Beyond the Big Bang

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Colloquium

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Synopsis

- This talk describes the development of the standard cosmological model
- The observations of the relic thermal radiation—the cosmic microwave background—have played an essential part, first in verifying the hot big bang model and more recently in matching with the predictions of inflation.
- With the success of this picture has come a new set of questions. Here we shall give an overview of one of these, the trans-Planckian problem, describing how the tool of effective field theory can be used to address it.

Overview

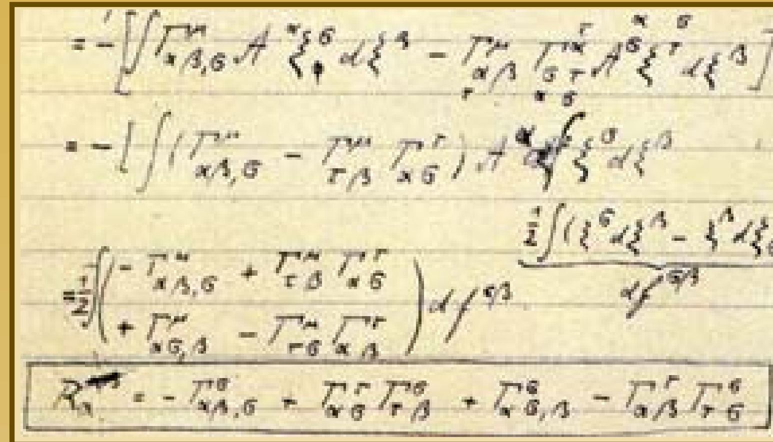
- The origins of a standard cosmological picture and its conceptual limits
- How inflation makes structure
- Conceptual problems of inflation
- An effective theory of initial conditions
- Observational outlook

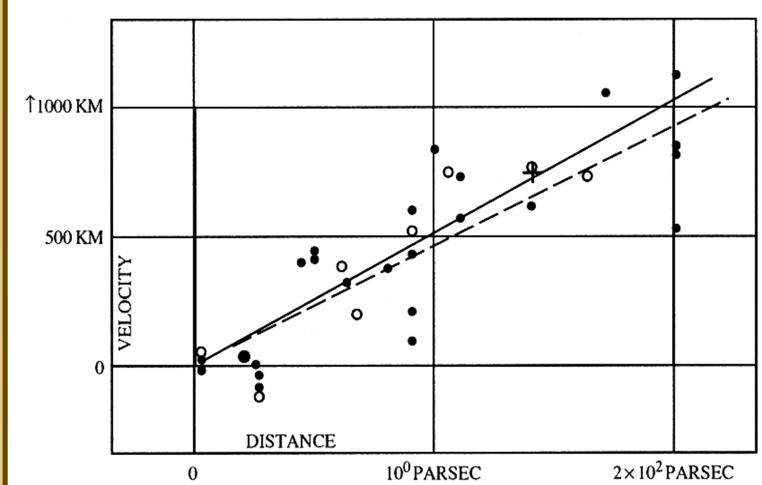
Hubble's discovery

- The development of a standard picture for the evolution of the universe began with two essential ingredients

- During the 1910's, Einstein developed his general theory of relativity
  - describing how the presence of matter or energy distorts the space-time geometry (gravity)

- Not much later, Hubble observed that galaxies tended to be receding from us more rapidly the further away they were
  - there had been a theoretical prejudice for a stationary universe, but Hubble's result demonstrated that the universe was expanding
  - $H = 500$ km s^{-1} Mpc^{-1} (too large)





Hubble's plot (1929)

General relativity

- To follow the expansion of the universe, we introduce a scale factor $a(t)$ that describes how distances are stretched as the universe evolves

- If over very large scales, the stuff of the universe is more or less uniformly distributed, treat it as a fluid
  - with a density $\rho(t)$
  - and a pressure $p(t)$

- Einstein's equations then tell how the scale factor evolves (geometry) depending upon what the universe contains (matter/energy)
  - the solutions are not static, but rather contract or expand
  - given an expansion now, whether it continues or eventually contracts depends upon the total density

$$ds^2 = dt^2 - a^2(t)\, d\mathbf{x} \cdot d\mathbf{x}$$

↓

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

↓

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\frac{1}{a}\frac{d^2 a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)$$

Friedman equations (1922)

Cosmological constant

- Before Hubble's discovery, Einstein had attempted to find a static solution to his equations

- One method is to introduce a constant vacuum energy, a cosmological constant
  - produces an unstable, static solution
  - also an exponentially expanding solution (de Sitter space, no matter)

- Although this solution was regarded as unimportant, this vacuum energy plays an important role and will recur several times in this lecture
  - particle-cosmology connection
  - a foundational aspect of inflation
  - currently most of the density of the universe behaves like a vacuum energy!

this term is small if the geometry changes slowly over an interval $1/M_{\rm pl}$

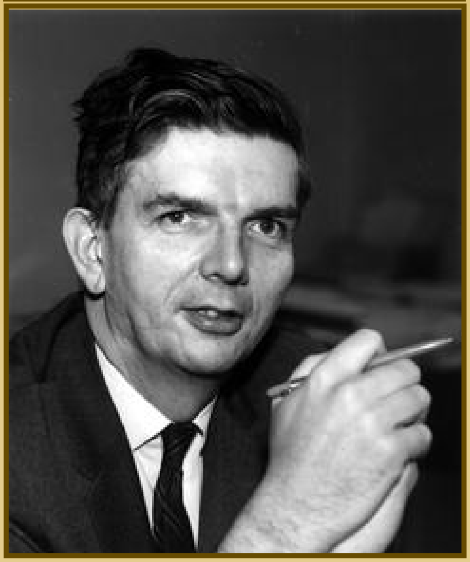
$$S = M_{\rm pl}^4 \int dv \left[\frac{\Lambda}{M_{\rm pl}^2} + \frac{R}{M_{\rm pl}^2} + \cdots \right]$$

but why is this small?

The development of a standard cosmological model

- So by the beginning of the 1930's, we had a basic theoretical framework plus the observation of the expansion

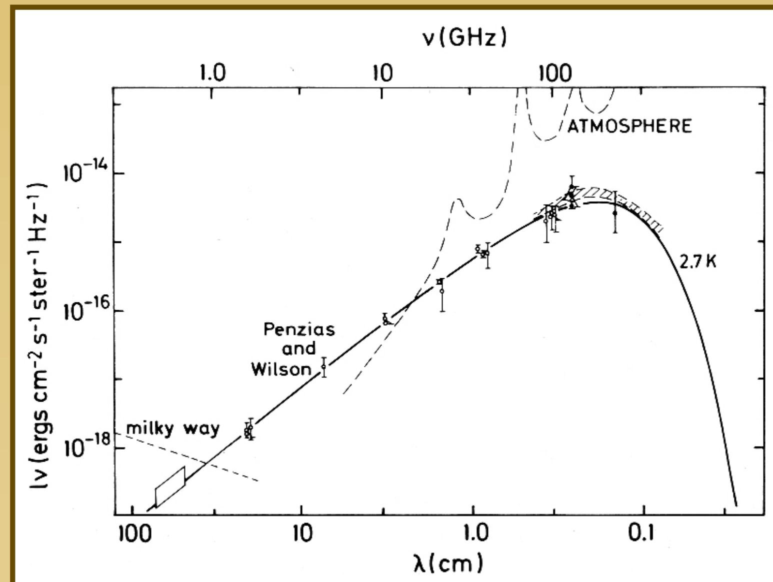
- But it was still many years before the 'hot big bang' model fully emerged
  - Tolman [1934]: expansion of the universe cools blackbody radiation
  - Gamow [1946]: early universe would have been radiation dominated and hot enough for nuclear reactions
  - Alpher-Bethe-Gamow [1948]: dynamic production of elements; blackbody radiation would be 25 K today (high)
  - Dicke/Zel'dovich [early 1960's]: detecting the blackbody radiation would test the hot big bang model
  - Dicke-Roll-Wilkinson: try to detect the radiation left from a 'bouncing' model
  - But 30 miles away in Holmdel, NJ…



The 2.7 K thermal cosmic background radiation

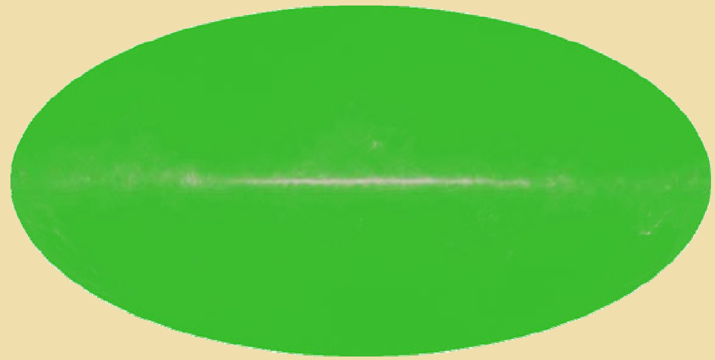
- Penzias & Wilson (1965) first measured the CMB
  - found excess isotropic "noise"
  - $T_0 = 3.5 \pm 1.0$ K at 7-cm wavelength
- Princeton group Dicke, Roll & Wilkinson (1966)
  - $T_0 = 3.0 \pm 0.5$ K at 3.2-cm wavelength
- So this, along with subsequent measurement, confirmed the big bang prediction
  - other popular models, such as the steady-state theory, were incompatible with these observations
- So now we have a good model for what happened back to nucleosynthesis, but what happens if we extrapolate further back?

'WMAP' ca. 1965



Conceptual problems

- Despite its remarkable success in explaining the evolution of the universe, some important pieces were missing
  - how did the very smooth thermal blackbody evolve into the extremely inhomogeneous universe we see locally?
- The simple big bang model, containing only matter and radiation, had some deep conceptual problems if extrapolated arbitrarily far back
- Some more aesthetic
  - flatness problem
  - diluting topological relics (if necessary)
- Some more troubling
  - the horizon problem



the universe at 300,000 years

Conceptual problems: the horizon problem

- Let us look at one of these problems in a little more detail
- Both radiation and matter dominated universes have a beginning
- Let us ask the question:

  how far could a signal travel from the beginning to the time corresponding to CMB?
- If each spatial direction expands by a factor $a(t)$

  matter: diluted by volume, a^3

  radiation: diluted by volume & redshift, a^4
- At the time of last scattering, the causally connected regions are only about one degree of the sky

particle horizon (expanding space):

$$r_{hor}(t) = \int_0^t \frac{c\, dt'}{a(t')}$$

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho$$

$$\text{mat}: \quad \frac{da}{dt} \propto a^{-1/2} \Rightarrow a_M(t) \propto t^{2/3}$$

$$\text{rad}: \quad \frac{da}{dt} \propto a^{-1} \Rightarrow a_R(t) \propto t^{1/2}$$

So the particle horizon is finite for both cases

But then how it possible that all of these disconnected regions look so similar?

Conceptual problems: the horizon problem

- To state the horizon problem a little more dramatically, we can compare
  - the size of the universe now, evolved back to the time of last scattering

  and
  - the size of a particle (causal) horizon using the old hot big bang model

  to find that the present universe at the time of last scattering would contain 10^5 separate causal regions

- The success of nucleosynthesis calculations means that the hot big bang works back to when the universe was only about 100 seconds old
  - at that time the present horizon would contain 10^{25} separate causal regions

- How did all these regions manage to look the same?

particle horizon (expanding space):

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Development of the Standard Model of Particle Physics

- During roughly the same time period, great progress was made in understanding the nature of particle interactions
  - ca. 1910: Rutherford & nuclei
  - 1960's: Glashow, Salam & Weinberg for the electroweak interactions; Gell Mann for the quarks; 't Hooft & Veltman later
- Cosmologically, one result of looking very far back in time is that we are then looking at a much hotter and denser universe
  - there would therefore be a natural connection between physics at the very smallest and very largest of scales
- Can we use ideas from field theory to address structure formation and the conceptual problems of the big bang?

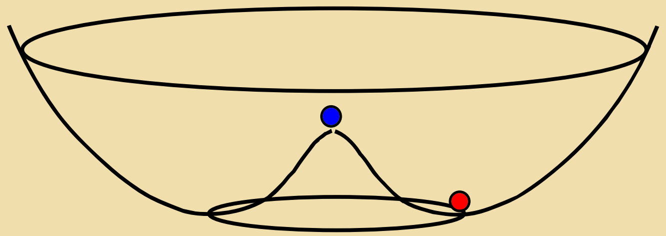
Geiger and Rutherford, ca. 1910

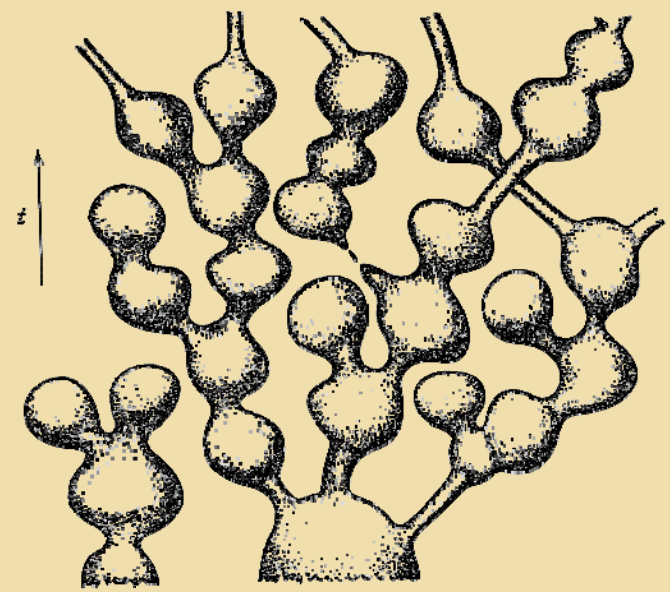
ATLAS detector at the LHC, 2005

Field theories in the early universe

- Many particle models have less symmetry in their vacuum state than are actually present in the dynamics
  - e.g. nature has an $SU(2)_W \times U(1)_Y$ symmetry but only a $U(1)_{EM}$ of this is manifest at low energies
- When we pass from a more symmetric state to a less symmetric state, we often have relics of the symmetric phase, defects (walls, strings, monopoles)
  - at one time cosmic strings were regarded as a good method for generating structure
- another instance of a particle theory in the early universe is inflation
  - originally devised to clean up some problems of the standard big bang
  - as well as remove unwanted defects

$$V(\boldsymbol{\varphi}) = -\tfrac{1}{2} m^2 \boldsymbol{\varphi}\cdot\boldsymbol{\varphi} + \tfrac{1}{24}\lambda(\boldsymbol{\varphi}\cdot\boldsymbol{\varphi})^2$$





Inflation: when a horizon is not a horizon

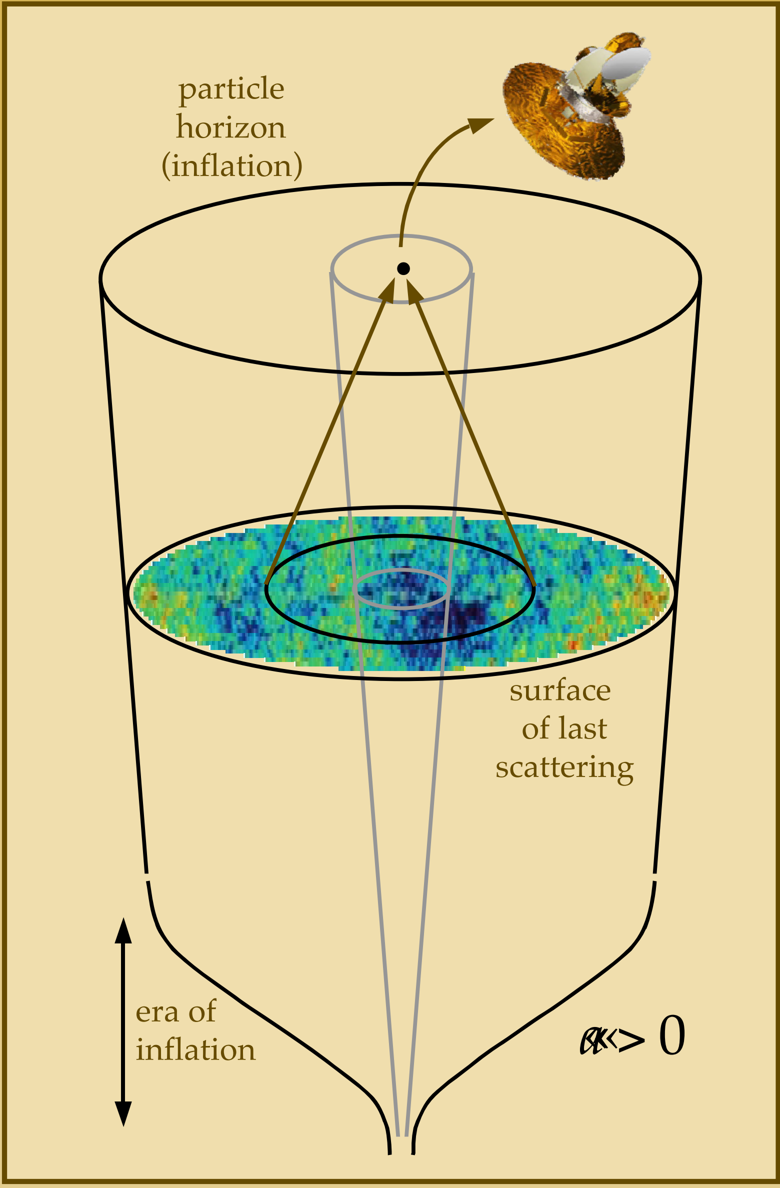
- How could we explain the uniformity of the universe on large scales?
- Let us return to that idea from the beginning, to include a vacuum energy,

$$\left(\frac{da}{dt}\right)^2 = \frac{1}{3}\Lambda a^2 \quad \Rightarrow \quad a(t) = e^{-H(t-t_0)}$$

- So with enough inflation, the observed universe could have evolved from a single causal region,

$$r_{hor}(t) = \int_0^t \frac{dt'}{e^{-H(t'-t_0)}} = \frac{e^{H(t-t_0)}}{H}$$

- What conditions does a field need to satisfy to yield this type of expansion
  - accelerated expansion is sufficient for inflation to occur



General properties of an inflationary model

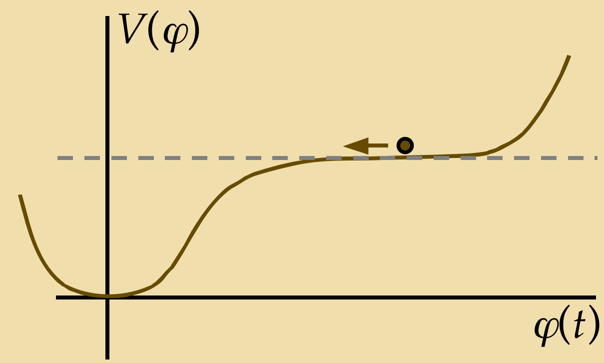
- One of the virtues of inflation is that it is quite easy to construct a field theory which produces an inflationary phase
- Consider a scalar field, $\varphi(t)$, which only depends on time, moving in a potential $V(\varphi)$
  - the potential term simply needs to be greater than the kinetic term for a sufficiently long period
- Very generally we require potential which
  - is sufficiently flat
  - has an accessible minimum very near a vanishing potential
- This is an attractive explanation, but how can we check whether it is correct?
  - structure formation

Scalar Lagrange density:

$$L = \frac{1}{2}\left(\frac{d\varphi}{dt}\right)^2 - V(\varphi)$$

From Einstein's equations:

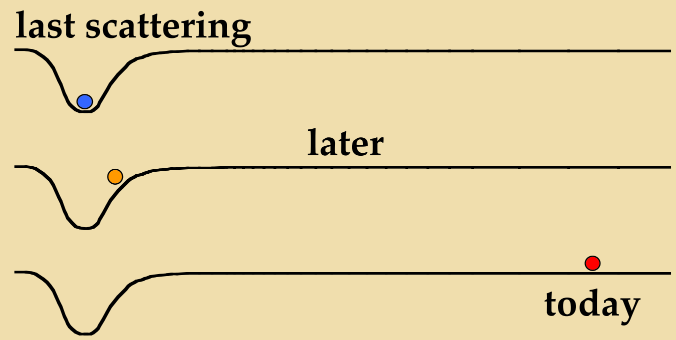
$$\frac{1}{a}\frac{d^2 a}{dt^2} = \frac{8\pi G}{3}\left(V(\varphi) - \left(\frac{d\varphi}{dt}\right)^2\right)$$

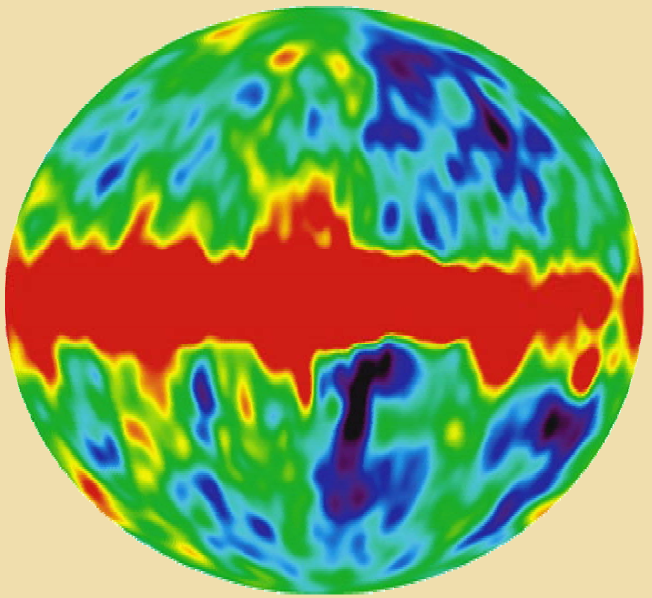


COBE and the size of inhomogeneities

- If ideas for the formation of structure were correct, the same primordial fluctuations that grew in to the large scale structures of the universe should have also left an imprint on the thermal background radiation
- Dense regions will be hotter while thin regions will be cooler (although in climbing out of the potential wells, the hot and cold photons switch roles)
- So if the universe was not quite uniform at recombination, there will be regions slightly hotter or colder than 2.7 K in the background radiation
- This is what was observed by the COBE satellite about 15 years ago
  - fluctuations at about 1 part in 10^5

A photon is a hot, dense region:

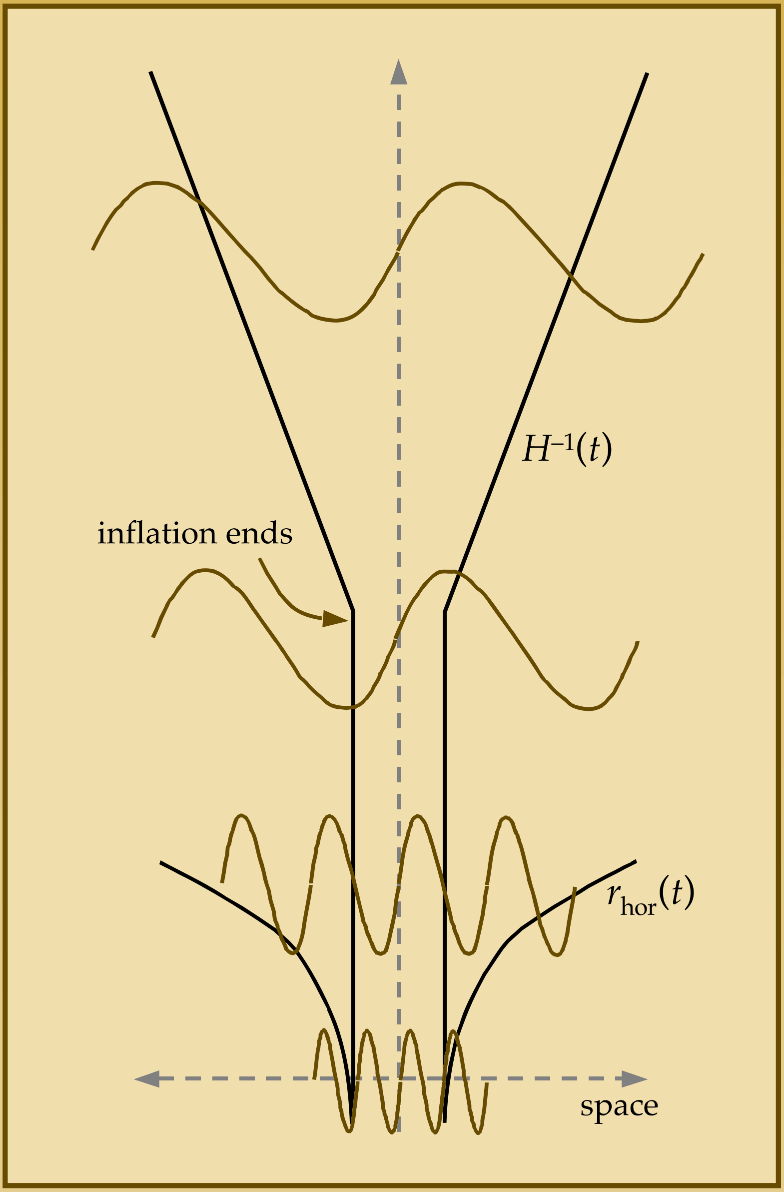




COBE 4 year sky map, ca. 1992

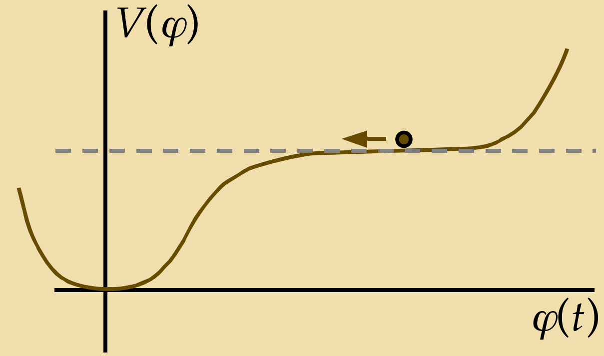
Inflation as a mechanism for structure formation

- One very nontrivial test of inflation is to ask what it predicts for the size and shape of the fluctuations seen by COBE
- Inflation is driven by the potential of a quantum field theory
- A quantum field always has inherent fluctuations
- Because of the rapid expansion of the background, any fluctuations are rapidly stretched
  - once they cross the horizon, they are essentially frozen into the background
  - later these fluctuations reenter the horizon and provide the primordial perturbations



Primordial perturbations from inflation

- What is the shape of the primordial perturbations in inflation?
  - easier to describe in a Fourier transform
  - if the typical structures are $1/k$ big, then the Fourier transform will be larger at k
- If the fluctuations are occurring during the slowly rolling state of inflation, we can treat the potential as constant (de Sitter space again) and solve for the variance exactly
- What emerges is a constant—a flat power spectrum
  - details in the potential (e.g. a slope) will translate into some structure in this power spectrum
- Note that we are implicitly choosing a particular state

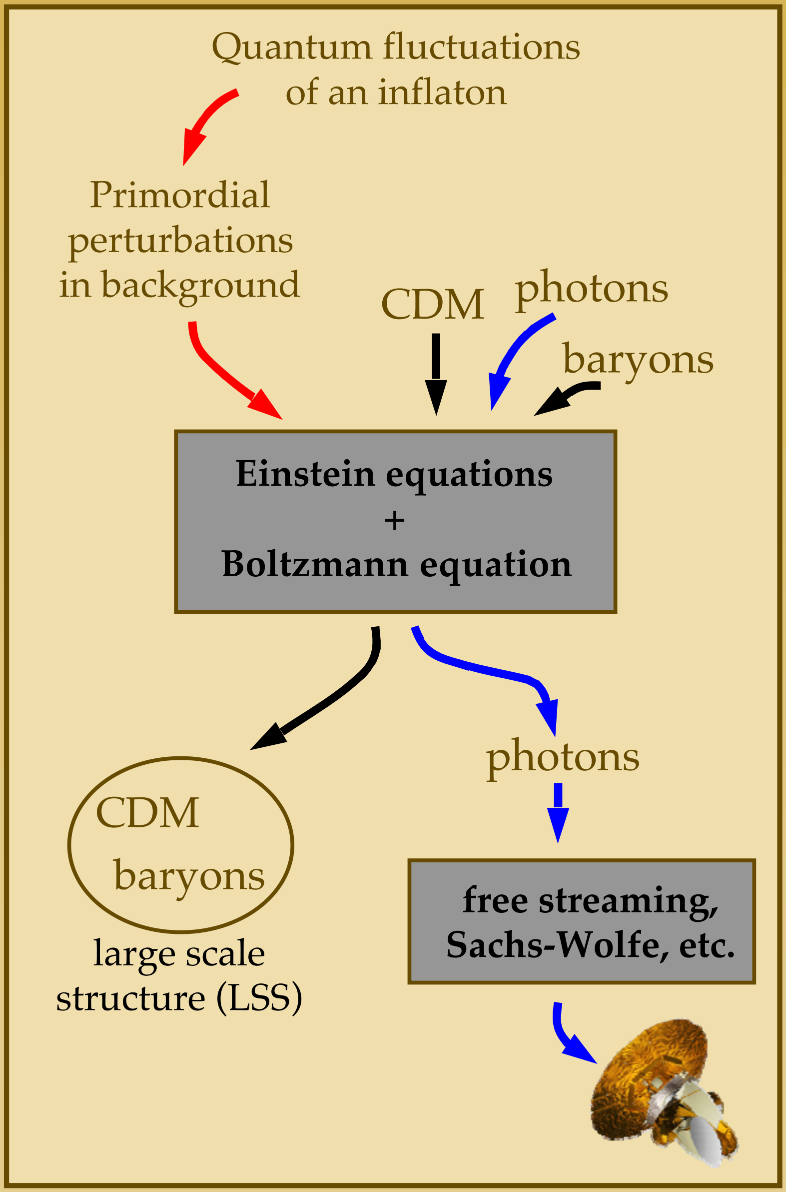


$$\langle 0 | \varphi(t,\mathbf{x})\varphi(t,\mathbf{y}) | 0 \rangle = \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})} \frac{2\pi^2}{k^3} P_k(t)$$

$$P_k(t_{\text{late}}) = \frac{H^2}{4\pi^2} + \cdots$$

The generic predictions of inflation

- Note that the primordial spectrum is not what appears in the CMB
- The input from inflation is that the primordial power spectrum is nearly flat and that only a “cosine” mode is excited (synchronizes the oscillations)
- The power spectrum is connected to it, however, by well understood classical physics—general relativity plus Boltzmann equations—for
  - radiation
  - cold dark matter
  - baryons, etc.
- What emerges is a set of synchronized acoustic oscillations in the CMB, correlated on ‘superhorizon’ scales



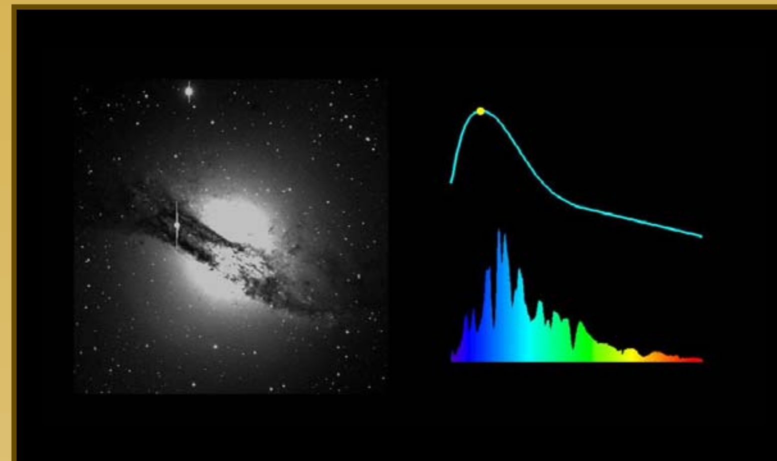
A new ingredient of the universe (an aside)

- Shortly before more precise measurements of the CMB were made, a new component of the universe was detected in careful observations of distant supernovae (type Ia)
  - dimming of supernovae is consistent with a recent acceleration in the expansion

$$\ddot{a}(\text{today}) > 0$$

  - it represents about 70% of the current density of the universe

- So far, all that is known about this component, is that it is consistent with a small, positive cosmological constant
  - cosmological constant, scalar fields, modified gravity, $w < -1$, …

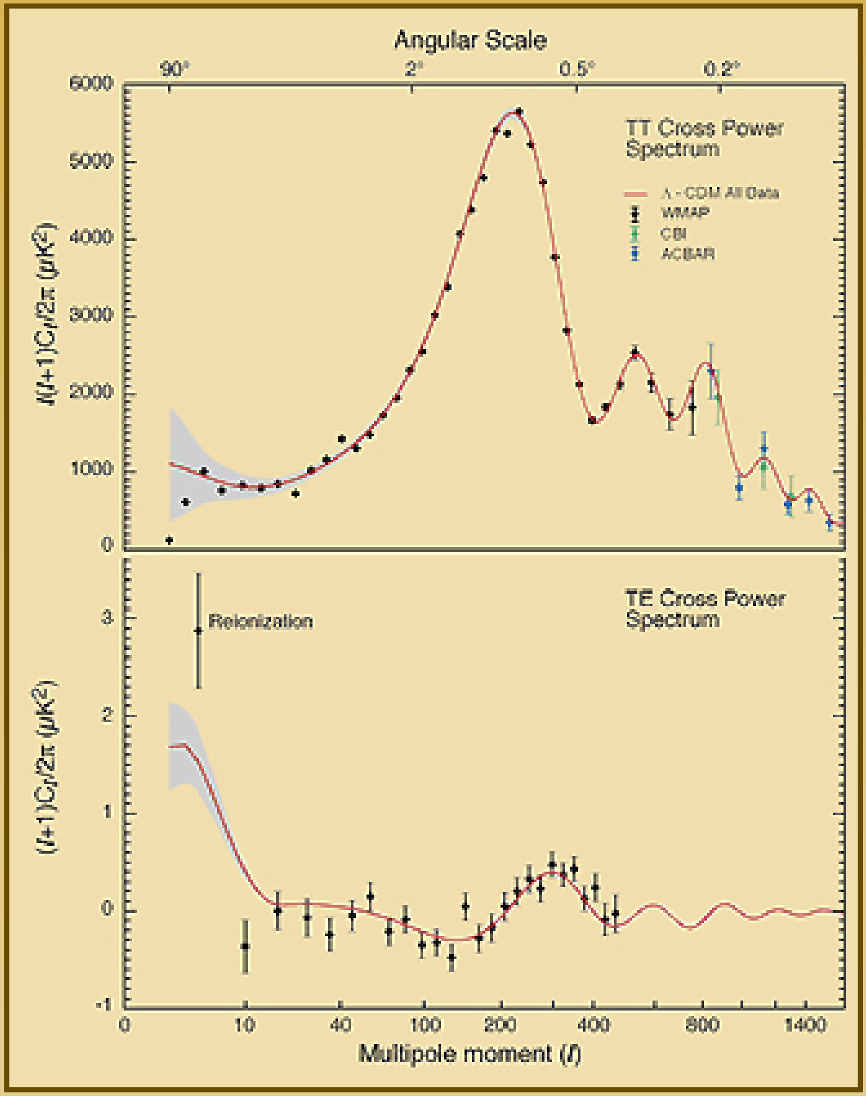


Supernova cosmology project

> **"There is something fascinating about science. One gets such a wholesale return of conjecture out of such a trifling investment of fact."**
>
> **Mark Twain (1874)**

WMAP (first year data, 2003)

- As we have seen, the CMB contains important information about the early universe
  - Holmdel [1965]: hot big bang
  - COBE [1992]: fluctuations
- But with WMAP (along with many other experiments), we are entering an era of precision cosmology
- Results:
  - age: 13.7 ± 0.2 billion years
  - $H_0 = 71 \pm 4$ km s^{-1} Mpc^{-1}
  - $\Omega_{tot} = 1.02 \pm 0.02$
  - $w_{\text{dark energy}} < -0.78$
  - polarization consistent with inflation
- The data can even be used to rule out particular inflationary models

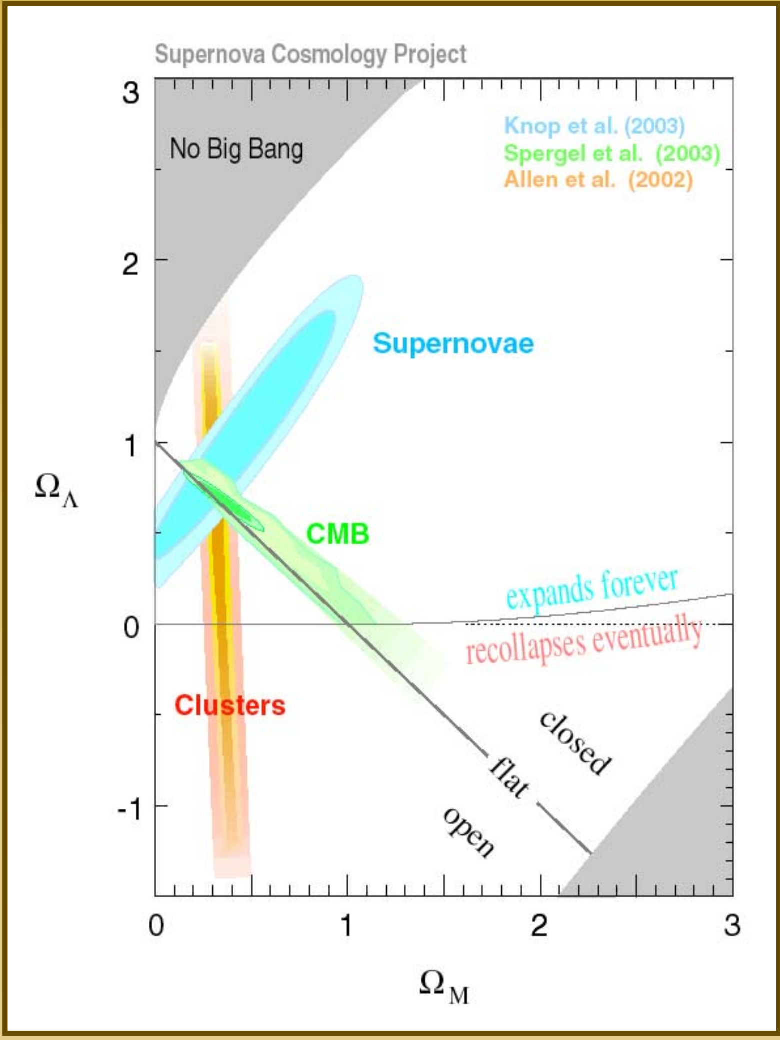


The ingredients of the universe

- WMAP, together with complementary observations from other experiments, is providing a more refined and precise picture of the universe
  - vacuum energy—73%
  - matter (non-baryonic)—23%
  - matter (baryonic)—4%
  - neutrinos, etc.

- The primordial perturbations extracted from the WMAP acoustic oscillations are remarkably consistent with inflation
  - very encouraging, but it is premature to state that we have seen inflation
  - but we can certainly rule out other models, e.g. defects, as the origin of structure

- How can we further test inflation?

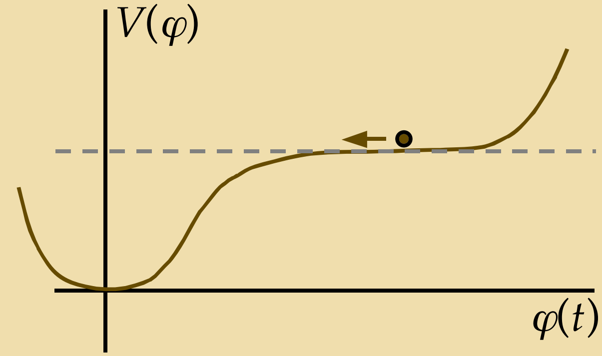


The conceptual problems of inflation

- A substantial amount of theoretical progress was made by extrapolating the old big bang model, with only matter and radiation, and determining what conceptual problems arose

- Similarly, if we attempt to use inflation as a final theory, then we encounter some very odd features R. Brandenberger
  - the trans-Planckian problem
  - the amplitude problem
  - the cosmological constant problem(s)
  - the singularity problem
  - who is the inflaton?

- Let us consider one of these, the trans-Planckian problem of inflation, in a little more detail



why is the potential so flat?

$$V(\varphi)/\Delta\varphi^4 \leq 10^{-12}$$

why is the minimum so close to zero?

$$L_{grav} = M_{\rm pl}^4 \frac{\Lambda}{M_{\rm pl}^2} + M_{\rm pl}^2 R$$

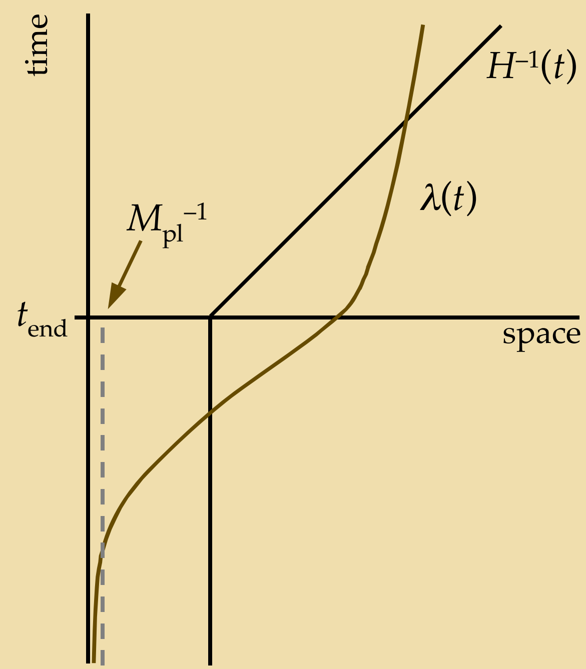
how big are the fluctuations when inflation begins?

The trans-Planckian problem

- This problem is like the old horizon problem in that it comes from extrapolating far enough into the past
- Let us ask the question:

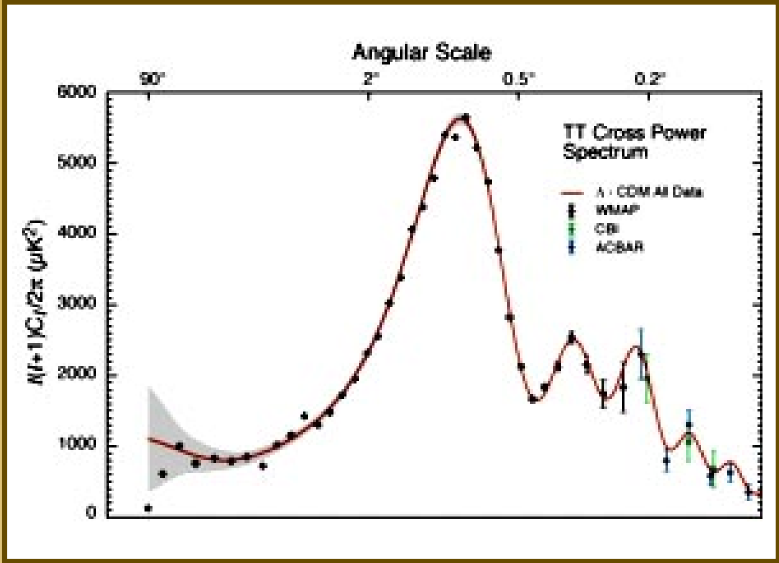
  How big was a fluctuation we see in the CMB when it first occurred during inflation?
- its size will be stretched as the universe expands
  - so the farther back we look, the smaller it was
- If inflation lasted sufficiently long—a bit more than the 65 *e*-folds needed to solve the horizon problem—the size of the fluctuation would be less than the Planck length

follow the evolution of a fluctuation with wavelength λ over time



The trans-Planckian opportunity

- The observation of the 2.7 K thermal spectrum helped to establish the hot big bang model, but even more physics was hidden in the tiny fluctuations about it
- Similarly the WMAP power spectrum confirms many of the expectations of inflation, but what do the fluctuations about it tell us about the universe
  - the very expansion of inflation could provide a means to observe the effects of physics of the smallest of scales at the very largest
- What we need is a consistent framework for treating how such effects would generically appear
  - i.e. we need an effective theory!



$$P_k = \frac{H^2}{4\pi^2} + \cdots$$

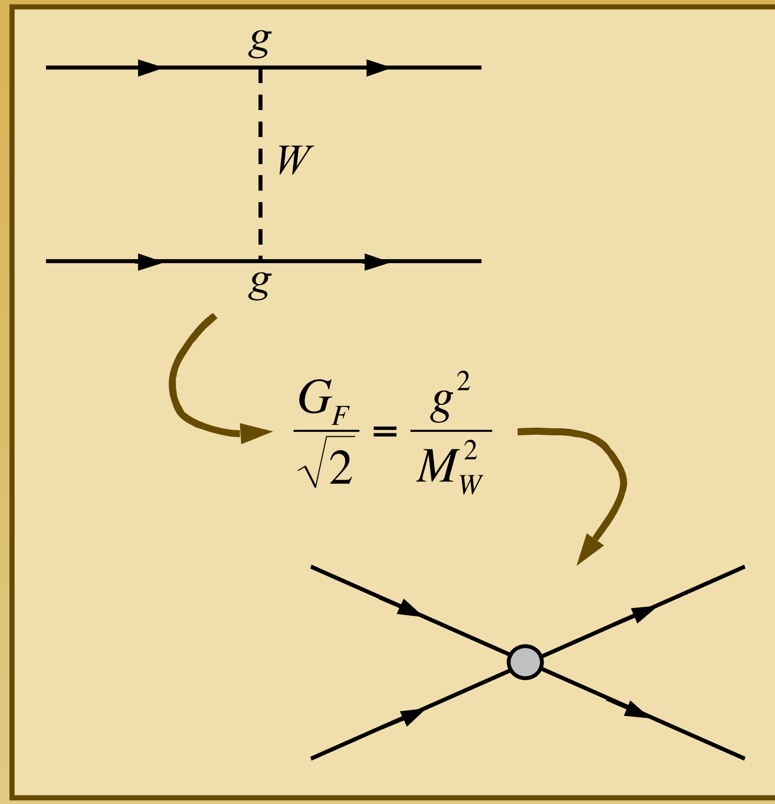
how large are the corrections?

The effective theory idea

- In ordinary field theory we have a well defined prescription for encoding the effects of new physics
  - identify the low energy fields and symmetries
  - write the most general Lagrangian from the former consistent with the latter
  - the nonrenormalizable operators correspond to the signatures of new physics

- In a quantum theory there are two aspects of any measurement
  - the operator
  - the state

- Because of the stretching of scales in inflation, we must be careful how we describe the short distance features of the state



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

$$\langle 0_{\rm eff} | \big(\varphi(x)\varphi(y) + \cdots\big) | 0_{\rm eff} \rangle$$

An effective treatment of the inflationary state

- The basic philosophy of the effective state idea is to construct a systematic way to encode our ignorance about the structure of the state at lengths smaller than those that have been tested
  - choose its long-distance structure phenomenologically (e.g. ‘vacuum’)
  - but provide a way of representing the *leading* signatures of new physics, *model-independently*

- The construction:
  - define a cut-off, M
  - define a state at an initial time, $t = t_0$
  - add general structure to the state at lengths below $1/M$
  - renormalize the boundary divergences from loops
  - renormalize the boundary geometry from the energy-momentum tensor

Mode construction:

Collins & Holman, 2005–2006

Operator construction:

Greene, Schalm, Shiu & van der Schaar, 2004–2005

Key results:

hep-th/0501158: flat space

hep-th/0507081: curved space

hep-th/0605107: renormalize the energy-momentum tensor

Future:

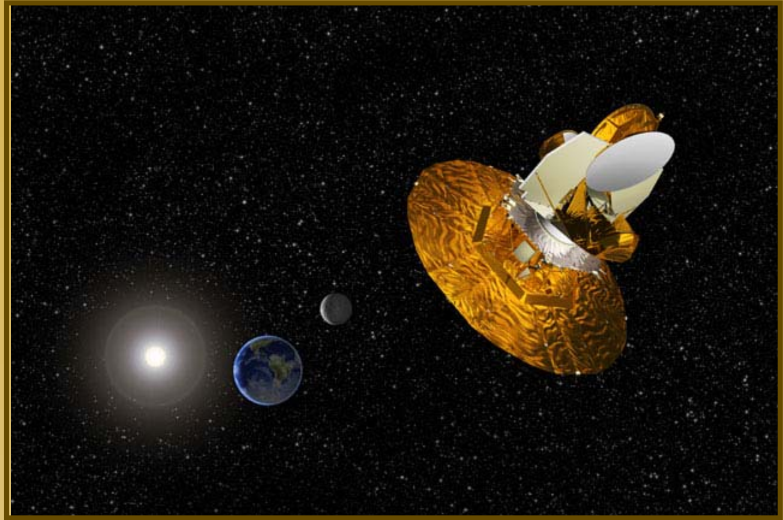
- fit to CMB
- compare to trans-Planckian models

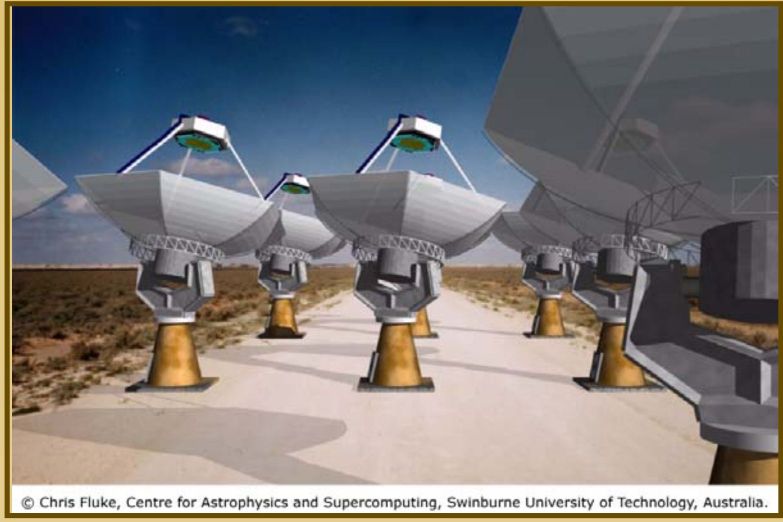
Observation of the primordial perturbations in the CMB

- What is the prospect for observing small effects in the primordial perturbations?

- Note that both matter, in the large scale structure, and radiation, in the CMB, trace these perturbations

- Radiation
  - WMAP (1 year): $l_{\max} = 300$
  - WMAP (6 year): $l_{\max} = 600$
  - Planck: $l_{\max} = 1500$
- Gravity waves
  - WMAP, Planck, balloons, CMBPOL
  - would help fix the value of $H_{\inf}$
- Large scale structure
  - Square kilometer array (10 x SDSS)
  - 21 cm high redshift gas
  - cosmic inflation probe (look to $z \approx 2$)





Observation of the primordial perturbations in the LSS

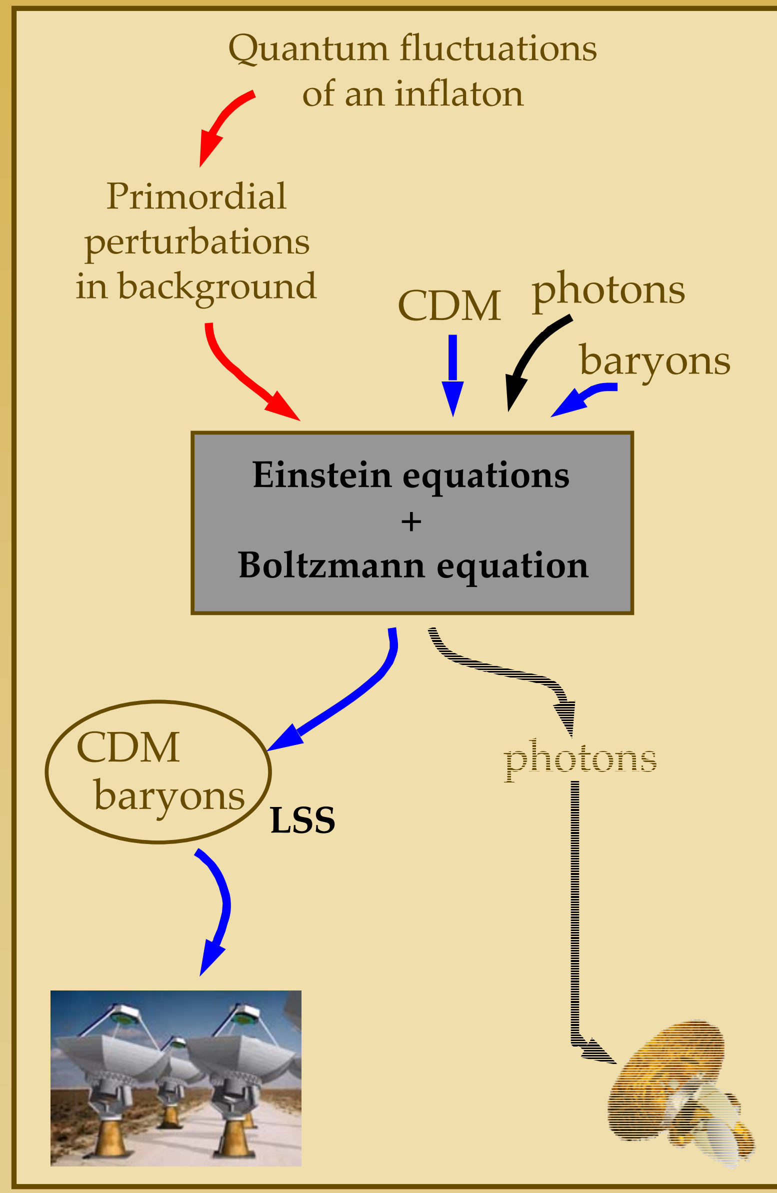
- The same acoustic peaks also appear in the large scale structure (SDSS), before the non-linear growth of perturbations sets in

- Future experiments to measure the large scale structure are being developed that will map much larger volumes of the universe (21 cm line)

- So how accurately will the power spectrum be measured?

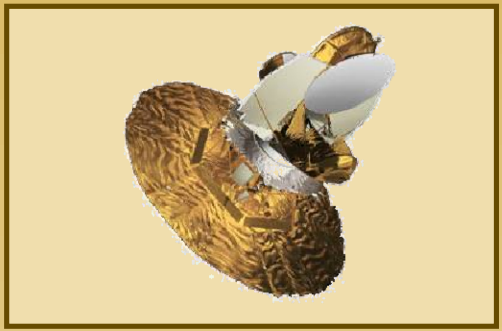
Spergel (ISCAP, 2005)

  - today 10^{-2}
  - soon (WMAP/Planck) 10^{-3}
  - planned galaxy surveys 10^{-4}
  - future galaxy surveys 10^{-5}
  - theoretical limit 10^{-6}

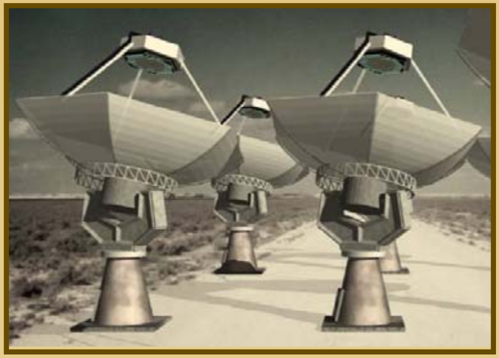


Conclusions

- This is a very exciting period for cosmology, recalling something of the flavor of particle physics in the early 1960's (prior to the Standard Model)
  - some important pieces have been confirmed experimentally
  - but many baffling aspects remain (conceptual problems of inflation, dark matter, vacuum energy, cosmological constant)
  - precision experiments and satellites



- The predictions of inflation have been observed in WMAP, but as a theory it has many open questions
  - trans-Planckian signal, which inflationary model, etc.



- Since these questions concern the universe in a very energetic state, particle theory provides the natural set of tools to address them
  - effective theory ideas