Ripples in the Cosmos

Hael Collins
University of Massachusetts, Amherst

University of Buffalo

Physics Department Colloquium

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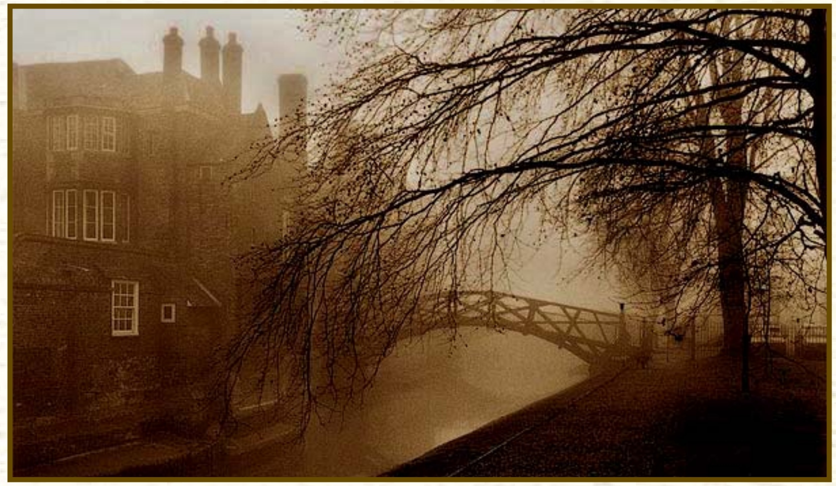
A prologue beside a river

- 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?

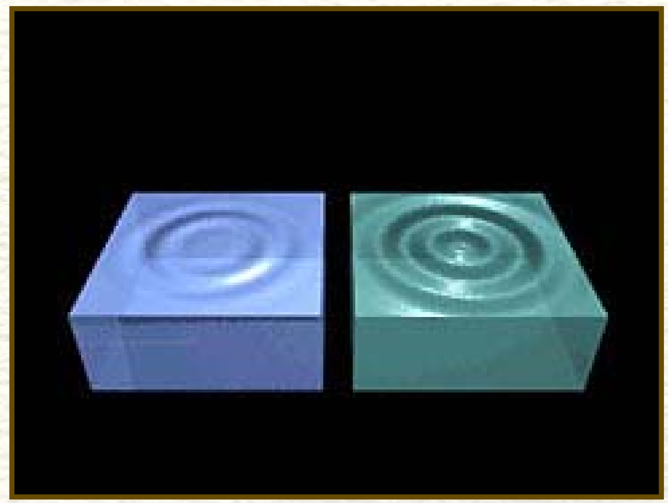
A prologue beside a river

- The pattern of ripples has two influences
  - initial disturbance (pebble)
  - fluid’s reaction (material properties)



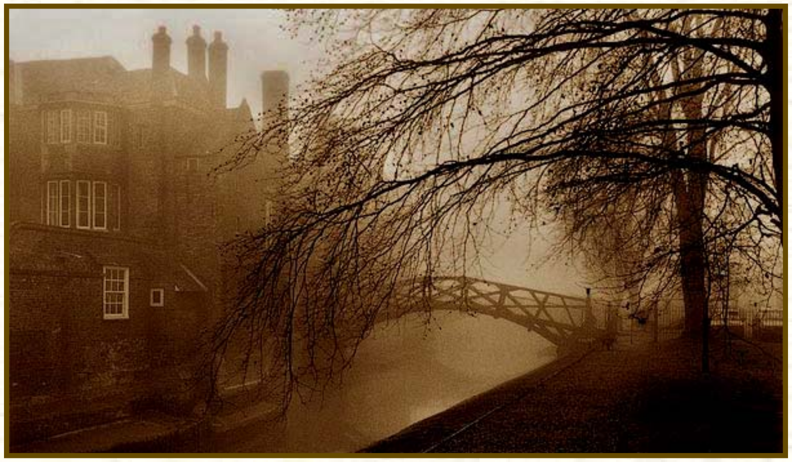
- The ripples reveal much—both about the stream and the pebbles

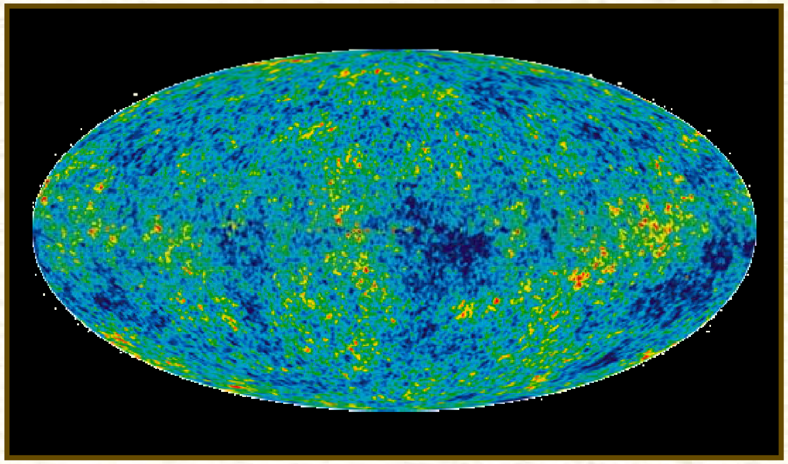
- Suppose that you were given a picture of the river’s surface, showing the troughs and crests



- What could you learn about
  - the <u>medium</u>—its density, viscosity, is it pure water or is some sludge mixed in?
  - the <u>initial disturbance</u>—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

Overview:

- the cosmic microwave background
- inflation and generating structure
- searching for substructures in the CMB
- 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)

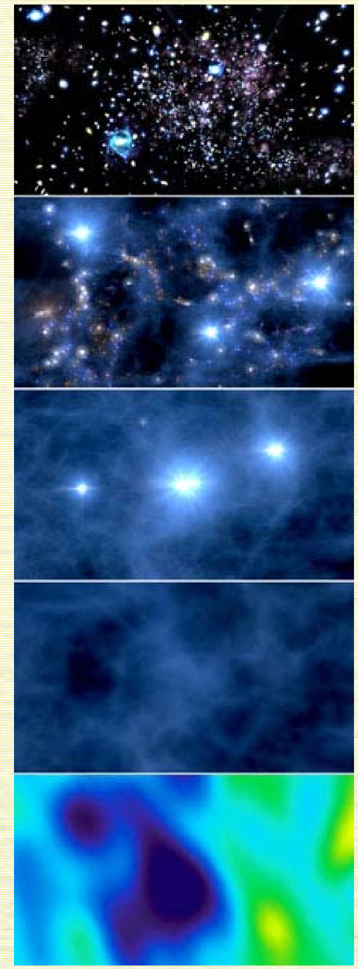
- Experimental prediction!

  we should see the faint relic glow from when

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

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

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)

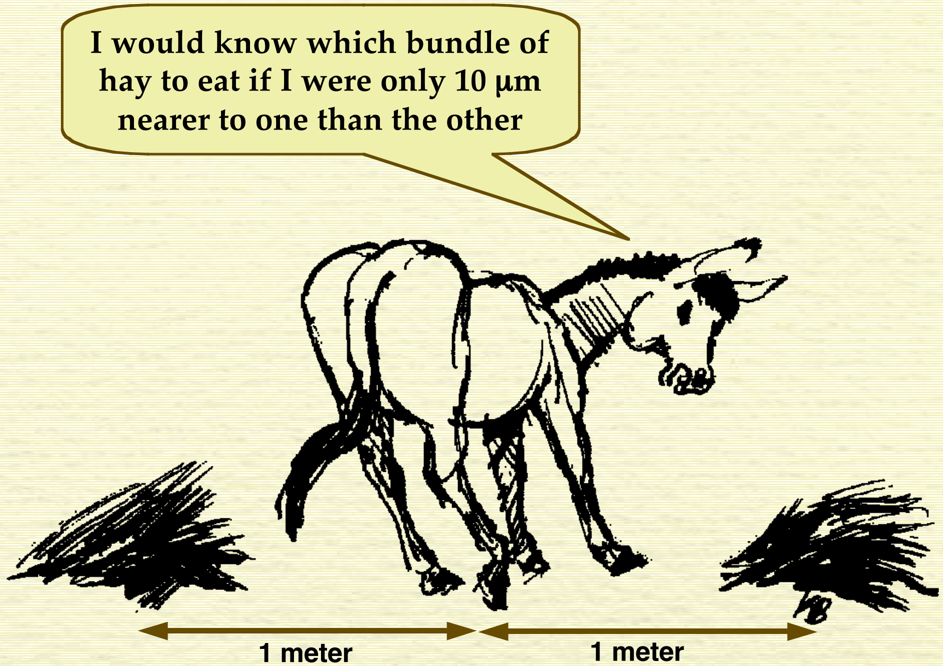
Childhood
(ca. 13.7 Gyrs ago)
1/1000th as big as today

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

Buridan's donkey — another parable

Let a donkey and two bundles of hay be lumps of matter in the early universe,



$\Rightarrow$ measure the CMB to a 0.001% precision

COBE (COsmic Background Explorer)

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

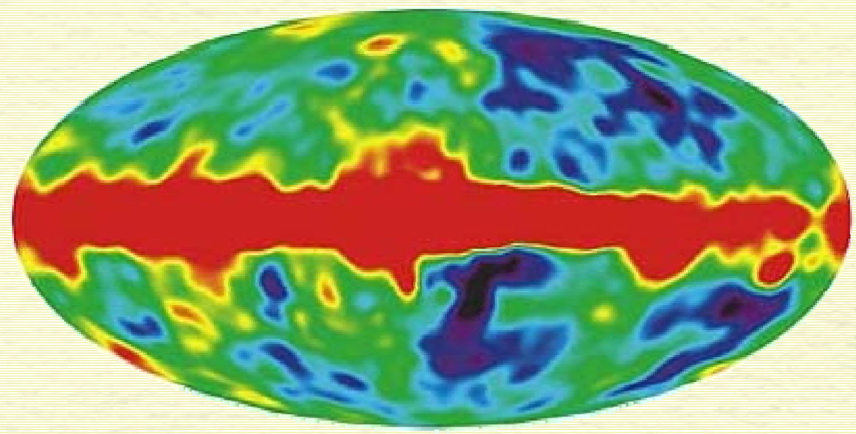
- But what made these ripples?

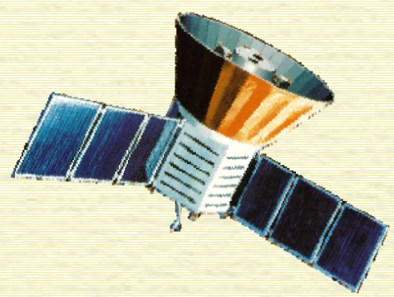
- From our prologue beside the river,
  - what part is from the initial fluctuations (pebbles or rain?)
  - what part is due to how the plasma responds (water)

- <u>A *seeming* detour</u>:
  Before explaining the origin of these ripples, let us first look at a paradox of the old hot big bang

The COBE Satellite

COBE DMR 4–Year Sky Map





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

<u>Question</u>: Why was the universe so smooth when only 300,000 years old?

A more serious paradox—a race between two photons

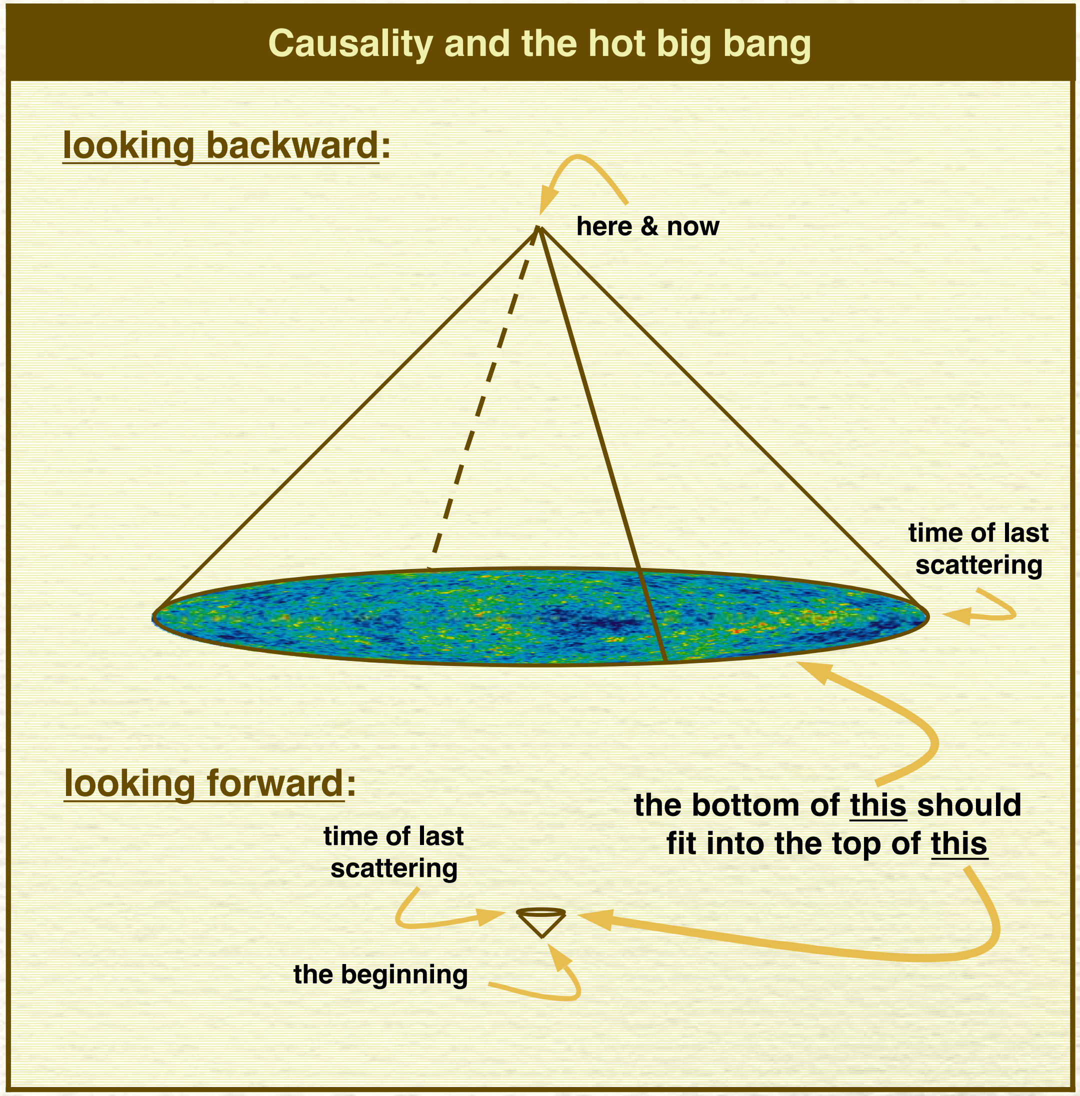
- How could the universe be so smooth at 300,000 years old?

- 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

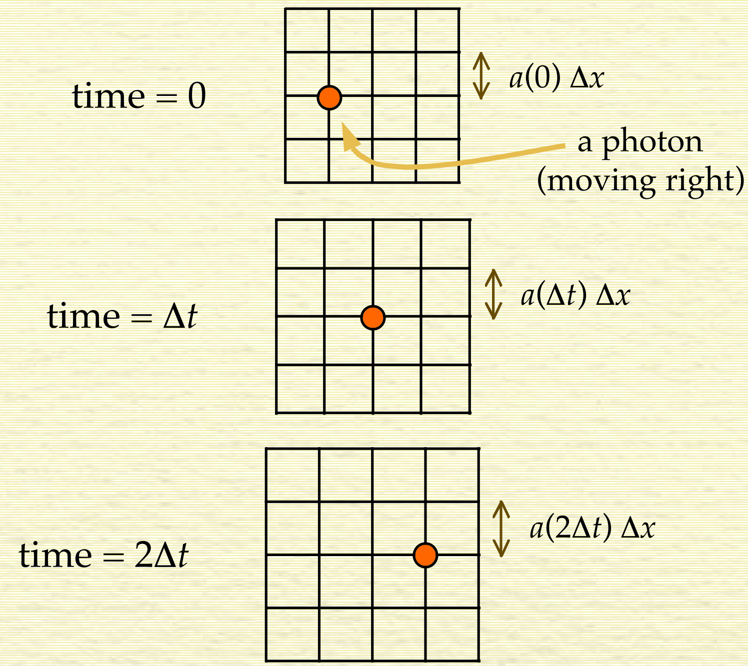
  But globally, general relativity helps:

  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

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

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!
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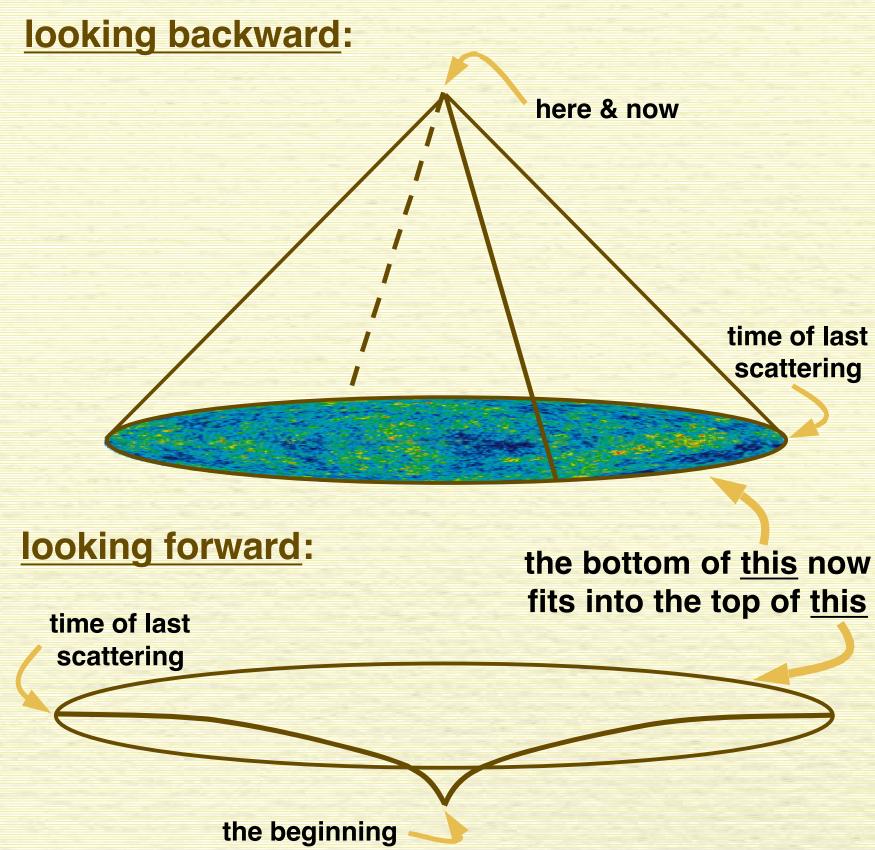
One way to fix this causality problem

If the expansion rate is accelerating, then the photon from the beginning can travel far enough



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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: $\varphi(t,x) \to \varphi_k(t)$
  - power spectrum: $P_k(t)$

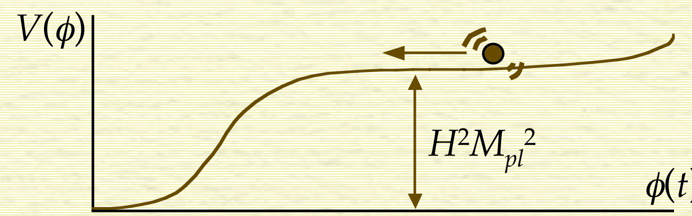
- To understand how inflation works, we shall follow a particular Fourier mode over time

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

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

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

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

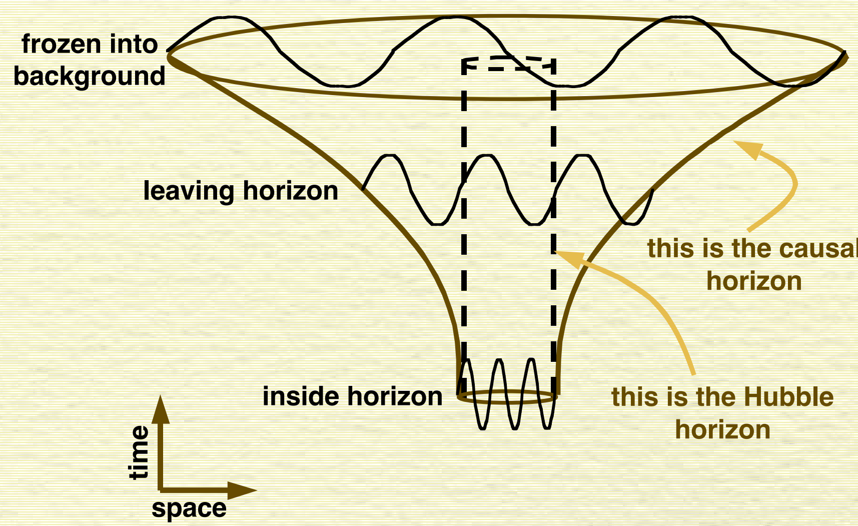
- Stage I: Inflation
  - inside horizon
  - leaves horizon
  - frozen into the background

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:



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

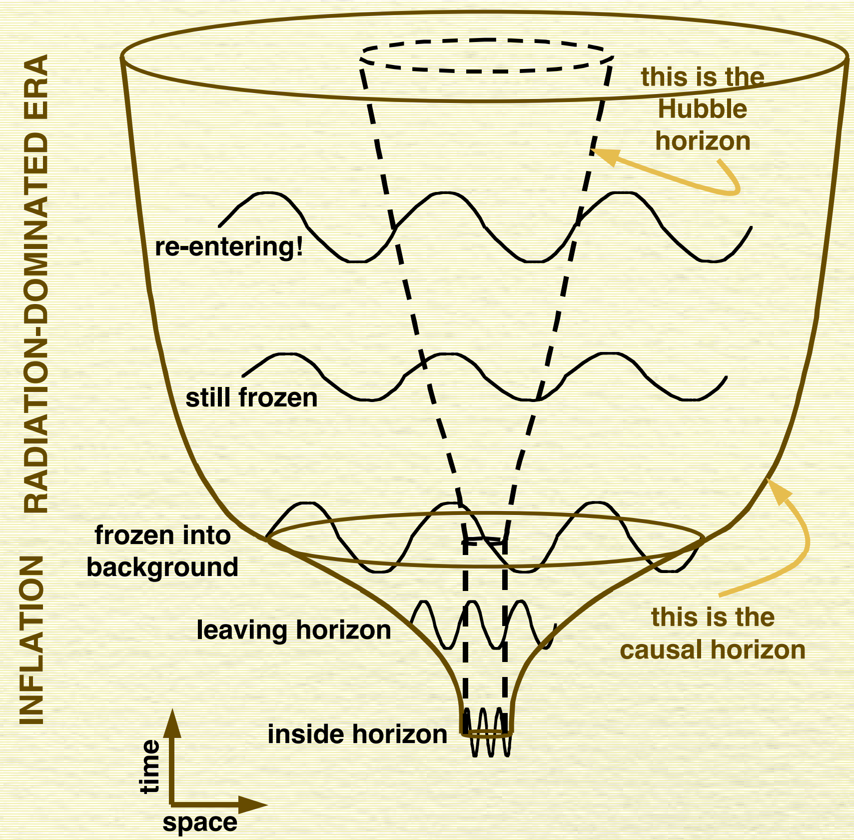
- Analogy:

primordial fluctuations	→	the pebbles
matter & radiation fluid	→	the river

- Together these make the beautiful pattern in the CMB

Second Stage: thawing out

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



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?)

What are the c_l's?

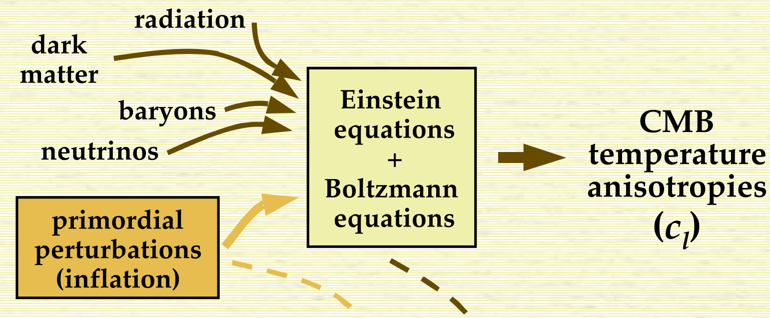
$$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

temperature difference

how much of a mode is present

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

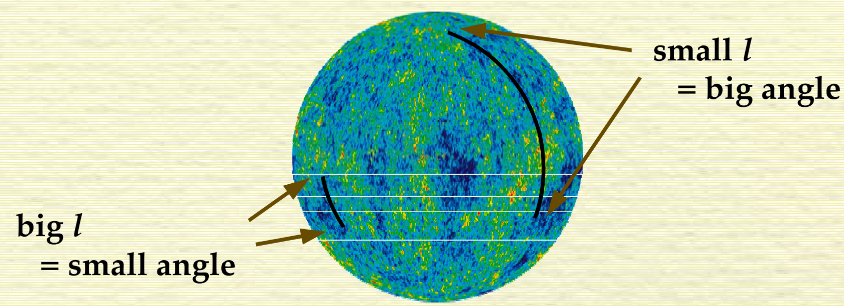
Predicting the CMB



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

Measuring the CMB

To us, the CMB looks like the inside of a sphere



The c_l's tell the likelihood two points are correlated

WMAP (Wilkinson Microwave Anisotropy Probe)

- So, what do we know about the primordial perturbations
  - 2 parameters (so far)

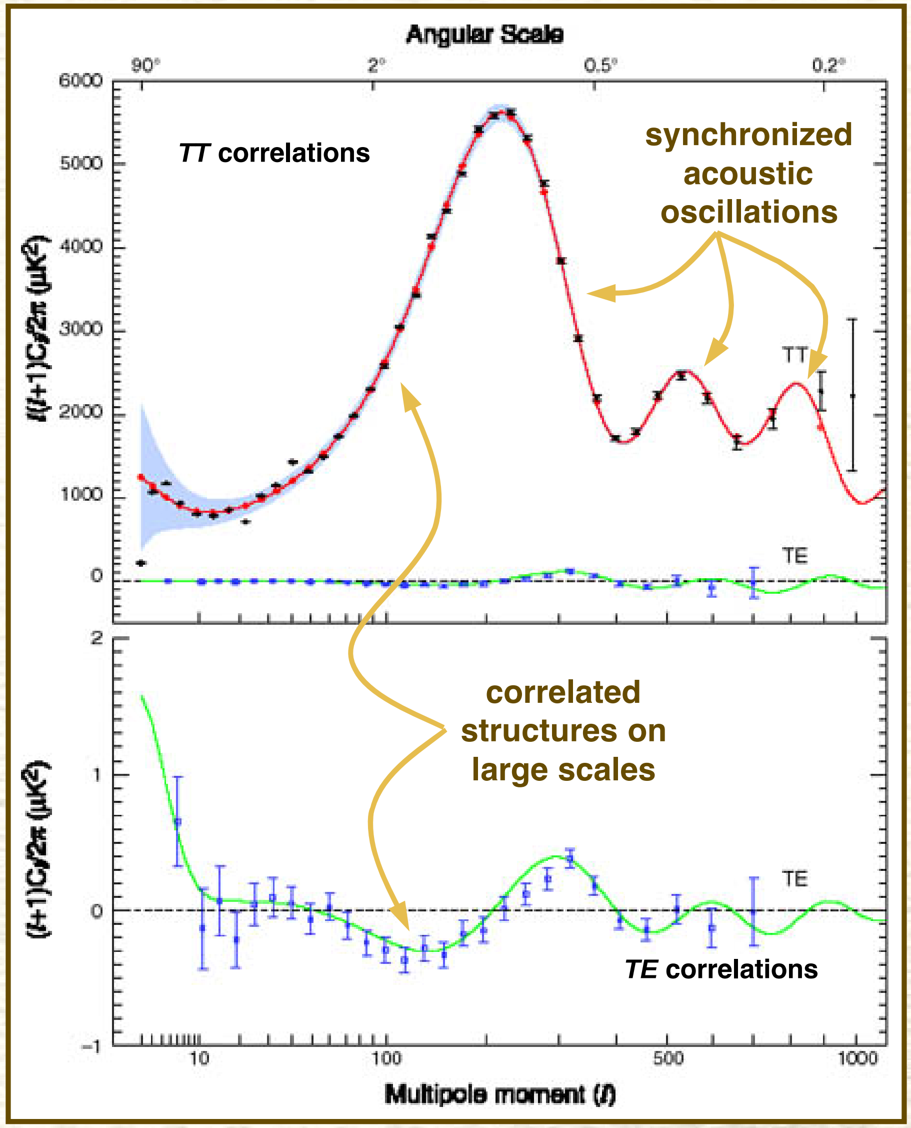
- Precision measurements of the CMB
  - WMAP, Acbar, Boomerang, CBI, VSA, DASI, . . .

6 Parameter Standard Cosmological Model

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

nearly flat primordial power spectrum

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



from the WMAP/NASA science team

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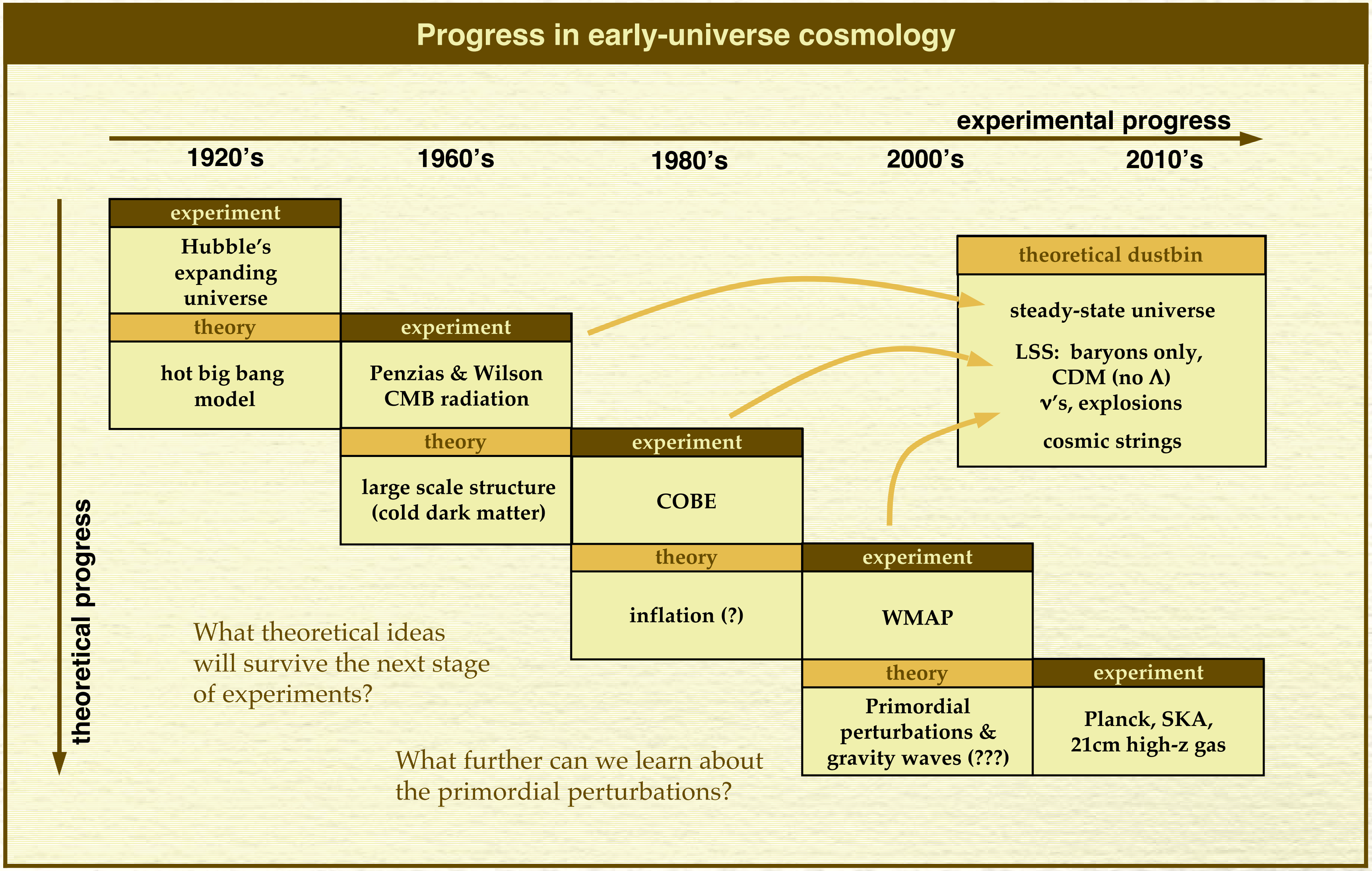
The interplay between theory and experiment



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 somthing 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? → **<u>open question</u>**

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

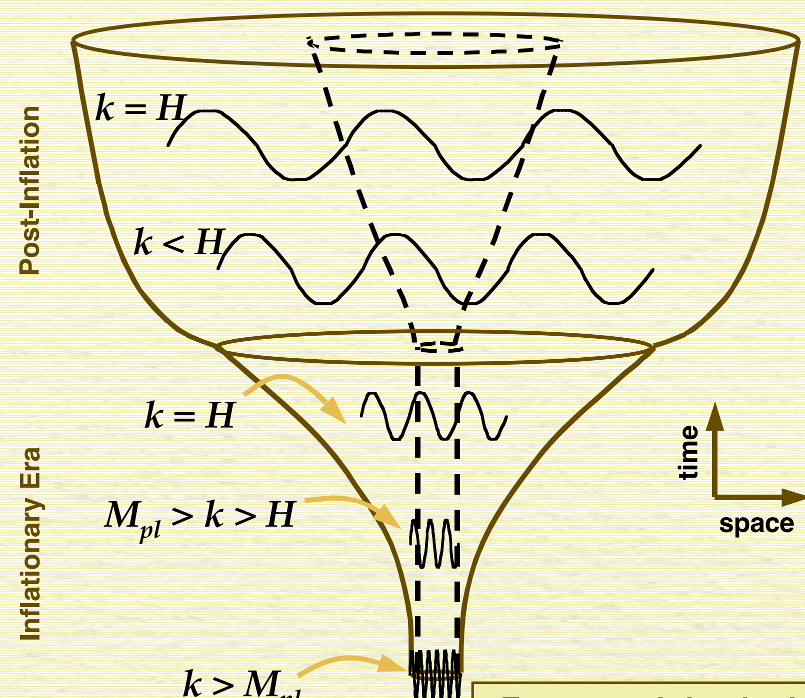
Before we become too optimistic:

“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)

The trans-Planckian problem

Let us look at a little fluctuation again, following farther back in time,



Far enough back, the wavelength is smaller than the Planck length!

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
  [Easther,Greene, Kinney, Shiu]

- Can is this be understood rigorously, in a controlled framework?

- Experimental Question:
  Can these 'trans-Planckian' signals be seen? What is their signature?

The "bottom-up" perspective

Start with an effective theory up to the Planck scale

↑

Determine the signal in the CMB

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

The "top-down" perspective

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
a-states (de Sitter space),etc.

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-Planckain 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?

- <u>The answer: Renormalization</u>
  - large momentum → short distance
  - cancel infinities with local operators

Radiative or loop corrections

From Feynman's original paper on QED,

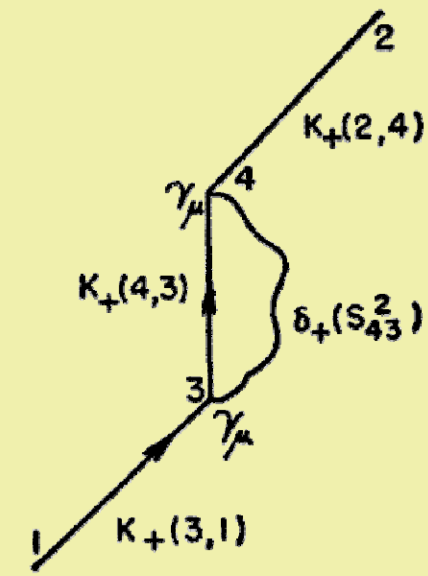


FIG. 2. Interaction of an electron with itself, Eq. (6).

'self-energy' correction to electron mass

$$m_0 \to m_R$$

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)

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

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

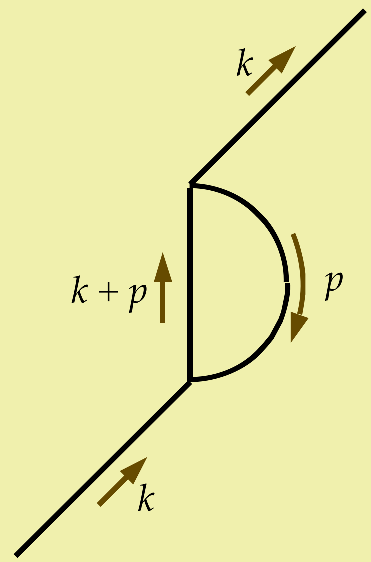
- Infinites are confined precisely to initial time
  - add boundary counterterms to Lagrangian

hep-th/0501158, hep-th/0507081

- Experimental prediction:
  For measurements made at scale Λ ($= k$ or H?) trans-Planckian effects suppressed by

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

Loop corrections for the inflaton



Interaction of an inflaton with itself

Boundary renormalization of Lagrangian, L

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

this part tells how operators evolve

this part tells how states evolve

this part cancels the boundary divergences

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)

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

(effective theory: k/M)

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

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

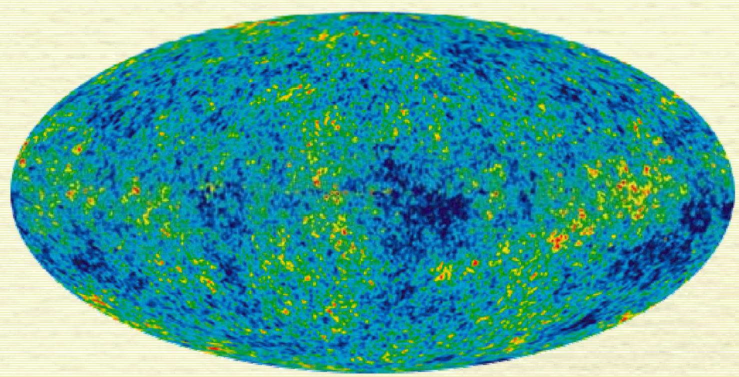
$$P_k = \frac{H^2}{4\pi^2}\left[1 - 2\frac{k}{M}d_1\cos\left(2k\eta + \phi\right) + \cdots\right]$$

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

- CMB experiments: (nearer future)
  - WMAP, Planck, . . .
  - precision: one part in 10^3 or so

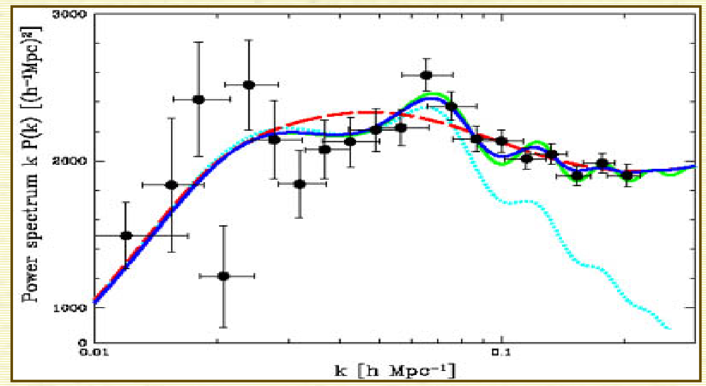
- Large scale structure experiment: (10–15 yr)
  - SKA, 21 cm high-z gas, cosmic inflation probe, etc.
  - precision: one part in 10^5 or 10^6 !

numbers from David Spergel's ISCAP talk

The same ripples appear in the LSS

The primordial perturbations influence the <u>large scale structure</u> (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 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?

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

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)?

How readily are various UV-completions distinguishable?

What is the trans-Planckian signal large scale structure?

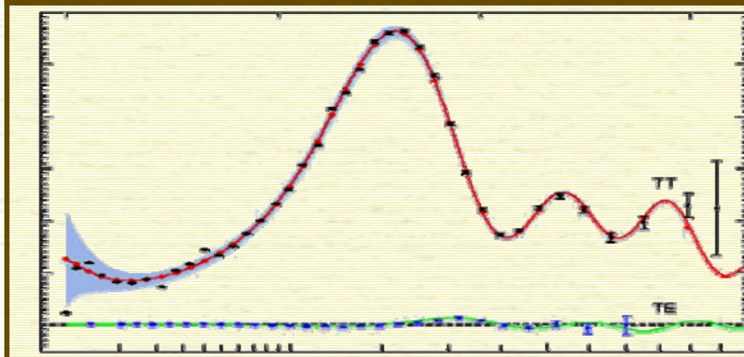
What current bounds does the LSS place on trans-Planckian physics?

What does a particular initial state imply for inflation?

Conclusions

- Cosmology is now a precision experimental science
  - mysterious cosmological 'standard model' [inflation + ΛCDM]
- 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

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

Precision measurements of the CMB & LSS