Born to Run:

What will we have learnt about inflation by 2030 if we do not detect f_{NL} or r?

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What if we don't find evidence for PNG?

- Single-field slow-roll inflation still easiest model to fit data
- Expansion of 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 ($f_{\mathrm{NL}} = 0$), nearly-scale invariant density perturbations

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

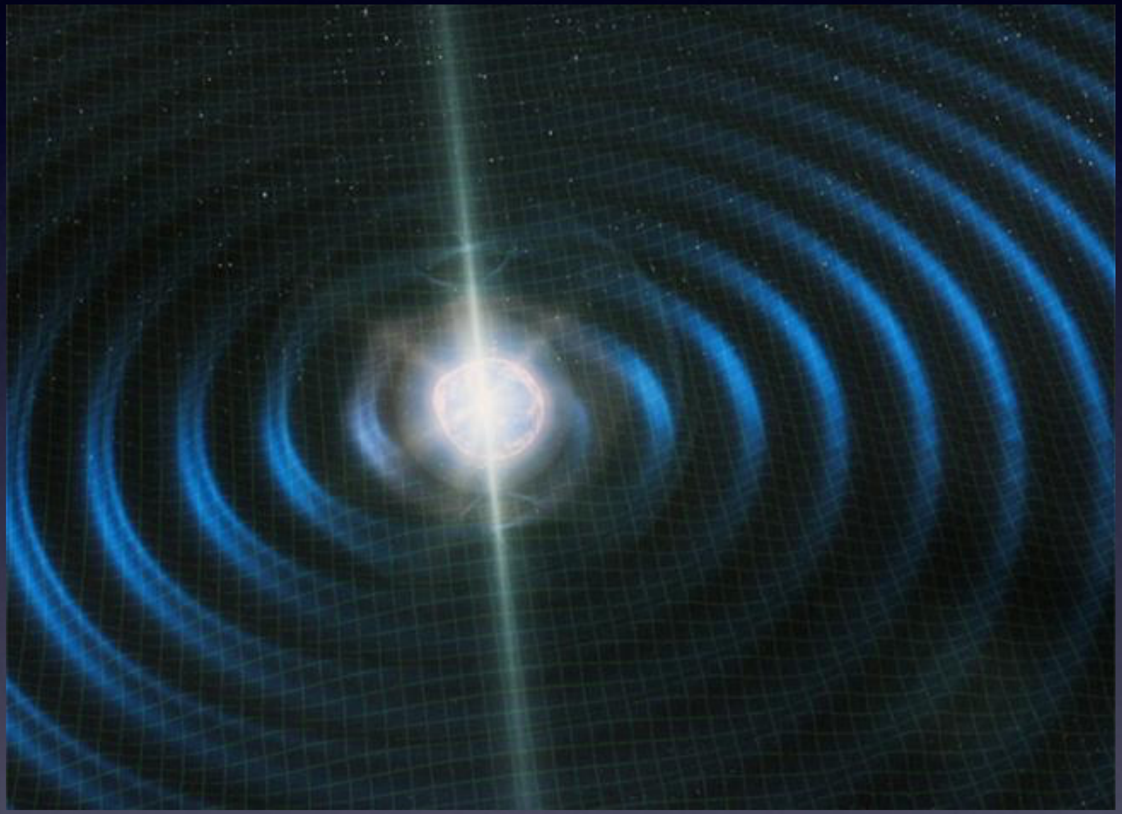
- The spectral index for this can be written in terms of the slow-roll parameters (assuming only two parameters are important)

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

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

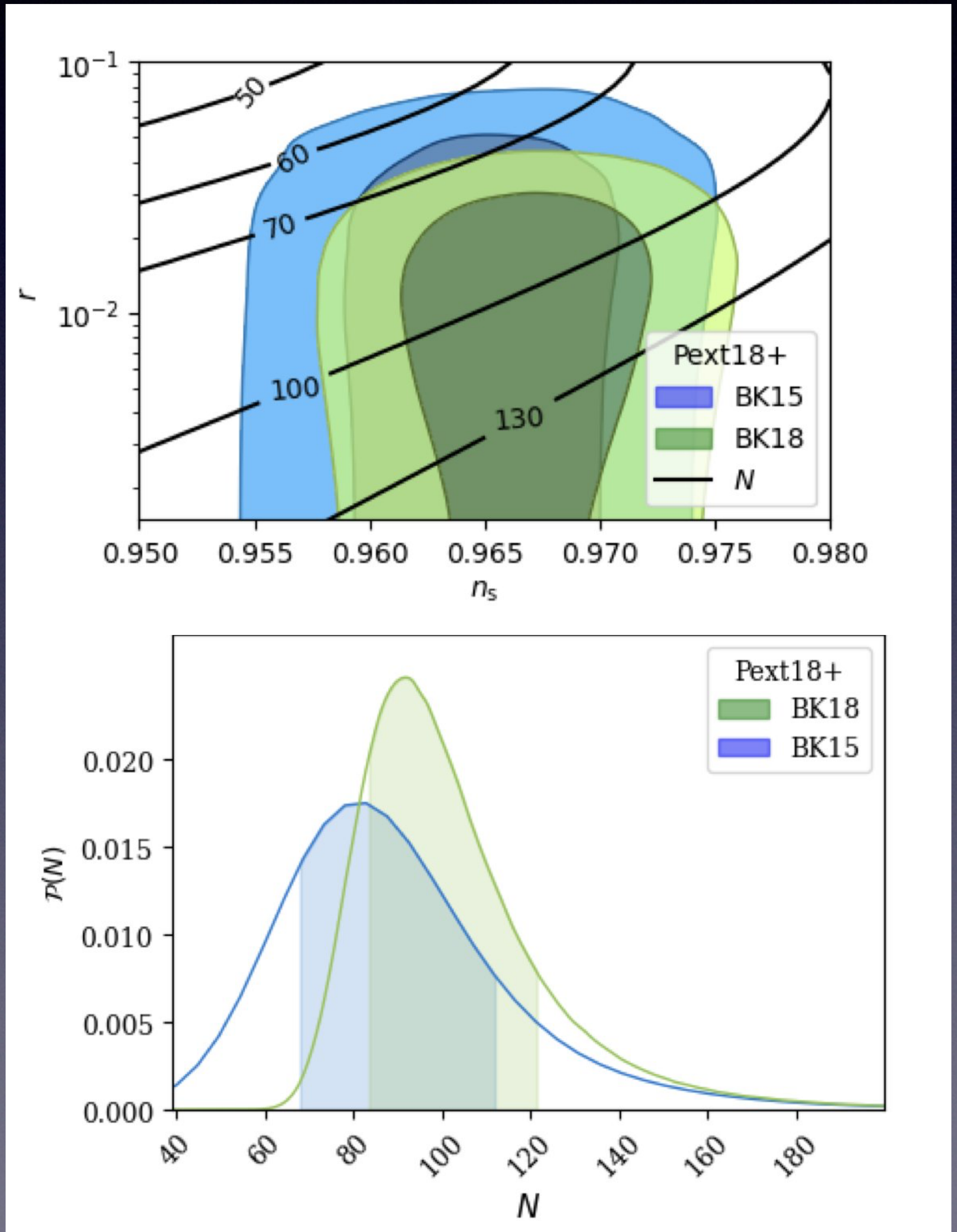
Primordial Gravitational Waves

- Gravitational waves are fluctuations of spacetime generated by accelerating masses (quadrupole moment)
- Small-scale GWs (100 km wavelength) have been detected from massive star relic binary inspired (e.g. Black hole-black hole binary systems)
- The accelerated expansion of the universe during also generates a spectrum of primordial gravitational waves (or tensor perturbations, $P_{\mathrm{T}}(k) = A_{\mathrm{T}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{T}}}$), with much larger wavelengths (horizon scale) too large to be detected directly by ground based interferometers
- But they can be inferred by their effect on the CMB polarisation: $r = \frac{A_{\mathrm{T}}}{A_{\mathrm{S}}} \approx 16\epsilon$



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):
  - $$\frac{d\epsilon}{dN} = 2\epsilon(\eta - \epsilon)$$
  - $$\frac{d\eta}{dN} = -\epsilon\eta$$



- 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

- Add 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 spectrum

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

- The slow roll predictions are now

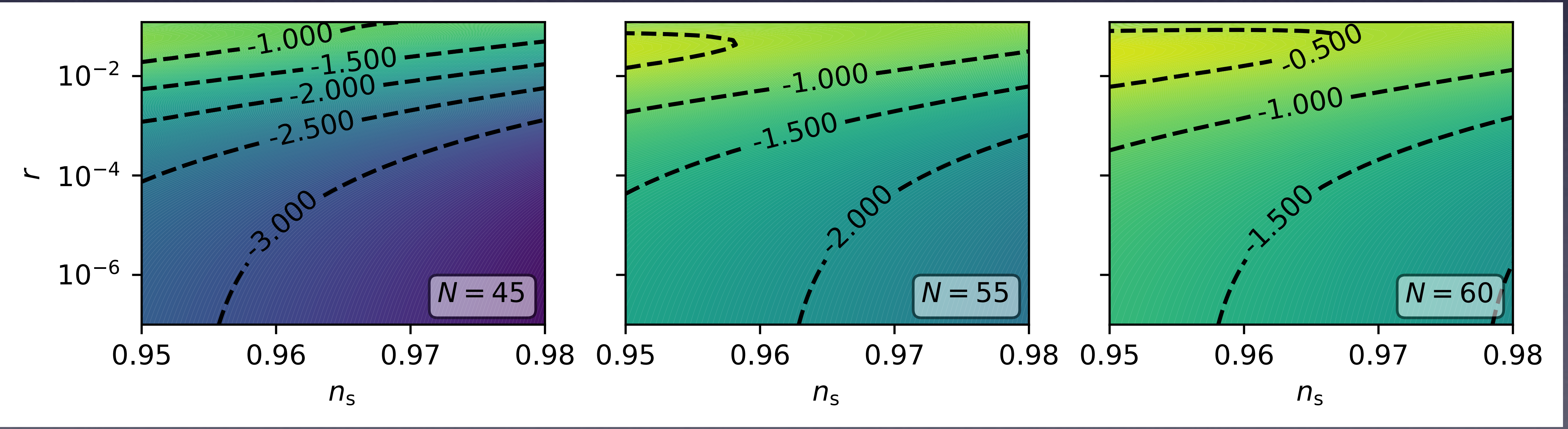
$$n_s = 1 + 2\eta - 4\epsilon - 2(1+\mathcal{C})\epsilon^2 - \frac{1}{2}(3-\mathcal{C})\xi,$$

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

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

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

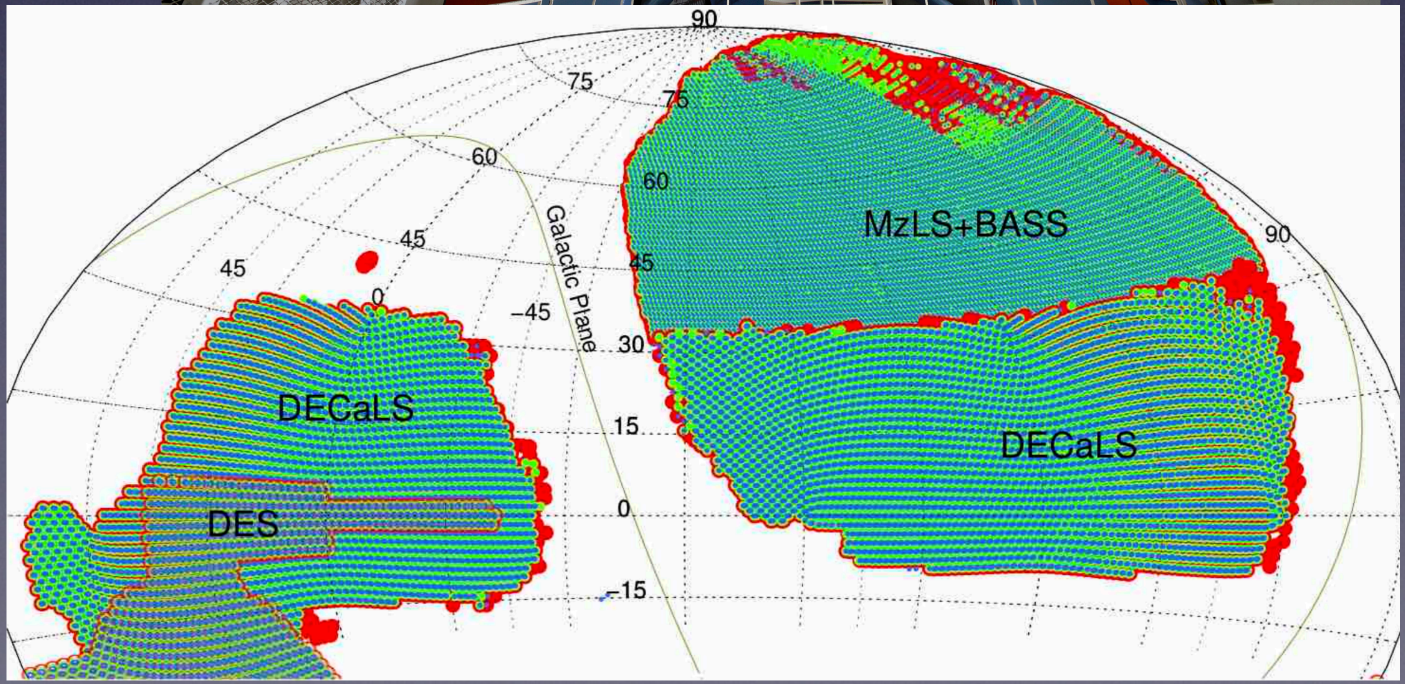


Running

- Constraints on the running are an order of magnitude too weak (0.013 ± 0.012 at 68% CL from *Planck*) to test this
- How do we measure the running?
- Need a longer lever-arm
  - Accurate measurements of structures 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

DESI

- The Dark Energy Spectroscopic Instrument (DESI) is a multi-object spectrograph designed to measure the distance (redshift) of 5000 galaxies simultaneously, using fibre optics.
- It is mounted on the 4m Mayall telescope at Kitt Peak observatory in Arizona
- 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
- The aim of the survey is to measure the Dark Energy properties through the baryon acoustic oscillations (standard rulers), but the huge 3D map of the galaxy distribution can also be used to measure the matter power spectrum

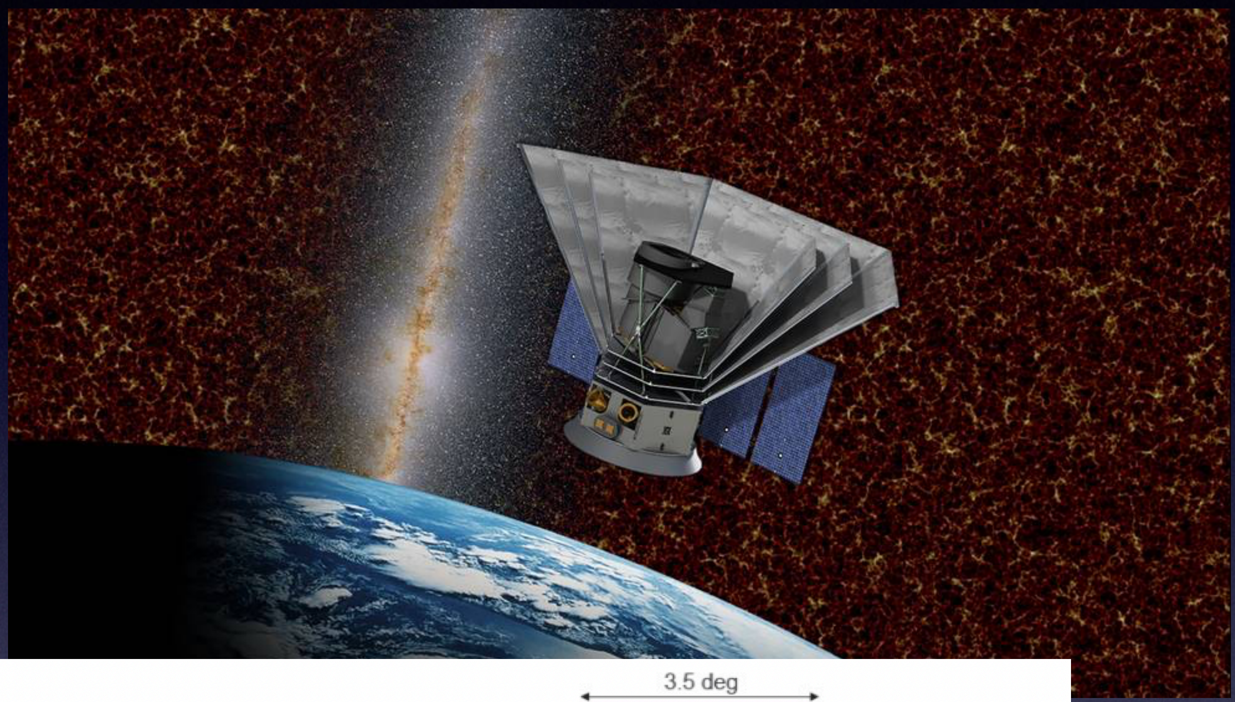


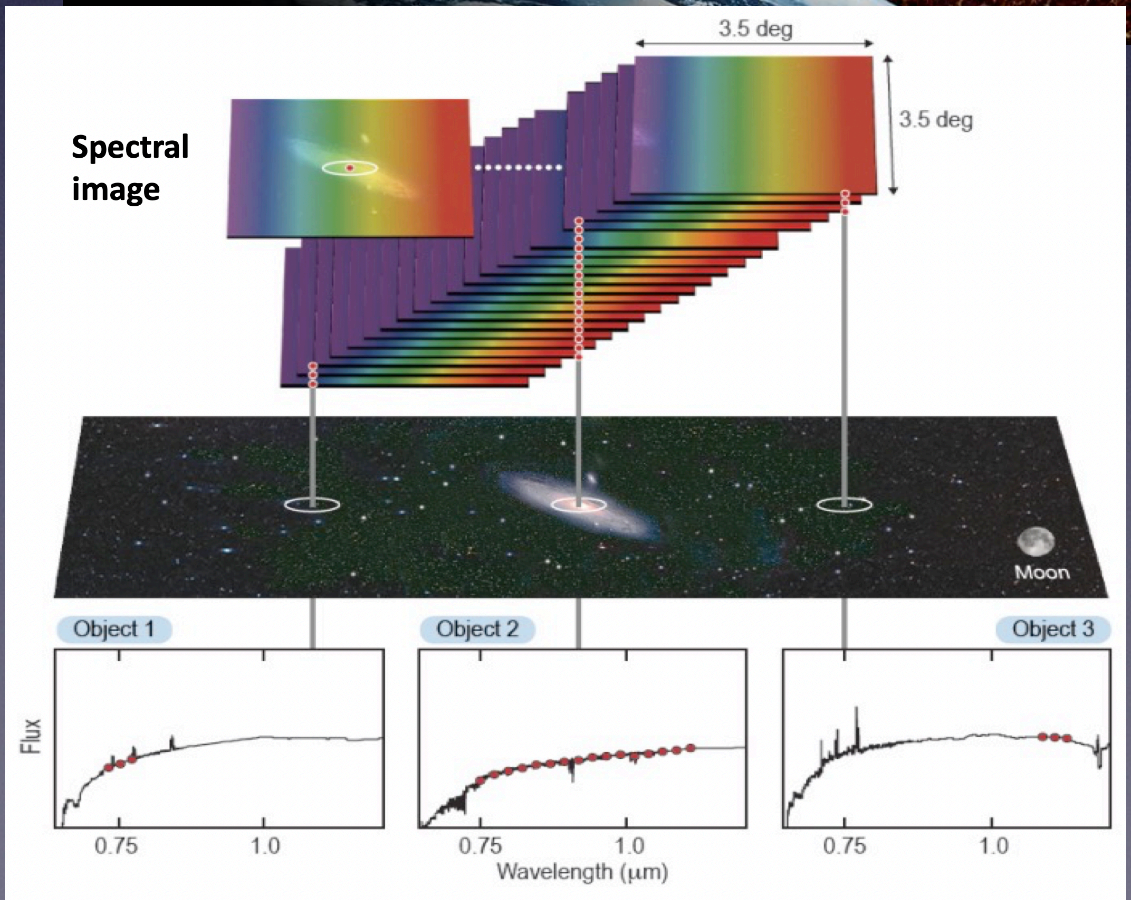
CHIME

- CHIME is the Canadian Hydrogen Intensity Mapping Experiment, a neutral hydrogen-mapping radio telescope near Penicton, British Columbia
- CHIME will map the distribution of matter through the emission of 21cm radiation from atomic hydrogen
  - The 'forbidden' electron spin-flip transition
- The survey will cover the entire (northern) sky, and the redshift range 0.8 < 2.5
- A similar experiment is being constructed in China, named Tianlai

SPHEREx

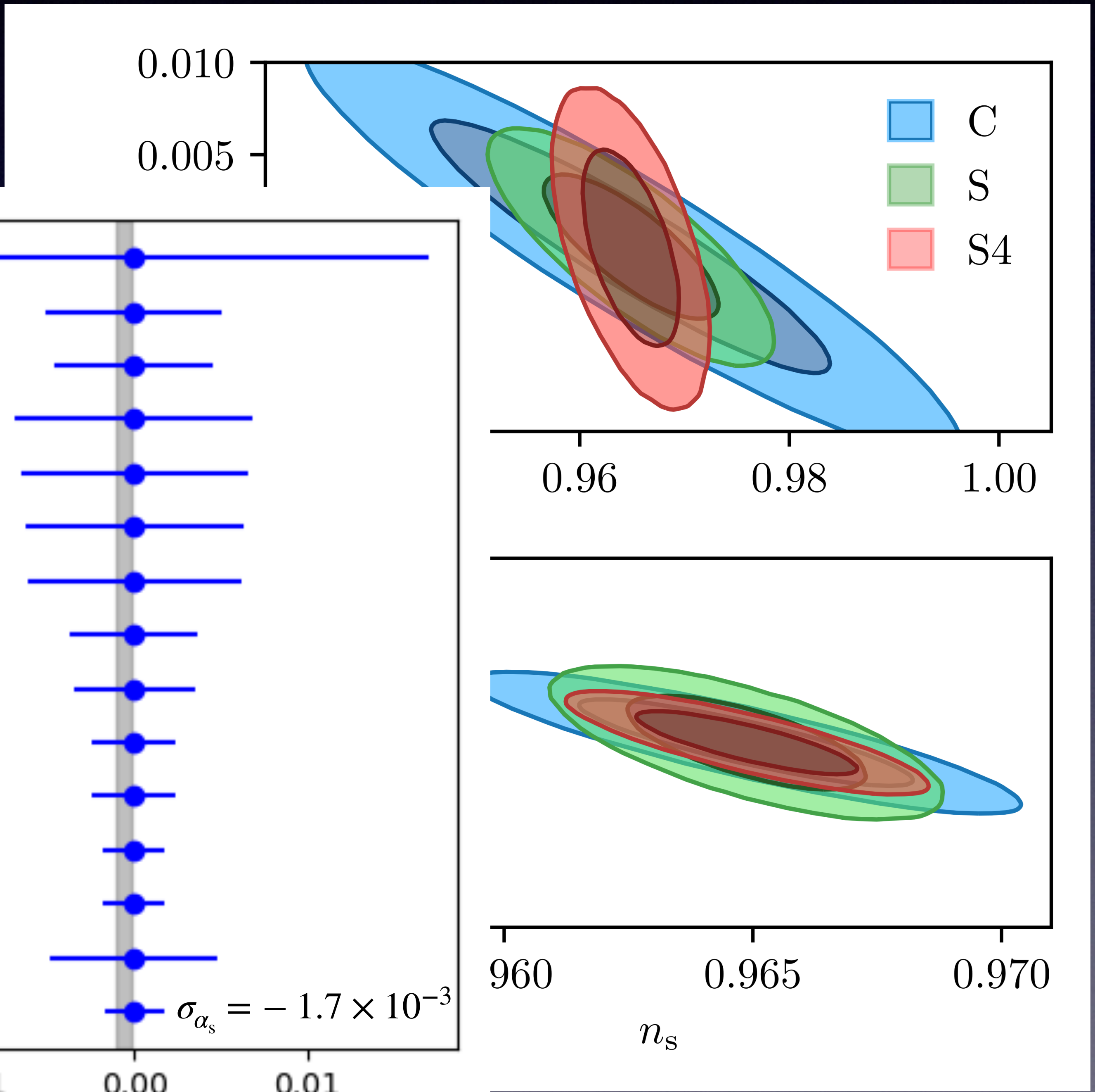
- SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer), is a NASA mid-size experiment, which KASI is a partner in. Launch date is scheduled for June 2024
- It is near infra-red space observatory that will perform a low-resolution spectroscopic all-sky survey
- The combination of all-sky and deep in redshift limit means that it will cover the largest volume of the surveys considered, reducing the error on the large-scale power spectrum through smaller sample variance
- However, the redshift dispersion will be large, leading to smearing in the radial direction

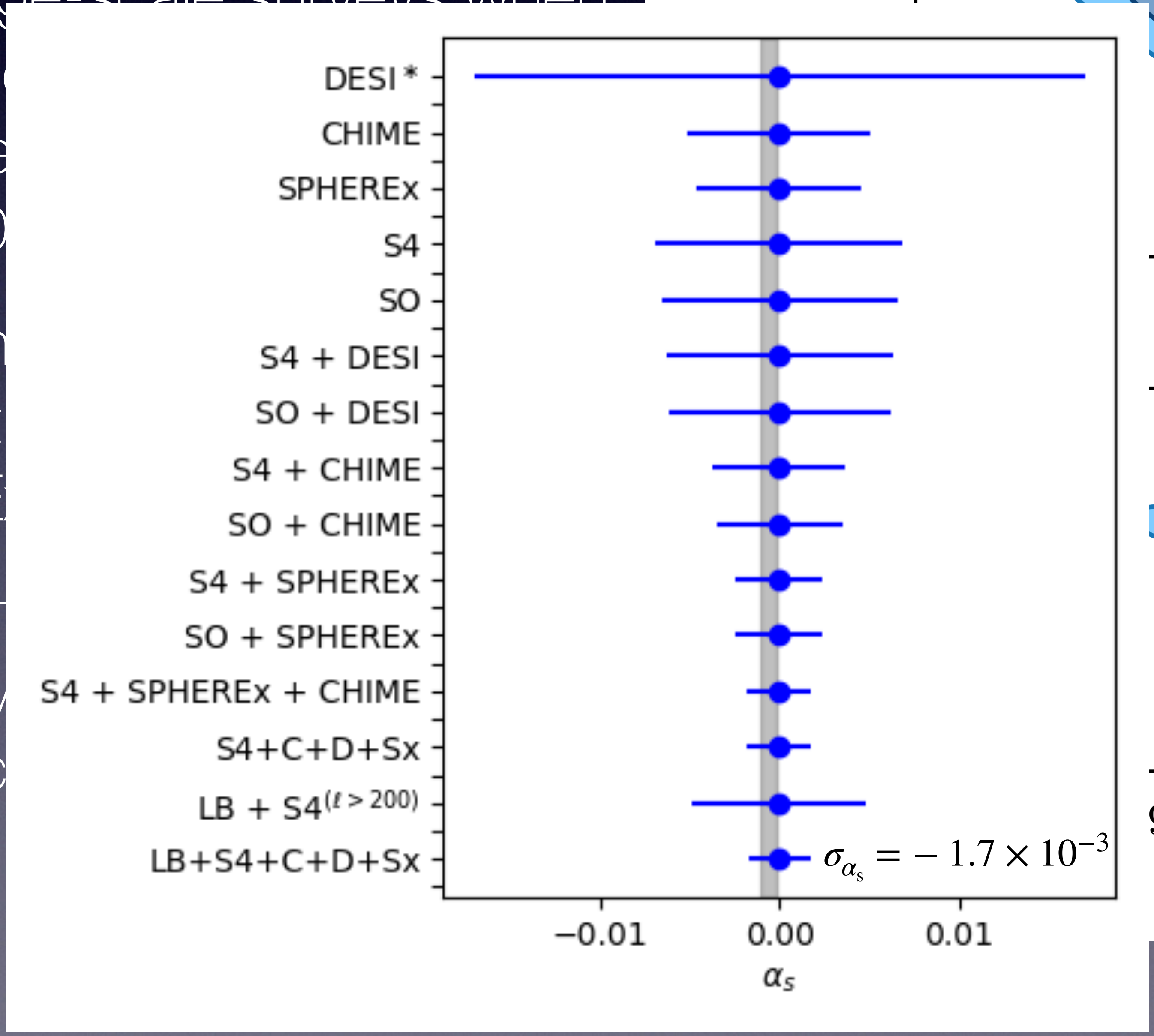




Measuring the running

- We predict the effectiveness of these large-scale surveys when combine… experime… at the 10…
- DESI is n… competit… SPHERE…
- None of t… running v… but the c… powerful…





Summary

- 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 smaller 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 experiments such as CMB S4, with a large-scale structure experiment such as SPHEREx.
- Even without detecting primordial gravitational waves, inflation becomes more testable by 2030

“We gotta get out while we're young
'Cause [Universes] like us, baby, we were born to run”

Thank you