Title: Model-Independent Constraints on Inflation from the CMB

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Abstract: I introduce a general method for constraining the shape of the inflationary potential from Cosmic Microwave Background (CMB) temperature and polarization power spectra. This approach relates the CMB observables to the shape of the inflaton potential via a single source function that is responsible for the observable features in the initial curvature power spectrum. The source function is, to an excellent approximation, simply related to the slope and curvature of the inflaton potential, even in the presence of large or rapidly changing deviations from scale-free initial conditions. Oscillatory features in the WMAP temperature power spectrum have led to interest in exploring models with features in the inflationary potential, but such cases are typically studied on a case-by-case basis. This formalism generalizes previous studies by exploring the complete parameter space of inflationary models in a single analysis.

I will present results from a Markov Chain Monte Carlo likelihood analysis of WMAP 7-year and other data sets that probe the inflationary potential both at large and small scales, and I will discuss constraints from upcoming high-sensitivity experiments.

Outline

- CMB and Inflation overview.
- General method to constrain the inflationary potential from CMB observations allowing for features.
  - Theoretical framework.
  - Analysis of data.
- Conclusions and future directions.

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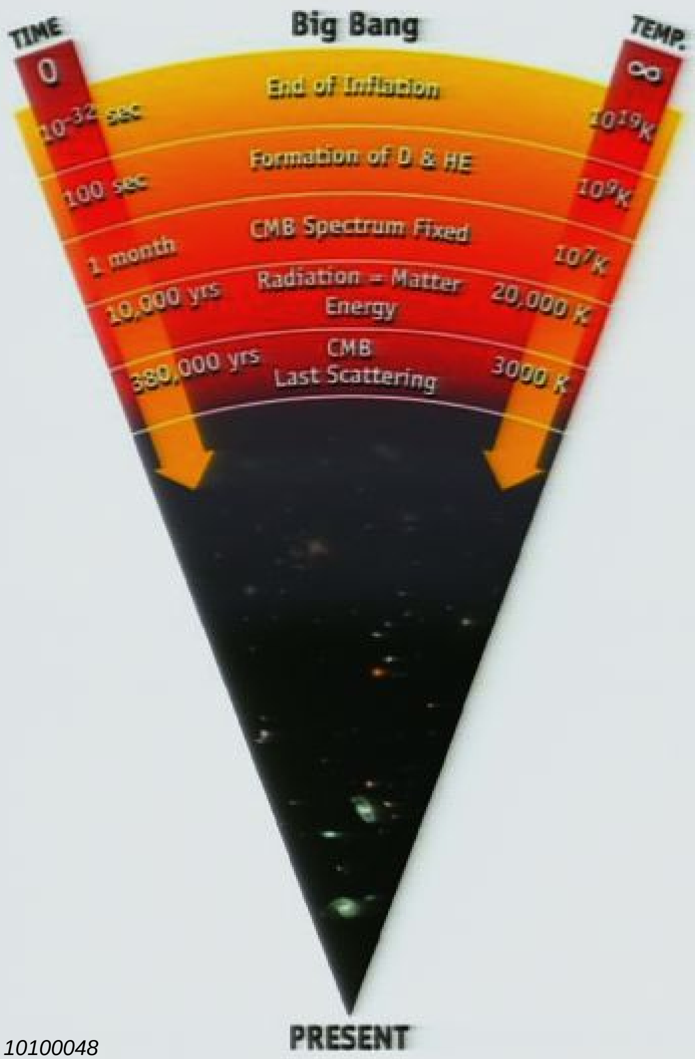
Cosmic History



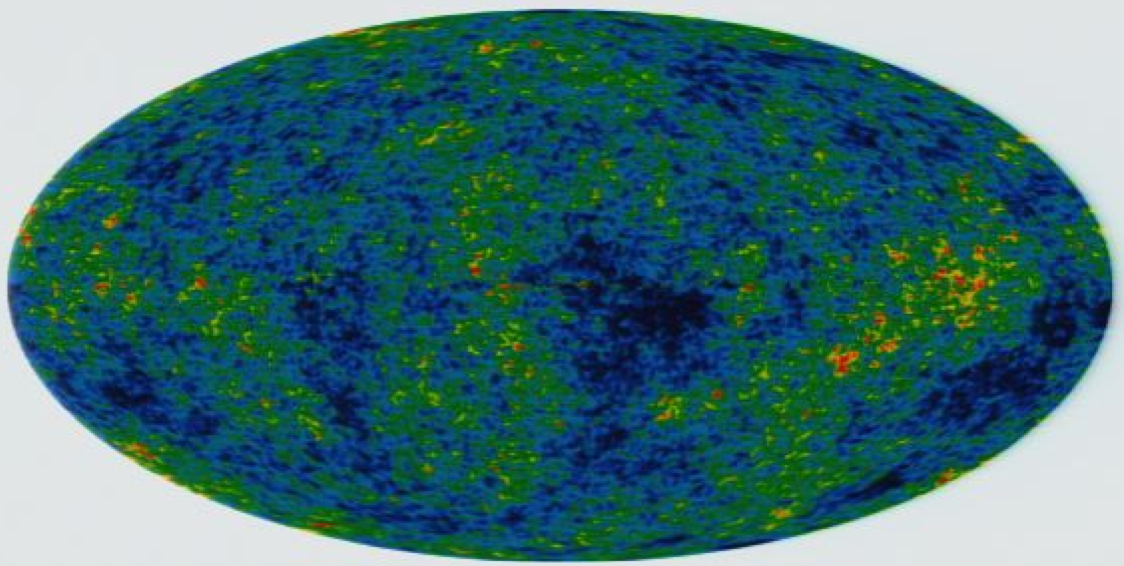
WMAP collaboration

- The universe began as a hot and dense plasma of particles in thermal equilibrium.
- Recombination ($z \approx 1100$): $p^+ + e^- \rightarrow H$
  Universe becomes transparent to CMB photons.

  Photons mainly freestream.
- Radiation from first stars and quasars reionizes the universe ($z \approx 10$) and $\sim 10\%$ of the photons re-scatter.
- We observe these photons at $T \approx 2.725$ K.

CMB Anisotropies

"Snapshot" of the Early Universe



WMAP collaboration

Gaussian random fluctuations: $\Delta T \approx 100\mu K$

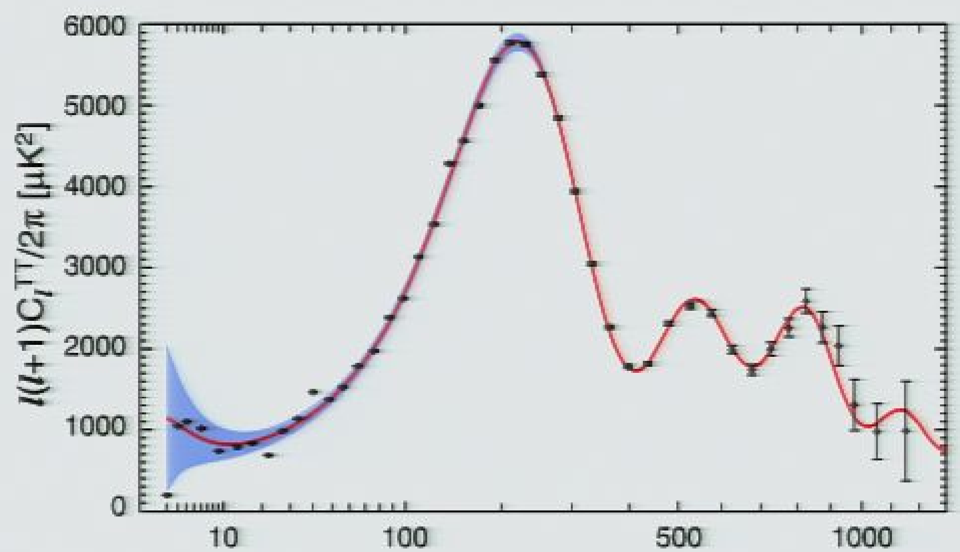
CMB Power Spectrum

Power spectrum: contains all the information for a Gaussian, isotropic field.

$$\Delta T\left(\hat{\mathbf{n}}\right) = \sum_{\ell m} T_{\ell m} Y_{\ell m}\left(\hat{\mathbf{n}}\right)$$

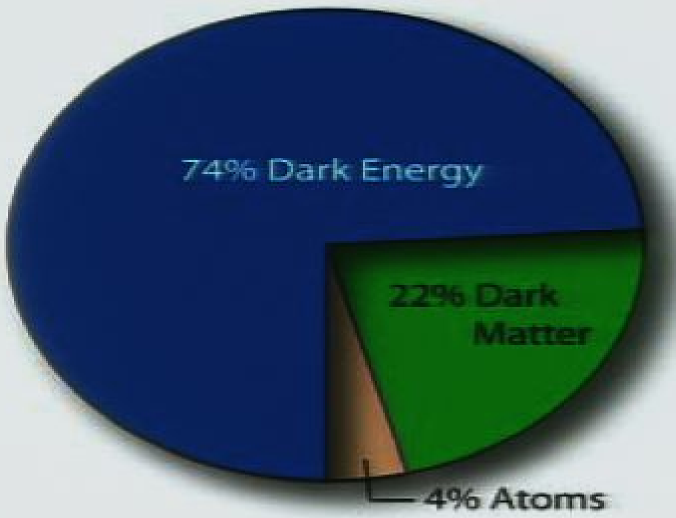
$$\langle T_{\ell m} T^*_{\ell' m'} \rangle = C_\ell^{TT} \delta_{\ell\ell'} \delta_{mm'}$$

It has been **predicted** and **measured** with good precision.



ΛCDM: the "Standard" Model of Cosmology

Homogeneous background

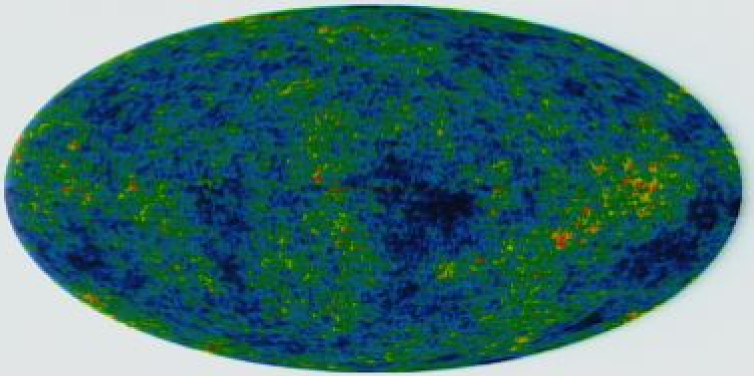


$$\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \tau, \theta$$

- Baryonic matter: 4%
- Cold dark matter: 22%
- Dark energy: 74%

Λ? CDM?

Perturbations



$$A_s, n_s$$

- Nearly-scale invariant
- Gaussian

Origin?

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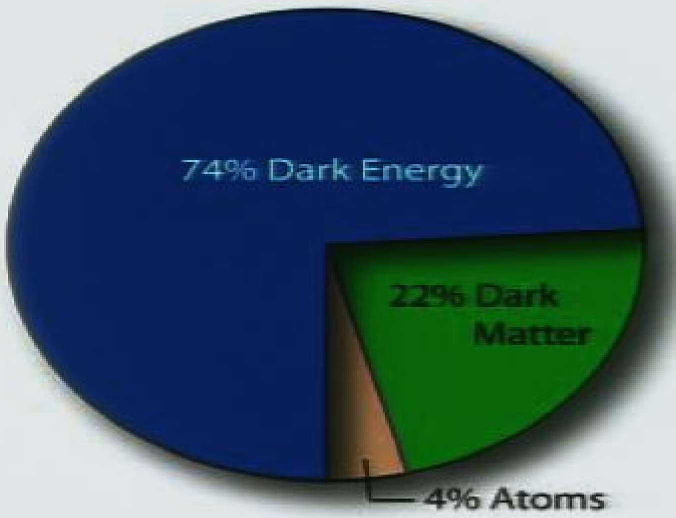

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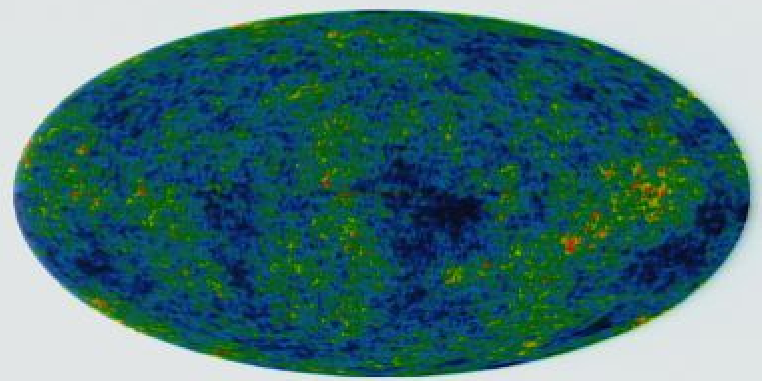

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What causes inflation?

The Dynamics of Inflation

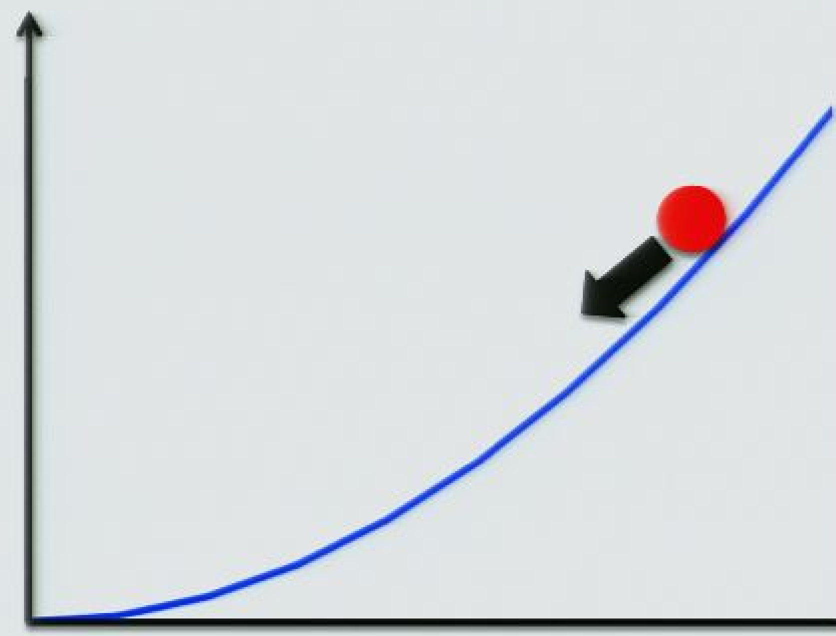
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2$$ ← expansion rate

$$= \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

↑ energy density

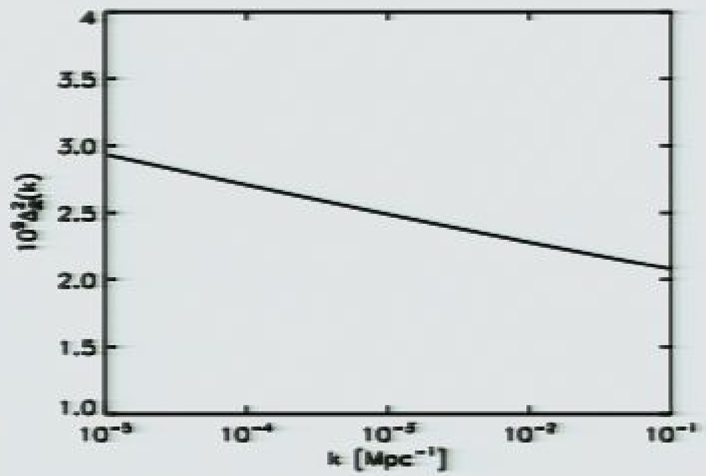
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

3H → friction

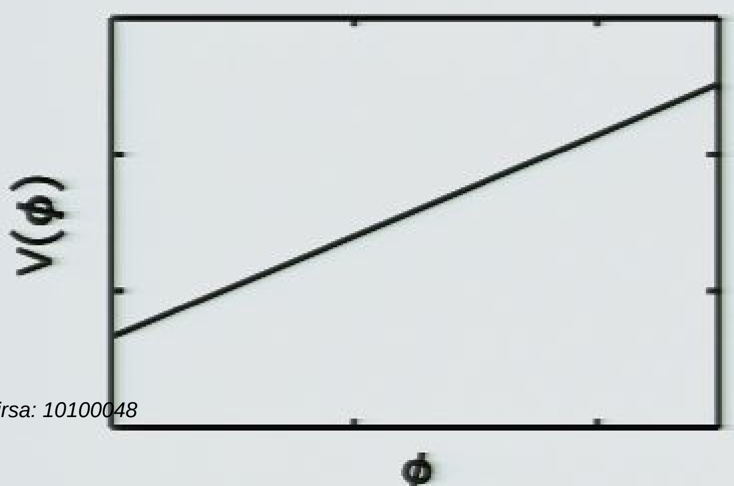


Connecting Theory with Observations

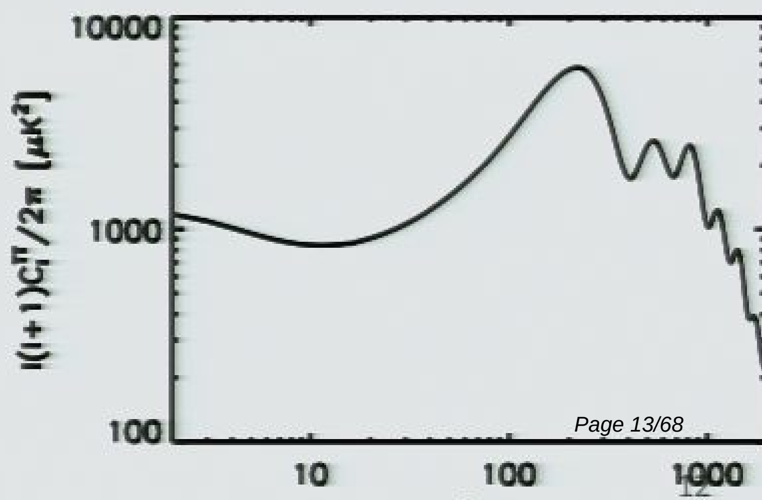
POWER SPECTRUM



INFLATIONARY POTENTIAL



CMB TEMPERATURE POWER SPECTRUM



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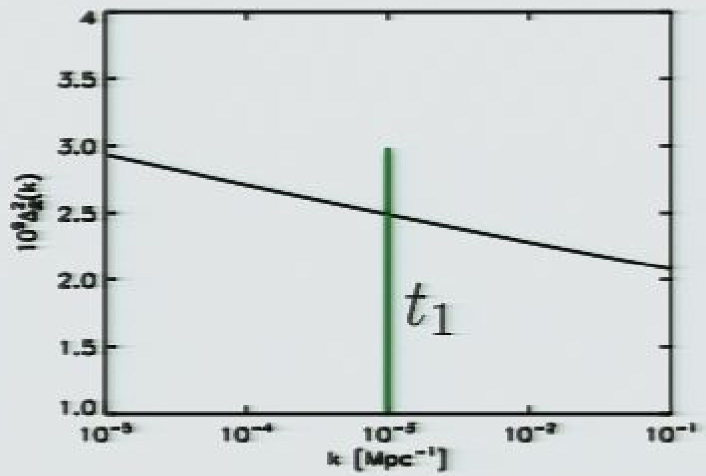

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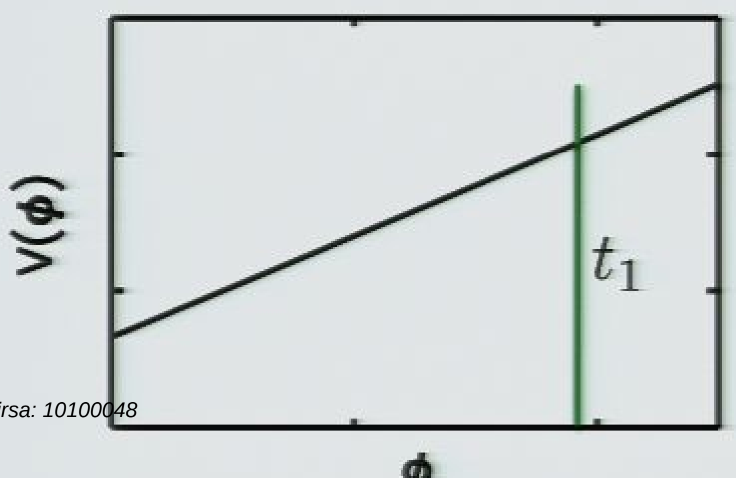

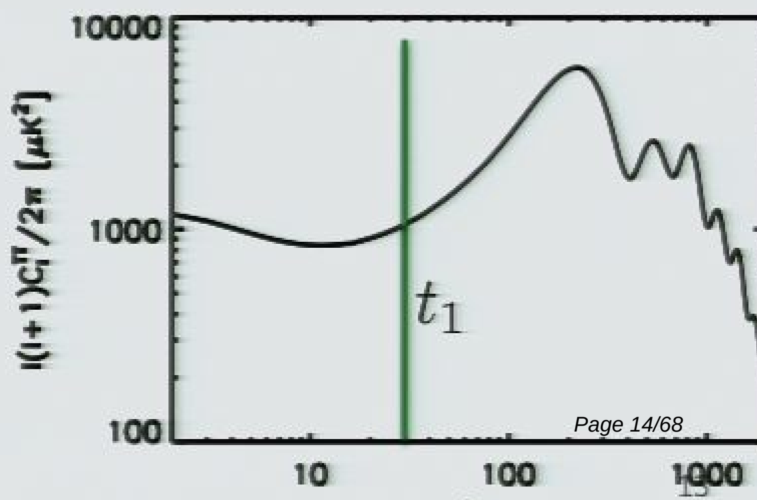

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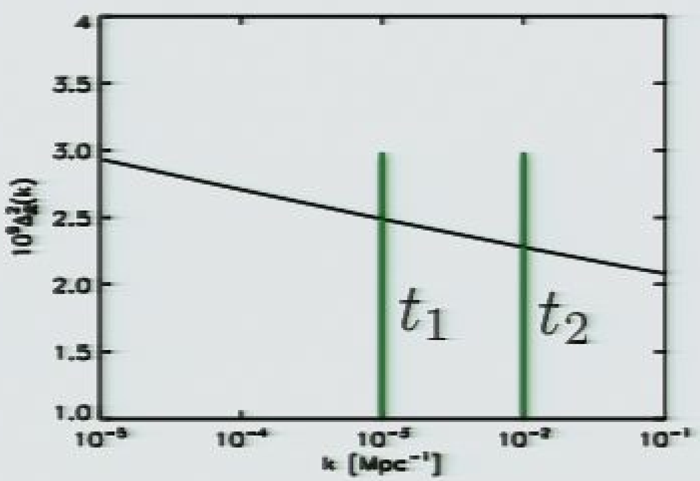

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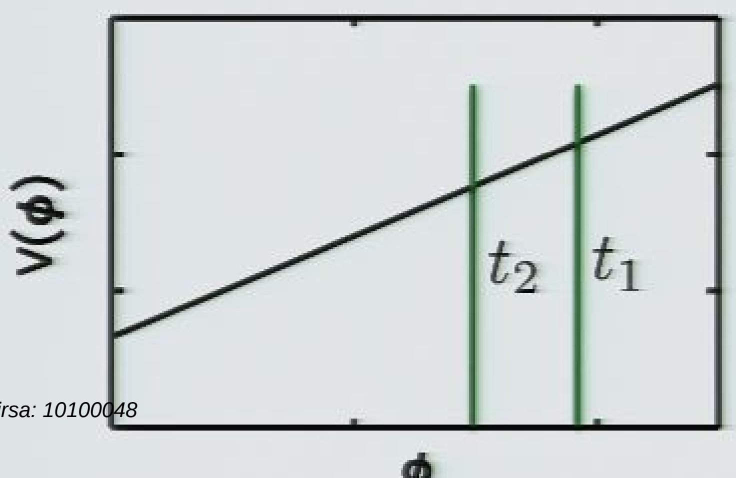

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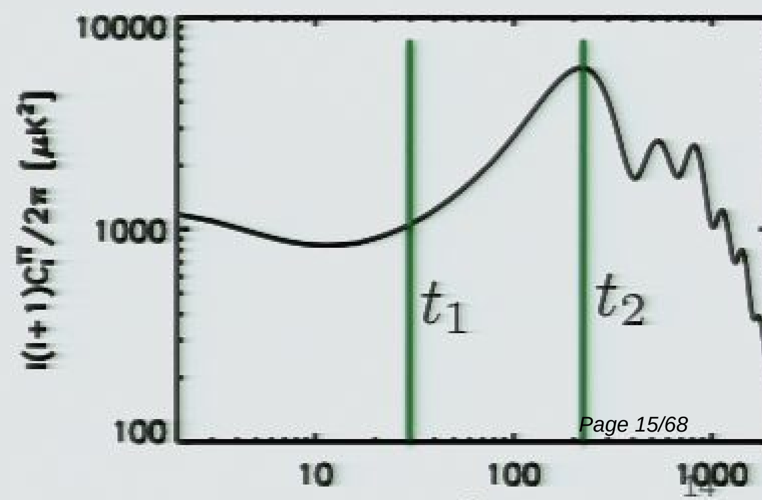


Connecting Theory with Observations

Goal: to shed light on the physics of inflation by using CMB observations

Standard Slow Roll

Technique for computing the initial curvature power spectrum for inflationary models where the scalar field potential is sufficiently flat and slowly varying.

$$\epsilon_H \equiv \frac{1}{2}\left(\frac{\dot{\phi}}{H}\right)^2$$

$$\eta_H \equiv -\left(\frac{\ddot{\phi}}{H\dot{\phi}}\right)$$

$$\delta_2 \equiv \frac{\dddot{\phi}}{H^2\dot{\phi}}$$

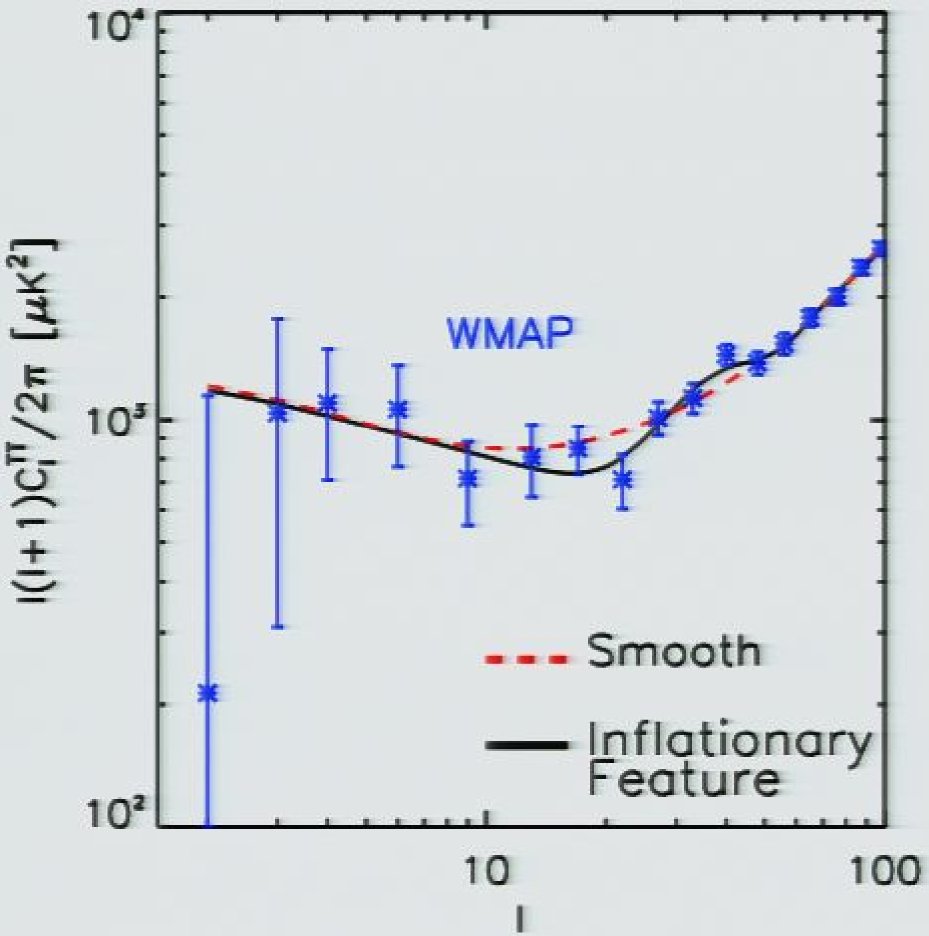
Linked to the **shape of the potential**

Slow-roll parameters

<< 1 and slowly varying

Slow roll approximation: $\Delta_{\mathcal{R}}^2 \approx \left[(1-(2C+1)\epsilon_H - C\eta_H)\frac{H^2}{2\pi|\dot{\phi}|}\right]^2$

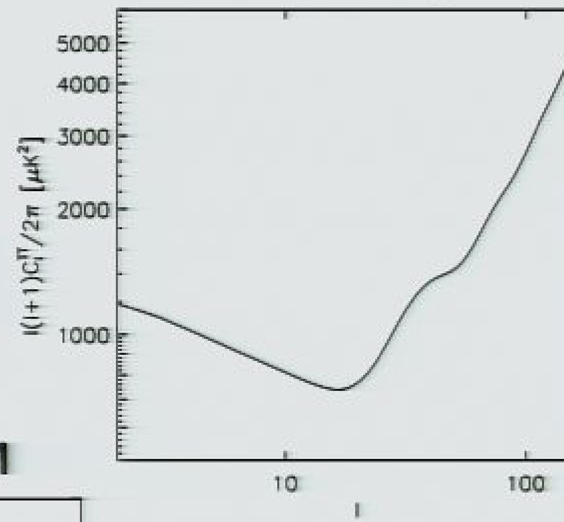
Inflationary Features



- Glitches in the temperature power spectrum of the CMB have led to interest in explorin[g] models with features in the inflaton potential.

✧ *L. Covi, J.Hamann, A. Melchiorri, A. Slozar and I. Sorbera, (2006)*

TEMPERATURE



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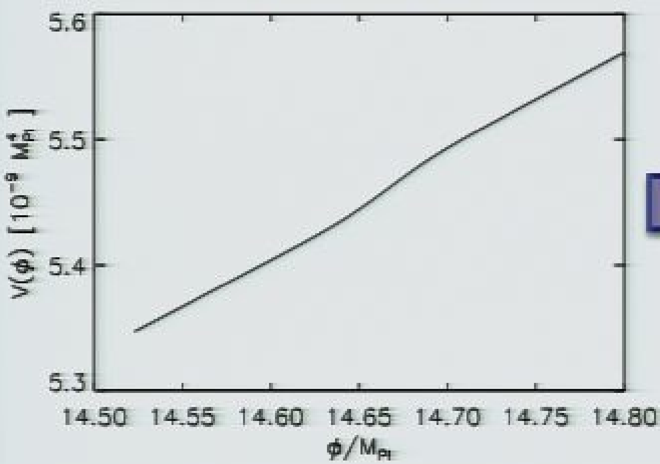

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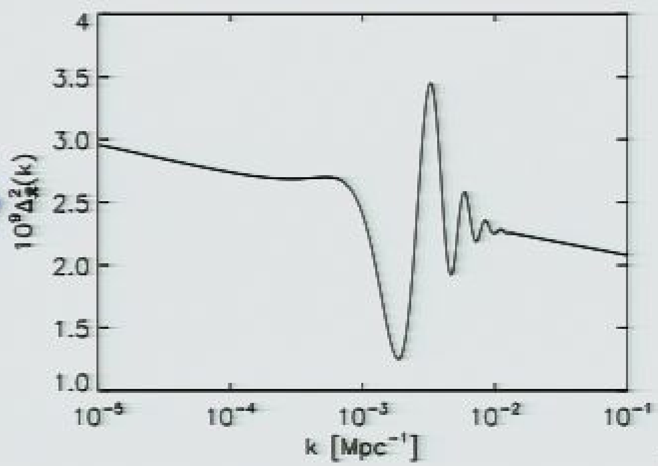
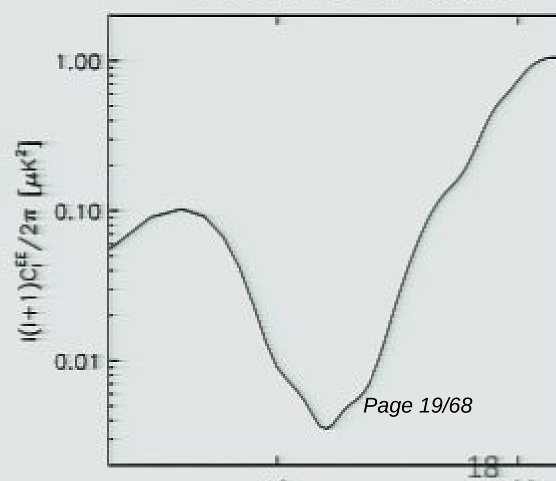
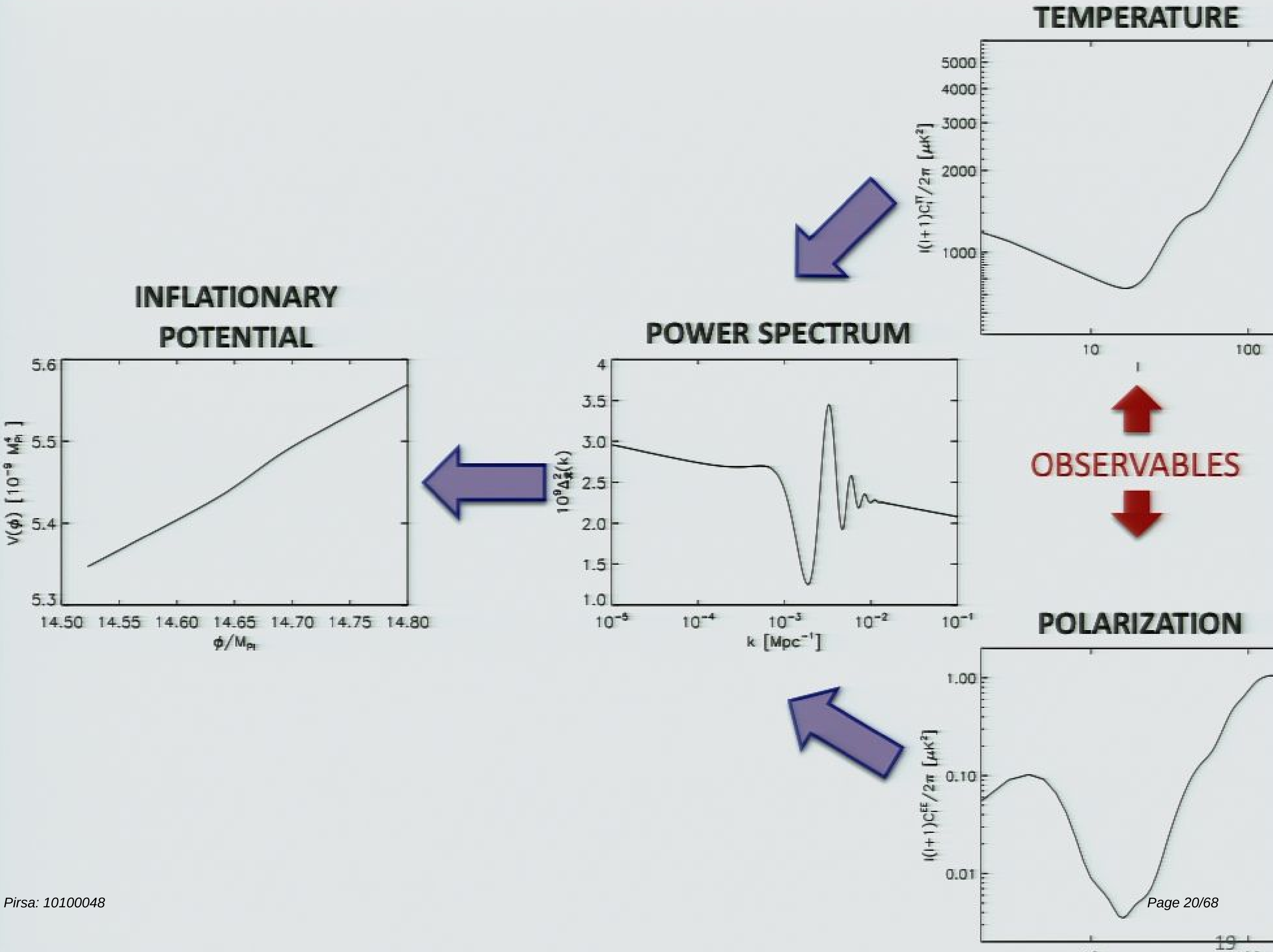


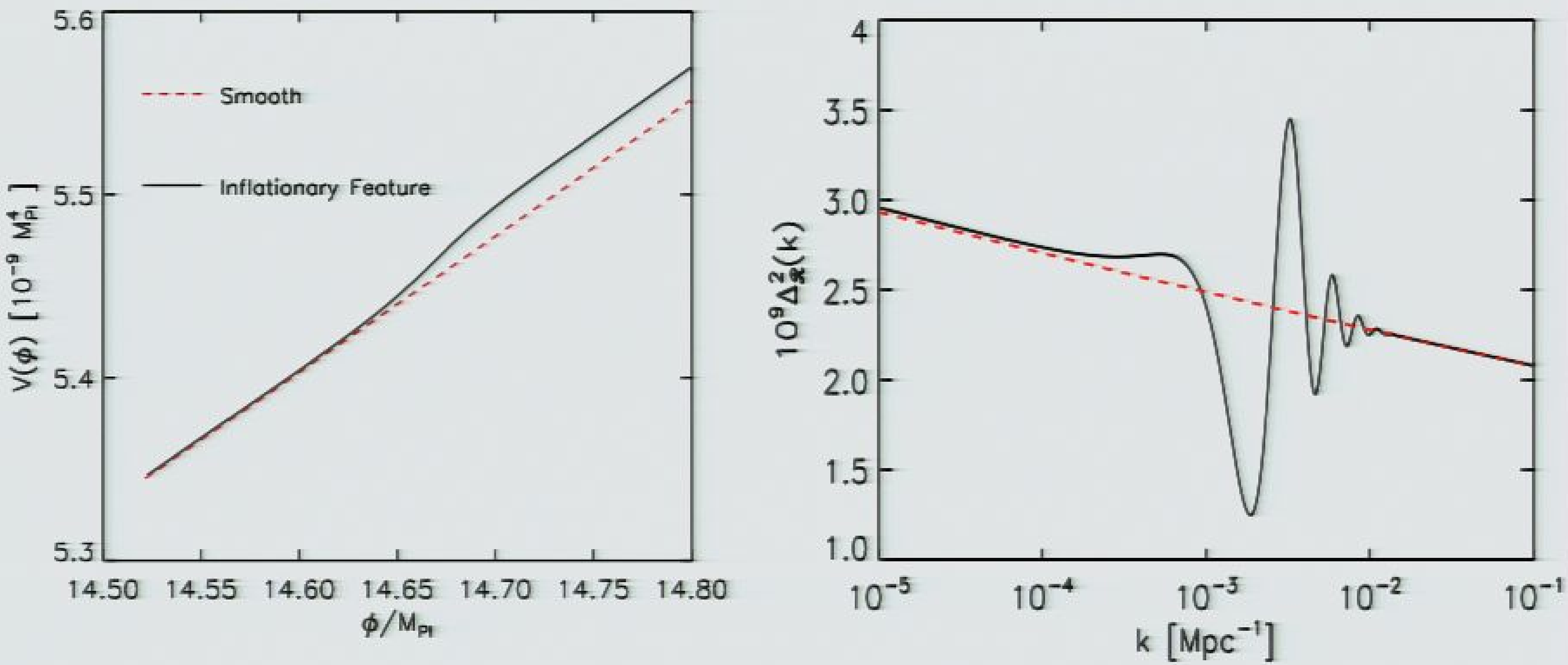
POLARIZATION



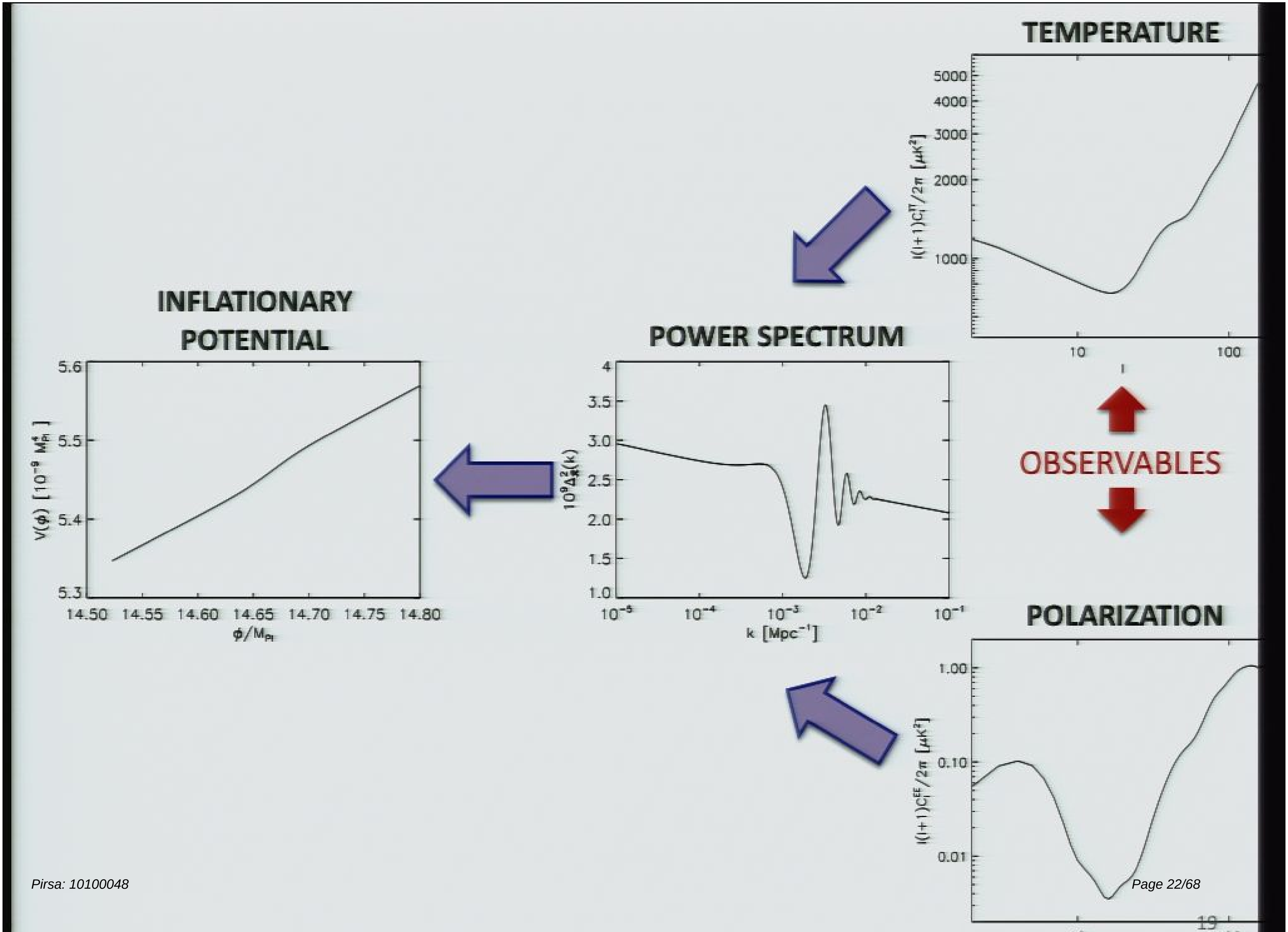

TEMPERATURE
INFLATIONARY POTENTIAL
POWER SPECTRUM
OBSERVABLES
POLARIZATION
V(φ) [10⁻⁹ M⁴Pl]
φ/MPl
10⁹Δ²R(k)
k [Mpc⁻¹]
l(l+1)C_l^TT/2π [μK²]
l(l+1)C_l^EE/2π [μK²]
l

Inflationary Features

The rolling of the inflaton across the feature produces ringing in the power spectrum.



M. Mortonson, C. Dvorkin, H.V. Peiris and W. Hu, PRD (2009)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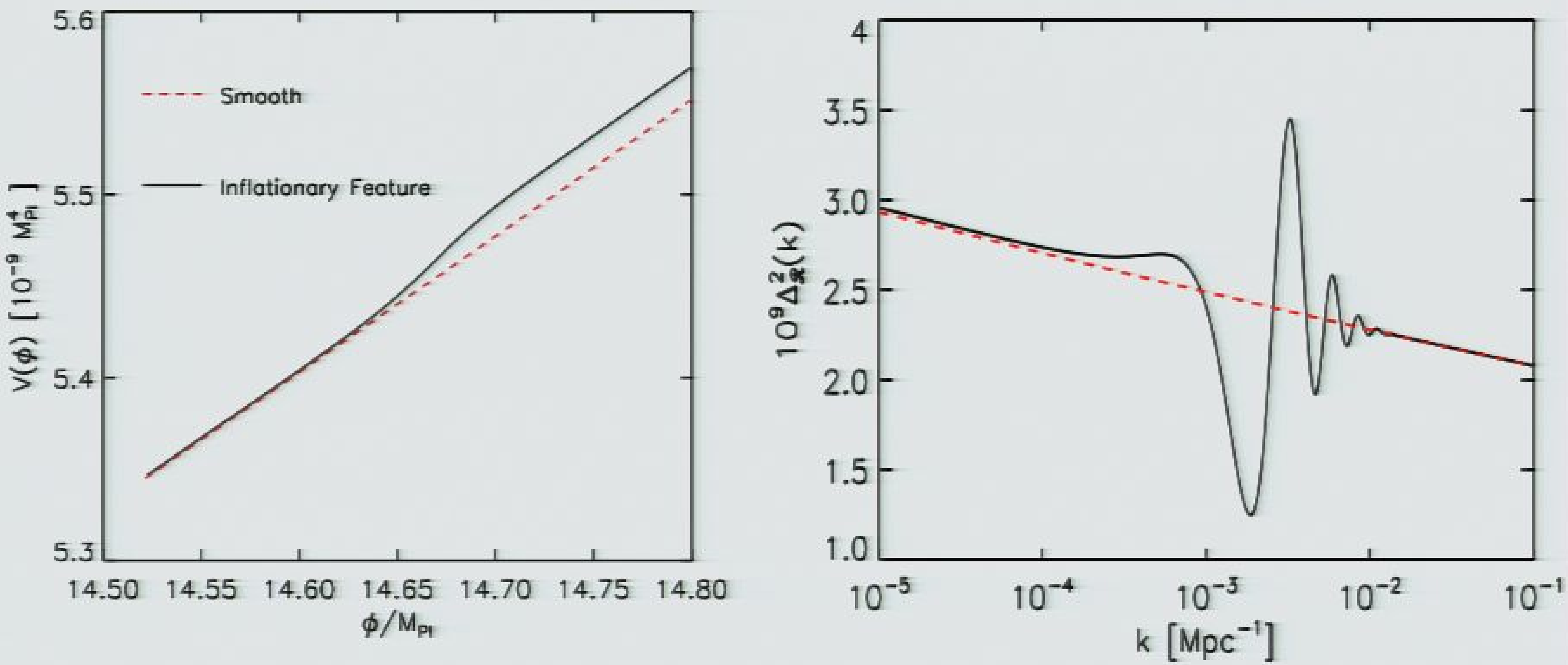

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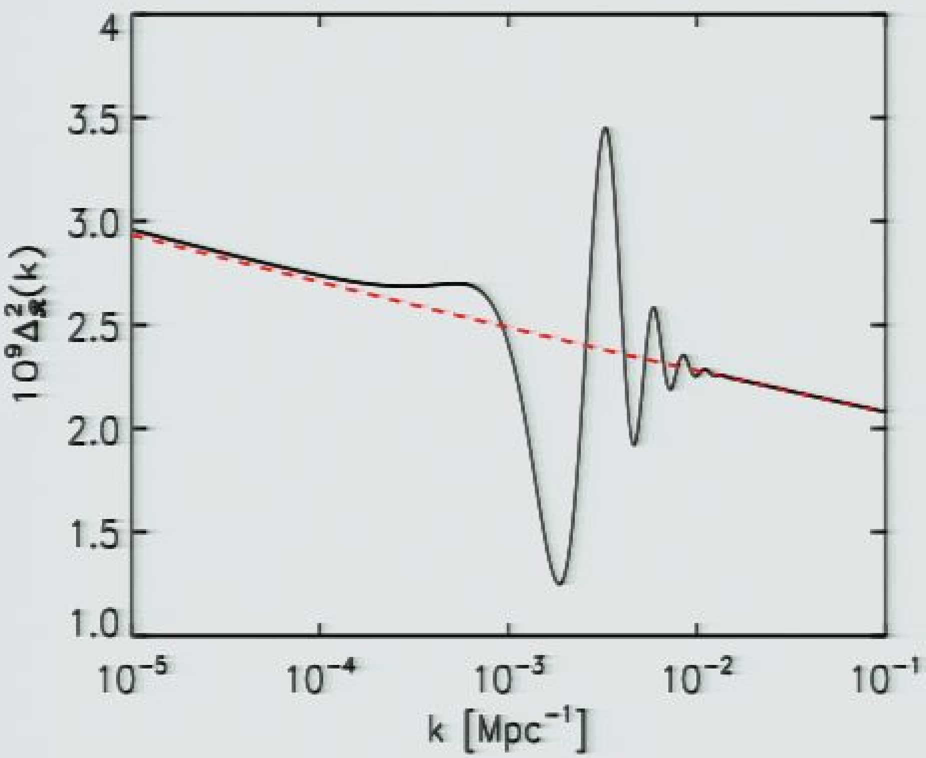
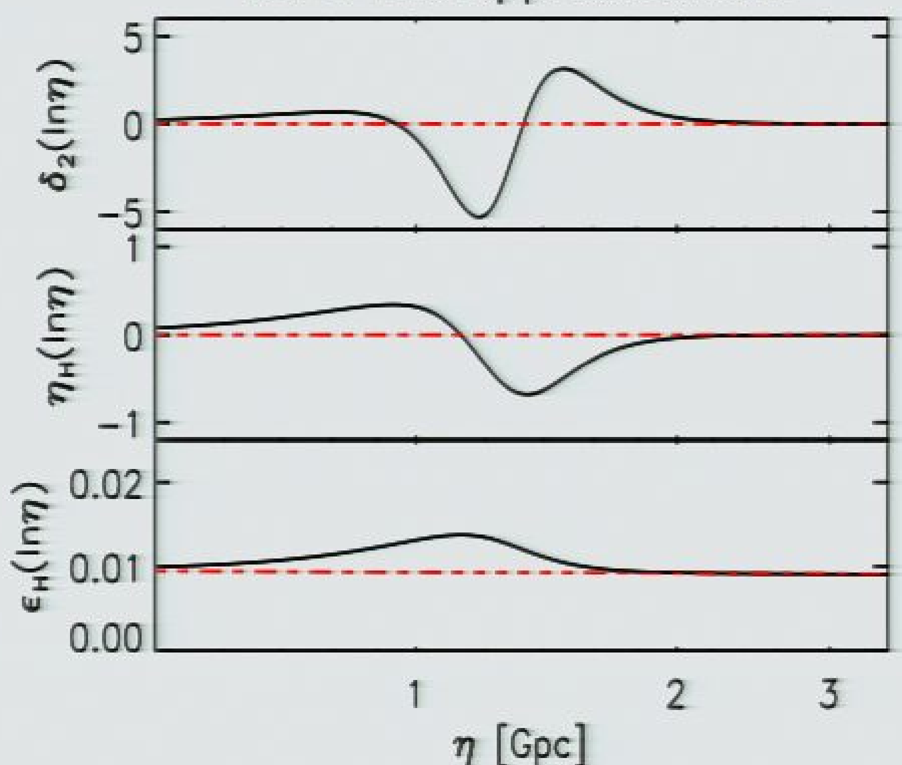
Breaking Slow Roll

- These models require order unity variations in the curvature power spectrum: slow-roll parameters are not necessarily small or slowly varying.

Standard slow roll:
not a valid approximation!





C. Dvorkin, W.Hu, PRD (2009)

Generalized Slow Roll

E. Stewart, PRD (200

- Field equation: $$\frac{d^2 y}{dx^2} + \left(1 - \frac{2}{x^2}\right) y = \frac{g(\ln x)}{x^2} y$$

  $(y = \sqrt{2k}u_k;\ x = k\eta)$

- "Perfect" slow roll: $$\frac{d^2 y_0}{dx^2} + \left(1 - \frac{2}{x^2}\right) y_0 = 0$$

Source function (linear in slow-roll parameters)

- GSR approximation: $$\frac{d^2 y}{dx^2} + \left(1 - \frac{2}{x^2}\right) y = \frac{g(\ln x)}{x^2} y_0$$

Solution can be constructed with a Green function approac

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BUT…

- Nodes in the power spectrum.
- Curvature is not constant for modes outside the horizon. 23

Our GSR solution for large features

- The curvature power spectrum depends on a single source function

$$\ln \Delta^2_{\mathcal{R}}(k) = G(\ln \eta_{\min}) + \int_{\eta_{\min}}^{\eta_{\max}} \frac{d\eta}{\eta} W(k\eta) G'(\ln \eta)$$
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- Source function on deviations from scale-invariance:

$$G' = \frac{2}{3} \left[\frac{f''}{f} - 3\frac{f'}{f} - \left(\frac{f'}{f} \right)^2 \right] \quad \text{with} \quad f = 2\pi\eta \frac{\dot{\phi}}{H}$$

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✓ Constant curvature for modes outside the horizon.
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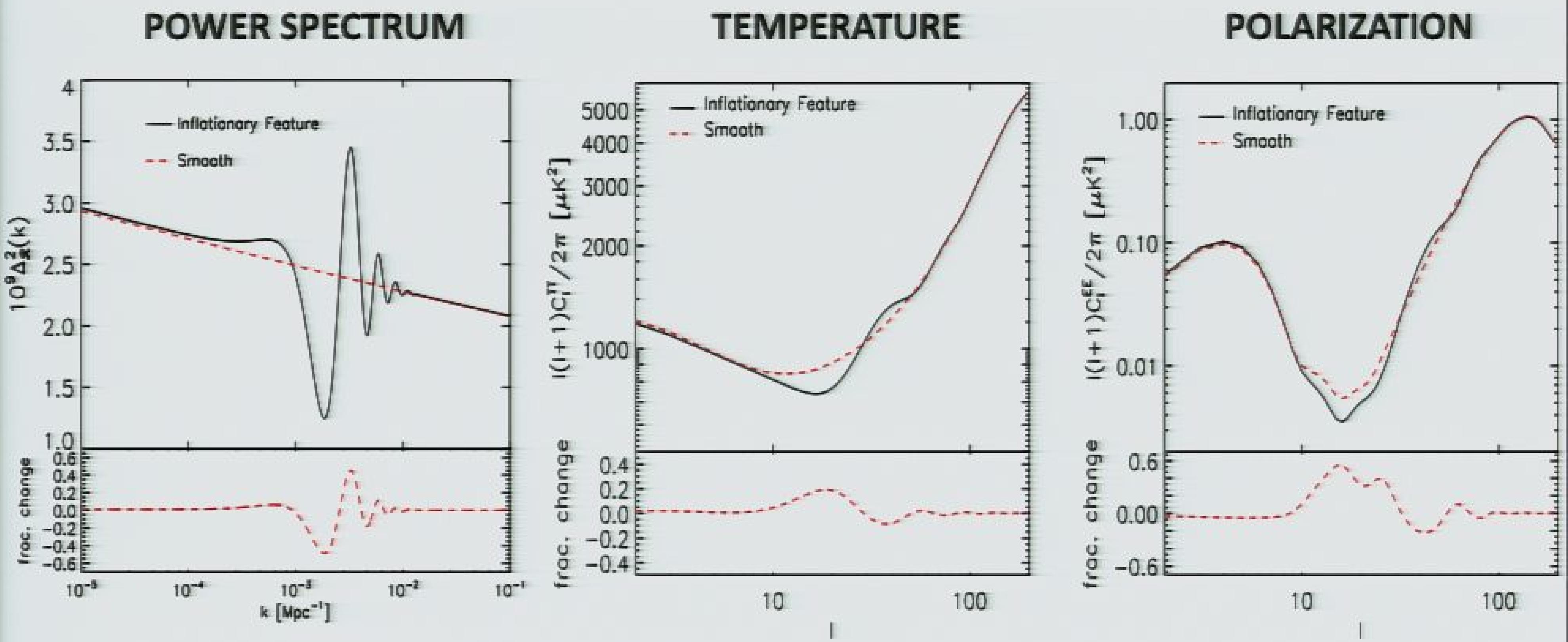
✓ Well controlled for time varying and order unity slow-roll parameters: percent level errors.
✓ Simple to relate to the inflaton potential: $G' \approx 3\left(\frac{V_{,\phi}}{V}\right)^2 - 2\left(\frac{V_{,\phi\phi}}{V}\right)$

Second order Generalized Slow Roll: Well controlled



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\begin{aligned}
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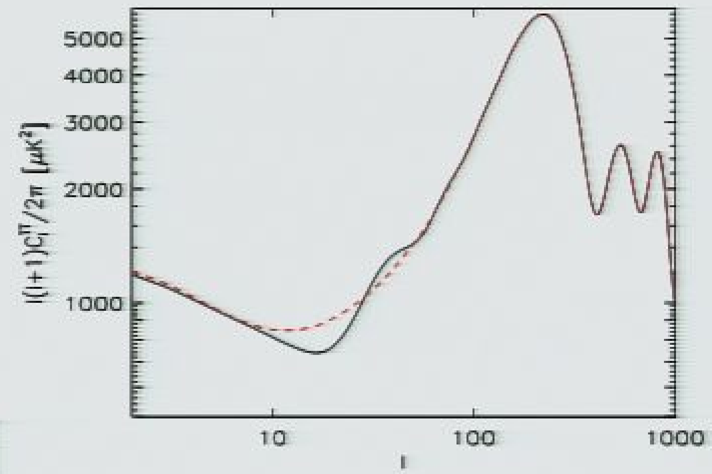
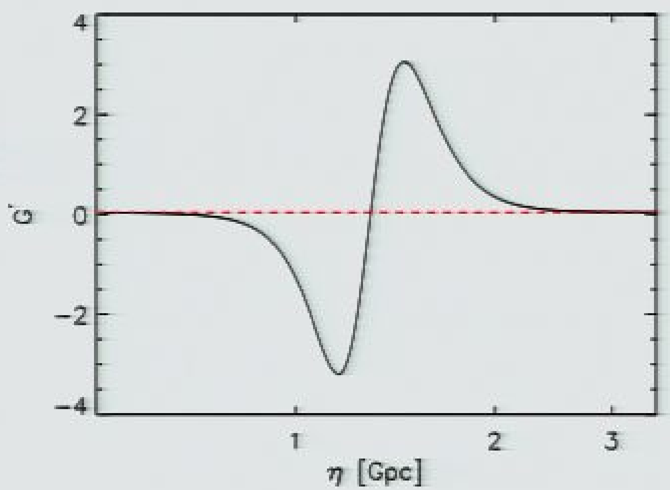
We can map observational constraints from the CMB onto constraints on the source…

- Power spectrum



- Source



…and use these empirical constraints to test any model of single-field inflation.

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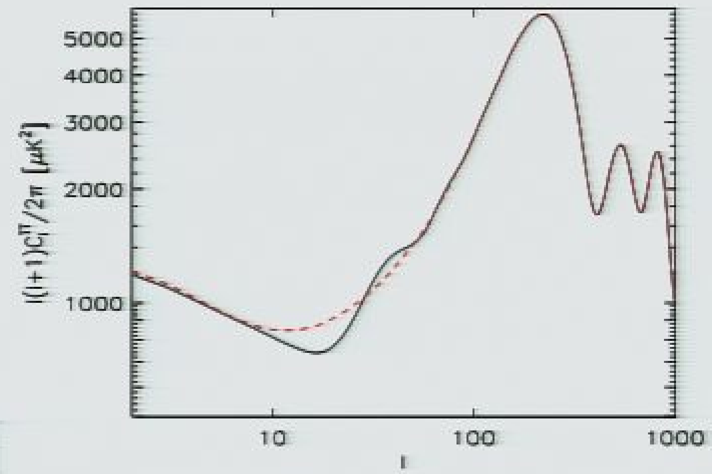

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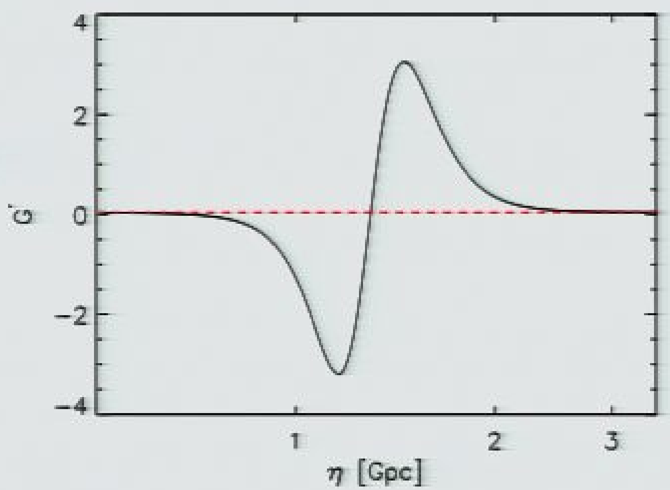
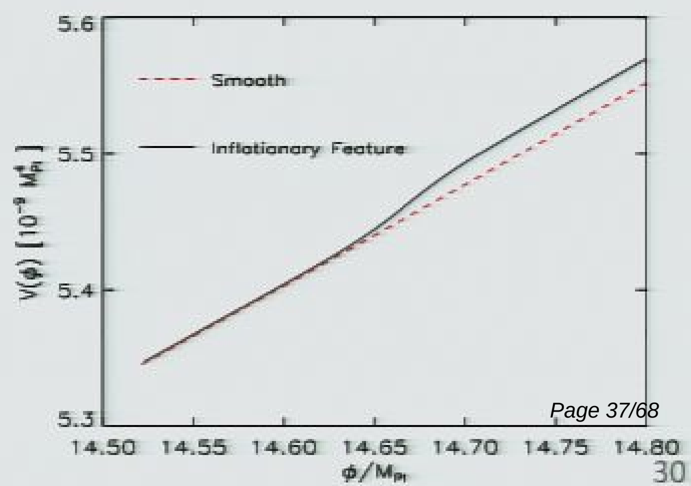


- Inflationary Model



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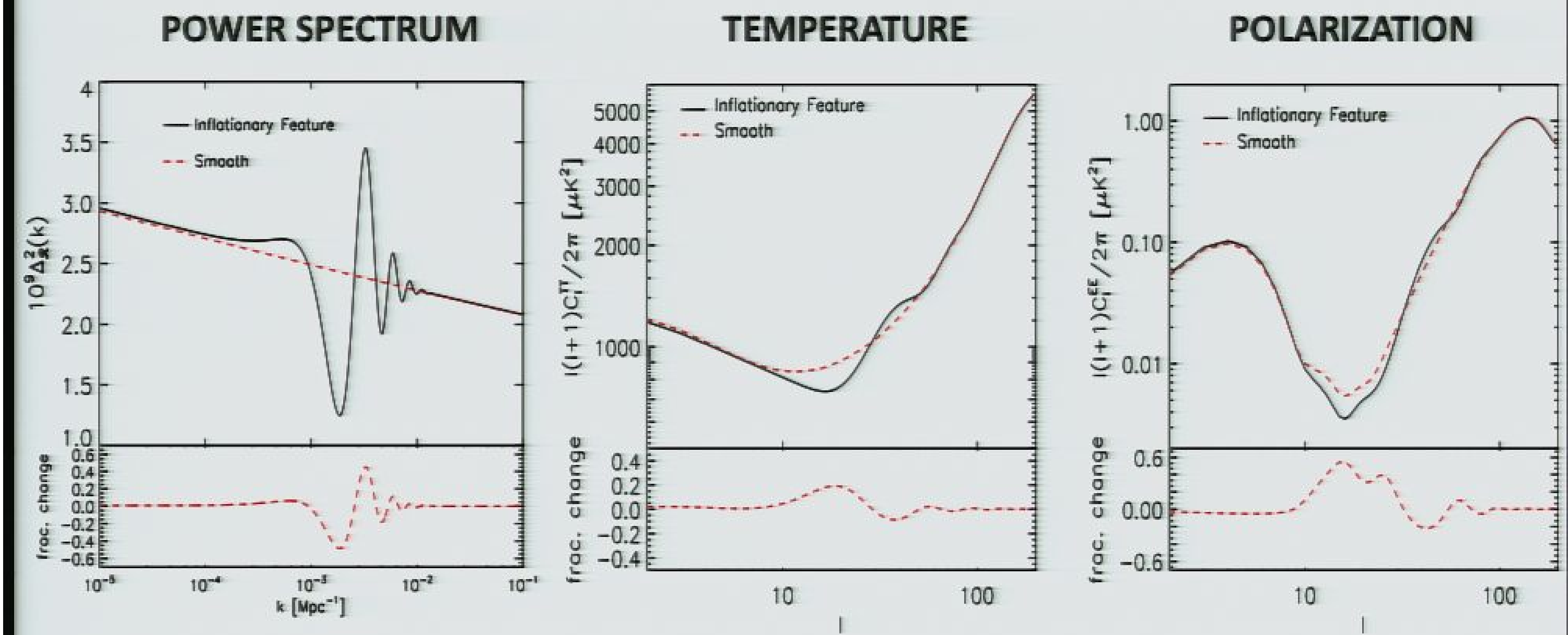
✓ Constant curvature for modes outside the horizon.

✓ We recover the slow-roll result for a constant source.

✓ Well controlled for time varying and order unity slow-roll parameters: percent level errors.

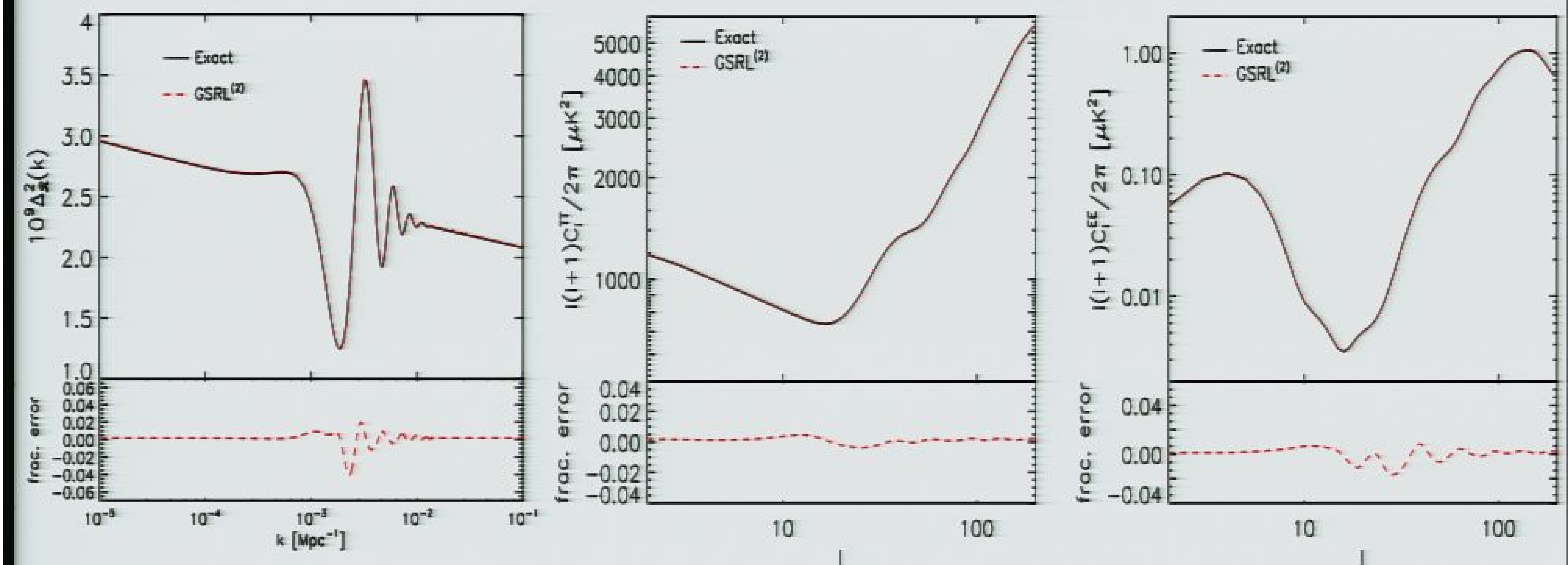
✓ Simple to relate to the inflaton potential: $G' \approx 3\left(\frac{V_{,\phi}}{V}\right)^2 - 2\left(\frac{V_{,\phi\phi}}{V}\right)$

Second order Generalized Slow Roll: Well controlled



Second order Generalized Slow Roll: Well controlled

POWER SPECTRUM **TEMPERATURE** **POLARIZATION**



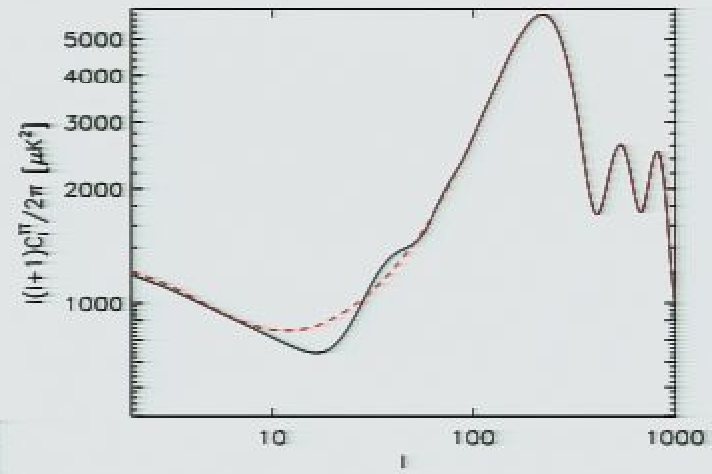
C. Dvorkin, W. Hu, PRD (2009)

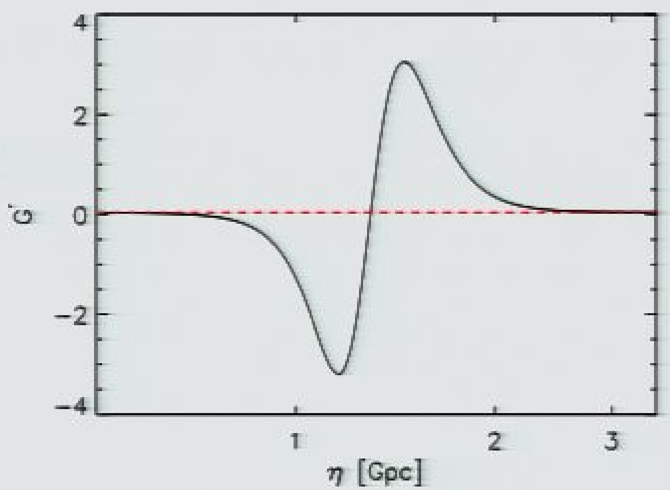
Accurate at <1% level for order unity features!

We can map observational constraints from the CMB onto constraints on the source…

- Power spectrum

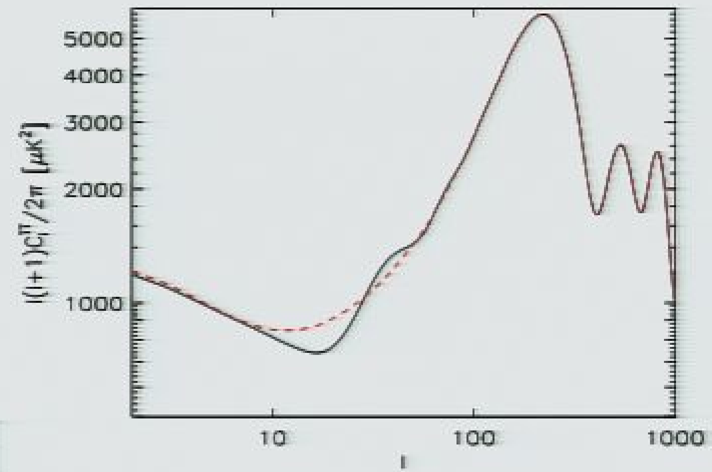
- Source





...and use these empirical constraints to test any model of single-field inflation.

- Power spectrum



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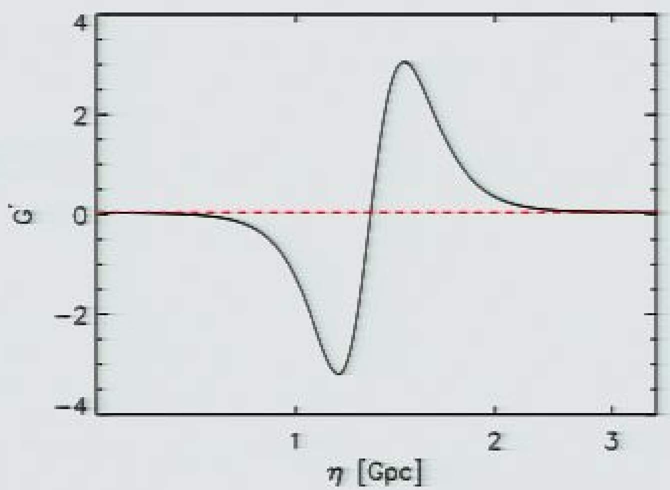
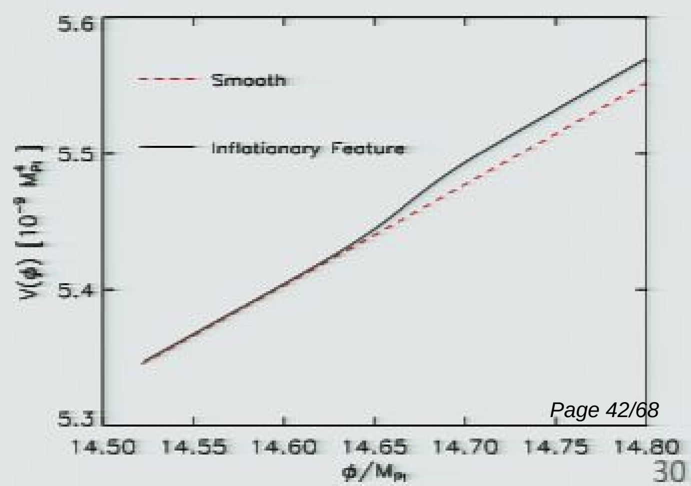


- Inflationary Model



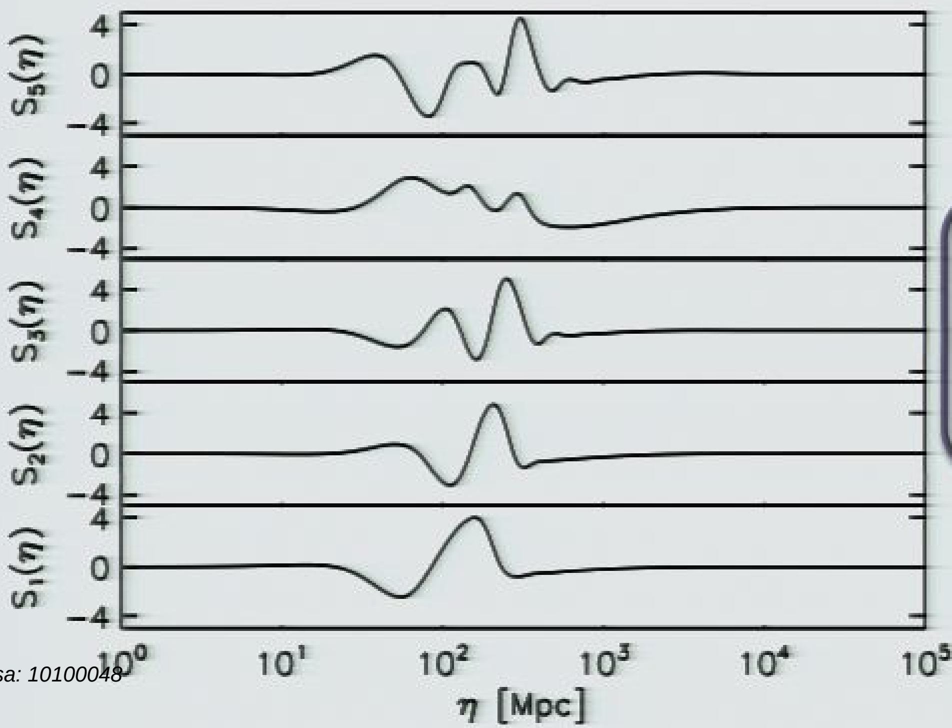
Outline

- CMB and Inflation overview.
- General method to constrain the inflationary potential from CMB observations allowing for features.
  - Theoretical framework.
  - Analysis of data.
- Conclusions and future directions.

Model-independent constraints

Principal components *(of covariance matrix of perturbations in the source)*: basis for a complete representation of observable properties of the source function.

$$G' = 1 - n_s + \sum_{a=1}^{N} m_a S_a(\ln \eta)$$



C. Dvorkin and W. Hu, PRD (2010)

Defined a priori from covariance matrix: avoids *a posteriori* bias whe[n] looking at the data.

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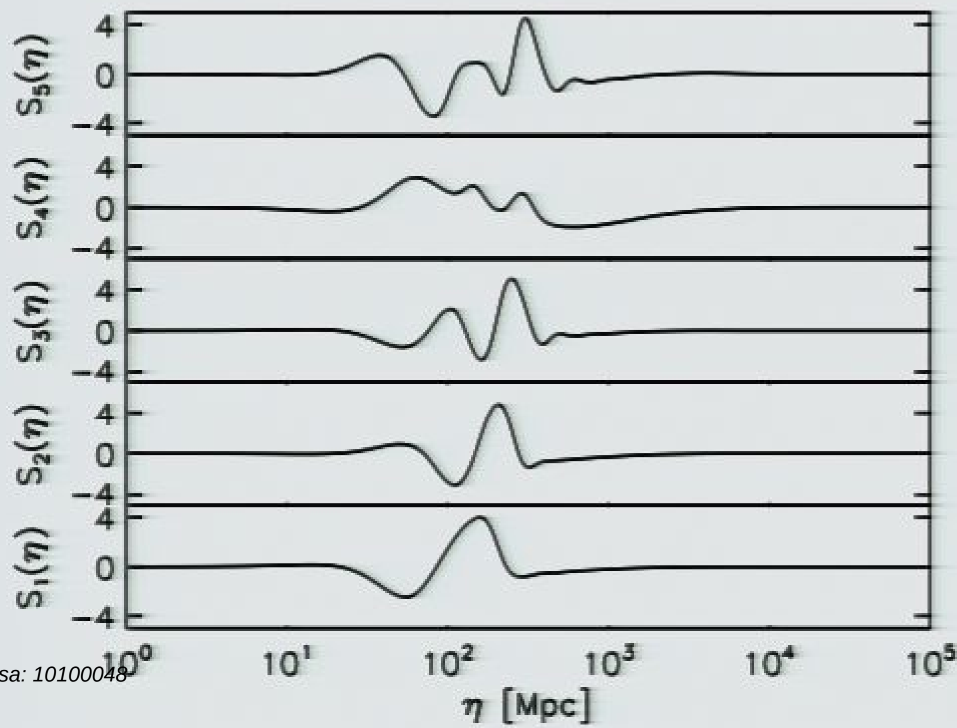

- **Ranked in order of observability.**
- **Keep 5 best measured modes.**

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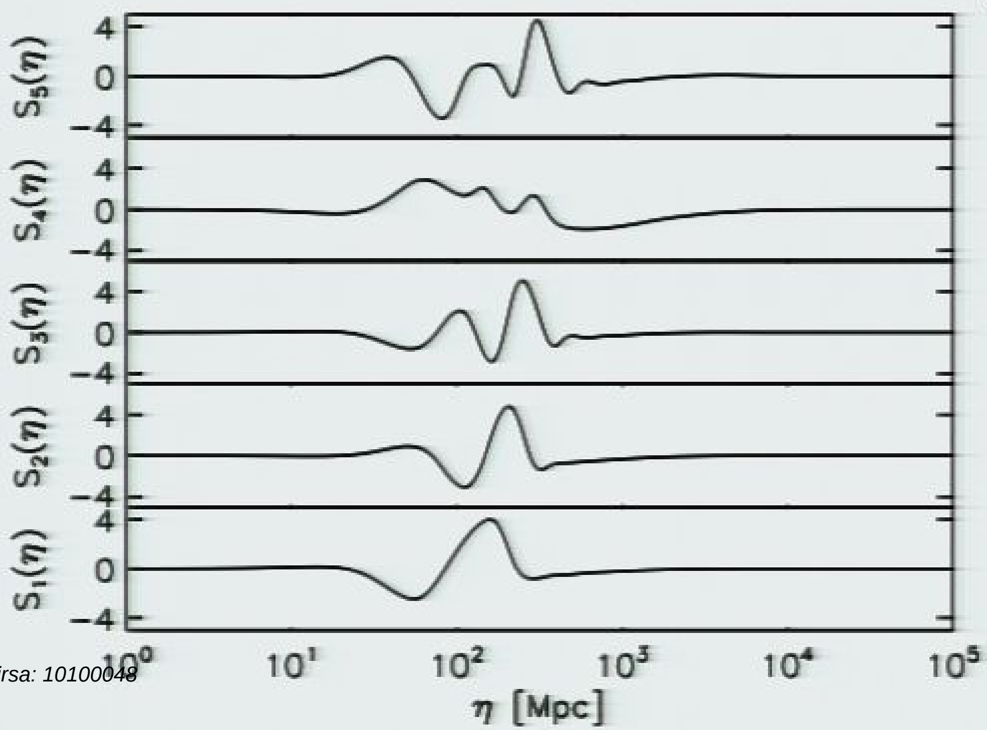

C. Dvorkin and W. Hu, PRD (2010)

- **Ranked in order of observability.**
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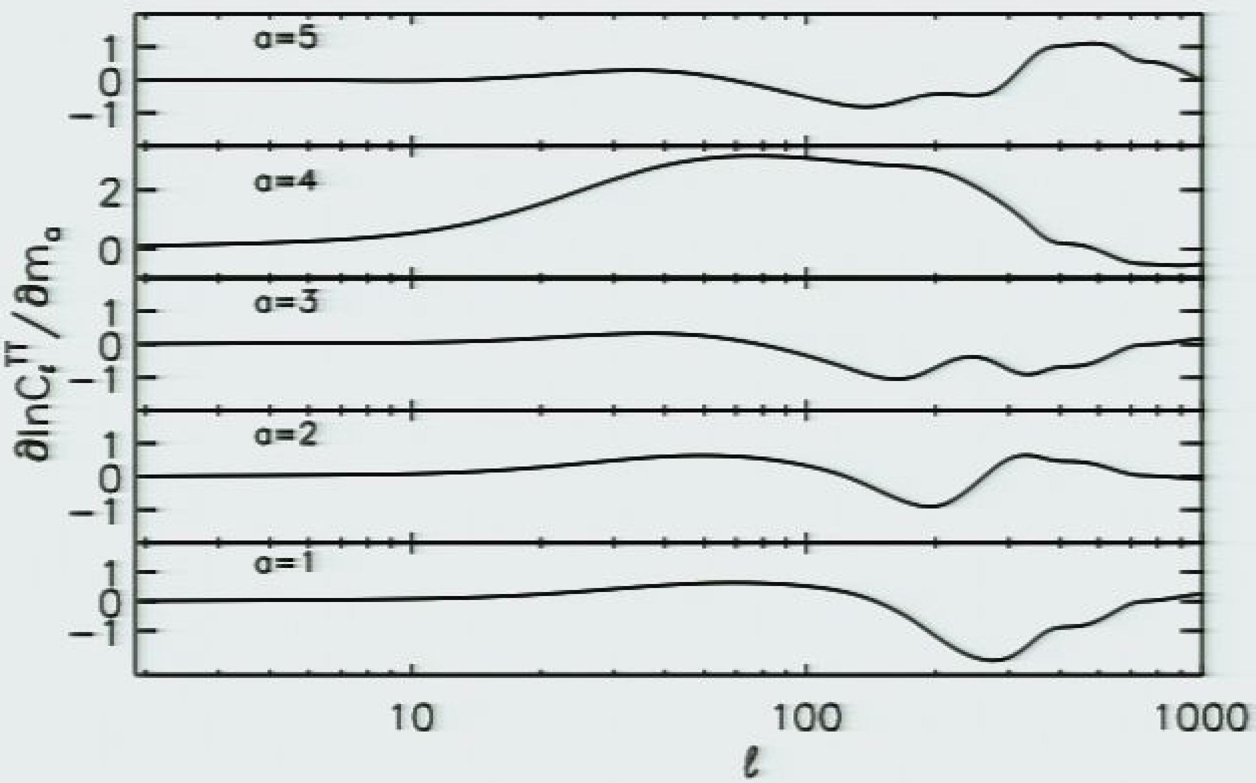
Lower order PC's in WMAP

- Have their weight in the region best measured by the data (angular scales around the first acoustic peak, l$\approx$200).



C. Dvorkin, W. Hu, PRD (2010)

Implementing GSR to the data

GSR allows efficient computation: $\Delta^2_{\mathcal{R}} = F(A_s, n_s, m_1, ..., m_N)$

- COSMOMC "Fast parameters": do not require computation of the CMB radiation transfer function.

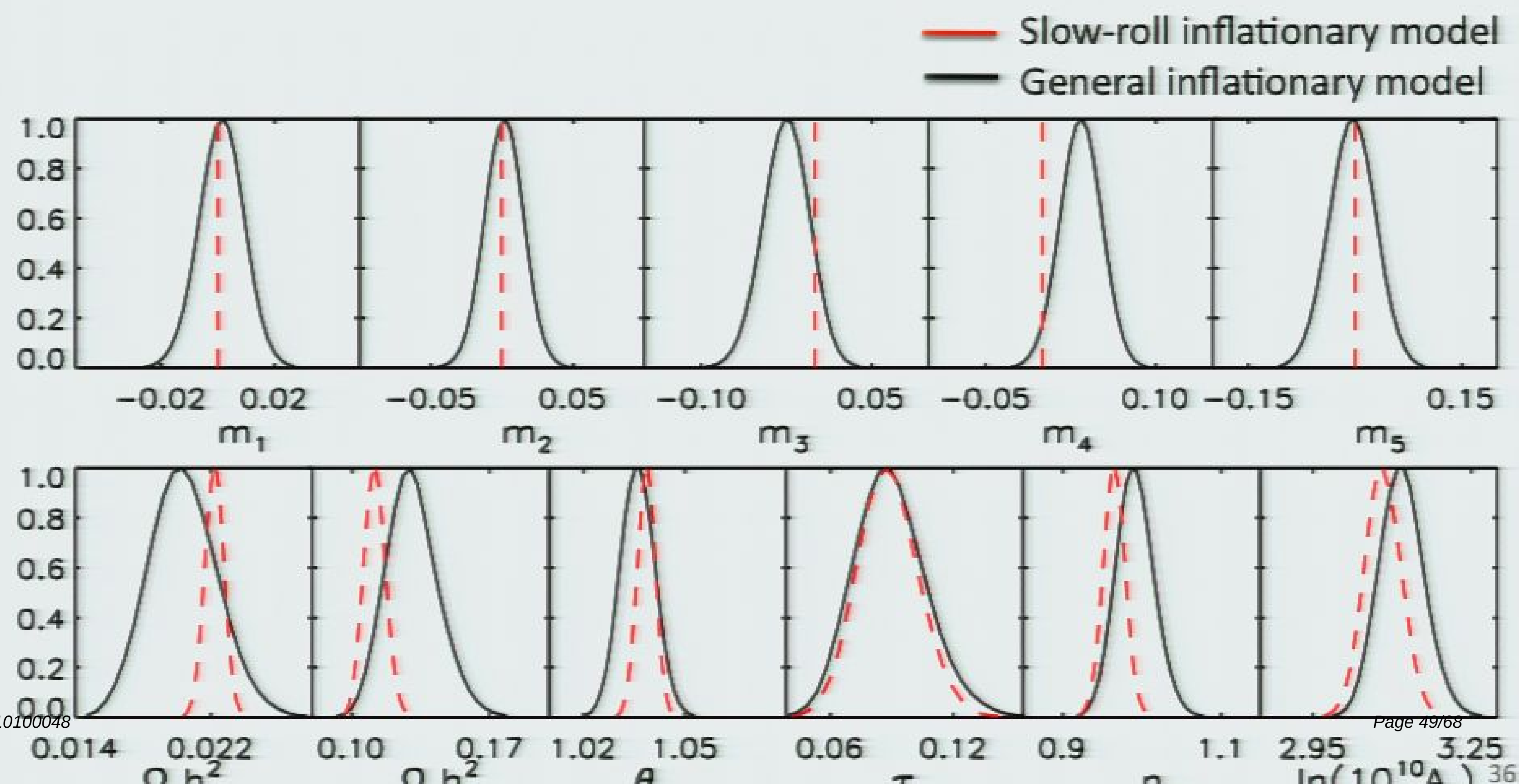
➡ Main bottleneck in the likelihood code:

- OMP parallelized **WMAP likelihood code** and improved its speed by ~ **5*Ncore**

Publicly available: http://background.uchicago.edu/wmap_fast/

WMAP7 constraints from MCMC's

- Non-zero values represent deviations from slow-roll and power-law spectrum.
- 1 out of 5 shows a 95% CL preference for a non-zero value, but only with a high cold dark matter density (which is disfavored by current SN and H0 data).



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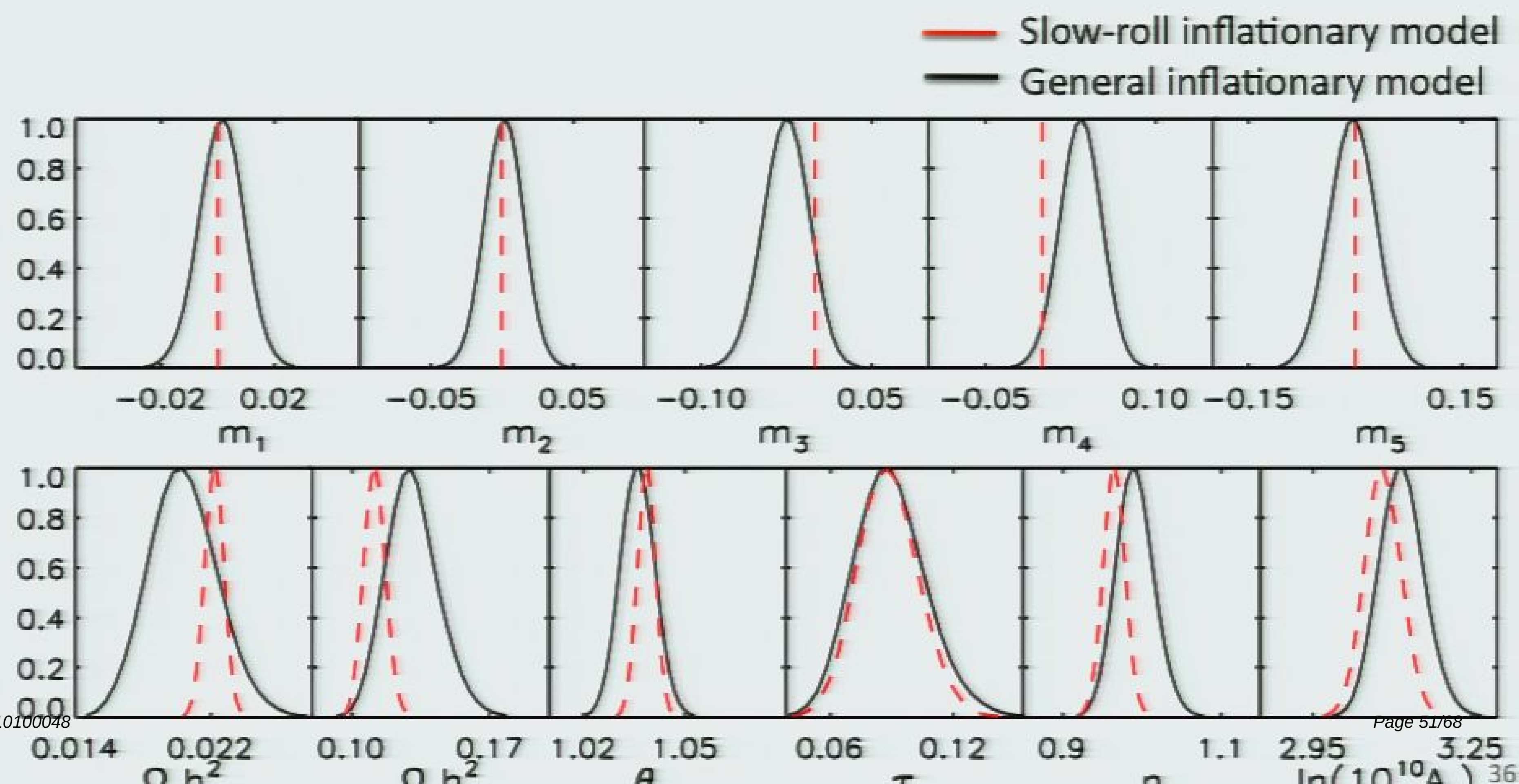
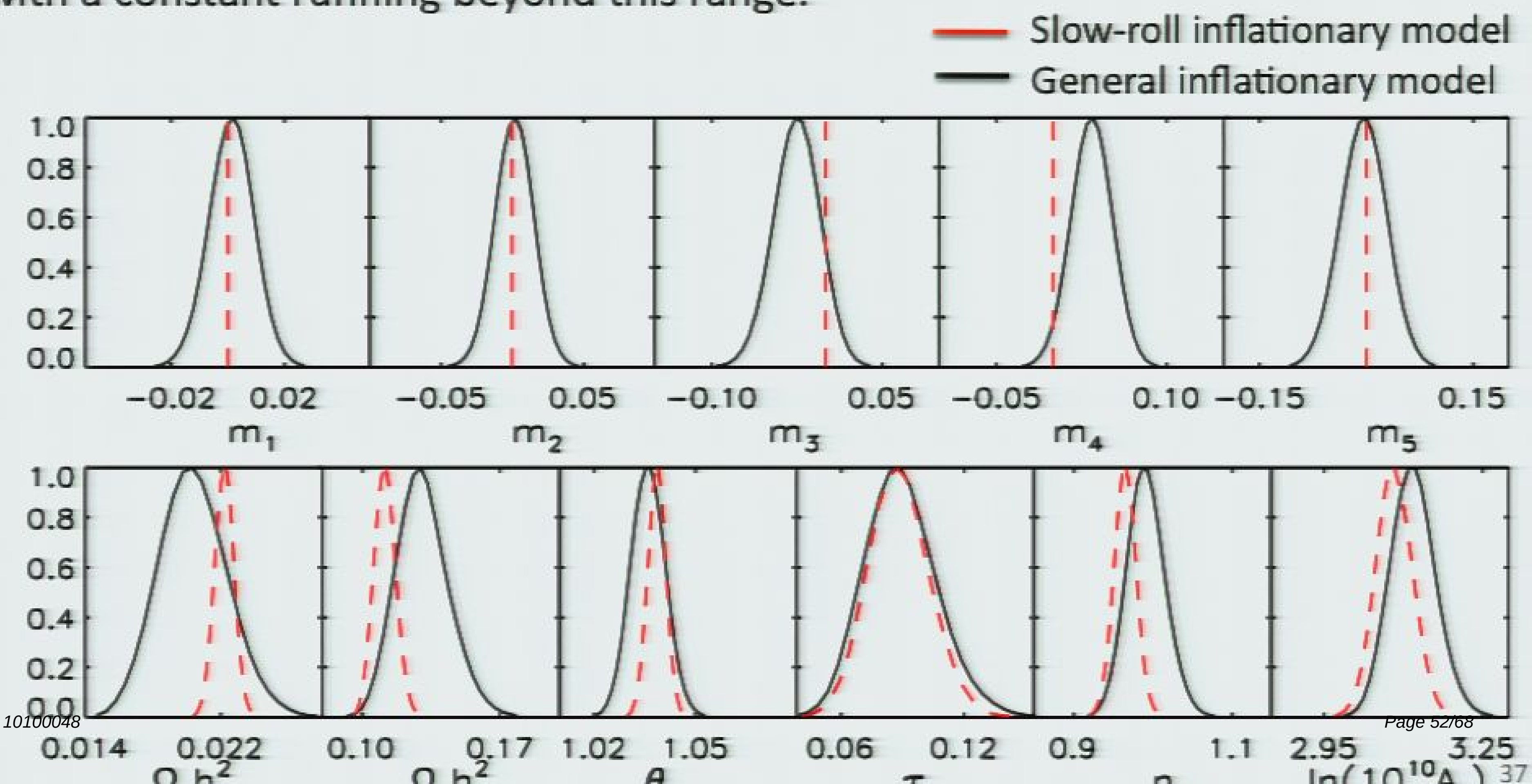


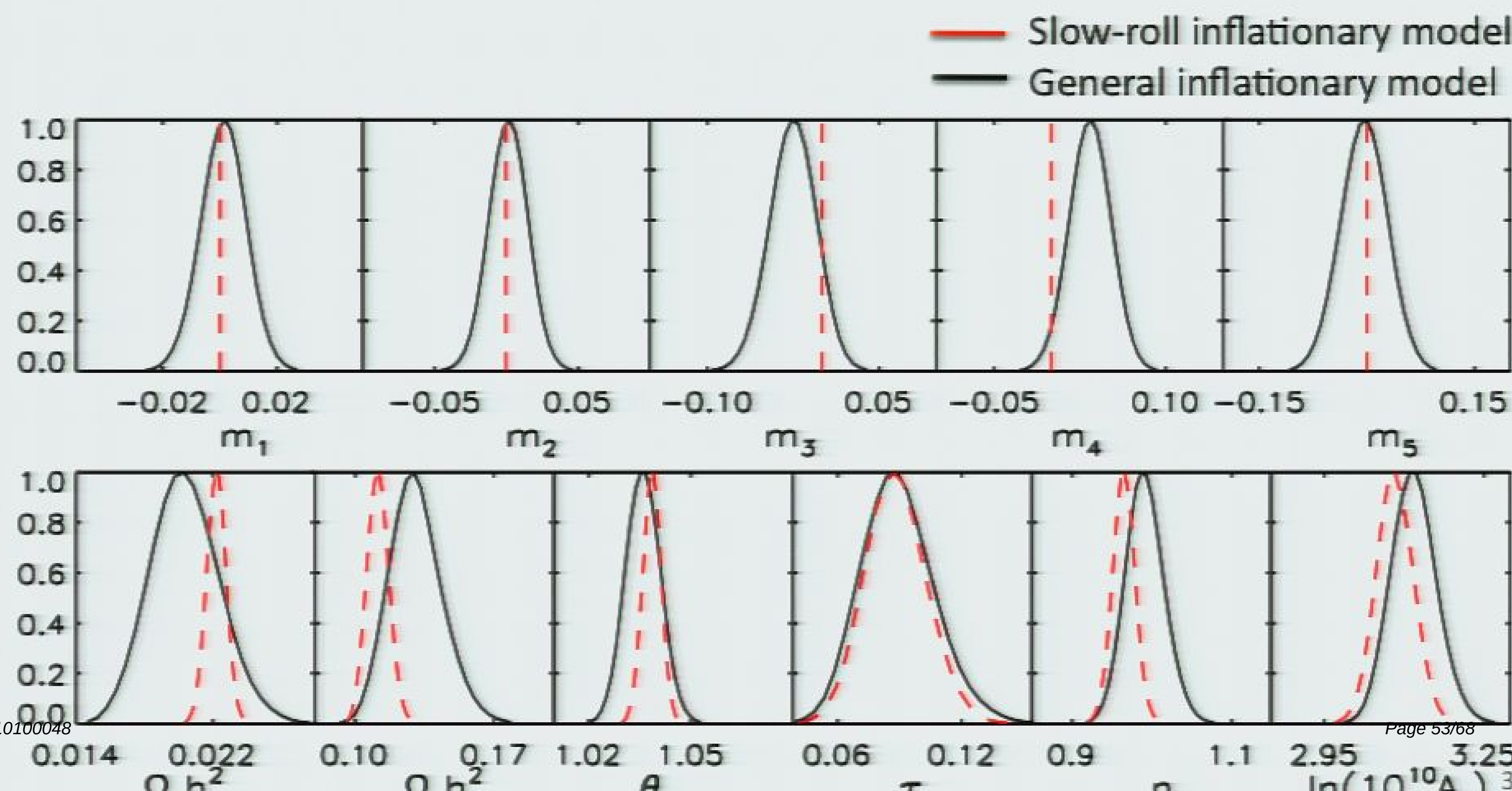
WMAP7 constraints from MCMC's

- Interestingly, the 4th component carries most of the information about running of the tilt.
- It resembles a local running of the tilt for l~30-800, but it is marginally consistent with a constant running beyond this range.



WMAP7 constraints from MCMC's

- Consistency with a smooth inflationary potential: $\Delta\chi^2 \approx 5$ (with 5 additional parameters); robust to inclusion of tensor modes, spatial curvature and SZ emissio



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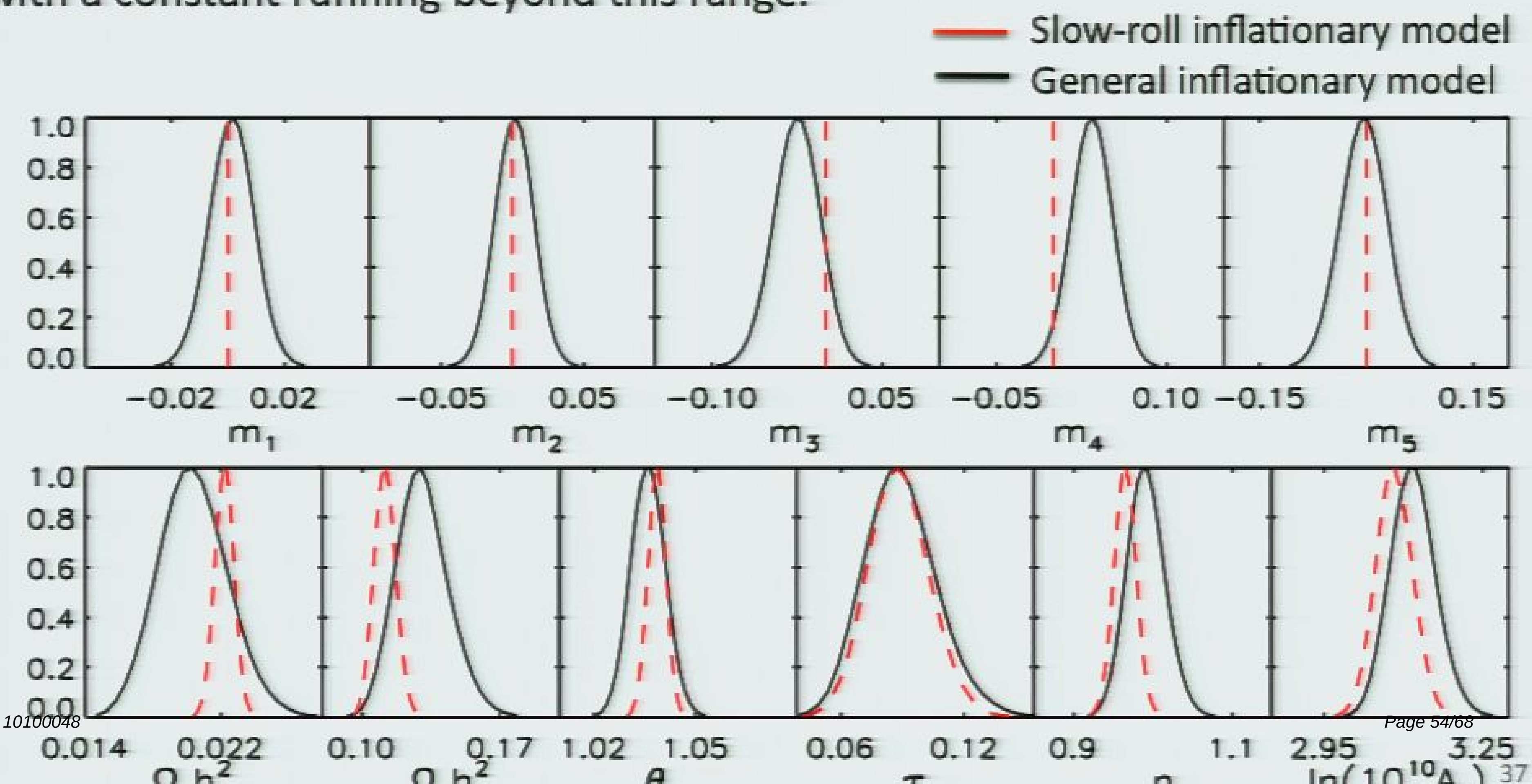

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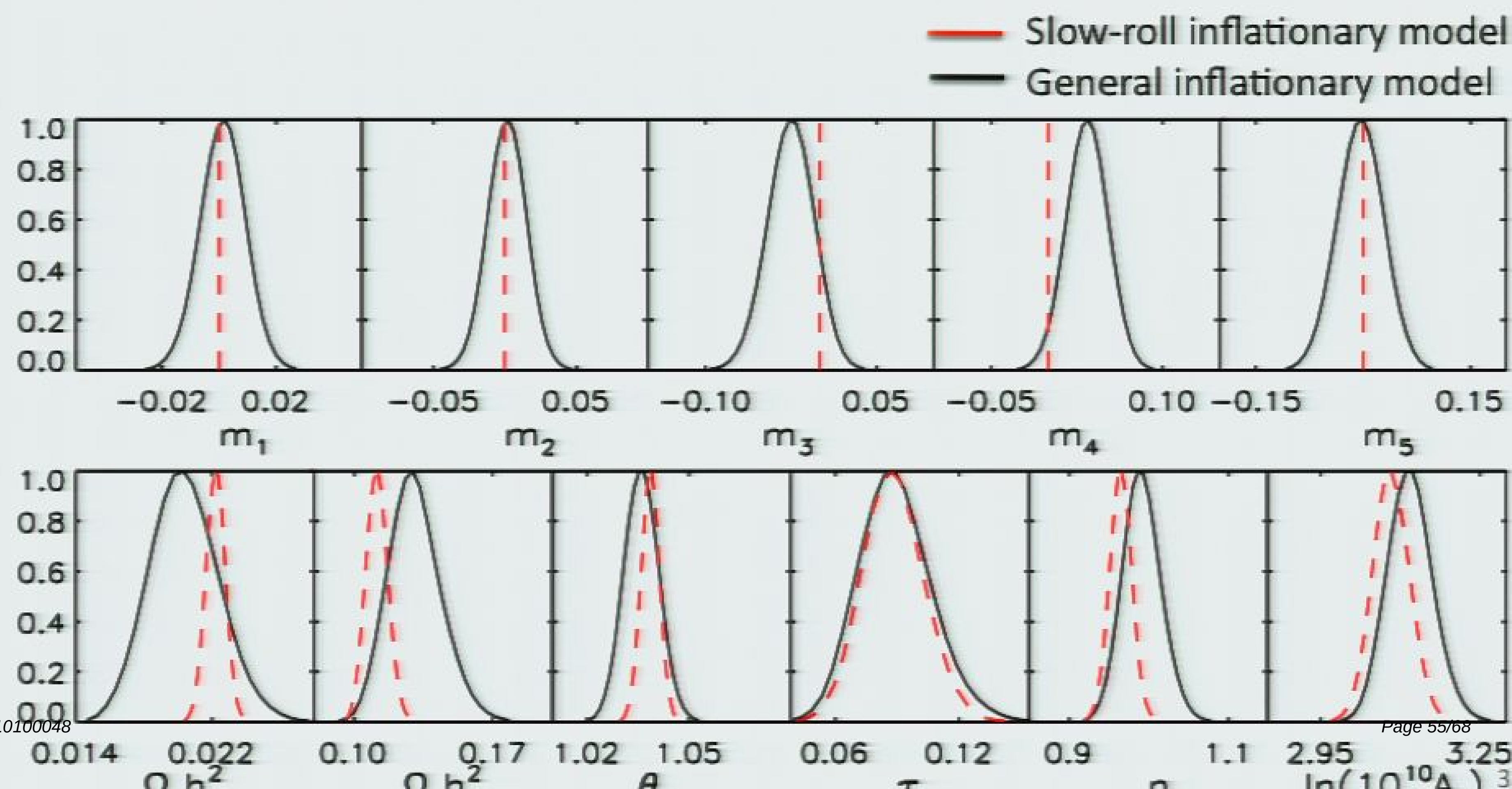
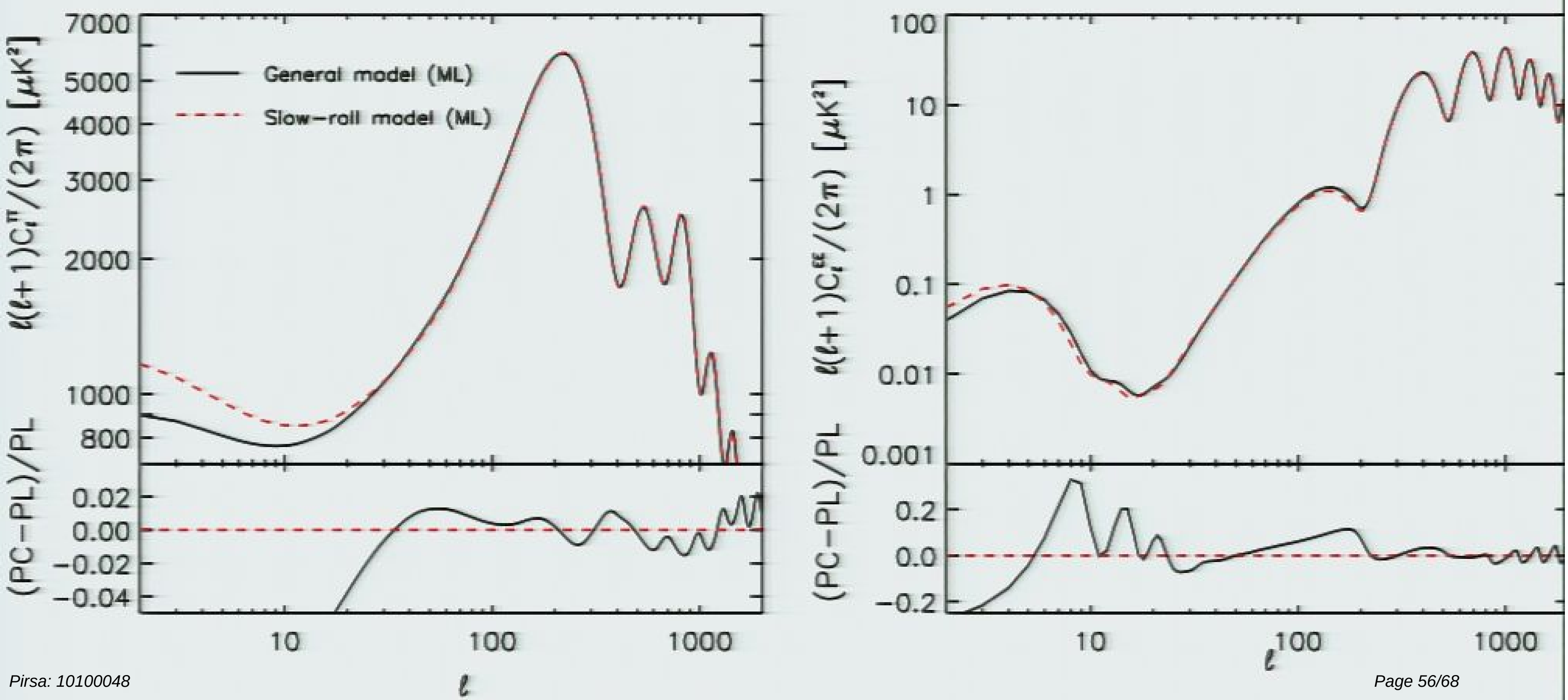


Future data: better constraints!

- Small-scale temperature measurements at l>1000 and future polarization data at better than 10% at l>100 (Planck) will improve inflationary constraint

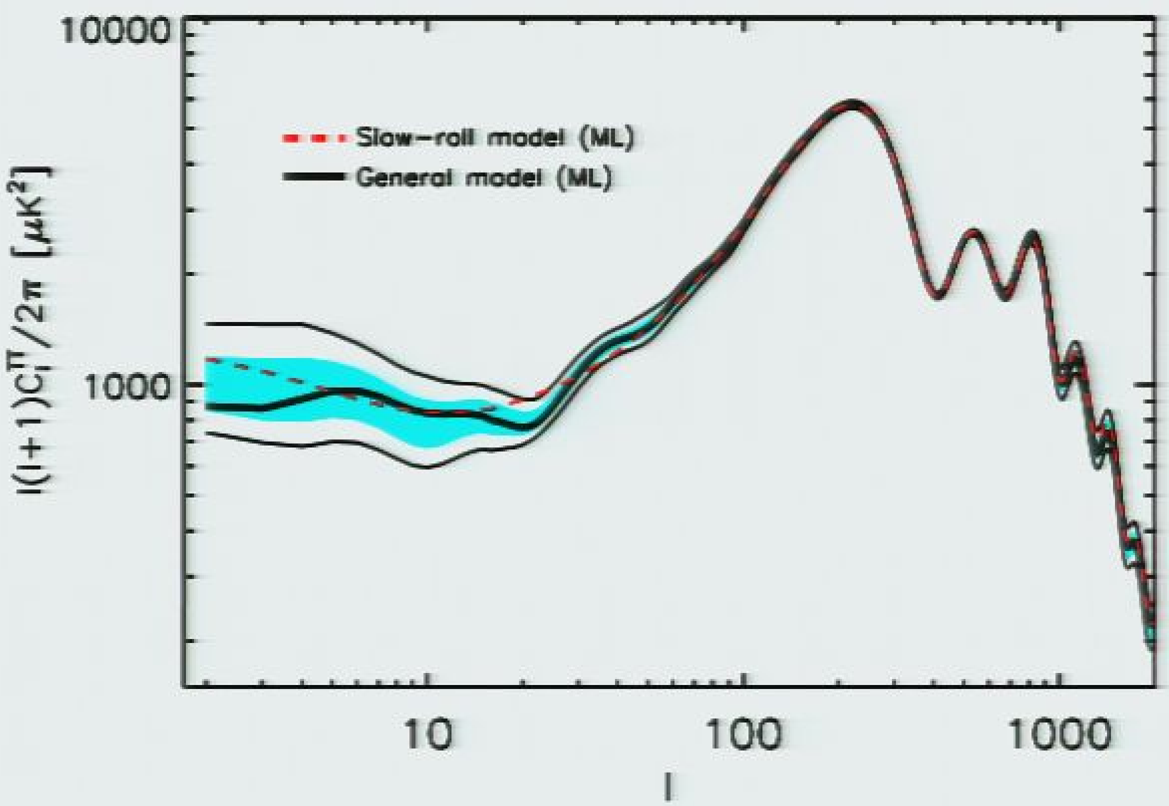


C. Dvorkin, W. Hu, PRD (2009)

Work in progress

Constraining the entire observable range of scales

- A complete basis of 20 PCs is required to account for large features in poorly constrained regions of the data.

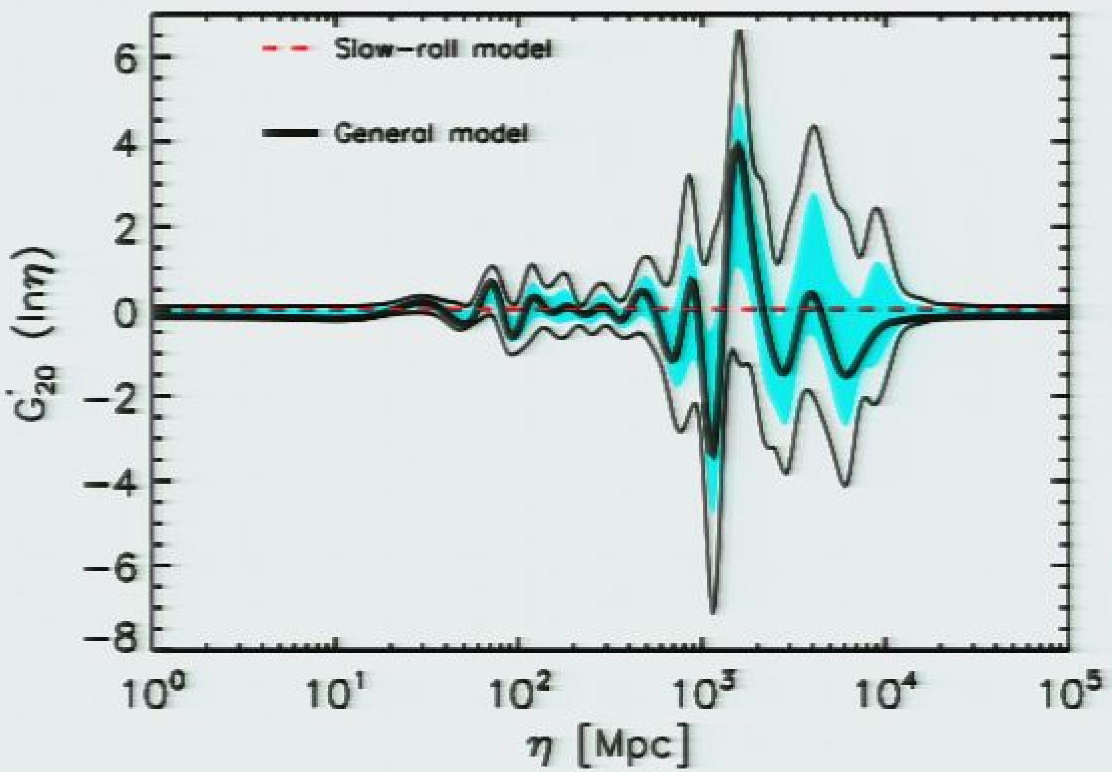


WMAP7 + BICEP + QUAD data; SN + H0 + BBN constraints.

C. Dvorkin and W. Hu, in preparation

Observational constraints on the source function

- Inflationary models outside these bounds are in tension with the data.



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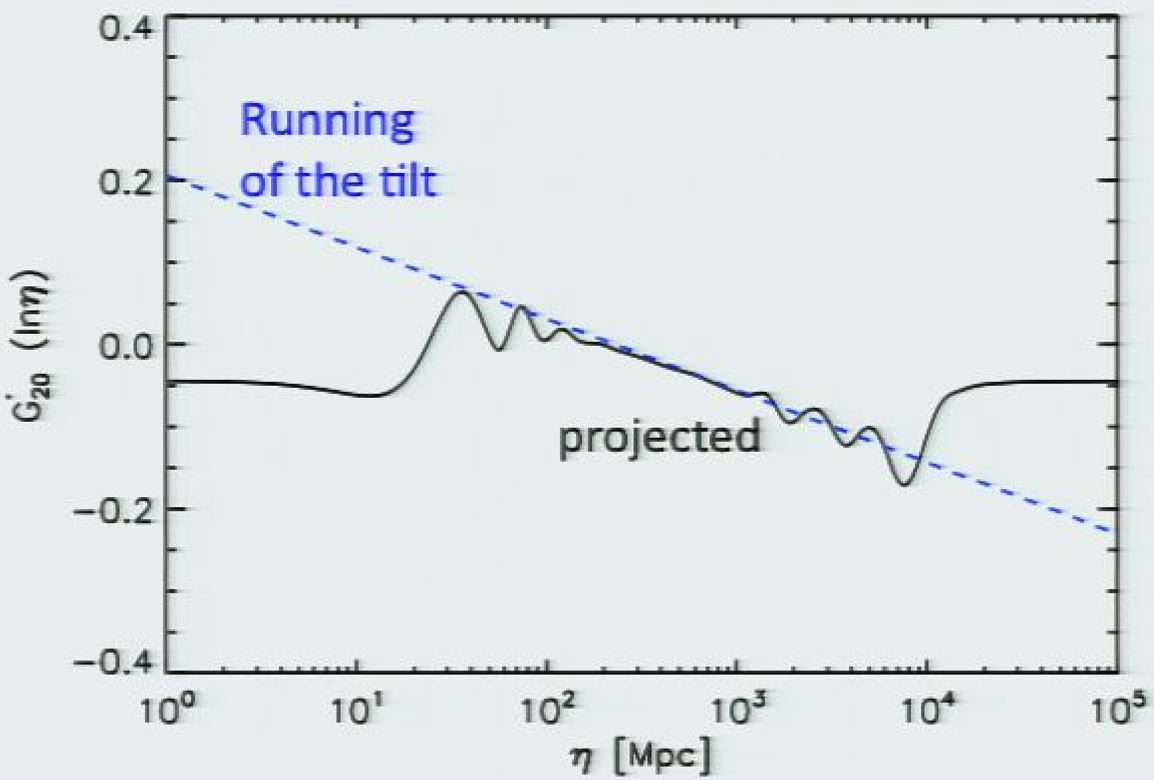
Testing models of inflation

In practice, one can project any inflationary model onto the PC basis, and assess its significance using our posteriors.



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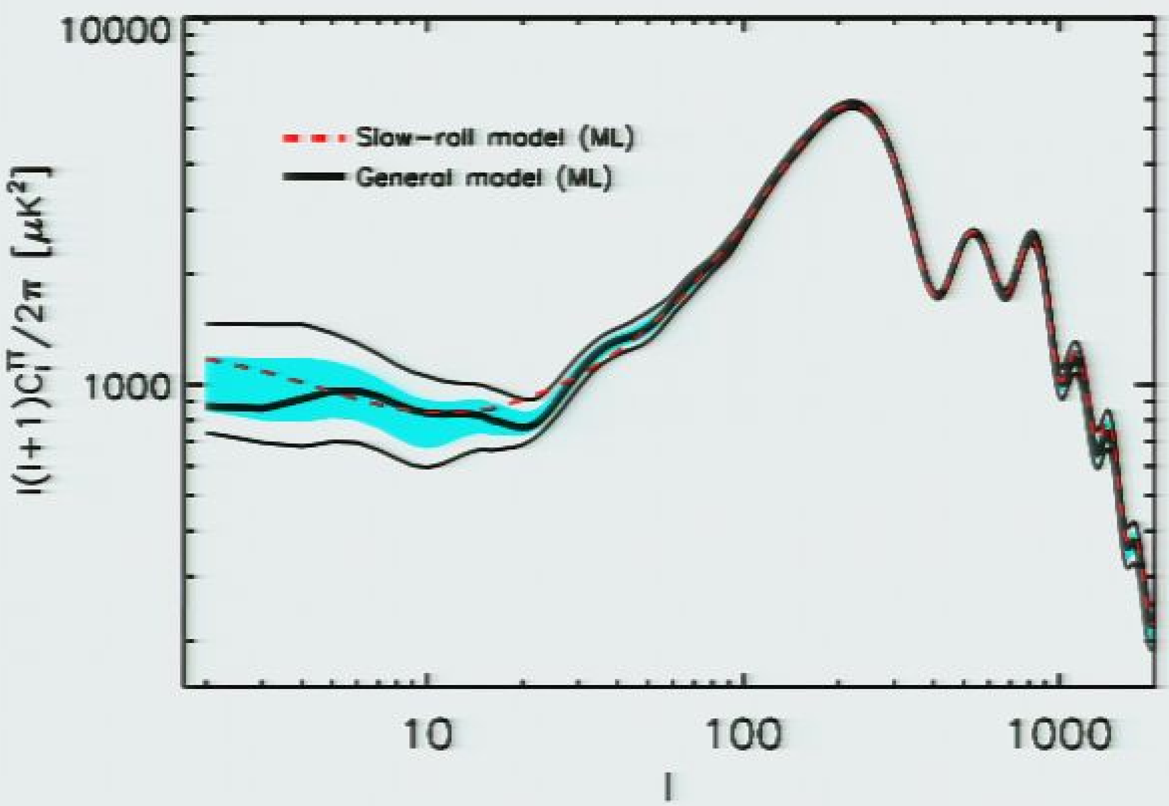

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C. Dvorkin and W. Hu, in preparation

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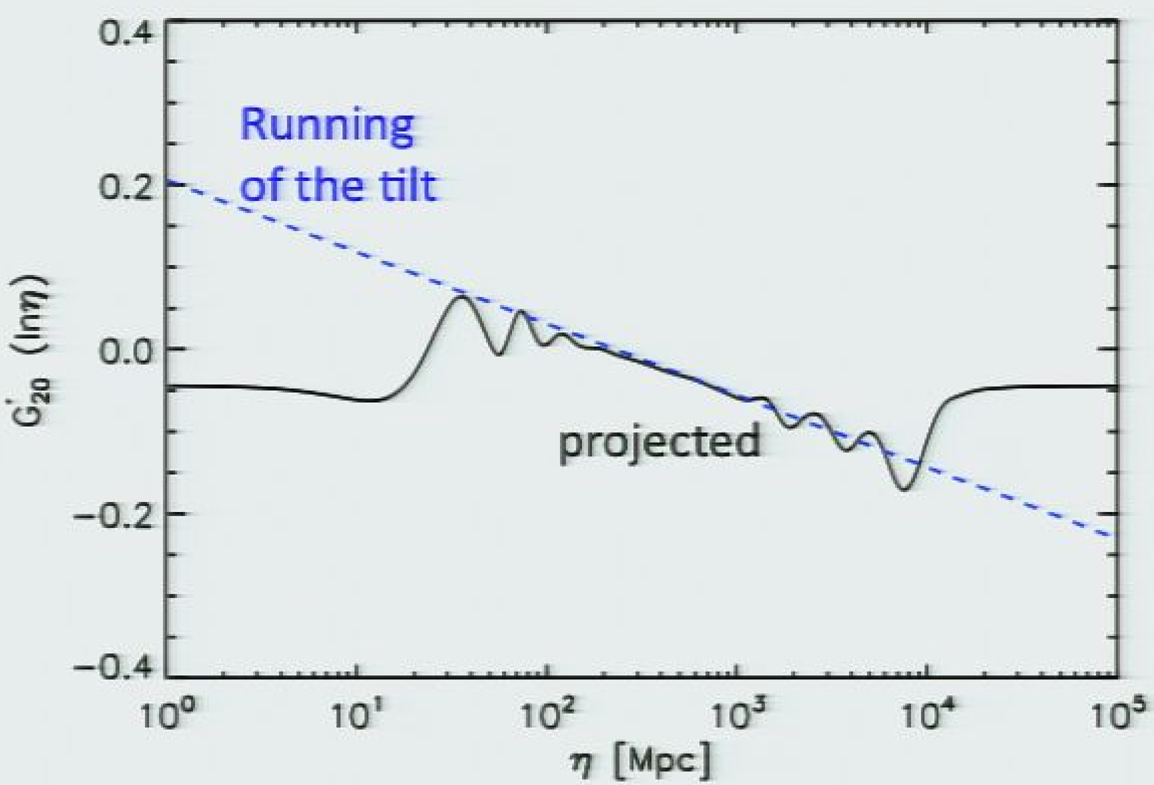
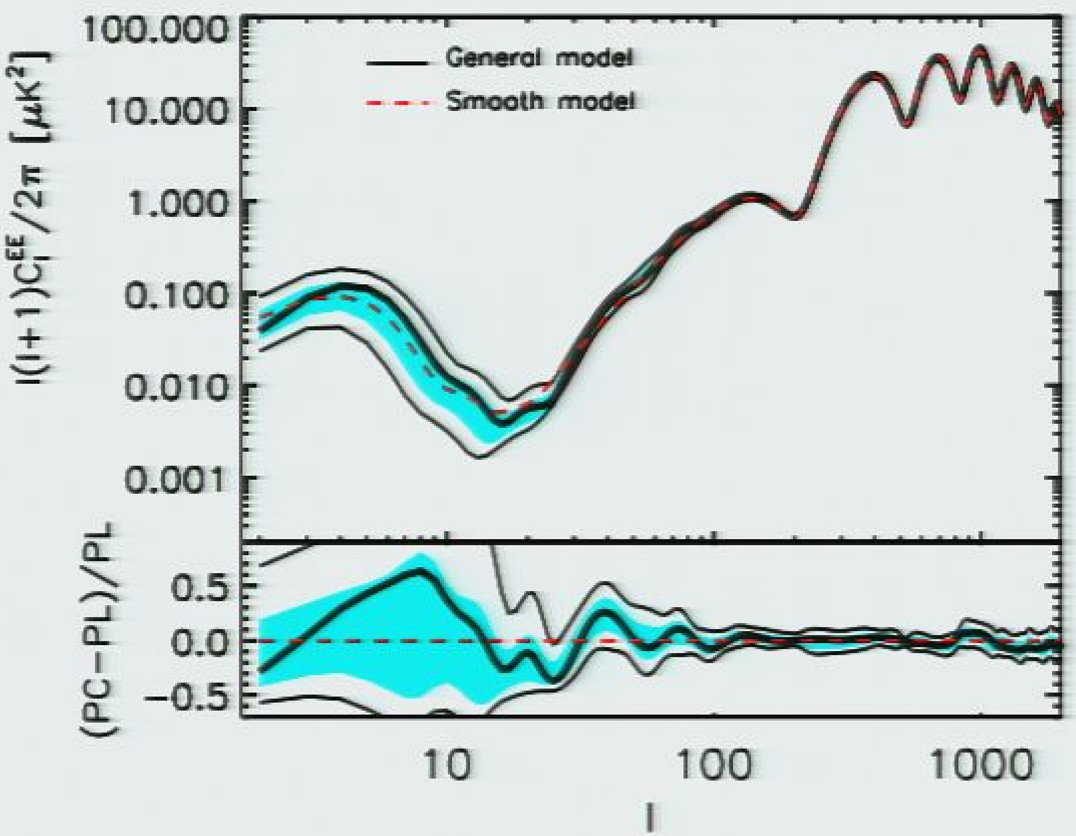


The Predictive Power of Polarization

- Measurements at l=20-40 (at the 40% level) will test the feature hypothesis at 2.5-3σ with Planck and 5-8σ with CMBPol.
  Caveat: confusion with reionization features.

M. Mortonson, C. Dvorkin, H.V.Peiris, W. Hu, PRD (2009)



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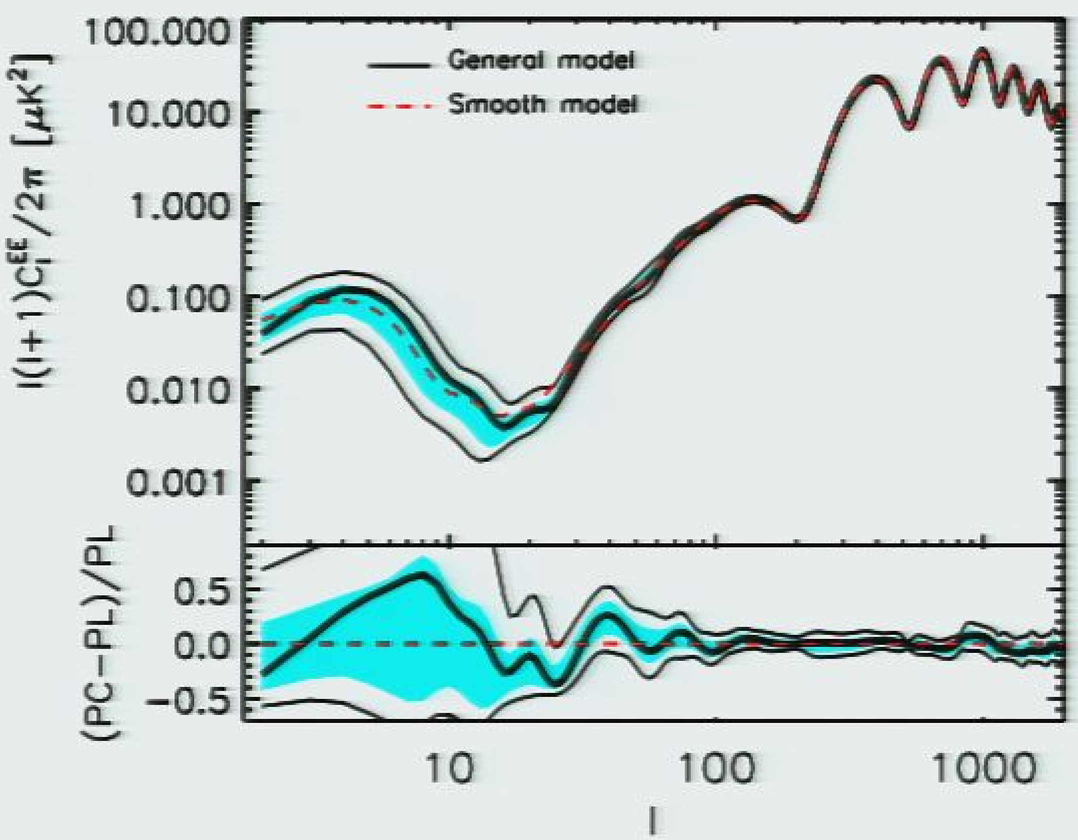
Model-independent test of single-field inflation

- Measurements lying outside these bounds could potentially rule-out single field inflation.



C. Dvorkin and W. Hu, in preparation

Conclusions and future directions

- Introduced a general formalism to constrain the inflationary potential from the data allowing for large amplitude and rapidly varying deviations from slow roll.
- Constraints around the first acoustic peak are consistent with a smooth inflationary potential.

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Future work:

- Extend analysis to the entire range of observable CMB scales.
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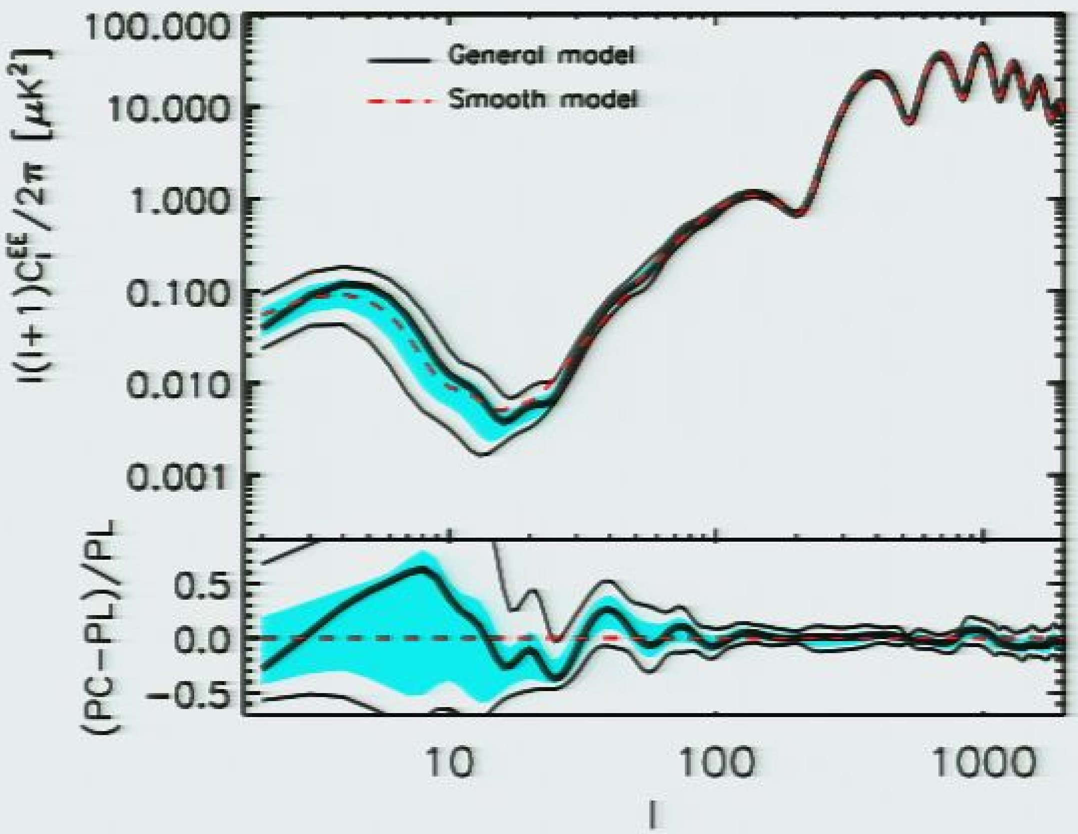

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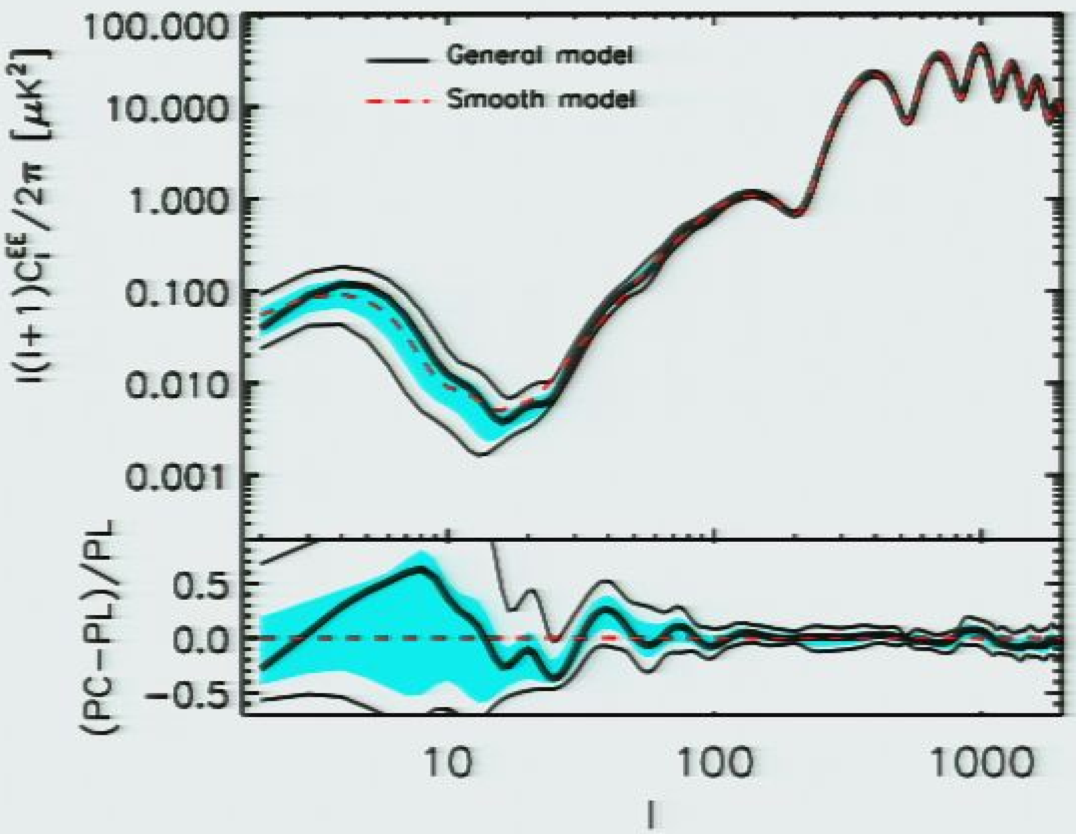

C. Dvorkin and W. Hu, in preparation