Constraining Inflation

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astro-ph/0603587, astro-ph/0604214, astro-ph/0609003, astro-ph/0611645

Inflation

- Inflation: accelerated expansion in early universe
  - Driven by gravity (e.g. R^2 term)
  - Particle physics (e.g. axion field, scalar singlet)
  - String/brane world scenarios
- Cosmology now providing useful constraints on fundamental physics

Inflation: Basic Predictions

- Universe:
  - Spatially flat (~1%)
  - Homogeneous and isotropic (1 part in ~10^{-4})
- Real action is in the perturbations...

Have to look at the bumps...

“Happy families are all alike;
every unhappy family is unhappy
in its own way”

Leo Tolstoy

Have to look at the bumps...

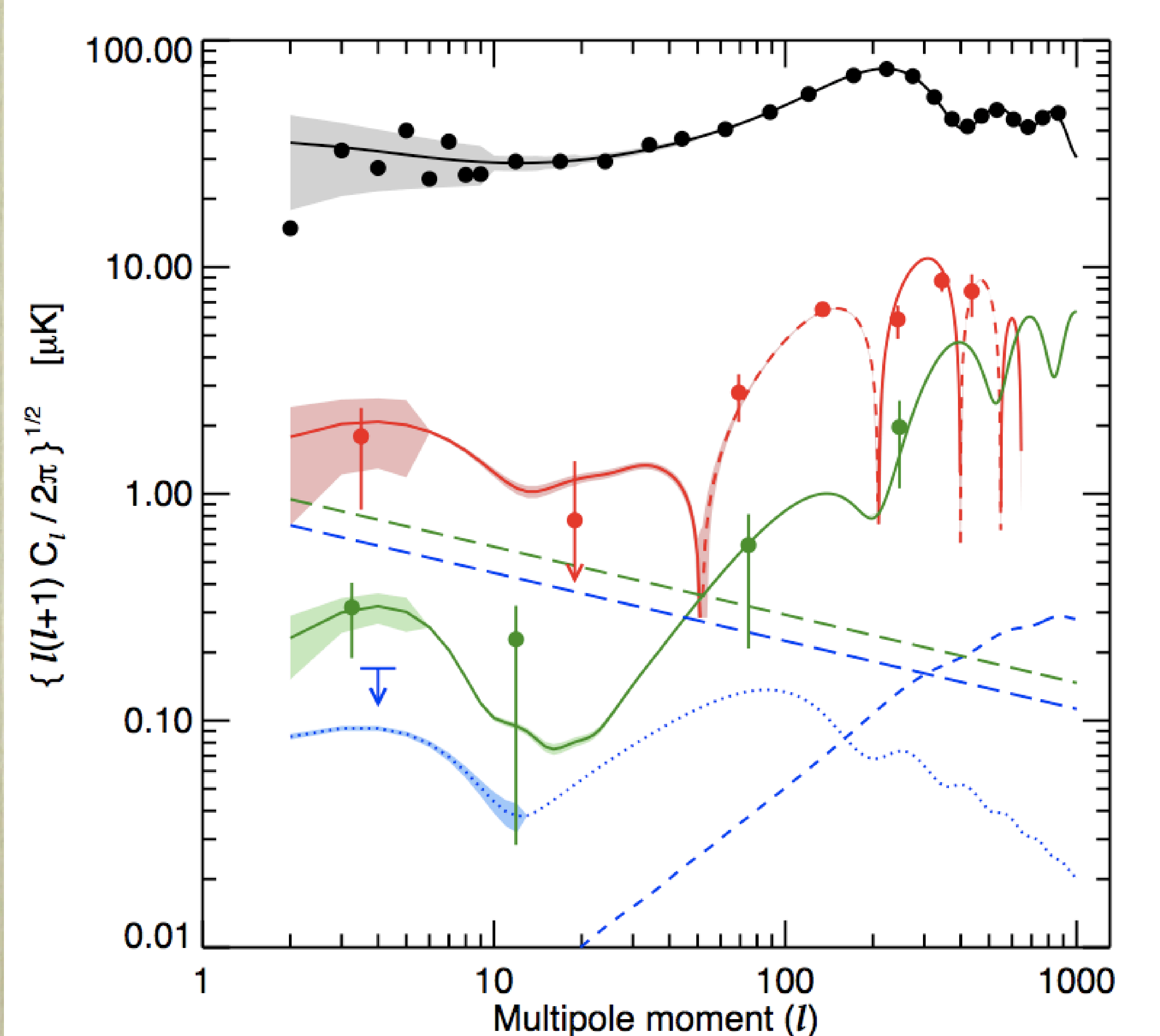
"Smooth universes are all alike;
every lumpy universe is
lumpy in its own way"

not Leo Tolstoy

Key Prediction...

- During "regular"expansion:
  - Comoving size of the universe growing
  - New modes continually "entering the horizon"

- Inflation gives these modes a *primordial* amplitude
  - Characteristic signature: <ET> and <EE>
  - Plus acoustic peaks.
  - Perturbations adiabatic
  - Exactly what we expect from inflation...
  - Could also see this in other models (e.g. ekpyrotic)



100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π }^1/2 [μK]

The Perturbation Spectrum

- Strong (but not ironclad) evidence for “red” spectrum
- Weaker but intriguing evidence for “running” index
- No evidence for tensor (gravity wave) component
  - Direct constraint on inflationary energy scale

Inflationary Parameters

- Spectral properties fixed by inflaton potential
  - Assuming single, minimally coupled field
  - "Slow roll" parameters
  - Depend weakly on scale (they change as field moves)
  - Scale dependence given by a hierarchy of equations
  - Specify "n-parameter" inflationary models
  - Constrain parameters with data...
- Add "prior" on number of e-folds

Flow Equations

$$
\begin{aligned}
\frac{d\epsilon}{dN} &= 2\epsilon(\eta - \epsilon) \\
\frac{d\eta}{dN} &= -\epsilon\eta + \xi \\
\frac{d\xi}{dN} &= \xi(\eta - 2\epsilon) + {}^{3}\lambda_H \\
\frac{d\left({}^{\ell}\lambda_{\mathrm{H}}\right)}{dN} &= \left[\frac{\ell - 1}{2}\eta + (\ell - 2)\,\epsilon\right]\left({}^{\ell}\lambda_{\mathrm{H}}\right) + {}^{\ell+1}\lambda_{\mathrm{H}}
\end{aligned}
$$

- Now using N (# of e-folds) as "time"
- Truncated hierarchy is closed
  - Truncate at a point, truncate everywhere.
  - Amounts to a fibering of parameter space

Markov Chain Results

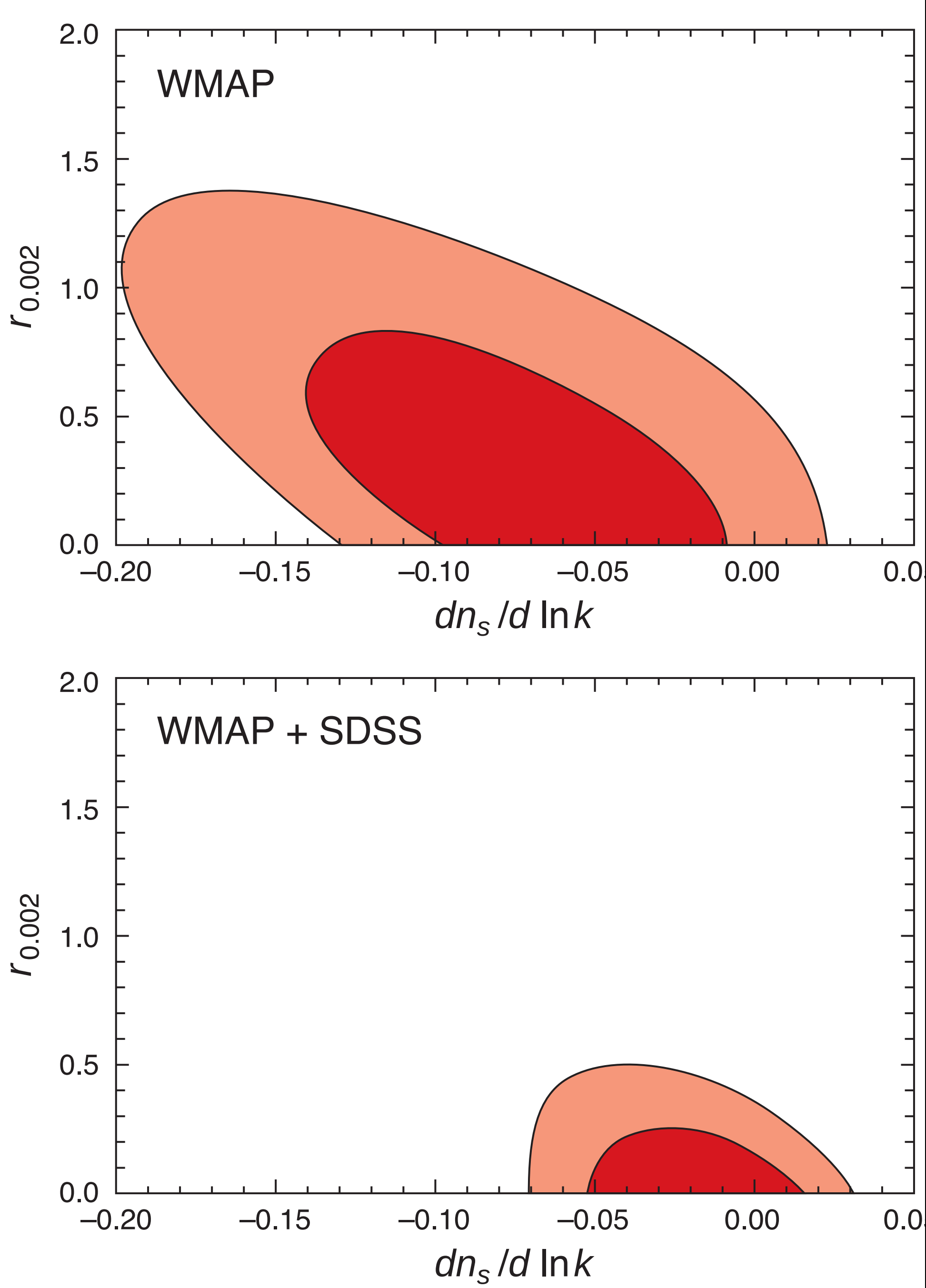
astro-ph/0603587 & astro-ph/0609003

- Ran Markov chains for 2 and 3 slow roll parameters
  - + Flatness prior + Ω_b + Ω_m + h + τ
  - Looked at WMAPII alone and WMAPII+SDSS

- 2 parameter case roughly equivalent to n_s + r
  - 3 parameter case probes running n_s + r + running
  - Naturally includes 2nd order effects in slow roll
  - Show only 3-parameter chains here.

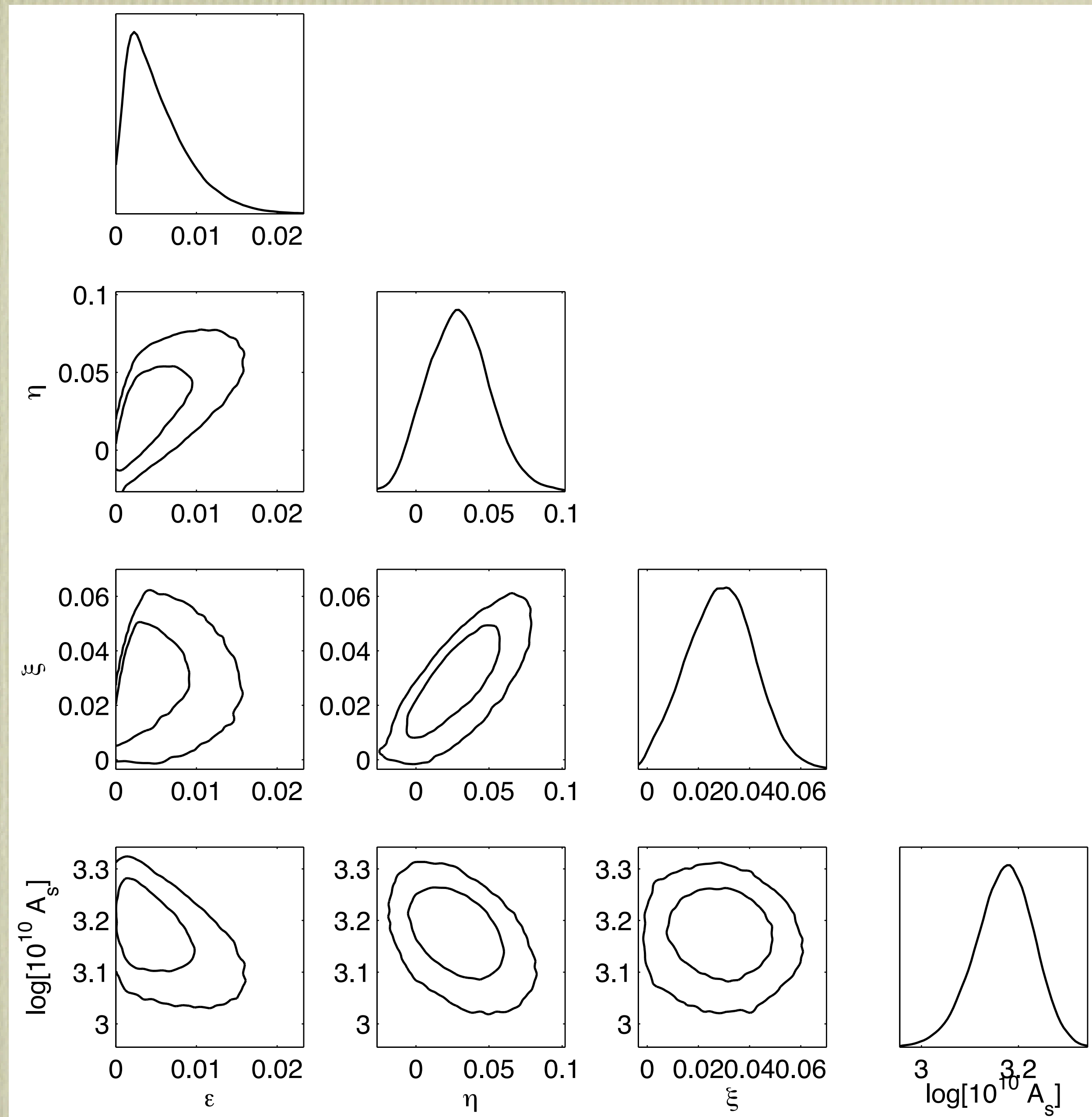
WMAP Analysis

- Spergel et al (2006)
- Centroid favors running <0
- Look at range of running
- Inflationary prior on tensor spectrum

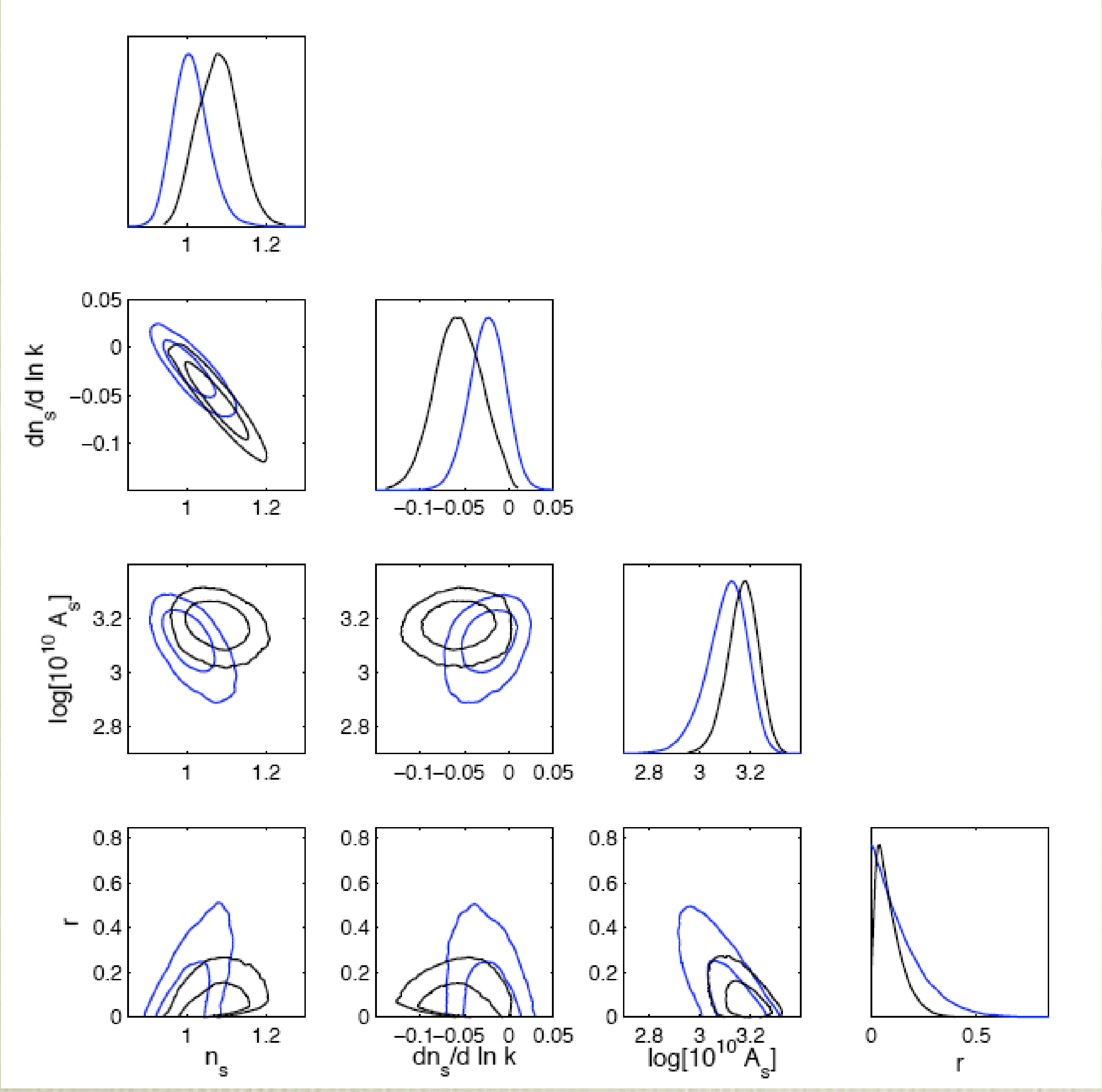


Slow Roll Parameters

WMAPII+SDSS
No N-prior



Comparison with WMAP analysis



Easther and Peiris

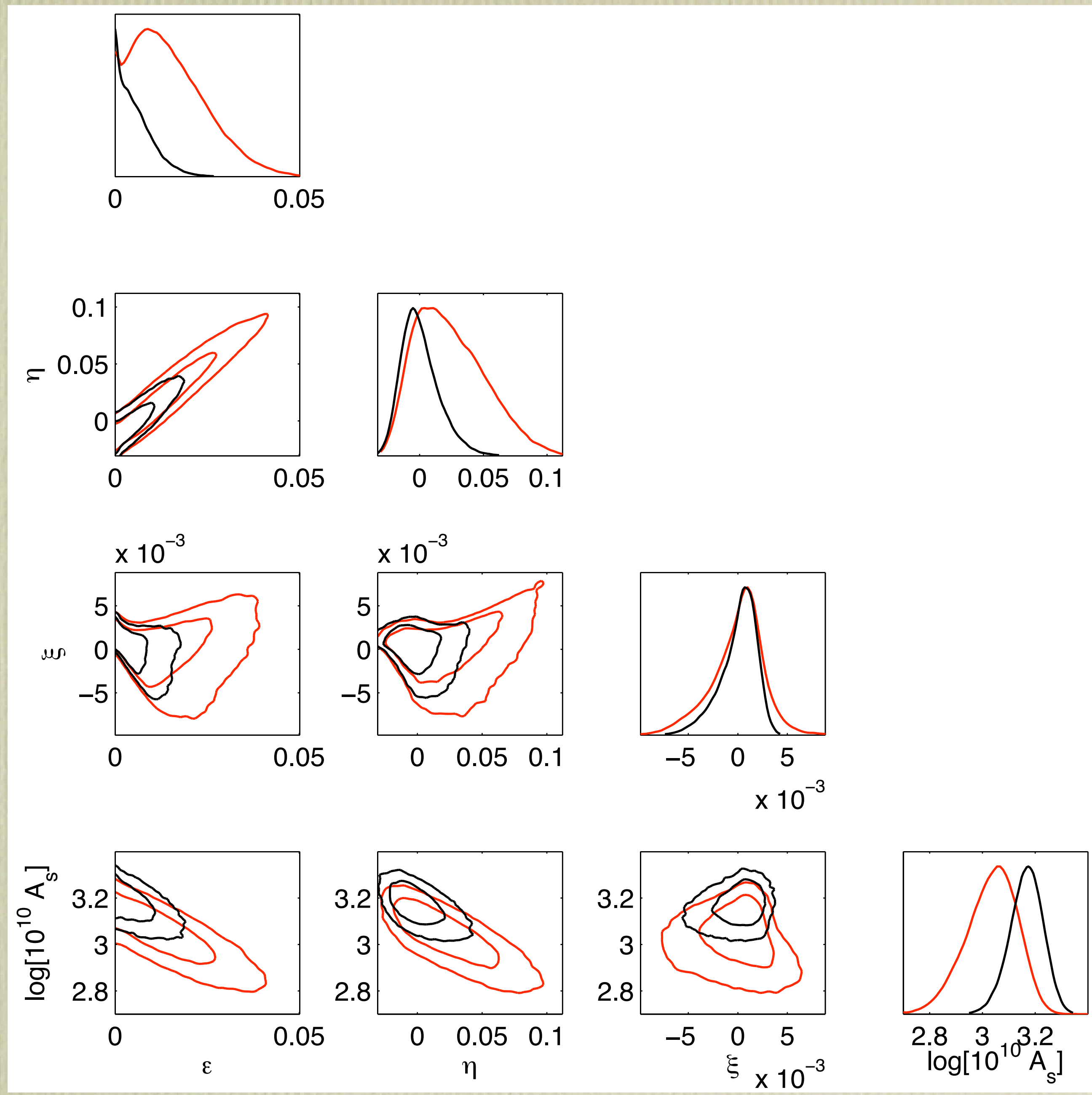
Spergel et al.

NB: Not expected to overlap...

Slow Roll Parameters N>30

WMAP+SDSS

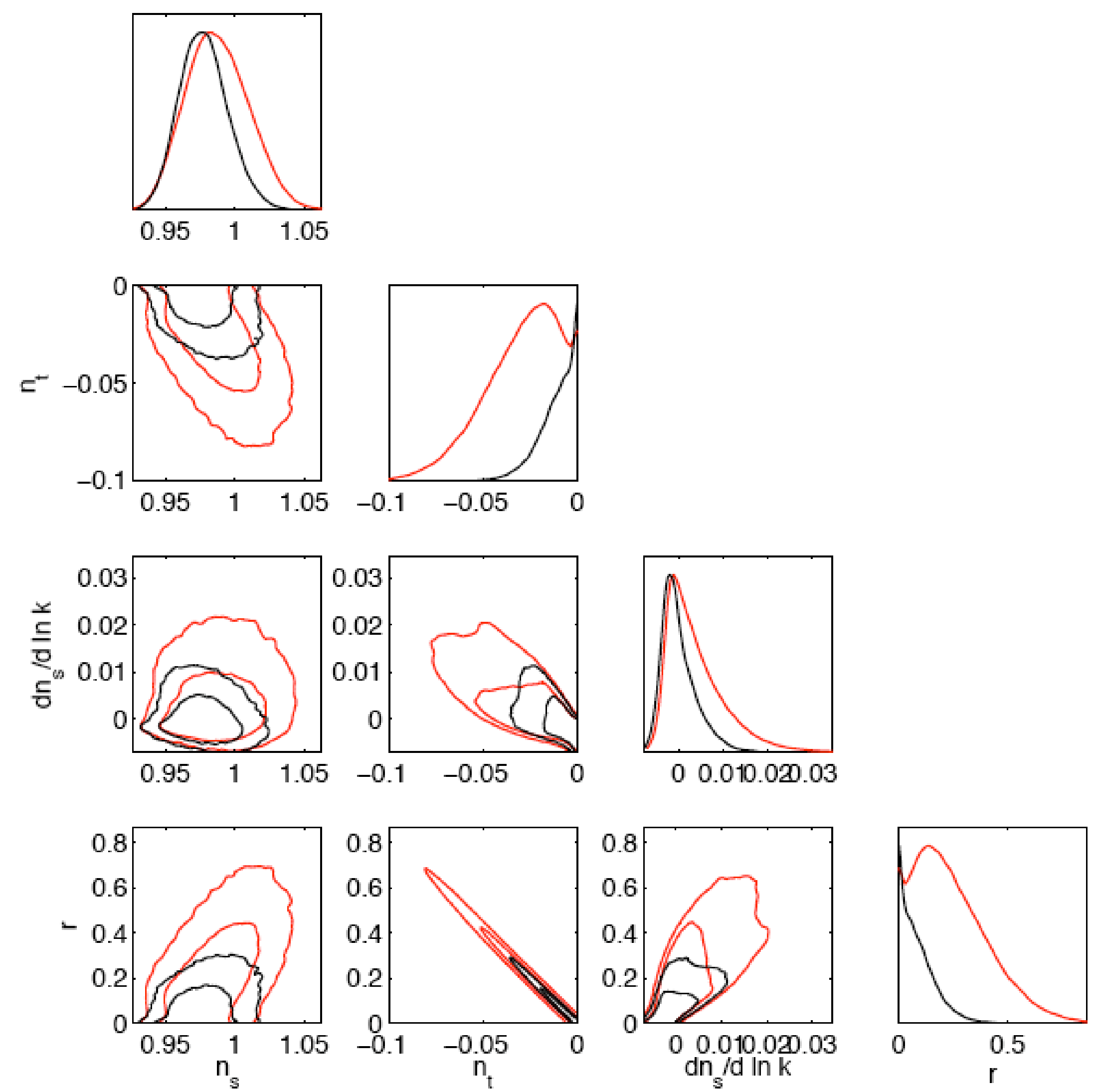
WMAP



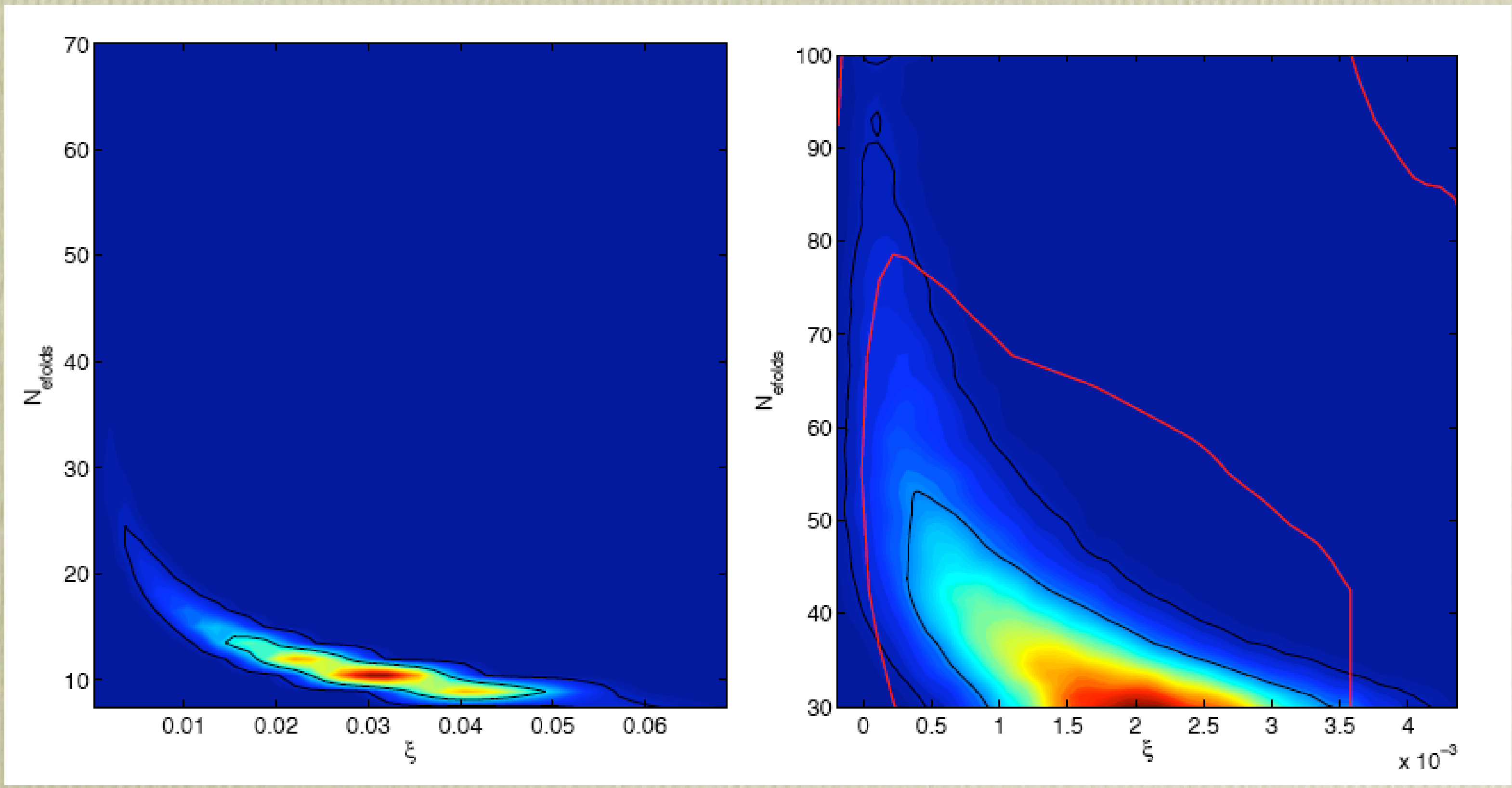
Standard Parameters N>30

WMAP+SDSS

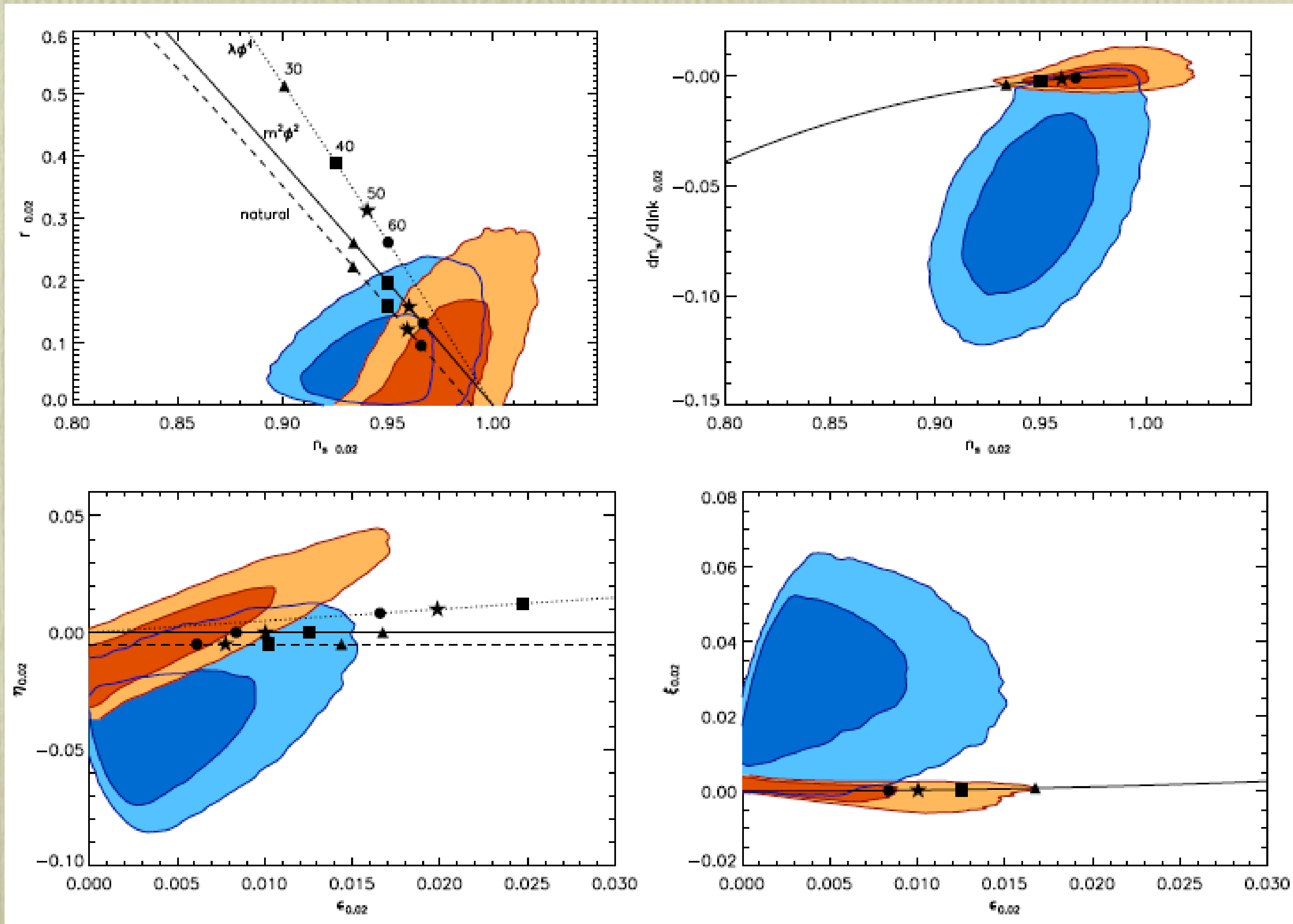
WMAP



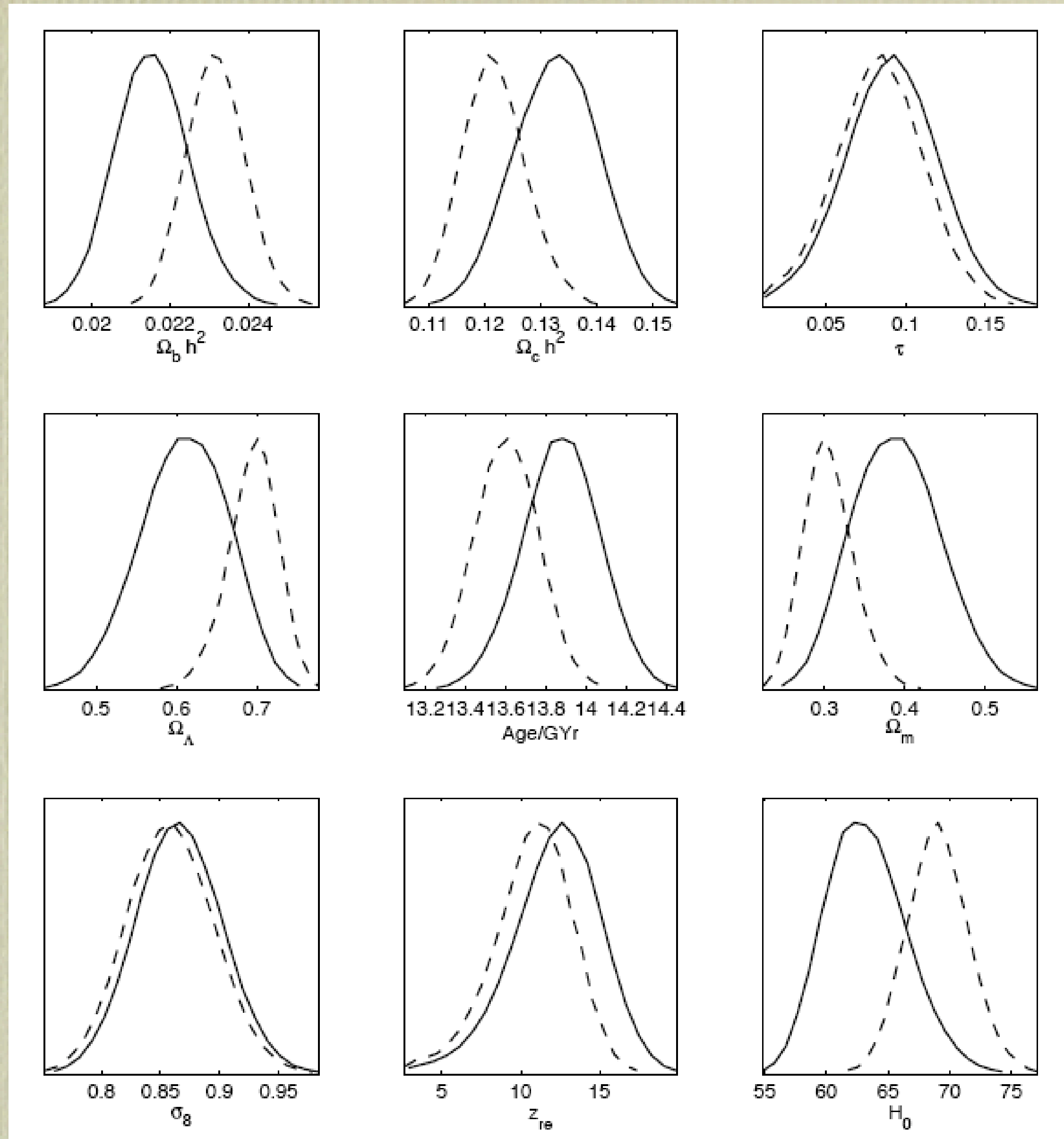
Number of e-folds correlated with ξ



Inflationary trajectories...



"Late" parameters and the N-prior



——— WMAP+SDSS

– – – – WMAP+SDSS
Spergel et al.

What Do We Really Learn?

- Three ways out:
  - Higher order terms non-trivial
  - There is a "feature" in the potential, multi-fields...
  - Future data will show less evidence for running
- Confirming the current WMAP centroid would cause serious problems for (minimal) inflation.
  - Seek single experiment / high-l probes of CMB
  - Better constraints on Ω_m etc to use as priors.
  - Evidence for running present at same level as in WMAP analysis

(Non)-Gaussianity

- Inflation predicts perturbations Gaussian
  - e.g. measure 2-point function
  - predict N-point function (zero for odd N)
- Real perturbations always slightly non-Gaussian
  - Second order perturbations couple modes
  - Small effect: barely detectable in “perfect” CMB data
  - Non-gaussianity can be built in: this can be large
  - Working on this now
  - Only weak constraints from present day data

The Future

- In ~5 Years:
  - Definitively test “simple” models of inflation
  - Via tensor spectrum

- Longer term:
  - Non-Gaussianity (theory and experiment)
  - Other fingerprints (post-inflation relics)
  - Real tests of specific models
  - Particle cosmology will get harder...