Features, Matching & the Physics of the Post-Inflationary Universe.

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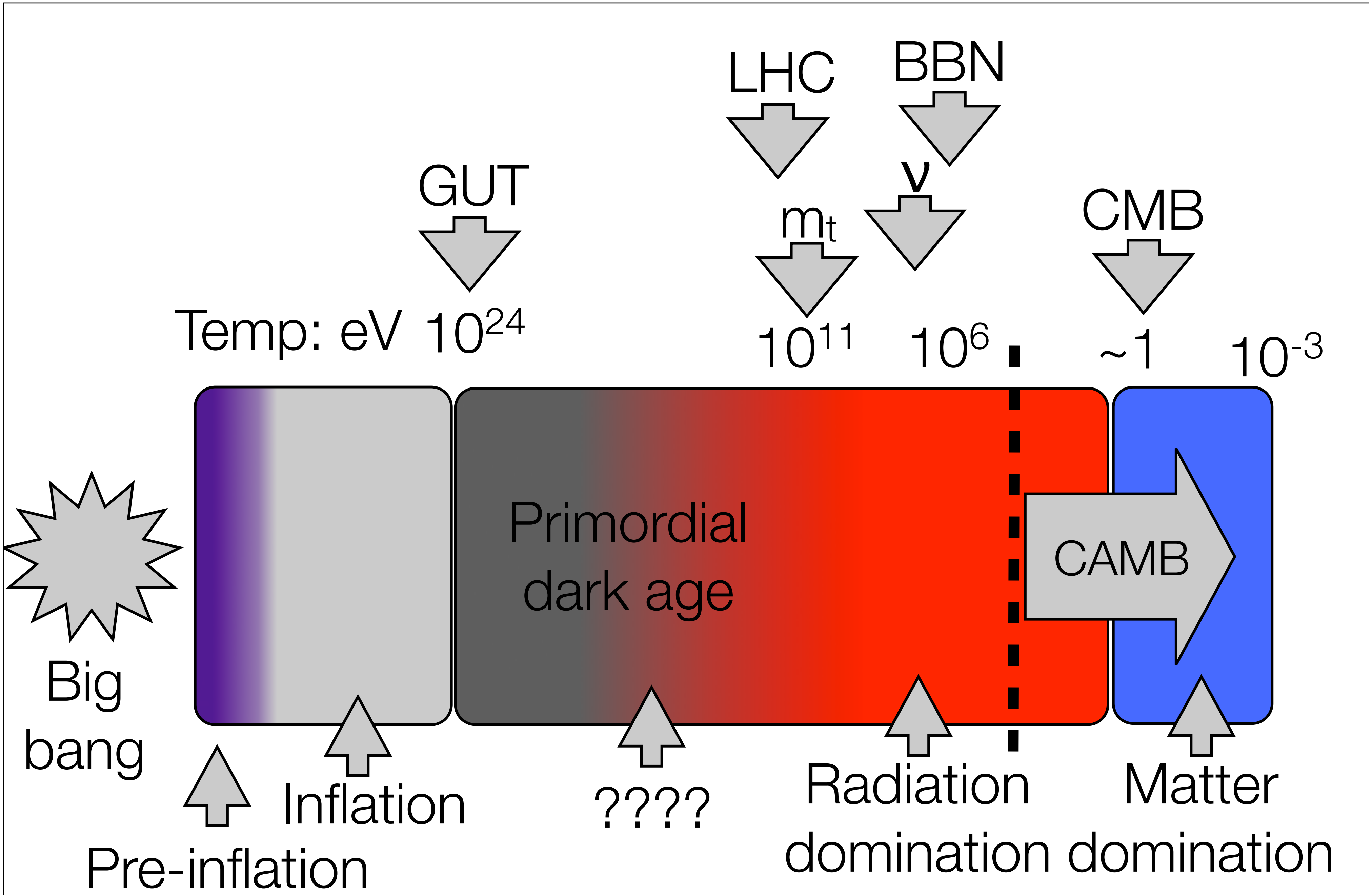
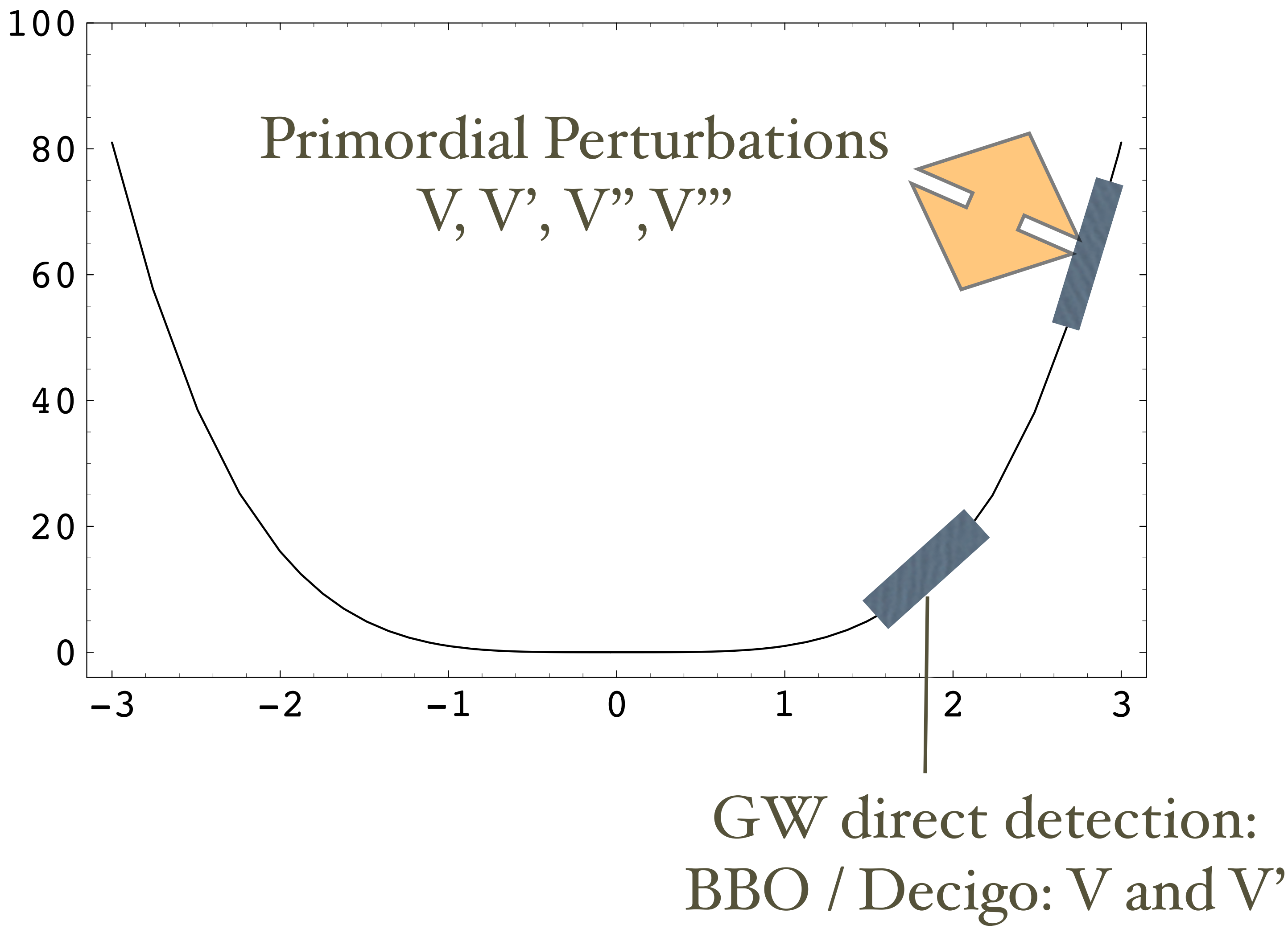
Concordance Cosmology

- Requires initial perturbations
  - Does not say where these perturbations come from
  - Does not *explain* flatness, homogeneity etc.
- Inflationary sector
  - Why *we* are *here* (here in Allahabad, not just anthropics!)
  - Insight into primordial universe *and* superTeV scale physics
- Concordance cosmology looked at tree: we explore the roots.


LHC
BBN
GUT
ν
m_t
CMB
Temp: eV 10^{24}
10^{11}
10^{6}
~1
10^{-3}
Primordial dark age
CAMB
Big bang
Inflation
????
Radiation domination
Matter domination
Pre-inflation

How Do We Think About Features?

- Zeroth message (coming from many directions)
  - Almost infinite number of “features” we can add
- First message: Analyze features self-consistently
    - e.g. 2 point + 3 point; <EE> and <ET> as well as <TT>
- Second message: Do we have a model?
  - Inflation / primordial universe coupled to rest of cosmology.
  - How do we select features? What does a “detection” mean?
  - How do we perform a self-consistent analysis?



Inflation: Cartoon Version

What We All Know...

- Inflationary perturbations are a function of the potential
  - Minimal inflation: potential defines the model
  - Also kinetic term, coupling to gravity, other fields.
  - MANY inflationary models
- To make predictions we need to know $\phi(k)$
  - i.e. mapping from field value to (comoving) scale in sky

The duration of inflation

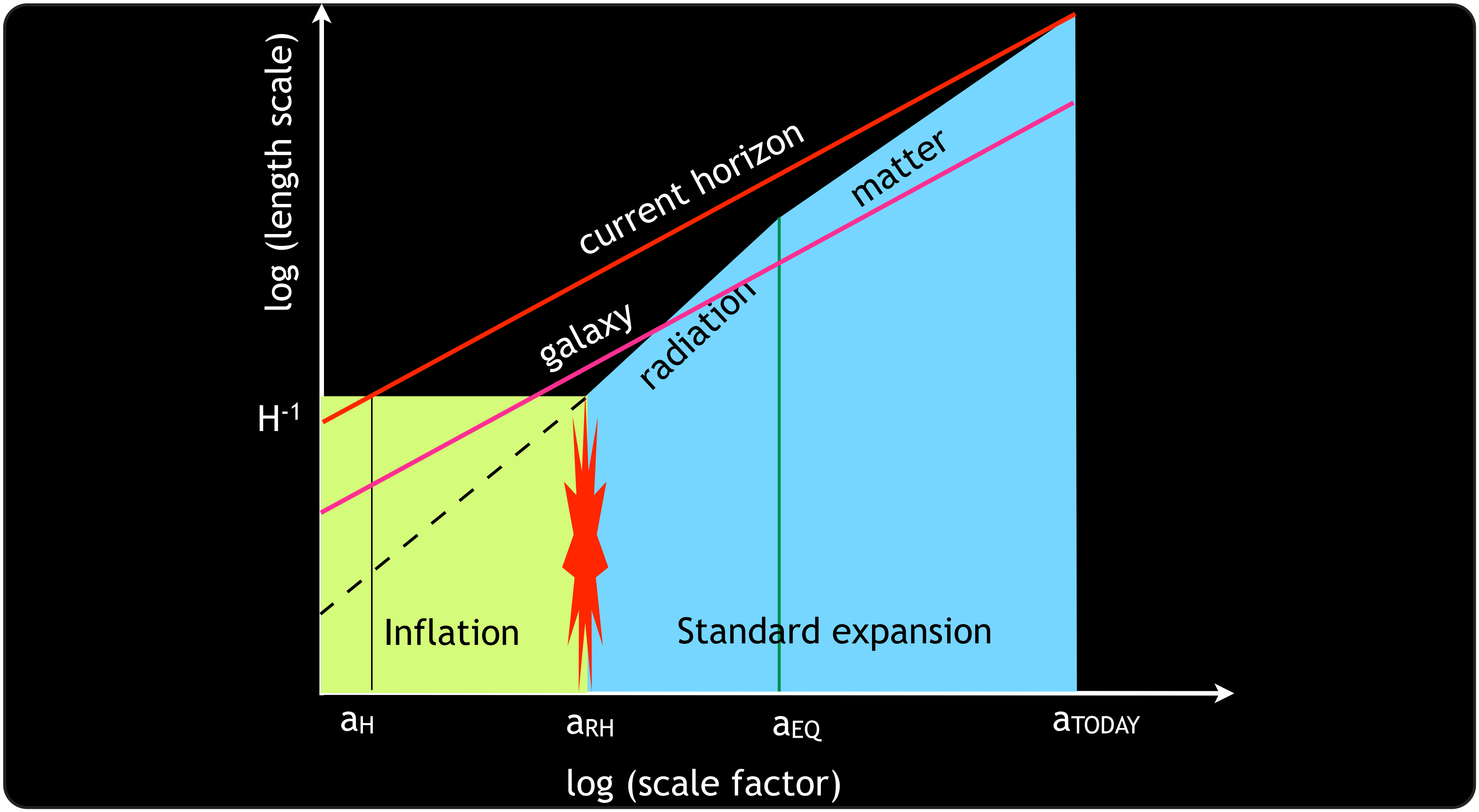
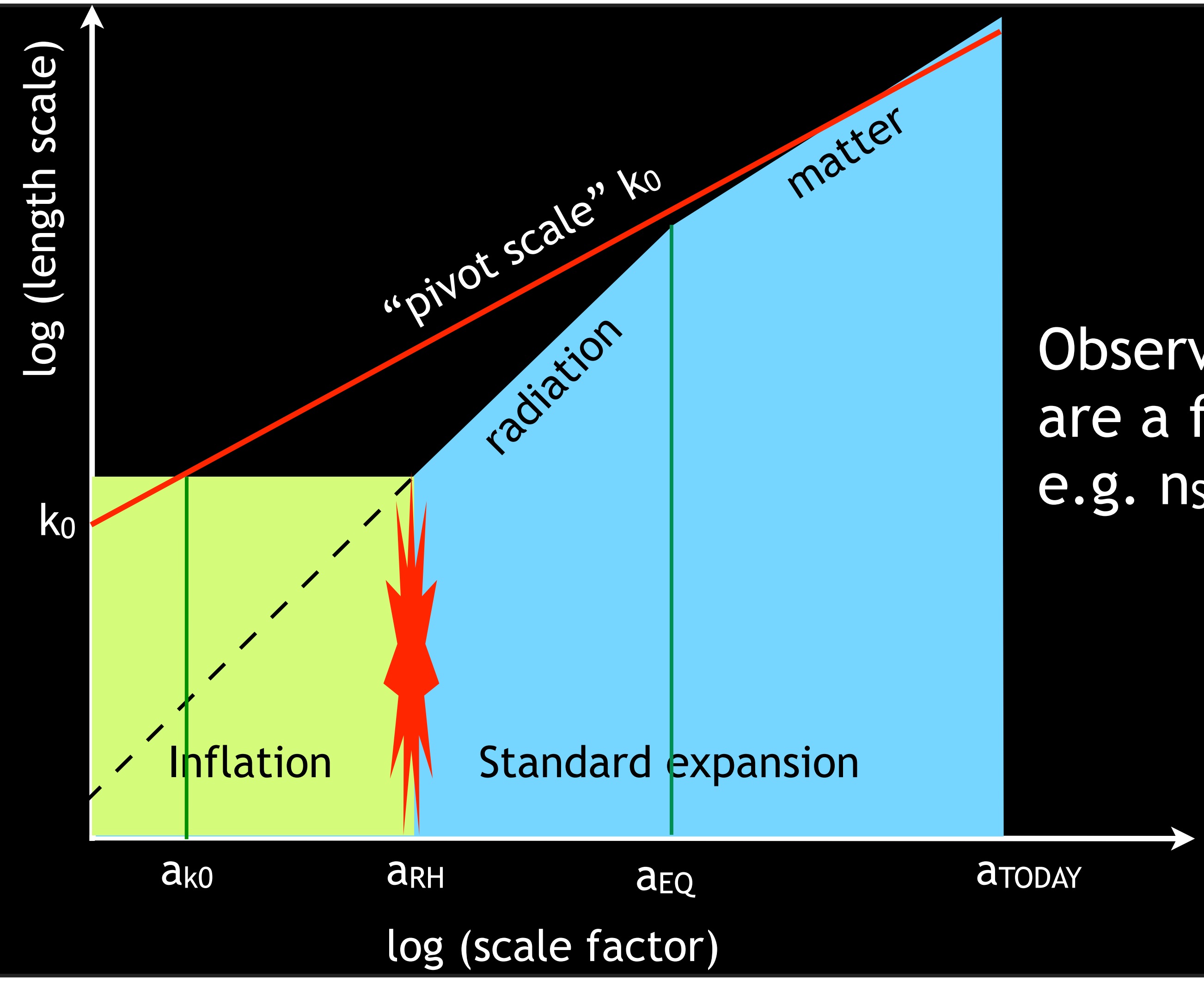


Figure: Peiris

What happens after inflation?

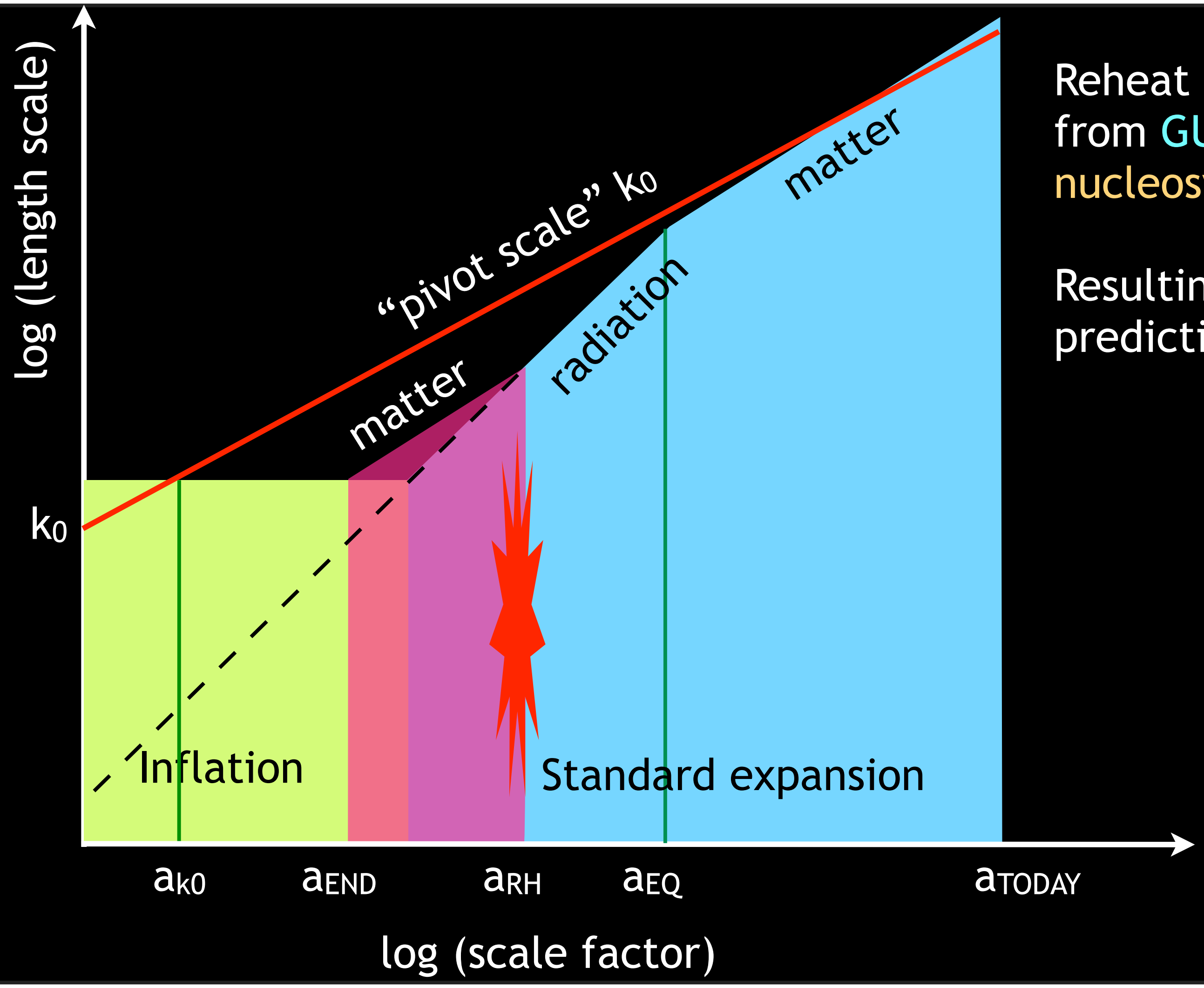
- During inflation, universe cold
  - Almost (no) particles
- Successful inflationary model must *reheat*
  - Take energy from inflaton; convert to standard model states
  - Hard limit: must reheat by MeV scales (nucleosynthesis, ν)
  - But inflation is (potentially) at GUT scales
  - Huge range of scales; largely unknown particle physics

Pivot Scale



Observable parameters are a function of scale!
e.g. $n_S[k(N_{efold})]$

Connecting measurements to model



Reheat temperature can vary from GUT scale (10^{15} GeV) to nucleosynthesis scale (1 MeV)!

Resulting uncertainty in predictions at a given "pivot"

Waiting for Thermalization

- In *simple* models, thermalization is *naturally* slow
  - Inflaton-other field couplings small (to protect slow roll)
  - Although can get nonlinearity [Easther, Gilmore, Flauger]
- Parametric resonance, rapid thermalization
  - But may generate massive meta-stable states (oscillons?)
- Moduli domination? (plus thermal inflation)
- Cosmic string networks
- Kination

Matching Equation

- Connects horizon entry and exit $$\frac{k}{a_0 H_0} = \frac{k}{a_\star H_\star}$$

- $$\frac{k}{H_0 a_0} = \frac{a_k H_k}{a_0 H_0} = \frac{a_k}{a_{end}} \frac{a_{end}}{a_{reh}} \frac{a_{reh}}{a_{eq}} \frac{a_{eq}}{a_0} \frac{H_k}{H_0}$$

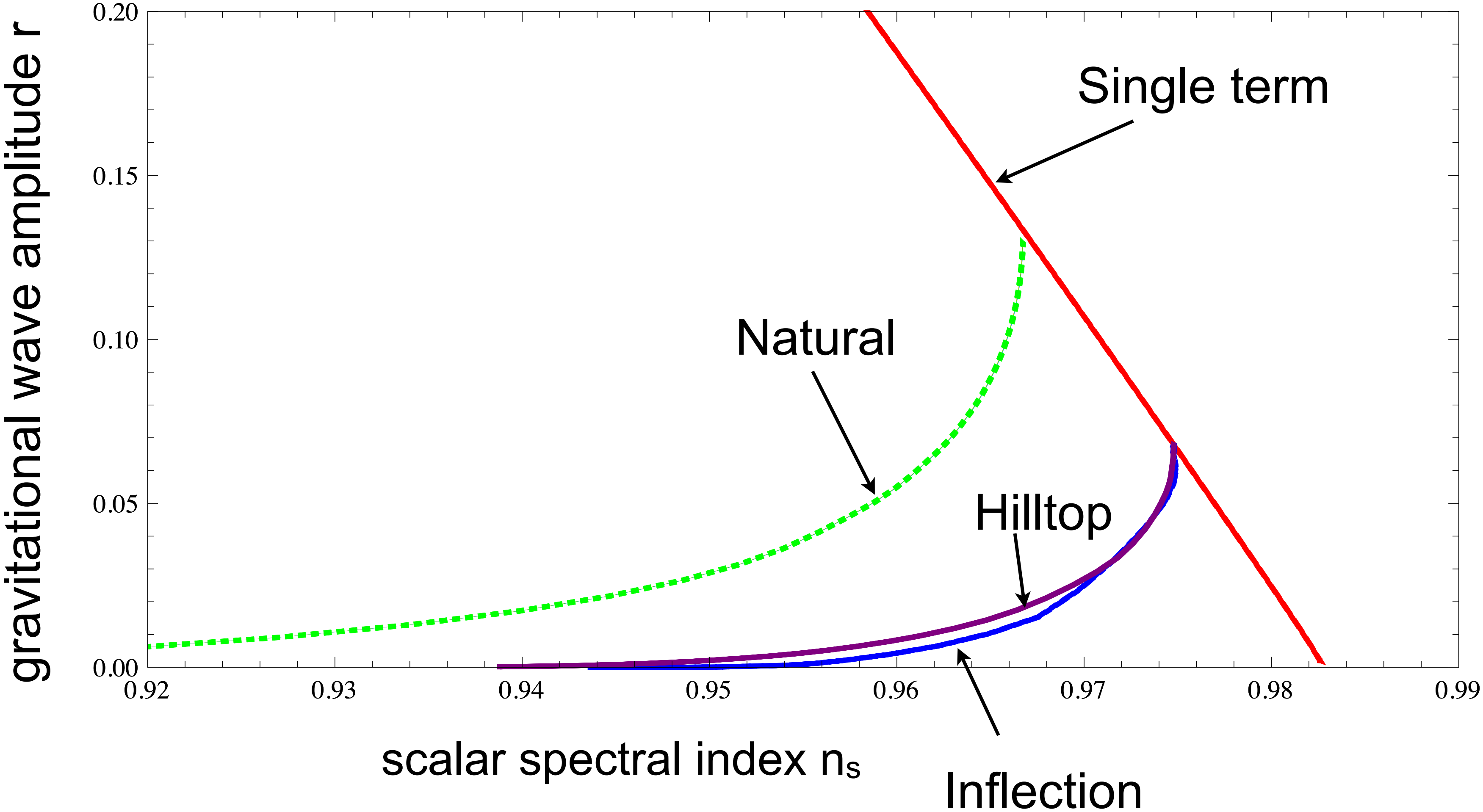
- $$N = \log\left[\frac{a_{end}}{a_{reh}} \frac{a_{reh}}{a_{eq}} \frac{a_{eq}}{a_0} \frac{H_k}{H_0}\right] - \log\left[\frac{k}{H_0 a_0}\right]$$

- Assume long matter dominated phase (GUT - TeV) ΔN ~ 9

- General equation of state, to MeV scale ΔN ~ 30

Spectral Parameters

- Primordial spectrum specified by empirical parameter
  - $P(k) = A_s \left(\frac{k}{k_0}\right)^{n_s(k)-1}$
  - $n_s(k) = n_s(k_0) + \alpha_s \log\left(\frac{k}{k_0}\right) + \cdots \quad ; \alpha_s \equiv \frac{dn_s(k)}{d\log k}$
- α is the *running:* $|n_s - 1| \sim N^{-1}$, $\log(k) \sim N$, $\alpha \sim -N^{-2}$, $10^{-3} > |\alpha| > 10^{-4}$
- Detectable with futuristic experiments
  - *Very* futuristic if we want to discriminate *between* models.

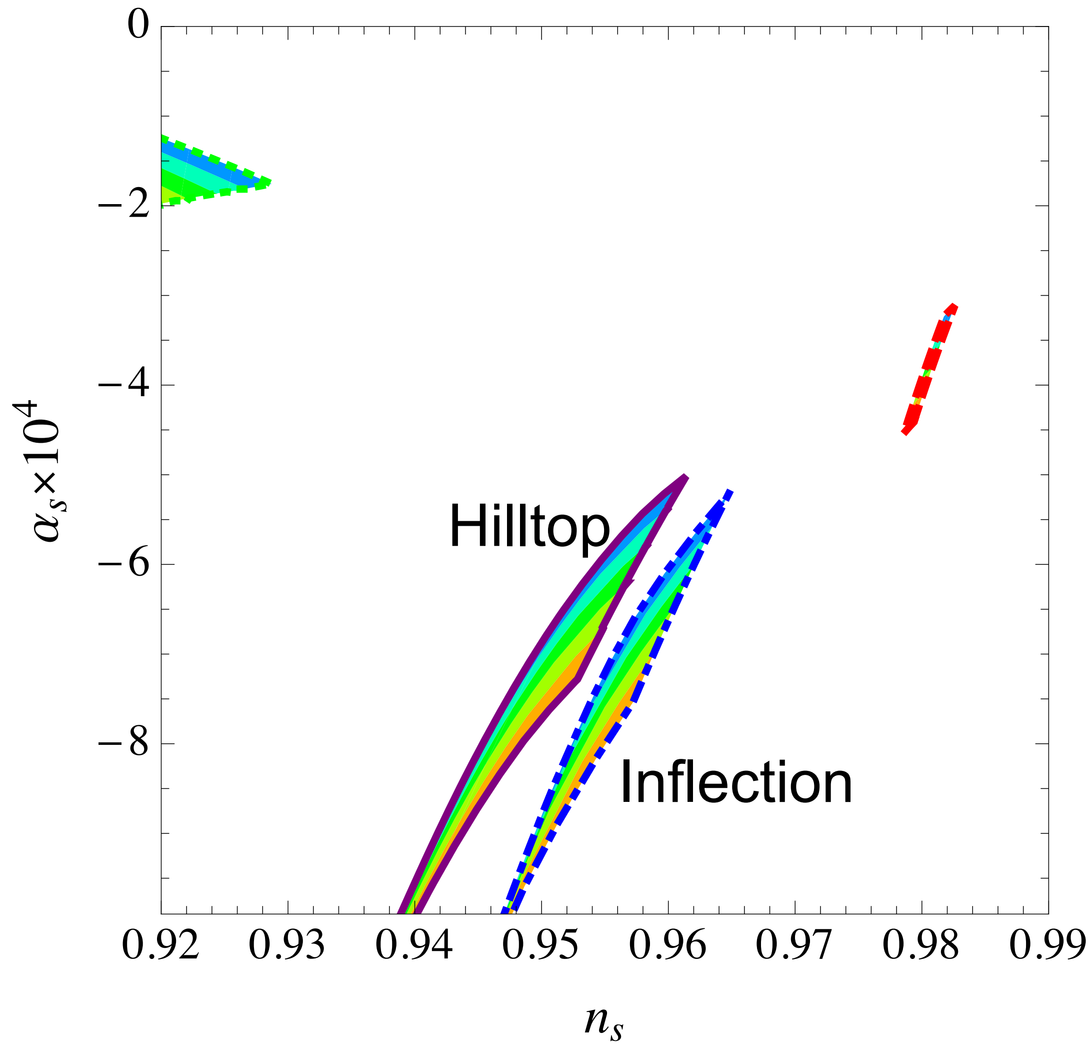


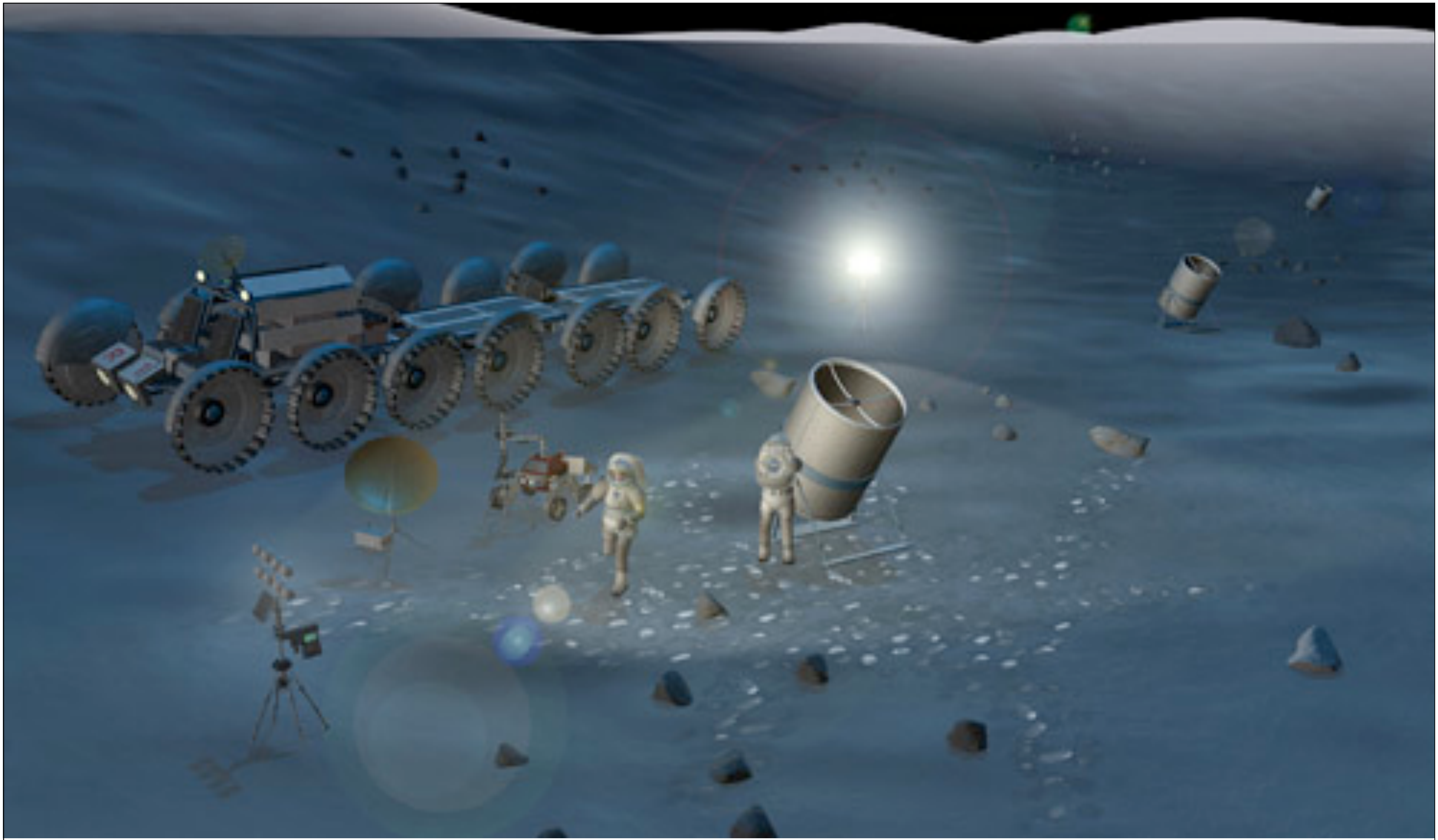
Spectral Index v. Tensor amplitude

$$P(k) = A_s\, k^{n-1}$$
$$r = A_{gw}/A_s$$

Models with r<0.01

- Detecting α: 5 x 10^{-4}
- Which model?
  - Degenerate in n_s
  - Need α to within 10^{-4}
  - Overlap for large ΔN
- Will wait a long time for this





A very, very long time...

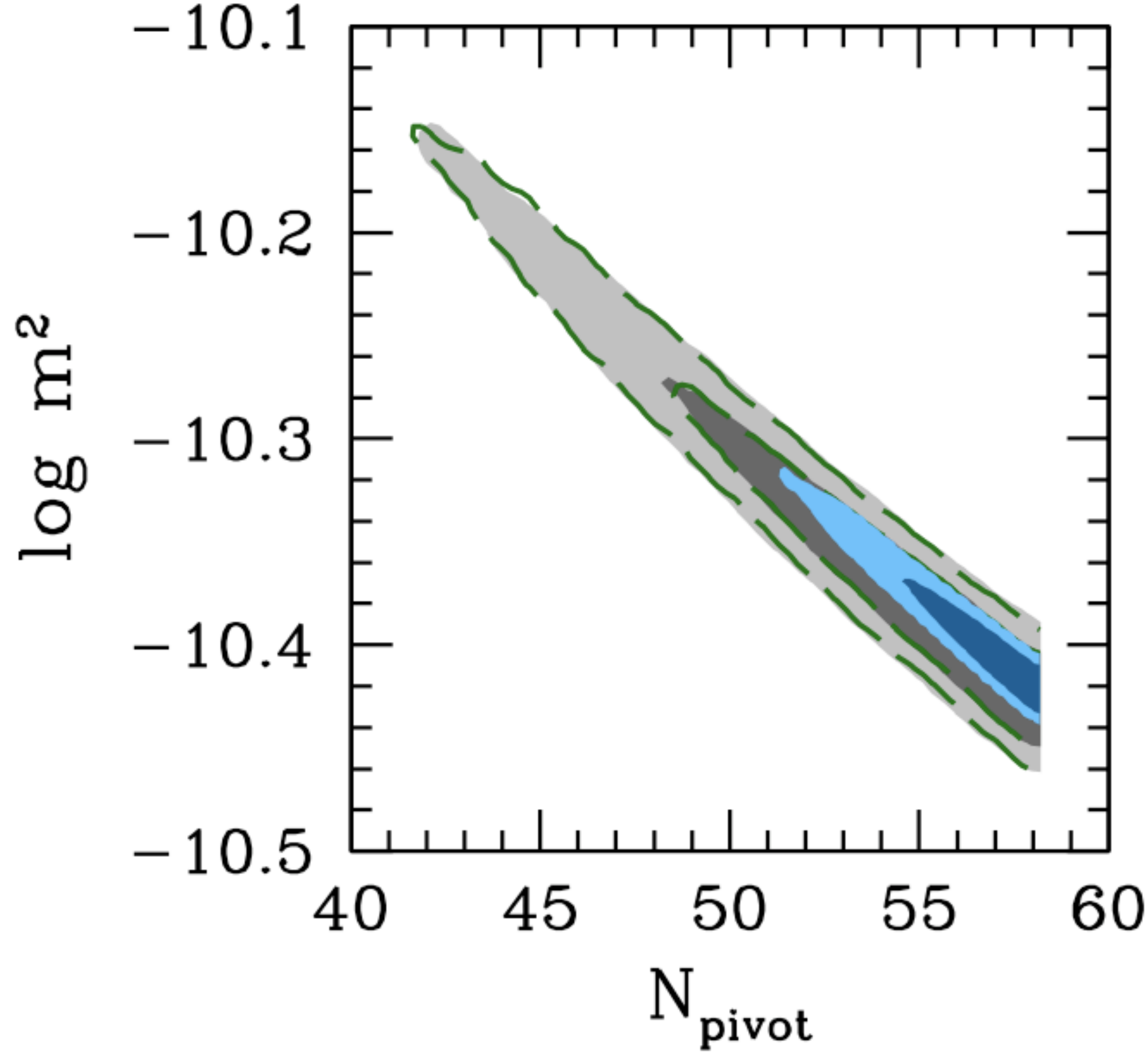
Given that n_s is a function of reheating...

- For *specific* inflationary model
  - Measure n_s and r accurately: Theory $\Delta n_s = \alpha\ \Delta N \sim 0.005$
  - Constrain post-inflationary expansion
  - Constrain physics between TeV and GUT scales
- How well can we do this?
  - Mortonson, Peiris & RE [ModeCode] arXiv:1007.4205
  - Adshead, RE, Pritchard and Loeb arXiv:1007.3748
  - Matters now, will matter more for Planck (+BOSS, LSST, etc)

What Do We Do About This?

- Chains for a specific inflationary model [potential]: prior
  - N_k is an *inflationary* parameter (stand-in for φ_k)
- Given a potential we *deduce* ρ_{end}
  - Constrain post-inflationary physics, given inflationary prior.
- Long term project: ModeCode (w. Mortonson and Peiris)
  - Starting to do with WMAP (and will really do it with Planck)
  - "Standard" bump model already implemented
  - Currently working on evidence calculation.

See: also Martin and Ringeval, MR&Trotta



MCMC Constraints for Quadratic Inflation

Peiris, Mortonson, Easther

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
	14.5	0.93	19.7	1.4
$+\ \sigma_r = 0.01$	3.5	0.26	8.6	0.41
CIP+Planck	1.69	-	1.2	-
	-	0.11	-	0.09
	13.7	0.87	14.5	1.14
$+\ \sigma_r = 0.01$	2.8	0.18	3.96	0.27
FFTT+Planck	0.41	-	0.29	-
	-	0.027	-	0.024
	7.0	0.45	11.0	0.91
$+\ \sigma_r = 0.01$	2.5	0.17	2.95	0.24

Fisher Forecasts for Future Experiments

W. Adshead, Pritchard and Loeb

What Does This Mean...

- Interpretation is subtle
  - We do not probe reheating (>TeV scales) on its own
  - We do not probe inflation on its own
  - Inflation and reheating history are *linked*
- Test **inflationary model + reheating history**
- Different inflation models require different reheating histories
  - *Any* hint about beyond TeV scale physics is worth having!
  - Definitive test of models that predict inflation and reheating

What About Features?

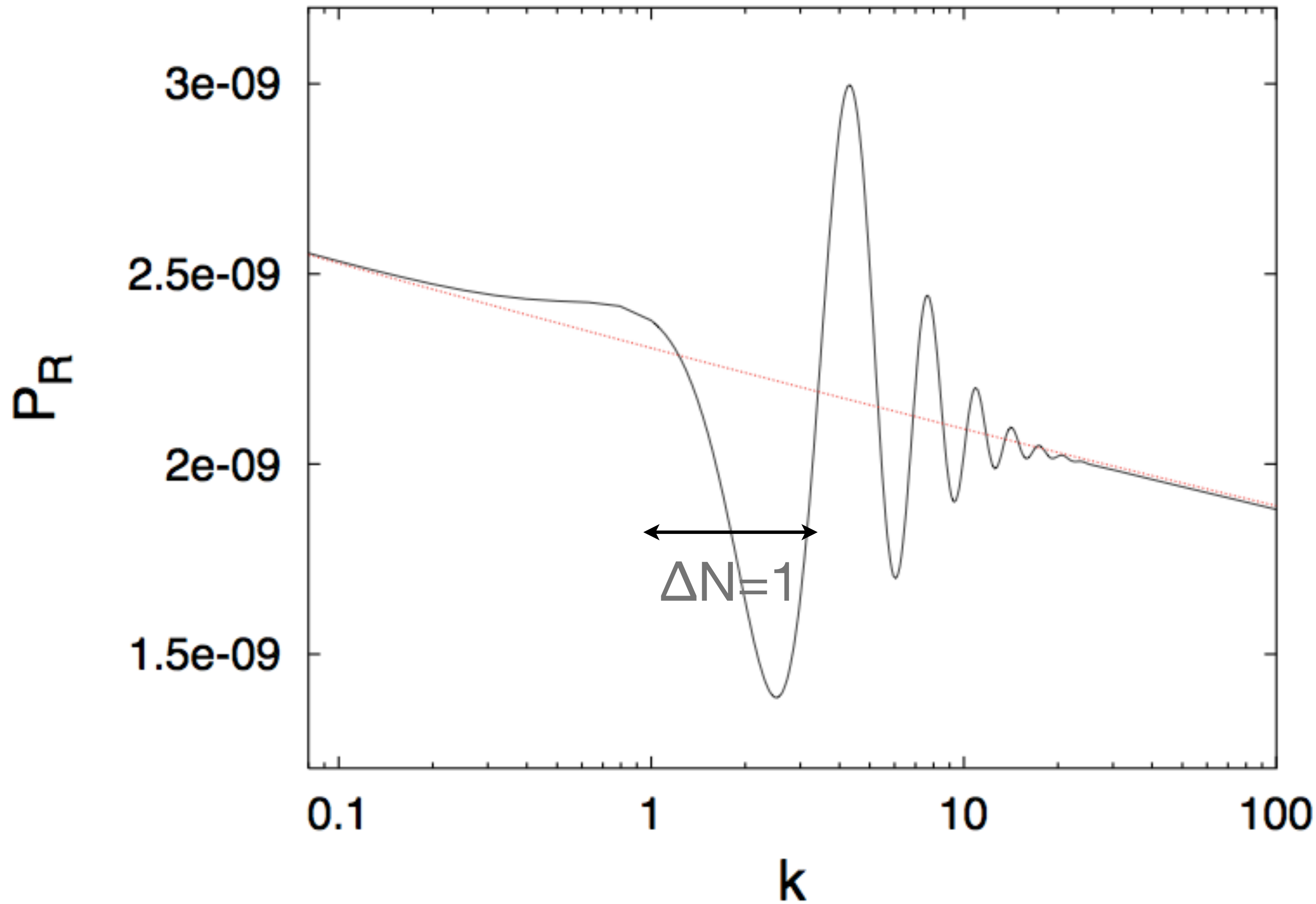
- Initial "feature" models were empirical

$$V(\phi) = \tfrac{1}{2}\, m^2\phi^2 \left(1 + c\tanh\left(\frac{\phi - b}{d}\right)\right)$$

  - Adams, Cresswell and Easther **astro-ph/0102236**
  - No *a priori* knowledge of location of feature on potential
- Look at published constraints on these models
  - Give range for height, width and *location* of the step
  - Usually with *prior* for post-inflationary expansion

During Standard Slow Roll...

- Large field, canonical scalar field $\varepsilon \sim 1/N$
  - $\log(k/k_{pivot}) = (N-N_{pivot})(1 + O(\varepsilon))$
- How accurately have we located the feature in k?
  - Much better than a factor of 2 in "ℓ"
  - Whole feature covers a "few e-folds" (about a decade in k?)
  - But central value localized to within a fraction of an e-fold.



Canonical Bump Model

Hamann, Covi, Melchiorri & Slosar

Consequences...

- Bump models:
  - Correlation between 2pt and 3pt well known
  - But we *also* have a correlation between 2pt and N
  - Bump put a “marker” on the smooth potential
- Less important for an *empirical* potential
  - Since we don’t know where the bump is *supposed* to be
  - But for a potential derived from fundamental theory...
  - Would already have exquisite constraint on reheating

Axion Mondromy...

- Inflationary potential: (modulation) x ϕ^p
  - "Long modulation" - 2 point modified, 3 point small
  - "Short modulation" - 2 point standard, resonant 3 point
  - Both at once...
- Long modulation: now will have multiple peaks in likelihood
  - So will have discrete range of options for N_{pivot}
  - Bumps are not evenly spaced in k (although correction probably too small to matter).

Conclusions

- Inflationary models coupled to post-inflationary history
- Easy to rule out bad models (since they *never* fit)
- But n_s and r parameter space is degenerate
  - Especially when we allow for post-inflationary history
- Empirical bump models
  - Bump location degenerate with post-inflationary history
- Given feature model *derived* from fundamental physics
  - Exquisite constraints on post-inflationary expansion