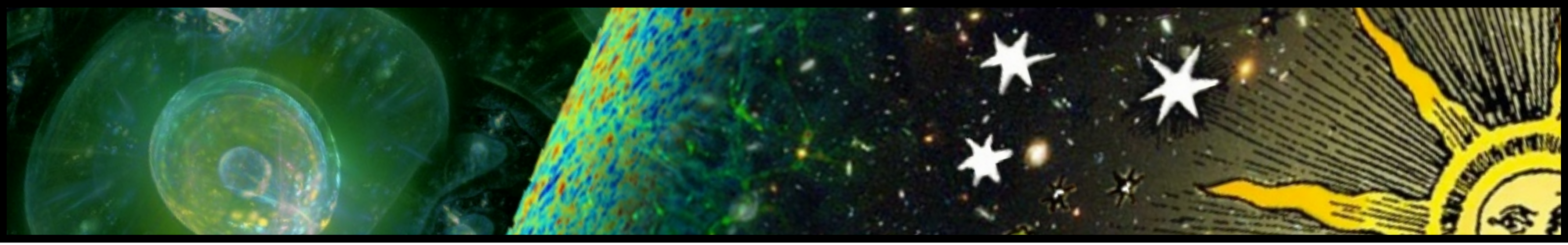


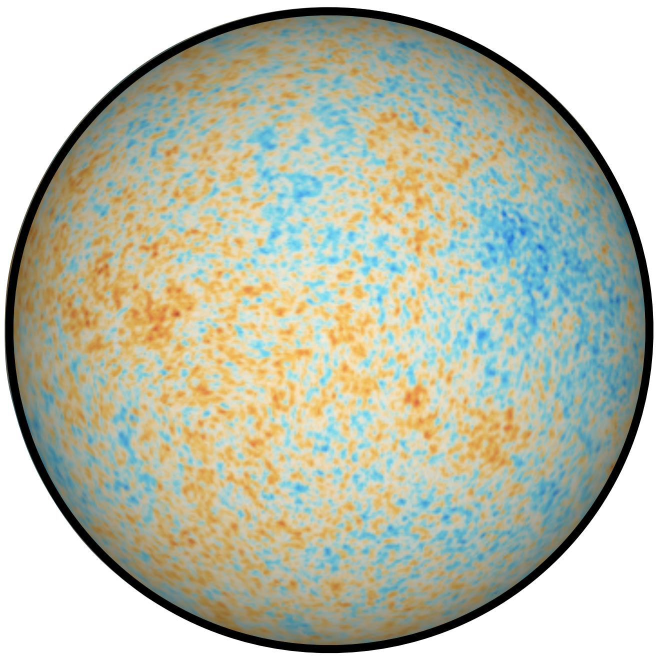
Cosmological Constraints on Inflation

Hiranya V. Peiris
University College London

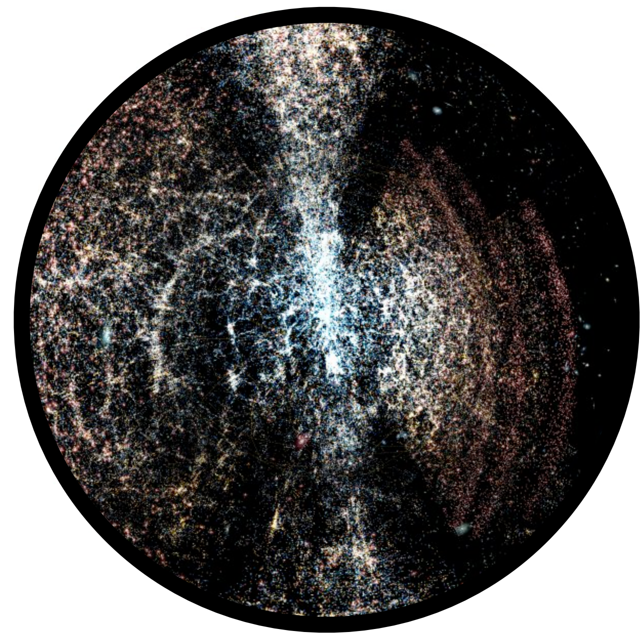
European Research Council

IDEAS

What is the physical origin of all the structure in the Universe?



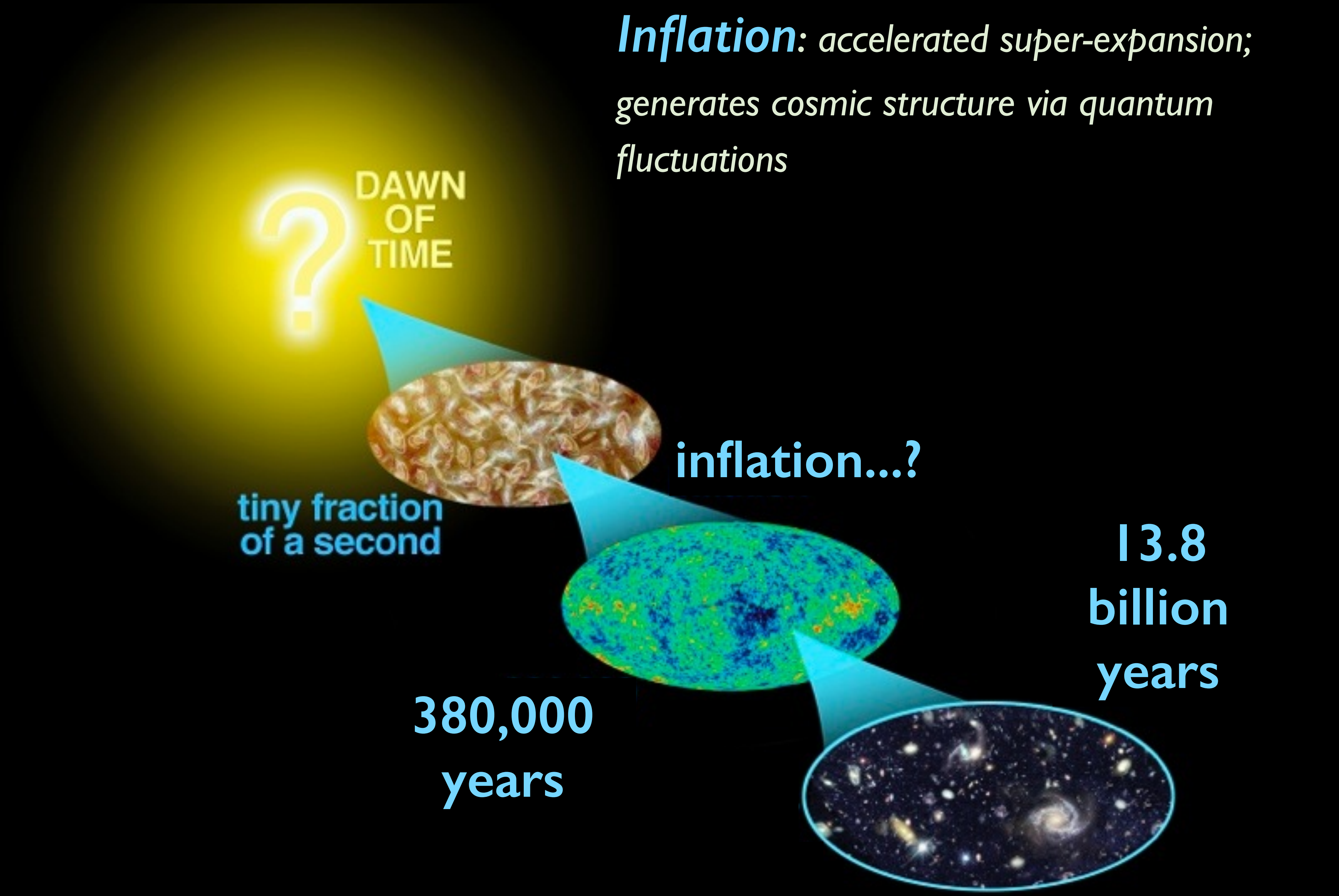
Cosmic Microwave Background
image: Planck



Large Scale Structure
image: SDSS

Short answer: **We don't know!**

***Inflation**: accelerated super-expansion; generates cosmic structure via quantum fluctuations*



Inflation

A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \qquad H \simeq \text{const}$$

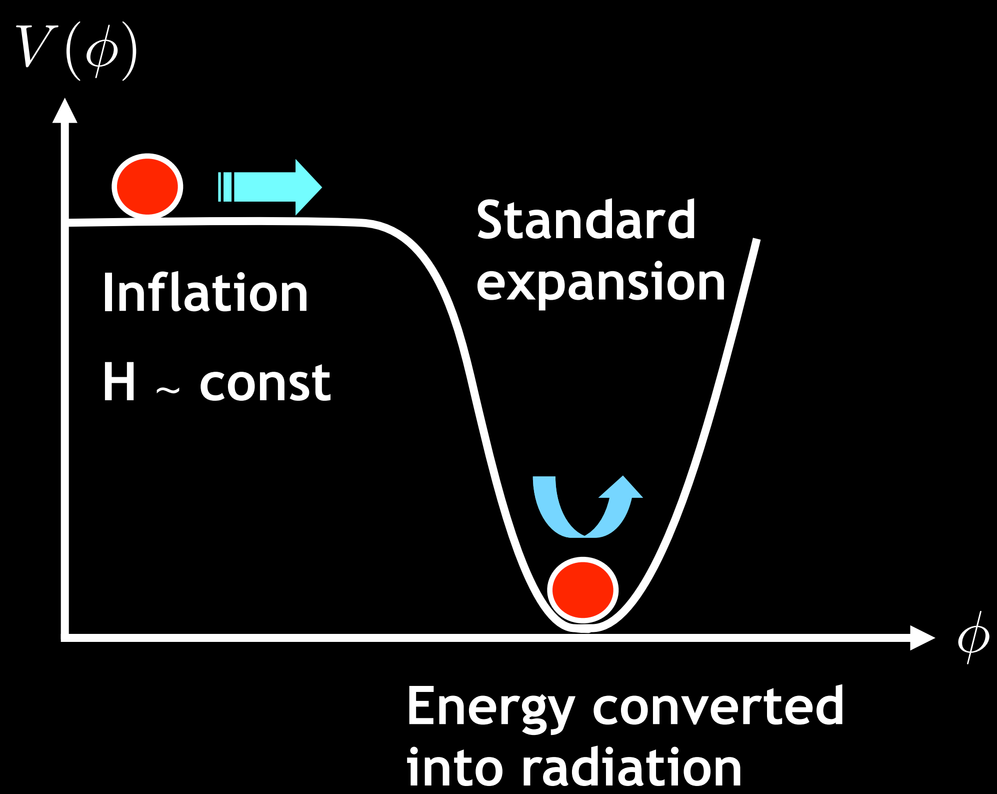
- Solves:
  - horizon problem
  - flatness problem
  - monopole problem

  i.e. explains why the Universe is so large, so flat, and so empty

- Predicts:
  - scalar fluctuations in the CMB temperature
    - nearly scale-invariant
    - approximately Gaussian
  - primordial tensor fluctuations (gravitational waves)

Inflation

Implemented as a slowly-rolling scalar field evolving in a potential:



$$\begin{aligned} H^2 &= \left(\frac{\dot{a}}{a}\right)^2 \\ &= \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right] \end{aligned}$$

expansion rate

density

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

friction

overdot = d/dt

Inflation

- Solves the flatness/horizon problems if the early universe inflates by factor ~10^{30}.
- Cosmological perturbations arise from quantum fluctuations, evolve classically.

$$P_\phi(k) \simeq \hbar \left(\frac{H}{2\pi}\right)^2$$

$$P_\mathcal{R} \simeq \frac{\hbar}{4\pi^2}\left(\frac{H^4}{\dot{\phi}^2}\right)^2_{k=aH}$$

scalar

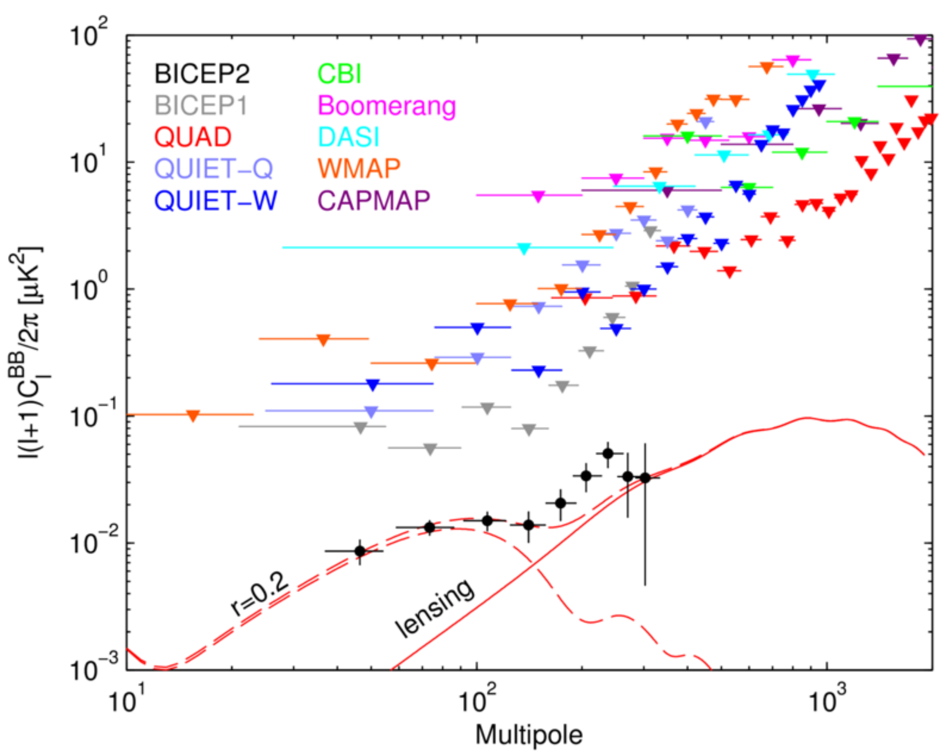
$$P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_\mathrm{Pl}}\right)^2_{k=aH}$$

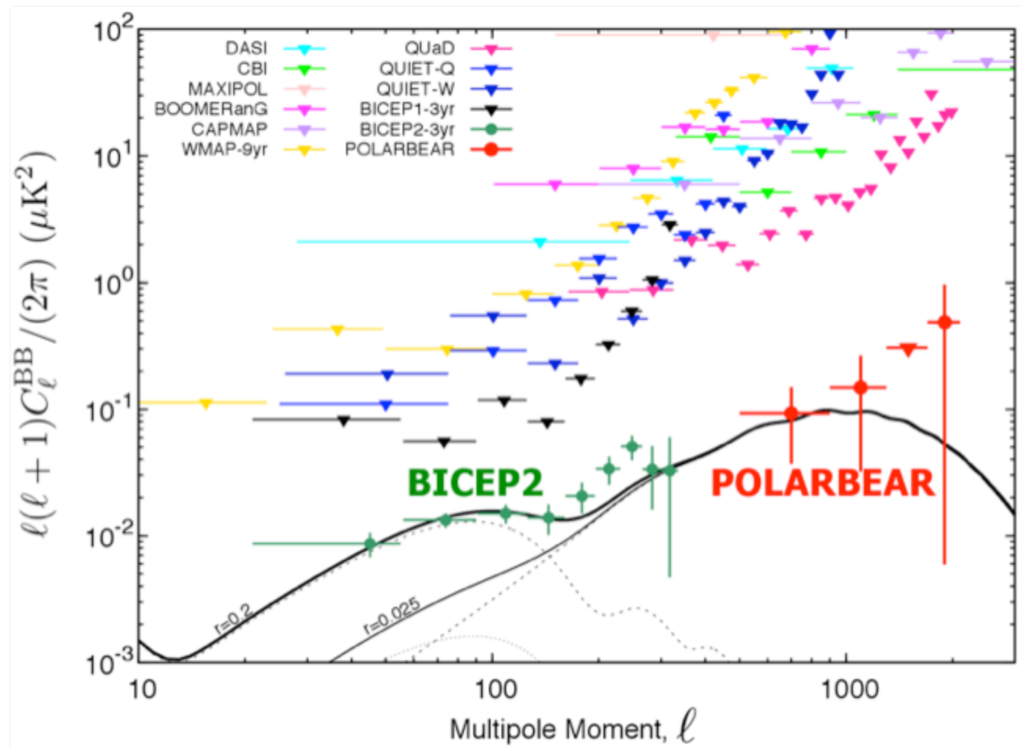
tensor

- Don't know the dynamics of inflation: parameterize weakly scale-dependent functions with a few numbers to pin down observationally.

$$P_\mathcal{R}(k) \simeq A_s \left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_h(k) \simeq A_t \left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_\mathcal{R}(k_0)}$$

Milestone: measurement of B-modes



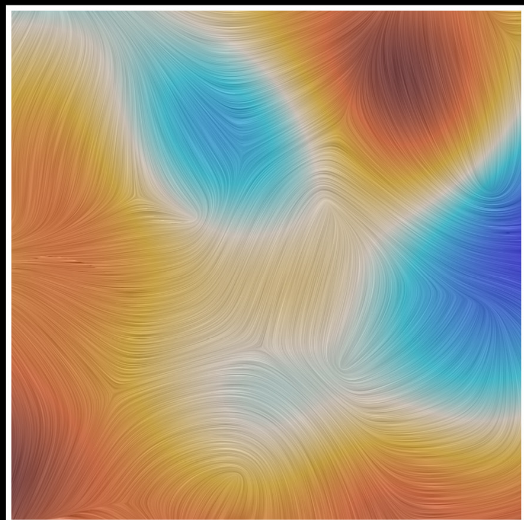


BICEP2 + PolarBear *BB* auto spectra and 95% upper limits from several previous experiments.

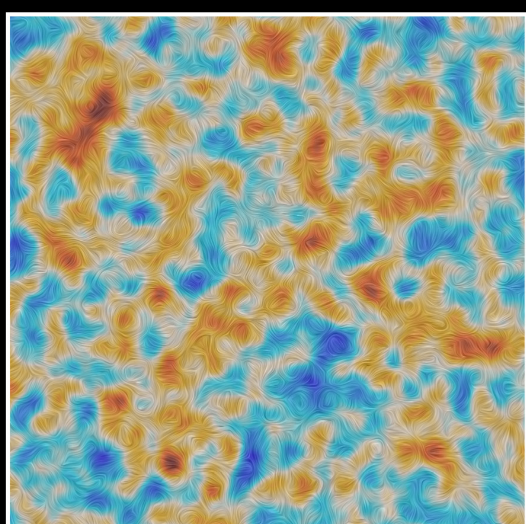
B2 errorbars include sample-variance from r=0.2

Figures: BICEP2

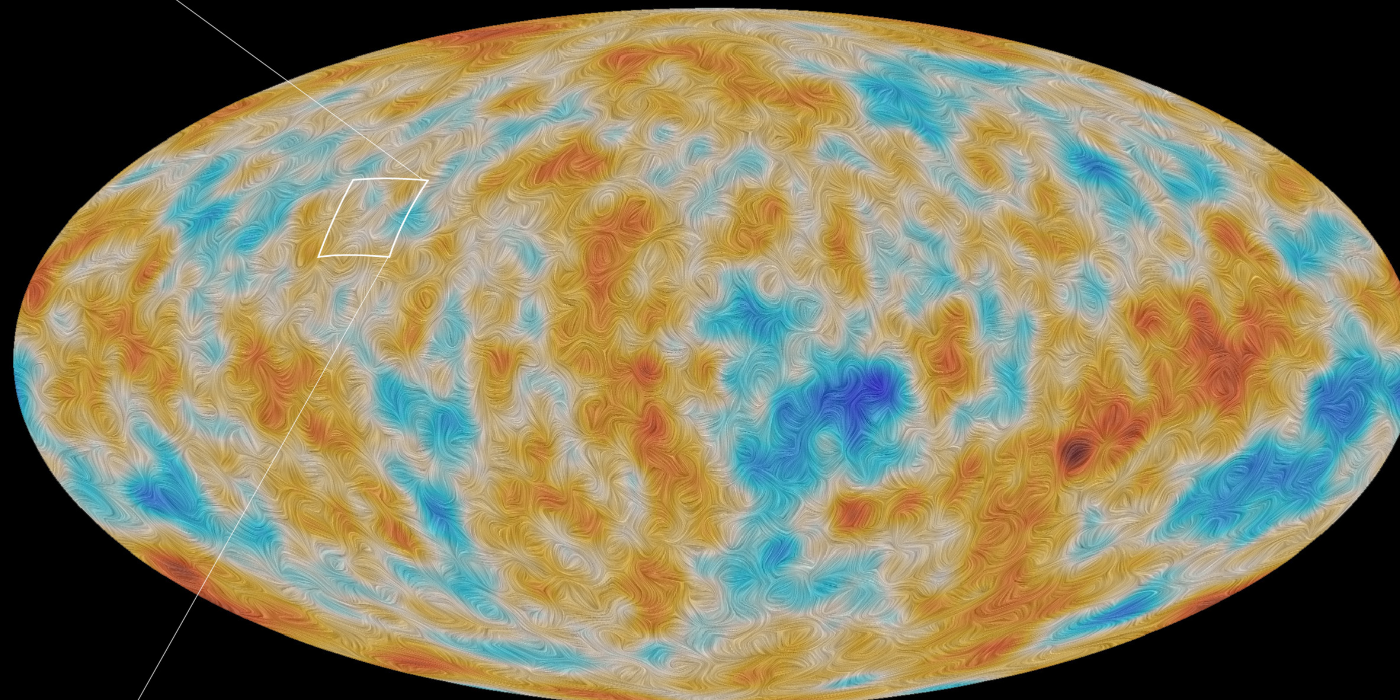
➔ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees

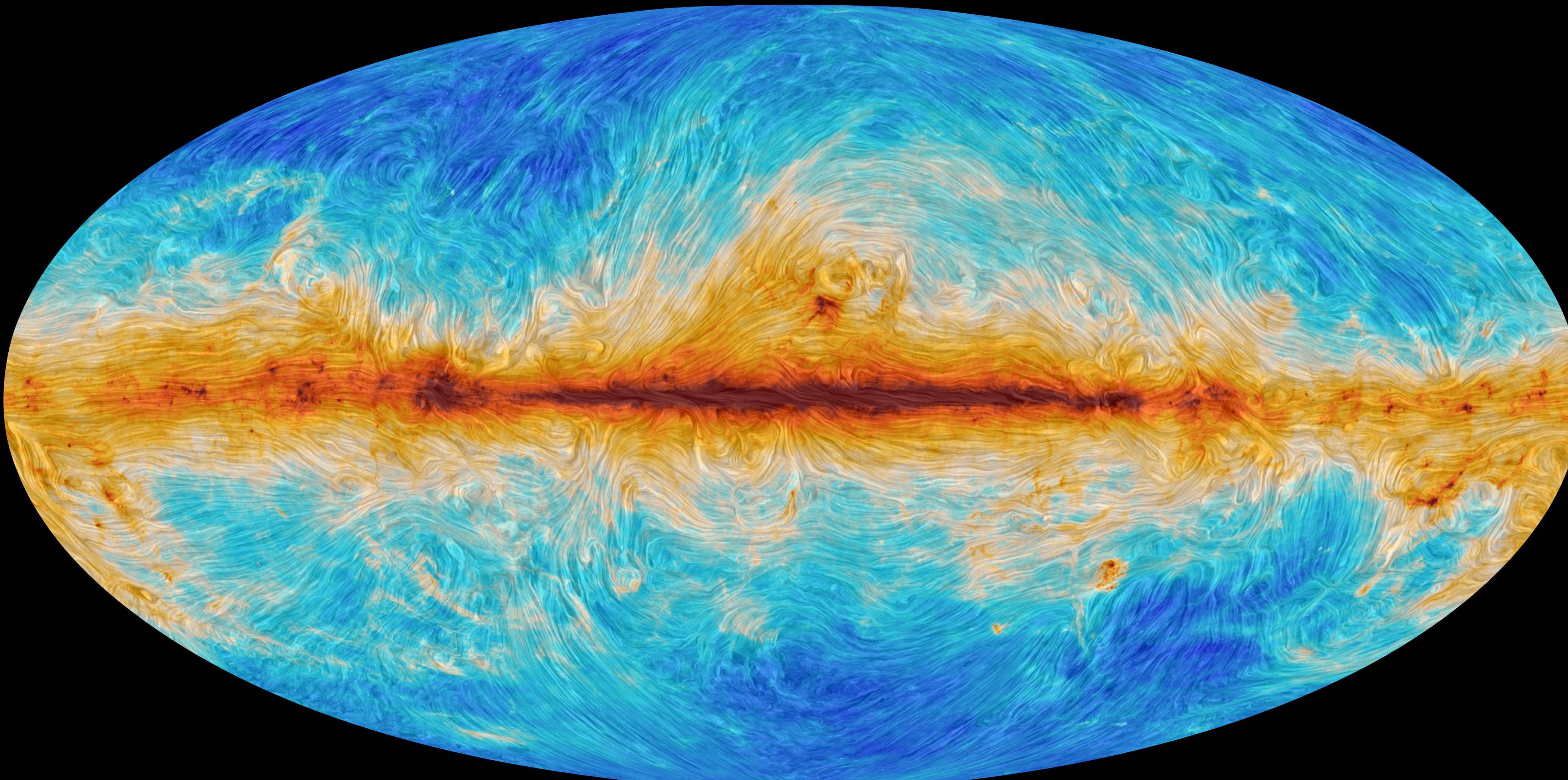


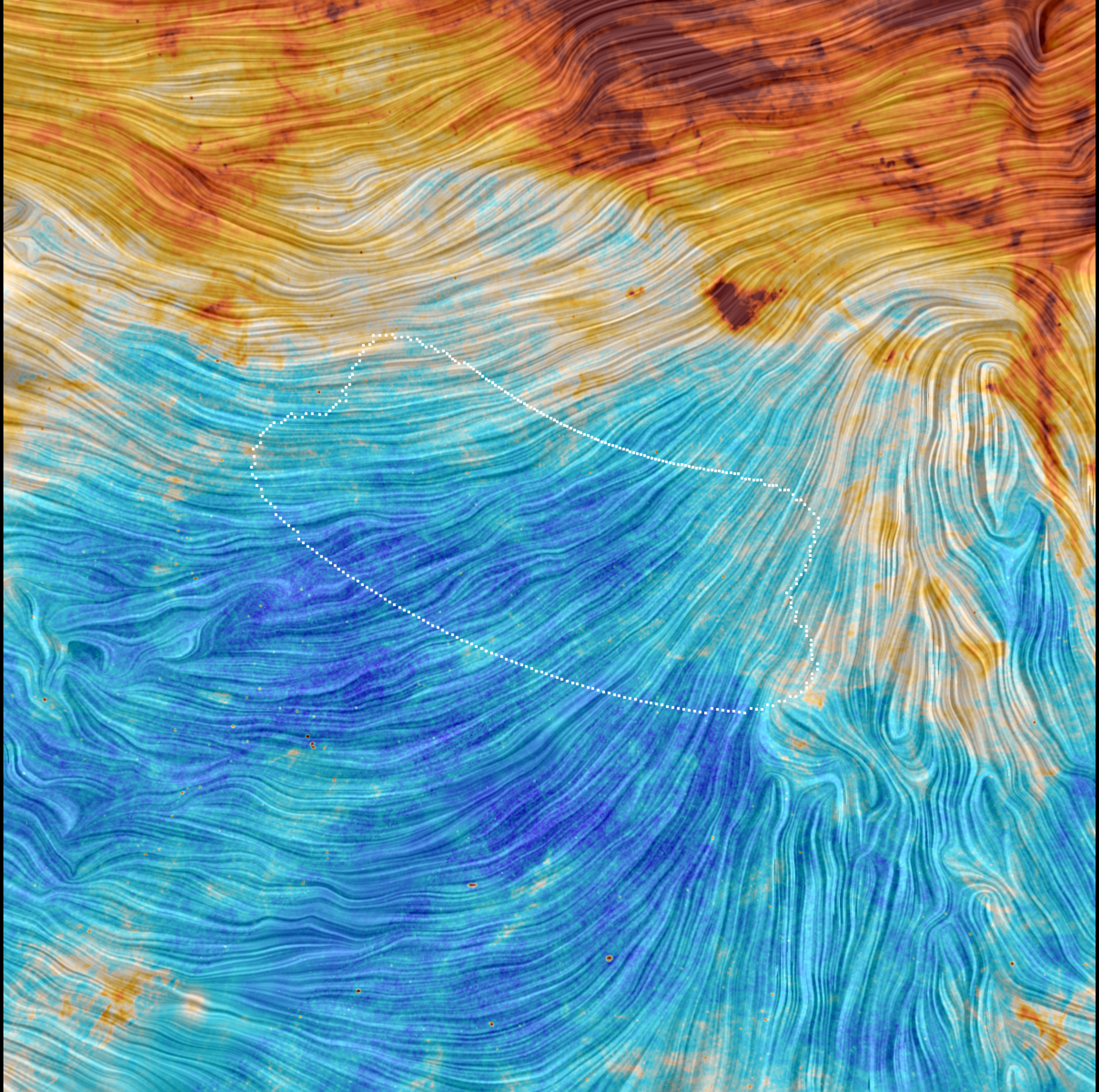
Filtered at 20 arcminutes



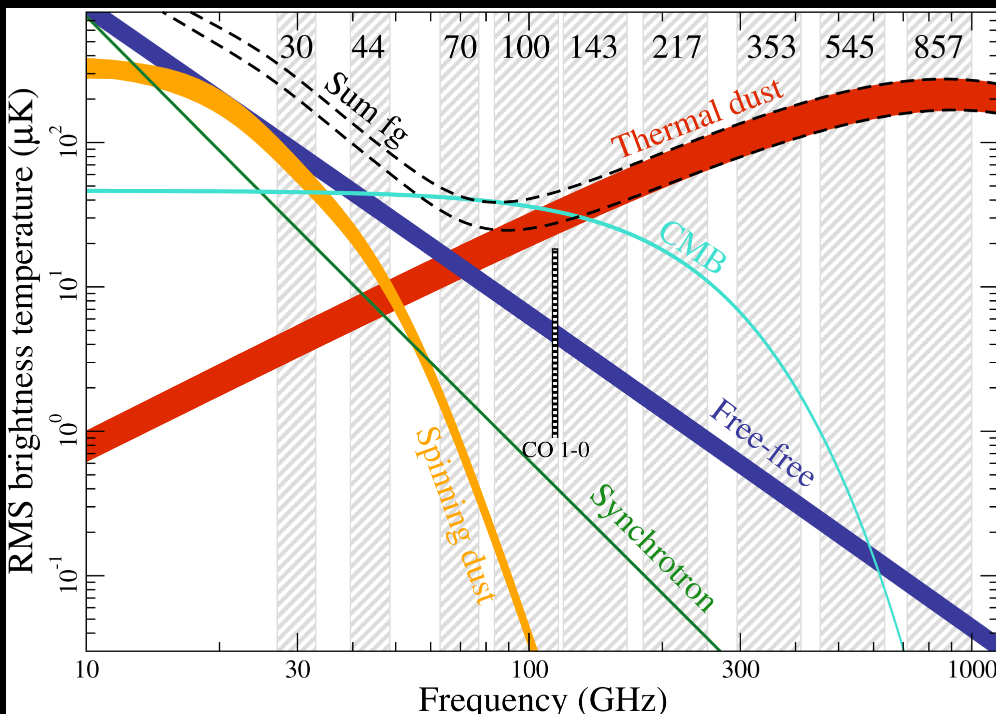
Full sky map
Filtered at 5 degrees

Credit: Planck Collaboration

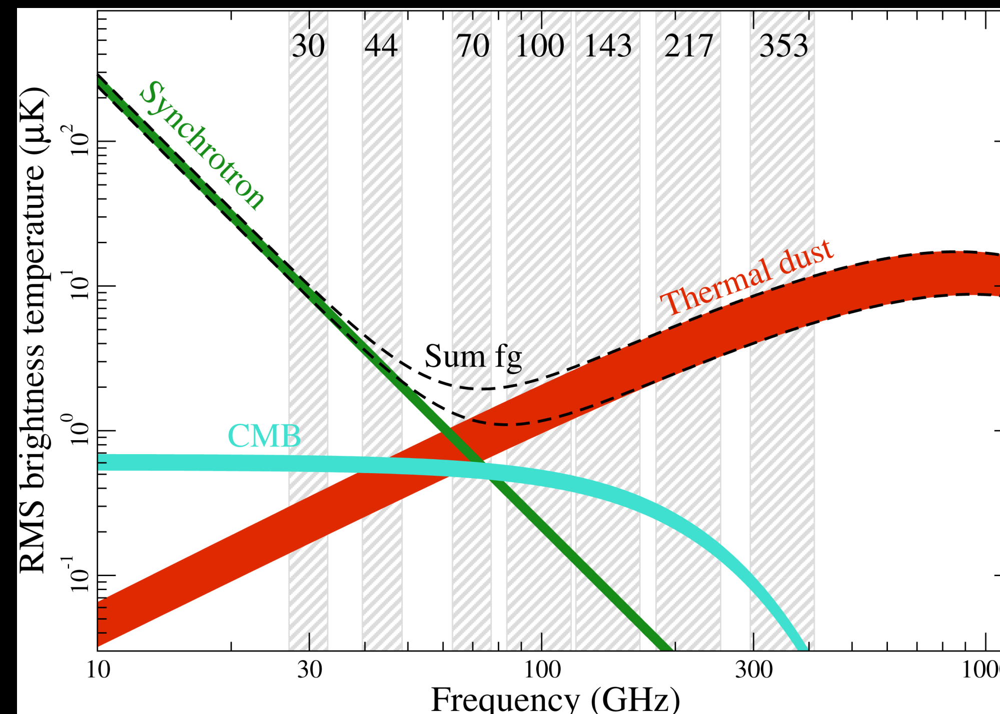




Frequency dependence of Galactic foregrounds



temperature

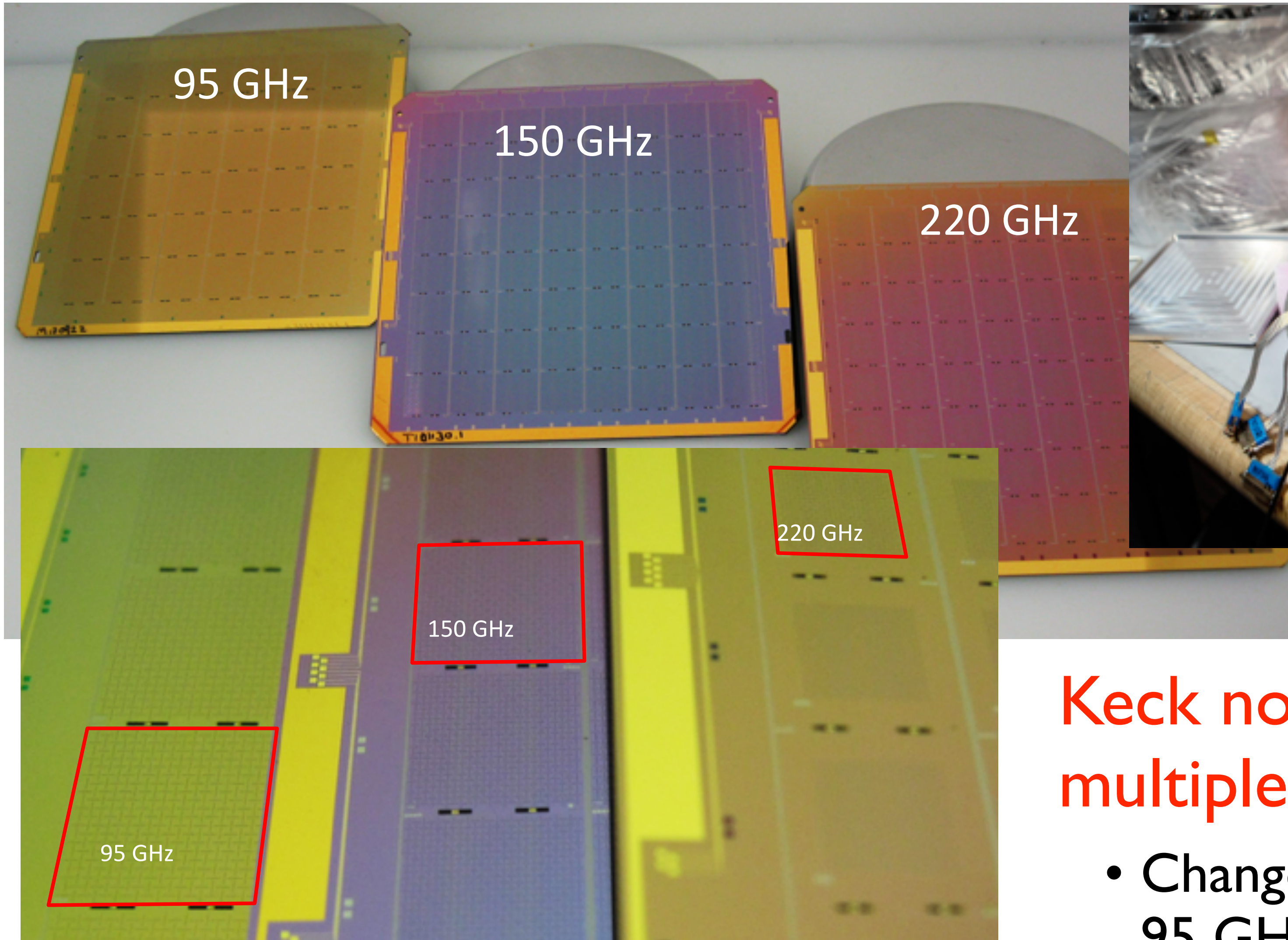


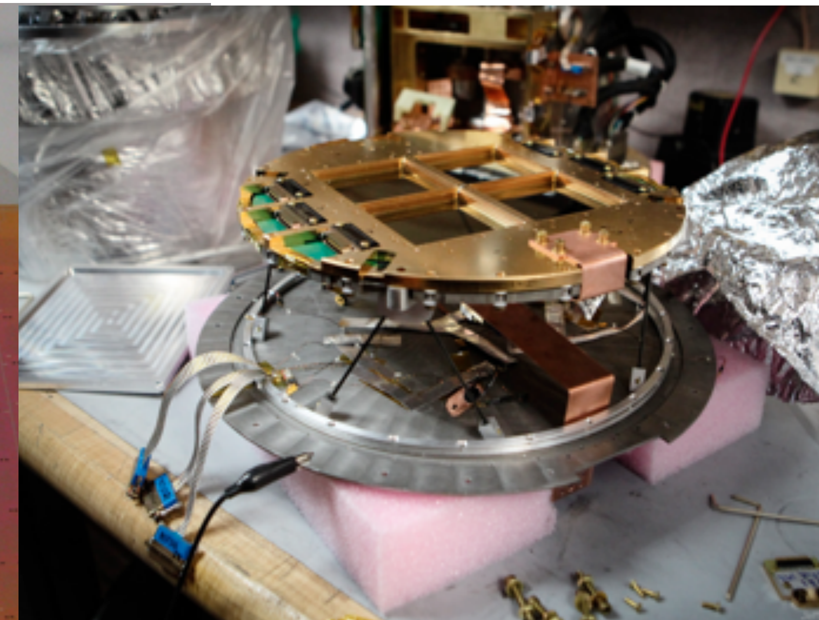
polarisation

BICEP2/Keck (2014):
150 GHz

Planck sensitive to dust
polarisation: 353 GHz

Keck 2014, 2015 multi-frequency upgrades



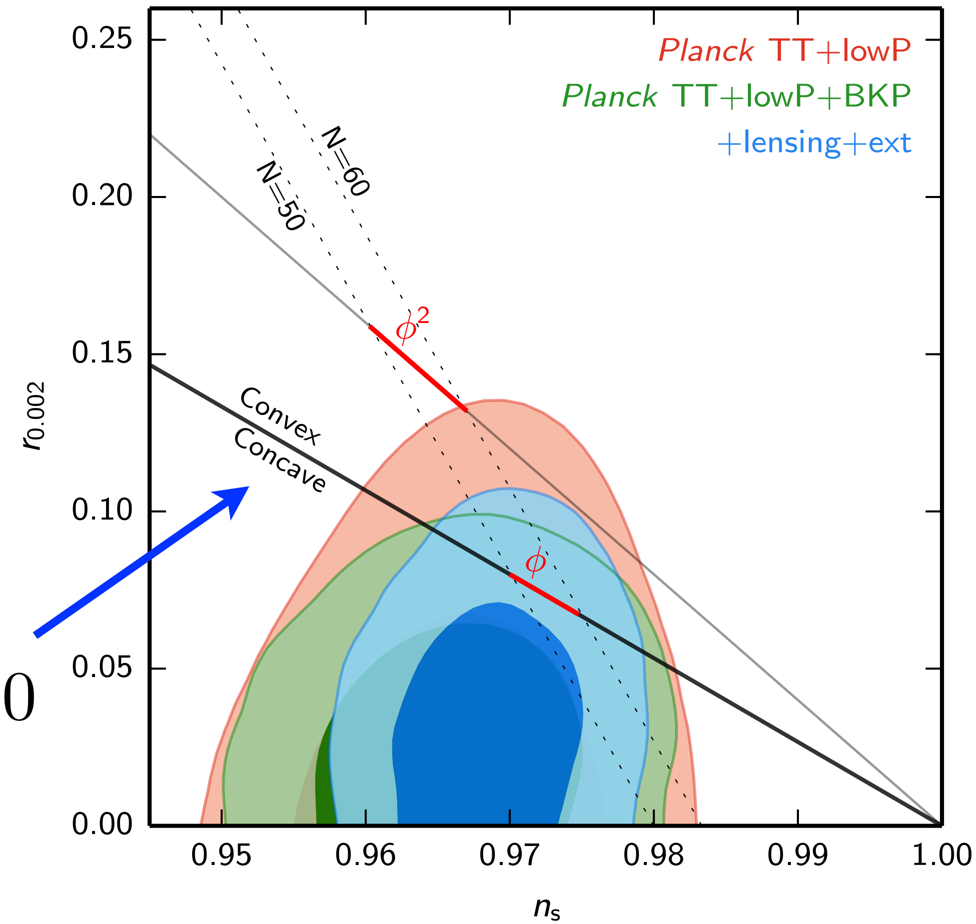


Keck now observing at multiple frequencies

- Changed 2 focal planes to 95 GHz in 2014
- Changed 2 focal planes to 220 GHz in 2015

From Zeeshan Ahmed on Wednesday….

Constraints on slow roll models: n_s-r parameterization



$V'' < 0$

BICEP/Keck+Planck (BKP) direct limit from BB:

$r_{0.05} < 0.12$ (95% CL)

Planck TT+lowP+BKP combined limit:

$r_{0.002} < 0.08$ (95% CL)

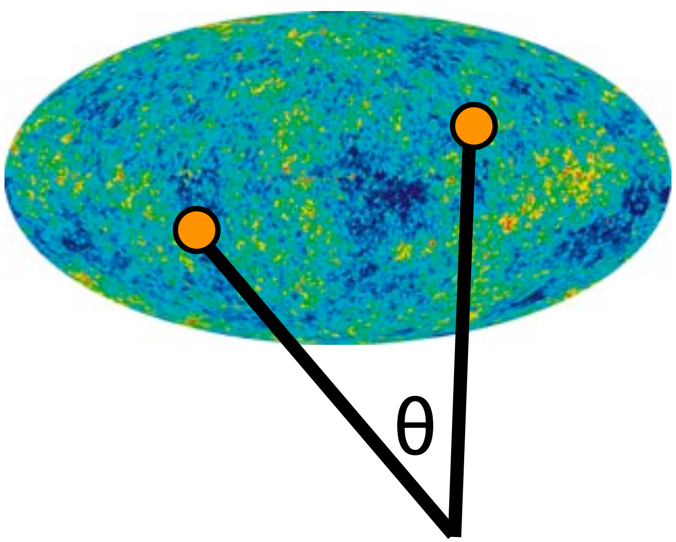
Planck TT+lowP:

$n_s = 0.9655 \pm 0.0062\,(5.6\sigma)$

$r_{0.002} < 0.11$ (95% CL)

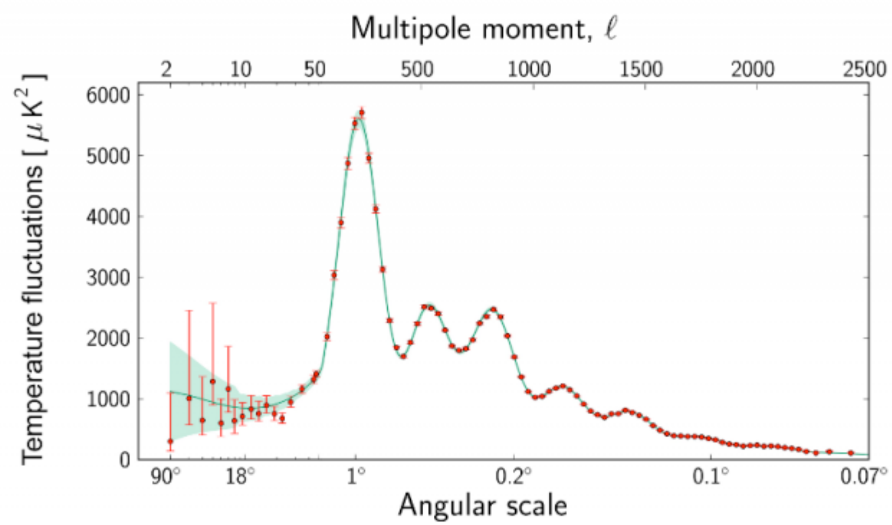
Non-Gaussianity: maximising physical information

Pre-Planck: constraints on inflation come mainly from **2-pt correlations**.
*Only captures all information if data are completely **Gaussian**.*



map
50 million pixels

radical data compression



angular power spectrum
2500 multipoles

Post-Planck: signals giving **physical** understanding are **non-Gaussian**.
Higher-order correlations can encode much information.

Primordial non-Gaussianity (PNG)

- Gaussian fluctuations: described by a simple sum of Fourier modes with random phases.

- Gaussian fluctuations fully described 2-pt correlation.

- NG is measured using higher order correlations (e.g. 3-pt function).

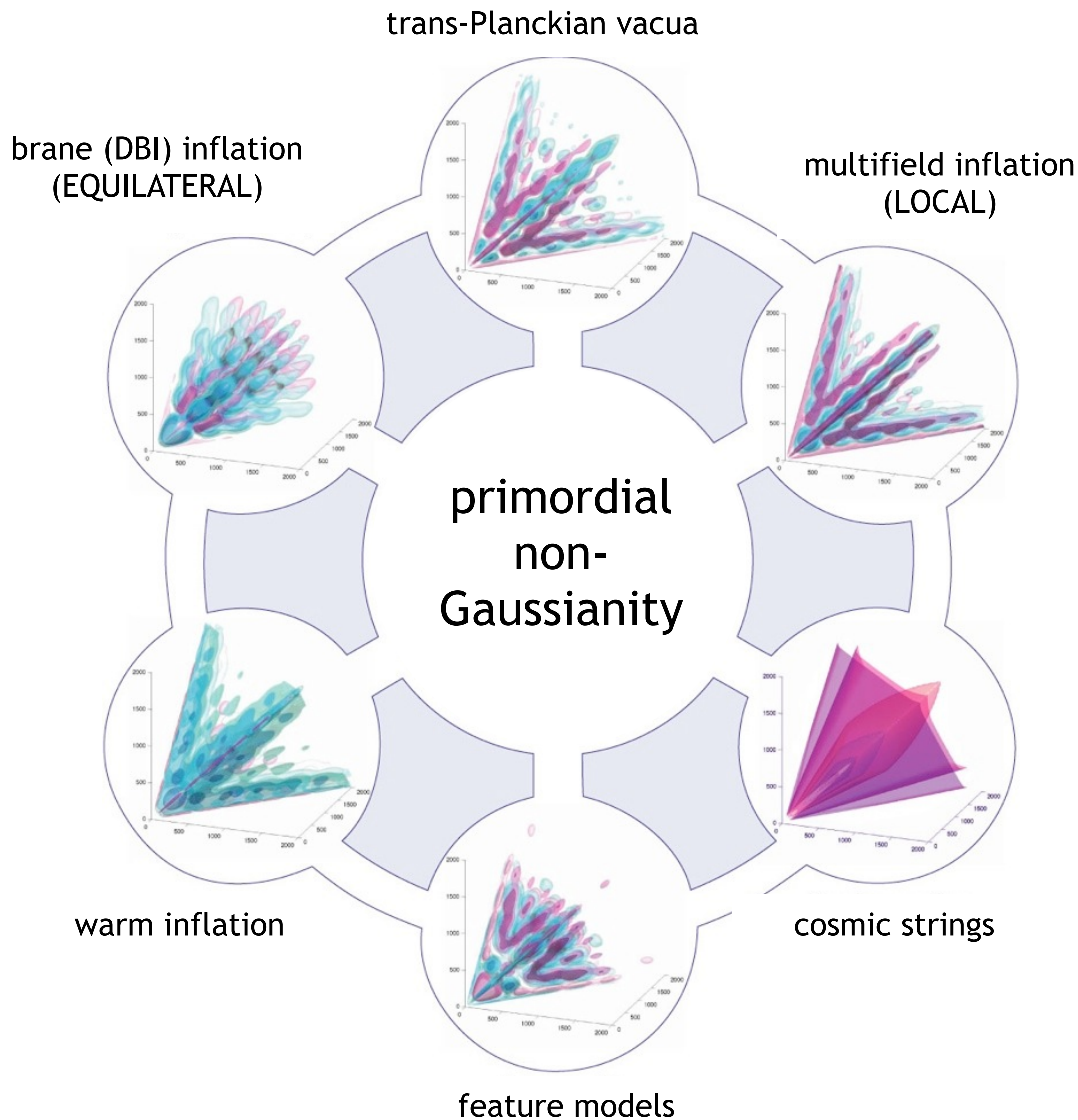
- A detection of f_{NL} >> 1 will immediately rule out the "textbook" picture of inflation.

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}^{\rm loc}\phi^2(\mathbf{x})$$

primordial potential

Gaussian field

Rich phenomenology



Different mechanisms lead to different 3-pt function "shapes", giving a fingerprint to track down the correct physics.

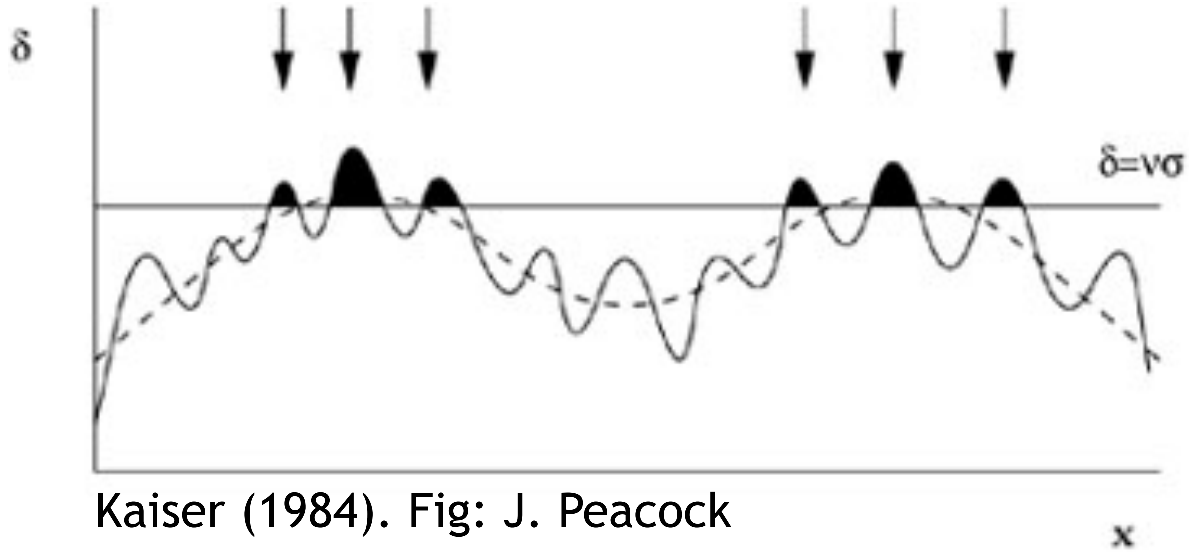
Figure: P. Shellard & J. Fergusson

Planck's PNG measurements

- Measured to 1 part in 10,000 (most precise cosmological measurement!)
- Bispectrum now a routine observable, like the spectral index
- Standard bispectrum configurations not detected by Planck; stringent constraints on local/equilateral/orthogonal etc shapes (68%)

Shape	ISW-lensing subtracted KSW
Local	2.5 ± 5.7
Equilateral	-16 ± 70
Orthogonal	-34 ± 33

Effect of PNG on large scale structure



Kaiser (1984). Fig: J. Peacock

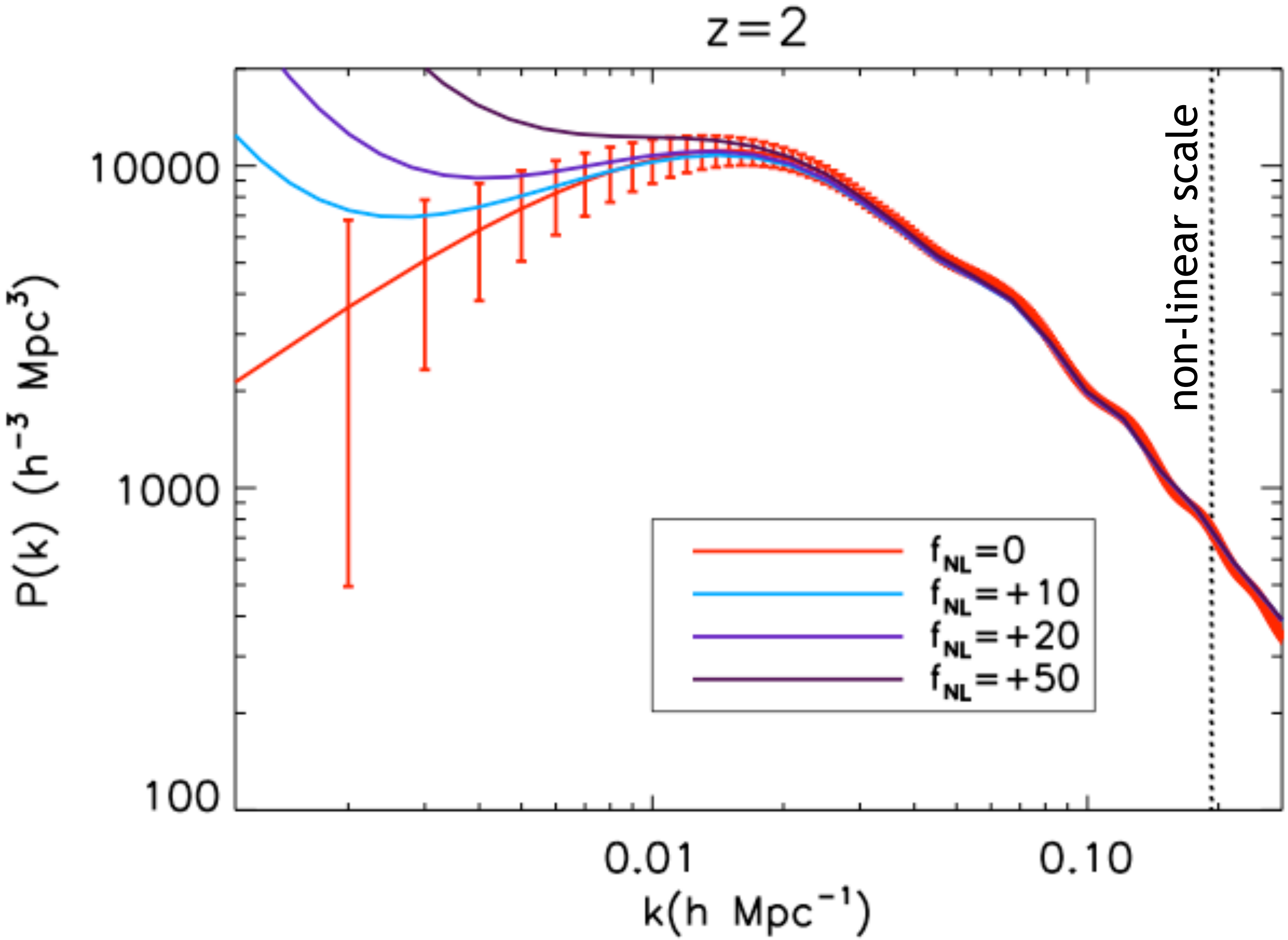
- **High-peak bias**: rare high-density fluctuation in large scale overdensity collapses sooner.

- Enhanced abundance of massive objects in overdense regions leads to enhanced clustering.

- Effect modified in NG case to lead to a scale dependent bias at large scales.

e.g. Dalal, Dore et al (2007), Matarrese & Verde (2008), Slosar et al (2008)

Effect on the halo power spectrum

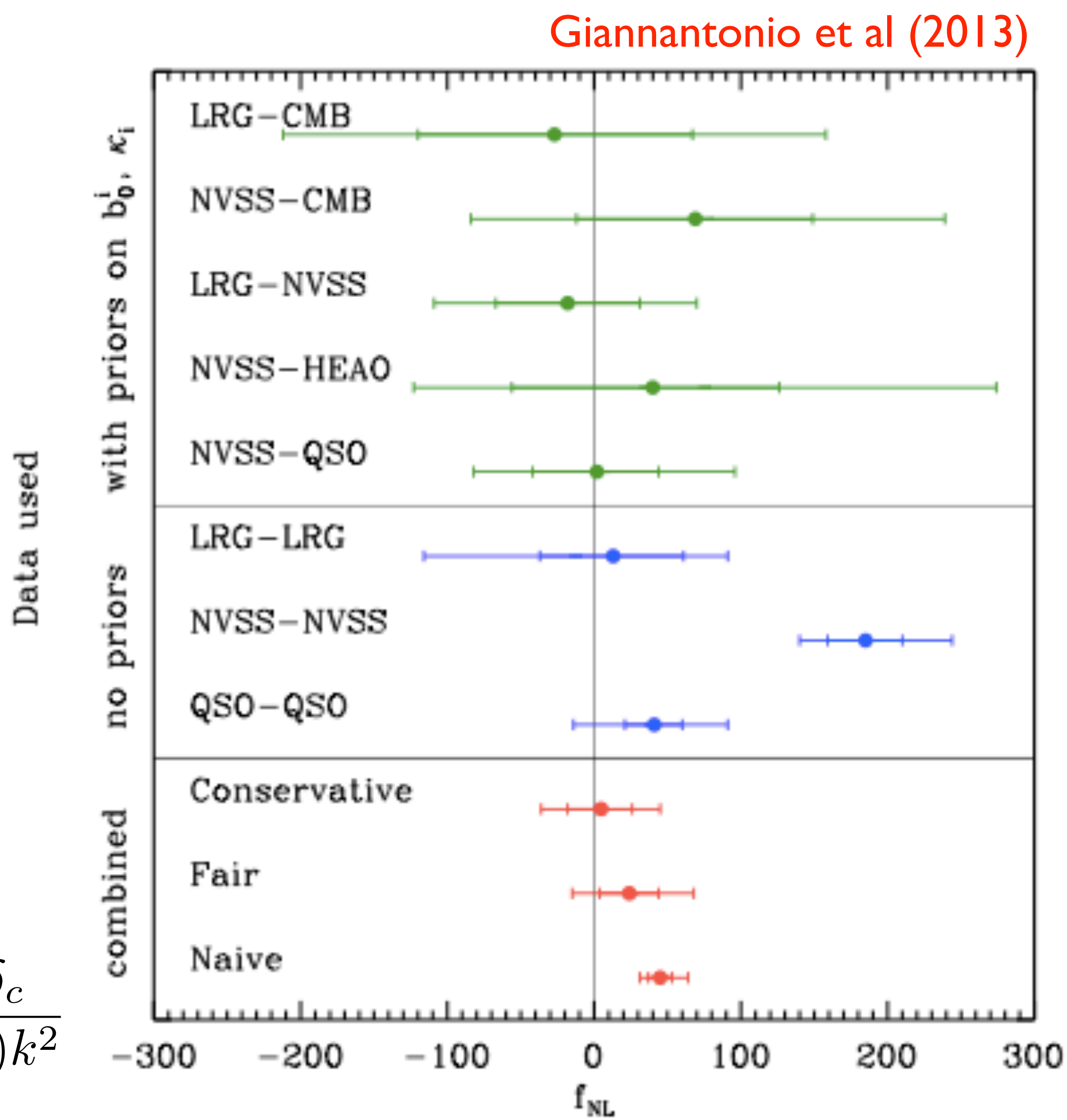


Power spectra at z=2 for a spectroscopic survey

Figure: HSLS white paper, HVP CMB/LSS Coordinator

The potential of quasar surveys for PNG

- **Quasars**: highly-biased LSS tracers, spanning large cosmological volumes

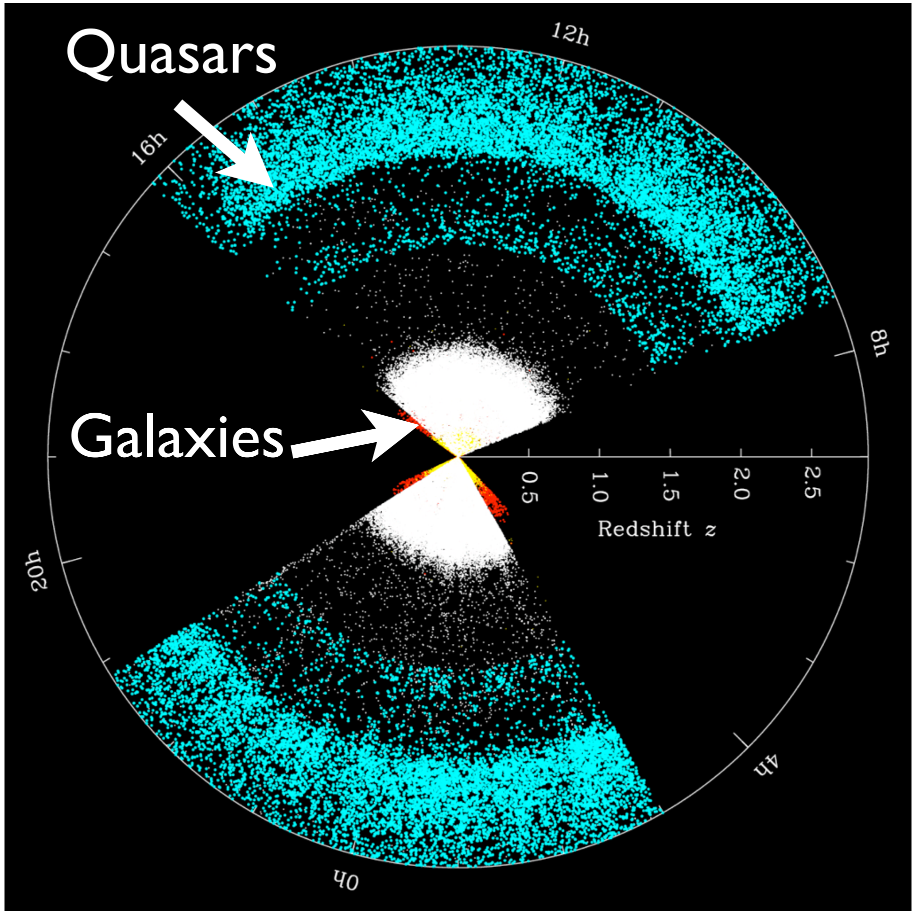


$$\Delta b(k,z) = f_{\rm NL}(b_g - 1)\frac{3\Omega_{\rm m}h_0^2\delta_c}{D(z)T(k)k^2}$$

PNG from blind mitigation of systematics in XDQSOz quasar sample

XDQSOz: 1.6 million QSO candidates from SDSS DR8 spanning z ~ 0.5-3.5 (800,000 QSOs after basic masking).

(Bovy et al.)

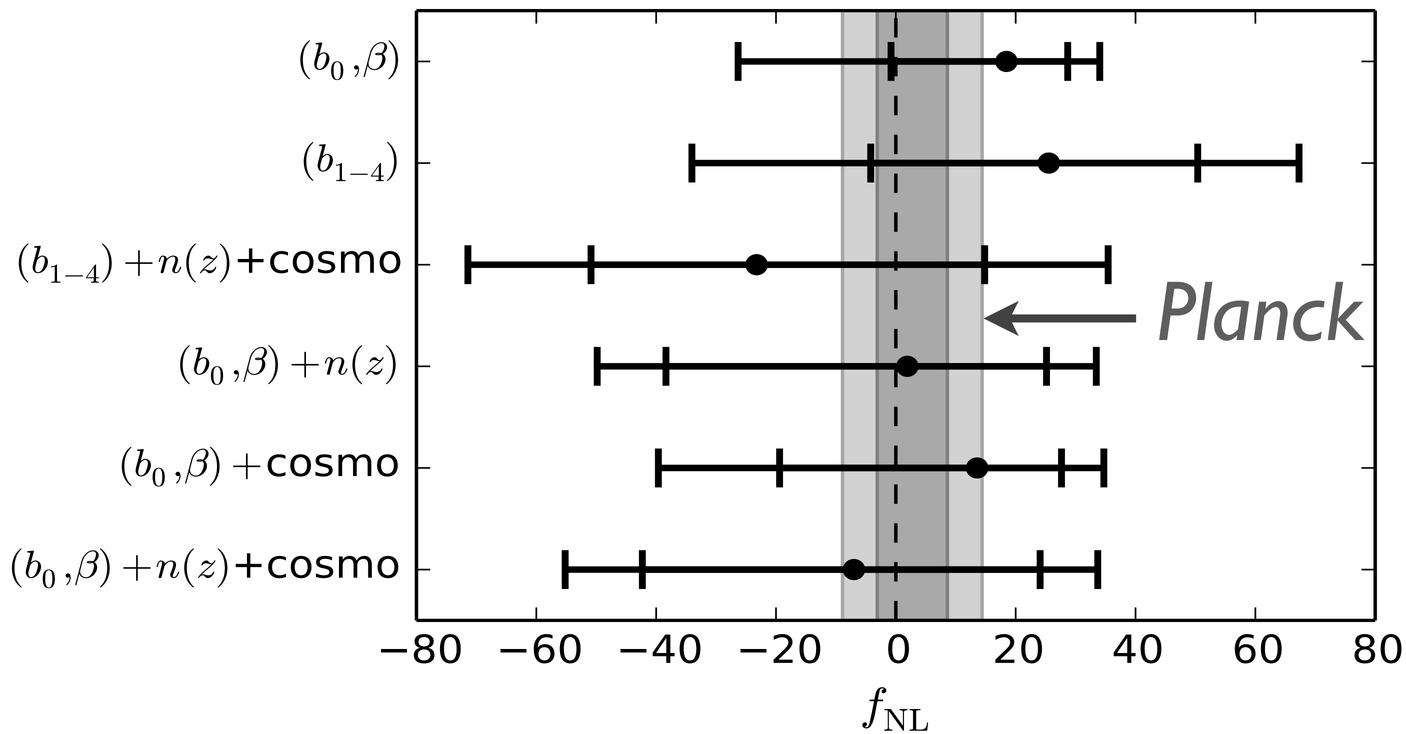


Boris Leistedt

Nina Roth

Leistedt & Peiris+ (MNRAS 2013, 2014), Leistedt, Peiris & Roth (PRL 2014)

Constraints on f_{NL}



$$-16 < f_{\rm NL} < 47 \ (2\sigma)$$

Fixed cosmology & n(z)

$$-49 < f_{\rm NL} < 31 \ (2\sigma)$$

Varying all parameters

- Comparable to WMAP9 from single LSS tracer(!)
- Robust to modelling & priors

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

Higher order terms

$$\Phi = \phi + f_{\rm NL}[\phi^2 - \langle\phi^2\rangle] + g_{\rm NL}[\phi^3 - 3\phi\langle\phi^2\rangle]$$

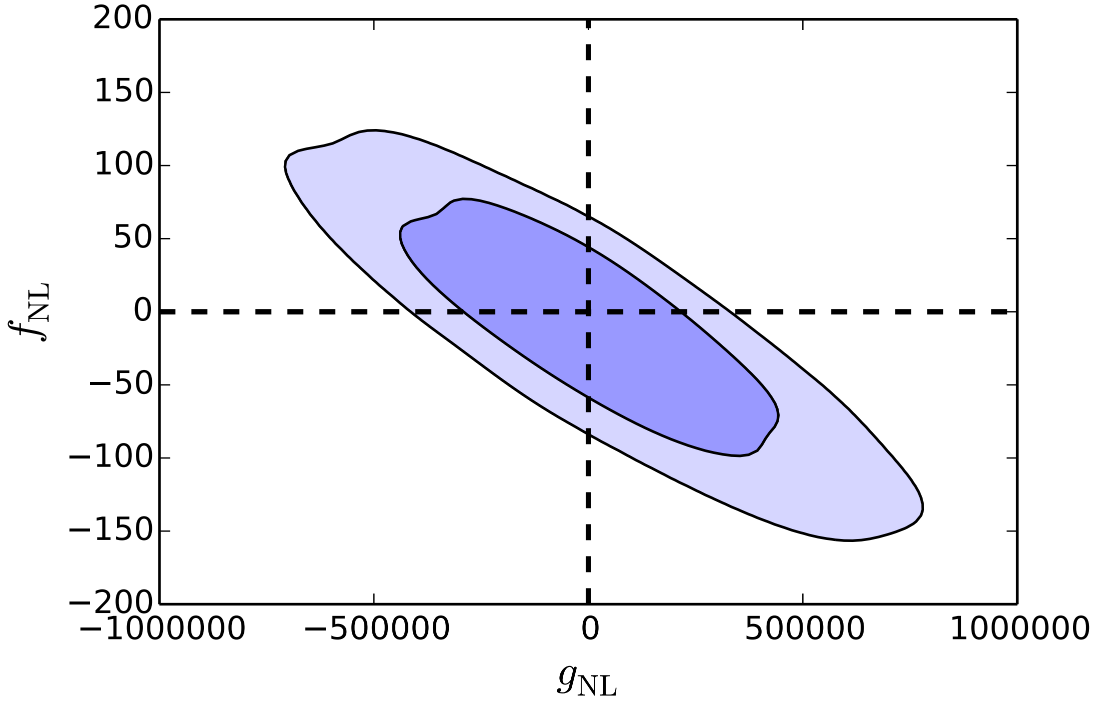
$|g_{NL}| < 10^6$ (CMB, LSS)

Degeneracy between f_{NL} and g_{NL} (Roth & Porciani 2012)

$$\Delta b \sim \frac{f_{\rm NL}\,\beta_f(M,z) + g_{\rm NL}\,\beta_g(M,z)}{k^2\,D(z)} \to k^{-2}$$

Smith, Ferraro & LoVerde (2012)

Constraints on g_{NL} ("kurtosis")



$$-2.7 < g_{\rm NL}/10^5 < 1.9 \ (2\sigma)$$

individually

$$-4.0 < g_{\rm NL}/10^5 < 4.9 \ (2\sigma)$$

joint with f_{NL}

- Comparable to Planck (2015) constraints on g_{NL}

$$-2.4 < g_{\rm NL}/10^5 < 0.6 \ (2\sigma)$$

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

LSST survey of 18,000 sq deg

(half the sky)

Large Synoptic Survey Telescope

- **LSST forecast:**
  - expected statistical $\sigma(f_{NL}) < 1$
  - systematic bias for a contamination model $f_{NL} \sim 30$,
  - correcting bias leads to conservative forecast $\sigma(f_{NL}) \sim 5$.

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

Inflation: score-card

A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \quad H \simeq \text{const}$$

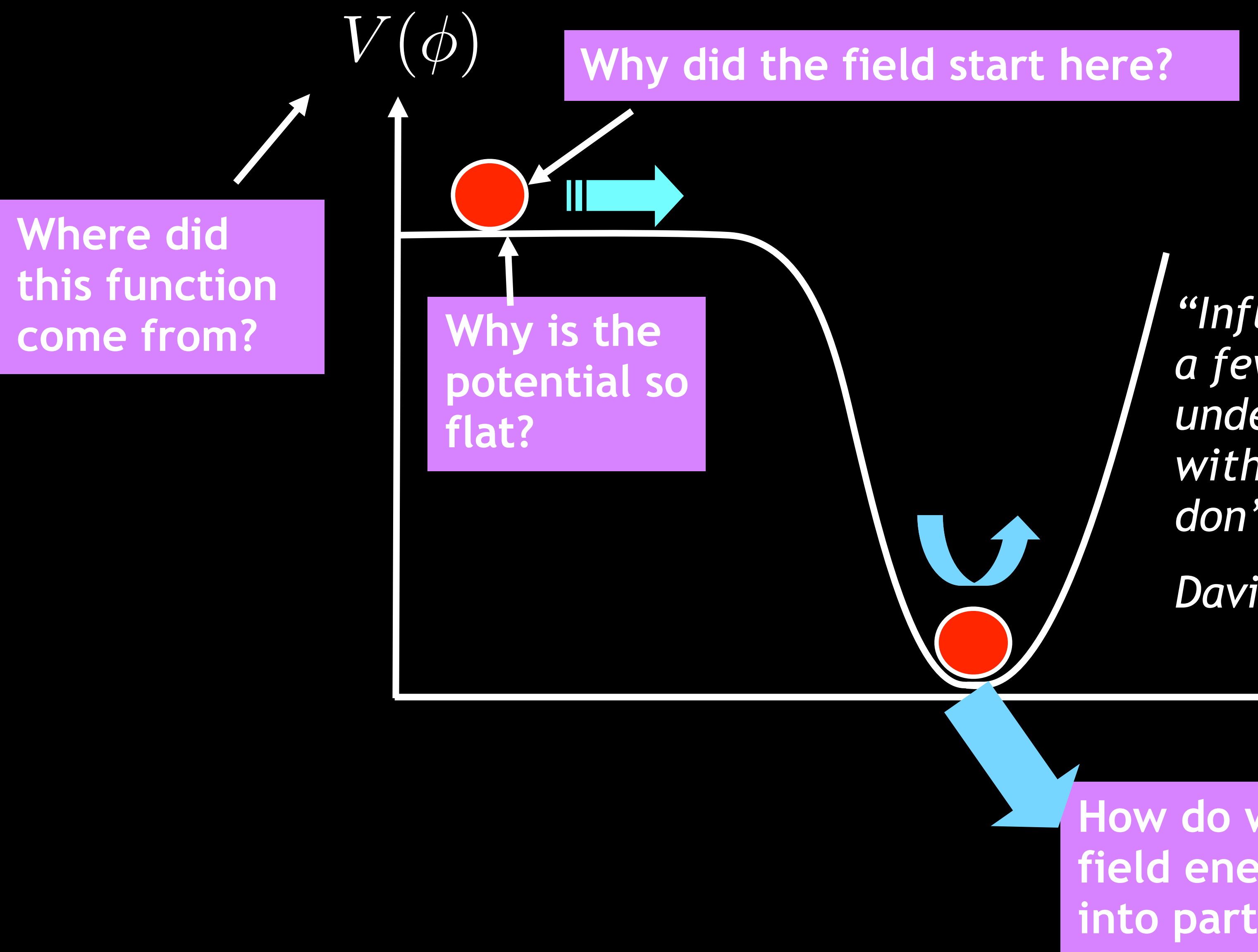
- Solves:
  - horizon problem
  - flatness problem (flatness tested at <1% level!)
  - monopole problem

  i.e. explains why the Universe is so large, so flat, and so empty

- Predicts:
  - scalar fluctuations in the CMB temperature
    - ✓ nearly but not exactly scale-invariant (>5σ!)
    - ✓ approximately Gaussian (at the 10^{-4} level!)

  ? primordial tensor fluctuations (gravitational waves)

What is the physics of inflation?



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

Towards a fundamental description of inflation

Toy picture of inflation: only a few dials we can turn. But if we hook it up to the high energy Franken-machine, there are numerous possibilities.

Figure: Layne Price

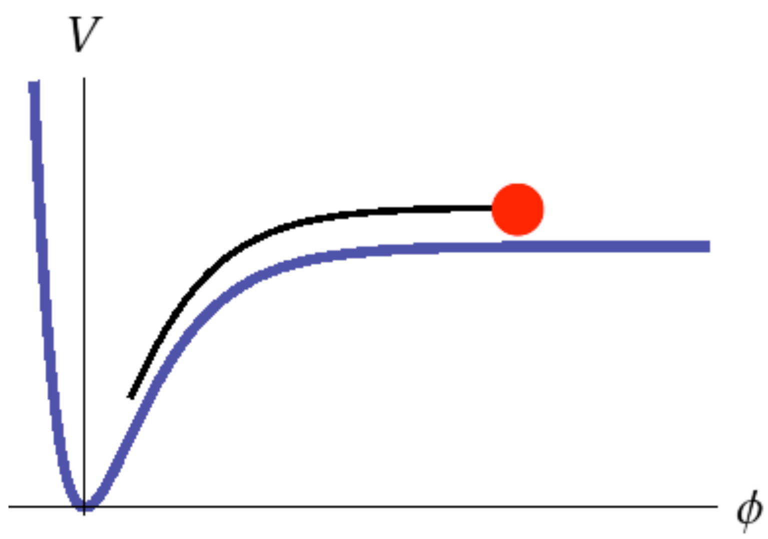
One field is simple; is it "natural"?

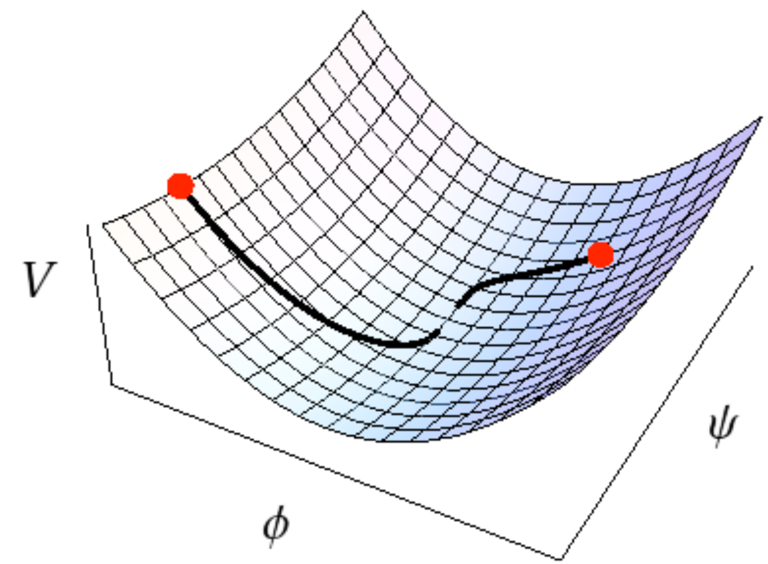
- Field content of particle physics models often a choice
  -e.g. construction of the Standard Model (chosen to match observations)

- Include a scalar field singlet as the "inflaton sector"
  -Must be coupled to other fields (for reheating)
  -But weakly coupled or tuned (to protect $V(\varphi)$ from loop corrections)
  -Often no physical motivation, beyond the need for inflation
  -No "guidance" on $V(\varphi)$

- Many fields are ubiquitous in "theories of everything"
  -e.g. string theory or supersymmetry - 100s of fields
  -Assisted inflation, N-flation, Random Matrix Theory approach, Inflation in a random landscape....

Numerical Study with N=100 fields



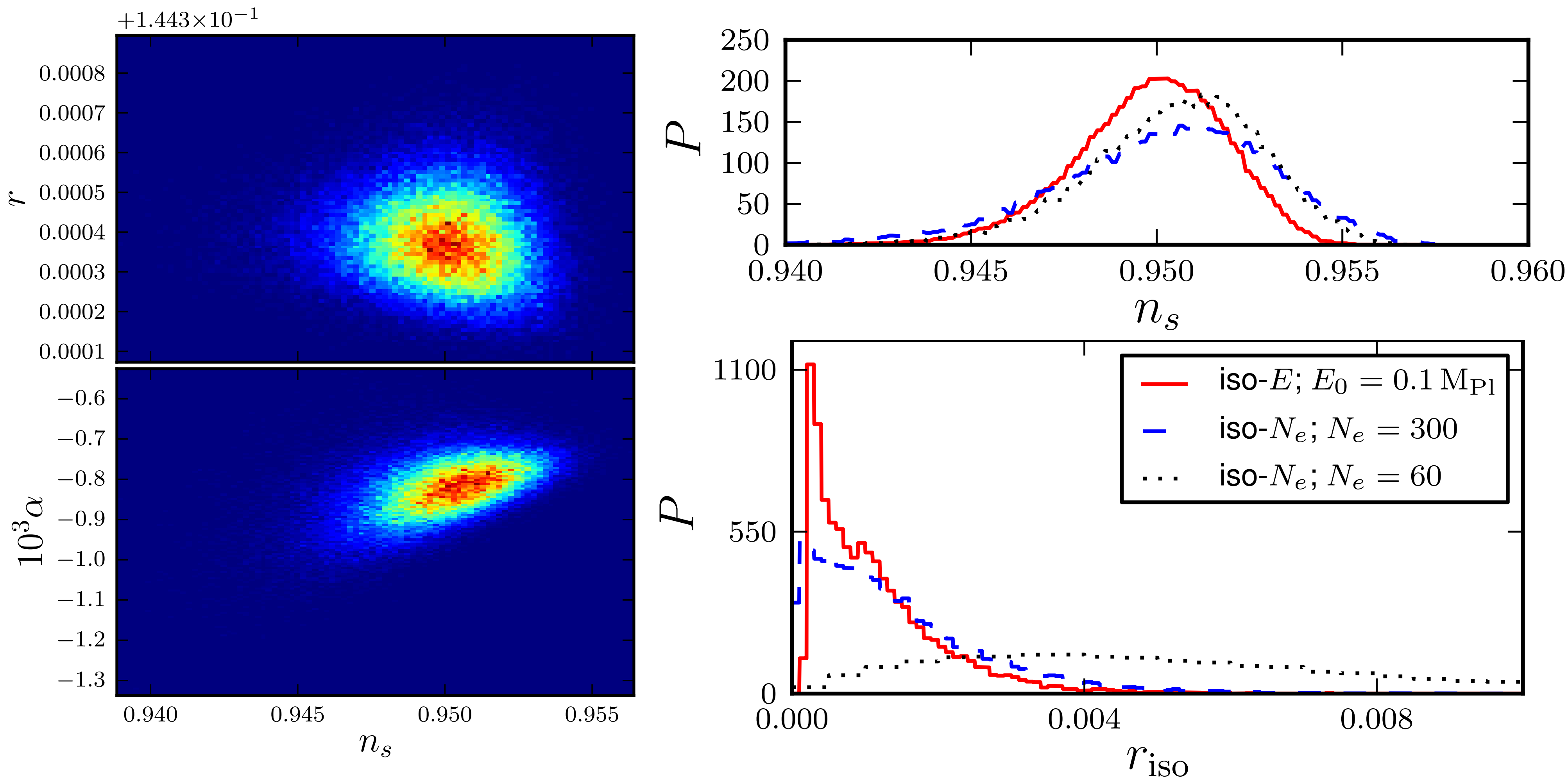


- Qualitatively different from single field behaviour
  - *-No unique downhill path, complex potentials*
  - *-Density & entropy perturbations*
  - *-Perturbations evolve outside horizon*
  - *-Sensitive to initial conditions*
  - *-Perturbation equations of motion: computational complexity ~ N^2*

Bayes' theorem: competing models succeed or fail based on their predictivity, not their simplicity

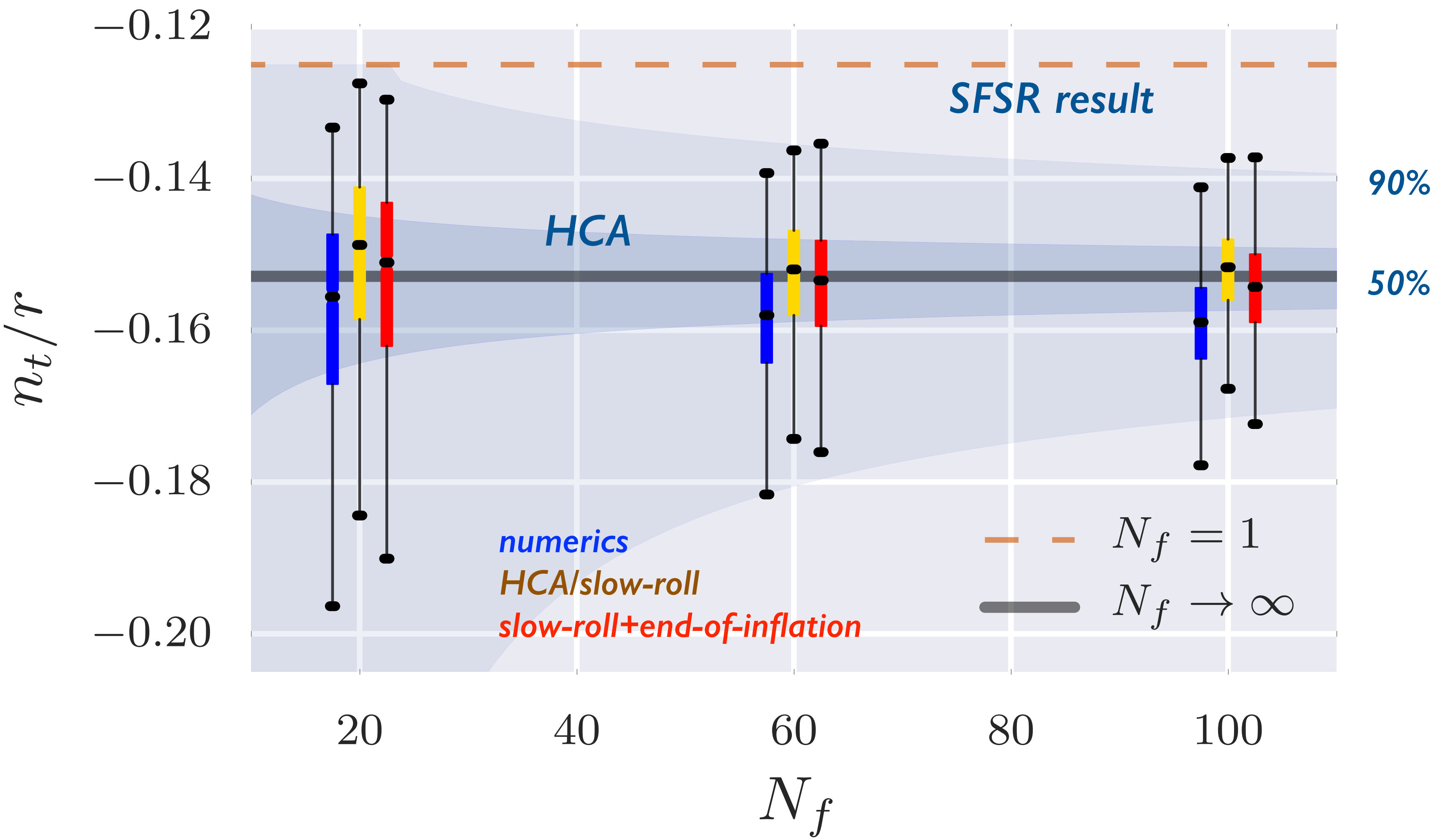
Assessing predictivity of many-field inflation

- Three classes of initial conditions
  - *fixed energy surface; fixed # e-folds before end of inflation; slow-roll velocities from uniform distribution of initial VEVs.*
- 100-fields: simplicity arising from complexity?



Easther, Frazer, Peiris, Price, (arxiv:1312.4035, PRL 2014)

Multifield inflation & consistency condition



- p=2, uniform distribution on λ_i, marginalising over initial conditions.

- Recent optimism re: testing consistency condition (Smith, HVP, Cooray 2006)

  Caligiuri & Kosowsky / Dodelson / Boyle et al. (2014)

Price, Peiris, Frazer, Easther (arxiv:1409.2498, PRL 2015)

Experimental landscape in 2025

- ***CMB:*** *ground-based (BICEP++,ACTpol, SPT3G, PolarBear,...), balloon-borne (EBEX, SPIDER,...), mission proposal for 4th generation satellite (CMBPol, EPIC, CoRE, LiteBird...), spectroscopy (PIXIE, PRISM proposal...)*

- ***LSS:*** *photometric (DES, PanSTARRS, LSST...), spectroscopic (HSC, HETDEX, DESI,...), space-based (Euclid,WFIRST...)*

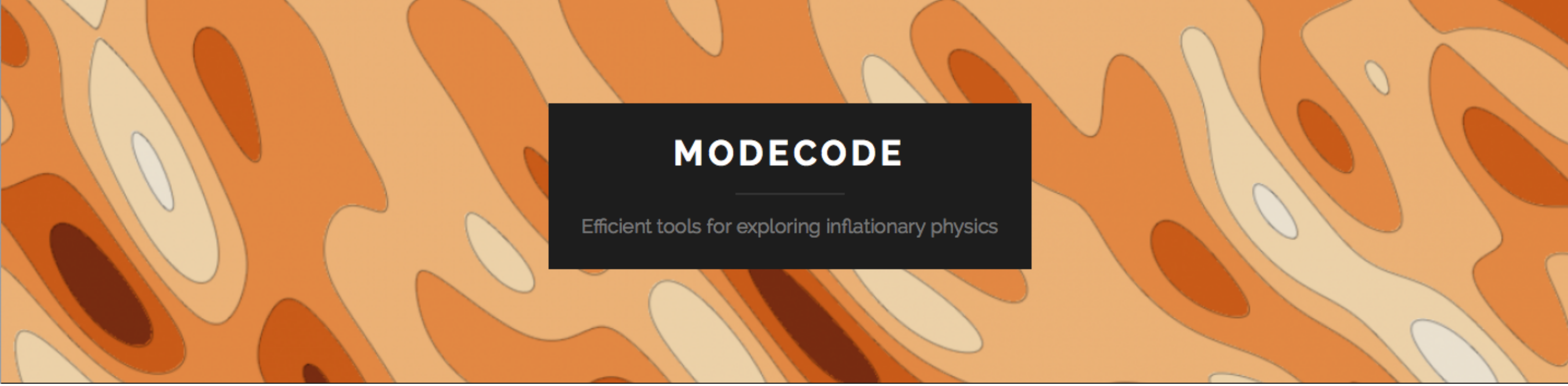
- ***21cm:*** *SKA and pathfinders...*

- ***GW:*** *Advanced LIGO, NGO pathfinder...*

Science goals tie early/evolved universe together; multi-goal; Cross-talk of data-types and probes critical for success

What observables should we invest in?

- ***Tensor modes:*** *small-field / large field, tells us about symmetries*
- ***Consistency condition:*** *departures from single-field inflation*
- ***NG:*** *non-null signal exists at some level; broken-scale-invariance shapes poorly explored*
- ***Flatness:*** *open universe at 10^{-4} level interesting for eternal inflation; closed universe problematic for inflation*
- ***Running / broken scale-invariance:*** *non-minimal physics*
- ***Isocurvature:*** *distinguish between single and multifield*
- ***μ-distortions:*** *more e-folds, decaying fields, reheating...?*
- ***Magnetic fields:*** *substantial fields detected at high-z and in voids*
- ***Cosmic defects:*** *end of inflation....*



www.modecode.org

ModeChord
MultiModeCode

Price, Frazer, Xu, Peiris, Easther, JCAP, 03, 005 (2015)


EarlyUniverse@UCL
www.earlyuniverse.org

Extra Slides

Multifield inflation & consistency condition

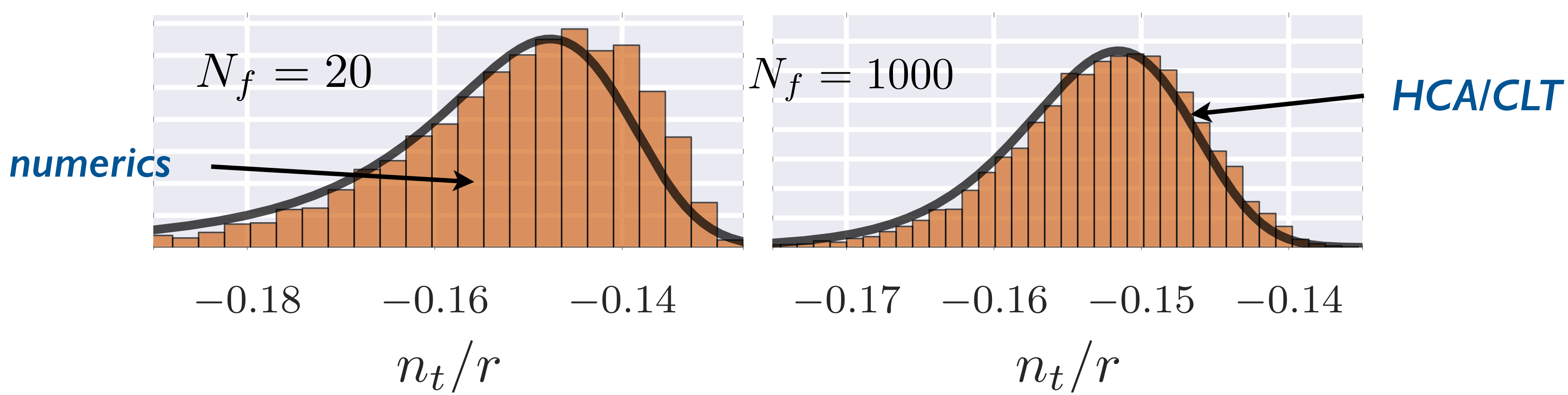
- Unambiguous prediction of single field slow roll (SFSR) models:

$$r = -8\, n_t$$

- Simplest generalisation of large-field SFSR: Nf-monomial models.

$$V = \frac{1}{p}\sum_{i=1}^{N_f} \lambda_i |\phi_i|^p$$

- **Result:** For Nf $\gg$ 1, n_t/r Gaussian-distributed, independent of Nf and p, depends only on first three moments (1,2,4) of P(λ).



Price, Peiris, Frazer, Easther (arxiv:1409.2498, PRL 2015)

Occam's razor vs Hierarchical Bayes

- **ORA**: simplest possible model capable of demonstrating desired behaviour. Lagrangian ~ single scalar field + couple of free parameters. Model exploration: understanding how model predictions change as parameters varied.

- **BHA**: describing models which are not simple (hundreds of scalar fields and hundreds/thousands of parameters). Draws parameters from one, or a few prior distributions. Parameters of the prior distribution are hyperparameters. Even in complicated models, only a few hyperparameters.

- Task of understanding how predictions for observables change with model parameters (ORA) is replaced by understanding how the probability distribution of observables change as hyperparameters are varied (BHA).

WiP: BHA for Nf-quadratic inflation

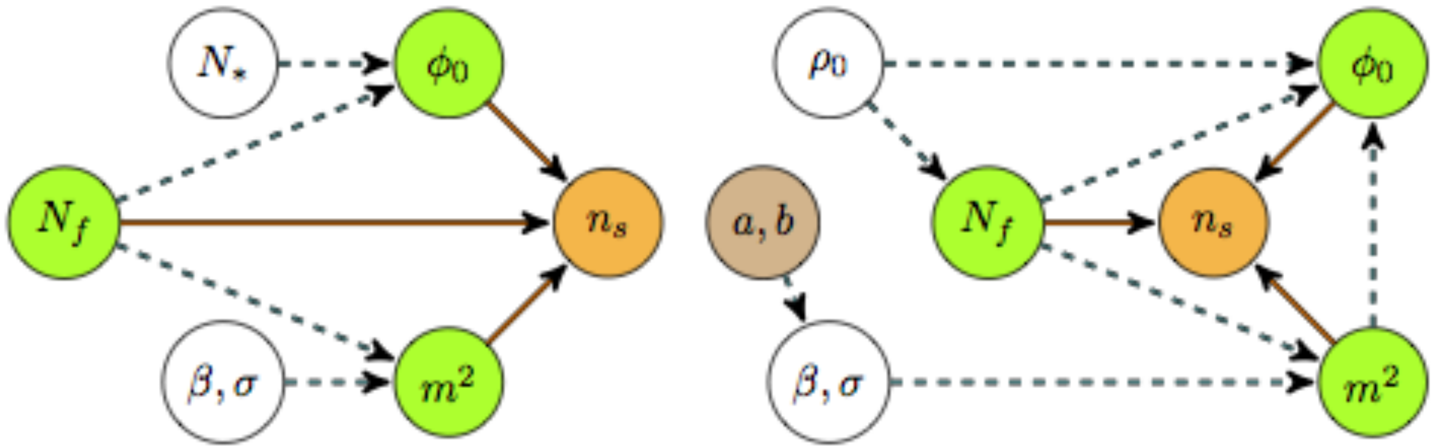
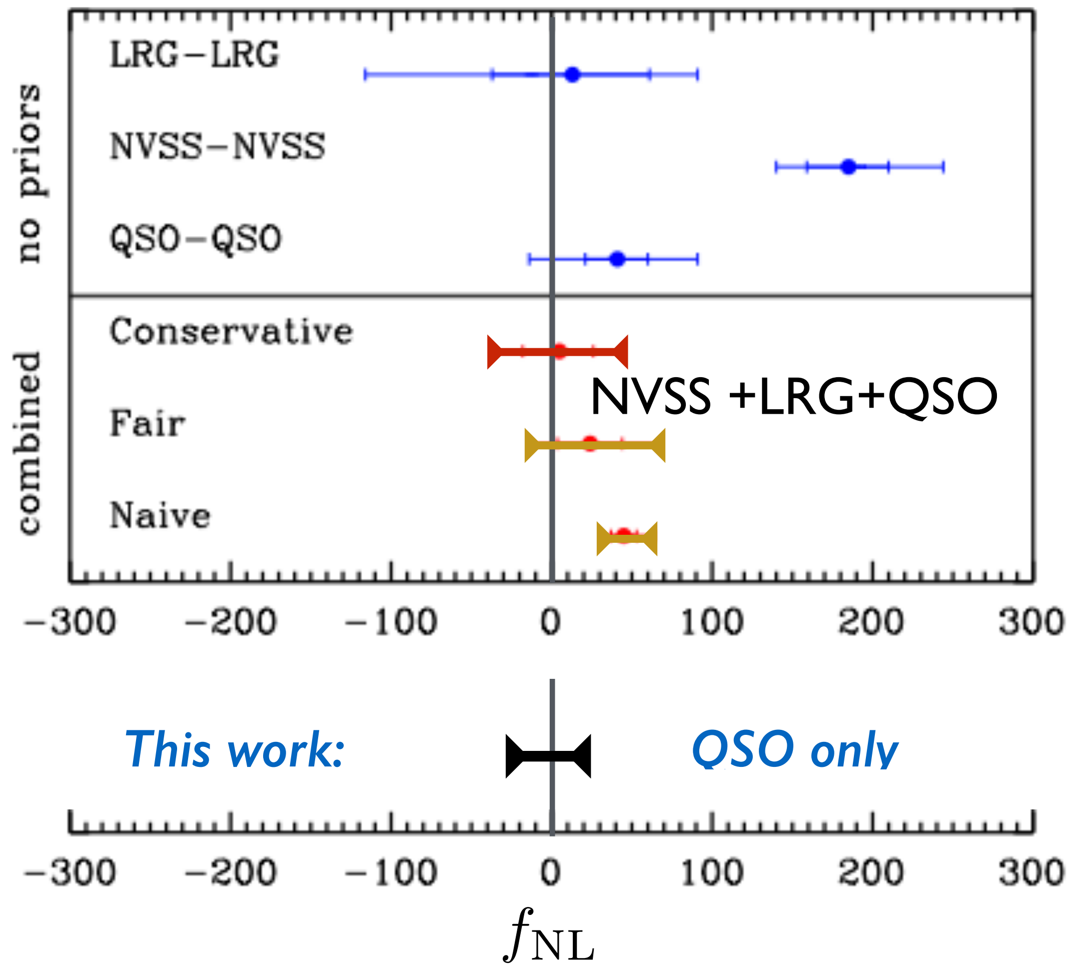


Figure 2. An example Bayesian network for the prediction of n_s from N_f–quadratic inflation with the potential (4.4) and masses set by the distribution (4.5). (*Left*) We use fixed values of β and σ^2, motivated by UV-theory and the desire to get density perturbations of the correct order, respectively. We assume that the number of fields is fixed and that any initial conditions on the horizon crossing surface, defined by N_*, is equally likely. (*Right*) We allow β to vary uniformly between two values a and b. We fix σ^2, but assume that the exact number of fields is unknown and, through EFT arguments, is dependent on the energy scale ρ_0 under consideration, which we fix. We then use a flat distribution on the initial conditions at the initial energy density ρ_0, so that the initial energy ρ_0 acts as a hyperparameter for both N_f and ϕ_0.

$$V(\phi_i) = \frac{1}{2}\sum_i^{N_f} m_i^2 \phi_i^2, \qquad P(m^2 \,|\, \sigma, \beta) = \frac{1}{2\pi m^2 \beta \sigma^2}\sqrt{(\beta_+ - m^2)(m^2 - \beta_-)}$$

Constraints on f_{NL}

Giannantonio *et al* (2013)



$$-16 < f_{\rm NL} < 47 \ (2\sigma)$$

Fixed cosmology & n(z)

$$-49 < f_{\rm NL} < 31 \ (2\sigma)$$

Varying all parameters

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

Numerical Study with N=100 fields

- Generalised numerical solver MODECODE (Peiris, Easther++) to multifield inflation (www.modecode.org).

- Test case with N=100 fields: N-quadratic inflation with canonical kinetic terms, minimally coupled, with potential

$$V = \frac{1}{2} m_\alpha^2 \phi_\alpha^2$$

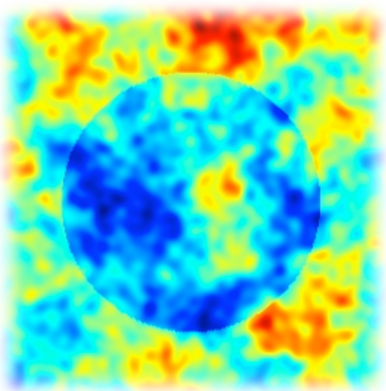
- Masses drawn from Marchenko-Pastur distribution with β=0.5.
  largest mass ratio 1/8.08, other masses equally spaced in cumulative PDF

- Solve full perturbation, compute isocurvature modes at end of inflation.
  identify inflationary trajectory, compute N-1 orthogonal perturbations (Gram-Schmidt)

Easther, Frazer, Peiris, Price, (arxiv:1312.4035, PRL 2014)

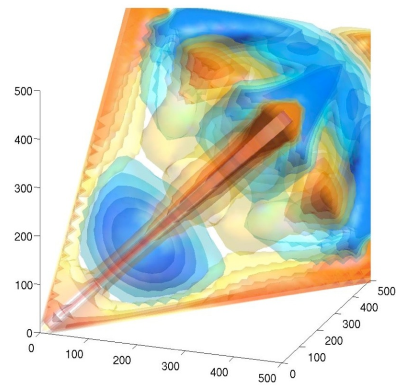
Beyond the Gaussian

pre-inflation



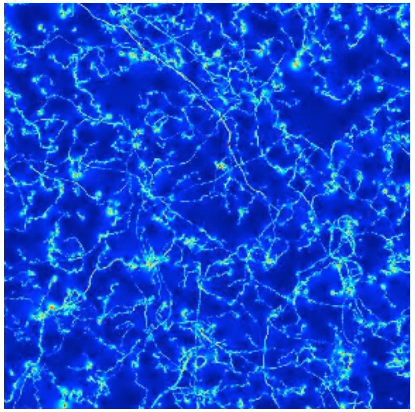
signatures of collisions between "bubble universes"

during inflation

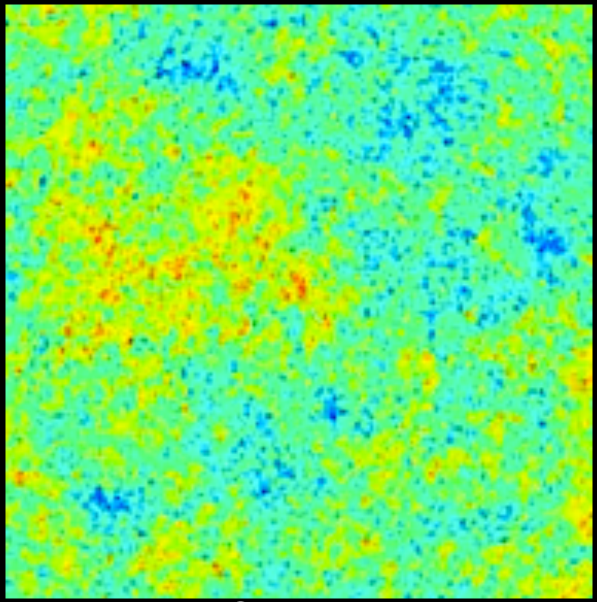


primordial non-Gaussianity: only probe of interactions during inflation

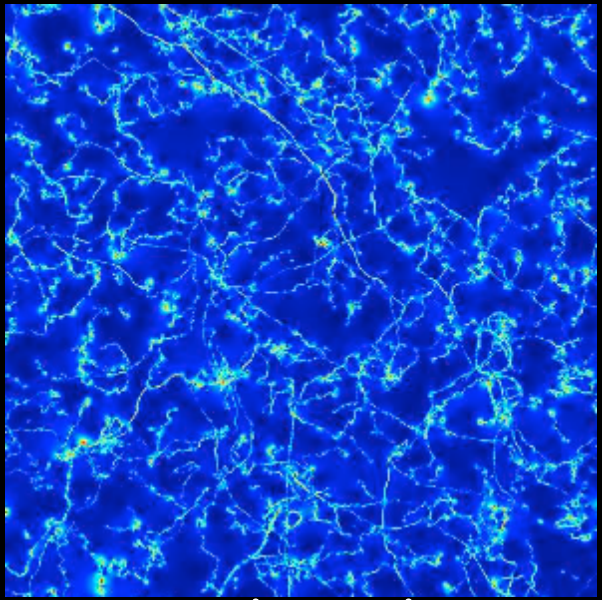
post-inflation



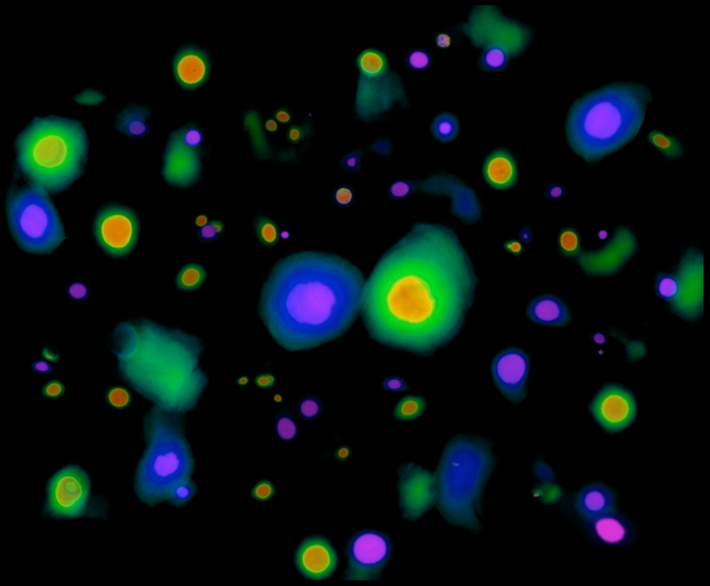
topological defects (cosmic strings, textures)



inflation



cosmic strings



textures