Title: Fingerprints of Inflation

Date: Sep 14, 2007 09:30 AM

URL: http://pirsa.org/07090028

Abstract:

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Richard Easther (Yale)
Peter Adshead, Thorsten Battefeld, Xingang Chen, Tom Giblin, Eugene Lim,
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What We All Know

- Standard hot big bang is highly fine-tuned
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- Inflation takes arbitrary initial conditions
  - Drives them towards "unstable" solution
  - Universe close to "least likely" state
  - Homogeneous, isotropic (smooth) and flat (k=0)
- Using a very generous definition of inflation
  - Could even stretch to ekpyrosis

But the Universe is Not Exactly Smooth...

- Inflation predicts this too...
  - Just as well for inflation

But the Universe is Not Exactly Smooth...

- Inflation predicts this too...
  - Just as well for inflation
- Inflation naturally generates perturbations
  - Amplitude can be calculated (standard result)
  - Described by a handful of parameters
  - Acoustic peaks, <TE> correlation in CMB.

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

Inflation:
A Victim of Its Own Success?

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  - Small departures from zero order result
  - CMB: parts in 10^5

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- Inflation drives universe towards "zero order" attractor
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  - CMB: parts in 10^5
- But we want to discriminate *between* inflation models
  - Differences between models necessarily small
  - Key to making connection with particle physics

Which Model of Inflation Is Right?

- Problem:
  - www.arXiv.org: Dozens of models of inflation
  - Best model is the one you (or your advisor) invented
  - All these models predict a flat, smooth universe
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  - Roughly scale invariant and Gaussian.
  - Many viable inflationary models

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- May need "second order" effects to break degeneracy.

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  - Odd scalars (running, features, etc)
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  - Non-Gaussianity and isocurvature
  - Relics of reheating
  - Initial conditions effects

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} Fingerprints

- Must have density perturbations
  - But no guarantee any other fingerprint is observable

Characterization of Perturbations

- Scalar Perturbation Spectrum:
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  - Current best fit: $0.96 \pm .16$ (WMAP3, LCDM)
- Two free parameters (A and n) but many models!
  - A and n depend on inflationary potential
  - Characterized in terms of slow roll parameters
  - And these are weakly scale dependent
  - And assumes a regular, single field model.

One More Thing to Worry About...

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  - Exotica: string networks, kination, thermal inflation

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- Number of e-folds nominally 55 ± 10?
  - 20% in (n-1)? (Kinney & Riotto, astro-ph/0511127)

So What Can We Do?

- Impose optimal inflationary prior on parameter fits
  - Slow roll reconstruction (w. Peiris, and also Adshead)
  - Gets best "value for money" from cosmological data

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- Impose optimal inflationary prior on parameter fits
  - Slow roll reconstruction (w. Peiris, and also Adshead)
  - Gets best "value for money" from cosmological data
- Think hard about "second order" signals
  - Most of these are invisible for most models
  - So a positive signal provides strong constraints
  - Often more challenging theoretically

Slow Roll Reconstruction

- Slow roll parameters form a hierarchy
  - $\epsilon, \eta, \xi, \lambda_3, \ldots$
  - Depends on derivatives of the potential
  - Or, in Hamilton-Jacobi form, $H(\Phi)$

Slow Roll Reconstruction

- Slow roll parameters form a hierarchy
  - ϵ, η, ξ, λ_3,...
  - Depends on derivatives of the potential
  - Or, in Hamilton-Jacobi form, $H(\Phi)$
- Get *flow hierarchy* that yields ϵ, η, ξ, λ_3,... as function of N
  - These parameters yield the power spectrum.
  - And its scale dependence
  - Use slow roll parameters in fits to data.

Flow Equations

$$
\begin{aligned}
\frac{d\epsilon}{dN} &= 2\epsilon(\eta - \epsilon) \\
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\frac{d\left({}^{\ell}\lambda_{\rm H}\right)}{dN} &= \left[\frac{\ell - 1}{2}\eta + (\ell - 2)\,\epsilon\right]\left({}^{\ell}\lambda_{\rm H}\right) + {}^{\ell+1}\lambda_{\rm H}
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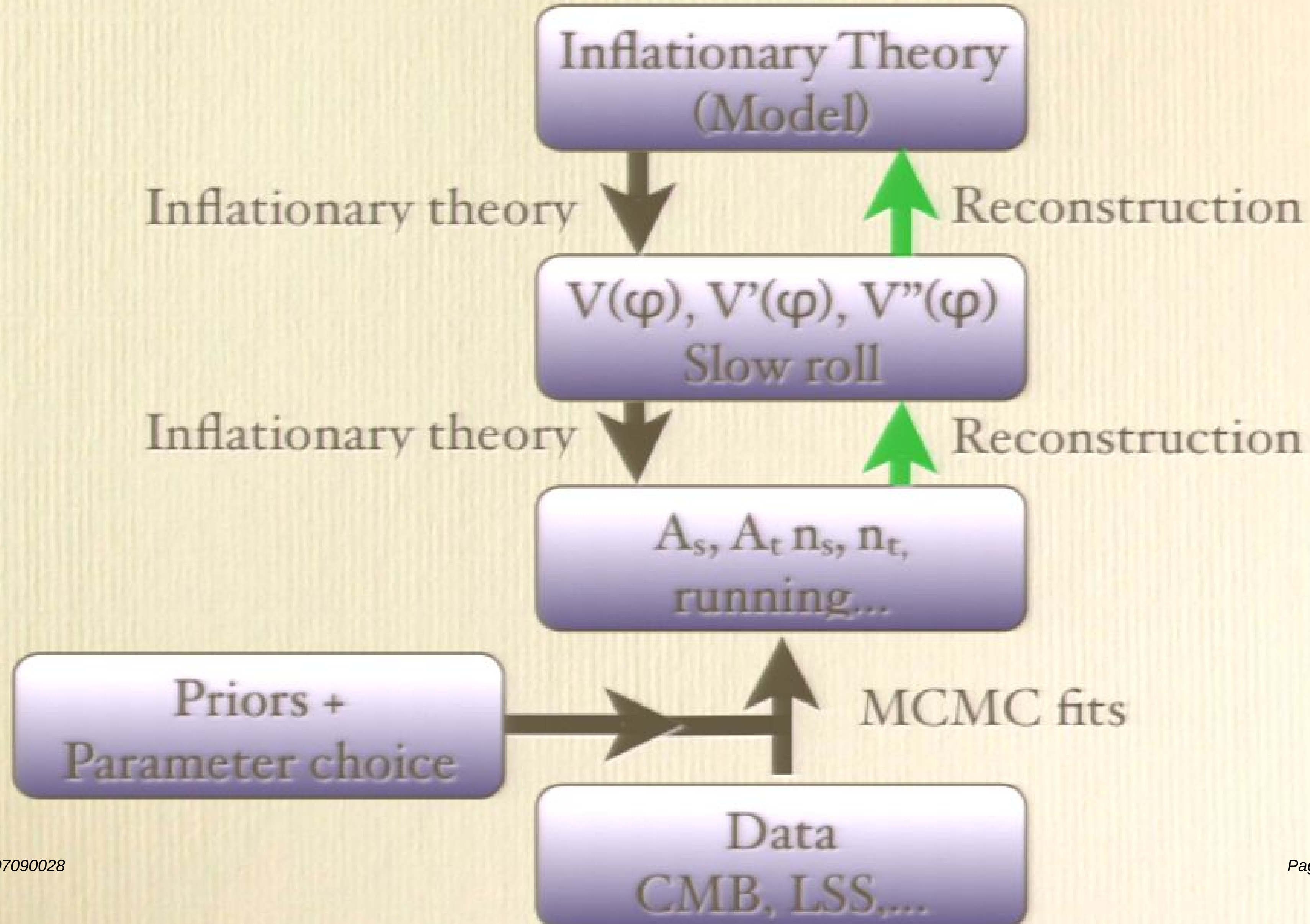
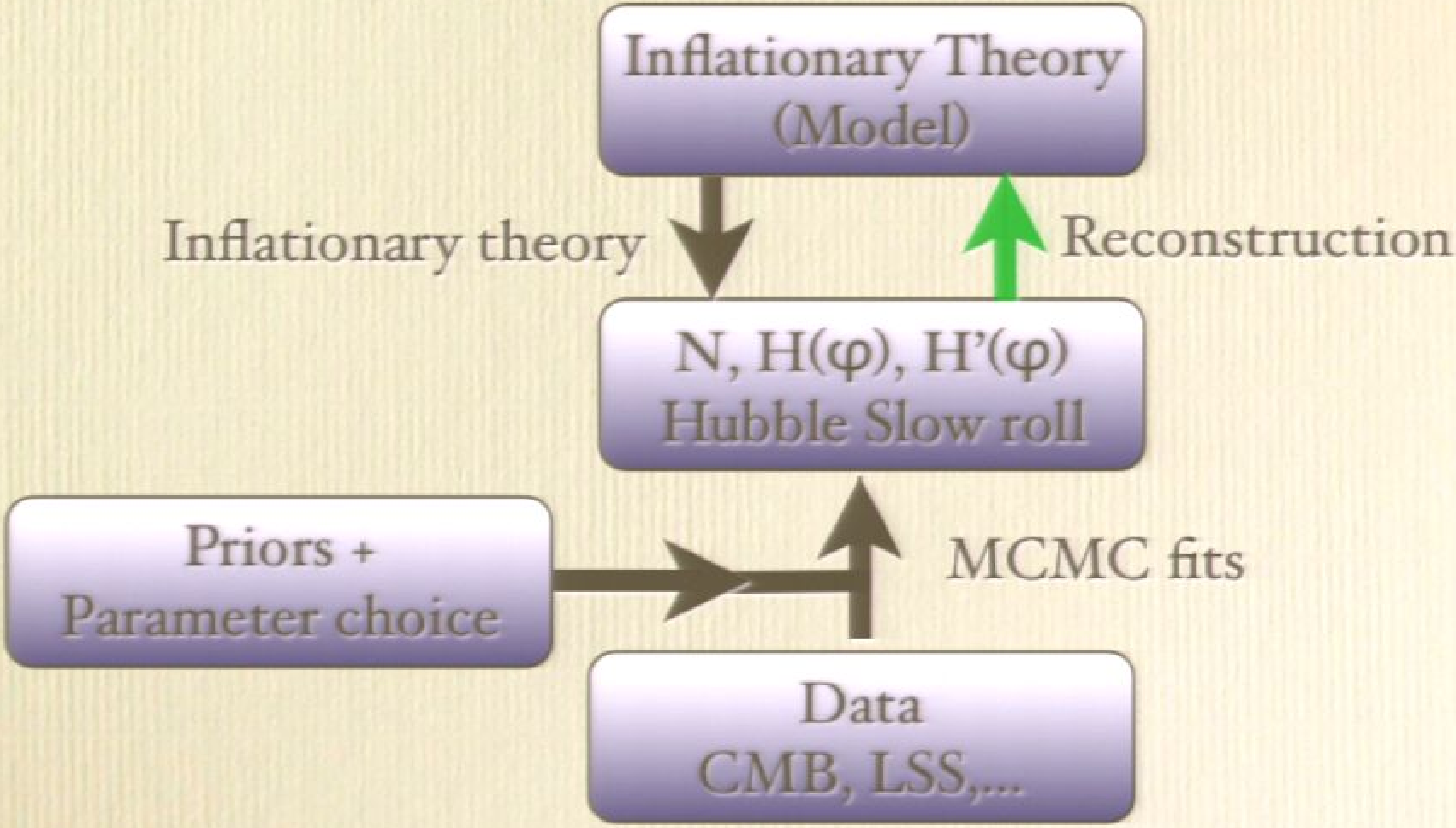
Fit to Data: Standard Process



Fit to Data: Slow Roll Reconstruction



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astro-ph/0604214

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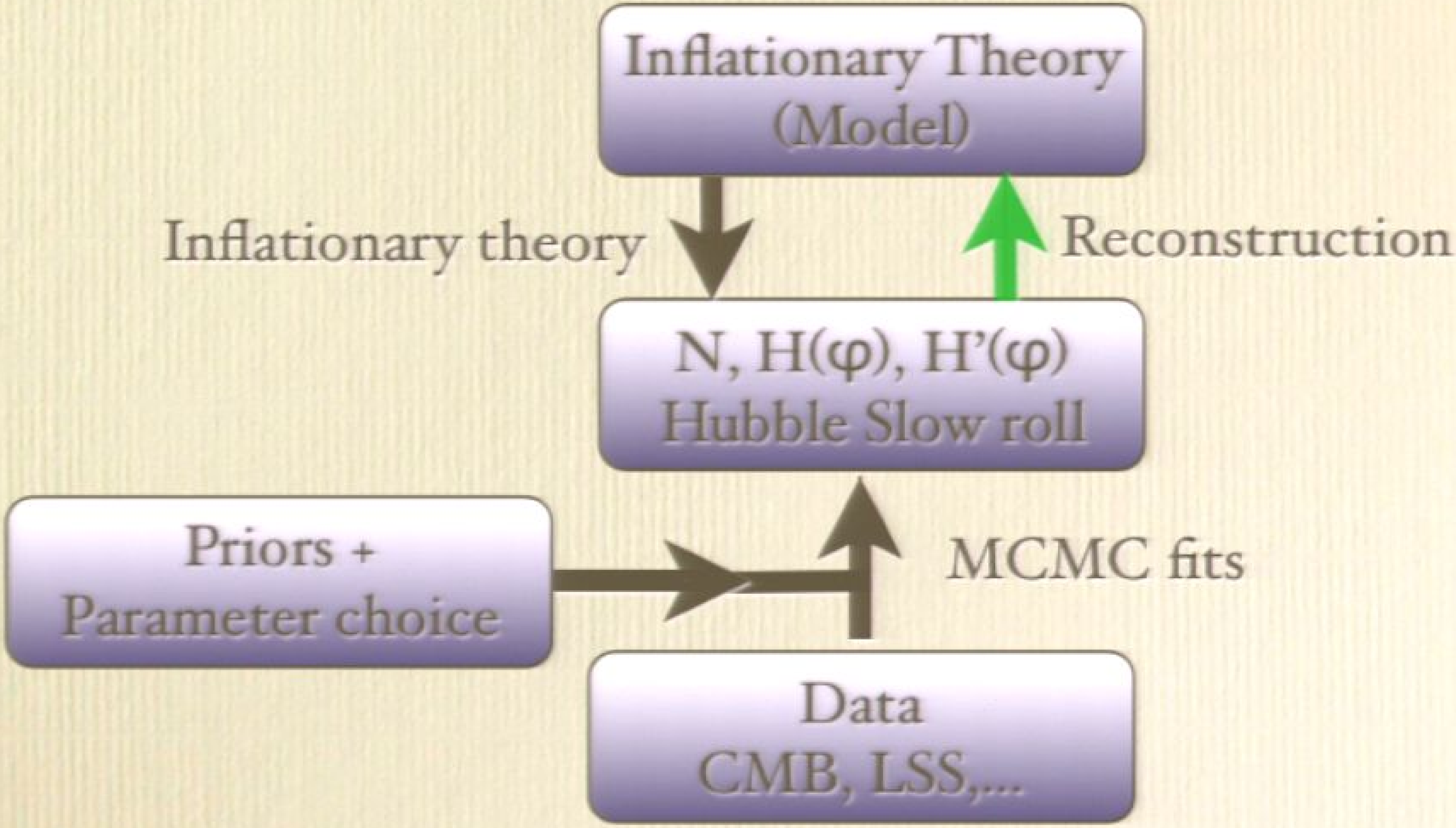

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$n > 0.9$
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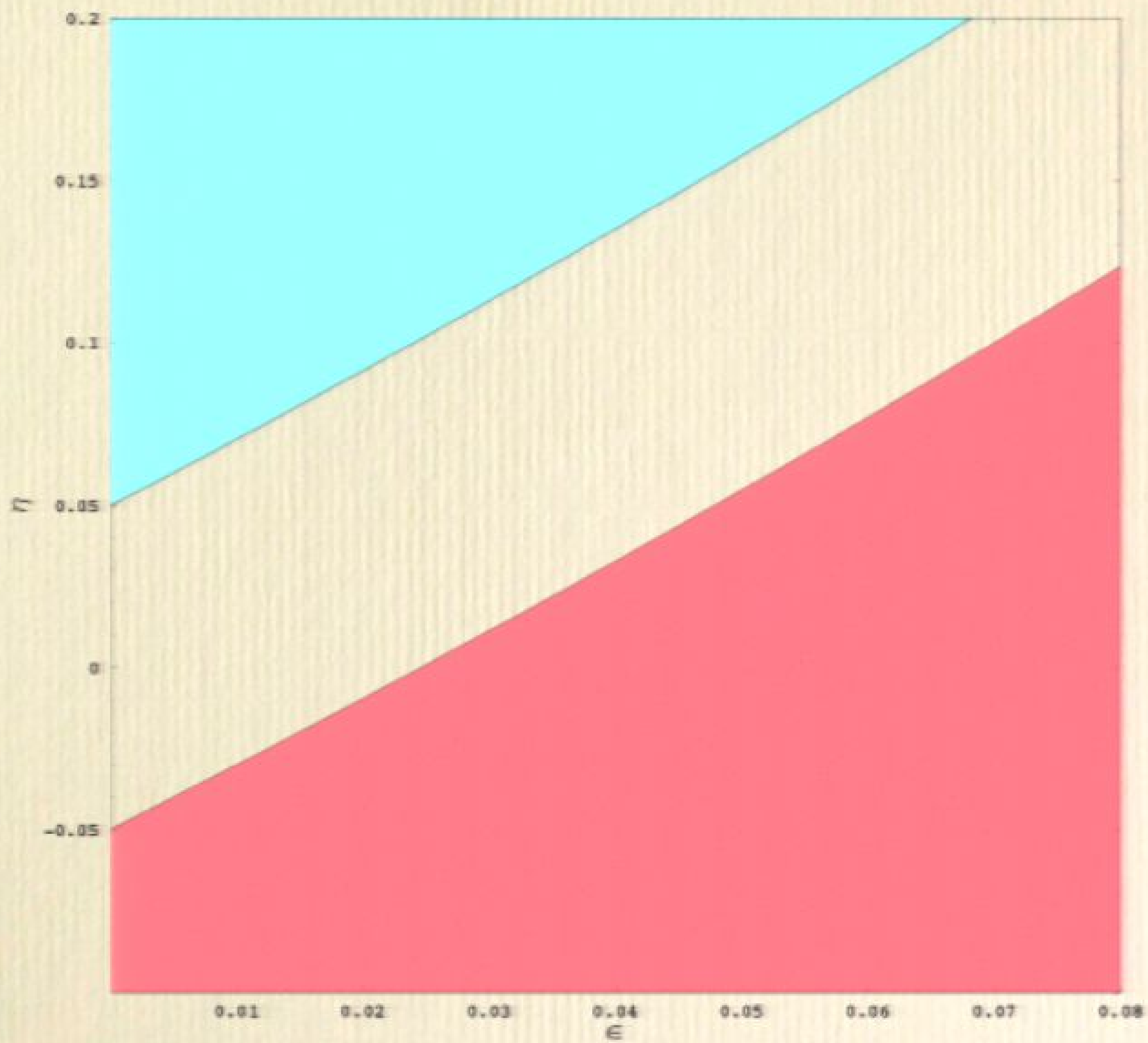

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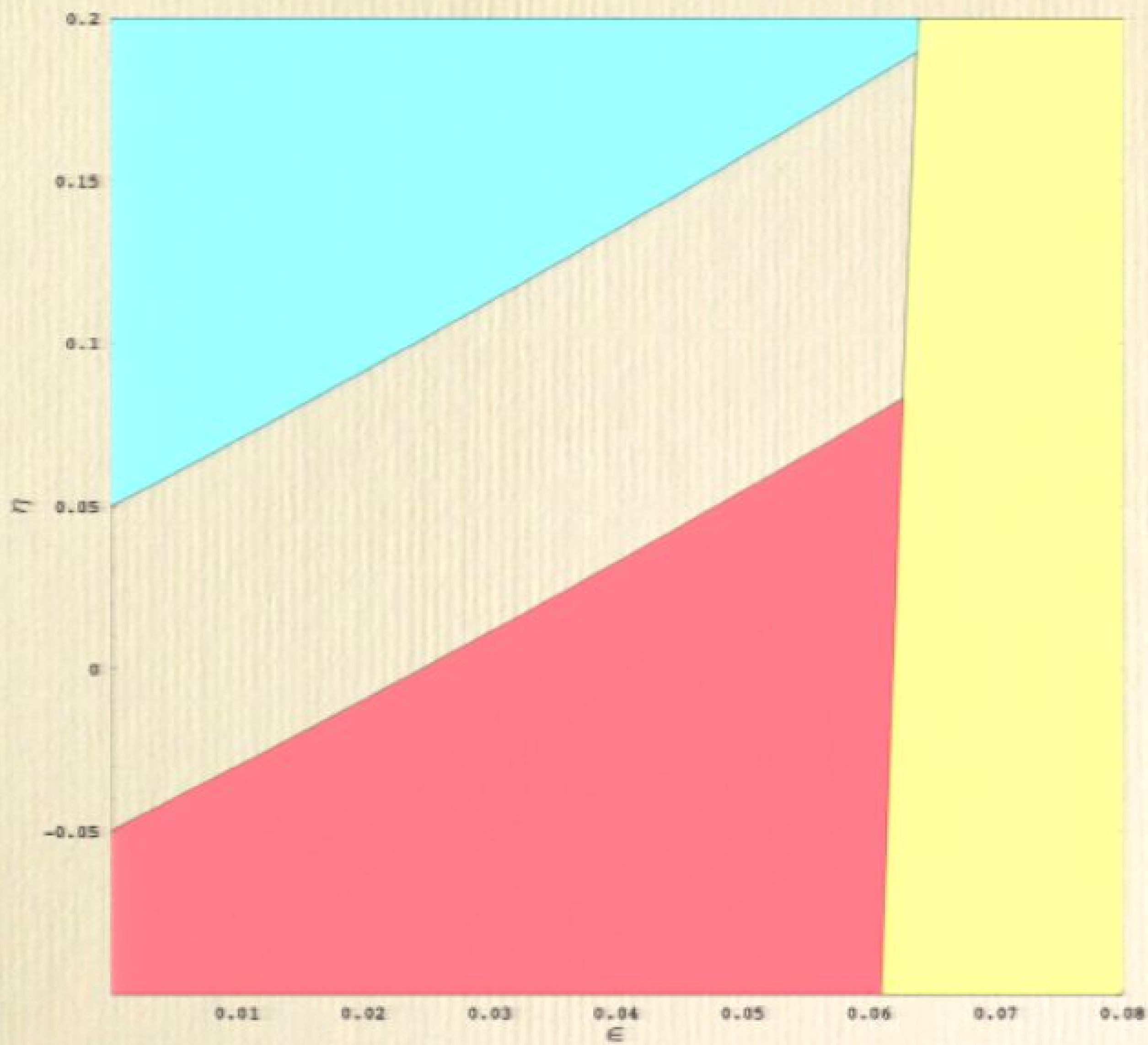

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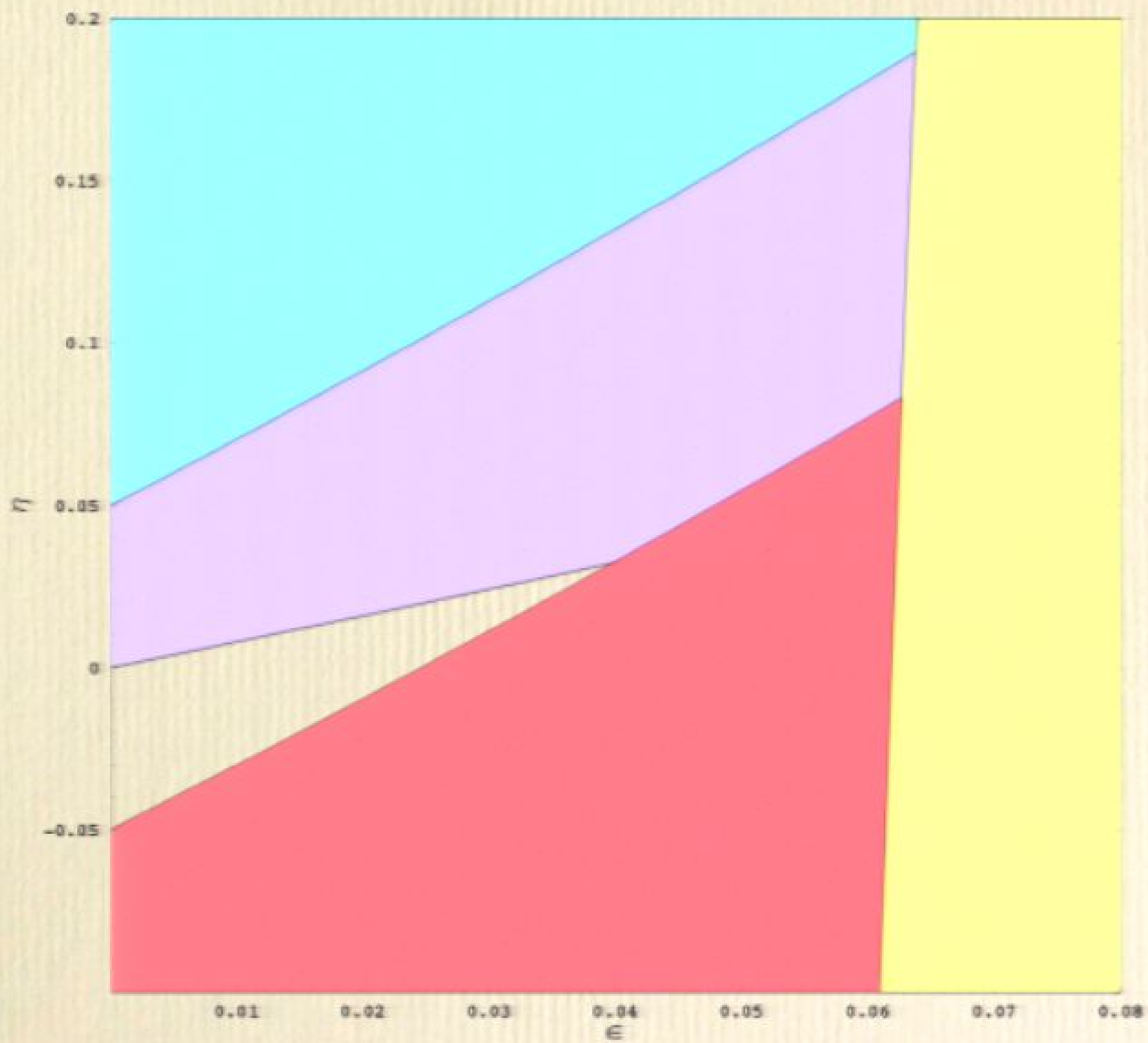

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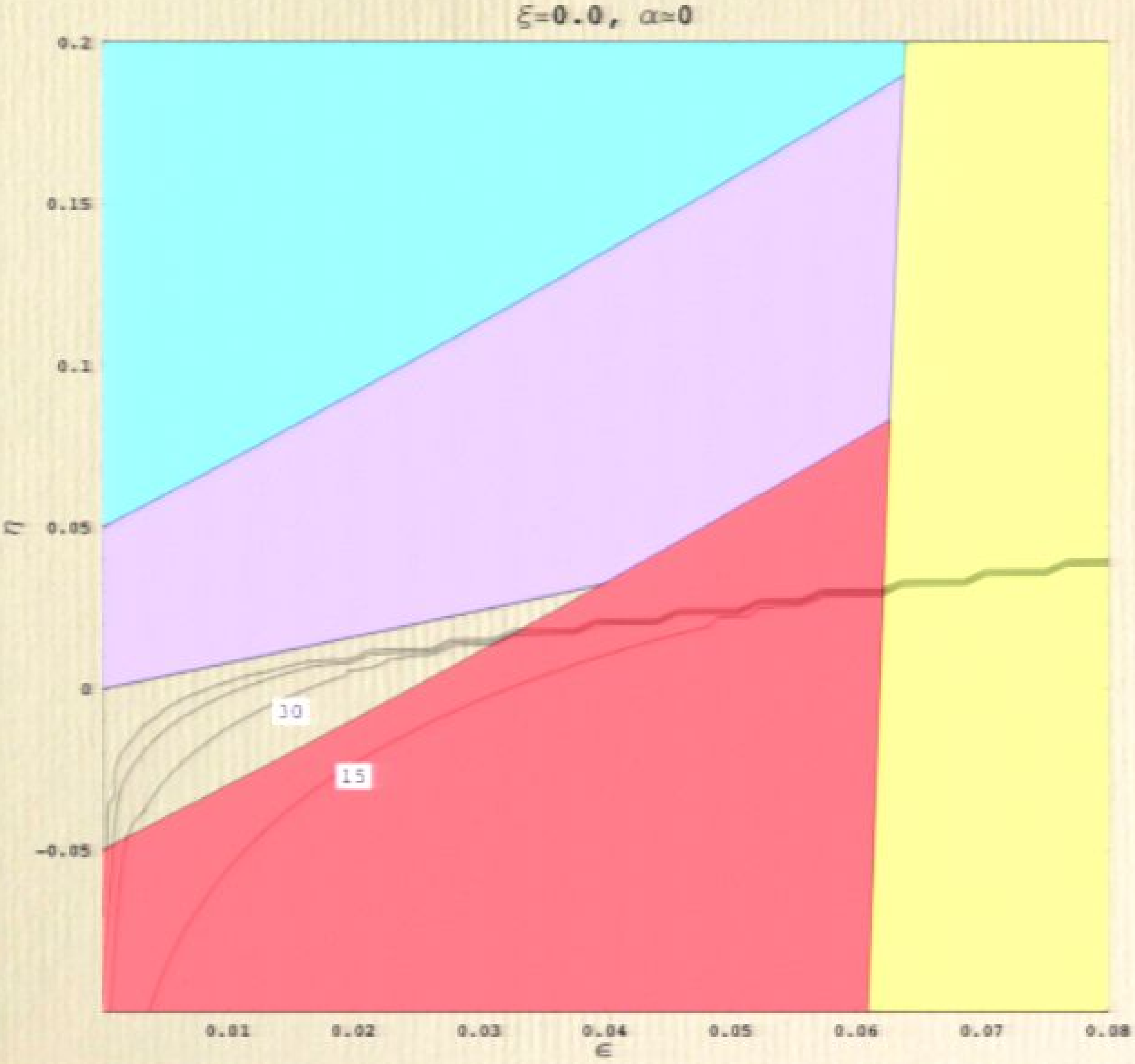

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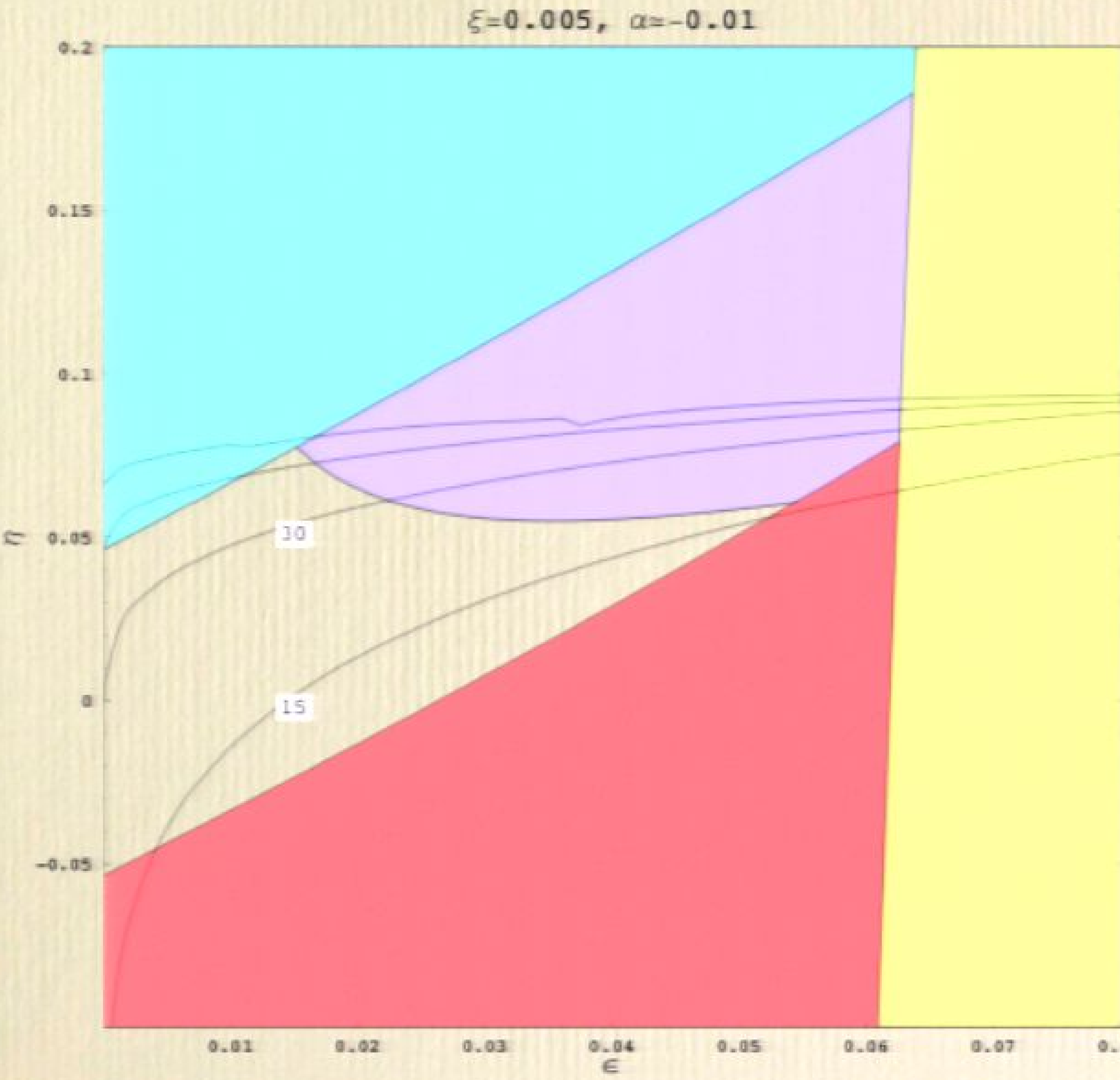

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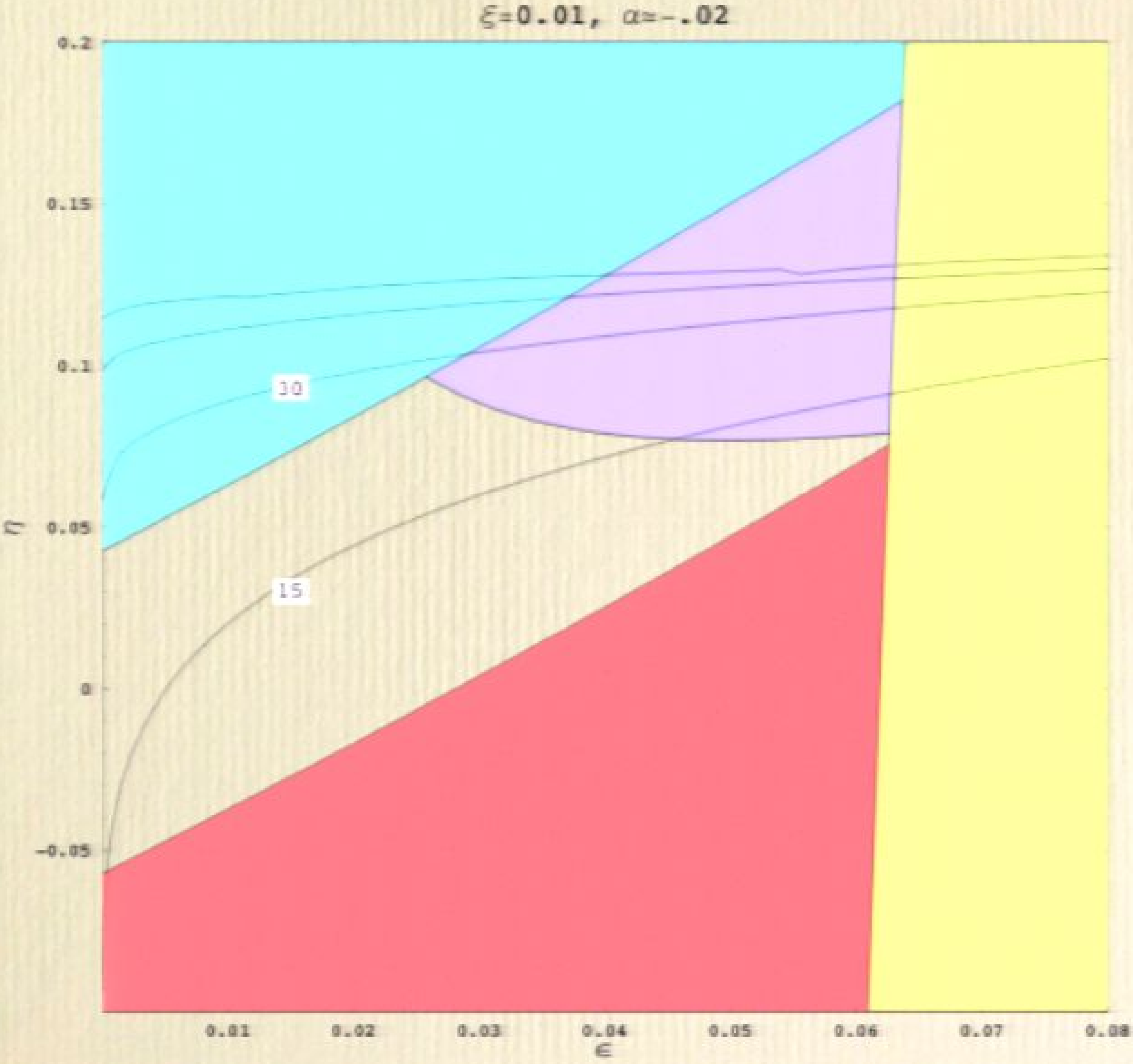

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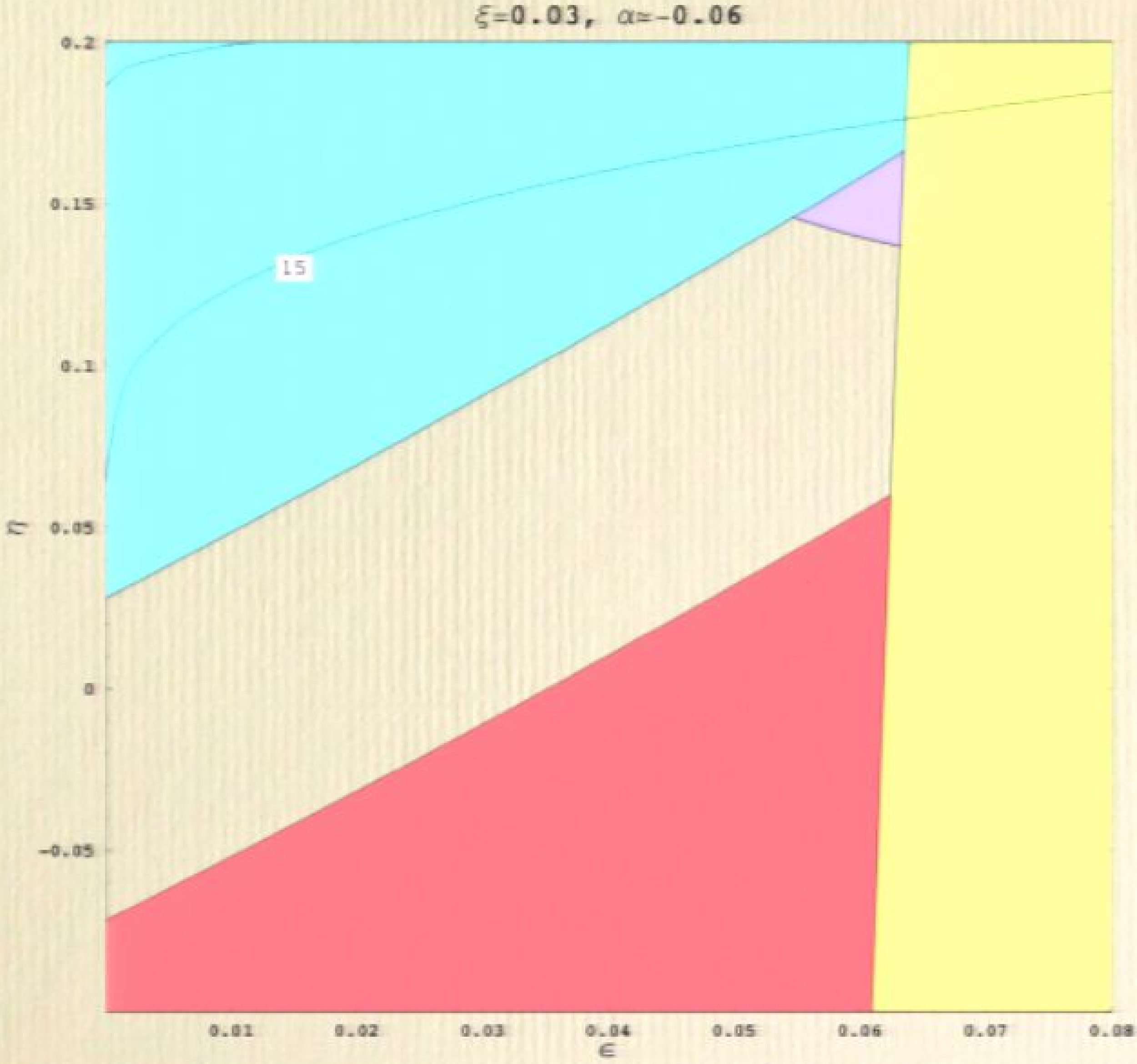

What we learn...

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- In the absence of higher order terms:
  - N strongly correlated with running
  - Large (negative) running requires N<30
  - N < 30 implies inflation below the TeV scale
- To simultaneously have a) valid slow roll expansion, b) large (negative) running and c) enough inflation:
  - Need a four parameter potential
  - Rules out all simple models of inflation

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

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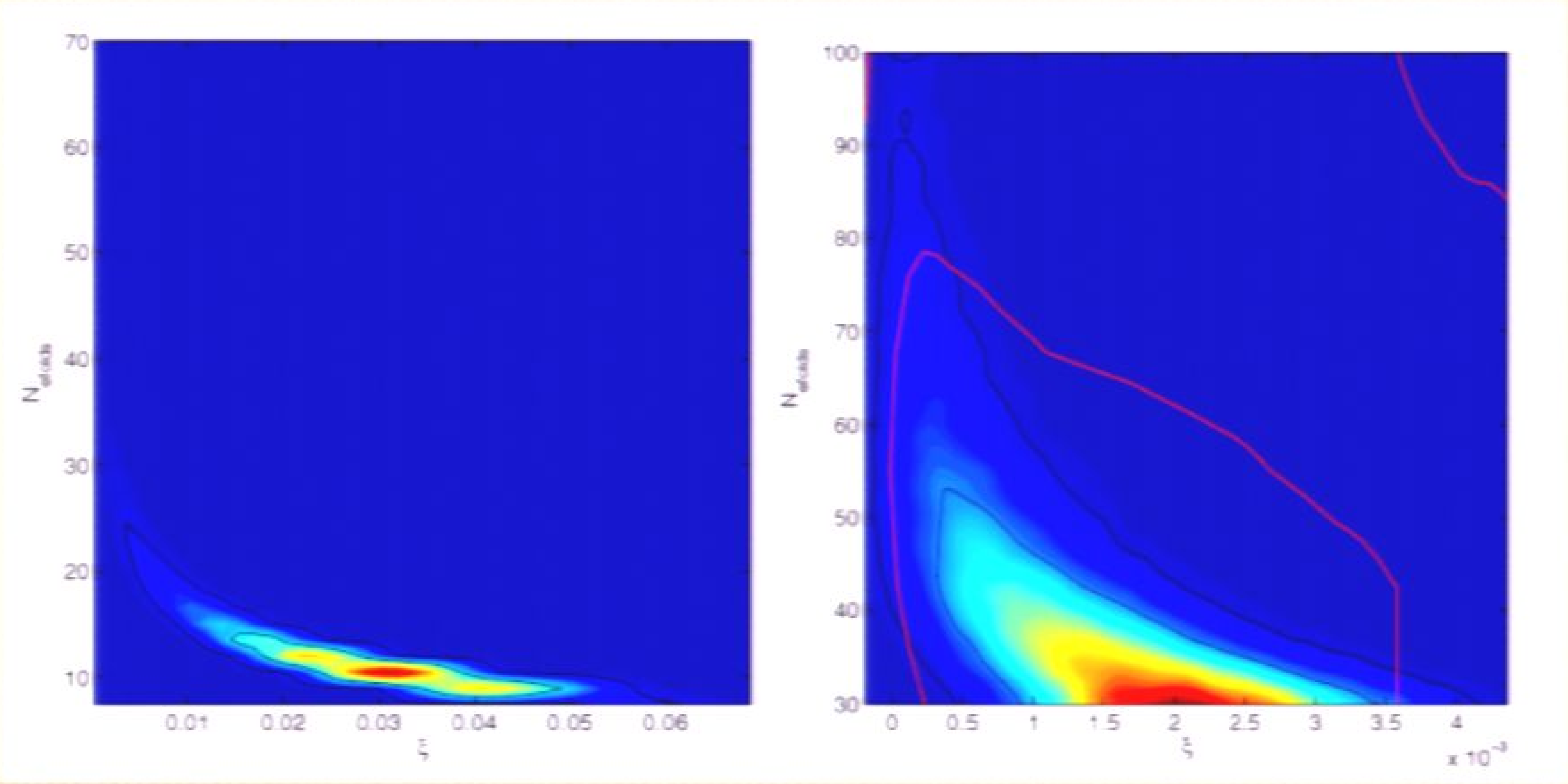
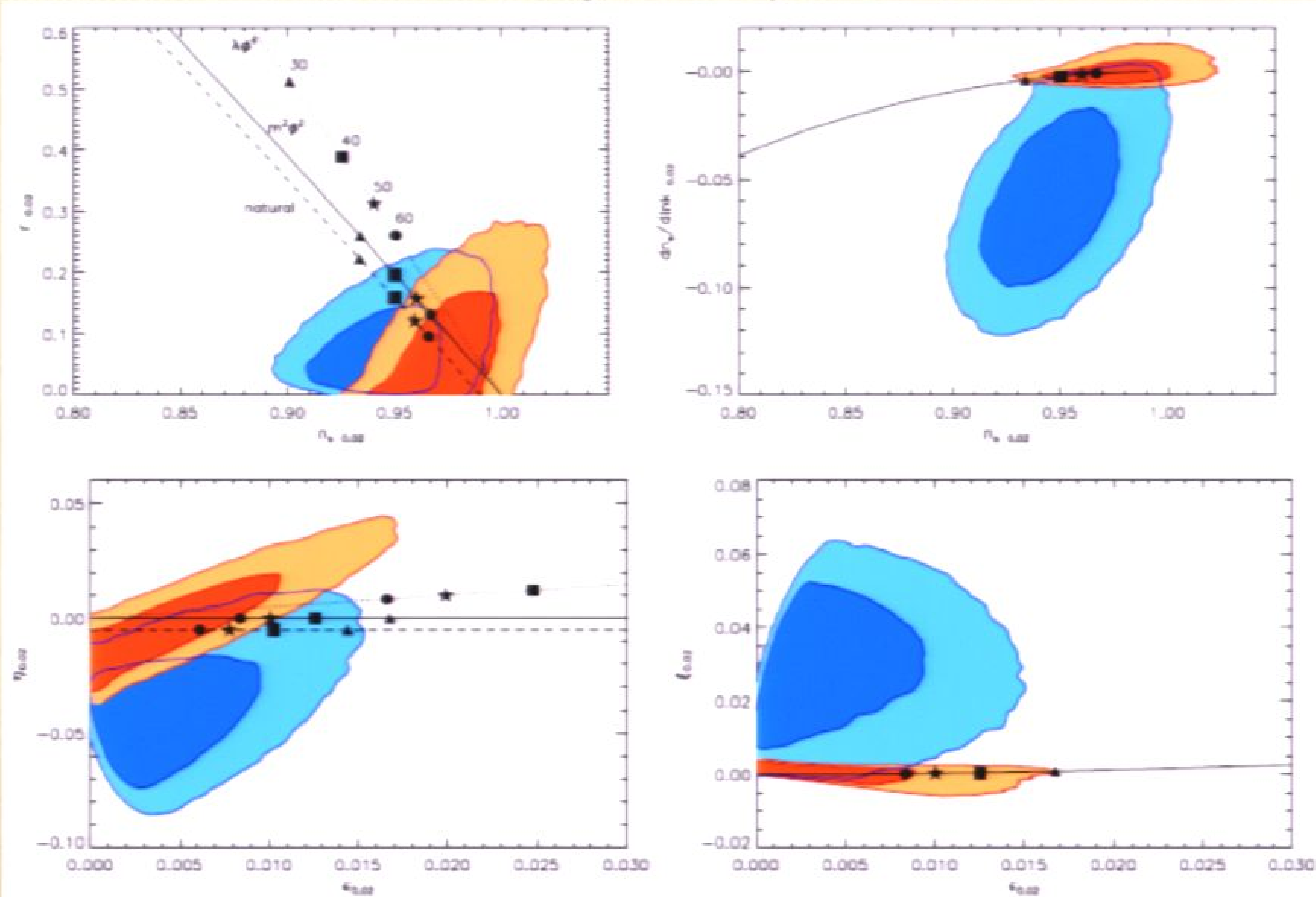
- Won't dwell on results here (in papers)

Number of e-folds correlated with ξ

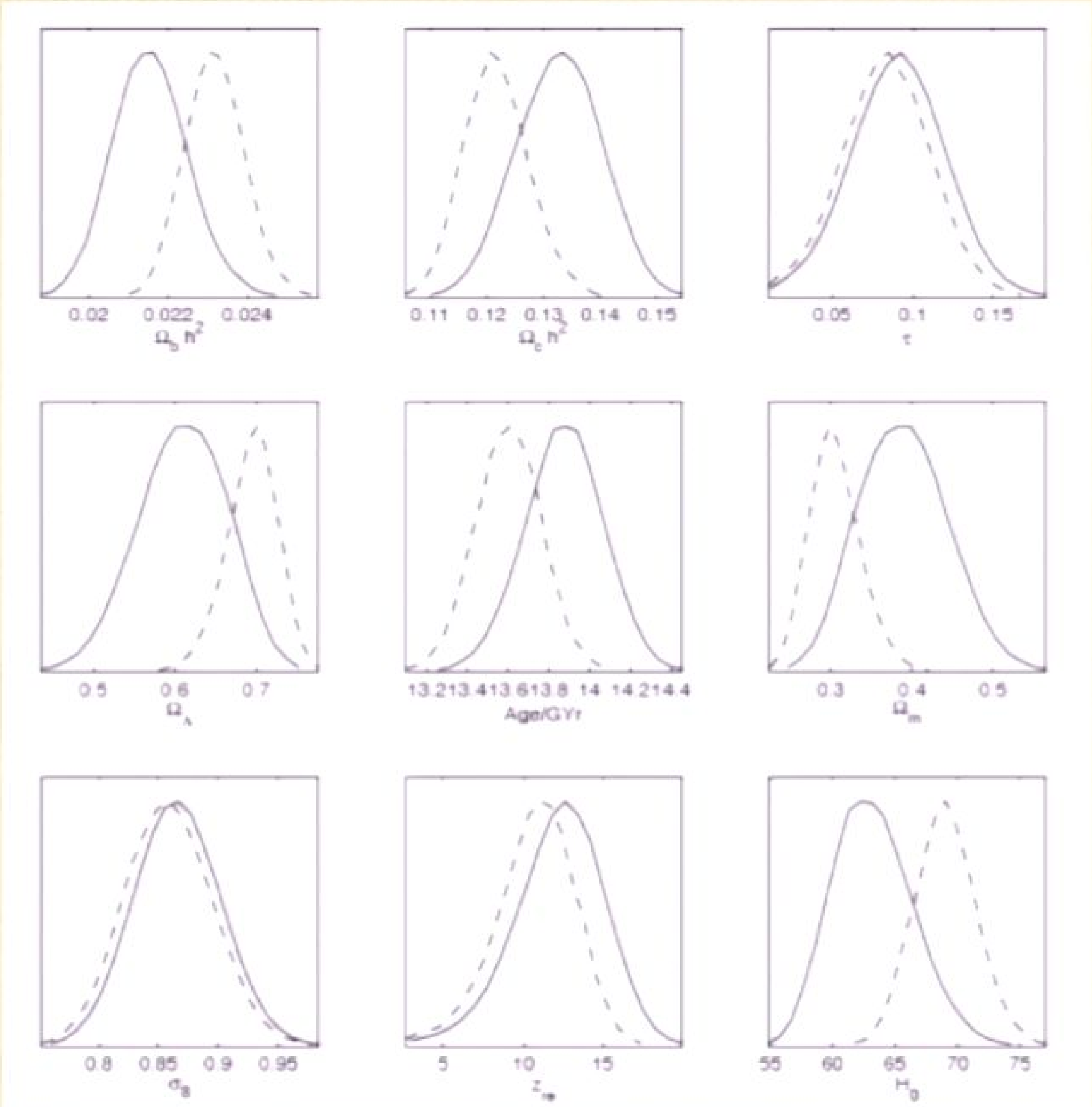


Inflationary trajectories...



3 parameters, WMAP + SDSS N>30

"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...
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- 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
  - Plus better constraints on Ω_m etc to use as priors.
  - Evidence for running similar to WMAP analysis
  - Strong running would put constraints on inflation

Current Work...

with Peter Adshead

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  - Likely experimental bounds on these models?
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- Correlation between ϵ and N
  - If N is small, then ϵ must be tiny
  - Self-consistency & mild prior on reheating physics.
- Two possible ends to inflation:
  - Smooth: might see in slow roll
  - Hybrid: no warning

Other Fingerprints...

- Tensor perturbations
  - CMB B-mode (and some contribution to <TT>)
  - Amplitude characterized relative to scalar modes
  - Current upper bound rules out $\lambda\varphi^4$ inflation (r~0.3)
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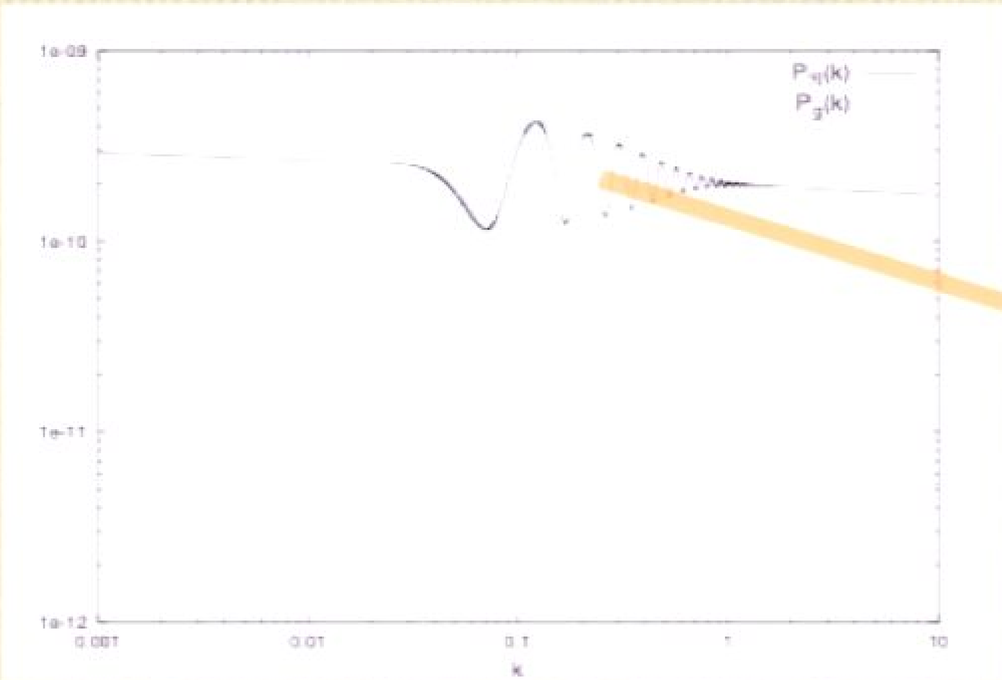
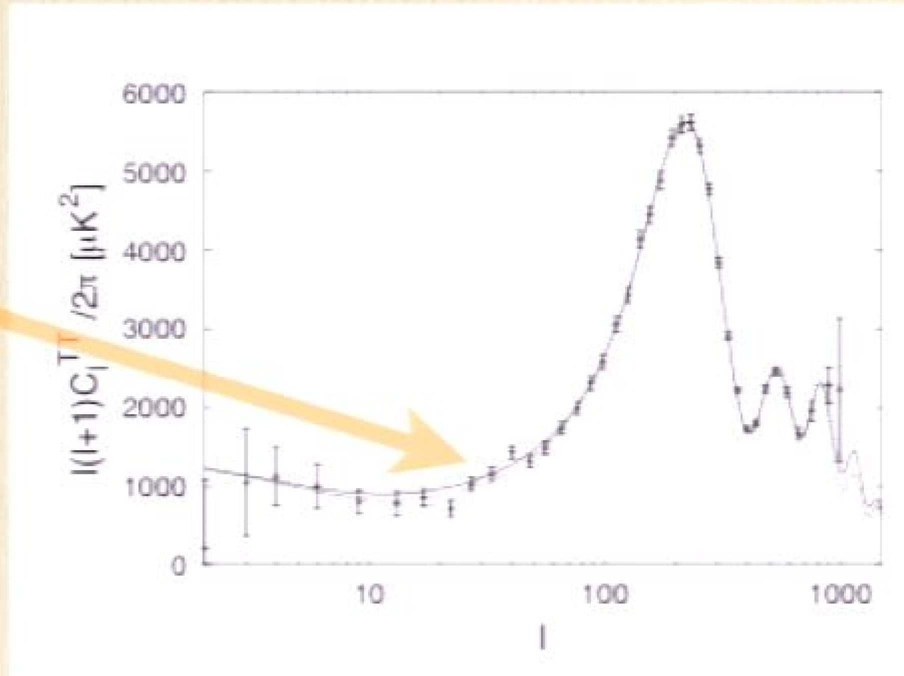
  - Serious test of $m^2\varphi^2$ inflation
  - May never get below $r \sim 0.001$?
- Of all the "secondary" observables...
  - Only tensors are widely argued to be detectable
  - But string models prefer very low r ($\sim 10^{-12}$)

Non-trivial Spectra





- Potentials with "steps"
  - Possibly found in some particle physics scenarios
  - Used to fit "glitch" in CMB C_l near l~30
  - Local violation of slow roll
  - My guess: this is pretty far-fetched!

Non-Gaussianity

Battefeld, Chen, Lim, Peiris and Smith

- Inflation produces Gaussian perturbations
  - Drawn from Gaussian distribution
  - Know variance (2 point function)
  - Compute all higher order moments

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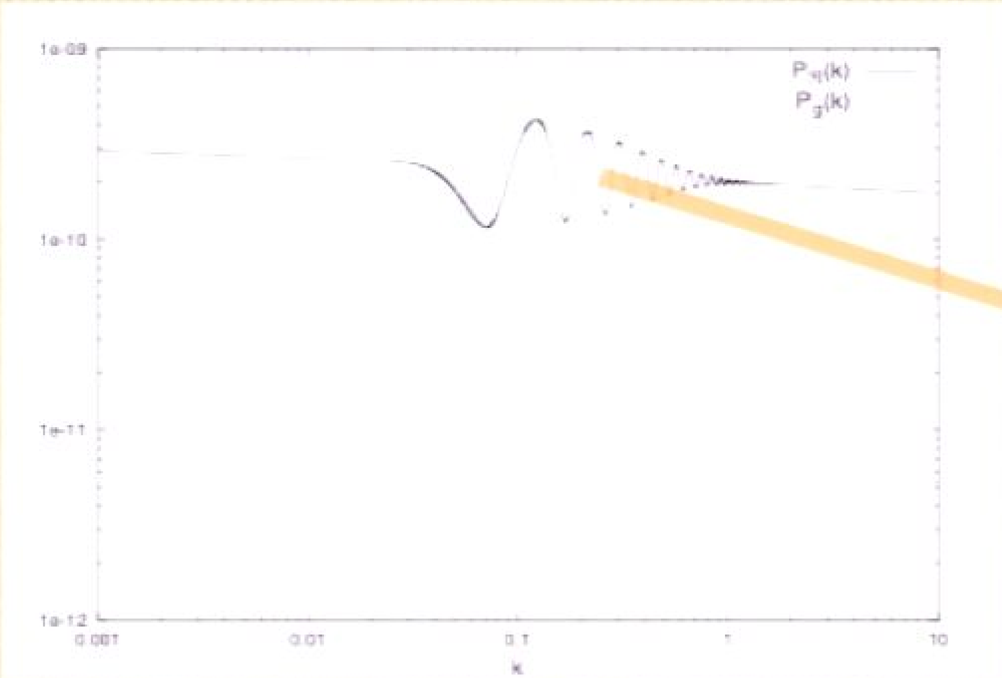

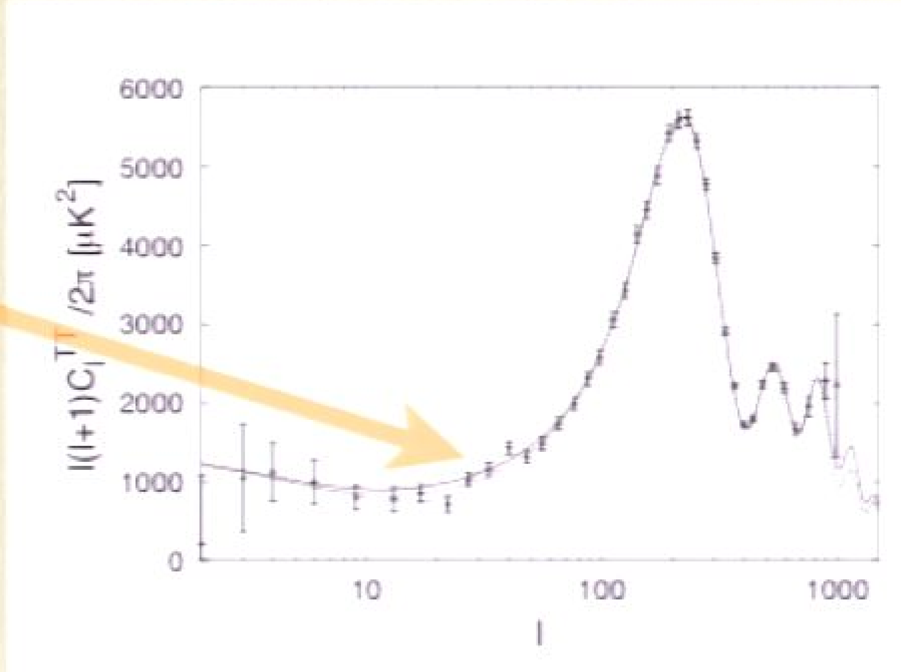

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- But non-Gaussianity is possible
  - Naively: parameterize via f_{nl} (3 point)
  - Has no scale dependence (not true in general)
  - Primordial $f_{nl} \sim \epsilon$ ($\sim$0.01) for standard slow roll
  - Cosmic variance limit $f_{nl} \sim 1$ (plus evolution effects)
  - Detection would rule out many models

Getting Non-Gaussianity

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  - Multiple fields
  - Variant kinetic terms
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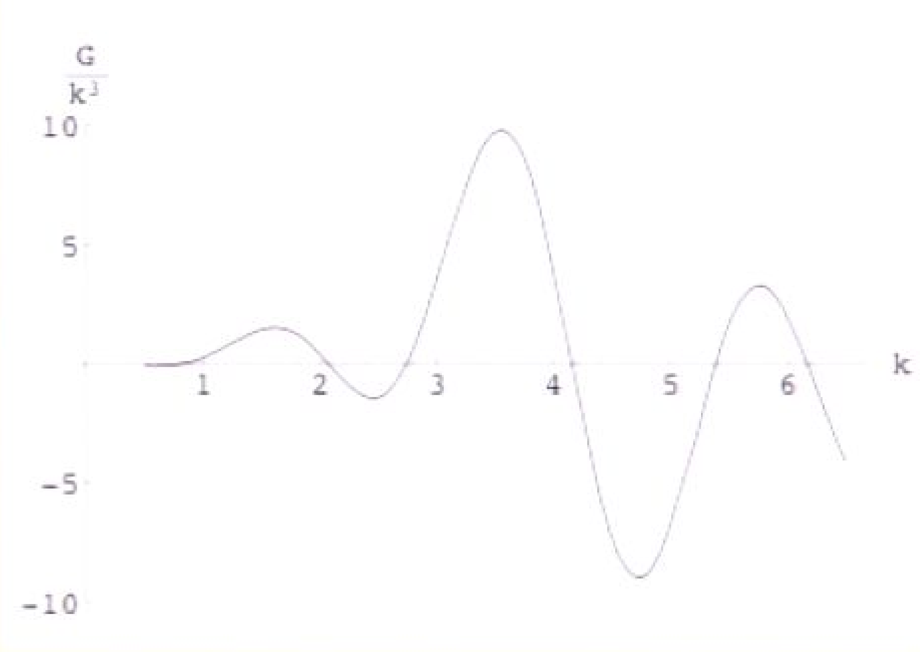
Getting Non-Gaussianity

- Move away from single field, slow roll
  - Multiple fields
  - Variant kinetic terms
  - DBI, string models.
- Local violation of slow roll (step model)
  - 3-point signal strongly k-dependent
  - Must go beyond f_{nl}
  - Chen, Easther and Lim astro-ph/0611645

Non-Gaussianity For Step Potential

- f_{nl} analog ~ O(10)
  - For "best fit" step



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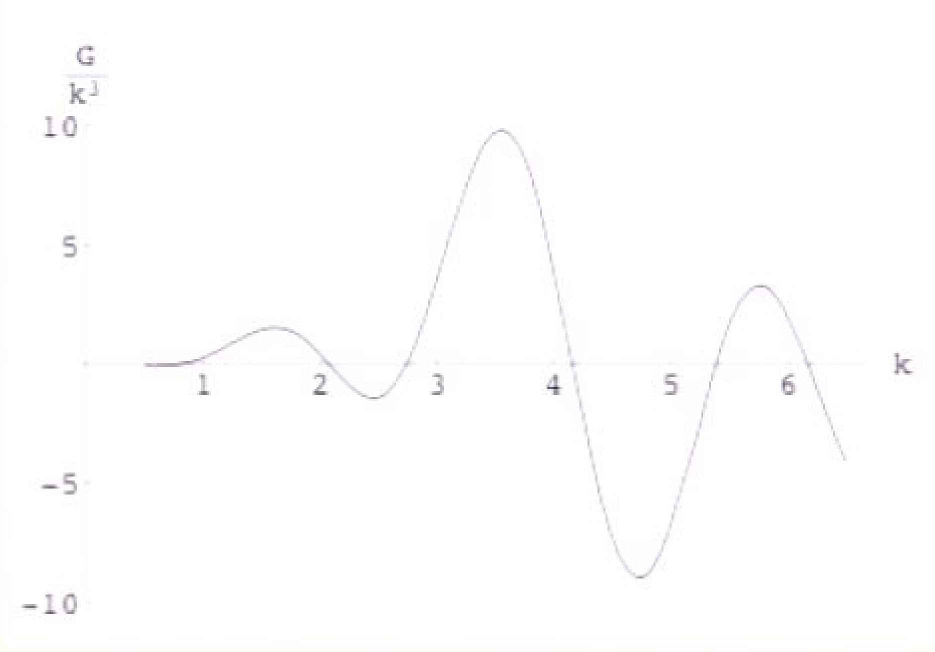

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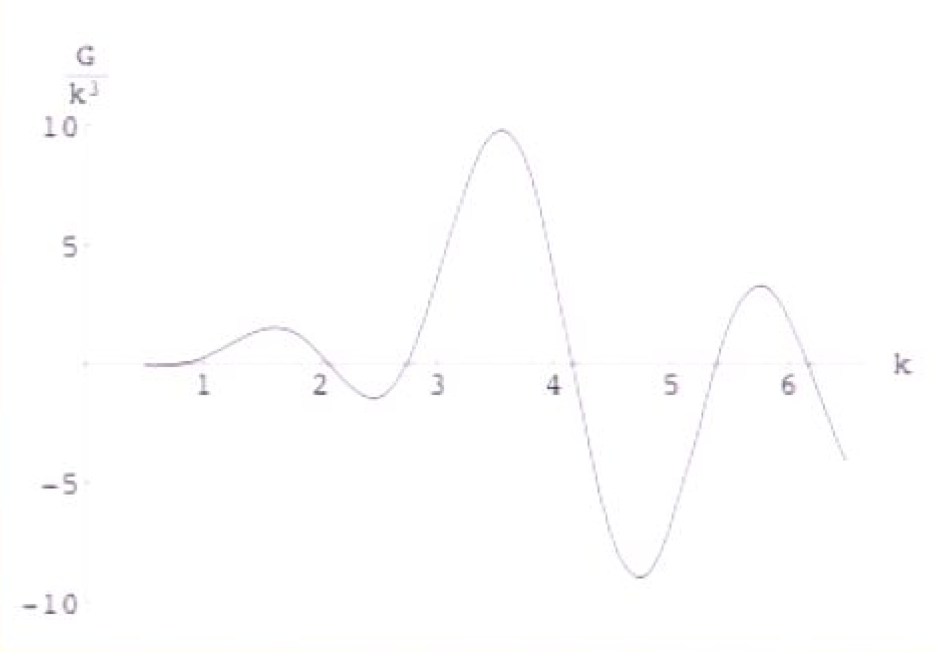

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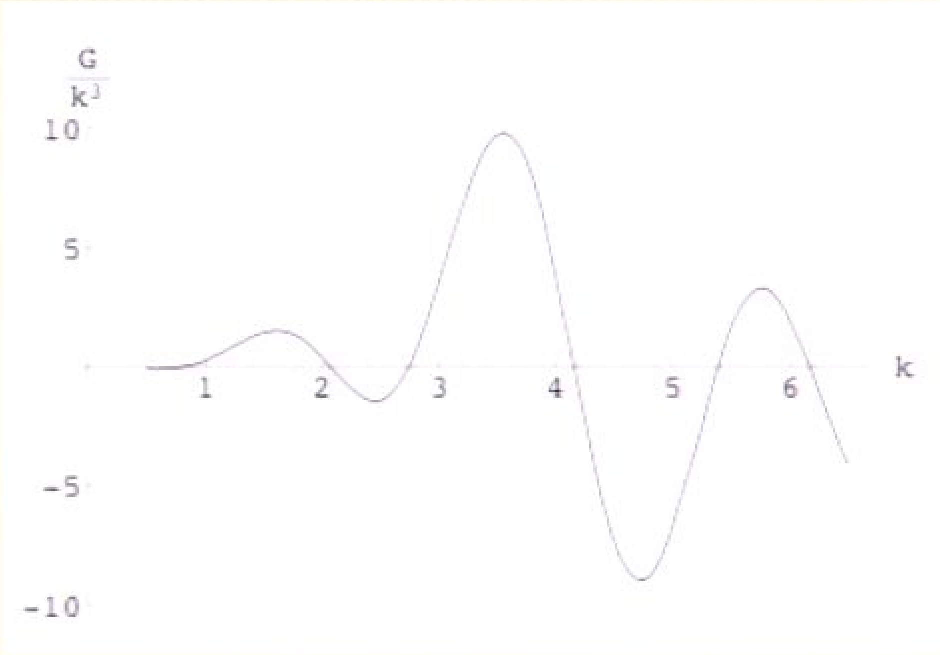
- Work in progress
  - Initial conditions / transients



Signs of the End of Inflation?

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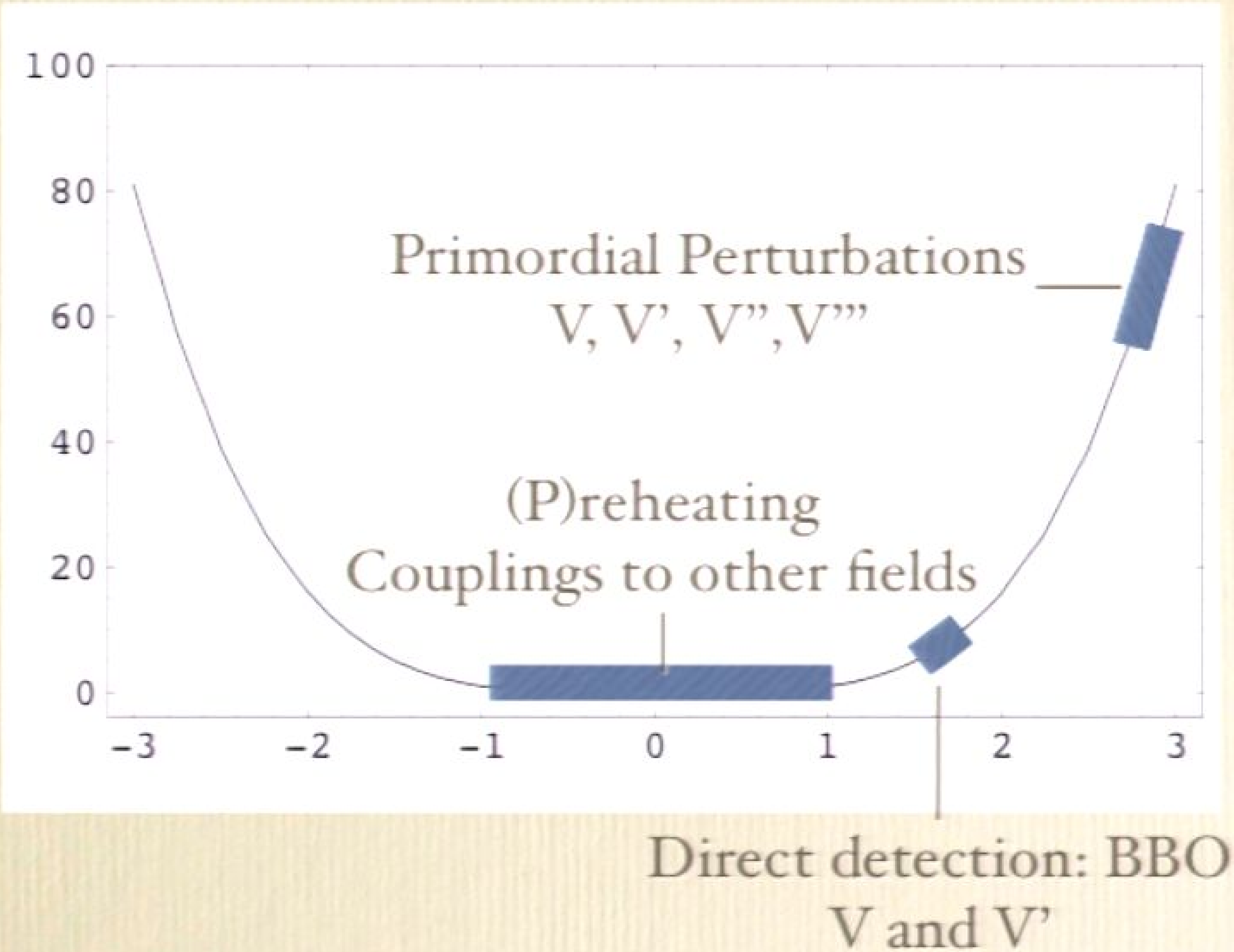
  - Either slowly (via tree level couplings)
  - Or rapidly, via resonance
- Resonance leads to bubble formation, turbulent motion
  - Large fluctuations at very small comoving scales.

Inflationary Observables



Parametric Resonance: A Quick Sketch (Continued)

- Initial state:
  - Inflaton field is oscillates around minimum
  - χ and χ_k are (initially) almost zero

$$\phi(t) = \Phi(t) \sin m_\phi t$$

$$\chi_k'' + 3H\chi_k' + (A(k) - 2q\cos 2z)\chi_k = 0$$

$$A(k) = \frac{k^2}{m_\phi^2 a^2} + 2q \quad z = m_\phi t \quad q = \frac{g^2\Phi^2}{4m_\phi^2}$$

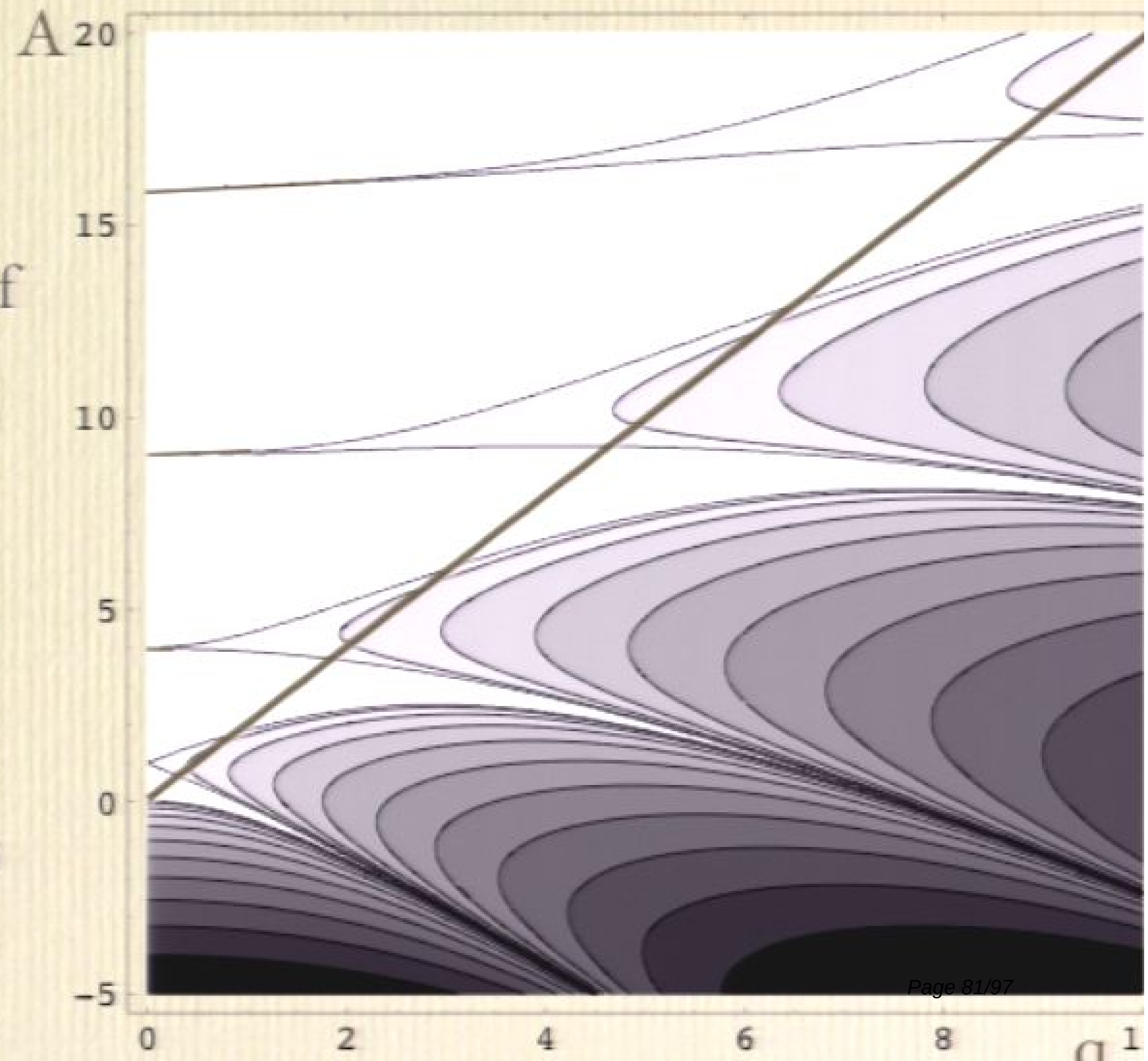
- We have a forced, damped oscillator
  - Quadratic inflaton potential: Mathieu Equation
  - Exact solutions in initial regime

Parametric Resonance: A Quick Sketch (Continued)

- A > 2q (from definitions)
- A and q evolve with time
- Modes move in and out of resonance

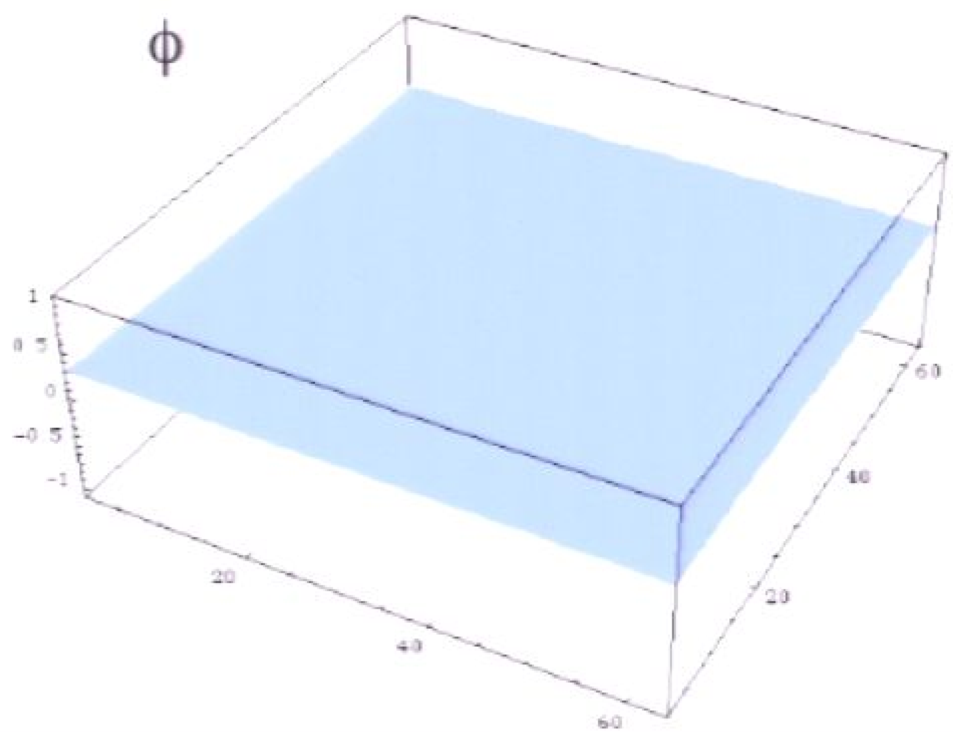
- White - Oscillatory
- Grey/Black - Resonance

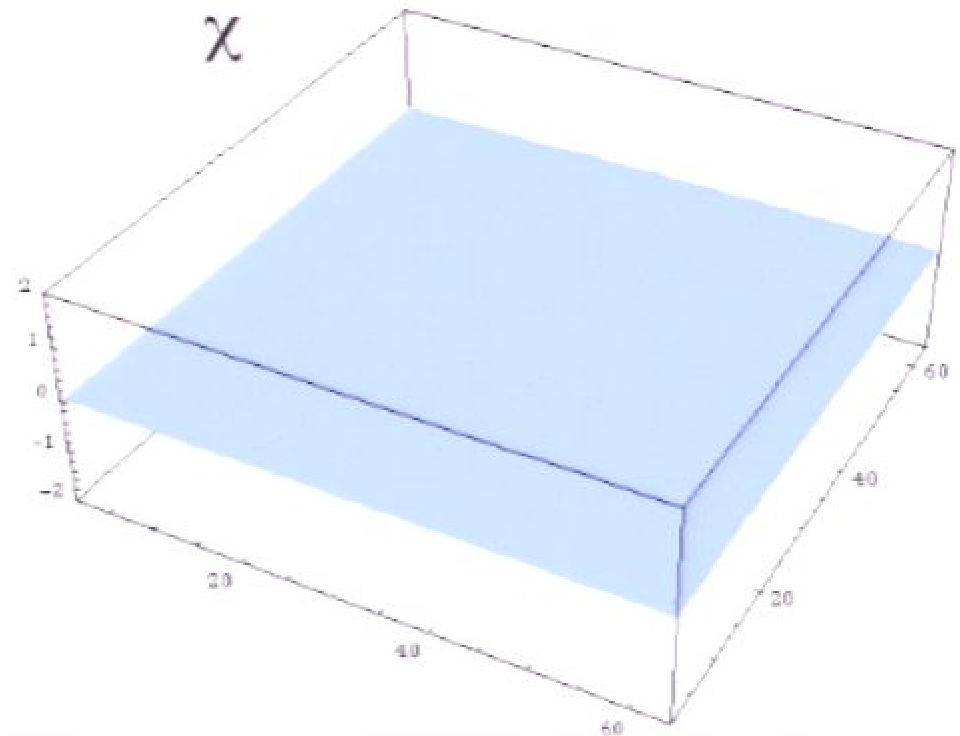
- Pump k-modes
  - Large inhomogeneities



Parametric Resonance: For Beginners

Simulations





- Evolution eventually becomes nonlinear
  - Backreaction on inflaton ends resonance
  - Fields rescaled.

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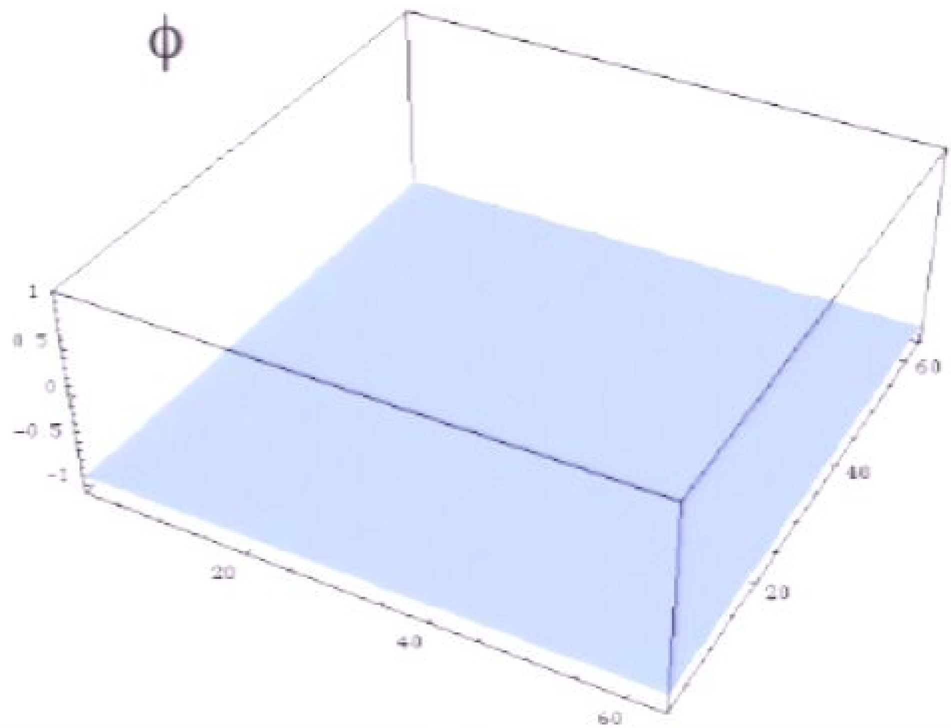

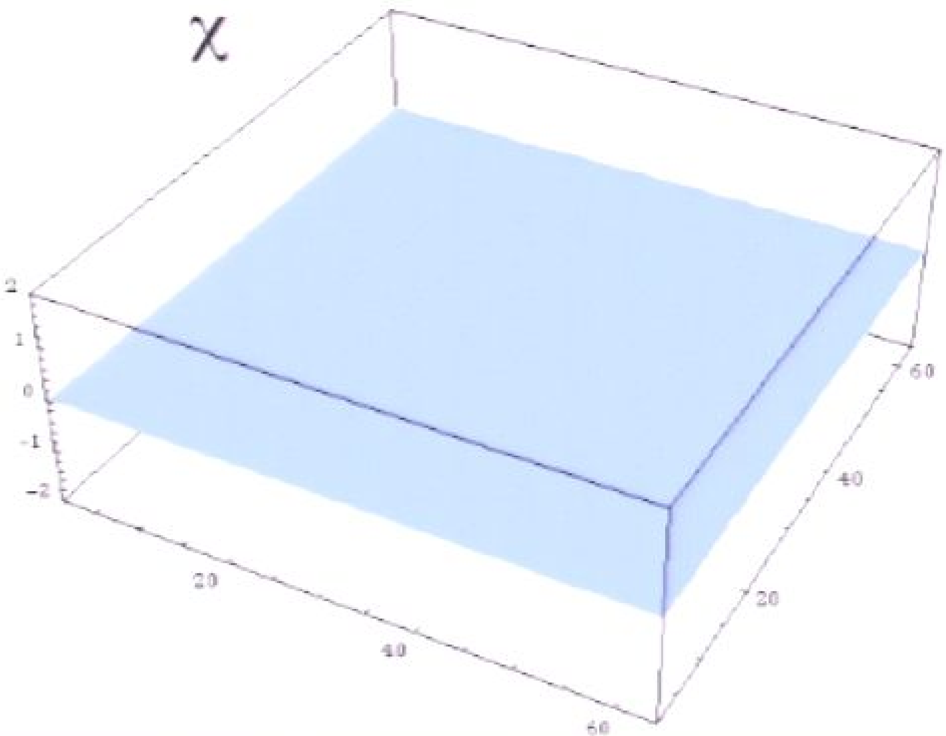

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Location of Peak

- Hubble size at end of inflation: $1/H_{end} \sim (V_{end})^{-1/2}$

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- Assume instantaneous preheating:
  - $\rho \sim T^4 \sim V_{end}$
  - $T_{max} \sim (V_{end})^{1/4}$
  - Growth since thermalization: $\sim T_{max} / T_{CMB}$

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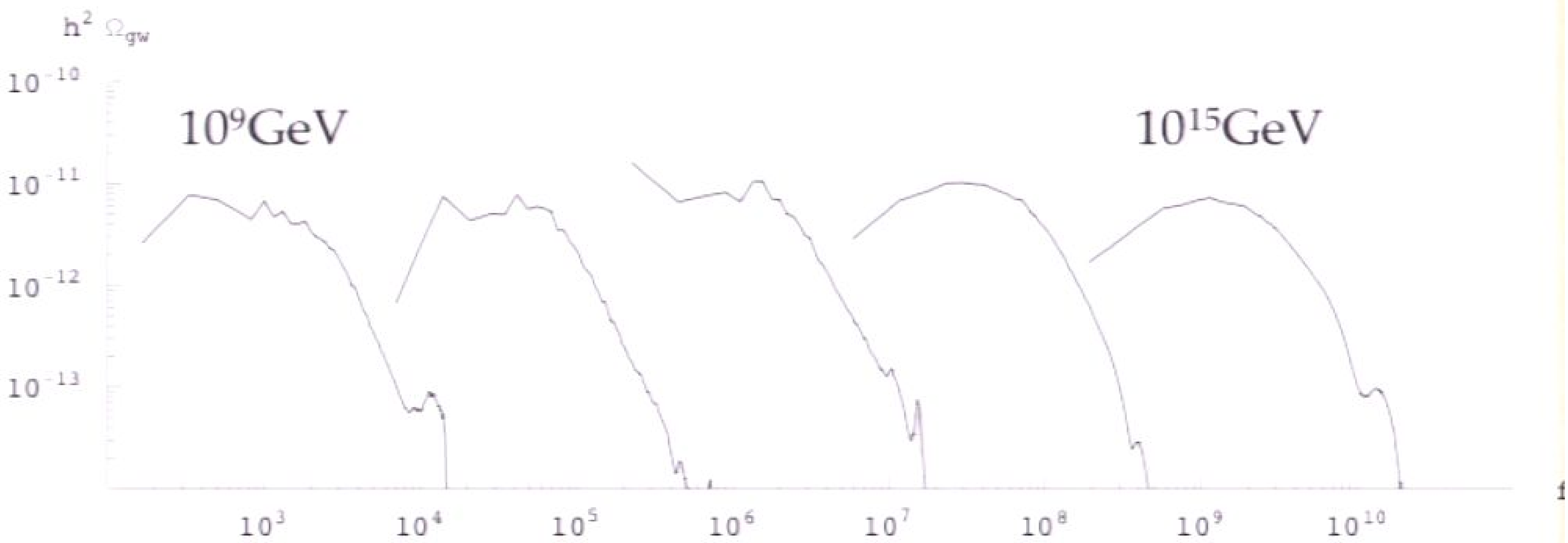
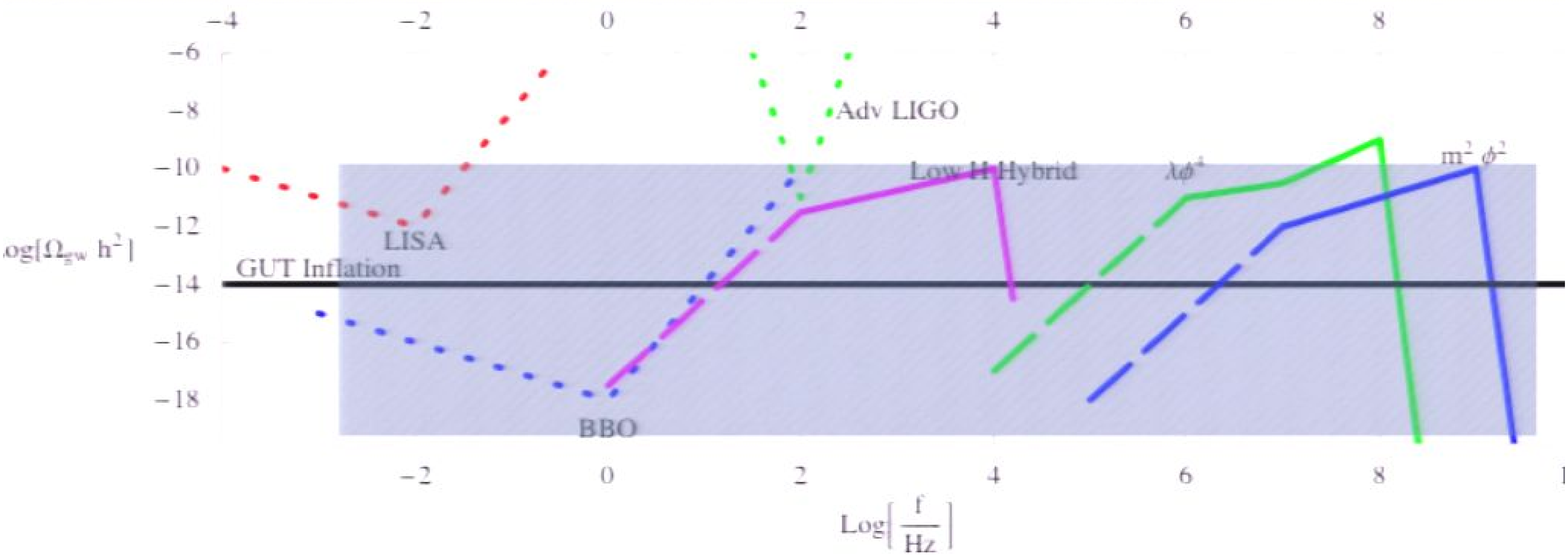
- But something like 10^{-10} of energy converted into gravitational radiation at phase transition
  - Provides upper bound on this signal
  - But can easily be lower
- Also depends on post-inflationary equation of state
  - Matter dominated phase (before thermalization)?
  - Second bout of inflation??

Resonance Parameters

$$\mu^2 = \frac{h^2 M^2}{\lambda} \qquad q = \frac{g^2 m_{pl}^2}{\mu^2} \sim 2 \times 10^6$$



Summary Plot



Remarks

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- Still work in progress
  - But opens a new window into inflationary physics
- Preheating involves tough physics
  - Nonlinear, nonequilibrium, field theory in expanding universe.
  - But "free" in many/most models of inflation
  - Uptick in theoretical work over the last year

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  - Preheating *can* generate generate background
  - Need to understand whether this signal is generic

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  - Preheating *can* generate generate background
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- Depends crucially on energy scale of inflation
  - *Most* string models at lower scales?

- Experiment: signal may be there, so worth considering

Summary...

- May be more to inflation than the scalar spectrum
  - But we can't be sure

- Inflationary *paradigm* in good shape
  - Little clue as to details of inflationary model
  - All inflationary models (roughly) similar

- Focus on "rare" fingerprints
  - Won't see them in most models (pessimist)
  - Strong constraints if you do see them (optimist)