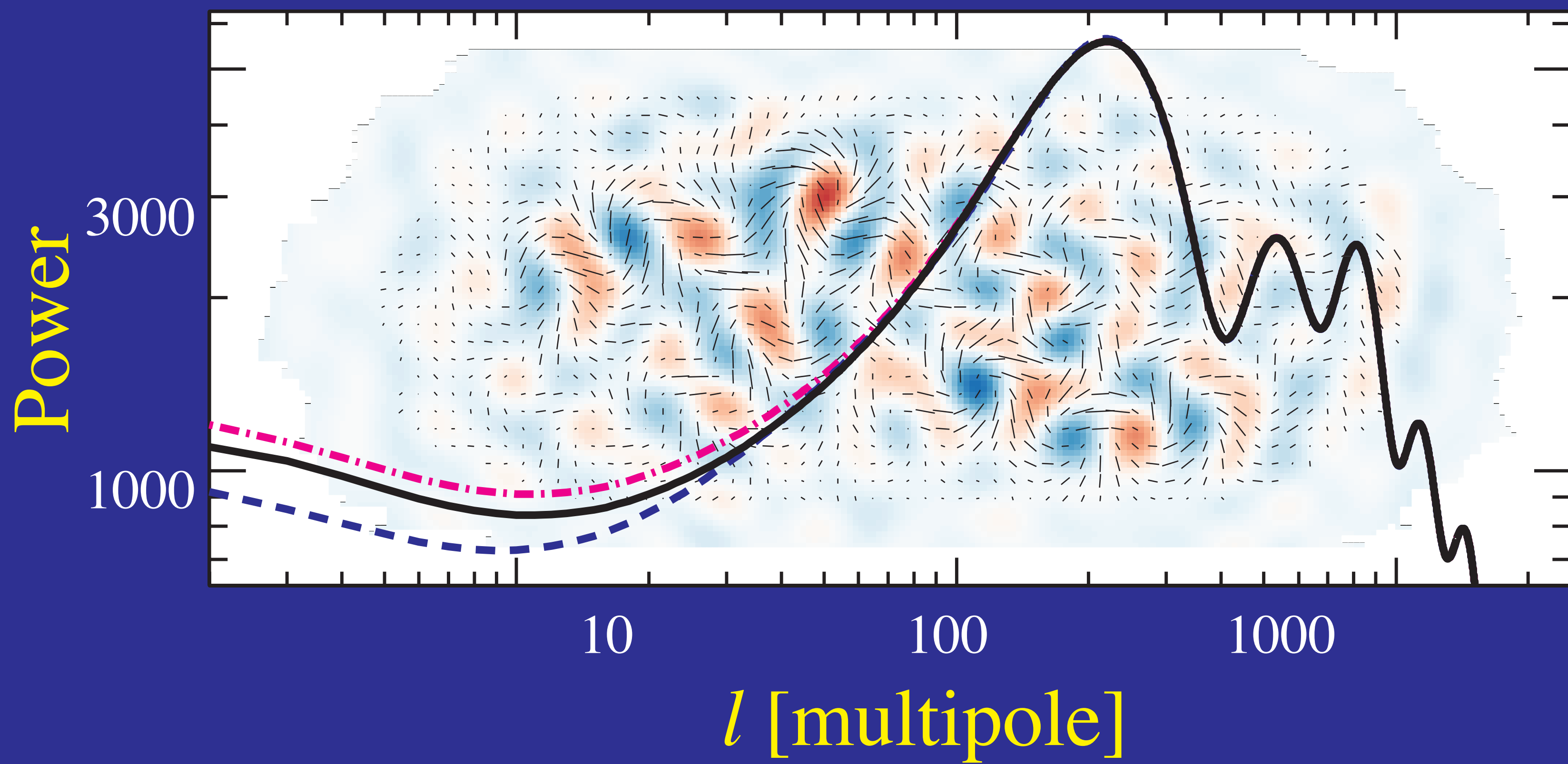
Features in Inflation
and Generalized Slow Roll



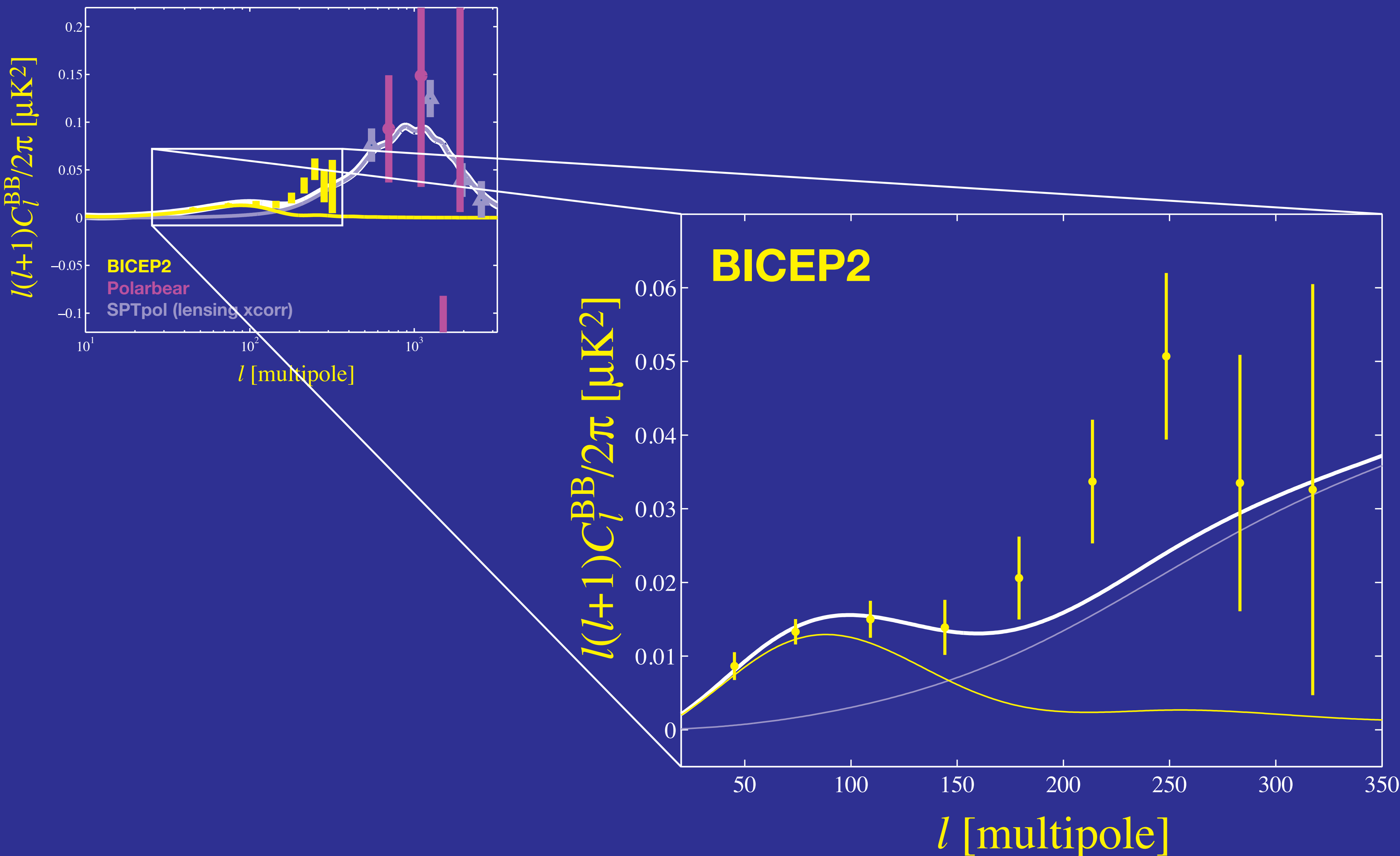
Wayne Hu

CosKASI, April 2014

BICEP Exercise

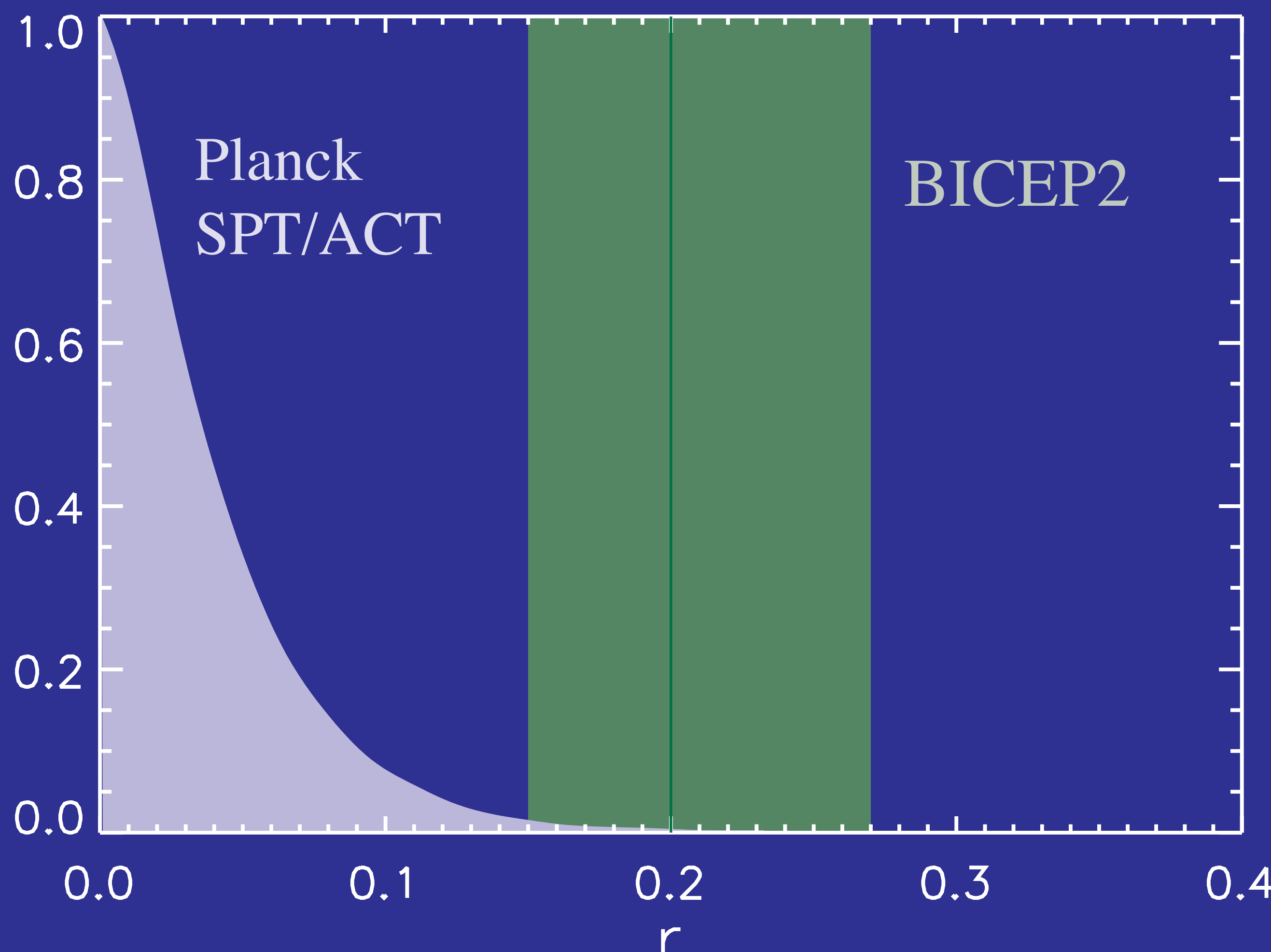
Year of the B-Mode

- Gravitational lensing B-modes (SPTPol, Polarbear...) detected
- Gravitational wave B-modes (BICEP2) measured



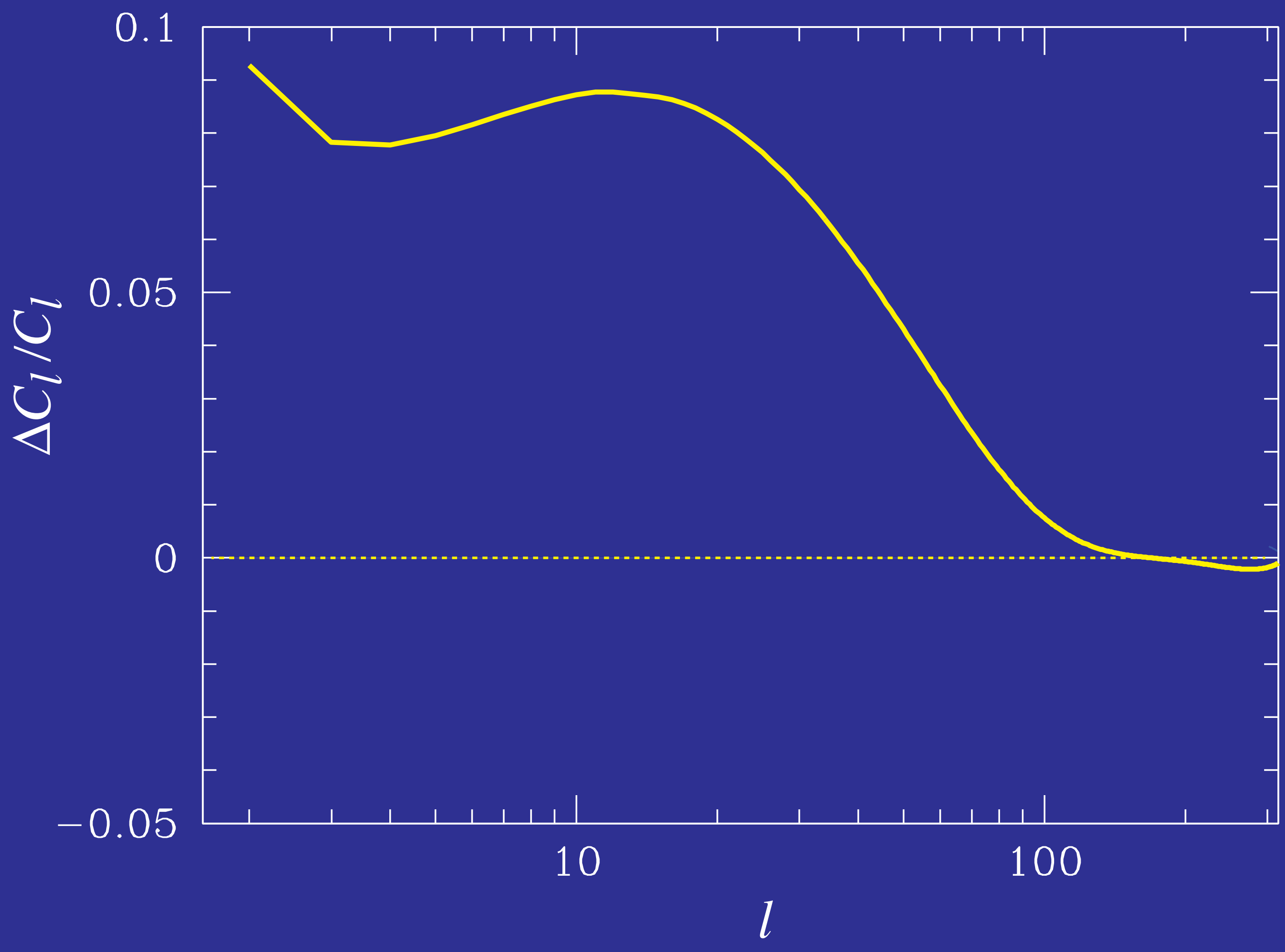
Tensor Tension

- In ΛCDM with power law scalar power spectra, Planck temperature power spectrum in tension with BICEP2 polarization detection



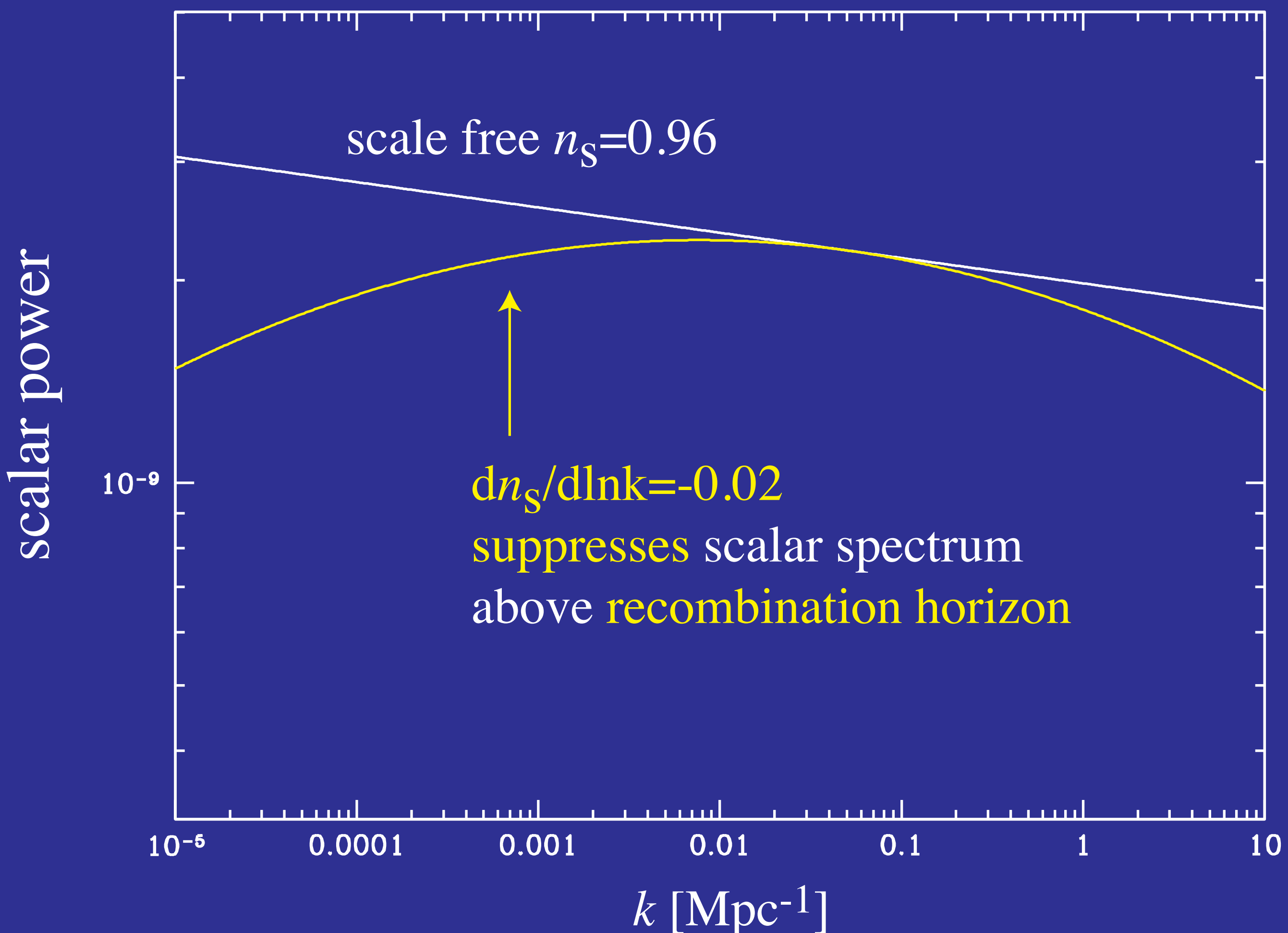
Tensor Temperature Excess

- r=0.2 and fixed acoustic peaks produces an excess in temperature power spectrum that is not observed (limits r<0.11 95% CL)
- Exacerbates a prexisting 2-3σ tension in ΛCDM at r=0



Running of the Tilt

- Introducing scale by running tilt changes inferences from temperature spectrum, weakening upper limit on r
- r=0.2 requires a large running of order the tilt, not compatible with scale-free potentials, more indicative of transient feature



Inflationary Features
and Generalized Slow Roll

Ordinary Slow-Roll Approximation

- Curvature power spectrum given by

$$\Delta^2_{\mathcal{R}}(k) = \left. \frac{H^2}{8\pi^2 M_{\rm pl}^2 \epsilon_H c_s} \right|_{k=1/s}$$

where $s = \int dN c_s/(aH)$ is the inflationary sound horizon and

$$\epsilon_H = -\frac{d\ln H}{dN} \ll 1$$

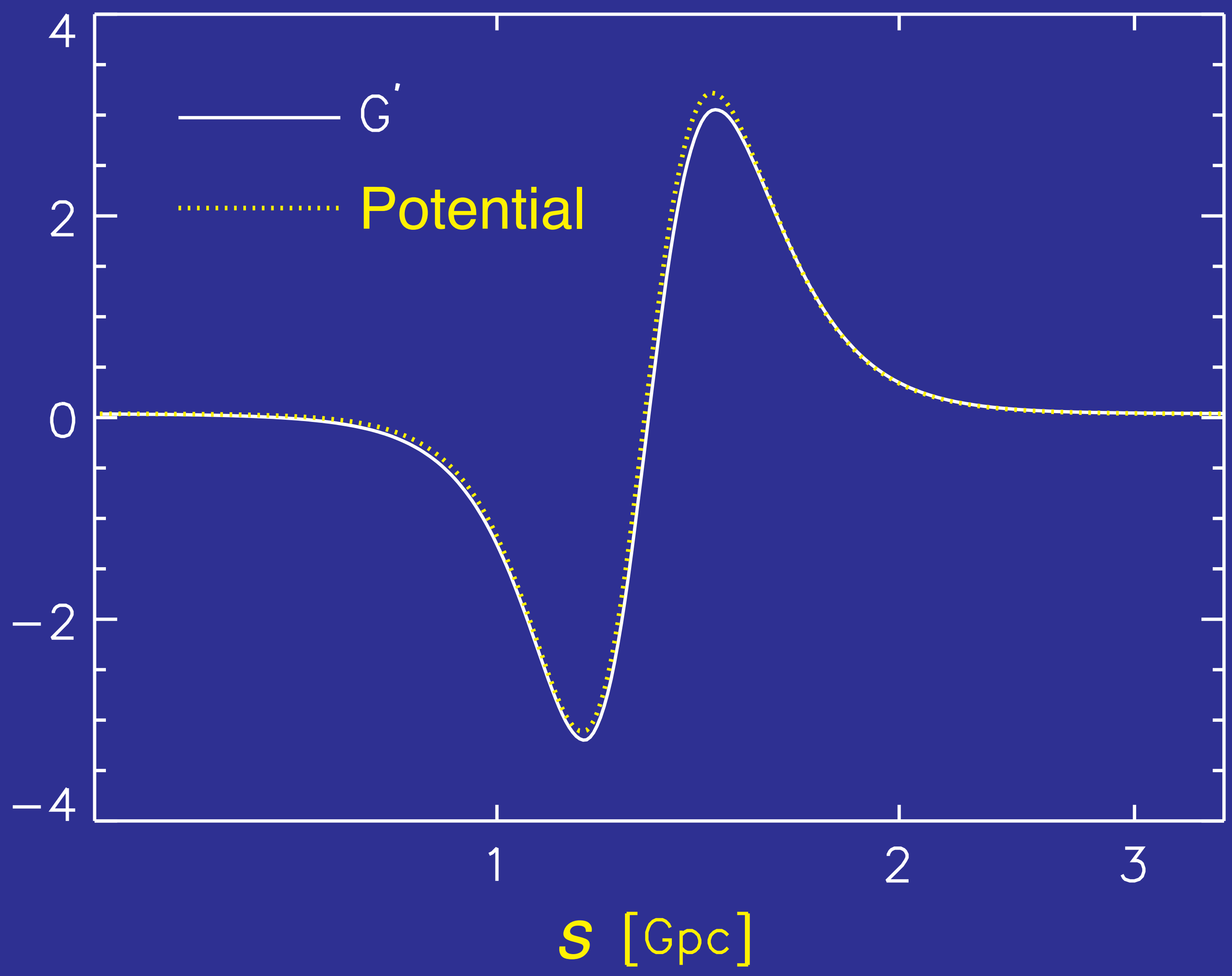
- The tensor-scalar ratio $r = 16\epsilon_H c_s$
- Scalars can be suppressed by making r evolve strongly with scale
- Evolution of slow-roll parameters violates the ordinary slow roll approximation but does not interrupt inflation if $\epsilon_H \ll 1$
- Not sufficient to introduce features directly into Δ^2_R

Generalized Slow-Roll Approximation

- Transient evolution in $\epsilon_H c_s$ preserves approximate de Sitter background
- Solve the Mukhanov-Sasaki equation iteratively with Green function technique using deviations from de Sitter as external source (Stewart 2002; Choe, Gong, Stewart 2004)
- Single source function G' captures power spectrum deviations up to order unity with percent level accuracy (Dvorkin & Hu 2010)
- Valid for any $P(X, \phi)$ or inflation EFT described by $(g_{00} + 1)^n$ operators (Hu 2011)
- Bispectrum for all terms including leading order modefunction correction terms for c_s^{-2} enhanced operators (Adshead, Hu, Miranda 2013)

GSR and the Potential

- GSR source function G' vs potential combination $3(V'/V)^2 - 2V''/V$

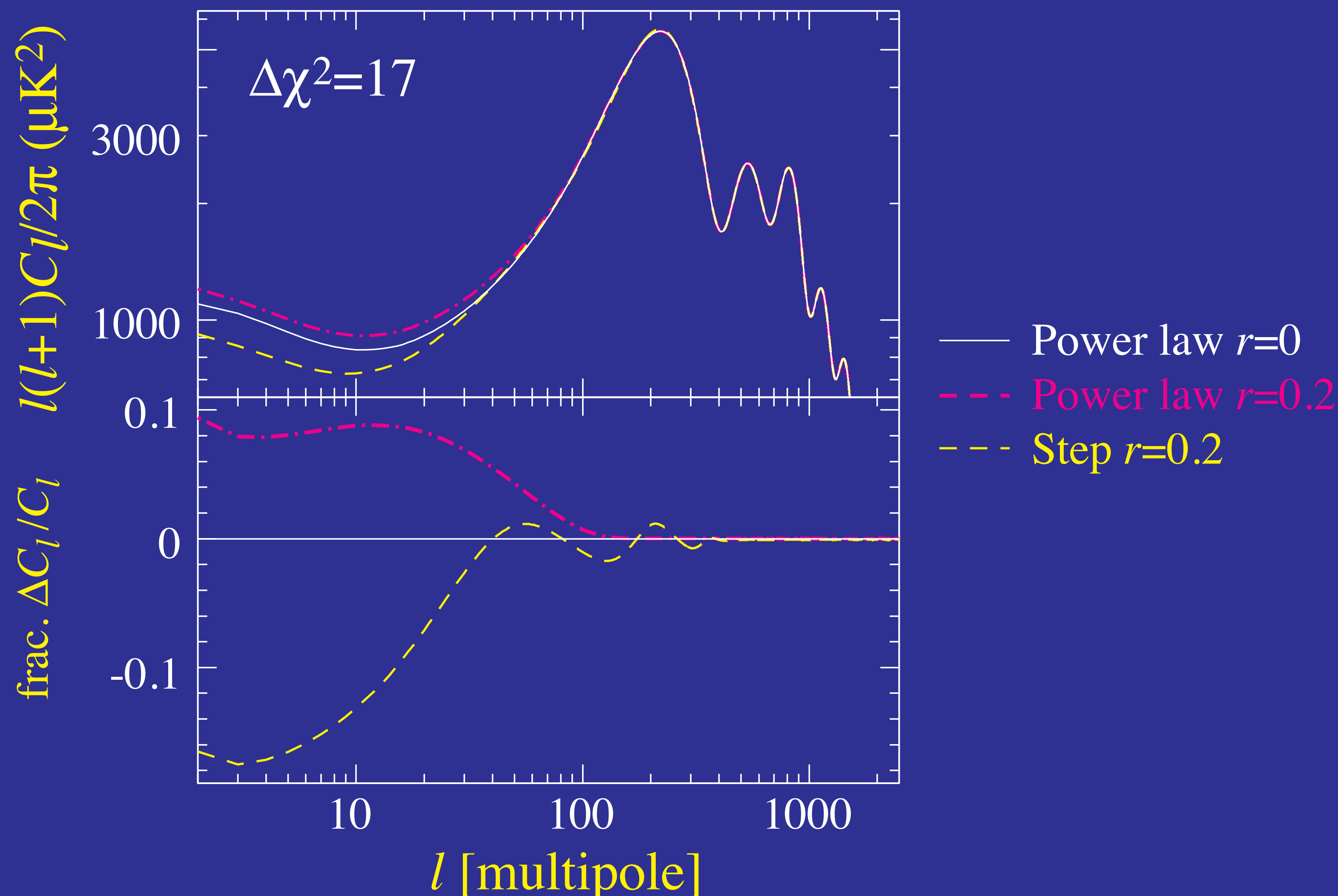


Dvorkin & Hu (2009)

Featuring the BICEP

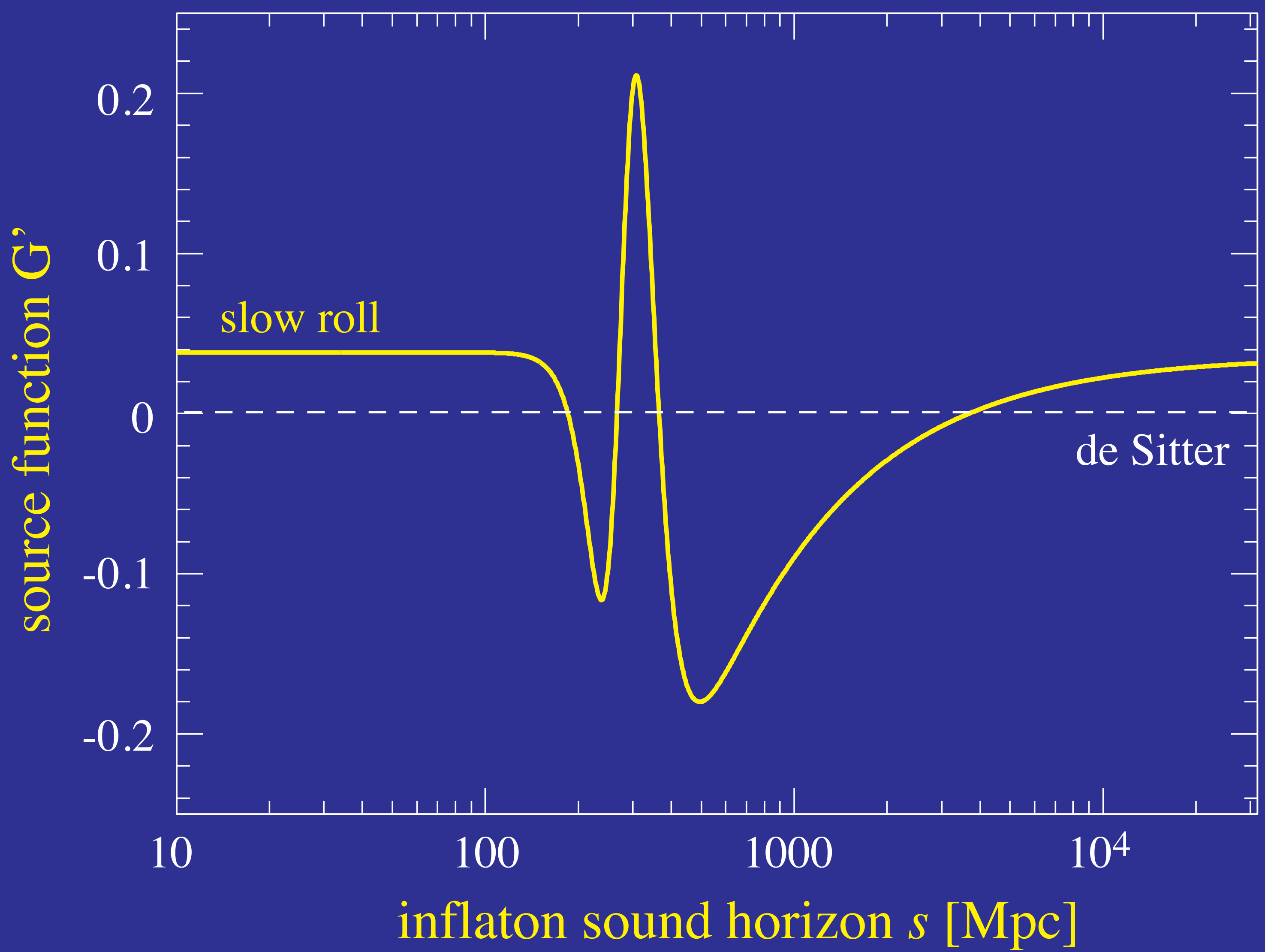
Tensor Temperature Excess

- Prefers sharper change than running, suppression over 1efold (excess exists even without tensors)
- Steps in power from steps in tensor scalar ratio $\epsilon_H c_s$



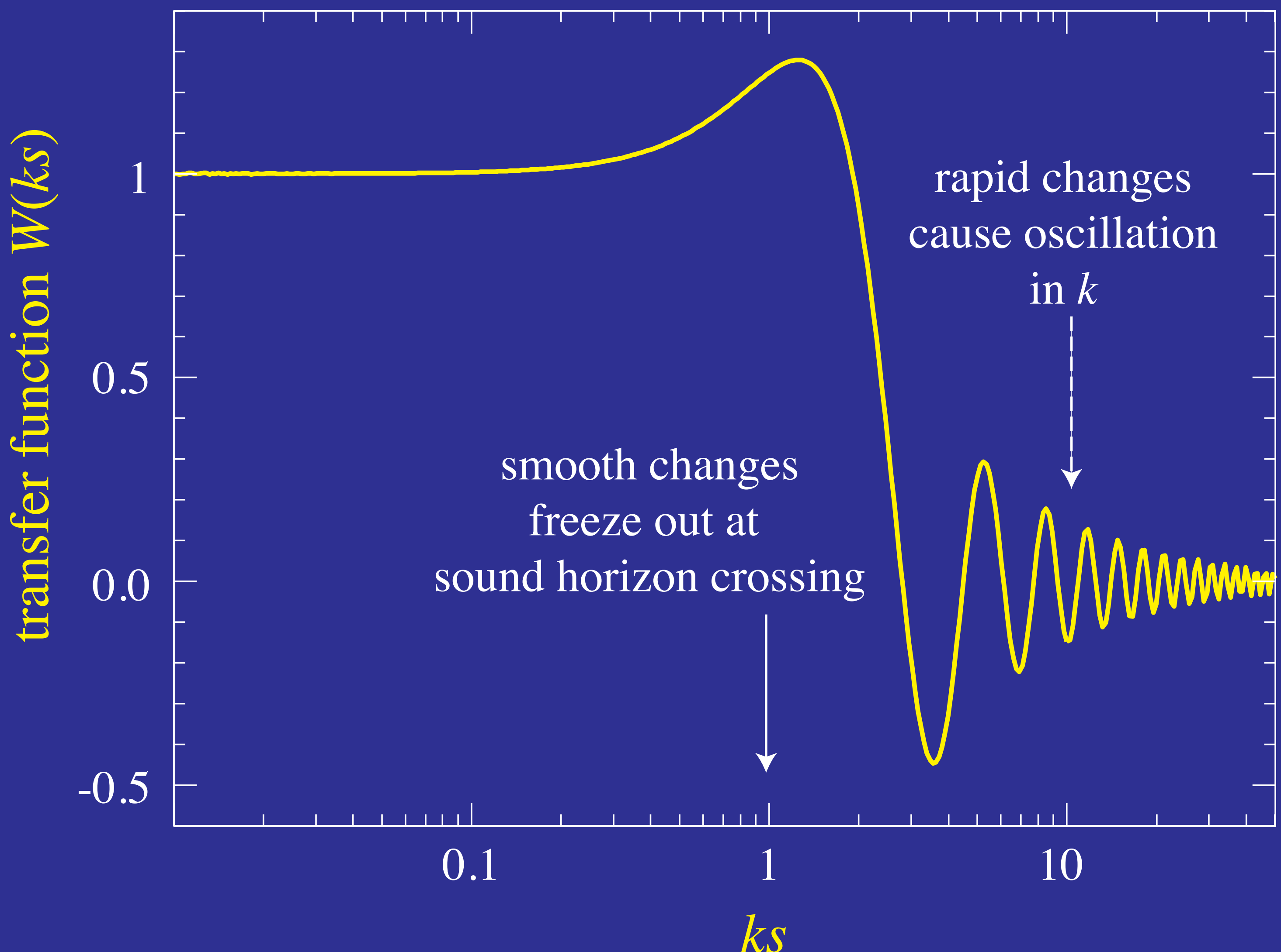
Freezeout of Curvature

- Source function G' deviations from de Sitter
- $G' = 1 - n_S$ is tilt in slow roll



Freezeout of Curvature

- De Sitter mode functions give *W*, linear transfer to curvature power
- For sharp features, curvature power oscillates or rings



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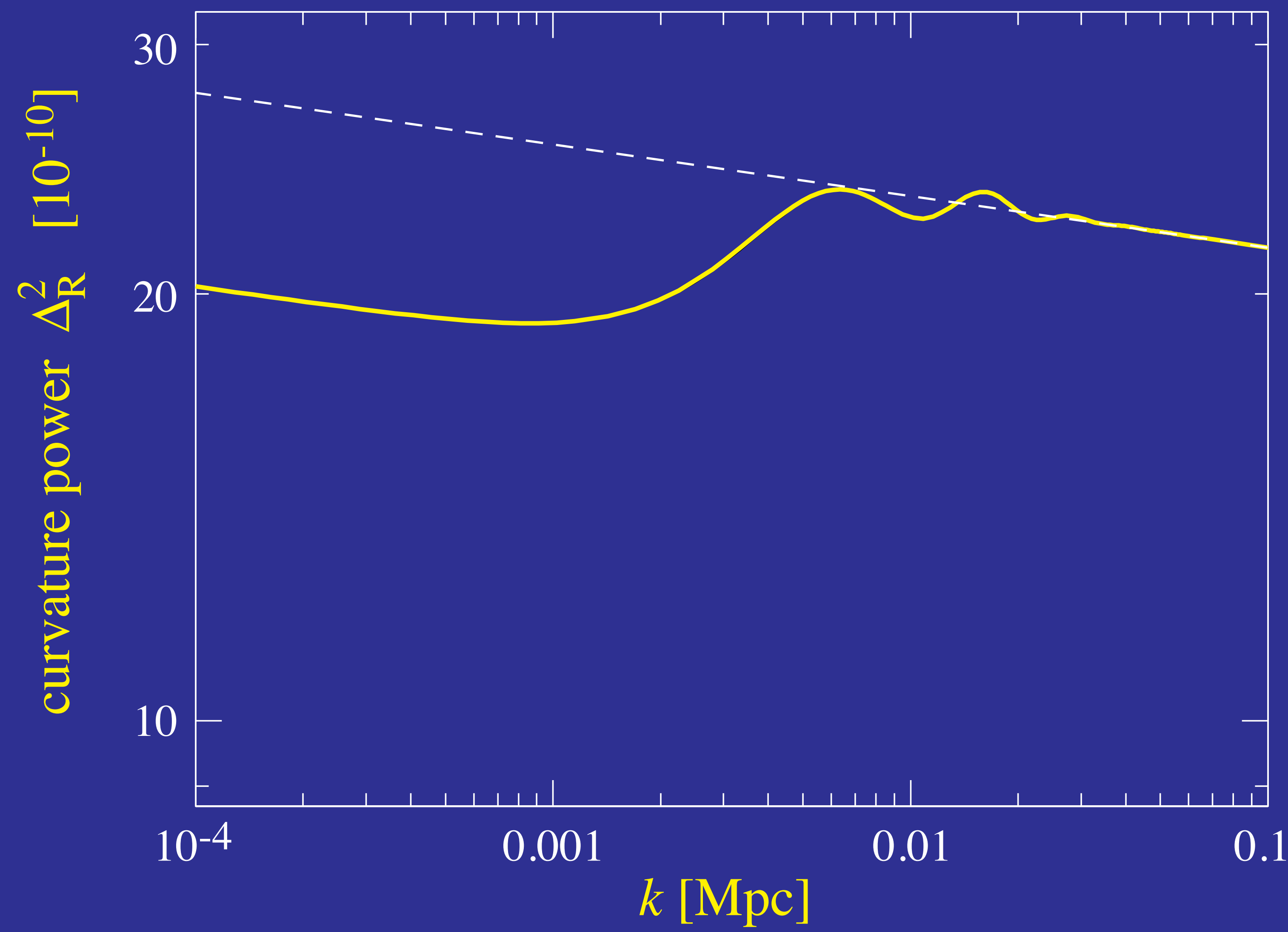
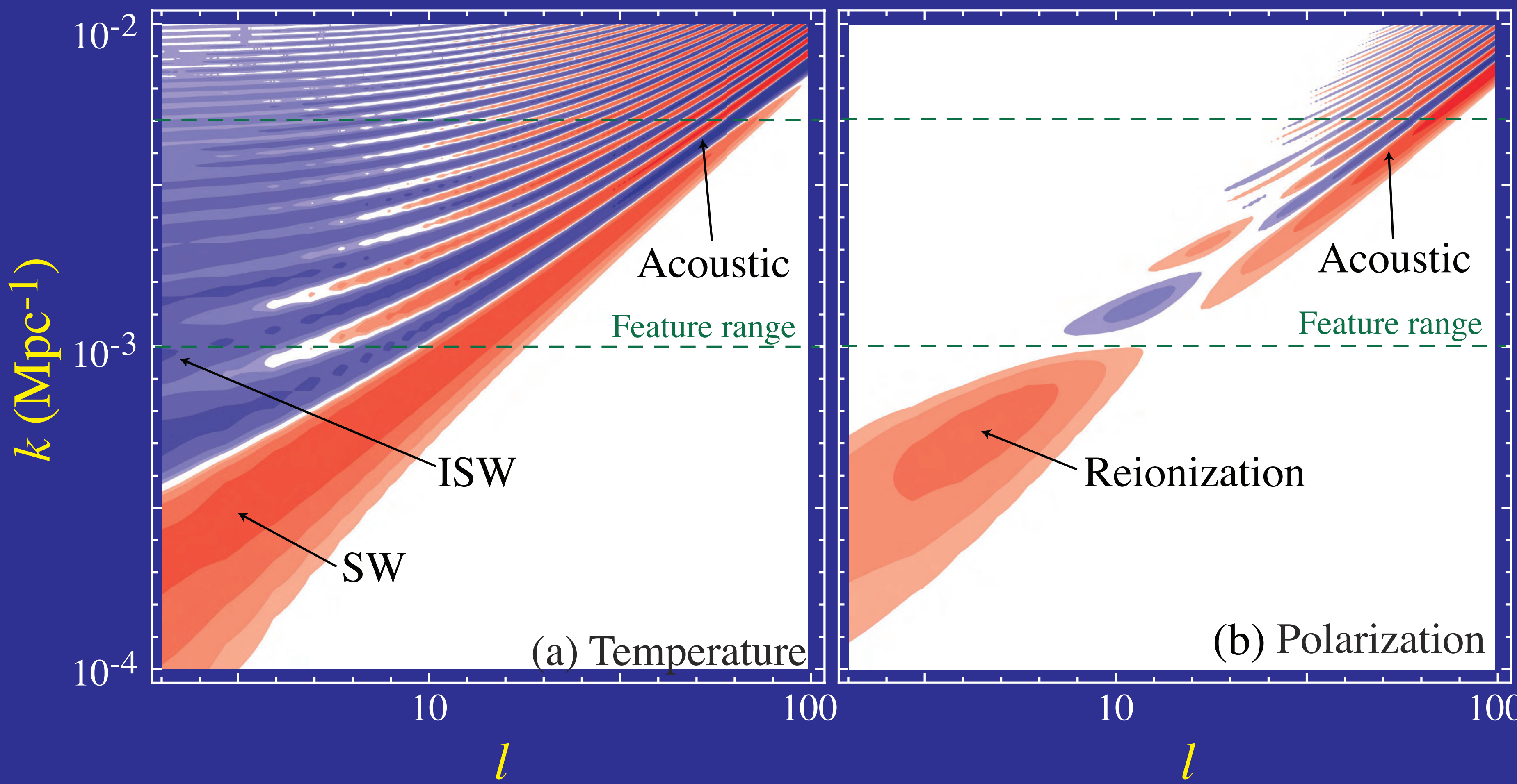


Transfer to Anisotropy

- Radiation transfer projects to temperature, E-polarization anisotropy
- Projection is sharp in the acoustic temperature regime, everywhere in E-polarization



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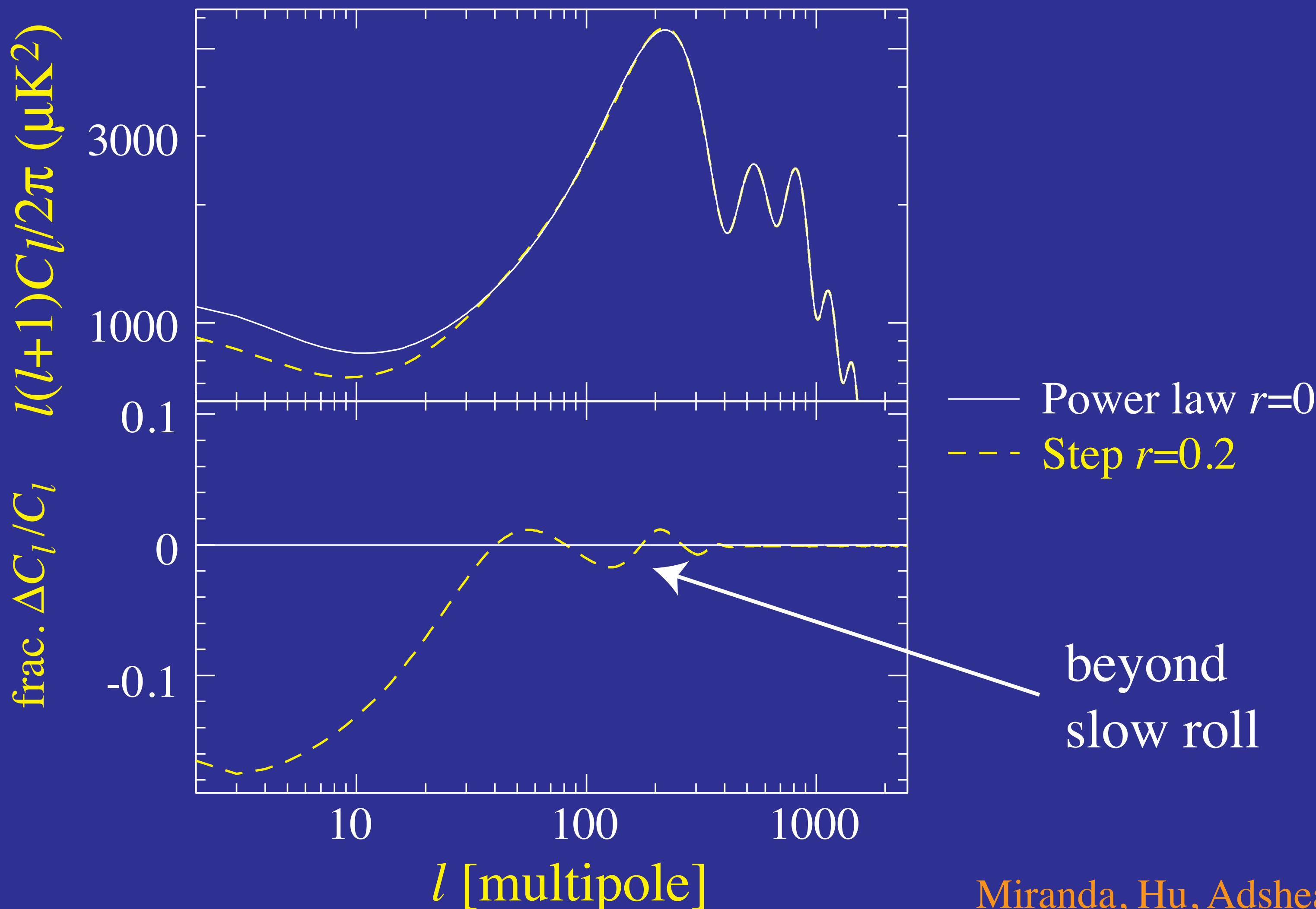
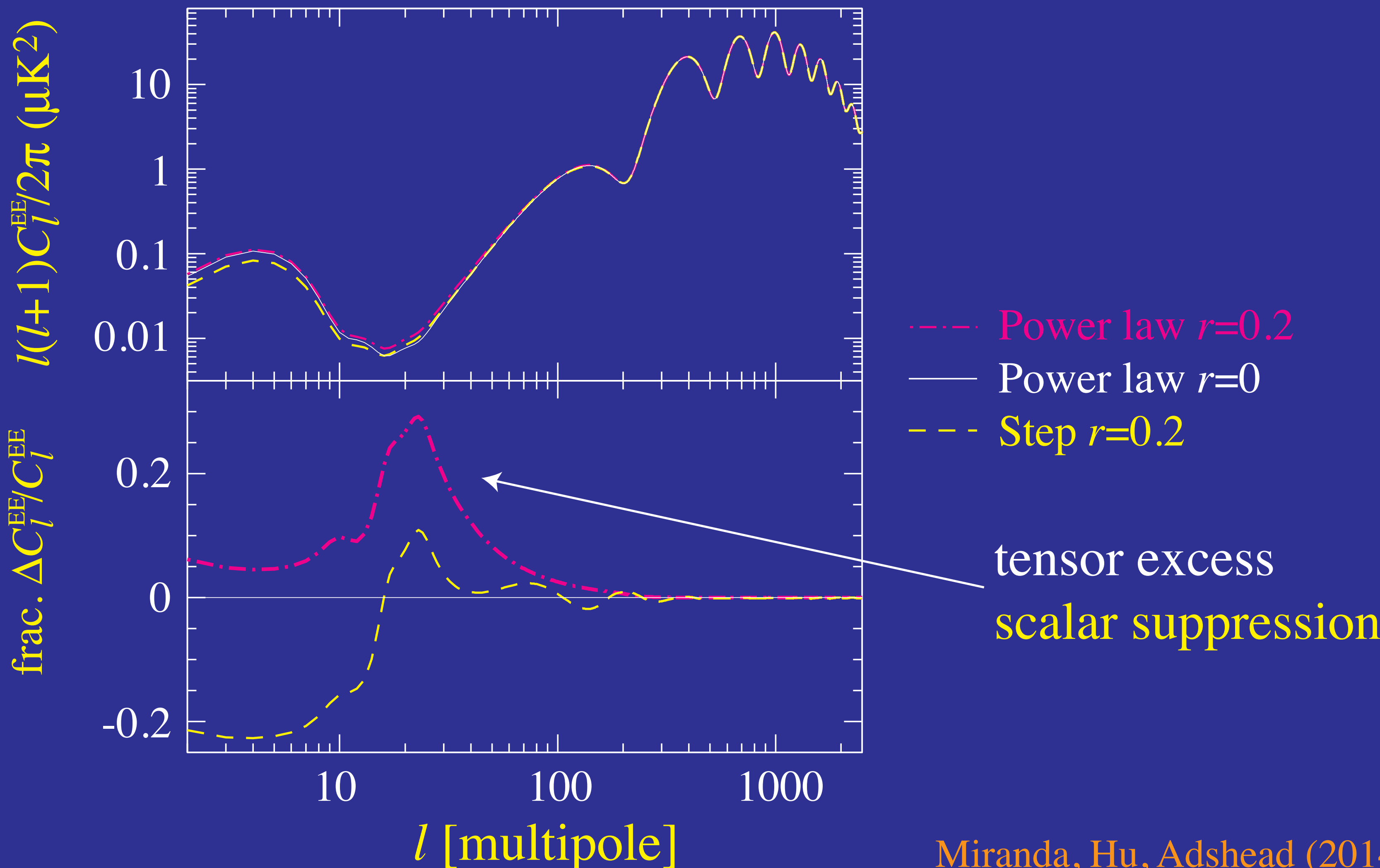


Miranda, Hu, Adshead (2014)

Polarization Predictions

- Matching tensor excess in E-mode polarization
- If scalars are suppressed by feature, E-modes compensated as well (as opposed to TT statistical fluke)

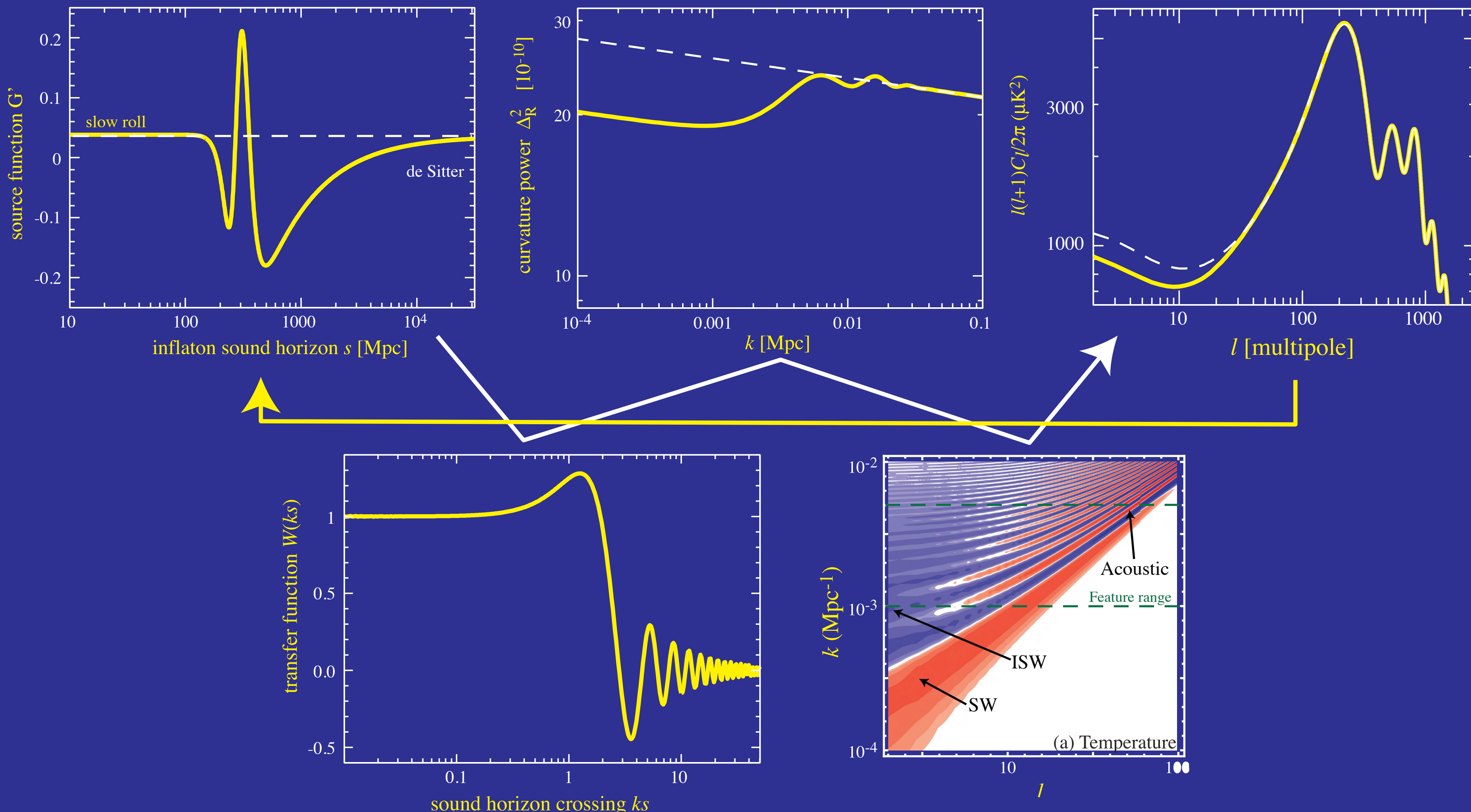


Miranda, Hu, Adshead (2014)

Reconstructing the Source

Inverse Problem

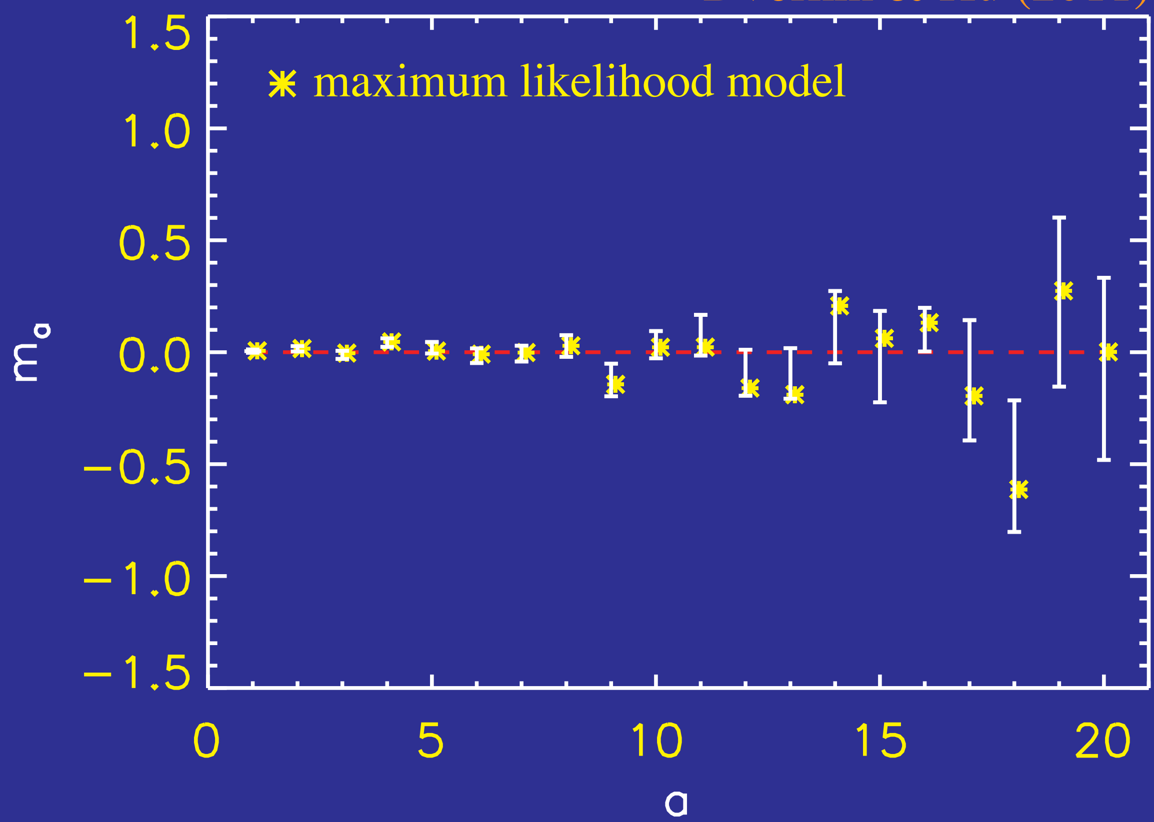
- Source function completely describes observable scalar properties
- Invert directly from observables to inflationary source
- Use transfer functions of a precomputed basis for rapid MCMC

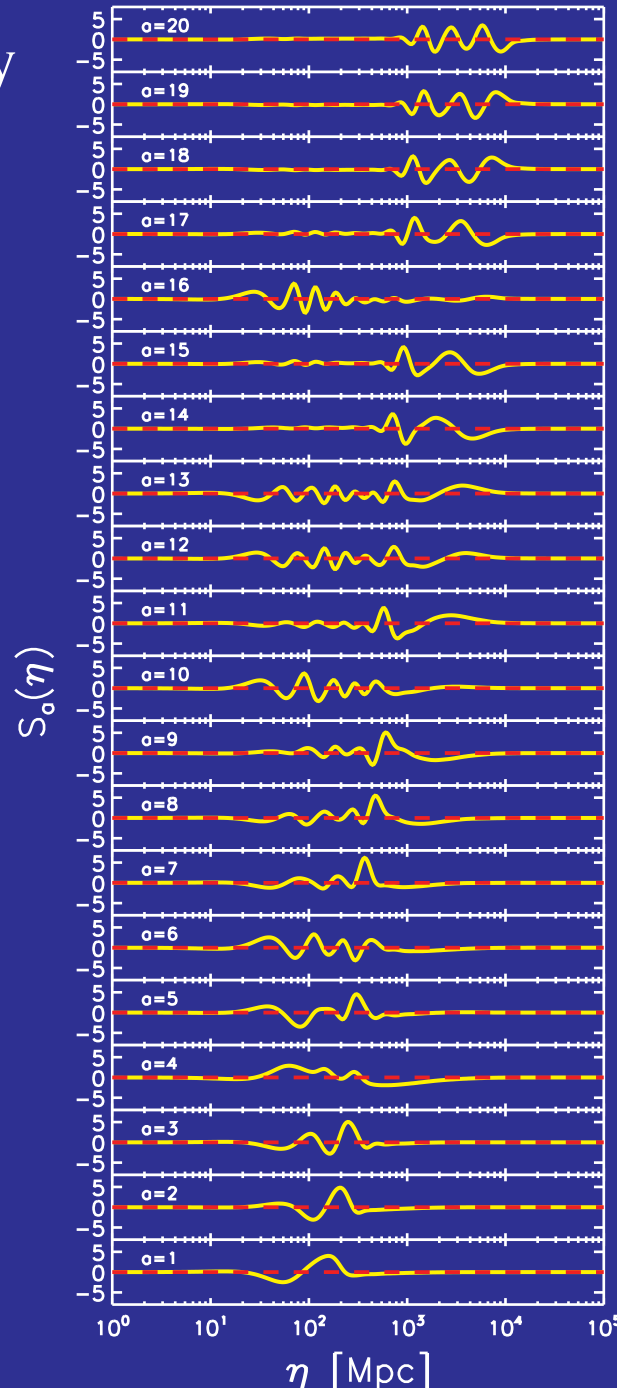


WMAP Basis

- Complete principal component basis for any observable feature with $\Delta N > 1/4$
- Cosmic variance and WMAP beam limit number to 20 components
- Maximum likelihood $2\Delta\ln L = 17$

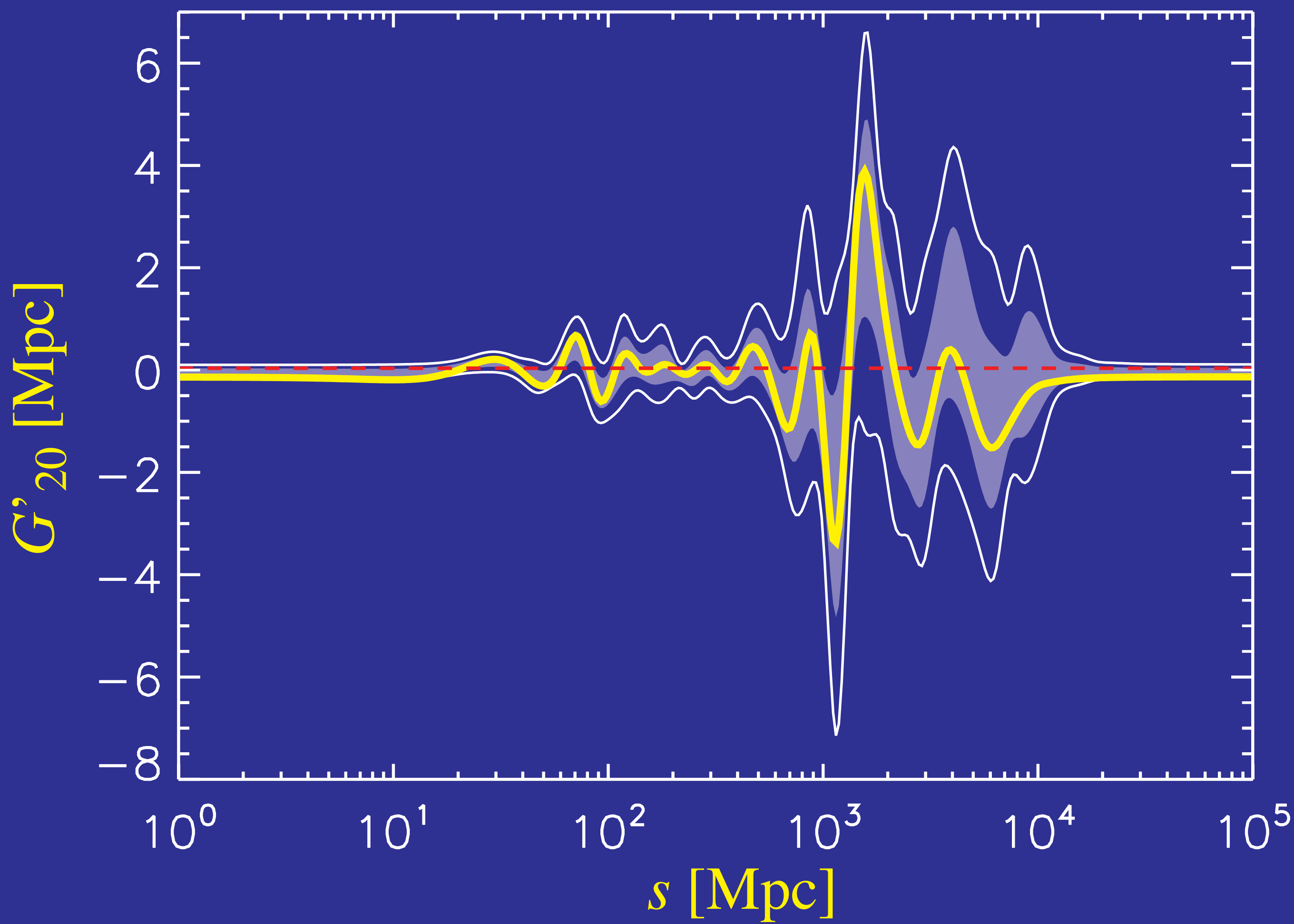
Dvorkin & Hu (2011)





Functional Constraints on Source

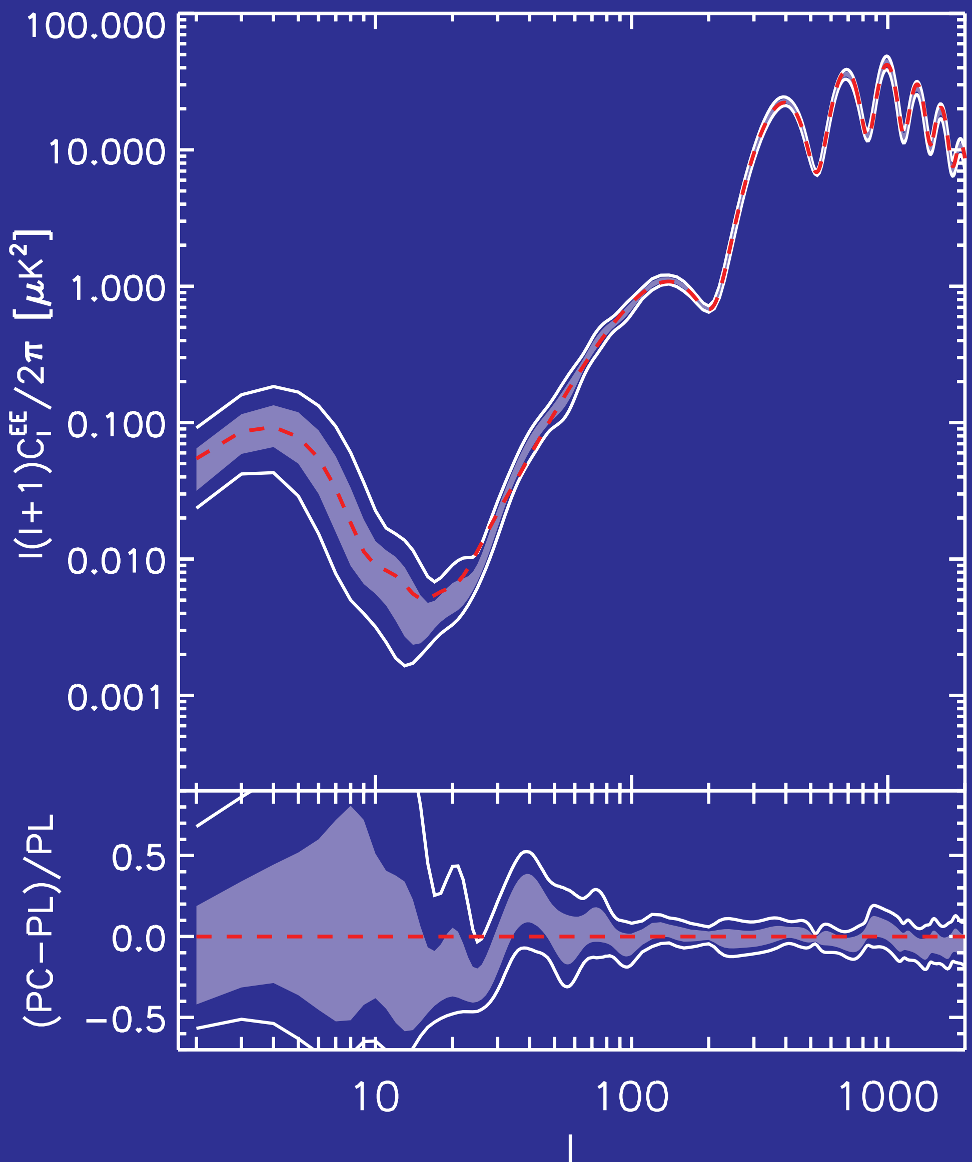
- 20 PC filter on source function from WMAP data
- Suppression at s>1000Mpc consistent with and Planck (in progress)
- BICEP2 changes preference for oscillation as tensors absorb and modify TT features



Dvorkin & Hu (2011)

Predicted Polarization

- If features are due to single field inflation (GSR) there must be corresponding ones in polarization

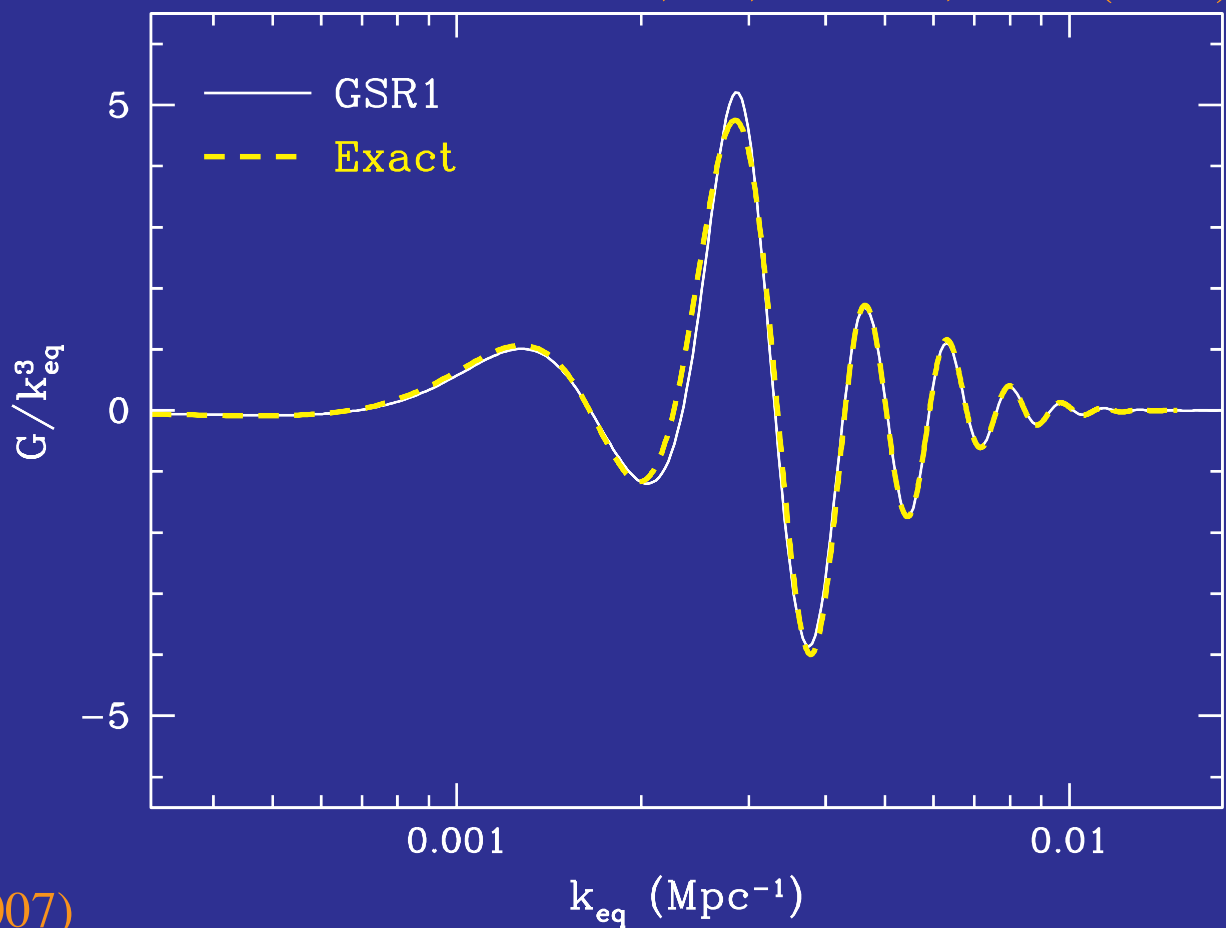


Dvorkin & Hu (2011)

Bispectrum Features

- Predicts features in the bispectrum
- Efficiently calculated through generalized slow-roll
- Bispectrum features related to the *l*~20-40 glitch are large but confined to too small a range to be observed

Adshead, Hu, Dvorkin, Peiris (2011)



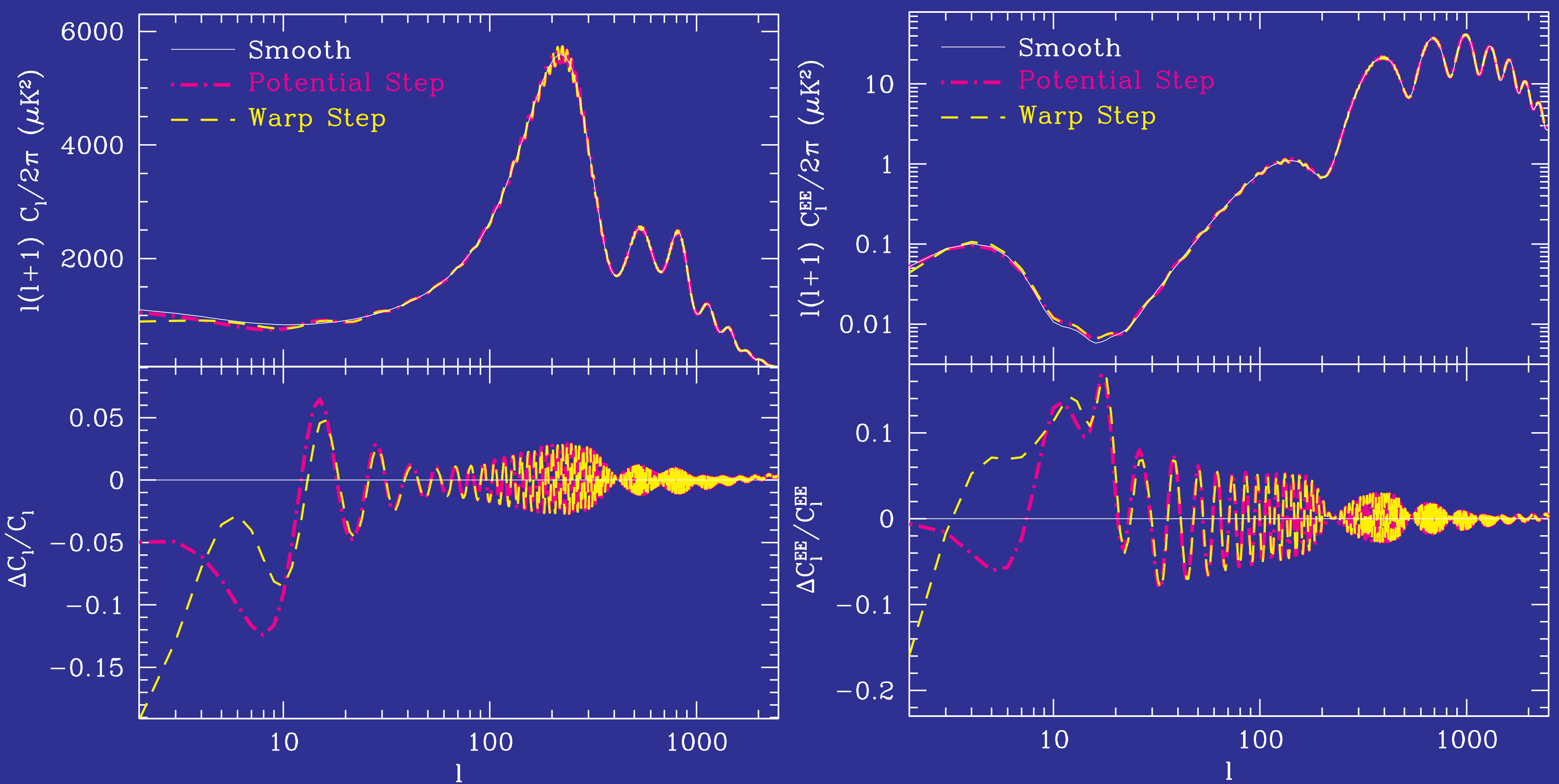
equilateral configuration

Chen et al (2007)

Sharp Steps

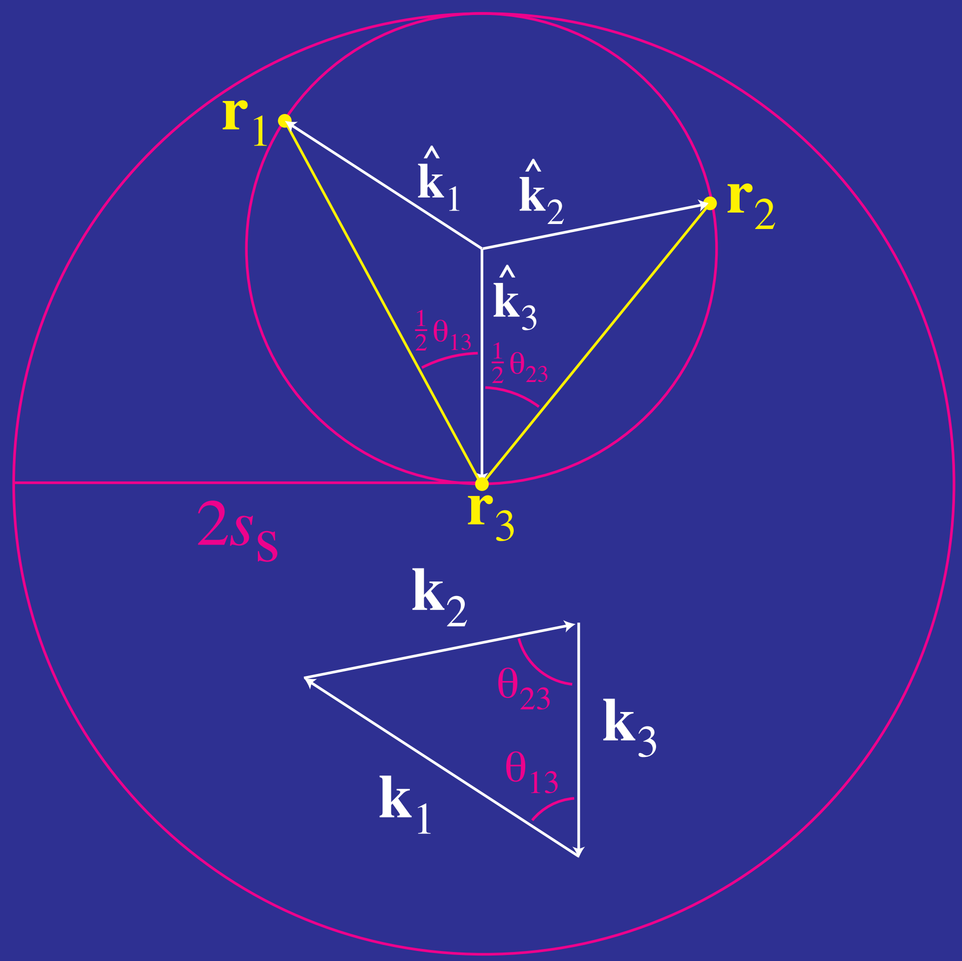
Oscillations in Planck Data

- Sharp step preferred in fits at $\Delta\chi^2$=11-15
- Chance noise realizations can produce spurious fits, matching E-polarization is key test



Sharp Real Space Feature

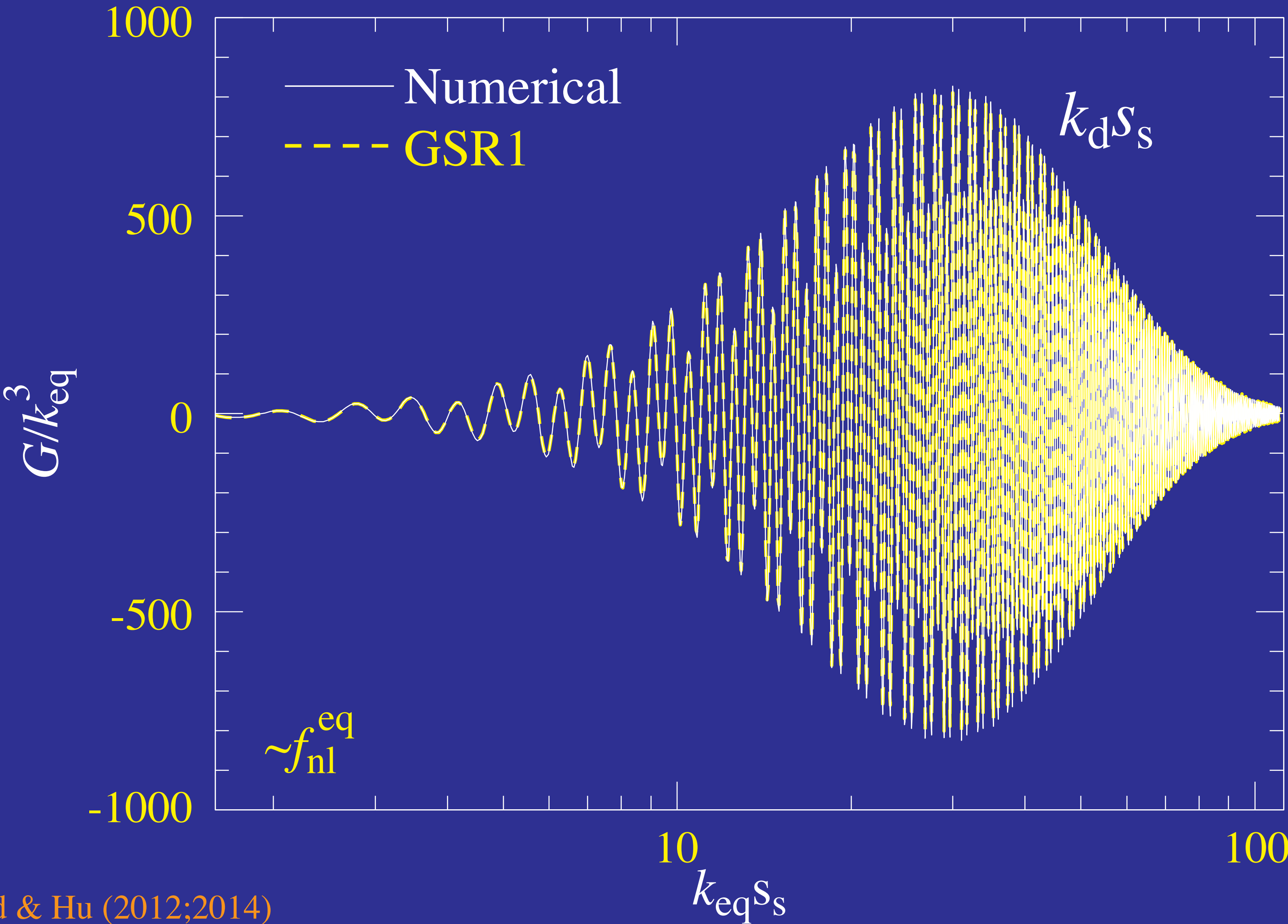
- Oscillatory high k power represents the Fourier transform of sharp correlation function feature with mild log divergence



Adshead, Dvorkin, Hu, Lim (2011)

Sharp Step

- Oscillatory high k power damped by finite width of feature
- For theoretical maximum k^2 to $k_d s_s$~100; S/N ~ power spectrum



Adshead & Hu (2012;2014)

Summary

- Planck-BICEP2 tension between TT and BB may indicate features in inflationary spectrum
- Step in tensor scalar ratio $r \propto \epsilon_H c_s$ significantly favored in ΛCDM
- Relatively sharp features preferred, beyond scope of ordinary slow roll approximation
- Ringing in spectrum highly constrained in acoustic regime, matching E-polarization predicted, testable
- Generalized slow roll technique accurately computes power spectrum and bispectrum
- Extremely sharp step separately preferred but can be mimicked by noise
- Conclusive tests in polarization and bispectrum