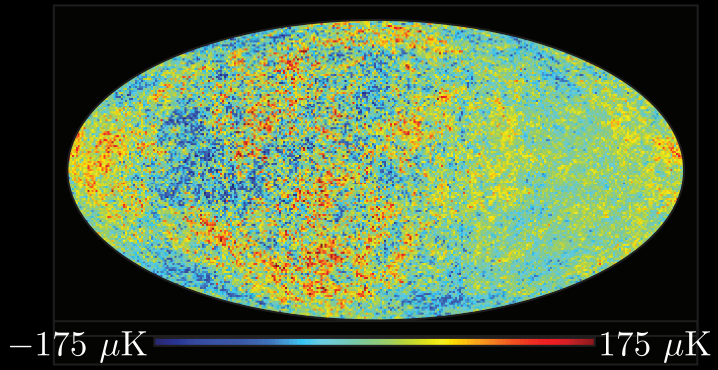
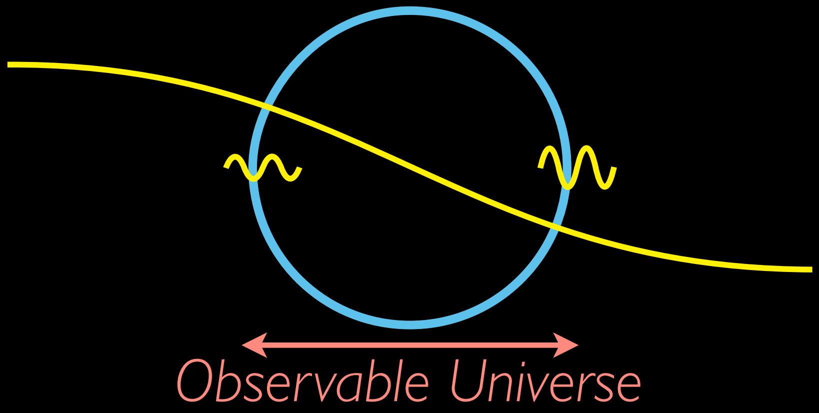
Looking Beyond the Cosmological Horizon





Adrienne Erickcek

in collaboration with Sean Carroll and Marc Kamionkowski

"A Hemispherical Power Asymmetry from Inflation" Phys. Rev. D78: 123520, 2008.

"Superhorizon Perturbations and the CMB" Phys. Rev. D78: 083012, 2008.

Everhart Lecture: March 10, 2009

sponsored by the GSC and the Department of Student Affairs

Part 1: The Birth of the Universe

I. Journey back to the Big Bang

- A brief history of the Universe
- The cosmological horizon

II. The Cosmic Microwave Background

- A baby photo of the Universe
- Mysteries of the CMB

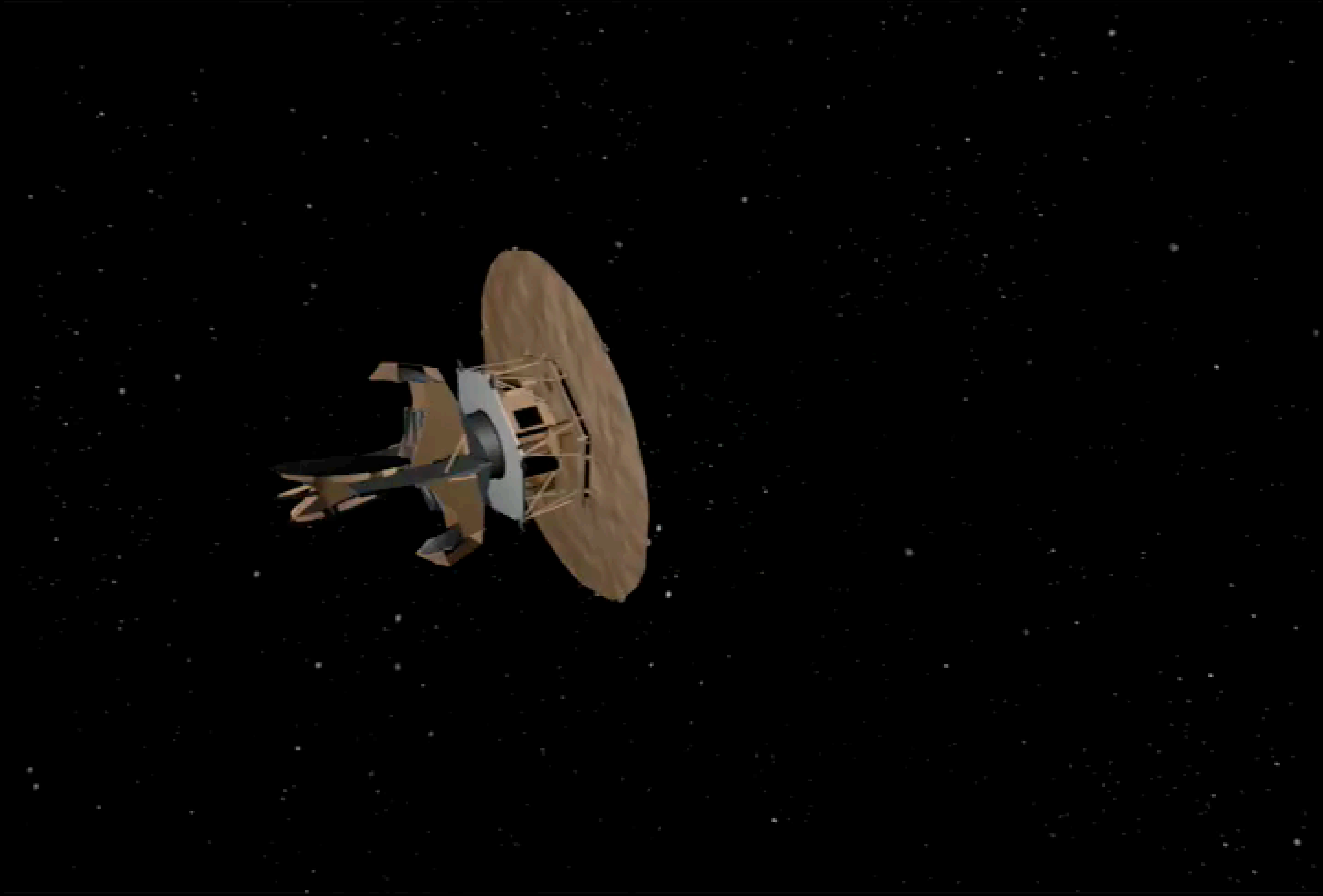
III. Inflation

- A crazy idea...
- But it works!
- More unanswered questions

Part 2: An Asymmetric Universe

Journey to the Big Bang

Journey to the Big Bang



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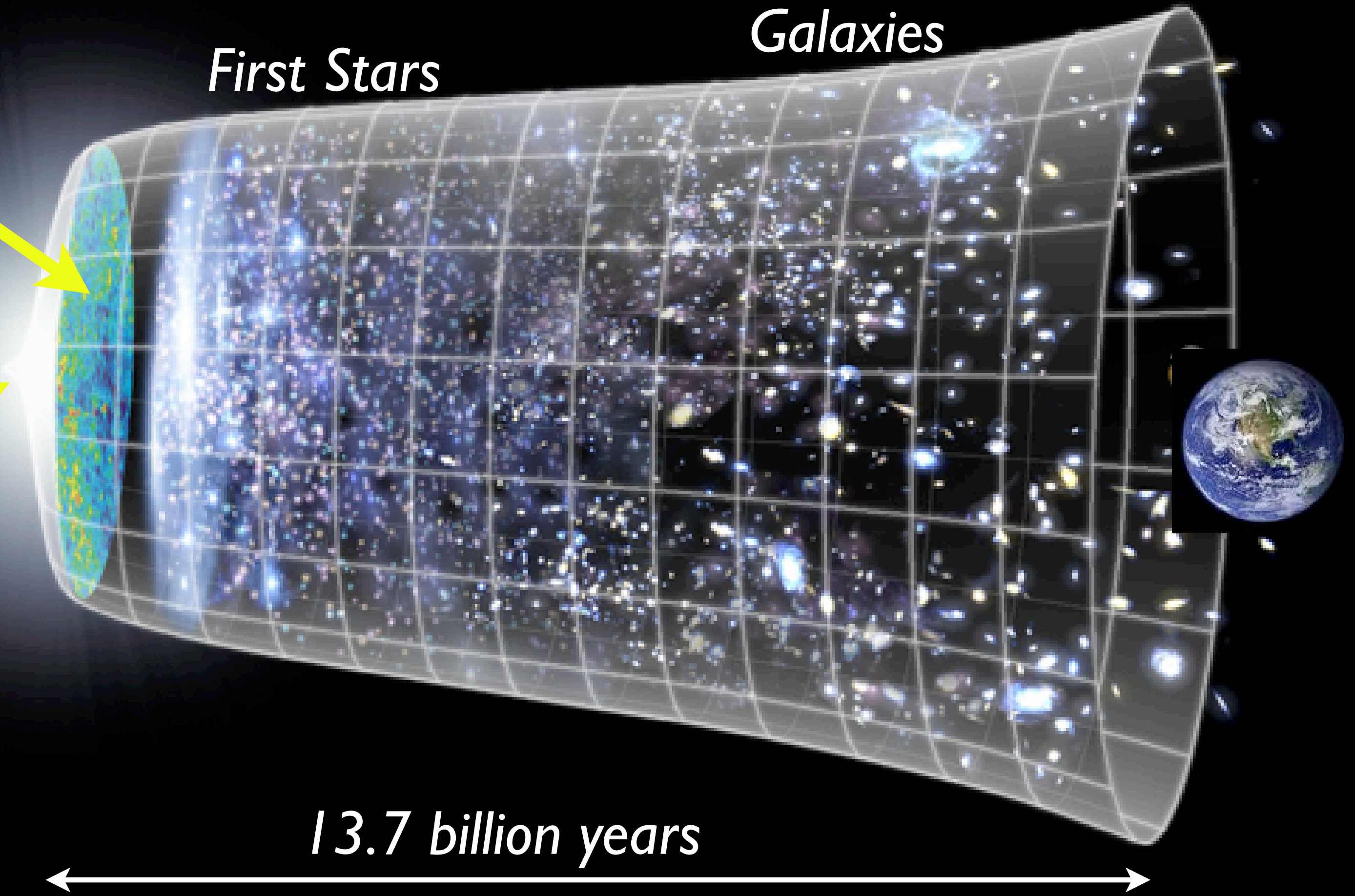
A Brief History of the Universe



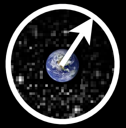
The Cosmic Microwave Background

Inflation: an instant of extremely rapid expansion

How do we know all of this? The Cosmologist's Toolbox:

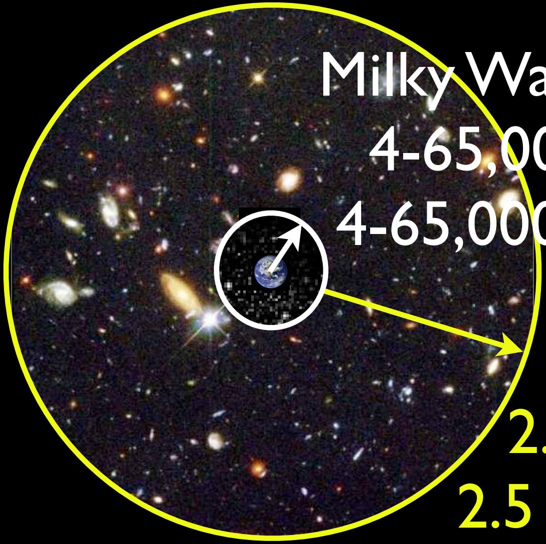
- Electromagnetic observations: looking out = looking back in time
- Quantities of light elements made 2-3 minutes after Big Bang

Looking Back in Time



Milky Way Stars
4-65,000 LY
4-65,000 Years

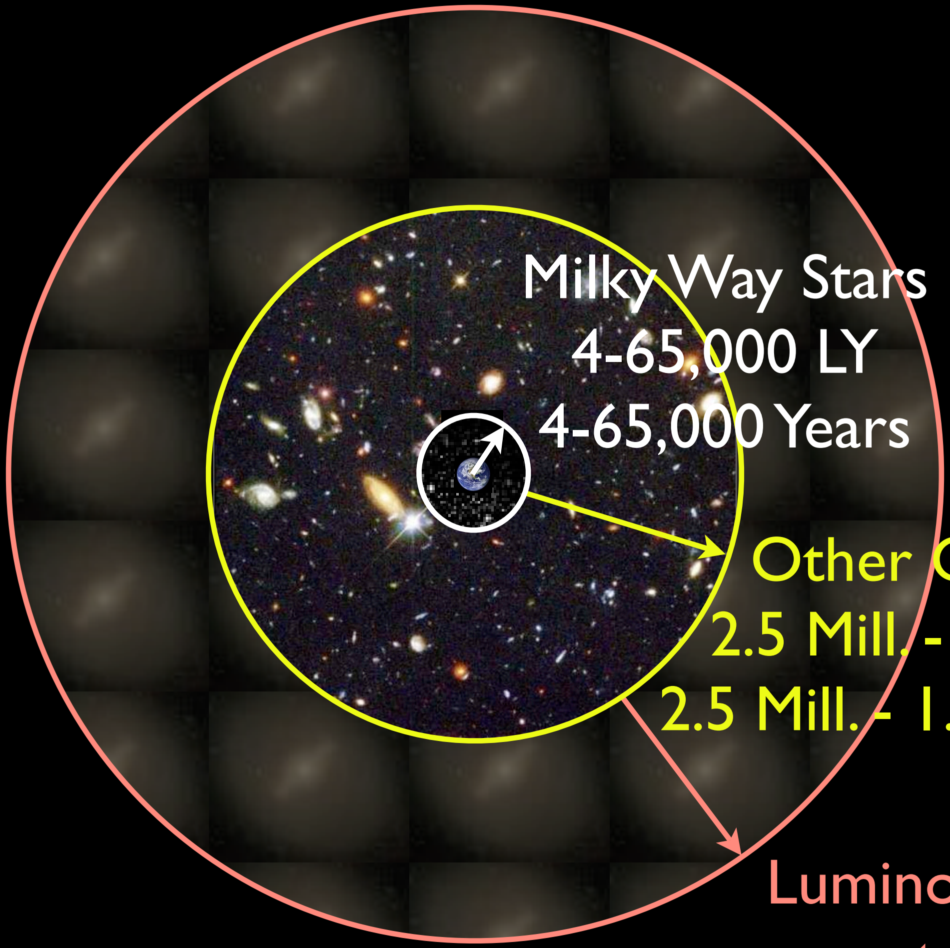
Looking Back in Time



Milky Way Stars
4-65,000 LY
4-65,000 Years

Other Galaxies
2.5 Mill. - 2.0 Bill. LY
2.5 Mill. - 1.9 Bill. Years

Looking Back in Time



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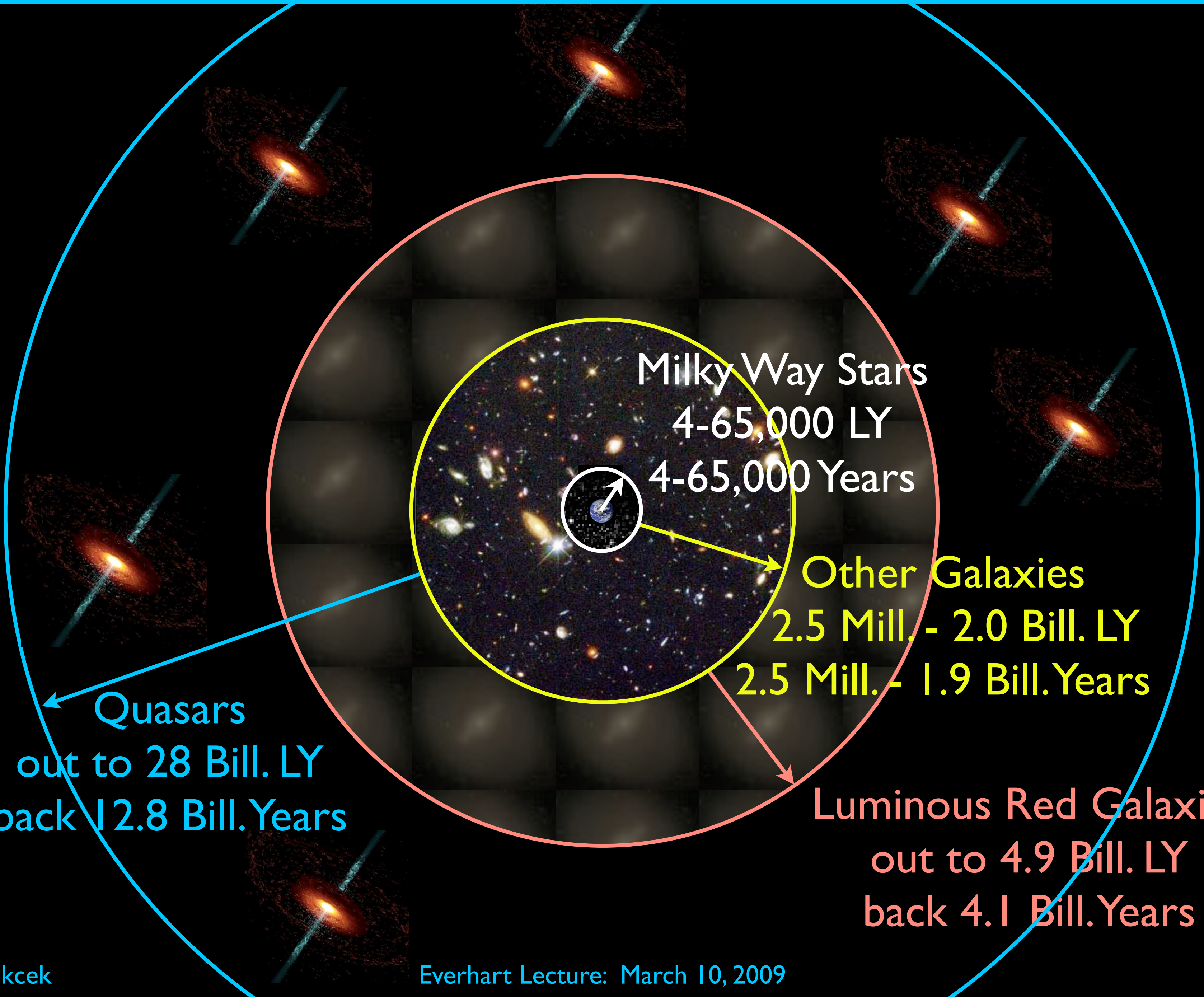
Luminous Red Galaxies
out to 4.9 Bill. LY
back 4.1 Bill. Years

Looking Back in Time



Milky Way Stars
4-65,000 LY
4-65,000 Years

Other Galaxies
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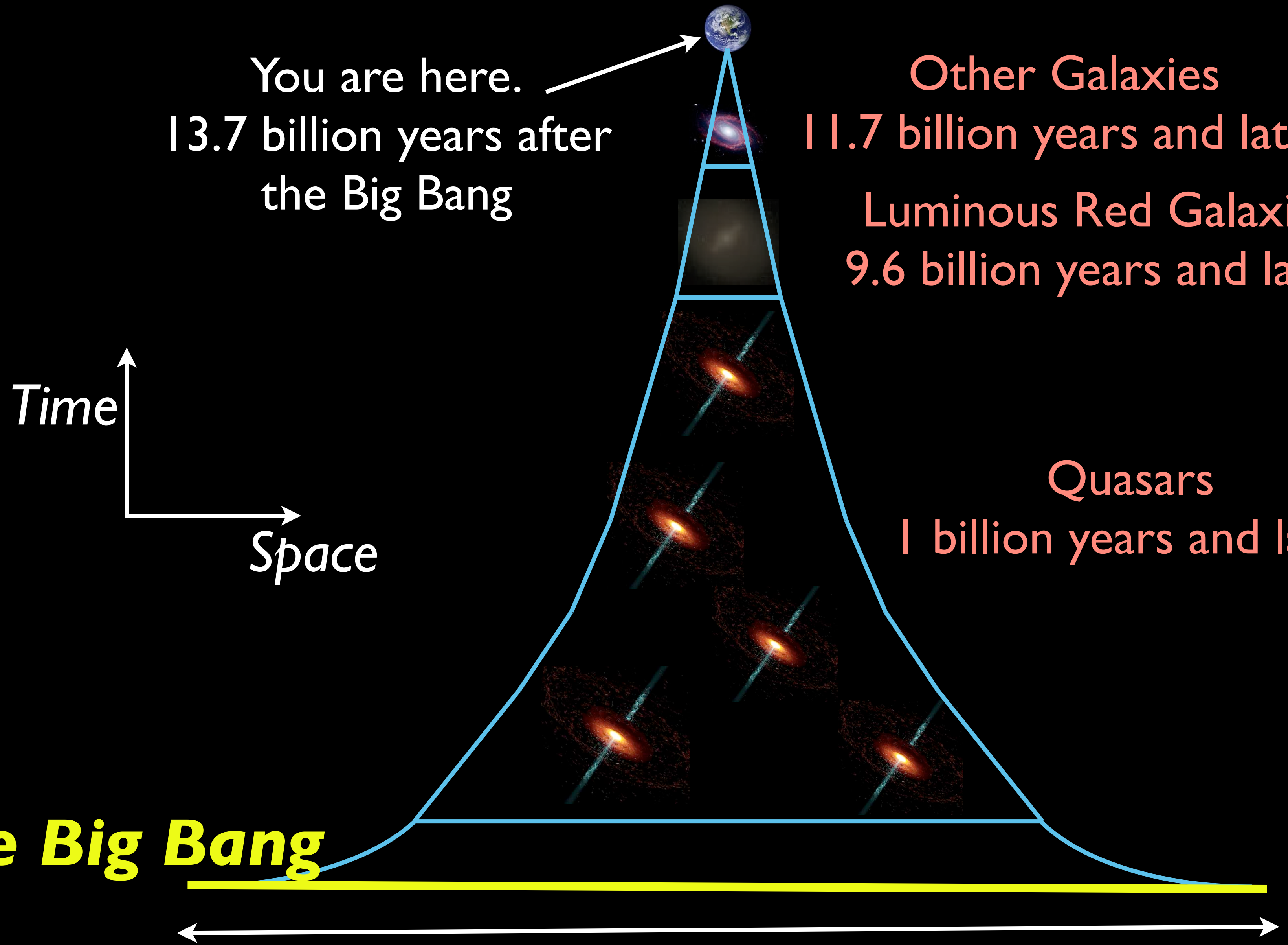
Luminous Red Galaxies
out to 4.9 Bill. LY
back 4.1 Bill. Years

Quasars
out to 28 Bill. LY
back 12.8 Bill. Years

Light Cones and the Cosmic Horizon



You are here.
13.7 billion years after
the Big Bang

Other Galaxies
11.7 billion years and later

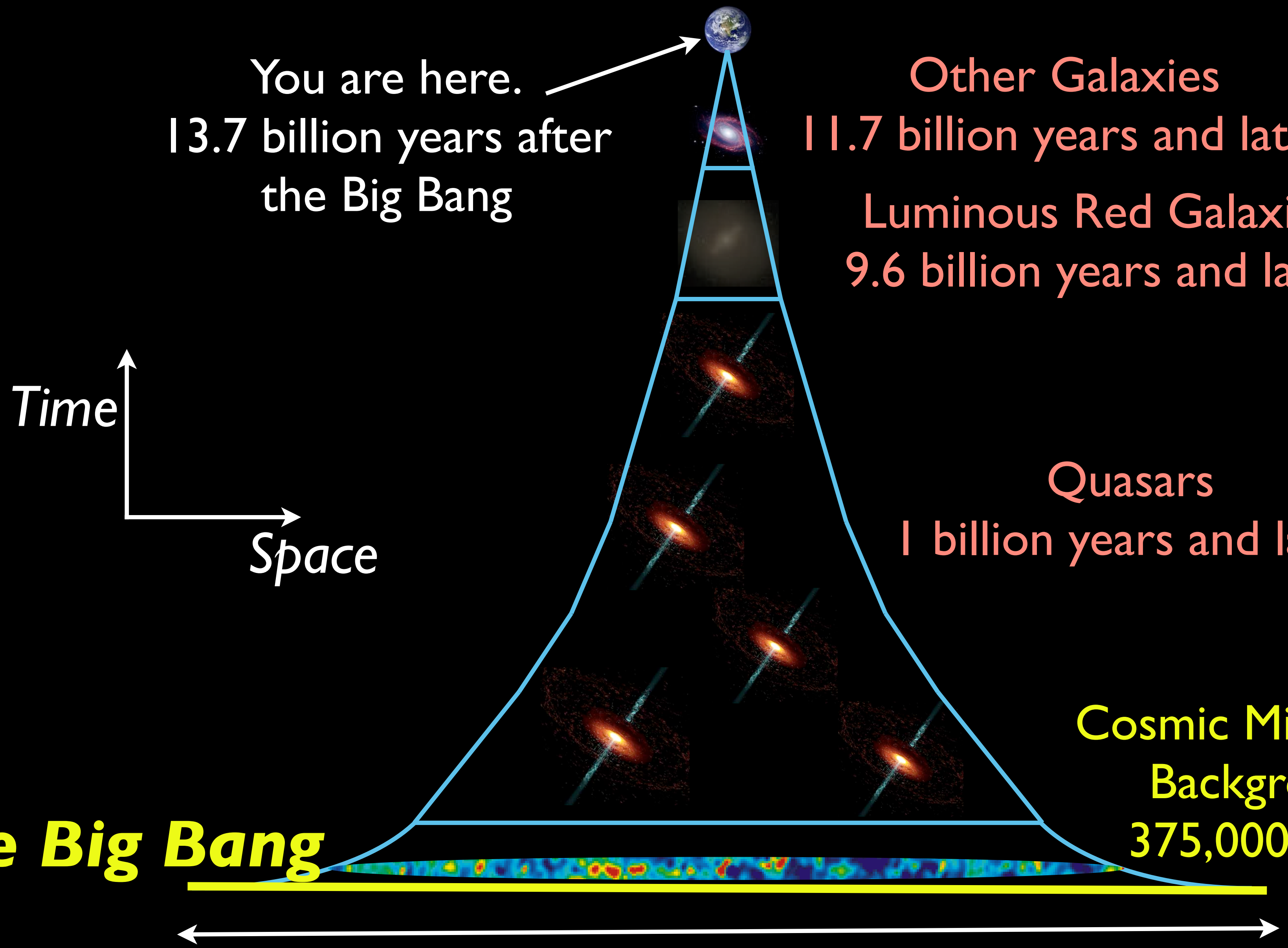
Luminous Red Galaxies
9.6 billion years and later

Quasars
1 billion years and later

The Big Bang

The Observable Universe: 93 billion lightyears across

Light Cones and the Cosmic Horizon



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Other Galaxies
11.7 billion years and later

Luminous Red Galaxies
9.6 billion years and later

Time

Space

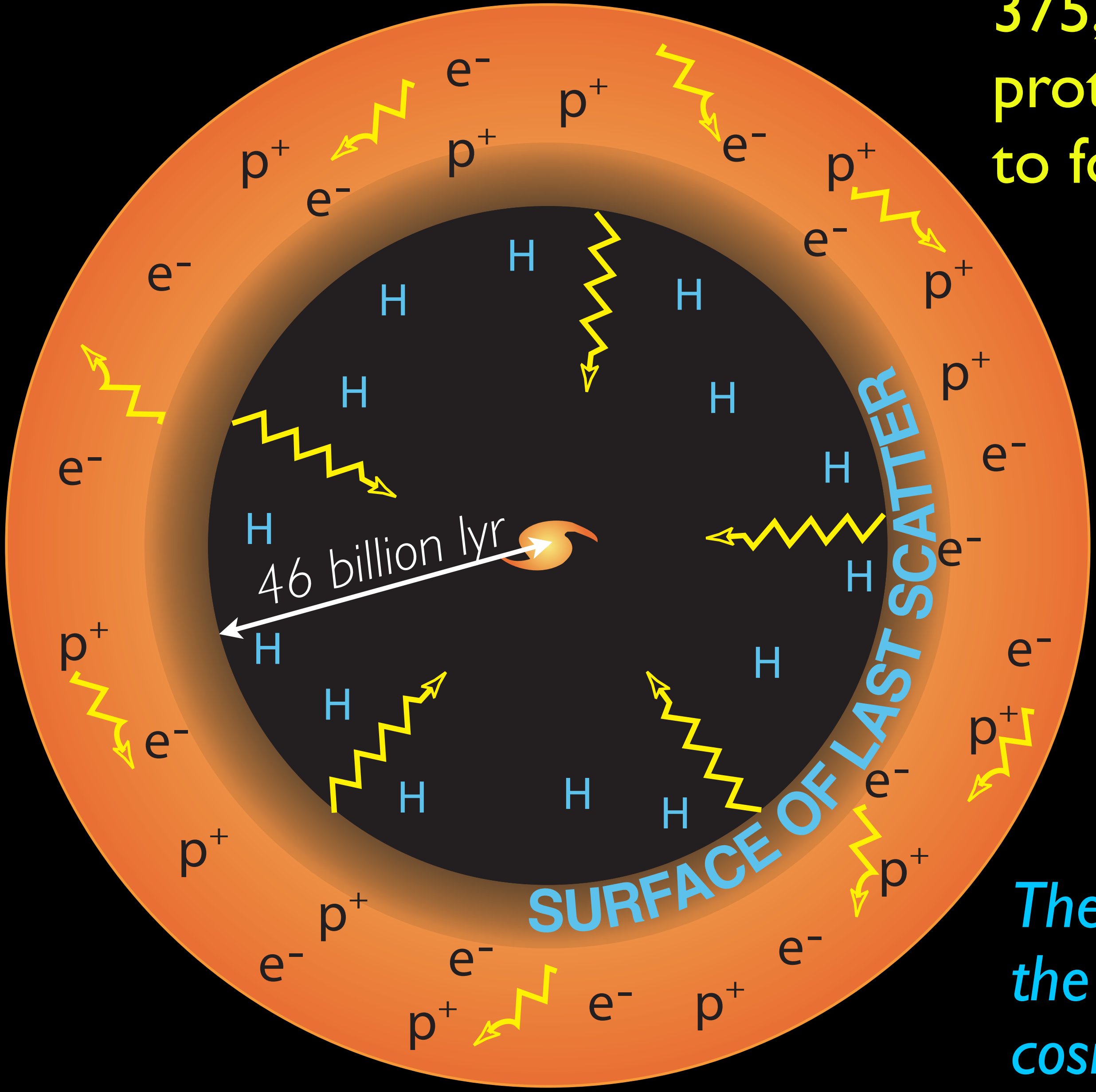
Quasars
1 billion years and later

Cosmic Microwave
Background
375,000 years

The Big Bang

The Observable Universe: 93 billion lightyears across

The Surface of Last Scatter



375,000 years after the Big Bang, protons and electrons combined to form hydrogen atoms.

- Before hydrogen formation, the Universe was filled with opaque plasma.
- After hydrogen formation, photons could travel freely; the Universe became transparent.

The photons that reach us from the last scattering surface make a cosmic microwave background.

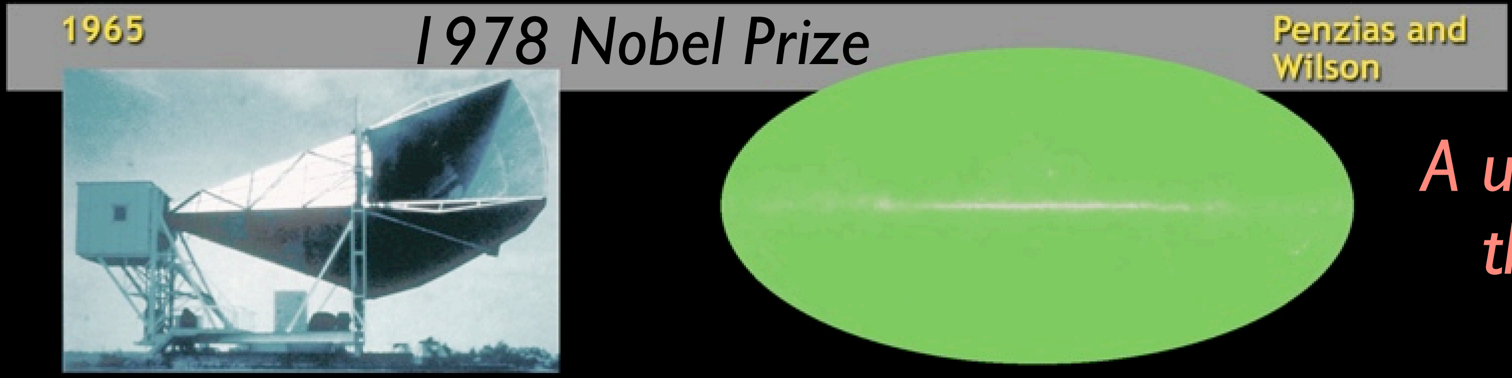
The Cosmic Microwave Background

NASA/WMAP Science Team

The Cosmic Microwave Background

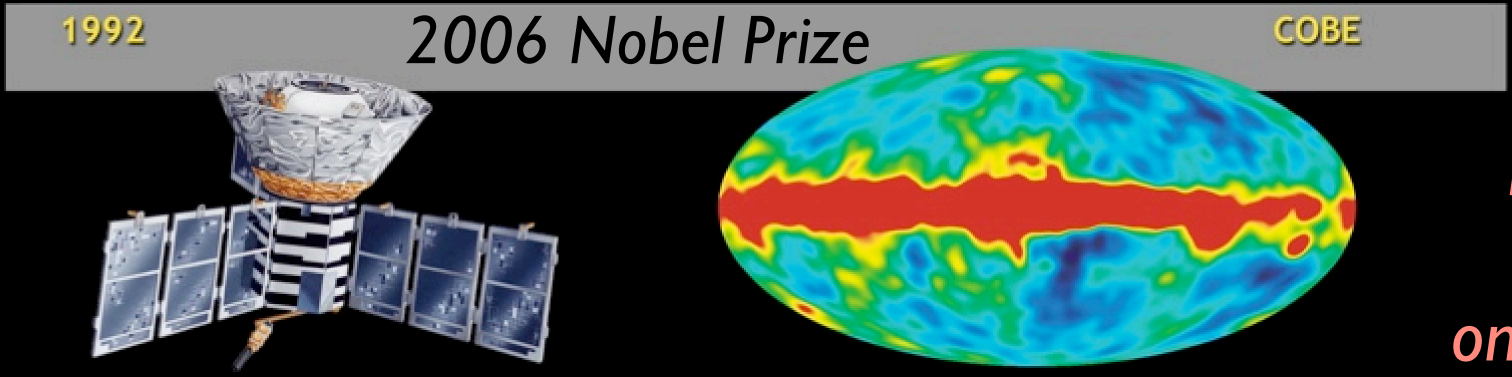
NASA/WMAP Science Team

A Partial History of the CMB



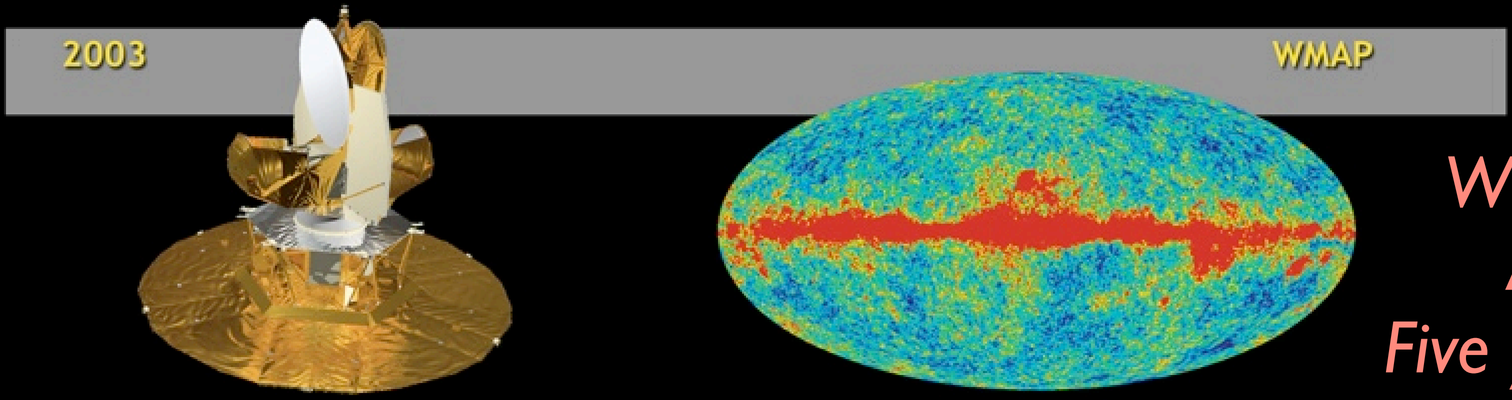
1978 Nobel Prize

A uniform glow outside the Galactic Plane:
T = 2.7 Kelvin



2006 Nobel Prize

First detection of fluctuations:
one part in 100,000



Wilkinson Microwave Anisotropy Probe
Five years of data so far...

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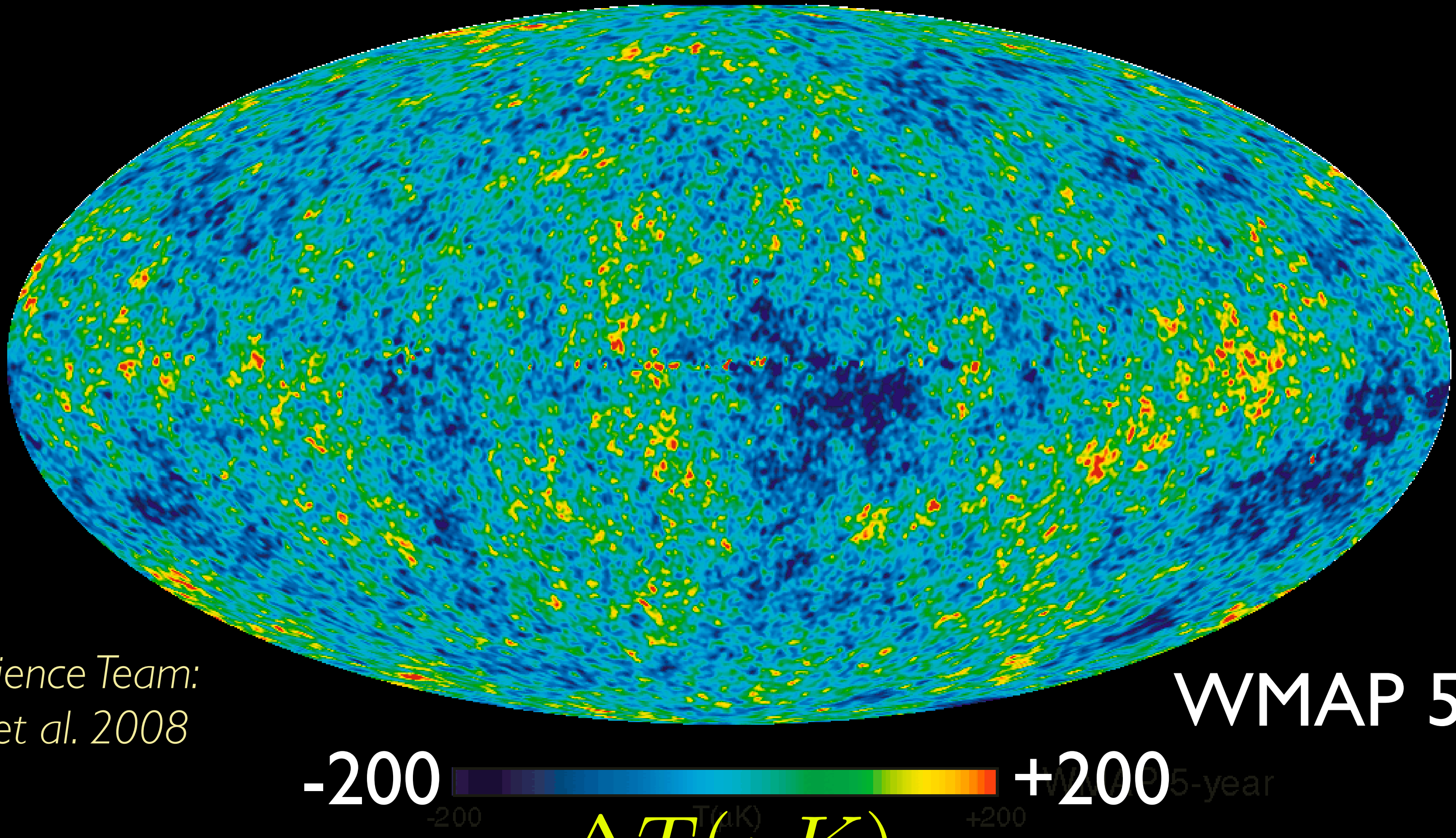
The Cosmic Microwave Background

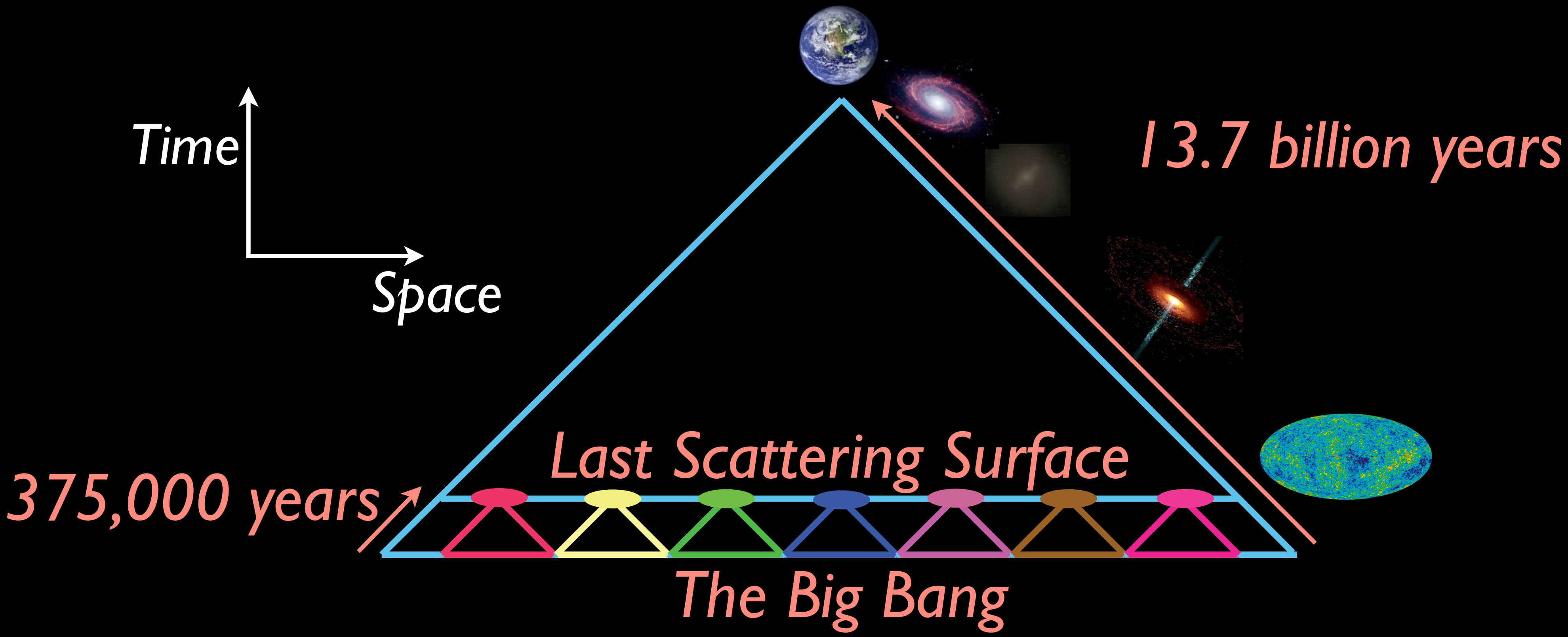


WMAP Science Team: Hinshaw, et al. 2008

- The CMB is perfect black-body radiation: $T = 2.726\,\mathrm{K}$
- There are very tiny (one part in 100,000) fluctuations.
- The characteristic size of these perturbations is 1°.

Mystery 1: The Horizon Problem

The CMB should not be so perfectly uniform!



- At the last scattering surface, the horizon was 1° across.
- Every 1° disk in the CMB is effectively a separate universe.
- These different patches should not have the same temperature!

Mystery 2: The Flatness Problem

The characteristic angular size of the CMB fluctuations tells us about the geometry of the Universe.

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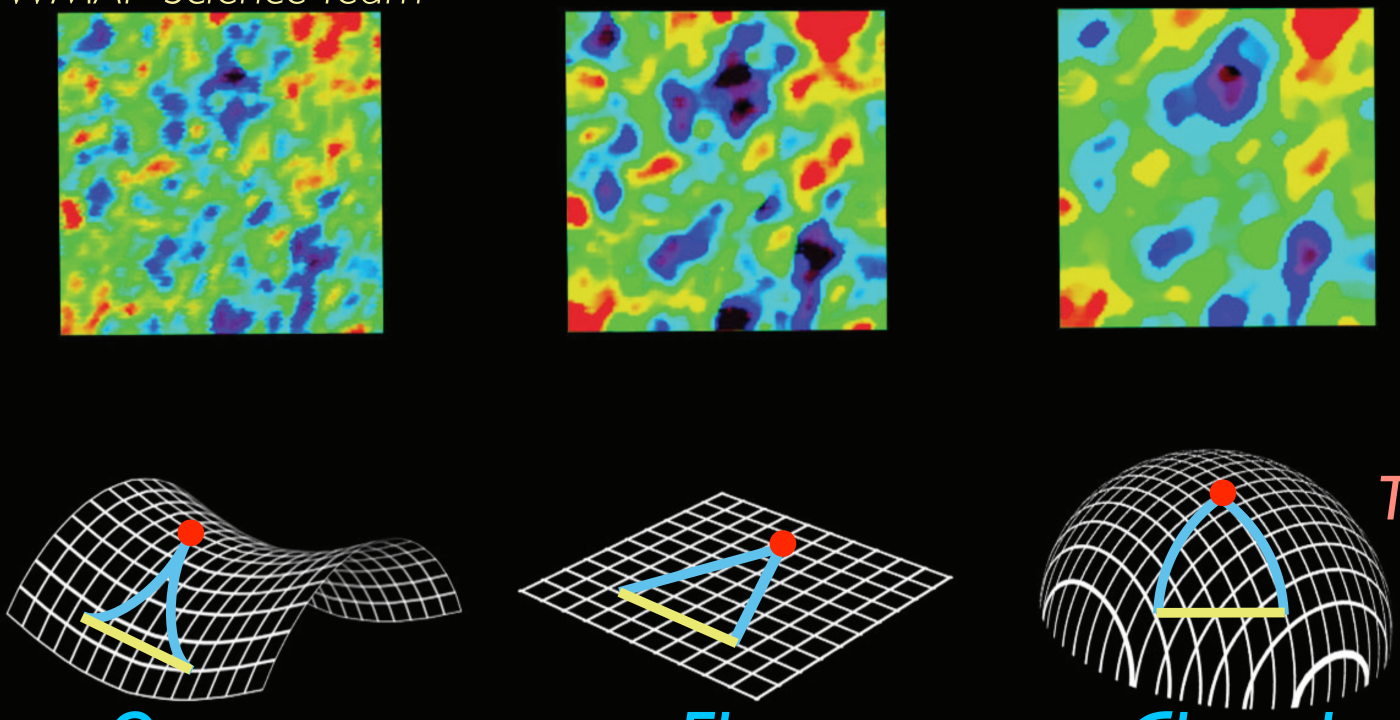

The physical size of the fluctuations is the horizon size at the last scattering surface.

The geometry of the Universe determines the angular size of the fluctuations.

Mystery 2: The Flatness Problem

The characteristic angular size of the CMB fluctuations tells us about the geometry of the Universe.

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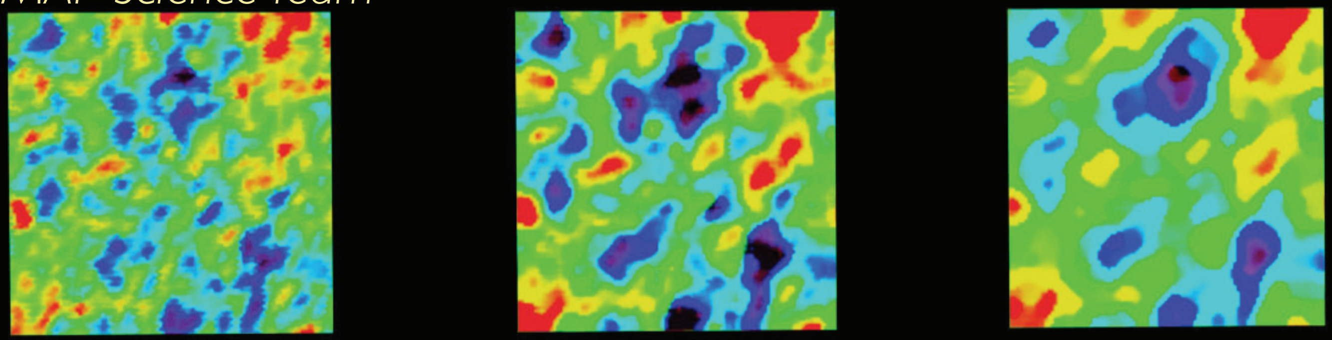
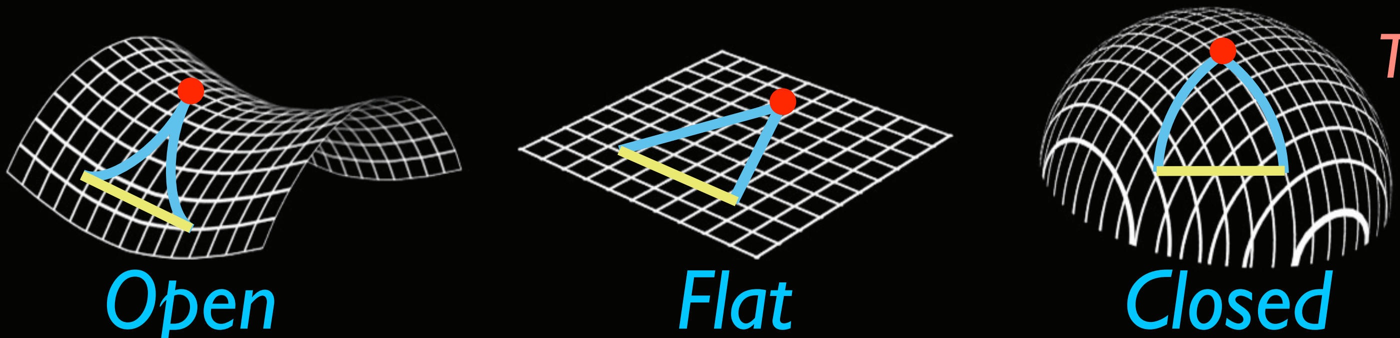


$\Omega < 1 \Rightarrow \theta_c < 1^\circ$ $\Omega = 1 \Rightarrow \theta_c \simeq 1^\circ$ $\Omega > 1 \Rightarrow \theta_c > 1^\circ$

The physical size of the fluctuations is the horizon size at the last scattering surface.



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$$\Omega \equiv \frac{\text{Energy in the Universe}}{\text{Energy required for flatness}}$$

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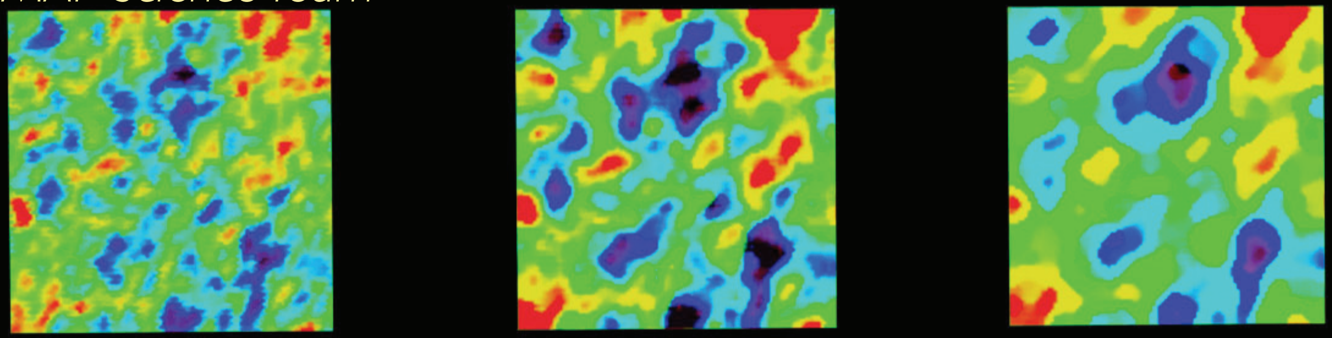

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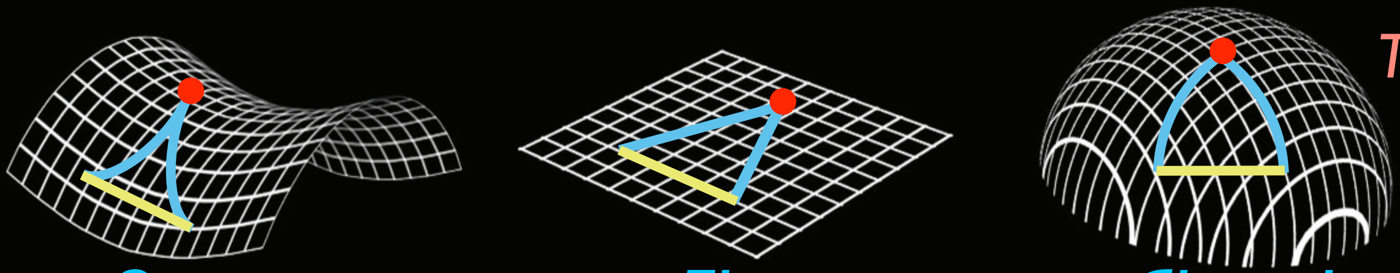

Open *Flat* *Closed*

The geometry of the Universe determines the angular size of the fluctuations.

$$\Omega \equiv \frac{\textit{Energy in the Universe}}{\textit{Energy required for flatness}} = 1.005 \pm 0.007 \text{ today}$$

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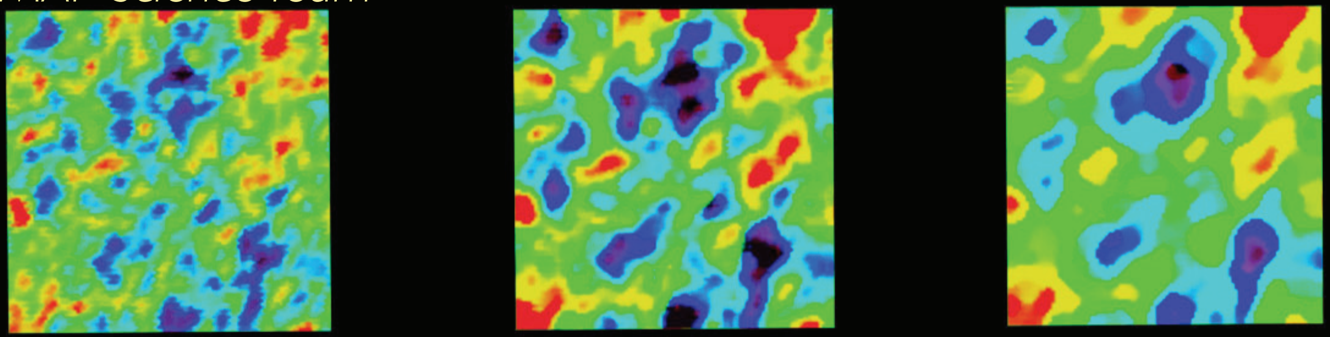

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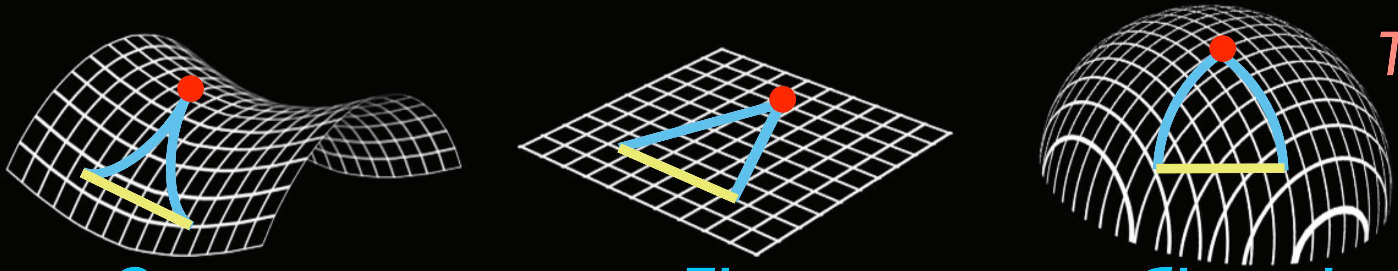

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The geometry of the Universe determines the angular size of the fluctuations.

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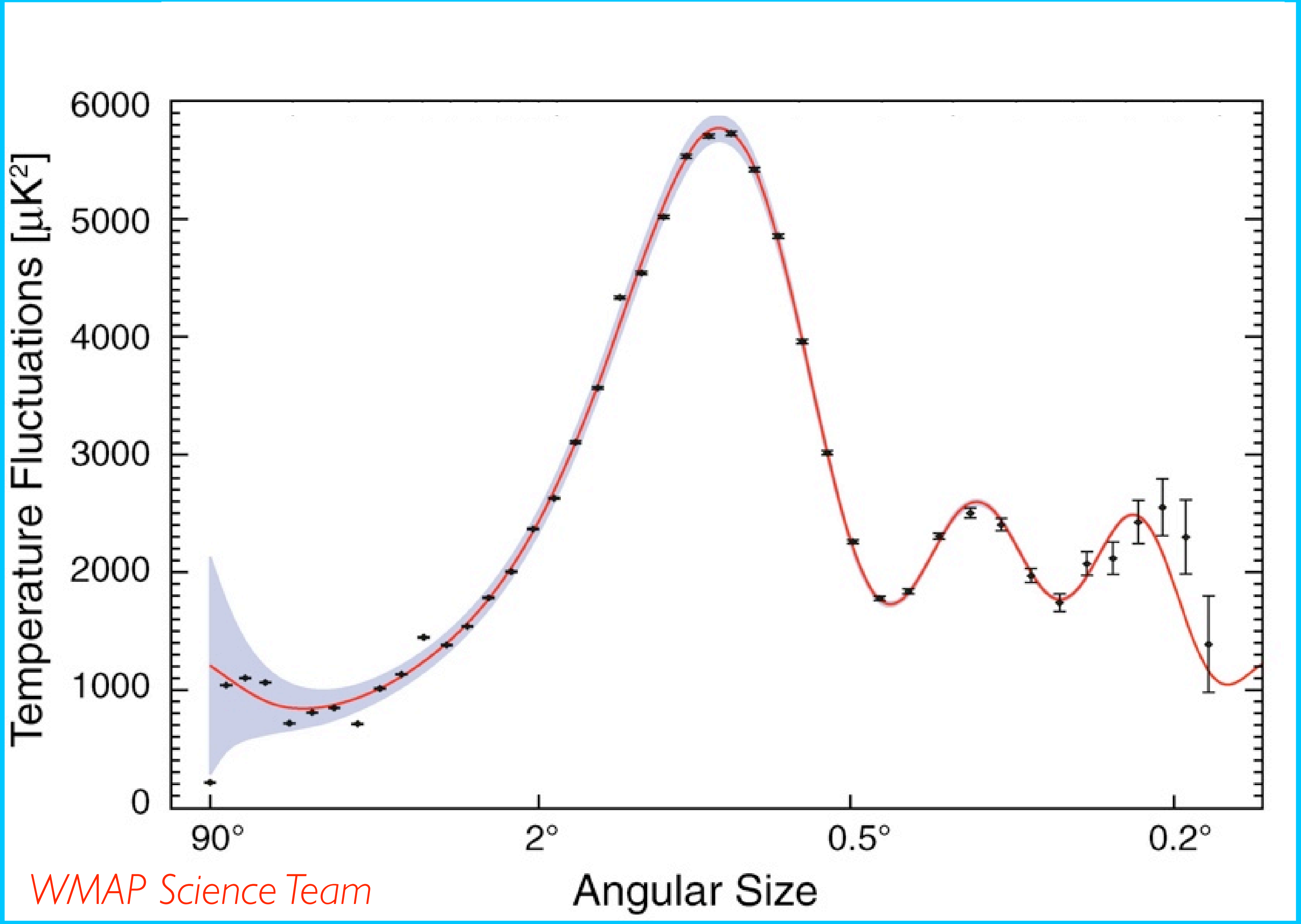
$\Rightarrow |\Omega - 1| < 10^{-16}$ 2 minutes after the Big Bang!

Mystery 3: Initial Fluctuations

CMB Power Spectrum



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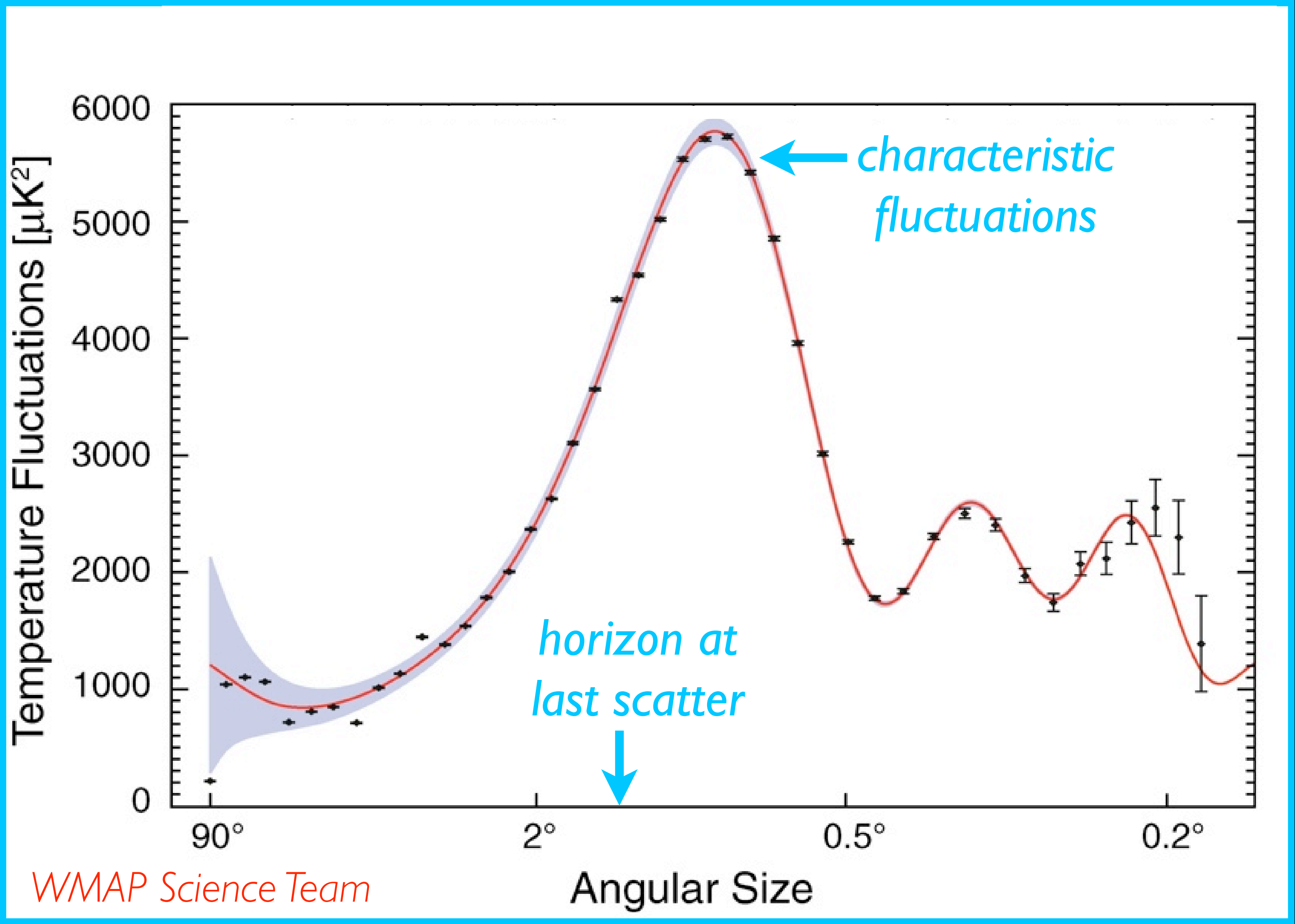

characteristic fluctuations

horizon at last scatter

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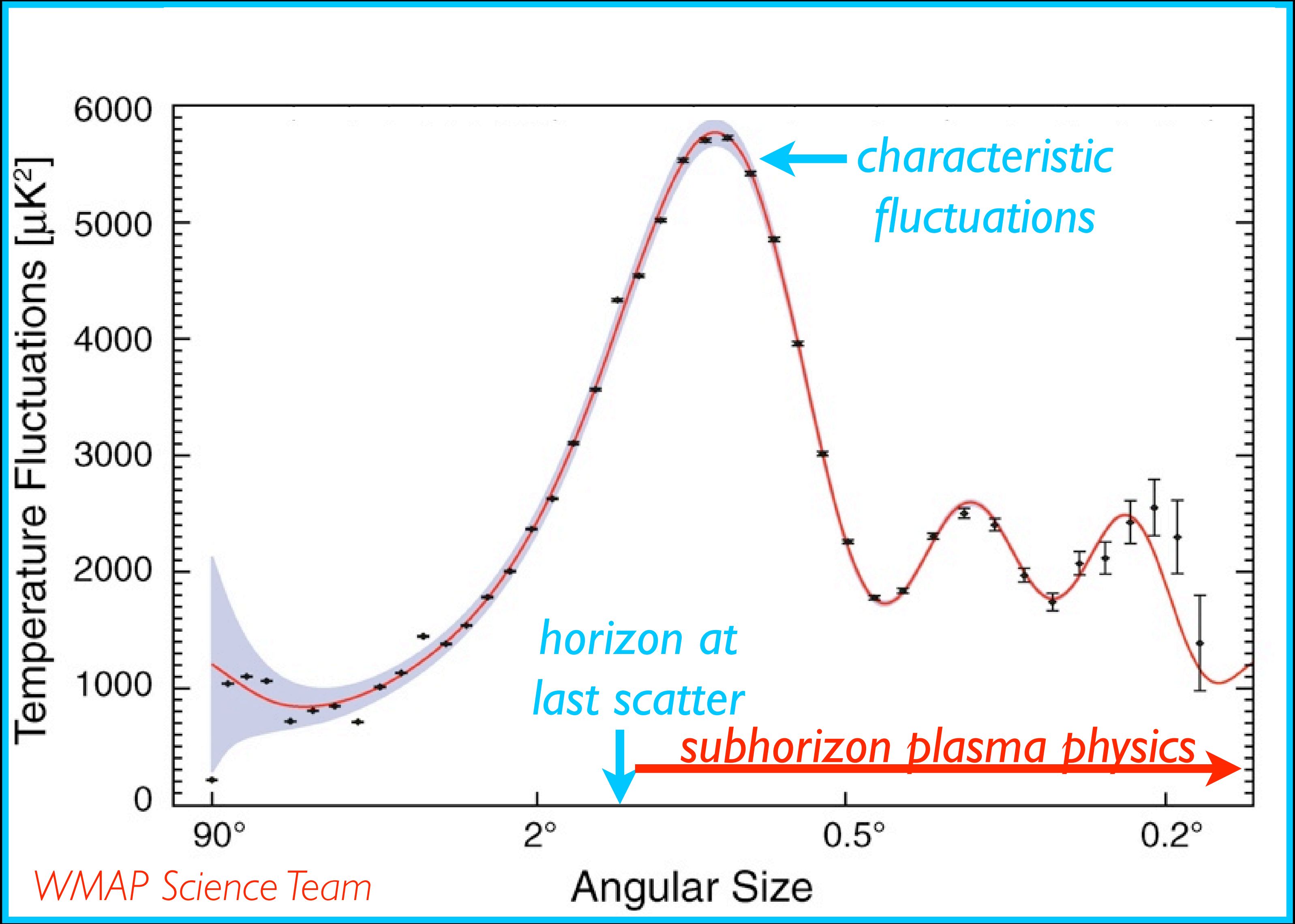
Mystery 3: Initial Fluctuations

CMB Power Spectrum



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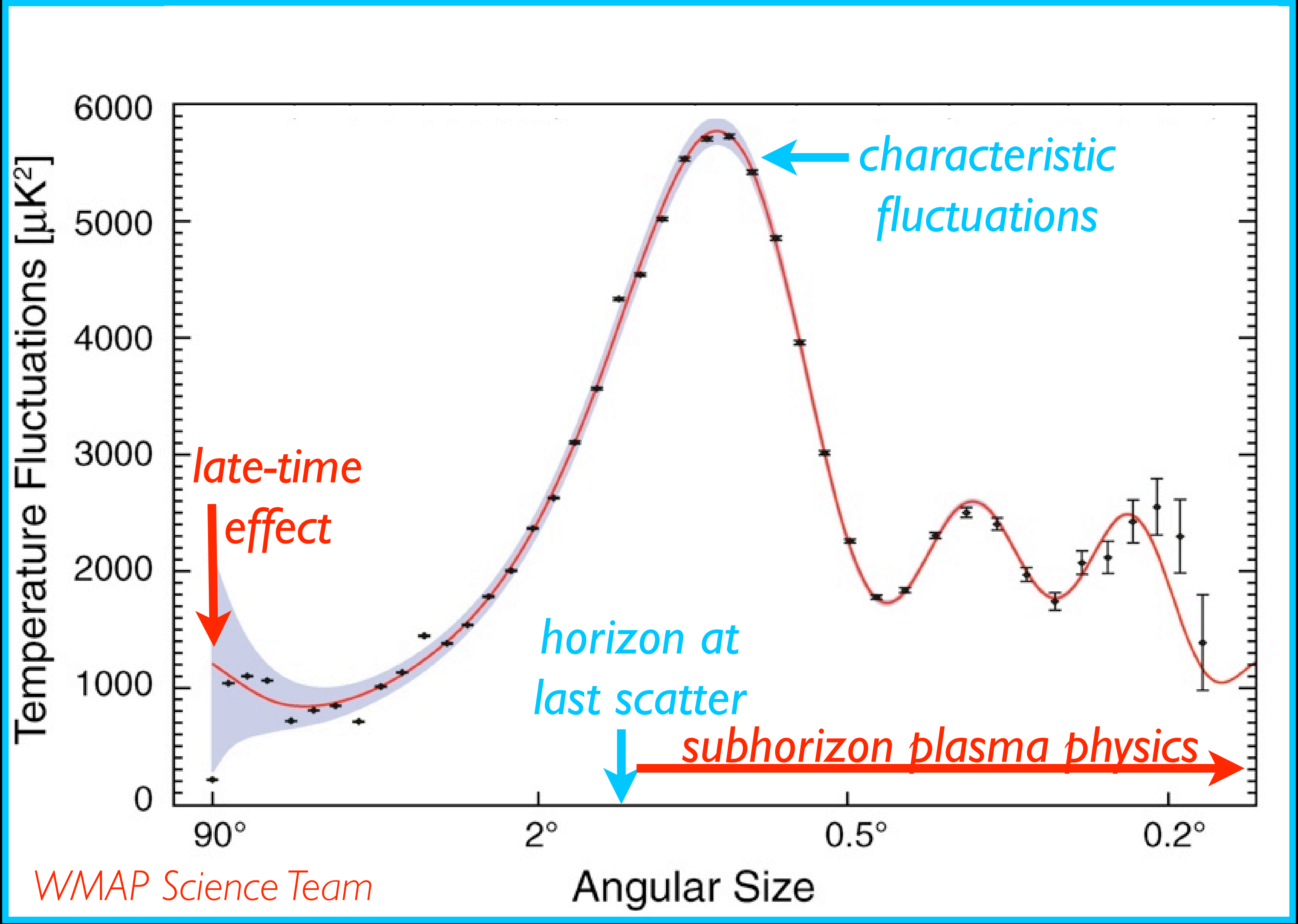

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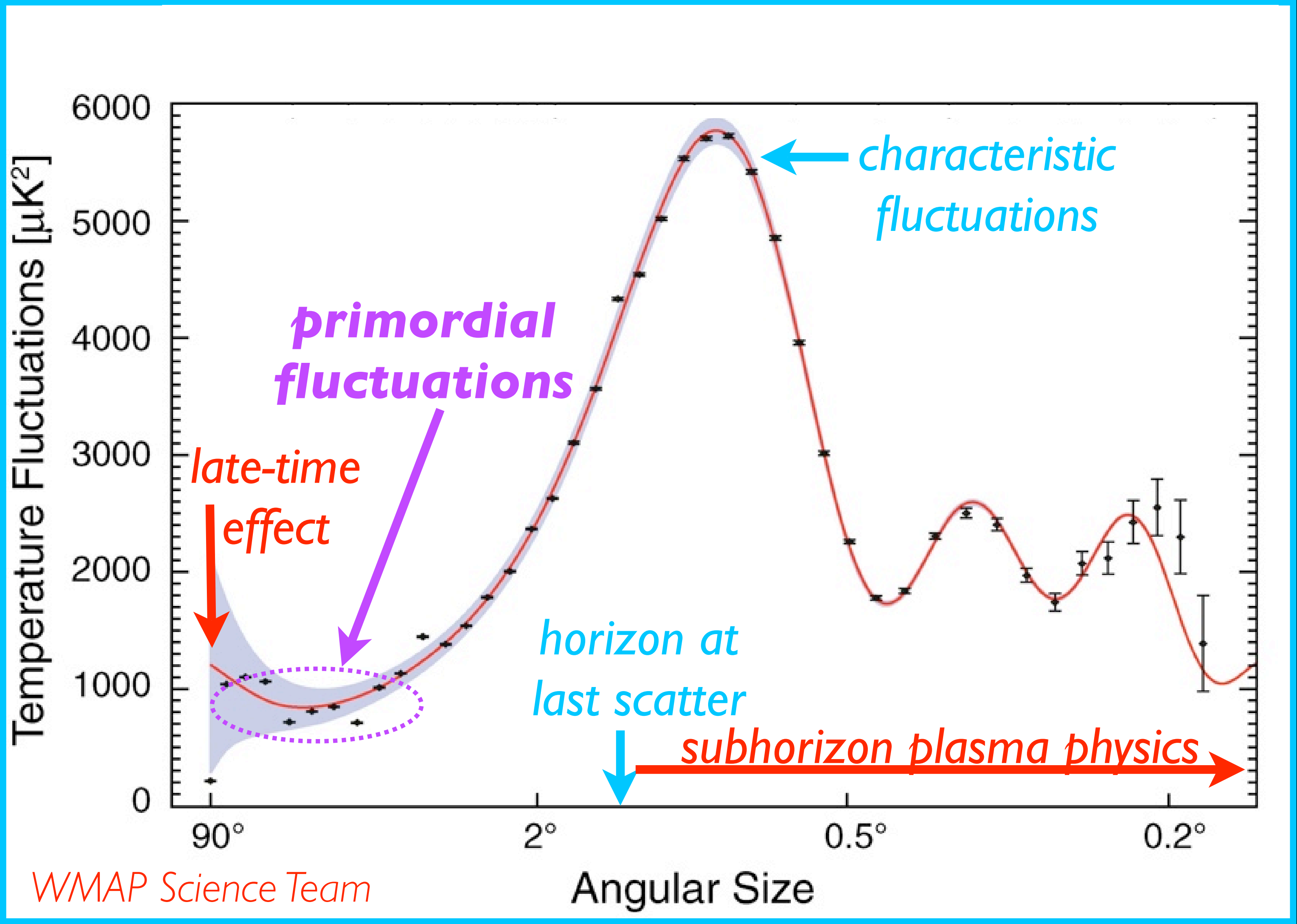

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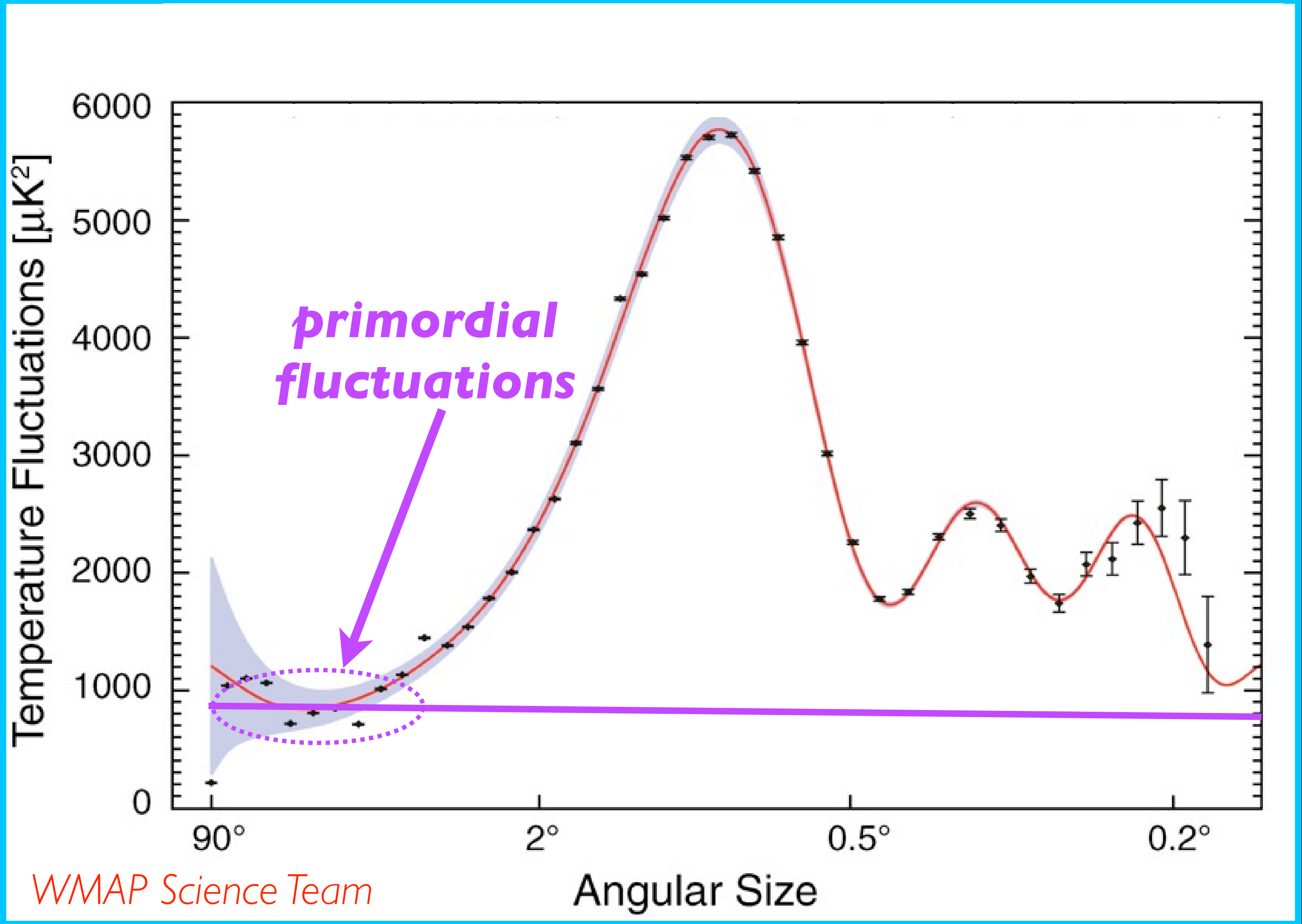

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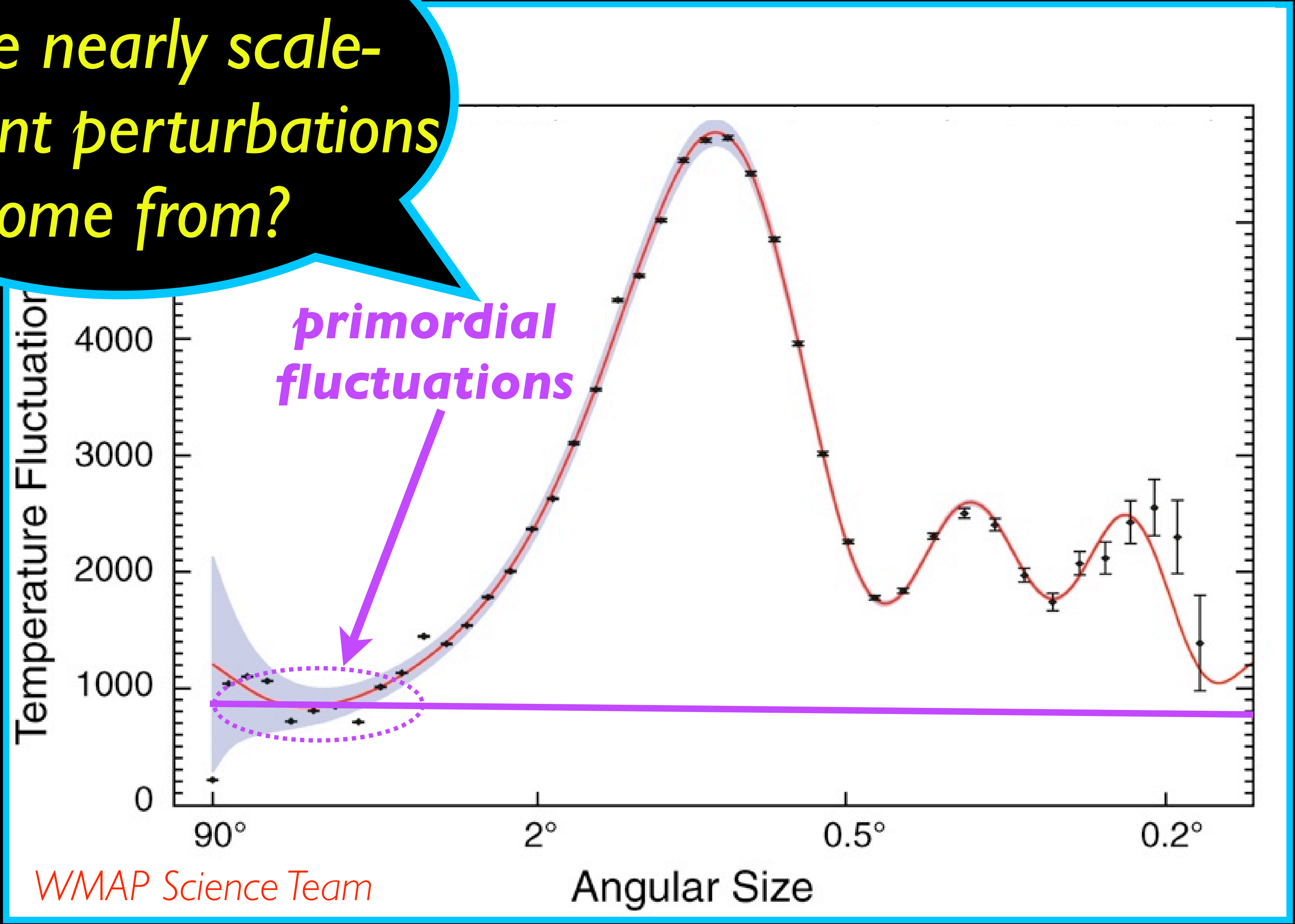
Mystery 3: Initial Fluctuations

Where did these nearly scale-invariant perturbations come from?

CMB Power Spectrum



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Mysteries of the CMB

Three big questions about the beginning of the Universe:

- Why is the CMB so homogeneous?
- Why is the Universe so flat?
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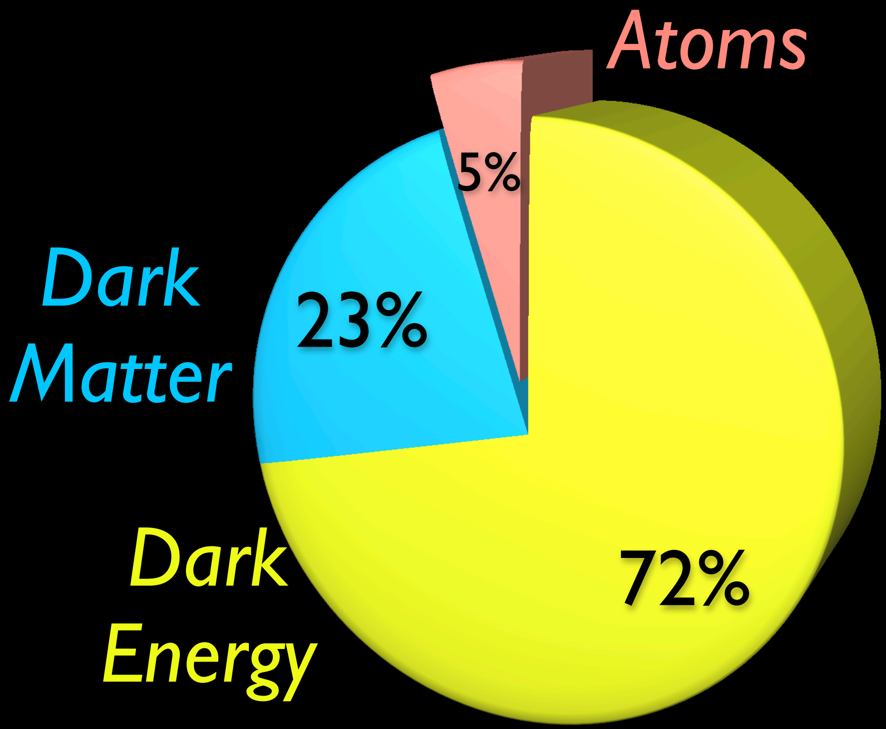
Breakdown of Energy in the Universe:



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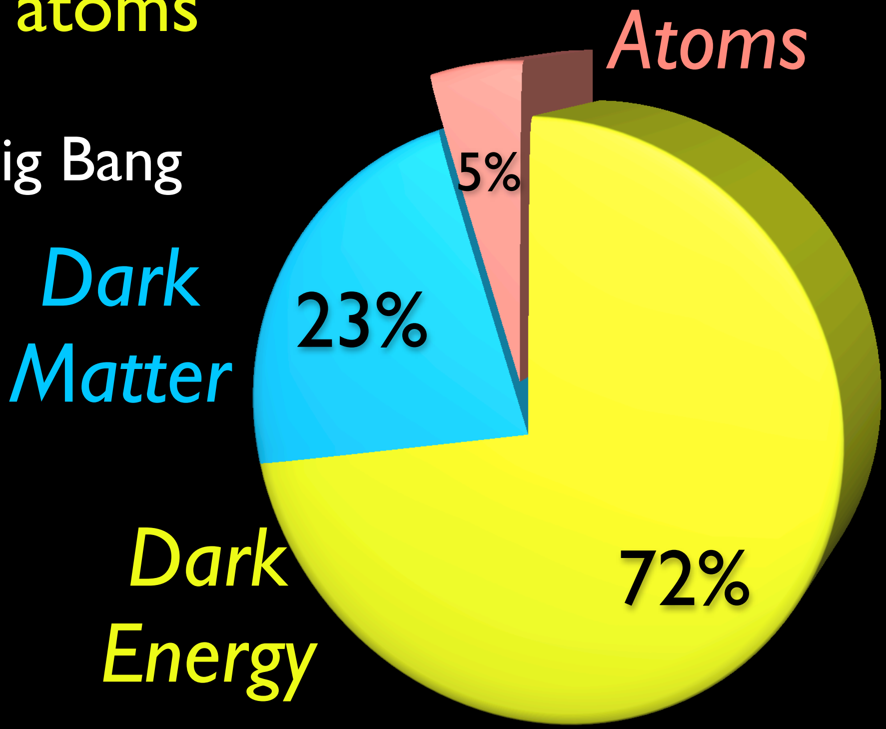
Breakdown of Energy in the Universe:

5% atomic matter: protons, electrons, atoms

- “stuff we know”
- supported by He produced 3 min. after Big Bang



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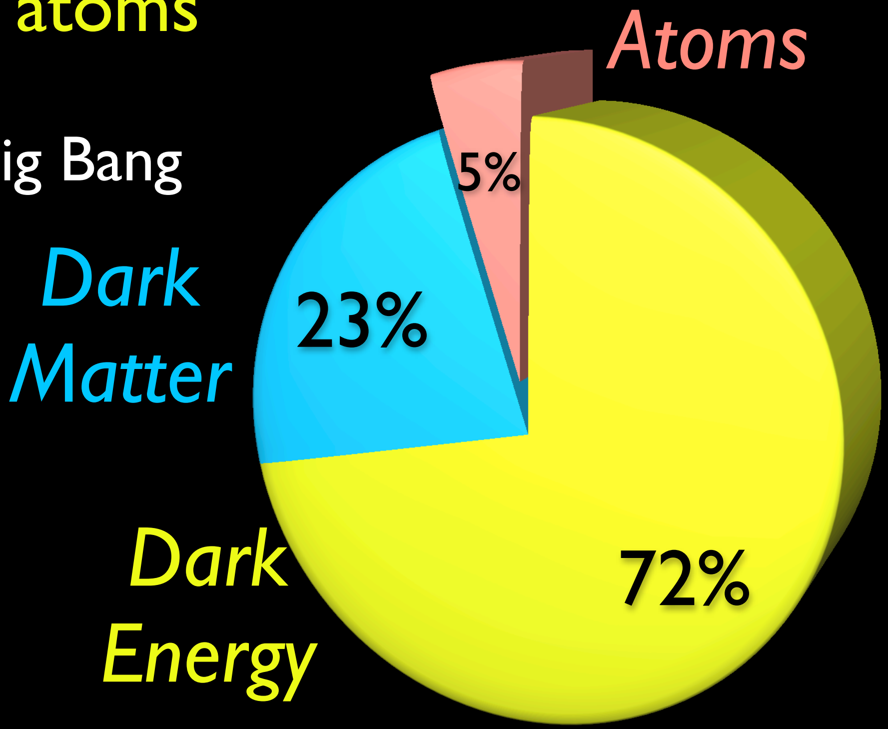
23% dark matter

- stable, neutral (at 3000 K) particle
- supported by galaxy motion



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- stable, neutral (at 3000 K) particle
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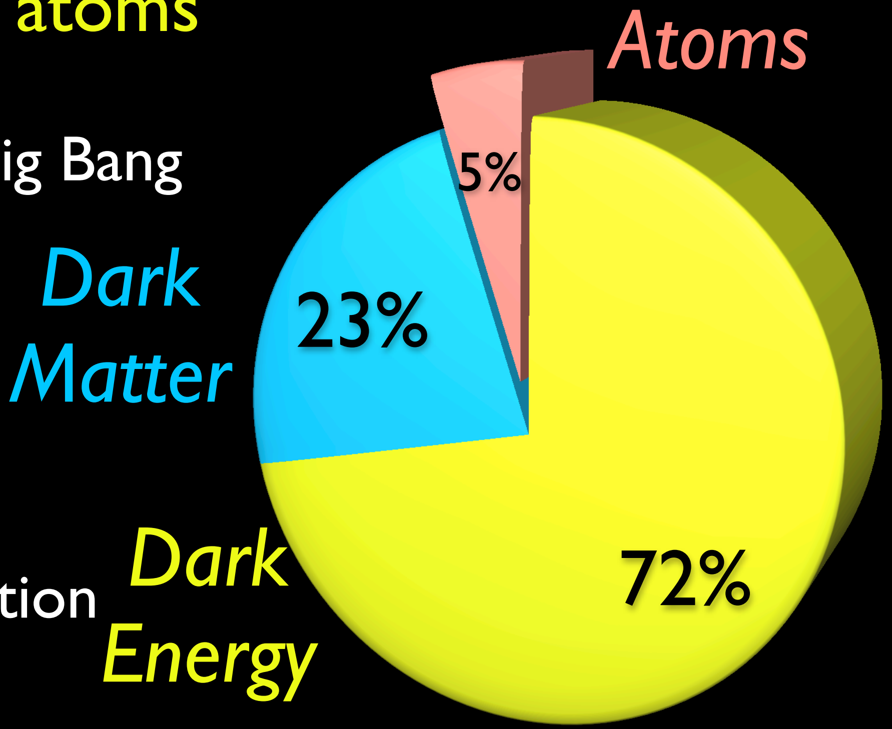
72% dark energy

- negative pressure causes cosmic acceleration
- supported by supernova observations

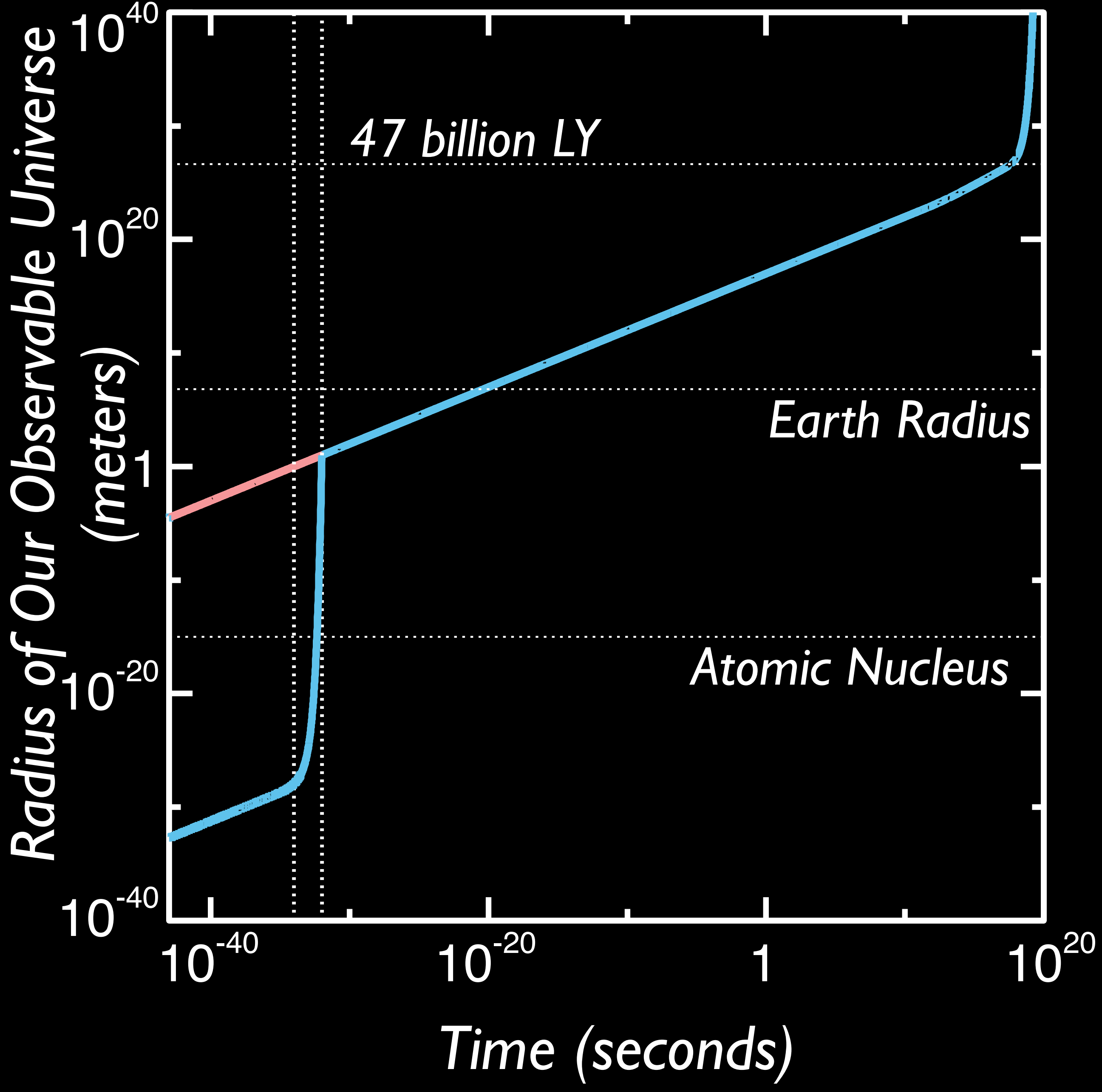


Inflation: Accelerated Expansion

The content of the Universe determines the expansion rate.

- radiation: $R(t) \propto \sqrt{t}$
- matter: $R(t) \propto t^{2/3}$

The expansion decelerates.



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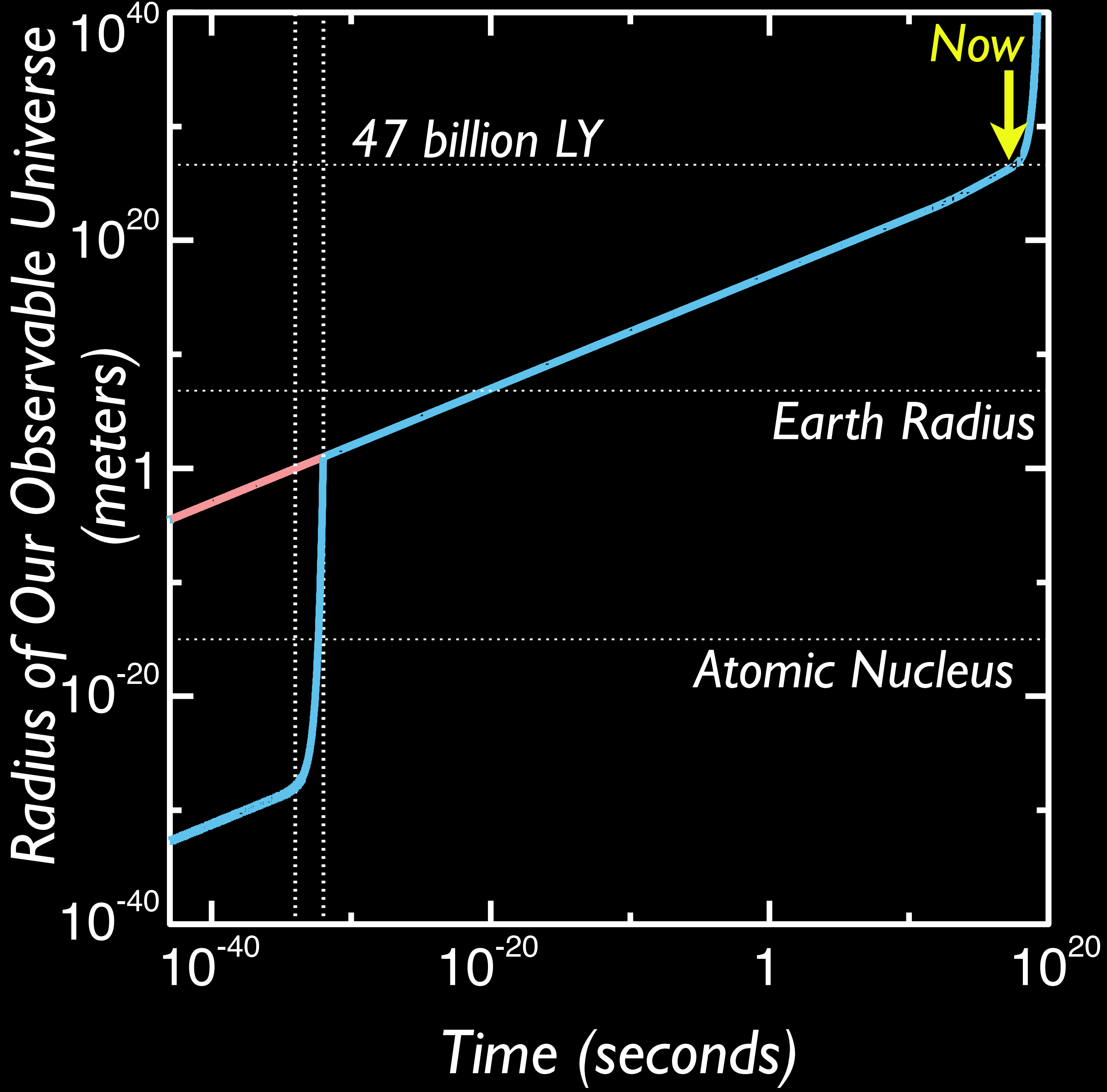

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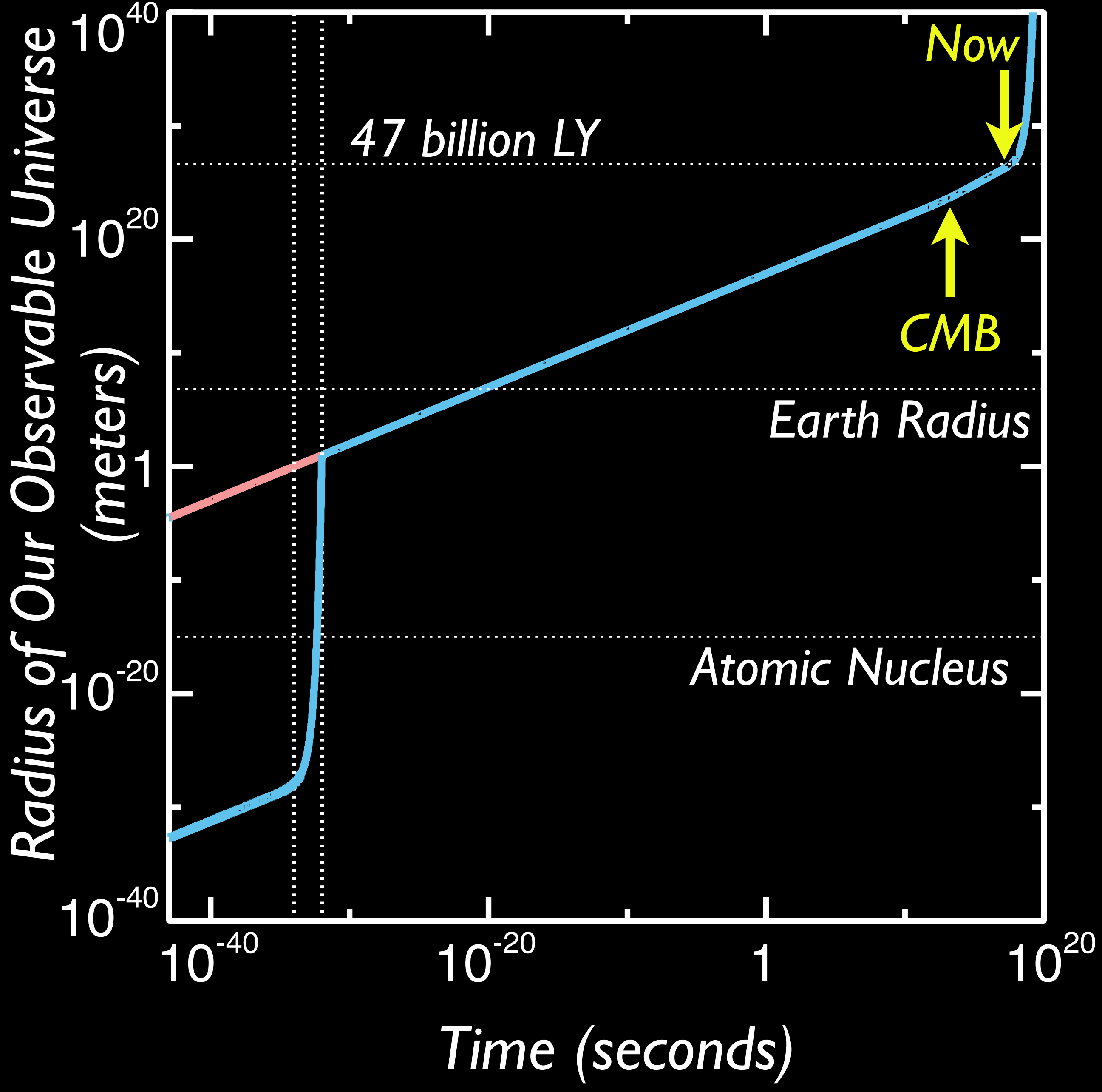

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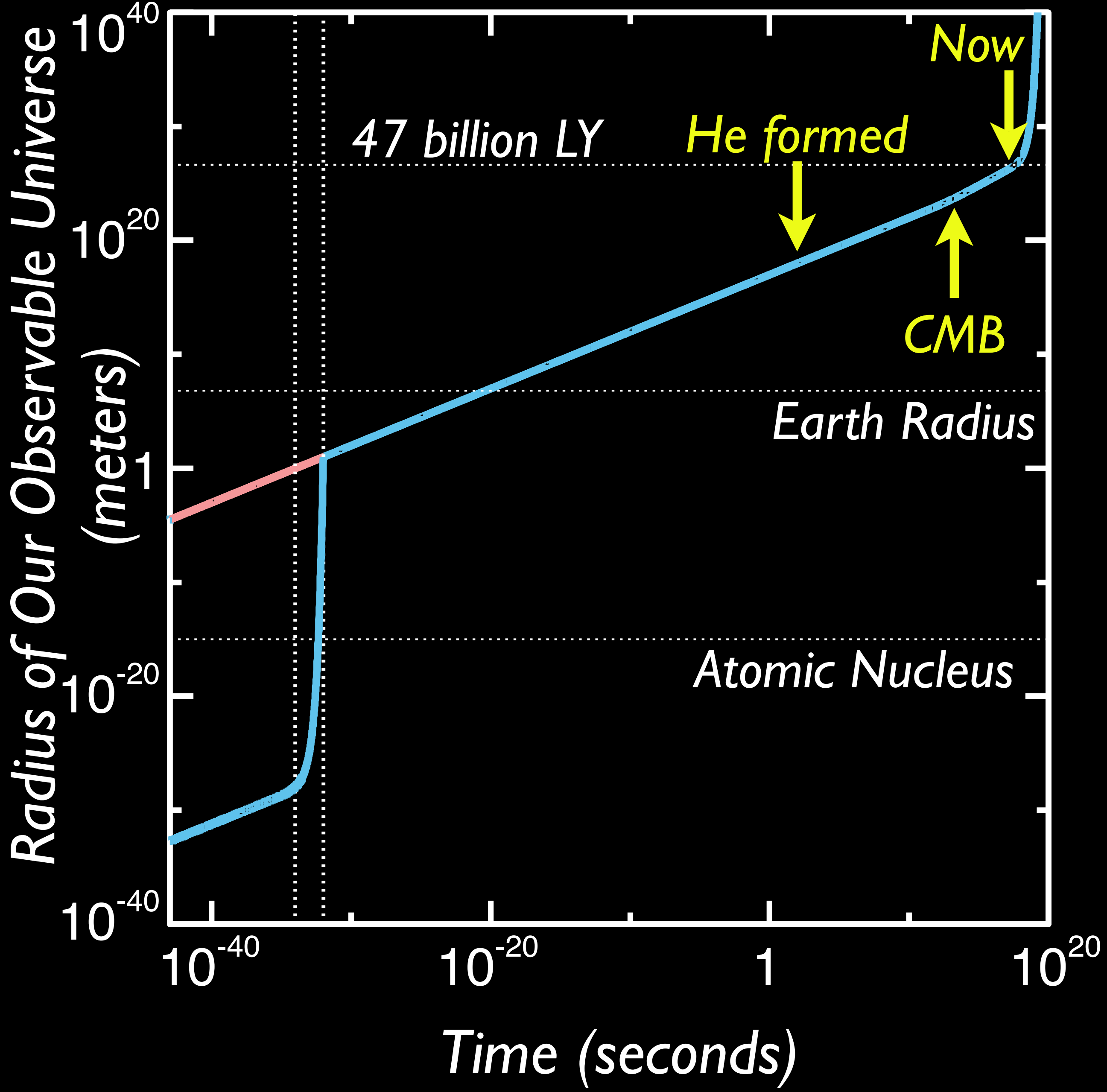

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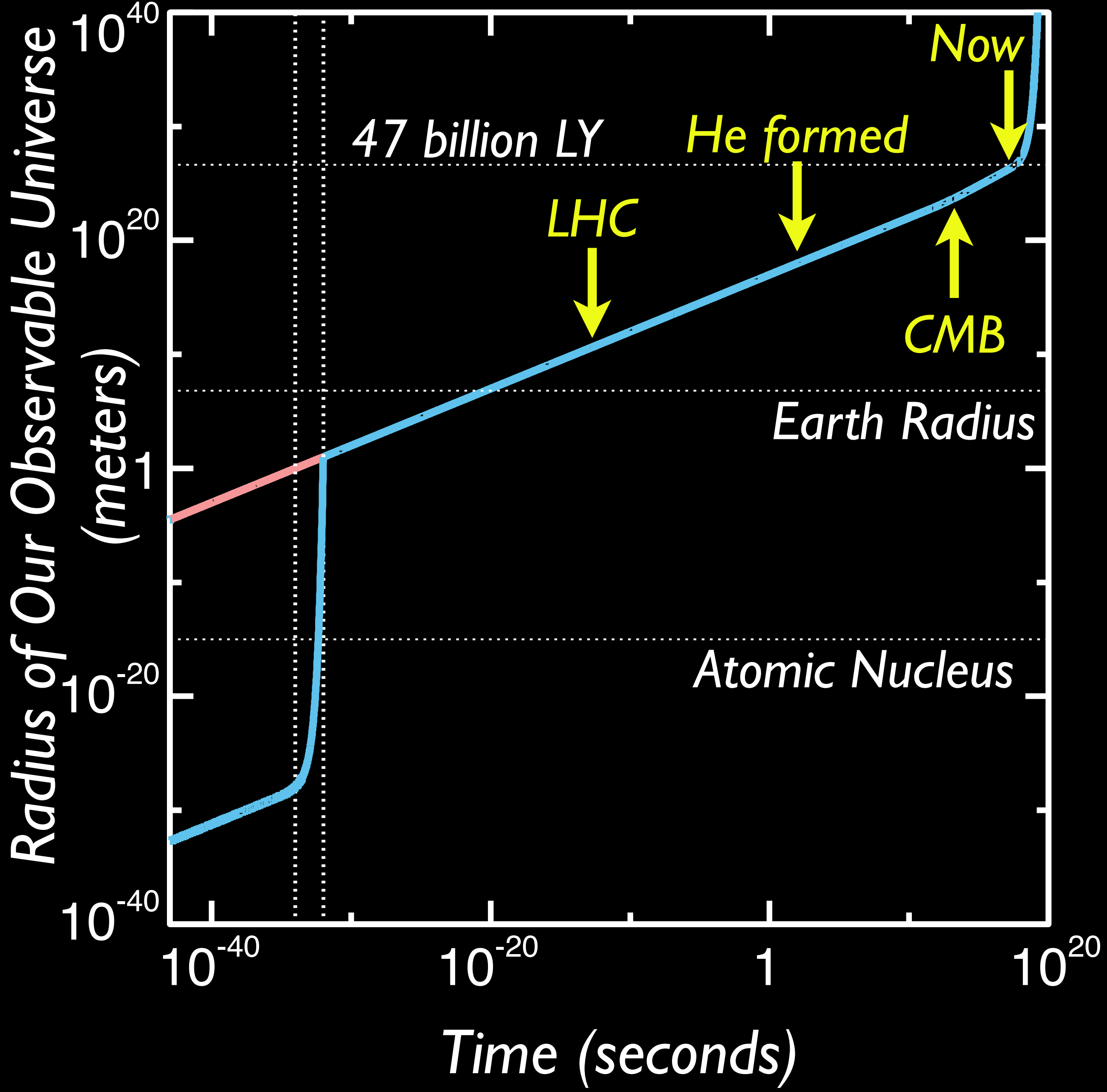

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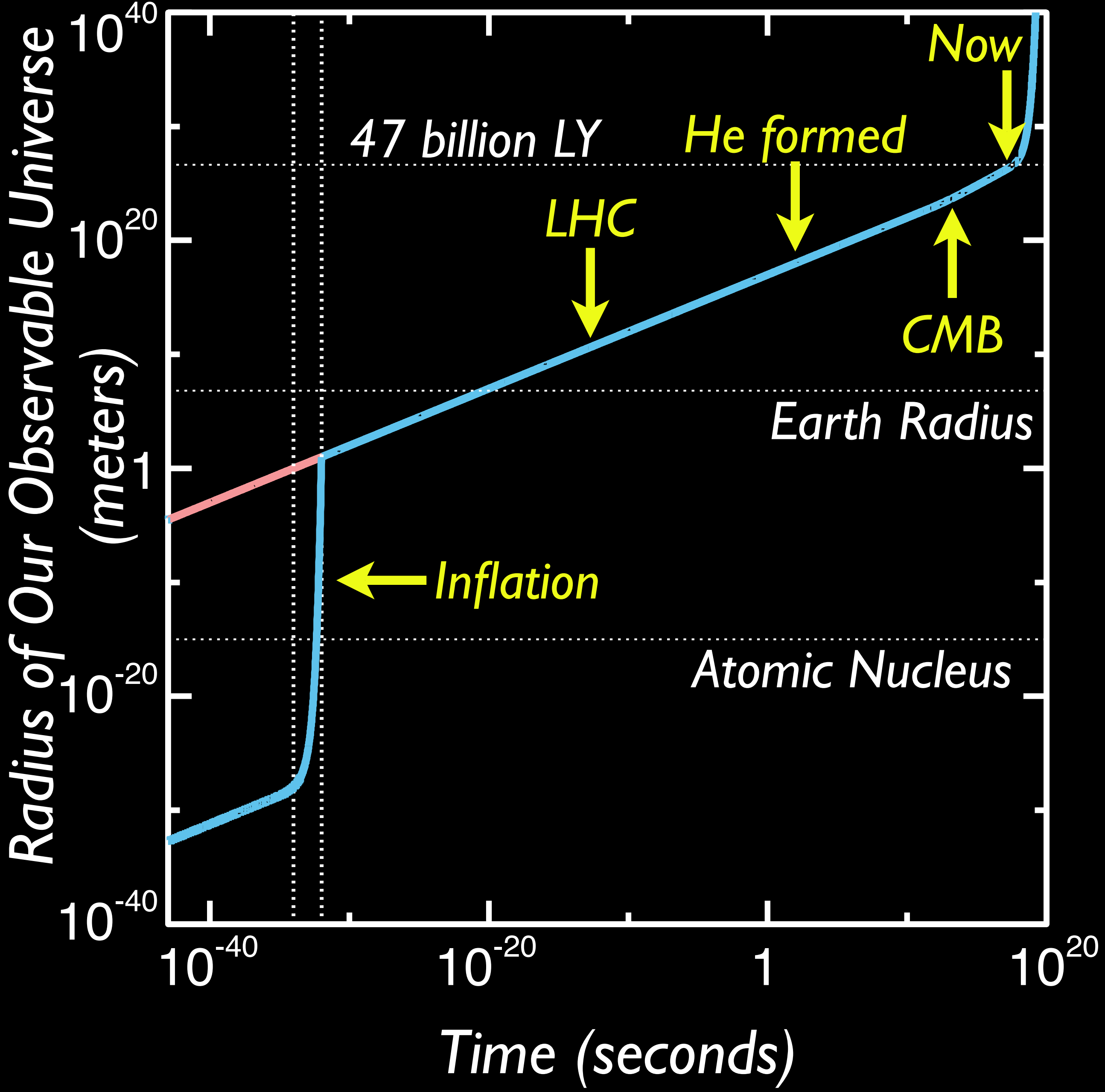
INFLATION

Alan Guth, 1981

The Universe's volume doubled at least 270 times *instantly*.



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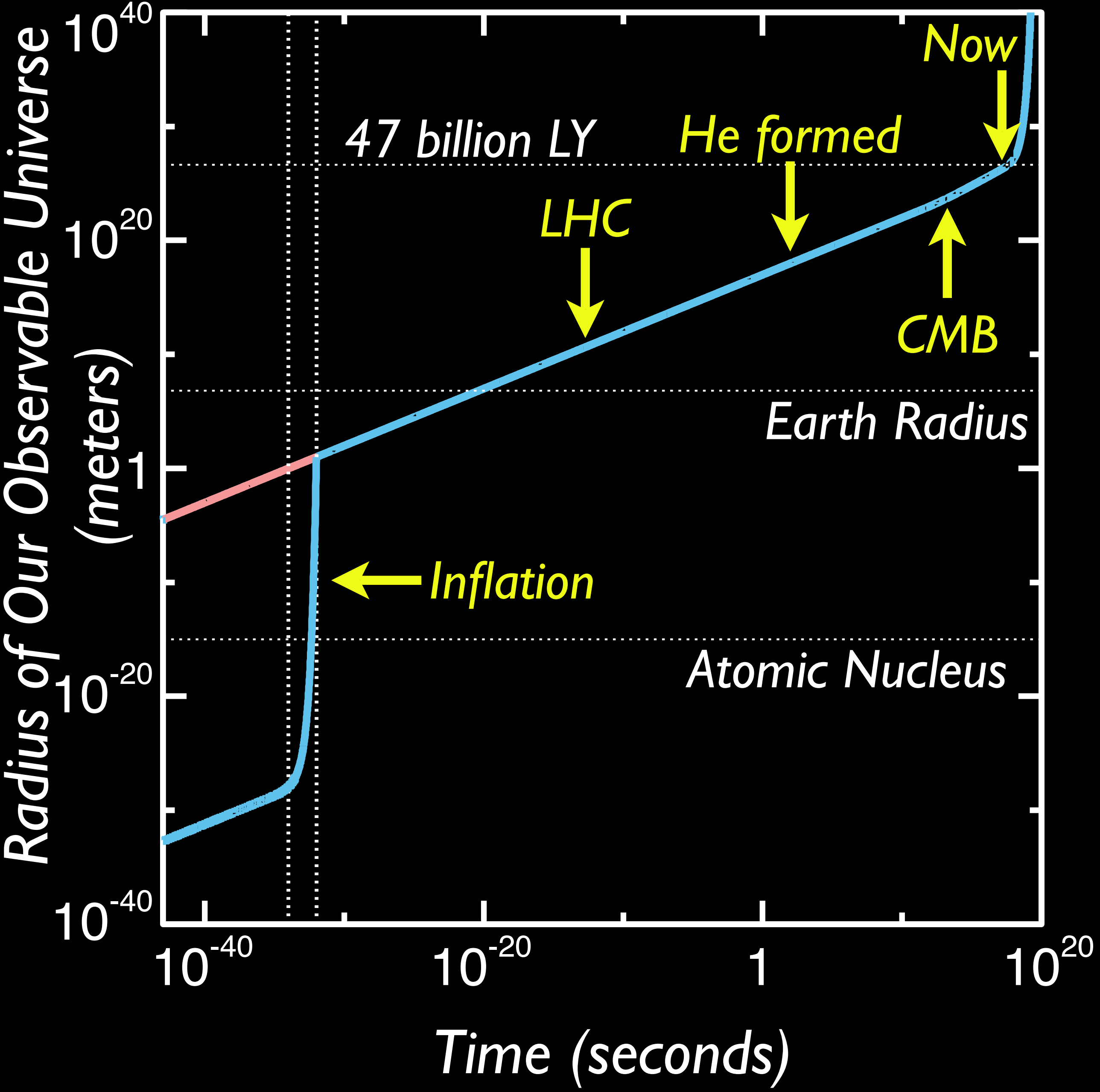
INFLATION

Alan Guth, 1981

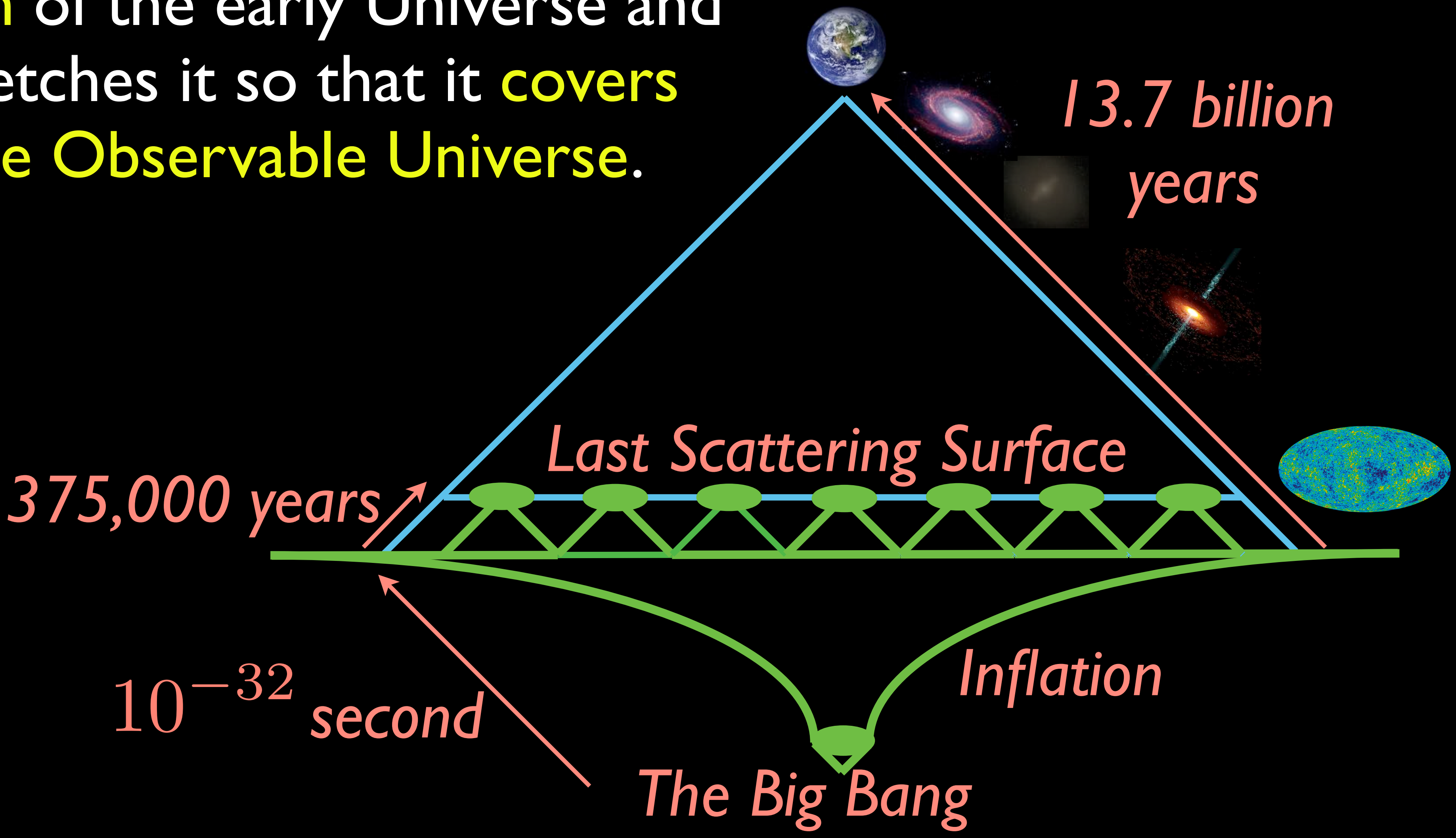
The Universe's volume doubled at least 270 times *instantly*.

- during inflation $R(t) \propto e^{Ht}$
- scalar field: energy density is not diluted by expansion.
- inflation ends when scalar field decays into radiation.

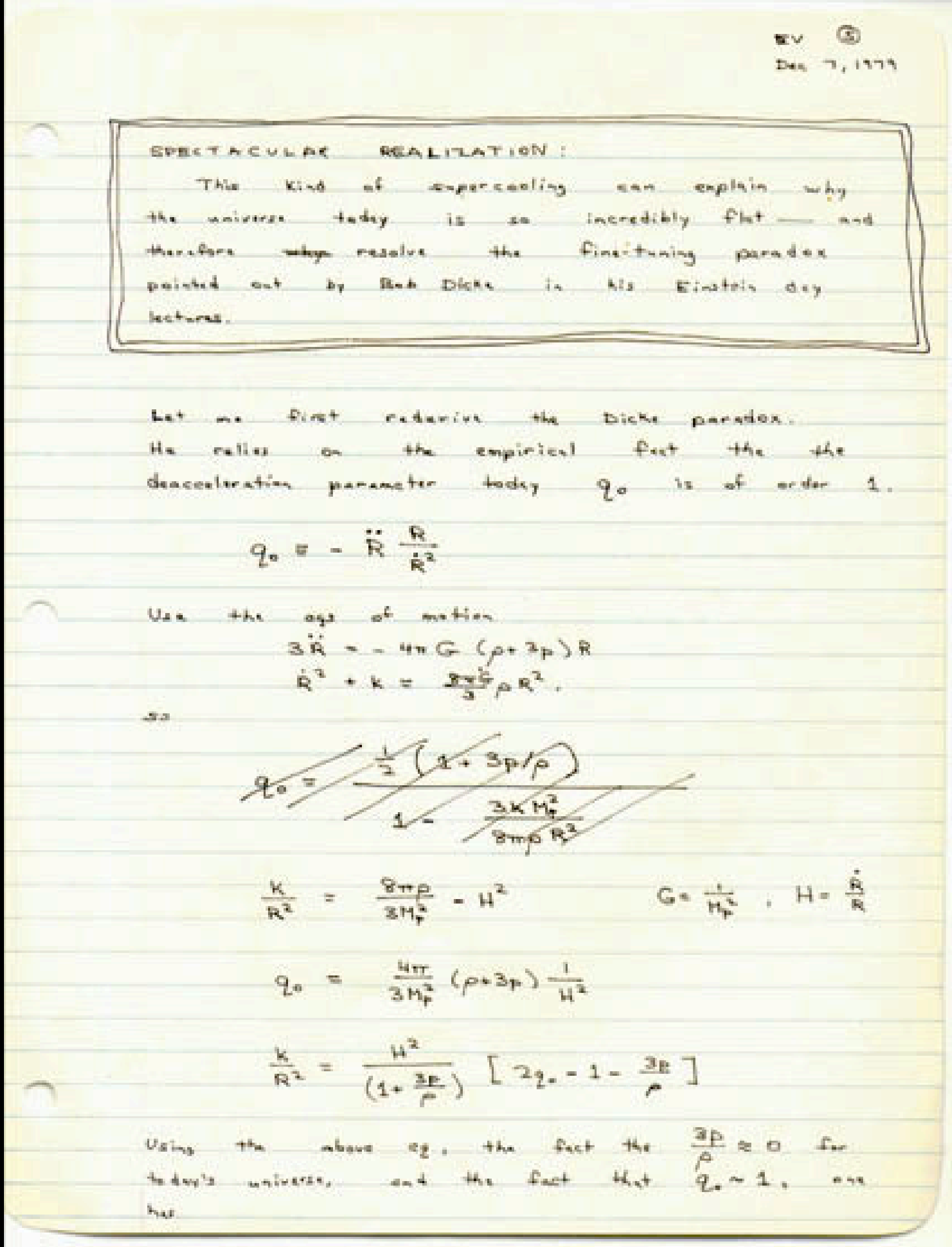


Inflation Solves the Horizon Problem

Inflation takes a tiny uniform patch of the early Universe and stretches it so that it covers the Observable Universe.



Inflation Solves the Flatness Problem



EV ③
Dec 7, 1979

SPECTACULAR REALIZATION:

This kind of supercooling can explain why the universe today is so incredibly flat — and therefore ~~[illegible]~~ resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deacceleration parameter today q_0 is of order 1.

$$q_0 \equiv - \ddot{R}\frac{R}{\dot{R}^2}$$

Use the eqs of motion

$$3\ddot{R} = -4\pi G(\rho + 3p)R$$
$$\dot{R}^2 + k = \frac{8\pi G}{3}\rho R^2 .$$

so

$$\cancel{q_0 = \frac{\frac{1}{2}\left(1 + 3p/\rho\right)}{1 - \frac{3kM_p^2}{8\pi\rho R^2}}}$$

$$\frac{k}{R^2} = \frac{8\pi\rho}{3M_p^2} - H^2 \qquad G = \frac{1}{M_p^2}, \quad H = \frac{\dot{R}}{R}$$

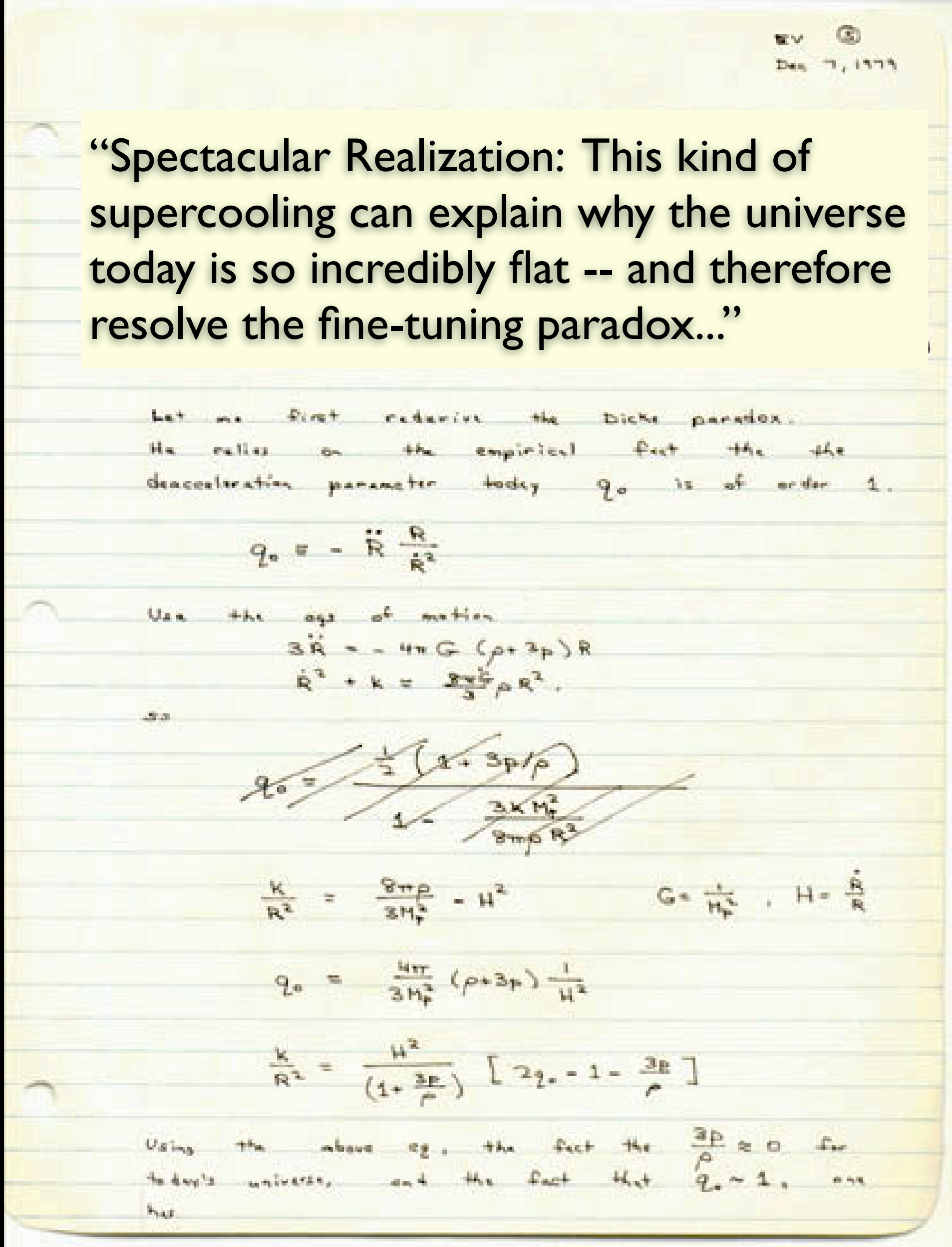
$$q_0 = \frac{4\pi}{3M_p^2}(\rho + 3p)\frac{1}{H^2}$$

$$\frac{k}{R^2} = \frac{H^2}{\left(1 + \frac{3p}{\rho}\right)}\left[2q_0 - 1 - \frac{3p}{\rho}\right]$$

Using the above eq., the fact the $\frac{3p}{\rho} \approx 0$ for today's universe, and the fact that $q_0 \sim 1$, one has

Alan Guth's Notebook: December 7, 1979.

Inflation Solves the Flatness Problem



“Spectacular Realization: This kind of supercooling can explain why the universe today is so incredibly flat -- and therefore resolve the fine-tuning paradox...”

EV ③
Dec 7, 1979

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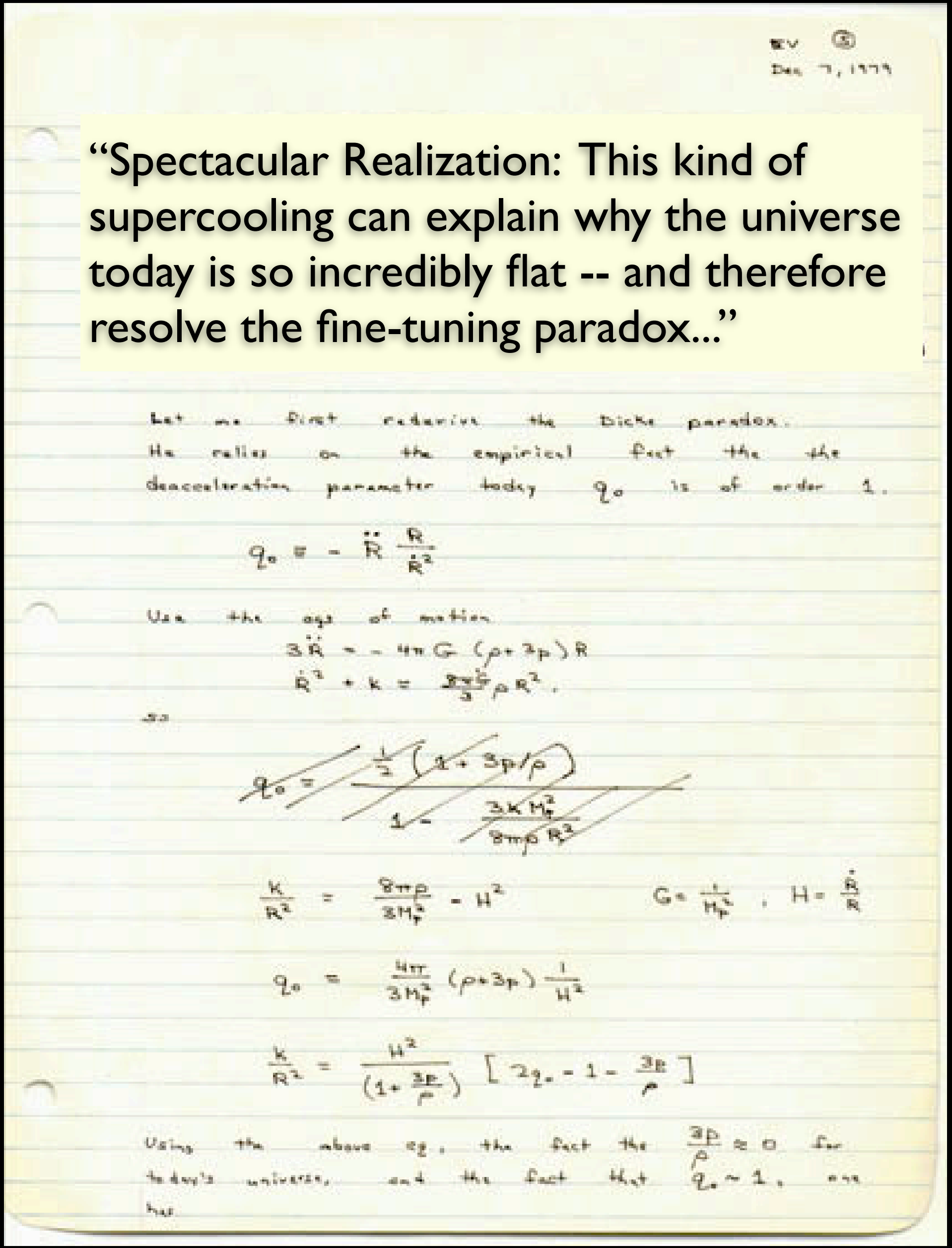

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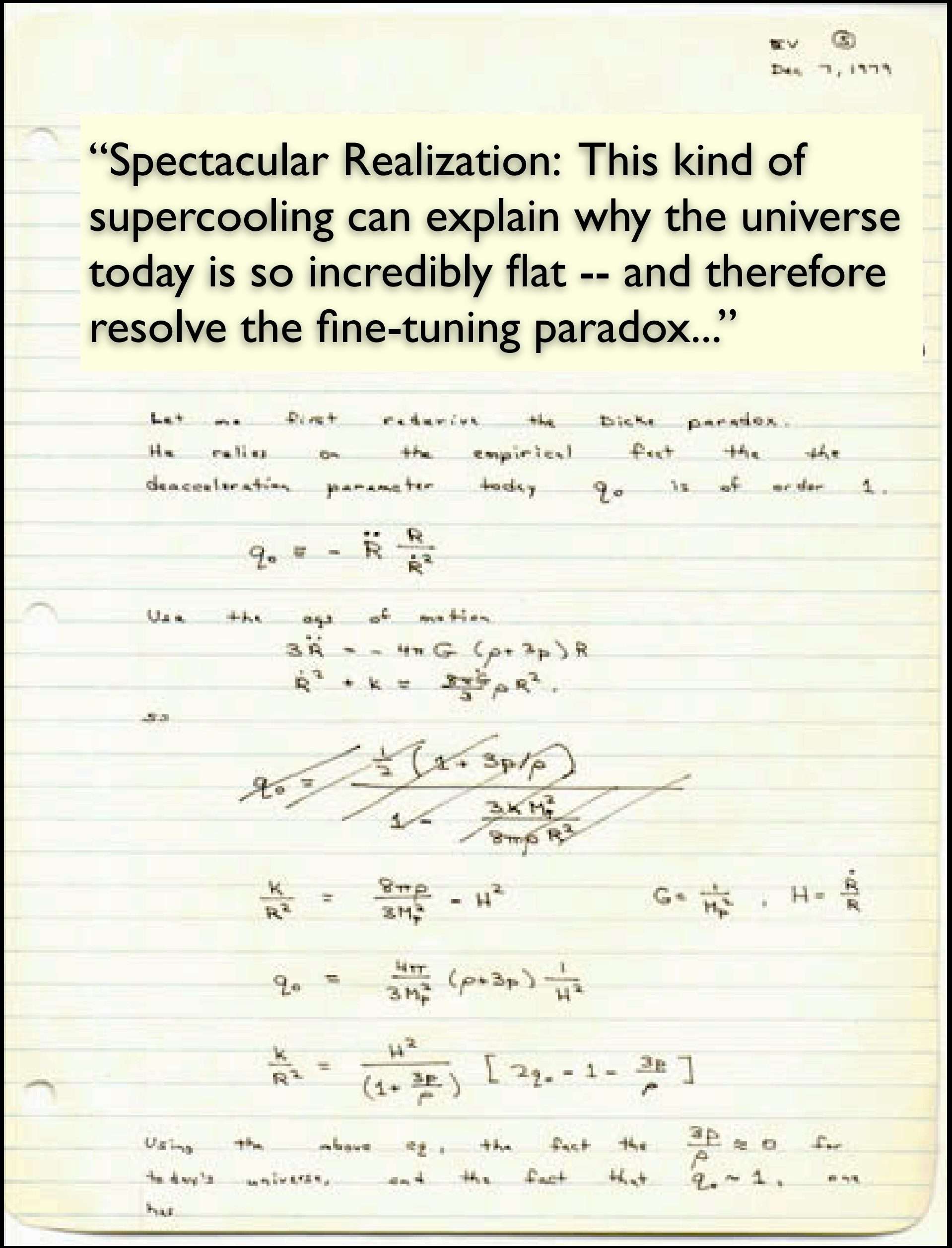

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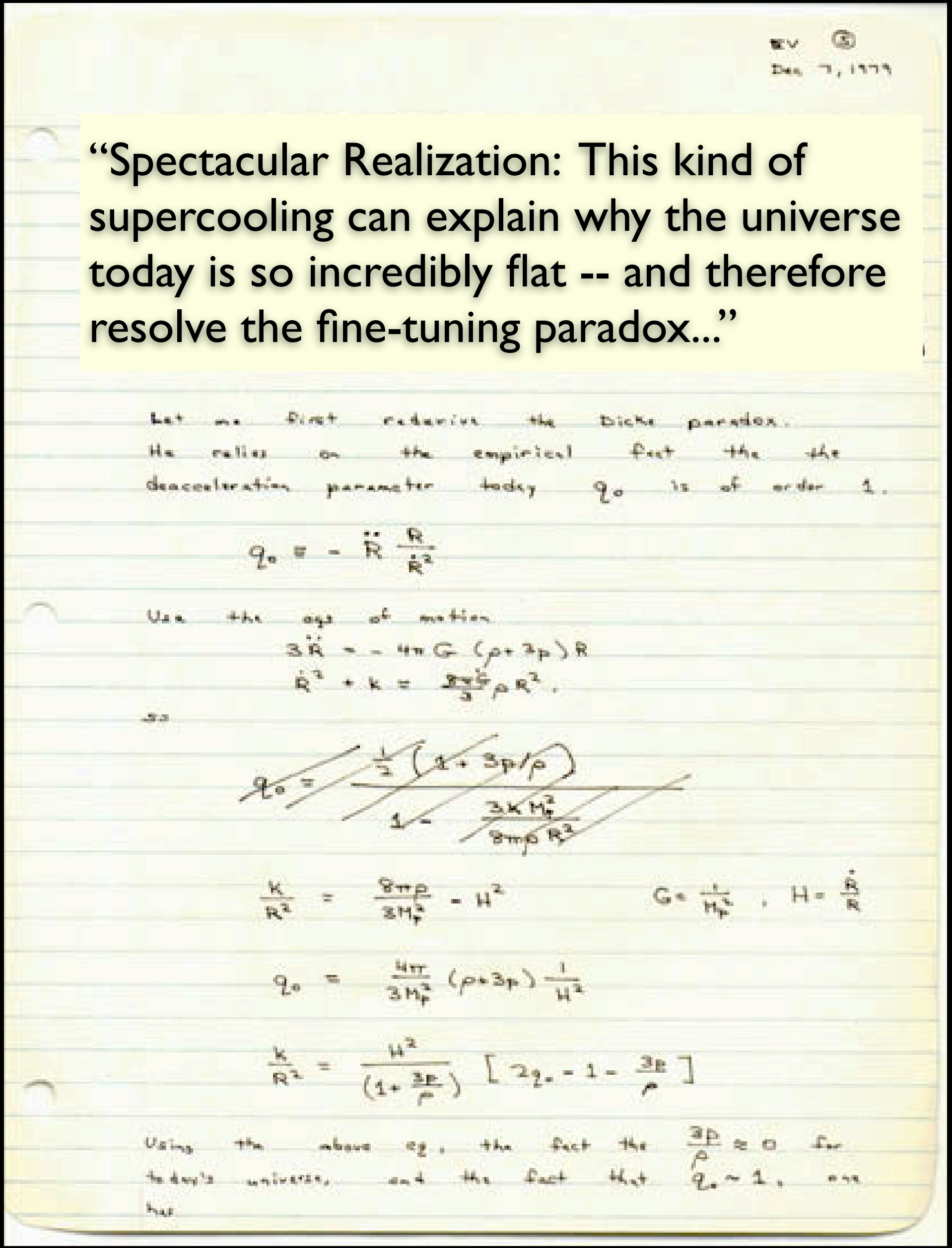

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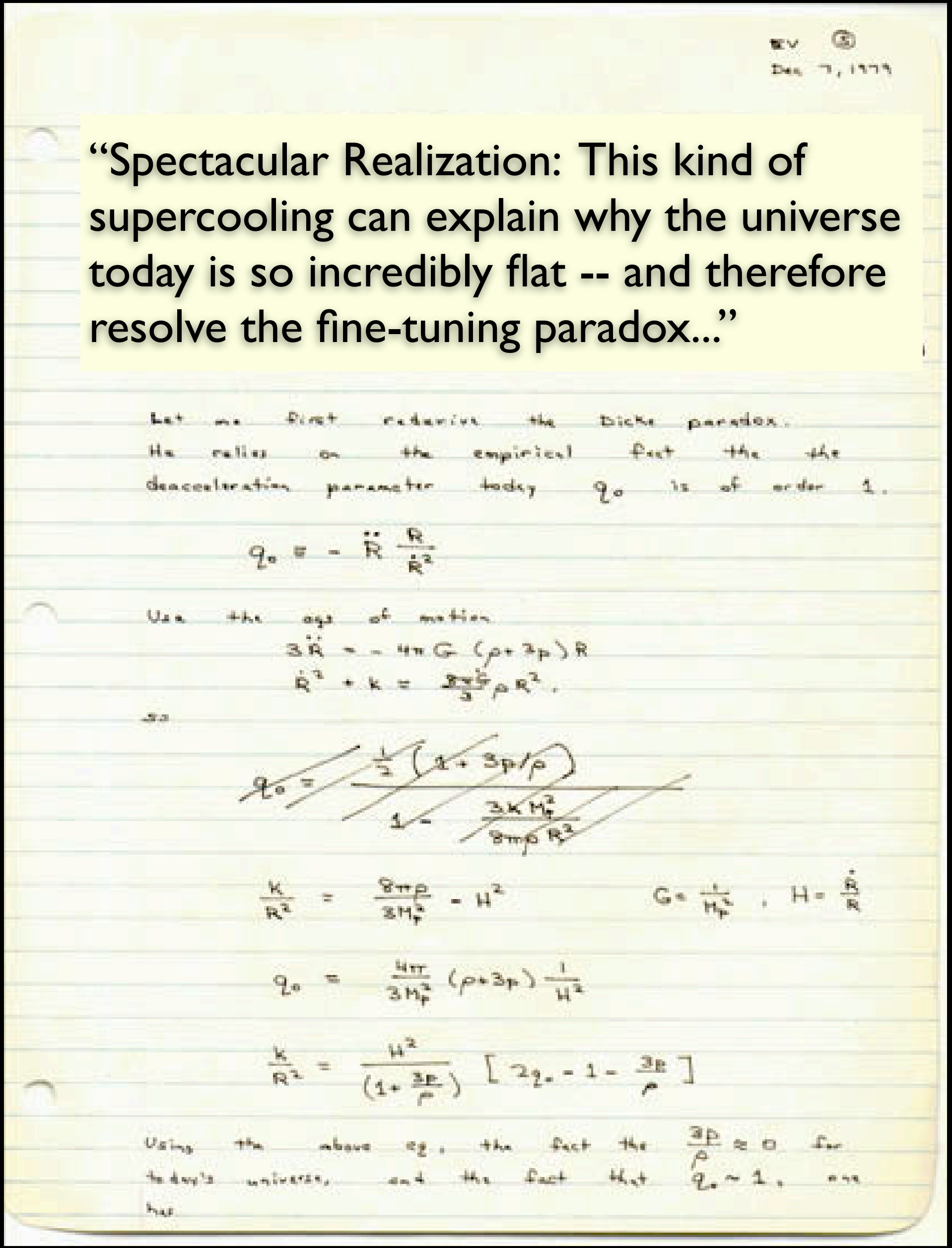

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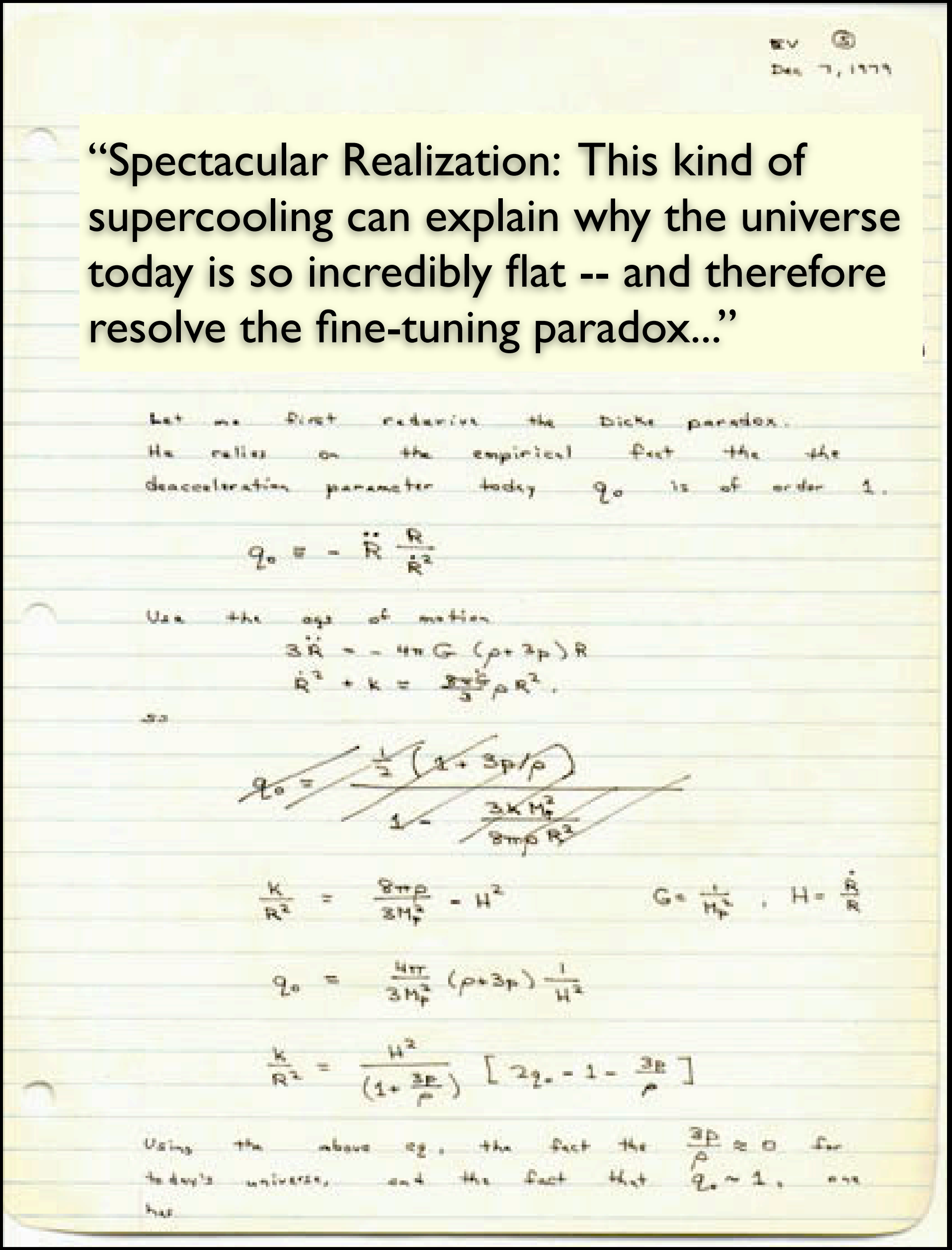

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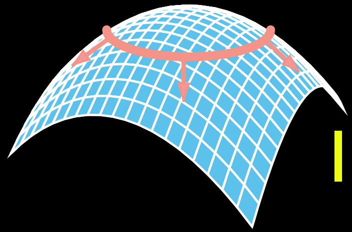
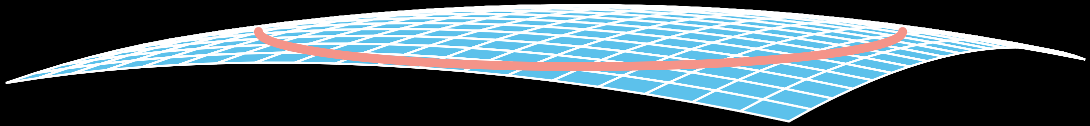
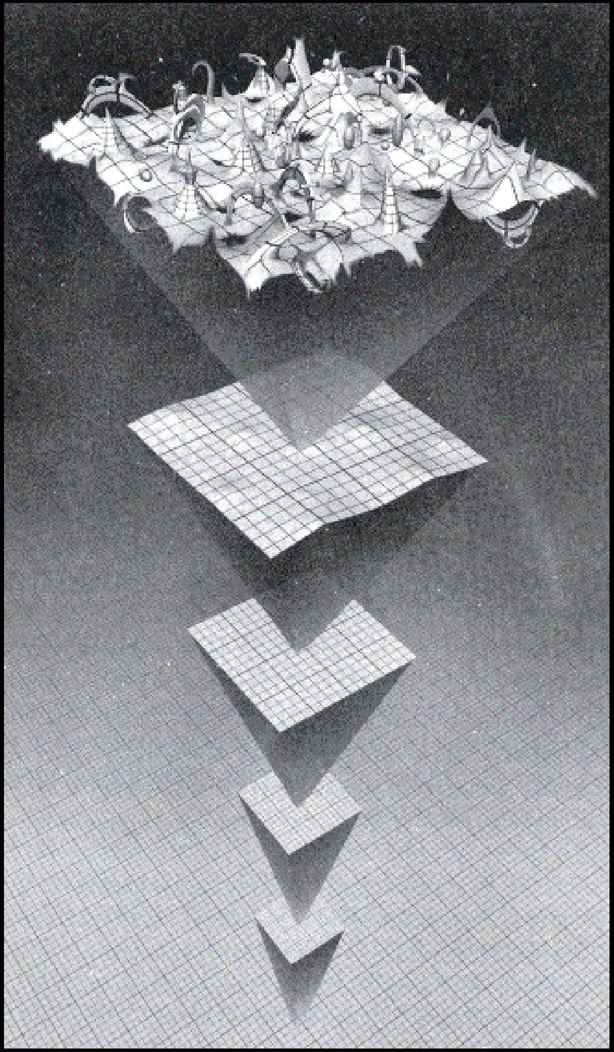


Inflation makes curved universes flat!



The Origin of Initial Fluctuations

The energy density during inflation is not uniform; quantum fluctuations lead to hot and cold regions.



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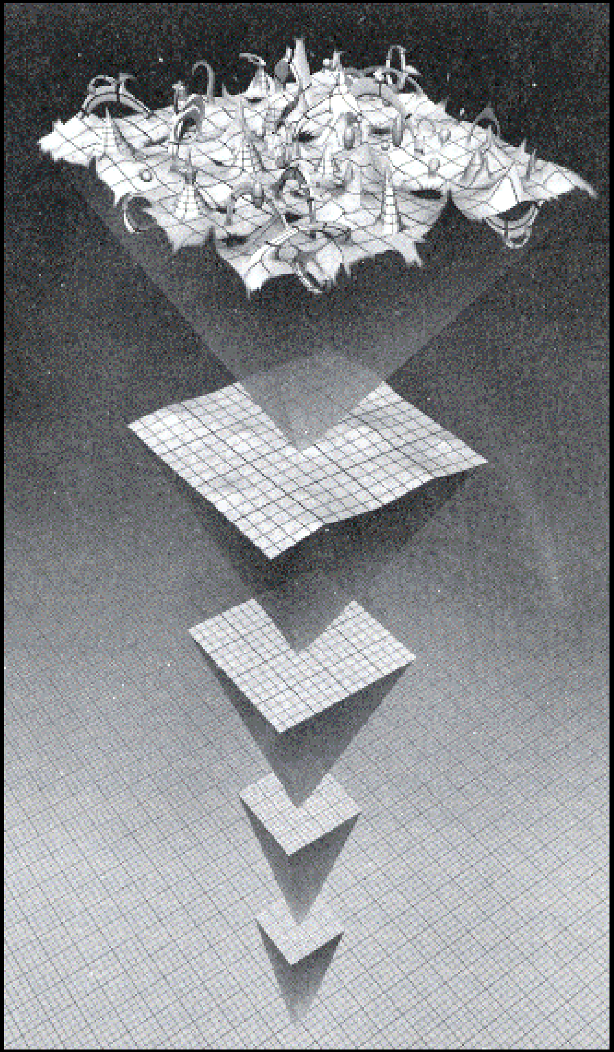

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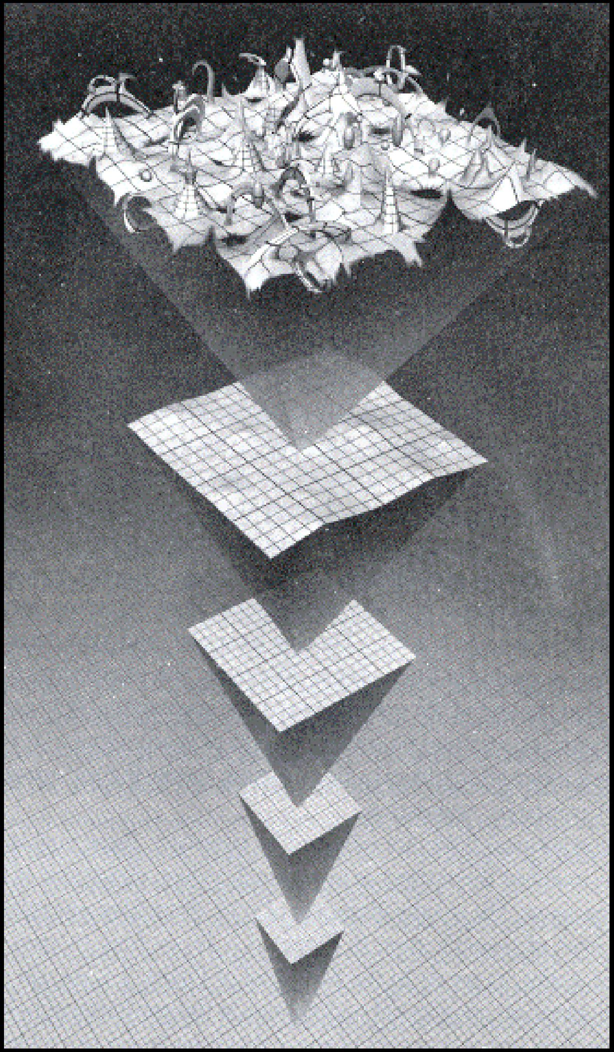

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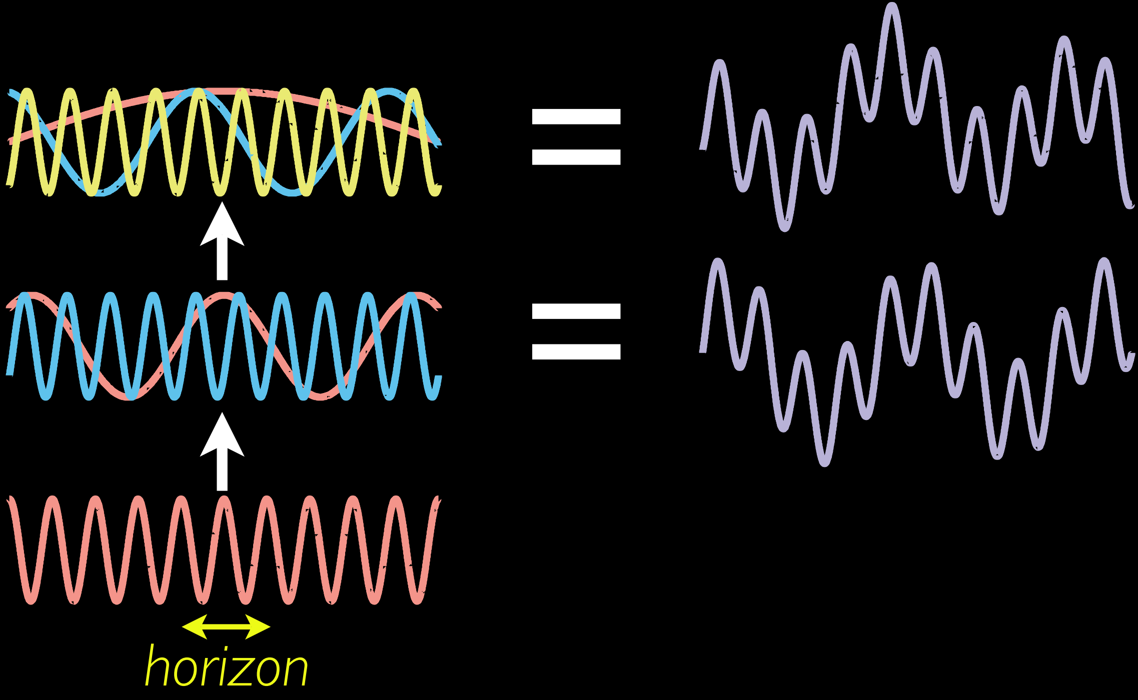

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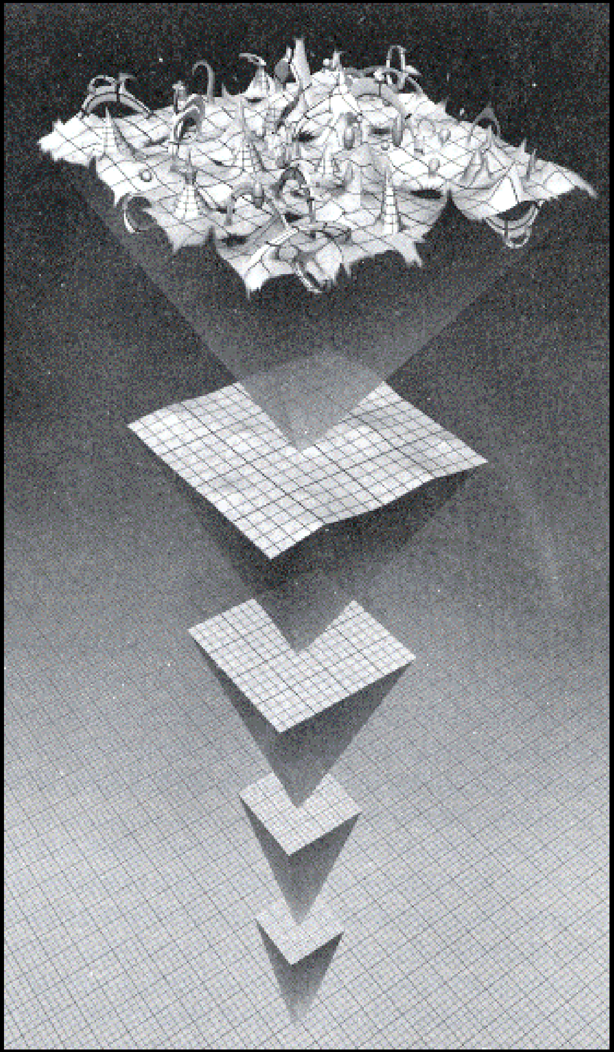

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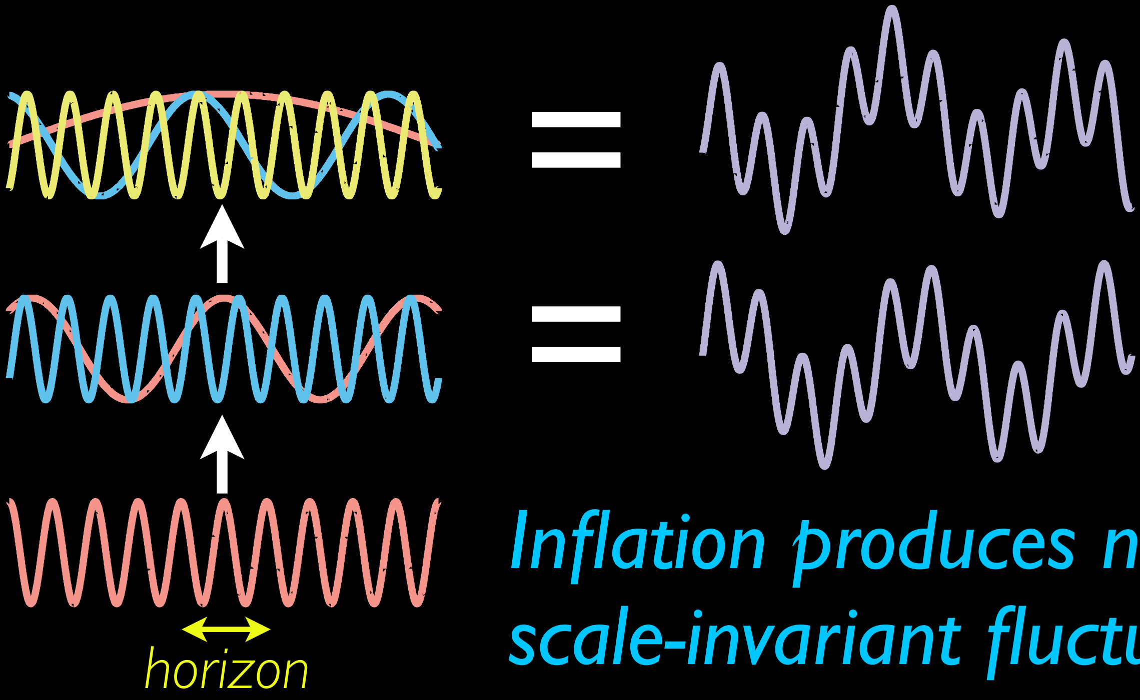
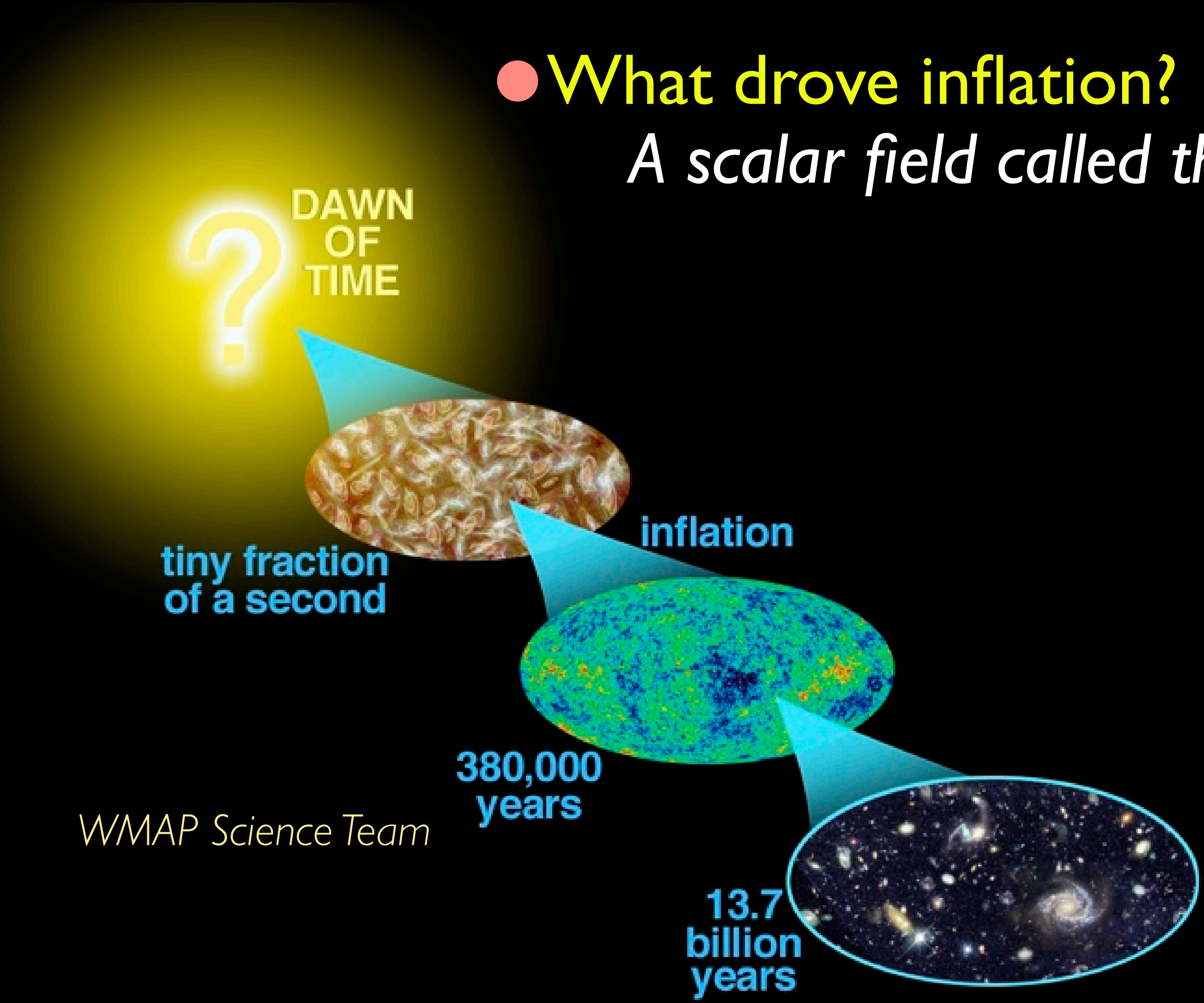


Inflation produces nearly scale-invariant fluctuations!

Unanswered Questions

- What drove inflation?

  A scalar field called the inflaton...



WMAP Science Team

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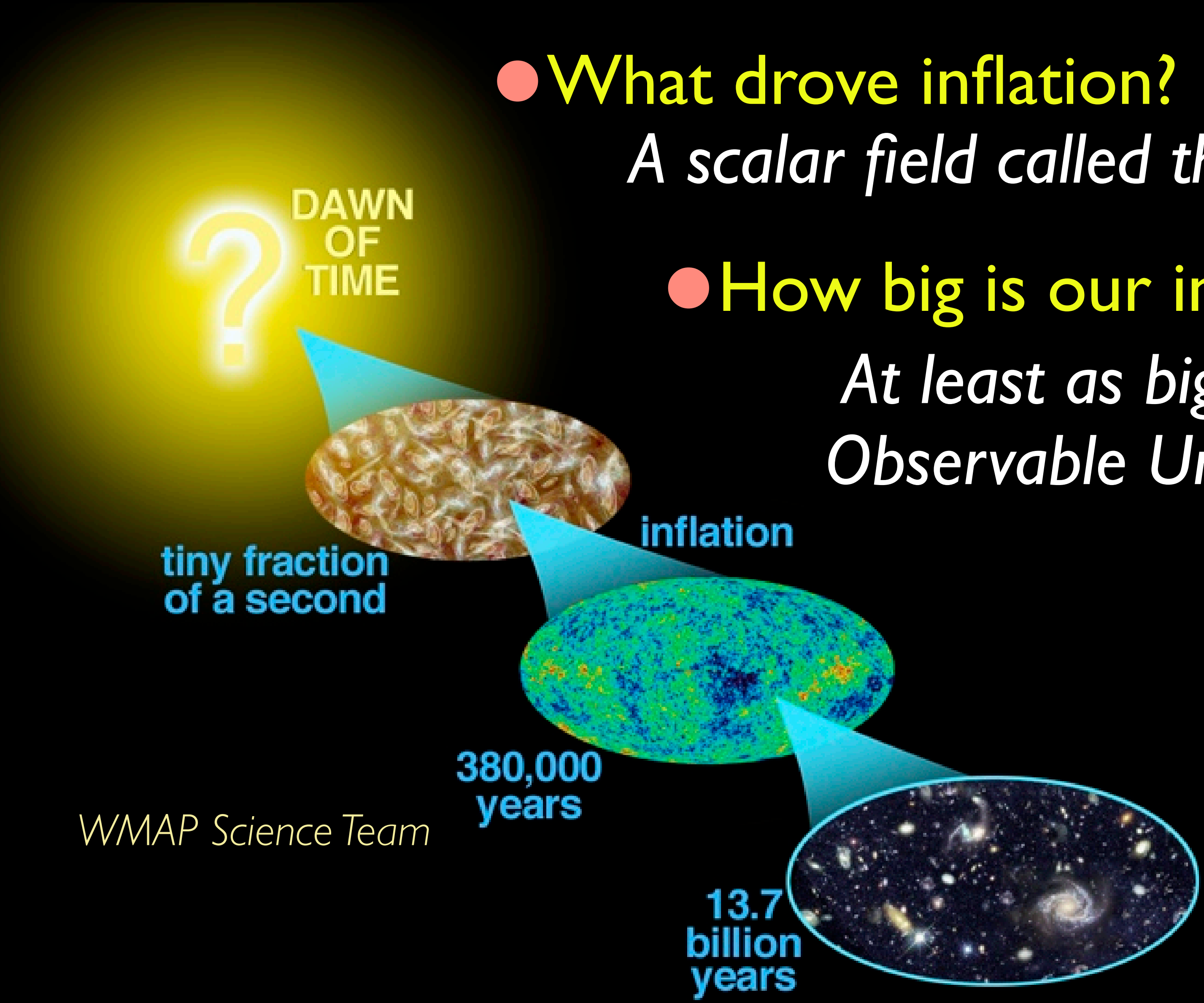
  At least as big as the Observable Universe...



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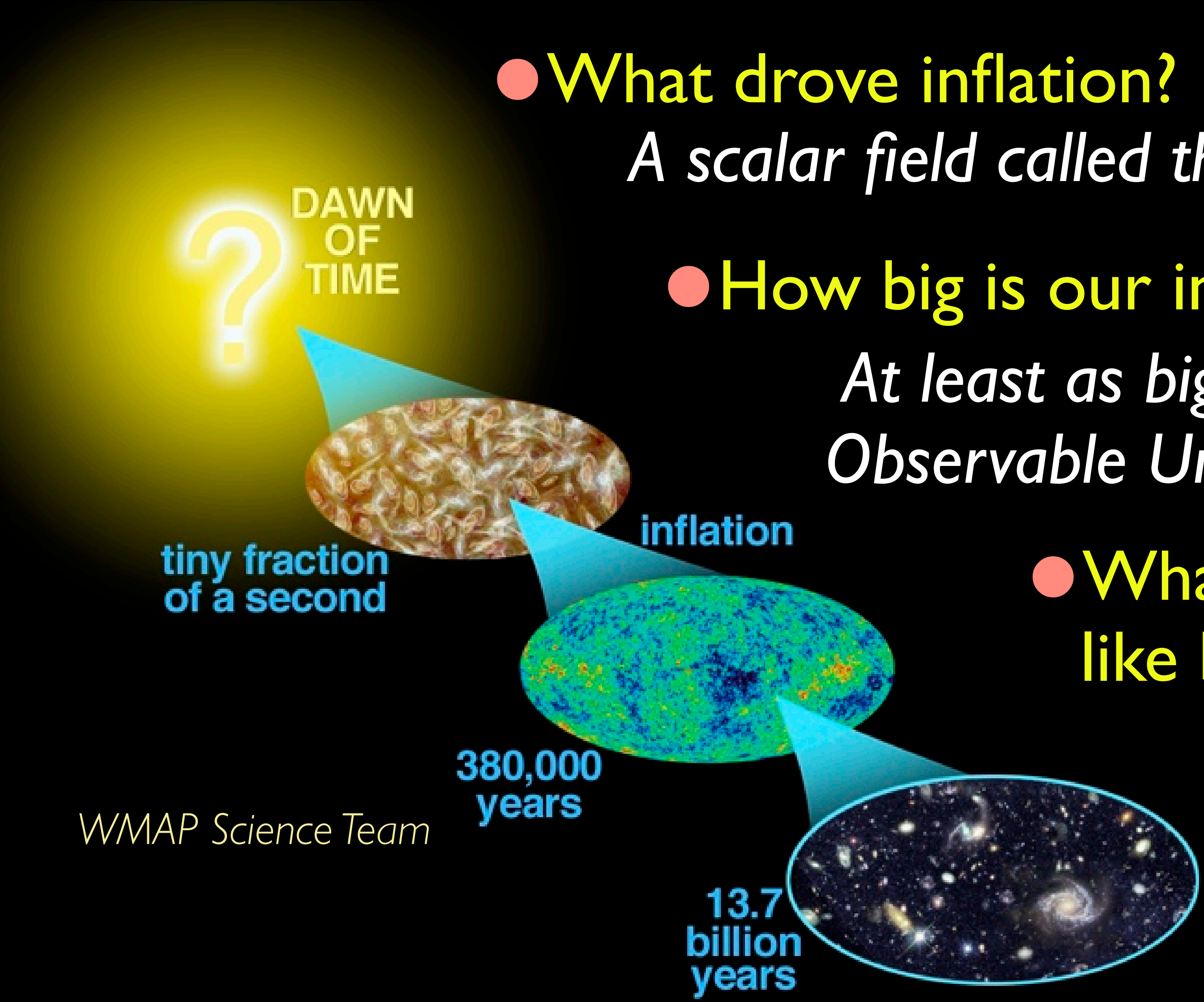

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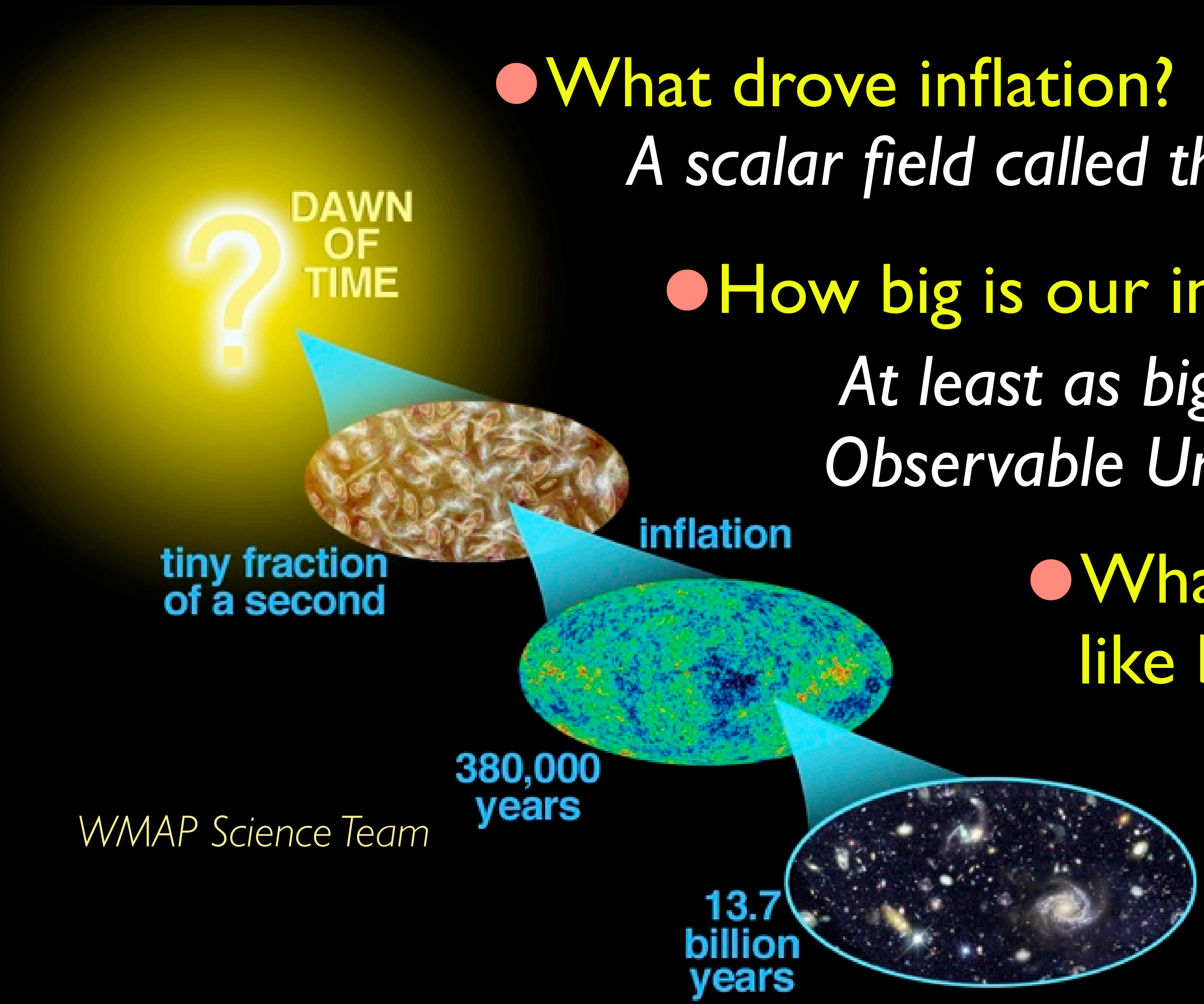

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The answers are lurking beyond the cosmological horizon.

Part 2: An Asymmetric Universe

I. Power Asymmetry from Superhorizon Structure

- What power asymmety?
- How can we make one?

II. Superhorizon Structure and the CMB

- How would we see superhorizon structure?
- Bad news...

III. A Power Asymmetry from the Curvaton

- What is a curvaton anyway?
- Does this model work?
- How do we test this model further?

An Asymmetric Universe!

The mean fluctuation amplitude in the CMB on large angular scales $(\theta > 4^\circ)$ is asymmetric!

Eriksen, Hansen, Banday, Gorski, Lilje 2004
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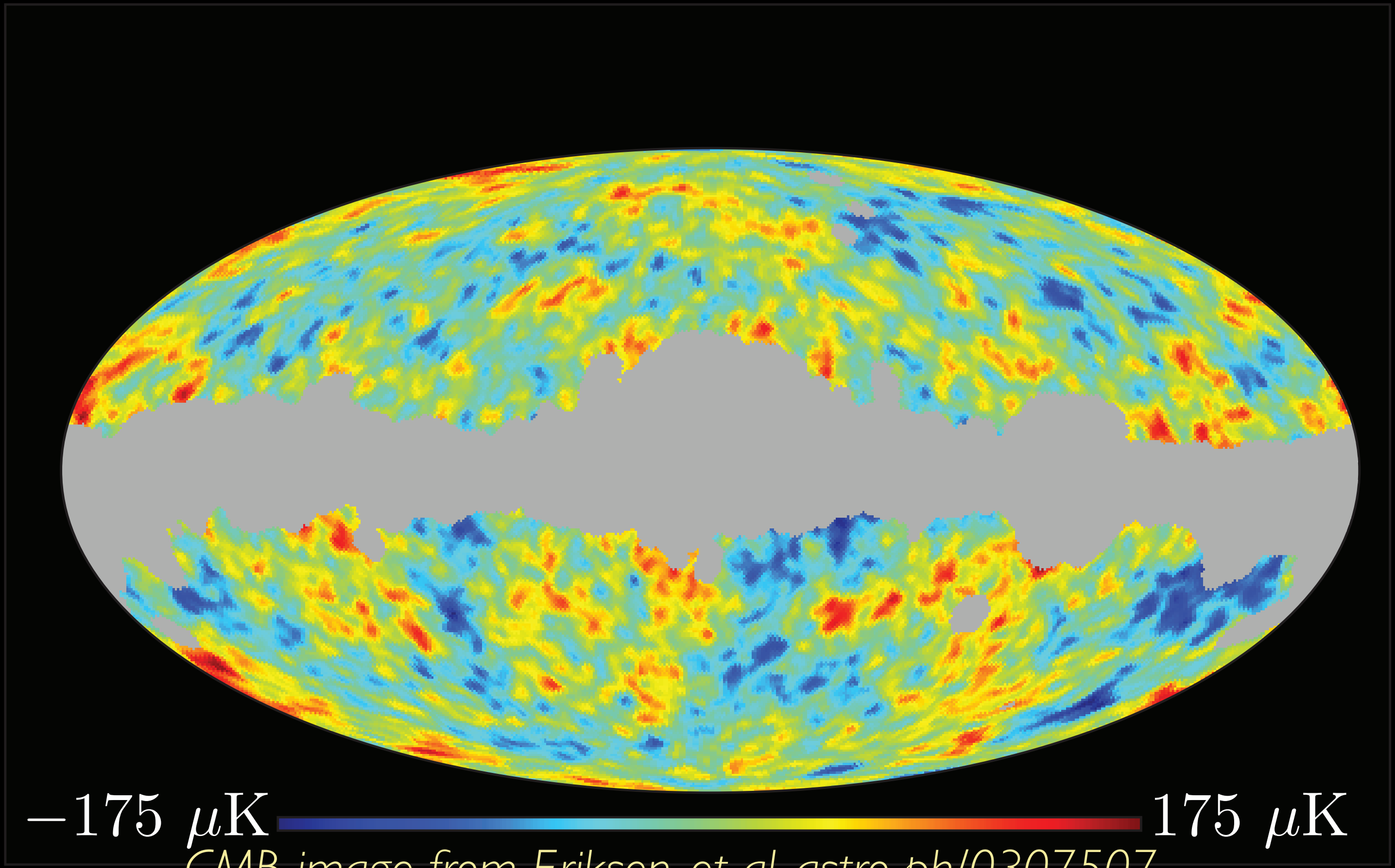

CMB image from Eriksen, et al. astro-ph/0307507

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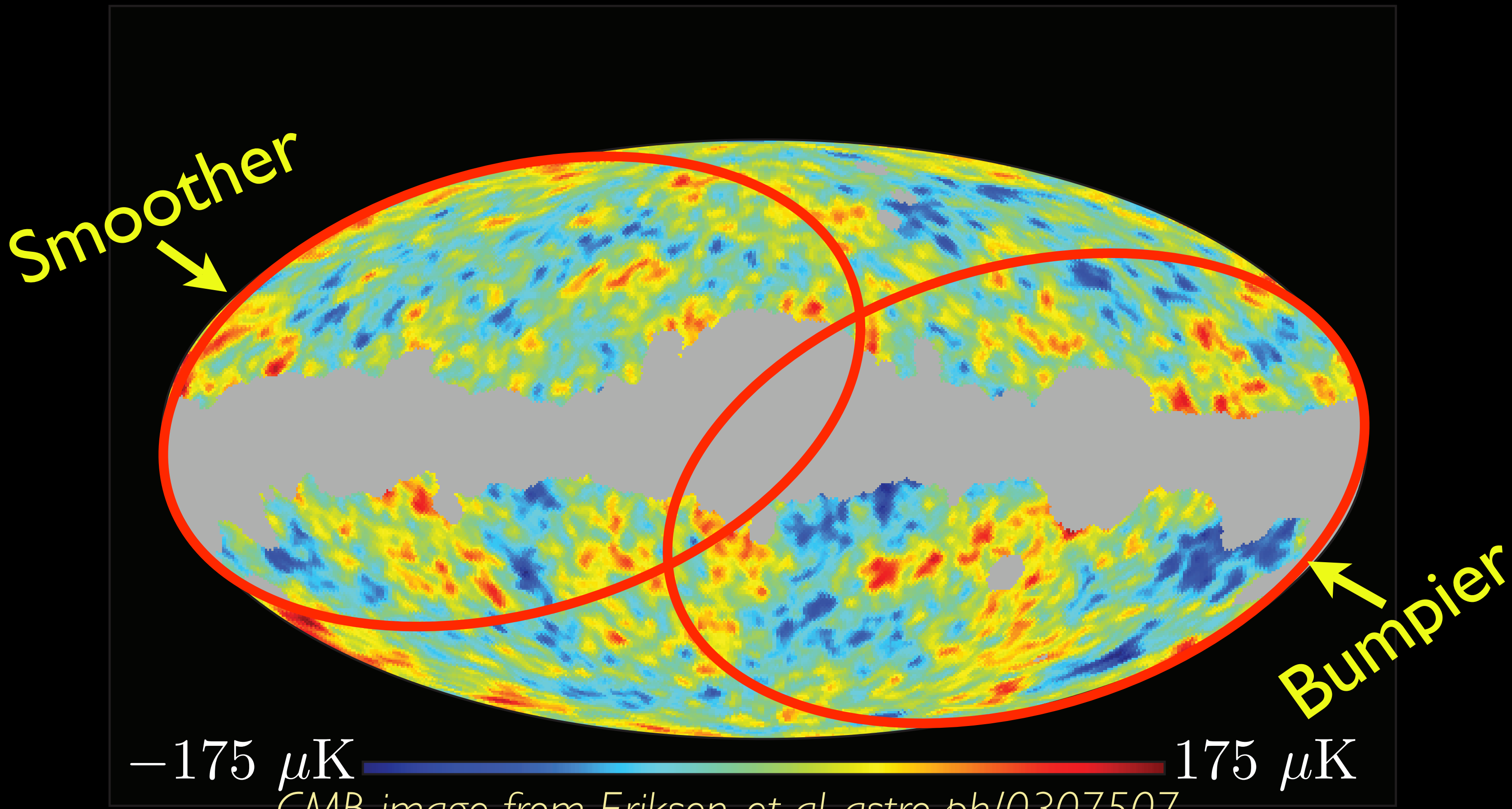

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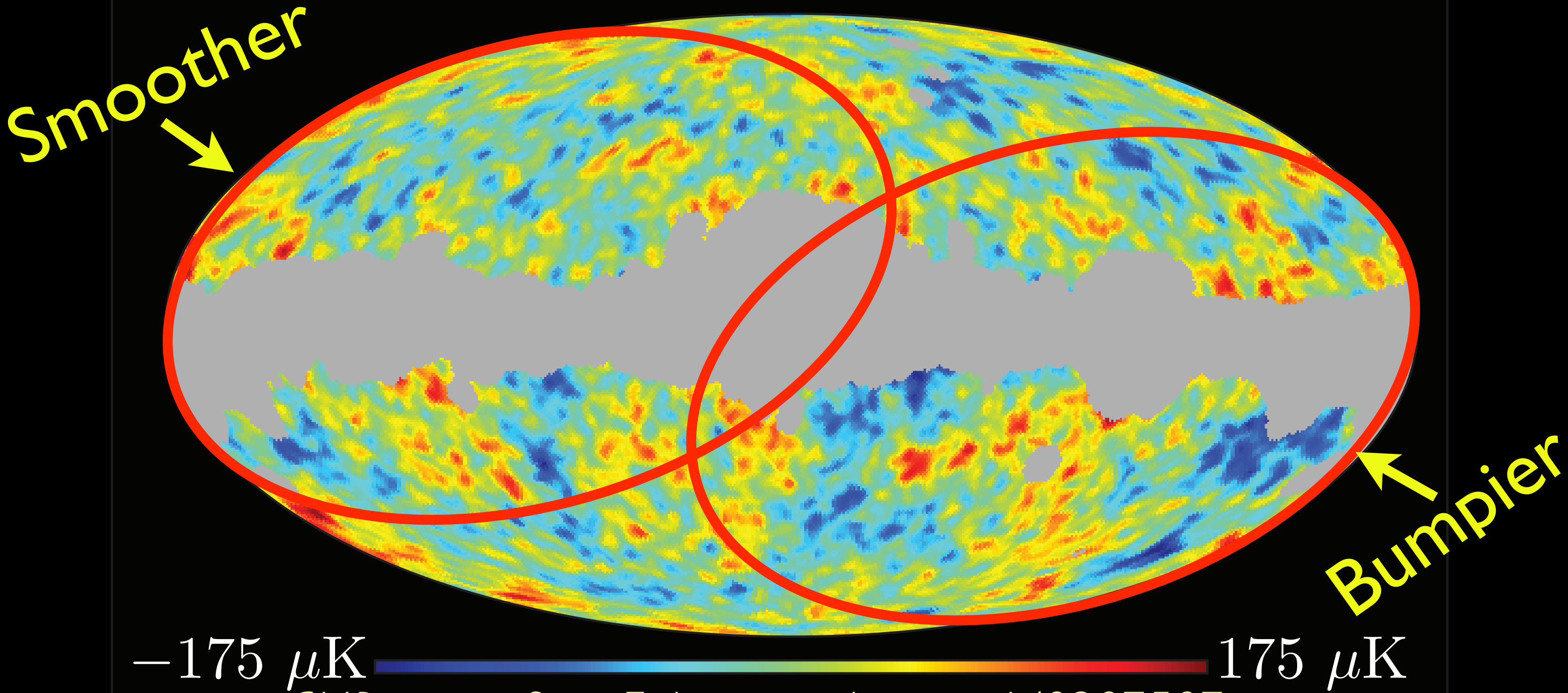
- Power asymmetry is maximized when the dividing plane is tilted with respect to the Galactic plane.
- The asymmetry is equally present at multiple frequencies.
- Fewer than 1% of simulated isotropic maps contain this much asymmetry.



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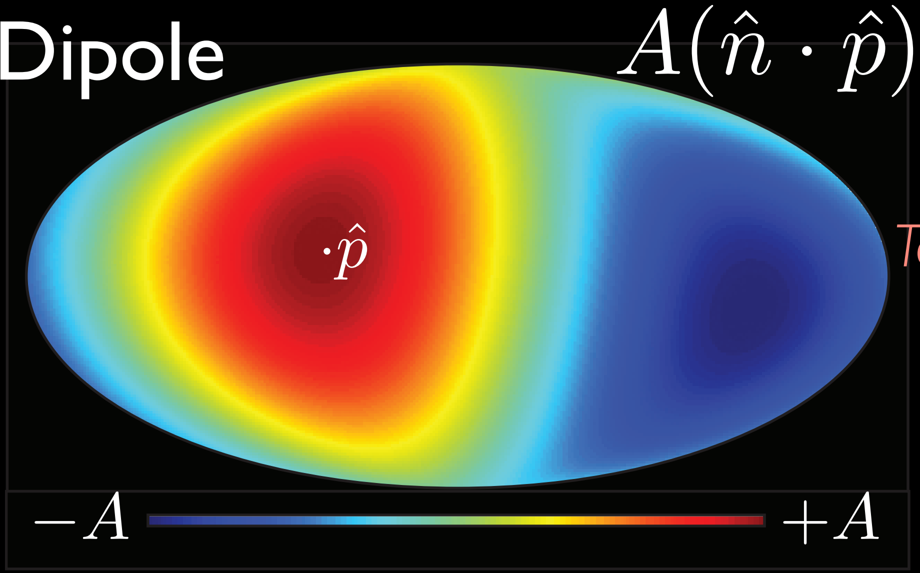
Hemispherical Power Asymmetry

Dipole



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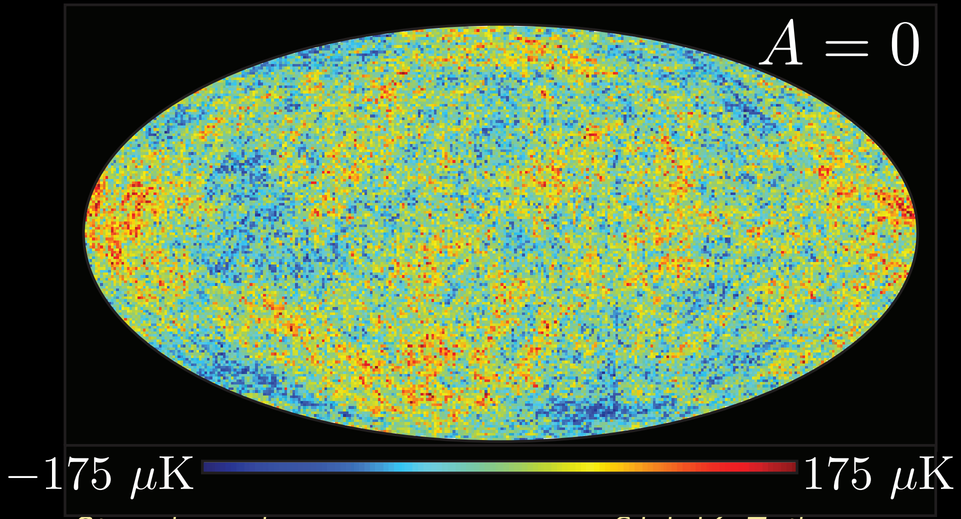
CMB Temperature

Gaussian field with isotropic power

Modulation Amplitude

"North" pole of asymmetry

Isotropic $s(\hat{n})$



Simulated maps courtesy of H. K. Eriksen

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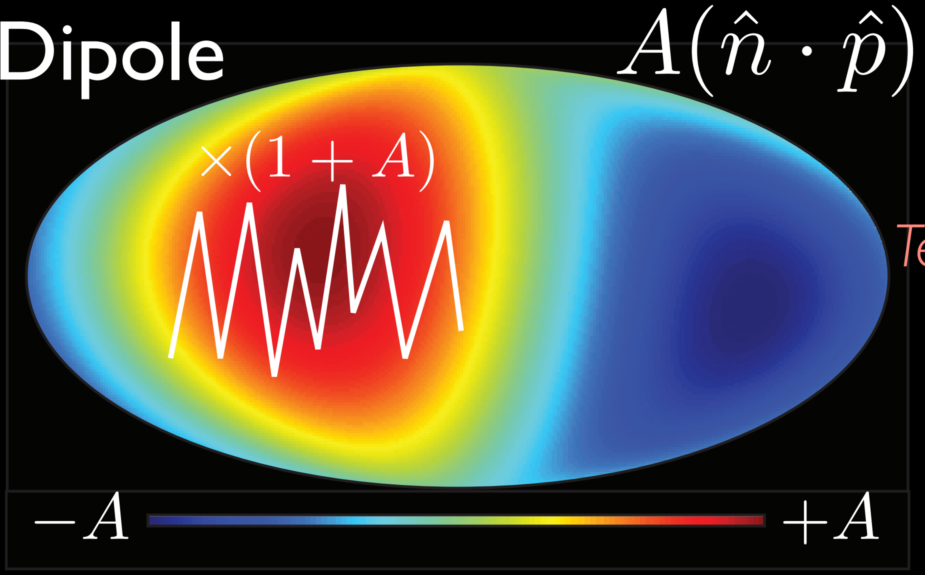

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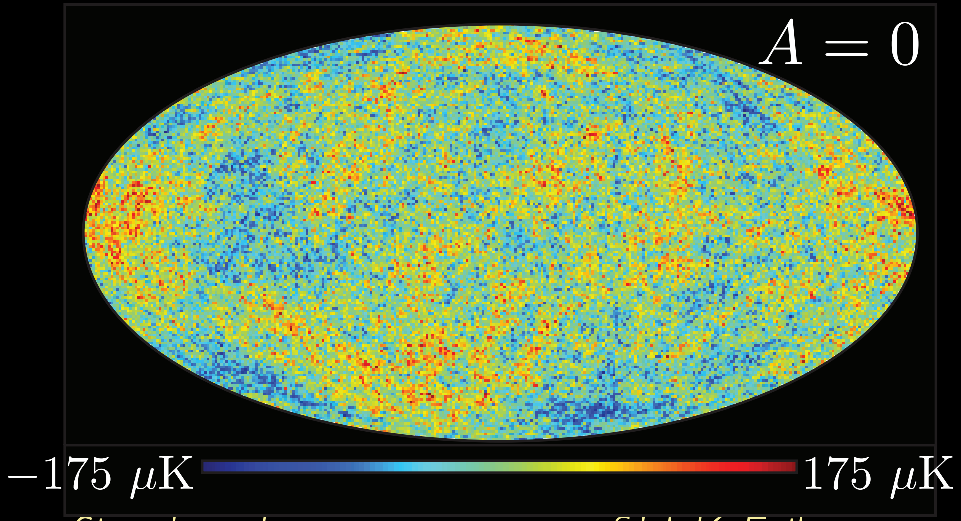

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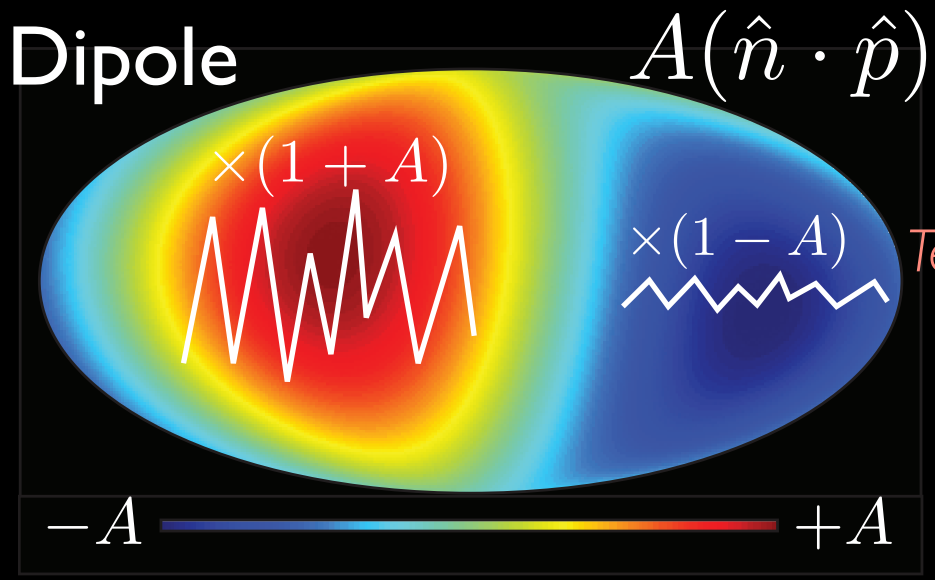

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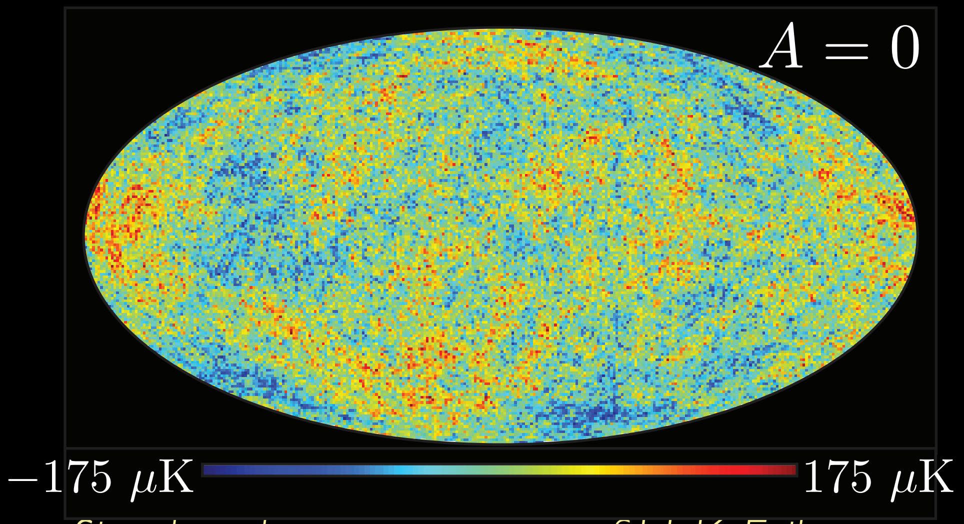

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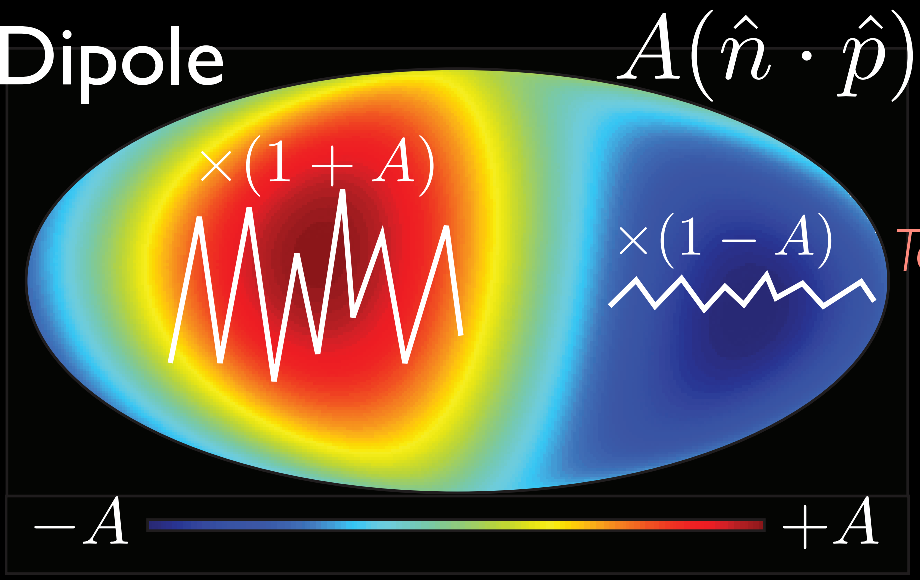

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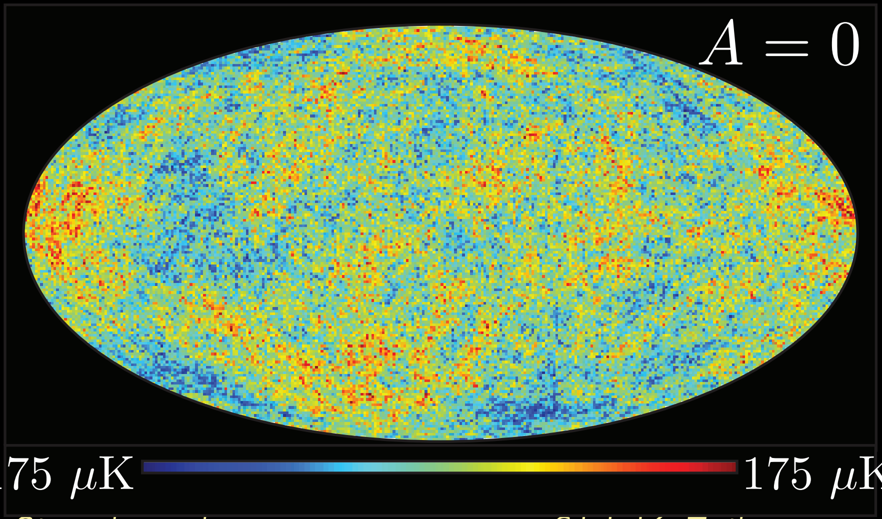

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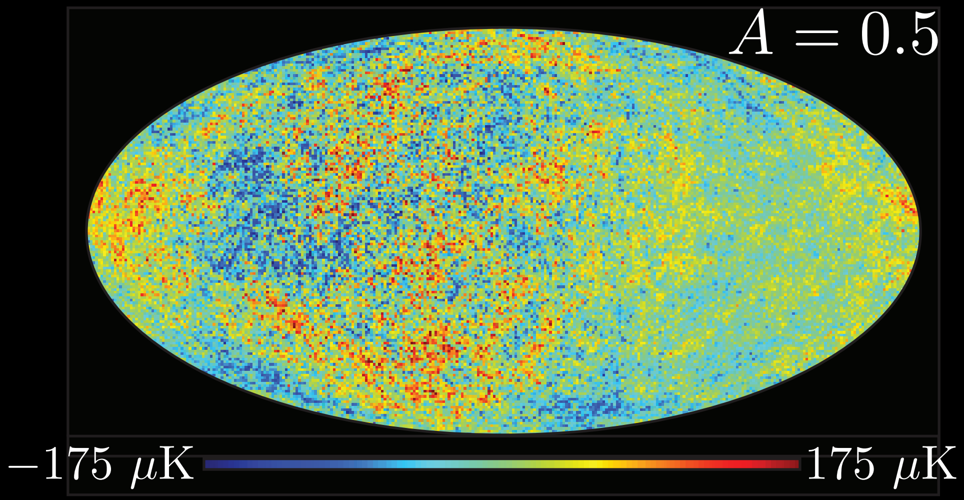

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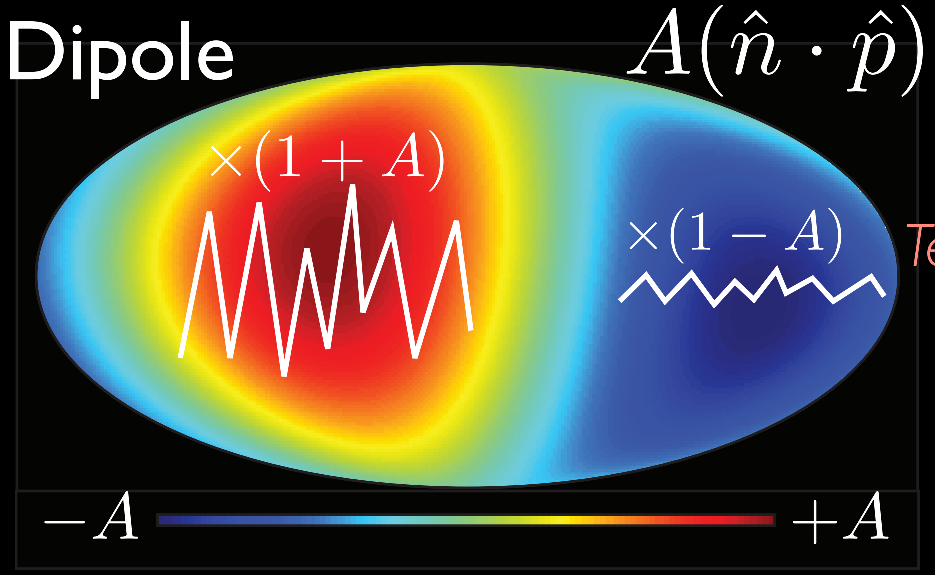

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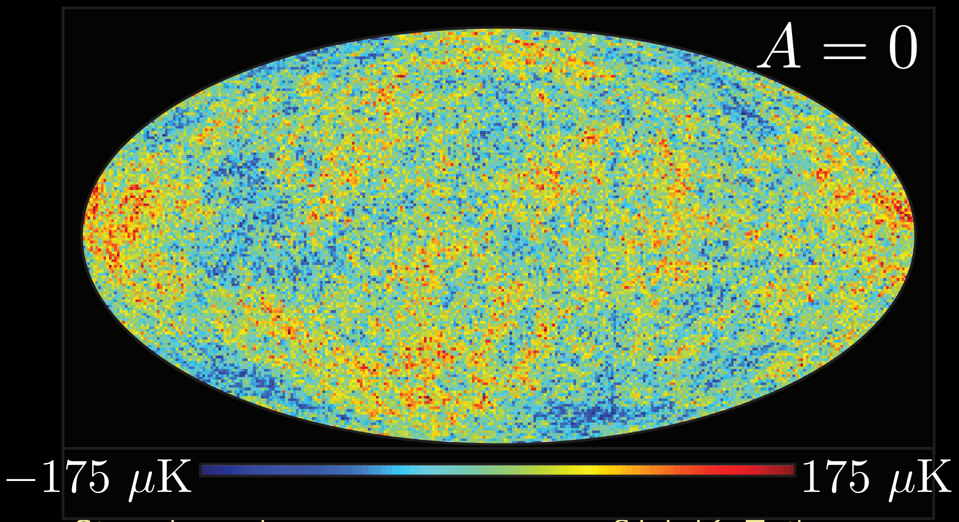

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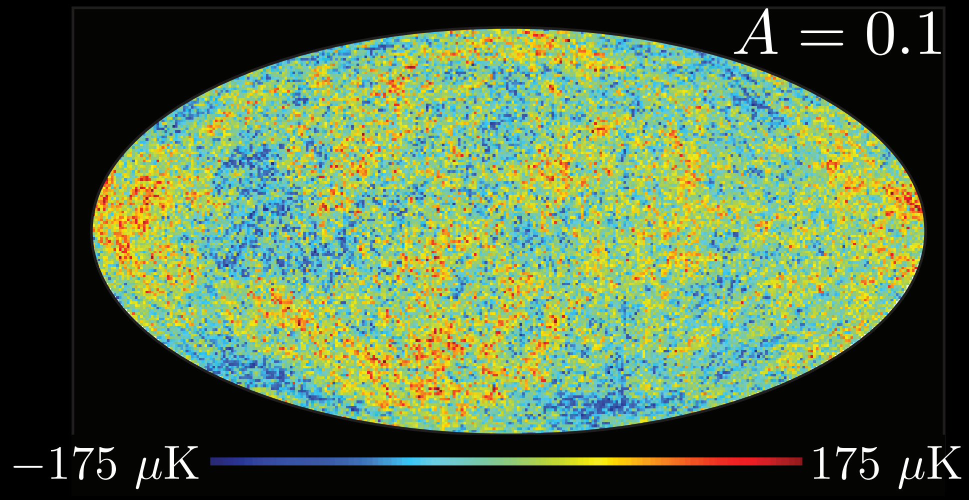

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Quantum Fluctuations Revisited

Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

Hawking 1982; Starobinsky 1982; Guth 1982; Bardeen, Steinhardt, Turner 1983

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expansion rate of the Universe

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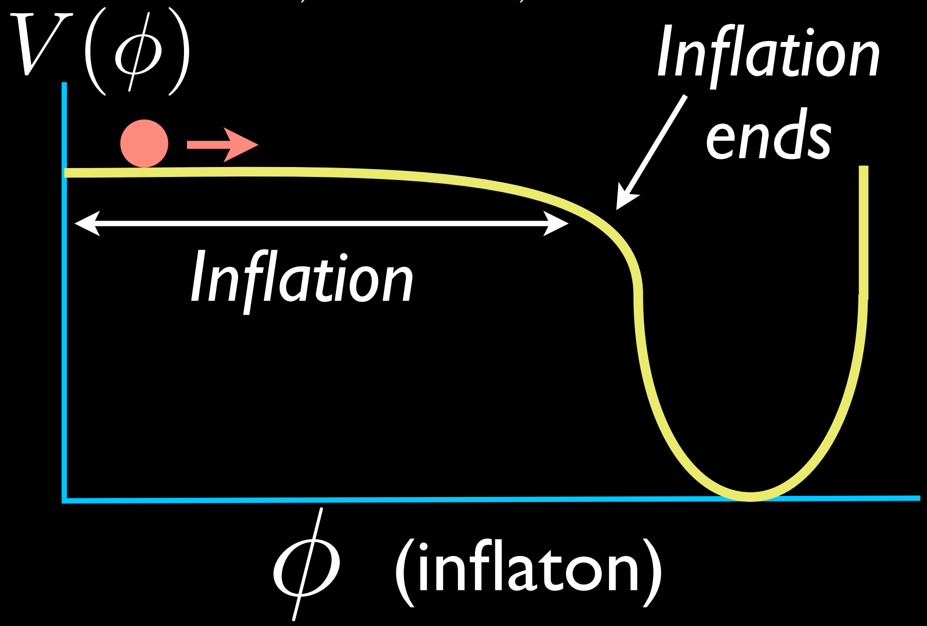
During inflation: $\rho \simeq V(\phi)$ *nearly constant*



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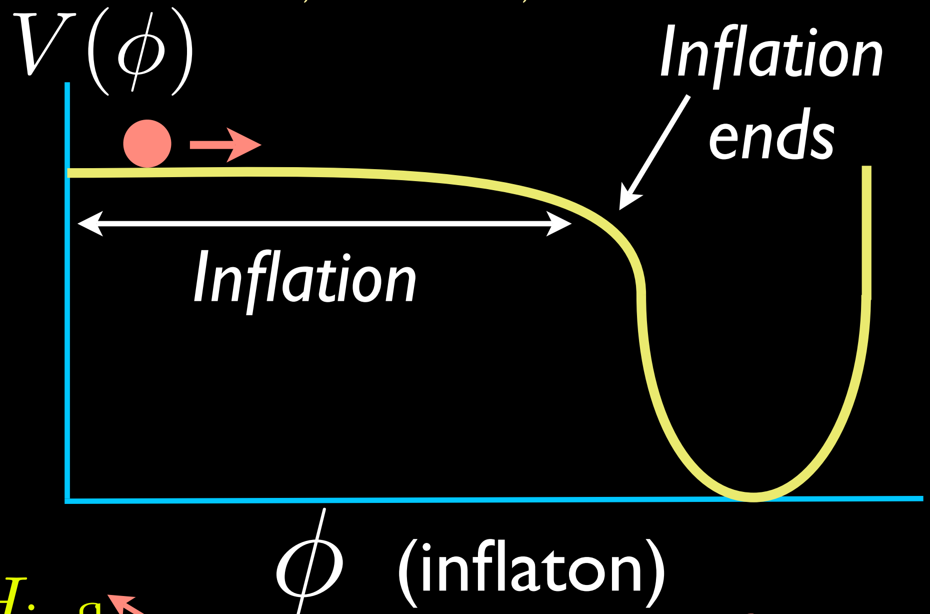
$$\frac{\dot{R}}{R} \equiv H = \sqrt{\frac{8\pi G}{3}\rho}$$

expansion rate of the Universe

energy density of the Universe

During inflation: $\rho \simeq V(\phi)$ *nearly constant*



Quantum fluctuations: $(\delta\phi)_{\mathrm{rms}} = \frac{H_{\mathrm{infl}}}{2\pi}$ *expansion rate during inflation*

Fluctuations in ϕ are equivalent to fluctuations in time: $\delta t = \frac{\delta\phi}{\dot{\phi}}$

Quantum Fluctuations Revisited

Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

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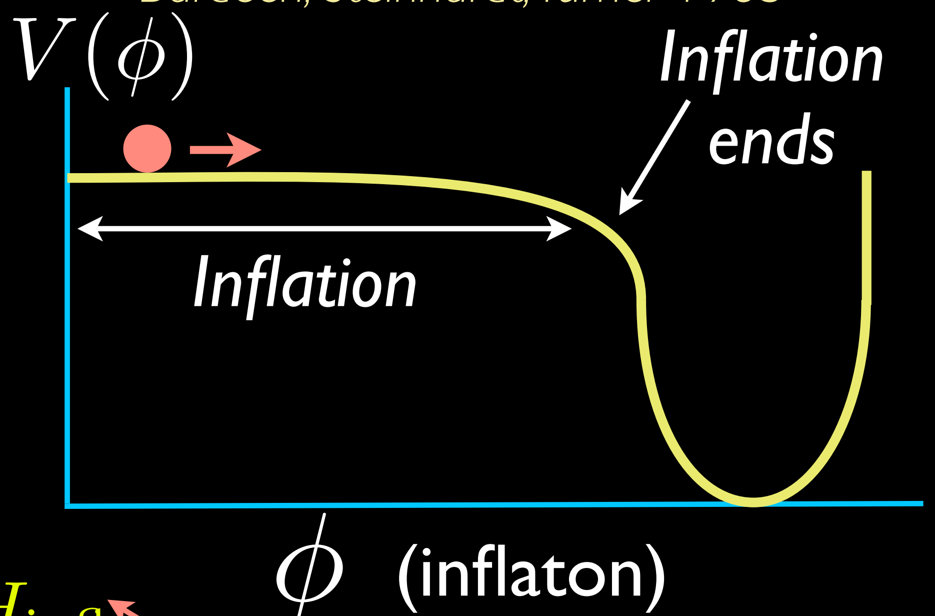

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how much space has expanded

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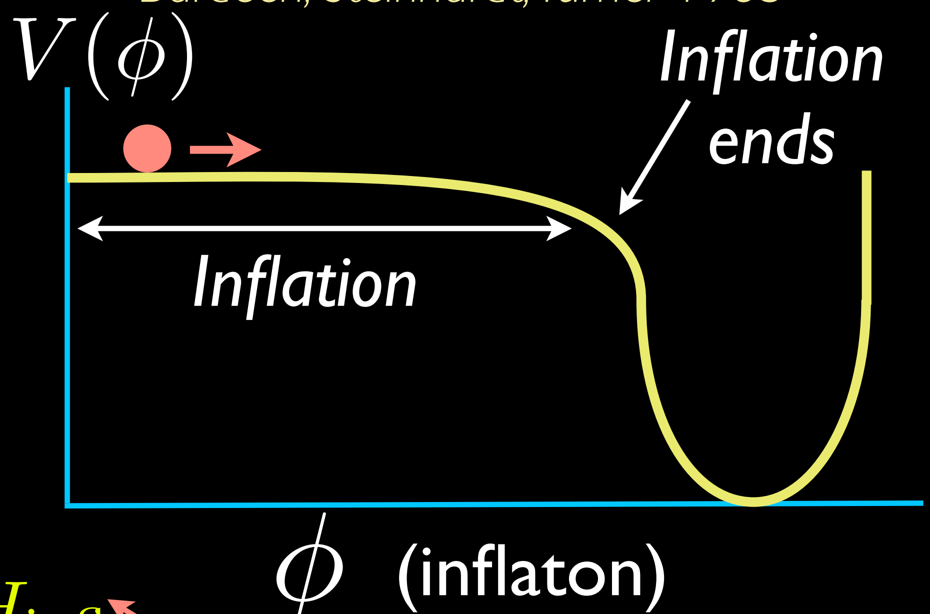

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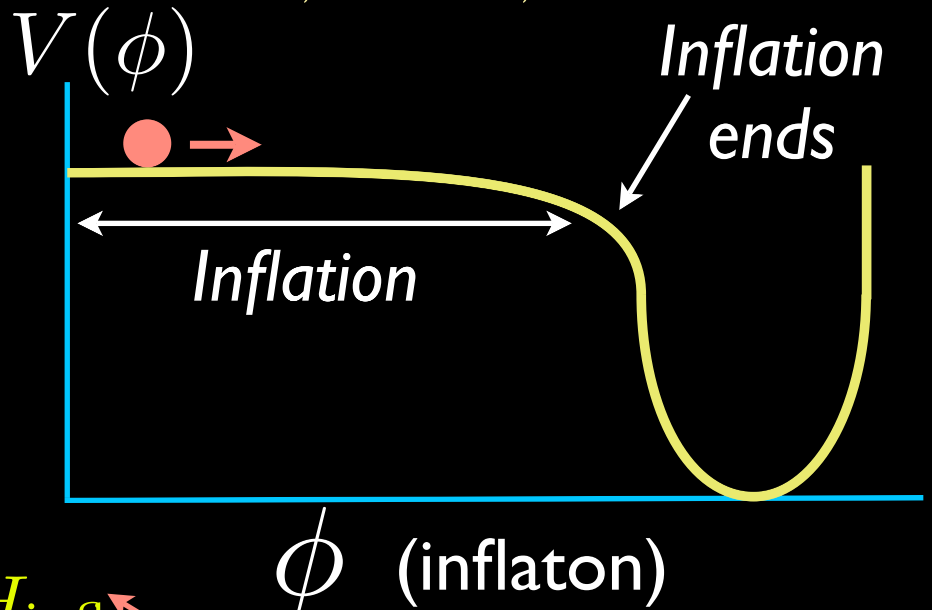

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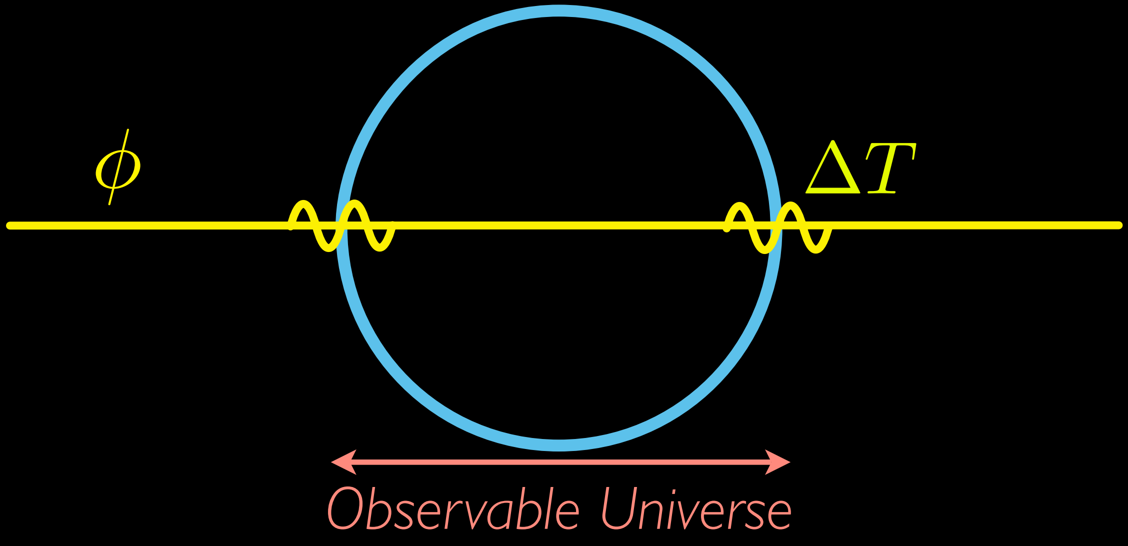
how much space has expanded

connection to quantum fluctuations

Asymmetry from a "Supermode"



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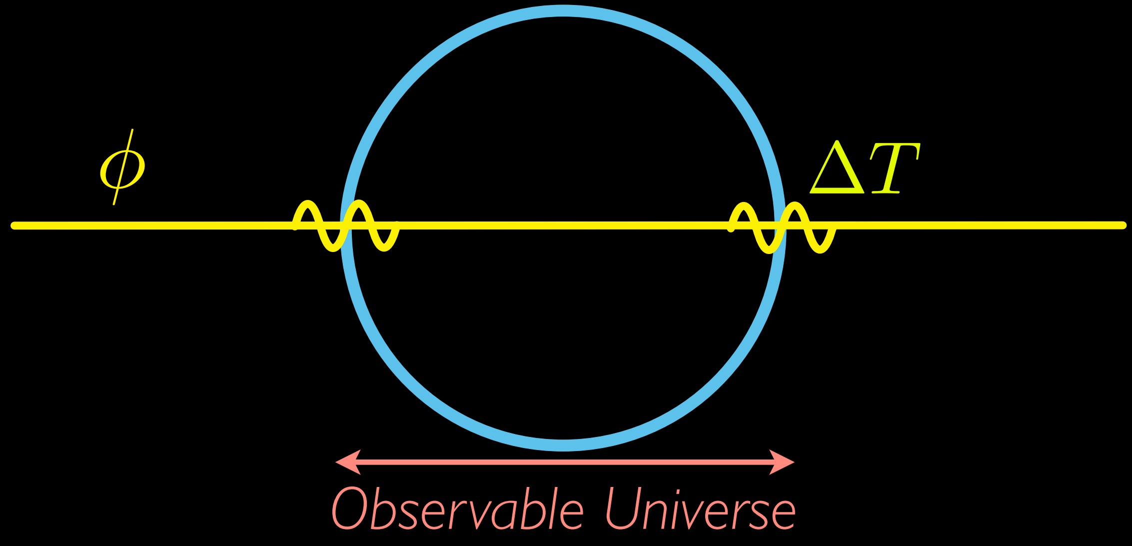

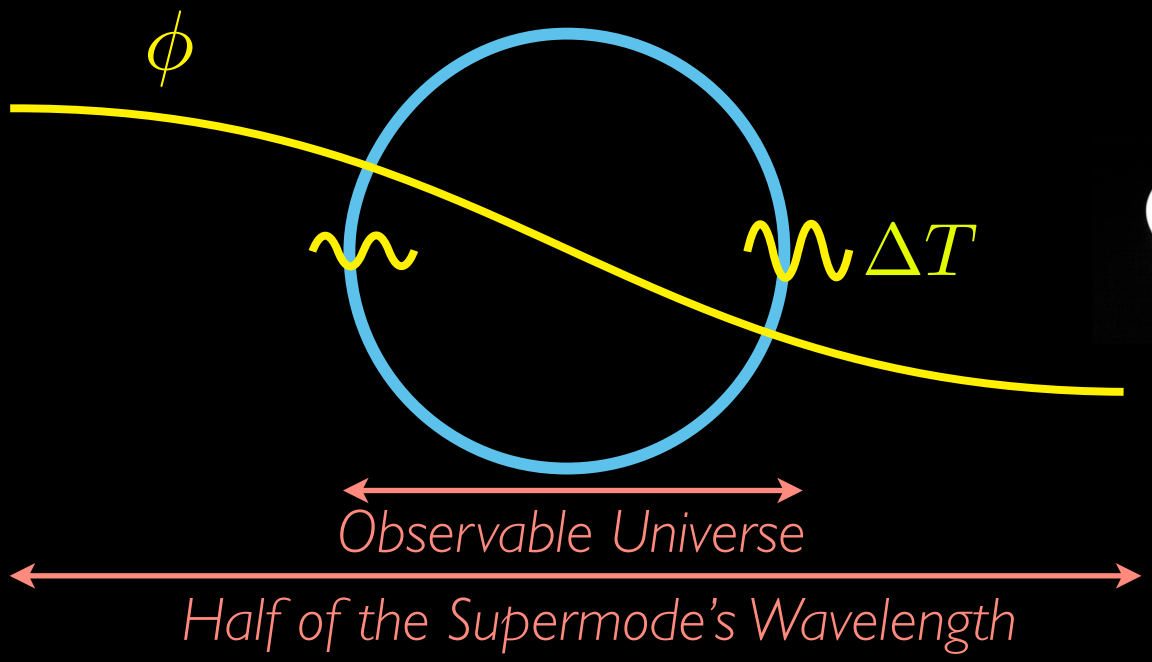

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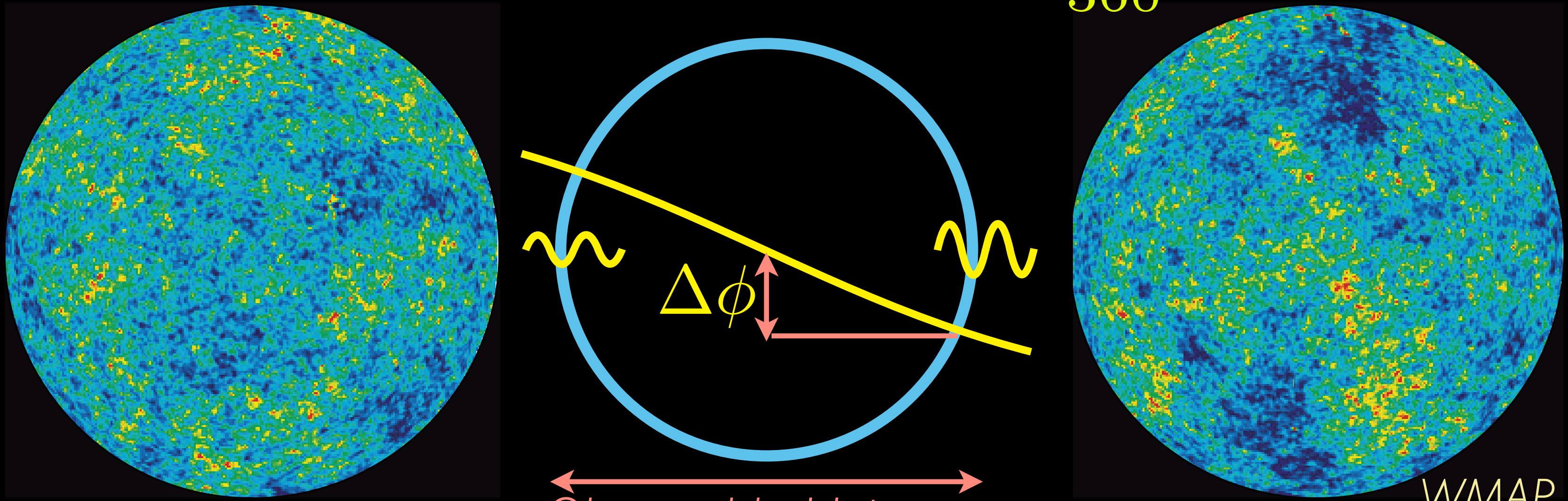
Create asymmetry by adding a large-amplitude superhorizon fluctuation: a “supermode.”

Erickcek, Kamionkowski, Carroll 2008

Asymmetry from a "Supermode"

The observed modulation amplitude: $A = 0.12 \pm 0.04$

Corresponding power asymmetry: $\dfrac{\Delta P}{P_{360^\circ}} = 0.2$



WMAP Science Team

Generating this much asymmetry requires a BIG supermode.

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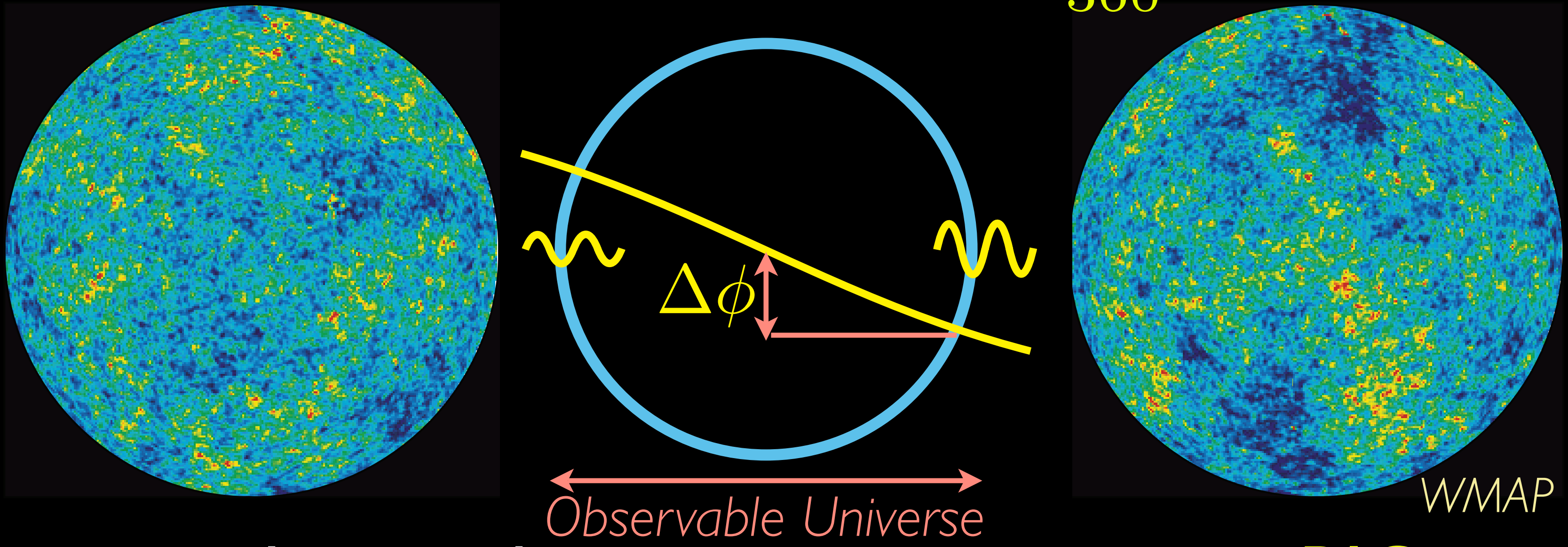

WMAP Science Team

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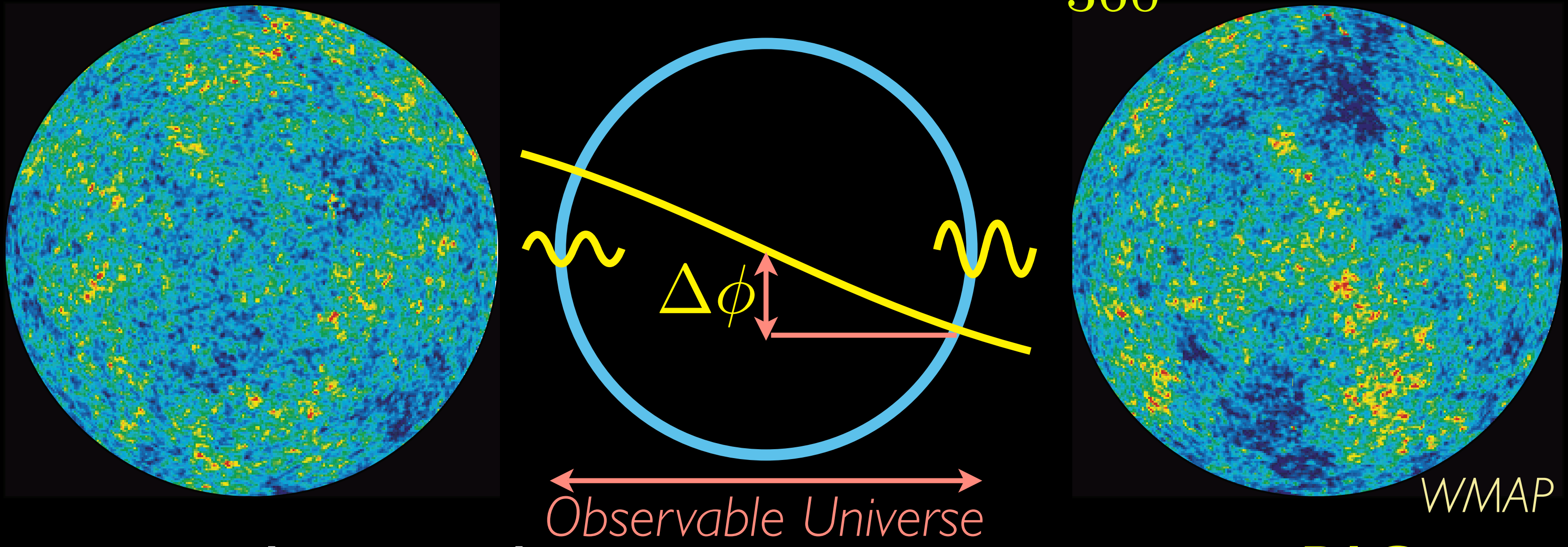

WMAP Science Team

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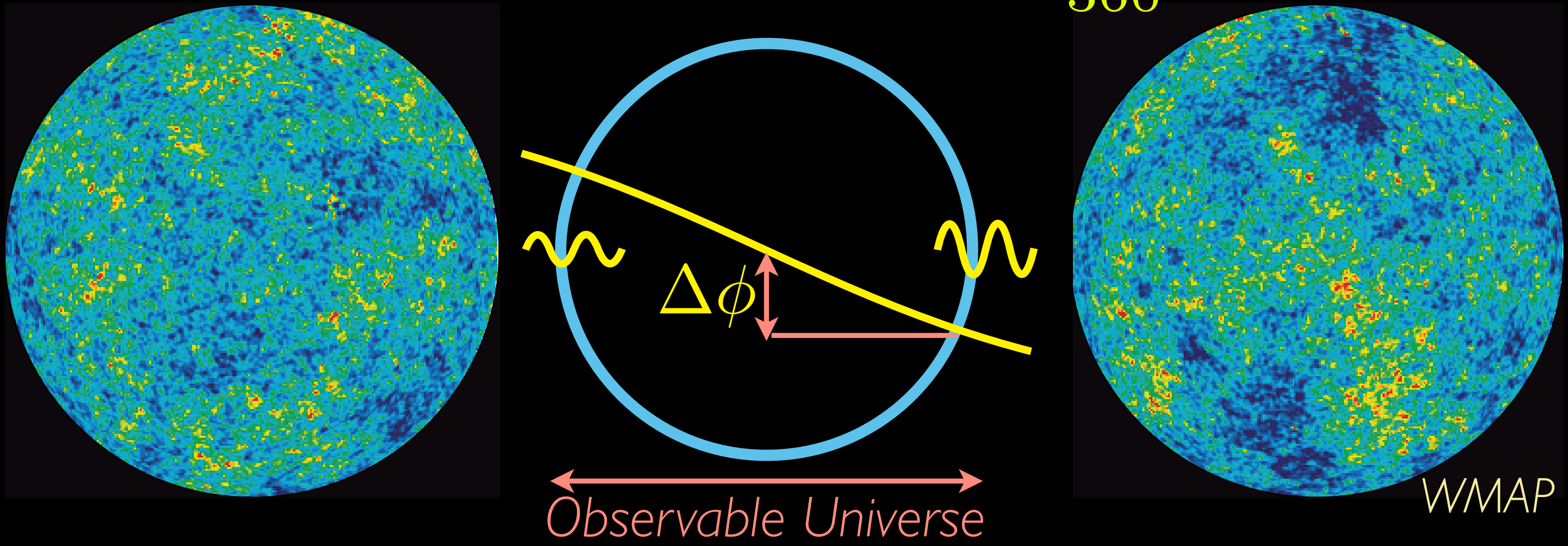

WMAP Science Team

Generating this much asymmetry requires a BIG supermode.

- Recall that the measured primordial fluctuations are scale-invariant.
- Different fluctuation wavelengths were created at different times during inflation, so the value of the inflaton varies with wavelength.
- The fluctuation power is not very sensitive to the inflaton value.

Dipole Concerns

With the supermode, the value of the inflaton field is very different on opposite sides of the Observable Universe.

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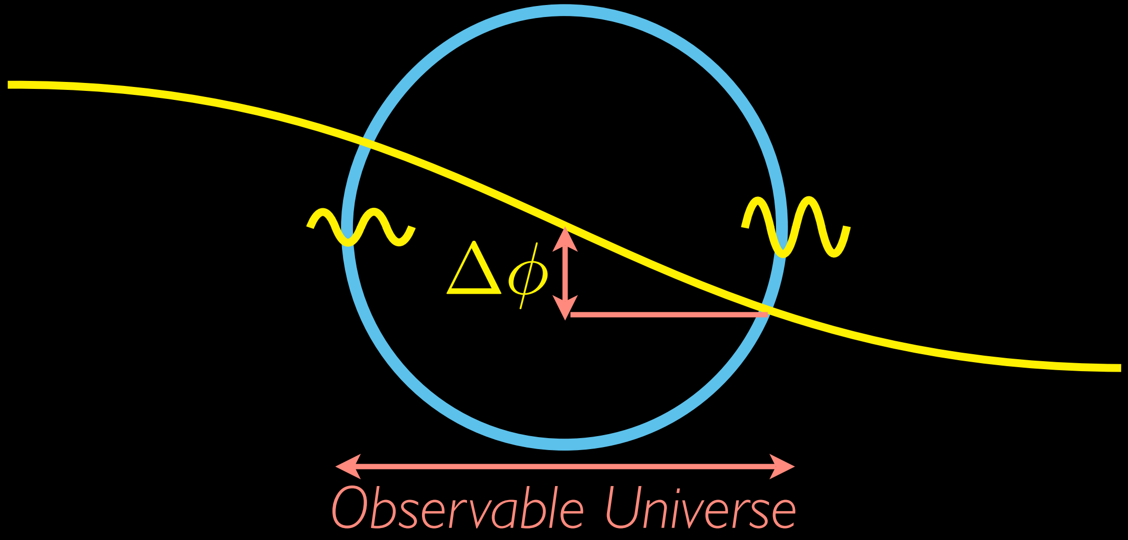

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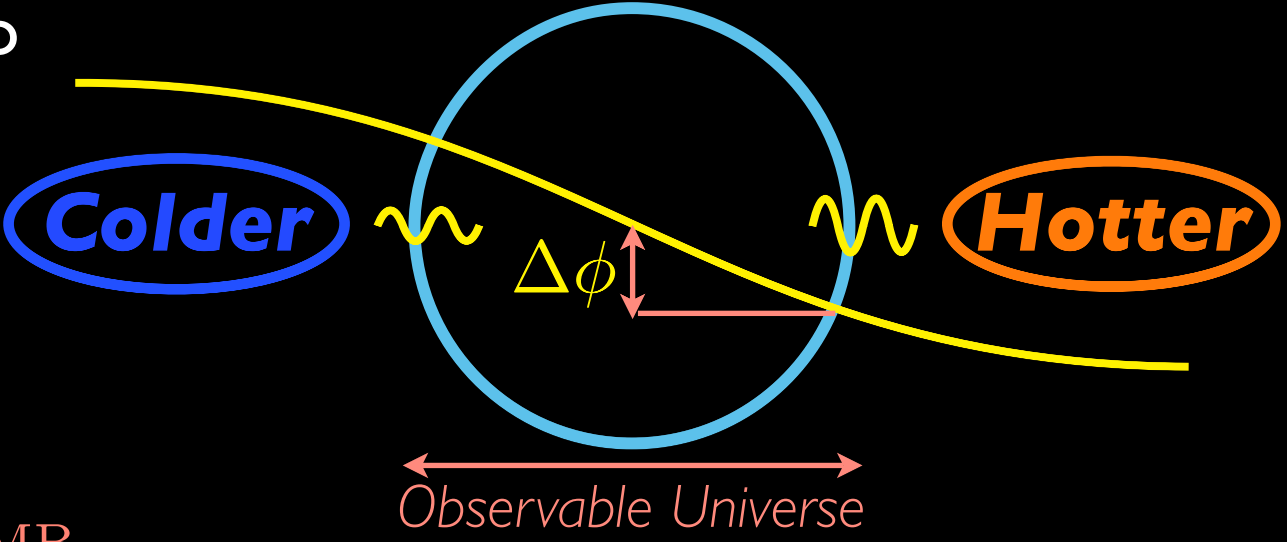
With the supermode, the value of the inflaton field is very different on opposite sides of the Observable Universe.

- The supermode leads to an asymmetric CMB fluctuation amplitude.
- Will it also lead to an asymmetric mean CMB temperature?

$$\underset{\text{inflaton}}{\Delta\phi} \Longrightarrow \underset{\text{grav. potential}}{\Delta\Psi} \Longrightarrow \Delta T_{\mathrm{CMB}}$$



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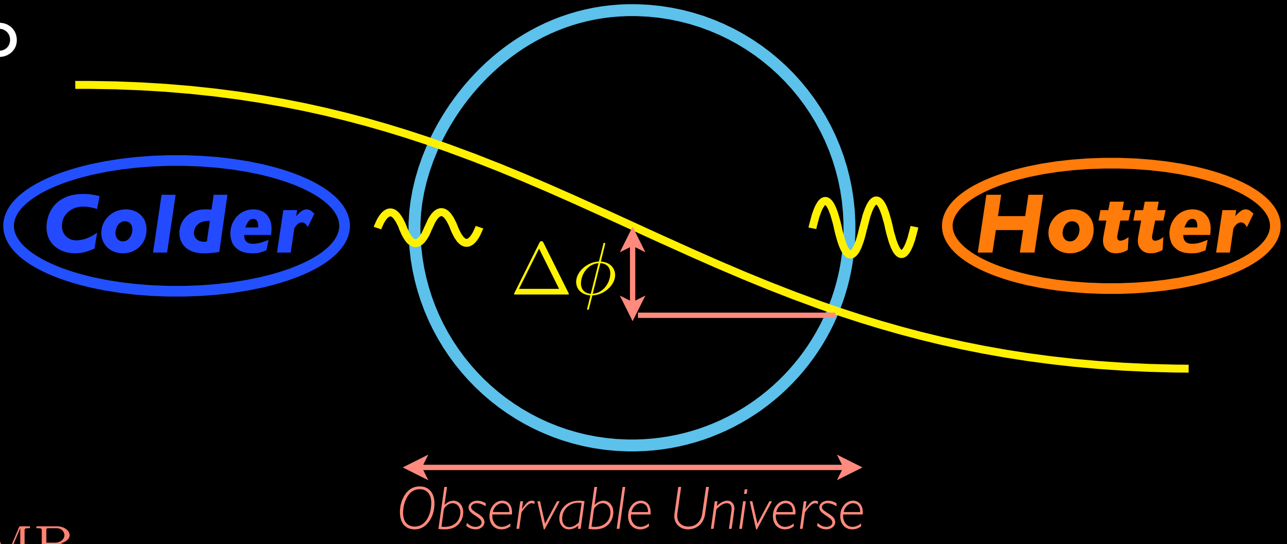
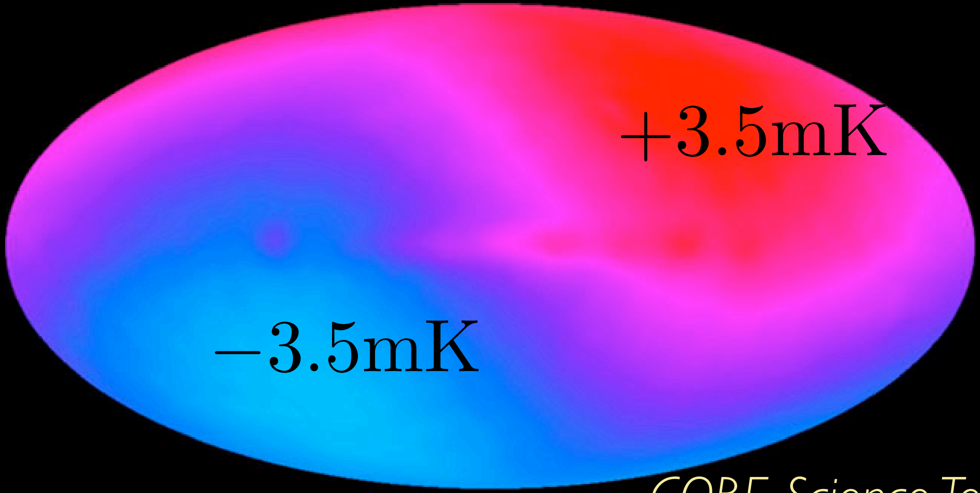
inflaton *grav. potential*



The CMB does contain a dipolar anisotropy.

- usually attributed to our motion relative to the CMB
- $\Delta T_{\rm CMB} = \pm 3.5\mathrm{mK}$



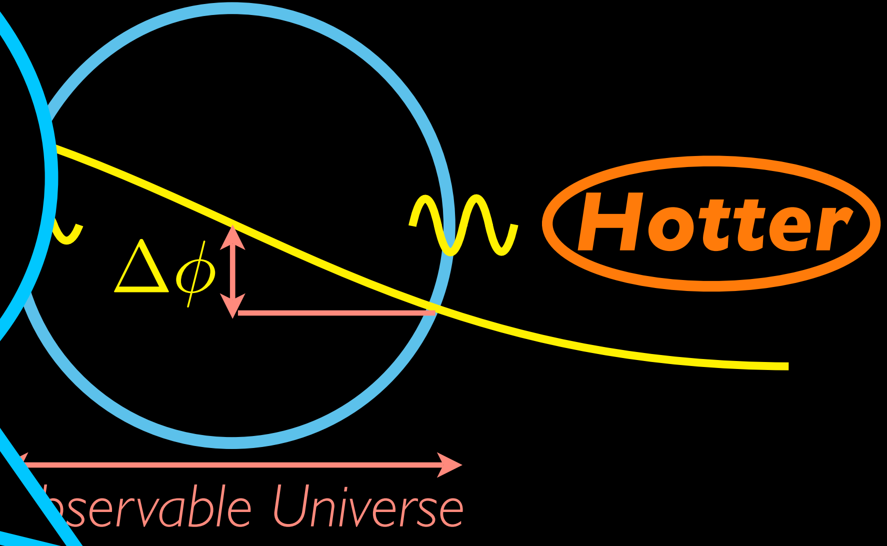
COBE Science Team

Dipole Concerns

With th… …alue of the inflaton field is very diff… …e Observable Universe.

Worry:

Will a supermode large enough to generate the observed power asymmetry also generate a temperature dipole that is too large to match observations?



te…

$\Delta\phi \Longrightarrow \Delta$ … $_{\rm CMB}$

inflaton *grav. potential*

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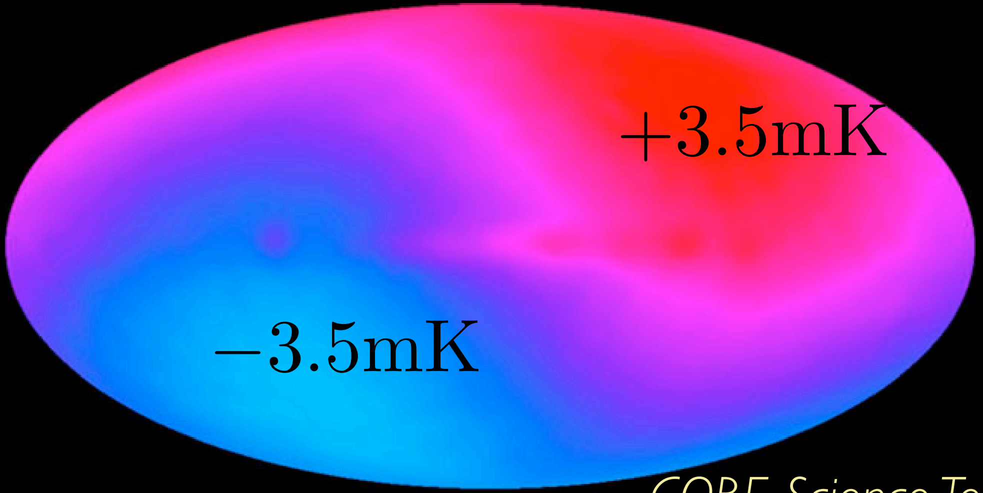

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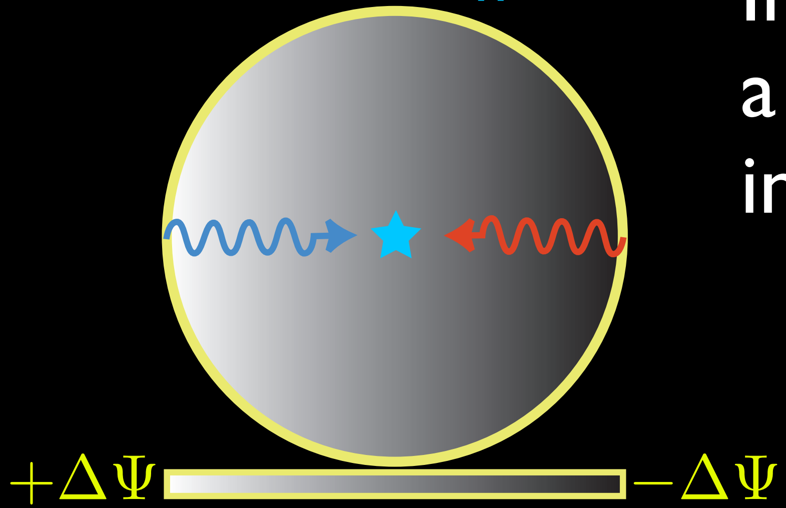
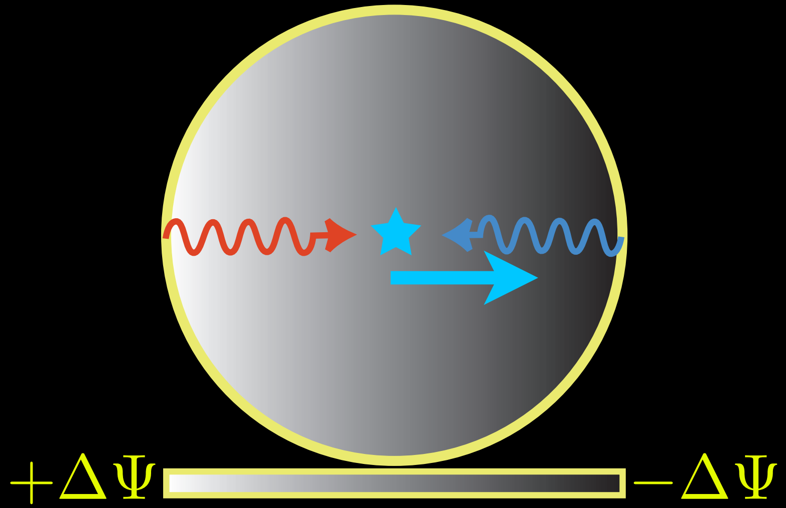
The Dipole Sometimes Cancels...

The SW Effect



Gravitational Gradient

The Doppler Effect



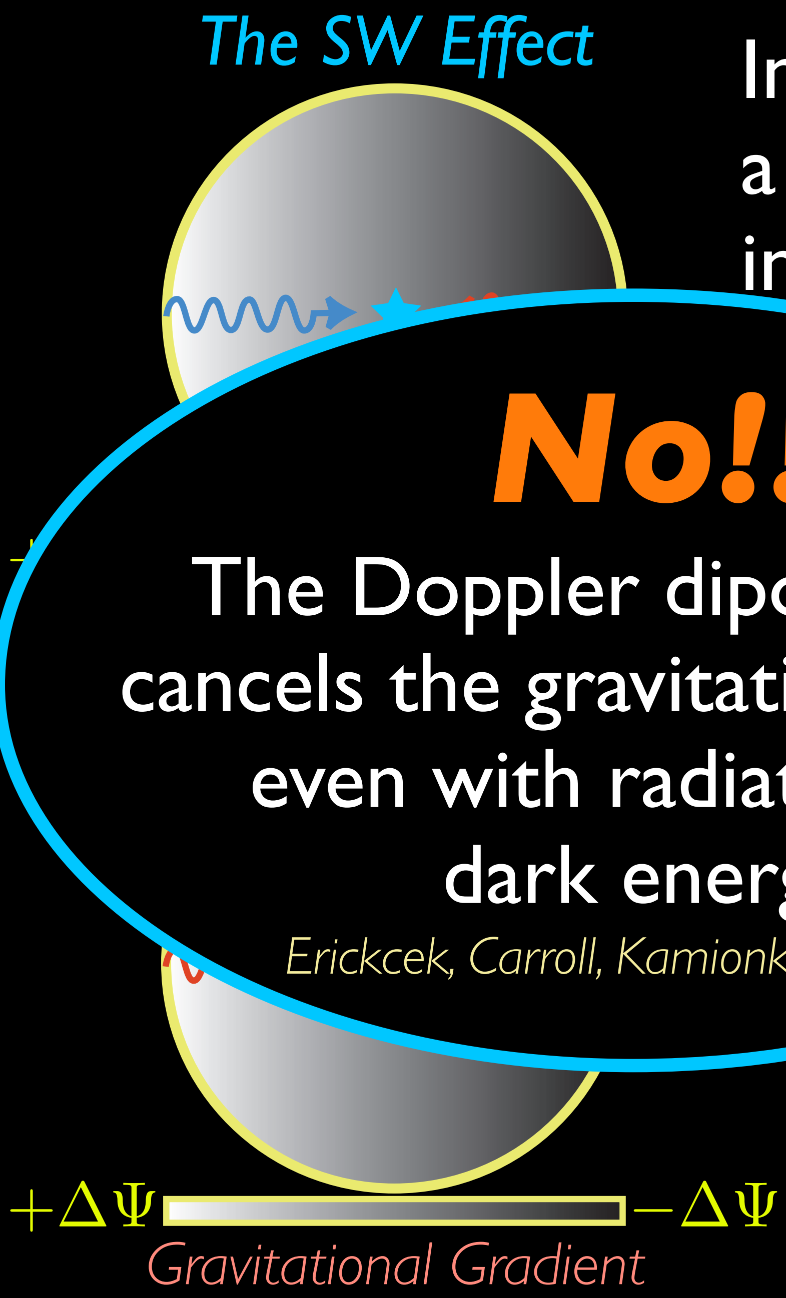
Gravitational Gradient

In a universe containing only matter, a superhorizon perturbation induces no CMB dipole. *Grishchuk, Zel'dovich 1978*

- There is a Sachs-Wolfe dipole due to gravitational redshifts.
- There is a Doppler dipole due to our motion down the gravitational slope.
- These two effects exactly cancel if the Universe contains only matter.

Will a superhorizon perturbation induce a CMB dipole in our Universe?

The Dipole Sometimes Cancels...



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Grishchuk, Zel'dovich 1978

Sachs-Wolfe dipole due to redshifts.

pler dipole due to our he gravitational slope.

effects exactly cancel if the tains only matter.

No!!

The Doppler dipole always cancels the gravitational dipole, even with radiation and dark energy.

Erickcek, Carroll, Kamionkowski 2008

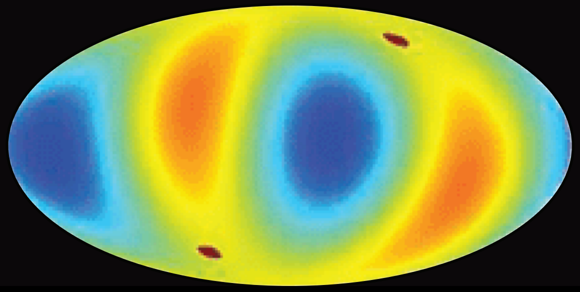
Will a superhorizon perturbation induce a CMB dipole in our Universe?

Going Beyond the CMB Dipole

Decompose the CMB into multipole moments:

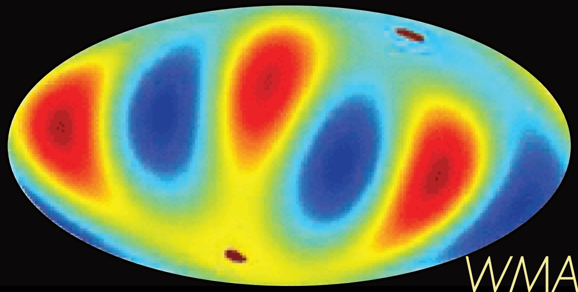
$$\frac{\Delta T}{T}(\hat{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{n})$$

$\ell = 2$



Quadrupole

$\ell = 3$



Octupole

WMAP Science Team

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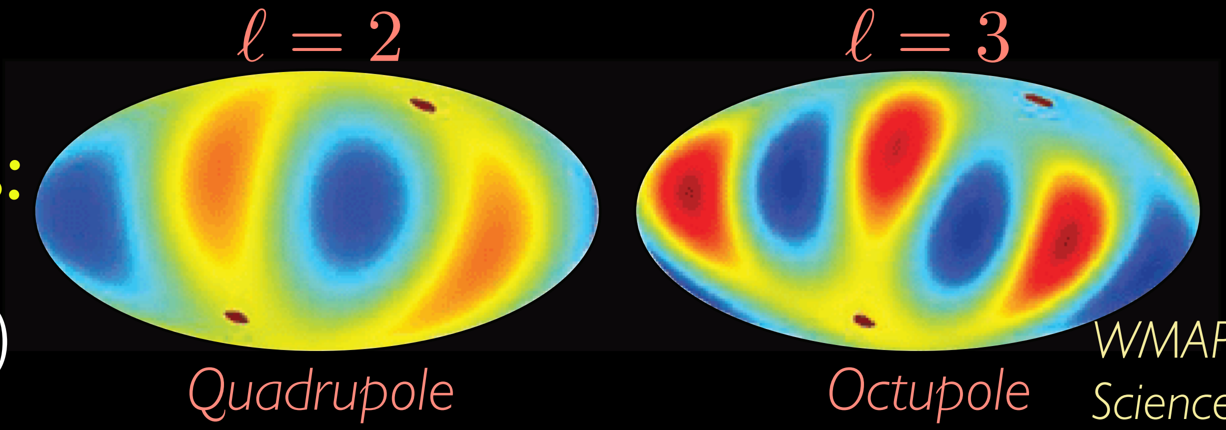

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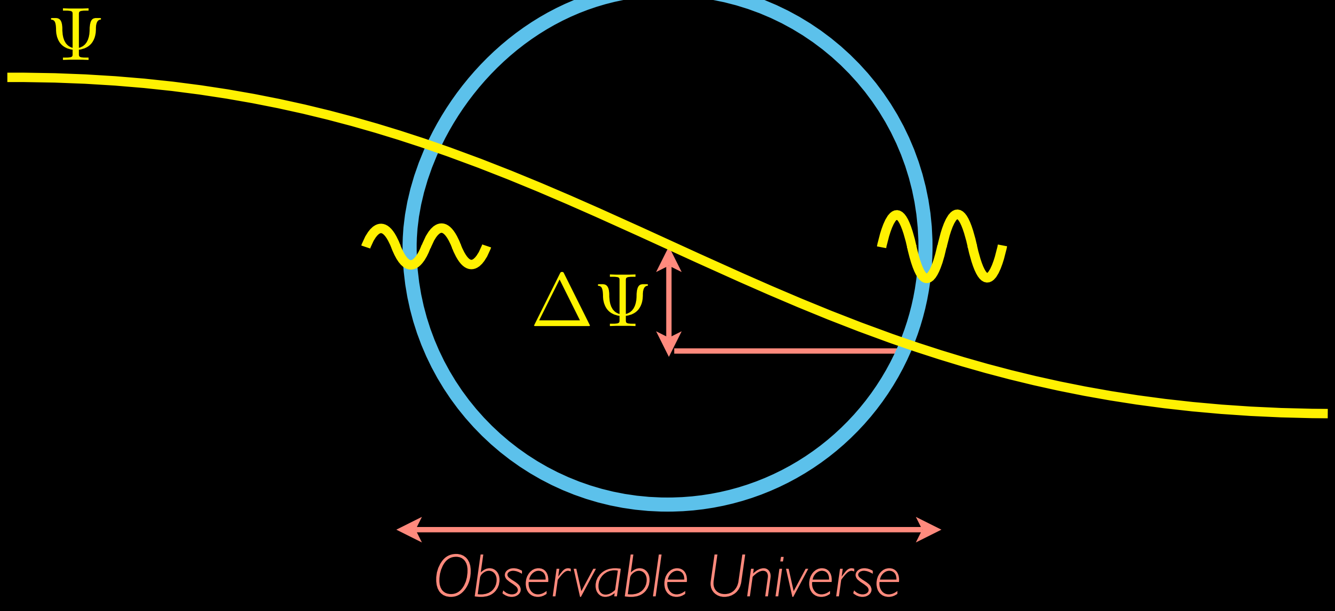
Supermode: $$\Psi(\vec{x},t) = \Psi_{\rm SM}(t)\sin\left[\left(\frac{2\pi}{L}\right)x + \varpi\right]$$

gravitational potential

phase of our location



Erickcek, Kamionkowski, Carroll 2008

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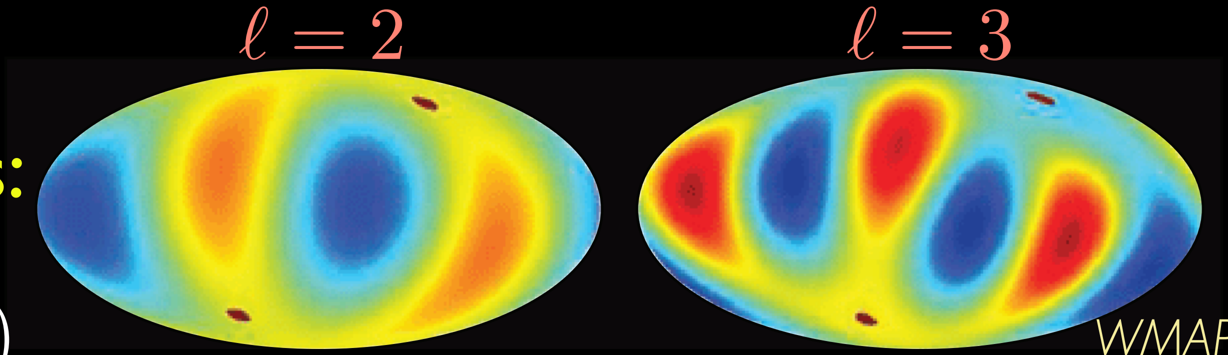

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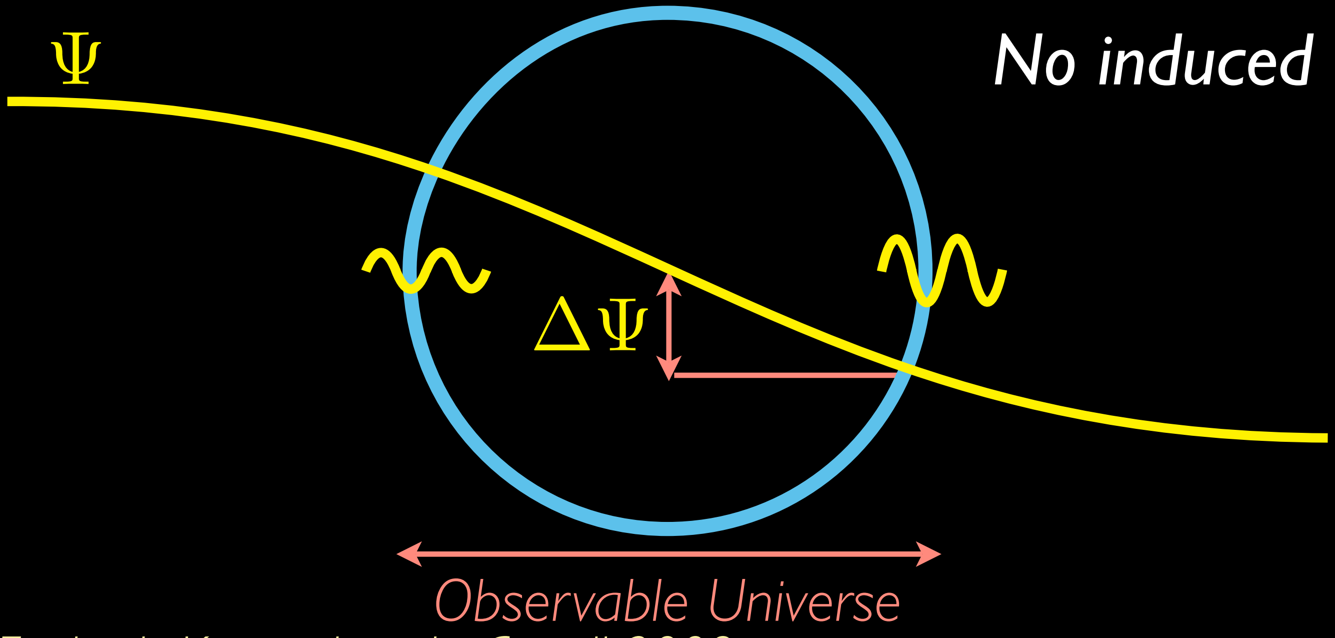
No induced quadrupole if $\varpi = 0$.



Erickcek, Kamionkowski, Carroll 2008

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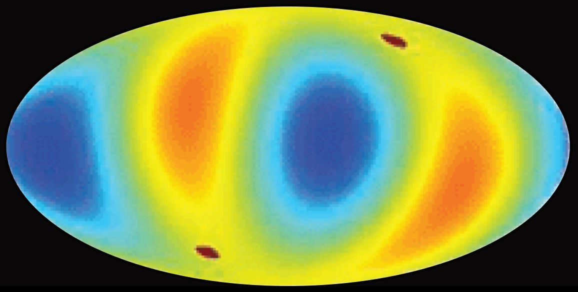

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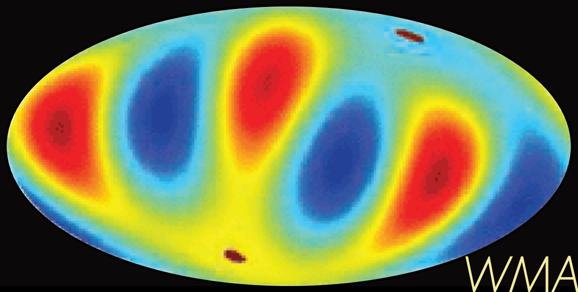

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WMAP Science Team

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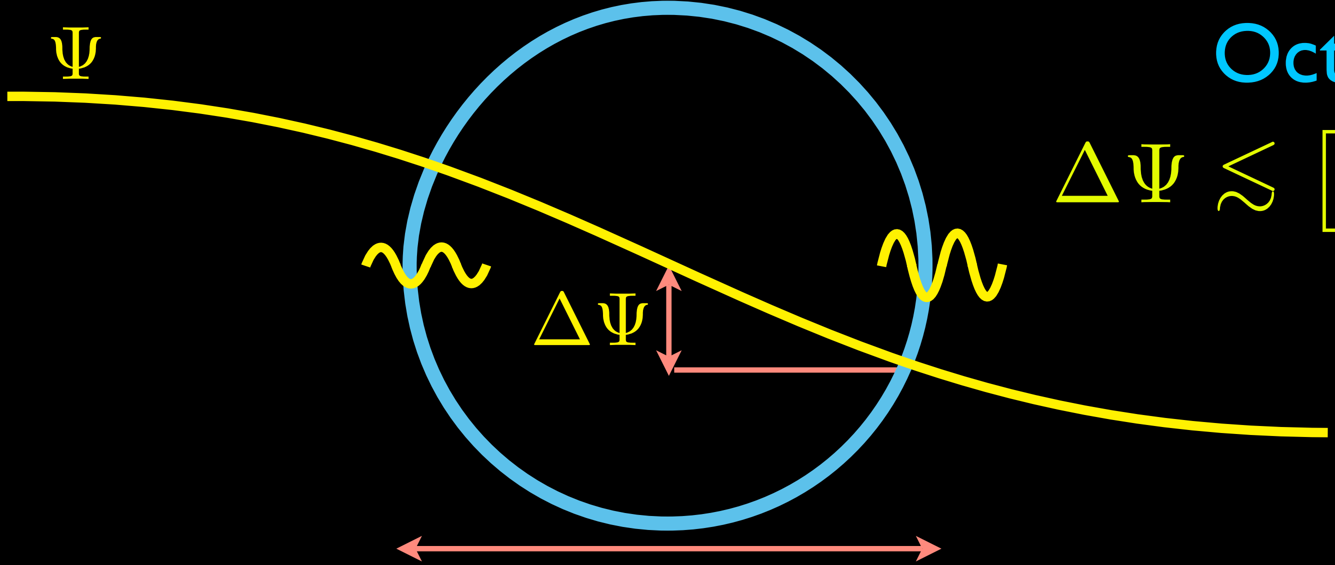

Octupole Constraint:

$$\Delta\Psi \lesssim \left[32|a_{30}^{\rm SM}|\right]^{1/3} = 0.095$$

Erickcek, Kamionkowski, Carroll 2008

Going Beyond the CMB Dipole

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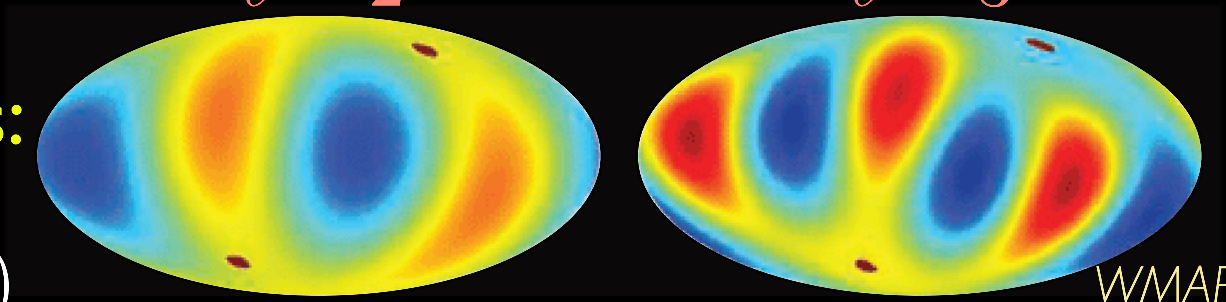

Quadrupole Octupole

WMAP Science Team

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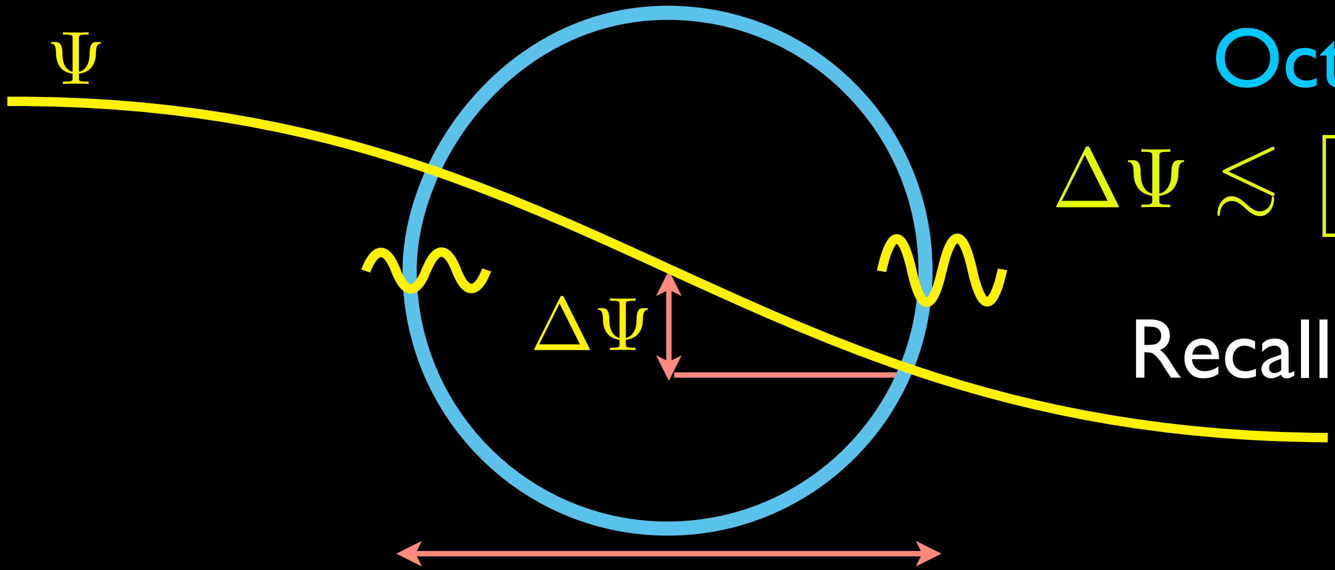
phase of our location



Observable Universe

Octupole Constraint:

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inflaton

Recall: $\frac{\Delta P}{P} \propto \Delta\phi \propto \Delta\Psi$

Erickcek, Kamionkowski, Carroll 2008

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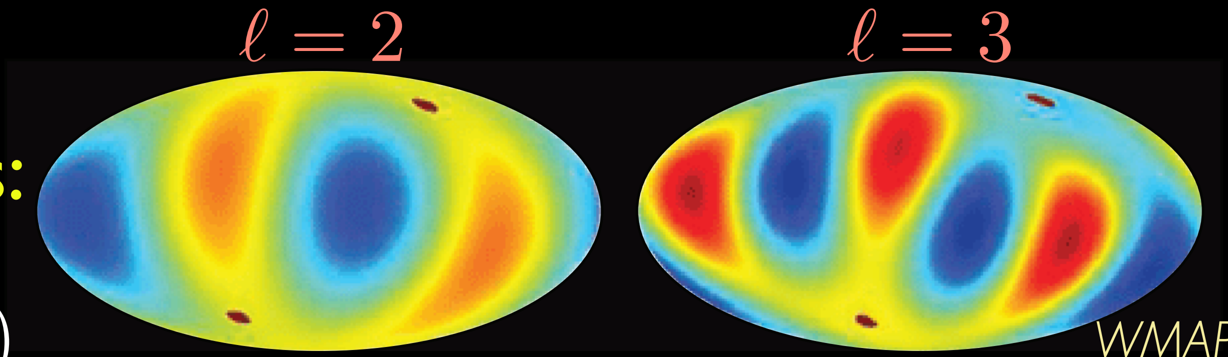

Quadrupole   *Octupole*

WMAP Science Team

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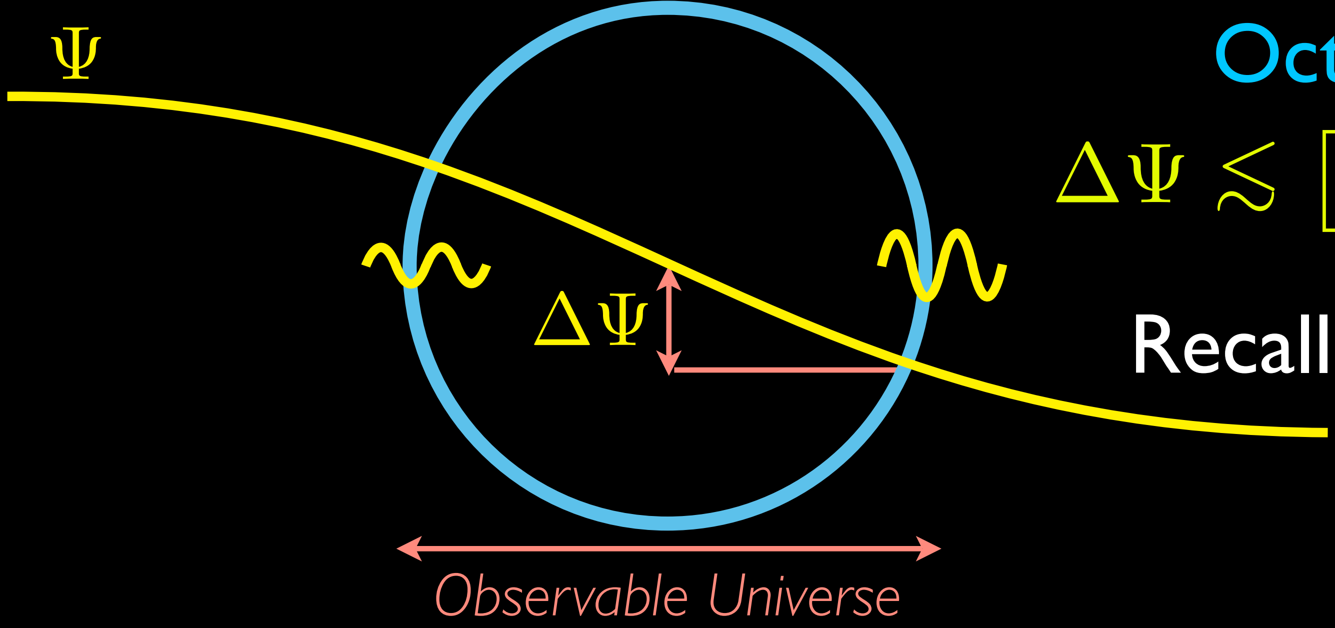

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$$\boxed{\frac{\Delta P}{P} \lesssim 0.01}$$

Erickcek, Kamionkowski, Carroll 2008

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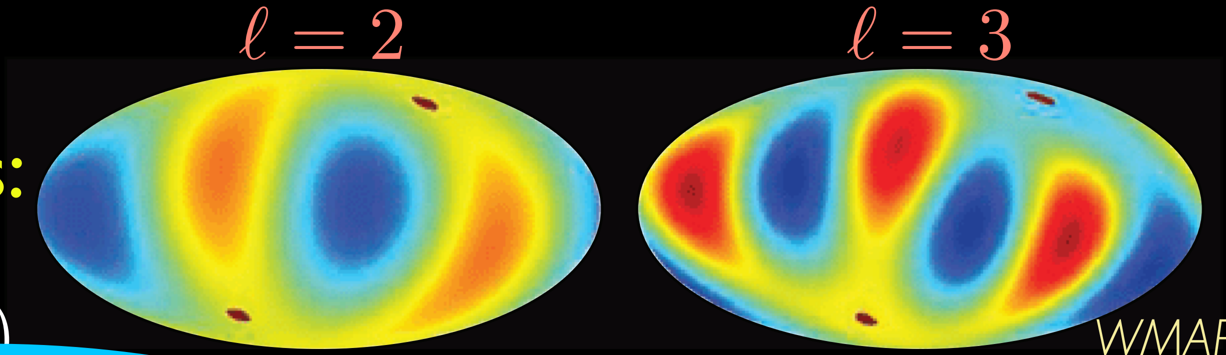

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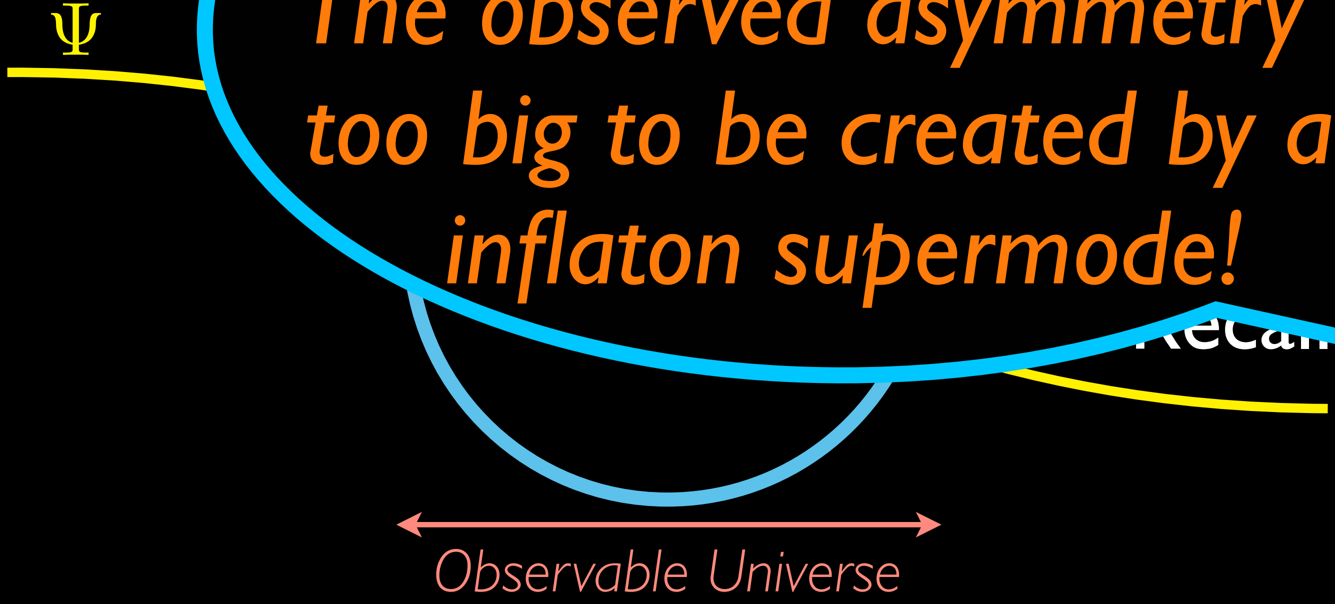
Superm

$+ \varpi \Big]$ ← *phase of our location*

Observed: $\frac{\Delta P}{P} \simeq 0.2$

The observed asymmetry is too big to be created by an inflaton supermode!



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$$\boxed{\frac{\Delta P}{P} \lesssim 0.01}$$

Erickcek, Kamionkowski, Carroll 2008

Back to the chalkboard...

The problem with the inflaton model is two-fold:

- The fluctuation power is weakly dependent on the inflaton's value, so the supermode must have a very large amplitude.
- The inflaton dominates the energy density of the universe, so a "supermode" in the inflaton field generates a huge potential perturbation.
  - CMB octupole places upper bound on $\Delta\Psi$.
  - $\Delta P \propto \Delta\phi \propto \Delta\Psi$ with no wiggle room.

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The solution: the primordial fluctuations could be generated by a secondary scalar field, the curvaton.

- In this model, there are two scalar fields: the inflaton and the curvaton.
- The fluctuation power depends strongly on the background curvaton value.
- The CMB constraints on $\Delta\Psi$ do not directly constrain ΔP. There is a new free parameter: the fraction of energy in the curvaton.

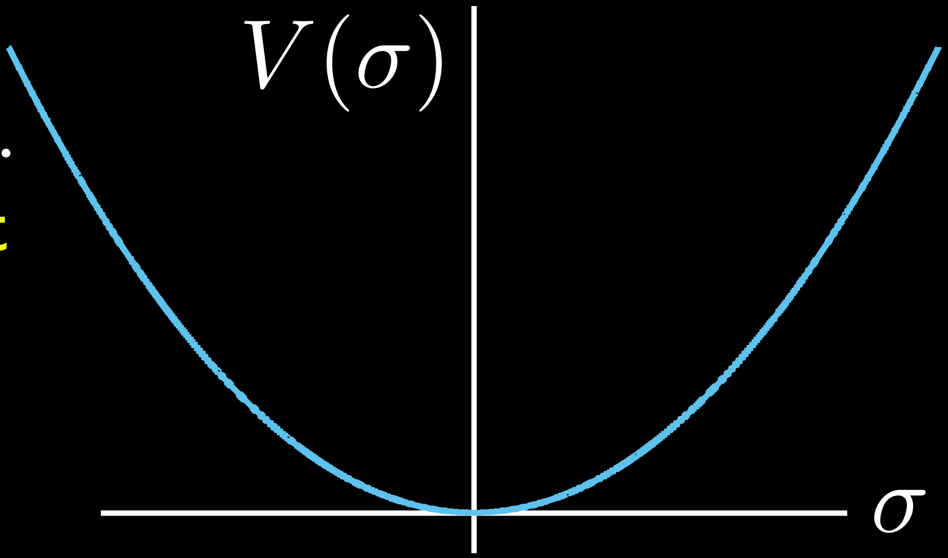
The Curvaton Model

Mollerach 1990; Linde, Mukhanov 1997; Lyth, Wands 2002; Moroi, Takahashi 2001; and others...

- The **inflaton** still dominates the energy density and **drives inflation**.
- The **curvaton** (σ) is a **subdominant scalar field** during inflation.

$$\rho_\sigma \ll \rho_\phi \qquad V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2$$

subdominant *potential*



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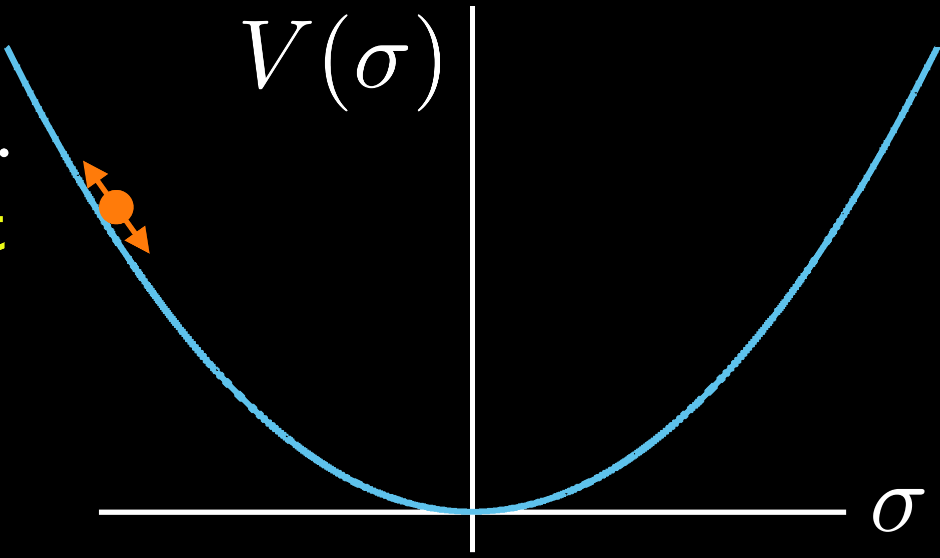

$$\rho_\sigma \ll \rho_\phi \qquad V(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2$$

subdominant *potential*

- During inflation, $m_\sigma \ll H$, and the curvaton is frozen at its initial value, but there are **quantum fluctuations**.

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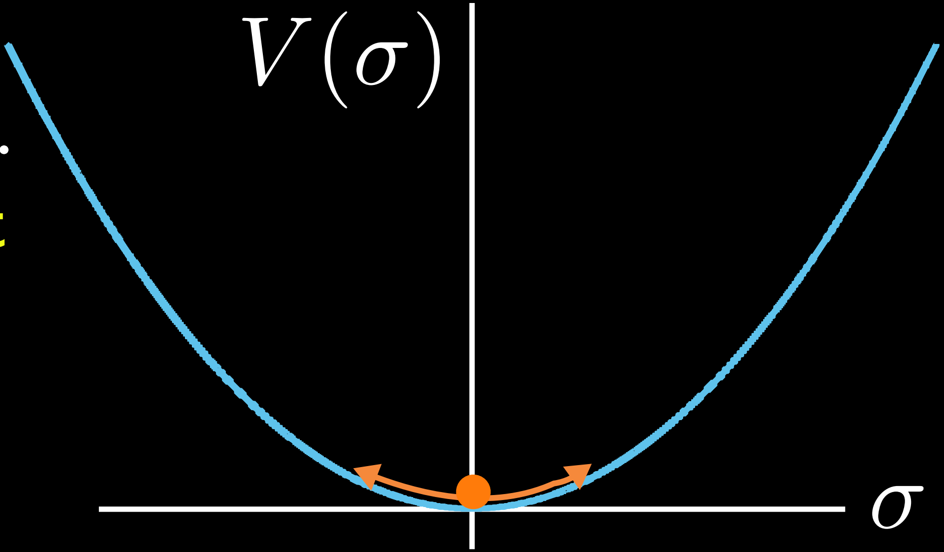
$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2$
potential

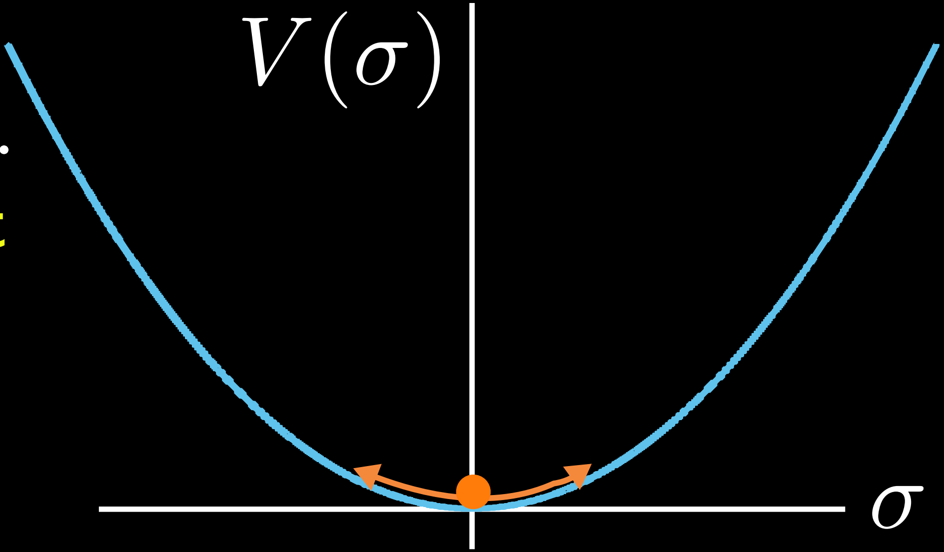


- During inflation, $m_\sigma \ll H$, and the curvaton is frozen at its initial value, but there are quantum fluctuations.
- After inflation, when $m_\sigma \simeq H$, the curvaton oscillates in its potential well. It is a pressureless fluid and behaves like cold gas.
- Still in the early Universe, the curvaton decays into radiation.

The Curvaton Model

Mollerach 1990; Linde, Mukhanov 1997; Lyth, Wands 2002; Moroi, Takahashi 2001; and others...

- The inflaton still dominates the energy density and drives inflation.
- The curvaton (σ) is a subdominant scalar field during inflation.



$\rho_\sigma \ll \rho_\phi$ *subdominant*

$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2$ *potential*

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- Still in the early Universe, the curvaton decays into radiation.

After the end of inflation and prior to curvaton decay, the fractional energy in the curvaton grows.

Power Spectrum from the Curvaton

Curvaton field fluctuations become gravitational potential fluctuations:

$$\Psi_{(\sigma)} = -\frac{R}{5}\frac{\delta\rho_\sigma}{\rho_\sigma} \quad \text{where} \quad R \simeq \frac{3}{4}\left.\frac{\rho_\sigma}{\rho}\right|_{\sigma\,\rightarrow \mathrm{rad.}} \quad \text{and} \quad R \ll 1$$

gravitational perturbation from curvaton $\left(\frac{\Delta T_{\mathrm{CMB}}}{T_{\mathrm{CMB}}} = \frac{\Psi}{3}\right)$

curvaton energy density

evaluated just prior to curvaton decay

keep the curvaton subdominant

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Fractional variation in the curvaton's energy density:

$$\frac{\delta\rho_\sigma}{\rho_\sigma} = 2\left(\frac{\delta\sigma}{\bar{\sigma}}\right) + \left(\frac{\delta\sigma}{\bar{\sigma}}\right)^2$$

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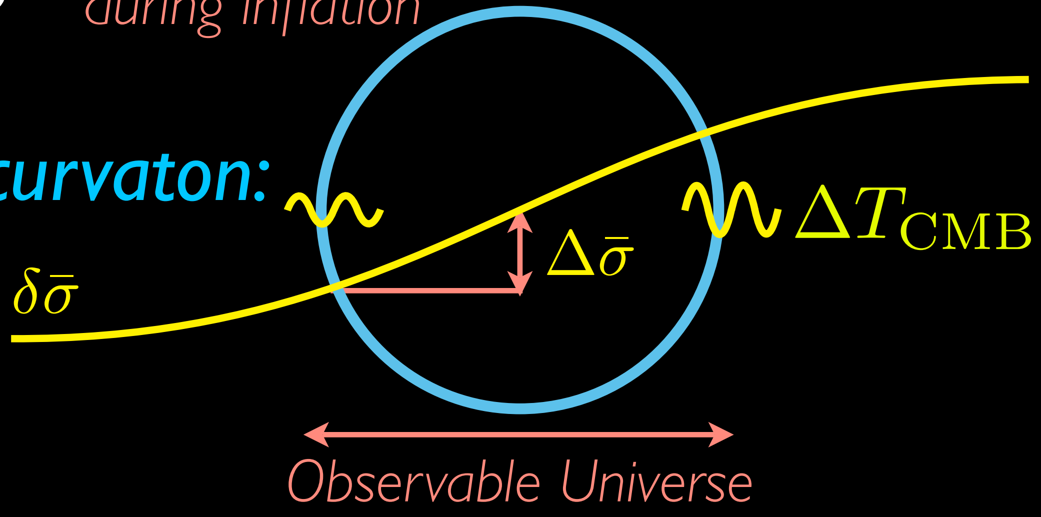

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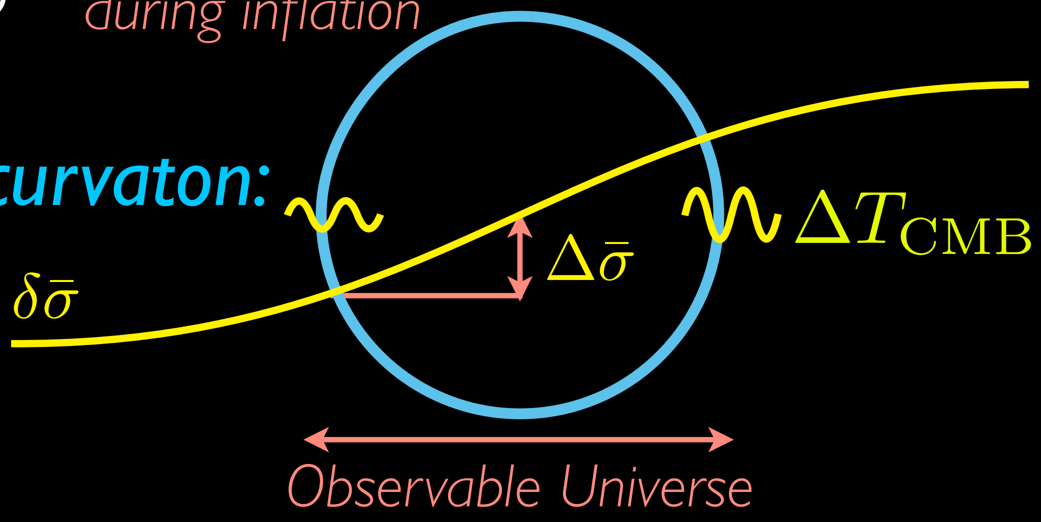
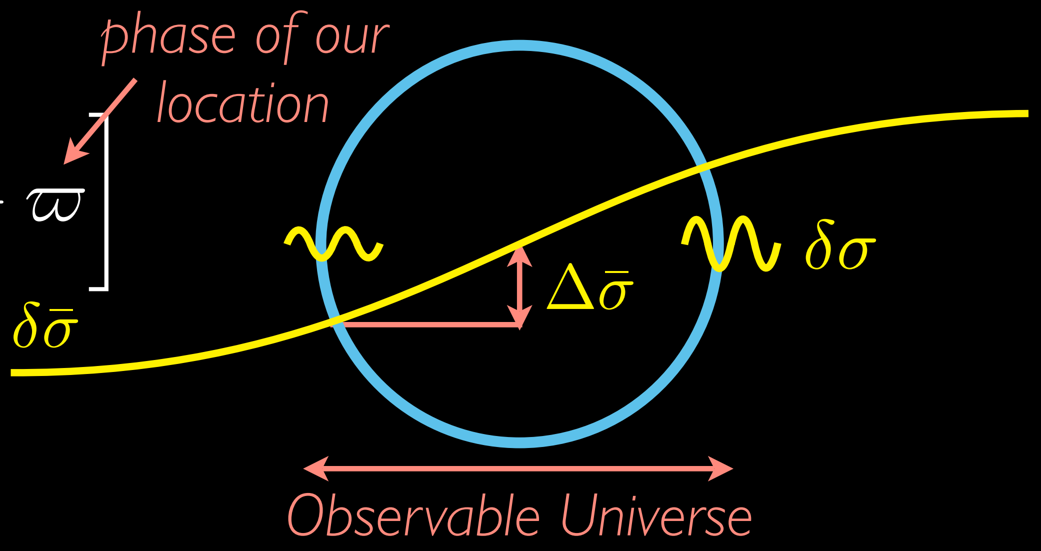
$$\boxed{\frac{\Delta P_{(\sigma)}}{P_{(\sigma)}} = 2\frac{\Delta\bar{\sigma}}{\bar{\sigma}}}$$



Curvaton Supermodes in the CMB

Curvaton supermode:

$$\delta\bar{\sigma}(\vec{x},t) = \bar{\sigma}_{\rm SM}(t)\sin\left[\left(\frac{2\pi}{L}\right)x + \varpi\right]$$



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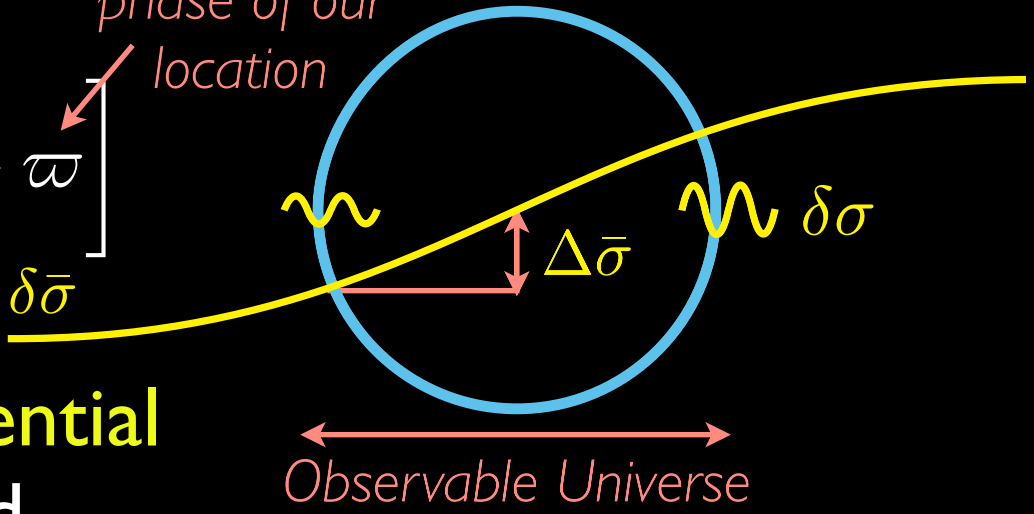

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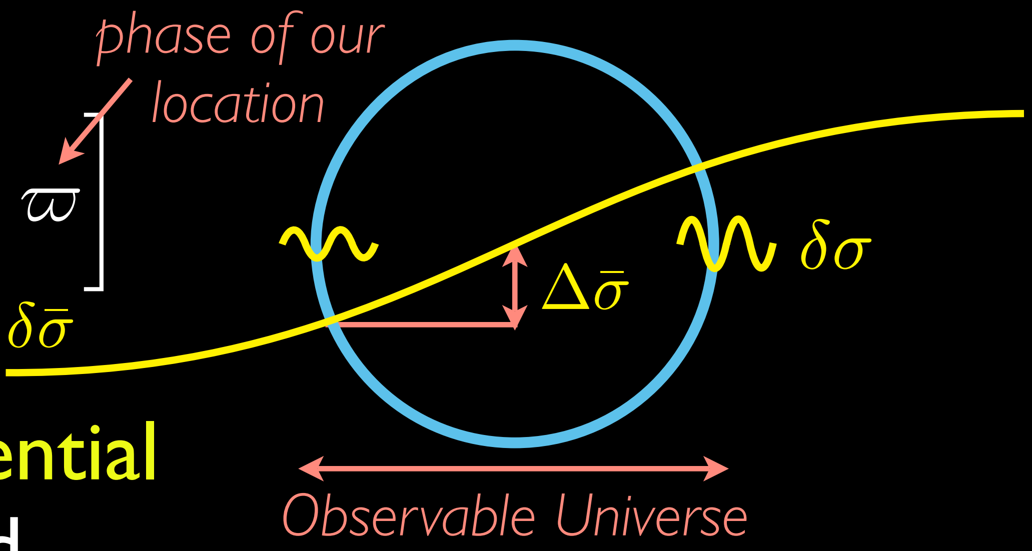

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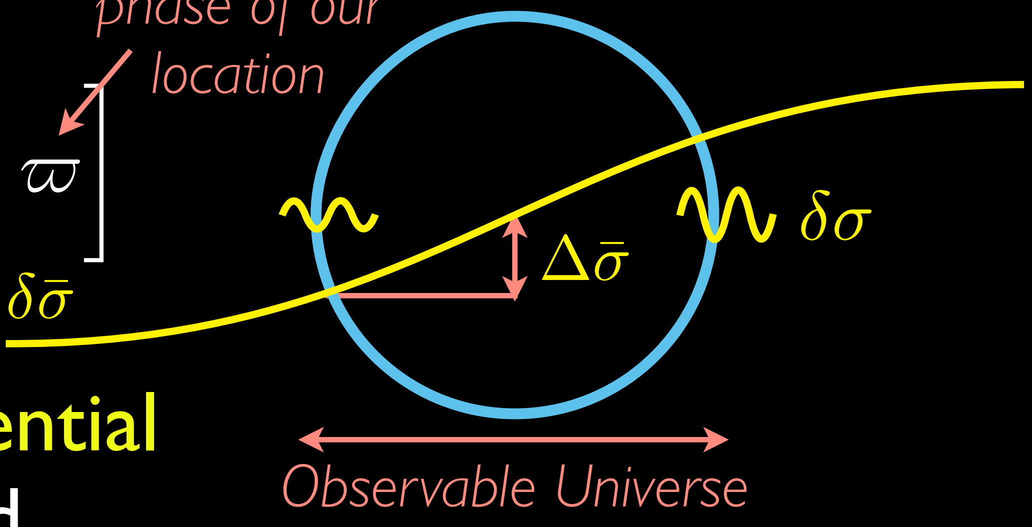

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The potential perturbation is not sinusoidal!

- The CMB quadrupole and octupole have complicated ϖ dependencies.
- There is no phase that eliminates the quadrupole for all values of $\bar{\sigma}_{\rm SM}$.

Curvaton Supermodes in the CMB

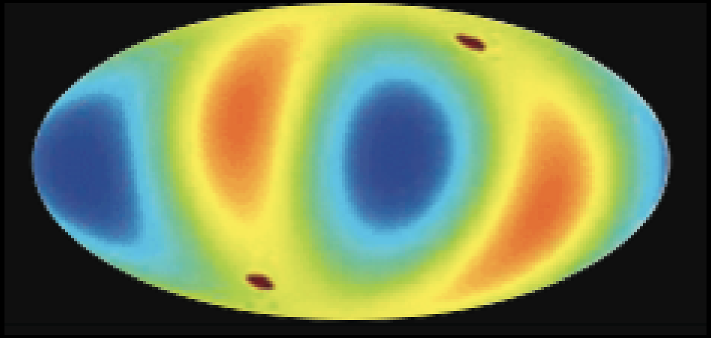
The CMB quadrupole implies an upper bound:

$$R\left(\frac{\Delta\bar{\sigma}}{\bar{\sigma}}\right)^2 \lesssim \frac{5}{2}\times 5.8|a_{20}^{\mathrm{SM}}| \text{ for } \varpi = 0$$

$\frac{\Delta P}{P}$

1.8×10^{-5}

Most other phases give similar bounds.



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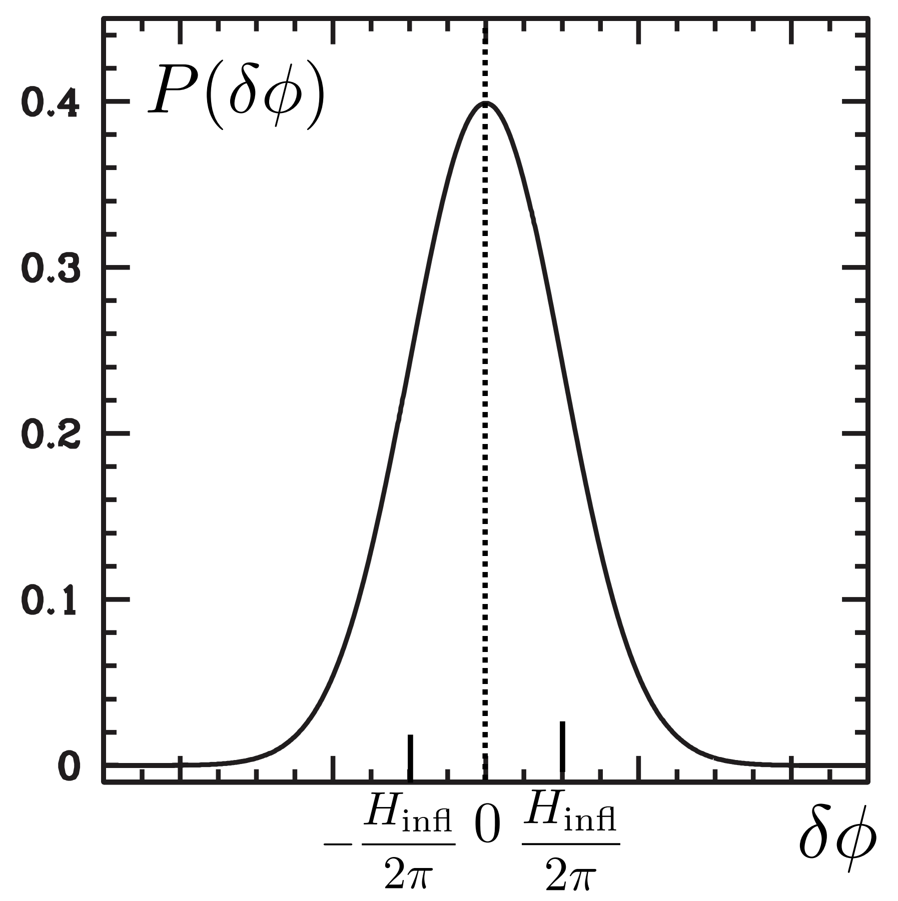
Non-Gaussianity and the Curvaton

The quantum fluctuations during inflation are Gaussian.



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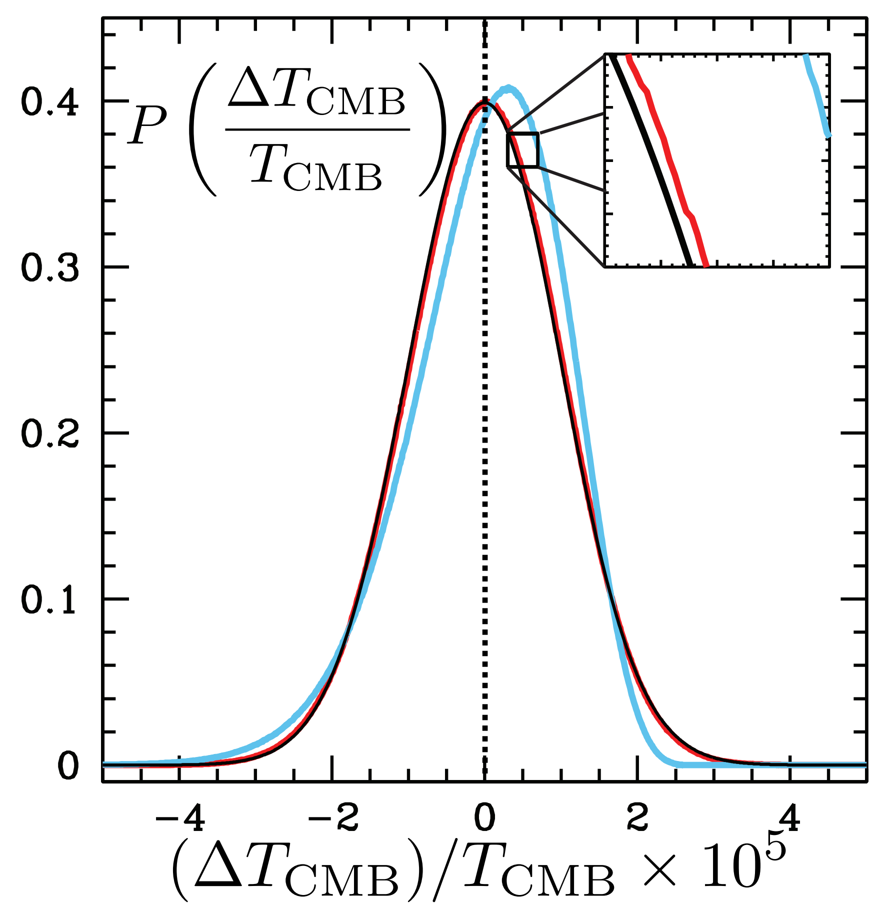

temperature fluctuation $\frac{\Delta T_{\mathrm{CMB}}}{T_{\mathrm{CMB}}} = \frac{\Psi}{3}$ *gravitational potential*

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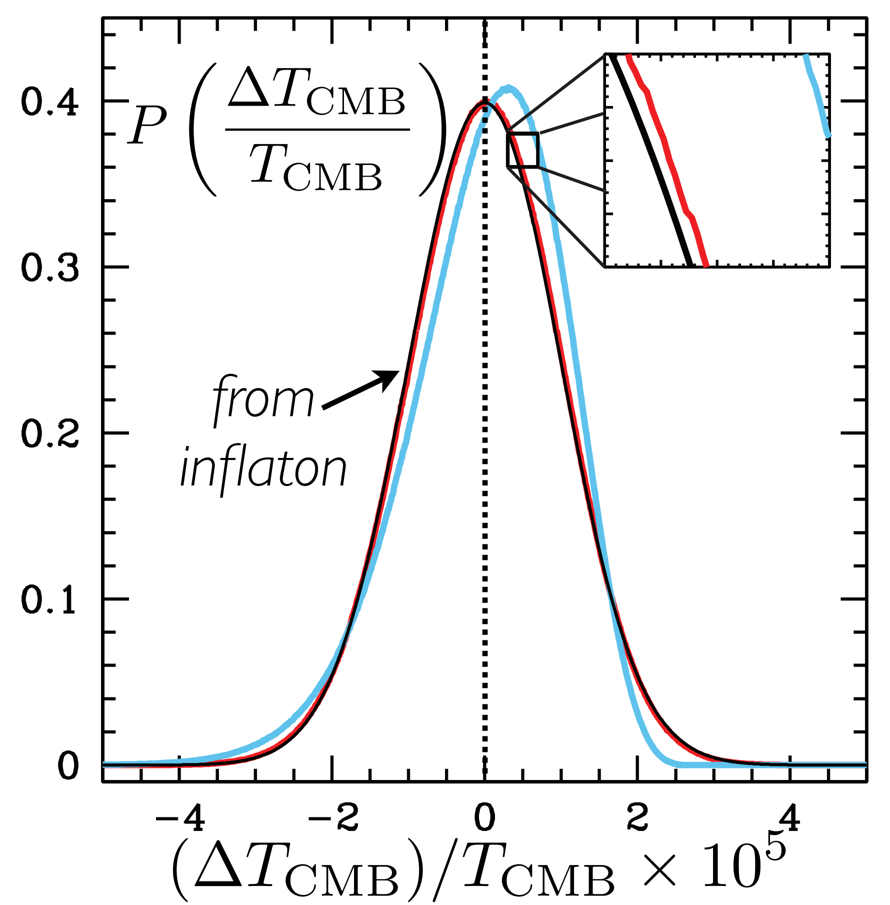

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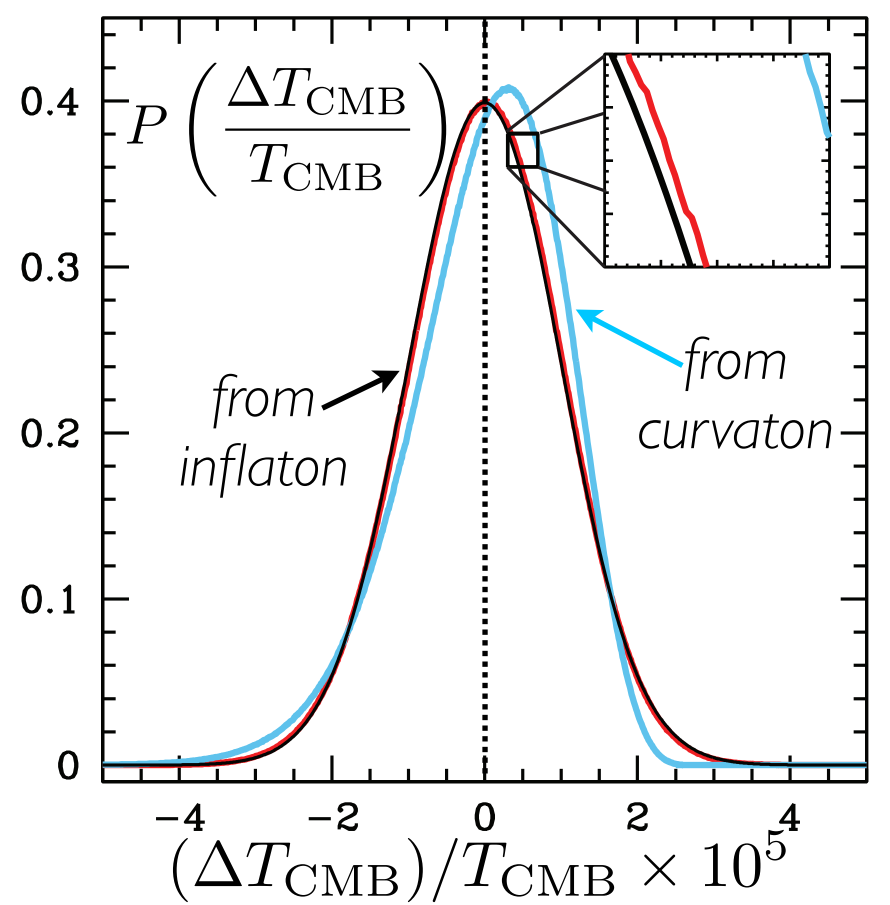

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$$\underbrace{\Psi}_{\text{gravitational potential fluctuation}} = -\frac{R}{5}\left[2\underbrace{\left(\frac{\delta\sigma}{\bar{\sigma}}\right)}_{\text{Gaussian fluctuation}} + \underbrace{\left(\frac{\delta\sigma}{\bar{\sigma}}\right)^2}_{\text{Gaussian fluctuation squared}}\right]$$

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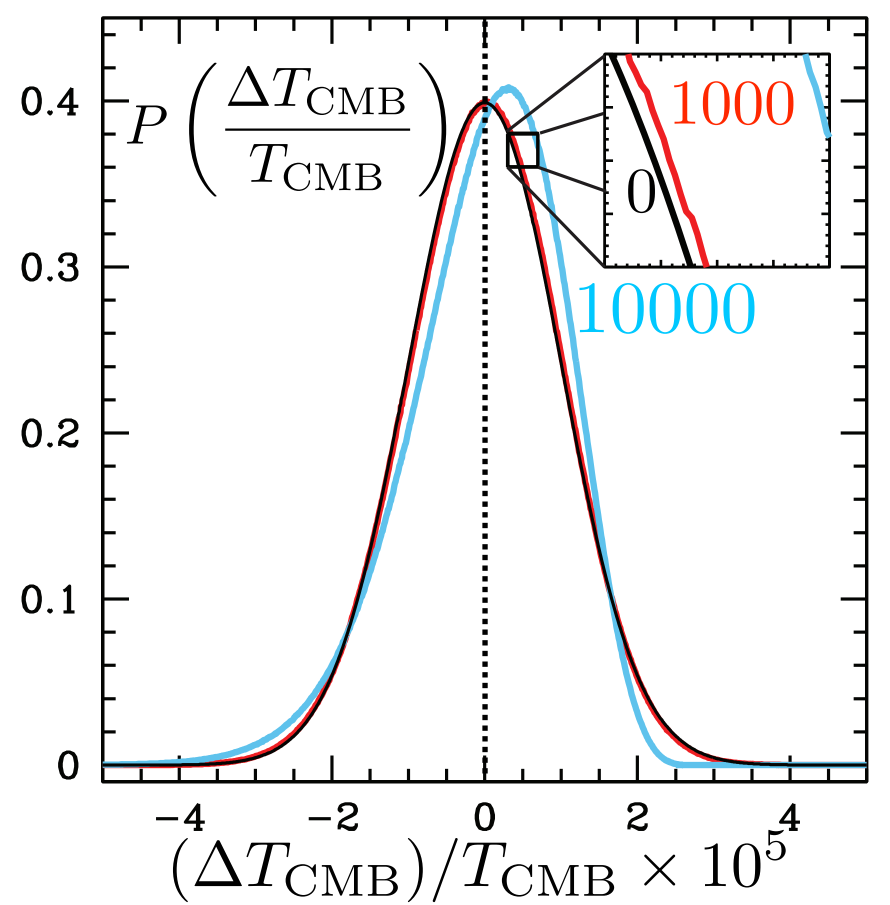

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gravitational potential fluctuation

↑ Gaussian fluctuation

↑ Gaussian fluctuation squared

Parametrize:

$$\Psi = \Psi_{\rm g} - f_{\rm NL}\Psi_{\rm g}^2$$

Constraining the Curvaton Model

The curvaton and inflaton both contribute to the CMB temperature fluctuations:

$$\xi \equiv \frac{\Delta P_{(\sigma)}}{P}$$

fractional power from curvaton

$$\frac{\Delta P}{P} = 2\xi \frac{\Delta\bar{\sigma}}{\bar{\sigma}}$$

power asymmetry

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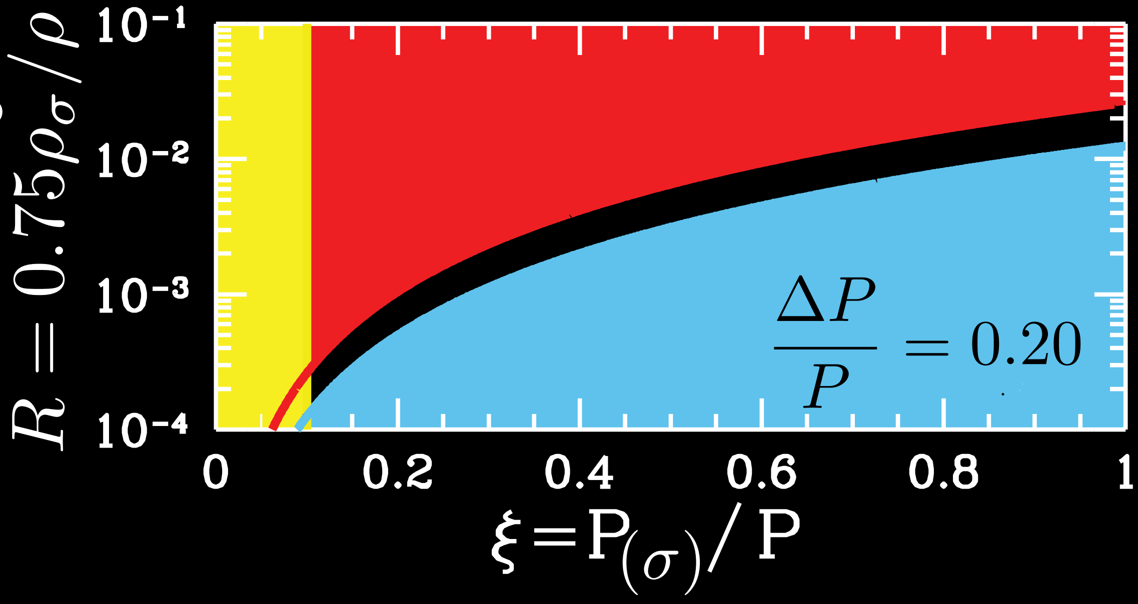
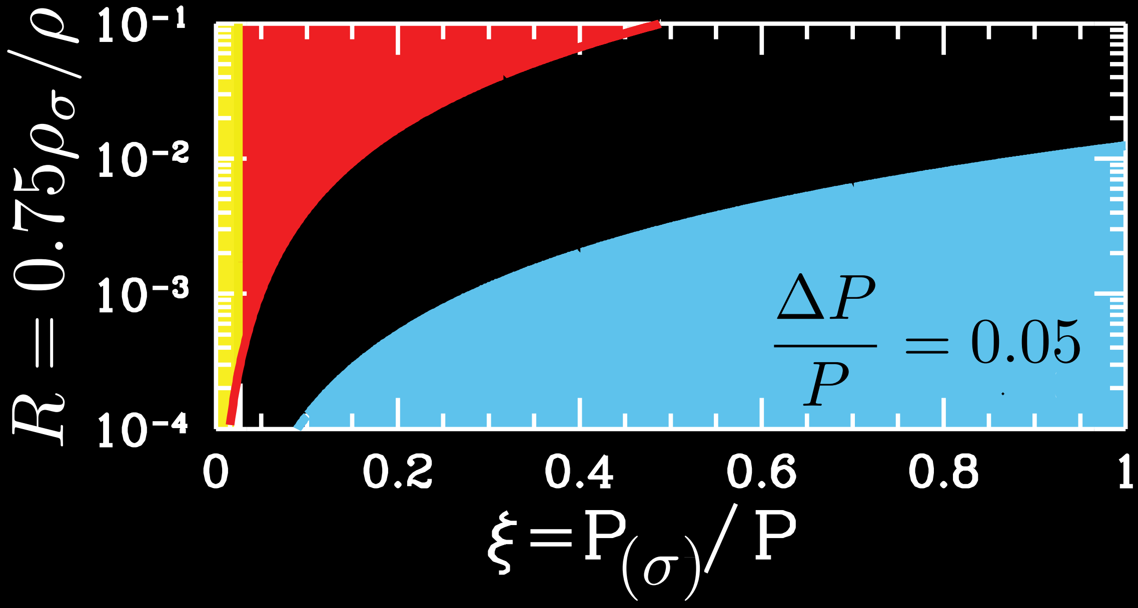
$$\frac{\Delta\bar{\sigma}}{\bar{\sigma}} \lesssim 1 \Longrightarrow \xi \gtrsim \frac{1}{2}\frac{\Delta P}{P}$$





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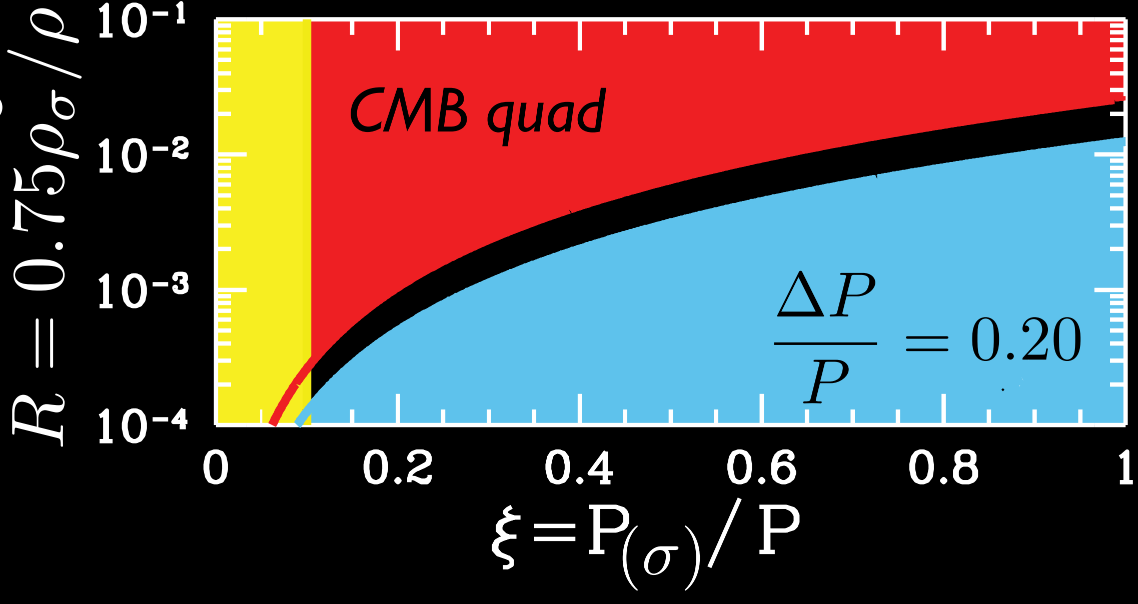
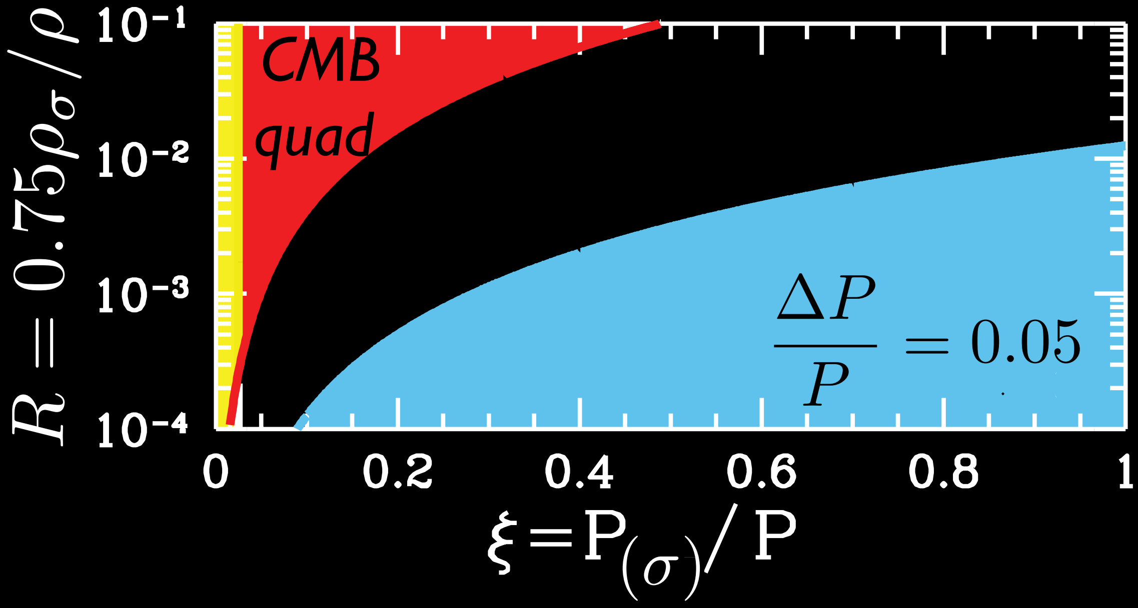
CMB Quadrupole:

$$R\left(\frac{\Delta\bar{\sigma}}{\bar{\sigma}}\right)^2 \lesssim \frac{5}{2}(5.8Q)$$





Constraining the Curvaton Model

Non-Gaussianity Constraints

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gravitational potential fluctuation

Gaussian fluctuation

Gaussian fluctuation squared

$$f_{\rm NL} \simeq \frac{5\xi^2}{4R}$$

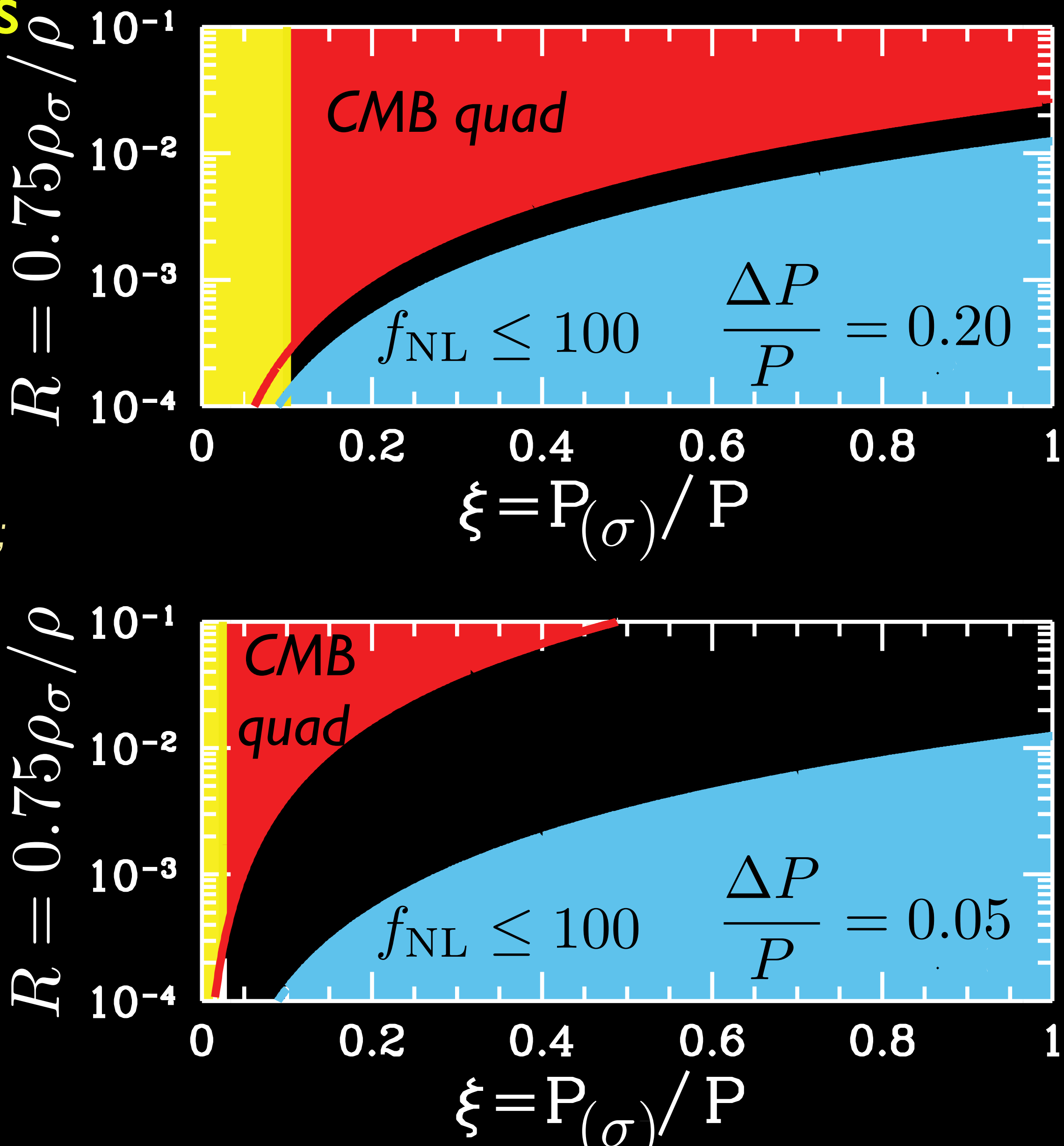
Lyth, Ungarelli, Wands 2003; Ichikawa, Suyama, Takahashi, Yamaguchi 2008

Amount of non-Gaussianity

Upper bound from WMAP:

$$f_{\rm NL} \lesssim 100$$

Komatsu et al. 2008
Yadav, Wandelt 2008



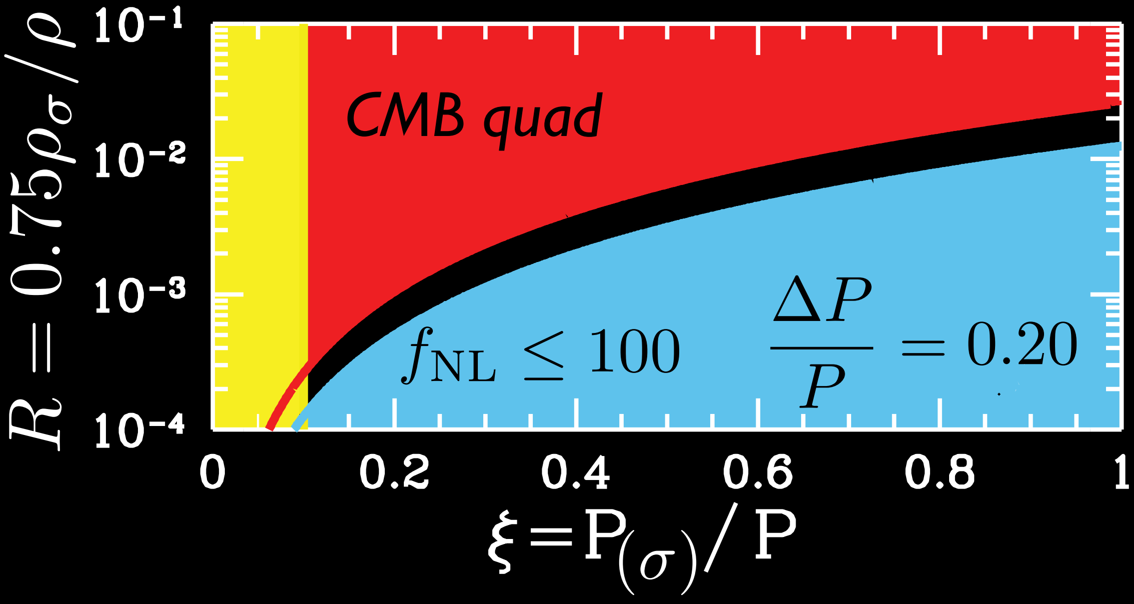
Constraining the Curvaton Model

The Allowed Region

$$\frac{5}{4f_{\mathrm{NL,max}}} \lesssim \frac{R}{\xi^2} \lesssim \frac{58\left|a_{20}^{\mathrm{SM}}\right|}{(\Delta P/P)^2}$$

Non-Gaussianity ↑ CMB Quadrupole

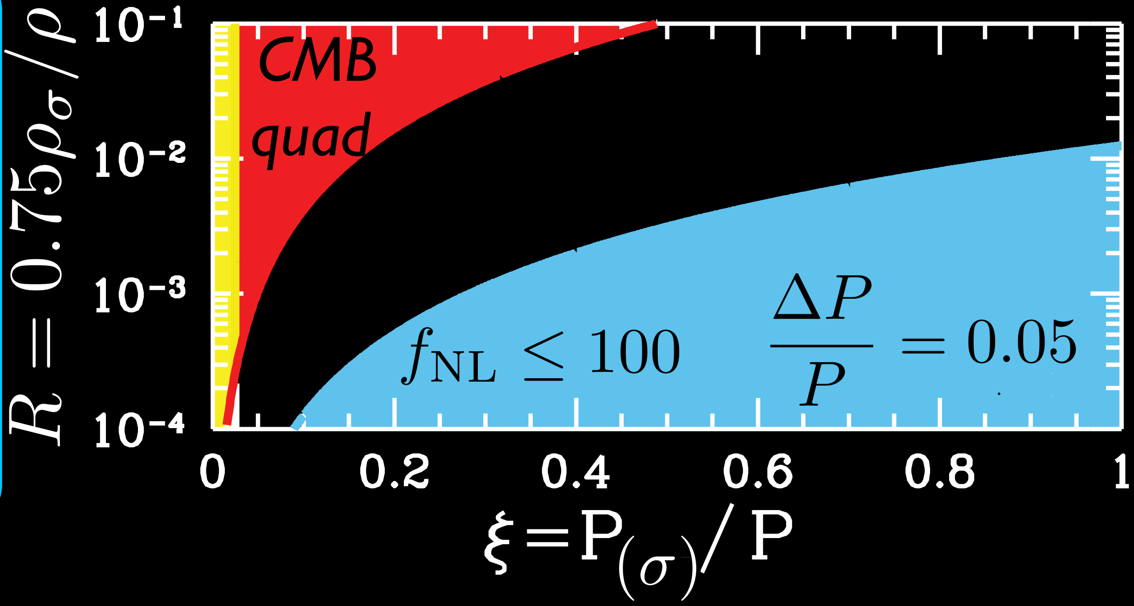
Allowed window



The Dealbreaker

The window for $\frac{\Delta P}{P} = 0.20$

disappears if $f_{\mathrm{NL,max}} \lesssim 50$



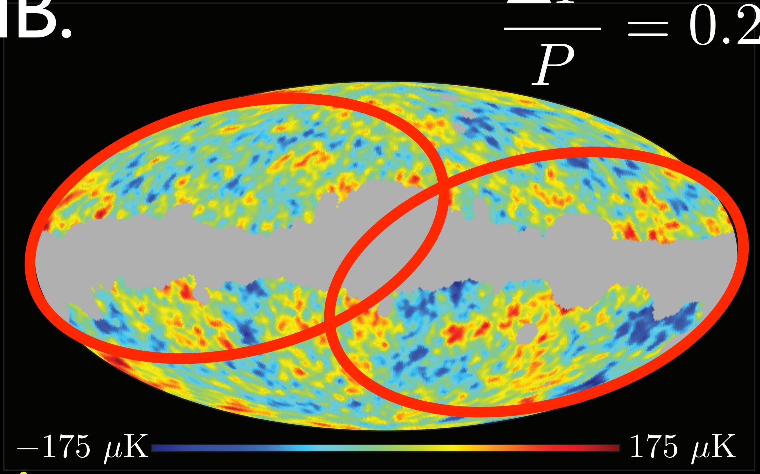
Summary: How to Generate the Power Asymmetry

There is a power asymmetry in the CMB.

- present at the 99% confidence level
- detected on large scales

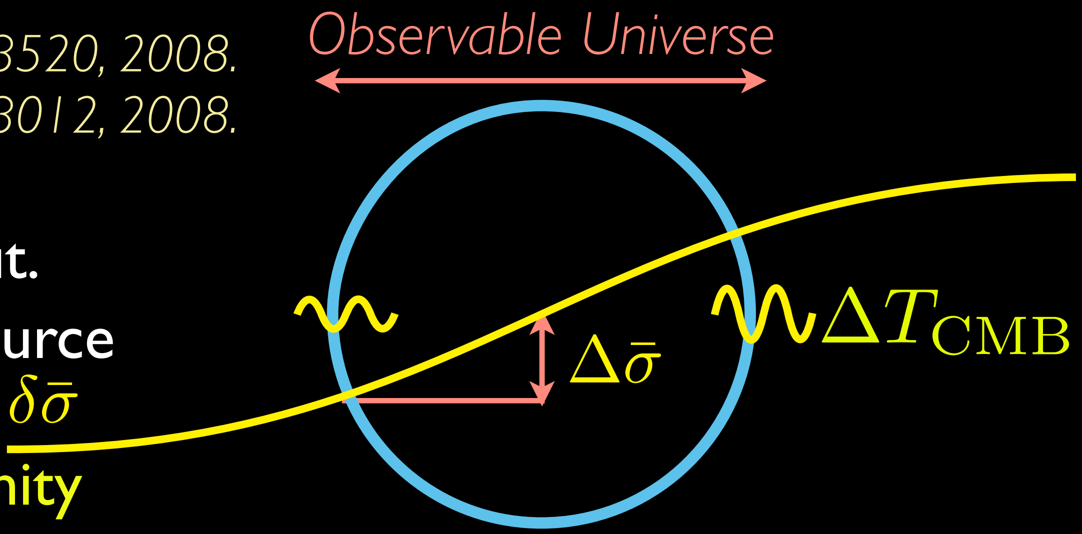
Hansen, Banday, Gorski, 2004
Eriksen, Hansen, Banday, Gorski, Lilje 2004
Eriksen, Banday, Gorski, Hansen, Lilje 2007

$$\frac{\Delta P}{P} = 0.20$$



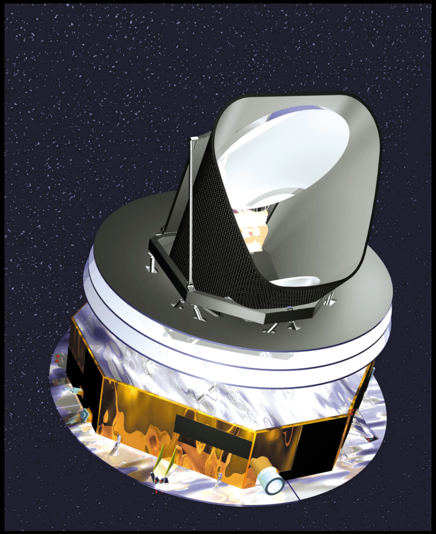
A superhorizon fluctuation during inflation generates a power asymmetry.

Erickcek, Kamionkowski, Carroll Phys. Rev. D78: 123520, 2008.
Erickcek, Carroll, Kamionkowski Phys. Rev. D78: 083012, 2008.

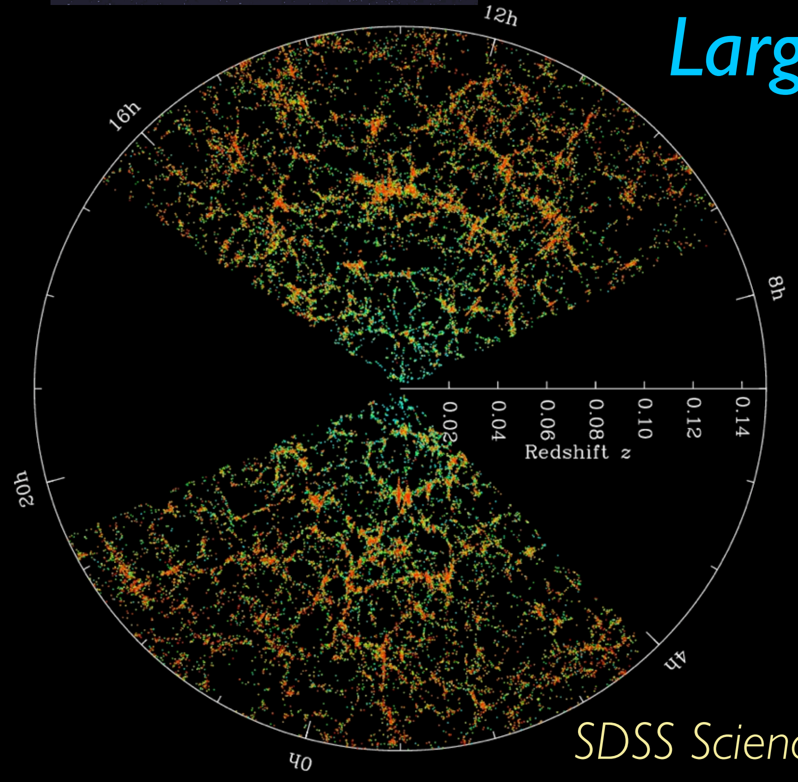


- Asymmetry from an inflaton superhorizon fluctuation is ruled out.
- A curvaton fluctuation is a viable source of the observed asymmetry.
- Significant departures from Gaussianity are required to generate asymmetry.
- The supermode's amplitude is too large to be a quantum fluctuation.

Future Observational Tests



The Planck Satellite: set to launch in April

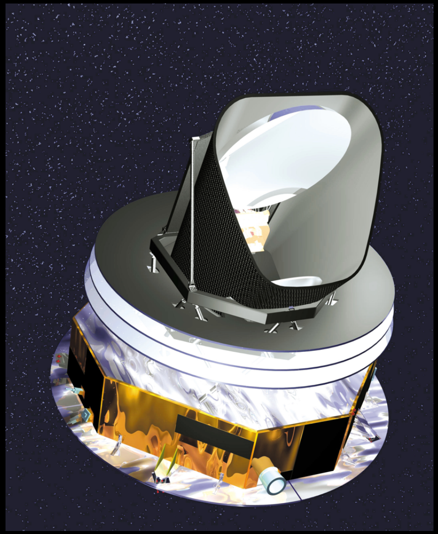


Large Scale Structure Surveys: in progress

Search for CMB polarization from inflationary gravitational waves: in progress

SDSS Science Team

Future Observational Tests



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- higher resolution CMB map
- more frequencies for better foreground subtraction
- measure $f_{\rm NL}$ with error bars of ± 10
- confirm power asymmetry both in temperature and polarization fluctuations?

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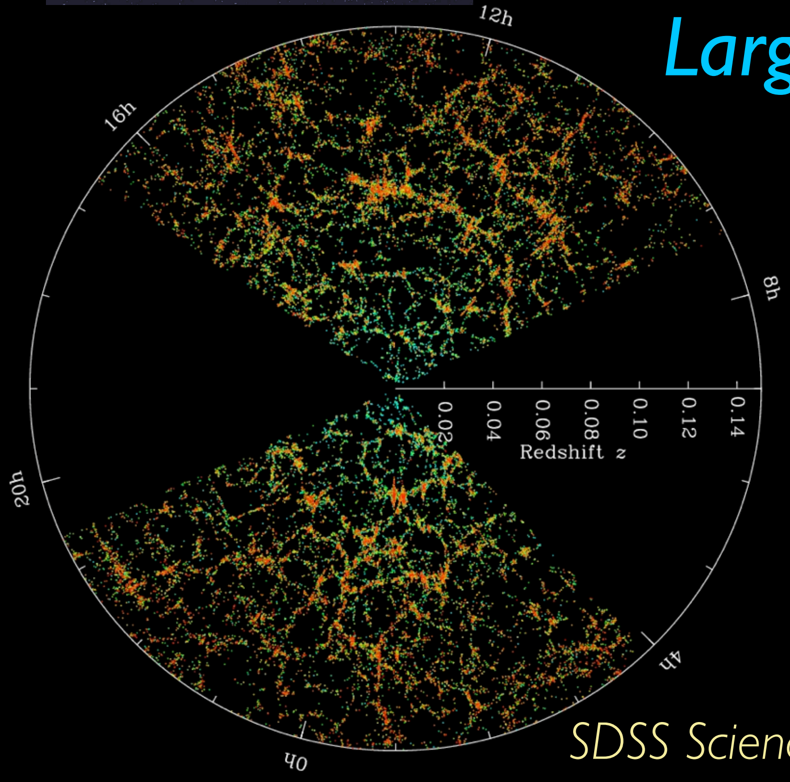

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Search for CMB polarization from inflationary gravitational waves: in progress

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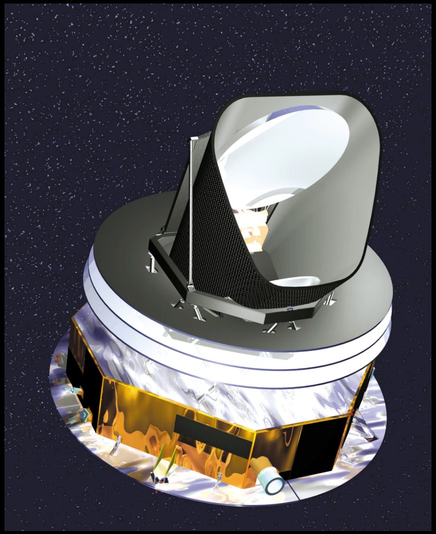

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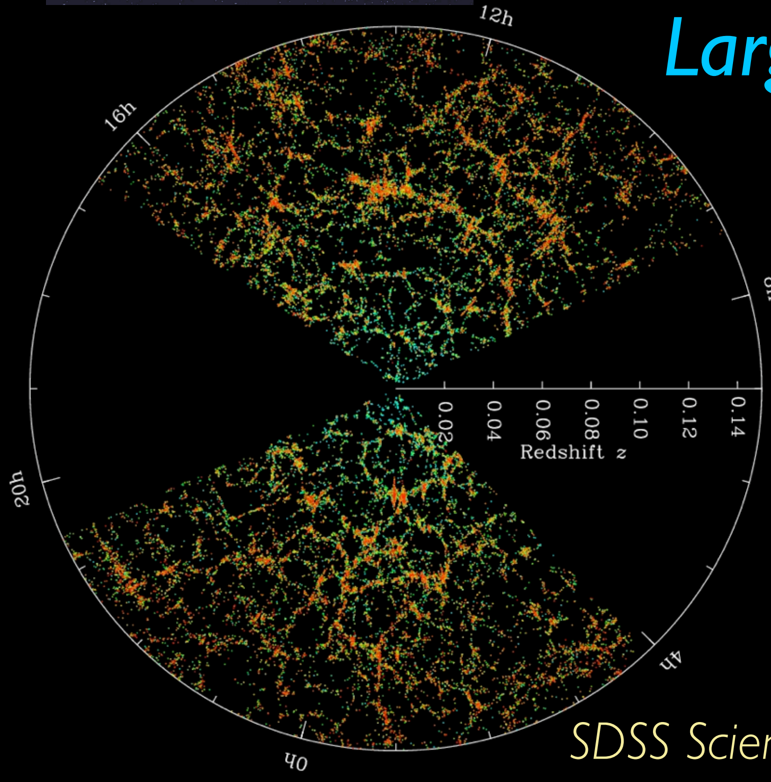

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Large Scale Structure Surveys: in progress

- measure $f_{\rm NL}$ through statistics of galaxy distribution with error bars of ± 10
- search for asymmetry in numbers of galaxies and quasars

Search for CMB polarization from inflationary gravitational waves: in progress

What have we learned?

	Standard Inflation	Curvaton Model with Relic Supermode

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How big is our inflationary patch?	*bigger than the Observable Universe*	*just a little bigger than the Observable Universe*
What was there before inflation?	?	*a subdominant scalar field with large fluctuations*
The power asymmetry?	*a statistical fluke*	*signature of superhorizon fluctuation in curvaton*

What have we learned?

	Standard Inflation	Curvaton Model with Relic Supermode
What drove inflation?	*the inflaton*	*the inflaton, but a different field created the initial fluctuations*
How big is our inflationary patch?	*bigger than the Observable Universe*	*just a little bigger than the Observable Universe*
What was there before inflation?	?	*a subdominant scalar field with large fluctuations*
The power asymmetry?	*a statistical fluke*	*signature of superhorizon fluctuation in curvaton*
Gaussian fluctuations?	*Yes:* $f_{\rm NL} \lesssim 1$	*No:* $f_{\rm NL} \gtrsim 50$

A Bit of Cosmology Humor

“Mature paradigm with firm observational support seeks a fundamental theory in which to be embedded.”

Classified Ad in Fermilab’s Newsletter
February 14, 2008

Inflation’s soulmate may be hiding beyond the cosmological horizon, but we can still find her!