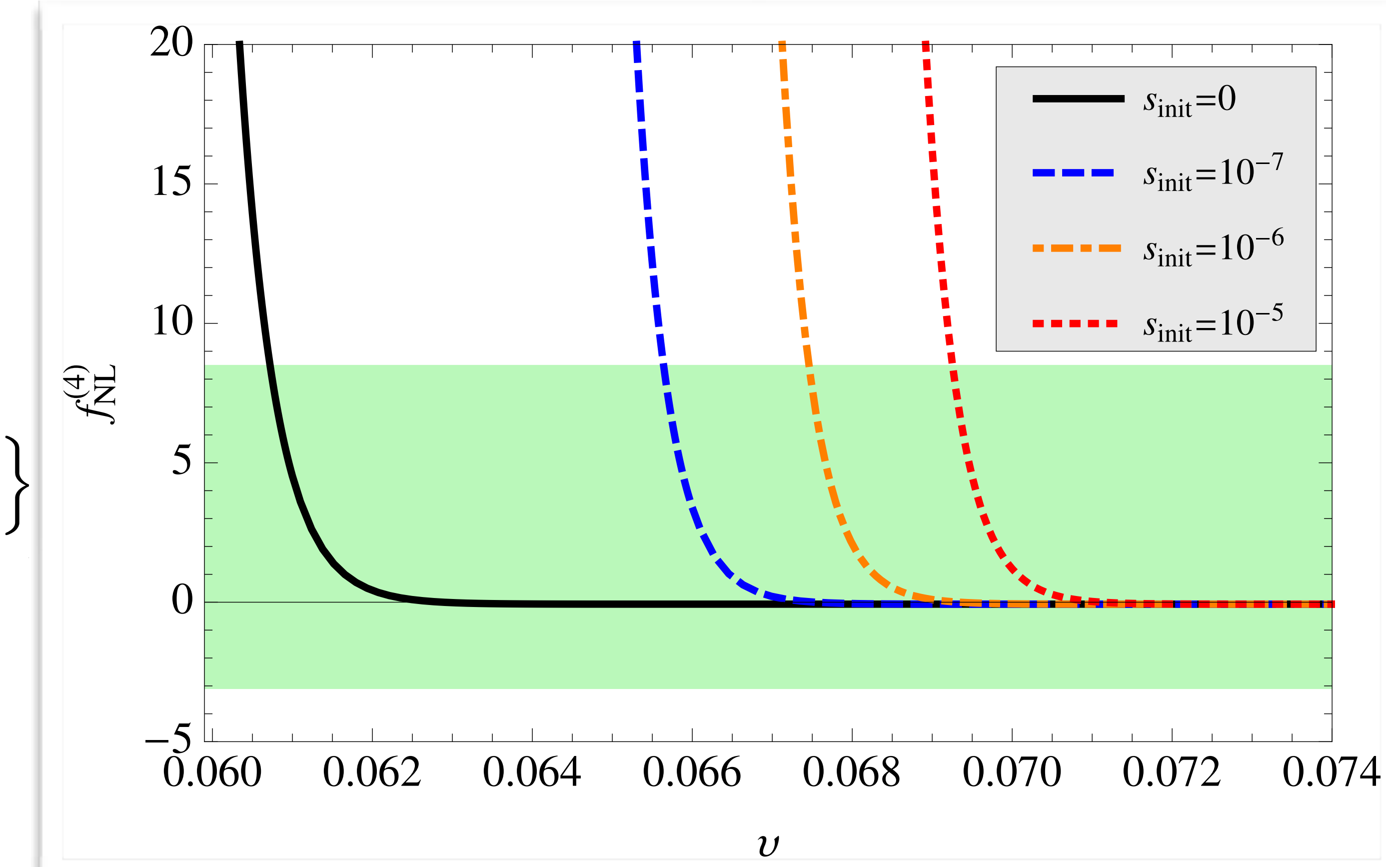
Quantum fluctuations give $\langle \Delta s \rangle \approx \dfrac{H}{2\pi} \sim 10^{-5} M_{\rm Pl}$

for the seesaw mass M =1TeV, e-folding number N =60

Non-Gaussianity (nonlinearity) f_{NL}

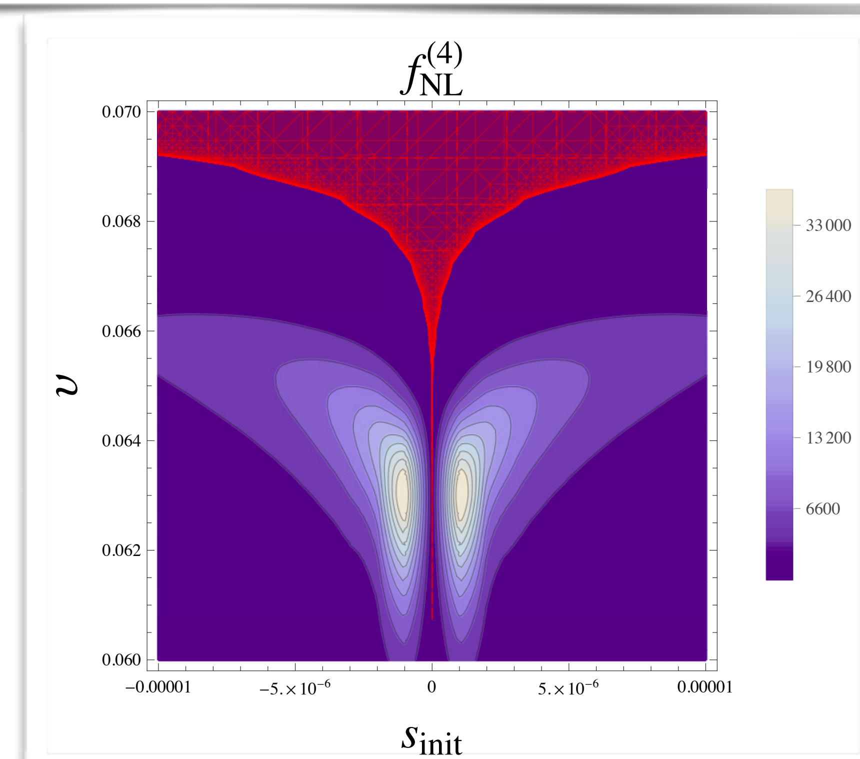
$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3 \right) B_\zeta(k_1, k_2, k_3)$$

$$B_\zeta(k_1, k_2, k_3) = \frac{6}{5} f_{NL}^{\text{local}} \Big\{ P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms} \Big\}$$



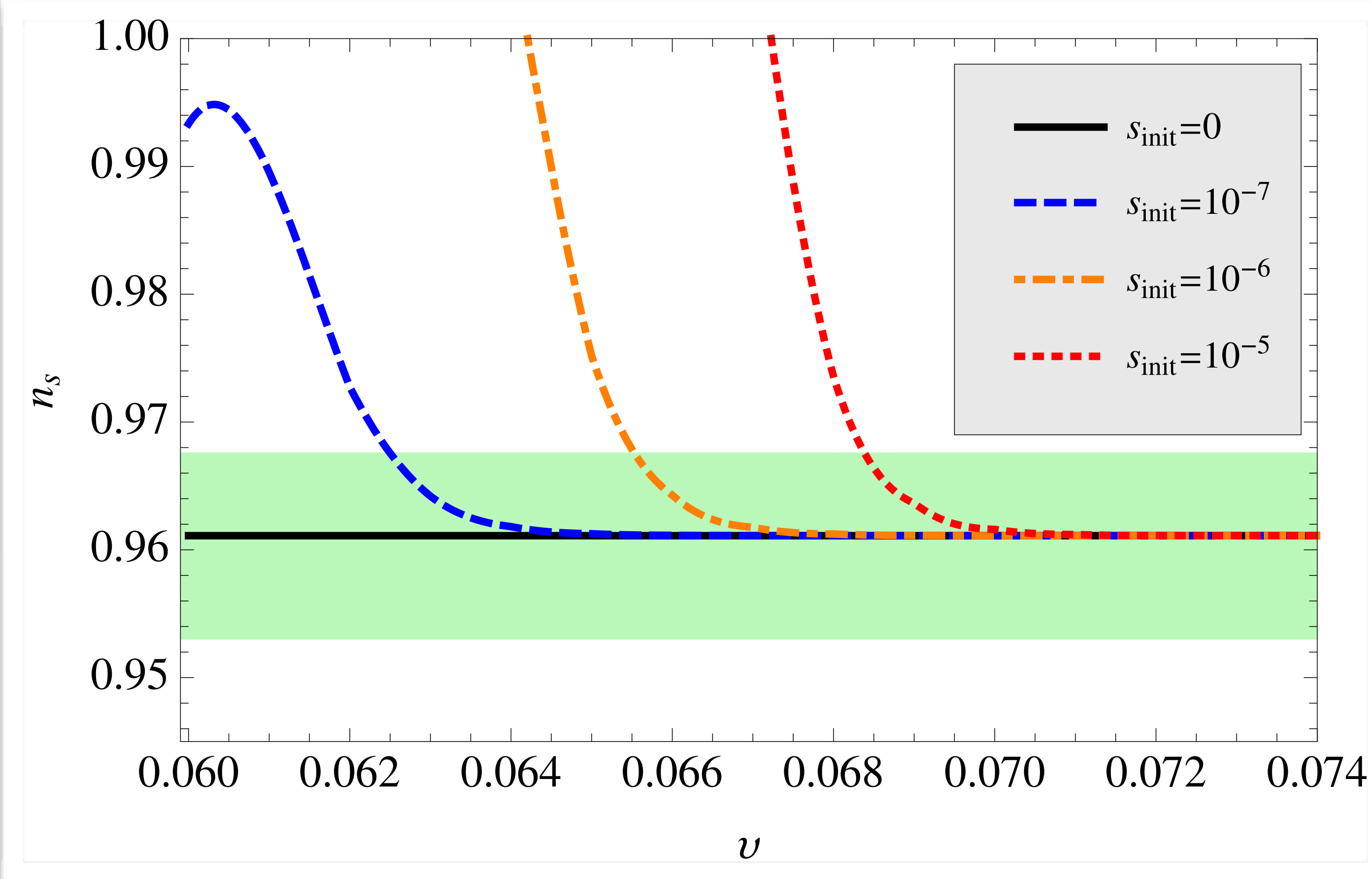
- Observation (Planck 2013):

$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8 \qquad\qquad (68\% \text{ C.L.})$$



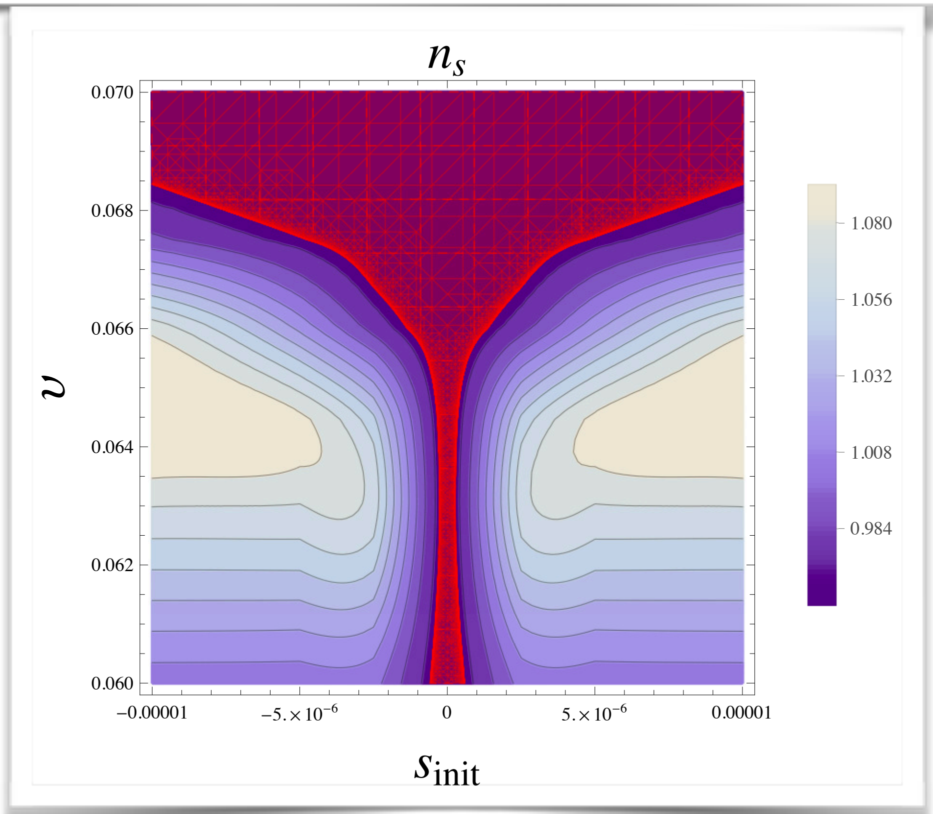
Scalar spectral index n_s

$$\mathcal{P}_S = A_s \left(\frac{k}{k_0}\right)^{\boxed{n_s}-1+\frac{1}{2}\frac{dn_s}{d\ln k}\ln\frac{k}{k_0}+\cdots}$$



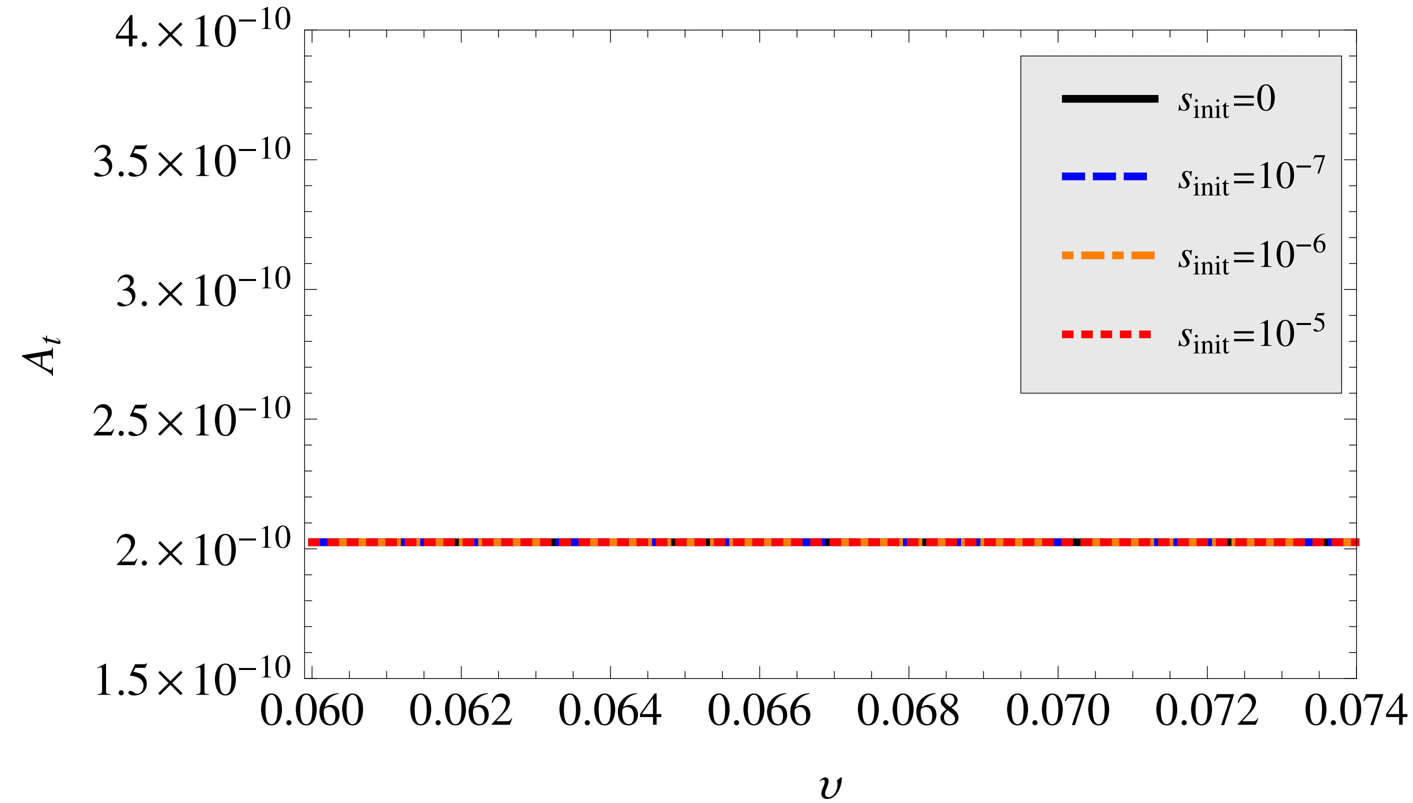
- **Observation (Planck 2013):**

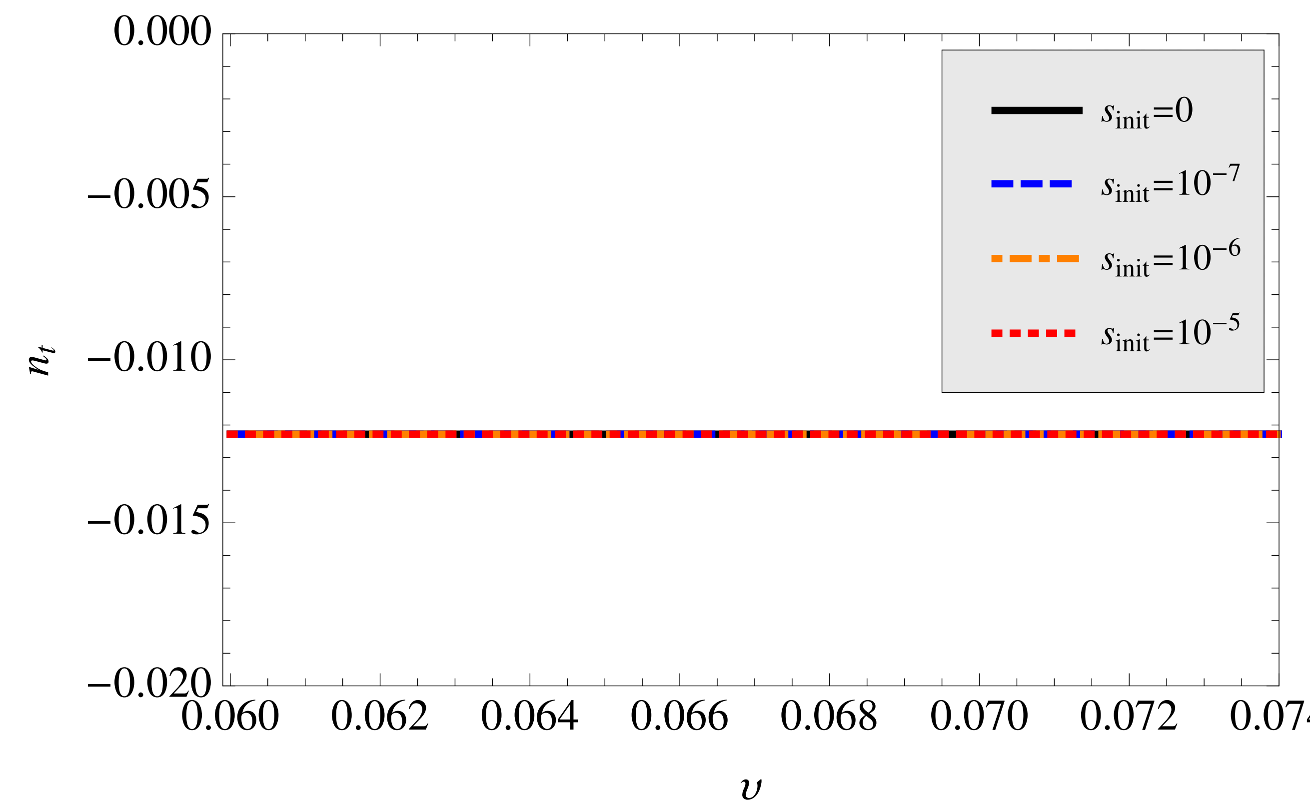
$$n_s = 0.9603 \pm 0.0073 \qquad (68\%\ \text{C.L.})$$



Tensor amplitude A_t and tilt n_t

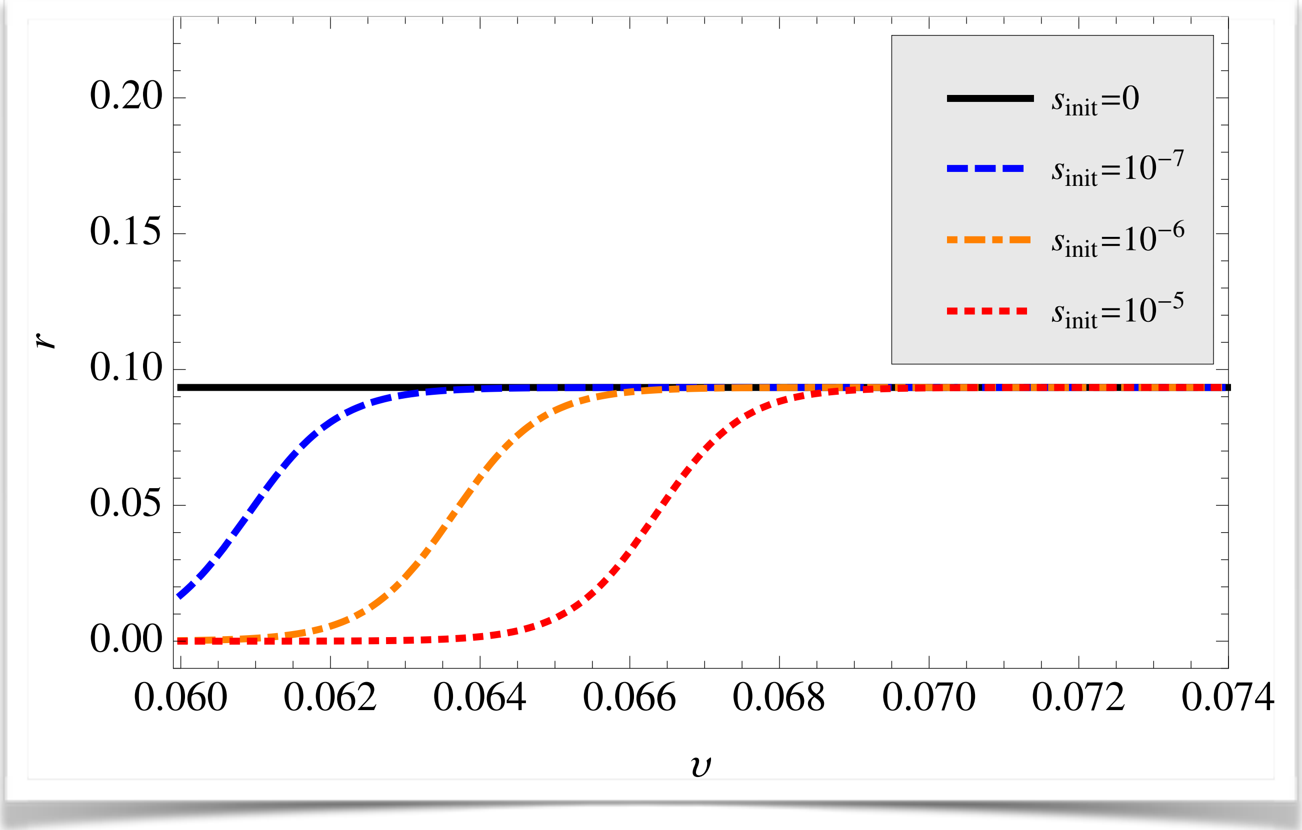
- No effects of multi-field on the tensor mode
- This is expected: tensor mode generated quantum mechanically at subhorizon, decouple from scalar mode
- Gravitational waves are same as in the single-field case

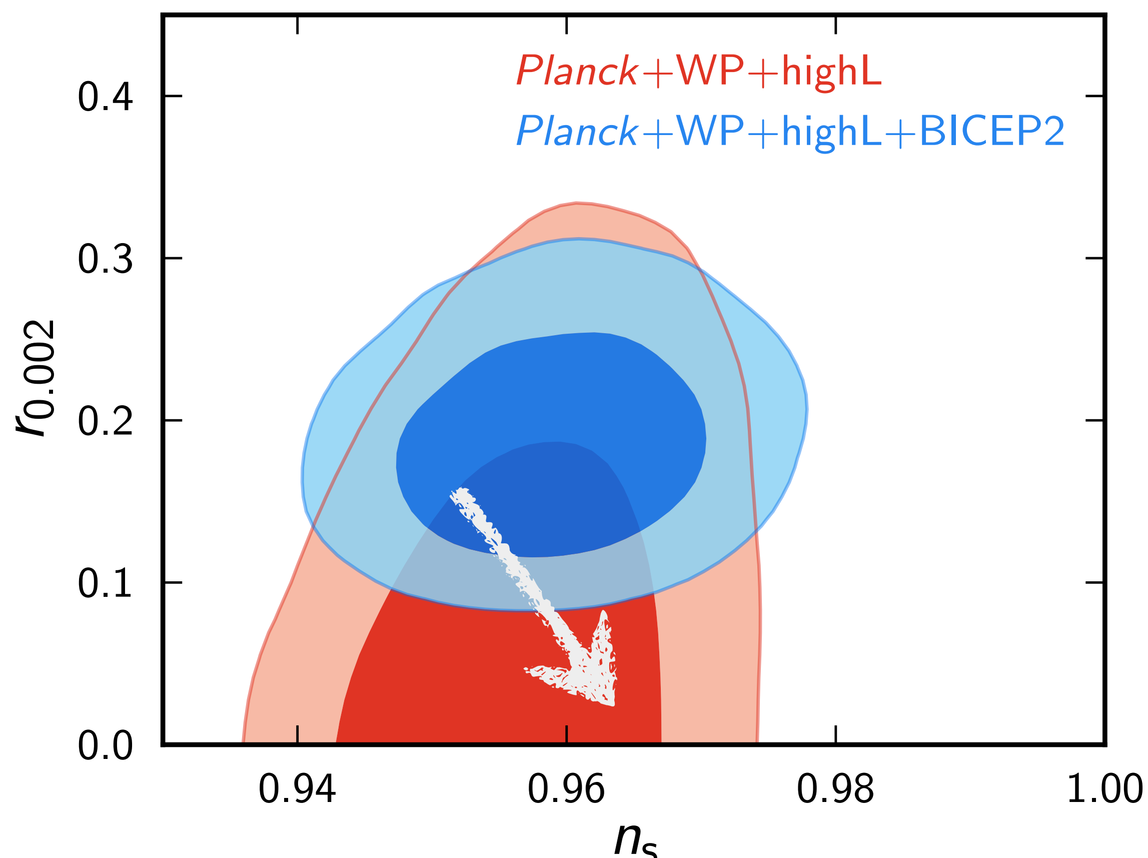


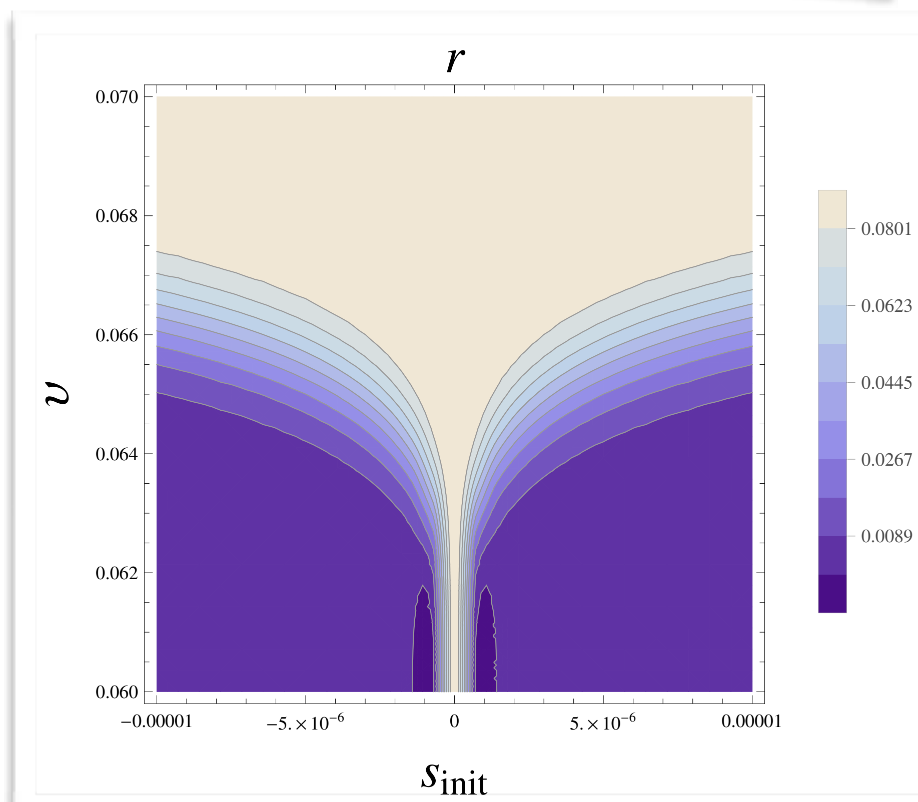


Tensor/scalar ratio $r = A_t / A_s$

- Multi-field: A_s enhanced, whereas A_t stays constant
- The ratio $r = A_t / A_s$ suppressed by the multi-field effects







A_s, f_{NL} and n_s

- Planck (2013):

$$
\begin{aligned}
A_s &= (2.23 \pm 0.16) \times 10^{-9} && (68\%\ \text{C.L.}),\\
n_s &= 0.9603 \pm 0.0073 && (68\%\ \text{C.L.}),\\
r &< 0.12 && (95\%\ \text{C.L.}),\\
f_{\rm NL}^{\rm local} &= 2.7 \pm 5.8 && (68\%\ \text{C.L.}).
\end{aligned}
$$

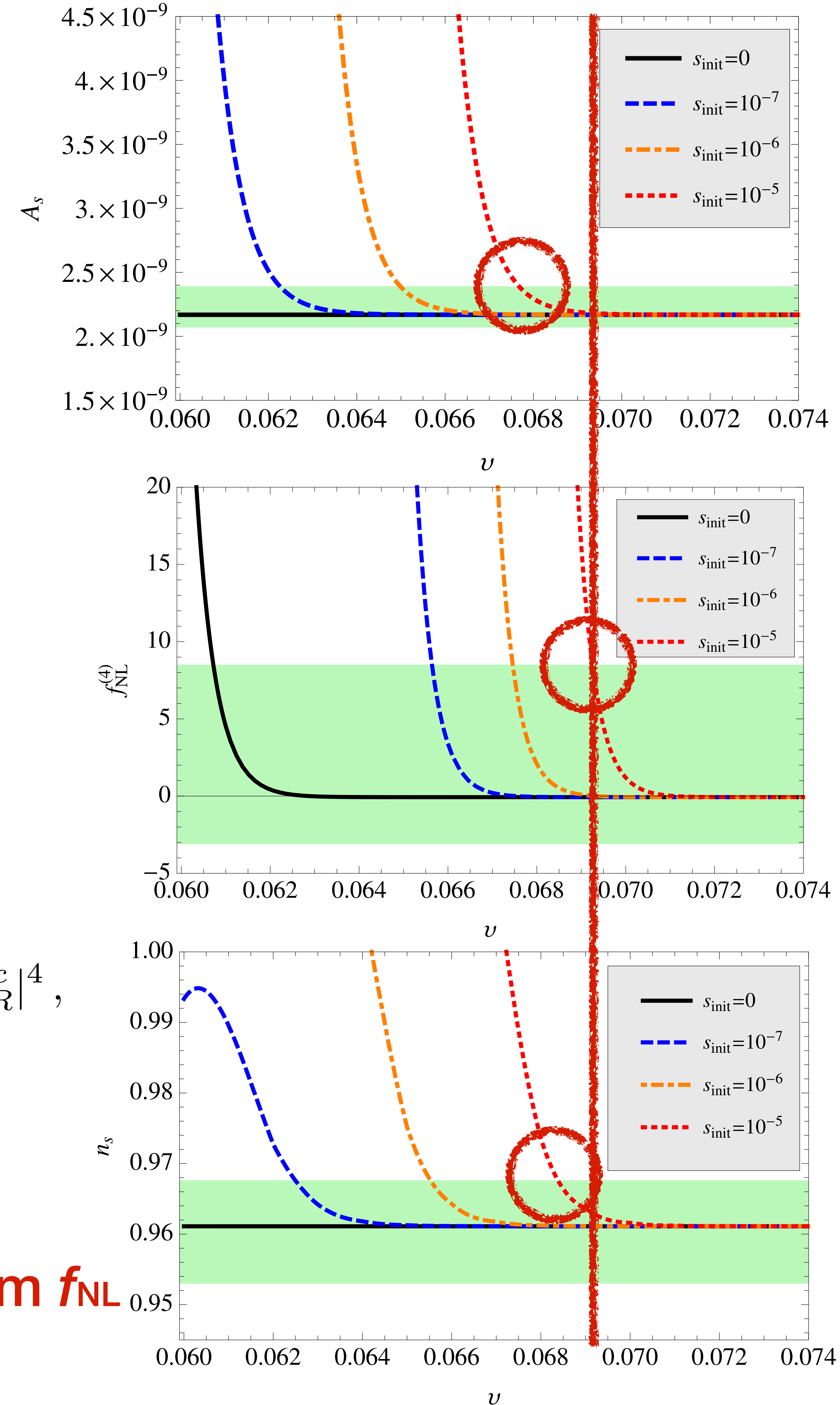
- Recall: quantum fluctuation gives $\Delta s \sim 10^{-5}$

- Kähler potential was

$$\Phi = \underbrace{1 - \frac{1}{3}\left(|N_R^c|^2 + |\varphi|^2\right)}_{\text{canonical terms}} + \frac{1}{4}\gamma\left(\varphi^2 + \text{c.c.}\right) + \frac{1}{3}\upsilon |N_R^c|^4\,,$$

fixed by A_s

$\upsilon > 0.069$ from f_{NL}



Summary

- Inflaton can be anything, but it's a good time to think about its origin in "beyond the Standard Model".
- Higgs inflation interesting. SUSY Higgs inflation more interesting.
- Avoid the η problem: non-canonical Kähler potential
- Multi-field signatures (e.g. non-Gaussianities) may be a clue to understand supergravity embedding of BSM.
- Analysed a concrete model based on SUSY seesaw

Thank you for your attention.