Testing Inflation

KICP Retreat

October 2009

Inflation Past

- Superhorizon correlations
  (acoustic coherence, polarization corr.)
- Spatially flat geometry
  (angular peak scale)
- Adiabatic fluctuations
  (peak morphology)
- Nearly scale invariant fluctuations
  (broadband power, small red tilt favored)
- Gaussian fluctuations
  (but $f_{\rm nl}$>few would rule out single field slow roll)

Inflation Present

- Tilt indicates that one of the slow roll parameters finite (ignoring exotic high-z reionization)
- Upper limit on gravity waves put an upper limit on V'/V and hence an upper limit on how far the inflaton rolls

Bread & Butter:

- Constraints in the r-n_s plane test classes of models
- Given functional form of V, constraints on the flatness of potential when the horizon left the horizon predict too many (or few) efolds of further inflation

Exotica:

- Non-Gaussian fluctuations at f_{nl}~50?
- Glitches and large scale anomalies

Inflation Future

- Planck can test Gaussianity down to f_{nl}~few and make a high significance detection if f_{nl}~50
- Planck will provide a high significance measurement of tilt (n_S-1)
- Planck will test constancy of tilt - significant deviation would rule out all standard slow roll models

- Gravitational wave power proportional to energy scale to 4th power
- B-modes potentially observable for $V^{1/4}$>3 x 10^{15} GeV with removal of lensing B-modes and foregrounds

- Measuring both the reionization bump and recombination peak tests slow roll consistency relation by constraining tensor tilt

Inflationary Observables

- Curvature Power Spectrum:

$$\Delta^2_{\mathcal{R}} \approx \frac{8\pi G}{2}\frac{1}{\epsilon}\left(\frac{H}{2\pi}\right)^2 , \quad \epsilon = \frac{1}{2}\frac{1}{8\pi G}\left(\frac{V'}{V}\right)^2$$

- Tilt

$$\frac{d\ln \Delta^2_{\mathcal{R}}}{d\ln k} = n_S - 1 = -4\epsilon - 2\delta$$

where

$$\delta = \epsilon - \frac{1}{8\pi G}\frac{V''}{V}$$

So for featureless potentials e.g. monomial ϕ^n, $\epsilon \sim |\delta|$

- Running $dn_S/d\ln k$ second order

Inflationary Observables

- Gravitational Wave (Tensor) Power Spectrum:

$$\Delta^2_{+,\times} = 16\pi G \left(\frac{H}{2\pi}\right)^2$$

reflects energy scale of inflation $H^2 \propto V \equiv E_i^4$

$$\Delta B_{\rm peak} \approx 0.024 \left(\frac{E_i}{10^{16}{\rm GeV}}\right)^2 \mu{\rm K}$$

- Tensor-Scalar Ratio, Tilt:

$$r \equiv 4\frac{\Delta^2_+}{\Delta^2_{\mathcal{R}}} = 16\epsilon\,, \qquad \frac{d\ln\Delta^2_+}{d\ln k} \equiv n_T = 2\frac{d\ln H}{d\ln k} = -2\epsilon$$

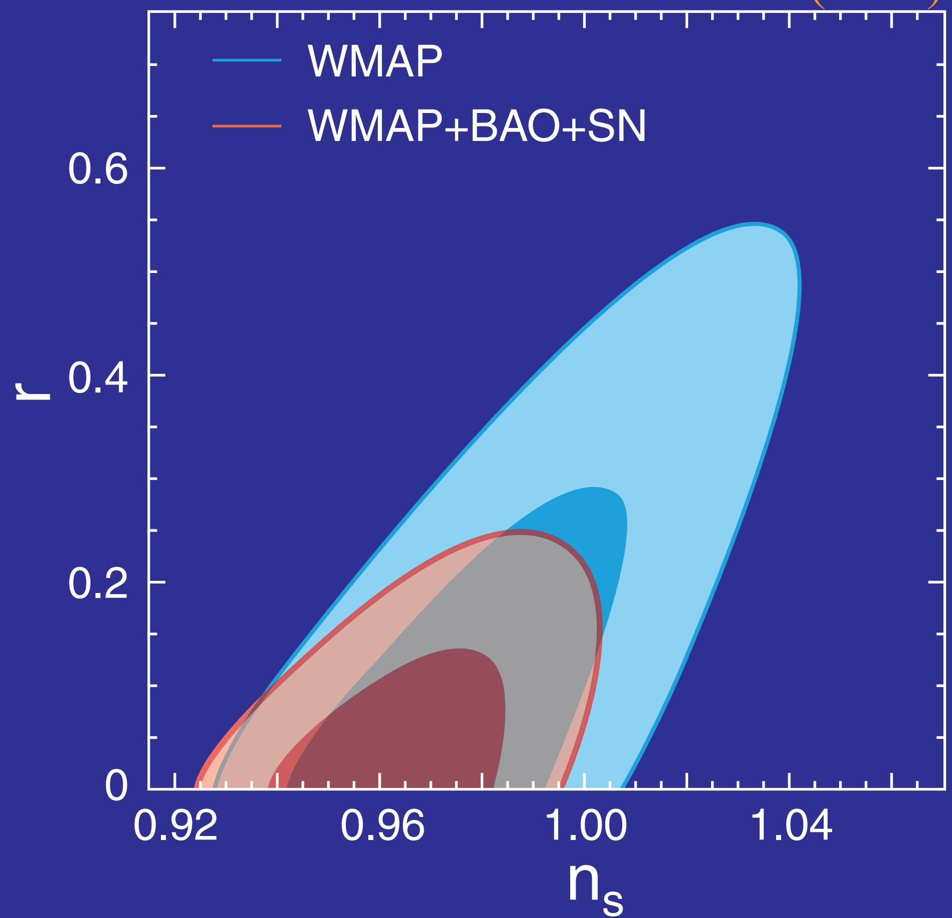
- Consistency:

$$r = -8n_T$$

Inflationary Constraints

- Tilt mildly favored over tensors as explaining small scale suppression
- Specific models of inflation relate r-n_s through V', V''
- Small tensors and $n_s\sim1$ may make inflation continue for too many efolds

Komatsu et al (2008)



Large Field, Small Field Models

- For detectable gravitational waves $r > 0.01$, scalar field must roll by order $M_{\rm pl} = (8\pi G)^{-1/2}$

$$\frac{d\phi}{dN} = \frac{d\phi}{d\ln a} = \frac{d\phi}{dt}\frac{1}{H}$$

- The larger ϵ is the more the field rolls in an e-fold

$$\epsilon = \frac{r}{16} = \frac{3}{2V}\left(H\frac{d\phi}{dN}\right)^2 = \frac{8\pi G}{2}\left(\frac{d\phi}{dN}\right)^2$$

- Observable scales span $\Delta N \sim 5$ so

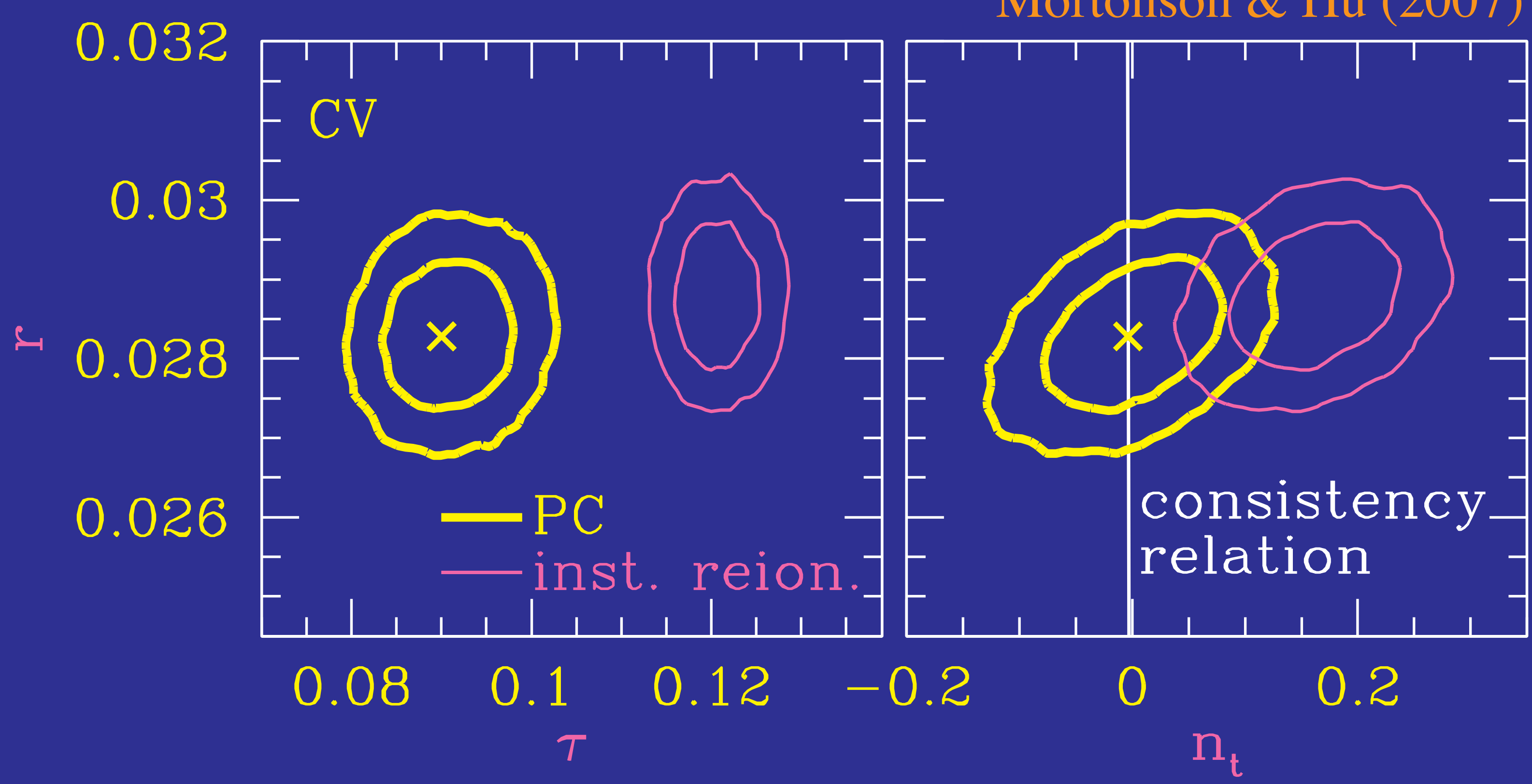
$$\Delta\phi > 5\frac{d\phi}{dN} = 5\left(\frac{r}{8}\right)^{1/2} M_{\rm pl} \approx 0.2\left(\frac{r}{0.01}\right)^{1/2} M_{\rm pl}$$

- Does this make sense as an effective field theory? Lyth (1997)
- Small field models where ϕ near maximum more reasonable?
- Large field existence proof: monodromy Silverstein & Westphal (2008) ...theorists running around in circles...

Consistency Relation & Reionization

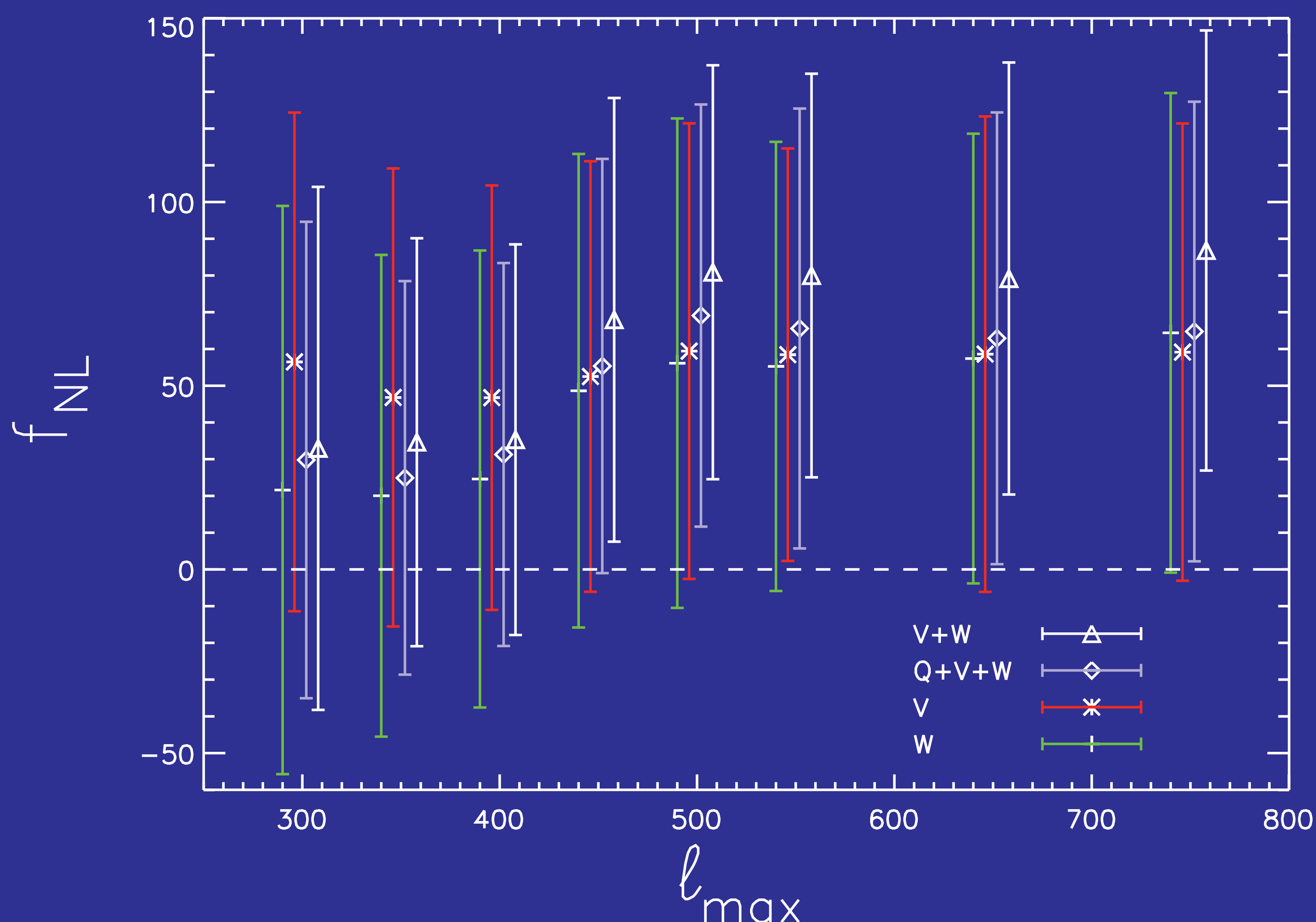
- By assuming the wrong ionization history can falsely rule out consistency relation
- Principal components eliminate possible biases

Mortonson & Hu (2007)



$f_{\rm nl}$ ($f_{\rm ml}$, $y_{\rm di}$...)

- Local second order non-Gaussianity: $\Phi_{\rm nl}=\Phi+f_{\rm nl}(\Phi^2-\langle\Phi^2\rangle)$
- WMAP3 Kp0+: $27<f_{\rm nl}<147$ (95% CL) (Yadav & Wandelt 2007)
- WMAP5 opt: $-4<f_{\rm nl}<80$ (95% CL) (Smith, Senatore & Zaldarriaga 2009)



Future Theoretical Directions

- Beyond single field, slow roll model building and phenomenology

  isocurvature

  potential features

  alignment and other large-scale anomalies

  non-Gaussianity

- Particle physics inspired model building

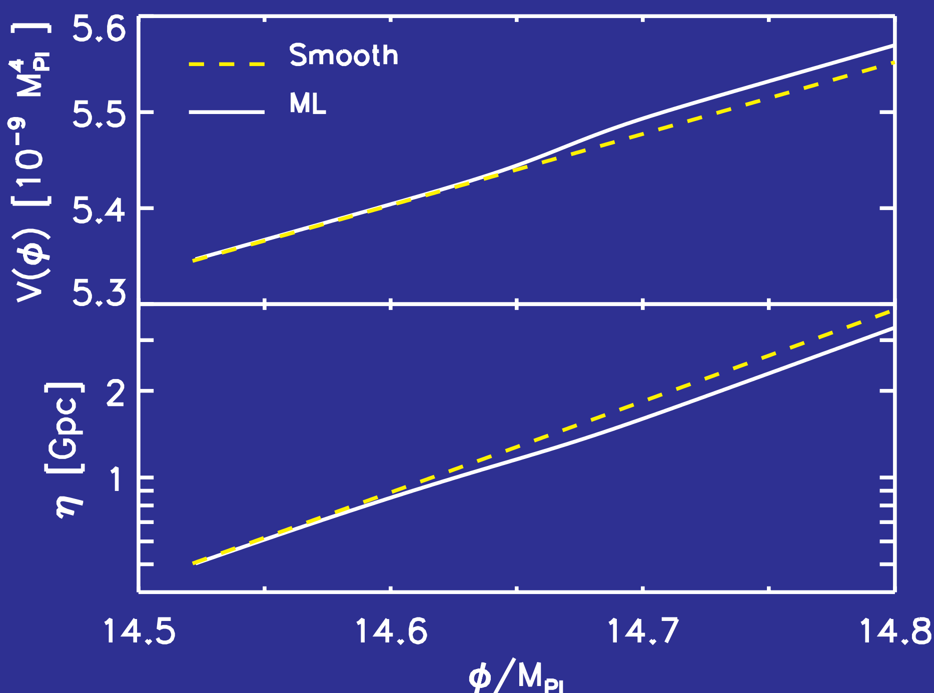
  SUSY (LHC)

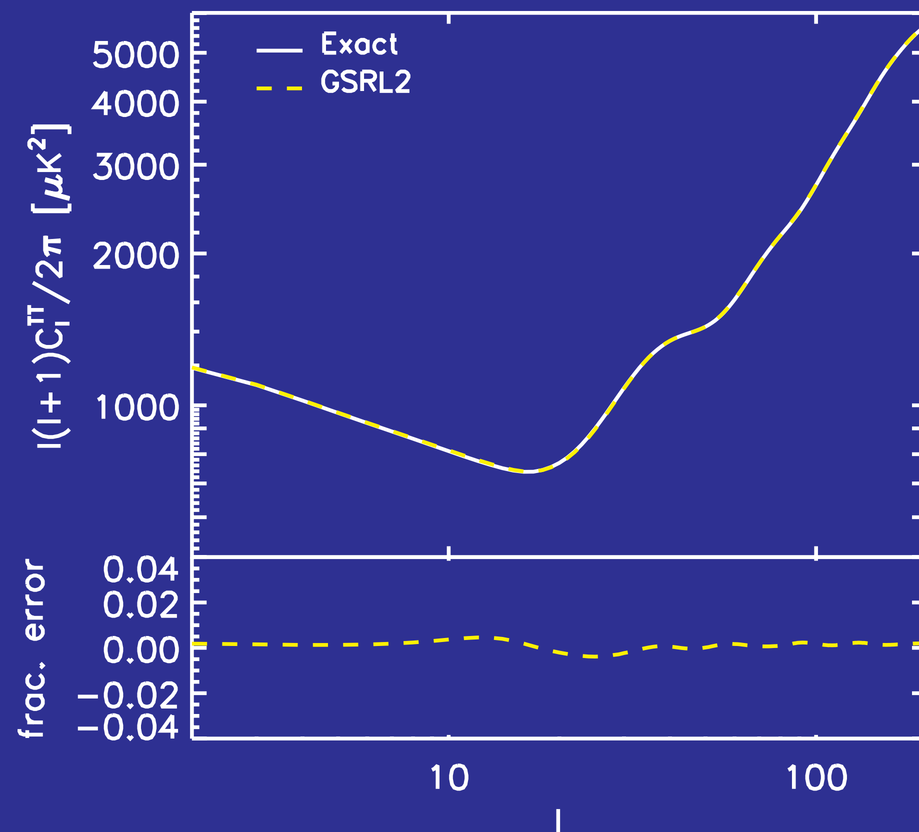
  string theory and landscape

- Foils to inflation (ekpyrosis?)
- Preheating, reheating, etc.

Features in Potential

- Features in the potential generate features in the CMB observables
- Inflationary explanations of WMAP glitches testable w. polarization
- Potential reconstruction works in presence of large features





Dvorkin & Hu (2007)

Advantage: KICP

- Flagship polarization experiments
- Chicago/Fermilab pioneers in inflation reconstruction, model building, CMB phenomenology
- Central developments in non-Gaussianity (scale dependent bias of rare objects, $f_{\rm NL}$ algorithm developed by fellows and students here)

Deuce (or is that Bruce?)

- Why a Center? Chicago is already a center with ongoing projects
- In absence of B detection is auxiliary science compelling? E-modes for $V(\phi)$ features and reionization, lensing, constraints on exotica (cosmic strings, parity violation, etc) compelling?
- Is "Testing Inflation" the right focus given experimental B mode thrust?

  Downplays other uses of CMB

  Narrow focus on only one inflationary test