Probing the Nature of Inflation

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Outline

CMB History

Inflation and the CMB

Inflation today

Inflation tomorrow

CMB History

Early days of the CMB

The CMB is todays workhorse of cosmology

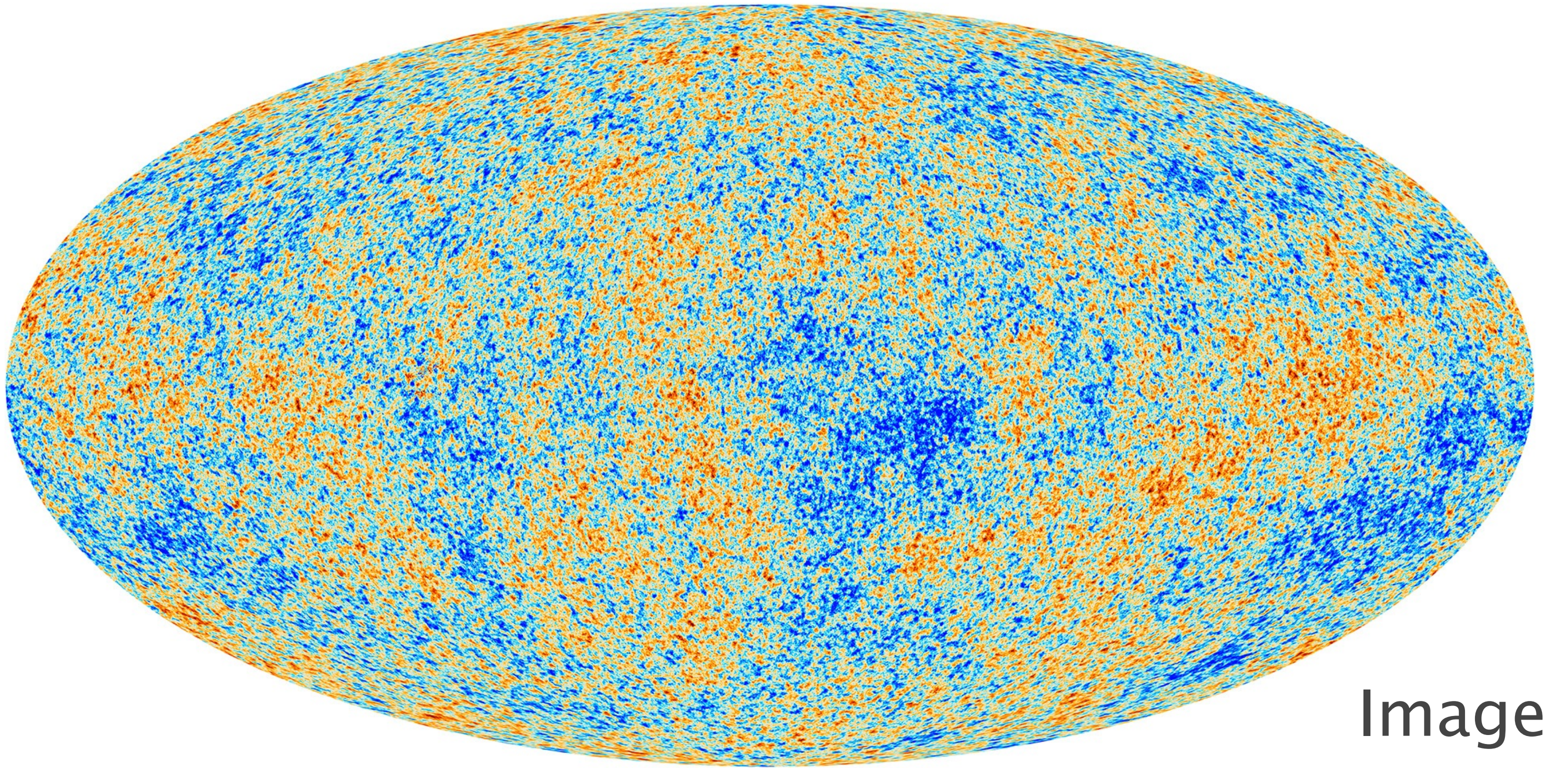


Image from Planck

What we observe is the light the leftover after neutral hydrogen formed, 378 000 years after the big bang

Early days of the CMB

This year marks the 50th anniversary of the CMB

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

Early days of the CMB

CMB was first observed by Penzias & Wilson (1965)

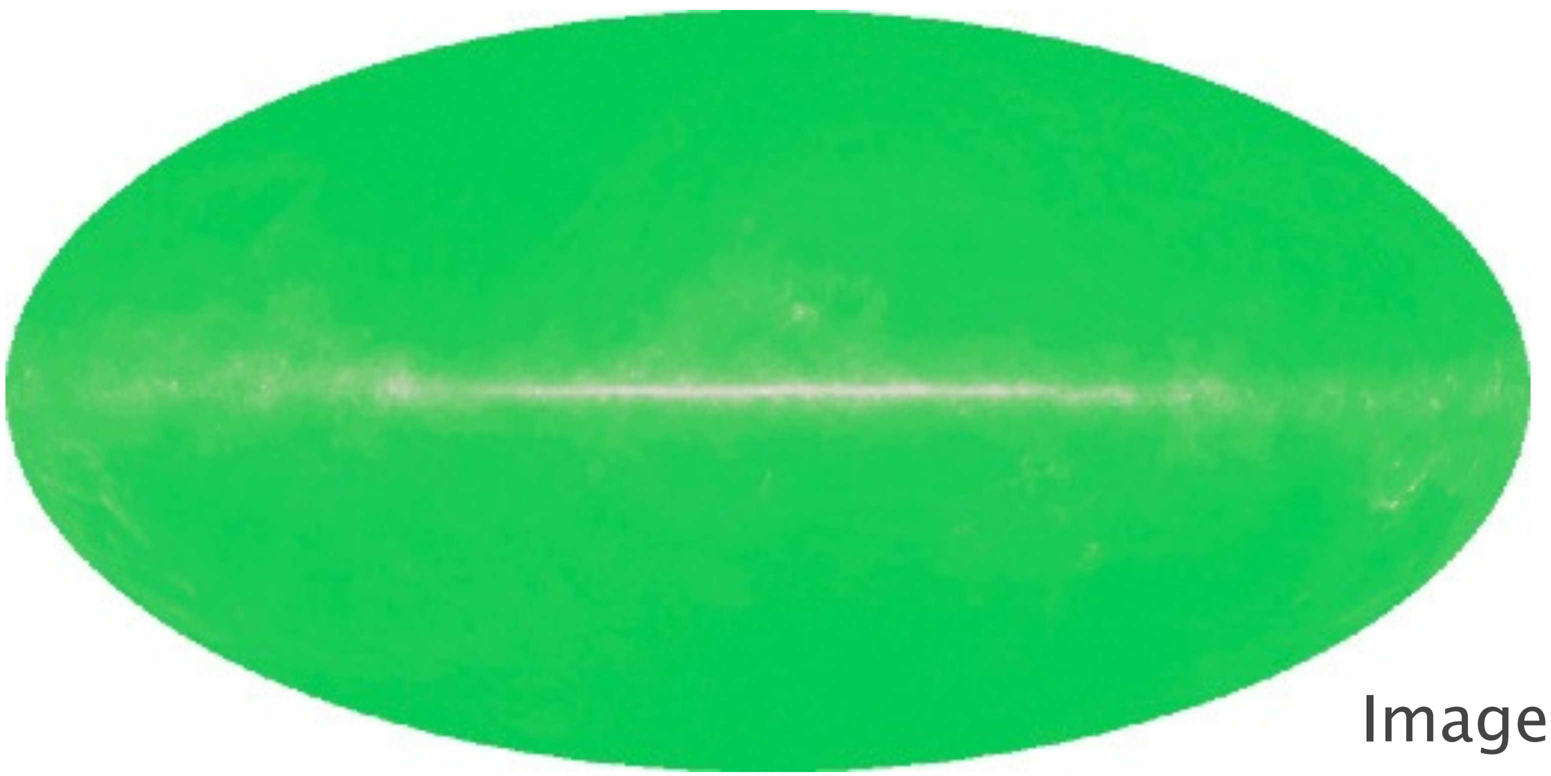


Image from WMAP

Consistent with a uniform temperature $T \sim 3\,\mathrm{K}$

Early days of the CMB

CMB dipole was first observed by Conklin (1969)

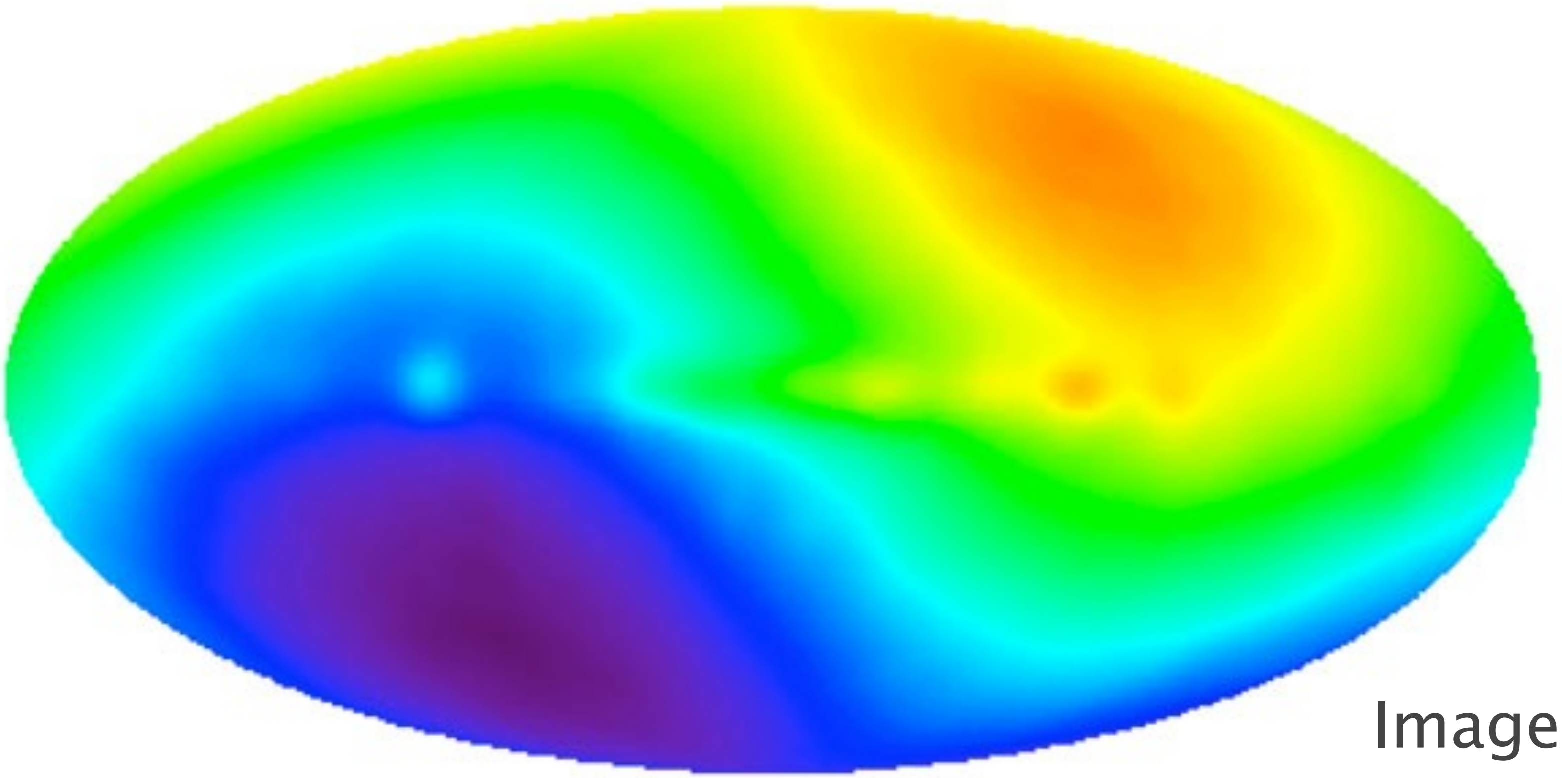


Image from COBE

Temperature fluctuation of $\Delta T \sim 3\,\mathrm{mK}$

Early days of the CMB

CMB anisotropy observed by COBE (1992)

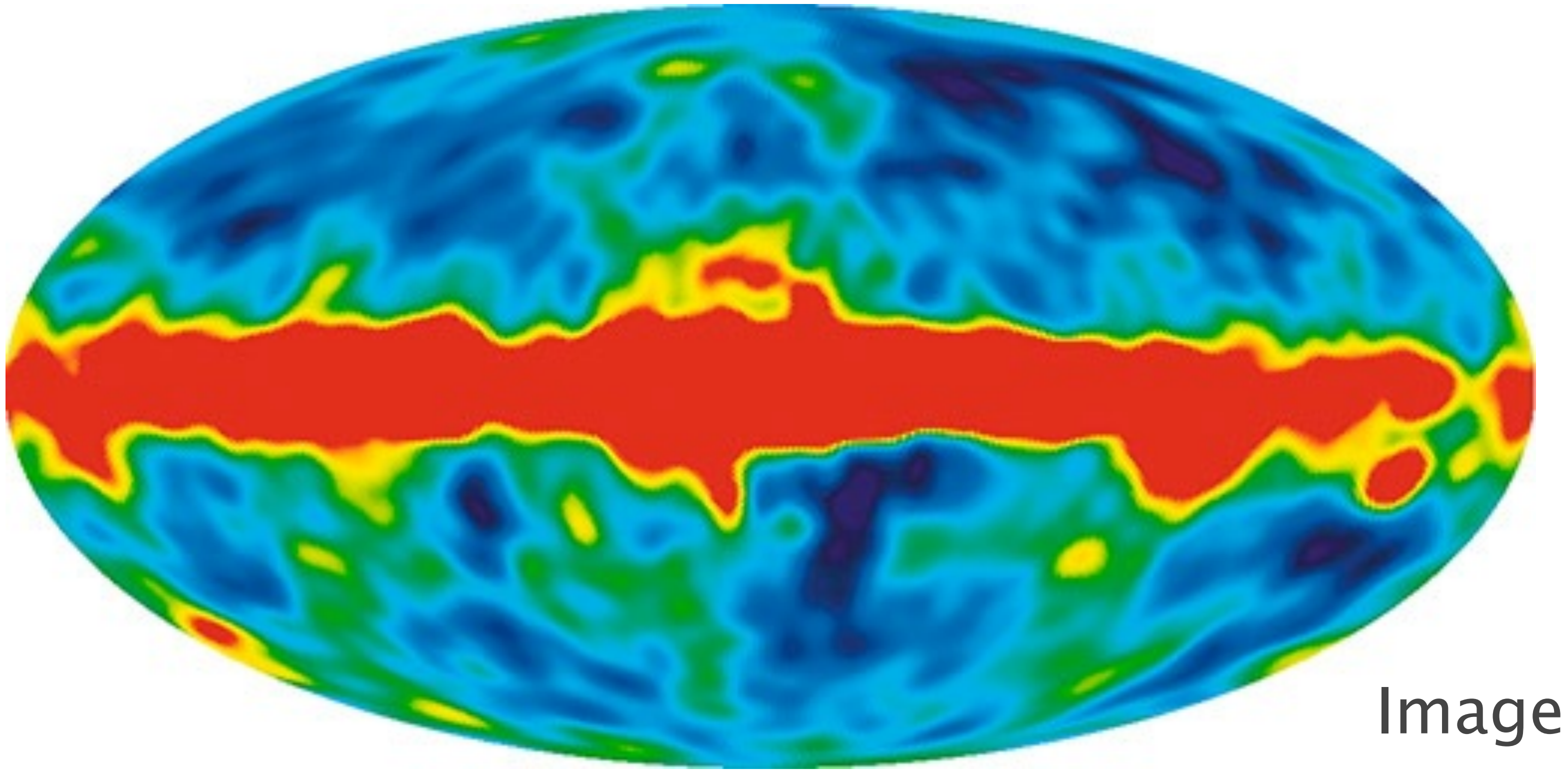
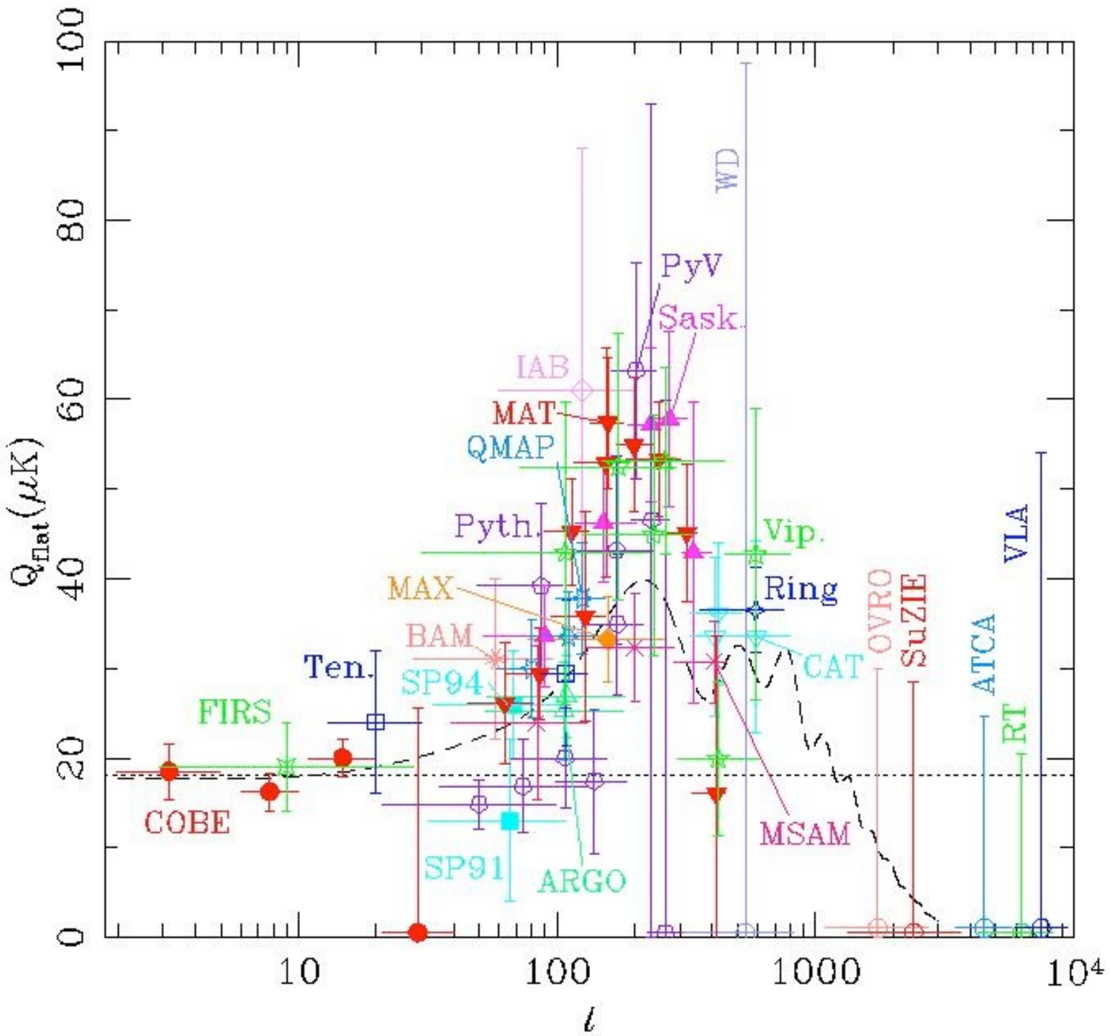


Image from COBE

First detection of primordial density fluctuations

Early days of the CMB

First acoustic peak observed (1993-2001)



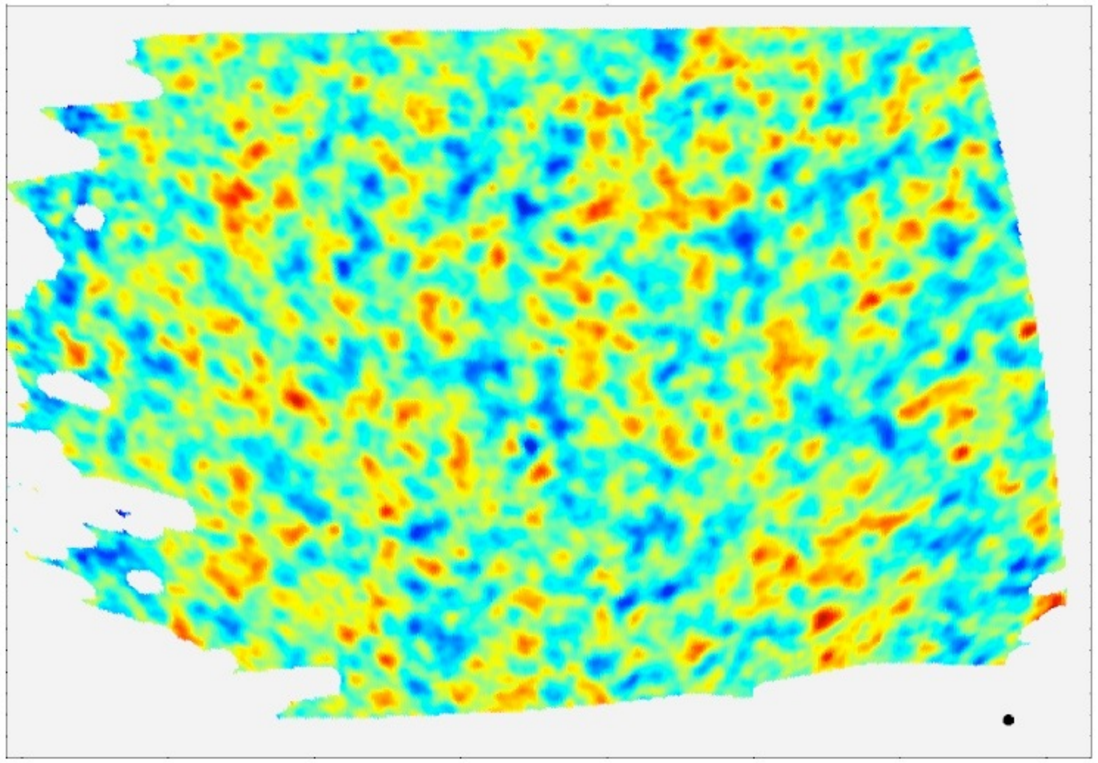
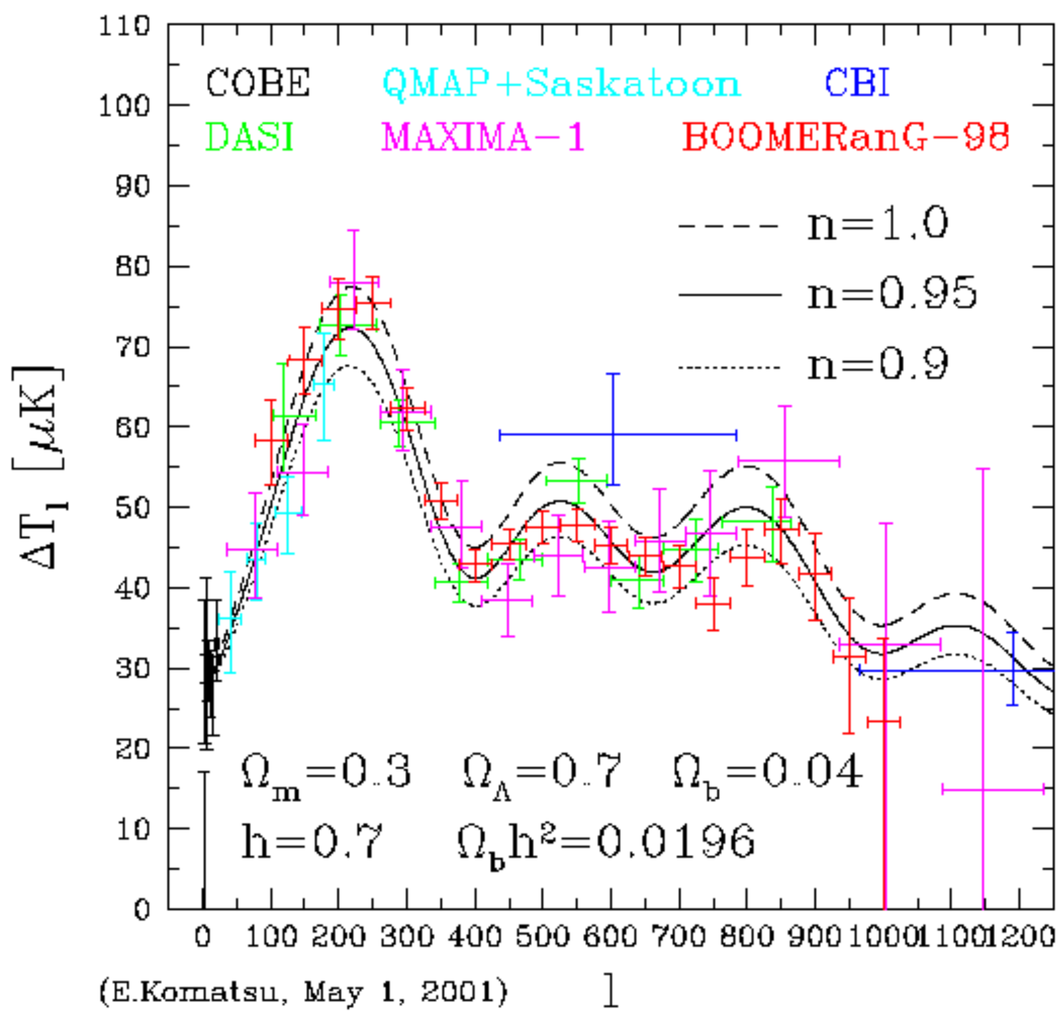


Image from Boomerang

Consistent with spatial flat universe

Early days of the CMB

First acoustic peak(s) observed (1993-2001)



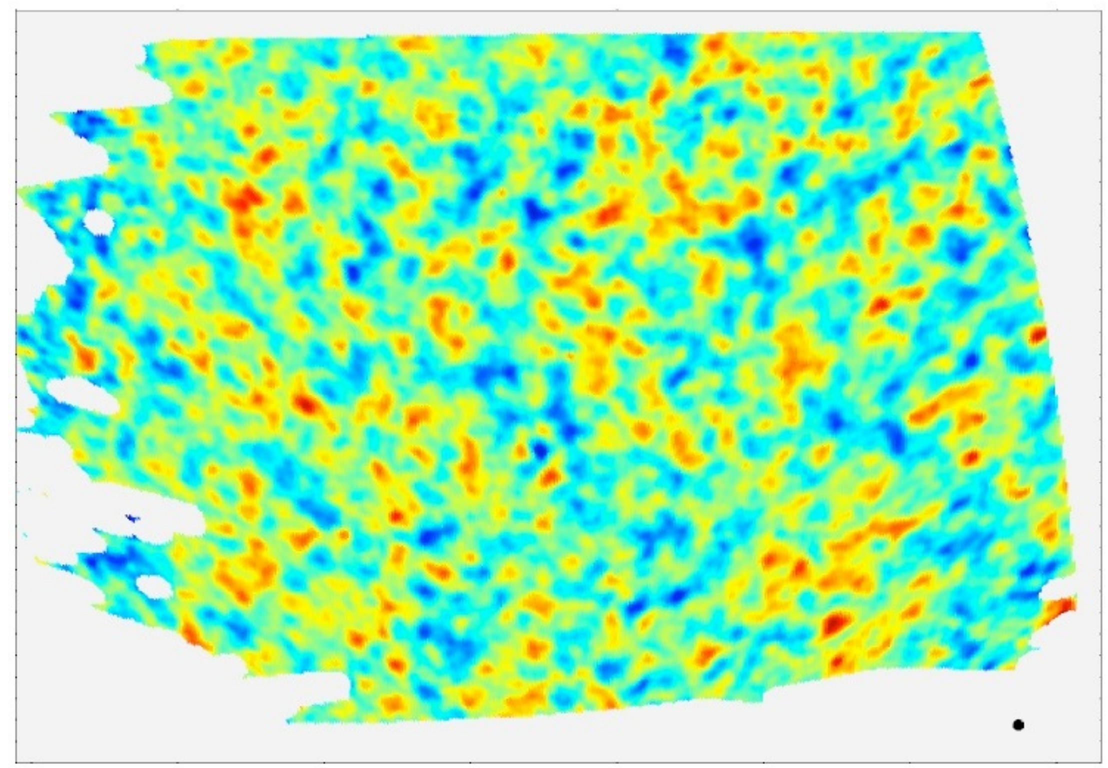


Image from Boomerang

Consistent with spatial flat universe

The CMB today

WMAP (2003-2012)

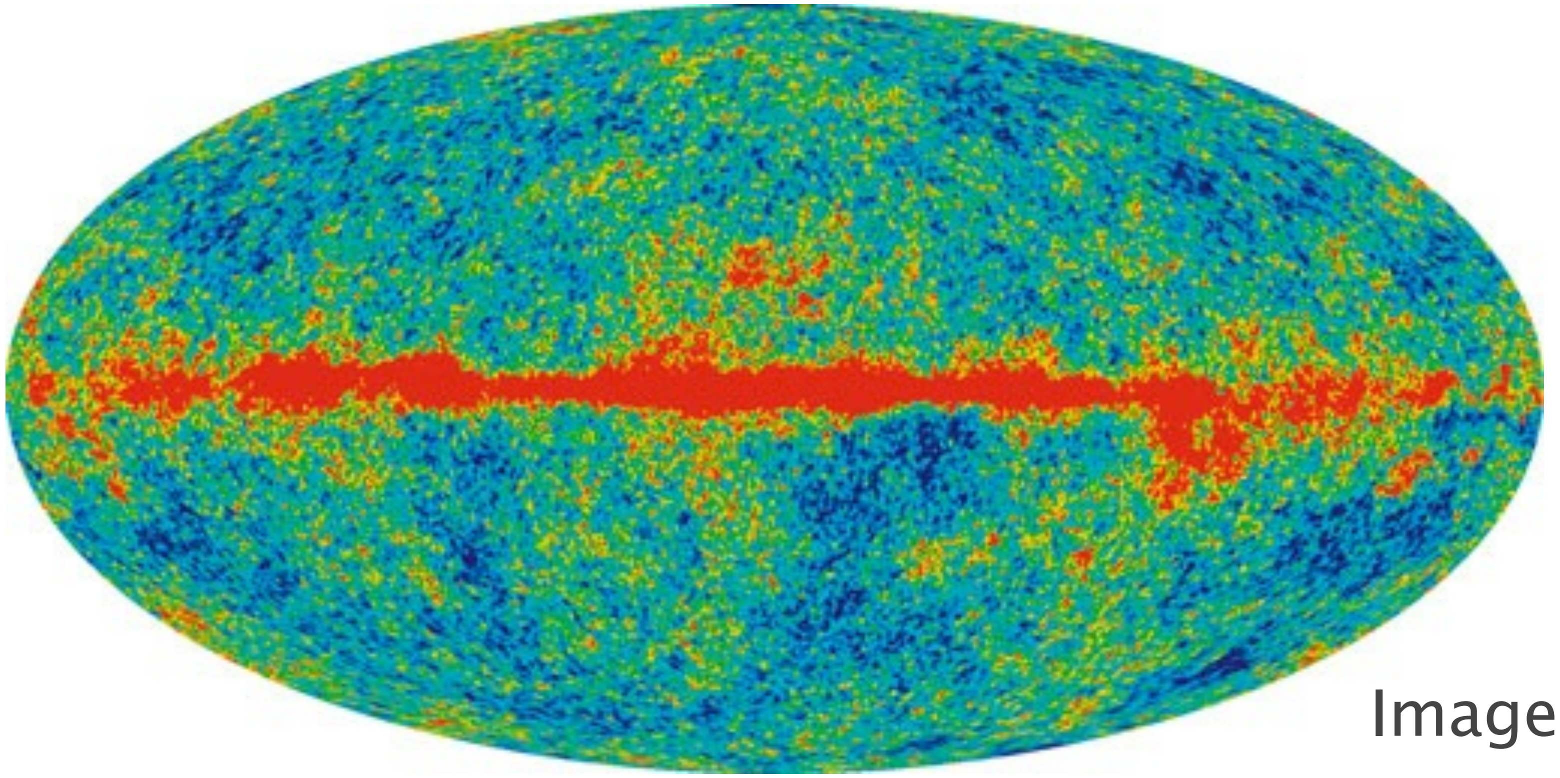


Image from WMAP

Cosmic variance limited to $\ell = 548$

The CMB today

Planck (2013-present)

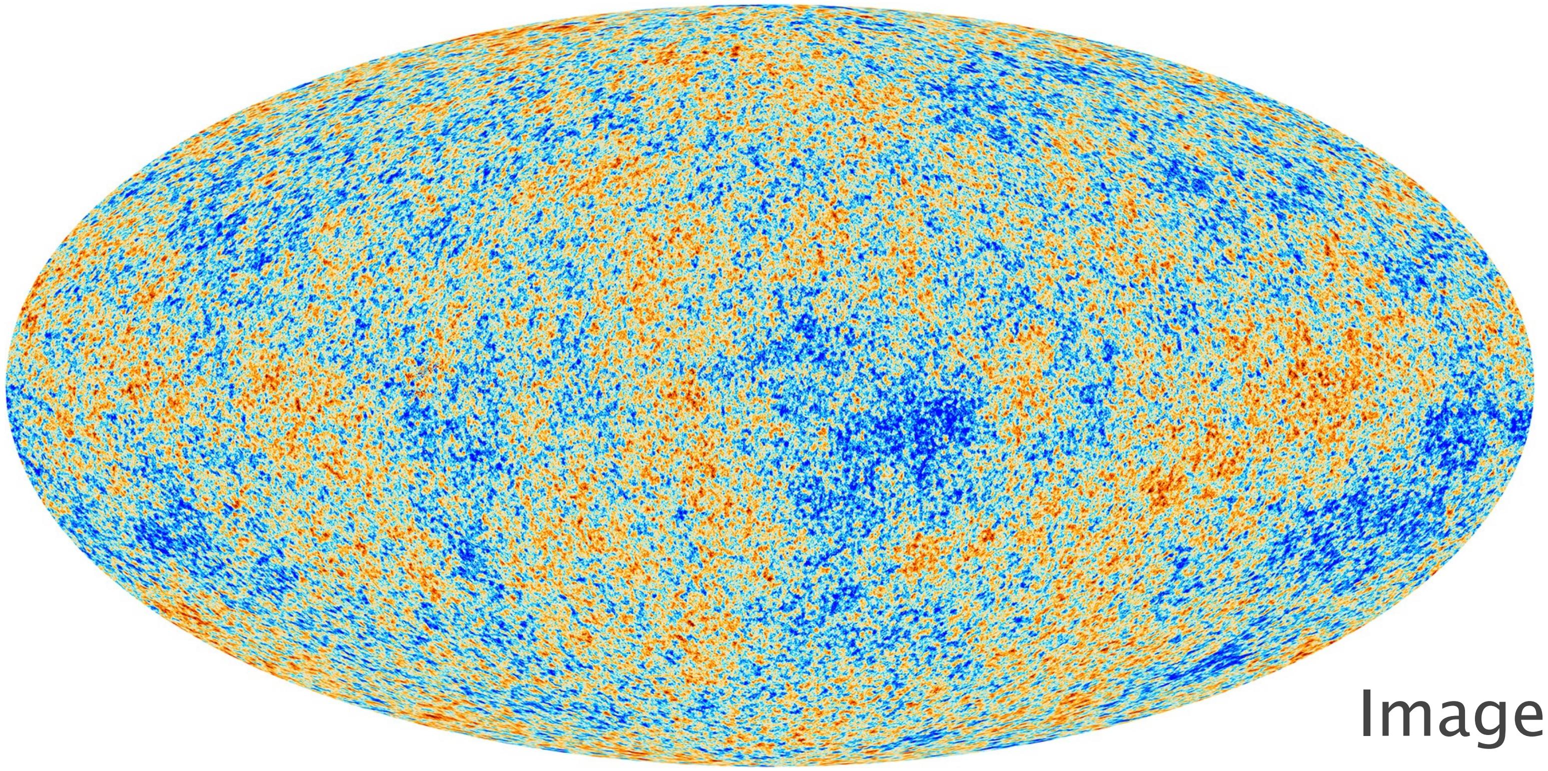
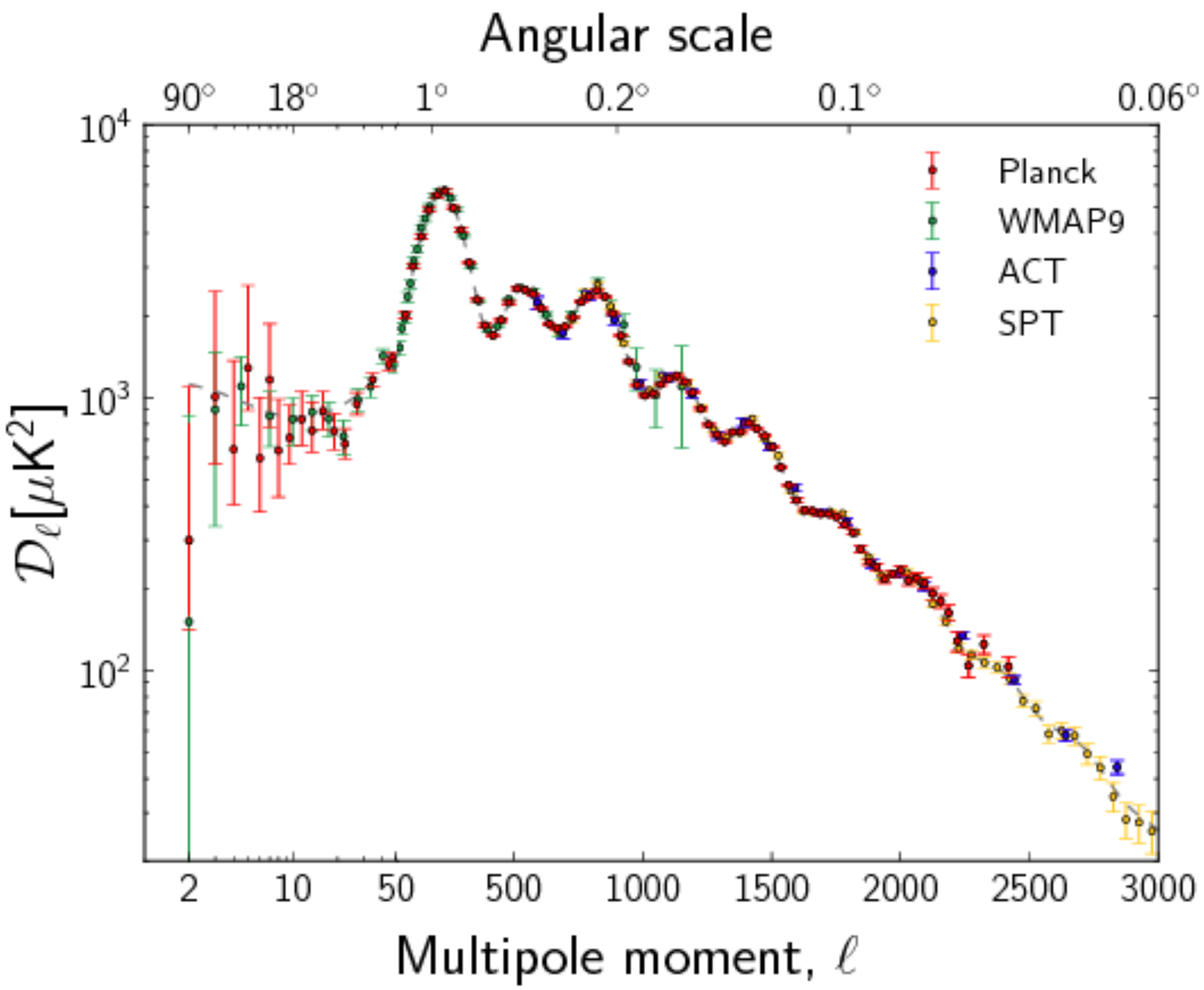


Image from Planck

Cosmic variance limited to $\ell \sim 1500$

The CMB today

Data (today):



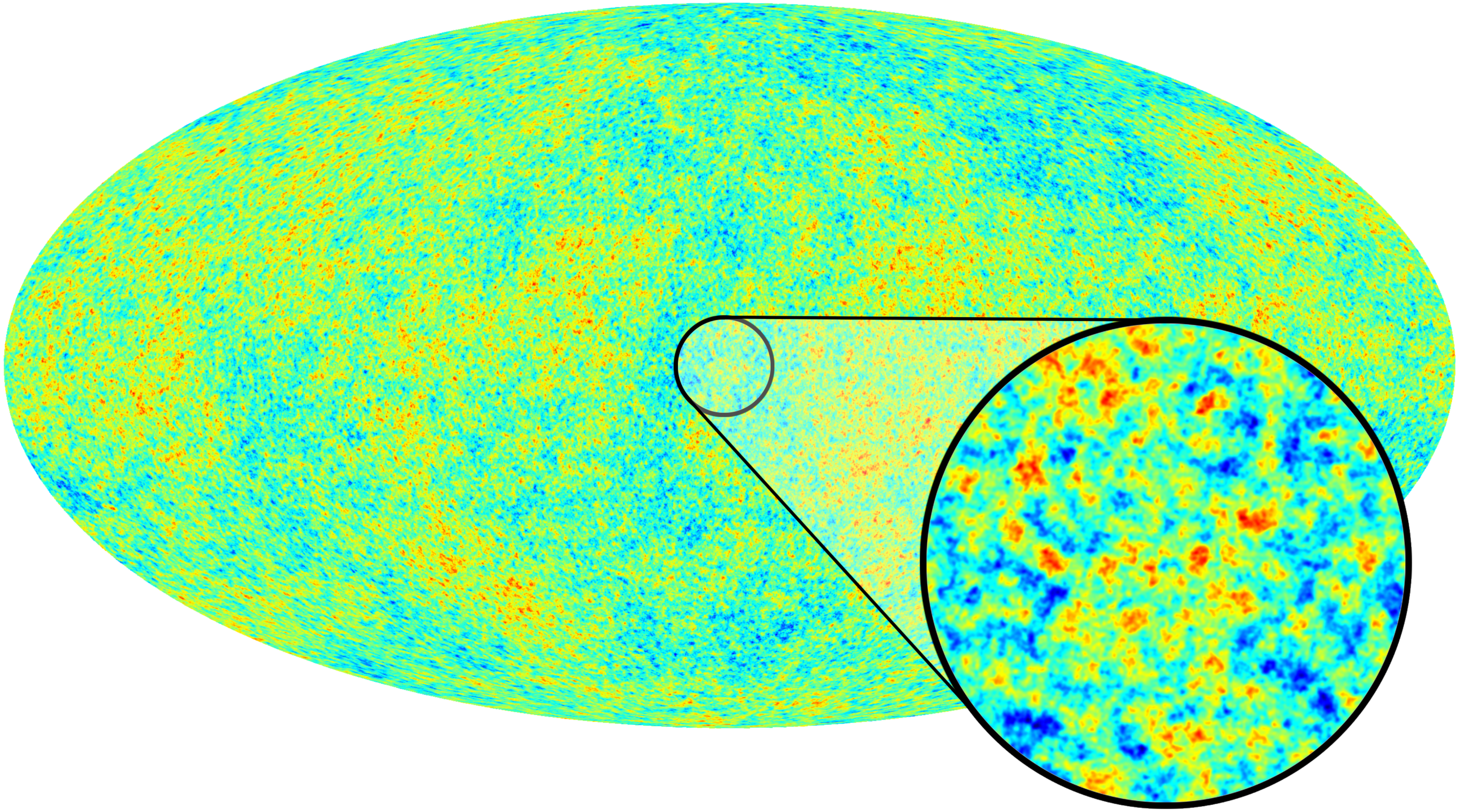
Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Precision measurement cosmological parameters

Inflation and the CMB

Inflation and the CMB

What we see is a snap-shot of the sound waves

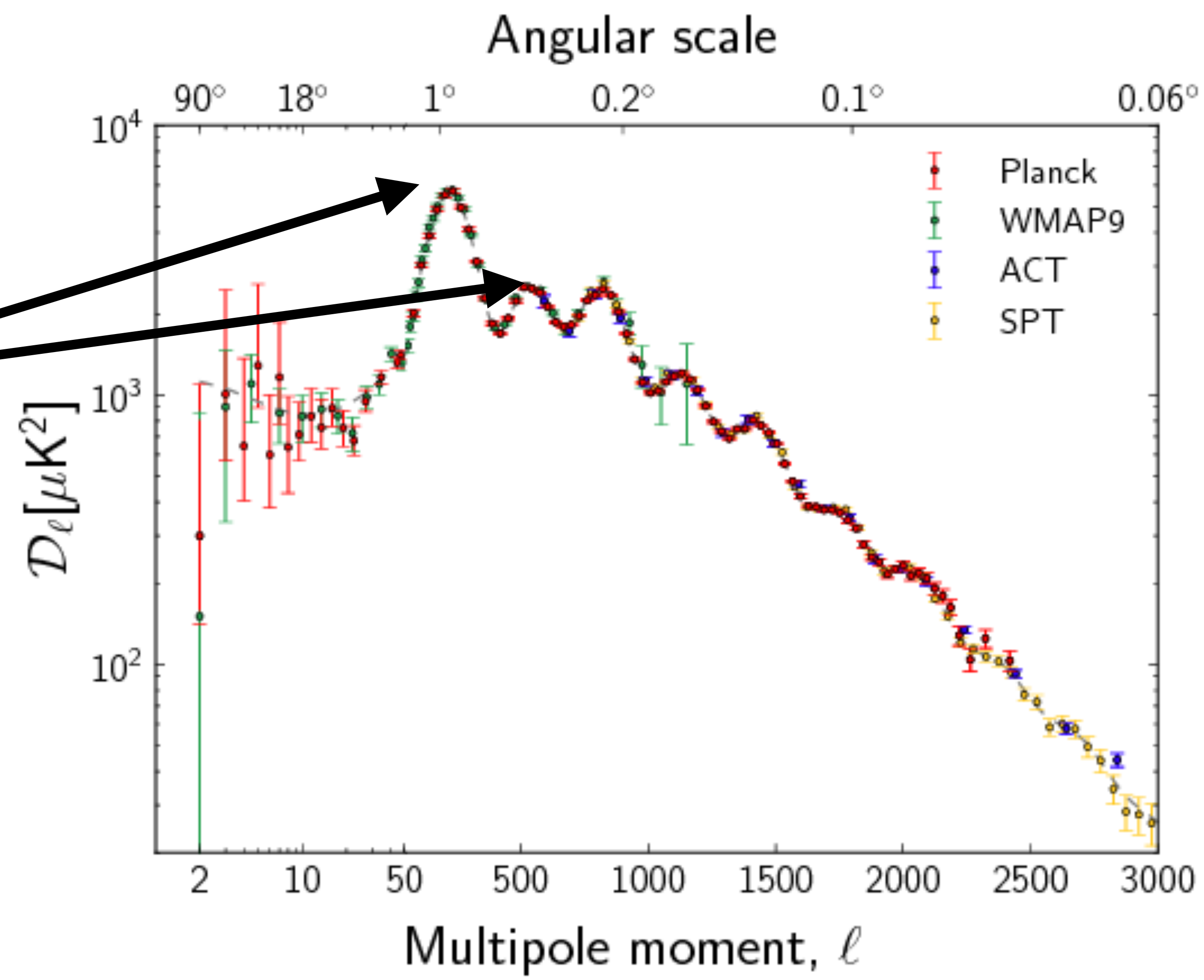


Inflation and the CMB

Acoustic peaks show that they are in-phase

$$\frac{\delta T}{T} \sim A_{\vec{k}} \cos(k r_s)$$

$$r_s = \int^{a_\star} \frac{da}{a^2 H} \frac{1}{\sqrt{3(1 + R_b(a))}}$$



Phase coherence is a stringent requirement of CMB

The CMB and Inflation

Any local source will have arbitrary phases

$$\frac{\delta T}{T} \sim A_k \cos kr_s + B_k \sin kr_s$$

Observed power spectrum requires $B_k = 0$

However, if mode existed outside the "horizon"

$$\frac{k}{aH} \ll 1 \rightarrow B_k \propto a^{-3} \rightarrow 0$$

Phase coherence "prove" modes are super-horizon

The CMB and Inflation

In a decelerating universe, this is hard to achieve

$$\partial_t(aH) = \ddot{a} < 0$$

Physical wavelengths only decrease w.r.t Hubble

Two options：

（1） Non-local production of fluctuations

（2） Change the matter content of the universe

What is Inflation?

A definition:

1. A period of quasi-dS expansion Guth

$$\frac{\dot{H}}{H^2} \ll 1$$

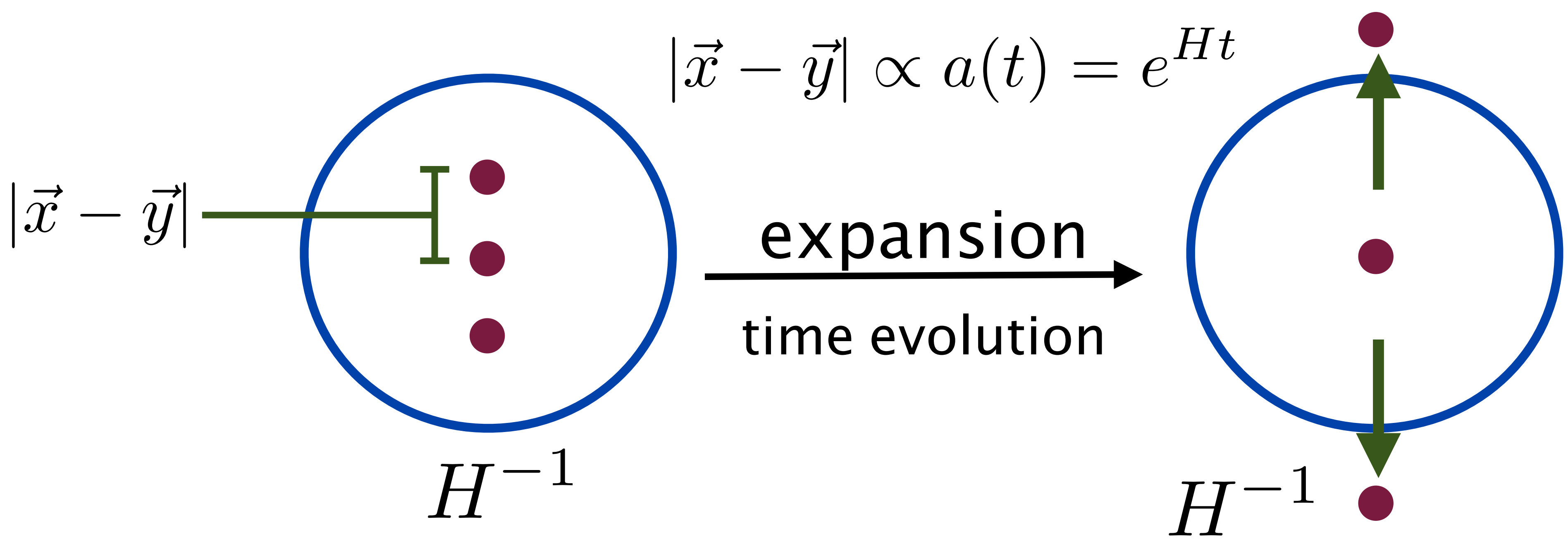
During inflation, fluctuations stretched

$$a \sim a_0 e^{Ht} \qquad \frac{k}{aH} \to 0$$

Long wavelengths evolve from short wavelengths

What is Inflation?

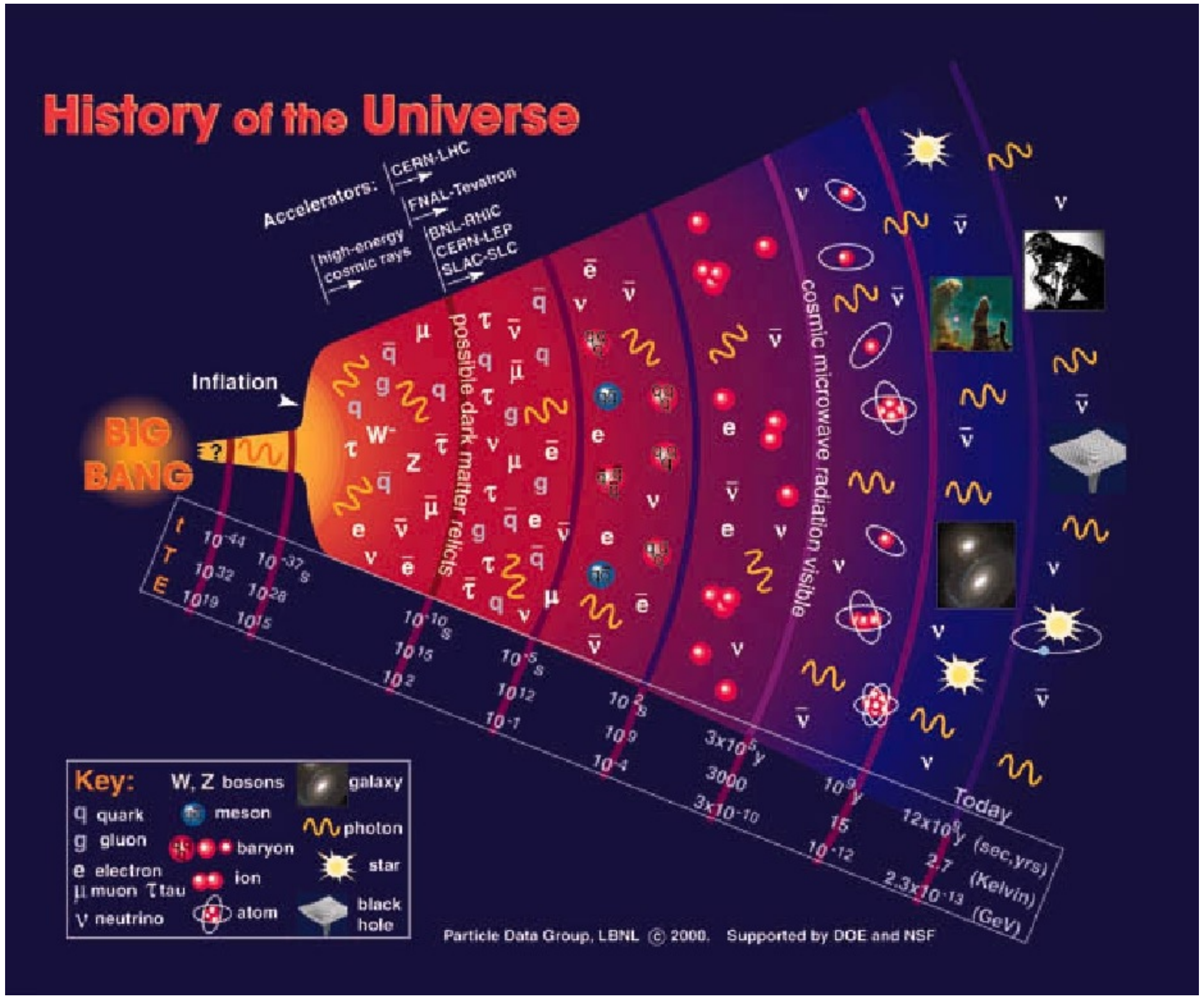
Production of fluctuations can be local



Even a cosmological constant has this effect

What is Inflation?

Inflation also requires that the phase ends



We must get the hot “big bang” eventually

What is Inflation?

A definition:

2. A physical clock

Linde; Albrecht & Steinhardt

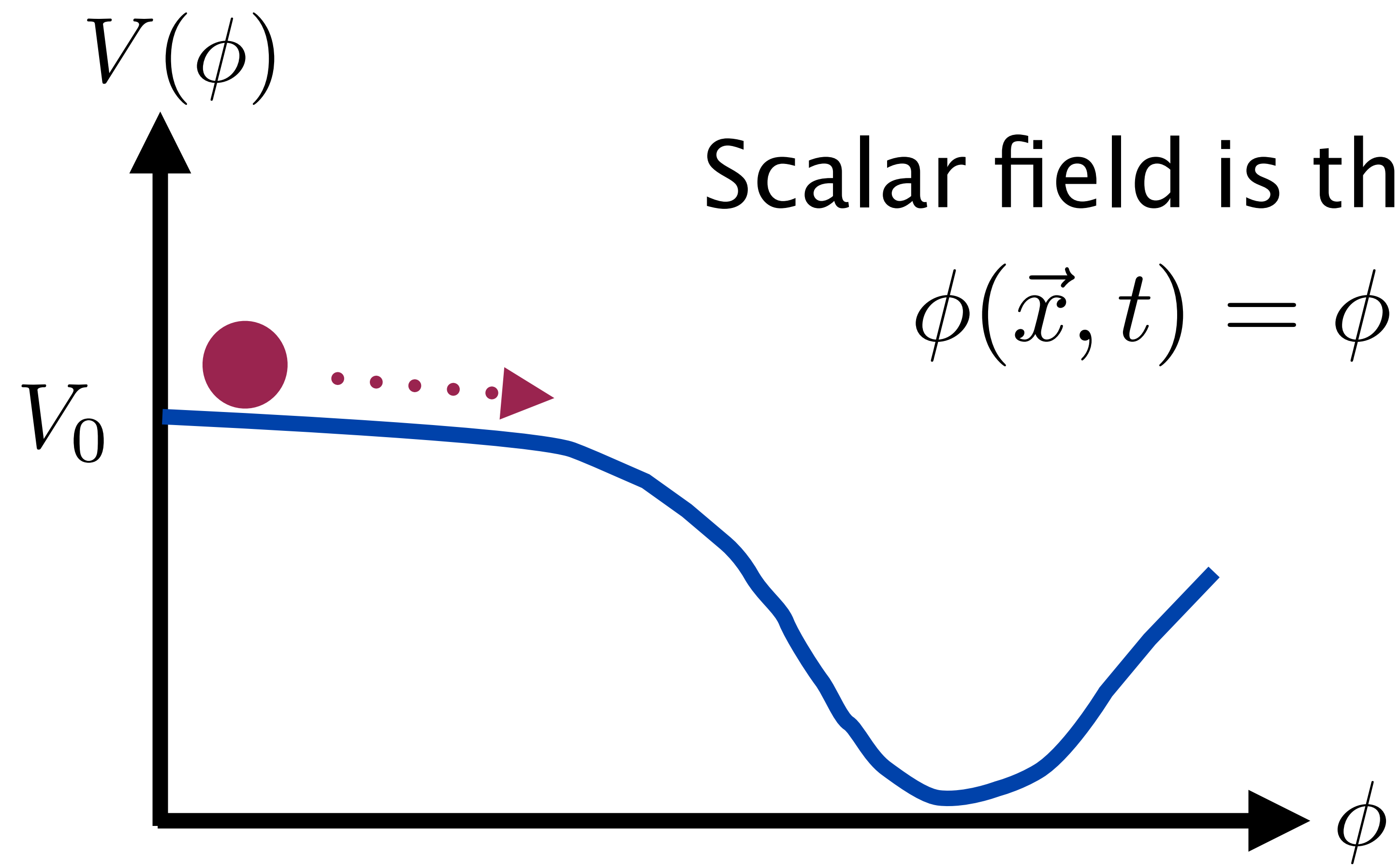
"End of inflation" needs a physical definition

Inflation must end everywhere at the same "time"

Different regions synched their clocks in the past

What is Inflation?

Slow-roll Inflation



Scalar field is the clock

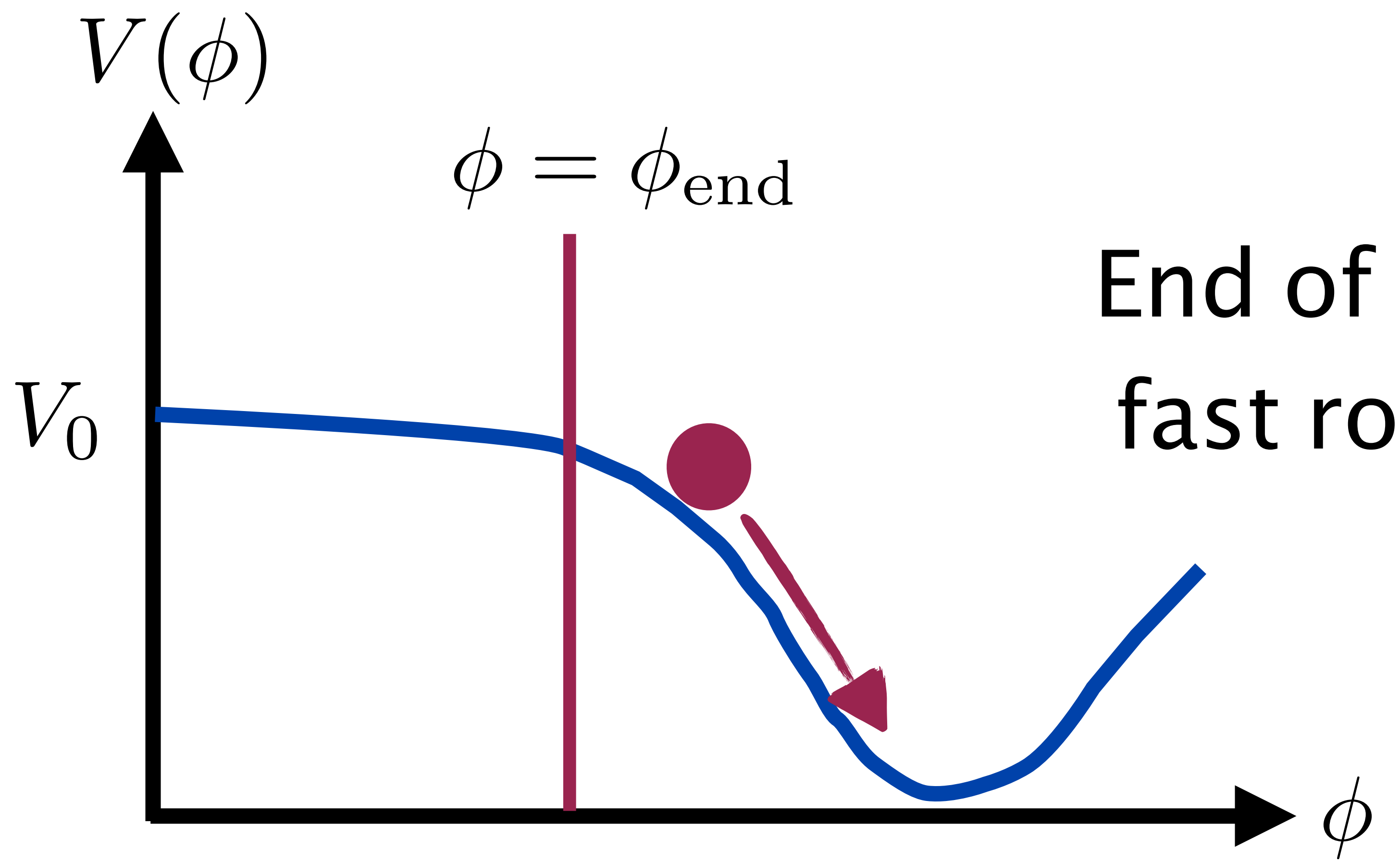
$$\phi(\vec{x}, t) = \phi(t)$$

$$H^2 \propto \frac{1}{2}\dot{\phi}^2 + V(\phi) \sim V_0$$

Slow-roll = Potential energy dominates

What is Inflation?

Slow-roll Inflation



End of inflation: fast roll begins

End of inflation defined by value of field

Afterwards, energy converted to radiation

What is Inflation?

No clock is perfect (uncertainty principle)

The amount of inflation will vary from place to place:

$$\zeta(x) \sim \frac{\delta a(x)}{a} \sim \frac{\dot{a}\delta t(x)}{a} \equiv H\delta t$$

RMS fluctuations of the clock $\sqrt{\langle(\delta t)^2\rangle} \sim \frac{H}{f_\pi^2}$

Time between "ticks" defines an energy scale f_π

For slow-roll inflation $\delta t \sim \frac{\delta\phi}{\dot{\phi}}$ and $f_\pi^2 = \dot{\phi}$

What is Inflation?

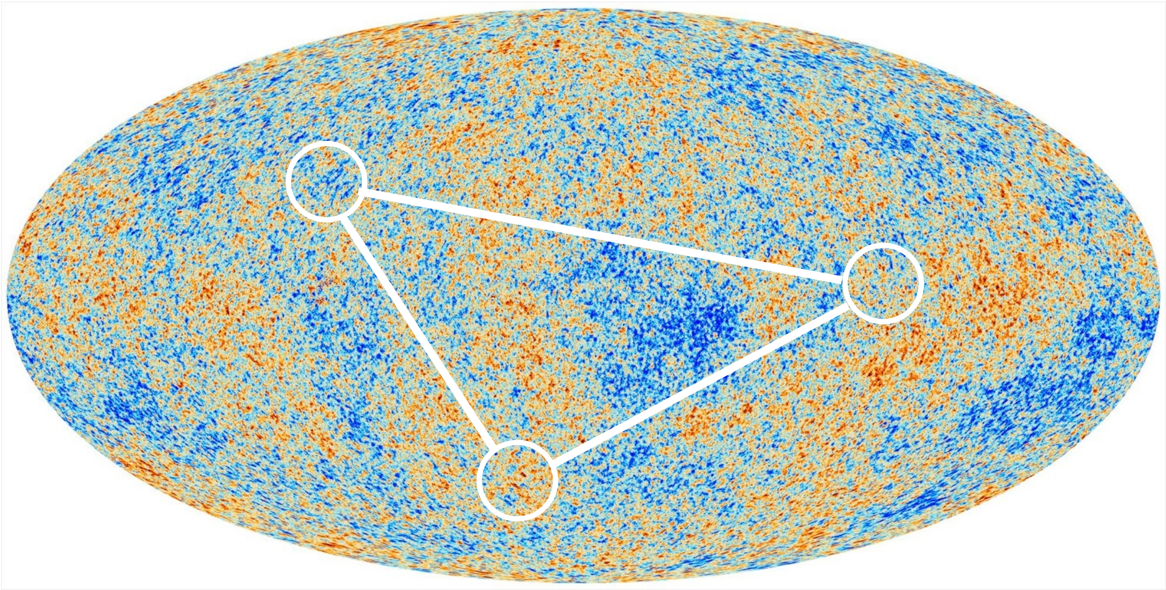
These are the adiabatic fluctuations

Determine CMB temperature fluctuations

$$\frac{\delta T(\mathbf{n})}{T} \sim \int d^3k F(\mathbf{k}\cdot\mathbf{n}, k)\zeta_{\mathbf{k}}$$

Think of

$$\langle \zeta(x_1)..\zeta(x_n)\rangle \rightarrow$$



What is Inflation?

Conditions have been formalized: EFT of Inflation

Creminelli et al.; Cheung et al.

Write a theory directly for the clock

Different models controlled by a few parameters

E.g. We may choose any $H(t)$ as long as

$$|\dot{H}| \ll H(t)^2$$

The CMB and Inflation

"Predictions" of (single-field) Inflation

On large scales:

- Homogeneous & Isotropic
- Universe is spatially flat

Density fluctuations are:

- Adiabatic (i.e. uniform in all energy densities)
- Nearly scale-invariant
- Gaussian

All of these 'predictions' are now supported by data

What is Inflation?

Raises the question: what was the clock?

We have lots of ways to make clocks

Slow-roll inflation is easiest to understand
(dynamics are very simple)

But, does the data prefer slow-roll inflation?

What is Inflation?

Raises the question: what was the clock?

Most "scalar fields" are not fundamental particles (e.g. temperature on earth)

I.e. Could the clock be an emergent phenomena, not at fundamental scalar field?

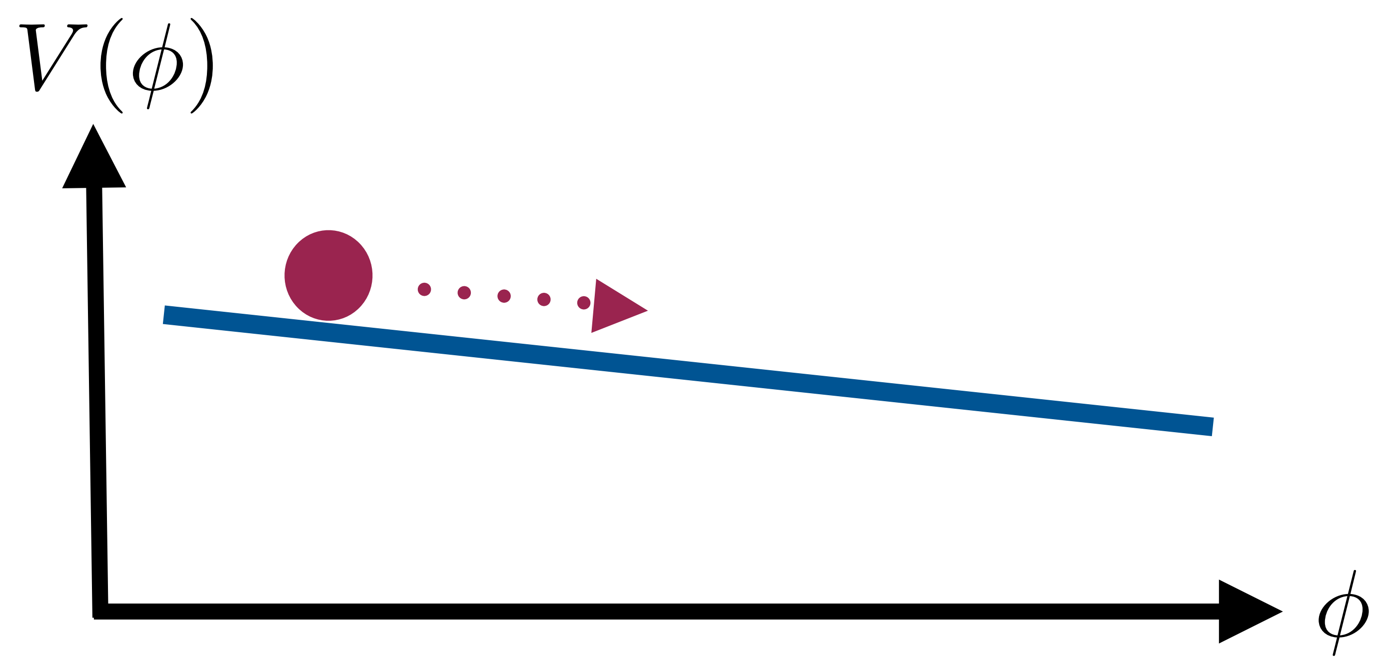
How would we tell ?

Can we rule out slow-roll?

Little non-gaussanity in (single-field) slow-roll Creminelli

Non-linearity controlled by a new scale: Λ

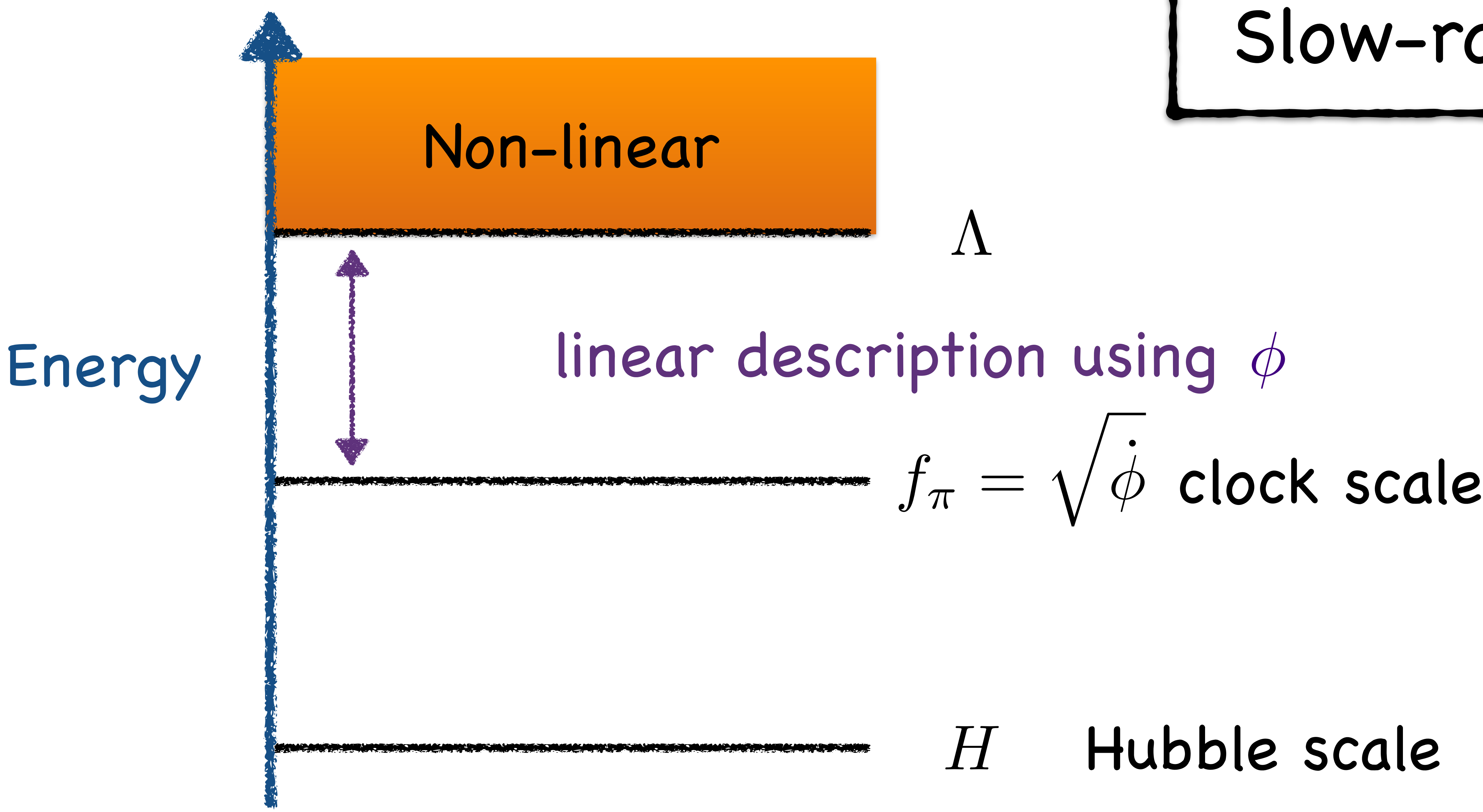
Slow-roll is very linear at energy $\dot{\phi}$



Can we rule out slow-roll?

Leads to a qualitatively picture:

Slow-roll



Can we rule out slow-roll?

This level of linearity is not necessary

E.g. K-inflation, DBI inflation,...

Armendáriz-Picón et al., Silverstein & Tong; Alishahiha et al.; ...

Non-linear kinetic energy

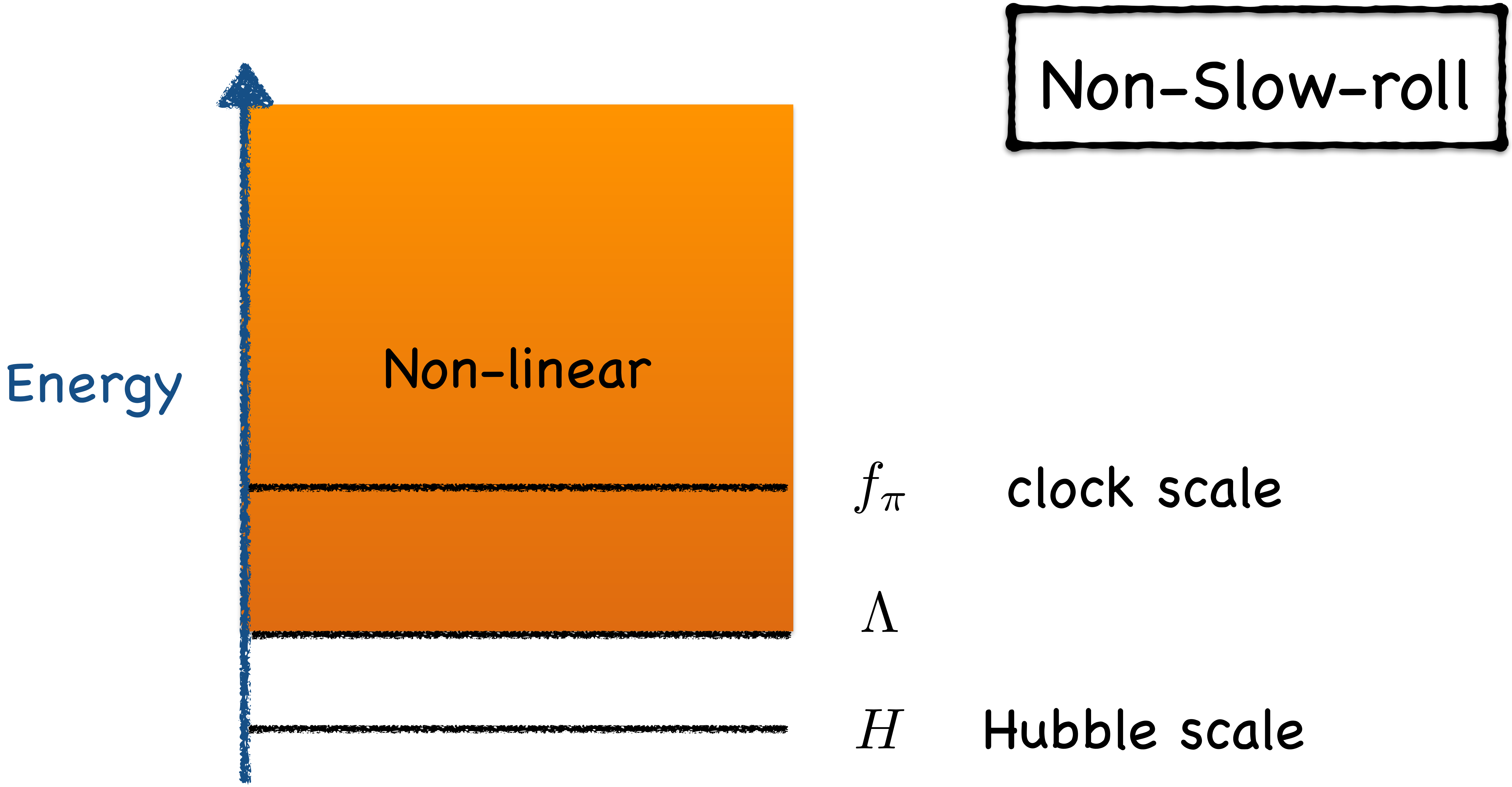
$$\text{K.E.} = F(\dot{\phi}^2) = \tfrac{1}{2}\dot{\phi}^2 + \frac{1}{\Lambda^4}\dot{\phi}^4 + \ldots$$

Not even approximately linear for $\Lambda^2 < \dot{\phi} = f_\pi^2$

Closely related to the theory of superfluids

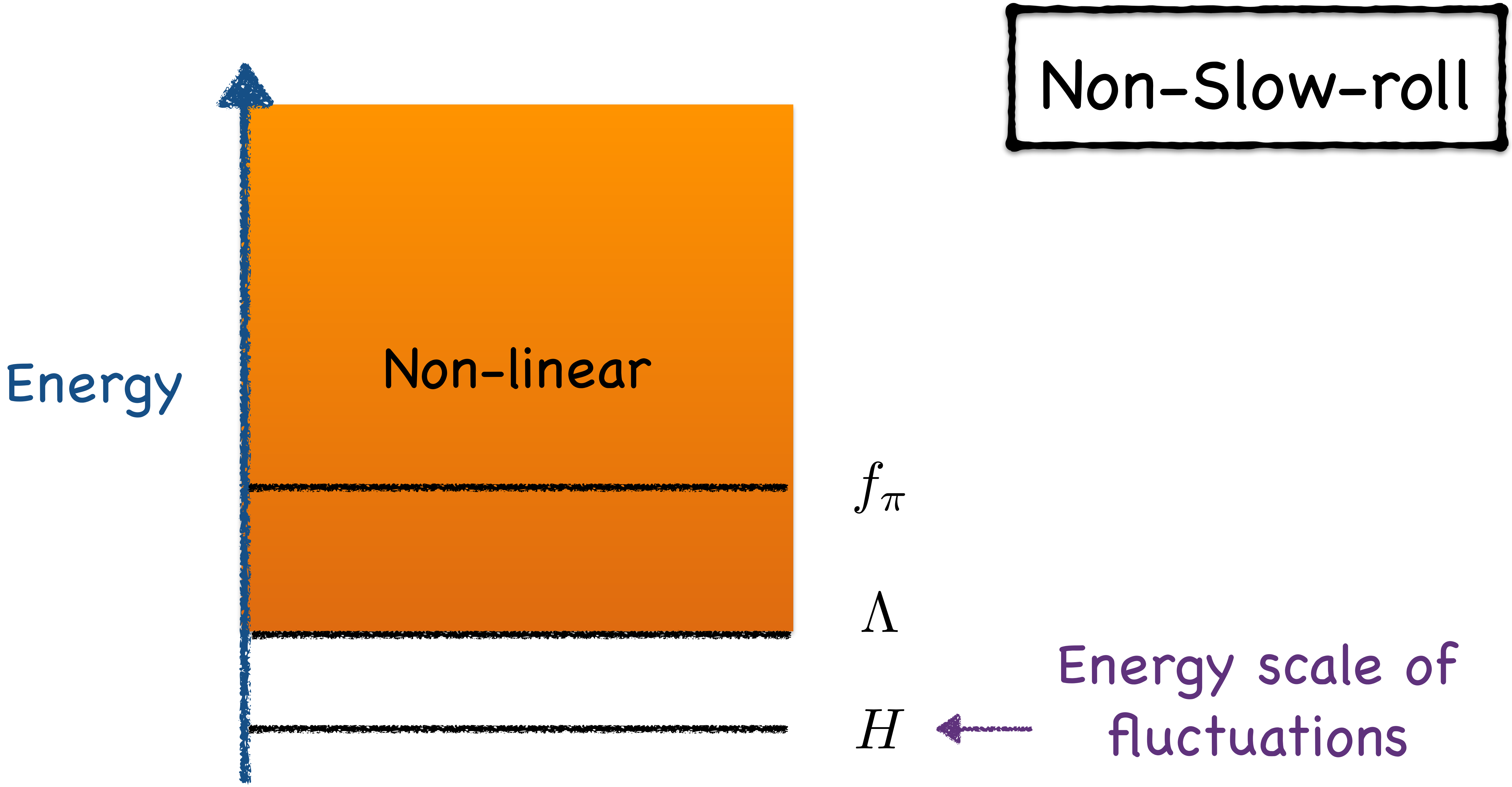
Can we rule out slow-roll?

Leads to two qualitatively different pictures: Baumann & DG



Can we rule out slow-roll?

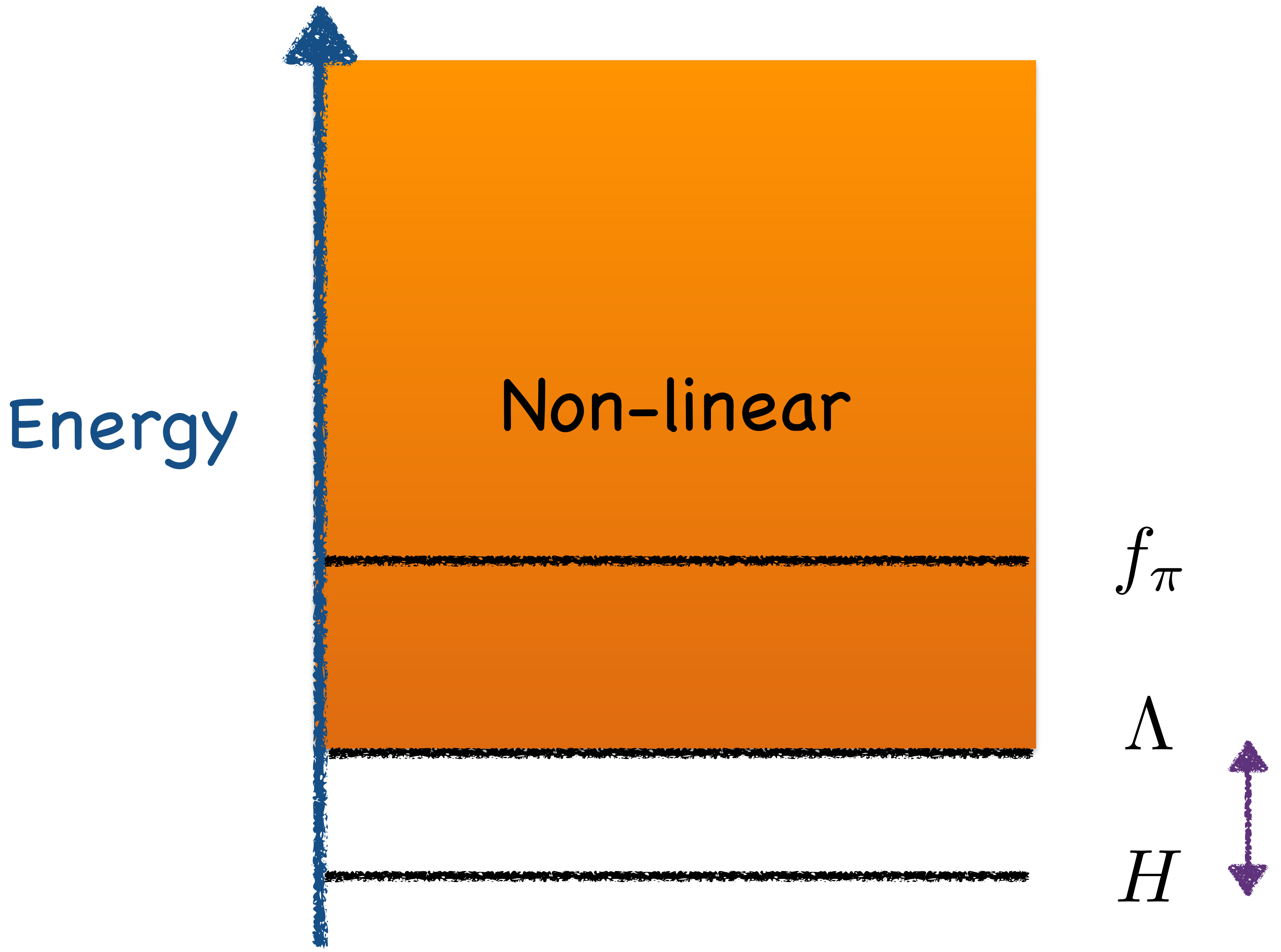
Leads to two qualitatively different pictures: Baumann & DG



Can we rule out slow-roll?

Leads to two qualitatively different pictures: Baumann & DG

Non-Slow-roll



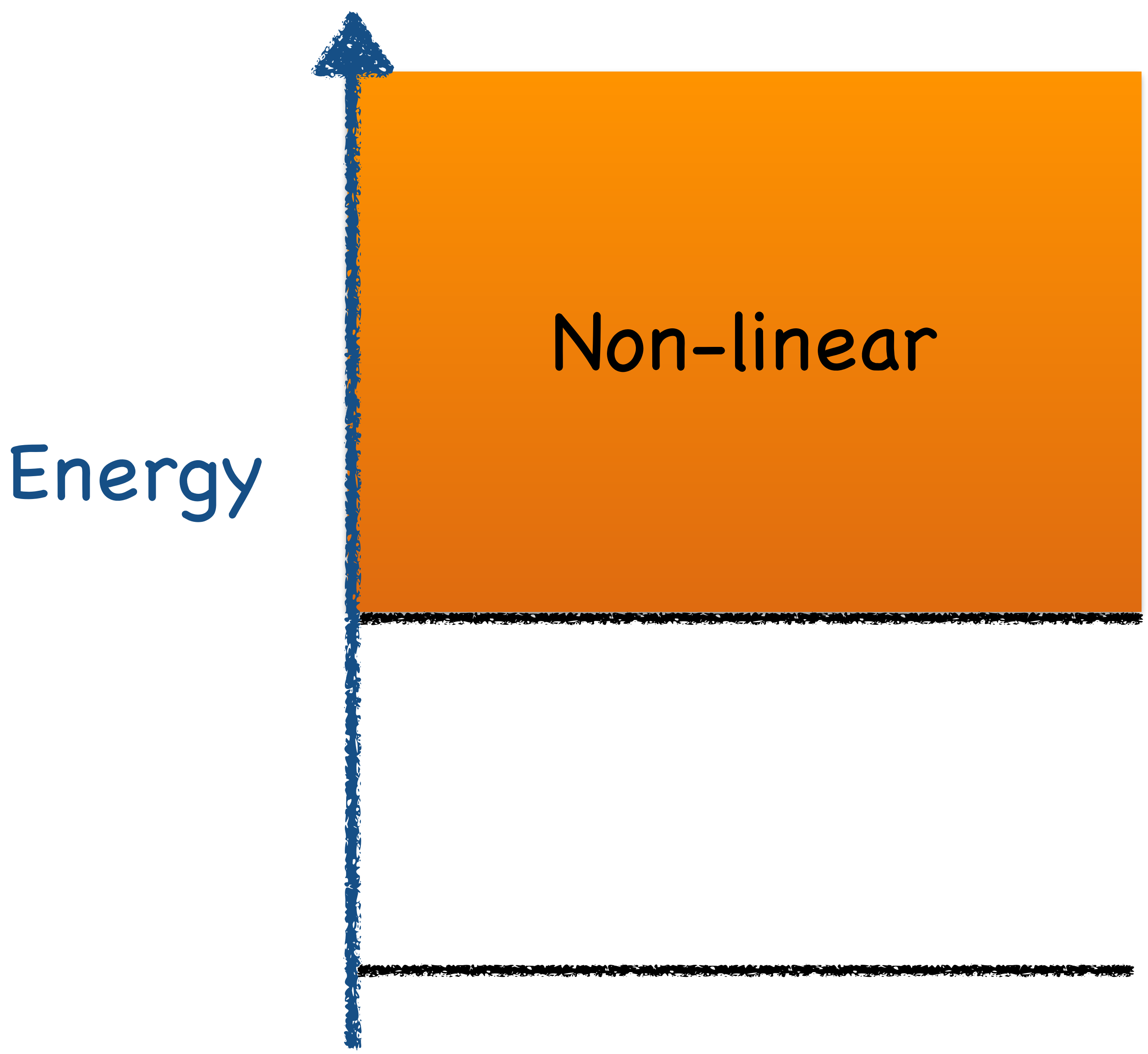
Non-linearity controlled by

$$\frac{H^2}{\Lambda^2} \ll 1$$

Can we rule out slow-roll?

Natural boundary between the pictures Baumann, DG & Porto

Boundary



$$\Lambda_\star = f_\pi$$

H Hubble scale

What do we know today?

What do we measure?

For this picture, 2 numbers matter:

1. Amplitude of the power spectrum

$$\langle \left(\frac{\delta T}{T}\right)^2 \rangle = 2.2 \times 10^{-9} \sim \frac{H^4}{f_\pi^4}$$

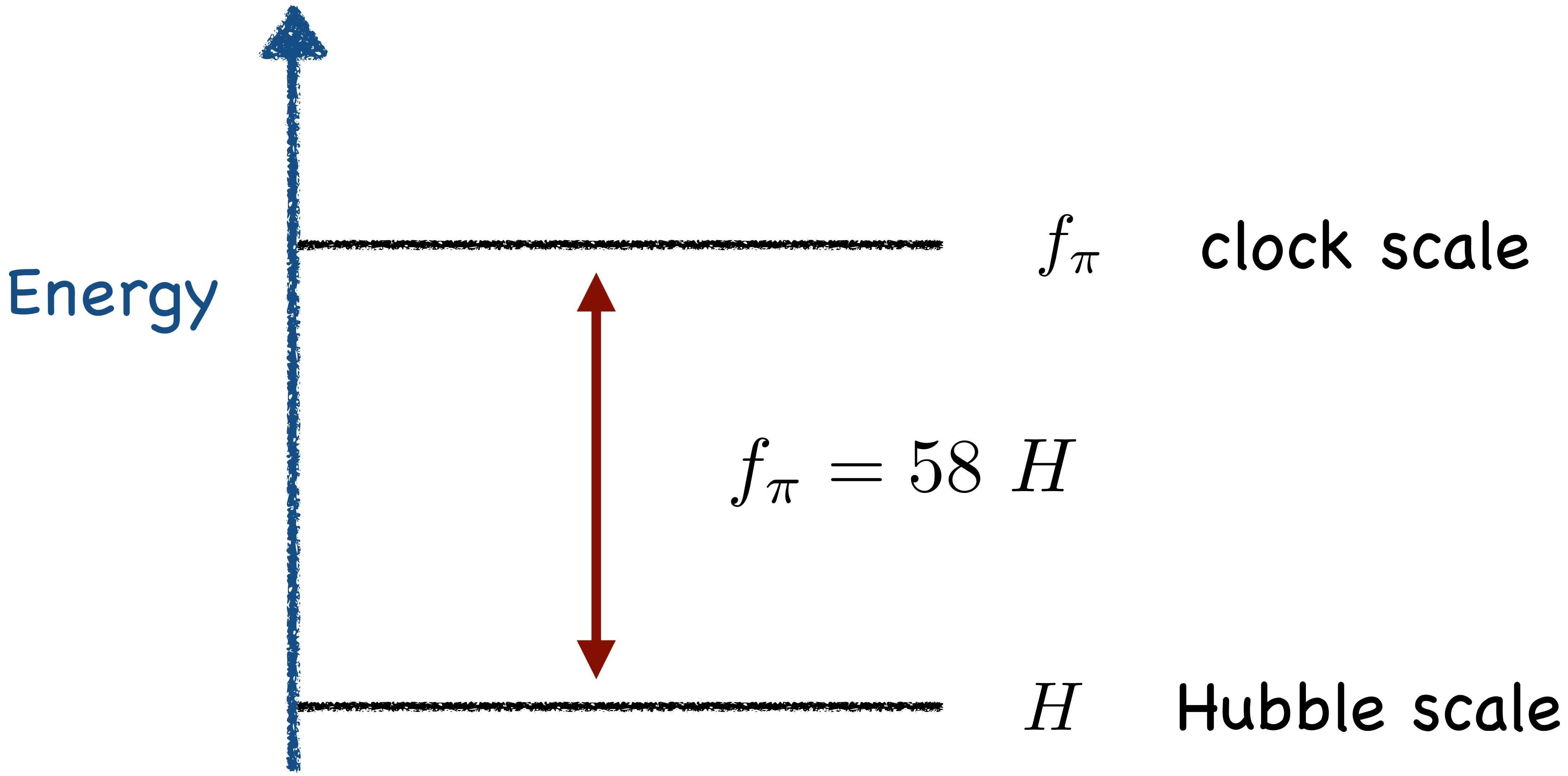
Very well measured from CMB

This fixes one ratio $f_\pi = 58\ H$

What do we measure?

For this picture, 2 numbers matter:

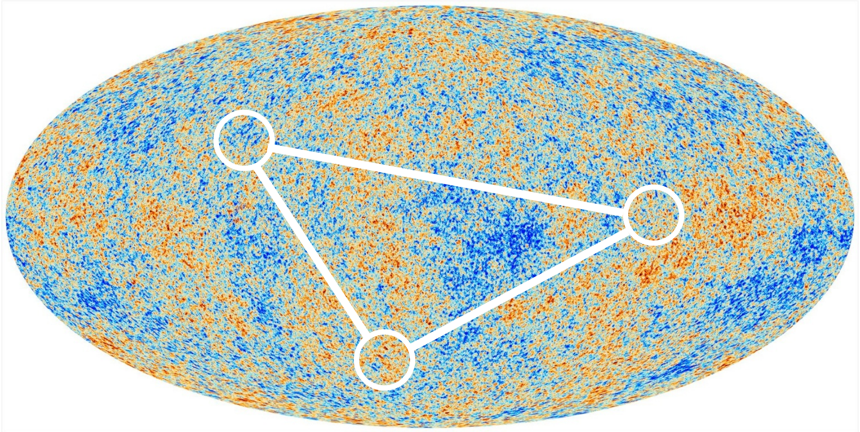
1. Amplitude of the power spectrum



What do we measure?

For this picture, 2 numbers matter:

2. Amount of non-gaussanity



Typically reported in terms of

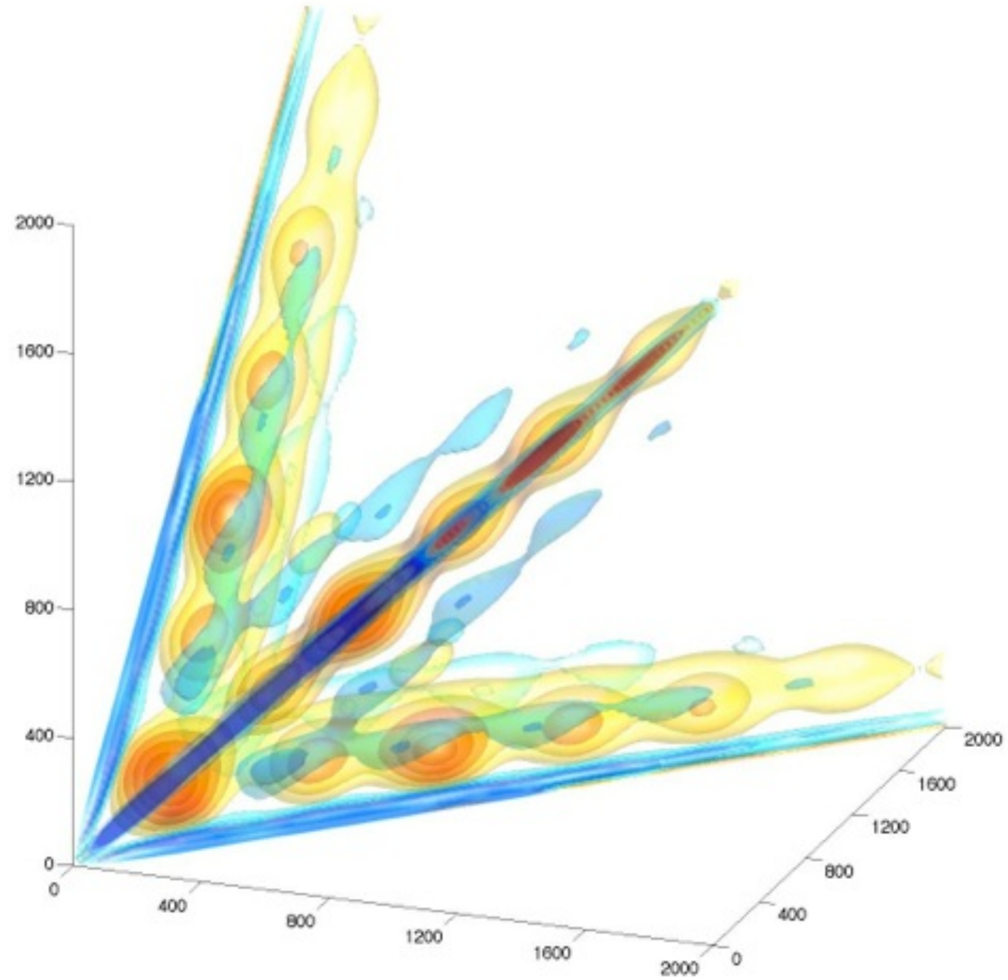
$$f_{\rm NL} \sim \frac{f_\pi^2}{\Lambda^2} \qquad \text{(or } f_{\rm NL}\zeta \sim \frac{H^2}{\Lambda^2}\text{)}$$

This is the amplitude for a bispectrum

However, there is no unique "shape" of bispectrum

Planck Limits

Planck reports limits on 3 templates:



Local

Peaked at:

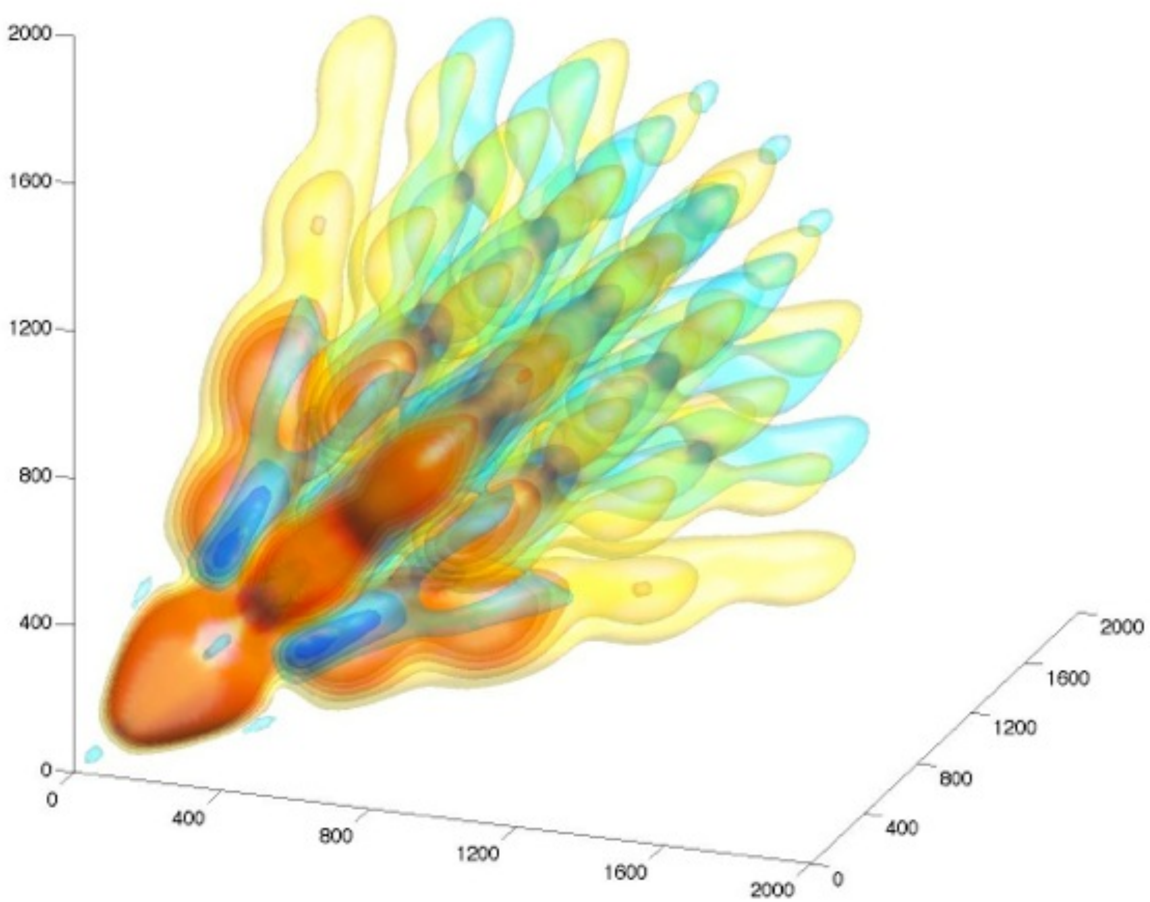
$k_1 \ll k_2 \sim k_3$

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$$ (68% C.I.)

Courtesy of Fergusson & Shellard

Planck Limits

Planck reports limits on 3 templates:



Equilateral

Peaked at:

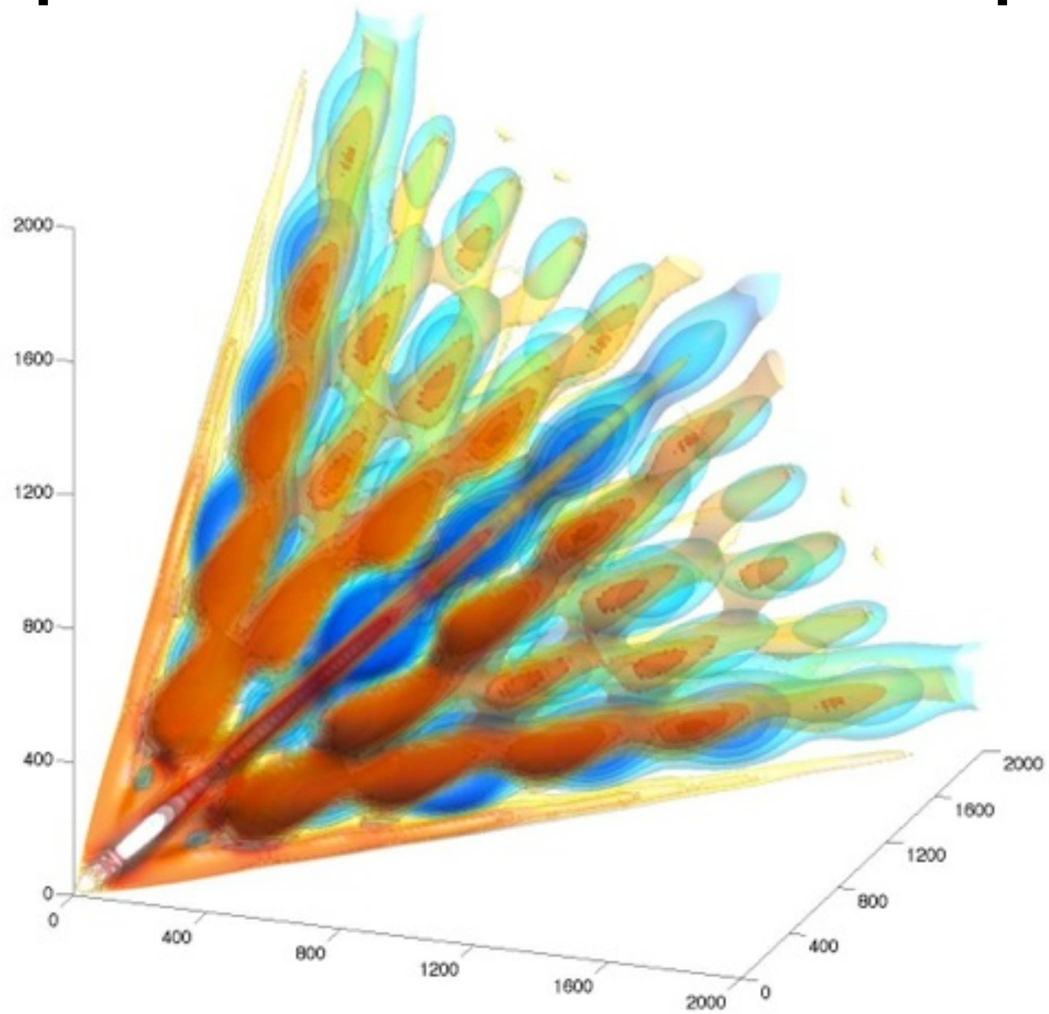
$$k_1 = k_2 = k_3$$

$$f_{\rm NL}^{\rm equil.} = -4 \pm 43$$ (68% C.I.)

Courtesy of Fergusson & Shellard

Planck Limits

Planck reports limits on 3 templates:



Orthogonal

Peaked at:

$$k_1 = k_2 = k_3$$

&

$$k_1 = k_2 = \frac{1}{2} k_3$$

$$f_{\rm NL}^{\rm ortho.} = -26 \pm 21$$ (68% C.I.)

Courtesy of Fergusson & Shellard

Planck Limits

Can be translated into lower bounds on non-linearity

For single-field, there is no "local" shape

Maldacena; Creminelli & Zaldarriaga

Equilateral and Orthogonal are related to two scales:

Planck (68 %) $\Lambda_1 > 4.5\,H$ $\Lambda_2 > 1.6\,H$

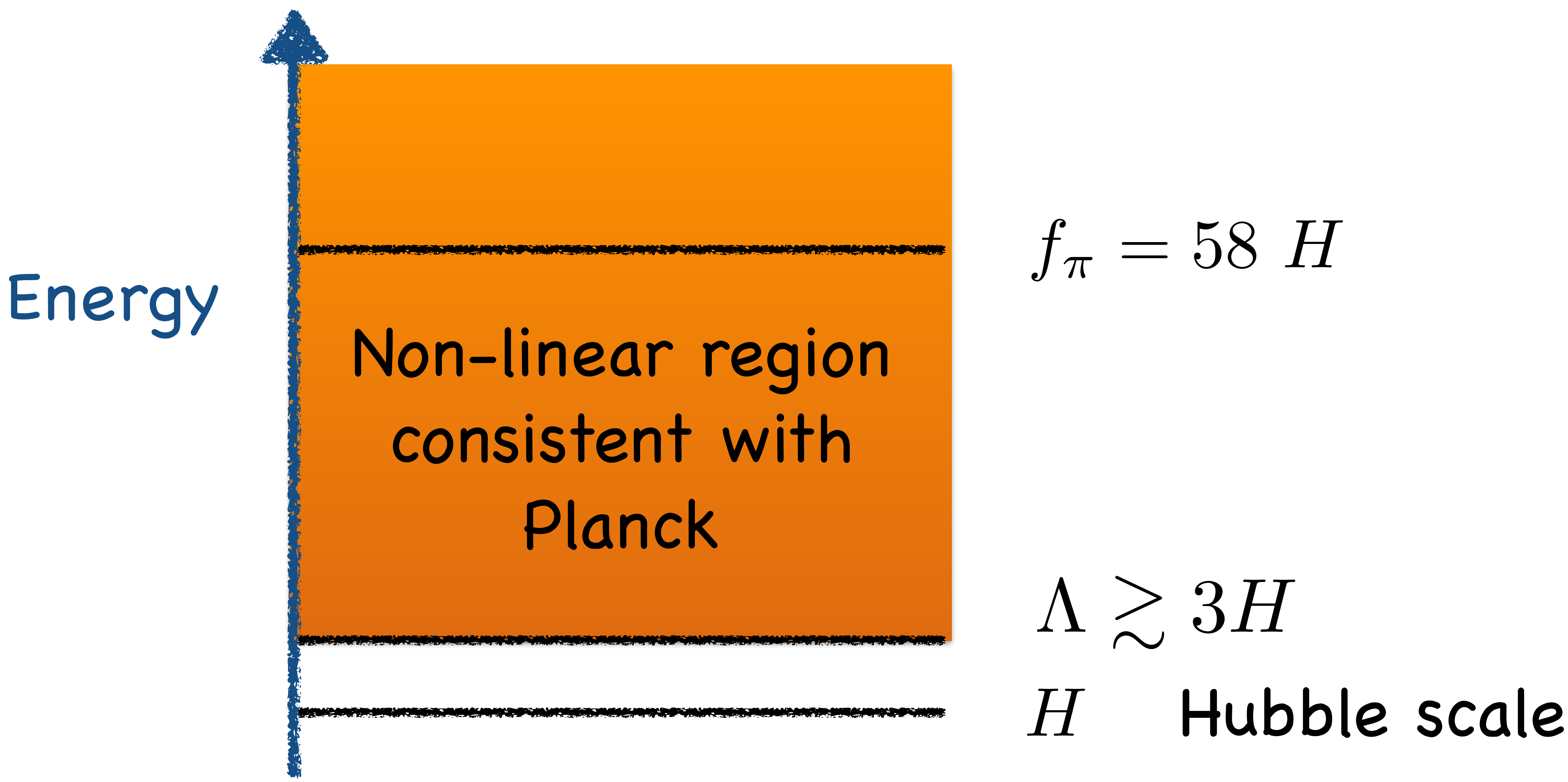
Consistent with gaussianity at 10^{-3} level

Still a weak result in terms of scales

Planck Limits

For this picture, 2 numbers matter:

2. Amount of non-gaussianity



Planck Limits

For this picture, 2 numbers matter:

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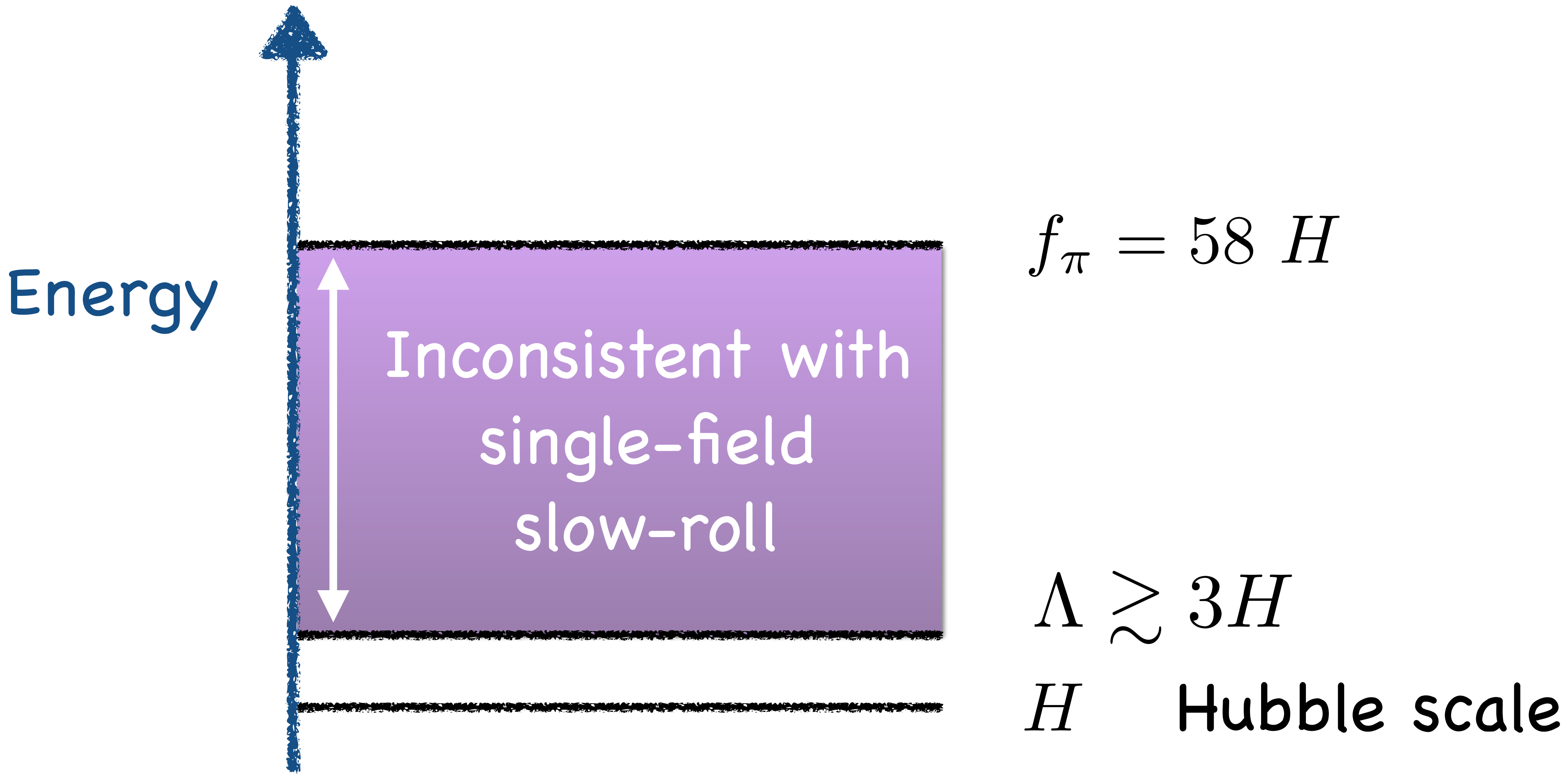
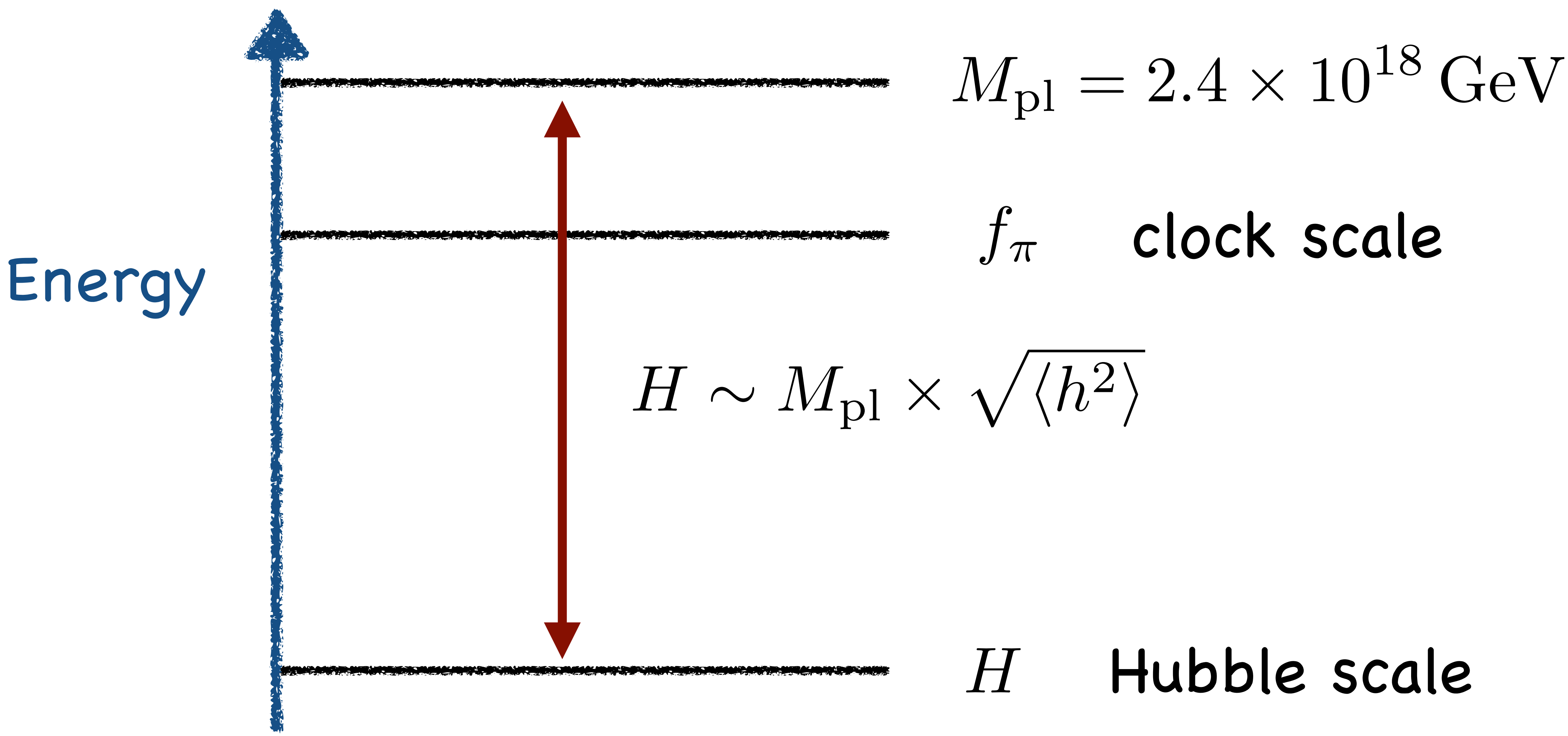


Aside: Tensor modes

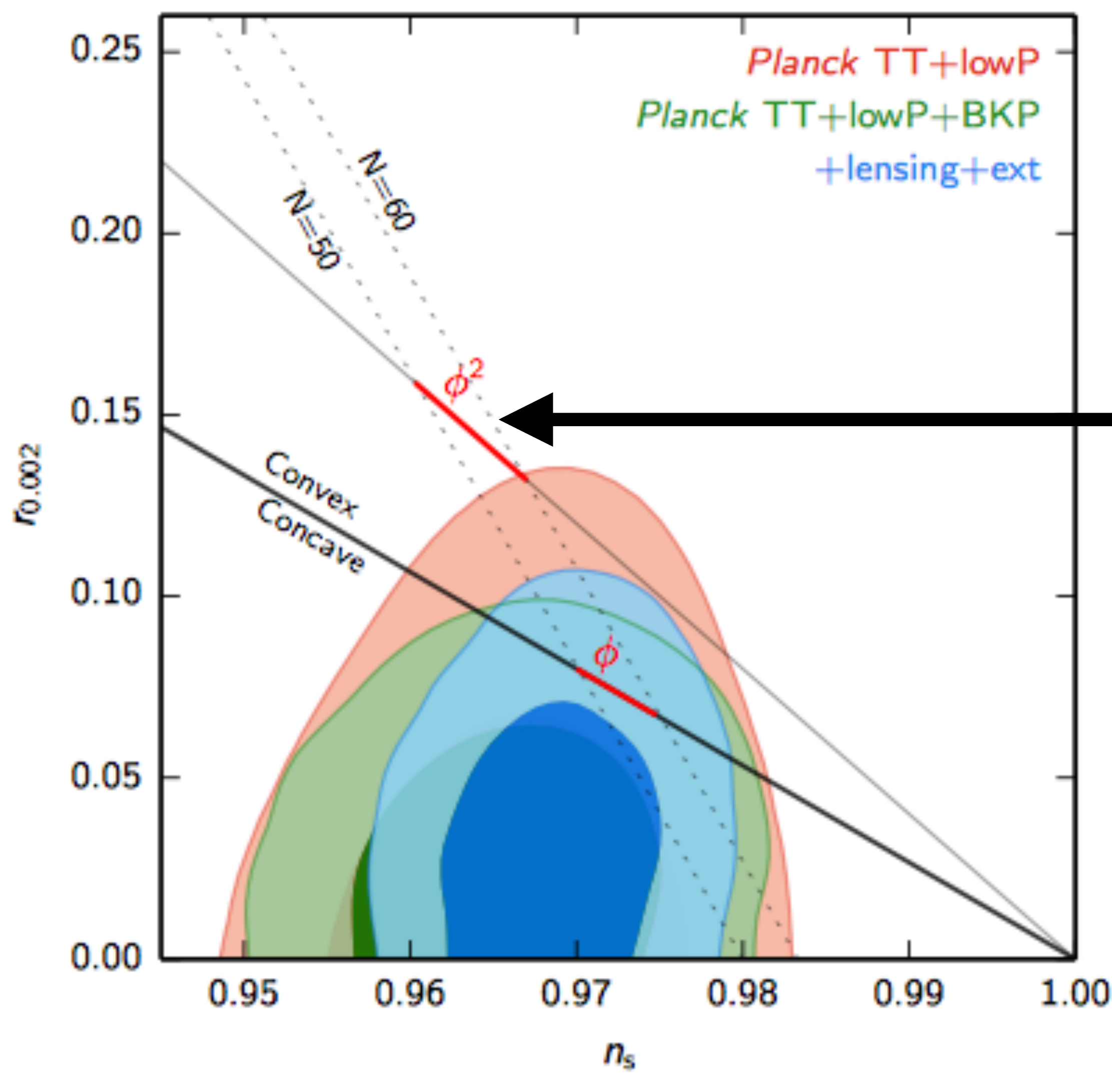
Tensors play a special role

Fixes the overall scale of Hubble



Aside: Tensor modes

Tensors have major model building implications



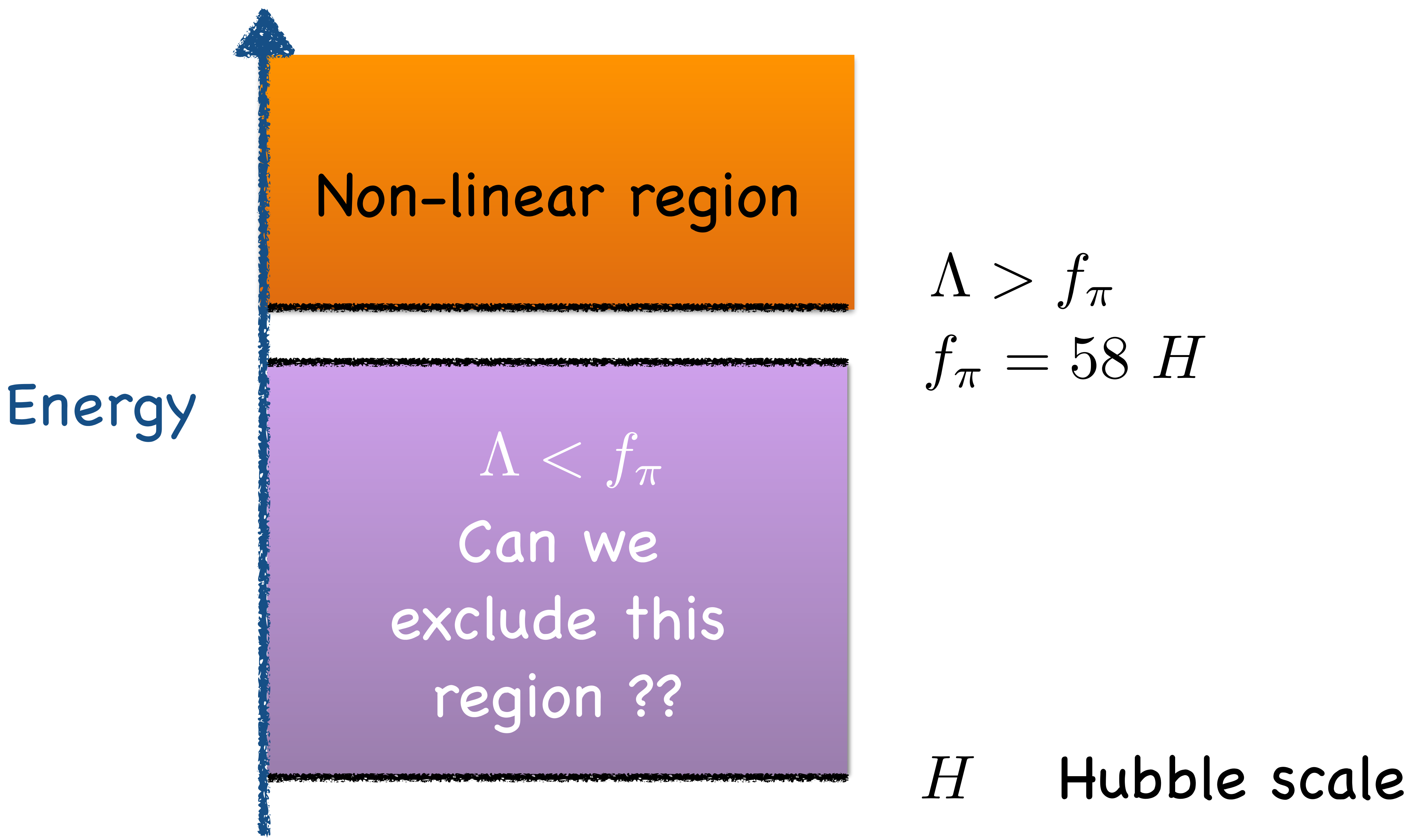
$$V(\phi) = \frac{1}{2}m^2\phi^2$$

Already a strong constraint on many popular ideas

How will we do better?

What is our goal?

One goal is to test the full non-slow-roll region



What is our goal?

One goal is to test the full non-slow-roll region

In terms of measurable parameters we need

$$f_{\rm NL}^{\rm equilateral} < 1 \ (2\sigma)$$

Best limit today is $\Delta f_{\rm NL}^{\rm equilateral} = 84 \ (2\sigma)$

WMAP to Planck (2015) was a factor of 4 improvement

How do we get there?

The brute force approach is to find more "modes"

When each bin is cosmic variance limited

$$\Delta f_{\mathrm{NL}} \sim \frac{10^5}{\sqrt{N_{\mathrm{modes}}}}$$

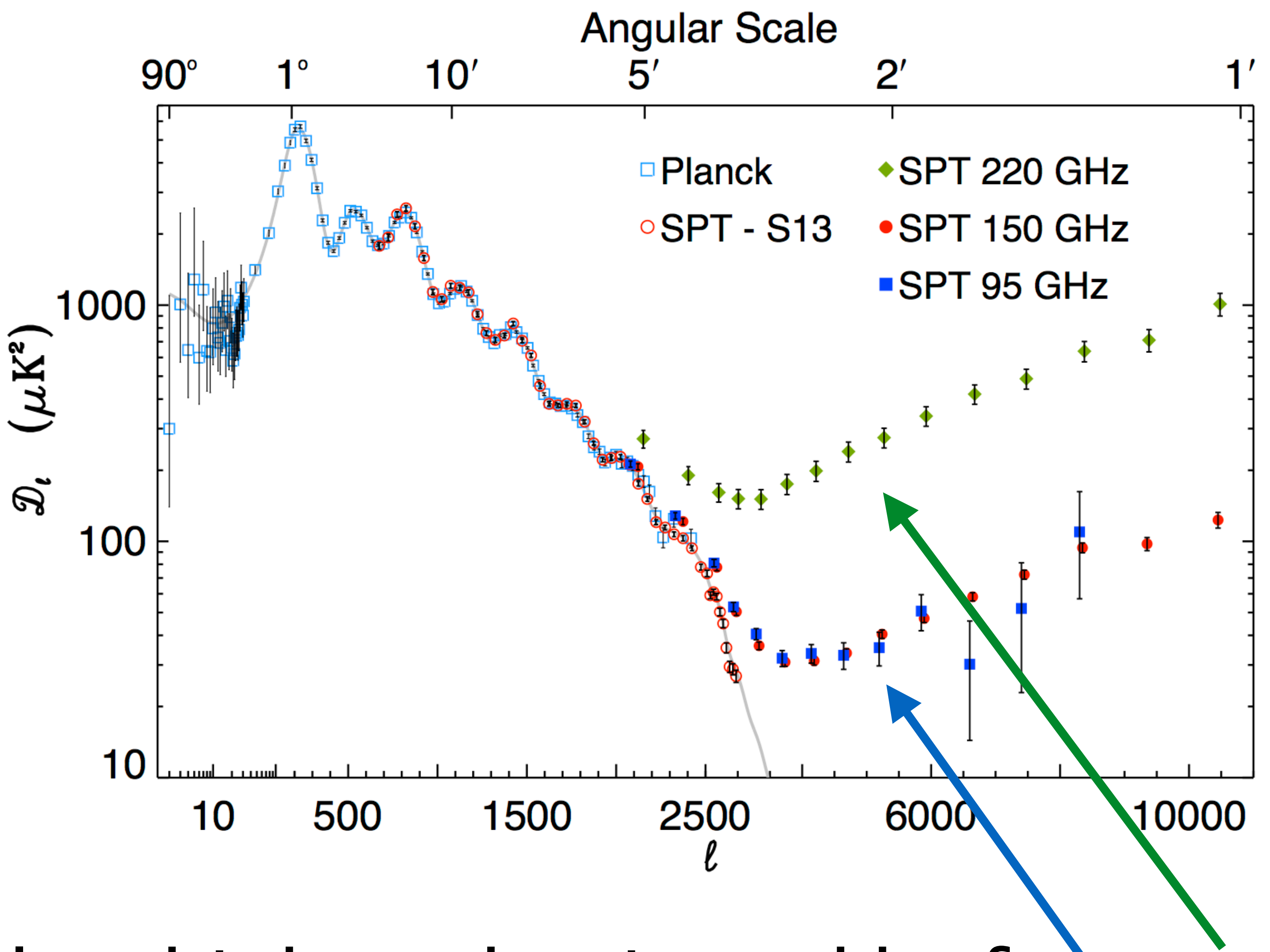
E.g. From Planck we get roughly

$$N_{\mathrm{modes,Planck}} \sim \ell_{\mathrm{max}}^2 \sim 2 \times 10^6$$

To improve by 10^2 we will need 10^{10} modes!

How do we get there?

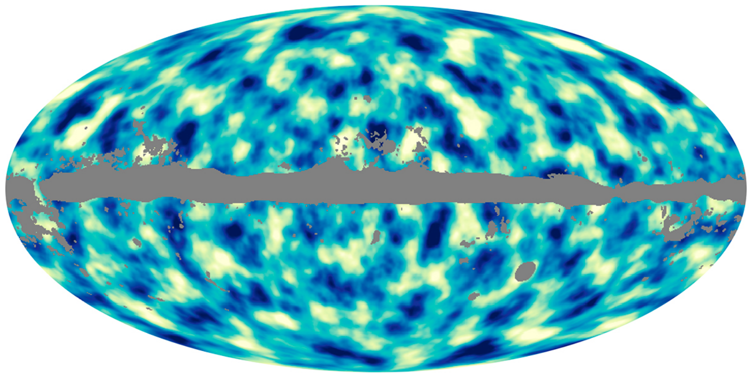
There aren't many more modes in the CMB

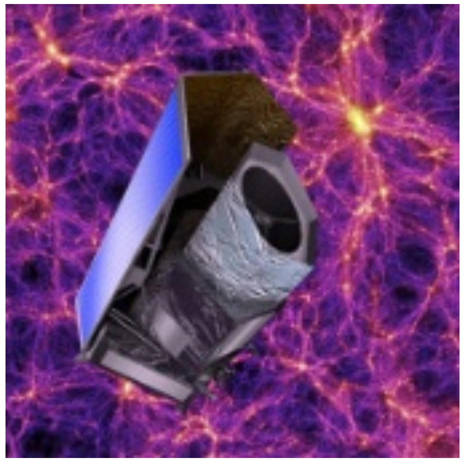


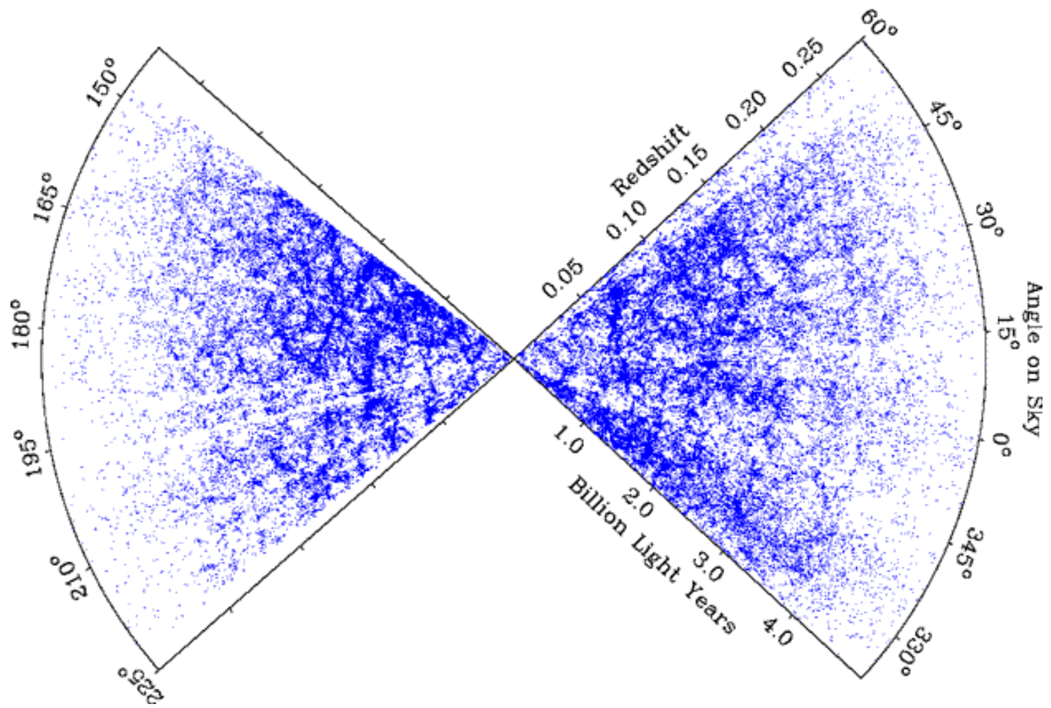
Small scales (high ℓ) dominated by foregrounds

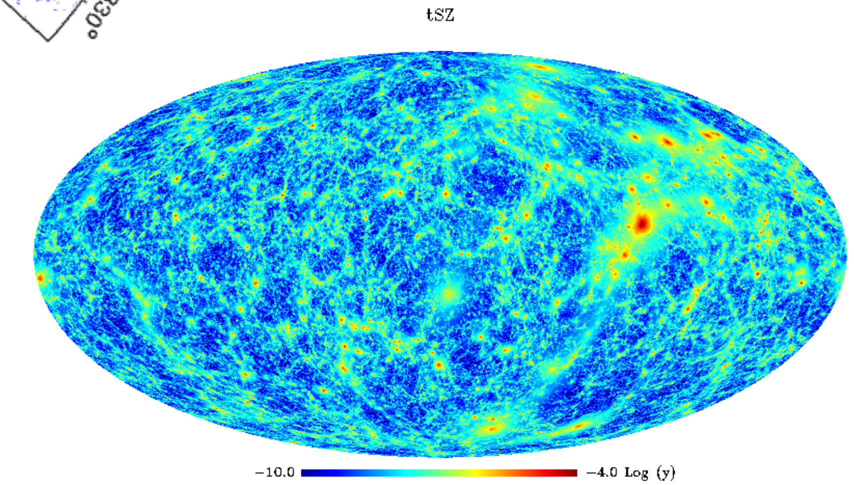
Large Scale Structure

Future will be dominated by Large Scale Structure









Large Scale Structure

Future will be dominated by Large Scale Structure

Basic advantage is that there are a lot more modes!

Reason 1 : LSS is 3d versus 2d CMB

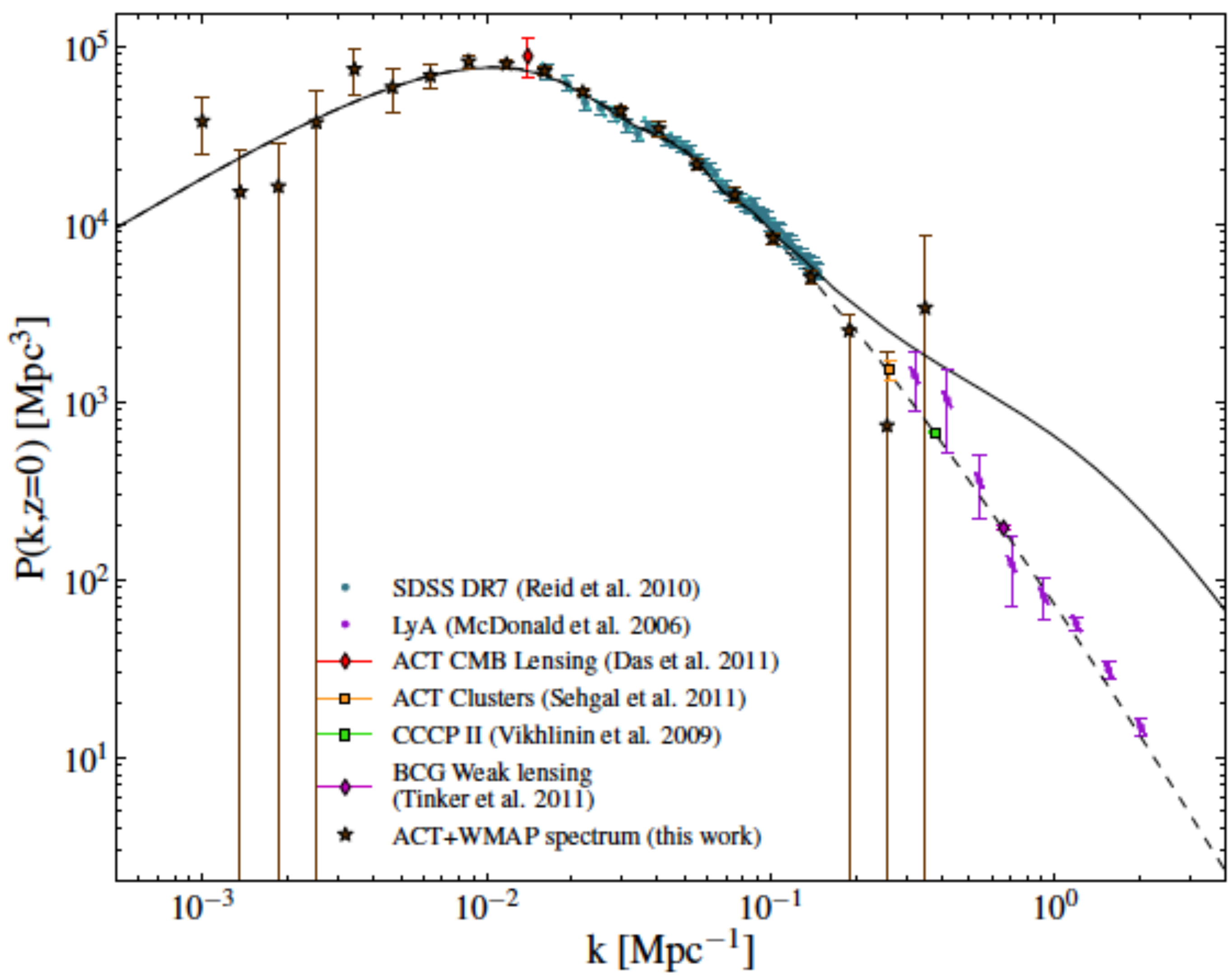
For same range of scales $N_{\rm modes} \sim 10^9$

Reason 2 : Large range of scales

Total number of linear modes $N_{\rm modes} \sim 10^{18}$

Large Scale Structure

CMB



$$N_{\rm modes}^{\rm CMB} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^2$$

$$N_{\rm modes}^{\rm LSS} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^3$$

Linear regime of LSS

Figure from Hlozek et al.

Large Scale Structure

LSS faces many new challenges

To take advantage of 3d modes we need:

- Very accurate redshifts
- Good model for galaxy formation
- Control of many many new systematics

For these (and other) reasons, no one has actually performed the analysis that will be needed

Summary

Summary

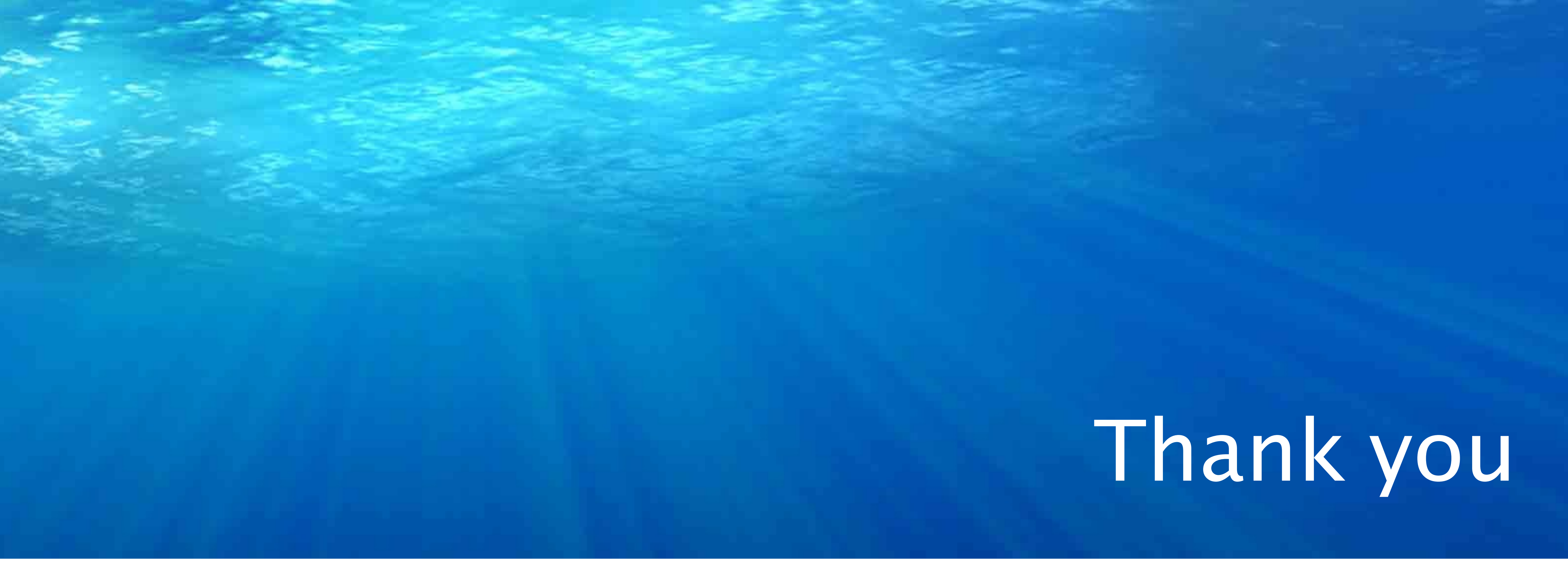
Inflation covers a lot more than slow-roll

Ultimately data should decide the correct picture

CMB data today is inconclusive

Large Scale Structure surveys are poised to overtake the CMB in raw sensitivity

CMB will remain vital through search for tensors
(and as a probe of the LSS between us and the CMB)



Thank you