Born to Run: Testing Inflation with large-scale surveys

David Parkinson
Korea Astronomy and Space Science Institute

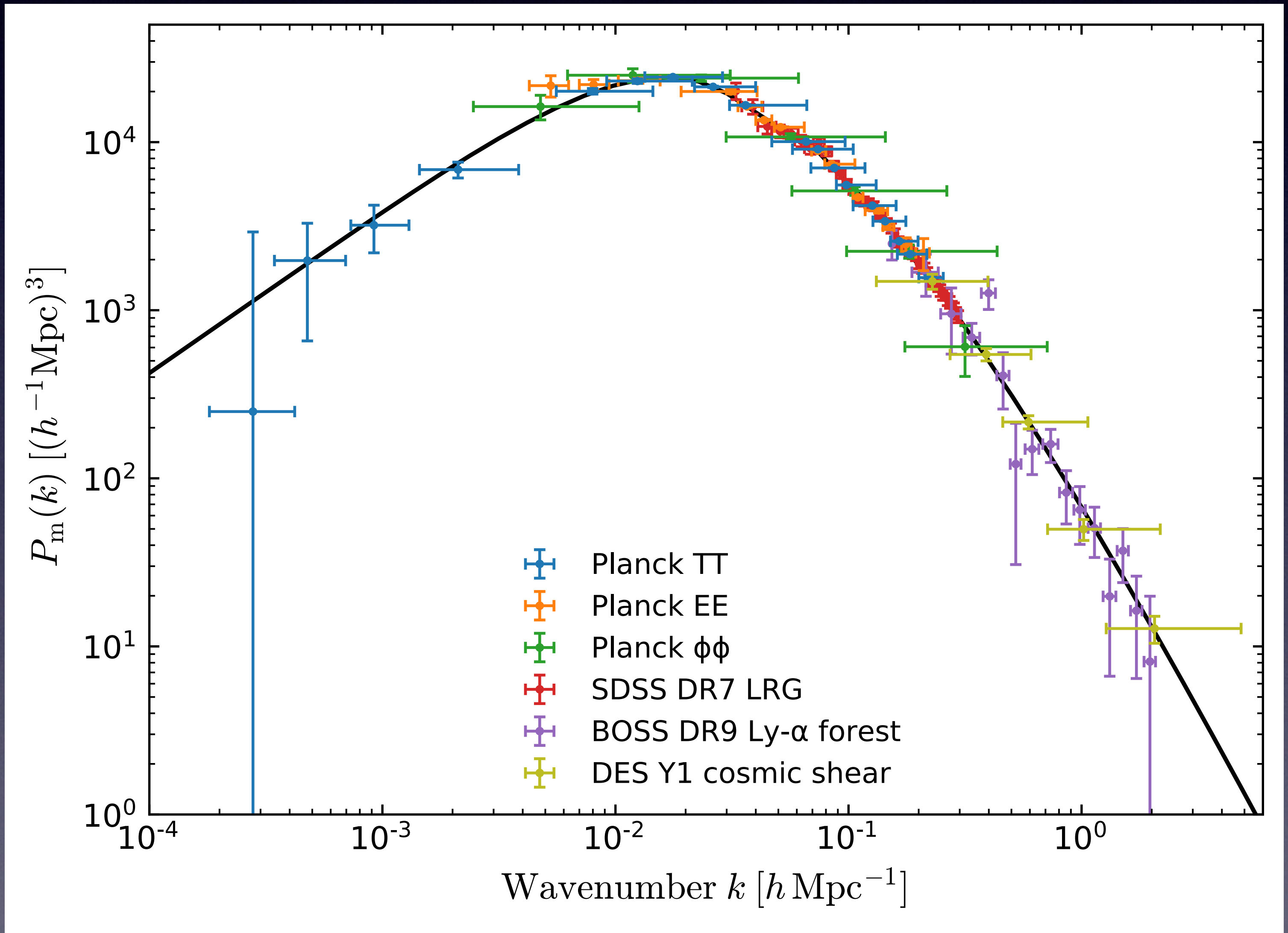
In collaboration with:
Richard Easther (Auckland), Benedict Bahr-Kalus (KASI)

Outline

- The primordial power spectrum
- Predictions of Inflation
- Extending slow-roll
- Measuring the running
- Summary

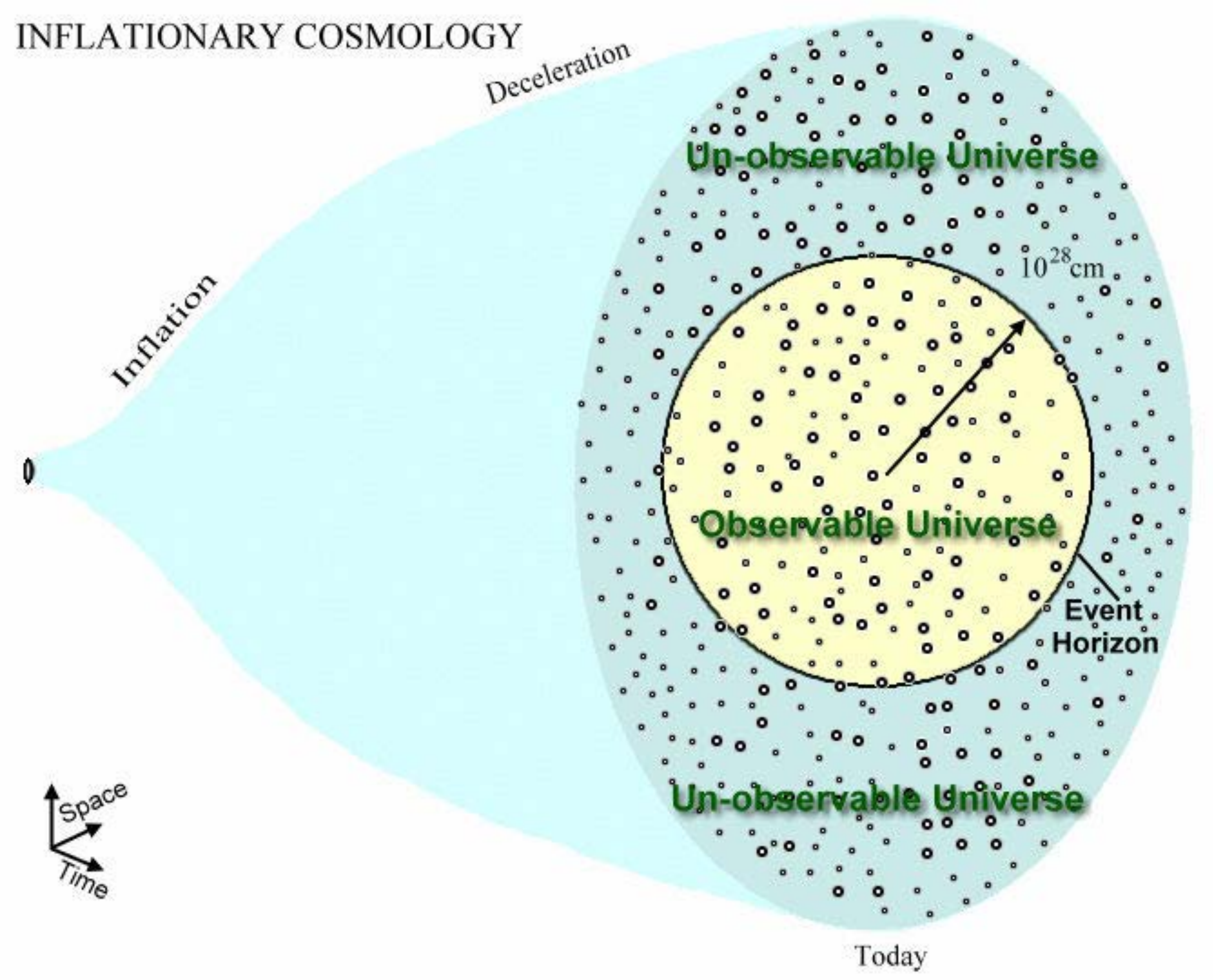
Matter power spectra

- The hot big bang seeds all structure in the Universe, which grows under gravity
- Can statistically describe/decompose the universe as being filled with density fluctuations - the **matter power spectra**
- Structure only only visible through discrete tracers
  - Galaxies and photons here are functioning as test particles - tracing out the gravitational field
- Low-redshift surveys have not measured spectrum of density fluctuations, only the transfer functions
  - Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)



Inflation

- There are a number problems with a purely relativistic early universe (flatness, horizon, relic problems)
- Inflation is a model that solves these problems by 'inflating' the entire observable universe from a small thermalised region
  - Accelerated expansion in the early universe
- But, to solve these problems, we need 'sufficient' inflation, which is about 60 e-folds (i.e. the scale-factor grows by a factor of *e* at least 60 times before inflation ends)



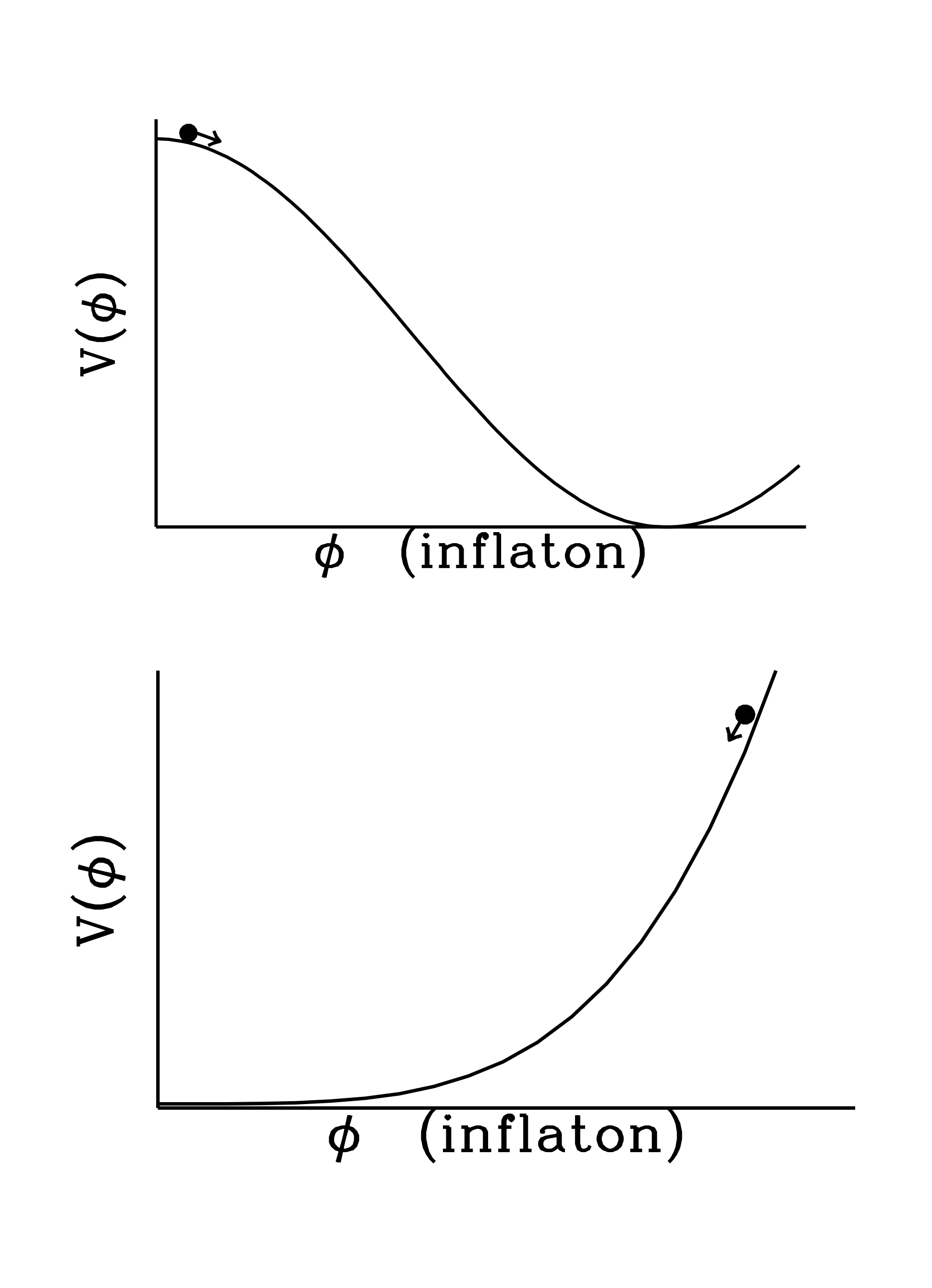
Slow-roll inflation

- Slow-roll inflation proposes the period of accelerated expansion generated by a single, minimally coupled scalar field
- If inflaton potential is flat enough, Klein-Gordon and Friedman equations can be approximated as

$$H^2 = \frac{8\pi G}{3} V$$

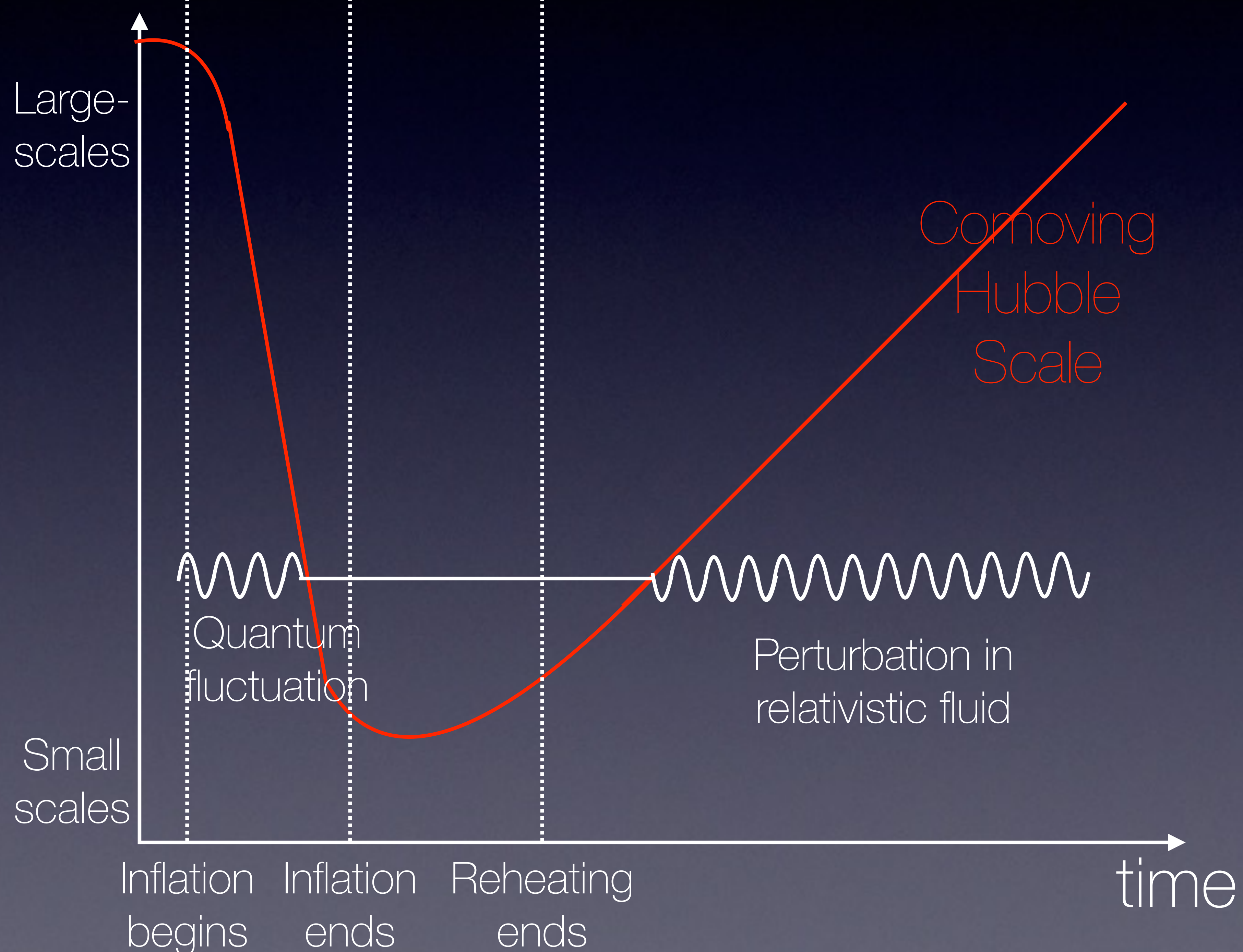
$$3H\dot{\phi} = -V'$$

- When these approximations break down, slow-roll is violated and inflation ends
- Slow-roll lasts long enough to solve the problems with the early universe
- Other advantage: <u>predicts density fluctuations in terms of slow-roll parameters</u>



Quantum fluctuations and the Horizon

- Every mode has an oscillation wavenumber, k
- The fluctuation evolves differently depending whether wavelength is larger or smaller than horizon
- Smaller - evolves as in flat spacetime
- Larger - evolves slowly, amplitude and phase become 'frozen-in' when they cross the horizon



Inflationary Predictions

- We expand the potential in terms of the slow-roll parameters

$$\epsilon(\phi) = \frac{m_P^2}{16\pi}\left(\frac{V'}{V}\right)^2,$$
$$\eta(\phi) = \frac{m_P^2}{8\pi}\frac{V''}{V}$$

- Inflation predicts a power spectrum of adiabatic, Gaussian-distributed, nearly-scale invariant density perturbations

$$\delta_H(k) = 1.91 \times 10^{-5}\left(\frac{k}{k_*}\right)^{(n-1)/2}$$

- The spectral index for this can be written in terms of the slow-roll parameters (assuming only two parameters are important)

$$n - 1 = -6\epsilon + 2\eta$$

- The slow-roll parameters need to be small, and so the spectral index is close to unity
- CMB and other data confirm n=0.965

Primordial Gravitational Waves

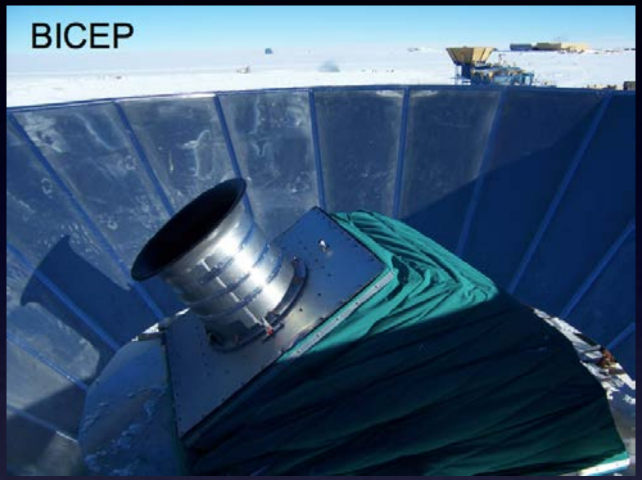
- The accelerated expansion of the universe also generates a spectrum of primordial gravitational waves (or tensor perturbations)
- The fluctuations that generated them are small, and so they can be linearised and modelled as a system of massless scalar fields
- The amplitude of each wavelength is given by Hubble parameter at time that wavelength crosses the horizon, and the spectral index is related to the first slow-roll parameter

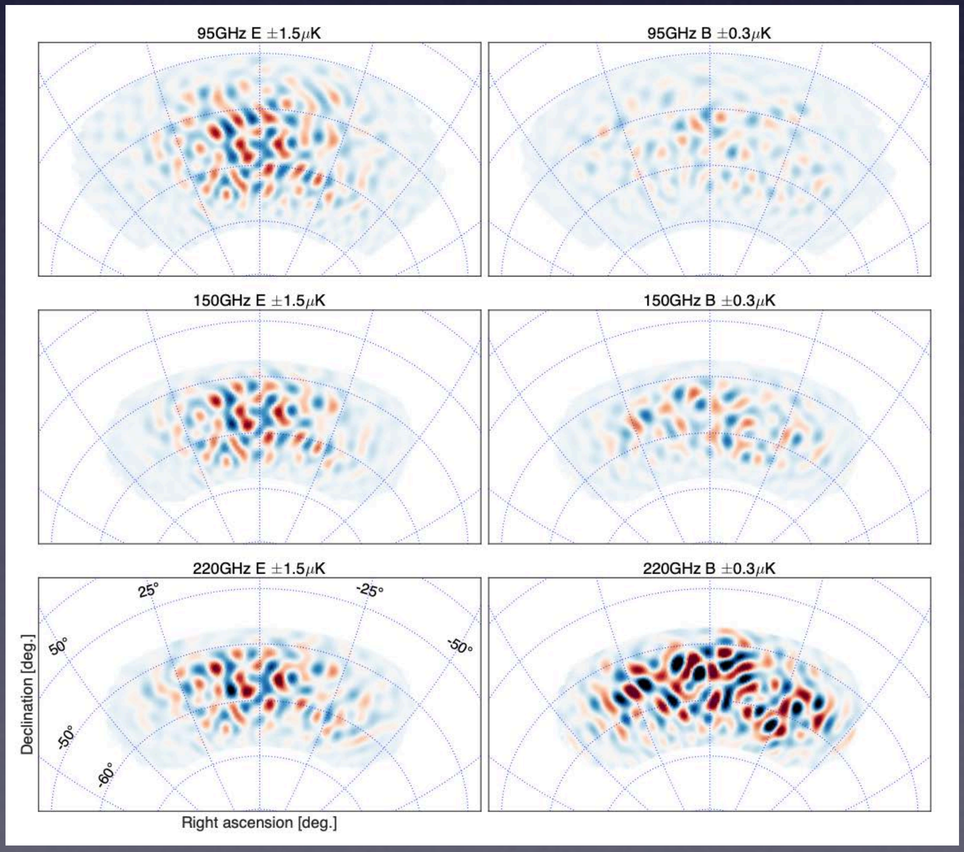
$$n_{\mathrm{grav}} = n_T = -2\epsilon$$

- These primordial gravitational waves have very long wavelengths, too large to be detected directly by ground based interferometers
- But they can be inferred by their effect on the CMB polarisation

BICEP/Keck

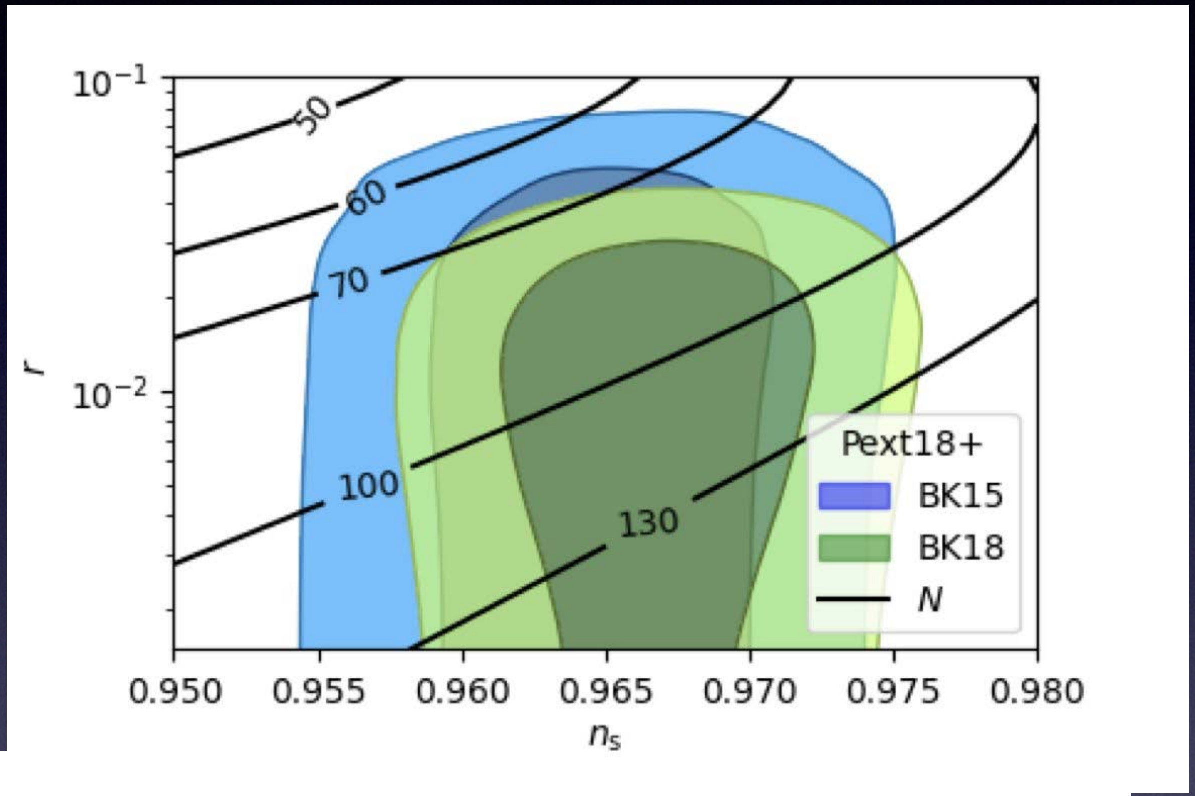
- Background Imaging of Cosmic Extragalactic Polarization
- BICEP2 is small [26 cm] refractive telescope at South Pole, with 512 bolometers working at 150 GHz. Observed 380 square degrees for three years [2010-2012]
- The Keck Array was five copies of BICEP2 running in parallel from 2012–2019, initially at 150 GHz but switching over time to 95 and 220 GHz. Area covered also roughly ~400 sq degrees
- BICEP3 is a single similar, but scaled up, receiver which commenced science observations in the 2016 Austral winter season [15]. BICEP3 contains ≈ 2500 detectors, and observed ~600 sq degrees.

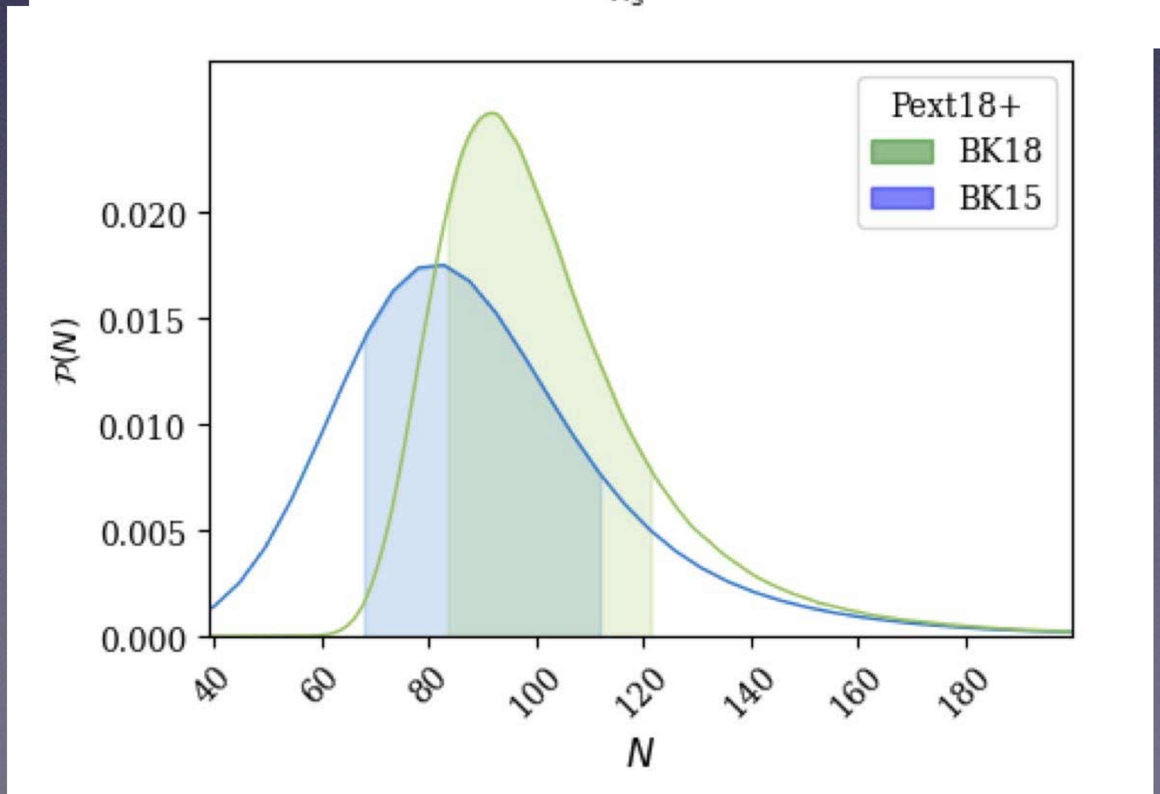




Inflation lasts too long

- With only two slow-roll parameters, we can uniquely predict the duration of inflation (N), as well as the values of the tensor to scalar ratio (r) and the spectral index (n_S)
- The latest bounds on r and n_S can be used to make a posterior probability distribution on N
- We find that, for the most recent Planck + BICEP/Keck compilation all simple inflationary models (two parameter, slow-roll) predict that inflation lasts for too long, N>70 at 95% cl





Expanding slow-roll

- What are possible explanations for this problem?
  1. Inflation ends abruptly much later, and the two parameter expansion does not describe the end of inflation (chasm-opening vs ski-slope)
  2. The universe after inflation ends is not relativistic, and there is some other unknown period before the hot big bang and BBN.
     - This is unlikely, as it would require a stiff fluid ($w=1$), but would change the required number of e-folds
  3. The two parameter model is incomplete, and needs to be expanded to (at least) three parameters
  4. Inflation happened, but is not driven by a simple scalar field, instead something radically different
  5. Inflation itself is completely wrong, and the universe did not accelerate at early times
- Here we explore option 3, expanding the slow-roll hierarchy

Higher-order terms

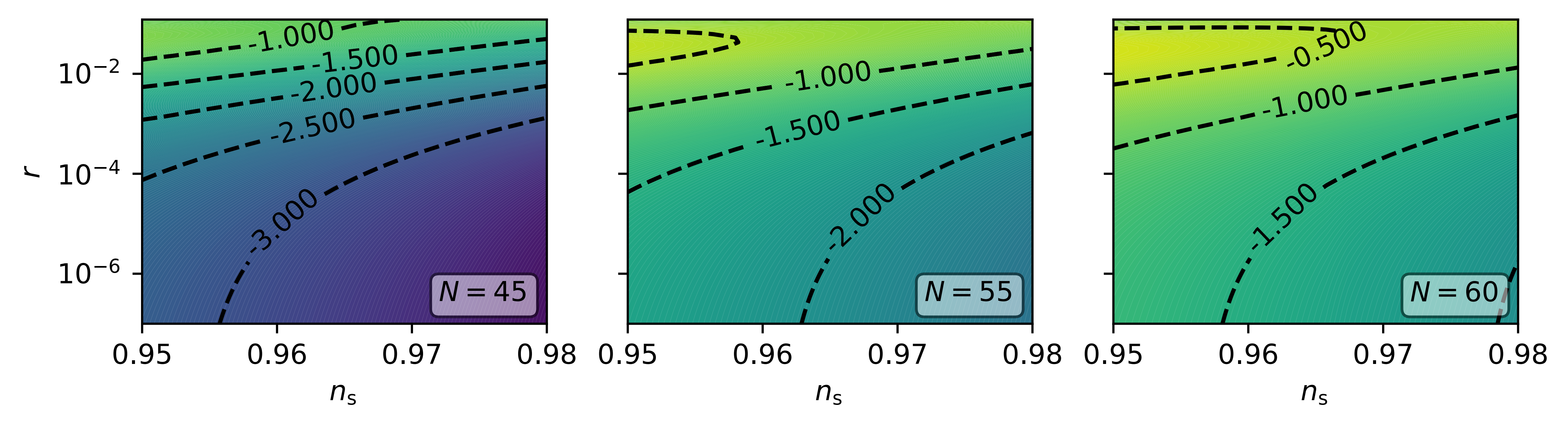
- But what if we add the next-to-leading order term in the potential ξ, to control the duration of inflation?
  - This would make the potential more complex, but allow for a small ε (which we know from the small *r*) and still have N~60
- But, this also changes the predictions

$$n_s = 1 + 2\eta - 4\epsilon - 2(1+\mathcal{C})\epsilon^2 - \frac{1}{2}(3-\mathcal{C})\xi,$$
$$r = 16\epsilon[1 + 2C(\epsilon - \eta)],$$
$$\alpha_s = -\frac{1}{1-\epsilon}\frac{d\phi}{dN}\frac{dn_{\rm s}}{d\phi}$$

- The introduction of the higher order term allows the other slow-roll parameters (ε, η) to be scale-dependent over the e-folds that generate the observable structures
- To a good approximation $\eta(N) = \eta_\star - \xi_\star \Delta N$ for astrophysically relevant modes, where ΔN is the number of e-folds after the pivot leaves the horizon.
- If η(N) is scale dependent, it follows that the spectral index will be scale dependent, and the running larger than you might expect

Change of prediction

- We can therefore predict what the running α_s will be ($10^3\,\alpha_s$ is plotted), for fixed values of n_s, r and N
- We see that, as the constraints on r get tighter in the future, and if there is no detection, the predicted (absolute) value of running will be larger

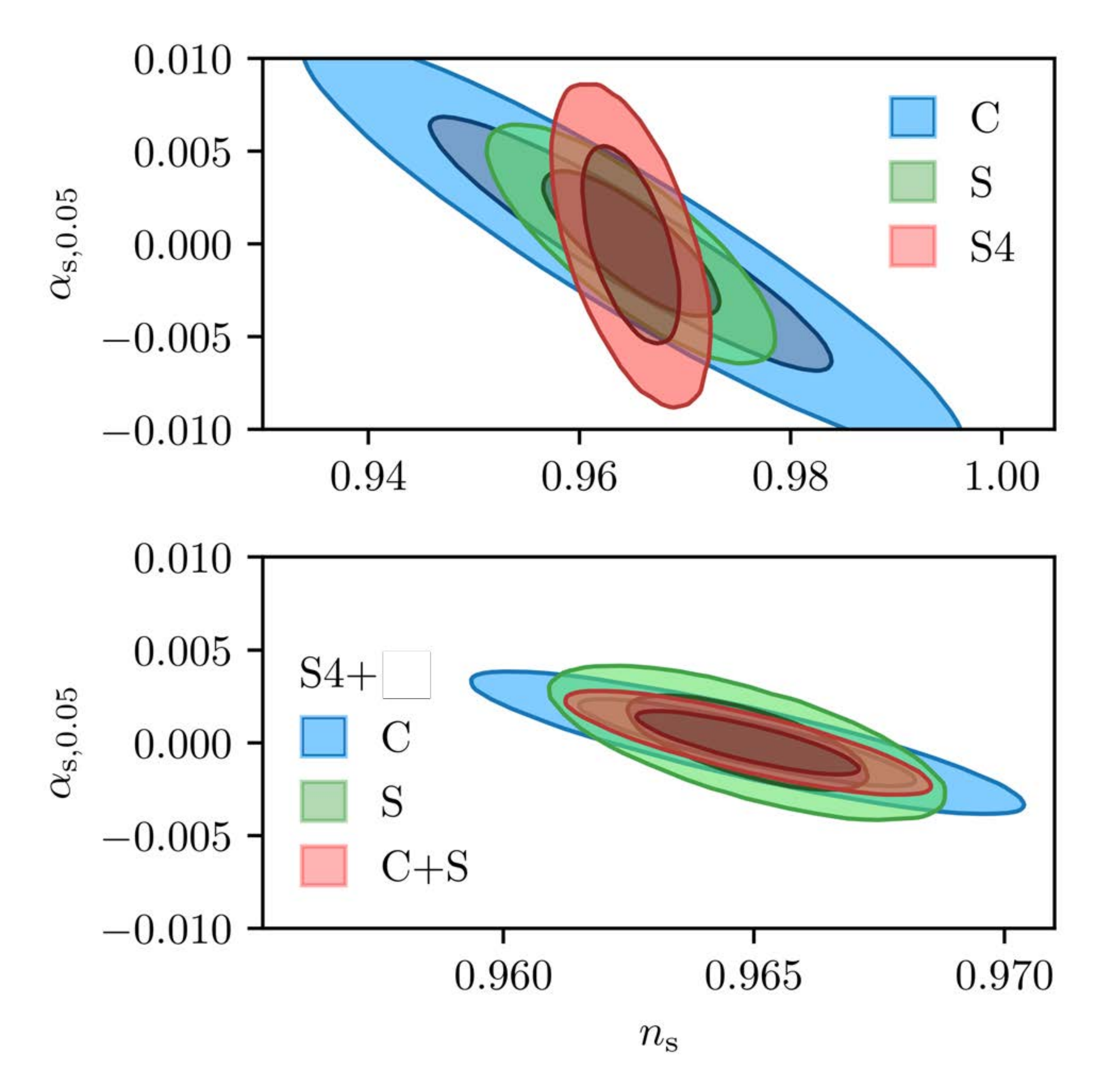


Running

- How do we measure the running?
- Need a longer lever-arm
  - Accurate measurements on both smaller and longer scales
- More precise measurements of spectral index on different scales
  - If n_s is different on different scales, can be reconciled with running

Measuring the running

- We consider how future (circa 2030) large-scale surveys can be combined with a CMB S4 experiment, to measure running at the 10^{-3} level
- C is CHIME (the Canadian Hydrogen Intensity Mapping Experiment), a neutral hydrogen-mapping radio telescope that will survey the whole northern sky
- S is SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer), a near infra-red space observatory that will perform a low-resolution spectroscopic all-sky survey
- None of these can measure the running very well individually, but the constraints become powerful in combination



Summary

- Inflation is the most successful early universe theory to explain observations of the primordial power spectrum
- Two parameter slow-roll models make predictions of n_s and r consistent with data, but prediction of duration N inconsistent with post-inflationary physics
- Prediction of duration can be changed if the slow-roll series is expanded to three terms
- A three-term slow-roll model predicts a larger value for the running of the primordial power spectrum
- If no primordial gravitational wave is detected by 2030, limits will approach $r<10^{-5}$. This will naturally predict a running $|\alpha_s| > 10^{-3}$.
- Such a large running might be at the limits of detectability, by combining the future surveys CMB S4, CHIME and SPHEREx.
- Even without detecting primordial gravitational waves, inflation becomes more testable by 2030