

Title: What does the CMB really tell us about inflation?

Date: Apr 04, 2006 04:00 PM

URL: <http://pirsa.org/06040002>

Abstract: The recently released WMAP 3-year data on the anisotropy and polarization of the Cosmic Microwave Background is a milestone in cosmology. For the first time, it is possible to rule out popular models of inflation in the early universe. However, the WMAP3 data contain interesting hints which indicate that it may be too early to declare a "slam dunk" for simple single-field models of inflation. I will comment on the successes and the limitations of the new data in the context of inflationary model-building, and discuss the next generation of theoretical tools which will be necessary to make sense of future high-precision data.

Outline

Lies

Damn Lies

Statistics

Bayesian Statistics

Outline

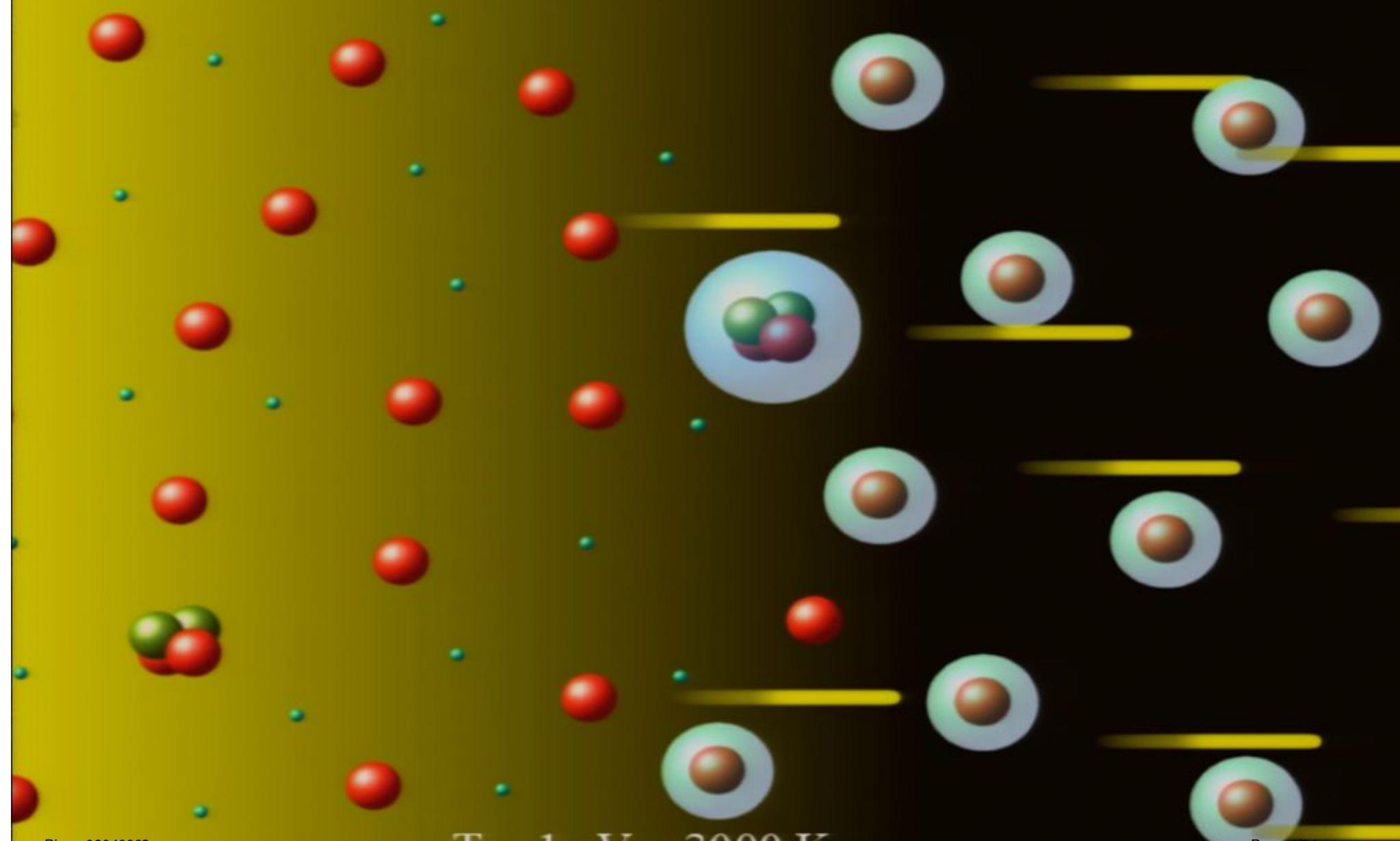
Lies

Damn Lies

Statistics

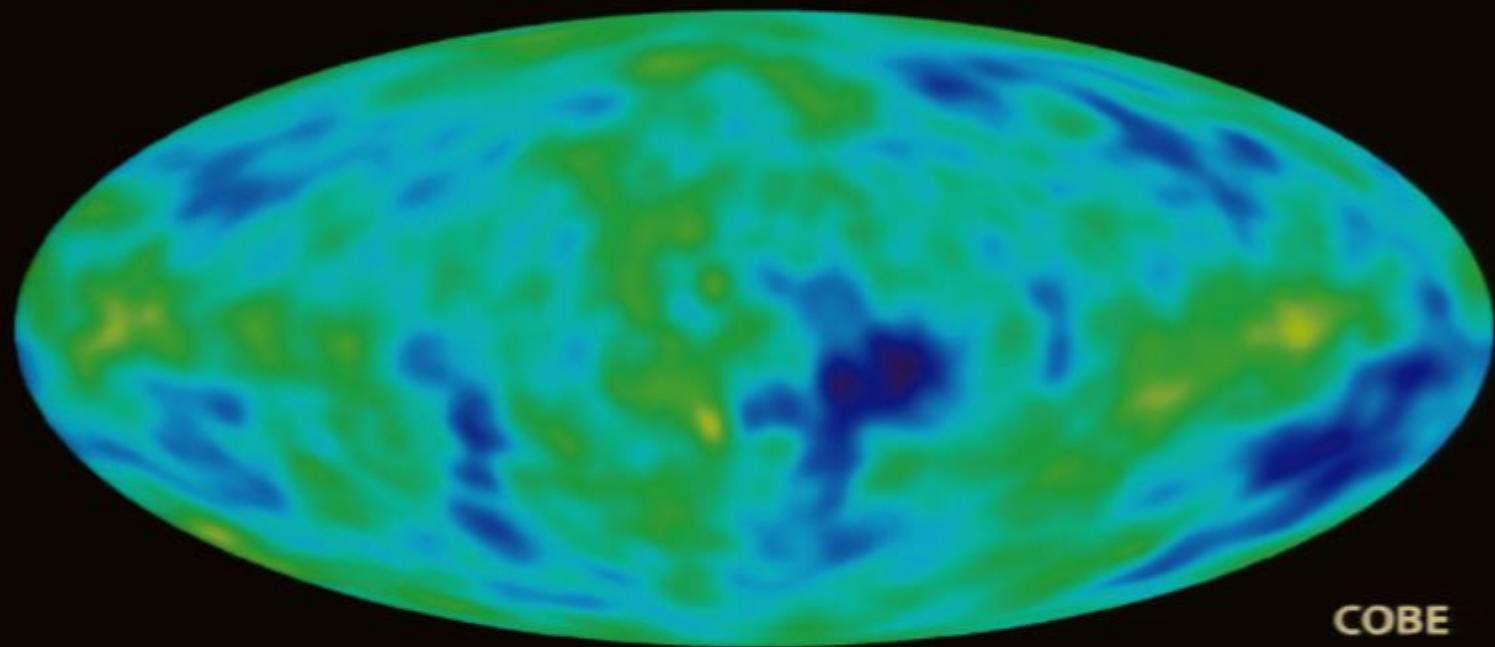
Bayesian Statistics

Recombination

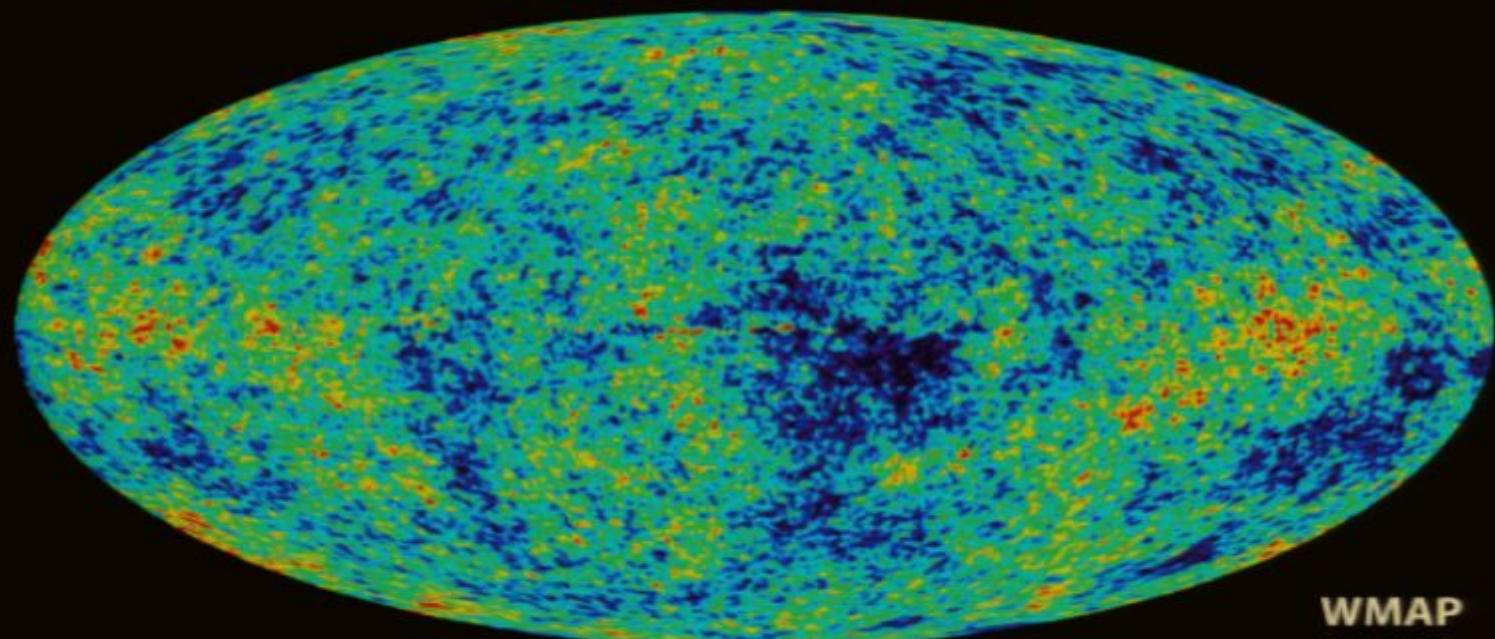


$T \sim 1 \text{ eV} \sim 3000 \text{ K}$

WOW!

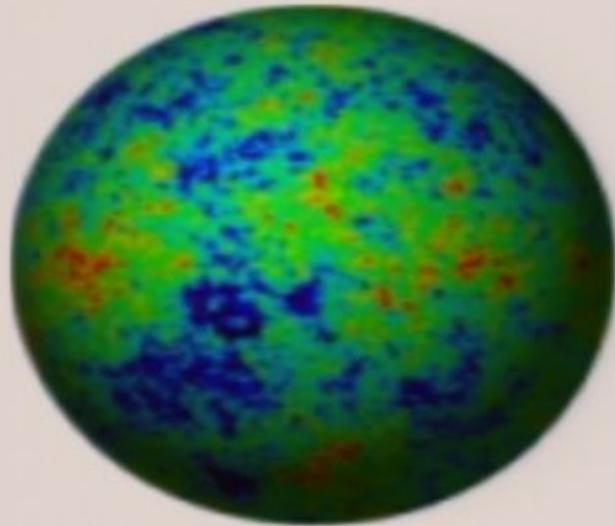


COBE



WMAP

CMB Parameters



$$\frac{\Delta T}{T} = \sum_{\ell,m} a_{\ell m} Y_{\ell m} (\theta, \phi)$$

Multipole spectrum $C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$

Parameters:

Ω_M , Ω_Λ , Ω_b , H_0 , r , n ... + Power spectrum

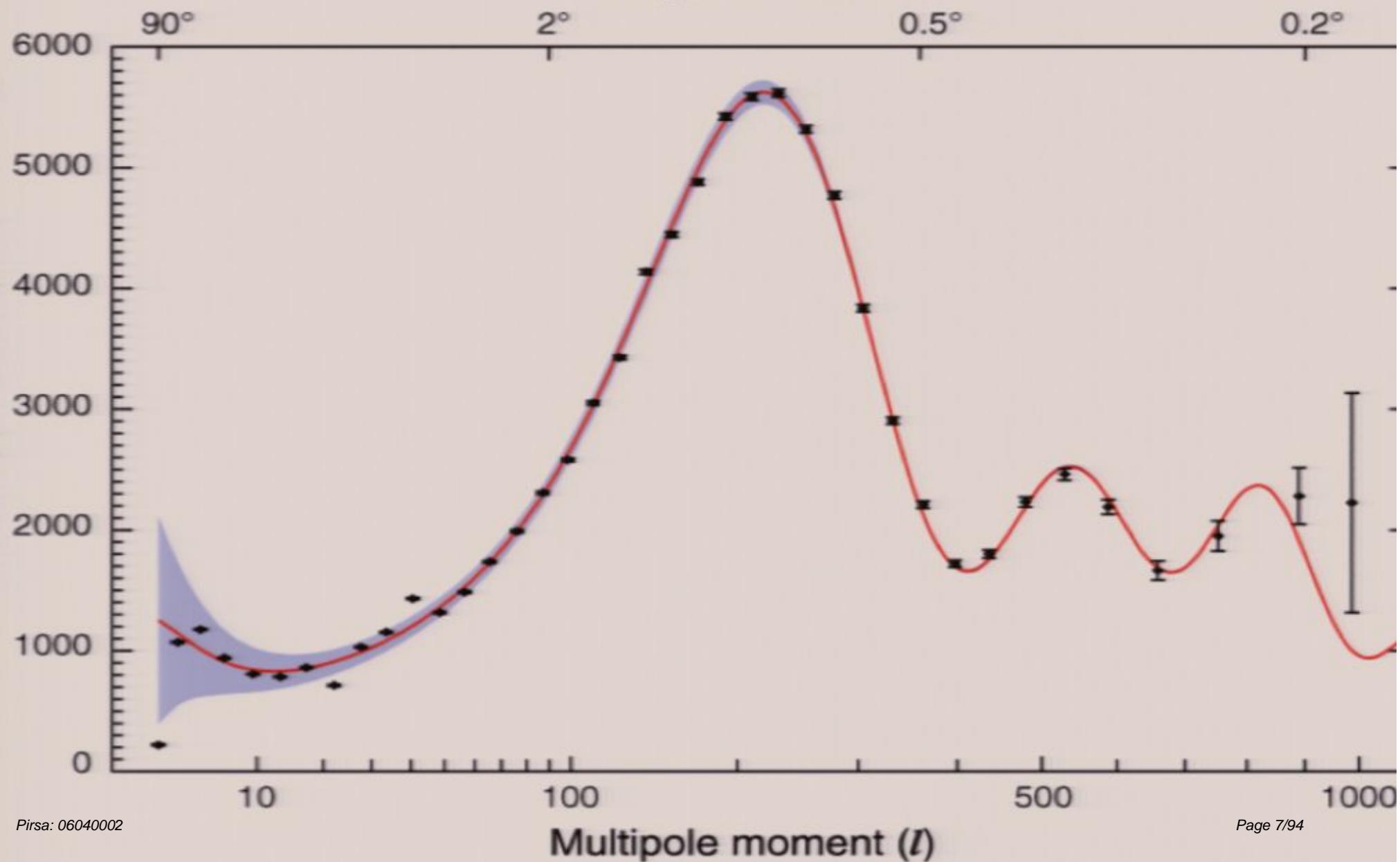


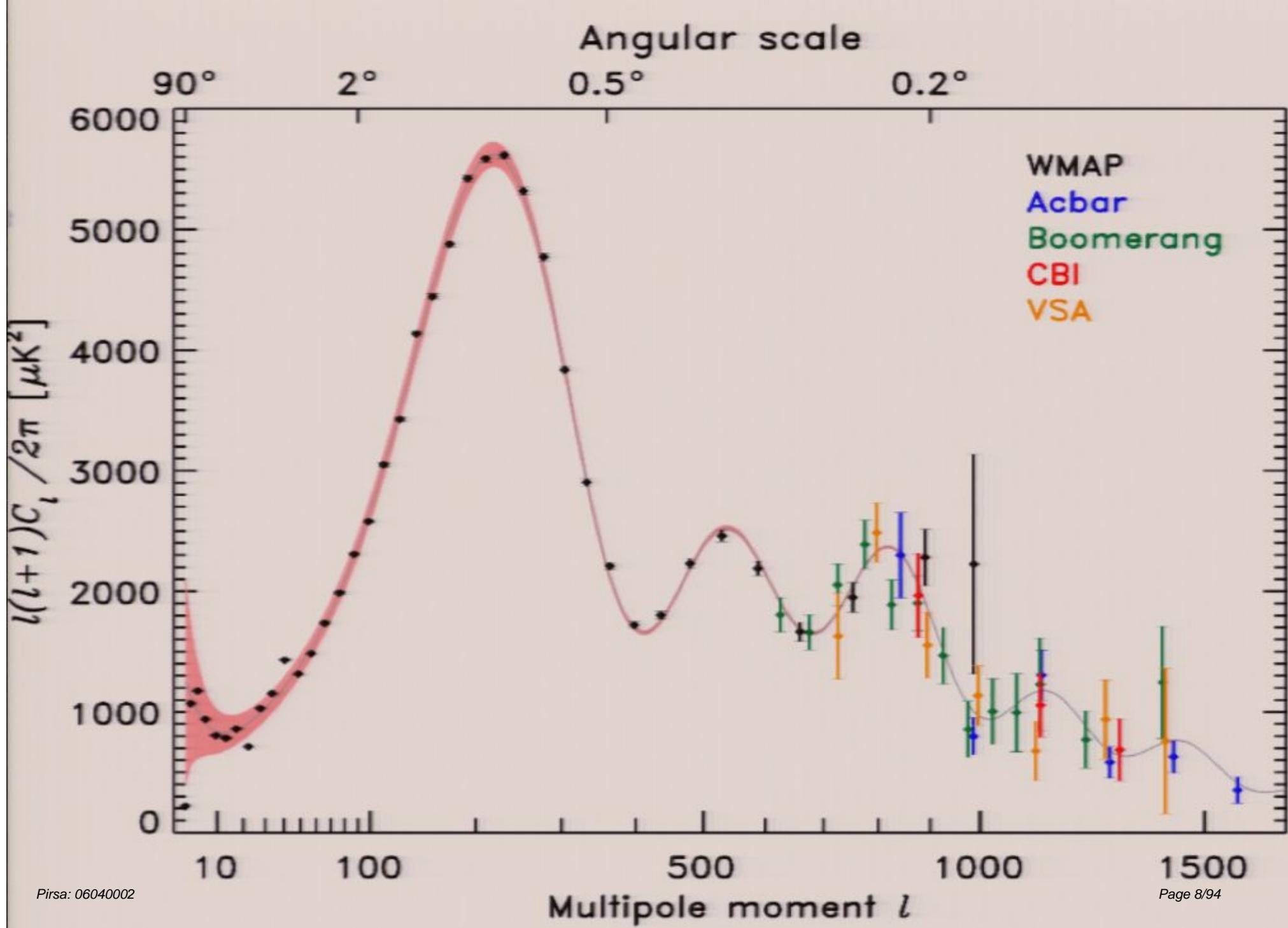
Boltzmann Equation



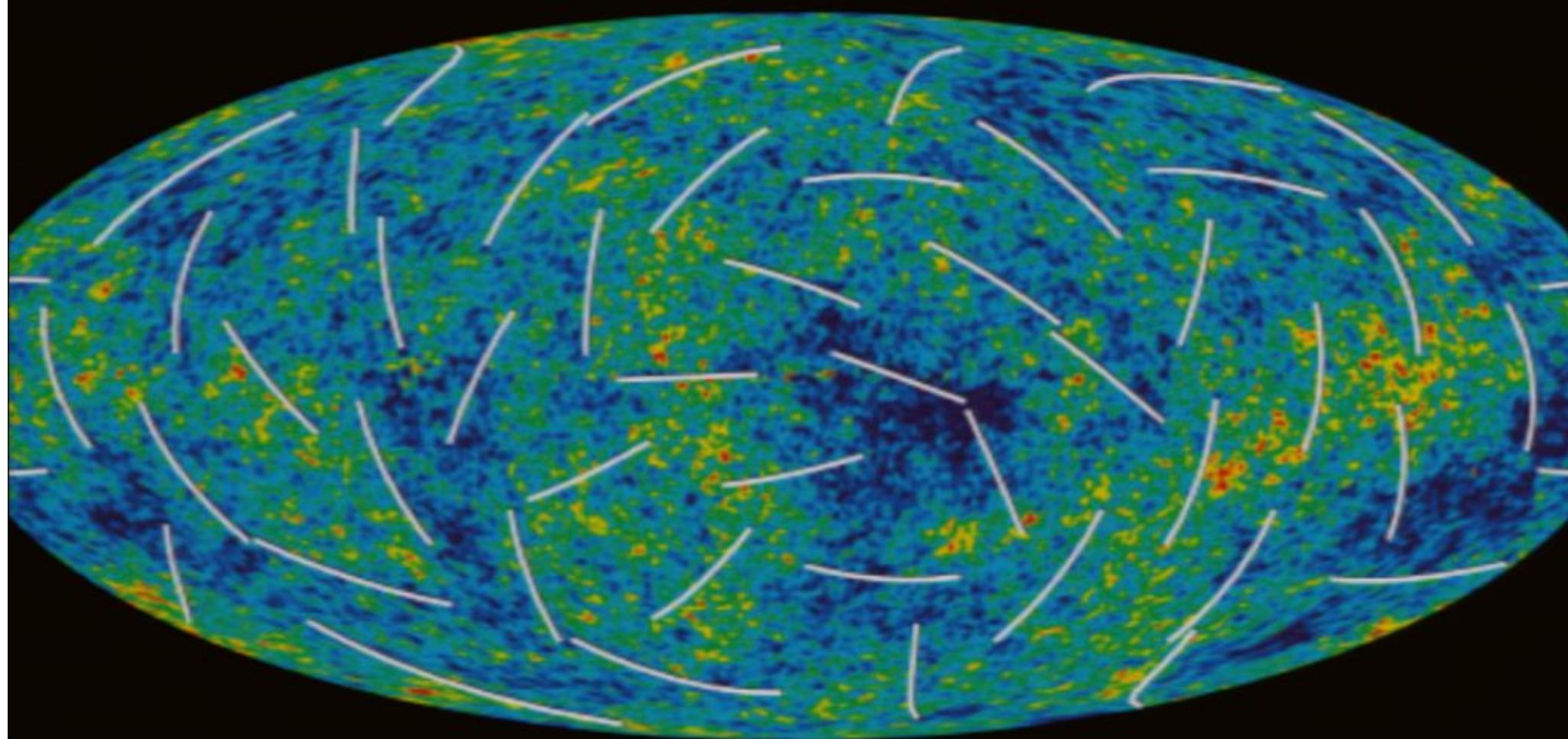
$\{C_\ell\}$

Angular Scale





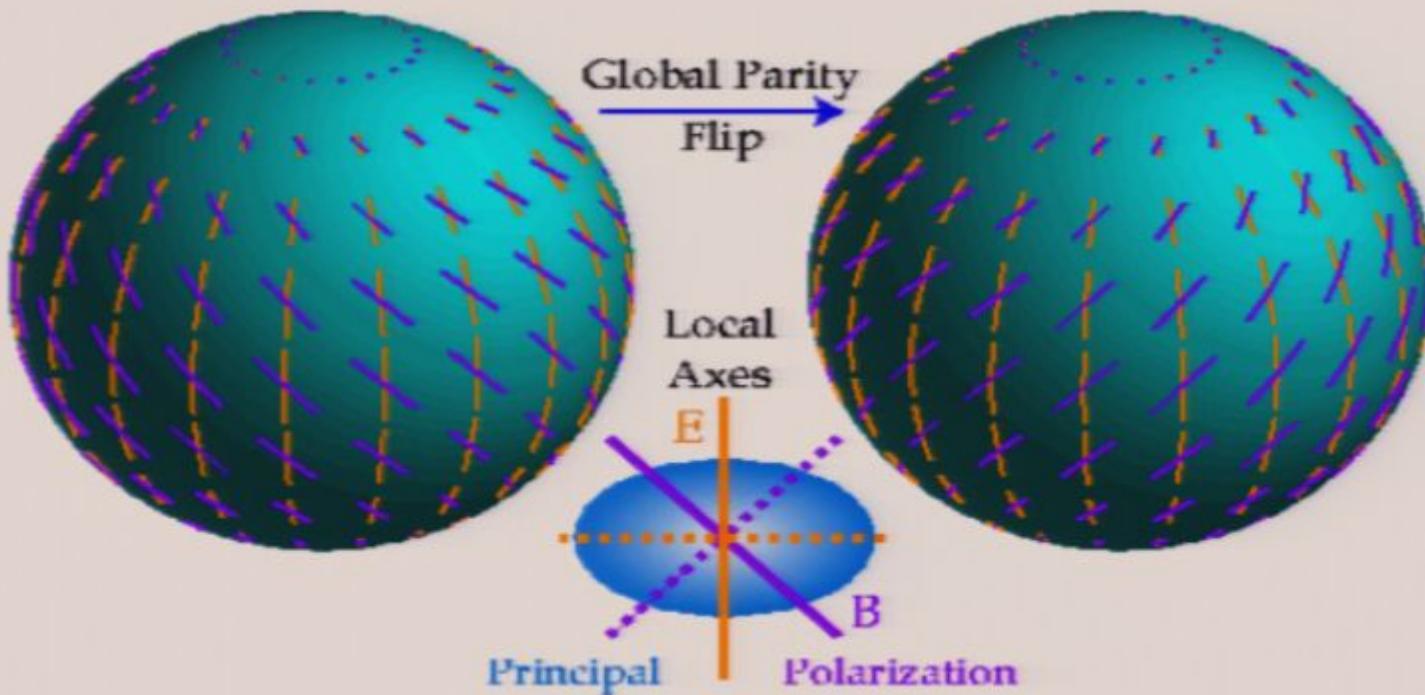
WMAP3: Polarization



Polarization

$$\left(\frac{P_{ab}}{T_0} \right) = \sum_{\ell,m} \left[a_{\ell m}^E Y_{(\ell m)}^E{}_{ab} + a_{\ell m}^B Y_{(\ell m)}^B{}_{ab} \right]$$

TENSOR HARMONICS



Polarization Spectra

Autocorrelation

$$C_{T\ell} \equiv \langle a_{\ell m}^{T*} a_{\ell m}^T \rangle \quad C_{E\ell} \equiv \langle a_{\ell m}^{E*} a_{\ell m}^E \rangle \quad C_{B\ell} \equiv \langle a_{\ell m}^{B*} a_{\ell m}^B \rangle$$

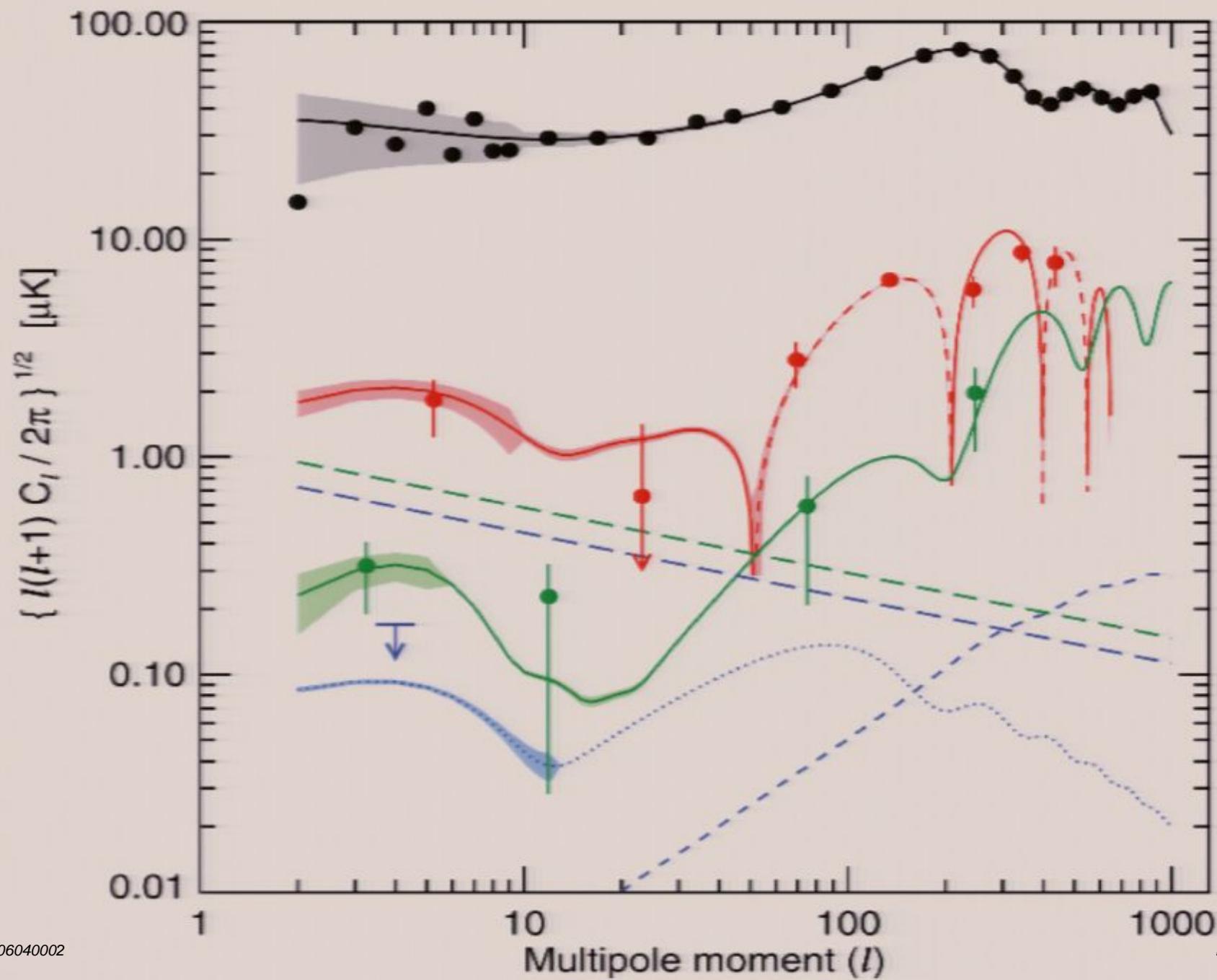
↑
Tensors only!

Cross correlation

$$C_{C\ell} \equiv \langle a_{\ell m}^{T*} a_{\ell m}^E \rangle$$

Parity: $\langle a^T a^B \rangle = \langle a^E a^B \rangle = 0$

Four spectra: T, E, B, C



Inflation



Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi}{3m_{\text{Pl}}^2} \left[\frac{1}{2}\dot{\phi}^2 + V(\phi) \right] \simeq \text{const.}$$

Inflation



Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi}{3m_{\text{Pl}}^2} \left[\frac{1}{2} \dot{\phi}^2 + V(\phi) \right] \simeq \text{const.}$$

Scalar field equation of motion:

$$\ddot{\phi} + 3 \left(\frac{\dot{a}}{a} \right) \dot{\phi} + V'(\phi) = 0 \quad a(t) \propto e^{\int H dt} \equiv e^N$$

Slow Roll Parameters

$\epsilon(\phi)$ Parameterizes equation of state:

$$\epsilon \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H'(\phi)}{H(\phi)} \right]^2 \simeq \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

$$p = \rho \left(\frac{2}{3}\epsilon - 1 \right)$$

Inflation $\longleftrightarrow \epsilon(\phi) < 1$

Slow Roll Parameters

$\epsilon(\phi)$ Parameterizes equation of state:

$$\epsilon \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H'(\phi)}{H(\phi)} \right]^2 \simeq \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

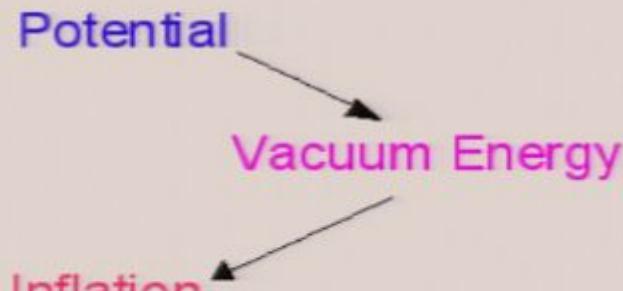
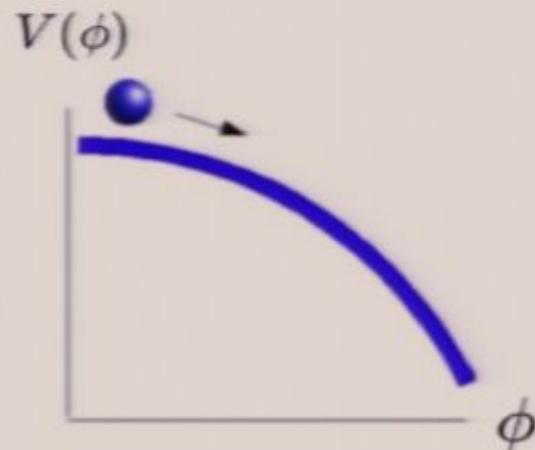
$$p = \rho \left(\frac{2}{3}\epsilon - 1 \right)$$

Inflation $\longleftrightarrow \epsilon(\phi) < 1$

Second slow roll parameter:

$$\eta \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H''(\phi)}{H(\phi)} \right] \simeq \frac{m_{\text{Pl}}^2}{8\pi} \left[\frac{V''(\phi)}{V(\phi)} \right] - \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

Inflation



Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi}{3m_{\text{Pl}}^2} \left[\frac{1}{2} \dot{\phi}^2 + V(\phi) \right] \simeq \text{const.}$$

slow roll

Scalar field equation of motion:

$$\ddot{\phi} + 3 \left(\frac{\dot{a}}{a} \right) \dot{\phi} + V'(\phi) = 0 \quad a(t) \propto e^{\int H dt} \equiv e^N$$

~~$\dot{\phi}$~~

Slow Roll Parameters

$\epsilon(\phi)$ Parameterizes equation of state:

$$\epsilon \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H'(\phi)}{H(\phi)} \right]^2 \simeq \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

$$p = \rho \left(\frac{2}{3}\epsilon - 1 \right)$$

Inflation $\longleftrightarrow \epsilon(\phi) < 1$

Slow Roll Parameters

$\epsilon(\phi)$ Parameterizes equation of state:

$$\epsilon \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H'(\phi)}{H(\phi)} \right]^2 \simeq \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

$$p = \rho \left(\frac{2}{3}\epsilon - 1 \right)$$

Inflation $\longleftrightarrow \epsilon(\phi) < 1$

Second slow roll parameter:

$$\eta \equiv \frac{m_{\text{Pl}}^2}{4\pi} \left[\frac{H''(\phi)}{H(\phi)} \right] \simeq \frac{m_{\text{Pl}}^2}{8\pi} \left[\frac{V''(\phi)}{V(\phi)} \right] - \frac{m_{\text{Pl}}^2}{16\pi} \left[\frac{V'(\phi)}{V(\phi)} \right]$$

Fluctuation parameters

Tensor fluctuations

$$P_T^{1/2} = \langle \delta\phi^2 \rangle^{1/2} \sim H \propto k^{n_T} \quad n_T = -2\epsilon$$

Fluctuation parameters

Tensor fluctuations

$$P_T^{1/2} = \langle \delta\phi^2 \rangle^{1/2} \sim H \propto k^{n_T} \quad n_T = -2\epsilon$$

Scalar fluctuations

$$P_S^{1/2} = \frac{\delta N}{\delta\phi} \delta\phi \sim \frac{H}{\sqrt{\epsilon}} \propto k^{n-1}$$

$$n = 1 - 4\epsilon + 2\eta$$

Fluctuation parameters

Tensor fluctuations

$$P_T^{1/2} = \langle \delta\phi^2 \rangle^{1/2} \sim H \propto k^{n_T}$$

Consistency condition

$$n_T = -2\epsilon = -\frac{P_T}{8P_S}$$

Scalar fluctuations

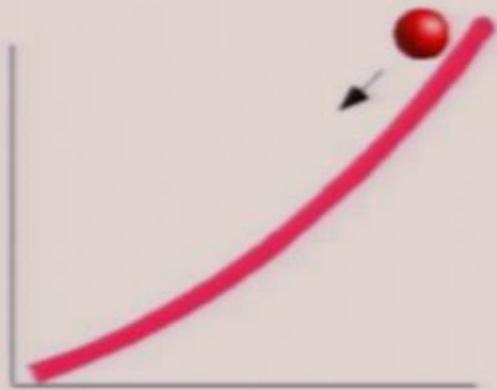
$$P_S^{1/2} = \frac{\delta N}{\delta\phi} \delta\phi \sim \frac{H}{\sqrt{\epsilon}} \propto k^{n-1}$$

$$n = 1 - 4\epsilon + 2\eta$$

Tensor/scalar ratio

$$r = \frac{P_T}{P_S} = 16\epsilon$$

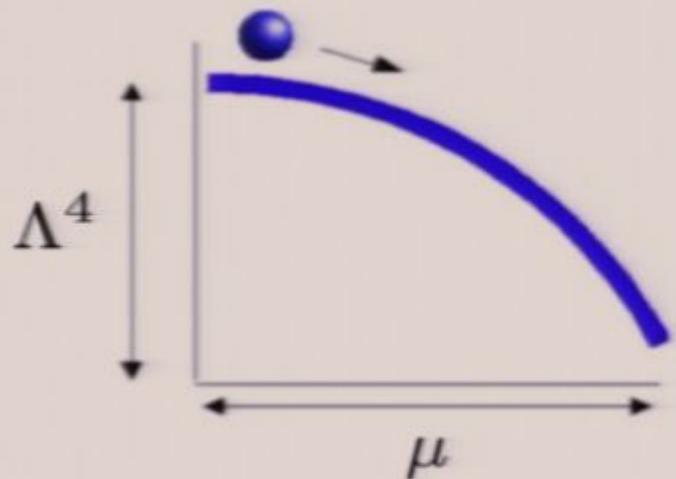
Inflation: zoology



Large field

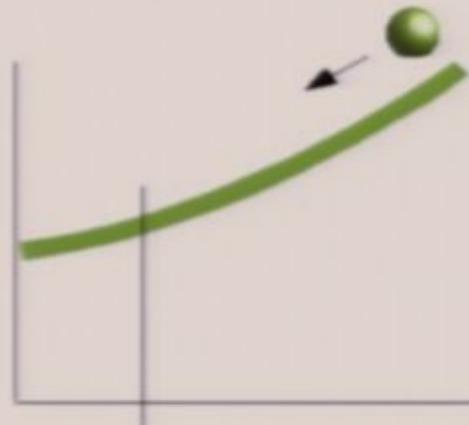
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 e^{\phi/\mu}$$



Small field

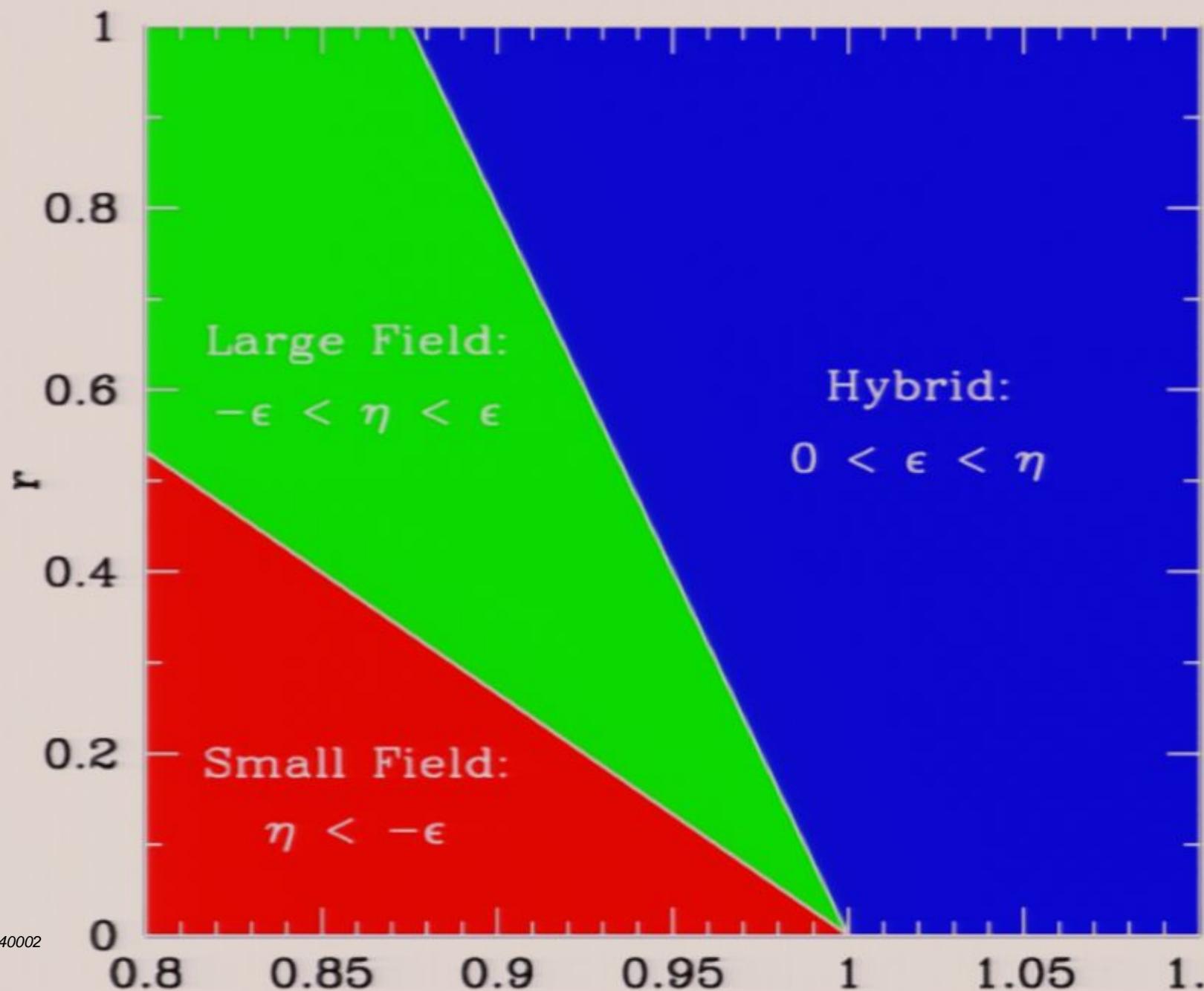
$$V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$$



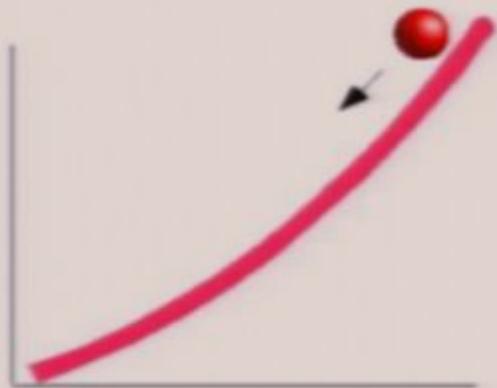
Hybrid

$$V(\phi) = \Lambda^4 [1 + (\phi/\mu)^p]$$

The zoo plot



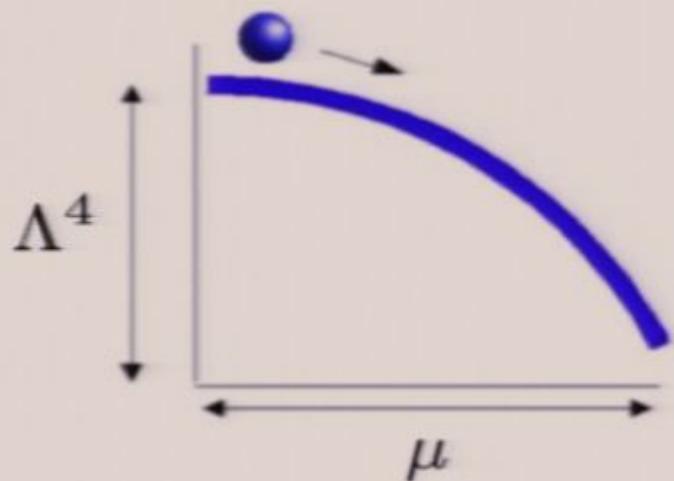
Inflation: zoology



Large field

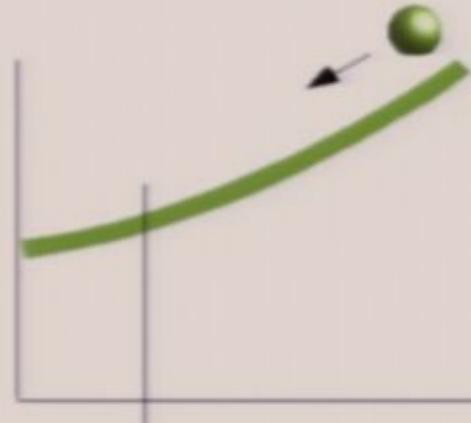
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 e^{\phi/\mu}$$



Small field

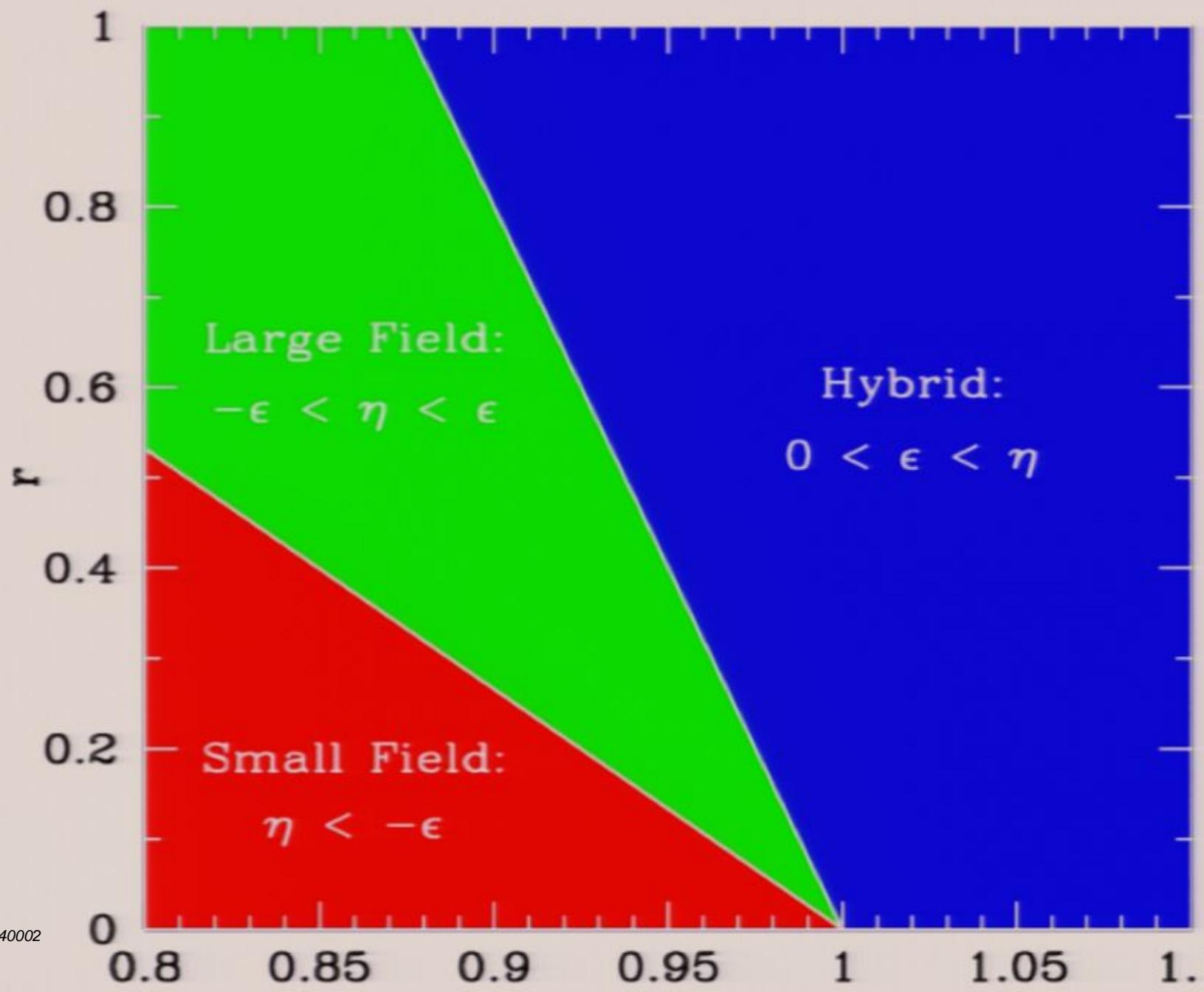
$$V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$$



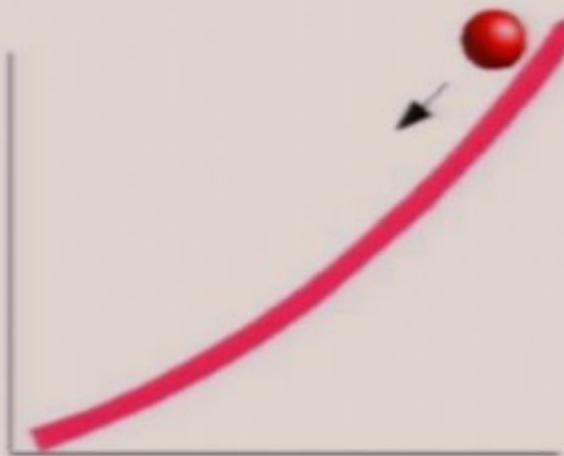
Hybrid

$$V(\phi) = \Lambda^4 [1 + (\phi/\mu)^p]$$

The zoo plot



Large-Field Models



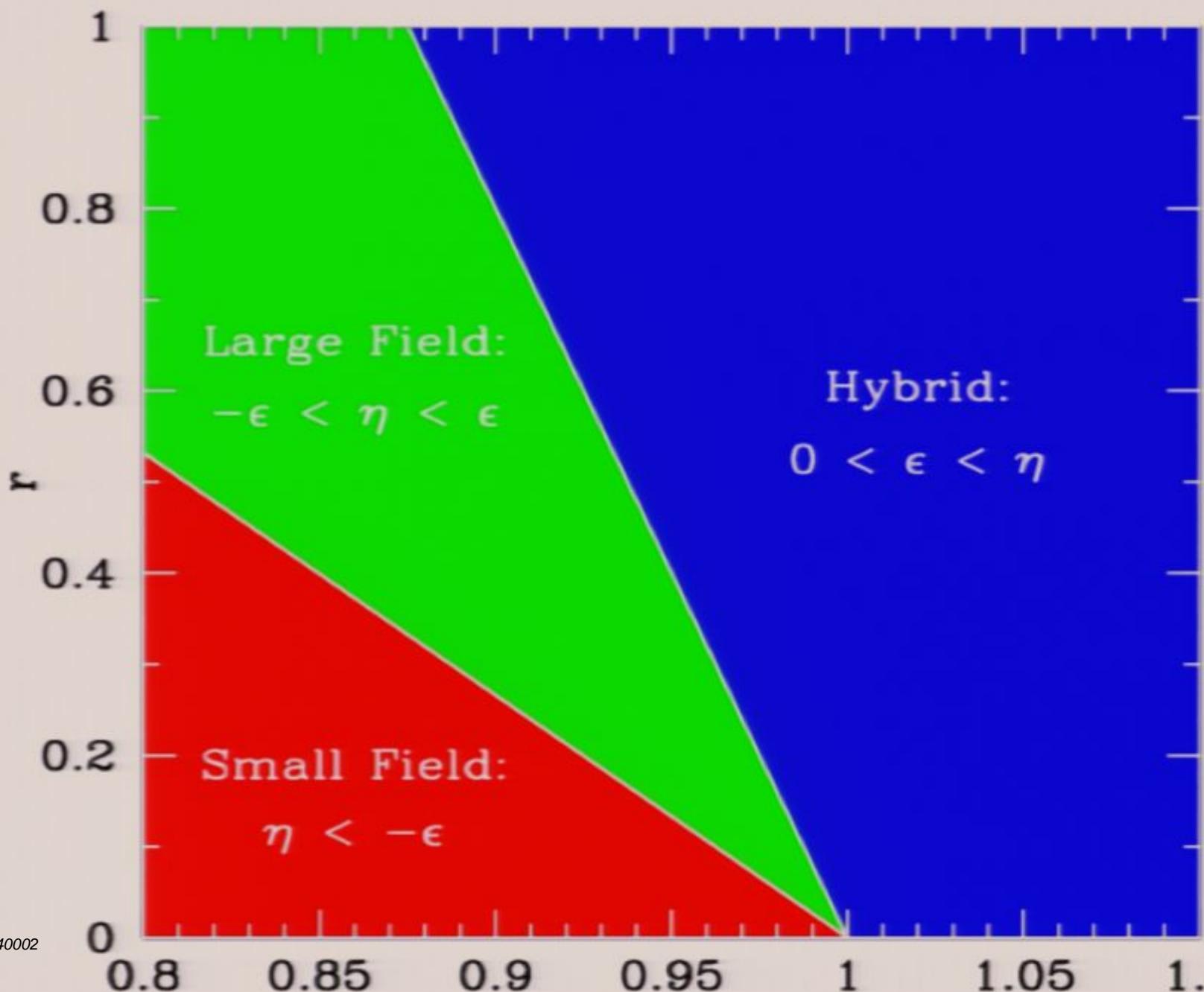
$$V(\phi) = \Lambda^4 \left(\frac{\phi}{\mu} \right)^p$$

Observables:

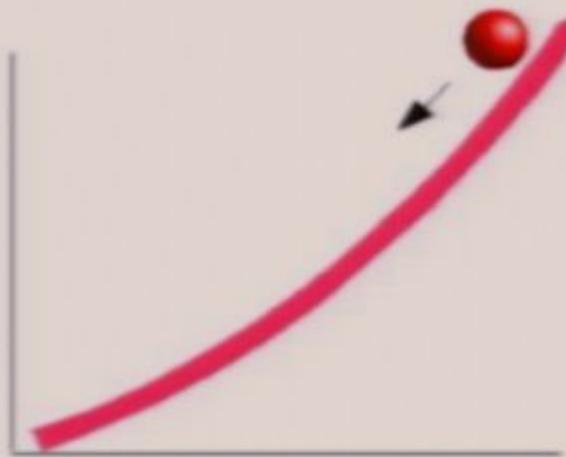
$$n = 1 - \frac{2 + p}{2N} \quad r = \frac{4p}{N}$$

$$N = 46 - 60$$

The zoo plot



Large-Field Models

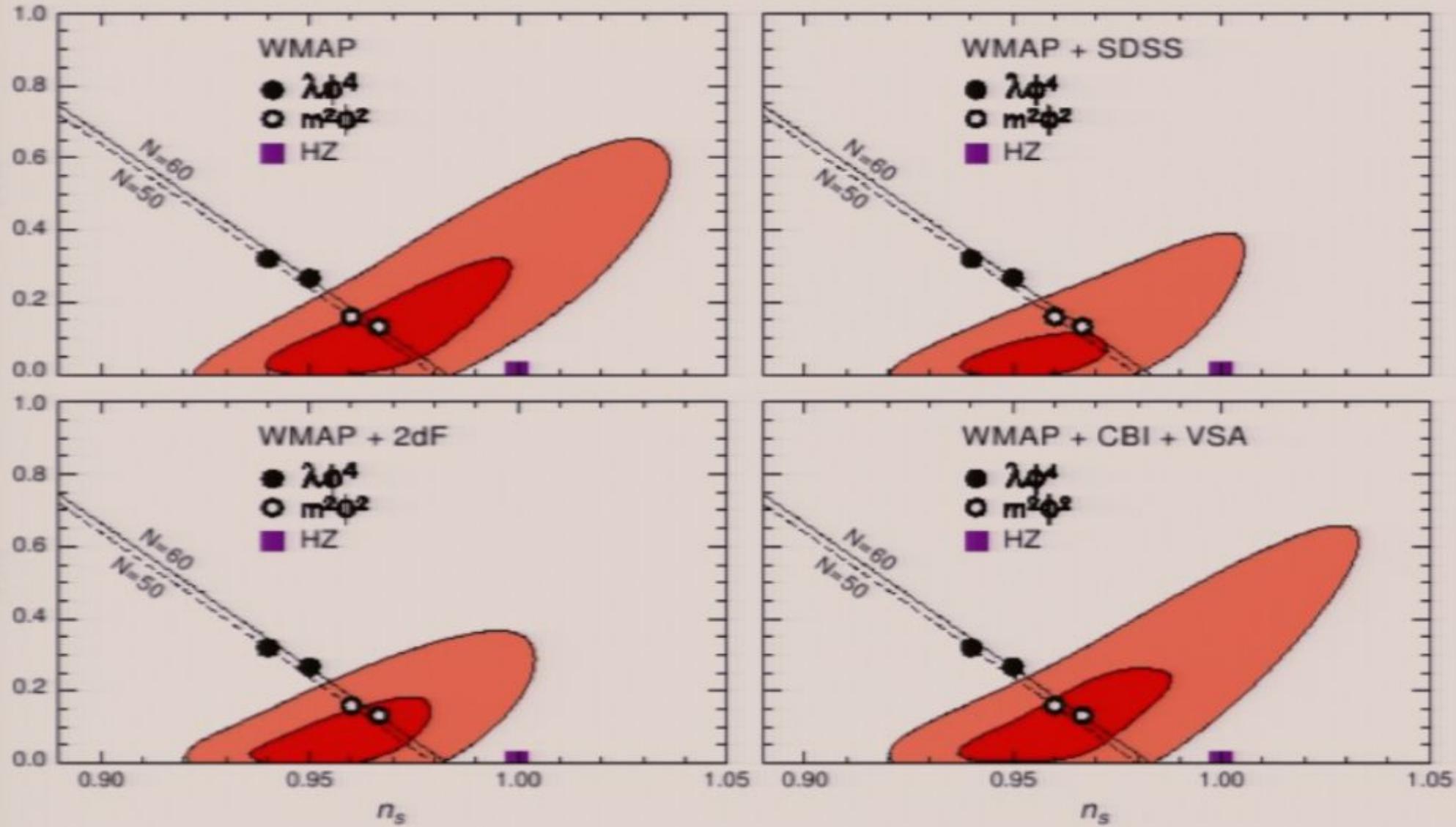


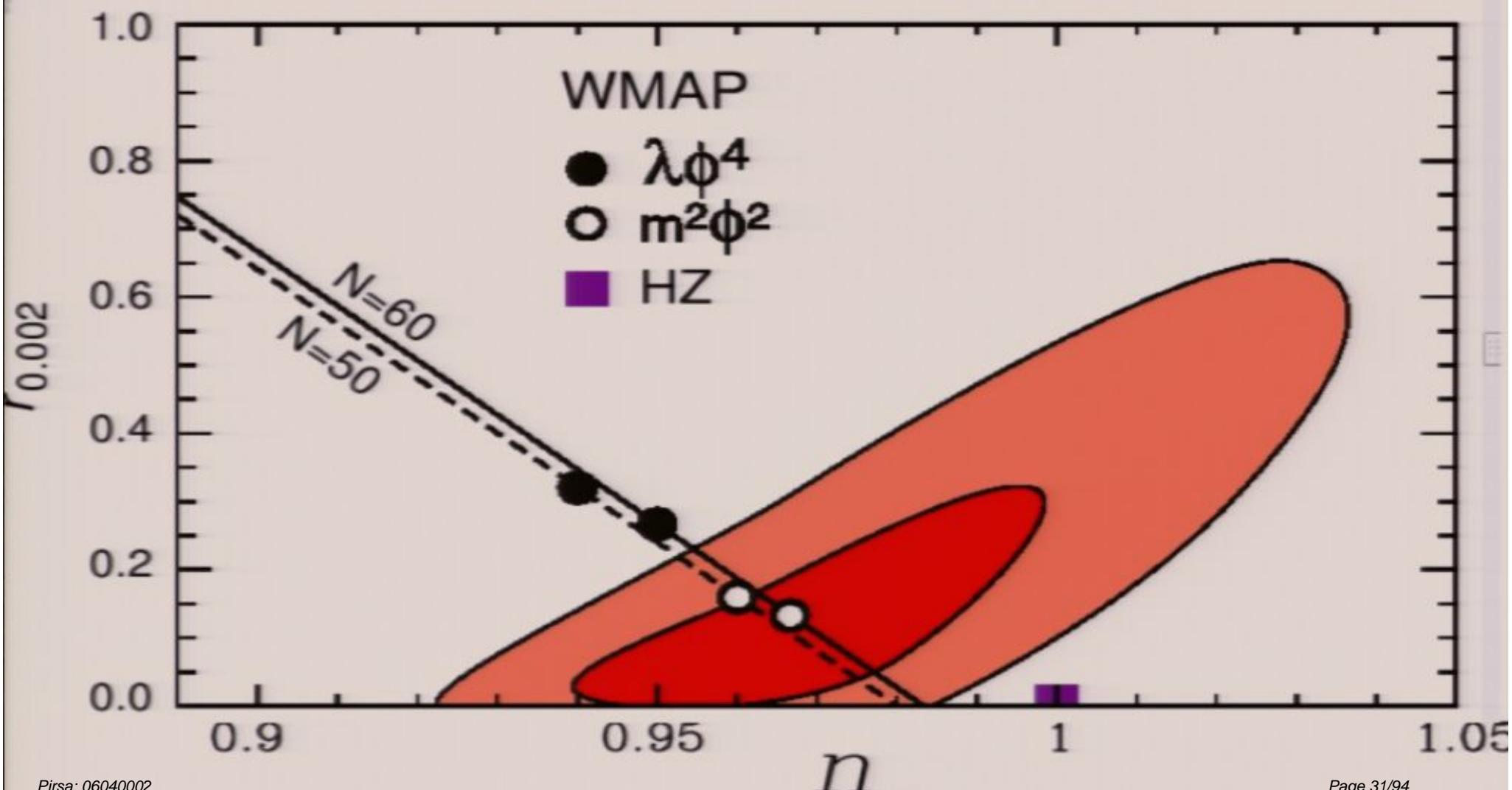
$$V(\phi) = \Lambda^4 \left(\frac{\phi}{\mu} \right)^p$$

Observables:

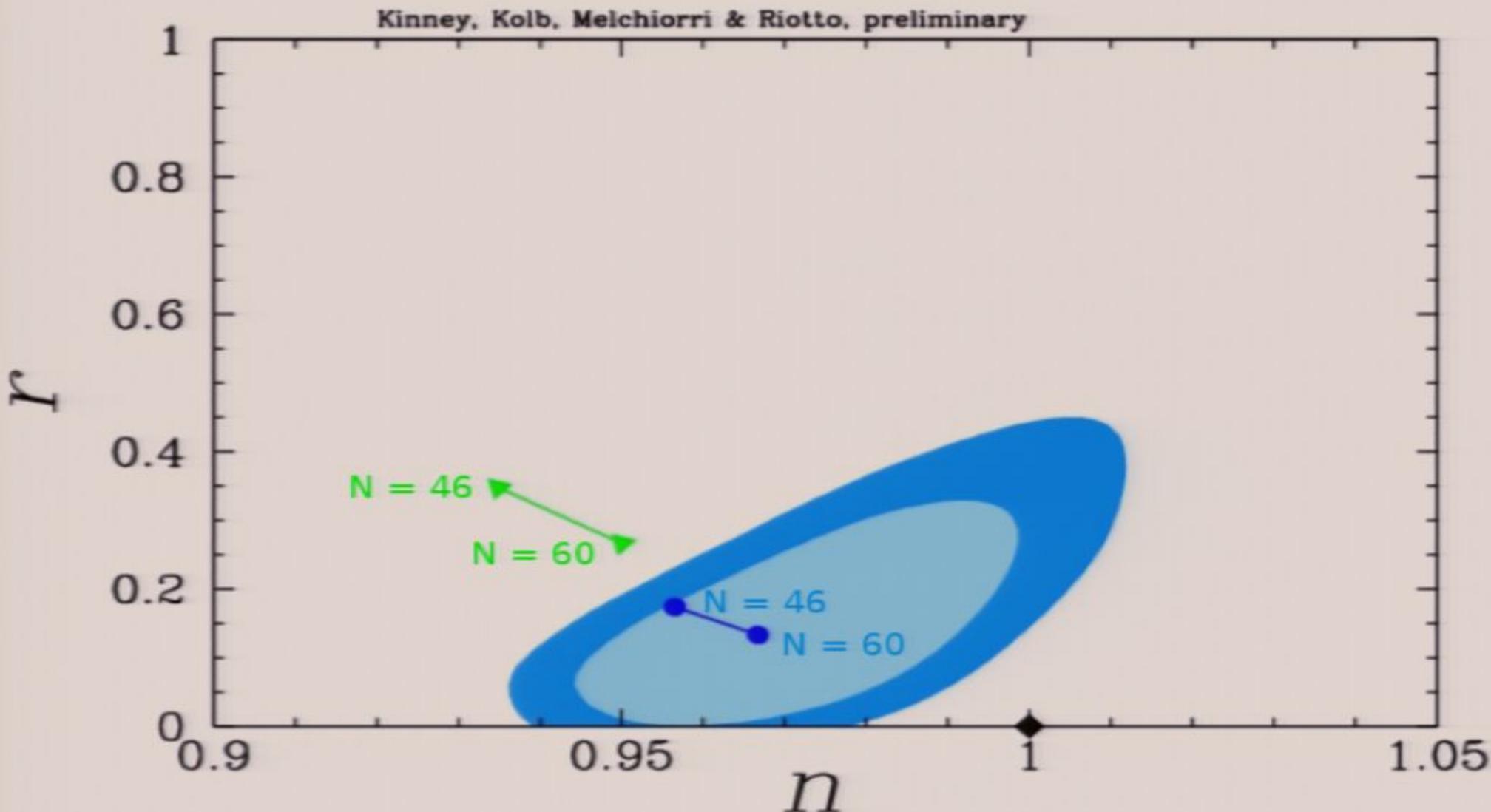
$$n = 1 - \frac{2 + p}{2N} \quad r = \frac{4p}{N}$$

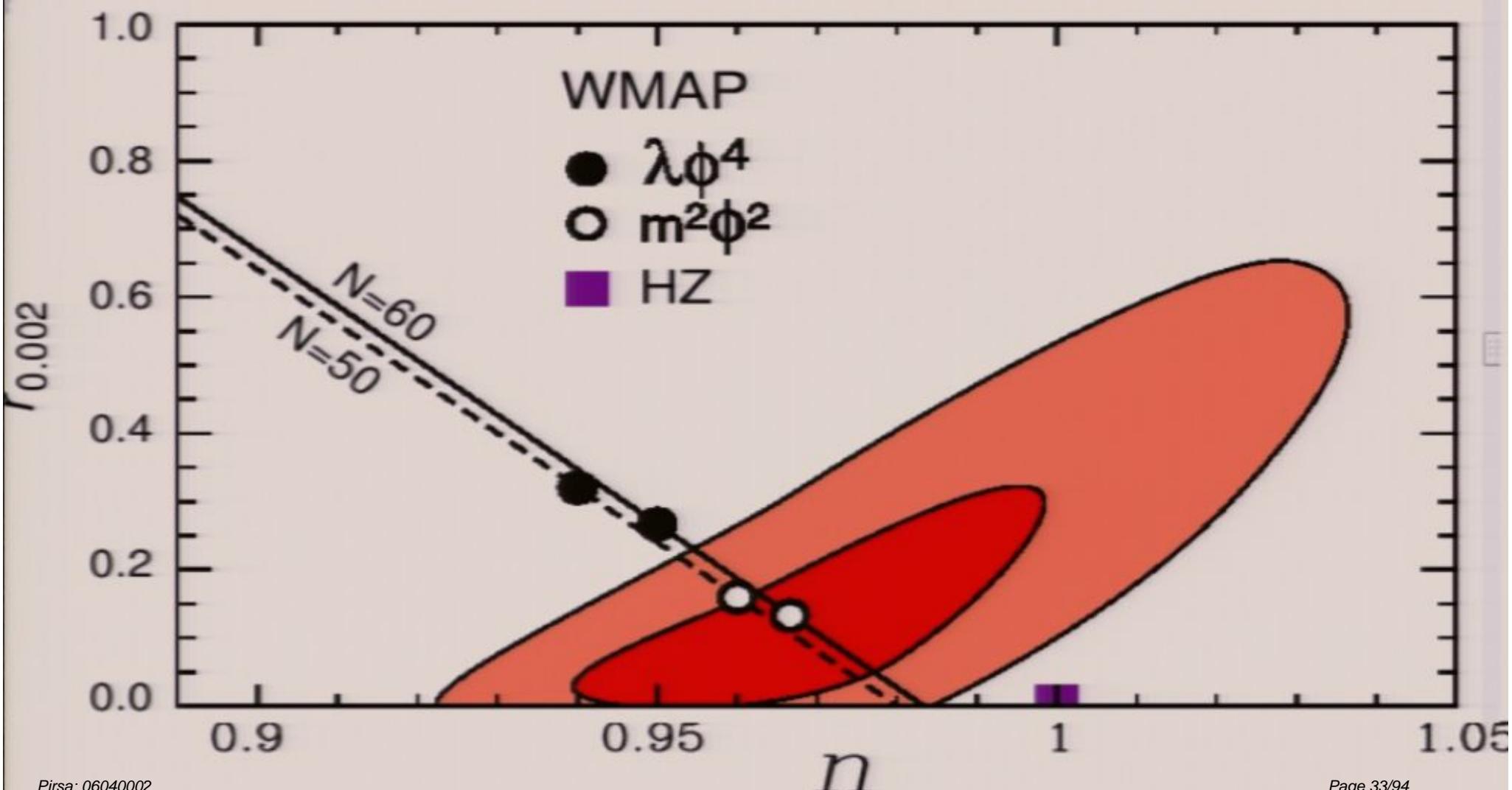
$$N = 46 - 60$$



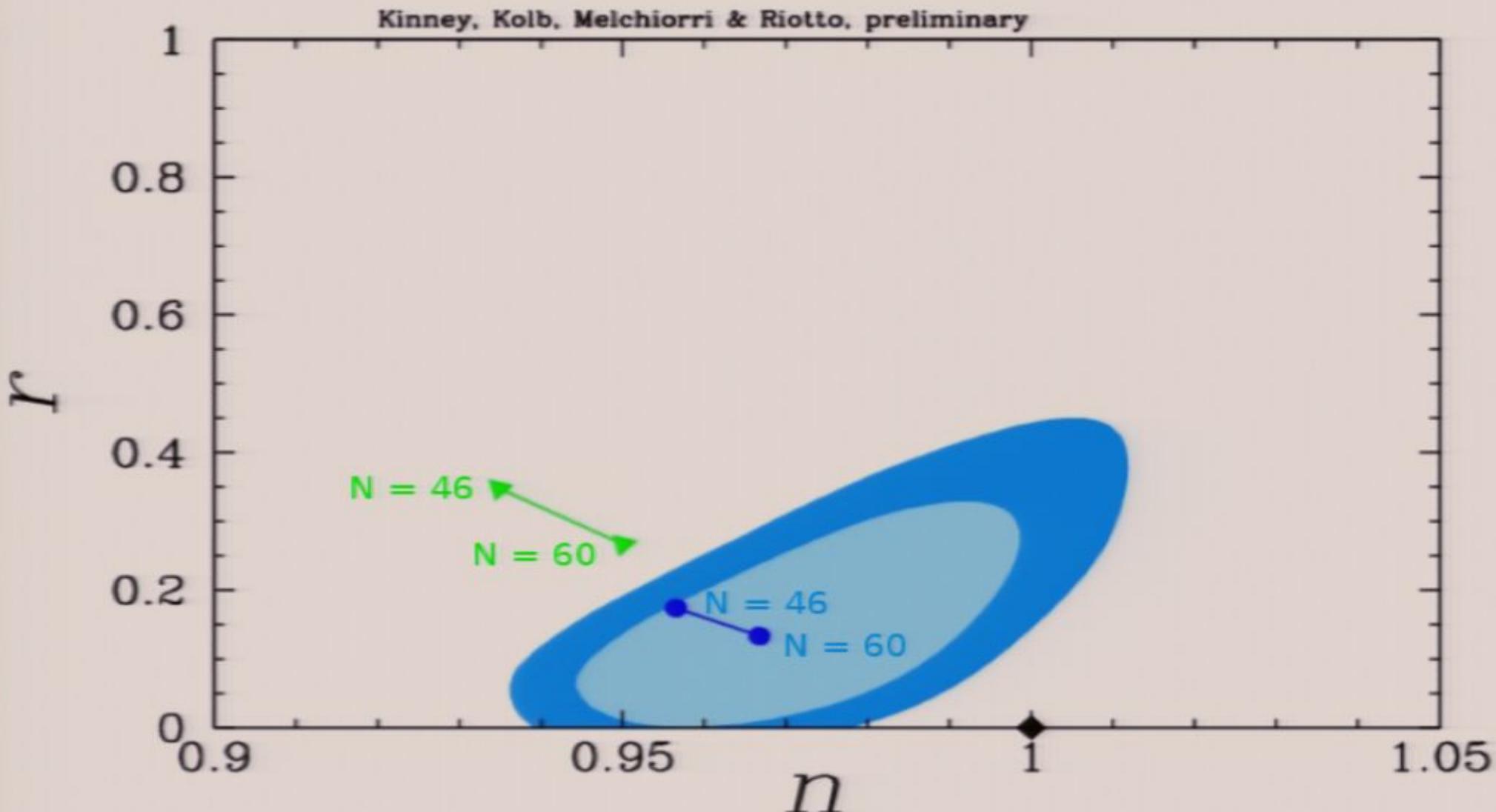


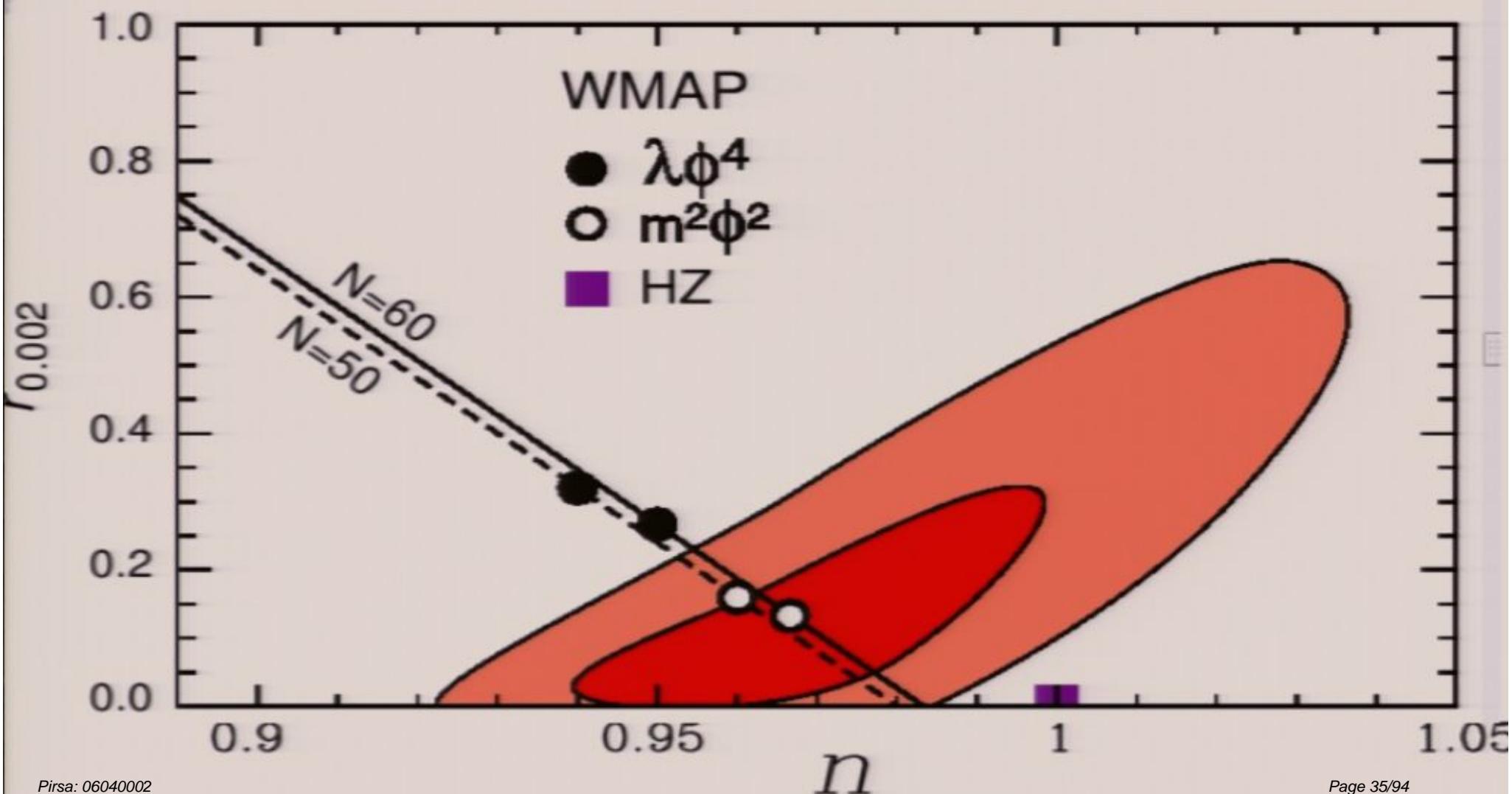
Spergel et al. chains (plotted incorrectly)



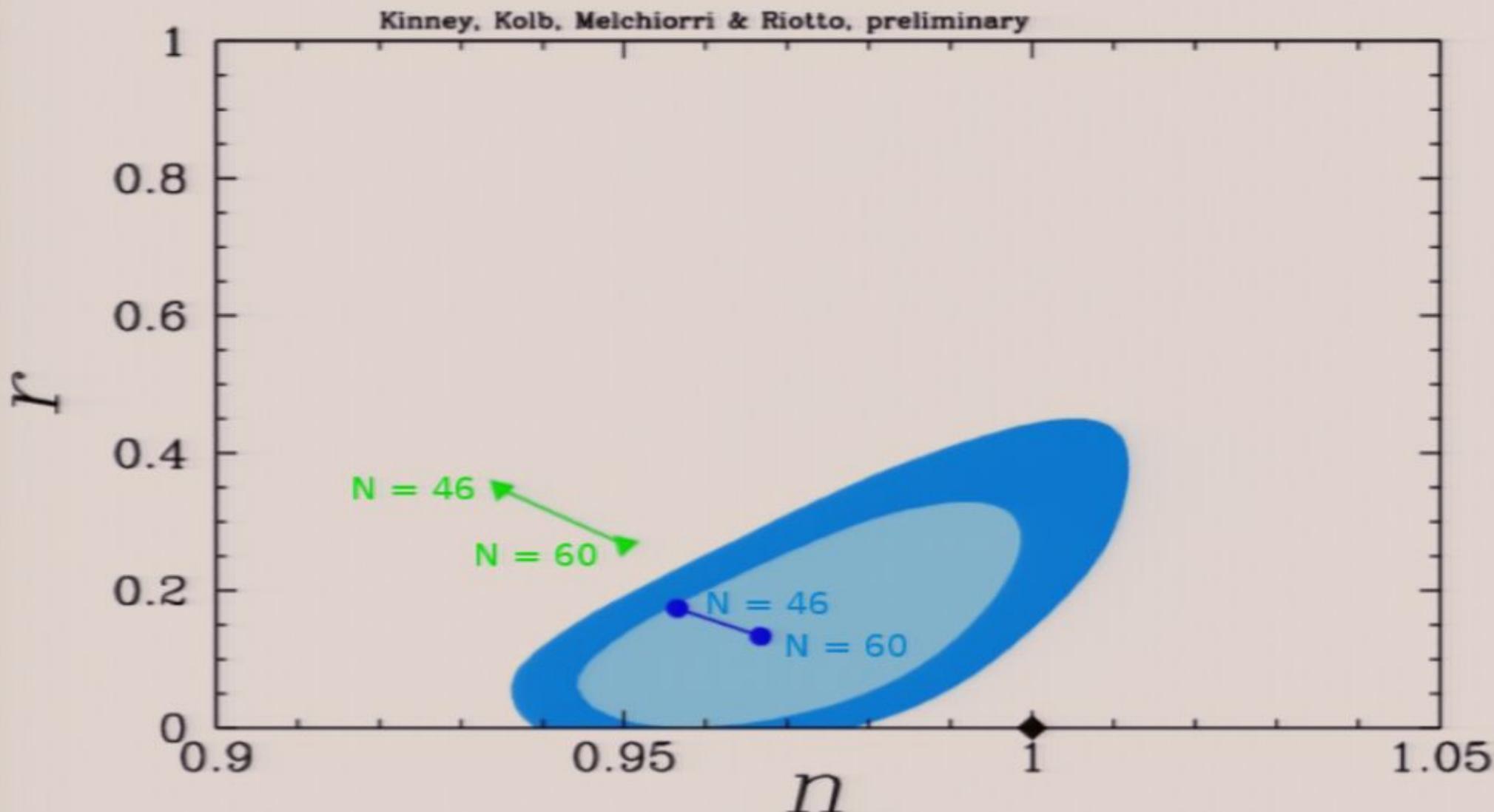


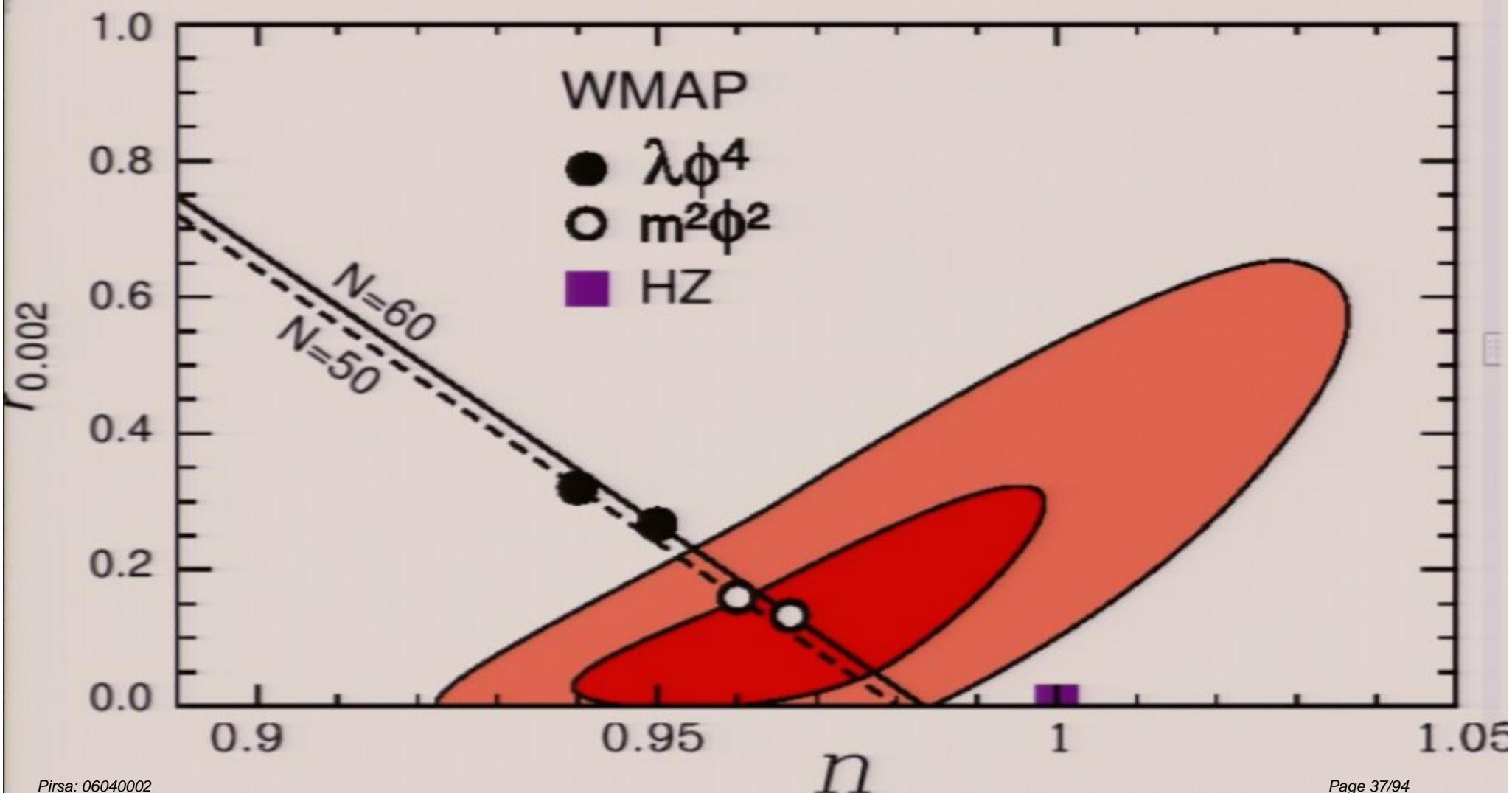
Spergel et al. chains (plotted incorrectly)



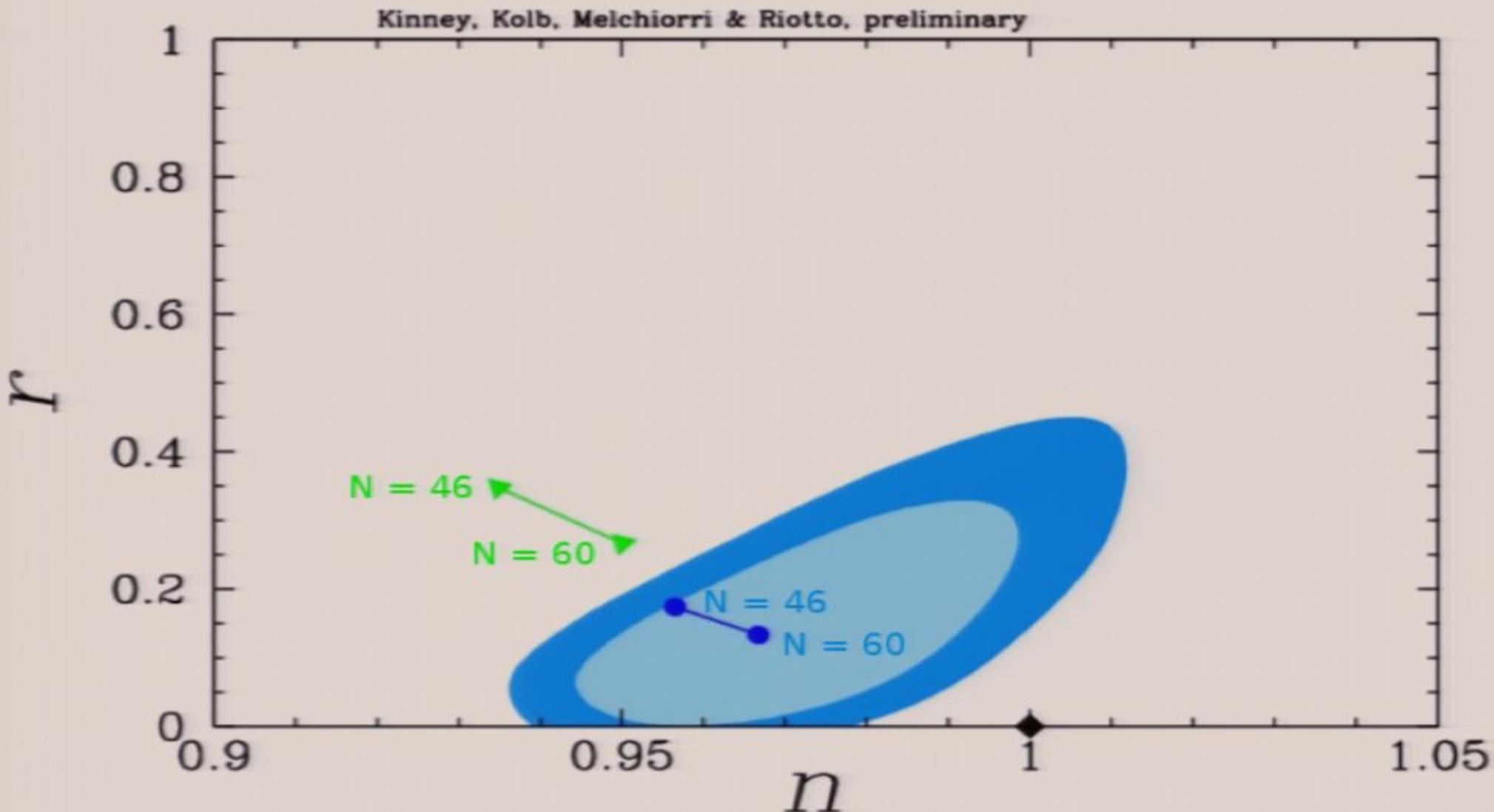


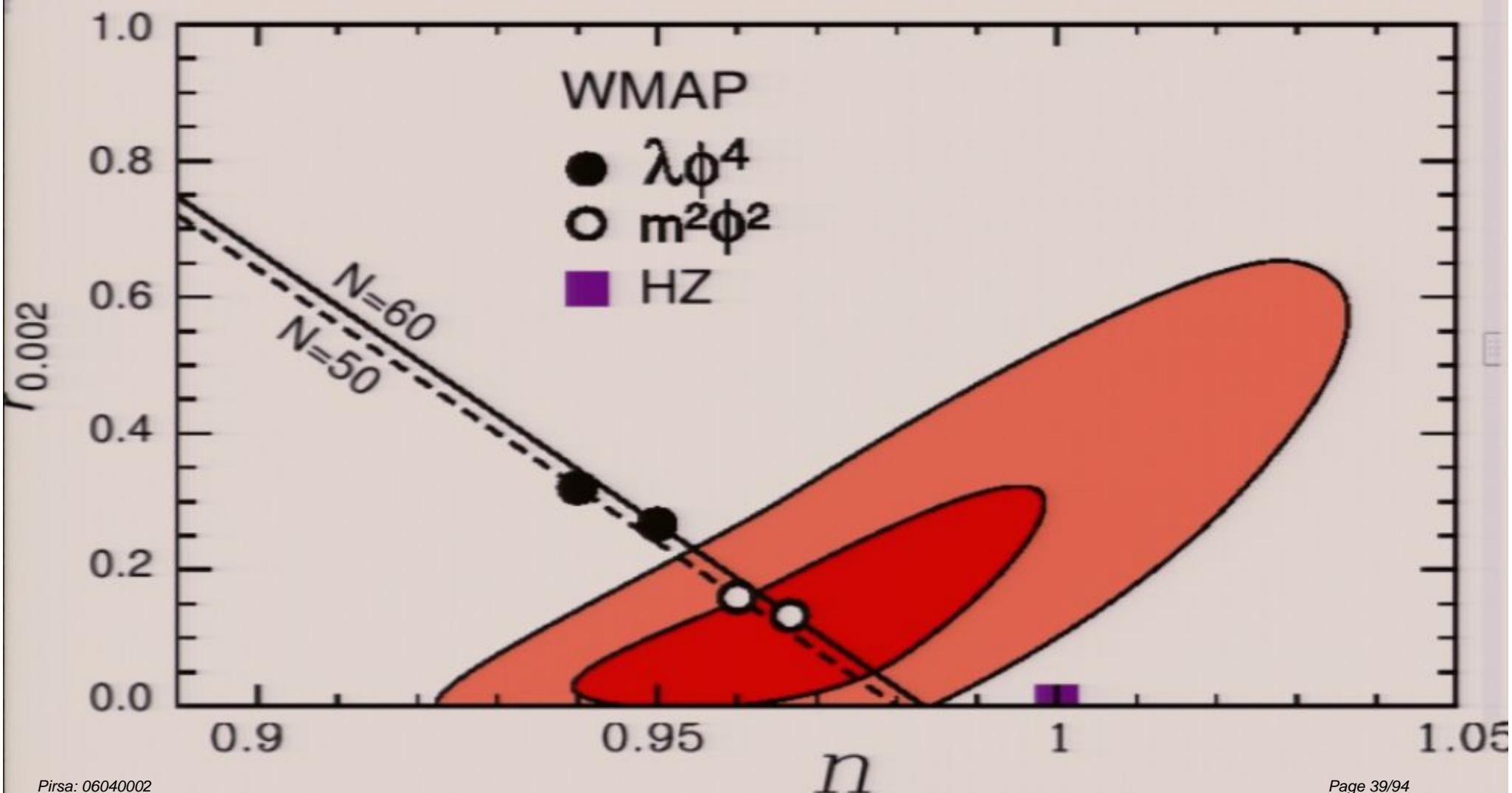
Spergel et al. chains (plotted incorrectly)



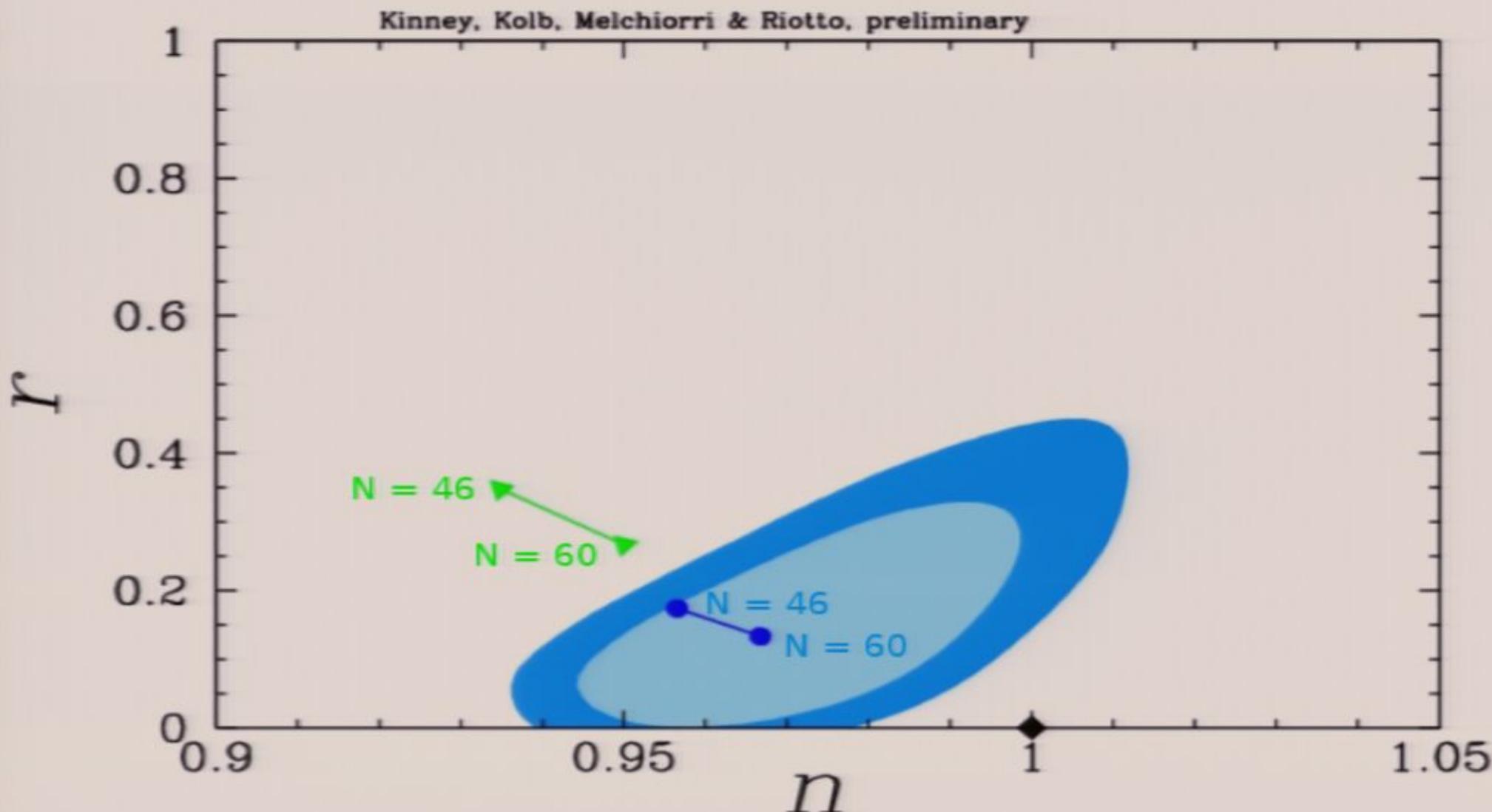


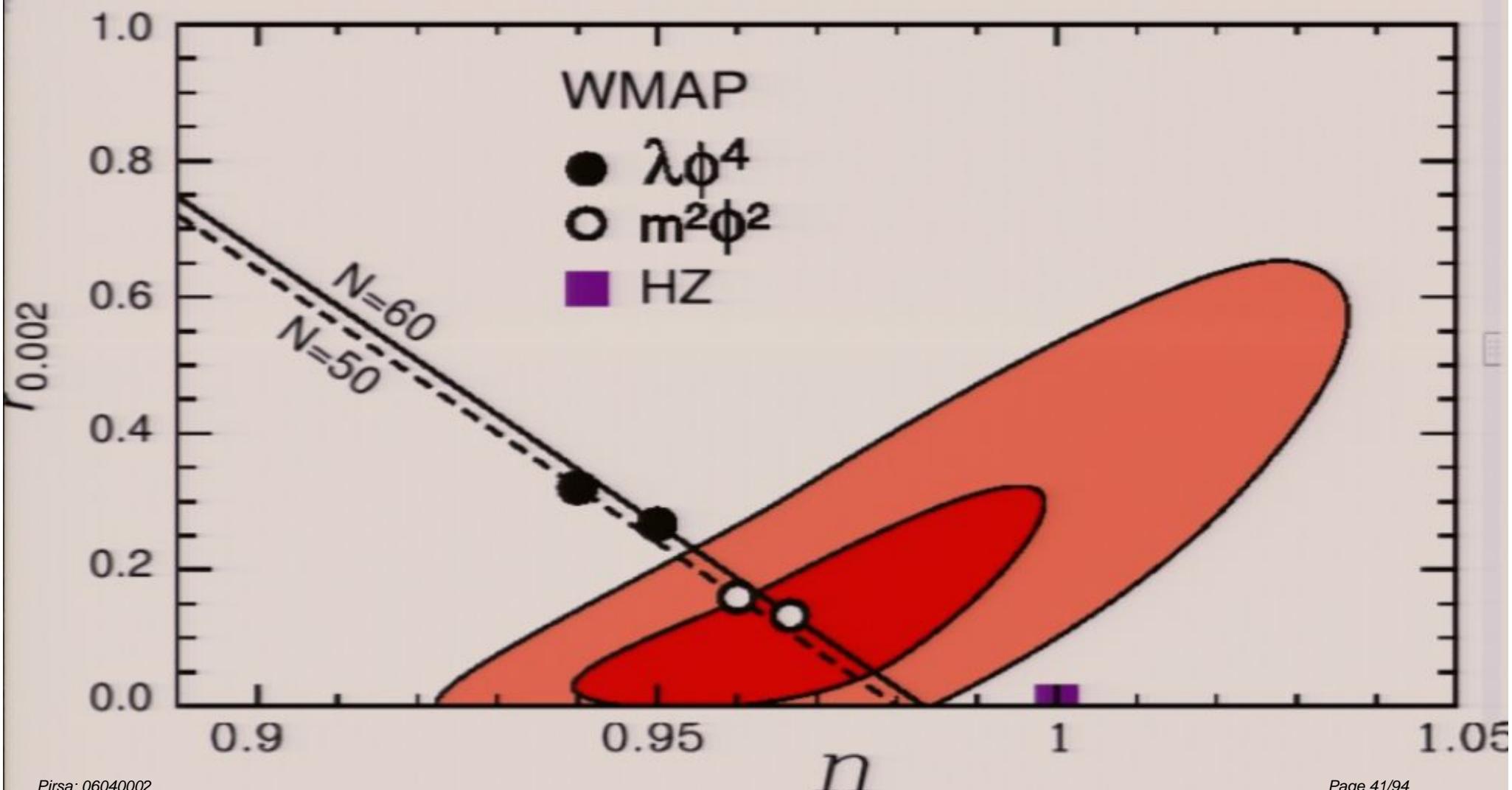
Spergel et al. chains (plotted incorrectly)



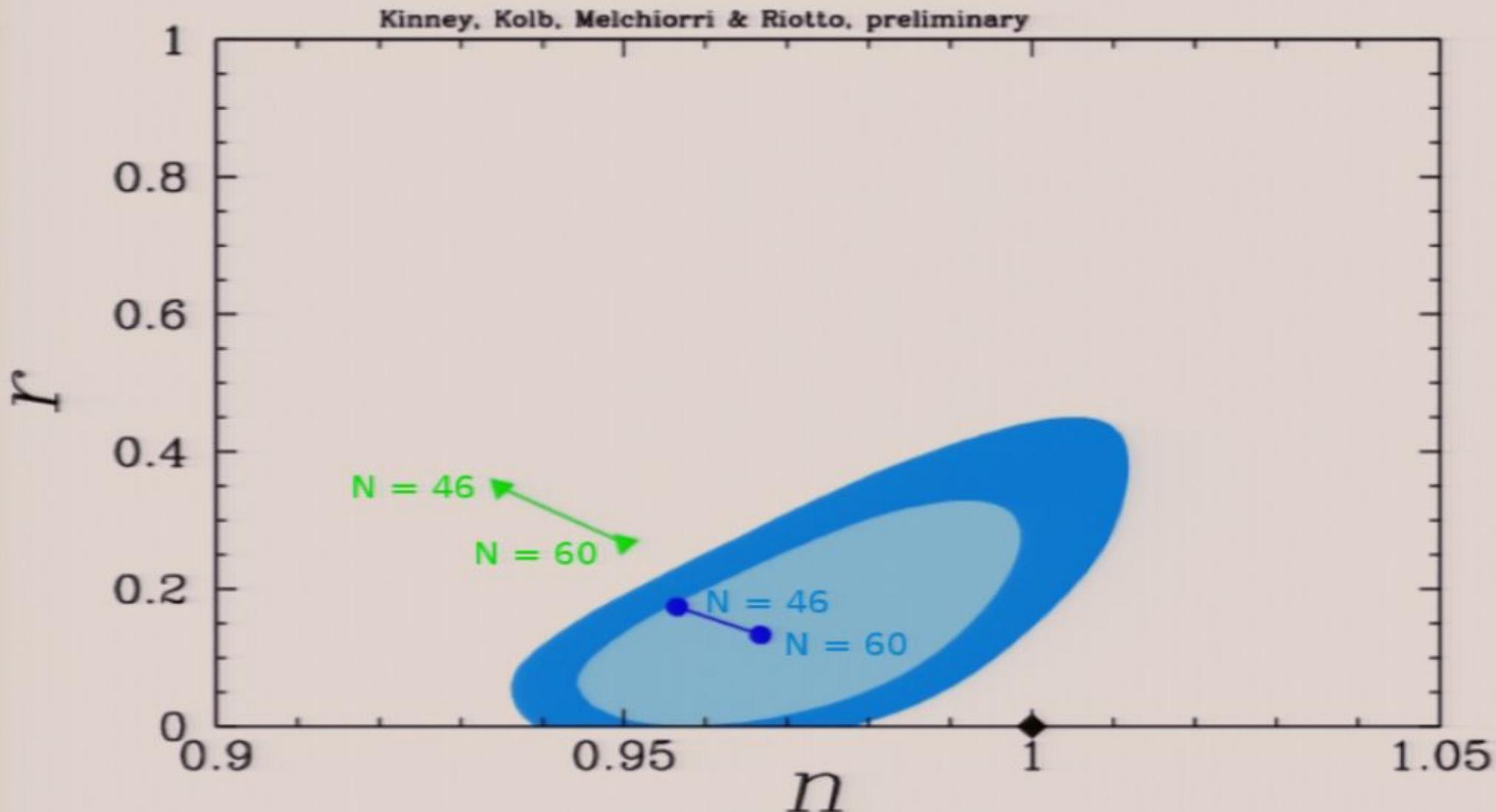


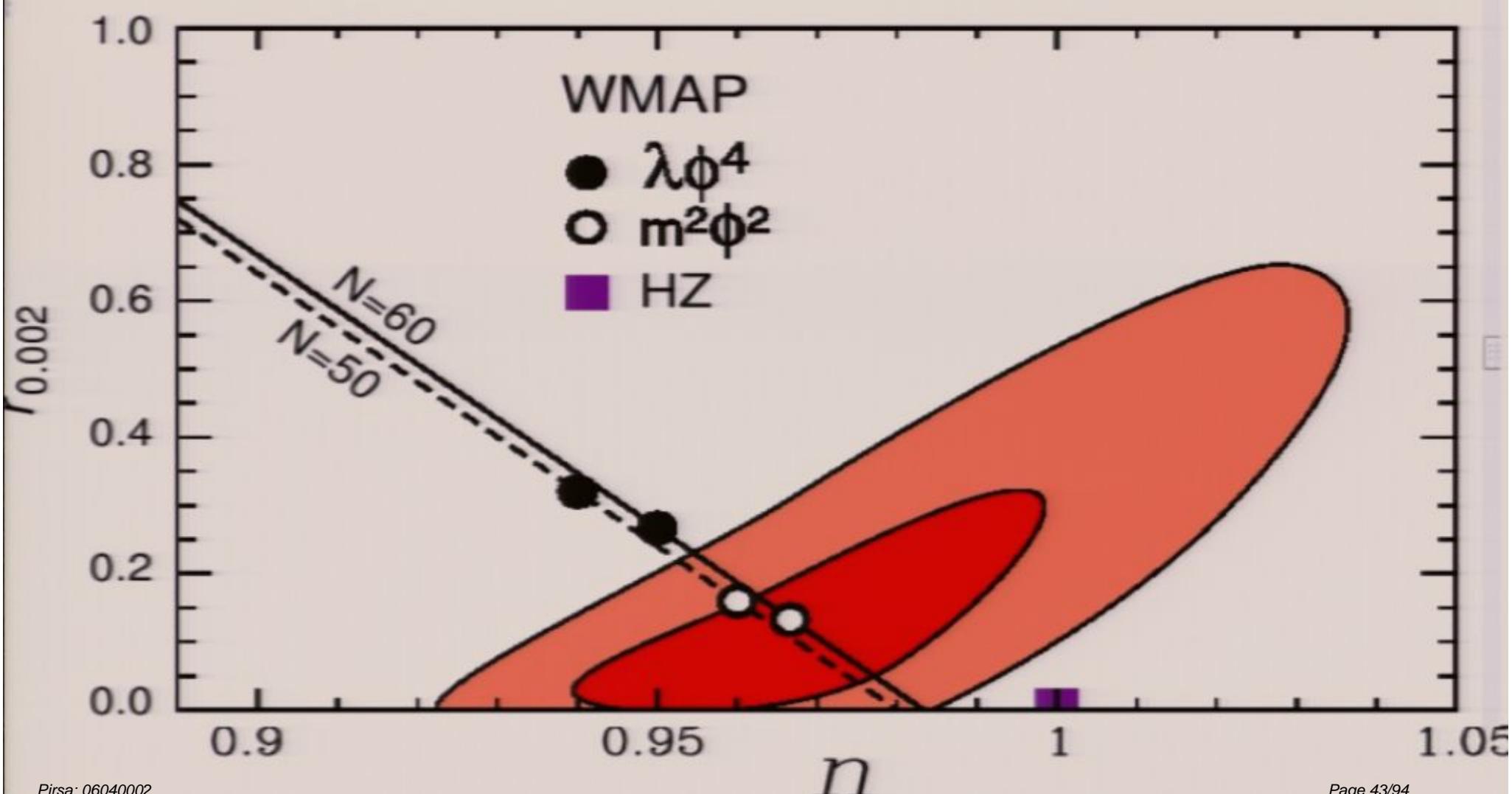
Spergel et al. chains (plotted incorrectly)



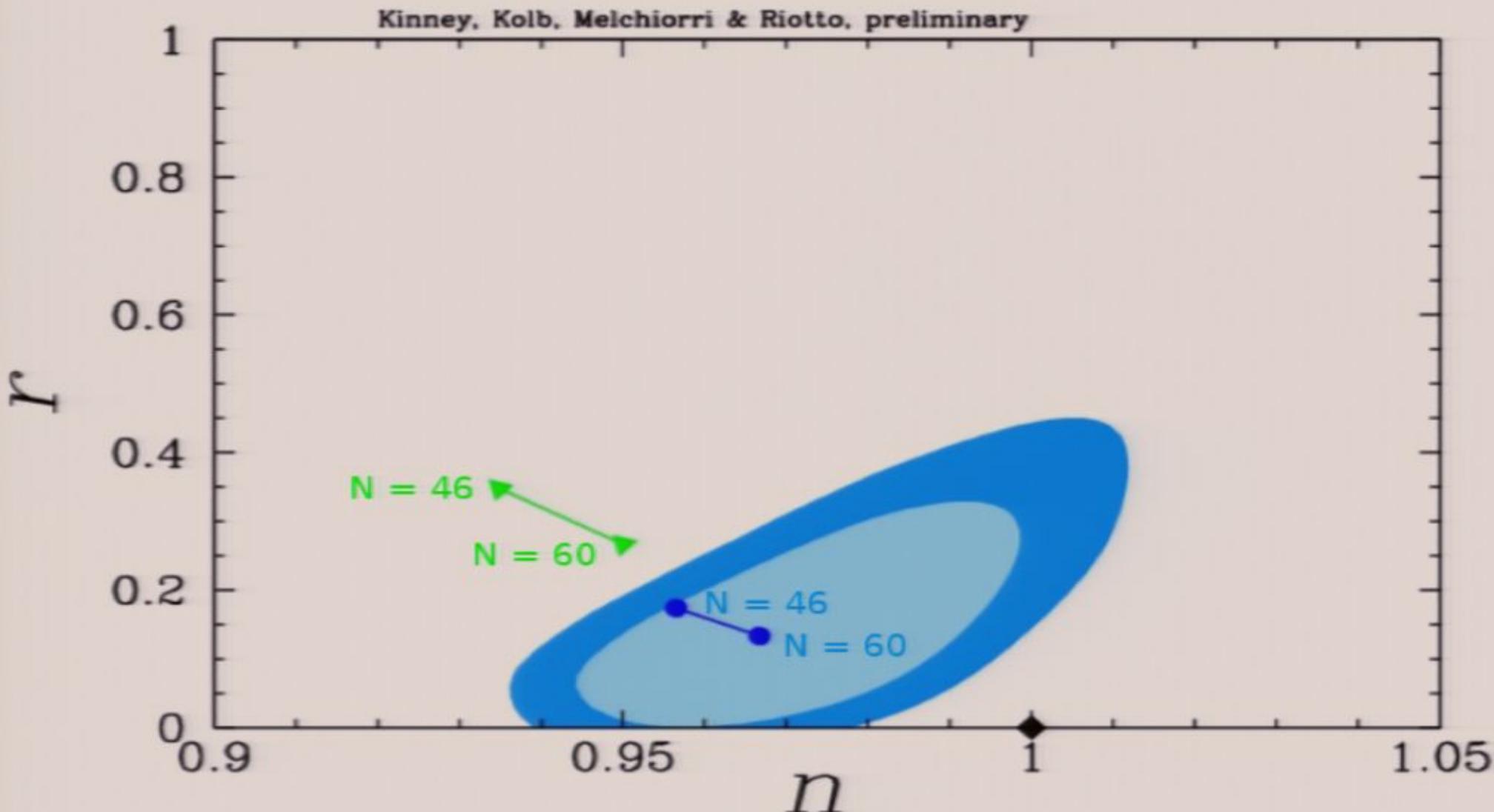


Spergel et al. chains (plotted incorrectly)

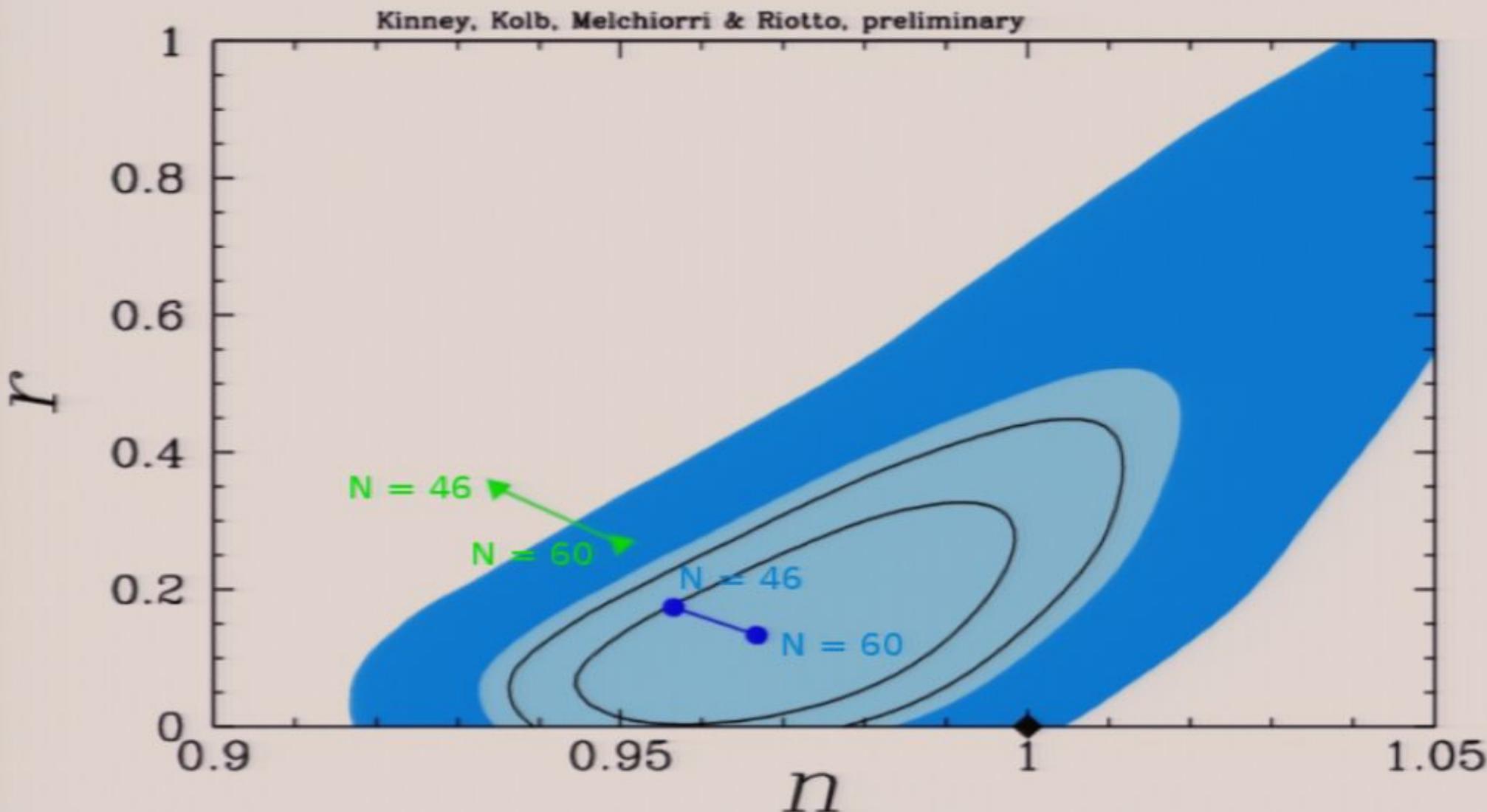




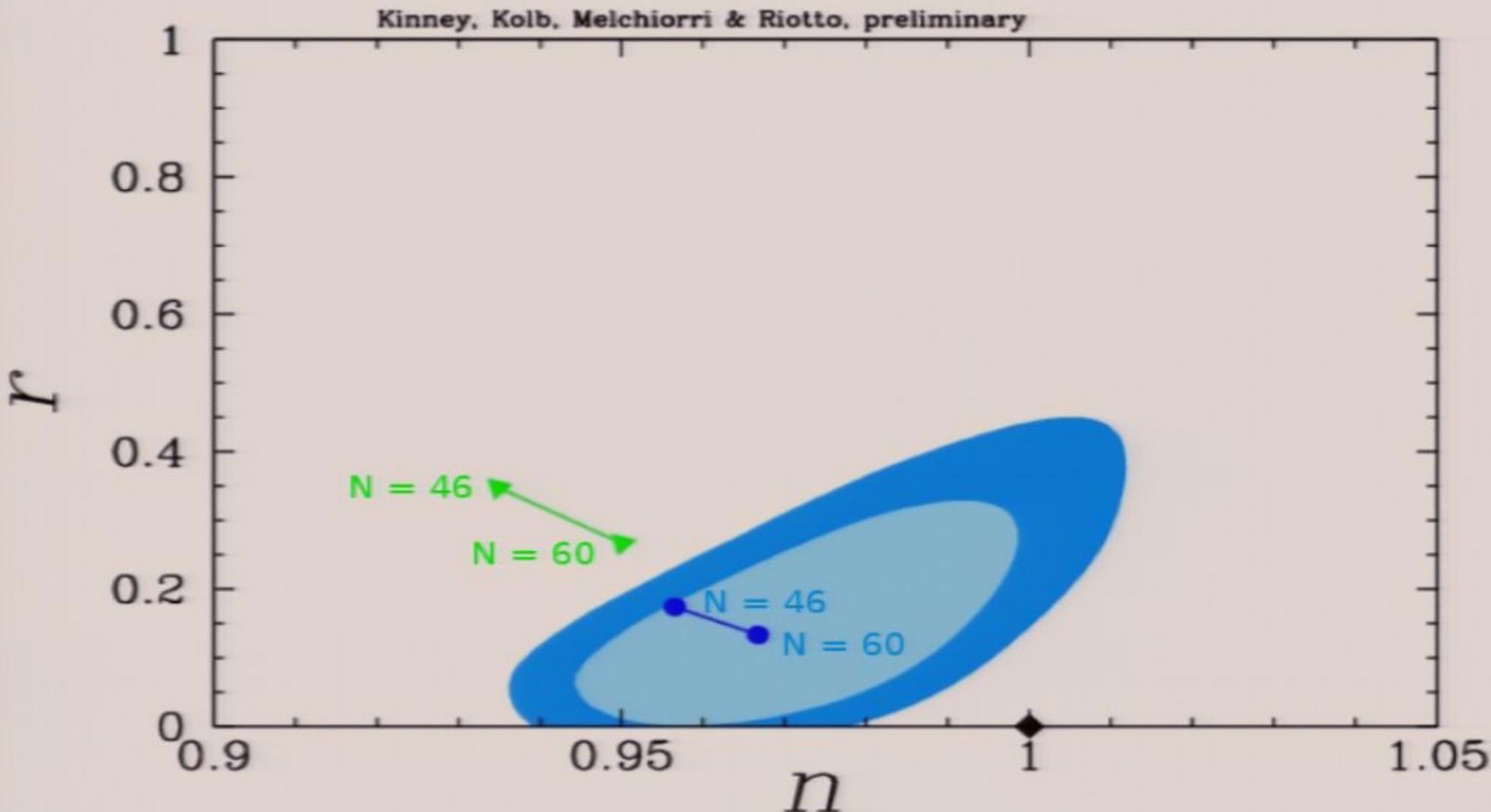
Spergel et al. chains (plotted incorrectly)

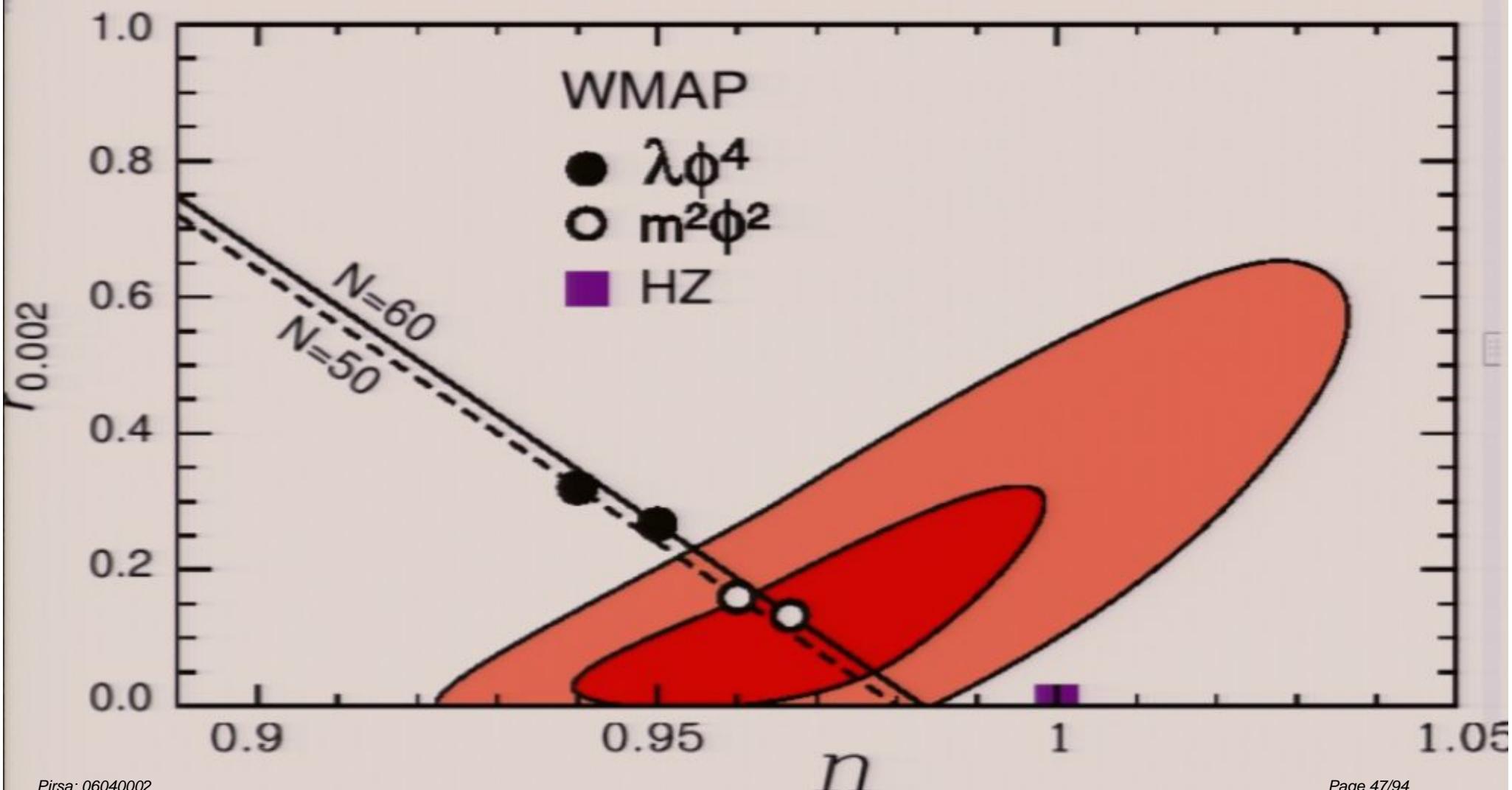


Spergel et al. chains (plotted correctly)

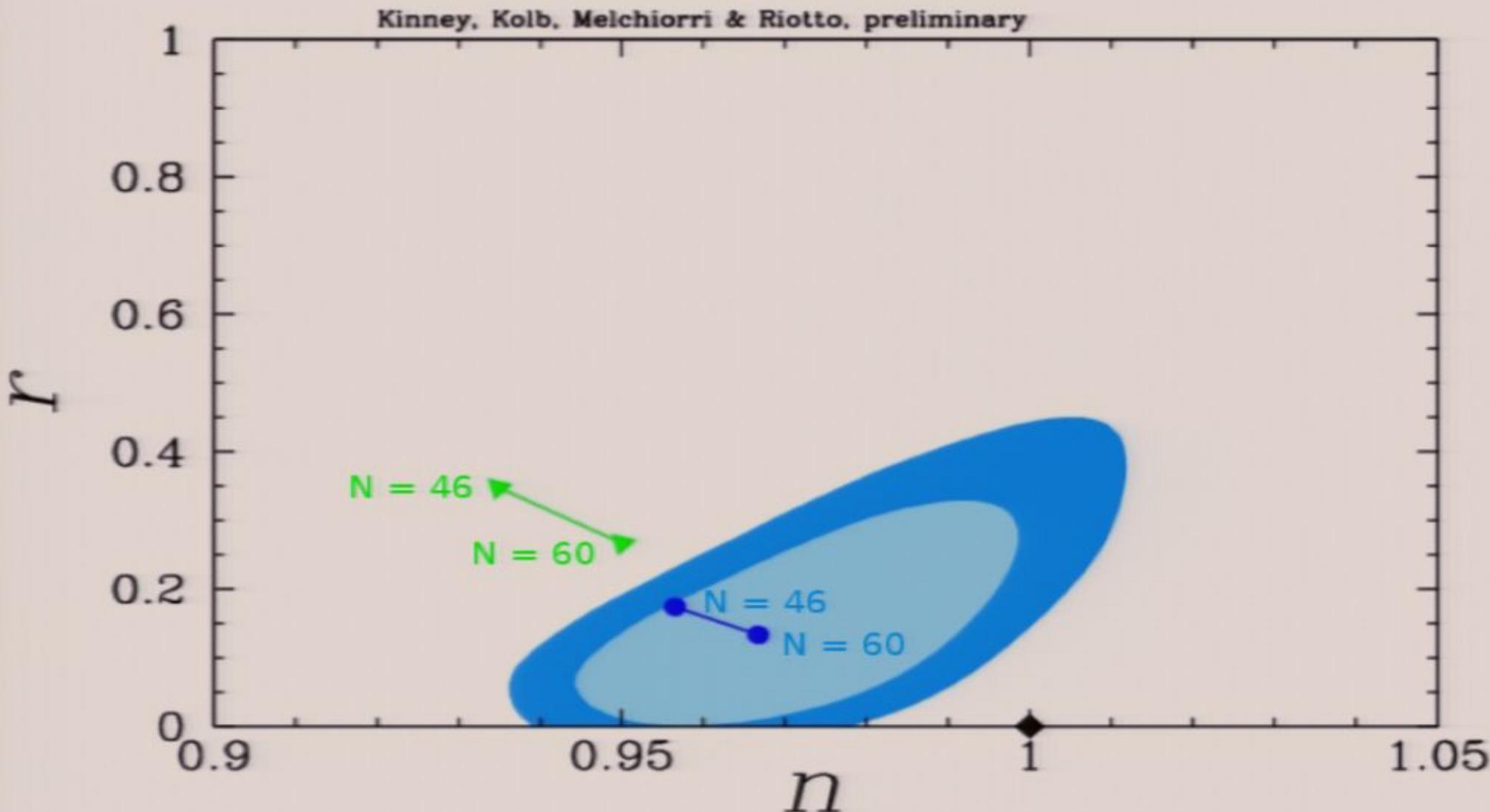


Spergel et al. chains (plotted incorrectly)

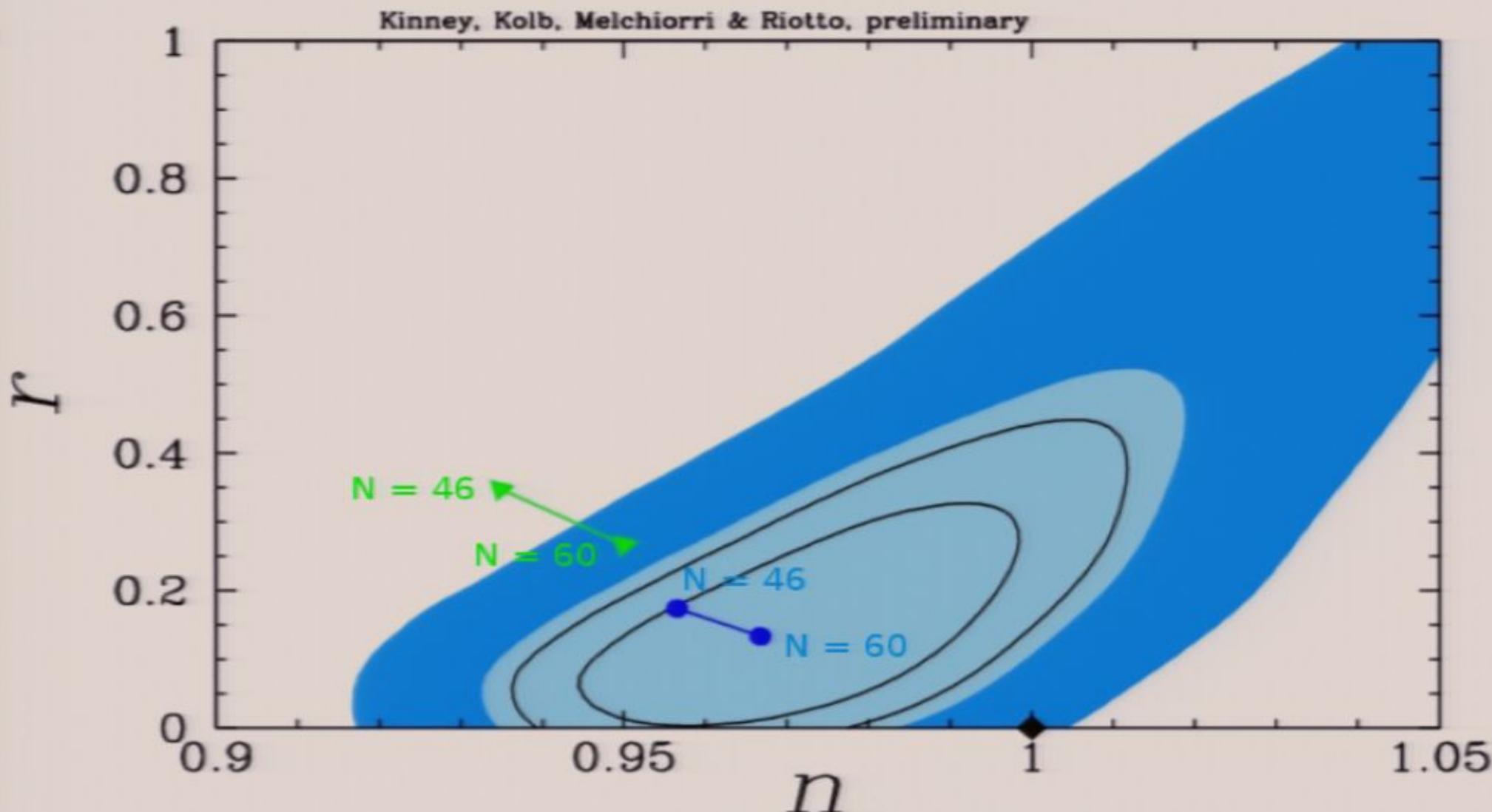




Spergel et al. chains (plotted incorrectly)



Spergel et al. chains (plotted correctly)

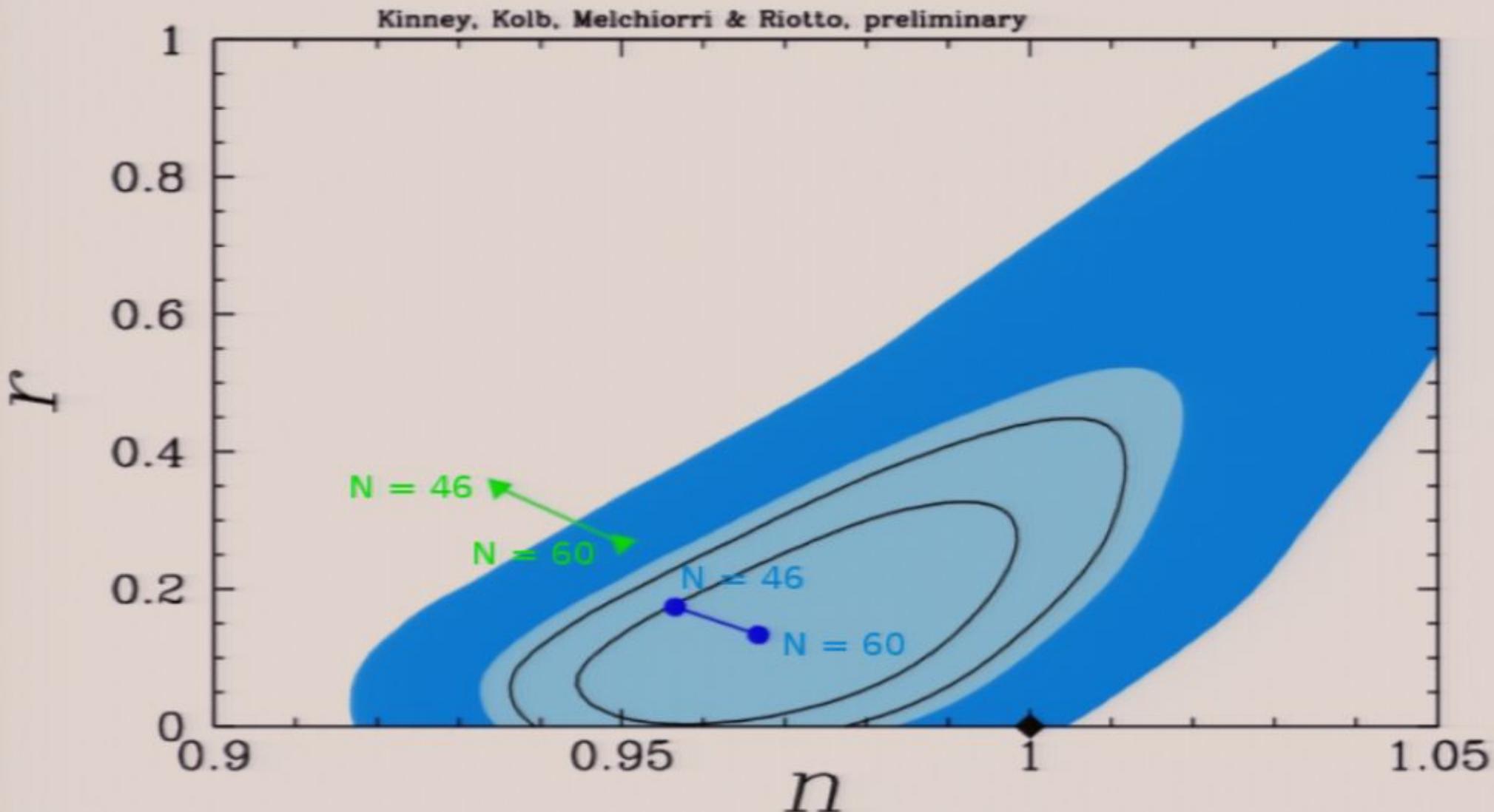


UB Center For Computational Research



U2: 800-node 2x Intel 3.2 GHz Xeon "Irwindale" cluster

Spergel et al. chains (plotted correctly)

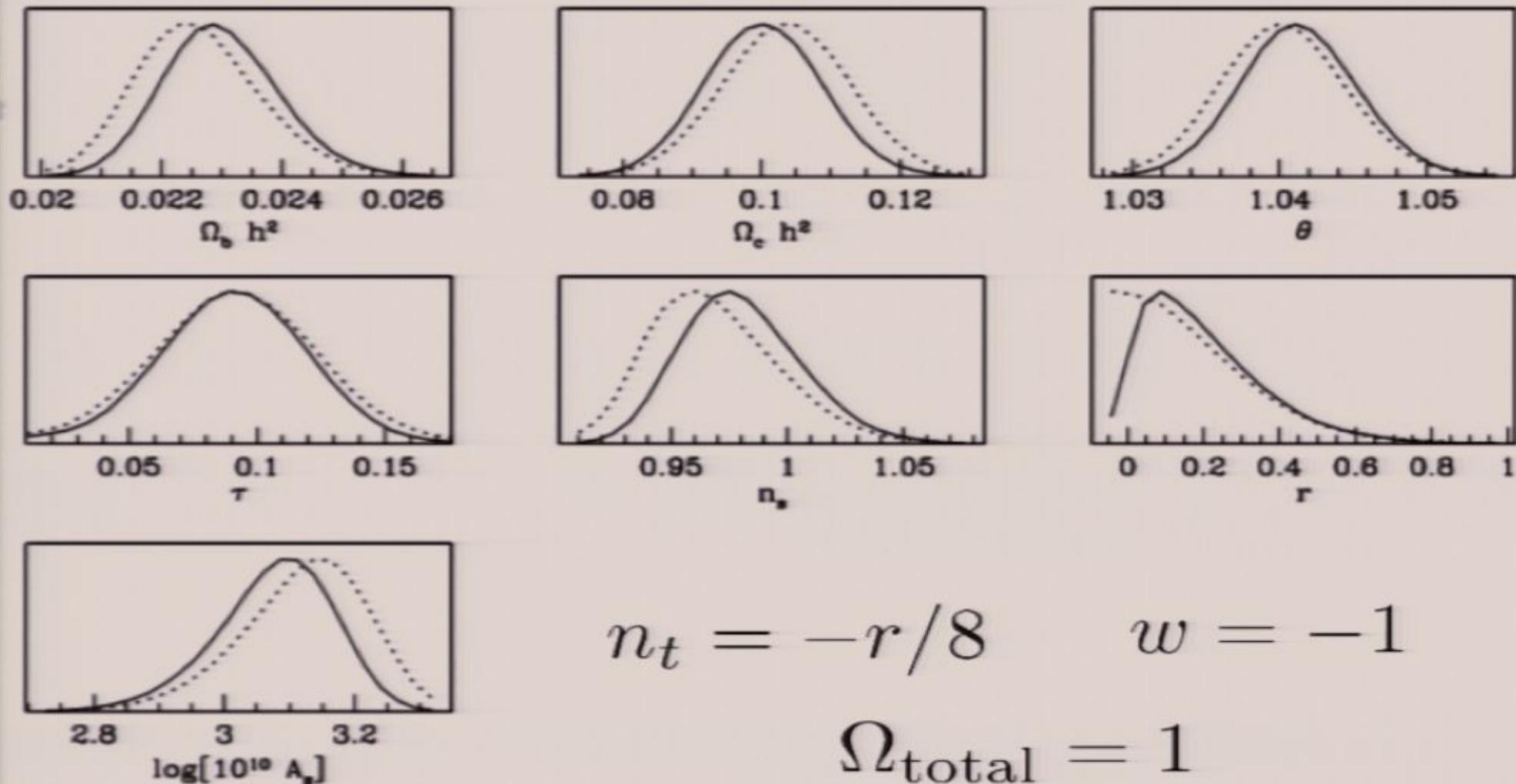


UB Center For Computational Research



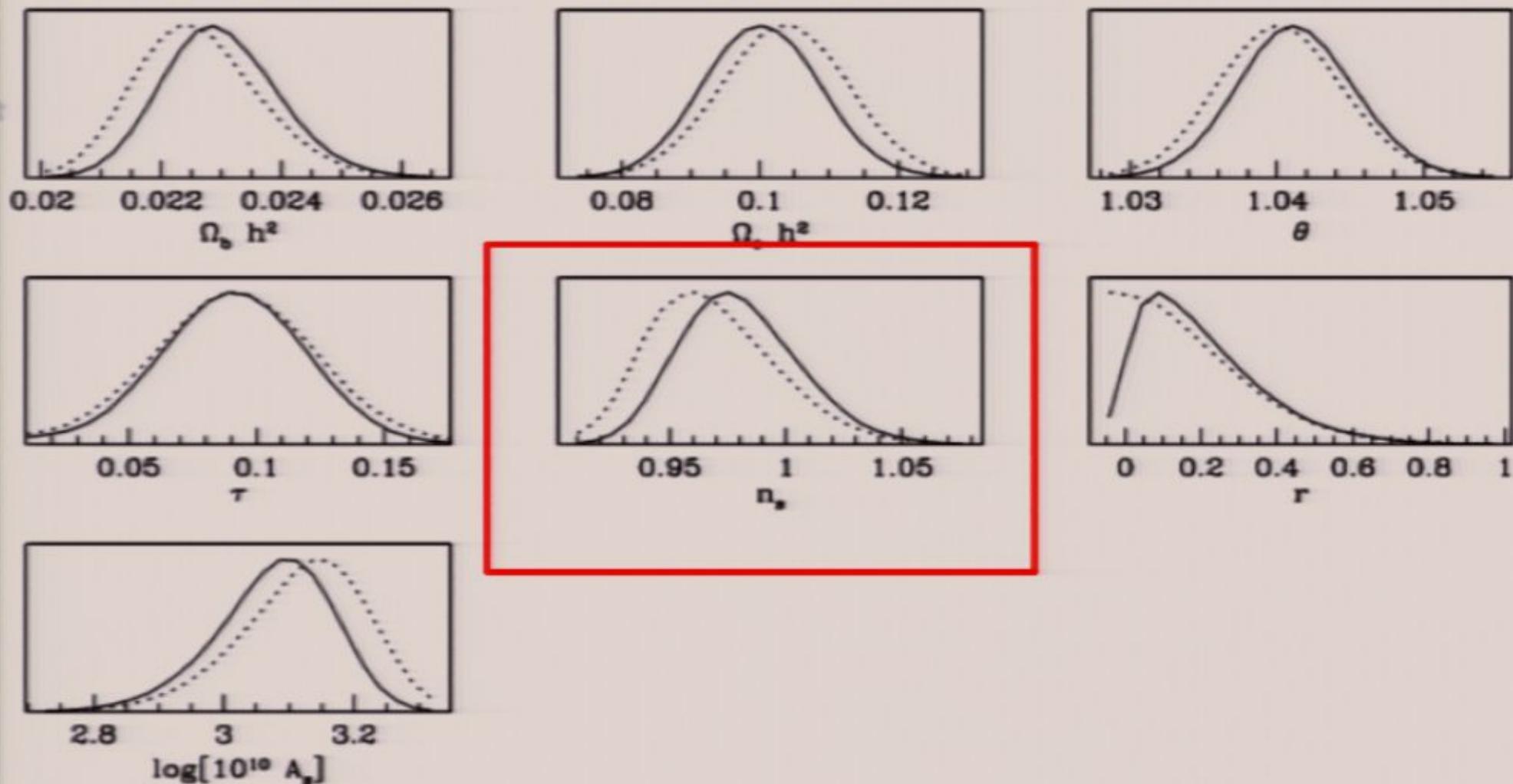
U2: 800-node 2x Intel 3.2 GHz Xeon "Irwindale" cluster

No running: 7 parameter fit



+HST + Age Prior

No running: 7 parameter fit



$$n_s = 0.980 \pm 0.025$$

Spergel, et al. 7 parameter fit

Parameter	Λ CDM + Tensor	Λ CDM + Running + Tensors
$\Omega_b h^2$	$0.02336^{+0.00085}_{-0.00133}$	$0.0220^{+0.0011}_{-0.0016}$
$\Omega_m h^2$	$0.1189^{+0.0084}_{-0.0136}$	$0.1258^{+0.0070}_{-0.0162}$
h	$0.792^{+0.036}_{-0.068}$	$0.744^{+0.050}_{-0.073}$
n_s	$0.987^{+0.019}_{-0.037}$	$1.21^{+0.13}_{-0.16}$
$dn_s/d\ln k$	set to 0	$-0.102^{+0.050}_{-0.043}$
r	0.55 (95% CL)	1.5 (95% CL)
τ	$0.091^{+0.031}_{-0.037}$	$0.111^{+0.029}_{-0.037}$
σ_8	$0.700^{+0.063}_{-0.065}$	$0.716^{+0.065}_{-0.068}$
$\Delta_{\mathcal{R}}^2(k = 0.05/Mpc)$	$(19.9^{+1.3}_{-1.8}) \times 10^{-10}$	$(20.9^{+1.3}_{-1.9}) \times 10^{-10}$

Spergel, et al. 7 parameter fit

Parameter	Λ CDM + Tensor	Λ CDM + Running + Tensors
$\Omega_b h^2$	$0.02336^{+0.00085}_{-0.00133}$	$0.0220^{+0.0011}_{-0.0016}$
$\Omega_m h^2$	$0.1189^{+0.0084}_{-0.0136}$	$0.1258^{+0.0070}_{-0.0162}$
h	$0.792^{+0.036}_{-0.068}$	$0.744^{+0.050}_{-0.073}$
n_s	$0.987^{+0.019}_{-0.037}$	$1.21^{+0.13}_{-0.16}$
$dn_s/d\ln k$	set to 0	$-0.102^{+0.050}_{-0.043}$
r	0.55 (95% CL)	1.5 (95% CL)
τ	$0.091^{+0.031}_{-0.037}$	$0.111^{+0.029}_{-0.037}$
σ_8	$0.700^{+0.063}_{-0.065}$	$0.716^{+0.065}_{-0.068}$
$\Delta_{\mathcal{R}}^2(k = 0.05/Mpc)$	$(19.9^{+1.3}_{-1.8}) \times 10^{-10}$	$(20.9^{+1.3}_{-1.9}) \times 10^{-10}$

Reanalysis (KKMR): $n_s = 0.986 \pm 0.03$

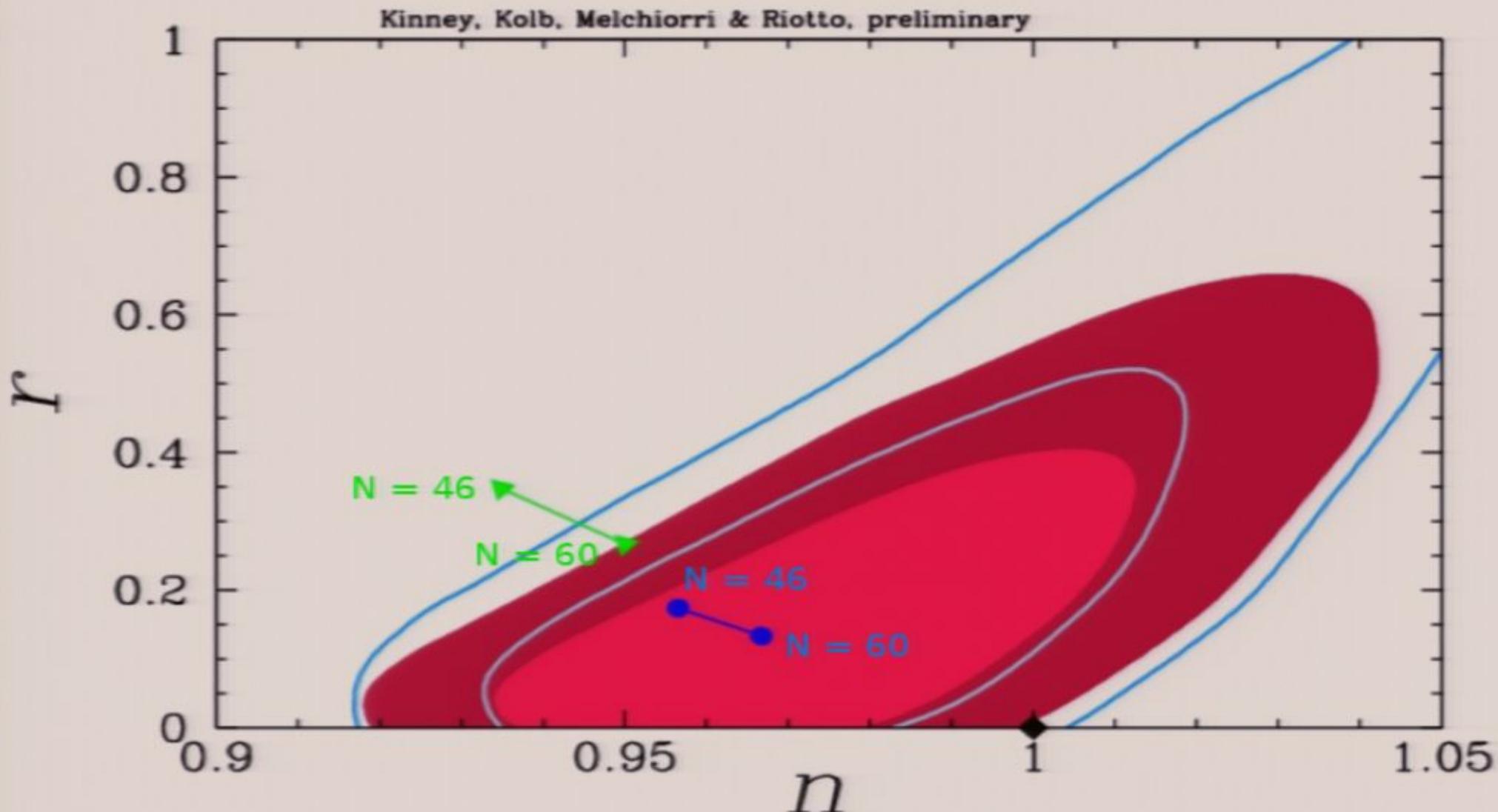
Spergel, et al. 7 parameter fit

Parameter	Λ CDM + Tensor	Λ CDM + Running + Tensors
$\Omega_b h^2$	$0.02336^{+0.00085}_{-0.00133}$	$0.0220^{+0.0011}_{-0.0016}$
$\Omega_m h^2$	$0.1189^{+0.0084}_{-0.0136}$	$0.1258^{+0.0070}_{-0.0162}$
h	$0.792^{+0.036}_{-0.068}$	$0.744^{+0.050}_{-0.073}$
n_s	$0.987^{+0.019}_{-0.037}$	$1.21^{+0.13}_{-0.16}$
$dn_s/d\ln k$	set to 0	$-0.102^{+0.050}_{-0.043}$
r	0.55 (95% CL)	1.5 (95% CL)
τ	$0.091^{+0.031}_{-0.037}$	$0.111^{+0.029}_{-0.037}$
σ_8	$0.700^{+0.063}_{-0.065}$	$0.716^{+0.065}_{-0.068}$
$\Delta_{\mathcal{R}}^2(k = 0.05/Mpc)$	$(19.9^{+1.3}_{-1.8}) \times 10^{-10}$	$(20.9^{+1.3}_{-1.9}) \times 10^{-10}$

Reanalysis (KKMR): $n_s = 0.986 \pm 0.03$

Spergel et al. 6-parameter fit: $n_s = 0.951 \pm 0.02$

Spergel et al. chains + KKMR chains



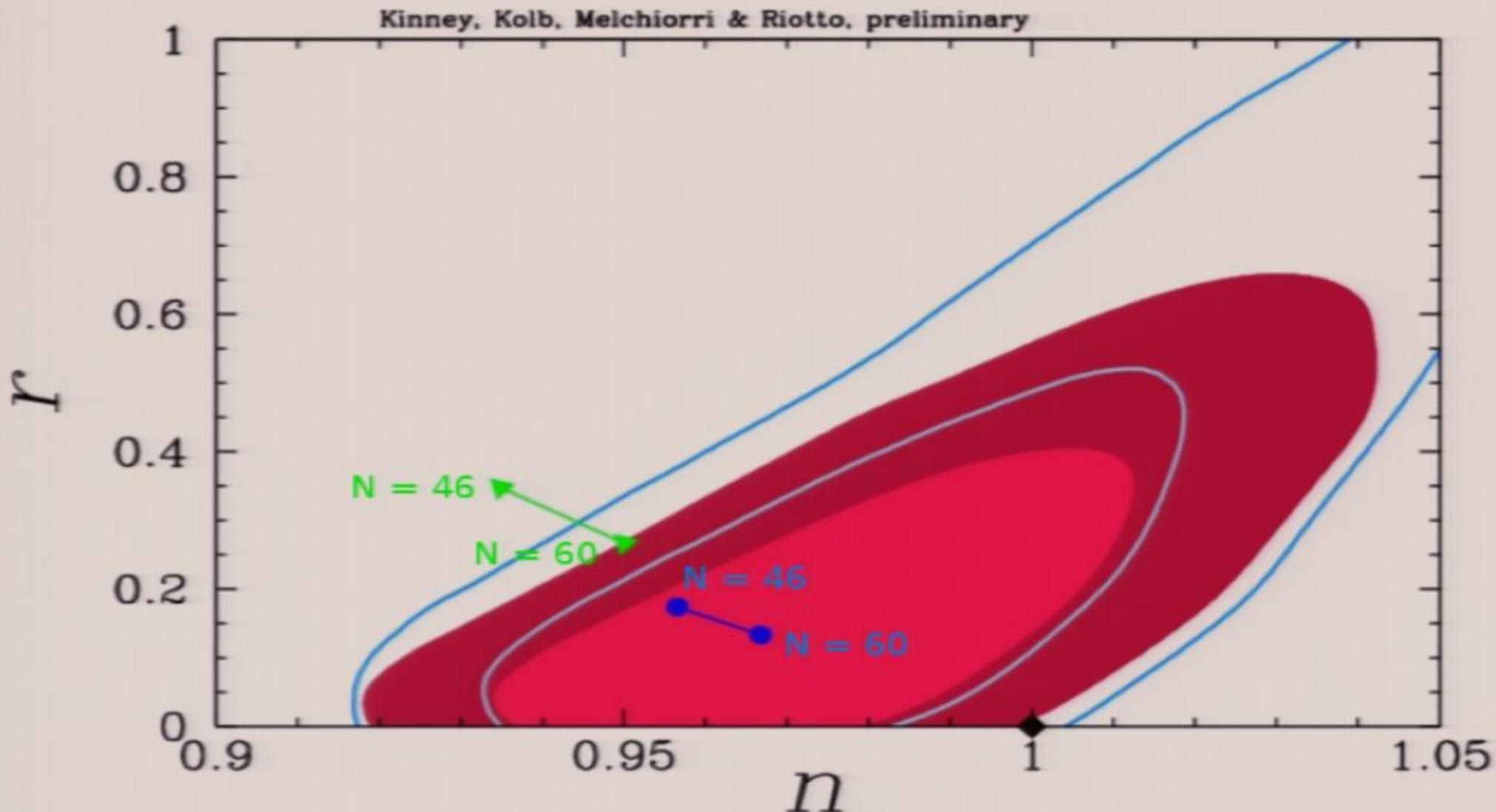
Spergel, et al. 7 parameter fit

Parameter	Λ CDM + Tensor	Λ CDM + Running + Tensors
$\Omega_b h^2$	$0.02336^{+0.00085}_{-0.00133}$	$0.0220^{+0.0011}_{-0.0016}$
$\Omega_m h^2$	$0.1189^{+0.0084}_{-0.0136}$	$0.1258^{+0.0070}_{-0.0162}$
h	$0.792^{+0.036}_{-0.068}$	$0.744^{+0.050}_{-0.073}$
n_s	$0.987^{+0.019}_{-0.037}$	$1.21^{+0.13}_{-0.16}$
$dn_s/d\ln k$	set to 0	$-0.102^{+0.050}_{-0.043}$
r	0.55 (95% CL)	1.5 (95% CL)
τ	$0.091^{+0.031}_{-0.037}$	$0.111^{+0.029}_{-0.037}$
σ_8	$0.700^{+0.063}_{-0.065}$	$0.716^{+0.065}_{-0.068}$
$\Delta_{\mathcal{R}}^2(k = 0.05/Mpc)$	$(19.9^{+1.3}_{-1.8}) \times 10^{-10}$	$(20.9^{+1.3}_{-1.9}) \times 10^{-10}$

Reanalysis (KKMR): $n_s = 0.986 \pm 0.03$

Spergel et al. 6-parameter fit: $n_s = 0.951 \pm 0.02$

Spergel et al. chains + KKMR chains



Small-field models

Effective Potential: $V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$

$p=2$

$$n - 1 = -\frac{1}{4\pi} \left(\frac{m_{\text{Pl}}}{\mu} \right)^2 \quad n > 0.9 \Rightarrow \mu/m_{\text{Pl}} > 0.9$$

$$r = 8(1 - n) \exp [-1 - N(1 - n)]$$

Small-field models

Effective Potential: $V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$

$p=2$

$$n - 1 = -\frac{1}{4\pi} \left(\frac{m_{\text{Pl}}}{\mu} \right)^2 \quad n > 0.9 \Rightarrow \mu/m_{\text{Pl}} > 0.9$$

$$r = 8(1 - n) \exp [-1 - N(1 - n)]$$

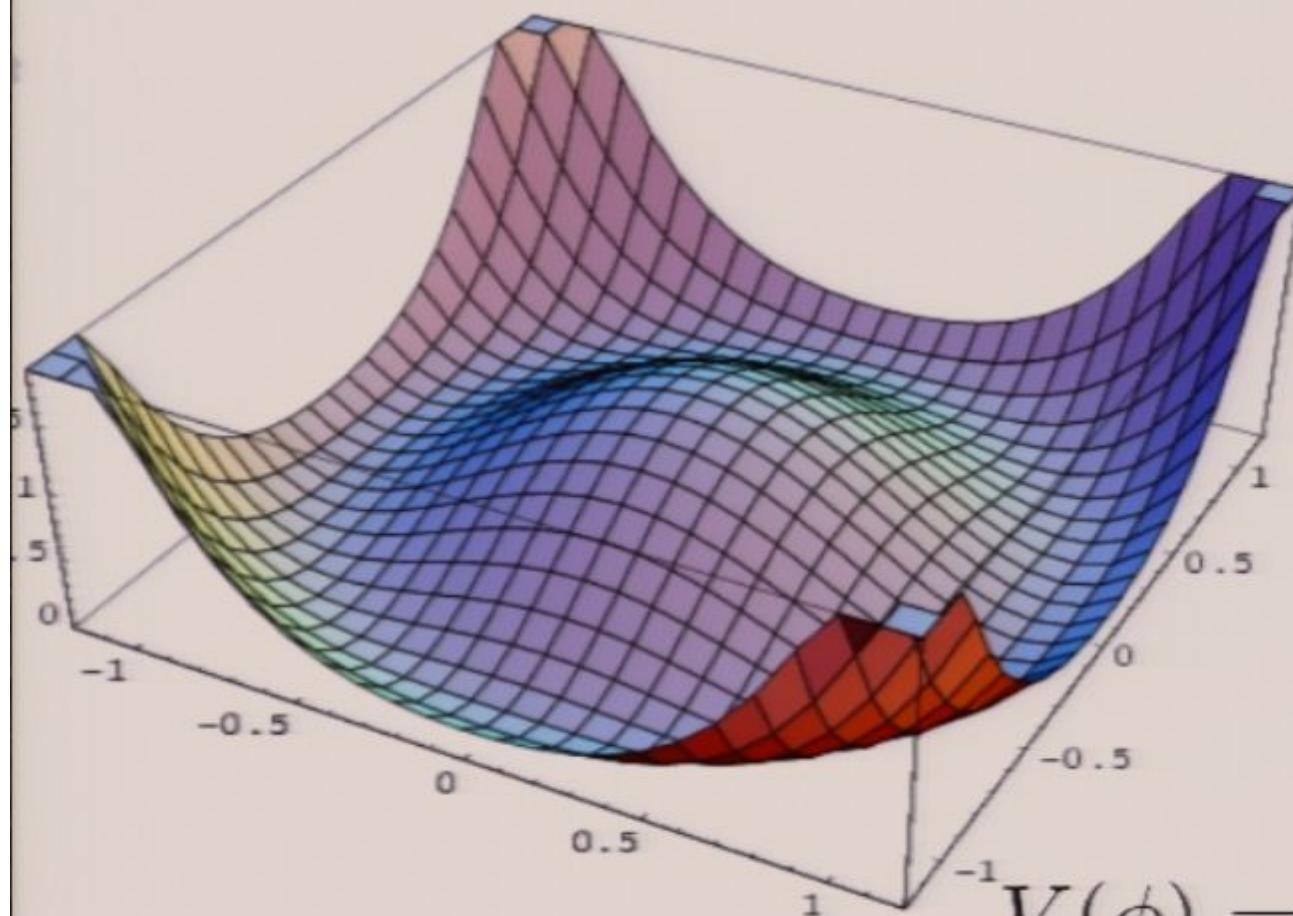
$p=4$

$$\delta \propto \left(\frac{\Lambda}{\mu} \right)^2 \xleftarrow{\text{No Planck scale!}}$$

$$n - 1 = -\frac{3}{N} = 0.93 - 0.95$$

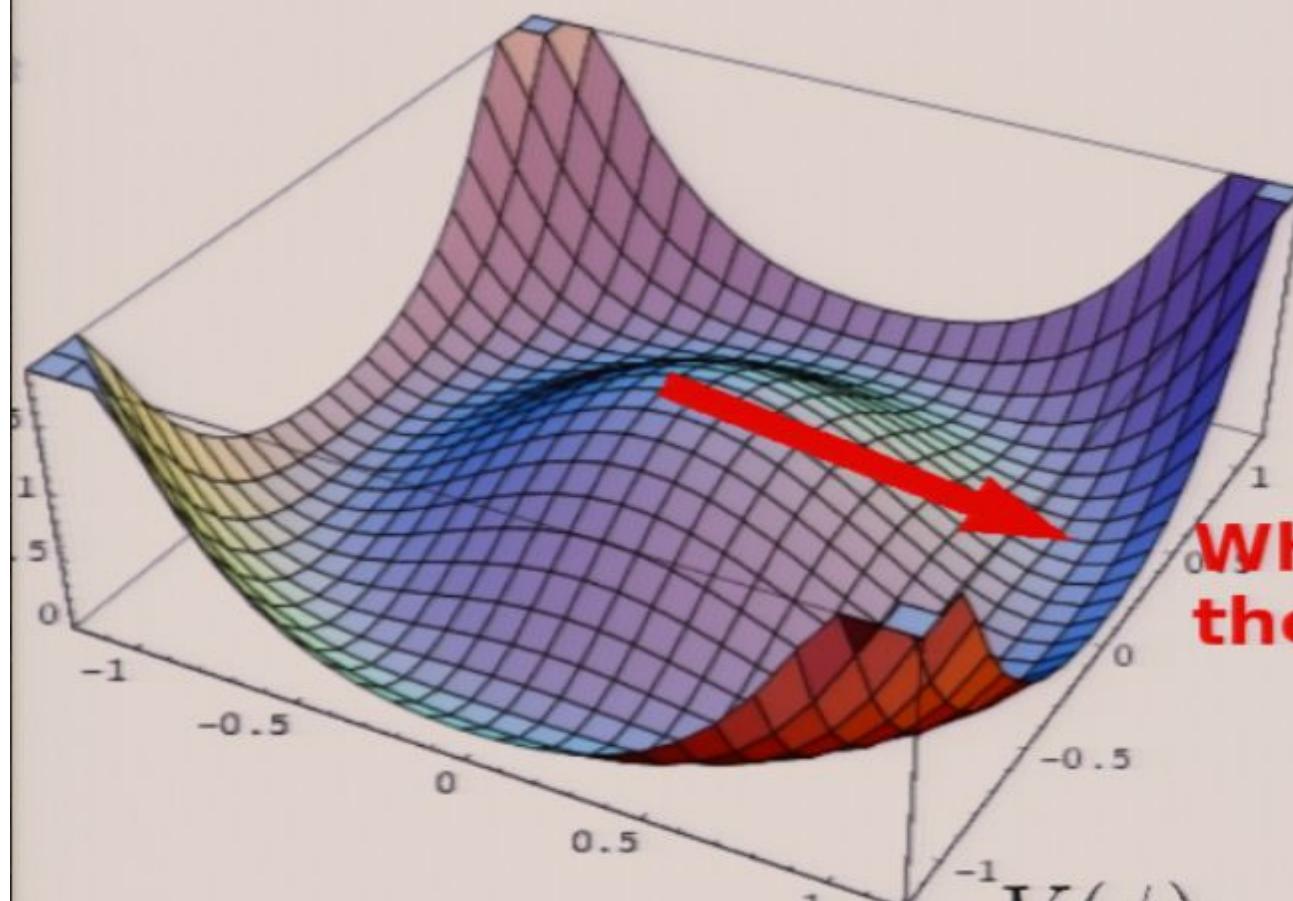
$$r \propto \left(\frac{\mu}{m_{\text{Pl}}} \right)^4 \ll 1$$

natural Inflation: pseudo-Nambu-Goldstone bosons



$$V(\phi) = \Lambda^4 \left[1 + \cos \left(\frac{\phi}{f} \right) \right]$$

natural Inflation: pseudo-Nambu-Goldstone bosons

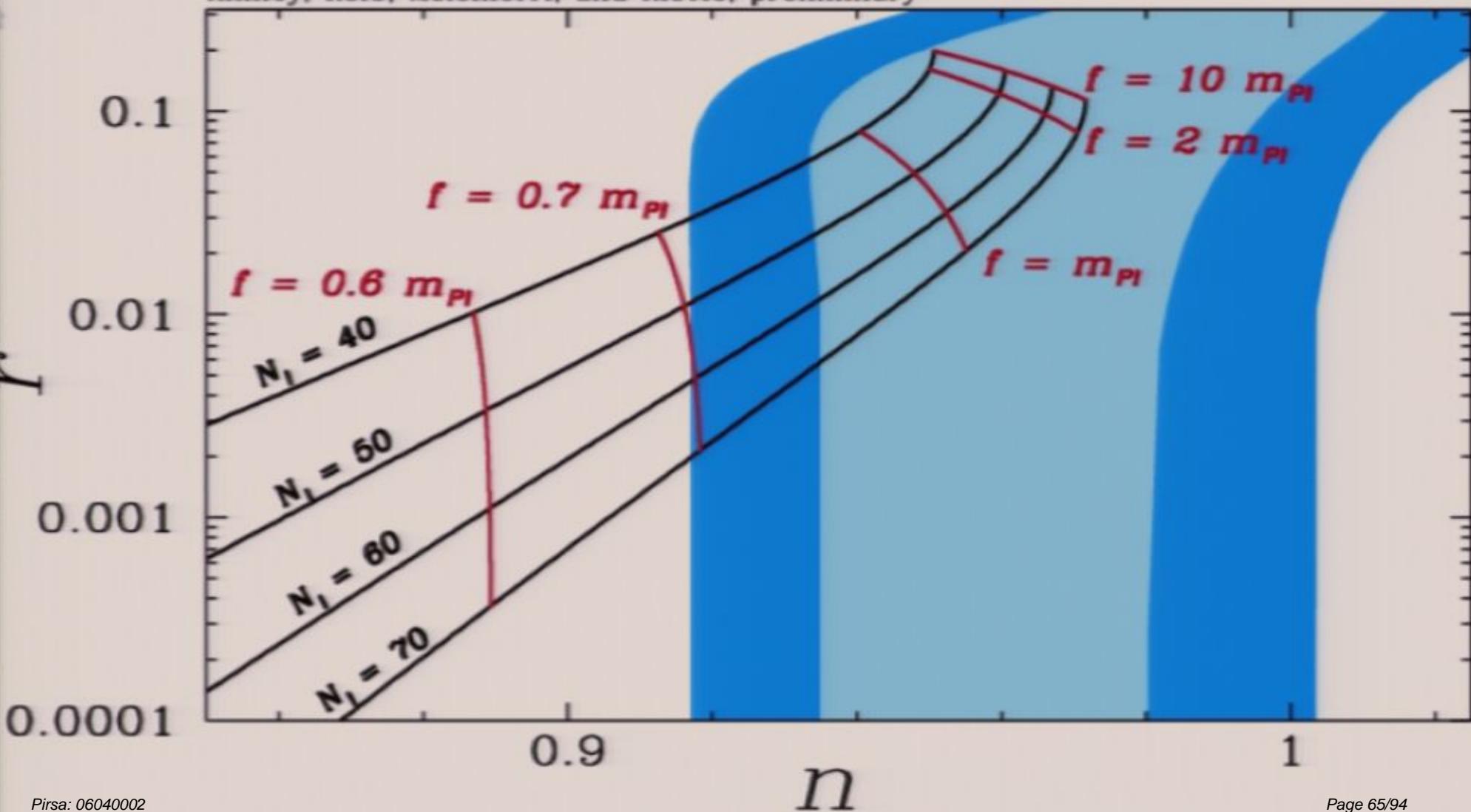


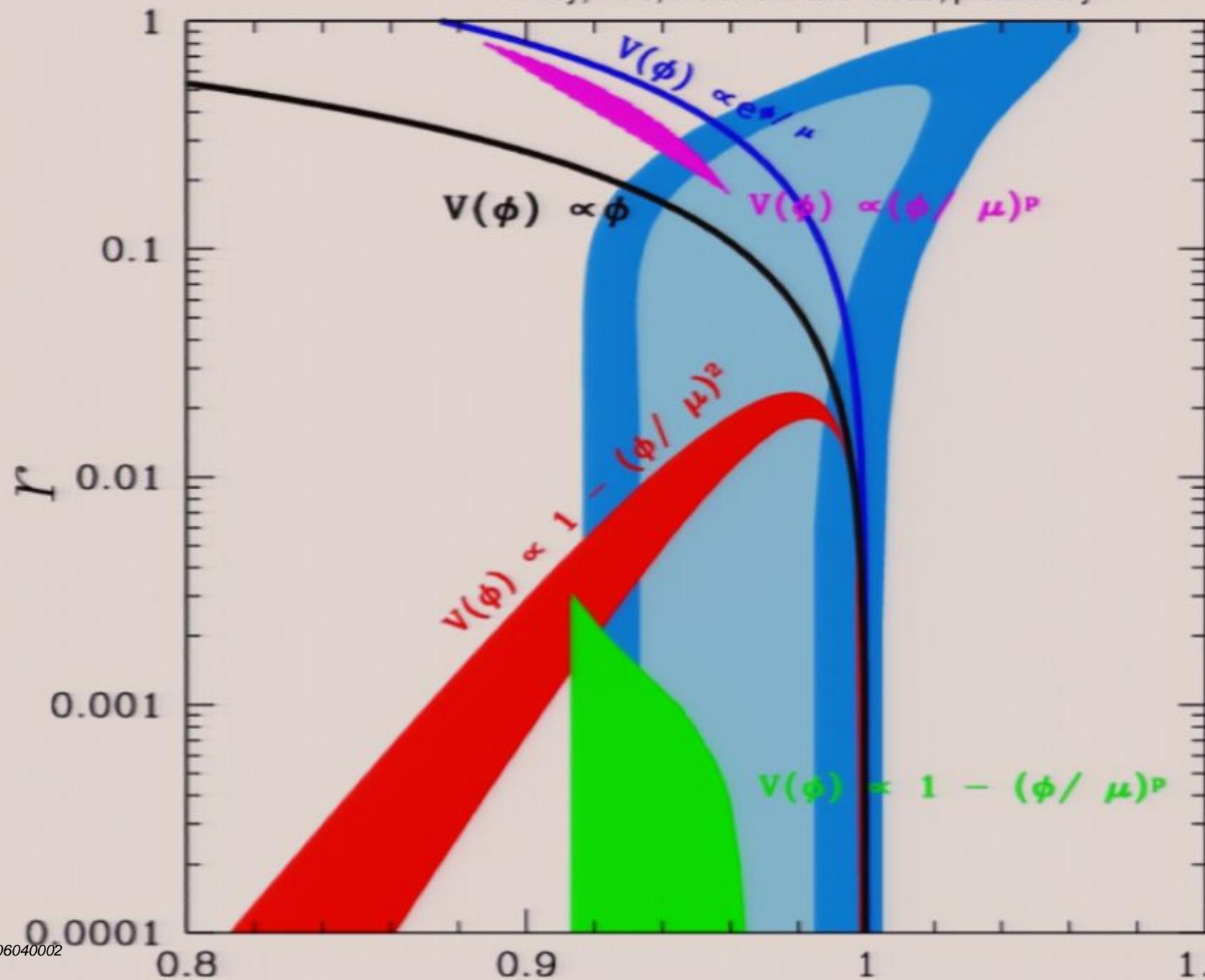
What is the width of the potential?

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right) \right]$$

Natural Inflation: WMAP3 limits

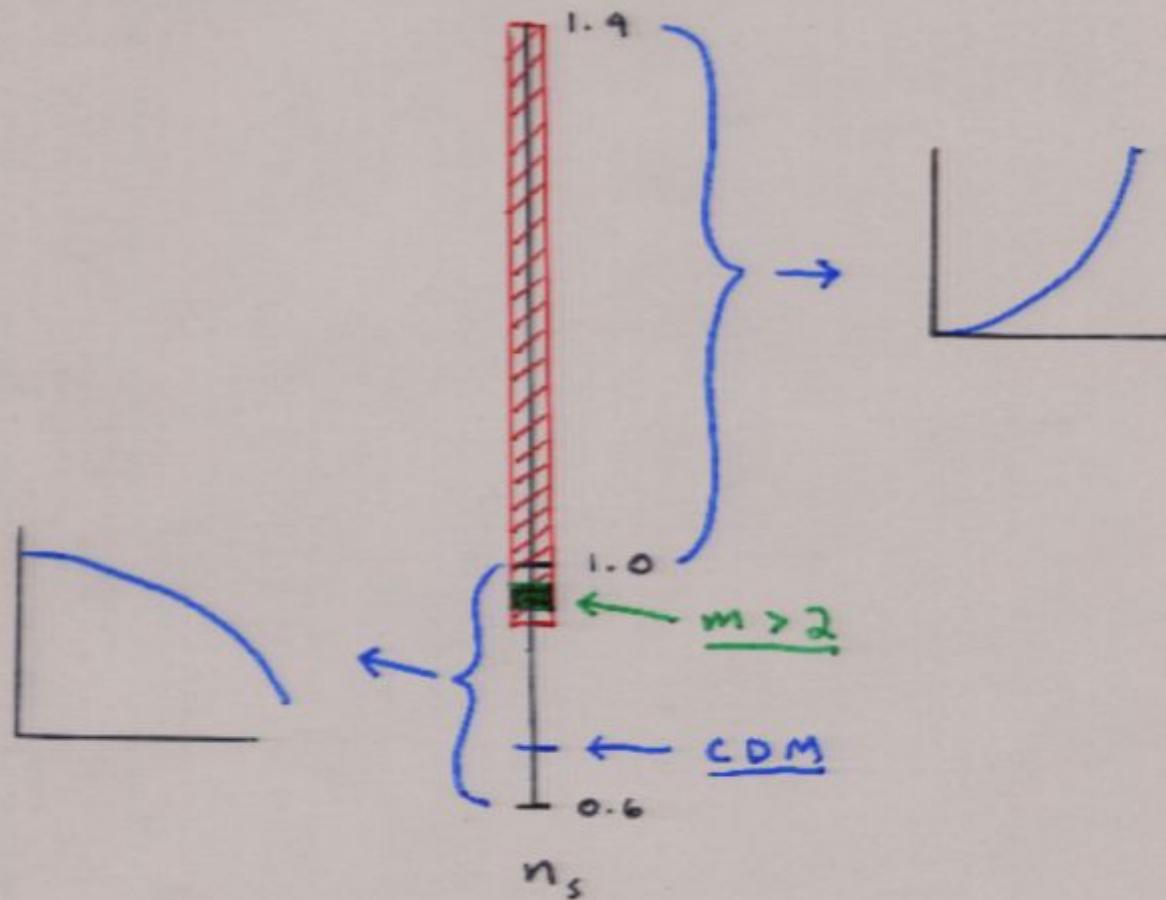
Kinney, Kolb, Melchiorri, and Riotto, preliminary



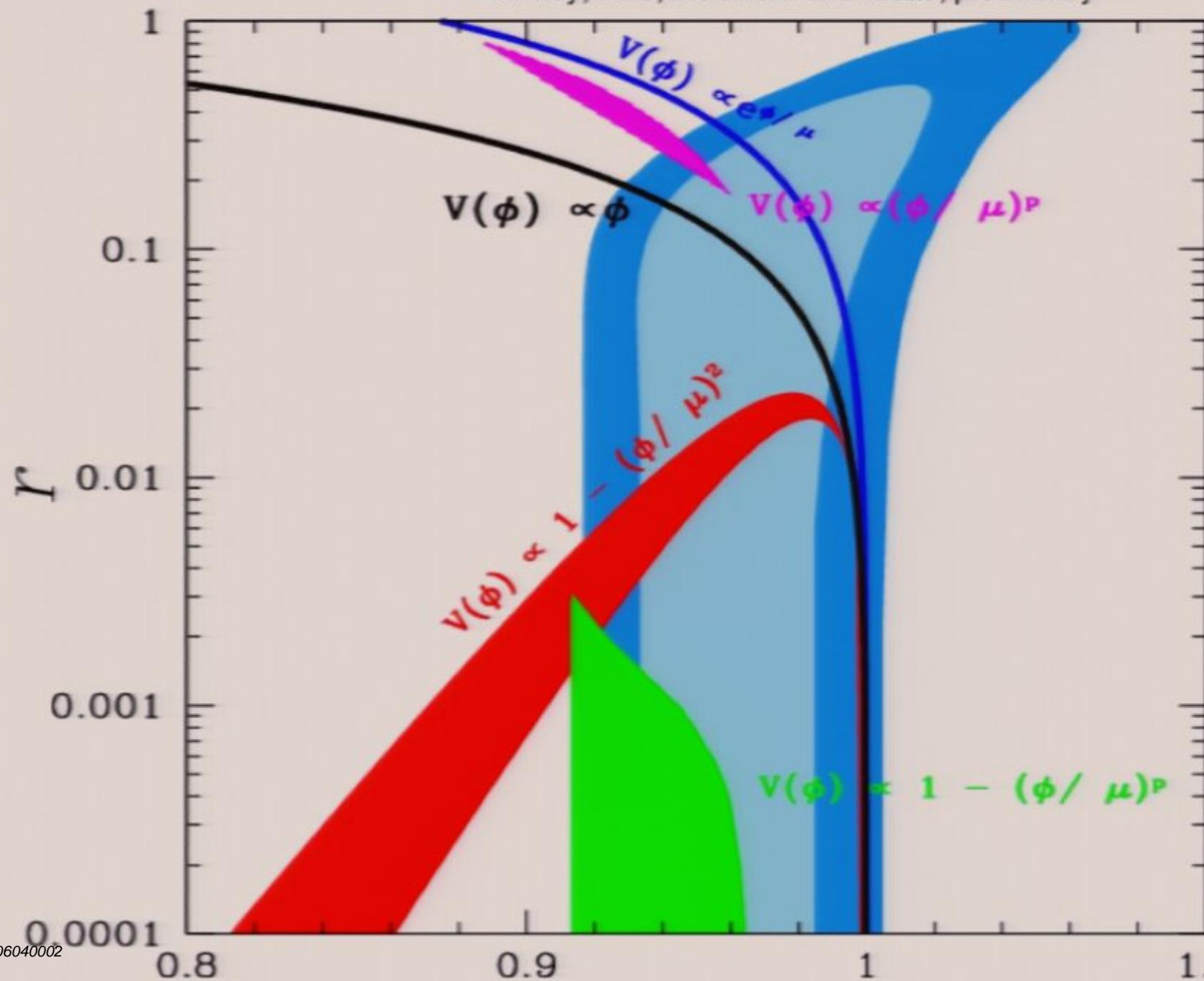


WHAT n_s TELLS YOU

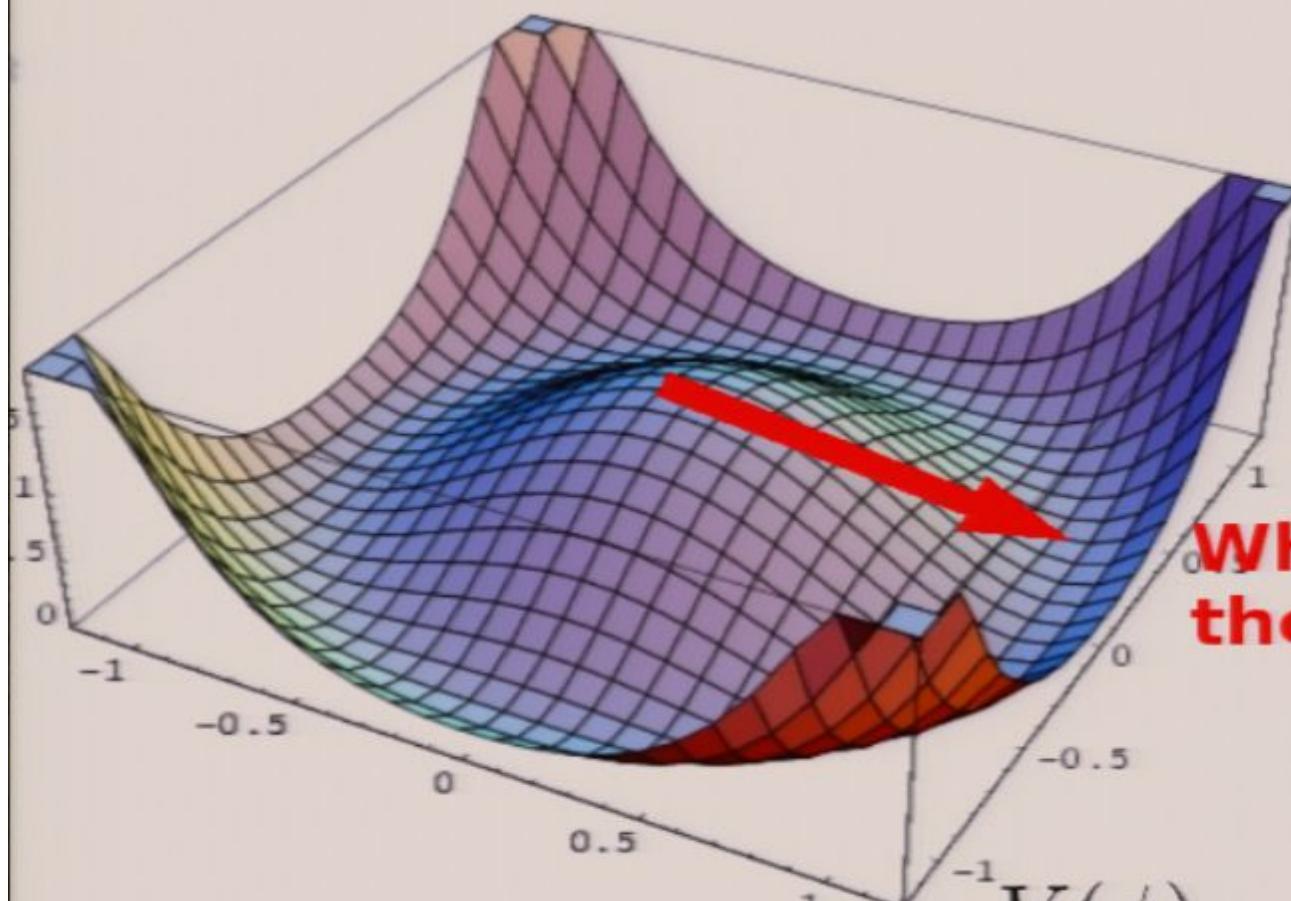
COBE 2-YEAR: $n_s = 1.4 \pm 0.5 =$ 



- Exotic models (e.g. multi-field) can do weird things.

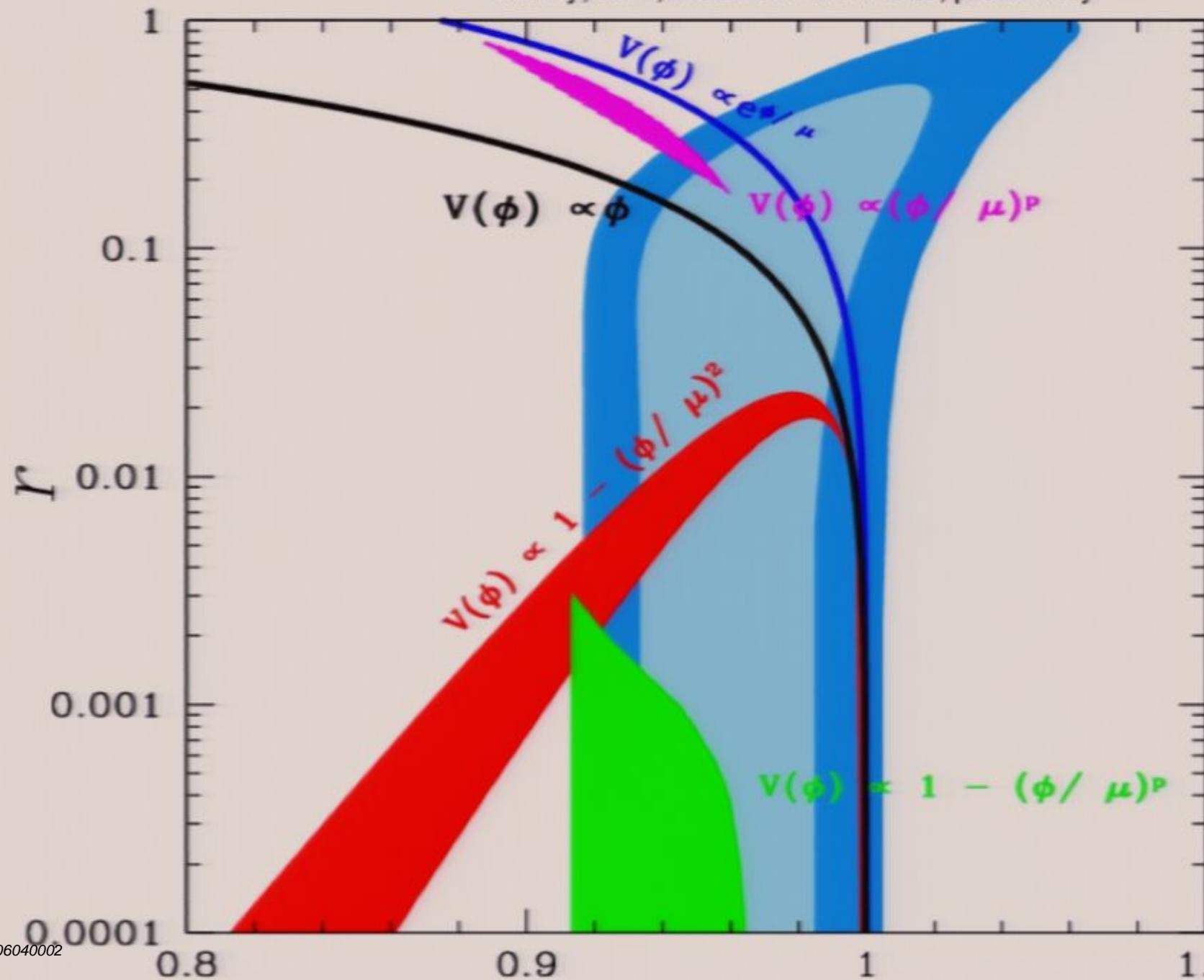


natural Inflation: pseudo-Nambu-Goldstone bosons

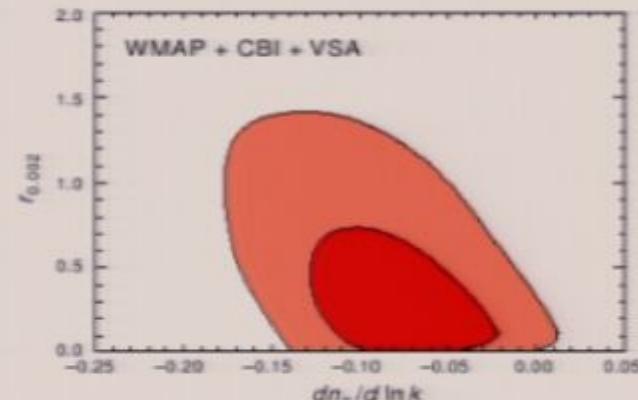
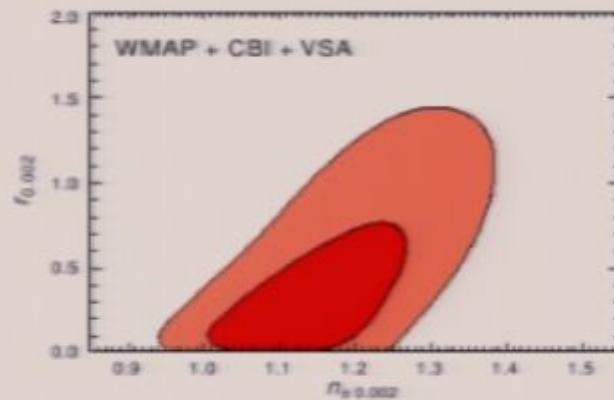
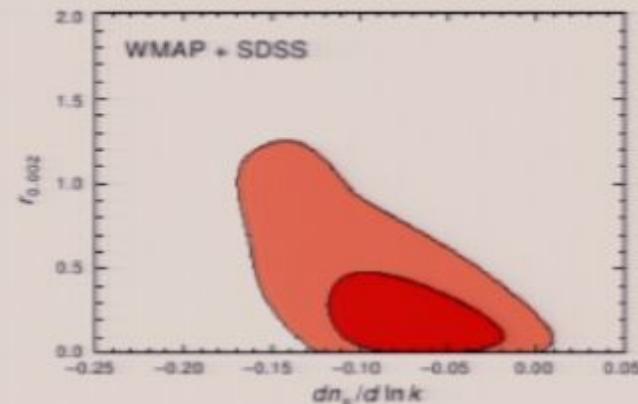
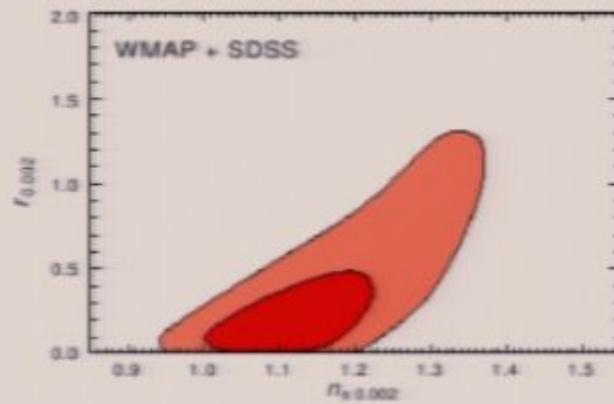
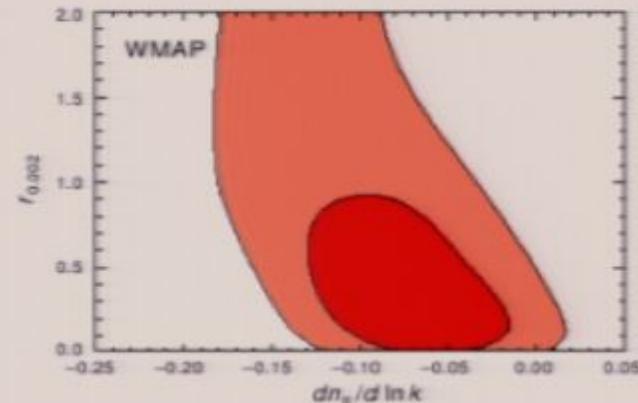
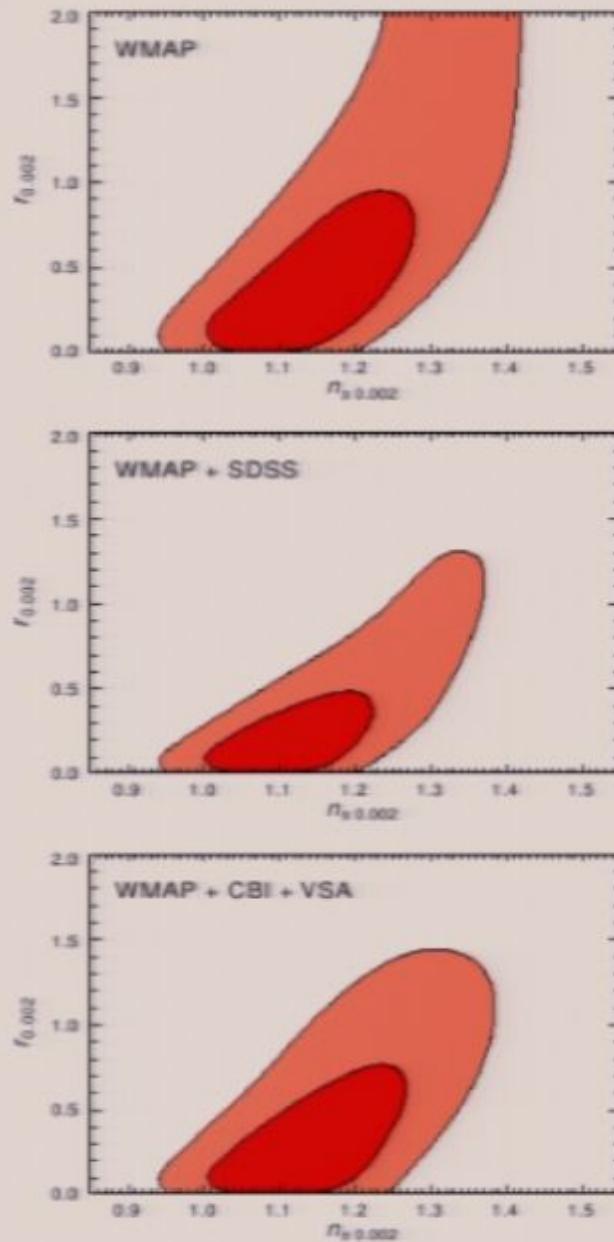


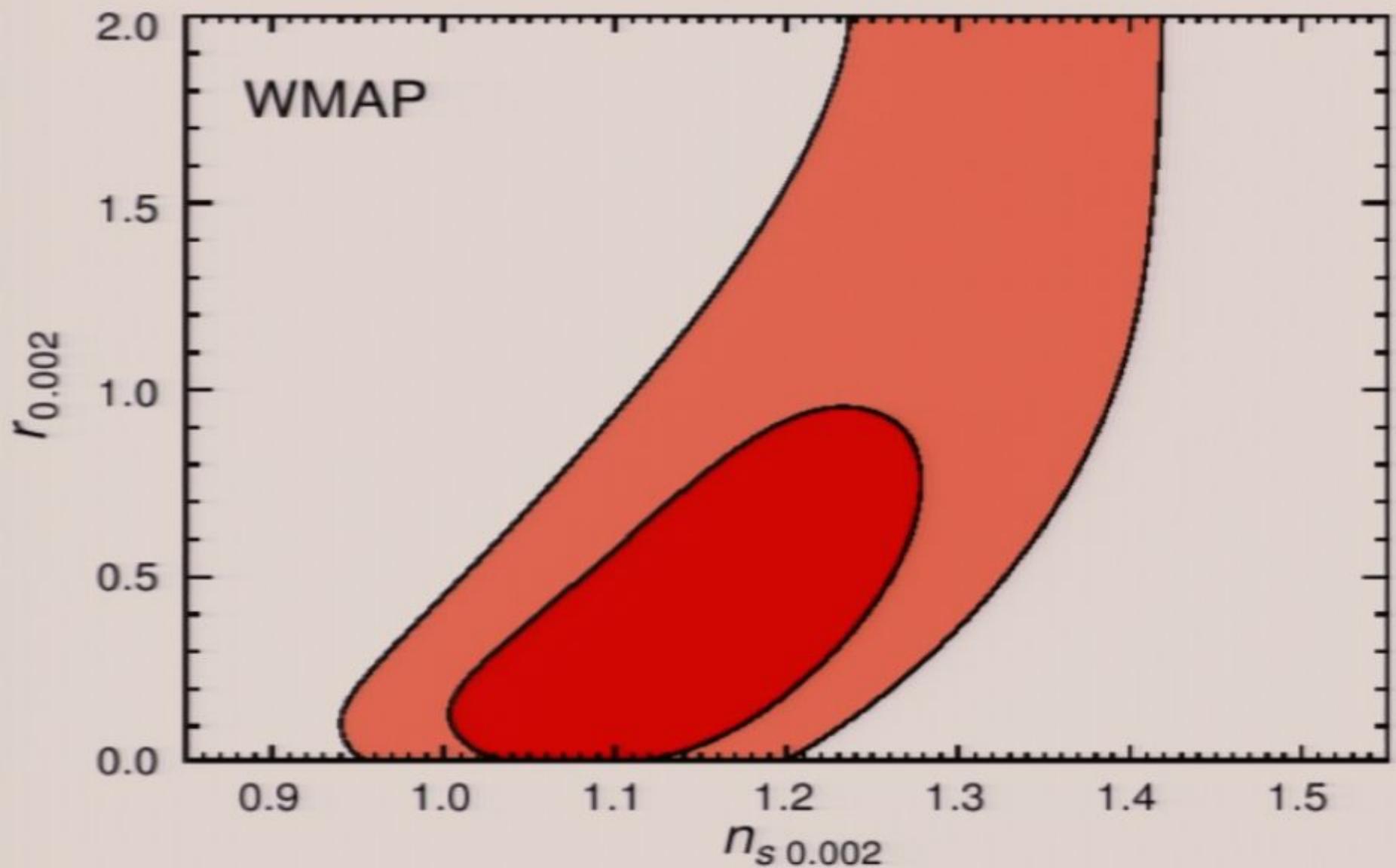
What is the width of the potential?

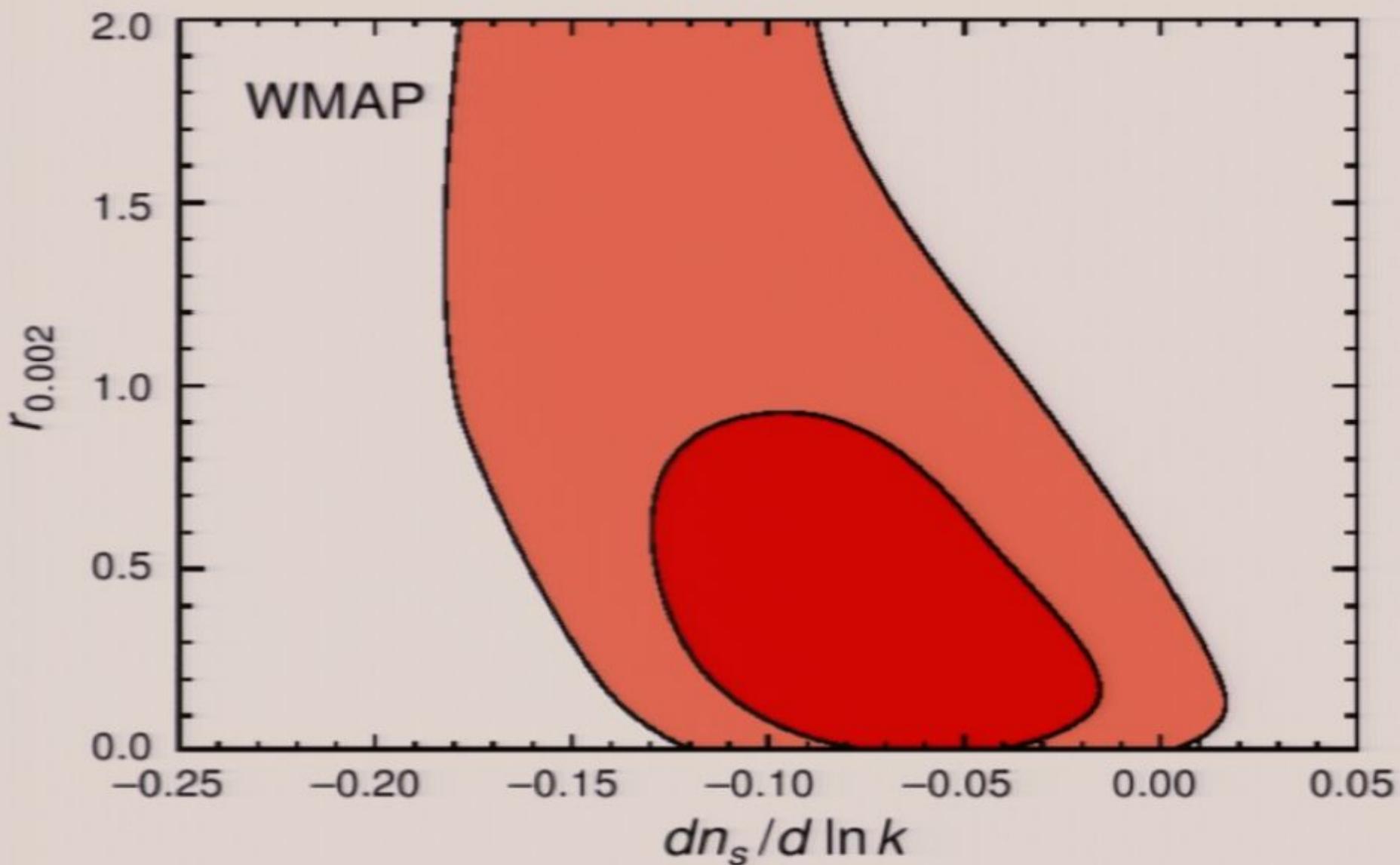
$$V(\phi) = \Lambda^4 \left[1 + \cos \left(\frac{\phi}{f} \right) \right]$$



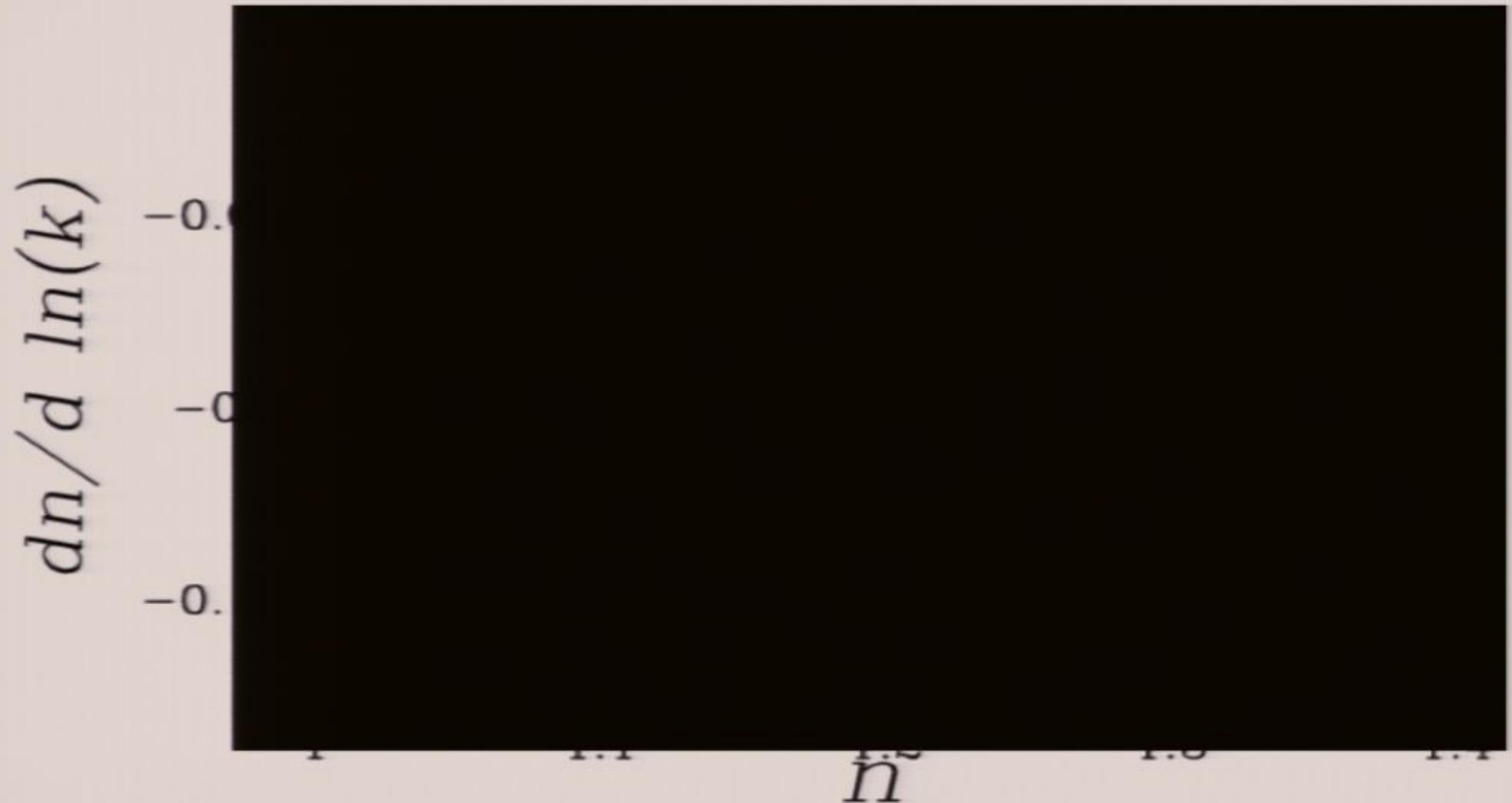
Running Spectral Index

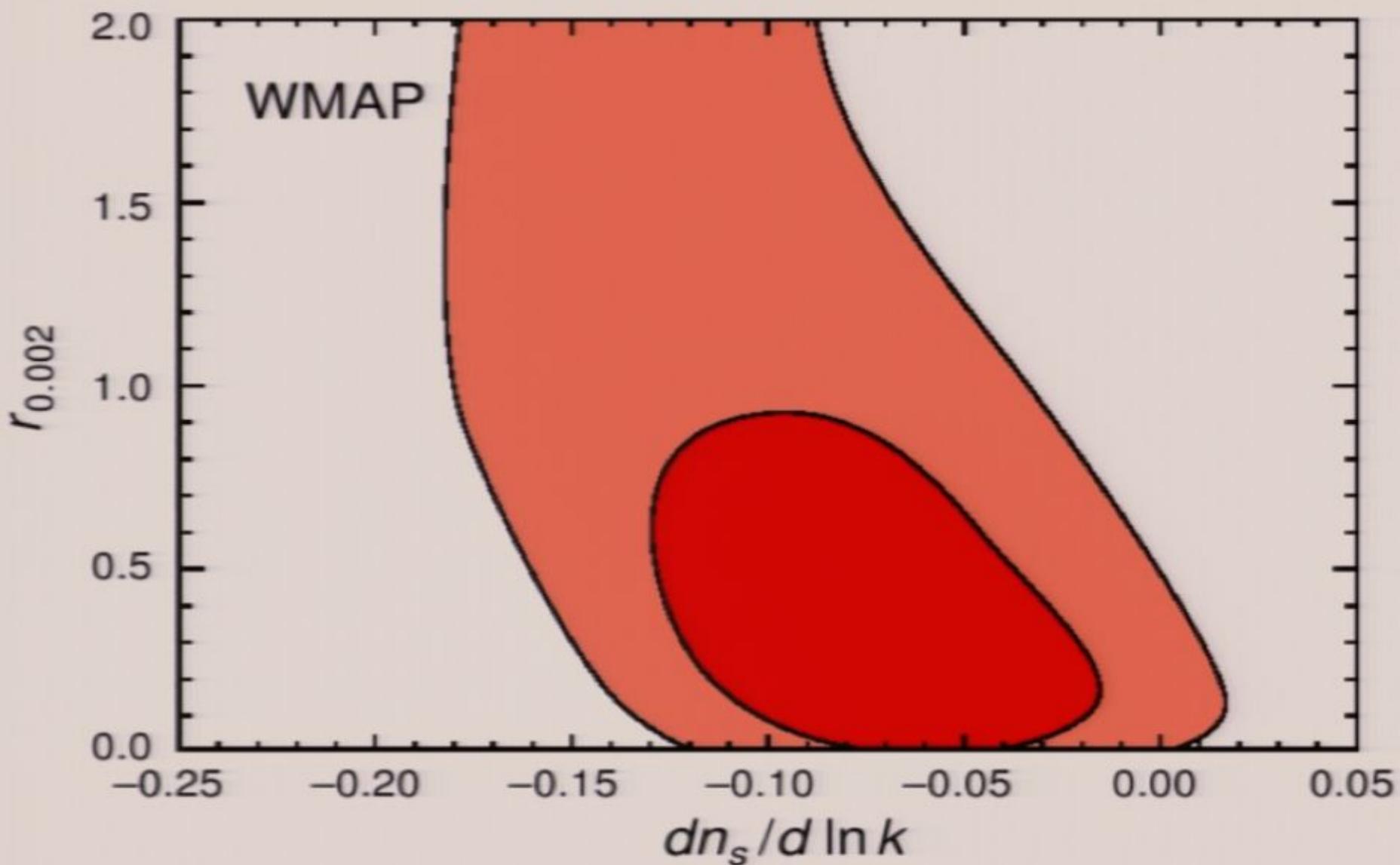




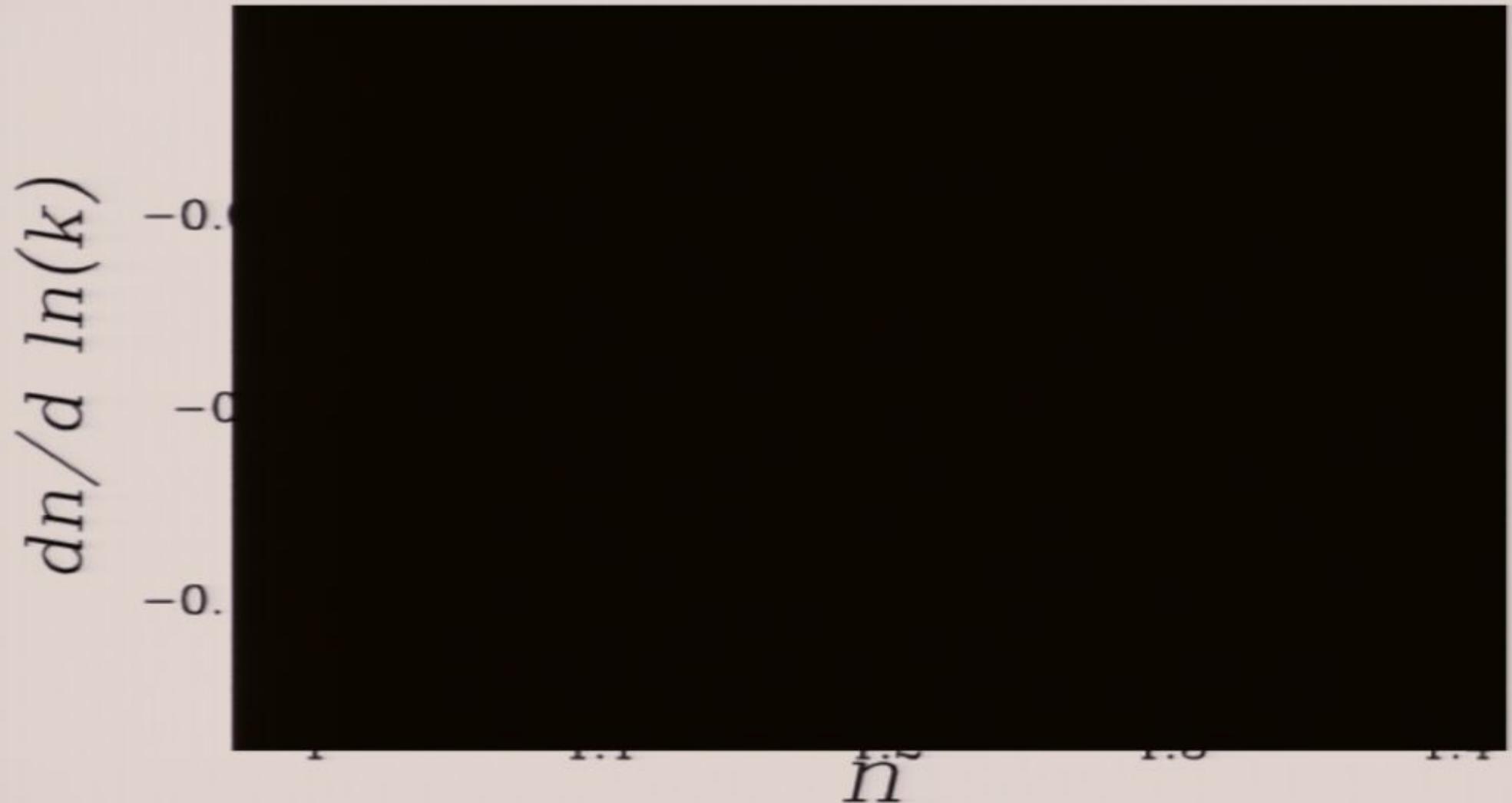


Working on it...





Working on it...



How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_{\mathcal{R}}^2(k)$	-22	20

How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_R^2(k)$	-22	20

How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_{\mathcal{R}}^2(k)$	-22	20

Summary: WMAP3 Is...

How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_R^2(k)$	-22	20

Summary: WMAP3 Is...

How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_R^2(k)$	-22	20

Summary: WMAP3 Is...

How many parameters do you need?

	Model	$-\Delta(2 \ln \mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d \ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta_R^2(k)$	-22	20

Summary: WMAP3 Is...

- Confusing

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.
- Unless it's **blue**.

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.
- Unless it's **blue**.
- Or **both**.

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.
- Unless it's **blue**.
- Or **both**.

- Exciting

- Evidence for running *stronger* than WMAP1

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.
- Unless it's **blue**.
- Or **both**.

- Exciting

- Evidence for running *stronger* than WMAP1
- Axis of Evil?

Summary: WMAP3 Is...

- Confusing

As far as I can tell:

- Harrison-Zeldovich is *not* ruled out
- $\lambda\phi^4$ is *not* ruled out
- The best-fit spectrum is **red**.
- Unless it's **blue**.
- Or **both**.

- Exciting

- Evidence for running *stronger* than WMAP1
- Axis of Evil?
- Simple hybrid models pretty much dead

Kinney, Kolb, Melchiorri and Riotto, preliminary

