

**Seeking finer structures in the CMB:  
An effective theory for an initial state of inflation**

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Physics Department Colloquium

February 6, 2007

## A prologue beside a river

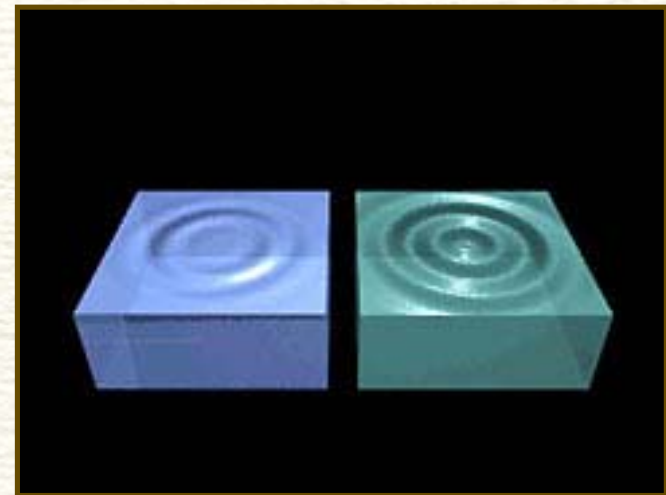
- Let us begin with something familiar
- Suppose that you are walking beside a river on a rainy day, casting pebbles into the water



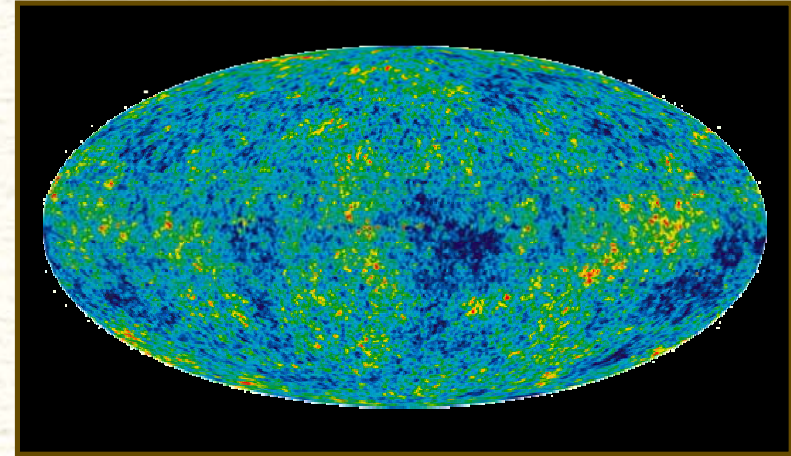
- What causes the ripples to appear the way they do?

# A prologue beside a river

- The pattern of ripples has two influences
  - initial disturbance (pebble)
  - fluid's reaction (material properties)
- The ripples reveal much—both about the stream and the pebbles
- Suppose that you were given a picture of the river's surface, showing the troughs and crests
- What could you learn about
  - the medium—its density, viscosity, is it pure water or is some sludge mixed in?
  - the initial disturbance—was it pebbles or raindrops? both? neither?



# A prologue beside a river



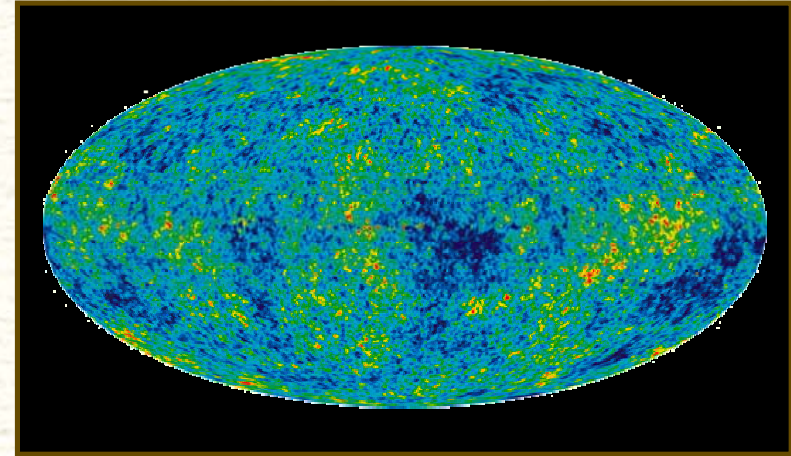
**initial disturbances**

+

**the medium**

- We shall study here the beautiful pattern of ripples in the faint radiation left over from an early epoch of the universe
- Here, we focus on the initial disturbances
  - what do we know about them
  - how do we know
  - what further secrets can be uncover

## A prologue beside a river



- We shall study here the beautiful pattern of ripples in the faint radiation left over from an early epoch of the universe
- Here, we focus on the initial disturbances
  - what do we know about them
  - how do we know
  - what further secrets can be uncover
- The favored model is inflation
  - an inherently quantum process
- These faint ripples in the CMB have important implications for *quantum field theory* at the shortest of scales!

## Overview:



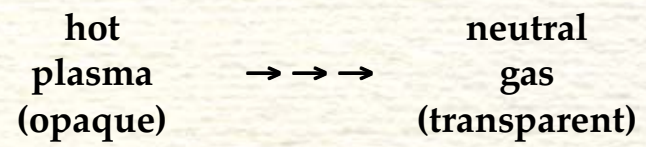
- the cosmic microwave background
- inflation and generating structure
- QFT and the trans-Planckian problem
- observations, speculations & conclusions

# The cosmic microwave background (CMB)

- Looking backwards in time,
  - lumps of stuff were smoother
  - the universe was denser & hotter
- Far enough back we reach a turning point:
  - the universe was hot and dense enough to become an opaque plasma





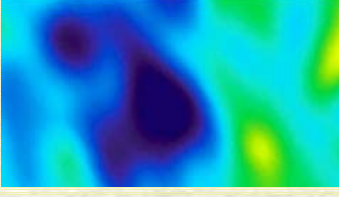
(recombination/last scattering)

• Experimental prediction!  
we should see the faint relic glow from when



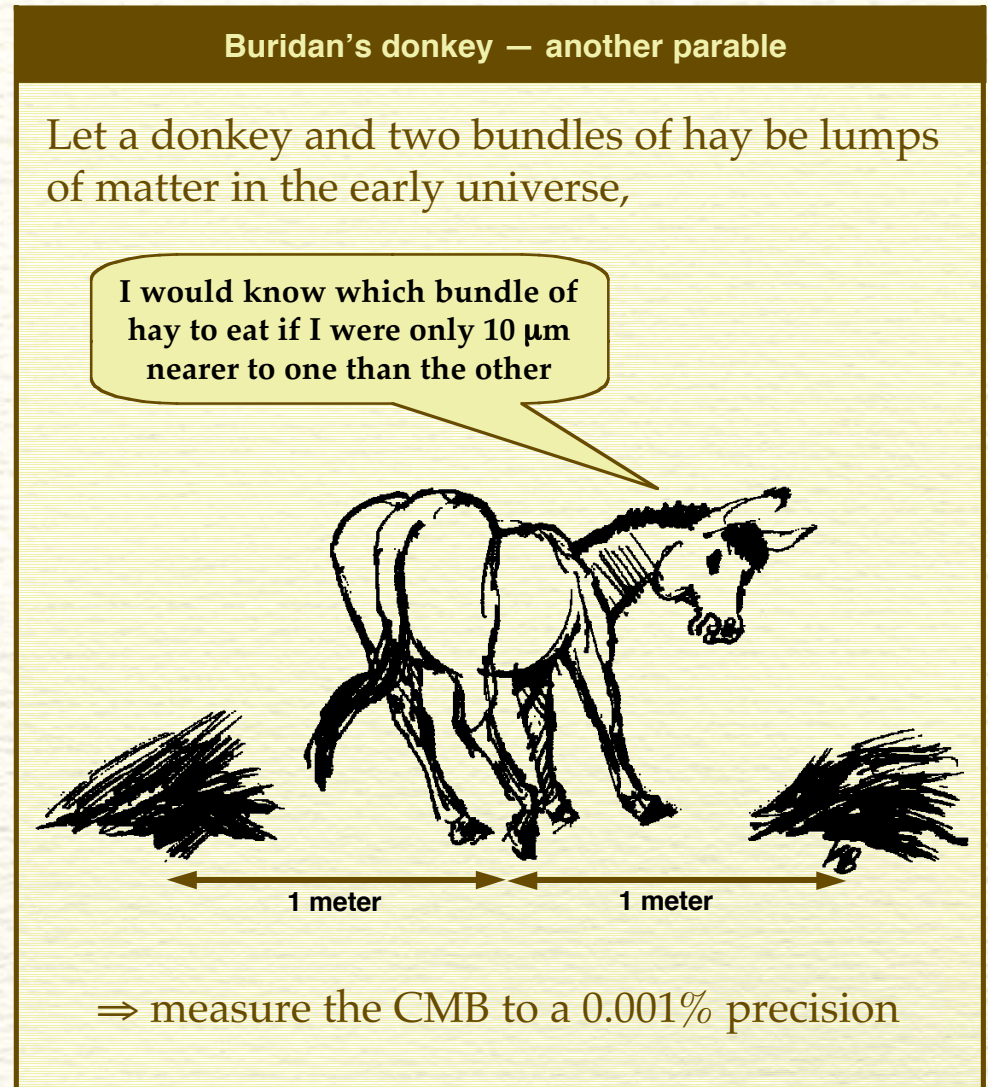
- This faint glow is the CMB
  - redshifted to microwave wavelengths

**Snapshots from the life of a universe**

<p><b>Maturity</b> (ca. today)</p>	
<p><b>Middle age</b> (ca. 10 Gyrs ago)</p>	
<p><b>Young adult</b> (ca. 13.3 Gyrs ago)</p>	
<p><b>Adolescence</b> (ca. 13.5 Gyrs ago)</p>	
<p><b>Childhood</b> (ca. 13.7 Gyrs ago) 1/1000<sup>th</sup> as big as today</p>	

## A bit of a paradox

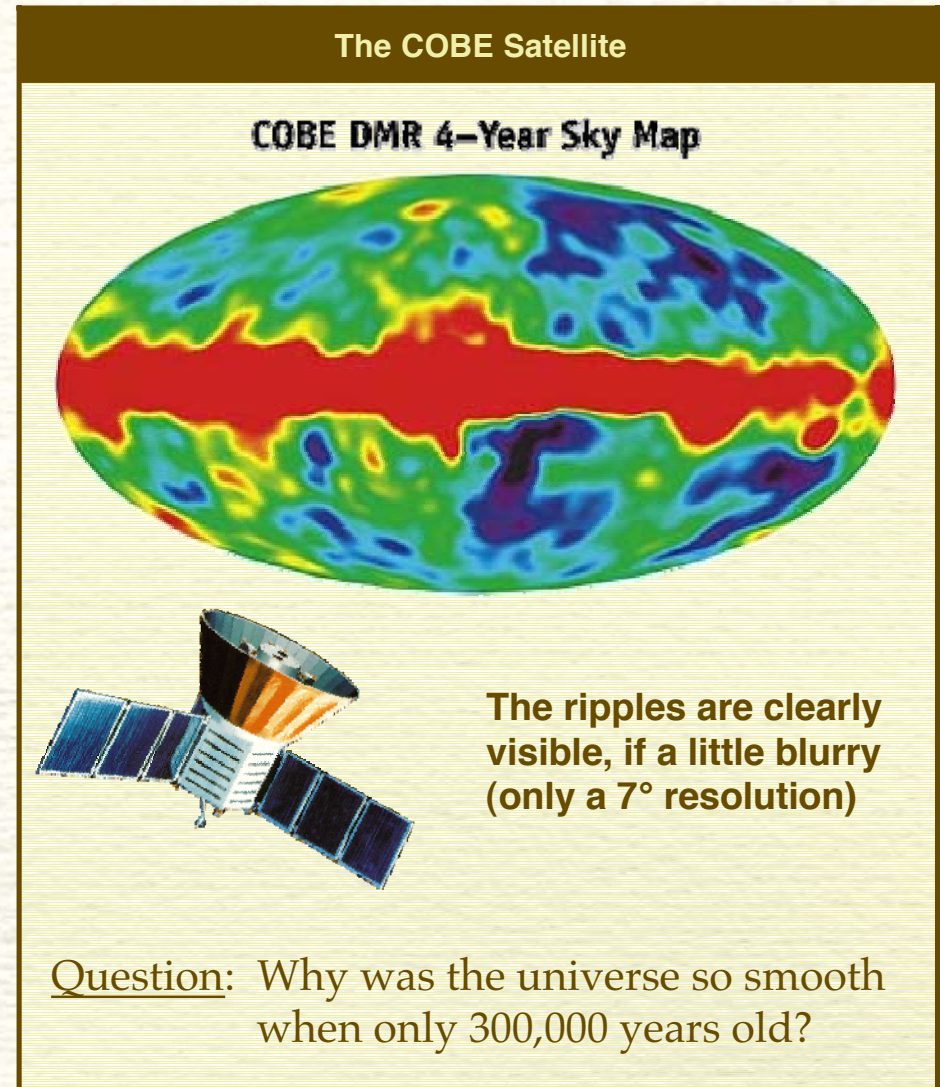
- Penzias & Wilson:  
In 1965 the CMB was finally seen
  - nearly perfect 2.7 K blackbody
- Not a *perfect* blackbody spectrum
- Perfect symmetry is quite boring
  - no structures could form
- How large would the fluctuations need to be in the CMB to explain structures today?
- Experimental prediction!  
1 part in 100,000 is enough





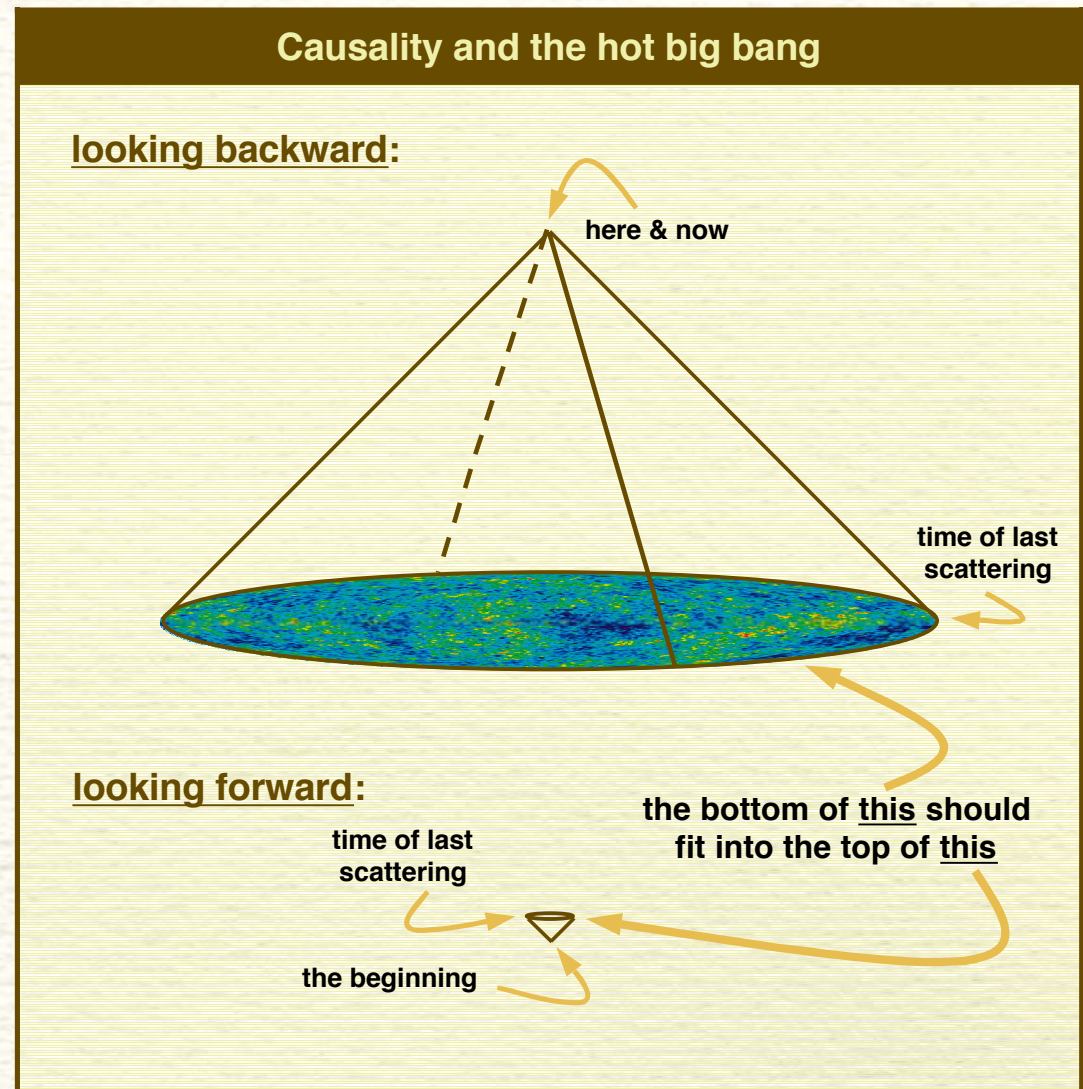
# COBE (COsmic Background Explorer)

- The COBE satellite (launched 1989) saw these tiny ripples in the CMB
- But 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 more serious paradox—a race between two photons

- How could the universe be so smooth at 300,000 years old?
- A thought-experiment:  
a race between two photons
  - » 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



# A race between two photons

- In general relativity space is not fixed, but can expand over time
- Locally, a photon moves at  $c$   
But globally, general relativity helps: the expansion of space adds to how far the photon travels
- If during some early era the universe expanded rapidly enough, Photon A could travel far enough!
- During that era space must expand at an *accelerating* rate
  - this mechanism is called inflation
- Question: How does this help explain the pattern of ripples in the CMB

**One way to fix this causality problem**

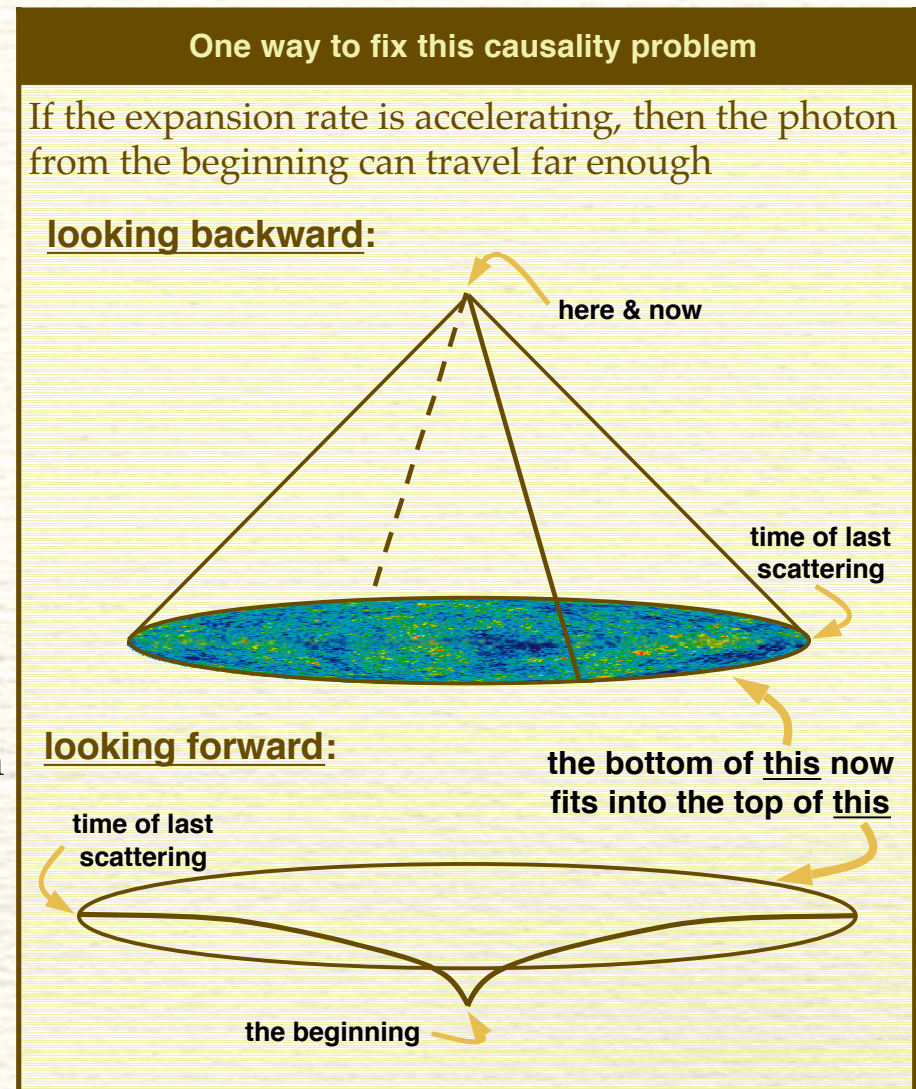
Consider an expanding coordinate grid  
The **scale factor**  $a(t)$  tells how the grid spacing grows

The total distance traveled over three time-steps is



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

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## Overview:

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

# Inflation—a few preliminaries

- How is inflation implemented?
- Typical ingredients:
  - quantum scalar field(s)
  - moving down a potential,  $V$
  - occurs at large energy,  $H$
- It is usually easier to work with Fourier (momentum) transforms
- Examples:
  - mode functions:  $\varphi(t,x) \rightarrow \varphi_k(t)$
  - power spectrum:  $P_k(t)$
- To understand how inflation works, we shall follow a particular Fourier mode over time

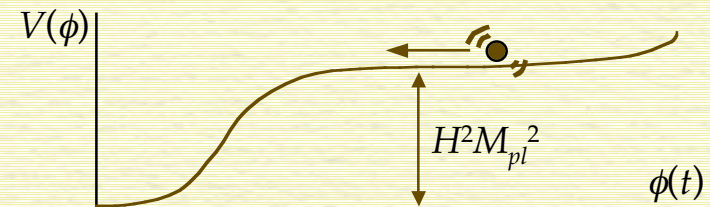
## Setting the stage

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



The **power spectrum**  $P_k(t)$  is related to the Fourier transform of a two-point correlator

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

# How inflation makes structure (I)

- 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

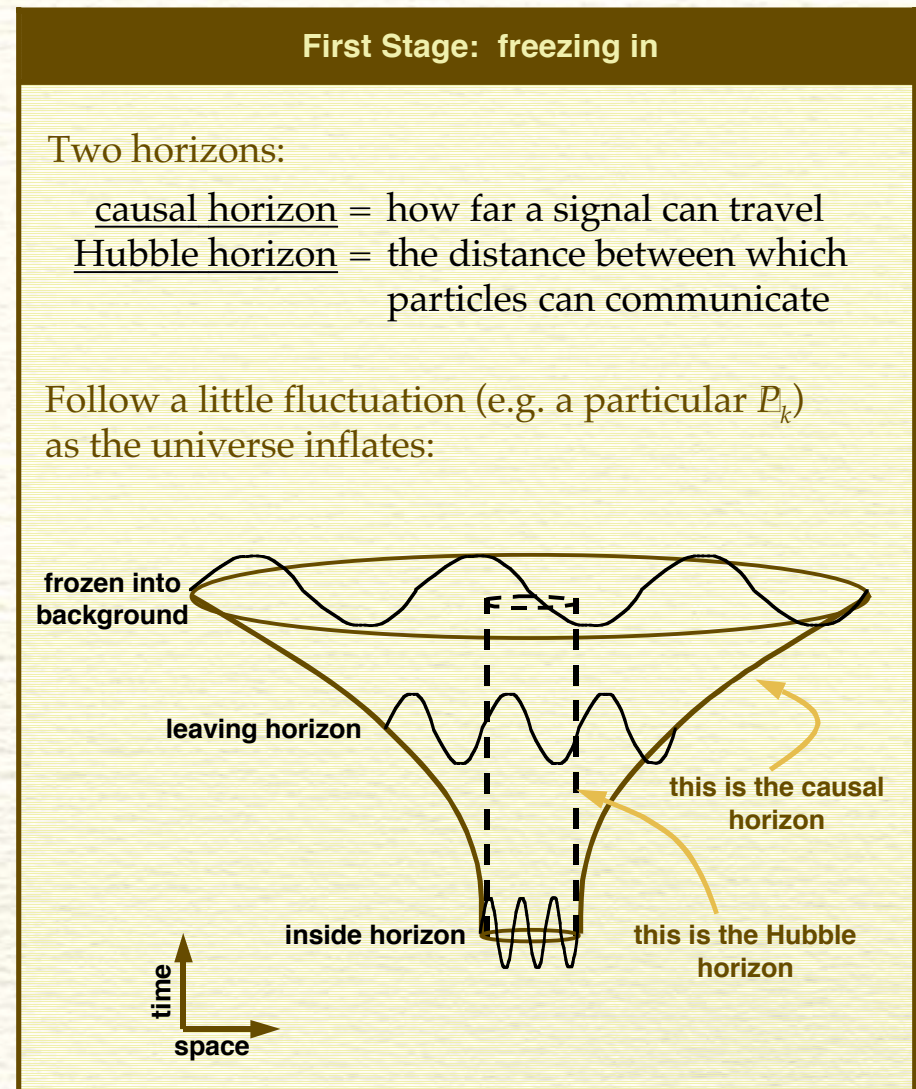


later looks like this



$$\lambda(t) = 2\pi / a(t)k$$

- Stage I: Inflation
  - inside horizon
  - leaves horizon
  - frozen into the background



## How inflation makes structure (II)

- Stage II: Post-Inflation
  - frozen into the background
  - the Hubble horizon expands
  - fluctuations reenter the horizon

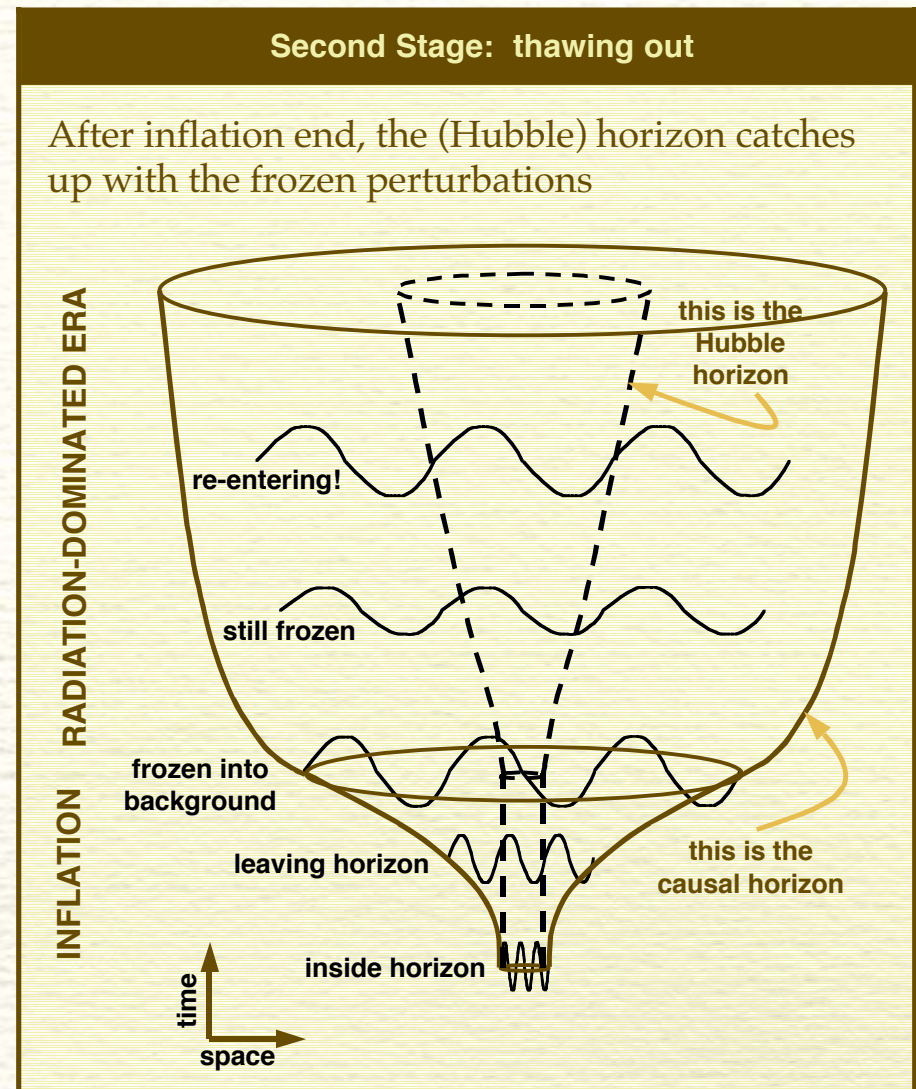
By freezing in a pattern of primordial fluctuations into the background, inflation provides the initial disturbance to the medium

- Analogy:

primordial fluctuations → the pebbles

matter & radiation fluid → the river

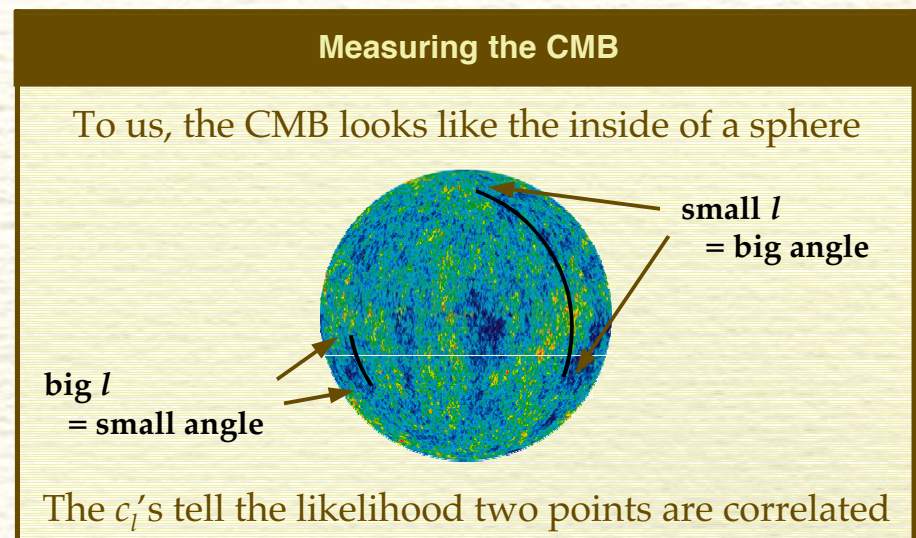
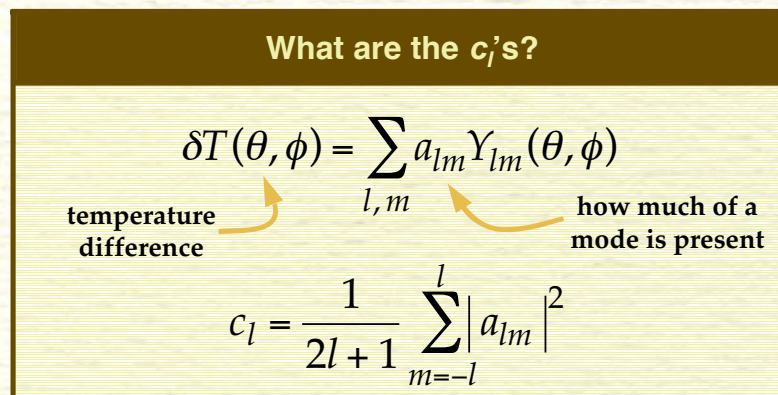
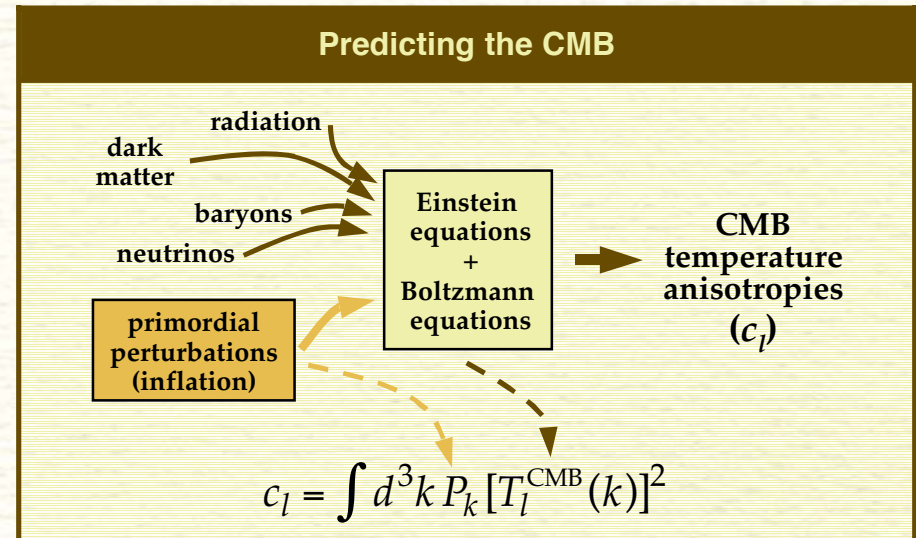
- Together these make the beautiful pattern in the CMB





# The predictions of inflation

- What does inflation predict
  - flat primordial power spectrum
  - nearly Gaussian
  - gravity waves
- These affect the matter/radiation medium to produce
  - correlated structures on all scales
  - synchronized acoustic oscillations
  - gravity waves—not seen (yet?)



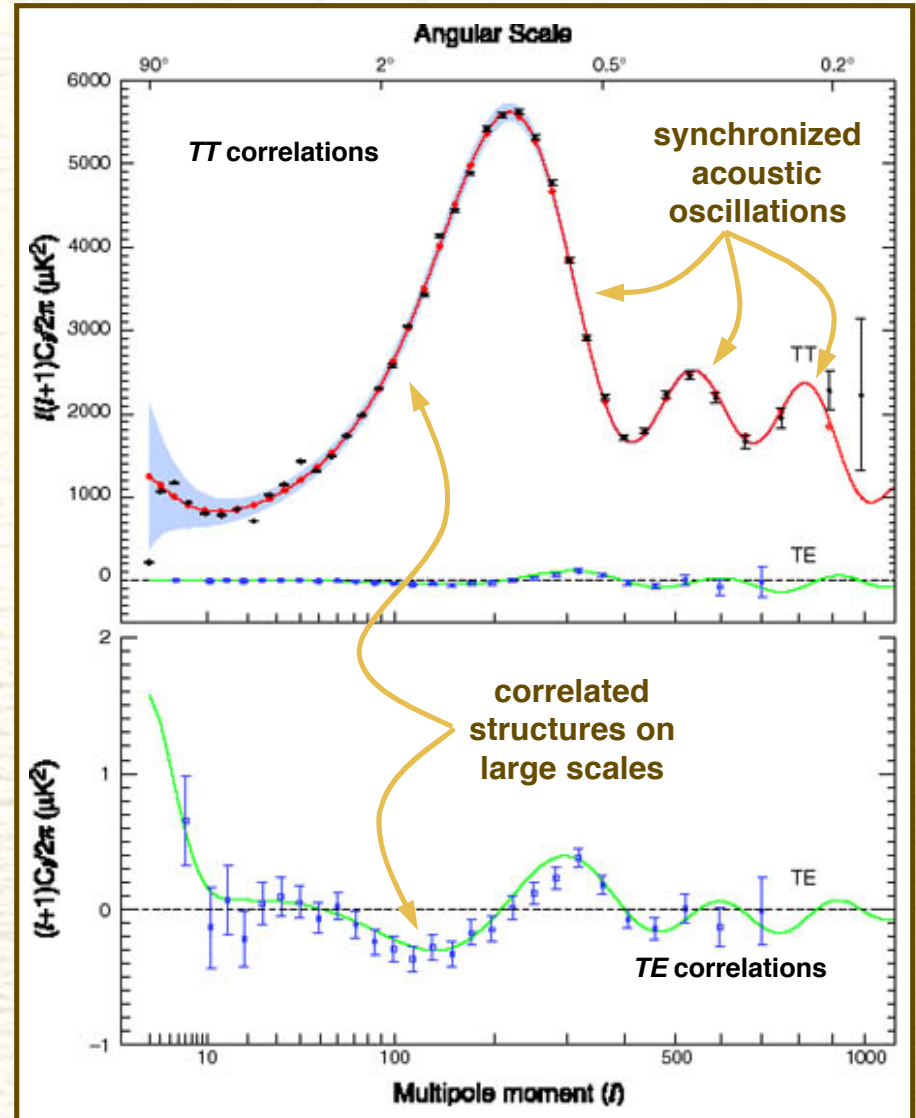
# WMAP (Wilkinson Microwave Anisotropy Probe)

- So, what do we know about the primordial perturbations
  - 2 parameters (so far)
- Precision measurements of the CMB
  - WMAP, Acbar, Boomerang, CBI, VSA, DASI, ...

**6 Parameter Standard Cosmological Model**

<b>Ingredients:</b>	$\Omega_b h^2, \Omega_m h^2$
<b>Dynamics:</b>	$H_0, \tau$
<b>Initial input:</b>	$A_s, n_s$

nearly flat primordial power spectrum  $\rightarrow n_s = 0.961 \pm 0.017$  [WMAP 3 year]

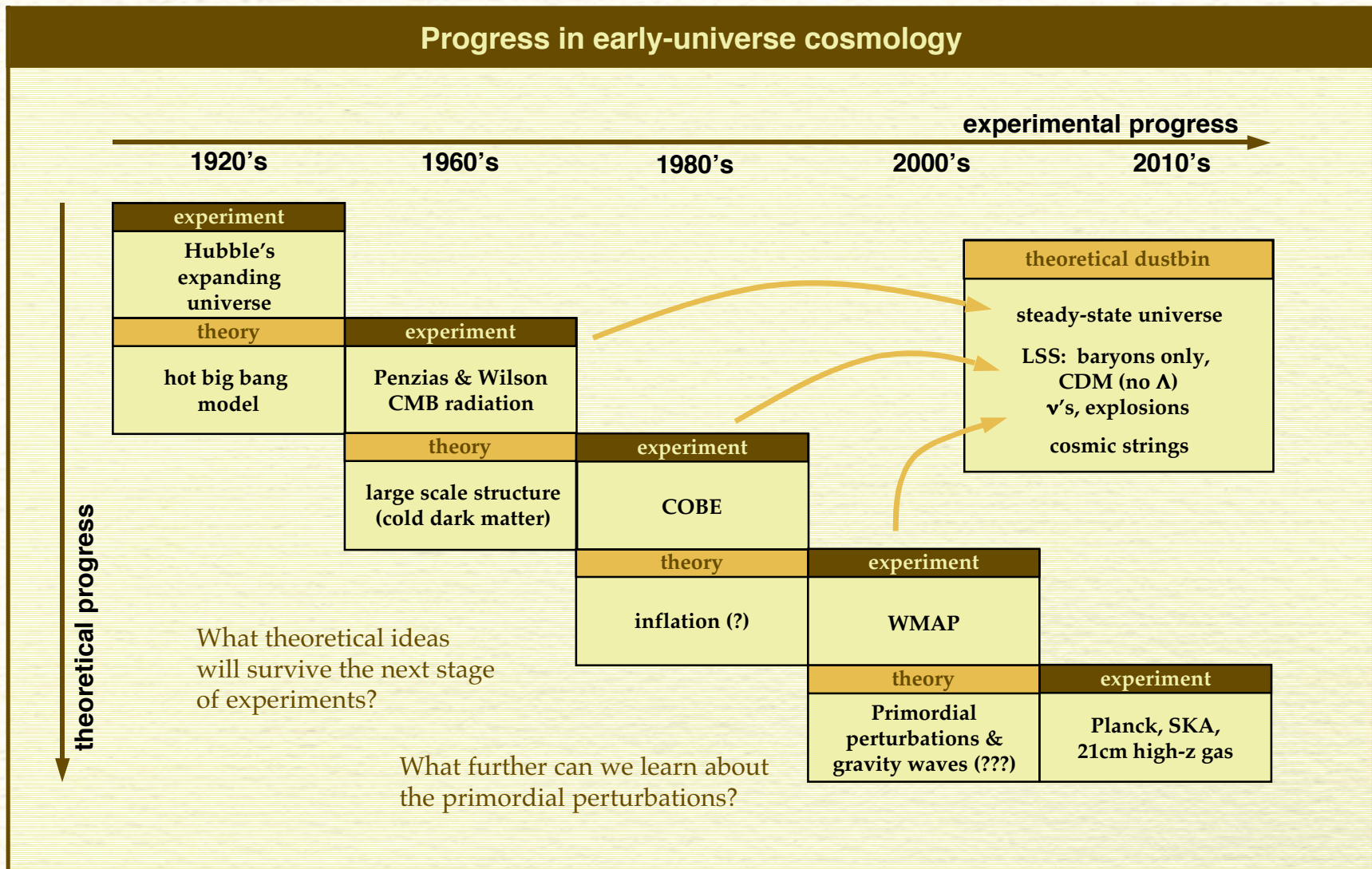


from the WMAP/NASA science team

## Overview:

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

# The interplay between theory and experiment



# Tugging at loose threads

- 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 something new and important about the universe

## Experimental side

What is the limit on what we can learn about the 'initial' perturbations?



From the CMB? or elsewhere?

## Examples of loose threads

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

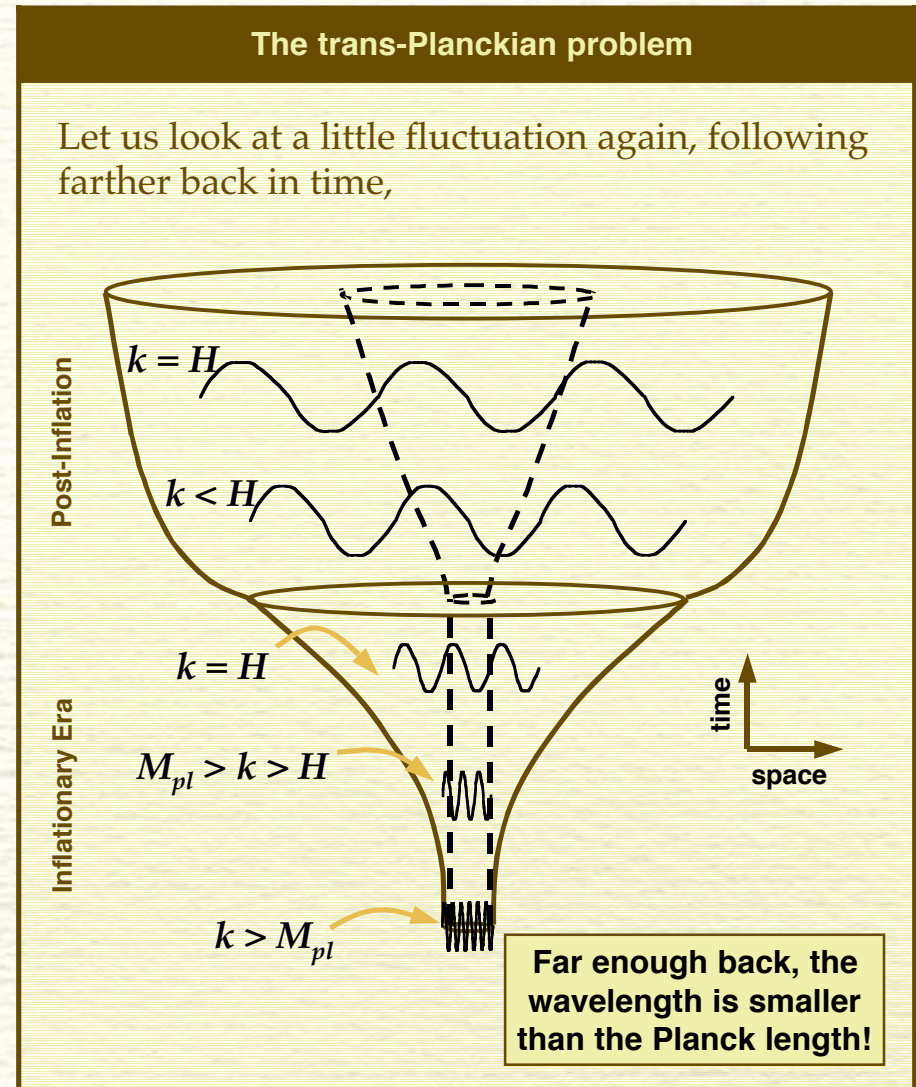
# One loose thread—the trans-Planckian problem

- Unresolved parts of inflation:  
[R. Brandenberger]
  - the trans-Planckian problem
  - what drives inflation?
  - the potential must be finely tuned
  - cosmological constant problem
  - singularity problem
  - the back-reaction problem

Before we become too optimistic:

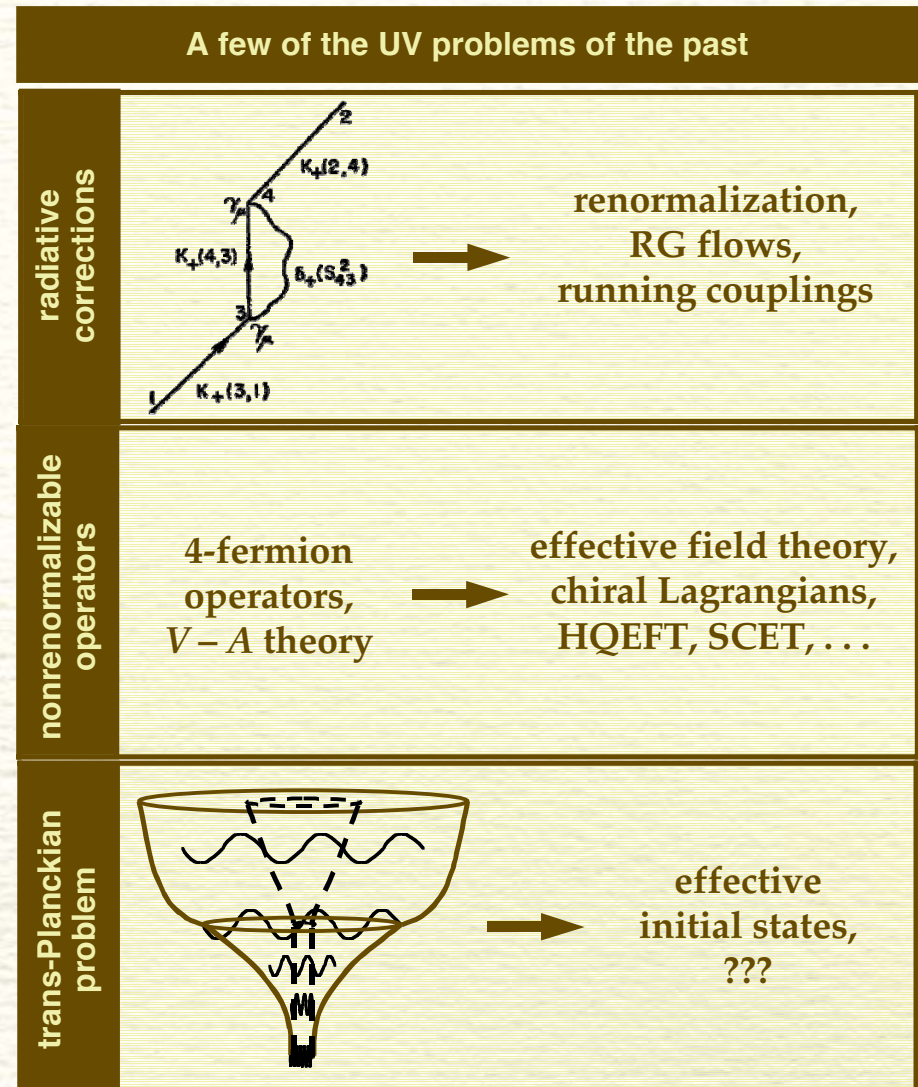
*“Inflation consists of taking a few numbers that we don’t understand and replacing it with a function that we don’t understand.”*

*David Schramm (1945–1997)*



# Implications for the foundations of quantum field theory

- The trans-Planckian problem —a new opportunity for quantum field theory
  - structure formation in inflation is inherently a quantum process
- UV problems in QFT's and their resolution has led to new insights
  - infinities  $\rightarrow$  renormalization & running of couplings
  - irrelevant operators  $\rightarrow$  effective field theories
- New structures in QFT's:
  - effective initial states
  - *boundary* renormalization



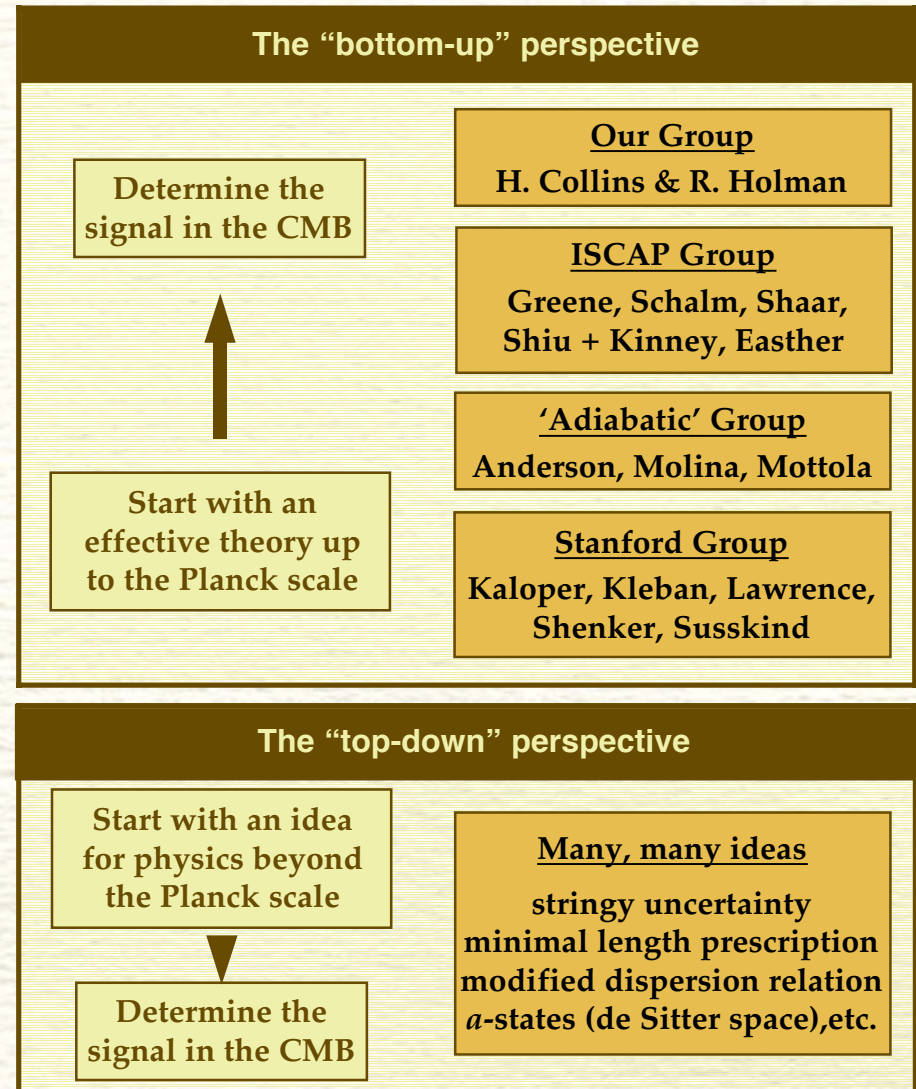
# Approaching the trans-Planckian problem

- What is the trouble with smaller than Planck length fluctuations?

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

gravity strong  
need a quantum theory of gravity!

- Connection between the large & small  
[David Schramm]
  - the CMB as a cosmic microscope  
[Easter, Greene, Kinney, Shiu]
- Can this be understood rigorously, in a controlled framework?
- Experimental Question:  
Can these 'trans-Planckian' signals be seen? What is their signature?





# The effective theory idea

- A basic tenet of physics:  
do not need a theory of all scales to understand a system at a particular, limited range of scales
- Applies to both approaches:
  - emergent (e.g. mesons)
  - reductionist (e.g. thermodynamics)
- In quantum field theory, the effective theory idea has a very precise formulation

Can we apply something of this philosophy to the trans-Planckian problem?

## The recipe for an effective field theory

### 1. Choose the relevant degrees of freedom

Fields, particles, etc.

Examples:

Chiral Lagrangians, HQEFT, SCET, Standard Model, . . .

### 2. Choose the symmetries

space-time, gauge, approximate

### 3. Construct all the interactions consistent with #1 and #2.

Two classes of interactions

- Renormalizable (long-distance)
- Nonrenormalizable (short-distance)

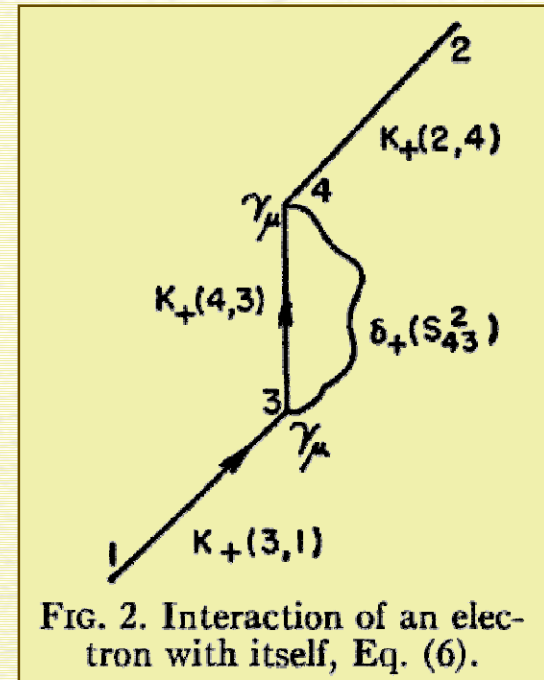
new physics hides among these!

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

- A much older incarnation 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  $\rightarrow$  short distance
  - cancel infinities with local operators

## Radiative or loop corrections

From Feynman's original paper on QED,



'self-energy' correction to electron mass

$$m_0 \rightarrow m_R$$

# The effective theory of an initial state

- In quantum field theory (or just QM)

We look at matrix elements:

expectation values of  
*operators in a state*

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

- In ordinary EFT choose a state
  - new physics can affect how it evolves

- Something is missing:
  - what if new physics appears in the state?

Collins & Holman, PRD 71:085009 (2005)

- The effective theory of an initial state is a method for adding new short-distance structures in the state

Collins & Holman, hep-th/0501158, hep-th/0507081,  
hep-th/0605107, hep-th/0609002

## An important matrix element

In inflation, one example is the two-point function (power spectrum)

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

But we do not really know the state at all scales; so replace

$$|0\rangle \Rightarrow |0_{\text{eff}}\rangle$$

## An effective initial state structure

State is fixed in terms of modes

$$\varphi_k - U_k^{\text{vac}} \neq 0 \quad \text{for } k > M$$

Describe a general state by how it differs from a standard 'vacuum'

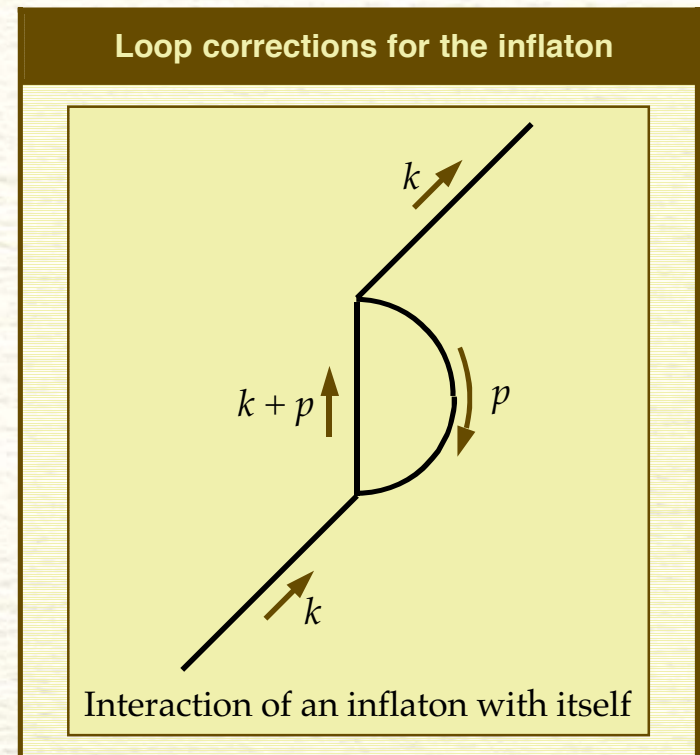
# Renormalization of the initial state

- The basic idea of the effective state is to use
  - standard vacuum up to a point ( $k < M$ )
  - add general structures beyond it ( $k > M$ )
- Renormalization:  
radiative corrections sum over of the new short-distance structures
  - a new class of infinities
- Infinities are confined precisely to initial time
  - add boundary counterterms to Lagrangian  
[hep-th/0501158](#), [hep-th/0507081](#)

## Experimental prediction:

For measurements made at scale  $\Lambda$  ( $= k$  or  $H$ ?)  
trans-Planckian effects suppressed by

$$\left(\frac{\Lambda}{M}\right)^n$$



**Boundary renormalization of Lagrangian,  $L$**

$$L = L_0 + L_I + L_{\text{bct}} \delta(t - t_0)$$

this part tells how operators evolve  $\rightarrow$   $L_0$

$\rightarrow$  this part tells how states evolve  $\rightarrow$   $L_I$

$\rightarrow$  this part cancels the boundary divergences  $\rightarrow$   $L_{\text{bct}}$

# Trans-Planckian ripples in the CMB

- So, we have returned to looking at the ripples & trying to learn about what produced them
  - What is the generic form of the trans-Planckian correction?
- Two standard classes of corrections (top-down & effective theory:  $H/M$ )

$$P_k = \frac{H^2}{4\pi^2} \left[ 1 - 2x \frac{H}{M} \cos\left(\frac{2M}{H} + \phi\right) + \dots \right]$$

(effective theory:  $k/M$ )

$$P_k = \frac{H^2}{4\pi^2} \left[ 1 - 2 \frac{k}{M} d_1 \cos(2k\eta + \phi) + \dots \right]$$

model-dependent  
order one constants

Natural UV cutoffs in expanding space-times  
Perimeter Institute, Sept. 2006

- A clear prediction for effects of new physics in the inflationary state!

## Corrections to the power spectrum

New short-distance effects in the state modify the power function slightly

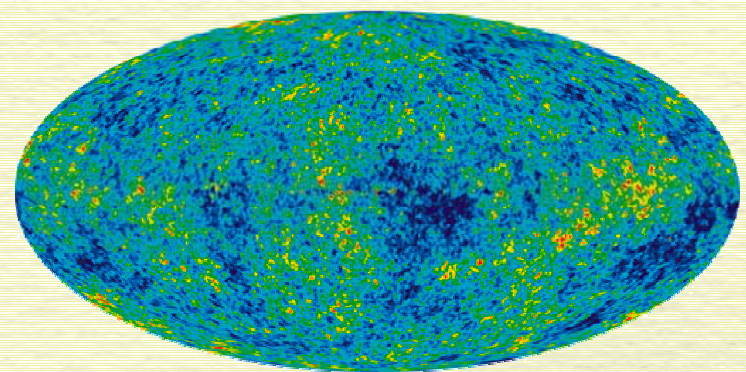
$$P_k = \frac{H^2}{4\pi^2} \left[ 1 - 2 \frac{k}{M} d_1 \cos(2k\eta + \phi) + \dots \right]$$

(order one term)

The power spectrum sets the initial data that makes the CMB ripples

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

## From the WMAP/NASA Science Team



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# Observations

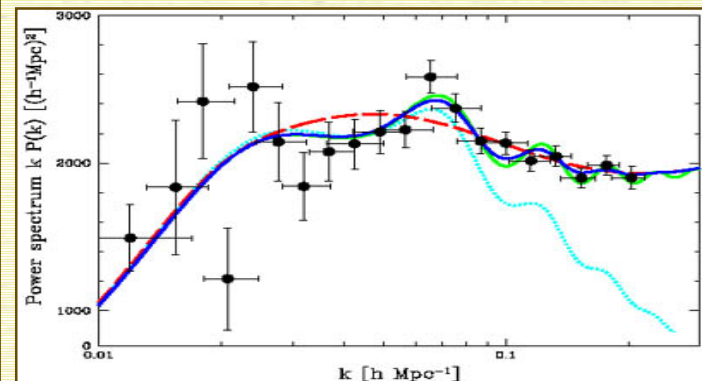
- Can we observe a trans-Planckian signal,
  - CMB or elsewhere?
- New effects suppressed by  $H/M$ 
  - $M$  = scale of new physics
  - Planck scale ( $M = M_{\text{pl}}$ )?
  - something in between ( $H < M < M_{\text{pl}}$ )?
- CMB experiments: (nearer future)
  - WMAP, Planck, . . .
  - precision: one part in  $10^3$  or so
- Large scale structure experiment: (10–15 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

## The same ripples appear in the LSS

The primordial perturbations influence the large scale structure (LSS) as well

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  $10^9 \text{ Mpc}^3$  volume of the universe



# Speculations

- Here, we looked at just one observational signal from the effective initial state
- But it opens new possibilities and many, many new questions!

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

How is their energy-momentum renormalized?

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

How readily are various UV-completions distinguishable?

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

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

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

Is there an initial time RG flow?

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

What is the trans-Planckian signal large scale structure?

What does a particular initial state imply for inflation?

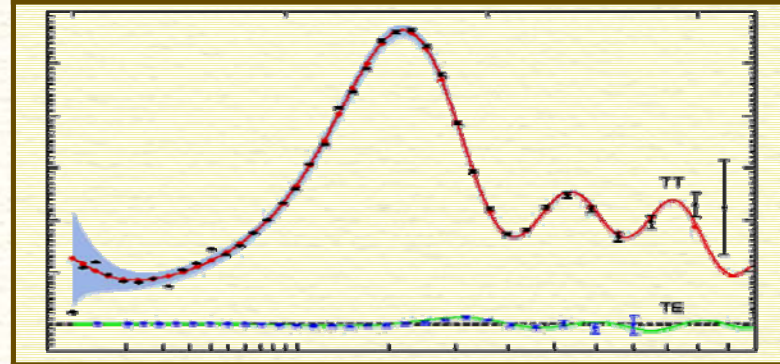
- Inflation presents new, unique challenges to our foundation for quantum field theory
  - UV effects in an expanding background
  - answers to formal questions  $\Rightarrow$  observable effects!



# Conclusions

- Cosmology is now a precision experimental science
  - mysterious cosmological ‘standard model’ [inflation +  $\Lambda$ CDM]
- Inflation, explains the origin of structure but has some loose threads
  - e.g. its trans-Planckian problem
- The effective state approach to the trans-Planckian problem has uncovered
  - a model-independent prediction for the signals from physics above the inflationary scale
  - fascinating new renormalizable structures for quantum field theories
- The long-range prospects for observing such effects are extremely good

WMAP precision measurements



Trans-Planckian corrections to the primordial power spectrum

$$P(k) = \frac{H^2}{4\pi^2} \left[ 1 - 2 \frac{k}{M} d_1 \cos(2k\eta + \phi) + \dots \right]$$

Precision measurements of the CMB & LSS

