Probing Fundamental Physics with CMB B-modes

Cora Dvorkin
Harvard University
(Hubble and ITC Fellow)

The Primordial Universe After Planck
30th IAP Colloquium
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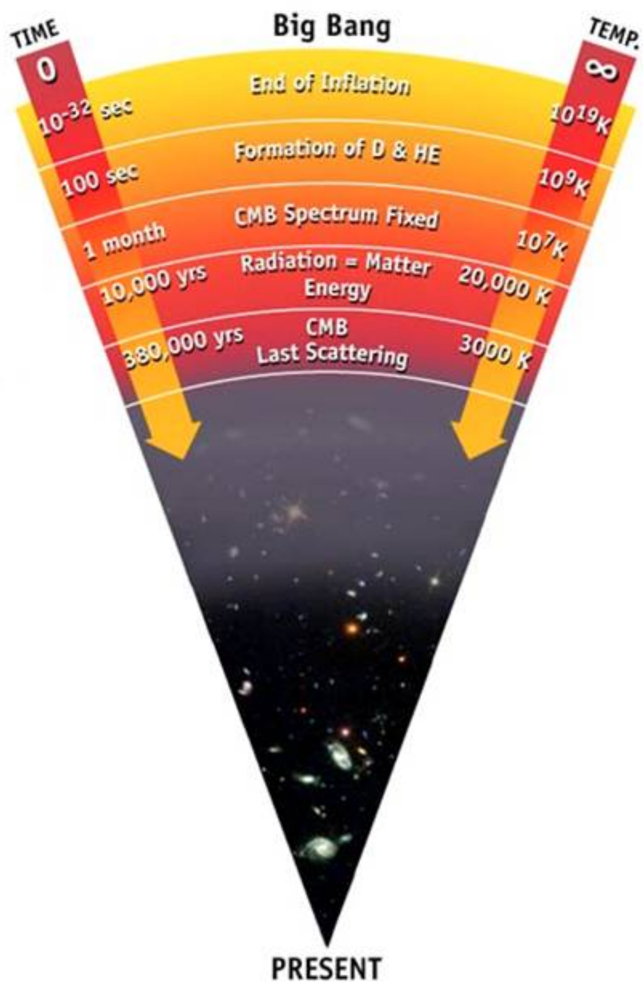
Cosmic History

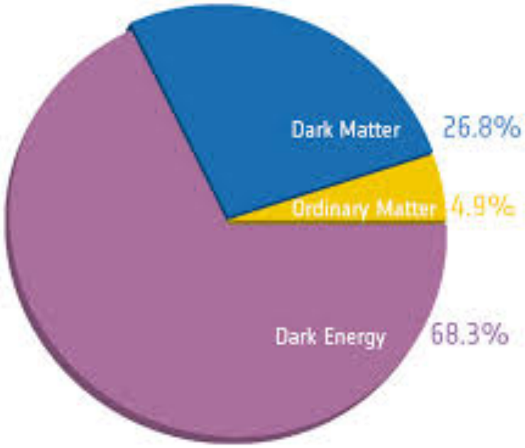


- The universe began as a hot and dense plasma of particles in thermal equilibrium.
- Recombination (z $\approx$1100): $p^+ + e^- \to H$
  Universe becomes transparent to CMB photons.

  Photons mainly freestream.
- Radiation from first stars and quasars reionizes the universe (z $\approx$10-20) and $\sim$10% of the photons re-scatter.
- We observe these photons at T $\approx$ 2.725 K.

ΛCDM: the "Standard" Model of Cosmology

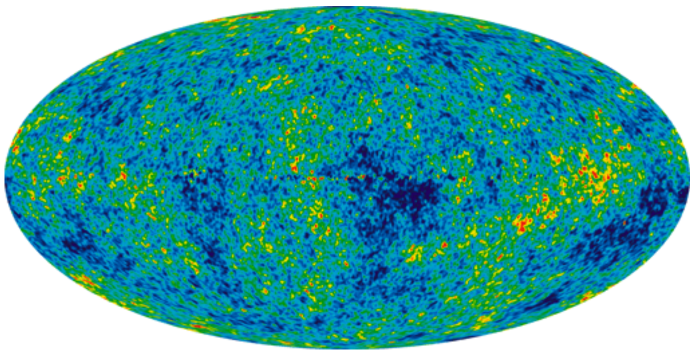
Homogeneous background



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

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

Perturbations



$$A_s, n_s$$

- Nearly scale-invariant
- Gaussian

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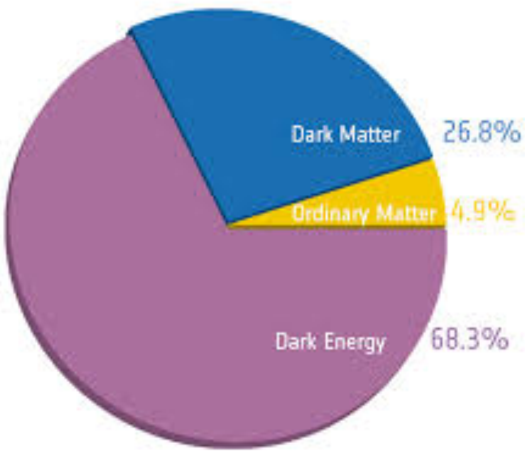

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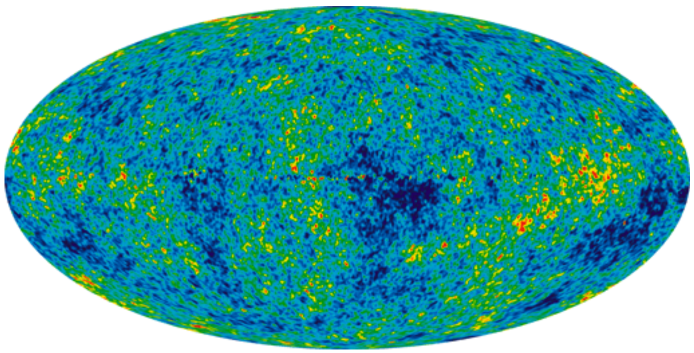
Λ? CDM?

Perturbations



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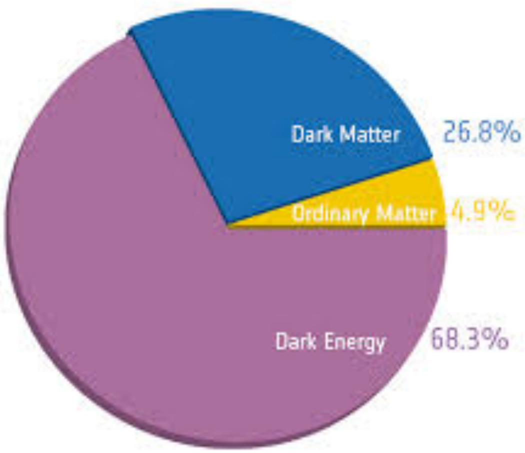
Origin?

After March 2014 (BICEP2):
Do we need new parameters in our Standard Model?

Homogeneous background



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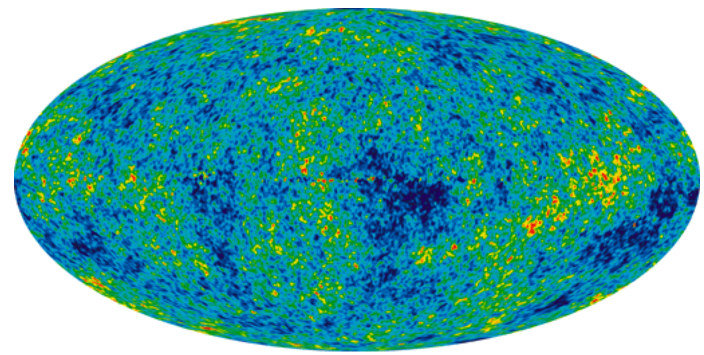
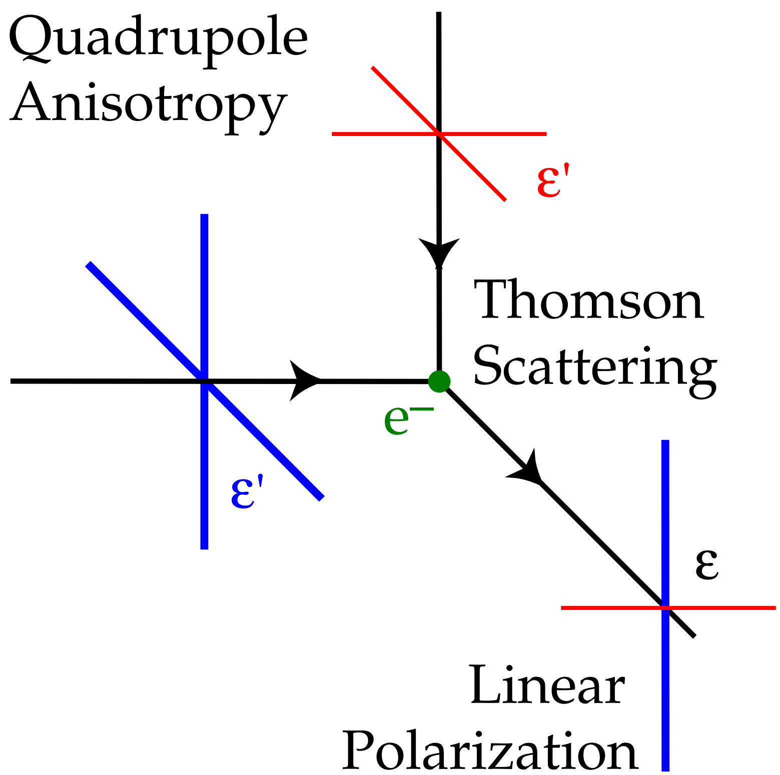


A_s, n_s***, r, n_t?***

- Nearly scale-invariant
- Gaussian

From Temperature Anisotropies to Polarization



W. Hu & M.White

Polarization is generated by Thomson scattering:

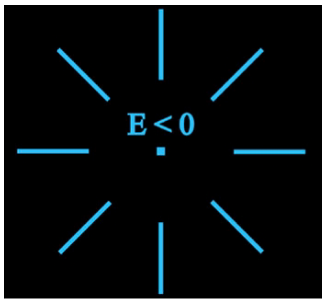
$$e^- \gamma \rightarrow e^- \gamma$$

Local temperature quadrupole

⇨ **Linear polarization**

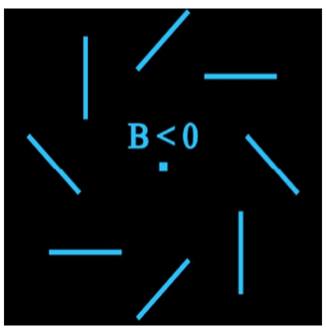
CMB polarization: E-B decomposition

Represent CMB polarization on the sky by a traceless symmetric tensor Π_{ab}



E-mode: "curl-free" field

$$\Pi_{ab} = \left(\nabla_a \nabla_b - \frac{1}{2} g_{ab} \nabla^2 \right) \phi$$



B-mode: "divergence-free" field

$$\Pi_{ab} = \left(\frac{1}{2} \epsilon_{ac} \nabla^c \nabla_b + \frac{1}{2} \epsilon_{bc} \nabla^c \nabla_a \right) \phi$$

This is the analog of the gradient/curl decomposition of a vector field

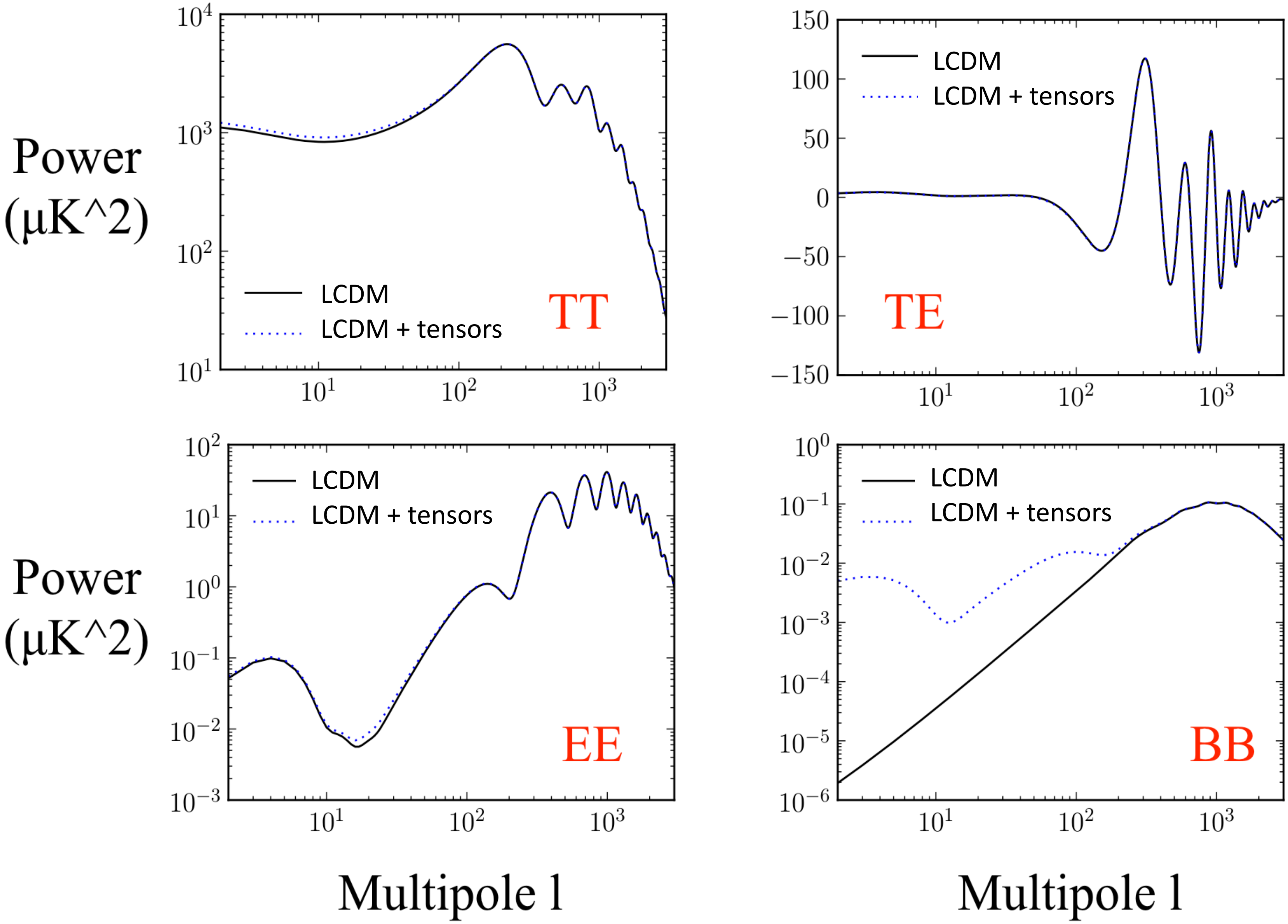
Generation of B-modes

Polarization is a spin-2 field: $(Q \pm iU)(\hat{\mathbf{n}}) \to e^{\mp i2\Psi}(Q \pm iU)(\hat{\mathbf{n}})$

$$(Q \pm iU)(\hat{\mathbf{n}}) = -\sum_{\ell m} (E_{\ell m} \pm iB_{\ell m})_{\pm 2} Y_{\ell m}(\hat{\mathbf{n}})$$

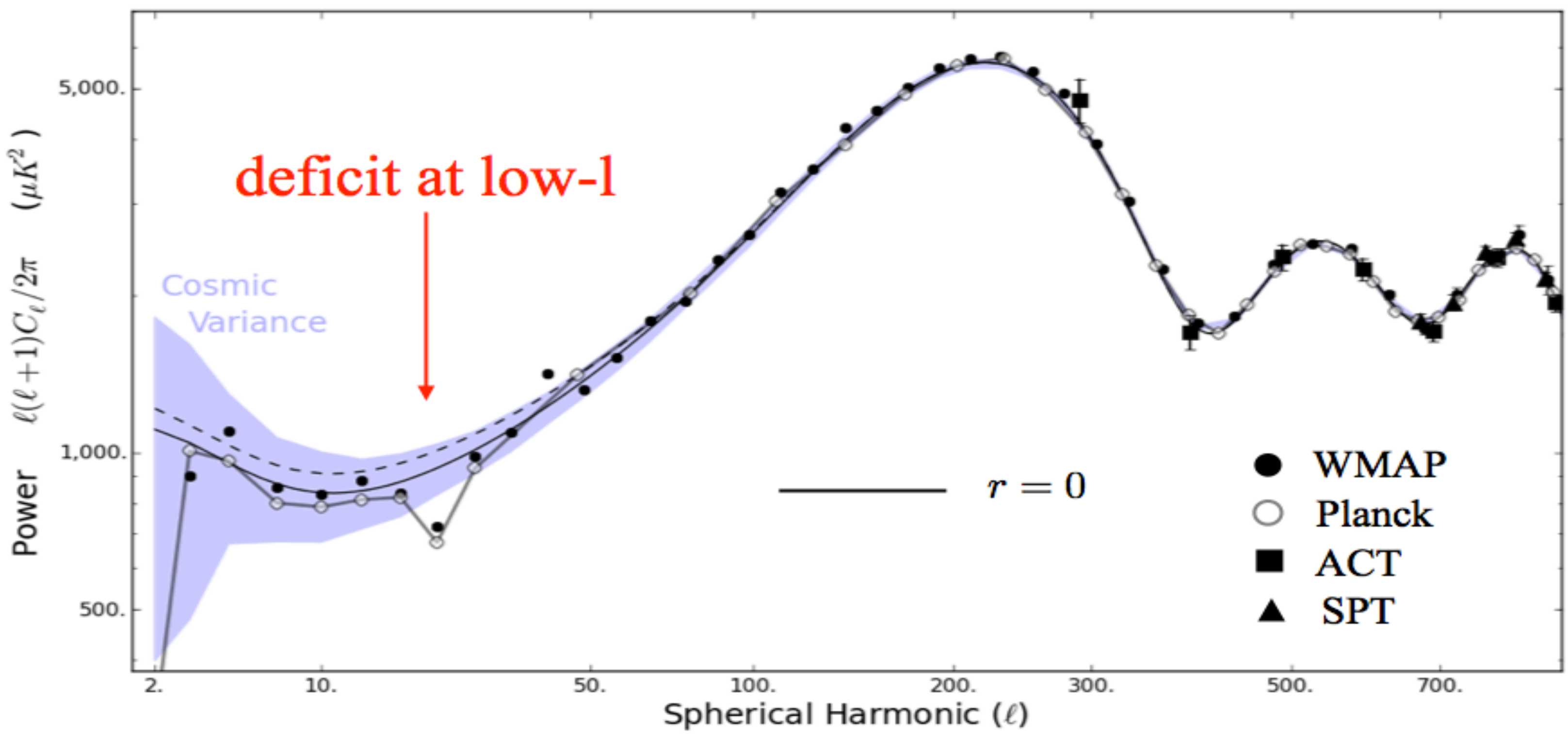
- Scalar sources + linear evolution ➡ E-modes.
- Gravitational waves (distorting space-time and creating a CMB quadrupole) or non-linear evolution ➡ B-modes.

How do primordial tensor modes affect the CMB temperature and polarization spectra?



Limits on tensor modes from the temperature data

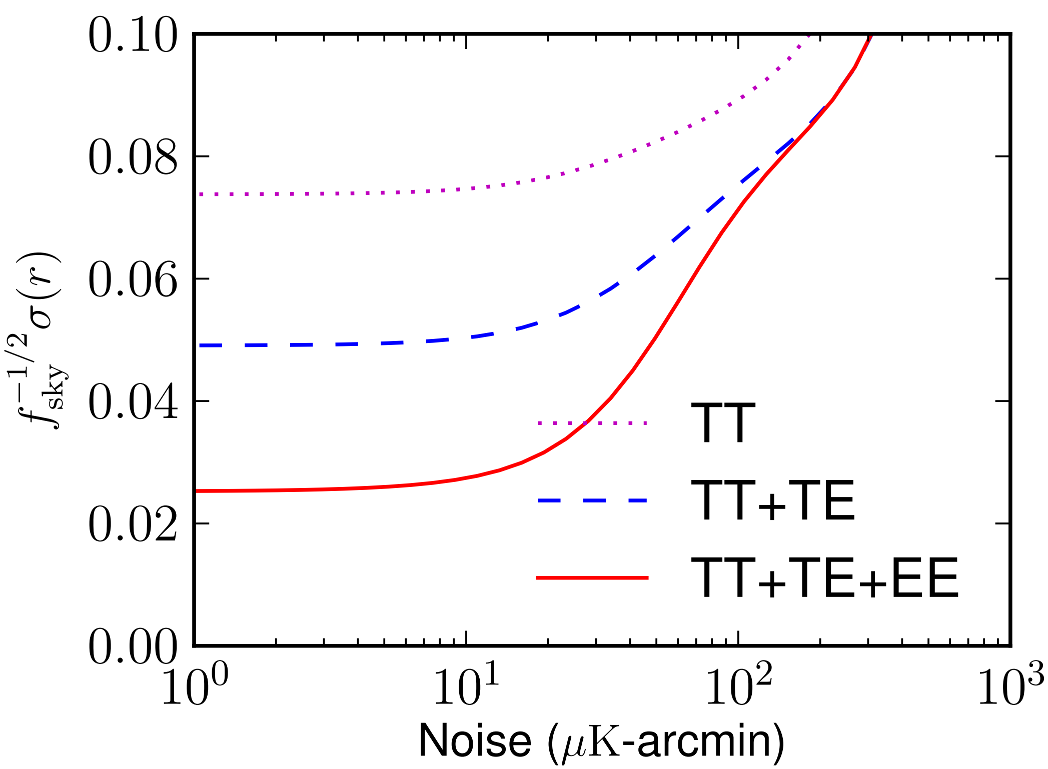
Tight constraint on the *tensor-to-scalar ratio (r)* from Planck temperature data: $r < 0.11$ (at the 95% CL).



*K. M. Smith, **C. Dvorkin**, L. Boyle, N. Turok, M. Halpern, G. Hinshaw, B. Gold, PRL (2014)*

Polarization Predictions

TE and EE are not yet very informative, but they will be soon (with Planck)



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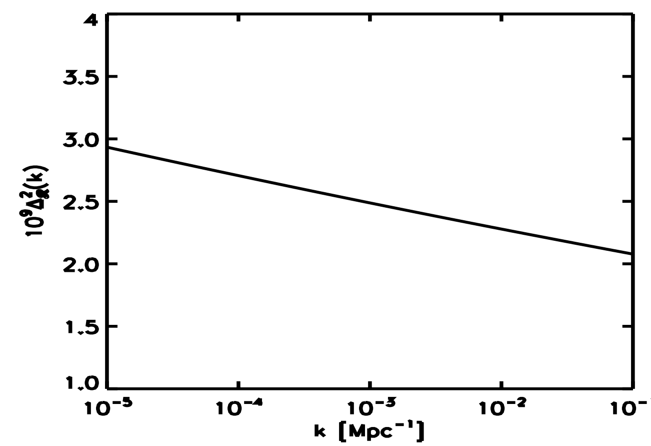
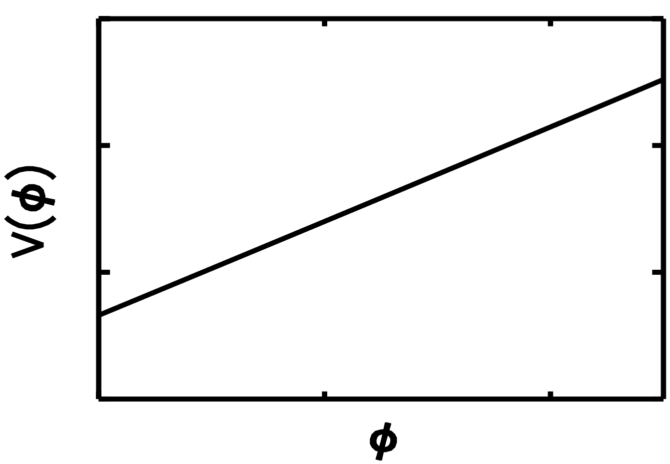
Connecting Theory with Observations

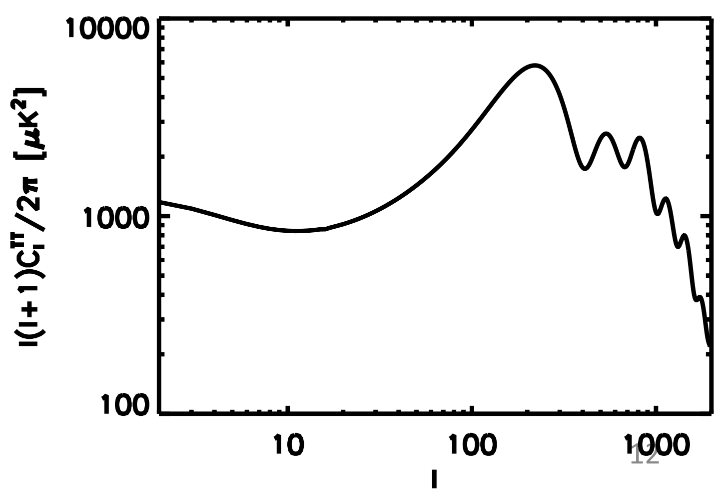
POWER SPECTRUM



INFLATIONARY POTENTIAL



CMB POWER SPECTRUM



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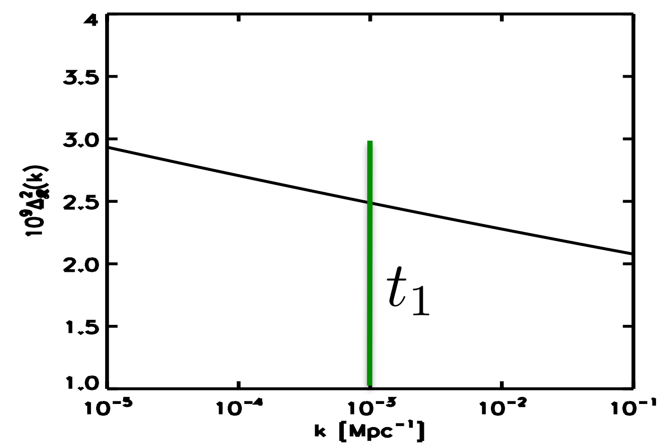

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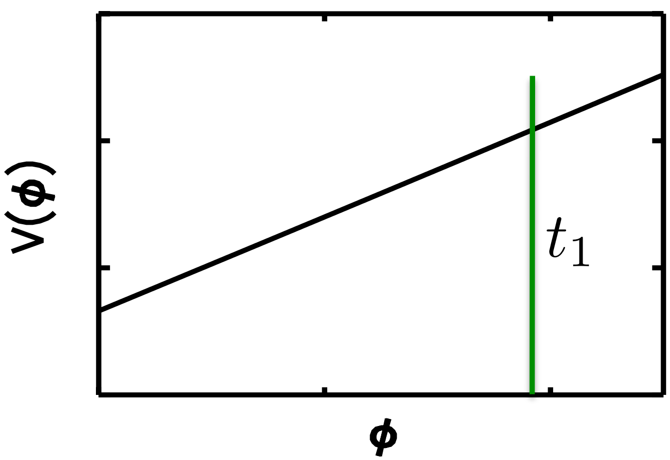

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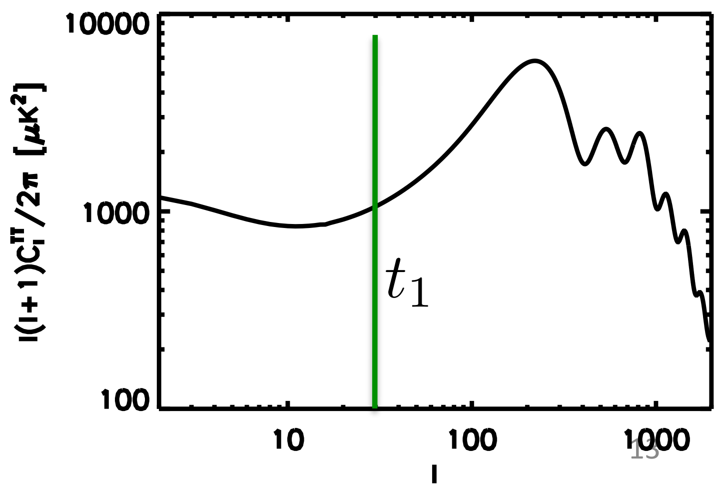

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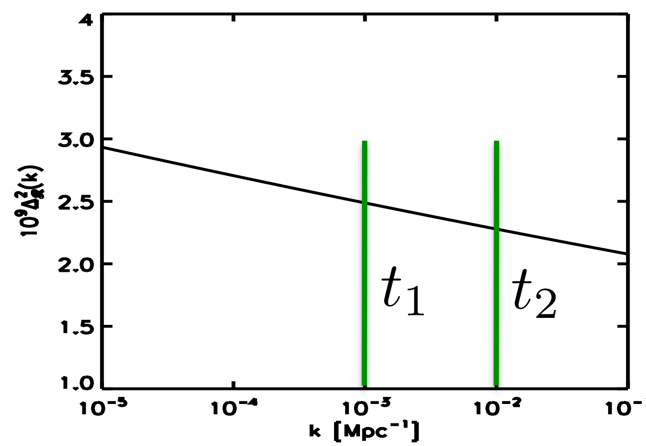

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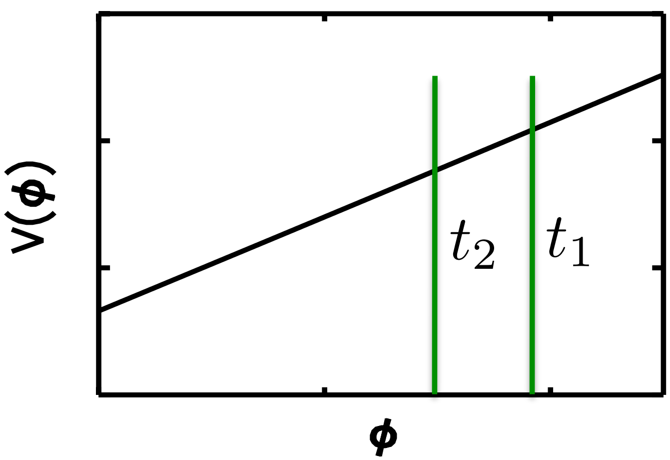

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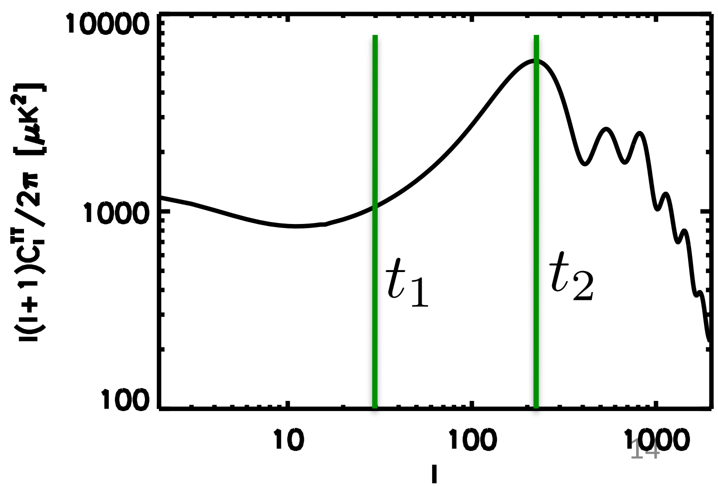
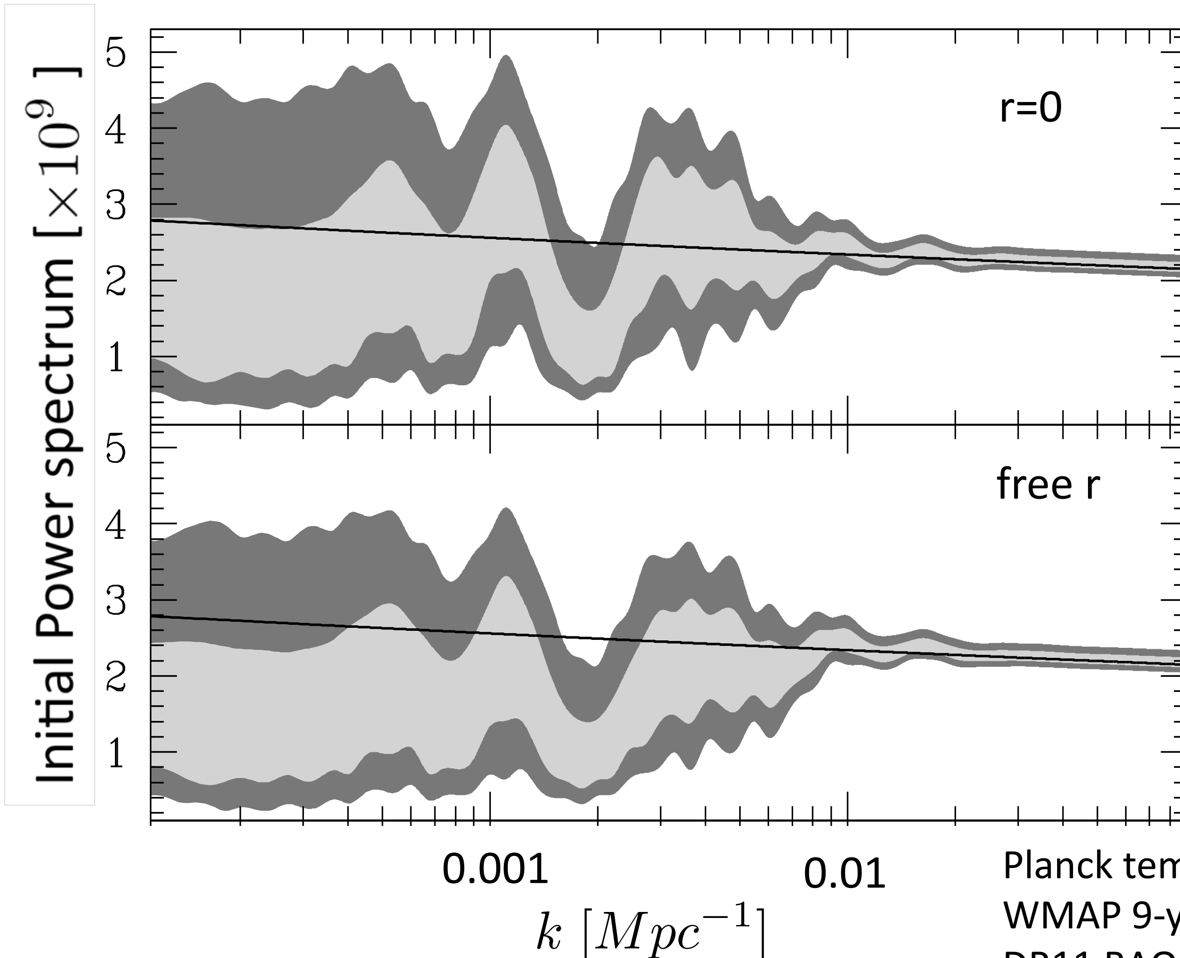


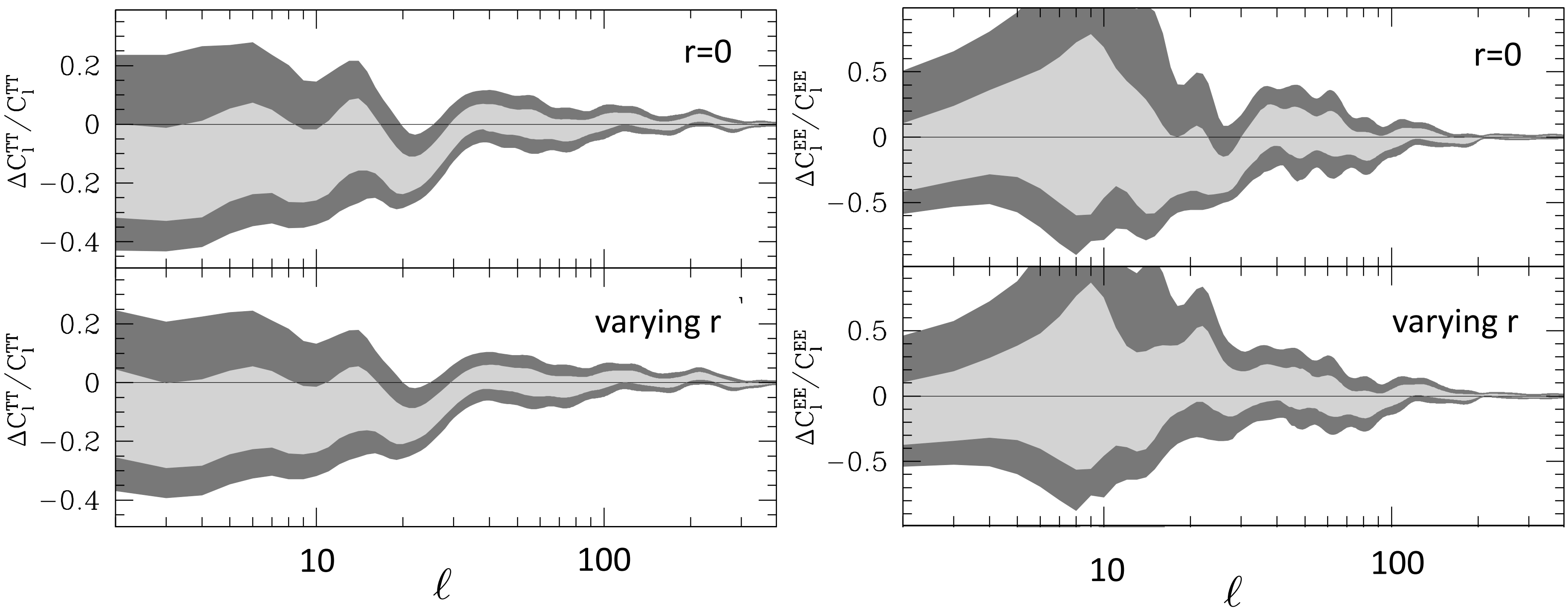
Primordial B-modes and Initial Curvature Power Spectrum reconstruction



Planck temperature data + WMAP 9-year polarization + DR11 BAO + SHOES H_0.

V. Miranda, W. Hu, and ***C. Dvorki****n, PRD submitted (2014)*

Polarization Predictions



V. Miranda, W. Hu, and ***C. Dvorki****n, PRD submitted (2014)*

Testing the single-field slow-roll consistency relation

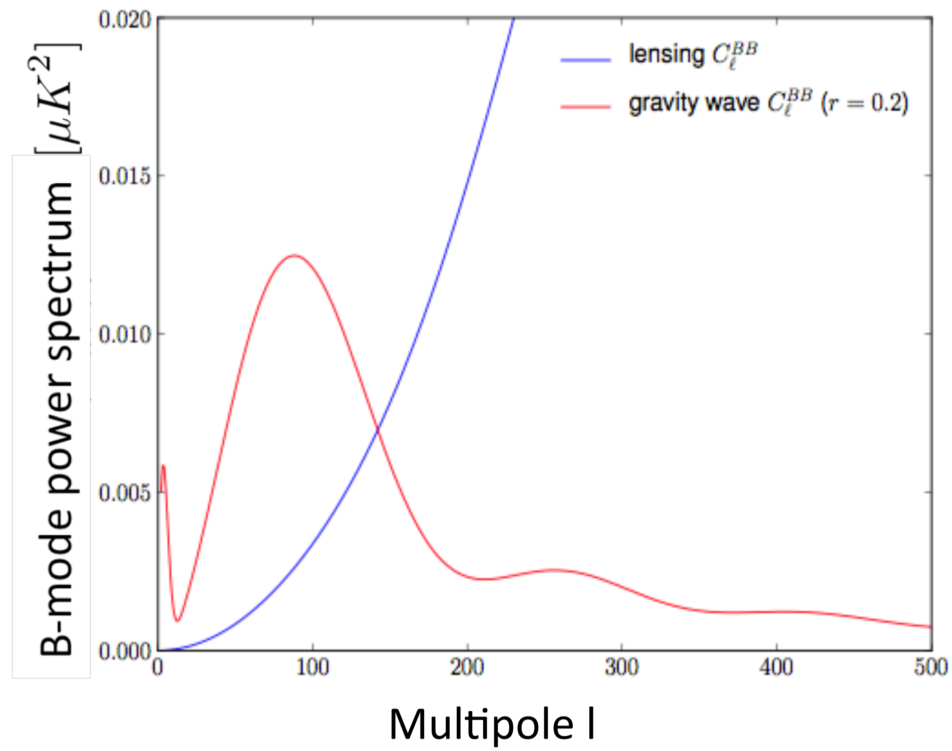
On CMB scales, the tensor power spectrum is predicted to be almost a power-law in most models of inflation:

$$\left(k^3/2\pi^2\right) P_T(k) = r\Delta_\zeta^2 \left(k/k_0\right)^{n_t}$$

Prediction from single-field slow-roll "consistency relation":

$$n_t = -r/8$$

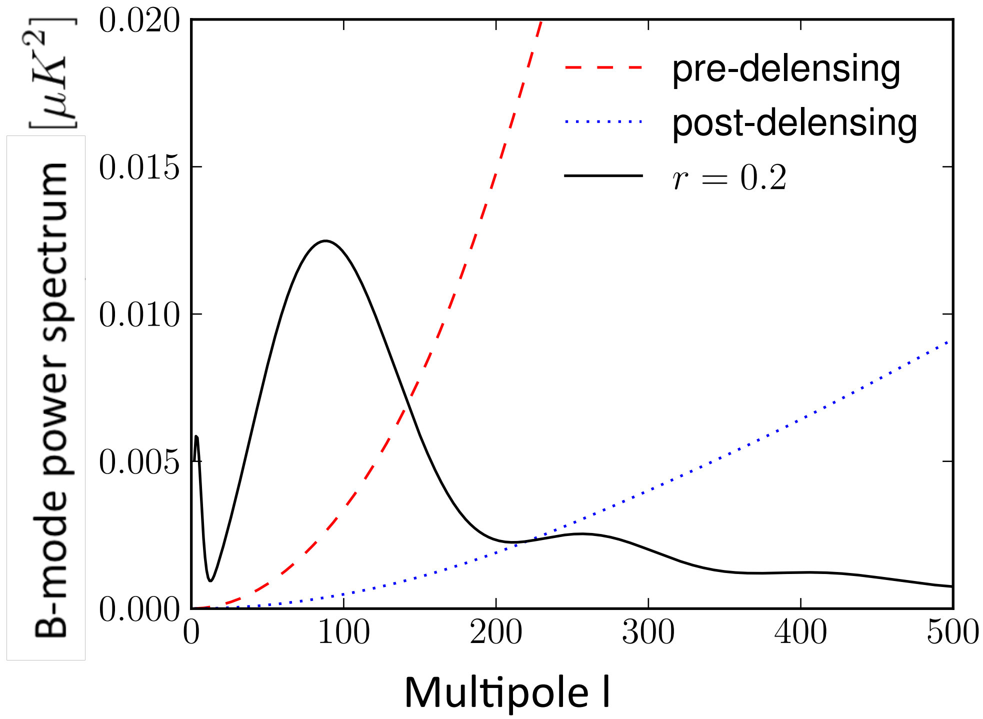
Relation between the amplitude and the tilt of the B-mode power spectrum.



Testing the single-field slow-roll consistency relation

"Delensing" is an algorithm that can separate the gravitational lensing B-modes (non-Gaussian) from the tensor B-modes (Gaussian), lowering the effective lensing.

U. Seljak and C. Hirata (2003)
M. Kesden, A. Cooray and M. Kamionkowski (2003)

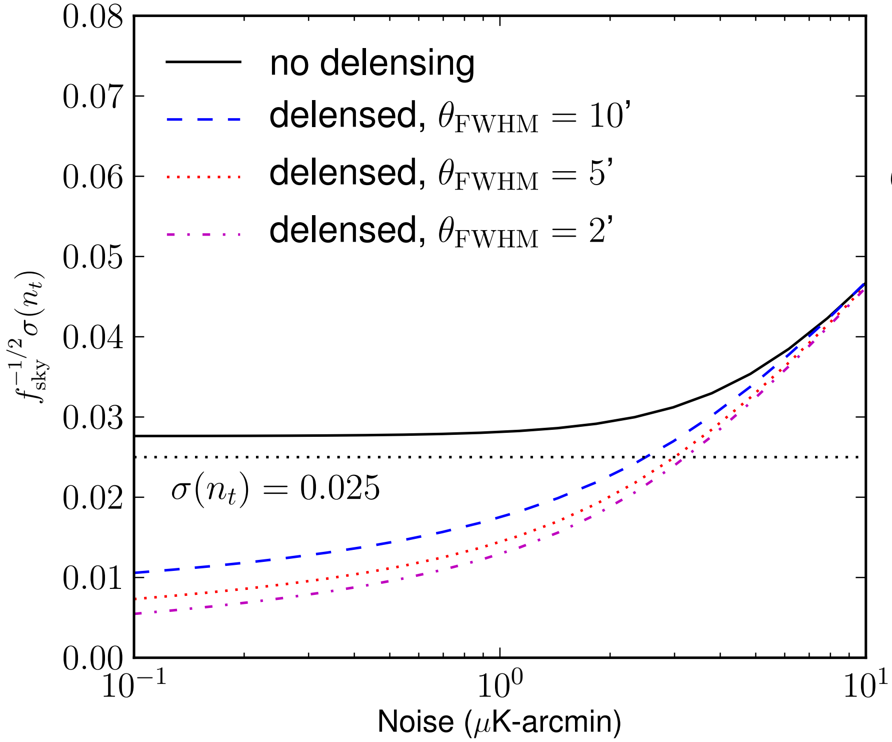


(see also Simard's poster)

L. Boyle, K. M. Smith, ***C. Dvorkin****, N. Turok, submitted to PRL (2014)*

Testing the single-field slow-roll consistency relation

We might be able to distinguish the consistency relation from scale invariance with a futuristic experiment such as the proposed "CMB Stage IV".



*W. Wu, J. Errard, **C. Dvorkin**, C. L. Kuo, A. Lee, et al., ApJ (2014)*

*L. Boyle, K. M. Smith, **C. Dvorkin**, N. Turok, submitted to PRL (2014)*

How do we know if a B-mode measurement is primordial?

- Foregrounds/CMB can be separated by making observations at different frequencies.

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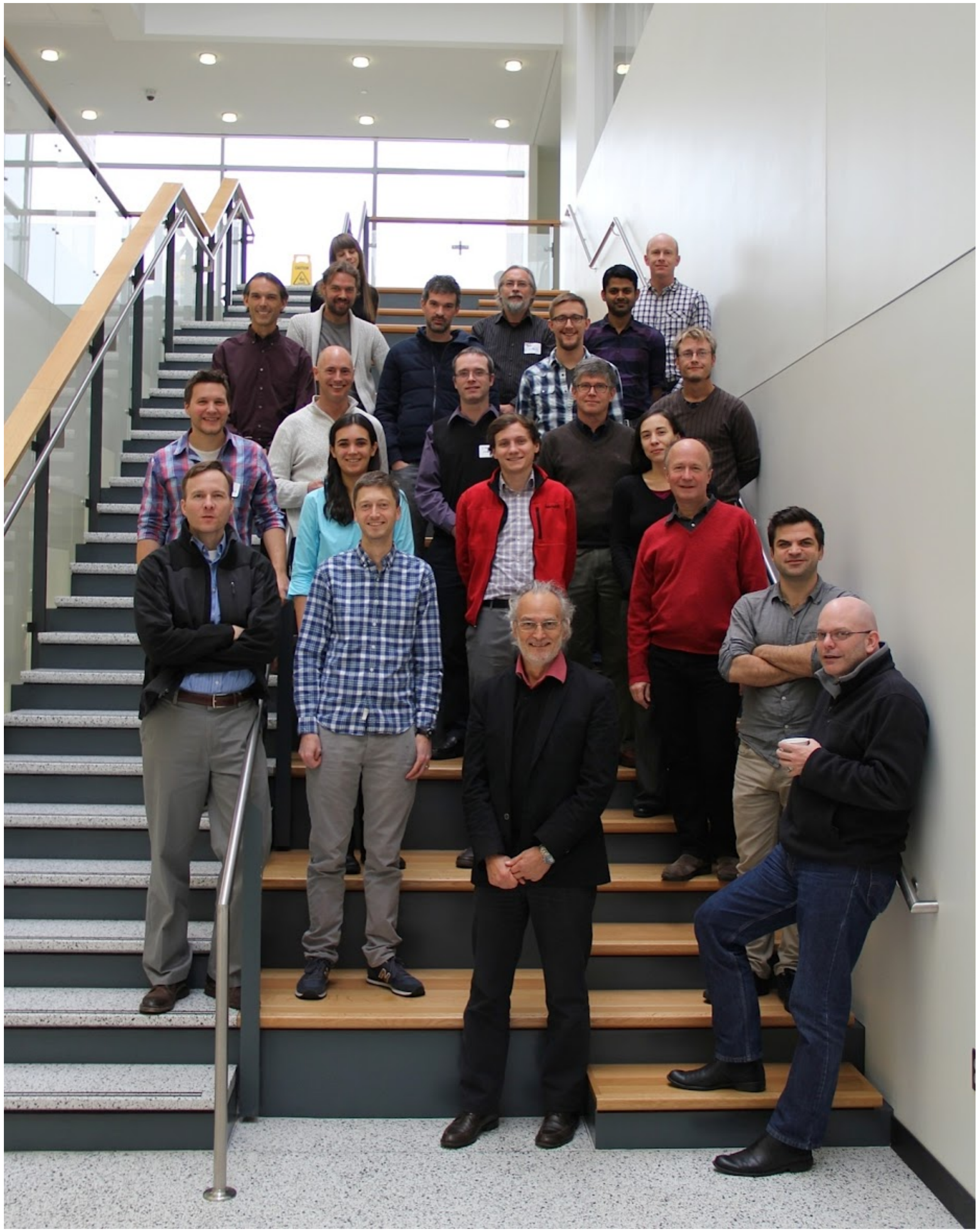
Is there a primordial signal in the BICEP2 measurement?

- The cross-correlation of BICEP2 and KECK maps with Planck maps at different frequencies will help to shed light on this question.

Analysis to appear very soon!



Conclusions and Future Directions

- Using Cosmic Microwave Background observations, we learned that our Universe can be described by a simple model (``LCDM").

- A primordial B-mode signal encodes a wealth of information about the physics of the very early universe:

- The amplitude of the signal is directly related to the energy scale of inflation.
- The shape of the signal could test the basic assumptions of single-field and slow-roll inflation (this would require "delensing" algorithms and an experiment such as the proposed "CMB Stage IV").
- A primordial B-mode signal would make the observed suppression in the initial curvature power spectrum even more pronounced. Predictions for the E-mode polarization could shed light on the origin of this suppression.

- A very difficult B-mode detection has been recently made.
  An important question remains: Is there a primordial signal buried under this measurement? (analysis to appear soon).