Ripples in the Cosmos

presented by

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Prologue: Beside a river

Imagine that you are waking beside a river on a rainy day, casting pebbles into the water

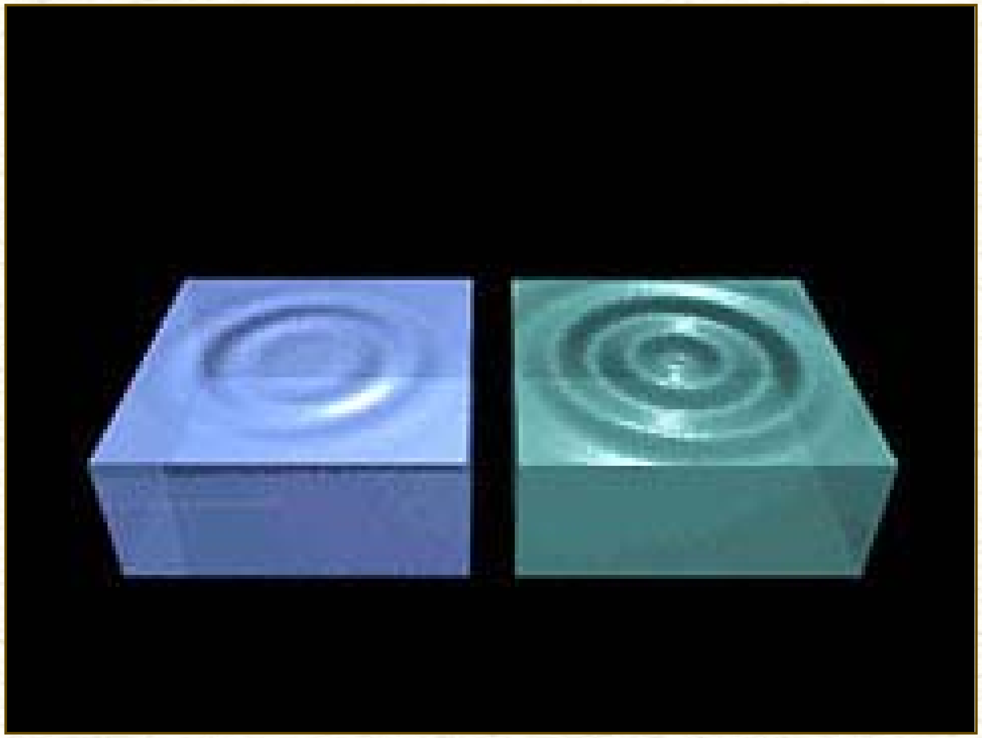
Why to the ripples appear as they do?

Two things fix the pattern of ripples

- initial disturbance (the pebble)
- fluid’s reaction (the water)

The ripples tell us much

- both about the stream & the pebbles



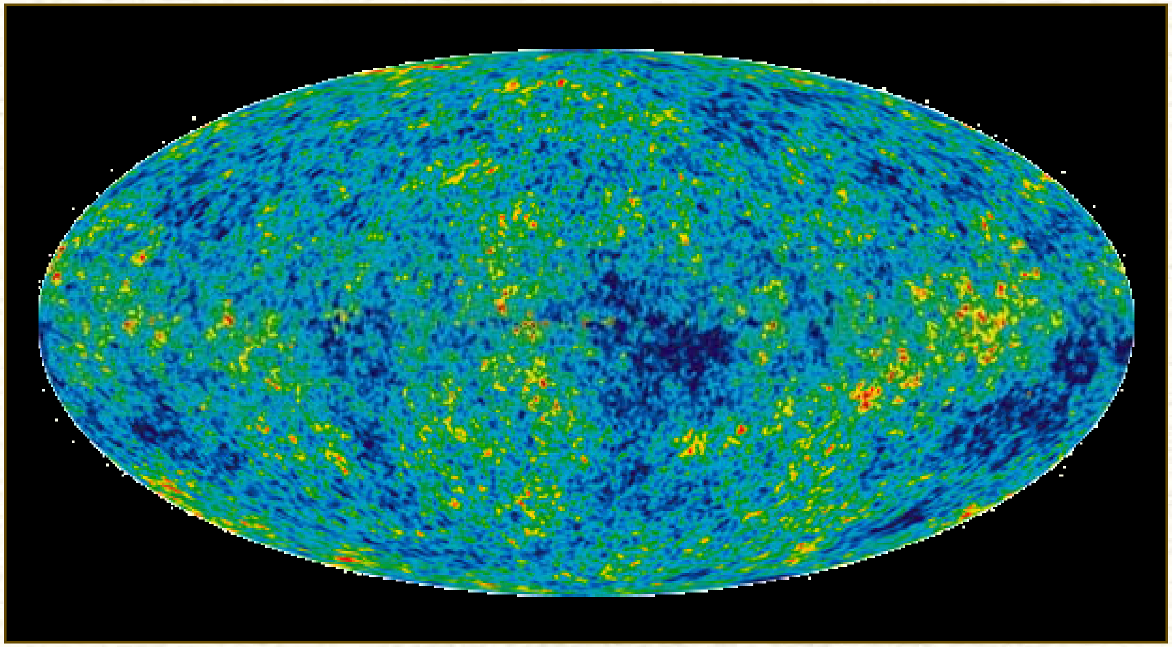
With just a picture of the surface,
the troughs and crests

What could you learn about

The Medium
(density/viscosity/etc.)

The Initial Disturbance
(pebbles/raindrops/etc.)

We shall study here the beautiful pattern of ripples in the faint radiation that comes from an early epoch of our universe



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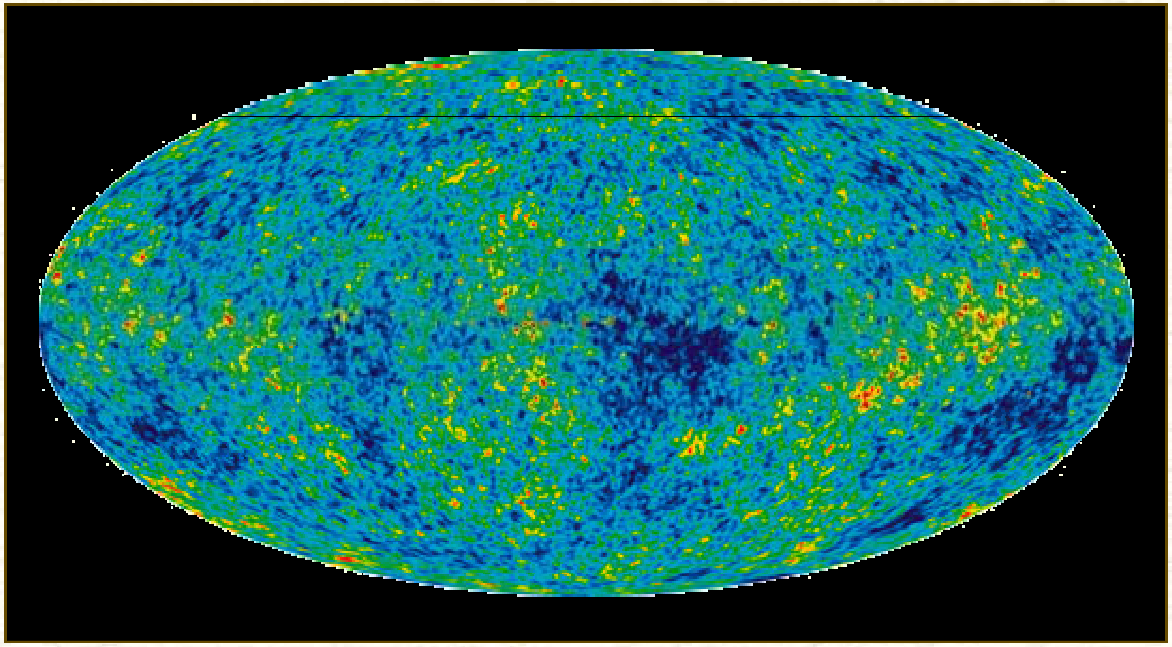


We focus on the initial disturbances

- what do we know about them
- how do we know
- what further secrets can be uncovered

Inflation: { quantum fluctuations / accelerated expansion }

Overview:

- the cosmic microwave background
- inflation and generating structure
- QFT and the trans-Planckian problem
- observations, speculations & conclusions

The cosmic microwave background (CMB)

Snapshots from the life of a universe

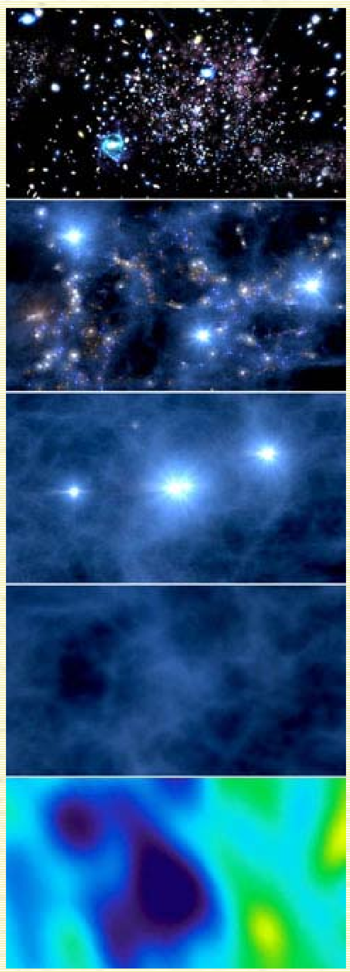
Maturity
(ca. today)

Middle age
(ca. 10 Gyrs ago)

Young adult
(ca. 13.3 Gyrs ago)

Adolescence
(ca. 13.5 Gyrs ago)

Childhood
(ca. 13.7 Gyrs ago)
1/1000th as big as today



Looking backwards in time:

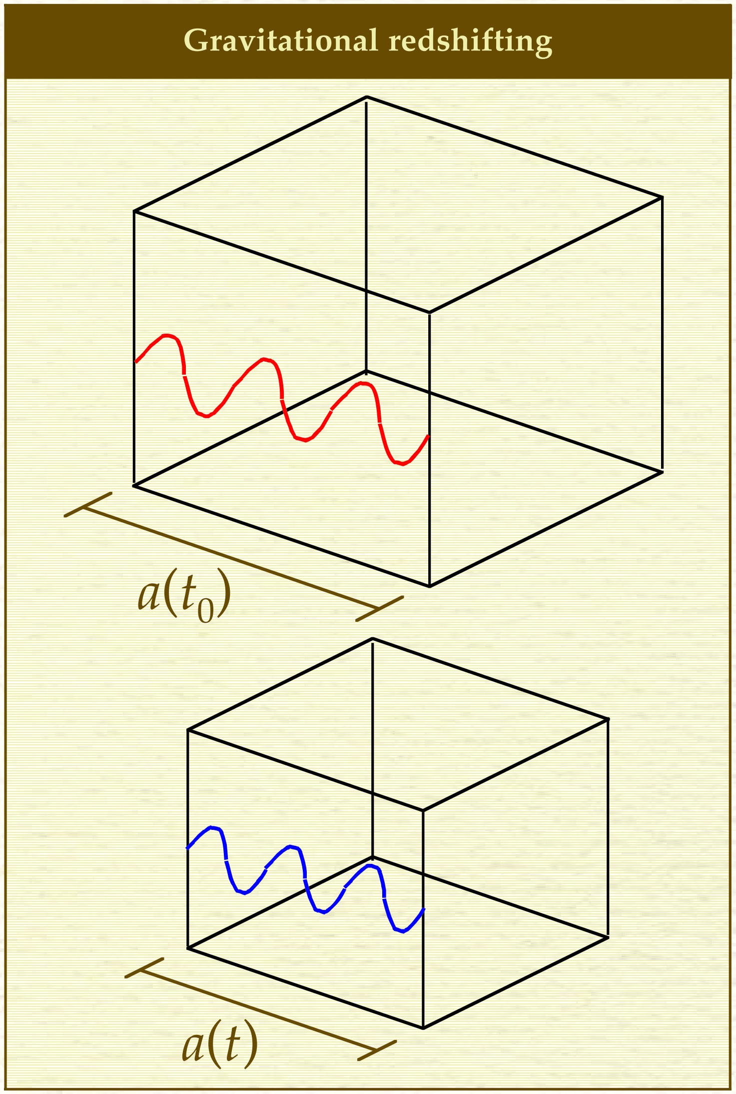
- lumps of stuff were smoother
- the universe was denser & hotter

Far enough back: a turning point:

- the universe was hot and dense enough to form an opaque plasma

(recombination/last scattering)

The cosmic microwave background (CMB)



Experimental prediction!

There is faint relic glow left from when

hot plasma (opaque)	→ → →	neutral gas (transparent)

This faint glow is the CMB

- redshifted to microwave wavelengths

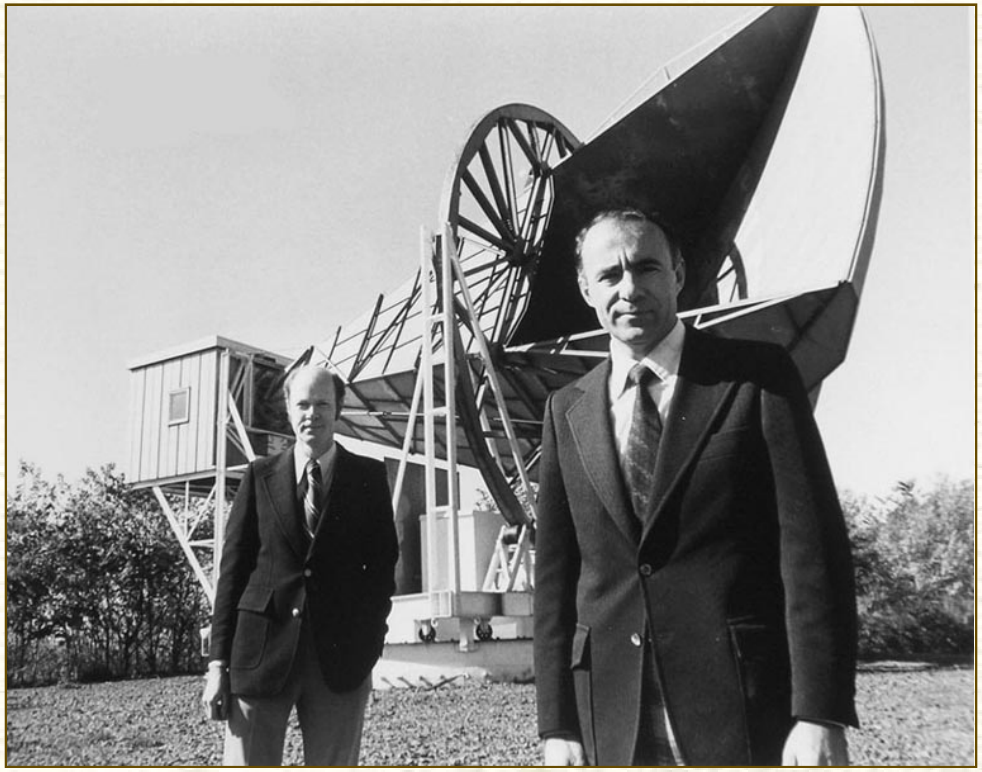
Introduce a scale factor $a(t)$

$a(t)$ = how much lengths change with time

Light gets stretched by the space-time:

$$\lambda(t) \propto \frac{1}{a(t)}$$

Discovery of the CMB

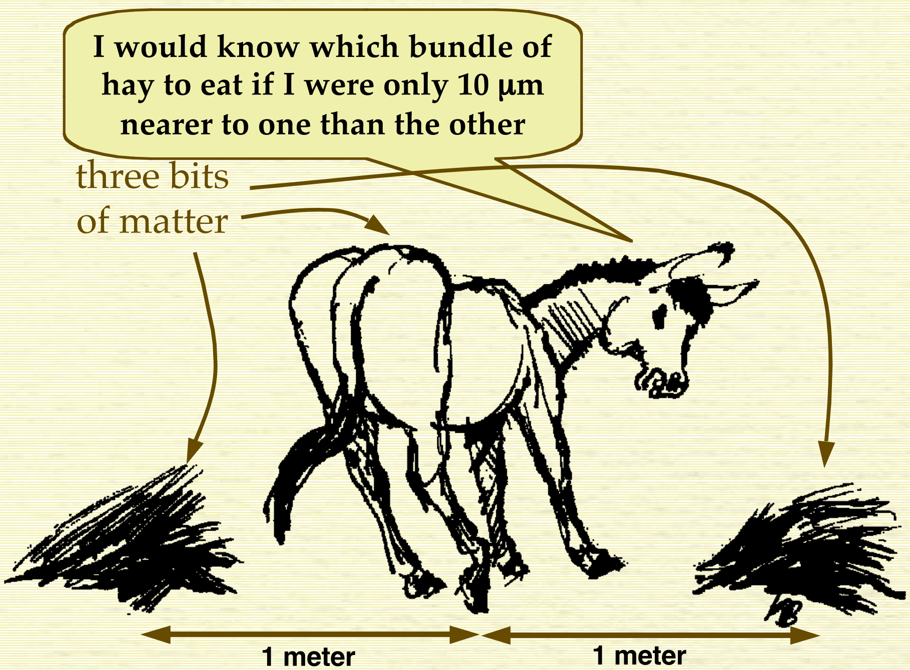


Penzias & Wilson at Holmdel, NJ
(1965)

first correctly saw the CMB
a nearly perfect 2.7 K backbody
(for a long time, it looked like a *perfect* blackbody)

The necessity of imperfections

Buridan's donkey — another parable



⇒ measure the CMB to a 0.001% precision

Perfect symmetry is quite boring

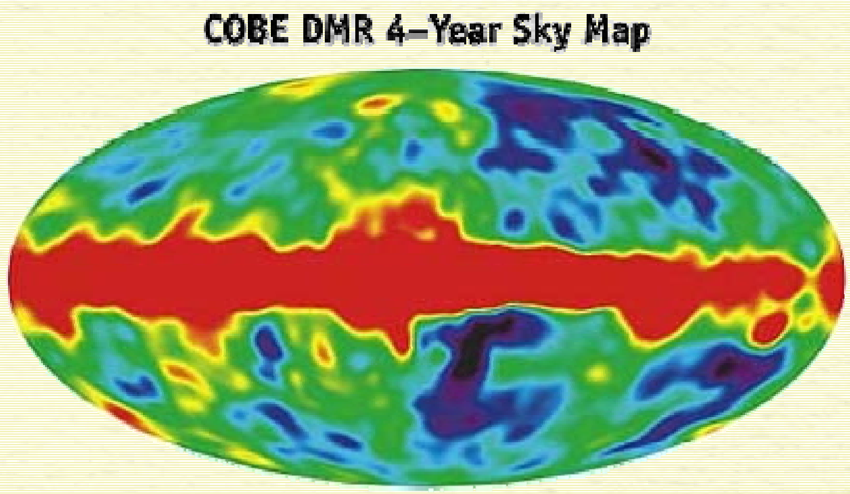
– no structures could form
– How big would the fluctuations need to be in the CMB to explain structures today?

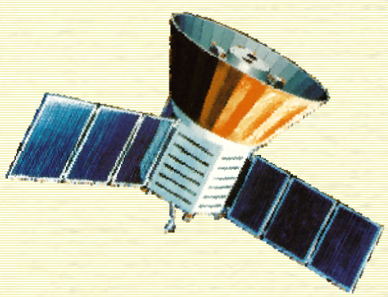
Experimental prediction!

- 1 part in 100,000 is enough

COBE (COsmic Background Explorer)

The COBE Satellite





The ripples are clearly visible, if a little blurry (only a 7° resolution)

Question: Why was the universe so smooth when only 380,000 years old?

The COBE satellite (launched 1989) first saw these ripples in the CMB

What made these ripples?

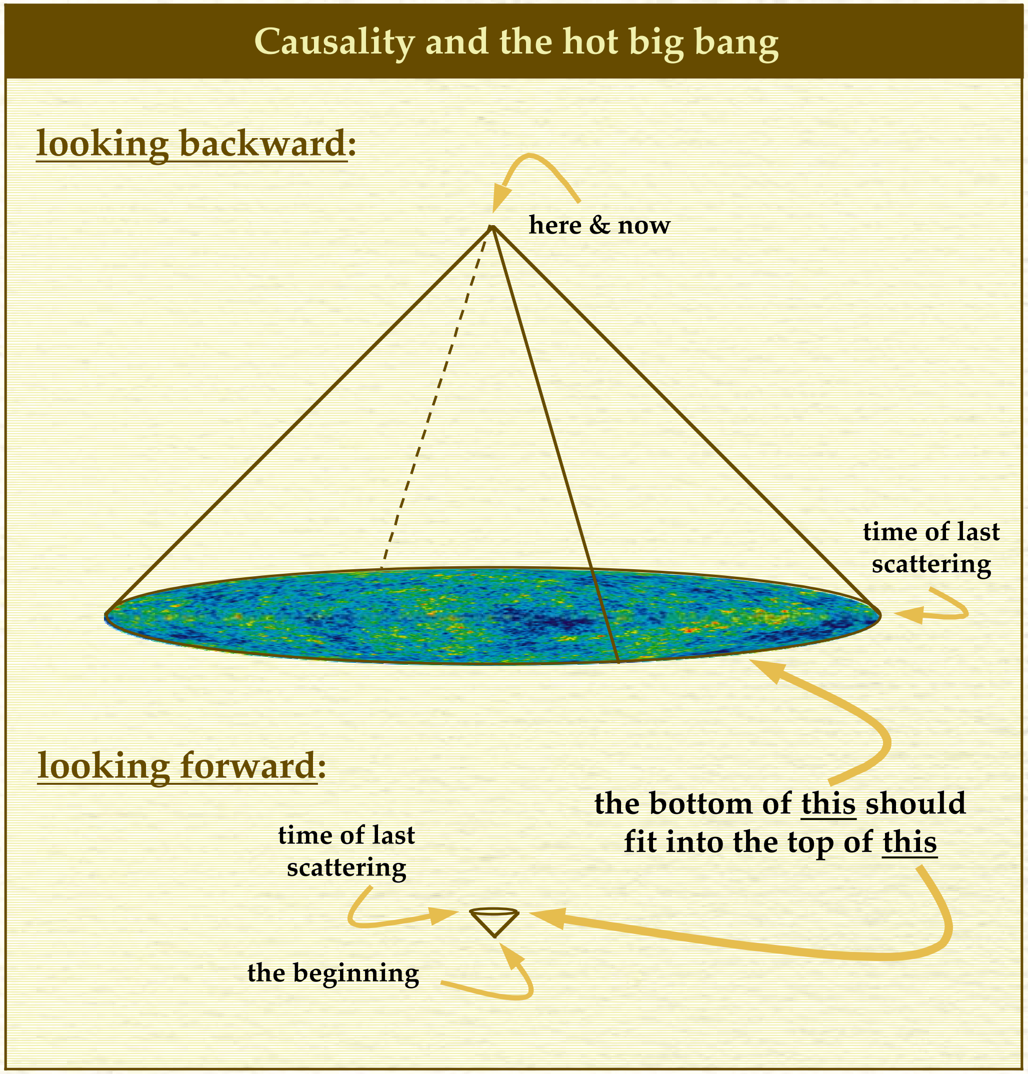
From our prologue beside the river,

- what part is from the initial fluctuations (pebbles or rain?)
- what part is due to how the plasma responds (water)

A *seeming* detour:

Before explaining the origin of these ripples, let us first look at a paradox of the old hot big bang

A paradox: A race between two photons



How could the universe be so smooth at 380,000 years old?

Thought-experiment:

Photon A

- starts at the 'beginning'
- ends when the CMB forms

Photon B (backwards)

- starts now
- goes backwards until the time the CMB forms

Causality requirement:

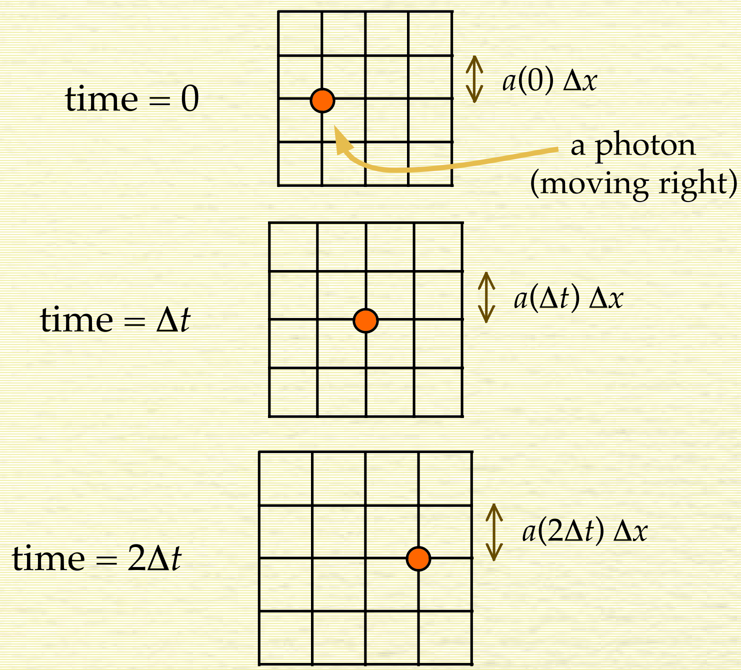
- Photon A should travel farther than Photon B

Resolving the paradox

One way to fix this causality problem

Consider an expanding coordinate grid

The **scale factor** $a(t)$ tells how the grid spacing grows



The total distance traveled over three time-steps is

$$\Delta x_0 + \Delta x_1 + \Delta x_2 = \frac{c\,\Delta t}{a(0)} + \frac{c\,\Delta t}{a(\Delta t)} + \frac{c\,\Delta t}{a(2\Delta t)}$$

$$\Delta x_{\text{total}} = c \int \frac{dt}{a(t)}$$

In general relativity space is not fixed,

– it can expand over time

Locally, a photon moves at c

Globally, general relativity helps:

– the expansion of space adds to how far the photon travels

Photon A *could* travel far enough

– If during an early era the universe expanded rapidly enough

During that era

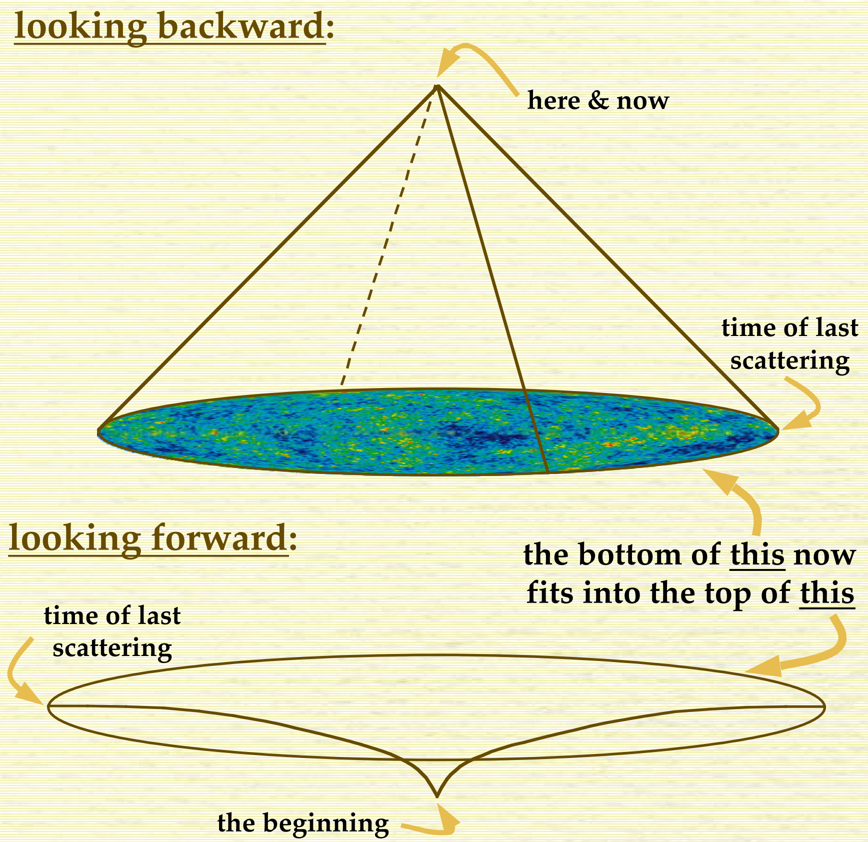
– space expands at an *accelerating* rate

– this mechanism is called inflation

Resolving the paradox

One way to fix this causality problem

With inflation:



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But how does inflation help
to explain the pattern of
ripples that we see in the CMB?

Overview:

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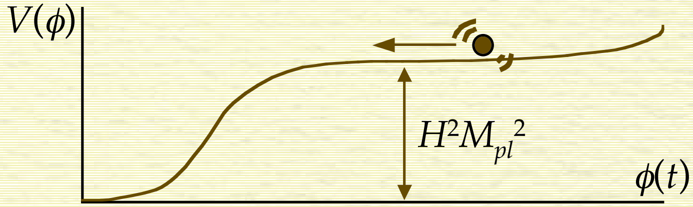
Inflation—a few preliminaries

Divide the scalar field into a

$$\phi(t) = \text{classical zero mode}$$
$$\varphi(t,x) = \text{quantum fluctuation}$$

The quantum part jiggles about as the field rolls down its potential



How is inflation implemented?

Typical ingredients:

- quantum scalar field(s)
- moving down a potential, V
- occurs at large energy, H

Work with Fourier transforms

- <u>mode functions</u>: $\varphi(t,x) \to \varphi_k(t)$

Follow a single Fourier mode over time

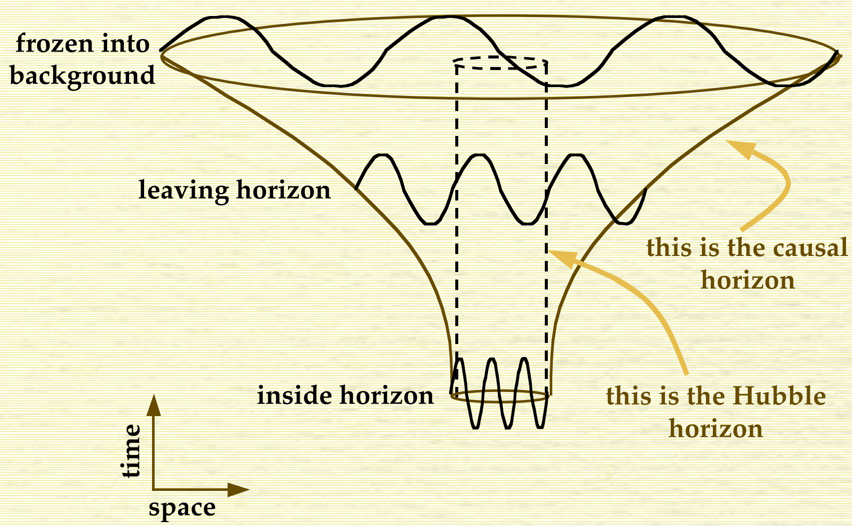
How inflation makes structure (I)

First Stage: freezing in

Two horizons:

causal horizon = how far a signal can travel
Hubble horizon = the distance between which particles can communicate

Follow a little fluctuation (e.g. a particular P_k) as the universe inflates:



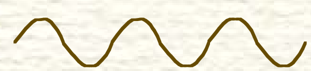
Two basic ingredients:

– the quantum fluctuations
– the rapid expansion

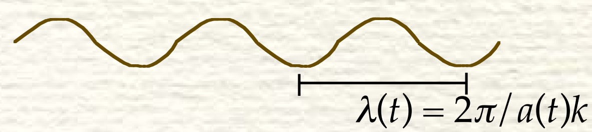
Like everything else, the quantum fluctuations are stretched

For example:

a Fourier mode that looks like this



later looks like this



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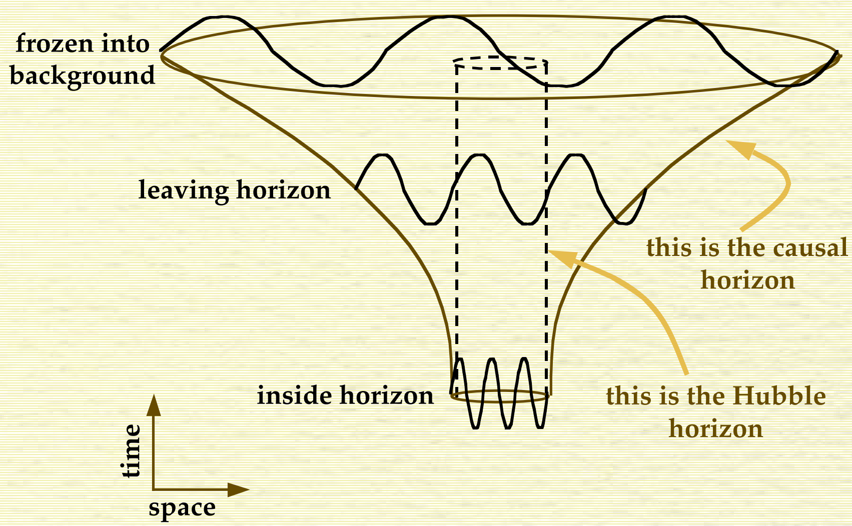


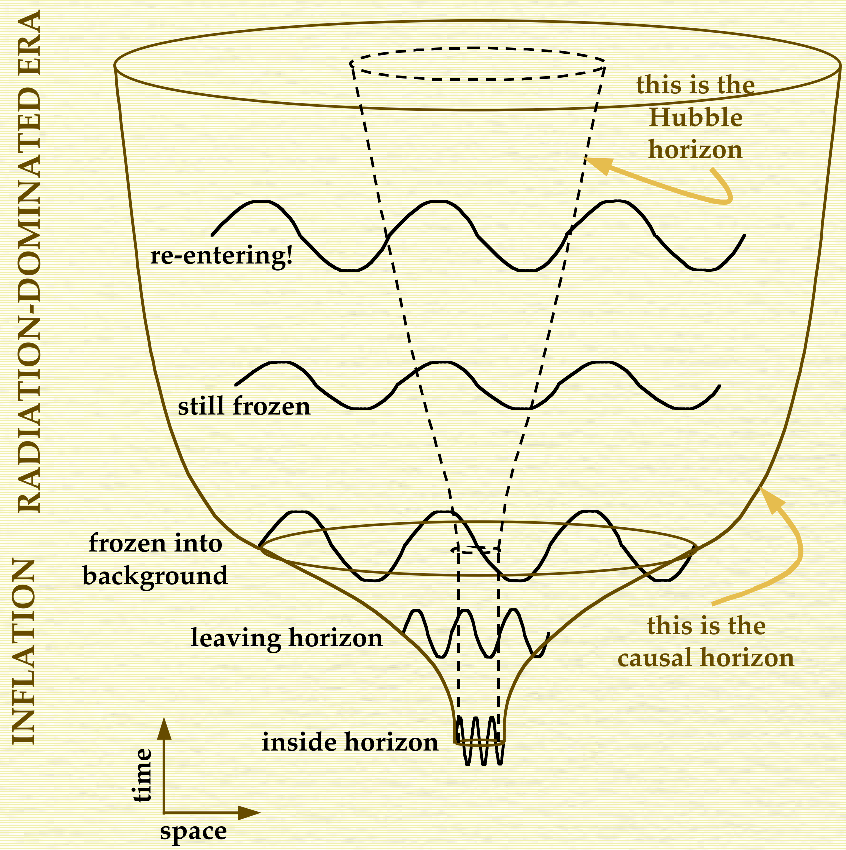
Stage I: Inflation

- inside horizon
- leaves horizon
- frozen into the background

How inflation makes structure (II)

Second Stage: thawing out

After inflation end, the (Hubble) horizon catches up with the frozen perturbations



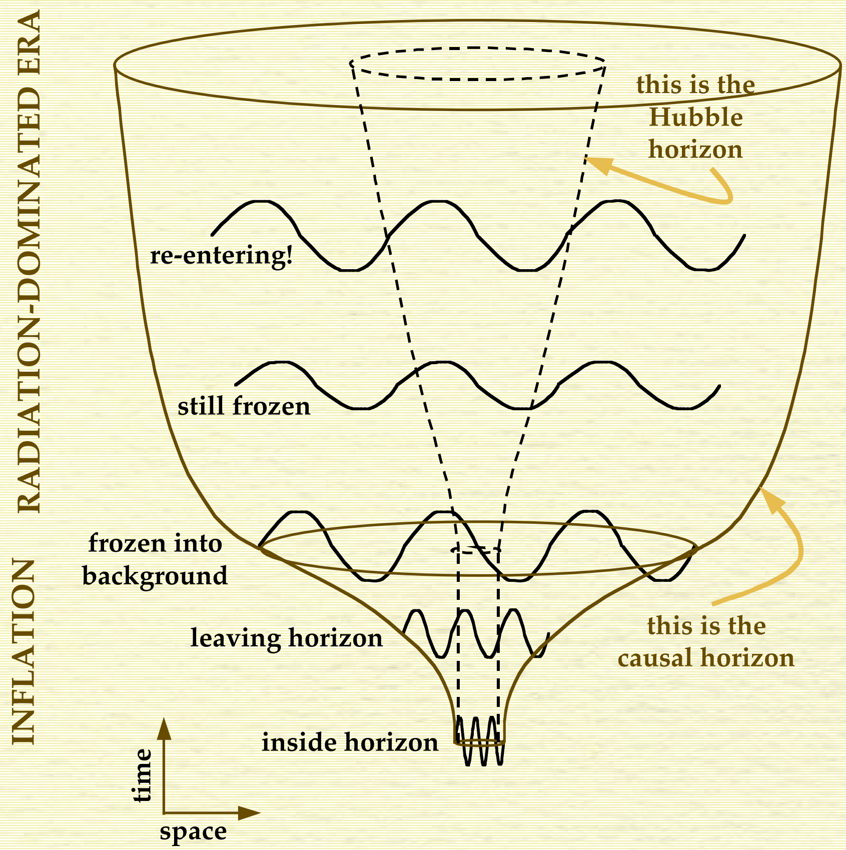
Stage II: Post-Inflation

- frozen into the background
- the Hubble horizon expands
- fluctuations reenter the horizon

How inflation makes structure (II)

Second Stage: thawing out

After inflation end, the (Hubble) horizon catches up with the frozen perturbations



– By freezing in a pattern of primordial fluctuations into the background, inflation provides the initial disturbance to the medium

- Analogy:
- primordial fluctuations → the pebbles
- matter & radiation fluid → the river
- Together these make the pattern in the CMB

The predictions of inflation

Let us work out *one* of the predictions of inflation:

The power spectrum, $P_k(t)$

$$\langle 0 | \varphi(t,x)\varphi(t,y) | 0 \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot(x-y)} \frac{2\pi^2}{k^3} P_k(t)$$

It tells how stuff in two different places is correlated

How are (scalar) distortions $\varphi(t,x)$ in the background space-time correlated?

The power spectrum

For a quantum field,

$$\varphi(t,x) = \int \frac{d^3k}{(2\pi)^3}\left[U_k(t)e^{ik\cdot x}a_k + U_k^*(t)e^{-ik\cdot x}a_k^{\leq}\right]$$

It is easy to calculate

$$\left\langle 0\middle|\varphi(t,x)\varphi(t,y)\middle|0\right\rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot(x-y)}U_k(t)U_k^{\leq}(t)$$

$$= \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot(x-y)}\,\frac{2\pi^2}{k^3}P_k(t)$$

to find

$$P_k(t) = \frac{k^3}{2\pi^2}U_k(t)U_k^{\leq}(t)$$

The power spectrum

For a (nearly) massless field,

$$\nabla^2\varphi = 0 \quad \Rightarrow \quad \left(\frac{d^2}{dt^2} + 3H\frac{d}{dt} + e^{-2Ht}k^2\right)U_k(t) = 0$$

The answer is

$$P_k(t) = \frac{k^3}{2\pi^2}U_k(t)U_k^{\leq}(t) = \frac{k^3}{2\pi^2}\frac{H^2}{2k^3}\left(1 + \frac{k^2}{H^2}e^{-2Ht}\right) \rightarrow \frac{H^2}{4\pi^2}$$

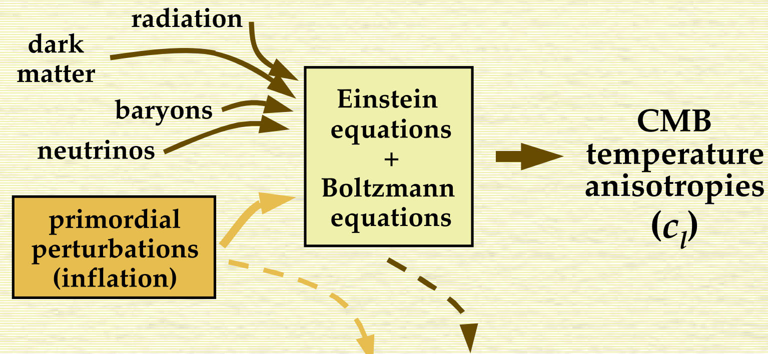
So the primordial power spectrum is (nearly) flat

The power spectrum

So the power spectrum of the cosmic microwave background is flat (pure noise)?

No, indeed! Inflation acts as the initial disturbance

We must still account for how the stuff of the universe reacts



$$c_l = \int d^3k \, P_k \times [T_l^{\mathrm{CMB}}(k)]^2$$

What are the c_l's?

We see the CMB as the radiation emitted 13.7 billion years ago

It looks like it comes from the inside of a sphere

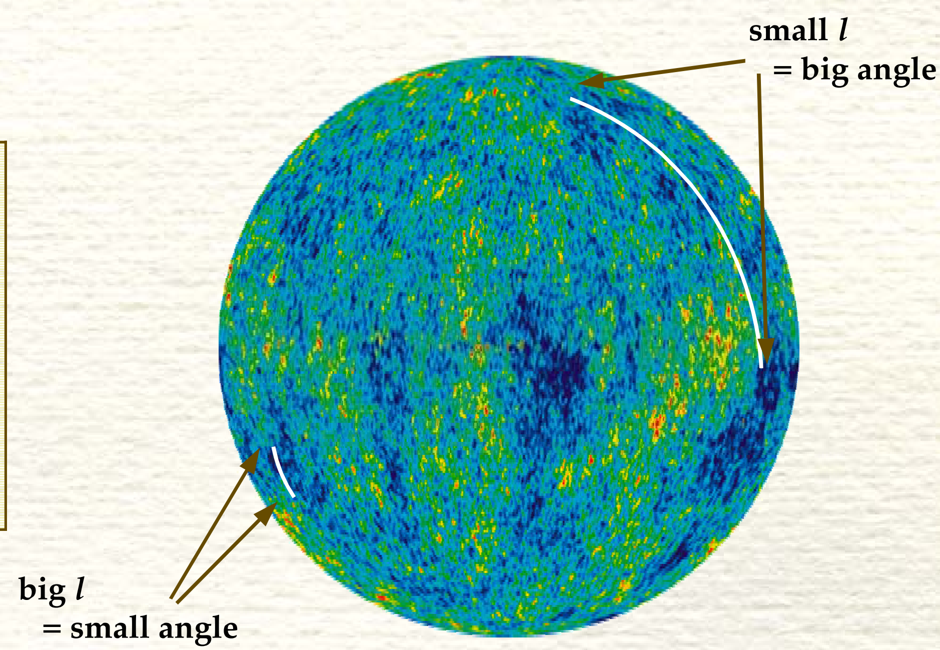
So decompose the data &predictions in spherical harmonics

$$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

temperature difference ($\delta T(\theta,\phi)$)

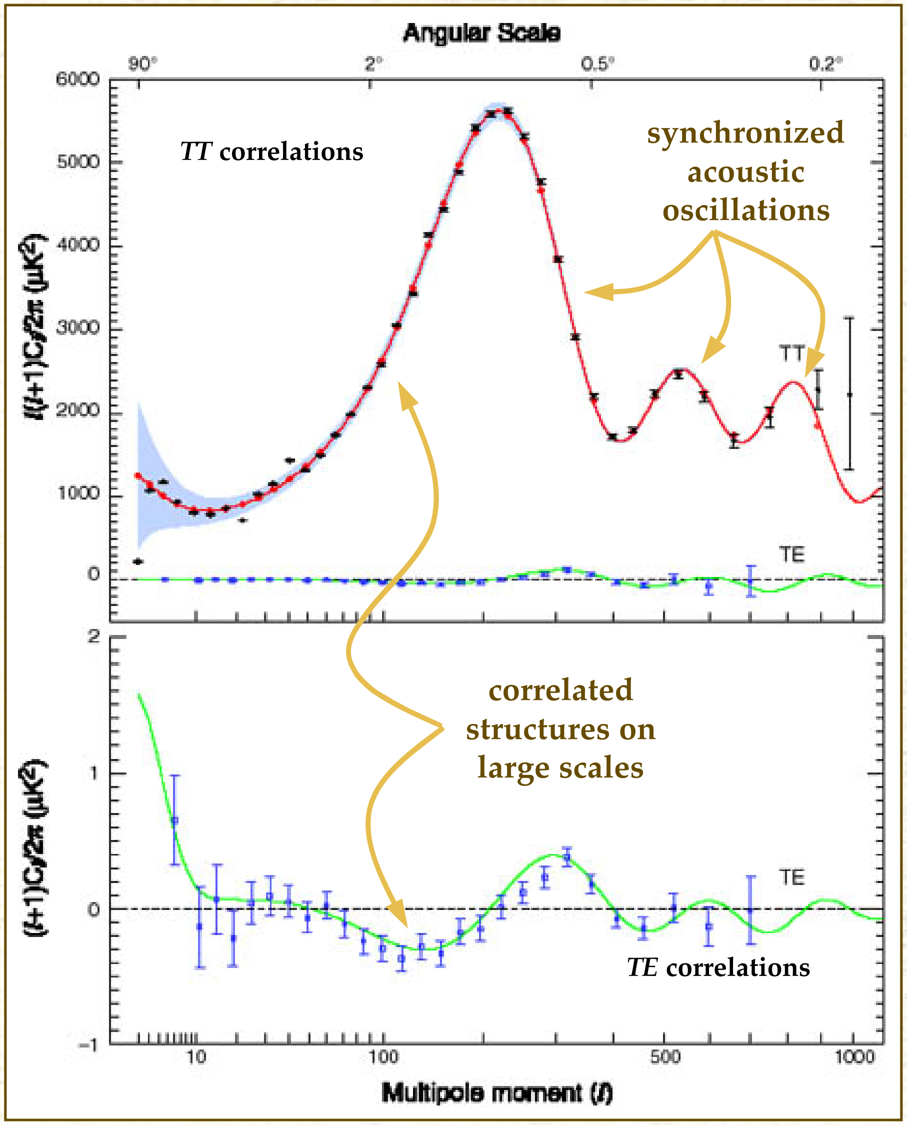
how much of a mode is present (a_{lm})

$$c_l = \frac{1}{2l+1}\sum_{m=-l}^{l} \left| a_{lm} \right|^2$$



WMAP

Wilkinson Microwave Anisotropy Probe



from the WMAP/NASA science team

Precision measurements during the last decade

WMAP, Acbar, Boomerang, CBI, VSA, DASI, . . .

6 Parameter Standard Cosmological Model	
Ingredients:	$\Omega_b h^2, \Omega_m h^2$
Dynamics:	H_0, τ
Initial input:	A_s, n_s

nearly flat primordial power spectrum

$n_s = 0.961 \pm 0.017$ [WMAP 3 year]

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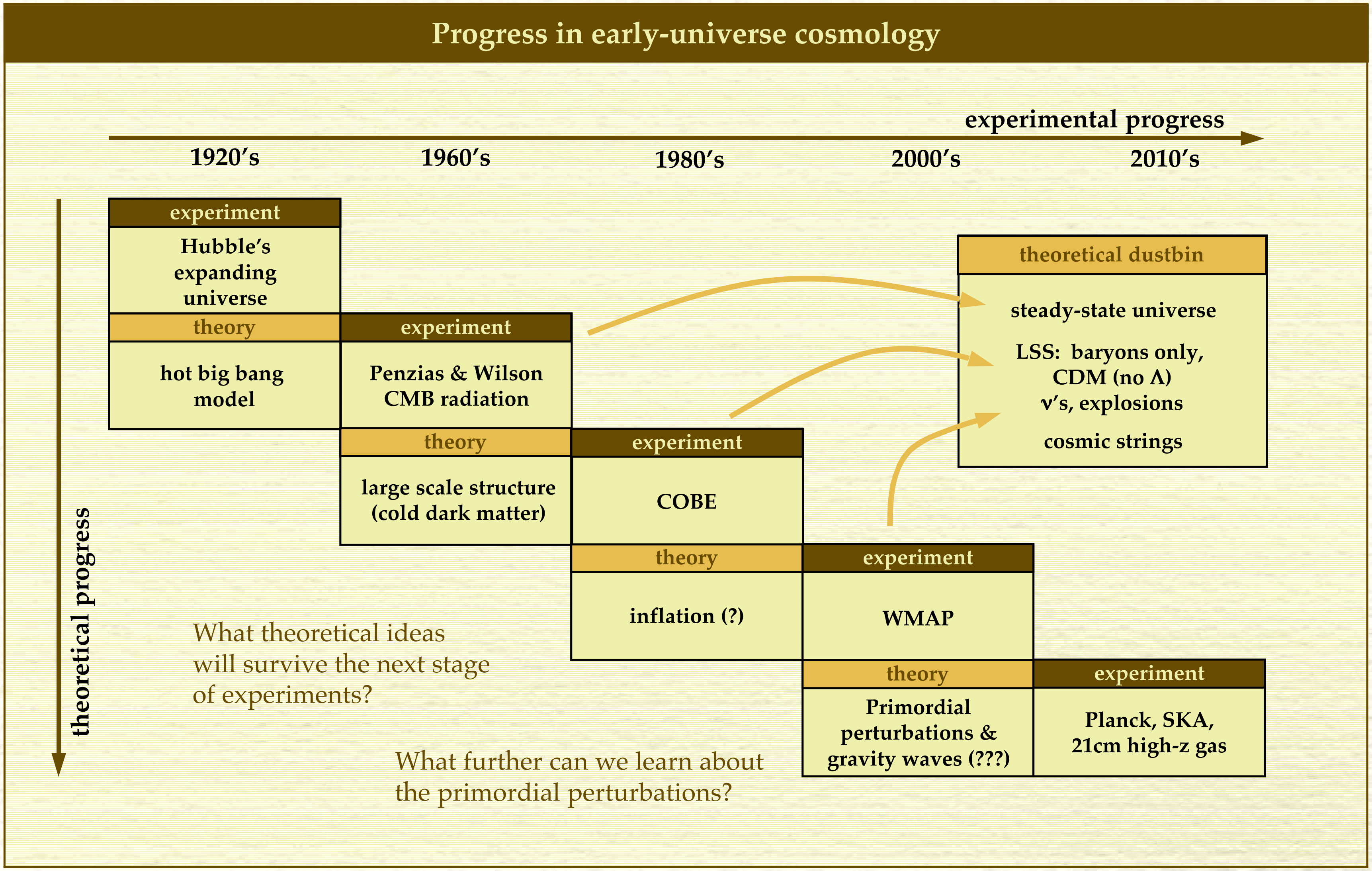
The interplay between theory and experiment



Tugging at loose threads

Loose threads of the past

No stable cosmological solutions in relativity → **the expanding universe**

Was the universe hotter & denser long ago? → **the cosmic microwave background**

Causality (horizon) problem → **inflation**

Fluctuations smaller than a Planck length? → **open question**

So far, we emphasized inflation's successes

But what are its shortcomings?

It is almost always worthwhile to pull at a loose thread in a theory

Either

- the theory falls apart
- or we learn somthing new and important about the universe

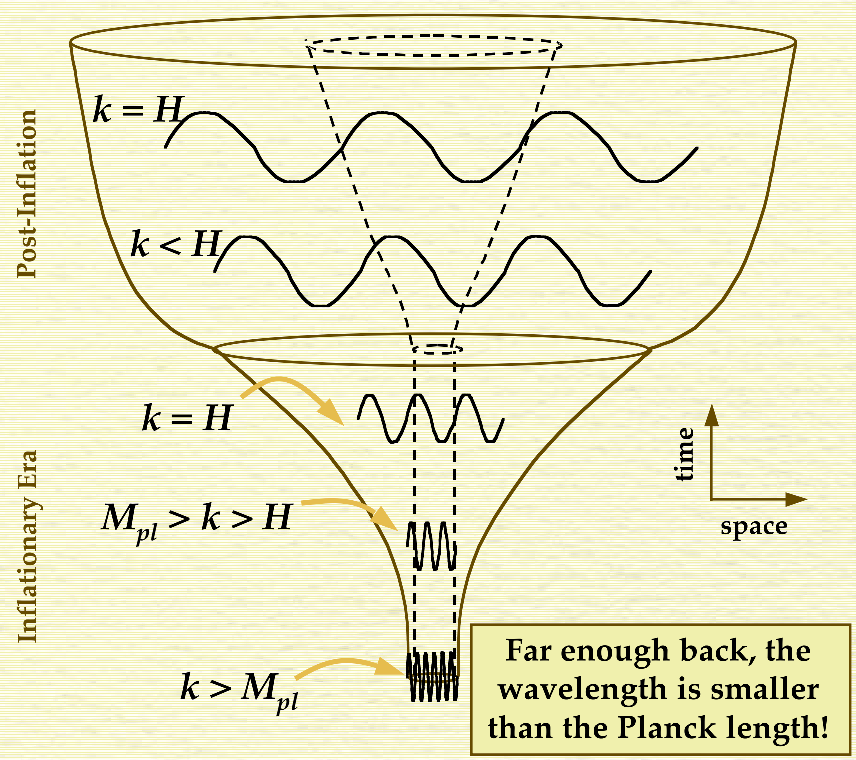
Experimental side

Is there a limit on what we can learn about the 'initial' perturbations?

From the CMB? or elsewhere?

One loose thread:
The trans-Planckian problem

Look at a little fluctuation again, following it farther back in time,



Unresolved parts of inflation:

– the trans-Planckian problem
– what drives inflation?
– the potential must be finely tuned
– cosmological constant problem
– singularity problem
– the back-reaction problem

"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand."

David Schramm (1945–1997)

Approaching the trans-Planckian problem

Well, what is wrong with a Planck-scale fluctuation?

$$l_{pl} = \sqrt{hG_N / 2\pi c^3} \approx 1.6 \times 10^{-33}\,\mathrm{cm}$$

At that scale, quantum corrections to gravity are big

We need a quantum theory of gravity!

The trans-Planckian problem is a
dramatic illustration of Schramm's
connection between the large & small

or Brian Greene's idea of using the CMB
as a sort of cosmic microscope

Approaching the trans-Planckian problem

The "Top-Down" Approach

Start with an idea for physics beyond the Planck scale

↓

Determine the signal in the CMB

Many, many ideas

stringy uncertainty
minimal length prescription
modified dispersion relation
α-states (de Sitter space),etc.

Approaching the trans-Planckian problem

The “Bottom-Up” Approach

Determine the signal in the CMB

↑

Start with an *effective* theory up to the Planck scale

Our Group
H. Collins & R. Holman

ISCAP Group
Greene, Schalm, Shaar, Shiu + Kinney, Easther

‘Adiabatic Group
Anderson, Molina, Mottola

Stanford Group
Kaloper, Kleban, Lawrence, Shenker, Susskind

Experimental Question:

Can these ‘trans-Planckian signal be seen? How do they appear?

An aside:

The old trans-Planckian problem (ca. 1940's)

From Feynman's original paper on QED,

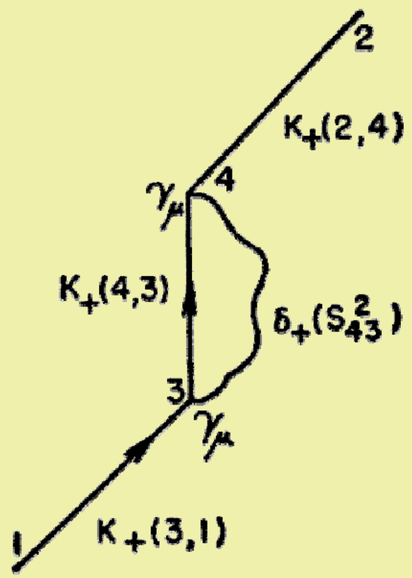


FIG. 2. Interaction of an electron with itself, Eq. (6).

'self-energy' correction to electron mass

$m_0 \rightarrow m_R$

An older version of the trans-Planckian problem

Interactions produce radiative corrections

Integrate over all momenta in a loop
- including trans-Planckian momenta
- also, these 'perturbative' corrections were infinite!

Why did Feynman not need to worry about quantum gravity in looking at e^-e^+ scattering?

The answer: Renormalization
- large momentum → short distance
- cancel infinities with local operators

The effective state idea

When we evaluated the two-point function,

$$\langle 0|\, \varphi(t,x)\varphi(t,y) |\, 0\rangle$$

we can include new physics in how the states evolve

But what if the new physics directly affects the initial state?

$$\langle 0|\, \varphi(t,x)\varphi(t,y) |\, 0\rangle \Rightarrow \langle 0_{\rm eff}|\, \varphi(t,x)\varphi(t,y) |\, 0_{\rm eff}\rangle$$

Two Effects:

1. Modify the mode functions
2. Modify the propagator (time-ordering)

The effective state idea

Modifying a state thus produces new divergences

But they are confined to a single 'initial time'

Thus the divergences are removed by adding
'initial time' counterterms

Experimental Prediction:

The primordial perturbations receive small corrections

$$P_k(t) = \frac{H^2}{4\pi^2}\left[\, 1 + O\left(\frac{H}{M}\right)\right]$$

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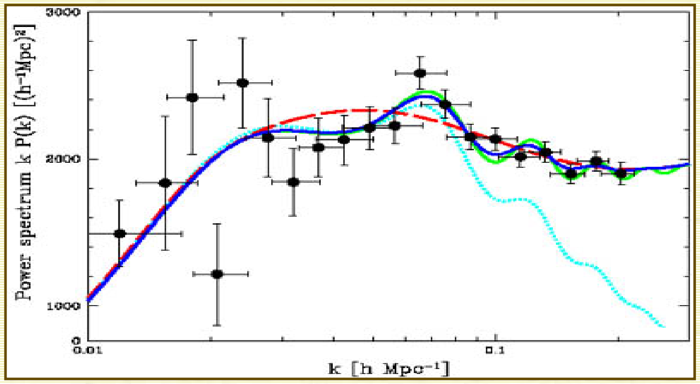
Observations

Ripples appear in Large Scale Structure

SDSS has also seen the first acoustic peak,



astro-ph/0608632

The galaxy survey future (next 10–15 years)

The square kilometer array (SKA) will look at a 10^9 Mpc^3 volume of the universe

Can we observe a trans-Planckian signal,

– CMB or elsewhere?

New effects suppressed by H/M

– M = scale of new physics

– Planck scale ($M = M_{pl}$)?

– something in between ($H < M < M_{pl}$)?

CMB experiments: (nearer future)

– WMAP, Planck, . . .

– precision: one part in 10^3 or so

Large scale structure experiment: (15 yr)

– SKA, 21 cm high-z gas, cosmic inflation probe, etc.

– precision: one part in 10^5 or 10^6 !

numbers from David Spergel's ISCAP talk

Speculations

Here we looked at just one aspect of
an effective initial state

But there are still many more questions to address

What is their connection to symmetry-breaking terms in an effective field theory?

What is their connection to the invariant states of de Sitter space?

Do they provide new sources for non-Gaussianities in the CMB?

How is their energy-momentum renormalized?

Is there an initial time RG flow?

How are specific models (composite inflaton, shortest distance, etc.) realized in the effective theory?

Are their other settings in which they could be applied, where boundary effects are important (CM)?

What current bounds does the LSS place on trans-Planckian physics?

What is the trans-Planckian signal large scale structure?

How readily are various UV-completions distinguishable?

What does a particular initial state imply for inflation?

Inflation presents new challenges to our understanding
of quantum theories, with potentially observable effects

Conclusions

Cosmology has now becomes a precision experimental science

But our theoretical understanding is still in its infancy

Questions:

What is the dark energy? the dark matter?
Did inflation make the primordial perturbations?
Does inflation make sense (loose threads)?

What I hope that you have learned today:

The inflationary picture
How inflation makes structure
The coming challenges to inflation

the end