New Physics from an All-Sky Polarization Experiment

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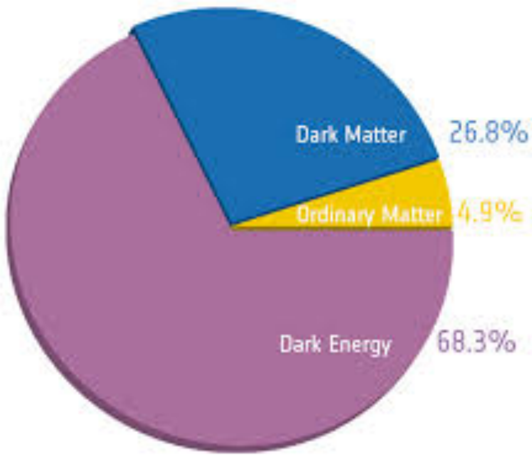
ΛCDM: the "Standard" Model of Cosmology

Homogeneous background

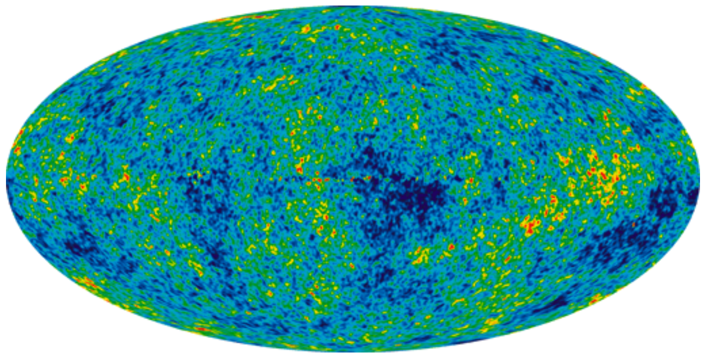


$$\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \tau, \theta$$

- Baryonic matter: 5%
- Cold dark matter: 27%
- Dark energy: 68%

Λ? CDM?

Perturbations

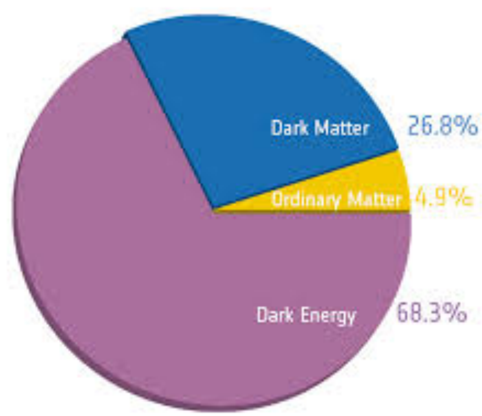


$$A_s, n_s$$

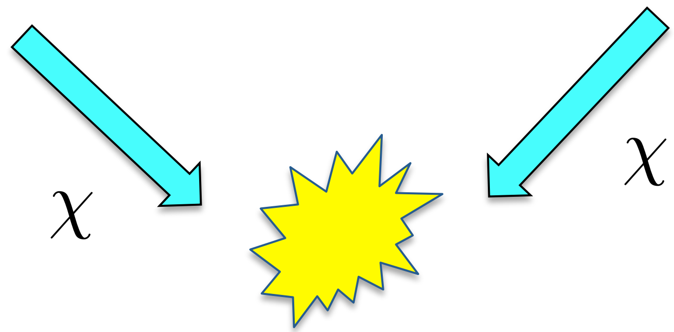
- Nearly scale-invariant
- Gaussian

Origin?

What is the particle nature of Dark Matter?



WIMP Dark Matter Annihilation



$$W^{\pm}, Z, b\bar{b}, h$$

FINAL PRODUCTS

$$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$$

Energy Injection in the CMB

FINAL PRODUCTS

$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$ →

- **Heat the plasma**
- **Ionize neutral hydrogen**
- **Excite H atoms**

Shull and van Steenberg, ApJ (1985)
Chen and Kamionkowski, PRD (2004)

Energy injected into the plasma per unit volume, per unit time:

$$\frac{dE}{dtdV} = n_{pairs} P_{ann} E_{ann} f(z)$$

Number of DM particle pairs

Annihilation probability per unit time

Energy released per annihilation

Fraction of energy absorbed by the plasma (depends on the model)

Slatyer, Padmanabhan and Finkbeiner (2009)

Energy Injection in the CMB

FINAL PRODUCTS

$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$ $\Rightarrow$

- **Heat the plasma**
- **Ionize neutral hydrogen**
- **Excite H atoms**

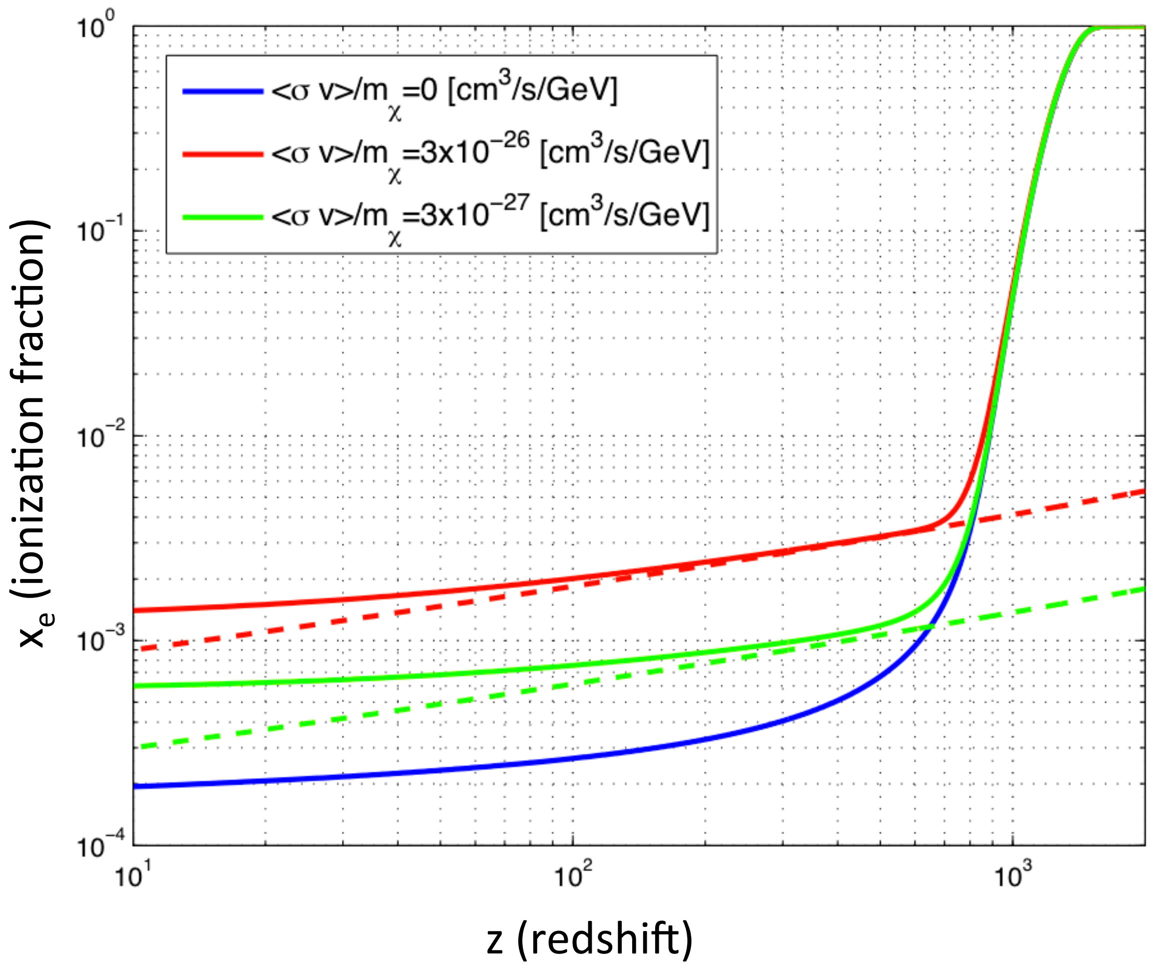
Shull and van Steenberg, ApJ (1985)
Chen and Kamionkowski, PRD (2004)

Energy injected into the plasma per unit volume, per unit time:

$$\frac{dE}{dtdV} = \rho_\chi^2 \left[\frac{f(z)\langle \sigma v \rangle}{m_\chi} \right]$$

(Majorana particle)

Free electron fraction evolution

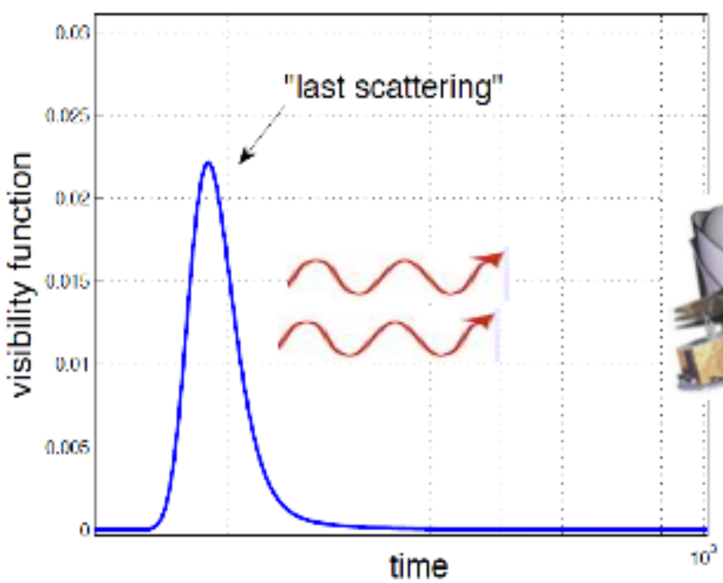


C. Dvorkin, K. Blum, and M. Zaldarriaga, Phys. Rev. D (2013)

Thomson scattering

“Visibility function”: probability that a photon last scattered at a time η.

$$g(\eta) = -e^{-\tau(\eta)}\dot{\tau}(\eta)$$



- Dark matter annihilation injects energy into the plasma.
- Ionizes hydrogen.

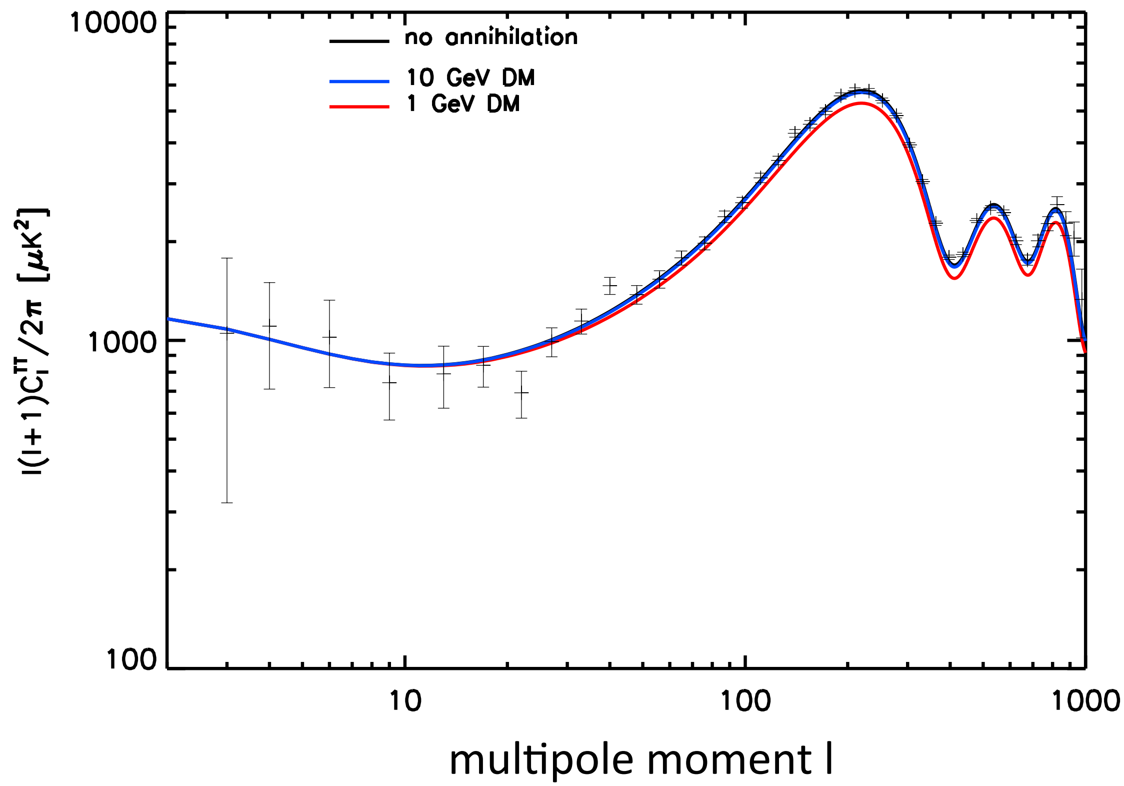
- Excess Thomson scattering:

$$T^{\rm obs}(\hat{\mathbf{n}}) \rightarrow T^{\rm rec}(\hat{\mathbf{n}})e^{-\Delta\tau},$$

with $\Delta\tau(\eta) = c\sigma_T \int_\eta^{\eta_0} d\eta' a(\eta') n_e(\eta')$

Effect on the CMB Temperature

A higher ionization suppresses the CMB temperature fluctuations.



Degeneracy:

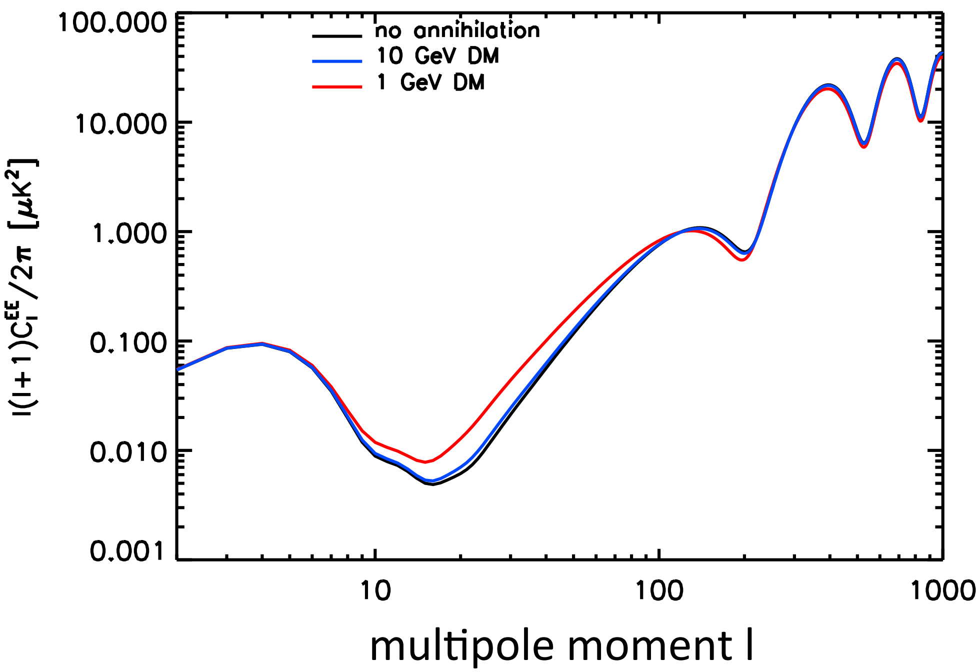
$$C_\ell \to e^{-2\Delta\tau} C_\ell$$
$$A_s \to e^{2\Delta\tau} A_s$$

Padmanabhan and Finkbeiner (2005)

Current CMB constraints are $\mathcal{O}(10)$ GeV $\longrightarrow$ Complementary to direct detection searches, that are most sensitive to $m_\chi \gtrsim 10$ GeV, due to kinematical considerations.

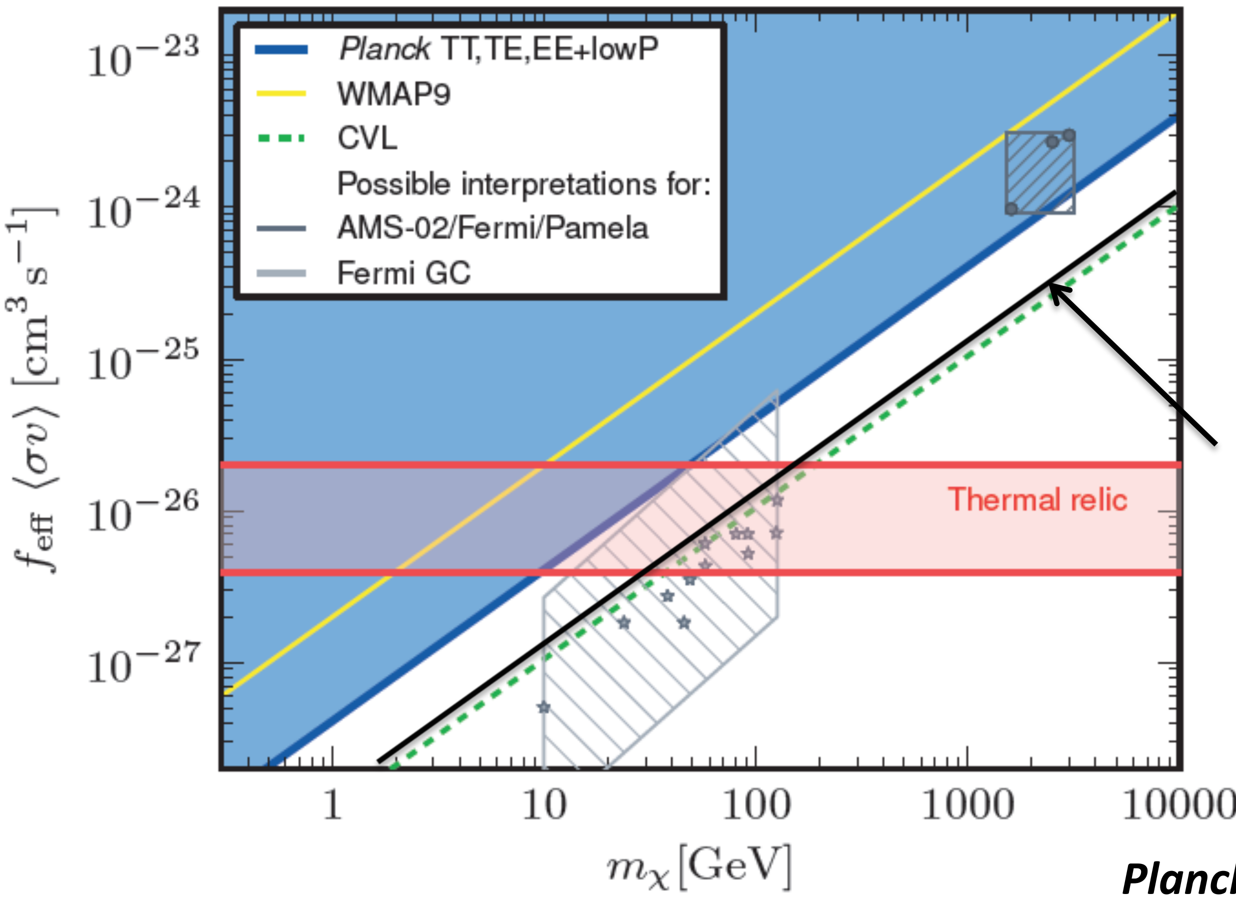
Effect on the CMB Polarization

A higher ionization enhances the polarization fluctuations at large scales.



- Screening of the observed spectrum at l>100.
- Re-scattering of photon generates extra polarization at large scales.

Forecasts for Dark Matter annihilation



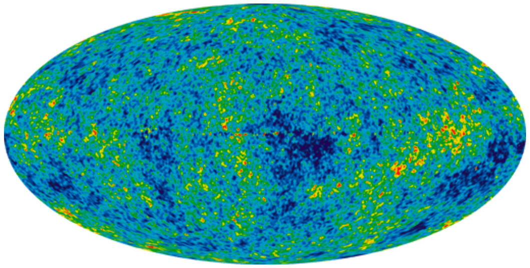
Planck's temperature noise + a LiteBIRD-type experiment, with DeltaP=2 muK-arcmin $\theta_{\rm FWHM}$=30 arcmin and f_{sky}=0.8.

Planck, paper XIII (2015)

$m_\chi > 193$ GeV (at the 95% CL)

(not sensitive to l_{min}<10)

What is the physics that seeded the first structures in the Universe?



The Physics of Inflation

Assuming inflation took place, what can we learn about it?

- What is the shape of the inflationary potential?
- Are there additional degrees of freedom?
- What is the energy scale of inflation?
- How far did the field travel?

Probing the shape of the inflationary potential and additional degrees of freedom

Standard Slow Roll

Technique for computing the initial curvature power spectrum $\Delta^2_{\mathcal{R}}$ for inflationary models where the scalar field potential is sufficiently flat and slowly varying.

Linked to the **shape of the potential**

$$
\left.\begin{aligned}
\epsilon_H &\equiv \frac{1}{2}\left(\frac{\dot{\phi}}{H}\right)^2 \\
\eta_H &\equiv -\left(\frac{\ddot{\phi}}{H\dot{\phi}}\right) \\
\delta_2 &\equiv \frac{\dddot{\phi}}{H^2\dot{\phi}}
\end{aligned}\right\}
$$

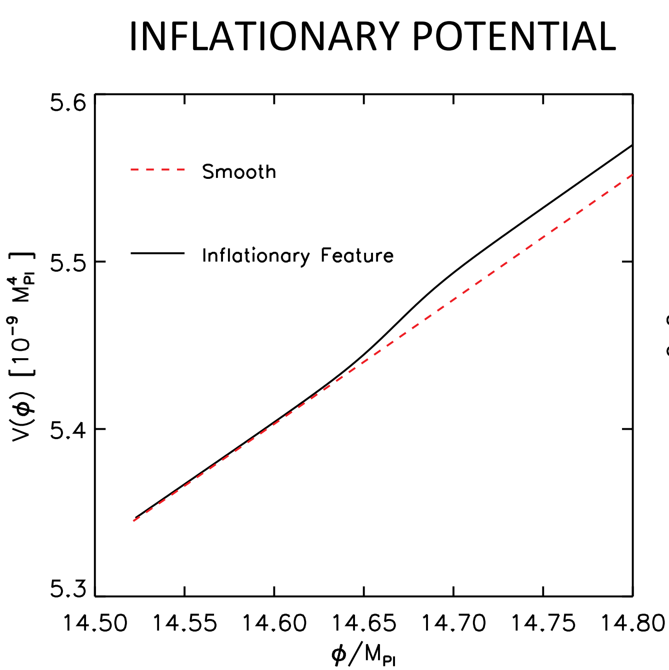
Slow-roll parameters

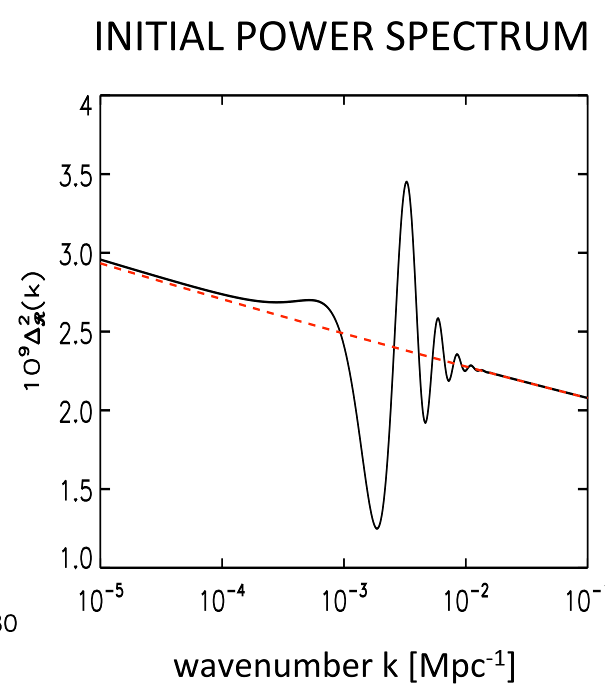
<< 1 and slowly varying

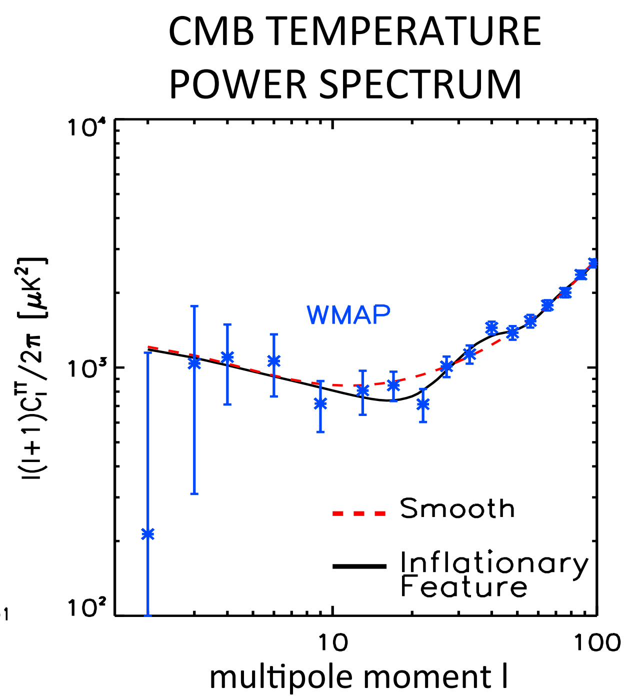
Slow-roll approximation: $\Delta^2_{\mathcal{R}} \approx \left[(1-(2C+1)\epsilon_H - C\eta_H)\,\frac{H^2}{2\pi|\dot{\phi}|}\right]^2_{k\eta\approx 1}$

Inflationary Features

The rolling of the inflaton across features in the inflationary potential produces ringing in the initial curvature and CMB power spectra.



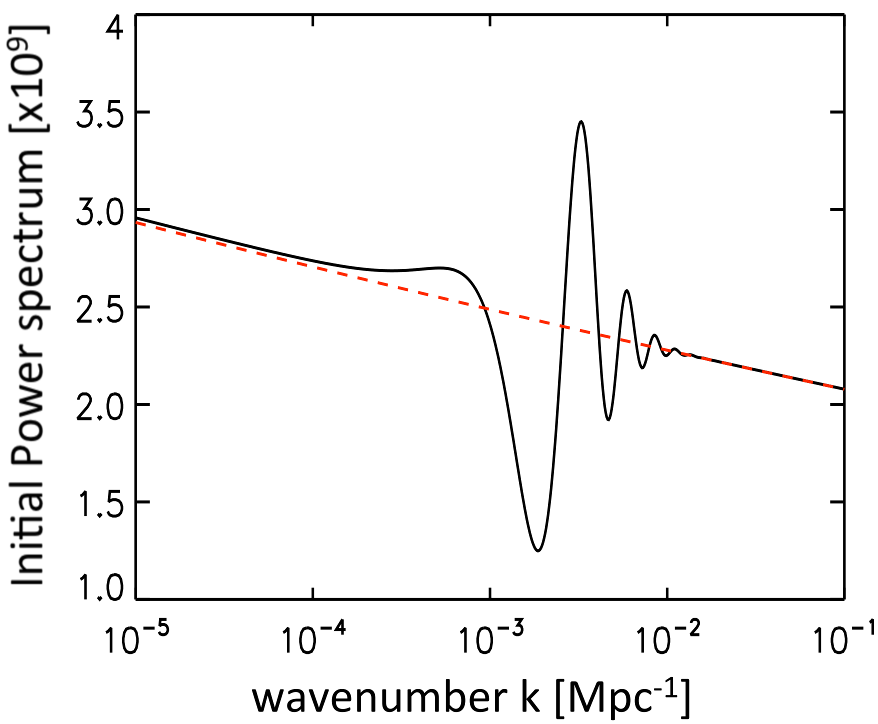




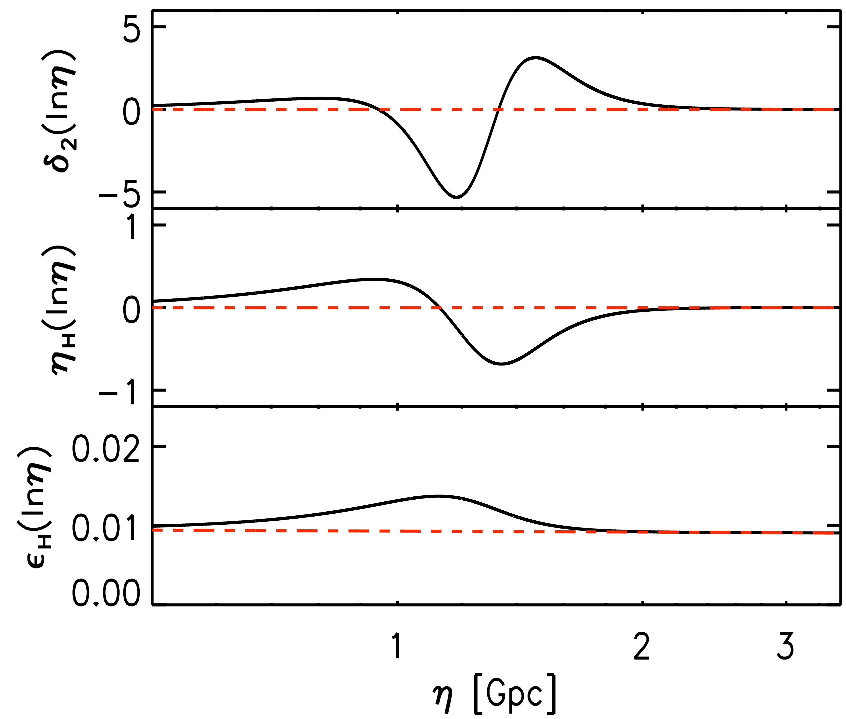
L.Covi, J.Hamann, A.Melchiorri, A.Slozar and I.Sorbera (2006)

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" approximation

- The curvature power spectrum depends on a single source function:

$$
\begin{aligned}
\ln \Delta_{\mathcal{R}}^2(k) \quad &= \quad G(\ln \eta_{\min}) + \int_{\eta_{\min}}^{\eta_{\max}} \frac{d\eta}{\eta} W(k\eta) G'(\ln \eta) \\
&\quad + \ln\left[1 + \frac{1}{2}\left(\int_{\eta_{\min}}^{\eta_{\max}} \frac{d\eta}{\eta} X(k\eta) G'(\ln \eta)\right)^2\right]
\end{aligned}
$$

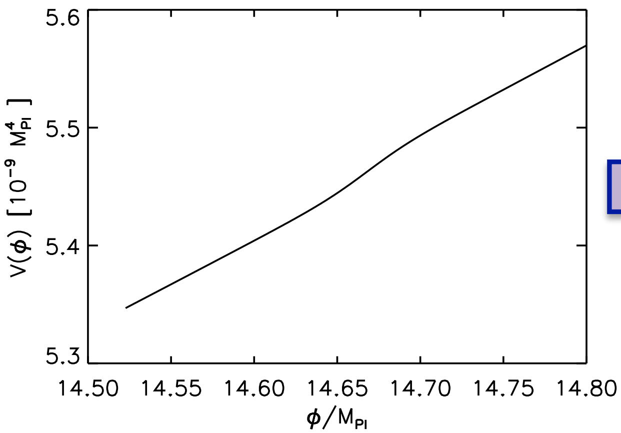
C.Dvorkin, W.Hu, PRD (2009)

✓ 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: $\boxed{G' \approx 3\left(\frac{V_{,\phi}}{V}\right)^2 - 2\left(\frac{V_{,\phi\phi}}{V}\right)}$

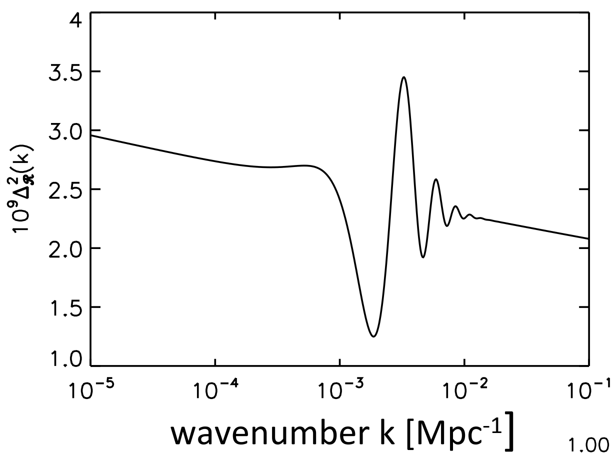
(also related to variations in the sound speed for non-canonical kinetic terms)

W. Hu, PRD (2011)

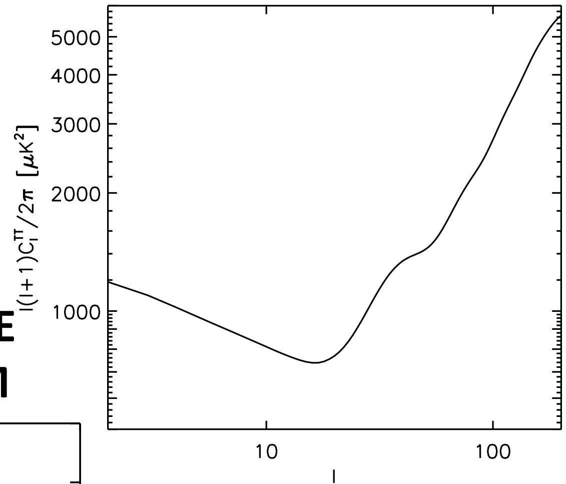
INFLATIONARY POTENTIAL



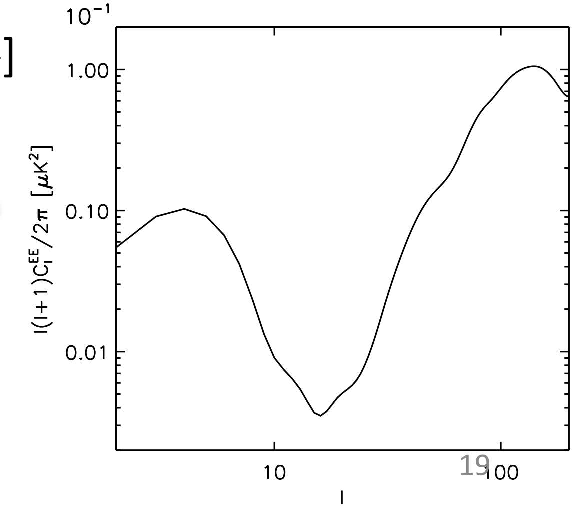
INITIAL CURVATURE POWER SPECTRUM

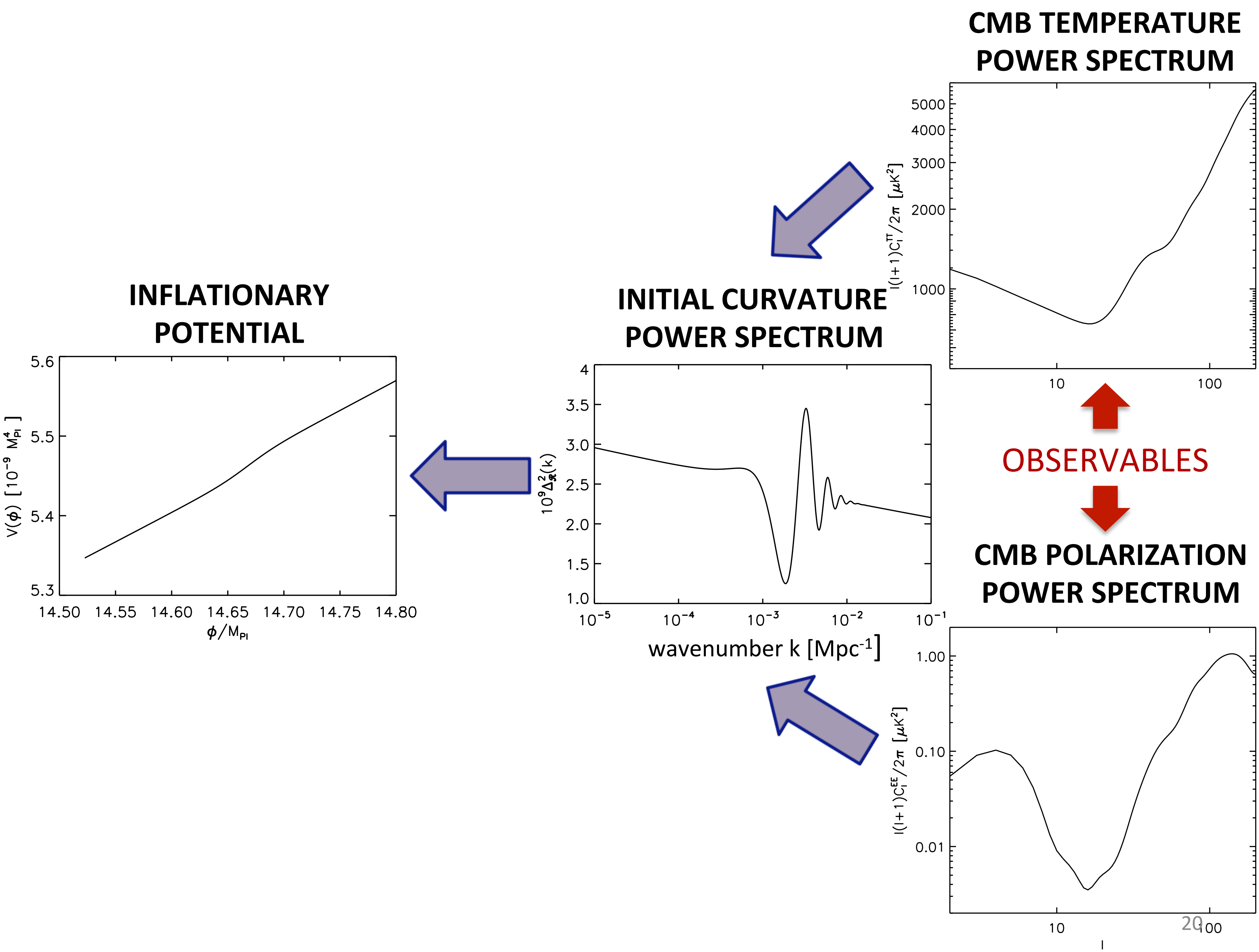


CMB TEMPERATURE POWER SPECTRUM



CMB POLARIZATION POWER SPECTRUM




CMB TEMPERATURE POWER SPECTRUM
INITIAL CURVATURE POWER SPECTRUM
INFLATIONARY POTENTIAL
OBSERVABLES
CMB POLARIZATION POWER SPECTRUM
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
5000
4000
3000
2000
1000
10
100
$10^9\Delta^2_{\mathcal{R}}(k)$
4
3.5
3.0
2.5
2.0
1.5
1.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
wavenumber k [Mpc^{-1}]
$V(\phi)$ [10^{-9} M_{Pl}^4]
5.6
5.5
5.4
5.3
14.50
14.55
14.60
14.65
14.70
14.75
14.80
ϕ/M_{Pl}
$l(l+1)C_l^{EE}/2\pi$ [μK^2]
1.00
0.10
0.01
10
100
l

Principal Component Basis

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

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

- Defined a priori from covariance matrix: avoids *a posteriori* bias when looking at the data.
- Ranked in order of observability.
- Non-zero values represent deviations from slow-roll and power-law spectrum.

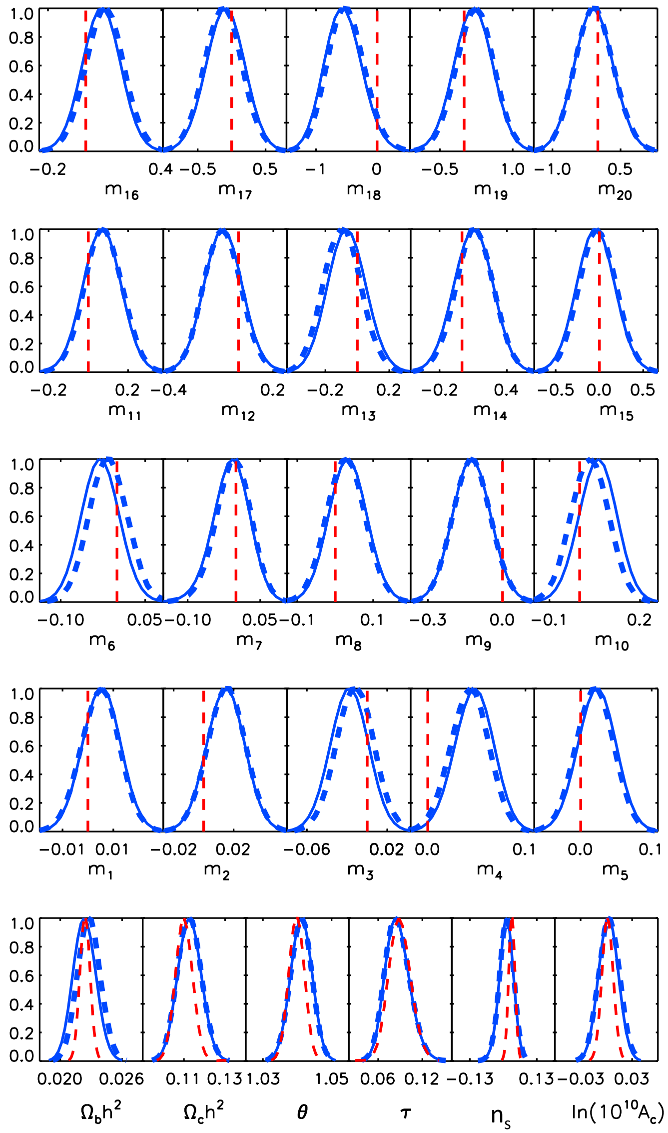
Likelihood analysis

MODEL: $p = \{\Omega_b h^2, \Omega_c h^2, \theta, \tau, A_s, n_s, m_1, ..., m_{20}\}$

$$\mathcal{L}(\mathbf{x}|\mathbf{p}) = \frac{1}{(2\pi)^{N/2}\sqrt{\det \mathbf{C}(\mathbf{p})}} \exp\left[-\frac{1}{2}\mathbf{x}^\dagger [\mathbf{C}(\mathbf{p})]^{-\mathbf{1}}\mathbf{x}\right]$$

CMB temperature and polarization data

Model-independent constraints on the shape of the inflationary potential



- 3 components out of 20 exceed the 90% CL significance for nonzero value.

No significant evidence for departures from slow-roll.

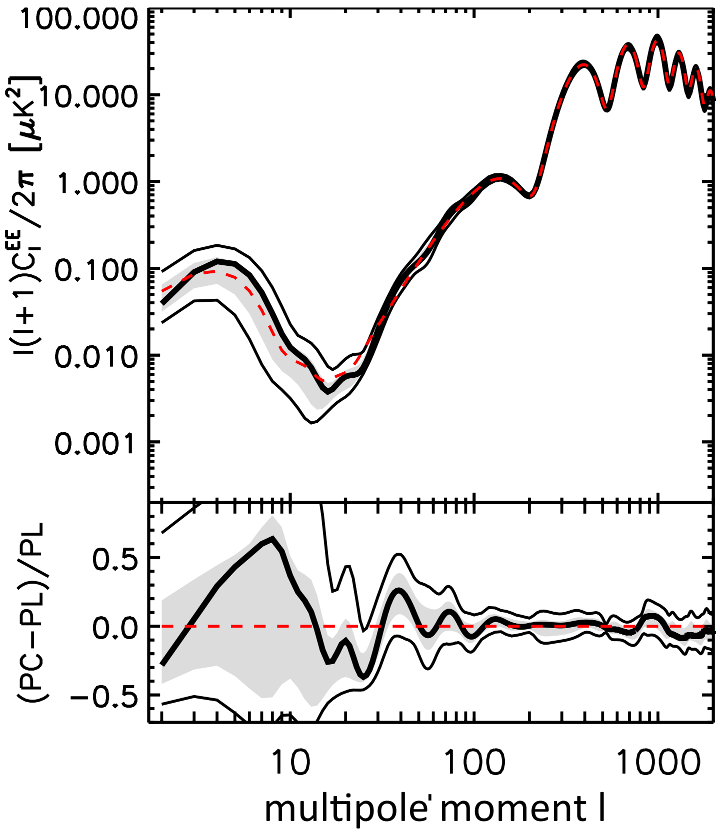
WMAP7 + BICEP1 + QUAD data;
SN + H0 + BBN constraints.

C.Dvorkin, W.Hu, PRD (2011)

Model-independent test of single-field inflation (with E-mode polarization)

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

PC = General Inflationary model
PL = Power-law model

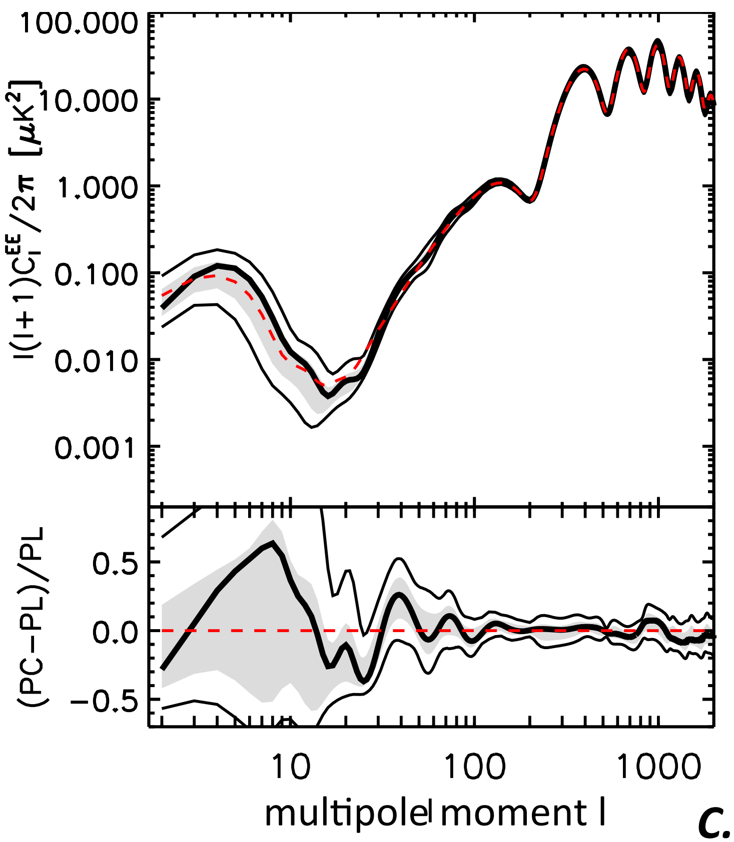


WMAP7 + BICEP1 + QUAD data; SN + H0 + BBN constraints.

C.Dvorkin, W.Hu, PRD (2011)

LITEBird could test this!

Polarization Predictions for Inflationary Features



C.Dvorkin, W.Hu, PRD (2011)

- E-modes constrained to the temperature measurements: feature model can be detected with temperature (Planck) + a polarization experiment such as LiteBIRD at the 7 sigma level.

Testing CMB Isotropy Anomalies

Testable Polarization Predictions for models of CMB isotropy anomalies

Any physical model proposed to explain the temperature anomalies provides testable predictions for the statistics of the polarization field.

Polarization predictions provide a means of going beyond a posteriori inferences.

Power asymmetry

Spontaneous isotropy breaking

Dipolar modulation: $\boxed{\phi(\mathbf{x}) = g_1(\mathbf{x})(1 + w_1 Y_{10}(\theta))}$

Dipole statistics: couplings between ℓ and $\ell \pm 1$ moments.

$$\langle X_{\ell m} Y_{\ell m} \rangle \propto w_1 R^{1\ell}_{\ell+1,m}$$

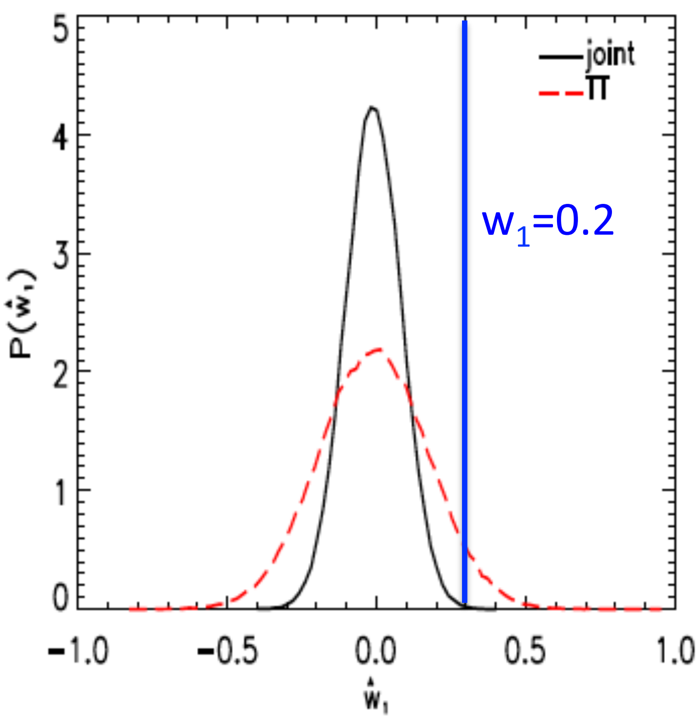
$$R^{1\ell}_{\ell' m} = (-1)^m \sqrt{\frac{3(2\ell+1)(2\ell'+1)}{4\pi}} \begin{pmatrix} 1 & \ell & \ell' \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & \ell & \ell' \\ 0 & m & -m \end{pmatrix}$$

C. Dvorkin, H.V.Peiris, W. Hu, PRD (2008)

Temperature and polarization estimators

- Unbiased minimum biased estimators can be constructed for each pair of fields, and a joint estimator for the combination of all the fields.

- If the observed dipole asymmetry is a statistical fluke, how well can temperature and polarization rule out a finite value of w_1=0.2 (best fit for TT)?



w_1>0.2 can be tested at the [81.6-86.4] % CL by EE and TT with Planck temperature noise and LiteBIRD polarization noise.

The combination of the four estimators (TT, EE, TE, ET) is even more powerful, testing w_1>0.2 at the 98.4% CL.

Conclusions

- We still have many open questions in Cosmology: Λ? CDM? Inflation?

LITEBird will be able to shed light on these puzzles!

➢ It will put stronger constraints (or detect!) dark matter annihilation through the E-mode polarization at intermediate scales.

➢ It will provide a model-independent test of single-field inflation via the E-mode power spectrum.

➢ It will test the origin of features (and other anomalies) seen in the CMB temperature at large scales.

➢ And much more! (better measurement of the tensor-to-scalar ratio, tighter constraints on the reionization optical depth, total neutrino mass, isocurvature perturbations, etc, etc...)