Title: Fingerprints of the early universe

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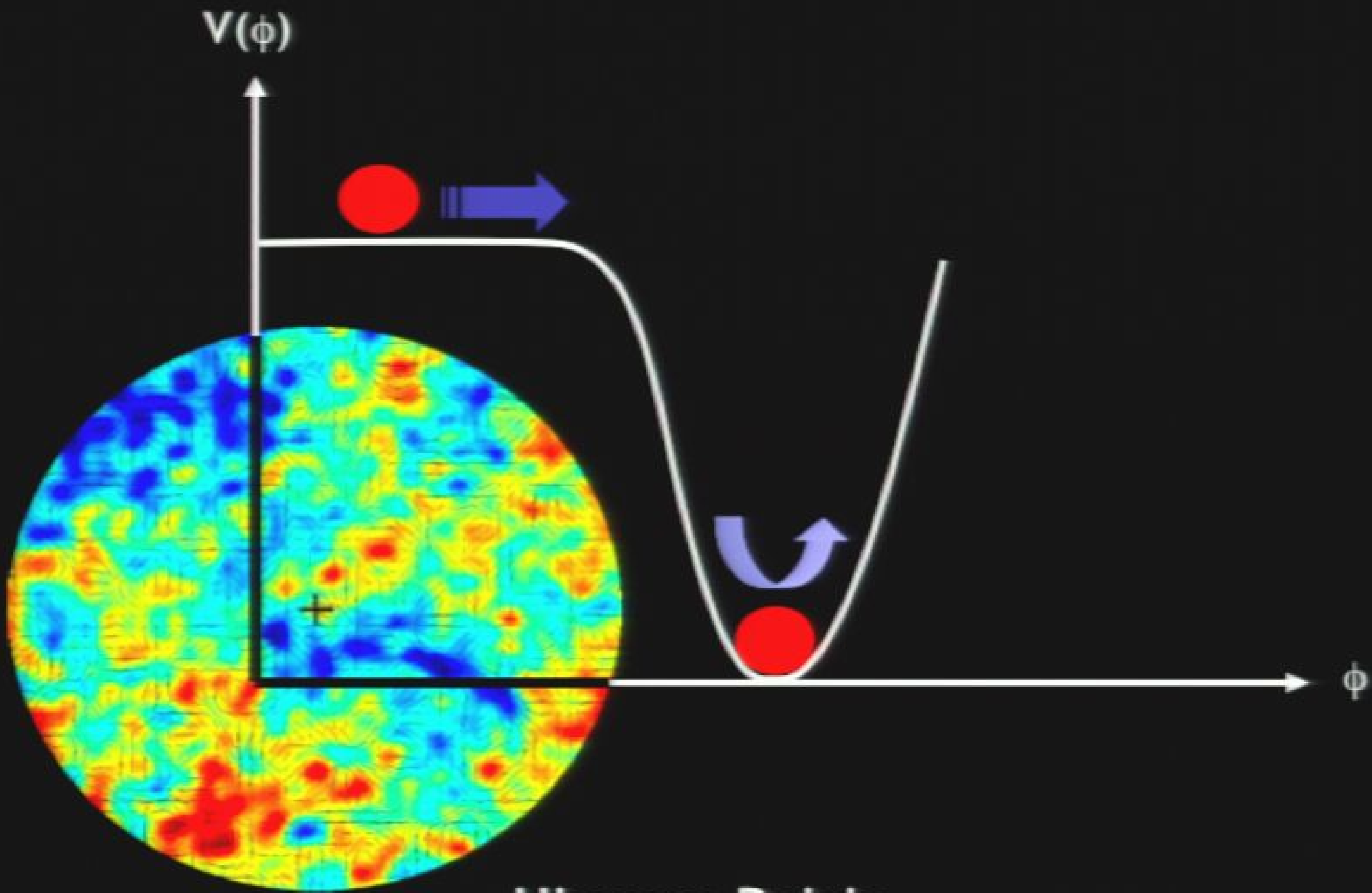
Abstract: I will review recent progress in testing with cosmological data the inflationary hypothesis for describing the very early universe. I will present snapshots of different aspects of confronting the theory with data, including a \'bottom-up\' approach: the latest results from a systematic reconstruction of the inflationary dynamics; and a \'top- down\' approach: testing specific string theoretic constructions that attempt to implement inflation, while predicting distinctive observables not found in simple field-theory models. I will discuss the ambiguities inherent in attempting to quantify generic predictions of the inflationary \'paradigm\' (as opposed to the predictions of specific models). Finally, I will discuss (in a manner accessible to theoreticians) the astrophysical complexities underlying an observational program to look for primordial tensor modes that will discriminate between inflation and alternative theories.

Fingerprints of the Early Universe

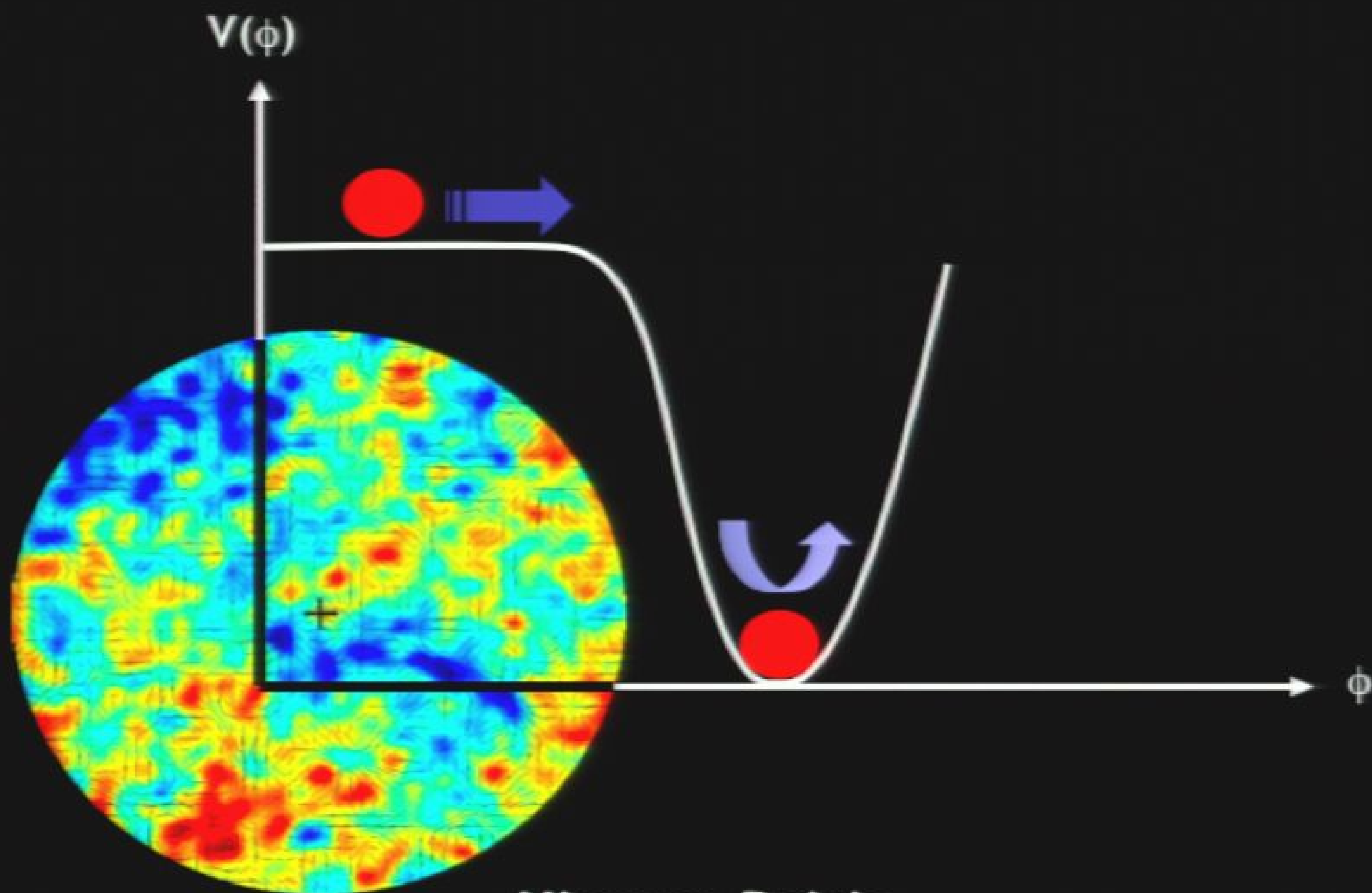


Hiranya Peiris

STFC Advanced Fellow

University of Cambridge

Fingerprints of the Early Universe



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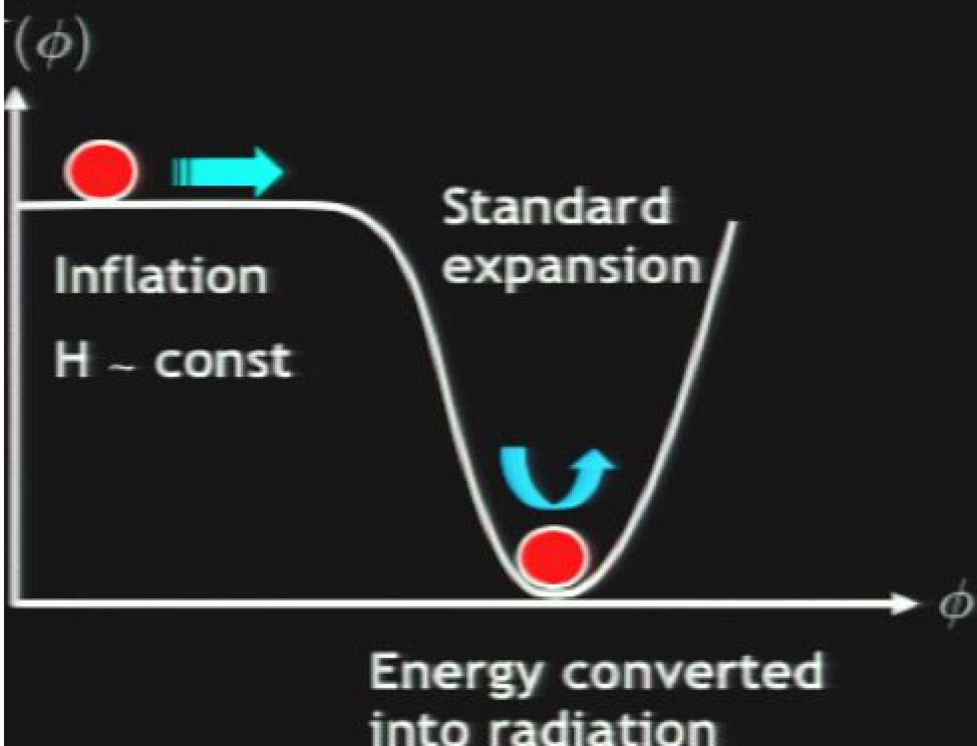
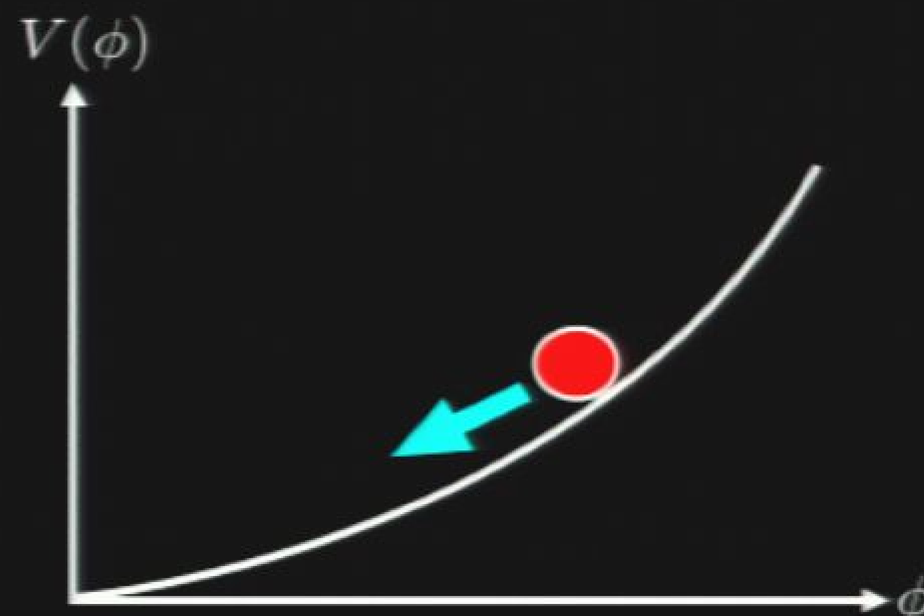
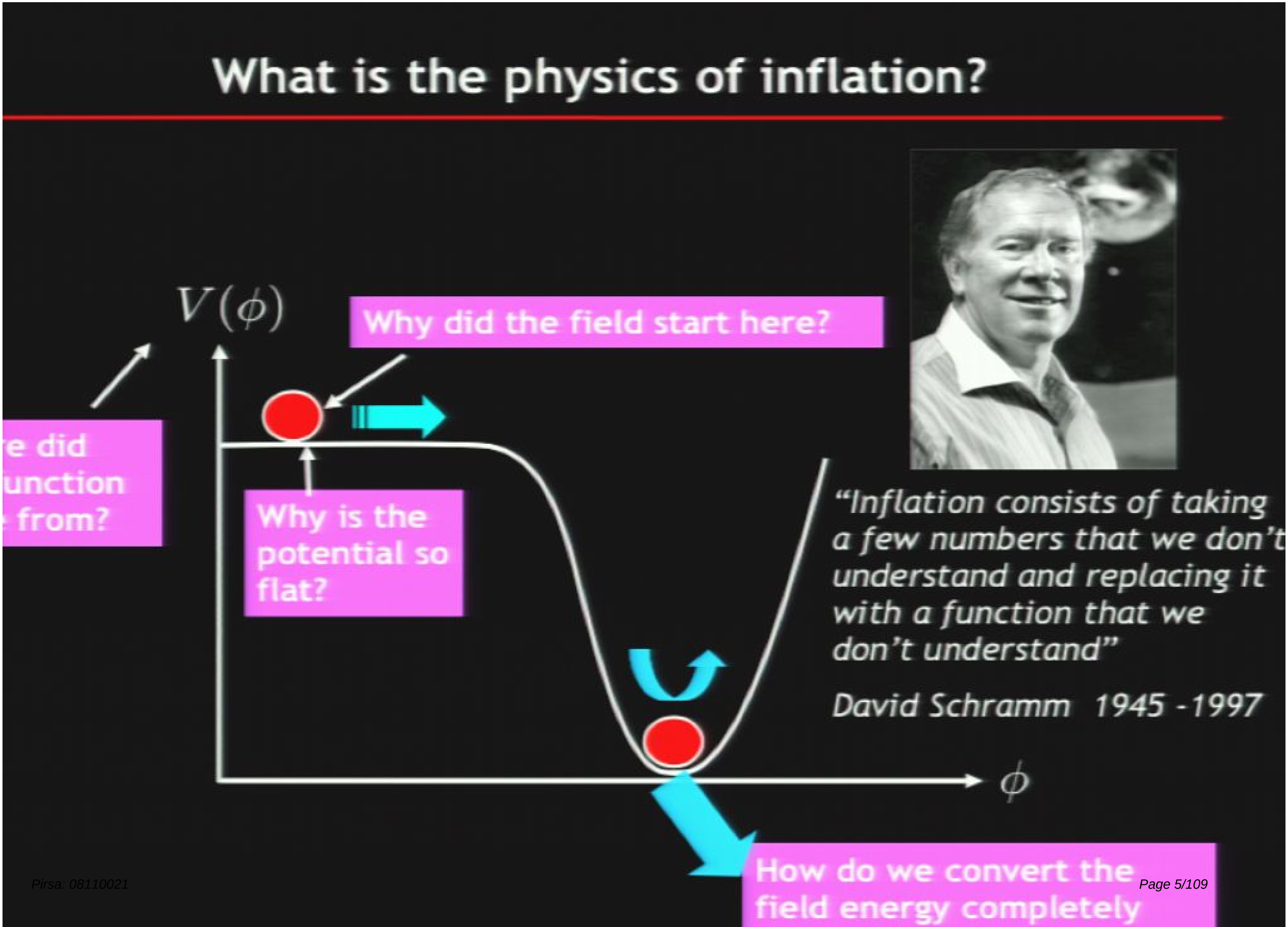
Inflation

Modelled as a scalar field (inflaton) evolving in a potential





any potentials from different physical motivations are consistent with the data


What is the physics of inflation?
$V(\phi)$
Why did the field start here?
e did
unction
from?
Why is the potential so flat?
ϕ
"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"
David Schramm 1945 -1997
How do we convert the field energy completely

Approaches to constraining inflationary models

- Empirical parameterizations: amplitude, tilt, “running”.

$$n_s(k) = n_s(k_0) + \frac{dn_s}{d\ln k}\ln\left(\frac{k}{k_0}\right)$$

  - adequate for current data, unnecessary approx for future.
  - useful for understanding generic predictions of simple models.

- Bottom-up direct “reconstruction” of inflationary potential.

- Top-down “model testing” of specific inflationary models.

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An old problem...

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Reconstructing the inflaton potential: In principle and in practice

Edmund J. Copeland*
School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9QH, United Kingdom

Edward W. Kolb†
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510
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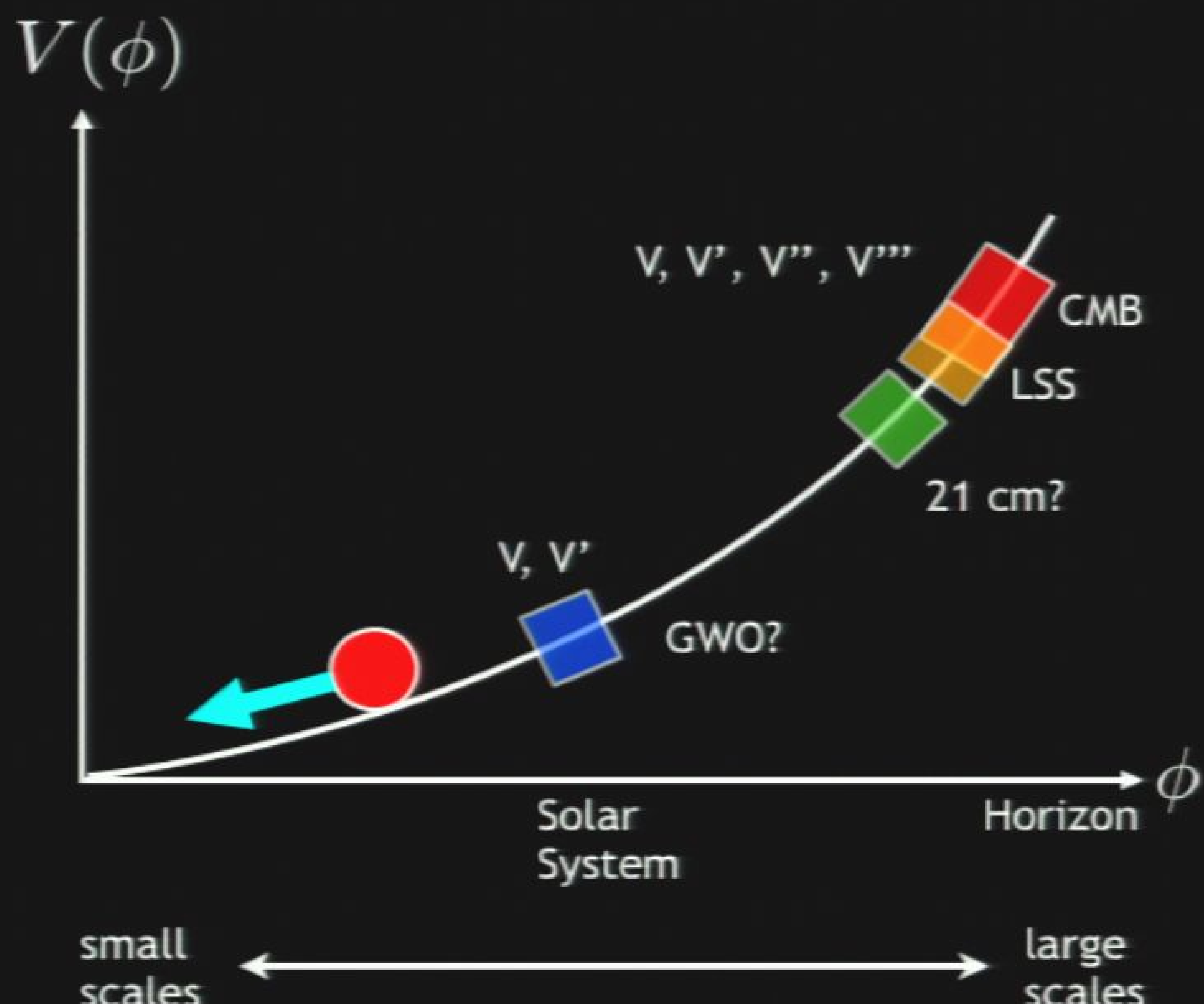
Andrew R. Liddle‡
Astronomy Centre, School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9QH, United Kingdom

James E. Lidsey§

Can we observe primordial perturbations, reconstruct potential?

Bottom-Up: reconstructing the potential



Density perturbations

- $P_S \sim A_S k^{n_s - 1}$ (n_s: "spectral index" - $n_s = n_s(k)$??)
- Just two parameters? (Many models)
- Perturbations are a function of potential
  - Cosmological scales from $\sim 1\ \mathrm{Mpc} - 10^4\ \mathrm{Mpc}$
  - Universe grows $\sim 10^{30}$ times larger during inflation
- CMB only samples a small piece of potential

The Hamilton-Jacobi approach

$$\dot{\phi} = -\frac{m_{Pl}^2}{4\pi} H'(\phi)$$ ← 2nd FRW eq.

$$\ldots'(\phi)]^2 - \frac{12\pi}{m_{Pl}^2} H^2(\phi) = -\frac{32\pi^2}{m_{Pl}^4} V(\phi)$$ ← 1st FRW eq.

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

$$H^2(\phi)\left[1 - \frac{1}{3}\epsilon(\phi)\right] = \left(\frac{8\pi}{3m_{Pl}^2}\right) V(\phi)$$ ← Re-writing

$\epsilon \propto \left(\frac{H'}{H}\right)^2$	$\eta \propto \frac{H''}{H}$	$\xi \propto \frac{H'''H'}{H^2}$	etc.
SLOPE	CURVATURE	JERK	

Exact background solution

- HSR hierarchy captures full inflationary dynamics
- Truncate it, get an approximate potential
- Truncated hierarchy has an exact solution

$$\frac{d^{(M+2)}H}{d\phi^{(M+2)}} = 0$$

$$H(\phi) = H_0 \left[1 + A_1 \left(\frac{\phi}{m_{\rm Pl}}\right) + ... + A_{M+1} \left(\frac{\phi}{m_{\rm Pl}}\right)^{M+1}\right]$$

$$\epsilon(\phi) = \frac{m_{\rm Pl}^2}{4\pi} \left[\frac{(A_1/m_{\rm Pl}) + ... + (M+1)(A_{M+1}/m_{\rm Pl})(\phi/m_{\rm Pl})^M}{1 + A_1(\phi/m_{\rm Pl}) + ... + A_{M+1}(\phi/m_{\rm Pl})^{M+1}}\right]^2$$

$$A_1 = \sqrt{4\pi\epsilon_0}$$

$$A_{\ell+1} = \frac{(4\pi)^\ell \, {}^\ell\lambda_{H,0}}{(\ell+1)! \, A_1^{\ell-1}}; \;\; \ell \geq 1$$

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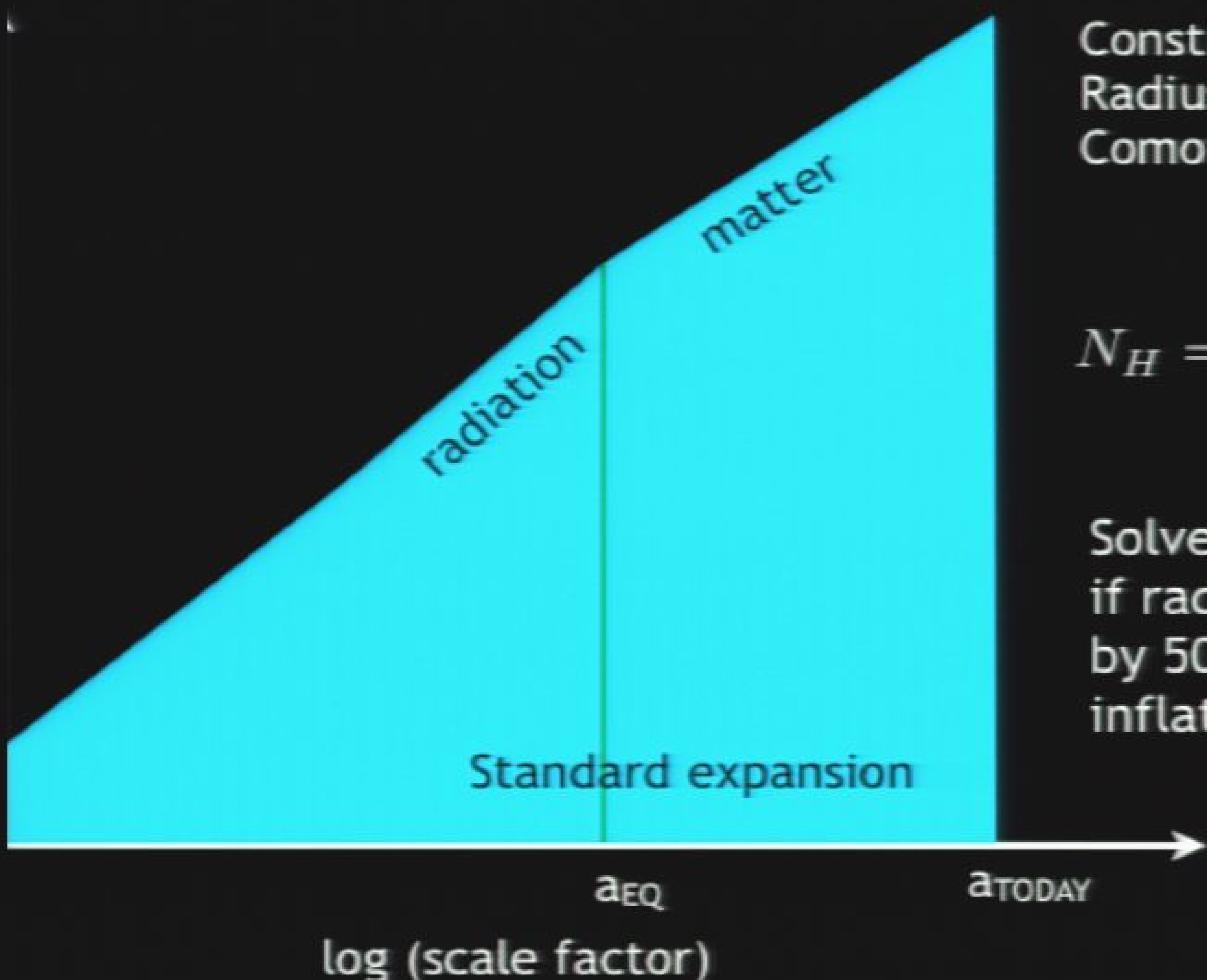
Algorithm: Slow Roll Reconstruction

- Pick HSR parameters at fiducial wavenumber corresponding to phi=0
- Calculate k as a function of phi
- Use analytic solutions to H, epsilon and eta to calculate the primordial power spectra
- Feed into e.g. CAMB to calculate CMB power spectra
- Apply physical consistency priors

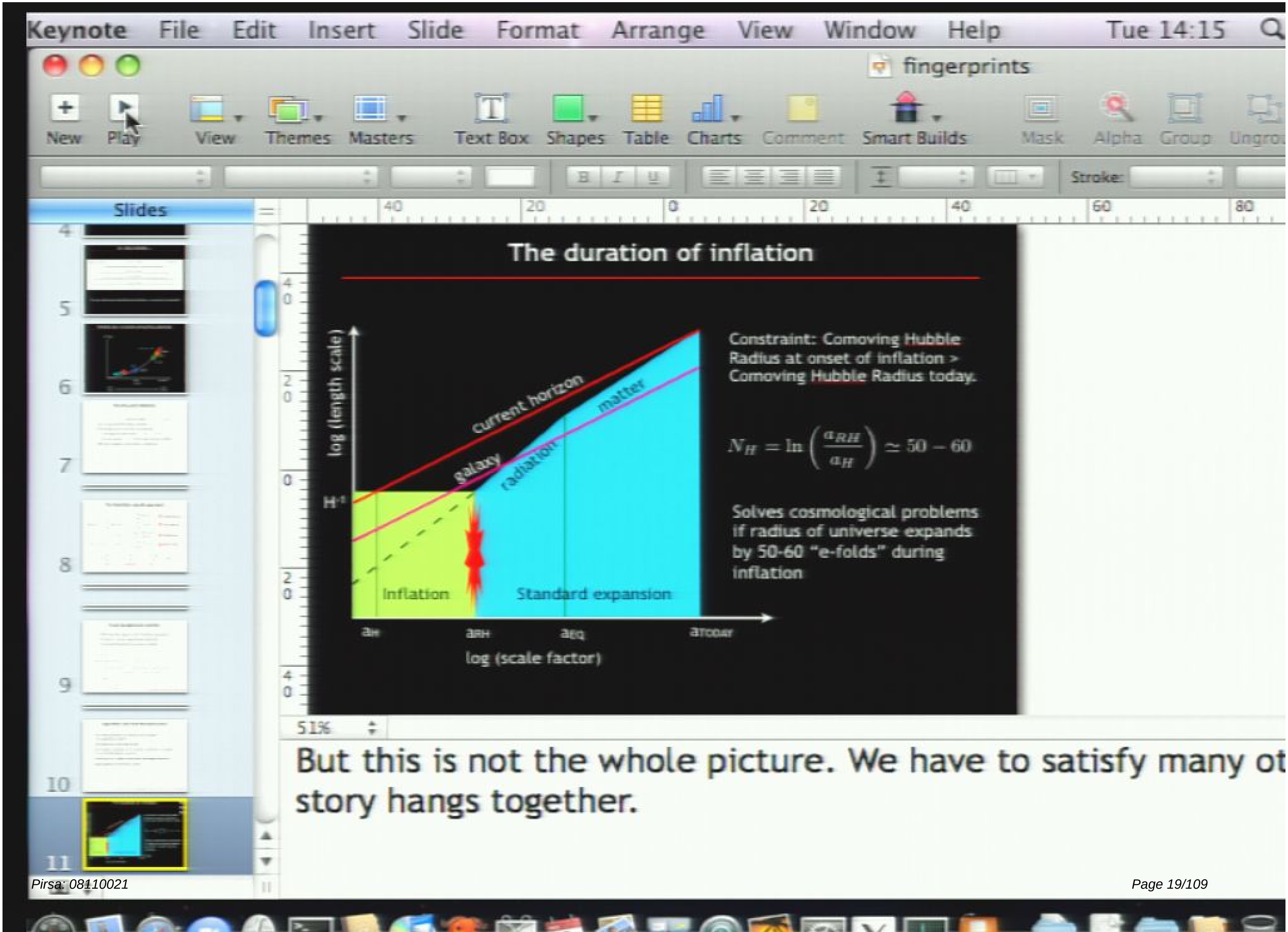
The duration of inflation



Constraint: Comoving Hubble Radius at onset of inflation > Comoving Hubble Radius today.

$$N_H = \ln\left(\frac{a_{RH}}{a_H}\right) \simeq 50 - 60$$

Solves cosmological problems if radius of universe expands by 50-60 “e-folds” during inflation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The duration of inflation
log (length scale)
current horizon
matter
galaxy
radiation
Inflation
Standard expansion
log (scale factor)
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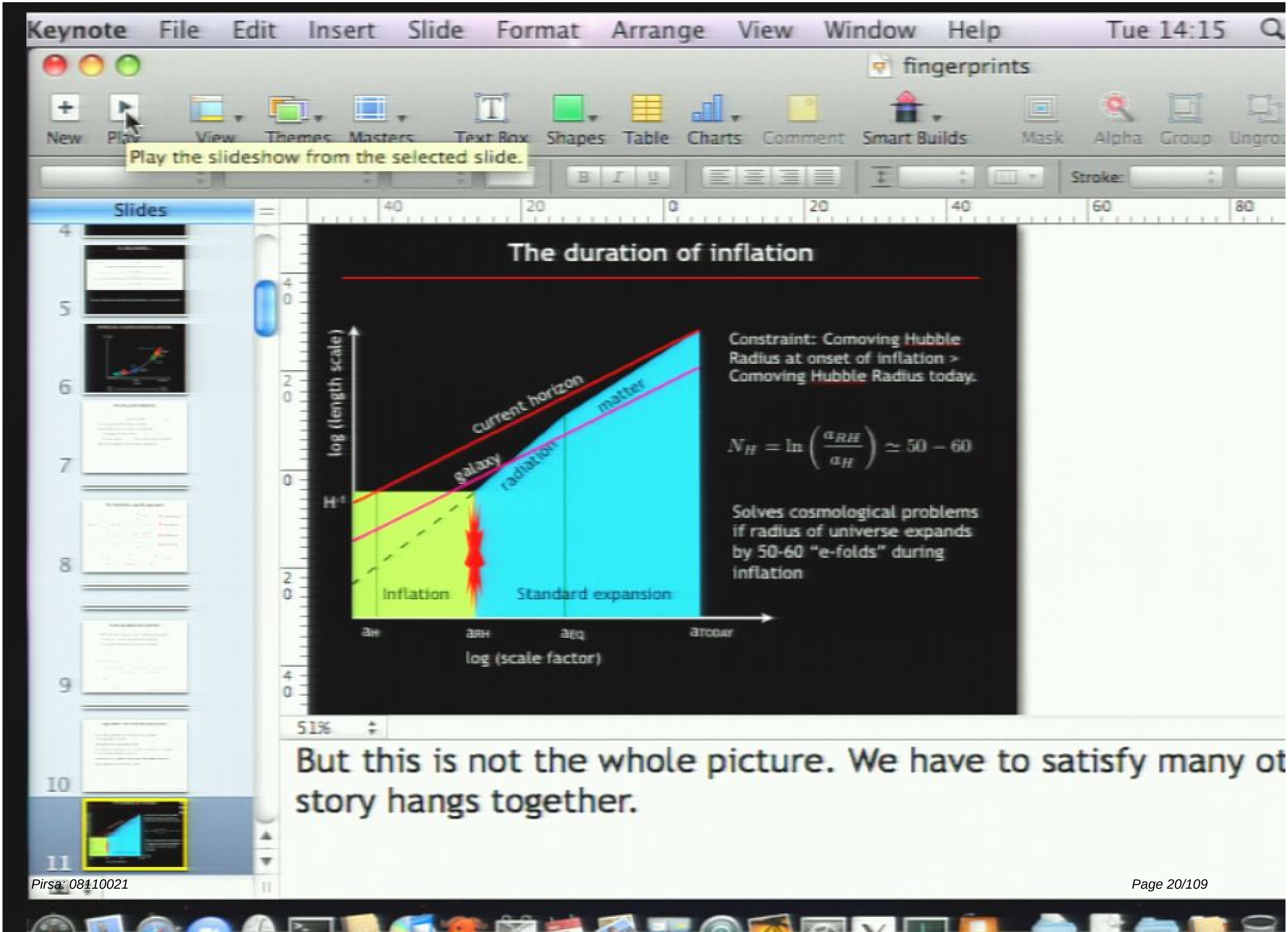
But this is not the whole picture. We have to satisfy many ot
story hangs together.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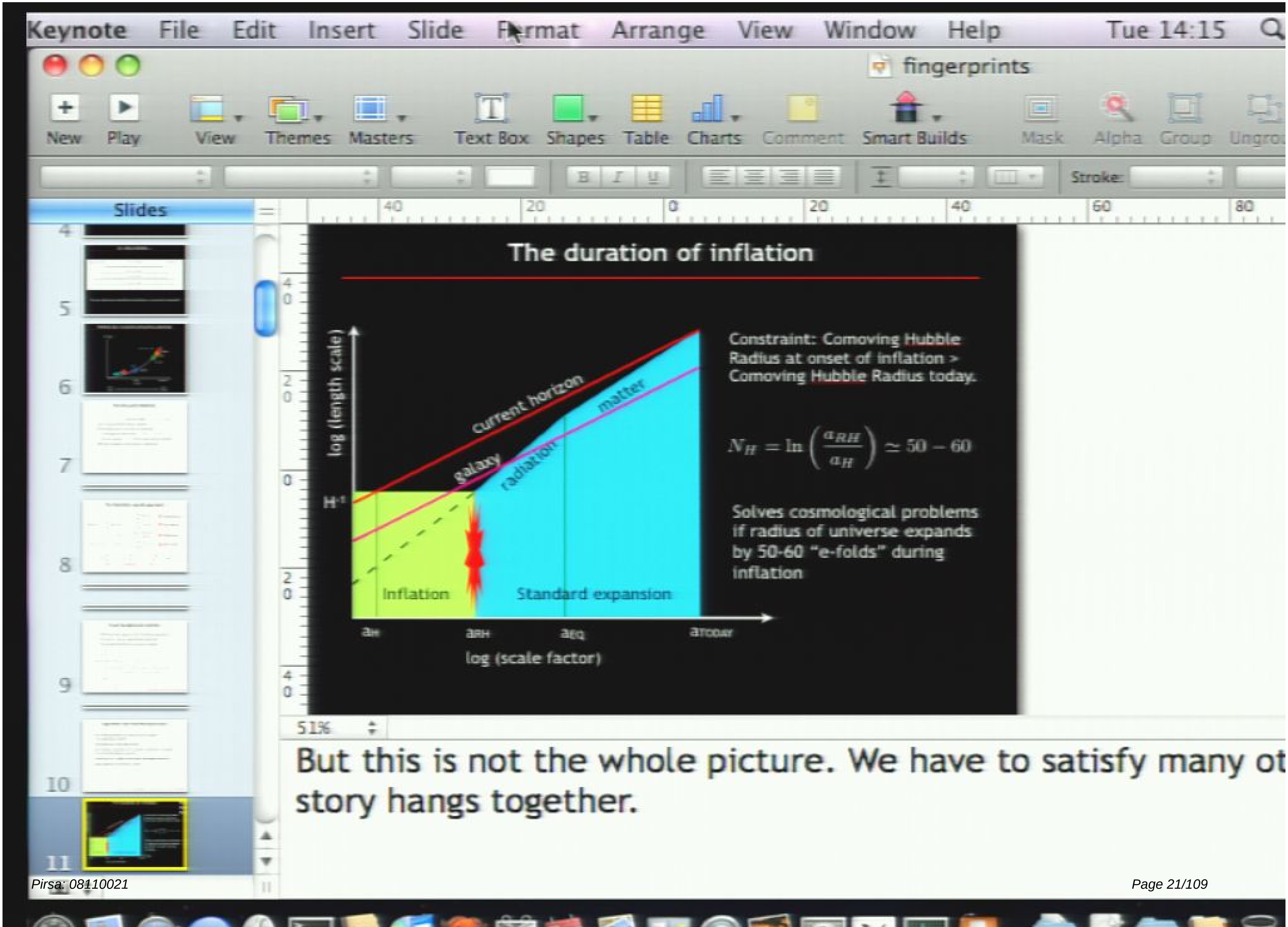
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51%
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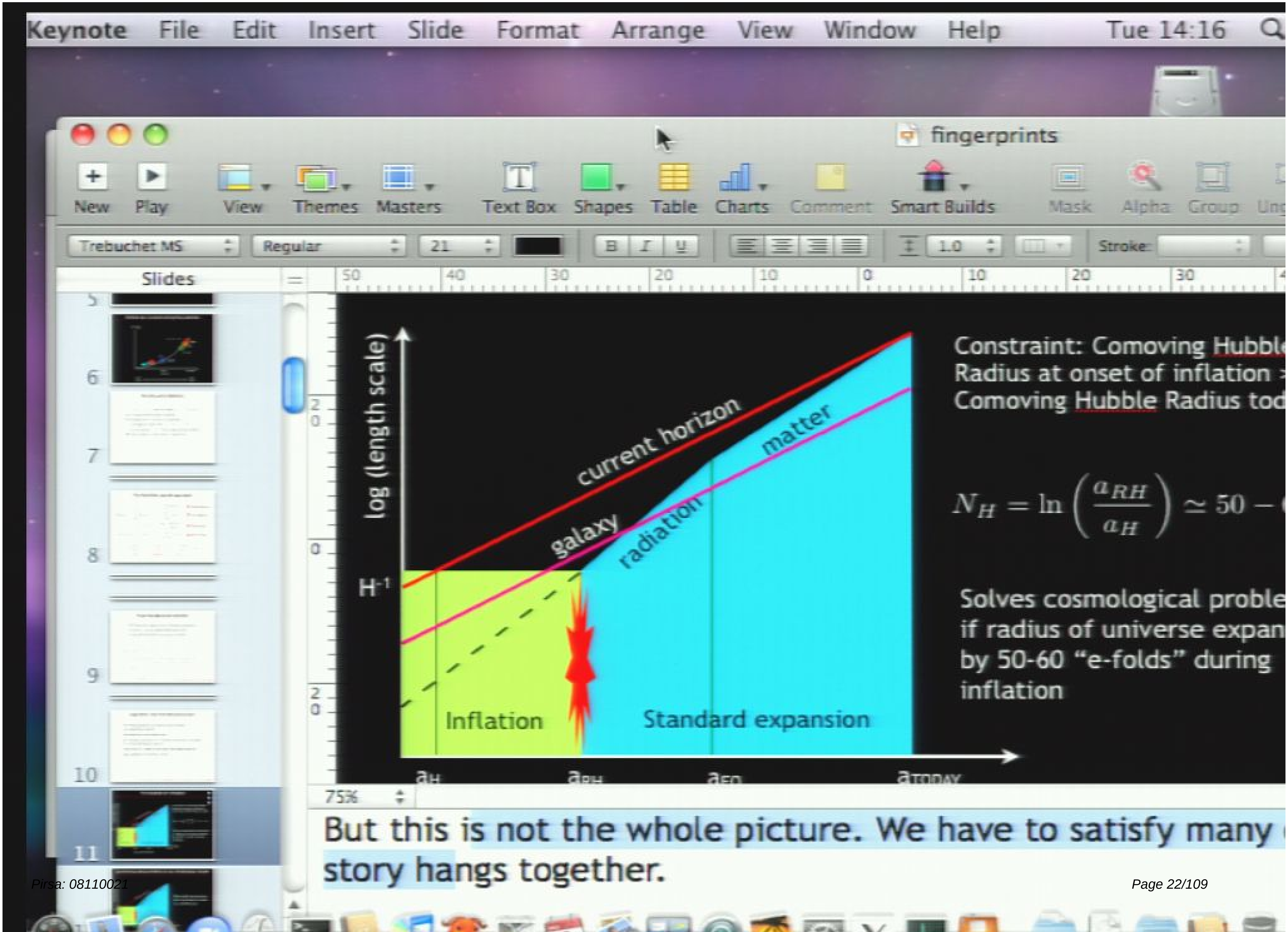
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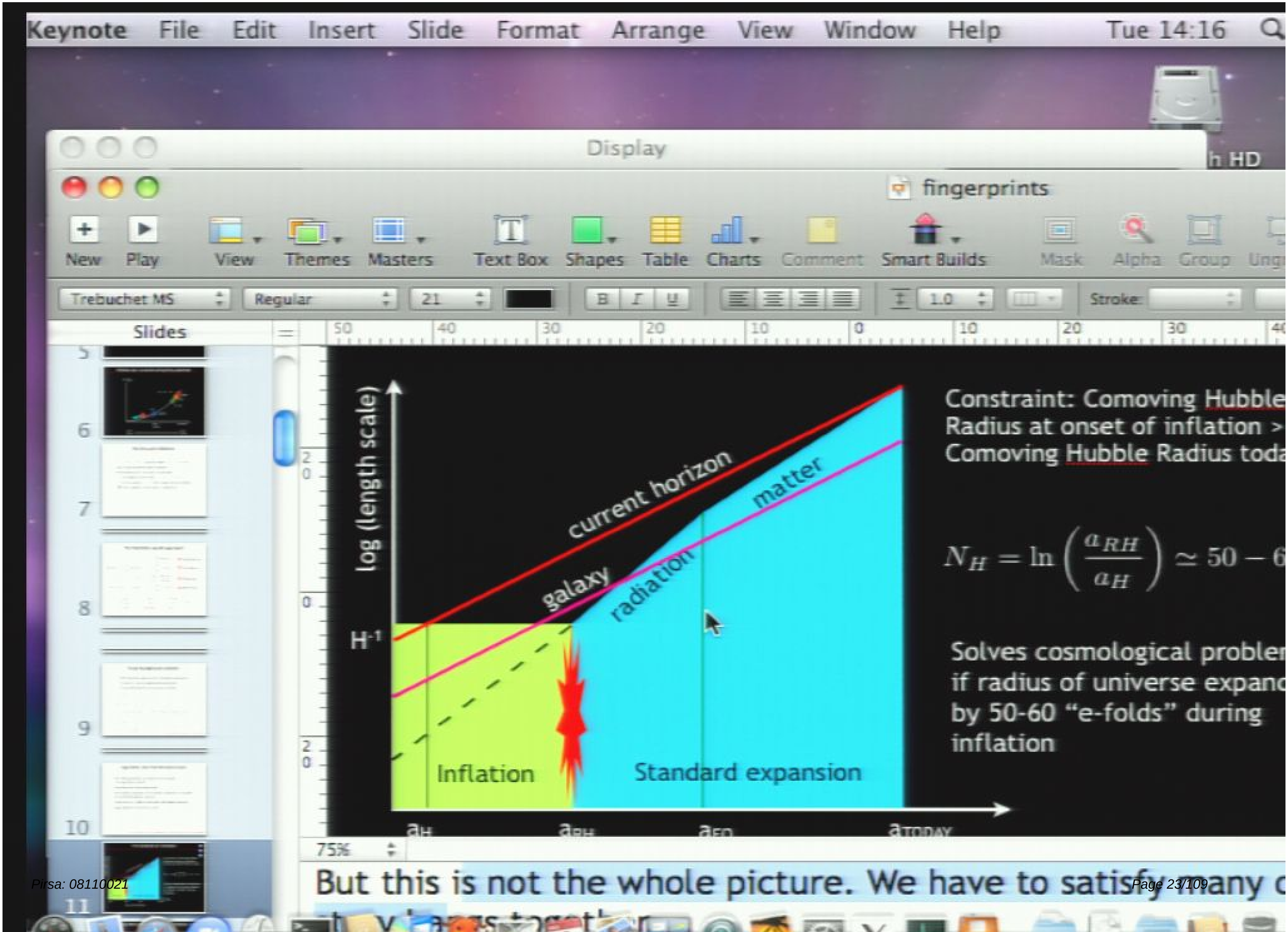
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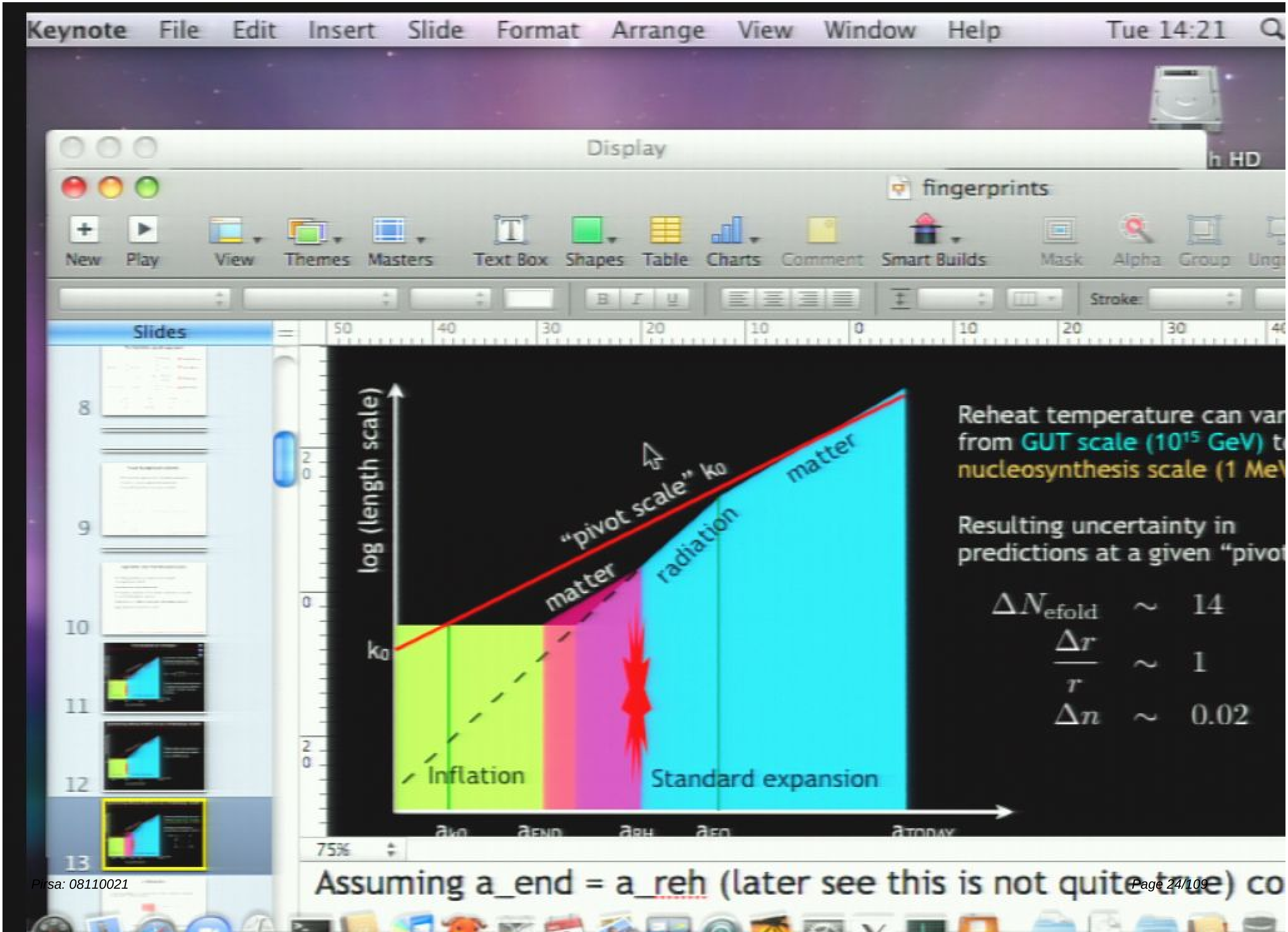
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Reheat temperature can var
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Resulting uncertainty in
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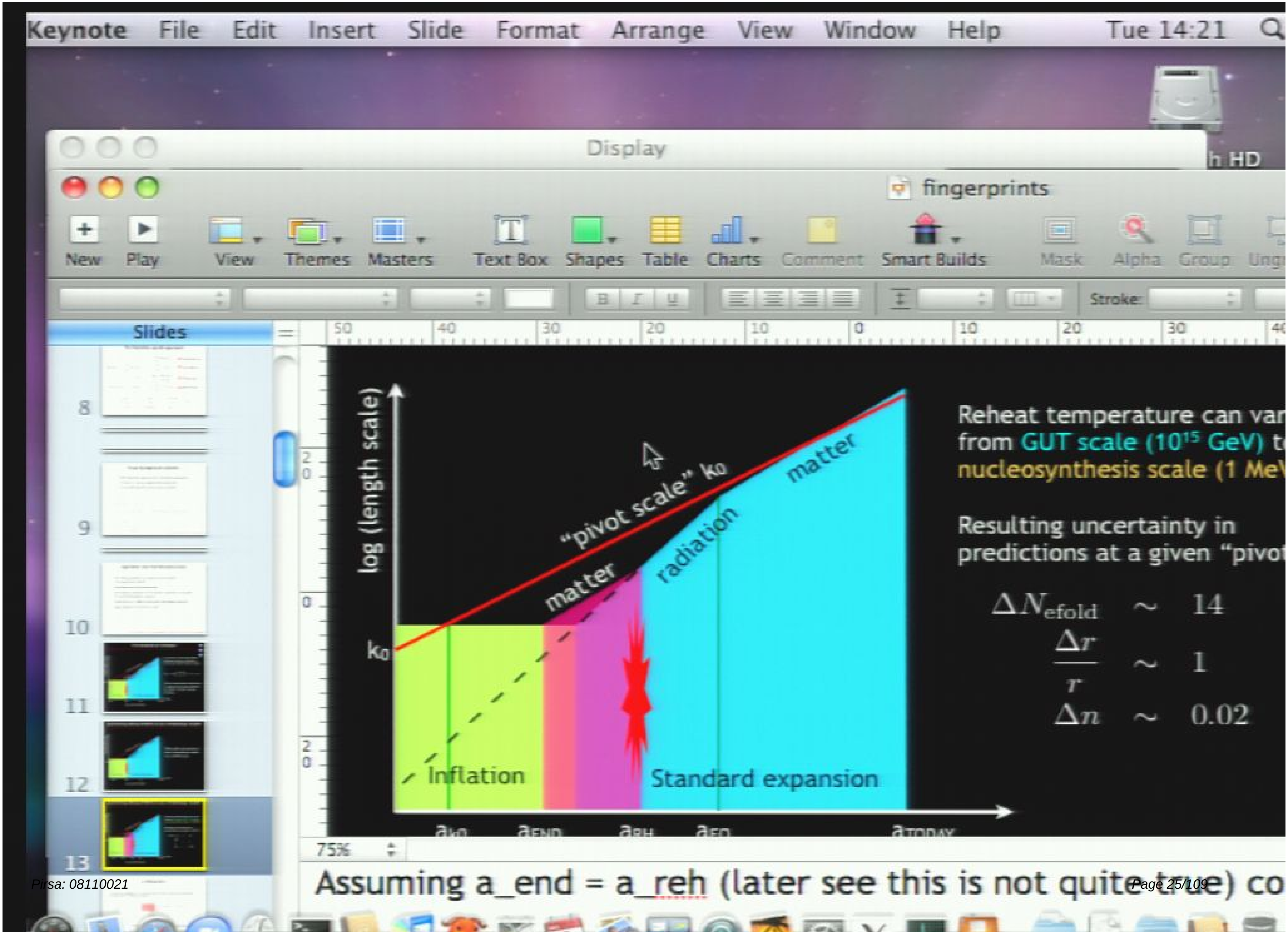
ΔN_efold ~ 14
Δr/r ~ 1
Δn ~ 0.02
Assuming a_end = a_reh (later see this is not quite true) co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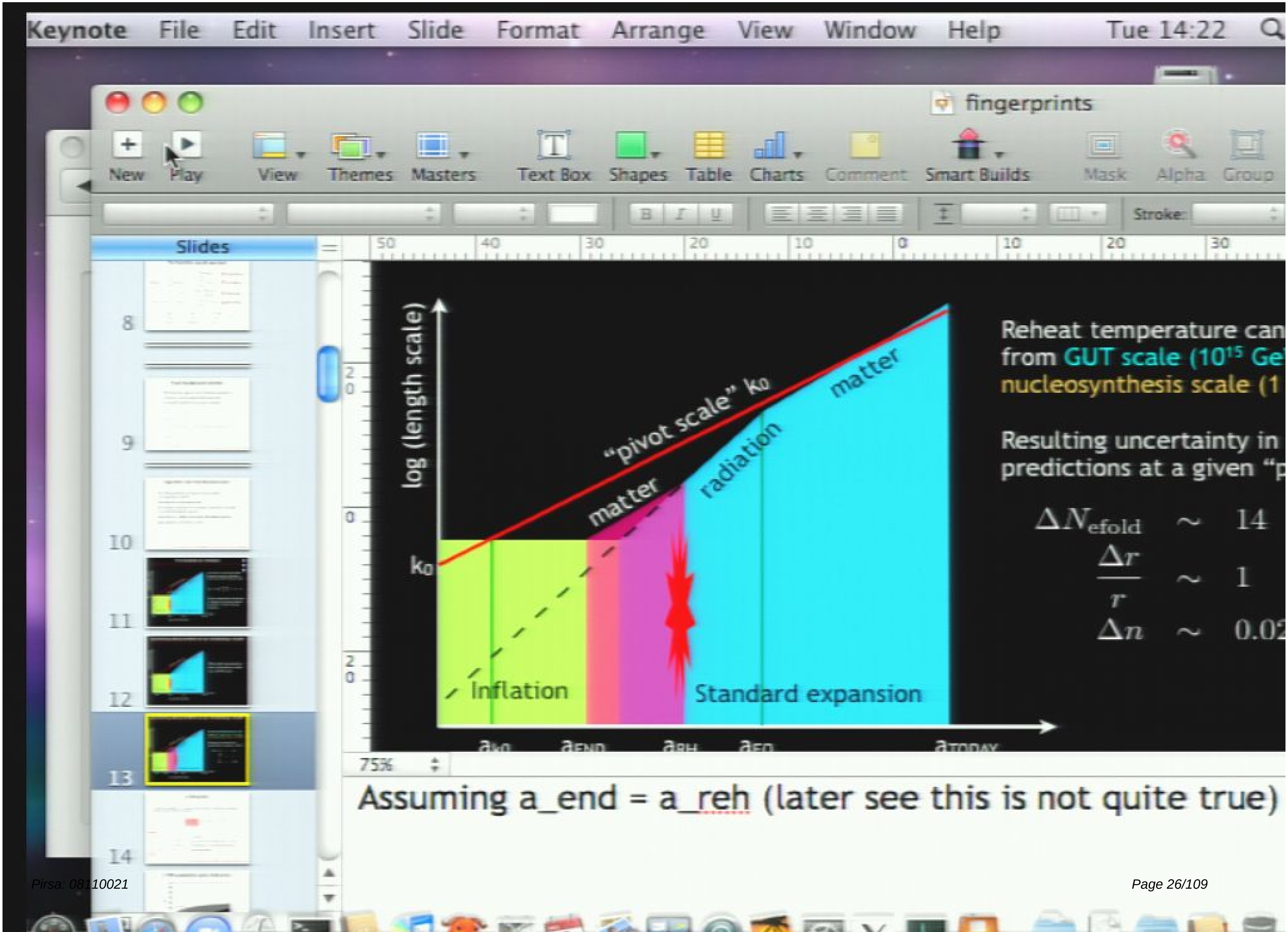
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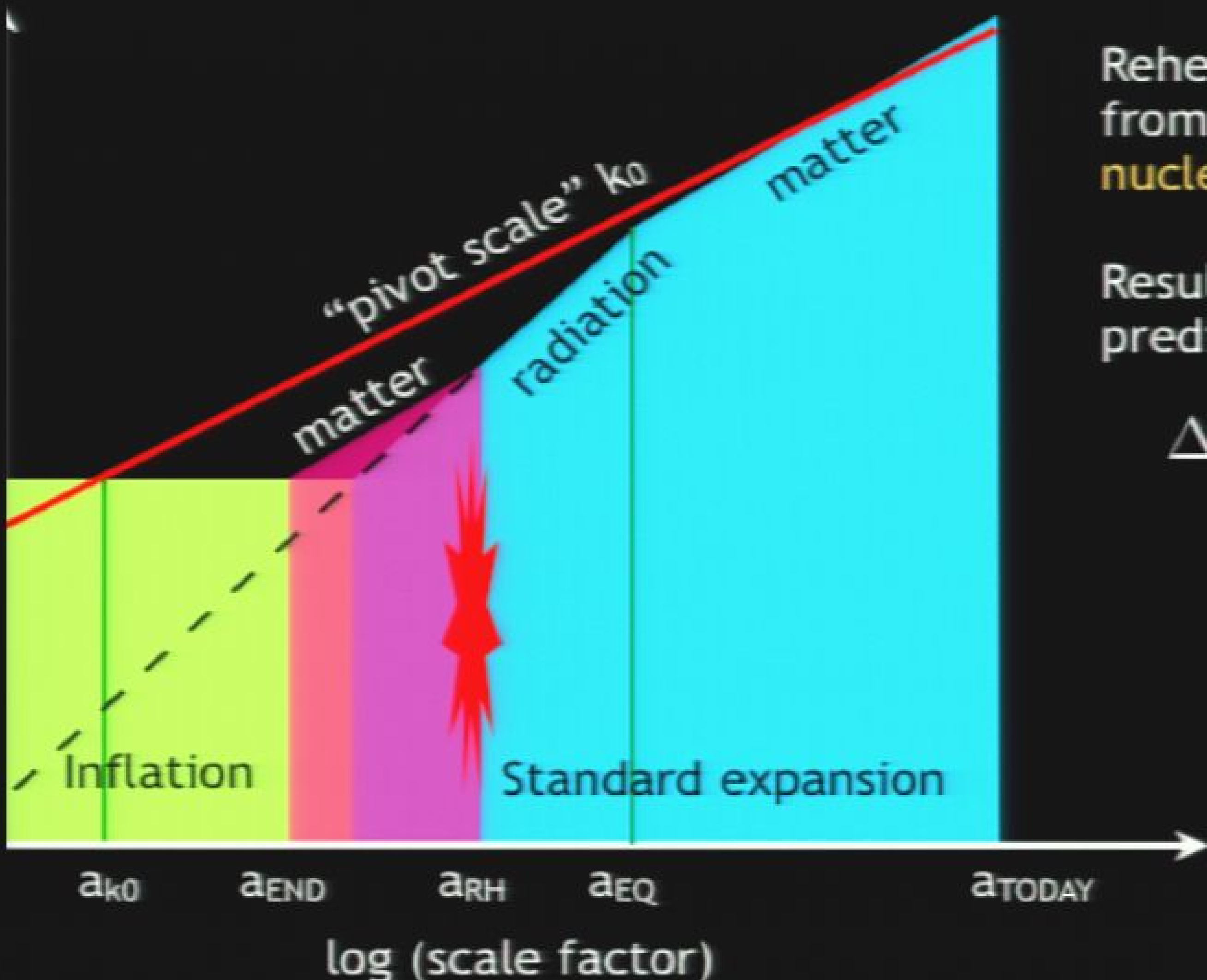

Reheat temperature can vary from GUT scale (10^{15} GeV) to nucleosynthesis scale (1 MeV)!

Resulting uncertainty in predictions at a given "pivot":

$$\Delta N_{\rm efold} \sim 14$$
$$\frac{\Delta r}{r} \sim 1$$
$$\Delta n \sim 0.02$$

e-fold priors

"Connection equation" in a universe that inflated, reheated, and passed through matter-radiation equality:

$$N(k) = -\ln\left(\frac{k}{\mathrm{Mpc}^{-1}}\right) + \frac{1}{6}\ln\left(\frac{H_{\mathrm{reh}}}{m_{\mathrm{Pl}}}\right) - \frac{2}{3}\ln\left(\frac{H_{\mathrm{end}}}{m_{\mathrm{Pl}}}\right) + \ln\left(\frac{H_k}{m_{\mathrm{Pl}}}\right) + 59.59.$$

ker

$N(k)$	$>$	15	"minimal"
T_{reh}	$>$	$10\ \mathrm{MeV}$	guarantees thermalized neutrino sector
T_{reh}	$>$	$10\ \mathrm{TeV}$	reheating occurs well above EW scale
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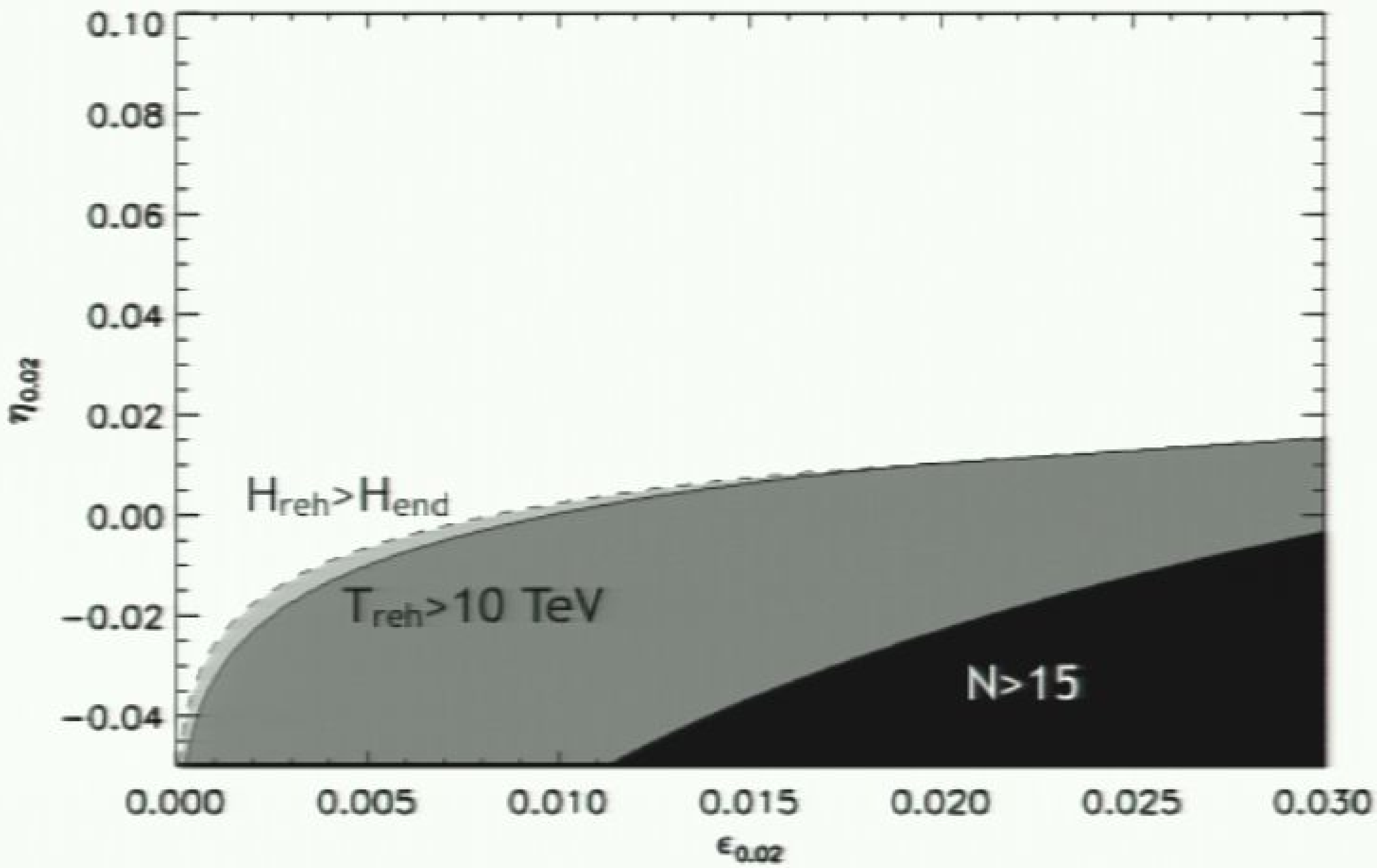

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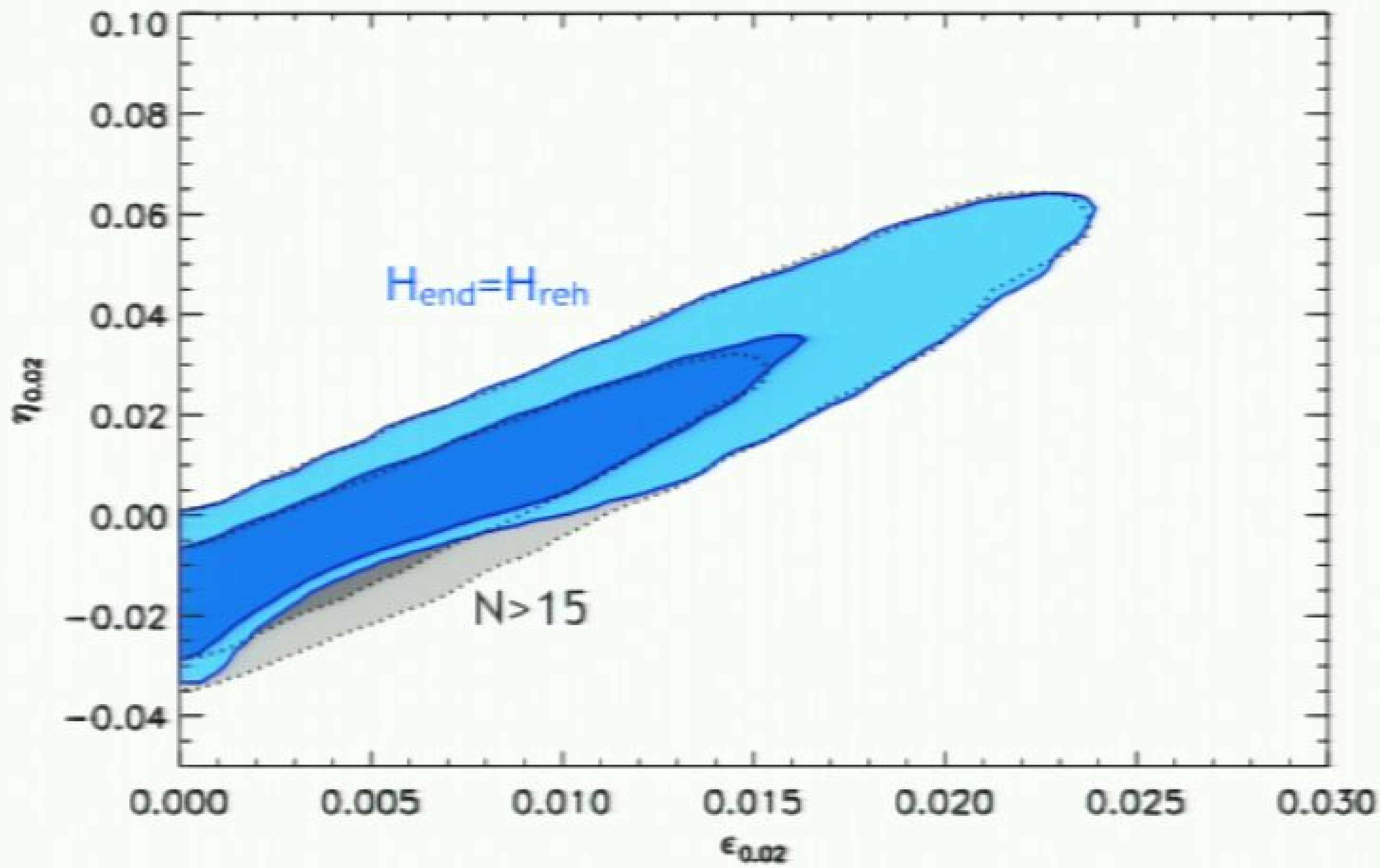

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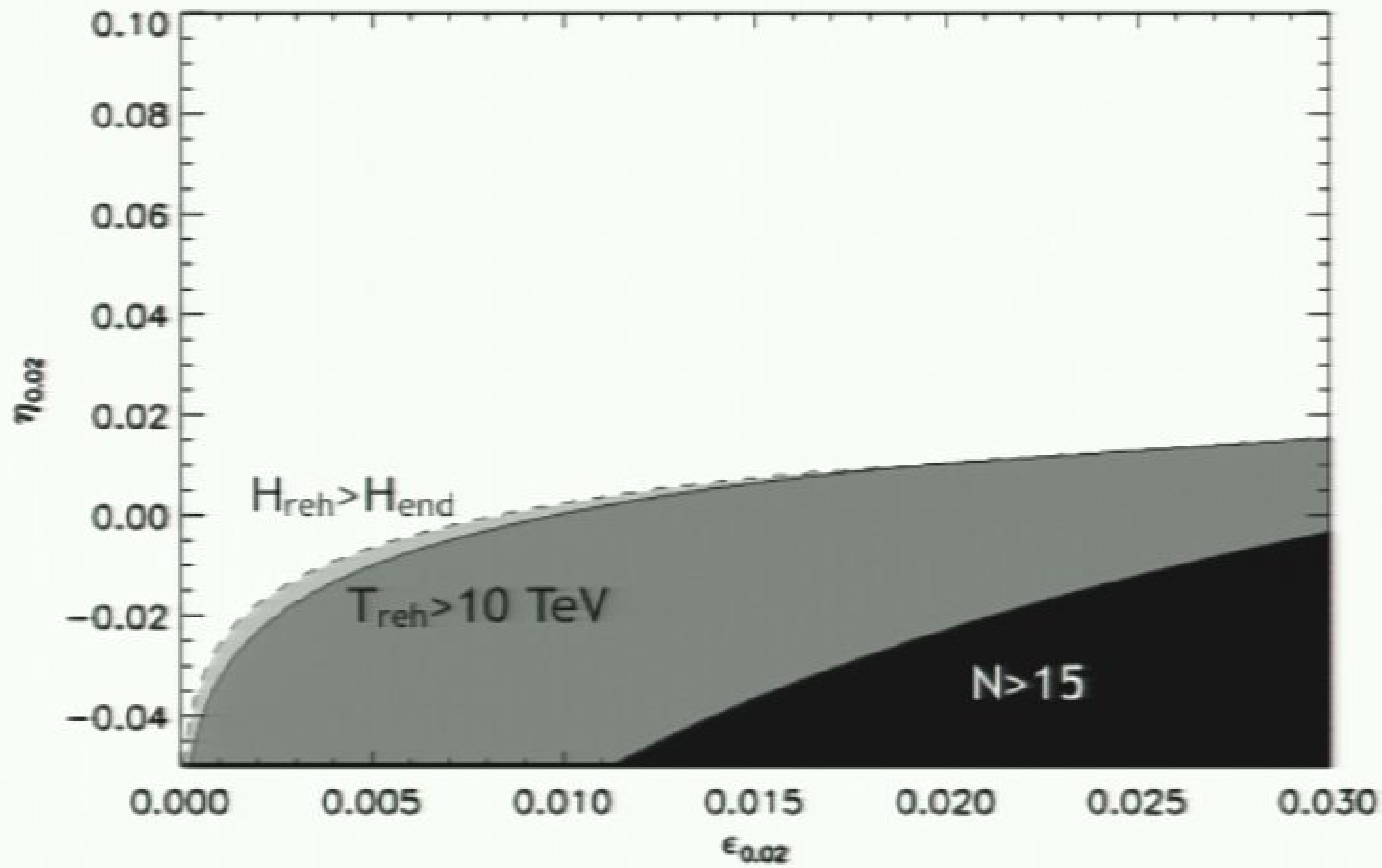

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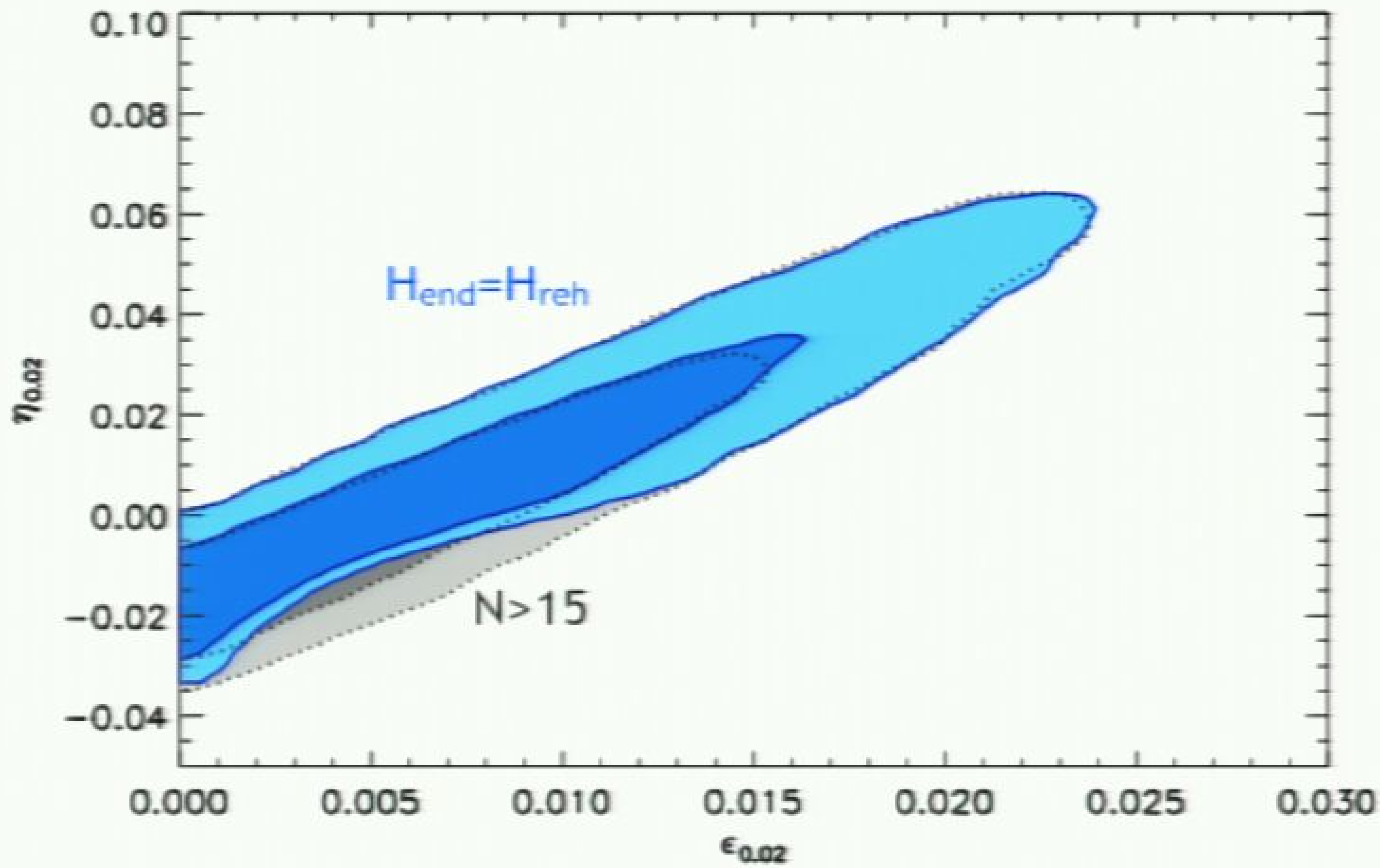

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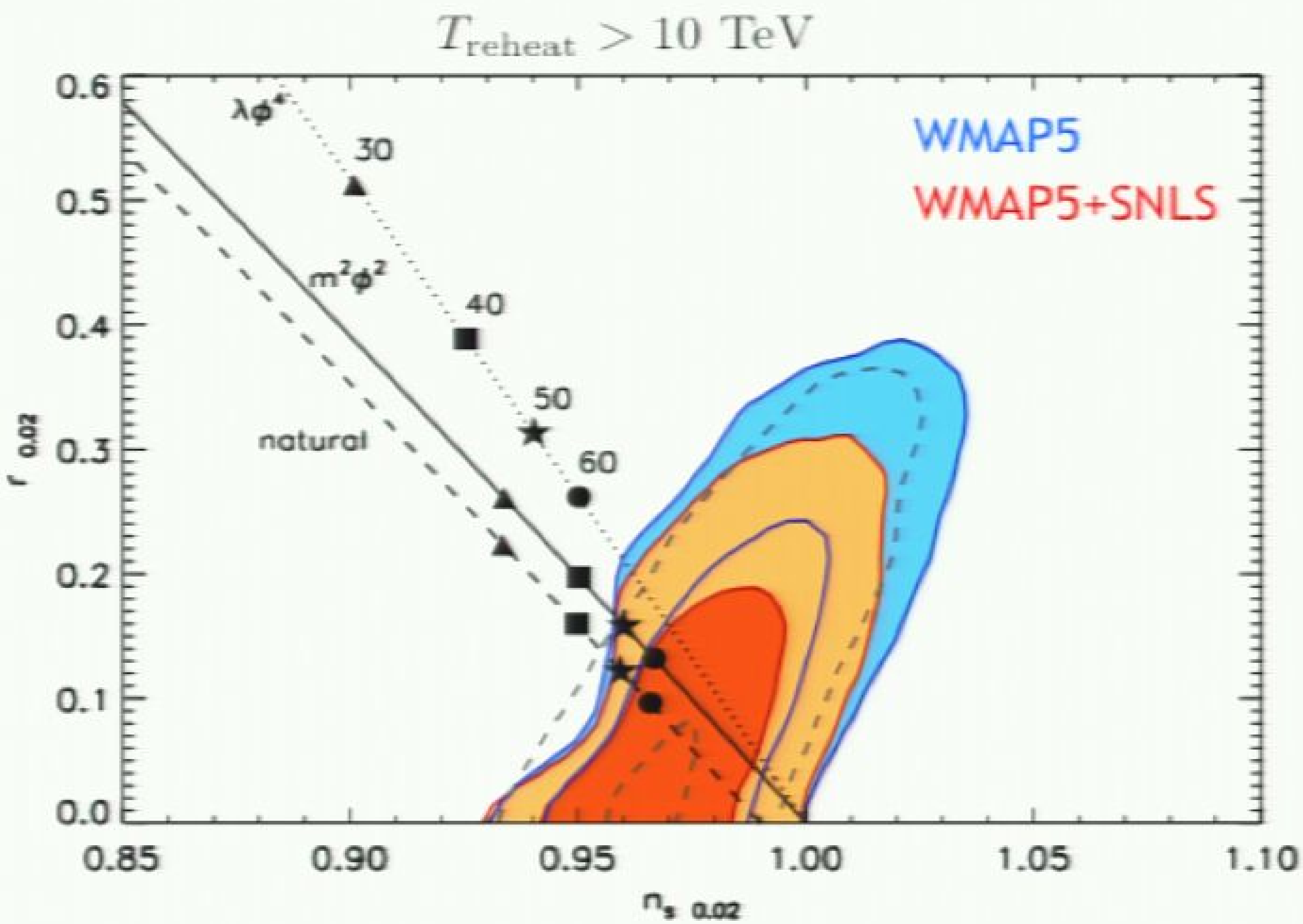
Bounds on spectral params at k=0.02 Mpc^{-1}



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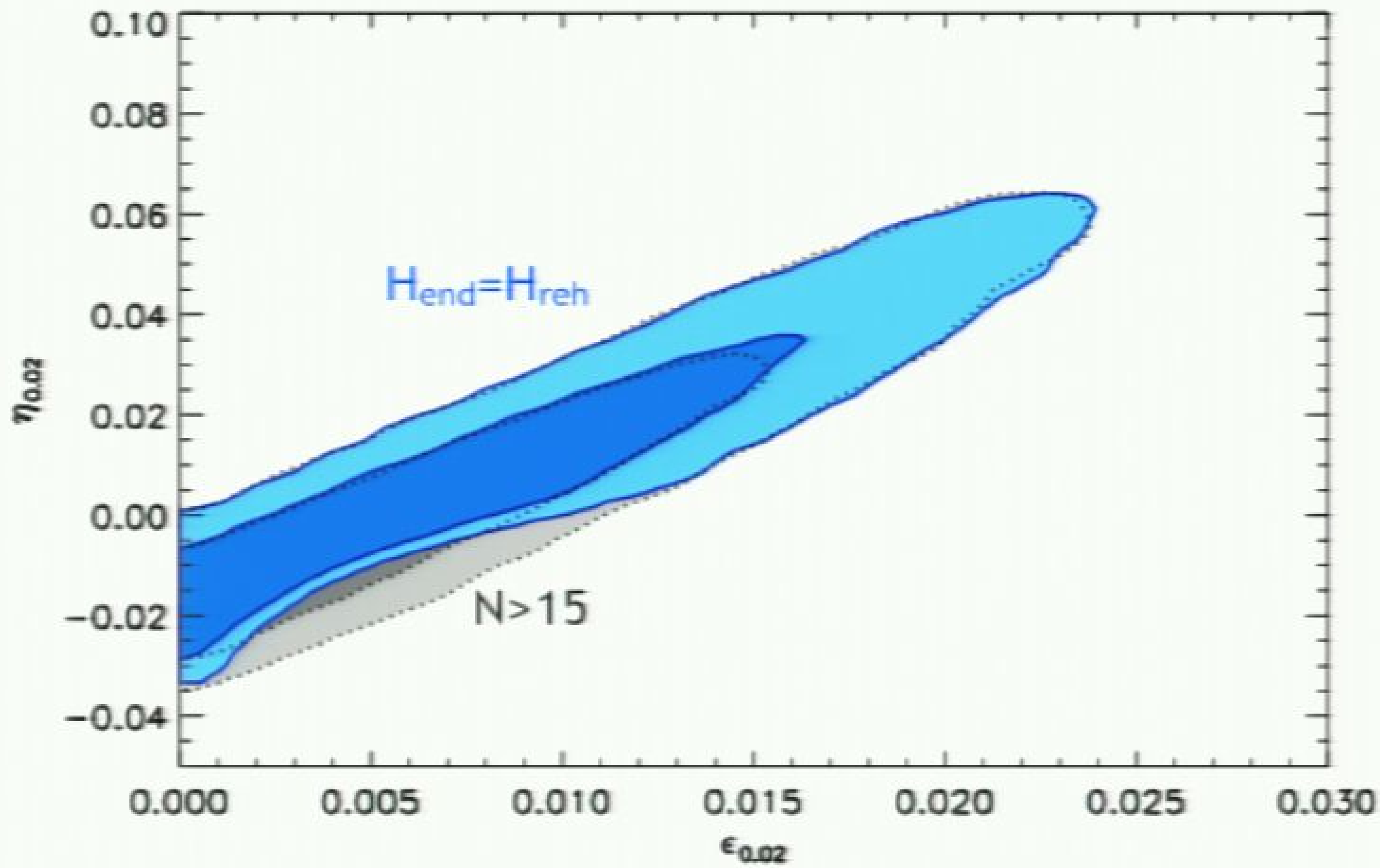

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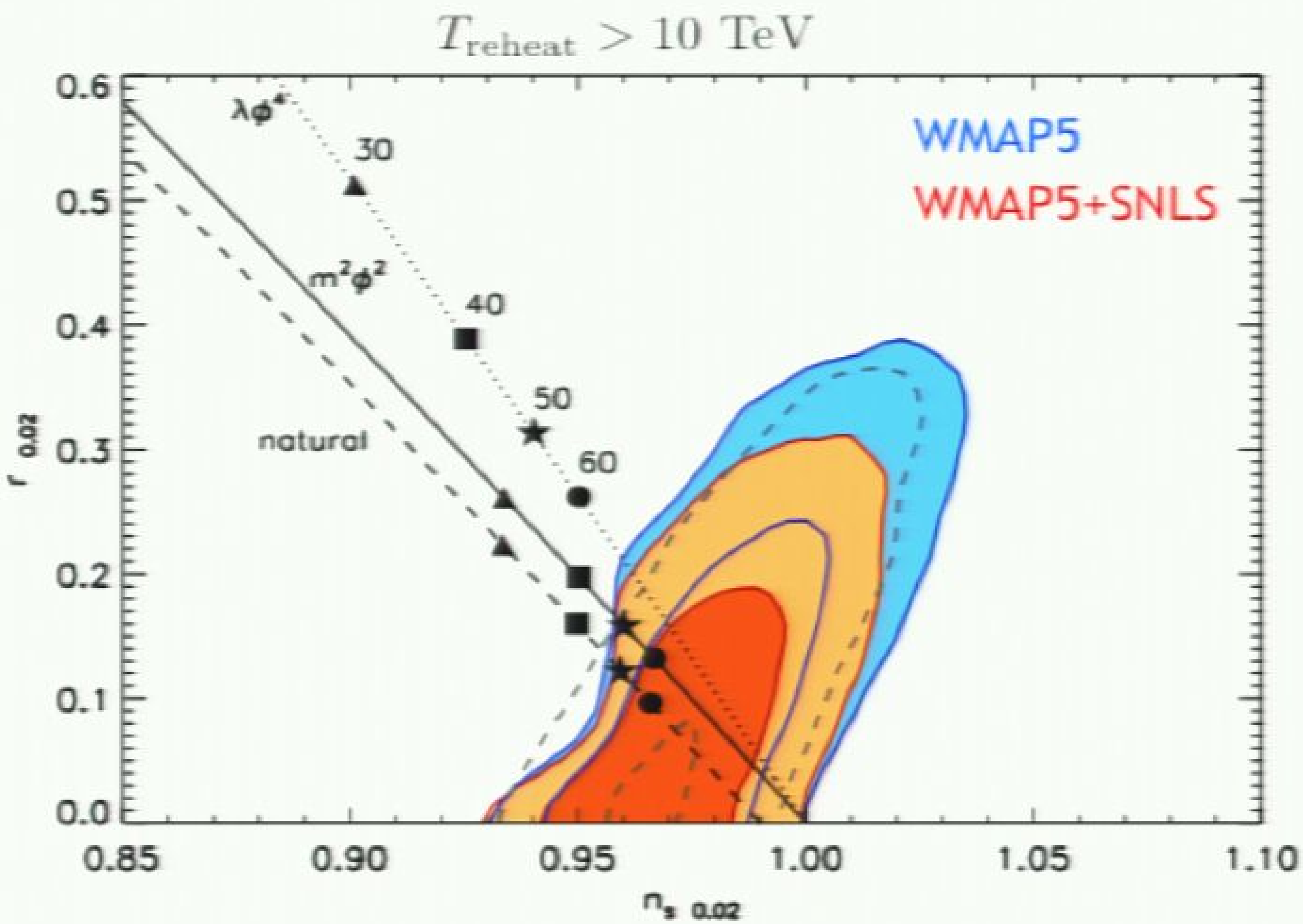

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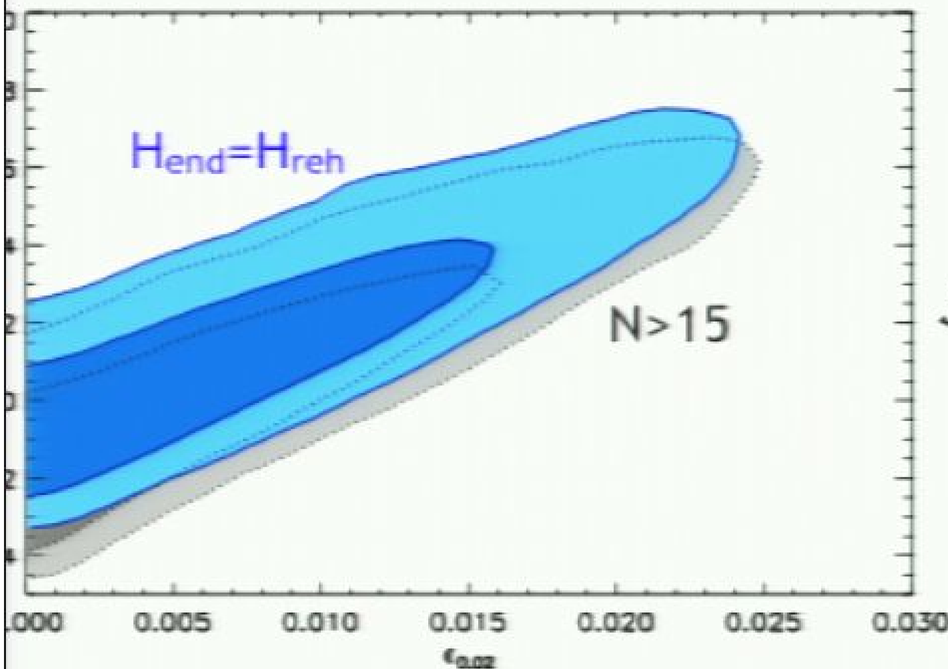

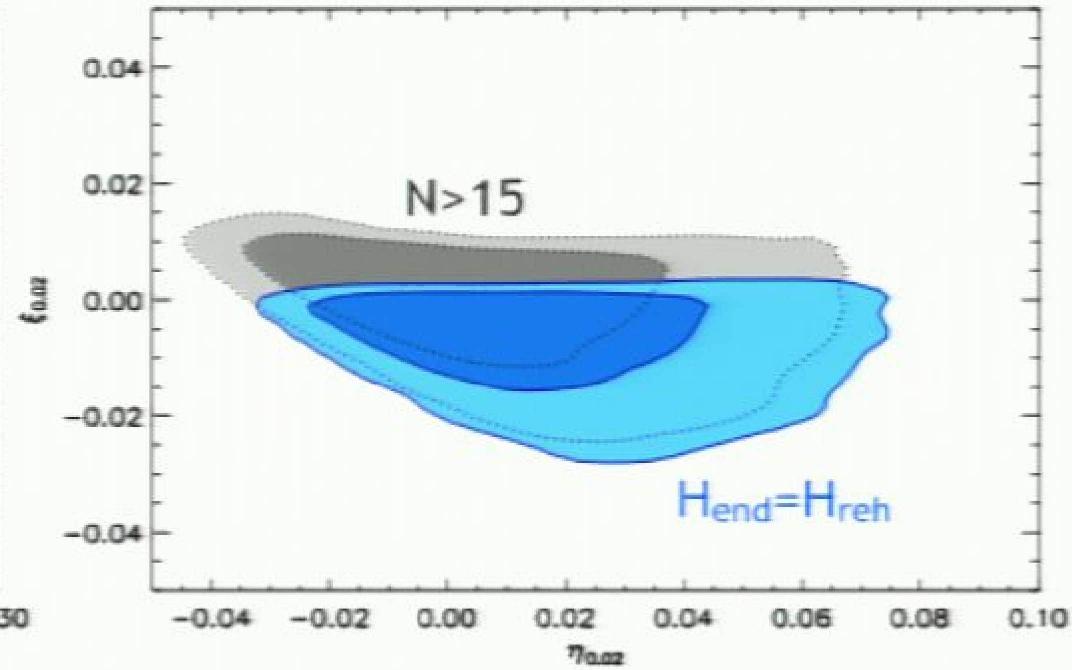

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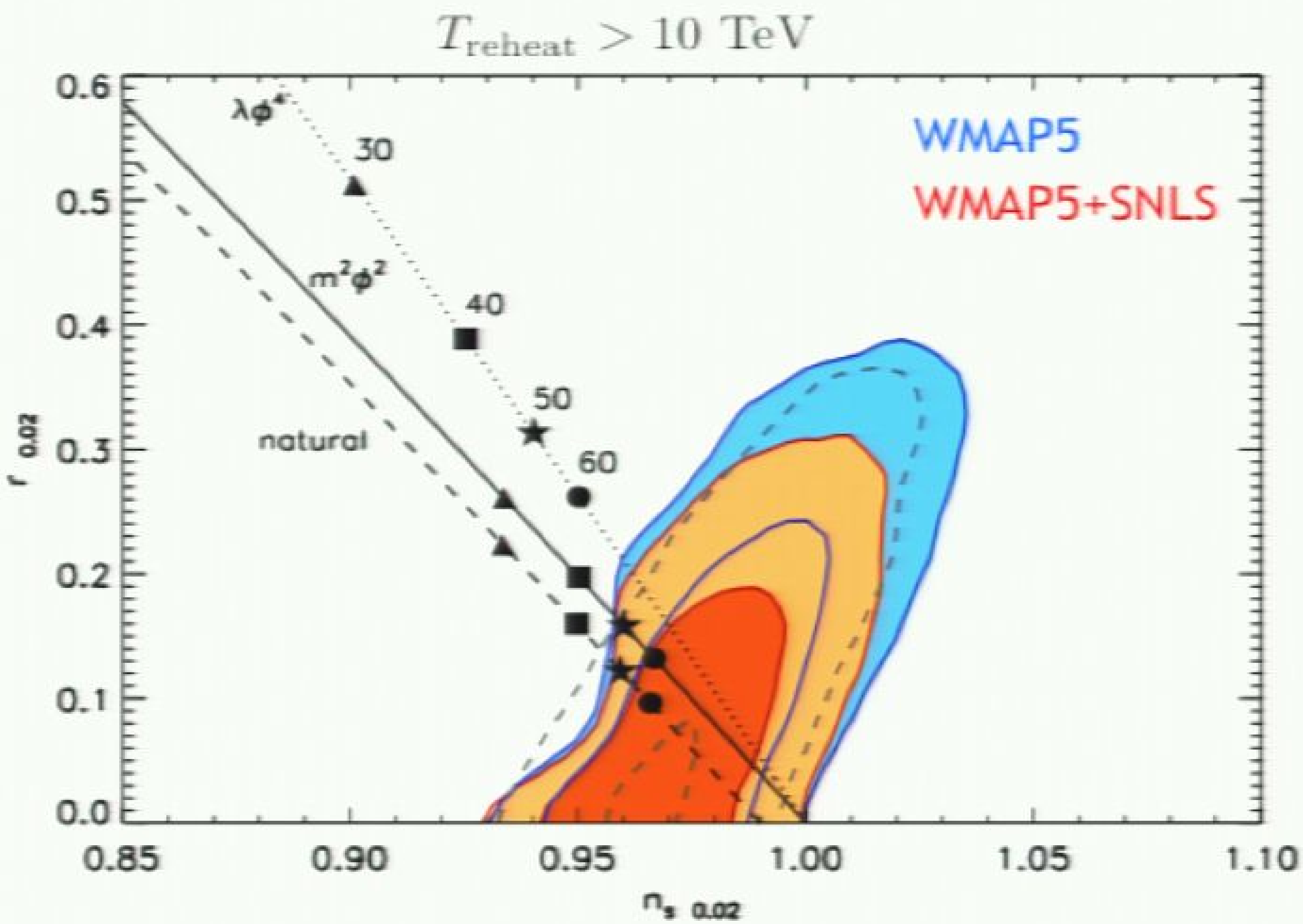

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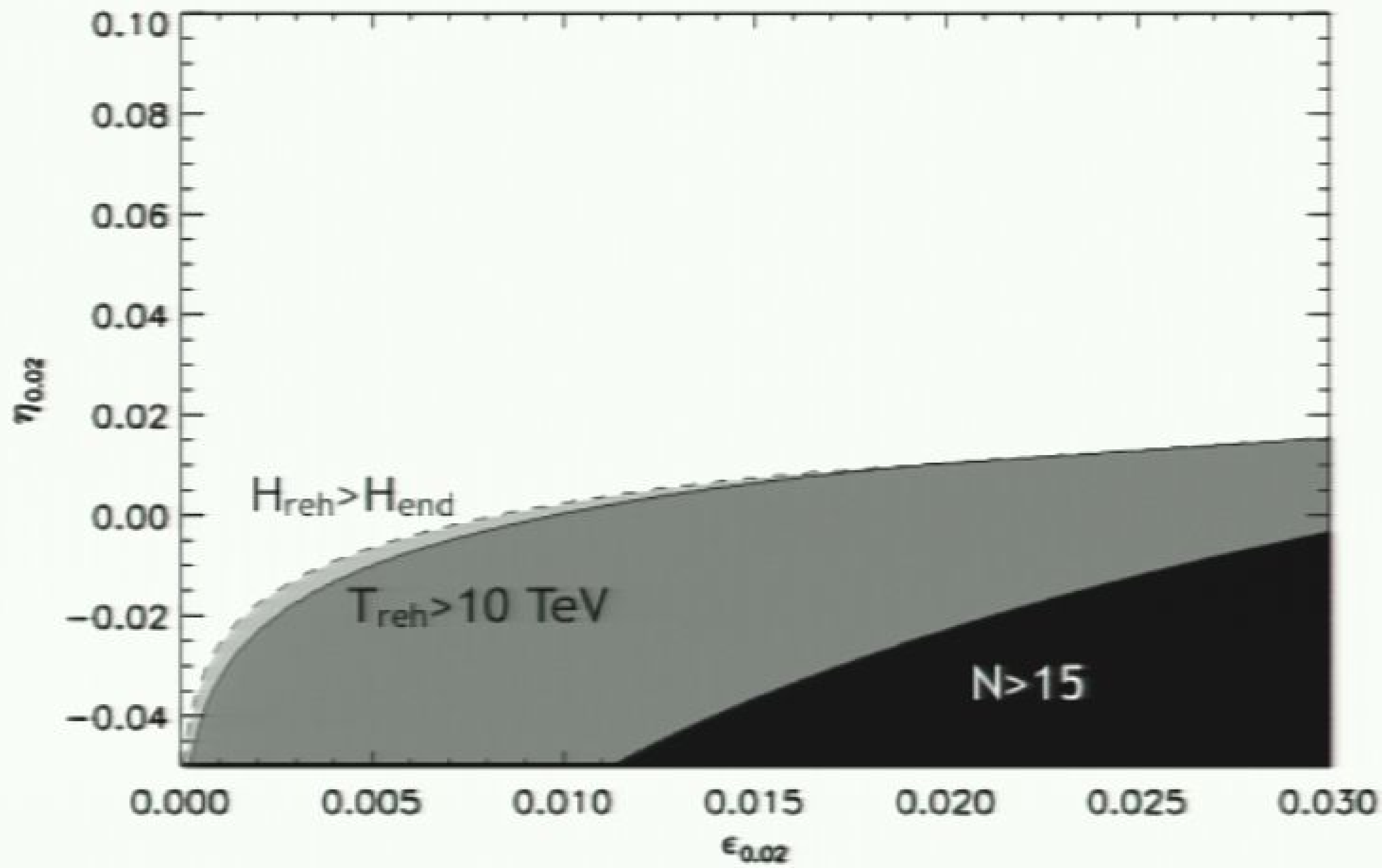

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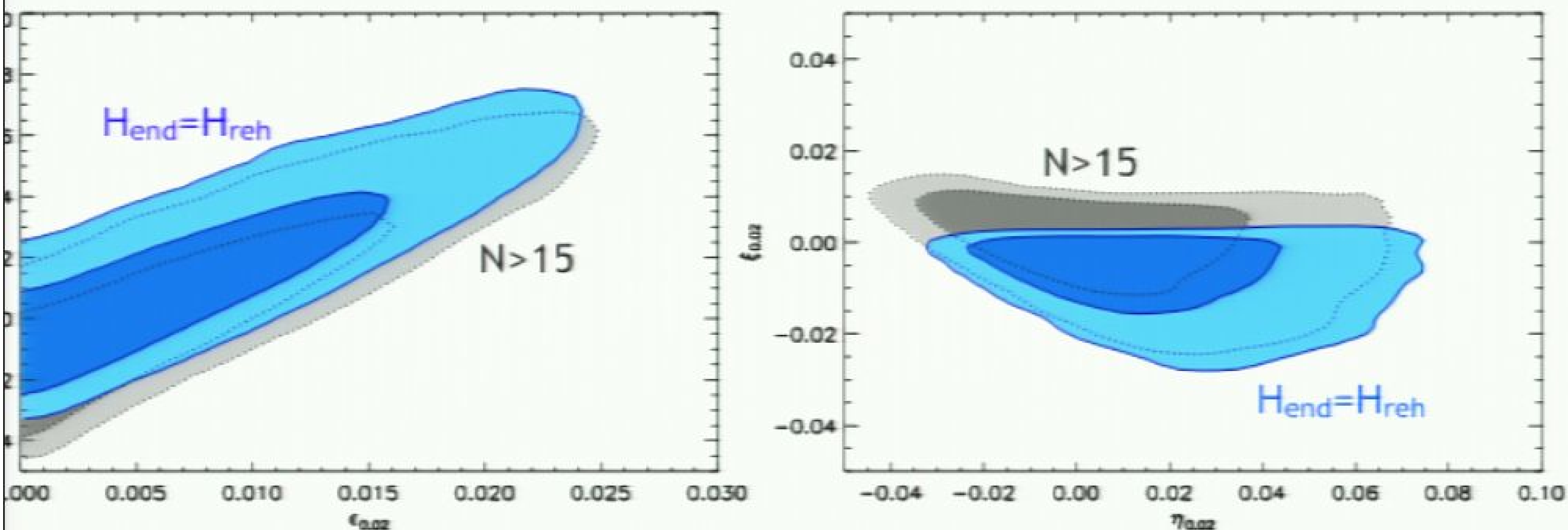

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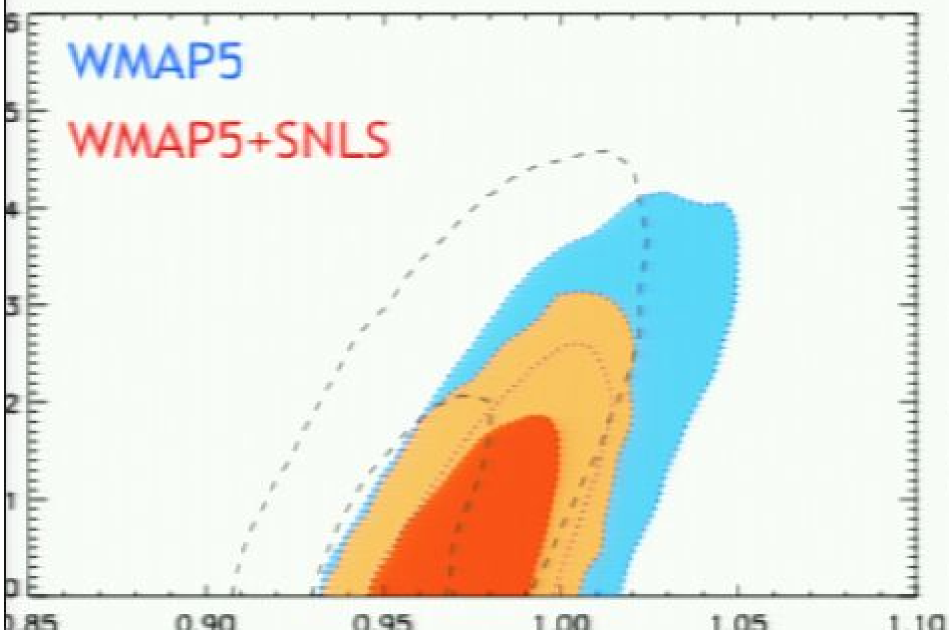

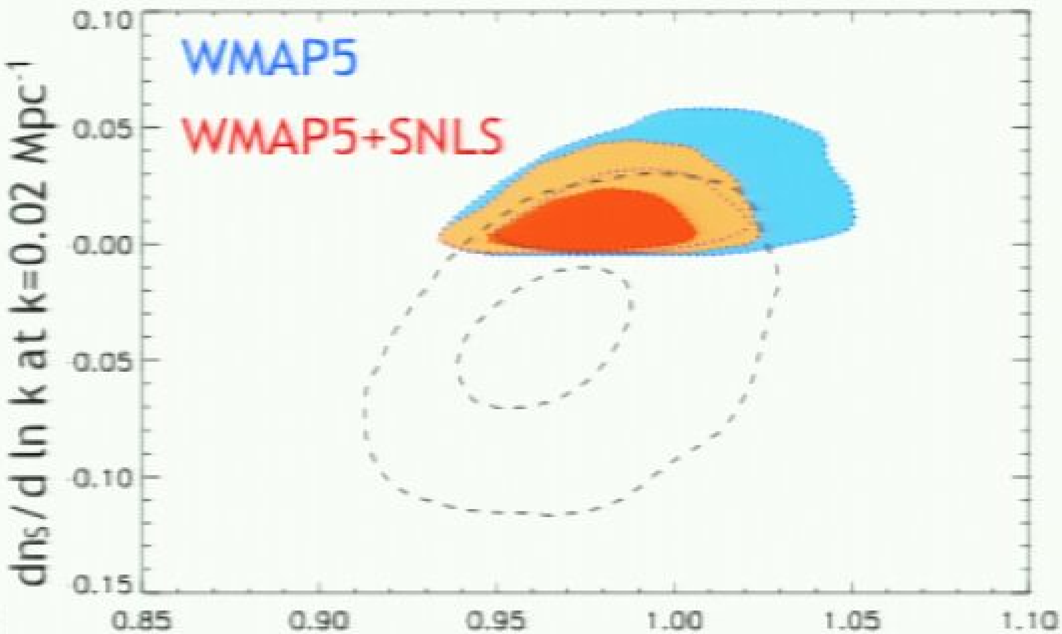

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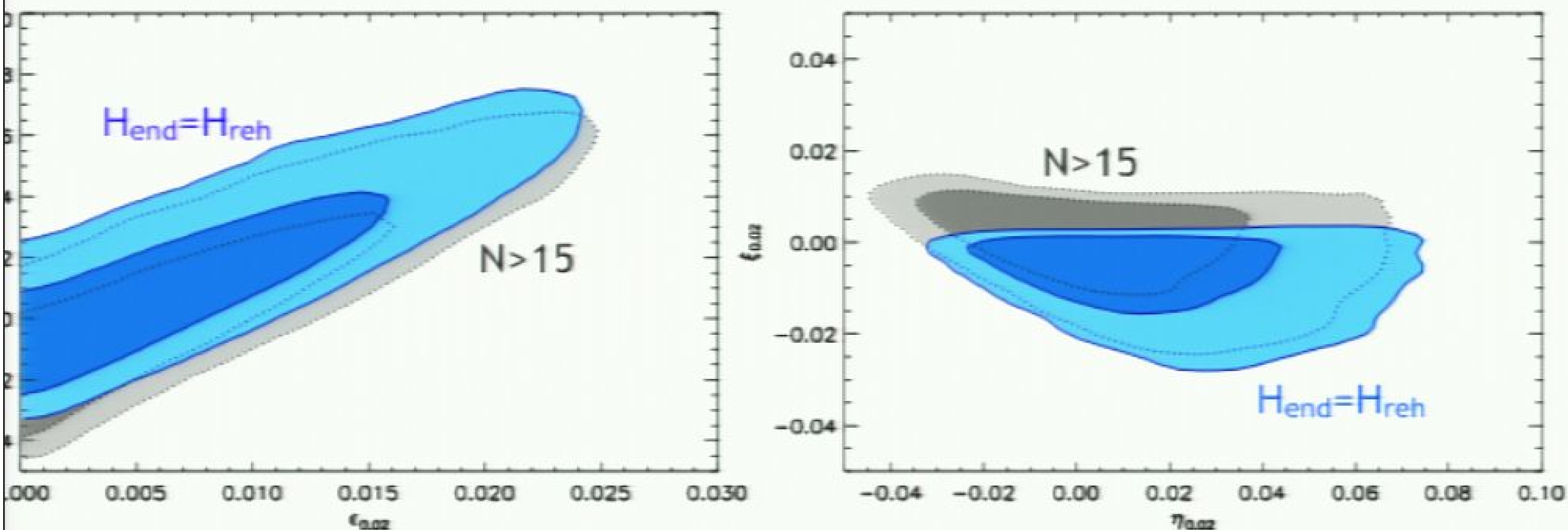

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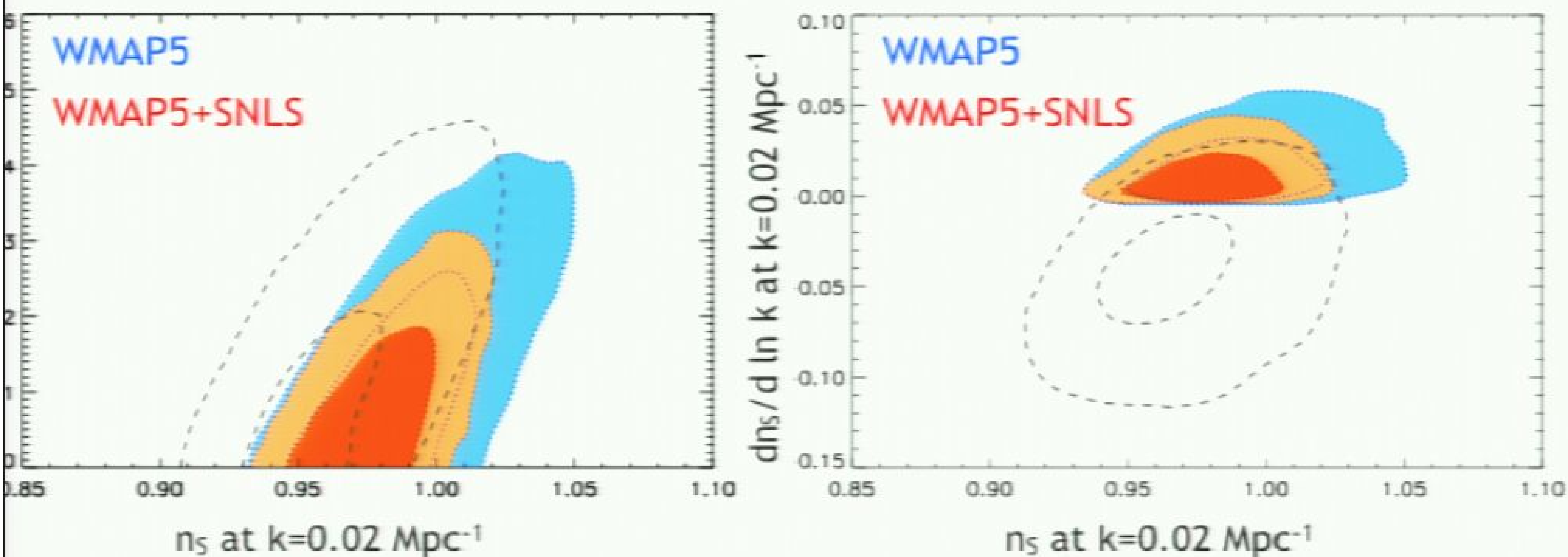

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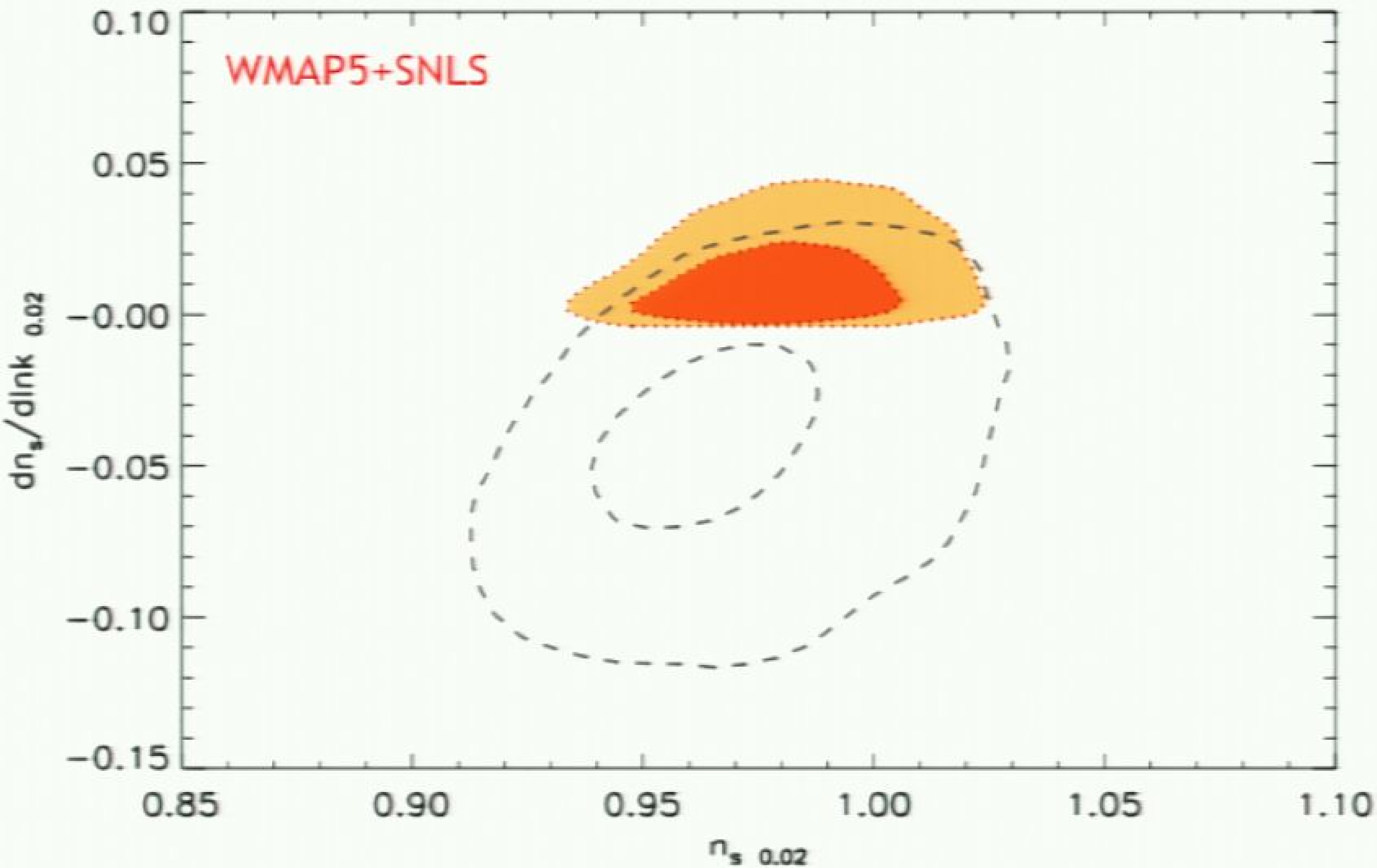
Primordial black hole overproduction



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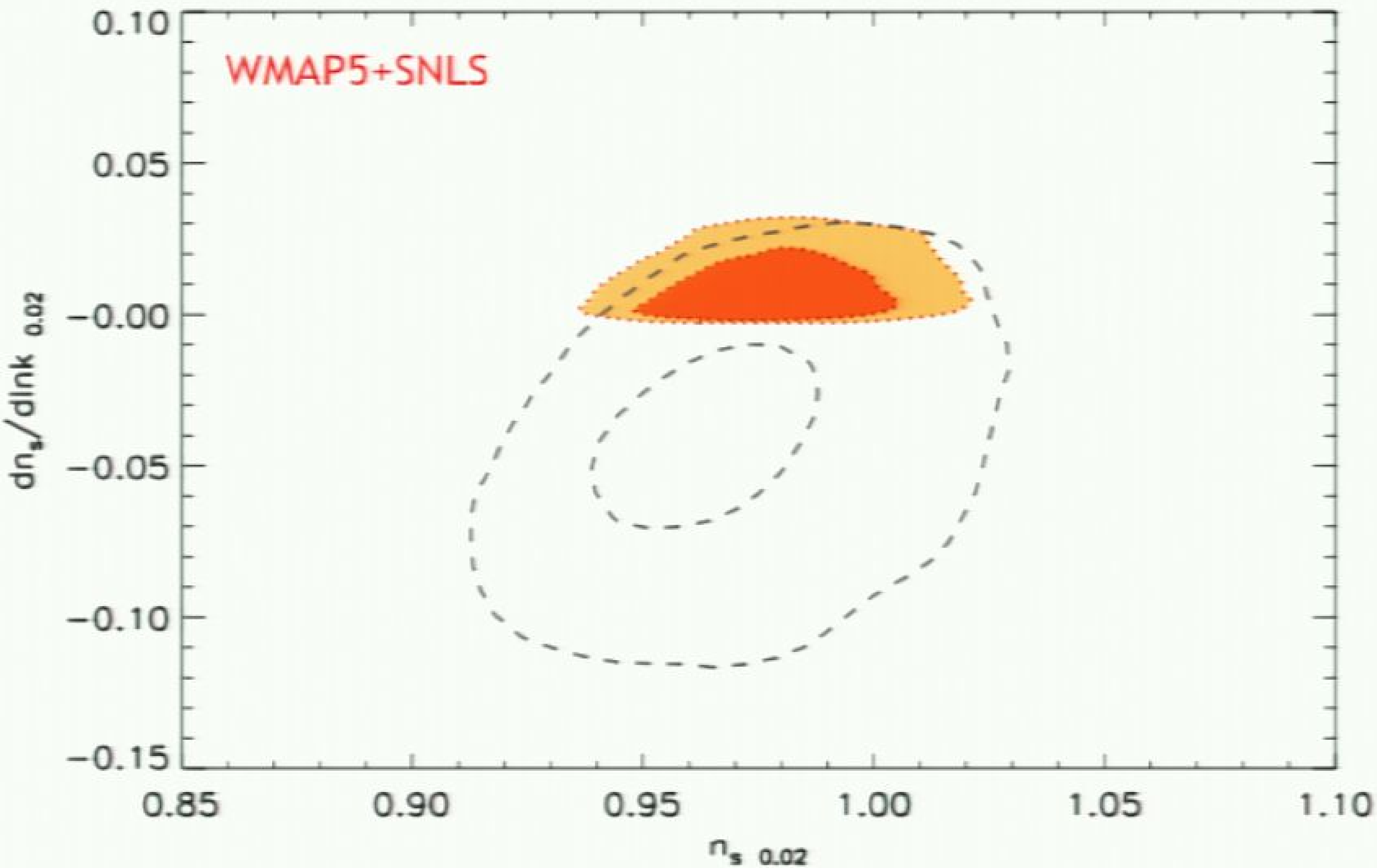

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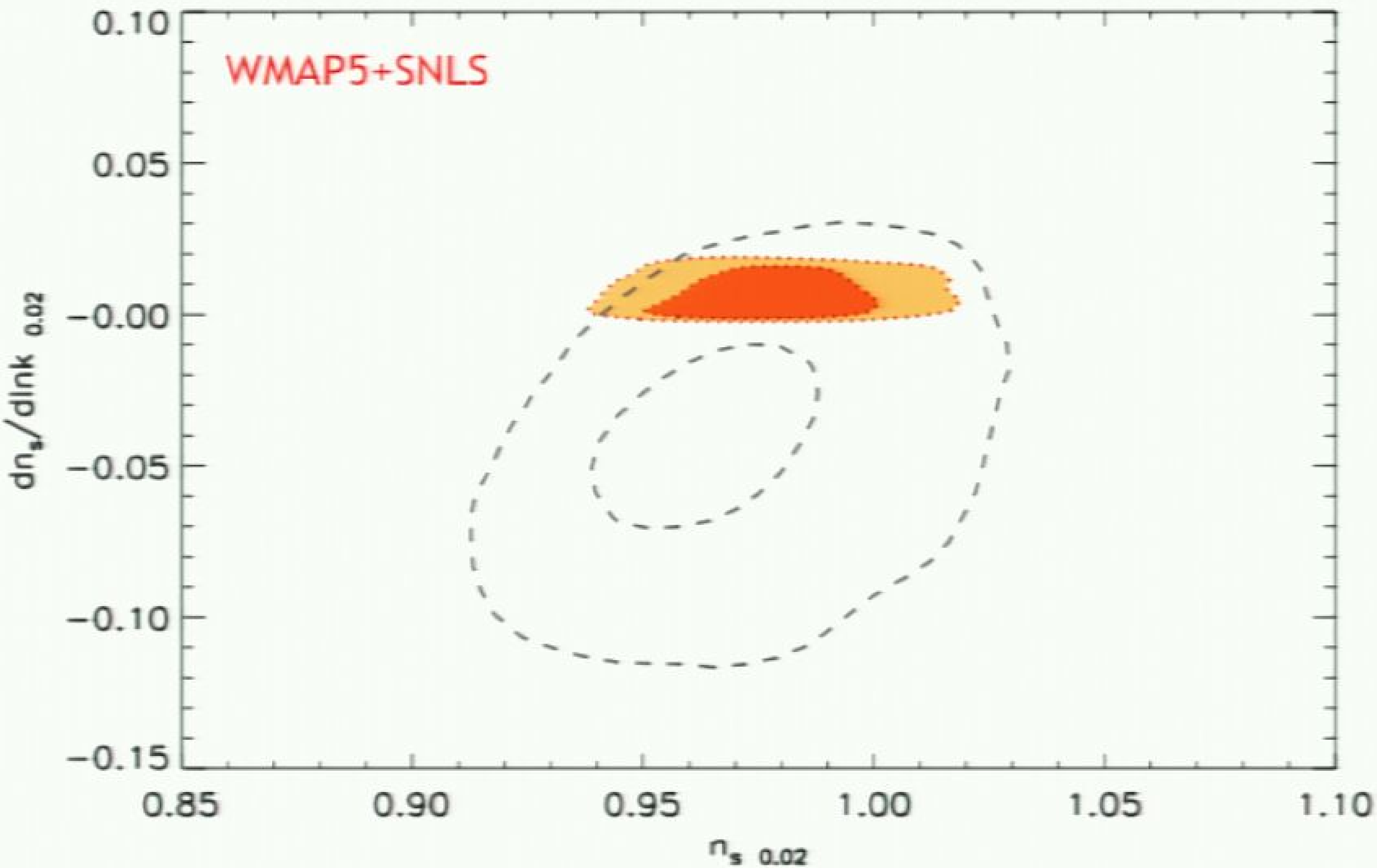

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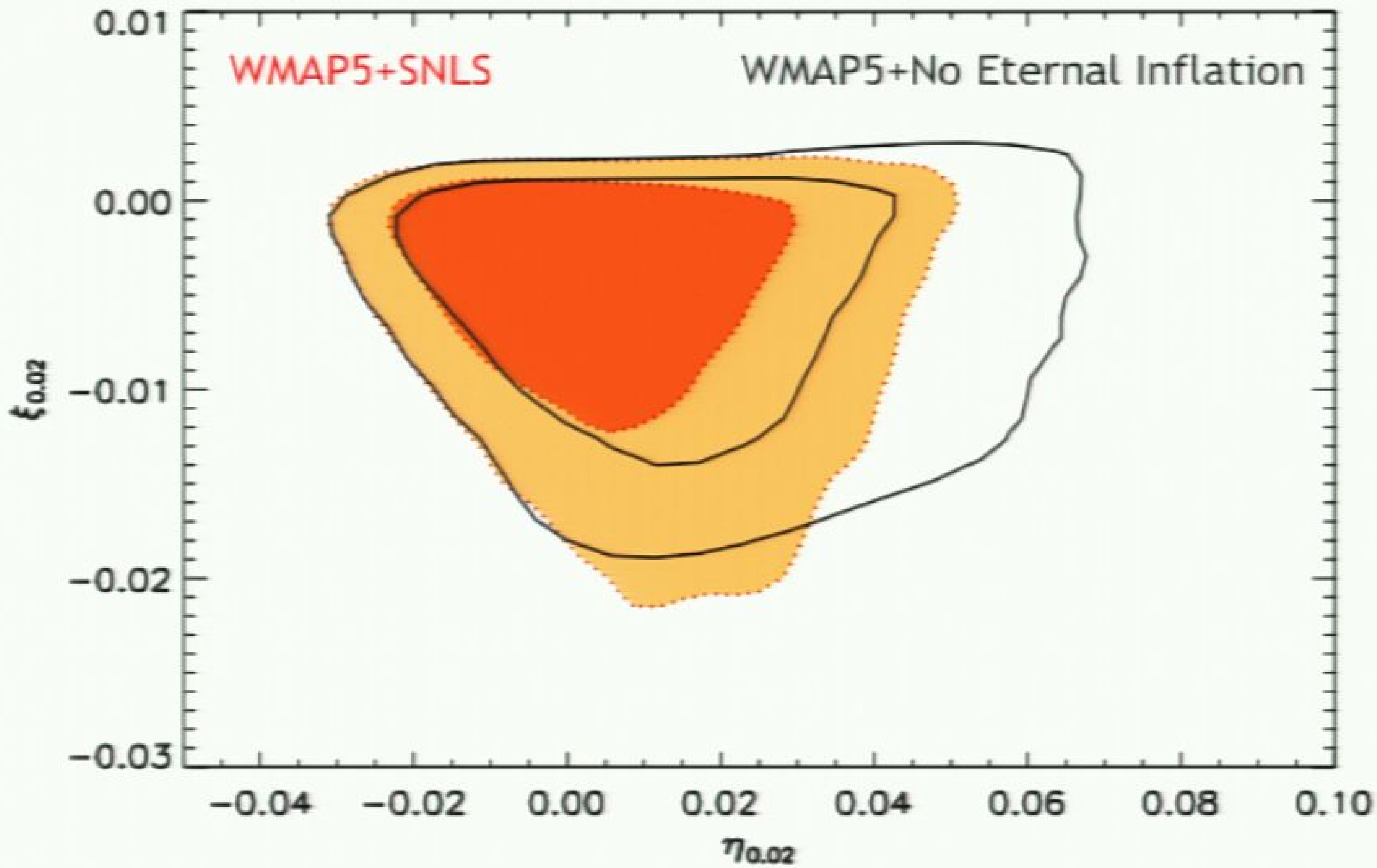
Eternal inflation in observable volume



WMAP5+SNLS roughly as constraining as no eternal inflation prior + WMAP5

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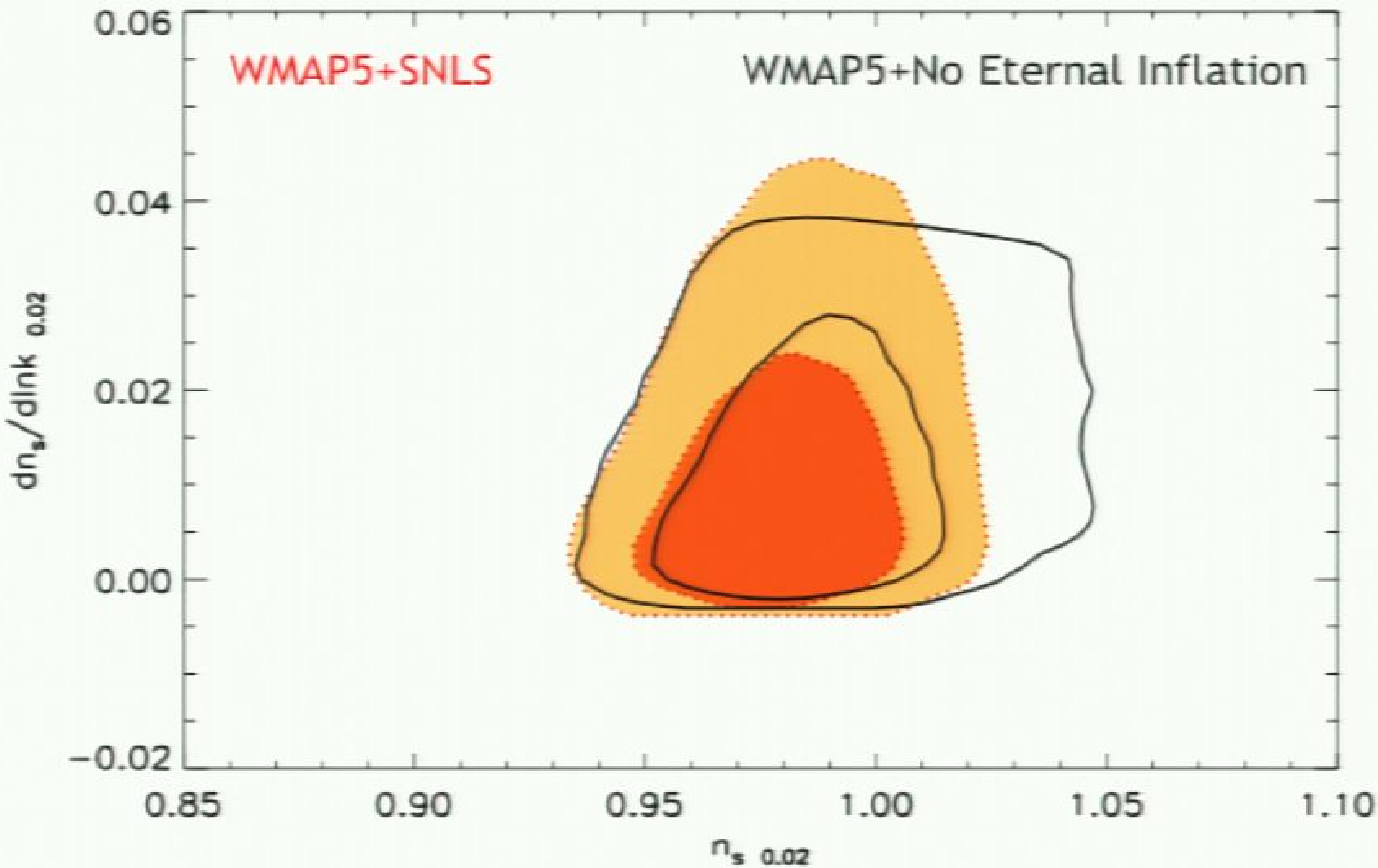

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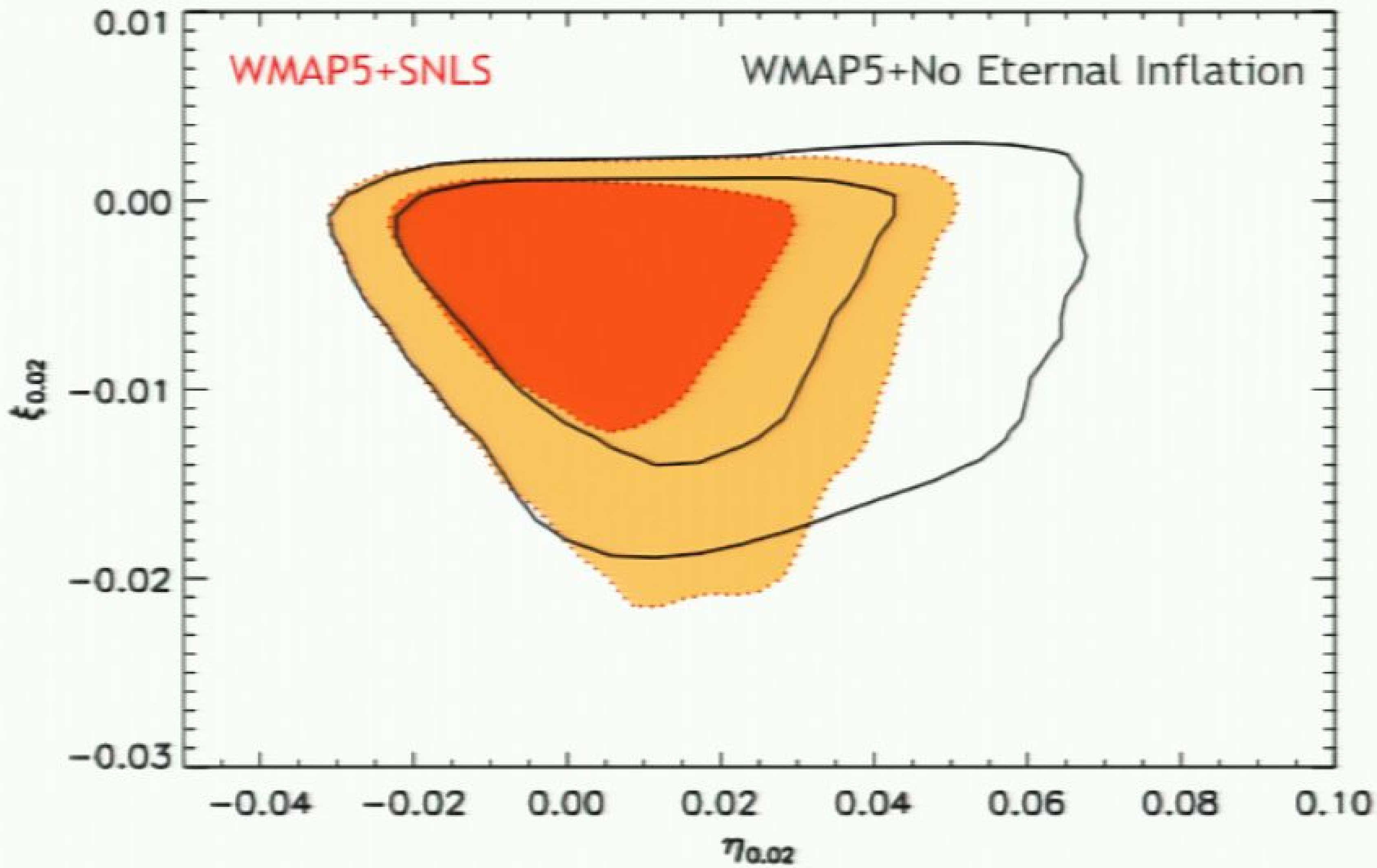

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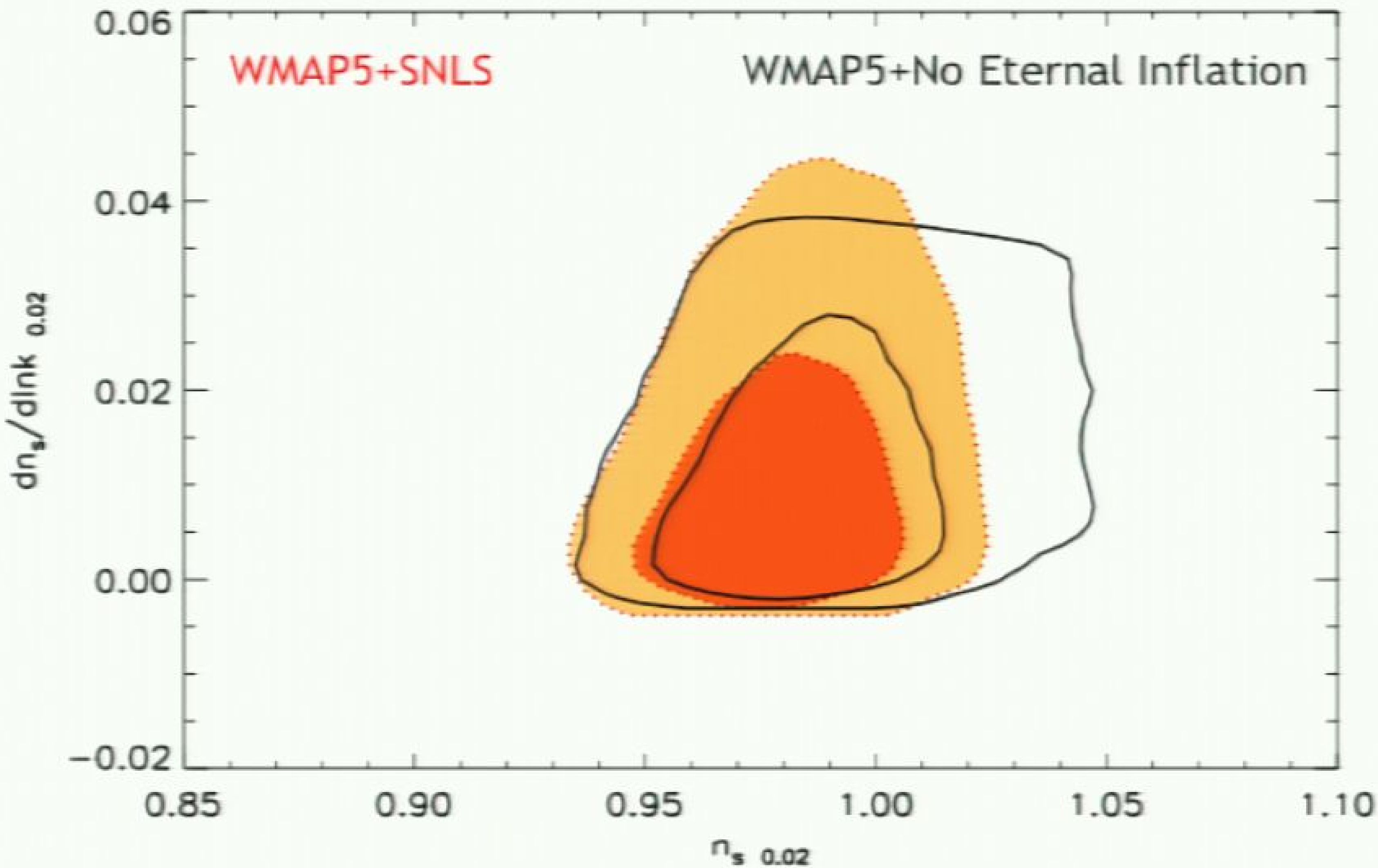

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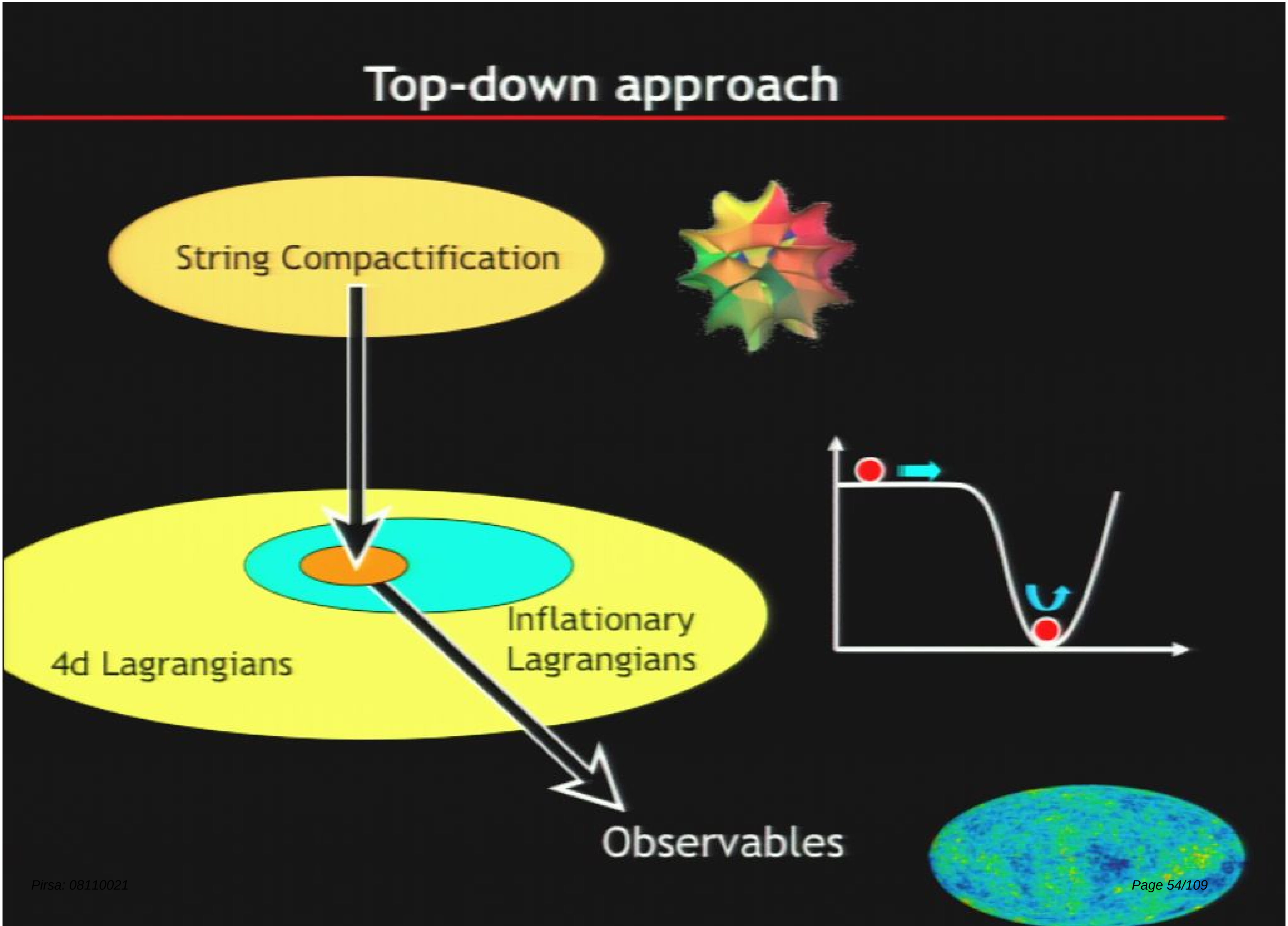
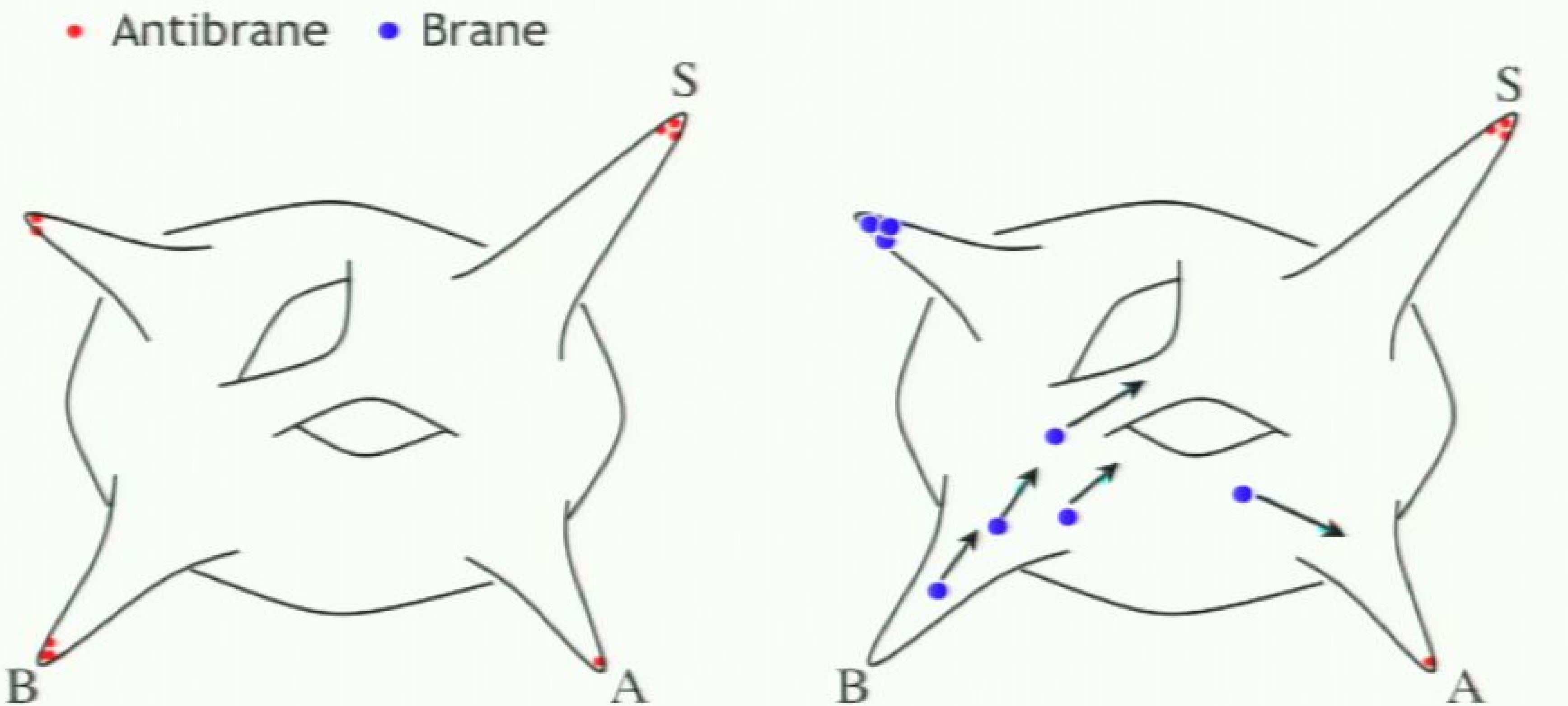
Summary

- 2 slow roll params: constraints roughly same as with {ns, r}
- 3 slow roll params: most {ns, r, dn/dlnk} parameter space allowed by data is ruled out by physical priors on:
  - duration of inflation
  - primordial BH overproduction
  - avoiding onset of eternal inflation in observable volume
- To constrain with data (rather than with priors), need a significant improvement over current data, e.g. Planck


Top-down approach
String Compactification
Inflationary
Lagrangians
4d Lagrangians
Observables

"IR" Multi-throat D-brane Inflation



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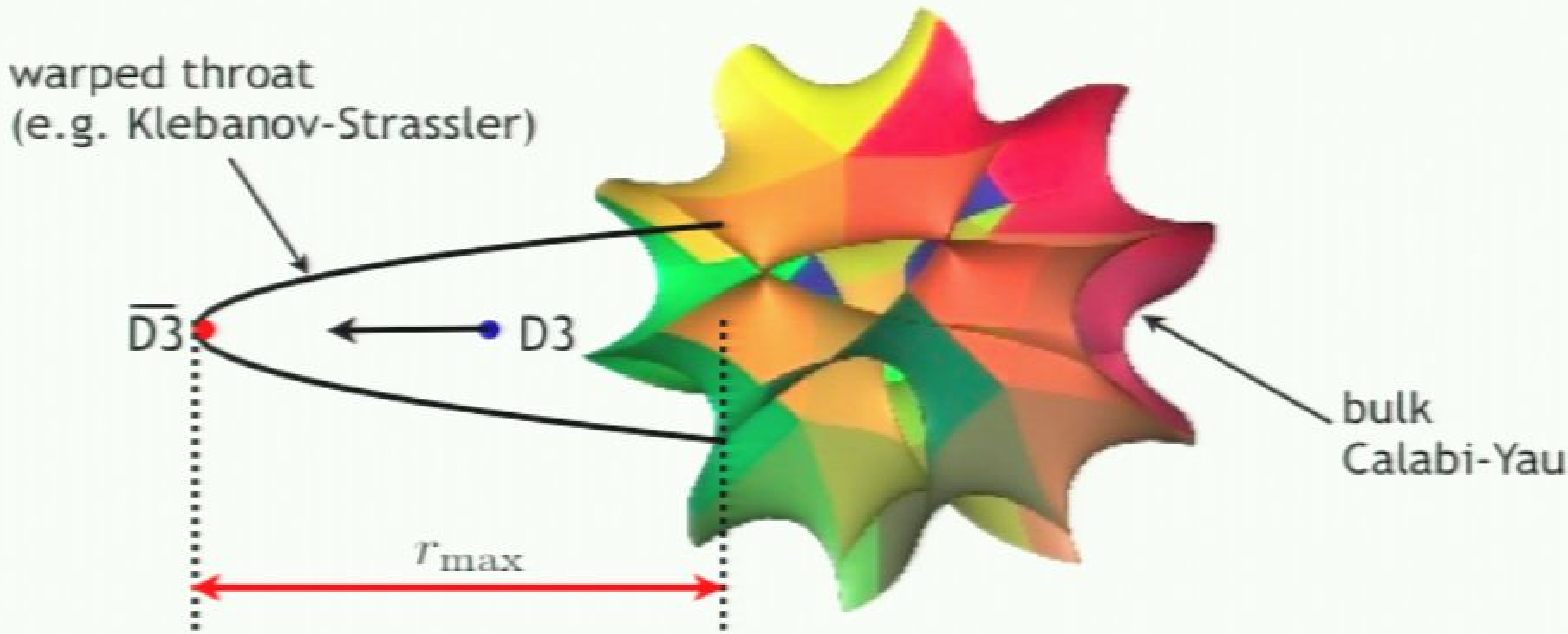
Contrast with "UV" DBI Inflation



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Differences between "UV" and "IR" models

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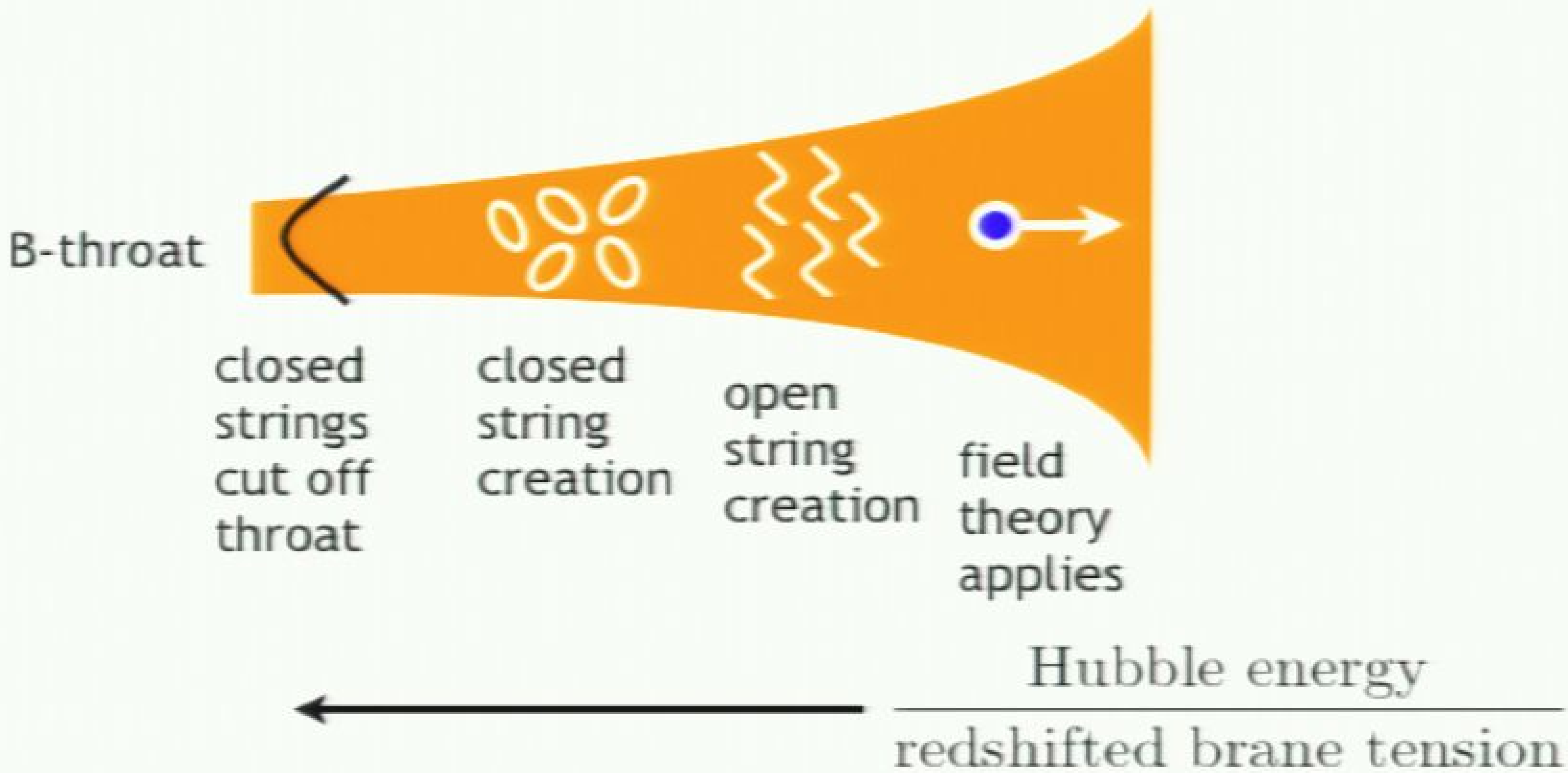
Distinctive observables of the "IR" model

- Large transient running of the scalar spectral index.



- Large non-Gaussian signature with opposite running from the "UV" case, and an undetectable gravitational wave background: $r < 10^{-6}$

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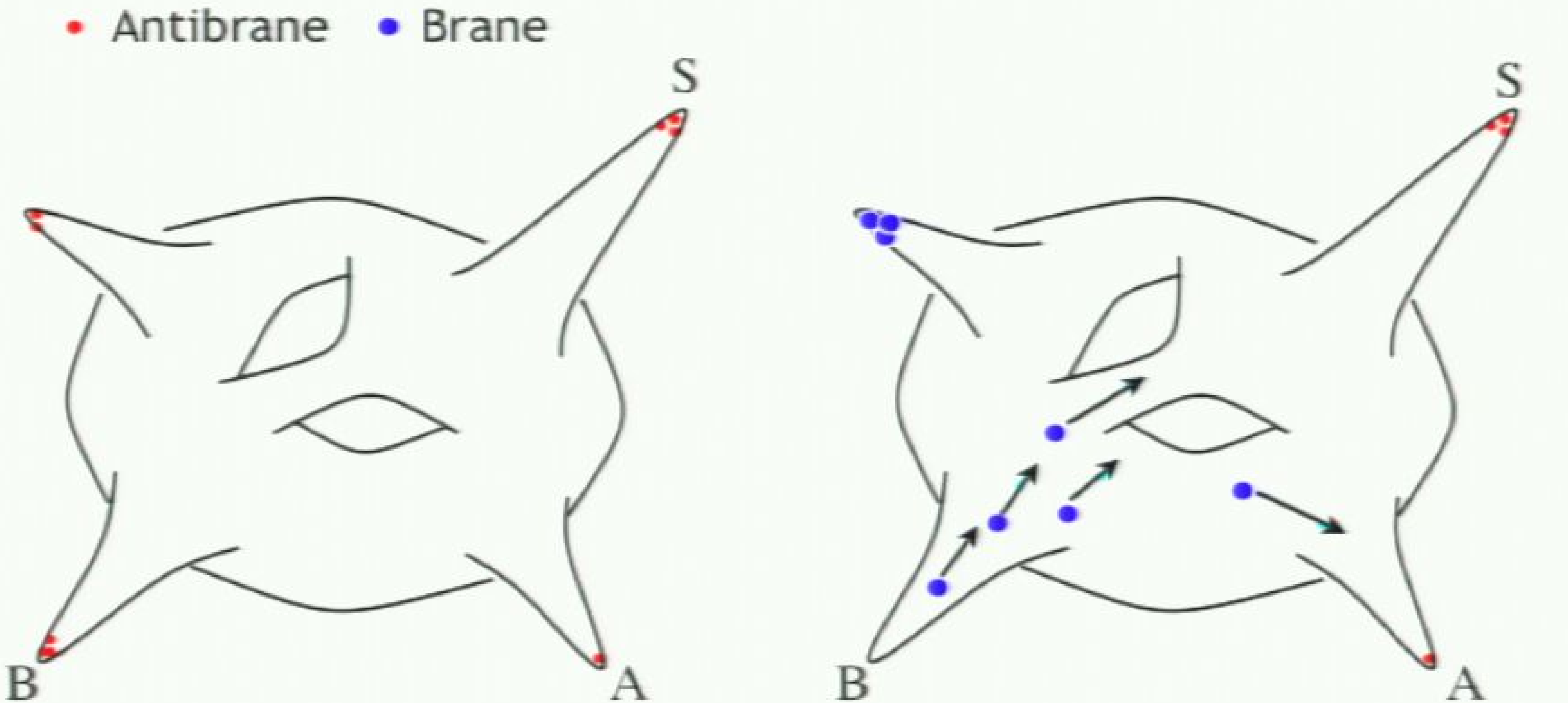

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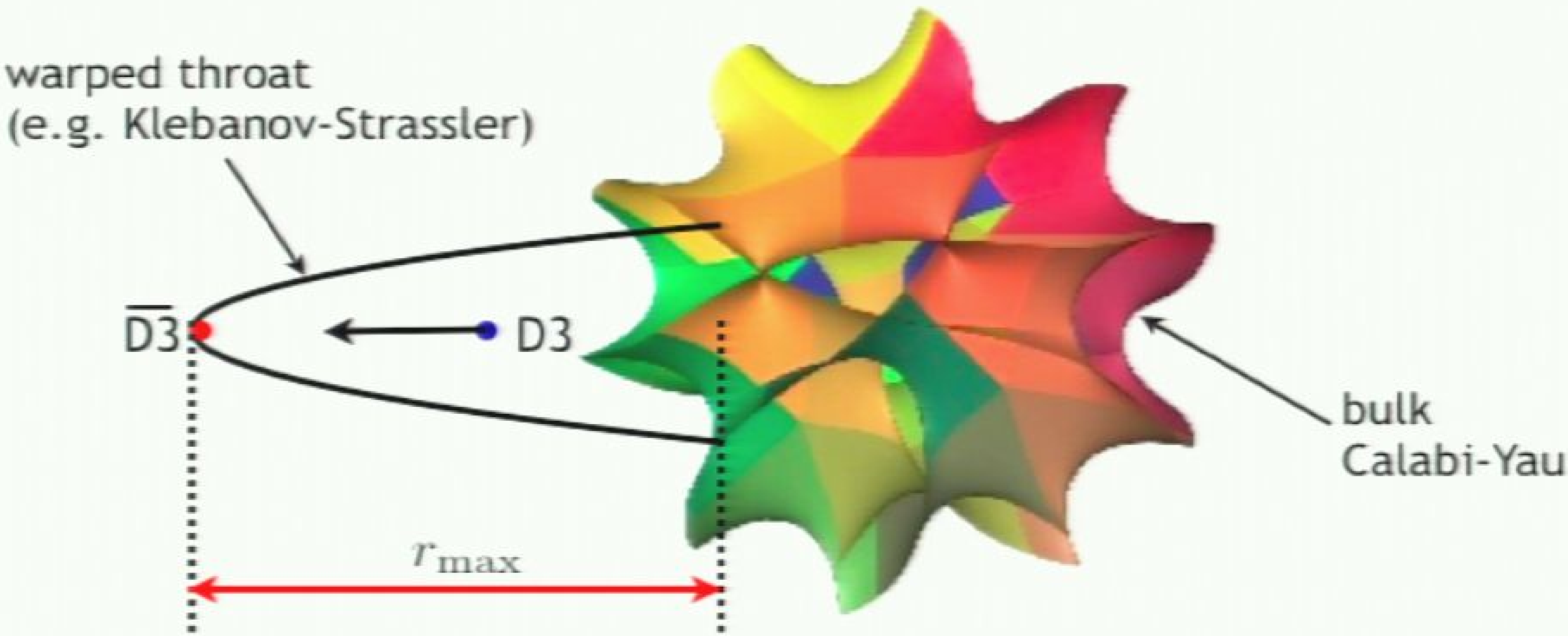

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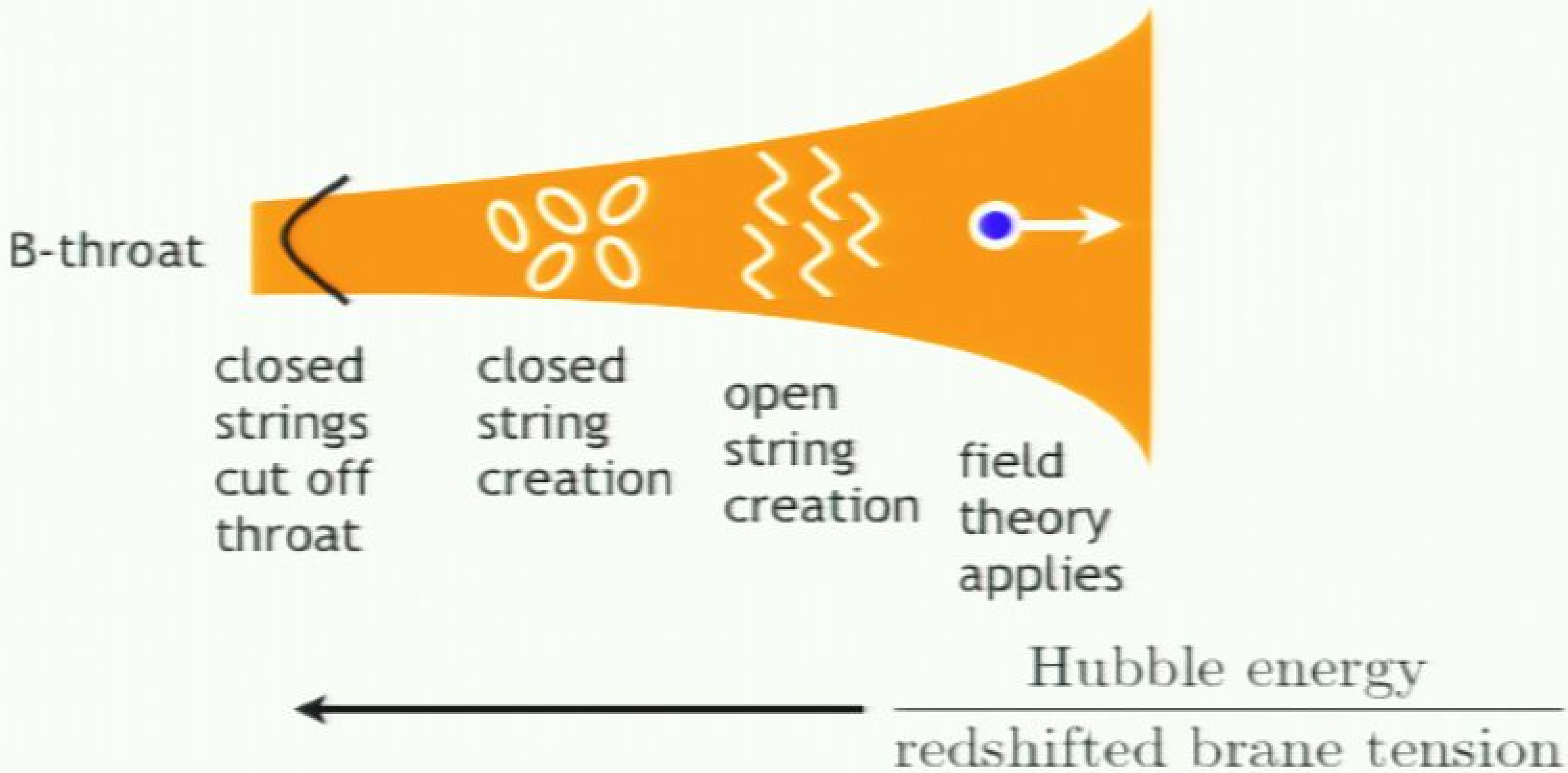

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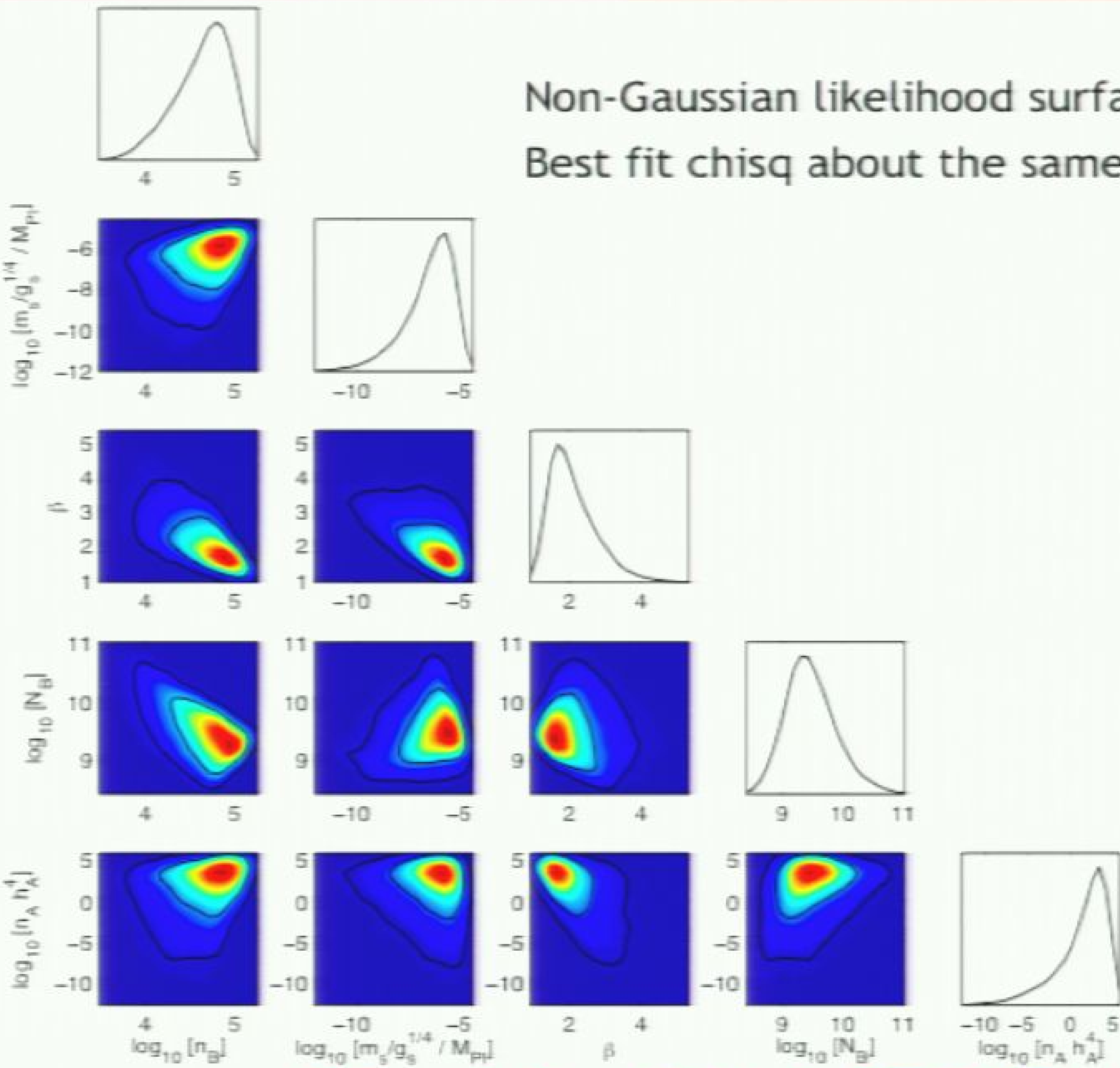

Non-Gaussian likelihood surface!

Best fit chisq about the same as LCDM.

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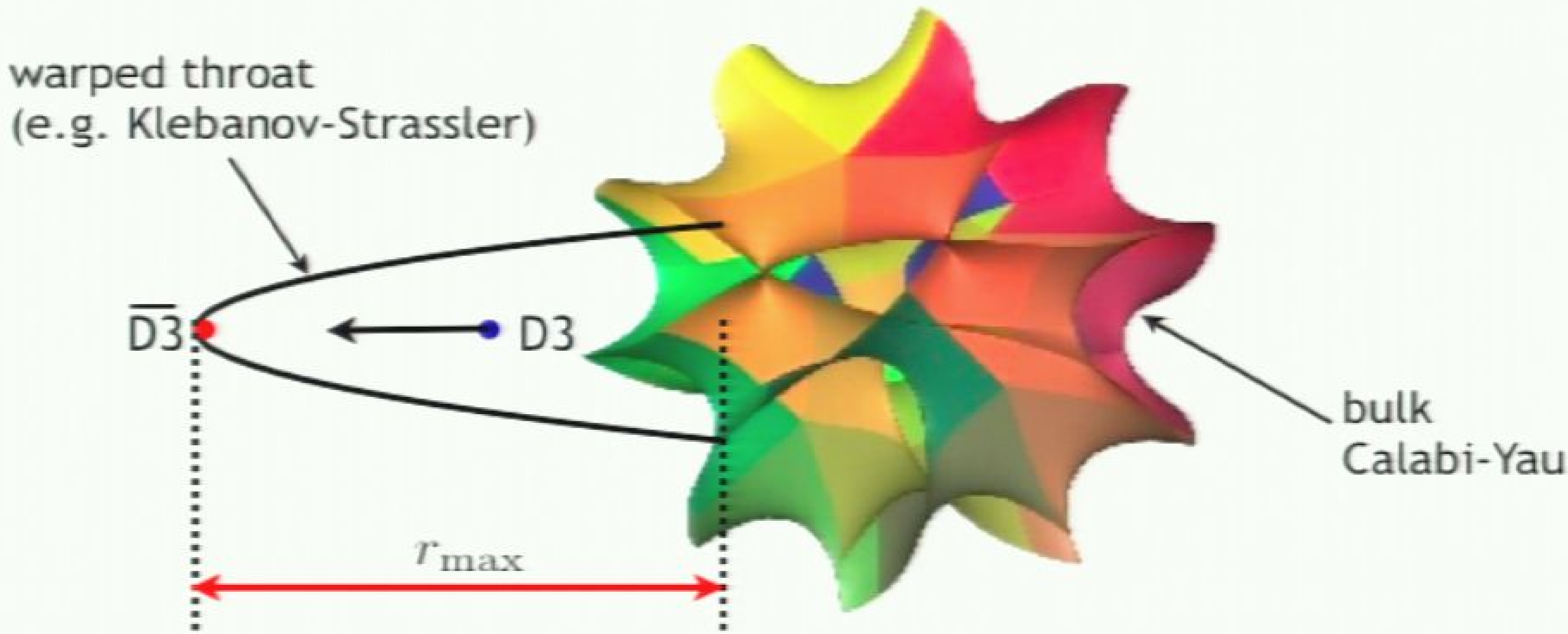

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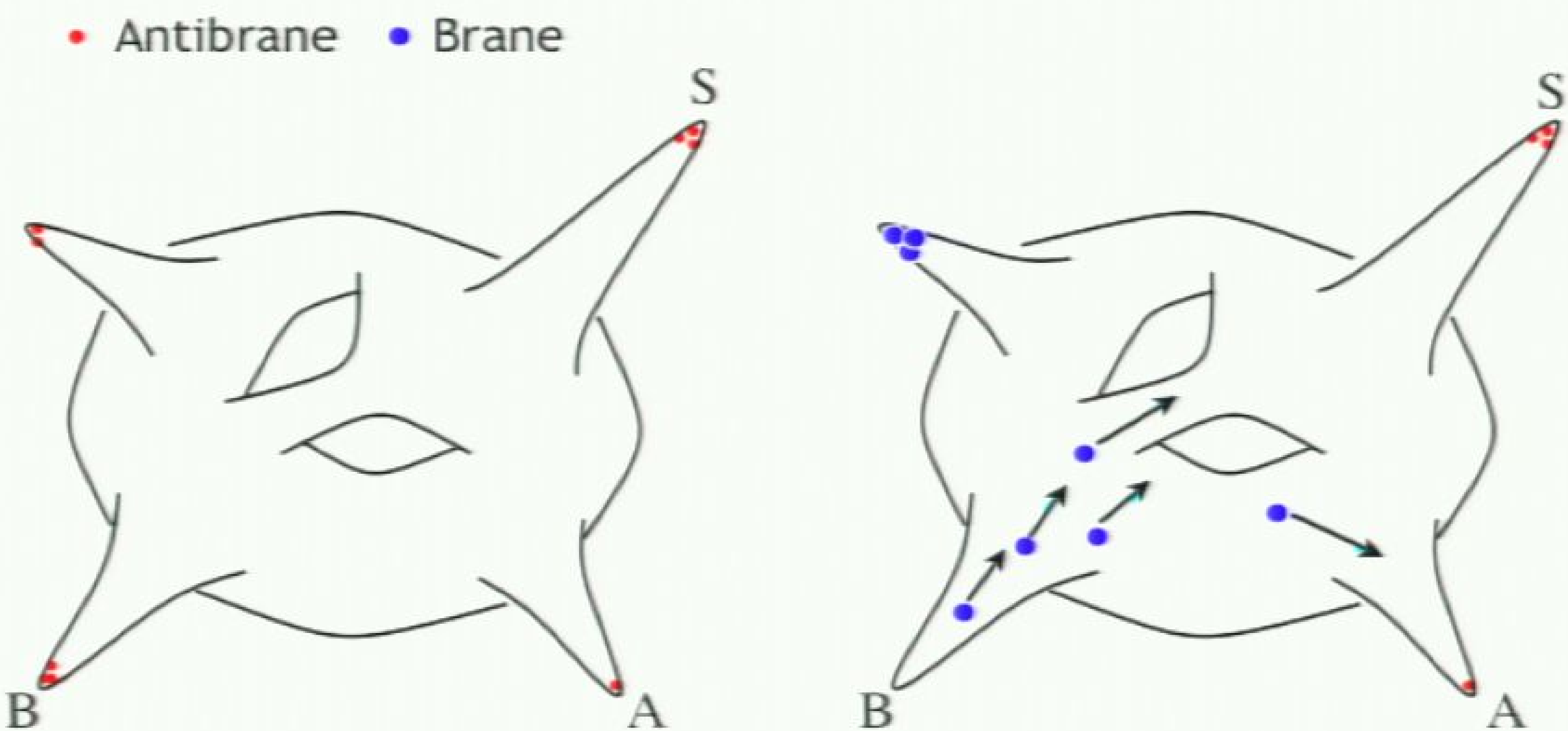

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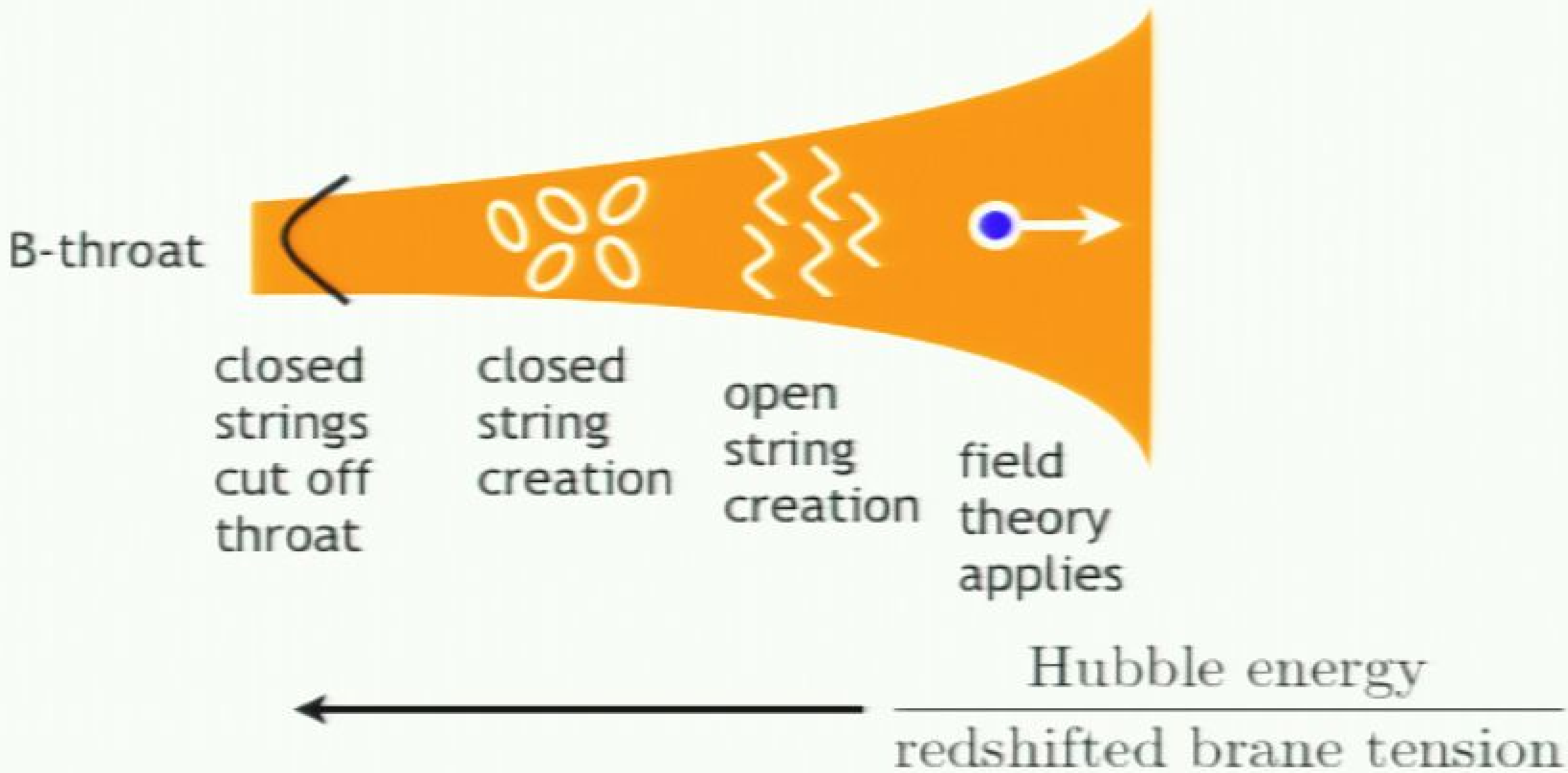

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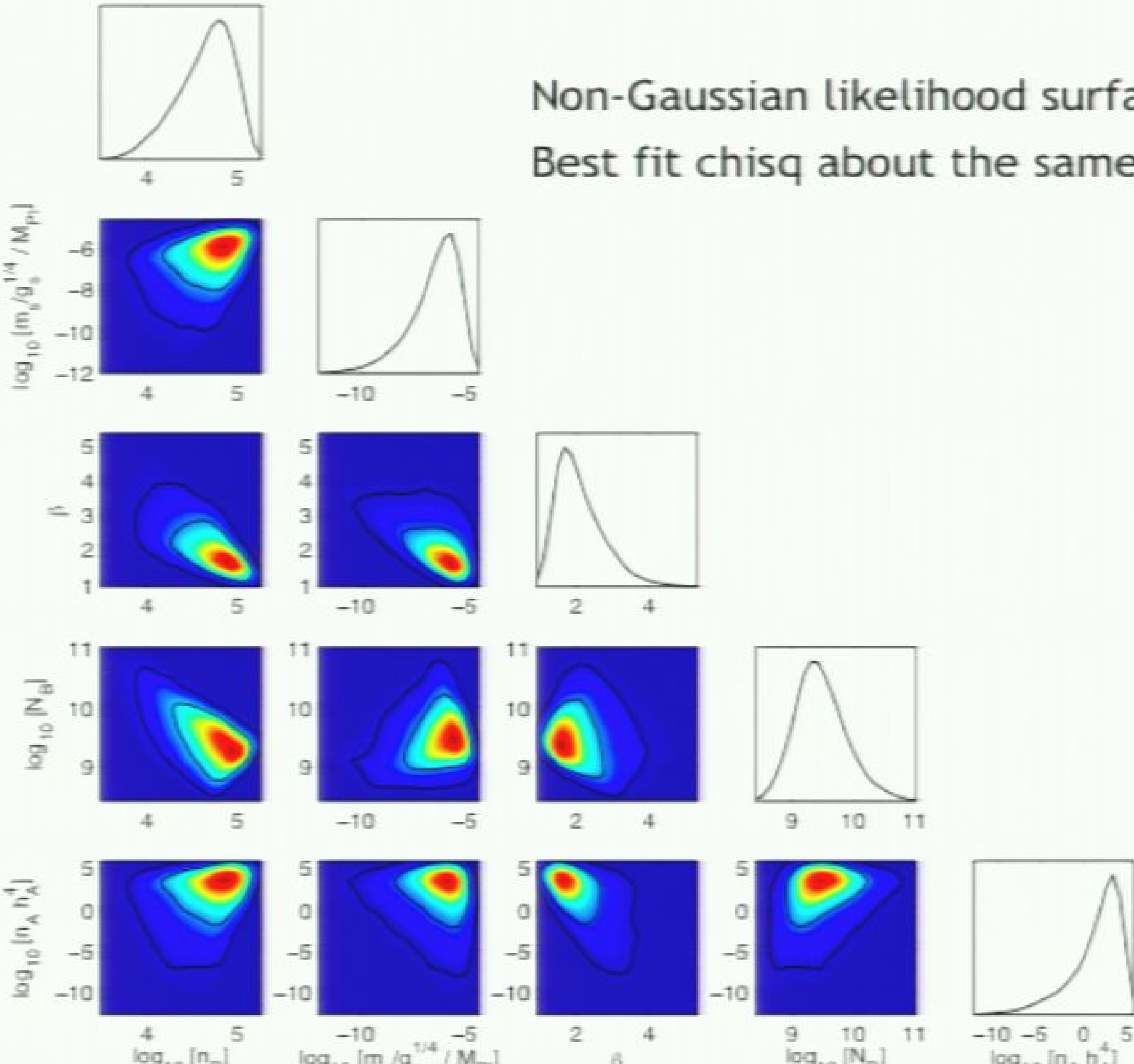

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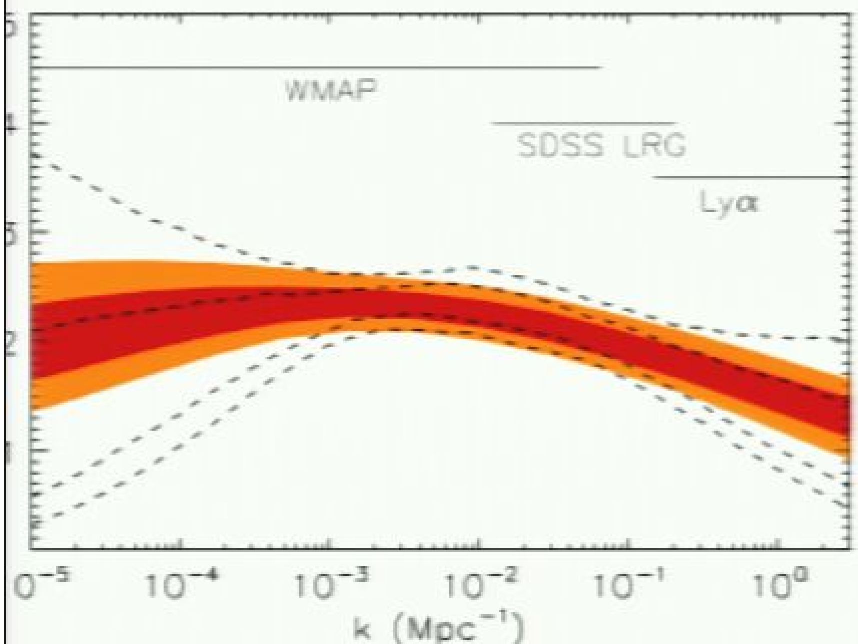
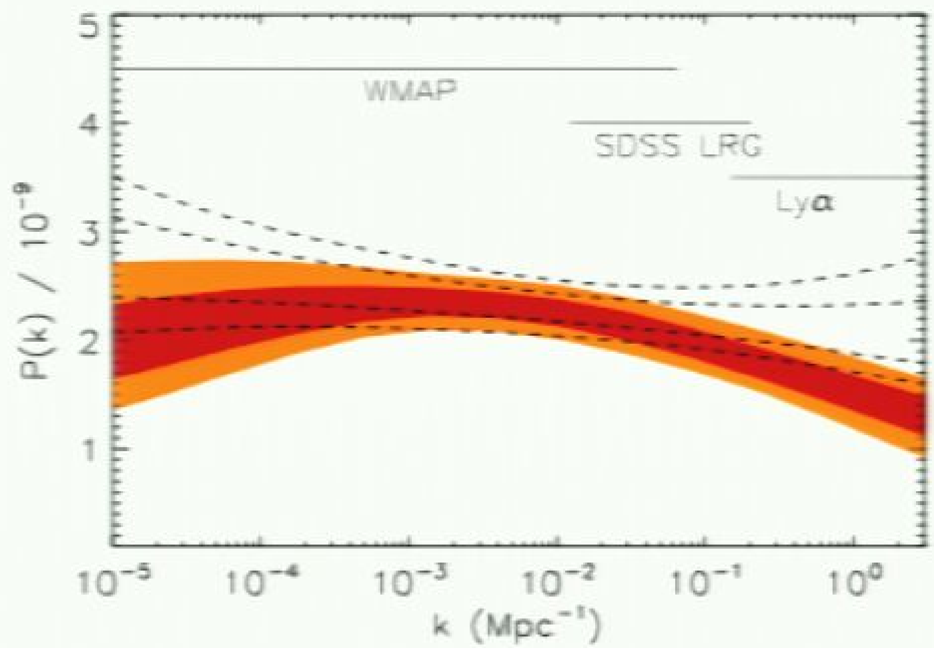


Comparison with constraints on empirical n_s, $dn_s/d\ln k$ prescription
[WMAP Collaboration, 2006]



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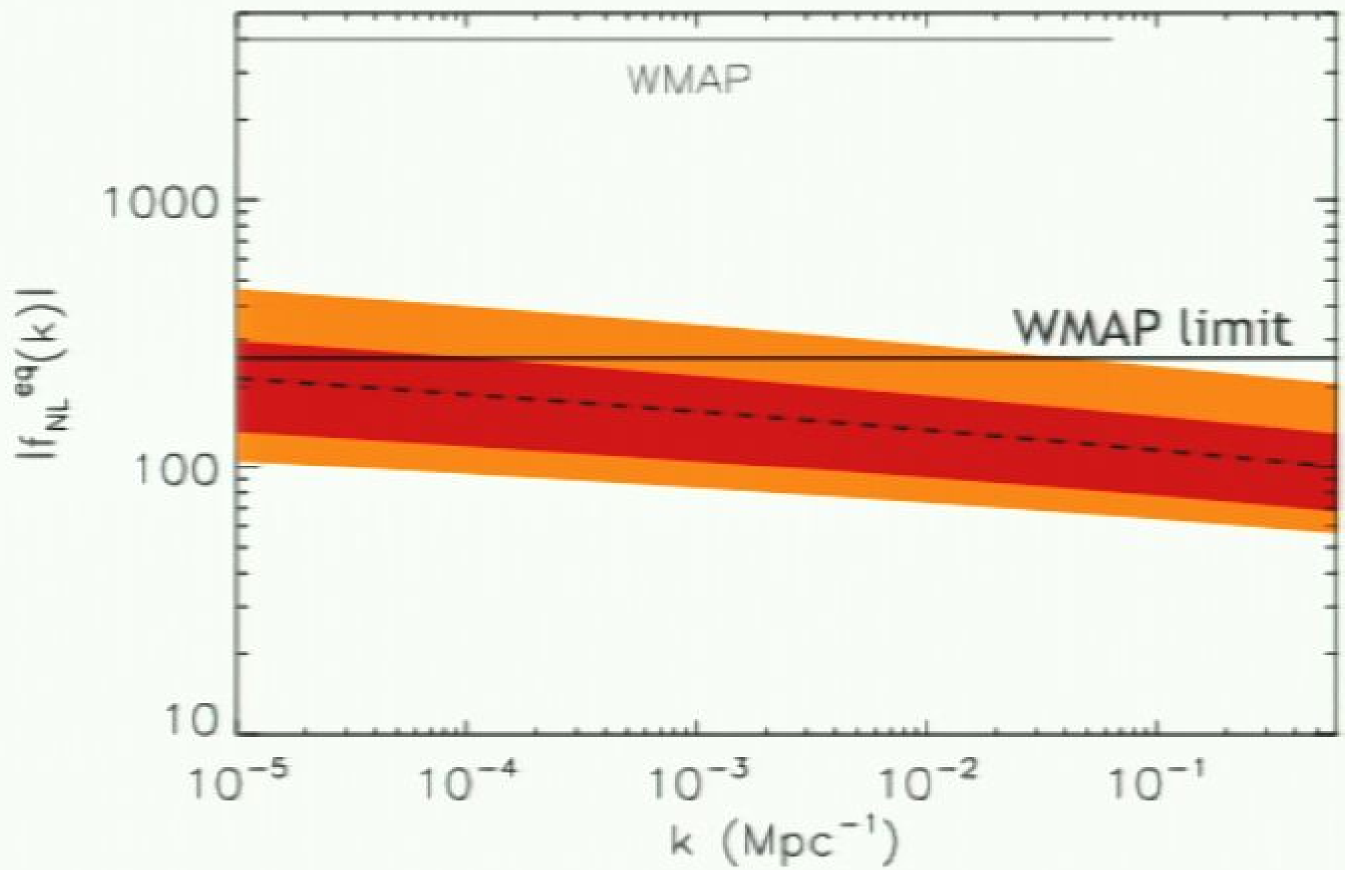

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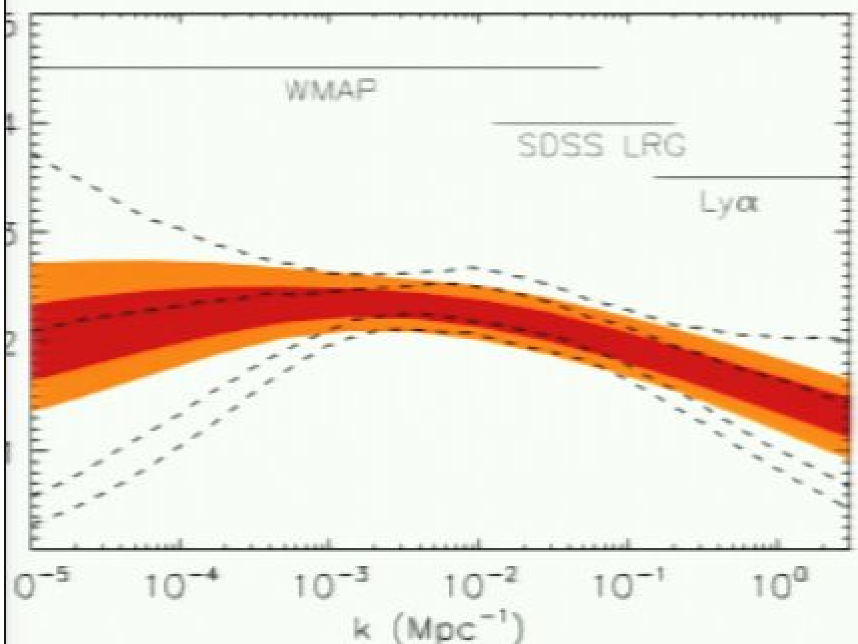

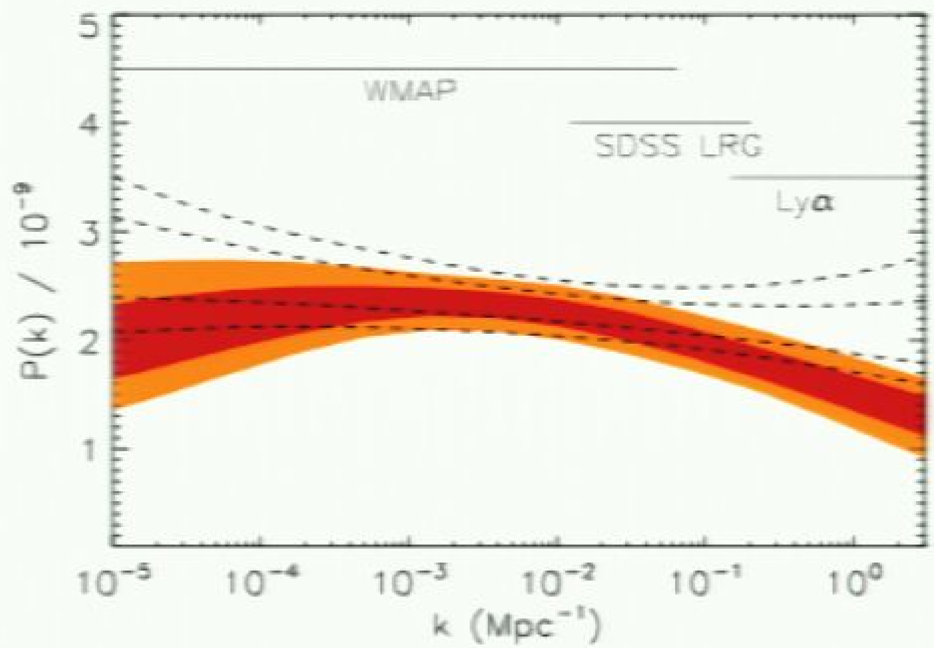

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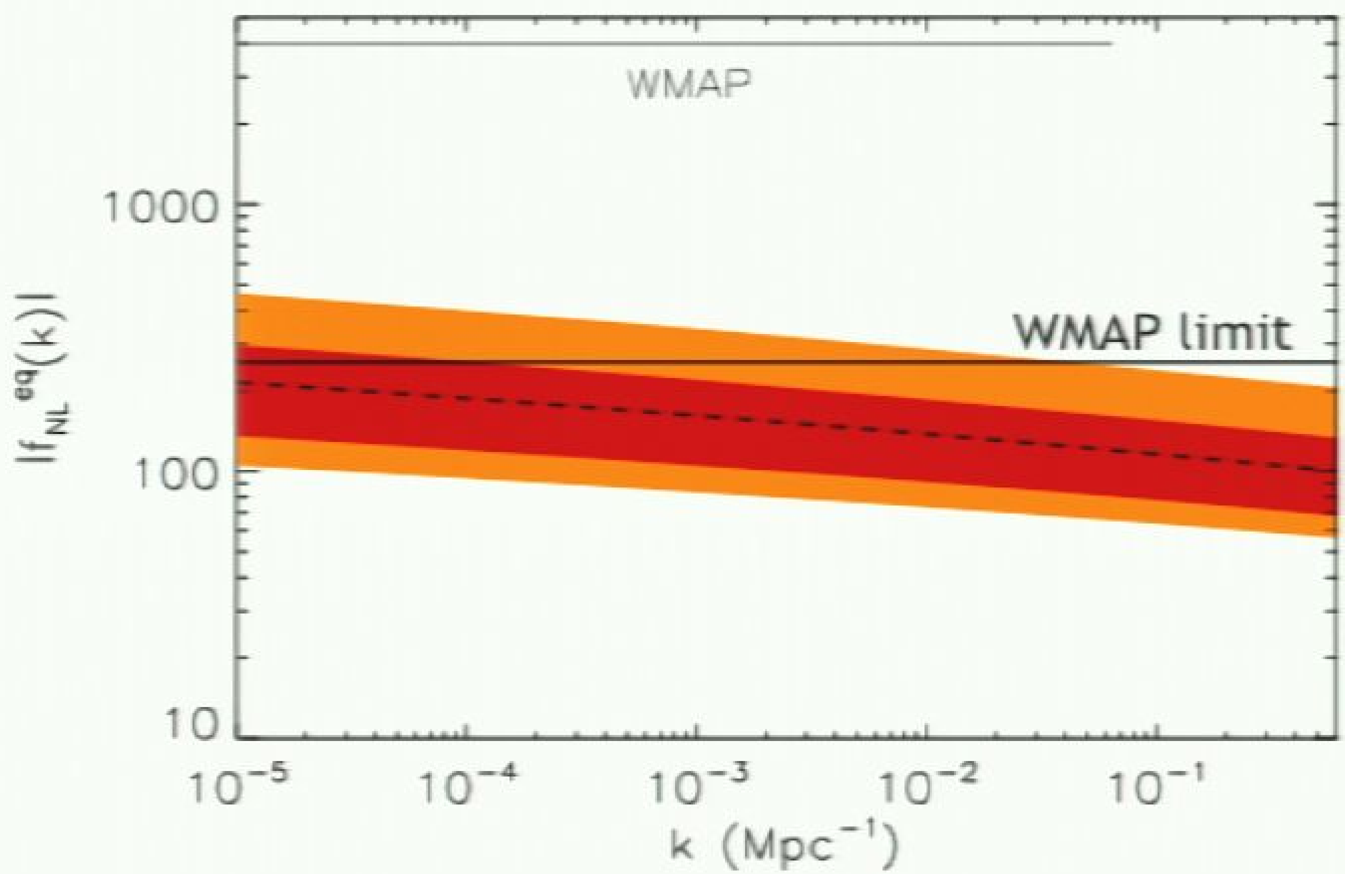

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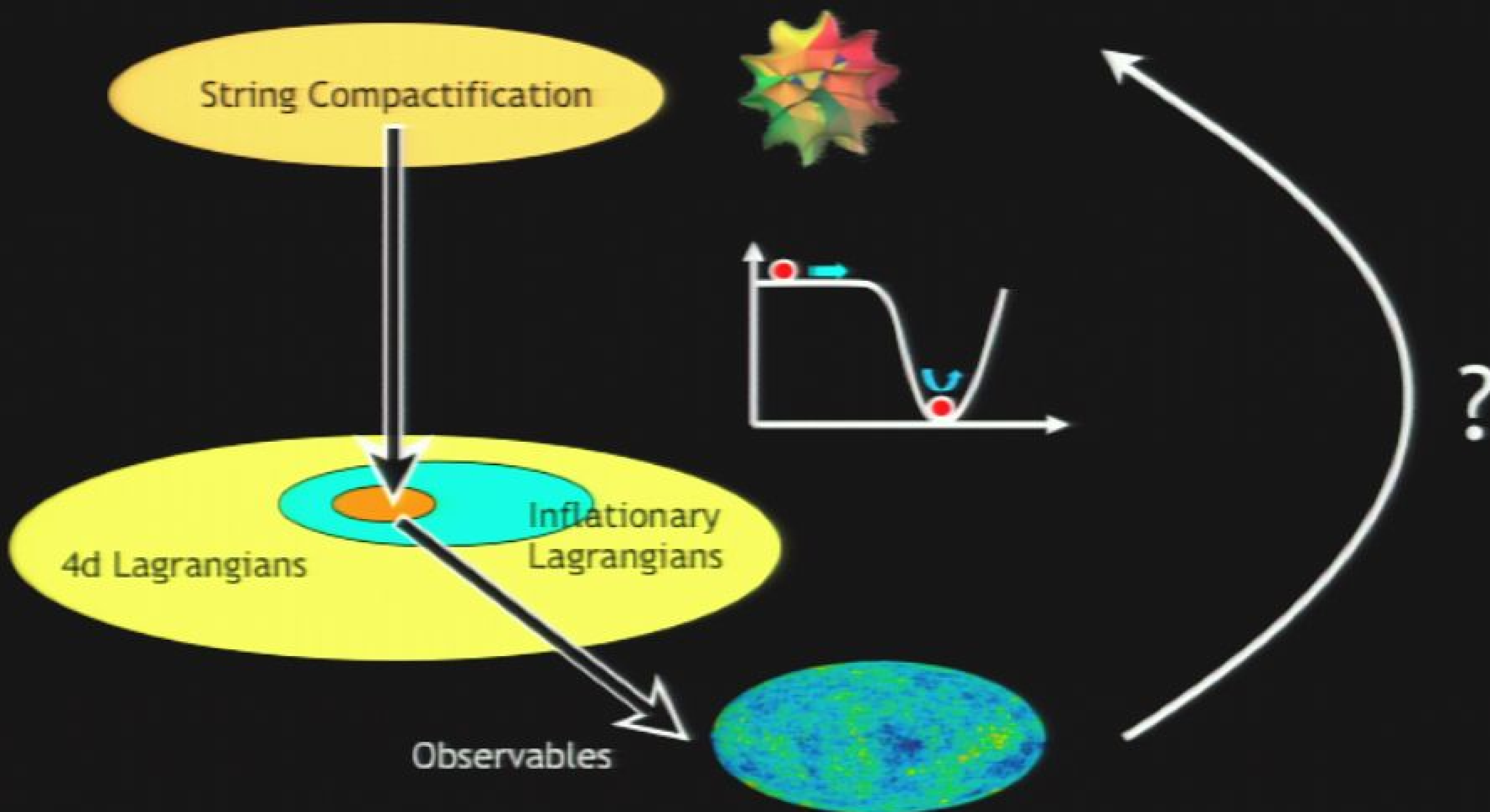
Dream: constrain string theory using observations



- Models predict distinctive observable signatures.

- Microphysics can be explicitly and self-consistently computed.

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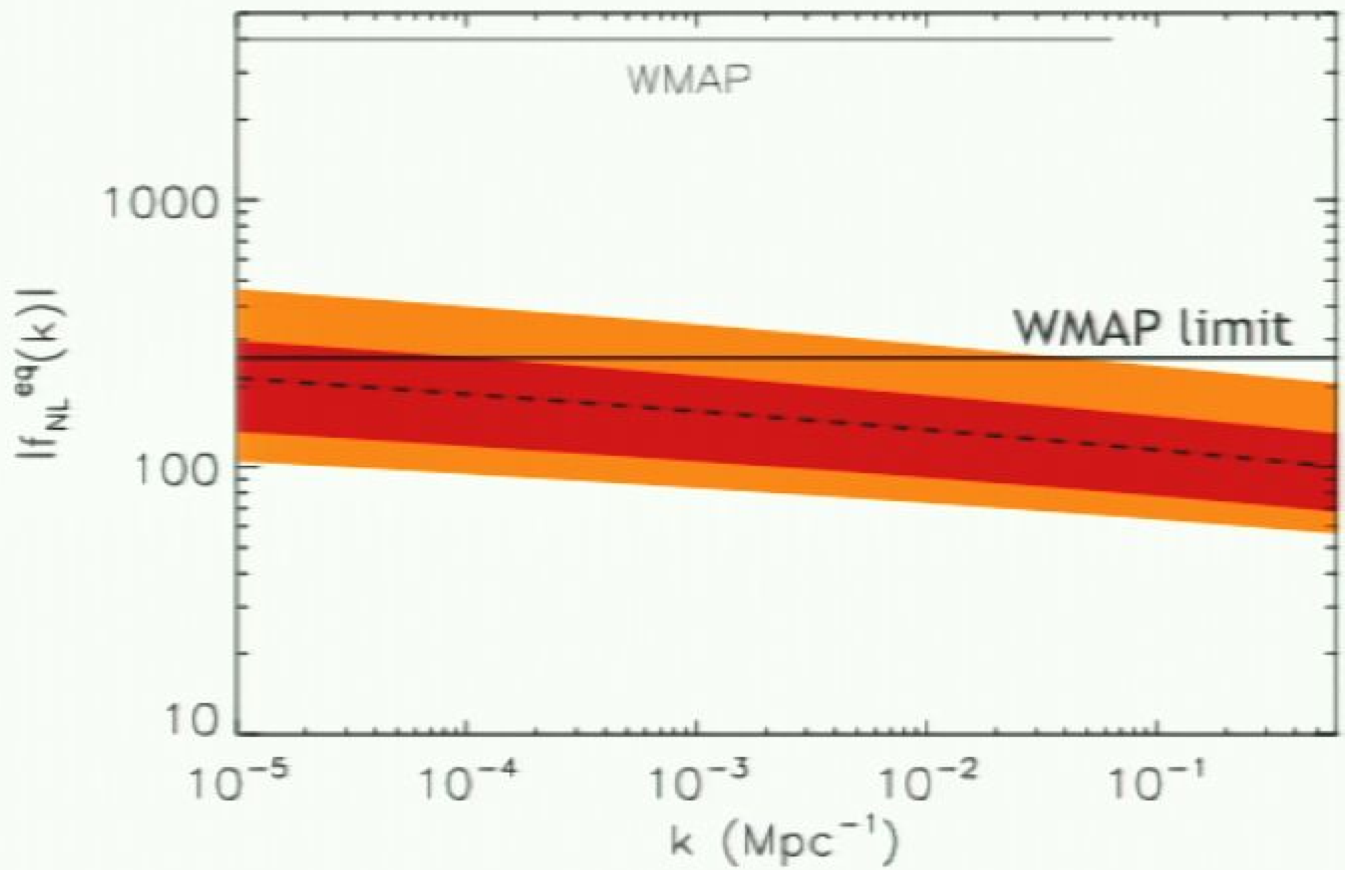

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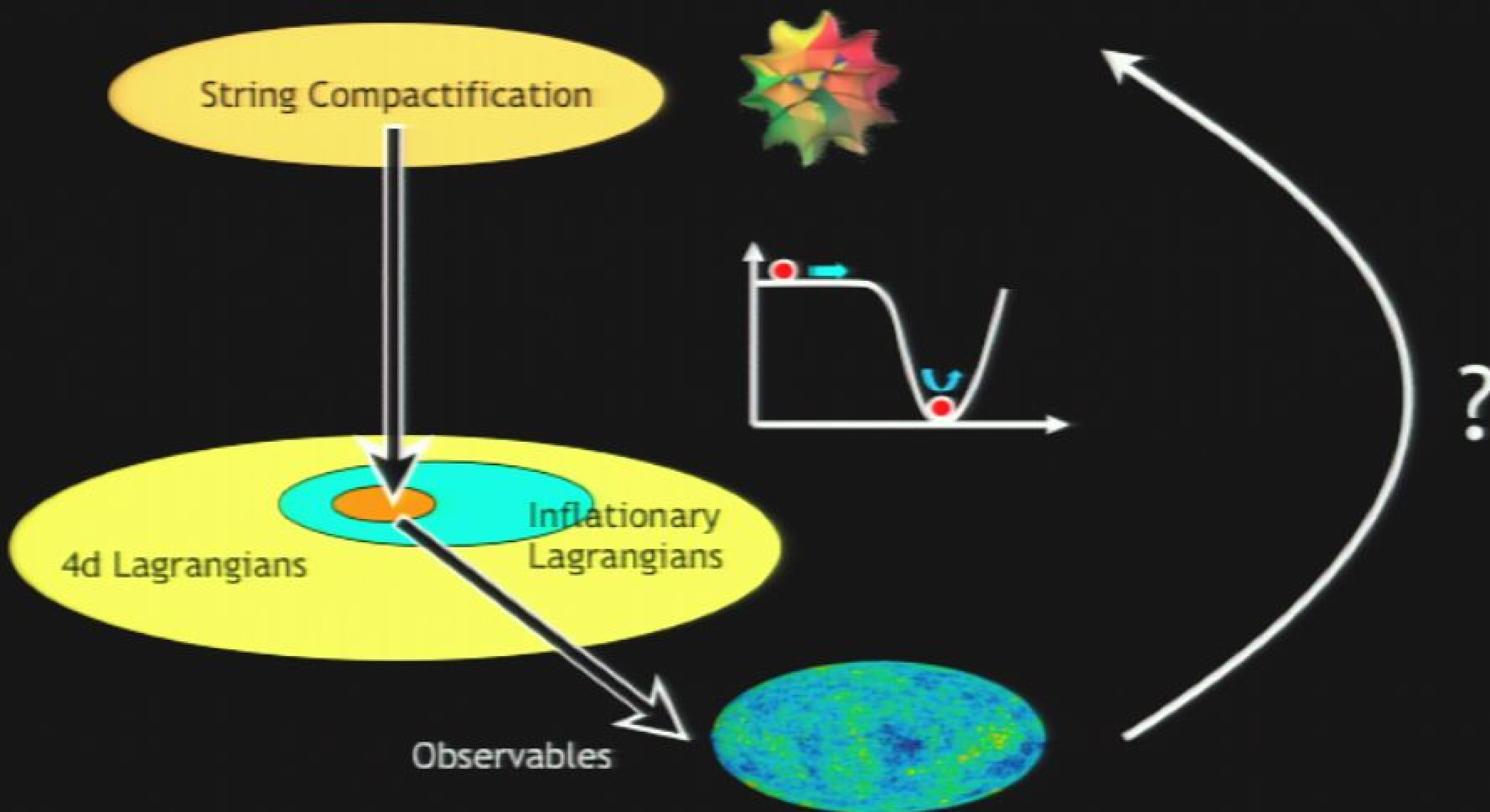

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Generic predictions of "natural" inflation models

- Is it possible to claim observable tensors are predicted by "natural" inflationary models with a red tilted spectrum, independent of "naturalness" definition?

- Boyle, Steinhardt & Turok (2006, hereafter BST) applied a naturalness definition to conclude:

$$r < 10^{-2} \quad \text{is very fine-tuned}$$

$$\text{if} \quad 0.95 < n_s < 0.98$$

- Observable tensors "naturally" expected?!

BST fine-tuning criterion

- Counts the number of "unnecessary features" occurring in potential during last 60 e-folds of inflation.
- A feature is a zero of η or its derivatives w.r.t ϕ.
- Hereafter, called Z_η.
- BST define $Z_\eta > 1$ as fine-tuned.

Initial conditions fine-tuning criterion

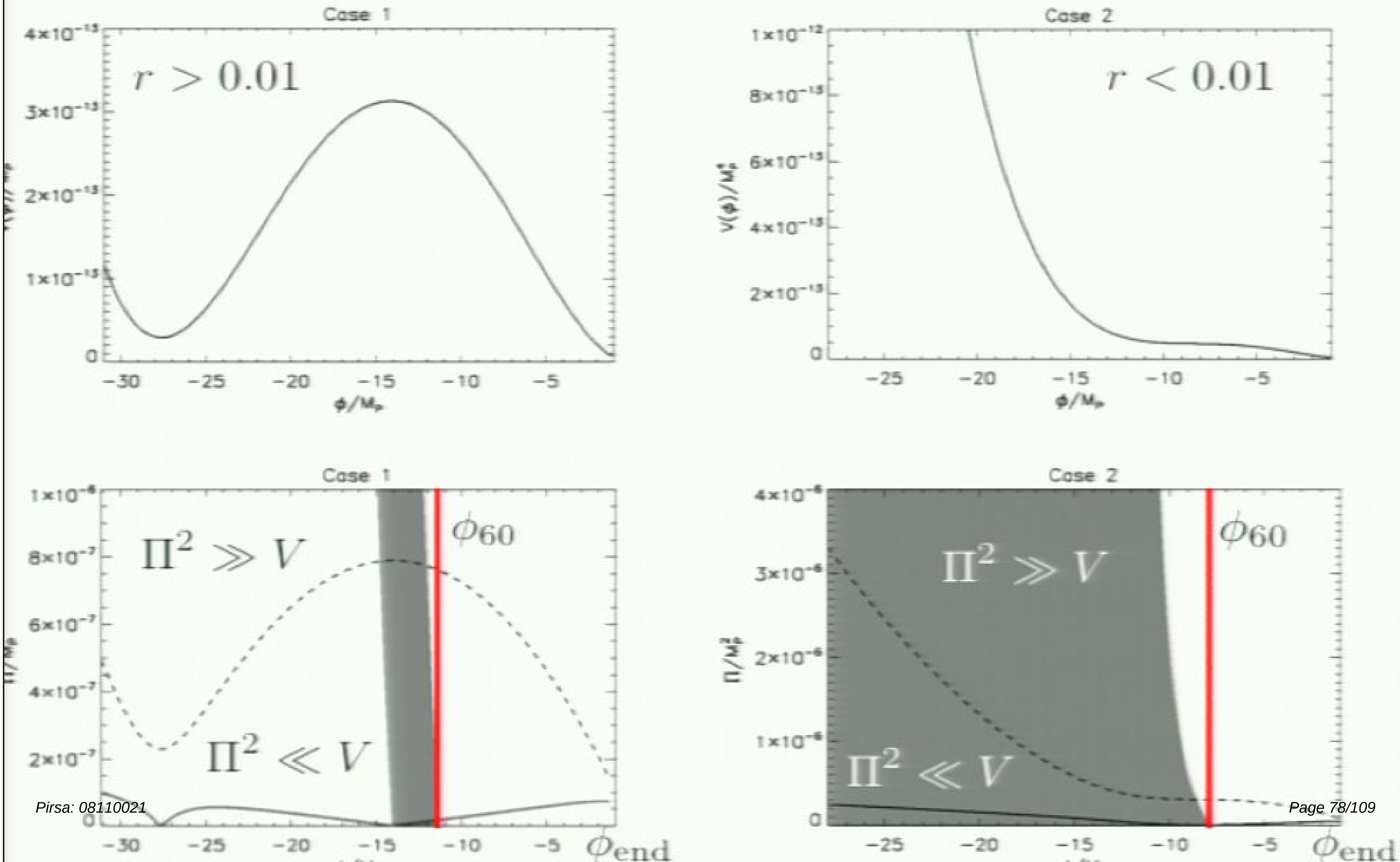
- Some potentials need a very special initial field configuration if nflation is to begin.

- Can be e.g. suppression of kinetic term vs potential term (to avoid overshoot problem) or absence of inhomogeneities in the nitial inflationary patch.

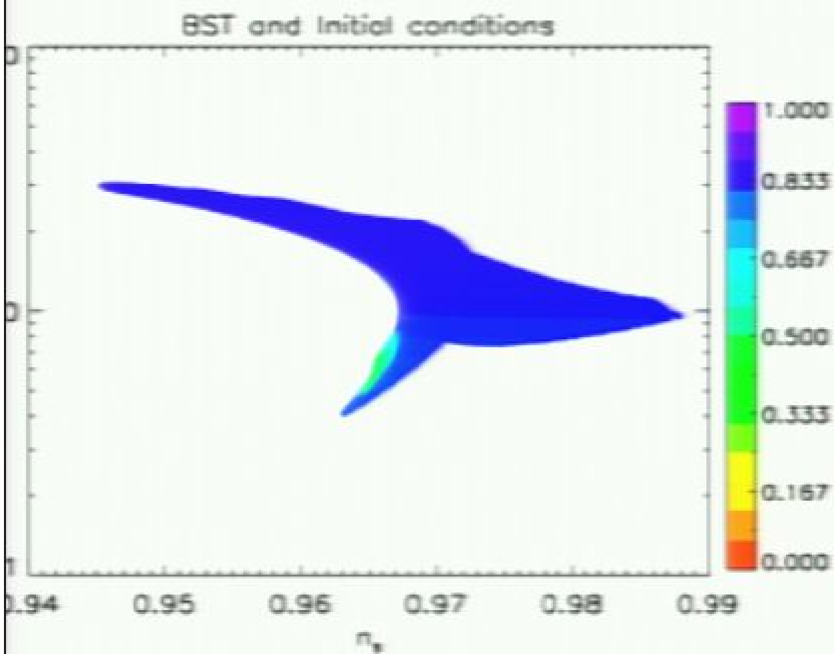
- Let's consider sensitivity to an initial large kinetic term.

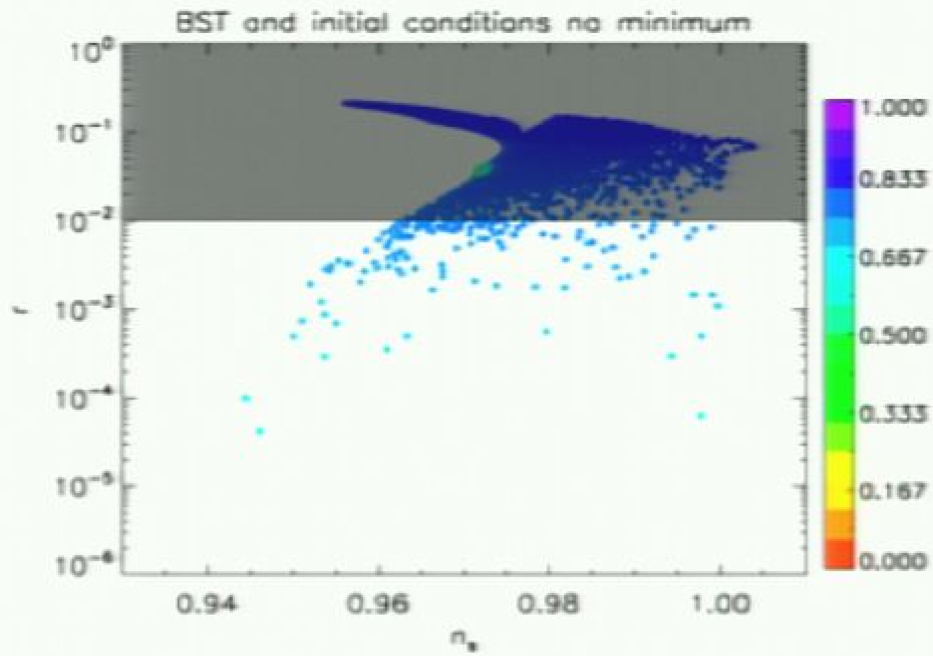
Examples of contradictory conclusions

$Z_\eta = 1, R_i = 0.14$ $\qquad$ $Z_\eta = 7, R_i = 0.78$



Combining the criteria





bined criteria non-fine-tuned region

inflation end assumptions dropped

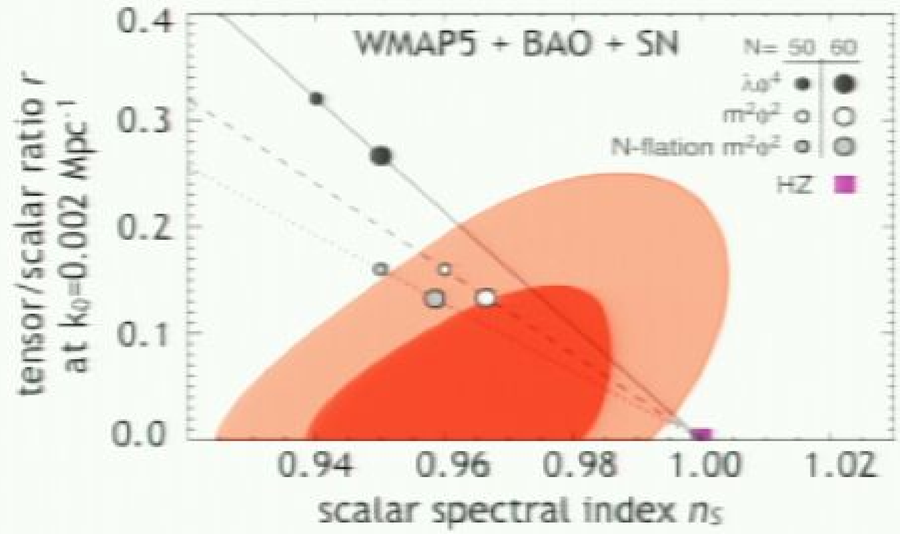
Ambiguities

- The "initial condition fine-tuning" criterion might appear at first glance to encode fine-tuning of the initial kinetic term.
- However, it encodes information about the functional form of the potential (e.g. steep/small plateau/steep potential).
- The fine tuning of the shape characterized by R_i is different from that of Z_η.
- Occam's razor cannot characterize fine-tuning of even a single property (e.g. potential shape) in an unambiguous way.

Measuring tensors

urrent constraint: $r_{\rm CMB} \leq 0.2$

ptimistic observable: $r_{\rm CMB} \geq 0.001$



measurement of tensors
ves 2 pieces of information:

The energy scale of inflation.

he measured scalar amplitude $P_s \sim \left(\frac{\delta\rho}{\rho}\right)^2 \sim 10^{-10}$ and $H^2 \simeq \frac{1}{3M_{\rm Pl}^2}V$ implies:

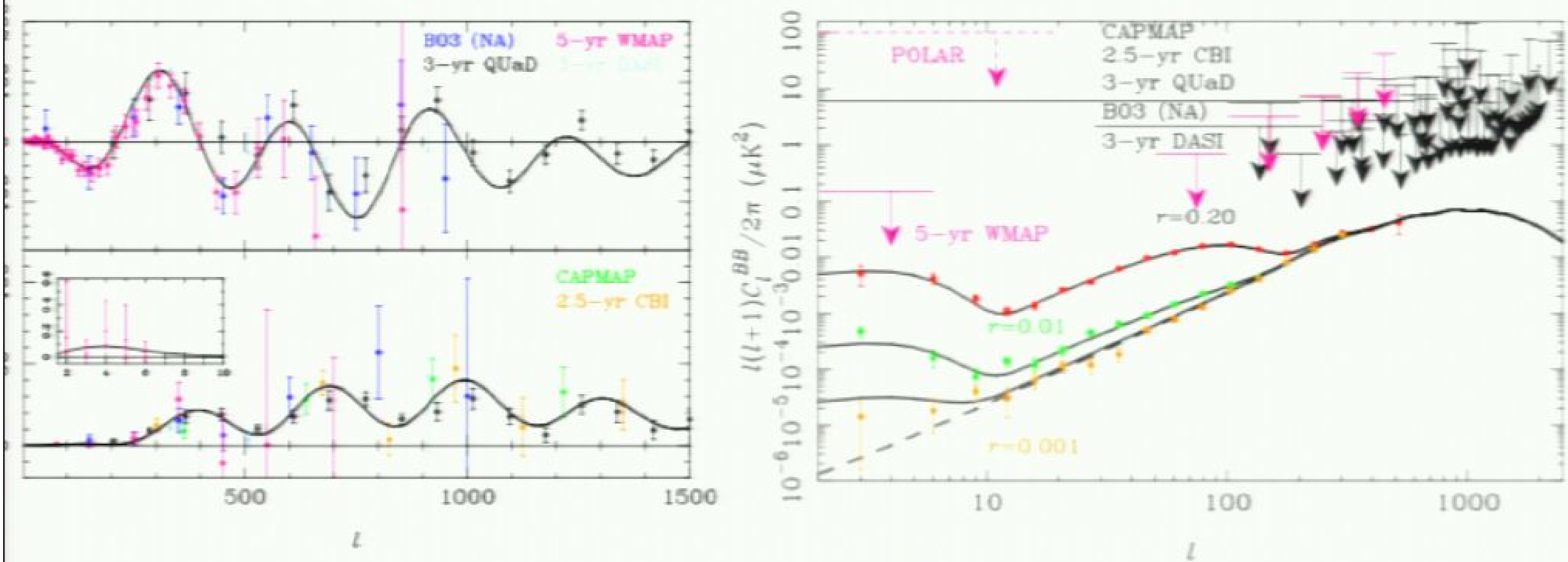
$$V^{1/4} \sim \left(\frac{r_{\rm CMB}}{0.001}\right)^{1/4} 10^{16}\ {\rm GeV}$$

Super-Planckian field variation.

bservable gravitational waves require $\Delta\phi > M_{\rm Pl}$ during inflation:

$$\frac{\Delta\phi}{M_{\rm Pl}} > \mathcal{O}(1)\sqrt{\frac{r_{\rm CMB}}{0.001}}$$ e.g. $V(\phi) = \frac{1}{2}m^2\phi^2$ requires $\Delta\phi \sim 15 M_{\rm Pl}$.

Current CMB polarization data



- Acoustic peaks at 'adiabatic' locations
- E-mode polarization and cross-correlation with ΔT
- Large-angle polarization from reionization

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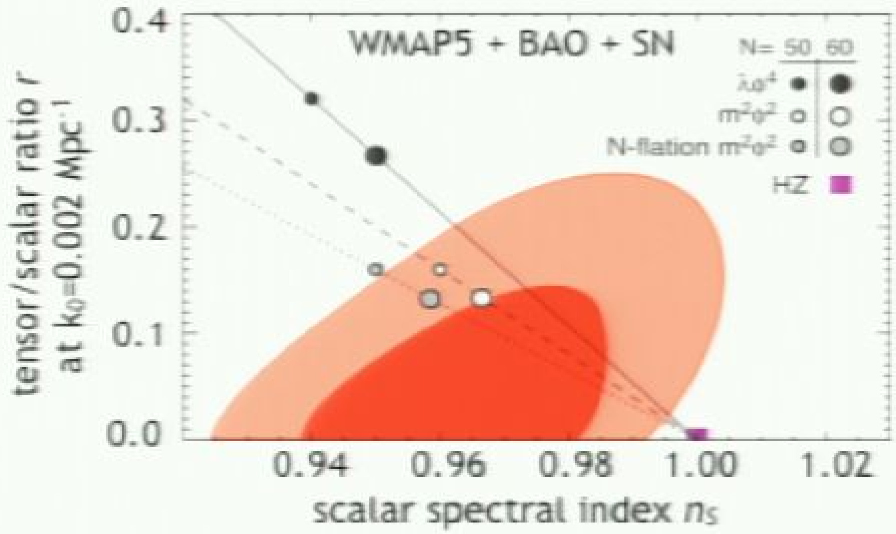
urrent constraint: $r_{\rm CMB} \leq 0.2$
ptimistic observable: $r_{\rm CMB} \geq 0.001$



measurement of tensors
ves 2 pieces of information:

The energy scale of inflation.

he measured scalar amplitude $P_s \sim \left(\frac{\delta\rho}{\rho}\right)^2 \sim 10^{-10}$ and $H^2 \simeq \frac{1}{3M_{\rm Pl}^2} V$ implies:

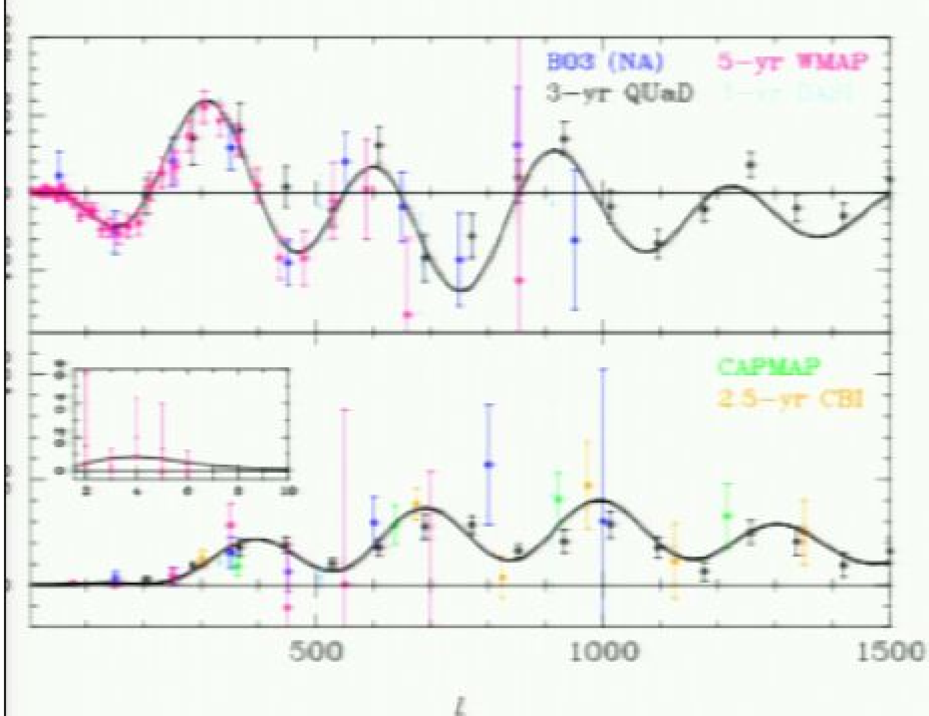
$$V^{1/4} \sim \left(\frac{r_{\rm CMB}}{0.001}\right)^{1/4} 10^{16}\ {\rm GeV}$$

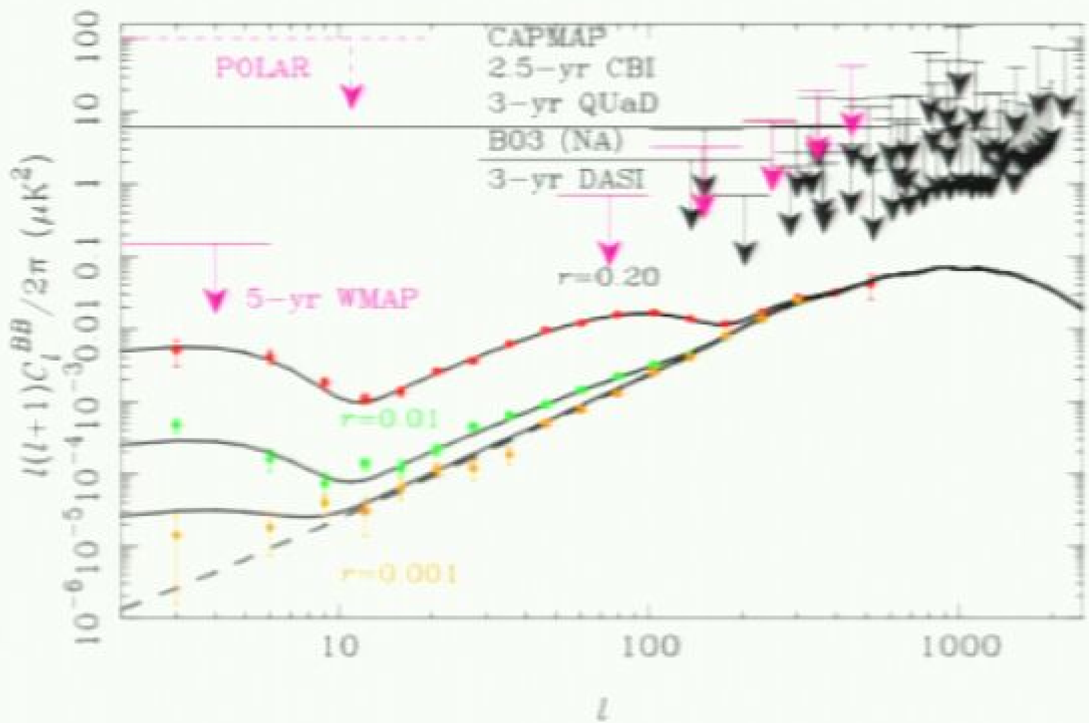
Super-Planckian field variation.

bservable gravitational waves require $\Delta\phi > M_{\rm Pl}$ during inflation:

$$\frac{\Delta\phi}{M_{\rm Pl}} > \mathcal{O}(1)\sqrt{\frac{r_{\rm CMB}}{0.001}}$$ e.g. $V(\phi) = \frac{1}{2}m^2\phi^2$ requires $\Delta\phi \sim 15 M_{\rm Pl}$.

Current CMB polarization data

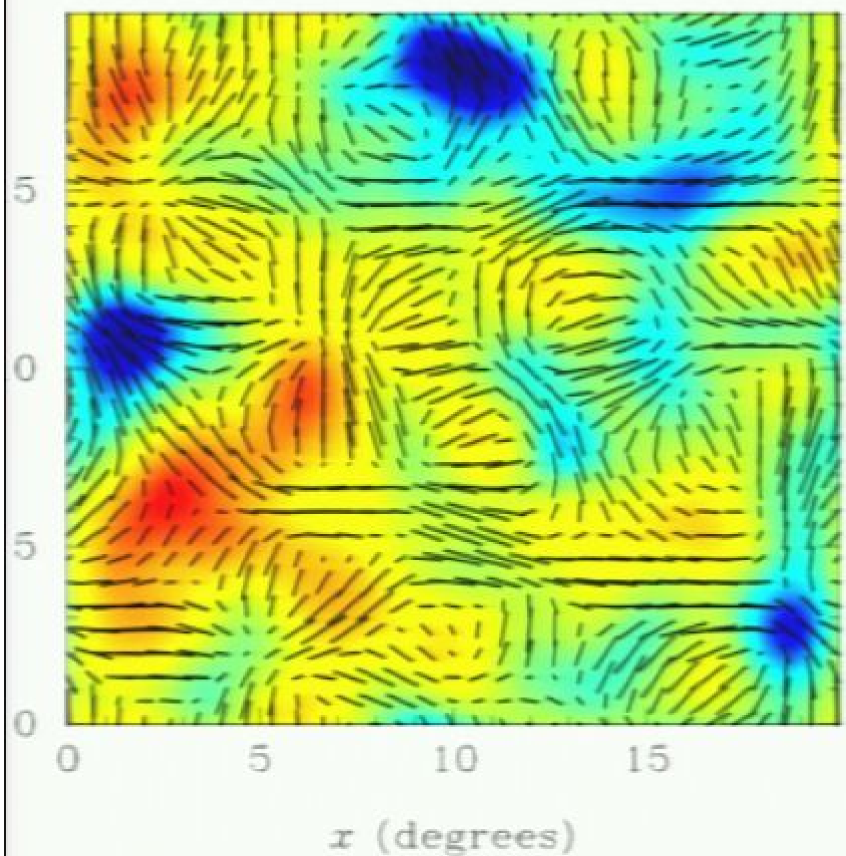




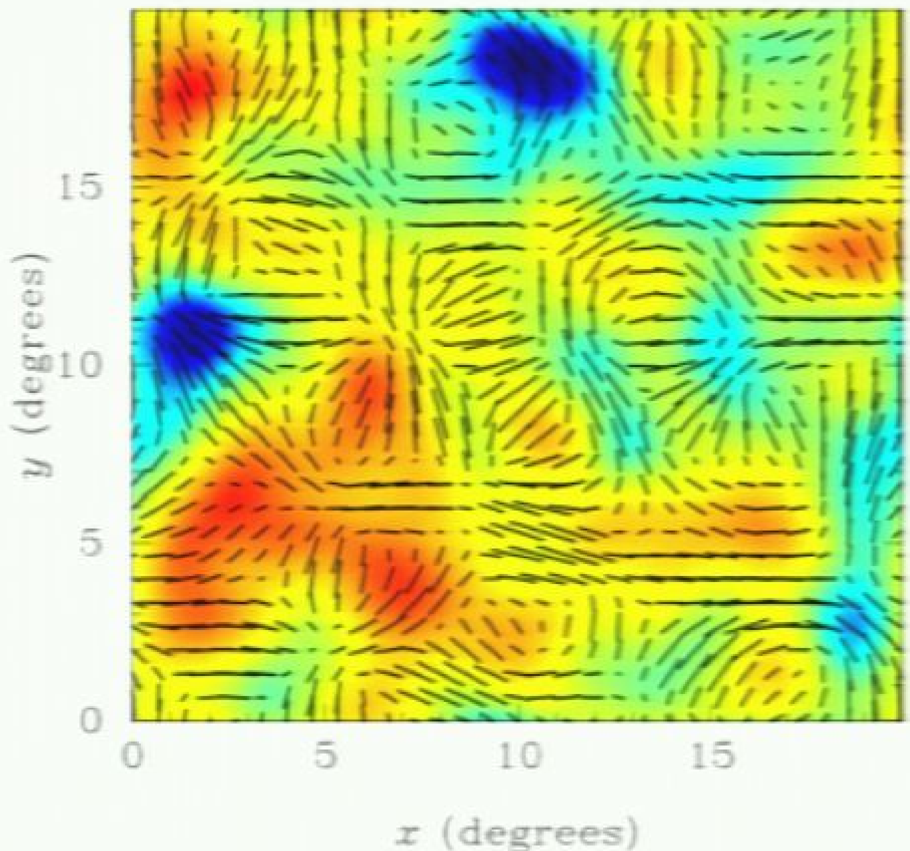
- Acoustic peaks at 'adiabatic' locations
- E-mode polarization and cross-correlation with ΔT
- Large-angle polarization from reionization

Tensors: B-mode contribution is small!

- R.m.s. B-mode signal from gravity waves $< 200\,\text{nK}$

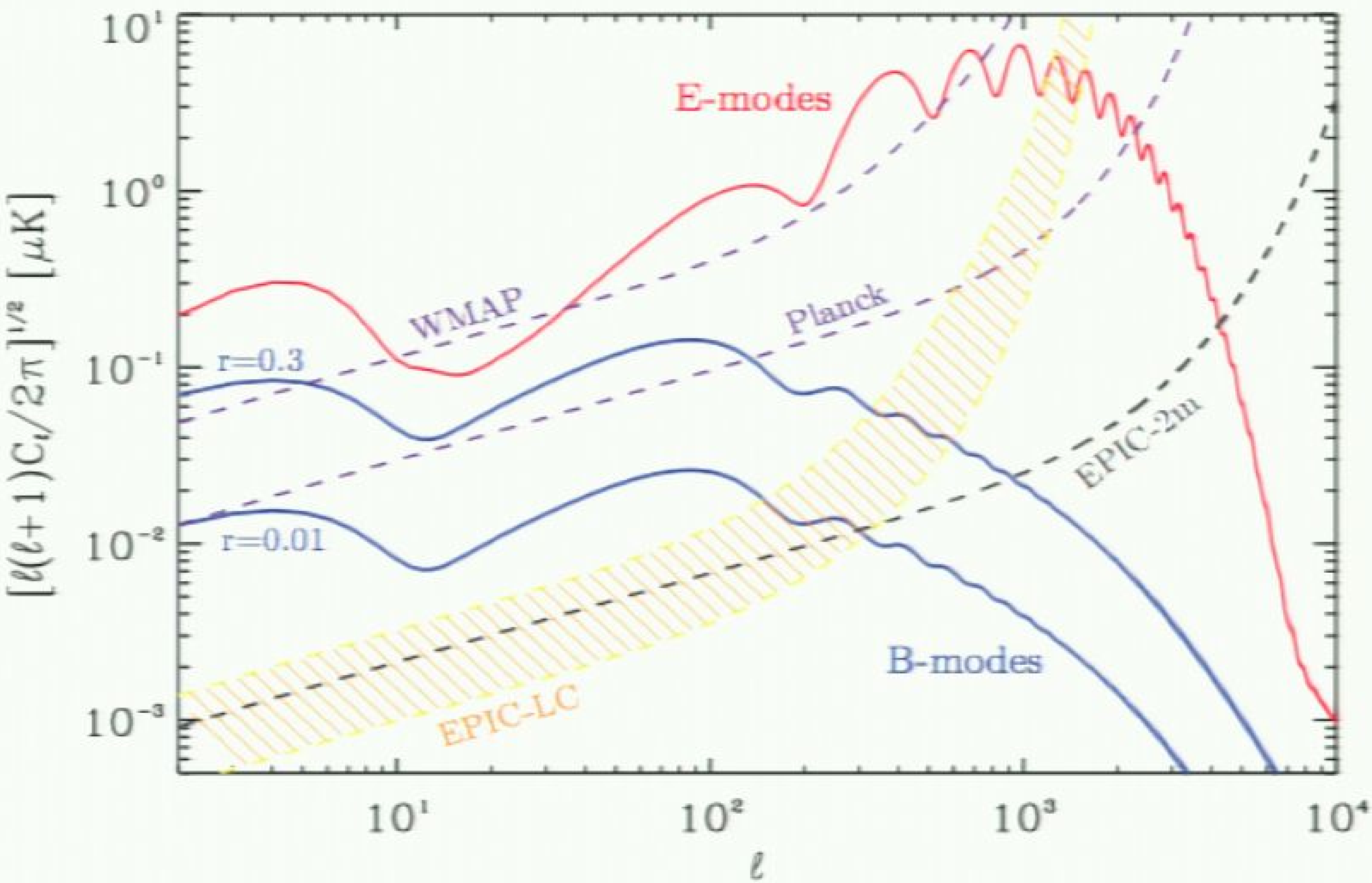


$r = 0.28$



$r = 0.0$

Relative Amplitudes of CMB power spectra



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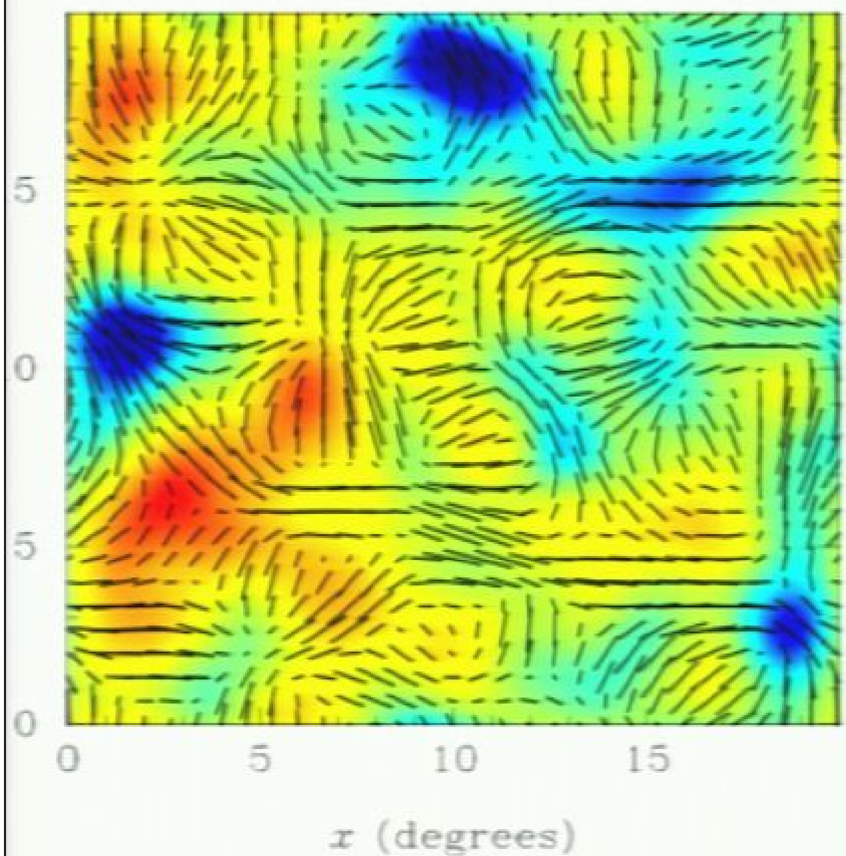

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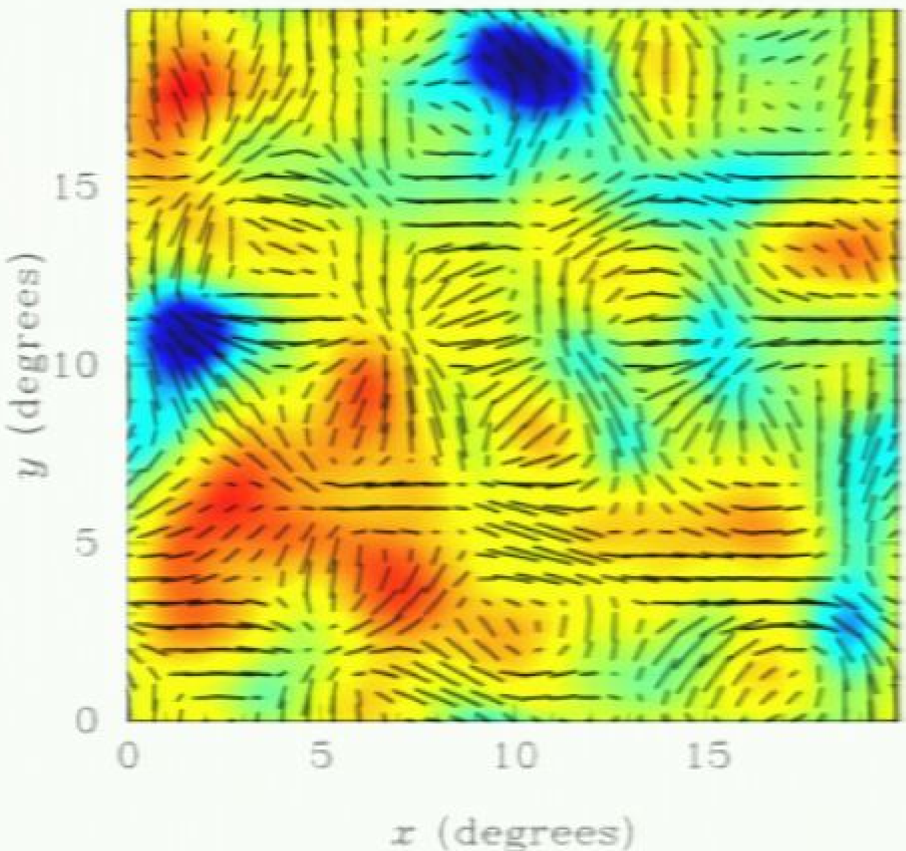

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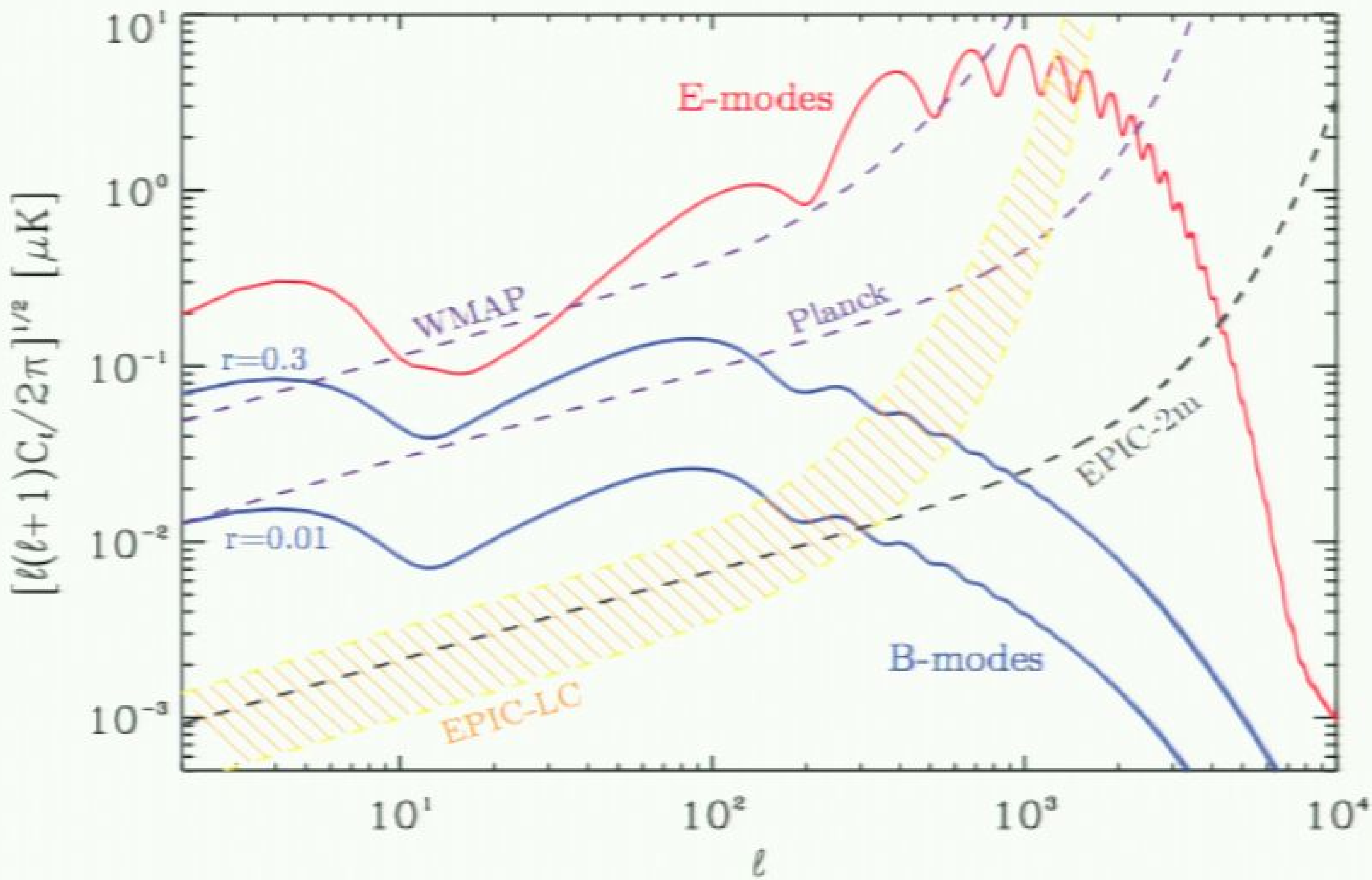
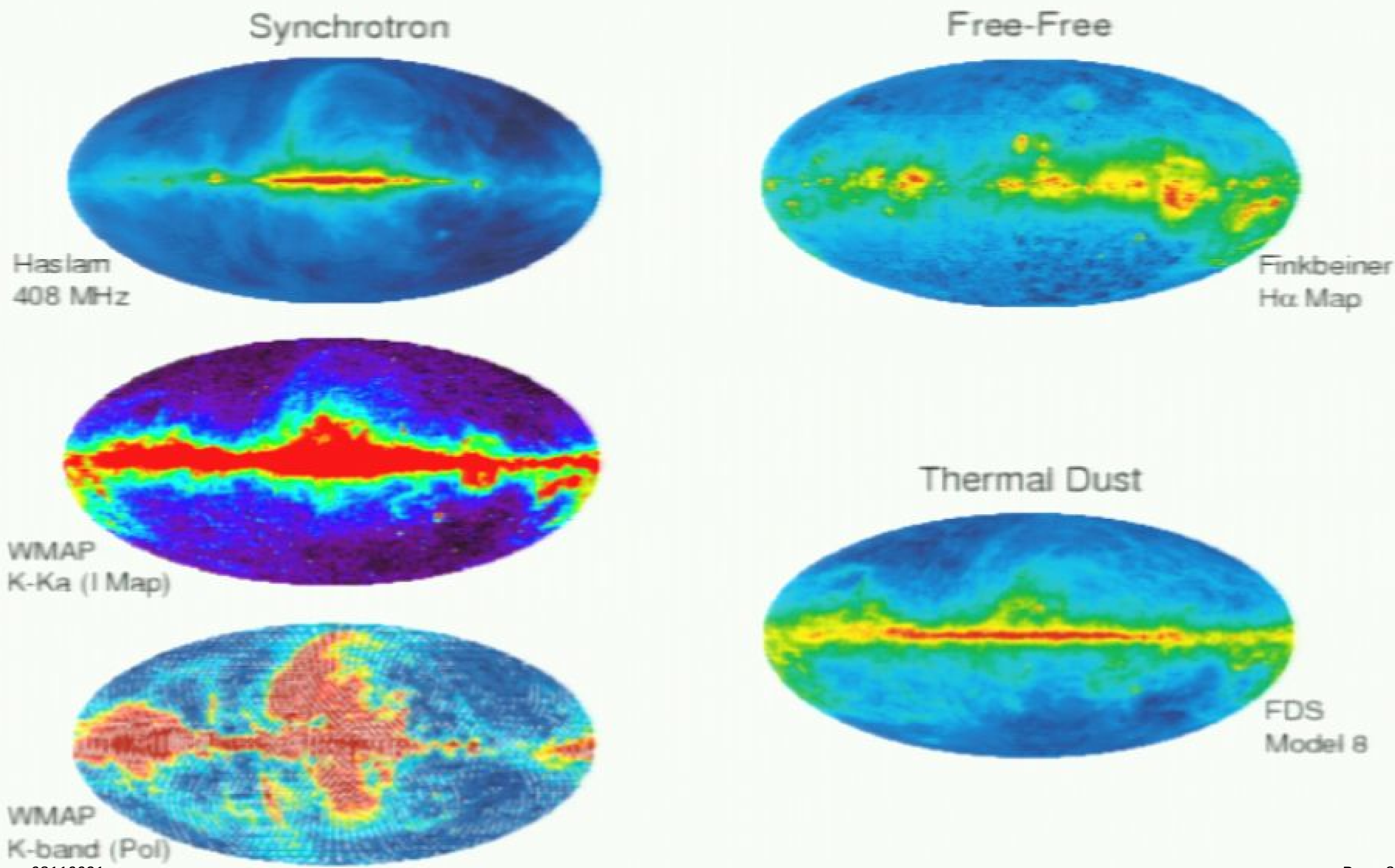
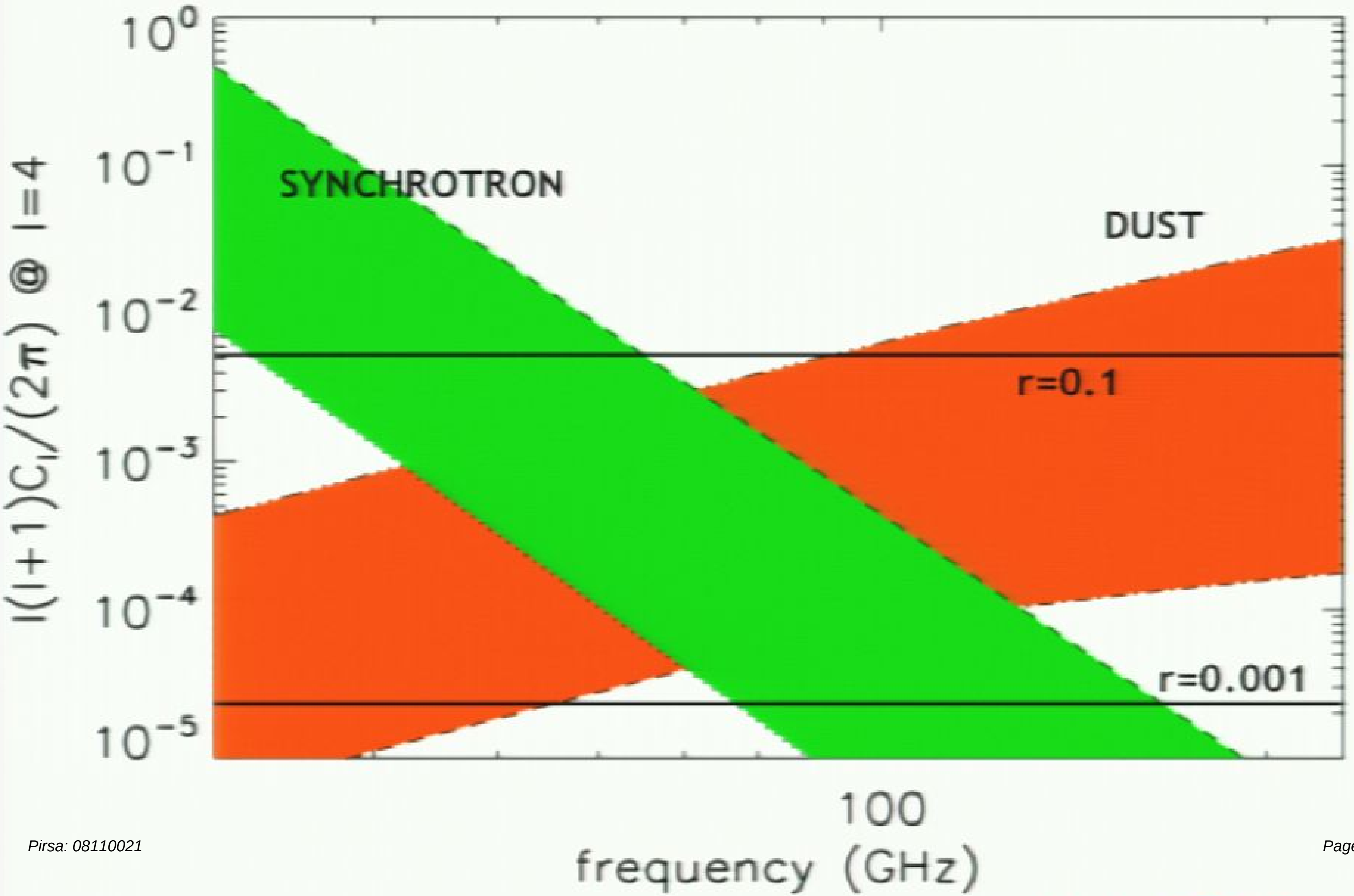


Main limitation: control of foregrounds



Foreground uncertainties vs CMB at l=4



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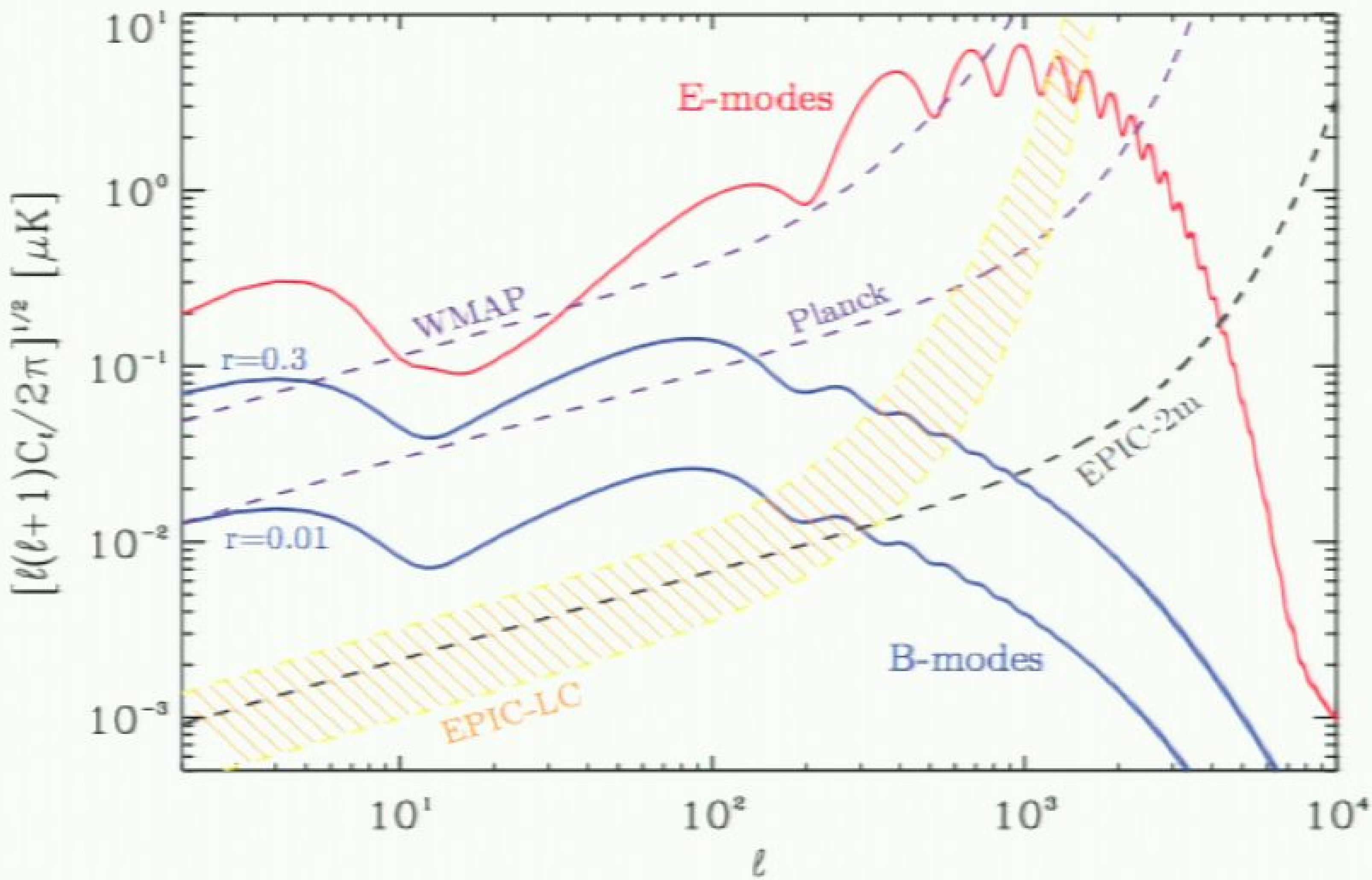
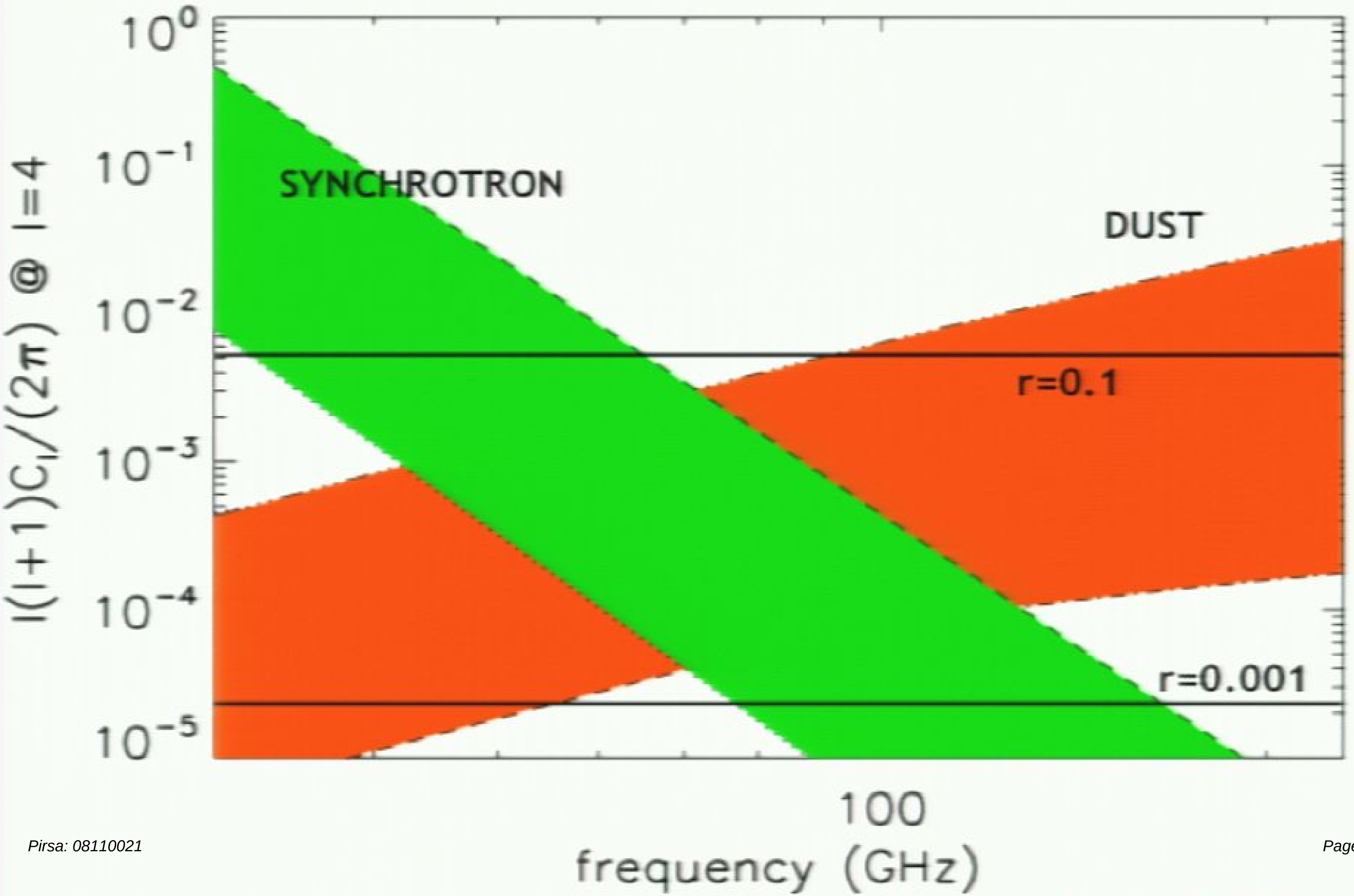
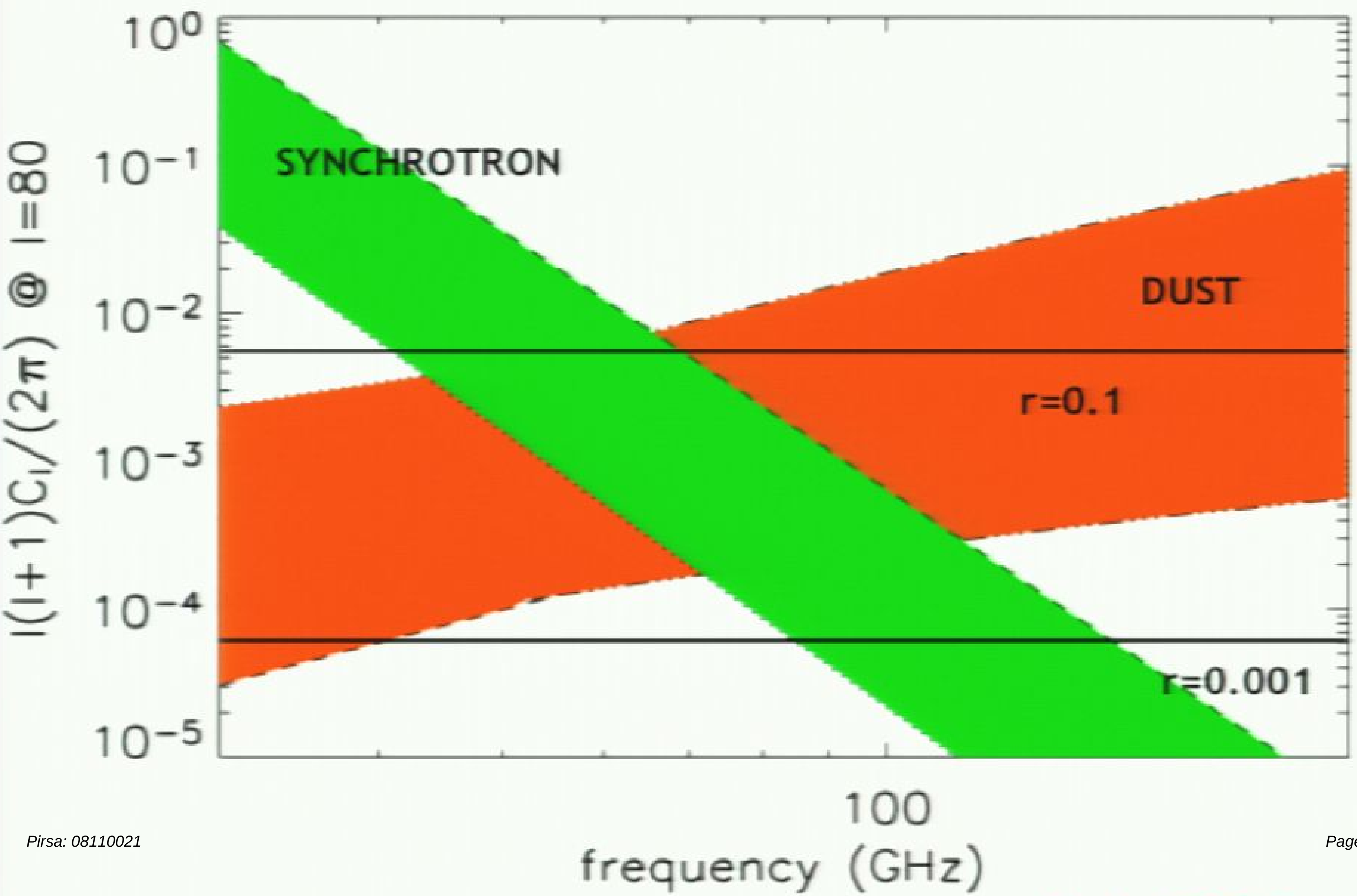


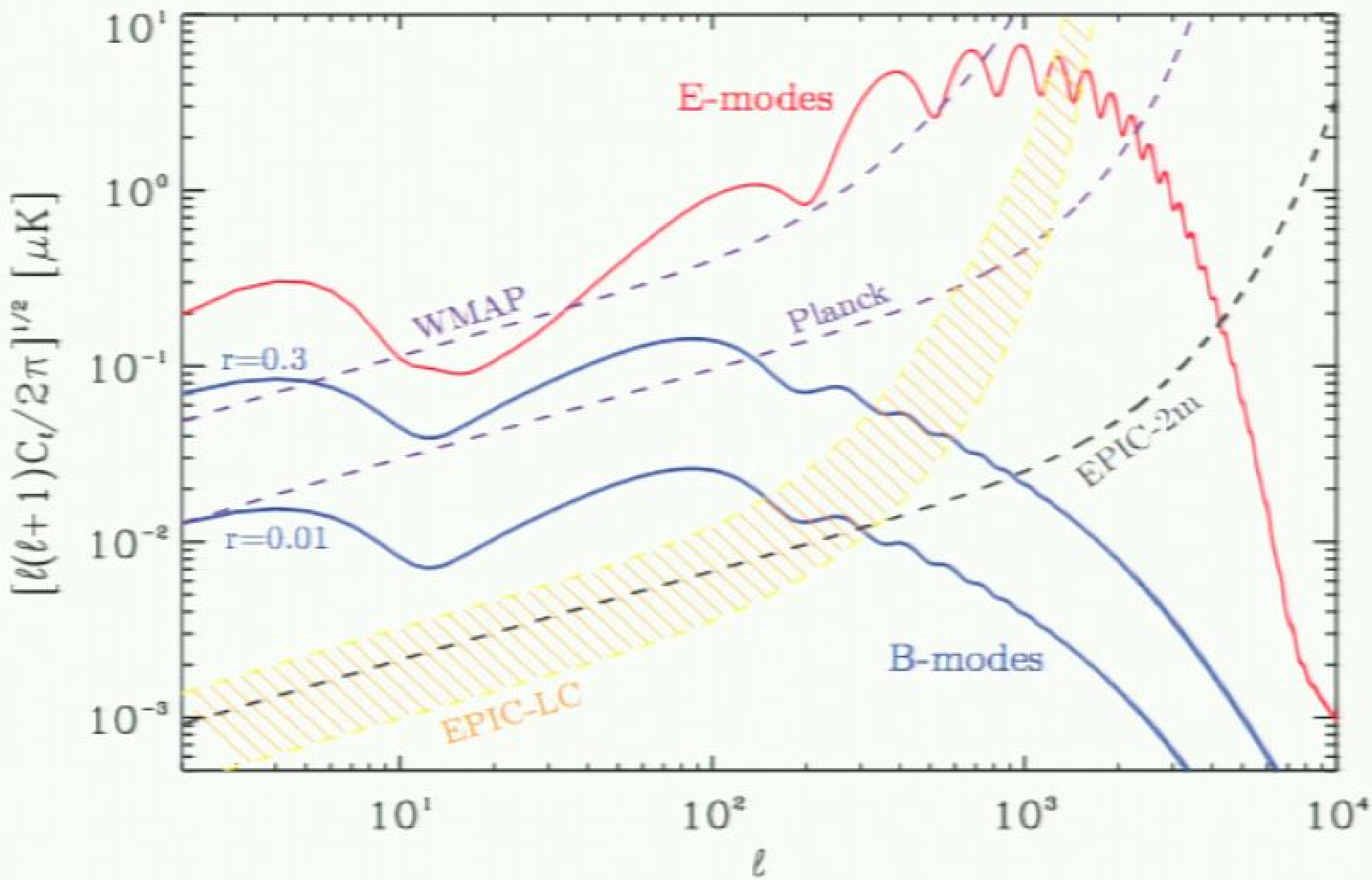
Foreground uncertainties vs CMB at l=4



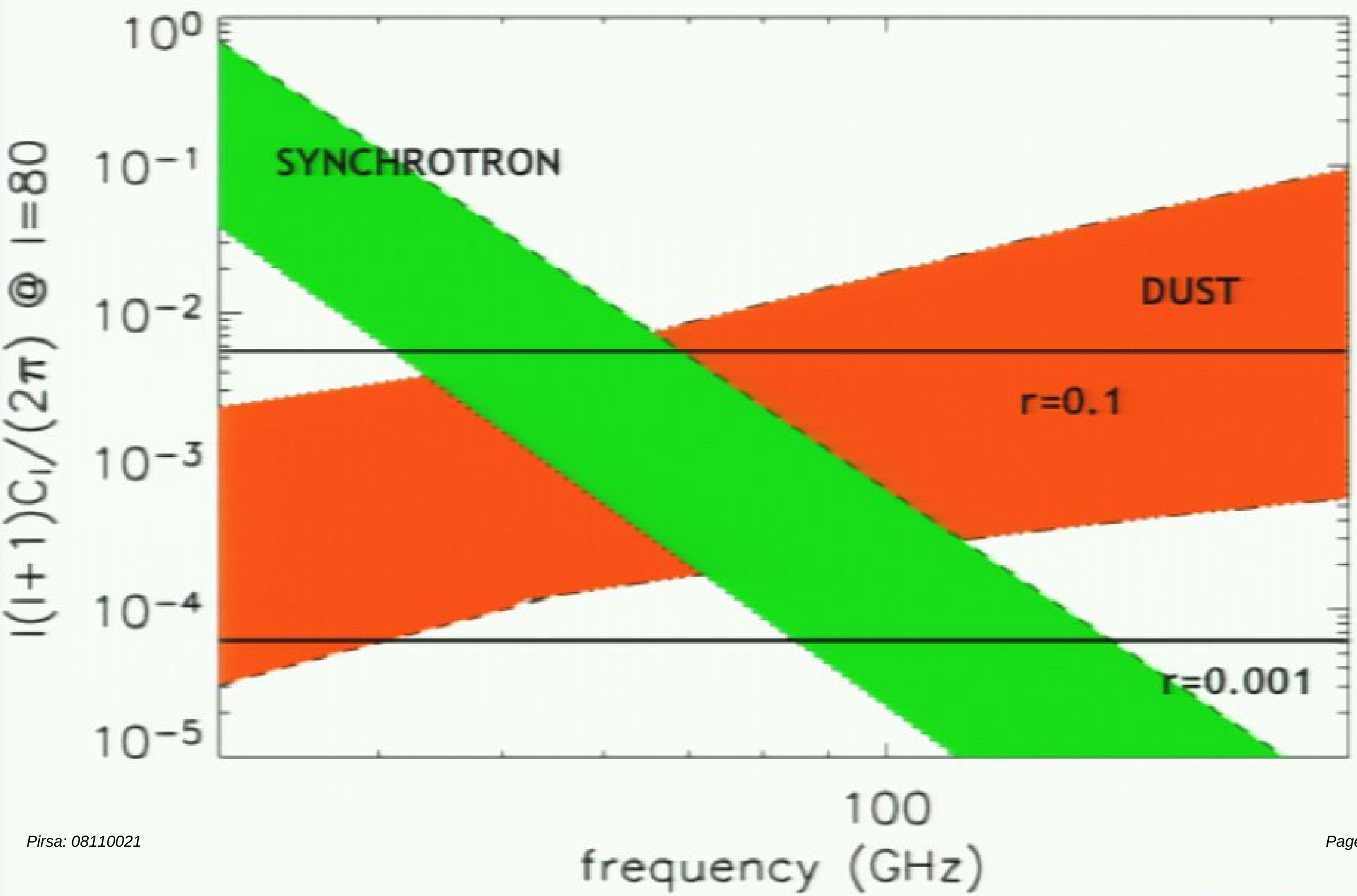
Foreground uncertainties vs CMB at l=80



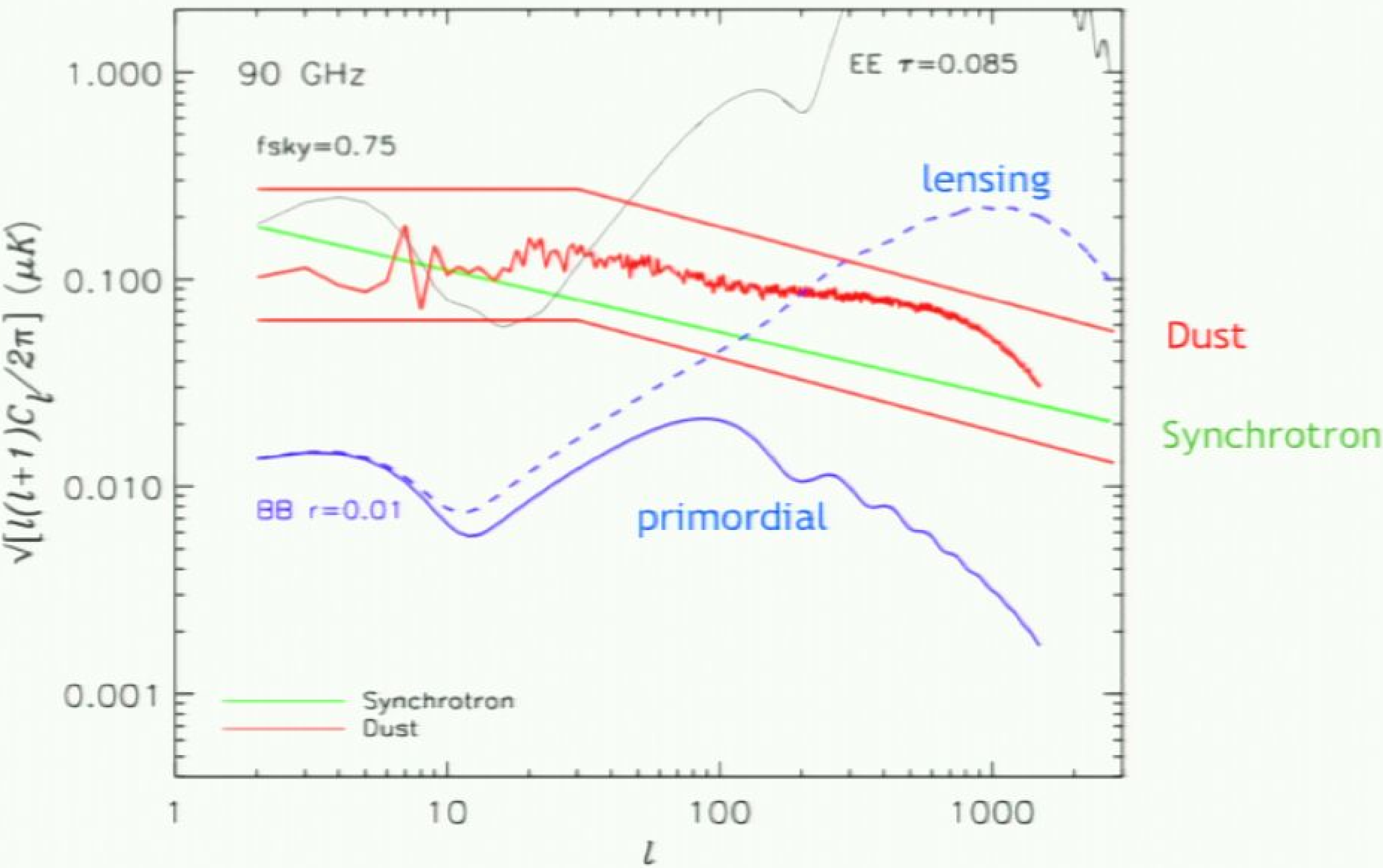
Relative Amplitudes of CMB power spectra



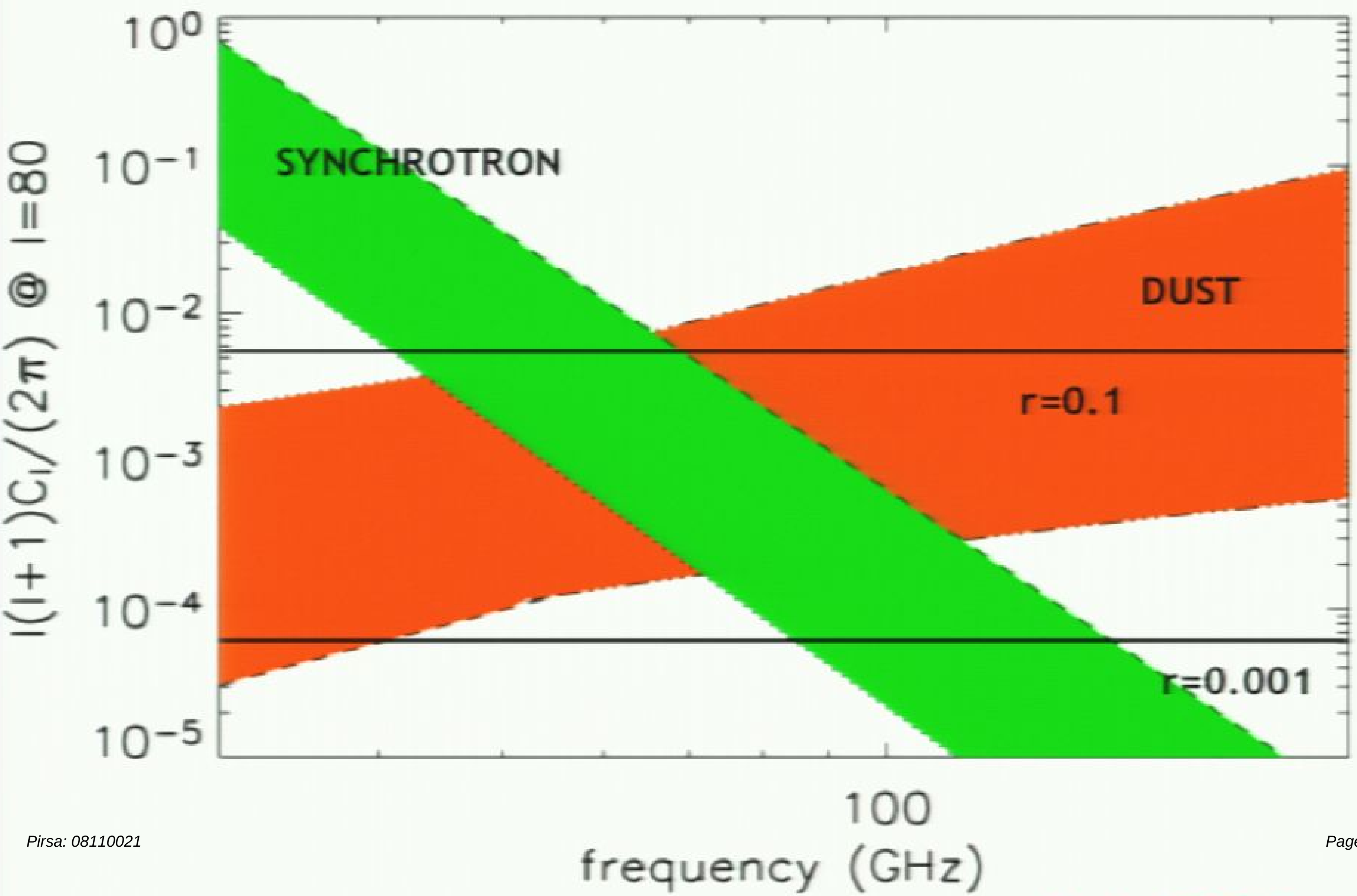
Foreground uncertainties vs CMB at l=80



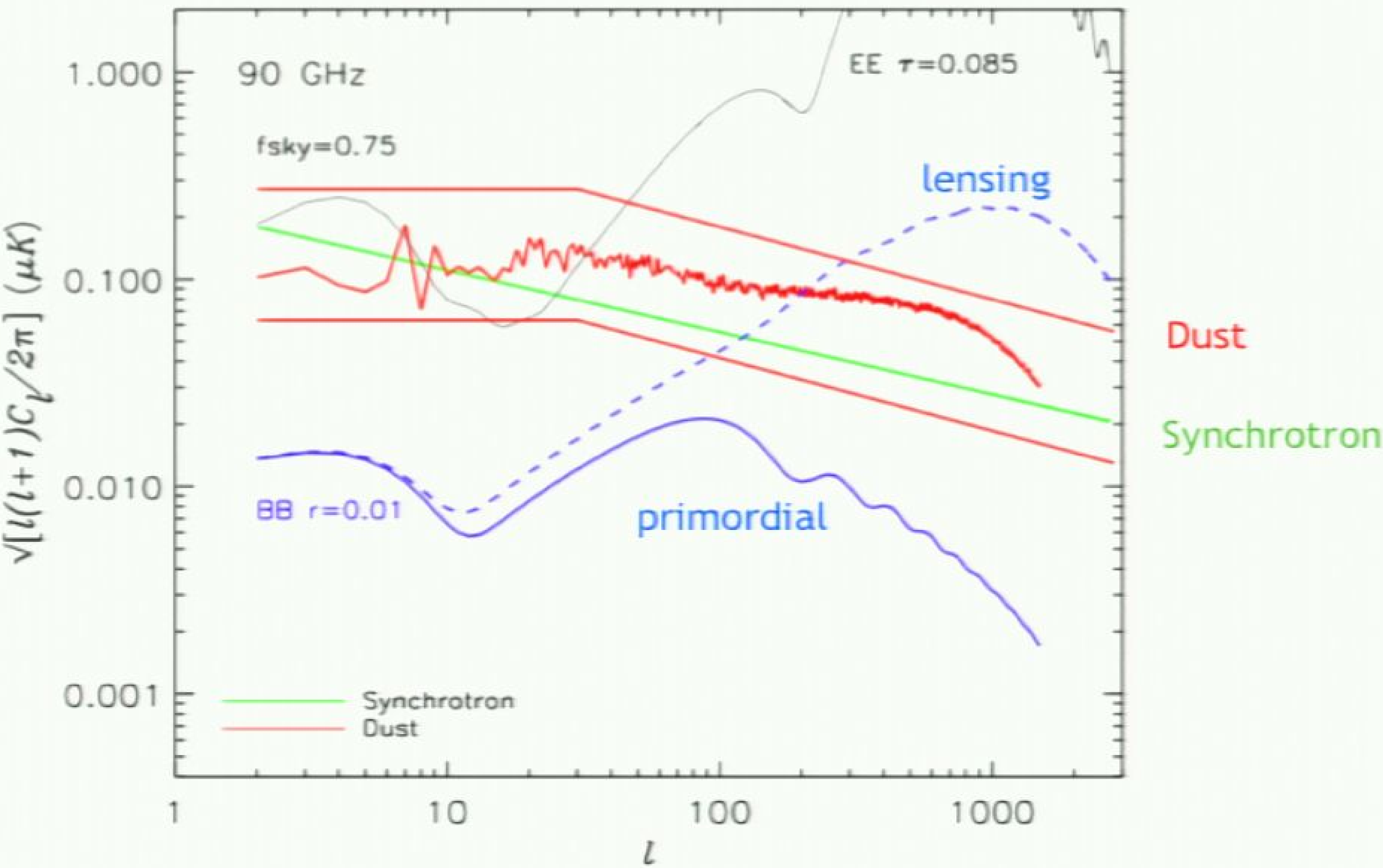
Foregrounds vs CMB at 90 GHz



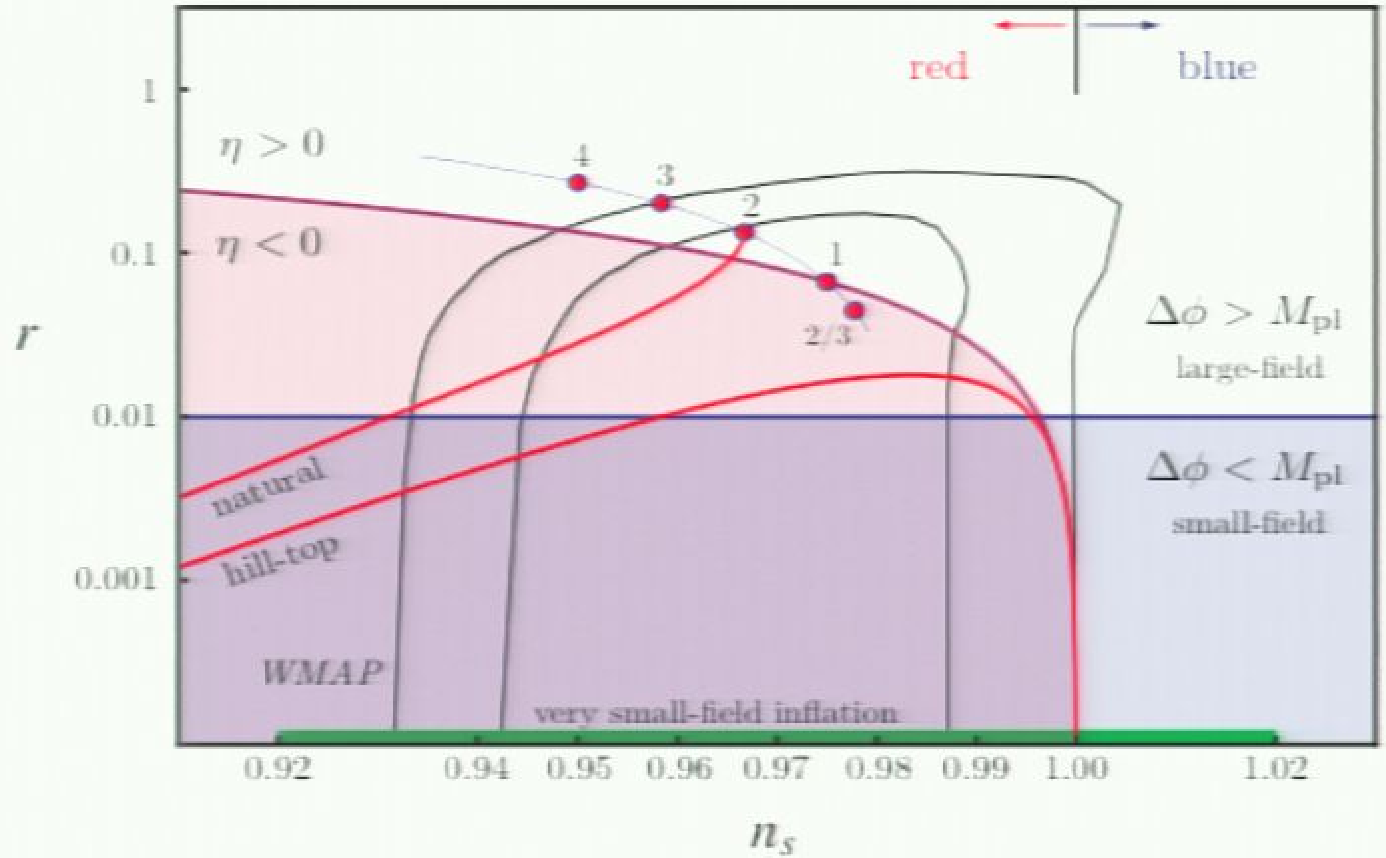
Foreground uncertainties vs CMB at l=80



Foregrounds vs CMB at 90 GHz

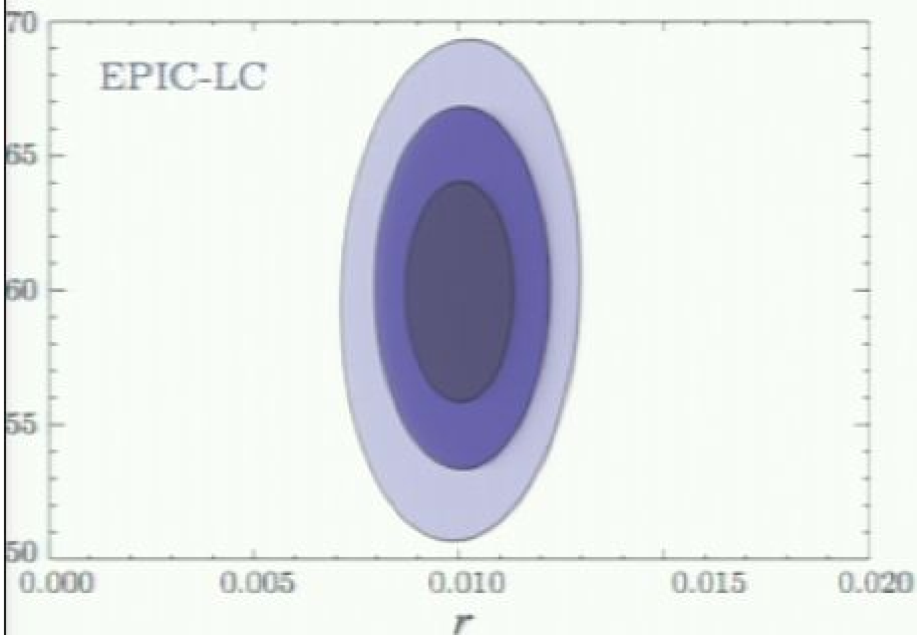


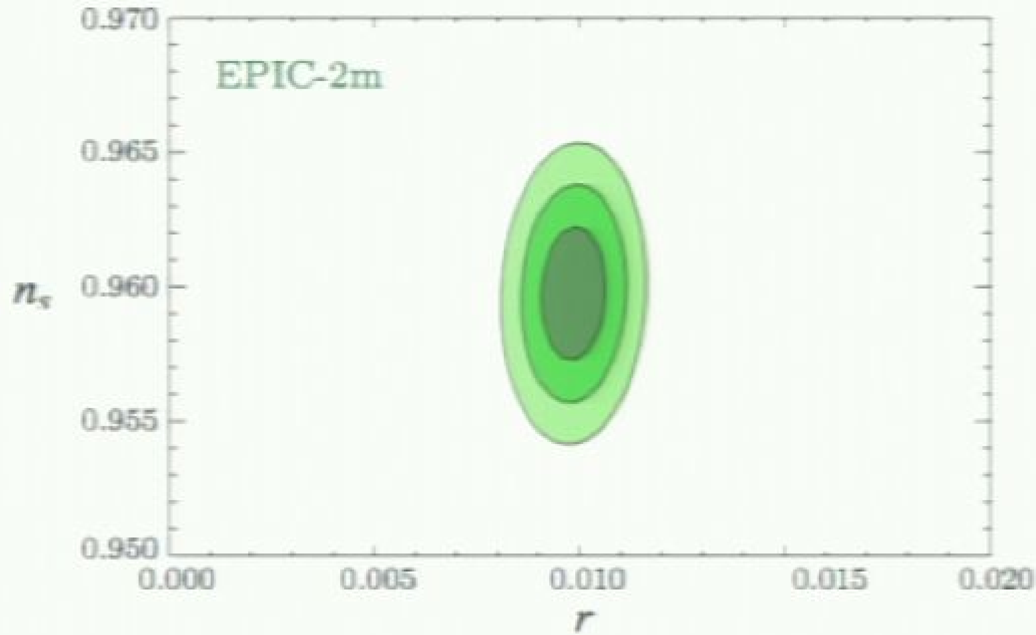
Current constraints on primordial parameters



- r determines whether model is large or small field.
- n_s determines whether spectrum is red or blue.
- a combination of n_s and r determines the curvature of the potential η.

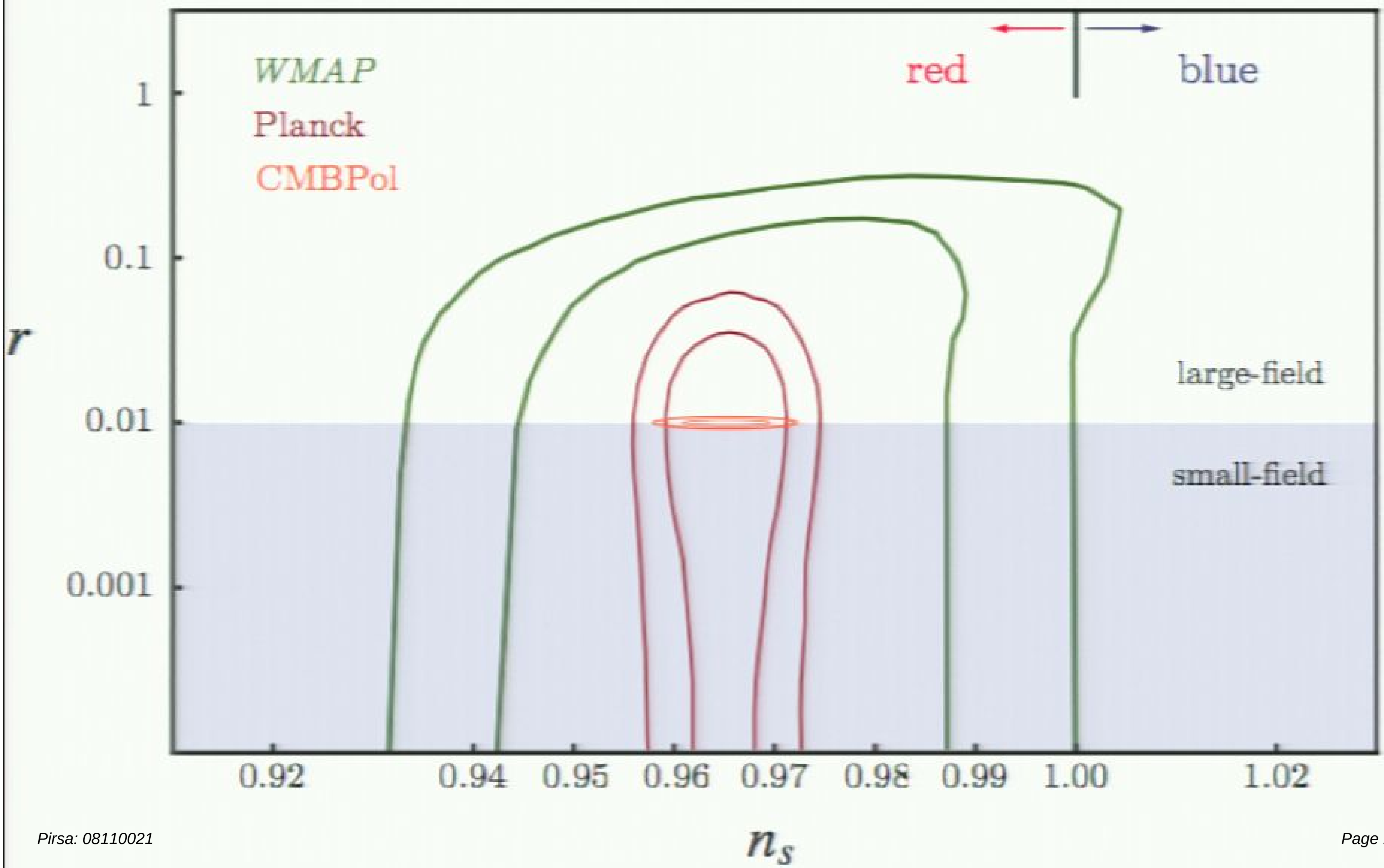
Forecasted CMBpol constraints for r=0.01





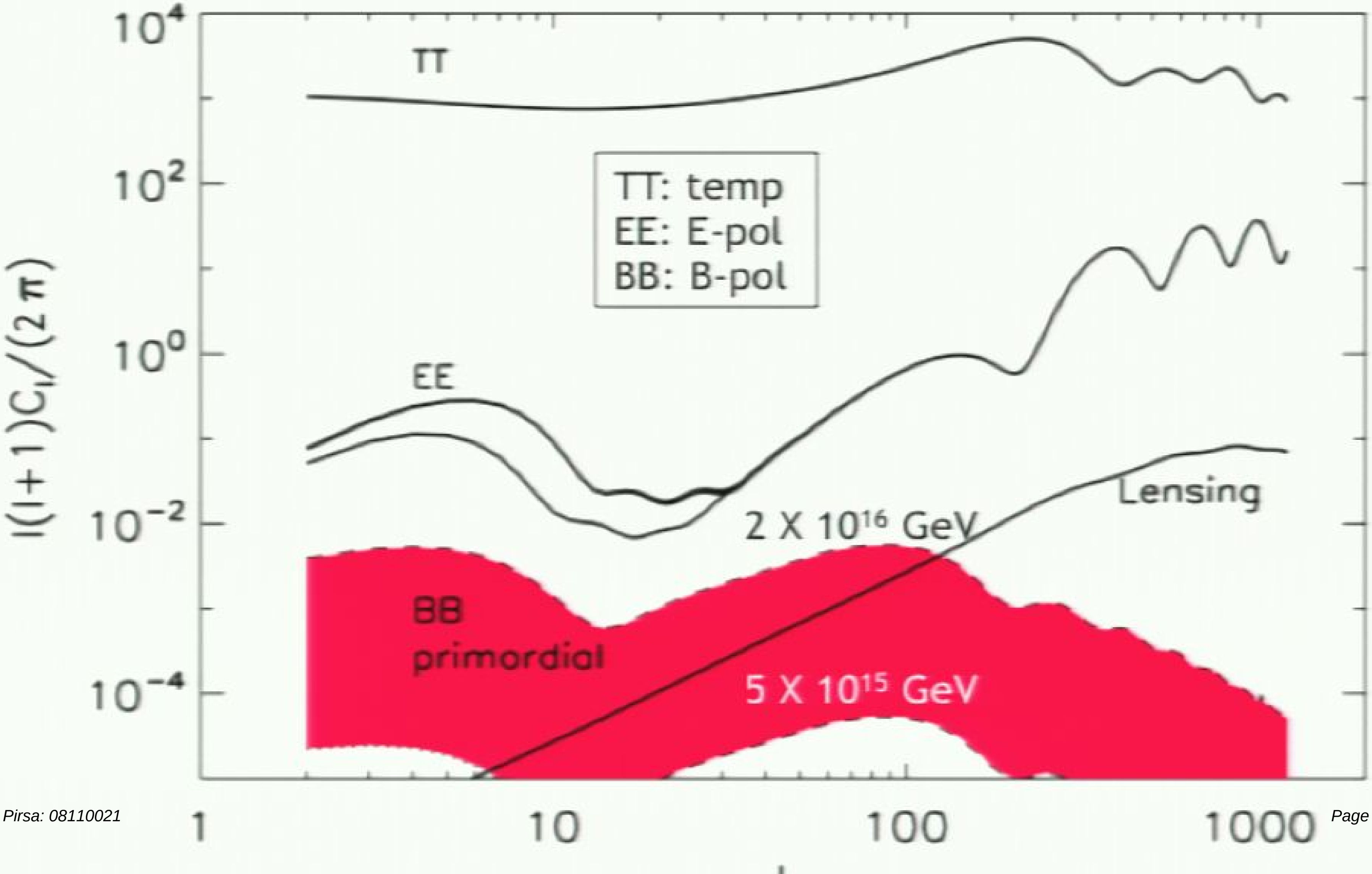
- *EPIC-LC*: "low cost" CMBpol proposal
- *EPIC-2m*: "mid cost" CMBpol proposal

Forecasted CMBpol constraints for r=0.01



Approximate range of primordial tensors accessible to upcoming experiments

$$V^{1/4} \simeq 3.3 \times 10^{16} r^{1/4} \text{ GeV}$$



What have we learned so far?

- Still testing basic aspects of the inflationary mechanism rather than its specific implementation.

- Reconstruction very useful for testing inflationary paradigm.

What have we learned so far?

- However, specific models have already been tested (e.g. large tensors, blue tilt).

- Many popular models on the verge of being tested seriously.

What have we learned so far?

- Beware "generic" fine-tuning criteria. Always question underlying assumptions.

- It is likely impossible to create a criterion specifying a "generic nflationary model" which is simultaneously:

(i) robust against small changes
(ii) does not eliminate seemingly reasonable models from consideration
(iii) leads to a definitive conclusion for the value of *r*.

Future observational prospects

- Go to small scales. Much better measurements of the primordial scalar power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT, SPT l~10000 (k~0.7/Mpc) [secondary effects]
  - Galaxies k~1/Mpc [non-linearity & bias]
  - Lyman alpha k~5/Mpc [gas phys. & radiation feedback]
  - Reionization k~50/Mpc [much is unknown]
- Detecting gravitational waves.
  - CMB: QUaD, BICEP, QUIET, CLOVER, PolarBeaR, EBEX, SPIDER, Planck, CMBPOL/B-Pol etc... [large scales]
  - GWO: direct detection of primordial gravitational waves (BBO) [solar system scales]
- Detecting primordial non-Gaussianity.
  - Can we detect f_{NL}~1 or f_{NL} >> 1?
  - Can we distinguish shape dependence? scale dependence?

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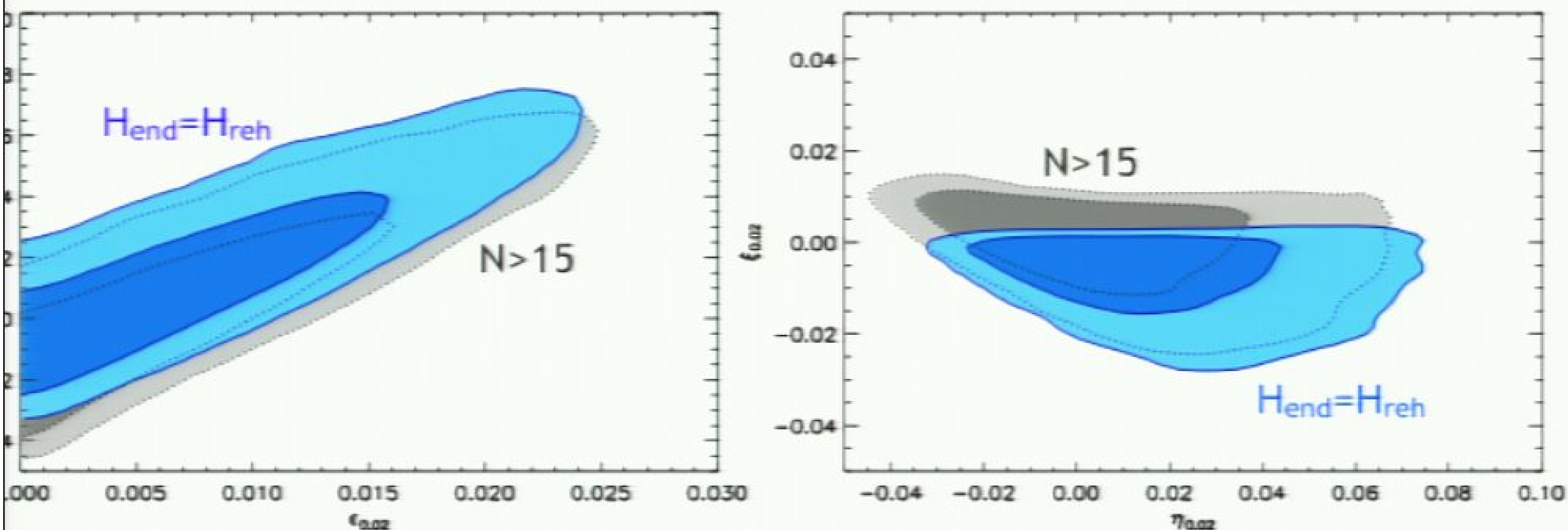
3 HSR parameters and e-fold priors



$$N(k) = -\ln\left(\frac{k}{\mathrm{Mpc}^{-1}}\right) + \frac{1}{6}\ln\left(\frac{H_{\mathrm{reh}}}{m_{\mathrm{Pl}}}\right) - \frac{2}{3}\ln\left(\frac{H_{\mathrm{end}}}{m_{\mathrm{Pl}}}\right) + \ln\left(\frac{H_k}{m_{\mathrm{Pl}}}\right) + 59.59.$$

Main effect is to eliminate models with large positive xi