Inflationary Cosmology

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Lecture Outline

- THEME: A simple cosmological model, a vacuum energy dominated flat universe with scale invariant Gaussian random phase fluctuations, fits a host of astronomical observations. What is the basis of this model? What are the key open questions?

I. Inflation: Motivation and Implications

II. General Relativity: Dynamics and Linear Theory

III. Microwave Background Fluctuations

IV. Open Questions and Future Observations

Minimal Cosmological Model

Inflation [V(ϕ)]

Baryogensis

Dark matter physics

Age of Universe

A , n, baryon density ($\Omega_b h^2$), matter density ($\Omega_m h^2$), h

Matter Transfer Function

Radiation Transfer Function

Conformal Distance $\eta(z)$

Luminosity Distance

Angular Diameter Distance

CMB Angular Power Spectrum

c_l

Matter Power Spectrum

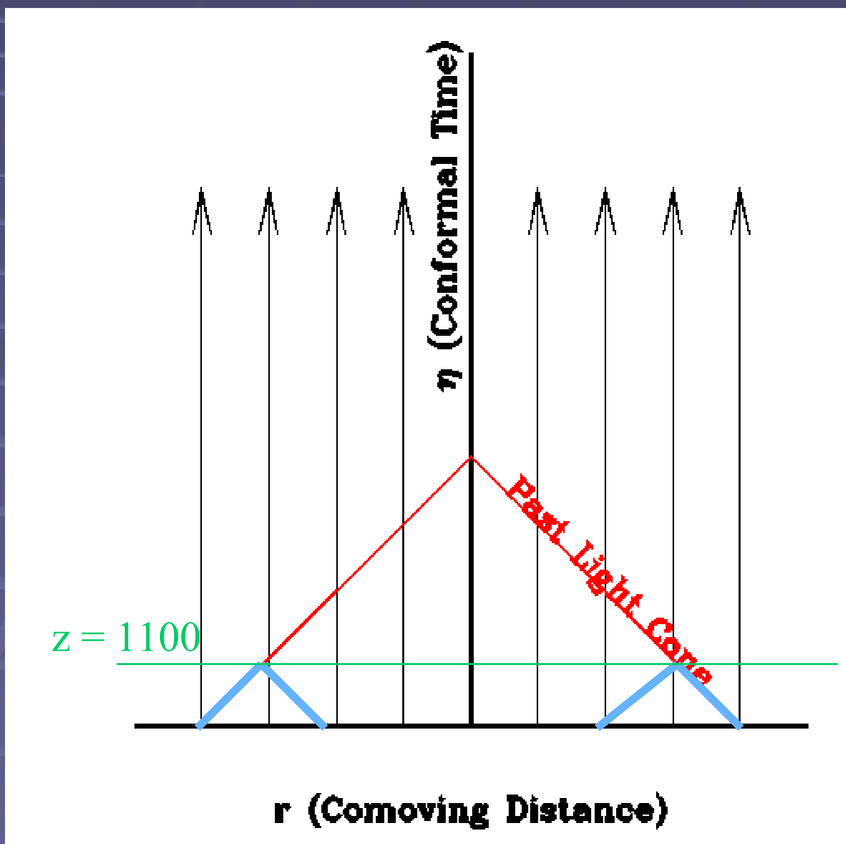
P(k,z)

Volume Tests

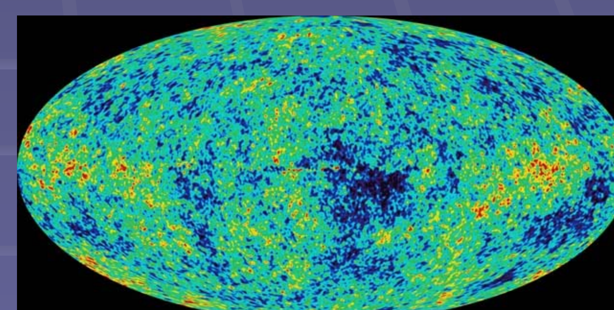
Problems with standard cosmology

- Imagine a large class taking an exam
- At the end, they all hand in exactly the same exam.
- You <u>know</u> there has to have been communication between them!

Problems with standard cosmology



- Imagine a large universe
- Regions out of causal contact have the same temperature.
- You know there has to have been communication between them!



Origin of Fluctuations Problem

- Each student's test has to differ from the other students by 0.01% (or equivalently the density of the universe must vary on superhorizon scales by 0.01%)
- Universe must be nearly smooth, but not completely smooth
  - Otherwise, no galaxies, no stars, no talk today…

The universe needs to be smooth, but not perfectly smooth

Flatness Problem

- Why is the universe so big?

curvature scale >> Planck length$=10^{-35}$ m

- Why is the universe so old?

age >> Planck time $=10^{-43}$ s

- Why is the energy of the universe so close to 0?

In an FRW cosmology, $\Omega = 1$ is an unstable fixed point

Today, $0.98 < \Omega < 1.02$

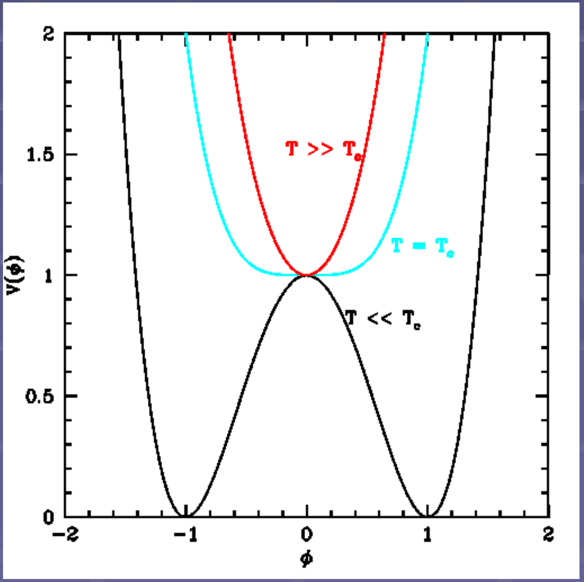
z=1000 $0.9998 < \Omega < 1.0002$

BBN $1-10^{-18} < \Omega < 1+10^{-18}$

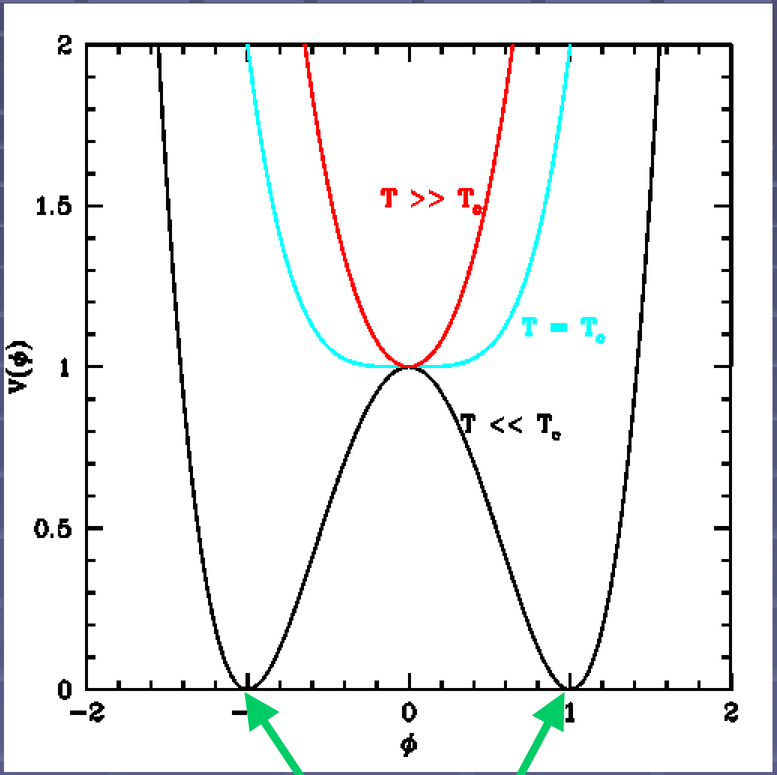
Symmetry breaking & Cosmology

- Symmetry breaking is a fundamental idea in modern particle physics
  - Electoweak $\Longrightarrow$ EM + Weak
  - Massless particles $\Longrightarrow$ Massive particles

$$V(\phi) = \lambda(\phi^2 - m^2)^2 + T^2\phi^2$$



Topological Relics



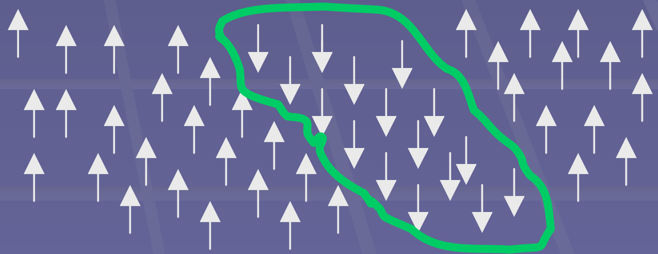
Domain Walls: N=1

Cosmic Strings: N=2

Monopoles: N=3

Multiple minima

Domain Wall



Monopole Problem

- ANY fundamental theory whose end product is the standard model of particle physics (SU(3) x SU(2) x U(1)) will produce monopoles

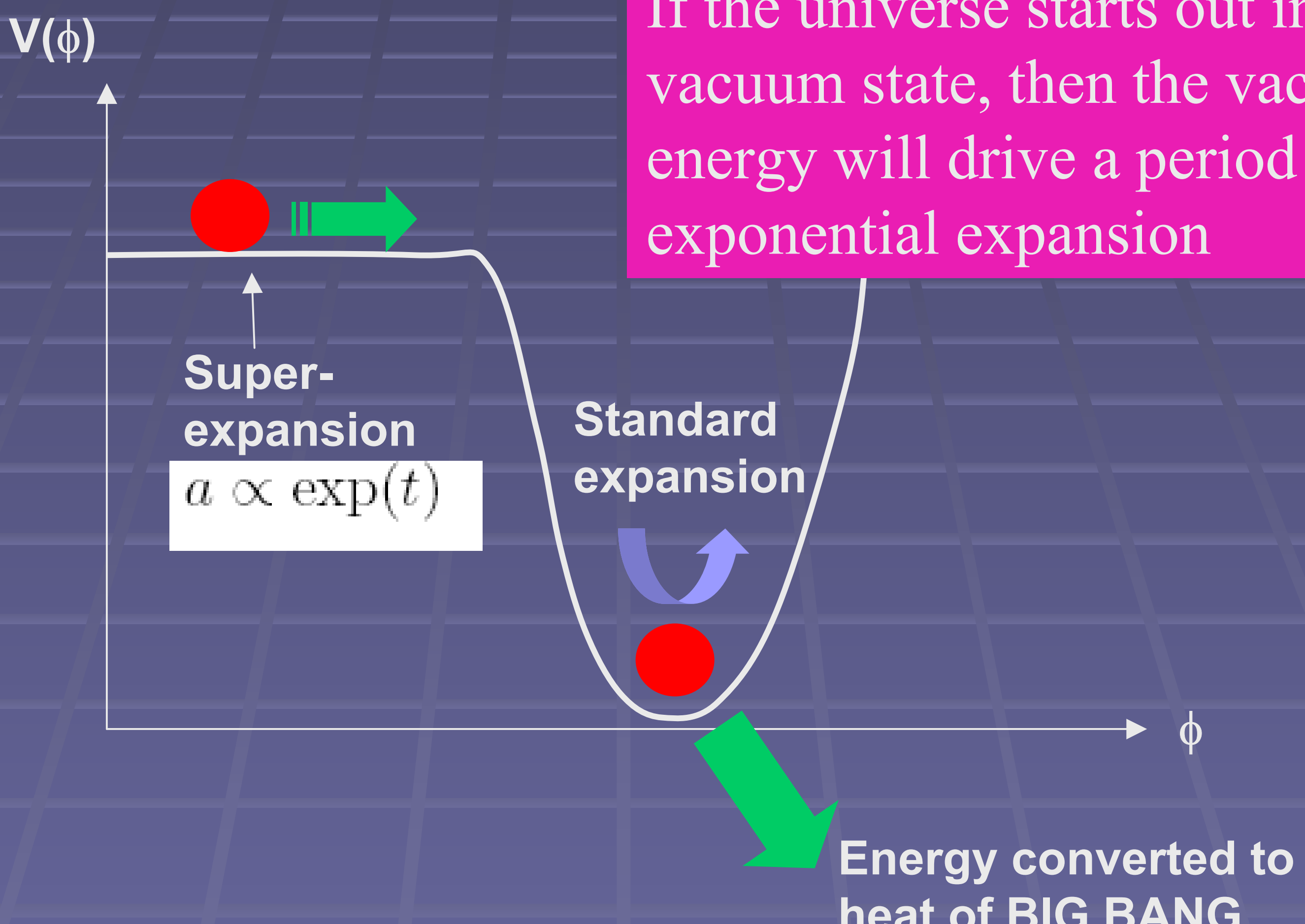
e.g. SU(5) ->

SU(3) x SU(2) x U(1)

The energy density in monopoles would dominate the energy of the universe

Phase Transitions aren't the Problem…. They are the Solution!

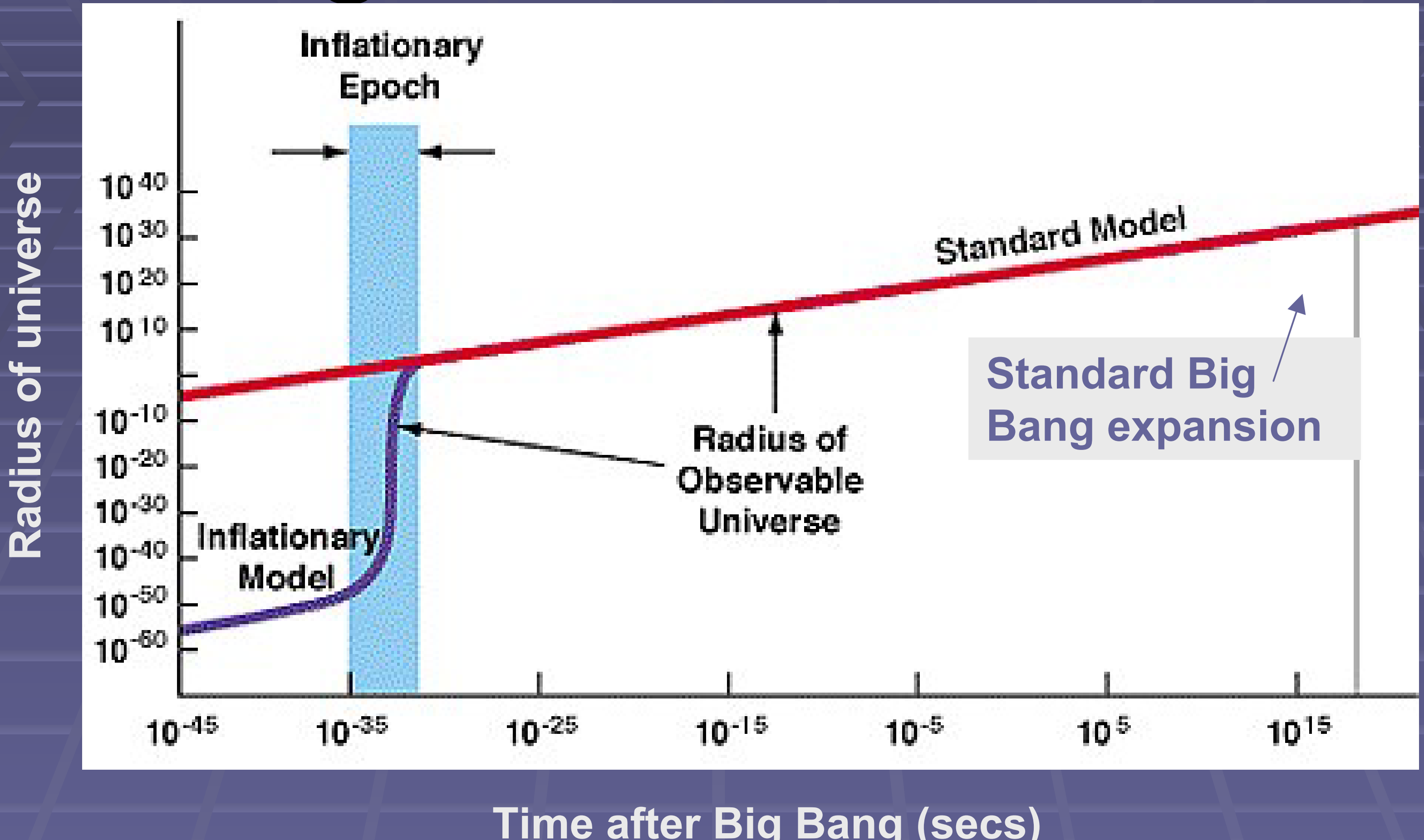
If the universe starts out in a false vacuum state, then the vacuum energy will drive a period of exponential expansion



Is Vacuum Energy Domination Plausible?

- Symmetry breakings are a fundamental part of modern physics.
- Universe appears to be vacuum energy dominated today
- If the vacuum energy is dominating now, why couldn’t it have dominated in the past?

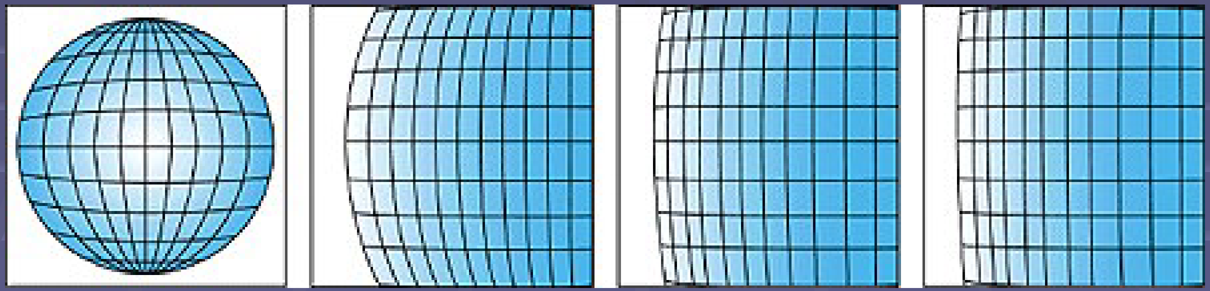
Solving the Horizon Problem



If super-expansion lasts long enough, CMB patches on opposite sides of the sky would have been close enough to communicate in the primordial times.

Inflation solves Flatness Problem

- If the super-expansion epoch lasts long enough, an initially highly curved region gets so blown up that a small region on it looks flat



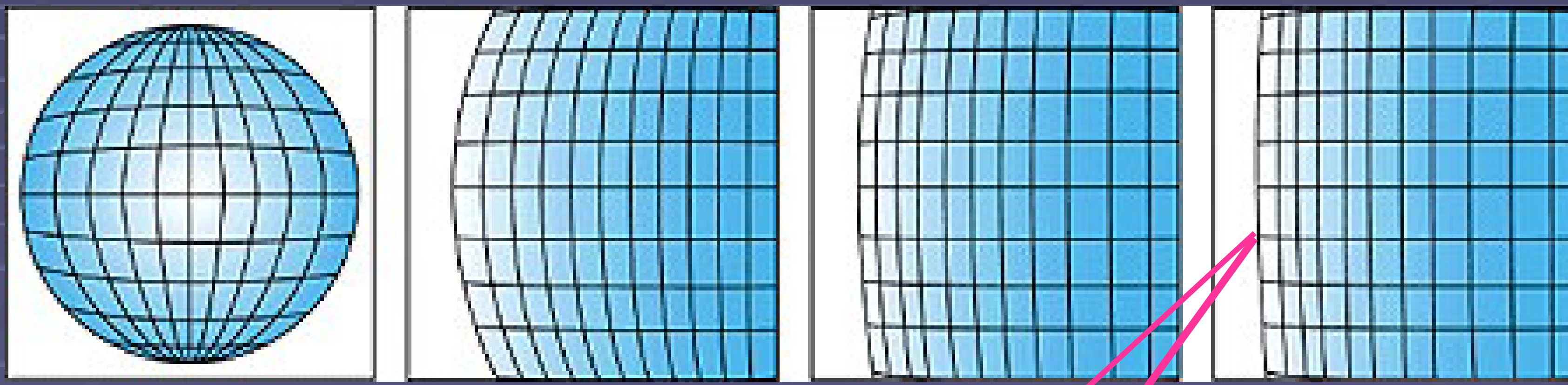
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3c^2} + \frac{c^2}{R_c^2 a^2}$$

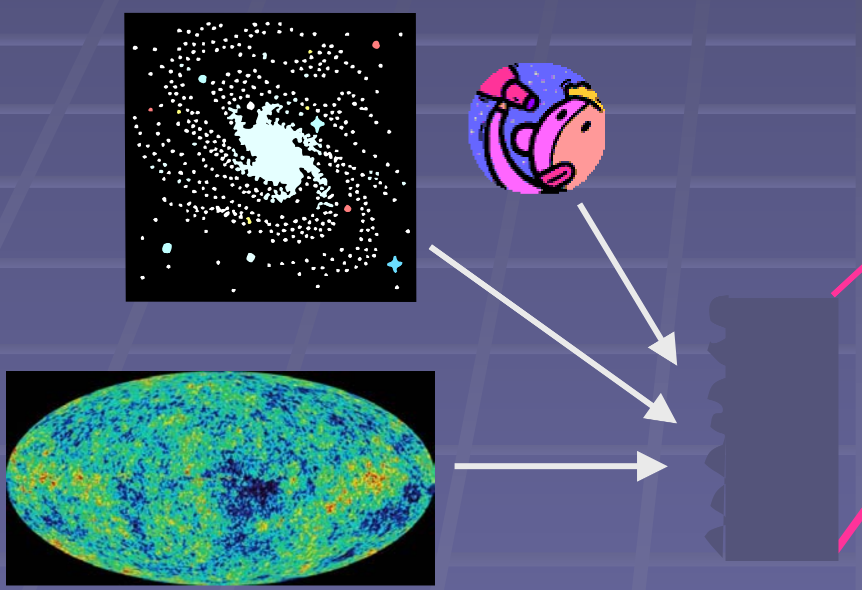
During inflation, $\Omega = 1$ is a stable fixed point

Inflation & Initial Conditions

- Inflation exponentially reduces the density of unwanted relics from the early universe
  - Goodbye, monopoles!
- Inflationary models are relatively insensitive to initial conditions
  - Acts as an “attractor” solution
  - Reduces the need for “fine-tuning” of initial conditions
- Eternal Inflation: solution to initial condition problem

Inflation creates quantum ripples





Inflation created quantum ripples that forms all the structures in the universe!

Predictions of Standard Inflation

- ✓ The geometry of the universe is flat.
- ✓ The fluctuations in the primordial density in the early universe had the same amplitude on all physical scales.
- ✓ That there should be, on average, equal numbers of hot and cold spots in the fluctuations of the cosmic microwave background temperature.

Gaussianity of Fluctuations

- No detectable three-point function
- One point function is a Gaussian distribution
- One number (an amplitude) characterizes the initial fluctuation spectrum

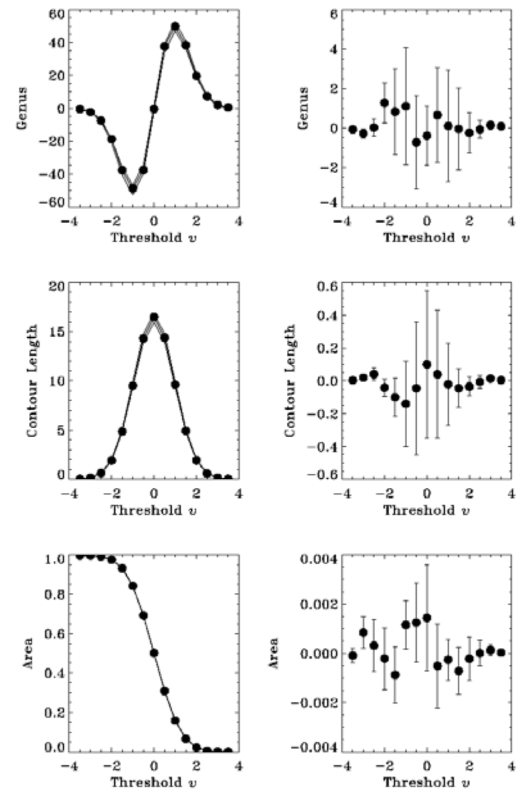
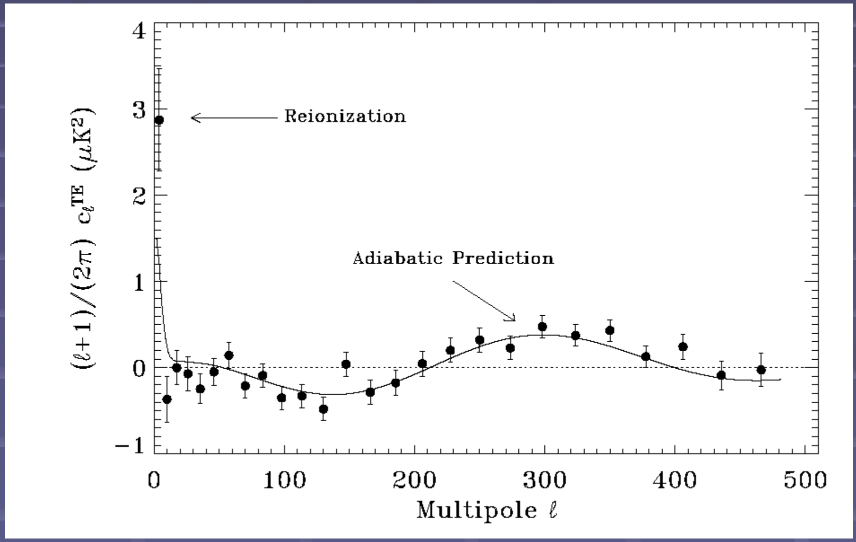


Fig. 2.— The left panels show the Minkowski functionals for *WMAP* data (filled circles) at *nside* = 128 (28′ pixels). The gray band shows the 68% confidence interval for the Gaussian Monte Carlo simulations. The right panels show the residuals between the mean of the Gaussian simulations and the *WMAP* data. The *WMAP* data are in excellent agreement with the Gaussian simulations.

Komatsu et al. 2003

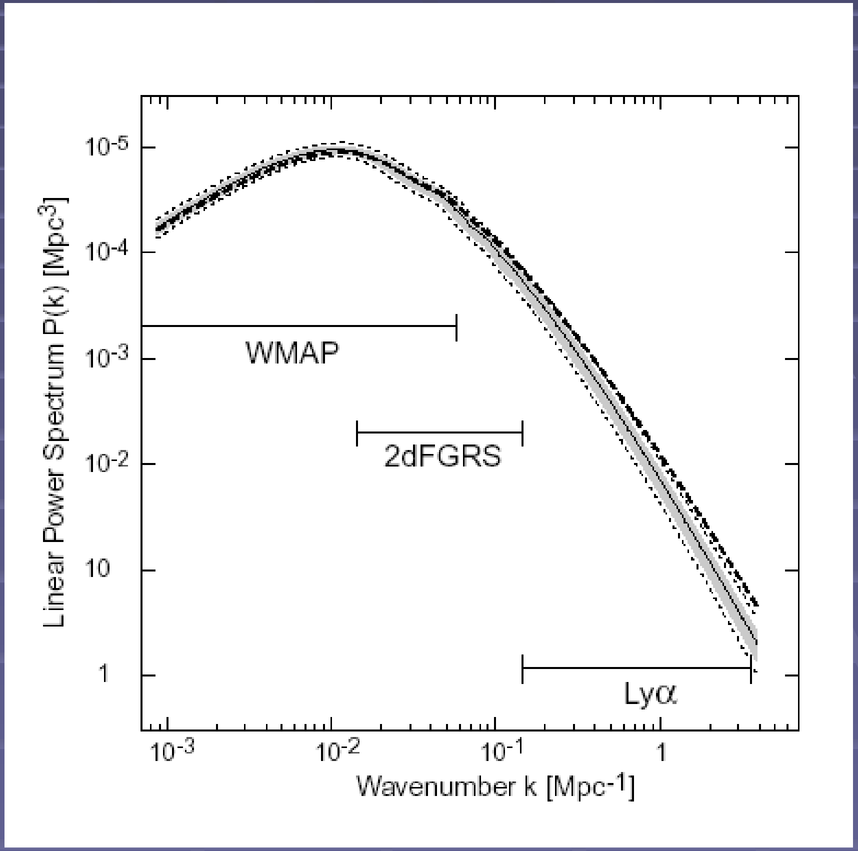
Primordial Fluctuations are Adiabatic

- The CMB TE data requires that there were superhorizon adiabatic fluctuations
- Inflation predicts these fluctuations.
- Without inflation, we need to put these fluctuations in as initial conditions



Fluctuations are (Nearly) Scale-Invariant

We have probed more than 11 orders-of-magnitude in mass scale and found that the primordial fluctuations are scale invariant!

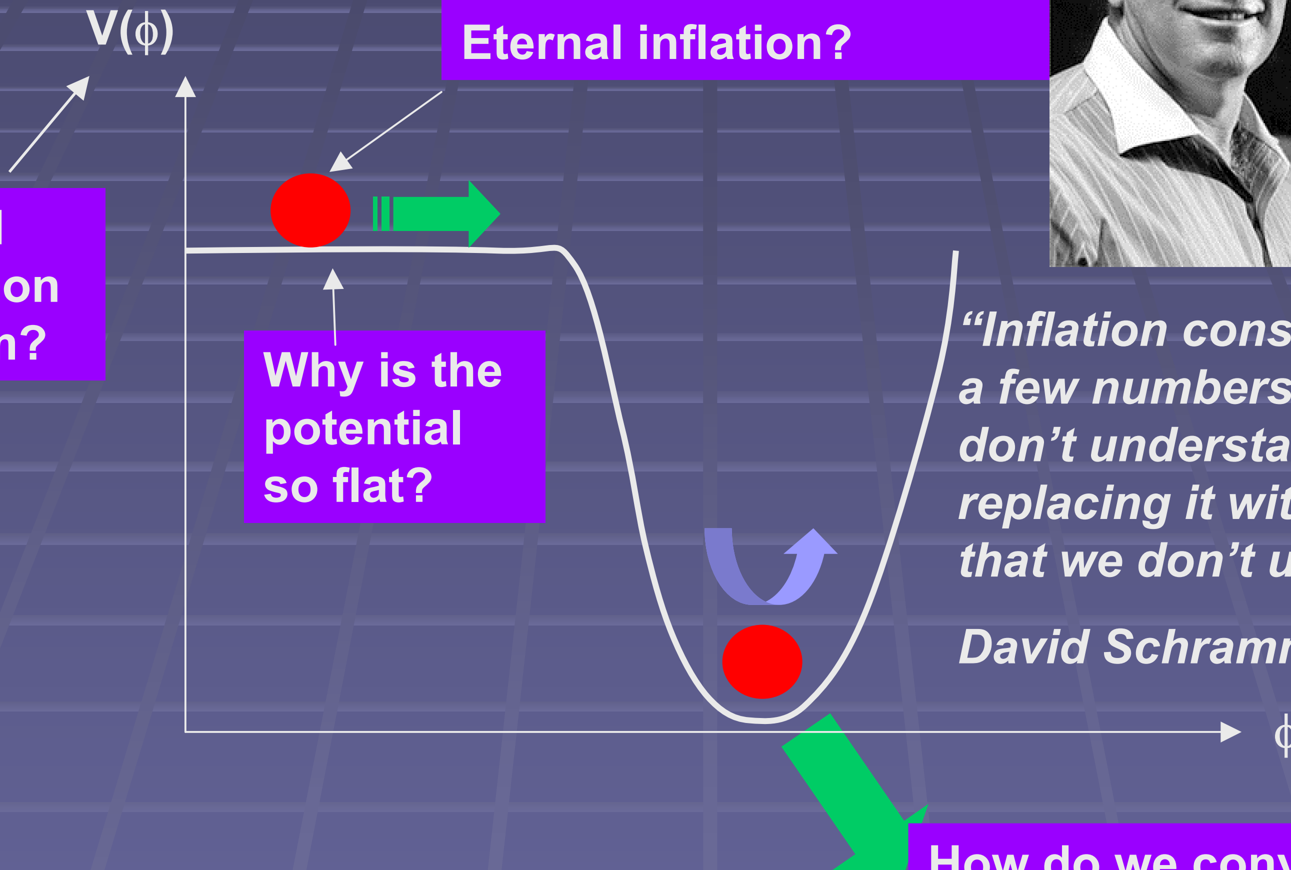


Inflation: Problems

Why did the field start here?

Eternal inflation?

Where did this function come from?



Why is the potential so flat?

How do we convert the field energy completely into particles?

"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

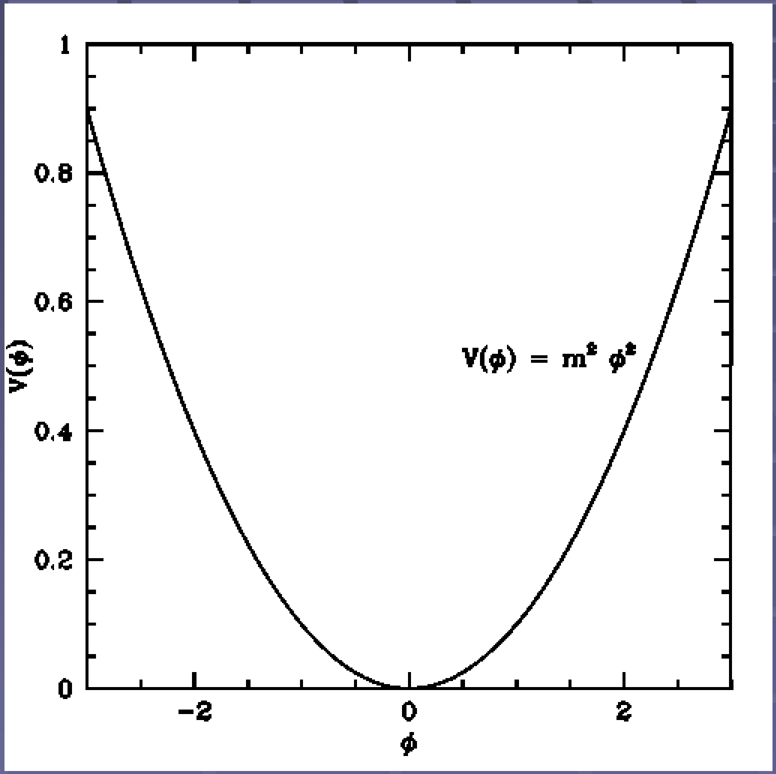
Is Inflation a Theory?

While the simplest versions of inflation have definite predictions (flat universe, Gaussian scale invariant spectrum of adiabatic fluctuations), inflationary models with more baroque forms of V(f) can produce non-flat universes, non-Gaussian fluctuations, non-adiabatic fluctuations, and deviations from scale invariance.

INFLATION IS A PRADIGM

Testing Specific Inflationary Models

- Cosmologist need to test simplest models
- Particle theorists need to motivate models
  - String theory
  - Multiple dimensional cosmologies



Testing the Simplest Models

- Deviations from scale invariance
  - $m^2\phi^2$ inflation predicts $n_s = 0.97$
  - WMAP + ACT (or Planck) should detect these deviation from scale invariance at greater than 3 σ
- Further tests of non-Gaussianity
- Gravity waves from inflation
  - $m^2\phi^2$ inflation predicts a gravity wave background at a level detectable by WMAP (with ~8 years of integration) and Planck

Conclusions

- Standard big bang models has a number of fundamental problems
- Inflationary scenario solves these problems by positing an inflaton potential
  - Inflaton potential form is currently ad-hoc

Simplest Versions of Inflation are Testable!