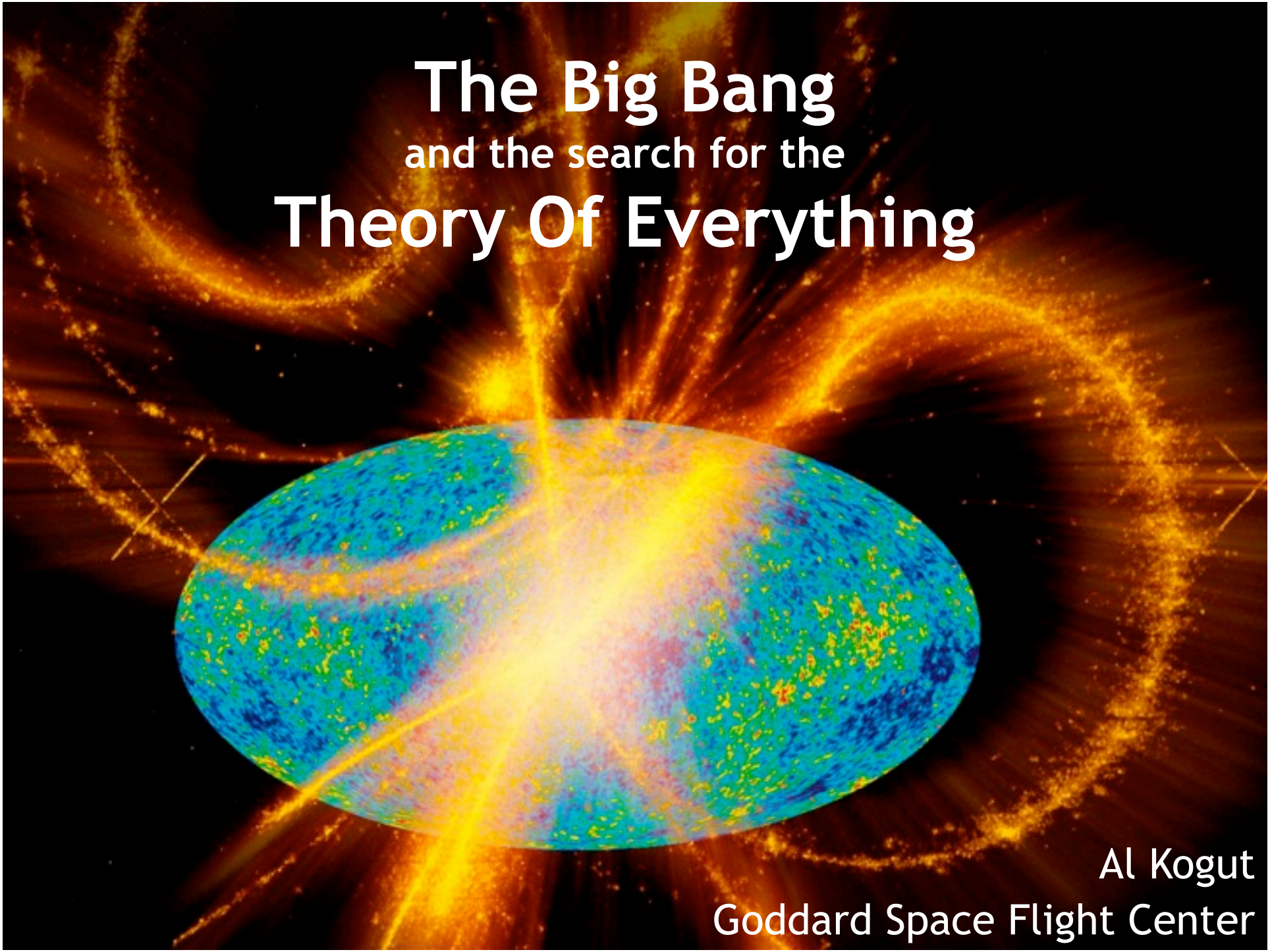

The Big Bang
and the search for the
Theory Of Everything
Al Kogut
Goddard Space Flight Center

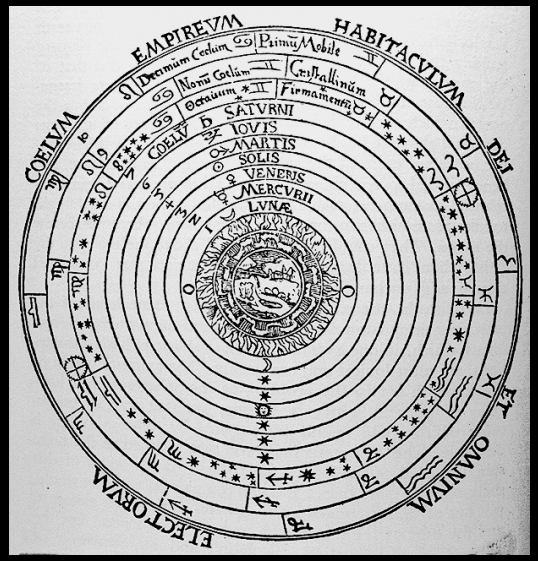
Cosmology: The Big Picture

What is all this stuff?

How did it form?

What will happen to it?

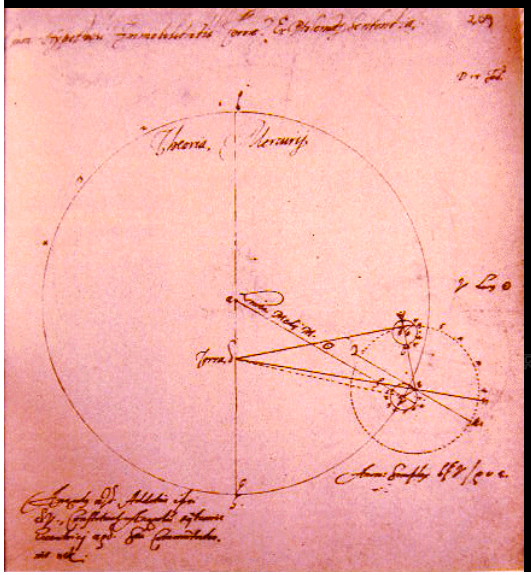
Aristotle/Ptolemaeus: A Calculable Cosmology

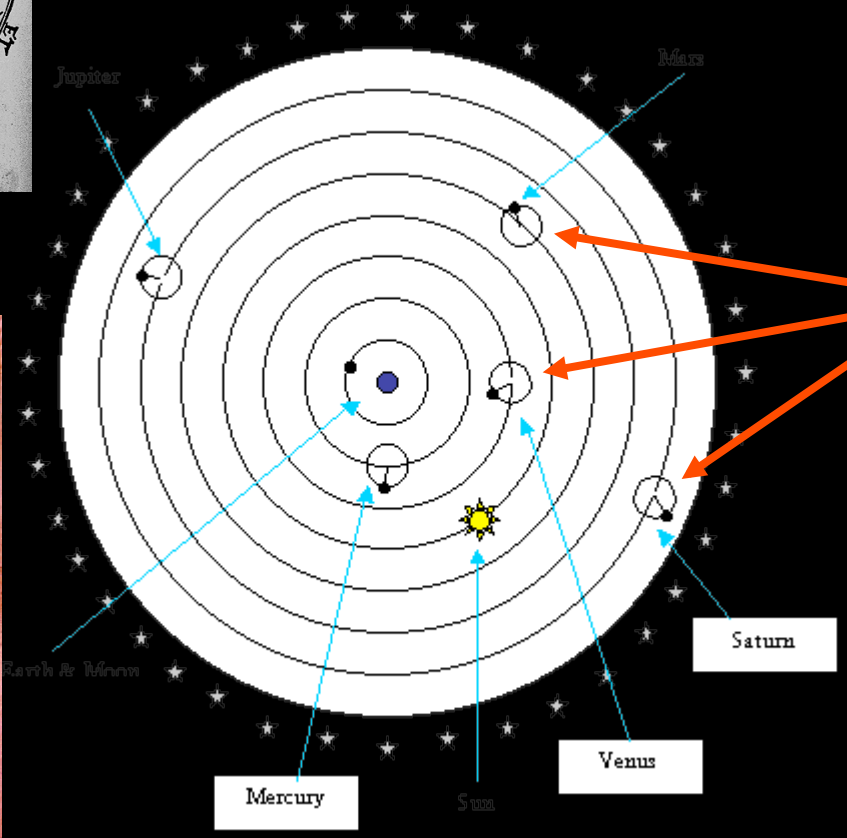


Aesthetics and Observation

Astonishingly successful

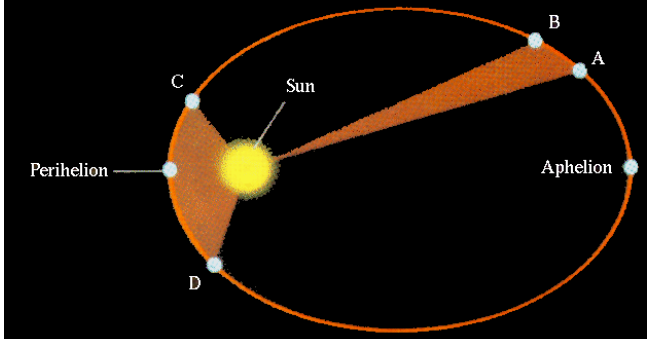
Modestly complicated





28 Epicycles

Beginnings of Modern Cosmology



Copernicus 1543/Kepler 1609

Simplified planetary motion

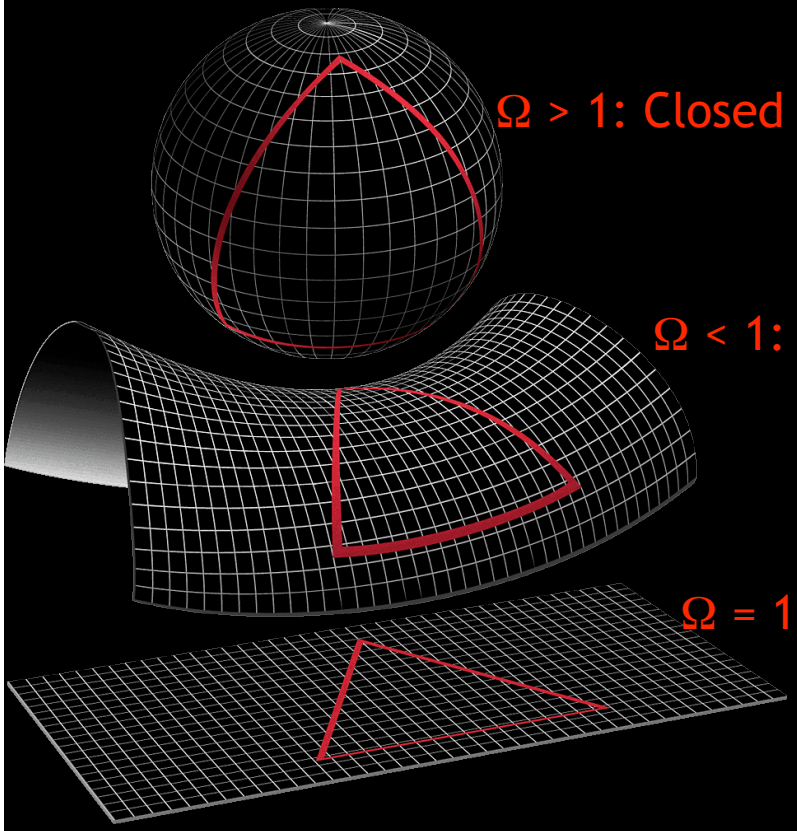
Newton 1687

Unified celestial/terrestrial forces

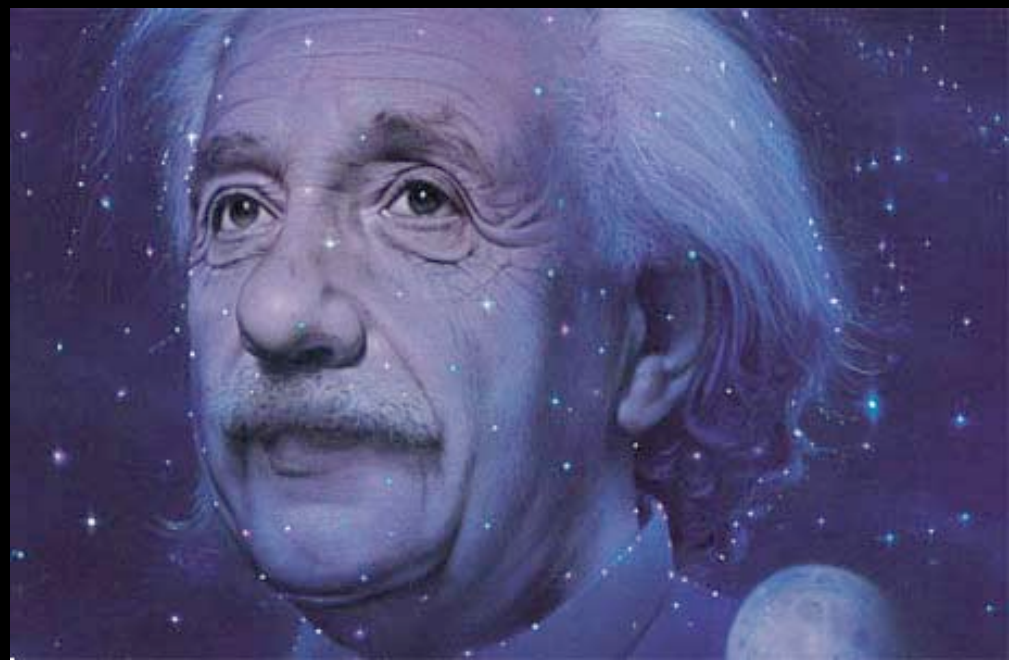
Hubble 1923

Existence of external galaxies

Einstein and Cosmology



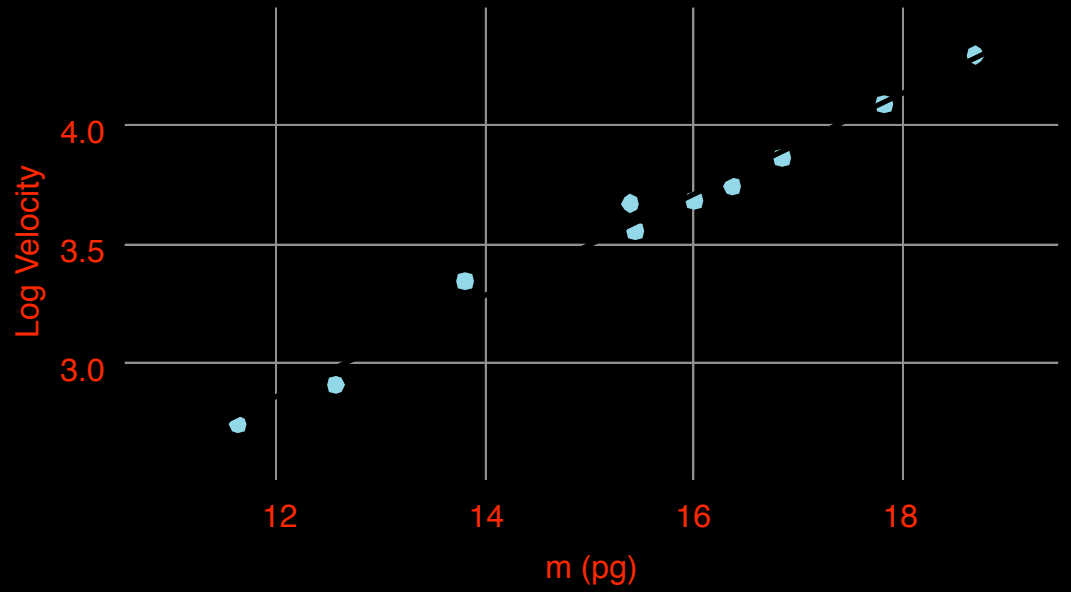
General Relativity:
Matter Shapes Spacetime



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

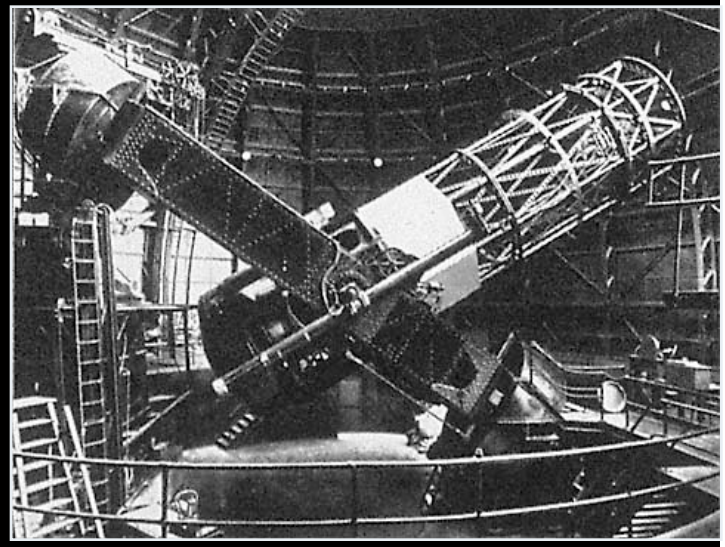
1929: Hubble Discovers Expanding Universe

Edwin Hubble



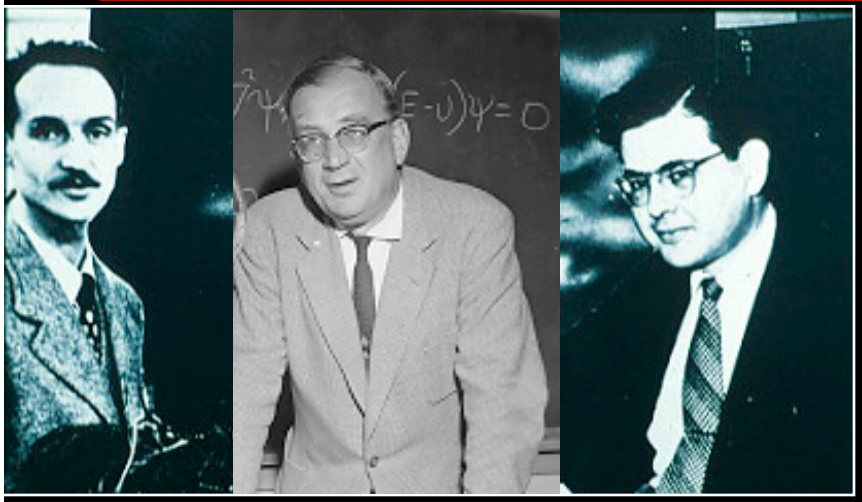
Universe is not static!

Einstein recants on Λ



Mt. Wilson 100 Inch Telescope

Hot Big Bang Theory



First postulated 1948

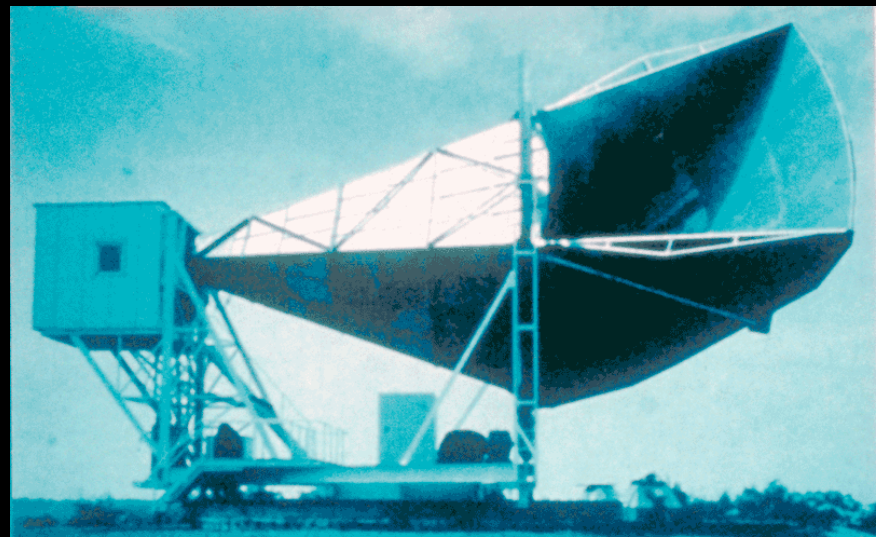
Universe was once much hotter and denser than today

Universe cools as it expands

Observable relics

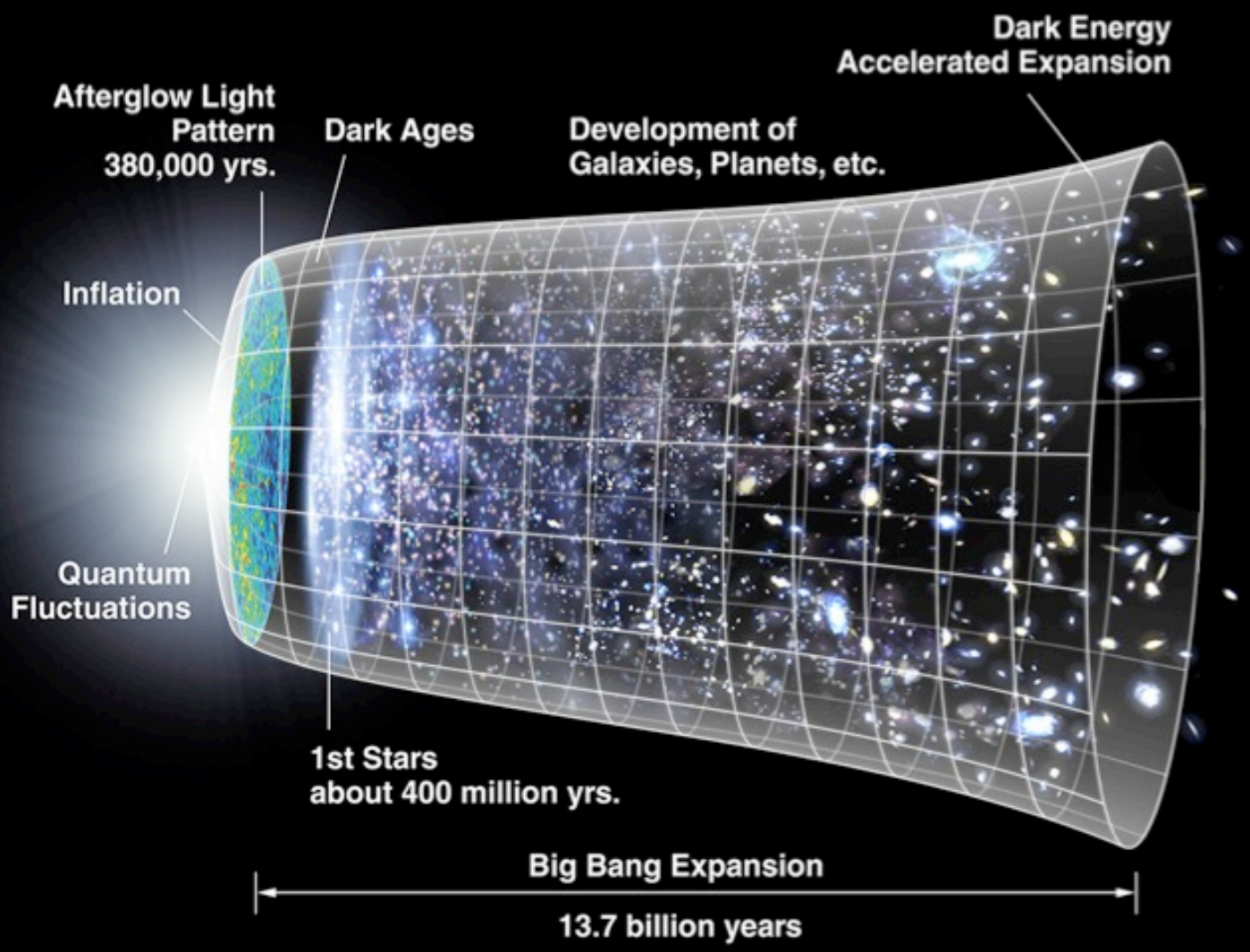
- Microwave Heat Radiation
- Light Elements (H, He, Li)

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



Heat radiation detected 1965

Big Bang Cosmology

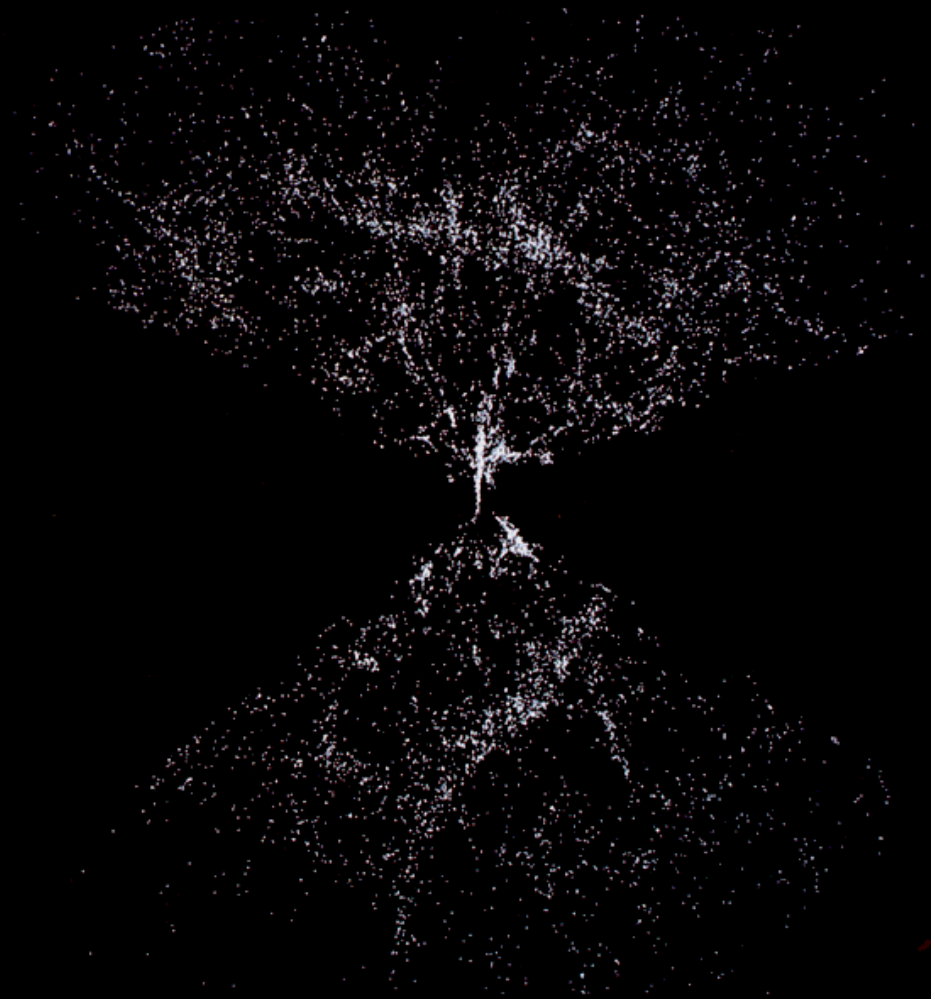


1980's: Trouble in River City

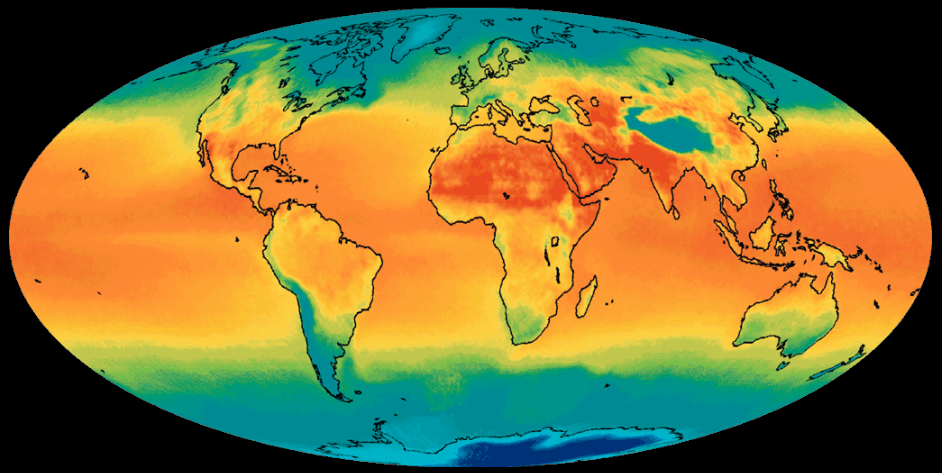
Stars revolve around galaxies
too fast for inferred gravity

Dark Matter:
Interacts with gravity
but not with light

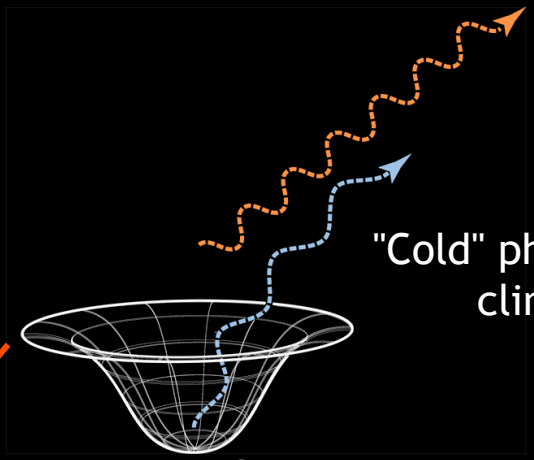
Universe is too lumpy to grow
via gravity alone

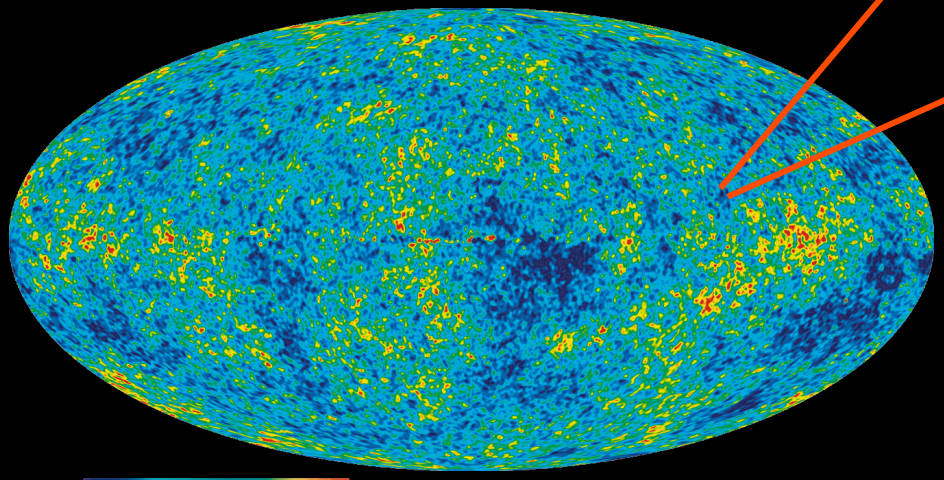


Microwaves Record The Initial Conditions



-63° Centigrade +37°
JUNE 1992



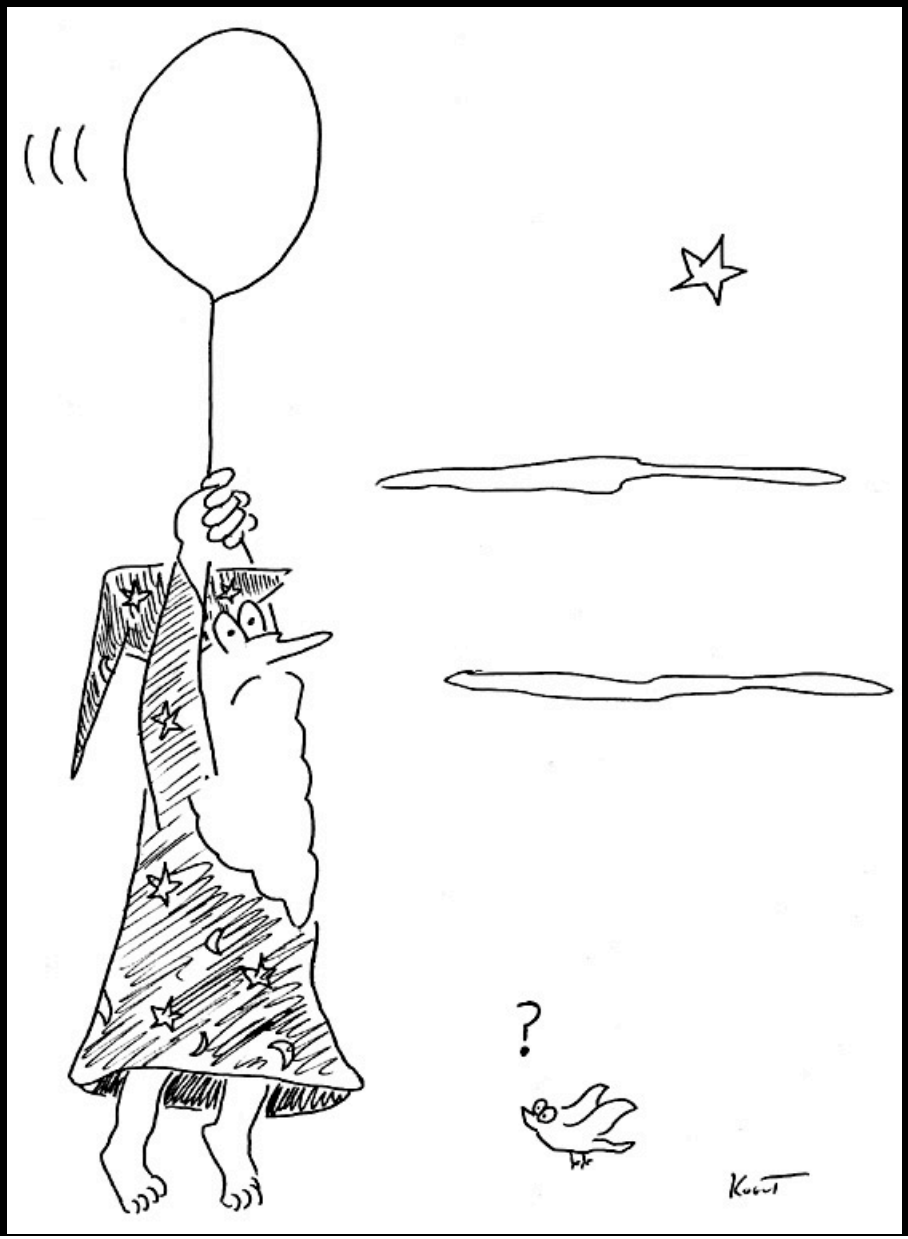


-200 Micro-Kelvin +200
379,000 Years After Big Bang

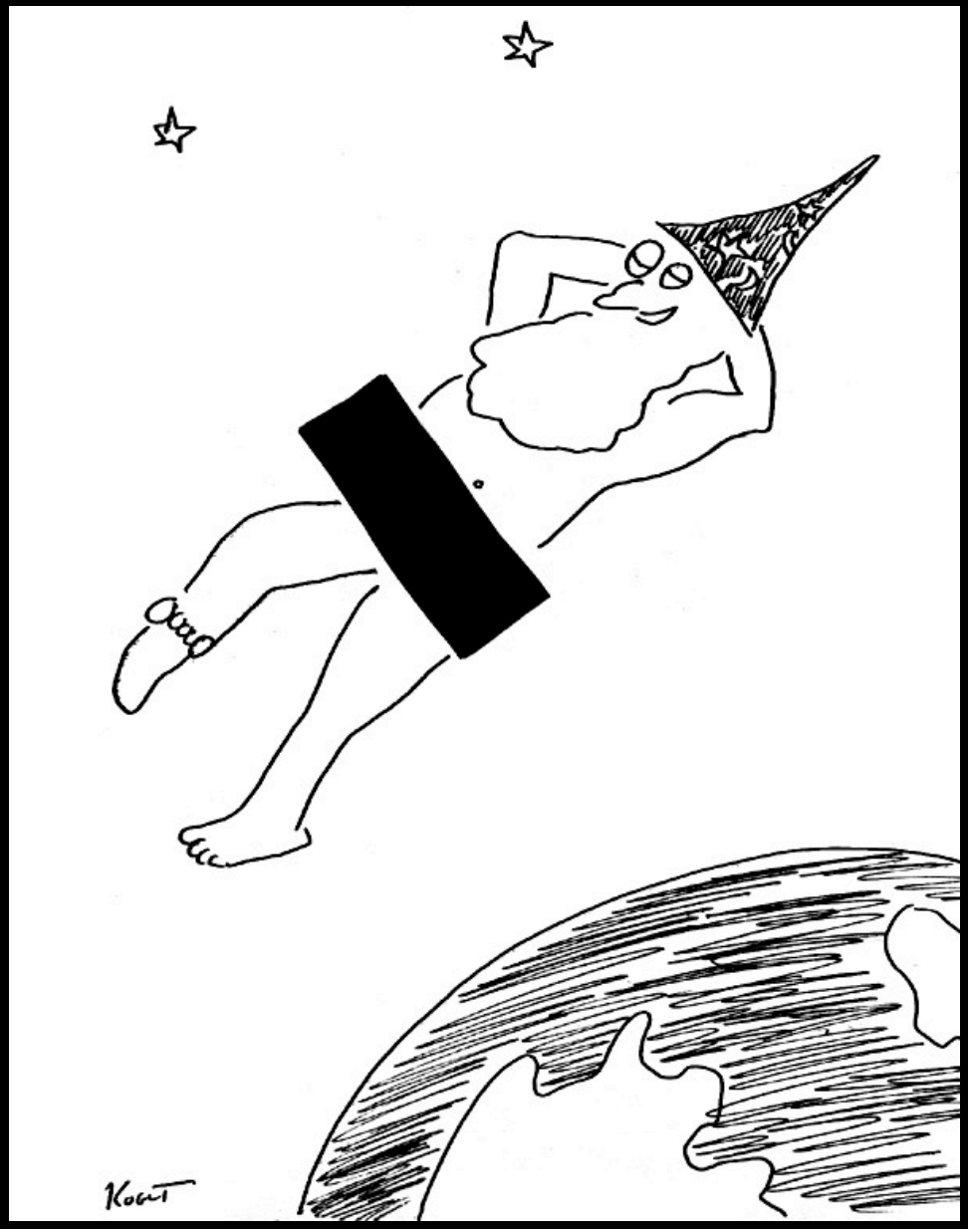
Fossil Remnant of
Early Universe

The Problem With Ground-Based Cosmology

Balloons Help, But Only A Little …



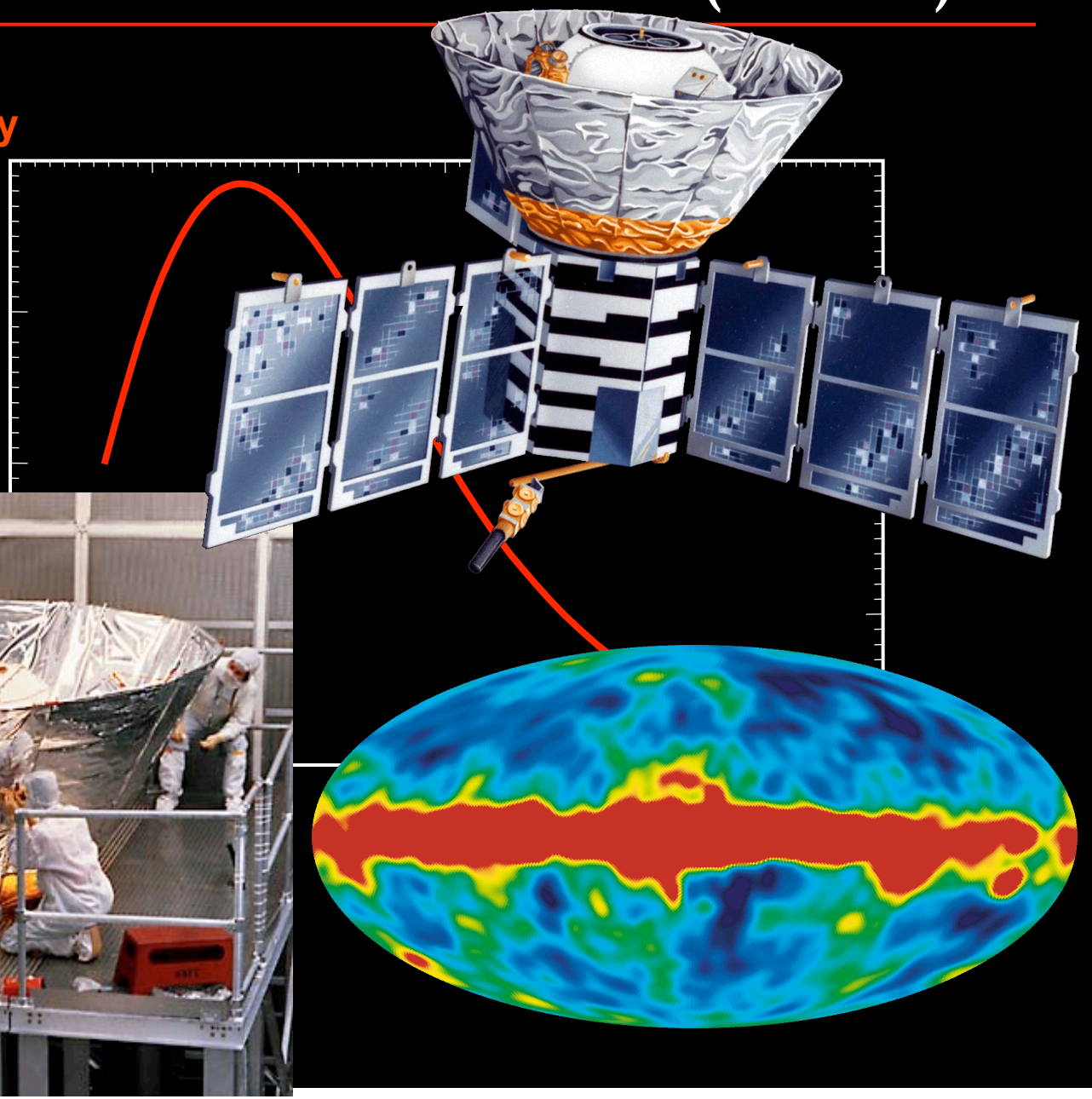
The Obvious Solution



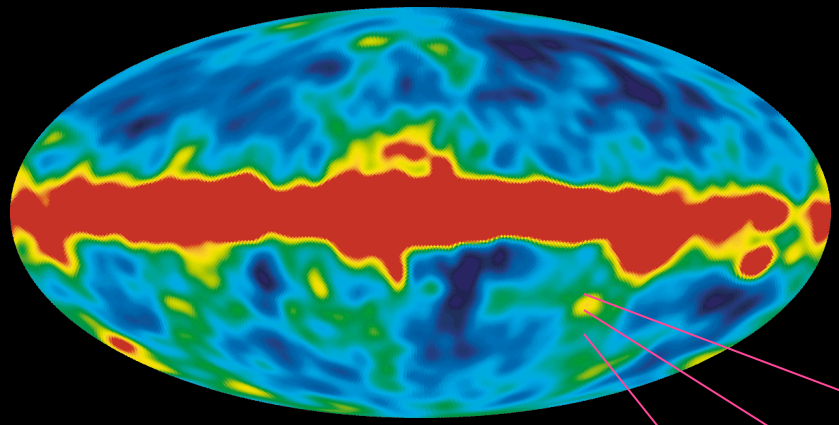
COSMIC BACKGROUND EXPLORER (COBE)

NASA's First Satellite Dedicated to Cosmology

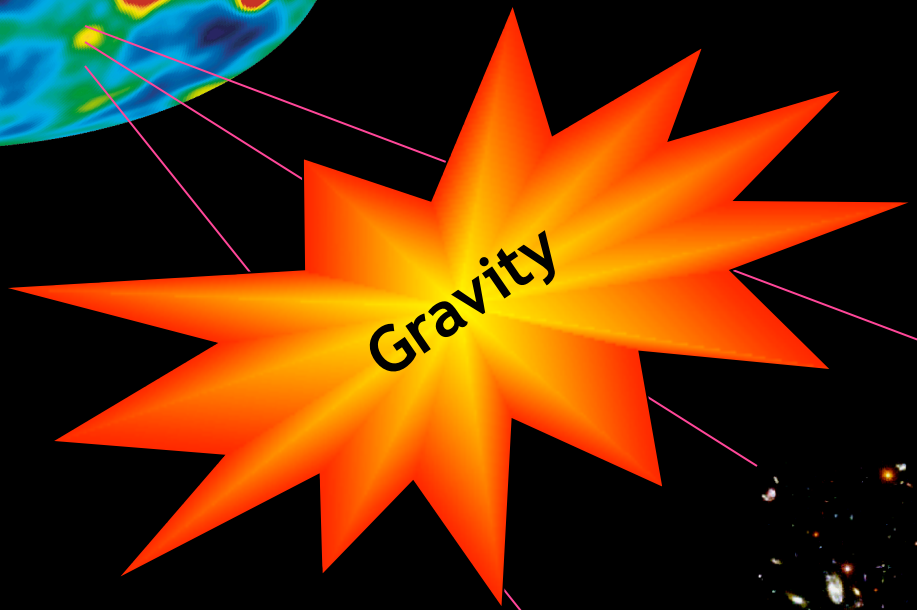
4-Year Mission
1989--1993



COBE and Cosmology



No “Little Bangs” After Big Bang

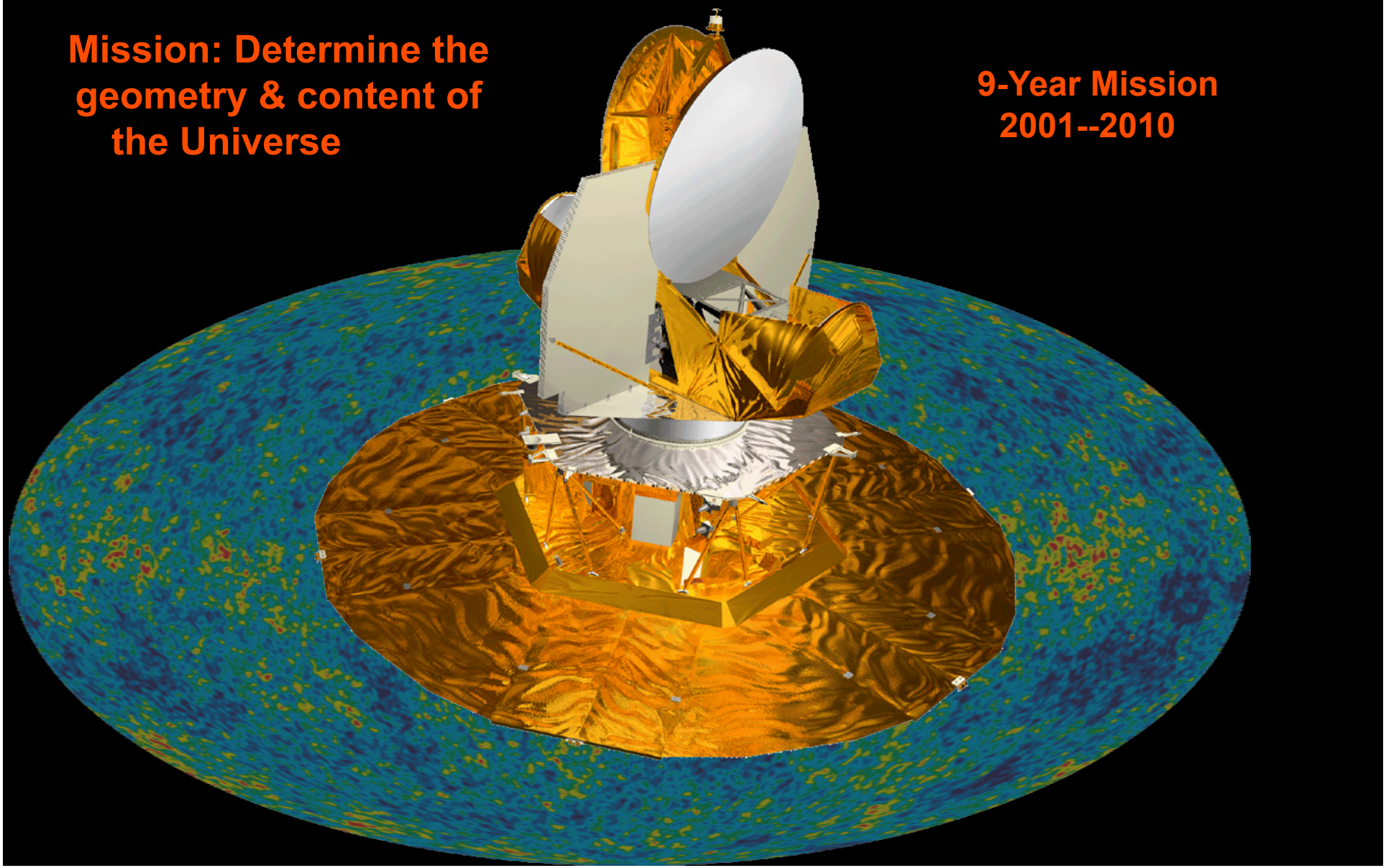


Gravity is dominant force shaping the universe

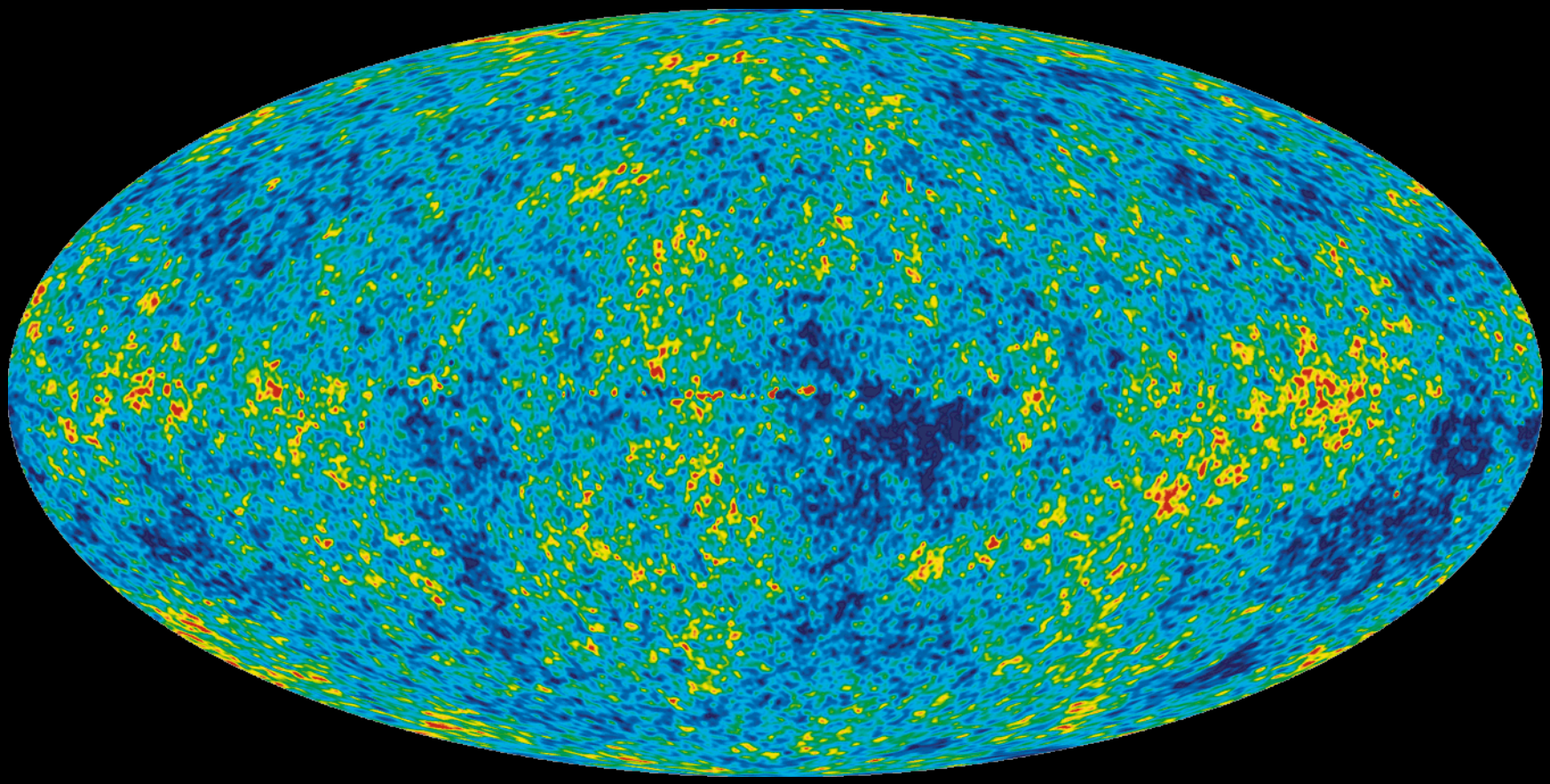
Wilkinson Microwave Anisotropy Probe (WMAP)

Mission: Determine the geometry & content of the Universe

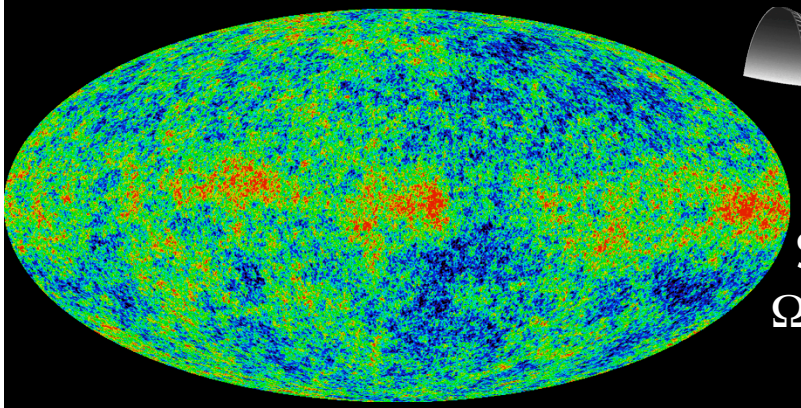
9-Year Mission 2001--2010

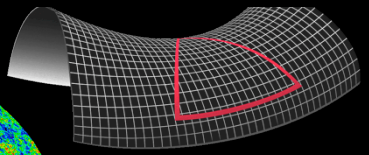


"Baby Picture" of the Universe



Geometry of Space-Time

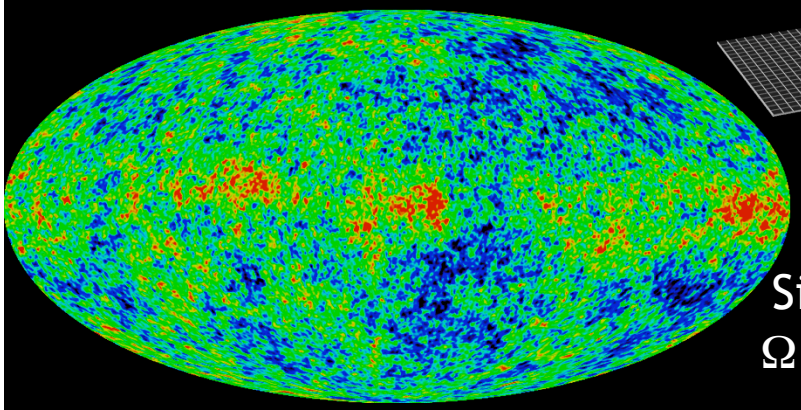


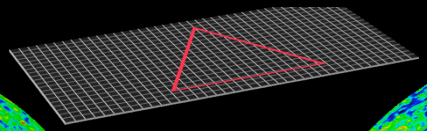


Simulation
Ω < 1 (Open)

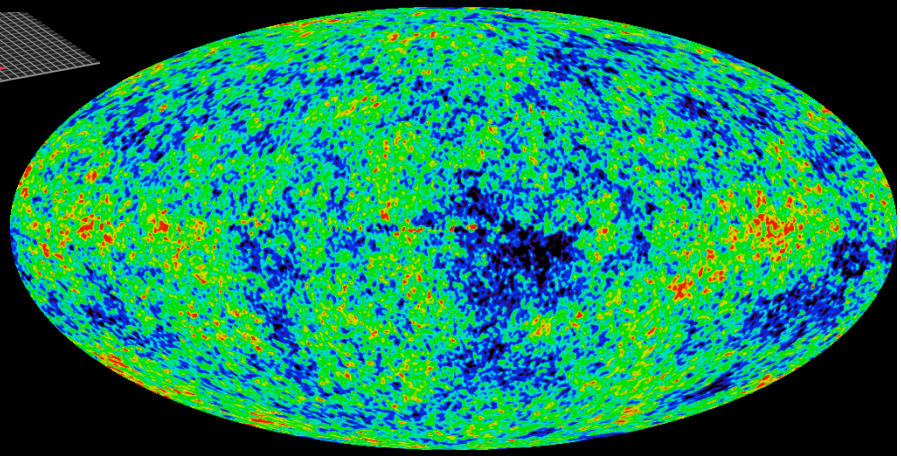
Spacetime is Flat:

Ω = 1.002 ± 0.006
Age = 13.7 ± 0.1 GYr

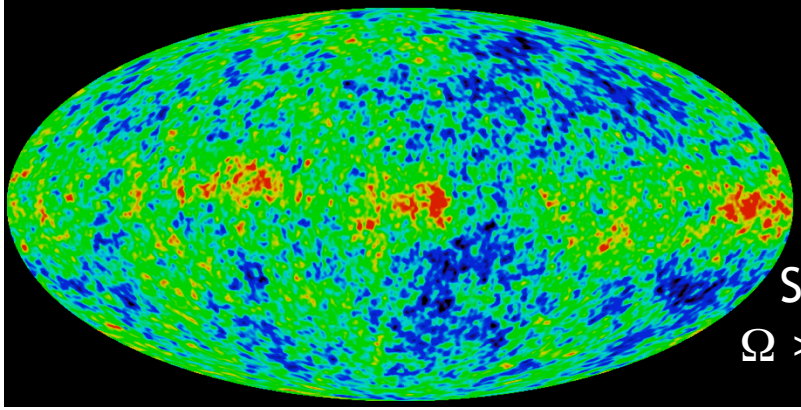


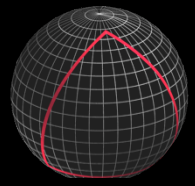


Simulation
Ω = 1 (Flat)



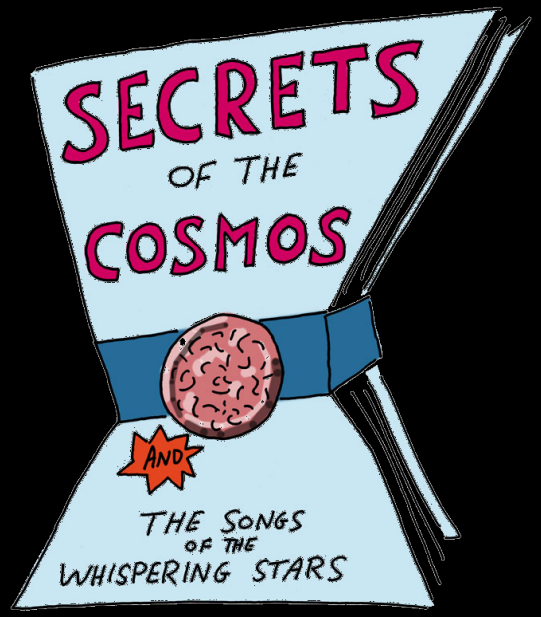
WMAP Data





Simulation
Ω > 1 (Closed)

A Precise Quantification of Ignorance



What Is Dark Matter?

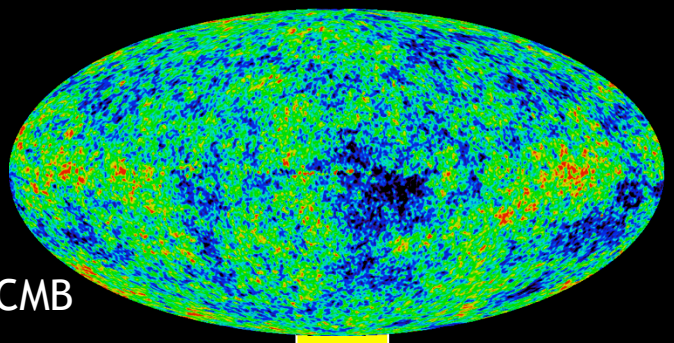
What Is Dark Energy?

Why Are They So Close?

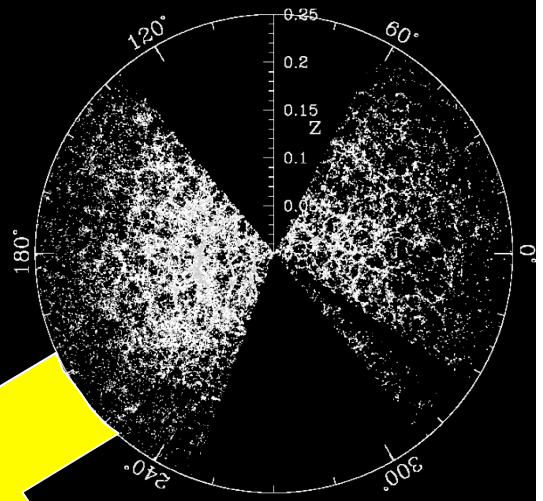
Cosmological Constant Λ: Was Einstein right the first time?

Precision Cosmology

Lensing



CMB



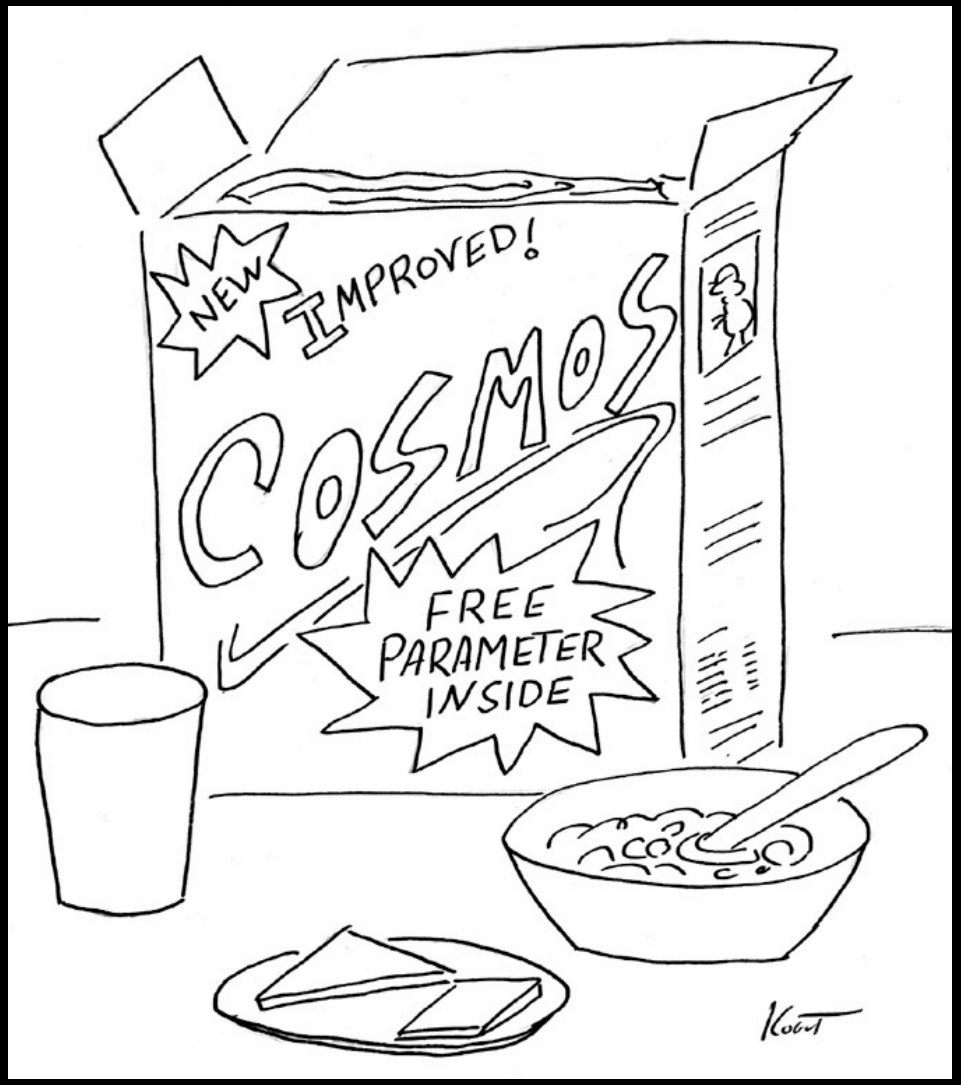
Galaxy Surveys

ΛCDM

"Standard Model" for cosmology

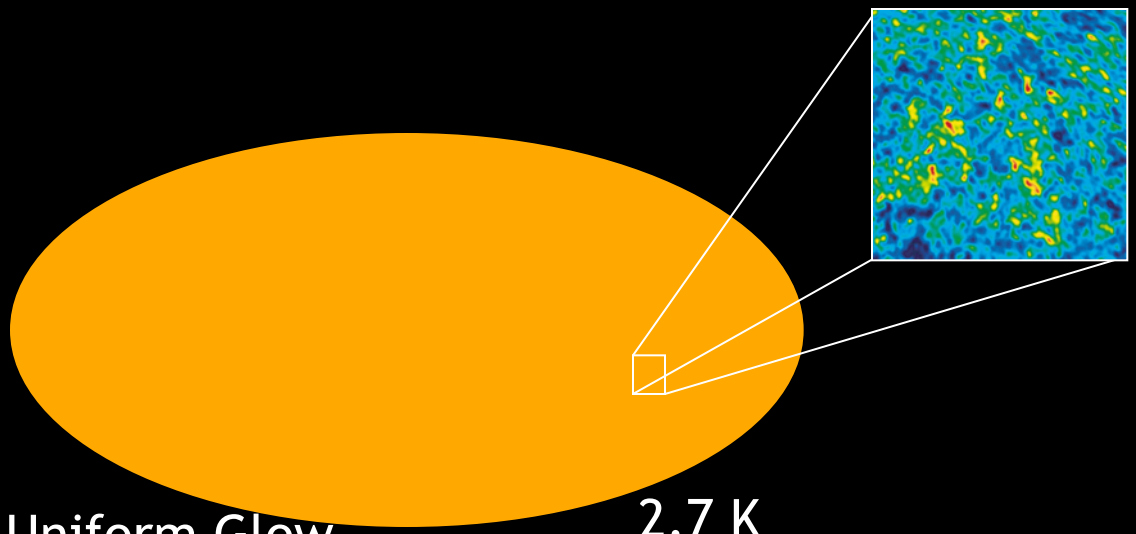
Successfully explains many disparate measurements

But ... A Few Loose Ends



Breakfast of Theorists

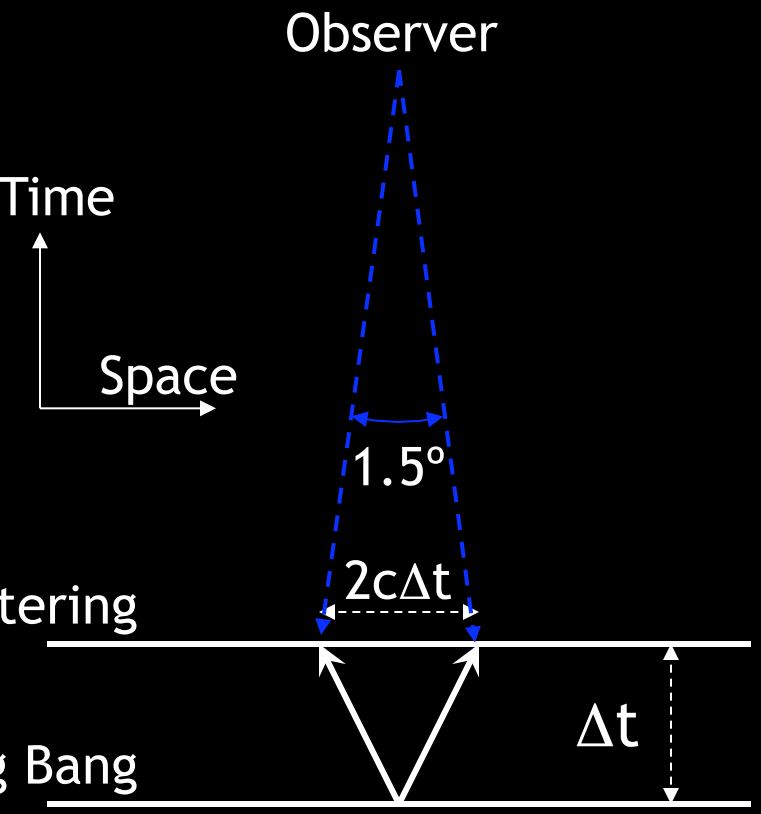
Why Is The CMB So Uniform?



$\frac{\Delta T}{T} < 10^{-4}$

Uniform Glow

2.7 K



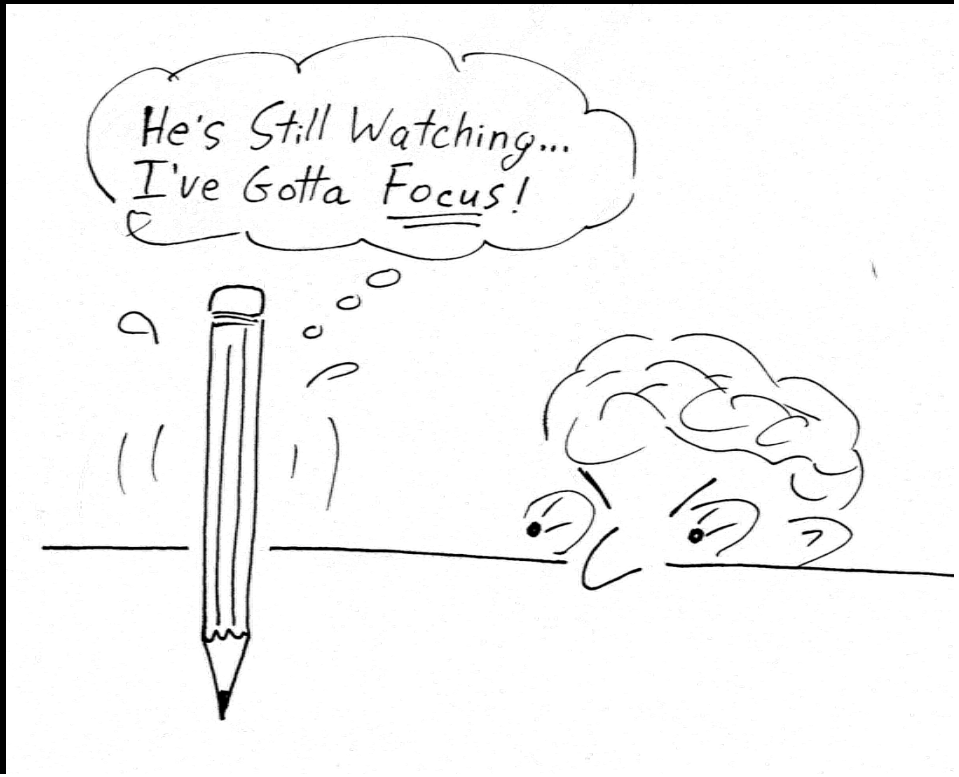
10,000 Causally disconnected regions

Why Is The Universe So Flat?

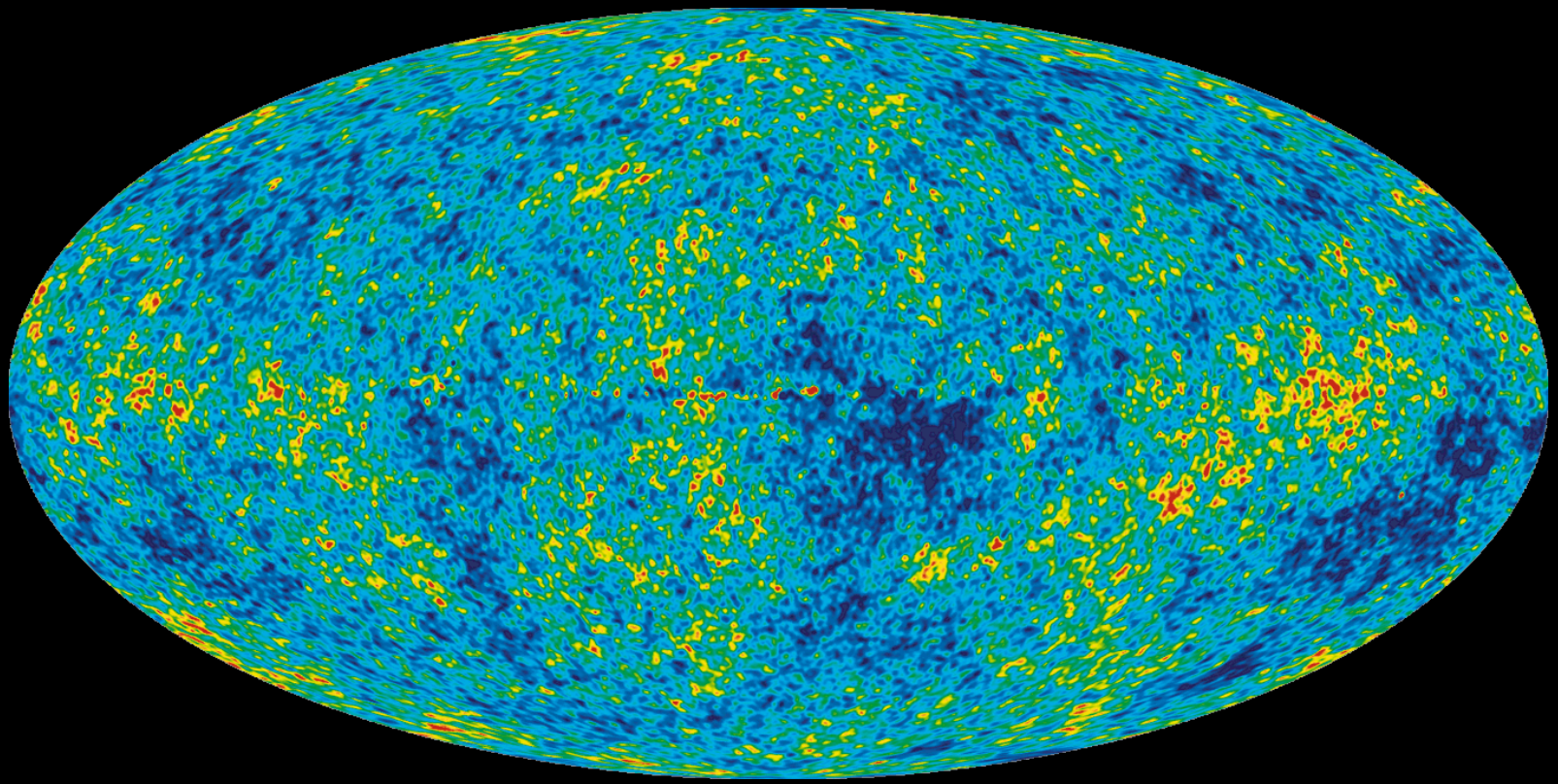
Now: $0.99 < \Omega < 1.01$

Then: $0.99999999999999999999999999999999999999$
$99999999999999999 < \Omega < 1.00000000000000000000$
$00000000000000000000000000000000000001$

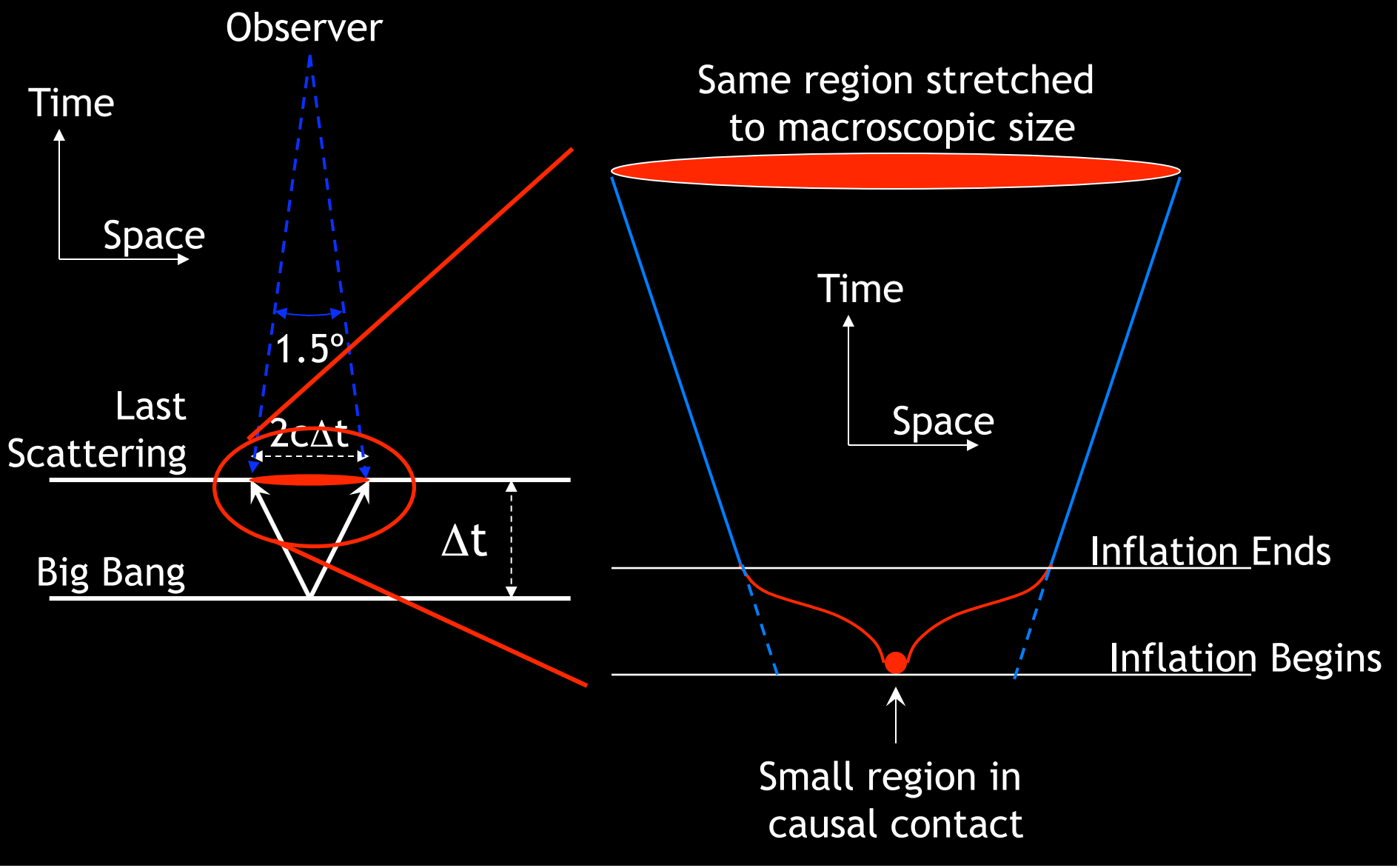
$\Omega = 1$ Is Unstable!



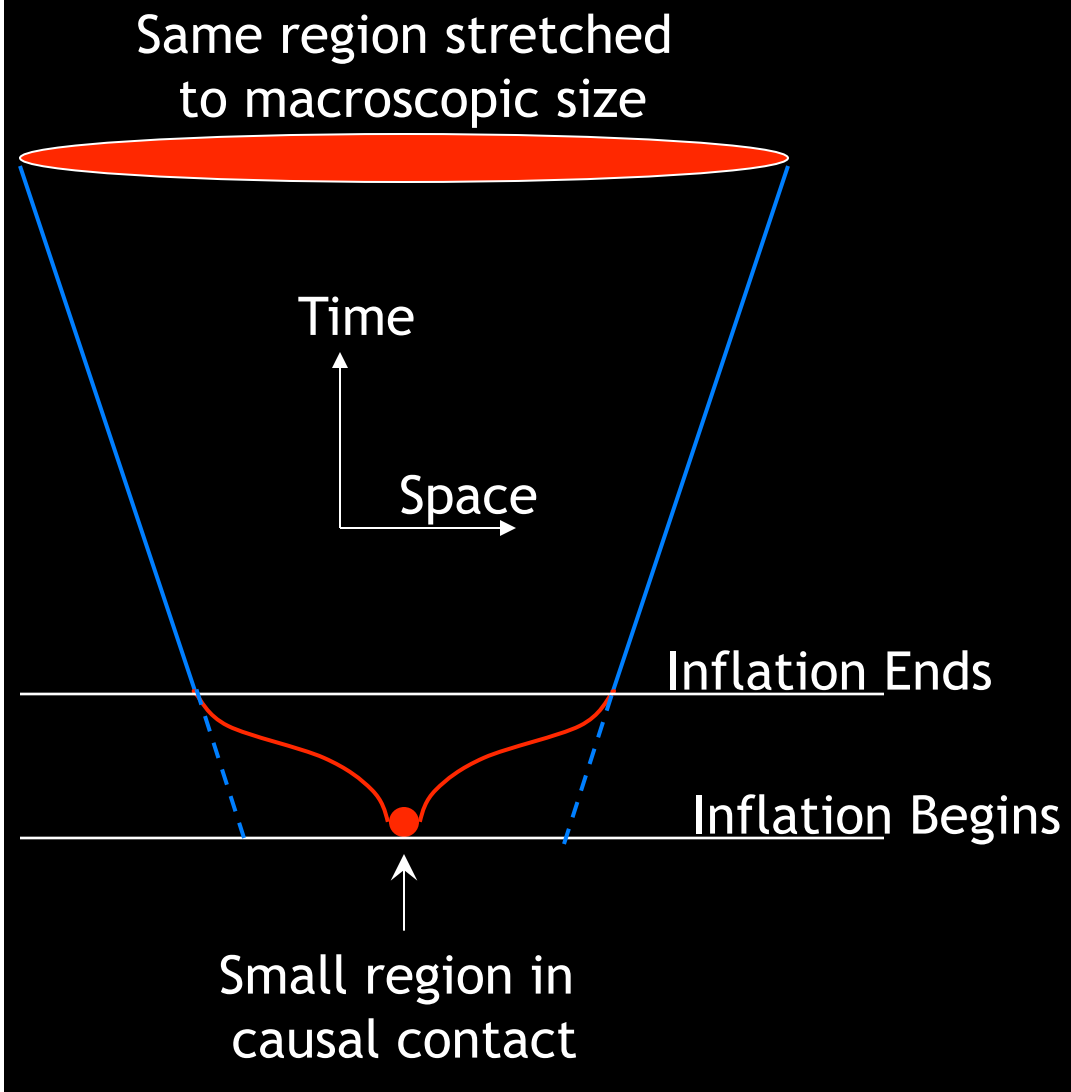
What Generated The Seeds of Structure?

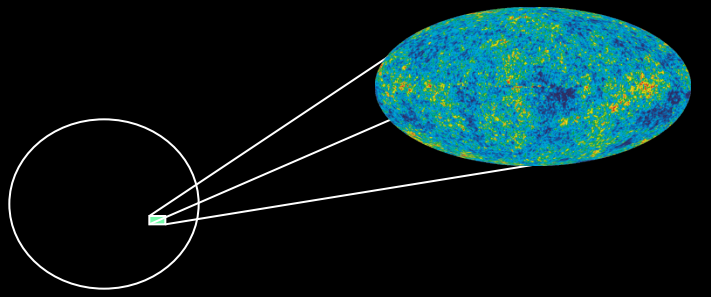


Solution: Cosmic Inflation

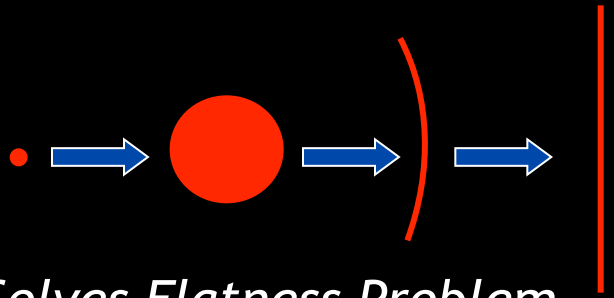


Solution: Cosmic Inflation

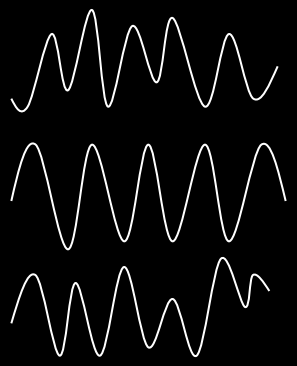




Solves Horizon Problem

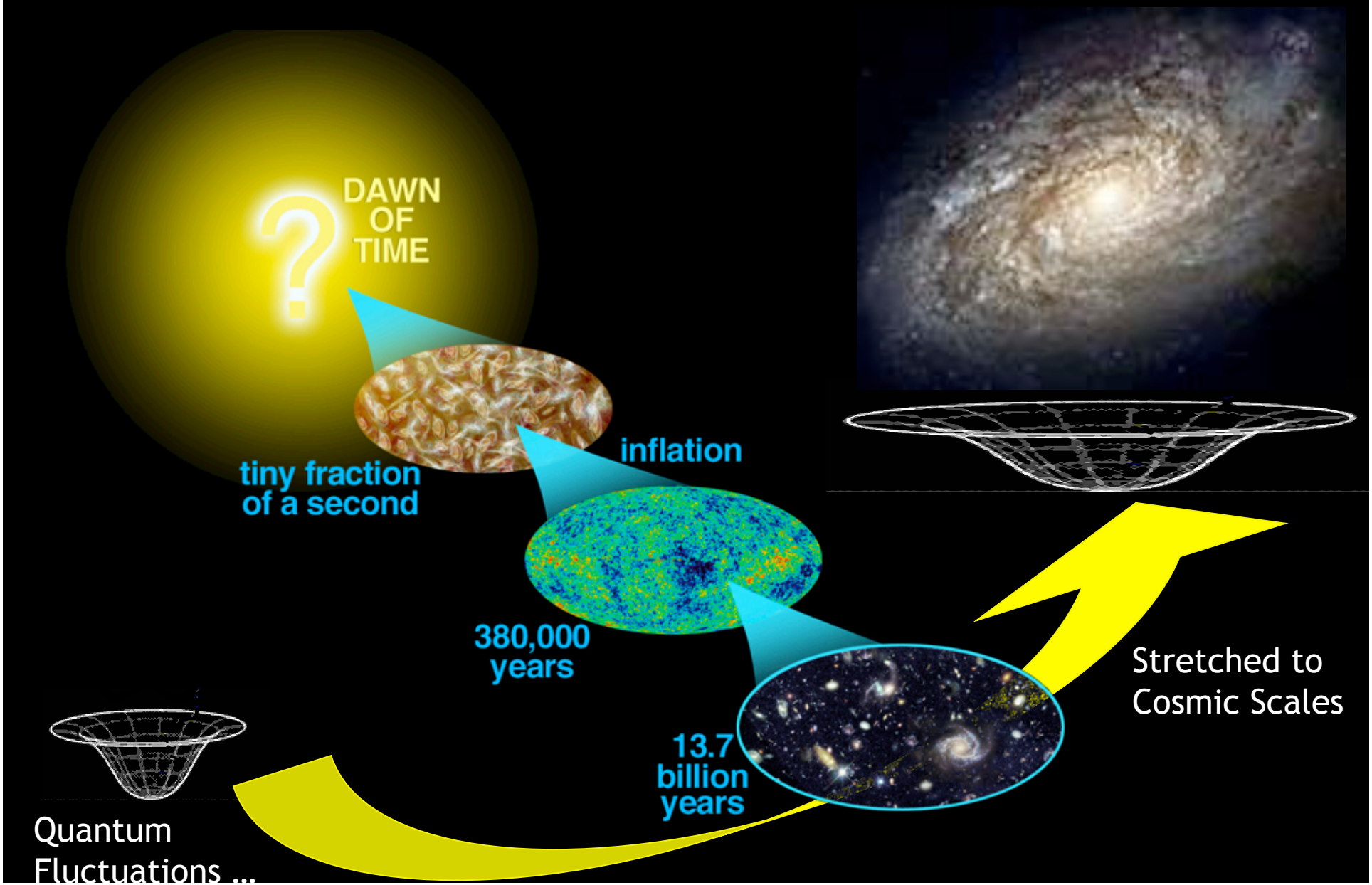


Solves Flatness Problem

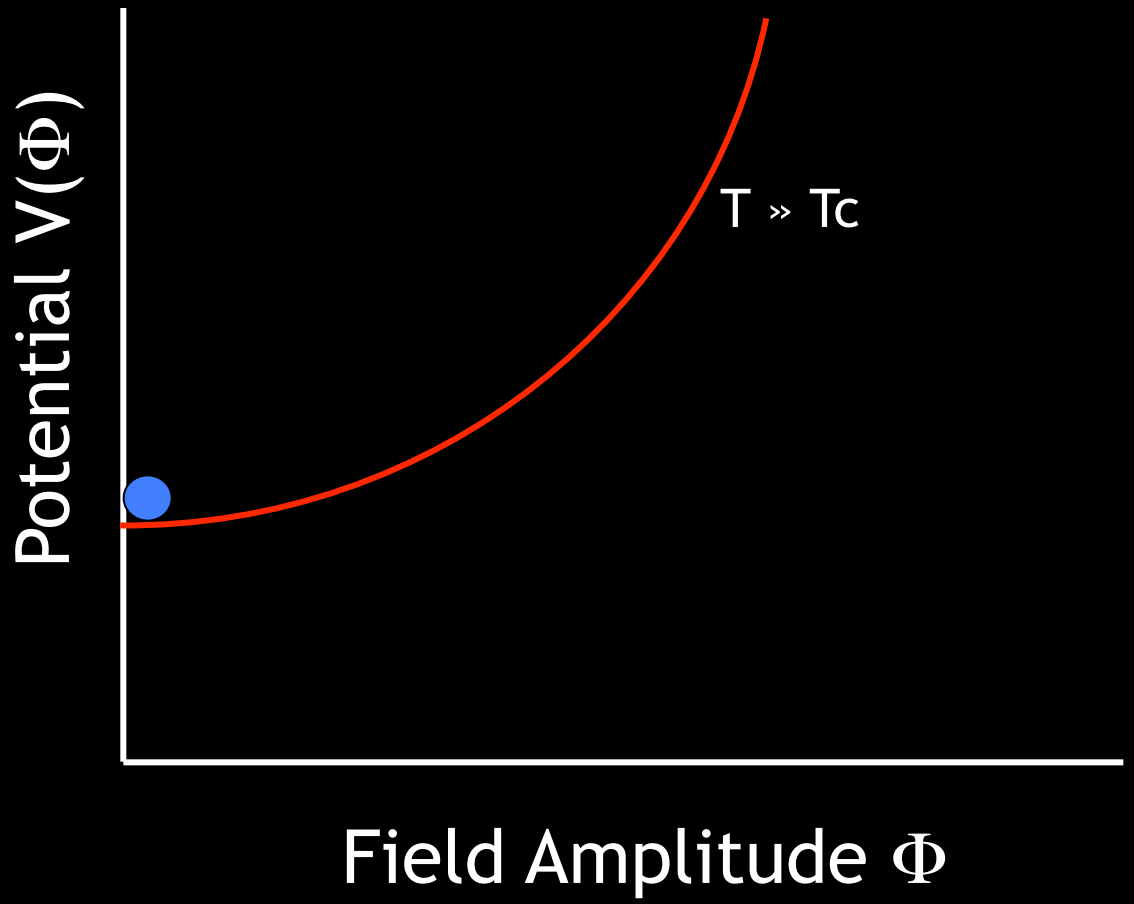


Scale-Invariant Fluctuations

Quantum Physics on a Cosmic Scale!

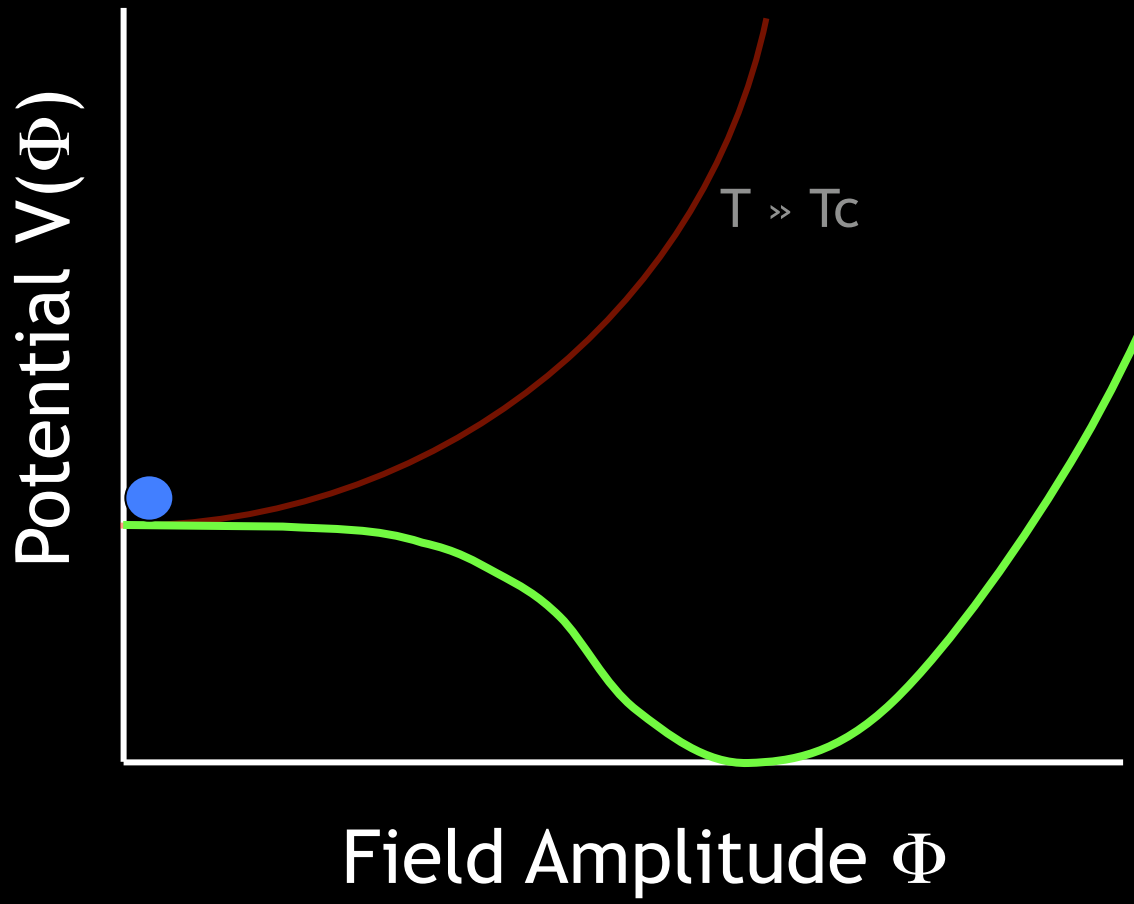


Physics of the Big Bang



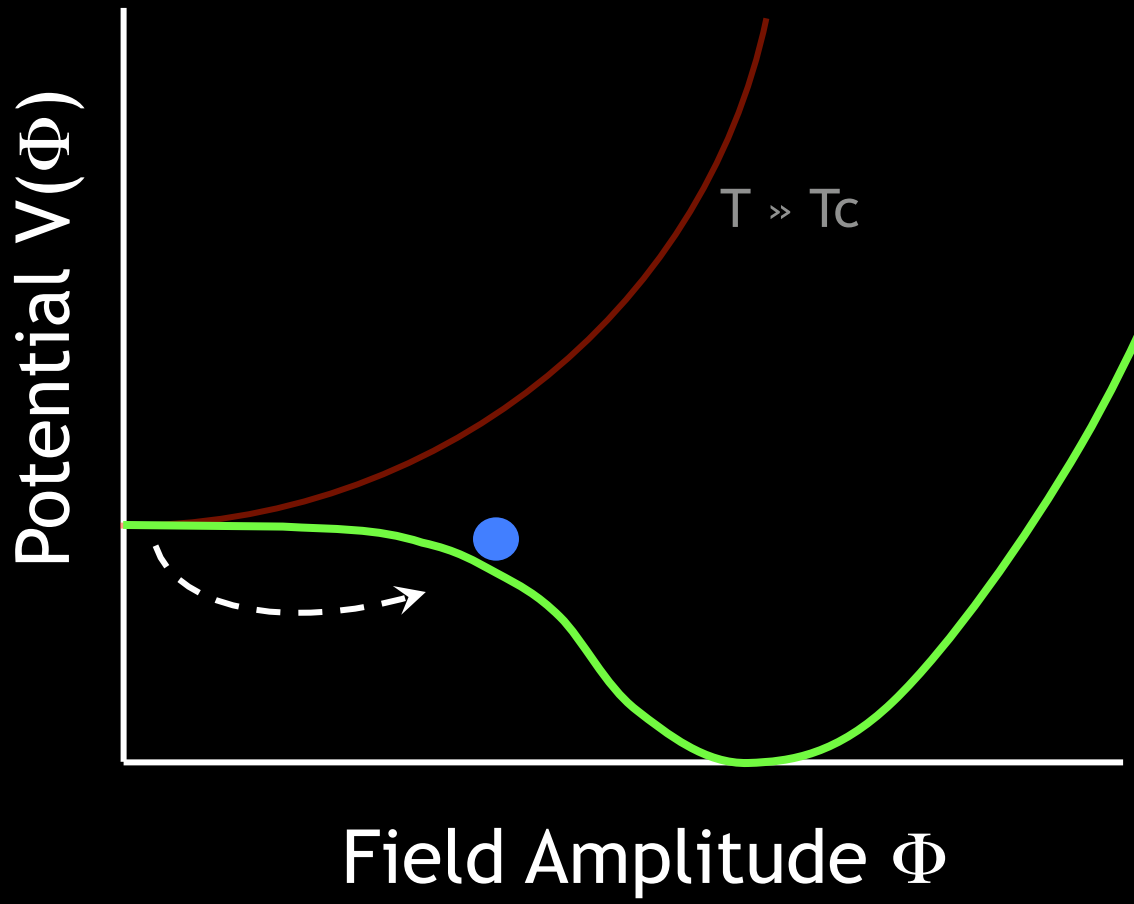
High Temperature:
Symmetric

Physics of the Big Bang



Low Temperature:
Broken Symmetry

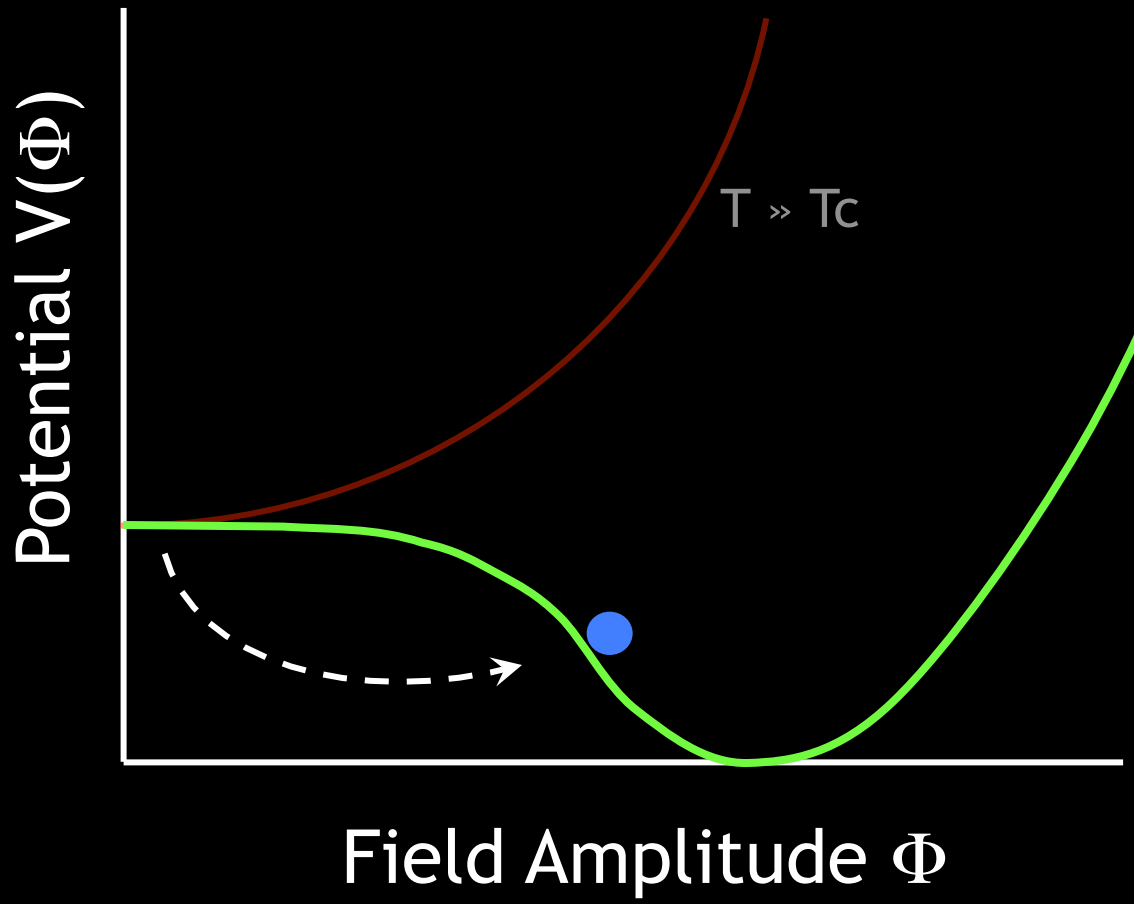
Physics of the Big Bang



Low Temperature:
Broken Symmetry

Inflation Begins

Physics of the Big Bang

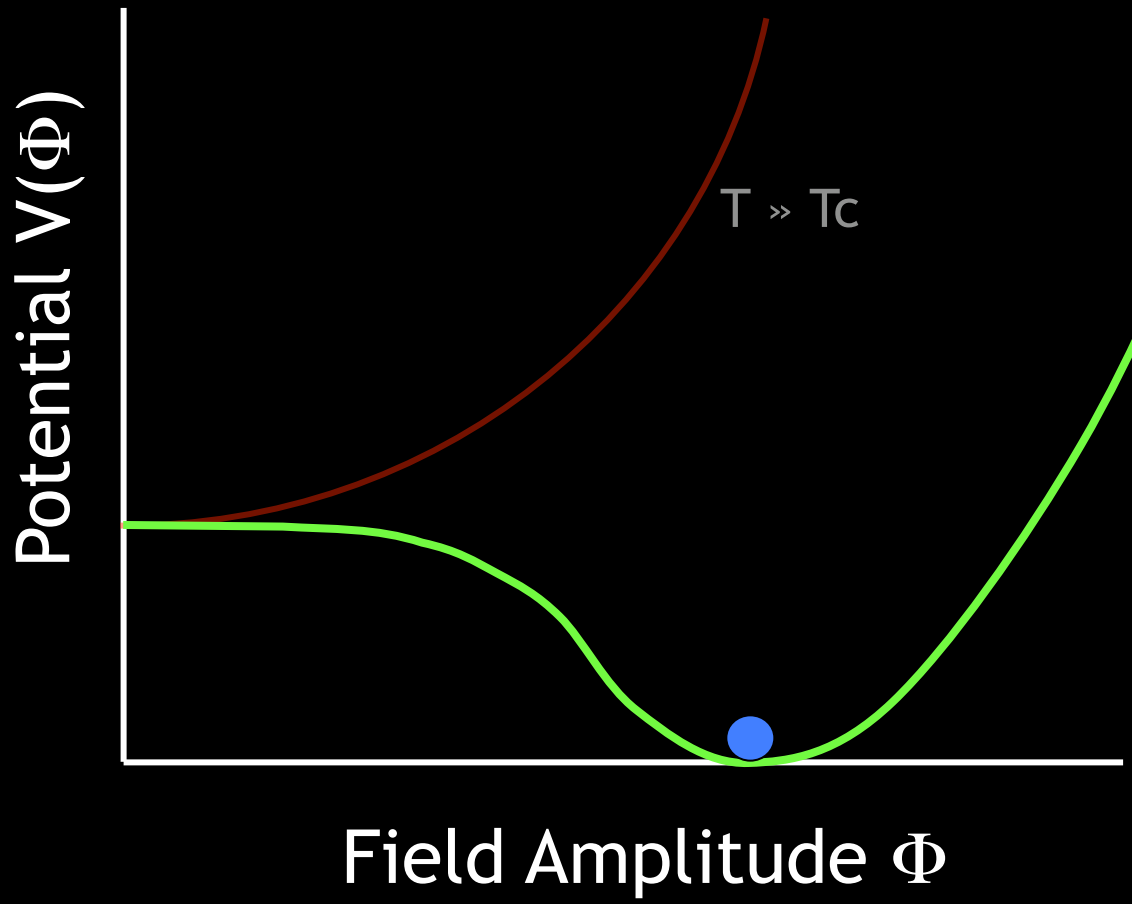


Low Temperature:
Broken Symmetry

Inflation Continues

Exponential Expansion
Quantum Fields Fluctuate
Gravity Waves Form

Physics of the Big Bang

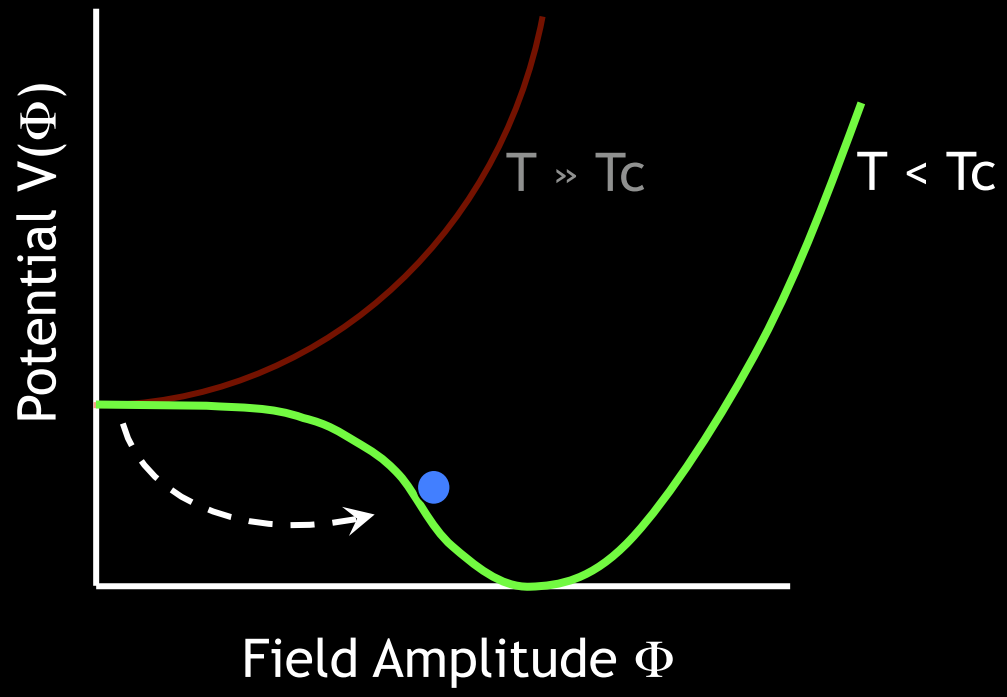


Low Temperature:
Broken Symmetry

Inflation Ends

Potential → Heat

Physics of the Big Bang



Inflationary Potential

Inflationary Condition $V >> \dot{\Phi}^2$

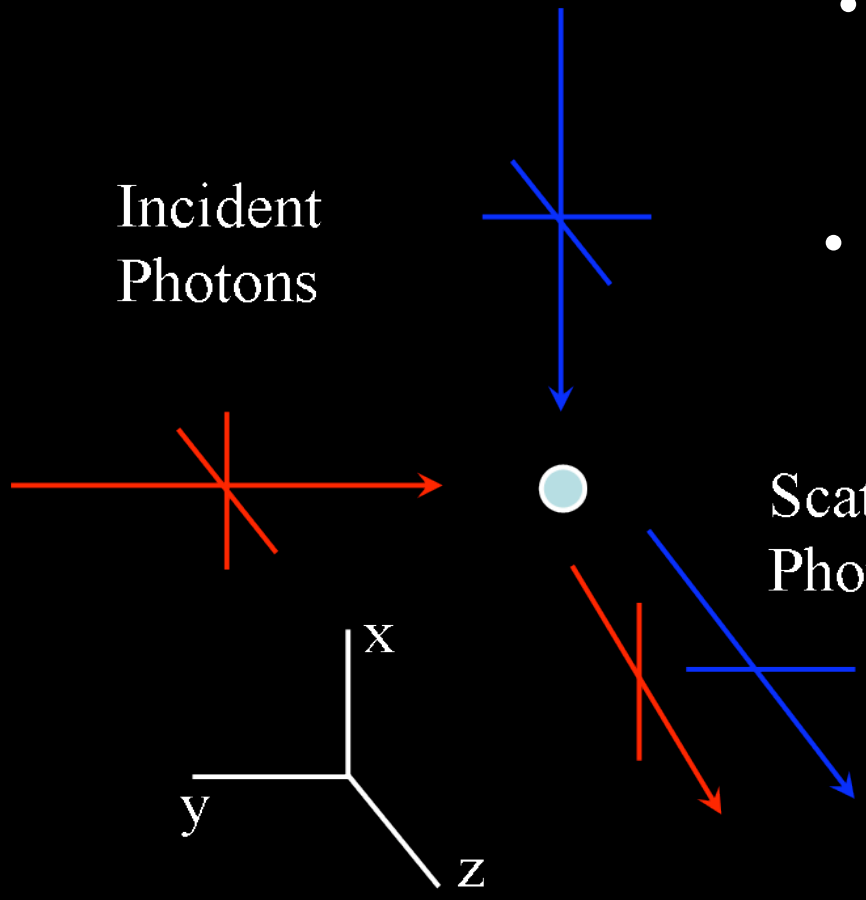
Hubble Constant $H \sim \frac{V}{M_{PL}^2}$

Gravity Waves $P_T \sim \frac{H^2}{M_{PL}^2}$

Energy Scale $V \sim \frac{P_T}{M_{PL}^4}$

Gravity Waves Measure Inflationary Field Amplitude and Shape!

Testing Inflation via CMB Polarization

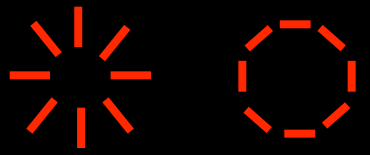


- Thomson scattering of anisotropic photon distribution by free electrons
- Quadropolar anisotropy produces net linear polarization

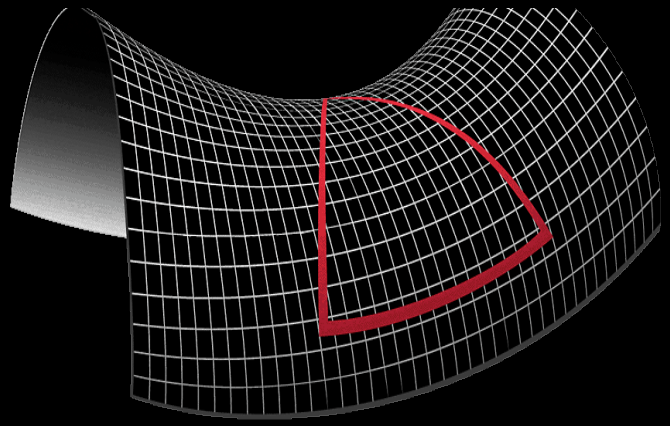
Whole New Look at Early Universe

Source Terms for Polarization

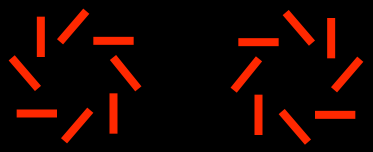
Temperature Quadrupole
Scalar Source
Gradient (“E mode”) Pattern



E Modes
Even Parity



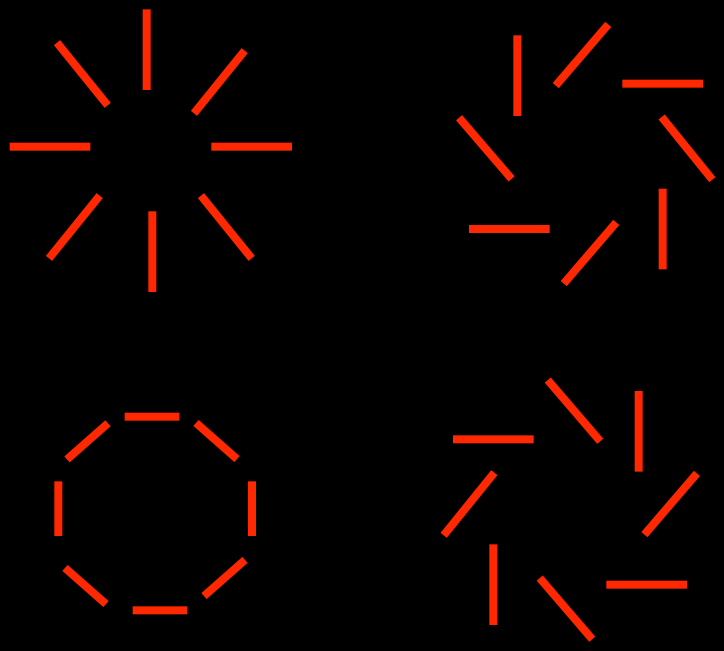
Gravity Wave
Tensor Source
Gradient (“E mode”) Pattern
Curl (“B mode”) Pattern



B Modes
Odd Parity

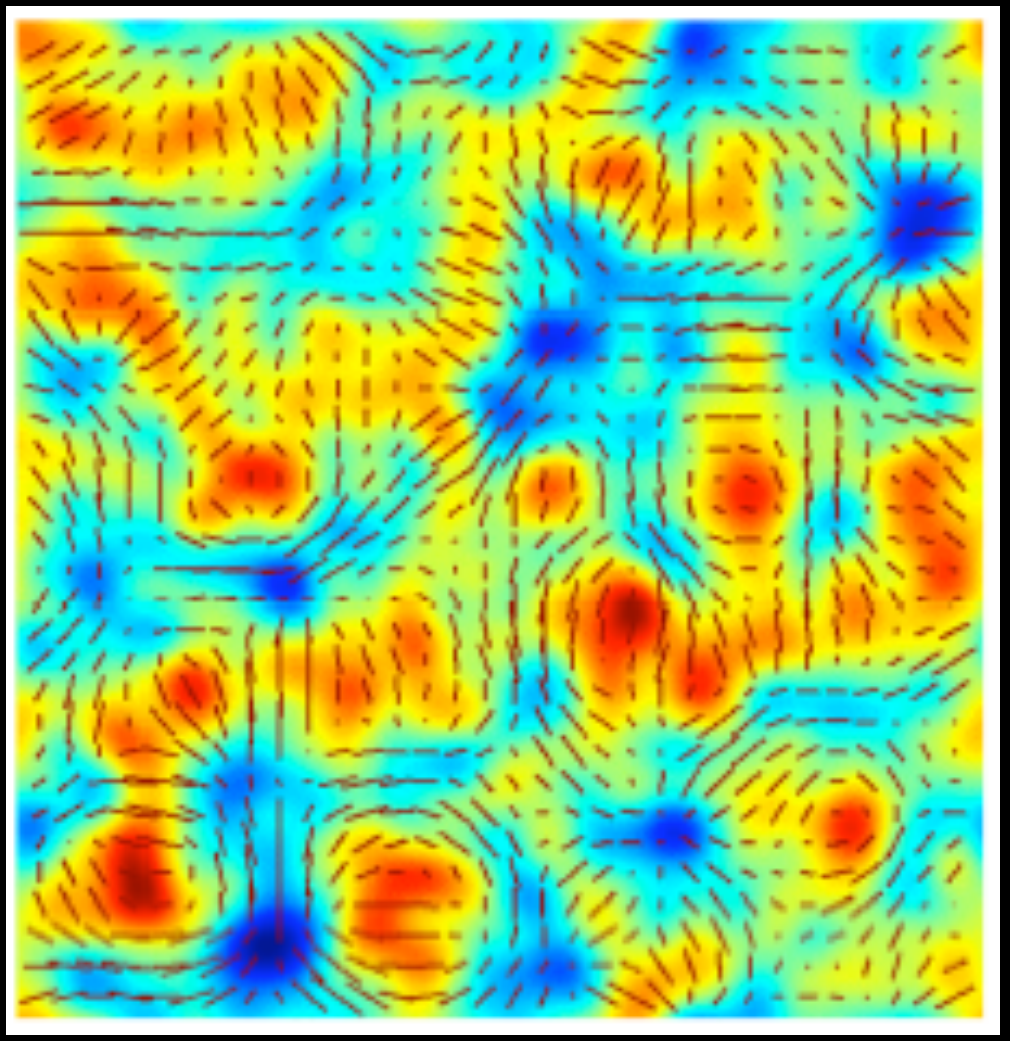
B-mode Polarization: “Smoking Gun” Signature of Inflation

Polarization Patterns



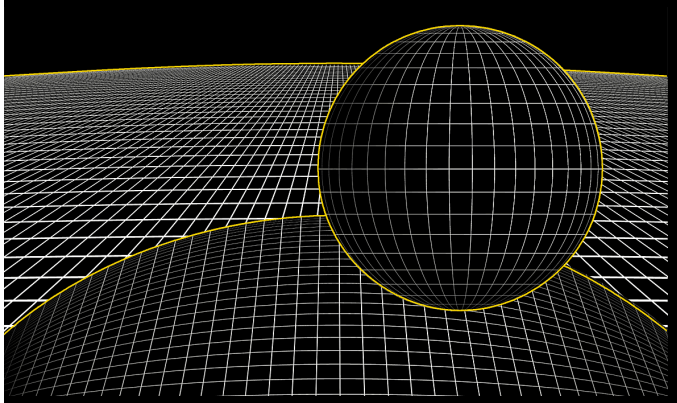
E Modes
Even Parity

B Modes
Odd Parity



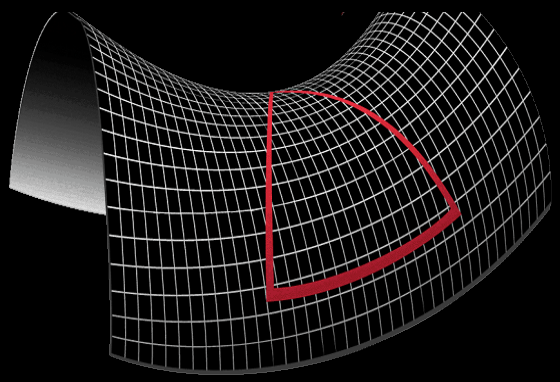
Superposition E + B

Polarization and Inflation

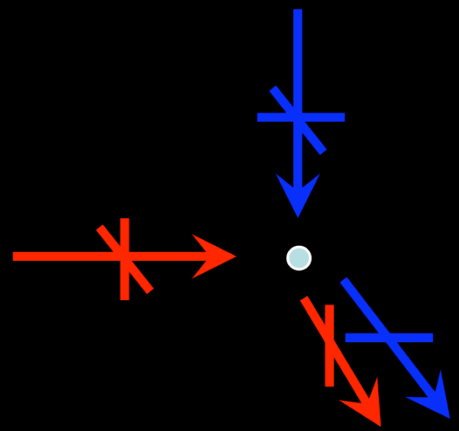


Inflating Space-Time …

So If You Observe
B-Mode Polarization …



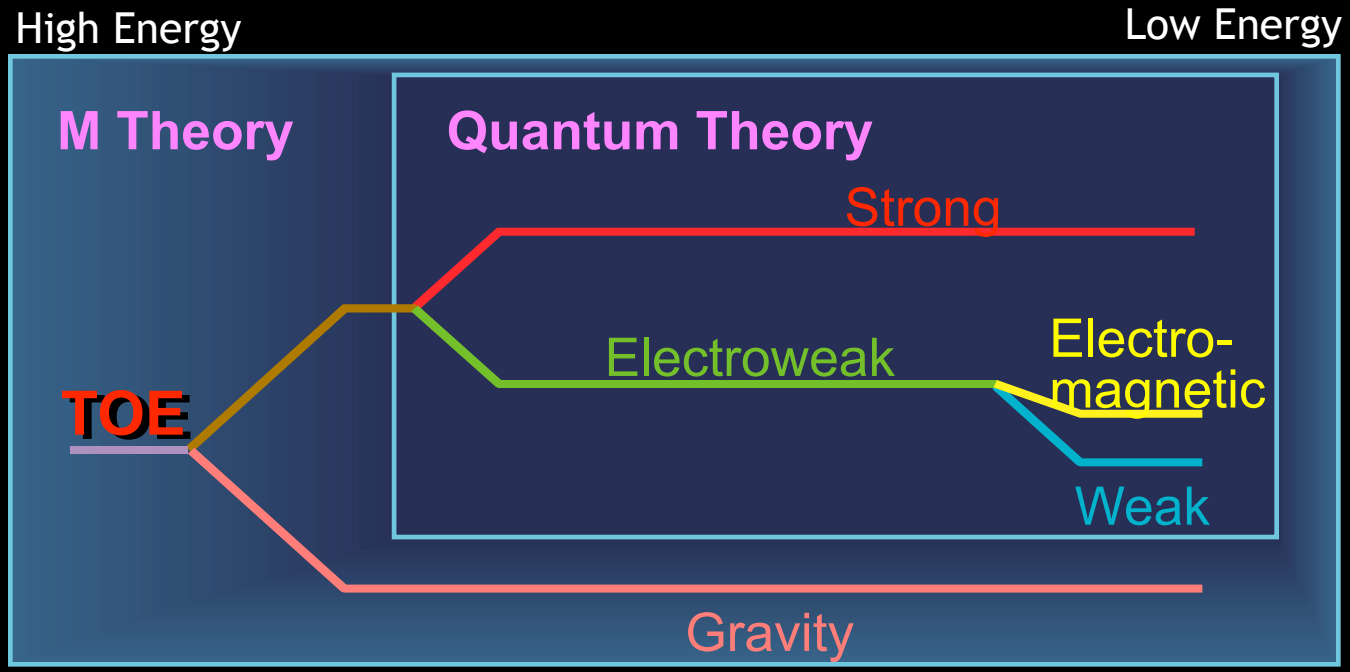
Creates Gravity-Wave
Background …



Which Sources
CMB Polarization

… You're Observing
Quantum Gravity
in Action

Towards a "Theory of Everything"

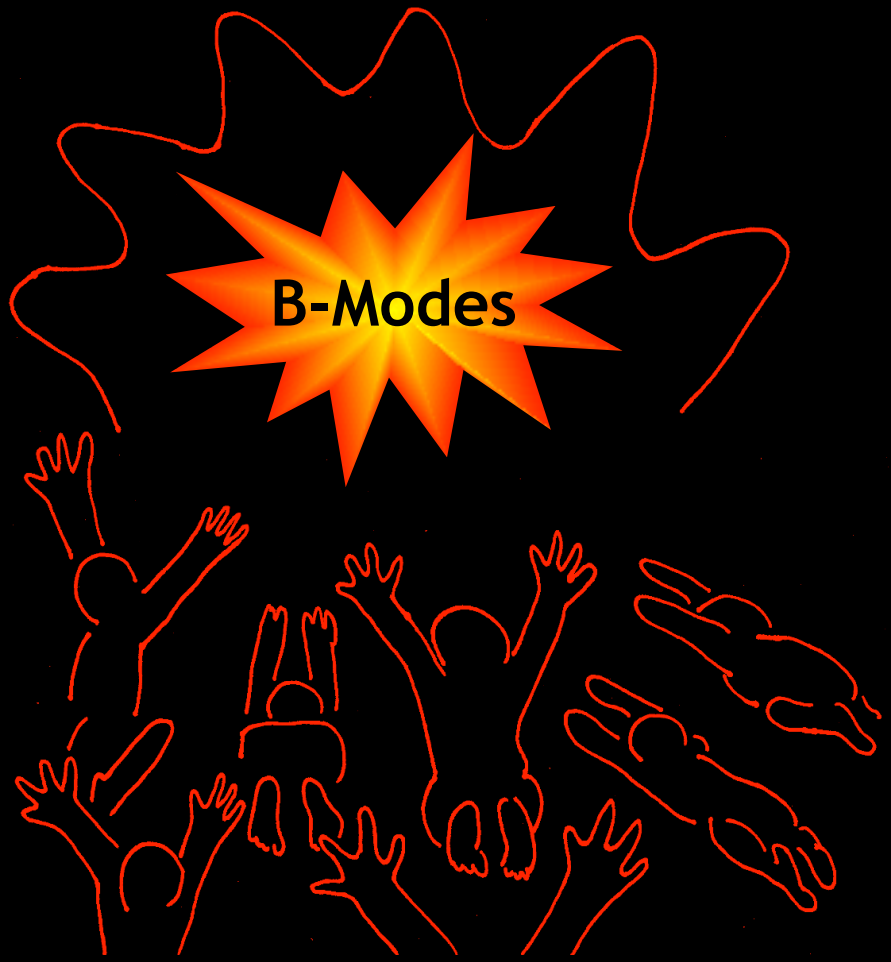


Inflation: Phase transition at ~10^{16} GeV

GUT Physics: Phase transition at ~10^{16} GeV

Coincidence or a hint of something fundamental?

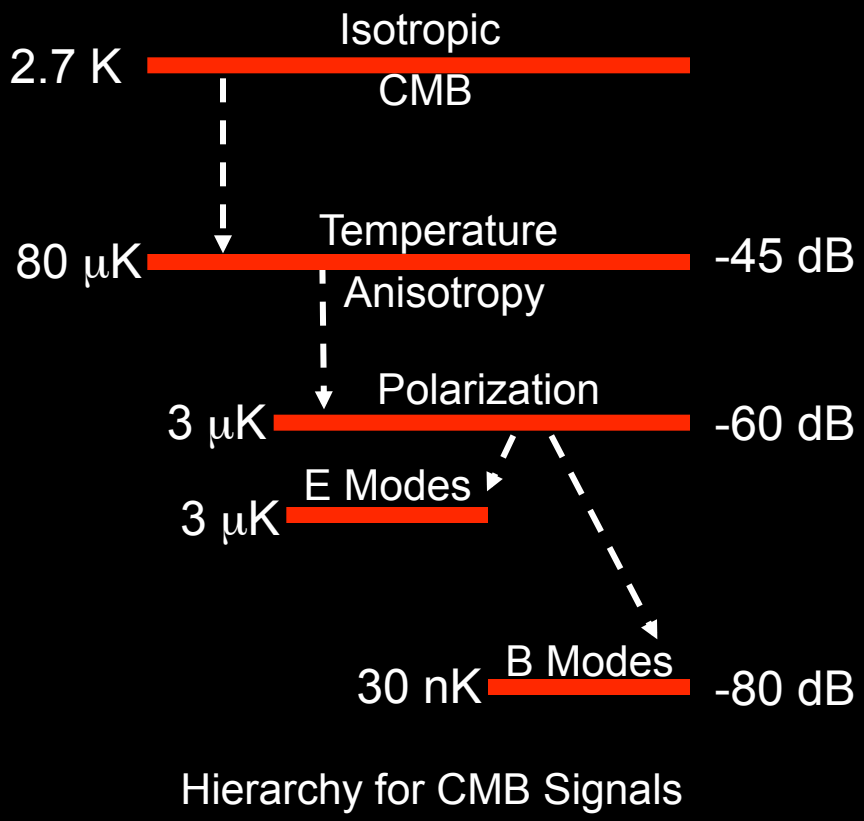
Why Bother With CMB Polarization?



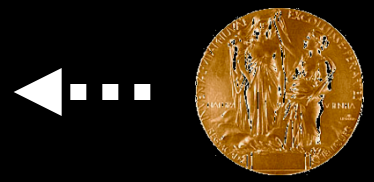
- Demonstrate inflation as physical reality
  - Observe universe as quantum system
  - Death to competing models
- Measure inflationary energy scale
  - Energy scale ~ (Observed Signal)$^{1/4}$
  - 10^{16} GeV : GUT physics!
- Observable "Theory of Everything"
  - Trans-Planckian physics
  - Quantum gravity in action

Explore Physics At Energies One Trillion Times Higher Than Particle Accelerators

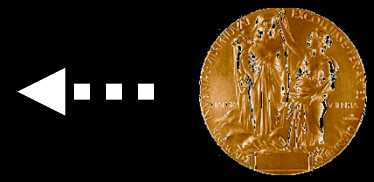
Show Me The … Polarization?



Hierarchy for CMB Signals



Nobel Prize 1978

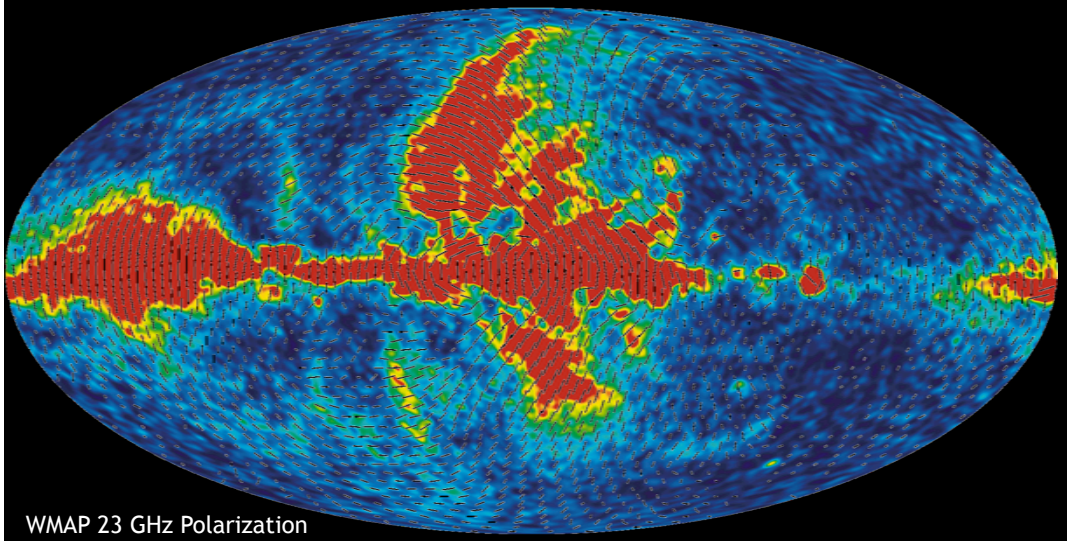


Nobel Prize 2006

Small But Measurable!

Theory Predicts Observable Signal

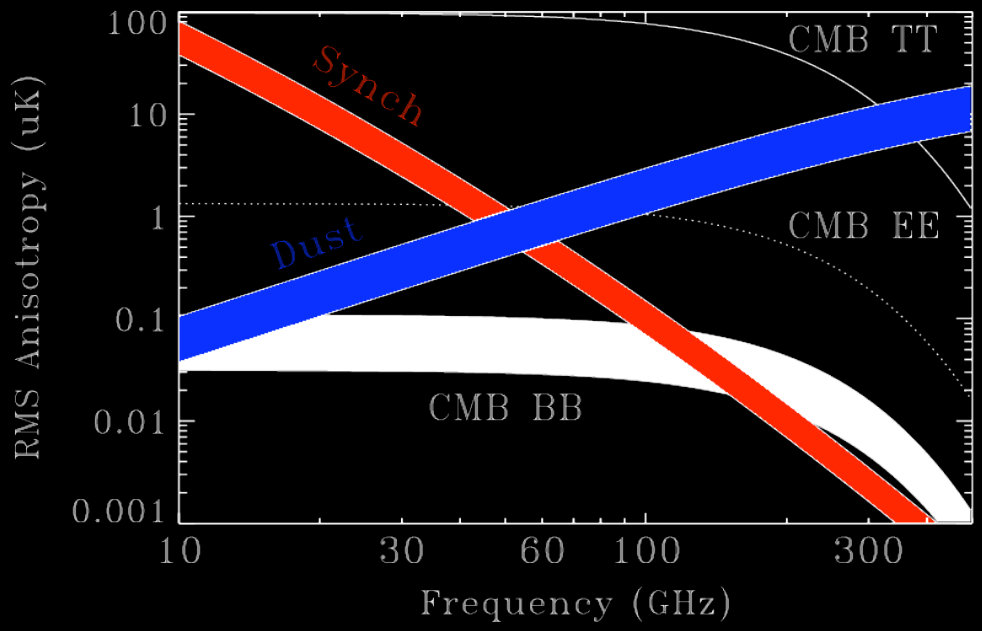
So What's The Problem?



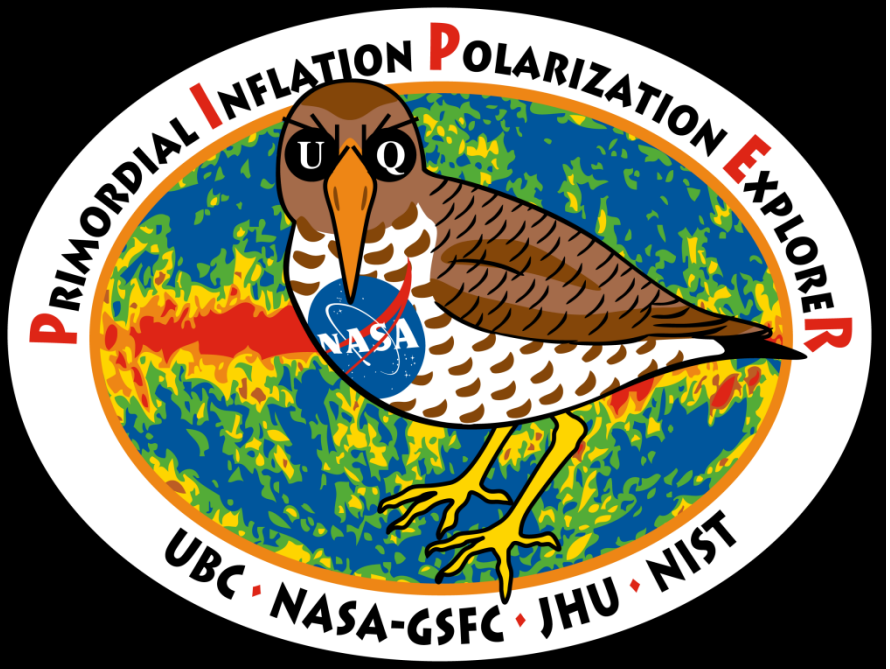
WMAP 23 GHz Polarization

Signal is faint
Foregrounds are bright
Everything is confusing

Many Measurements
Now Underway



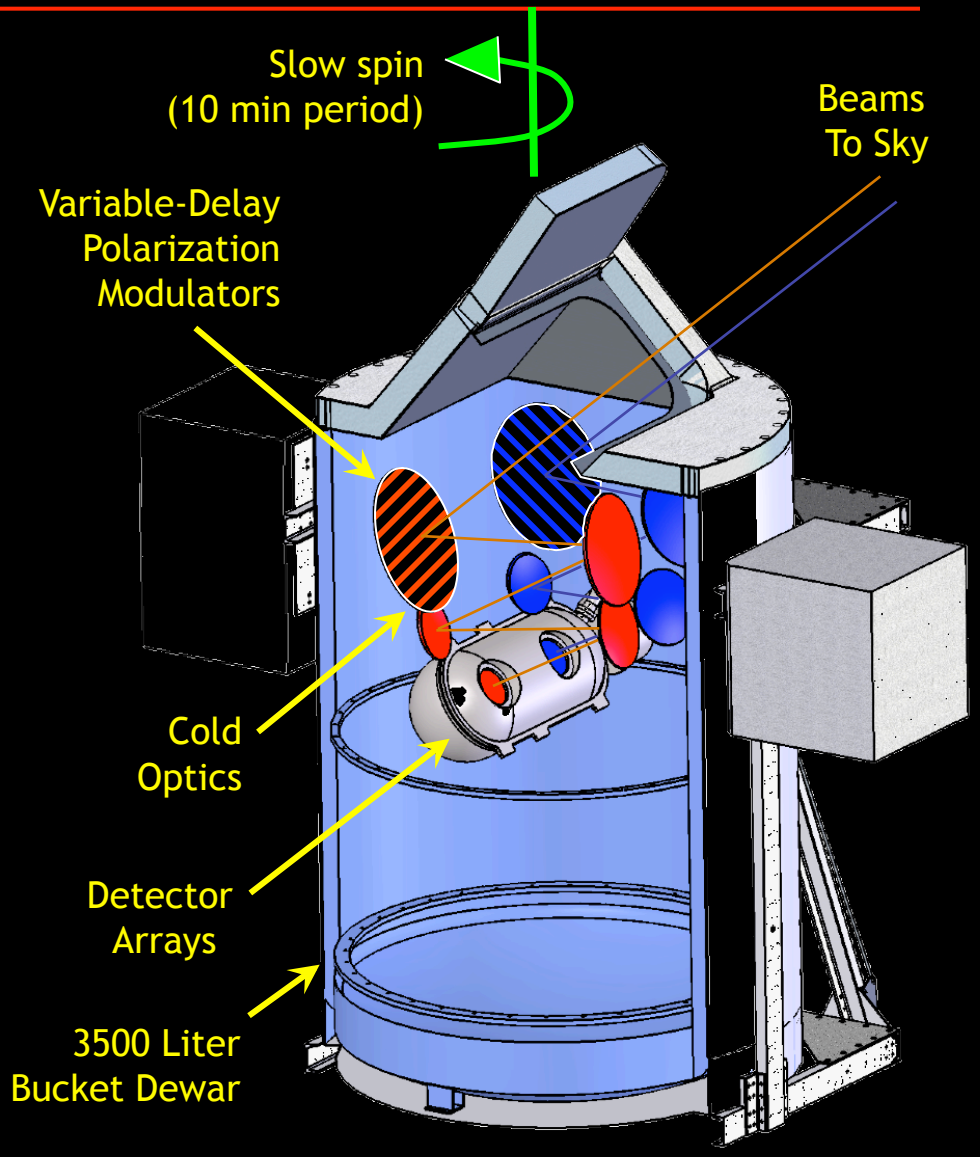
PIPER: The Brute-Force Approach



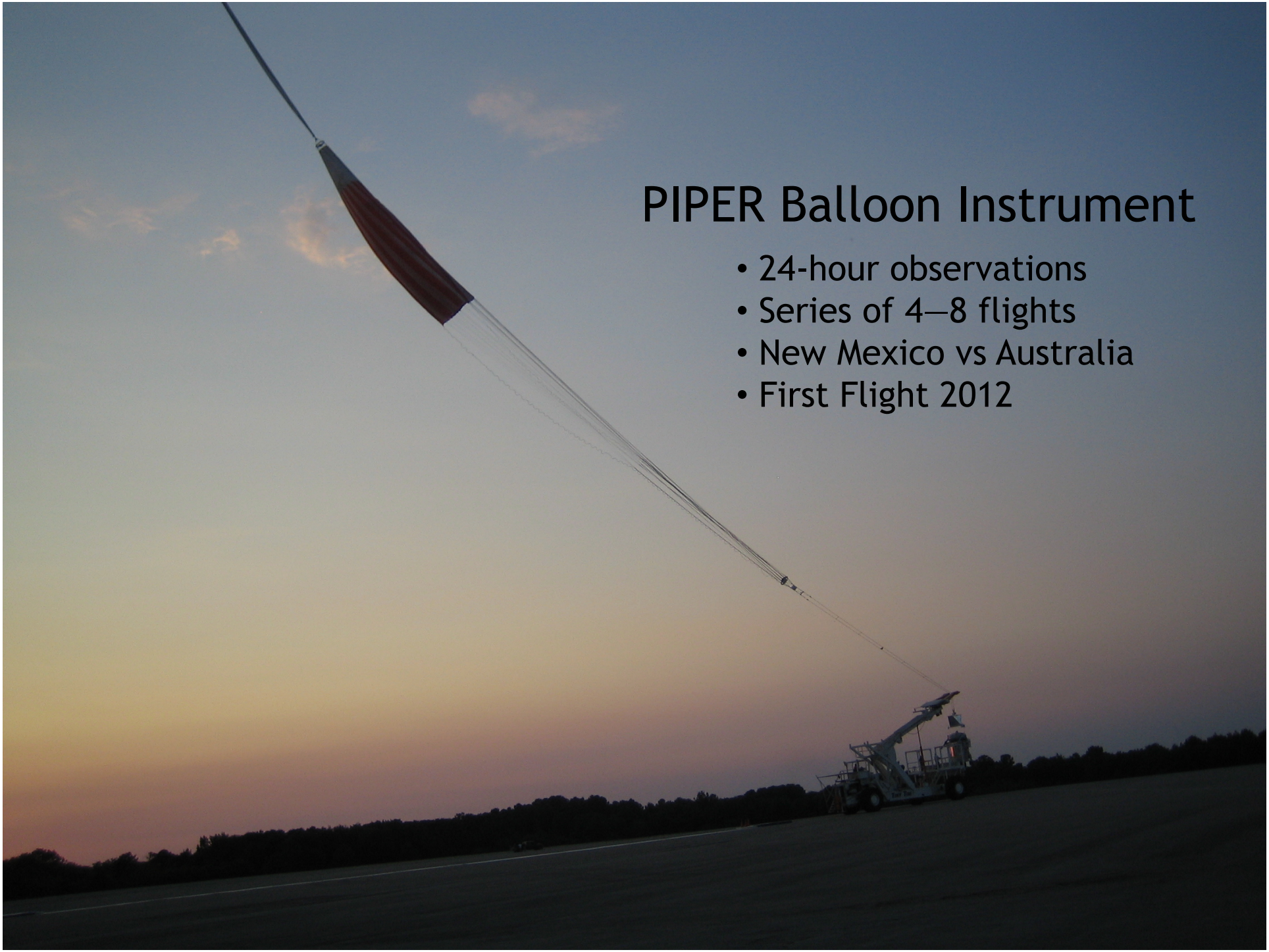
Primordial Inflation Polarization Explorer

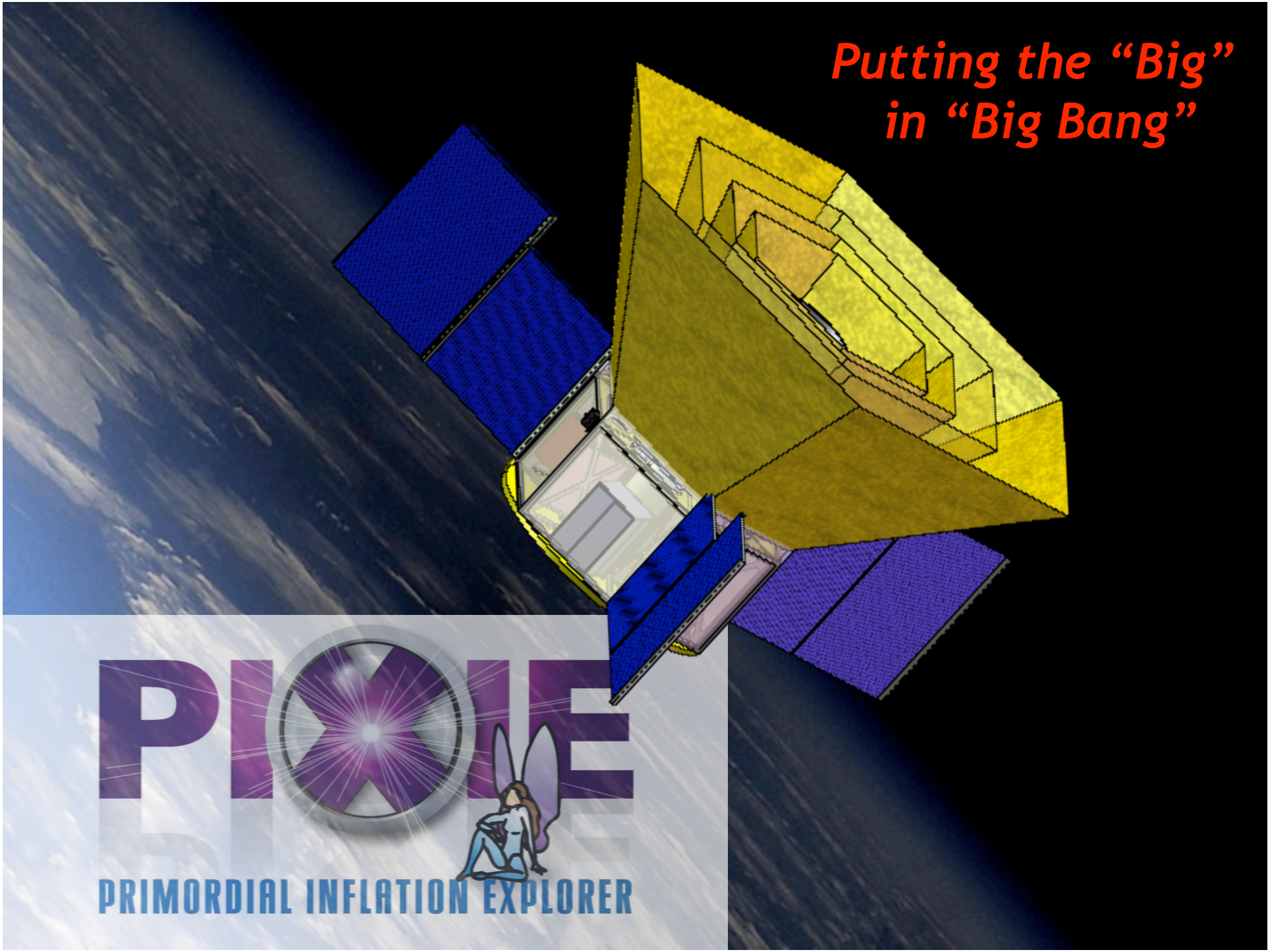
Balloon-Borne Instrument

- Twin 1.5 K Telescopes
- 5000 superconducting detectors
- “Flying Cold Tub” Gondola
- 2012 Scheduled Launch

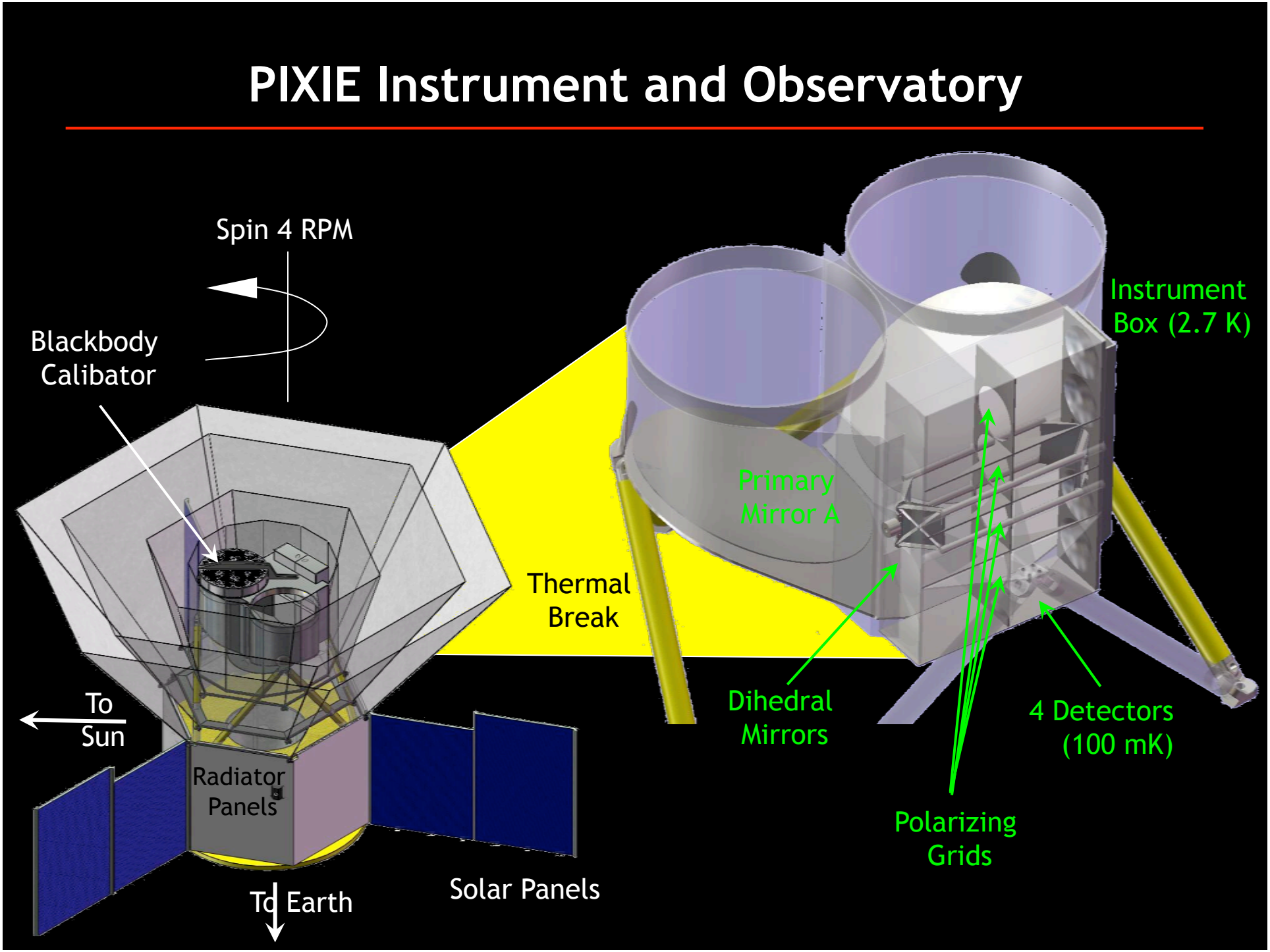


Goal: Statistical Detection of Gravity Waves

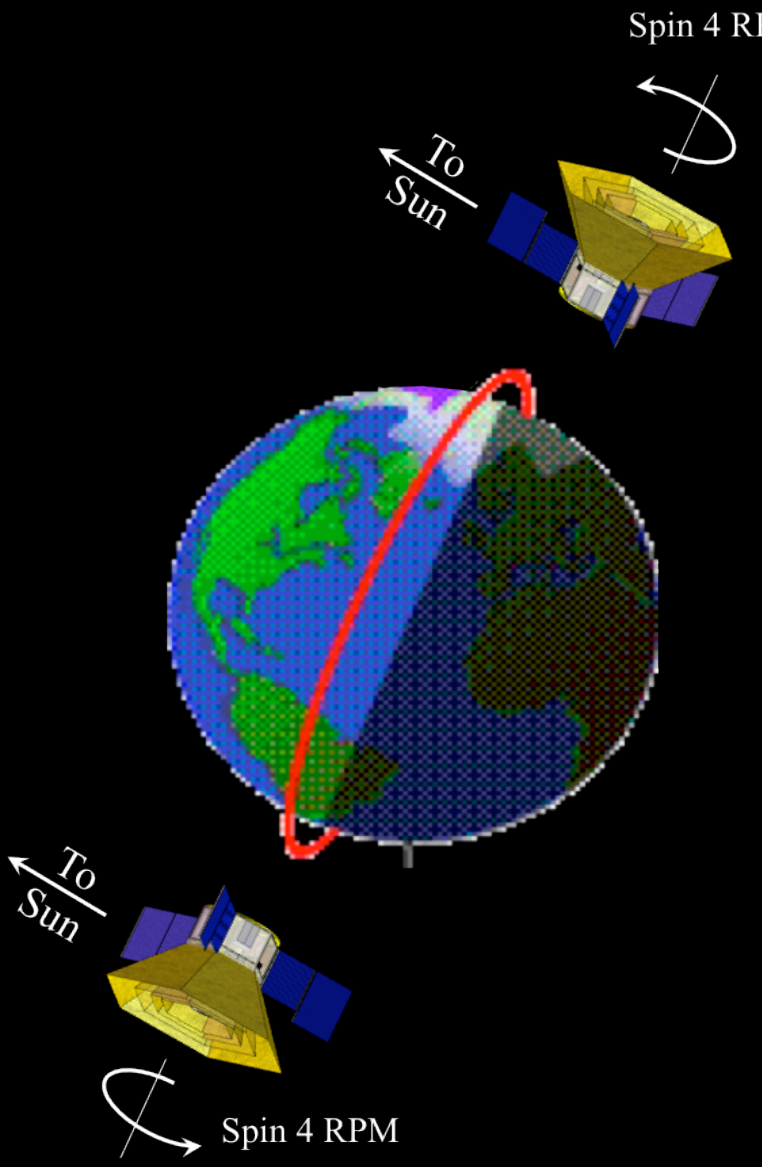

PIPER Balloon Instrument
• 24-hour observations
• Series of 4—8 flights
• New Mexico vs Australia
• First Flight 2012


Putting the "Big"
in "Big Bang"
PIXIE
PRIMORDIAL INFLATION EXPLORER

PIXIE Instrument and Observatory



PIXIE Mission



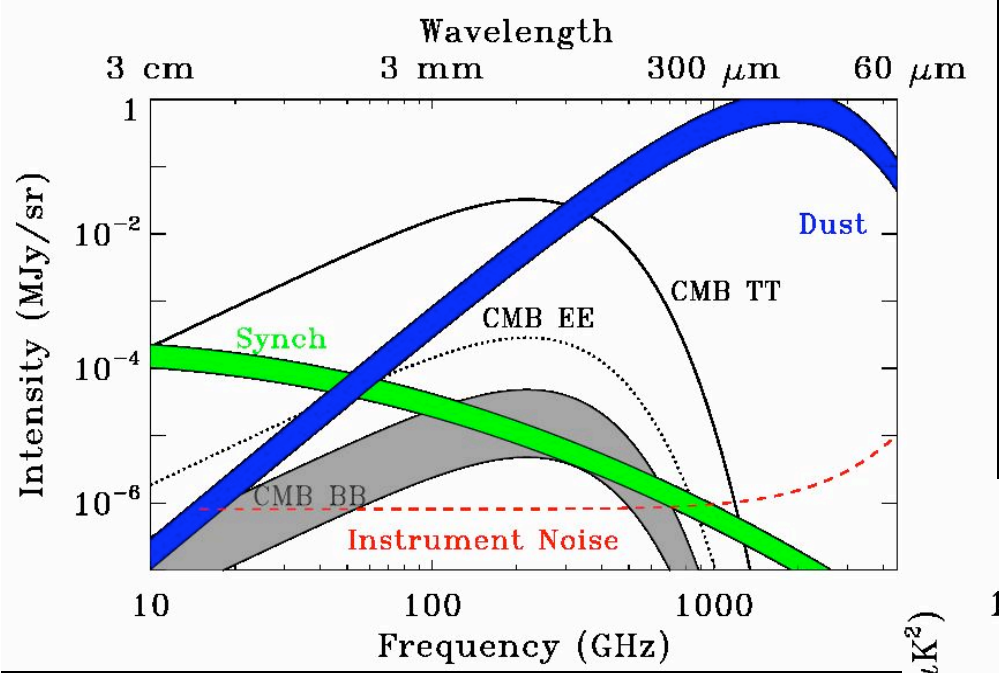
Polar sun-synchronous orbit

* 1450 km altitude
* Remain in sun
* Continuous view to deep space

“Spin and Stare” Operation

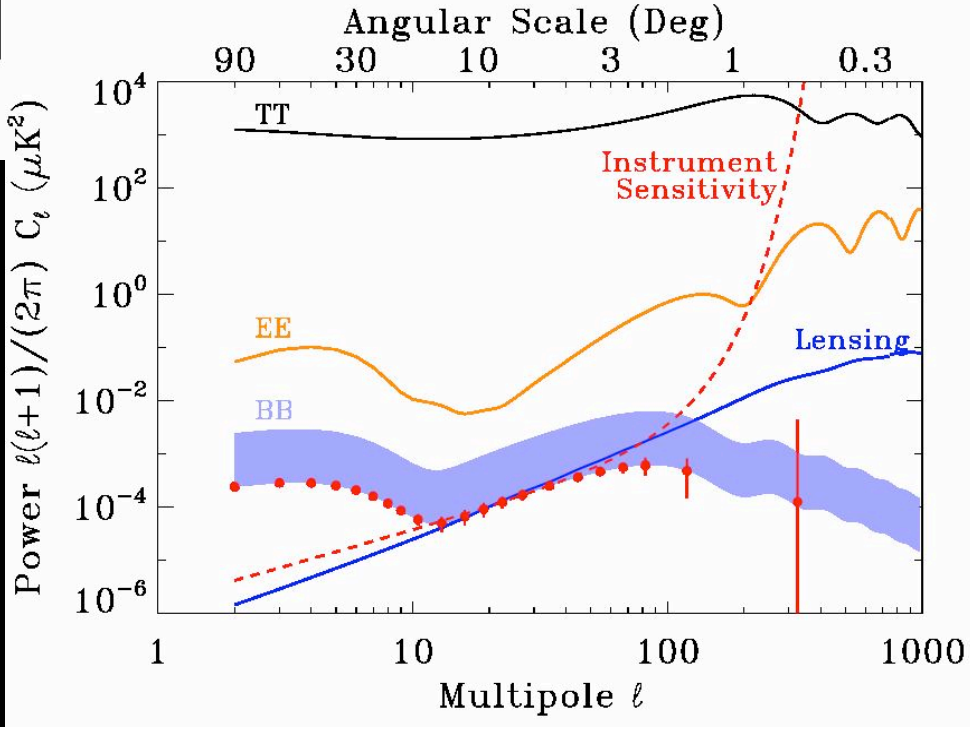
* Observe full sky every 6 months
* 4-Year mission
* Launch 2017

PIXIE Science: Primordial Gravity Waves

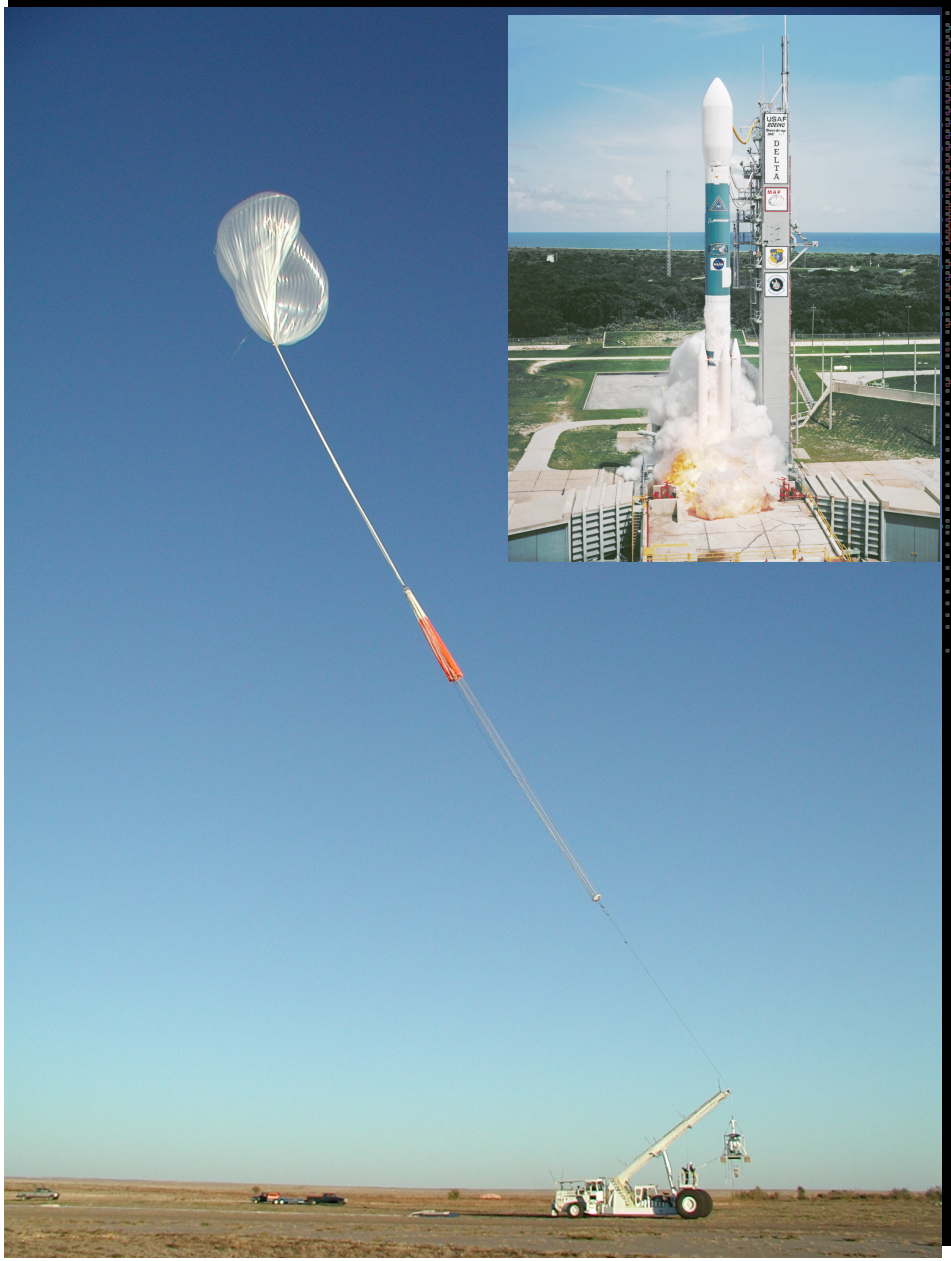


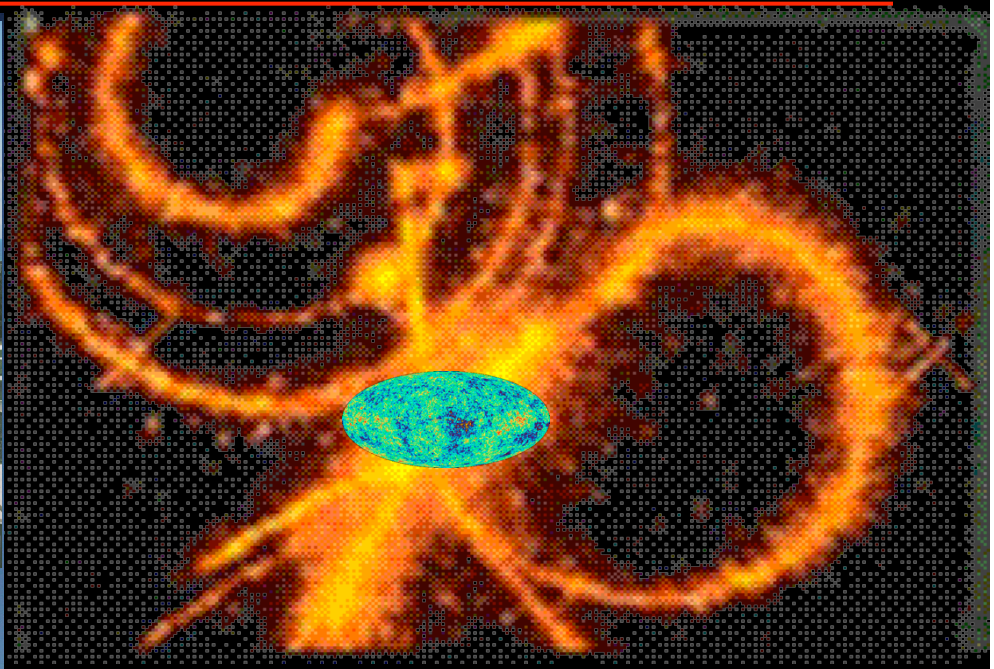
Sensitivity + Frequency Coverage

Measure Polarization
to characterize
Quantum Gravity



Observing Quantum Gravity?



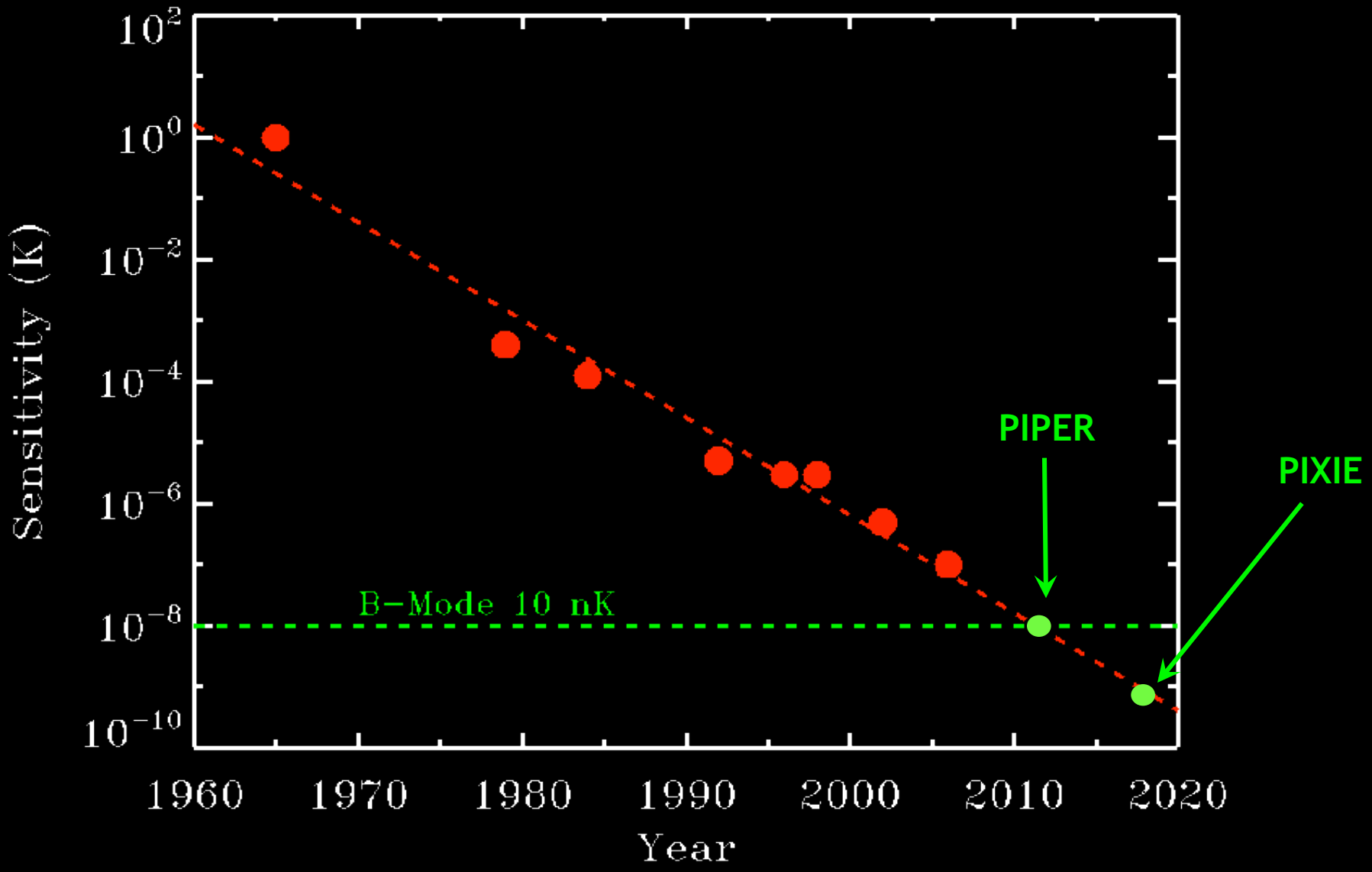


Gravity waves -- moving ripples in space-time -- leave tiny pattern in relic light

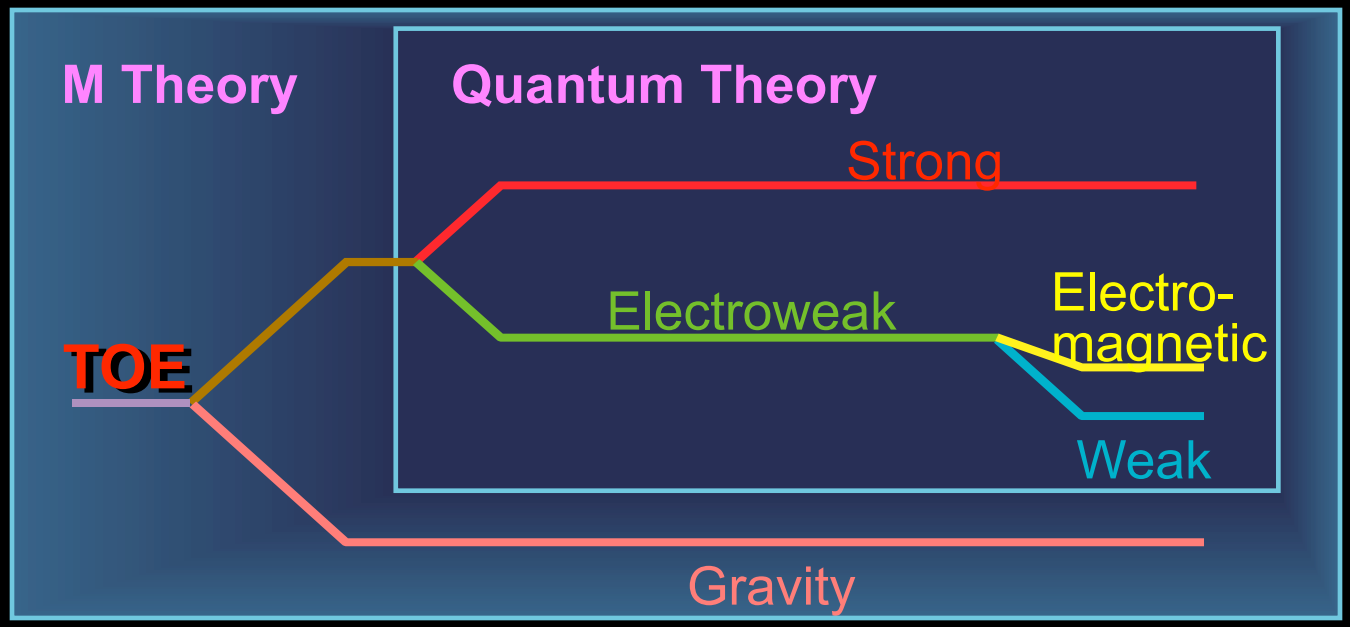
"Smoking Gun" signature of inflation

Could observers provide hint to solve Einstein's greatest quest?

Plausible Achievability



An Observable "Theory of Everything" ?



Intersection of Particle Physics and Cosmology

Coming Soon From a Spacecraft Near You:

Inflation,
Quantum Gravity,
And the
Theory of Everything!