Inflation

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The basics of Inflation

- Inflation was proposed to address several problems of the conventional Big Bang theory:

    - The horizon problem.

    - The flatness problem.

    - The monopole problem.

The basics of Inflation

Guth '81.

- A period of accelerated expansion solves all these problems.
- One way to do that is to have a period of time where the energy density of the universe is dominated by an effective cosmological constant.

$$\rho = -P \quad \Rightarrow \quad H^2 = \frac{8\pi G}{3}\rho$$

- The universe increases its size by a huge factor in a tiny amount of time:

$$a(t) \sim e^{Ht}$$

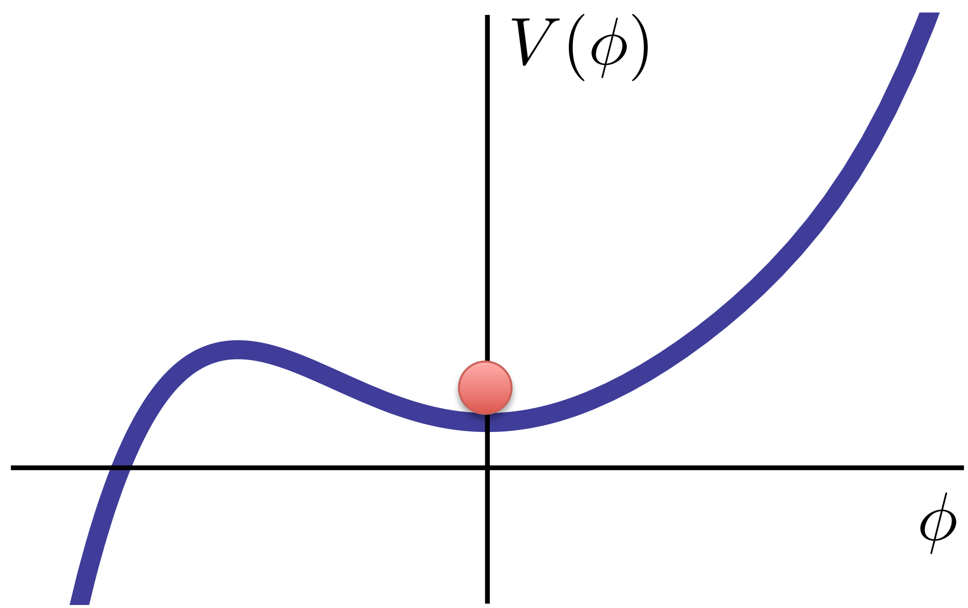
The basics of Inflation

- The simplest model where we can explain inflation is a scalar field theory coupled to gravity

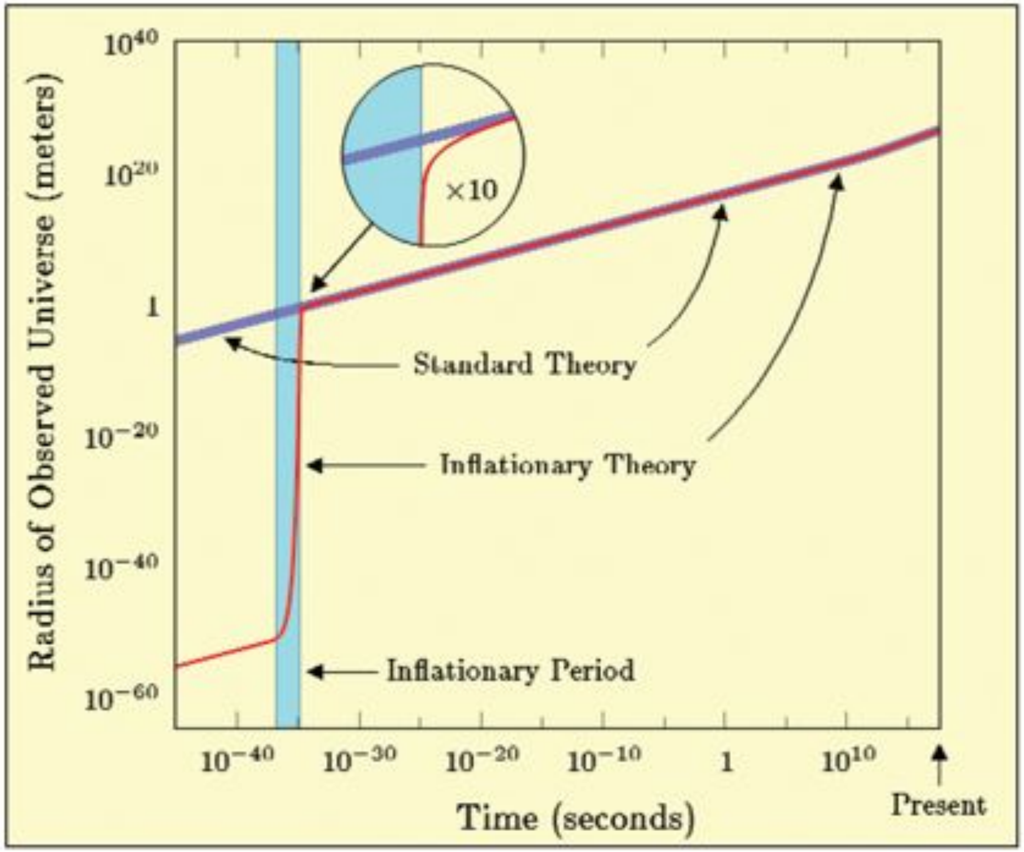
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

$$\rho = \cancel{\frac{1}{2}\dot{\phi}^2} + V(\phi)$$

$$P = \cancel{\frac{1}{2}\dot{\phi}^2} - V(\phi)$$



The basics of Inflation



Guth '02.

Inflation has to end to give rise to a radiation dominated universe.

We measure the amount of inflation in terms of the total expansion during that time, the number of e-folds:

$$N = \int_{a_i}^{a_f} d\ln a = \int_{t_i}^{t_f} H(t)dt > 60$$

The Slow Roll Regime

- Inflation has to be sustained for a while so we need to ensure that the field behaves effectively like a cosmological constant.

- This is true if the field in the slow roll regime where one requires the following parameters to be small:

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

$$\eta = M_P^2 \frac{V''}{V}$$

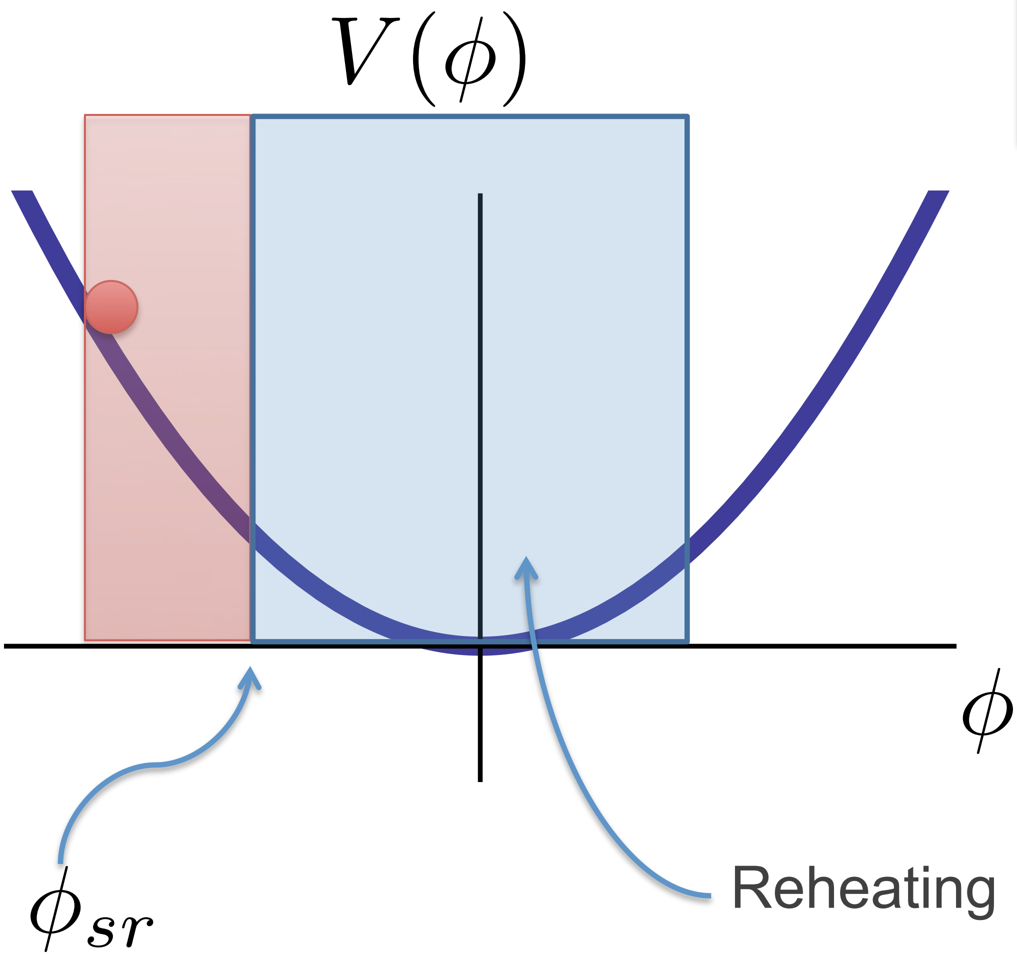
This imposes important restrictions in the form of the potential.

Simplest Example

- The simplest model we can think of is chaotic inflation

Linde ‘83.

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$



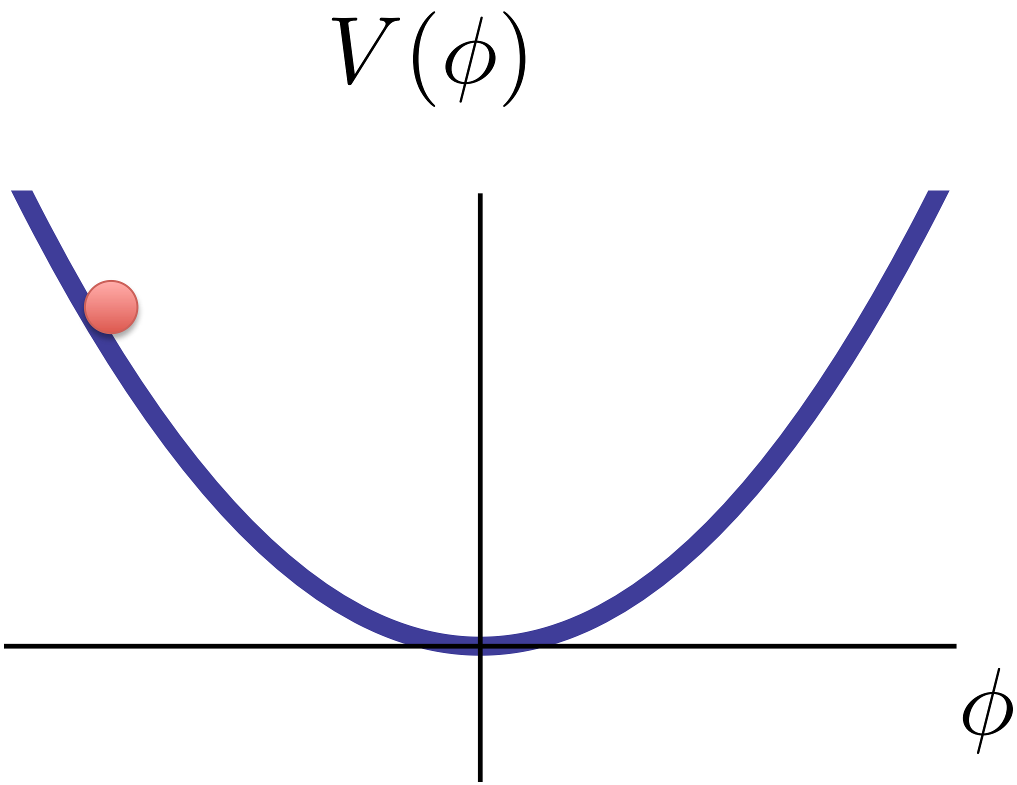
$$\epsilon = \eta = 2 \left(\frac{M_P}{\phi} \right)^2$$

To satisfy the slow roll conditions we must have:

$$\phi_{sr} > \sqrt{2} M_P$$

Simplest Example

- On the other hand, the number of e-folds in this model is given by:



$$N(\phi) \approx \frac{1}{4}\left(\frac{\phi}{M_P}\right)^2$$

So, in order to solve the Big Bang problems we need:

$$\phi_{CMB} \sim 15 M_P$$

- This means that the mass has to be small compared to Planck mass.

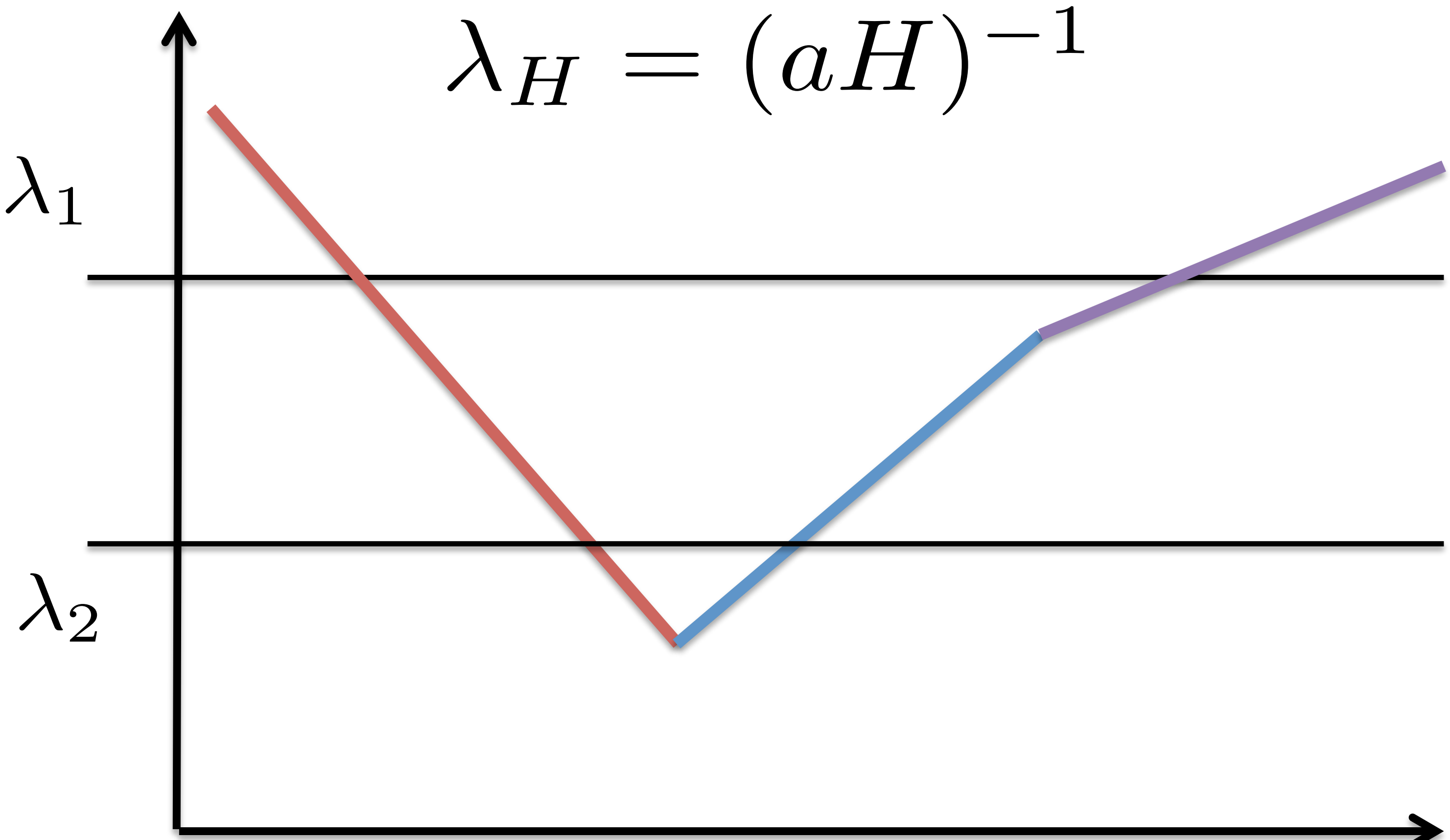
$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

Information from the background

- The inflationary period has to last for 60 e-folds.
- Scale of inflation must be above TeV.
- Many questions open up:
    - What is the shape of the potential? Is it fine tuned?
    - What is the microphysical origin of this scalar field?
    - What is the energy scale of inflation?
    - What are its interactions?
    - How does one enter the inflationary period?

Perturbations

- The most important aspect of inflation is not the background, but the fact that it gives us a causal mechanism to generate the primordial fluctuations.



Perturbations

- Inflation produces two different types of perturbations:
  - Scalar perturbations.

$$P_S = \frac{H^2}{M_P^2}\left(\frac{H^2}{\dot{\phi}^2}\right)$$

  - Tensor perturbations.

$$P_T = \frac{H^2}{M_P^2}$$

$$r = \frac{P_T}{P_S} = \frac{8}{M_P^2}\left(\frac{\dot{\phi}}{H}\right)^2$$

Perturbations in slow roll language

- The power spectrum are normally parametrized in the following way:
  - Scalar perturbations.

$$\Delta_S^2 = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

  - Tensor perturbations.

$$\Delta_T^2 = \mathcal{A}_T \left(\frac{k}{k_*}\right)^{n_T}$$

$$\mathcal{A}_s = \frac{V_{inf}}{24\pi^2 M_P^4 \epsilon}$$

$$n_s - 1 \approx 2\eta - 6\epsilon$$

$$r = 16\epsilon$$

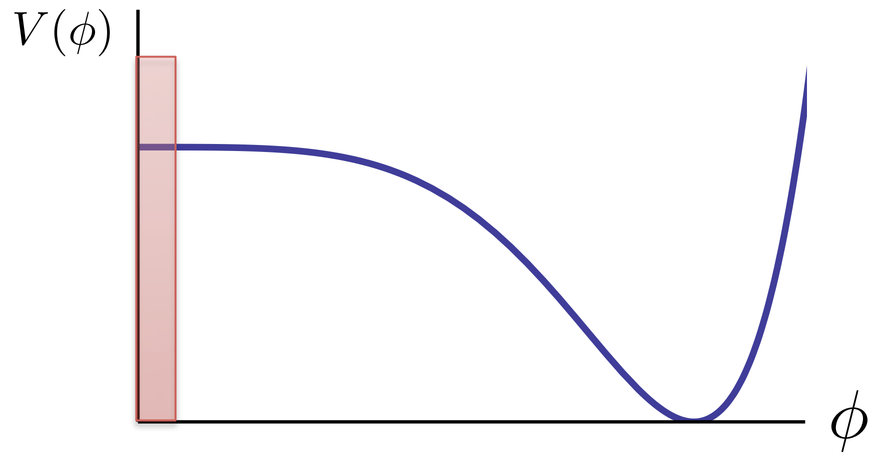
$$\mathcal{A}_T = \frac{2V_{inf}}{3\pi^2 M_P^4}$$

$$n_T = -2\epsilon$$

Types of inflationary potentials

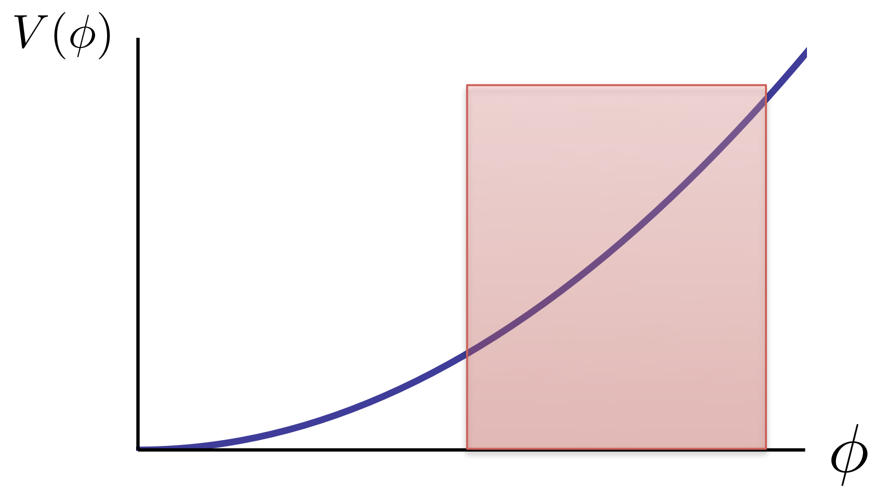
- There is a way to clasify the types of potentials:
  - Small field inflation.

$$V(\phi) \approx V_0 \left[1 - \left(\frac{\phi}{m}\right)^4\right]$$



  - Large field inflation.

$$V(\phi) = \frac{1}{2}m^2\phi^2$$



Lyth bound

Lyth '97.

- There is a simple relation between the field range travelled by the inflaton and tensor to scalar ratio.

$$r = \frac{P_T}{P_S} = \frac{8}{M_P^2}\left(\frac{\dot{\phi}}{H}\right)^2 \qquad dN = H dt$$

$$r = \frac{8}{M_P^2}\left(\frac{d\phi}{dN}\right)^2 \longrightarrow \frac{\Delta\phi}{M_P} = \int dN \sqrt{\frac{r}{8}}$$

$$\frac{\Delta\phi}{M_P} = \mathcal{O}(1)\left(\sqrt{\frac{r}{0.01}}\right)$$

Lyth bound

- Observing gravity waves tells us something about the scale of inflation and the type of potential.

$$V_{inf}^{1/4} = 1.06 \times 10^{16}\ GeV \left(\frac{r}{0.01}\right)^{1/4}$$

$$\frac{\Delta\phi}{M_P} = \mathcal{O}(1)\left(\sqrt{\frac{r}{0.01}}\right)$$

- and a consistency condition,

$$r = -8n_T$$

Types of inflationary potentials

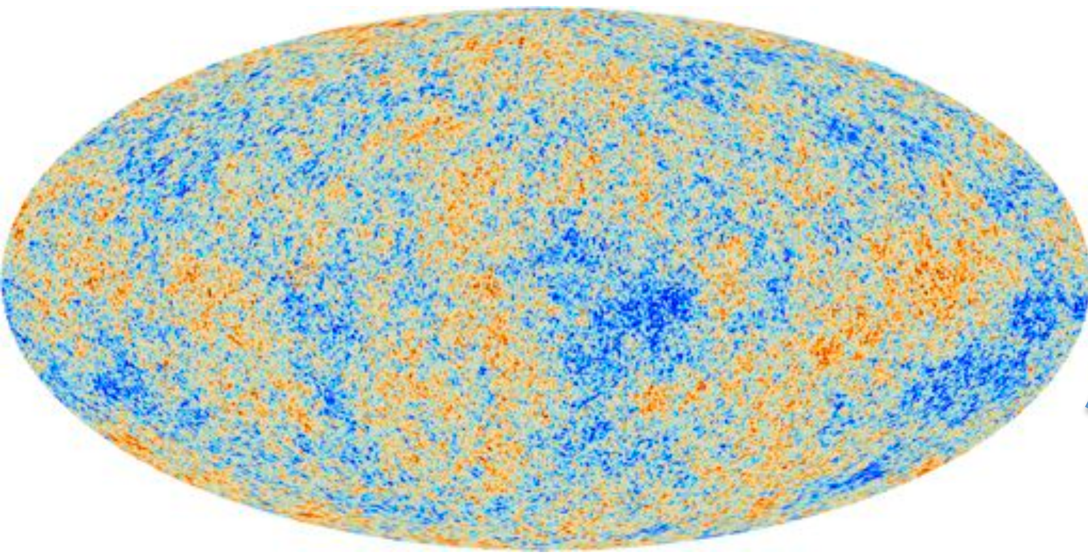
- There are many other ways to have inflation where the potentials are much more complicated:

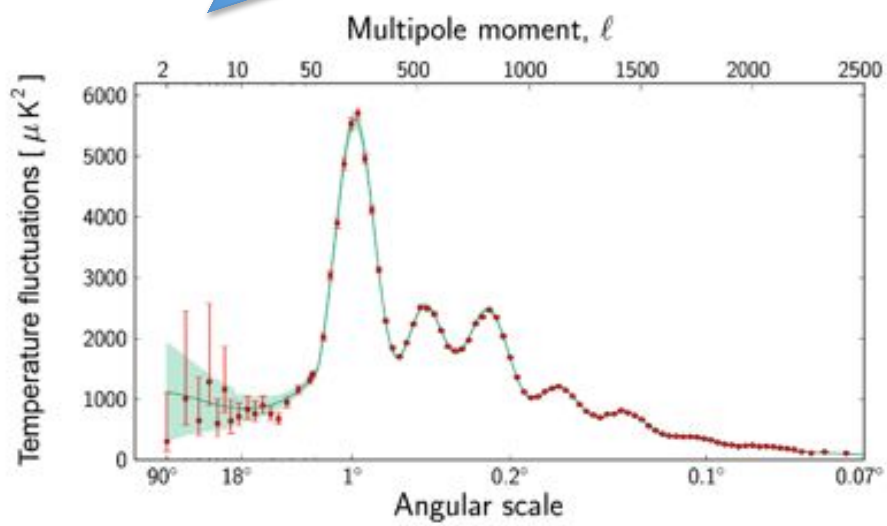
  - Multiple fields.

  - Non canonical kinetic terms.

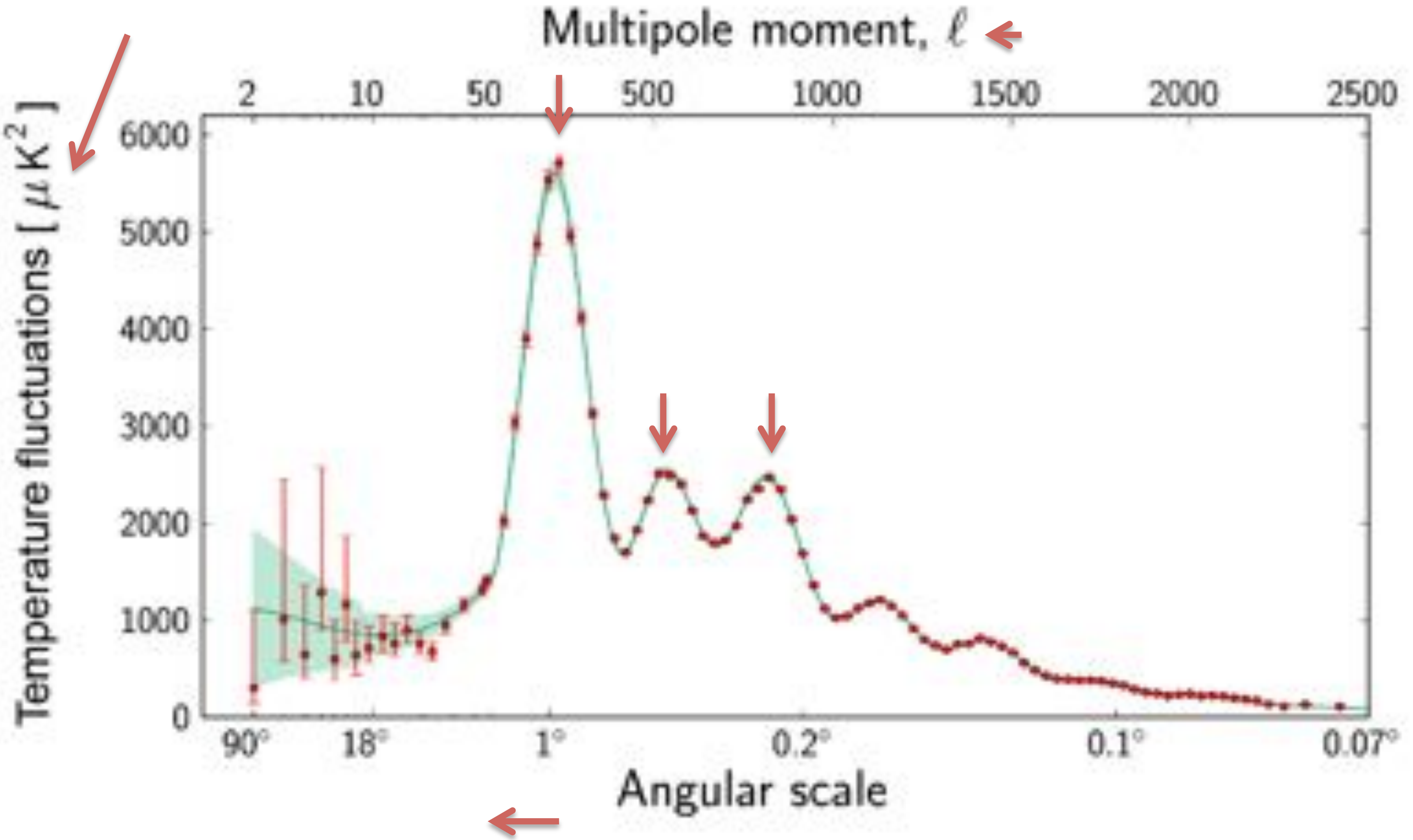
  - Features on the potential. Steps, curves, etc…

Planck results





The most famous CMB plot

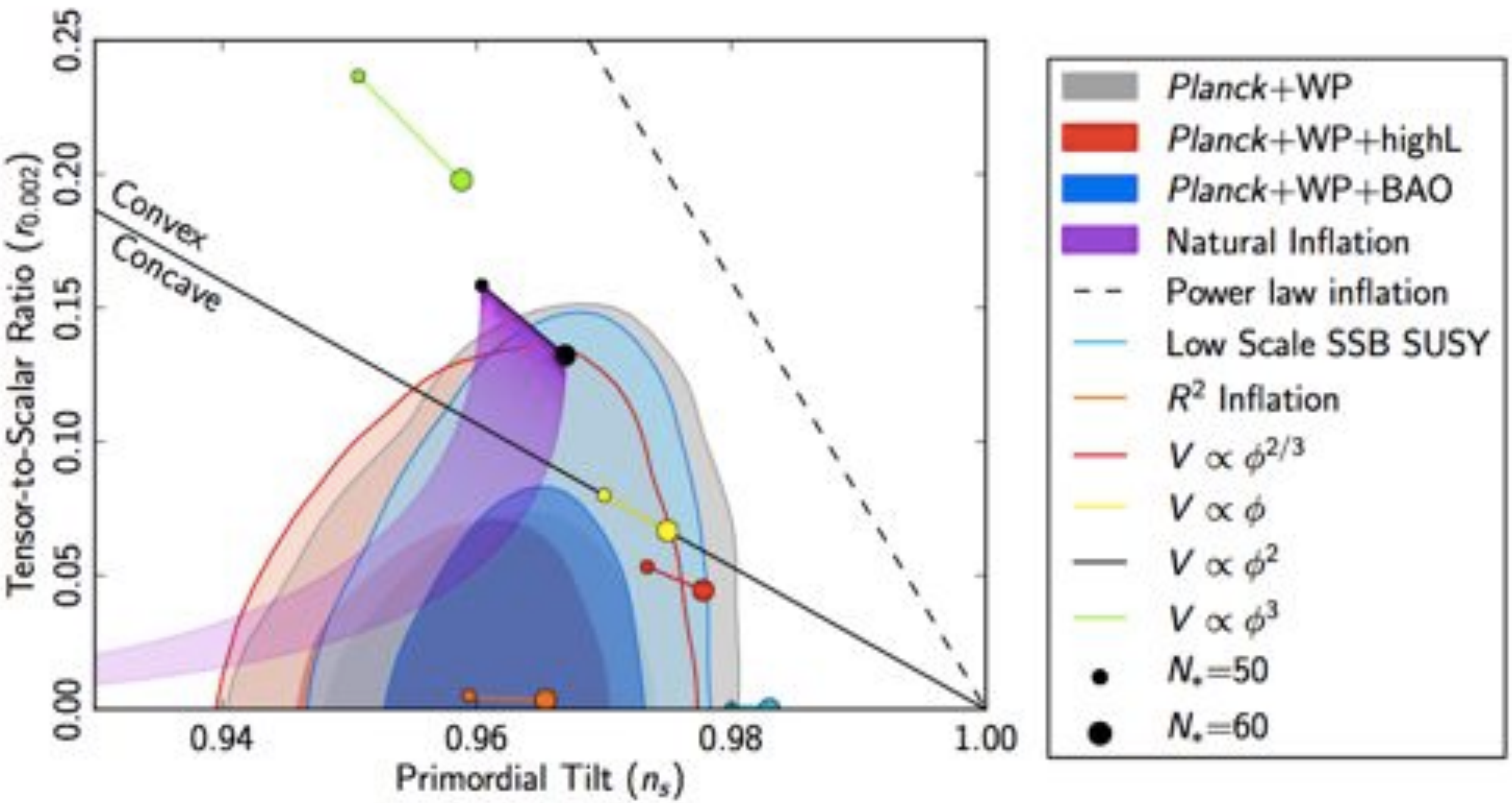


Planck Results

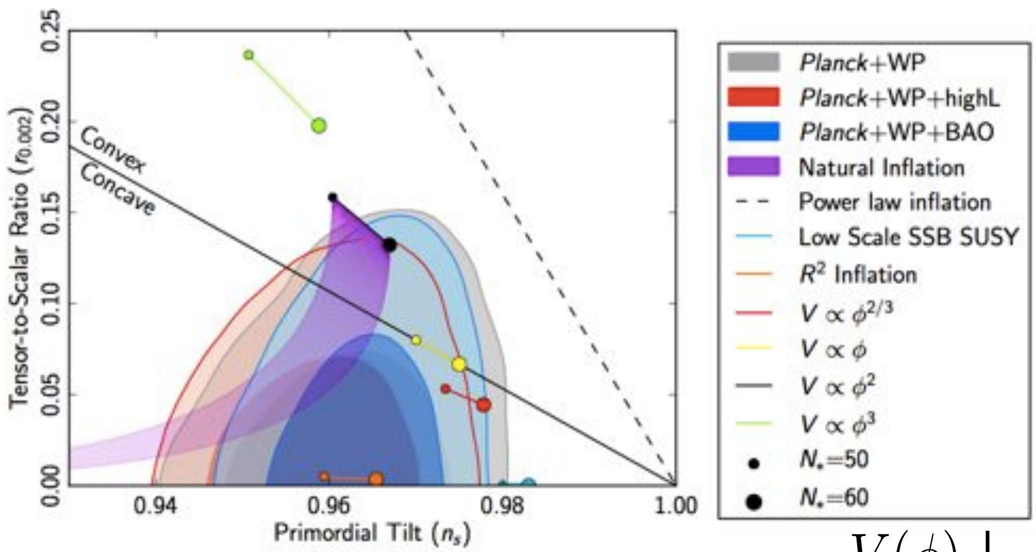
- Analysing the data from Planck we see:

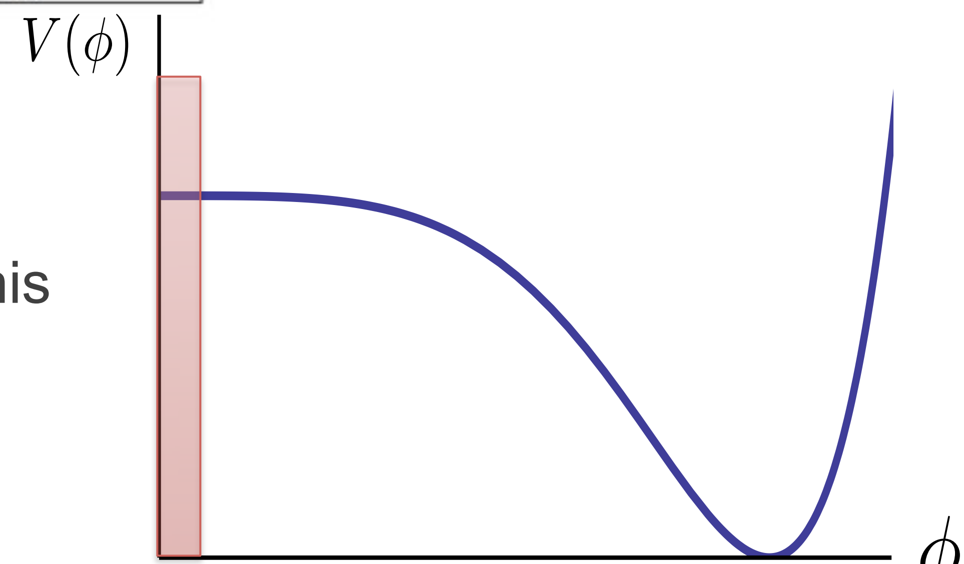
  - The universe is almost perfectly flat.
  - The scalar perturbations are adiabatic. (No evidence for isocuvature).
  - Nearly scale invariant.
  - Nearly perfectly Gaussian.

Planck Results



Planck Results





Planck data suggests that this type of small field inflation is more likely.

Is there something else ?

Hints at large scales ?

- There seem to be a number of intriguing facts about the power spectrum at low l, large scales.
- Nothing too significant, but nevertheless worth looking at carefully.

  - It seems to be a consistent lack of power at large scales, small l.

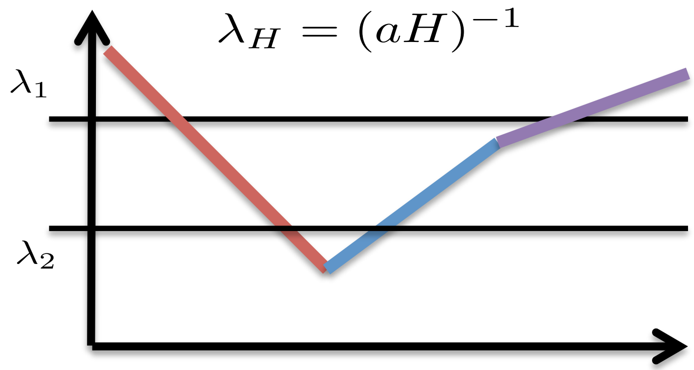
  - Alignment of low multiples.

  - Power asymmetry .

Could this be a hint of something interesting?

Power Supression at low l

- Remember that large scales are the first ones to leave the horizon during inflation.



- We may be seeing the effects of the onset of inflation.
- For this we need to be lucky, only around 60 e-folds.
- The field may be rolling faster during the first few e-folds.

Contaldi et al. '03.

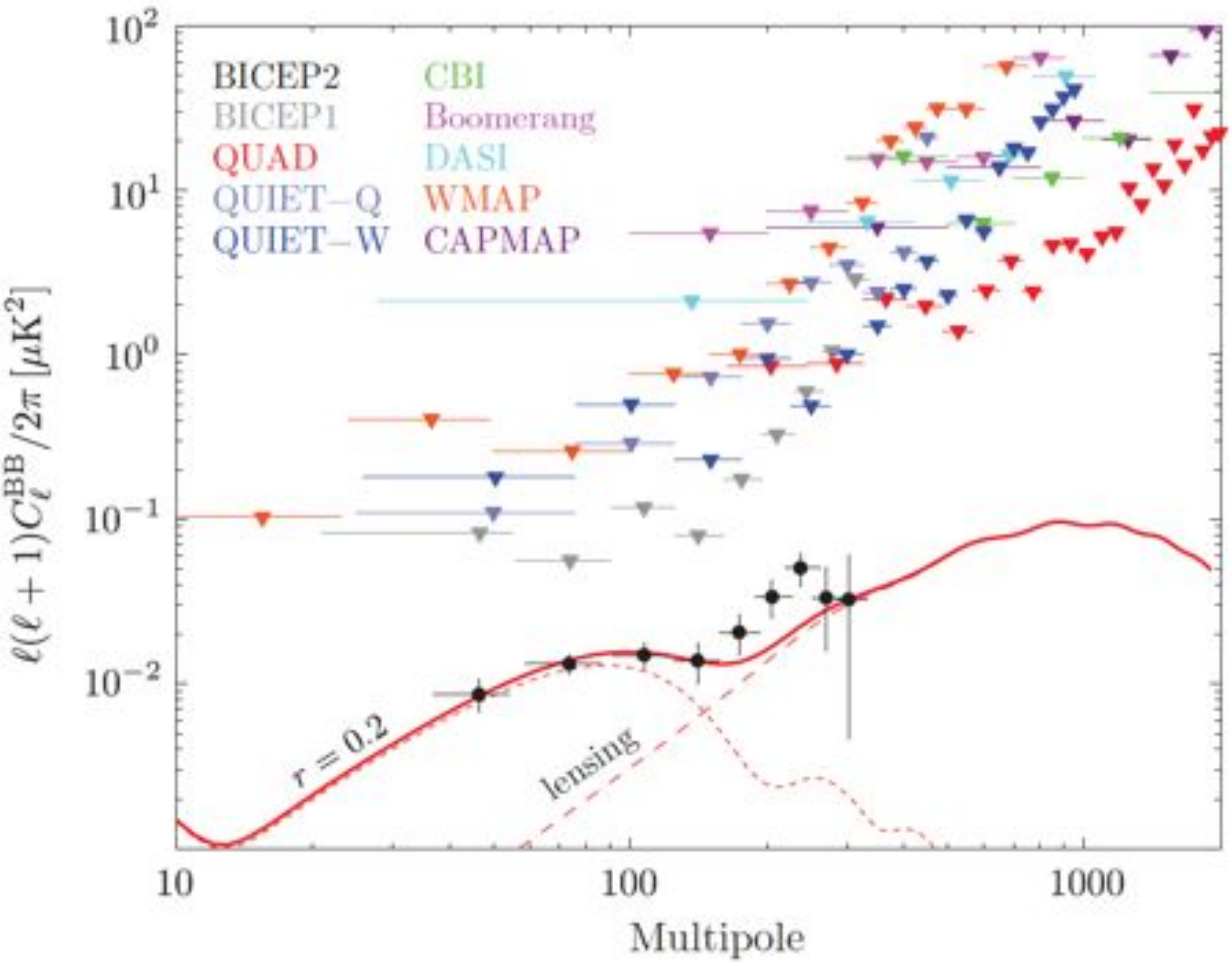
$$P_S = \frac{H^2}{M_P^2}\left(\frac{H^2}{\dot{\phi}^2}\right)$$

Seeing the an anisotropic stage

- The same argument applies to isotropy.
- We know the universe is isotropic at late times, but it could have been very anisotropic at the begining of inflation.
- Does this leave an imprint in the low-l power spectrum?
- This happens fast unless there is an anisotropic stress component during inflation.
- There could be a way to see both these effects in one single model.

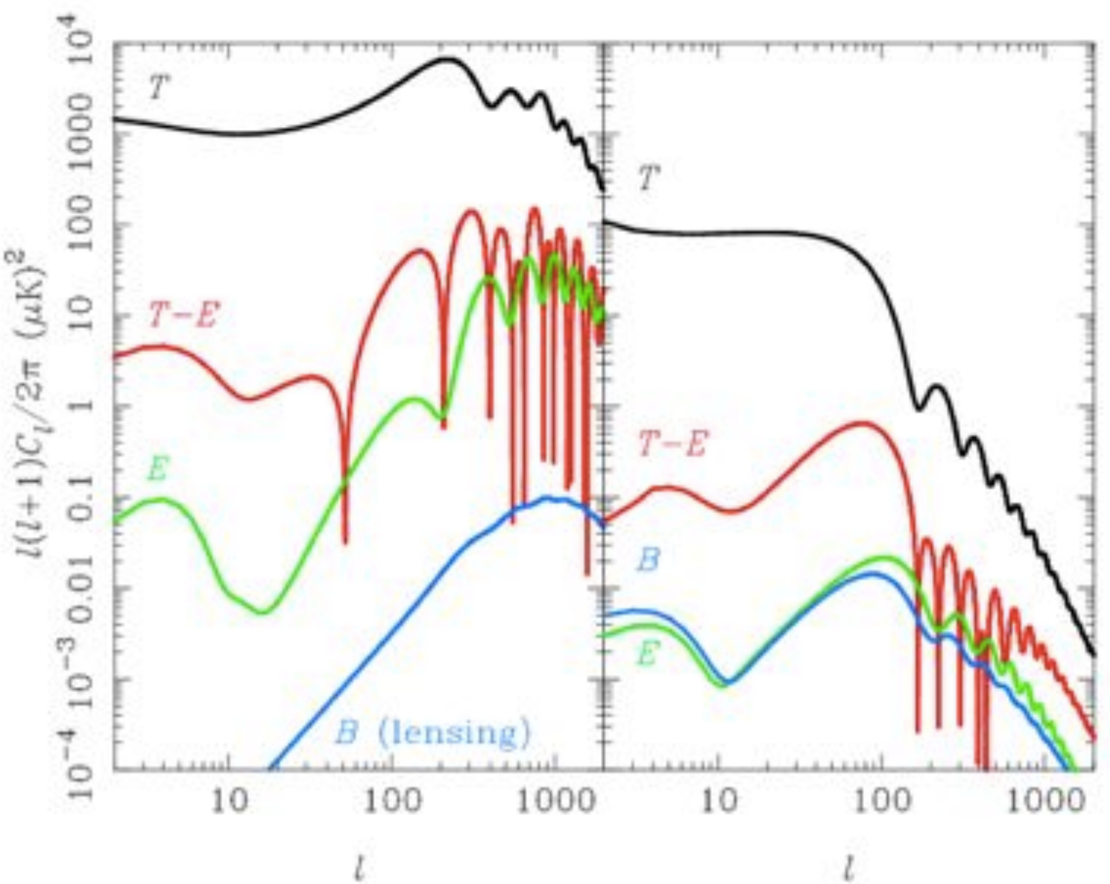
J.J.B.-P. and M. Minamitsuji in preparation.

BICEP2 Result



Tension between Planck and Bicep2 ?

- If this is real it would create more tension at low-l.



- Planck

$$r < 0.1$$

- BICEP2

$$r = 0.2$$

r=0.24

Taken from : Challinor, astro-ph/1210.6008

Fundamental implications of BICEP2

- Taking the value of BICEP2, we get that the inflaton field has to cover a transplanckian distance:

$$\frac{\Delta\phi}{M_P} \approx 10$$

- How can we make sure that the potential stays flat for all this path.

- We will have unsupressed corrections to the potential of the form:

$$\delta V = V_{inf}\left[\sum_n c_n \left(\frac{\phi}{M_P}\right)^n\right]$$

Fundamental implications of BICEP2

- This fine tuning is also necessary in the case of small field but now is much more severe.

- As an example, lets look at a term like,

$$\delta V = V_{inf} \left(\frac{\phi}{M_P} \right)^2 \qquad \delta\eta = \mathcal{O}(1)$$

- In other words we have to impose that

$$m_\phi << H$$

- And not of the order of the cutoff of the theory.

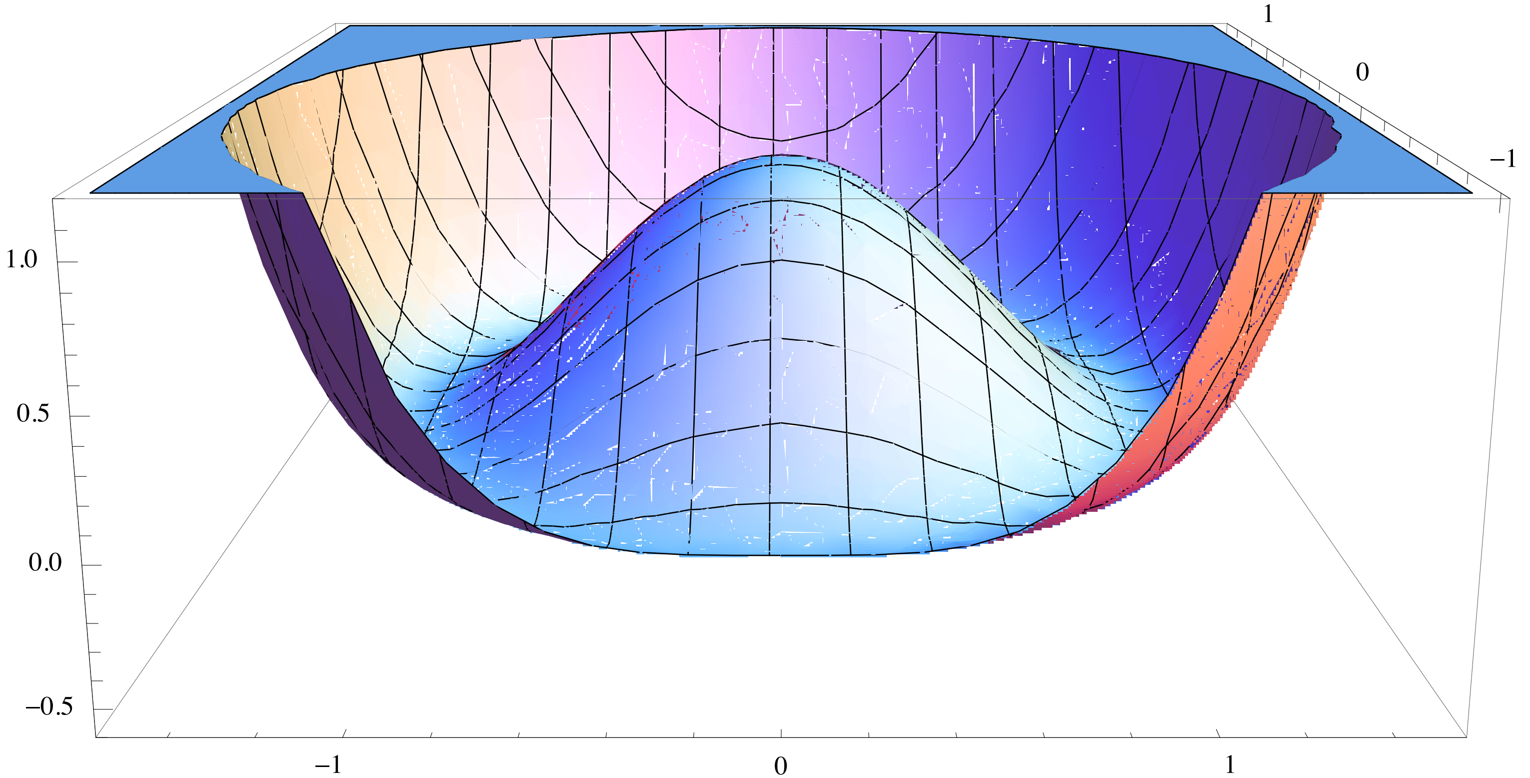
Good models of large r ?

- The best option seems to be to make use of a symmetry that prevents these corrections to appear.
- Axion field with a shift symmetry of the form

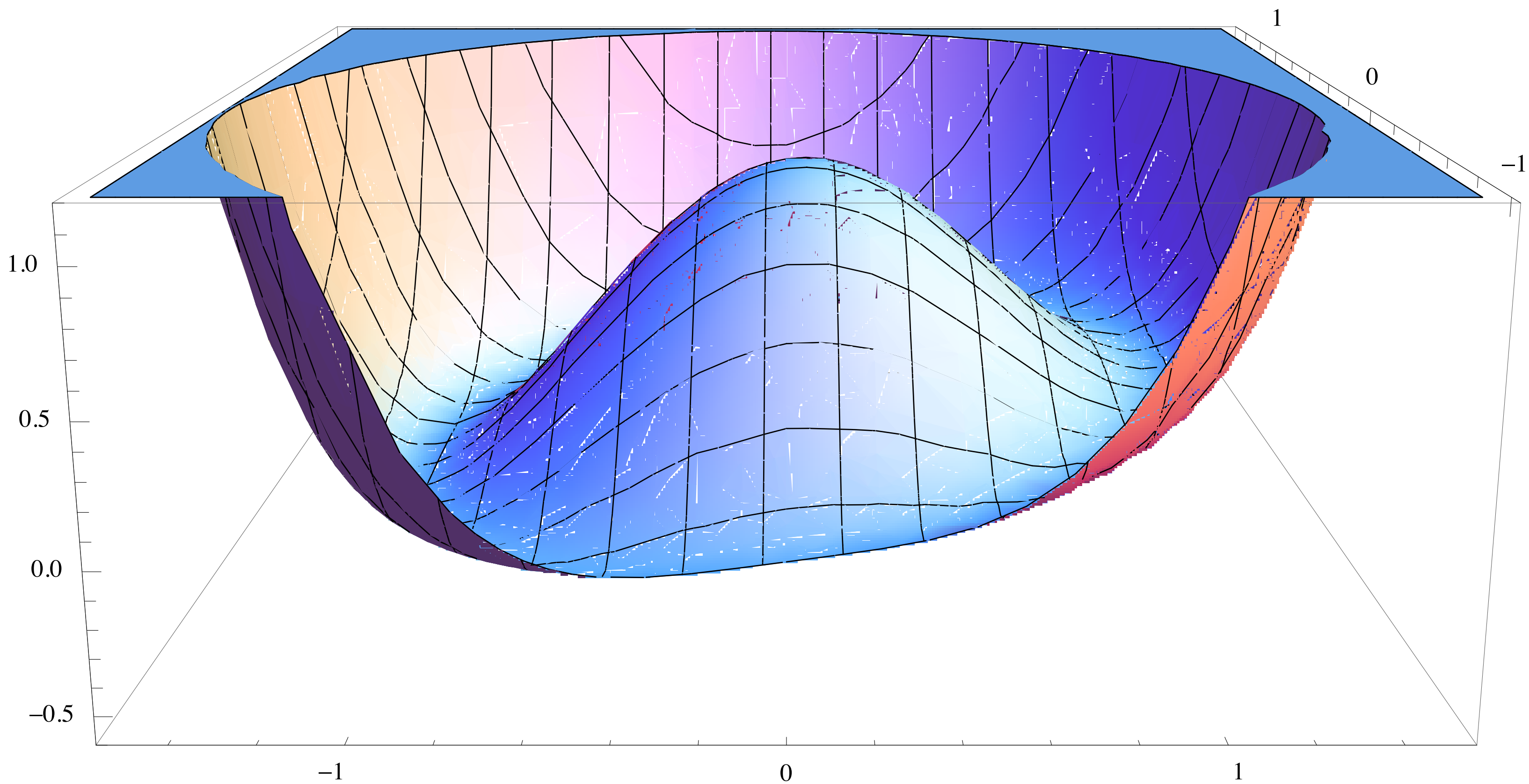
$$\phi \to \phi + C$$

- Non-perturbative corrections can induce a potential of the form:

$$\delta V = \Lambda^4 \left(1 + \cos\left(\frac{\phi}{f}\right)\right)$$



$$\psi = f e^{i \frac{\phi}{f}}$$



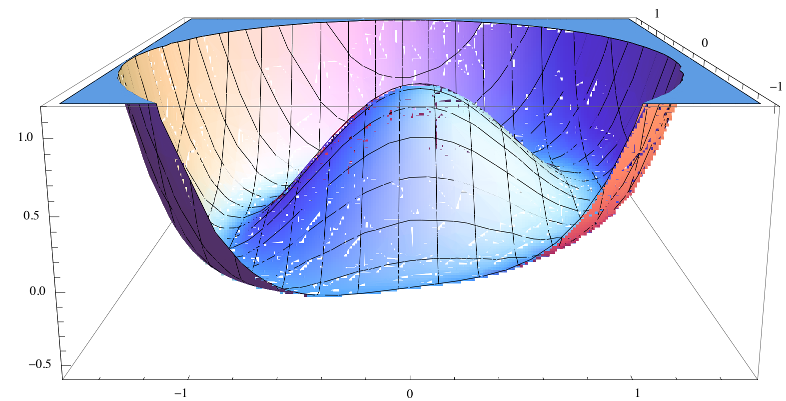
$$\psi = f e^{i\frac{\phi}{f}}$$

Natural Inflation

- In order to make this model agree with BICEP2 we need the parameter

$$f > M_p$$

$$\delta V = \Lambda^4 \left(1 + \cos\left(\frac{\phi}{f}\right)\right)$$



- This is a challenge for models of fundamental physics and string theory.

- There are several ways around this…

  - N-flation (Assisted inflation many fields around the minimum)
  - Extending the range of field space (monodromy inflation, axion alignement…)

Looking ahead

- Would BICEP2 results hold?
  - If they here to stay, it means very strong evidence of inflation.
  - We need to think hard about the inflaton potential and its origin.
  - Opportunity to learn something about its origin in connection to particle physics.
  - Can we measure the gravitational wave tilt?

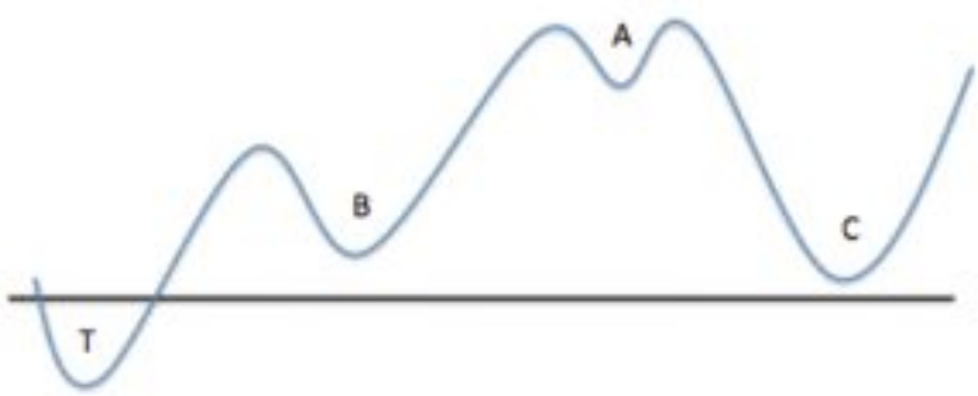
Open issues

- How did inflation started?
- Initial conditions, how did we get to the right place in the potential?
- Is our vacuum the only one in the theory?
- Can we embed inflation in string theory?

Inflation in the Landscape

- In a theory with many vacua we could have a much more complicated structure at the largest possible scales.

- Inflation happens when the field gets stack in one of these vacua.

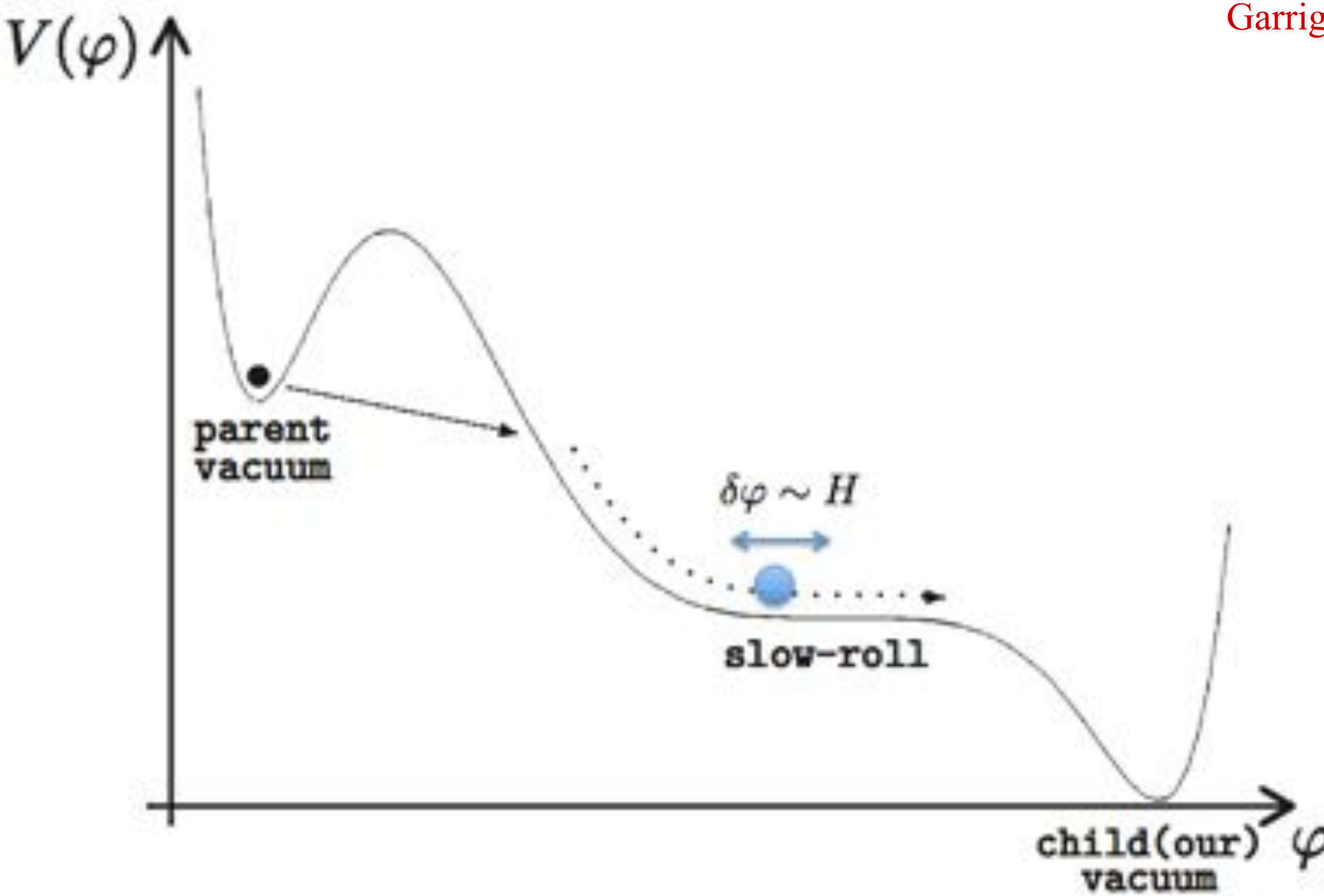


Taken from Garriga '13.

- On the other hand this type of inflation is not slow roll inflation and it will end by bubble nucleation to the vicinity of our vacuum.

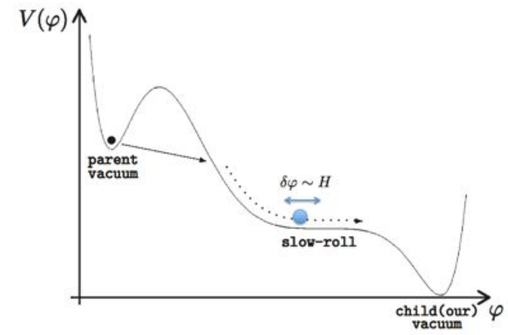
Inflation in the Landscape

Garriga '13.



Inflation in the Landscape

- Can we have any observational evidence for this?



Maybe (IF there is not too much inflation inside the bubble)

- The universe created this way is an open universe.

Bucher and Turok '95

Garriga, Montes, Sasaki and Tanaka

Many others…

- Maybe there something special at low-l due to the initial rolling of the field. Bousso, Harlow and Senatore '13.

- Bubble collisions. Kleban et al; Johnson et al.; Aguirre et al.

Conclusions

I am sure I will not get here with any time left…