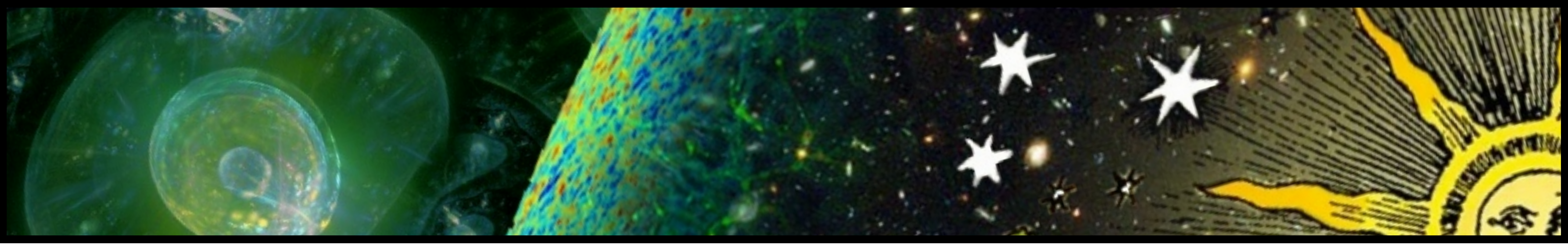
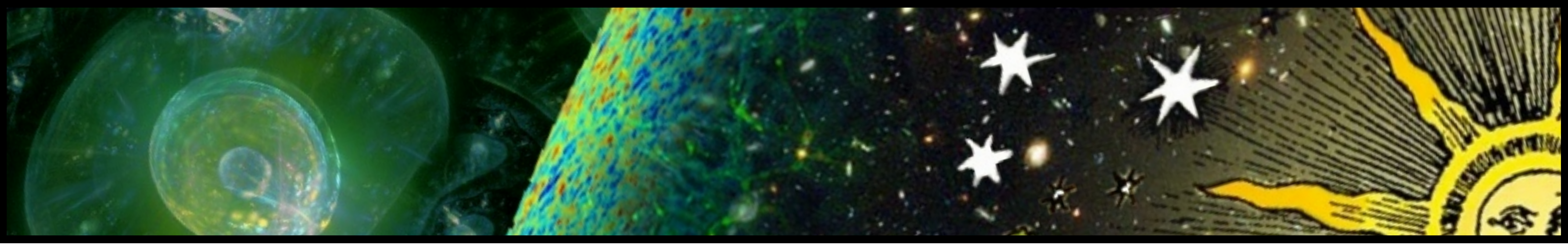


Cosmological inflation: From observations to fundamental physics

Hiranya V. Peiris
University College London

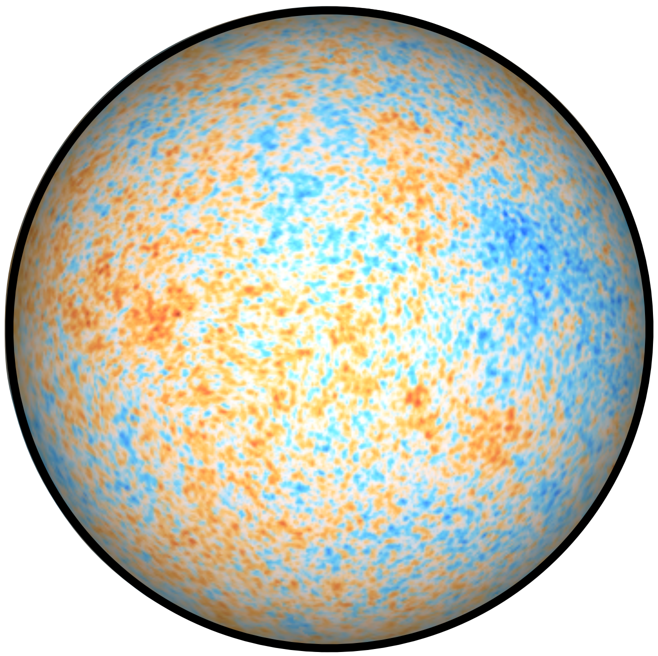
Science & Technology Facilities Council
European Research Council
IDEAS



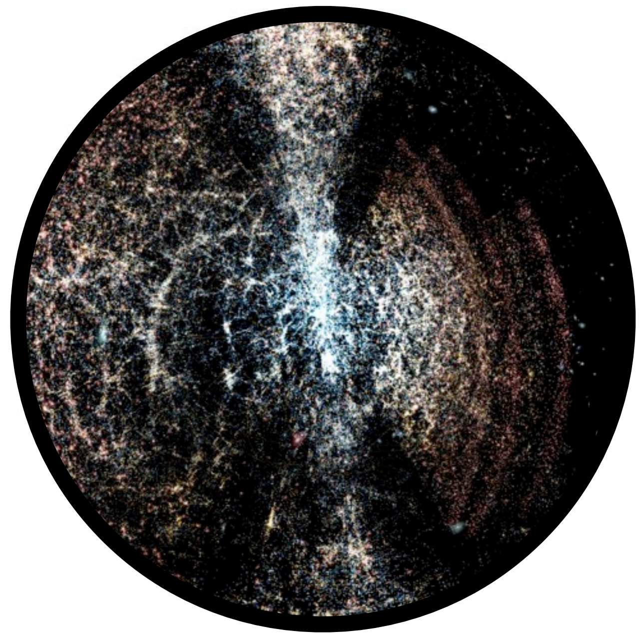
Roadmap

- Inflation in a post-Planck world
- Towards understanding the physics of inflation
  - *Primordial non-Gaussianity from large scale structure*
  - *Single vs multi-field?*
  - *Testing top-down models*
  - *Predictions from the landscape?*
- Strategies for future progress

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

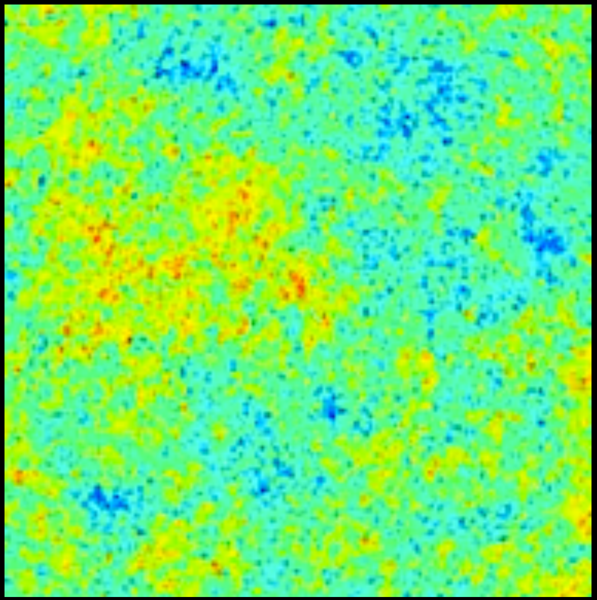


Cosmic Microwave Background
image: Planck

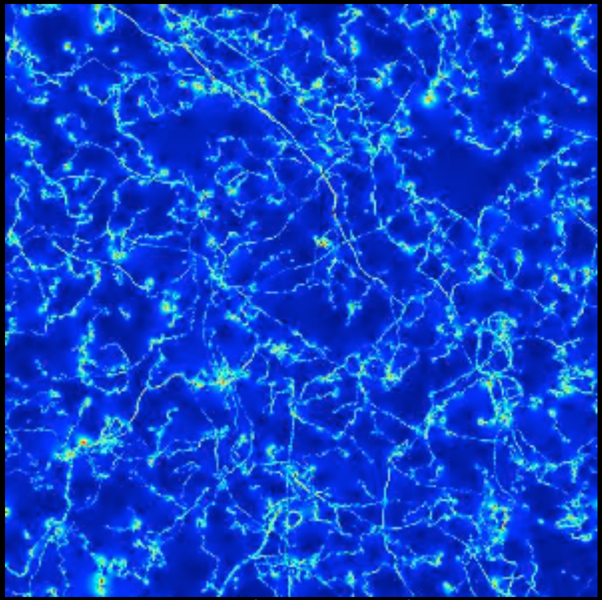


Large Scale Structure
image: SDSS

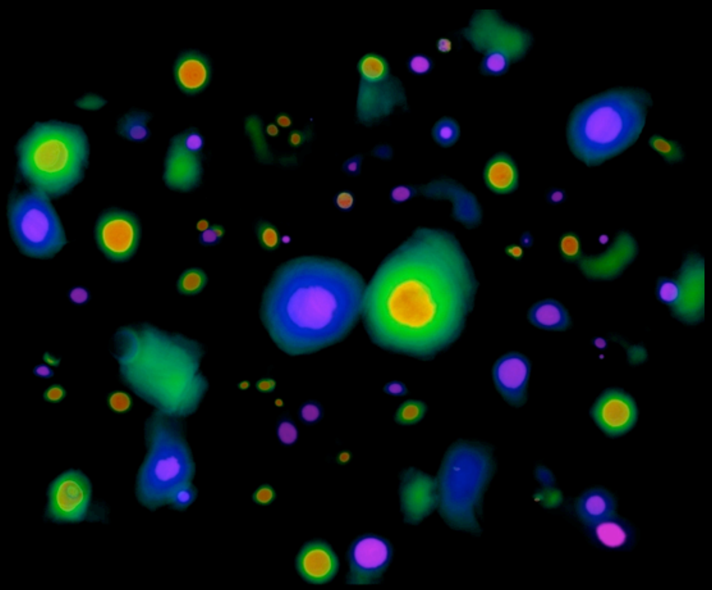
Short answer: We don't know!



inflation

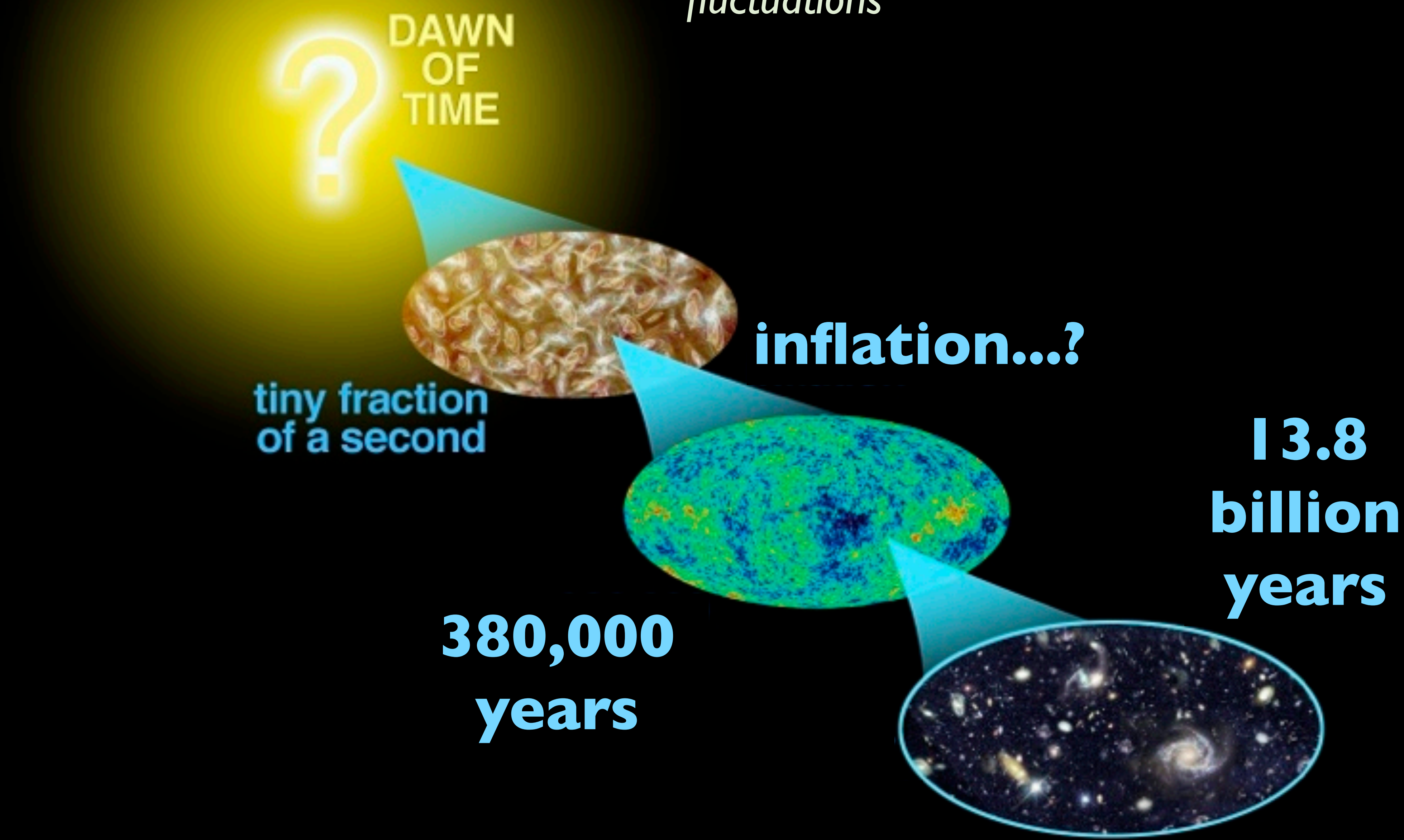


cosmic strings



textures

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



Inflation

A period of accelerated expansion

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

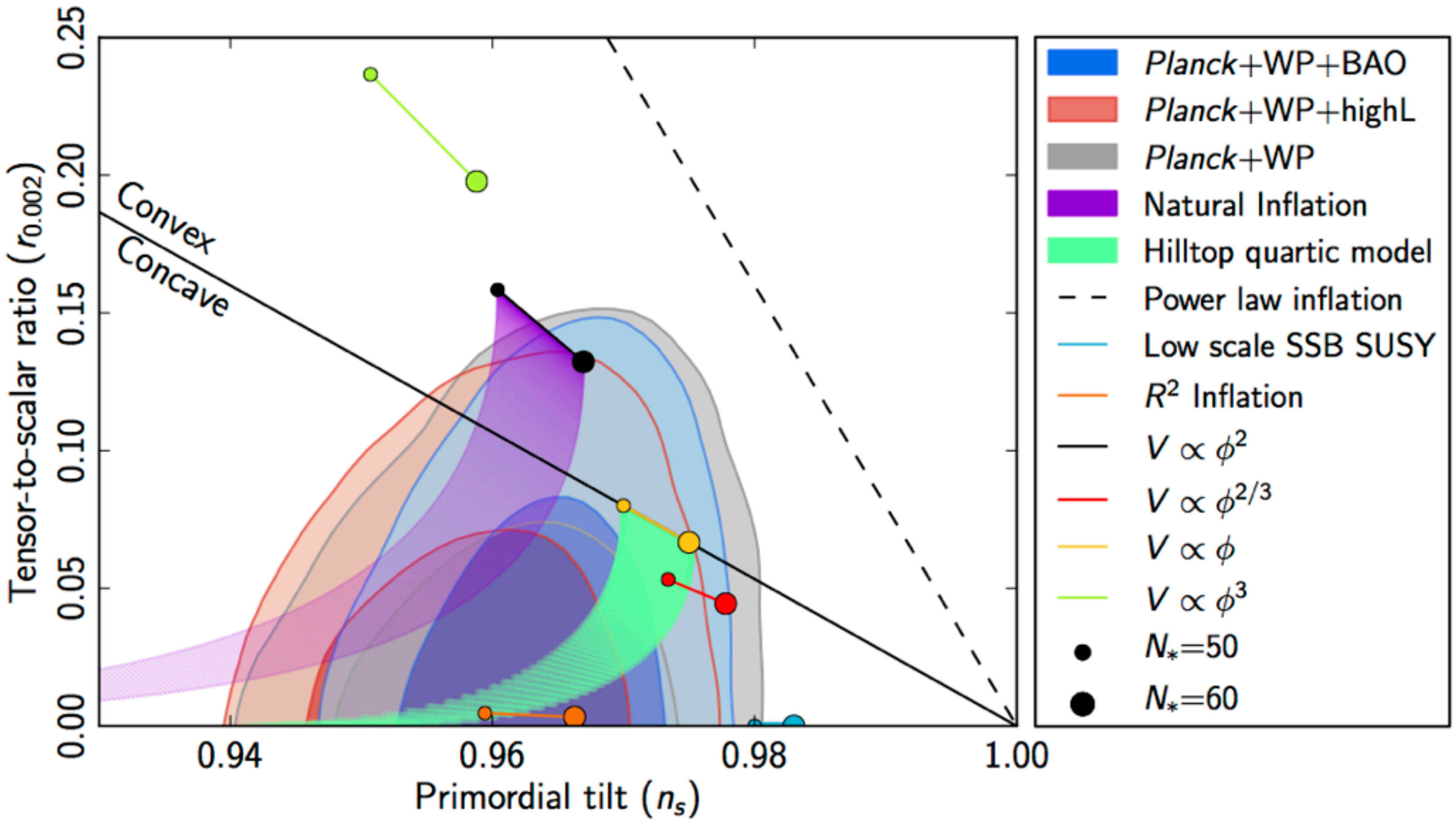
- Solves:
  - horizon problem
  - flatness problem
  - monopole problem

  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)

Known-knowns in a post-Planck world

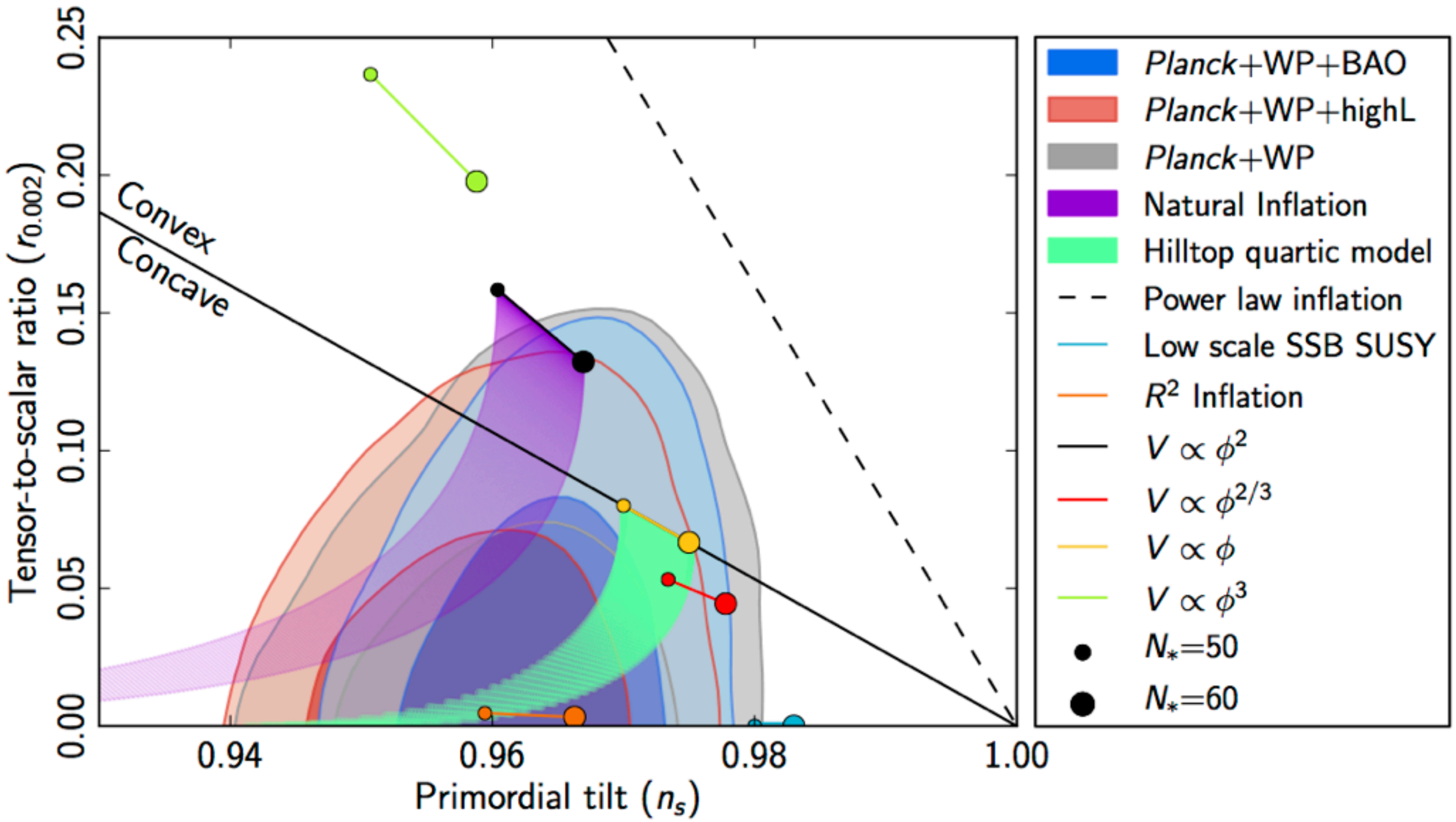
- Exact scale invariance (n_s=1) ruled out at >5σ by a single experiment
- While convex potentials are still allowed, Planck hints that flattened potentials are preferred



Planck+WP: $n_s = 0.9603 \pm 0.0073 \quad r_{0.002} < 0.12$ (95% CL)

Known-knowns in a post-Planck world

- Planck does not exclude or suggest many active fields during inflation
- However, single-field models are arguably "simplest" allowed by data



Planck+WP: $n_s = 0.9603 \pm 0.0073 \quad r_{0.002} < 0.12$ (95% CL)

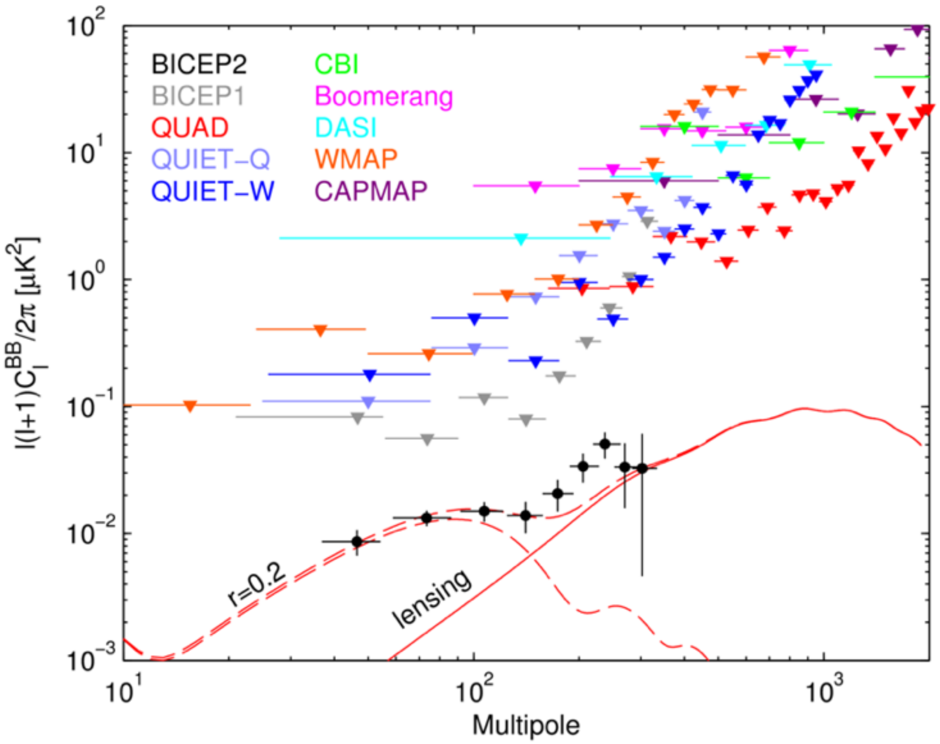
Planck's primordial non-Gaussianity (PNG) measurements

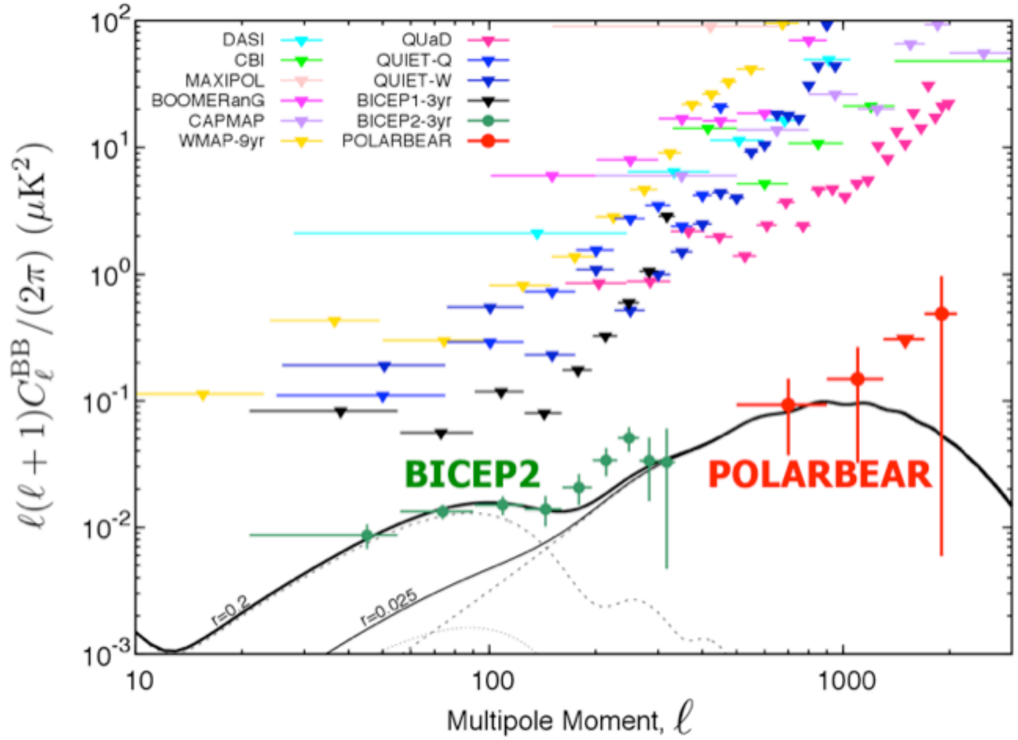
- Measured to 1 part in 10,000 (most precise cosmological measurement!)
- Bispectrum now a routine observable, like the spectral index
- Standard bispectrum configurations not detected by Planck; stringent constraints on local/equilateral/orthogonal etc shapes

Shape	ISW-lensing subtracted KSW
Local	2.7 ± 5.8
Equilateral	-42 ± 75
Orthogonal	-25 ± 39

DBI	11 ± 69
EFT1	8 ± 73
EFT2	19 ± 57
Ghost	-23 ± 88

Milestone: measurement of B-modes





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

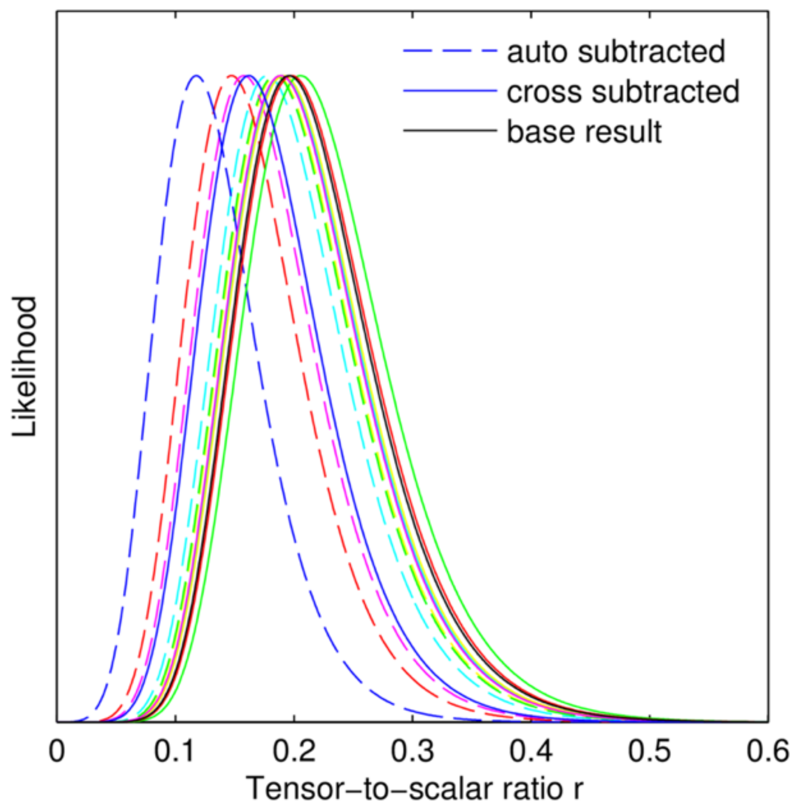
B2 errorbars include sample-variance from r=0.2

Figures: BICEP2

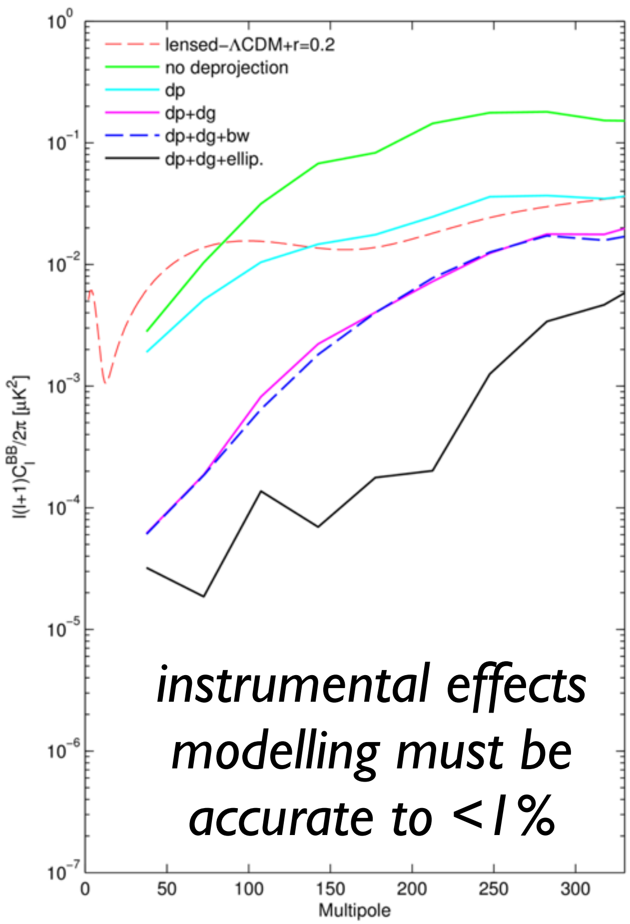
BICEP2 thoughts

Is the signal cosmological? My desiderata: want to see confirmation at different frequencies, different experiments, different parts of the sky.

"Extraordinary claims require extraordinary evidence."



(Known) FG modelling can bring down the signal to r~0.1

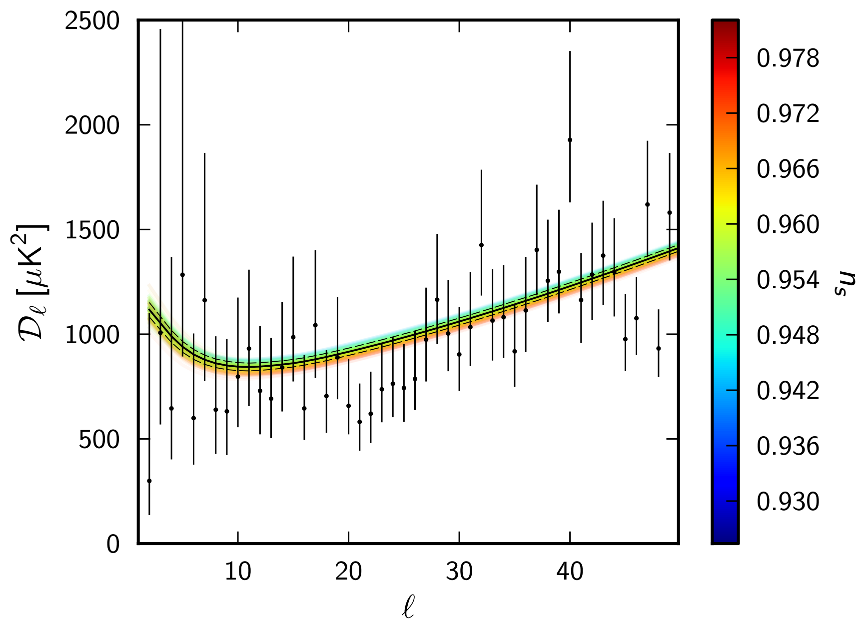


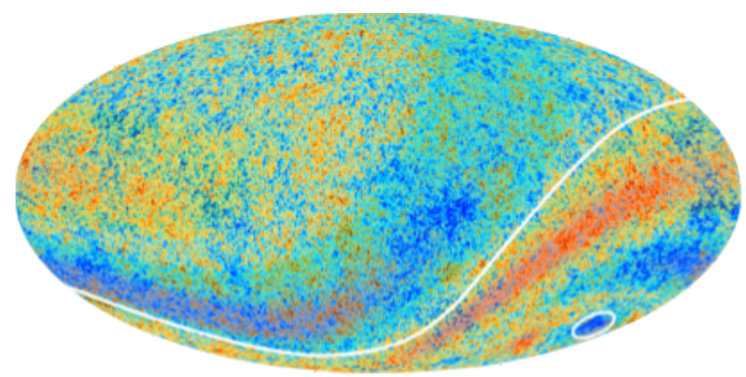
Figures: BICEP2

What if: tension with low l TT?

- If r~0.2, "anomalies" at large scales may acquire new significance.
  - -Broken scale-invariance / "features"? *(Abazajian et al 2014, Miranda et al 2014)*
  - -Anticorrelated isocurvature? *(Kawasaki et al 2014)*
  - -Inflation after false vacuum decay *(Bousso et al 2014)*
  - -Link to hemispherical asymmetry? *(Chluba et al 2014)*
  - .....

- Polarization critical to testing these ideas *(see e.g. Mortonson, Dvorkin, HVP, Hu 2009, Dvorkin, HVP, Hu 2008)*





Figures: ESA/Planck

Inflation: score-card

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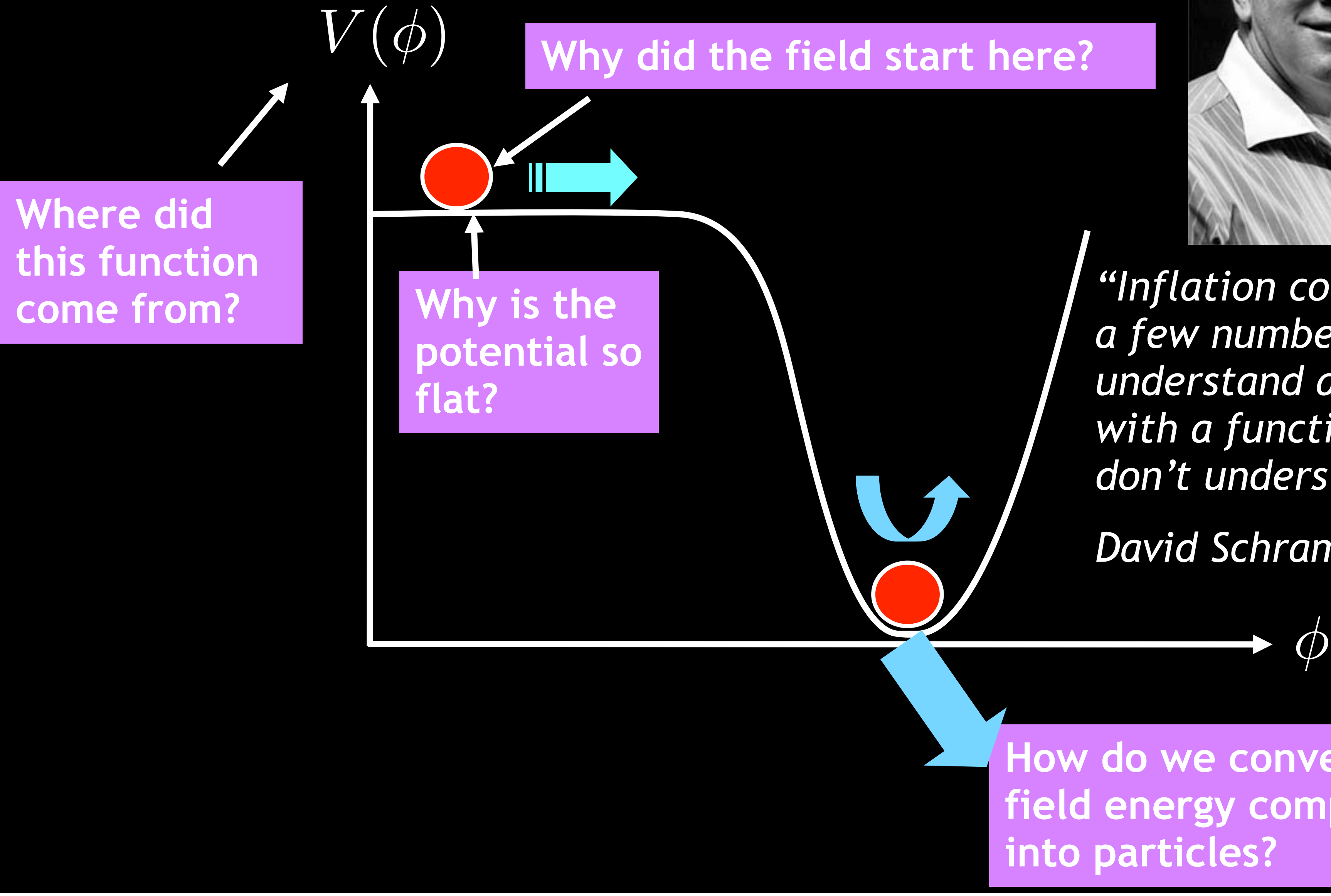
  i.e. explains why the Universe is so large, so flat, and so empty

- 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

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

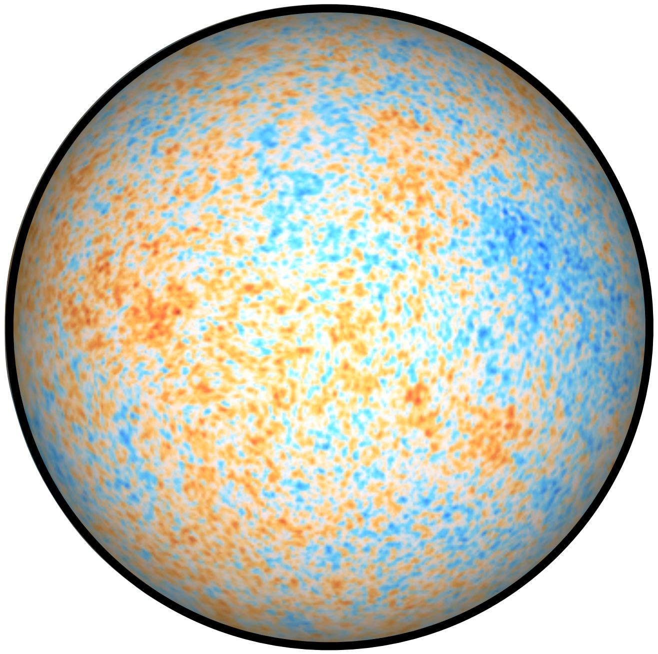


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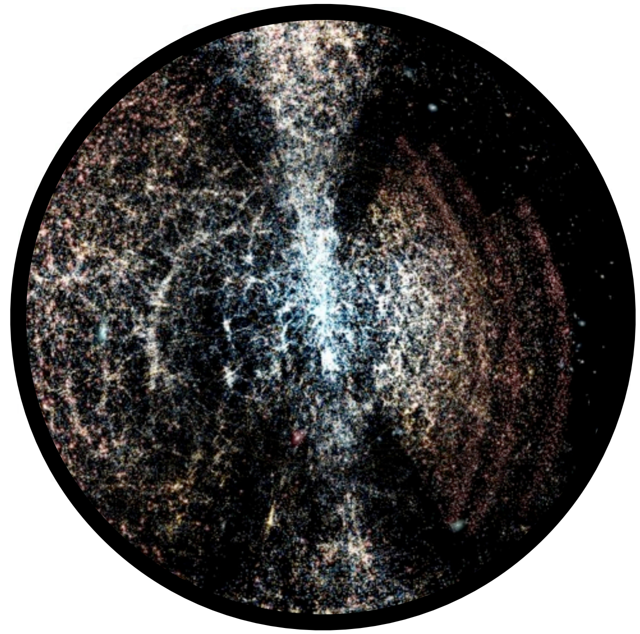
image: Planck



Large Scale Structure
image: SDSS

We see a model working in practice. Does it work in principle?

From phenomenology to physics

Phenomenology

GR + broken time-translation invariance+ homogeneity + isotropy + initial conditions

1. Are core cosmological assumptions valid?

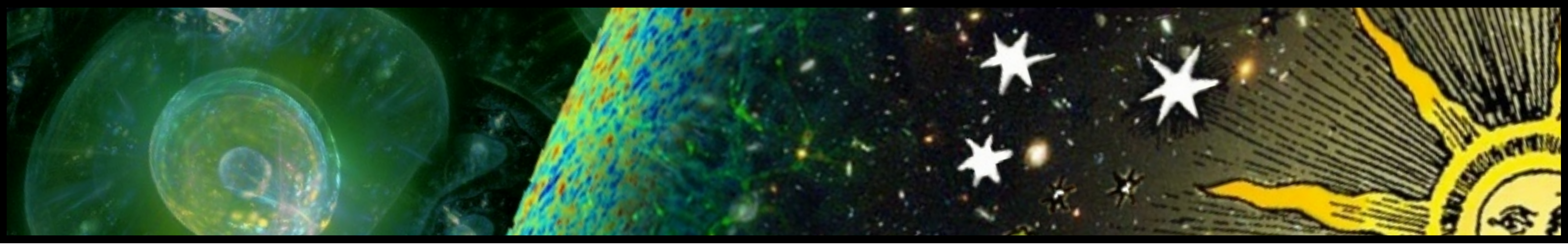
Physics

"Inflation" appears to work in practice. Does it work in principle?

2. What is the physics of inflation?

3. How did inflation begin?

4. What happened after inflation ended?



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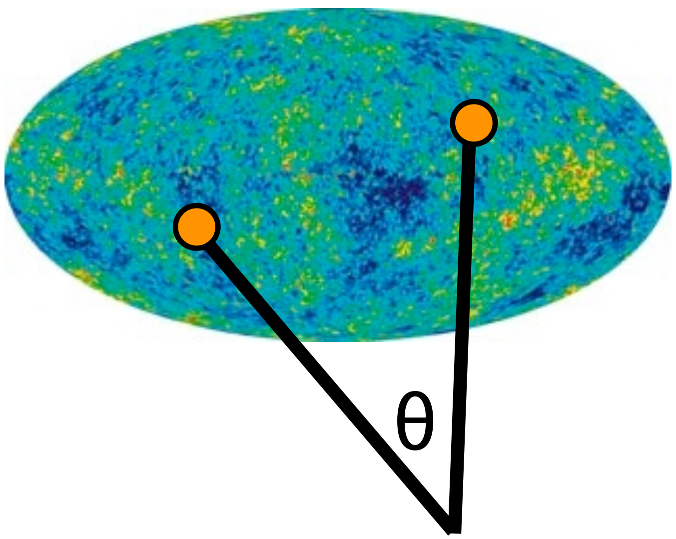
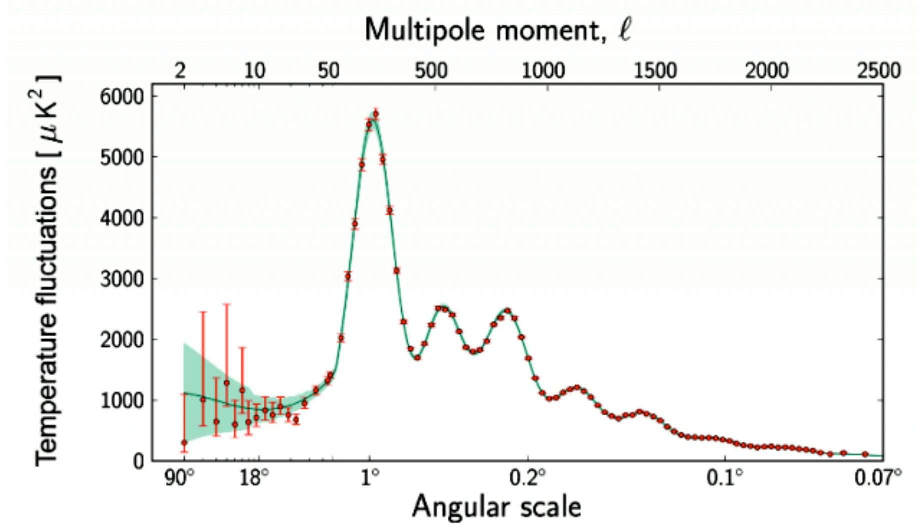
Non-Gaussianity: maximising physical information

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

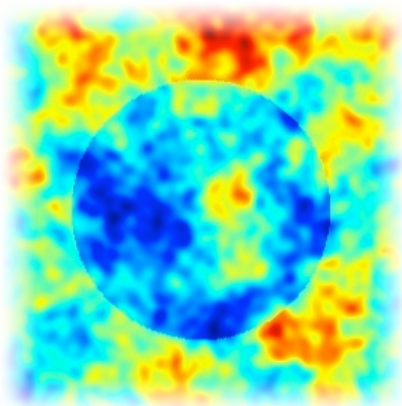


angular power spectrum
2500 multipoles

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

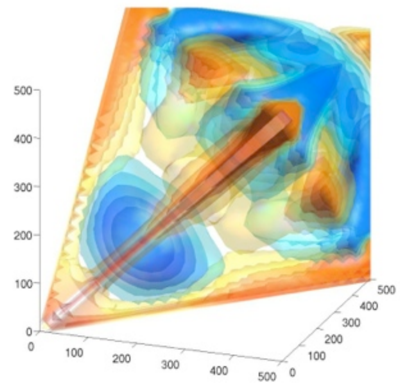
Beyond the Gaussian

pre-inflation



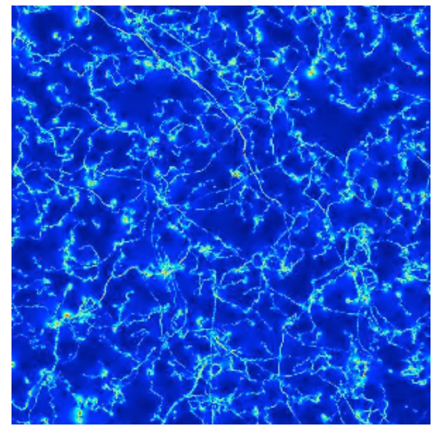
signatures of collisions between "bubble universes"

during inflation



primordial non-Gaussianity: only probe of interactions during inflation

post-inflation



topological defects (cosmic strings, textures)

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).

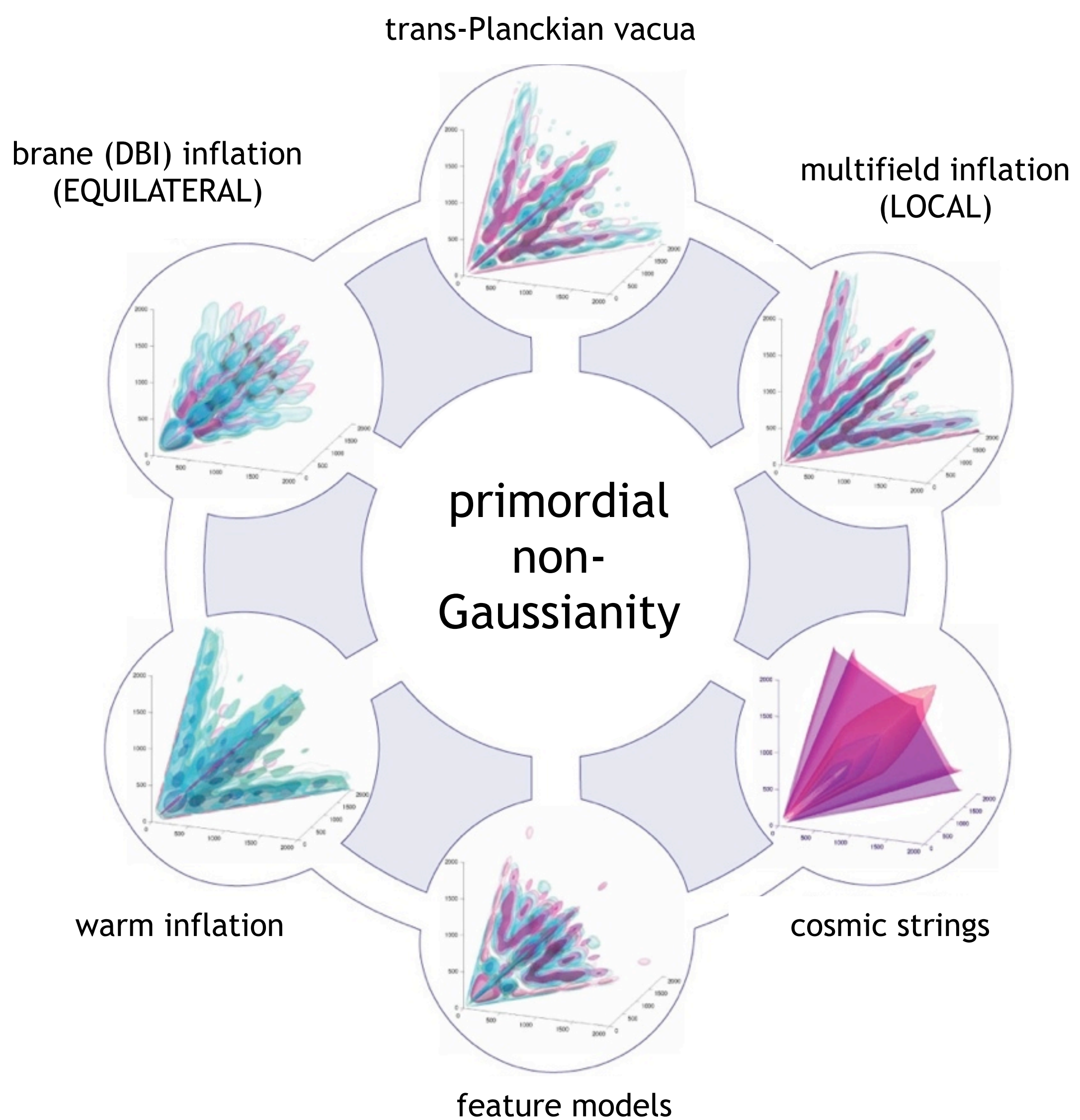
- A detection of $f_{NL} >> 1$ will immediately rule out the "textbook" picture of inflation.

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

primordial potential

Gaussian field

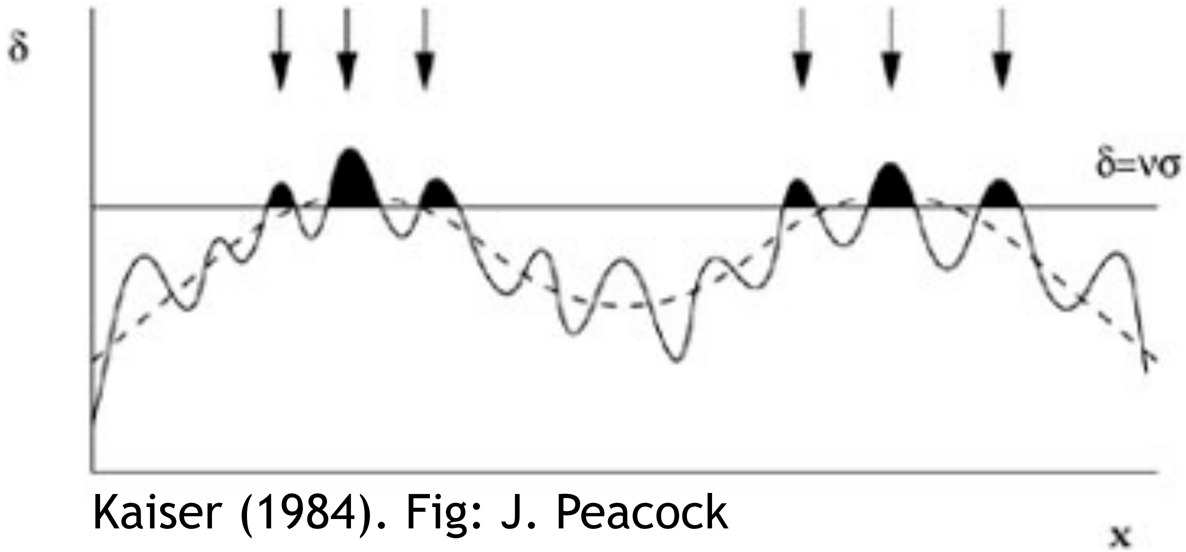
Rich phenomenology



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

Figure: P. Shellard & J. Fergusson

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.

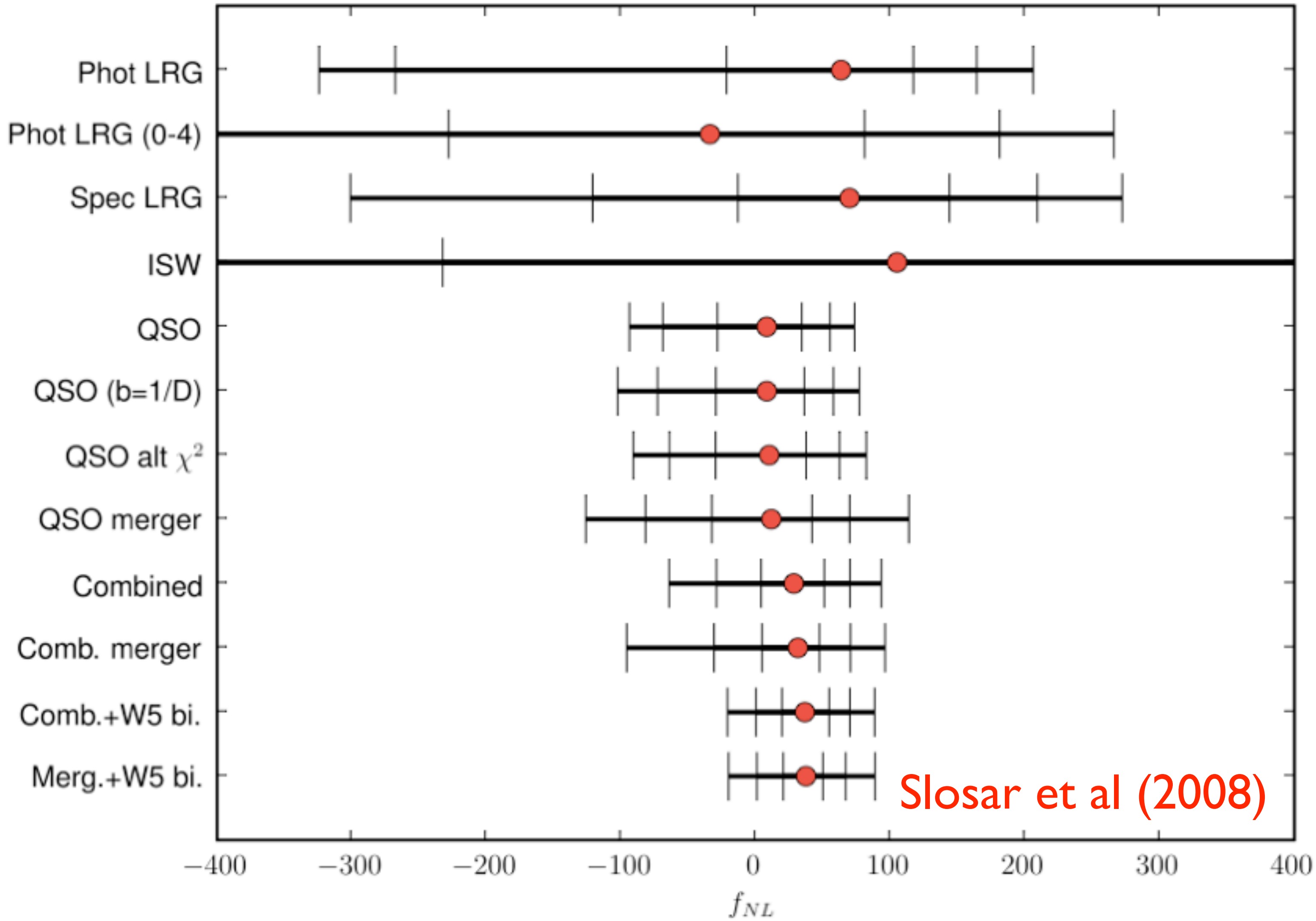
•Enhanced abundance of massive objects in overdense regions leads to enhanced clustering.

•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)

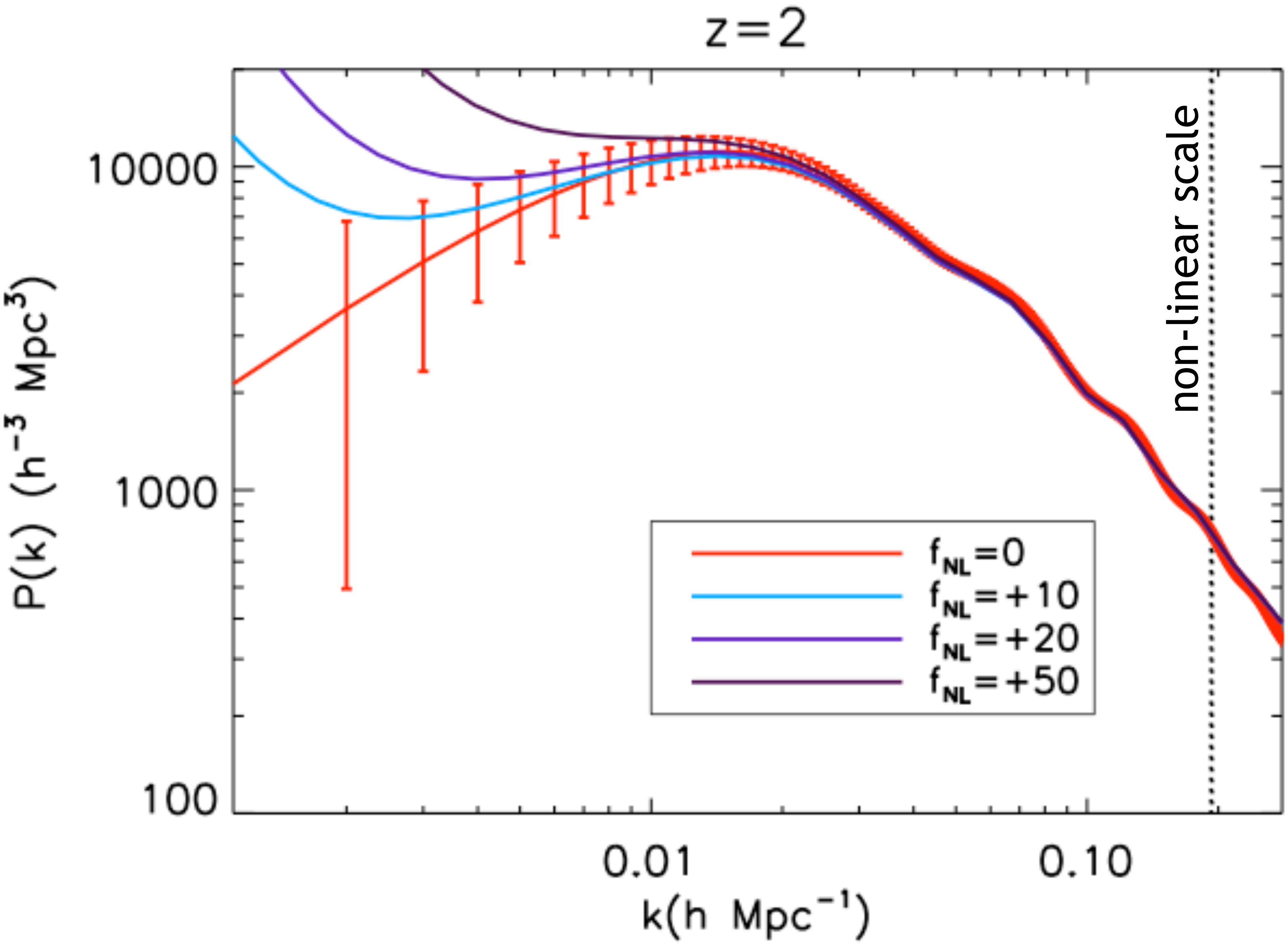
PNG from large scale LSS angular power spectrum

"Local" PNG $\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}^{\rm loc}\phi^2(\mathbf{x})$ imprints halo bias $\Delta b \propto k^{-2}$



scale-dependent halo bias (Dalal et al 2008)

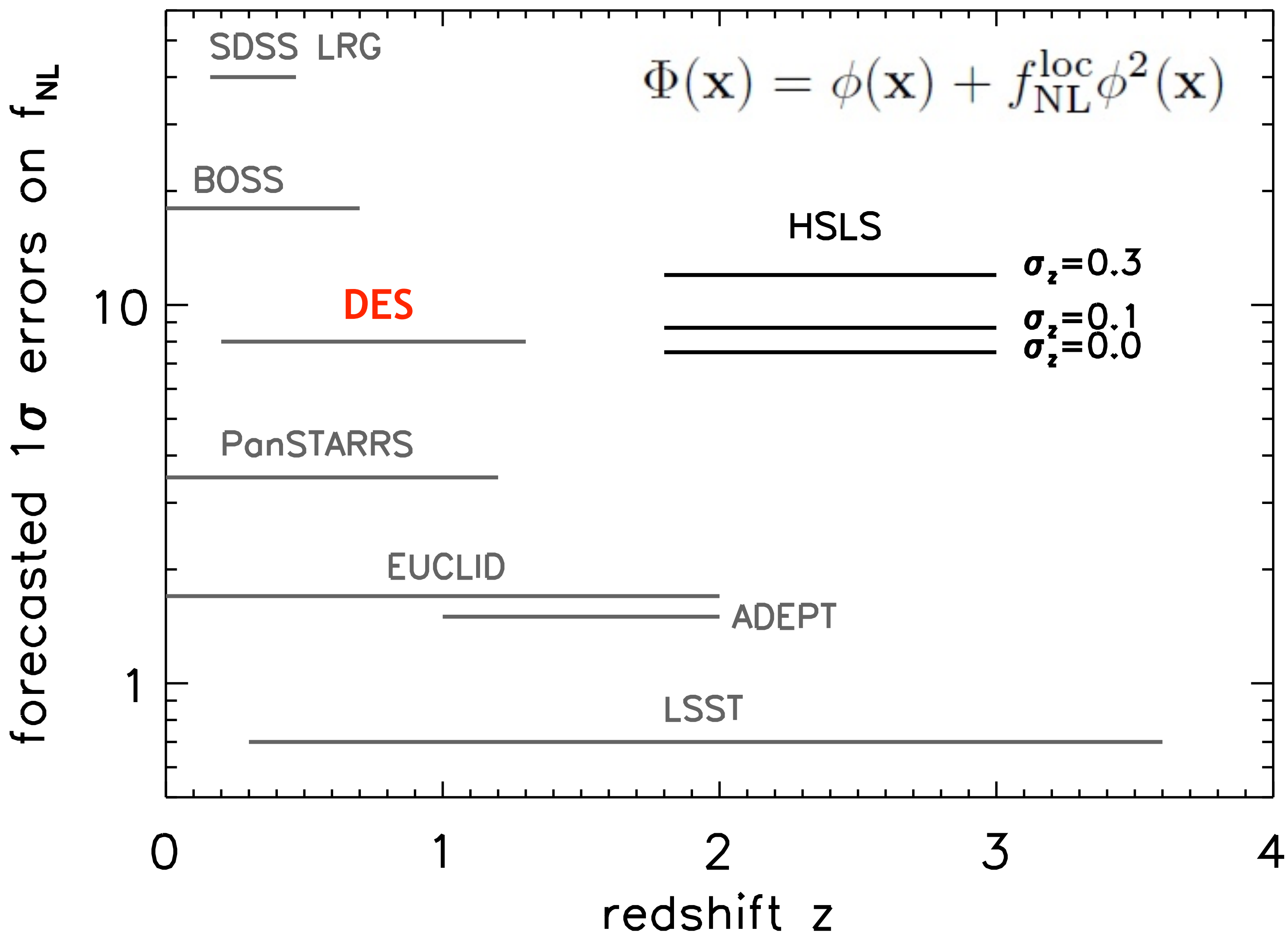
Effect on the halo power spectrum



Power spectra at z=2 for a spectroscopic survey

Figure: HSLS white paper, HVP CMB/LSS Coordinator

LSS forecast for "local" shape



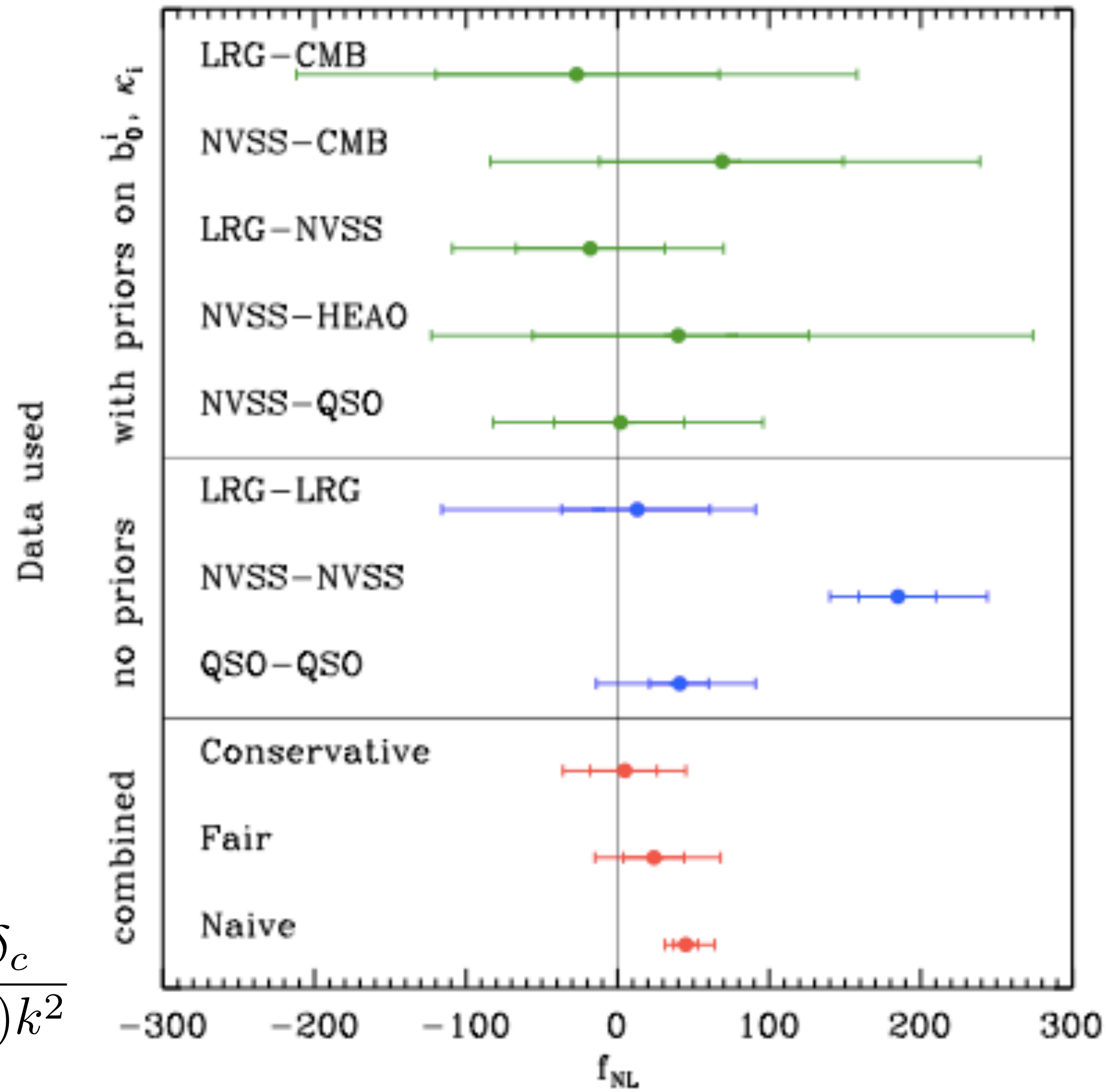
Constraints on f_{NL} assuming Planck priors on the cosmological parameters

Figure: HSLS white paper, HVP CMB/LSS Coordinator

The potential of quasar surveys for PNG

Giannantonio et al (2013)

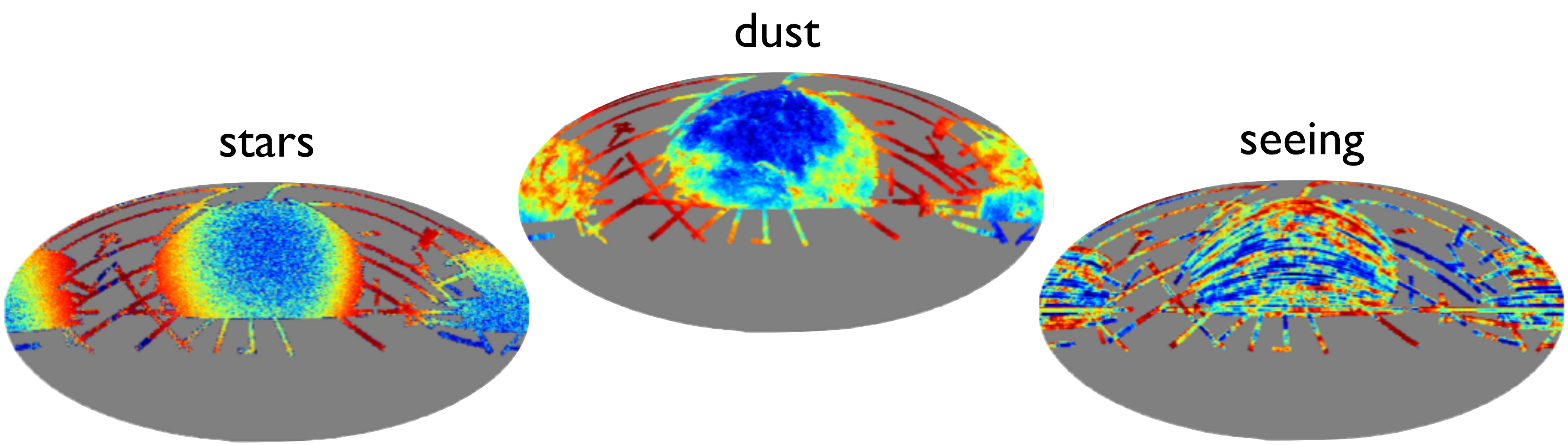
- **Quasars**: highly-biased LSS tracers, spanning large cosmological volumes



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

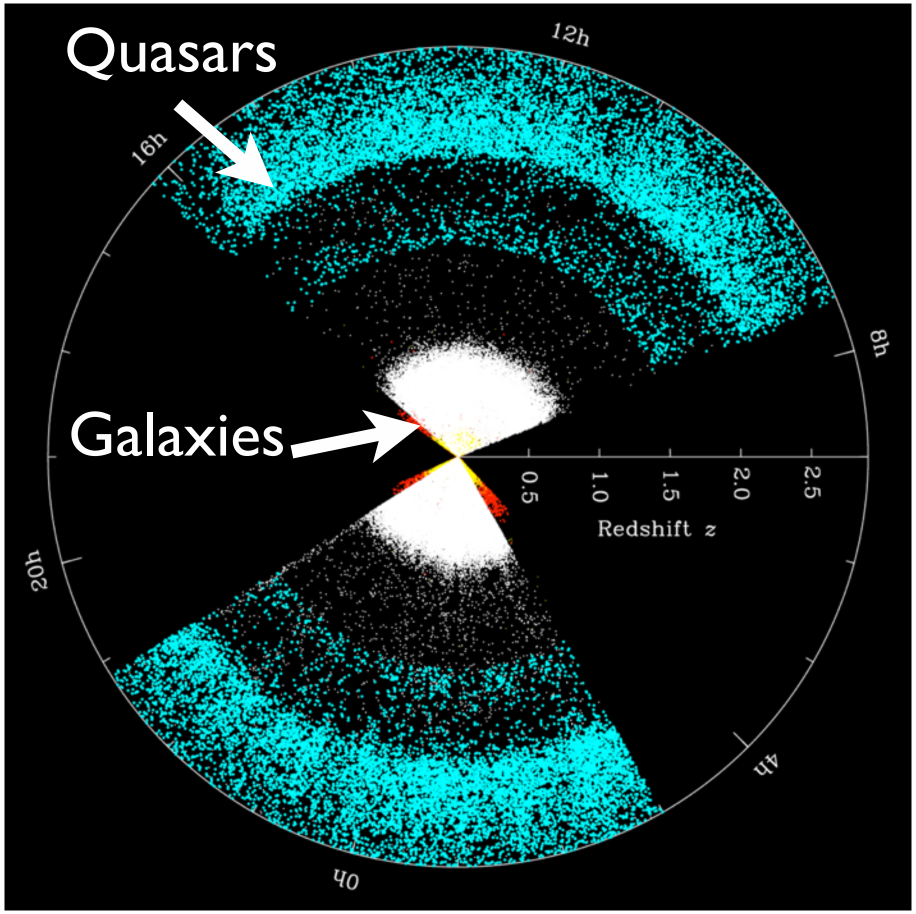
Systematics in quasar surveys

- Anything that affects point sources or colours
  seeing, sky brightness, stellar contamination, dust obscuration, calibration etc..
- Create spatially varying depth & stellar contamination



PNG from blind mitigation of systematics in XDQSOz quasar sample

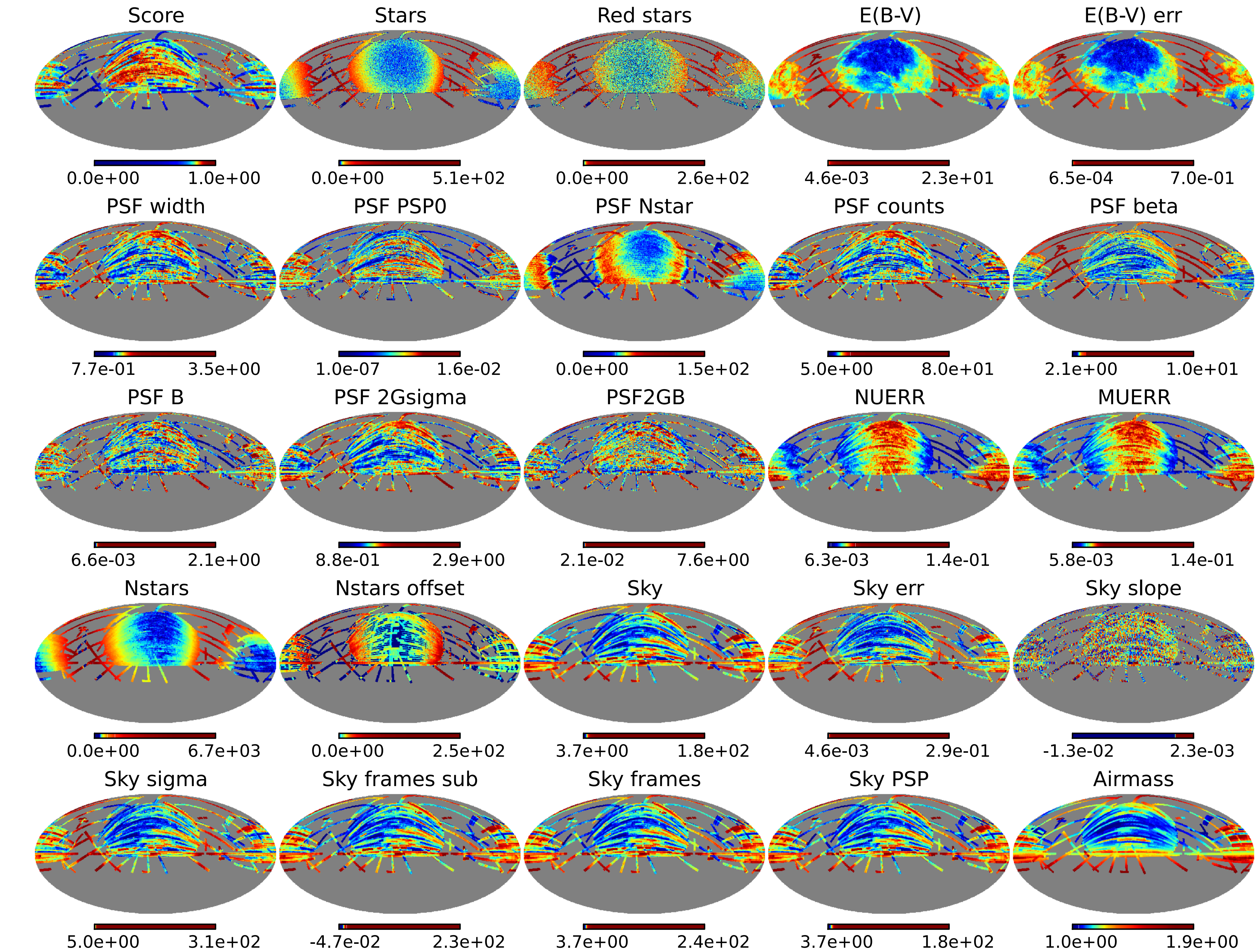
XDQSOz: 1.6 million QSO candidates from SDSS DR8 spanning z ~ 0.5-3.5 (800,000 QSOs after basic masking).



Boris Leistedt

Nina Roth

Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (1405.4315)



Monday, 30 June 14

Extended mode projection

- Create set of input systematics

  220 templates + pairs ⇒ >20,000 templates

- Decorrelate systematics

  20,000 templates ⇒ 3,700 uncorrelated modes

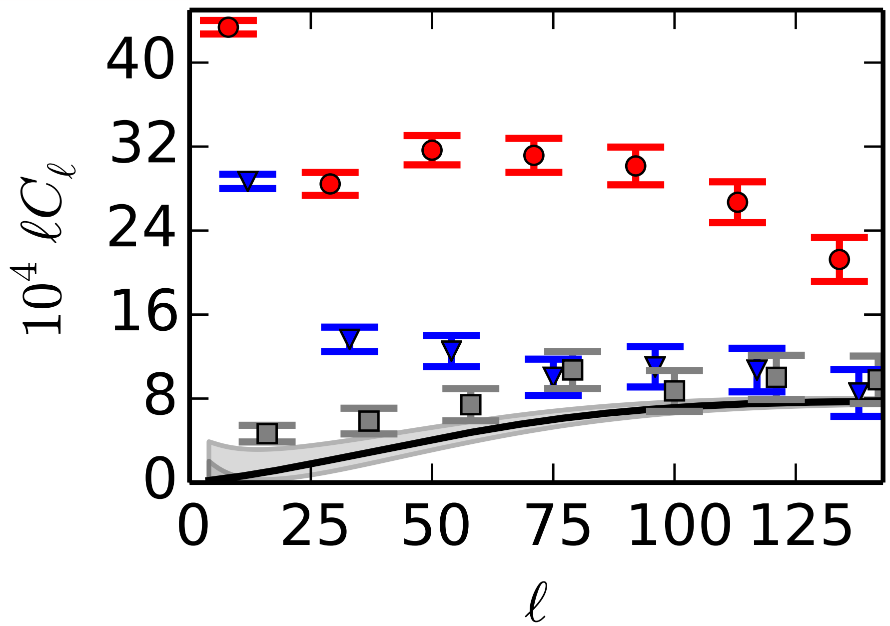
- Ignore modes most correlated with data

  3,700 null tests; project out modes with red chi2>1

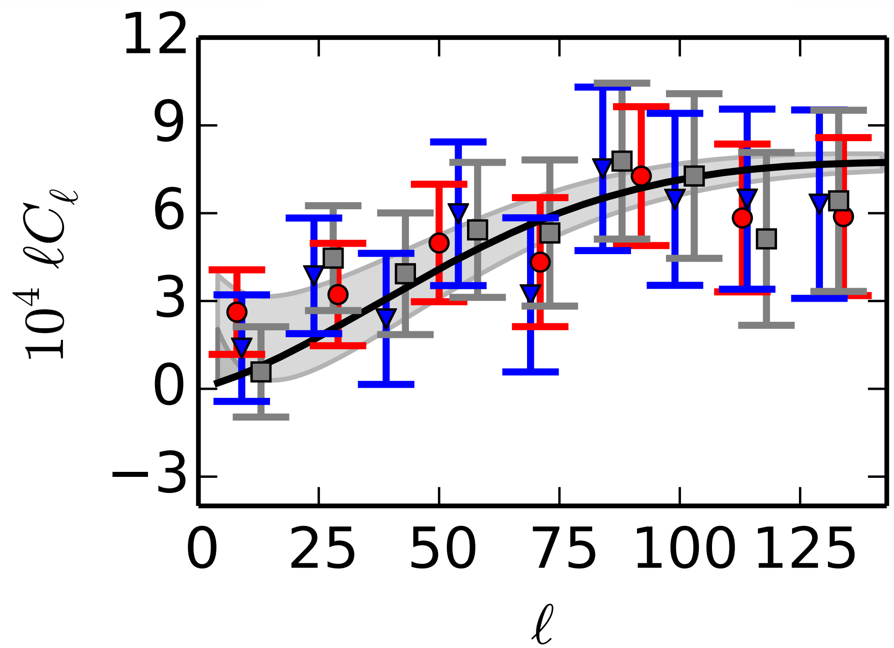
Sacrificing some signal in favour of robustness

⇒ **Blind mitigation of systematics**

Blind mitigation of systematics



Raw spectra

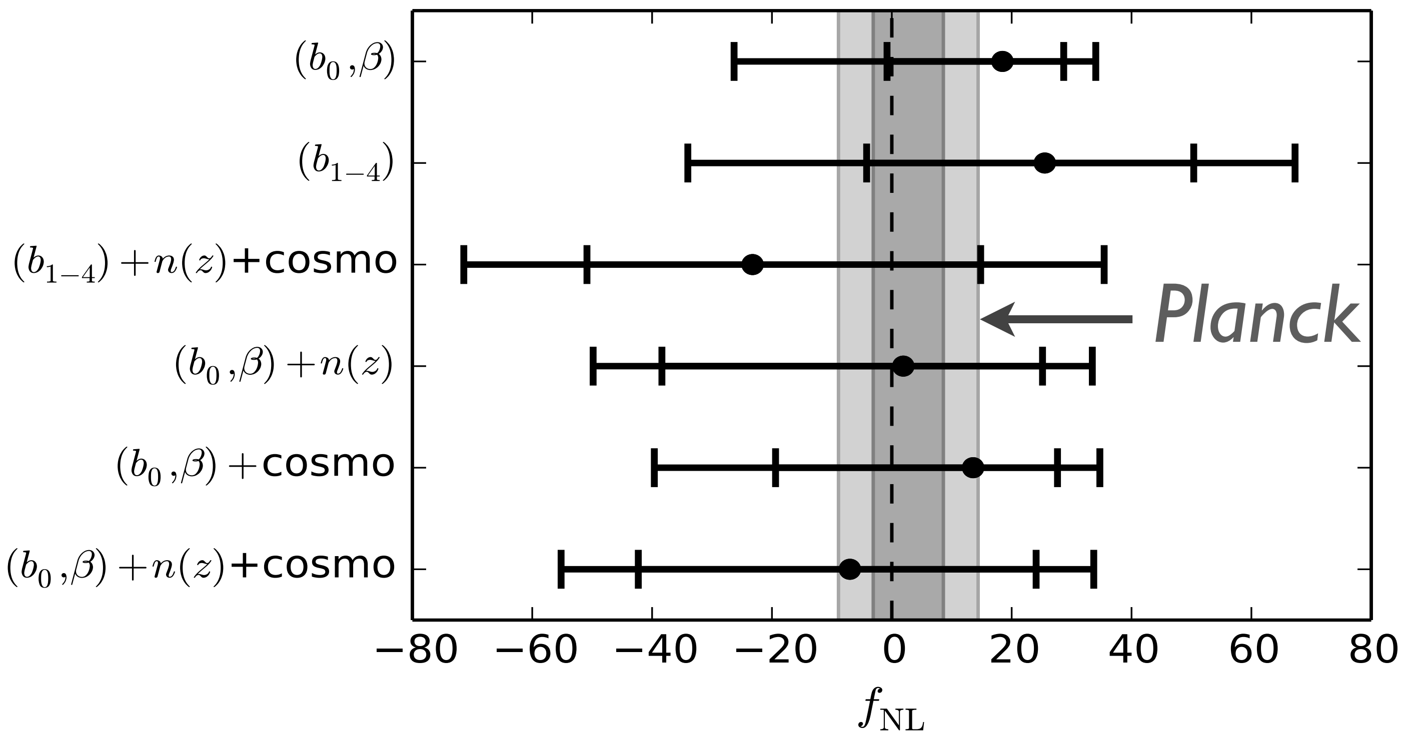


Clean spectra

- Example: one of 10 spectra (auto + cross in four z-bins) in likelihood
- Grey bands: -50 < f_{NL} < 50; colours: basic masking + m.p.

Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (1405.4315)

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 (1405.4315)

Higher order terms

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

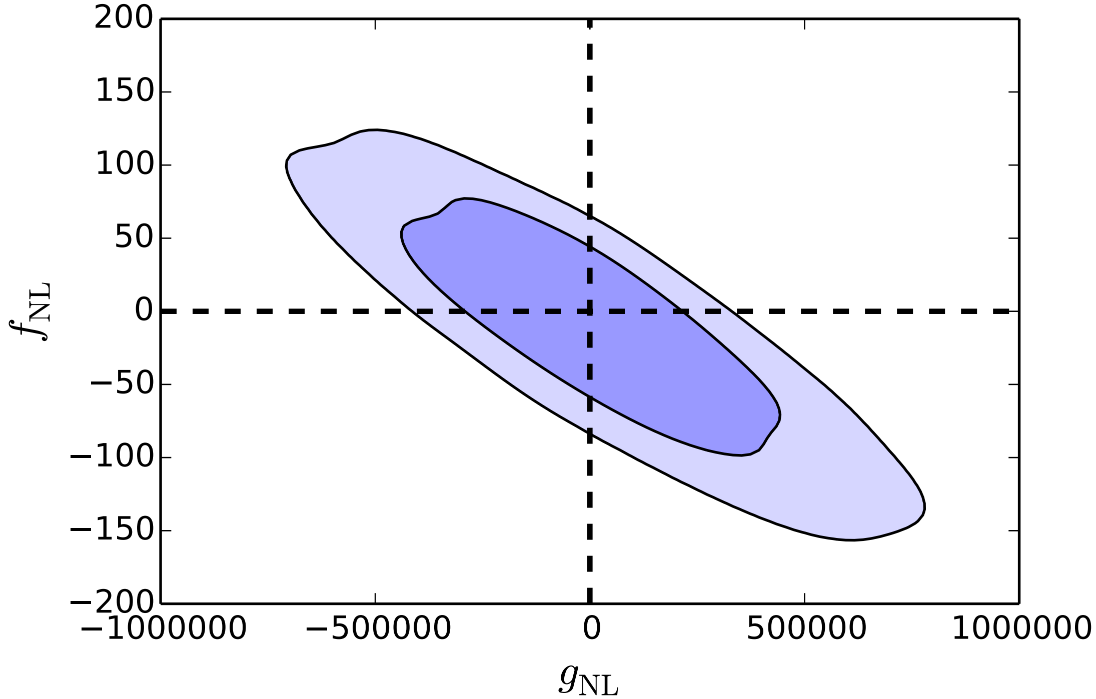
$|g_{NL}| < 10^6$ (CMB, LSS)

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}



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

individually

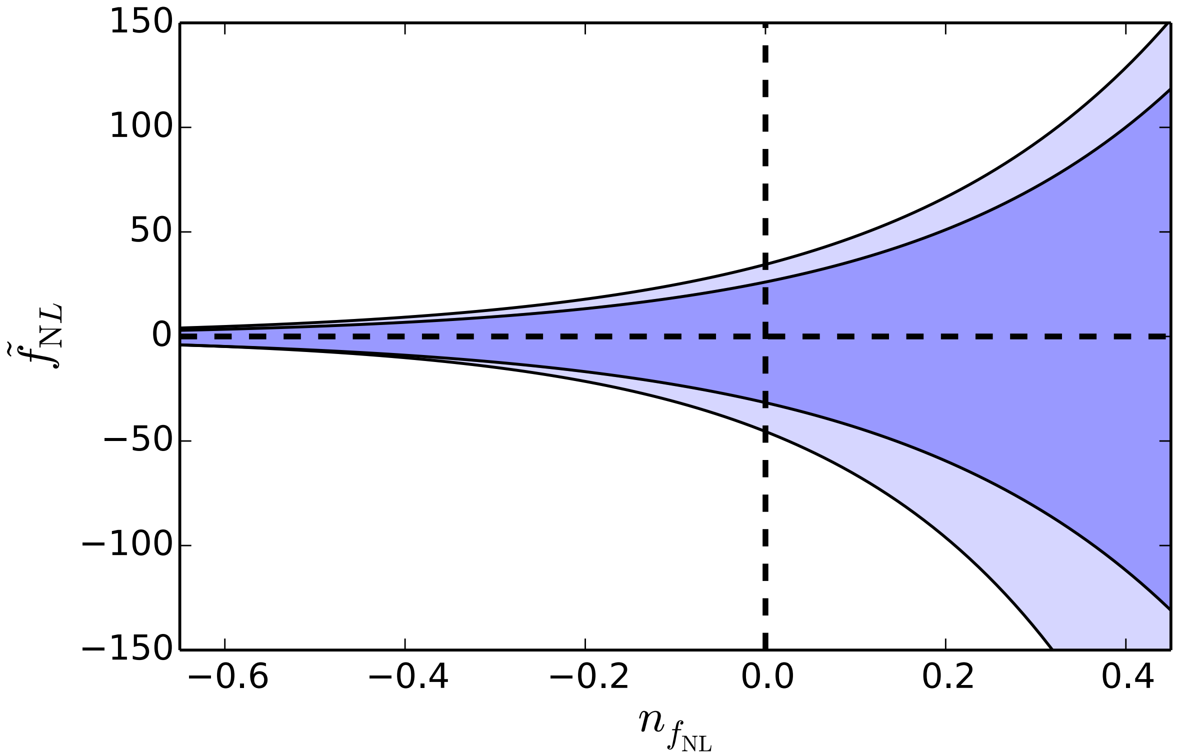
$$-4.0 < g_{\rm NL}/10^5 < 4.9 \ (2\sigma)$$

joint with f_{NL}

- Best available constraint on g_{NL}

Leistedt, Peiris & Roth (1405.4315)

Extended model with running

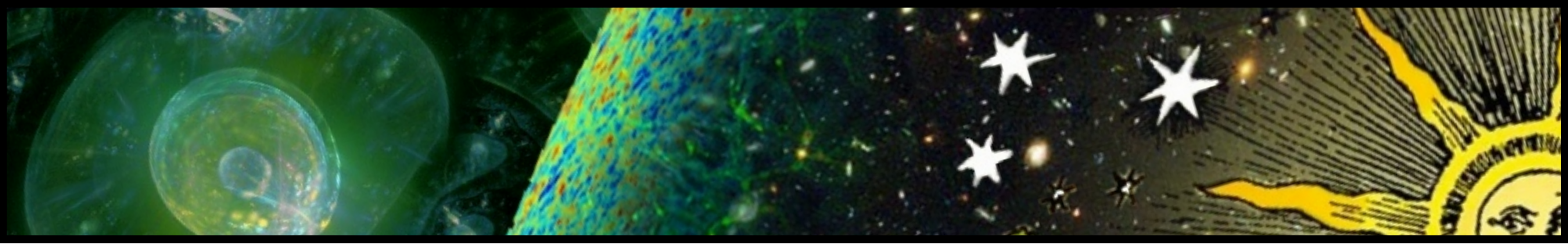


$$b(k) \propto k^{-2+n_{f_{\rm NL}}}$$

Constrains single field inflation with a modified initial state, or models with several light fields.

Leistedt, Peiris & Roth (1405.4315)

Agullo and Shandera (2012), Dias, Ribero and Seery (2013)



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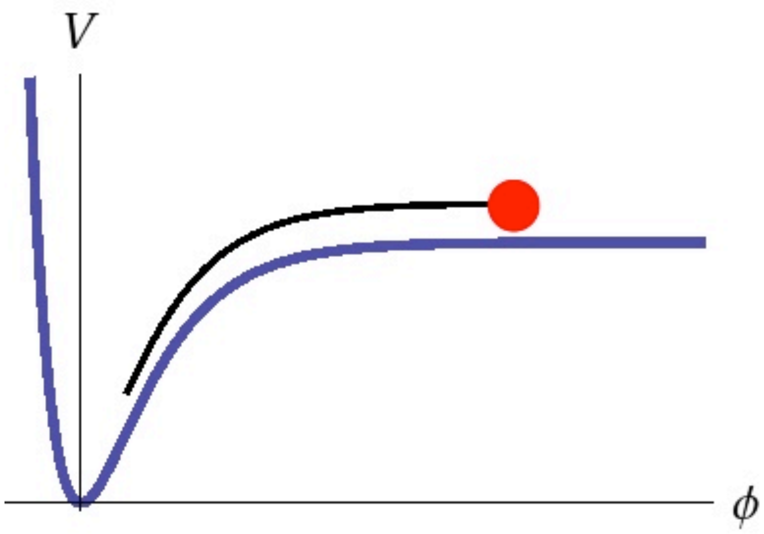
One field is simple; is it "natural"?

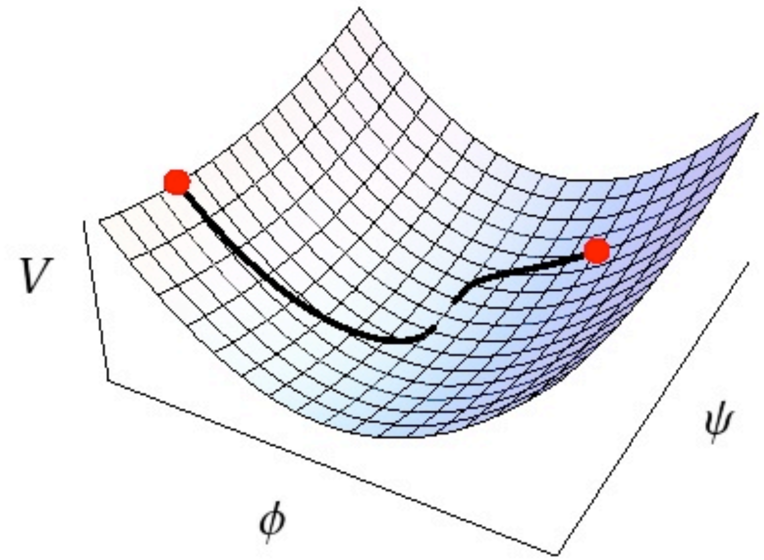
- Field content of particle physics models often a choice
  -e.g. construction of the Standard Model (chosen to match observations)

- 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

Numerical Study with N=100 fields

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

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

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

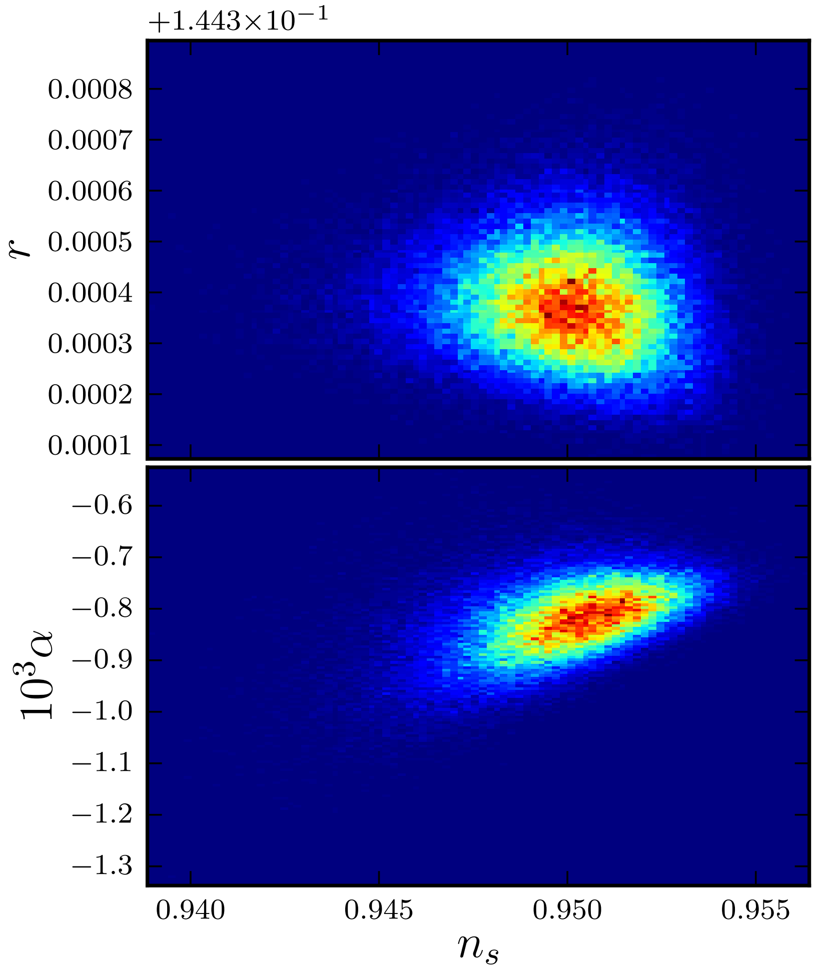
- Masses drawn from Marchenko-Pastur distribution with β=0.5.
largest mass ratio 1/8.08, other masses equally spaced in cumulative PDF

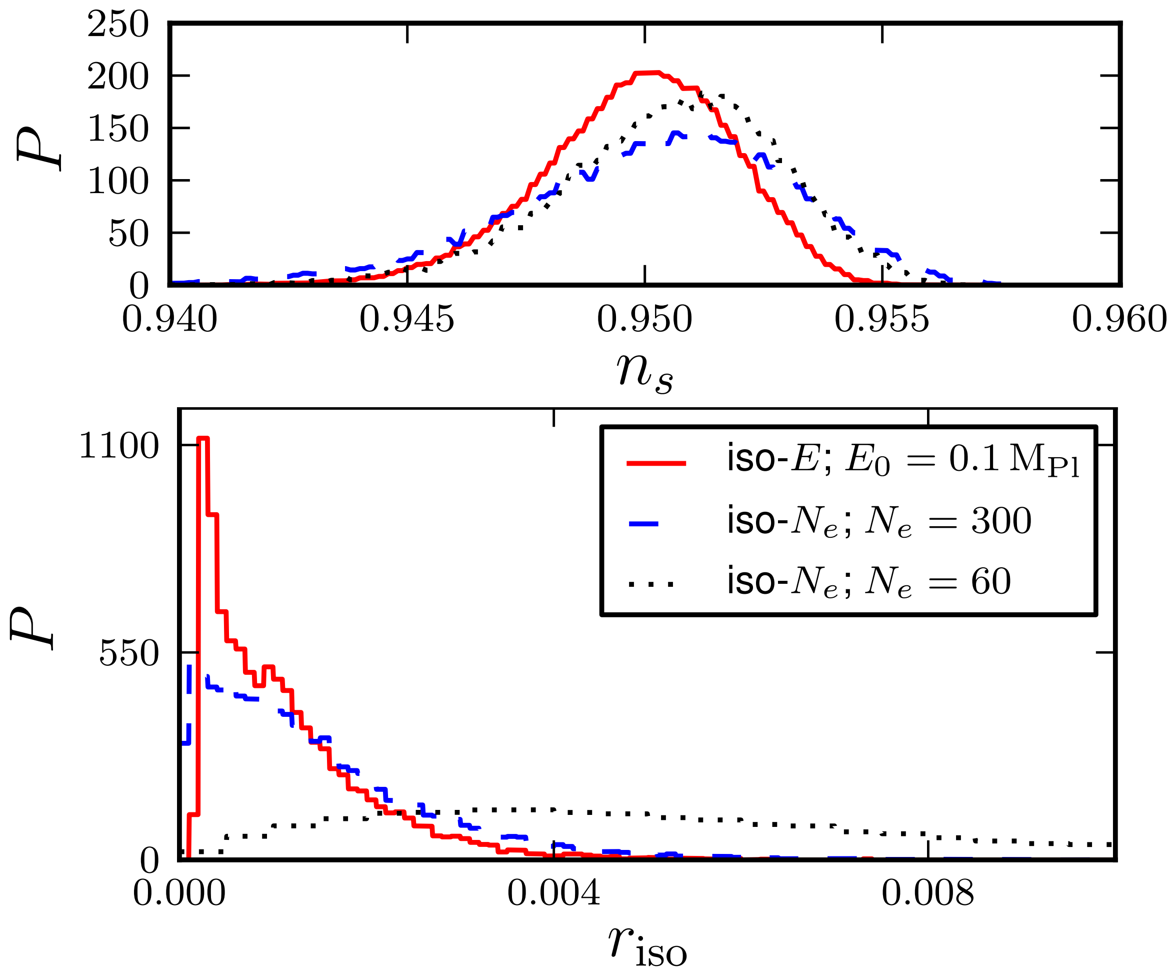
- Solve full perturbation, compute isocurvature modes at end of inflation. *identify inflationary trajectory, compute N-1 orthogonal perturbations (Gram-Schmidt)*

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

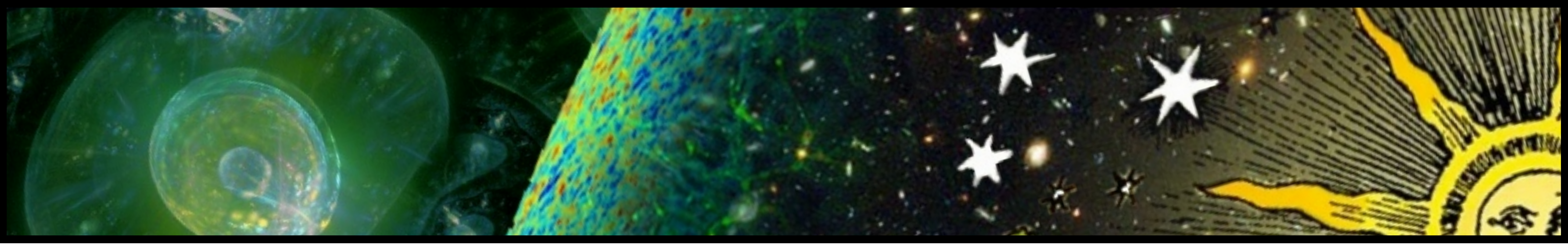
Assessing predictivity of many-field inflation

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





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



Roadmap

- Inflation in a post-Planck world
- Towards understanding the physics of inflation
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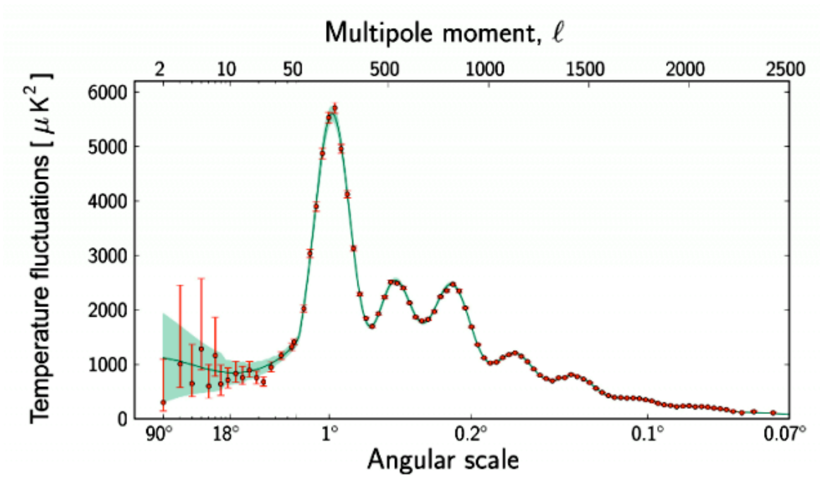
Model-building in a post-Planck world

- No NG detection: stalls progress via "bottom up" approach (e.g. reconstruction via measuring EFT observables...).

- "Top down" approach (model-building first) looks more promising.

- Non-generic correlations between 2pt+3pt+... observables provide powerful constraints on such models



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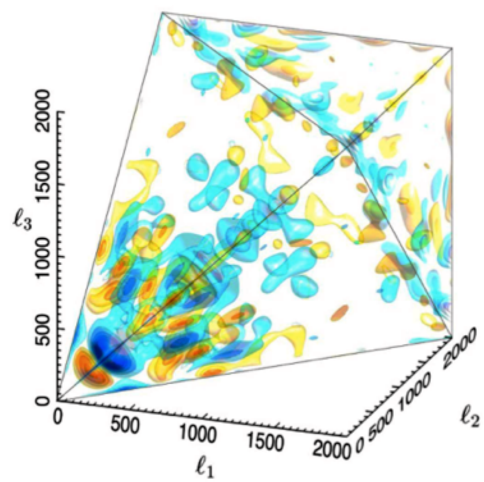


Axion monodromy inflation

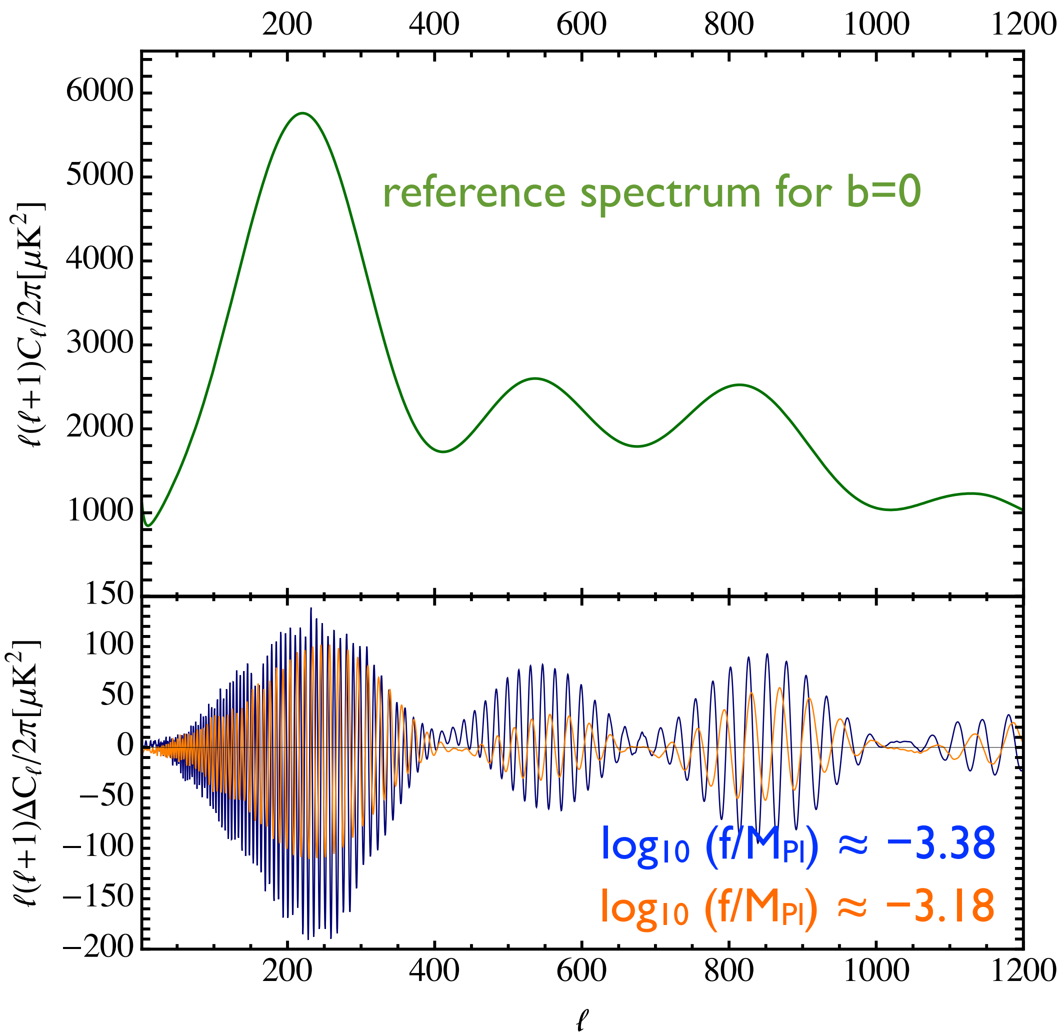
- Large field range, wrapped around a compact direction
- High scale, detectable tensors, theoretical "control"
- Wrapping provides extra scale: modulated spectrum?

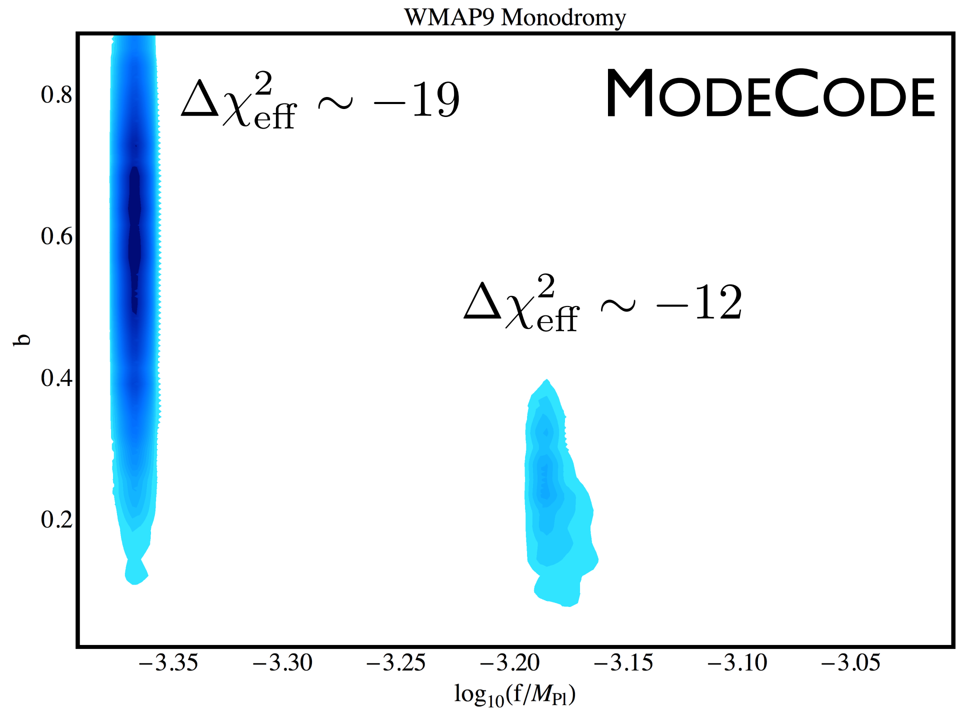
$$V(\phi) = \mu^3 \left[\phi - bf \left(\cos\left(\frac{\phi}{f} + \psi \right) - c \right) \right]$$

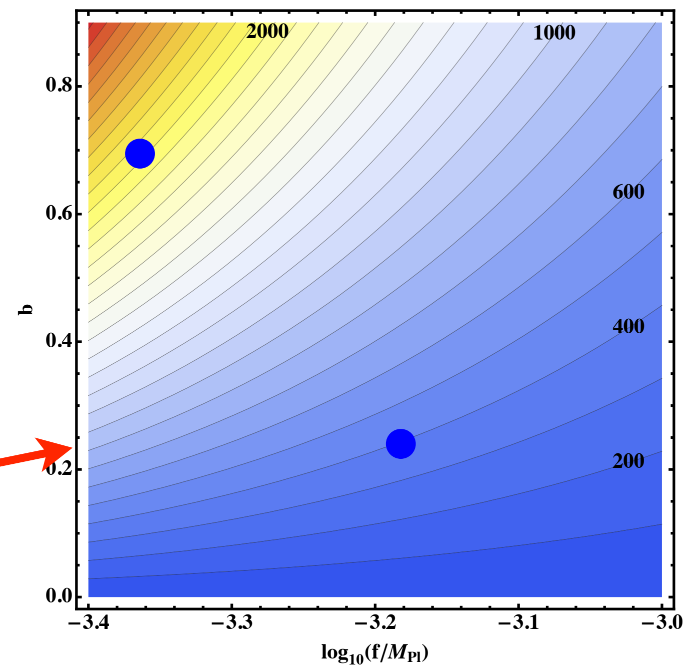
- Amplitude of perturbations set by μ
- Axion decay constant f: sub-Planckian, f > few x 10-4
- Modulations: $0 \leq b < 1$ to prevent trapping

Silverstein and Westphal: arXiv:0803.3085, Flauger, McAllister, Pajer, Westphal and Xu: arXiv:0907.2916, Flauger and Pajer: arXiv:1002.0833

Power spectrum modulations

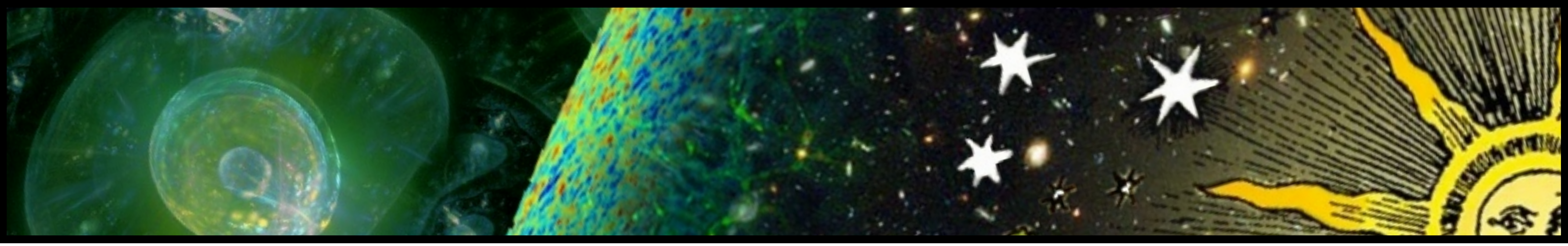






Axion monodromy: fit to power spectrum yields predictions for polarisation and resonant NG

Peiris, Easther and Flauger (JCAP 2013, arXiv:1303.2616)



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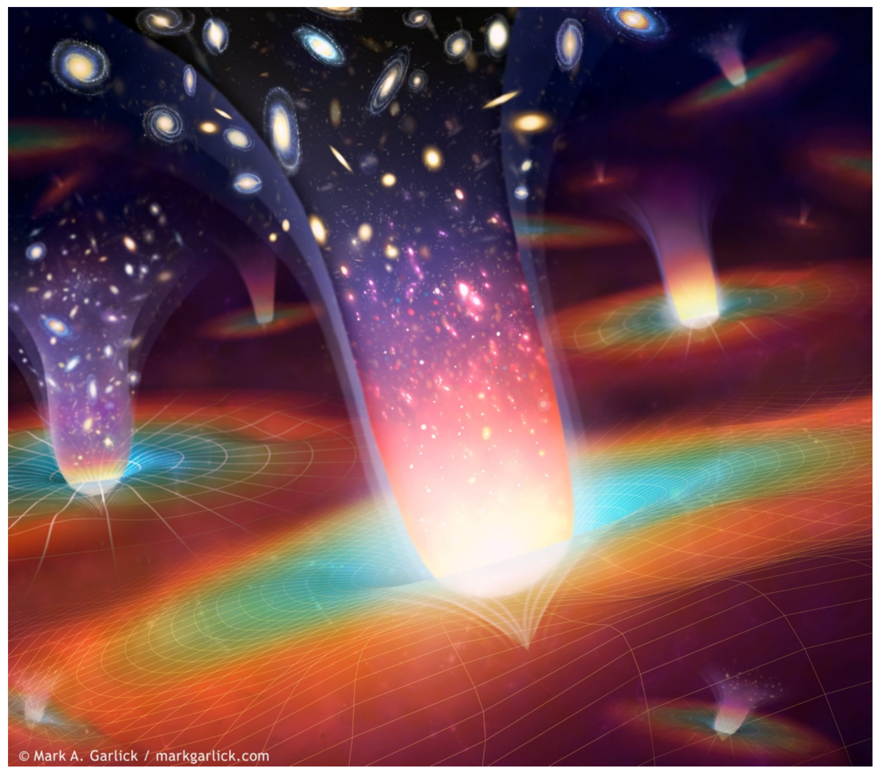
Eternal inflation

- Current fundamental theories do not predict a unique vacuum.

- There is observational evidence for accelerated expansion both in the early and late universe.

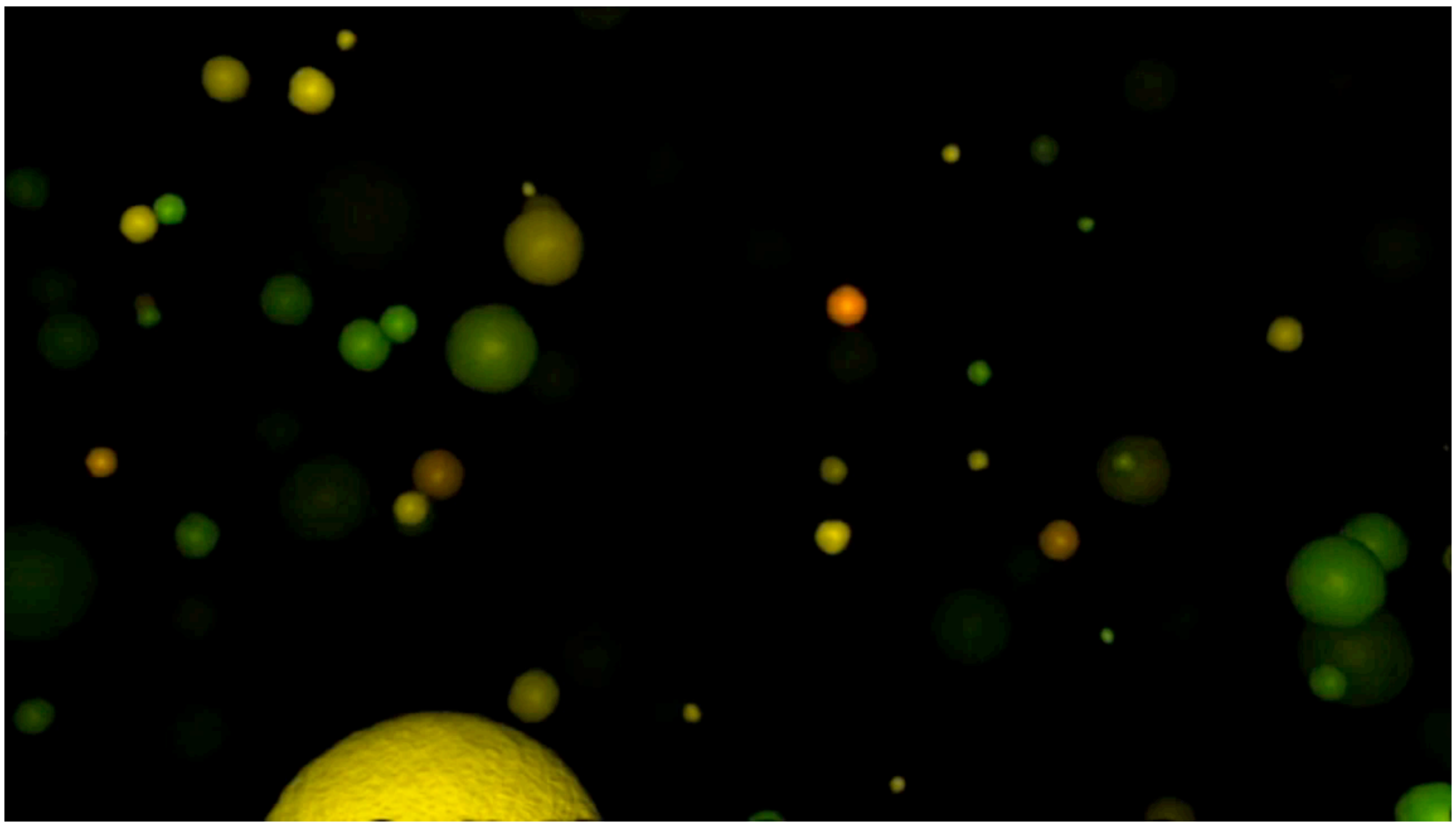
- Strongly motivates that we inhabit an eternally inflating universe.



Eternal inflation

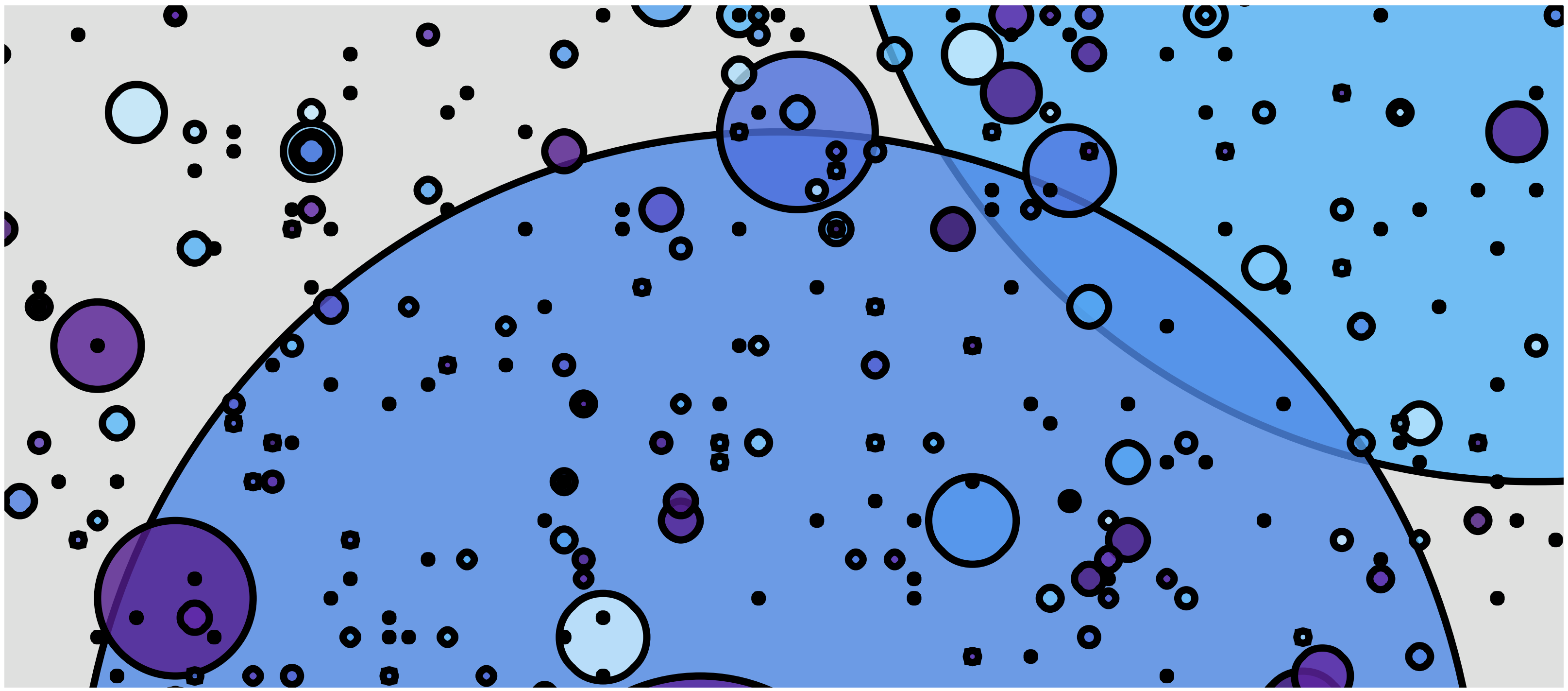
- With positive vacuum energy, bubbles form, but space expands between them: inflation can become eternal.

- When rate of bubble formation < rate of expansion, accelerated expansion never ends everywhere, only inside "bubble universes".



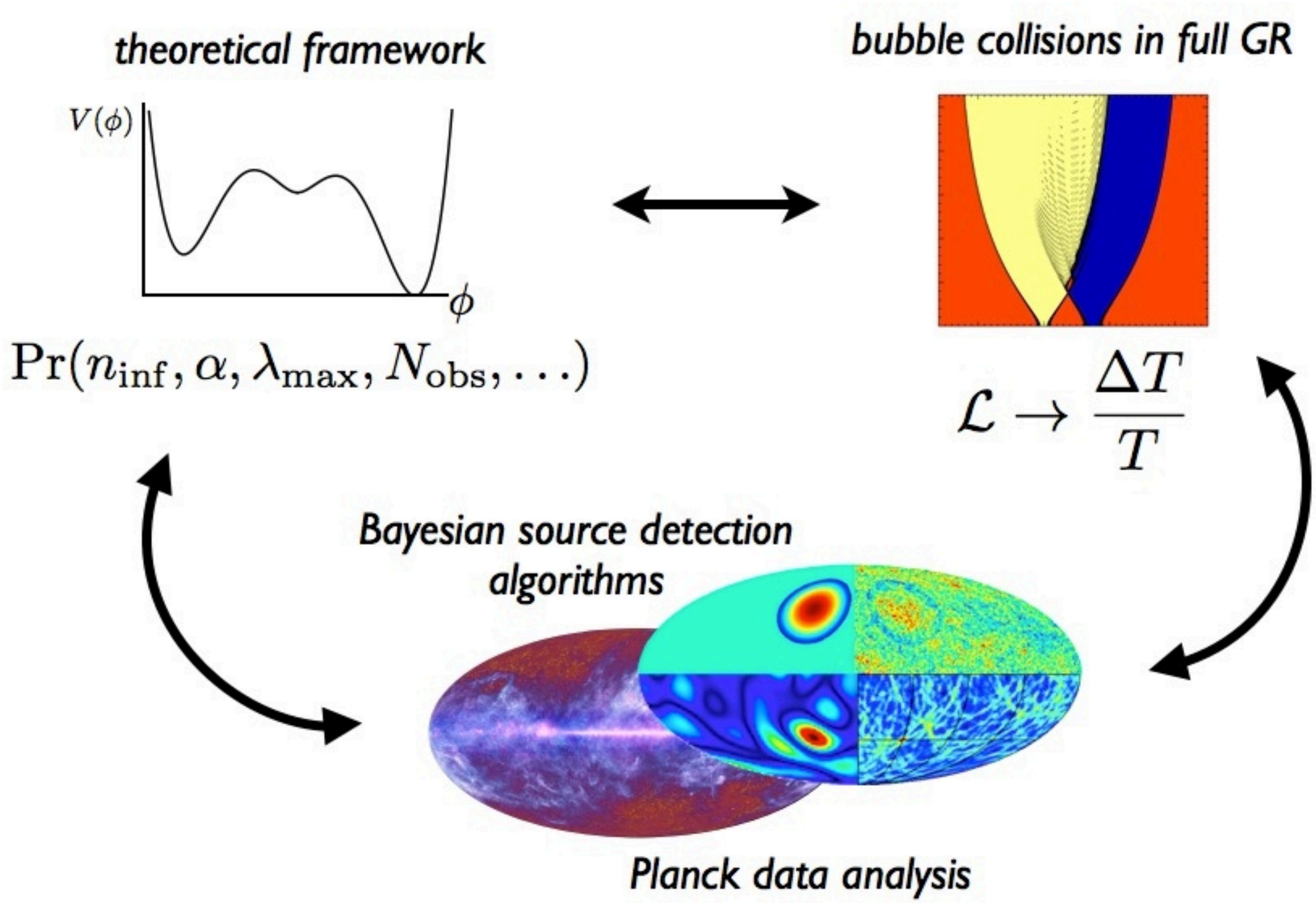
Observational tests?

- The collision of our bubble with others provides an observational test of eternal inflation.



- **Harsh reality**: relics from very early universe get erased by too much inflation. But important proof of principle that a "multiverse" can make quantitative & testable predictions.

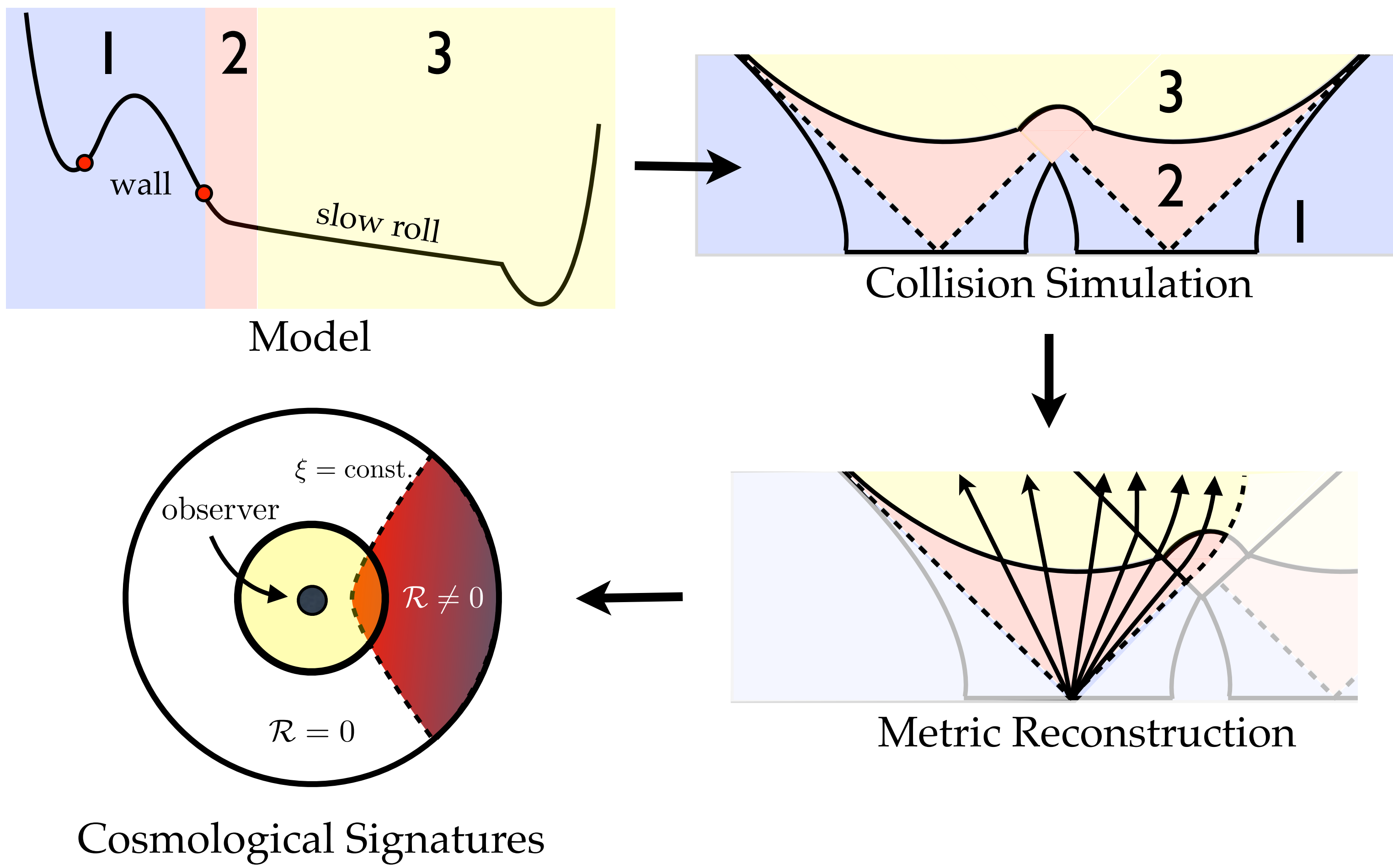
What are the theoretical priors?



Need relativistic numerical simulations to determine full set of dynamics that occur in bubble collisions + specific signals of collisions in the CMB.

huge center of mass energy in collision; non-linear potential, non-linear field eqs.

Simulations in full General Relativity

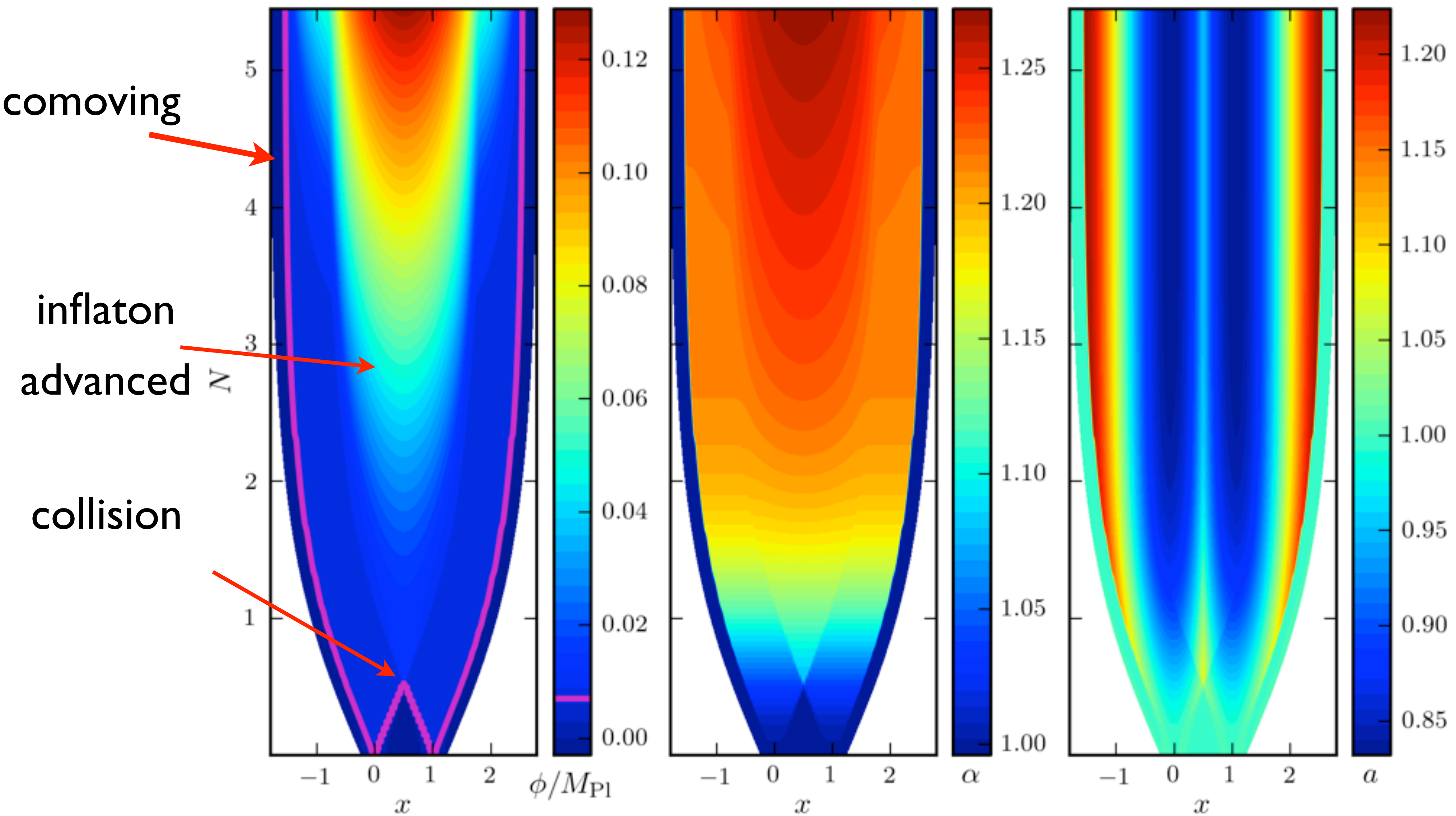


Collision symmetry *SO*(2,1): 1+1 relativistic simulations in models yielding O(1) collision signatures per CMB sky. *Evolution code: 4th order convergence, AMR, adaptive simulation boundaries. Initial conditions with CosmoTransitions.*

Wainwright, Johnson, HVP, Aguirre, Lehner, Liebling (JCAP 2014, arxiv:1312.1357), also see Johnson, HVP & Lehner (JCAP 2012, arXiv:1112.4487)

Example

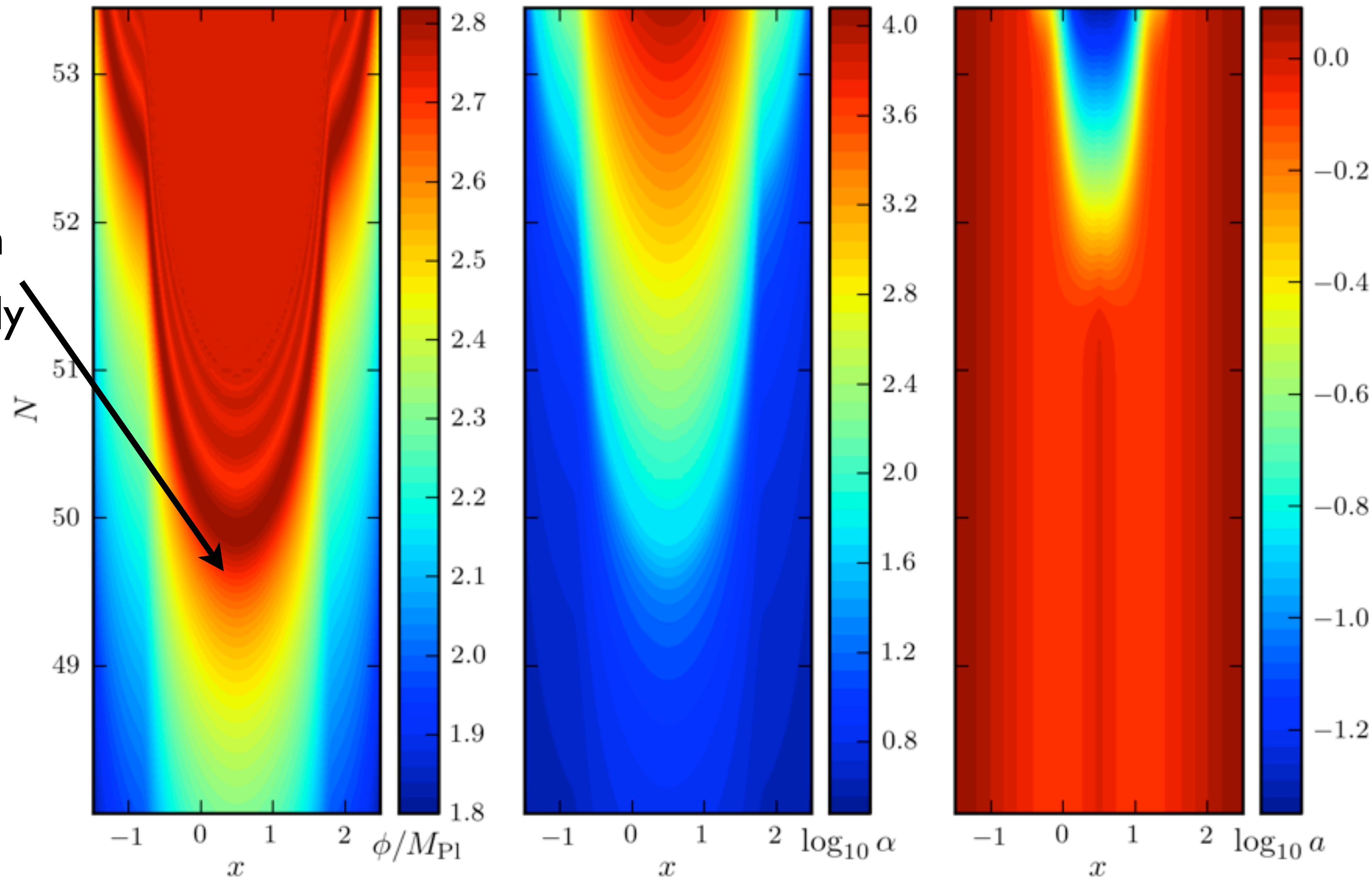
- The bubbles are evolved all the way from nucleation.....



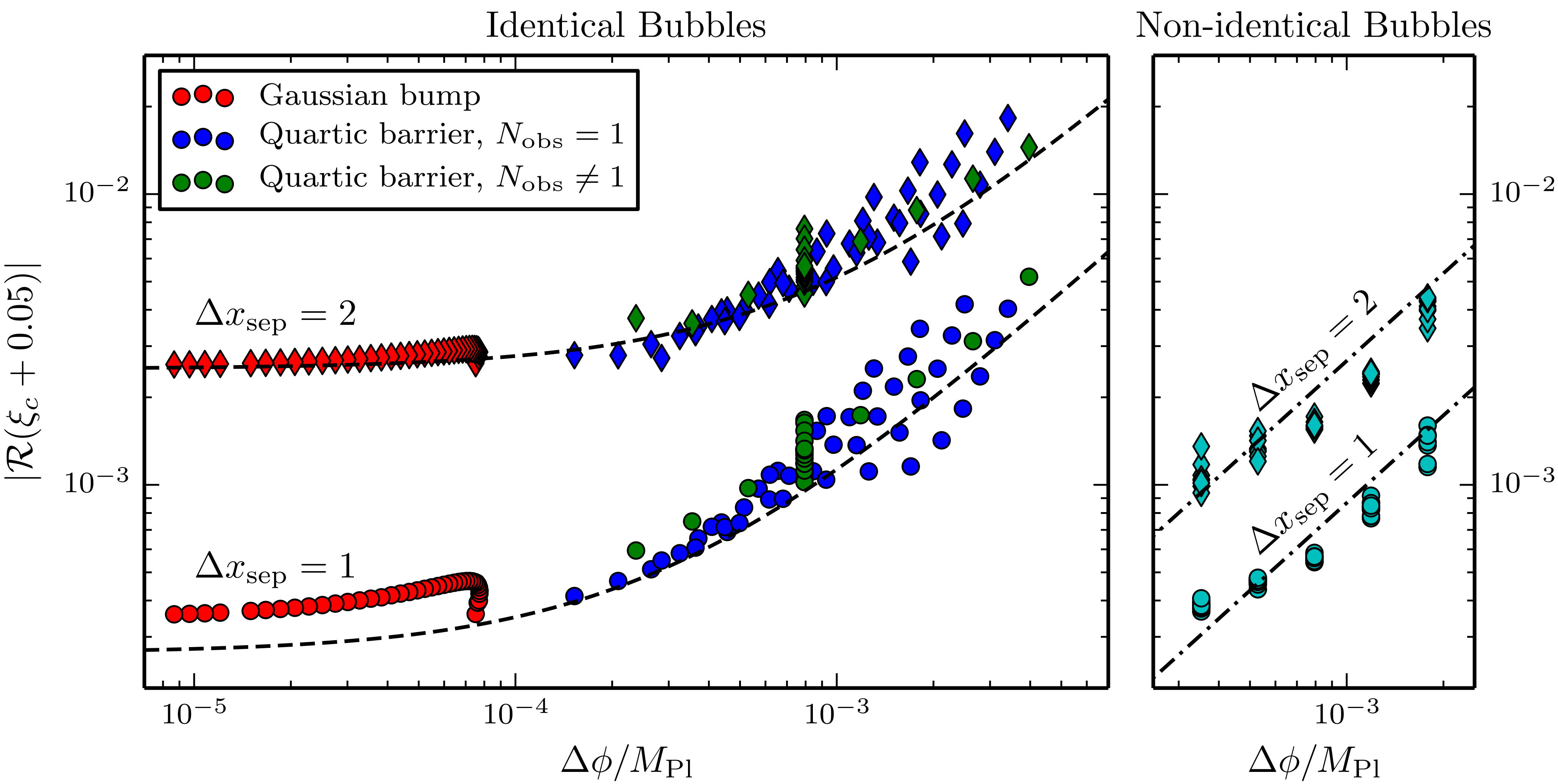
Example

- .... to the end of inflation inside each bubble.

Inflation ends early

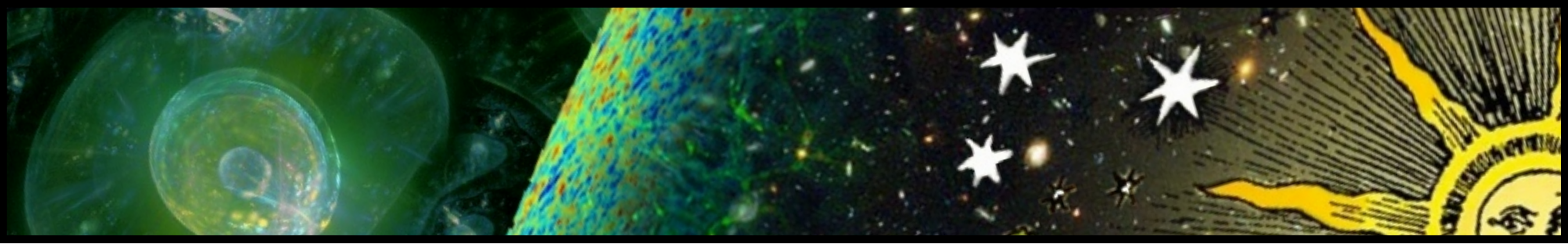


Linking tunnelling physics with observations



Amplitude of observational signature determined by collision barrier width and initial bubble separation!

Wainwright, Johnson, Aguirre, HVP (to be submitted)



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Experimental landscape in 2024

- ***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/late 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*
- **Running / broken scale-invariance:** *non-minimal physics*
- **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*
- **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....*

Life under a "standard model": A balanced portfolio for progress

Standard cosmological model is phenomenological.

GR + broken time-translation invariance+ homogeneity + isotropy + initial conditions

Two paths to a paradigm shift

Nima Arkani-Hamed, quoting John Wheeler

Conservative Radicalism

Give up principles / model assumptions one-by-one and explore consequences. Must be done rigorously - principles are precious - beware epicycles.

Radical Conservatism

Take the model seriously and explore its predictions in hitherto untested regimes. Eventually it will break. This is how paradigm shifts in physics have typically happened.


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