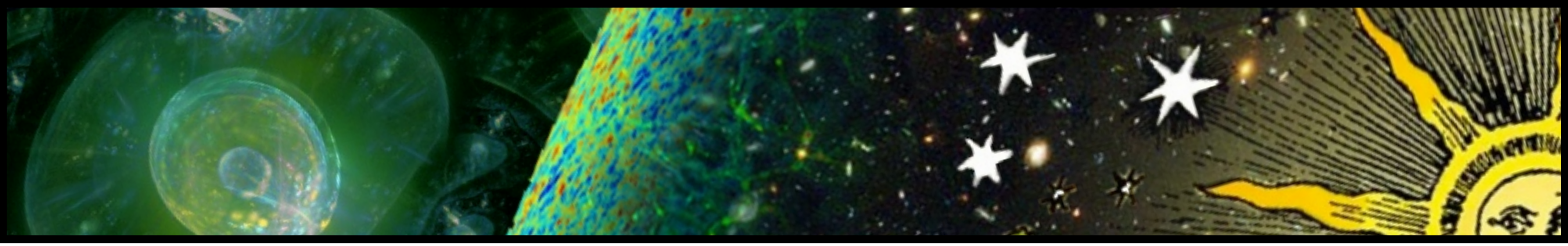


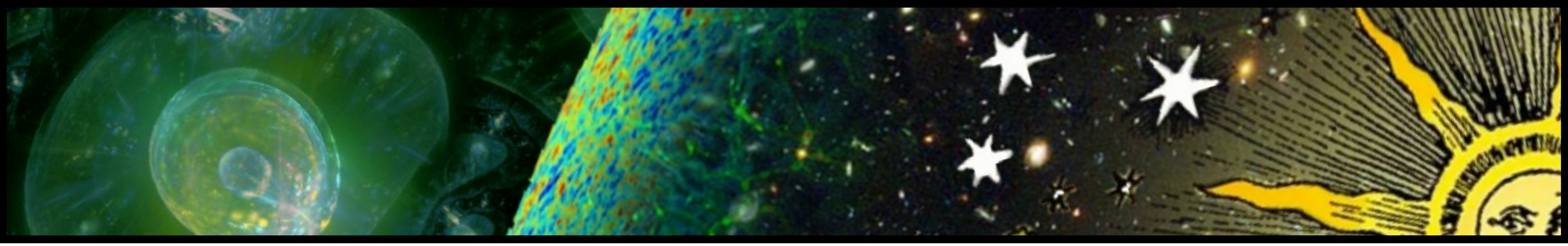
# Cosmological inflation: From observations to fundamental physics

**Hiranya V. Peiris**
*University College London*

Science & Technology Facilities Council

erc
European Research Council

IDEAS



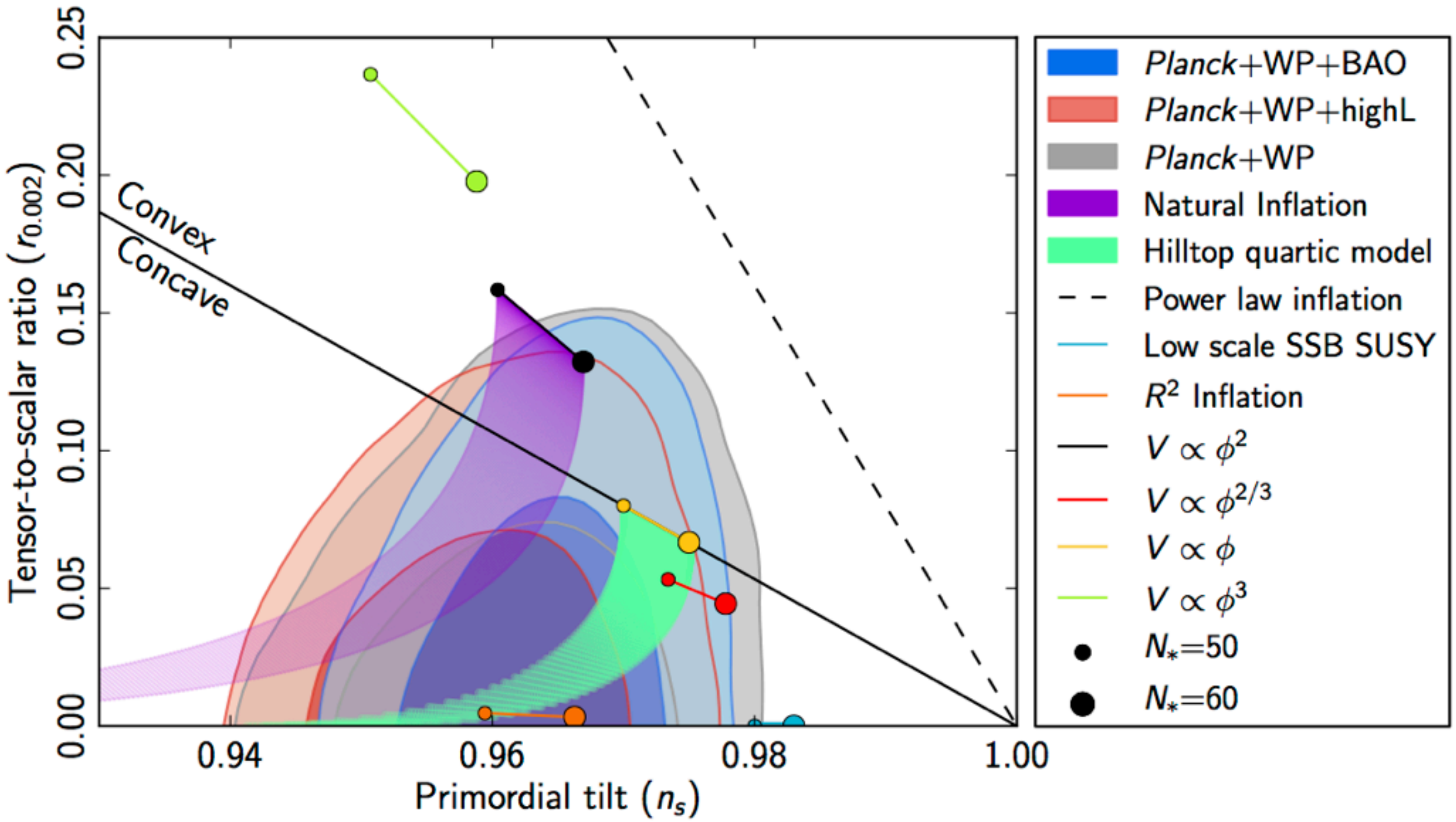
# *Roadmap*

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

(Part of) the Planck team

# *Known-knowns in a post-Planck world*

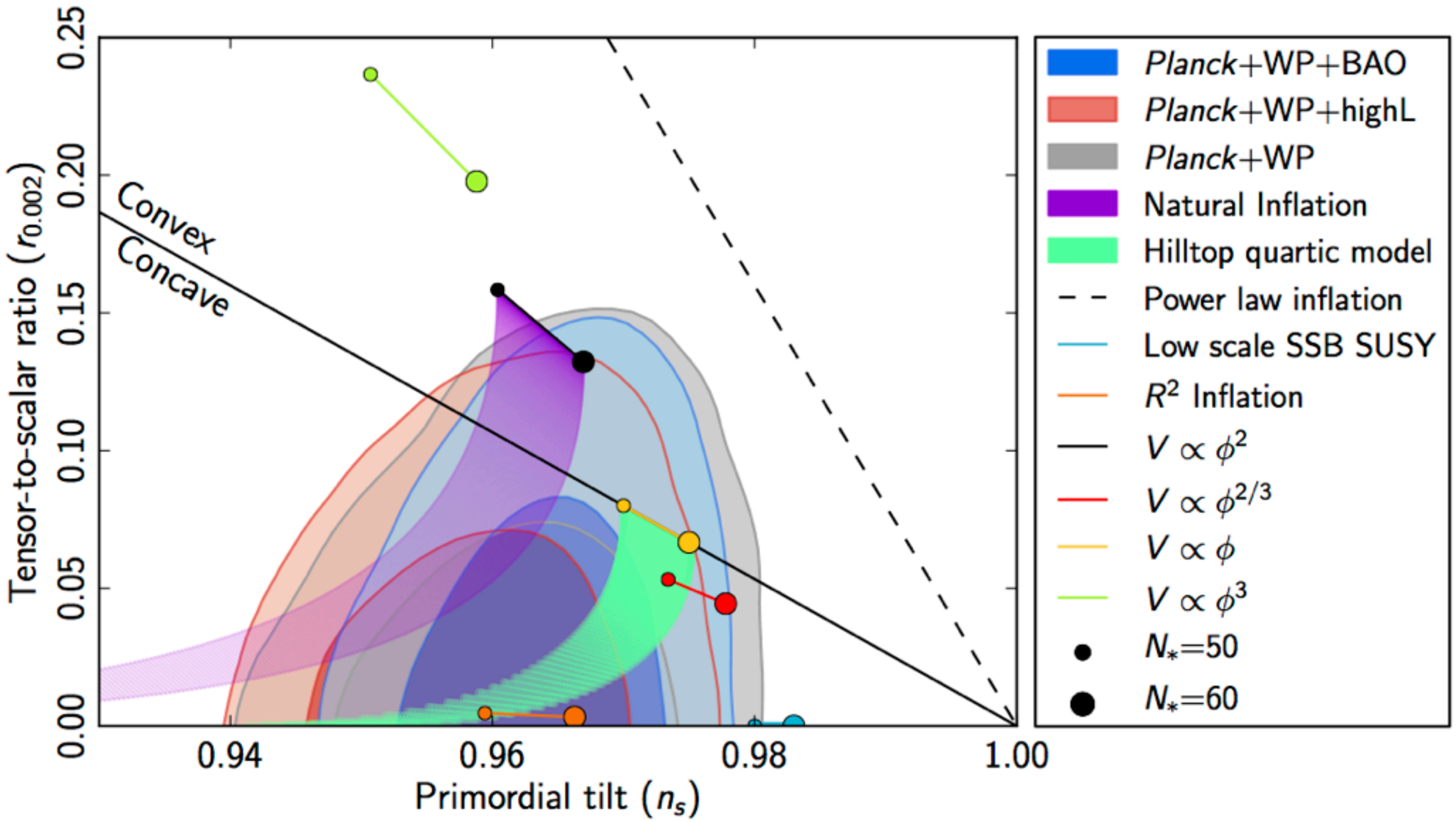
- Exact scale invariance ($n_s$=1) ruled out at >5σ by a single experiment
- While convex potentials are still allowed, Planck hints that flattened potentials are preferred




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
- 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*

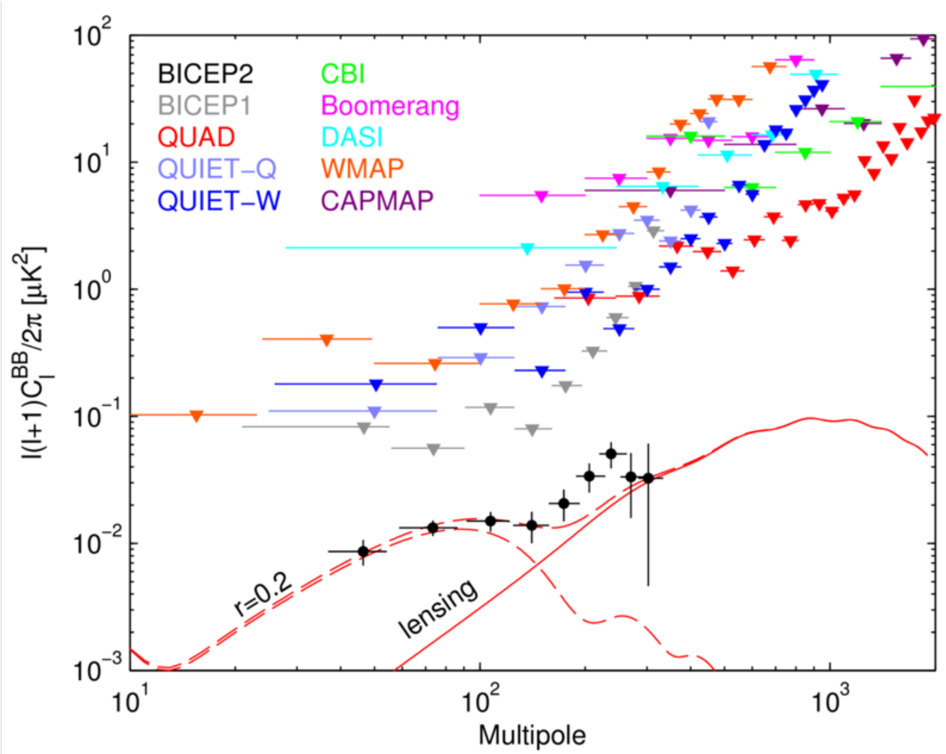
- Measured to 1 part in 10,000 (most precise cosmological measurement!)
- Bispectrum now a routine observable, like the spectral index
- Standard bispectrum configurations not detected by Planck; stringent constraints on local/equilateral/orthogonal etc shapes

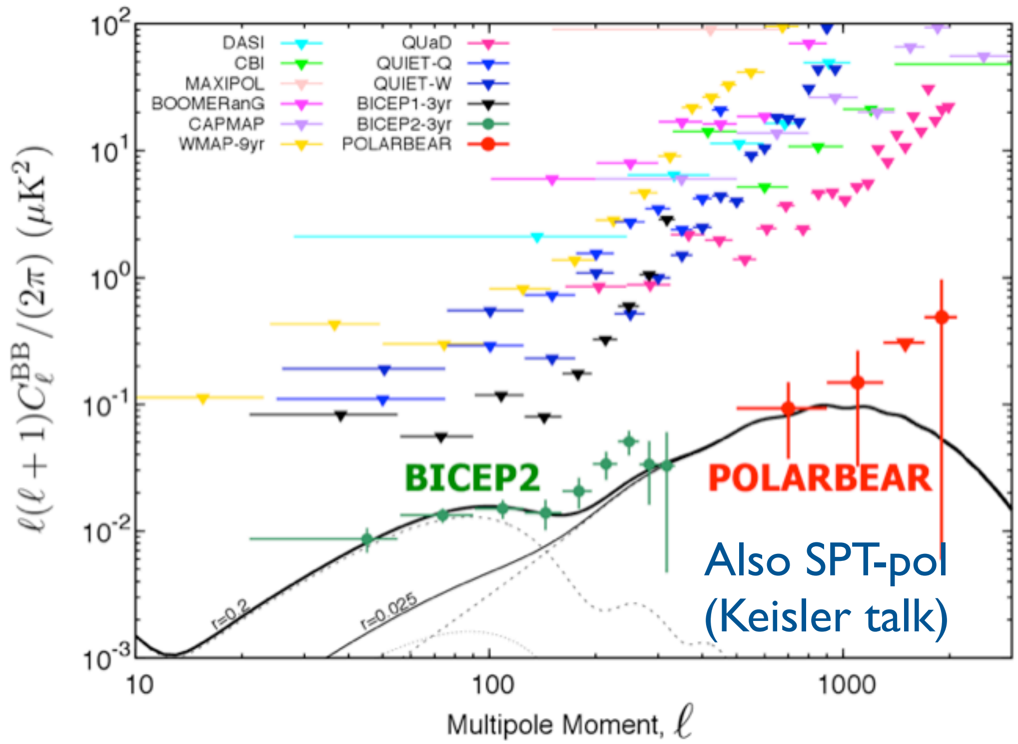
| Shape | ISW-lensing subtracted KSW |
|---|---|
| Local | 2.7 ± 5.8 |
| Equilateral | -42 ± 75 |
| Orthogonal | -25 ± 39 |

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

- *higher order terms and broken-scale-invariance shapes poorly explored*

# *Milestone: measurement of B-modes*




Also SPT-pol
(Keisler talk)

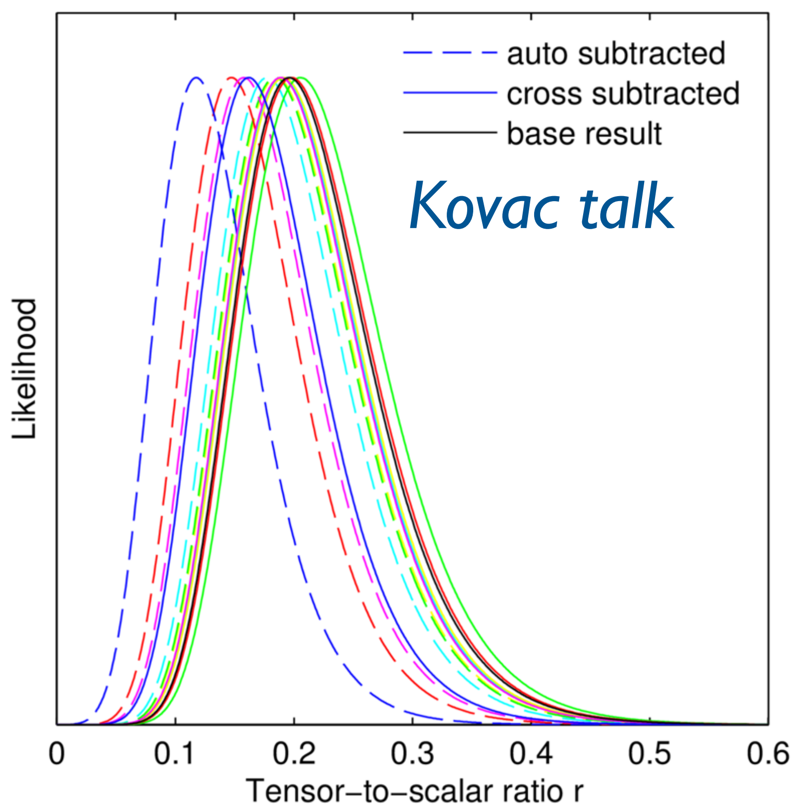
BICEP2 + PolarBear *BB* auto spectra and 95% upper limits from several previous experiments.

*B2 errorbars include sample-variance from r=0.2*

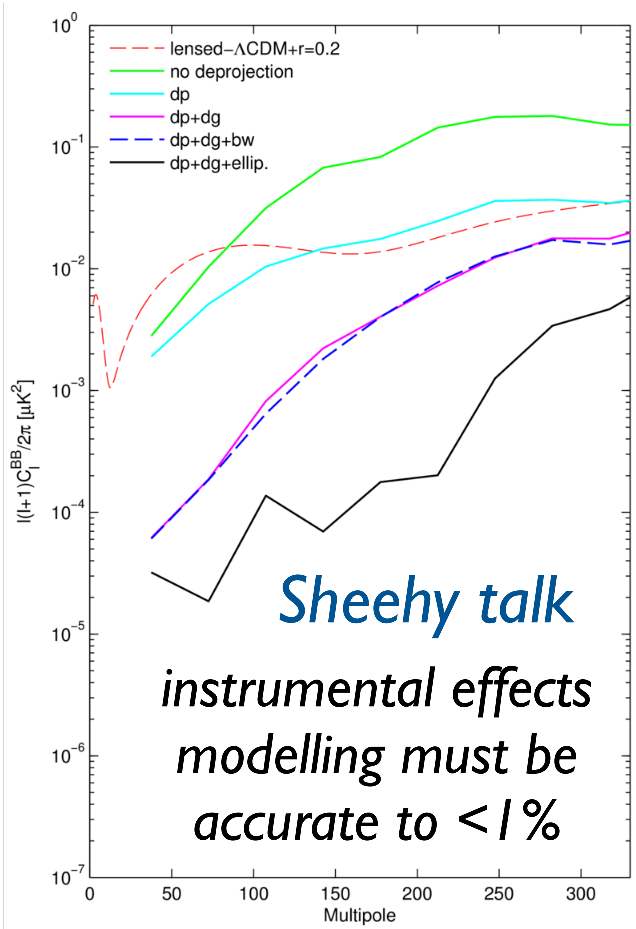
*Figures: BICEP2*

# *BICEP2 thoughts*

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



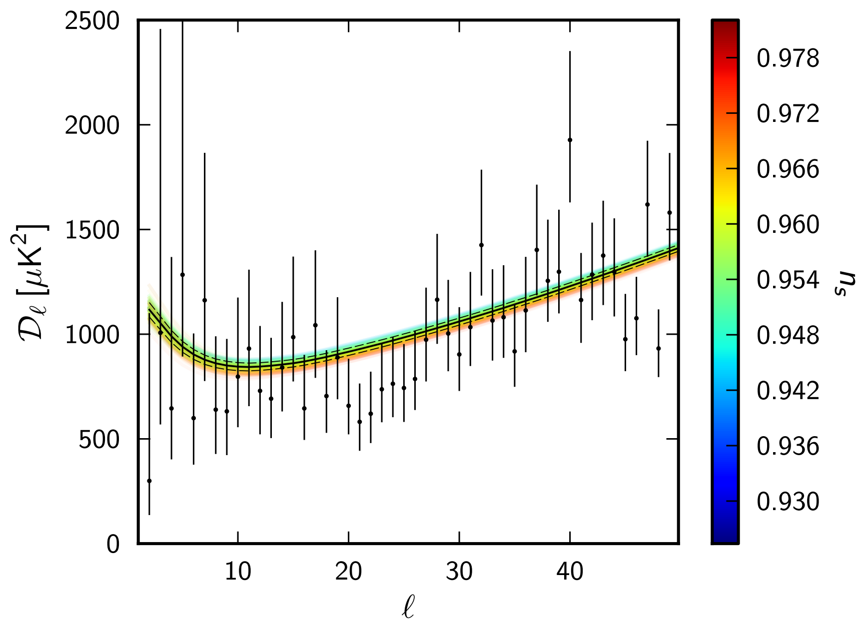

*(Known) FG modelling can bring down the signal to r<0.1*

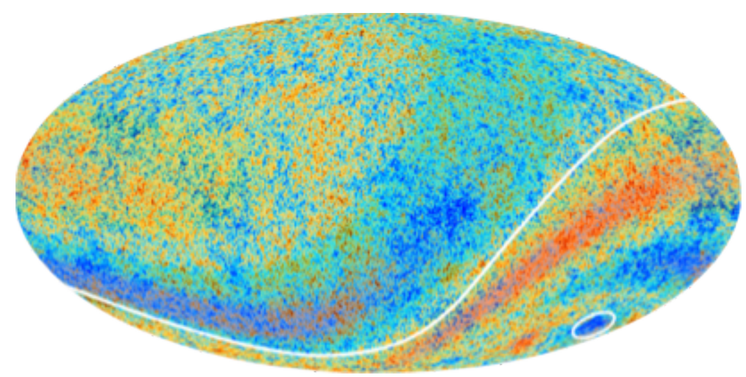



*Figures: BICEP2*

# *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

A period of accelerated expansion

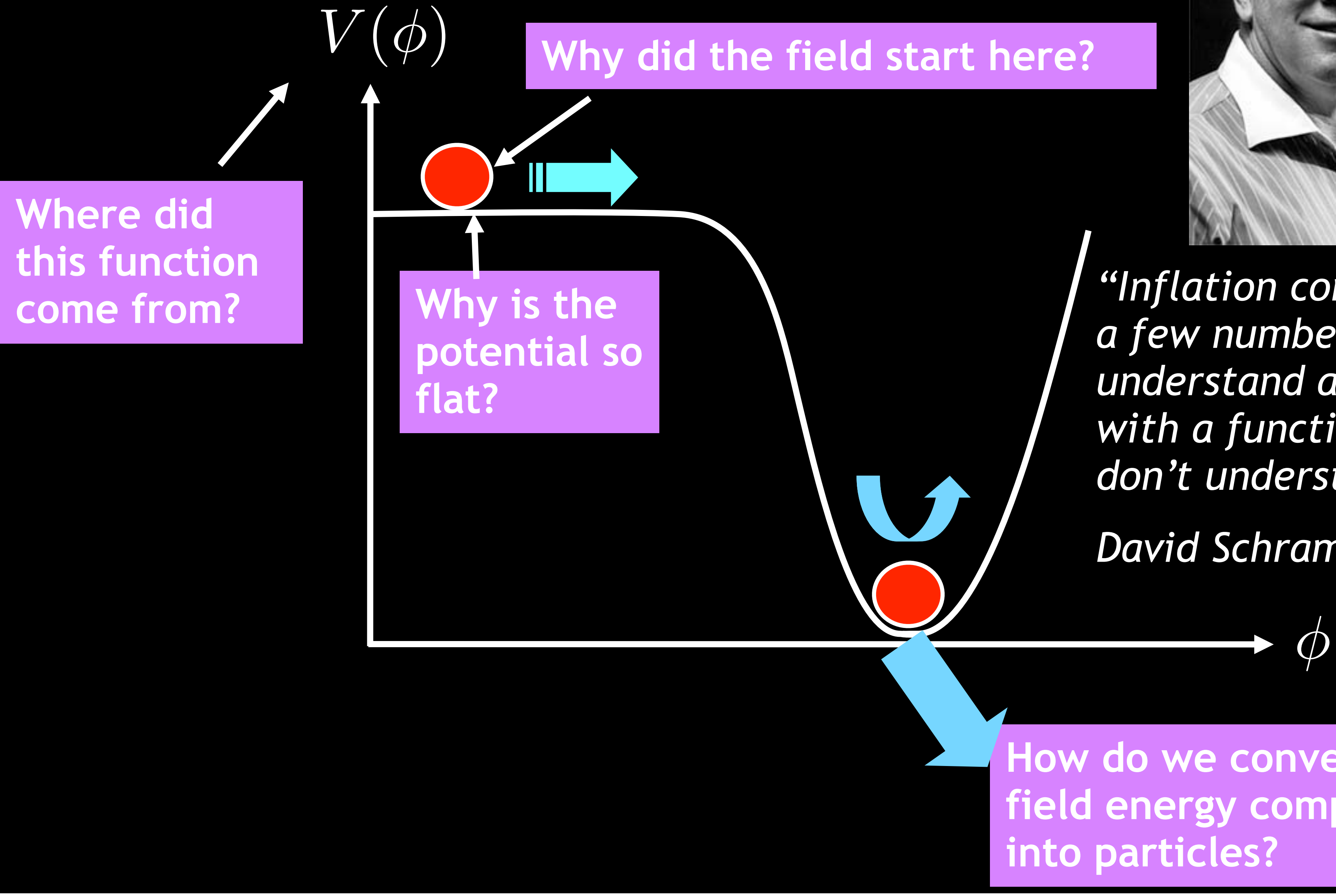
$$ds^2 = -dt^2 + e^{2Ht} dx^2 \qquad H \simeq \mathrm{const}$$

- 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 but not exactly scale-invariant (>5σ!)
    - ✓ approximately Gaussian (at the $10^{-4}$ level!)
  - ? primordial tensor fluctuations (gravitational waves)

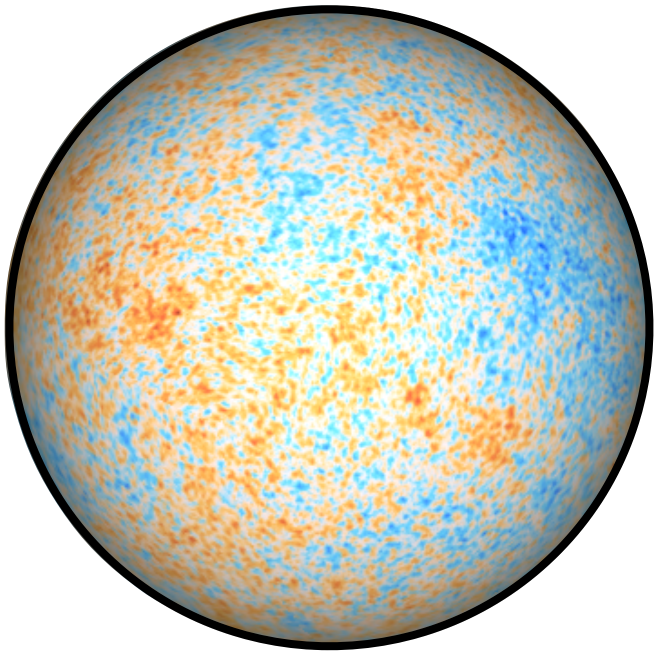
# What is the physics of inflation?



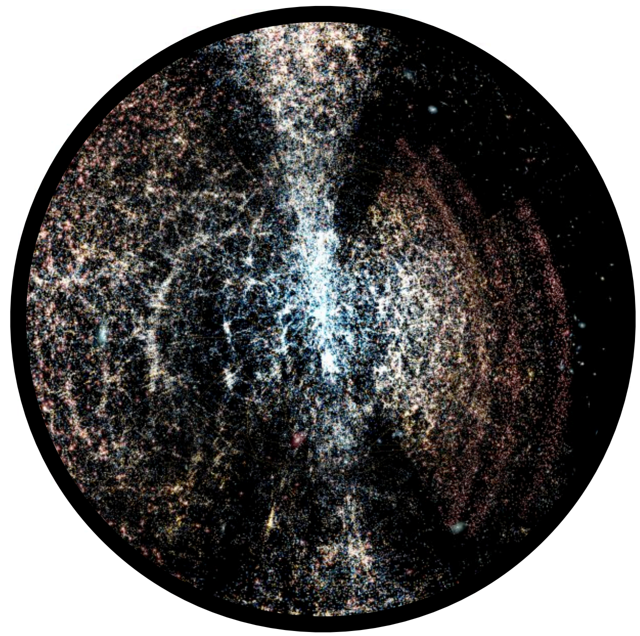

*"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"*

*David Schramm 1945 -1997*

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



**Cosmic Microwave Background**
*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

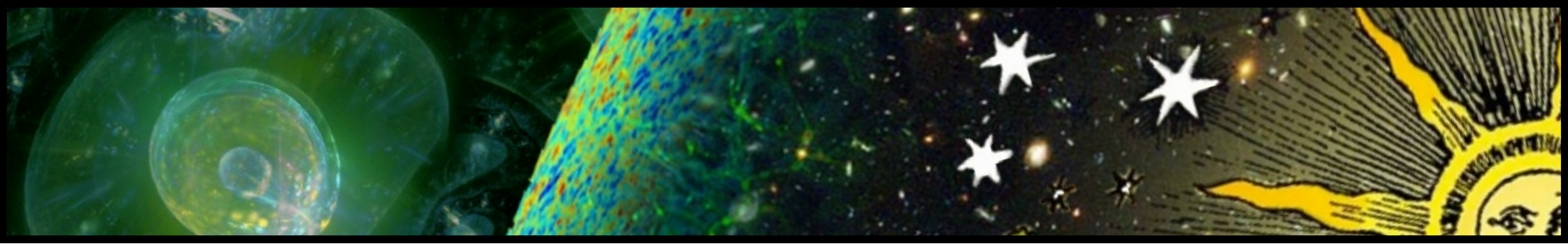
*"Inflation" appears to work in practice. Does it work in principle?*

**2. What is the physics of inflation?**

**3. How did inflation begin?**

**4. What happened after inflation ended?**

**Requires progress in data analysis, theory, interface.**



# ***Roadmap***

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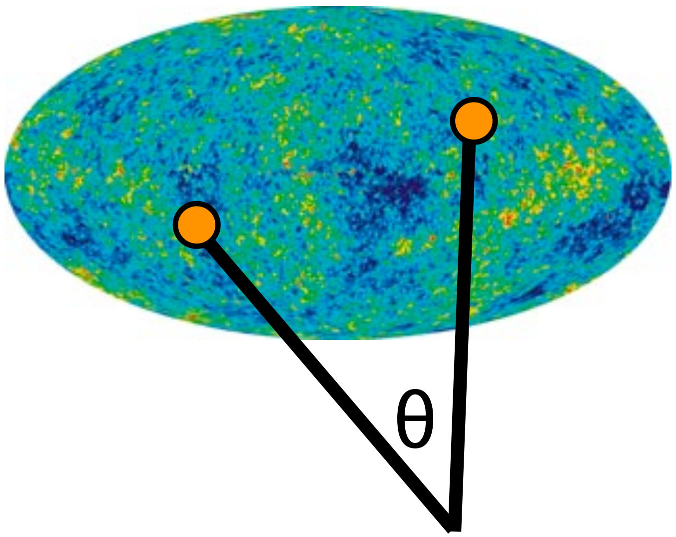
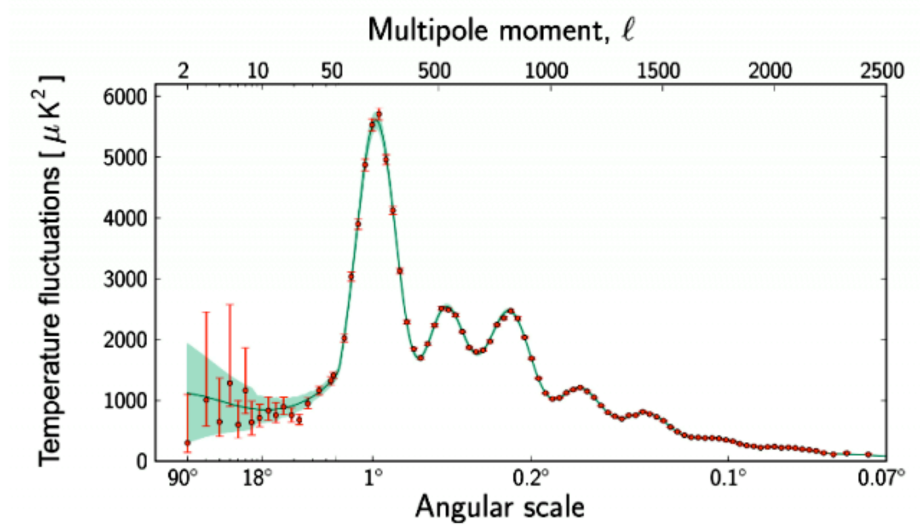
- Strategies for future progress

# *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***.




radical data compression



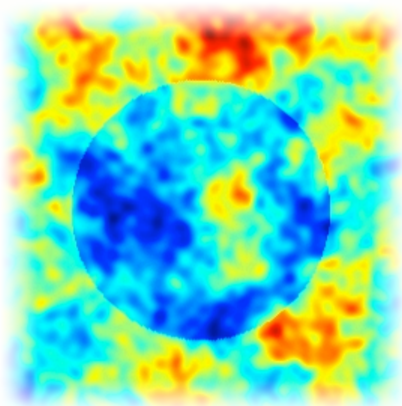

map
50 million pixels

angular power spectrum
2500 multipoles

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

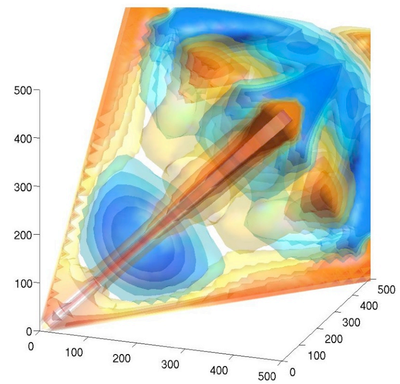
# Beyond the Gaussian

**pre-inflation**



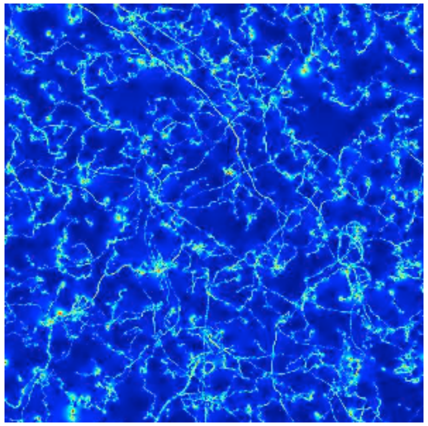
*signatures of collisions between "bubble universes"*

**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).

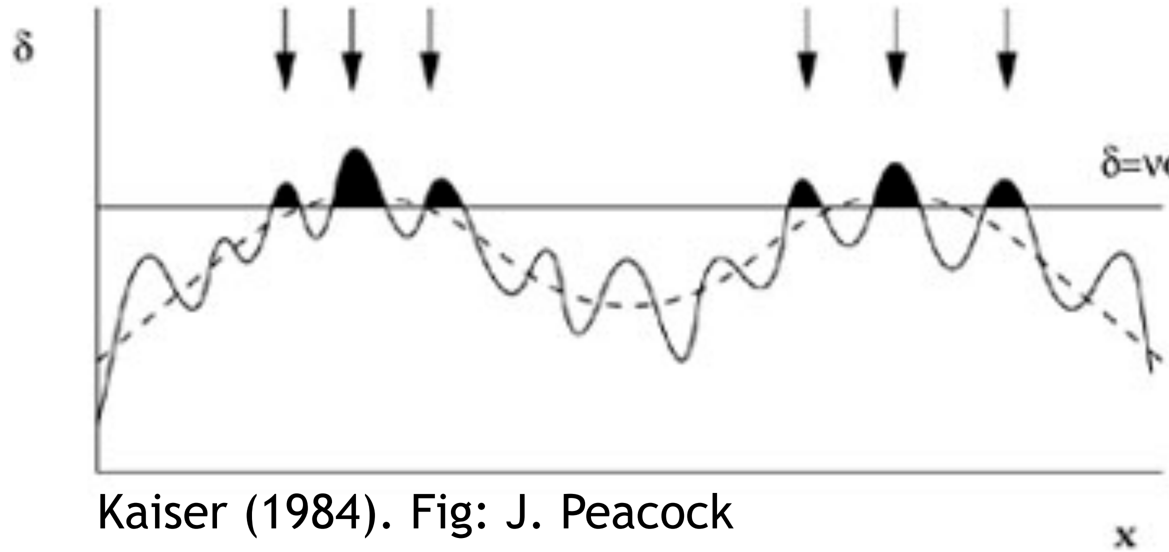
- A detection of $f_{NL}$ >> 1 will immediately rule out the "textbook" picture of inflation.

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

primordial potential

Gaussian field

# *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.

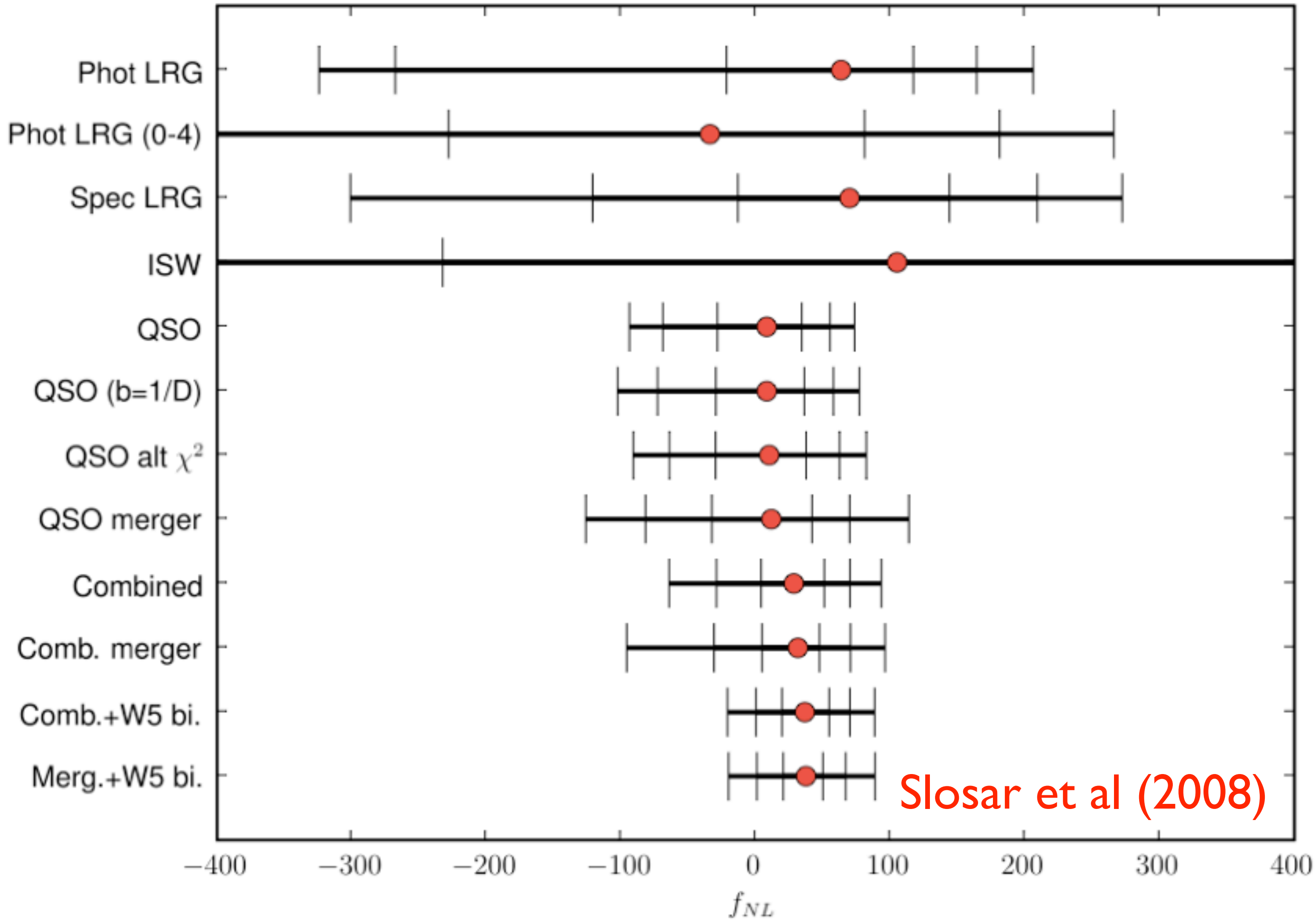
•Enhanced abundance of massive objects in overdense regions leads to enhanced clustering.

•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)

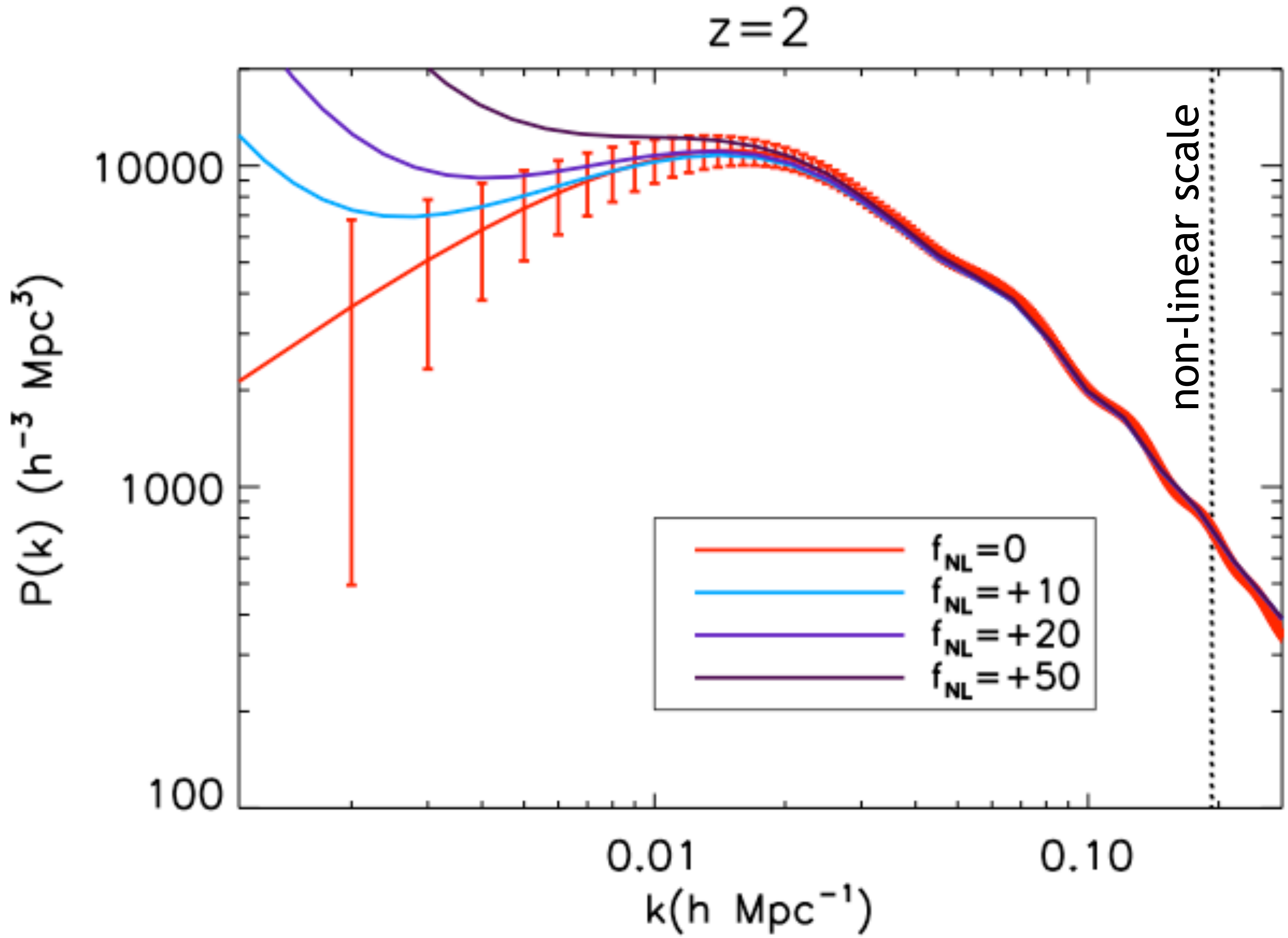
# PNG from large scale LSS angular power spectrum

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




*scale-dependent halo bias (Dalal et al 2008)*

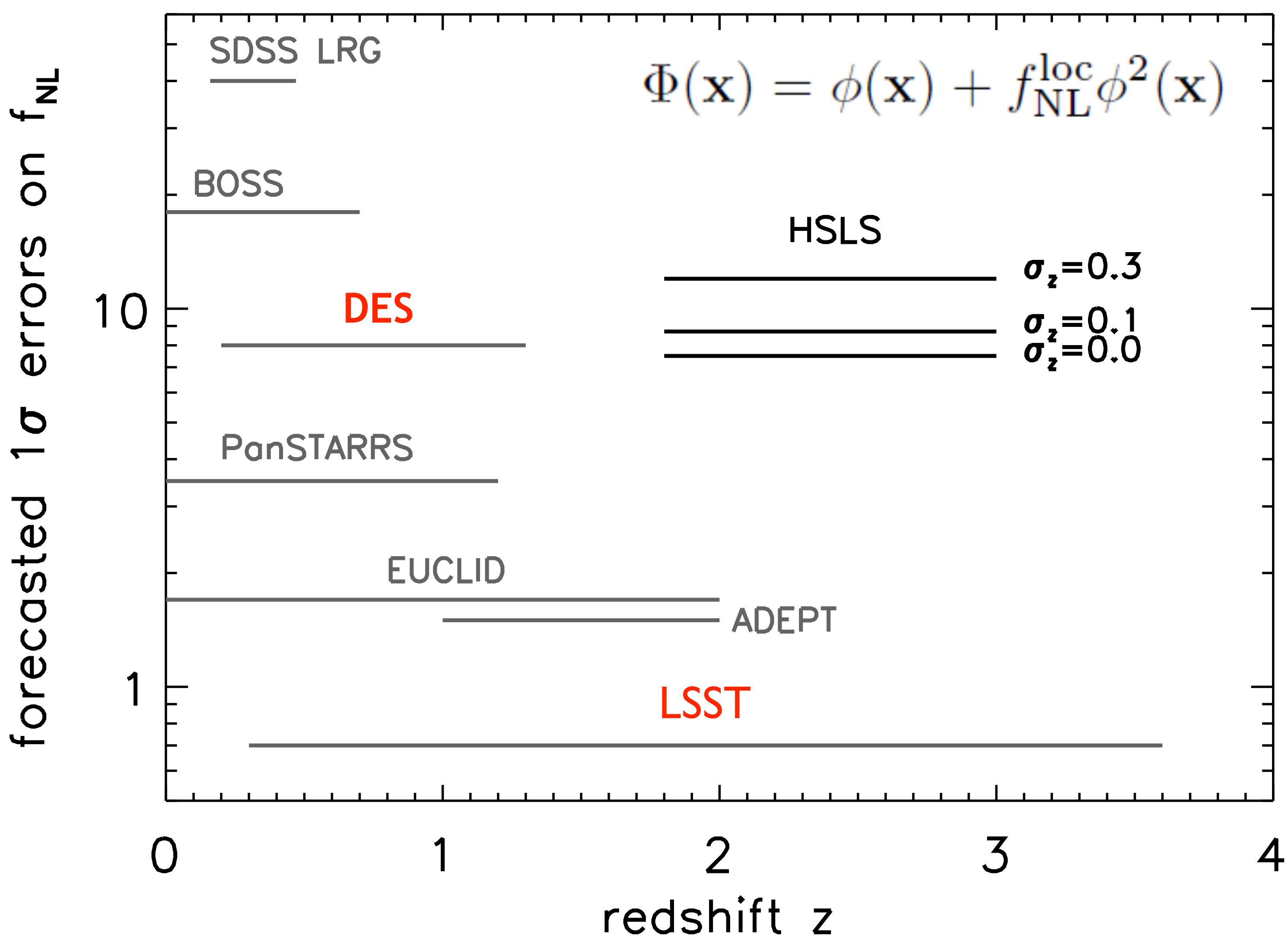
# *Effect on the halo power spectrum*




Power spectra at z=2 for a spectroscopic survey

*Figure: HSLS white paper, HVP CMB/LSS Coordinator*

# LSS forecast for "local" shape



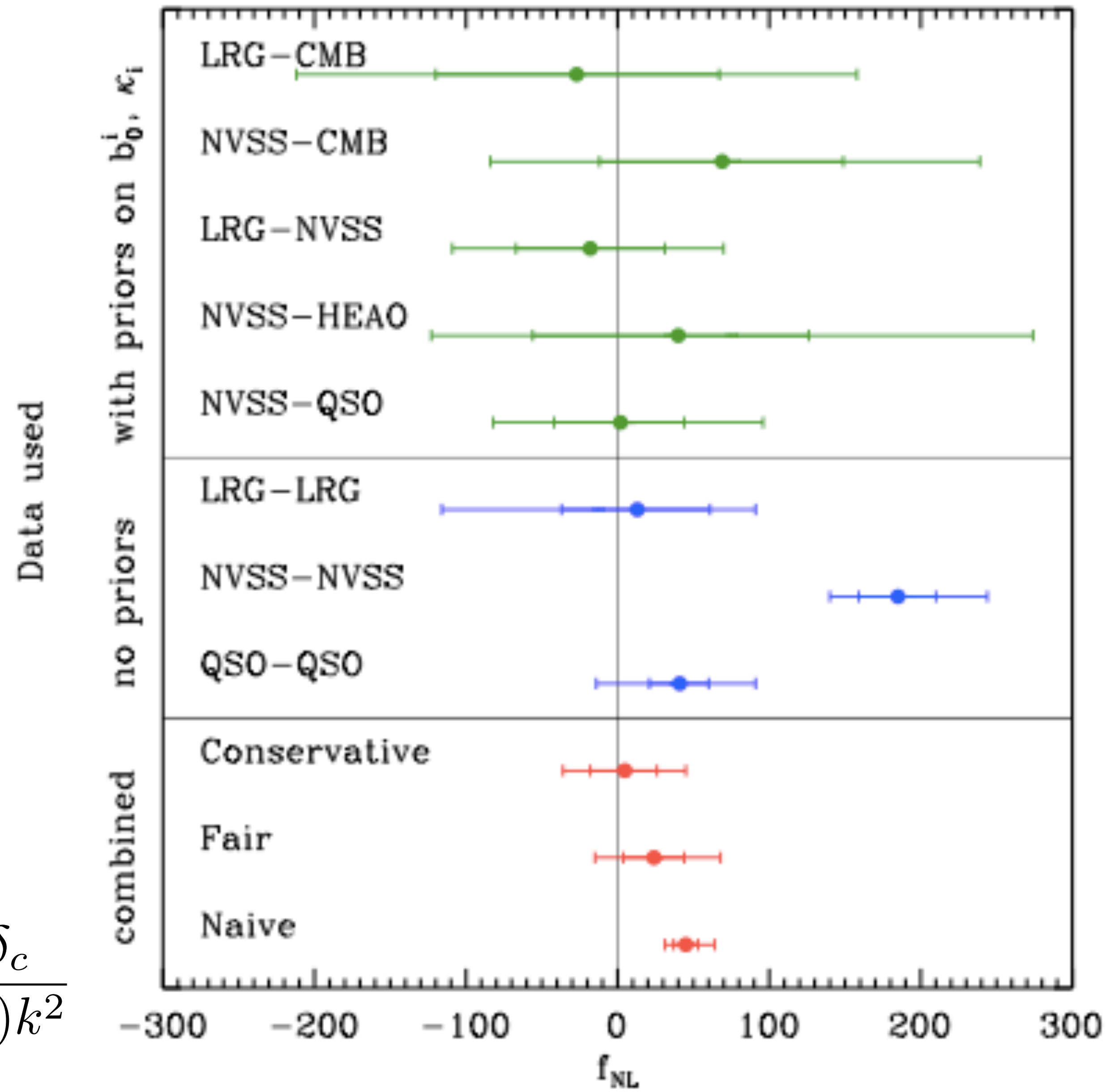

Constraints on $f_{NL}$ assuming Planck priors on the cosmological parameters

*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

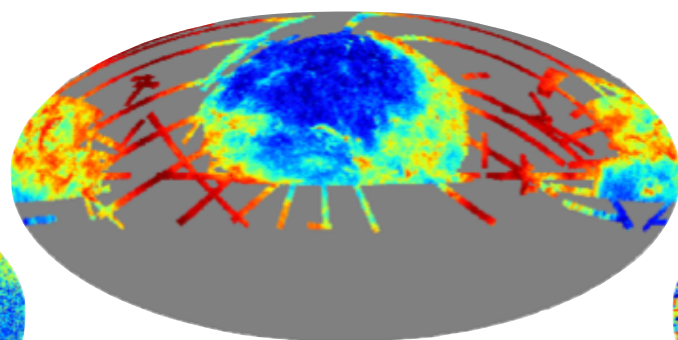



$$\Delta b(k, z) = f_{\rm NL}(b_g - 1)\frac{3\Omega_{\rm m} h_0^2 \delta_c}{D(z)T(k)k^2}$$

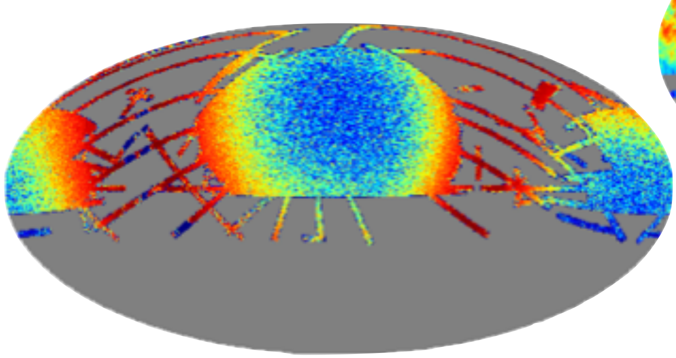
# *Systematics in quasar surveys*

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

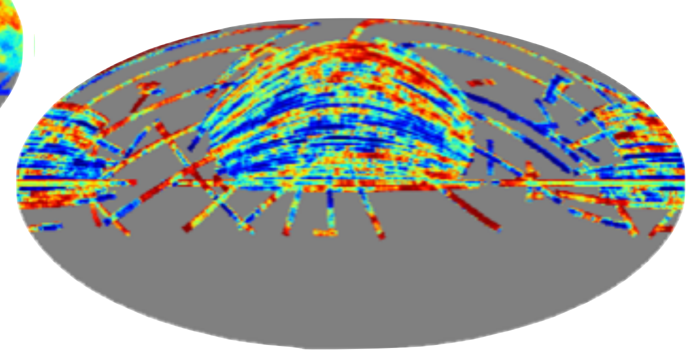
dust



stars



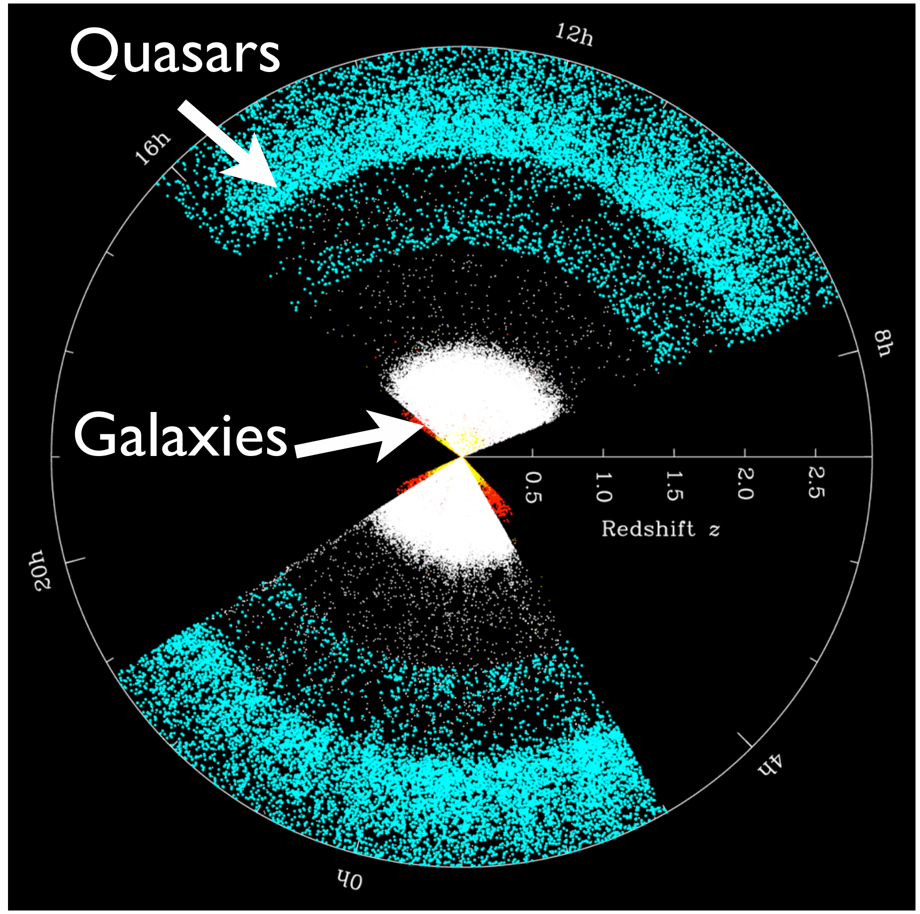
seeing



# 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*

*See Boris' talk Wed CMB/LSS session!*

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

# Estimating angular power spectra

- Power spectra must be estimated from cut-sky data
- Critical on large-scales due to the cut-induced variance

CMB mask

$f_{\rm sky} > 0.7$

LSS mask

$f_{\rm sky} < 0.2$

# The QML and PCL estimators

- Quadratic Maximum Likelihood (QML): optimal, requires a model of the pixel-pixel covariance matrix:

$$\mathbf{C}(\theta_{ij}) = \langle x_i x_j \rangle = \sum_\ell \left( \frac{2\ell+1}{4\pi} \right) \mathcal{C}_\ell \; P_\ell(\cos\theta_{ij}) + \mathbf{N}_{ij}$$

Covariance matrix

Theory spectrum

Noise, systematics, ...

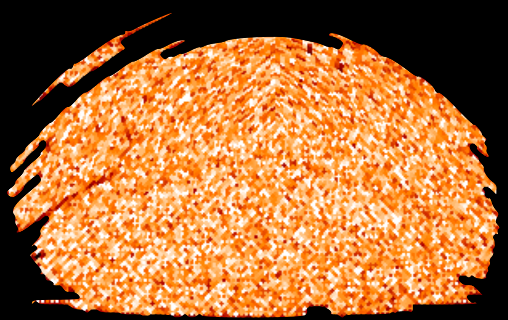
- Pseudo-spectrum estimator (PCL) = QML with diagonal pixel-pixel covariance, i.e. a flat power spectrum

(= uncorrelated pixels)

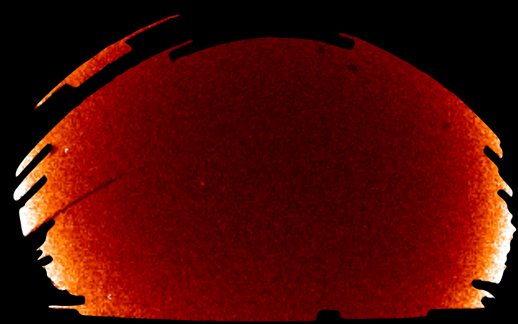
# Systematics and mode projection

- PCL suboptimal with complex masks and systematics
- QML with mode projection: marginalises over linear contamination models, using systematics templates $\vec{c}_k$

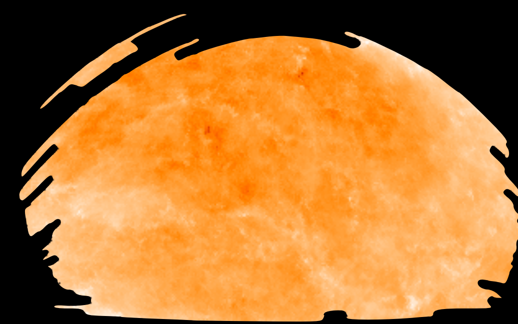
$$\mathbf{C} \ = \ \sum_{\ell} \mathcal{C}_\ell \mathbf{P}_\ell + \mathbf{N} + \sum_{k \in \mathrm{sys}} \xi_k \vec{c}_k \vec{c}_k^{\,t} \quad \text{with} \ \ \xi_k \rightarrow \infty$$



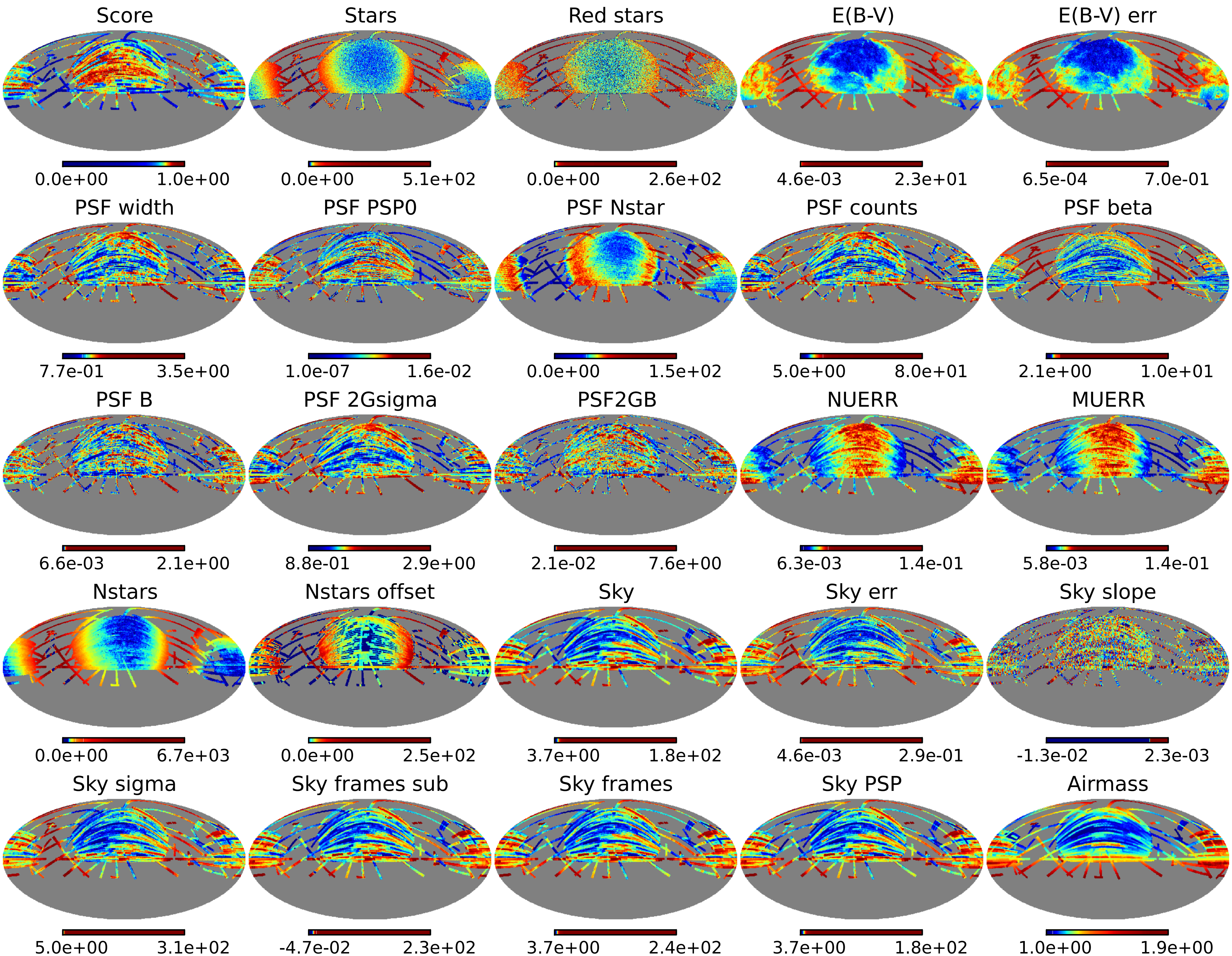
quasar catalogue



stars



dust extinction


Score
0.0e+00
1.0e+00
Stars
0.0e+00
5.1e+02
Red stars
0.0e+00
2.6e+02
E(B-V)
4.6e-03
2.3e+01
E(B-V) err
6.5e-04
7.0e-01
PSF width
7.7e-01
3.5e+00
PSF PSP0
1.0e-07
1.6e-02
PSF Nstar
0.0e+00
1.5e+02
PSF counts
5.0e+00
8.0e+01
PSF beta
2.1e+00
1.0e+01
PSF B
6.6e-03
2.1e+00
PSF 2Gsigma
8.8e-01
2.9e+00
PSF2GB
2.1e-02
7.6e+00
NUERR
6.3e-03
1.4e-01
MUERR
5.8e-03
1.4e-01
Nstars
0.0e+00
6.7e+03
Nstars offset
0.0e+00
2.5e+02
Sky
3.7e+00
1.8e+02
Sky err
4.6e-03
2.9e-01
Sky slope
-1.3e-02
2.3e-03
Sky sigma
5.0e+00
3.1e+02
Sky frames sub
-4.7e-02
2.3e+02
Sky frames
3.7e+00
2.4e+02
Sky PSP
3.7e+00
1.8e+02
Airmass
1.0e+00
1.9e+00

# *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

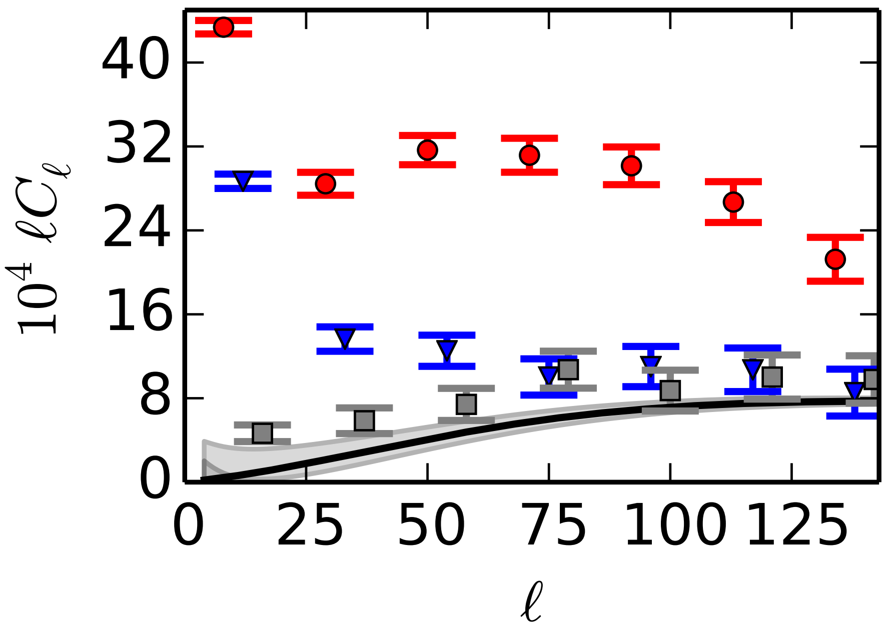
  *3,700 null tests; project out modes with red chi2>1*

Sacrificing some signal in favour of robustness

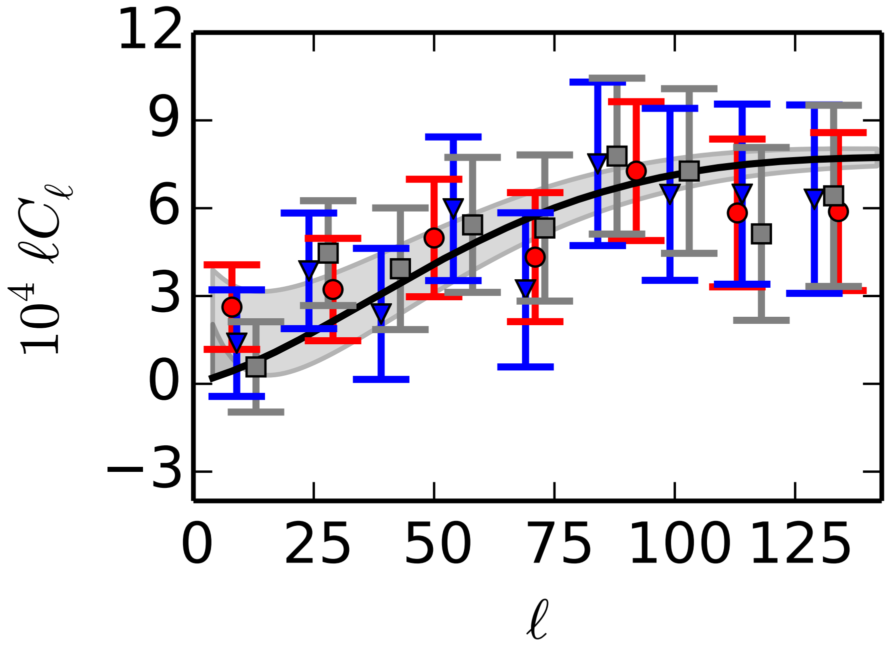
⇒ **Blind mitigation of systematics**

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

# *Blind mitigation of systematics*




***Raw spectra***



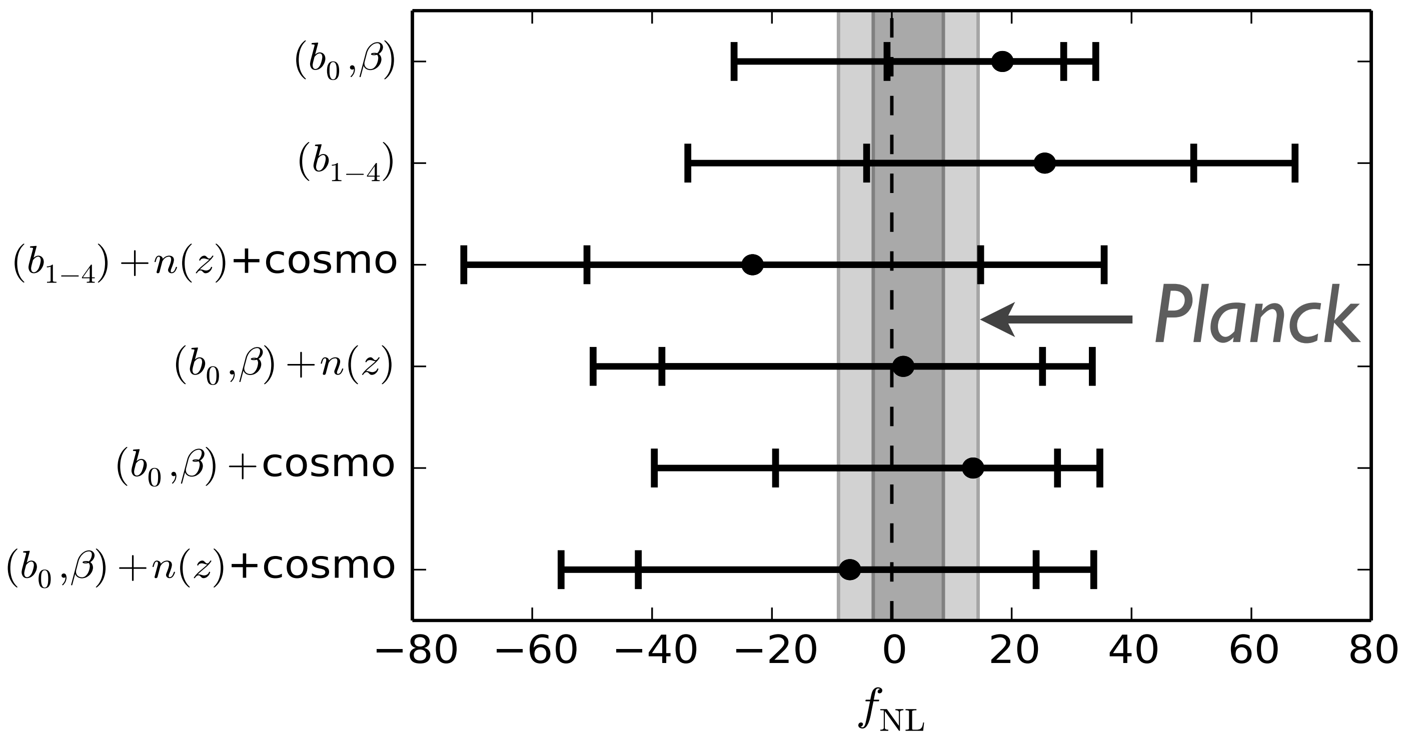

***Clean spectra***

- 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*

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

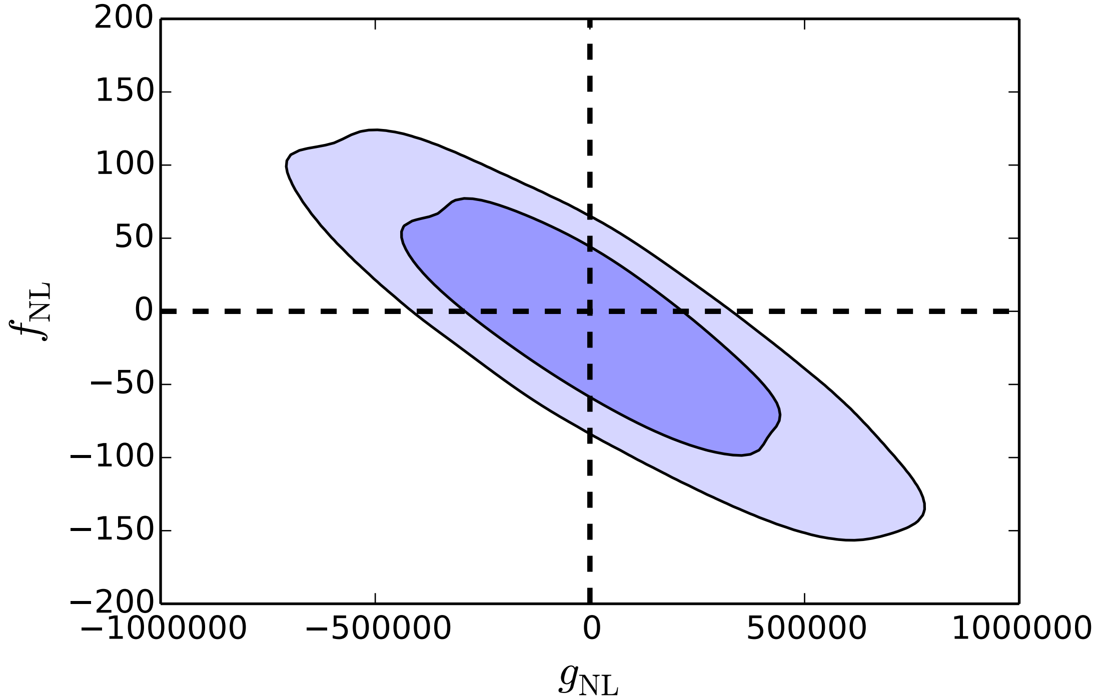
$|g_{NL}| < 10^6$ (CMB, LSS)

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

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

Smith, Ferraro & LoVerde (2012)

# Constraints on $g_{NL}$




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

*individually*

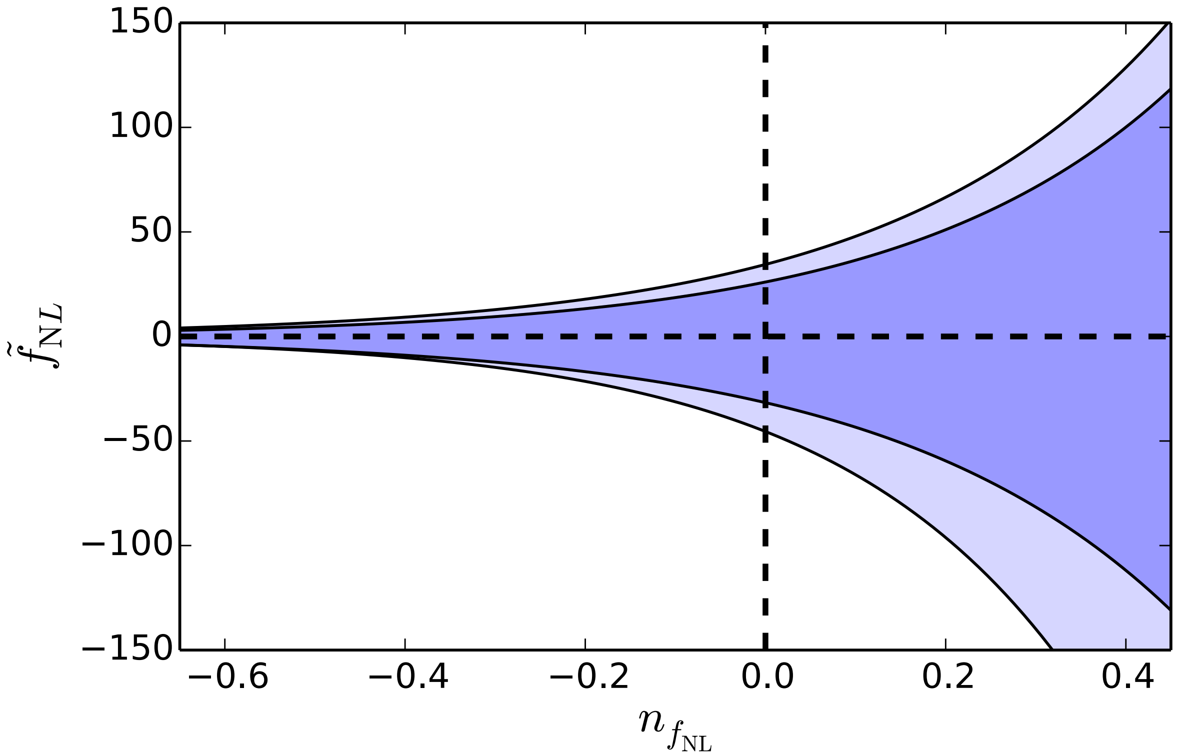
$$-4.0 < g_{\rm NL}/10^5 < 4.9 \ (2\sigma)$$

*joint with $f_{NL}$*

- Best available constraint on $g_{NL}$

Leistedt, Peiris & Roth (1405.4315)

# *Extended model with running*

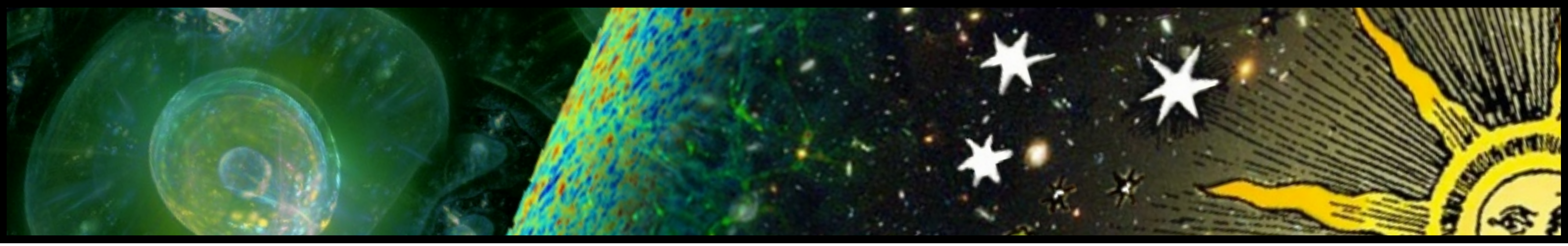



$$b(k) \propto k^{-2+n_{f_{\mathrm{NL}}}}$$

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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  - *Single vs multi-field?*
  - *Predictions from the landscape?*
- Strategies for future progress

# *Maximally separated collaboration!*

*Layne Price (Auckland)*

*Jonathan Frazer (Bilbao)*

*Richard Easther (Auckland)*

*with*
*Jiajun Xu (New York)*
*Jonathan White (Tokyo)*

*Also Jonny's talk Monday*

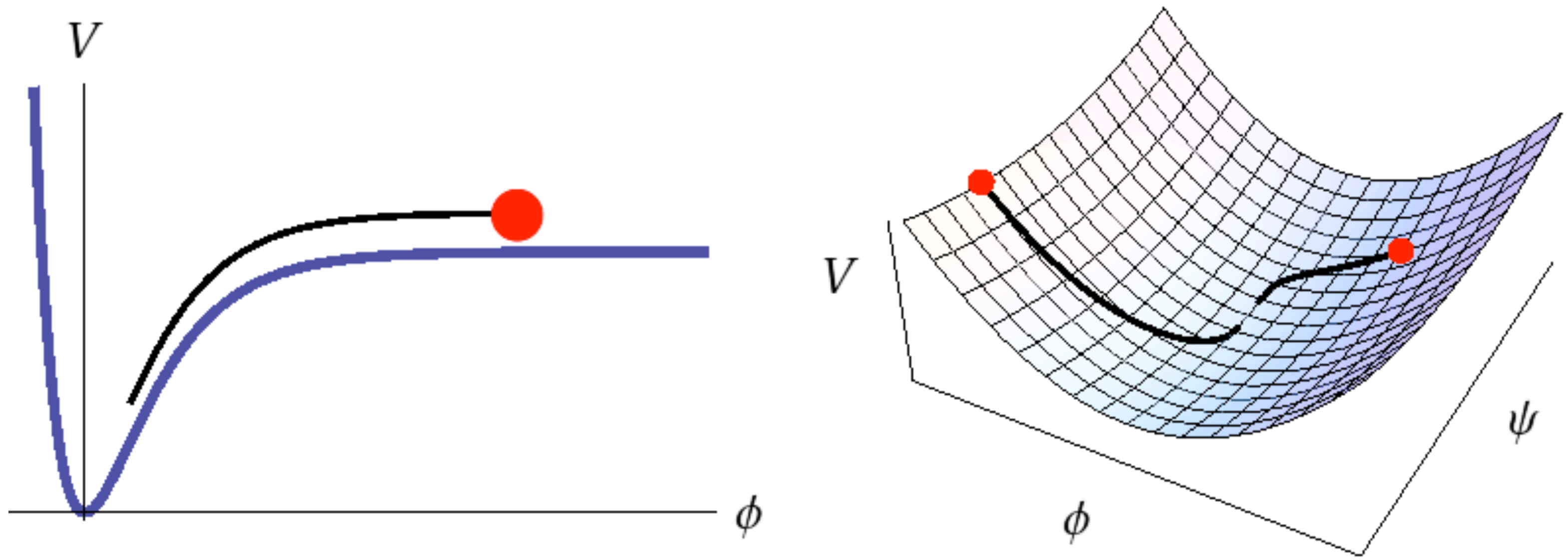
# ***One field is simple; is it "natural"?***

- 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

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

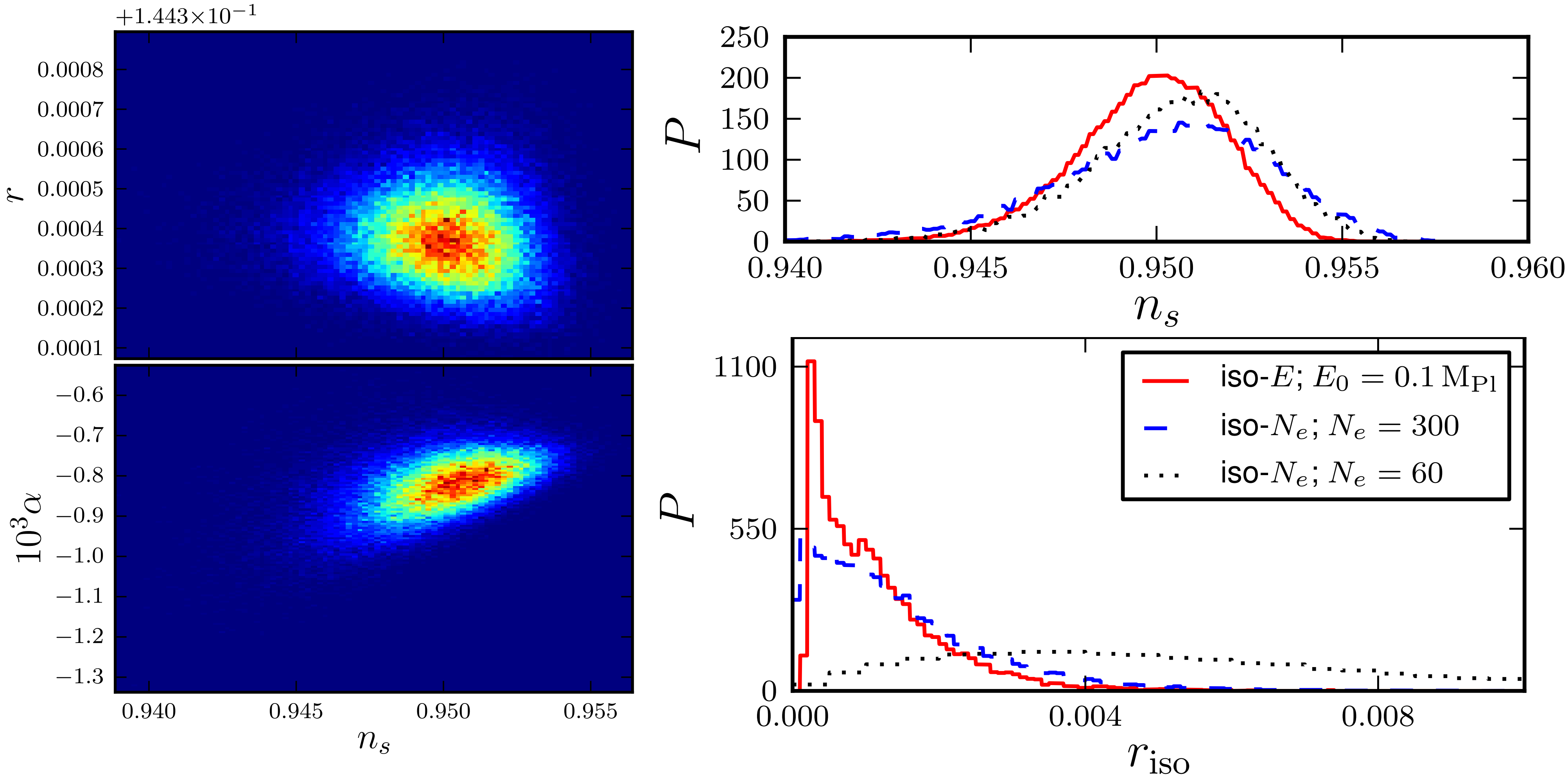
- Masses drawn from Marchenko-Pastur distribution with $\beta$=0.5.
  *largest mass ratio 1/8.08, other masses equally spaced in cumulative PDF*

- 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)

# *Multifield inflation & consistency condition*

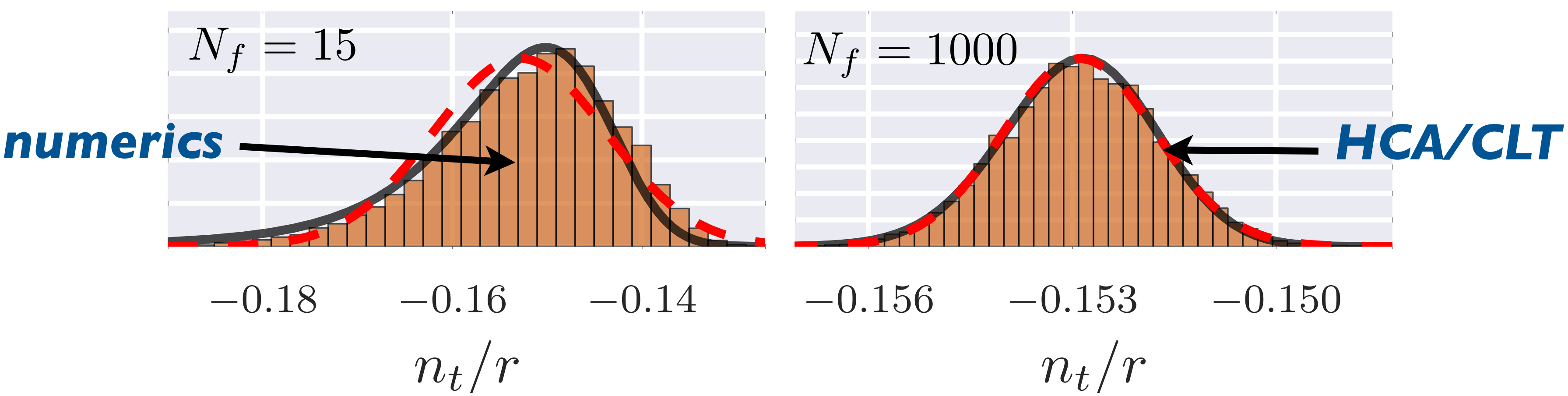
- Unambiguous prediction of single field slow roll (SFSR) models:

$$r = -8\, n_t$$

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

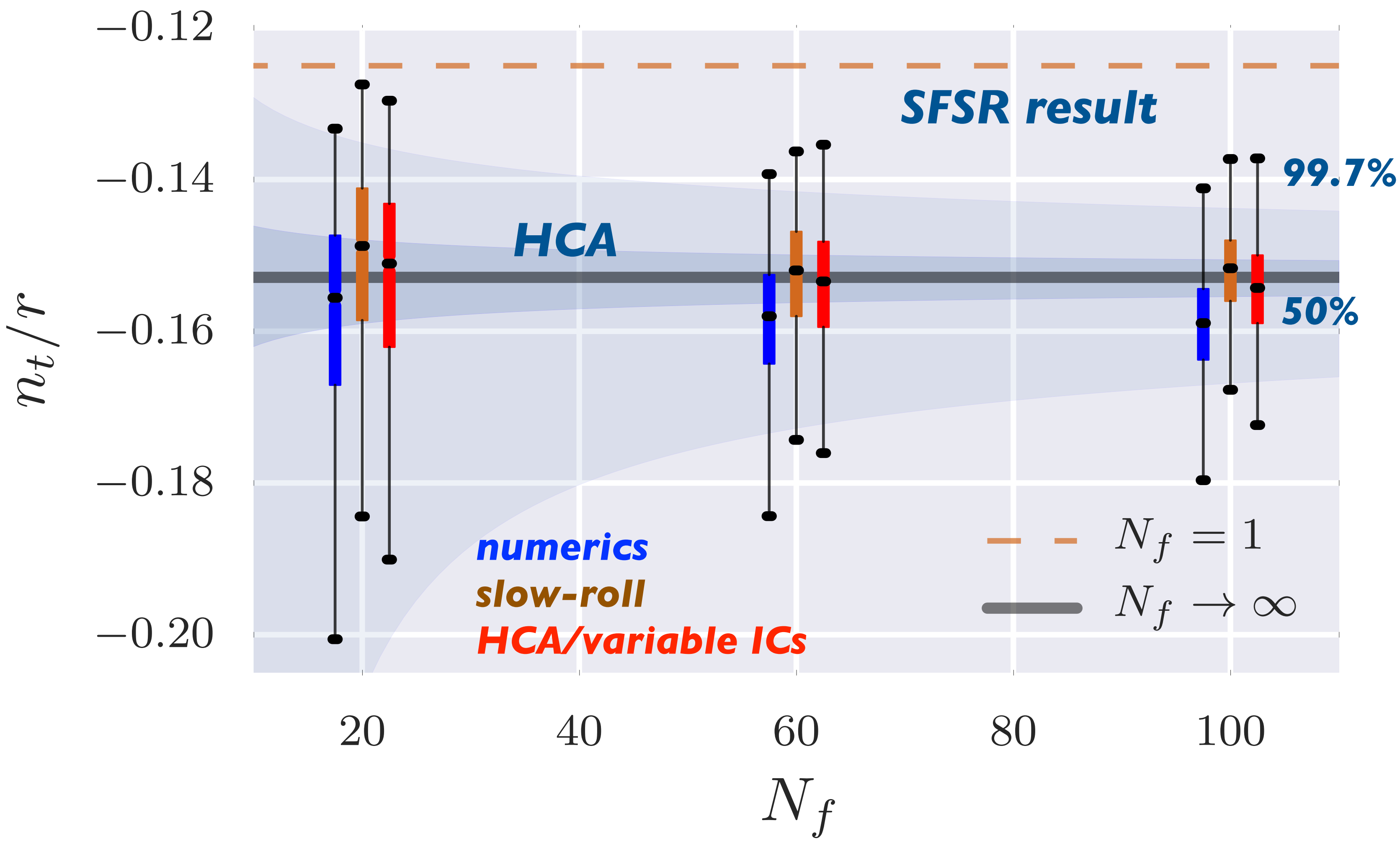
$$V = \frac{1}{p}\sum_{i=1}^{N_f} \lambda_i |\phi_i|^p$$

- **Result:** For Nf ≫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 (in prep)

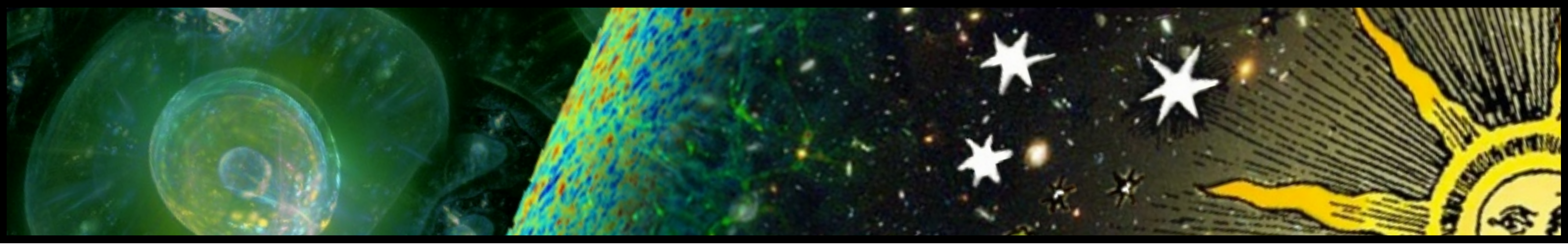
# *Multifield inflation & consistency condition*




- p=2, uniform distribution on $\lambda_i$, 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 (in prep)

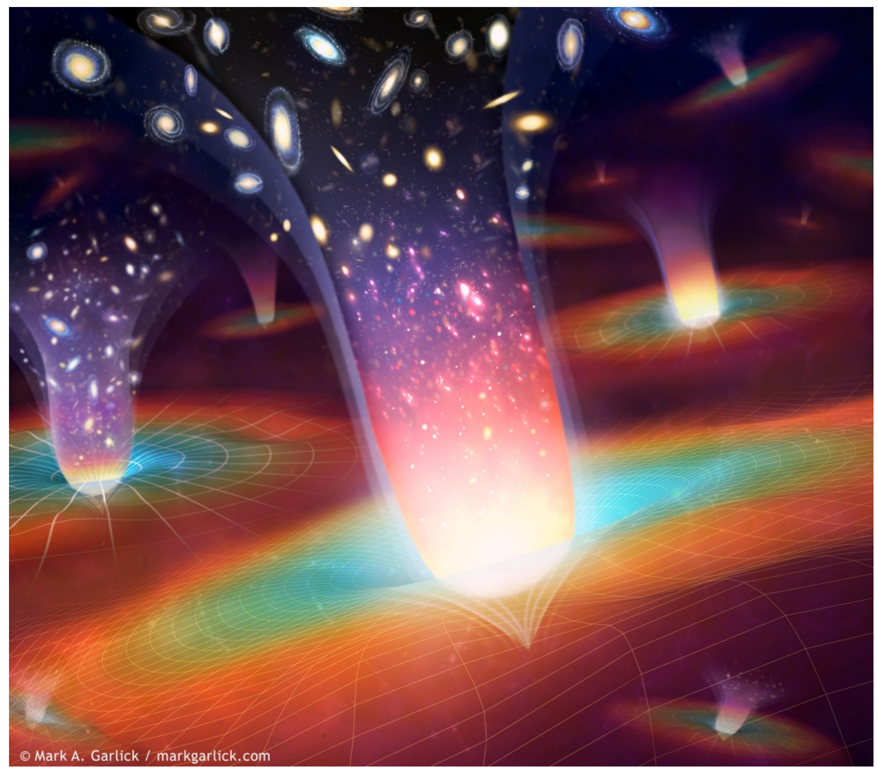


# *Roadmap*

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

# *Eternal inflation*

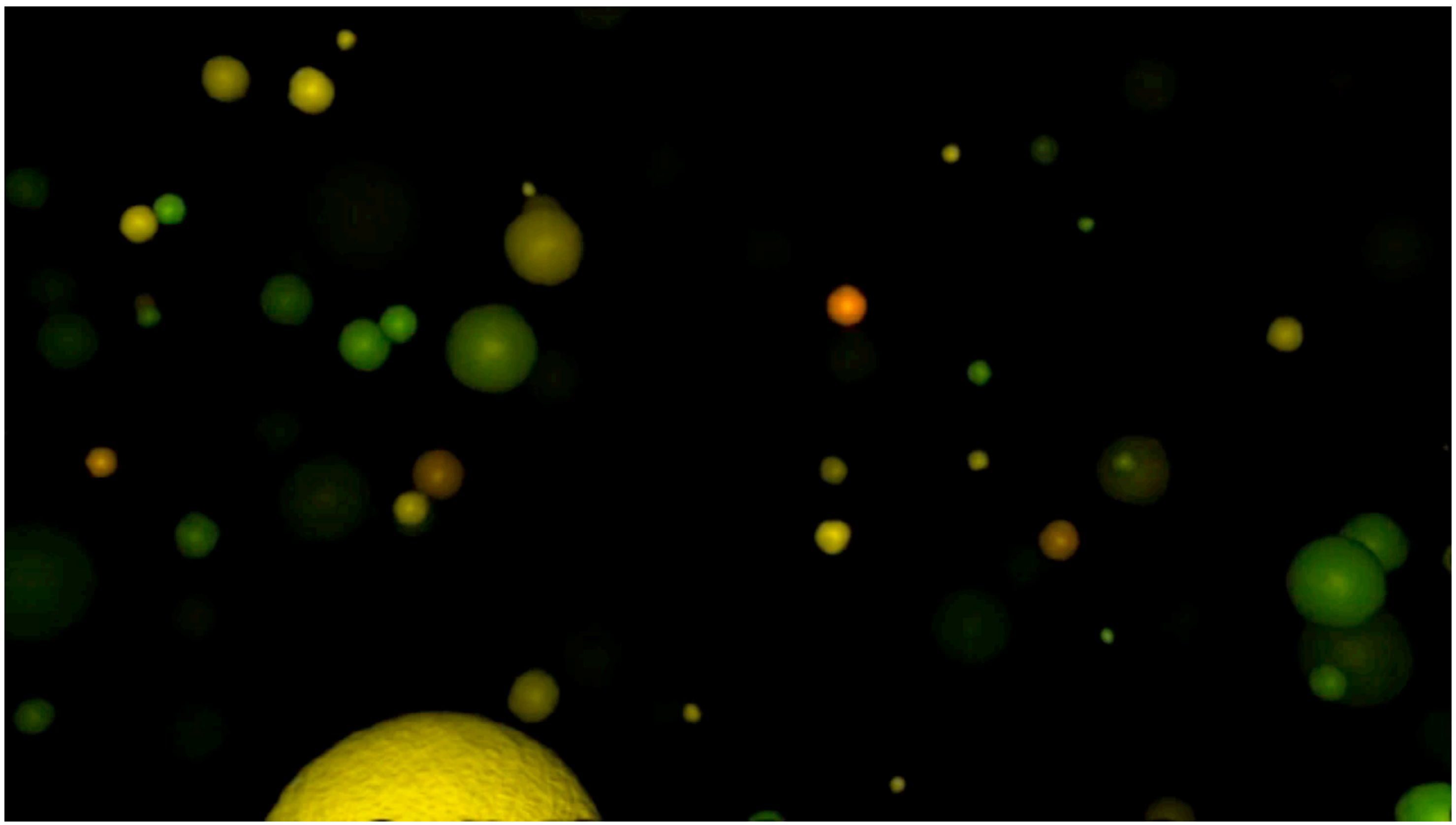
- Current fundamental theories do not predict a unique vacuum.
- There is observational evidence for accelerated expansion both in the early and late universe.
- Strongly motivates that we inhabit an eternally inflating universe.



# *Eternal inflation*

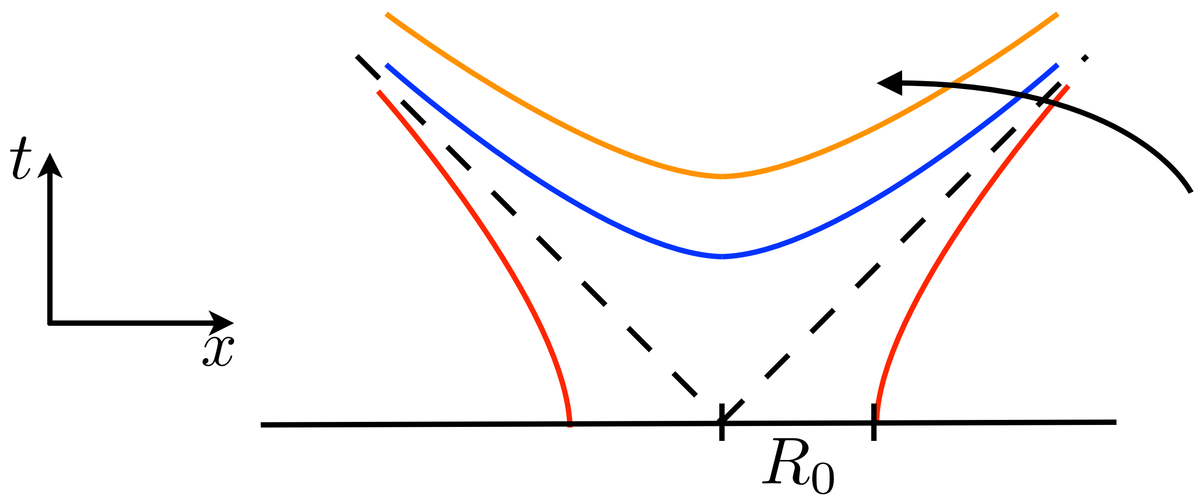
- With positive vacuum energy, bubbles form, but space expands between them: inflation can become eternal.

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



# *The universe in a bubble*

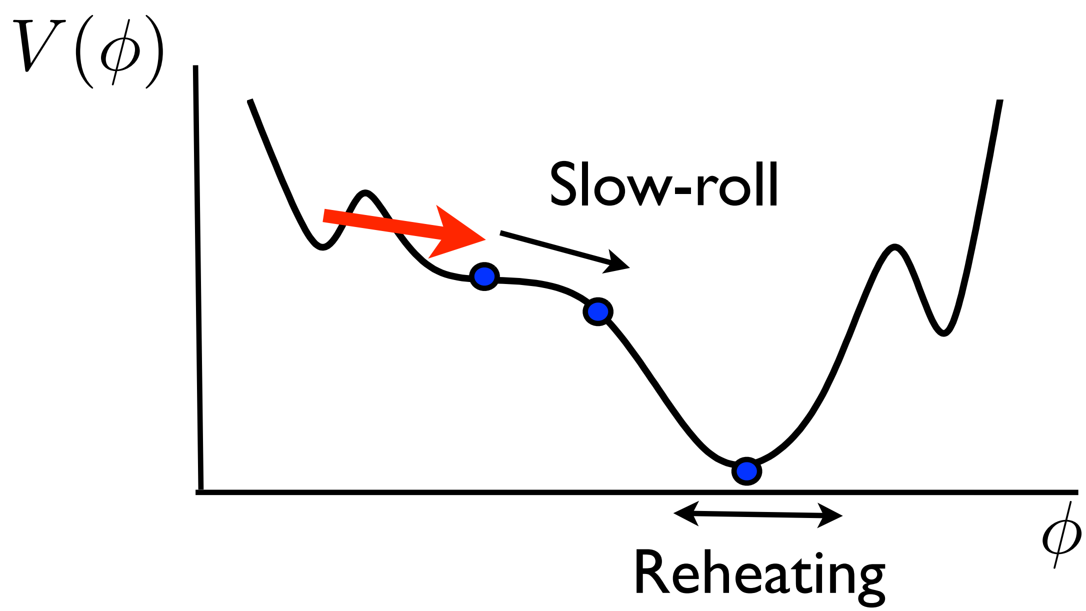
Inflation does not end everywhere; single bubbles contain a curvature dominated open universe.




Infinite open FRW universe.

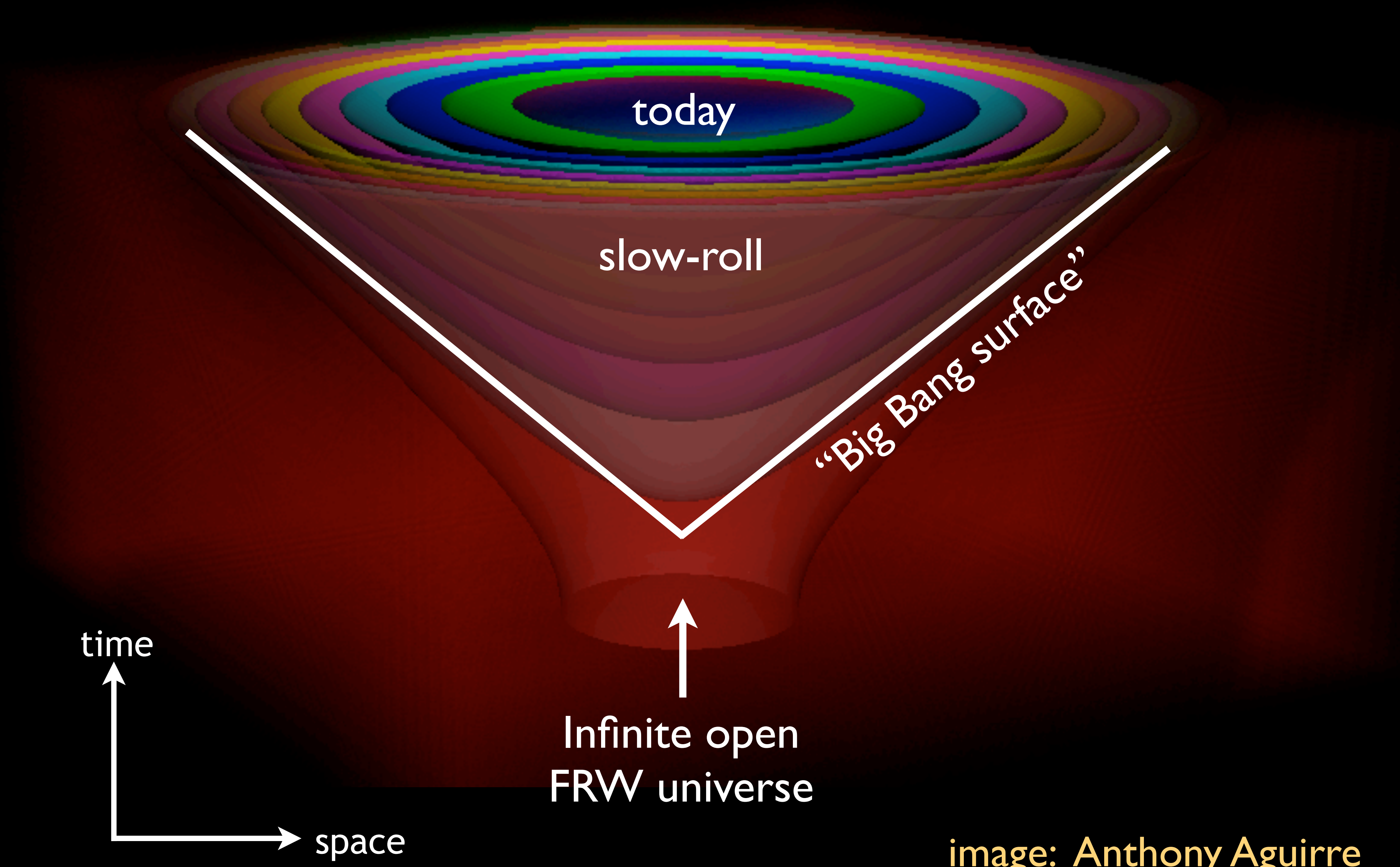
# *The universe in a bubble*

Open inflation: An epoch of slow-roll inflation inside the bubble makes a viable cosmology.



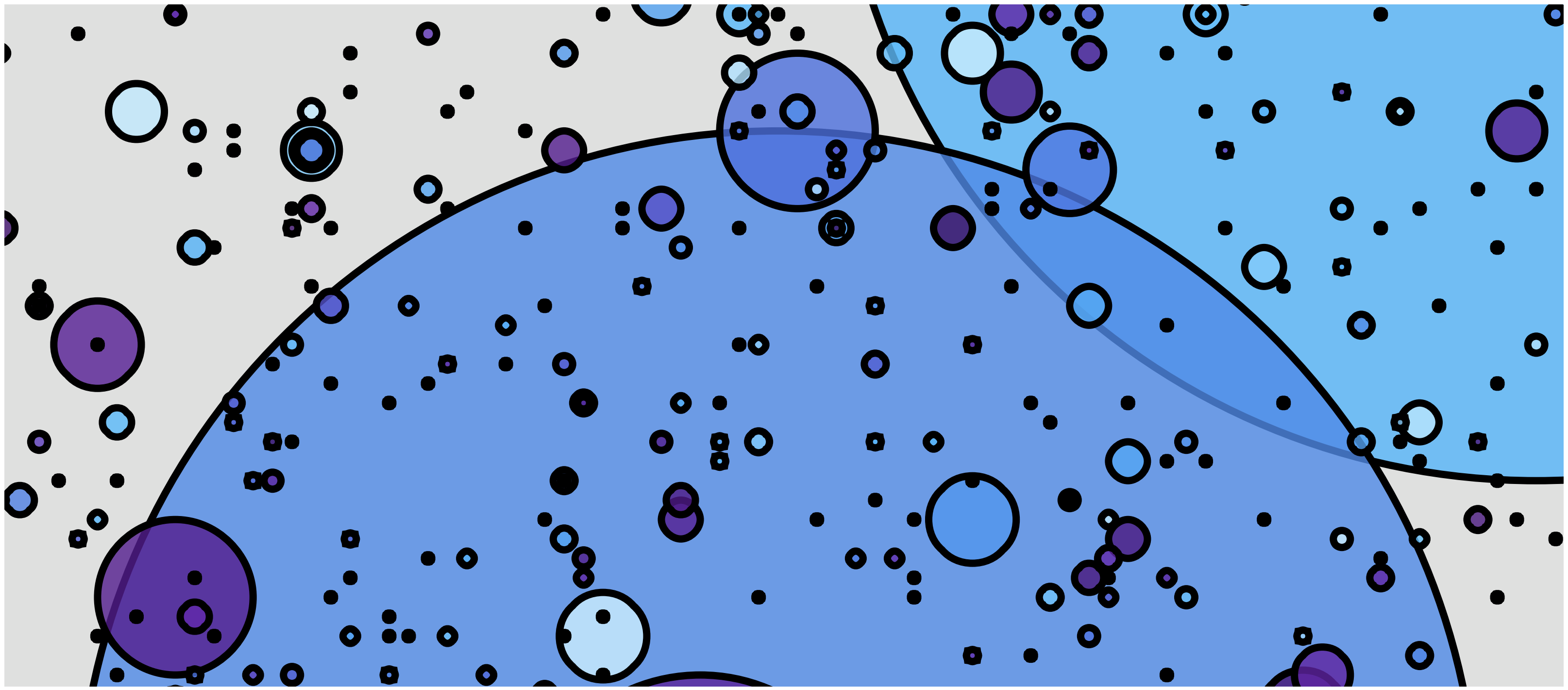

Bucher, Goldhaber, Turok

# History of a pocket universe



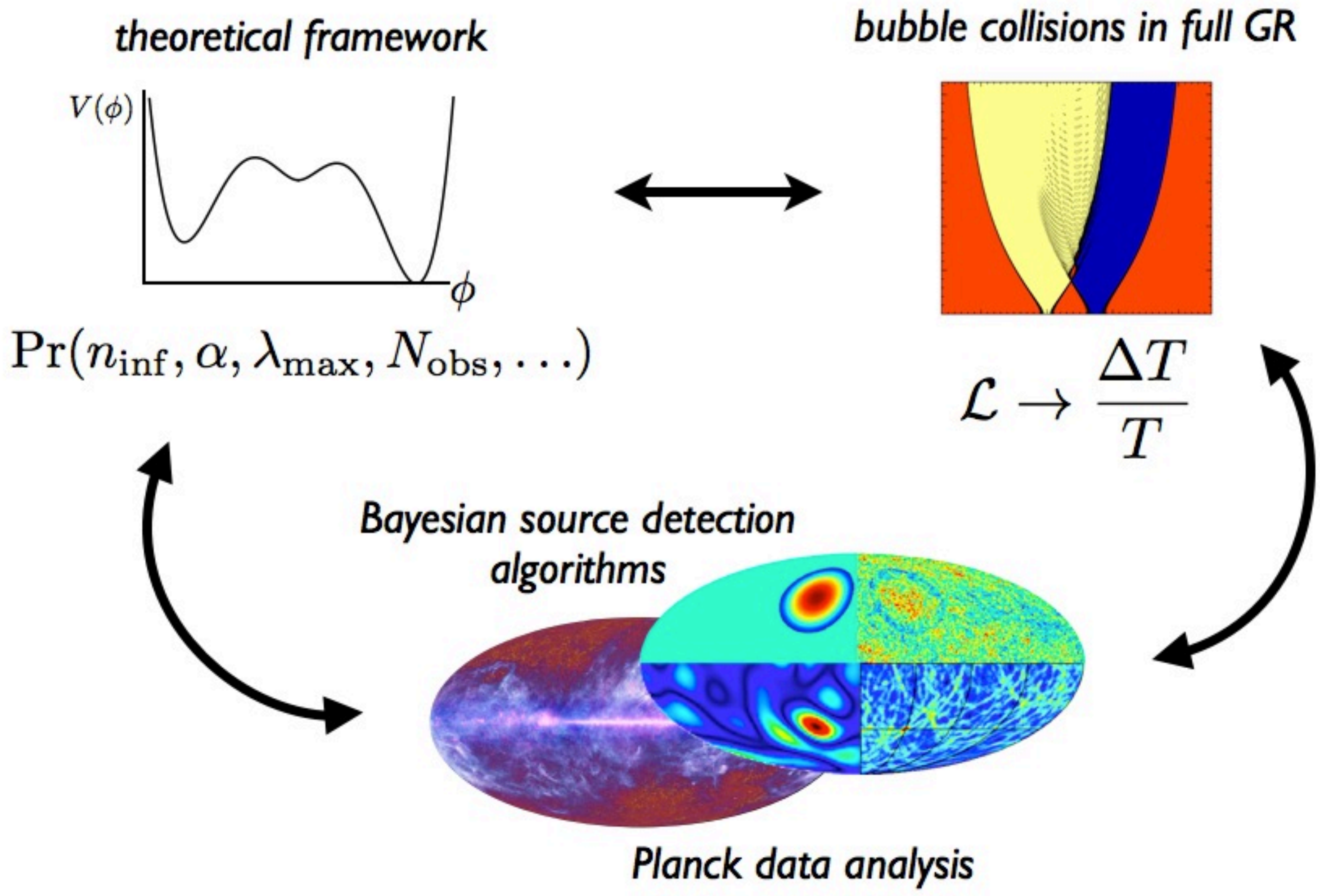
# Observational tests?

- 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.

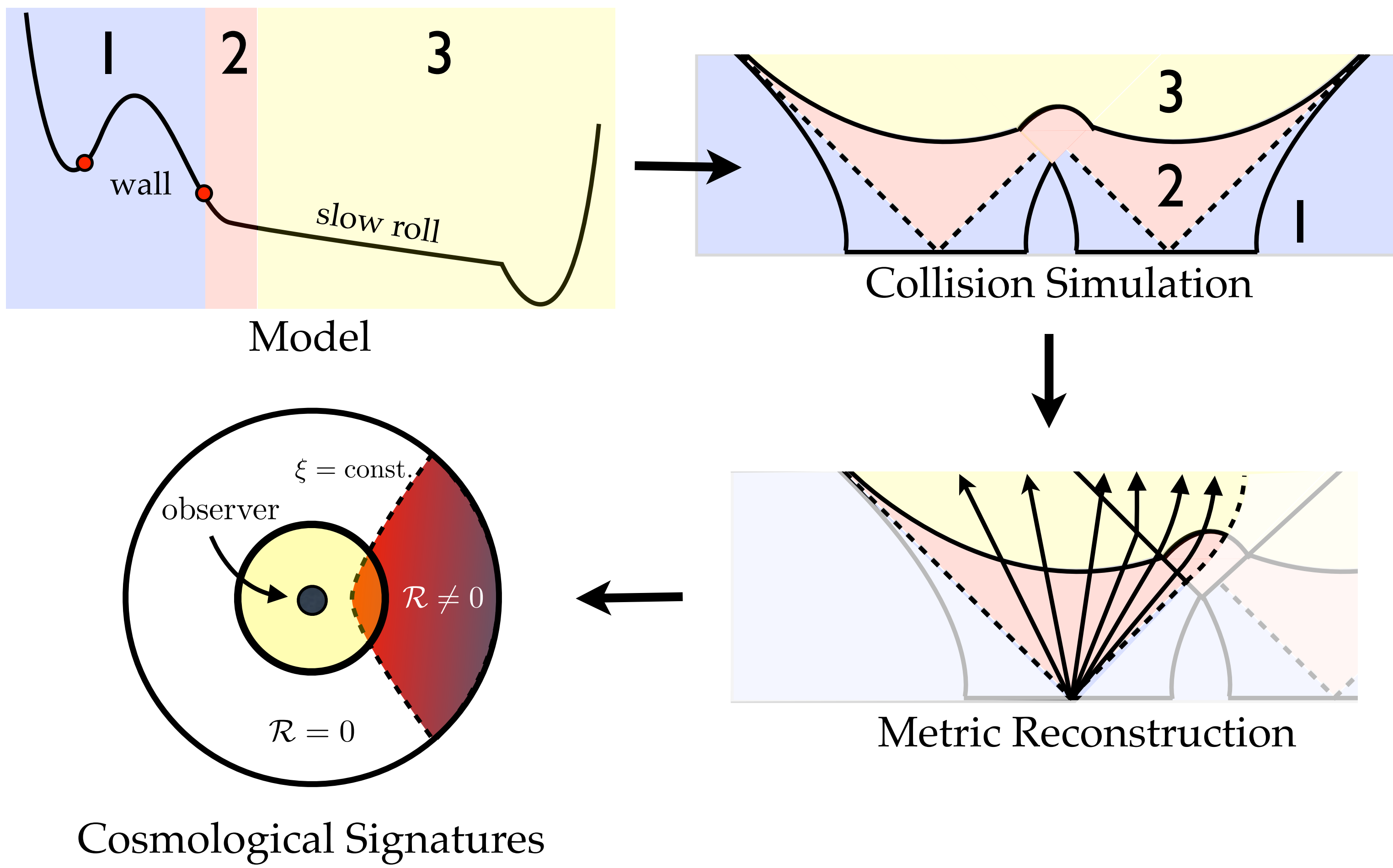
# *What are the theoretical priors?*




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

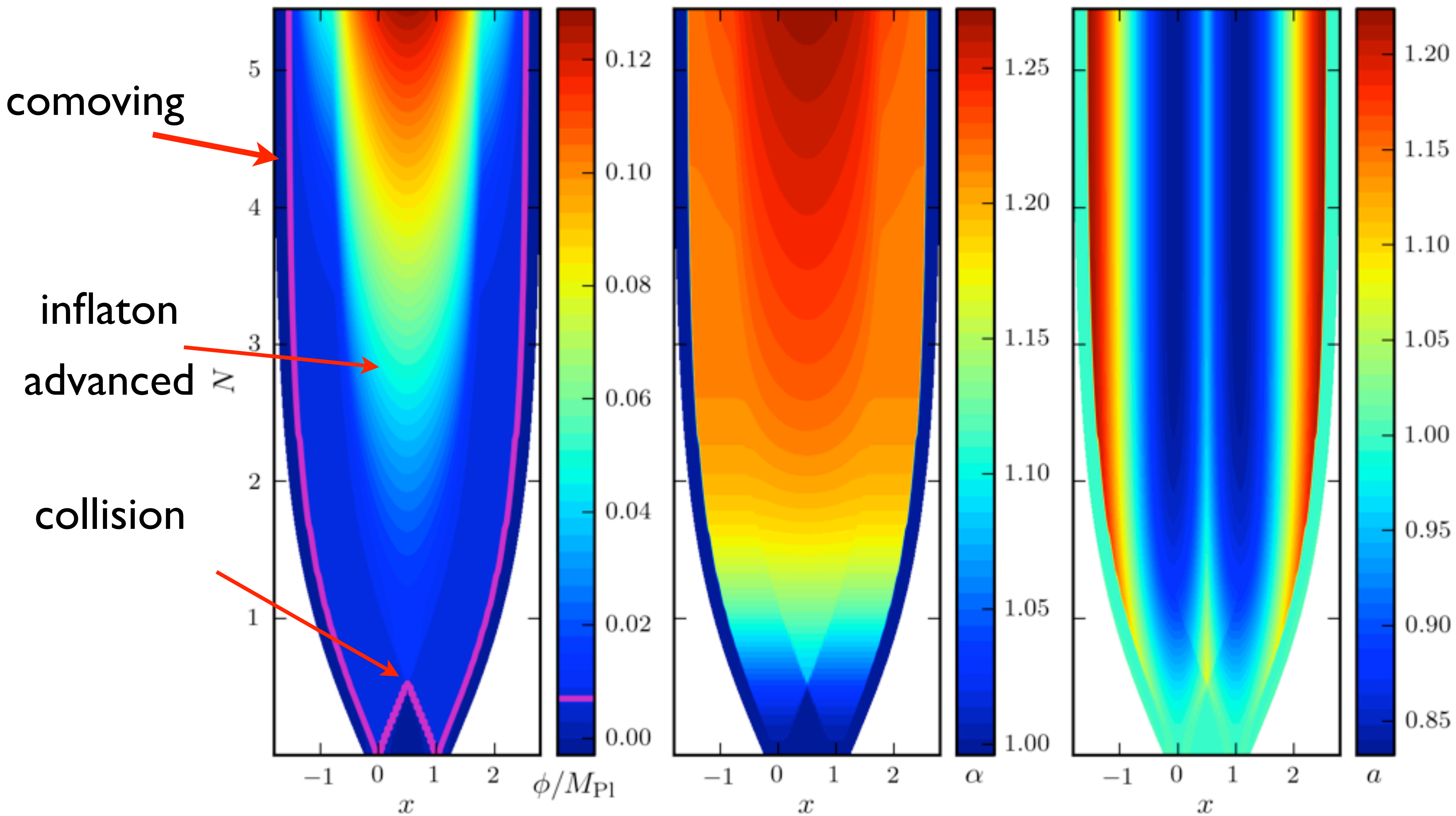



Collision symmetry *SO*(2,1): 1+1 relativistic simulations in models yielding O(1) collision signatures per CMB sky. *Evolution code: 4th order convergence, AMR, adaptive simulation boundaries. Initial conditions with CosmoTransitions.*

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

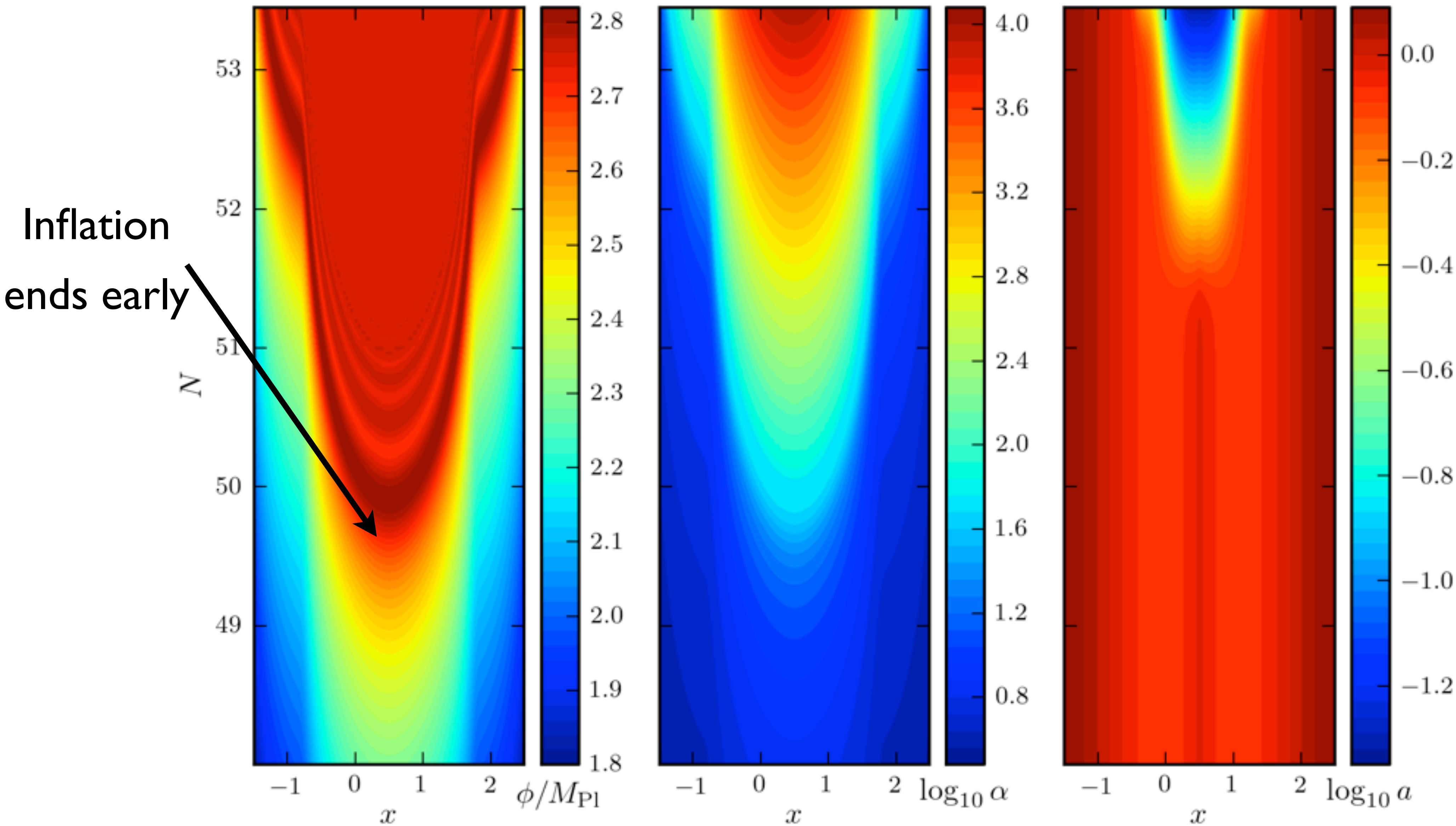
# *Example*

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

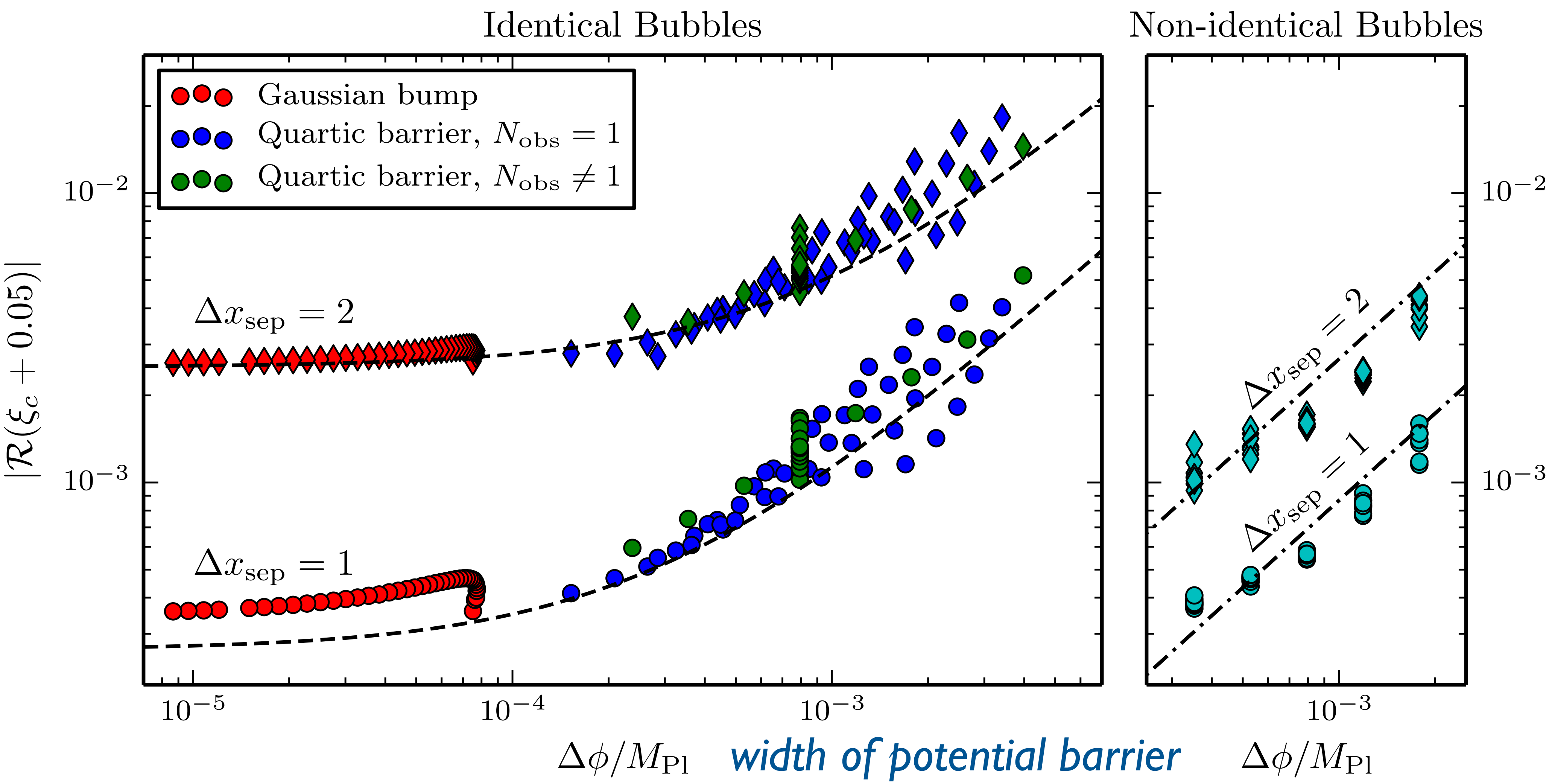


# *Example*

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

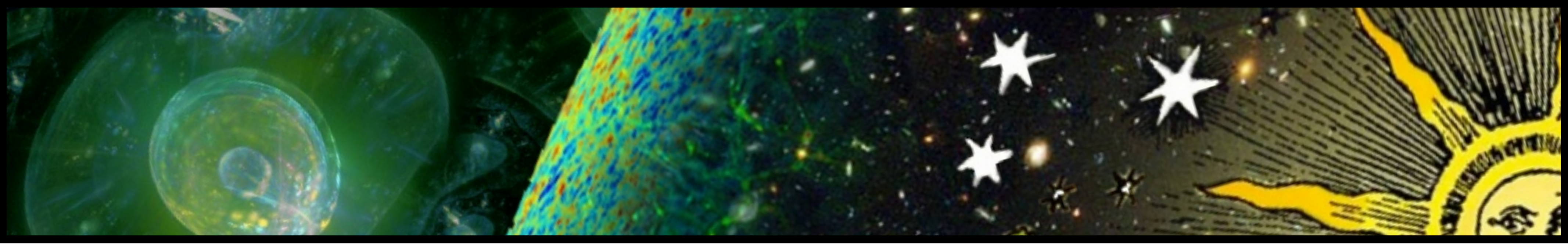


# Linking tunnelling physics with observations




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

Wainwright, Johnson, Aguirre, HVP (arxiv:1407.2950)



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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*
- ***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....*


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