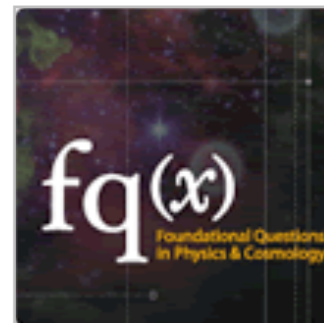


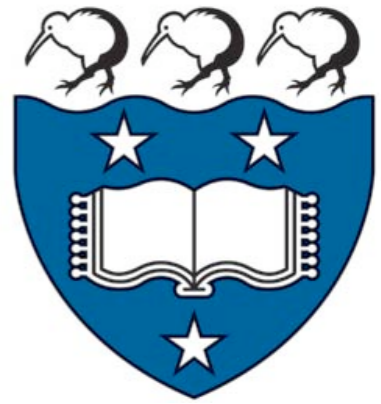


The Universe After Inflation

Richard Easther

+ Adshead, Amin, Bridges, Finkel, Giblin, Lim, Loeb, Mortonson, Peiris, Pritchard

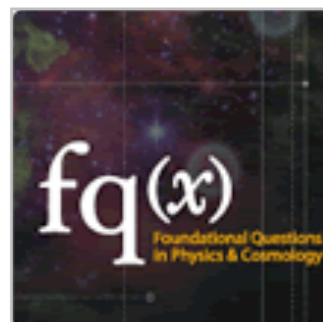




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- GUT scales to \sim TeV scales ($\times 10^{12}$)
 - Physics *and* properties of the universe unconstrained

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- Probes: dark matter, baryogenesis, power spectrum

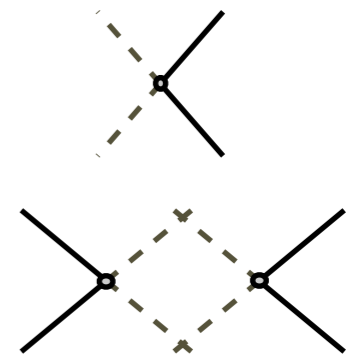
Some Possibilities...

1. Delayed Reheating

- Minimal assumption

- Thermalization: couple inflaton to other fields

- Coupling weak to protect potential from loops

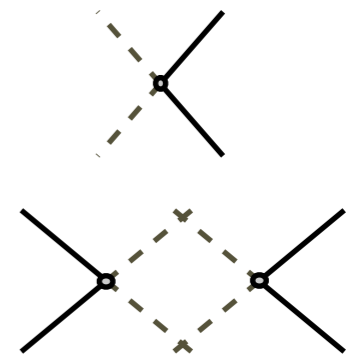


1. Delayed Reheating

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- Field oscillates at bottom of potential: $a(t) \sim t^{2/3}$

- Looks like dust: $H \sim t^{-1}$, $\rho \sim E^4 \sim t^{-2} \sim a^{-3}$, $E \sim a^{-3/4}$

- $\delta\rho/\rho \sim a(t)$ during matter domination

- Inflaton condensate will fragment

- Start at GUT scale, nonlinear by 10^{12} GeV.

2. Parametric Resonance

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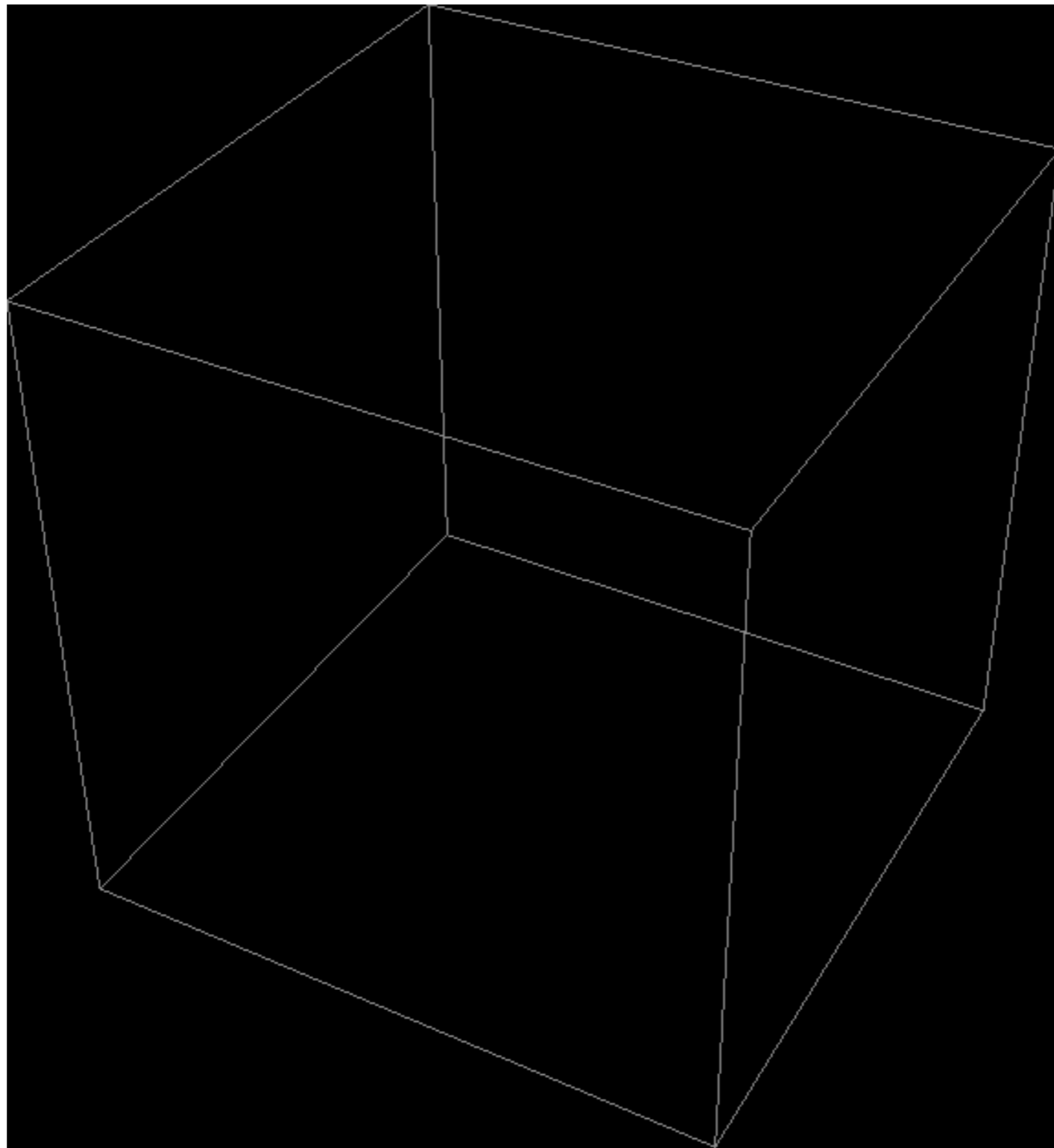
- Turbulent dynamics of scalar fields coupled to gravity
 - First proposed in late 80s / early 90s, hard problem
- Personal interest: gravitational waves from resonance
 - Signal (potentially) visible today
- Resonance *may* lead to prompt thermalization
 - But can leave universe with an arbitrary equation of state

3. Oscillons

- Non-perturbative, meta-stable excitations of a scalar field
 - Like a soliton, but stationary
 - Existence condition: $2V(\varphi) - V''(\varphi) \varphi^2 < 0$
 - $V(\varphi) = \Lambda^4[(1 + \beta^2 \varphi^2)^\alpha - 1]$

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- Oscillons *generated* by resonance
 - Long matter-dominated phase in post-inflationary universe



Oscillon Formation

Amin, RE and Finkel: [arXiv:1003.3011](https://arxiv.org/abs/1003.3011), + Flauger and Hertzberg [1106.3335](https://arxiv.org/abs/1106.3335)

4. Primordial black holes

- Need: Rising power at short scales or nonlinear dynamics
 - Contribute *mass* and *radiation* to universe
 - Constraints: BBN, microlensing, x-ray background, dark matter abundance.

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- Need: Rising power at short scales or nonlinear dynamics
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 - Constraints: BBN, microlensing, x-ray background, dark matter abundance.
- But very small PBH (~ 1 gram) decay *before* BBN
 - Leaves no trace behind??
 - Again a matter dominated phase (and gravitational waves)

Could add...

5. Kination

6. Cosmic string networks

7. Thermal inflation

8. Moduli domination

9. Non-standard phase transitions

10. etc

Consequences...

Predictions of inflationary models

- Consider n_s for a specified inflationary model
 - Observed value: function of *post-inflationary* horizon growth
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- Probe: combination of inflation + post-inflationary growth

Constraining Inflation

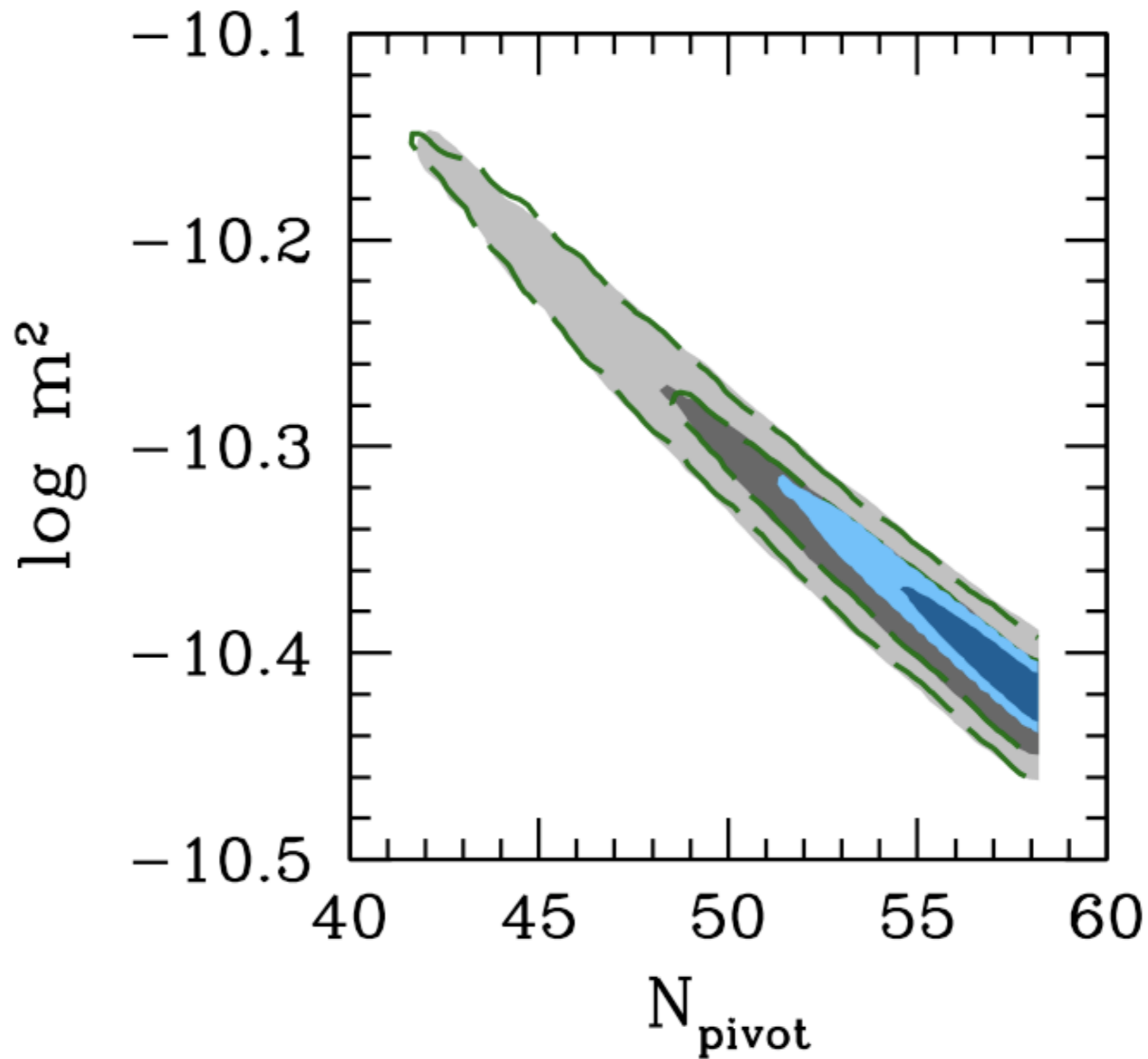
- Want to test specific inflationary models
 - Parameter estimation and mode selection
 - ModeCode <http://zuserver2.star.ucl.ac.uk/~hiranya>

Mortonson, Peiris & RE [ModeCode] arXiv:1007.4205
See: also Martin, Ringeval & Trota

Constraining Inflation

- Want to test specific inflationary models
 - Parameter estimation and mode selection
 - ModeCode <http://zuserver2.star.ucl.ac.uk/~hiranya>
- Chains for a specific inflationary model [potential]: prior
 - N_k is an *inflationary* parameter (stand-in for φ_k)
 - But constraining post-inflationary physics as well
 - Via the matching relationship

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MCMC Constraints for Quadratic Inflation

Peiris, Mortonson, Easter

Grey -- WMAP7 (data)

Blue -- Planck (simulation)

	Natural		ϕ^n	
	N	f	N	n
fiducial values	51	$\sqrt{8\pi}$	51	2
Planck	5.1	-	3.6	-
	-	0.33	-	0.25
+ $\sigma_r = 0.01$	14.5	0.93	19.7	1.4
	3.5	0.26	8.6	0.41
CIP+Planck	1.69	-	1.2	-
	-	0.11	-	0.09
+ $\sigma_r = 0.01$	13.7	0.87	14.5	1.14
	2.8	0.18	3.96	0.27
FFTT+Planck	0.41	-	0.29	-
	-	0.027	-	0.024
+ $\sigma_r = 0.01$	7.0	0.45	11.0	0.91
	2.5	0.17	2.95	0.24

Forecasts for Future Experiments

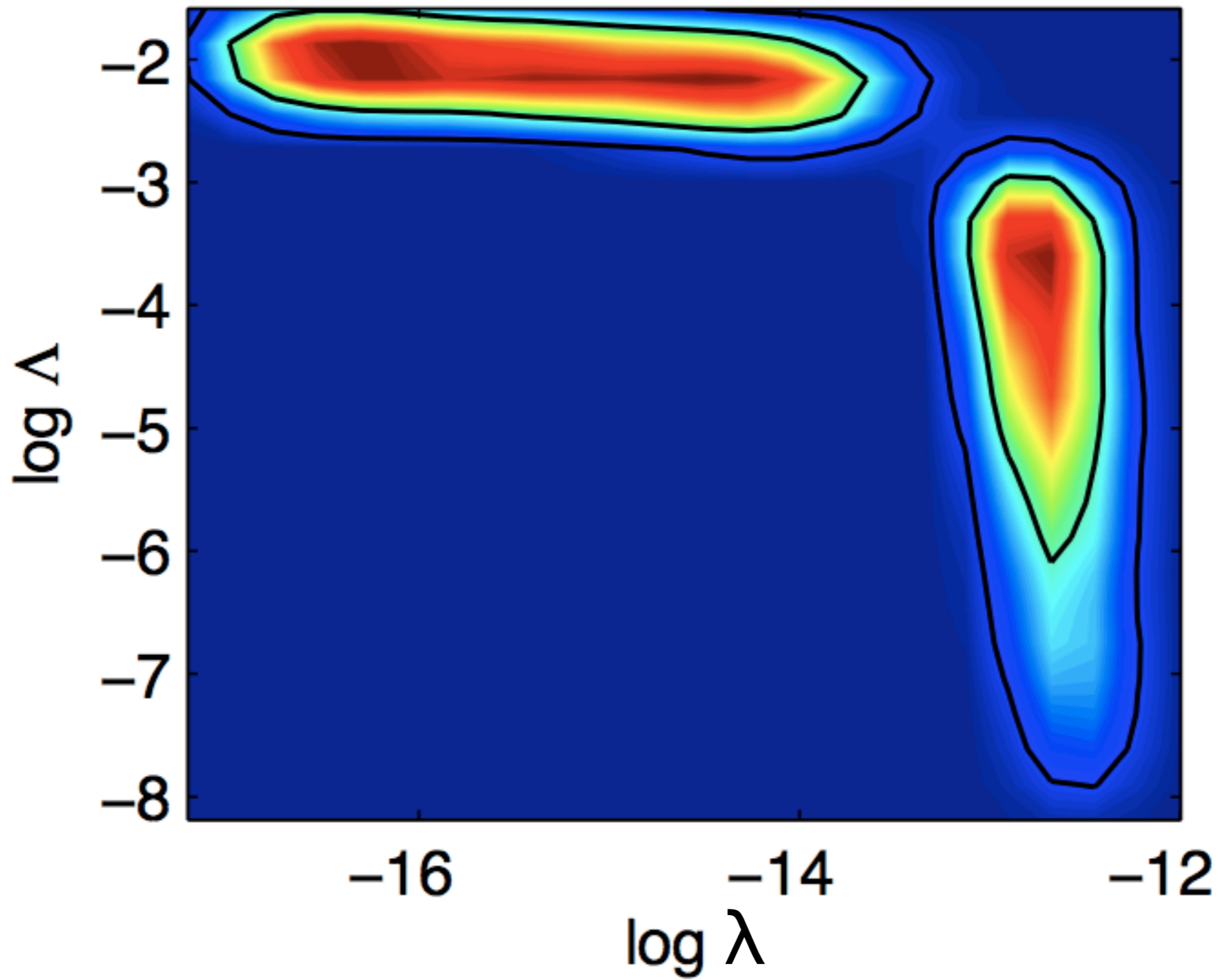
W. Adshead, Pritchard and Loeb

Work in Progress...

- Changing sampler to MultiNest
 - Better probe of “non-elliptical” parameter regions
 - Easy computation of Bayesian Evidence
 - Finished “soon”

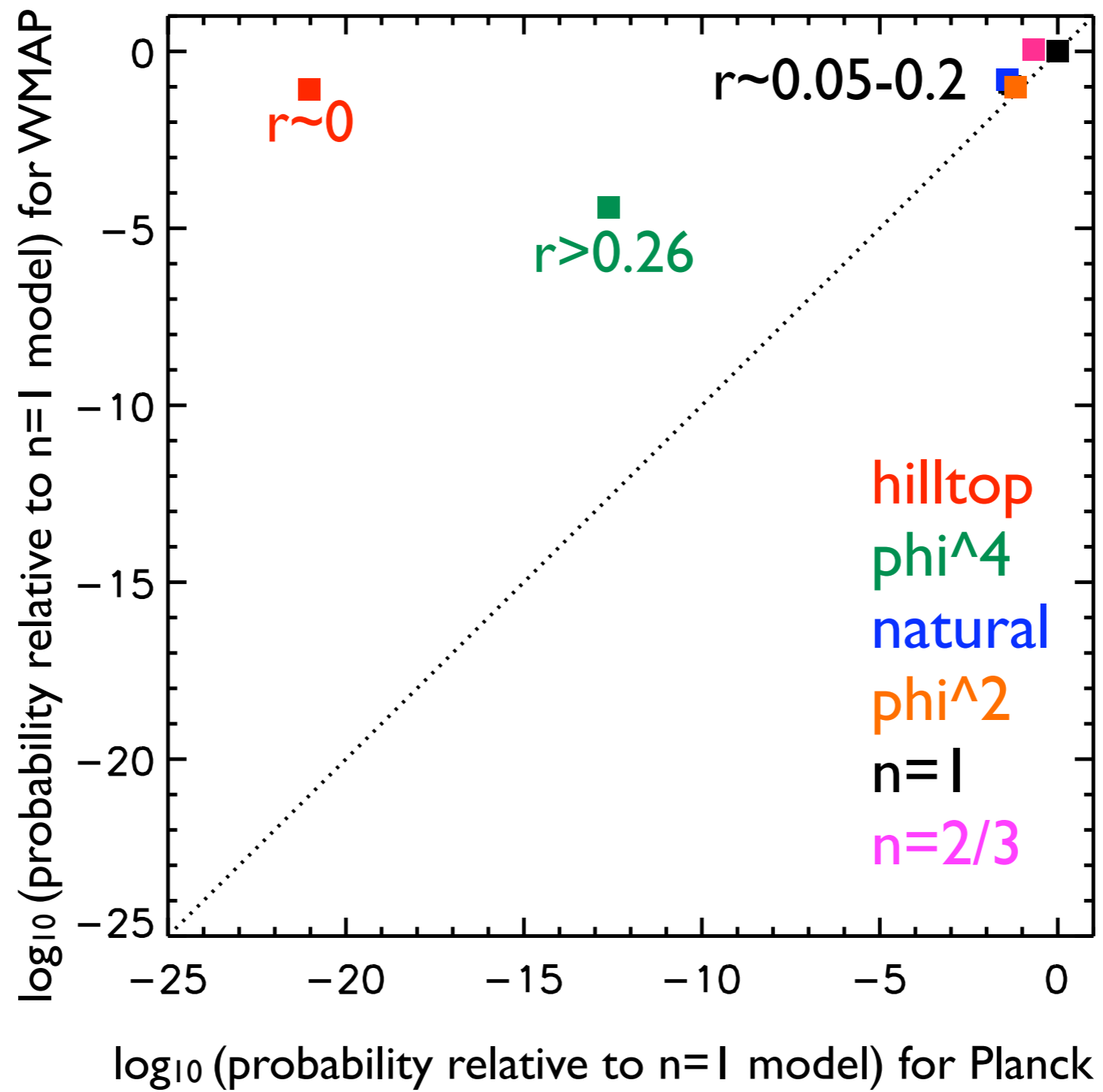
Work in Progress...

- Changing sampler to MultiNest
 - Better probe of “non-elliptical” parameter regions
 - Easy computation of Bayesian Evidence
 - Finished “soon”
- Testing with WMAP and Planck simulations
 - Code well documented, easily extensible, publicly available.
 - Numerical computation of power spectrum (no slow roll)



$$V(\phi) = \Lambda^4 - \frac{\lambda}{4}\phi^4$$

PRELIMINARY



Bayesian Evidence / Model Selection

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Summary...

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- Post-Planck can ask:
 - Does a model require a period of non-thermal expansion?
 - Is a complete model (with reheating included) compatible with the data?
 - Sensitive to integrated expansion history of the universe
- Vast scope for interesting physics after inflation
 - Worth thinking about...