Designing surveys to test Inflation using running

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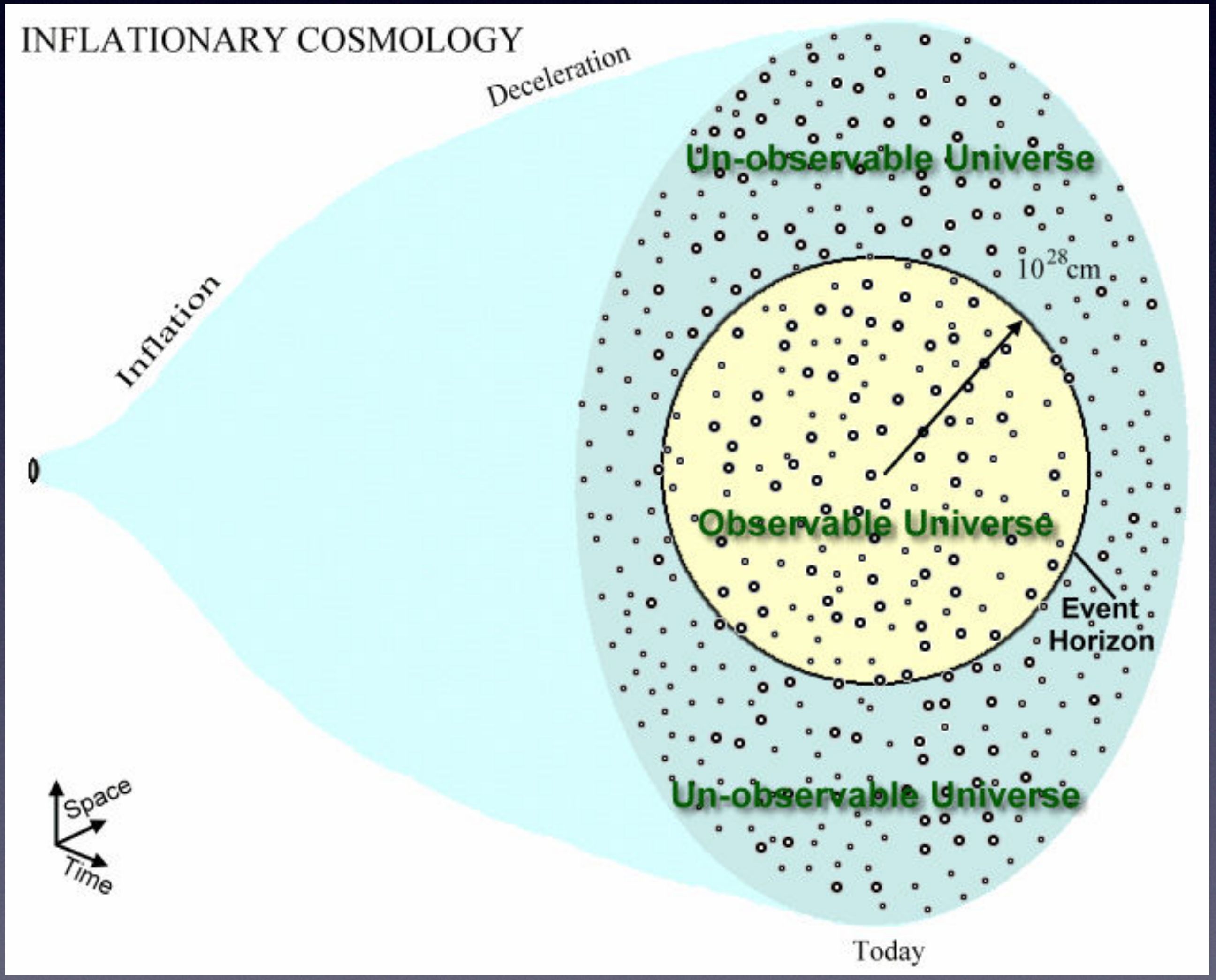
Outline

- Predictions of Inflation
- Extending slow-roll and the running
- Large-scale surveys
- Designing future surveys for the running
- Summary

Inflation

- Inflation is a model that predicts the Universe by 'inflating' the entire observable universe from a small thermalised region
  - Accelerated expansion in the early universe
  - Generates 'exo-universes', beyond our observable horizon, that explain why we look special
- But, to solve the flatness, isotropy and relic 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)



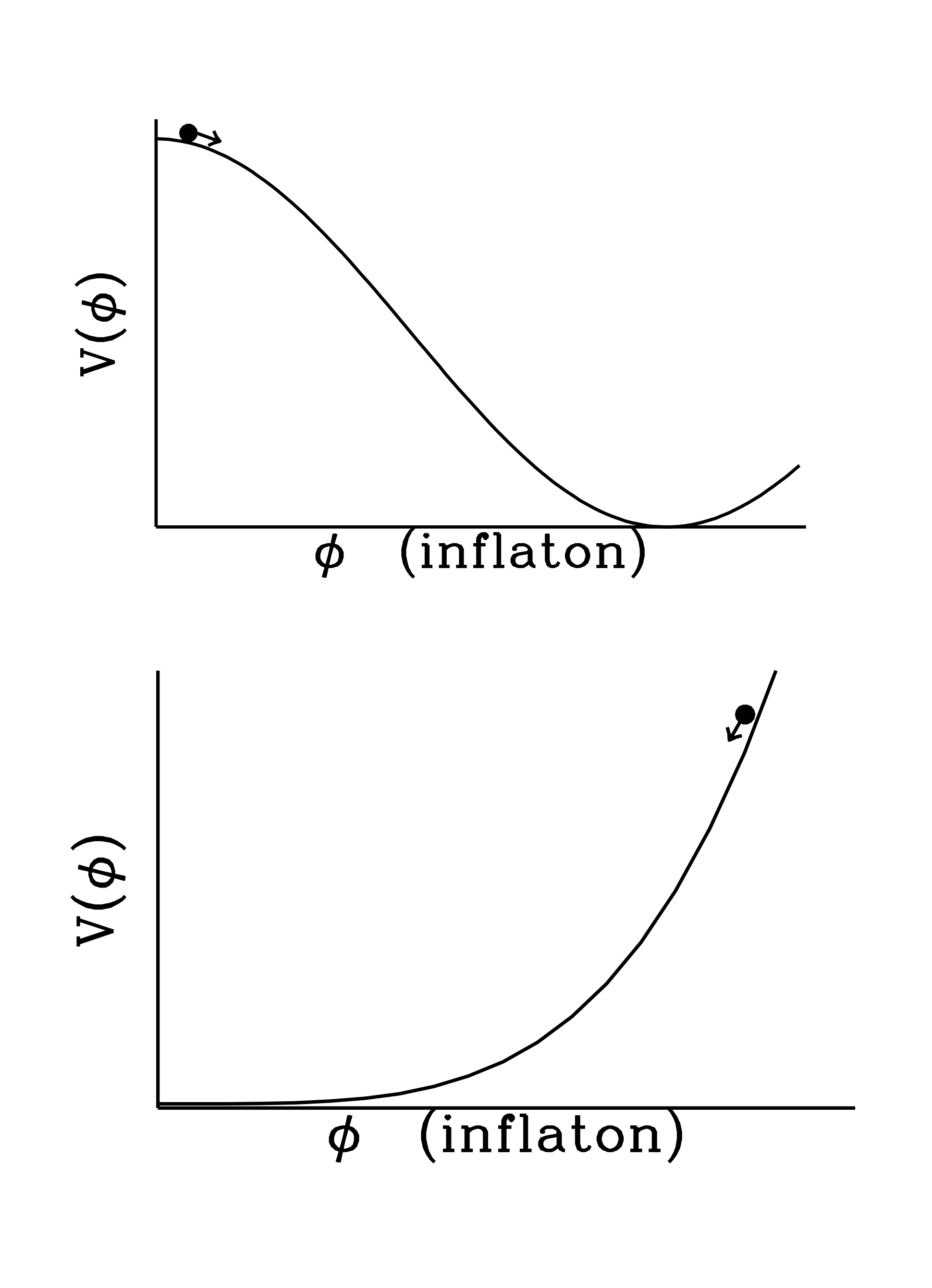
Slow-roll inflation

- 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

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

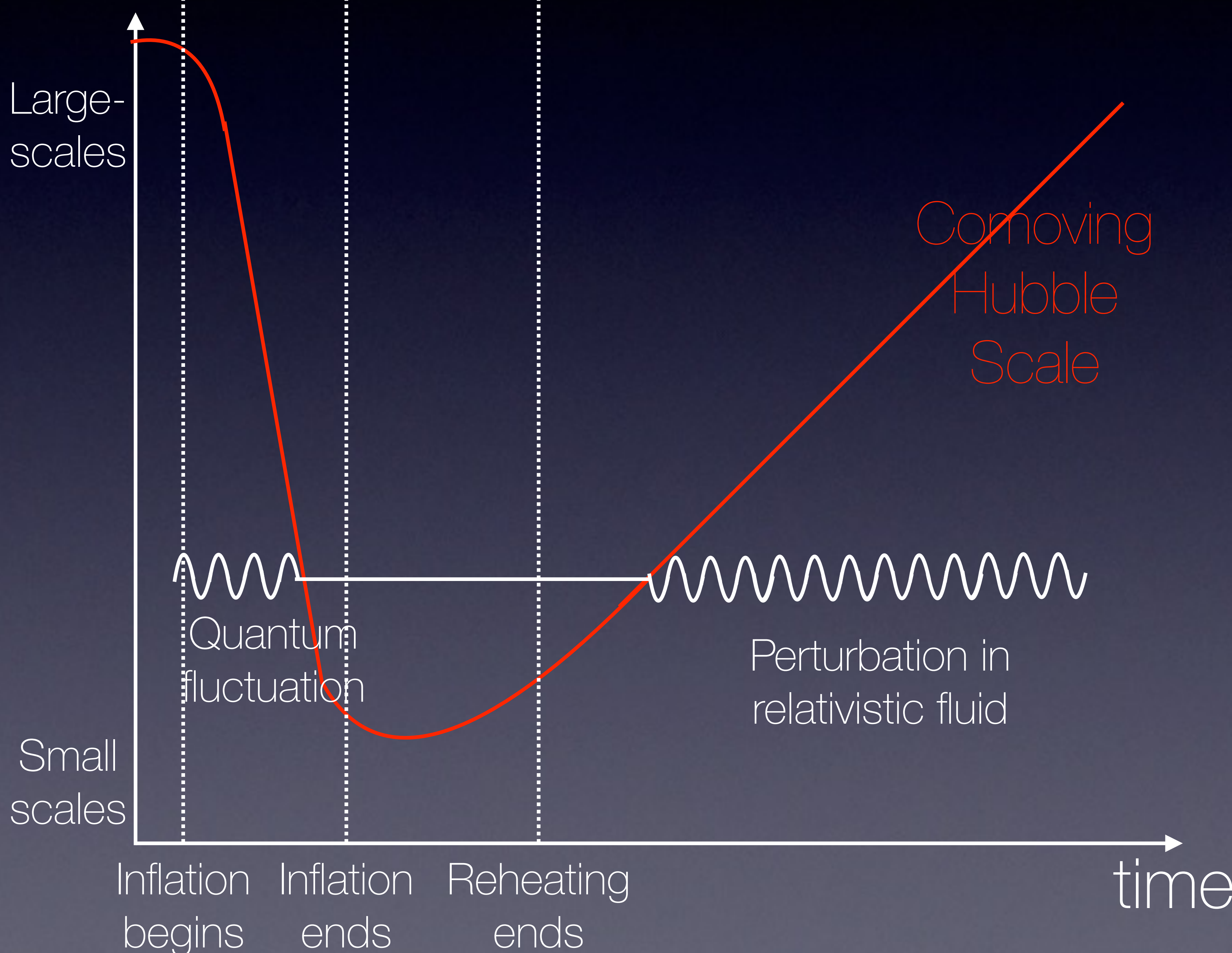
$$3H\dot{\phi} = -V'$$

- 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: predicts a spectrum of density fluctuations



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
  - Hubble horizon equivalent to particle horizon in matter- or radiation-dominated universes
- Smaller (*k*»*aH*) - evolves as in flat spacetime, oscillates
- Larger (*k*«*aH*) - evolves slowly, so amplitude and phase become ‘frozen-in’ when they cross the horizon



Inflationary Predictions

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

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

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

$$P(k) = A_S\left(\frac{k}{k_*}\right)^{n_s-1}$$

- Amplitude related to energy scale of inflation

$$A_s \sim \frac{1}{24\pi^2 m_P^4}\frac{V}{\epsilon}\bigg|_{k_*}$$

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

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

- 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

Consistency relation

- We have three free parameters in our (slow-roll) inflation model:
  - Energy scale of inflation, V
  - Slope of potential, V'
  - Curvature of potential, V''
- We have four observables
  - amplitude of density power spectrum, A_S
  - tilt of density power spectrum, n_S
  - amplitude of gravitational wave power spectrum, A_T
  - tilt of gravitational wave power spectrum, n_T
- More constraints than degrees of freedom implies a relation between some of the observables: a consistency relation

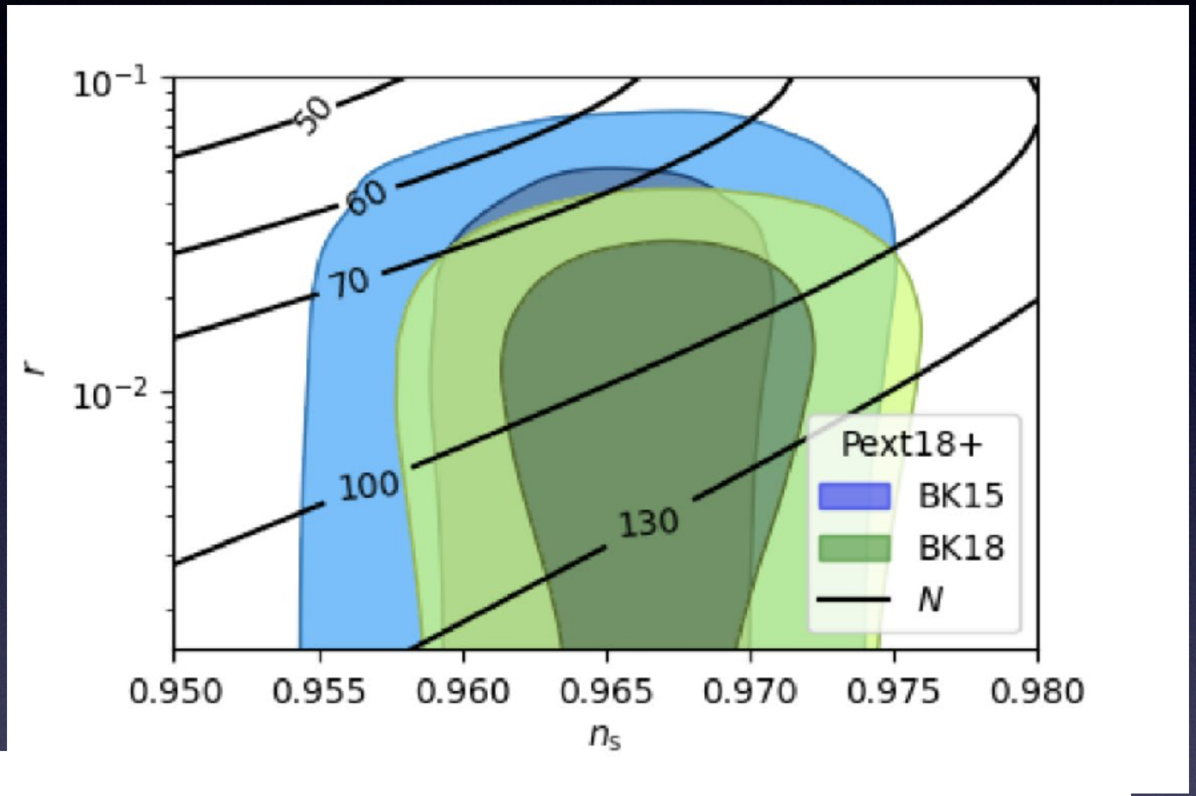
$$\frac{A_T}{A_S} = r = 16\epsilon$$

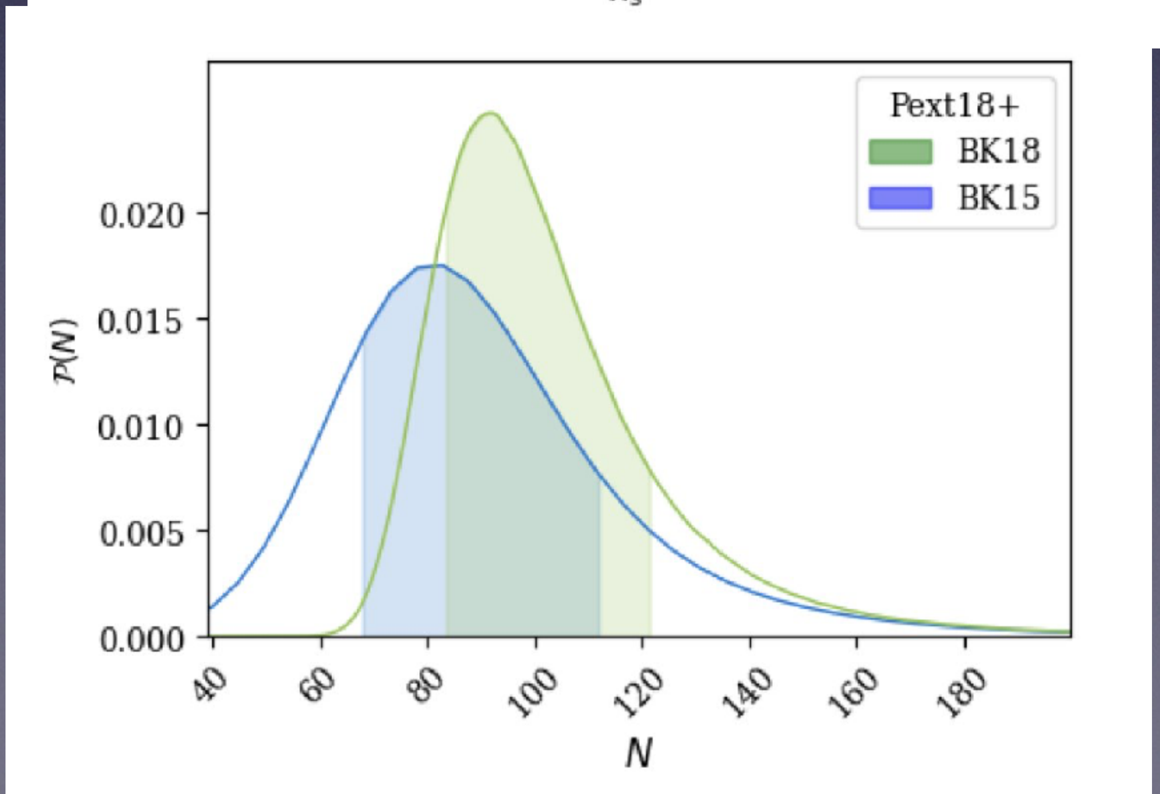
or, equivalently

$$n_T = -\frac{r}{8}$$

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, introducing a running (α_S) into the primordial power spectra

$$P(k) = A_S \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)}$$

- The slow roll predictions are now

$$n_s = 1 + 2\eta - 4\epsilon - 2(1+\mathcal{C})\epsilon^2 - \frac{1}{2}(3-\mathcal{C})\xi,$$

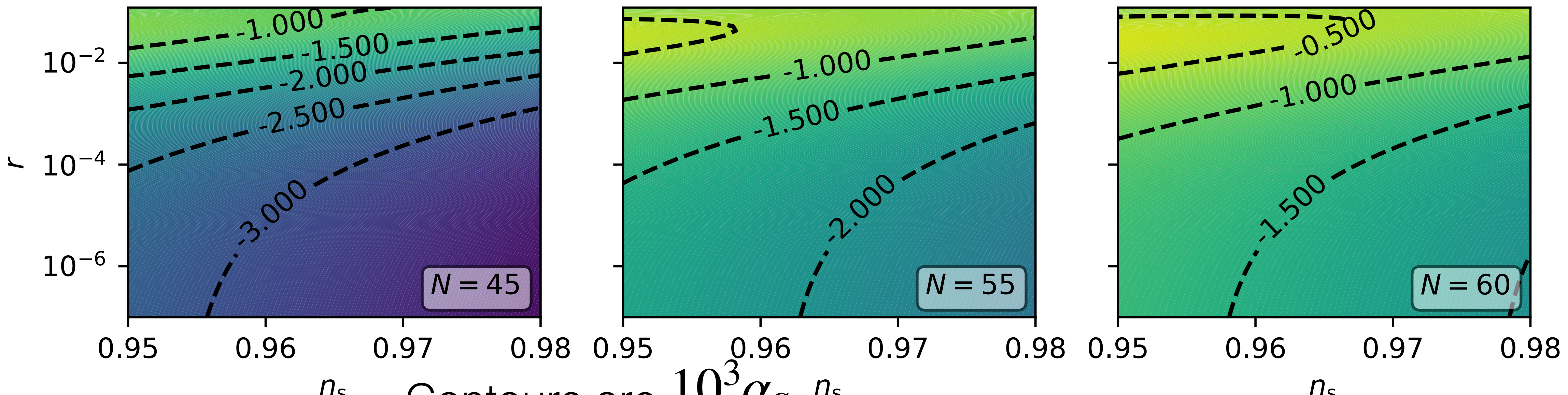
$$r = 16\epsilon[1 + 2C(\epsilon - \eta)],$$

$$\alpha_s = -\frac{1}{1-\epsilon}\frac{d\phi}{dN}\frac{dn_\mathrm{s}}{d\phi}$$

- 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
- If η(N) is scale dependent, it follows that the spectral index will be scale dependent, and the running larger than expected

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



Contours are $10^3\alpha_S$

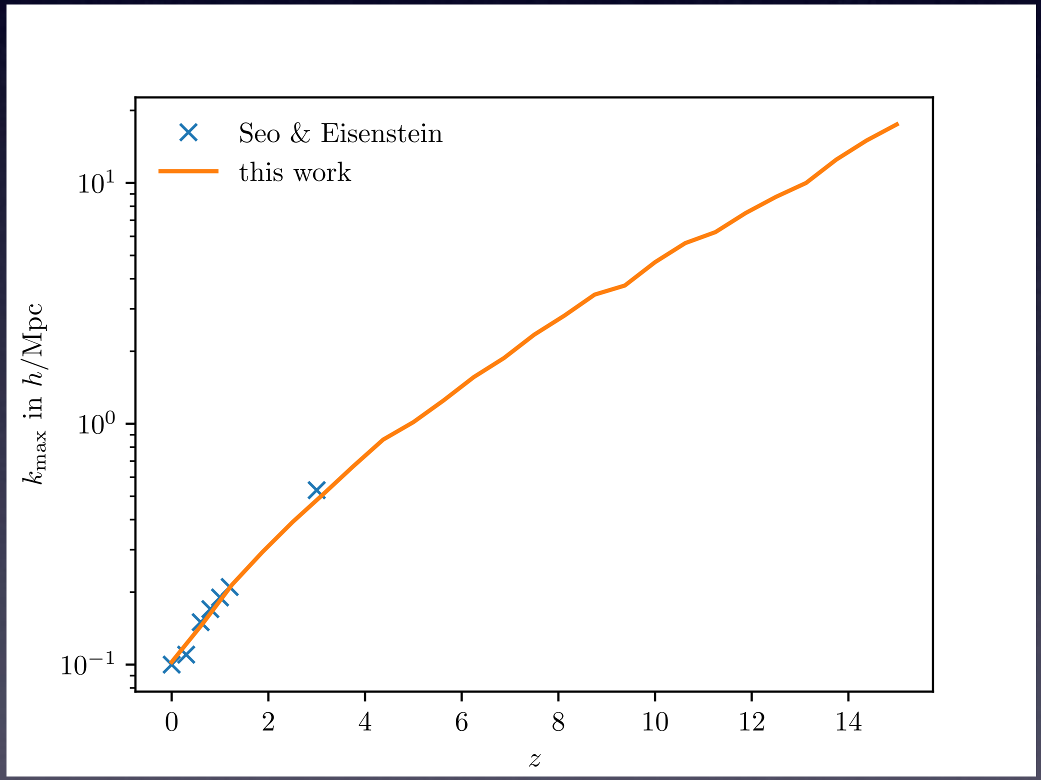
Equivalence classes

- Where will these constraints leave Inflation in 2030 (and after)?
- Considering the Taylor expansion of the potential, there are three options:
  - $V' \gg V''$ (large gravitational wave amplitude), which requires $r \gtrsim 0.01$, and is close to being ruled out
  - $V' \sim V''$ (moderate gw amplitude), which would be ruled out if $r \lesssim 10^{-4}$ (possible limit by 2030)
  - $V' \ll V''$ (low-energy inflation or no primordial gw), corresponding to potentials with a near stationary inflexion point
- Without the detection of primordial gravitational waves, we enter this third regime, which would require a large running, $|\alpha_s| > 10^{-3}$
- In this way, the running would replace the gw amplitude an important test of the inflationary model

Measuring the running using future surveys

Optimal surveys for Running

- Constraints on the running are an order of magnitude too weak ($\alpha_s = 0.013 \pm 0.012$ at 68% CL from the Planck surveyor) to test this explanation
- To measure running, need accurate measurements of structures on both smaller and longer scales
  - Large-scales: all-sky surveys
  - Small-scales: higher redshift to take advantage of linear theory at smaller wavenumber k
- Three independent options:
  - Optical: DESI → SPHEREx → SPHEREnext
  - Radio (IM): CHIME (SKA) → REACH
  - CMB: Planck → CMB-S4 → Voyager2050



Fisher forecast

- The current cosmological data is not powerful enough to measure the running at the level that matches the slow-roll inflation prediction
- However, with future CMB and large-scale structure surveys, it might be within reach by 2030
- We can use the Fisher matrix formalism to predict the effectiveness of future surveys to measure parameters

$$F_{ij} \equiv \left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial\theta_i \partial\theta_j} \right\rangle$$

- Here *L* is the forecast likelihood, and θ are the parameters to be measured
- We forecast the precision on the constraint on the running, but we also marginalised over the other cosmological parameters, including the spectral index n_s
- We assume a set of fiducial cosmological parameters informed by the best fit of Planck18. We set the fiducial α_s and r to be zero

Radio: Intensity Mapping

- Intensity Mapping maps the distribution of matter through the emission of 21cm radiation from atomic hydrogen
  - The ‘forbidden’ electron spin-flip transition
- CHIME is the Canadian Hydrogen Intensity Mapping Experiment, a neutral hydrogen-mapping radio telescope near Penicton, British Columbia
  - CHIME will cover the entire (northern) sky, and the redshift range 0.8 < 2.5
- REACH is Radio Experiment for the Analysis of Cosmic Hydrogen
  - Will cover a redshift range from z = 7.5 to z = 28

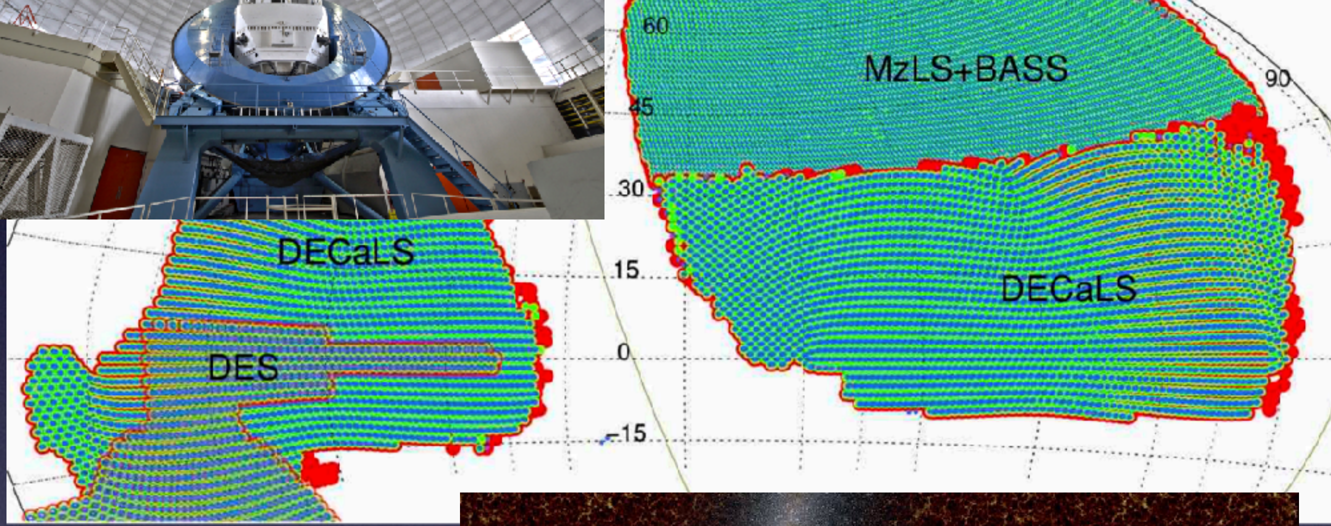
REACH

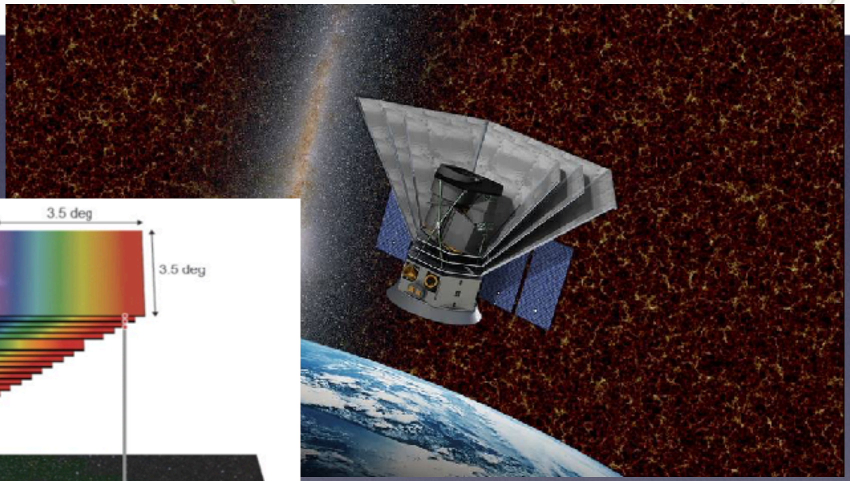
RADIO EXPERIMENT FOR THE ANALYSIS OF COSMIC HYDROGEN

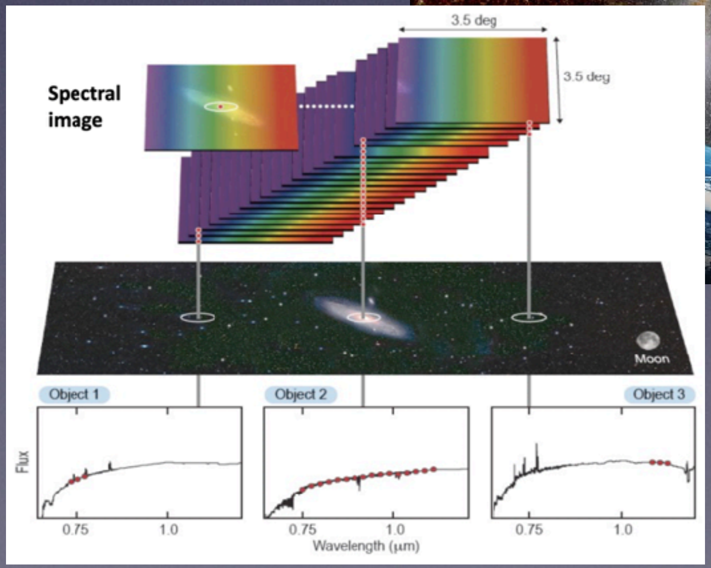
Artist impression of first stars. Adolf Schaller for STScI.

Optical

- The Dark Energy Spectroscopic Instrument (DESI) is a multi-object spectrograph designed to measure the distance (redshift) of 5000 galaxies simultaneously, using fibre optics.
    - The DESI survey will cover most of the northern sky and part of the south, with an estimated target of 35 million galaxies to be surveyed
- SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer), near infra-red space observatory that will perform a low-resolution spectroscopic all-sky survey.
    - Launch date is scheduled for early 2025
    - Small mission (20cm mirror, 68.1kg payload)
- SPHERENext is our proposed successor to SPHEREx, with a larger aperture, will go deeper and detect more sources

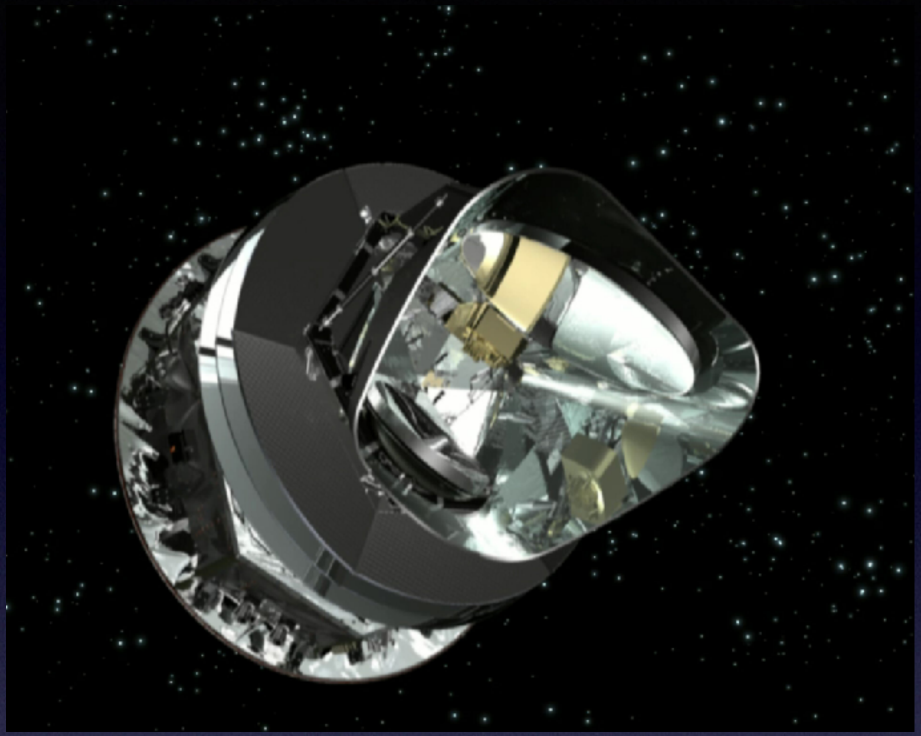




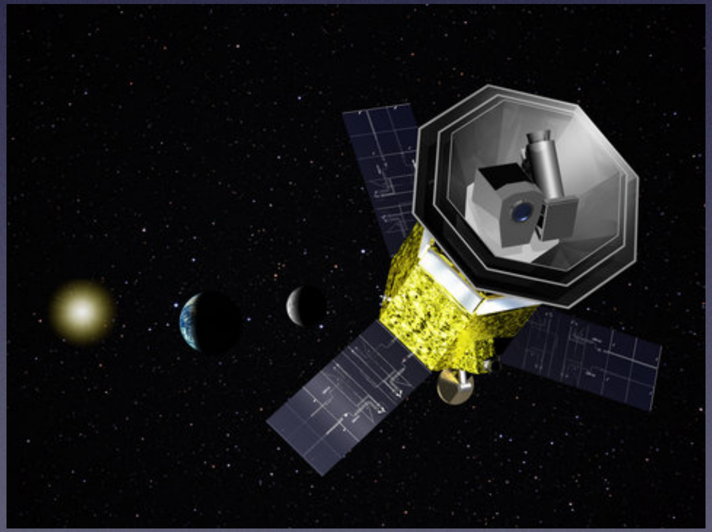


CMB

- Planck is a space-based CMB anisotropy observatory, covering the whole sky, which is cosmic variance limited down to ℓ<1800.
  - Primarily measures temperature anisotropies, with some polarisation sensitivity
- CMB-S4 is a a ground-based CMB experiment being constructed at both the South Pole and Atacama desert sites
- LiteBIRD is the Lite (Light) satellite for the studies of B-mode polarization and inflation from cosmic background Radiation Detection
  - Satellite CMB observatory covering the wavelength range 40 to 400 GHz.
- Voyage2050 is proposed CMB spectral distortion experiment (based on white paper by J. Chluba et al, https://arxiv.org/abs/1909.01593)



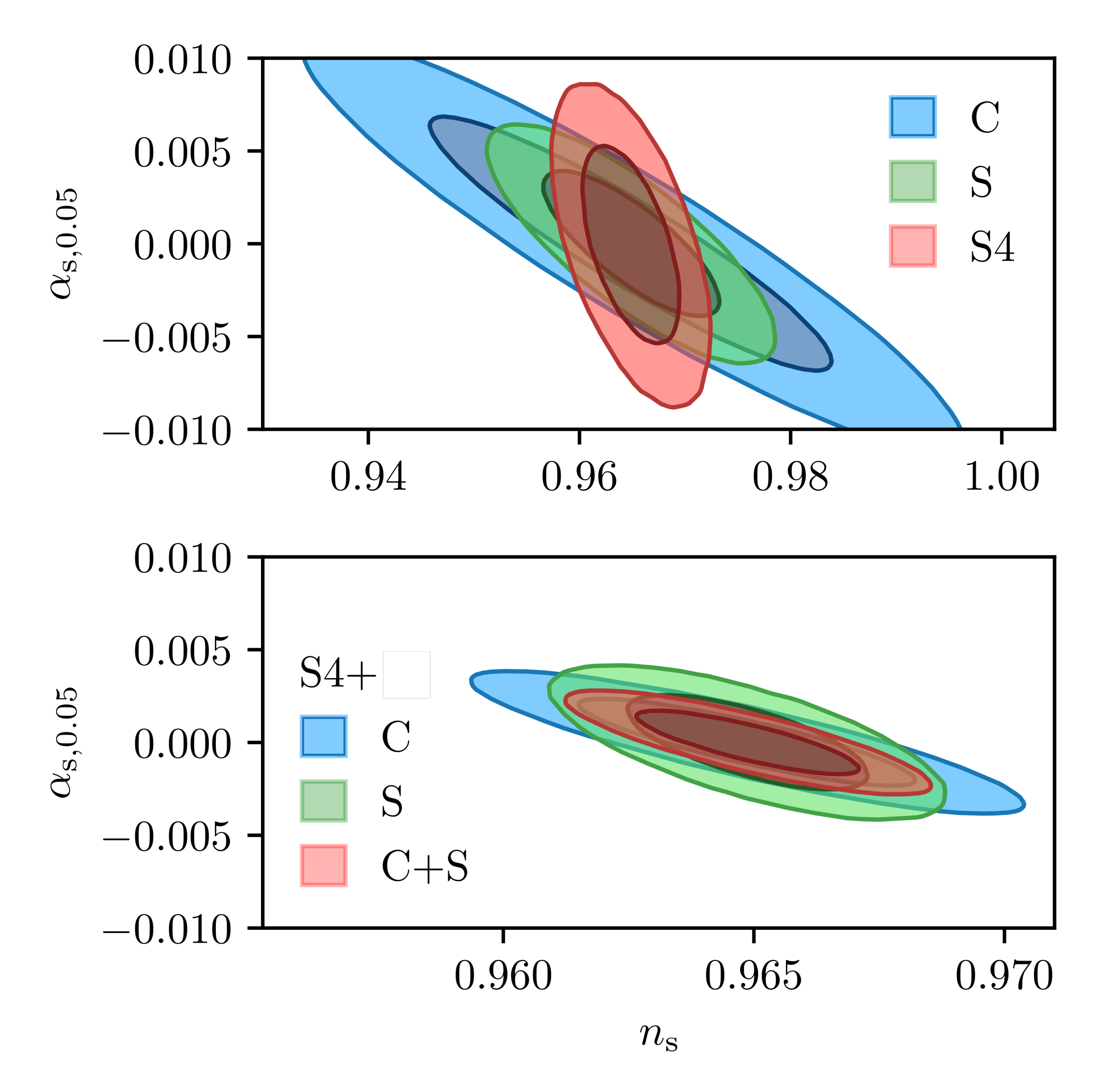
https://www.esa.int



https://cmb.sites.stanford.edu

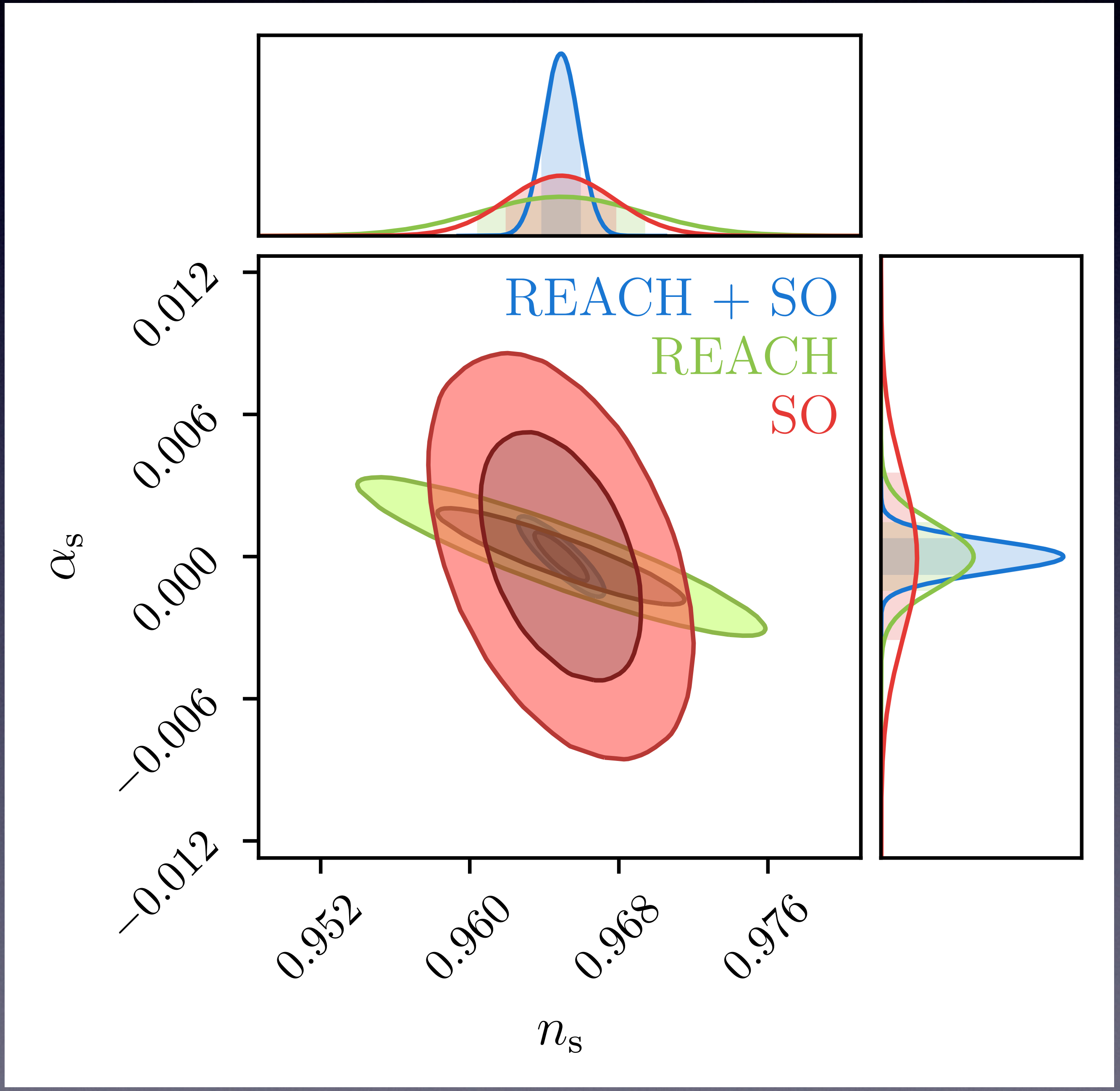
Measuring the running

- We predict the effectiveness of large-scale surveys when combined CHIME and SPHEREx with a CMB S4 experiment, to measure running at the 10^{-3} level
- None of these can measure the running very well individually, but the constraints become powerful in combination
- Constraints on the tensor to scalar ratio will reach $r < 10^{-4}$ at 95% probability



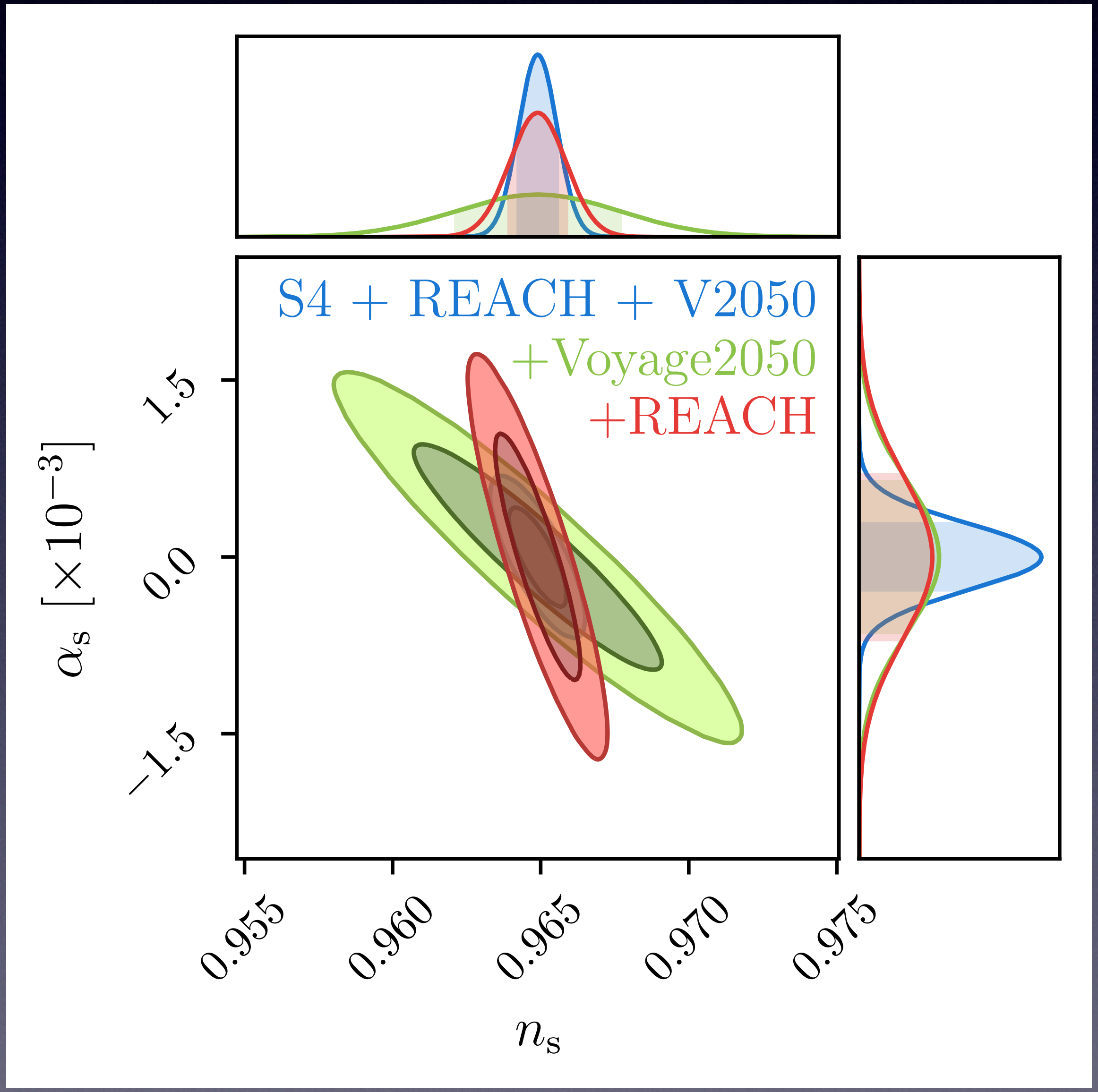
Measuring the running (2)

- REACH improves on CHIME due to the higher redshift and so number of small-scale (linear) k modes that can be measured
- Constraints on running (again in combination with Simons Observatory, but without SPHEREx), start to get close to the 10^{-3} level



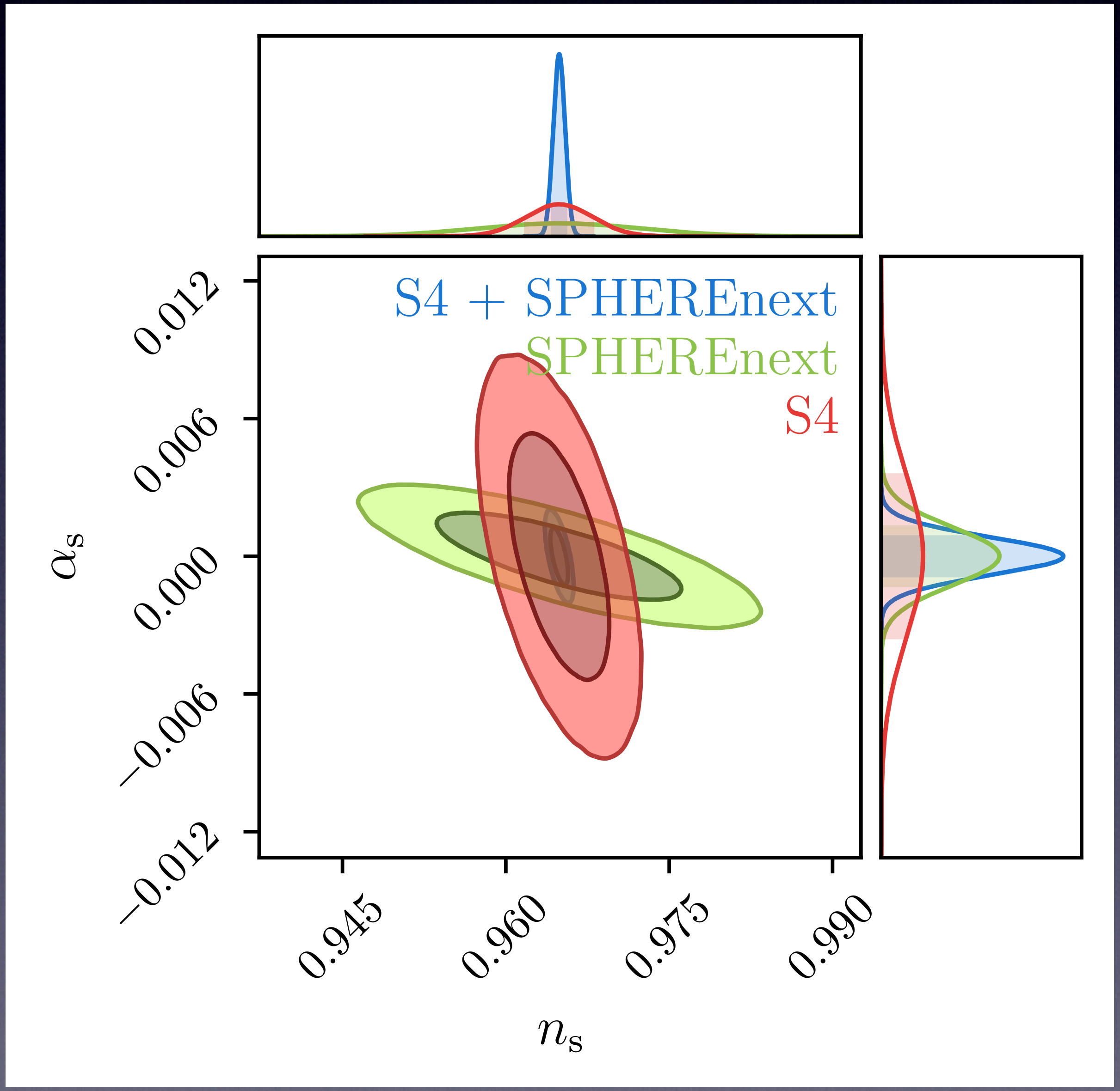
Measuring the running (3)

- Voyager2050 has a very different degeneracy direction, because it is sensitive to the matter power spectral on scales $k \sim 10^3 \mathrm{M}pc^{-1}$ through CMB spectral distortions
- Constraints on running in combination with REACH, are below the 10^{-3} level



Measuring the running (4)

- SPHEREnext again significantly improves on SPHEREx, increasing V_{eff} from 29 Gpc^3 to 180 Gpc^3
- Redshift bin with the highest redshift accuracy has a mean redshift of z = 1.48, allowing us to extend our scale range to k_{max} = 0.24 h/Mpc
- Precision achieved is $\sigma_{\alpha_s} = 1.6 \times 10^{-3}$ by itself



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 CMB S4 experiment with radio IM surveys such as CHIME and REACH, or optical/NIR galaxy surveys such as SPHEREx (and SPHEREnext).
- A combination of all surveys should reach $\sigma_{\alpha_s} = 6.7 \times 10^{-4}$
- Even without detecting primordial gravitational waves, inflation becomes more testable after 2030