SUSY, Seesaw, CMB

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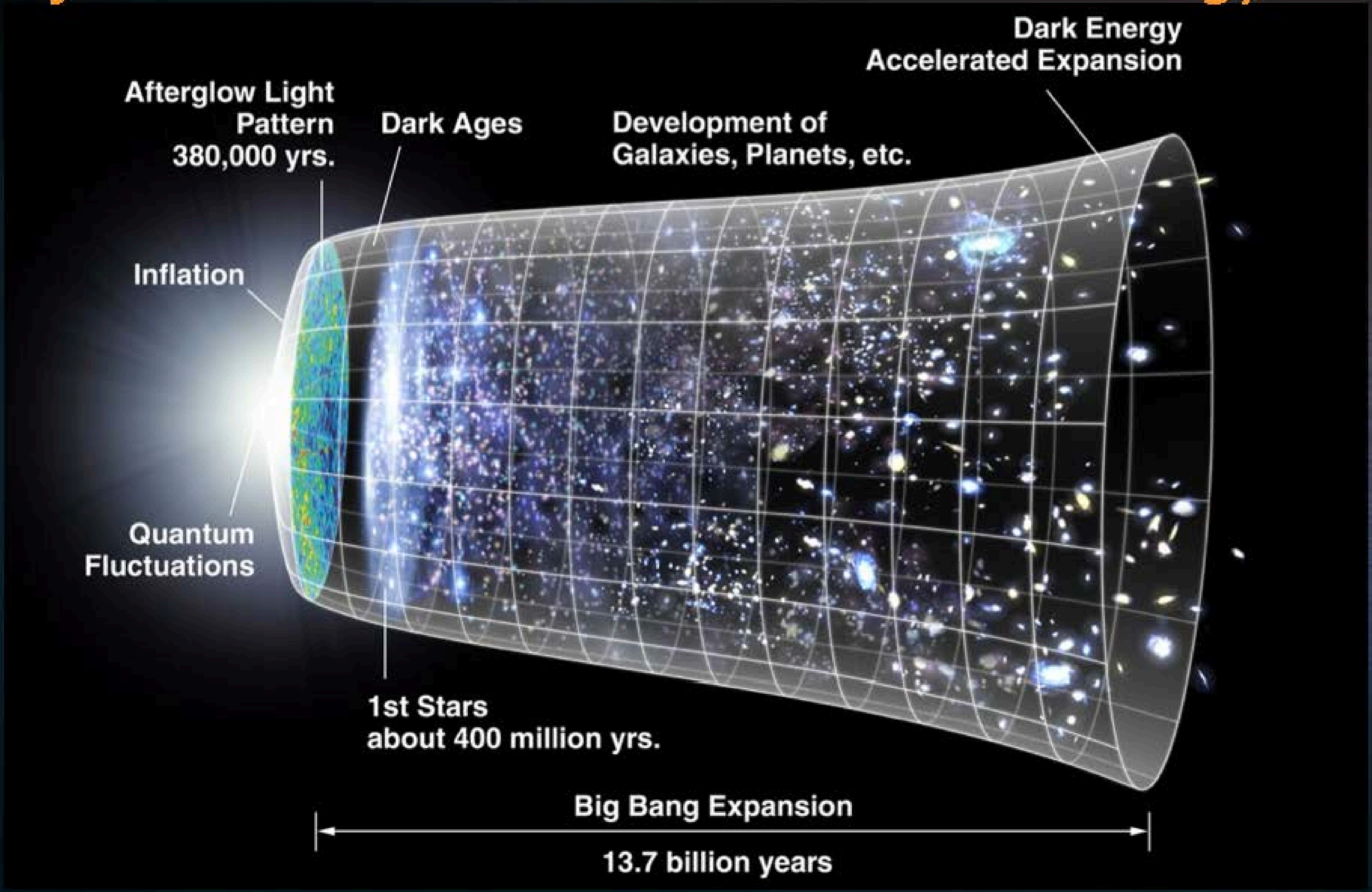
Based on [arXiv:1112.2391, 1212.6828, 1311.1317] with M. Arai & N. Okada

Inflation is essential in modern cosmology.

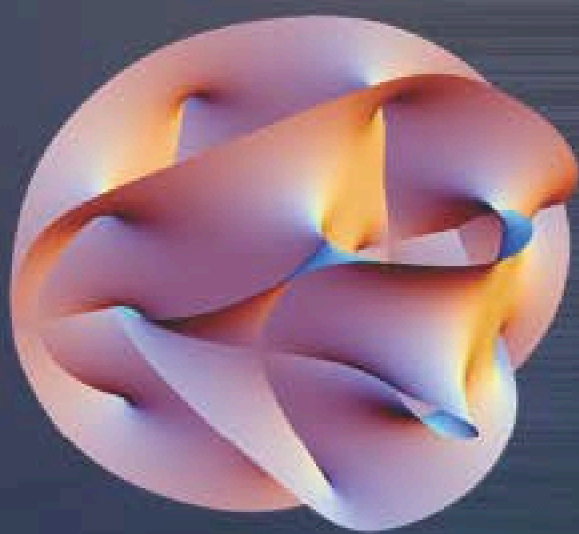


But, what is the physics behind?

3 approaches of inflationary cosmology

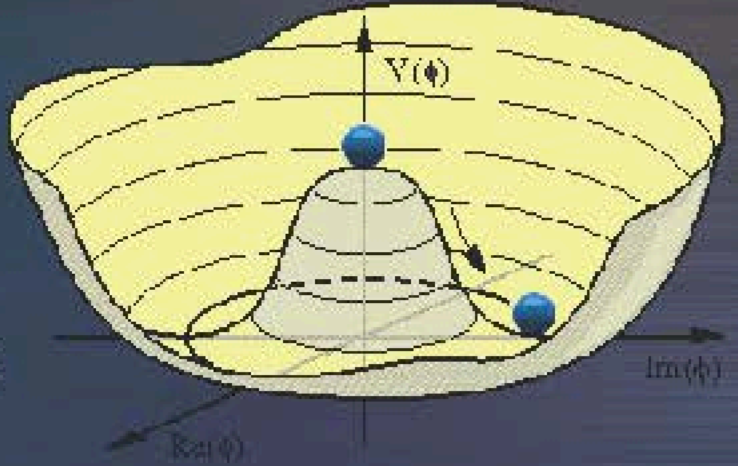
- Toy model approach
  - Simple Lagrangian, generic fields
  - $V = \lambda\phi^4, m^2\phi^2, \ldots$
- Top-down approach
  - Start from string, M- or F-theory
  - D-branes, Calabi-Yau moduli, landscape...
- Bottom-up approach
  - Low-energy spectrum (SM + extension)
  - Predictability & falsifiability

Can Higgs be the inflaton?



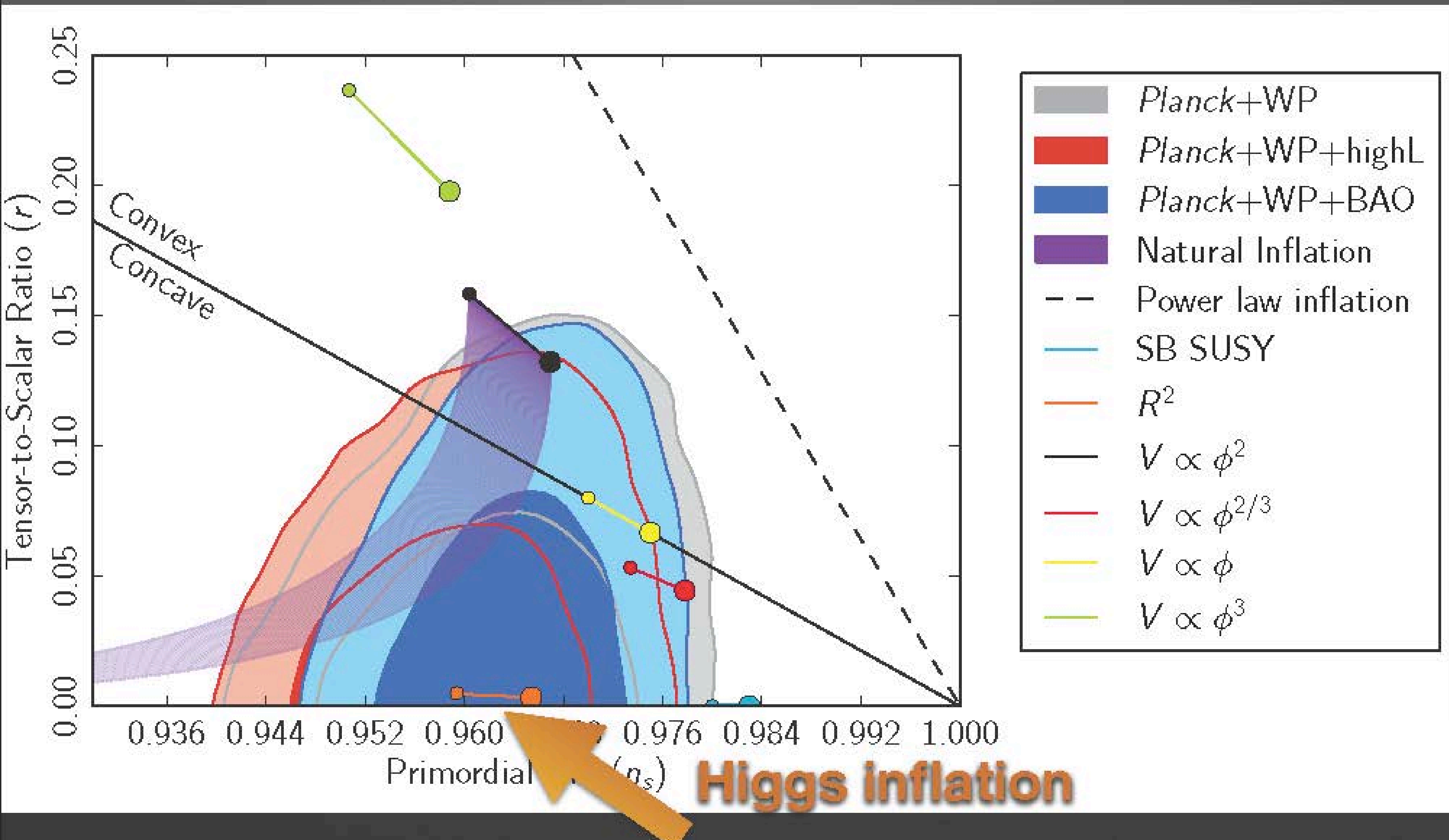
Higgs inflation

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



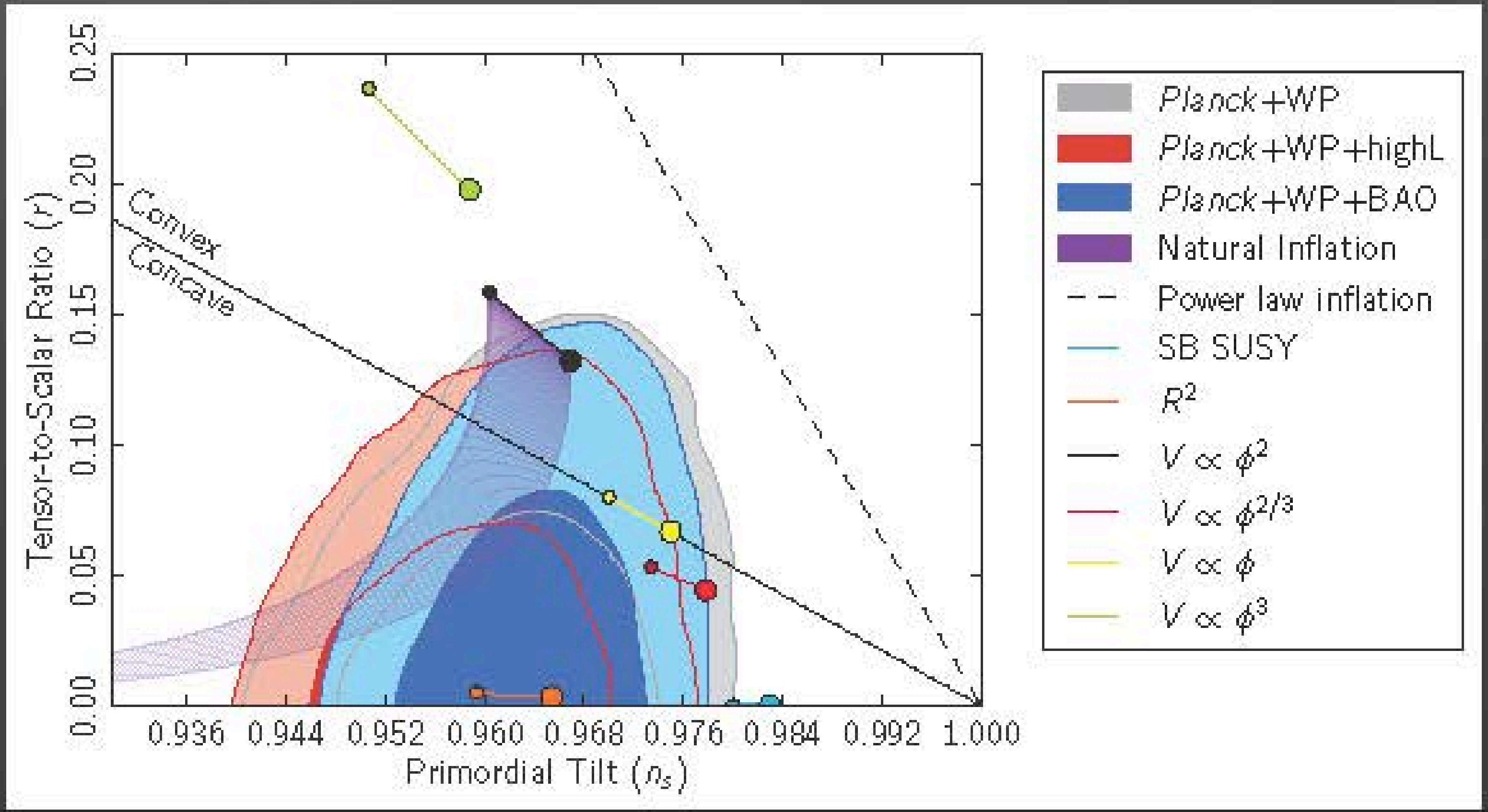
- How can ever be the same field?
  - Nonminimal coupling to gravity [Cervantes-Cota, Dehnen 1995] [Bezrukov Shaposhnikov 2008]
  - Non canonical kinetic term [Germani Kehagias] [Nakayama Takahashi] [many others]
  - Other curvature perturbation [Langlois Vernizzi] [many others]

Planck (2013) [arXiv: 1303.5062]



Bottom-up inflation models

- Standard Model — Higgs inflation
  - GUT
  - SM + B-L
- Minimal SUSY SM (MSSM)
  - NMSSM
  - SUSY GUT
  - SUSY Seesaw
  - SUSY B-L



Supersymmetric models

- SUSY (still) attractive? (hierarchy problem, gauge coupling unification, …)
- UV completion: superstrings
- In general, it is not easy to implement inflation in supersymmetric setup —“the η problem”
- To circumvent the η problem —a hint: Higgs inflation

The η problem

- Supergravity with canonical Kähler potential K, generic superpotential W, and F-term SUSY breaking yields slow-roll parameter $\eta \sim O(1)$
- To circumvent?
- Noncanonical K, special W, and/or D-term SUSY breaking.

Higgs inflation

- Good
  - Inflaton as a known particle
  - CMB spectrum fits well
- Bad
  - Potential unstable against radiative corrections
  - CMB amplitude $\approx 10^{-9} \Rightarrow \xi \approx 10^4$

Higgs @ 125 GeV may suggest no physics up until $\sim 10^{17}$ GeV. However, we need to account for

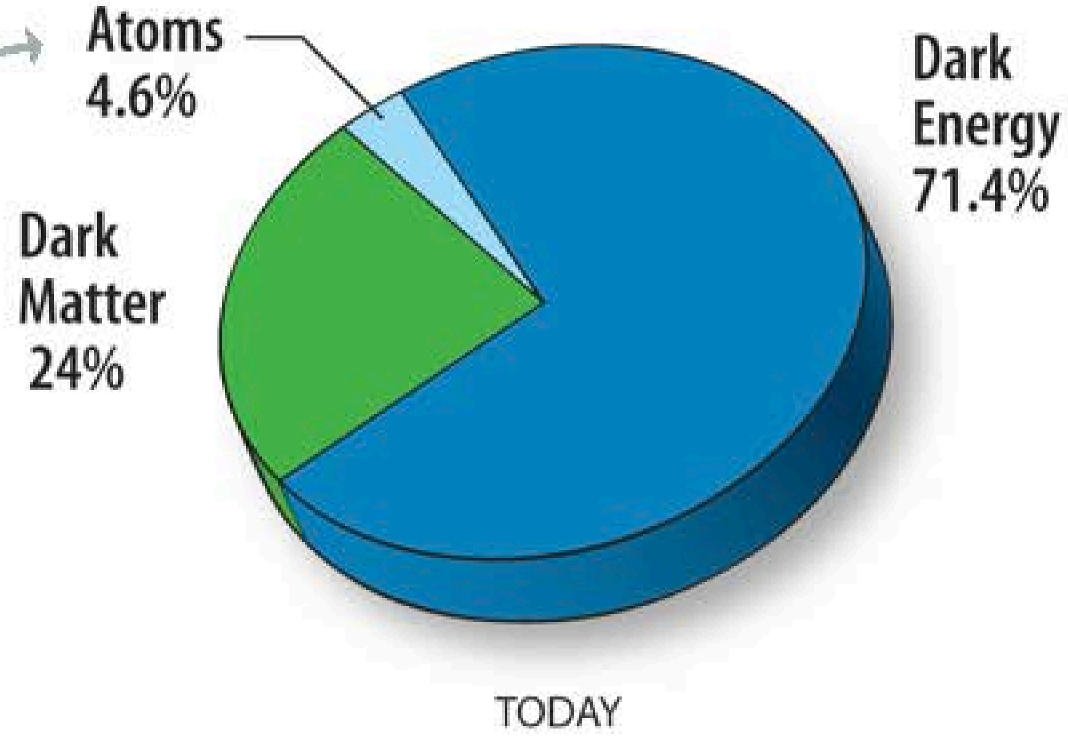
Neutrino oscillations

And baryogenesis

Baryon Asymmetry of the Universe

Baryon asymmetry

$$Y_B \equiv \frac{n_B}{s} = 8.7 \times 10^{-11}.$$



Sakharov's conditions for baryogenesis

(1) Baryon number violation
(2) C and CP violation
(3) Deviation from thermal equilibrium

Baryogenesis

- Baryon asymmetry: $Y_B \equiv \frac{n_B}{s} = 8.7 \times 10^{-11}$.

- **Difficult in SM -- unlikely in EW (strong 1st order phase transition)**

- **In GUT – not possible if $T_{RH} < M_{GUT}$**

- **Between GUT and EW:**
  - B+L conserved
  - Hence, B-L needs to be violated
  - N_R gets large Majorana mass – leptogenesis *and* seesaw

$$Y_B = -\frac{8N_f + 4N_H}{22N_f + 13N_H} Y_L = -\frac{8}{23} Y_L.$$

Our first model:
Higgs-lepton inflation in SUSY-seesaw

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

SUSY seesaw: MSSM + NR

Superpotential

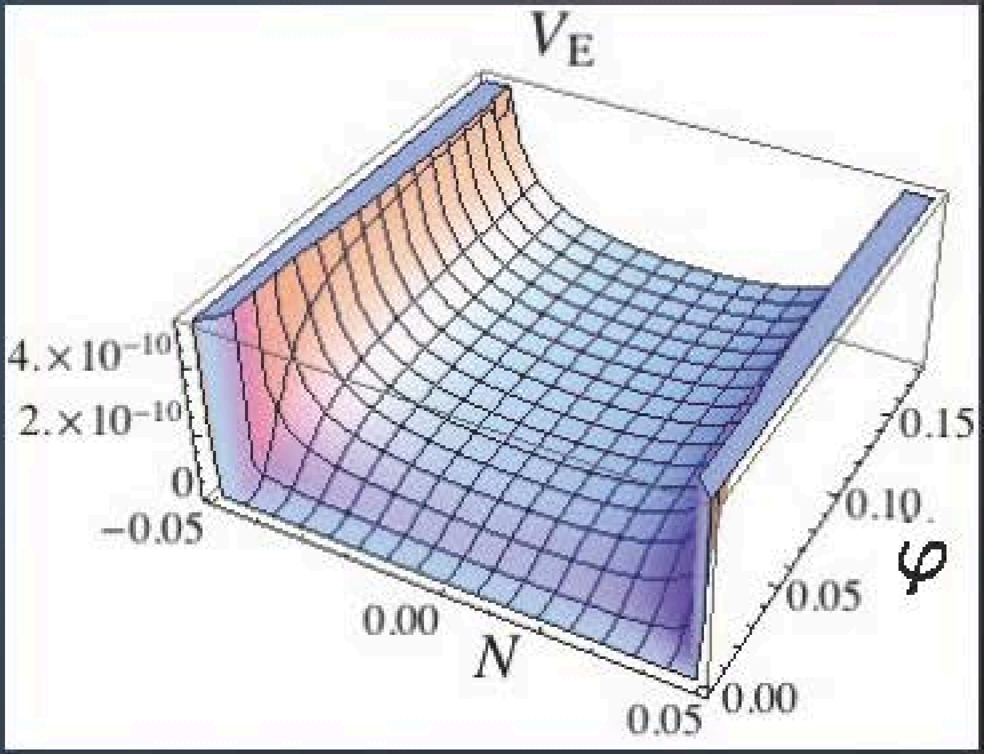
Right-handed neutrinos

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

D-flat direction

NB: y_D can be very small

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



Kähler potential

Noncanonical

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

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

Seesaw relation

⇒ nonminimal coupling ξ

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

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

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

Neutrino sector

- Oscillation data

$$\sin^2 2\theta_{12} = 0.87, \quad \sin^2 2\theta_{23} = 1.0, \quad \sin^2 2\theta_{13} = 0.092$$

$$\Delta m_{12}^2 = m_2^2 - m_1^2 = 7.59 \times 10^{-5} \mathrm{eV}^2,$$

$$\Delta m_{23}^2 = |m_3^2 - m_2^2| = 2.43 \times 10^{-3} \mathrm{eV}^2.$$

- Seesaw relation

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

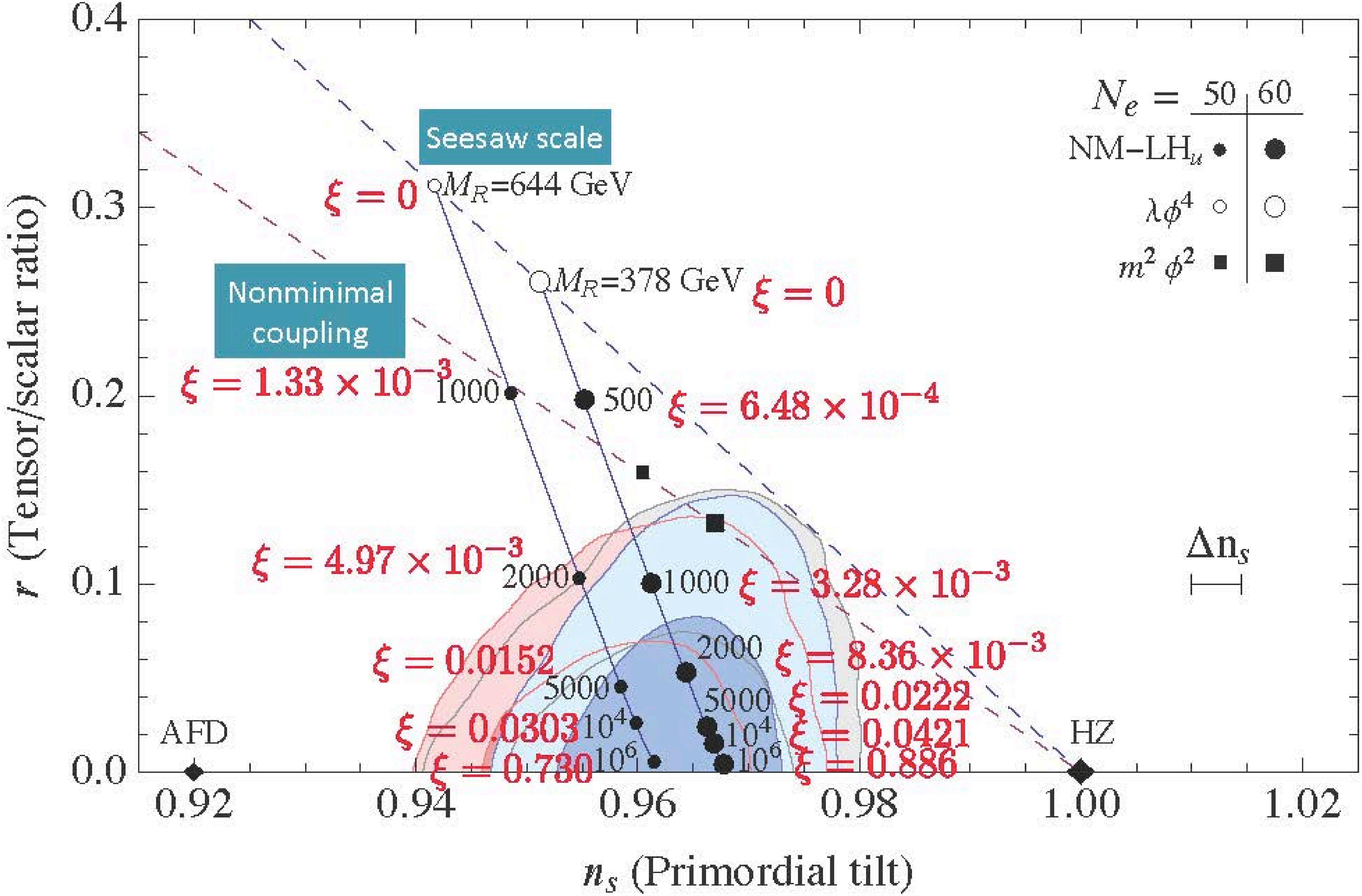
$$m_\nu^2 \approx \Delta m_{32}^2 = 2.43 \times 10^{-3}\ \mathrm{eV}^2$$

$$\langle H_u \rangle \approx 174$$

$$y_D = \left(\frac{M_R}{6.14 \times 10^{14}\ \mathrm{GeV}} \right)^{\frac{1}{2}}.$$

- Baryon asymmetry -- leptogenesis

Planck (2013)



r (Tensor/scalar ratio)
n_s (Primordial tilt)
0.0
0.1
0.2
0.3
0.4
0.92
0.94
0.96
0.98
1.00
1.02
N_e = 50 | 60
NM–LH$_u$
$\lambda\phi^4$
$m^2\phi^2$
Δn_s
Seesaw scale
Nonminimal coupling
M_R=644 GeV
M_R=378 GeV
$\xi = 0$
$\xi = 0$
$\xi = 1.33 \times 10^{-3}$
$\xi = 6.48 \times 10^{-4}$
$\xi = 4.97 \times 10^{-3}$
$\xi = 3.28 \times 10^{-3}$
$\xi = 0.0152$
$\xi = 8.36 \times 10^{-3}$
$\xi = 0.0222$
$\xi = 0.0303$
$\xi = 0.0421$
$\xi = 0.730$
$\xi = 0.886$
1000
500
2000
1000
2000
5000
5000
10^4
10^4
10^6
10^6
AFD
HZ

Higgs-lepton inflation: better than Higgs inflation

- Based on a well-motivated particle theory *MSSM*
- Nonminimal coupling OK but not insanely large ✔
- Radiative corrections under control *SUSY*
- Small nonzero neutrino masses *Seesaw*
- Baryon asymmetry *Leptogenesis*
- Compatible with WMAP/Planck ✔
- Falsifiability and Predictability ✔

An even better model of inflation?

- In the Higgs-Lepton model, R-parity violation in Kahler
  - — acceptable, but aesthetically not very appealing
- $\xi \lesssim O(1)$ is good, but $\xi = 0$ is not strictly special
  - Stress tensor RG…
  - Conformal coupling: $\xi = -⅙$

Our proposal:
inflation at small negative ξ in B-L extended MSSM

Our second model:
B-L Higgs inflation in SUSY B-L model

[Arai, SK, Okada, arXiv:1311.1317]

SUSY B-L model

SUSY Seesaw model (MSSM + N_R)

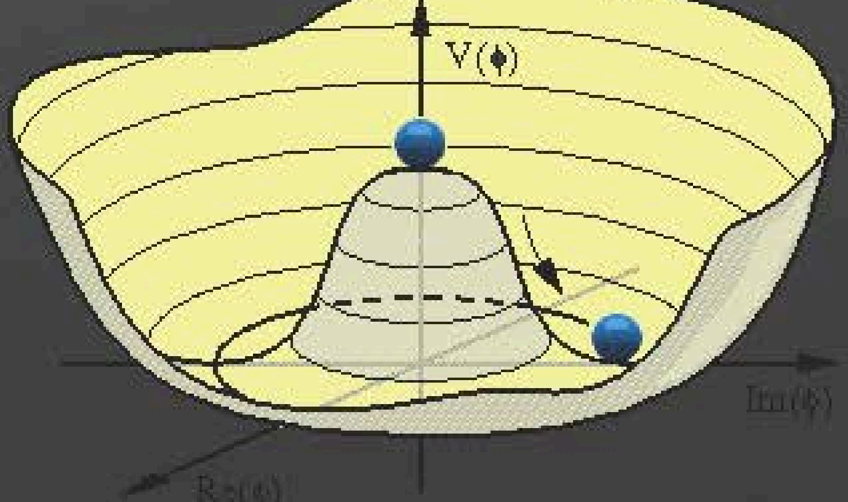
$$W = W_{\rm MSSM} + y_D N^c L H_u + M N^c N^c$$

What is the origin of this? $M = \lambda \langle \Phi \rangle$

$$W = W_{\rm MSSM} + y_D N^c L H_u + \lambda \Phi_- N^c N^c + \kappa S(\Phi_- \Phi_+ - v^2)$$

Unique if one assigns *B-L* charges

	L	H_u	N^c	Φ_+	Φ_-	S
B-L =	-1,	0,	+1,	+2,	-2,	0
R' =	0,	+1,	+1,	0,	0,	+2



Charges of the superfields

[Lazarides, Shafi (1998)]

	Q	u	d	L	e	H	H	N	S	Φ_+	Φ_-
B	⅓	-⅓	-⅓	0	0	0	0	0	0	0	0
L	0	0	0	1	-1	0	0	-1	0	-2	2
R	½	½	½	½	½	1	1	½	2	-1	1
B-L	⅓	-⅓	-⅓	-1	1	0	0	1	0	2	-2
R'= R-$L/2$	½	½	½	0	1	1	1	1	2	0	0

Our supergravity embedding

- Superpotential

$$W = \mu H_u H_d + y_u u^c Q H_u + y_d d^c Q H_d + y_e e^c L H_d$$
$$+ y_D N^c L H_u + \lambda \Phi_- N^c N^c + \kappa S(\Phi_- \Phi_+ - v^2)$$

- Kähler potential $K = -3\Phi$

$$\Phi = 1 - \frac{1}{3}\Big(|\Phi_+|^2 + |\Phi_-|^2 + |S|^2 + \cdots\Big)$$
$$+ \frac{\gamma}{2}\Big(\Phi_+ \Phi_- + \Phi_+^* \Phi_-^*\Big) + \frac{\zeta}{3}|S|^4$$

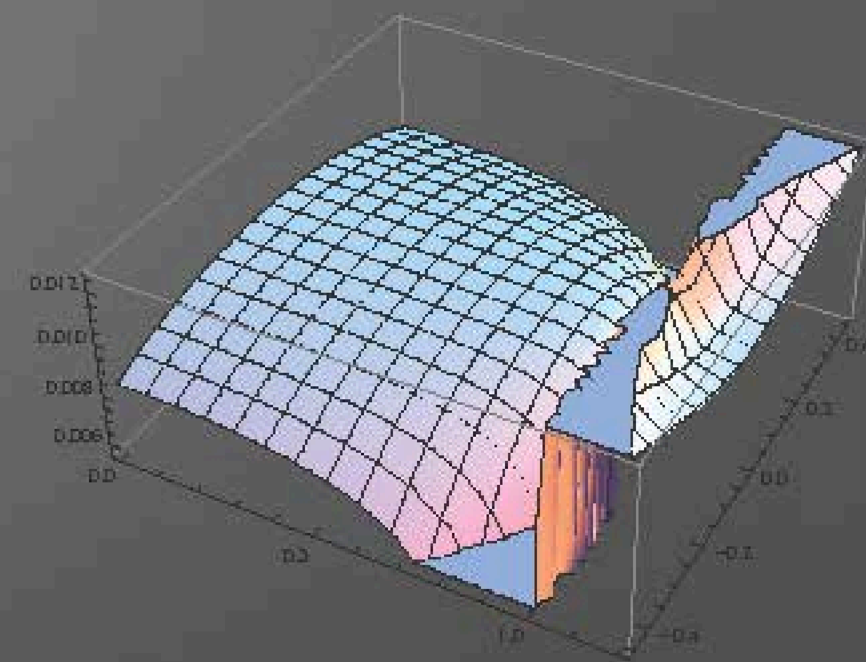
noncanonical

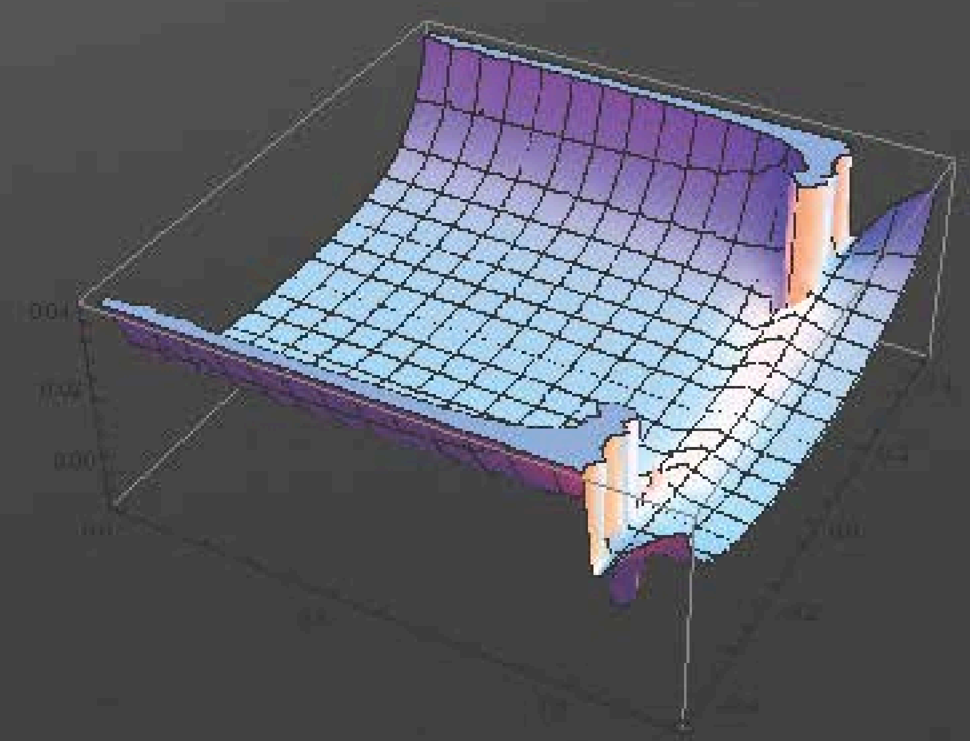
- Both preserve *B-L* symmetry and *R* symmetry

Inflaton dynamics

- During inflation
- 3 fields S, Φ_+, Φ_-
- 4 parameters κ, v, γ, ζ
- D-flat direction: $|\Phi_+| = |\Phi_-| = \phi/2$
- Taking $\zeta > 0 \Rightarrow$ stable at $S = 0$
- Simplifies to a single field model
- Potential $V_{\mathrm{E}} = \dfrac{\kappa^2}{16}\left(\dfrac{\varphi^2 - 4v^2}{1 - |\xi|\varphi^2}\right)^2$
- Nonminimal coupling parameter

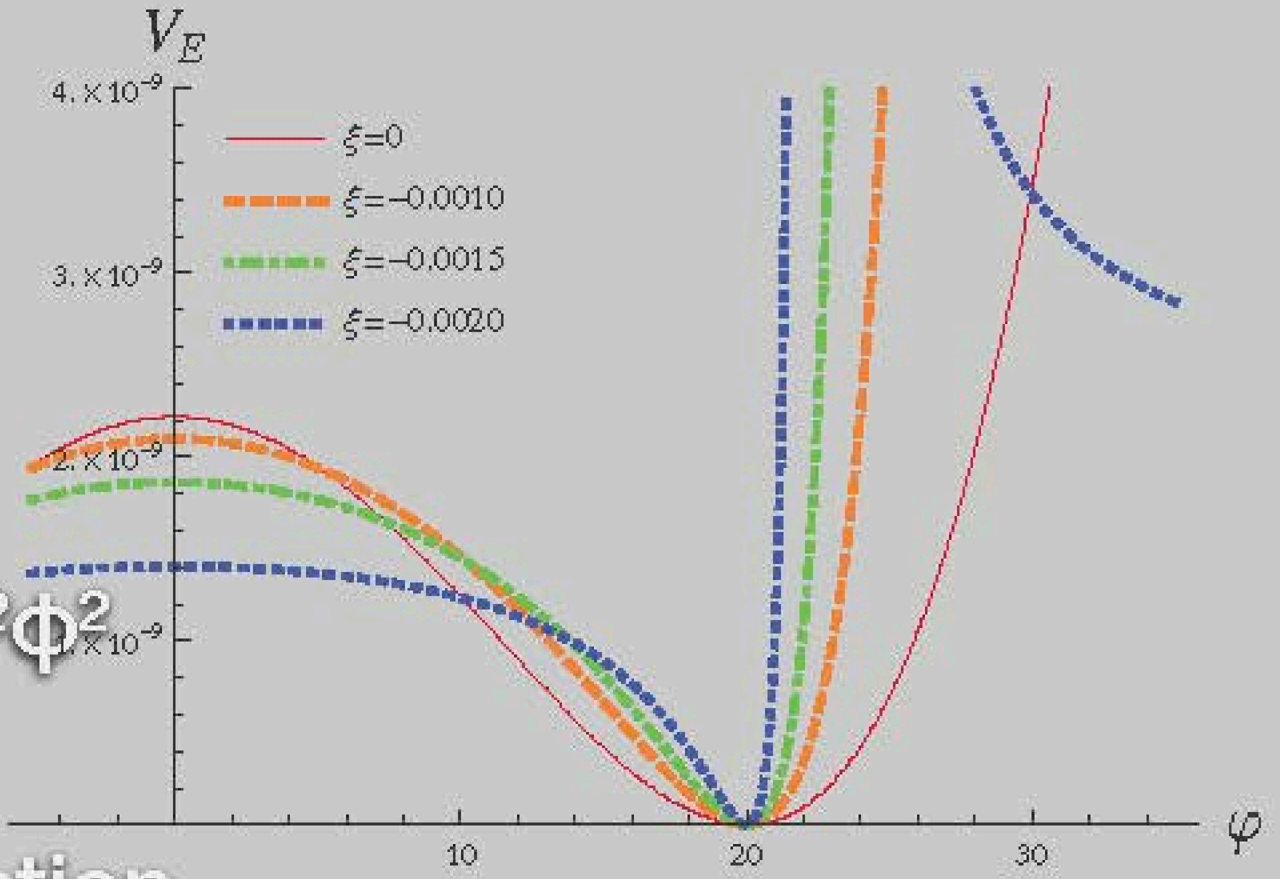
$$\xi = \frac{\gamma}{4} - \frac{1}{6}$$





Inflaton dynamics

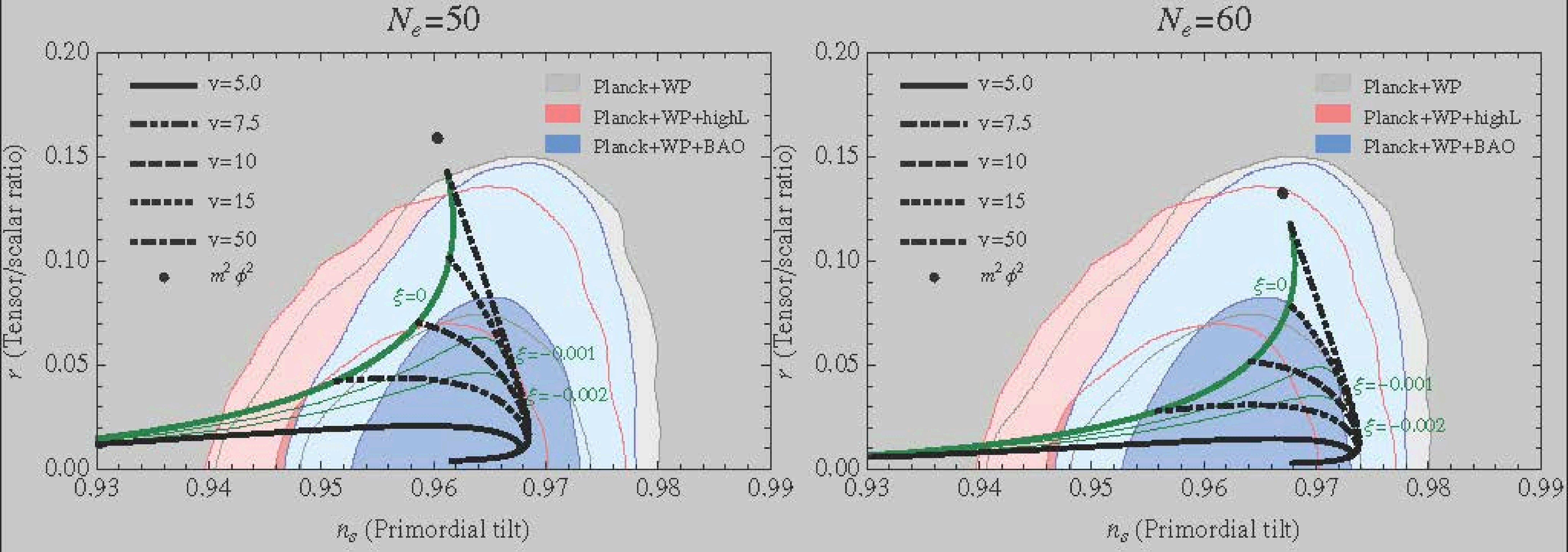
$$V_{\rm E} = \frac{\kappa^2}{16}\left(\frac{\varphi^2 - 4v^2}{1-|\xi|\varphi^2}\right)^2$$



- When ξ=0, v=0 ⇒ V=$\lambda\phi^4$
- When ξ=0, v large ⇒ V=$m^2\phi^2$
- When $4|\xi|v^2 \rightarrow 1$, Higgs inflation
- When ξ=0, double well

[Linde Noorbala Westphal, 2011]

CMB spectrum



Reheating temperature

- Let us consider perturbative decay of inflaton

$$W = \mu H_u H_d + y_u u^c Q H_u + y_d d^c Q H_d + y_e e^c L H_d$$
$$+ y_D N^c L H_u + \boxed{\lambda \Phi_- N^c N^c} + \kappa S(\Phi_- \Phi_+ - v^2)$$

- There are two decay channels

1. ϕ → NN, ÑÑ [right-handed (s)neutrinos]

2. ϕ → Z'Z' [U(1)$_{B\text{-}L}$ gauge boson]

- Γ ≳ H and $H^2 = \frac{\rho}{3M_{\rm P}^2} = \frac{g_* \pi^2 T^4}{90 M_{\rm P}^2}$

$$\Rightarrow \quad T_{\rm RH} \lesssim \left(\frac{90}{g_* \pi^2}\right)^{\frac{1}{4}} \sqrt{M_P \Gamma}$$

$\Phi \to NN, \tilde{N}\tilde{N}$

- Inflaton oscillates at $\langle \Phi_- \rangle = v$
- Seesaw mass $M_R = \lambda v$
- $y_D \lesssim O(1)$, $v \approx O(10)\, M_P \Rightarrow \lambda \lesssim 10^{-6}$
- Inflaton mass $m \approx 10^{13}$ GeV
- Decay rate $\Gamma \approx \dfrac{\lambda^2}{16\pi} m$
- Reheating temperature: $T_{\mathrm{RH}} \approx \dfrac{M_R}{10^{12}\ \mathrm{GeV}} \times 10^7\ \mathrm{GeV}$

Gravitino problem bound
$T_{RH} \lesssim 10^6$ - 10^7 GeV

$\phi \to Z'Z'$

- When Z' mass smaller than m/2
- Decay width $\Gamma(\phi \to Z'Z') \approx \frac{1}{32\pi}\frac{m^3}{v^2}$
- Reheating temperature

$$T_{\mathrm{RH}} \approx 10^6 \ \mathrm{GeV}$$

Gravitino problem bound
$T_{RH} \lesssim 10^6 - 10^7$ GeV

Thermal leptogenesis

- When $T_{RH} > M_R$, the right-handed (s)neutrinos are thermally produced
- Their decay ⇒ lepton number ⇒ sphaleron transition ⇒ BAU
- Yield: $Y_B \sim Y_L \sim \frac{a\epsilon_i}{g_*} \sim 10^{-10}, \quad a \lesssim \mathcal{O}(1), \quad g_* \sim 200$
- Needs resonance enhancement [Flanz, Paschos, Sarkara, Weiss 1996] [Pilaftsis 1997]
- $\phi \to NN$, $\tilde{N}\tilde{N}$ channel: $T_{\rm RH} \approx \frac{M_R}{10^{12}\ {\rm GeV}} \times 10^7\ {\rm GeV}$
  - $M_1 \approx M_2 \ll T_{RH} \ll M_3$
- $\phi \to Z'Z'$ channel: $T_{\rm RH} \approx 10^6\ {\rm GeV}$
  - All 3 N_i can be light, at least two degenerate

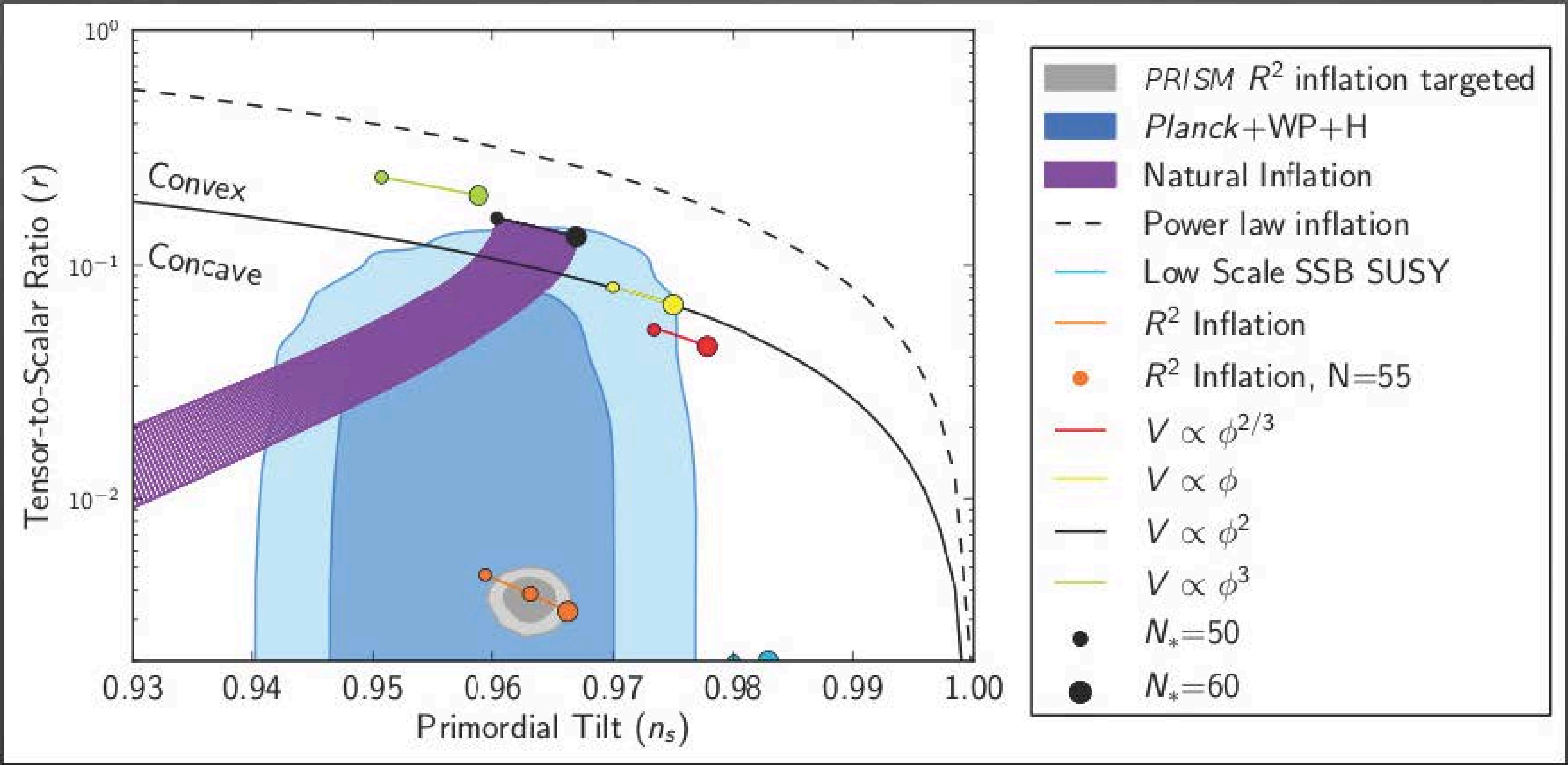
Nonthermal leptogenesis

- When $T_{RH} < M_R$, the right-handed (s)neutrinos are produced by inflaton decay
- Their decay ⇒ lepton number ⇒ sphaleron transition ⇒ BAU
- Yield: $$Y_B \sim Y_L \sim \frac{T_{\rm RH}}{m} \sum {\rm Br}_i \epsilon_i \sim 10^{-10}$$
  $$T_{\rm RH} \sim 10^7 \ {\rm GeV}, \quad m \sim 10^{13} \ {\rm GeV}$$
- $Br_i\varepsilon_i$ ~ 10^{-4} — resonant leptogenesis
- At least 2 of M_i degenerate

What will we see in the future?

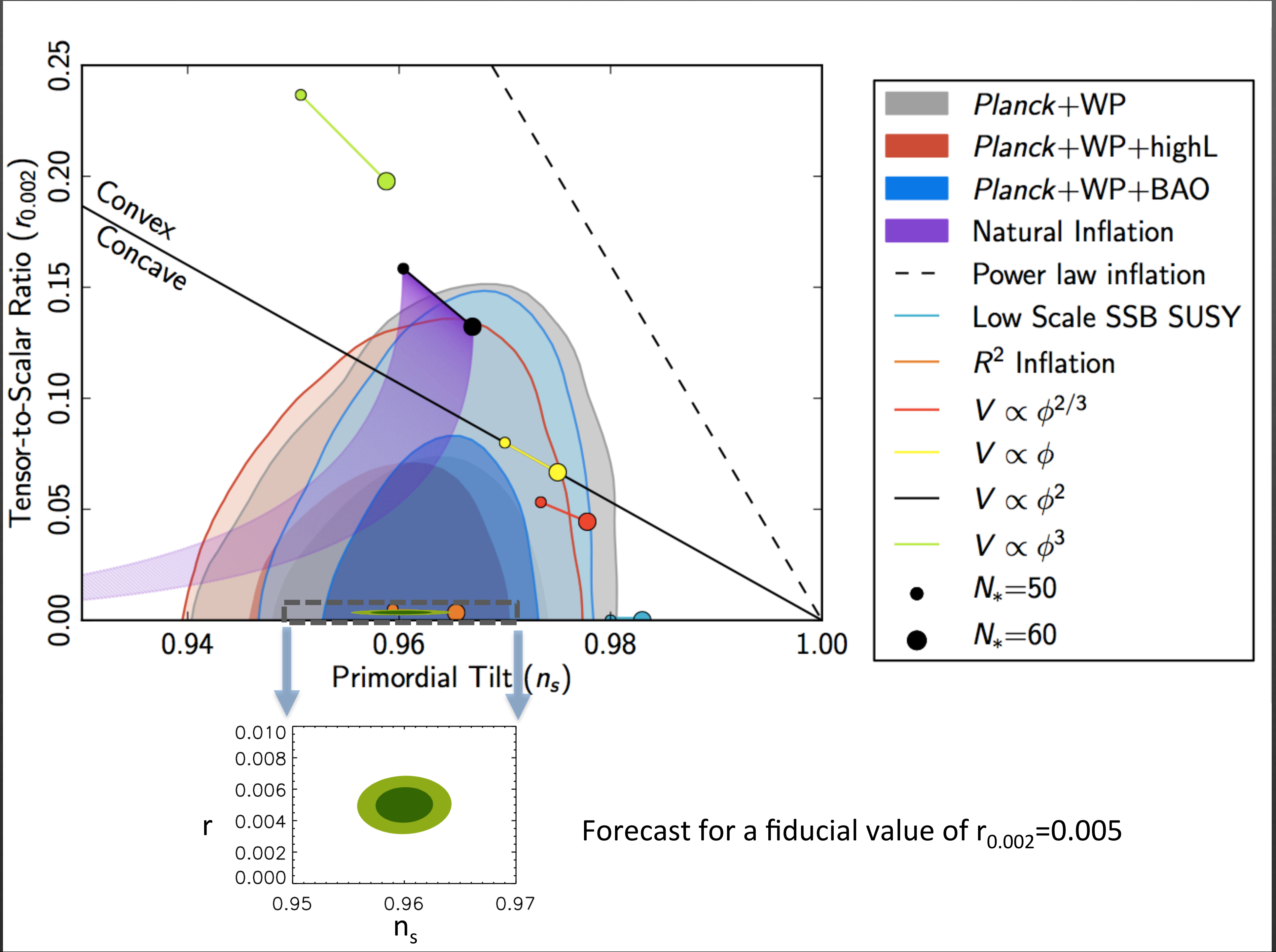
Future CMB observation

$r = 5 \times 10^{-4}$ at 5σ PRISM white paper [1306.2259]



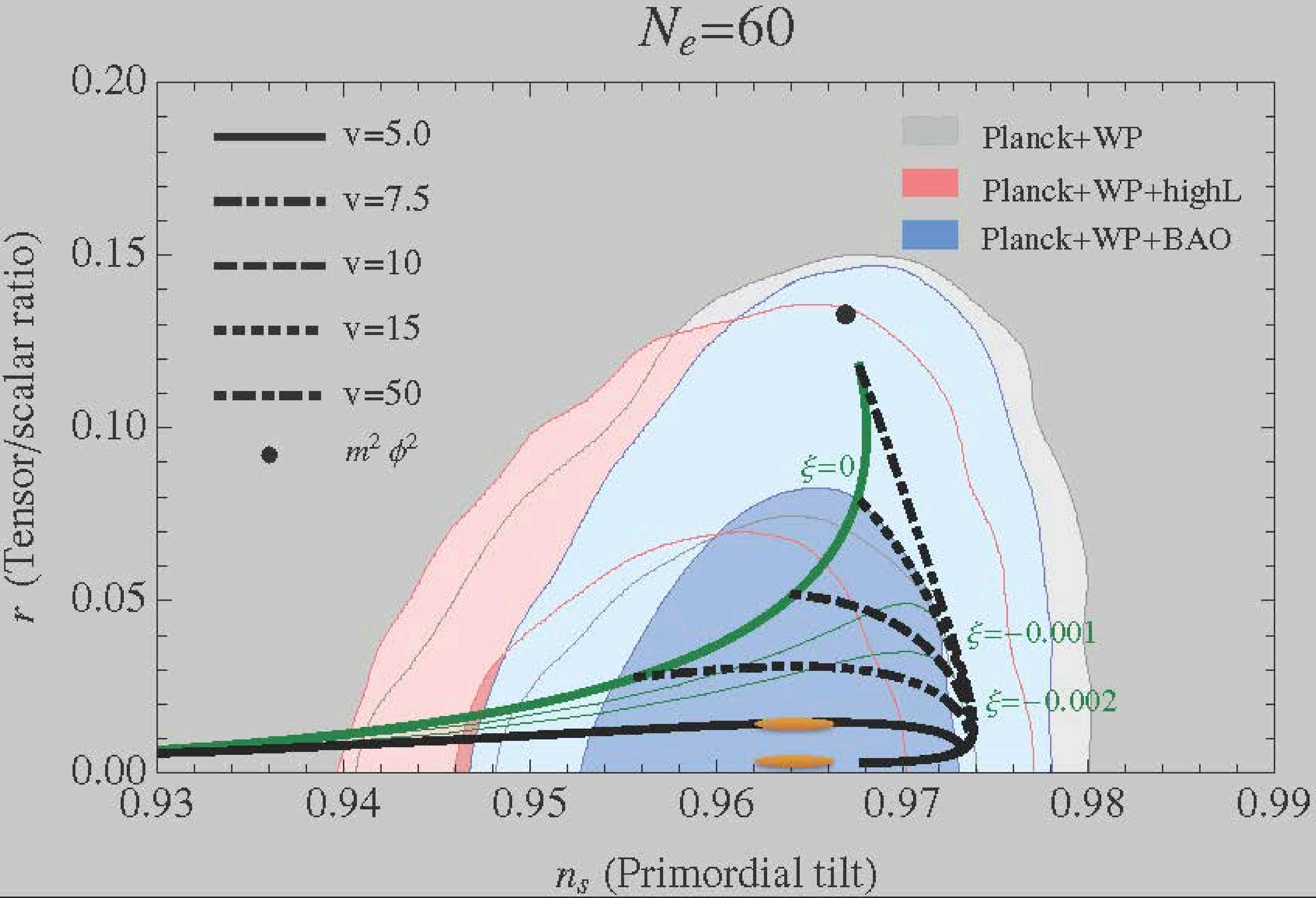
Future CMB observation

PRISM white paper [1306.2259]



Forecast for a fiducial value of $r_{0.002}$=0.005

Future CMB observation



Summary

- A new model of inflation based on SUSY B-L
- R-symmetric superpotential and Kähler potential
- Fits well with WMAP & Planck
- Seesaw mechanism and leptogenesis
- B-L broken at super-Planck, no cosmic strings
- No exotic coloured particles (unlike generic GUT)

Thank you for your attention.

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