Cosmology on the beach, Puerto Vallarta, Mexico 13/01/2011

Inflation in a general reionization scenario

Stefania Pandolfi, University of Rome "La Sapienza"

"Harrison-Zel'dovich primordial spectrum is consistent with observations"

S.Pandolfi, A. Cooray, E. Giusarma, E. W. Kolb, A. Melchiorri, O. Mena, P.Serra
Phys.Rev.D82:123527,2010 , arXiv:1003.4763v1[astro-ph.CO]

"Impact of general reionization scenario on reconstruction of inflationary parameters"

S. Pandolfi, E.Giusarma, E.W.Kolb, M. Lattanzi, A.Melchiorri, O.Mena, M.Pena, P.Serra, A.Cooray, Phys.Rev.D82:087302,2010,arXiv:1009.5433 [astro-ph.CO]

Outline

- Inflation
- Harrison-Zel'dovich model
- CMB Observables and present status
- Parametrizations of Reionization History
  - Sudden Reionization
  - Mortonson & Hu PC's
- Analysis and Results I and II
- Forecast future constraints: the Planck mission
- Conclusions

Inflation 1

- Period of accelerating expansion in the very early Universe
- It explains why the Universe is approximately homogeneous and spatially flat
- Dominant paradigm for explaining the initial conditions for structure formation and CMB anisotropies
- Two types of metric perturbation created during inflation: scalar and tensor (or GW perturbation)

The simplest way: the Inflaton ϕ

$$\rho = V(\phi) + \frac{1}{2}\dot{\phi}^2$$

$$p = -V(\phi) + \frac{1}{2}\dot{\phi}^2$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Inflation 2

- The slope of the inflaton's potential must be sufficiently shallow to drive exponential expansion
- The amplitude of the potential must be sufficiently large to dominate the energy density of the Universe

- **Slow-roll condition**

  Having inflation requires that the "slow-roll" parameters

$$\varepsilon << 1 \; ; \; |\eta| << 1$$

$$\varepsilon = \frac{1}{16\pi G}\left[\frac{V'(\phi)}{V(\phi}\right]^2$$

$$\eta = \frac{1}{8\pi G}\frac{V''(\phi)}{V(\phi)}$$

$$' \equiv d/d\phi$$

Zoology of models Within these condition the number of models available to choose from is large depending of the relation between the two slow-roll parameters.

CMB Observables

- Key observational tests that can be predicted from a given inflationary model are

  n : spectral index of density perturbations

  r : ratio of the gravitational waves to density perturbations

- These are related to the slow-roll parameters at the lowest order in the SRA as

$$n \cong 1 - 4\varepsilon + 2\eta$$

$$r \equiv \frac{P_T}{P_R} = 16\ \varepsilon$$

Harrison-Zel'dovich spectrum

- Inflation predicts $n \approx 1$ but $n \neq 1$

- A major point to clarify is if HZ's **n=1** is ruled out from currrent observations or not.

- If $n \neq 1$ this would provide an indication for the dynamical evolution of the expansion rate as perturbation are being produced

WMAP7

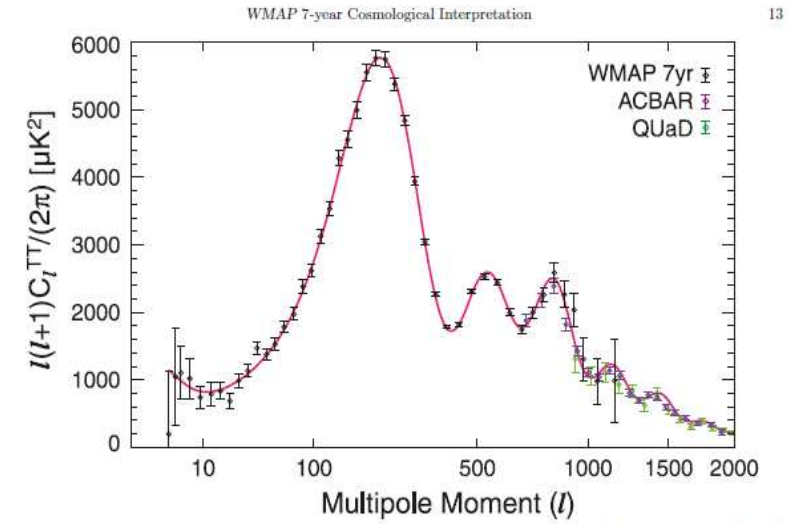


FIG. 7.— The *WMAP* 7-year temperature power spectrum (Larson et al. 2010), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at $l \geq 690$, where the errors in the *WMAP* power spectrum are dominated by noise. We do not use the power spectrum at $l > 2000$ because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting 6-parameter flat ΛCDM model to the *WMAP* data alone (see the 3rd column of Table 1 for the maximum likelihood parameters).

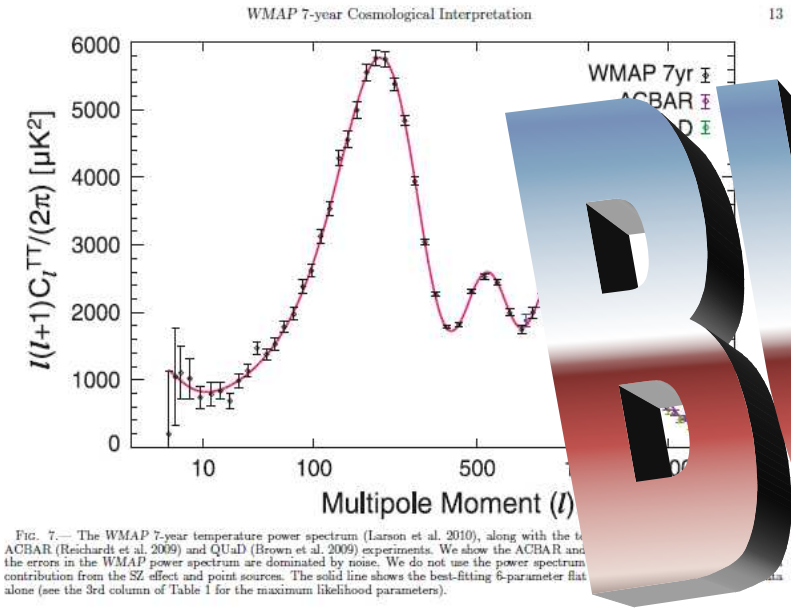
Class	Parameter	ML	*WMAP* 7-year Mean[c]
Primary	$100\Omega_b h^2$		$2.249^{+0.056}_{-0.057}$
	$\Omega_c h^2$		0.1120 ± 0.0056
	Ω_Λ		$0.727^{+0.030}_{-0.029}$
	n_s		0.967 ± 0.014
	τ		0.088 ± 0.015
	$\Delta^2_{\mathcal{R}}(k_0)$[d]		$(2.43 \pm 0.11) \times 10^{-9}$

Model	Parameter[a]	7-year *WMAP*[b]	*WMAP*+ACBAR+QUaD[c]	*WMAP*+BAO+H_0
Power-law[d]	n_s	0.967 ± 0.014	$0.966^{+0.014}_{-0.013}$	0.968 ± 0.012

The 7-year *WMAP* data combined with BAO and H_0 exclude the scale-invariant spectrum by 99.5% CL, if we ignore tensor modes (gravitational waves).

Komatsu, E., et.al (2010)

WMAP7



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BUT...

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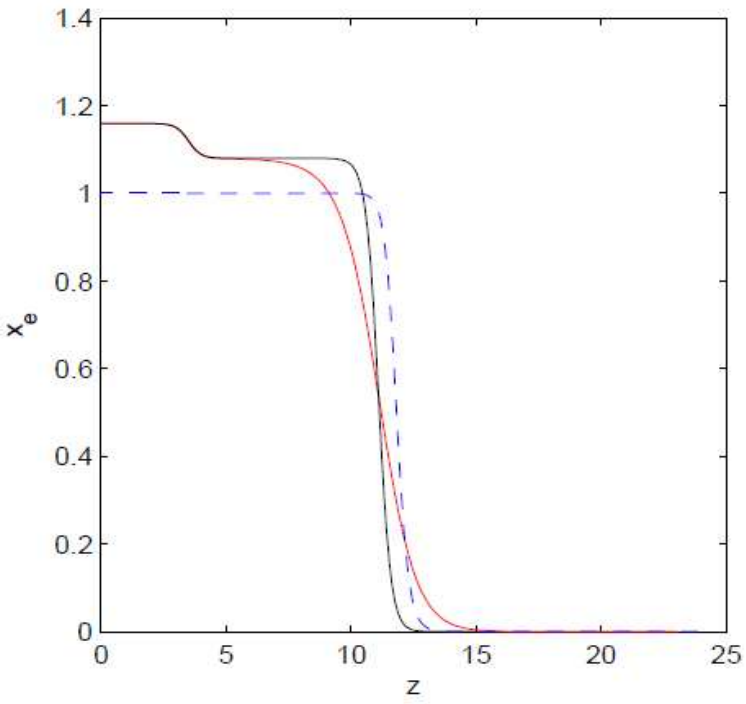
Sudden Reionization

$$y(z_{re}) = (1 + z_{re})^{3/2}$$

$$x_e(y) = \frac{f}{2}\left[1 + \tanh\left(\frac{y - y(z_{re})}{\Delta_y}\right)\right]$$

CAMB Notes, Antony Lewis



As we don't know precisely the details of the reionization history we should consider more general reionization scenarios

MH's Reionization

Following Mortonson & Hu we can parametrize the reionization history as a free function of the redshift by decomposing the free electron fraction as

$$x_e(z) = x_e^f(z) + \sum_\mu m_\mu S_\mu(z)$$

- The principal components $S_\mu(z)$ are the eigenfunctions of the Fisher matrix of an ideal, cosmic variance limited, experiment.

$$F_{ij} = \sum_{\ell=2}^{\ell_{\max}} \left(\ell + \frac{1}{2}\right) \frac{\partial \ln C_\ell^{EE}}{\partial x_e(z_i)} \frac{\partial \ln C_\ell^{EE}}{\partial x_e(z_j)} \qquad F_{ij} = (N_z+1)^{-2} \sum_{\mu=1}^{N_z} S_\mu(z_i) \sigma_\mu^{-2} S_\mu(z_j)$$

- m_μ are the amplitudes of the $S_\mu(z)$
- $x^{fid}(z)$ is the WMAP fiducial model at which the FM is computed

M. J. Mortonson and W. Hu ApJ 686, L53 (2008)

Results - part I

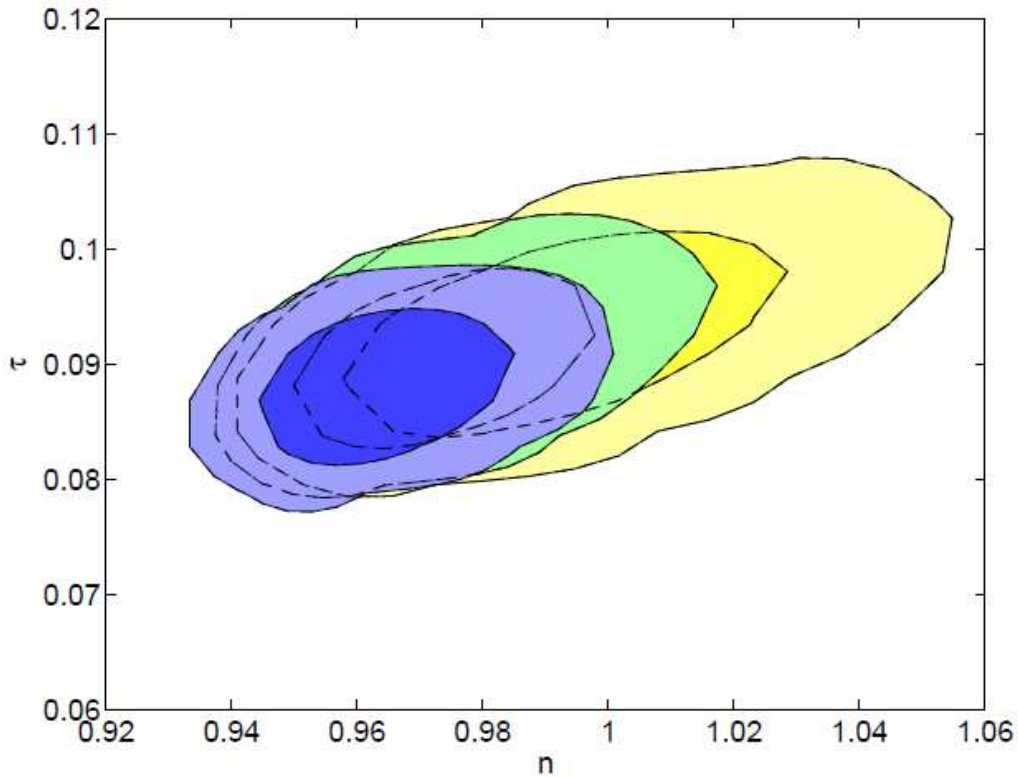
Dataset	Ionization	n (68% c.l.)	95% c.l.
WMAP7	sudden	0.965 ± 0.014	$n \leq 0.993$
CMB All	sudden	0.959 ± 0.013	$n \leq 0.984$
WMAP7	MH	0.993 ± 0.023	$n \leq 1.042$
CMB All	MH	0.975 ± 0.017	$n \leq 1.011$
CMB All+LRG-7	MH	0.966 ± 0.014	$n \leq 0.994$
CMB All+BAO	MH	0.965 ± 0.014	$n \leq 0.995$
CMB All+BAO	MH+$w(z)$	0.985 ± 0.018	$n \leq 1.025$
Planck	MH	0.972 ± 0.007	$n \leq 0.986$

CMB All = WMAP7 +BICEP +QUAD +ACBAR

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Optical Depth

It is interesting to consider the constrains on the optical depth, derived by integrating $x_e(z)$ up to z=32



WMAP7 alone

CMB all

CMB all + BAO

Contours at 68% and 95% c.l in the n vs τ plane for different dataset

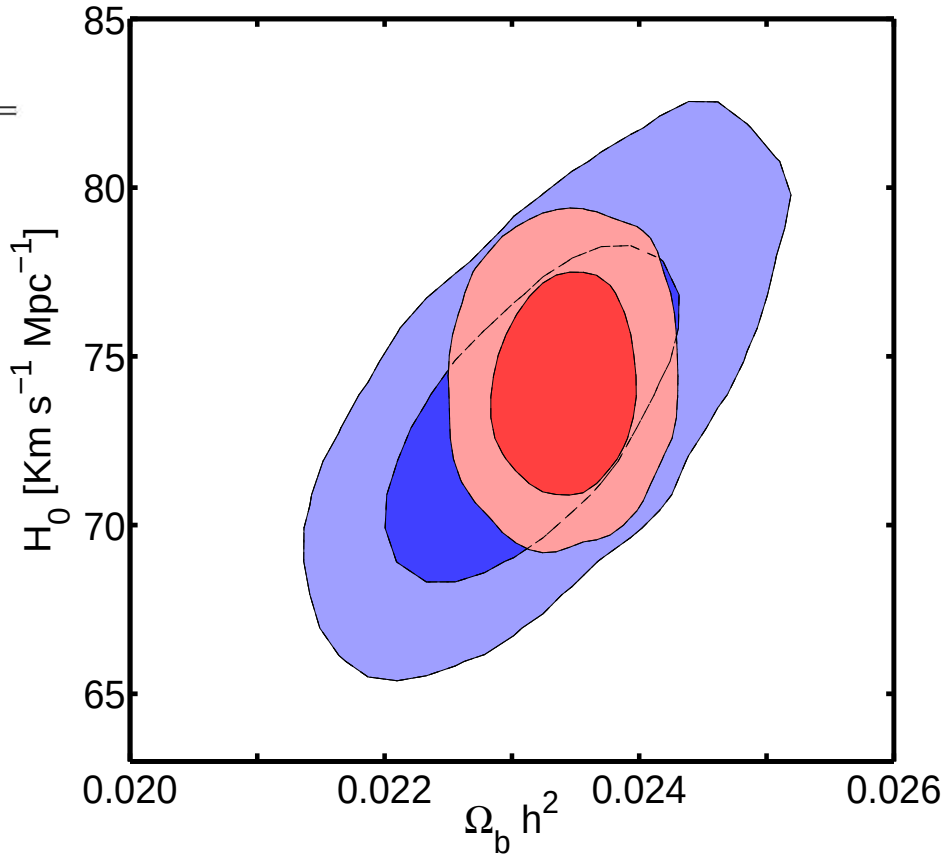
Cosmology with HZ's n=1?

Parameter	Constraint (68% c.l.)
$\Omega_b h^2$	0.0234 ± 0.0004
$\Omega_c h^2$	0.106 ± 0.005
H_0 (km s^{-1}Mpc^{-1})	74.2 ± 2.1
Age (Gyr)	13.6 ± 0.1
Ω_Λ	0.765 ± 0.022

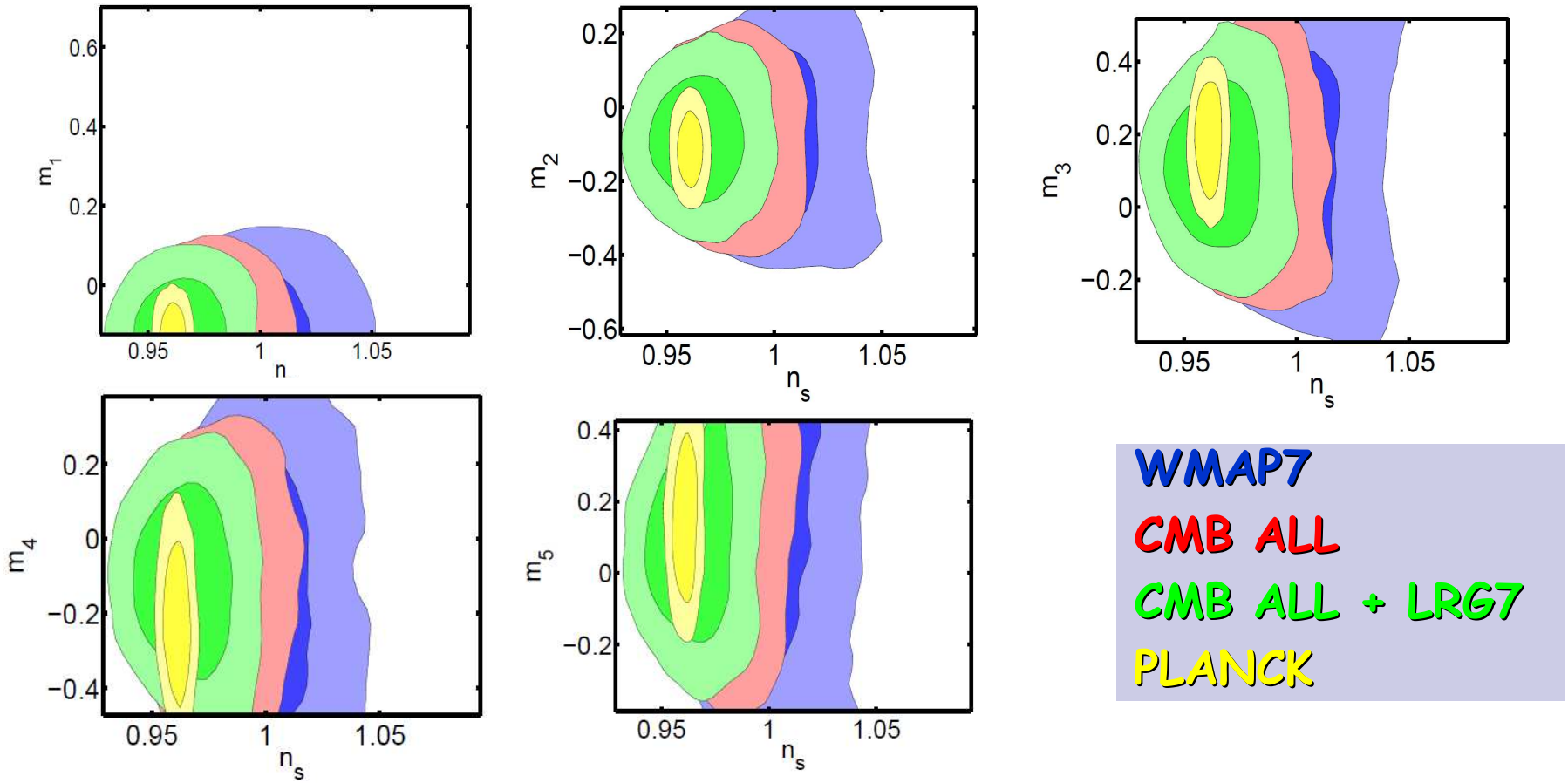
MH reionization

WMAP7, n parameter

WMAP7, n=1



Principal Components



68% and 95% c.l. WMAP7 constraints in the m_μ vs.n plane in a generalized reionization scenario described by the MHU parametrization.

Part II

- + Tensors modes

  ⇒ r

- + Running of the scalar spectral index

  ⇒ $$n_{run} = \frac{d\,n}{d\ln k}$$

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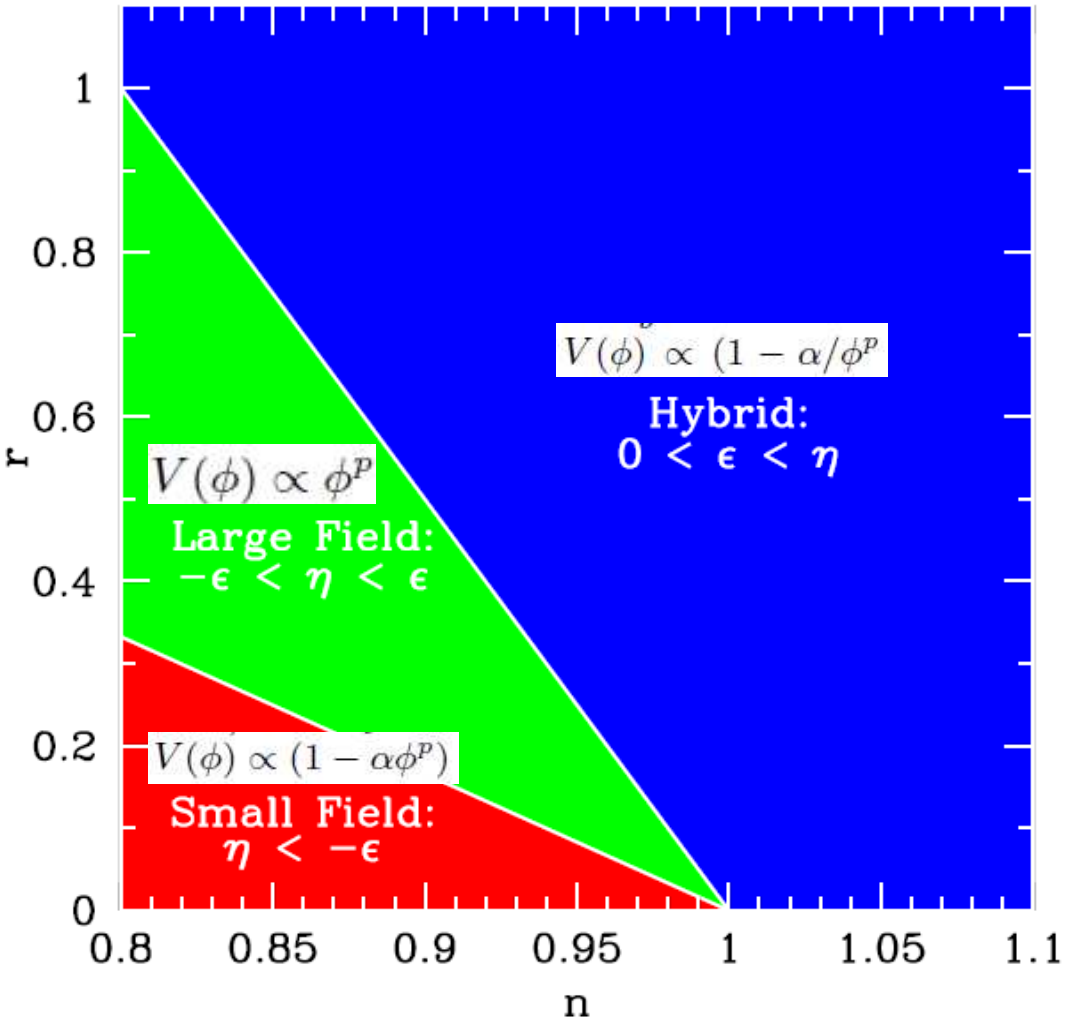
Zoology of the inflationary models



Results, part IIa : tensor

Sudden Reionization

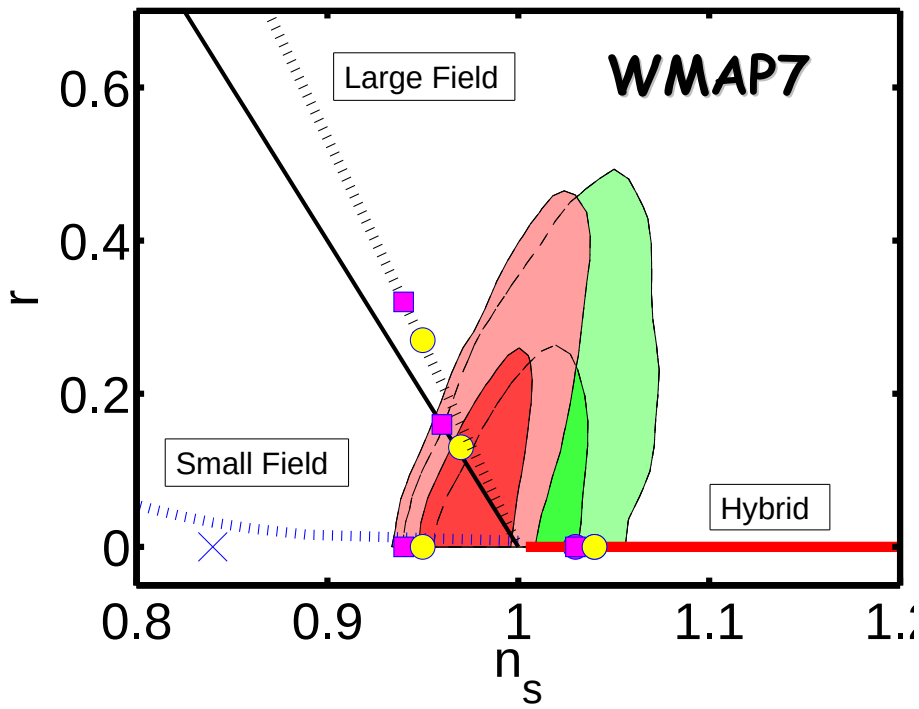
MH's Reionization

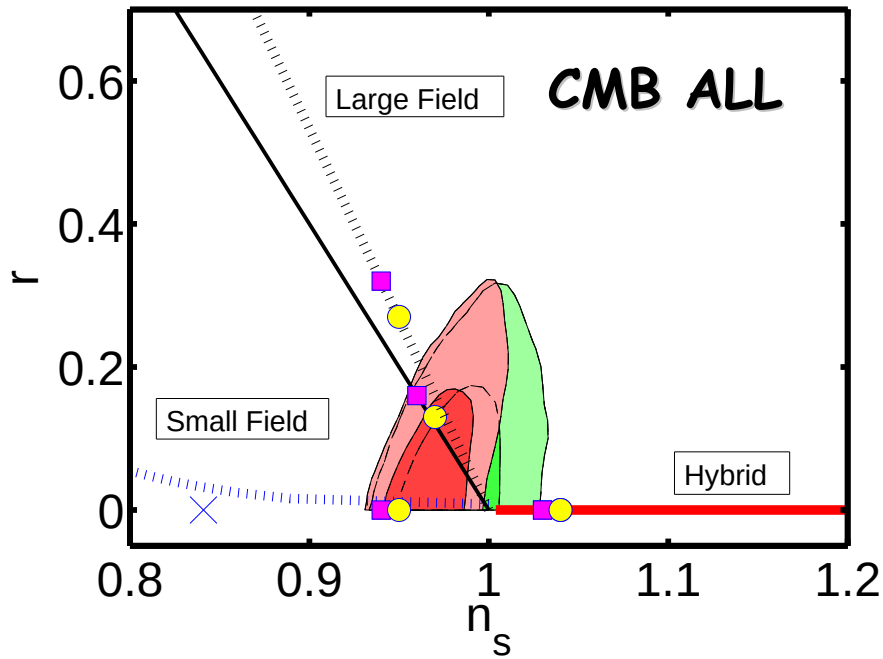
solid curves p=2

dashed curves p=4

N = 60

N = 50





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Results, part IIb : tensor + running

Sudden Reionization

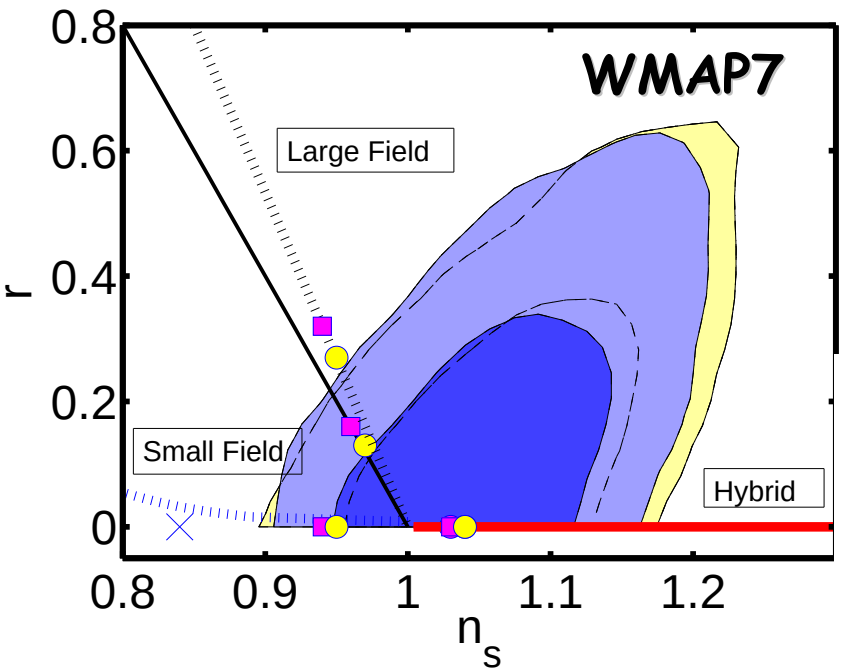
MH's Reionization

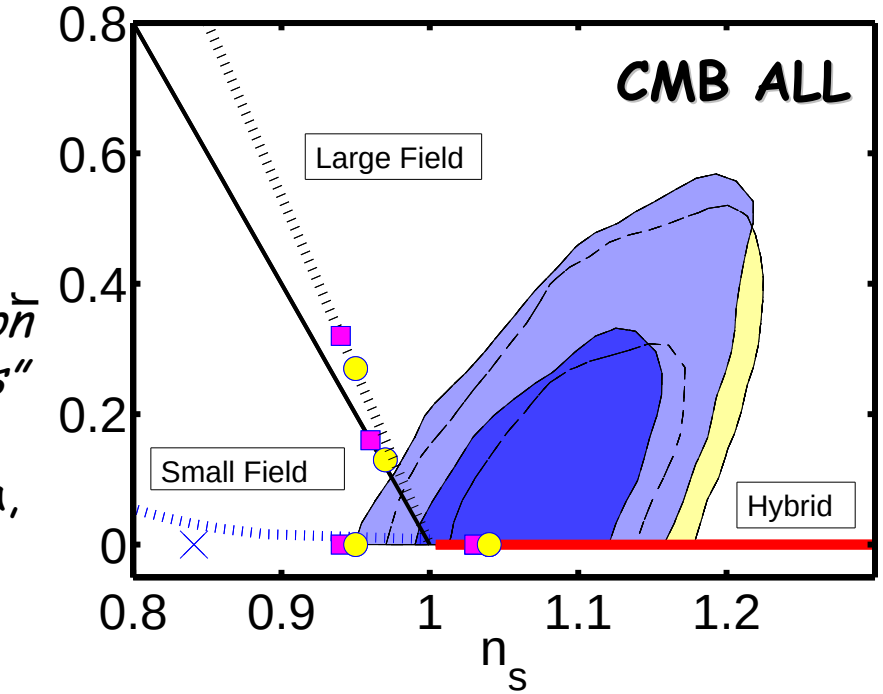
solid curves p=2

dashed curves p=4

N = 60

N = 50





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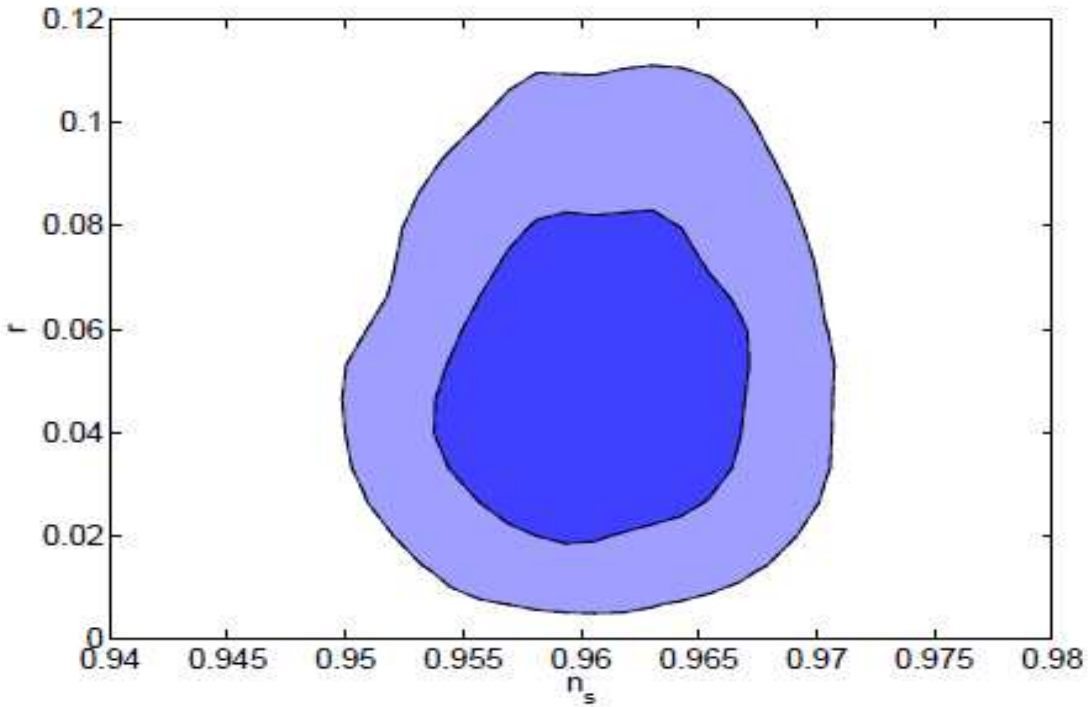
Forcasts from Planck



n = 0.96

r = 0.05

sudden reionization

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Conclusions

- Inflation predicts $n \cong 1$ but $n \neq 1$

- WMAP7 data $n = 0.967 \pm 0.014 \ (68\% \ CL)$

  but assuming Sudden Reionization

- A modified Reionization history weakens the bound on the spectral index; hybrid models are back allowed by data.

- Assuming an HZ primordial spectrum and a modified Reionization lead a viable cosmology

- Near future data from the Planck satellite mission are needed to solve this question

The end

For inflation produced by a single scalar field, during the slow-roll phase, the kinetic energy of the field is negligible and the potential is nearly constant:

$$\rho_\phi = V(\phi) + \frac{\dot{\phi}^2}{2} \approx V(\phi) \approx \text{const.}$$

This gives rise to a (quasi-) de Sitter phase: $H^2 = \frac{8\pi G}{3} V(\phi)$

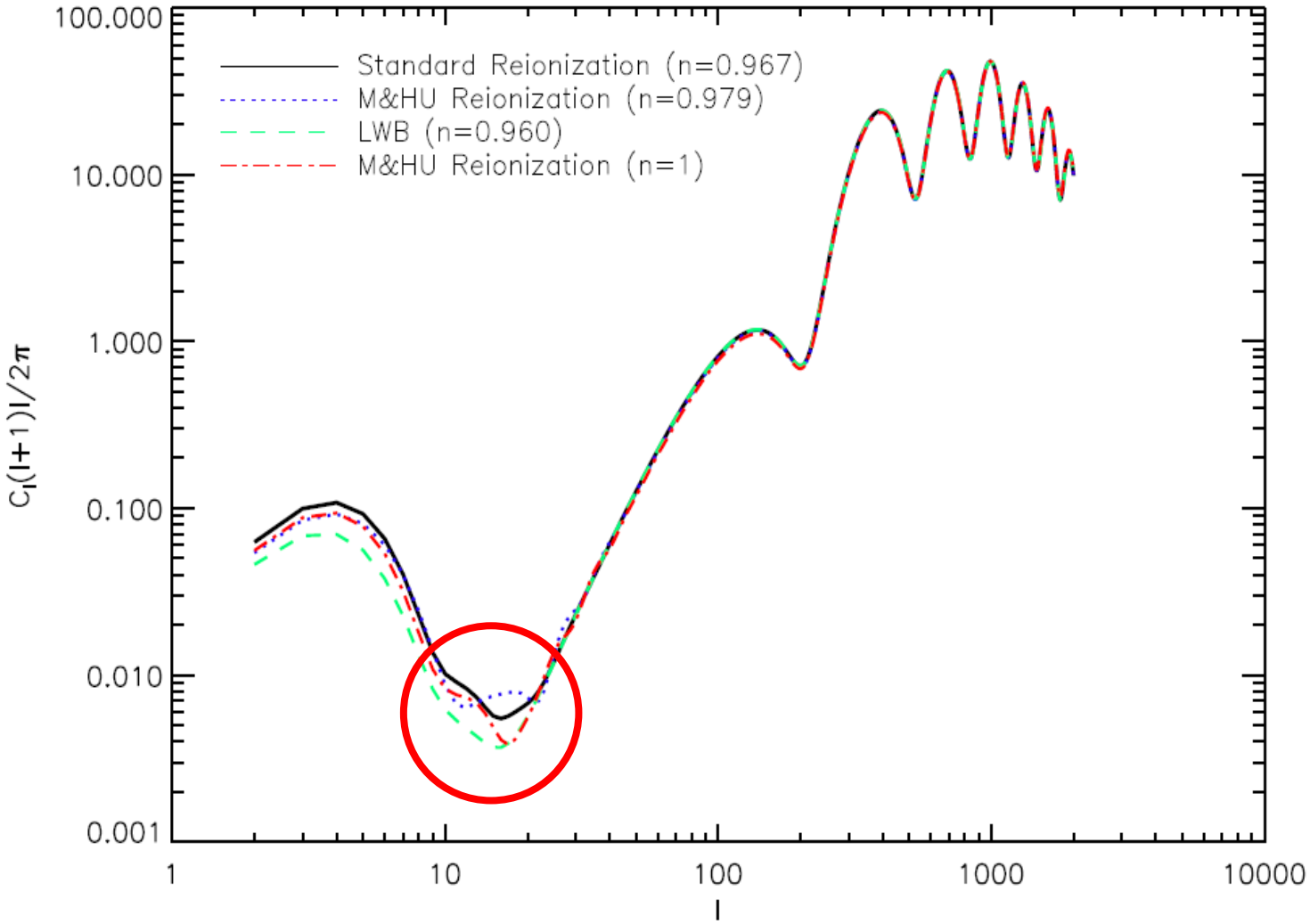
The perturbations in the field are proportional to the value of the Hubble parameter *at the time of horizon crossing:*

$$(\Delta\phi)_k = \left(\frac{H_{hc}}{2\pi}\right)^2 = \frac{2G}{3\pi} V(\phi)^2$$

Since $V(\phi)$ is not actually constant, but slowly-varying, we expect a *weak dependence of the amplitude of the perturbations on the wavenumber*

➡ If the perturbations were originated from the dynamics of a scalar field the spectrum should not be *exactly* scale invariant

Polarization Power Spectrum



Monte Carlo Reconstruction

Kinney astro-ph/0206032

- Taking higher derivatives of H, one can construct an infinite hierarchy of slow-roll parameters

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

- The evolution of the slow-roll parameters is described by the flow equations

$$\begin{aligned}
\frac{d\epsilon}{dN} &= \epsilon(\sigma + 2\epsilon), \\
\frac{d\sigma}{dN} &= -5\epsilon\sigma - 12\epsilon^2 + 2\lambda_{\rm H}^{(2)}, \\
\frac{d\lambda_{\rm H}^{(\ell)}}{dN} &= \left[(\ell-1)\frac{\sigma}{2} + (\ell-2)\epsilon\right]\lambda_{\rm H}^{(\ell)} + \lambda_{\rm H}^{(\ell+1)}
\end{aligned}$$

- Given a solution to these equations, the observable quantities can be evaluated. To second order in slow roll, these are given by

$$\begin{aligned}
r &= 16\epsilon[1 - C(\sigma + 2\epsilon)], \\
n - 1 &= \sigma - (5 - 3C)\epsilon^2 - \frac{1}{4}(3 - 5C)\sigma\epsilon \\
&\quad + \frac{1}{2}(3 - C)\lambda_{\rm H}^{(2)}, \\
n_{run} &= -\left(\frac{1}{1-\epsilon}\right)\frac{dn}{dN} \ ,
\end{aligned}$$

The solution to the flow equations also allows one to reconstruct the form of the potential V(ϕ)

Monte Carlo reconstruction of the inflationary potentials

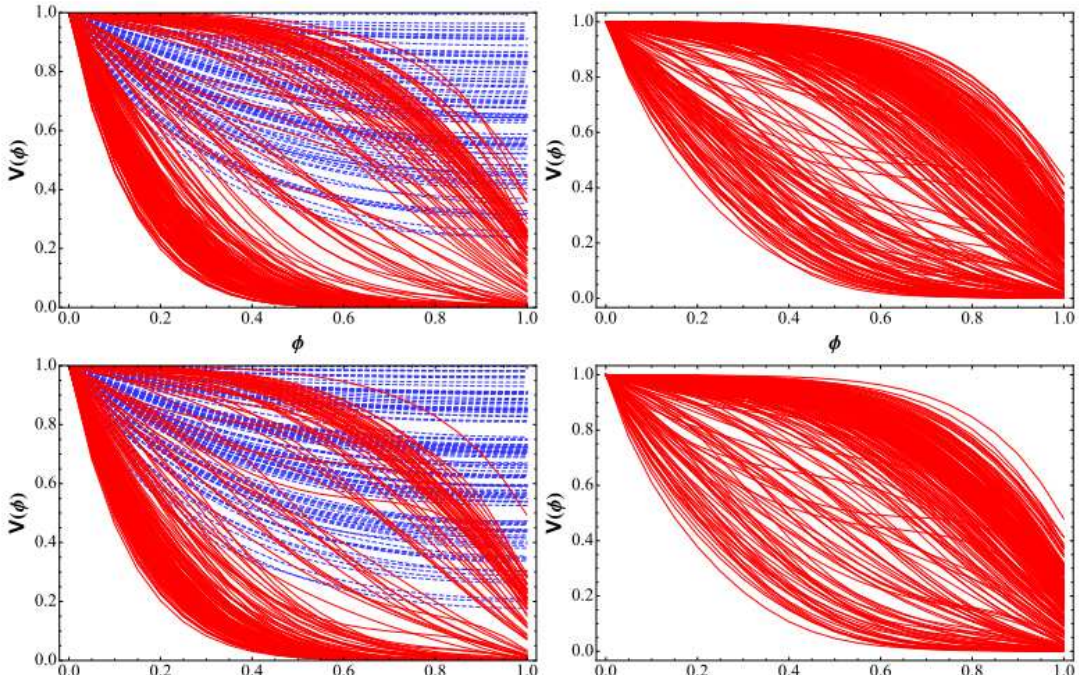
Kinney astro-ph/0206032

WMAP7 - Sudden

CMBALL - Sudden

WMAP7 – MH

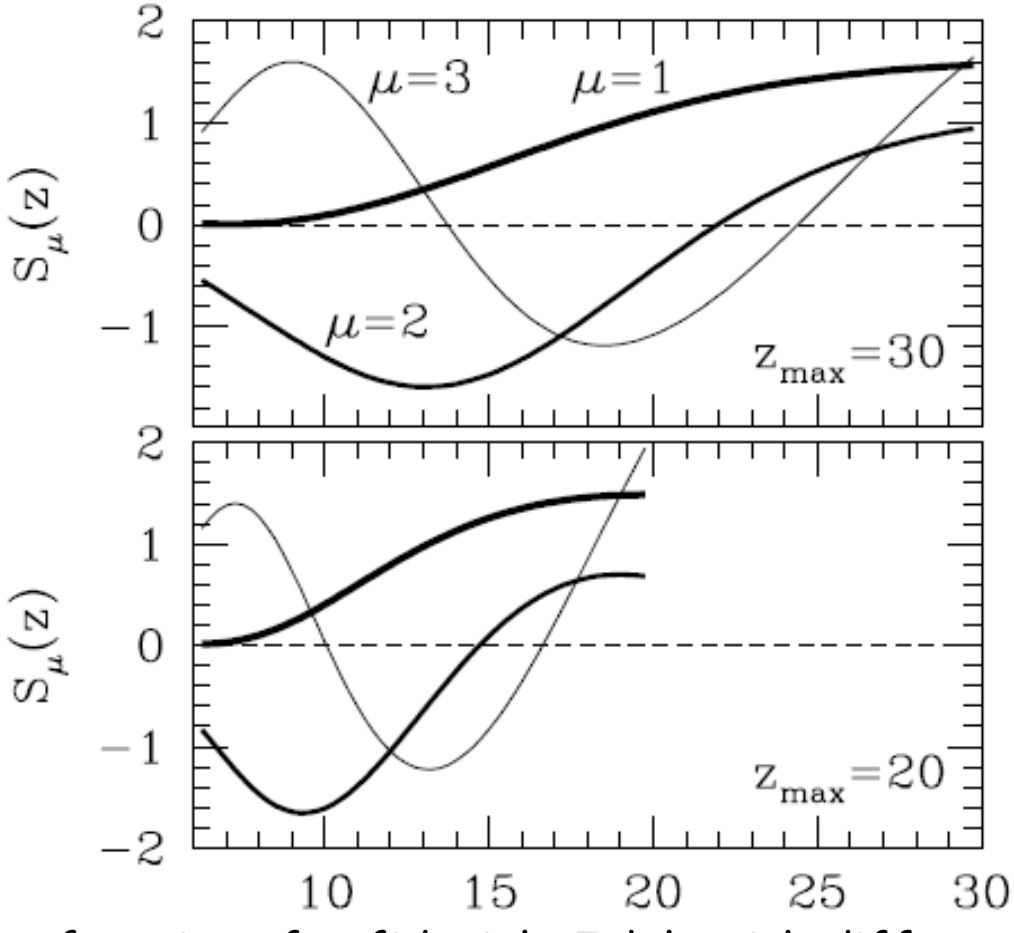
CMBALL – MH



	WMAP7		CMB-ALL	
	Sudden	MH	Sudden	MH
n	$0.913 \leq n \leq 1.221$	$0.918 \leq n \leq 1.234$	$0.968 \leq n \leq 1.216$	$0.984 \leq n \leq 1.260$
r	$r \leq 0.665$	$r \leq 0.688$	$r \leq 0.551$	$r \leq 0.619$
$n_{\rm run}$	$-0.098 \leq n_{\rm run} \leq 0.037$	$-0.098 \leq n_{\rm run} \leq 0.050$	$-0.099 \leq n_{\rm run} \leq -0.001$	$-0.117 \leq n_{run} \leq -0.001$

TABLE II: 99% c.l. observational limits used in the reconstruction of the inflationary potential, for the four cases considered in the text.

MH's Reionization



Eigenfunctions for fiducial models with different z_max and constant x_e=0.15 (top), x_e=0.3 (bottom). For both fiducial models z_min=6