The post Planck curvaton

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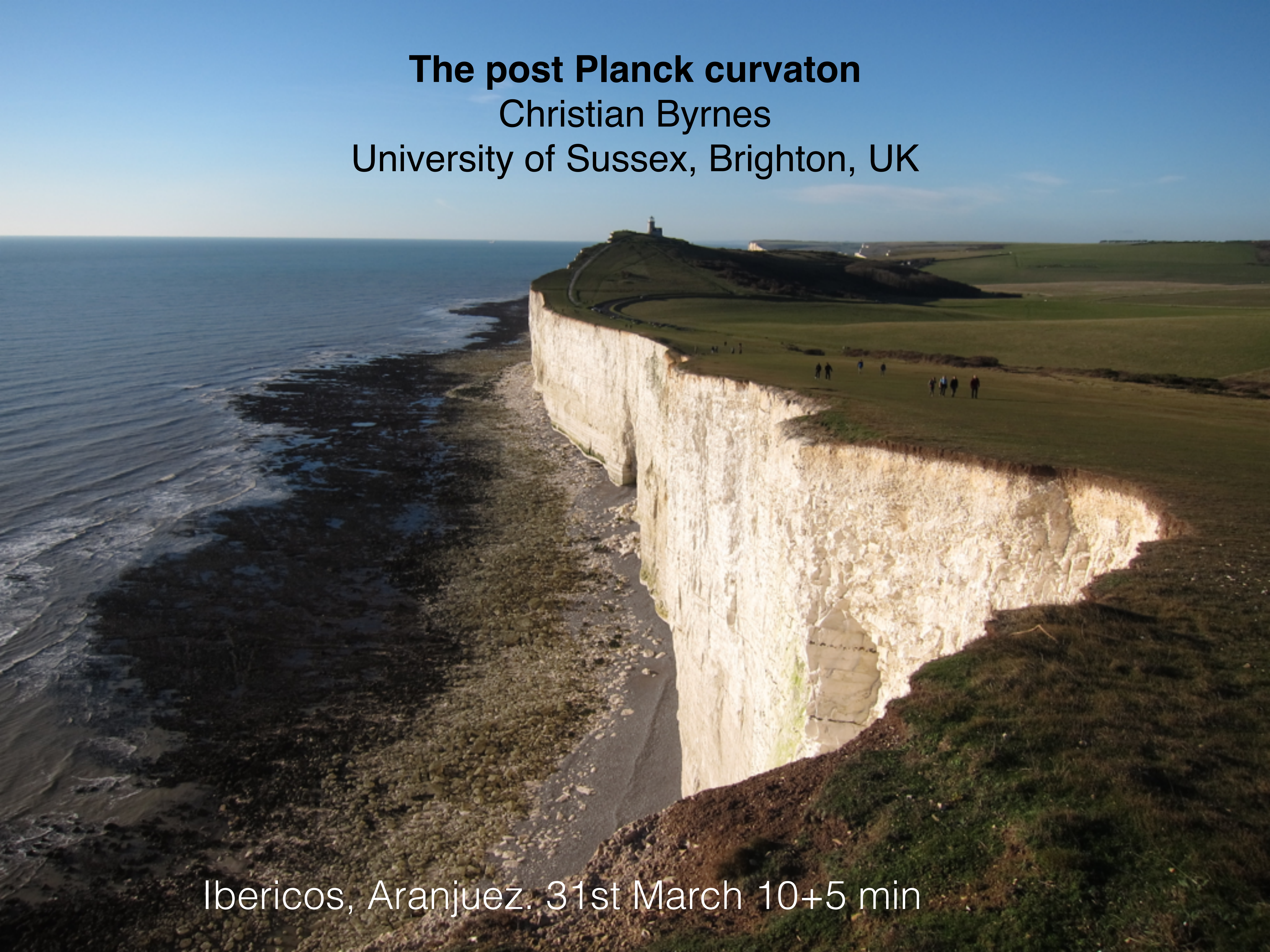
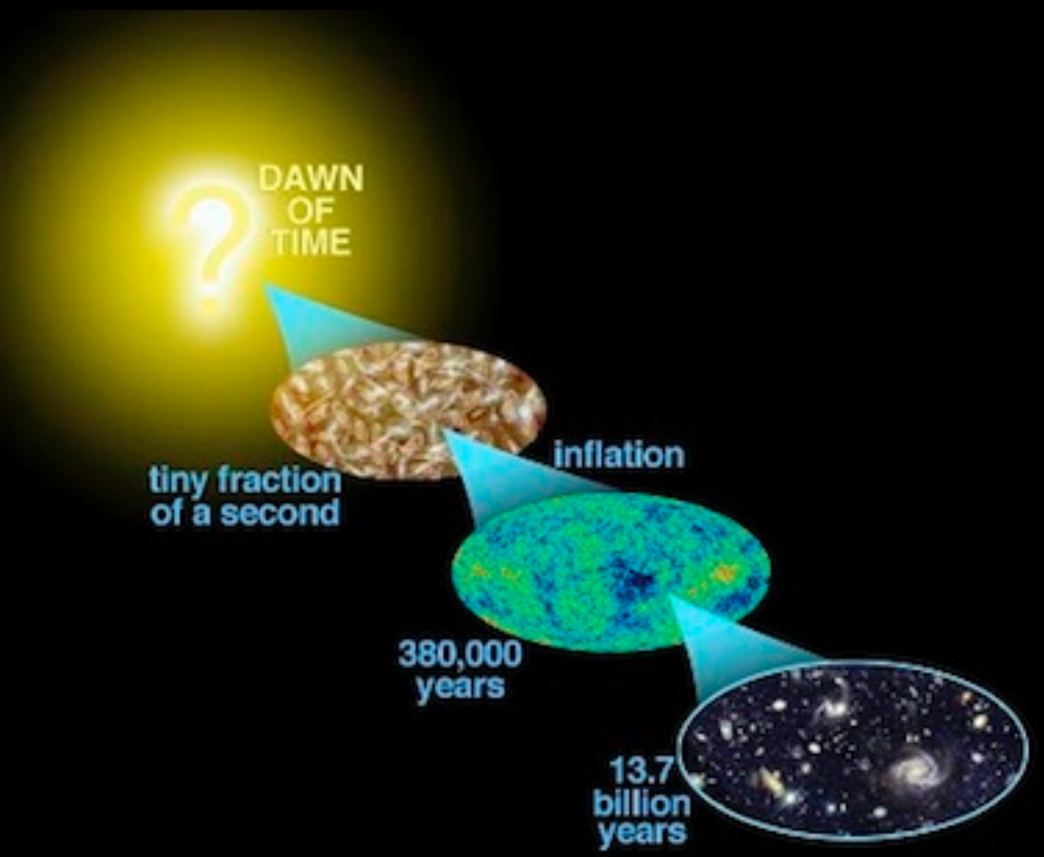
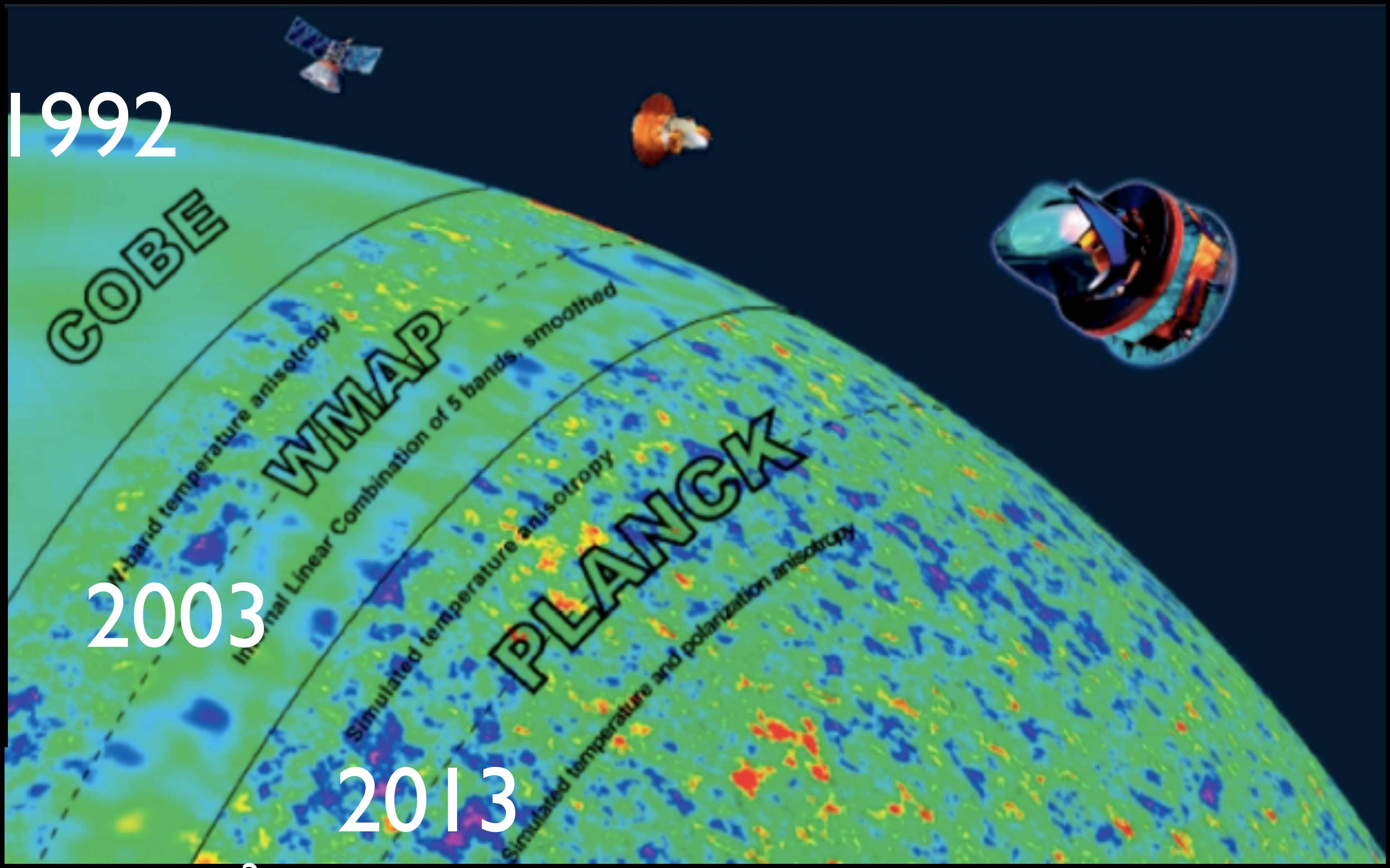


Ibericos, Aranjuez. 31st March 10+5 min

What have we learnt from the precision era?

- Planck completes a trilogy of CMB experiments
- Planck: much better sensitivity and 3 times better resolution than WMAP





We observe so much yet see so little…

- It is a highly non trivial and remarkable and disappointing statement that we can explain the statistical property of 10^7 CMB pixels with just two numbers (+ background parameters)
- We have only measured the amplitude and spectral index of the power spectrum
- Is this a sign that inflation was simple?
- Was only one light field present during inflation?

A worked example: The curvaton scenario

- An alternative model to single-field inflation for the origin of structures. The inflaton drives inflation while the curvaton generates curvature perturbations (hence the name)

- This multi field model allows but does not require isocurvature perturbations and large non-Gaussianity to be generated. Neither of these have been observed. Is that bad news for the model?

- The curvaton is a light field which

1. has a subdominant energy density during inflation
2. Is long lived (compared to the inflaton)
3. Generates the primordial curvature perturbation (in the "pure" curvaton limit with negligible inflaton perturbations)

Enqvist and Sloth, Lyth and Wands (gave the name, 1000 cites), Moroi and Takahashi '01

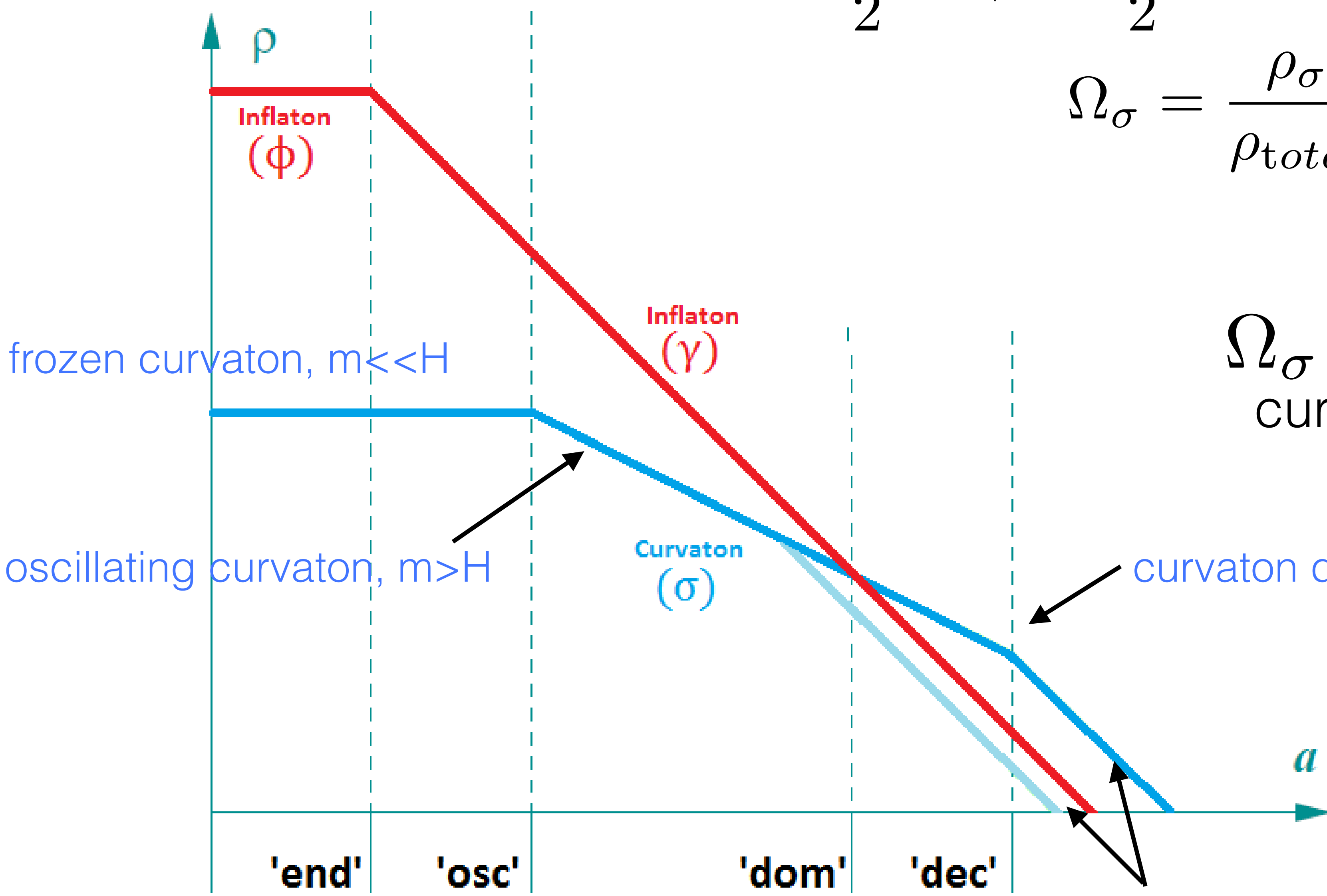
Curvaton (σ) background evolution:

Log of scale factor versus log of energy density

$$V = \frac{1}{2}M^2\phi^2 + \frac{1}{2}m^2\sigma^2$$

$$\Omega_\sigma = \frac{\rho_\sigma}{\rho_{total}}$$ measured at the curvaton decay time

$\Omega_\sigma = 1$ is an attractor if the curvaton decays late enough



curvaton decays into radiation

The curvaton may decay before or after it becomes dominant

The longer the curvaton lives, the larger its relative energy density becomes, as measured by r_{dec}

The simplest curvaton scenario

$$V = \frac{1}{2}M^2\phi^2 + \frac{1}{2}m^2\sigma^2$$

- Parameter constraints were originally made by Bartolo and Liddle (2002), the data allowed so much freedom they restricted the model to i) the Gaussian case ii) negligible inflaton perturbations
- CB, Cortes and Liddle (2014) revisited the model with Planck & BICEP data. We drop their assumptions, observations have improved a lot
- Rob Hardwick & CB (2015) performed the first Bayesian analysis of the curvaton scenario, a model comparison technique which penalises unwanted free parameters (Occam's razor)
- The additional three curvaton parameters are its mass m, its field value at horizon crossing sigma* and its decay rate Gamma

The models

- Baseline LCDM model copying the Planck constraints on inflation paper, with amplitude and spectral index of the perturbations but no tensors or non-Gaussianity
- Quadratic single-field inflation (1 free parameter)
- 3 variations on the curvaton scenario (all with 4 free parameters)

1. Mixed inflaton-curvaton scenario (most general case)
2. Pure curvaton scenario (negligible inflaton perturbations)
3. Dominant curvaton scenario (negligible inflaton perturbations and the curvaton dominates the background density before it decays)

Each scenario is a subset of the one above

Cases 2 and 3 predict negligible tensor perturbations. Case 3 also f_{NL}=-5/4

The priors - these need to be specified

Model Scenarios	Prior ranges and constraints ($M_P = 1$)
Single field inflaton	$-4 > \log_{10}(M) > -6.75$
Mixed inflaton-curvaton	$-4 > \log_{10}(M) > -15.3$
	$\log_{10}(M/2) > \log_{10}(m) > -39$
	$\lvert\sigma_*\rvert < 0.01$
	$\log_{10}(m) > \log_{10}(\Gamma_\sigma) > -39$=BBN energy scale
Pure curvaton	Mixed inflaton-curvaton subset with extra constraint:
	negligible inflaton perturbations $\mathcal{P}_\zeta^\phi \lesssim 0.01\mathcal{P}_\zeta^{total}$
Dominant curvaton decay	Pure curvaton subset with extra constraint:
	The curvaton dominates the background energy density before decay
ΛCDM concordance	$1.02 > n_s > 0.9$
	$3.2 > \ln(10^{10}\mathcal{P}_\zeta) > 3.0$
	$r = f_{NL} = 0$

In addition, we follow the Planck analysis in discarding parameter space which does not match $10^{-7} > \mathcal{P}_\zeta > 10^{-11}$

A log prior is standard for parameters where the order of magnitude is unknown

The curvaton vev has to be small in order to have a curvaton scenario

Planck 2 Results + Bicep/Keck

Model Scenarios	$\Delta\chi^2_{eff}$	$\ln(\mathcal{E}/\mathcal{E}_{ref})$
Single field inflaton	6.6	−5.2
Mixed inflaton-curvaton	3.7	−4.9
Pure curvaton	4.7	−4.7
Dominant curvaton decay	4.7	−4.6

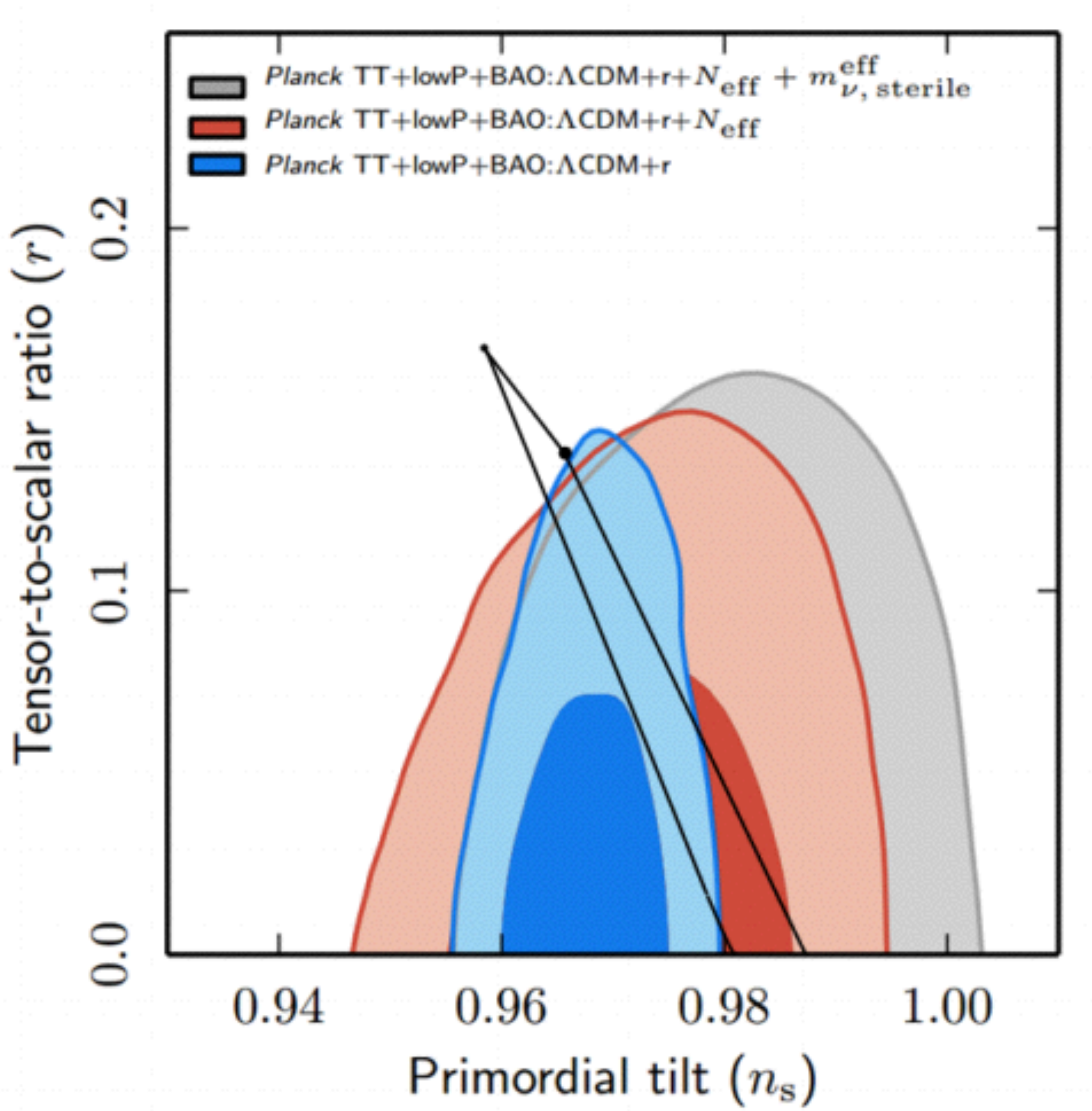
$\Delta\chi^2_{eff}$	$\ln(\mathcal{E}/\mathcal{E}_{ref})$
10.4	−7.0
2.7	−5.4
4.8	−4.7
4.8	−4.7

Results from using Planck TT + low P + BAO data on the left
The effective chi squared values give the best fit
The right hand column gives the Bayesian evidence ratios. All are disfavoured relative to the LCDM reference model, but there is no preference between the 4 inflationary scenarios we considered
The curvaton is not disfavoured, despite having 3 extra parameters
With Bicep/Keck data included, the curvaton becomes weakly/moderately favoured

The Jeffrey's scale

$\lvert\ln(\mathcal{E}/\mathcal{E}_{ref})\rvert$	**Interpretation**
< 1	*Inconclusive*
$1 - 2.5$	*Weak evidence*
$2.5 - 5$	*Moderate evidence*
> 5	*Strong evidence*

Curvaton Post Planck 2



The lower big black dot = single quadratic field with instant reheating (N=58)

Top black dot has early matter era generated by curvaton but negligible curvaton perturbations (N=48)

Curvaton scenario lies anywhere between black lines, the pure curvaton scenario also has r=0

Why does the curvaton do so well?

- The quadratic single-field model is not a good fit
- The vast majority of the parameter space matches the dominant pure curvaton scenario, which has f_{NL}=-5/4
- This explains why the evidence ratios are so similar for all three cases
- The "tight" f_{NL} constraint does not change our results much, it needs to decrease by an order of magnitude (unless f_{NL} is detected)
- Our results are not very sensitive to the choice of priors
- However we do force the curvaton VEV to be very small compared to the inflatons, we are not testing whether the curvaton scenario is likely
- Restricting to quadratic potentials, the curvaton scenario is favoured

Conclusions

- The latest Planck constraints remain broadly consistent with the simplest models of inflation
- We have only two measured non-zero observables, related to the primordial perturbations, the amplitude and spectral index of the power spectrum
- The data is still not good enough to discriminate between single and multi field models of inflation, and perhaps never will be
- In the context of quadratic potentials, the curvaton is preferred over single field inflation, despite having 3 extra free parameters
- Discriminating between $f_{NL}\sim 1$ and 0 is very important

How non-Gaussianity could favour the curvaton

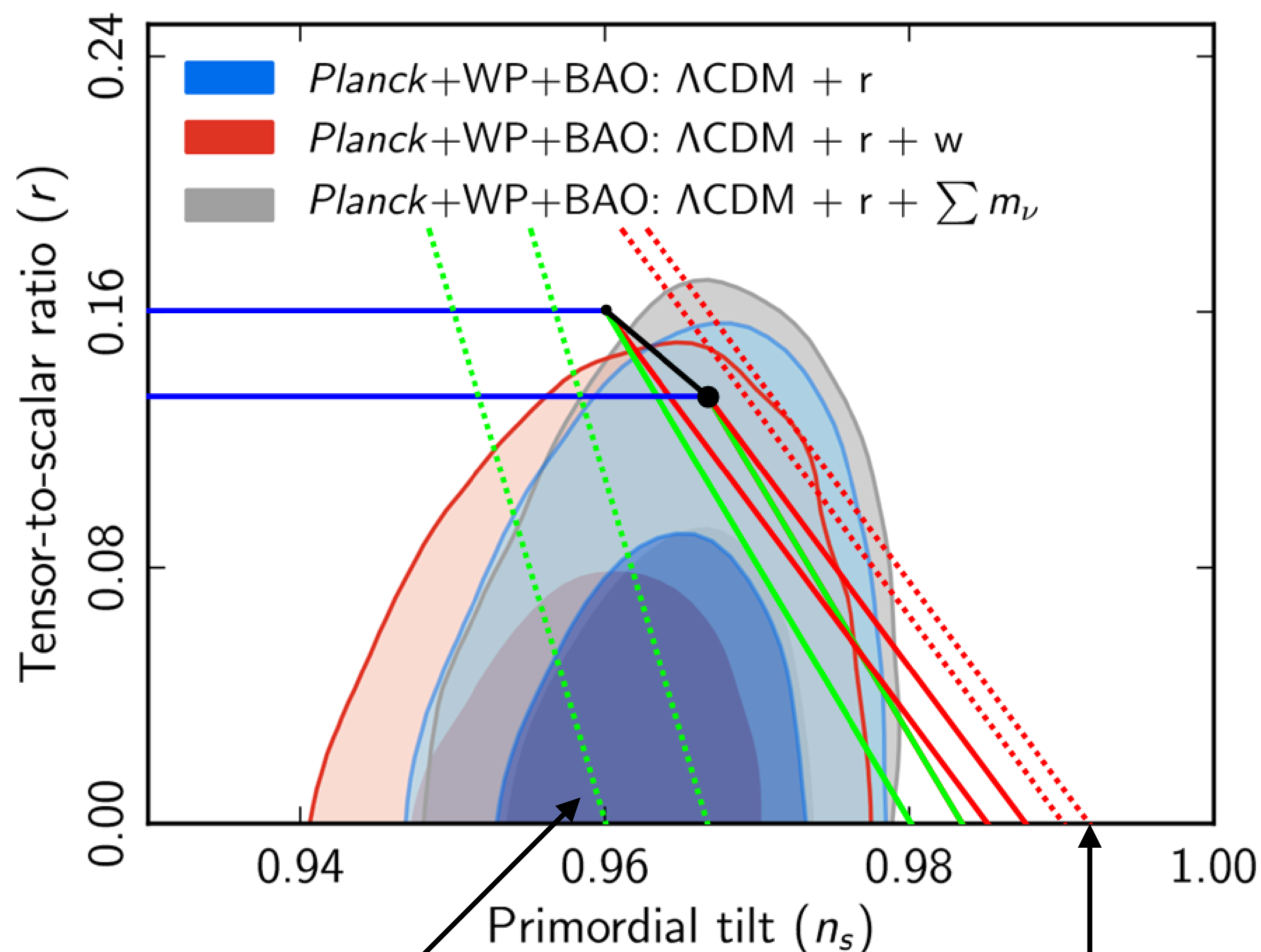
- If non-Gaussianity was detected in the future, how quickly could we favour the curvaton over the base LCDM scenario?
- We assume all cosmological data remains the same except f_{NL}
- If f_{NL}=-5/4: the curvaton "attractor" value we need an error bar of 0.4. This would correspond to a 3-sigma detection
- If f_{NL}=10.8, the current 2-sigma upper bound from Planck then we need an error bar of about 2.6 (and the dominant curvaton scenario is ruled out). This would correspond to a 4-sigma detection
- The latter case should be "easily" achieved with Euclid, the former case maybe achievable in ~ 2 decades with Euclid, DESI, SKA…

Filling the n_s-r plane

$$V = \lambda\phi^4 + \frac{1}{2}m^2\sigma^2$$

For this simple potential, the mixed inflaton-curvaton scenario can lie anywhere between the outer dashed green and red lines

Credit: Robert Hardwick (MSc project)



$N = 50$ *and* $\eta_\sigma \simeq 0$

$N = 60$ *and* $\eta_\sigma \simeq \frac{1}{4}\eta_\phi$

Model independent curvaton statements

- The pure curvaton scenario has a suppressed tensor spectrum, a detection of r can force us into the mixed inflaton-curvaton scenario
- By tuning the inflaton potential, any value of n_s and r can be achieved with a quadratic curvaton
- A detection of (local) $f_{NL}<-5/4$ would rule out all quadratic curvaton models (but not non-qadratic curvaton potentials)
- A constraint $|f_{NL}|<1$ would be a very strong hint against all curvaton scenarios, independently of the potential of either field (even independently of the number of curvaton and inflaton fields)

We lack guidance

- We lack targets for the observables, there is no minimum amplitude of isocurvature perturbations or non-Gaussianity which multi field inflation must have
- Testing local f_{NL}~1 is an important observational target, but only for some classes of multi field models (includes curvaton and modulated reheating)
- The data is not good enough to distinguish between many classes of models, in some cases it will never ever be (two models can predict the same CMB spectrum)
- If there is no wasted parameter space in the more complex model, even Bayesian evidence does not favour the "simpler" model

- We definitely need both fundamental physics and observations to make progress

Summary of observables

- Observables which are very important for learning about inflation, but do not in general discriminate between the single and multi field scenarios include:

1. The running of the spectral index
2. The tensor to scalar ratio
3. Non-Gaussianity away from the squeezed limit
4. Most anomalies

- A smoking gun of multi field inflation could be one of:

A. Squeezed limit (close to local) non-Gaussianity

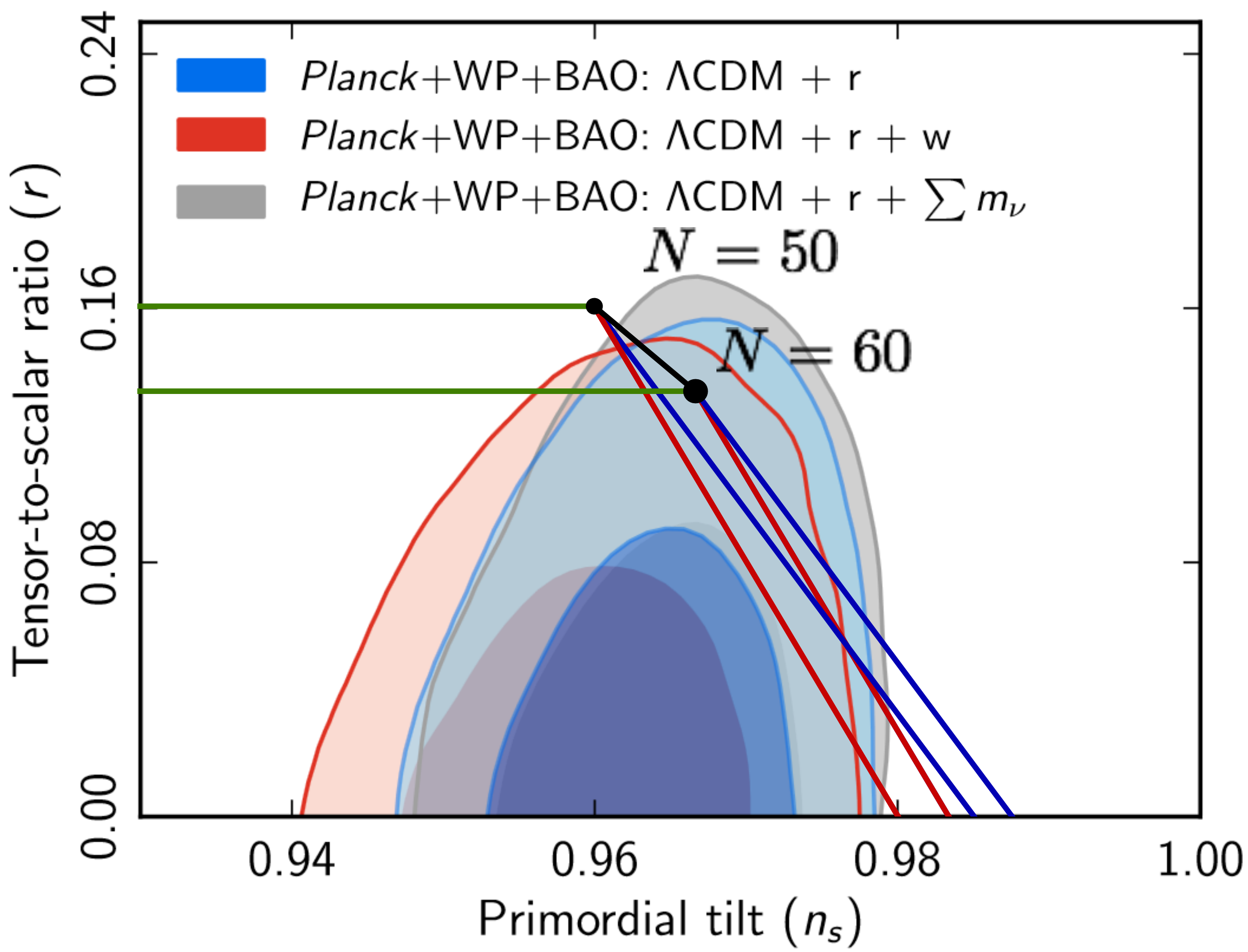
B. Isocurvature perturbations

C. Deviation from the single field consistency relation $r_T = -8n_T$

What non-Gaussianity does the (quadratic) curvaton predict?

- The curvature perturbation is approximately $\zeta \simeq \Omega_\sigma \frac{\delta\rho_\sigma}{\rho_\sigma} \simeq \Omega_\sigma \left(\frac{\delta\sigma}{\sigma} + \left(\frac{\delta\sigma}{\sigma} \right)^2 \right)$
- Local non-Gaussianity is generated: $f_{NL} \sim 1/\Omega_\sigma$
- The Planck constraint $f_{NL} < 10$, tells us $\Omega_\sigma > 0.1$. A priori, $\Omega_\sigma \sim 10^{-5}$ (and $f_{NL} \sim 10^5$) was possible.
- If the curvaton dominates before decay, $\Omega_\sigma = 1$ and $f_{NL} = -5/4$
- In terms of a linear scale on $-5/4 < f_{NL} < 10^5$ - 99.99% has already been ruled out
- In terms of a linear scale on $10^{-5} < \Omega_\sigma < 1$ - 10% has been ruled out
- A highly subdominant curvaton is totally ruled out, so the dominant curvaton case becomes our "prediction". Detecting $f_{NL}=3$ or 7 seems unlikely, although it is compatible with the model

Curvaton post Planck1



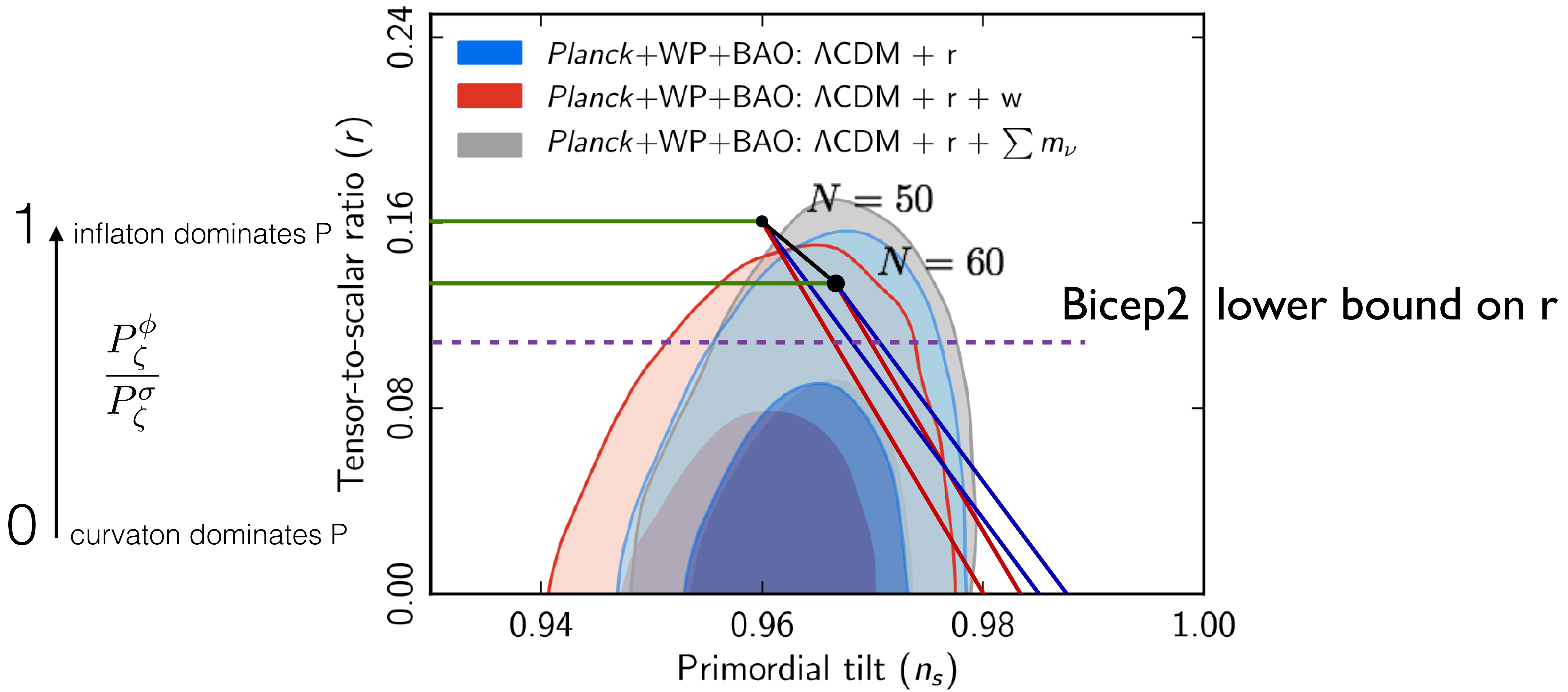
The uncertainty in matching the Planck pivot scale to N is significant. We don't know the expansion history of the universe between inflation and BBN. Smaller values of N are possible, which the data prefers.

Red lines are for a negligible curvaton mass

Blue lines have m_sigma=m_phi/2 (it is hard to make the curvaton heavier, and a bluer spectrum results)

Green lines are the inflating curvaton regime, where it drives a second period of inflation

Curvaton post Planck1 and BICEP2



Red lines are for negligible curvaton mass, blue lines have m_sigma=m_phi/2. Green lines are the inflating curvaton regime, where it drives a second period of inflation.

BICEP2 adds a lower bound on the tensor to scalar ratio, which requires that the inflaton perturbations contribute at least 50% of the total curvature perturbation. If confirmed, this rules out the original curvaton scenario, in which the inflaton perturbations and hence r are negligible.

The early universe is very poorly constrained

- The curvaton scenario really is different from single-field inflation
- During inflation we have a second, perturbed degree of freedom
- From the end of inflation until after the curvaton decays, the universe behaves very differently. Both at the homogeneous and the perturbed level.
- What was the background equation of state during baryogenesis? Did isocurvature perturbations exist? Are the perturbations on these small scales Gaussian? We have no idea.
- Because the perturbations are so tiny, f_{NL}=-5/4 is a small correction, except when the amplitude of perturbations is large. For small scale perturbations where power spectrum bounds are very weak, this value has a huge effect. Example: Primordial black hole formation rates - S. Young & CB 2013

When f_{NL}=-5/4 makes a big difference

- In order for primordial black holes to form in the very early universe, the amplitude of perturbations needs to be much larger (otherwise the required order unity perturbations will never occur)
- For Gaussian perturbations, one needs zeta~0.1 on the relevant (small) scales in order to form an observable number of primordial black holes
- The curvaton prediction for f_{NL} does not depend on the amplitude of perturbations
- With zeta~0.1, even f_{NL}=-5/4 has a big effect, especially on the tail of the pdf
- This leads to (at least) an order unity change on the allowed amplitude of the power spectrum on small scales

Sam Young & CB 2013