# Inflation and majoron dark matter in the seesaw mechanism

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Based on **arXiv:1404.3198**

In collaboration with:
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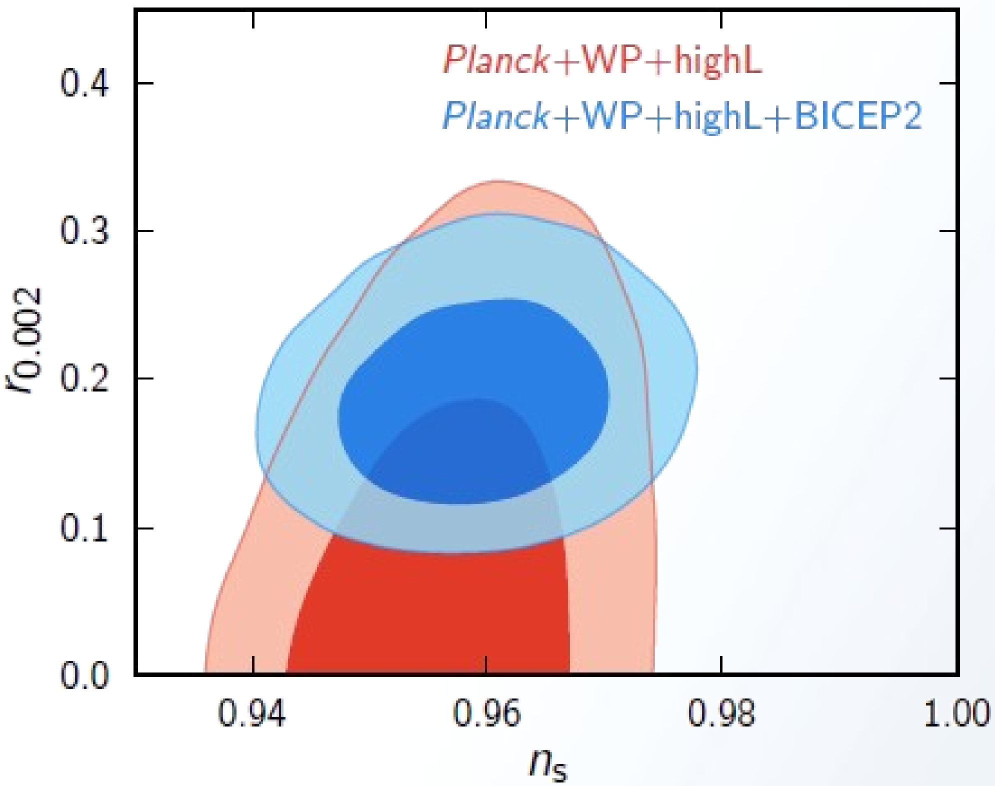



$$r = 0.2^{+0.07}_{-0.05}$$

**If BICEP2 results hold up to scrutiny, we have first direct evidence for inflation happening at energy scale:**

$$E \approx H^2 \approx 10^{16}\,\mathrm{GeV}$$

**Successful inflationary scenario should:**

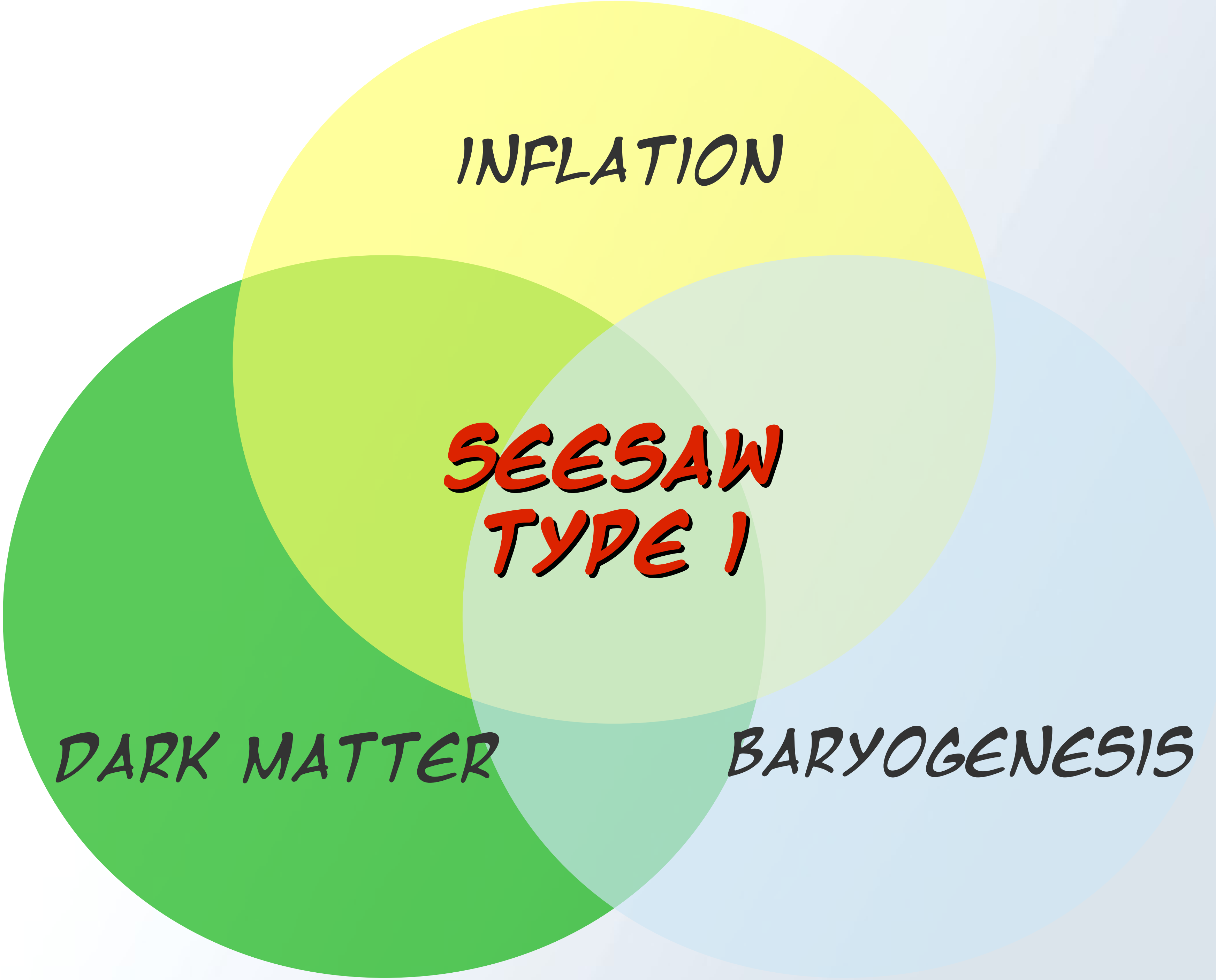
* **Solve observational cosmology conundrums (flatness, isotropy, ...),**
* **Seed cosmological perturbations,**
* **Recover hot Big Bang cosmology,**
* **Be testable.**

**Additionally, it would be nice if it addressed other open problems in HEP:**

**Neutrino masses**

**Dark Matter**

**Baryon asymmetry**


INFLATION
SEESAW
TYPE I
DARK MATTER
BARYOGENESIS

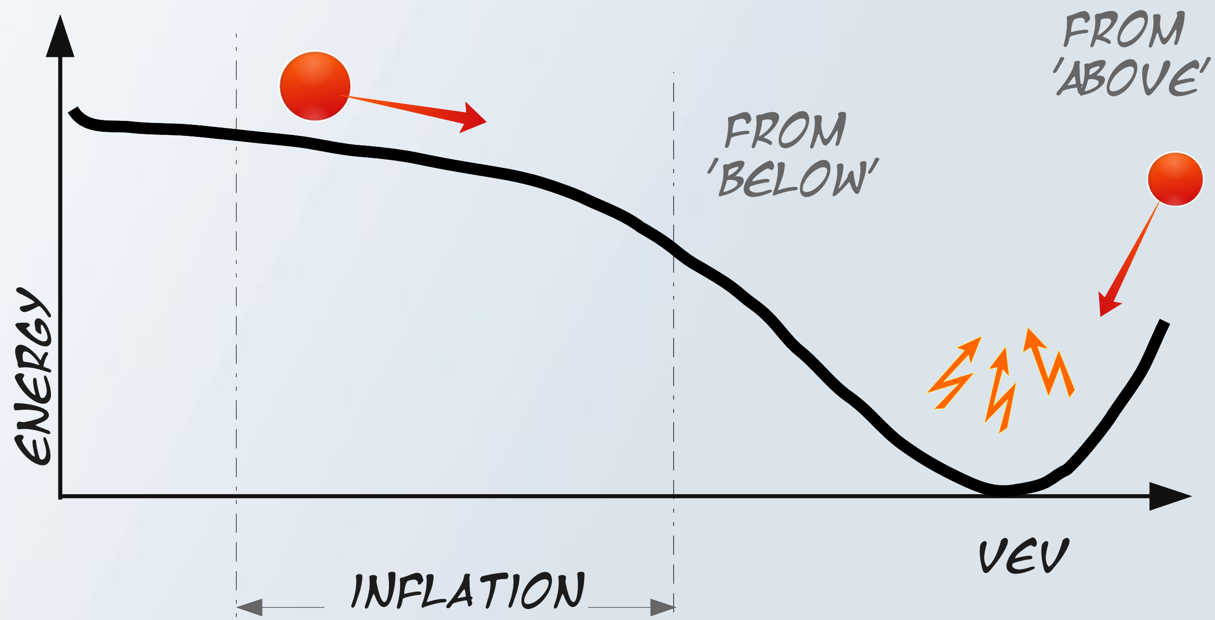
**Inflation, driven by scalar field *V*, is realized when the inflaton *slowly rolls* down to the minimum.**

**The spectral index, tensor to scalar ratio and the running of the spectral index are functions of the << 1 slow-roll parameters.**

$$n_s \simeq 1 - 6\epsilon + 2$$

$$r \simeq 16\epsilon \ ,$$

$$\alpha = 16\epsilon\eta - 24\epsilon^2 - 2\zeta^2$$



**At the renormalizable level, the SM contains an accidental U(1) symmetry. Let's promote it to a global symmetry and spontaneously break it at high scale;**

$$\mathcal{L}_{seesaw} = Y_D\, \ell\, i\tau_2 \Phi^* \nu_R + Y_N \sigma\, \overline{\nu_R^c} \nu_R$$

**Neutrinos then pick up a tiny mass via the usual Seesaw mechanism:**

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_D v_2 \\ Y_D v_2 & Y_N v_\mathrm{L} \end{bmatrix} \quad \Rightarrow \quad m_\nu \simeq \frac{(Y_D v_2)^2}{Y_N v_\mathrm{L}}$$

$$Y_N \approx \frac{10^{14}\ \mathrm{GeV}}{v_\mathrm{L}}$$

**The scalar potential, at tree level, contains**

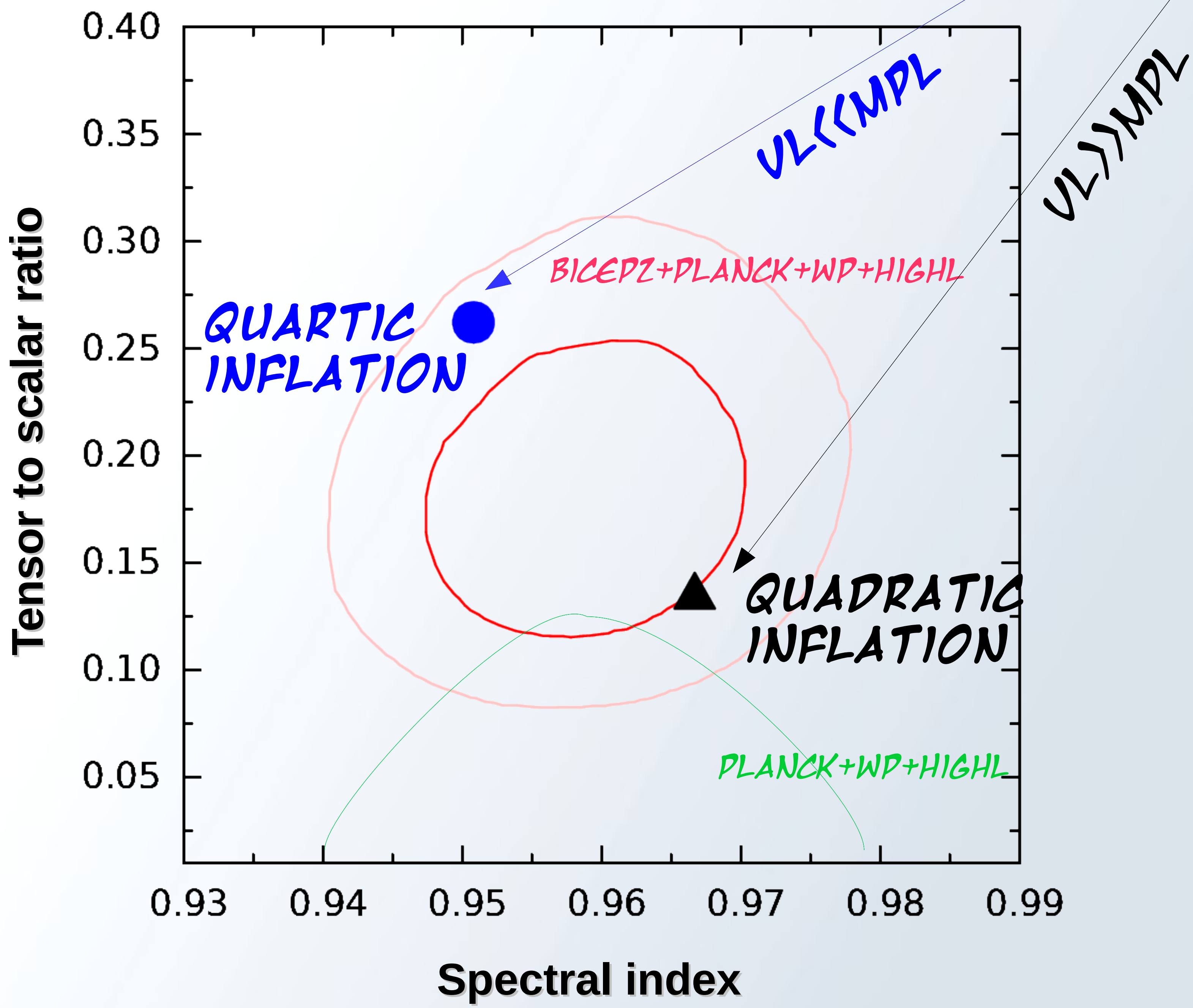
$$V_{\mathrm{tree}} = \lambda \left( \sigma^\dagger \sigma - \frac{v_{\mathrm{L}^2}}{2} \right)^2 + \lambda_{\mathrm{mix}} (\sigma^\dagger \sigma)(\Phi^\dagger \Phi) + V_\Phi$$

**After identifying the inflaton with the real part of the U(1) field, we have the following Higgs Inflation potential**

$$\boxed{V = \lambda \left[ \frac{1}{4} \left( \rho^2 - v_{\mathrm{L}}^2 \right)^2 \right]}$$

***Note that the textbook quartic and quadratic potentials are particular cases of this one..***

$$V = \lambda \left[ \frac{1}{4} \left( \rho^2 - v_{\rm L}^2 \right)^2 \right]$$



## However, the couplings with the RH neutrinos will correct the potential and induce quantum smearing

$$V = \lambda \left[ \frac{1}{4} \left( \rho^2 - v_{\mathrm{L}}^2 \right)^2 + a \log \left[ \frac{\rho}{v_{\mathrm{L}}} \right] \rho^4 + V_0 \right]$$

$$a \simeq \frac{1}{16\pi^2 \lambda} \left(20\lambda^2 + 2\lambda \left( \sum_i (Y_N^i)^2 \right) - \sum_i (Y_N^i)^4 \right)$$

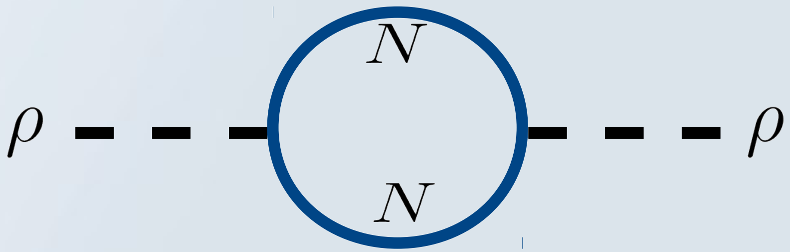
**Because of the smallness of amplitude of curvature perturbations, correction comes from RH neutrinos only.**

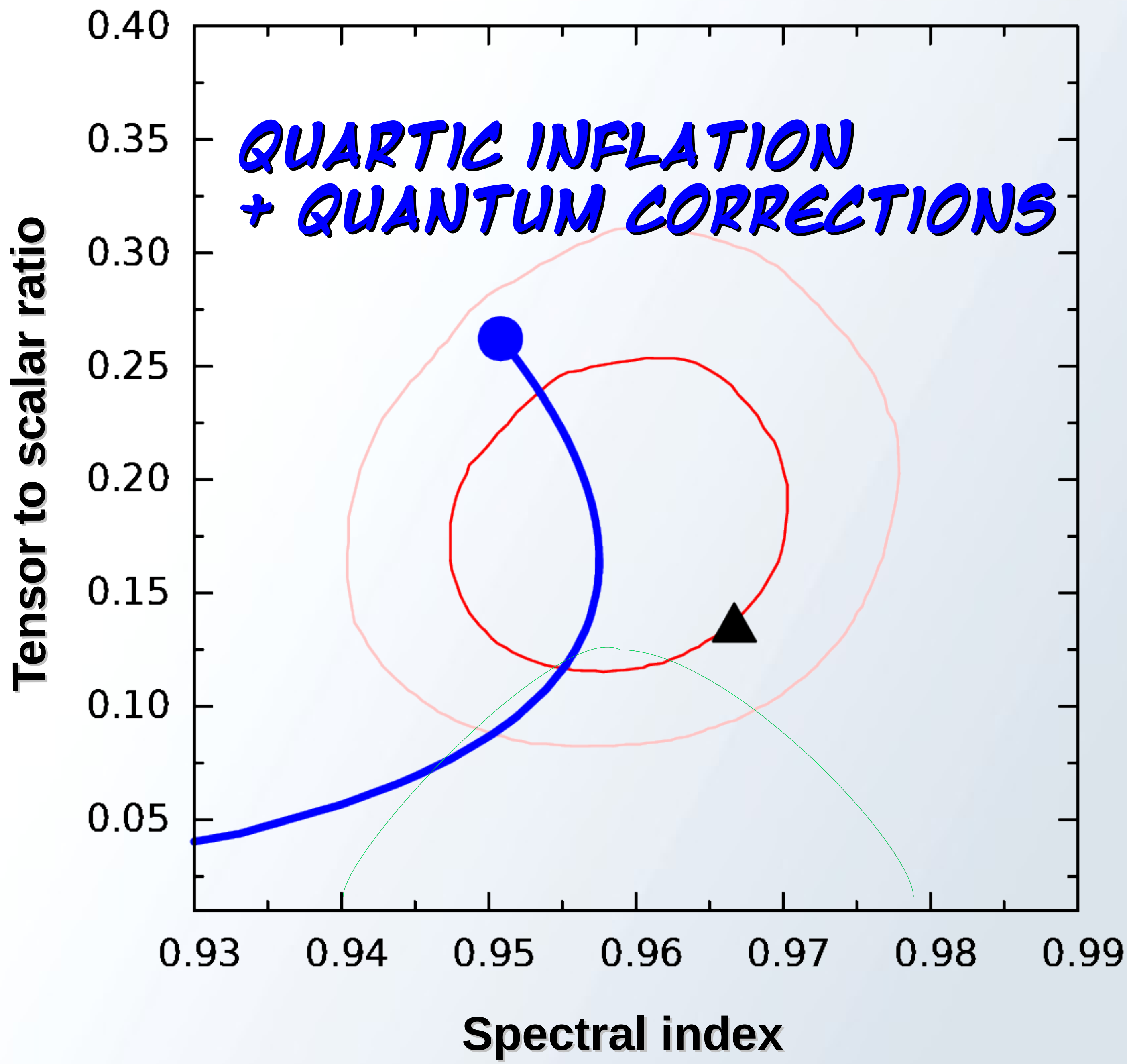
$$V = \lambda \left[ \frac{1}{4} \left( \rho^2 - v_{\rm L}^2 \right)^2 + a \log \left[ \frac{\rho}{v_{\rm L}} \right] \rho^4 + V_0 \right]$$

$$a \simeq \frac{1}{16\pi^2 \lambda} \left( 20\lambda^2 + 2\lambda \left( \sum_i (Y_N^i)^2 \right) - \sum_i (Y_N^i)^4 \right)$$

**Expect strong effect on quartic inflation but not on Higgs inflation;**

$$v_{\rm L} > Mp \rightarrow Y_N \ll 1$$




Quartic inflation
+ quantum corrections
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Tensor to scalar ratio
0.93
0.94
0.95
0.96
0.97
0.98
0.99
Spectral index

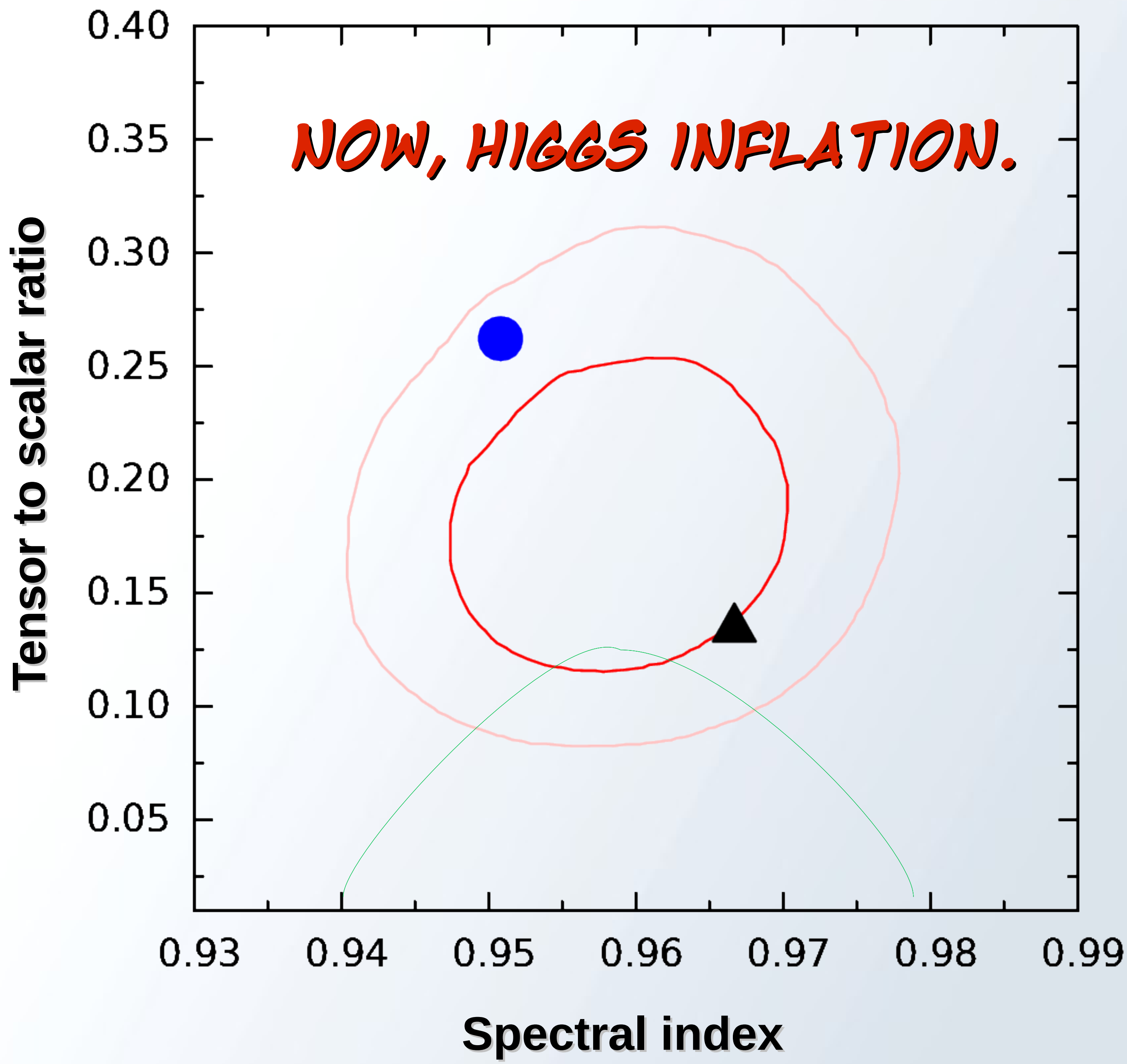
# Quartic potential + CW (N=60)

Small solutions ($0.01 \lesssim r \lesssim 0.02$)

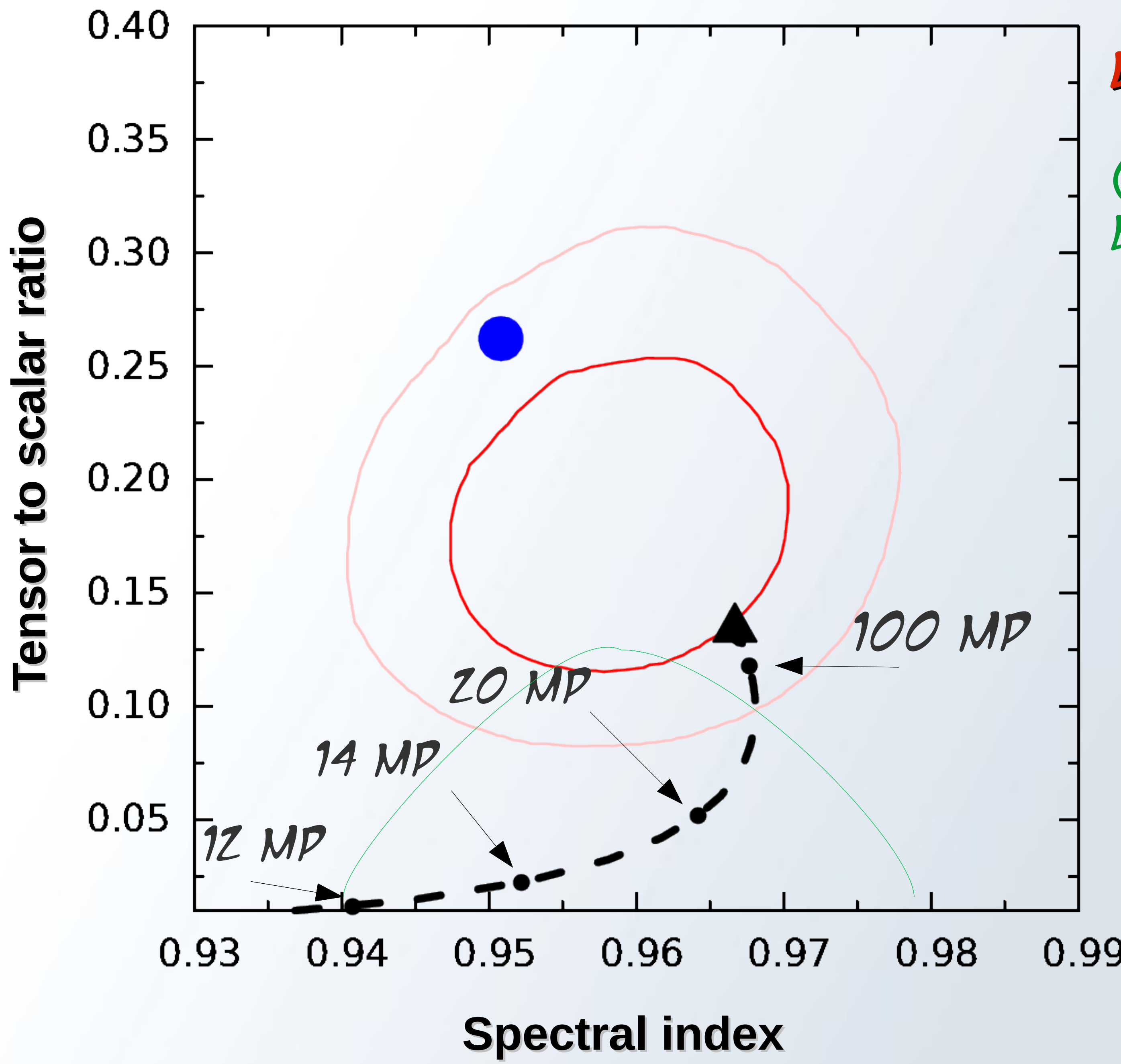
| $a$ | $\|Y_N\|$ | $\log_{10}(\|\lambda\|)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|---|
| -0.01307 | 0.00135604 | -11.7856 | 0.890248 | 0.0100493 | 7.9222 | 1.02256 | 15.1923 | 2.49121 |
| -0.01305 | 0.00142537 | -11.6983 | 0.899145 | 0.0137211 | 7.32328 | 1.10535 | 15.5053 | 2.49559 |
| -0.01304 | 0.00145721 | -11.6596 | 0.903321 | 0.0158434 | 6.92563 | 1.14582 | 15.6575 | 2.49774 |
| -0.01303 | 0.00148709 | -11.624 | 0.907307 | 0.0181559 | 6.47185 | 1.18552 | 15.8065 | 2.49987 |
| -0.01302 | 0.00151498 | -11.5914 | 0.911098 | 0.0206547 | 5.97014 | 1.22435 | 15.9522 | 2.50198 |

Large solutions ($0.1 \lesssim r \lesssim 0.2$)

| $a$ | $\|Y_N\|$ | $\log_{10}(\|\lambda\|)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|---|
| -0.01279 | 0.00172752 | -11.3556 | 0.952953 | 0.101404 | -4.68889 | 1.82249 | 18.3706 | 2.54494 |
| -0.01265 | 0.00167379 | -11.4057 | 0.957019 | 0.141706 | -6.48511 | 1.98152 | 19.1795 | 2.56674 |
| -0.01261 | 0.00165322 | -11.4258 | 0.957343 | 0.150727 | -6.71294 | 2.01234 | 19.3554 | 2.57247 |
| -0.01256 | 0.00162674 | -11.4521 | 0.957507 | 0.160678 | -6.9129 | 2.04476 | 19.5497 | 2.57934 |
| -0.0125 | 0.00159495 | -11.4843 | 0.957484 | 0.170937 | -7.07347 | 2.07664 | 19.7519 | 2.5872 |
| -0.0124 | 0.00154397 | -11.5373 | 0.957174 | 0.184759 | -7.2355 | 2.1174 | 20.0299 | 2.59943 |
| -0.0123 | 0.00149676 | -11.5877 | 0.956735 | 0.195481 | -7.33264 | 2.14748 | 20.2527 | 2.61069 |
| -0.0122 | 0.00145363 | -11.635 | 0.956276 | 0.20395 | -7.39978 | 2.17037 | 20.4349 | 2.62107 |
| -0.0121 | 0.00141436 | -11.679 | 0.95584 | 0.210759 | -7.45154 | 2.18826 | 20.5865 | 2.63068 |
| -0.0119 | 0.00134587 | -11.7579 | 0.955081 | 0.220938 | -7.53147 | 2.21422 | 20.8243 | 2.64788 |
| -0.0116 | 0.00126256 | -11.8579 | 0.954217 | 0.230944 | -7.62064 | 2.23887 | 21.0753 | 2.66959 |

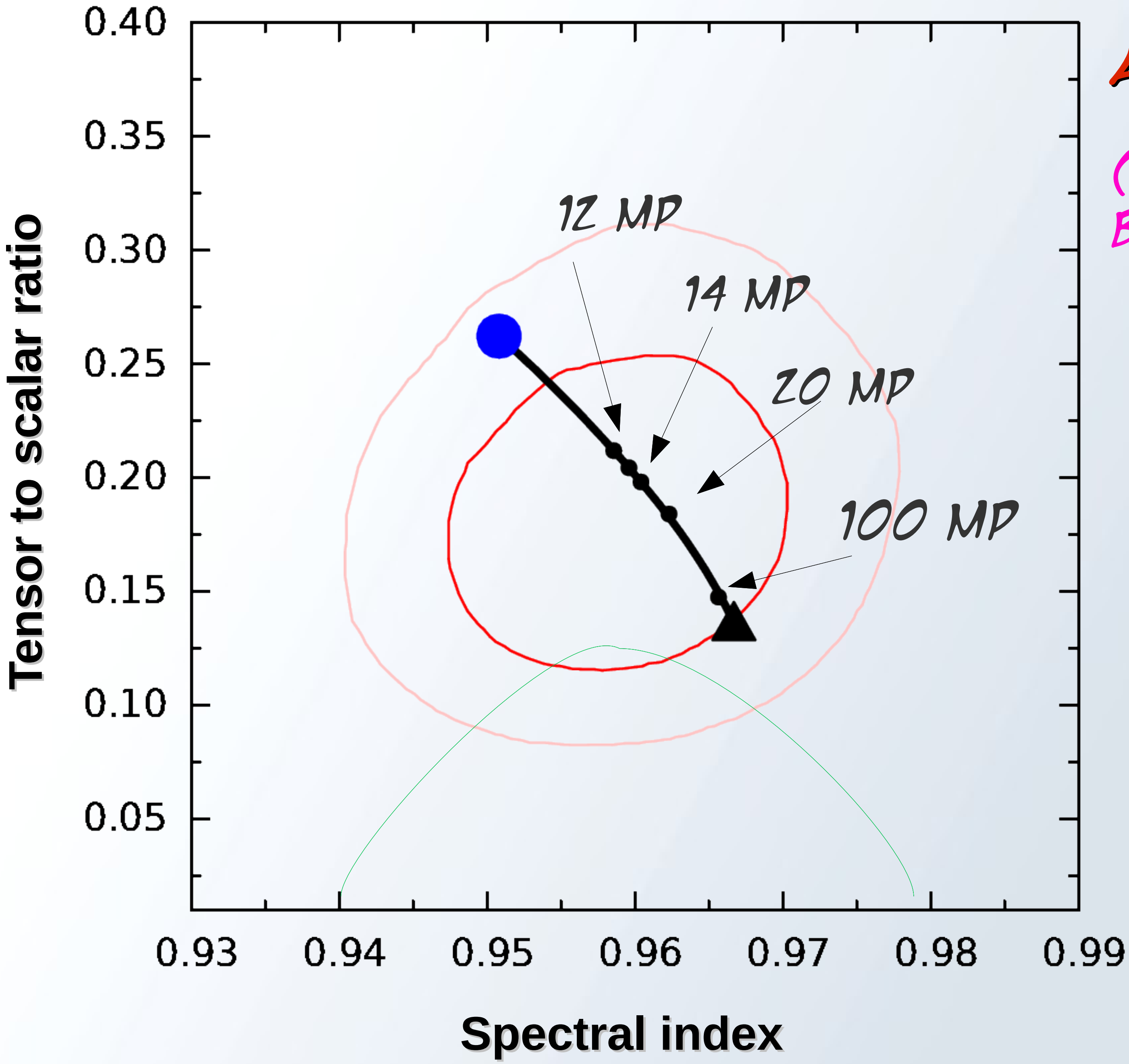


Now, Higgs inflation.
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.93
0.94
0.95
0.96
0.97
0.98
0.99
Tensor to scalar ratio
Spectral index



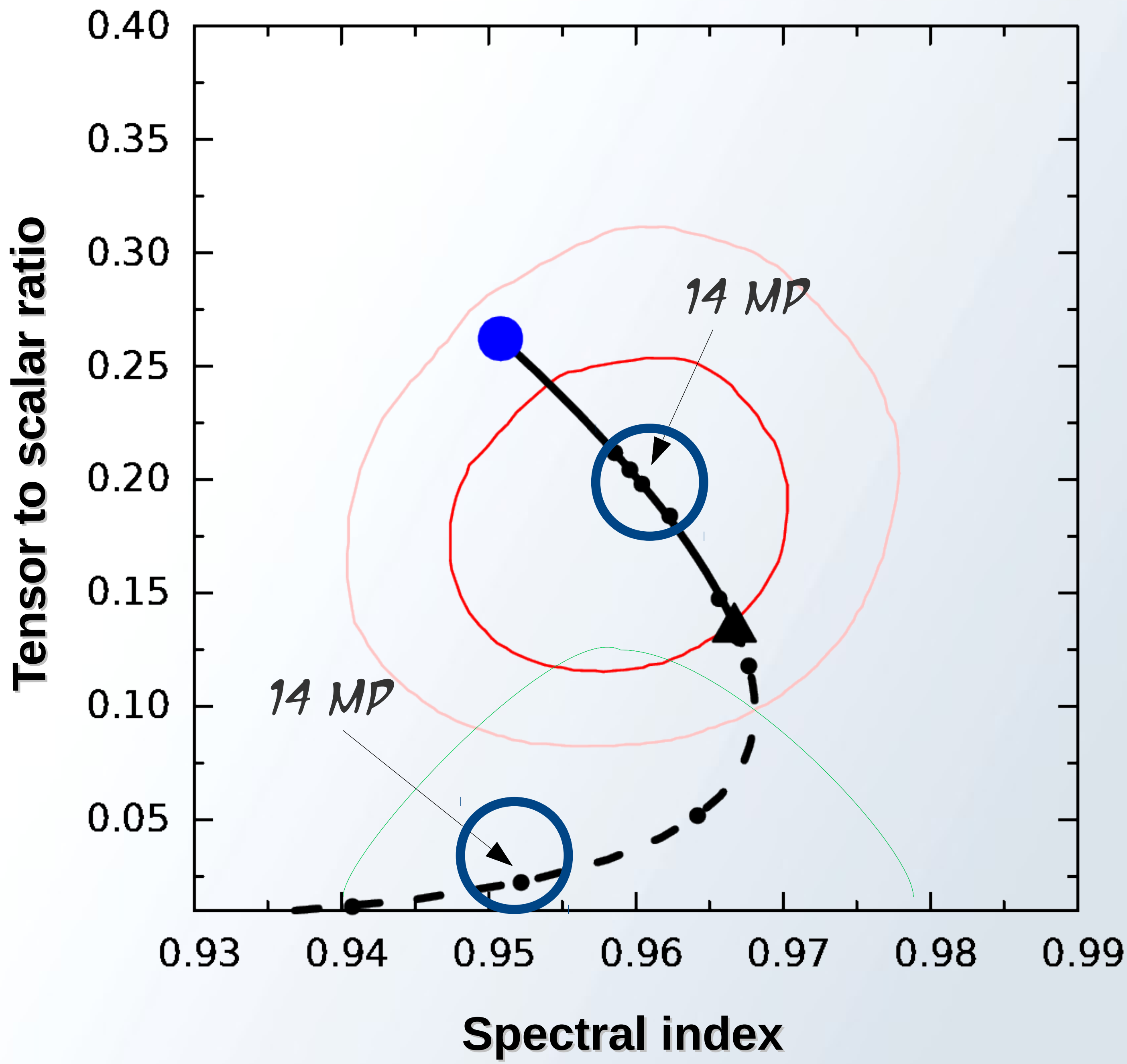

BELOW VEV

(FAVORED BY PLANCK)

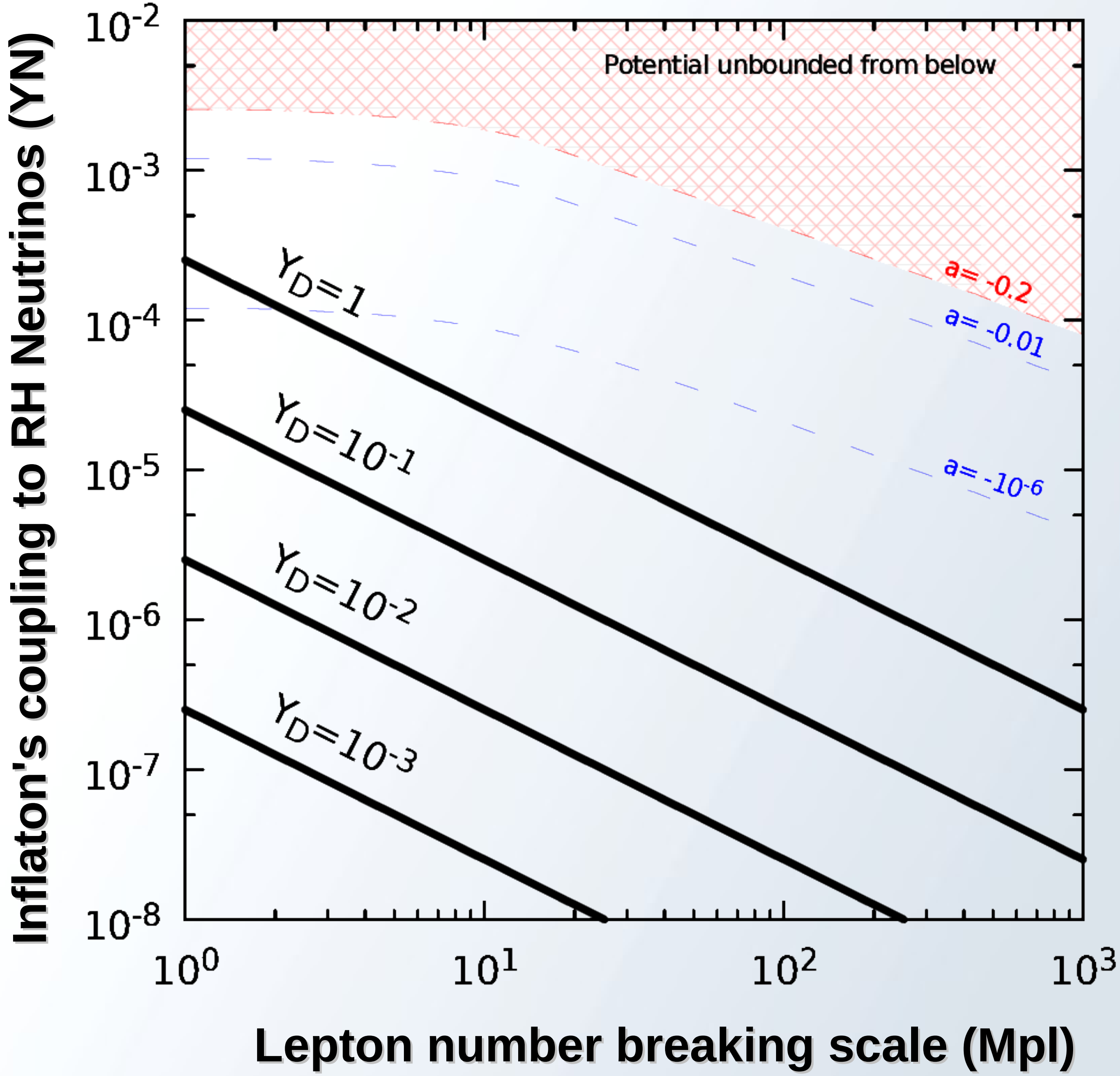



**ABOVE VEV**

(FAVORED BY BICEP2)



0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Tensor to scalar ratio
0.93
0.94
0.95
0.96
0.97
0.98
0.99
Spectral index
14 MP
14 MP


Potential unbounded from below
a= -0.2
a= -0.01
a= -10-6
YD=1
YD=10-1
YD=10-2
YD=10-3
10-2
10-3
10-4
10-5
10-6
10-7
10-8
100
101
102
103
Inflaton's coupling to RH Neutrinos (YN)
Lepton number breaking scale (Mpl)

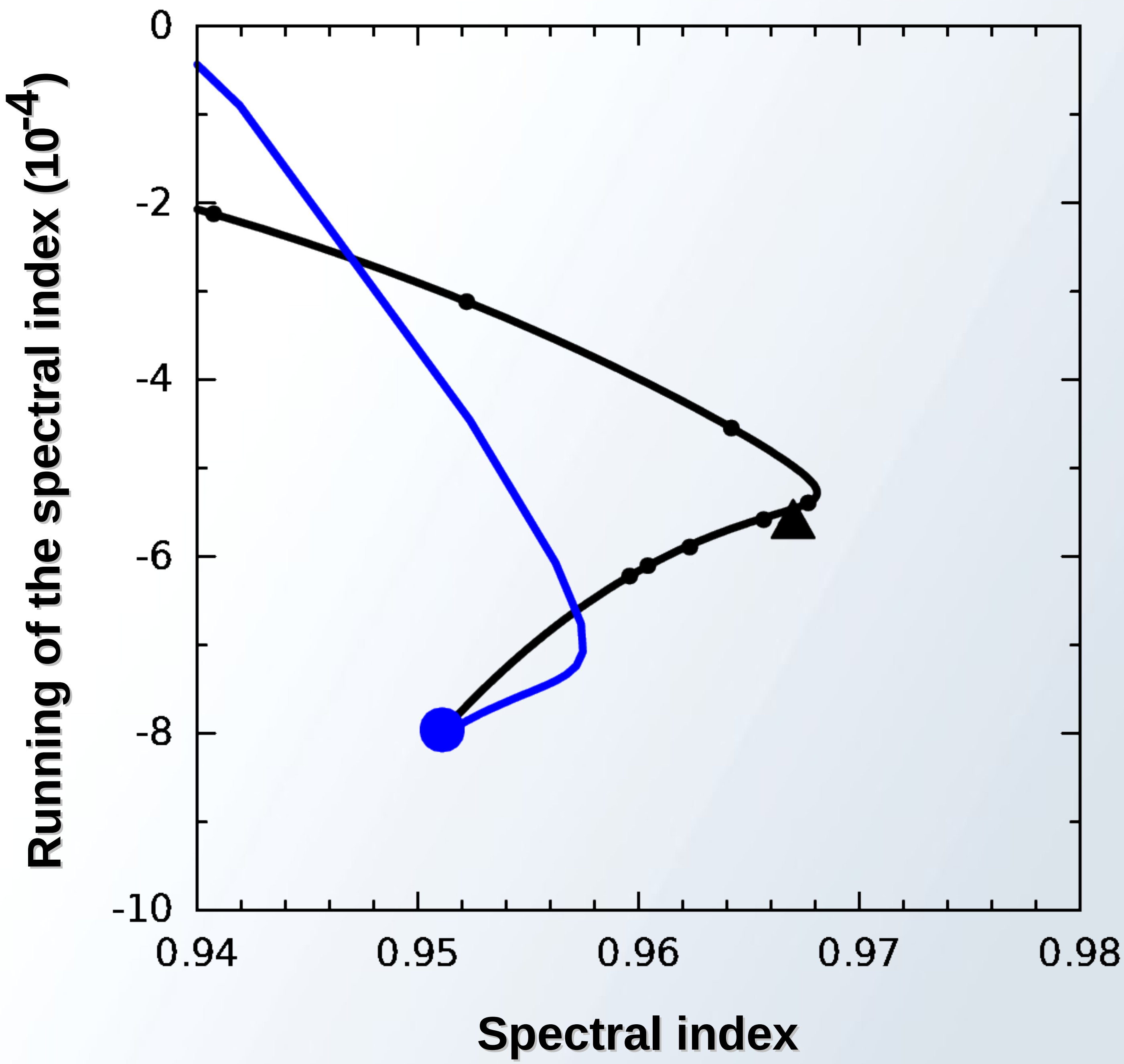
# 'Higgs' inflation (N=60)

Solutions above the VEV ($\rho > v_{\rm L}$)

| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 1. | -12.8521 | 0.951168 | 0.260263 | -7.96468 | 2.30678 | 22.2218 | 3.14626 |
| 5. | -13.0093 | 0.954908 | 0.237136 | -7.05625 | 2.25373 | 24.2634 | 6.61037 |
| 10 | -13.2351 | 0.958581 | 0.211972 | -6.37463 | 2.1914 | 28.1285 | 11.5137 |
| 20. | -13.599 | 0.962148 | 0.184081 | -5.89025 | 2.11546 | 37.1396 | 21.4642 |
| 50. | -14.2262 | 0.964453 | 0.159253 | -5.80242 | 2.04021 | 66.1458 | 48.6058 |
| 100 | -14.7789 | 0.965456 | 0.147557 | -5.72255 | 2.00167 | 115.805 | 98.5958 |
| 500. | -16.1392 | 0.966211 | 0.137189 | -5.66368 | 1.96554 | 515.506 | 498.588 |
| 1000. | -16.7367 | 0.9663 | 0.135828 | -5.6565 | 1.96065 | 1015.47 | 998.587 |

Solutions below the VEV ($\rho < v_{\rm L}$)

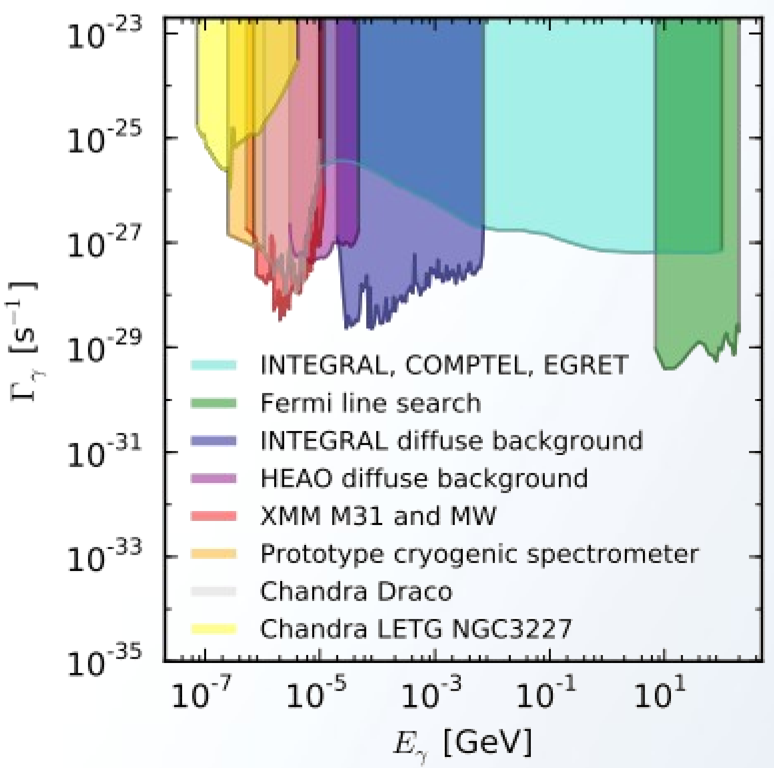
| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 8. | -13.9086 | 0.87488 | 0.000385304 | -0.150585 | 0.452484 | 0.111018 | 6.70982 |
| 9. | -13.5255 | 0.900769 | 0.00148882 | -0.460638 | 0.6344 | 0.27599 | 7.69622 |
| 10. | -13.3033 | 0.918822 | 0.00377031 | -0.949789 | 0.800289 | 0.541141 | 8.68529 |
| 15. | -13.1004 | 0.95579 | 0.0279442 | -3.49461 | 1.32046 | 3.17548 | 13.6523 |
| 20. | -13.2562 | 0.964198 | 0.0518562 | -4.54129 | 1.54118 | 7.05055 | 18.6357 |
| 30. | -13.5959 | 0.967596 | 0.0798131 | -5.09597 | 1.71661 | 16.0451 | 28.6191 |
| 50. | -14.0675 | 0.96807 | 0.102141 | -5.30133 | 1.8258 | 35.3404 | 48.6058 |
| 500. | -16.1213 | 0.966555 | 0.131662 | -5.63496 | 1.94544 | 484.653 | 501.416 |
| 1000. | -16.7278 | 0.966472 | 0.133065 | -5.64214 | 1.9506 | 984.613 | 1001.42 |

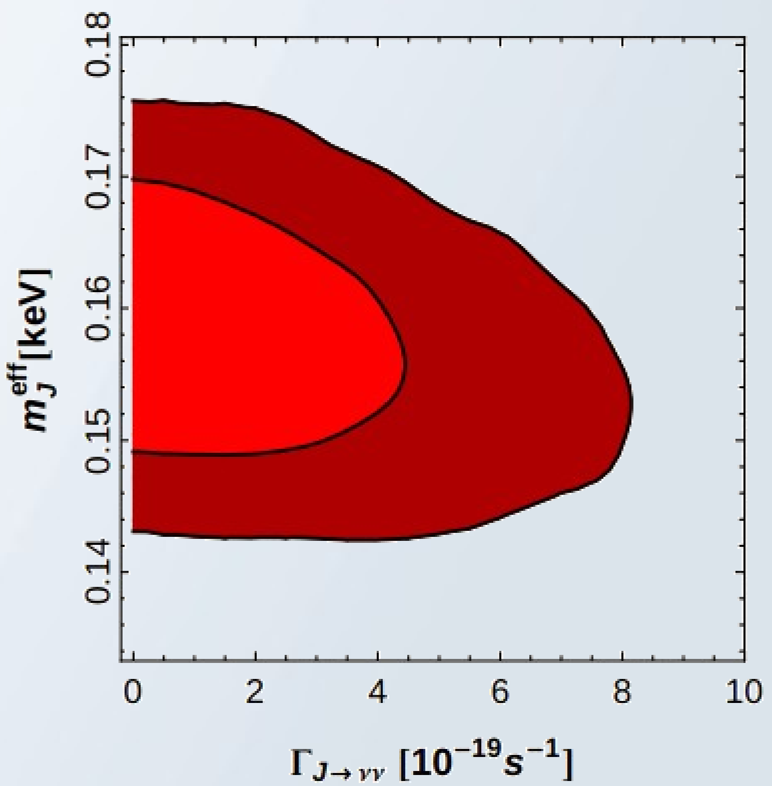


Running of the spectral index ($10^{-4}$)
0
-2
-4
-6
-8
-10
0.94
0.95
0.96
0.97
0.98
Spectral index

# DARK MATTER

**In the presence of soft explicit lepton number violating operators, the majoron becomes pNGB ... and good DM candidate!**



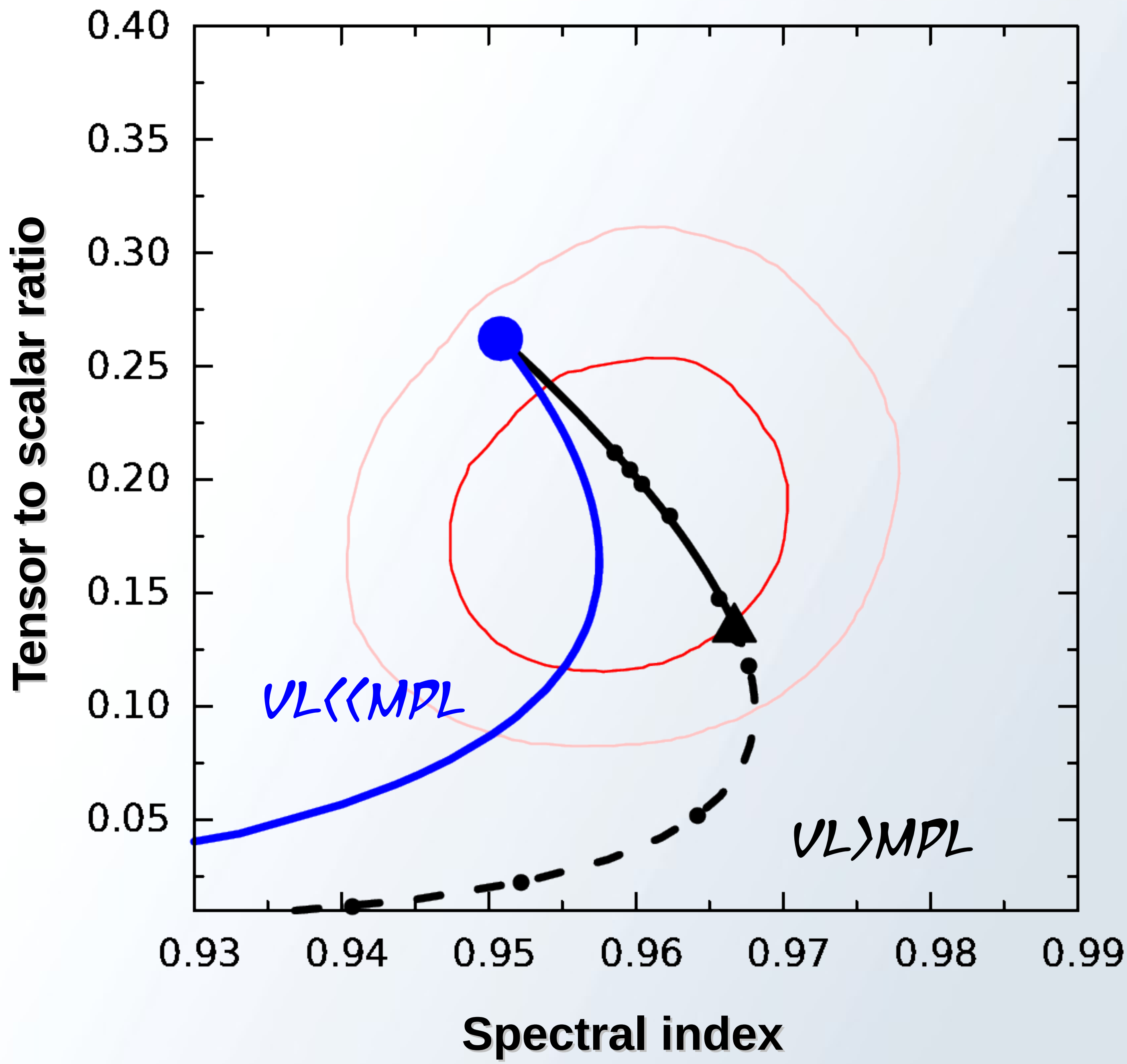




[Lattanzi et al.'13]

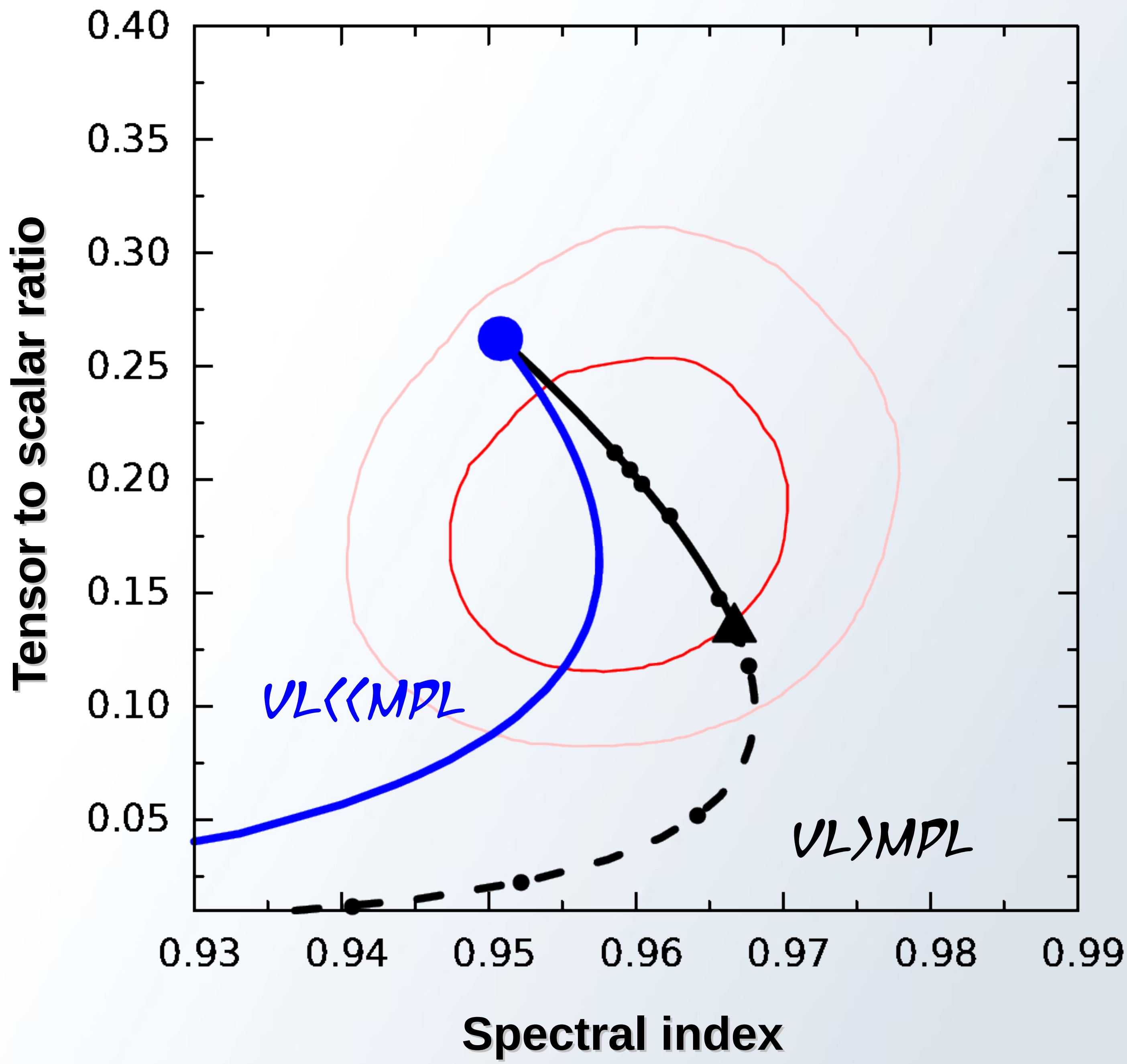
# TO CONCLUDE ...

**Neutrino physics is the most 'known unknown' BSM physics.**
**A direct coupling inflaton - right handed Neutrinos offers four main advantages:**

*** Economy/minimality of description,**
*** Reconciles small VEV inflation with observations via radiative corrections,**
*** (W)DM candidate; the Majoron,**
*** Baryogenesis via leptogenesis.**



0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Tensor to scalar ratio
0.93
0.94
0.95
0.96
0.97
0.98
0.99
Spectral index
VL<<MPL
VL>MPL



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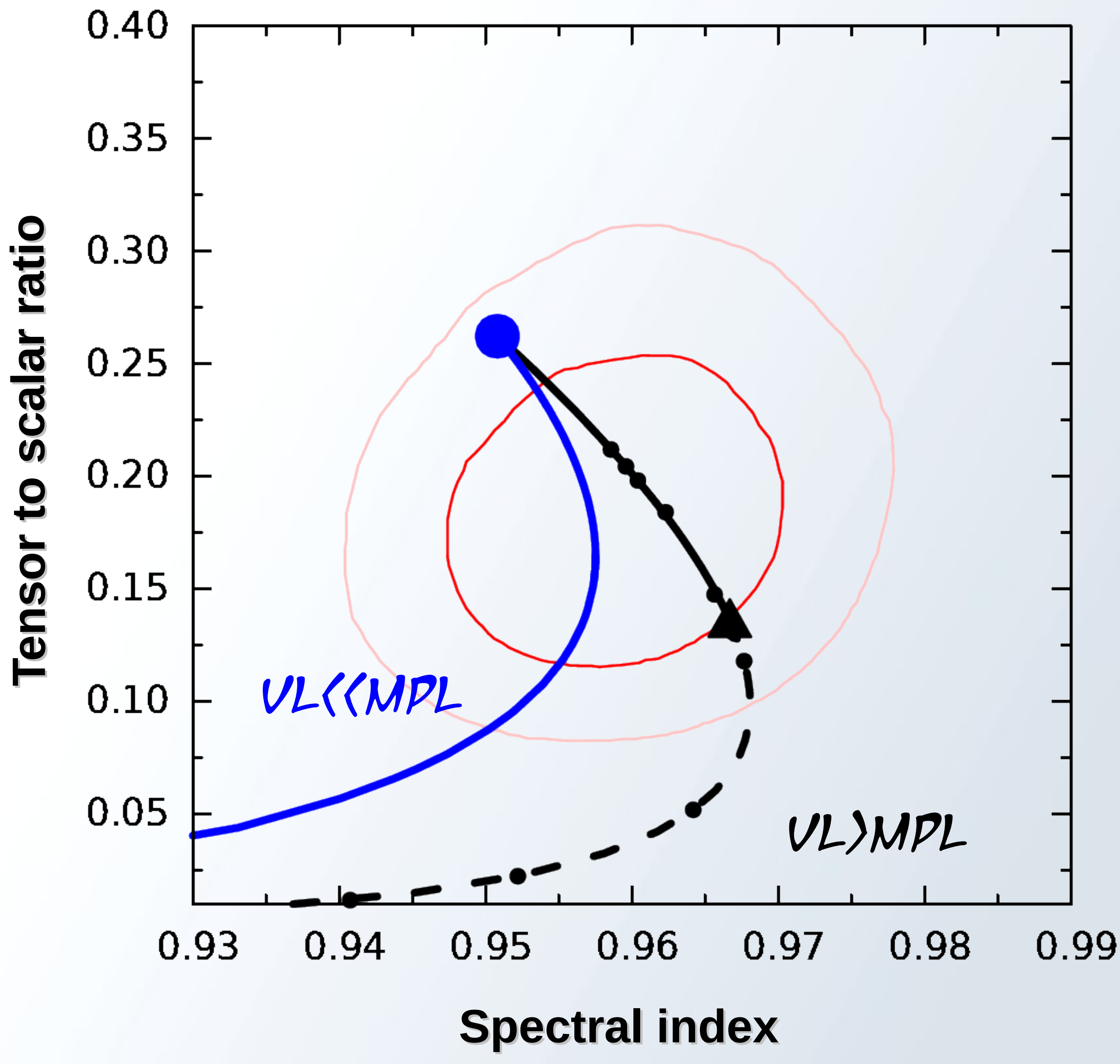
Spectral index
VL<<MPL
VL>MPL



Tensor to scalar ratio
0.40
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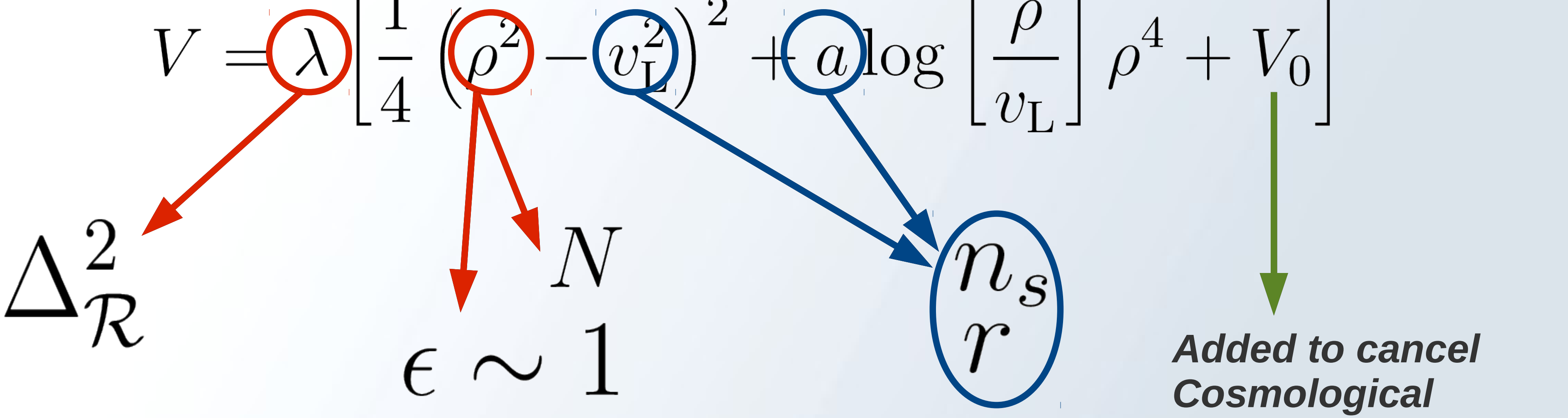
0.25
0.20
0.15
0.10
0.05
0.93
0.94
0.95
0.96
0.97
0.98
0.99
Spectral index
VL<<MPL
VL>MPL

# BACK UP SLIDES

# For the analysis, we have 5 unknowns for 5 equations

$$V = \lambda \left[ \frac{1}{4} \left( \rho^2 - v_{\mathrm{L}}^2 \right)^2 + a \log \left[ \frac{\rho}{v_{\mathrm{L}}} \right] \rho^4 + V_0 \right]$$



# SLOW ROLL 101

$$\epsilon(\rho) = \frac{1}{2} M_P^2 \left( \frac{V'}{V} \right)^2$$

$$\eta(\rho) = M_P^2 \left( \frac{V''}{V} \right)$$

$$\zeta^2(\rho) = M_P^4 \left( \frac{V' V'''}{V^2} \right)$$

$$N = \frac{1}{\sqrt{2} M_P} \int_{\rho_e}^{\rho_0} \frac{d\rho}{\sqrt{\epsilon(\rho)}}$$

$$\Delta_{\mathcal{R}}^2 = \left. \frac{V}{24\,\pi^2\, M_P^4\, \epsilon(\rho_0)} \right|_{k_0 = 0.05\,\mathrm{Mpc}^{-1}} = 2.215 \times 10^{-9}$$

# 'Higgs' inflation for N=50 & 60, Rolling from Above VEV

$N = 60$

| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\mathrm{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 1. | -12.8521 | 0.951168 | 0.260263 | -7.96468 | 2.30678 | 22.2218 | 3.14626 |
| 2. | -12.8815 | 0.951978 | 0.25545 | -7.74718 | 2.29604 | 22.562 | 3.8637 |
| 3. | -12.9202 | 0.952955 | 0.249498 | -7.50094 | 2.28254 | 23.0408 | 4.73084 |
| 4. | -12.9637 | 0.953953 | 0.243258 | -7.26609 | 2.26814 | 23.6163 | 5.65686 |
| 5. | -13.0093 | 0.954908 | 0.237136 | -7.05625 | 2.25373 | 24.2634 | 6.61037 |
| 10 | -13.2351 | 0.958581 | 0.211972 | -6.37463 | 2.1914 | 28.1285 | 11.5137 |
| 20. | -13.599 | 0.962148 | 0.184081 | -5.89025 | 2.11546 | 37.1396 | 21.4642 |
| 50. | -14.2262 | 0.964453 | 0.159253 | -5.80242 | 2.04021 | 66.1458 | 48.6058 |
| 100 | -14.7789 | 0.965456 | 0.147557 | -5.72255 | 2.00167 | 115.805 | 98.5958 |
| 500. | -16.1392 | 0.966211 | 0.137189 | -5.66368 | 1.96554 | 515.506 | 498.588 |
| 1000. | -16.7367 | 0.9663 | 0.135828 | -5.6565 | 1.96065 | 1015.47 | 998.587 |

$N = 50$

| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\mathrm{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 1. | -12.6206 | 0.941649 | 0.310956 | -11.3769 | 2.41172 | 20.3379 | 3.14627 |
| 5. | -12.7963 | 0.946513 | 0.280634 | -9.9908 | 2.35065 | 22.4694 | 6.61038 |
| 10. | -13.0397 | 0.950995 | 0.249462 | -9.03211 | 2.28246 | 26.4347 | 11.5137 |
| 20. | -13.4203 | 0.955119 | 0.216534 | -8.39114 | 2.2031 | 35.5614 | 21.4642 |
| 50. | -14.0576 | 0.957488 | 0.189065 | -8.36171 | 2.12964 | 64.6746 | 48.6058 |
| 100. | -14.6149 | 0.958582 | 0.176047 | -8.25826 | 2.09199 | 114.387 | 98.5958 |
| 500. | -15.9786 | 0.959404 | 0.164617 | -8.18128 | 2.05717 | 514.137 | 498.588 |
| 1000. | -16.5765 | 0.959501 | 0.163124 | -8.17186 | 2.05249 | 1014.1 | 998.587 |

# 'Higgs' inflation for N=50 & 60, Rolling from Below VEV

$N = 60$

| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 8. | -13.9086 | 0.87488 | 0.000385304 | -0.150585 | 0.452484 | 0.111018 | 6.70982 |
| 9. | -13.5255 | 0.900769 | 0.00148882 | -0.460638 | 0.6344 | 0.27599 | 7.69622 |
| 10. | -13.3033 | 0.918822 | 0.00377031 | -0.949789 | 0.800289 | 0.541141 | 8.68529 |
| 15. | -13.1004 | 0.95579 | 0.0279442 | -3.49461 | 1.32046 | 3.17548 | 13.6523 |
| 20. | -13.2562 | 0.964198 | 0.0518562 | -4.54129 | 1.54118 | 7.05055 | 18.6357 |
| 30. | -13.5959 | 0.967596 | 0.0798131 | -5.09597 | 1.71661 | 16.0451 | 28.6191 |
| 50. | -14.0675 | 0.96807 | 0.102141 | -5.30133 | 1.8258 | 35.3404 | 48.6058 |
| 500. | -16.1213 | 0.966555 | 0.131662 | -5.63496 | 1.94544 | 484.653 | 501.416 |
| 1000. | -16.7278 | 0.966472 | 0.133065 | -5.64214 | 1.9506 | 984.613 | 1001.42 |

$N = 50$

| $v_L(M_P)$ | $\log_{10}(\lambda)$ | $n_s$ | $r$ | $\alpha\,(10^{-4})$ | $V^{1/4}\,(10^{16}\,\text{GeV})$ | $\rho_0\,(M_P)$ | $\rho_e\,(M_P)$ |
|---|---|---|---|---|---|---|---|
| 8. | -12.946 | 0.874579 | 0.00134678 | -0.527008 | 0.618695 | 0.207459 | 6.70982 |
| 9. | -12.9936 | 0.89998 | 0.0040165 | -1.24784 | 0.813044 | 0.452589 | 7.69622 |
| 10 | -13.0397 | 0.917353 | 0.0084827 | -2.15712 | 0.980135 | 0.808746 | 8.68529 |
| 15. | -13.247 | 0.951336 | 0.0425007 | -5.61654 | 1.4664 | 3.8323 | 13.6523 |
| 20. | -13.4203 | 0.958636 | 0.0705787 | -6.7882 | 1.66464 | 7.91985 | 18.6357 |
| 30. | -13.6755 | 0.961454 | 0.101501 | -7.39708 | 1.82293 | 17.1049 | 28.6191 |
| 50. | -14.0576 | 0.961707 | 0.125717 | -7.63539 | 1.9231 | 36.5294 | 48.6058 |
| 500. | -15.9623 | 0.959781 | 0.158559 | -8.14358 | 2.03798 | 485.996 | 501.416 |
| 1000. | -16.5684 | 0.959689 | 0.160095 | -8.15303 | 2.0429 | 985.962 | 1001.42 |