Inflation: the Universe at Pole Position

Diederik Roest
Van Swinderen Institute for
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University of Groningen

Extrapolations

Attractors

Conclusions

CMB

Prezi

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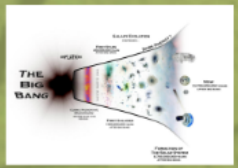
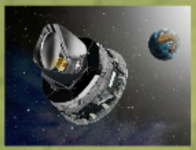


Deliverables of inflation:

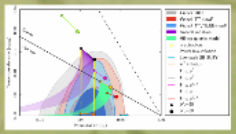
- a Universe that is almost perfectly smooth inside the Hubble patch
- ready-made fluctuations with a nearly constant amplitude on super-horizon scales

- scalar and tensor fluctuations, coming from the inflaton and the space-time metric
- can be probed by temperature and polarization anisotropies in CMB, resp.

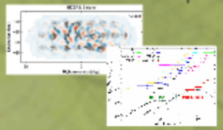


Planck - launched in 2009 - results in 2013 and 2015

Planck 2015 constraints



Polarization anisotropies



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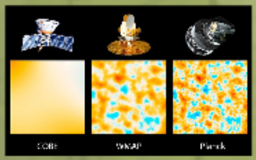
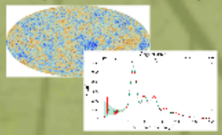
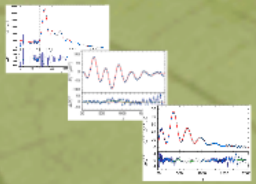
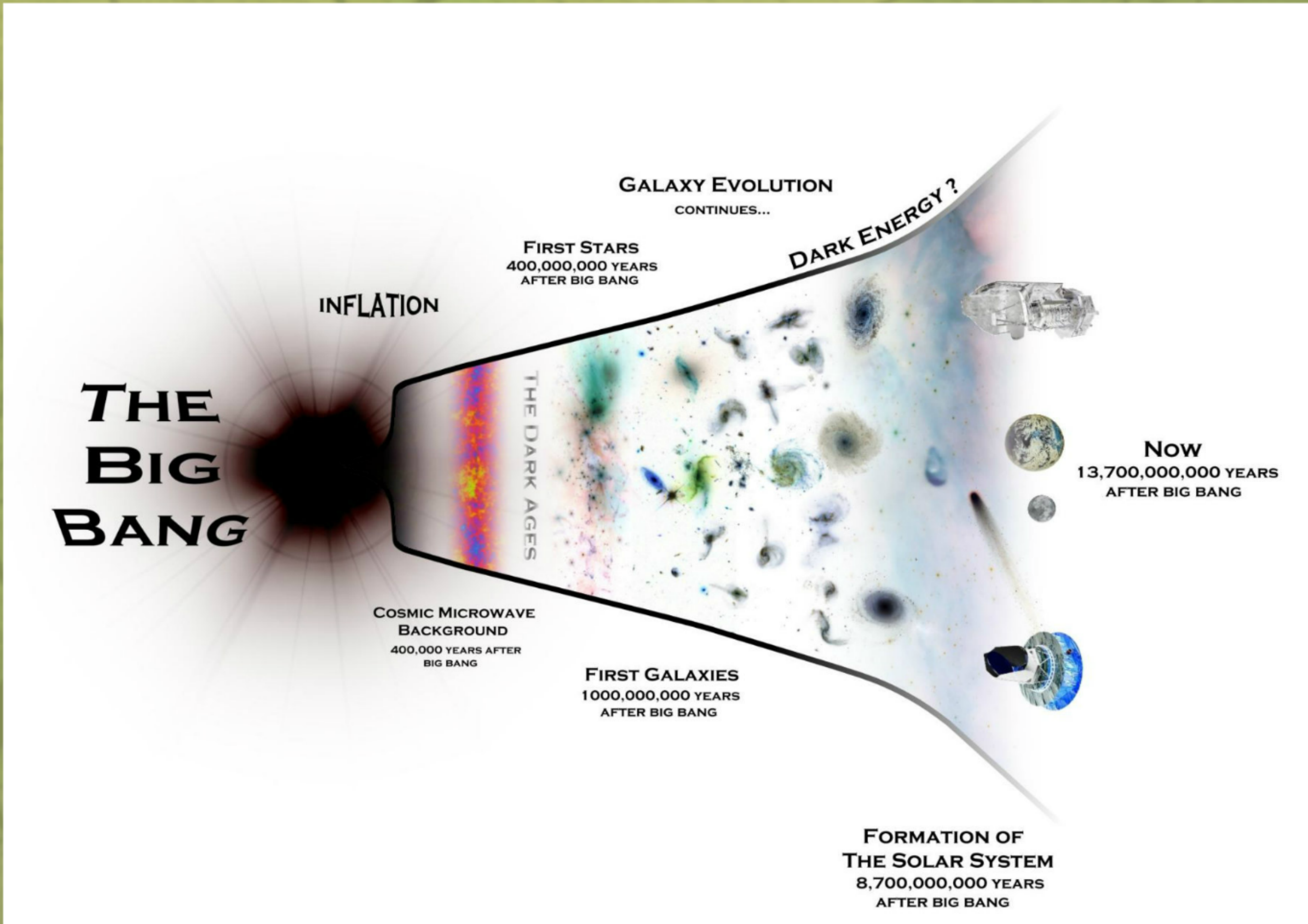


Temperature anisotropies



Allows one to fit amplitude and first scale dep.




THE BIG BANG
INFLATION
FIRST STARS
400,000,000 YEARS AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
THE DARK AGES
COSMIC MICROWAVE BACKGROUND
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1000,000,000 YEARS AFTER BIG BANG
NOW
13,700,000,000 YEARS AFTER BIG BANG
FORMATION OF THE SOLAR SYSTEM
8,700,000,000 YEARS AFTER BIG BANG

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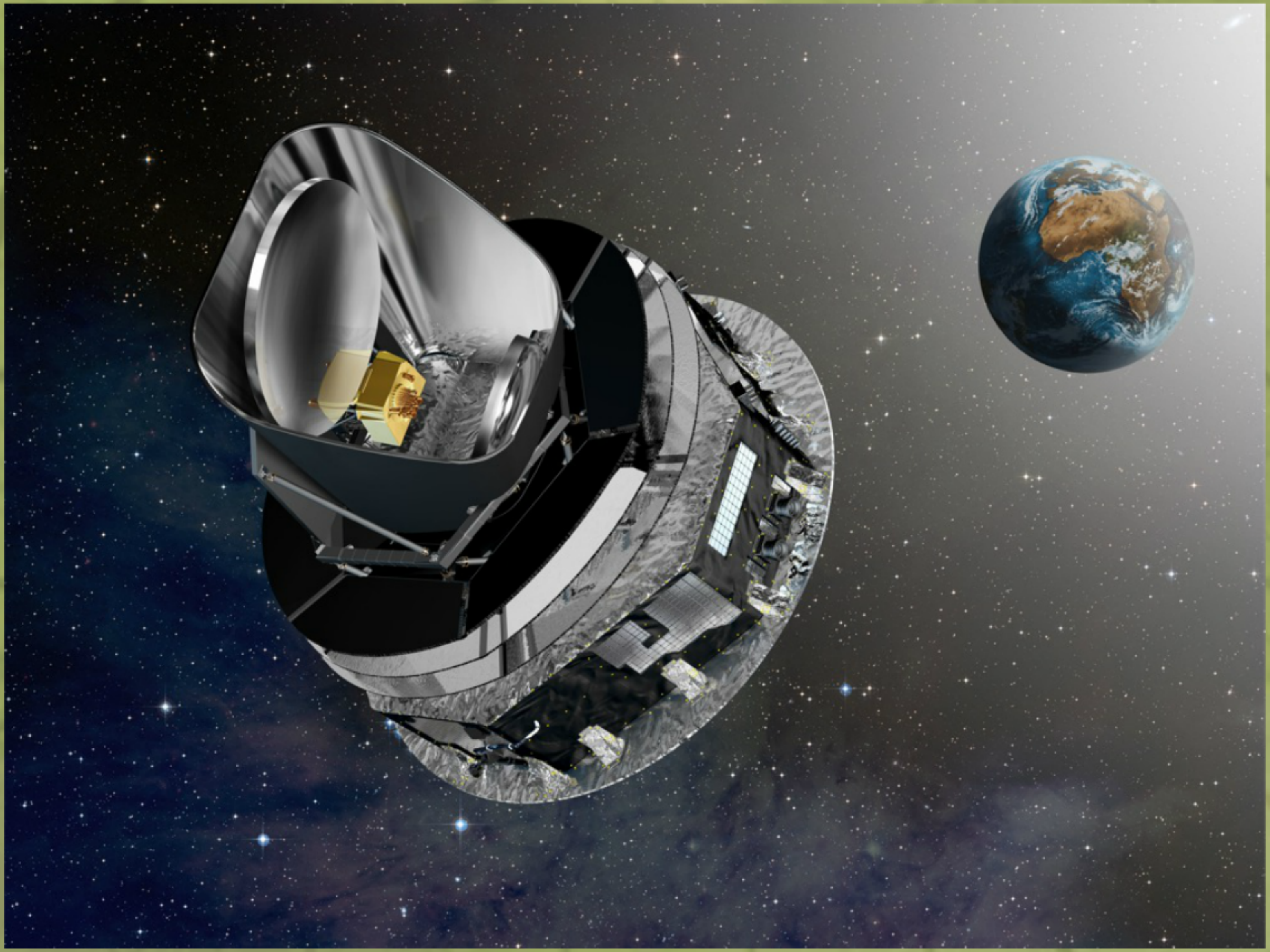

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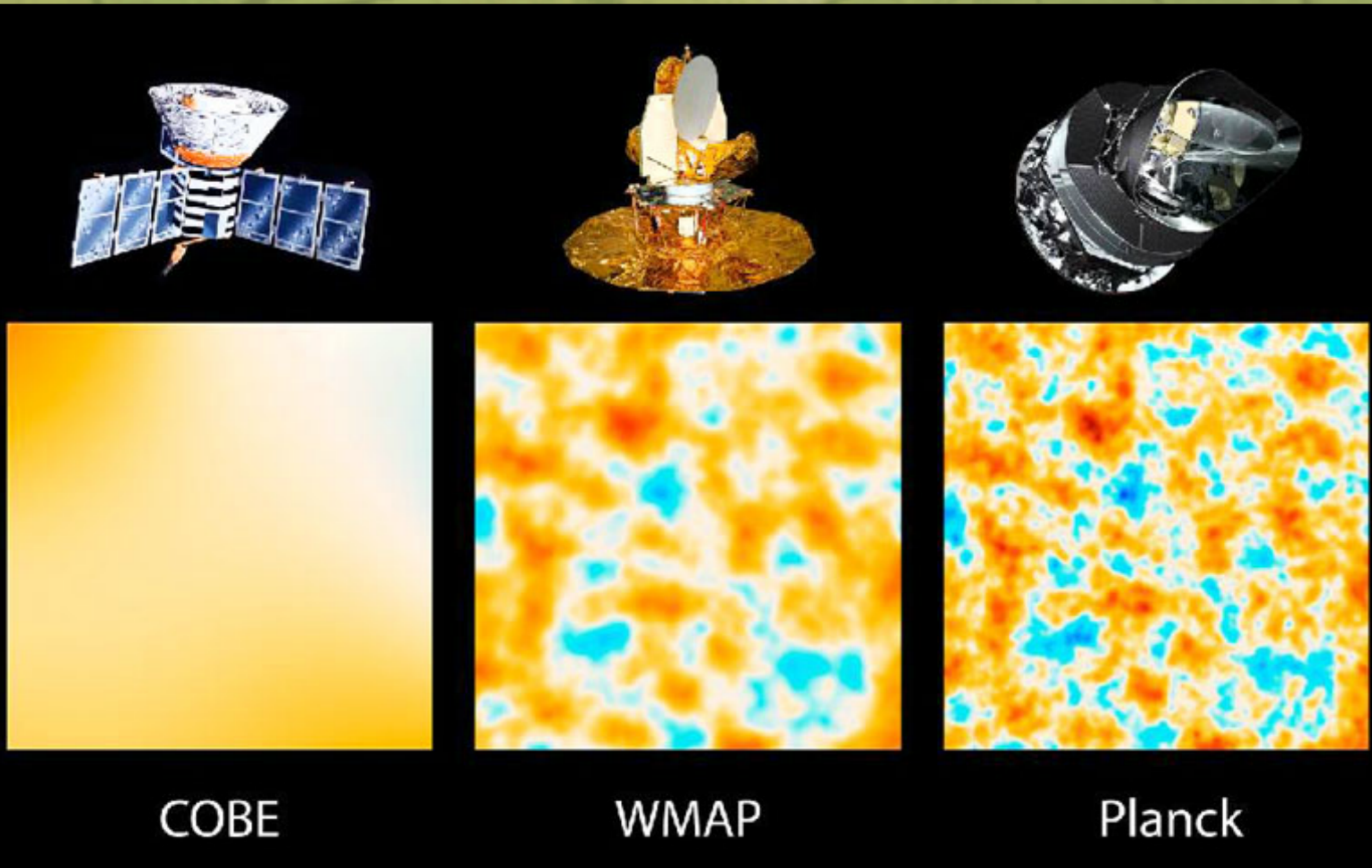
COBE
WMAP
Planck

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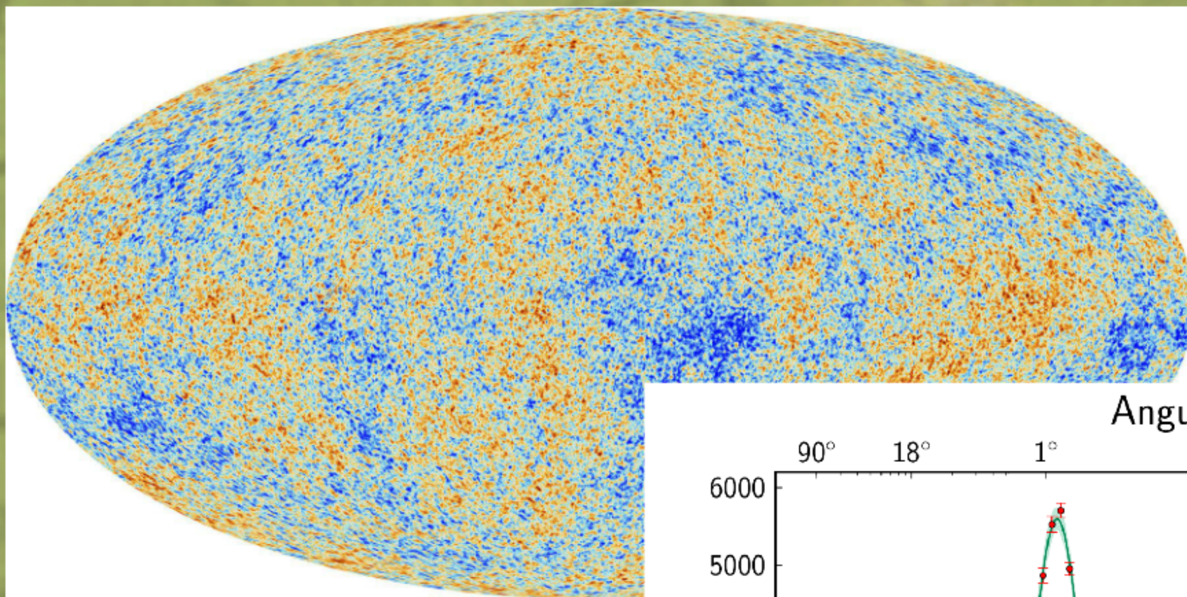

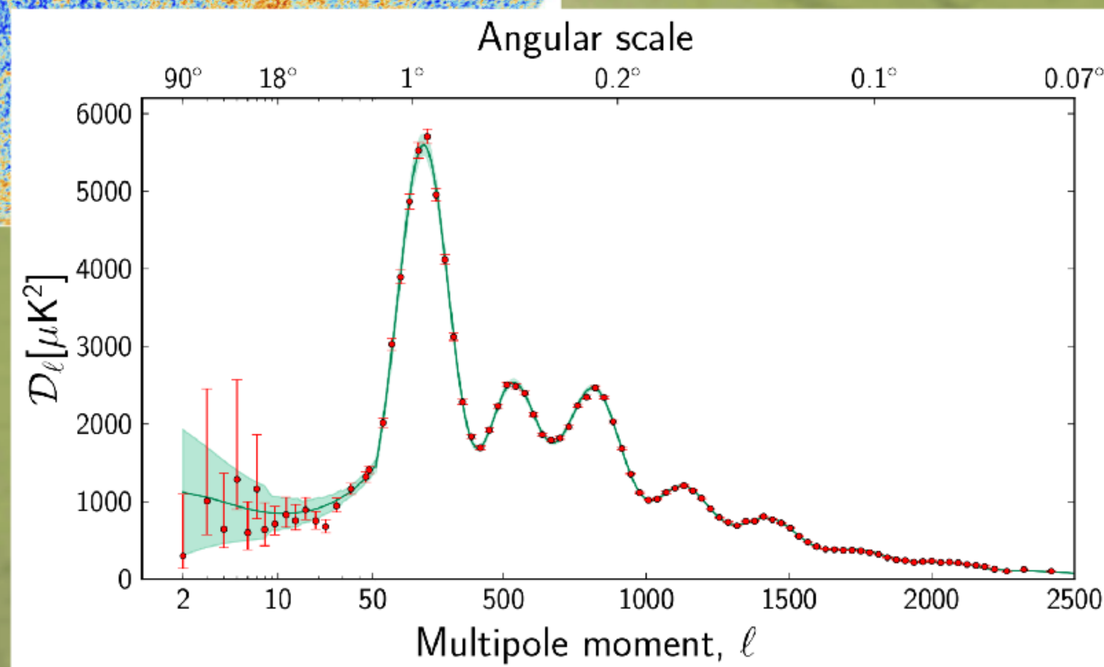

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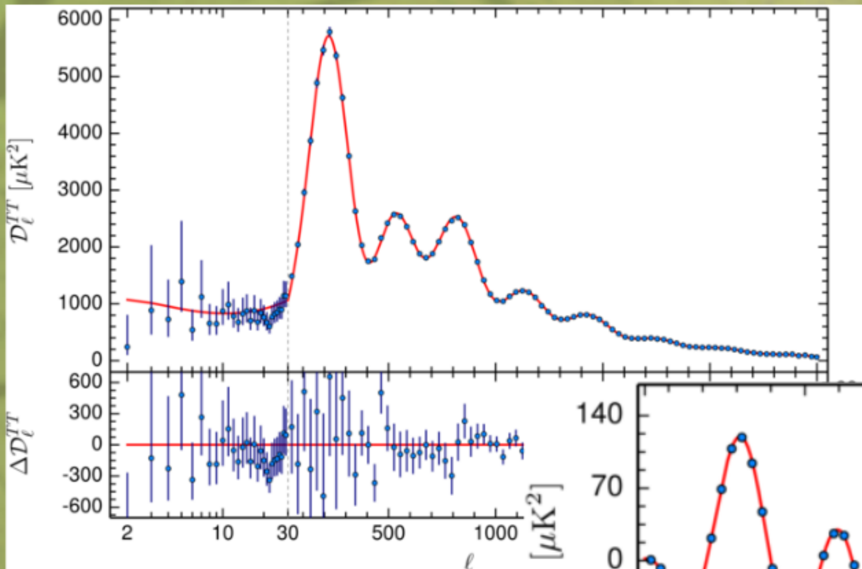
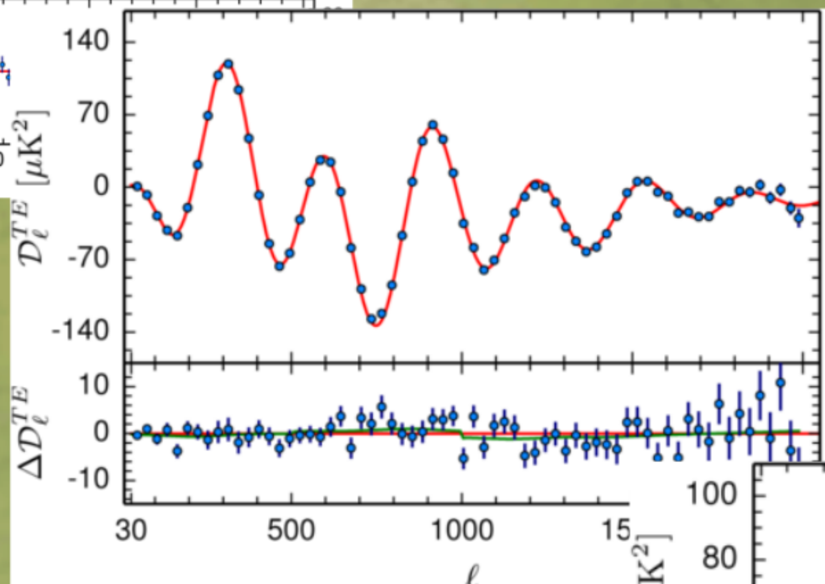
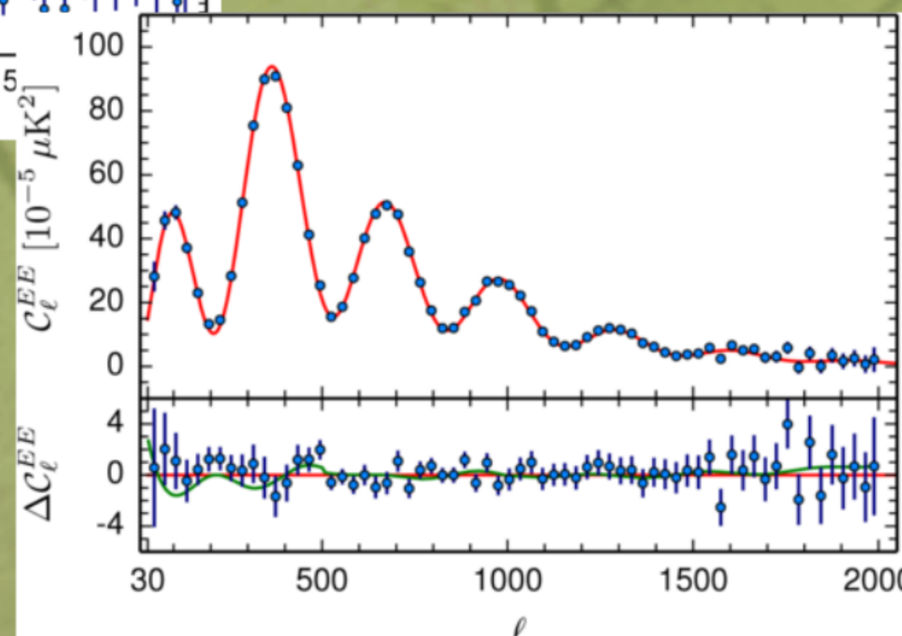
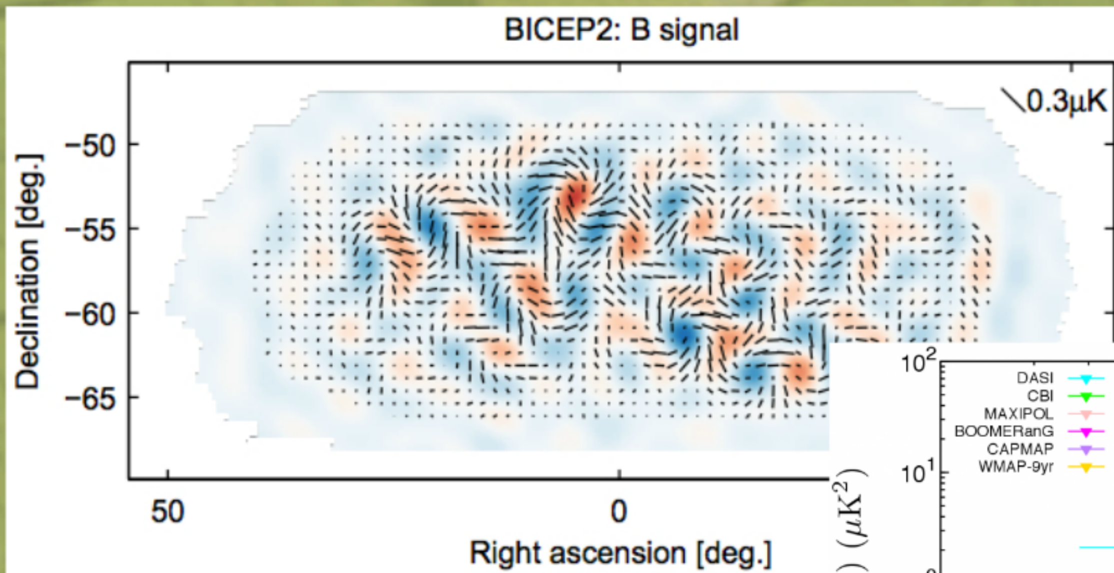
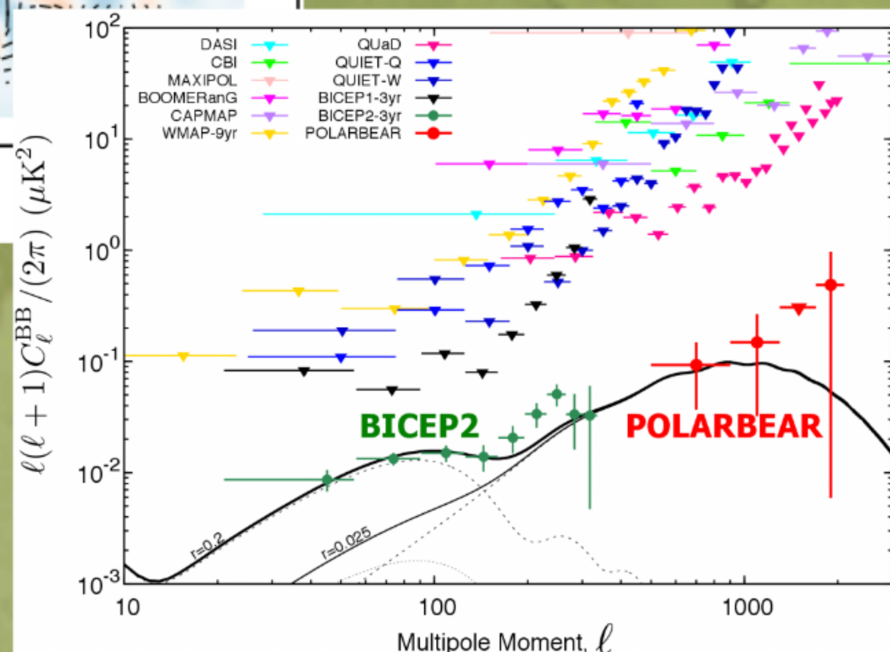

6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
2
10
30
500
1000
ℓ


140
70
0
-70
-140
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
-10
$\Delta\mathcal{D}_\ell^{TE}$
30
500
1000
ℓ


100
80
60
40
20
0
C_ℓ^{EE} [10^{-5} μK^2]
4
0
-4
ΔC_ℓ^{EE}
30
500
1000
1500
2000
ℓ

Polarization anisotropies





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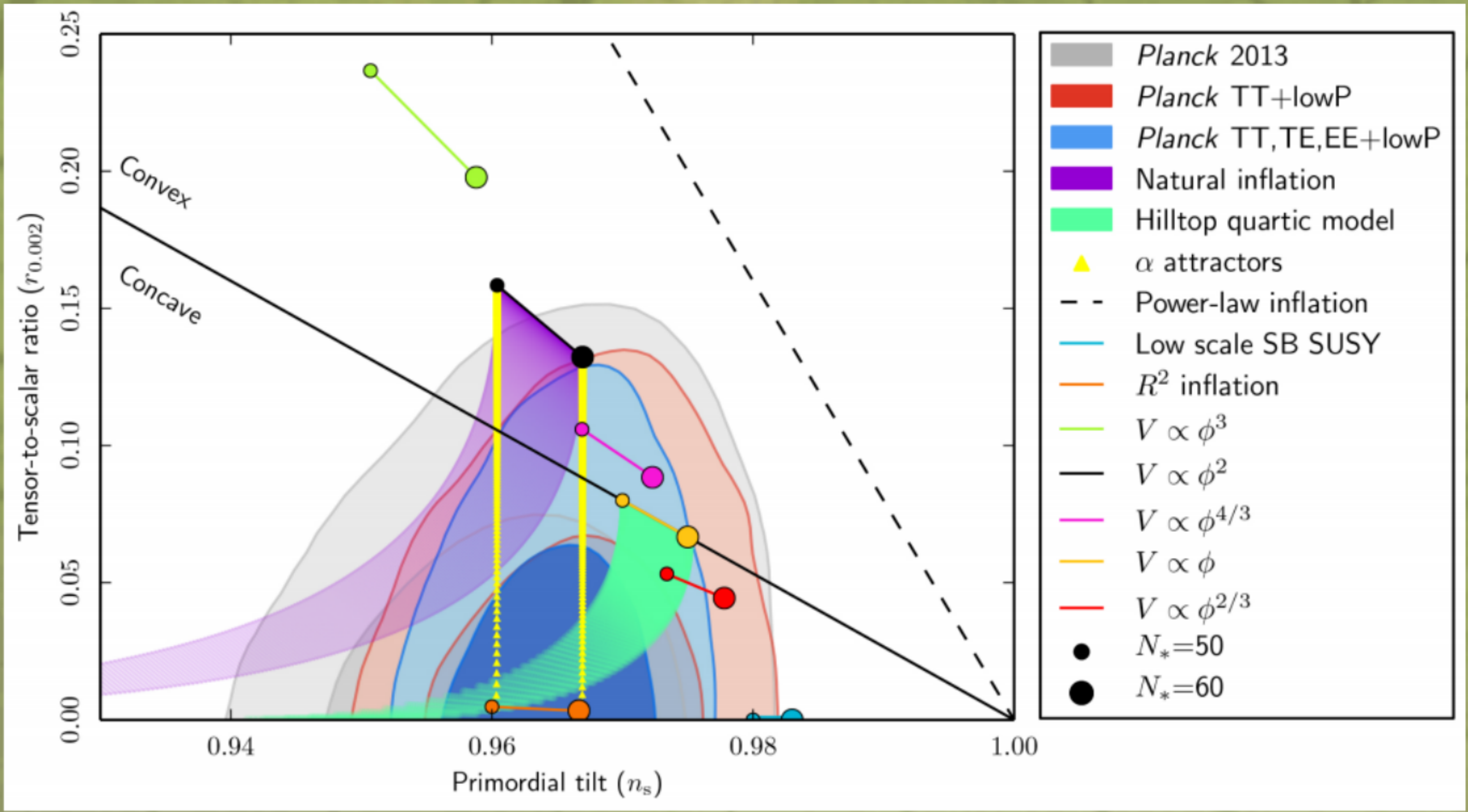
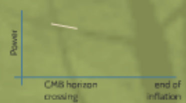


Prezi

Extrapolations

Observed temperature anisotropies in CMB give information on primordial scalar fluctuations:



Moment of CMB horizon crossing is expressed in number of e-folds before the end of inflation:

$$e^N = \frac{a_{\rm end}}{a_{\rm CMB}} \qquad N \sim 50 - 60$$

Measured both power and first scale dependence:

$$P|_{\rm CMB} = 2 \cdot 10^{-9} \quad \text{"amplitude"}$$

$$\frac{d}{dN} P|_{\rm CMB} = n_s - 1|_{\rm CMB} = -0.0397 \pm 0.0073 \quad \text{"spectral index"}$$

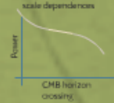
Only upper bounds on second-order scale dep. "running"

Tensor fluctuations can be probed by means of temperature and/or polarization anisotropies.

Characterized similar to scalars by:
- amplitude (phrased as r = tensor-to-scalar ratio of amplitudes)
- spectral index (first scale derivative)
- higher-order derivatives

Not yet detected. General prediction of inflation, but not their amplitude.

Assume that this expression holds for a range of e-folds:
very definite predictions for higher-order scale dependences



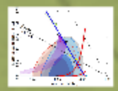
Expansion in 1/N

Note that there is an intriguing relation between measured numbers:

Suggests perturbation theory in number of e-folds:
- right order of magnitude for Planck results
- higher-order terms observationally irrelevant
- subleading terms are not unambiguously defined

Is there any natural expectation for these parameters that are not specified by inflation?

The expected tensor-to-scalar ratio



Class I:

Class II:

Predictions

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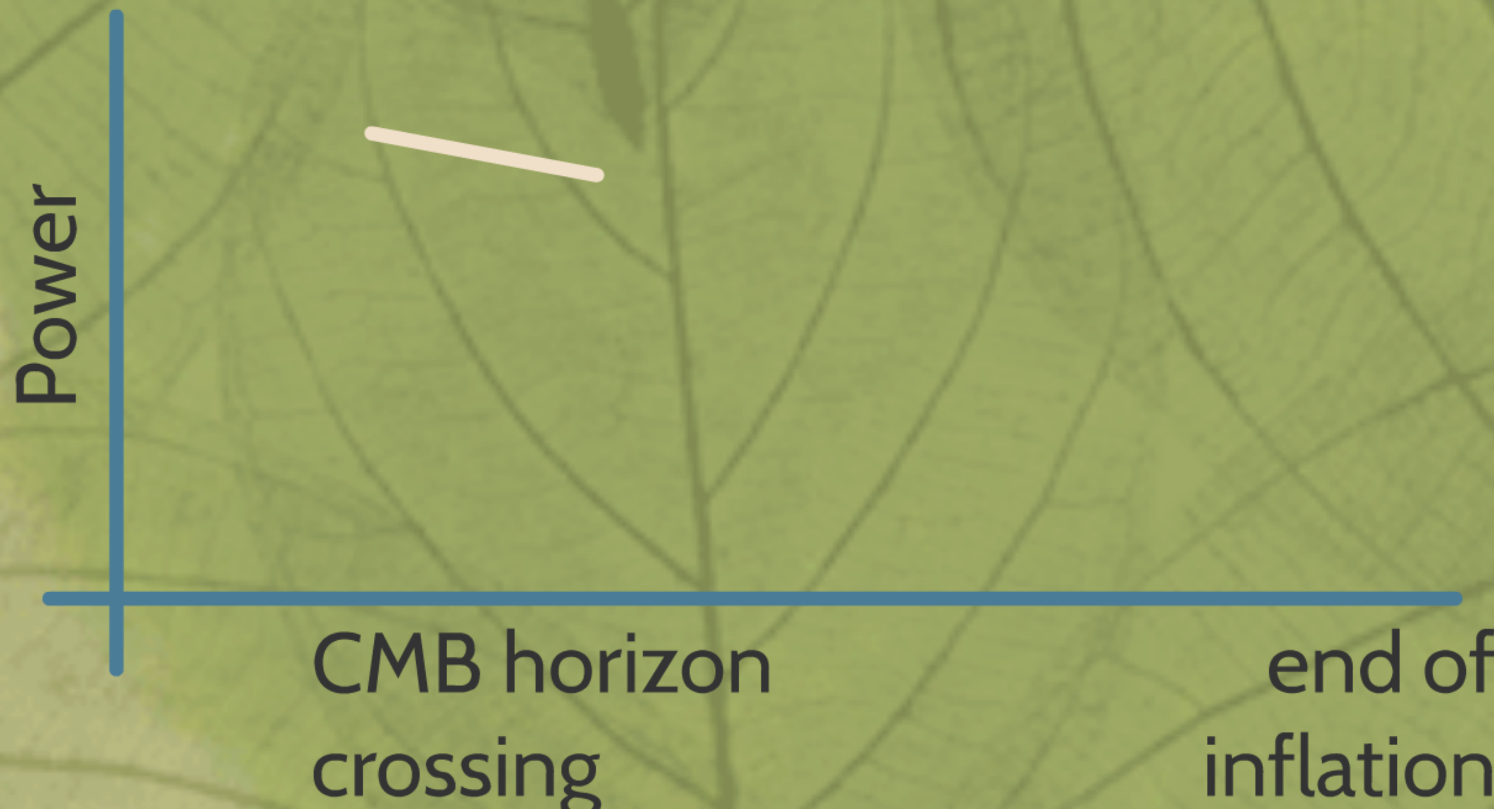

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Expansion in 1/N

Note that there is an intriguing relation between measured numbers:

$$n_s = 1 - \frac{p}{N} + \ldots$$

Suggests perturbation theory in number of e-folds:

- right order of magnitude for Planck results
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[Mukhanov 2013, DR - JCAP 2013]

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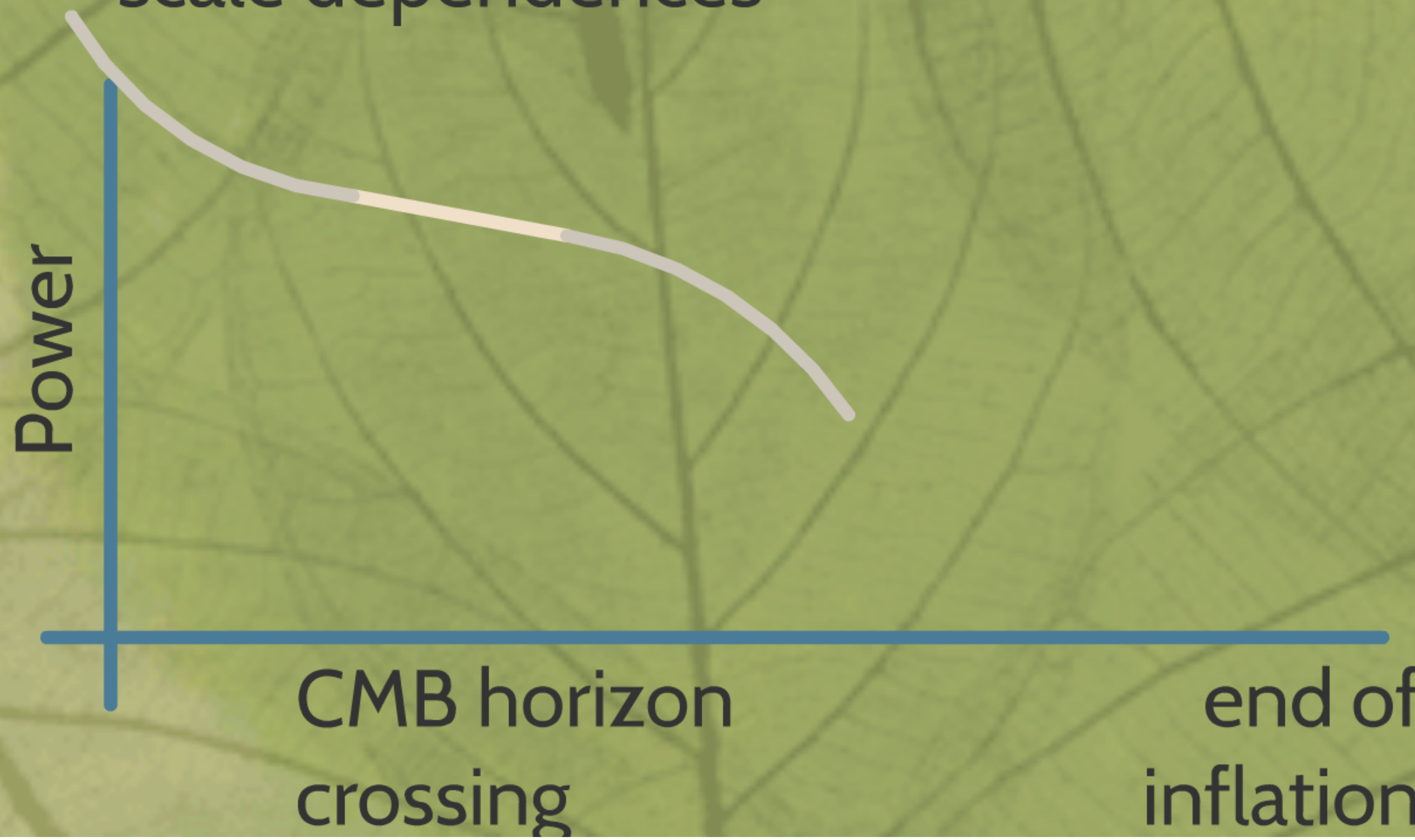


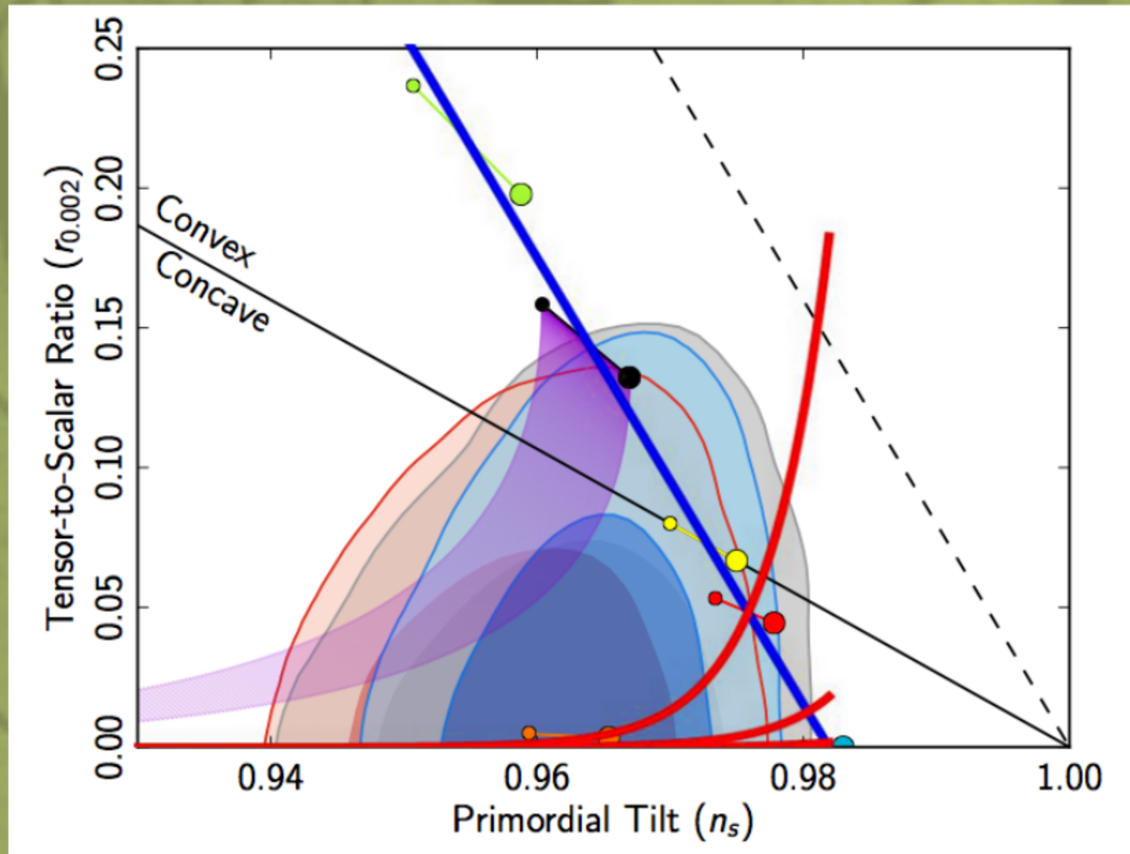
The expected tensor-to-scalar ratio

$$n_s = 1 - \frac{p}{N}$$

$$p > 1$$

Class I: $r \simeq \frac{1}{N^p}$

Class II: $r = \frac{p-1}{N}$



[D.R. - JCAP 2013]

Predictions

Assuming 1/N spectral index:
- Definite value for running.
- Not all tensors possible, two universality classes.

Always minimum redshift:

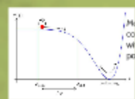
$$n_s < 1 - \frac{1}{N} \approx 0.98$$

Spectral index yields p=2 and predicts tensors:

$$n_s = 1 - \frac{2}{N} \quad \Rightarrow \quad r \approx 0.14 \quad / \quad r < 0.01$$

"*either unobservably small or close to the present observational limit*" (DR, 2013)

Attractors



Modelled by minimally coupling GR to a scalar with kinetic and potential energy:

Model:

Observables:

(expansion)

(scalar power)

(scale dep)

(tensor/scalar)

Plateau inflation

Planck is pointing towards plateau-like potentials:

$$\mathcal{L} = \sqrt{-g}[\tfrac{1}{2}R - \tfrac{1}{2}(\partial\varphi)^2 - V(\varphi)]$$

Plateau at infinite / finite distance, with (inverse) polynomial / exp fall-off.

Pole inflation

Redefinition to trivial potential:

Plateau in potential implies a singularity in kinetic term! Behaviour close to singularity is crucial.

[Galante, Kallosh, Linde, DR - PRL 2015]

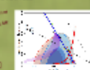
Pole inflationary predictions

Behaviour at N≈60 determined by leading pole in Einstein-frame kinetic term:

$$K_E = \frac{a_p}{\rho^p} + \dots$$

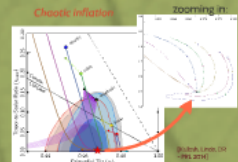
Independent of subleading terms in K and fully independent of V: robustness of attractor!

[Galante, Kallosh, Linde, DR - PRL 2015]



Chaotic inflation

zooming in:



[Kallosh, Linde, DR - PRL 2014]

Non-minimal coupling

Additional coupling between gravity and inflationary sector:

Generalization of Higgs inflation.

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Superconformal attractor

Realized in theories with spontaneously broken superconformal symmetry.

Theory fully determined by
- constant curvature of internal manifold
- symmetry breaking function

[Ferrara, Kallosh, Linde, Porrati '13; Kallosh, Linde, DR - JHEP 2015]

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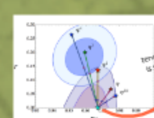

Tensor-to-scalar ratio is set by curvature of internal manifold!

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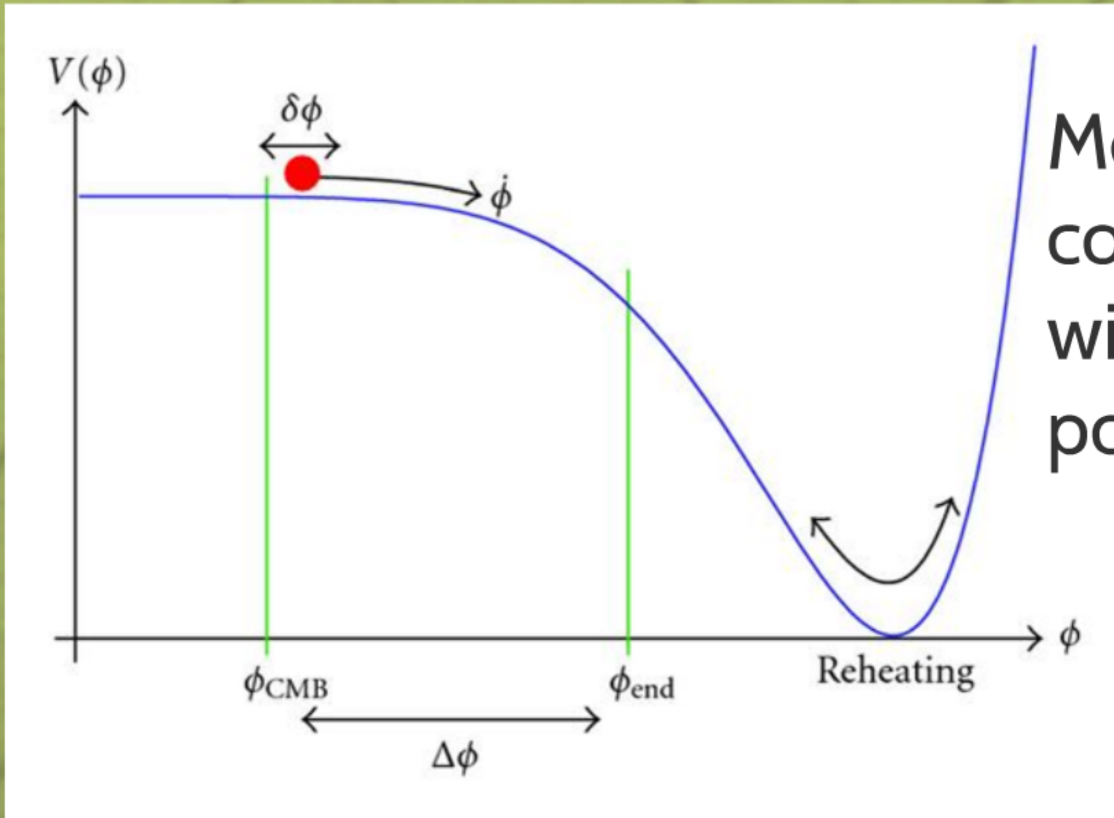


Modelled by minimally coupling GR to a scalar with kinetic and potential energy.

Model:

$$V = V(\phi)$$

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta = \frac{V''}{V}$$

Observables:

$$N = -\int_{\phi_{end}}^{\phi_{CMB}} \frac{V}{V'}$$ (expansion)

$$P \simeq V/\epsilon$$ (scalar power)

$$n_s = 1 + 2\eta - 6\epsilon$$ (scale dep)

$$r = 16\epsilon$$ (tensor/scalar)

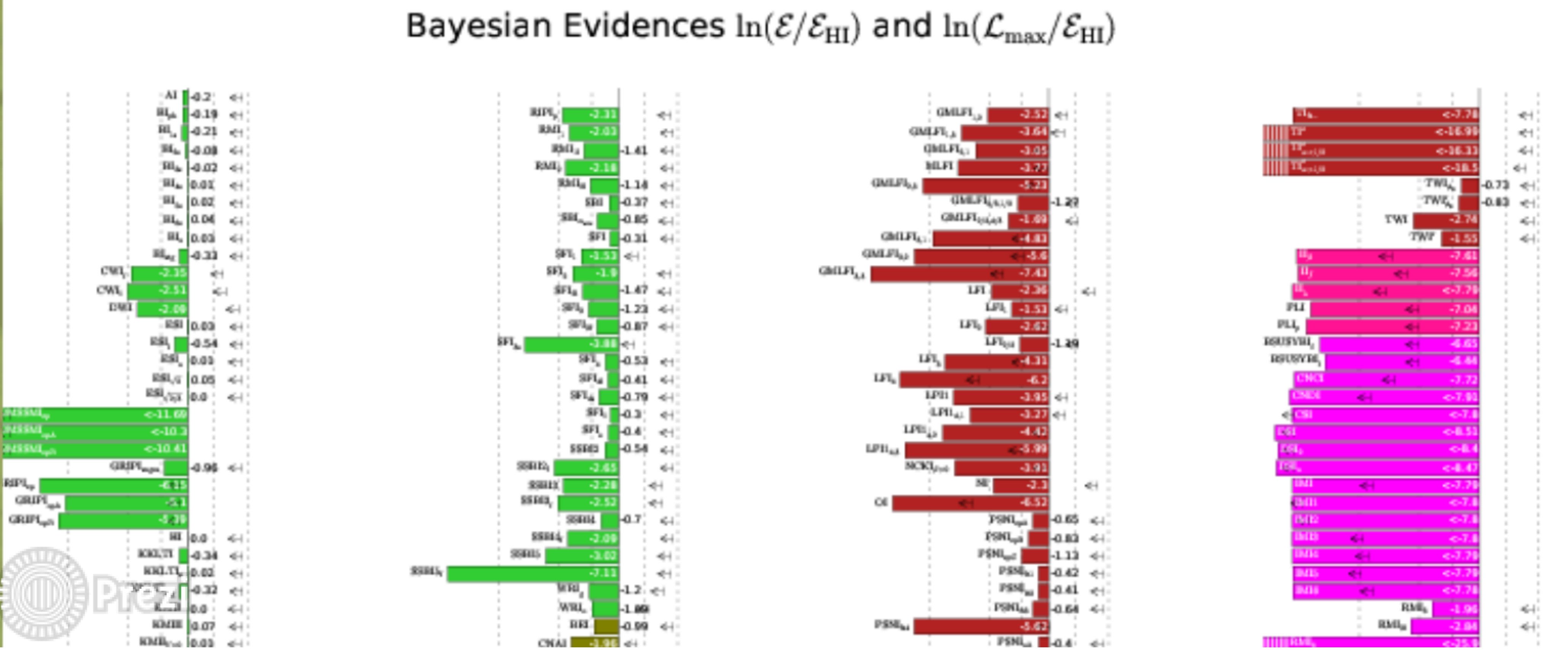
Prezi

The Best Inflationary Models After Planck

Jerome Martin, Christophe Ringeval, Roberto Trotta, Vincent Vennin

(Submitted on 12 Dec 2013 (v1), last revised 3 Jun 2014 (this version, v3))

We compute the Bayesian evidence and complexity of 193 slow-roll single-field models of inflation using the Planck 2013 Cosmic Microwave Background data, with the aim of establishing which models are favoured from a Bayesian perspective. Our calculations employ a new numerical pipeline interfacing an inflationary effective likelihood with the slow-roll library ASPIC and the nested sampling algorithm MULTINEST. The models considered represent a complete and systematic scan of the entire landscape of inflationary scenarios proposed so far. Our analysis singles out the most probable models (from an Occam's razor point of view) that are compatible with Planck data, while ruling out with very strong evidence 34% of the models considered. We identify 26% of the models that are favoured by the Bayesian evidence, corresponding to 15 different potential shapes. If the Bayesian complexity is included in the analysis, only 9% of the models are preferred, corresponding to only 9 different potential shapes. These shapes are all of the plateau type.



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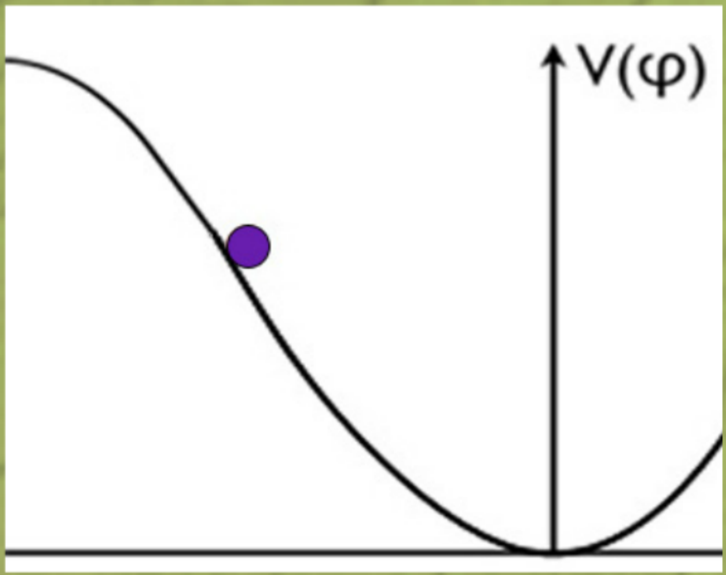
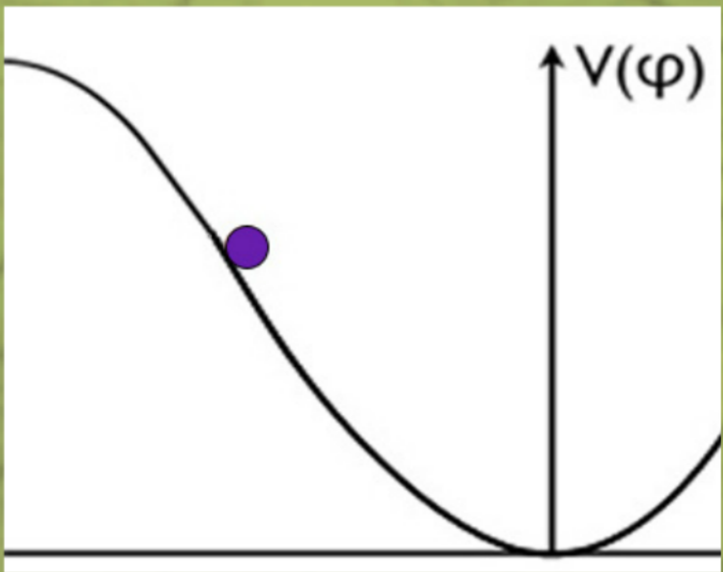


Plateau at infinite / finite distance, with (inverse) polynomial / exp fall-off.

Prezi

Pole inflation



Redefinition to trivial potential:

$$\frac{1}{2}R - \frac{1}{2}\left(\frac{\partial\varphi}{\partial\rho}\right)^2(\partial\rho)^2 - \frac{1}{2}m^2(\rho_0-\rho)^2$$

Similar to V in terms of Hubble!

Plateau in potential implies a singularity in kinetic term!
Behaviour close to singularity is crucial.

[Galante, Kallosh, Linde, DR - PRL 2015]

Prezi

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Behaviour at N=60 determined by leading pole in Einstein-frame kinetic term:

$$K_{\rm E} = \frac{a_p}{\rho^p} + \dots$$

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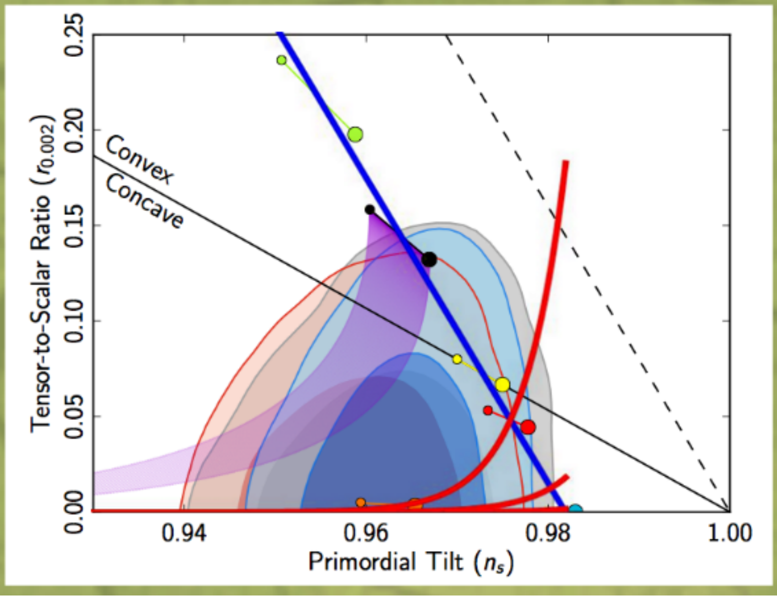
$$n_s = 1 - \frac{p}{p-1}\frac{1}{N}$$

$$r = \# \left(\frac{a_p}{N^p}\right)^{\frac{1}{p-1}}$$

Note: same coeff in ns and power in r [Mukhanov 2013; DR 2013]



Prezi

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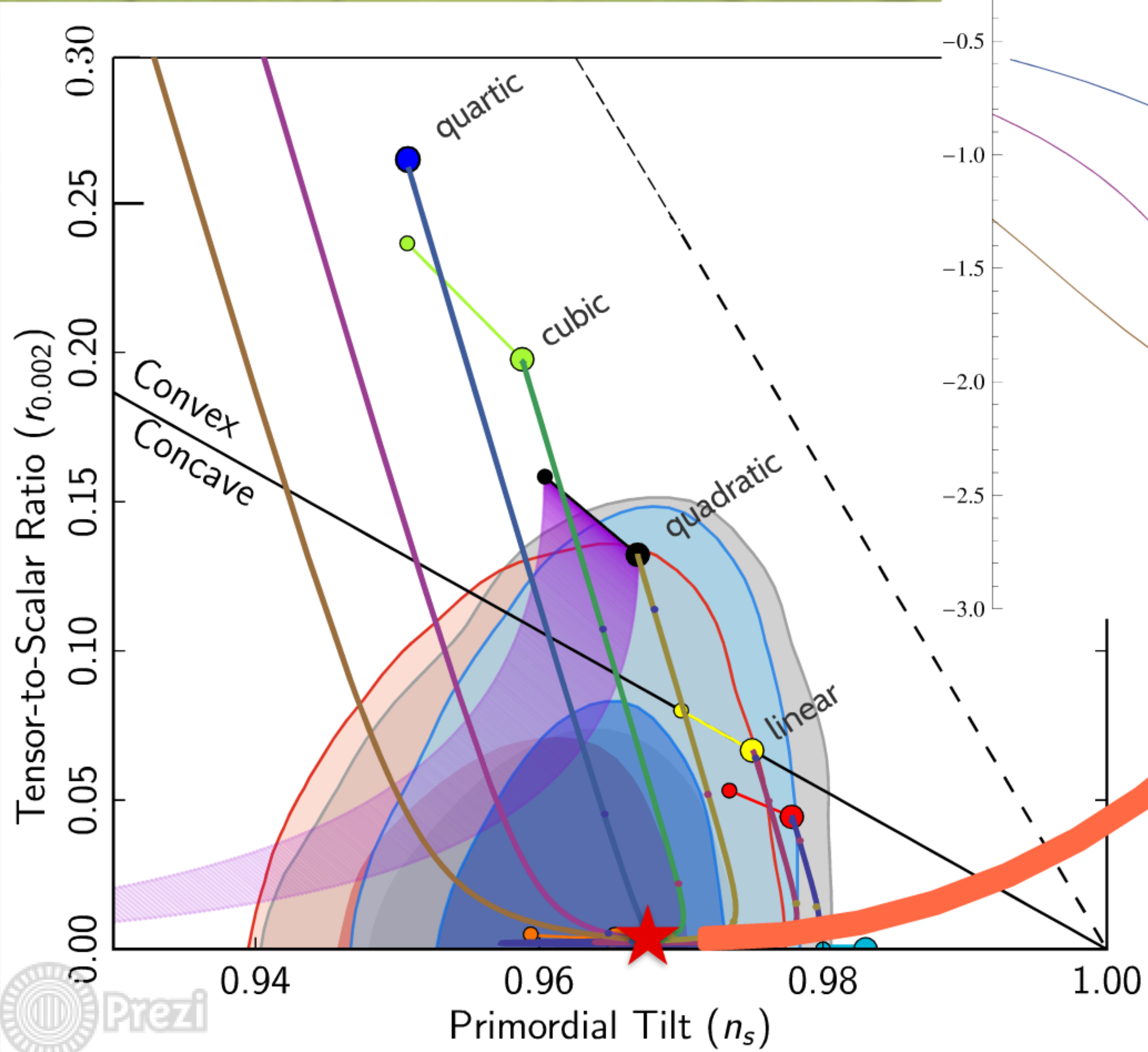

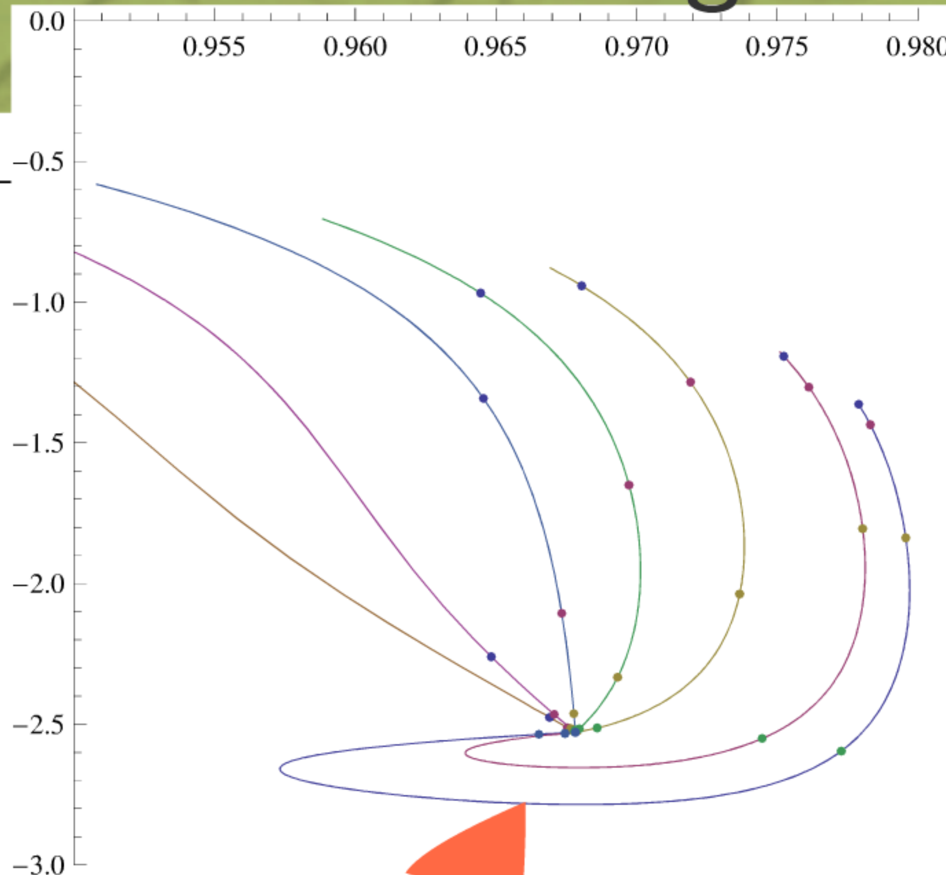

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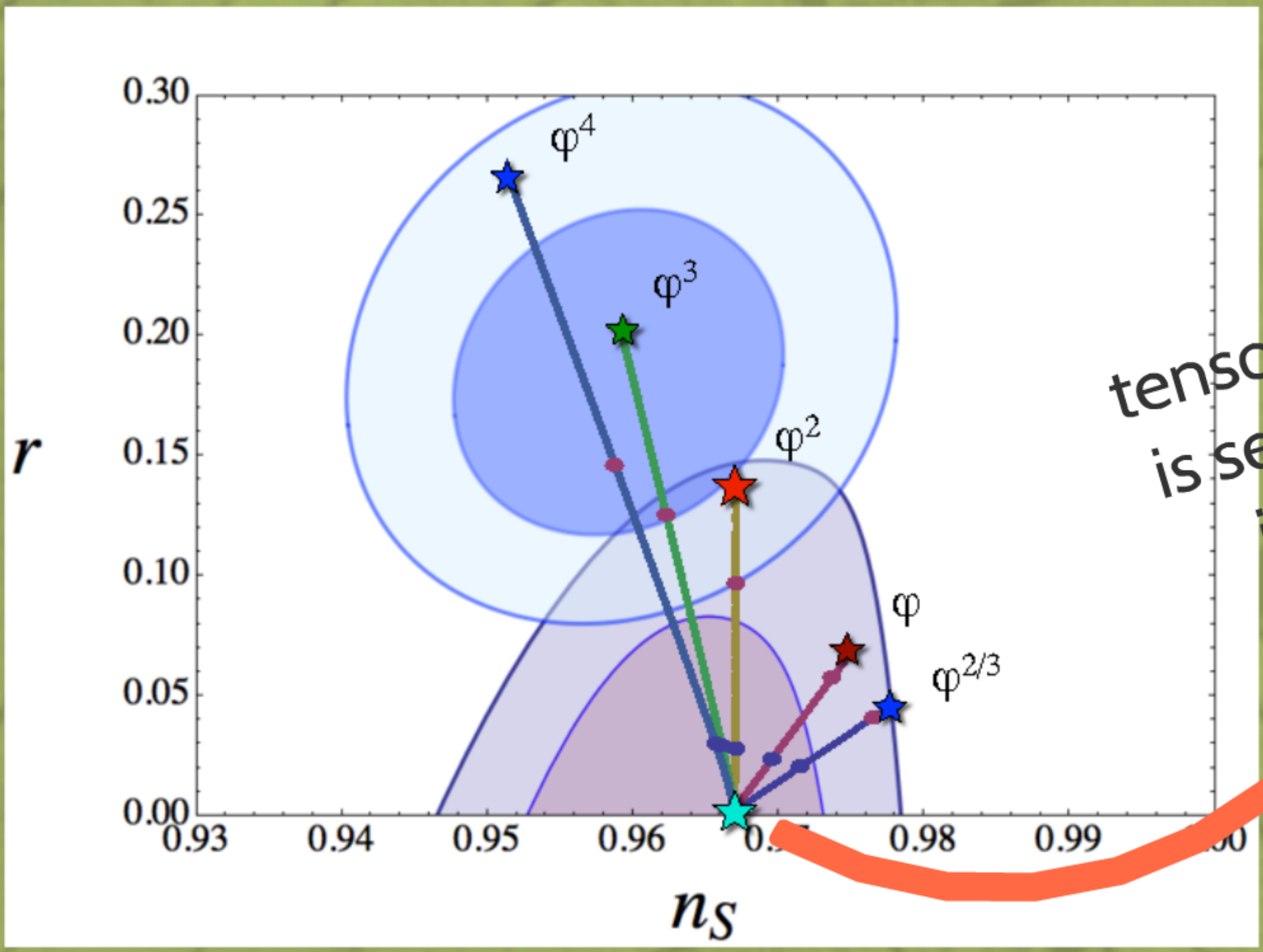

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Conclusions

CMB

CMB provides unique probe into very early Universe

Theory of inflation can be tested by looking for imprint of quantum fluctuations:

- CMB temperature anisotropies arise from scalar fluctations
- CMB polarization anisotropies predicted from tensor fluctuations

Extrapolation

Model-independent 1/N expansion leads to simple expressions:

$$n_s = 1 - \frac{p}{p-1}\frac{1}{N}$$

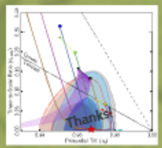
$$r = \# \left(\frac{a_p}{N^p}\right)^{\frac{1}{p-1}}$$

up to subleading corrections. Universal predictions for key observables; can be tested in near future!

Attractors

Strong preference for case p=2 from theory & exp:

- internal manifold with curvature leads to alpha-attractors with r of the order of 1/N^2
- natural permille value of r
- specific value for running
- testable predictions for near future



Pole inflation

Convenient to model by pole structure in kinetic term (fully equivalent to plateau inflation):

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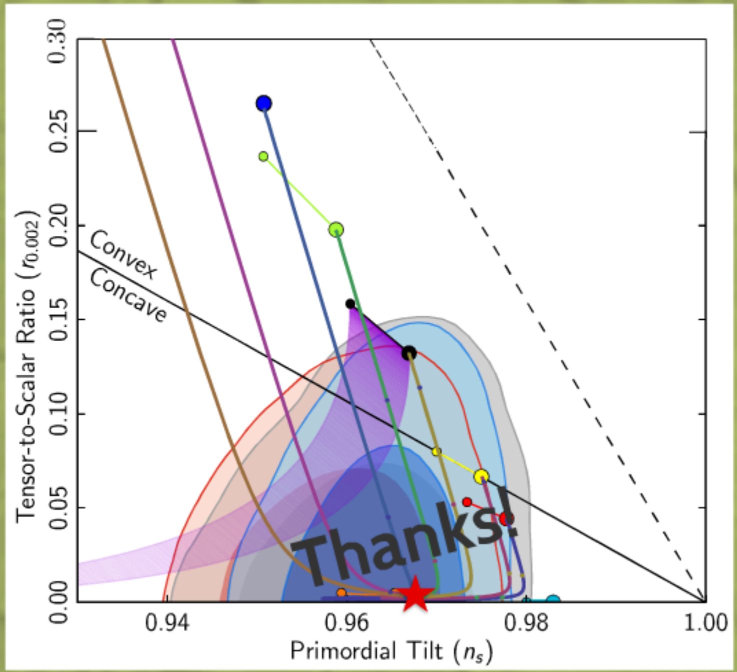

Prezi

Thanks!
0.96
0.98
Primordial Tilt (n_s)