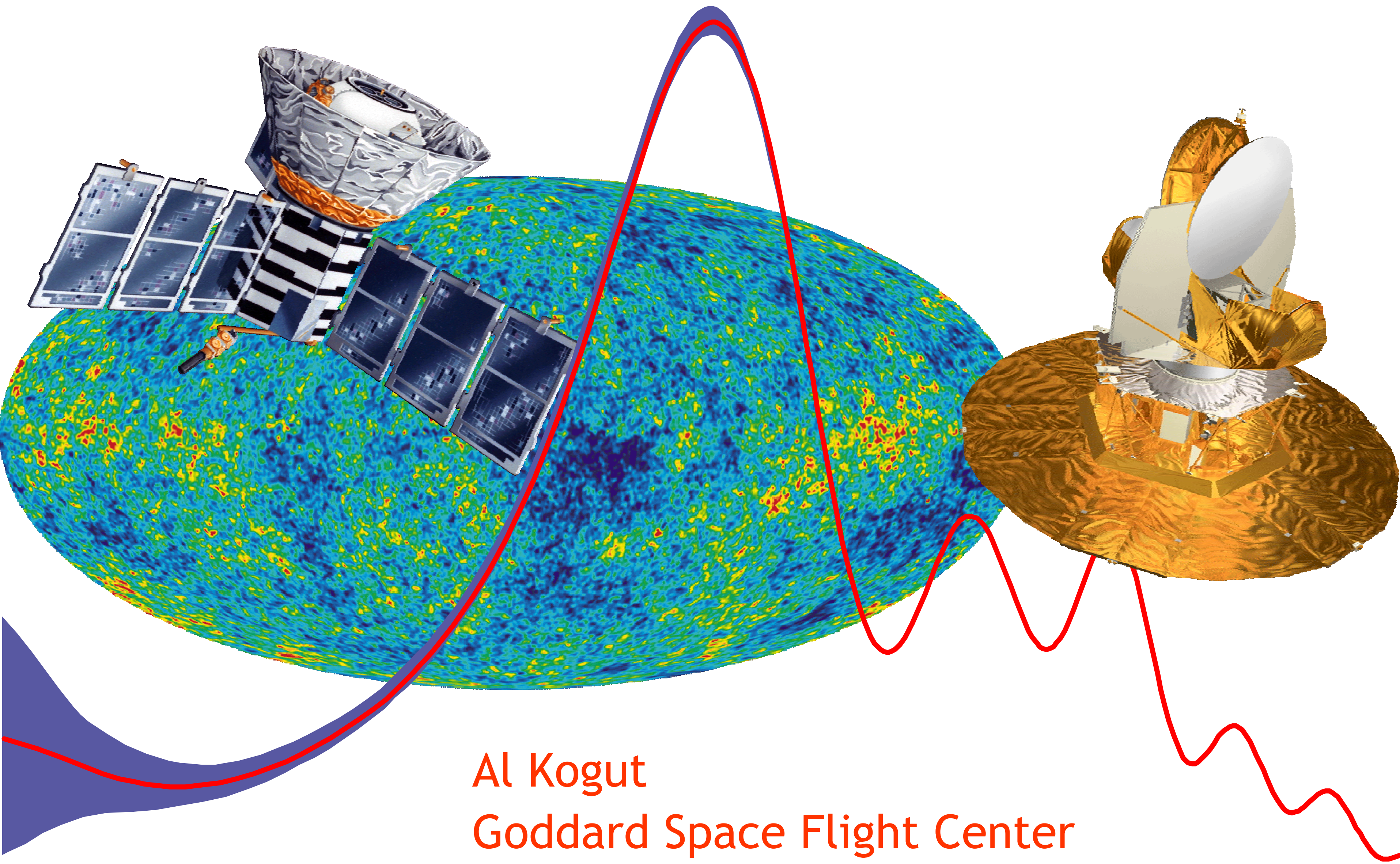
The Biggest Picture: Cosmology and the Cosmic Microwave Background



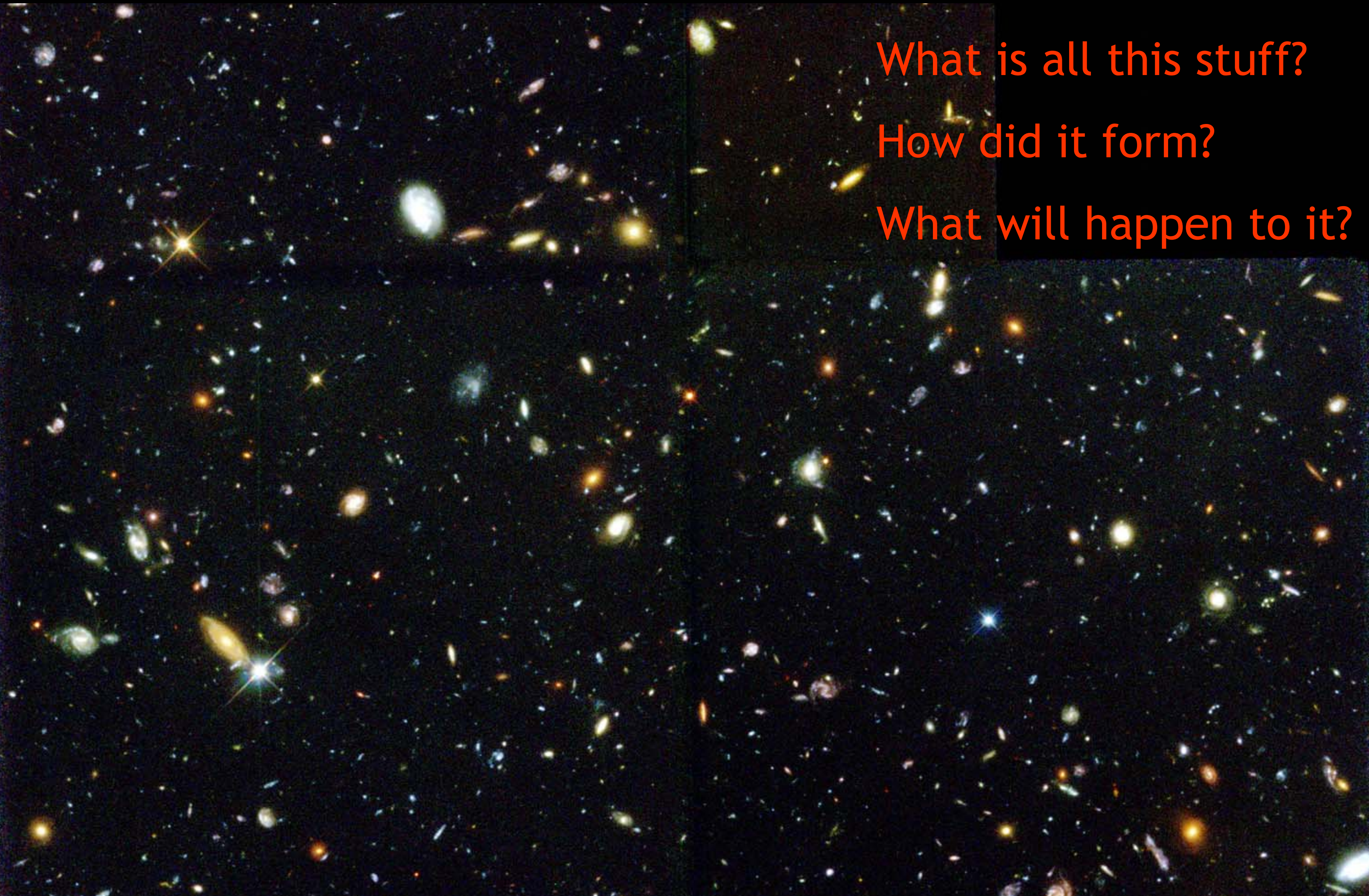
Al Kogut
Goddard Space Flight Center

Cosmology: The Big Picture

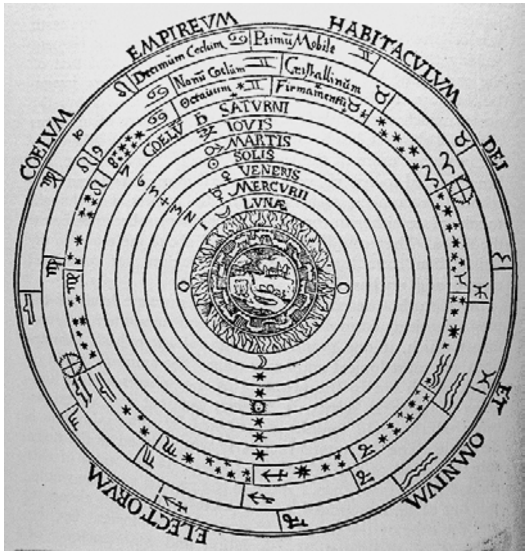
What is all this stuff?

How did it form?

What will happen to it?



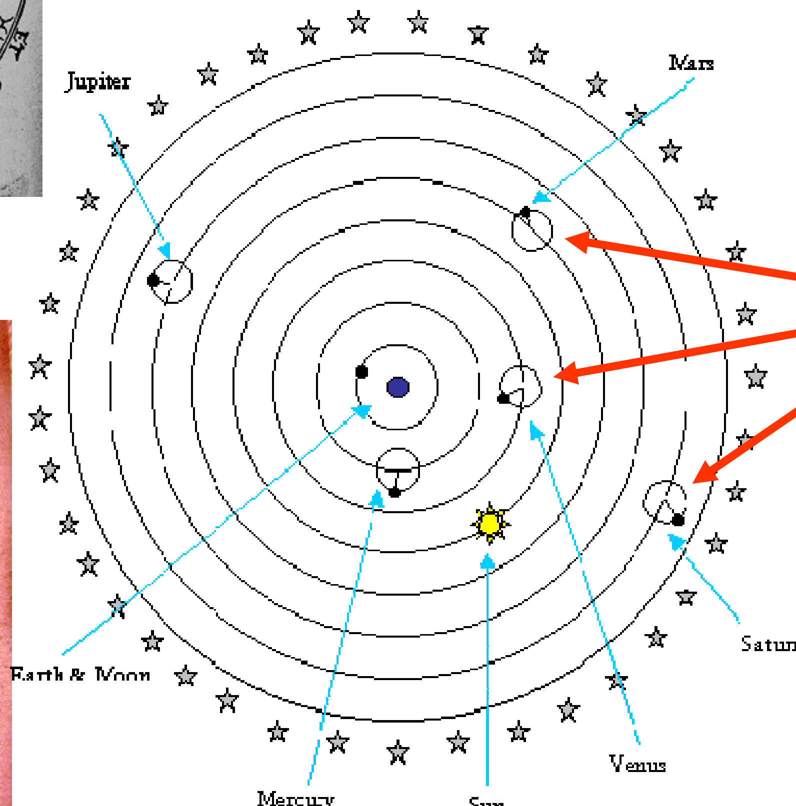
Aristotle/Ptolemaeus: A Calculable Cosmology



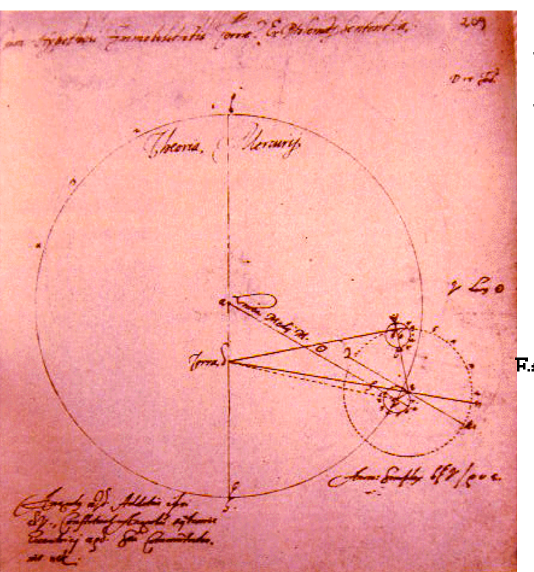
Aesthetics and Observation

Astonishingly successful

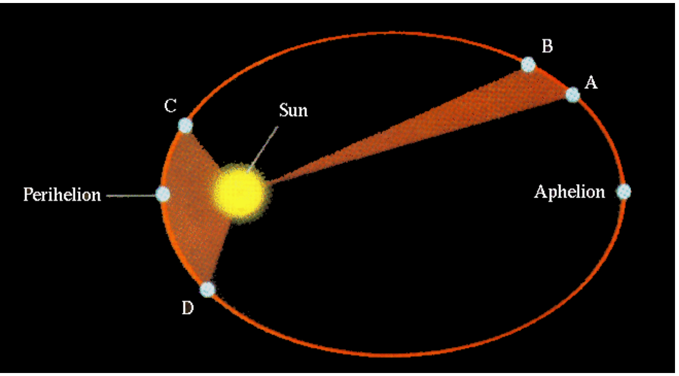
Modestly complicated



28 Epicycles



Beginnings of Modern Cosmology



Copernicus 1543/Kepler 1609

Simplified planetary motion

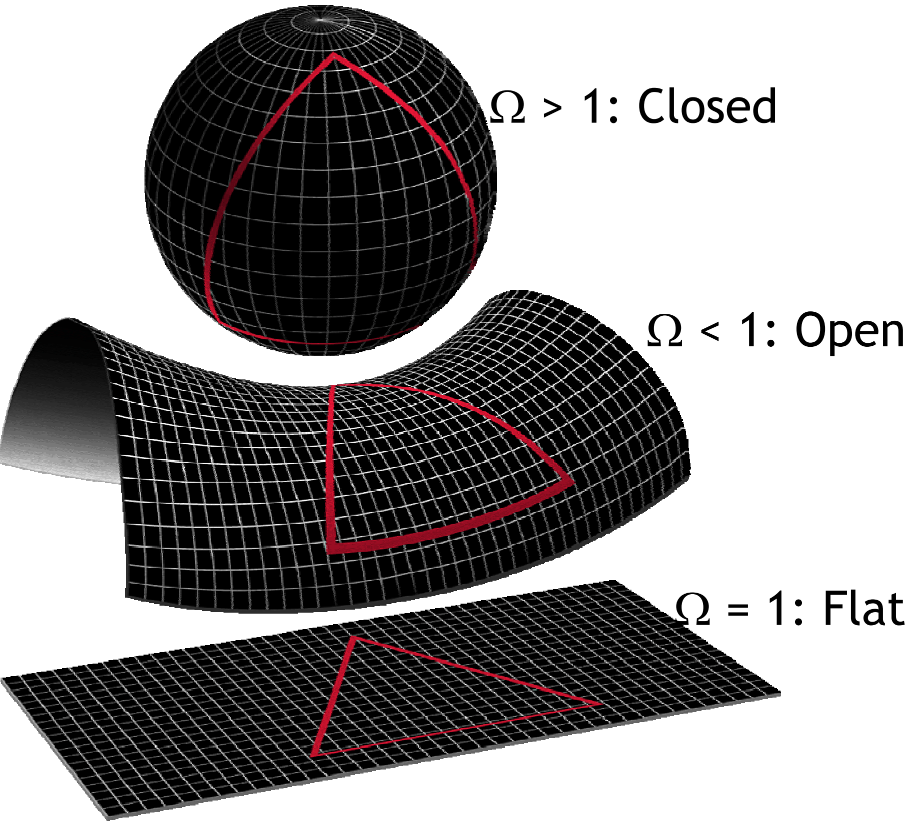
Newton 1687

Unified celestial/terrestrial forces

Hubble 1923

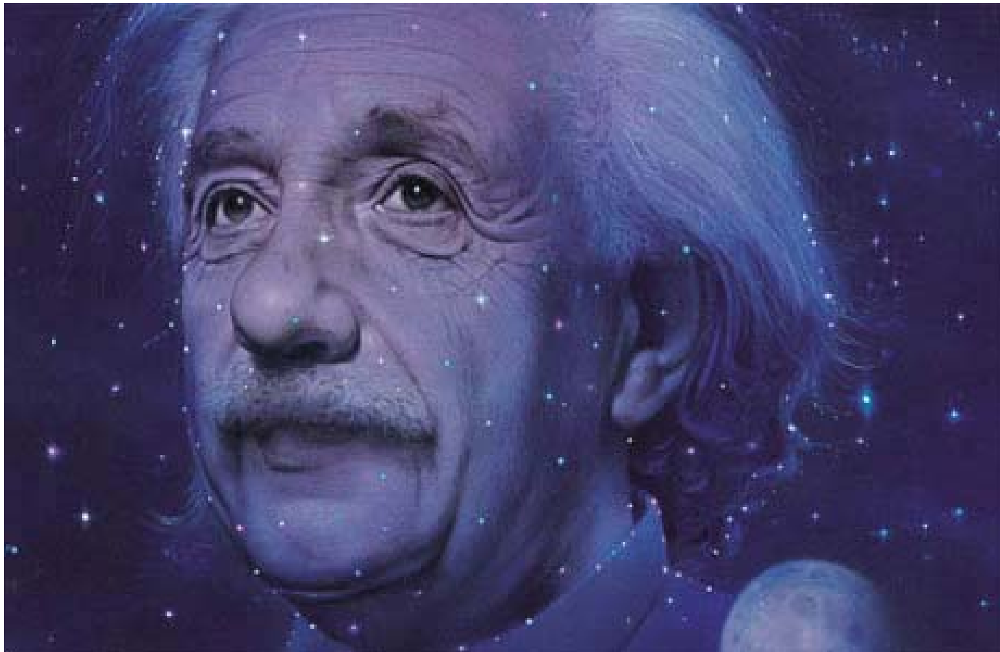
Existence of external galaxies

Einstein and Cosmology



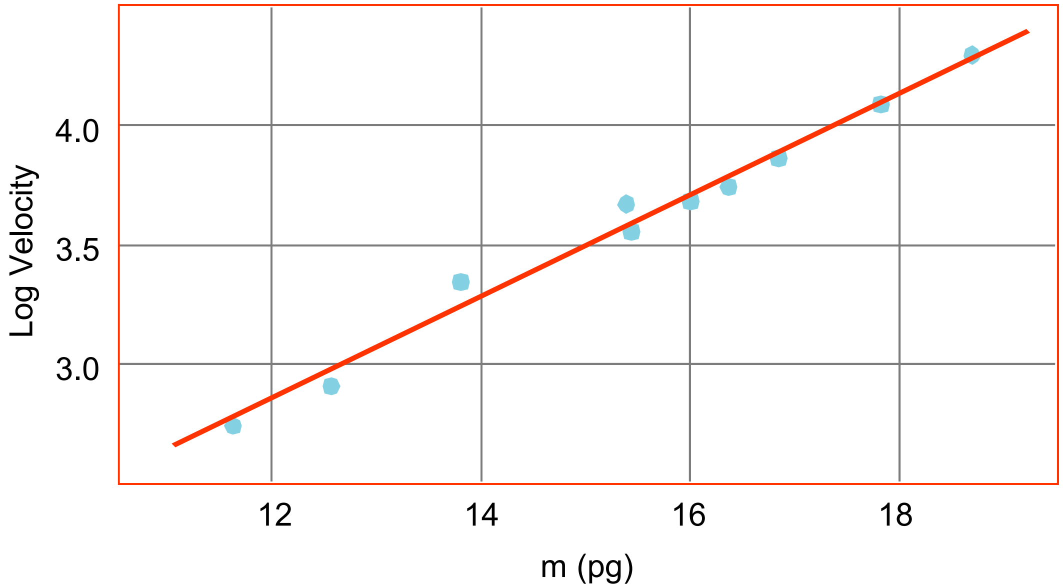
General Relativity:
Matter Shapes Spacetime

Static universe requires repulsive force to counteract gravity:
Cosmological Constant Λ



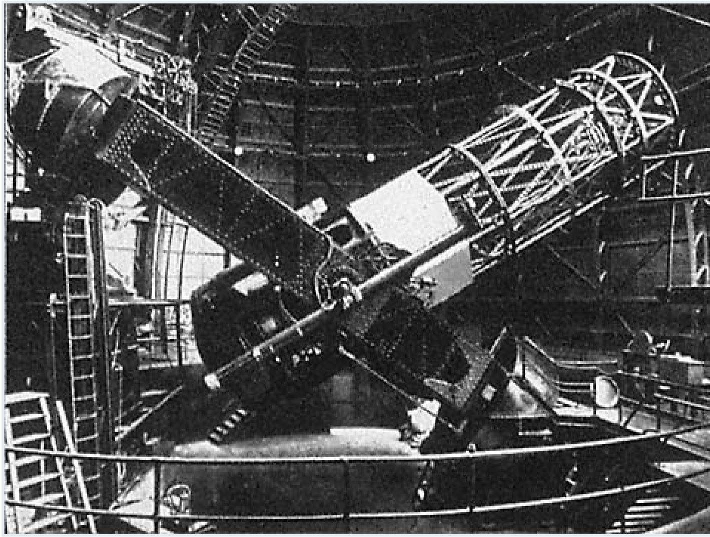
1929: Hubble Discovers Expanding Universe

Edwin Hubble



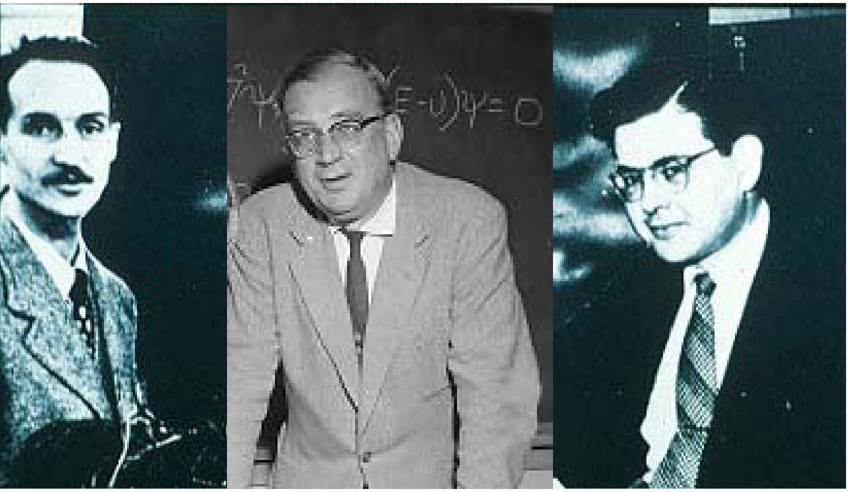
Universe is not static!

Einstein recants on Λ



Mt. Wilson 100 Inch Telescope

Hot Big Bang Theory



First postulated 1948

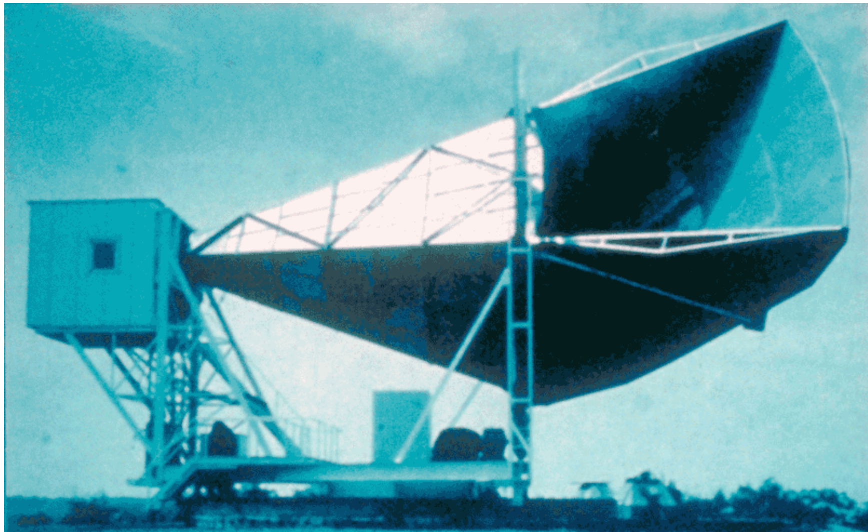
Universe was once much hotter and denser than today

Universe cools as it expands

Observable relics
- Microwave Heat Radiation
- Light Elements (H, He, Li)

Link to present-day galaxies deferred to "initial conditions"

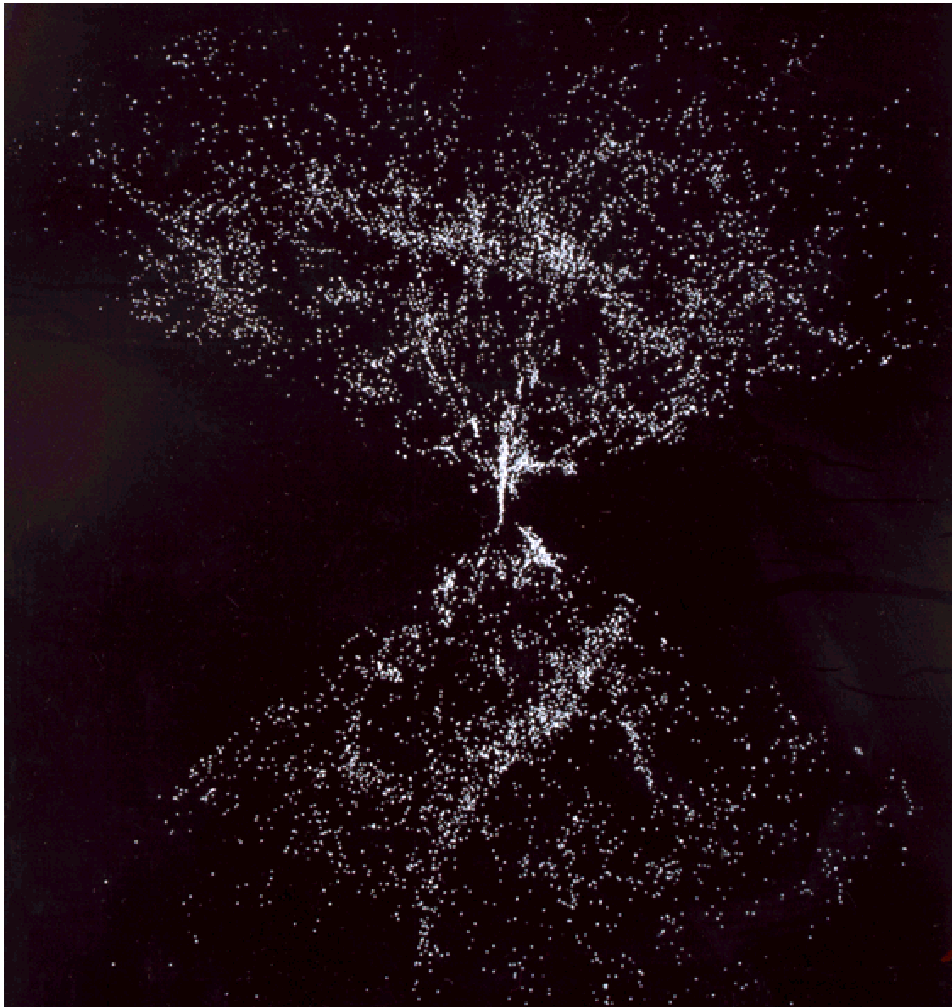
Heat radiation detected 1965



1980's: Trouble in River City

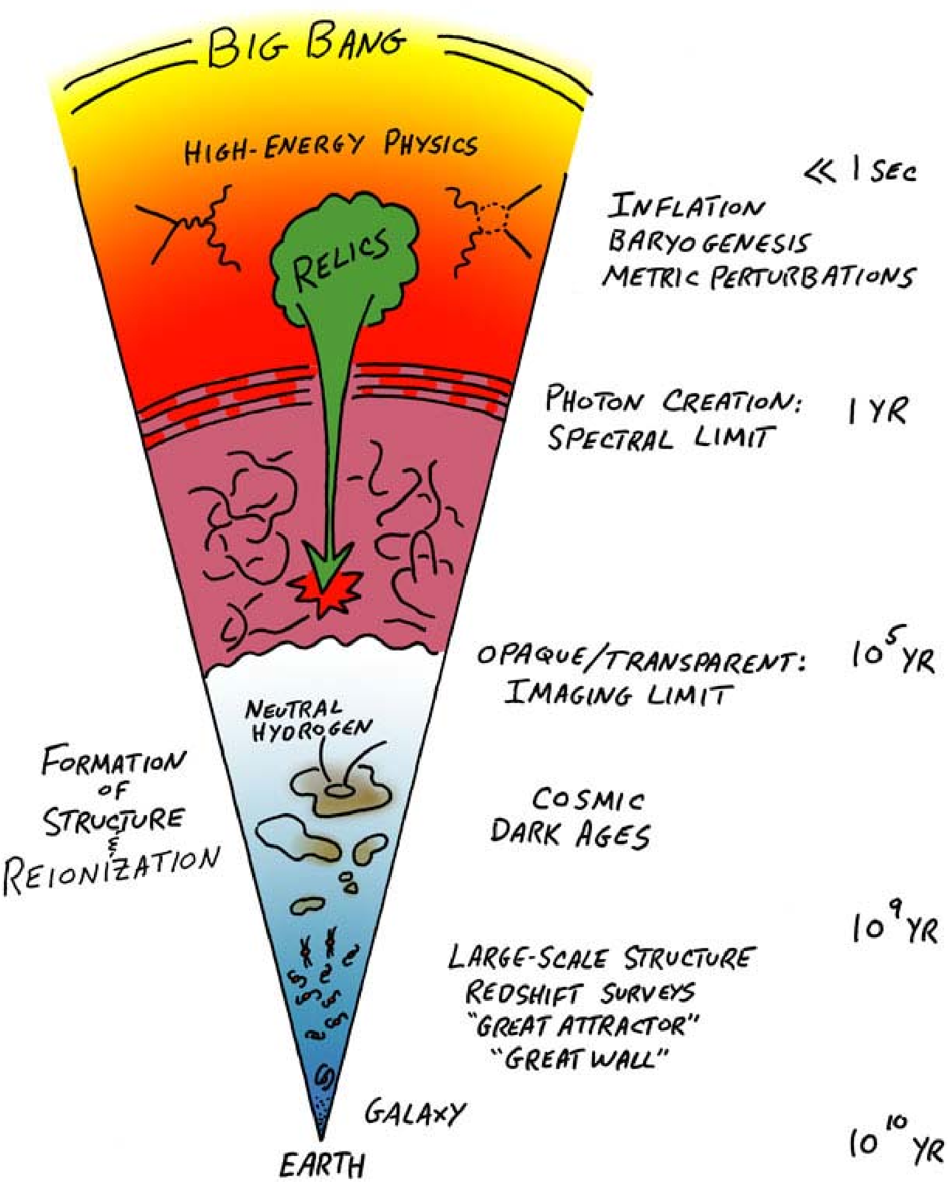
Stars revolve around galaxies
too fast for inferred gravity

Dark Matter:
Interacts with gravity
but not with light



Universe is too lumpy to grow
via gravity alone

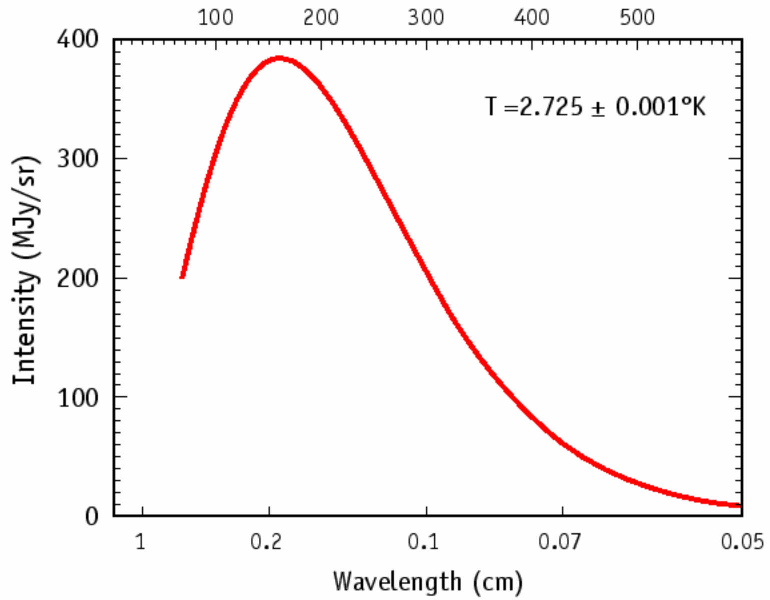
Solution: Look At Microwave Background

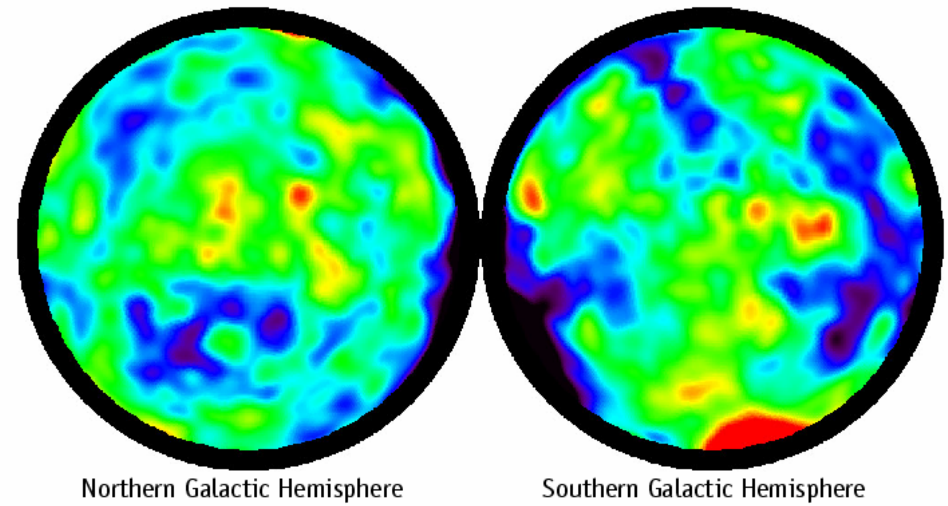


Fossil Relic of Early Universe

- GUT Physics at 10^{16} GeV
- Inflation/Phase Transitions
- Geometry of Space-Time
- Contents of Universe
- Gravity & Structure Formation

CMB and the Early Universe





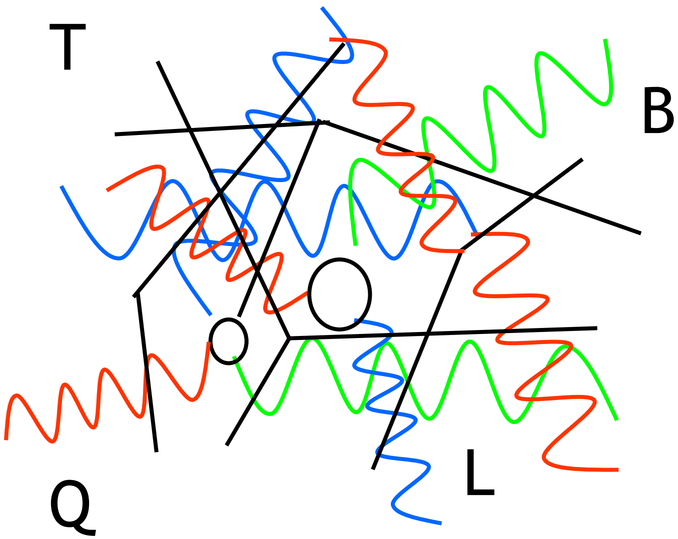
CMB Spectrum: Energetics

- Phase transitions (GUT physics)
- Relic decay (dark matter)
- Reionization (first stars)

CMB Anisotropy: Dynamics

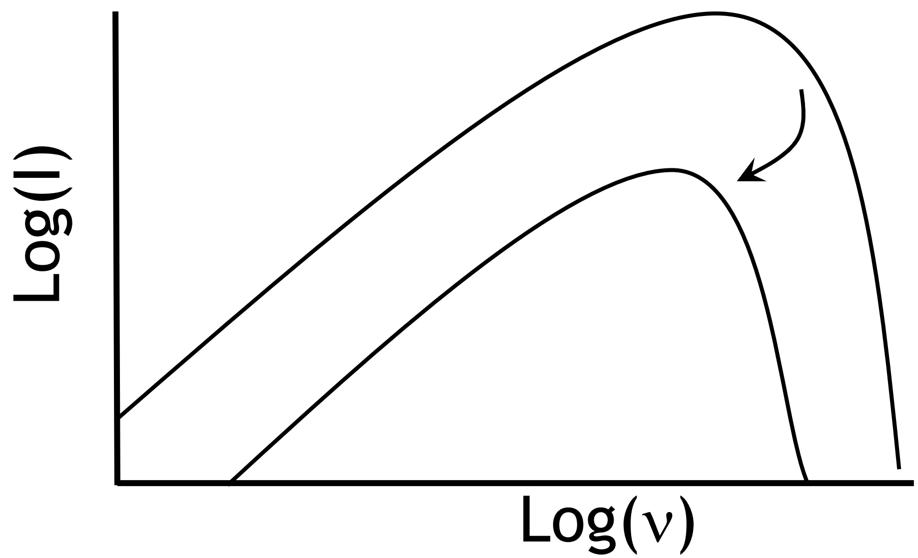
- Density distribution (Seeds)
- Global parameters (Ω, Λ, H_0, …)
- Inflationary physics

Cosmology and Thermodynamics



Thermal Equilibrium:

- Interaction rates » Hubble Expansion
- Fully characterized by temperature plus list of conserved quantum numbers



Adiabatic Expansion

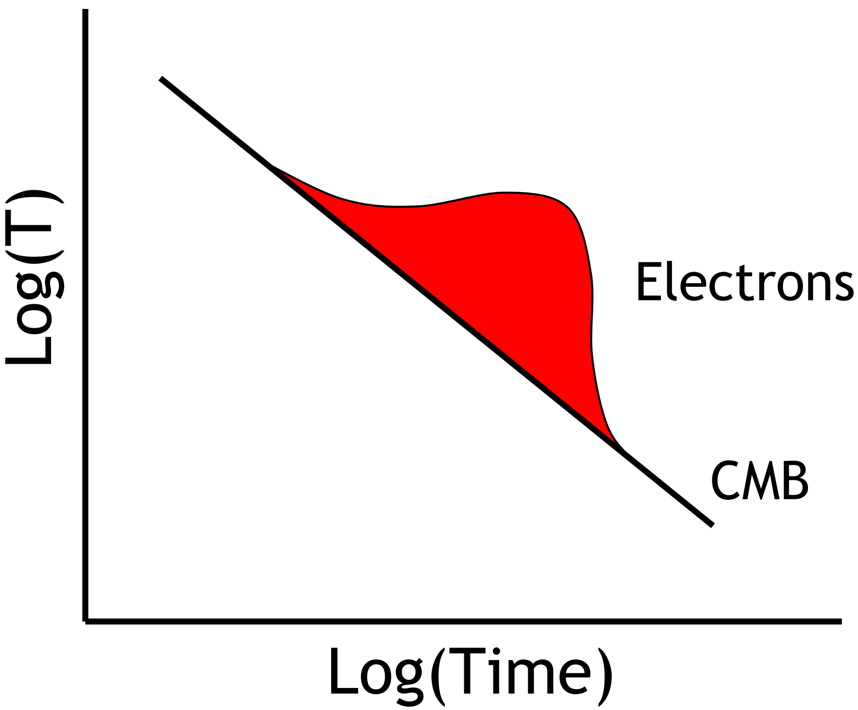
$\lambda(t) = \lambda_0 a(t)$

$\nu(t) = \nu_0 / a(t)$

$N = [\exp(h\nu/kT) - 1]^{-1} = \text{constant}$

$T = T_0/a(t) = T_0(1 + z)$

Detecting A Plasma 101



Energetics of Evolving Universe

- Energy release heats electrons
- Evolve toward new equilibrium
- Potentially observable distortions

Electron-Ion Interactions

- Free-free emission
- Reionization/First stars

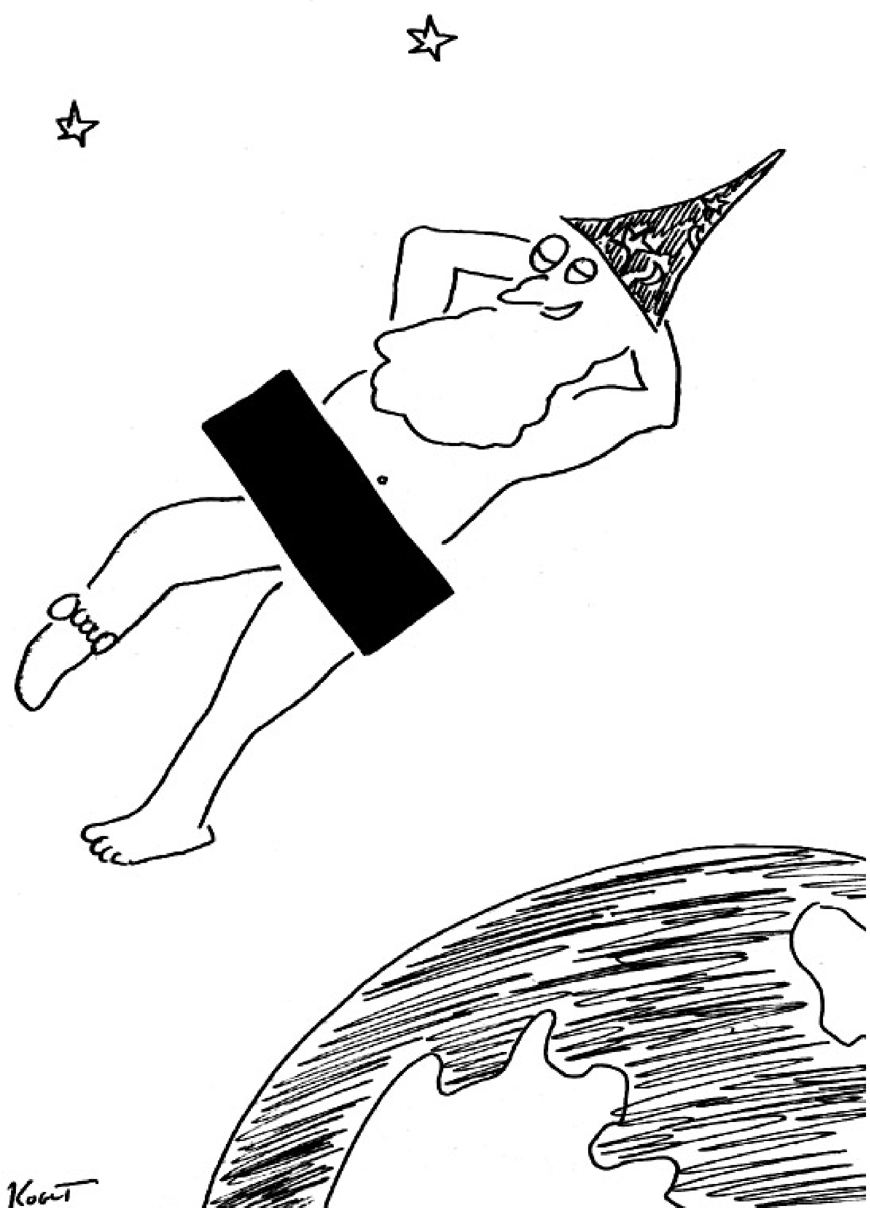
Photon-Electron Interactions

- Compton Scattering
- Structure Formation
- Relic Decay

The Problem With Ground-Based Cosmology

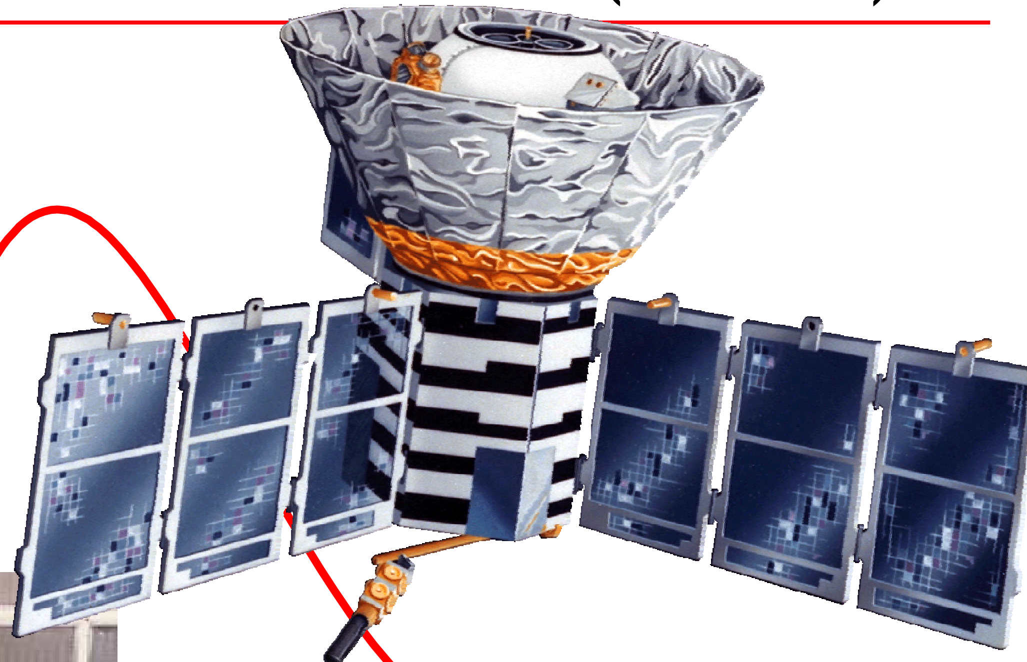
Balloons Help, But Only A Little …

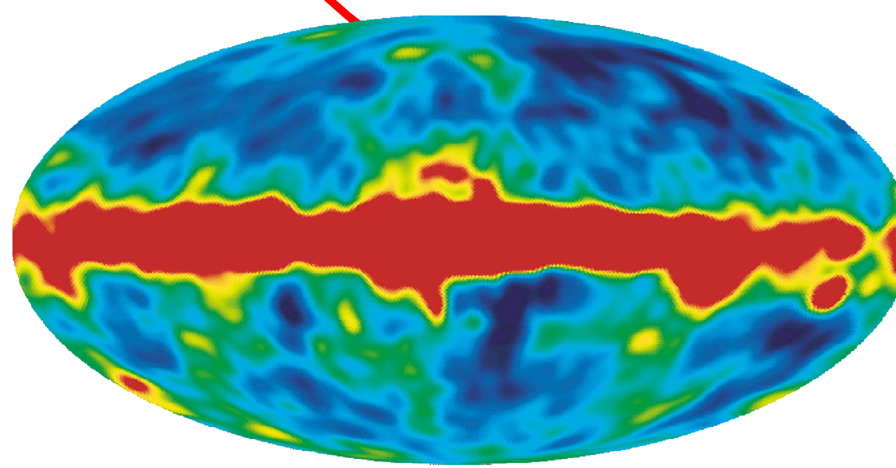
The Obvious Solution



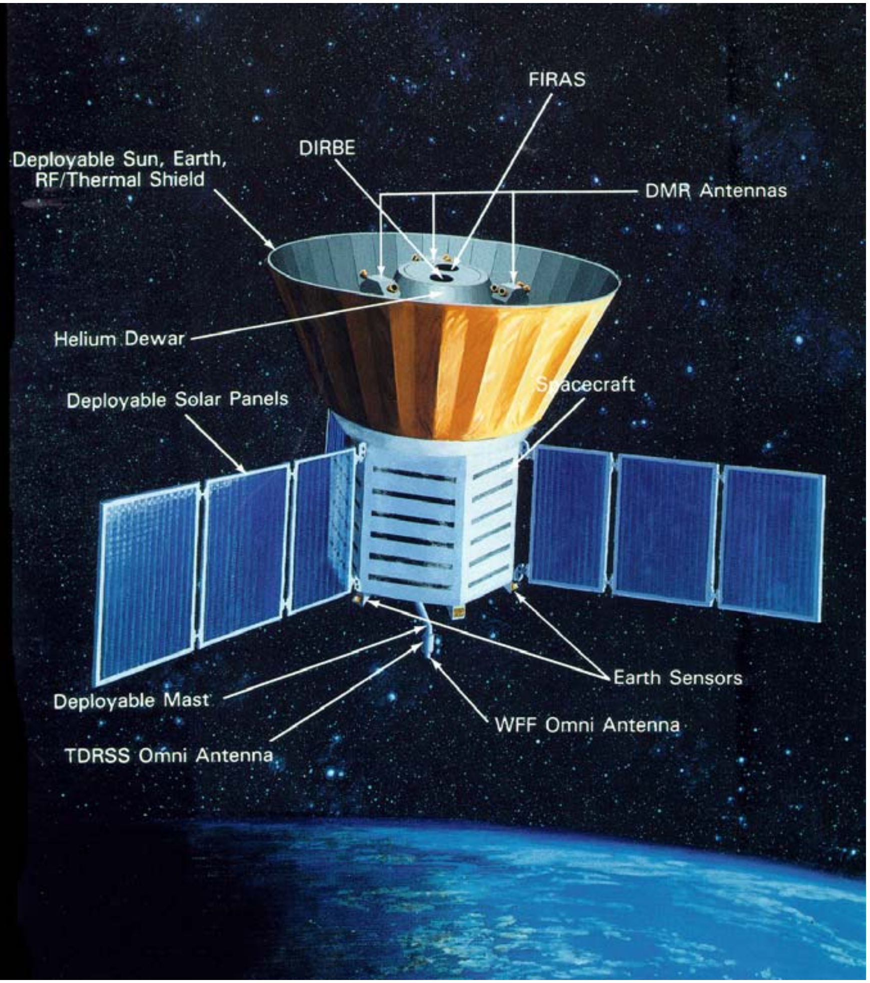
COSMIC BACKGROUND EXPLORER (COBE)

NASA's First Satellite
Dedicated to Cosmology





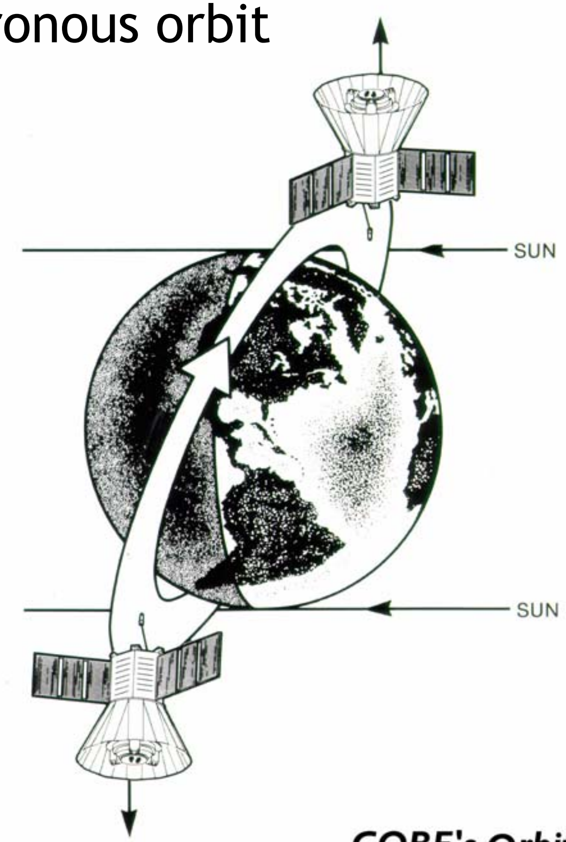
COBE Overview



3 Instruments to measure CMB and diffuse IR background

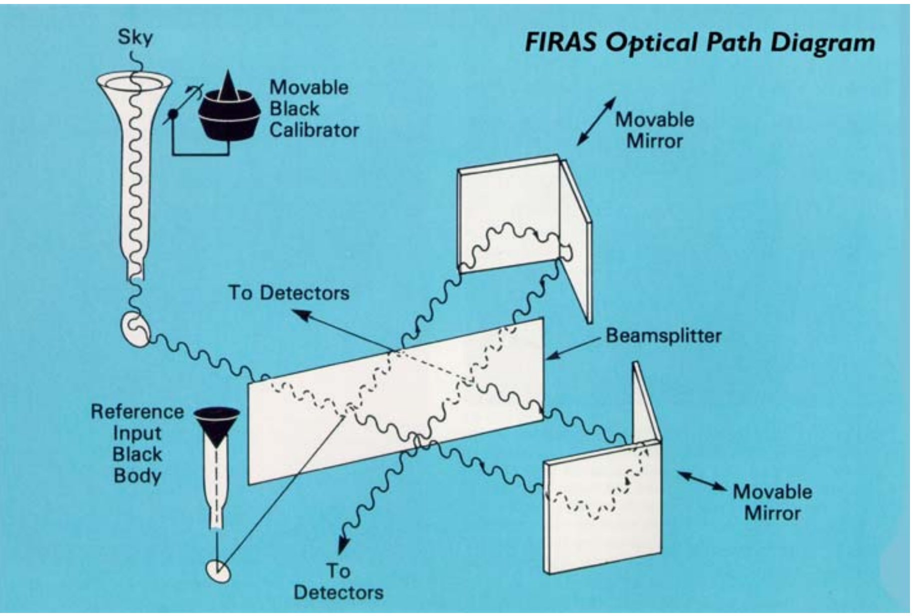
Launched November 1989

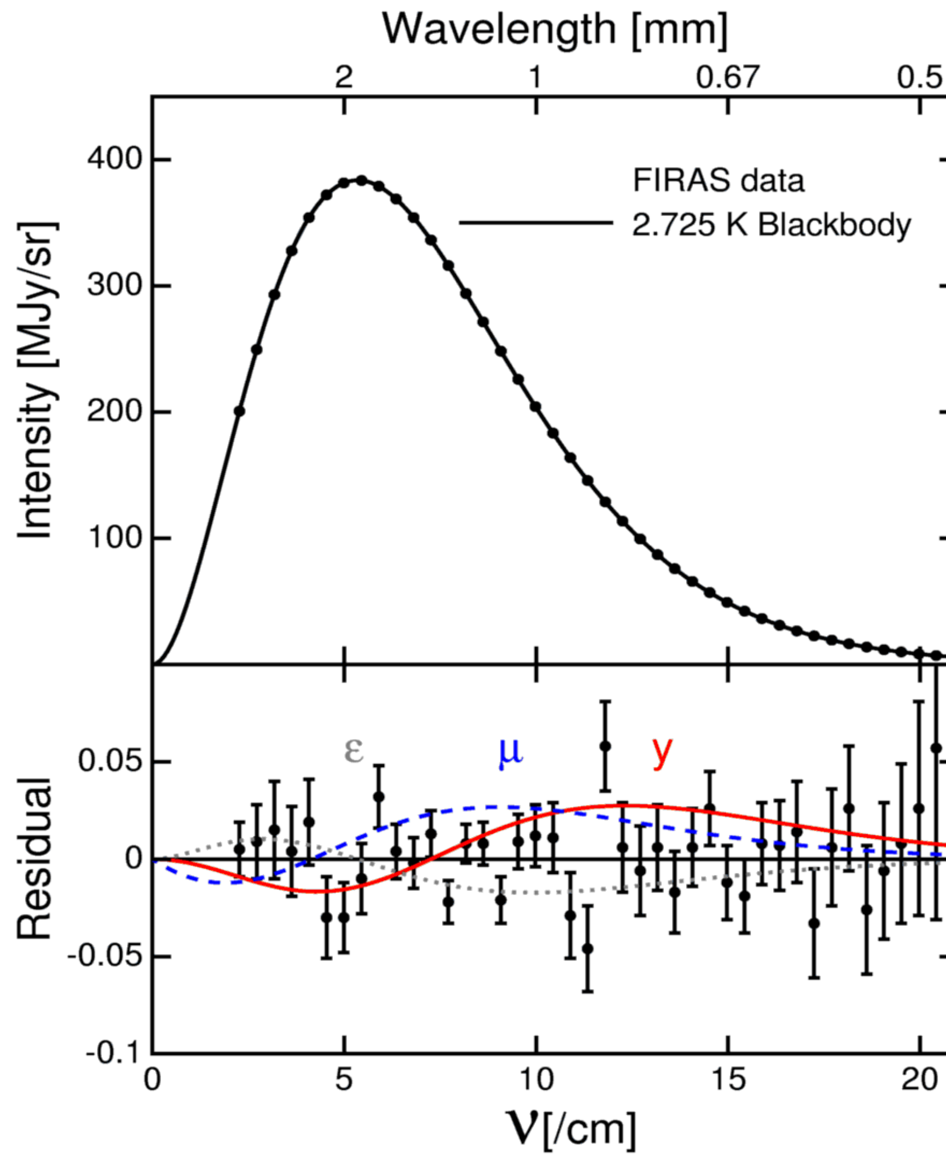
Polar sun-synchronous orbit



COBE's Orbit

Far Infrared Absolute Spectrophotometer
50 ppm Measurement of Blackbody Spectrum





PI John Mather (GSFC)

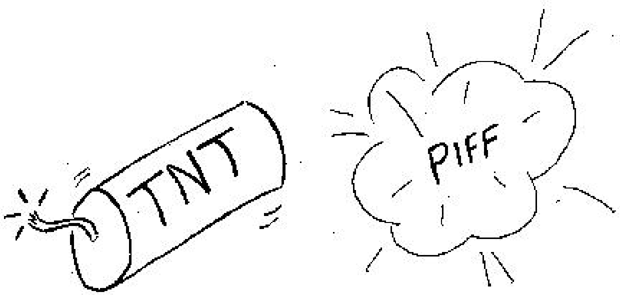
Differential Spectrometer

External Blackbody Calibrator

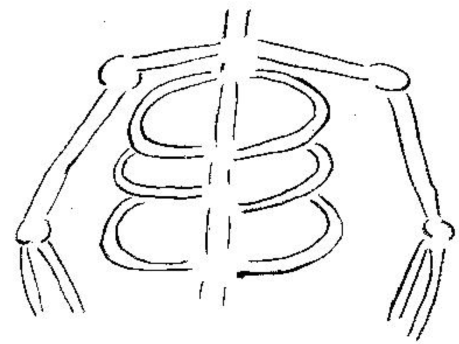
Mather et al. 1990, APJ, 354, L37
Fixsen & Mather 2002, ApJ, 581, 817

Cosmology From CMB Spectrum

Energy Budget: $\Delta E/E < 6 \times 10^{-5}$ for $10^3 < z < 10^7$

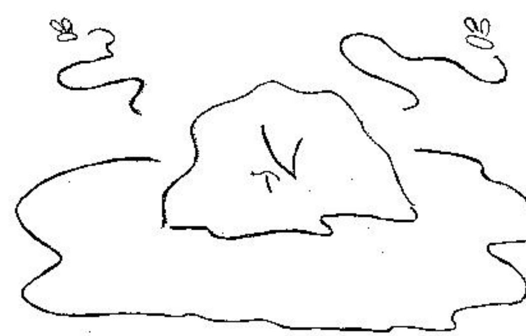


No "Little Bangs"
After Big Bang



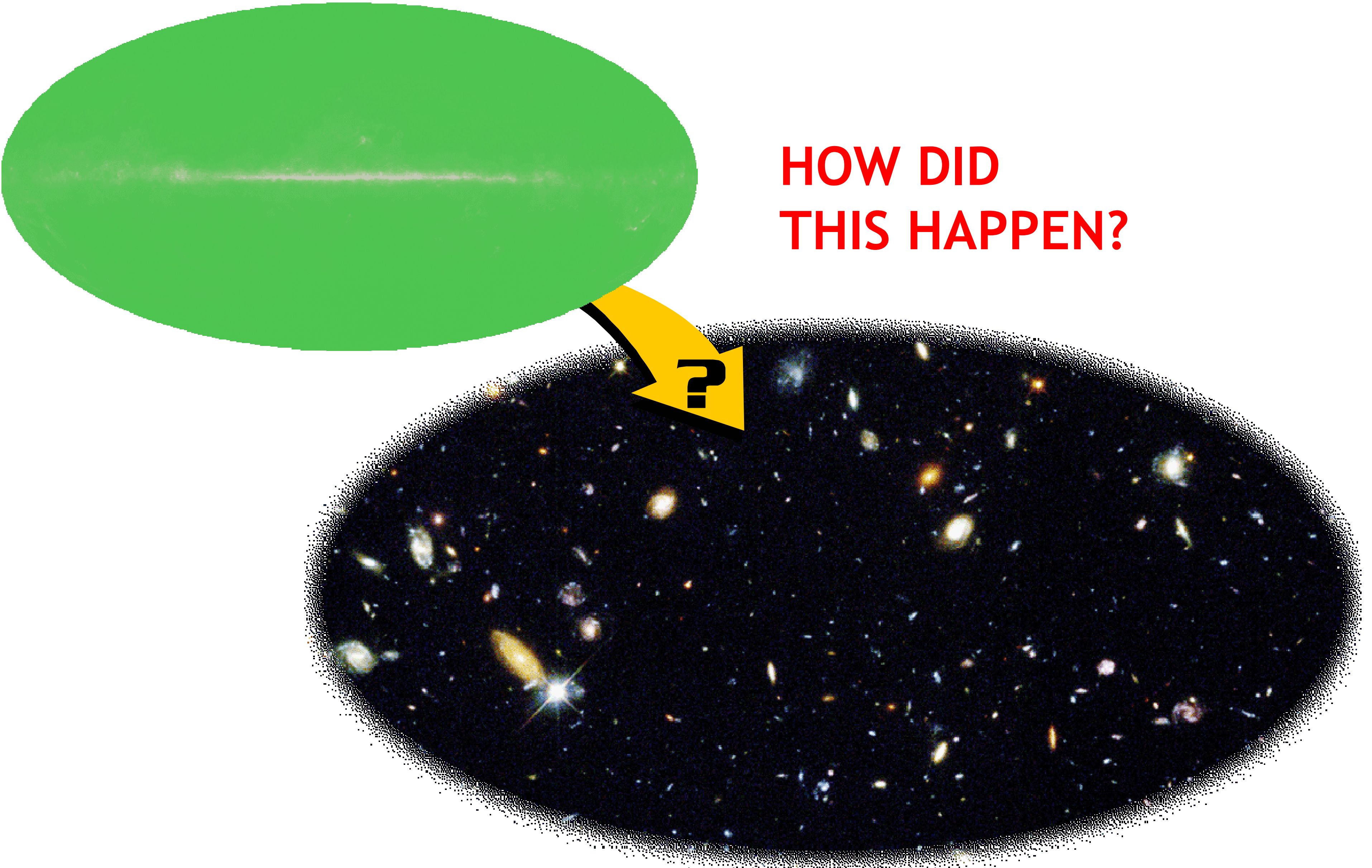
X-Ray Background
From Discrete Sources

Steady State Model
Ruled Out



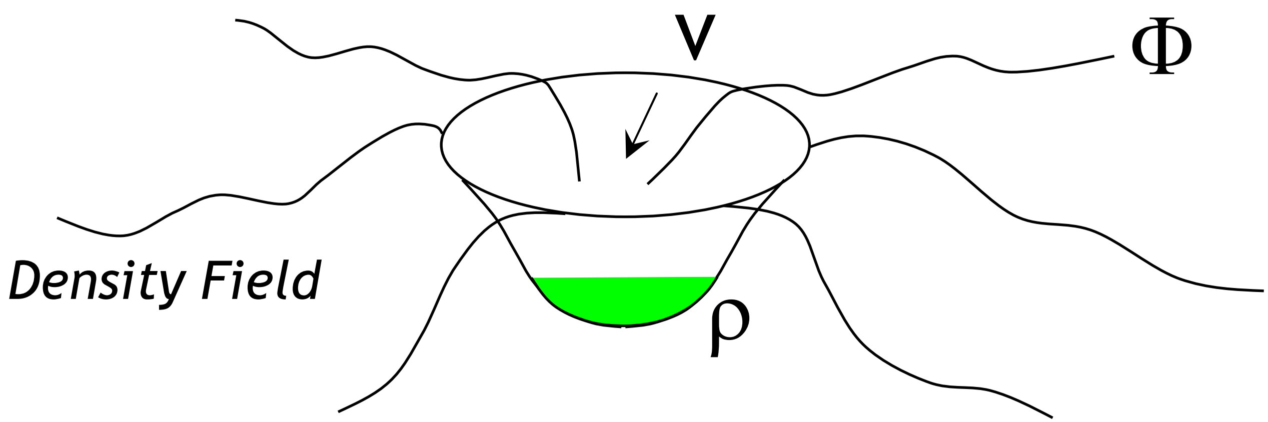
Heavy Neutrino
Decay Limits ($B\gamma < 10^{-7}$)

Still Left With The Big Question



HOW DID
THIS HAPPEN?

Observing The Initial Conditions



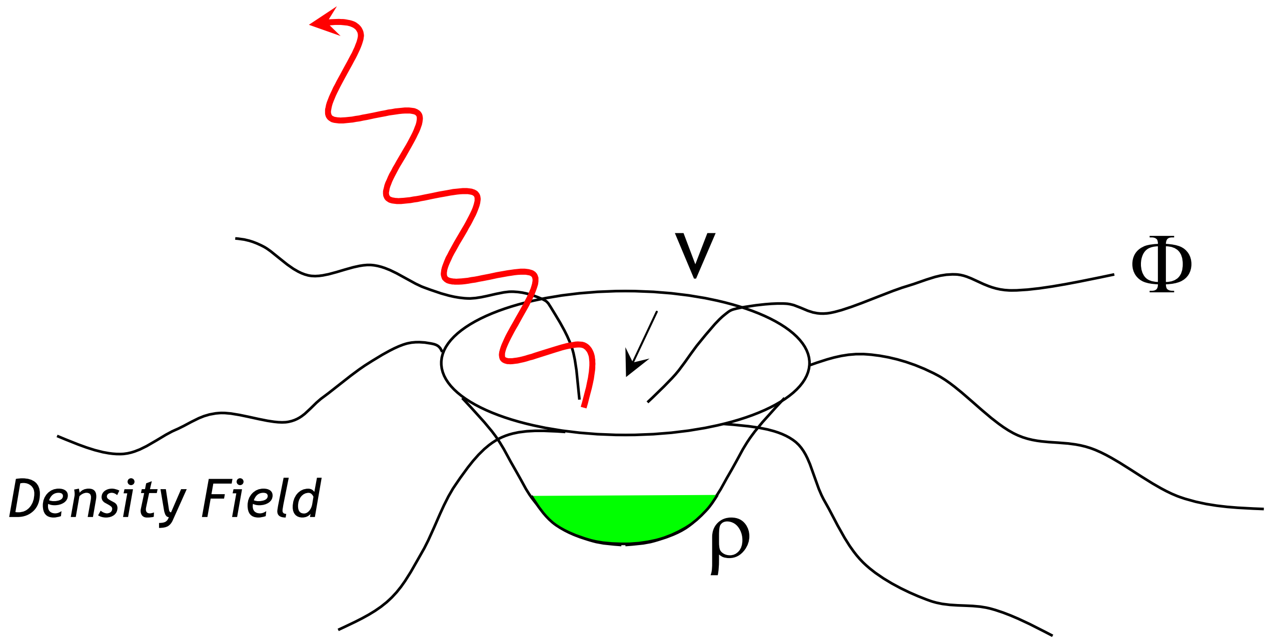
Gravity links density ρ, velocity v, and potential Φ

$\nabla^2\Phi = 4\pi G\rho$ (Poisson)

$\partial\rho/\partial t + \nabla\bullet(\rho v) = 0$ (Continuity)

$\partial v/\partial t + (v\bullet\nabla)v = -\nabla\Phi$ (Euler)

Observing The Initial Conditions



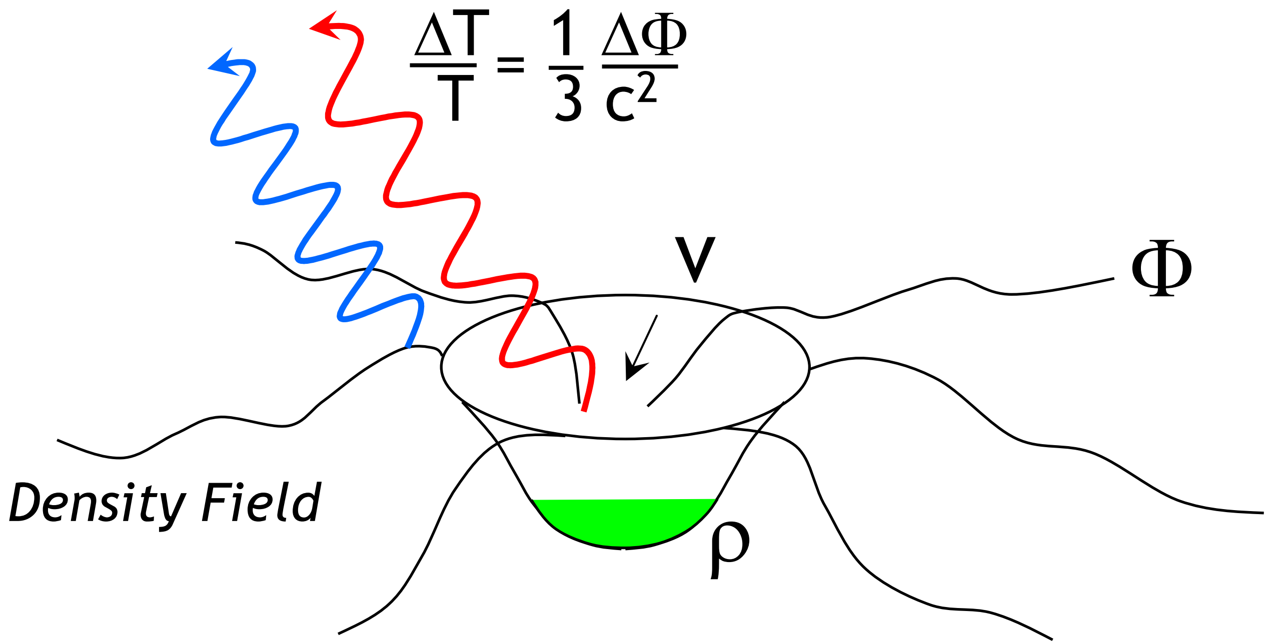
Gravity links density ρ, velocity v, and potential Φ

$$\nabla^2\Phi = 4\pi G\rho \qquad \text{(Poisson)}$$

$$\partial\rho/\partial t + \nabla\bullet(\rho v) = 0 \qquad \text{(Continuity)}$$

$$\partial v/\partial t + (v\bullet\nabla)v = -\nabla\Phi \qquad \text{(Euler)}$$

Observing The Initial Conditions

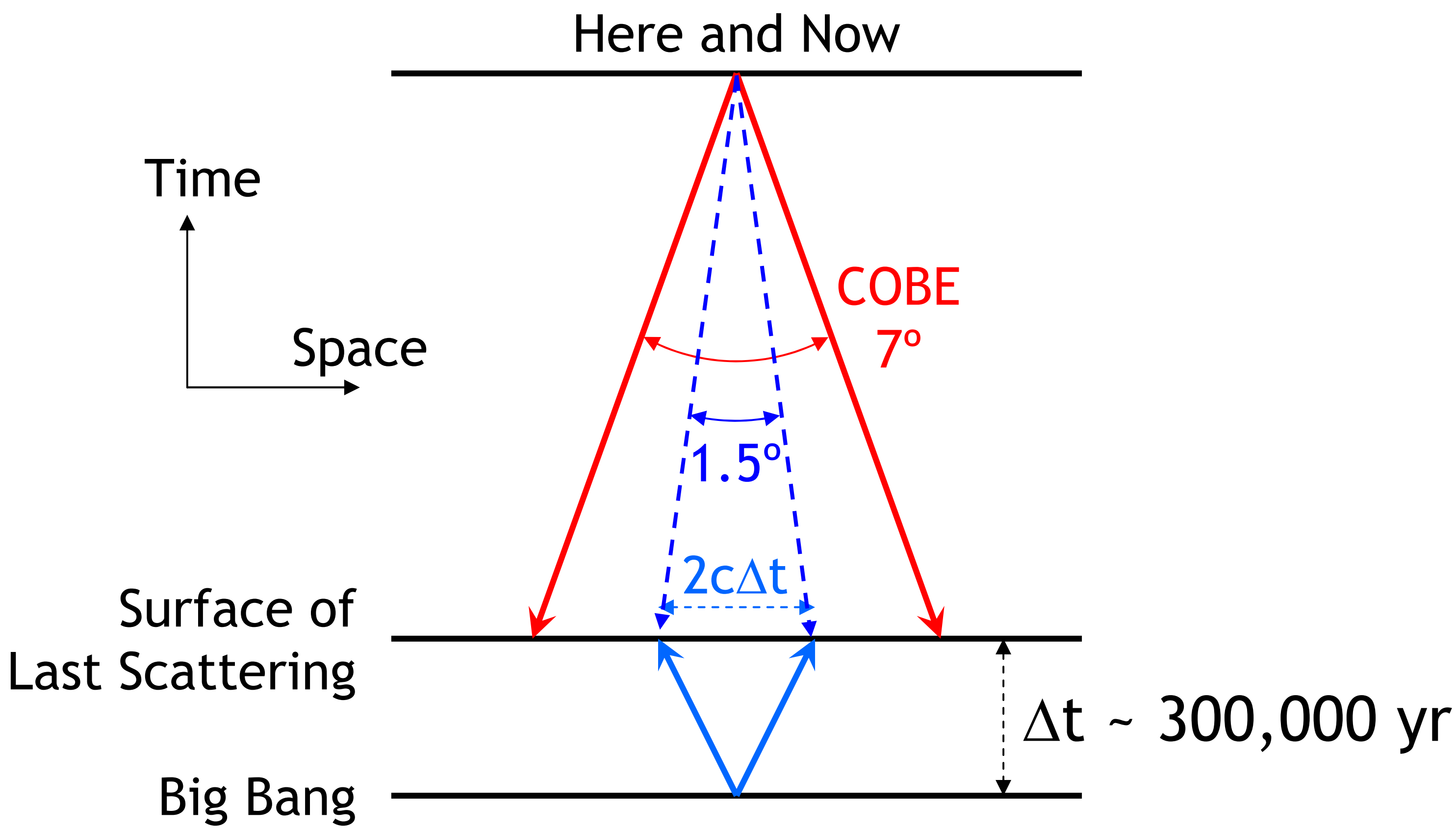


Gravity links density ρ, velocity v, and potential Φ

$\nabla^2\Phi = 4\pi G\rho$	(Poisson)
$\partial\rho/\partial t + \nabla\bullet(\rho v) = 0$	(Continuity)
$\partial v/\partial t + (v\bullet\nabla)v = -\nabla\Phi$	(Euler)

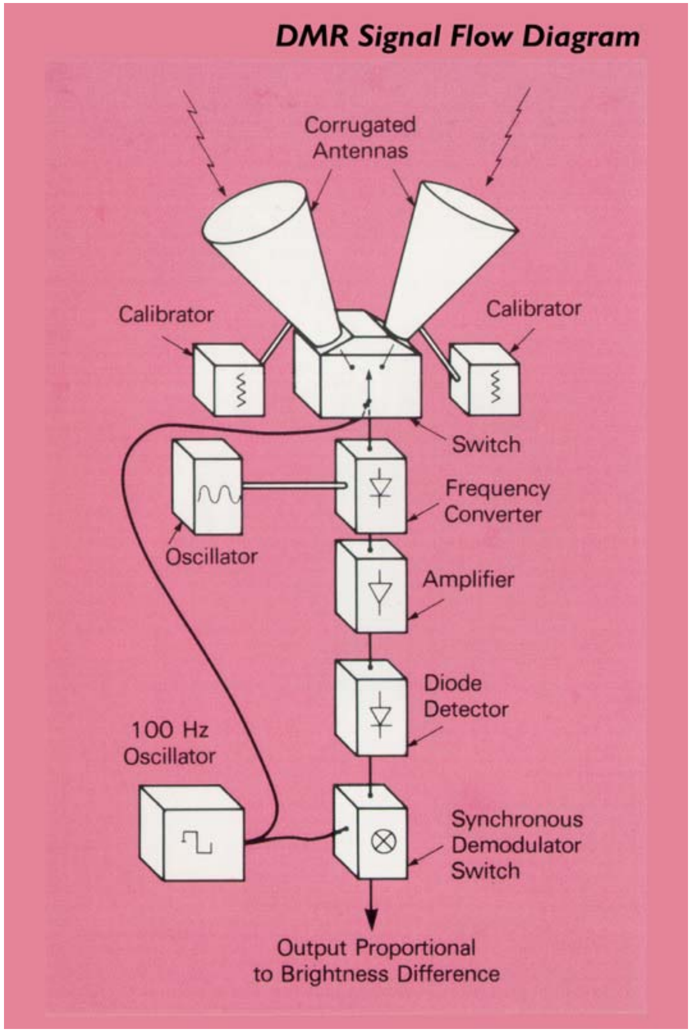
Observe potential $\Delta\Phi$ via CMB anisotropy ΔT

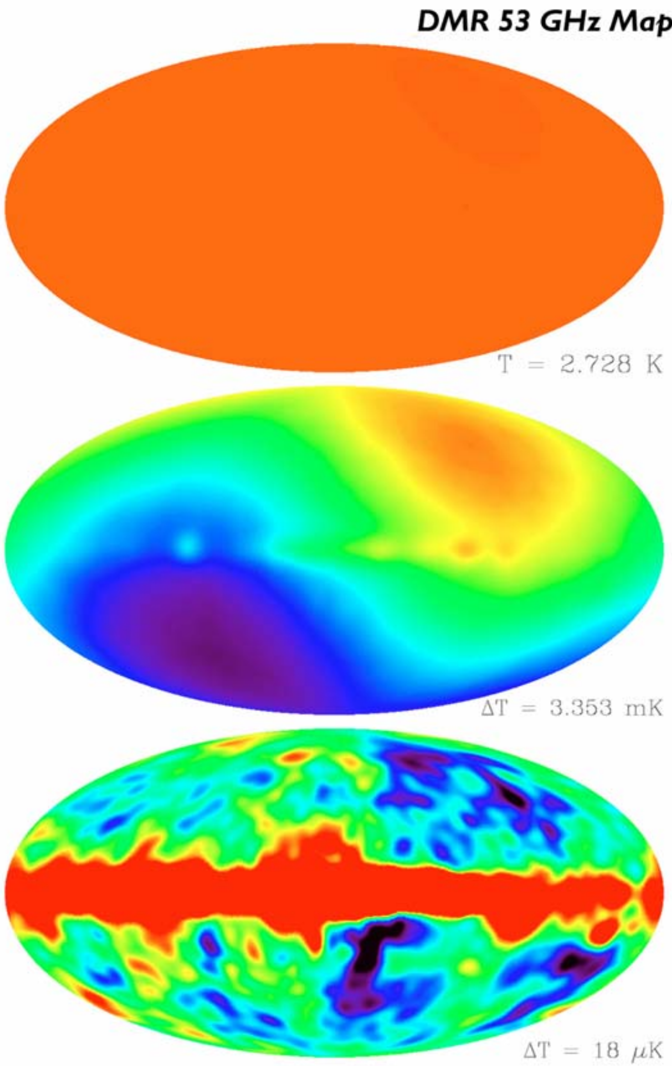
Imaging Primordial Density Field



Angular Scales > 1.5° Reflect Primordial Structure

Differential Microwave Radiometers





Monopole (2.7 K)

Dipole (Velocity)

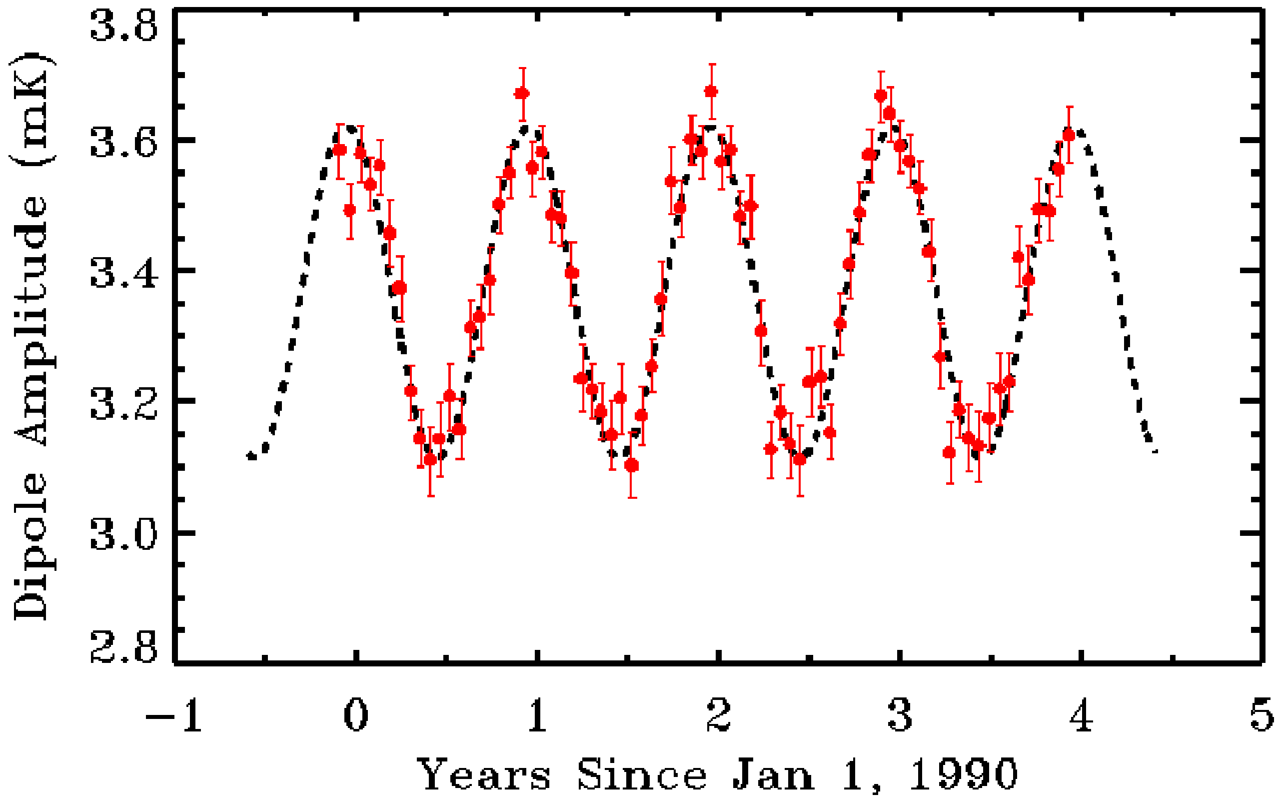
Higher Moments (Primordial)

PI George Smooth (UCB)

Smoot et al. 1992, APJ, 396, L1
Bennett et al. 1996, ApJ, 464, L1

Eppur Si Muove!

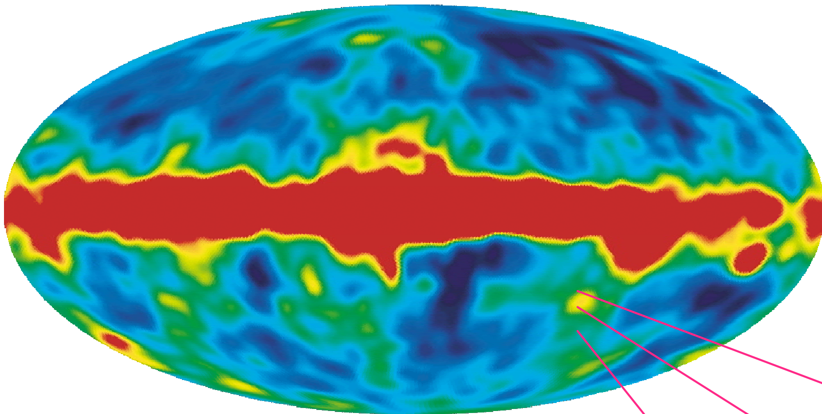
CMB Dipole Modulated by Earth's Velocity About The Sun



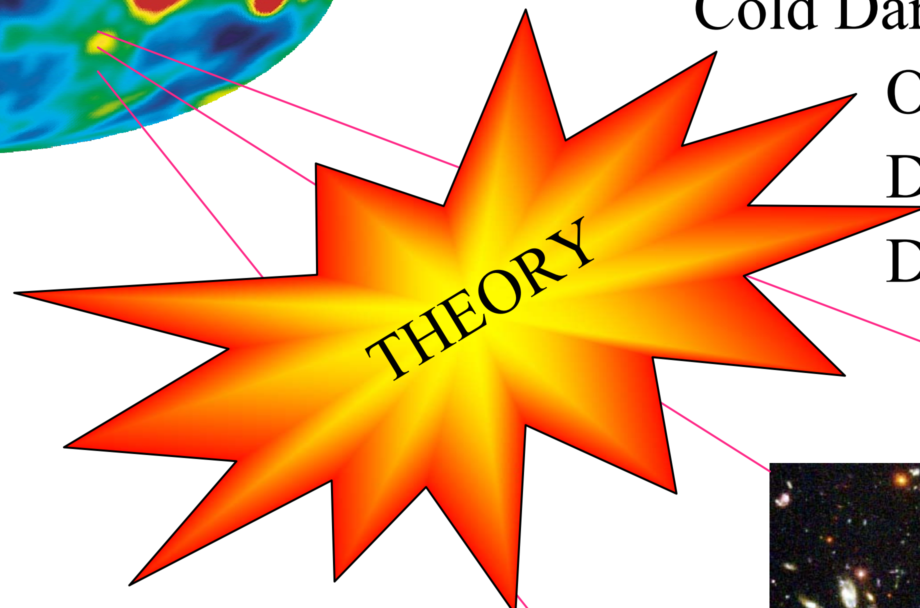
$\Delta T = T_0 \beta \cos(\theta)$ where $\beta = v/c$

Absolute Calibration Standard!

Structure Formation: The Next Step



What is the basic structure and content of the Universe?

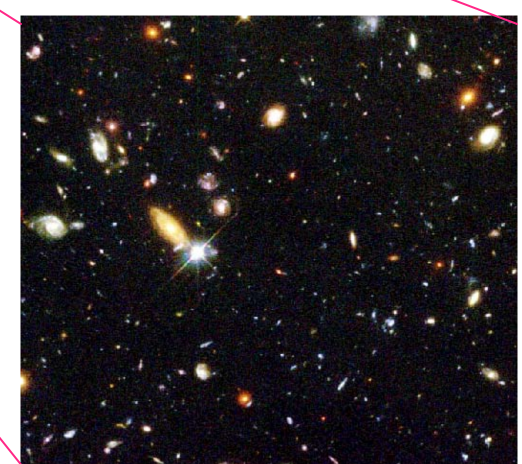


Cold Dark Matter Models:

Open? Closed?

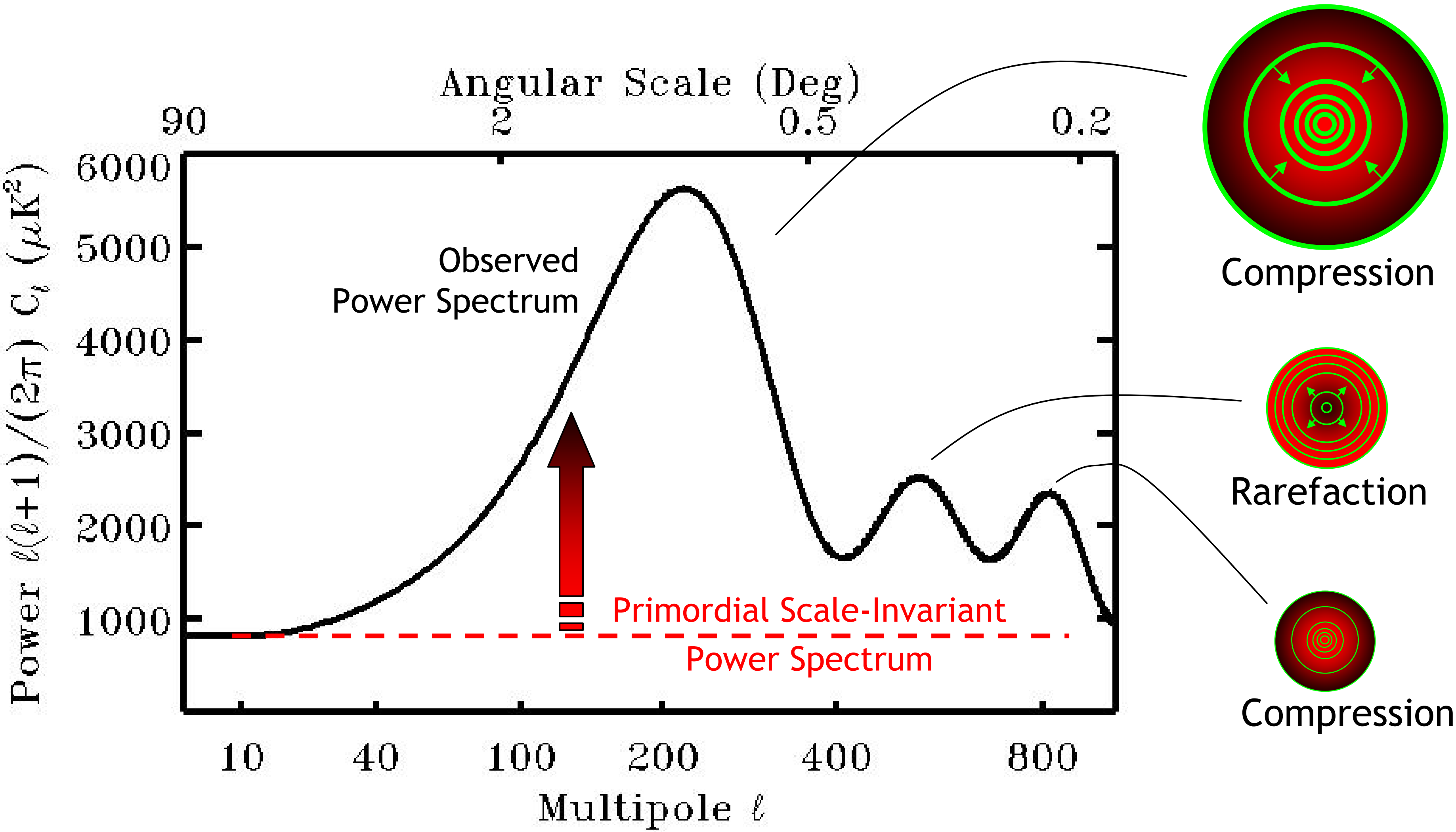
Dark matter?

Dark Energy?



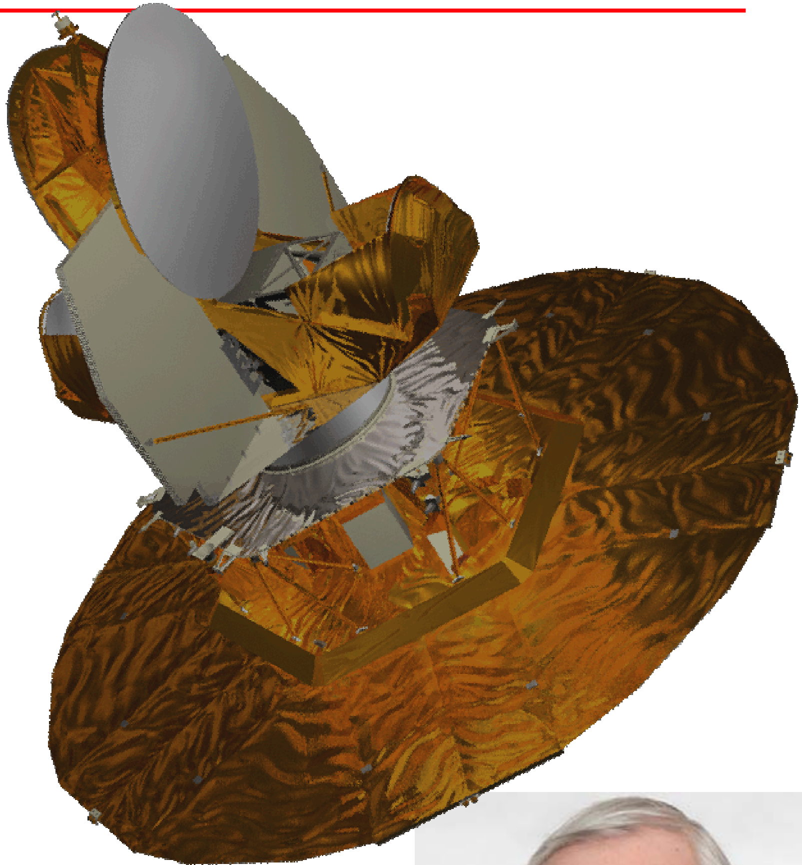
Being close but wrong might mean that we are close,
But might equally well mean that we are wrong.
-- Ed Turner

Acoustic Oscillations in Primordial Plasma



Peaks and troughs depend on cosmology and constituents in calculable fashion

Wilkinson Microwave Anisotropy Probe



Science Team

GODDARD
Charles Bennett (P.I.)
Robert Hill
Gary Hinshaw
Al Kogut
Michele Limon
Nils Odegard
Janet Weiland
Edward Wollack

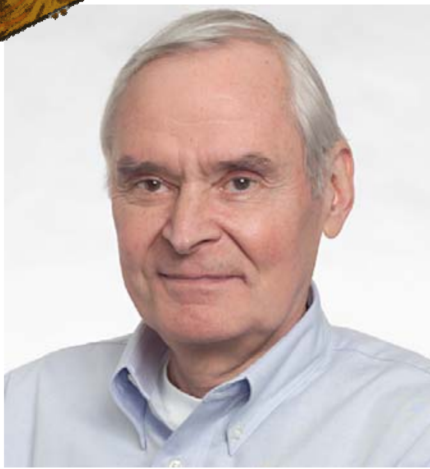
PRINCETON U.
Norman Jarosik
Eiichiro Komatsu
Micheal Nolta
Lyman Page
David Spergel

U. CHICAGO
Stephan Meyer

UCLA
Edward Wright

U. BRIT COLUMBIA
Mark Halpern

BROWN U.
Greg Tucker

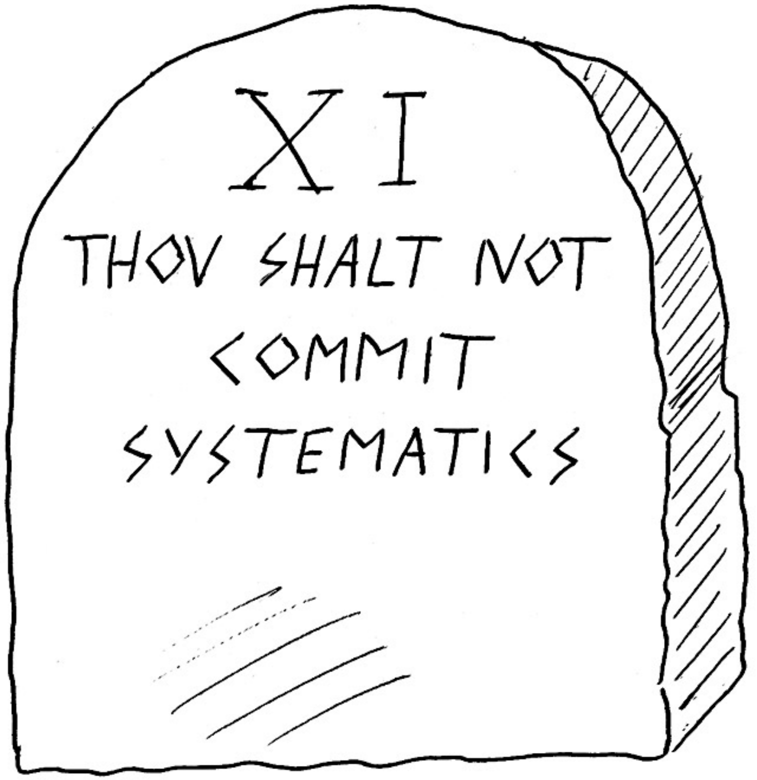


Prof. David T. Wilkinson
1935 - 2002

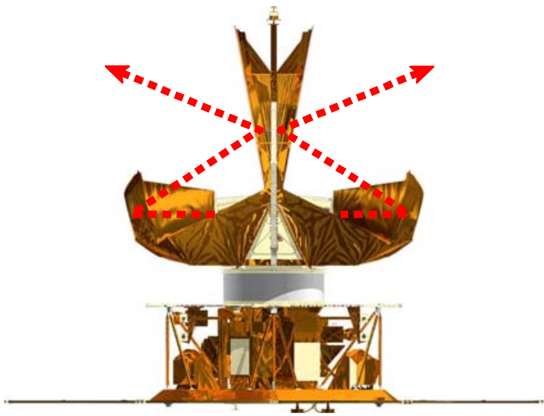
WMAP Design Strategy

- Differential Optics
- Multiple Channels
- Multiple Frequencies
- Interleaved Scan Pattern
- Stable Calibration
- L2 Orbit Far From Earth

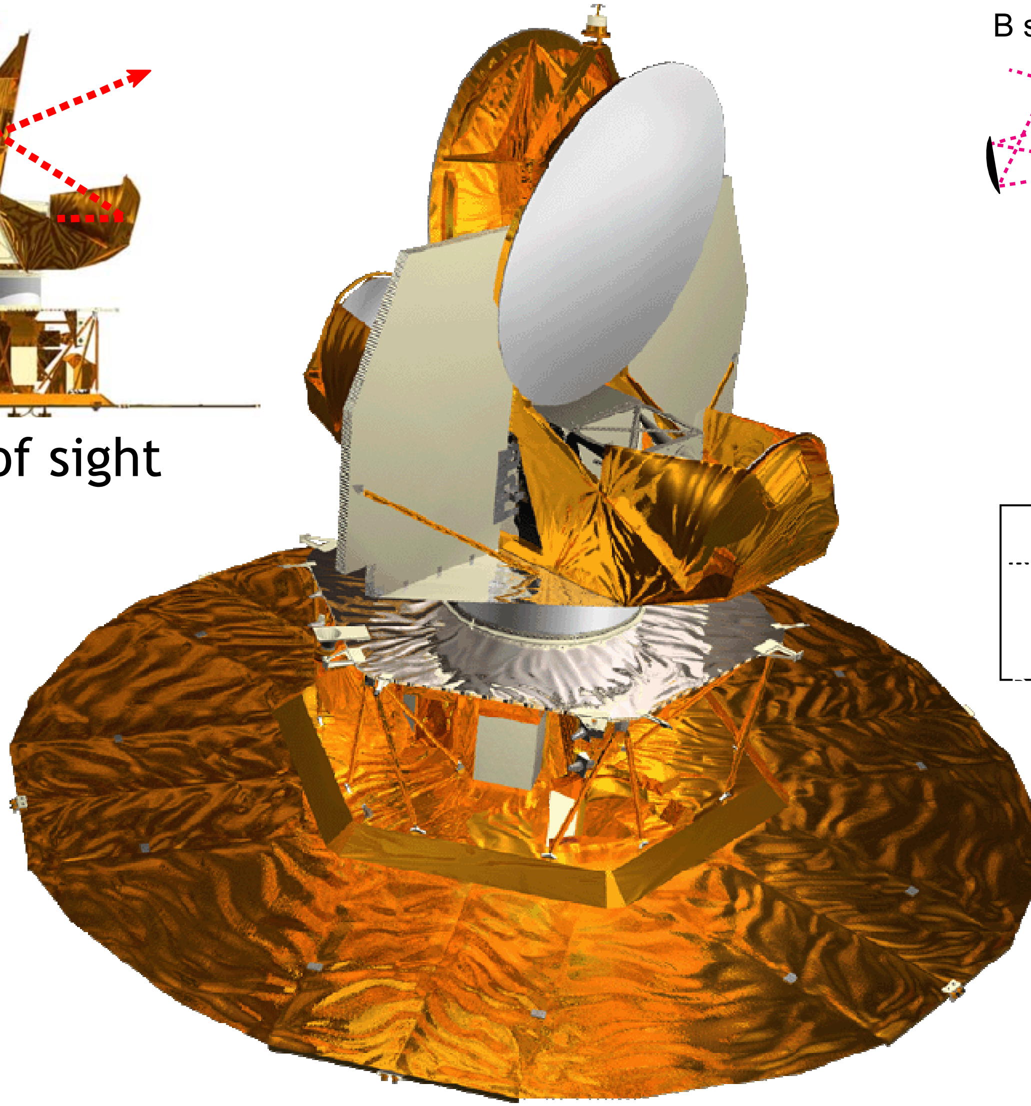
The 11th Commandment

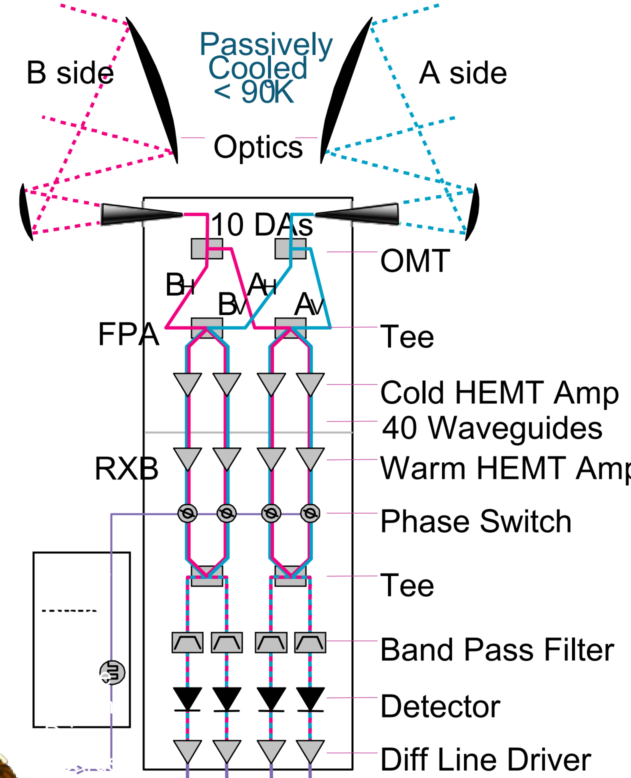


WMAP Differential Optics



2 lines of sight

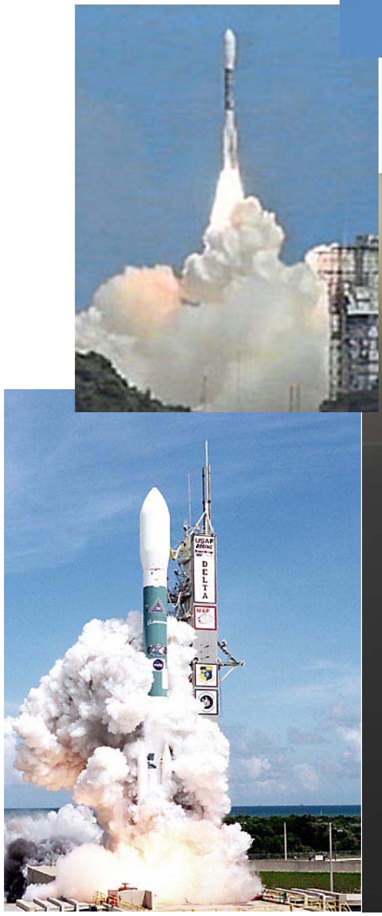


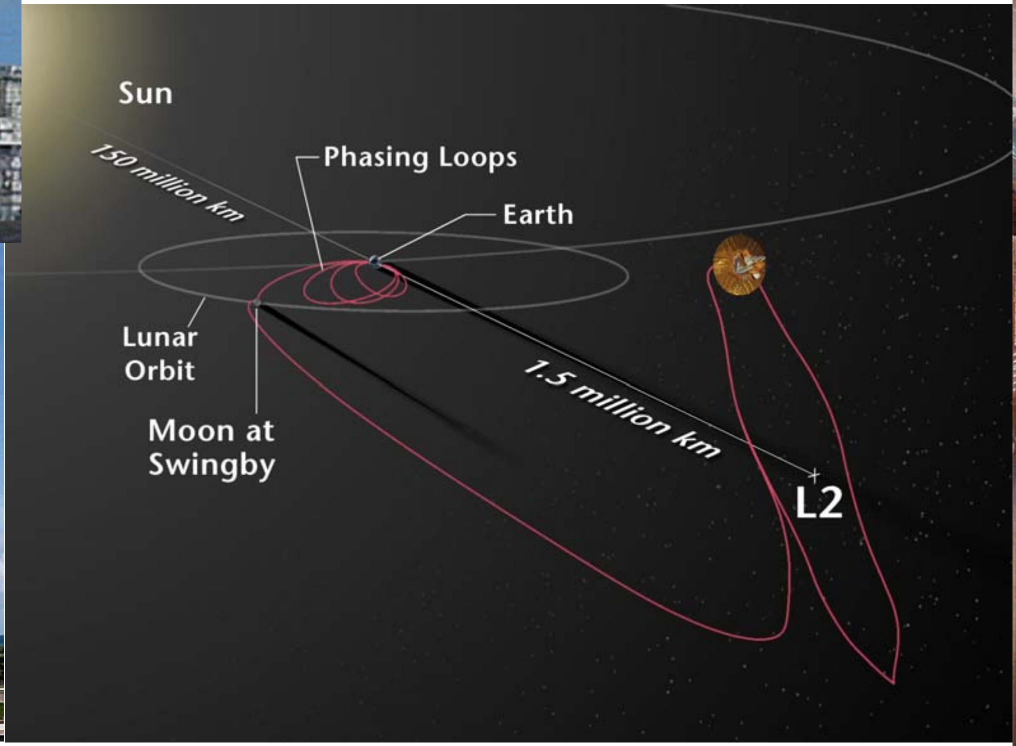


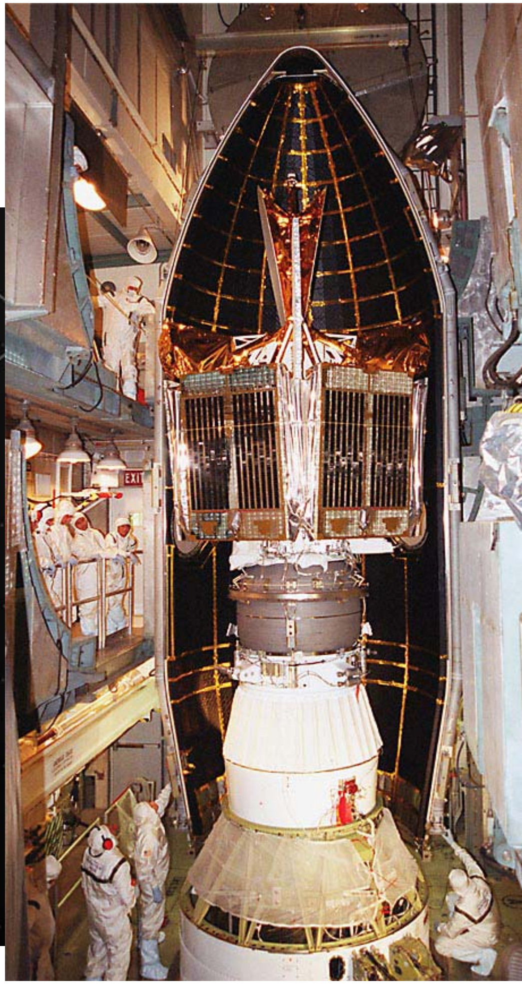
Differential Receiver

WMAP Launch

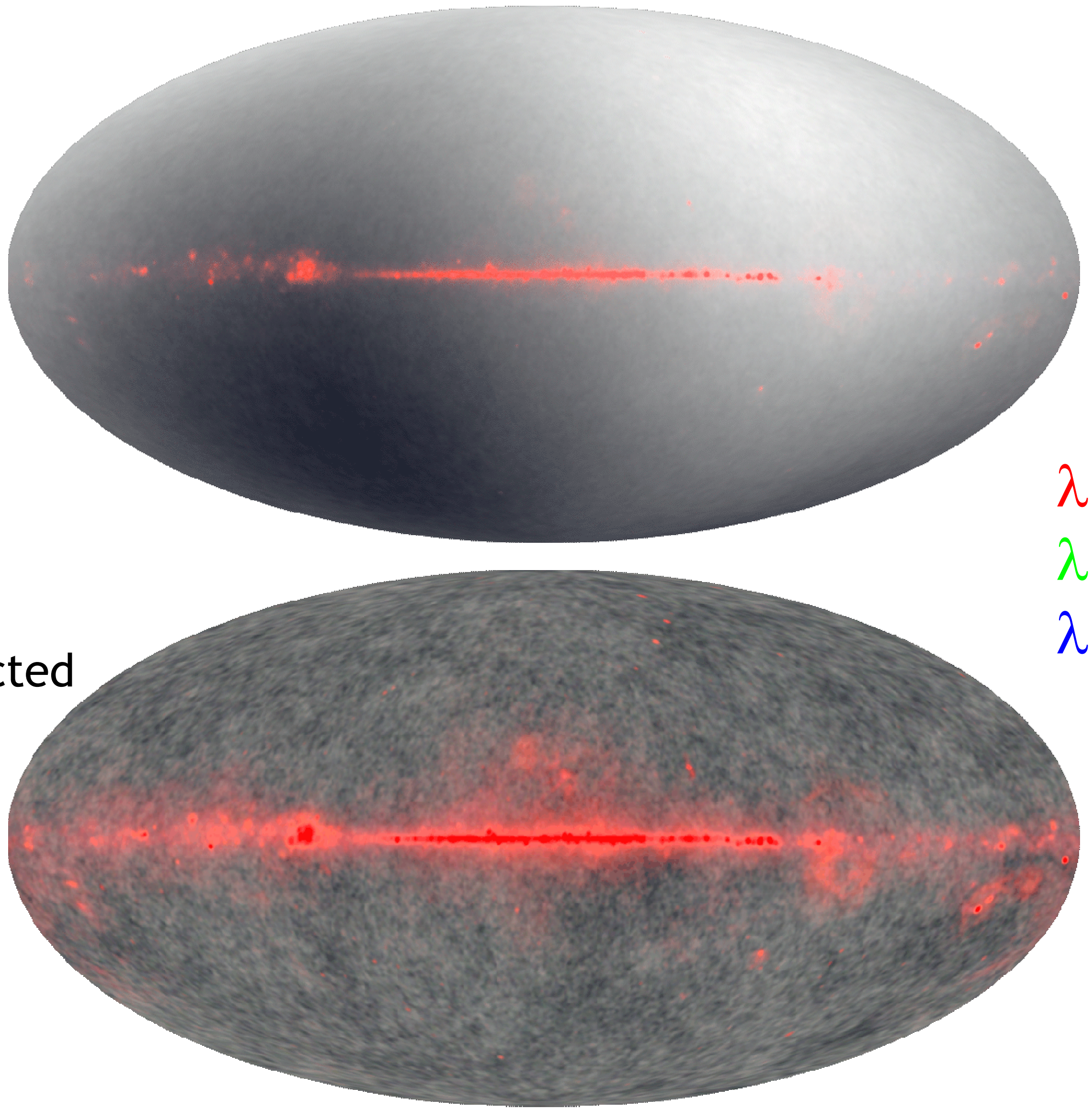
Launch June 30, 2001
3-Month Cruise to L2







3-Color Sky Maps



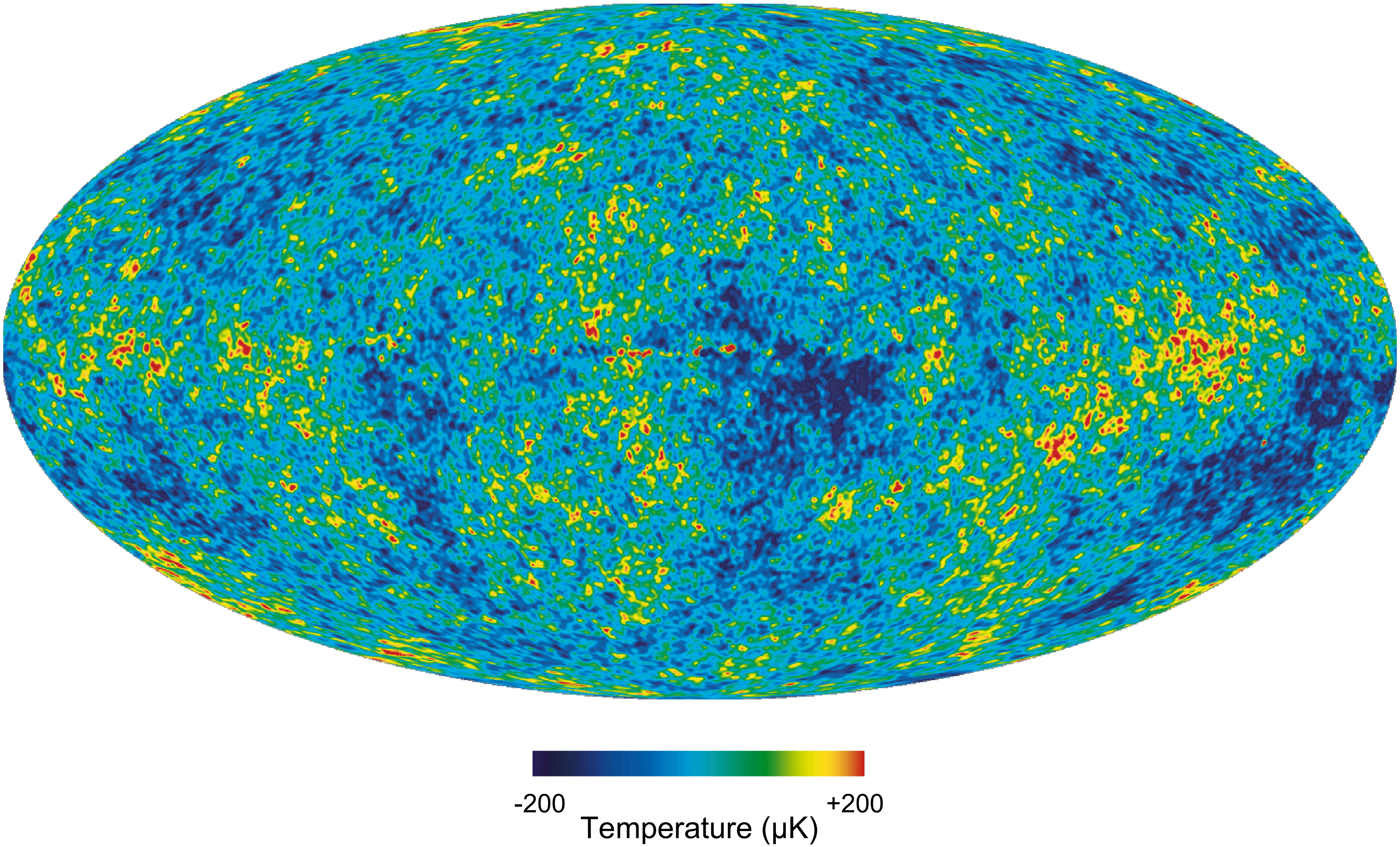
λ = 7.3 mm
λ = 4.9 mm
λ = 3.2 mm

Dipole- subtracted

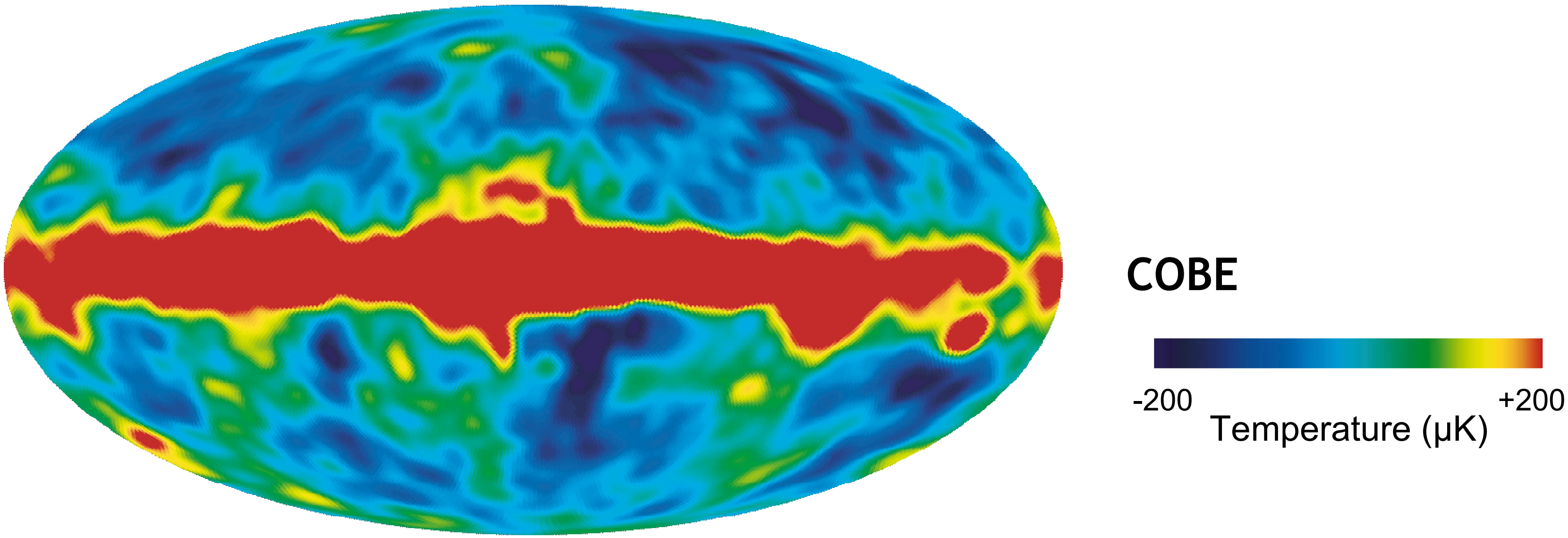
Bennett et al. (2003) ApJS, 148, 1

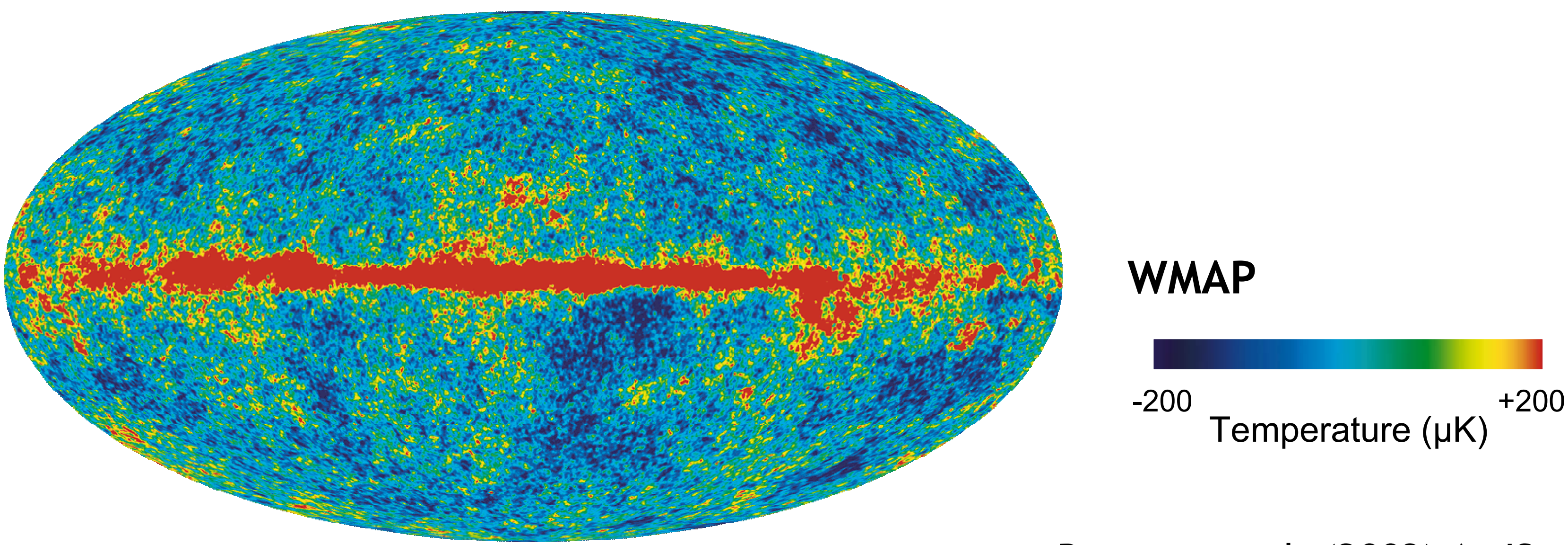
"Baby Picture" of the Universe

WMAP



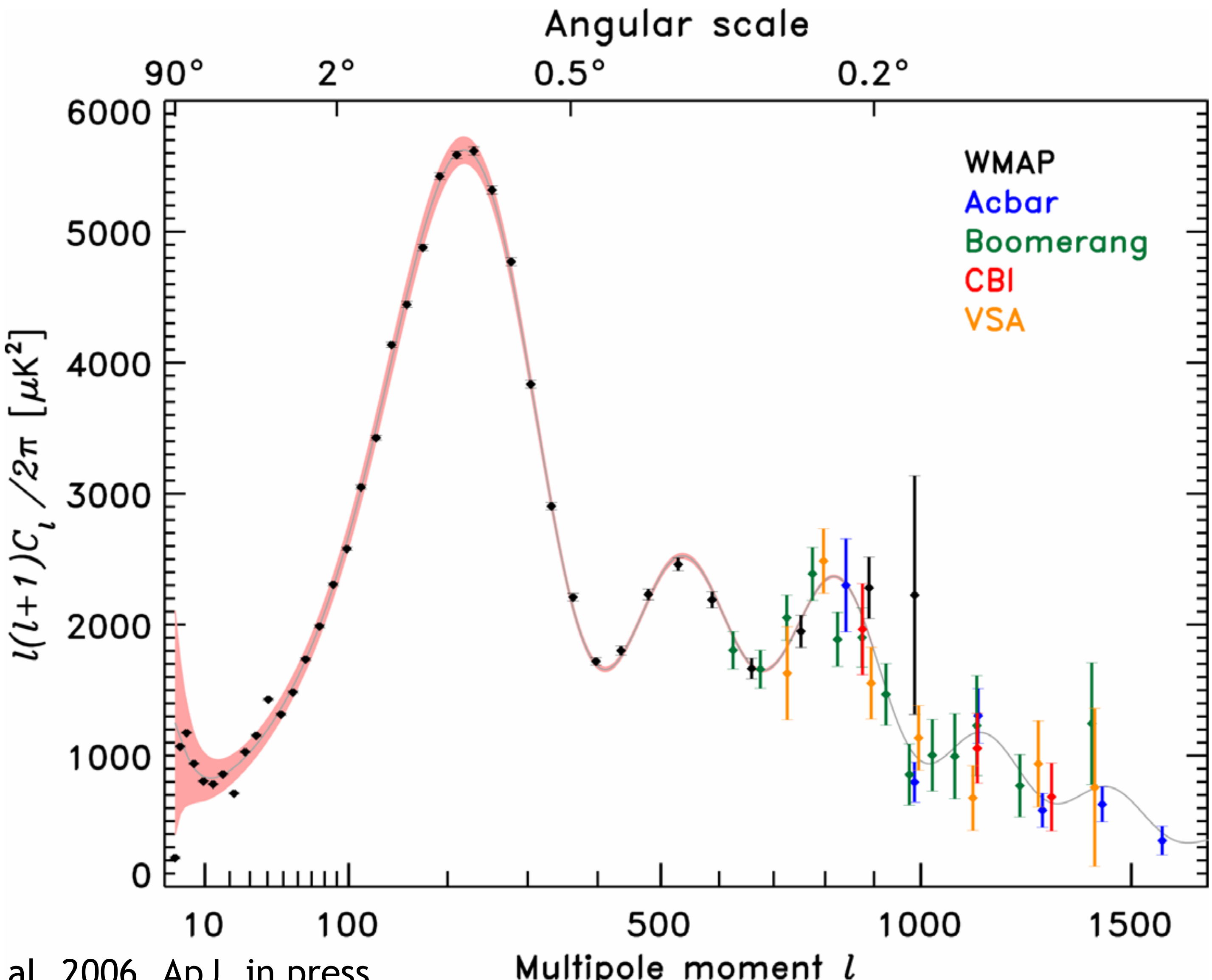
COBE vs WMAP





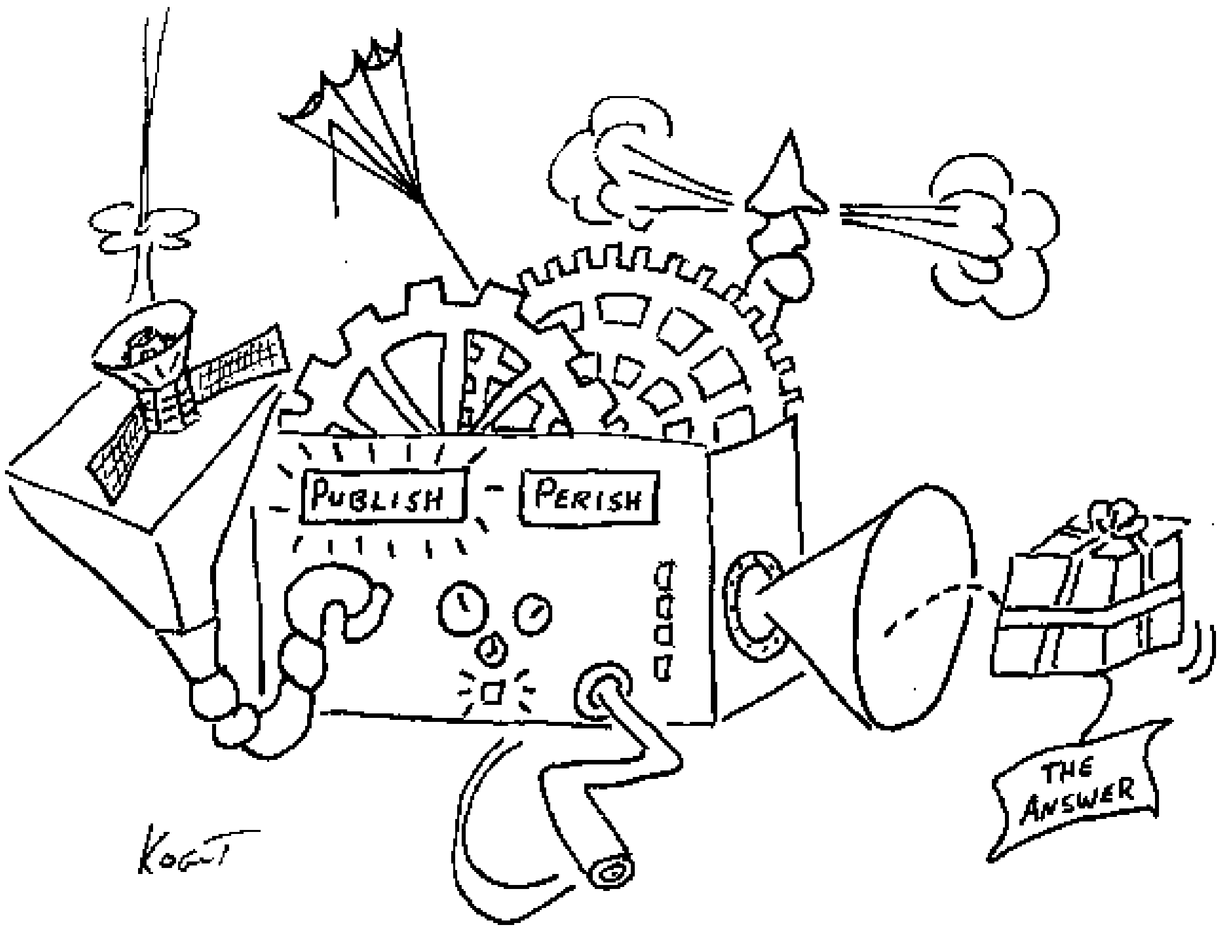
Bennett et al. (2003) ApJS, 148, 1

Angular Power Spectrum

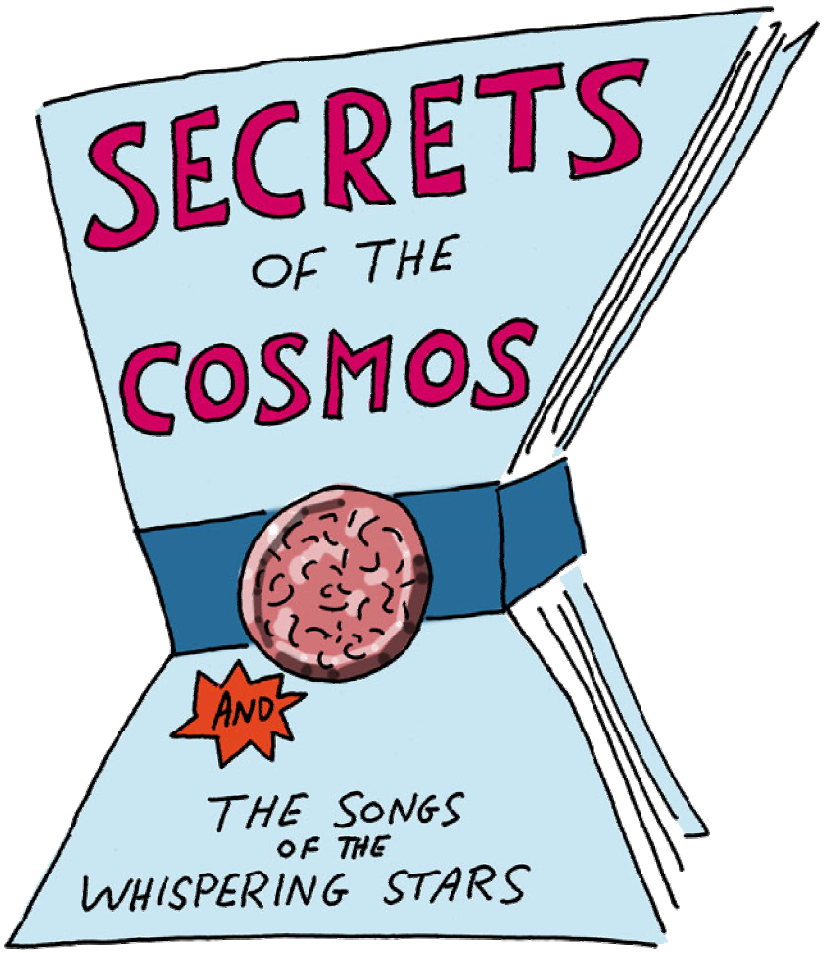


Hinshaw et al. 2006, ApJ, in press
astro-ph/0603451

But What Does It Mean …



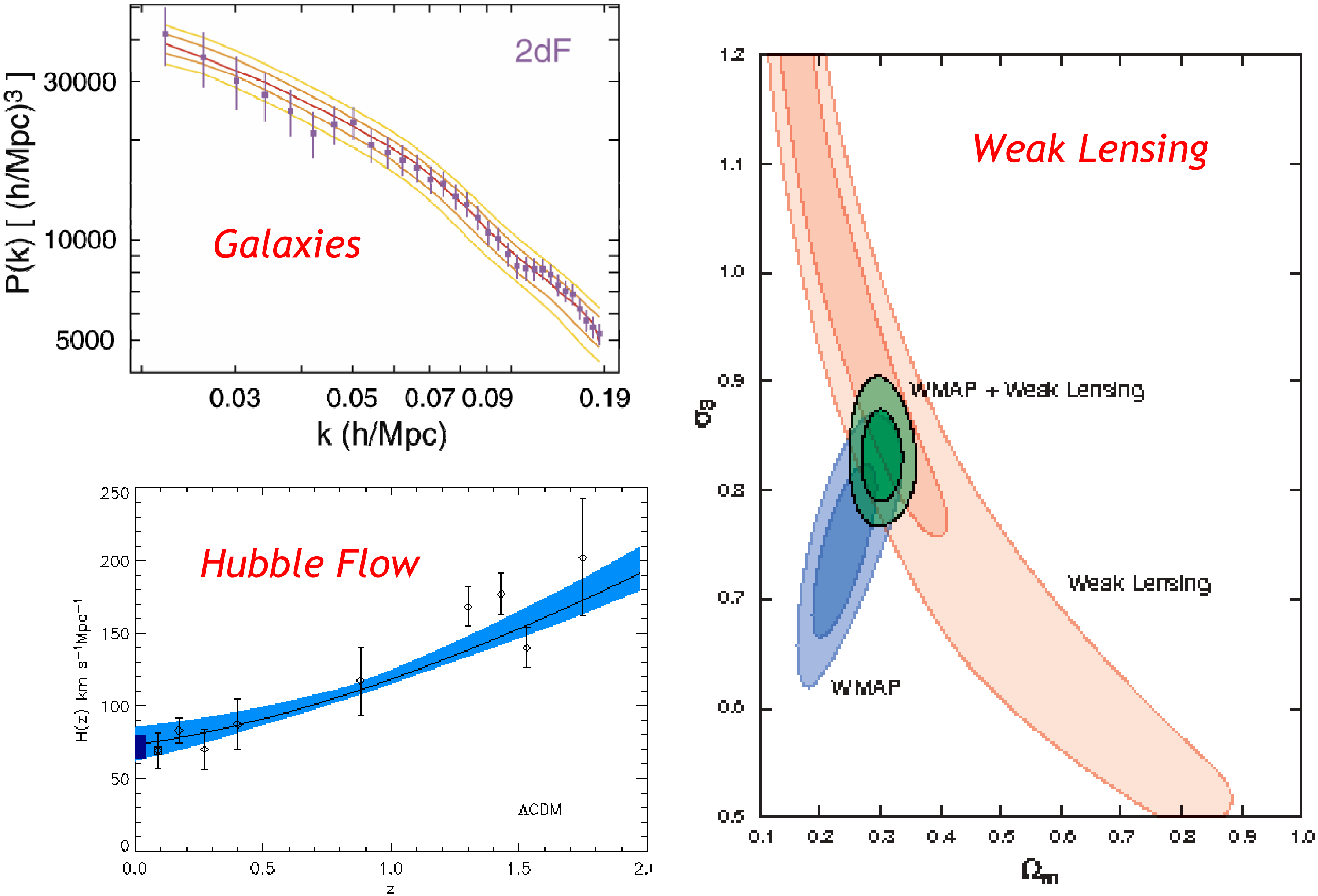
ΛCDM: Standard Model of Cosmology



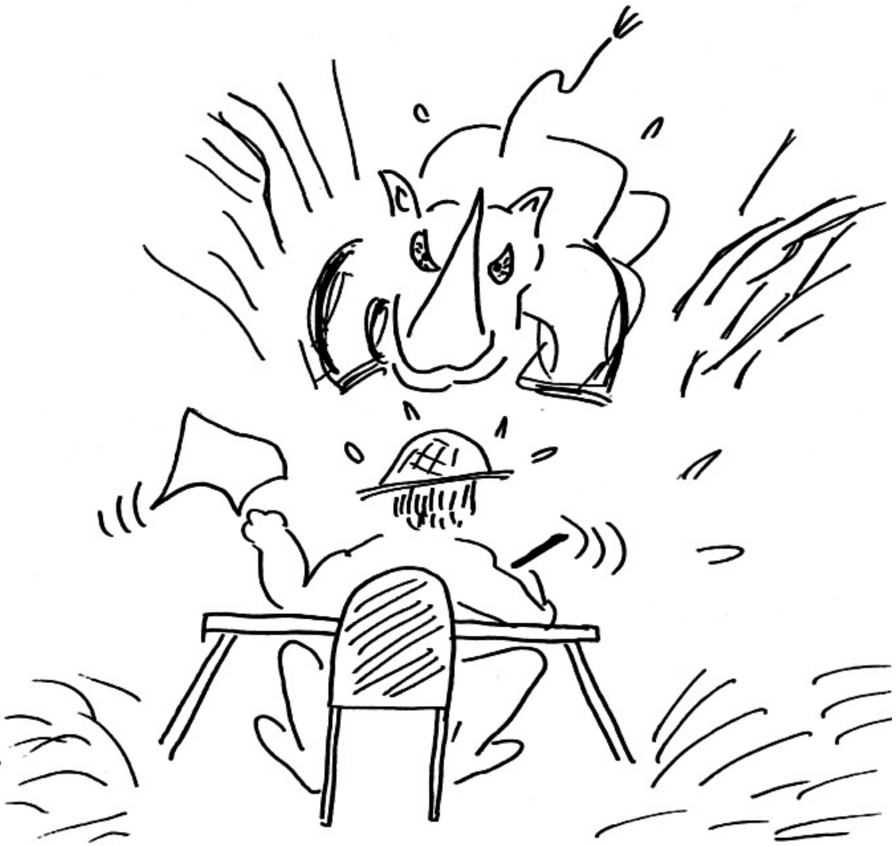
6 parameters describe multiple independent data sets!

Expansion	h	$= 0.704 \pm 0.015$
Baryons	Ω_b	$= 0.044 \pm 0.004$
Matter	Ω_m	$= 0.268 \pm 0.018$
Structure	σ_8	$= 0.776 \pm 0.032$
Scalar Index	n	$= 0.947 \pm 0.015$
Reionization	τ	$= 0.073 \pm 0.027$
Dark Energy	Ω_Λ	$= 0.732 \pm 0.018$

WMAP Predictions vs Other People's Data



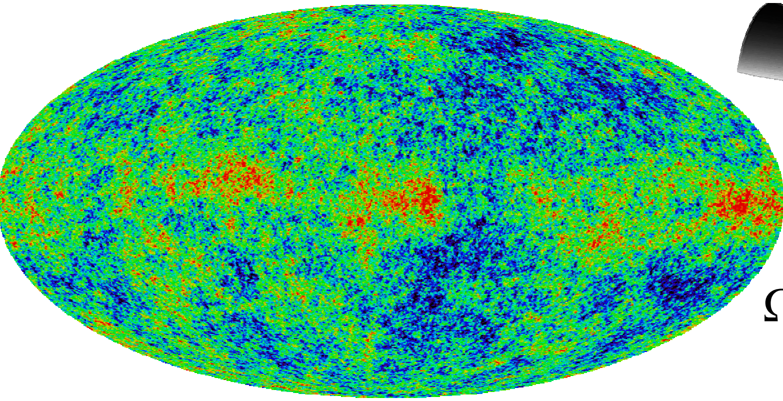
Adding Parameters to Model

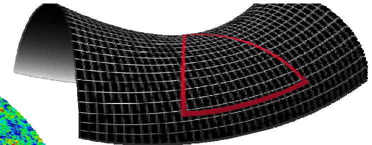


With seven free parameters, you can fit a charging rhino.

Curvature	$\Omega_k = -0.024 \pm 0.015$
Equation of State	$w = -1.06^{+0.13}_{-0.08}$
Topology	$L < 1.2\ R_H$
Global Rotation	$\varpi/H_0 < 5 \times 10^{-9}$
Neutrino Mass	$\Sigma m_\nu < 1.0$ eV
Running Index	$dn_s/d\ln k = -0.06 \pm 0.03$
Tensor Modes	$r < 0.28$

Geometry of Space-Time

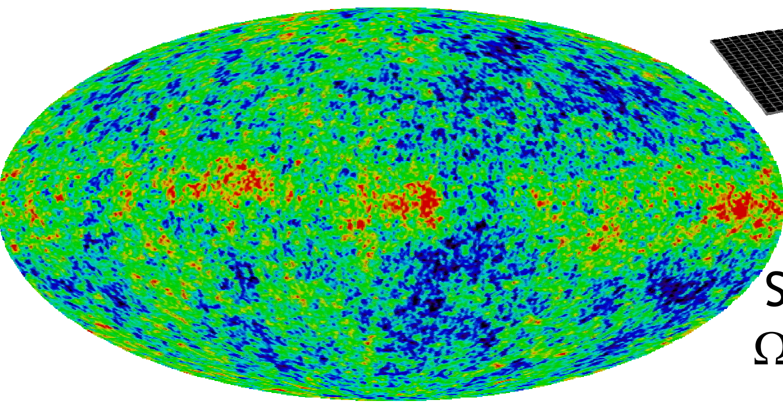


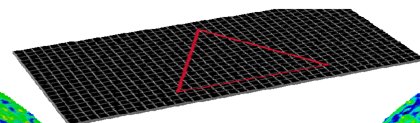


Simulation
$\Omega < 1$ (Open)

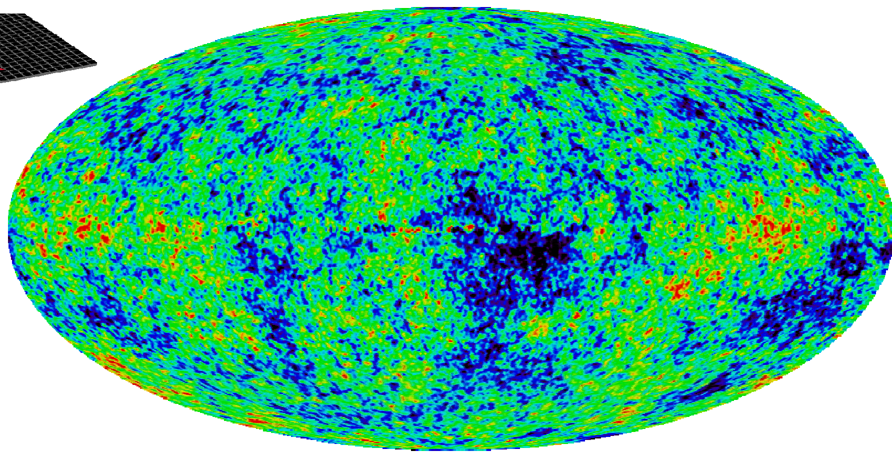
Spacetime is Flat:

$\Omega = 0.976 \pm 0.016$
Age = 13.7 ± 0.2 GYr

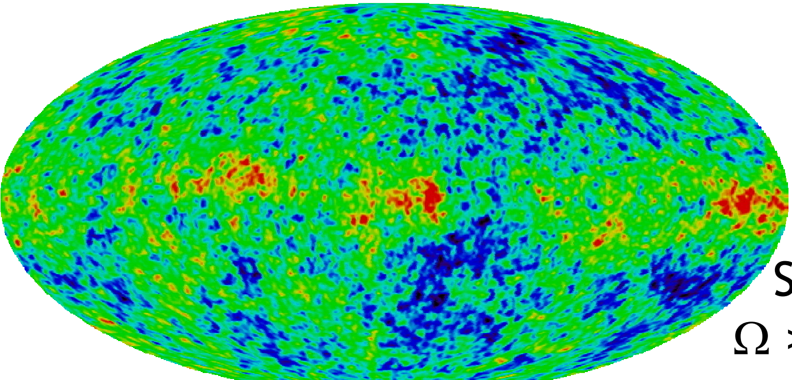


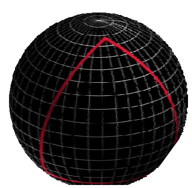


Simulation
$\Omega = 1$ (Flat)



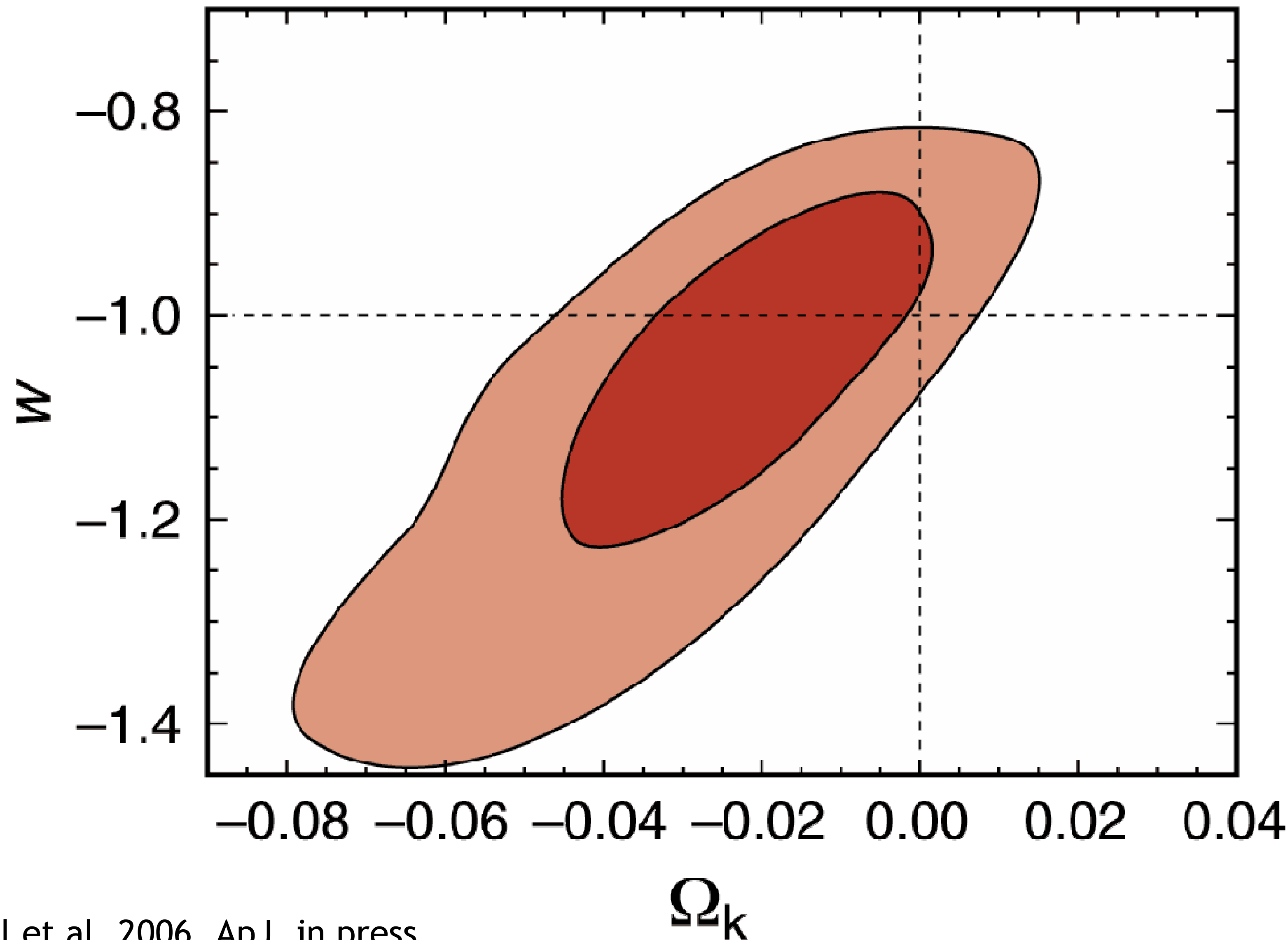
WMAP Data





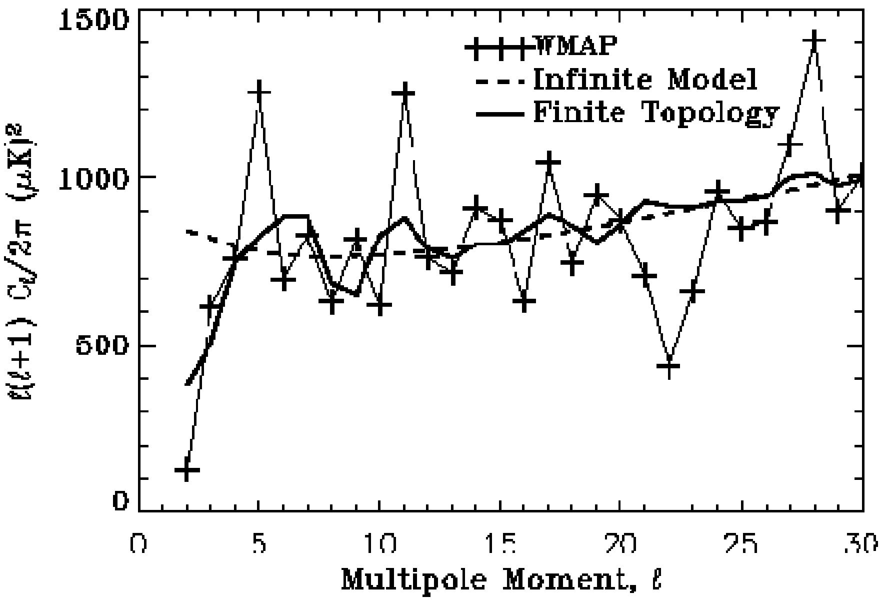
Simulation
$\Omega > 1$ (Closed)

Cosmological Constant



Spergel et al. 2006, ApJ, in press
astro-ph/0603453

Compact Universe



Low power at largest scales

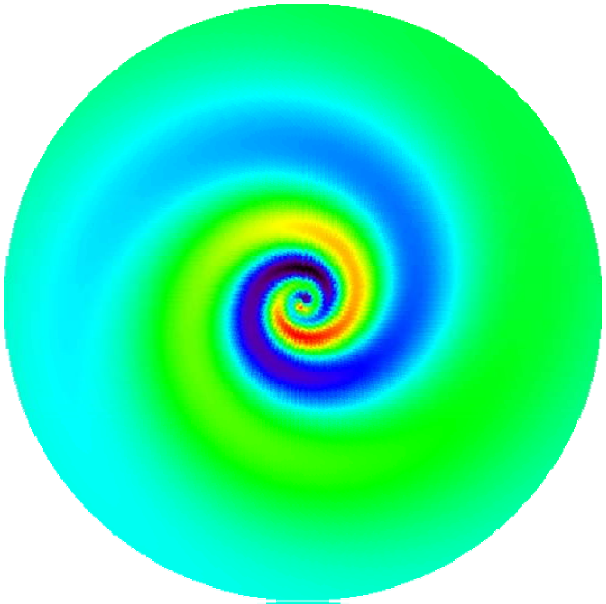
Cut-off from finite size?

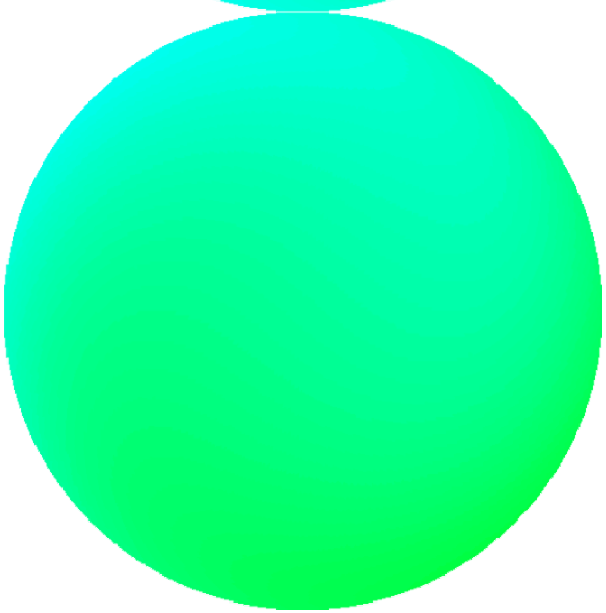
"Smoking Gun" not found

- Circles in the sky
- Full covariance test
- Cell size > 1.2 x Hubble

Cornish et al. 2004, PRL, 92, 201302
Phillips & Kogut 2006, ApJ, 645, 820

Global Rotation and Shear





Anisotropic Spacetime

$$\frac{\Delta T}{T} = (p^i u^i)_R - (p^i u^i)_E - \int_R^E p^j p^k \, \sigma_{jk} \, dt$$

Bianchi VII_h Models

Amplitude	$\frac{\sigma}{H_0}$
Pitch	$x = \sqrt{\frac{h}{1 - \Omega_0}}$
Focusing	Ω_0

Limit Shear $\frac{\sigma}{H_0} < 10^{-9}$, Vorticity $\frac{\varpi}{H_0} < 5 \times 10^{-9}$

Best Fit $\frac{\sigma}{H_0} = (5 \pm 1) \times 10^{-10}$ but $\Omega_0 = 0.5$

Kogut et al. 1997, PRD, 55, 1901
Jaffe et al. 2006, A&A, 460, 393J
Bridges et al. 2006, astro-ph/0605325

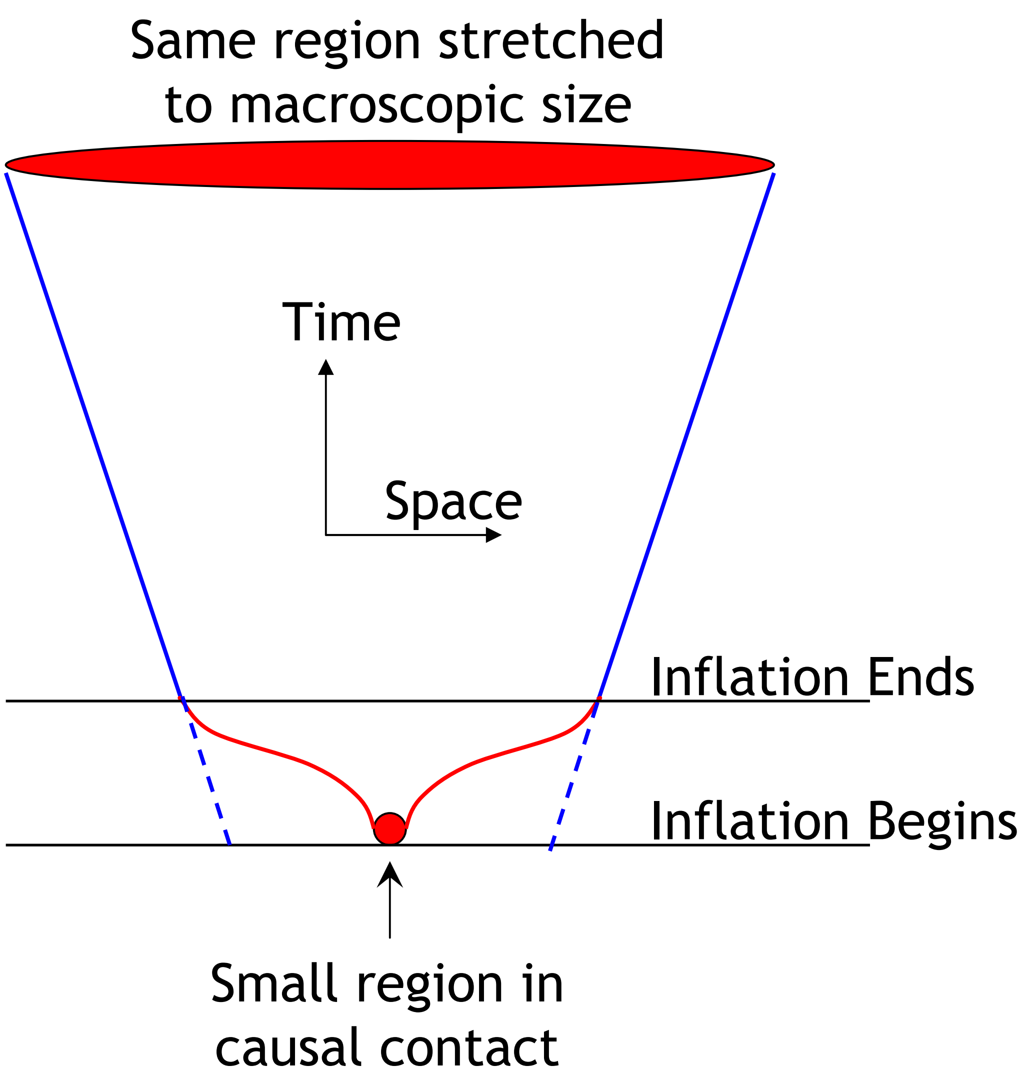
Motivation for Inflation

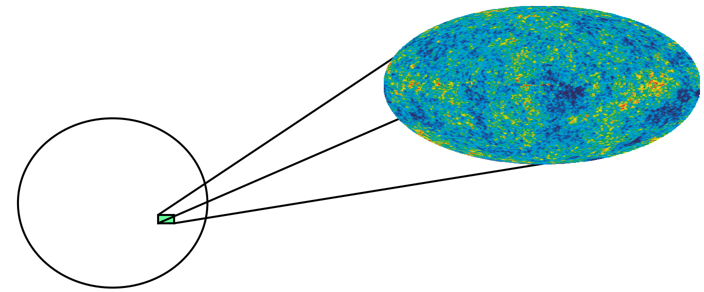
$\Omega = 1$ Is Unstable!

Now: $0.99 < \Omega < 1.01$

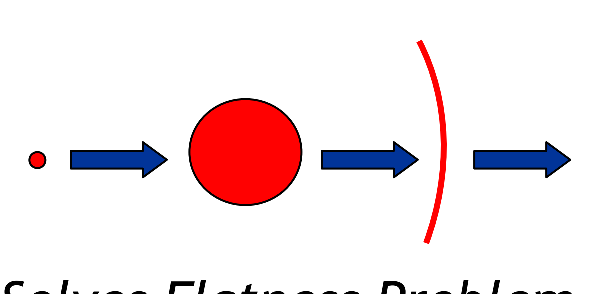
Then: $0.9999999999999999999999999999999999999999$
$9999999999999999999 < \Omega < 1.000000000000000000000$
$00000000000000000000000000000000000001$

Inflation 101

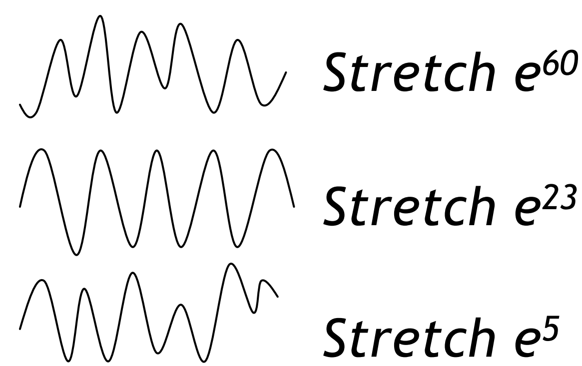




Solves Horizon Problem



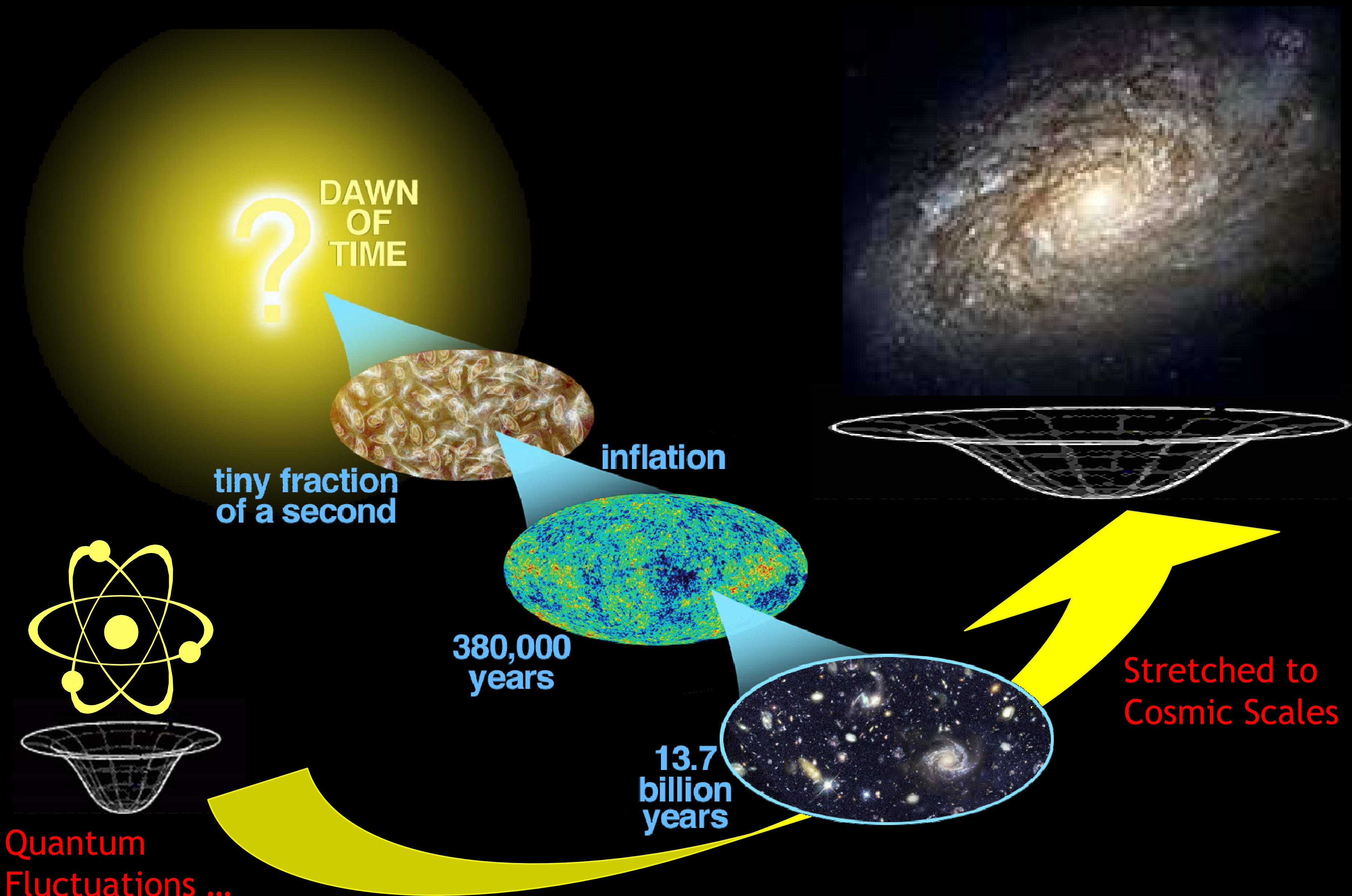
Solves Flatness Problem



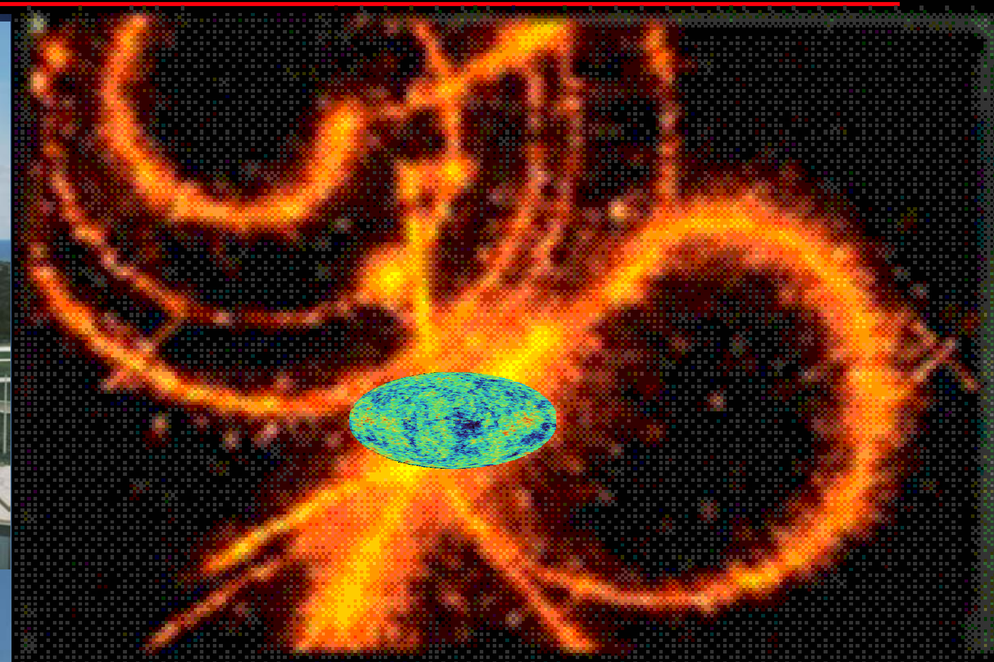
Scale-Invariant Fluctuations

Guth 1981, Linde 1982, Albrecht & Steinhardt 1982

Quantum Physics on a Cosmic Scale!



Observing Quantum Gravity?

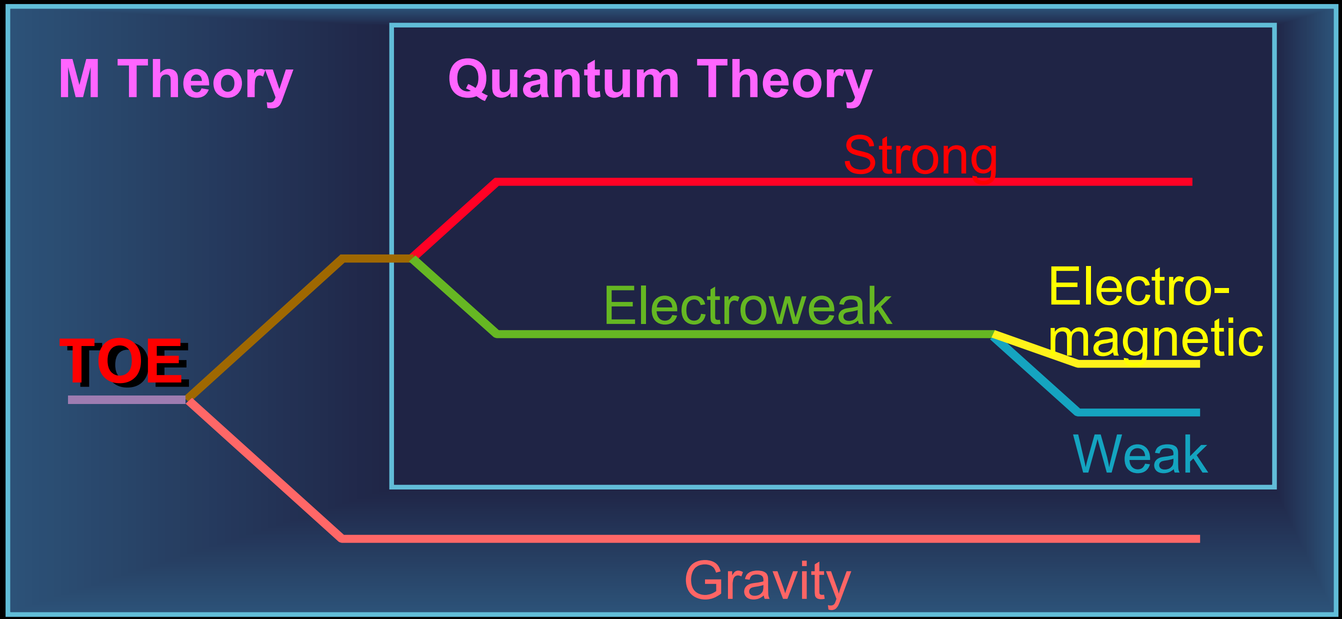


Gravity waves -- moving ripples in space-time -- leave pattern in CMB polarization

"Smoking Gun" signature of inflation

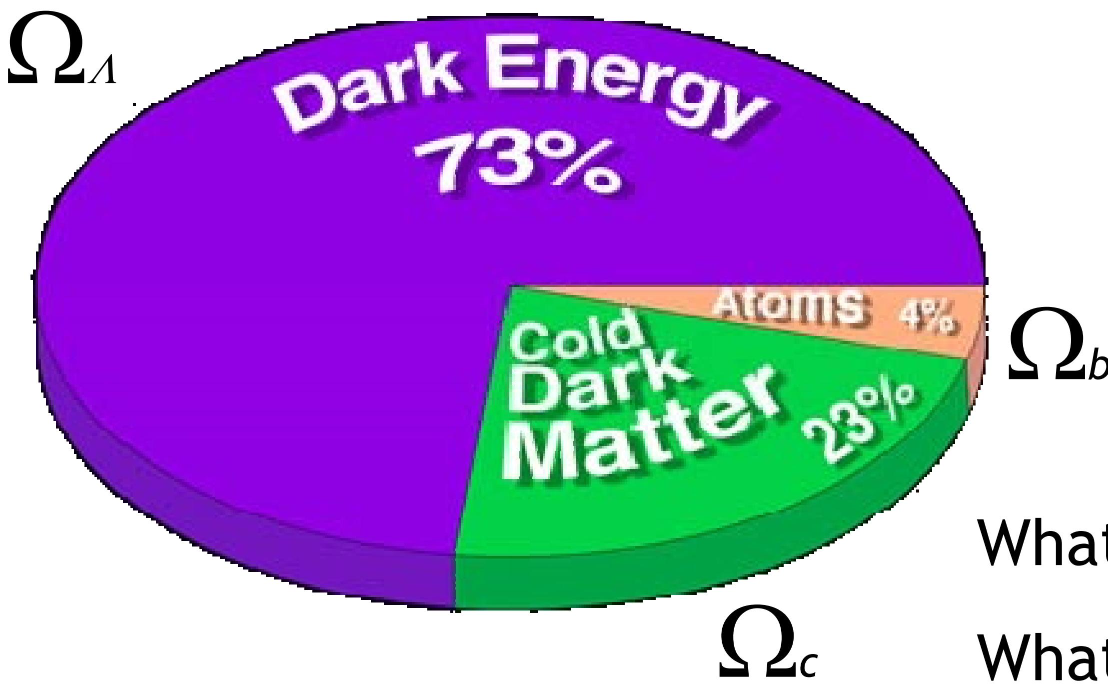
Amplitude proportional to inflationary energy scale

Towards a "Theory of Everything"



Intersection of Particle Physics and Cosmology

A Precise Quantification of Ignorance



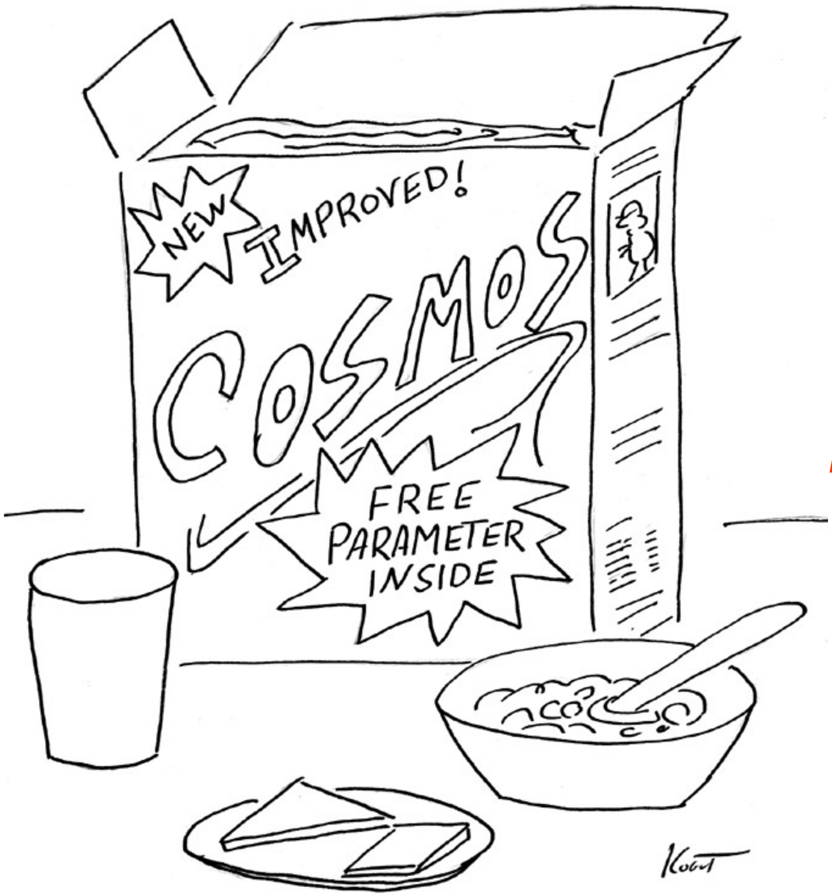
What Is Dark Matter?

What Is Dark Energy?

Why Are They So Close?

Dark Energy Consistent with Cosmological Constant:
Was Einstein right after all?

The Future …



Breakfast of Theorists

Now have the "Big Picture" of cosmology

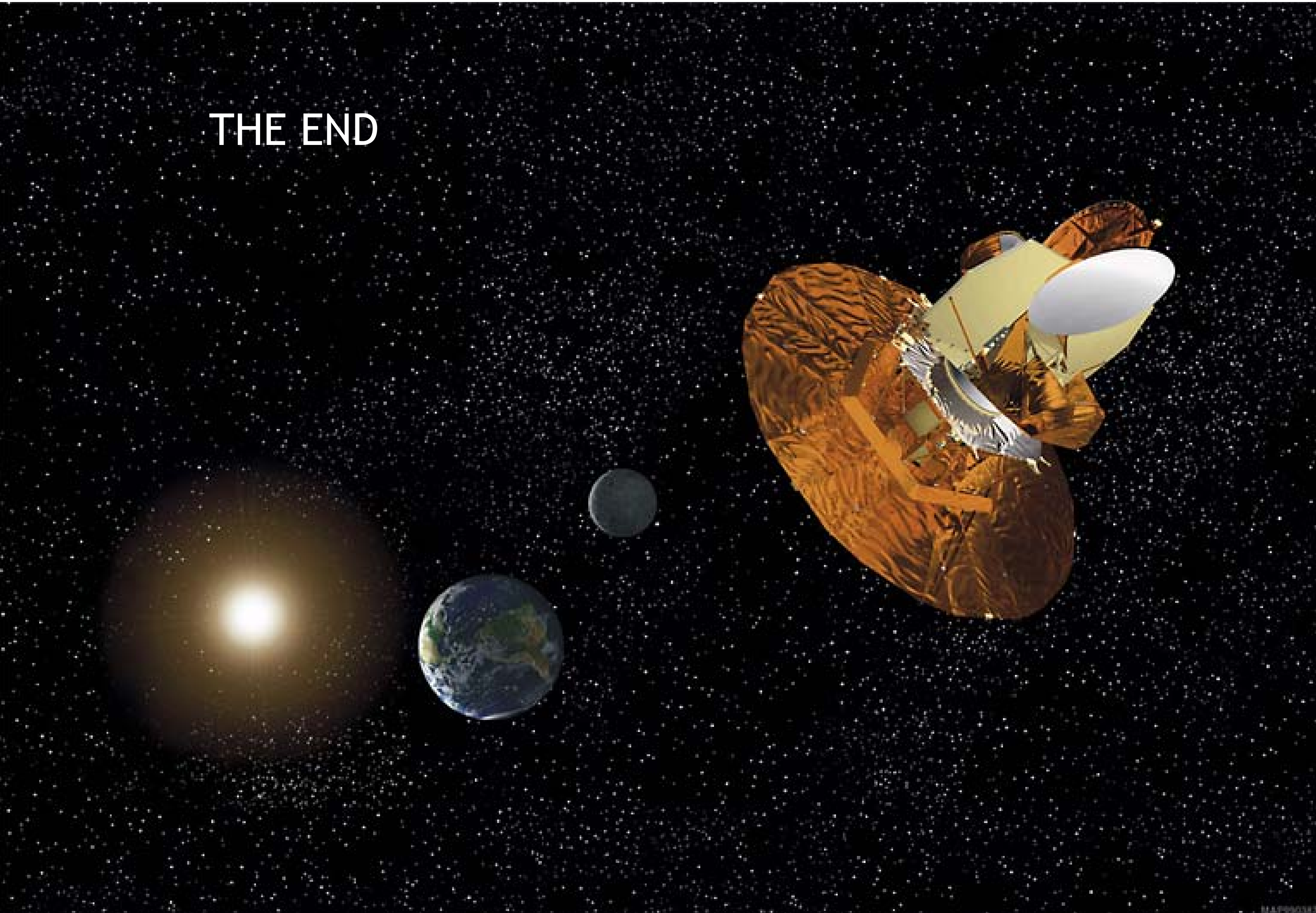
- Consistent theory fits many observations
- Flat universe dominated by dark matter and dark energy
- Stars, planets, chili dogs, etc account for only 4% of the total

Model has 6 free parameters

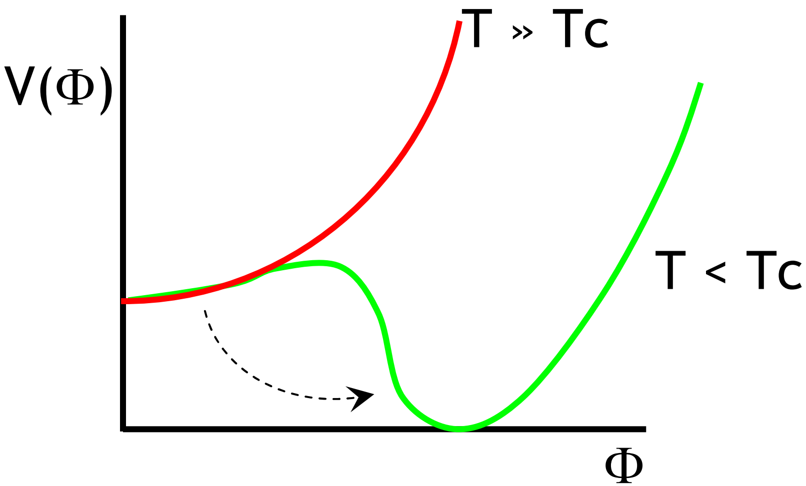
- Not so different from Ptolemy's 28
- Unknown stuff dominates the universe
- Will our picture last 1500 years?

New data in the pipeline

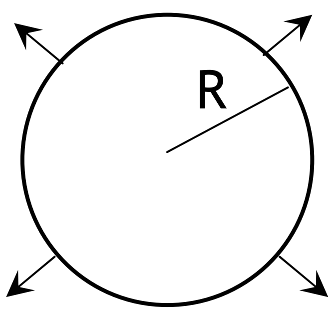
- WMAP, other CMB data: Polarization!
- Supernovae, other astronomical data
- Particle physics "Theory of Everything"


THE END

Inflation 101



Phase transition at T=Tc
drives exponential expansion



$$\frac{d^2R}{dt^2} = - \frac{GM}{R^2}$$

Case 1: Matter-Dominated

$$M = \text{Const}, \ \frac{d^2R}{dt^2} < 0$$

Case 2: Vacuum Energy Density

$$M = -V_0R^3, \ \frac{d^2R}{dt^2} = R$$

$$R(t) = R_0 \exp(t)$$

Inflate Space-Time To Force Local Flatness