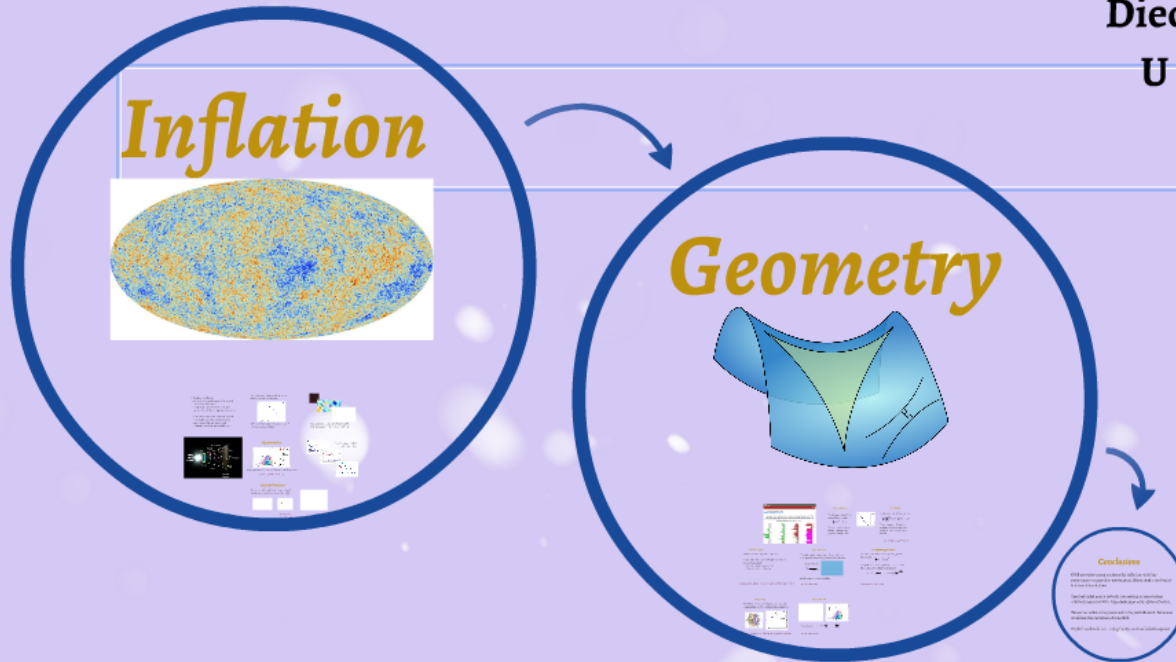
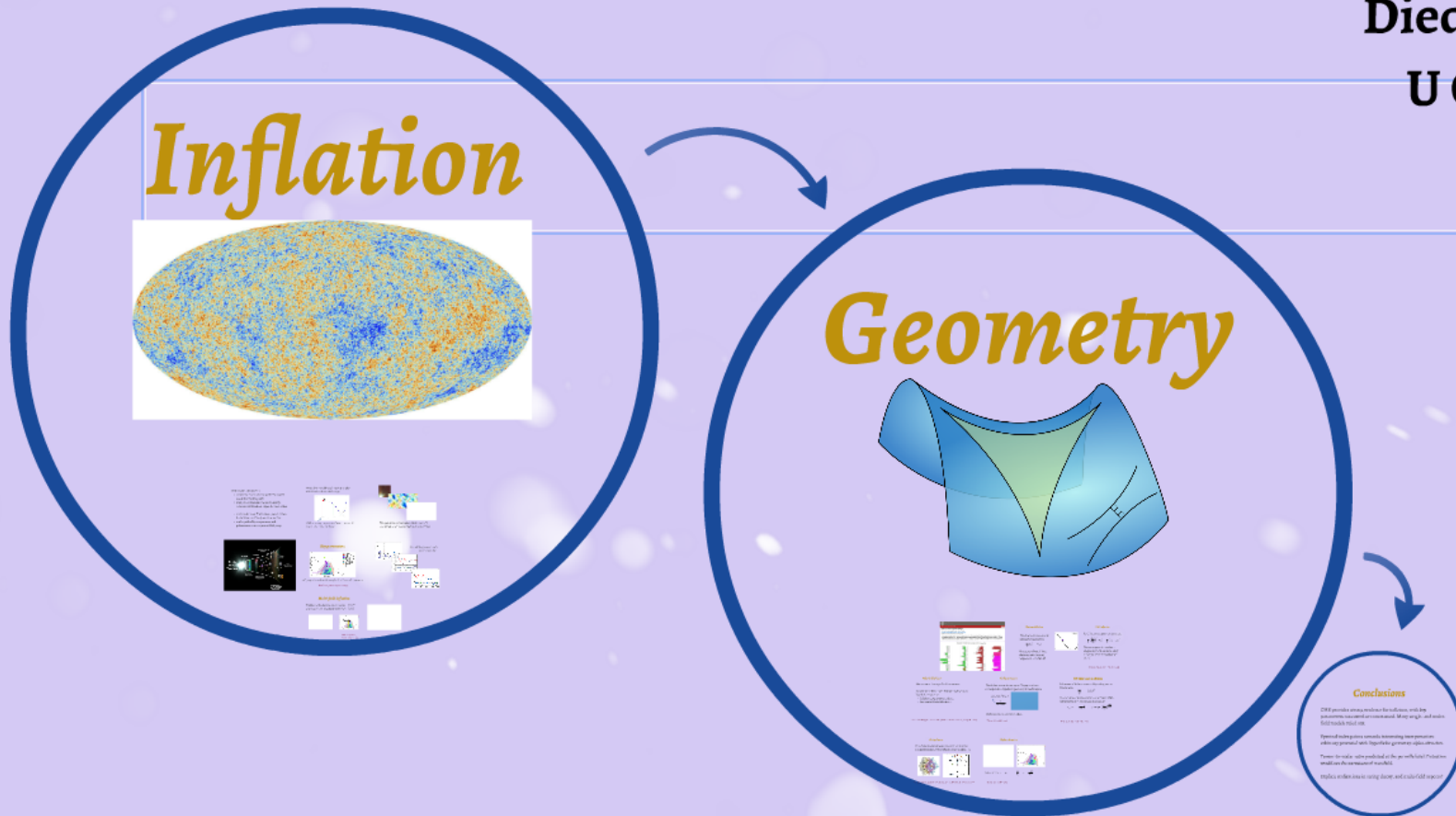


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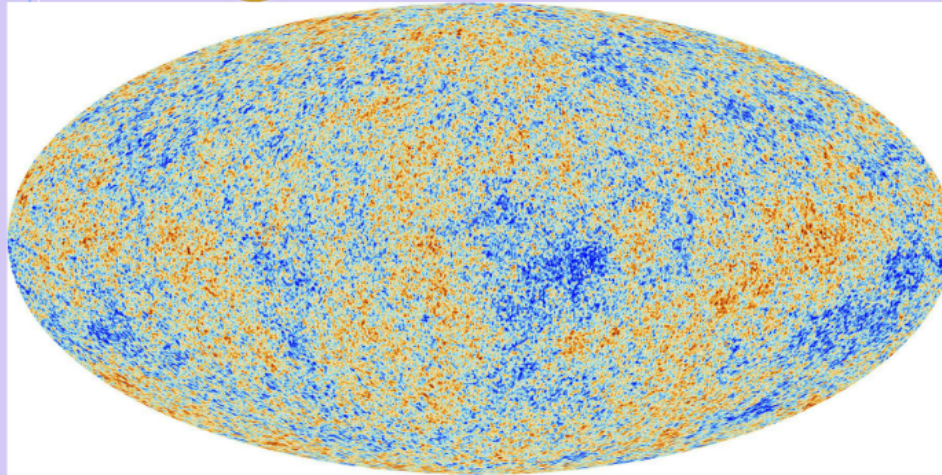


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
**COSMO@Paris**  
**August 28, 2017**

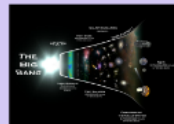
# Inflation





**Deceleration of inflation**  
→ A horizon that is almost perfectly smooth inside the 10000 pixels resolution of the mission with a scale one order of magnitude larger than the satellite resolution and lower frequencies, coming from the inflation and the quantum metric perturbations measured in CMB maps.

From the recently reported data on scalar perturbations and tensor modes.  
  
This prediction is confirmed by the data in general relativity of inflation.

  
The prediction is consistent with the data in general relativity of inflation.



**Key parameters**  
  
Only upper bound on the amplitude of tensor fluctuations.  
(Planck 2015, ACT+SWL15+16)

**Tensor-to-scalar ratio**  
  
Tensor-to-scalar ratio is predicted to be small.

**Multi-field inflation**  
Number of fields with lower tensor-to-scalar ratio.  
  


# THE BIG BANG

INFLATION

GALAXY EVOLUTION  
CONTINUES...

DARK ENERGY?

FIRST STARS  
400,000,000 YEARS  
AFTER BIG BANG

THE DARK AGES

COSMIC MICROWAVE  
BACKGROUND  
400,000 YEARS AFTER  
BIG BANG

FIRST GALAXIES  
1,000,000,000 YEARS  
AFTER BIG BANG

Now  
13,700,000,000 YEARS  
AFTER BIG BANG

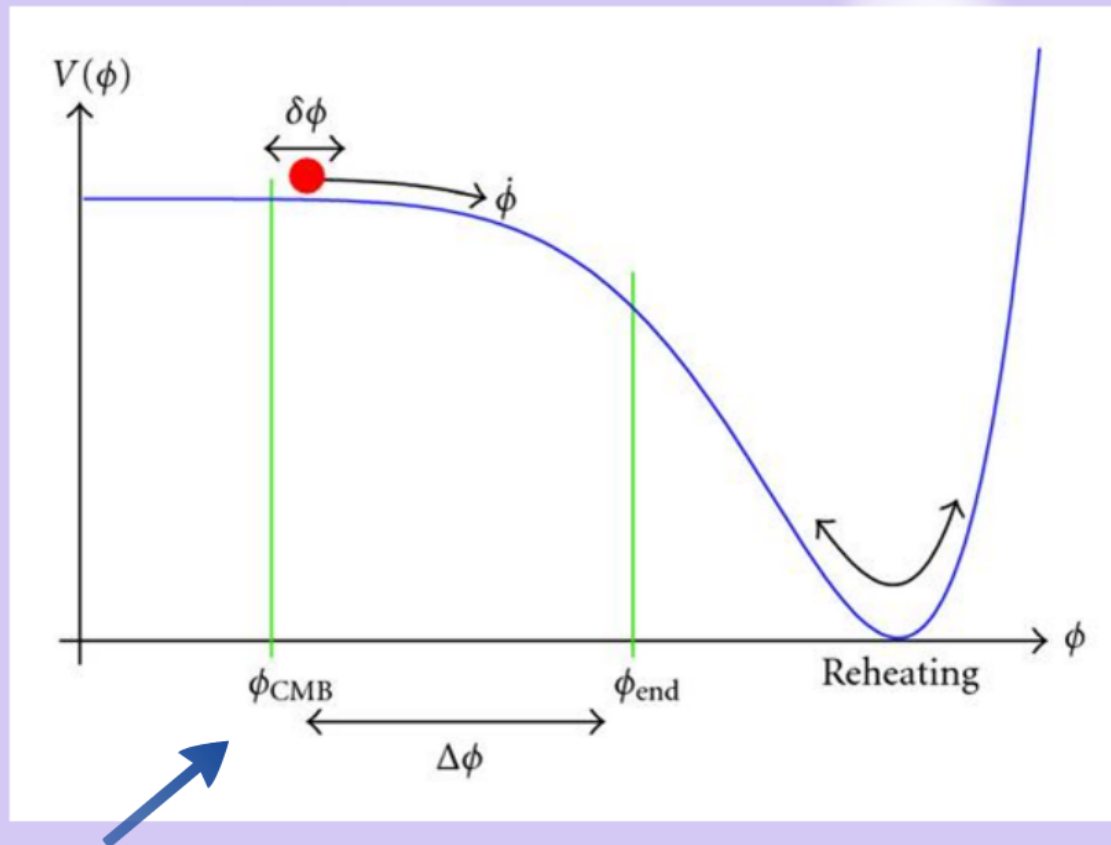
FORMATION OF  
THE SOLAR SYSTEM  
8,700,000,000 YEARS  
AFTER BIG BANG

## Deliverables of inflation:

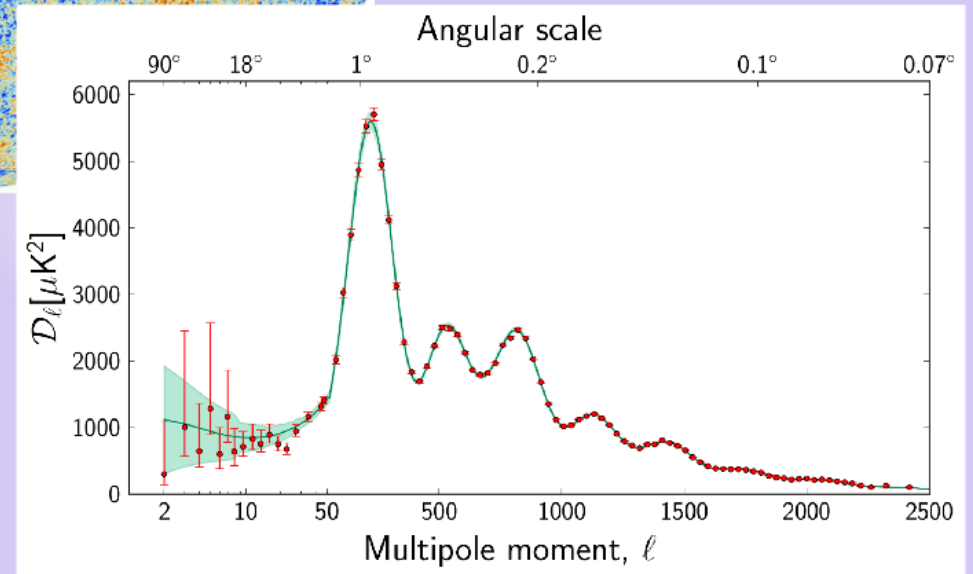
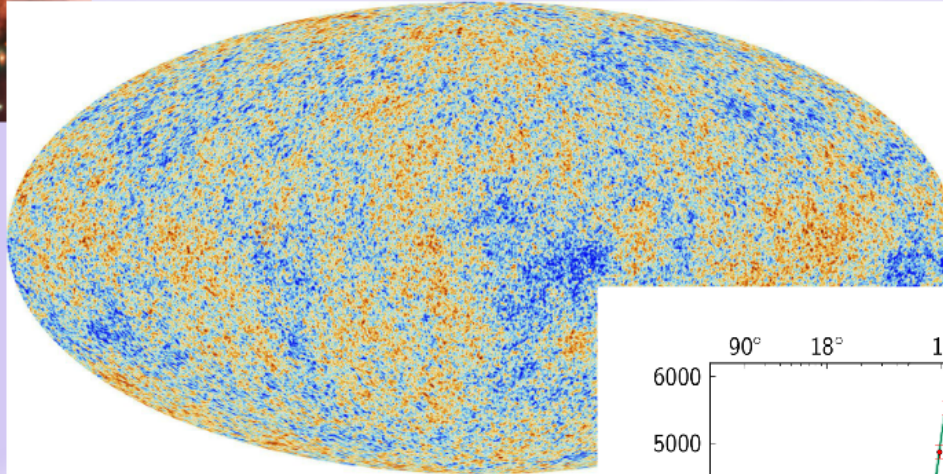
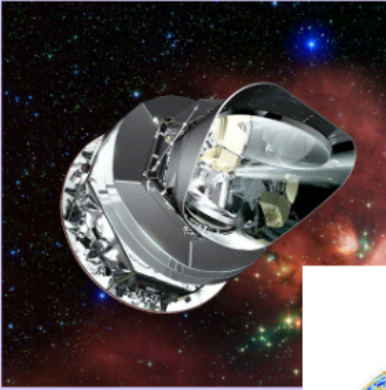
- a Universe that is almost perfectly smooth inside the Hubble patch
- ready-made fluctuations with a nearly constant amplitude on super-horizon scales
- scalar and tensor fluctuations, coming from the inflaton and the space-time metric
- can be probed by temperature and polarization anisotropies in CMB, resp.



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

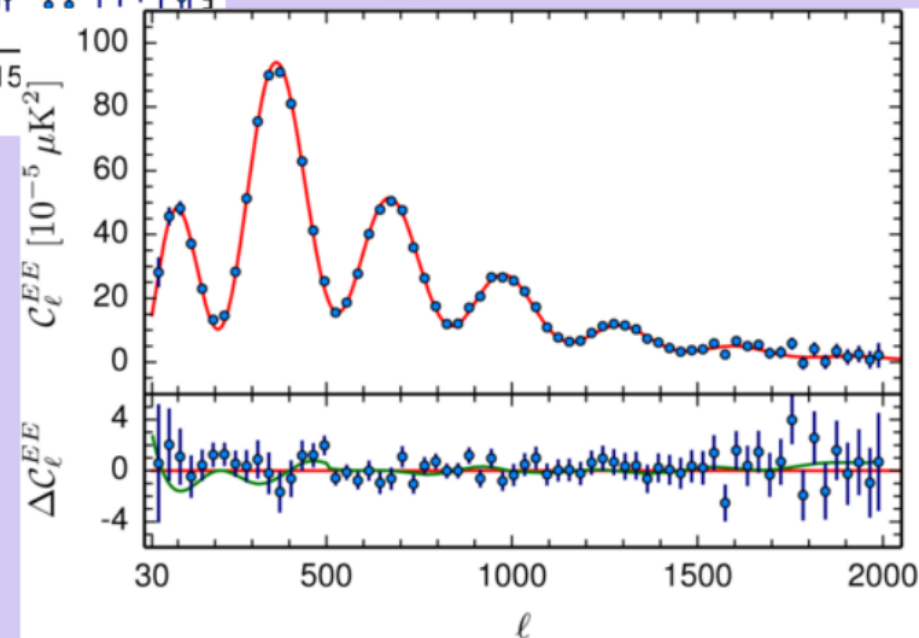
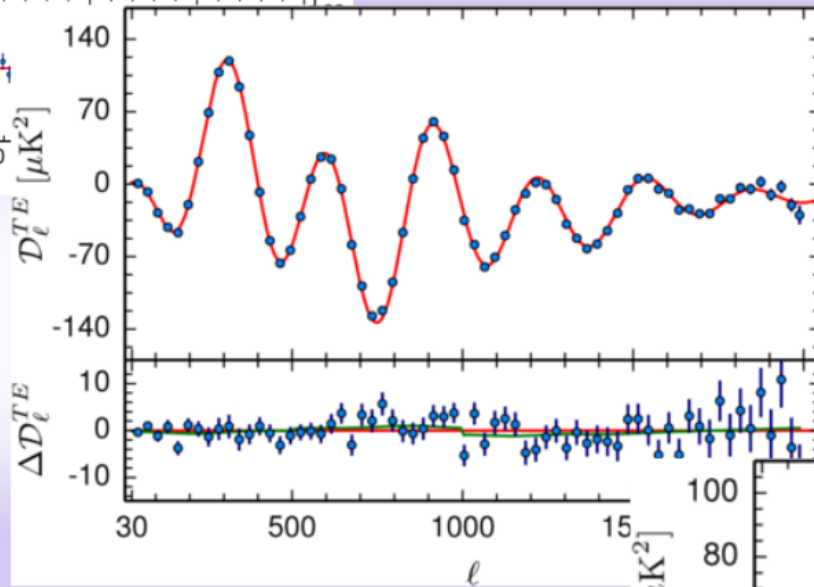
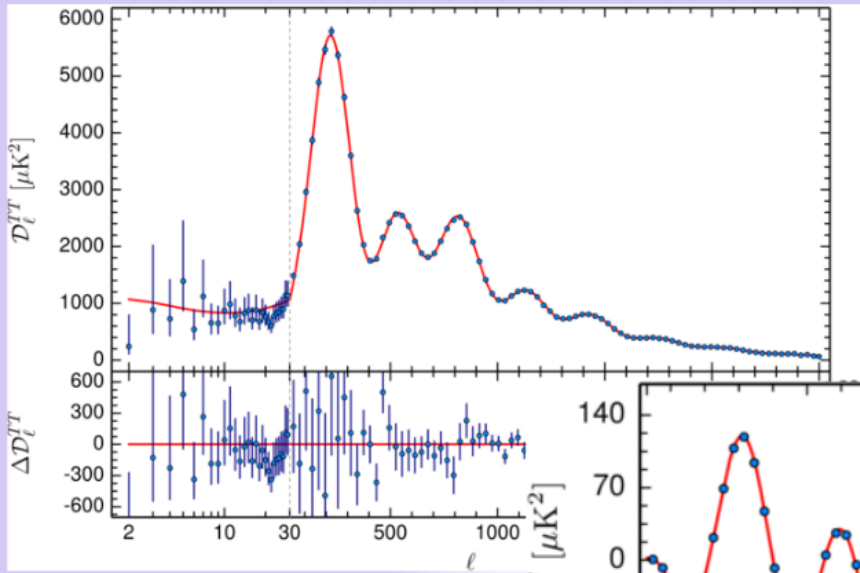


CMB anisotropies generated some amount  $N$  prior to the end of inflation.



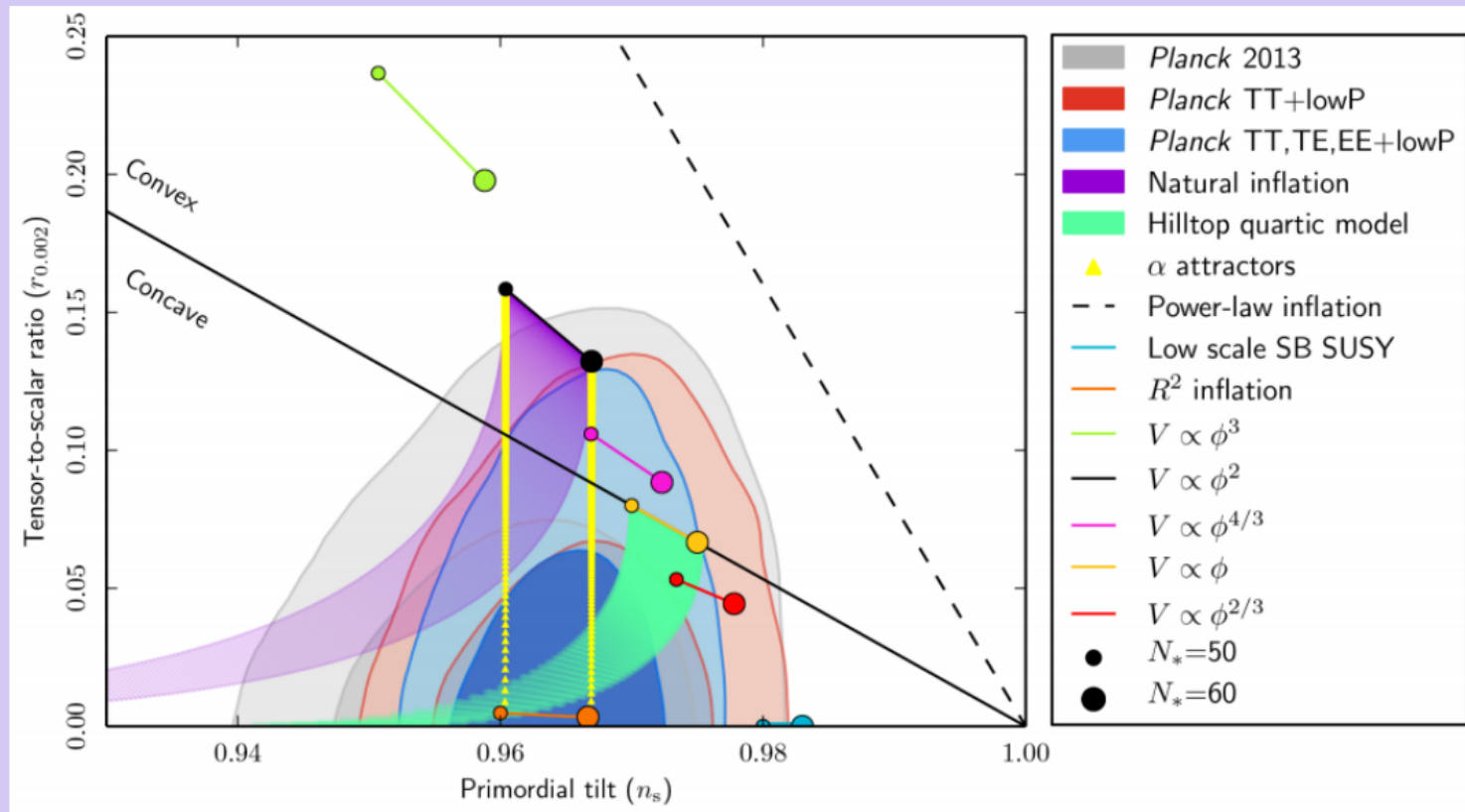
Temperature anisotropies allow one to fit amplitude and spectral index of scalar fluct.

Beautiful agreement with  
polarization data:





# Key parameters

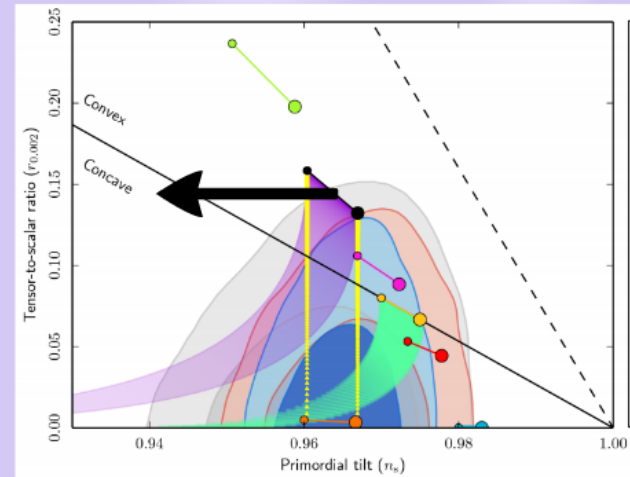
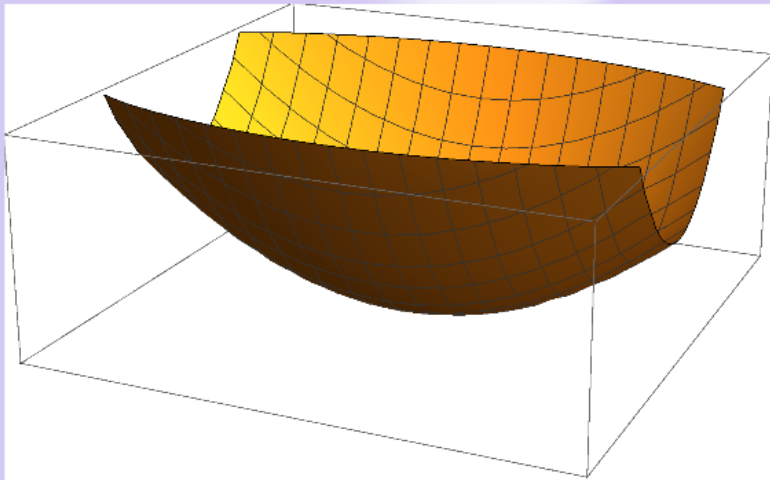


Only upper bound on the amplitude of tensor fluctuations.

[Planck 2015, BICEP2/KECK 2015]

# Multi-field inflation

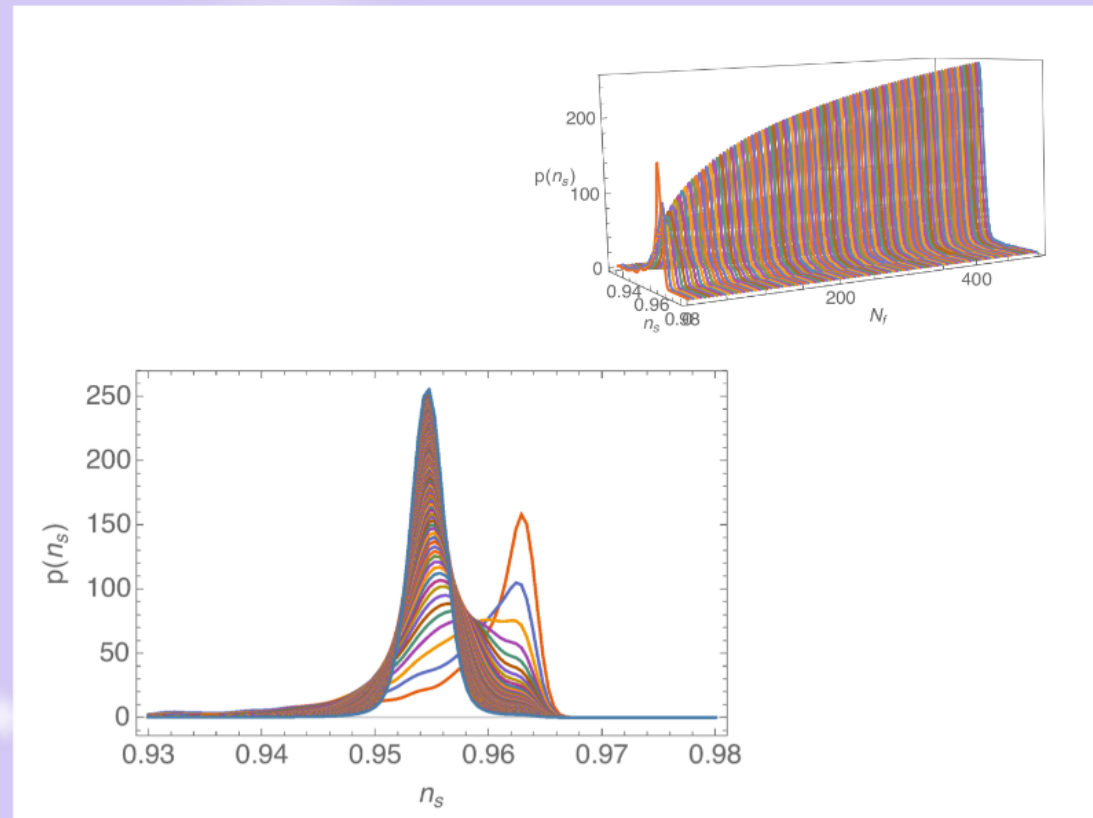
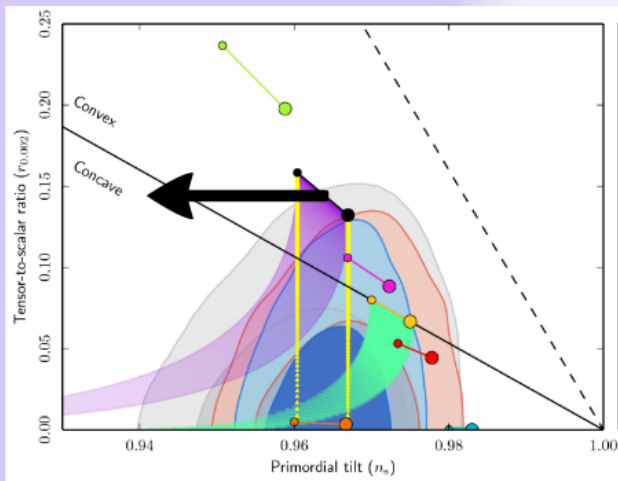
Number of fields with kinetic terms  $(\partial\phi_i)^2$   
and masses, i.e. quadratic potentials  $m_i^2\phi_i^2$



[Easter, Frazer,  
Peiris, Price - 2013]

# inflation


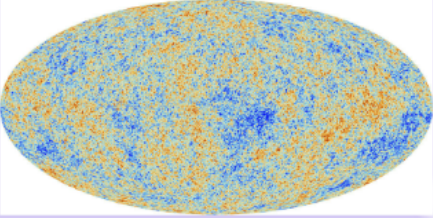
kinetic terms  $(\partial\phi_i)^2$   
potentials  $m_i^2\phi_i^2$




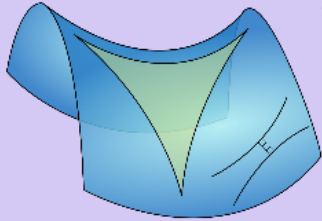
[Easter, Frazer,  
Peiris, Price - 2013]

Diederik Roest  
U Groningen

# Inflation



# Geometry



### Conclusions

CMB provides strong evidence for inflation, with key features: isotropy, homogeneity, large-scale structure, and acoustic oscillations.

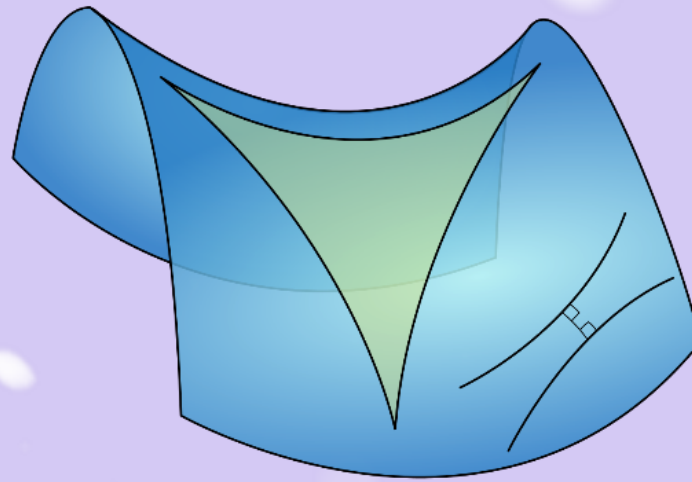
Open questions remain: the initial conditions, the reheating phase, and the generation of primordial perturbations.

Future: to make the prediction of the per-meth CMB fluctuation map on the measurement of modes.

Public relations: using data and visualization.

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# Geometry



**Multi-field inflation**  
 Models for primary gravitino production in the preheating phase.  
 Planck,  $n_s = 0.964 \pm 0.005$   
 Primordial tensor-to-scalar ratio  $r < 0.12$  (95% CL)  
 Planck,  $r < 0.12$  (95% CL)

**Single-field inflation**  
 Models for primary gravitino production in the preheating phase.  
 Planck,  $n_s = 0.964 \pm 0.005$   
 Primordial tensor-to-scalar ratio  $r < 0.12$  (95% CL)  
 Planck,  $r < 0.12$  (95% CL)

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### Conclusions

CMB provides strong evidence for inflation, with key parameters measured or constrained. Many single- and multi-field models ruled out.

Spectral index points towards interesting interpretation: arbitrary potential with hyperbolic geometry: *alpha-attractors*.

Tensor-to-scalar ratio predicted at the permille level. Detection would set the curvature of manifold.

Explicit realizations in string theory, and multi-field aspects?





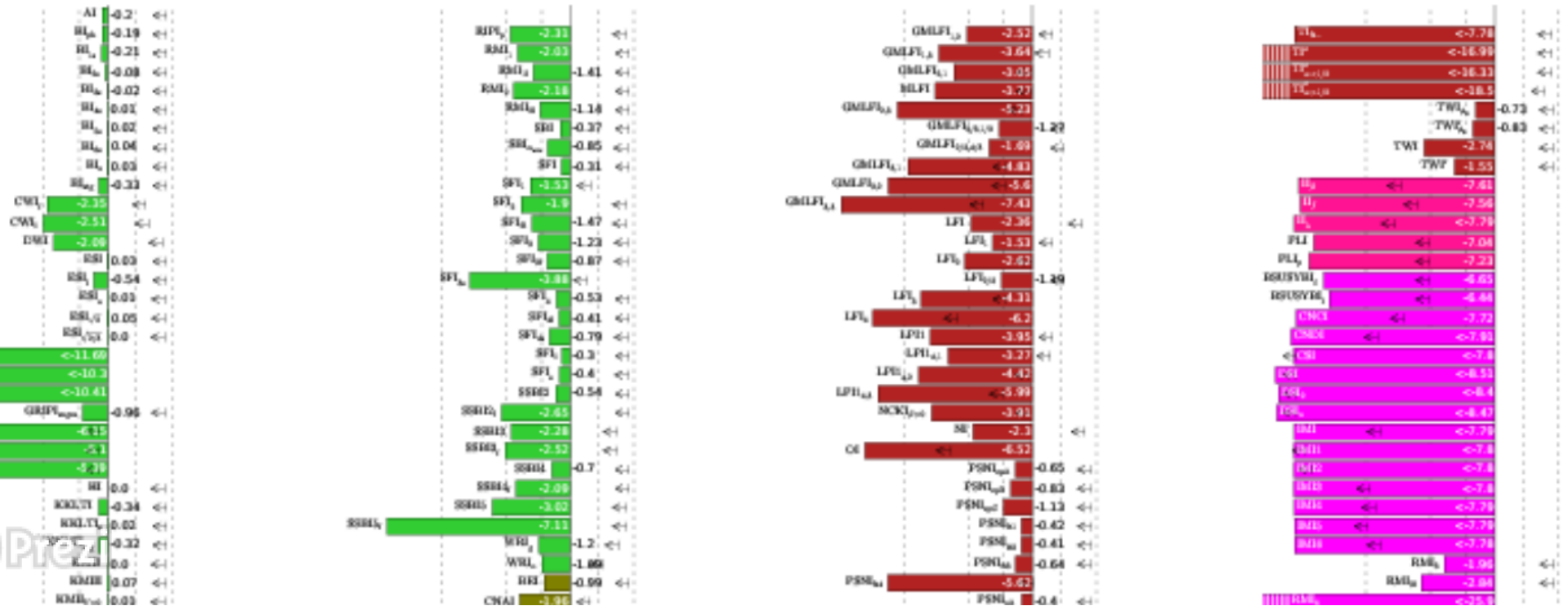
# The Best Inflationary Models After Planck

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.

## Bayesian Evidences $\ln(\mathcal{E}/\mathcal{E}_{HI})$ and $\ln(\mathcal{L}_{max}/\mathcal{E}_{HI})$

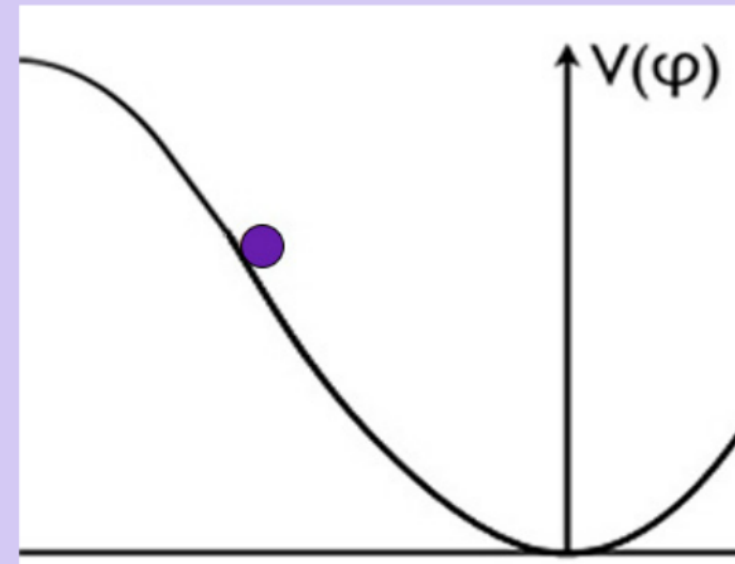


## *Plateau inflation*

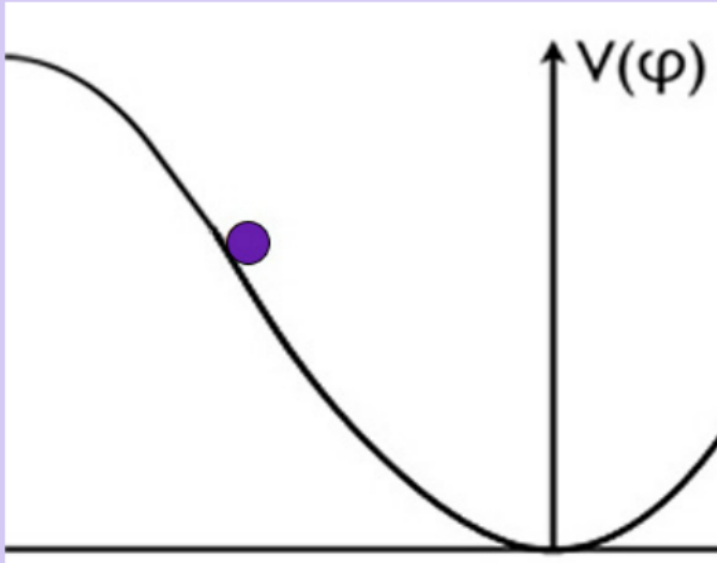
Planck is pointing towards plateau-like potentials:

$$-\frac{1}{2}(\partial\varphi)^2 - V(\varphi)$$

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



## *Pole inflation*



Redefinition to quadratic potential:

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

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

## *Pole inflationary predictions*

Behaviour at  $N=60$  determined by leading pole in kinetic term:

$$\left(\frac{a_p}{\rho^p} + \dots\right) (\partial\rho)^2$$

Independent of subleading kinetic terms and fully independent of  $V$ : robustness of attractor!


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



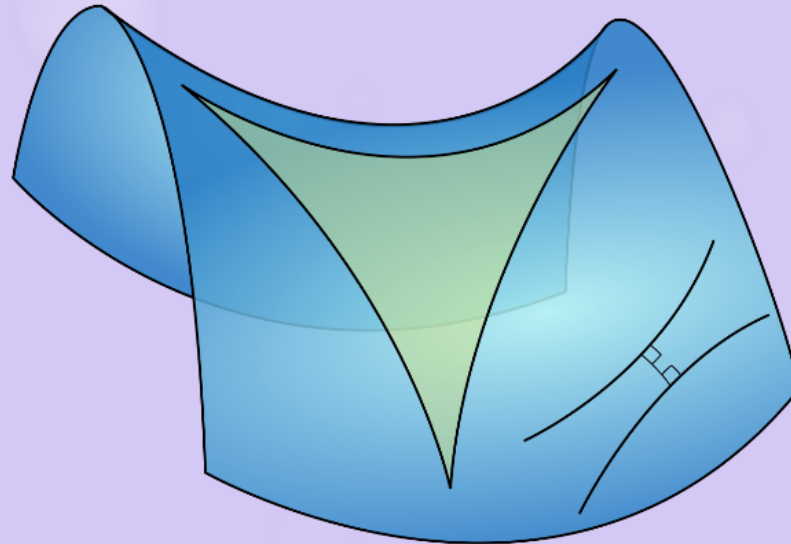
## Alpha-attractors

Planck data points towards  $p=2$ . Very special case:  
corresponds to hyperbolic geometry of moduli space

$$g_{ij}(\phi)(\partial\phi^i)(\partial\phi^j)$$



$$\frac{1}{1 - \phi_i\phi^i/\alpha}\delta_{ij}$$

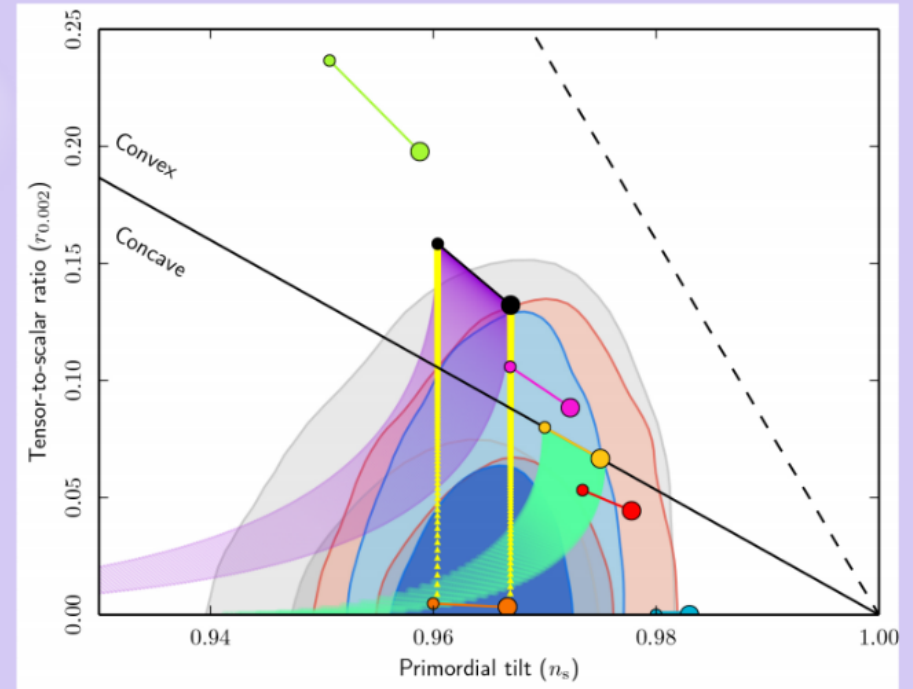
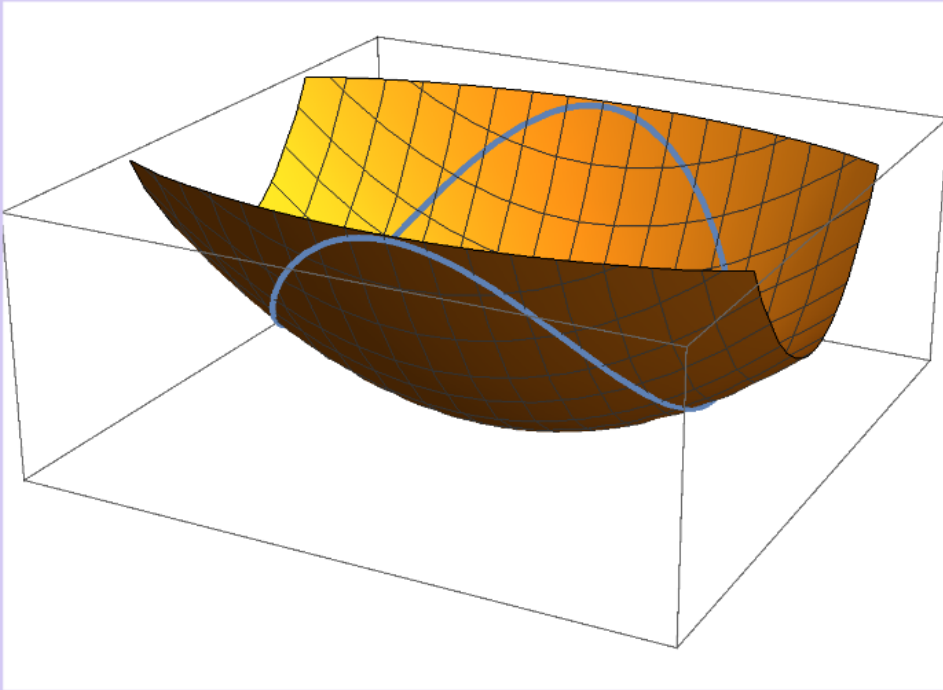


Single parameter: curvature alpha





# Alpha-attractors

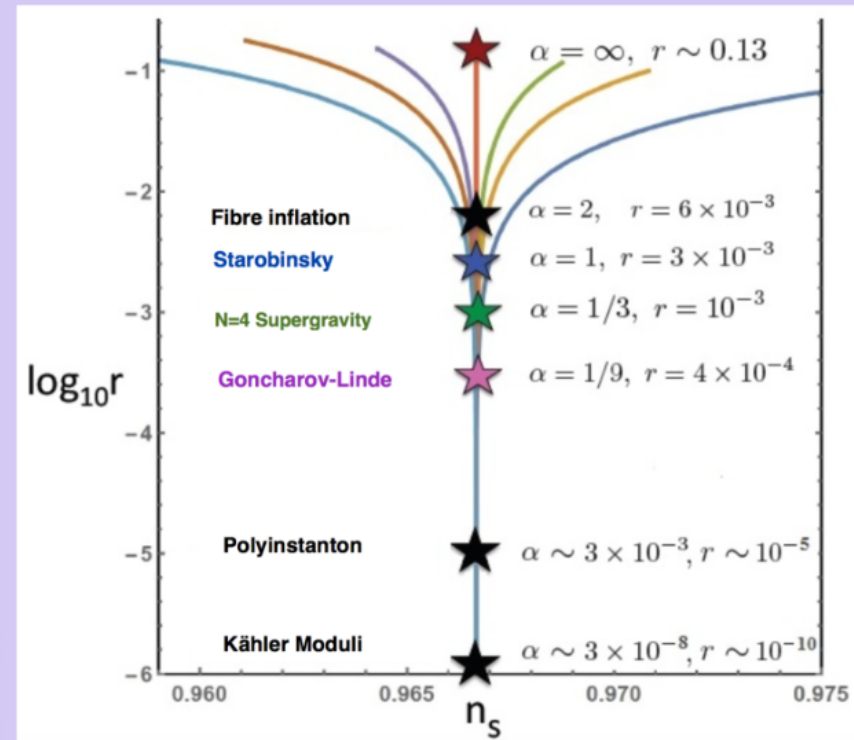
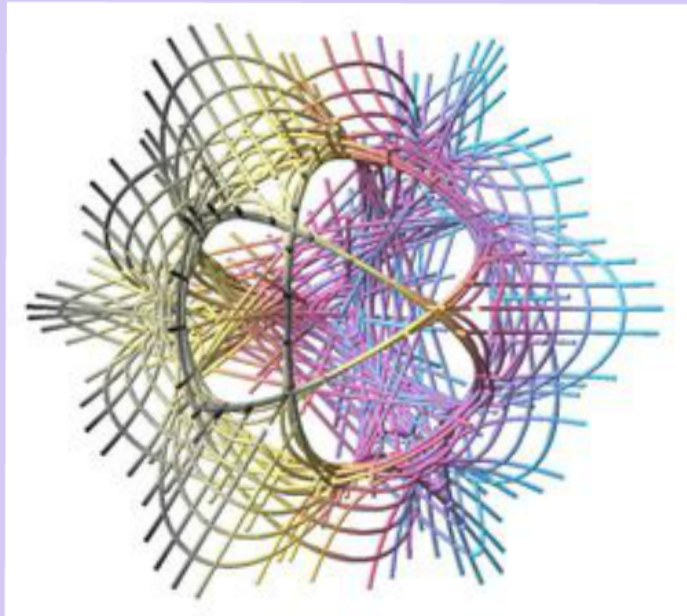


Robust predictions: 
$$n_s = 1 - \frac{2}{N} \quad r = \frac{12\alpha}{N^2}$$



# String theory

Hyperbolic moduli spaces very common in string compactifications. Fibre inflation leads to  $\alpha = 2$ :



## *Multi-field effects?*


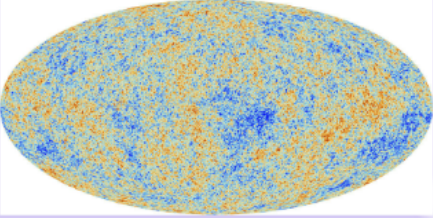
Above results for single-field trajectories.

Possible to perform multi-field generalization in hyperbolic geometry?


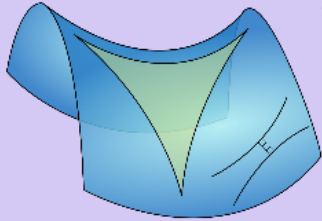
- Inflation along a non-geodesic...
- Geometrical destabilization...

Diederik Roest  
U Groningen

# Inflation



# Geometry



### Conclusions

CMB provides strong evidence for inflation, with key features: isotropy, homogeneity, large-scale structure, and acoustic oscillations.

Open questions remain: the tensor-to-scalar ratio  $r$ , the primordial spectrum, and the reheating phase.

Thanks to the CMB, we have a picture of the early universe that is consistent with the predictions of inflation.

Further observations using CMB and other probes are needed.

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# Conclusions

CMB provides strong evidence for inflation, with key parameters measured or constrained. Many single- and multi-field models ruled out.

Spectral index points towards interesting interpretation: arbitrary potential with hyperbolic geometry: *alpha-attractors*.


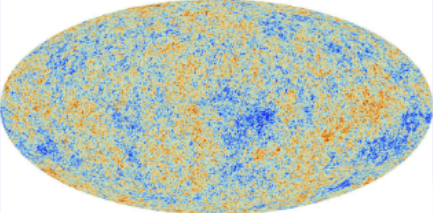
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Explicit realizations in string theory, and multi-field aspects?


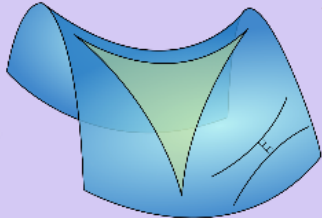


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# Inflation



# Geometry



### Conclusions

CMB provides strong evidence for inflation, with key features: isotropy, homogeneity, large-scale structure, and acoustic oscillations.

Open questions remain: the tensor-to-scalar ratio  $r$ , the primordial spectrum, and the nature of dark matter and dark energy.

Future CMB experiments (e.g., CMB-S4, LiteB) will improve constraints on inflation and the early universe.

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