Open Problems in Inflationary Cosmology

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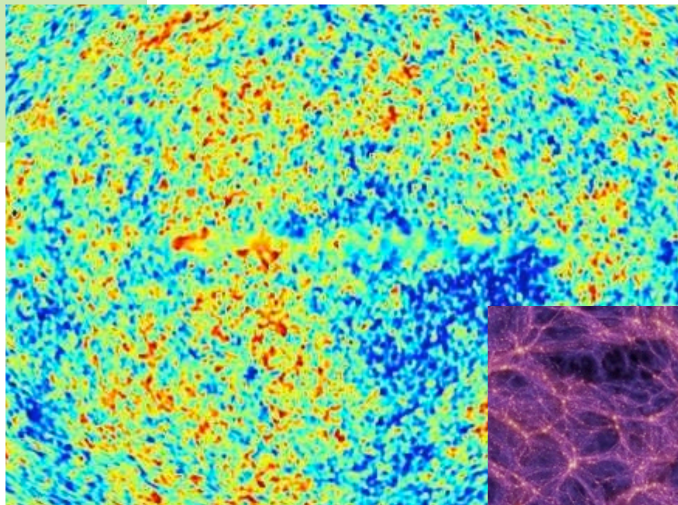
Was ***inflation*** the primordial origin of all structure in the universe?

10^{-34} sec.

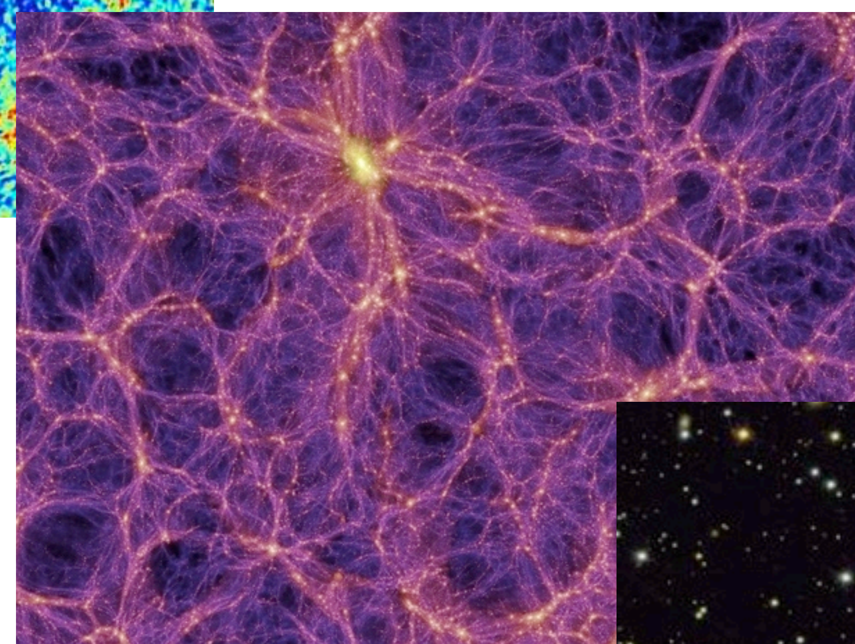
?

Eva Silverstein

380,000 yrs.

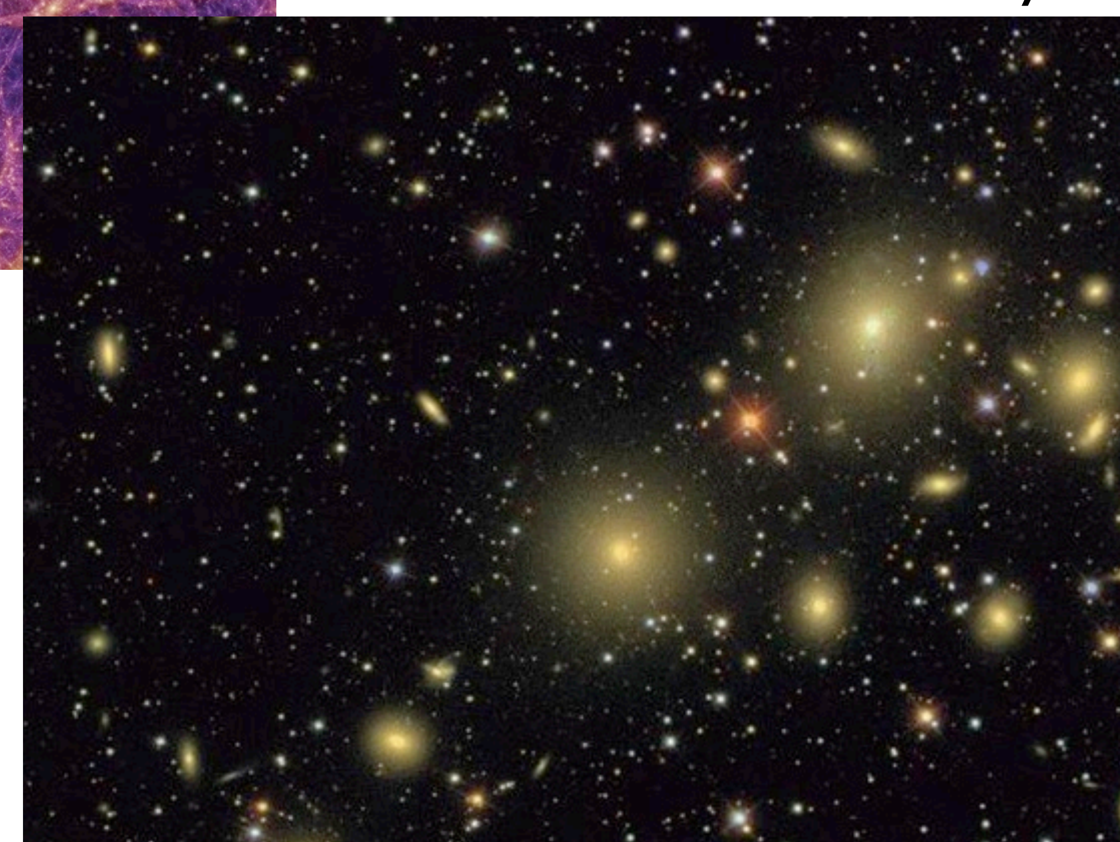


Anthony Lewis

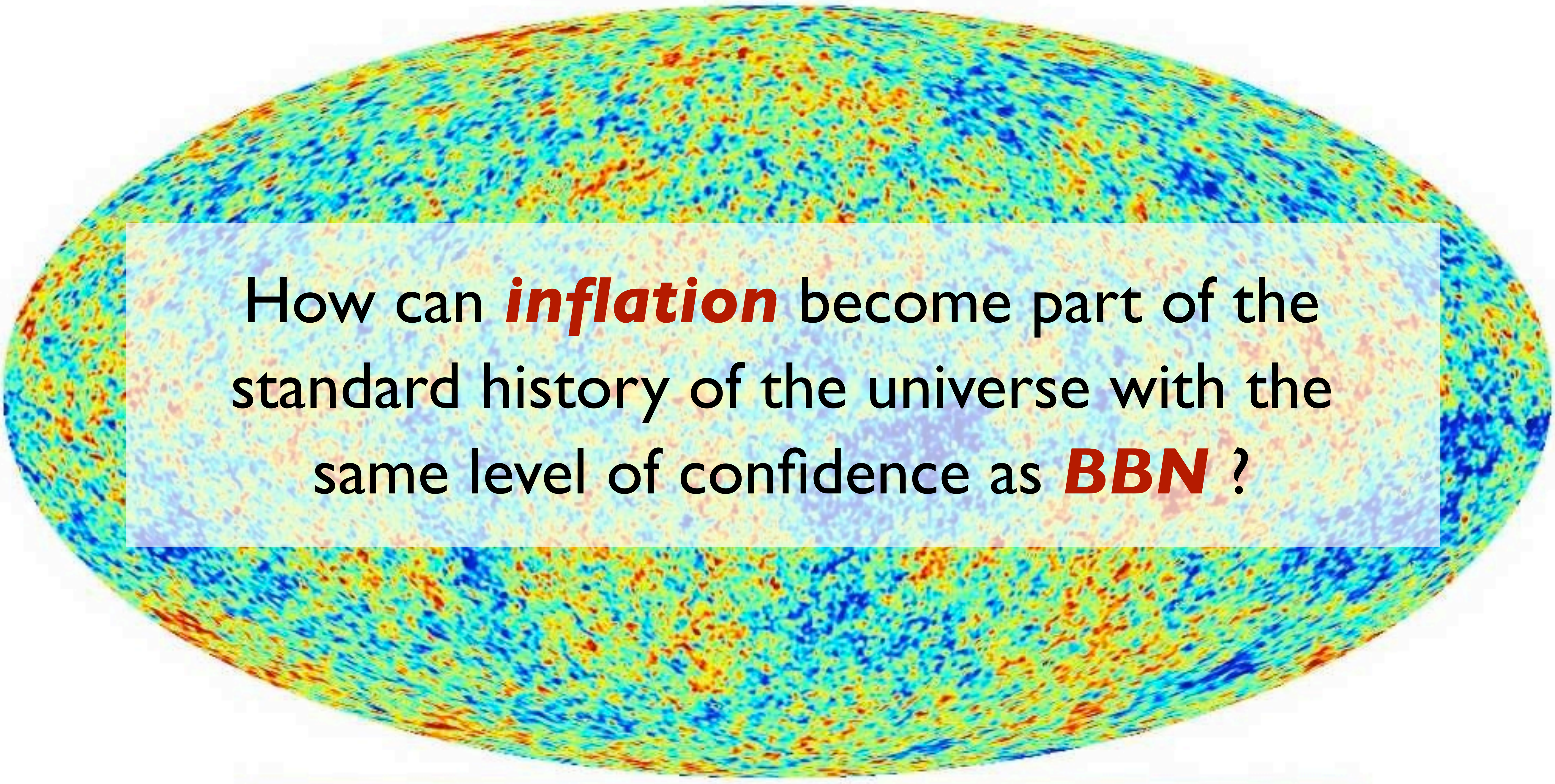


Volker Springel

13.7 billion yrs.



Licia Verde



How can ***inflation*** become part of the standard history of the universe with the same level of confidence as ***BBN*** ?

Outline

Observations

Theory

1. Current Observations

"What do we really know?"

2. Status

"What is Inflation?"

3. Problems

"Physics thrives in crisis"

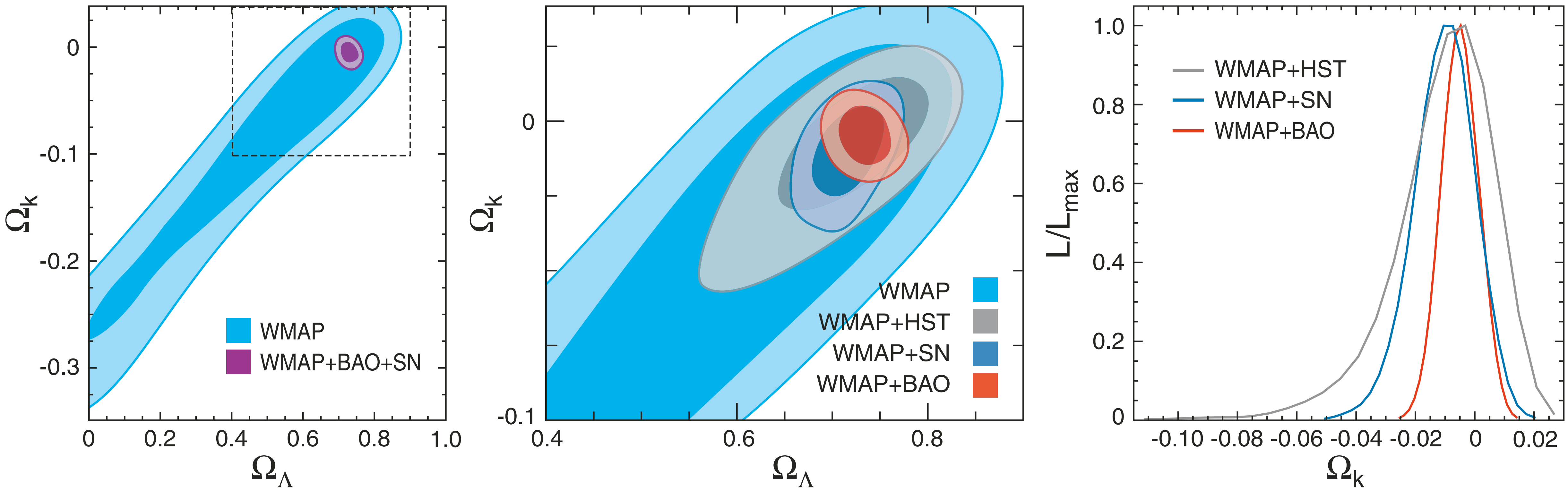
Steven Weinberg

4. Future Observations

"How can we learn more?"

Current Observations

The homogeneous universe is well-described by a ***flat FRW*** background.



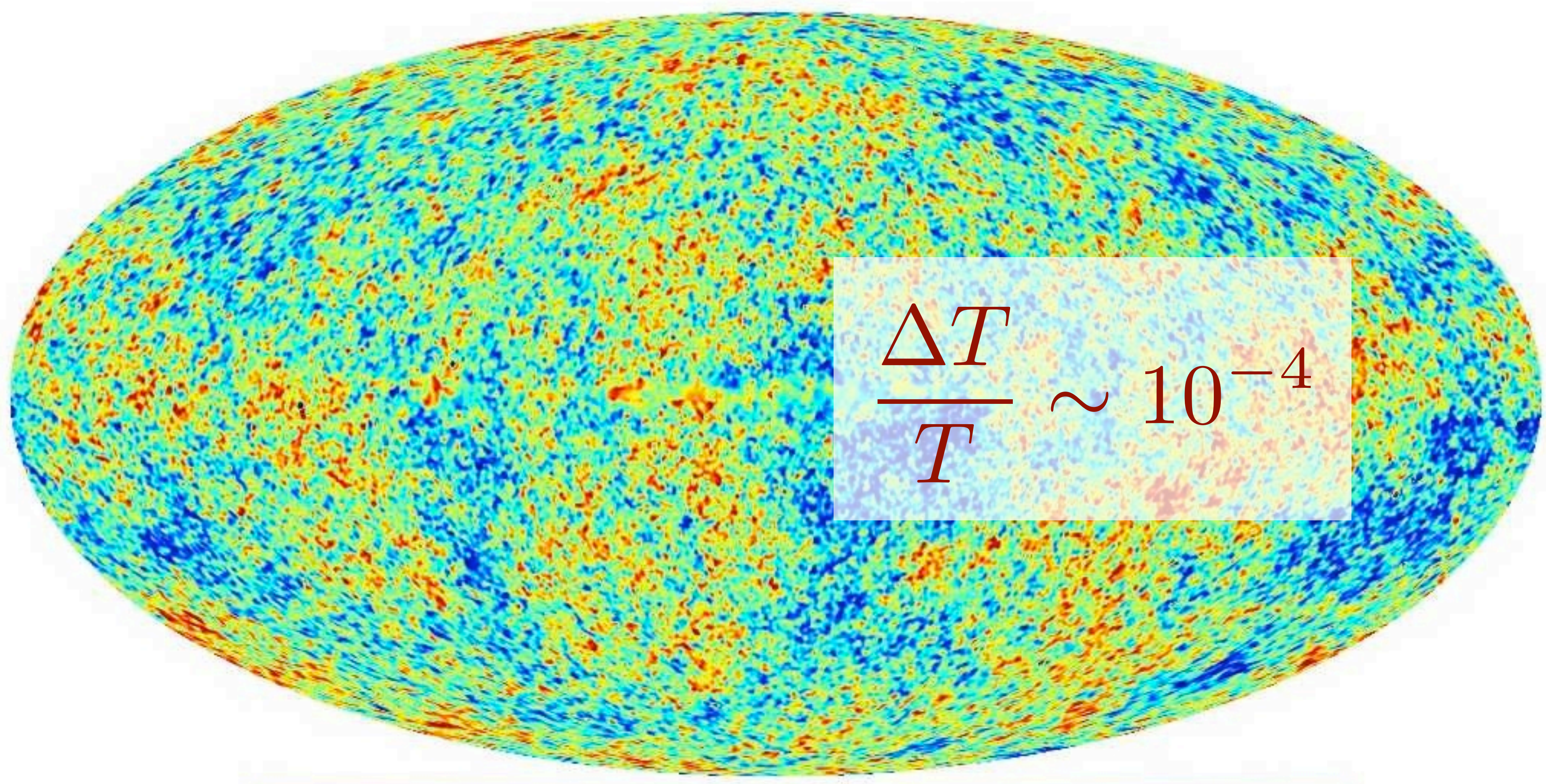
$$-0.0181 < \Omega_k < 0.0071$$

WMAP

The homogeneous universe is well-described by a ***flat FRW*** background.

(Primordial) density ***fluctuations*** are:

- ***small***



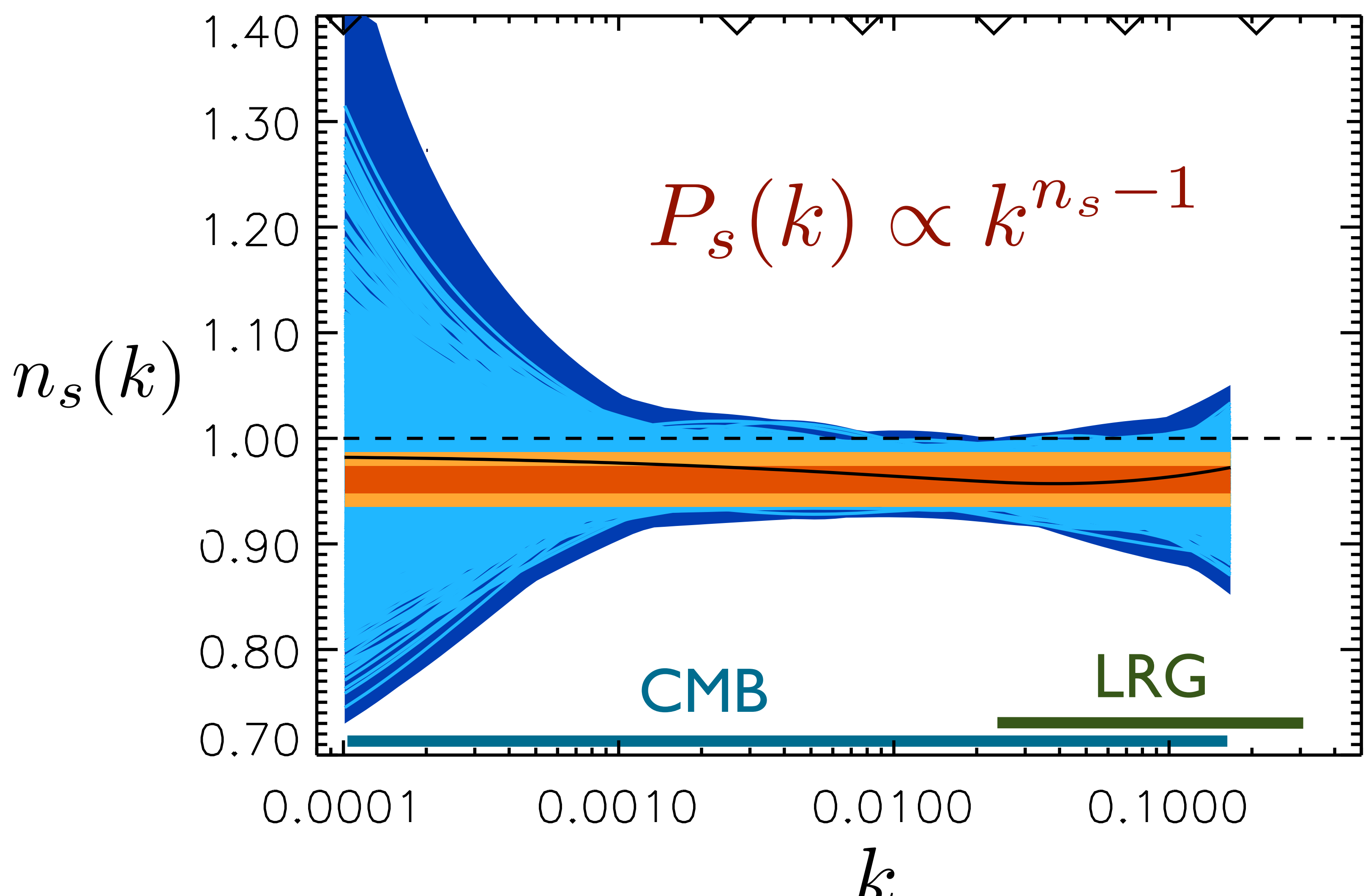
$$\frac{\Delta T}{T} \sim 10^{-4}$$

COBE

The homogeneous universe is well-described by a ***flat FRW*** background.

(Primordial) density ***fluctuations*** are:

- ***small***
- ***scale-invariant***

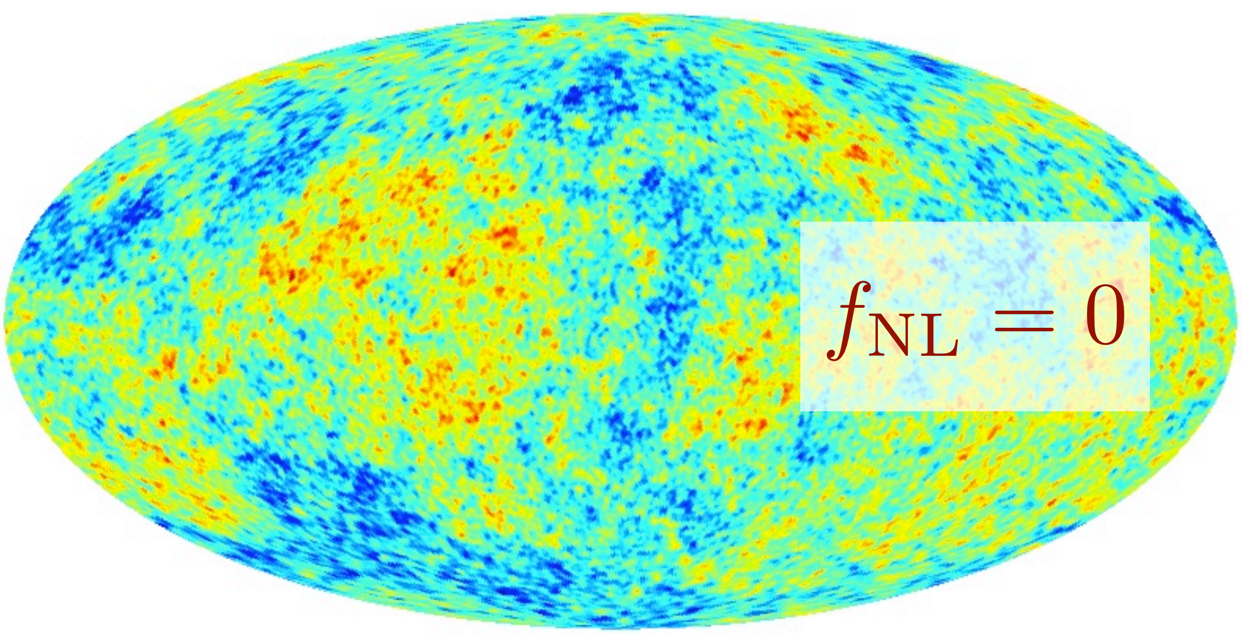


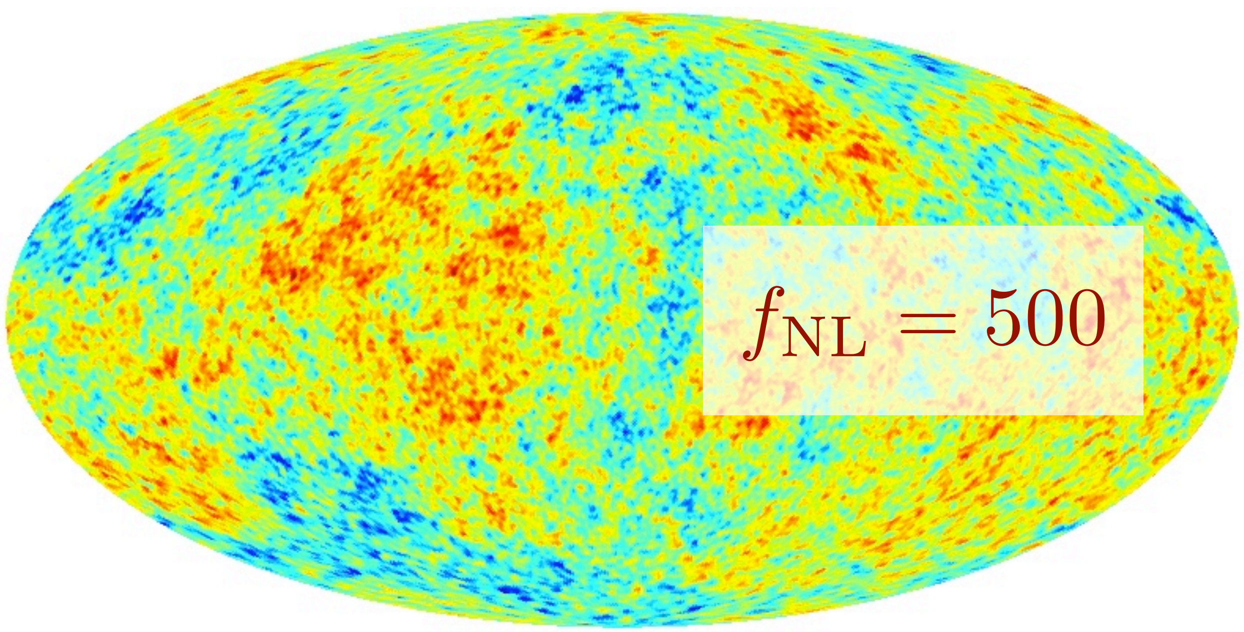
Peiris and Verde (2010)

The homogeneous universe is well-described by a ***flat FRW*** background.

(Primordial) density ***fluctuations*** are:

- ***small***
- ***scale-invariant***
- ***Gaussian***



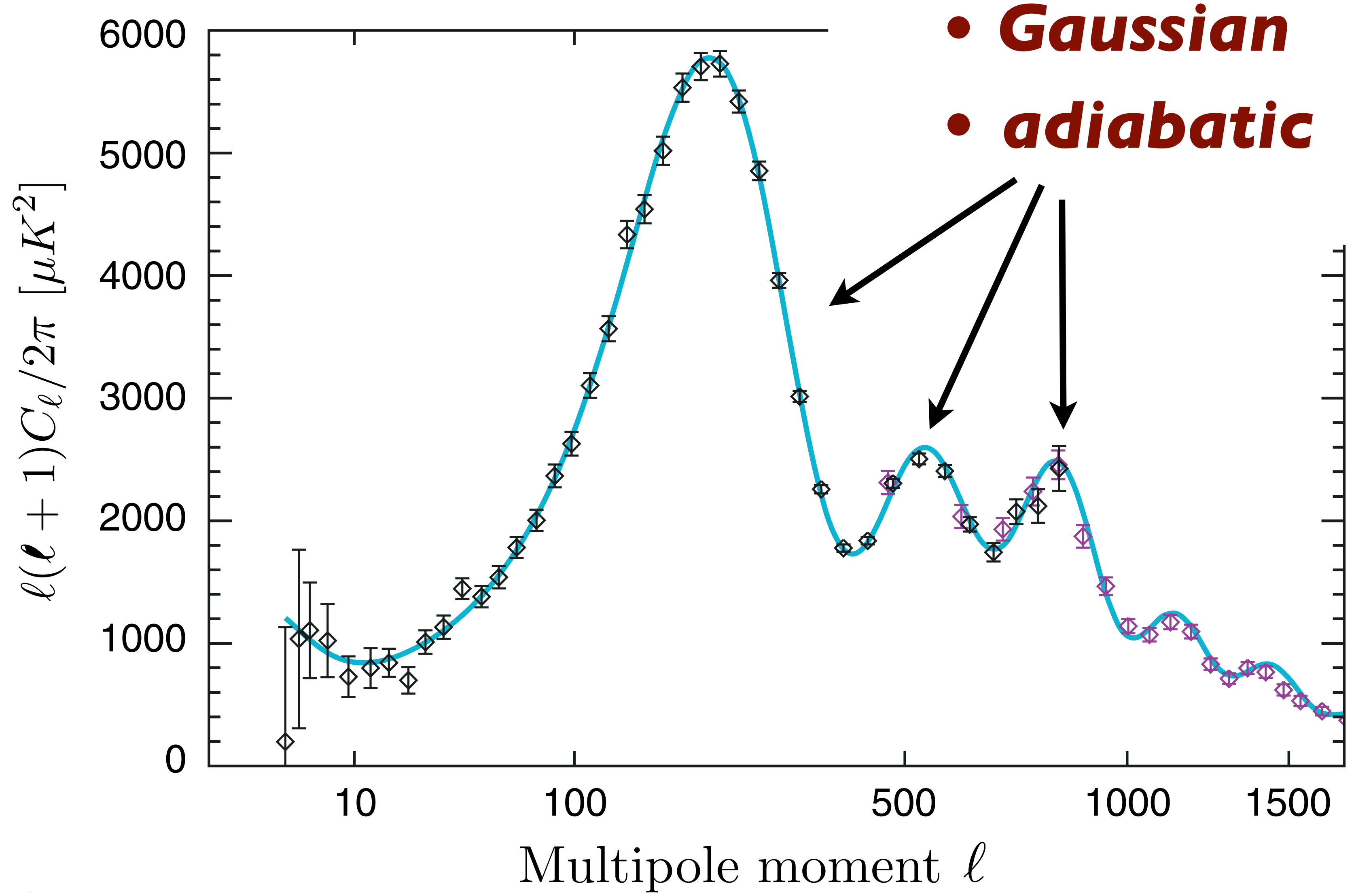


1% non-Gaussianity

The homogeneous universe is well-described by a ***flat FRW*** background.

(Primordial) density ***fluctuations*** are:

- ***small***
- ***scale-invariant***
- ***Gaussian***
- ***adiabatic***



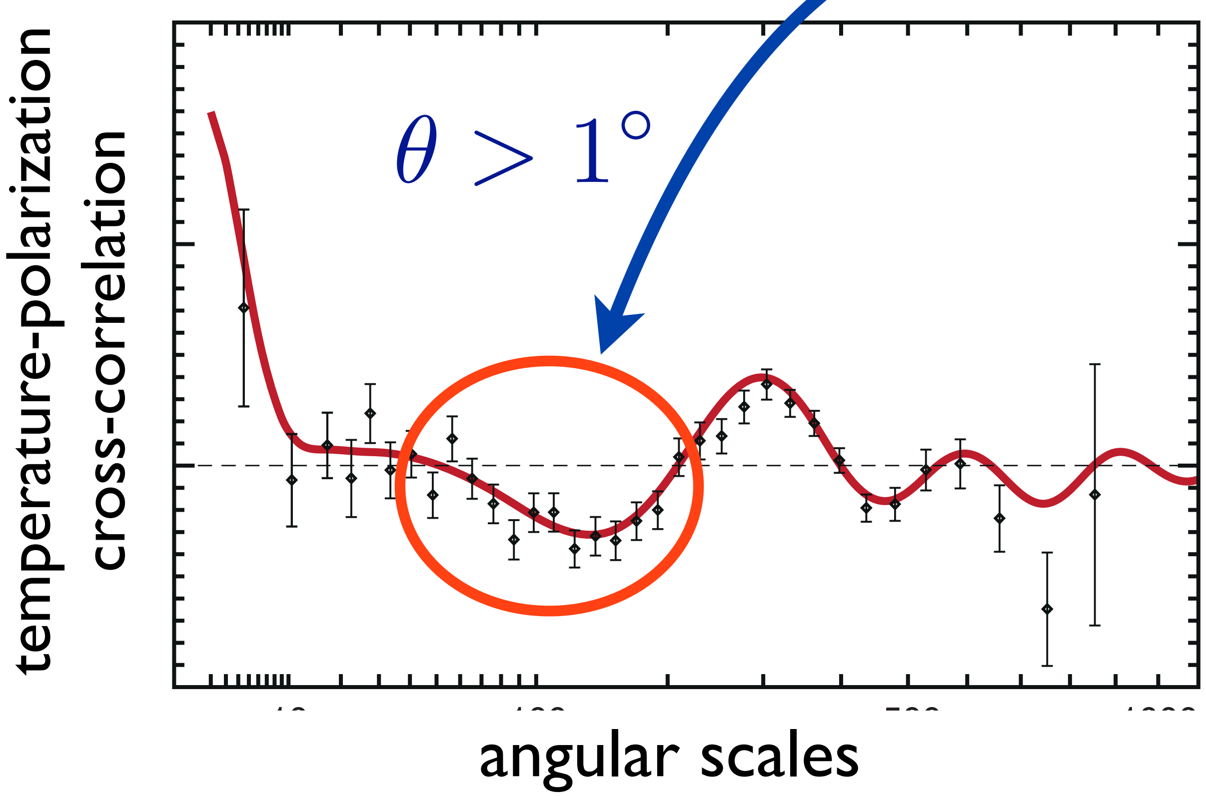
WMAP

The homogeneous universe is well-described by a ***flat FRW*** background.

(Primordial) density ***fluctuations*** are:

- ***small***
- ***scale-invariant***
- ***Gaussian***
- ***adiabatic***
- ***superhorizon***

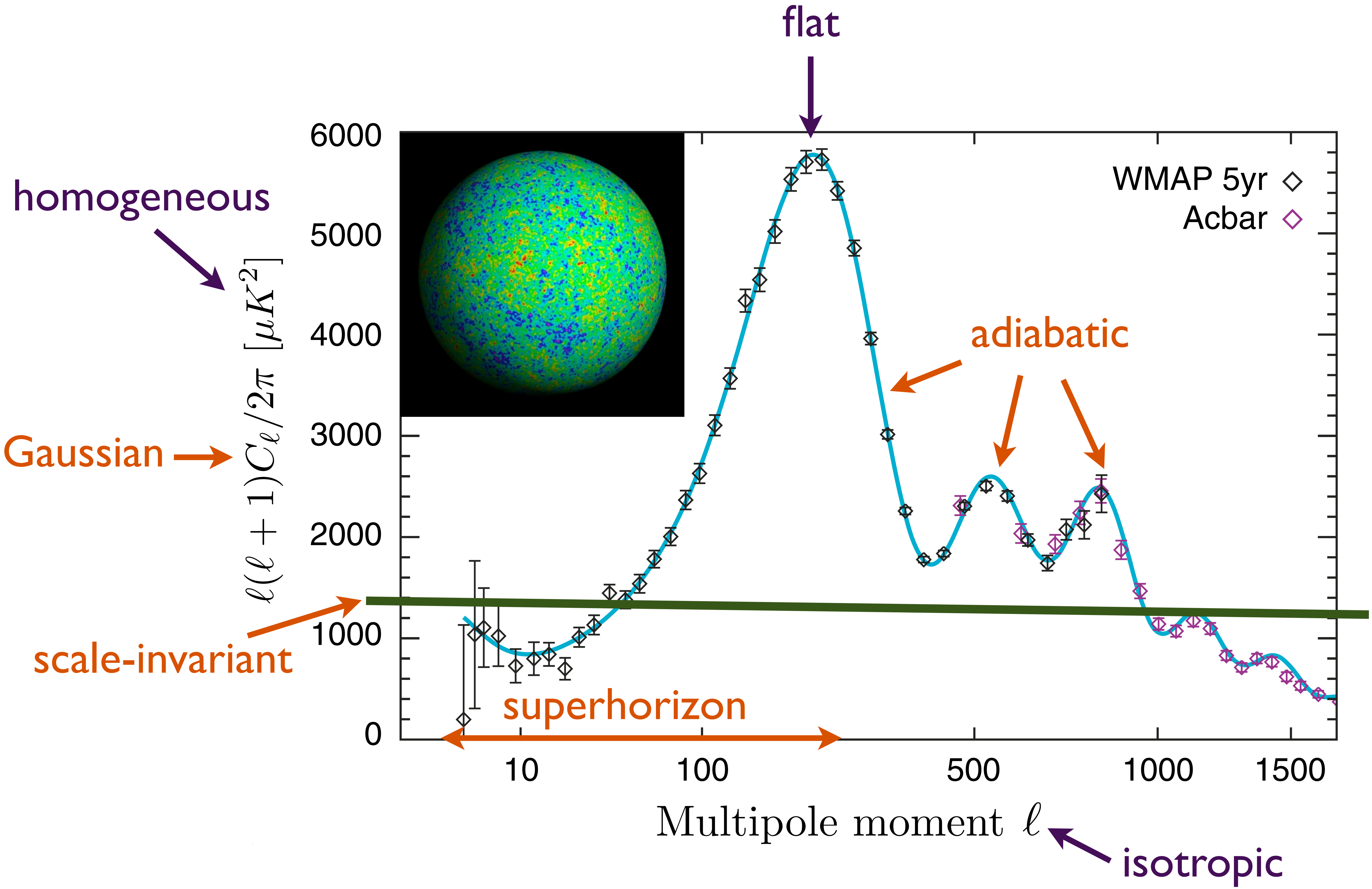
$\langle TE \rangle$



WMAP

Inflation is an elegant explanation for the data:

Guth (1980)



Theory

Inflation

We need a definition:

$$-\dot{H} \ll H^2$$

where $\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \mathrm{d}\vec{x}^{\,2}$

$$H = \frac{\dot{a}}{a}$$

Inflation

$$-\dot{H} \ll H^2$$

There exist many different microscopic realizations of inflation, BUT only a few distinct mechanisms (effective theories)

Inflation

$$-\dot{H} \ll H^2$$

approximate ***time-translation symmetry***

Inflation

$$-\dot{H} \ll H^2$$

inflation has to end, so ***symmetry is spontaneously broken***

Goldstone boson

fluctuations in the 'clock'

$$\pi \sim \delta t \sim \frac{\delta\phi}{\dot{\phi}}$$

$$\zeta \sim \frac{\delta a}{a} = H\pi$$

curvature perturbations

Inflation

$$-\dot{H} \ll H^2$$

tests of ***minimal inflation*** = tests of *(pseudo)*-***Goldstone***

fluctuations are predicted to be: ← nearly ***massless***

$$\frac{m_\pi^2}{H^2} = \frac{|\dot{H}|}{H^2} \ll 1$$

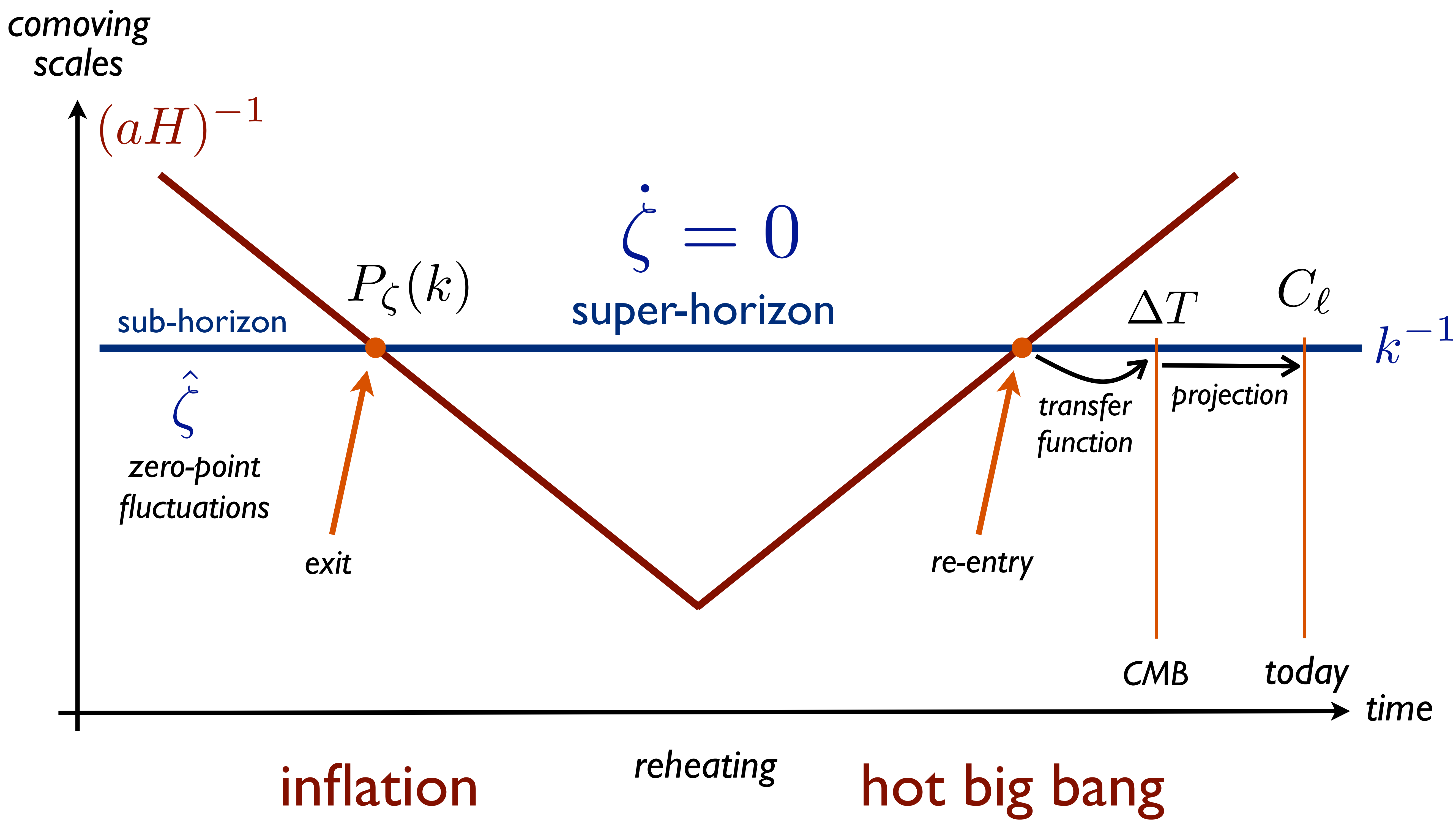
- ***scale-invariant***
- ***Gaussian***
- ***adiabatic***
- ***superhorizon***

Inflation

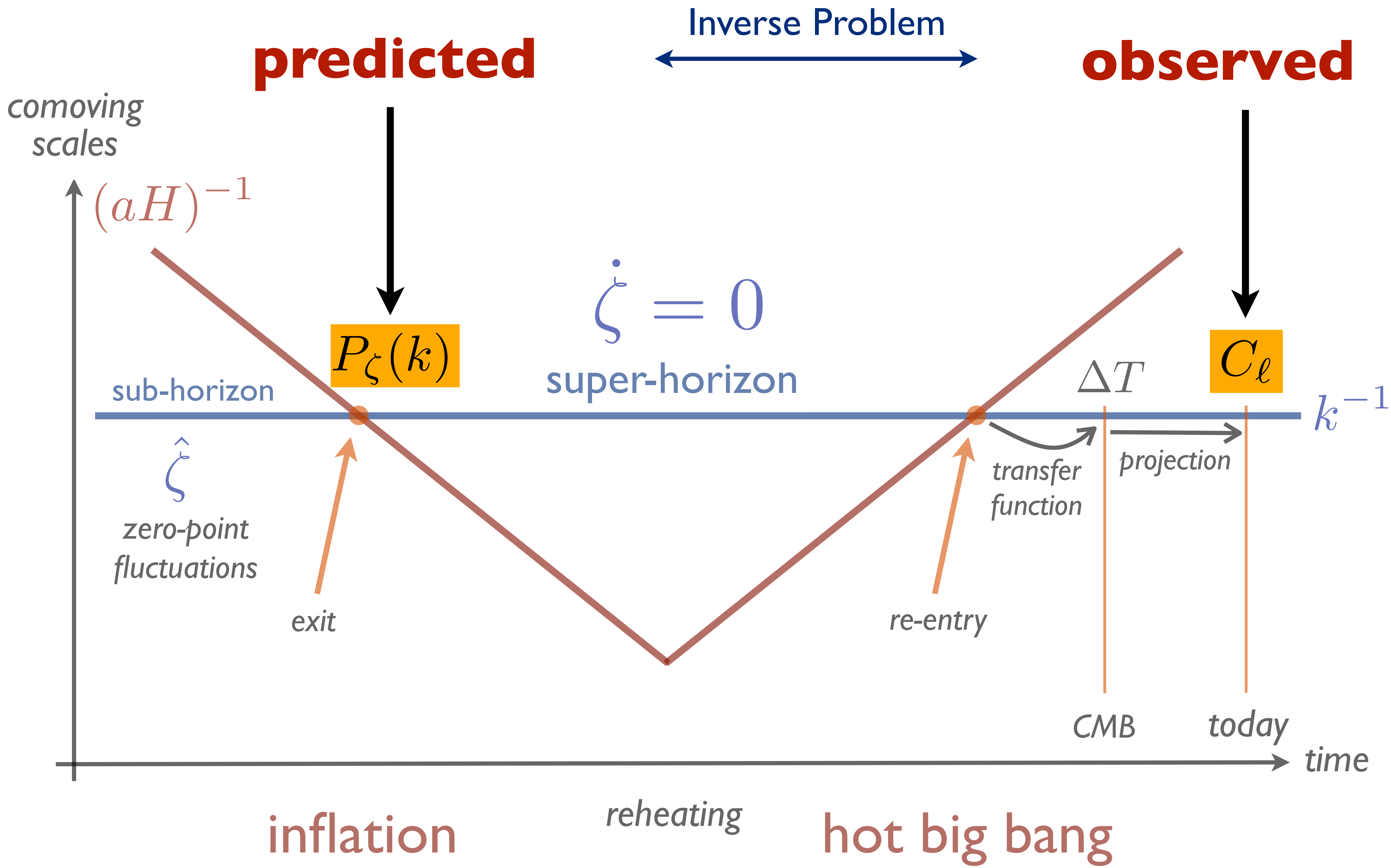
$$-\dot{H} \ll H^2$$

implies a ***shrinking Hubble sphere***

$$\frac{d}{dt}(aH)^{-1} < 0$$



comoving scales
$(aH)^{-1}$
$\dot{\zeta} = 0$
$P_\zeta(k)$
super-horizon
sub-horizon
ΔT
C_ℓ
k^{-1}
$\hat{\zeta}$
zero-point fluctuations
transfer function
projection
exit
re-entry
CMB
today
time
reheating
inflation
hot big bang



Inverse Problem
predicted
observed
comoving scales
$(aH)^{-1}$
$\dot{\zeta} = 0$
$P_\zeta(k)$
C_ℓ
ΔT
sub-horizon
super-horizon
k^{-1}
$\hat{\zeta}$
zero-point fluctuations
exit
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hot big bang

Classic Predictions

scalar fluctuations

$$P_\zeta \sim \frac{H^4}{M_{\rm pl}^2 \dot{H}}$$

tensor fluctuations

$$P_h \sim \frac{H^2}{M_{\rm pl}^2}$$

power spectra teach us about:

$$H(t)$$

Cheung et al.
Senatore et al.

Non-Gaussianity

in the ***effective theory of inflation***

quasi-dS		Goldstone		curvature perturbation
$H(t)$	$\longrightarrow$	π	$\longrightarrow$	$\zeta = H\pi$

$\downarrow$

~~Lorentz symmetry~~ $\longrightarrow$ $\mathcal{L}_2 \propto \dot{\pi}^2 - \boxed{c_s^2}(\partial_i \pi)^2$

speed of sound

$\downarrow$

non-linearly realized symmetry $\longrightarrow$ $\mathcal{L}_3 \propto \frac{1}{\boxed{c_s^2}} \dot{\pi}(\partial_i \pi)^2 + \frac{\mathcal{O}(1)}{\boxed{c_s^2}} \dot{\pi}^3$

Cheung et al.
Senatore et al.

Non-Gaussianity

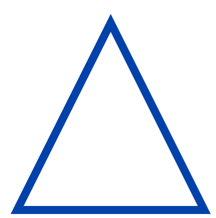
in the ***effective theory of inflation***

$$\mathcal{L}_3 \propto \frac{1}{c_s^2}\,\dot\pi(\partial_i\pi)^2 + \frac{\mathcal{O}(1)}{c_s^2}\,\dot\pi^3$$

- large interactions from small sound speed: $f_{\rm NL} \sim \dfrac{1}{c_s^2}$

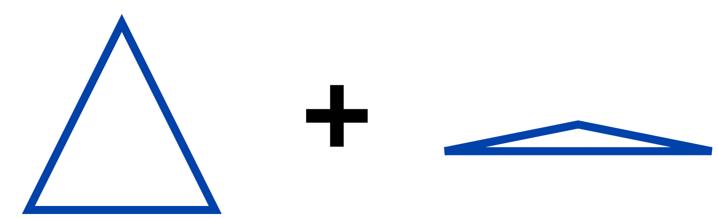
- two distinct shapes:

<u>*equilateral*</u>



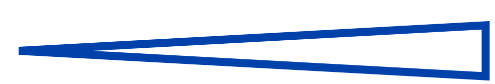
$$-214 < f_{\rm NL}^{\rm equil.} < 266$$

<u>*orthogonal*</u>



$$-410 < f_{\rm NL}^{\rm ortho.} < 6$$

- vanishing squeezed limit:

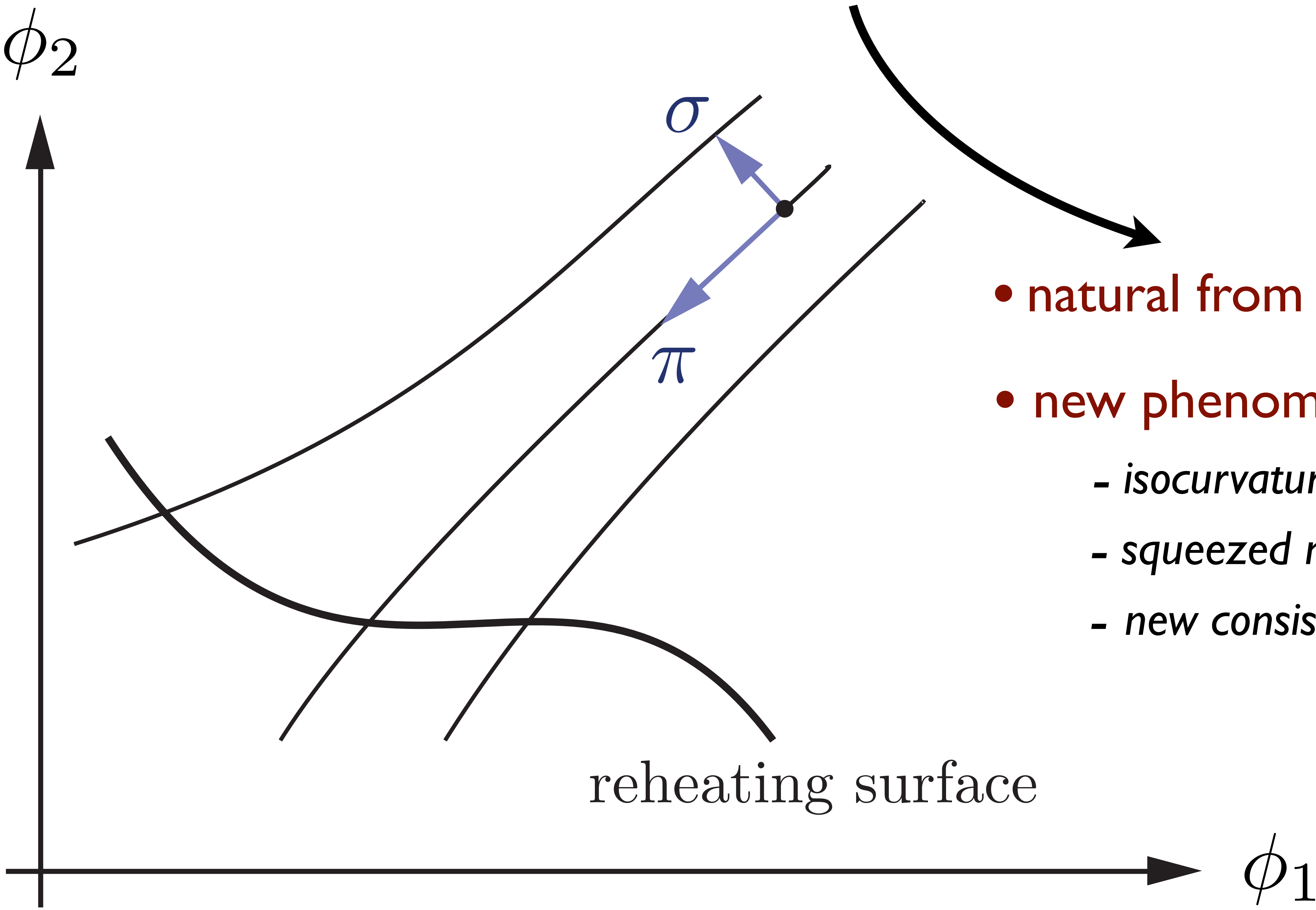


$$= 0$$

Maldacena

Senatore and Zaldarriaga

Multi-Field Inflation



- natural from the top-down?
- new phenomenology?
  - *isocurvature fluctuations*
  - *squeezed non-Gaussianity*
  - *new consistency conditions*

What is the "theory space" of multi-field inflation?

Challenges

before — ***Initial Conditions***

How did inflation start?

- *singularity*
  - inflation is past-geodesically incomplete.
  - is there really a horizon problem in QG?
- *patch problem*
- *overshoot problem*
- *eternal inflation?*
- *measure problem*

during — ***Lagrangian***

What is the physics of inflation?

- *UV-sensitivity:*
  - eta problem
  - gravitational waves
  - non-Gaussianity
- *naturalness / fine-tuning*

after — ***Reheating***

How did inflation end?

- *observational signatures?*

before **Initial Conditions**

How did inflation start?

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  - ***eta problem***
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after **Reheating**

How did inflation end?

- *observational signatures?*

So far we have discussed fluctuations
around a given quasi-de Sitter background

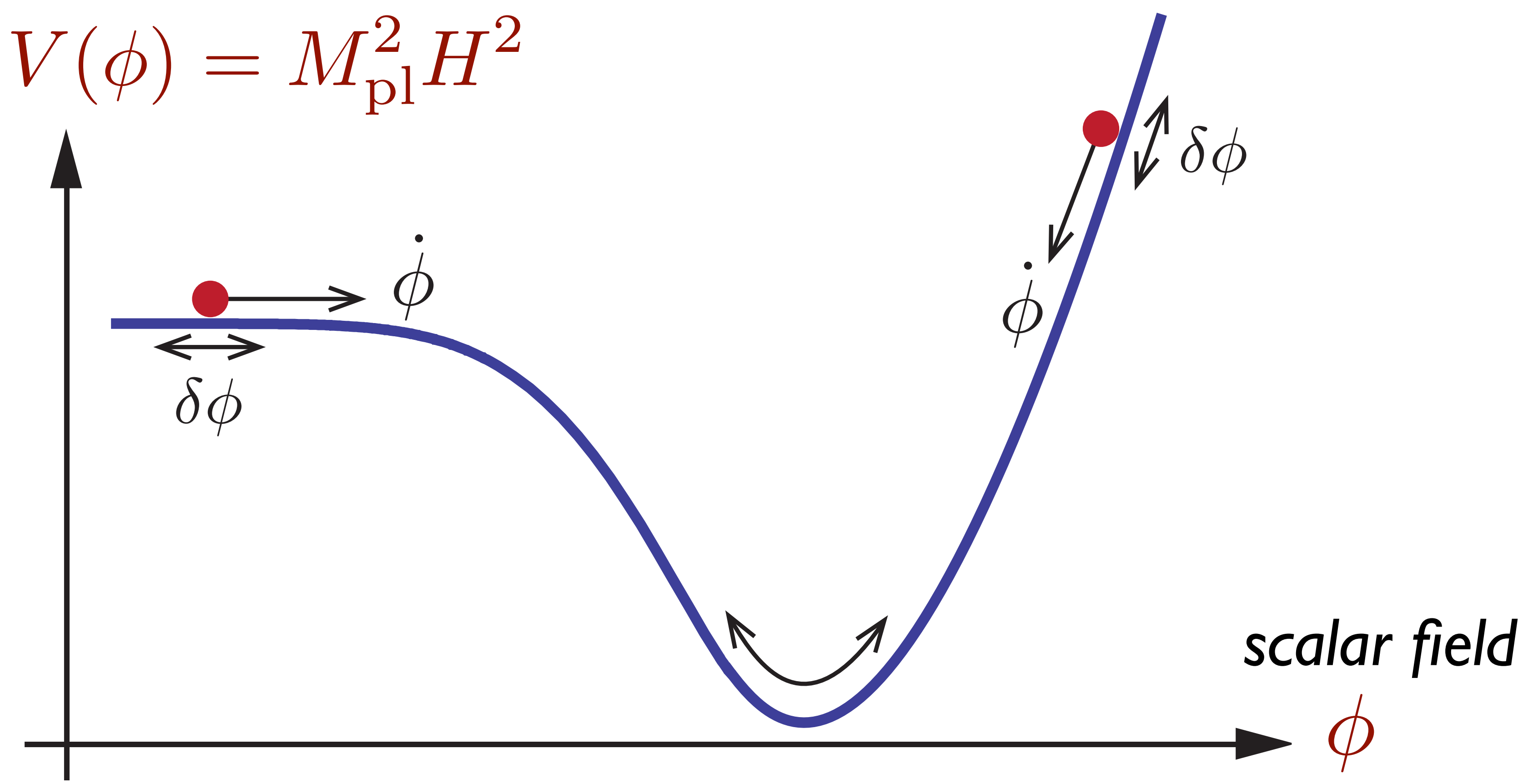
$$H(t)$$

but we haven't said how this
background arises in the first place.

PROBLEM 1:

Why is the inflaton so light ?

The Eta Problem



slow-roll inflation:

$$\varepsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

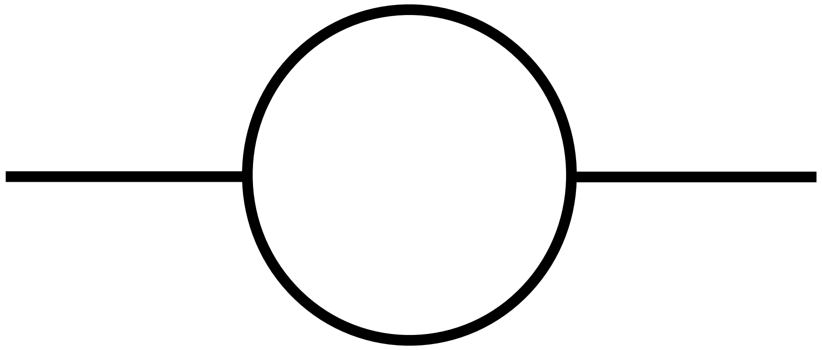
$$\eta = M_{\rm pl}^2 \frac{V''}{V} \ll 1$$

Why is the inflaton so light ?

$$\eta \approx \frac{m_\phi^2}{H^2} \ll 1$$

The Eta Problem

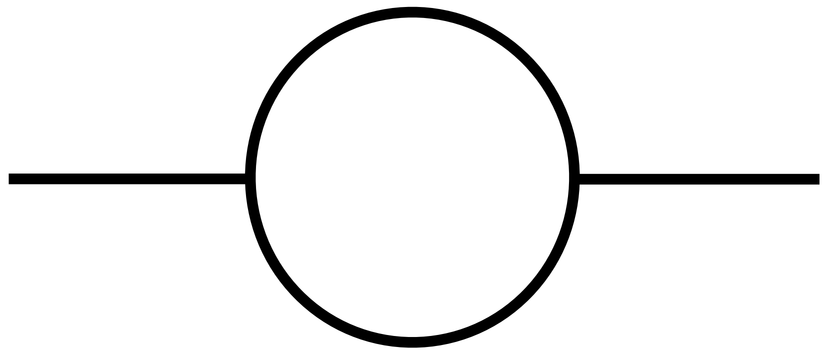
like the Higgs ***hierachy problem***



$$m_\phi^2 \sim \Lambda_{\mathrm{uv}}^2 \gg H^2$$

The Eta Problem

like the Higgs ***hierachy problem***



$$m_\phi^2 \sim H^2$$

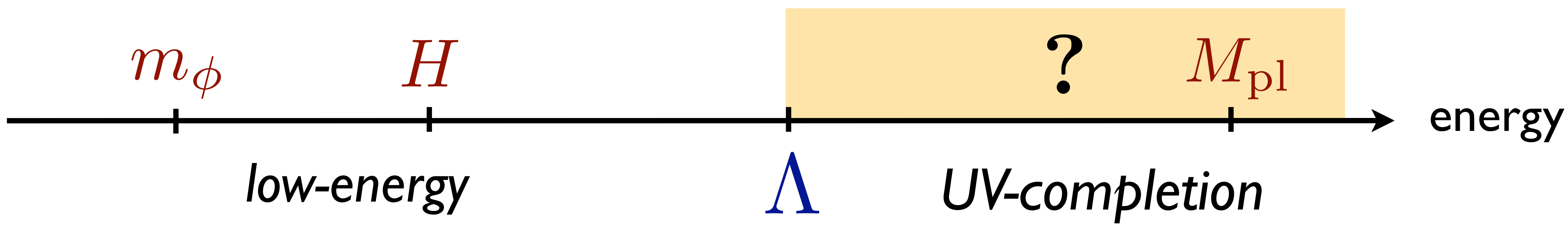
supersymmetry ameliorates the problem,
but ***doesn't solve it***.

↓

need ***fine-tuning*** or ***additional symmetry***

(1 part in 100) (easy to *assume*, hard to *explain*)

The Eta Problem



low-energy effective field theory

UV-completion
e.g. string theory

integrate out massive particles or parameterize our ignorance

slow-roll potential ***high-energy corrections***

$$V_0(\phi) \quad + \quad \sum_\delta \frac{\mathcal{O}_\delta(\phi)}{\Lambda^{\delta-4}}$$

In inflation, even Planck-suppressed interactions cannot be ignored !

The Eta Problem

Inflation is sensitive to
dimension-6 Planck-suppressed operators

$$\Delta V = V_0 \frac{\phi^2}{M_{\rm pl}^2} \quad \longrightarrow \quad \Delta\eta = 1$$

Can we forbid corrections with a ***symmetry*** ?

The Eta Problem

shift symmetry

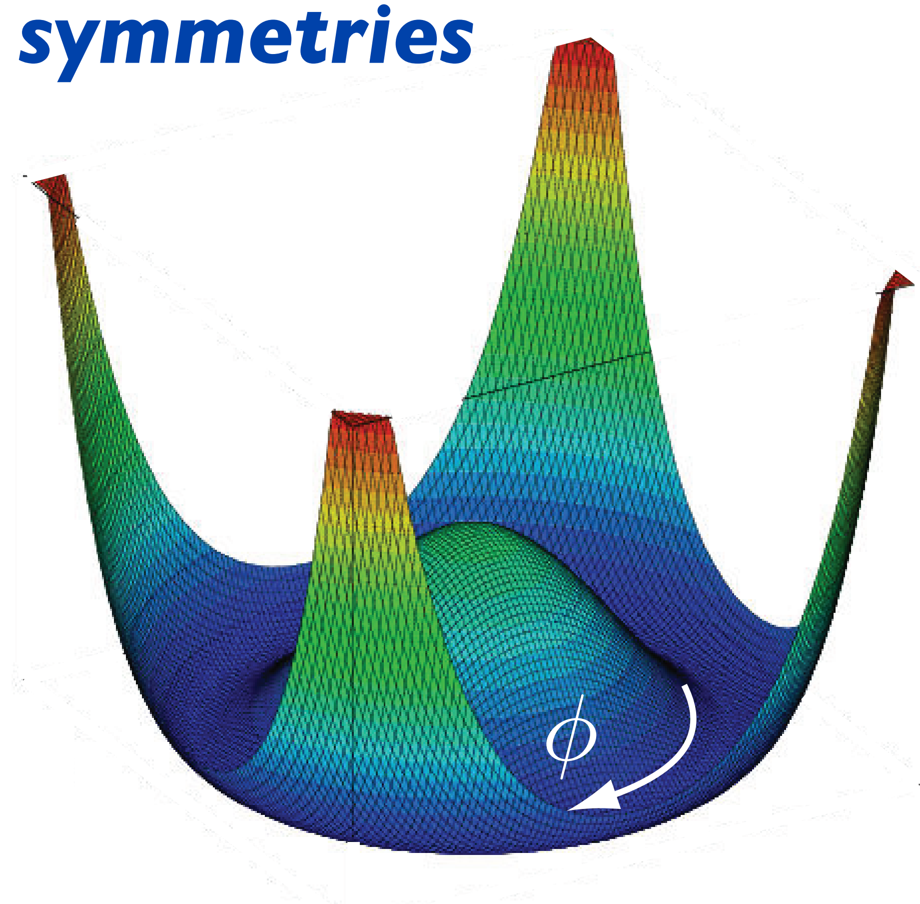
$$\phi \rightarrow \phi + const.$$

$$\cancel{V_0 \frac{\phi^2}{\Lambda^2}}$$

$$\updownarrow$$

spontaneous breaking of global symmetries

Many models implement this solution in supergravity.



The Eta Problem

BUT:

How does the symmetry arise from the top-down?

What is the UV-completion?

The Eta Problem

BUT:

"Quantum gravity breaks global symmetries."

Confirmed by many examples in string theory.

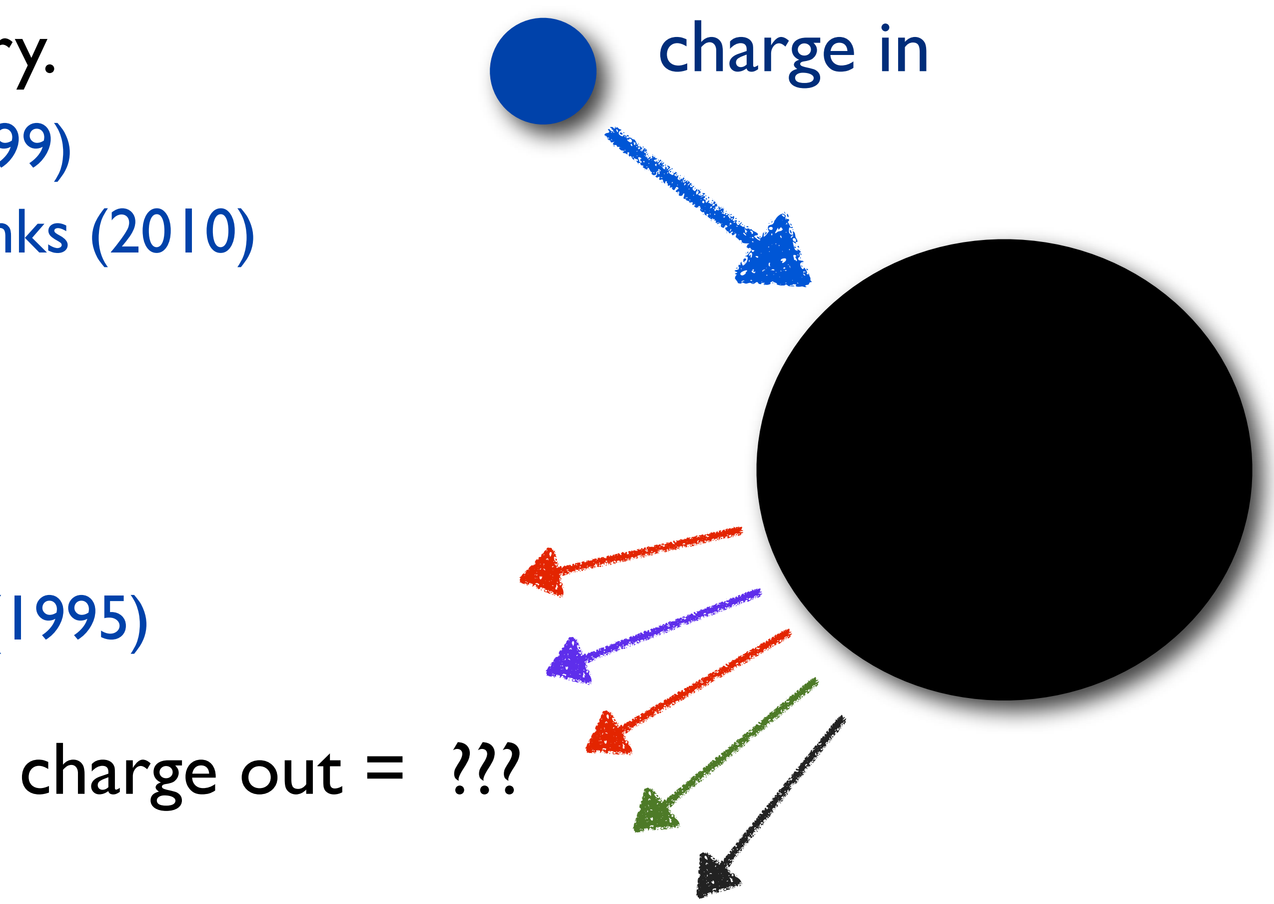
Banks et al. (1999)

Seiberg and Banks (2010)

More generally:

Black hole evaporation breaks global symmetries

e.g. Kallosh et al. (1995)



Planck-suppressed operators reintroduce the eta problem !

The Eta Problem

"Quantum gravity breaks global symmetries."

protecting the inflation from this is the real challenge:

1. compute the symmetry breaking effects in ***string theory***

   see Eva Silverstein's talk

2. find a sufficiently powerful symmetry in ***field theory***

   e.g. "Inflating with Baryons"
   DB and Daniel Green

Every model of inflation has to address the eta problem.

Some classes of models have observational signatures that dramatically enhance the UV sensitivity:

→ ***Gravitational Waves***

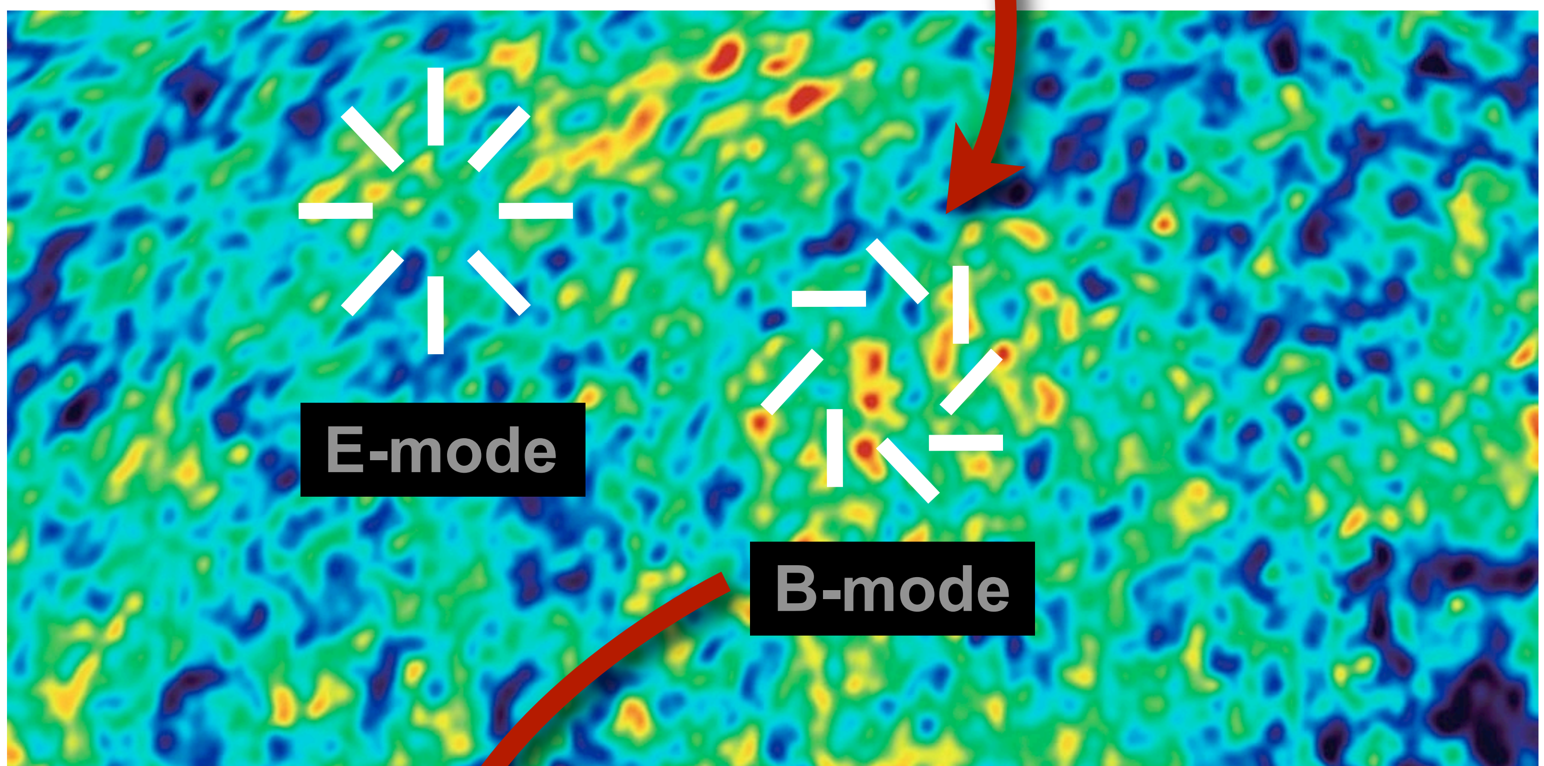
Non-Gaussianity

PROBLEM 2:

Is large ‘r’ UV-completable ?

Gravitational Waves

CMB Polarization

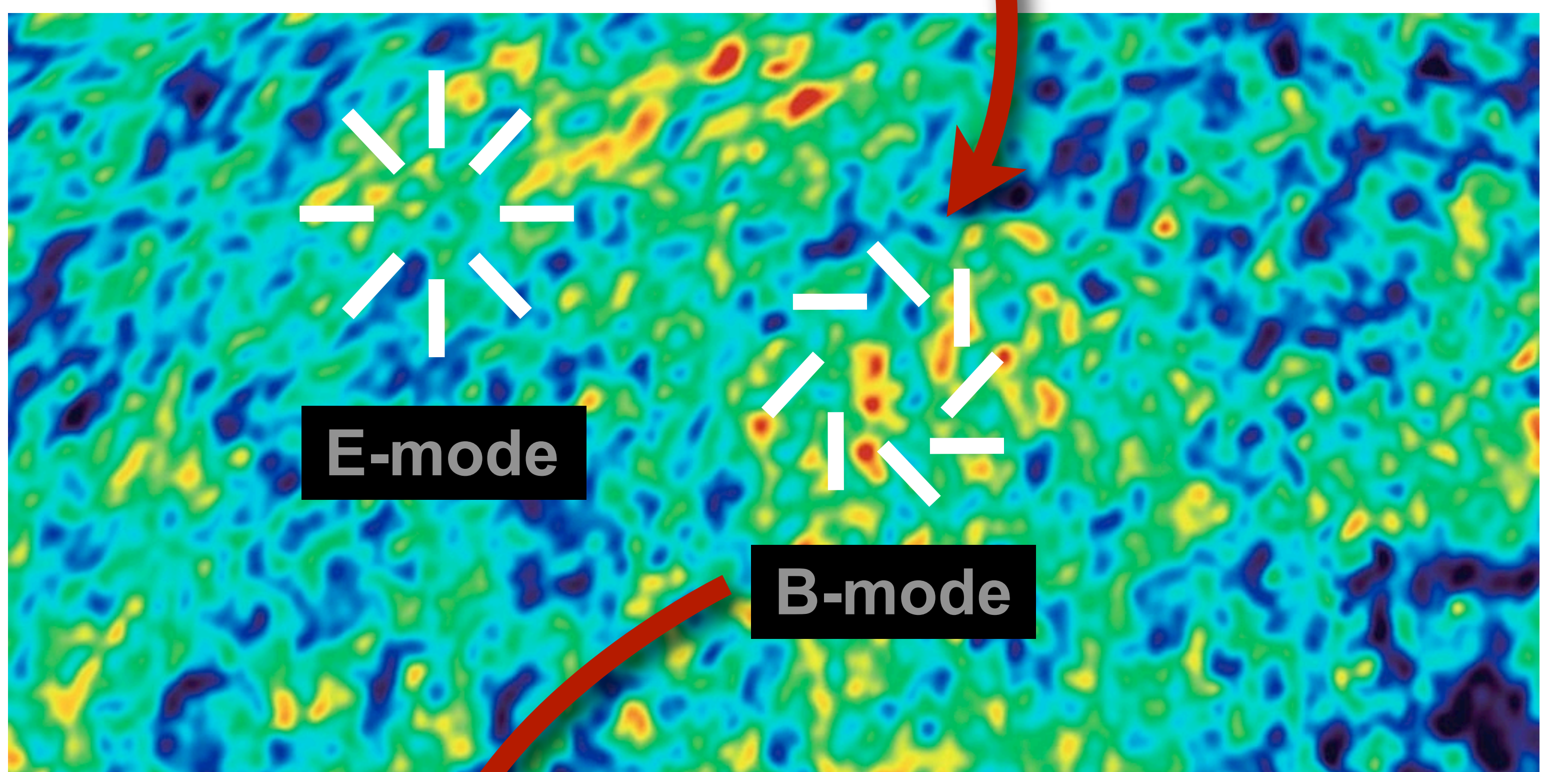


measures: $$\frac{H}{M_{\rm pl}}$$

energy scale of inflation

Gravitational Waves

CMB Polarization



observable if:

tensor-to-scalar ratio:

gravity waves

density fluctuations

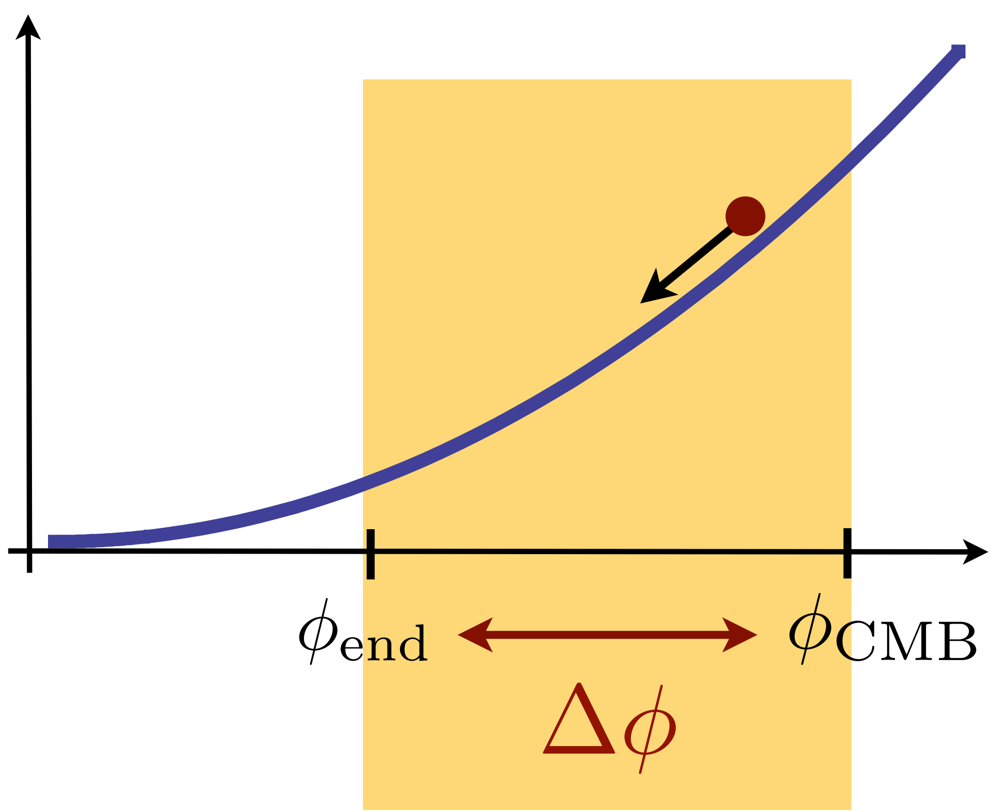
$$r \equiv \frac{P_t}{P_s} \gtrsim 0.01$$

Gravitational Waves

The Lyth Bound

$$\boxed{\frac{\Delta\phi}{M_{\rm pl}} \approx \left(\frac{r}{0.01}\right)^{1/2}}$$

Lyth (1996)



observable gravitational waves

$$\boxed{r \gtrsim 0.01}$$

$\longrightarrow$

super-Planckian field variation

$$\boxed{\Delta\phi \gg M_{\rm pl}}$$

This makes an effective field theorist nervous and a string theorist curious!

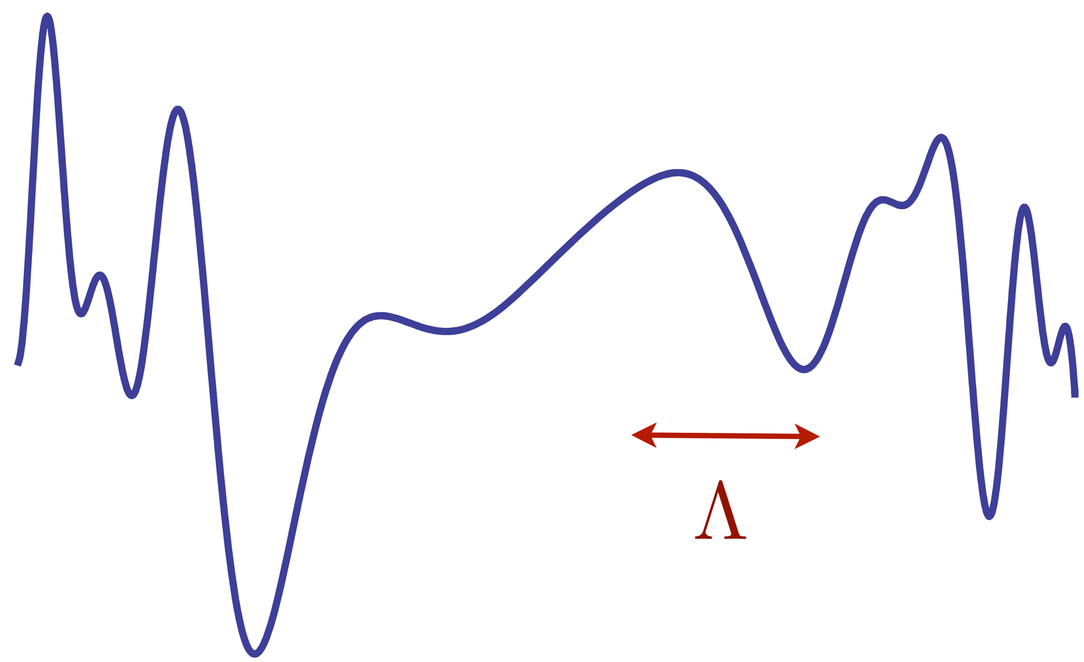
Gravitational Waves

observable gravitational waves

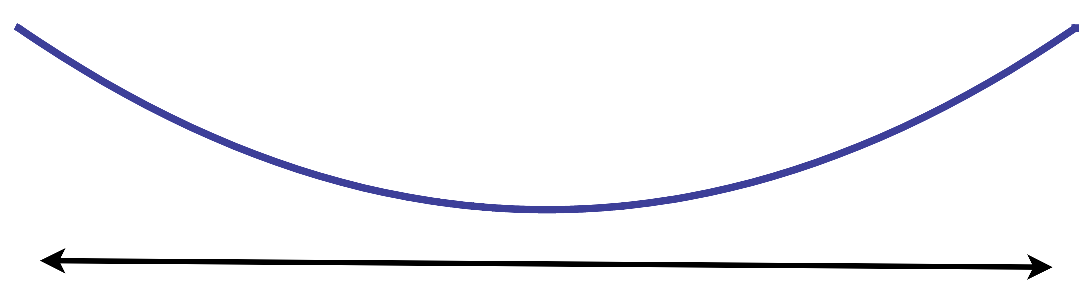
$$\Delta\phi \gg M_{\rm pl} \gtrsim \Lambda \quad \longrightarrow \quad \Delta V = \phi^4 \sum_n c_n \left(\frac{\phi}{\Lambda}\right)^n$$

an infinite series of corrections, of arbitrarily high dimension, can become important

Hence, we expect:



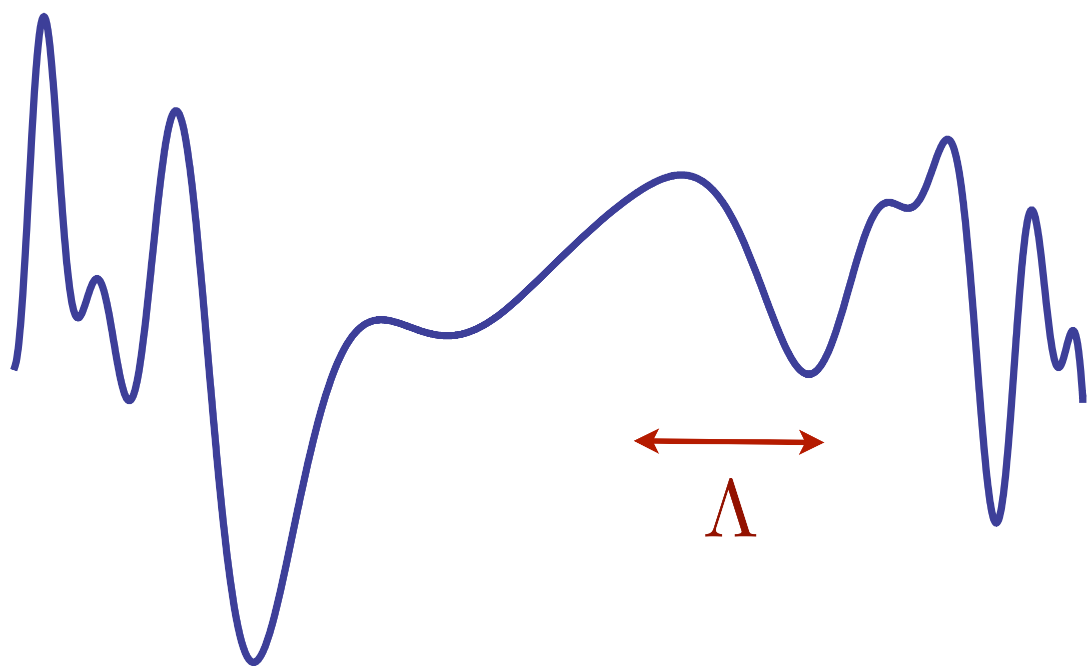
... while we need:



$\text{few} \times M_{\rm pl}$

Gravitational Waves

$$\Delta V = \phi^4 \sum_n c_n \left(\frac{\phi}{\Lambda}\right)^n$$



What is the UV-completion of large-field inflation?

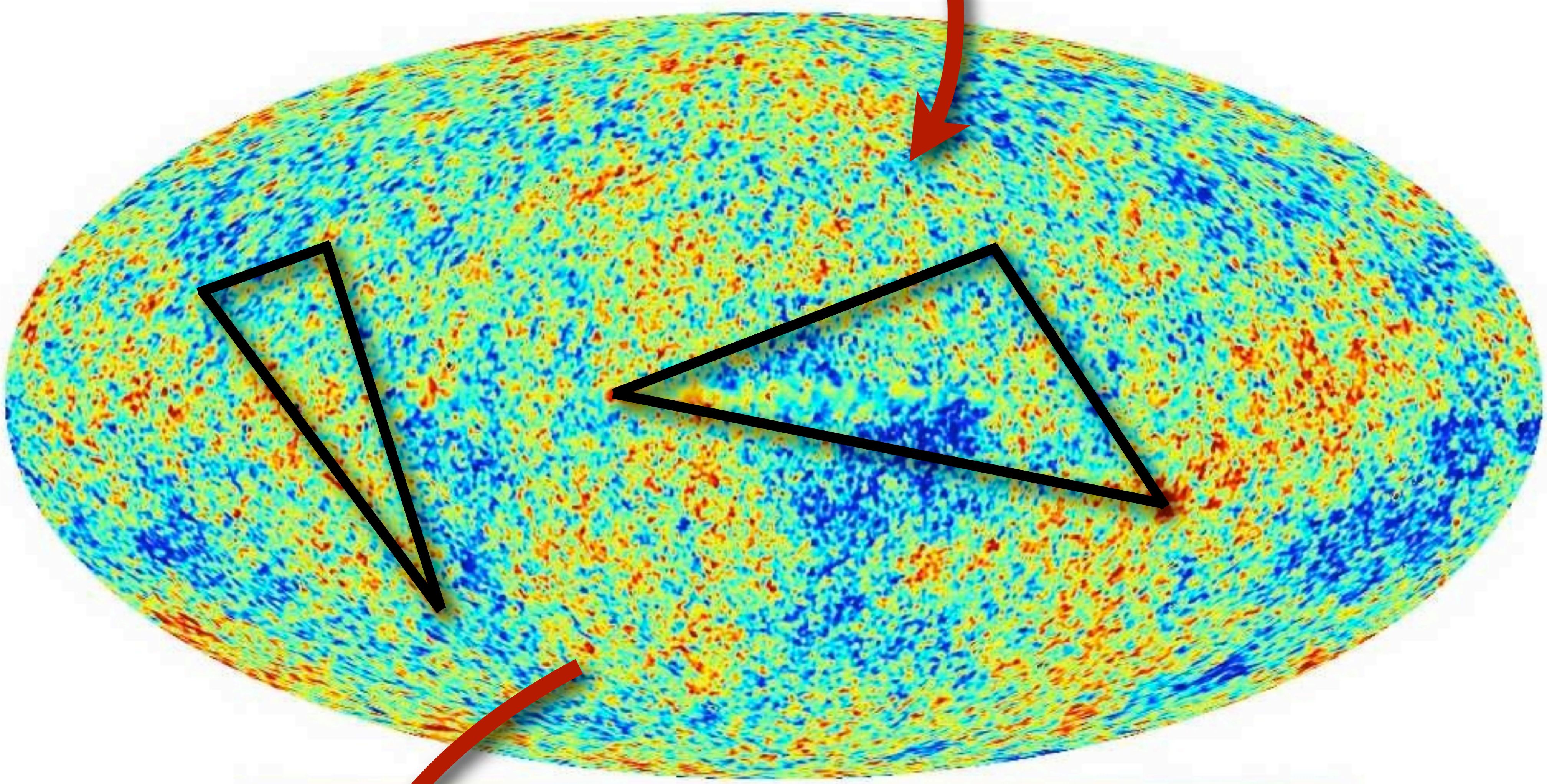
→ Opportunity for String Inflation!

see Eva Silverstein's talk

PROBLEM 3:

Is small 'c_s' UV-completable ?

Non-Gaussianity



measures: ***inflaton interactions***

(going beyond free-fields)

Non-Gaussianity

slow-roll inflation

$\mathcal{L} = (\partial\phi)^2 - V(\phi)$ $\longrightarrow$ small self-interactions $\longrightarrow$ *<u>Gaussian</u> fluctuations*

+ higher-derivative corrections

$$\Delta\mathcal{L} = \sum_{n=2}^{\infty} c_n \frac{(\partial\phi)^{2n}}{\Lambda^{2n}}$$

$\downarrow$

<u>non-Gaussian</u> fluctuations $\longleftarrow$ $c_s \ll 1$

$\uparrow$

observable if and only if: $\boxed{(\partial\phi)^2 \sim \Lambda^4}$ $\longleftarrow$ ***UV completion ?***

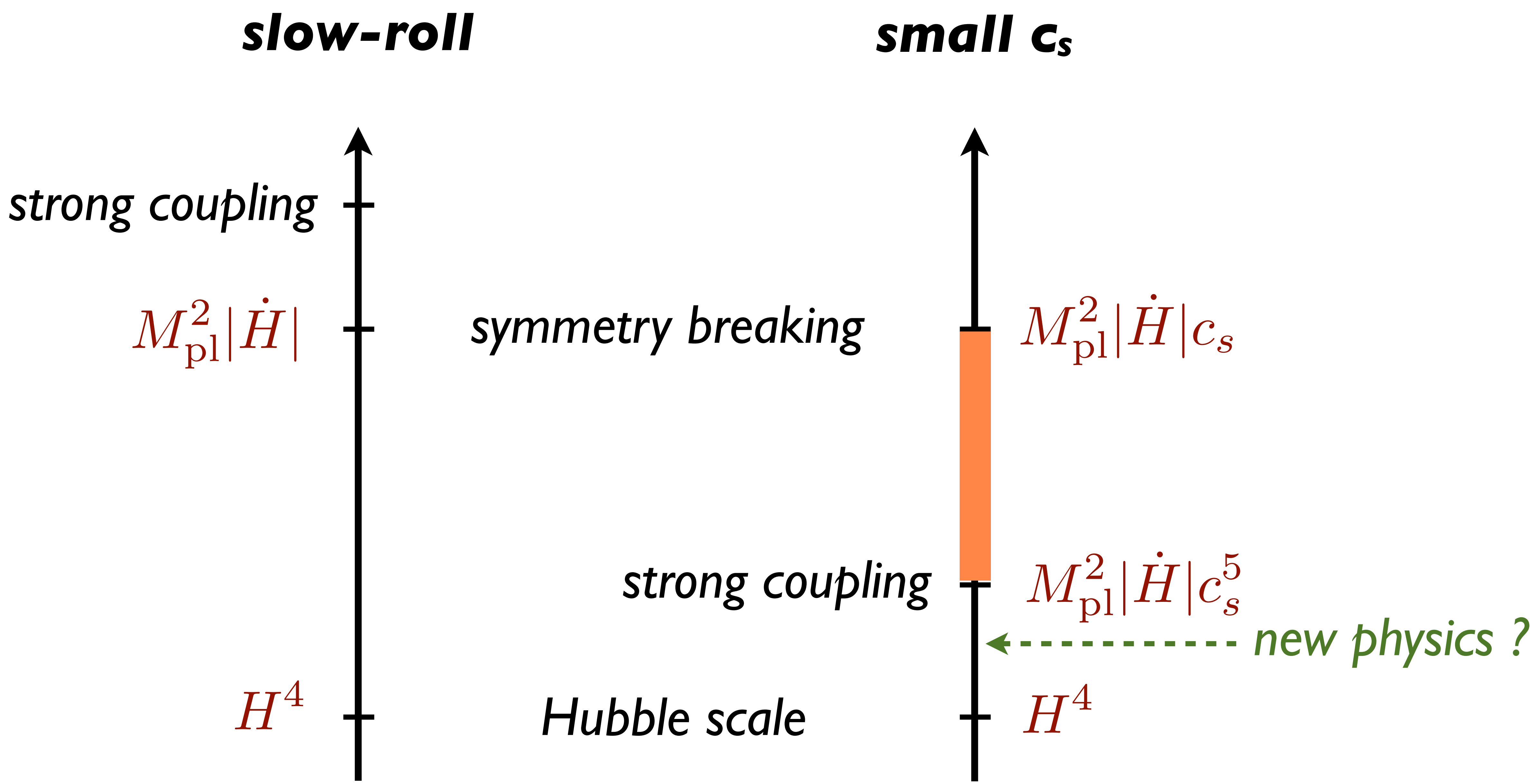
see DBI inflation

breakdown of the derivative expansion !

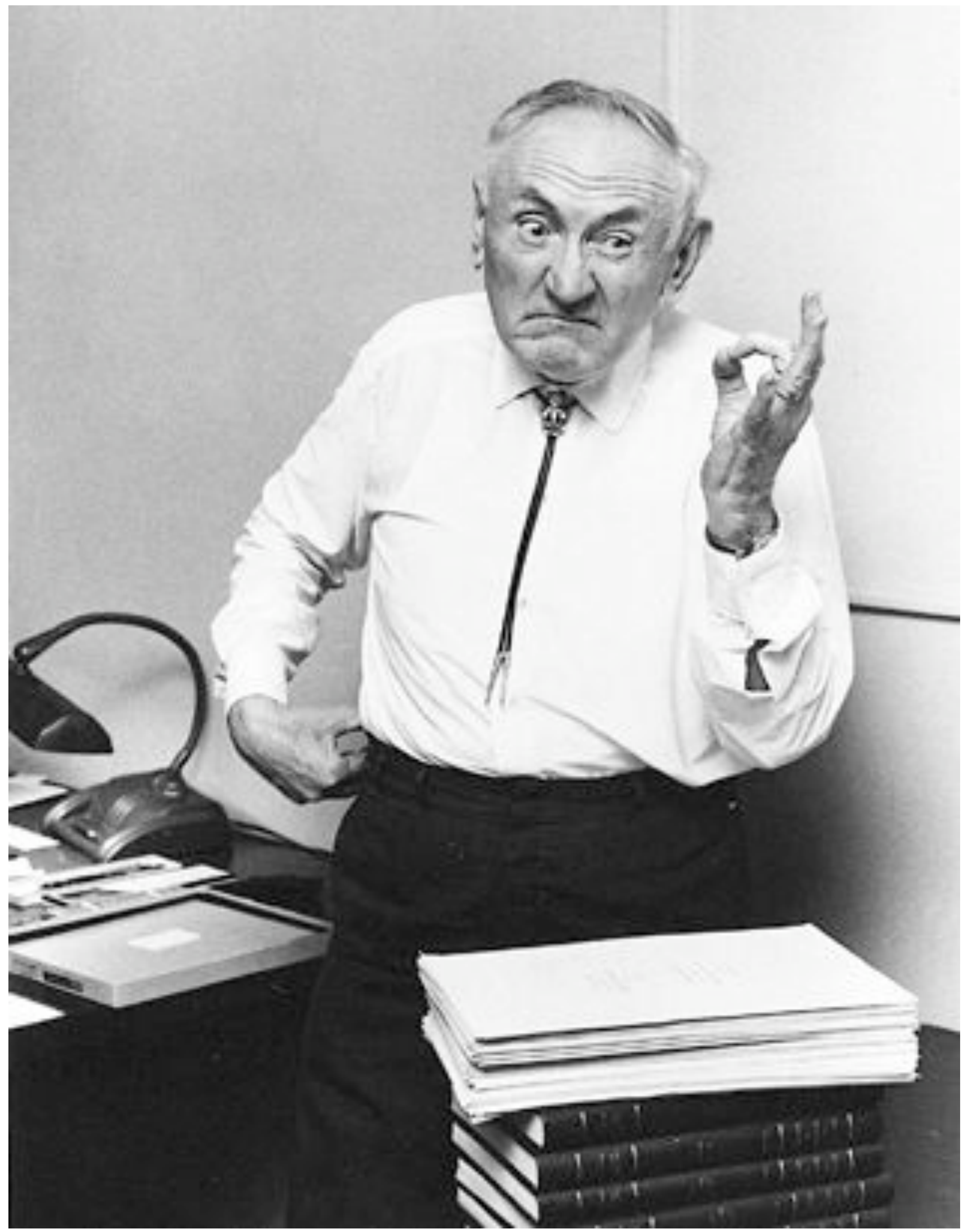
Non-Gaussianity

Can also see the problem in the
effective theory of the Goldstone fluctuations:

DB and Daniel Green (to appear)

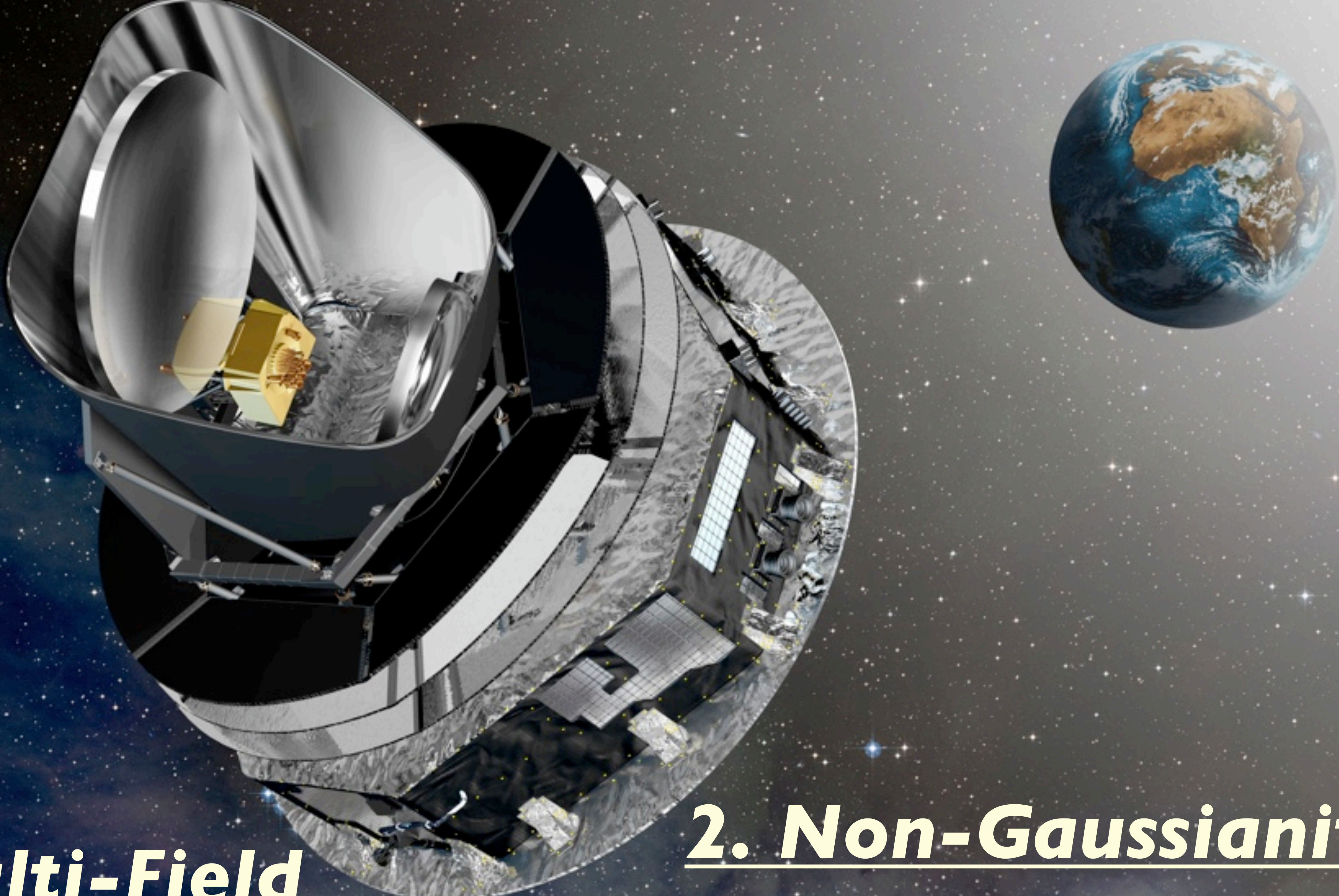


“Why should I care about UV-completion?”



Future Observations

1. Gravitational Waves



2. Non-Gaussianity

3. Multi-Field Inflation

Can we falsify inflation?

Can we falsify inflation ?

Can we falsify ...

the paradigm?	single-field?	multi-field?
$\Omega_k > \zeta \sim 10^{-4}$	$f_{\rm NL}^{\rm local} > 1$	$\tau_{\rm NL} > (f_{\rm NL})^2$?
$n_t = 2\frac{\dot{H}}{H^2} > 0$	$\lvert n_t \rvert \neq 8 c_s r$	$\lvert n_t \rvert > 8r$
superhorizon vector modes		
?	?	?

Conclusions

$$V_0 \frac{\phi^2}{M_{\rm pl}^2}$$

eta problem

Inflation is sensitive to Planck-scale physics!

gravitational waves

$$\Delta\phi \gg M_{\rm pl}$$

non-Gaussianity

$$(\partial\phi)^2 \sim M_{\rm pl}^4$$

before **Initial Conditions**

How did inflation start?

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- *patch problem*
- *overshoot problem*
- *eternal inflation?*
- *measure problem*

during **Lagrangian**

?

What is the physics of inflation?

- *UV-sensitivity:*
  - eta problem
  - gravitational waves
  - non-Gaussianity
- *naturalness / fine-tuning*

after **Reheating**

How did inflation end?

- *observational signatures?*

The End