Title: What do we know about inflation?

Date: Sep 10, 2007 12:00 PM

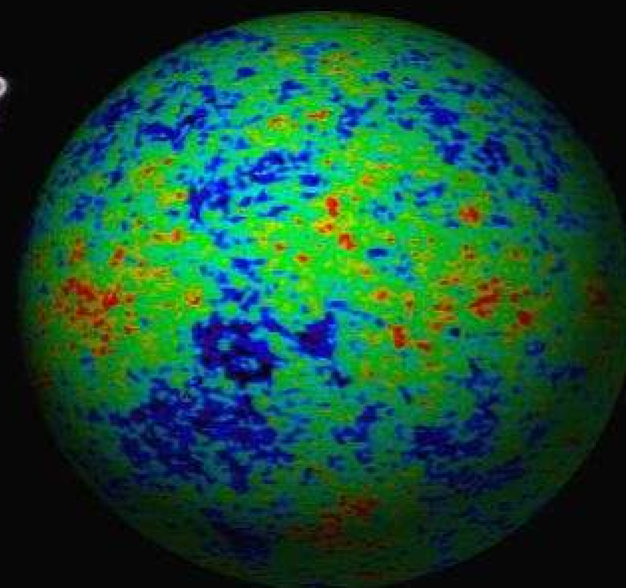
URL: http://pirsa.org/07090023

Abstract:

/hat do we know about inflation?

/ill Kinney

University at Buffalo *The State University of New York*



rontiers of Modern Cosmology

'erimeter Institute

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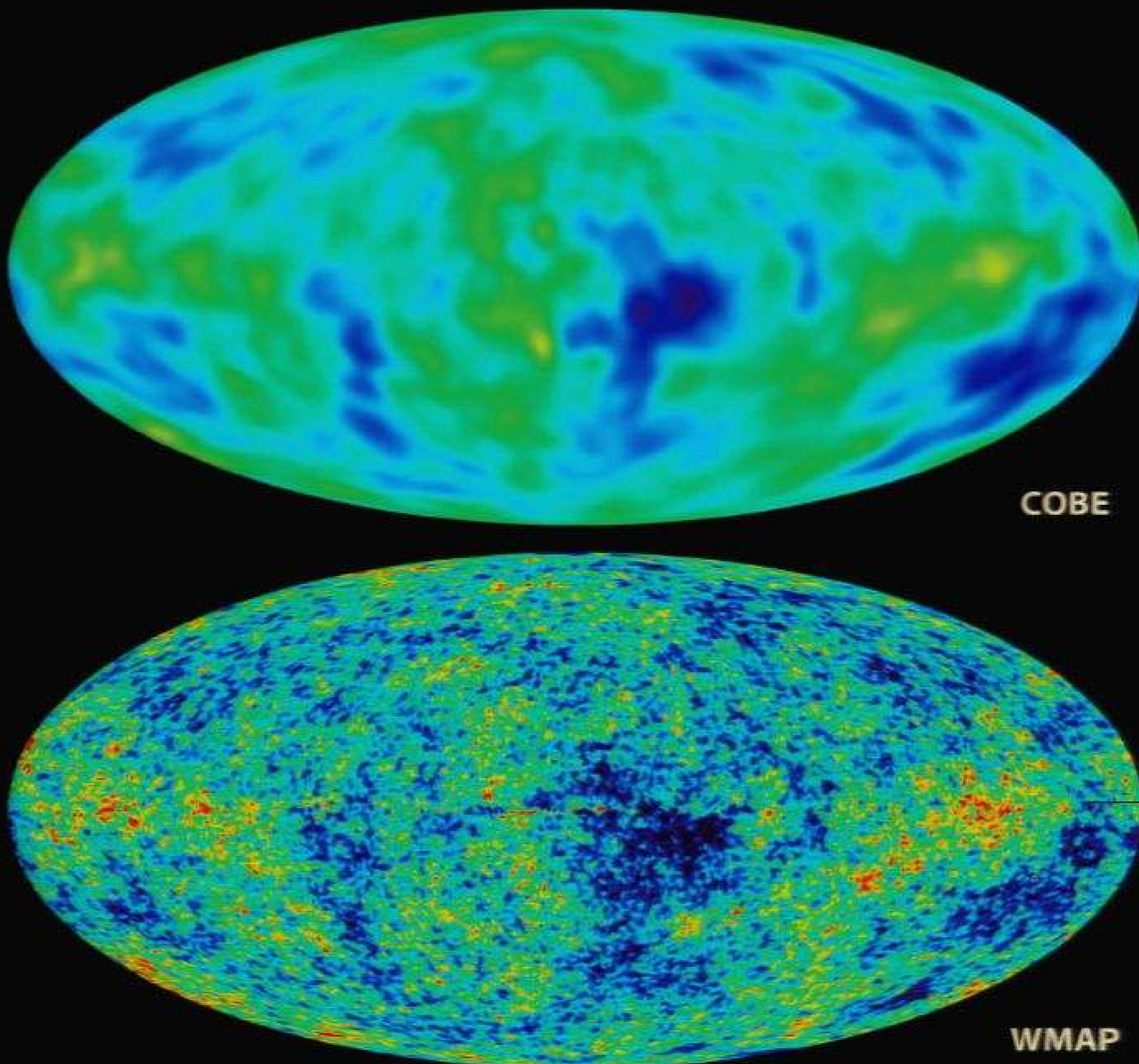
Primordial Perturbations

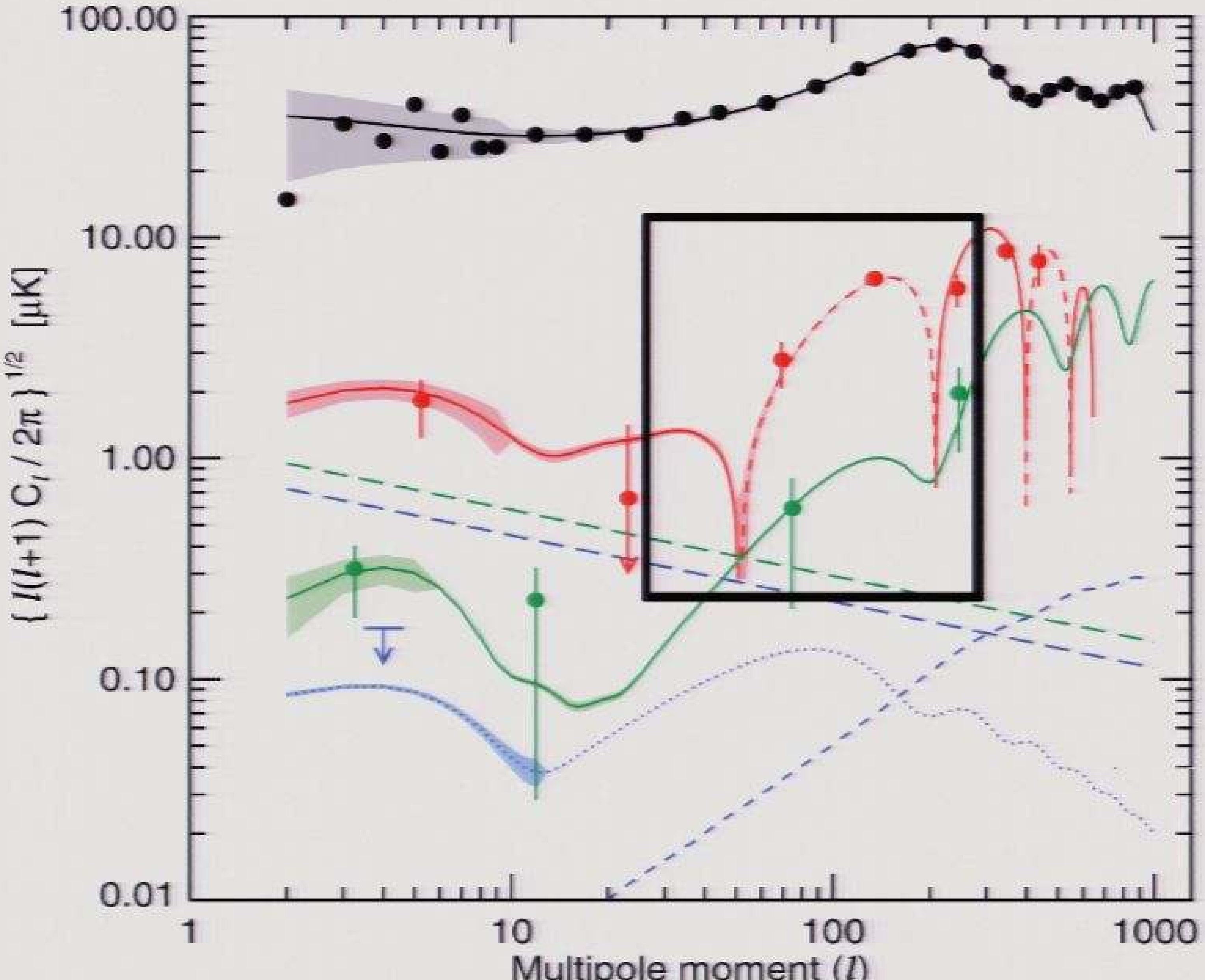


(Figure courtesy of the NASA/WMAP science team)

Things we know

- There are superhorizon correlations in the CMB

The WMAP3 data set



(Figure: NASA/WMAP science team)

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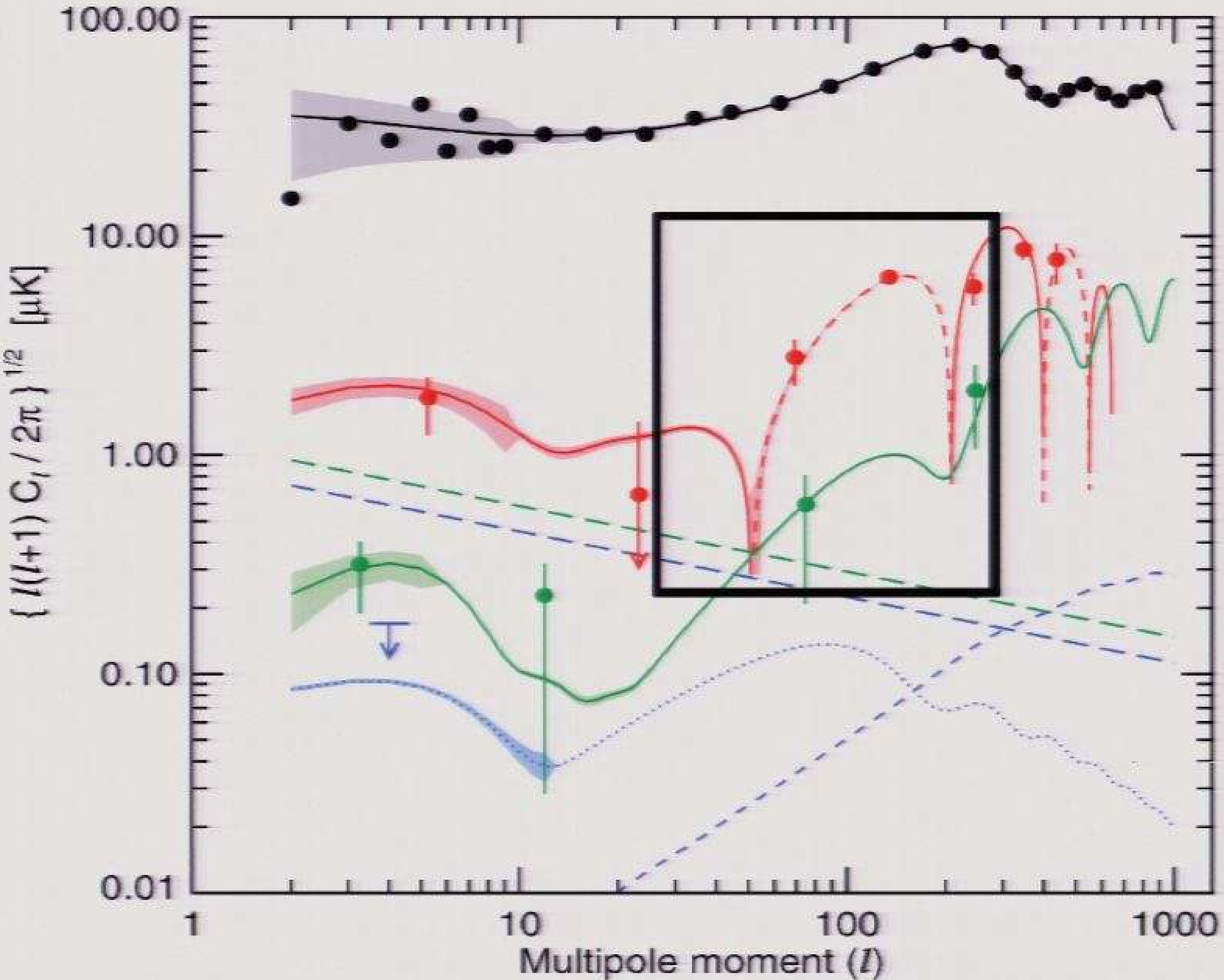

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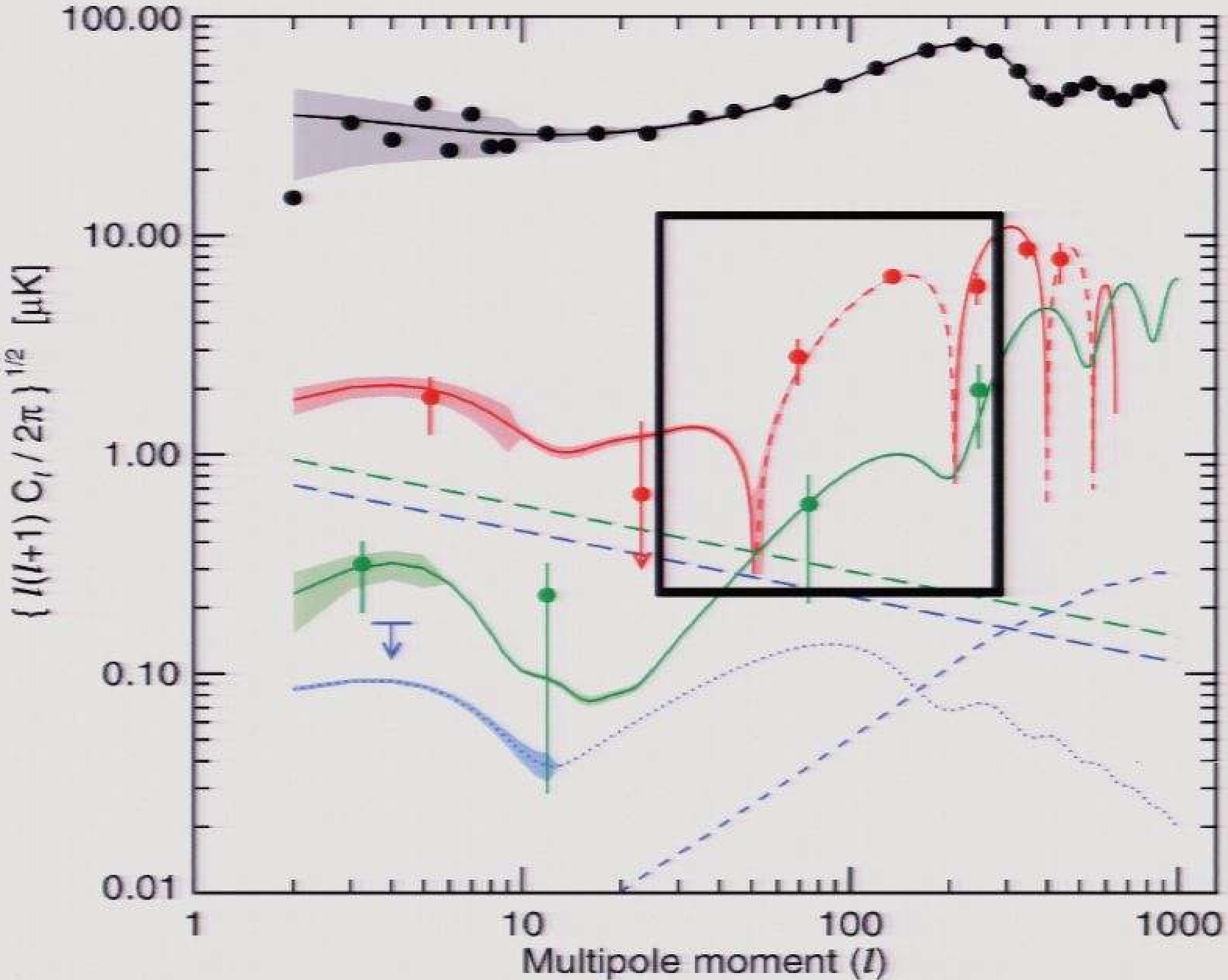


(Figure: NASA/WMAP science team)

Things we know

- There are superhorizon correlations in the CMB

Either:

(1) Inflation happened

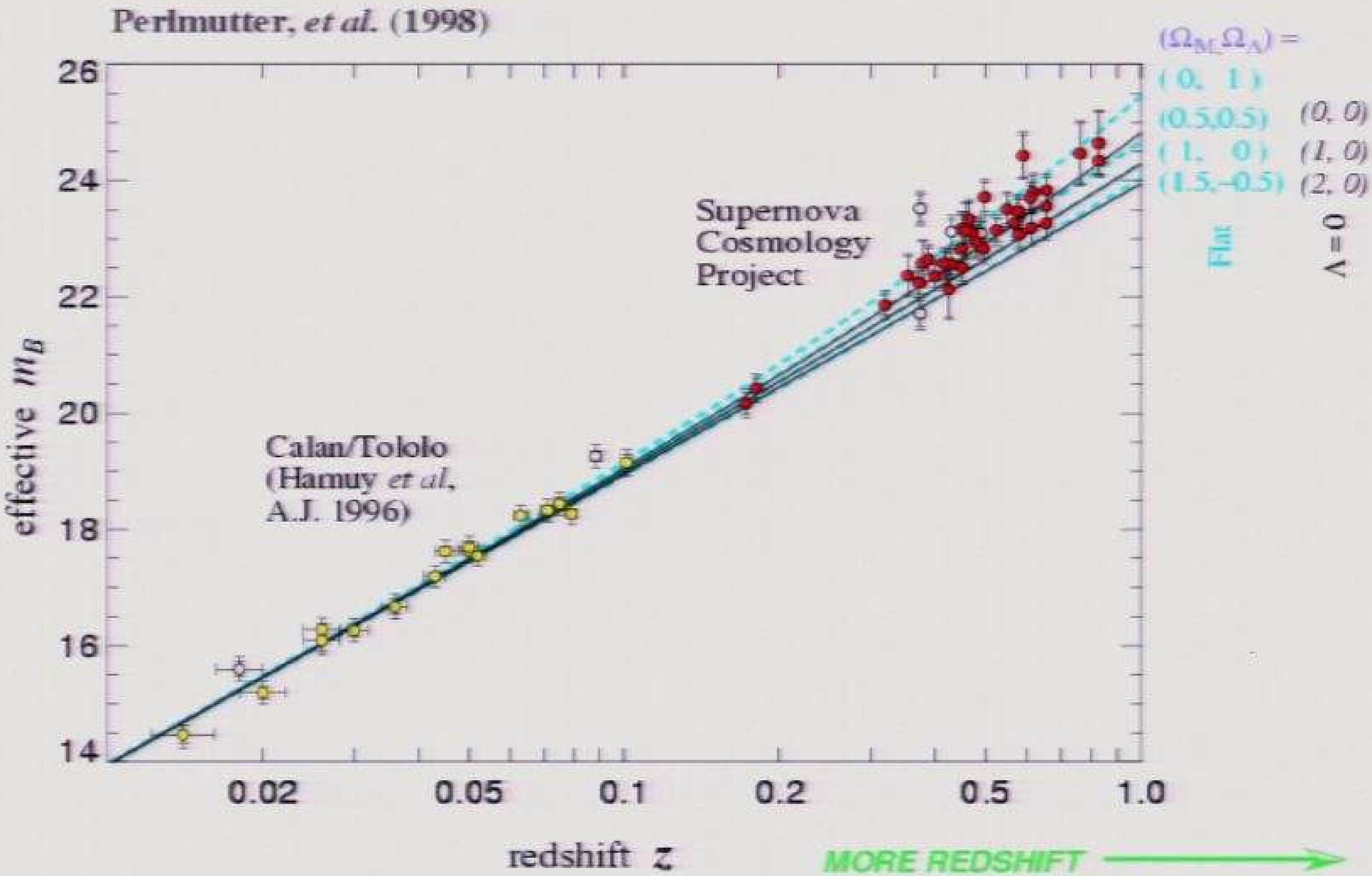
(2) There are extra dimensions

(3) The universe is cyclic

(4) The speed of light varies

Things we know

- Inflation can happen *in the real world*.



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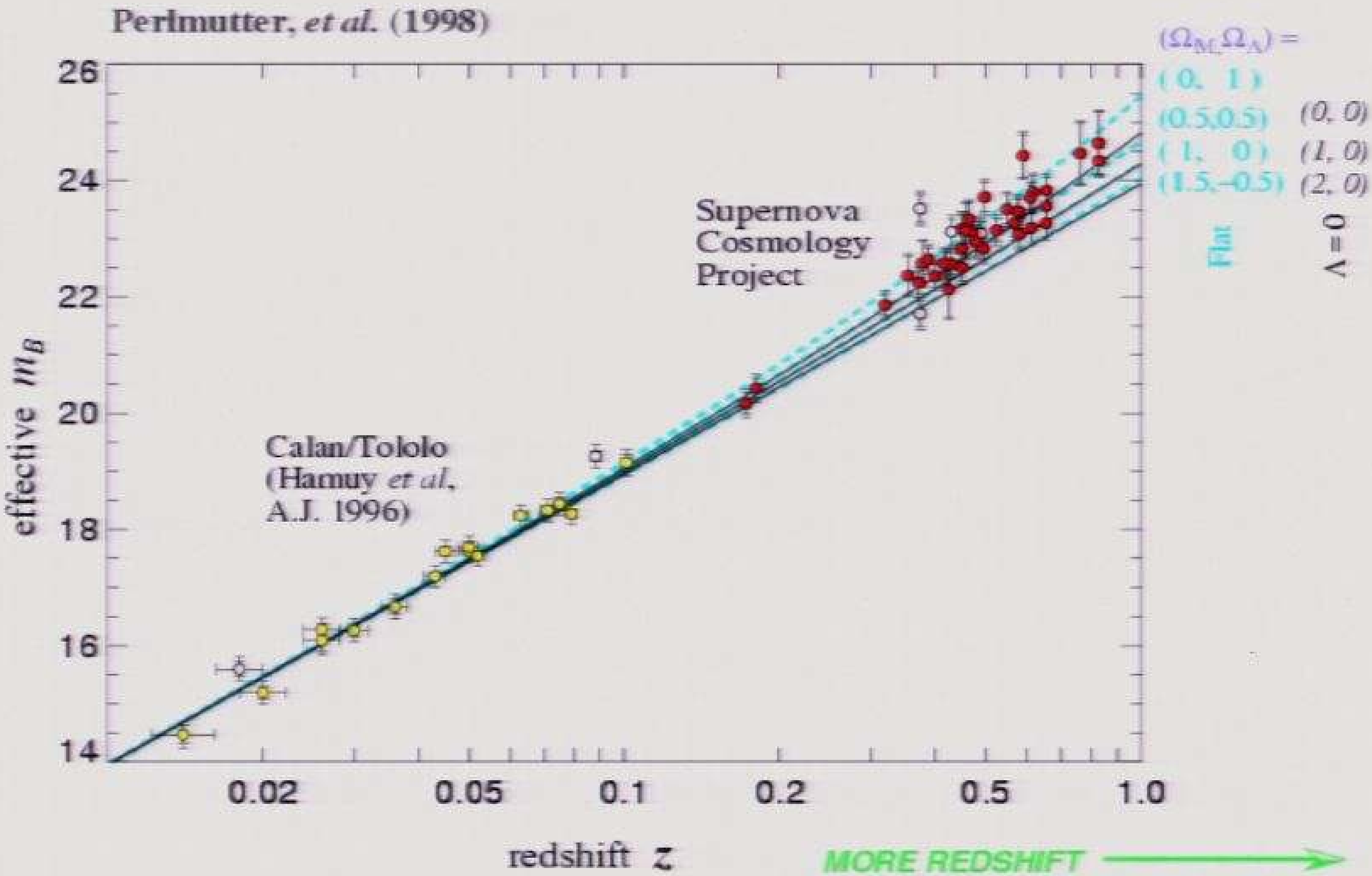
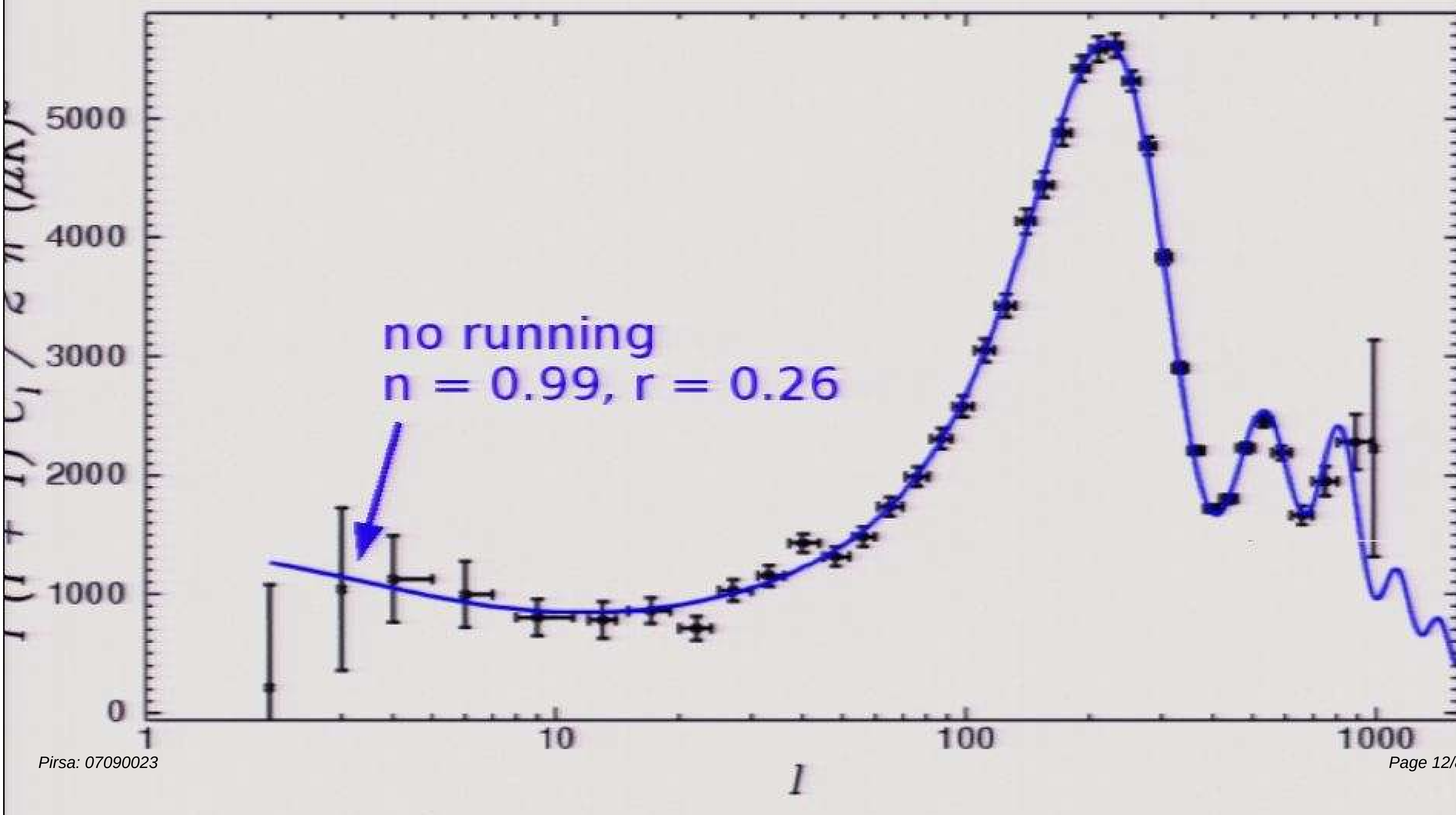


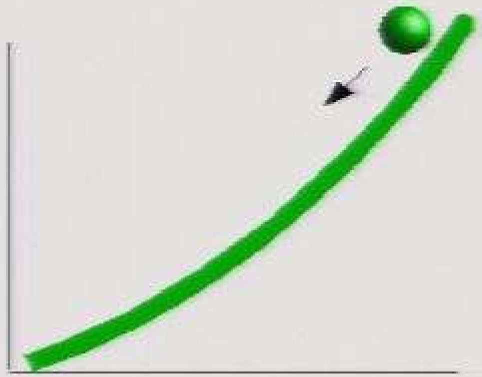
MORE REDSHIFT →
(More total expansion of universe since the supernova explosion)

Things we know

- Inflation fits the data *extremely* well.



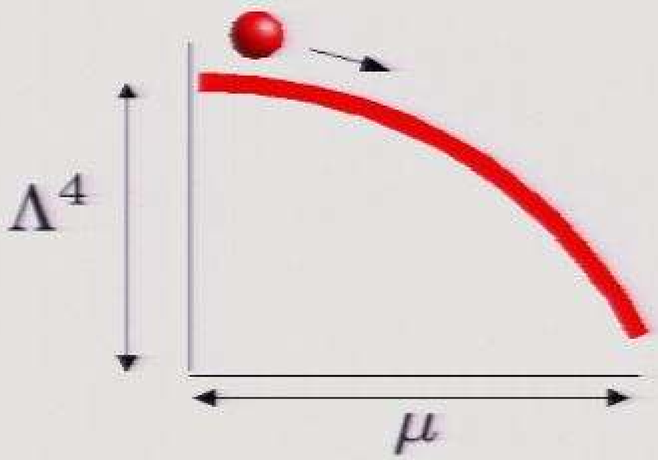
Inflation: zoology



Large field

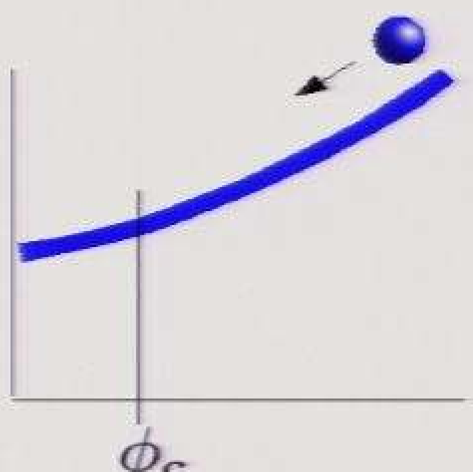
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

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



Small field

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



Hybrid

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

Fluctuation parameters

Tensor fluctuations

$$P_{\mathrm{T}}^{1/2} = \langle \delta\phi^2 \rangle^{1/2} \sim H \propto k^{n_{\mathrm{T}}}$$

Scalar fluctuations

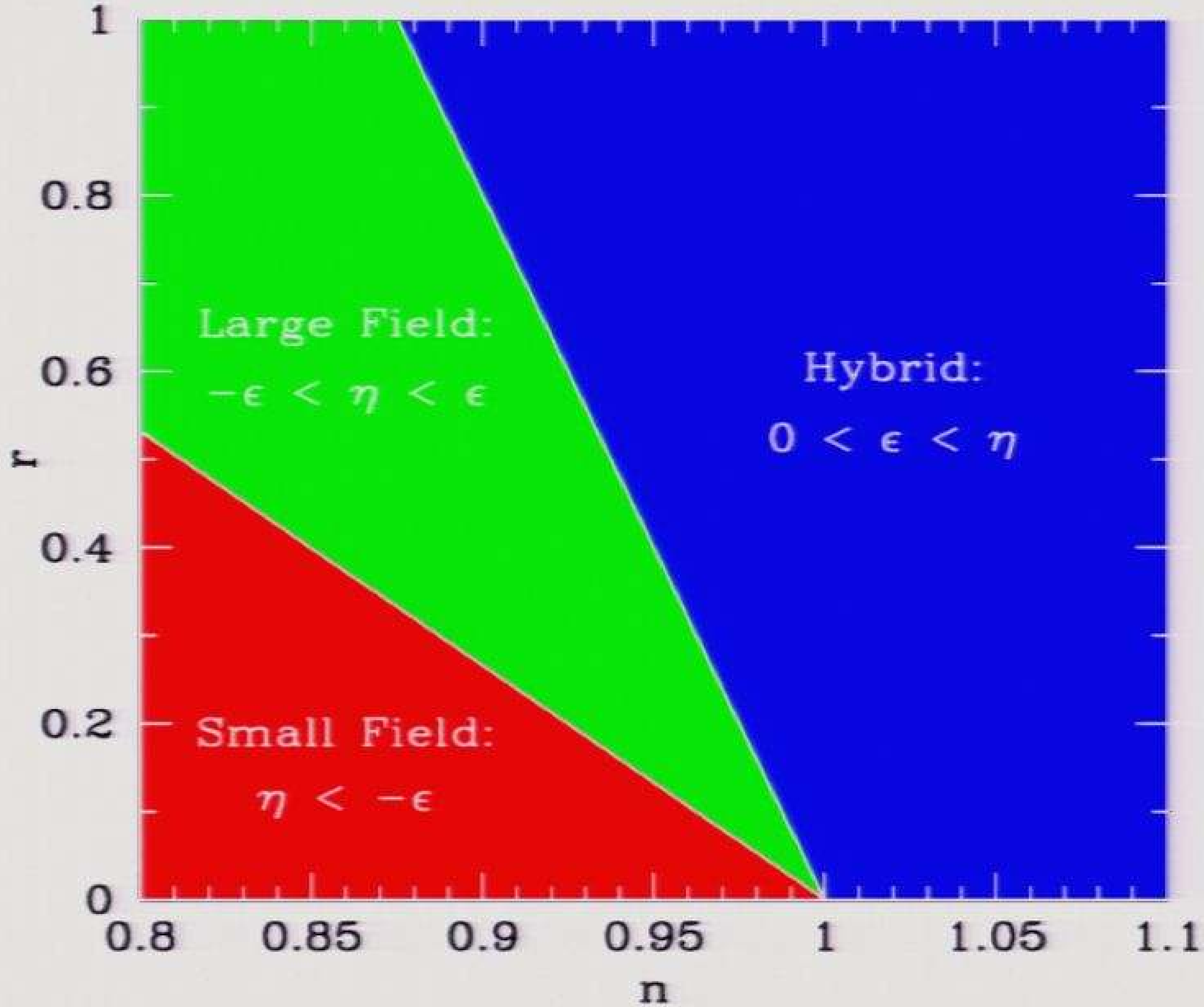
$$P_{\mathrm{S}}^{1/2} = \frac{\delta N}{\delta\phi}\delta\phi \sim \frac{H}{\sqrt{\epsilon}} \propto k^{n-1}$$

Tensor/scalar ratio

Consistency condition

$$r \equiv \frac{P_{\mathrm{T}}}{P_{\mathrm{S}}} = 16\epsilon = -8n_{\mathrm{T}}$$

The zoo plot



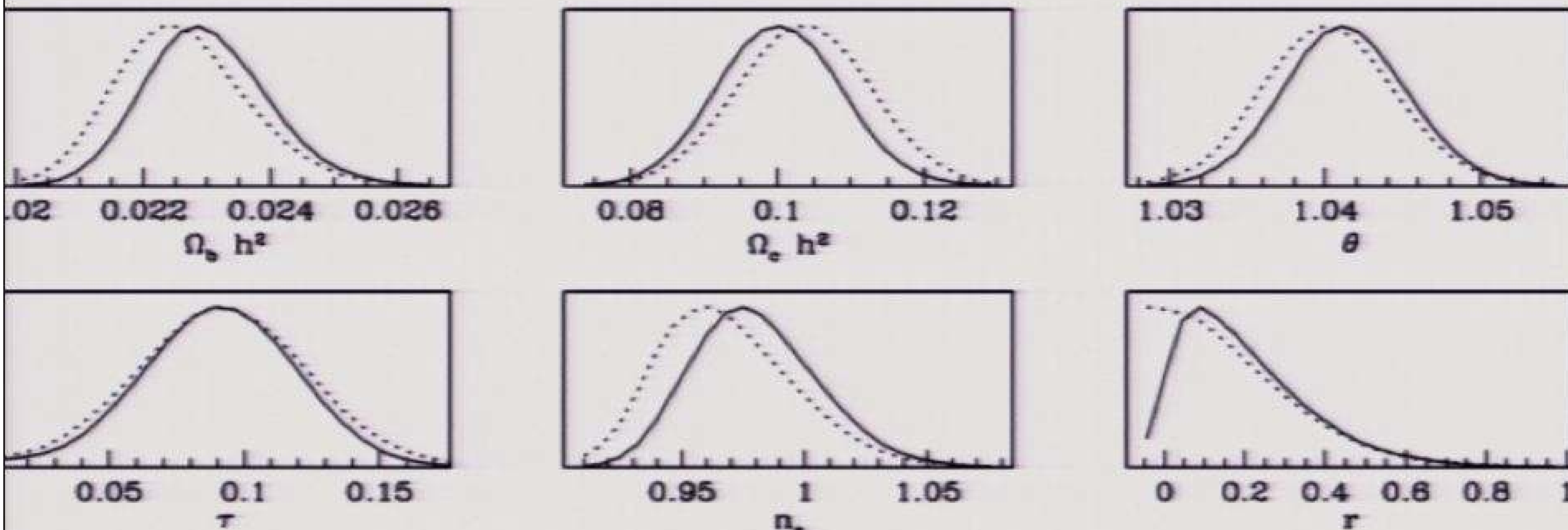
Dodelson, WHK, Kolb,astro-ph/9702166

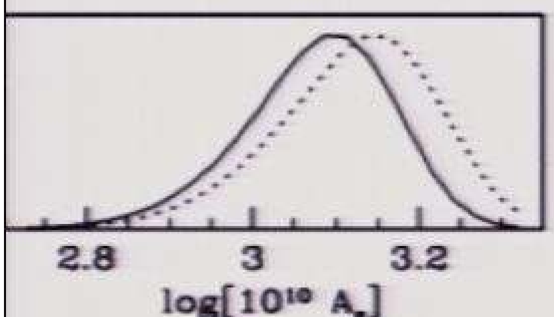
UB Center For Computational Research

2: 800-node 2x Intel 3.2 GHz Xeon “Irwindale” cluster

ode: COSMOMC (Lewis and Bridle, astro-ph/0205436)

No running: 7 parameter fit





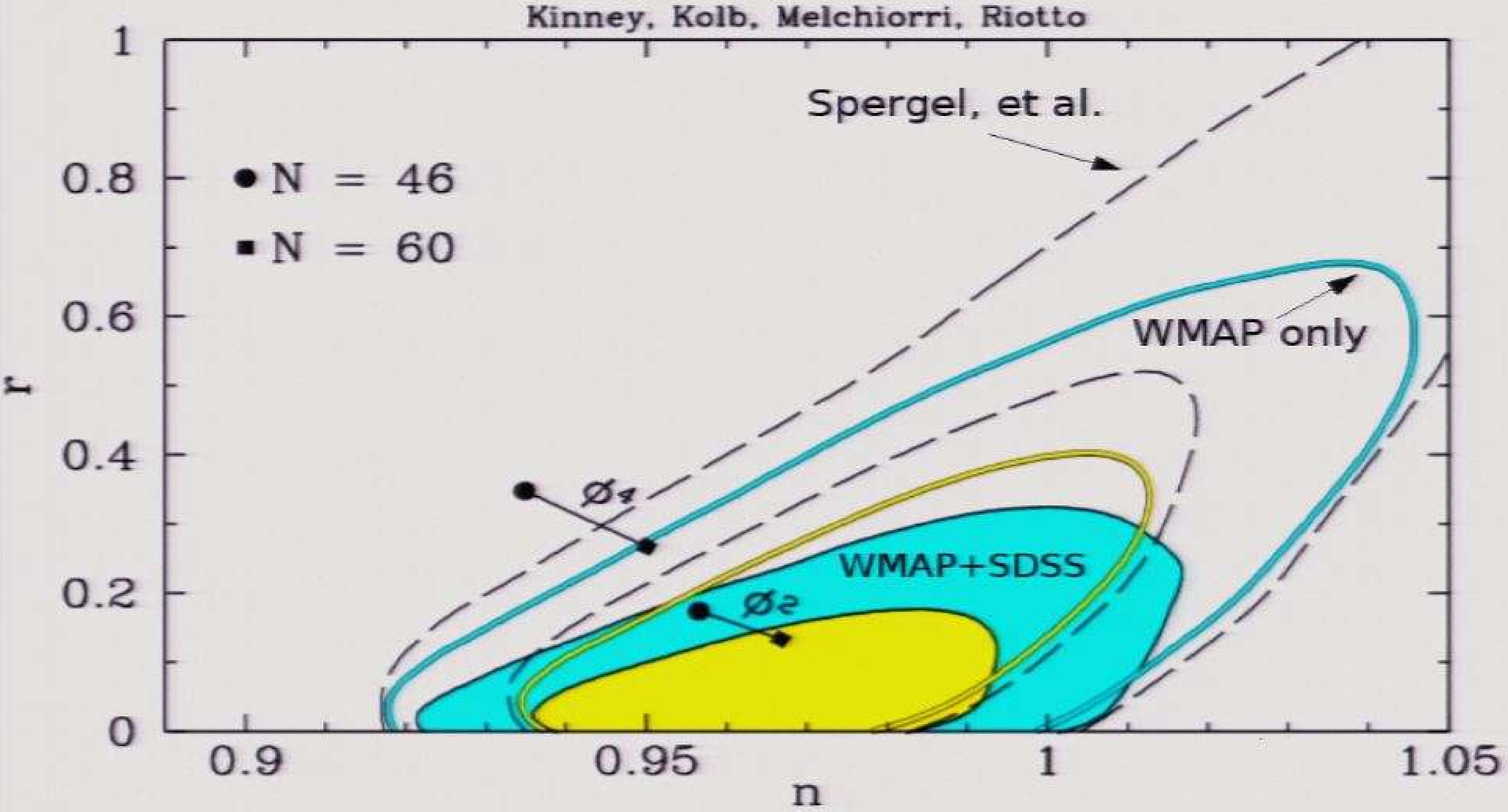
$$n_t = -r/8 \qquad w = -1$$

$$\Omega_{\rm total} = 1$$

HST prior: $h = 0.72 \pm 0.08$

Tophat age prior: $t_0 = 10 - 20$ Gyr

WMAP3 limits on inflation



WHK, Kolb, Melchiorri, Riotto, astro-ph/0605338

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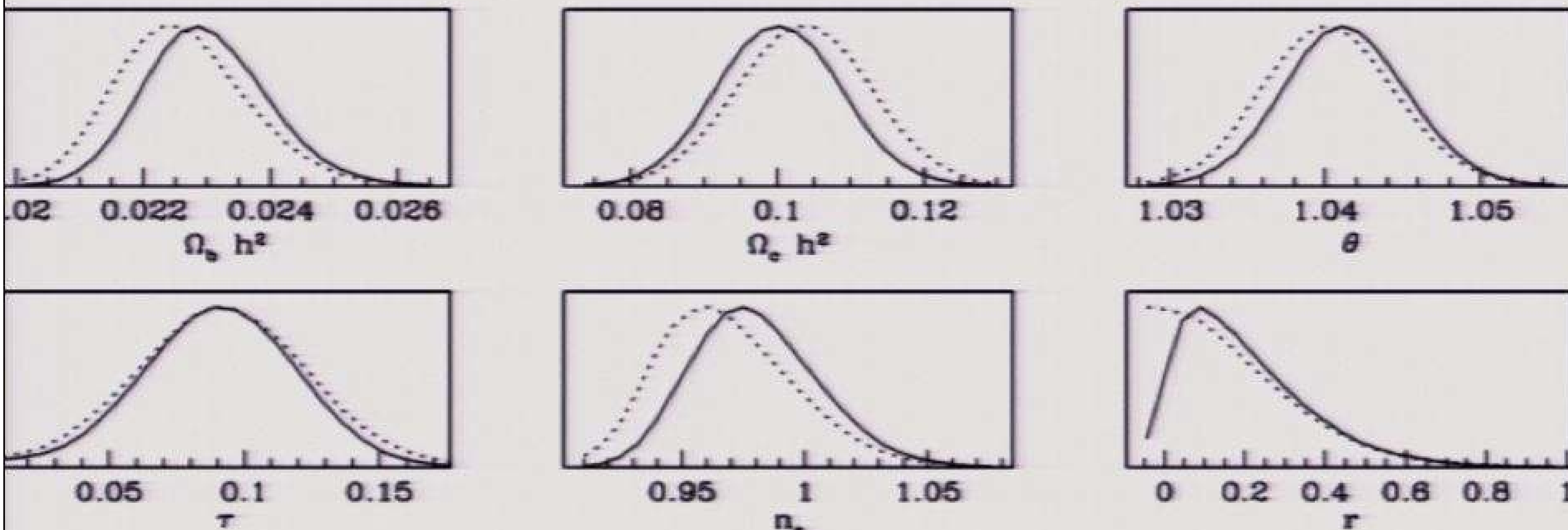

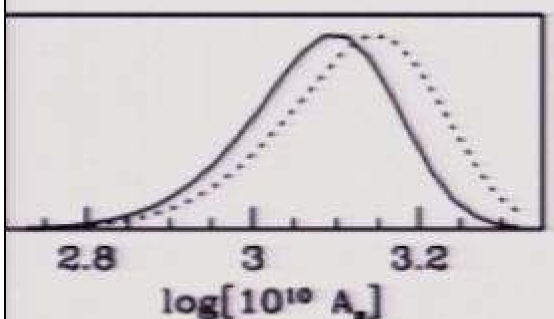

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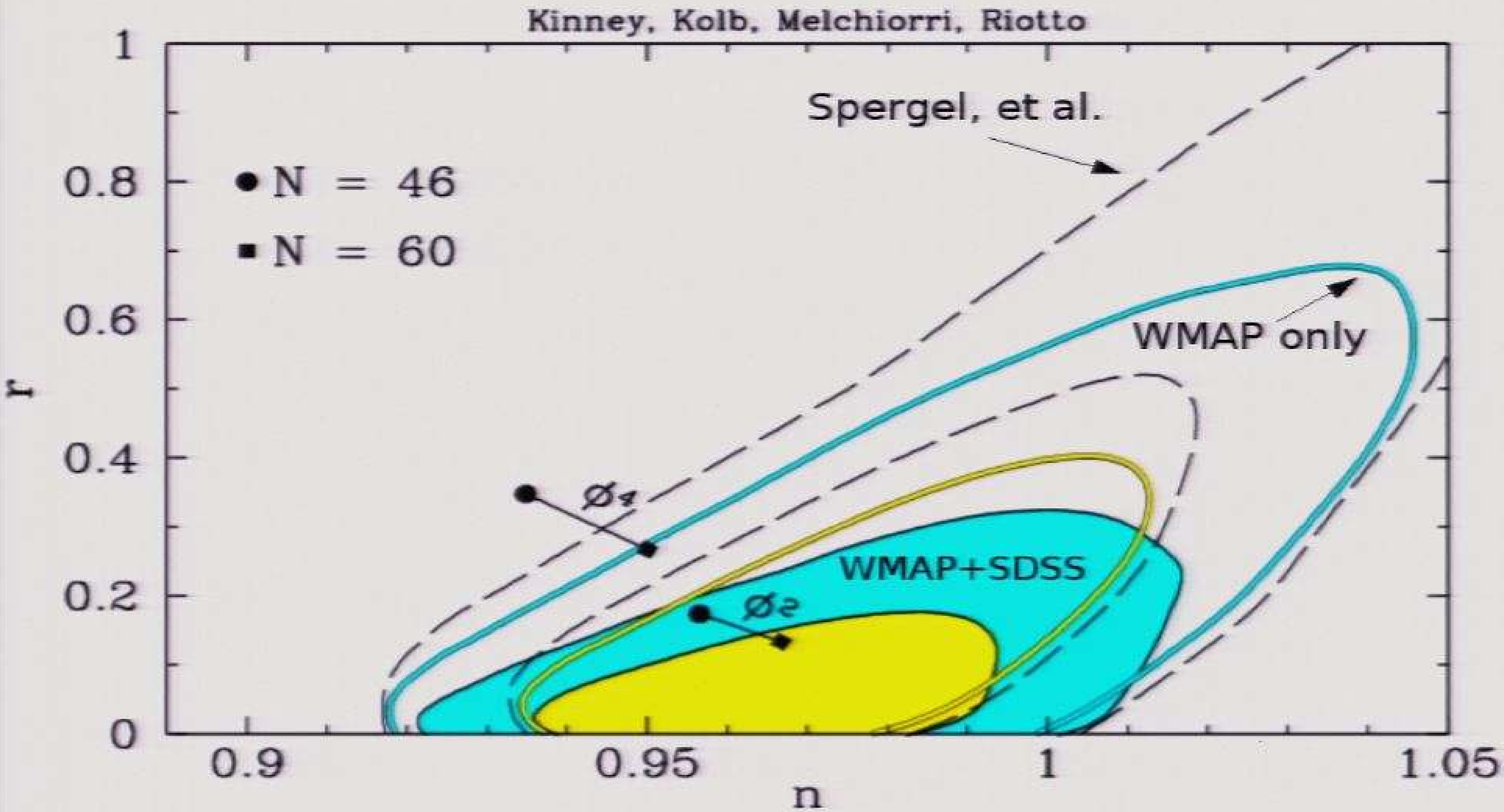

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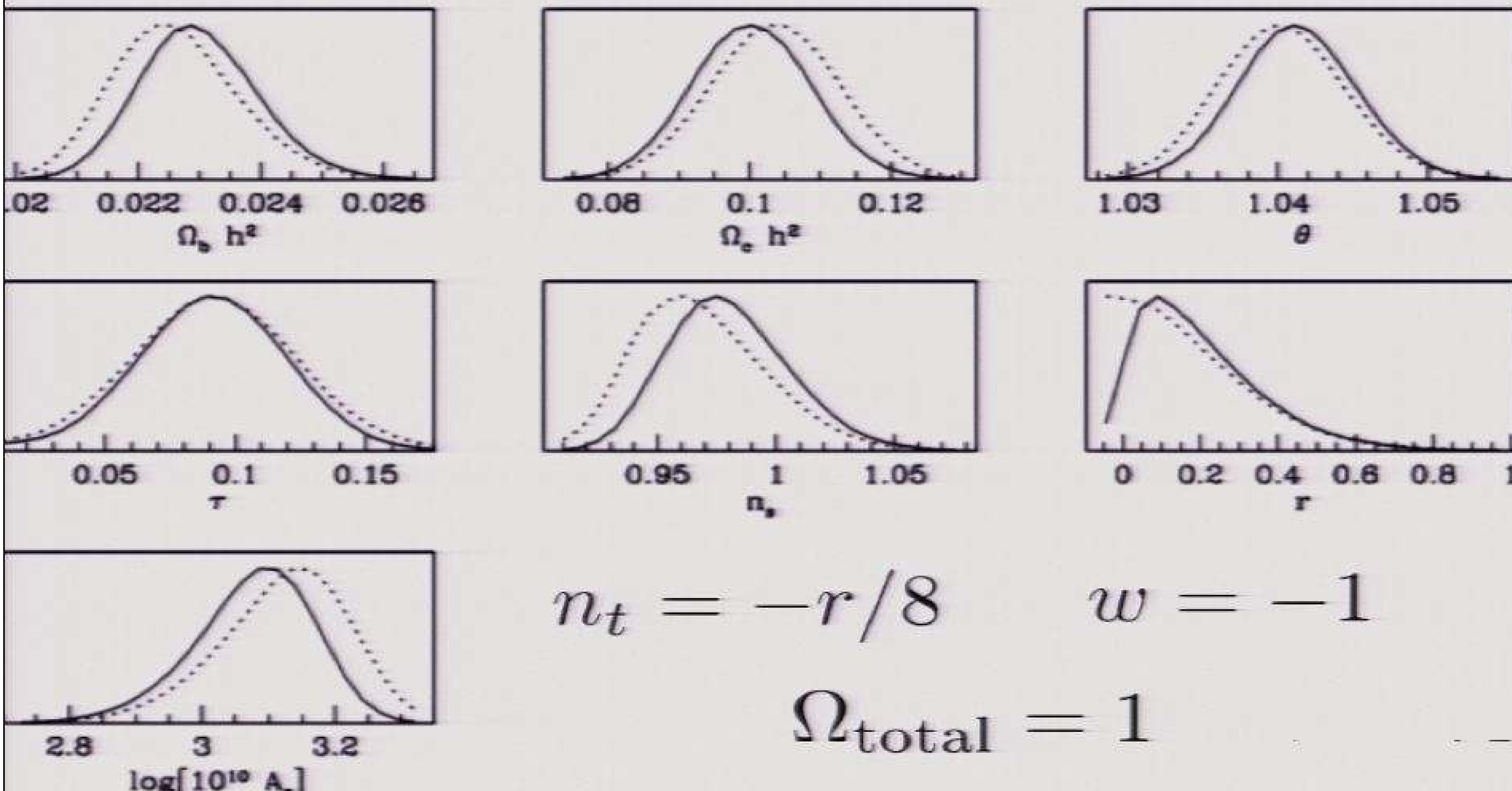

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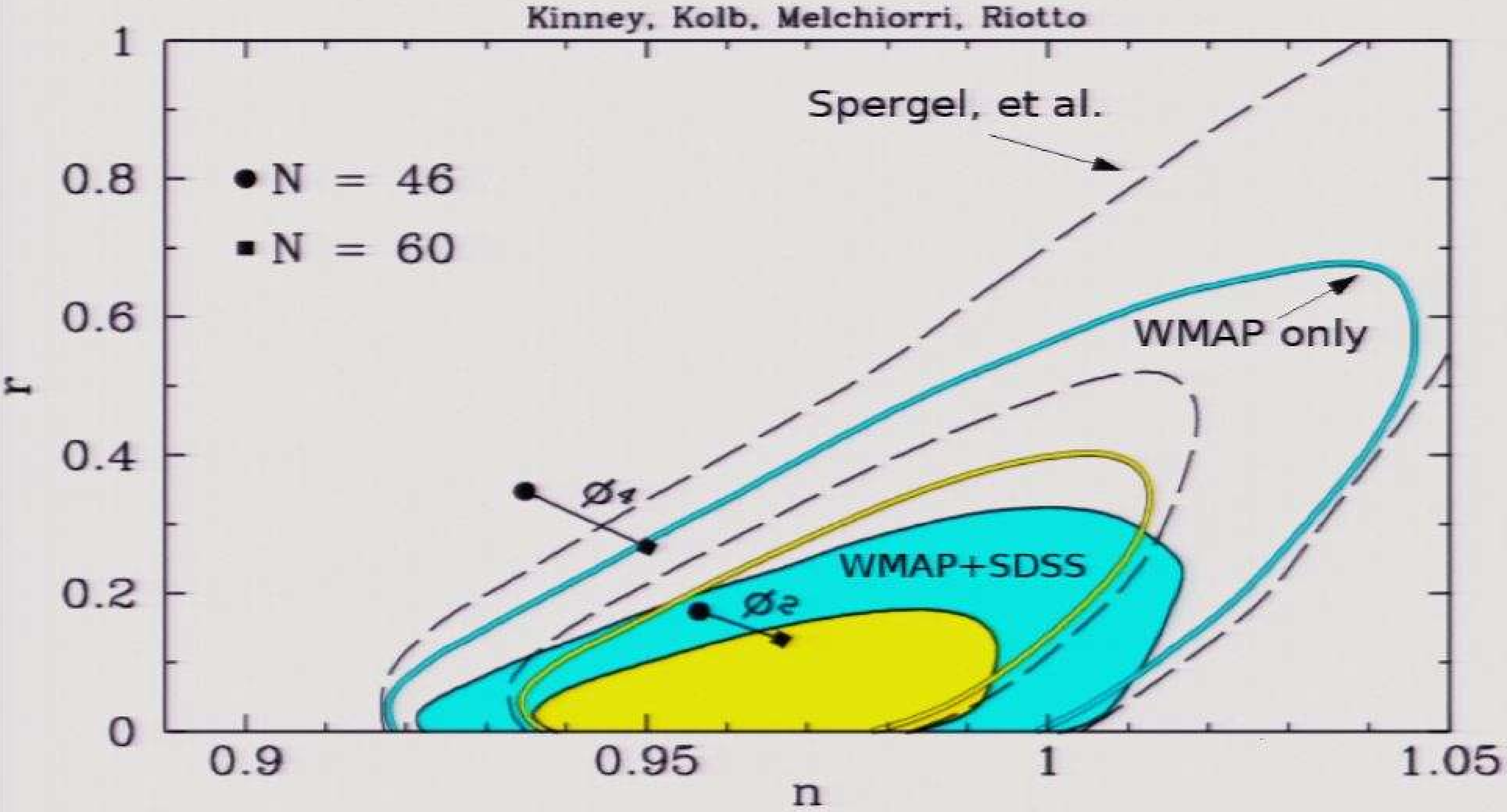

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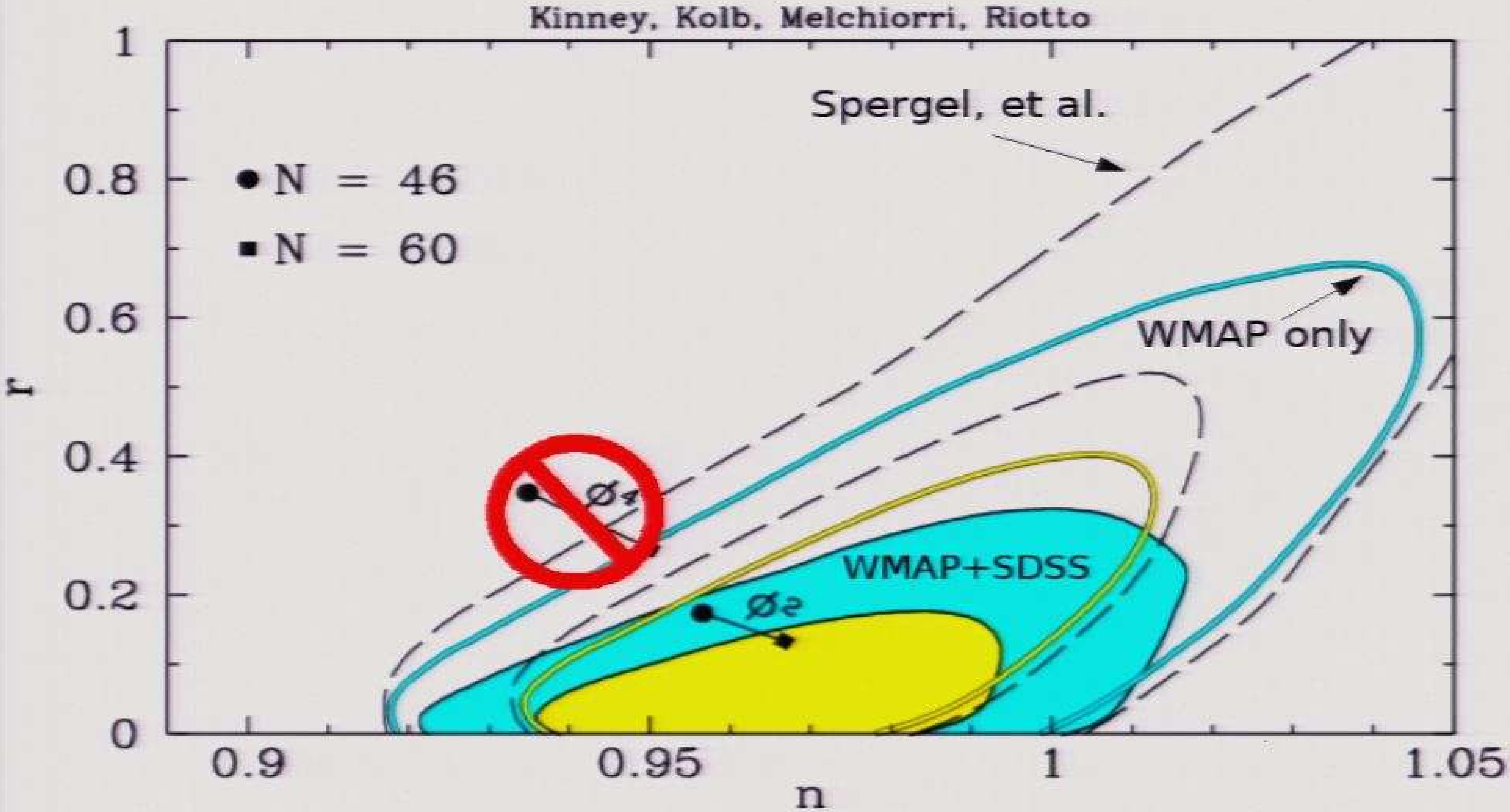

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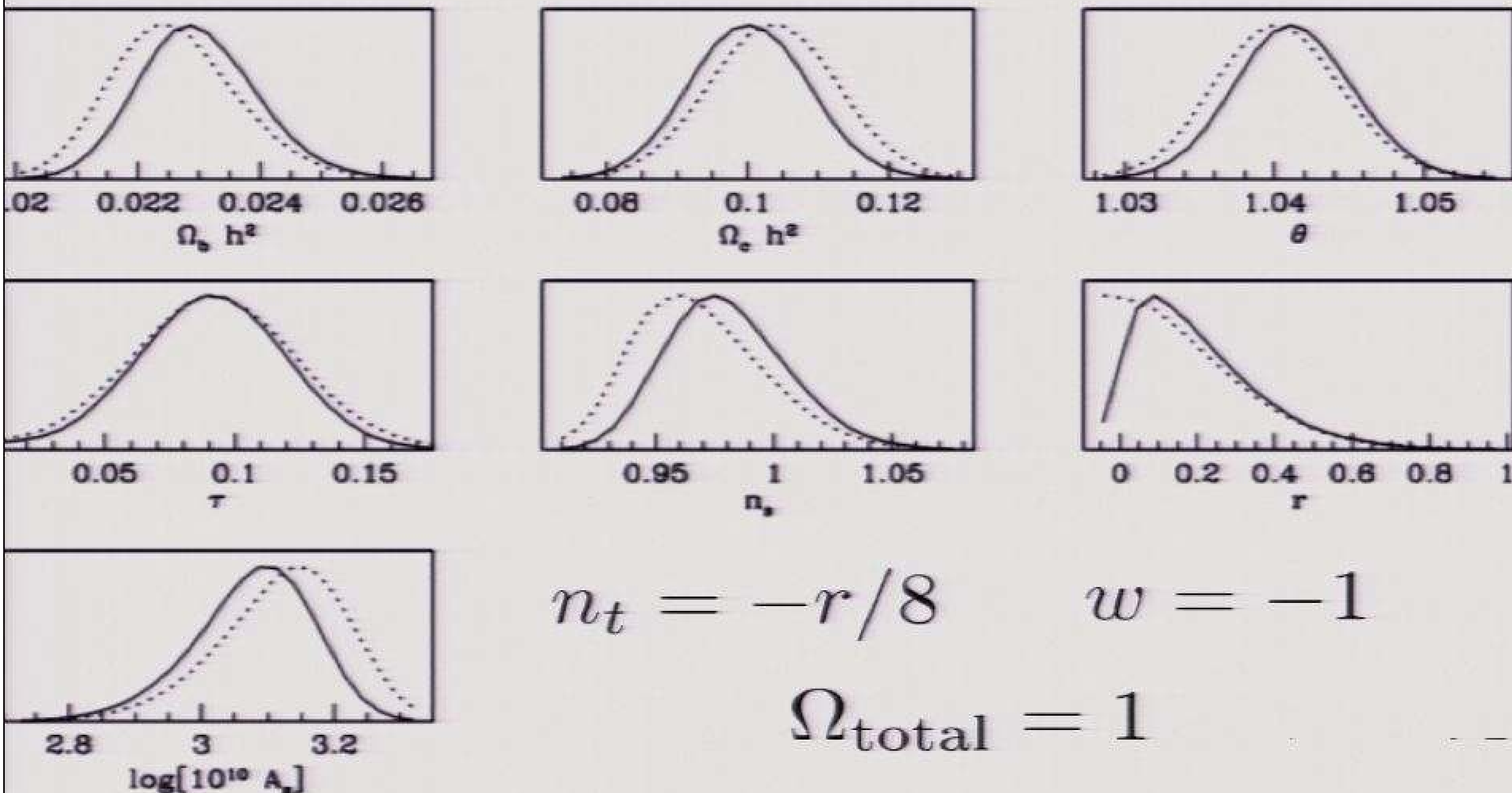

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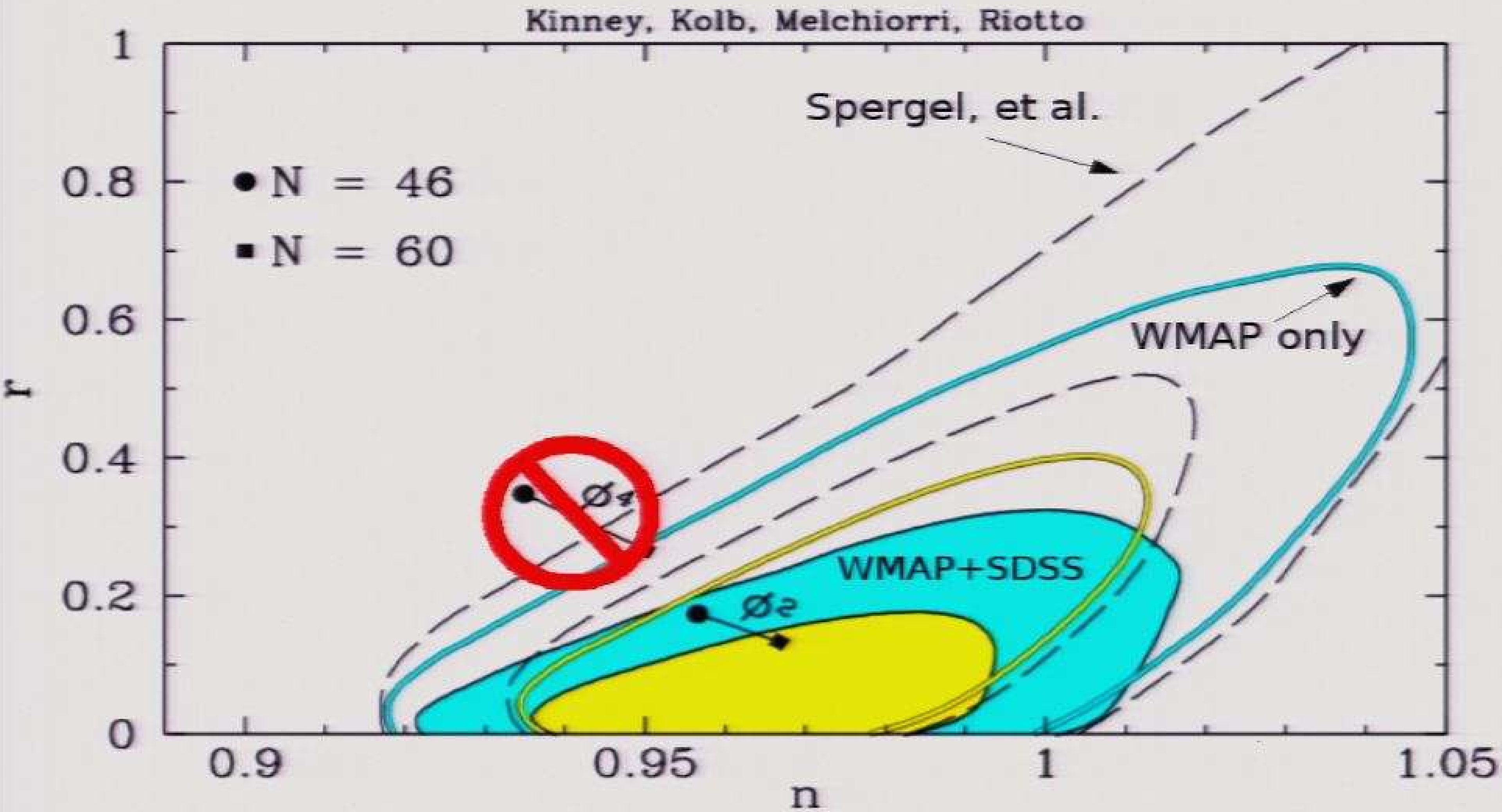

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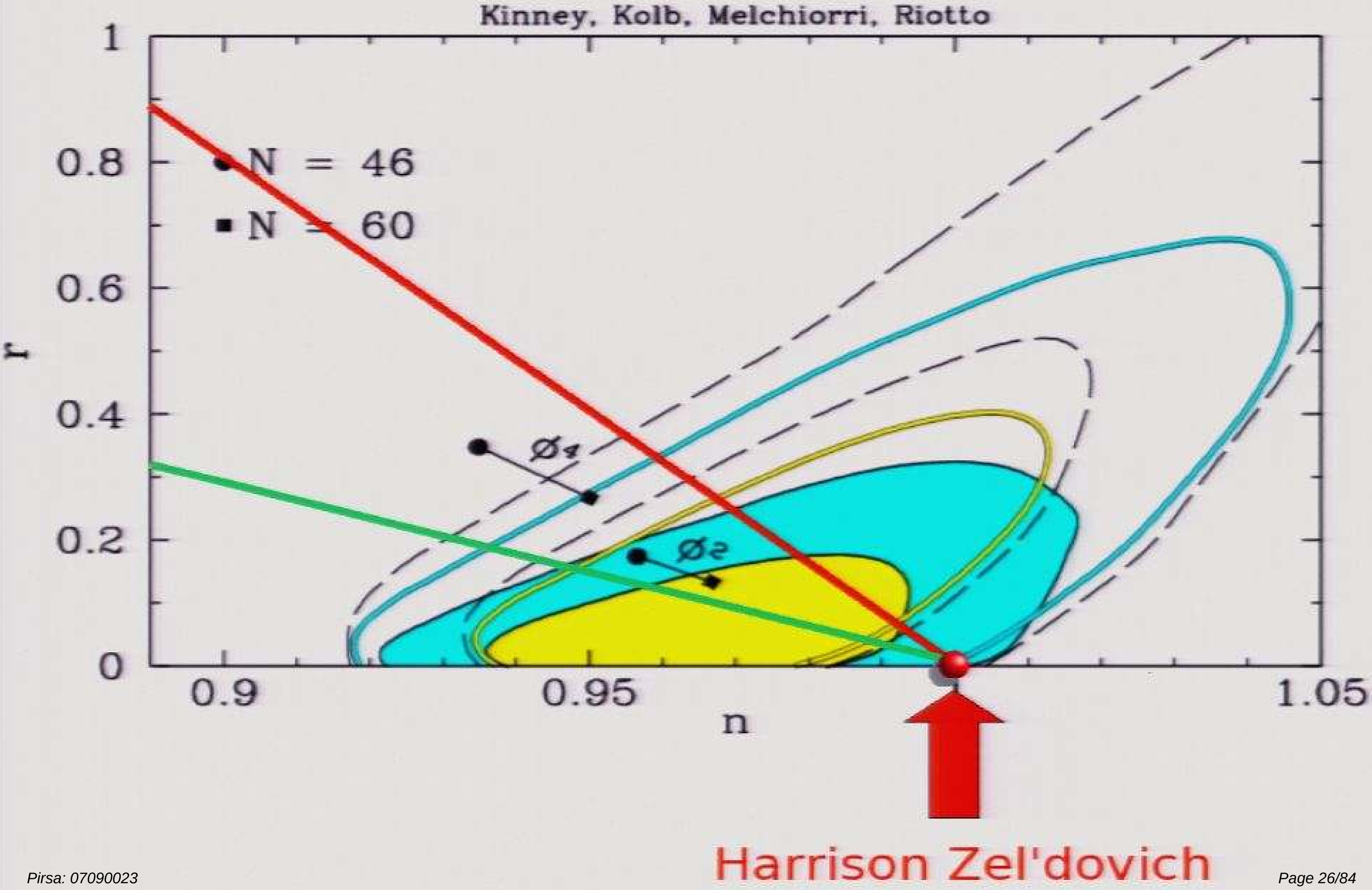

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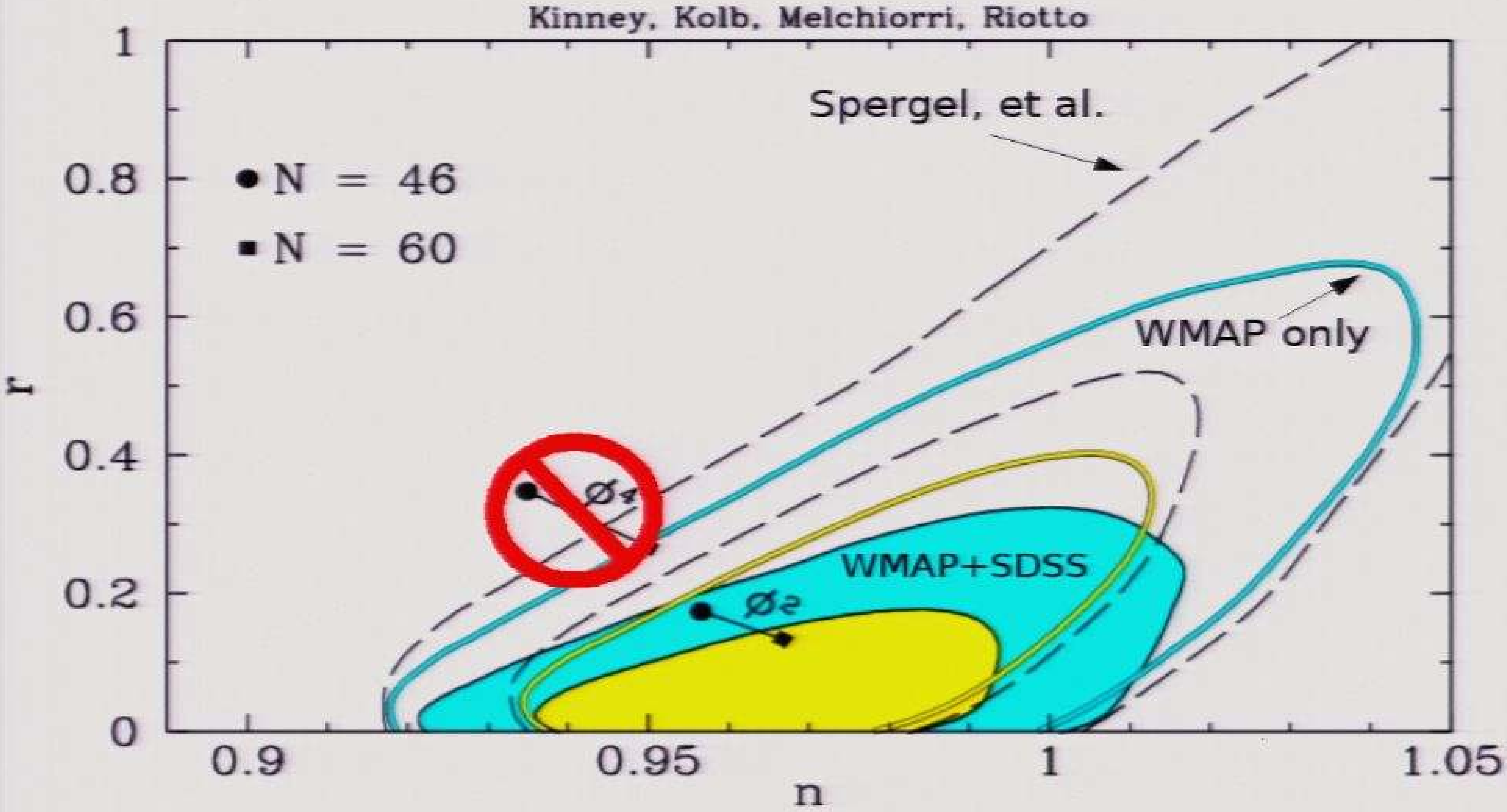

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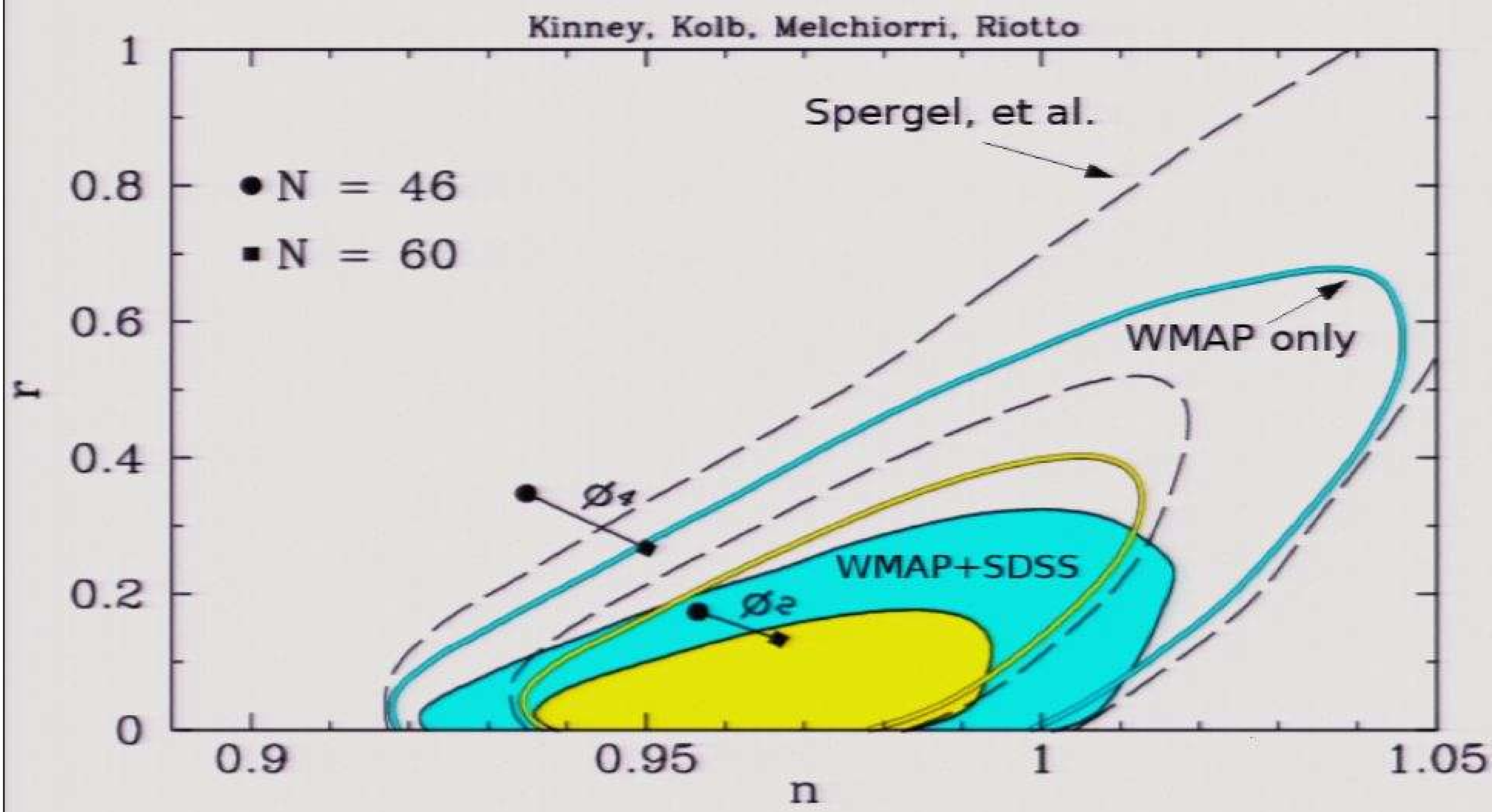

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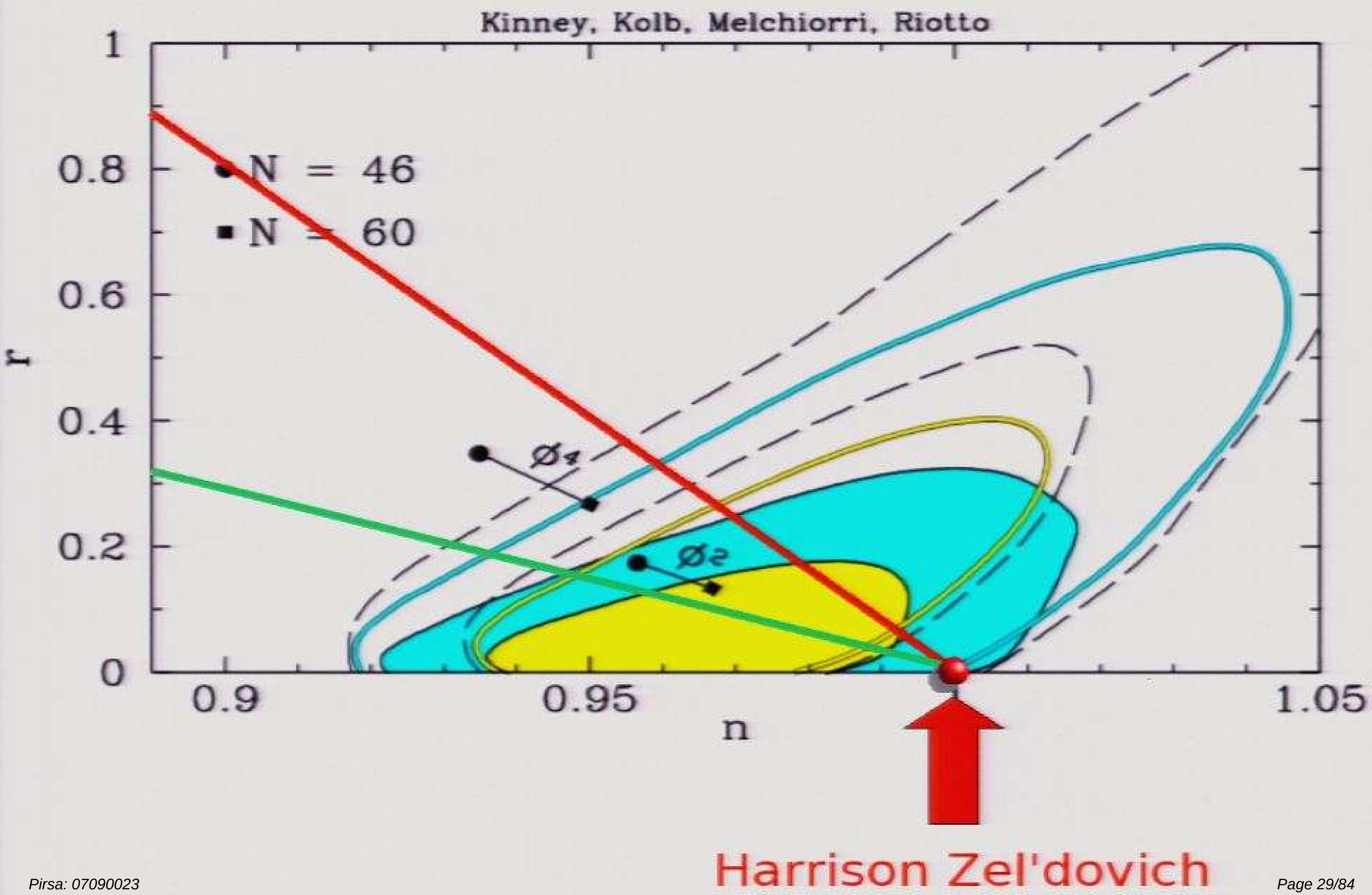
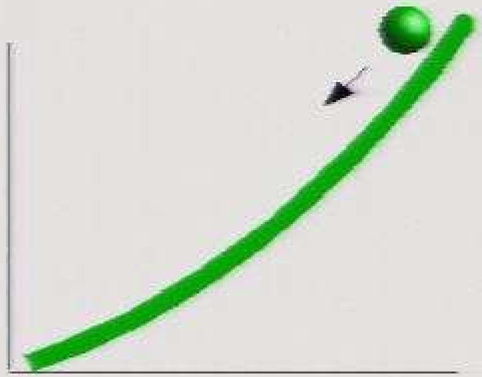


Things we know



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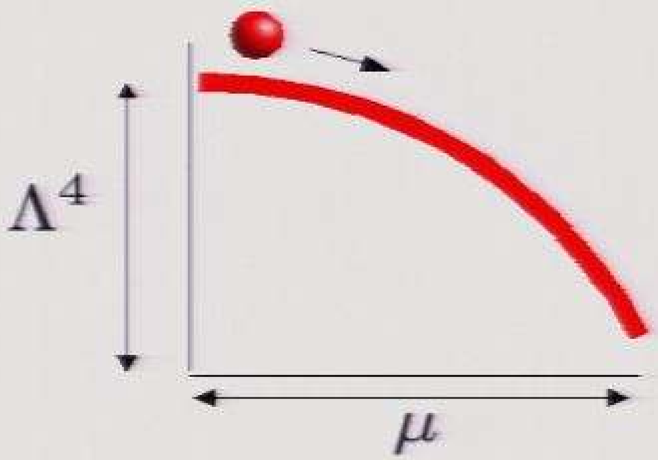

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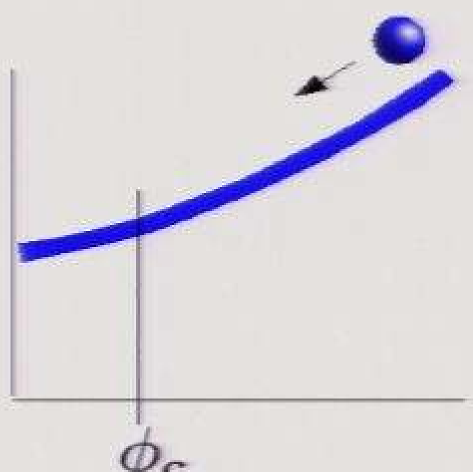
$$r = 0$$

$$n > 1$$



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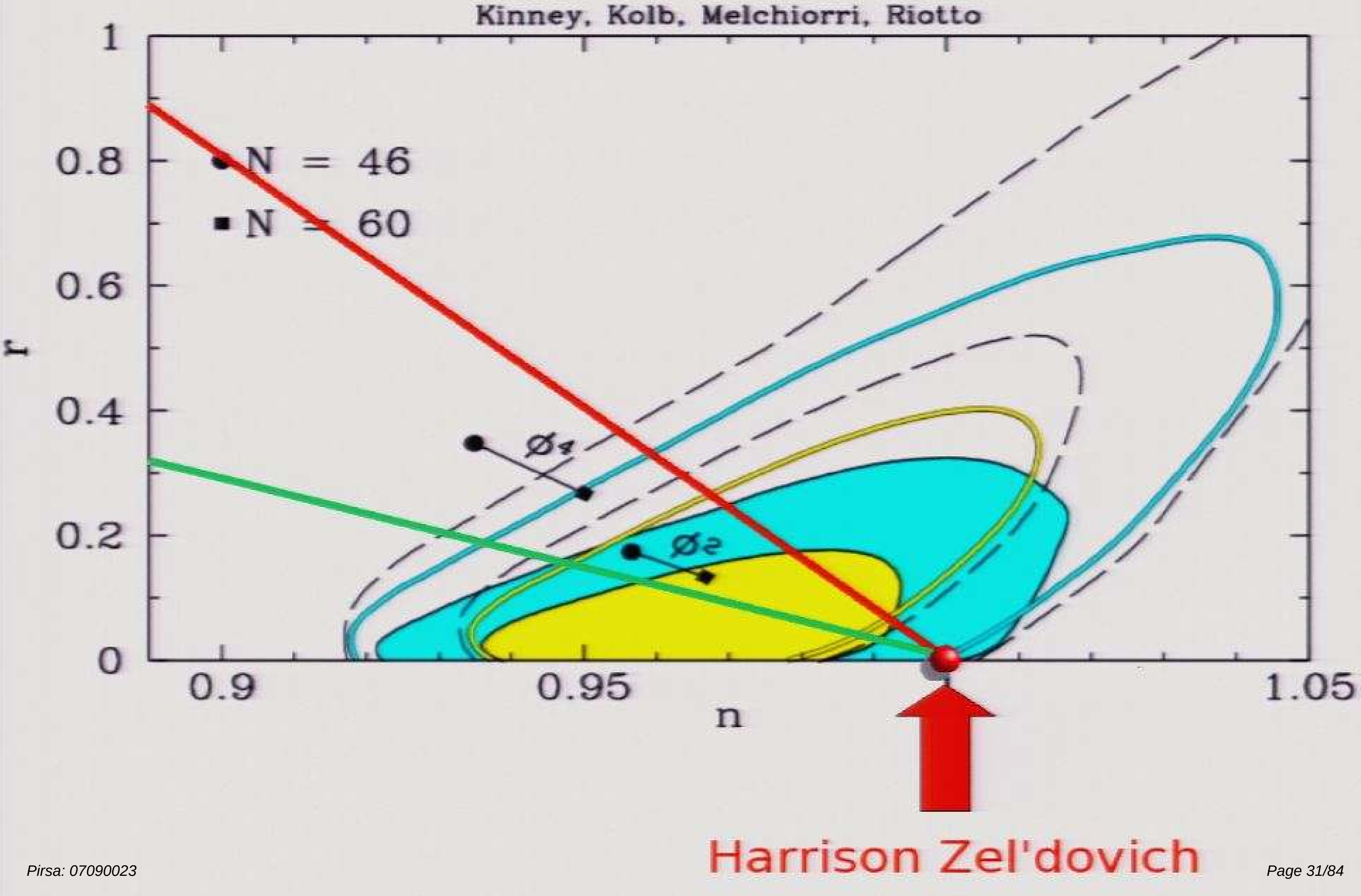

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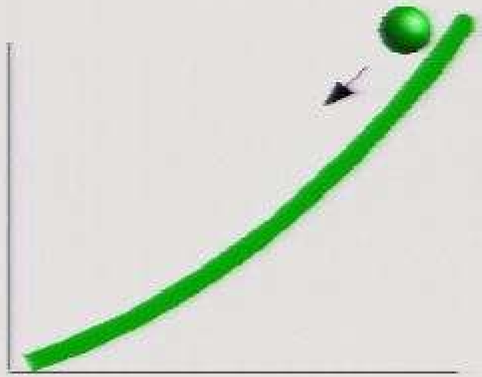

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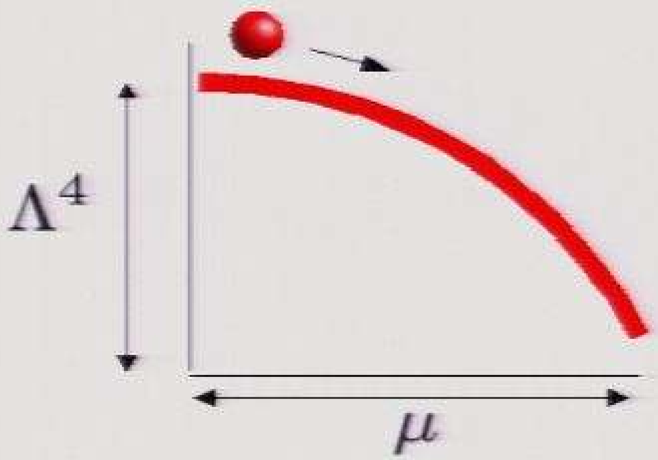

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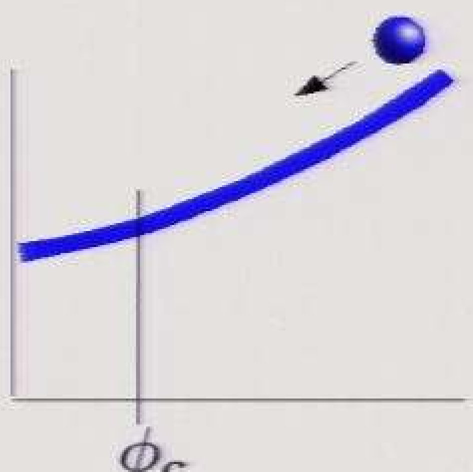

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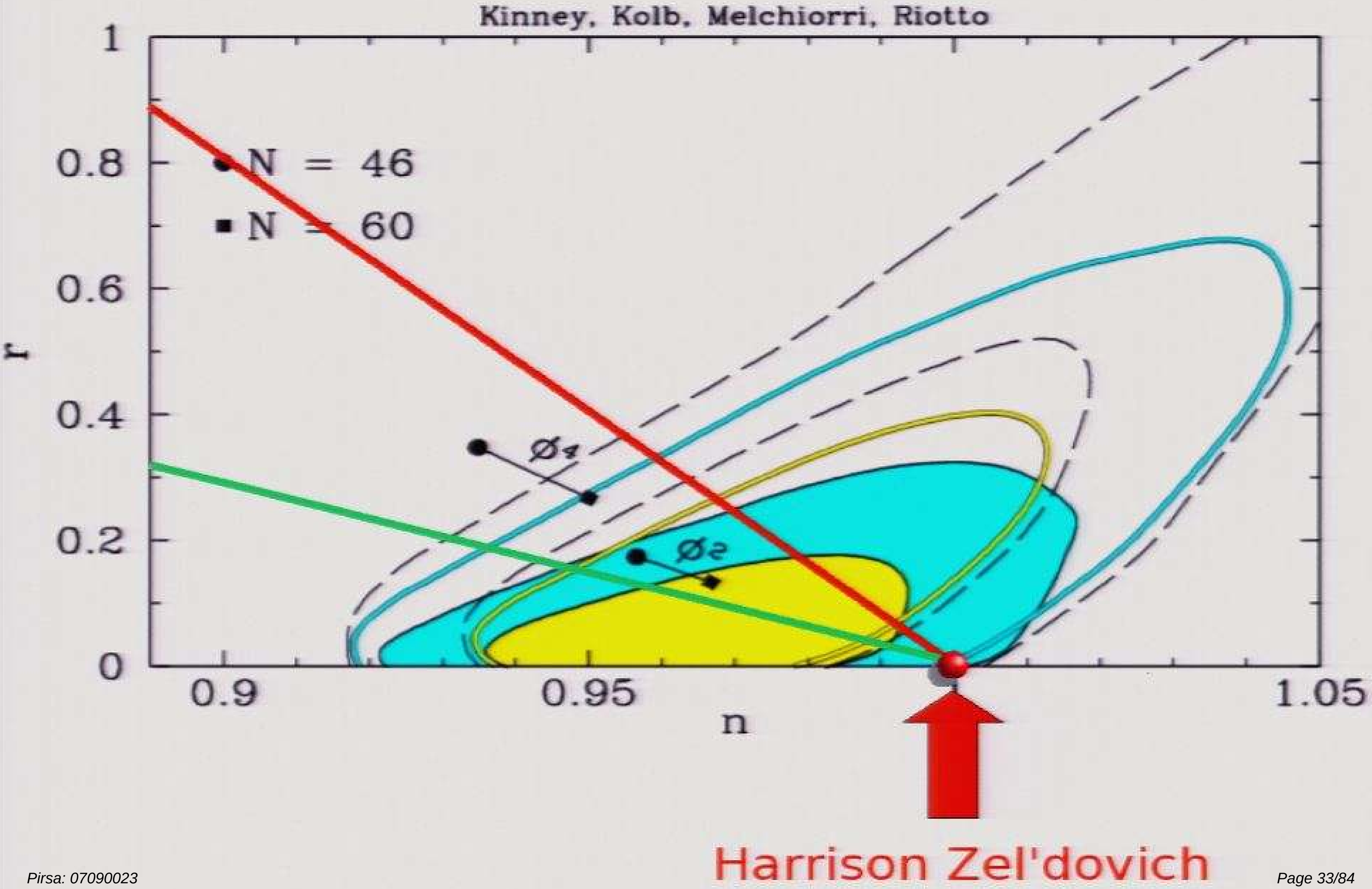
WMAP3 limits on inflation



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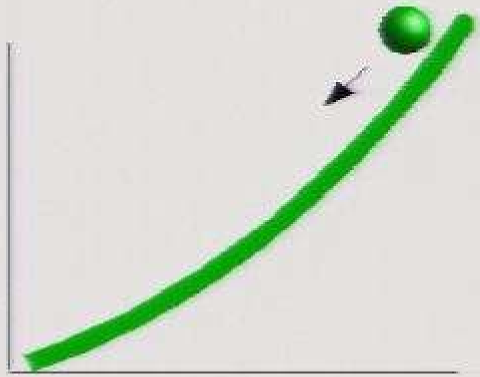

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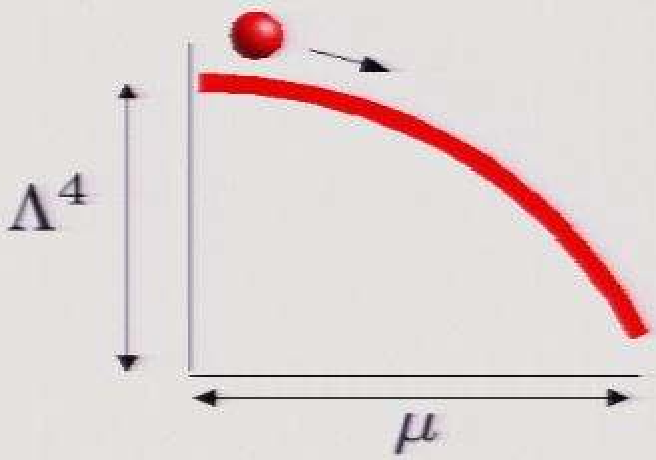

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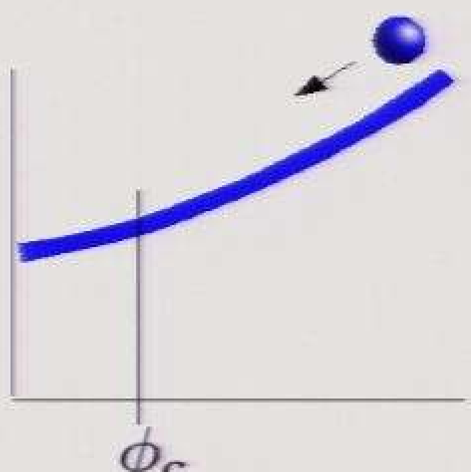

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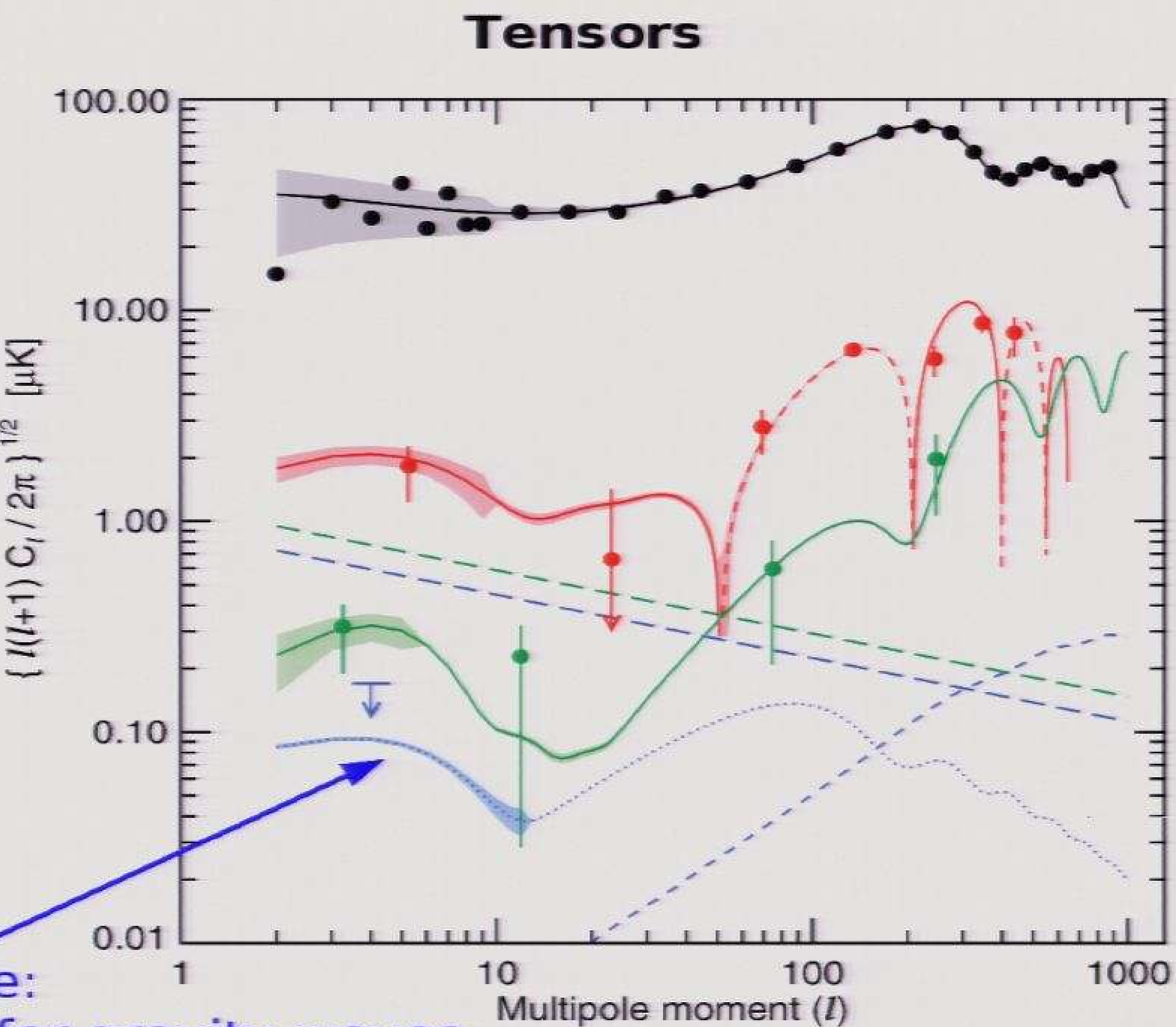
Things we don't know



mode:
gnal for gravity waves

(Figure: NASA/WMAP science team)

Tensors: what does inflation predict?

- Typical inflation model:

"Height" of potential: $\Lambda \sim M_{\rm GUT}$

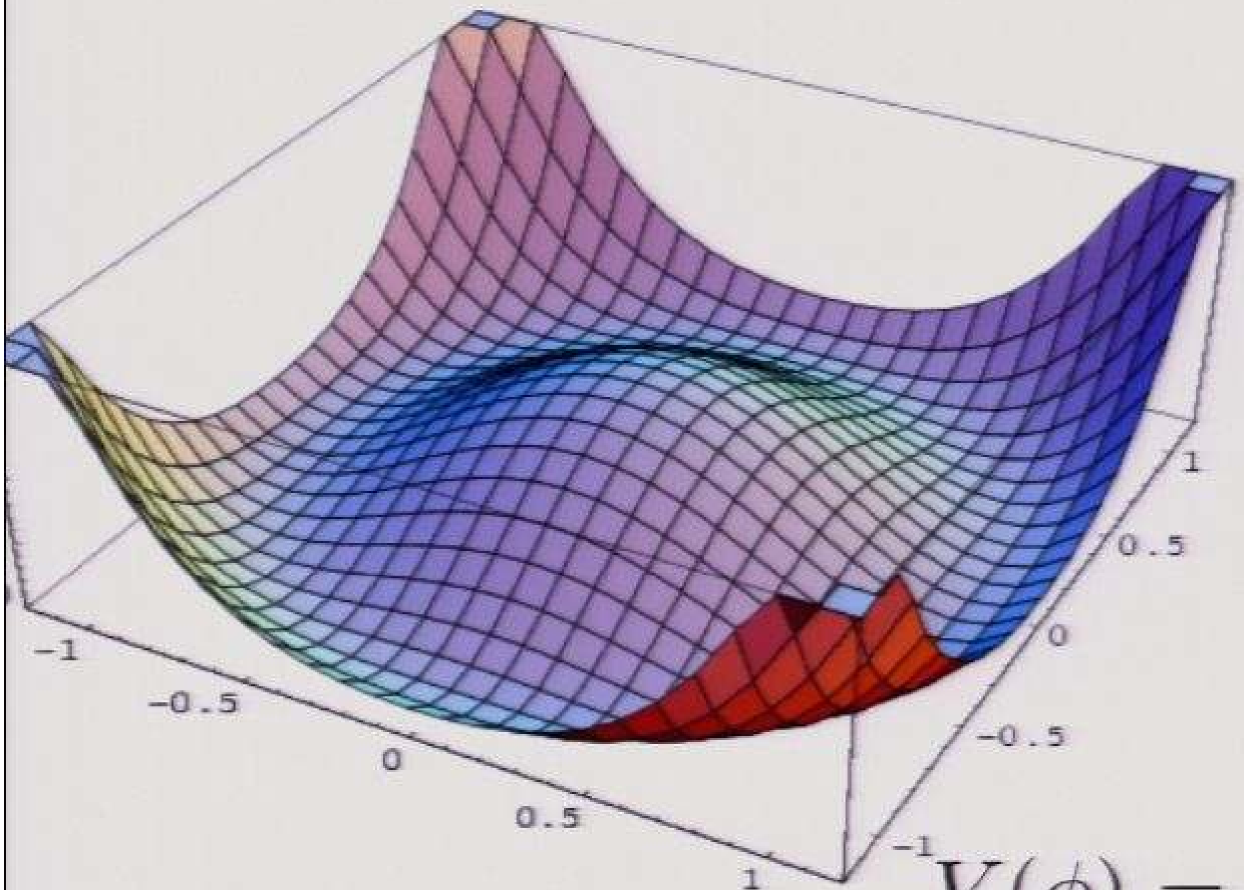
"Width" of potential: $\mu \sim m_{\rm Pl}$

$$r \geq 0.01$$

Slam dunk for next-gen CMB experiments!

(Lyth, hep-ph/9606387: problems for EFT?)

tural Inflation: pseudo-Nambu-Goldstone bosons



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

Frieman, Freese & Olinto, PRL **65** (1990) 3233

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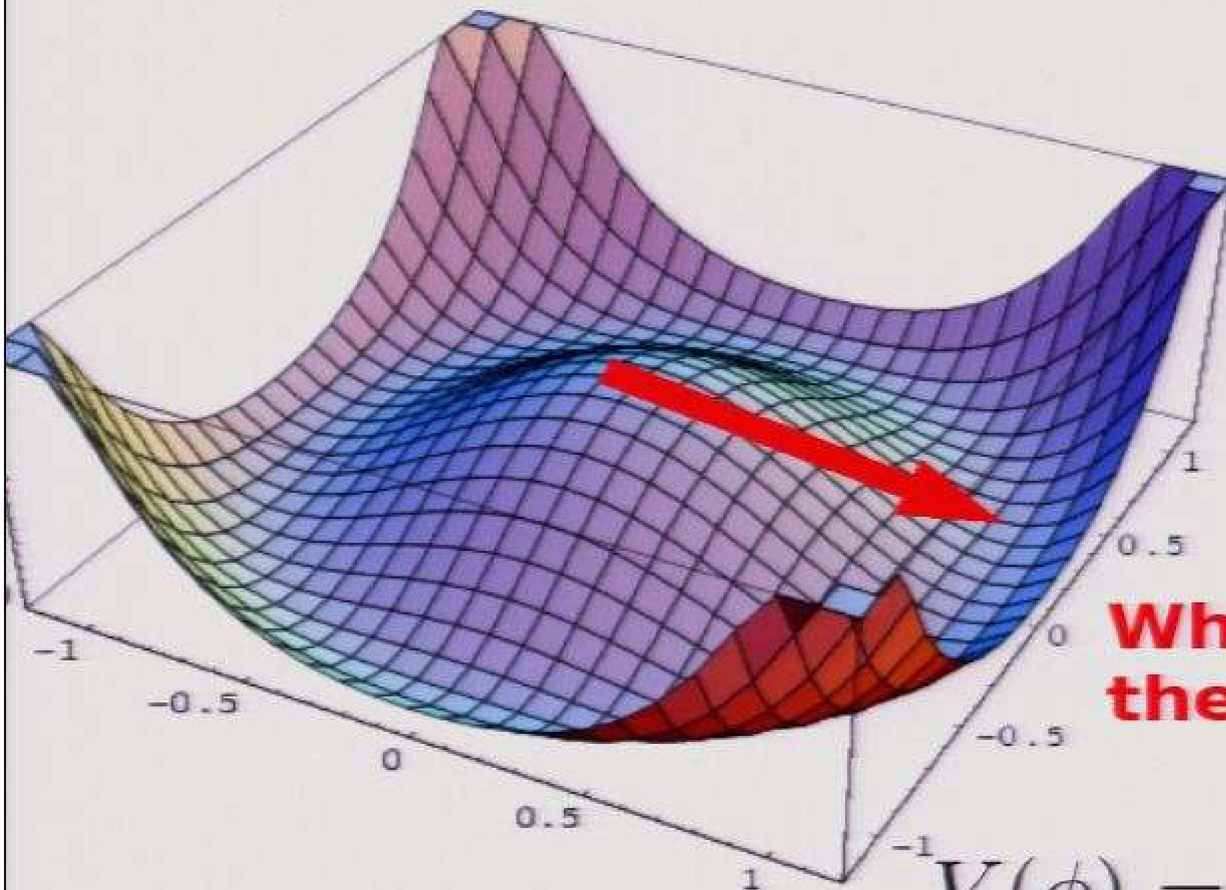

What is the width of the potential?

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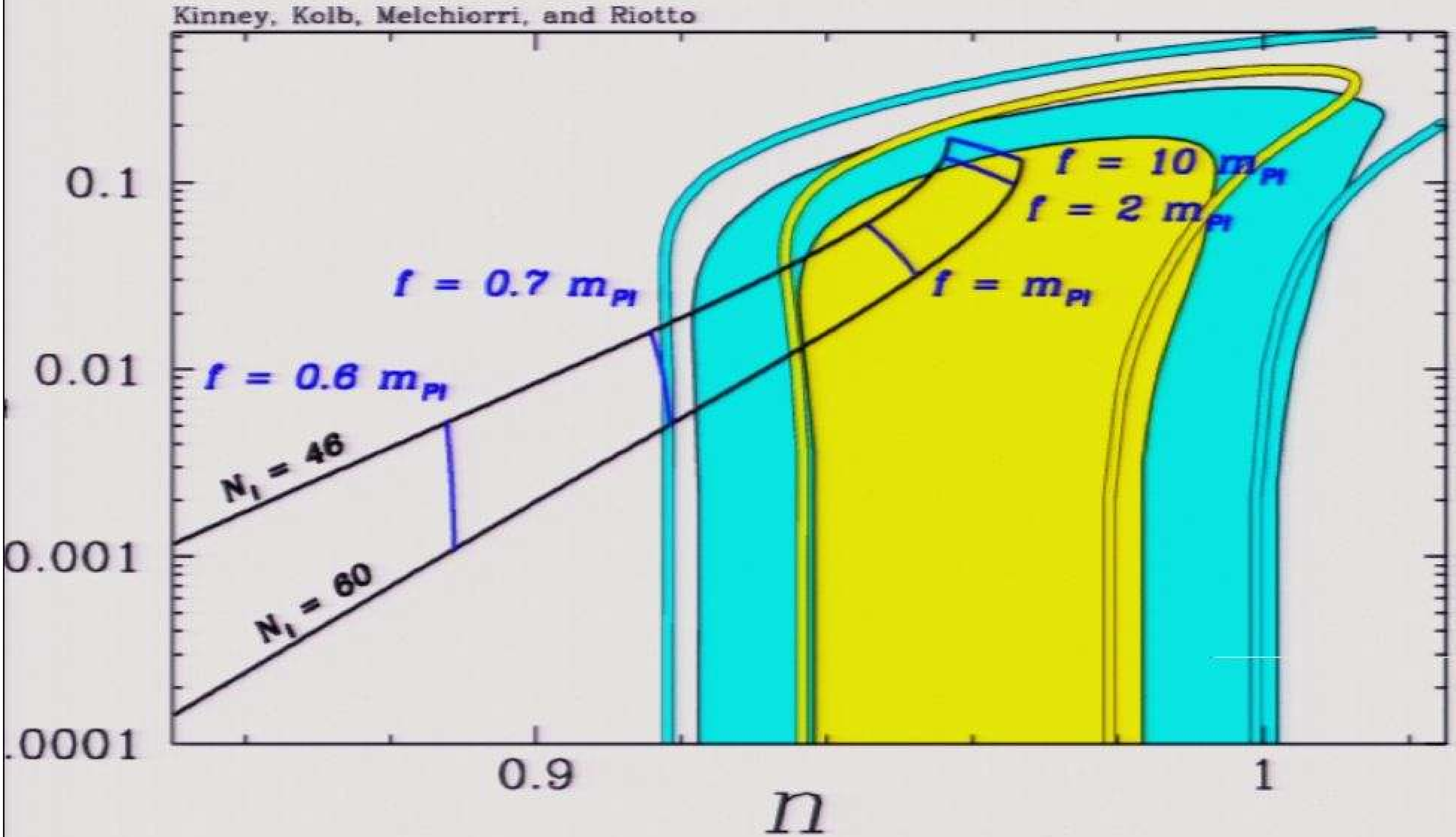
Frieman, Freese & Olinto, PRL **65** (1990) 3233

Natural Inflation: WMAP3 limits



Savage, Freese, WHK, hep-ph/0609144

Tensors: what does inflation predict?

- Does a red spectrum *imply* $r > 0.01$?

  Boyle, Steinhardt, Turok, arXiv:astro-ph/0507455
  Pagano, Cooray, Melchiorri, Kaminokowski, arXiv:0707.2560

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Counterexample:

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

$$\delta \propto \left(\frac{\Lambda}{\mu}\right)^2 \qquad r \propto \left(\frac{\mu}{m_{\rm Pl}}\right)^4 \ll 1$$

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

Knox & Turner, astro-ph/9209006; WHK & Mahanthappa, hep-ph/9512241

A more detailed counterexample

Generic gauge theory:

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} Tr\left[F_{\mu\nu} F^{\mu\nu}\right] - \lambda \left(\phi^\dagger \phi - v^2\right)^2$$

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Scalar sector:
$SO(3) \rightarrow SO(2)$

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Gauge sector: $U(1)$

Scalar sector:
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WHK & Mahanthappa, hep-ph/9512241

A more detailed counterexample

Generic gauge theory:

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Gauge sector: $U(1)$

Scalar sector: $SO(3) \to SO(2)$

Pseudo-Goldstone mode θ, one-loop mass:

$$M^2(\theta) = g^2 v^2 \sin^2(\theta / v)$$

$$V(\theta) = \frac{3}{64\pi^2} \left[M^2(\theta)\right]^2 \ln\left(\frac{M^2(\theta)}{v}\right)$$

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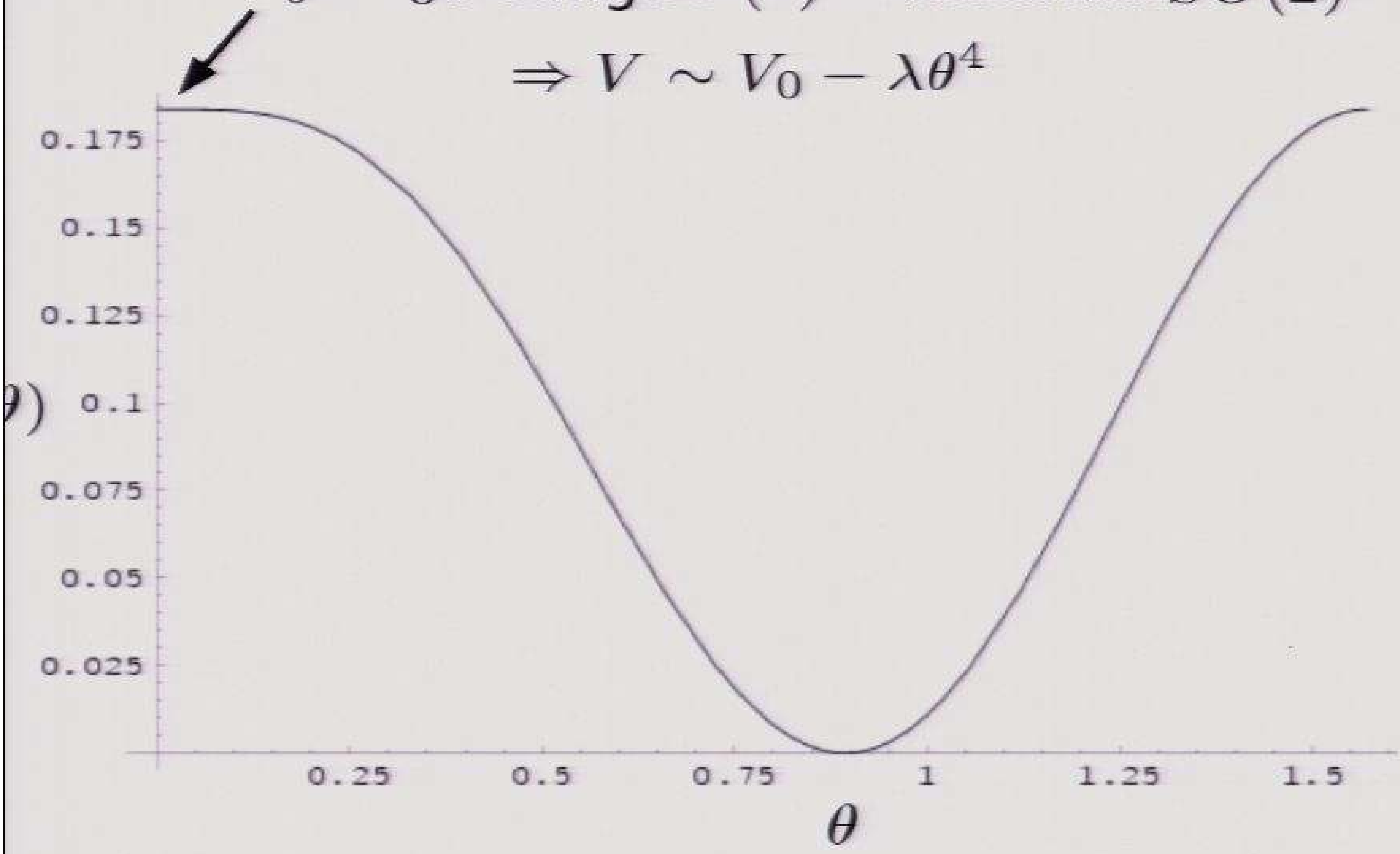
Inflaton mass suppressed to *all loops*

$\theta = 0$: Gauge $U(1)$ = Residual $SO(2)$

$\Rightarrow V \sim V_0 - \lambda\theta^4$



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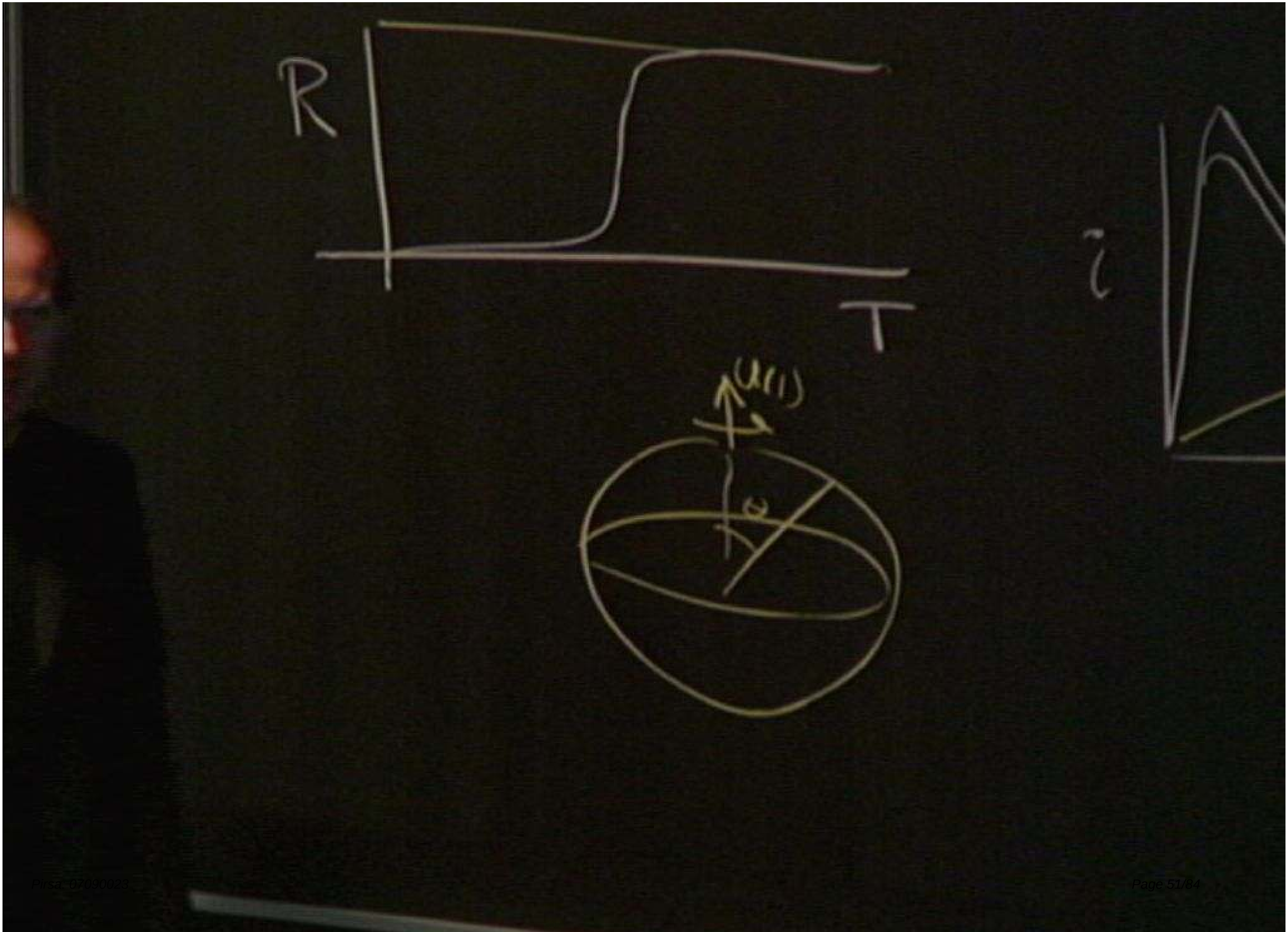
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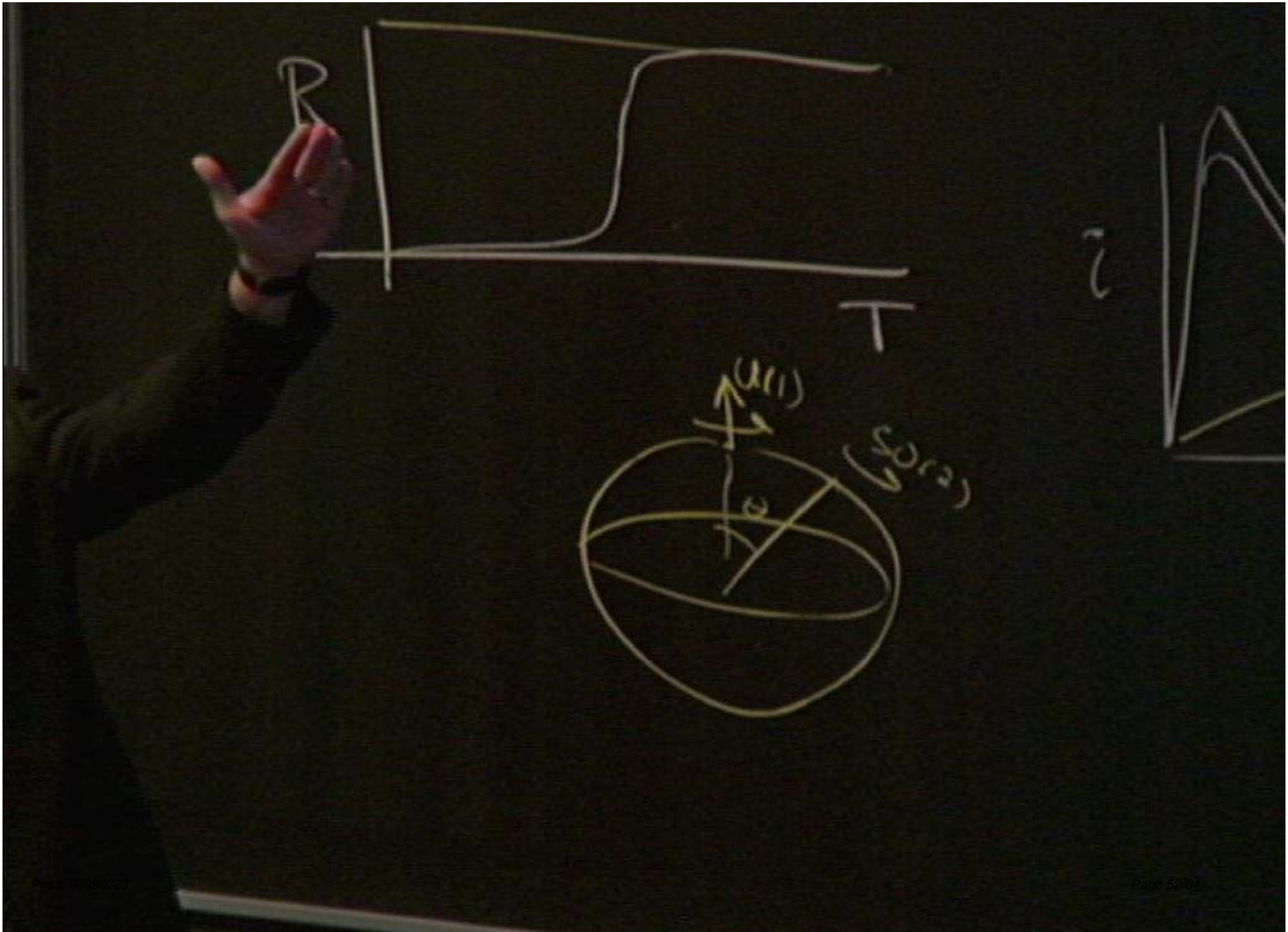
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U(1)
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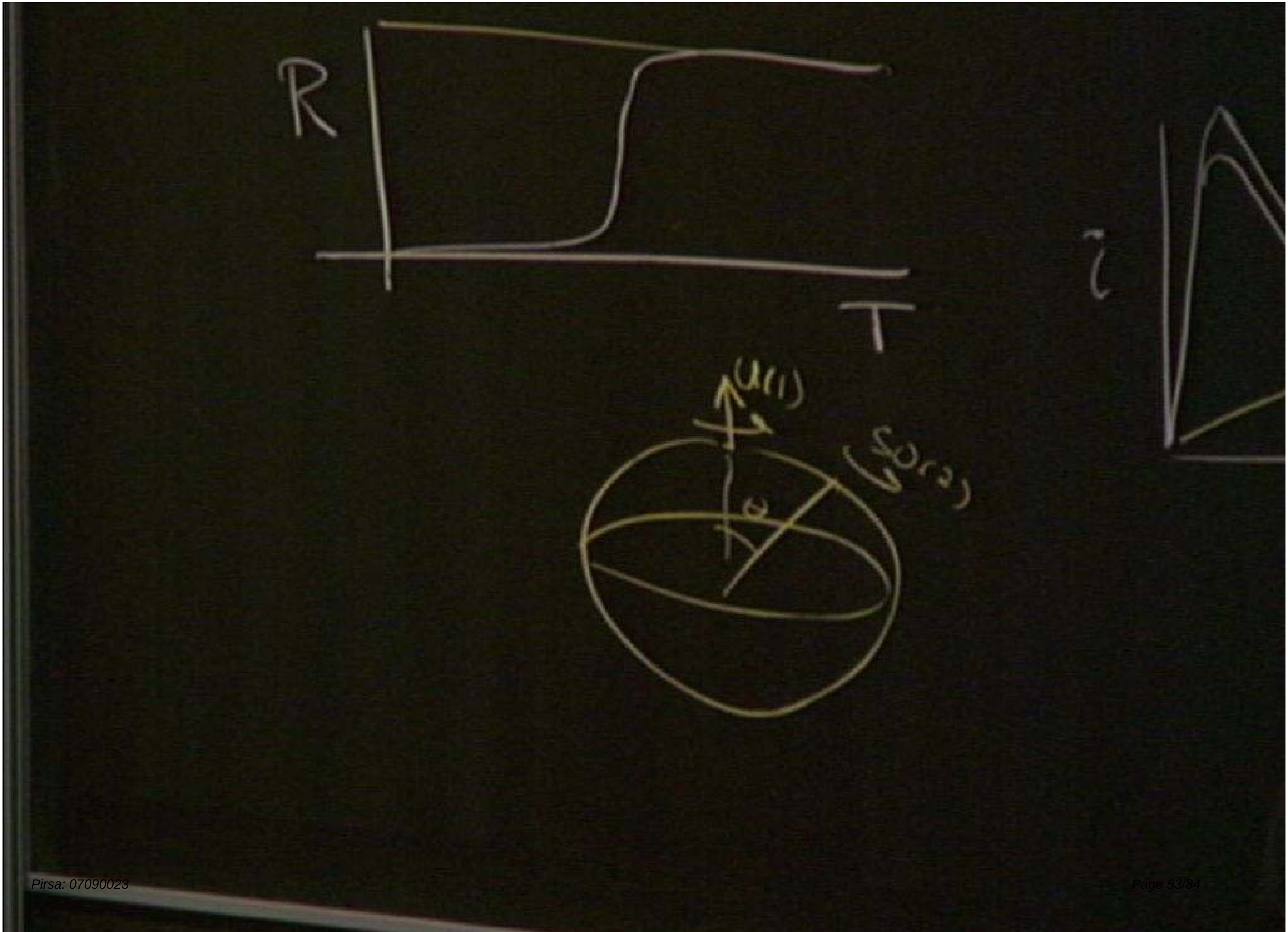
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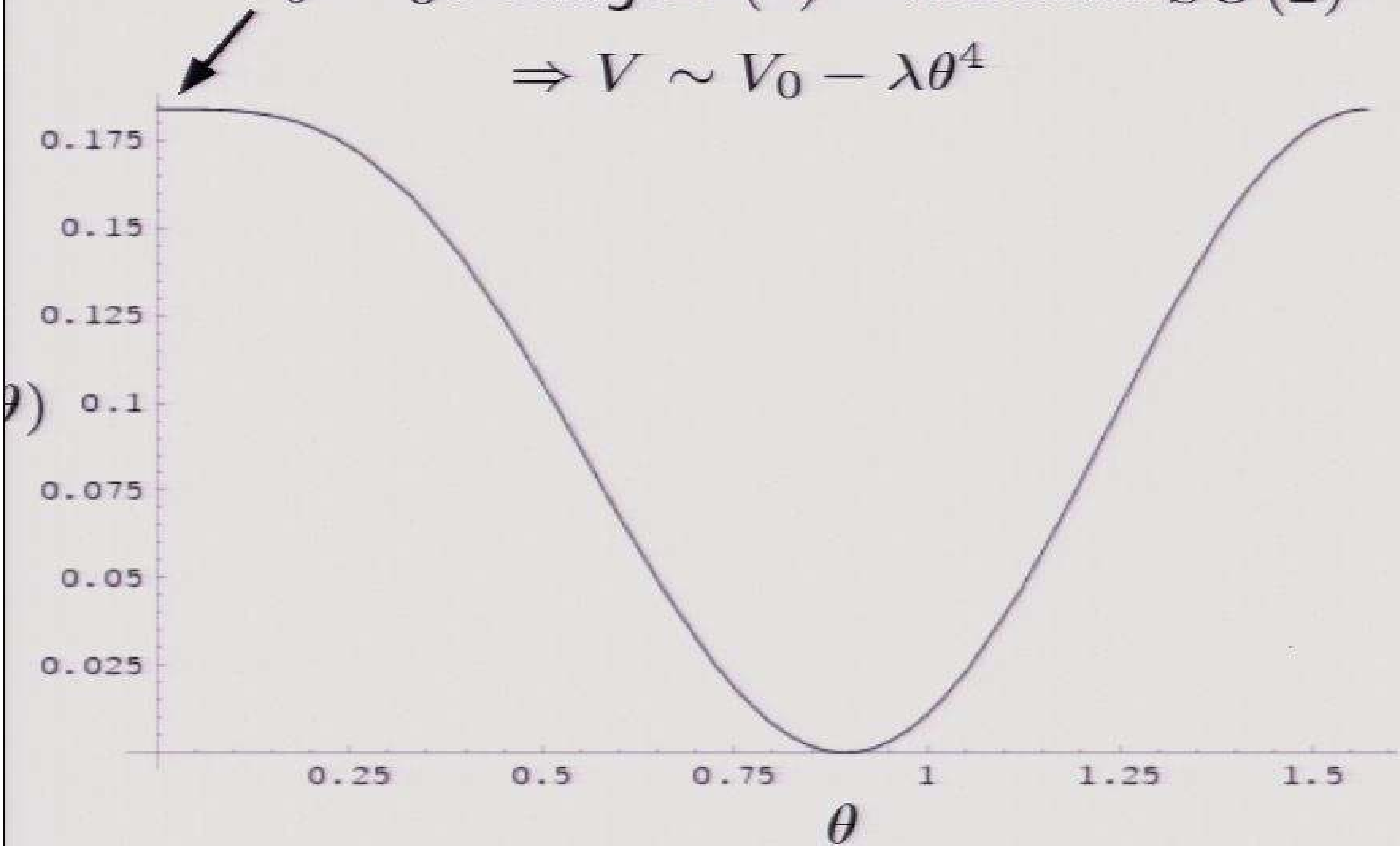
$$\Rightarrow V \sim V_0 - \lambda\theta^4$$



WHK & Mahanthappa, hep-ph/9512241

A more detailed counterexample

Generic gauge theory:

$$\mathcal{L} = \boxed{(D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} Tr\left[F_{\mu\nu}F^{\mu\nu}\right]} - \boxed{\lambda\left(\phi^\dagger\phi - v^2\right)^2}$$

Gauge sector: $U(1)$

Scalar sector:
$SO(3) \rightarrow SO(2)$

Pseudo-Goldstone mode θ, one-loop mass:

$$M^2(\theta) = g^2 v^2 \sin^2(\theta/v)$$

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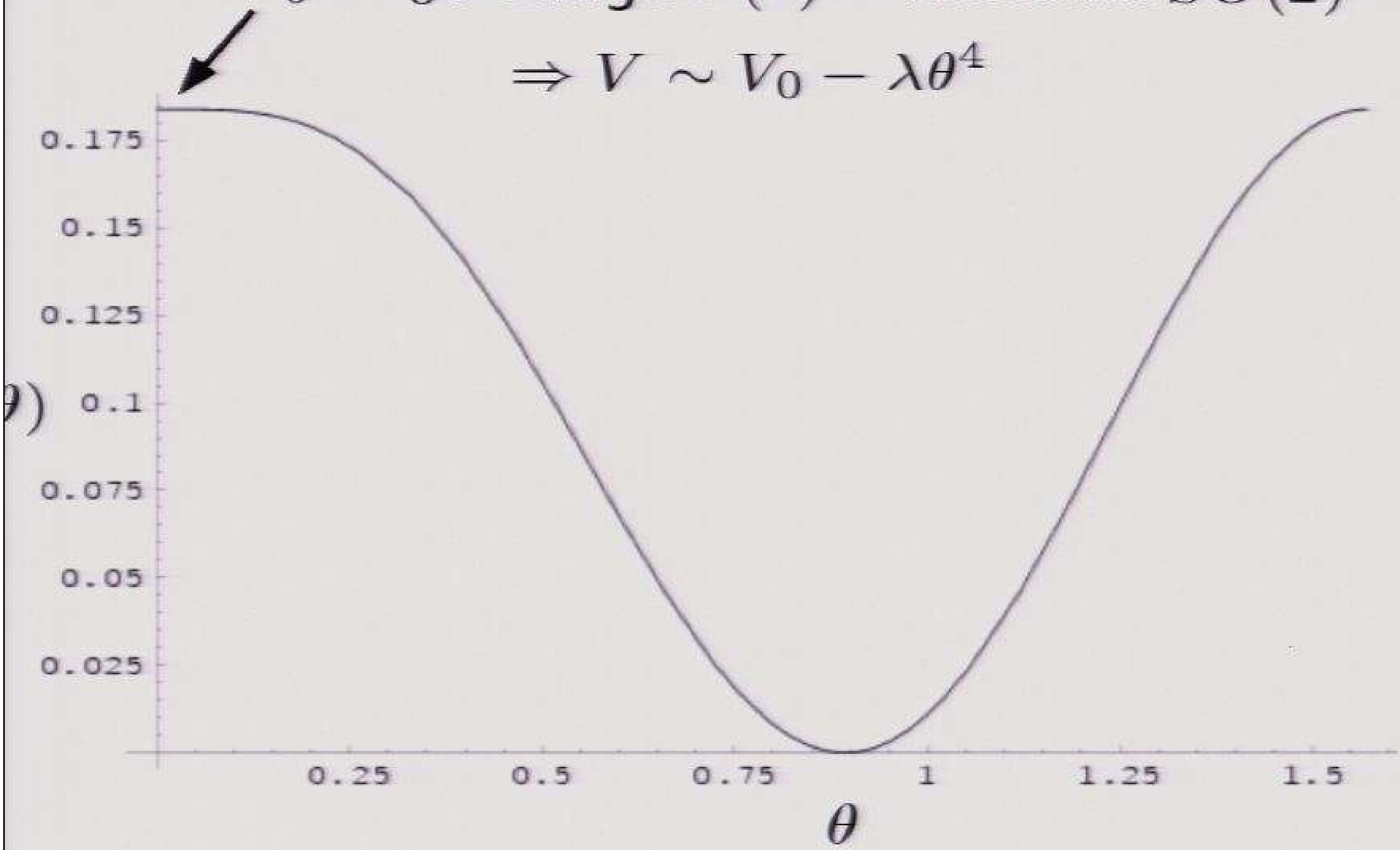

WHK & Mahanthappa, hep-ph/9512241

Toward inflation on the landscape

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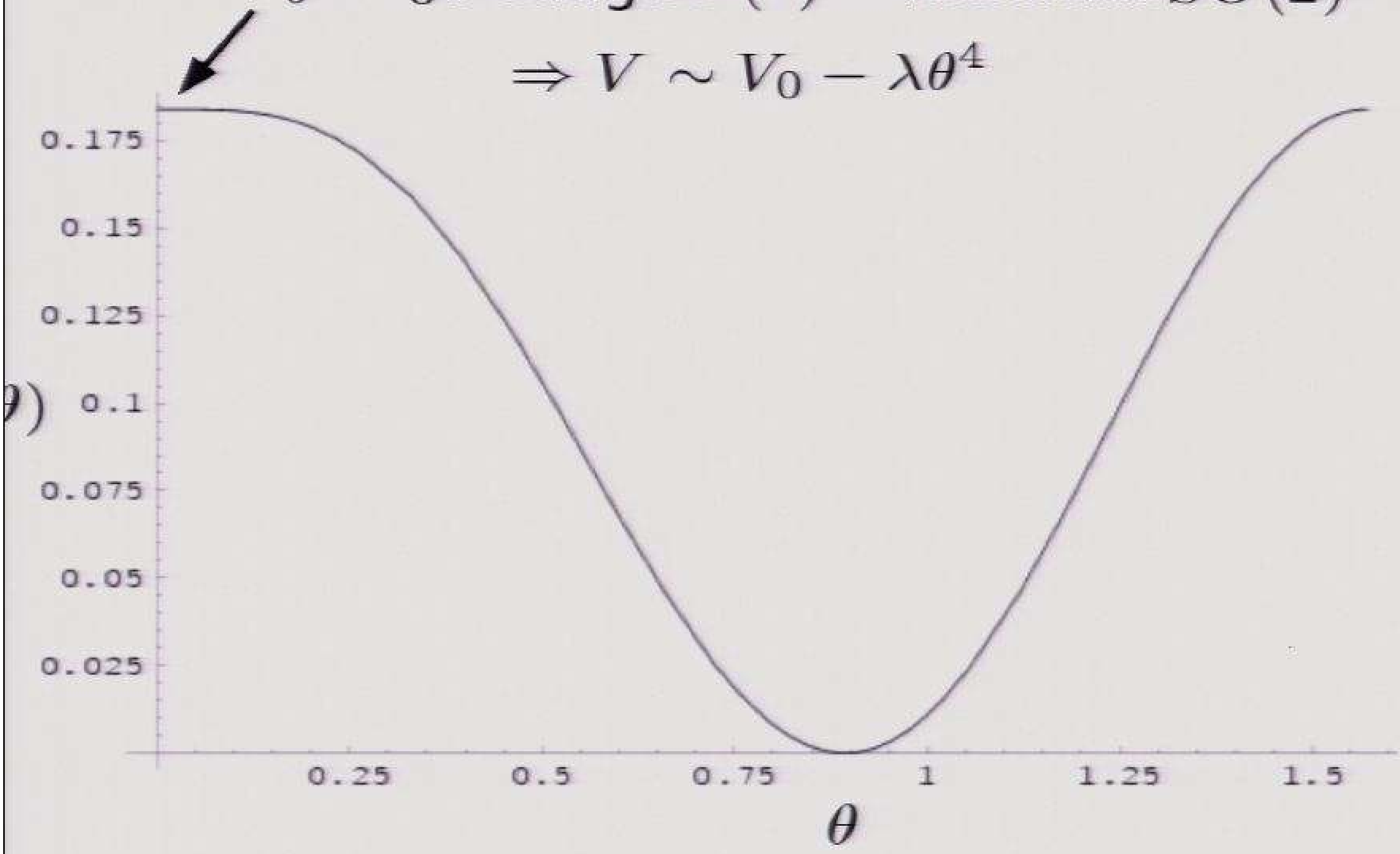

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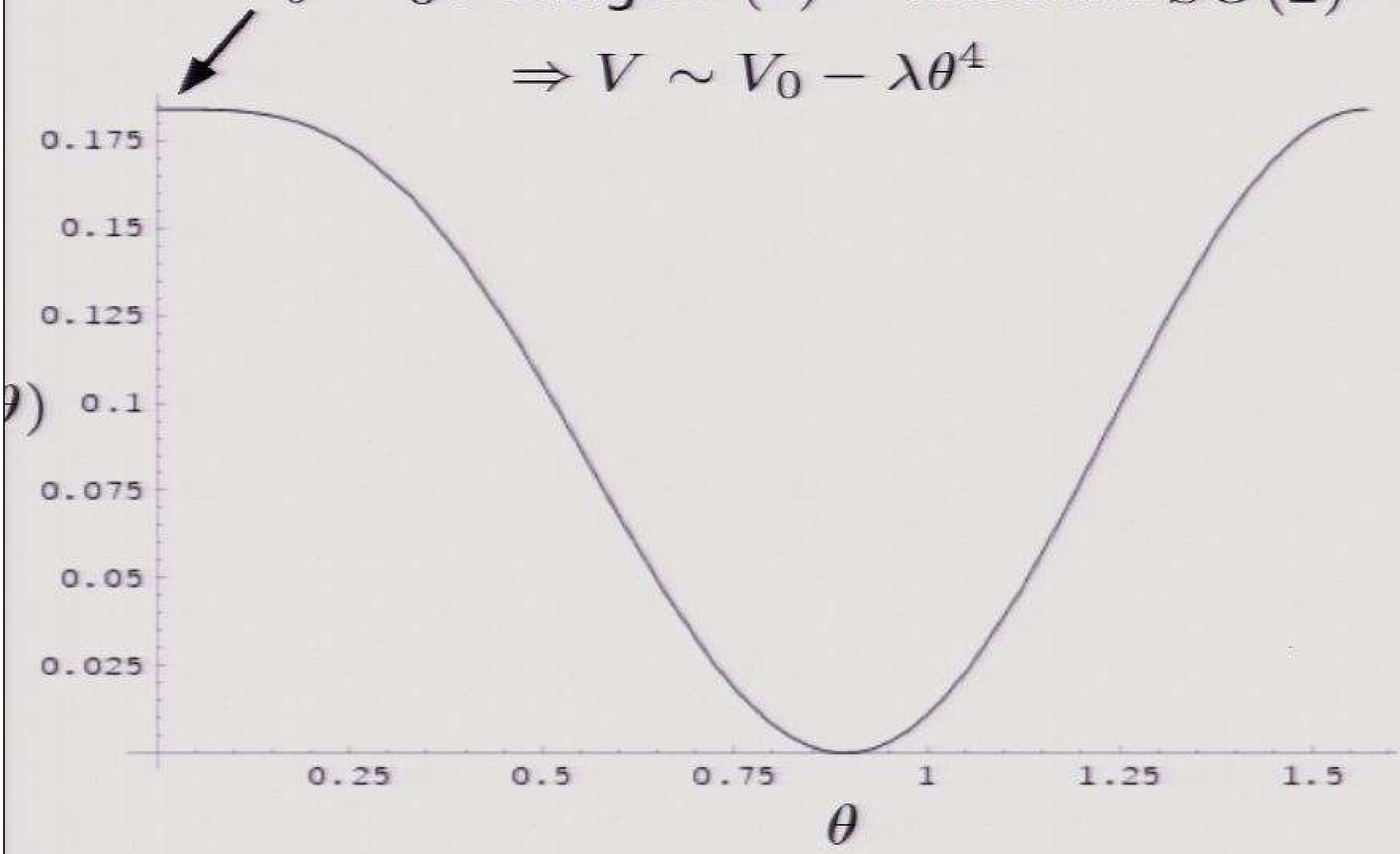


WHK & Mahanthappa, hep-ph/9512241

Toward inflation on the landscape

The slow roll hierarchy

First-order slow roll parameters:

$$\epsilon \equiv \frac{m_{\rm Pl}^2}{4\pi}\left[\frac{H'(\phi)}{H(\phi)}\right]^2 \qquad \eta \equiv \frac{m_{\rm Pl}^2}{4\pi}\left[\frac{H''(\phi)}{H(\phi)}\right]$$

Observables:

$$r \simeq \epsilon$$

$$n - 1 \simeq 4\epsilon - 2\eta \equiv \sigma$$

Evolution:

$\frac{d}{dt} \rightarrow \frac{d}{d\phi} \Rightarrow$ infinite slow roll hierarchy:

$$^{\ell}\lambda_{\rm H} \equiv \left(\frac{m_{\rm Pl}^2}{4\pi}\right)^{\ell} \frac{(H')^{\ell-1}}{H^{\ell}} \frac{d^{(\ell+1)}H}{d\phi^{(\ell+1)}}$$

(Liddle, Parsons & Barrow, astro-ph/9408015)

Flow equations

$N \equiv$ # of e-folds before end of inflation

$$\frac{d}{dN} \propto \sqrt{\epsilon}\frac{d}{d\phi} \qquad dN > 0 \Rightarrow dt < 0$$

$$\frac{d\epsilon}{dN} = \epsilon\left(\sigma + 2\epsilon\right)$$

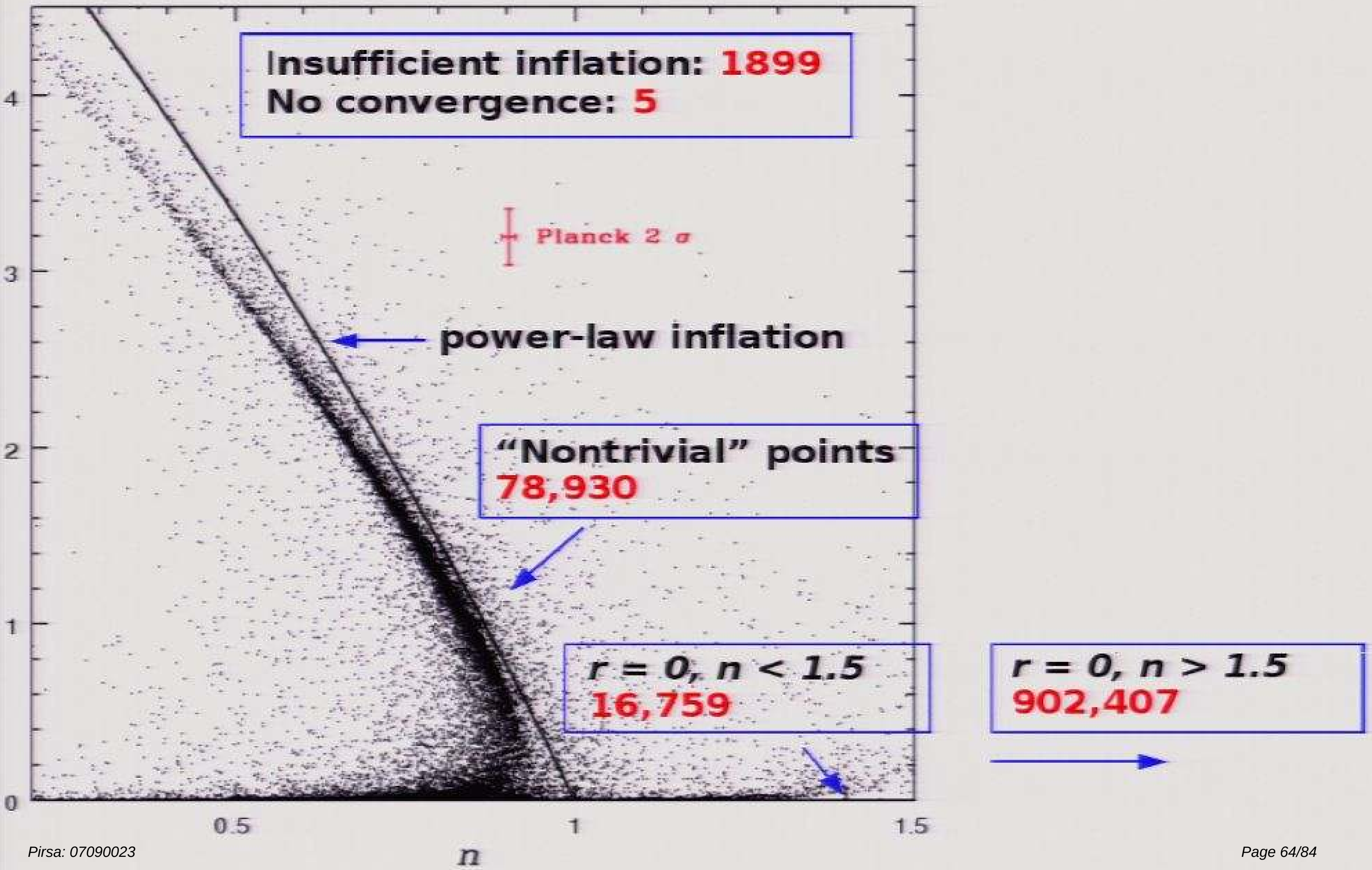
$$\frac{d\sigma}{dN} = -5\epsilon\sigma - 12\epsilon^2 + 2\left({}^2\lambda_{\rm H}\right)$$

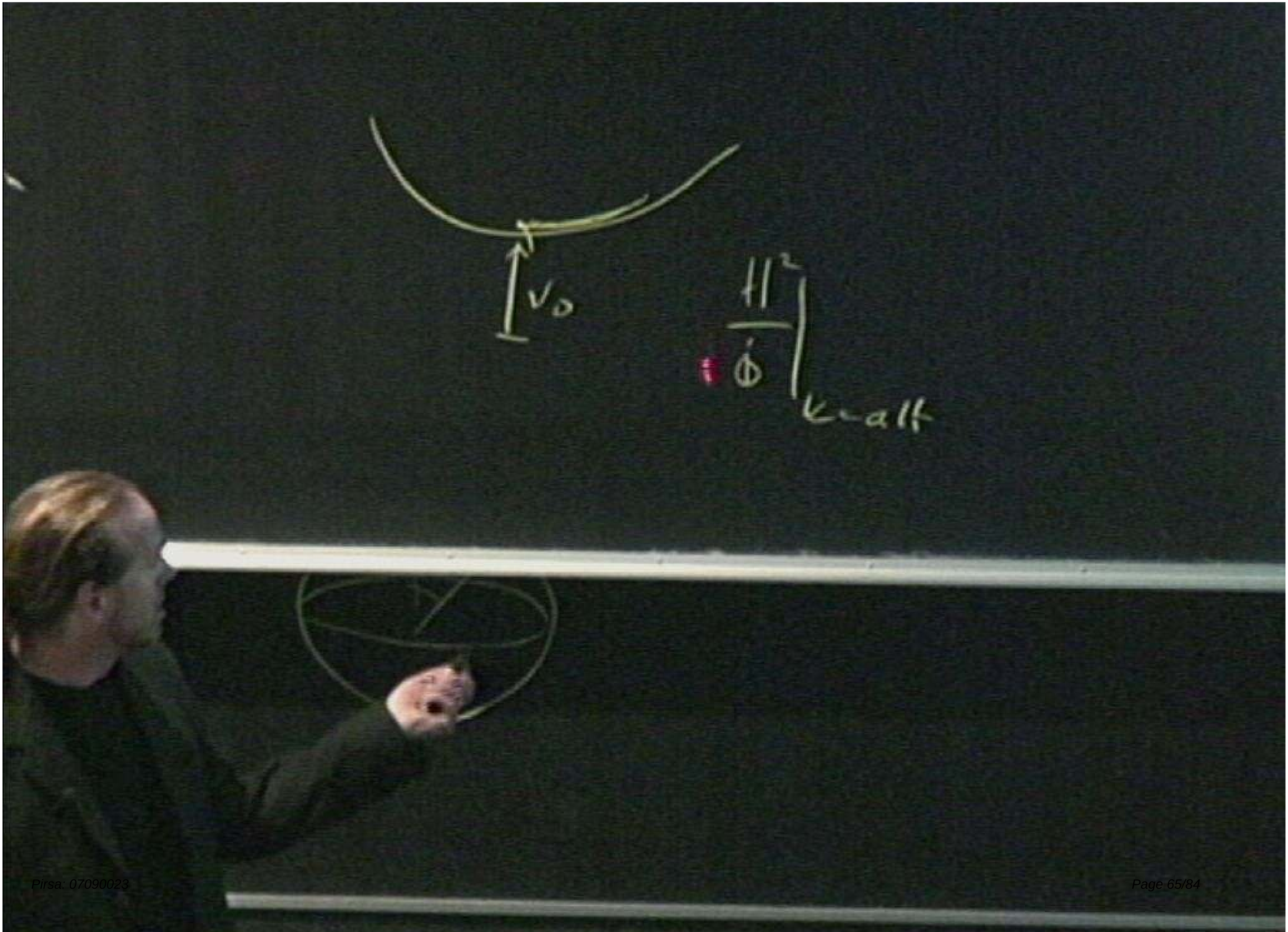
$$\frac{d\left({}^\ell\lambda_{\rm H}\right)}{dN} = \left[\frac{1}{2}\left(\ell - 1\right)\sigma + \left(\ell - 2\right)\epsilon\right]\left({}^\ell\lambda_{\rm H}\right) + {}^{\ell+1}\lambda_{\rm H}$$

(WHK, astro-ph/0206032, Schwarz, *et al.*, astro-ph/0106020)

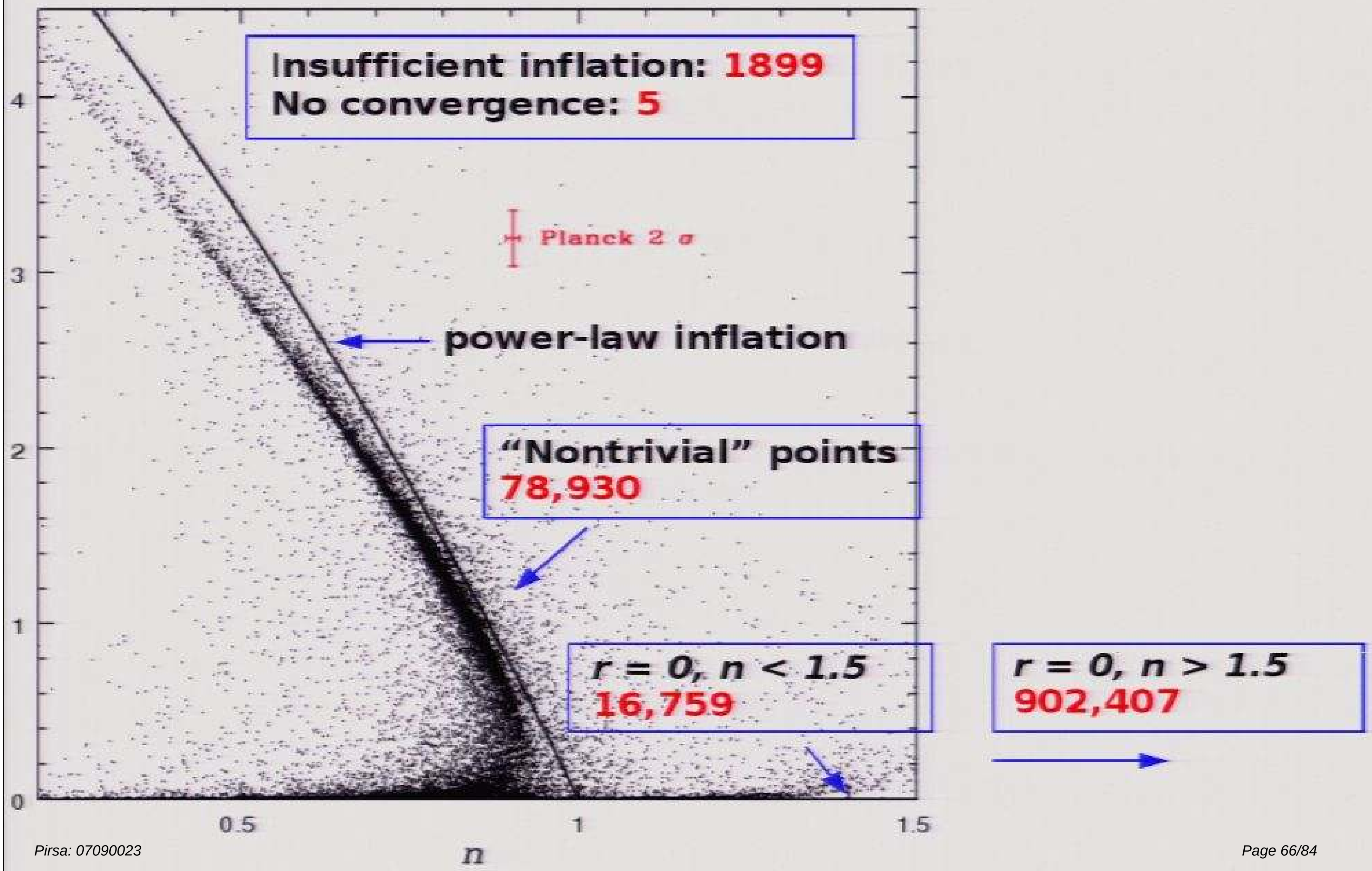
- Infinite set of differential equations (exact!)
- Completely specify evolution of spacetime.
- Model-independent parameterization: no potential. (Liddle, astro-ph/0307286: no physics either!)

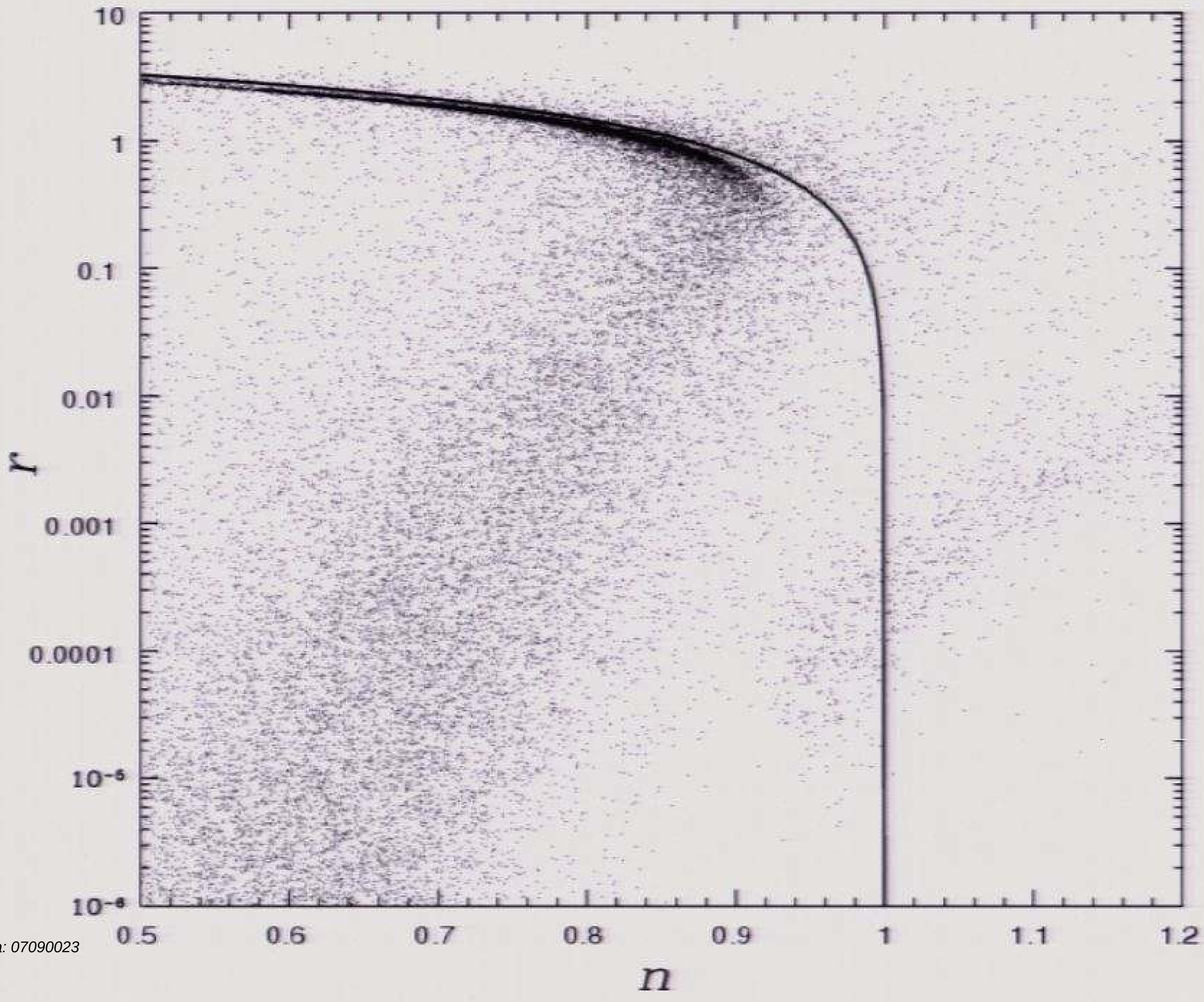
Monte Carlo of 1,000,000 inflation models




V_0
$\frac{H^2}{\dot\phi}\Big|_{k=aH}$

Monte Carlo of 1,000,000 inflation models

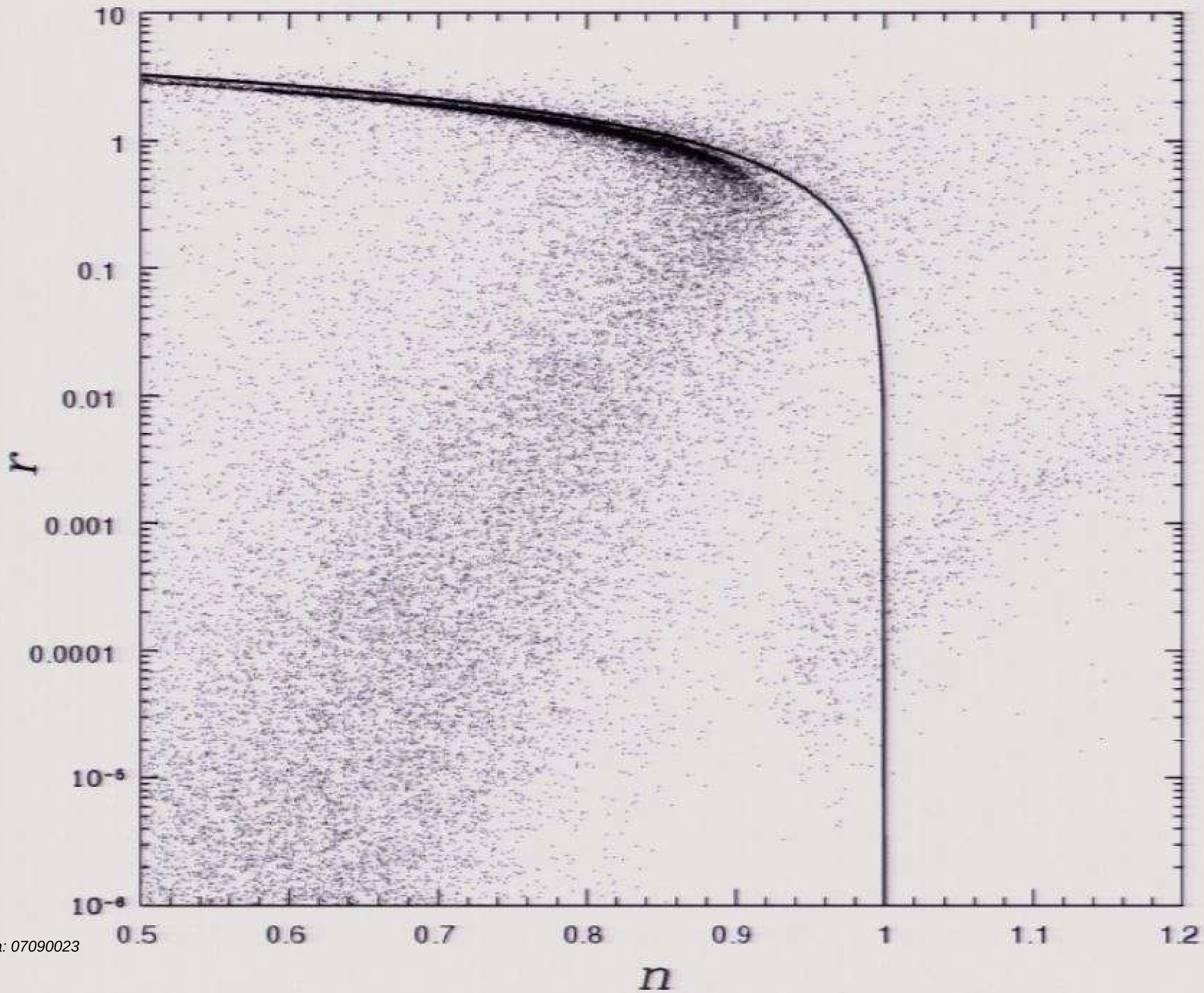



10
1
0.1
0.01
0.001
0.0001
10^{-5}
10^{-6}
r
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
n

Freaks in the landscape

How to look for "freak" models consistent with data:

- Stochastically generate models with flow eqs.
- Keep models which violate slow roll conditions
- Numerically calculate *exact* power spectra
- Keep models which are *statistically indistinguishable* from WMAP3 best-fit.


10
1
0.1
0.01
0.001
0.0001
10⁻⁵
10⁻⁶
r
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
n

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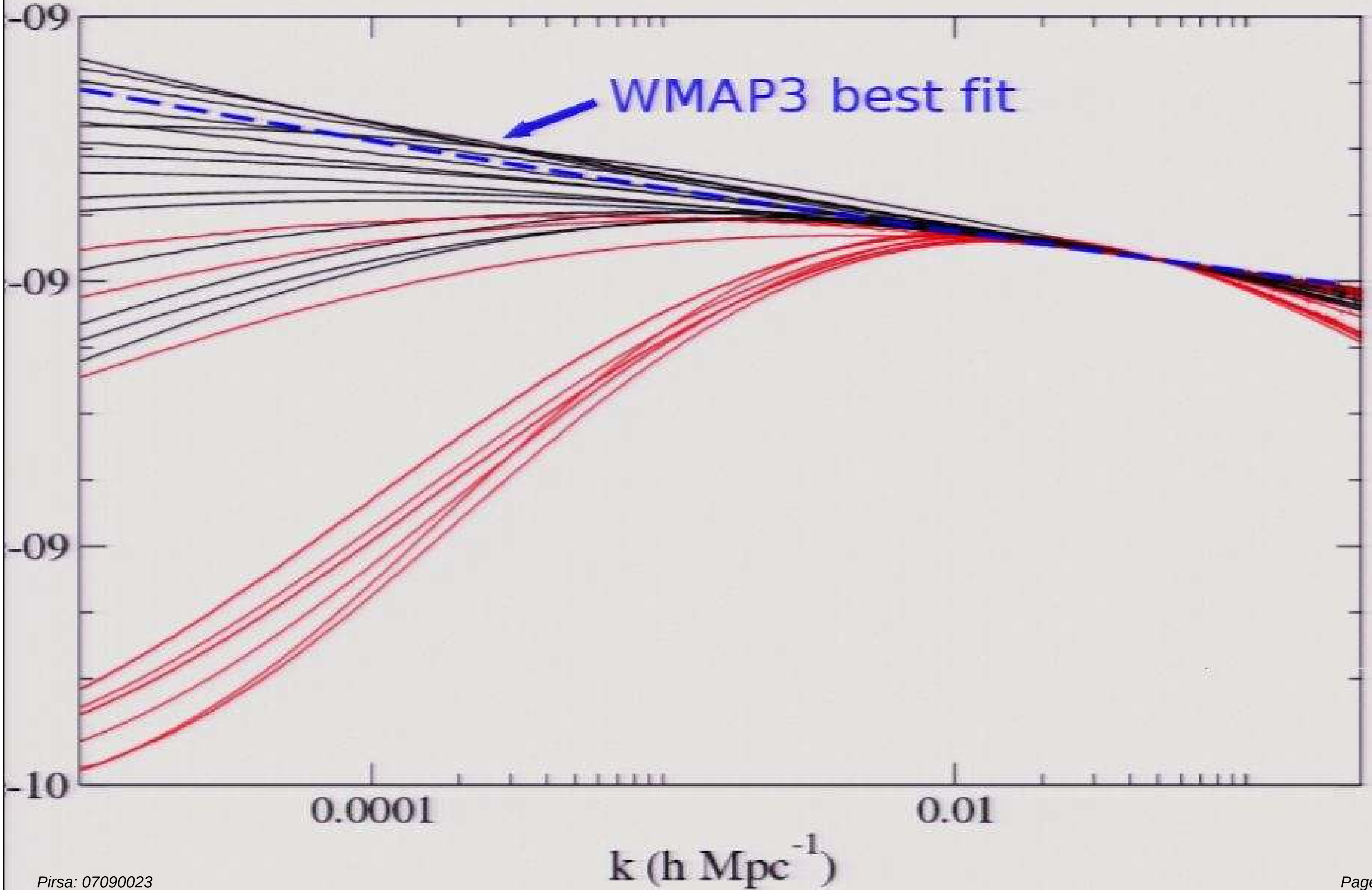
Freak power spectra



Powell, WHK arXiv:0706.1982

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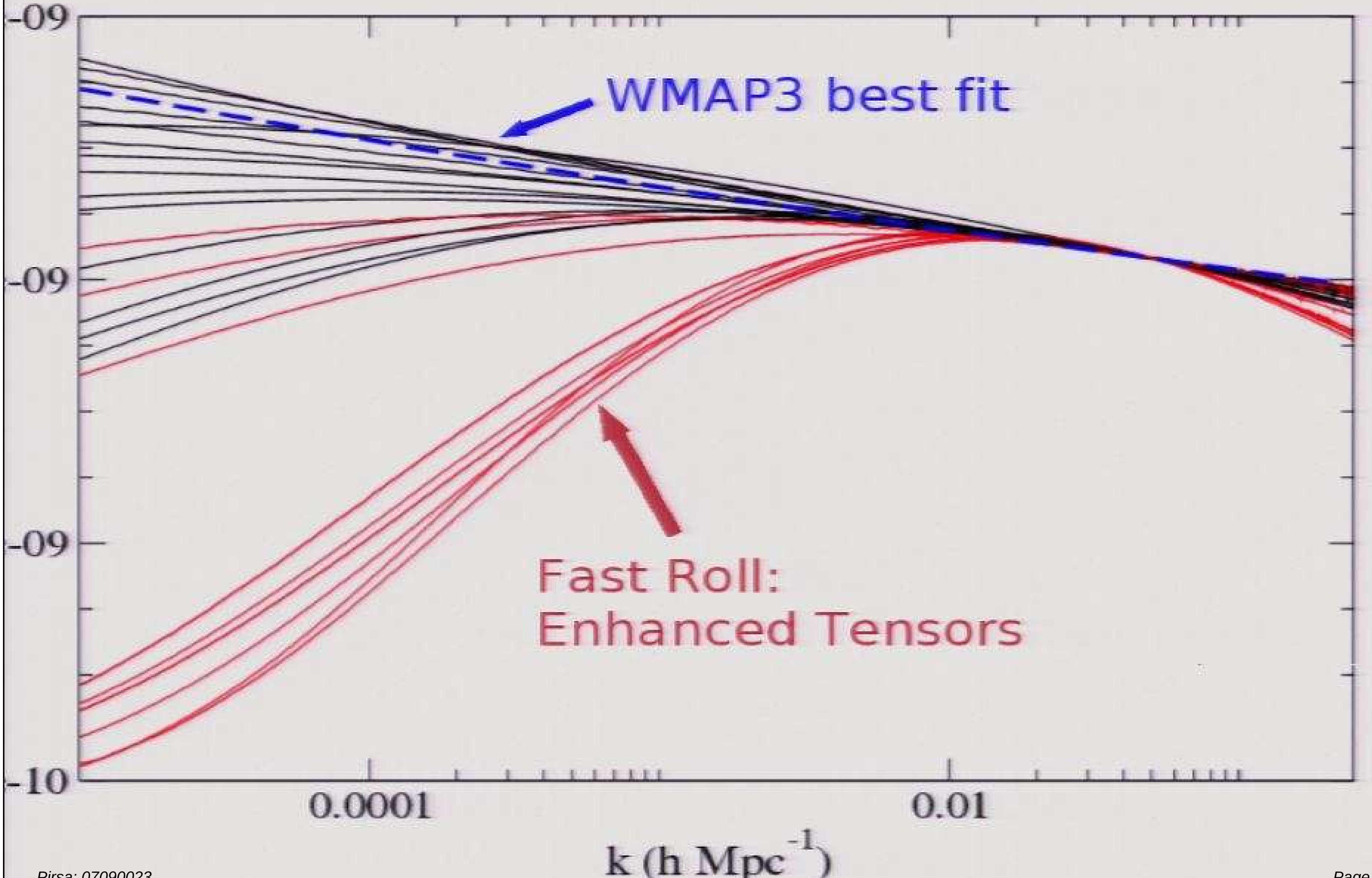

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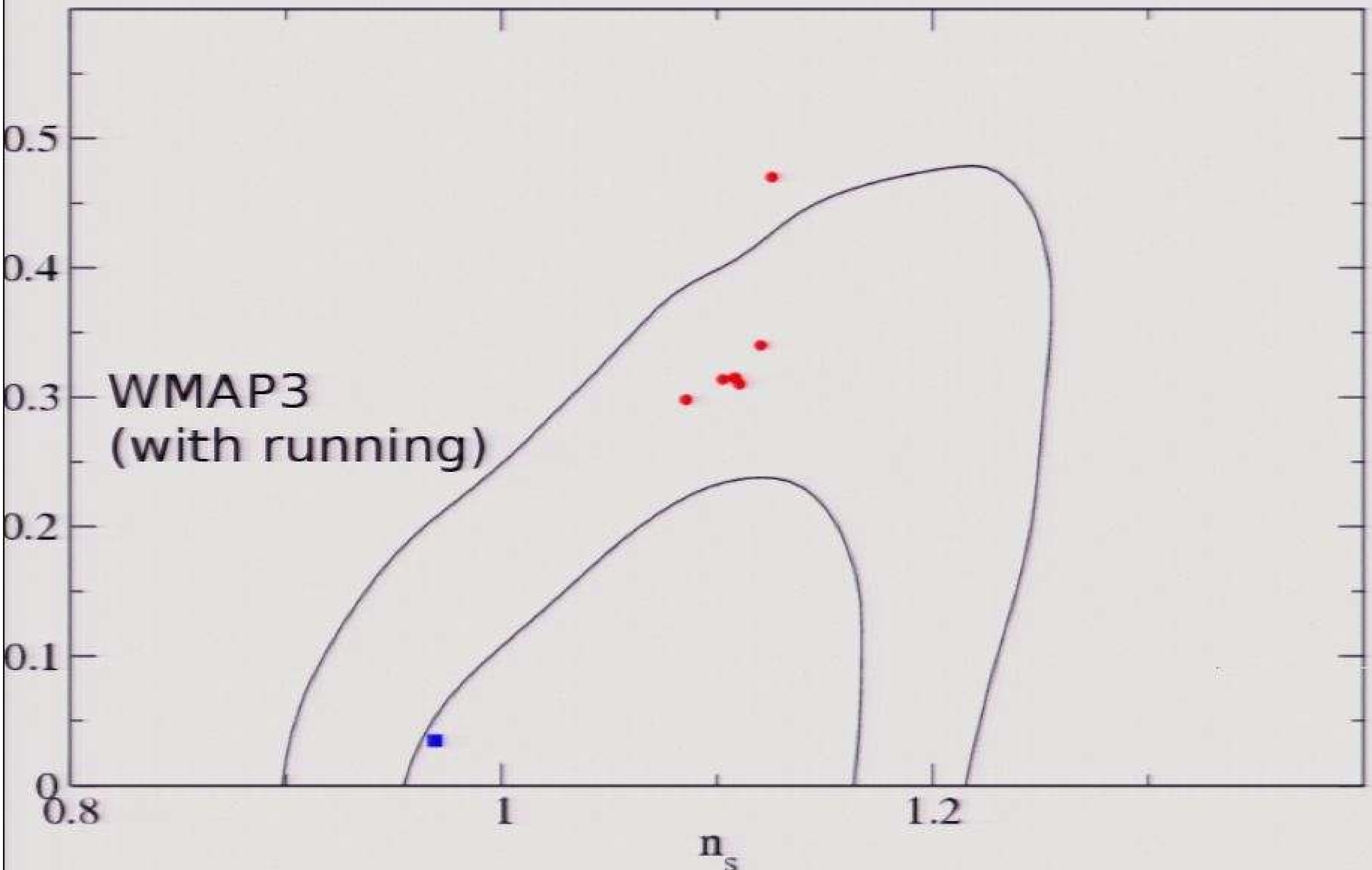
Fast roll and enhanced tensors



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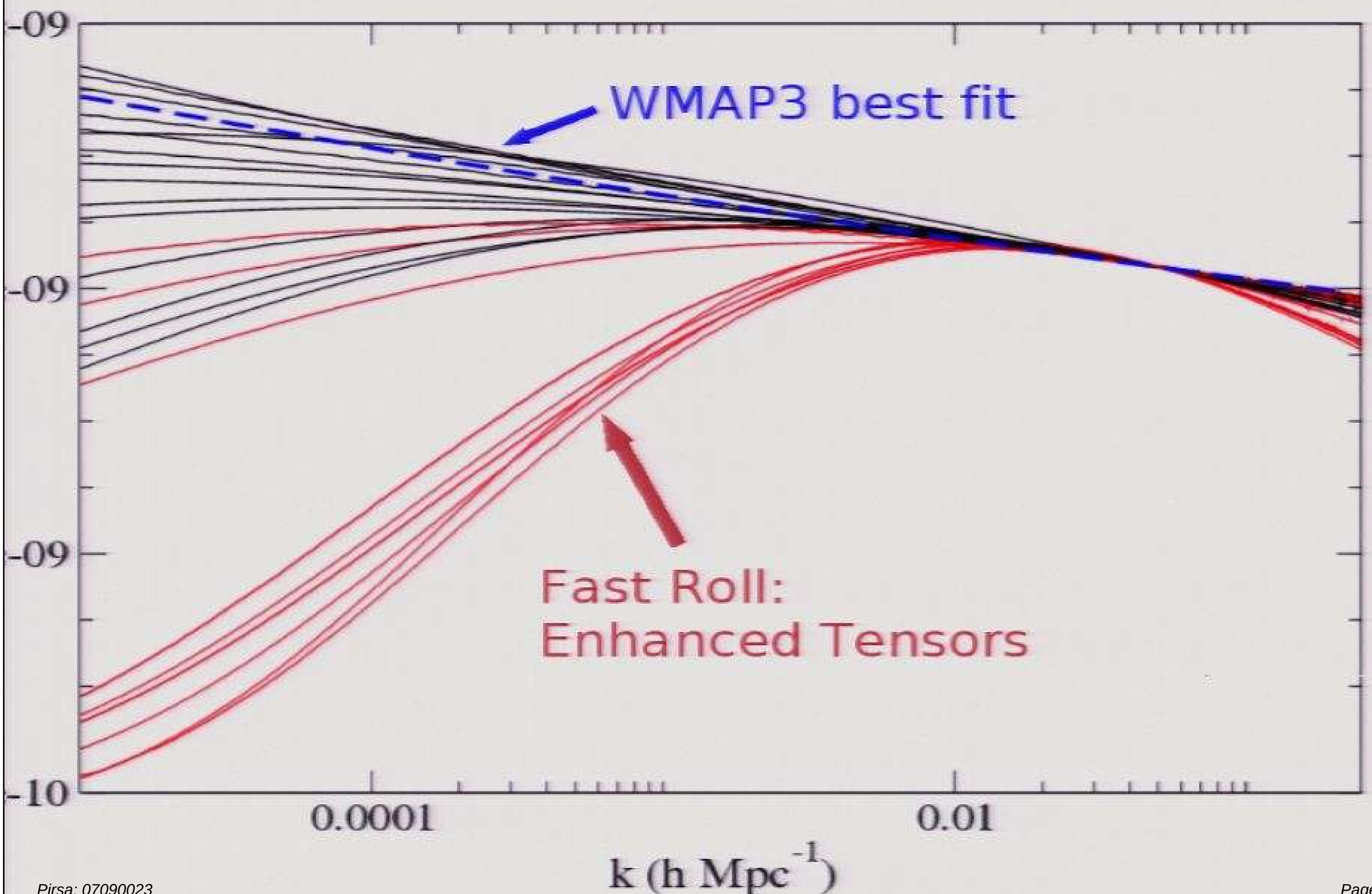
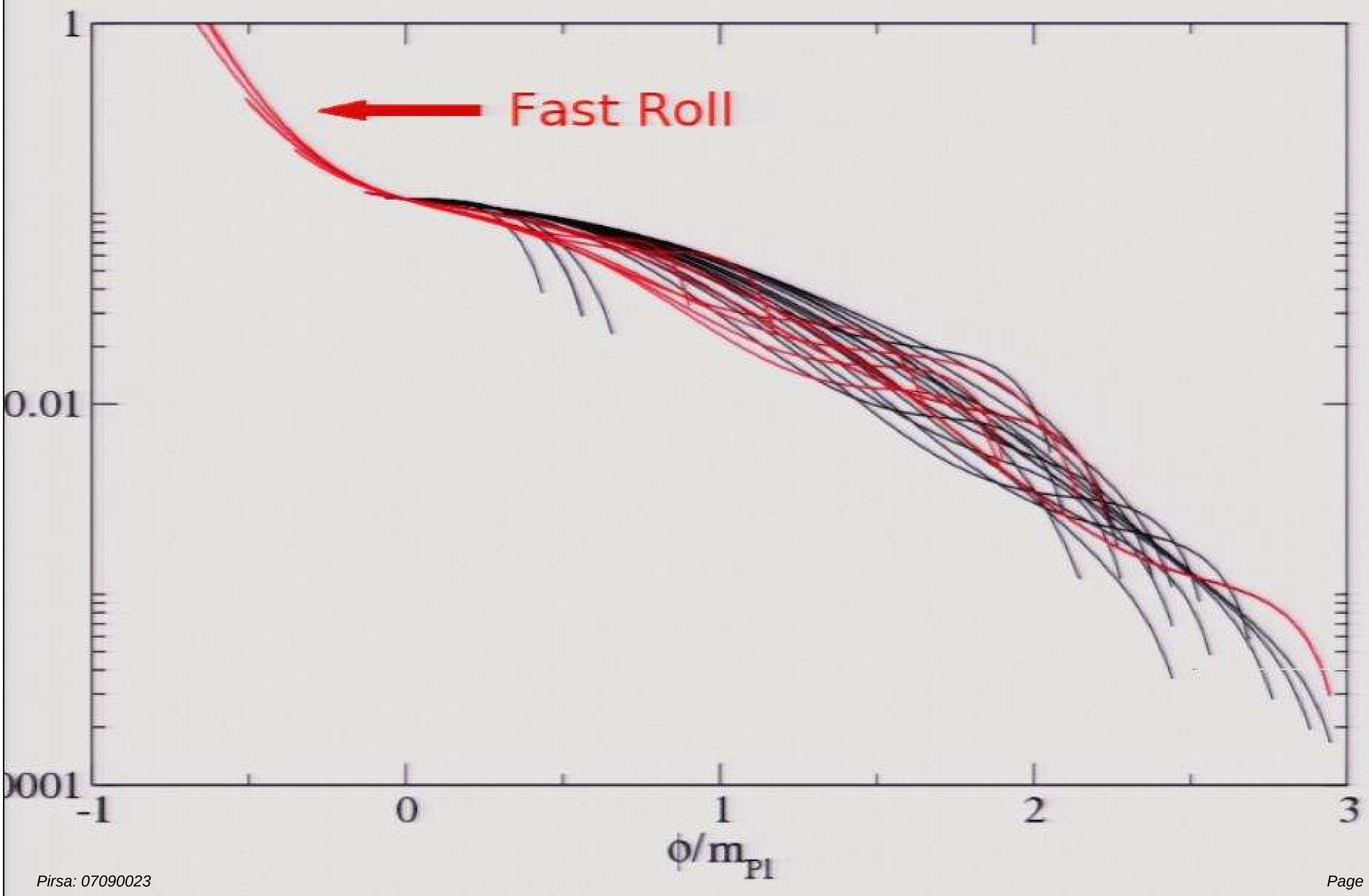
Freak power spectra



Powell, WHK arXiv:0706.1982

Freak potentials



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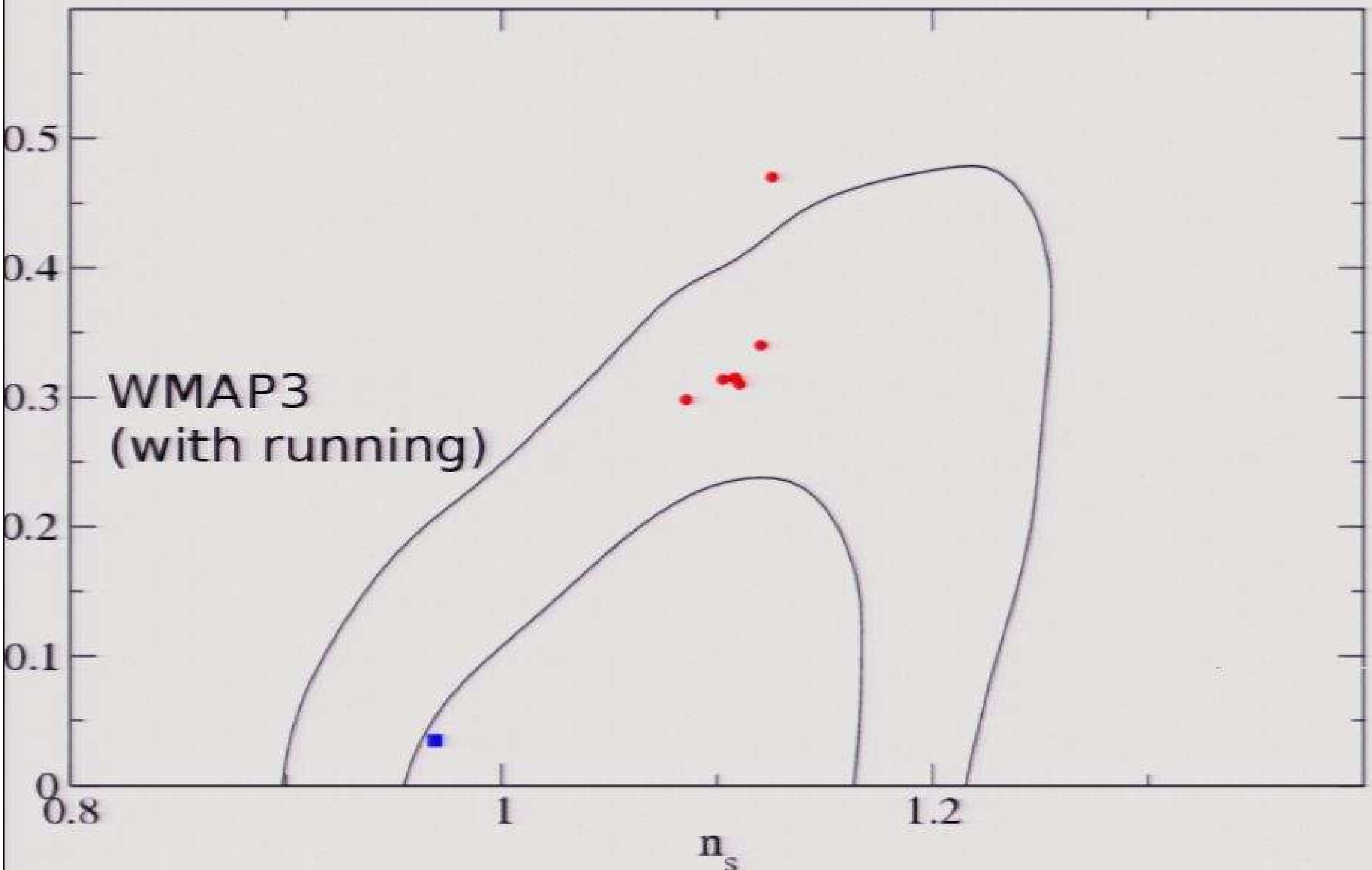

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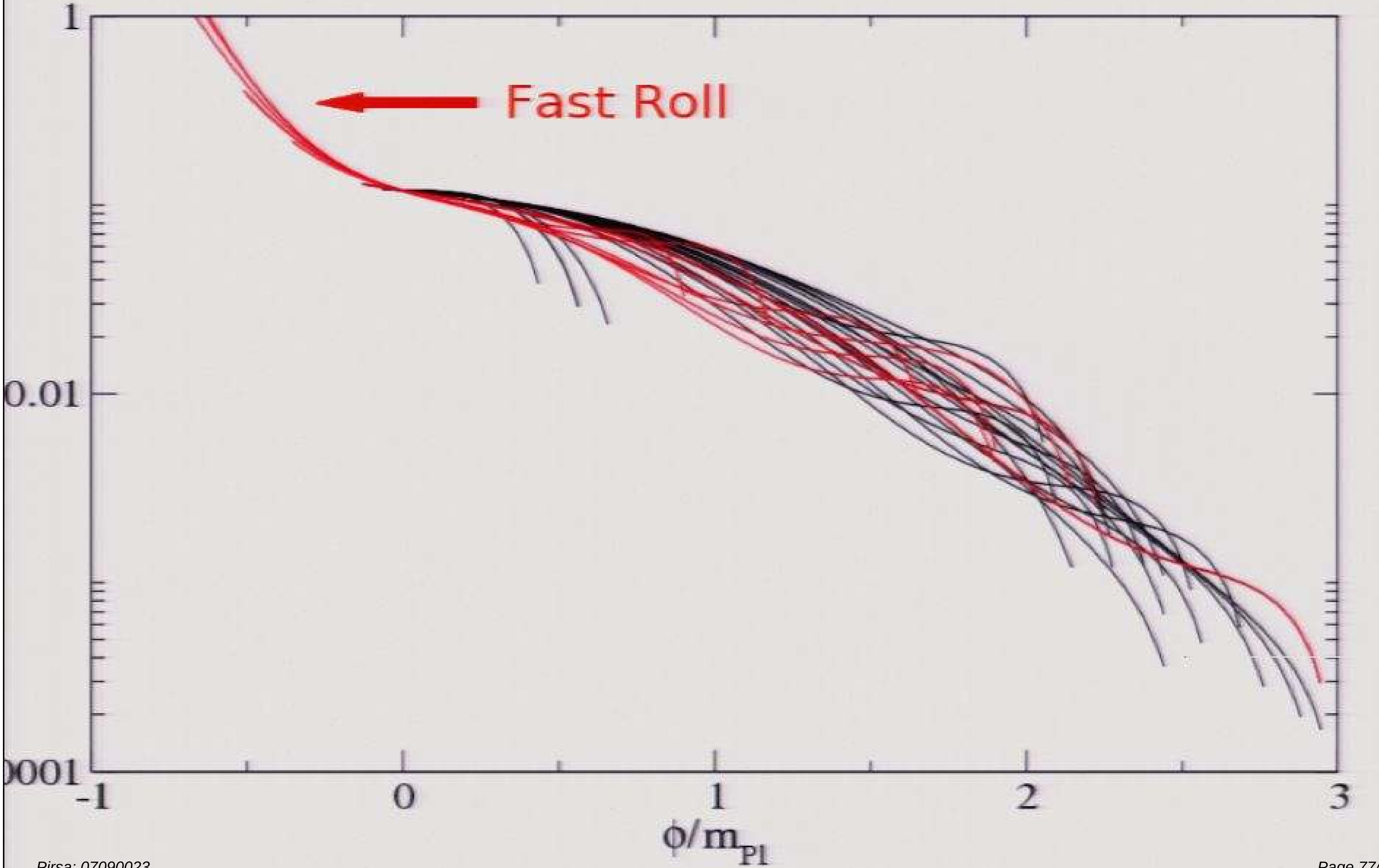


Powell, WHK arXiv:0706.1982

How many e-folds?

Number of e-folds which maps to the horizon today:

$$N = 60 + \frac{1}{3}\ln\left(\frac{T_{\rm RH}}{10^{16}\ {\rm GeV}}\right) - \frac{1}{3}\ln\gamma$$

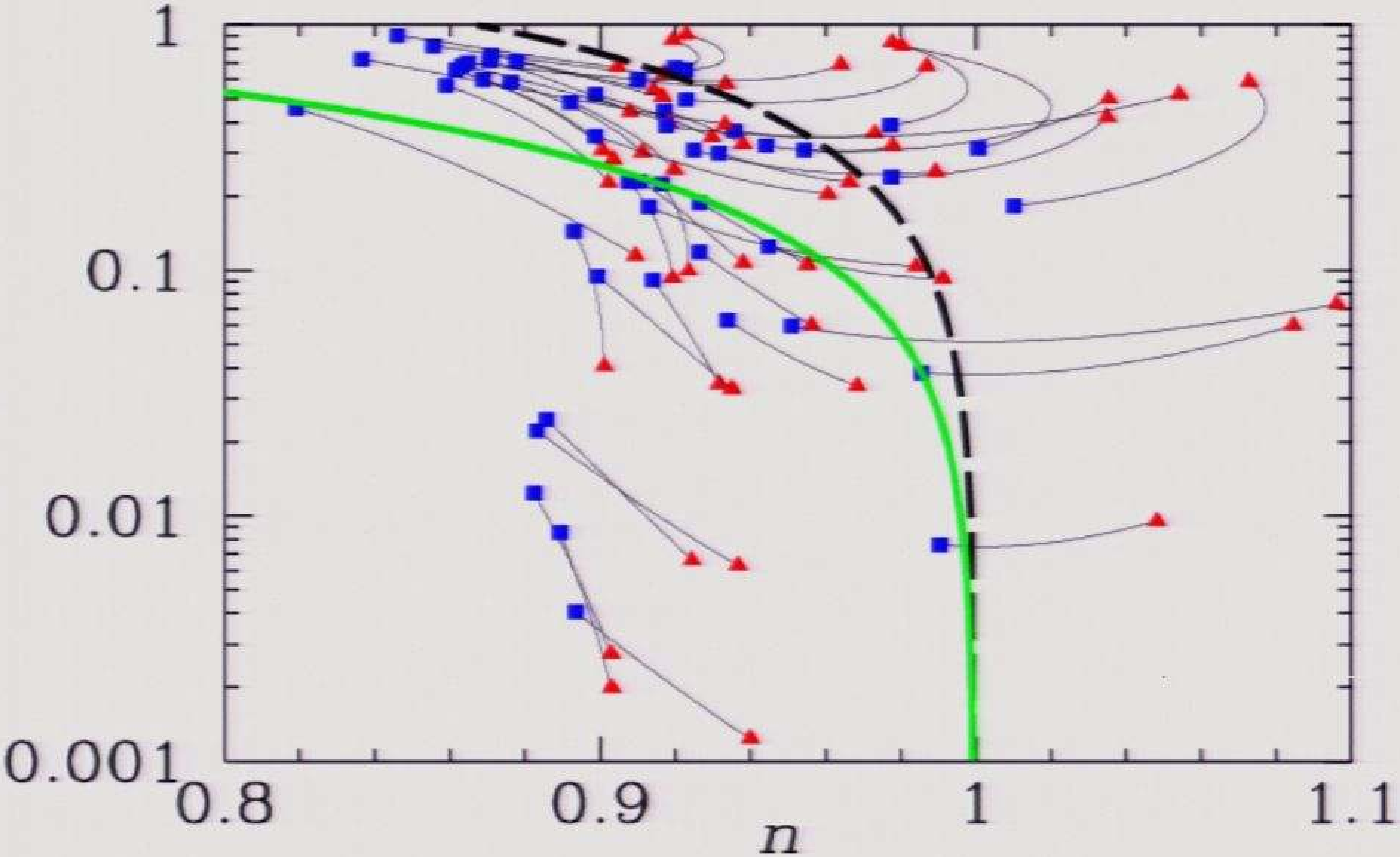
Reheat Temperature

Entropy production

Uncertainty in reheat temperature

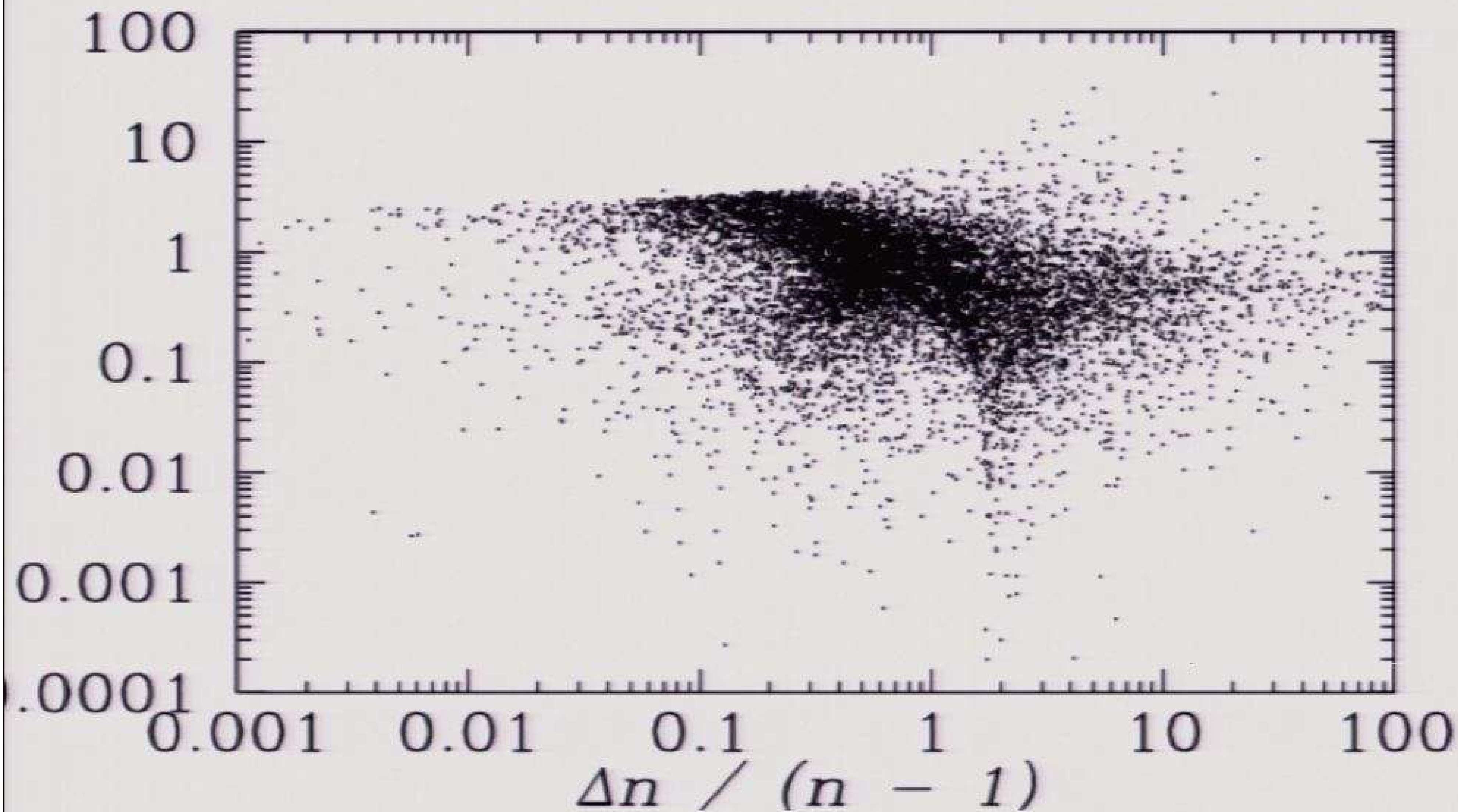
$$\Rightarrow N = [46, 60] - \frac{1}{3}\ln\gamma$$

Flow from N = 46 to N = 60

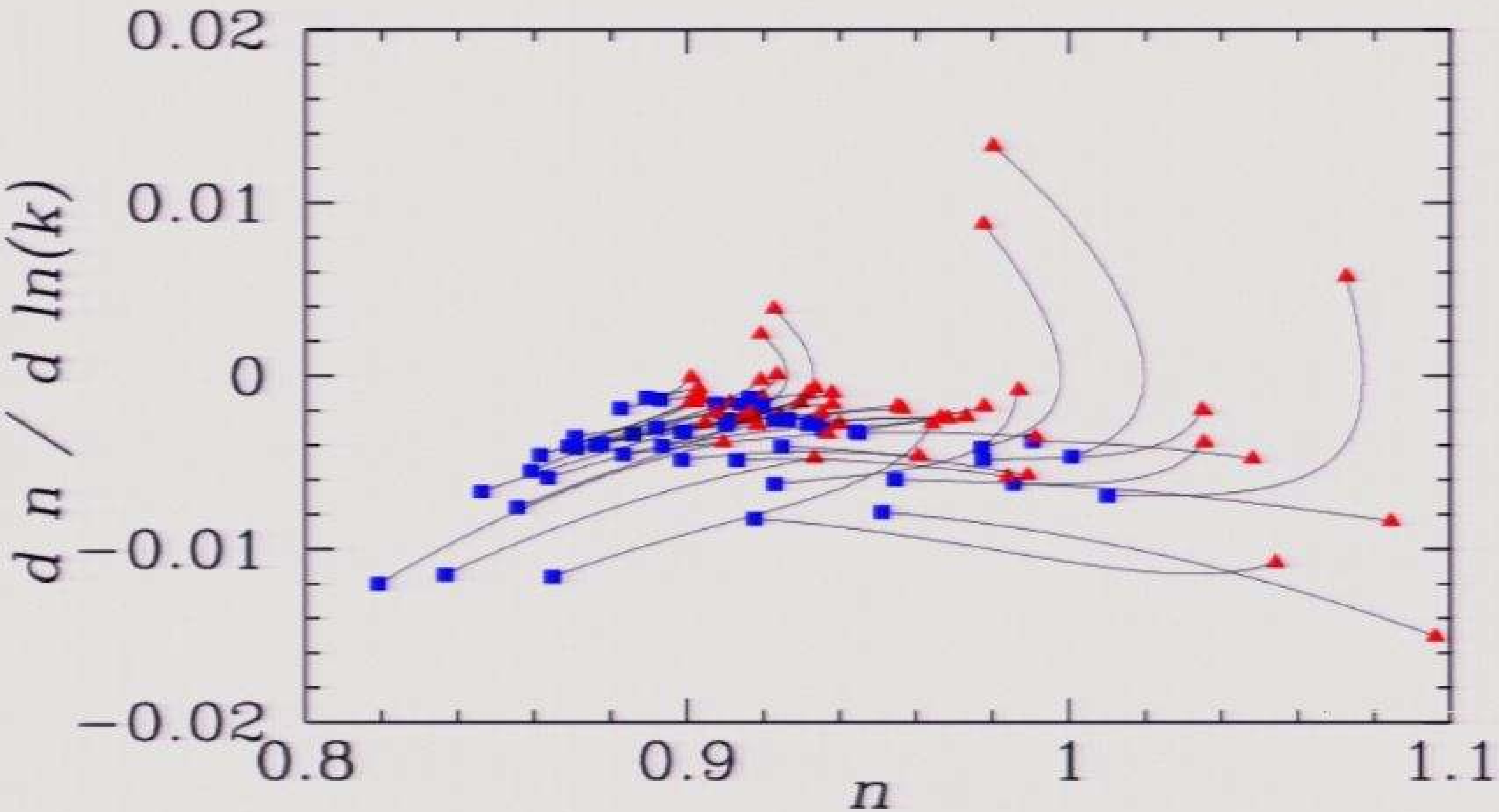


WHK, Riotto, astro-ph/0511127

Theoretical errors in inflationary observables

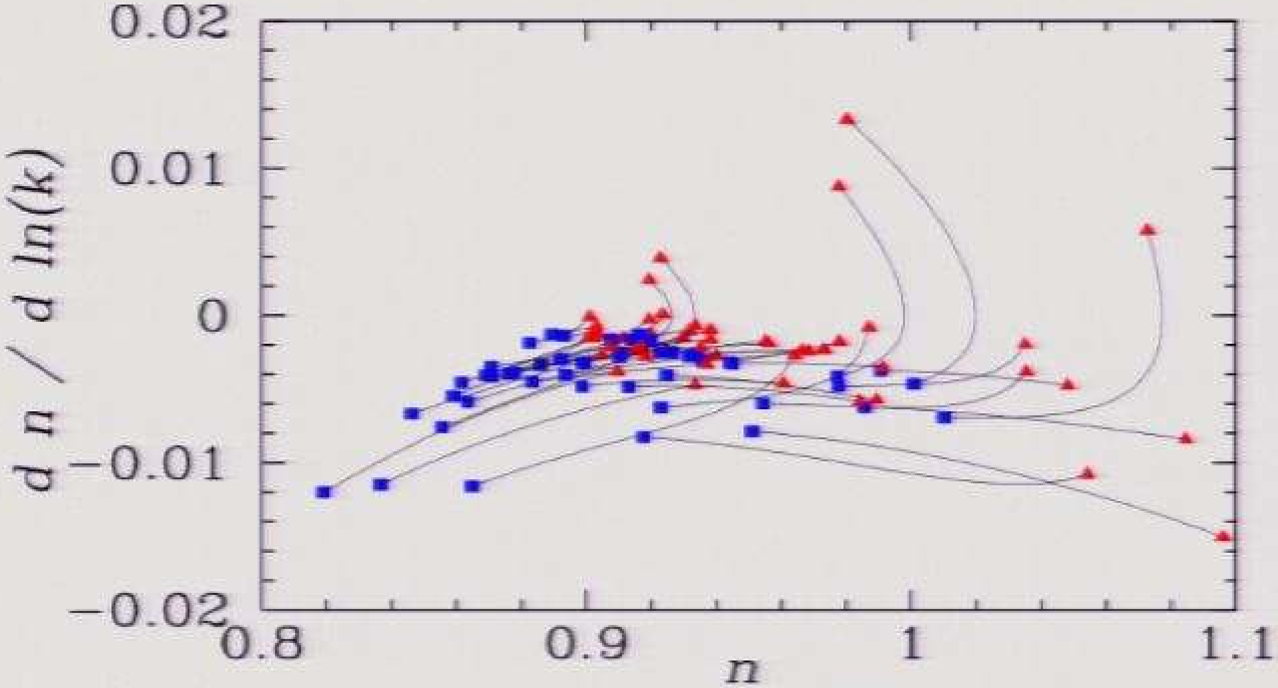


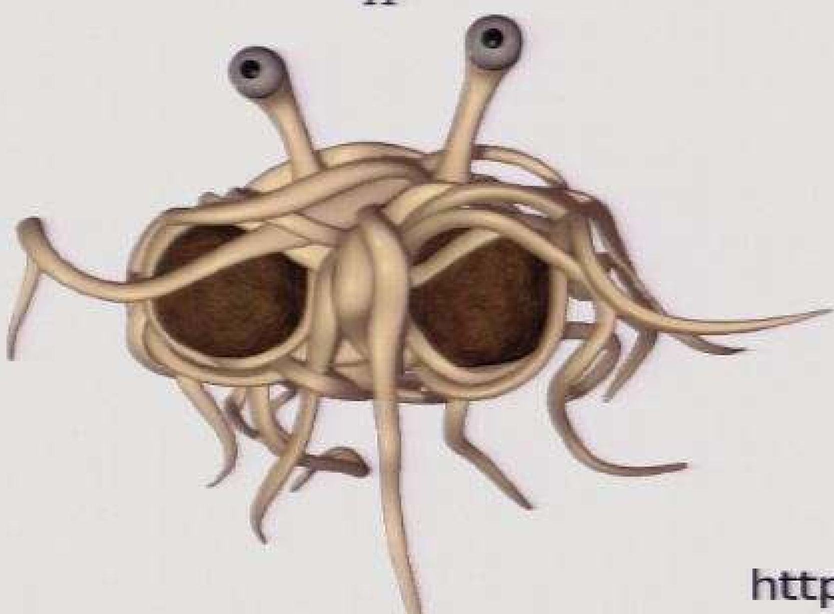
WHK, Riotto, astro-ph/0511127



0.02
0.01
0
−0.01
−0.02
0.8
0.9
1
1.1
n
$d\,n\,/\,d\,\ln(k)$

Coincidence? I think not...





http://www.venganza.org

Known knowns / known unknowns

Things we know:

- Inflation fits the data *really well.*
- $\lambda\phi^4$ / tree-level hybrid models ruled out.

Known knowns / known unknowns

Things we know:

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- $\lambda\phi^4$ / tree-level hybrid models ruled out.

Things we don't know:

- What is the energy scale of inflation?

  Key physics: CMB polarization / BBO

- Fast roll / exotic models (*e.g.* DBI)?

  Key physics: CMB polarization / non-Gaussianity

- How to map e-folds to physical scales?

  Key physics: reheating.