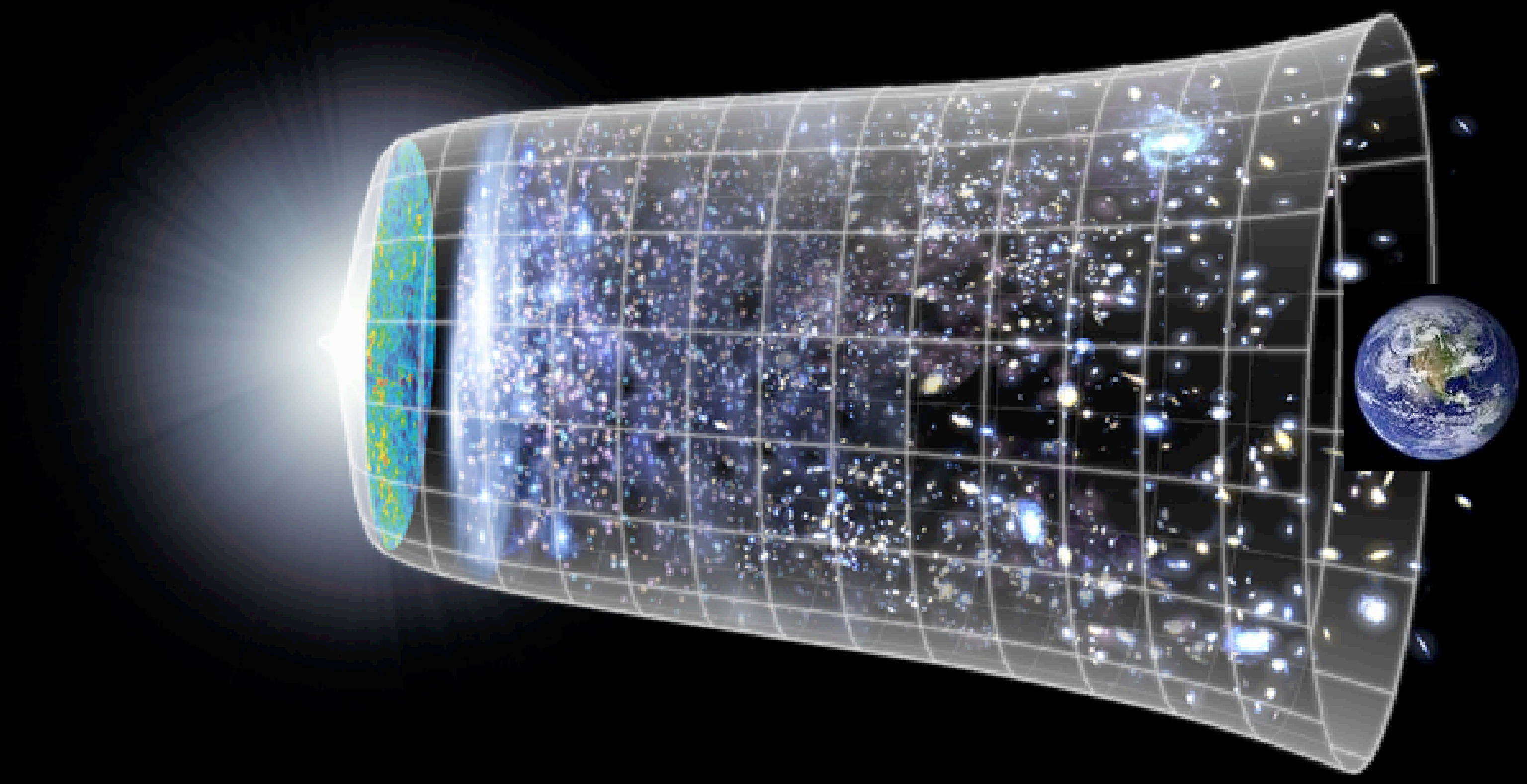
Cosmology 101

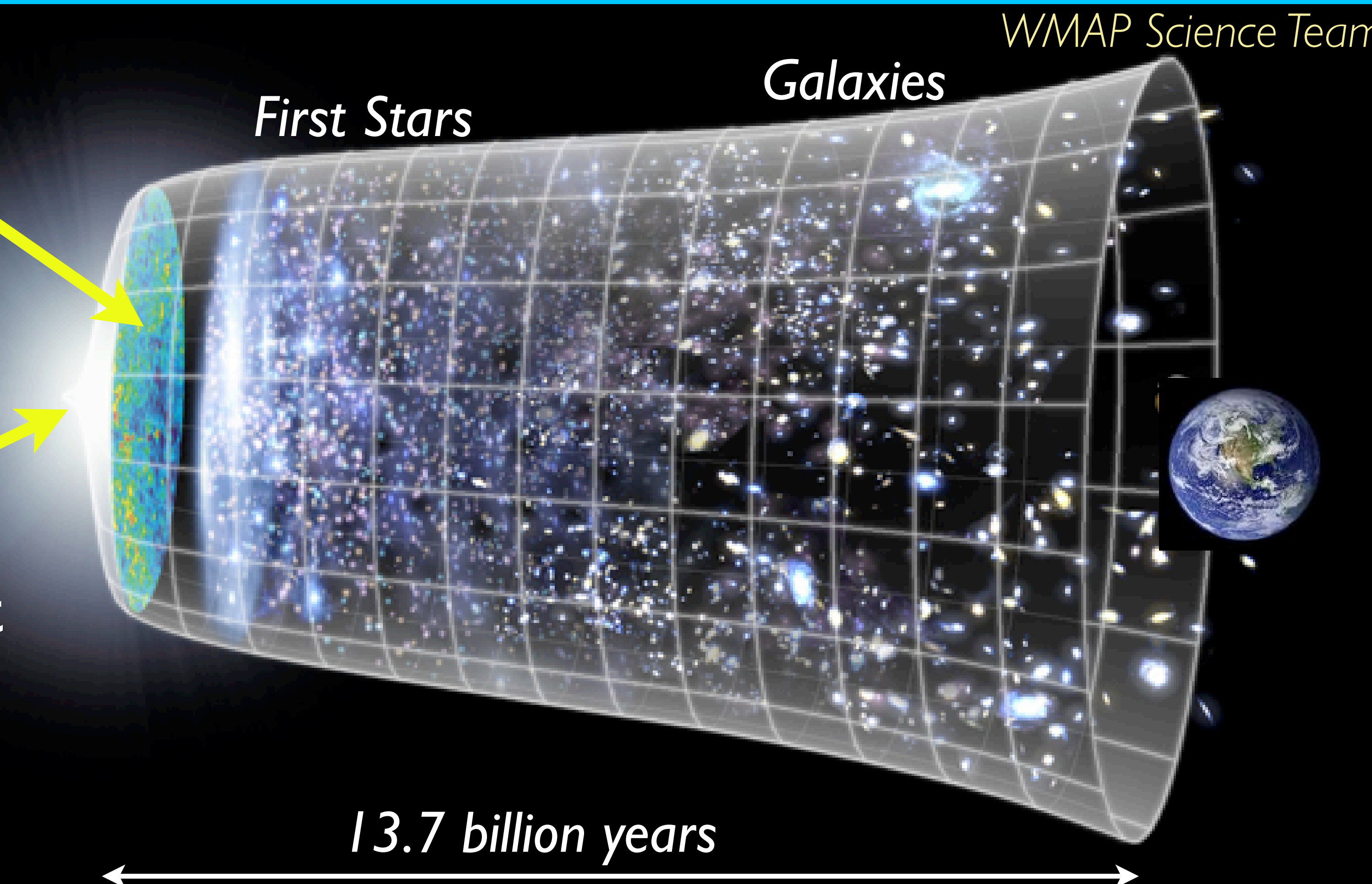


NASA/WMAP Science Team

Adrienne Erickcek
CITA & Perimeter Institute

A Brief History of the Universe

The Cosmic Microwave Background



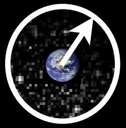
Inflation: an instant of extremely rapid expansion

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

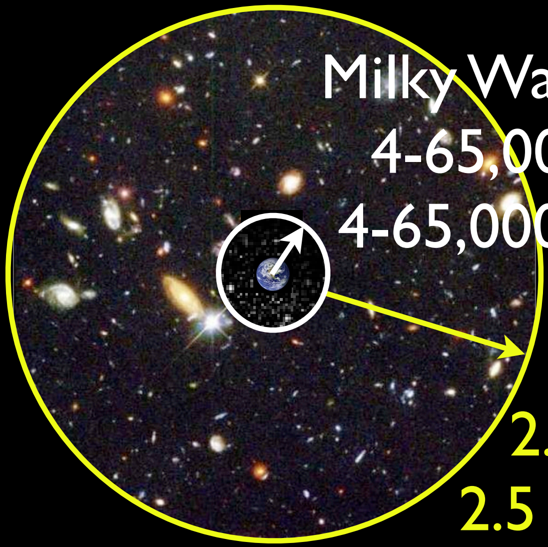
- Electromagnetic observations: looking out = looking back in time
- Quantities of light elements made 2-3 minutes after Big Bang

Looking Back in Time

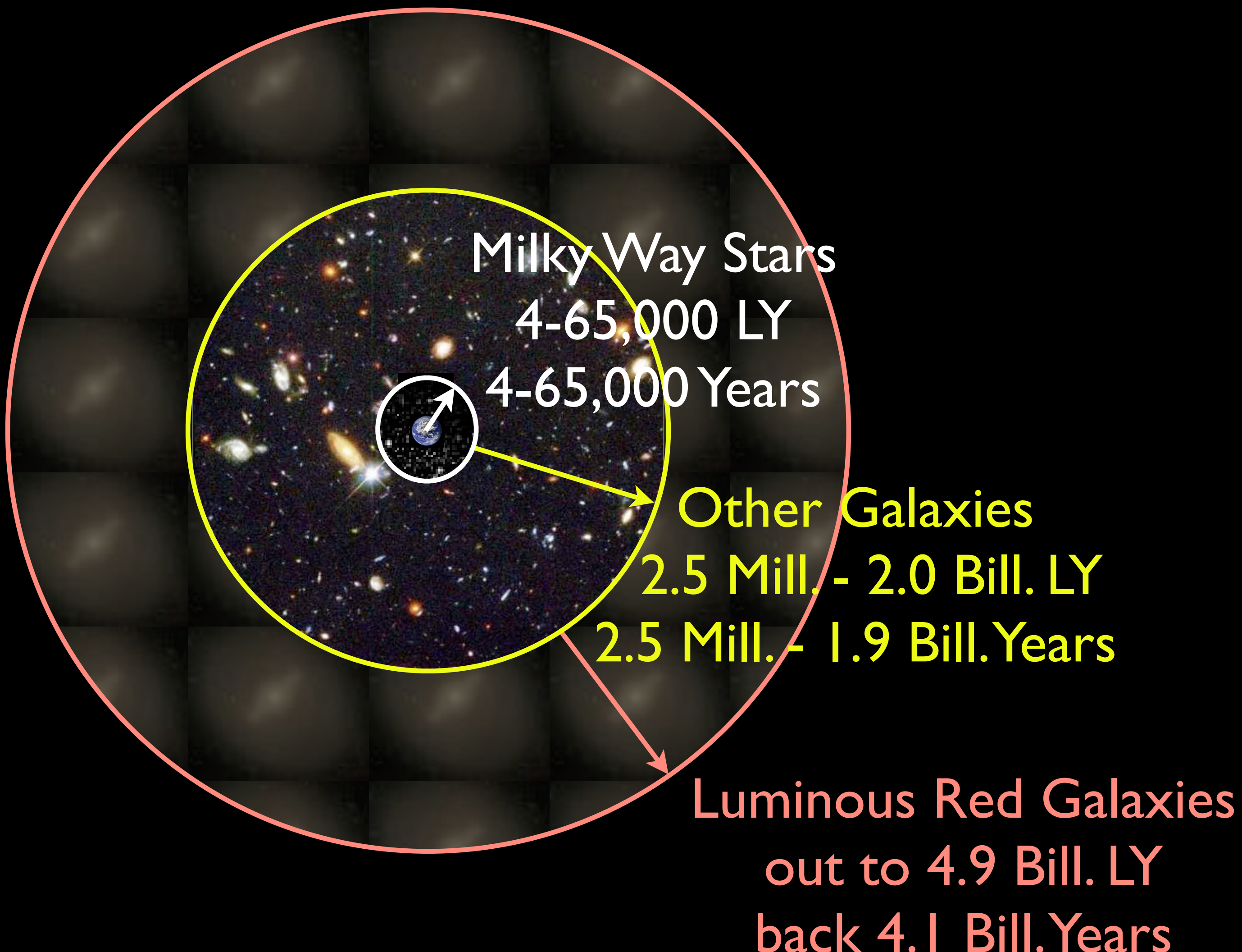
Milky Way Stars
4-65,000 LY
4-65,000 Years



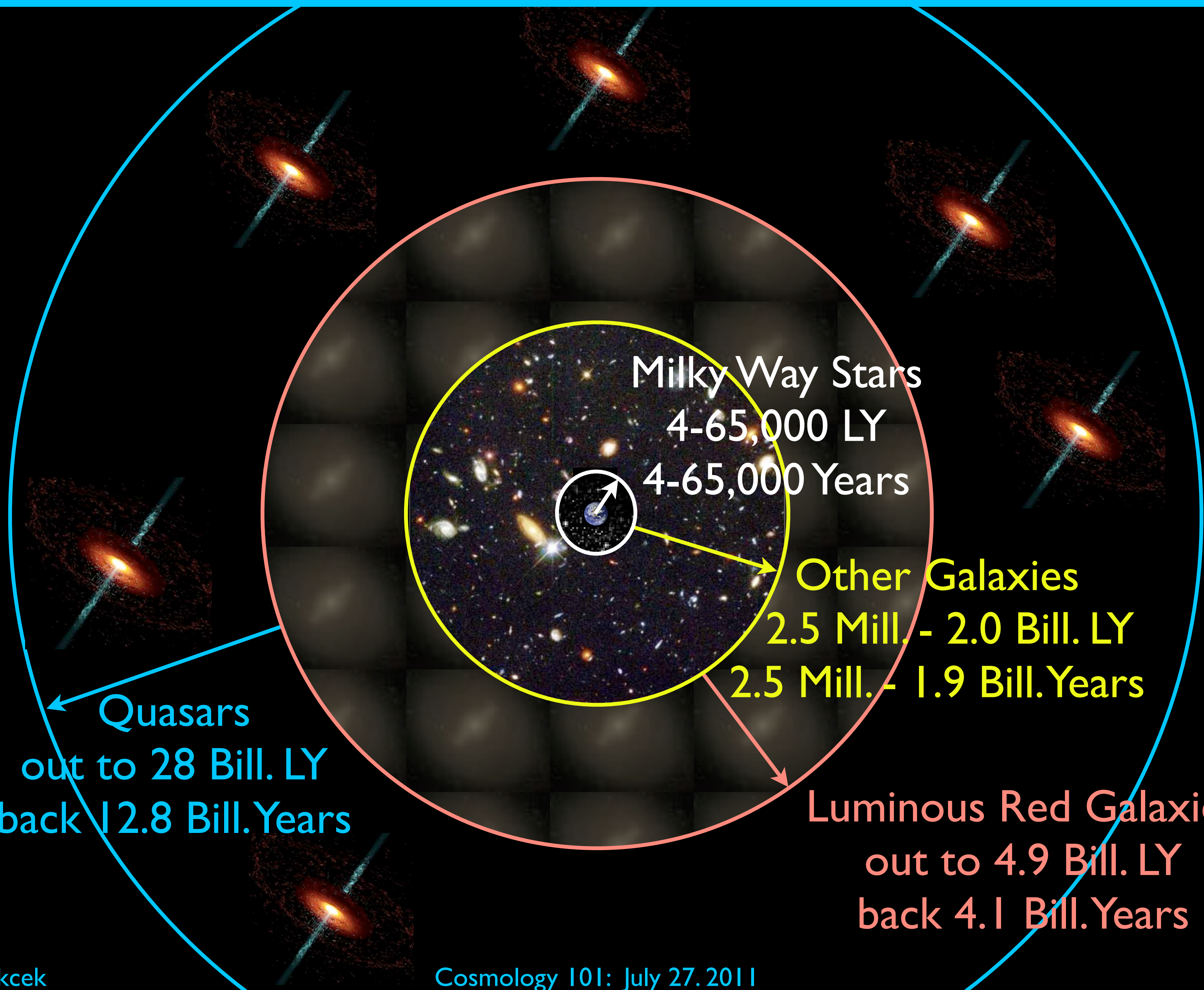
Looking Back in Time



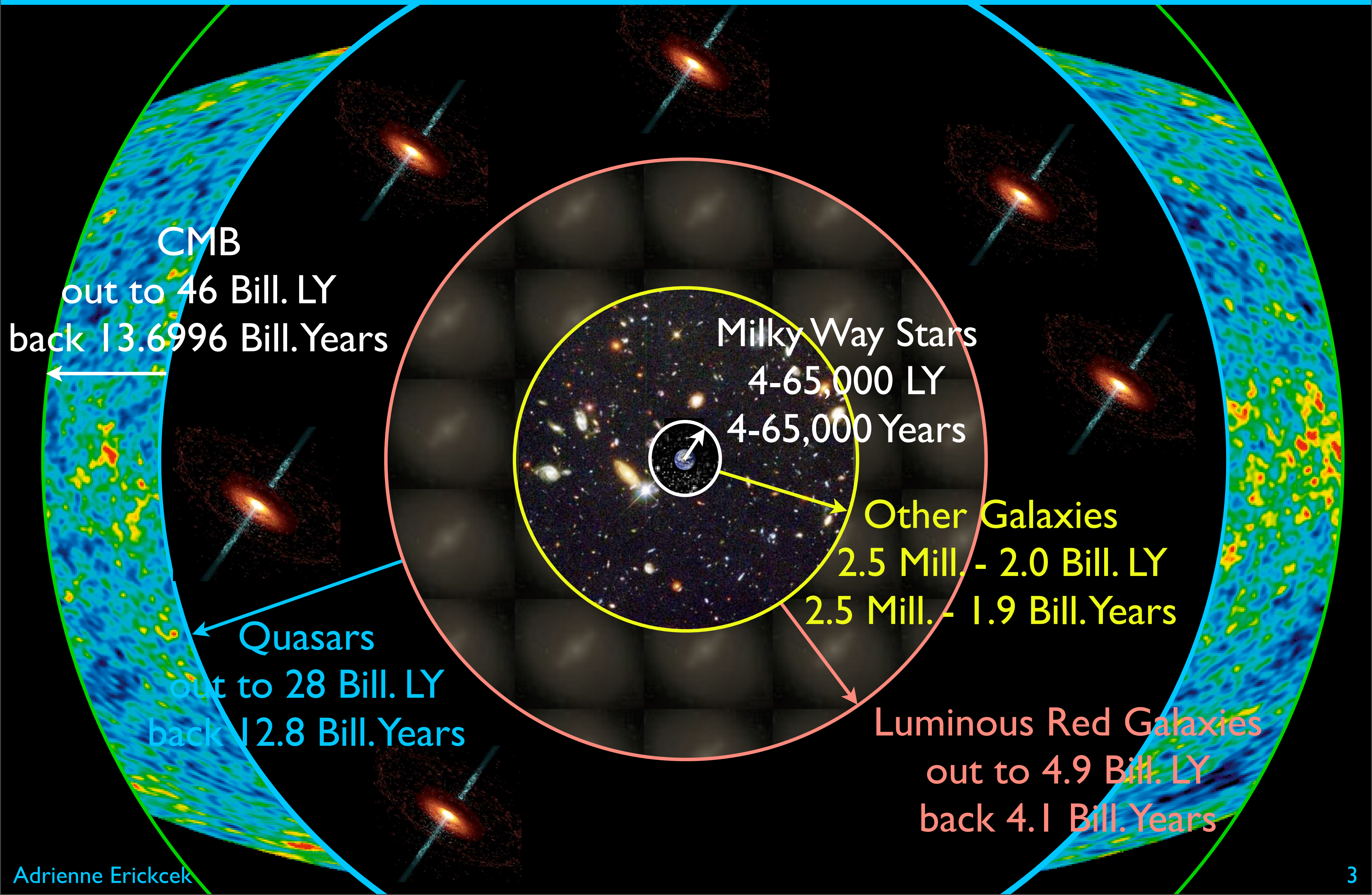
Looking Back in Time



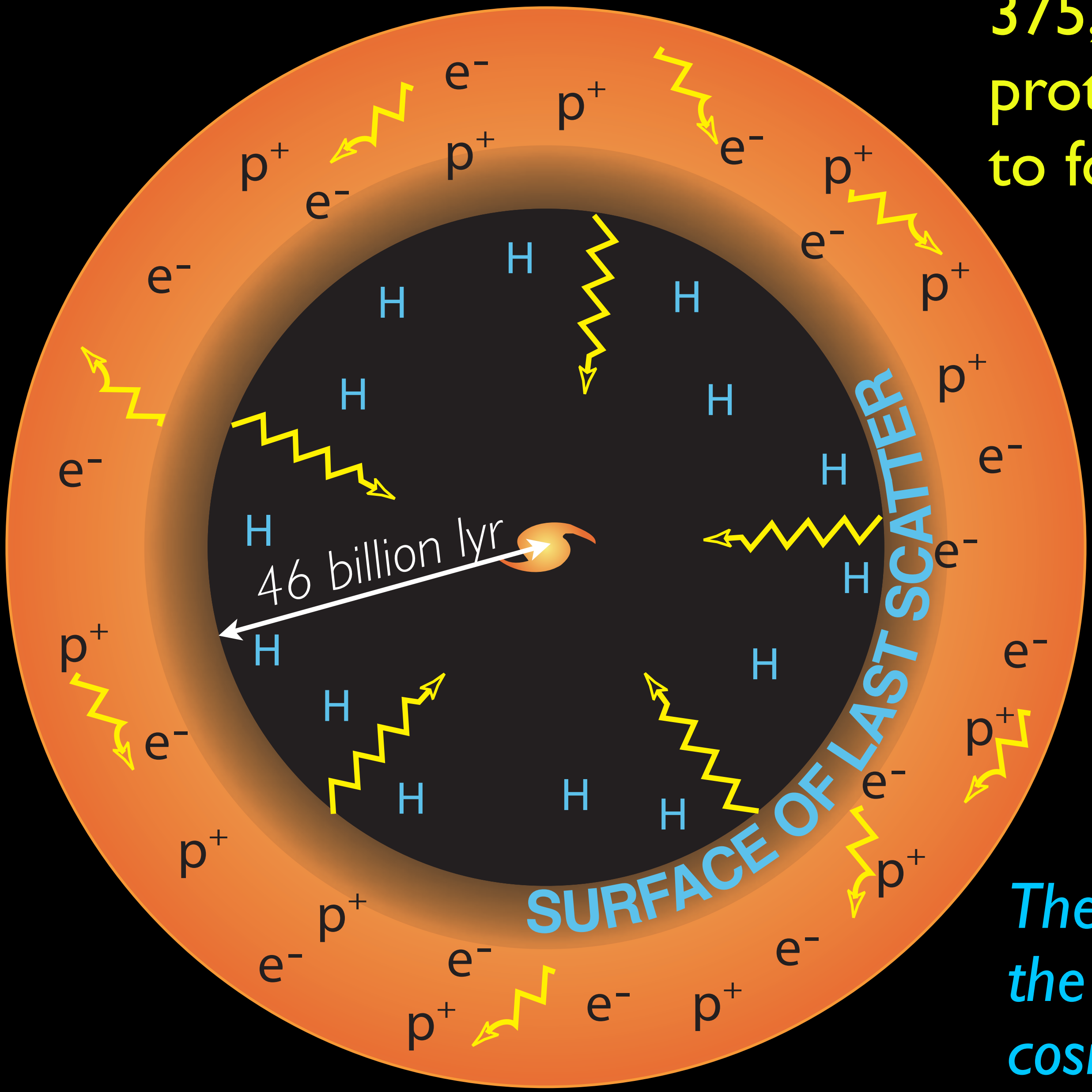
Looking Back in Time



Looking Back in Time



The Surface of Last Scatter

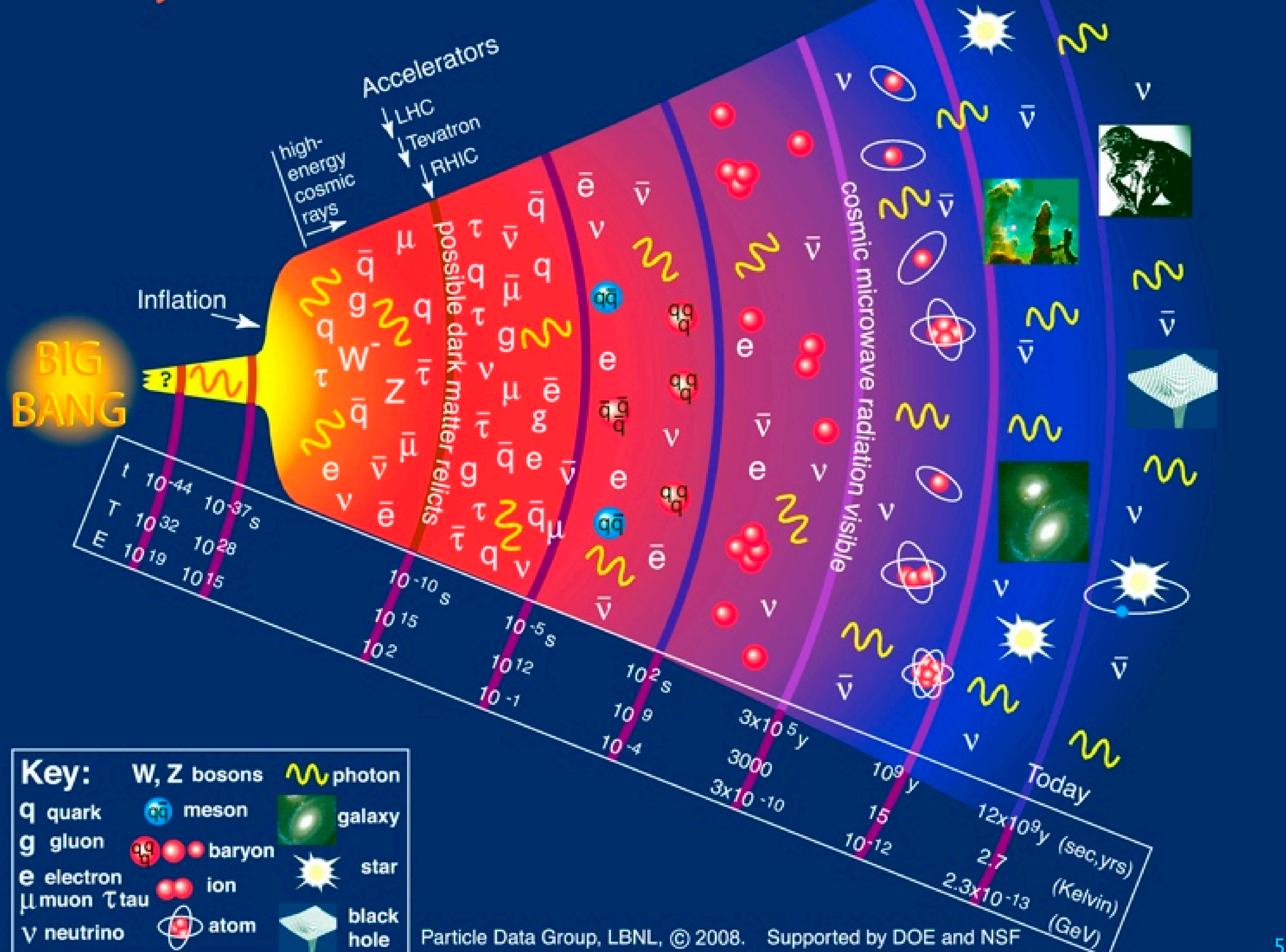


375,000 years after the Big Bang, protons and electrons combined to form hydrogen atoms.

- 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.

History of the Universe

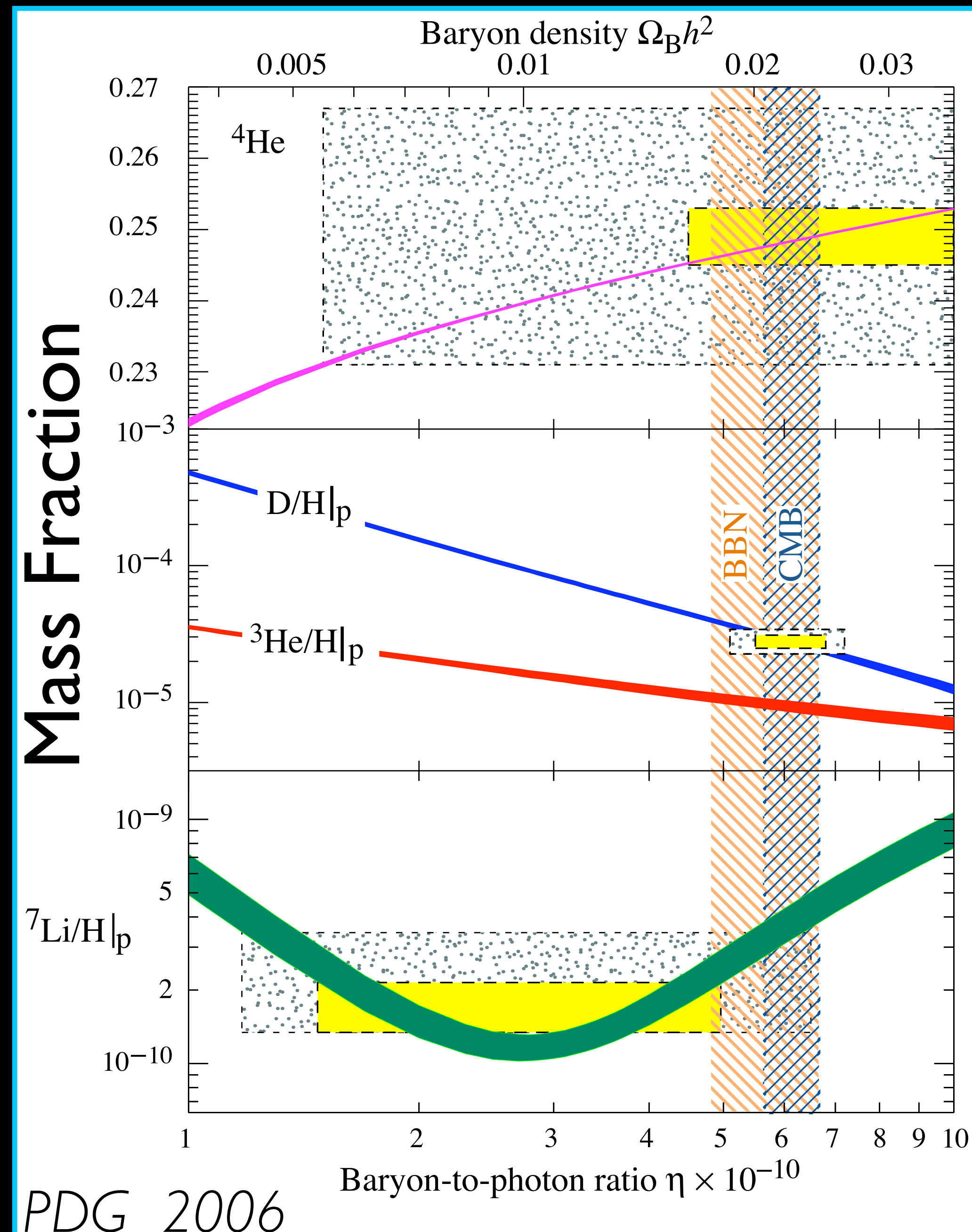


Big Bang Nucleosynthesis

$$10^{-5}\ \mathrm{sec} \lesssim t \lesssim 1\ \mathrm{sec}$$
$$100\ \mathrm{MeV} \gtrsim T \gtrsim 1\ \mathrm{MeV}$$
$$p + e^- \rightleftarrows n + \nu$$
$$p + \bar{\nu} \rightleftarrows n + e^+$$

$$1\ \mathrm{sec} \lesssim t \lesssim 4\ \mathrm{min}$$
$$1\ \mathrm{MeV} \gtrsim T \gtrsim 0.08\ \mathrm{MeV}$$
$$n \longrightarrow p + e^- + \bar{\nu}$$

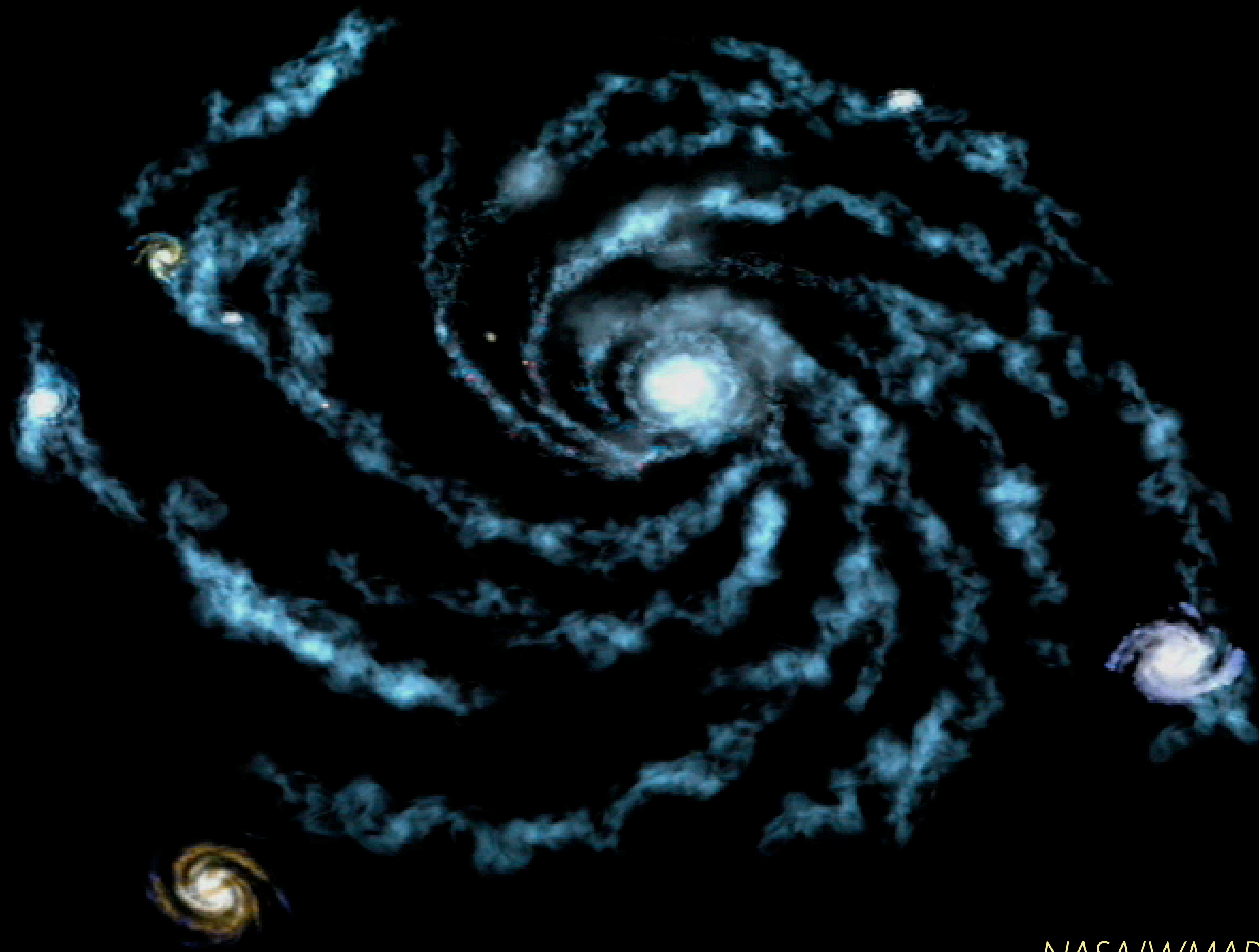
$$T \simeq 0.08\ \mathrm{MeV}\ t \simeq 4\ \mathrm{min}$$
$$n + p \longrightarrow D$$
$$D + D \longrightarrow {}^3\mathrm{He} + n$$
$${}^3\mathrm{He} + D \longrightarrow {}^4\mathrm{He} + p$$



The Cosmic Microwave Background

NASA/WMAP Science Team

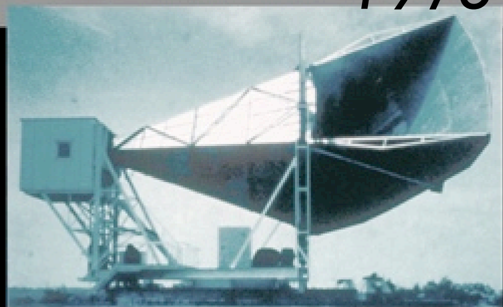
The Cosmic Microwave Background



NASA/WMAP Science Team

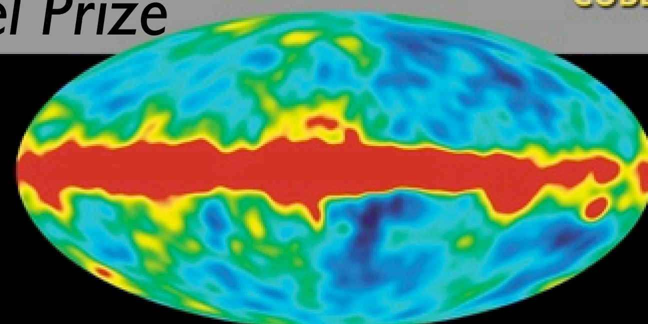
A Partial History of the CMB

1965 — *1978 Nobel Prize* — Penzias and Wilson



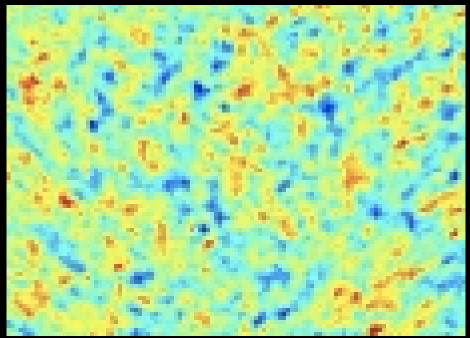
A uniform glow outside the Galactic Plane: T = 2.7 Kelvin

1992 — *2006 Nobel Prize* — COBE



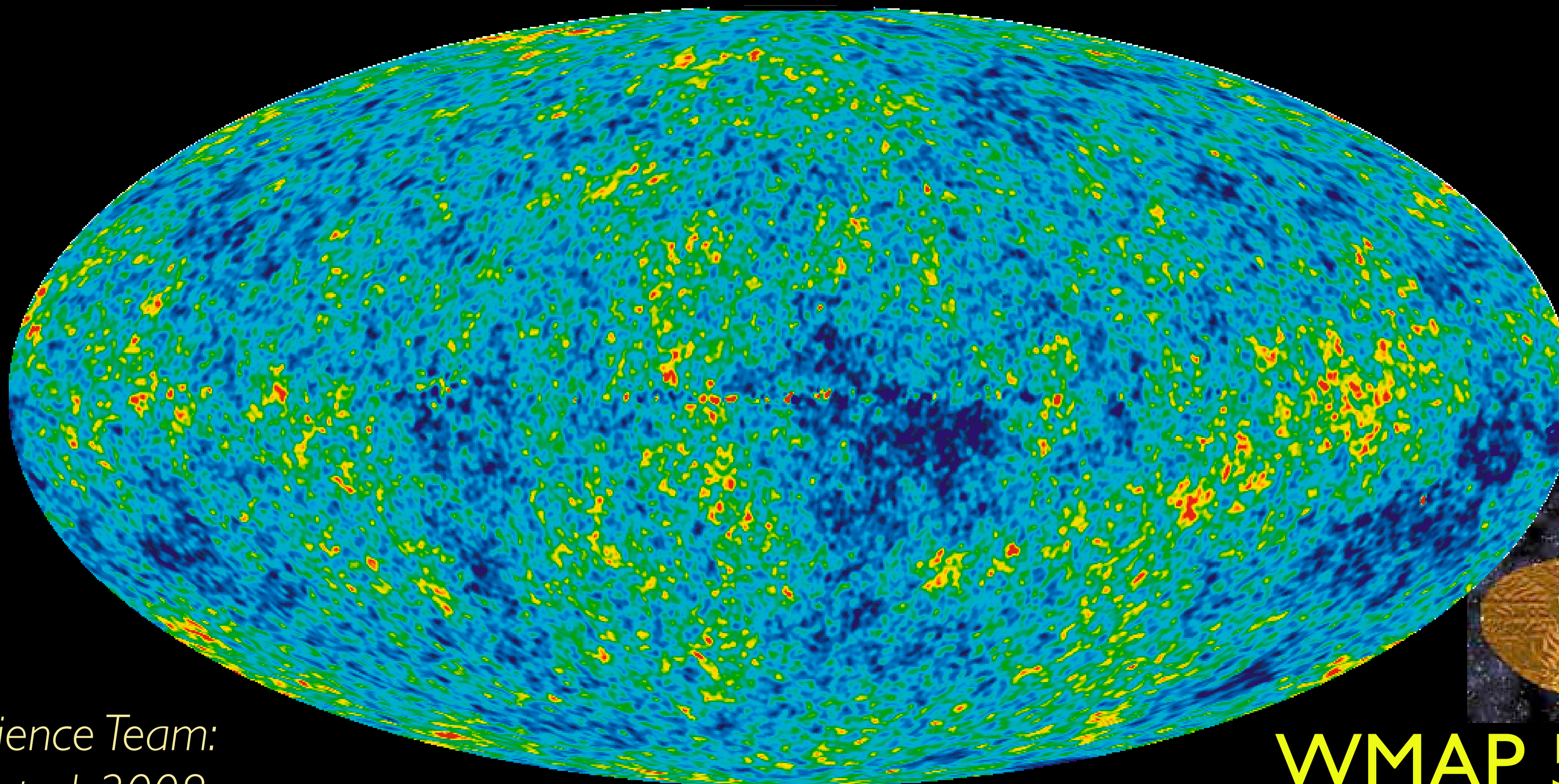
First detection of fluctuations: one part in 100,000

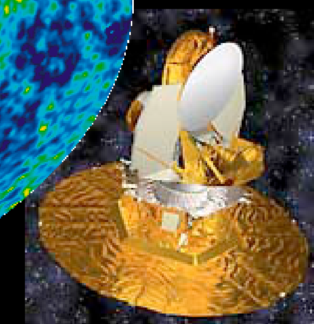
2000 — *2009 Dan David Prize* — BOOMERANG



First high-resolution map of fluctuations: characteristic size of 1°

The Cosmic Microwave Background





WMAP Science Team: Hinshaw, et al. 2008

WMAP 5-year

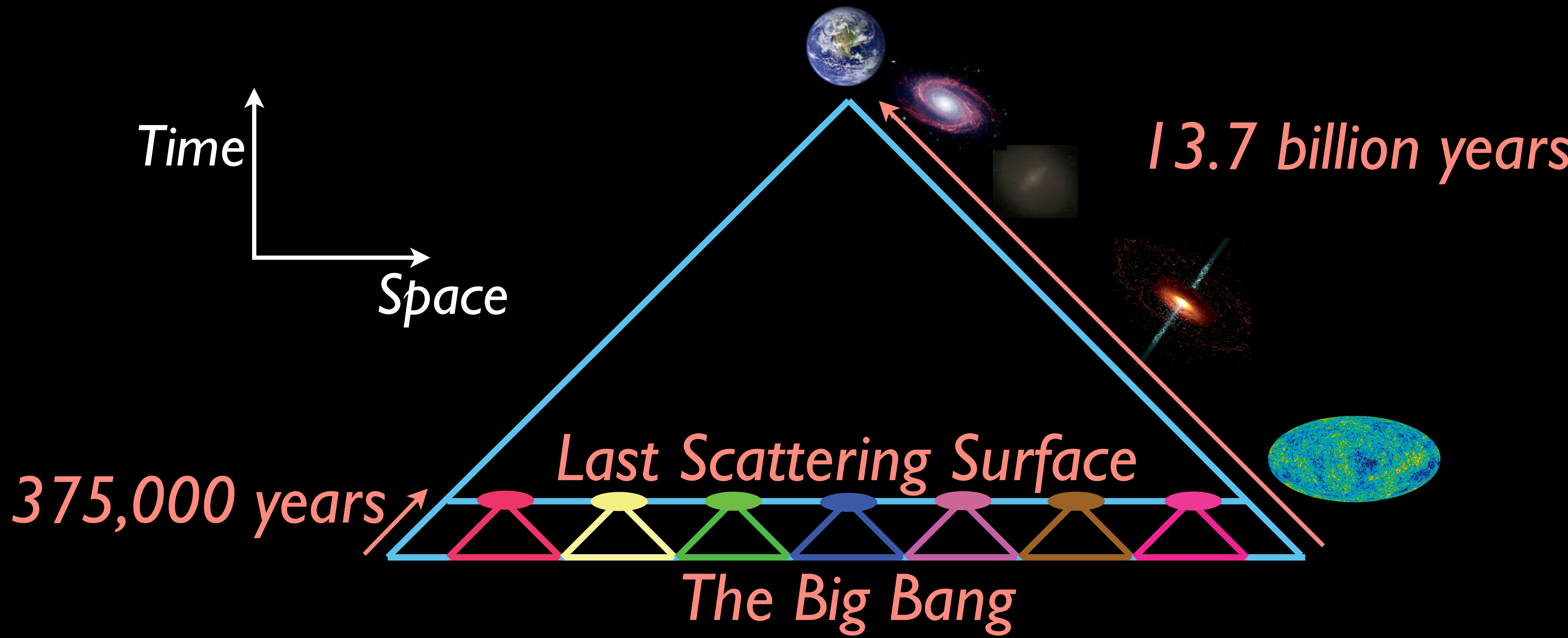
-200 +200

$\Delta T(\mu K)$

- 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!

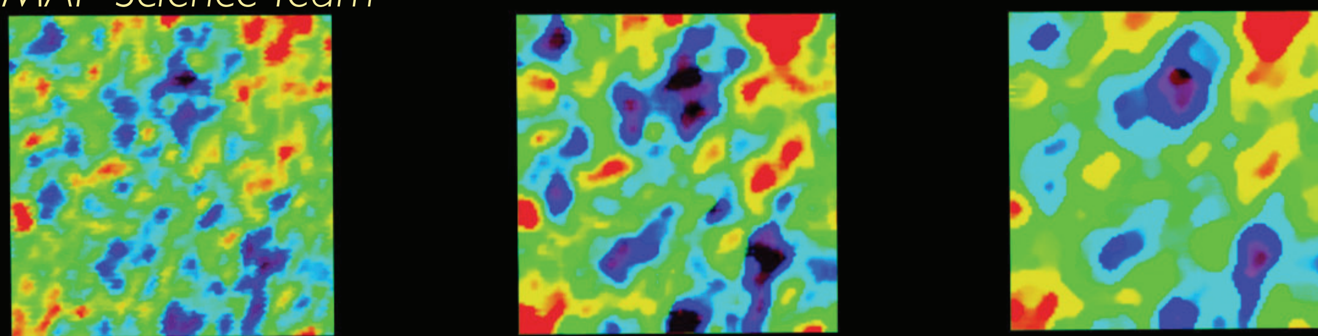


- At the last scattering surface, the **horizon** was 1° across.
- Every 1° **disk** in the CMB is effectively a **separate universe**.
- These different patches should not have the same temperature!

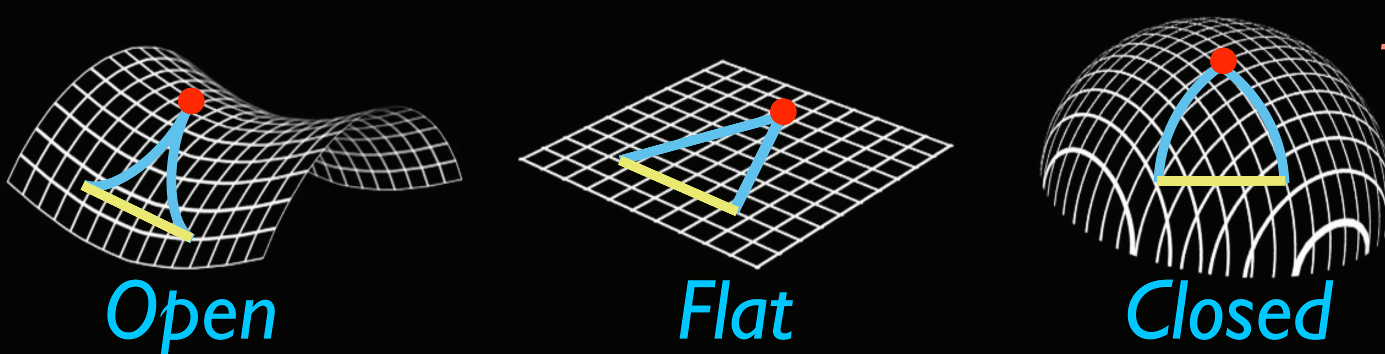
Mystery 2: The Flatness Problem

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

WMAP Science Team



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

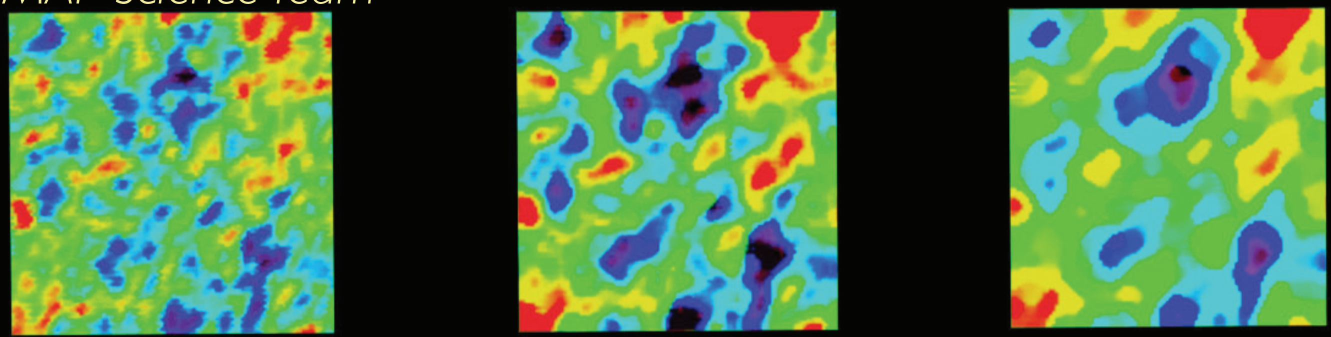


The geometry of the Universe determines the angular size of the fluctuations.

Mystery 2: The Flatness Problem

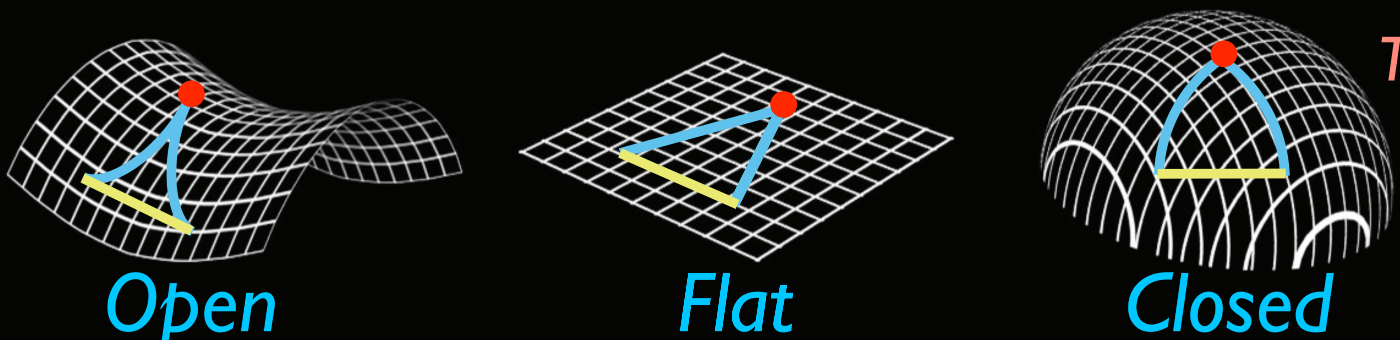
The characteristic angular size of the CMB fluctuations tells us about the geometry of the Universe.

WMAP Science Team



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

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



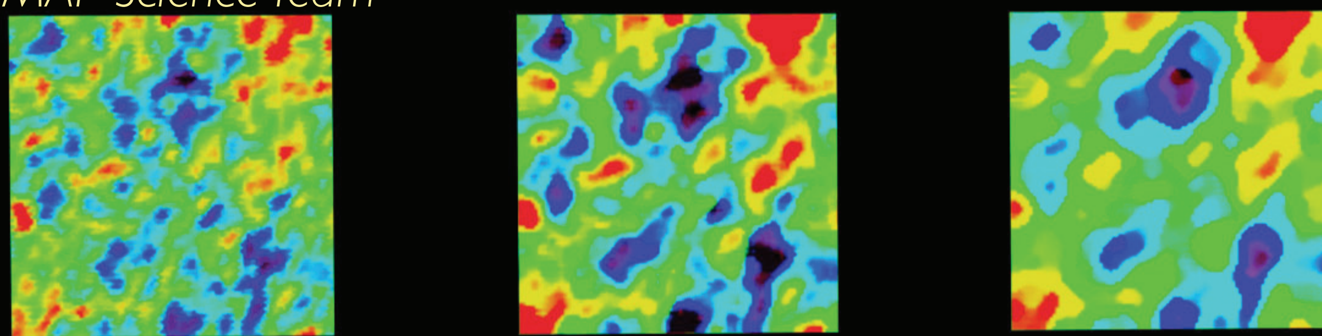
The geometry of the Universe determines the angular size of the fluctuations.

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

Mystery 2: The Flatness Problem

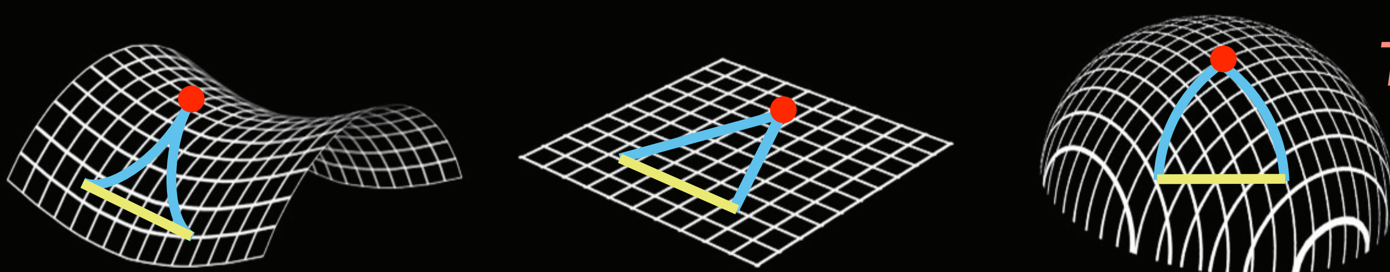
The characteristic angular size of the CMB fluctuations tells us about the geometry of the Universe.

WMAP Science Team



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

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



Open *Flat* *Closed*

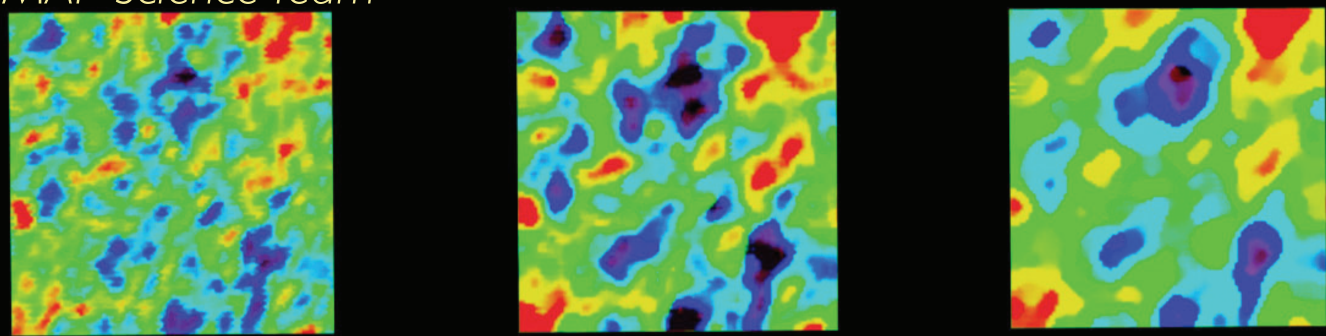
The geometry of the Universe determines the angular size of the fluctuations.

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

Mystery 2: The Flatness Problem

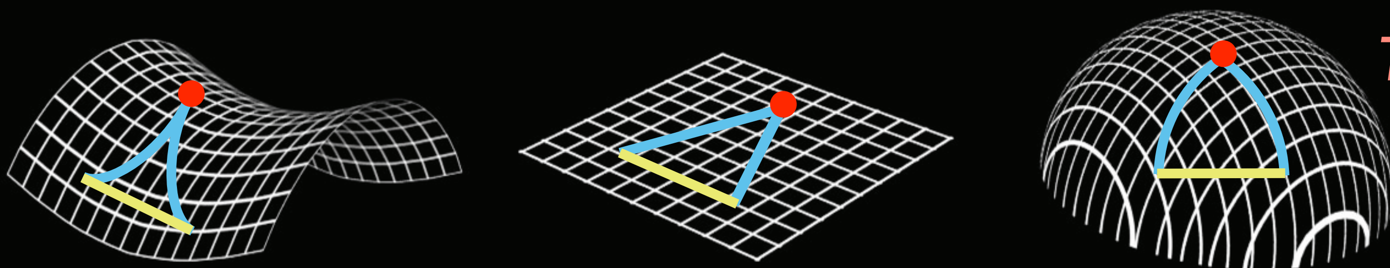
The characteristic angular size of the CMB fluctuations tells us about the geometry of the Universe.

WMAP Science Team



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

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



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

Open *Flat* *Closed*

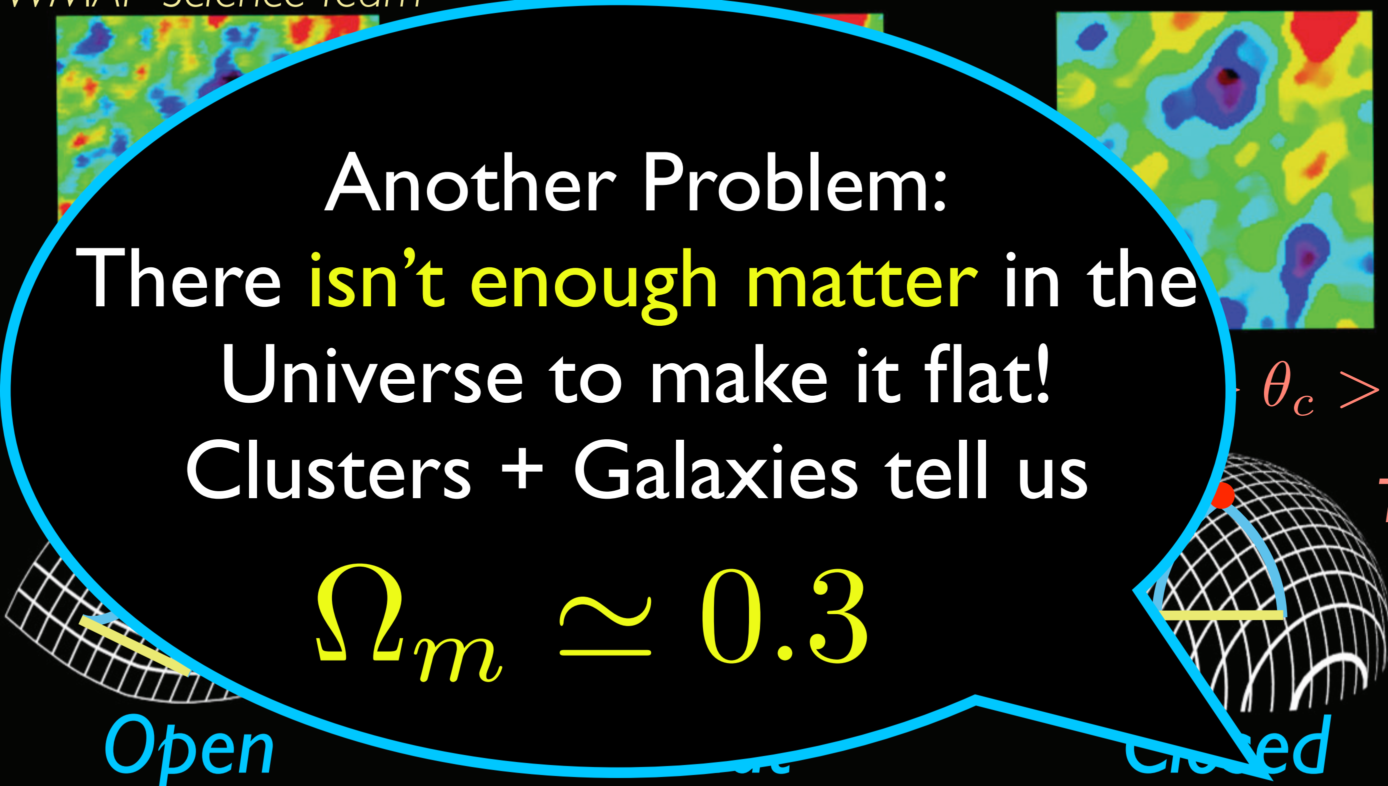
$$\Omega \equiv \frac{\text{Energy in the Universe}}{\text{Energy required for flatness}} = 1.005 \pm 0.007 \text{ today}$$

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

Mystery 2: The Flatness Problem

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

WMAP Science Team



Another Problem:
There isn't enough matter in the Universe to make it flat!
Clusters + Galaxies tell us

$$\Omega_m \simeq 0.3$$

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

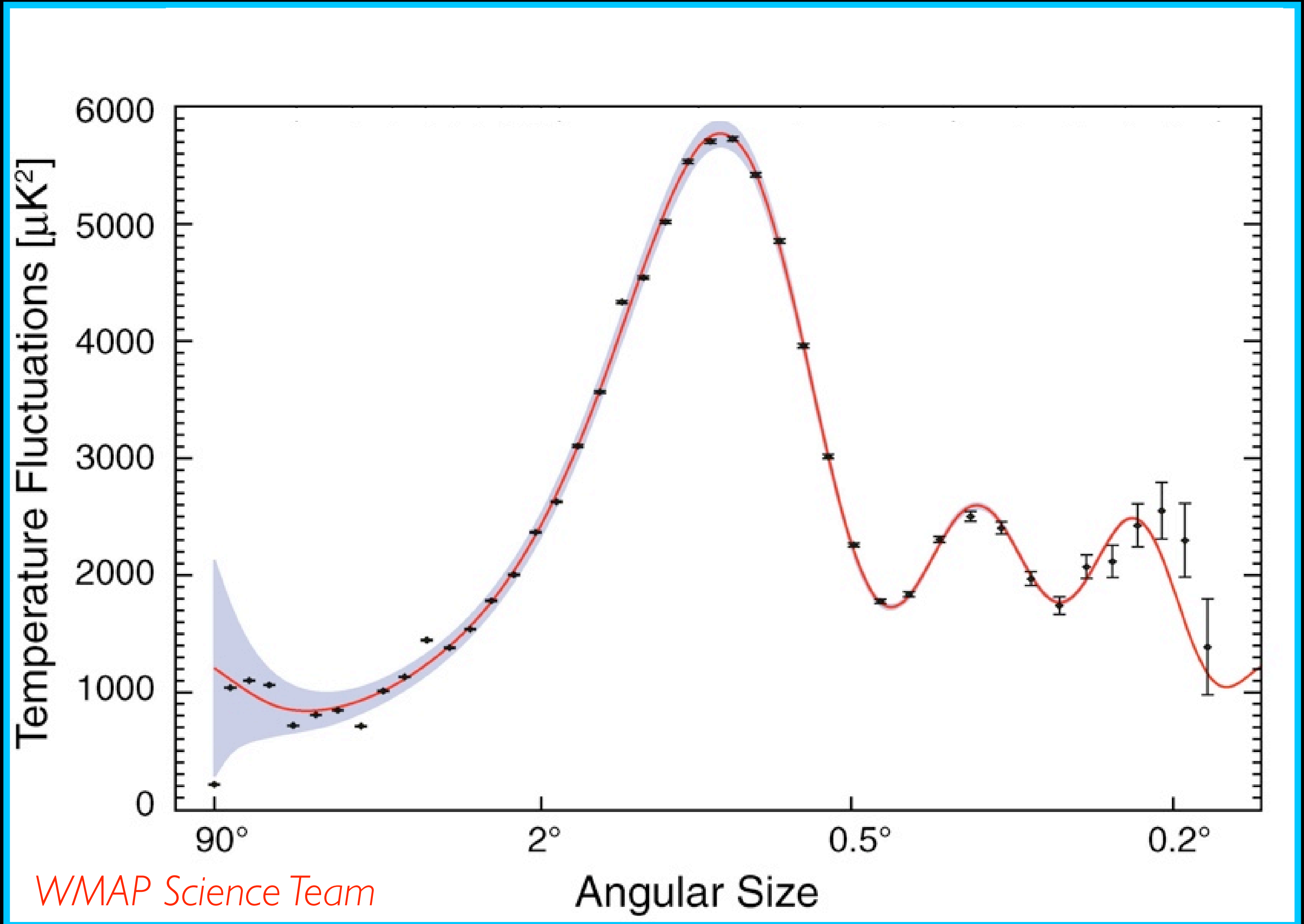
The geometry of the Universe determines the angular size of the fluctuations.

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

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

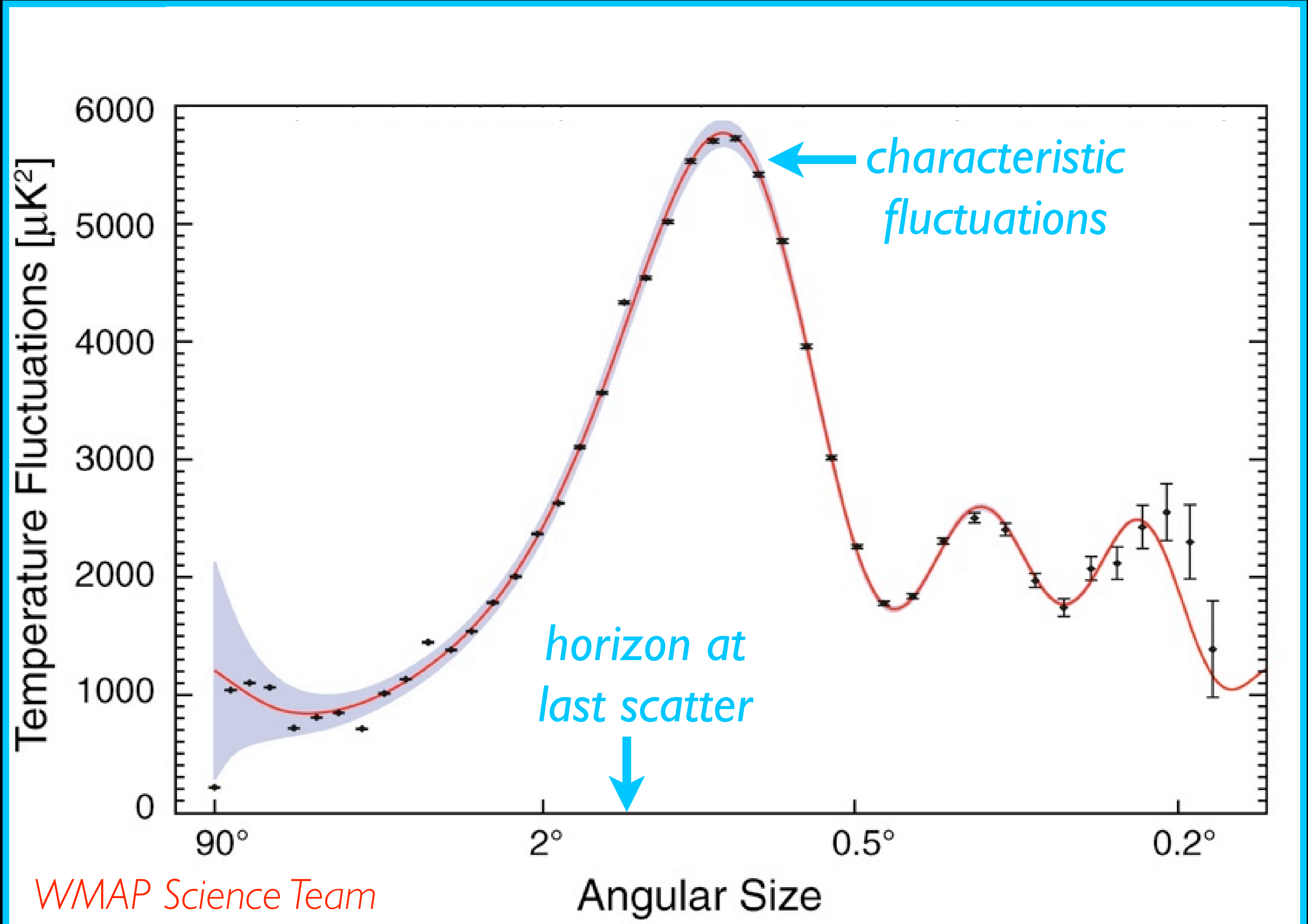
Mystery 3: Initial Fluctuations

CMB Power Spectrum



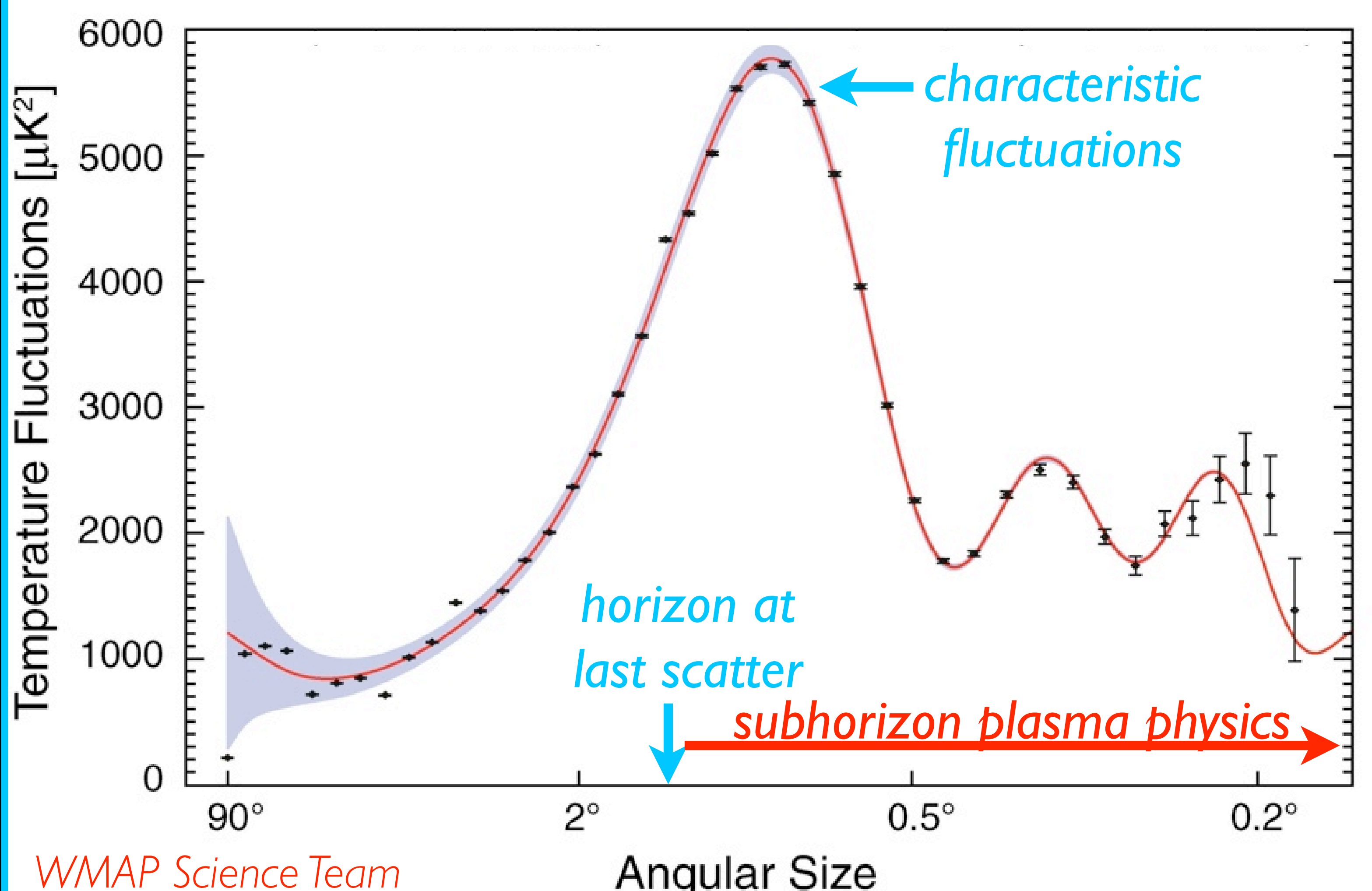
Mystery 3: Initial Fluctuations

CMB Power Spectrum



Mystery 3: Initial Fluctuations

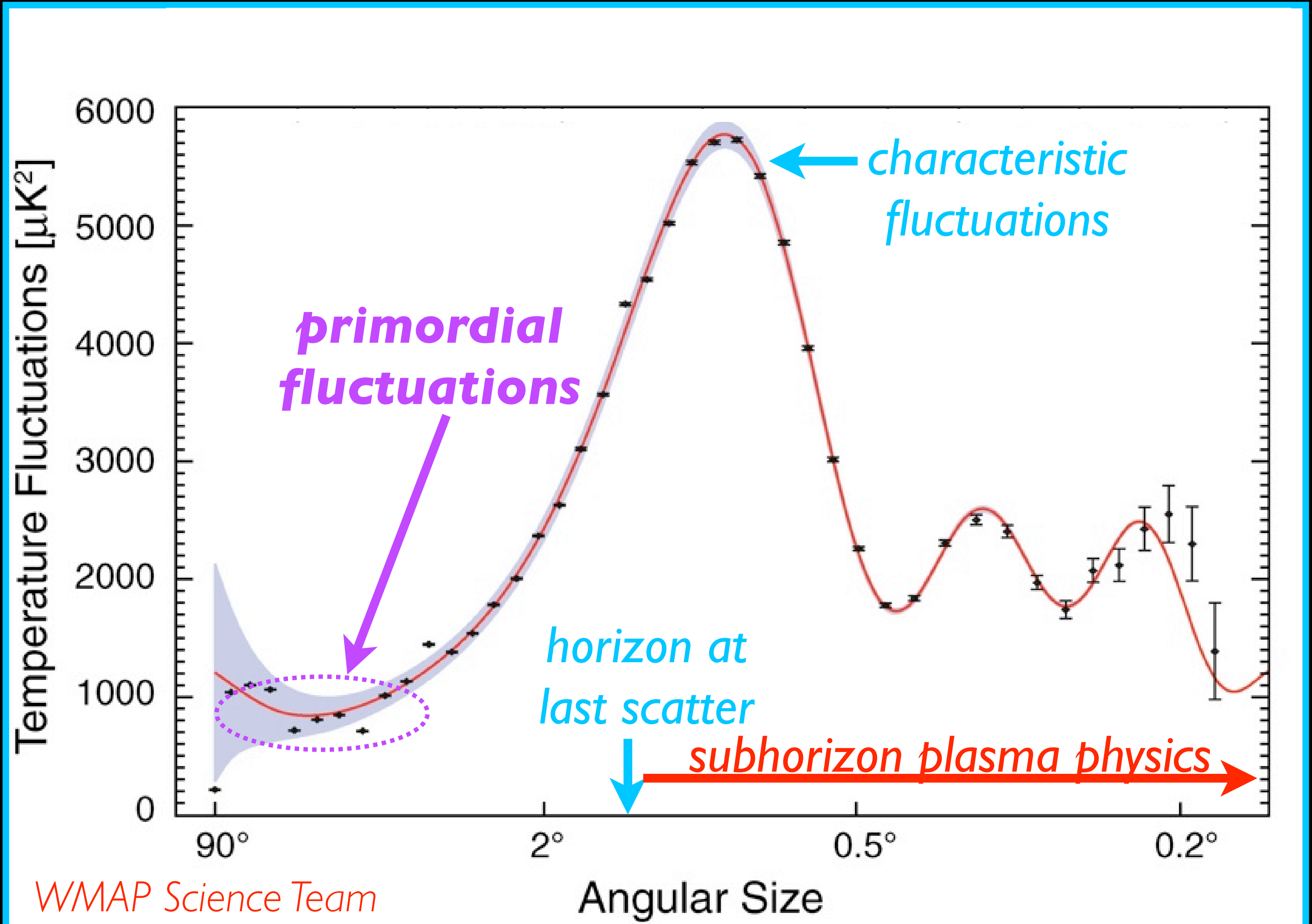
CMB Power Spectrum



WMAP Science Team

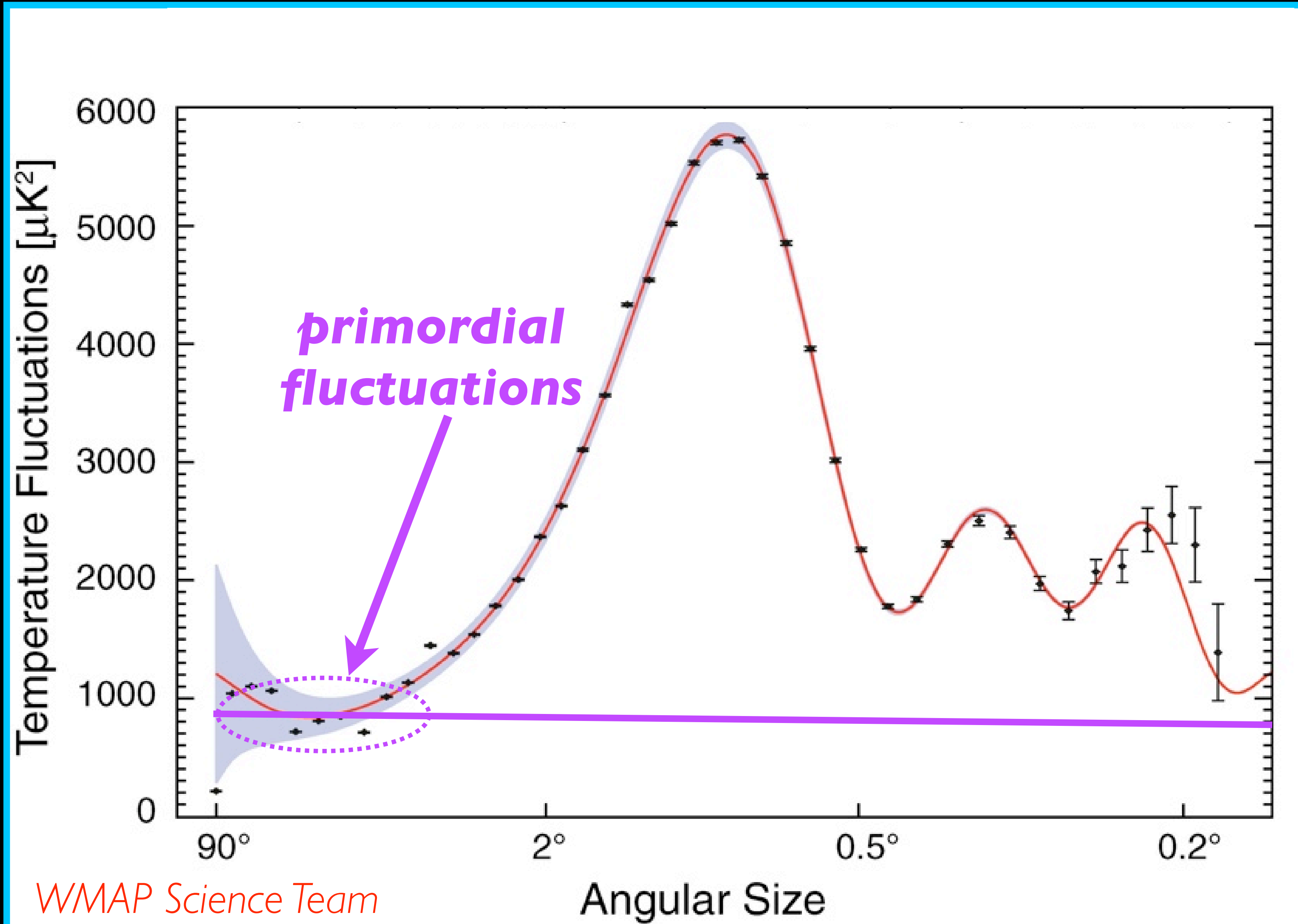
Mystery 3: Initial Fluctuations

CMB Power Spectrum

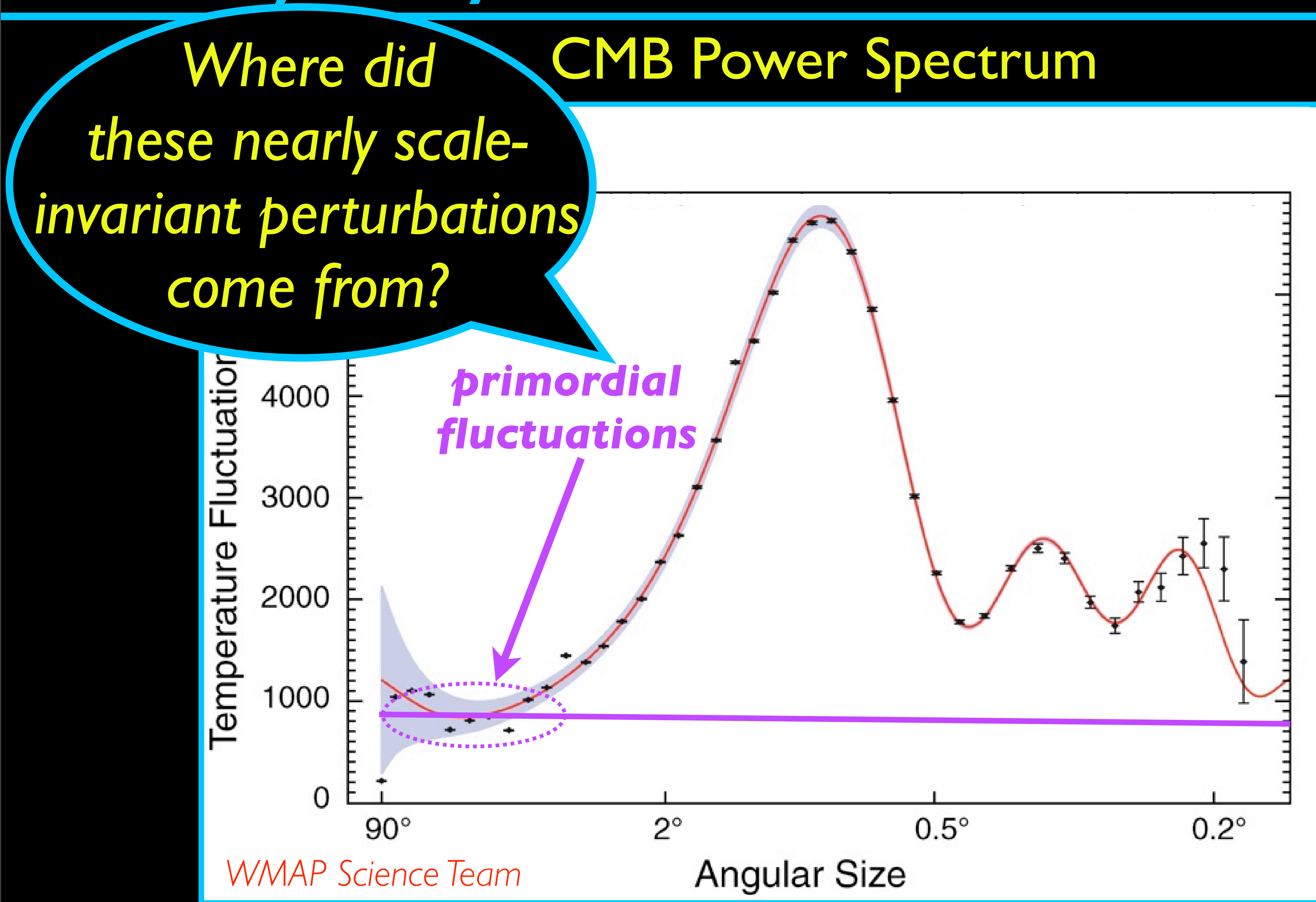


Mystery 3: Initial Fluctuations

CMB Power Spectrum

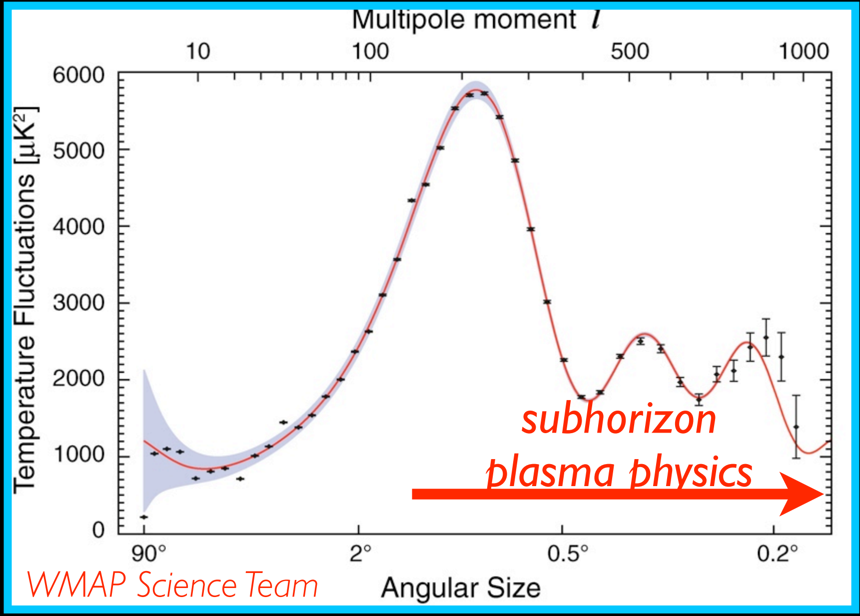


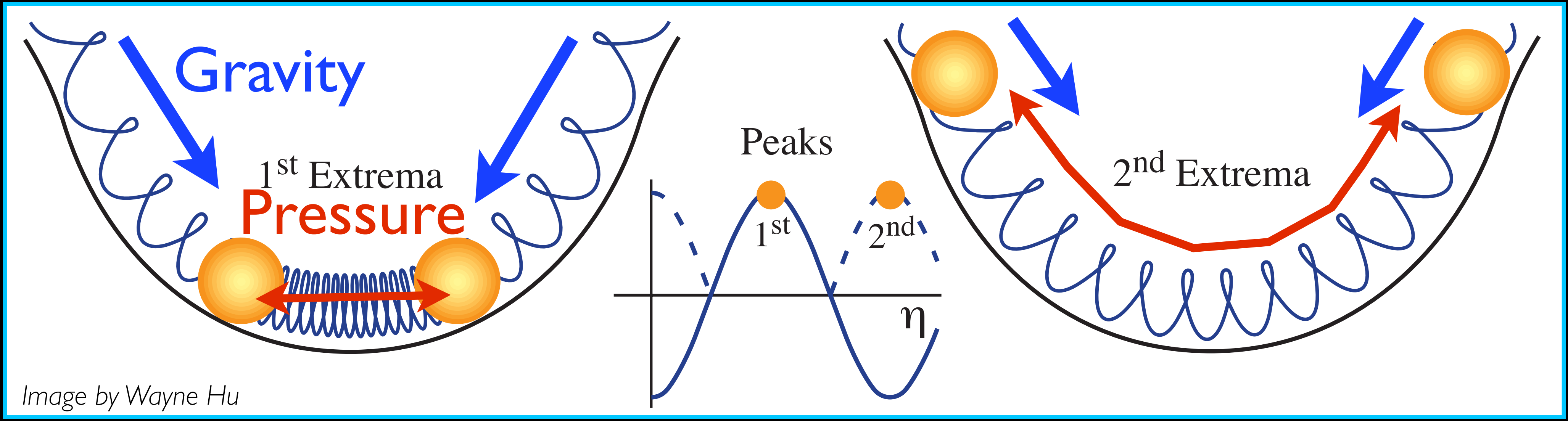
Mystery 3: Initial Fluctuations



Mystery 4: Unknown Matter

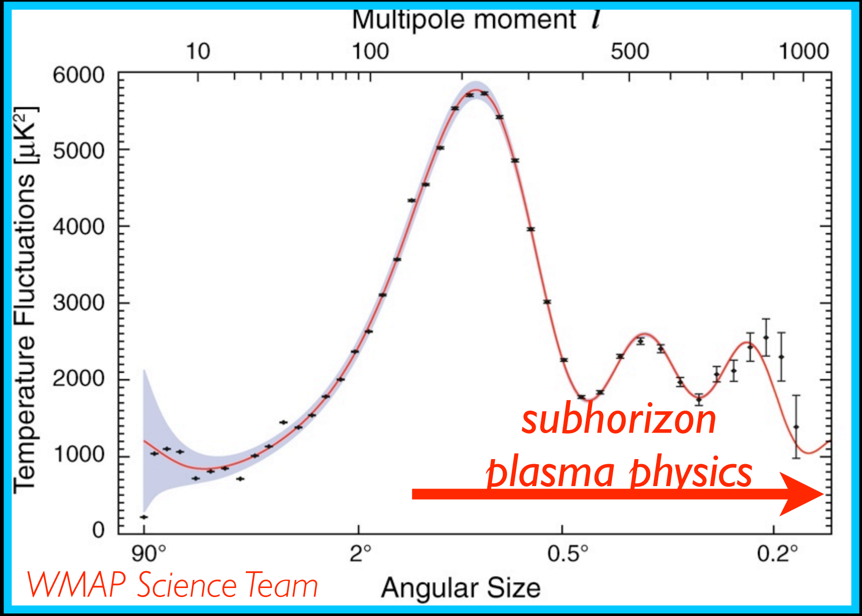
- The baryon-photon fluid has pressure proportional to its density.
- The dueling forces of gravity and pressure lead to acoustic oscillations in the CMB power spectrum.

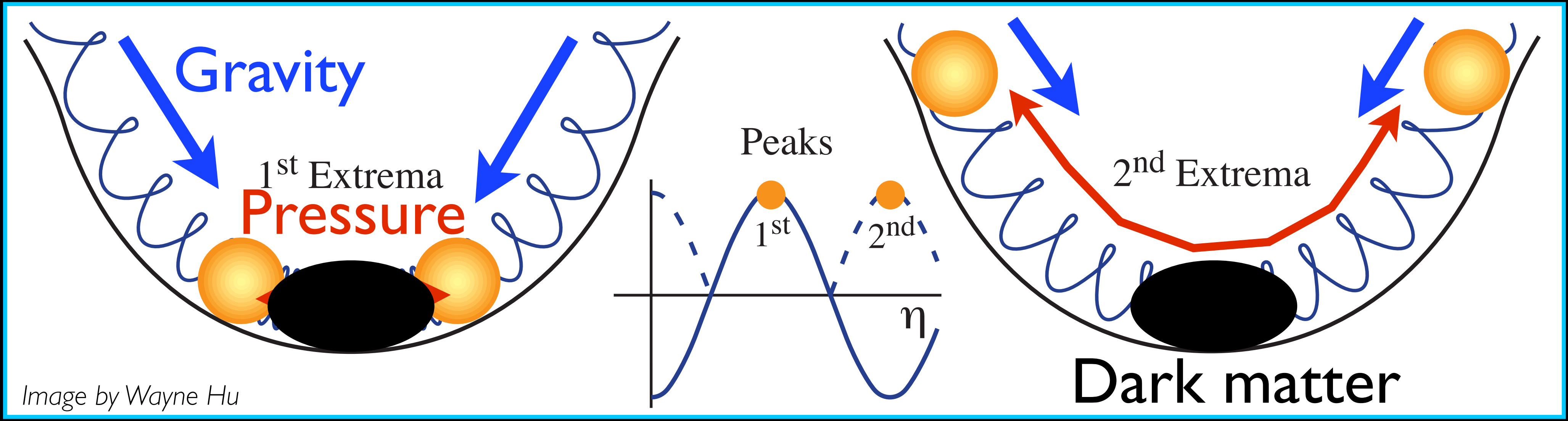




Mystery 4: Unknown Matter

- The baryon-photon fluid has pressure proportional to its density.
- The dueling forces of gravity and pressure lead to acoustic oscillations in the CMB power spectrum.
- But the CMB also requires pressureless dark matter: $\Omega_b \simeq 0.05$ & $\Omega_{dm} \simeq 0.23$
- Dark matter must be neutral and stable.





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?
- What is the origin of the initial fluctuations?

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?
- What is the origin of the initial fluctuations?

INFLATION!

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?
- What is the origin of the initial fluctuations?

INFLATION!

Breakdown of Energy in the Universe:

4% baryonic matter: protons, electrons, atoms

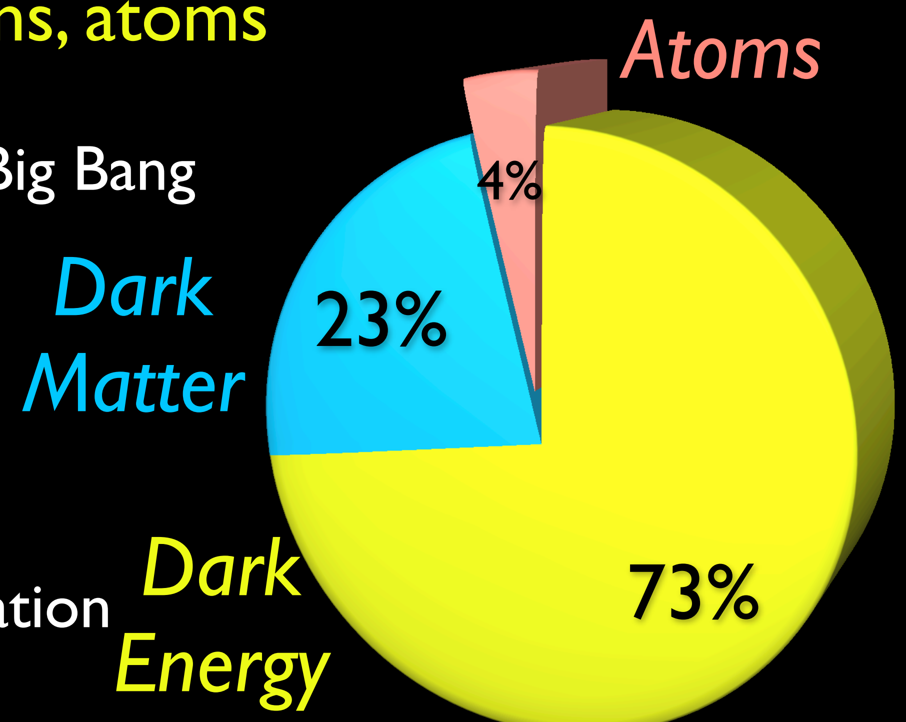
- "stuff we know"
- supported by He produced 3 min. after Big Bang

23% dark matter

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

73% dark energy

- negative pressure causes cosmic acceleration
- supported by supernova observations

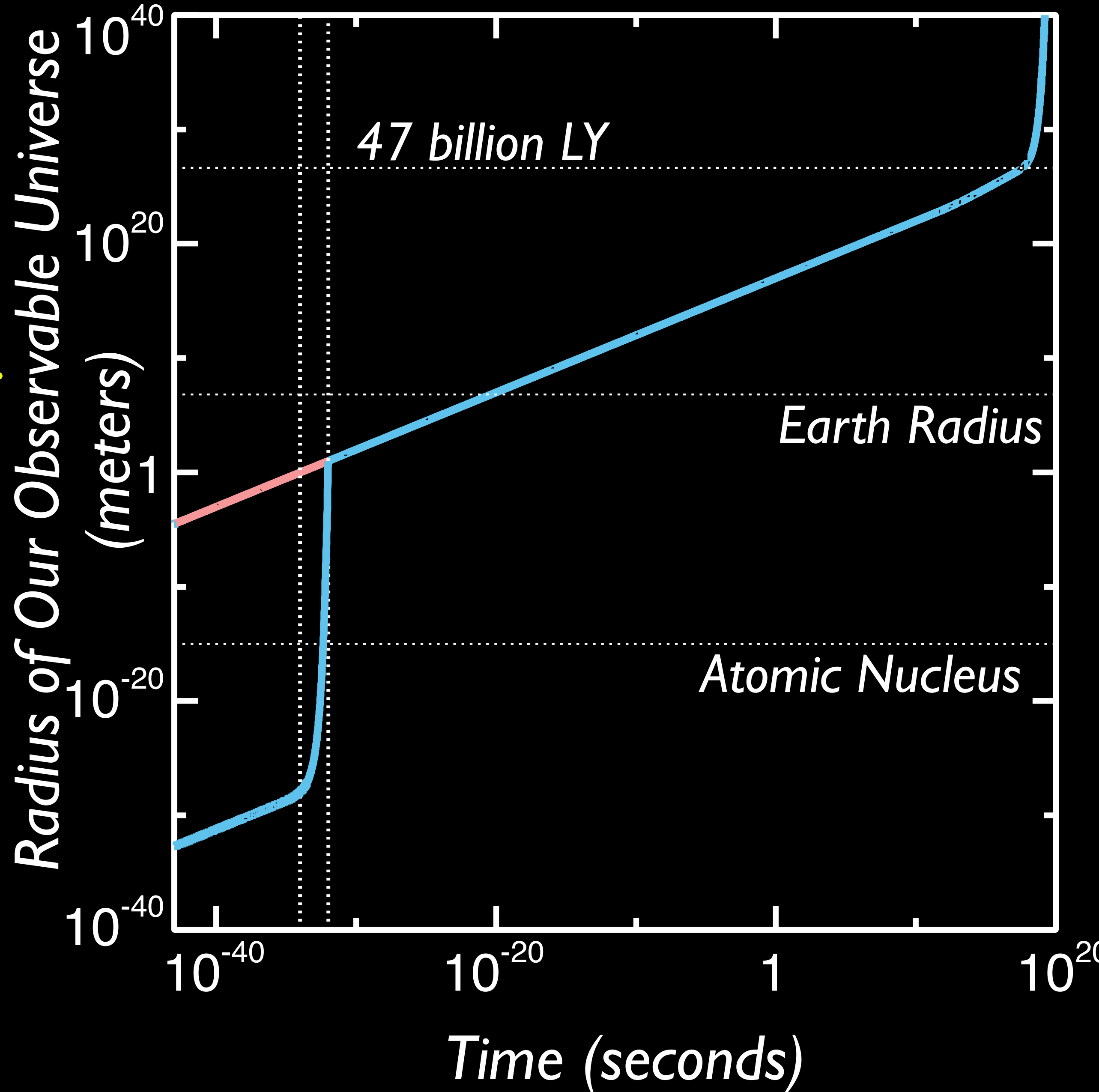


Inflation: Accelerated Expansion

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.

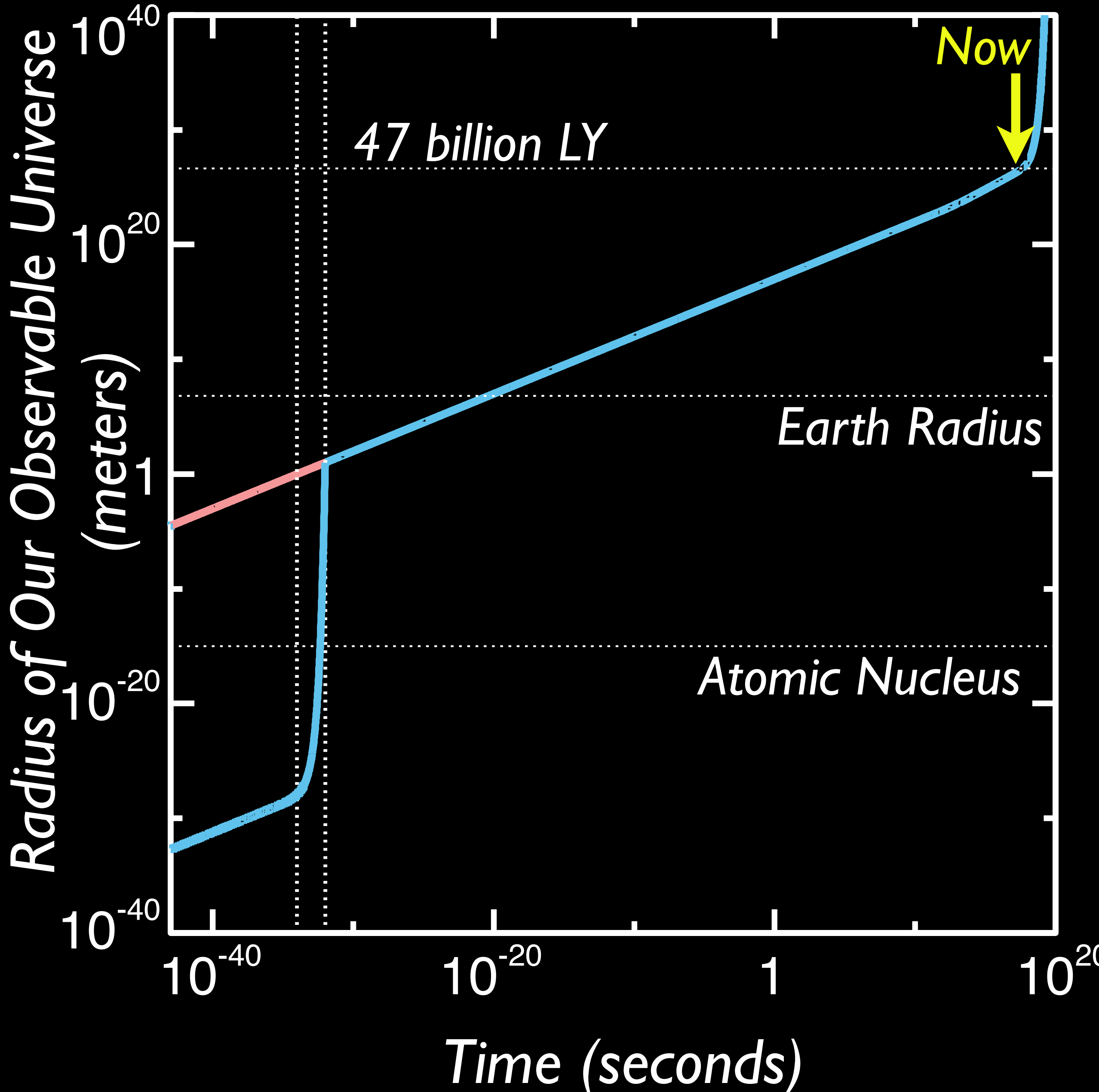


Inflation: Accelerated Expansion

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.

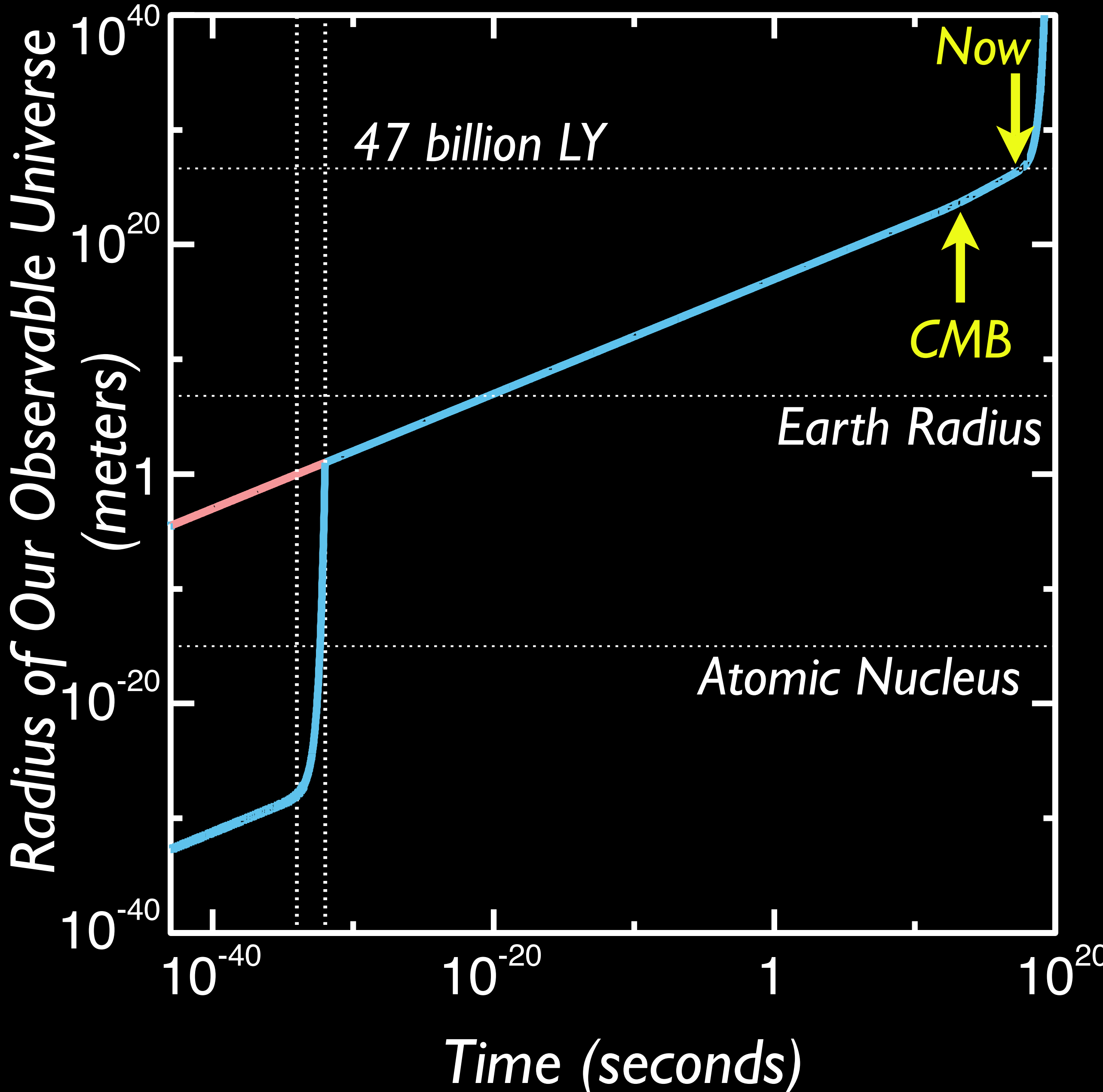


Inflation: Accelerated Expansion

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.

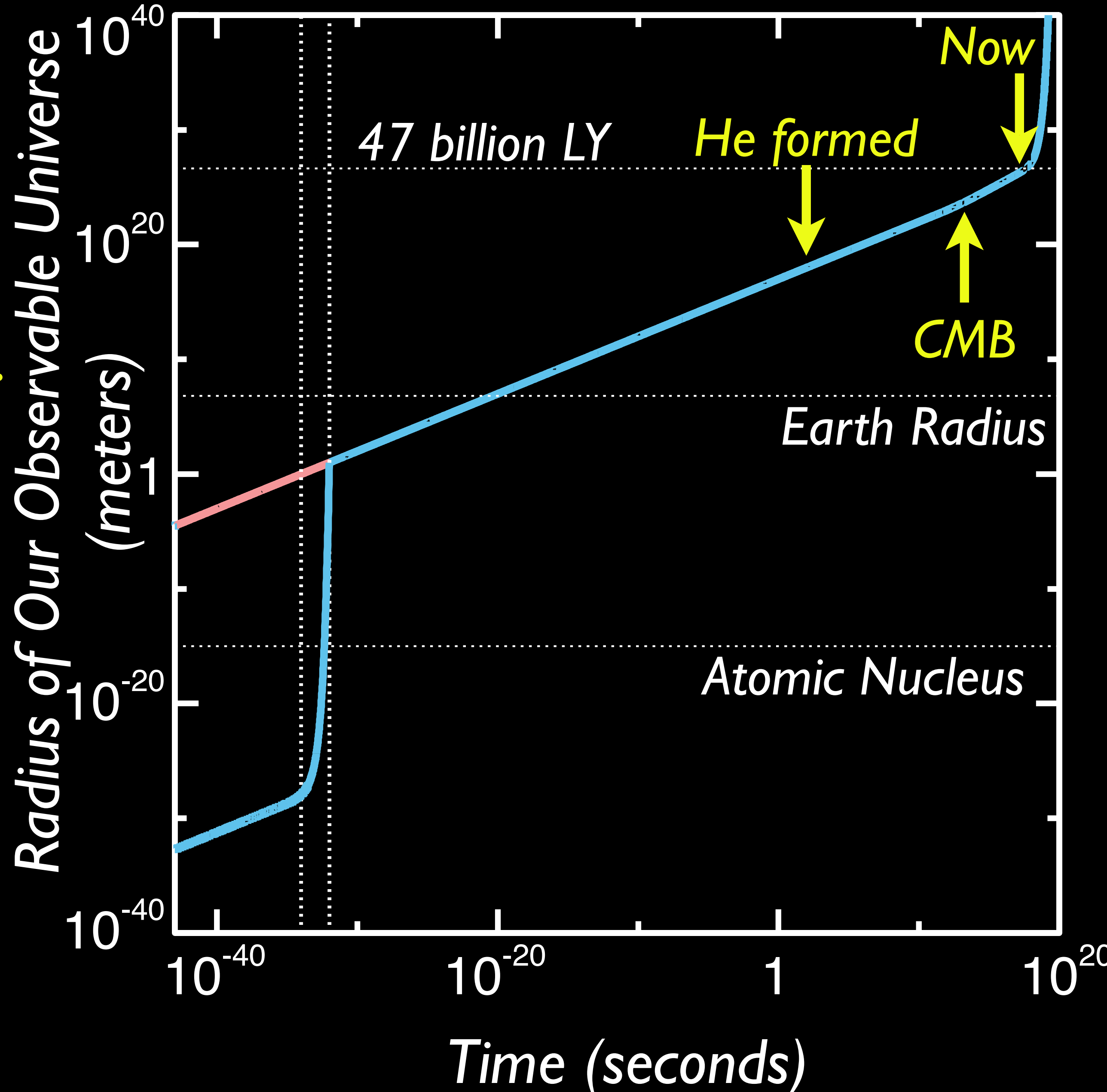


Inflation: Accelerated Expansion

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.

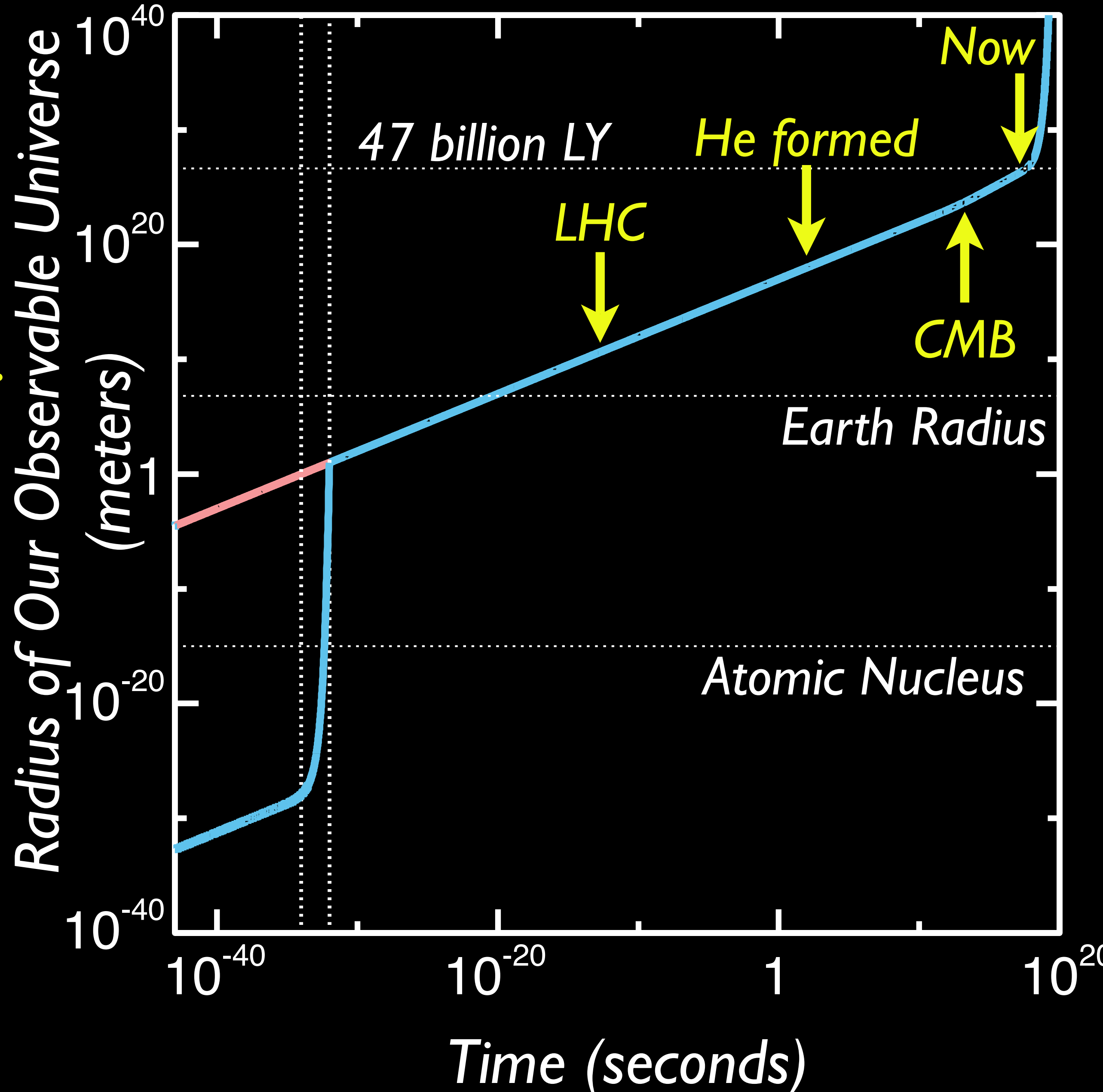


Inflation: Accelerated Expansion

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.



Inflation: Accelerated Expansion

The content of the Universe determines the expansion rate.

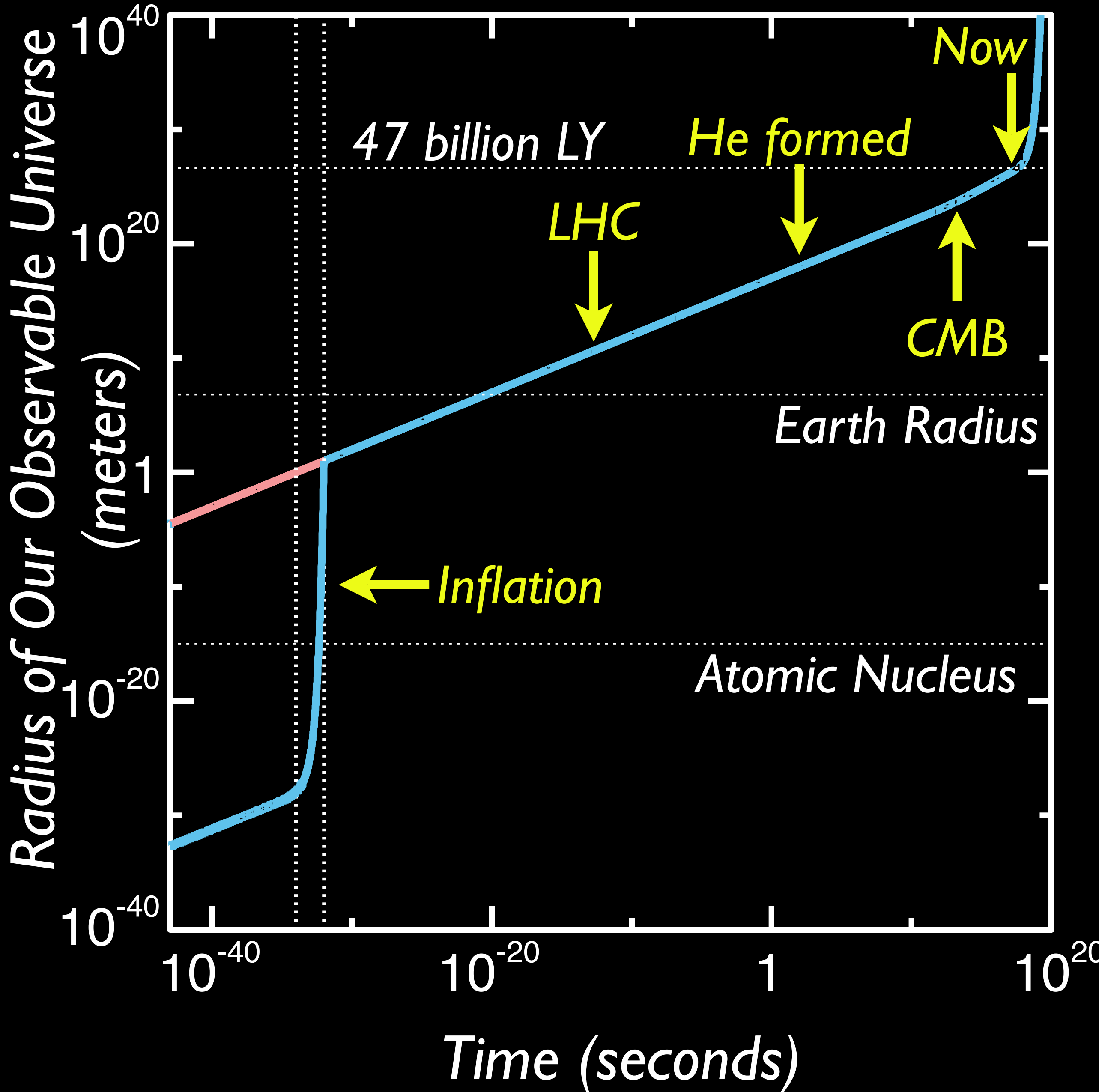
- radiation: $R(t) \propto \sqrt{t}$
- matter: $R(t) \propto t^{2/3}$

The expansion decelerates.

INFLATION

Alan Guth, 1981

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



Inflation: Accelerated Expansion

The content of the Universe determines the expansion rate.

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

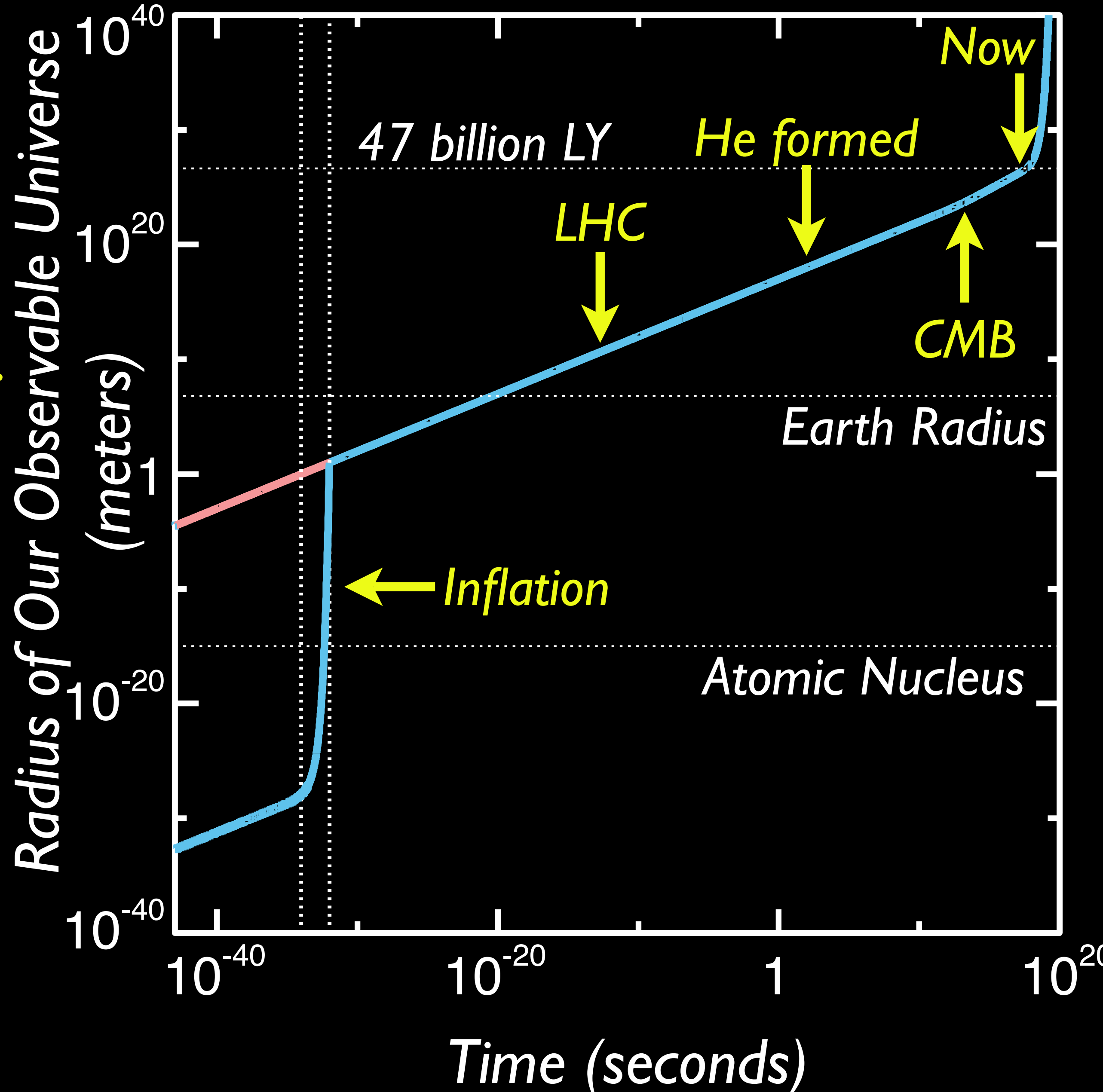
The expansion decelerates.

INFLATION

Alan Guth, 1981

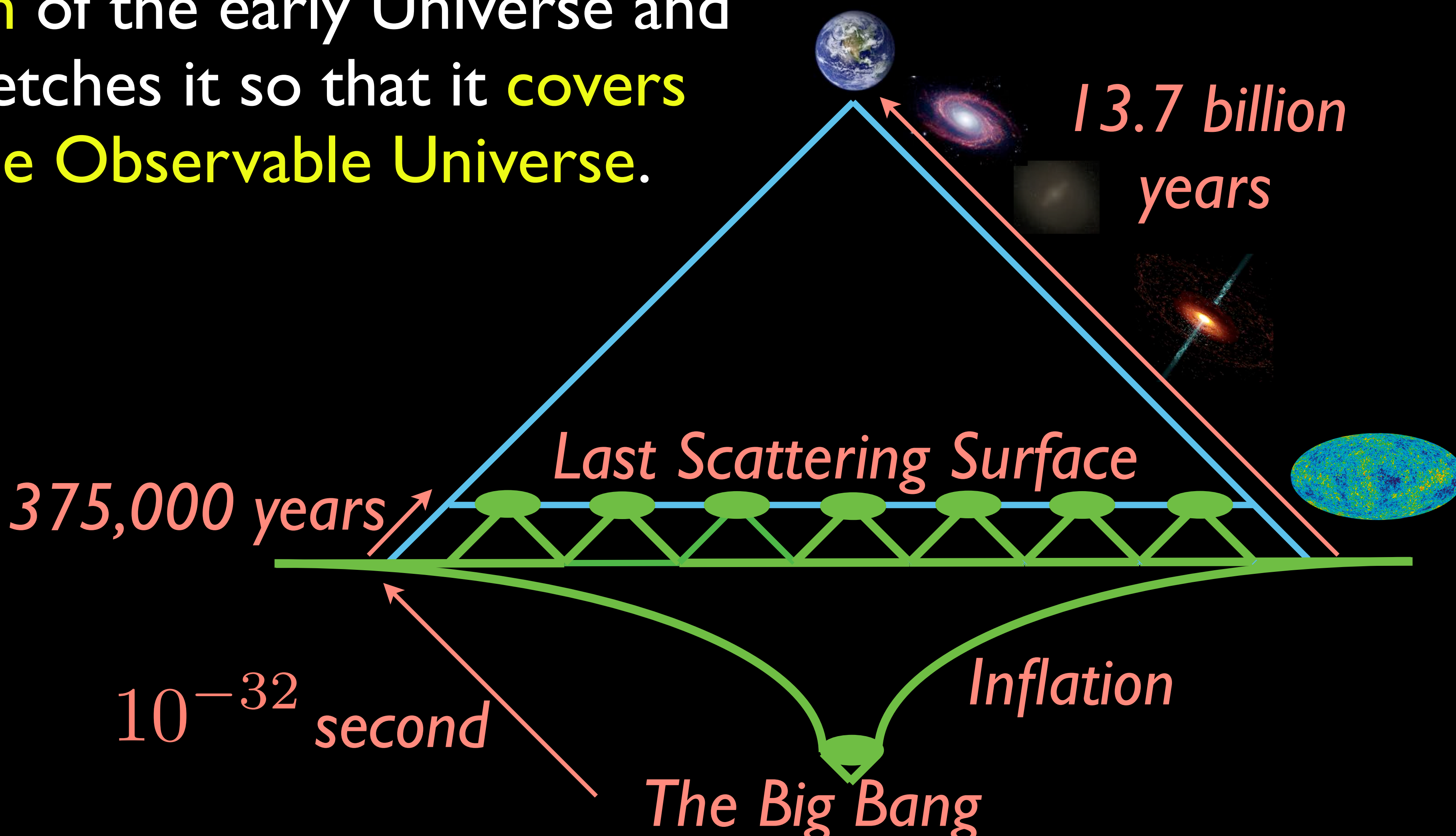
The Universe's volume doubled at least 270 times *instantly*.

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

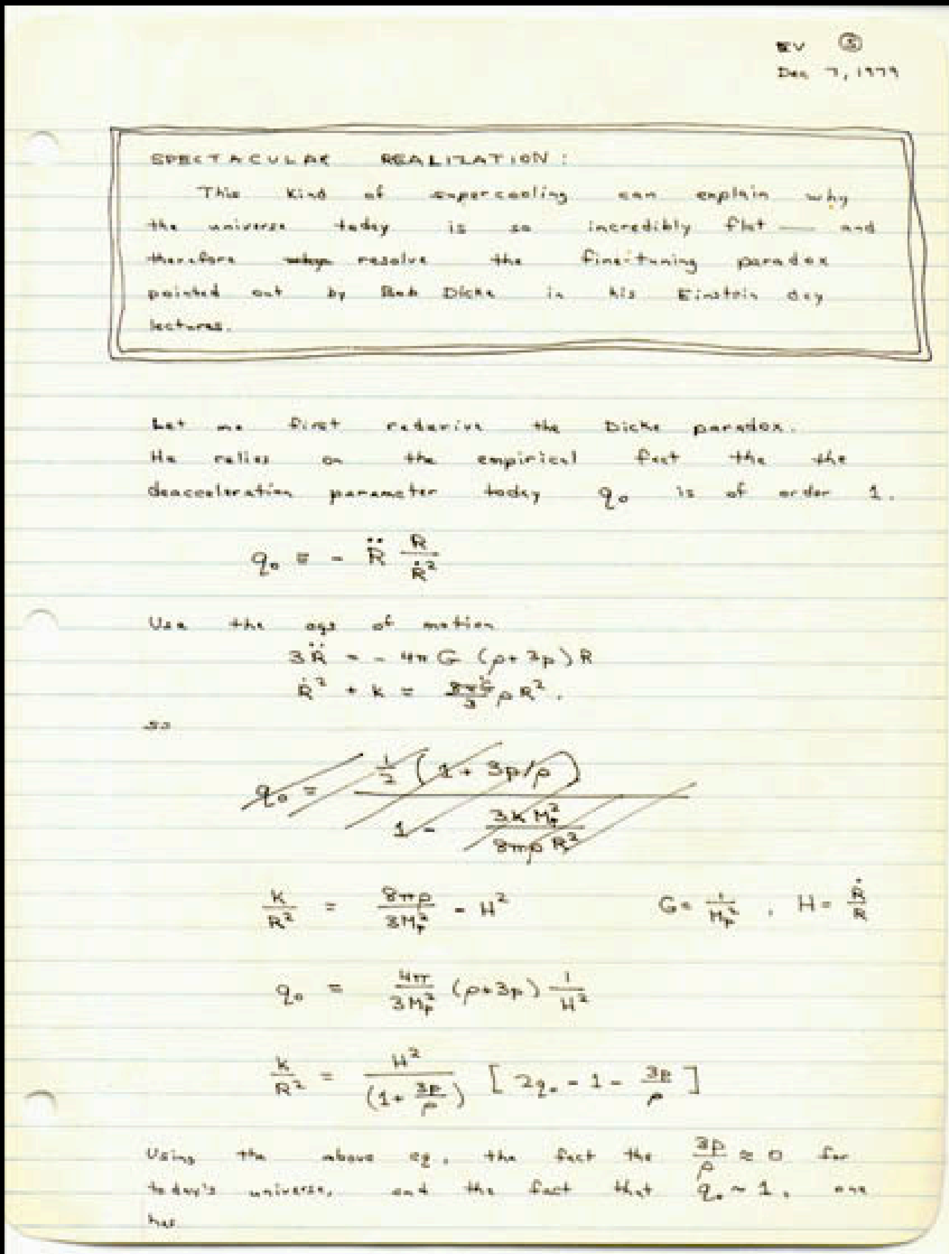


Inflation Solves the Horizon Problem

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



SV ③
Dec 7, 1979

SPECTACULAR REALIZATION:
This kind of supercooling can explain why the universe today is so incredibly flat — and therefore 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

$$q_0 = \frac{\frac{1}{2}(1 + 3p/\rho)}{1 - \frac{3 k M_p^2}{8\pi \rho R^2}}$$

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

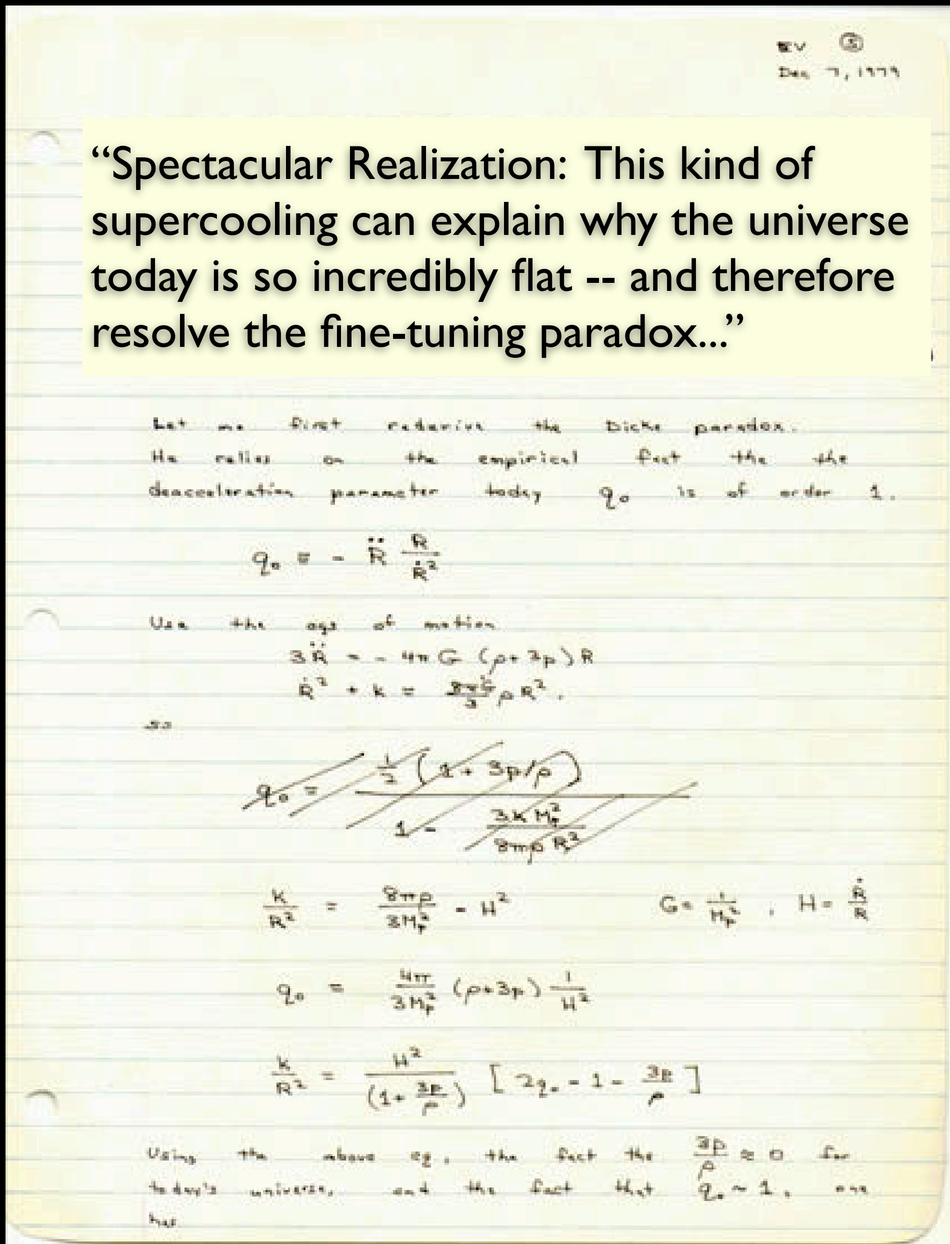
$$q_0 = \frac{4\pi}{3M_p^2}(\rho + 3p)\frac{1}{H^2}$$

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

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

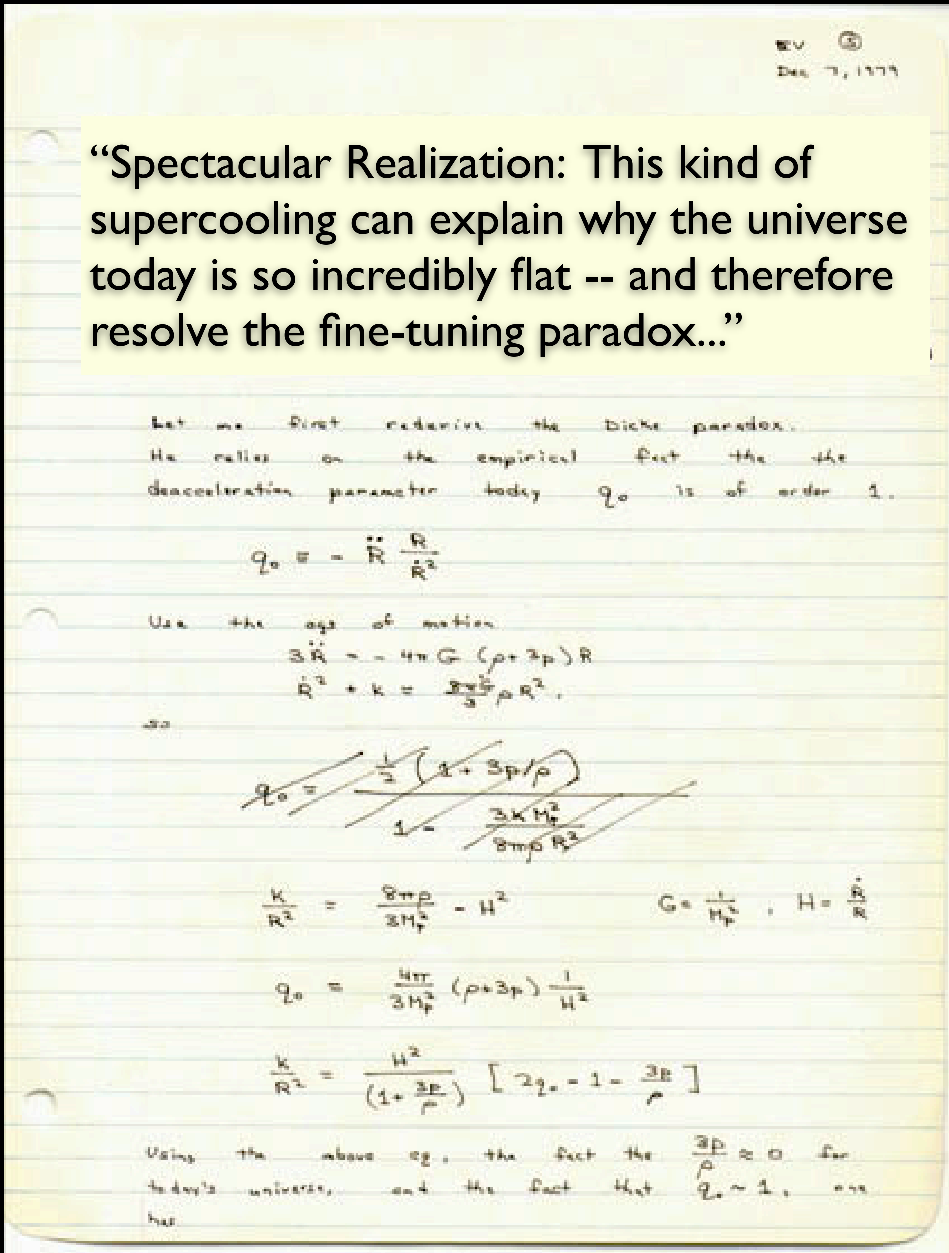
Alan Guth's Notebook: December 7, 1979.

Inflation Solves the Flatness Problem



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...”

SV ③
Dec. 7, 1979

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deceleration 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

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

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

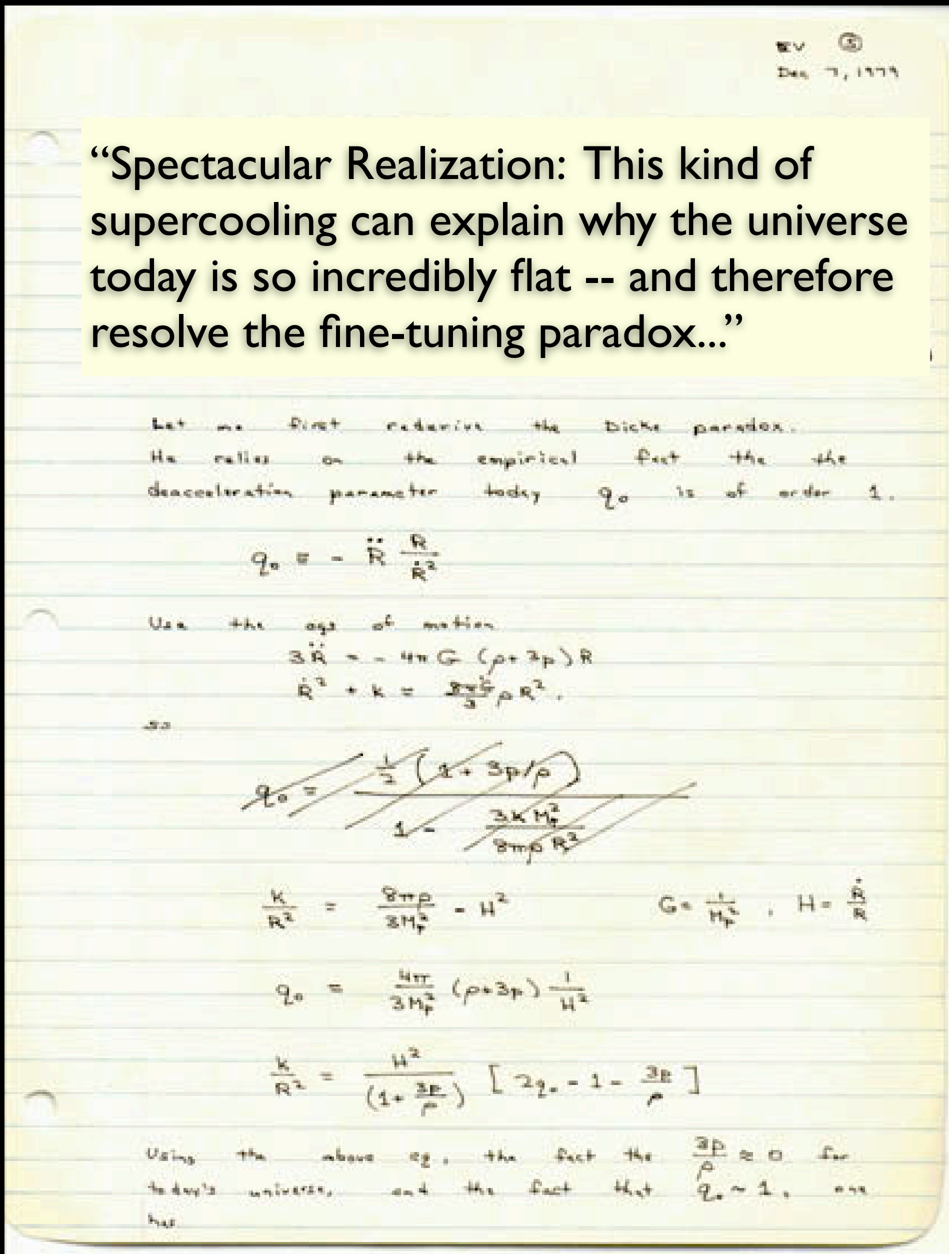
$$\frac{k}{R^2} = \frac{H^2}{\left(1 + \frac{3p}{\rho}\right)}\left[2q_0 - 1 - \frac{3p}{\rho}\right]$$

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.

Recall that $\Omega = 1$ **is unstable**; a Universe that is initially curved will become even more curved as it evolves.

Inflation Solves the Flatness Problem

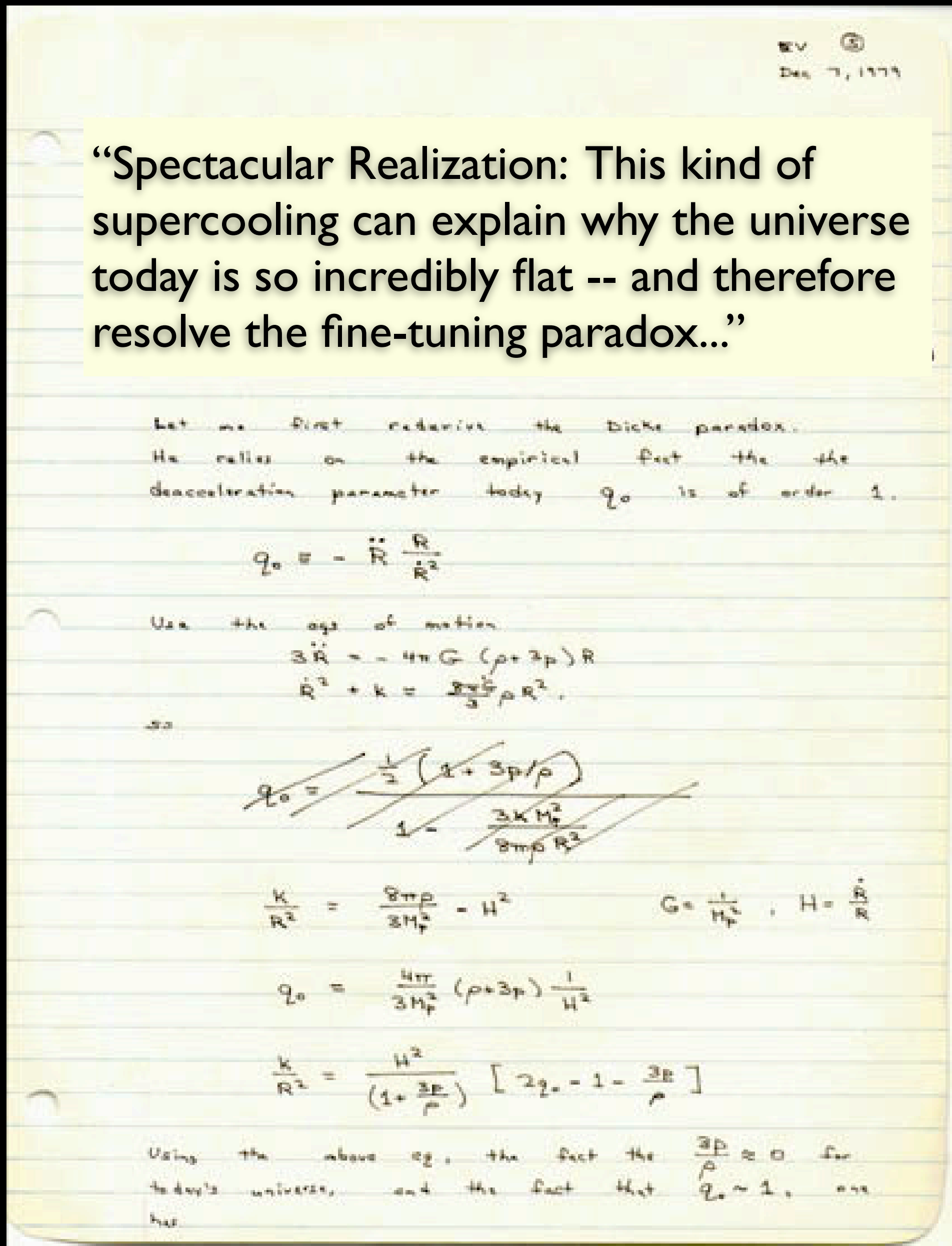


Alan Guth's Notebook: December 7, 1979.

Recall that $\Omega = 1$ **is unstable**; a Universe that is initially curved will become even more curved as it evolves.

$$\frac{d}{dt}\underbrace{|\Omega - 1|}_{\text{curvature}} = -2\underbrace{\left(\frac{dR}{dt}\right)^{-3}}_{\text{expansion rate of Universe}}\frac{d^2R}{dt^2}$$

Inflation Solves the Flatness Problem



Alan Guth's Notebook: December 7, 1979.

Recall that $\Omega = 1$ **is unstable**; a Universe that is initially curved will become even more curved as it evolves.

expansion rate of Universe

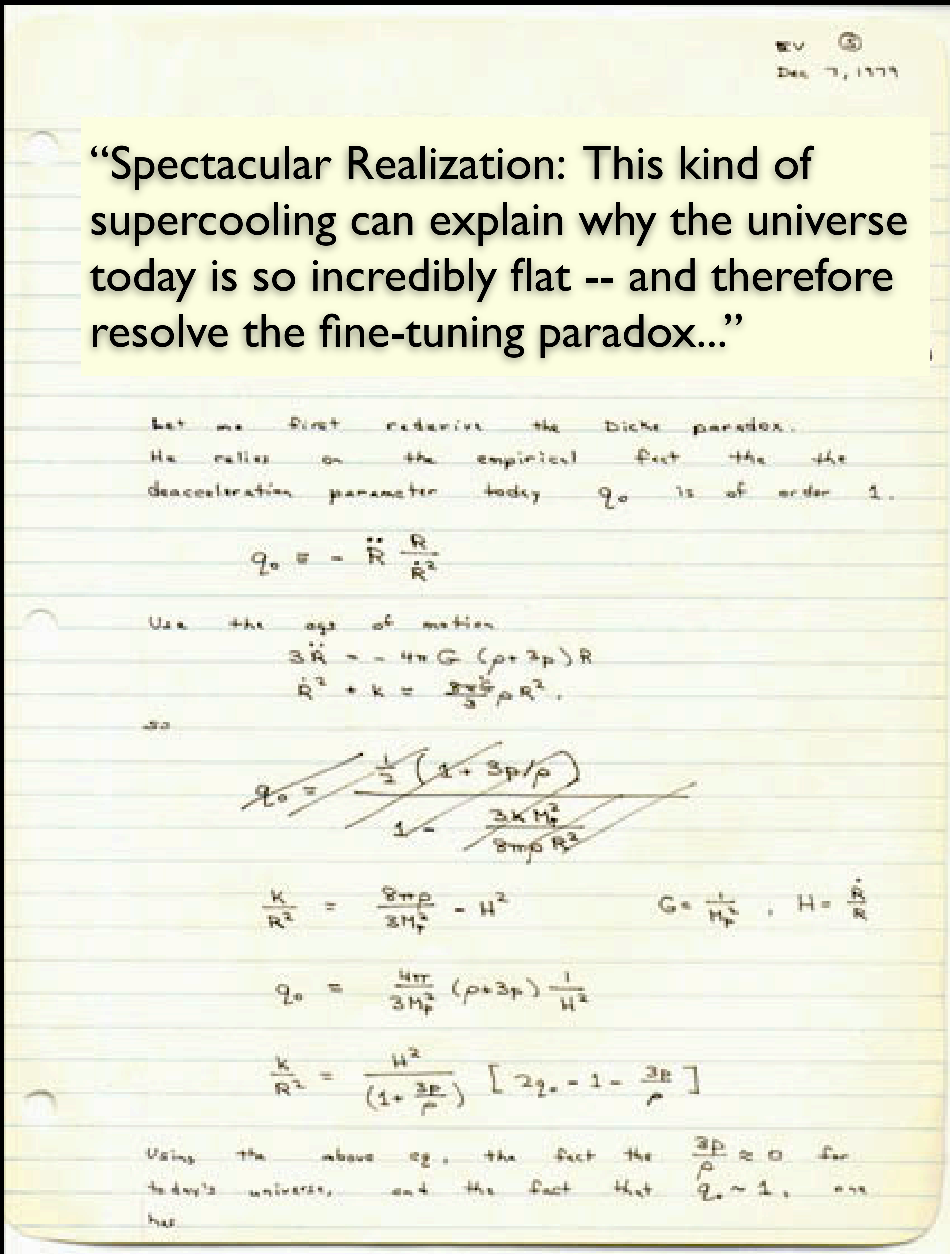
curvature

$$\frac{d}{dt}|\Omega - 1| = -2\left(\frac{dR}{dt}\right)^{-3}\frac{d^2R}{dt^2}$$

decelerating

$$\frac{\mathrm{d}}{\mathrm{d}t}|\Omega - 1| > 0$$

Inflation Solves the Flatness Problem



Alan Guth's Notebook: December 7, 1979.

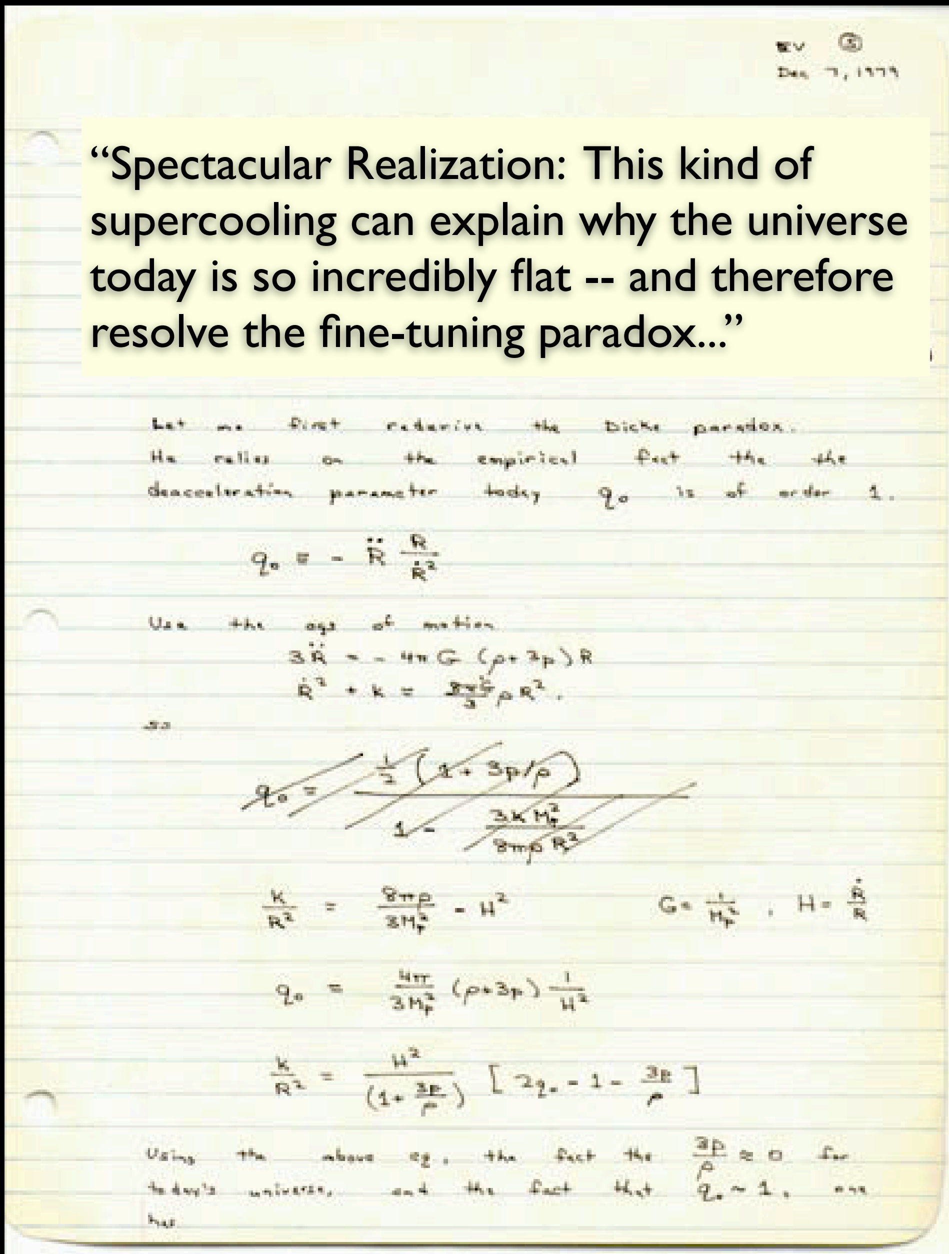
Recall that $\Omega = 1$ **is unstable**; a Universe that is initially curved will become even more curved as it evolves.

$$\underbrace{\frac{d}{dt}|\Omega - 1|}_{\text{curvature}} = -2\,\underbrace{\left(\frac{dR}{dt}\right)^{-3}}_{\text{expansion rate of Universe}}\frac{d^2R}{dt^2}$$

decelerating: $\frac{d}{dt}|\Omega - 1| > 0$

accelerating: $\frac{d}{dt}|\Omega - 1| < 0$

Inflation Solves the Flatness Problem


EV (5)
Dec. 7, 1979

Let me first rederive the Dicke paradox. He relies on the empirical fact that the deceleration 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

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

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

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

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

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

Alan Guth's Notebook: December 7, 1979.

Recall that $\Omega = 1$ **is unstable**; a Universe that is initially curved will become even more curved as it evolves.

expansion rate of Universe

curvature

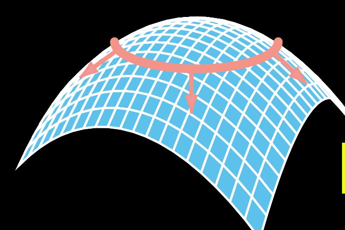
$$\frac{d}{dt}|\Omega - 1| = -2\left(\frac{dR}{dt}\right)^{-3}\frac{d^2R}{dt^2}$$

decelerating

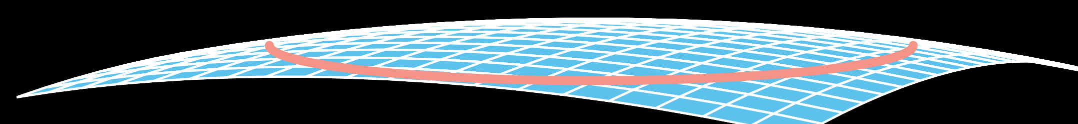
$$\frac{d}{dt}|\Omega - 1| > 0$$

accelerating

$$\frac{d}{dt}|\Omega - 1| < 0$$

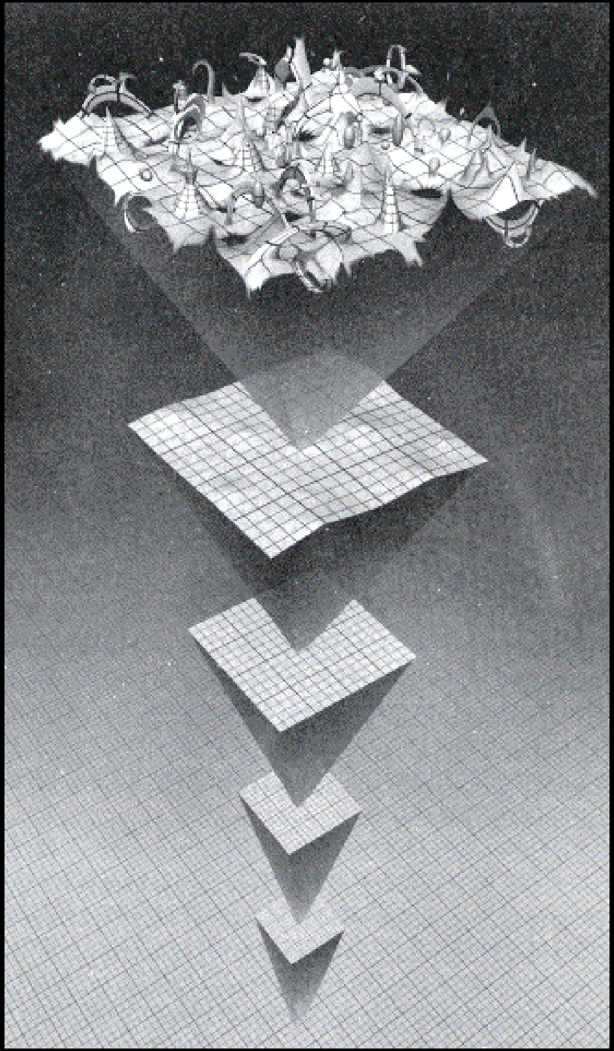


Inflation makes curved universes flat!



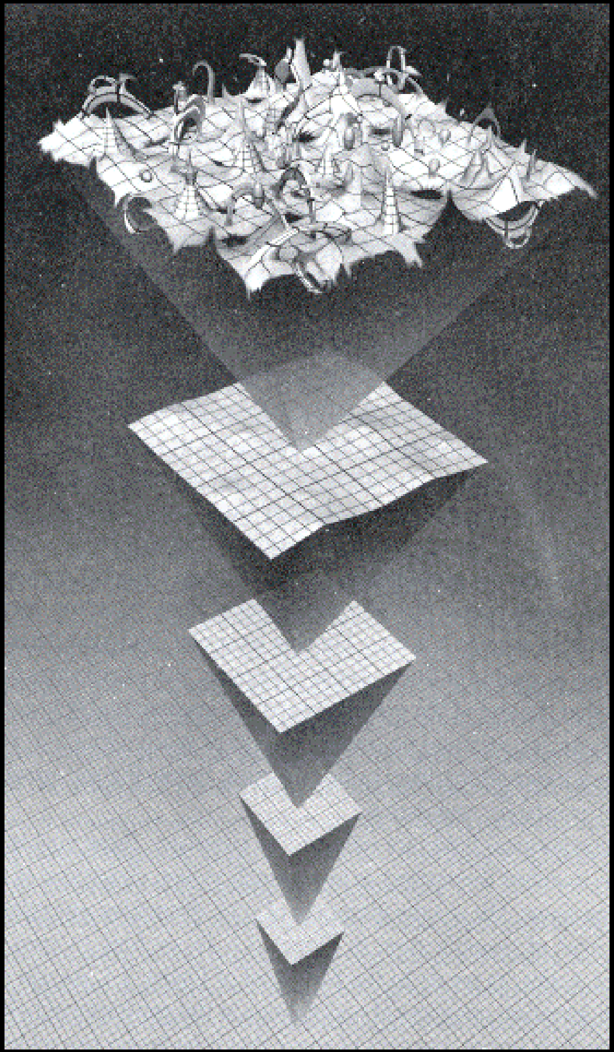
The Origin of Initial Fluctuations

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



The Origin of Initial Fluctuations

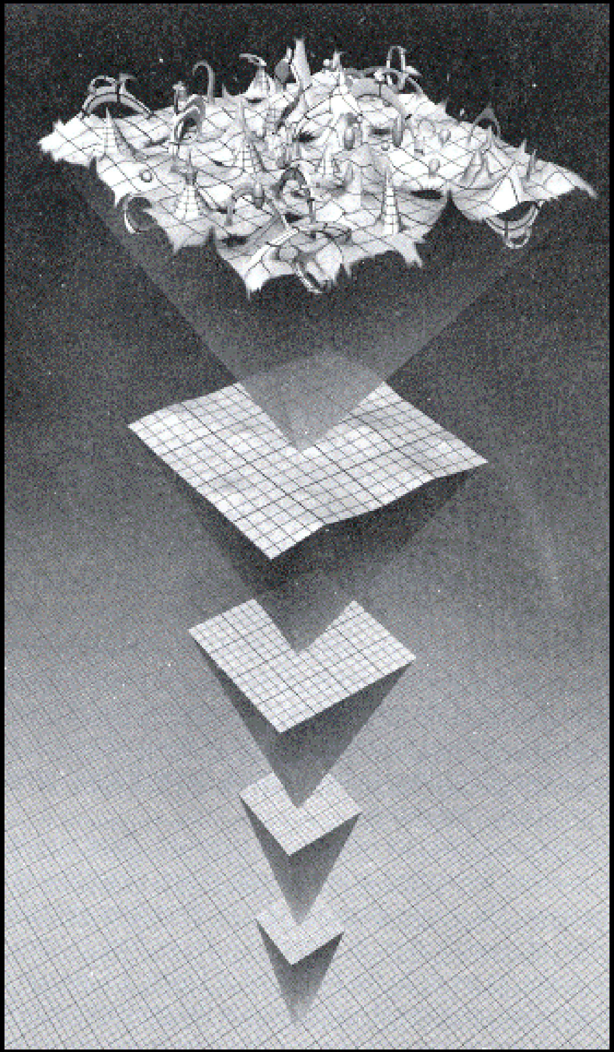
The energy density during inflation is not uniform; quantum fluctuations lead to hot and cold regions.



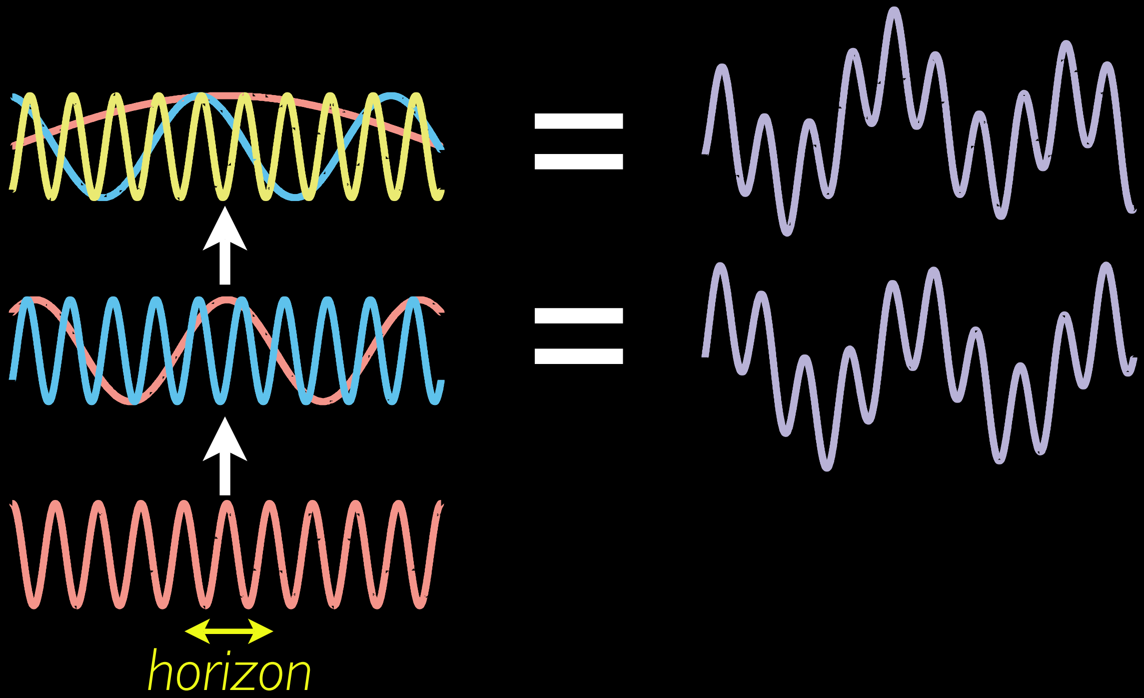
- In a decelerating Universe, quantum fluctuations pop in and out of existence.
- During inflation, quantum fluctuations are stretched outside the horizon and are frozen.

The Origin of Initial Fluctuations

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

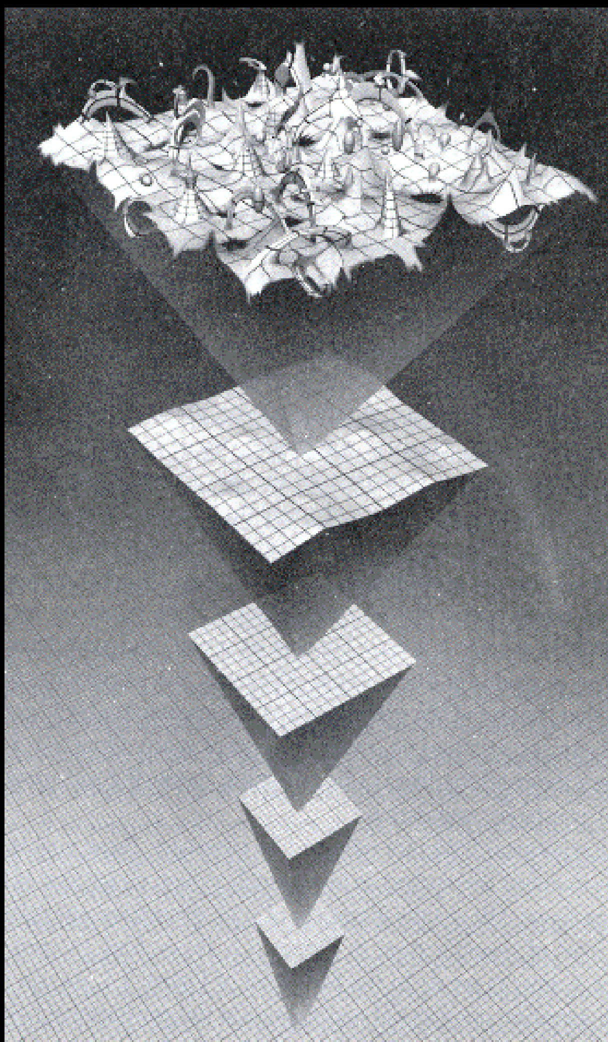


- In a decelerating Universe, quantum fluctuations pop in and out of existence.
- During inflation, quantum fluctuations are stretched outside the horizon and are frozen.

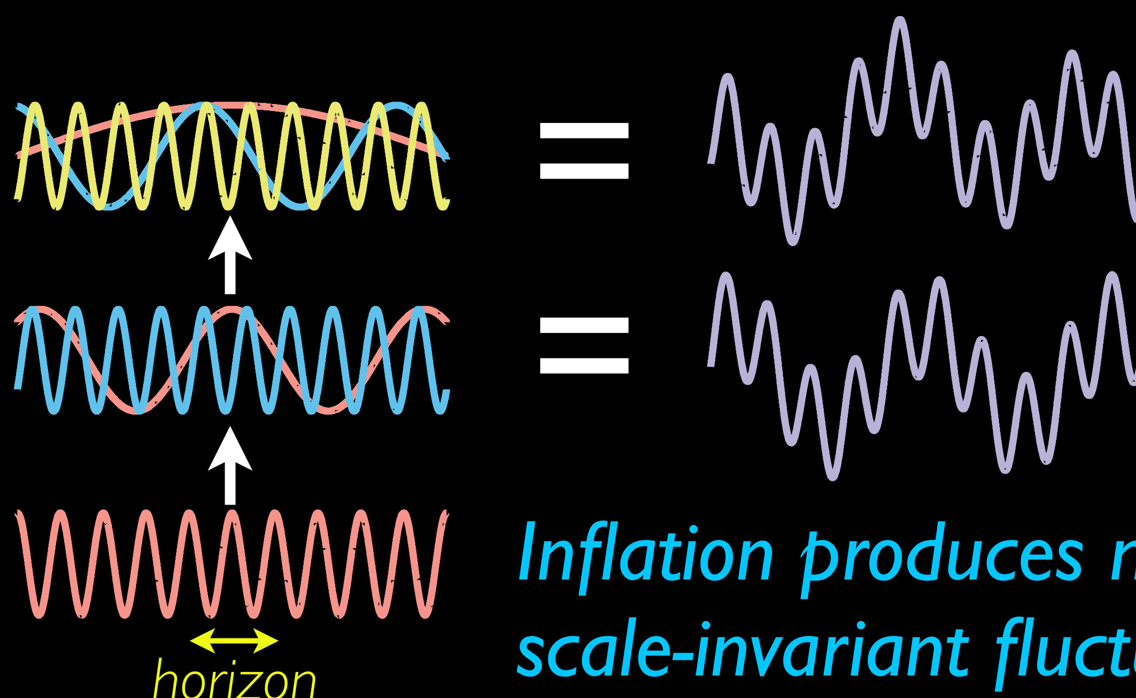


The Origin of Initial Fluctuations

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



- In a decelerating Universe, quantum fluctuations pop in and out of existence.
- During inflation, quantum fluctuations are stretched outside the horizon and are frozen.

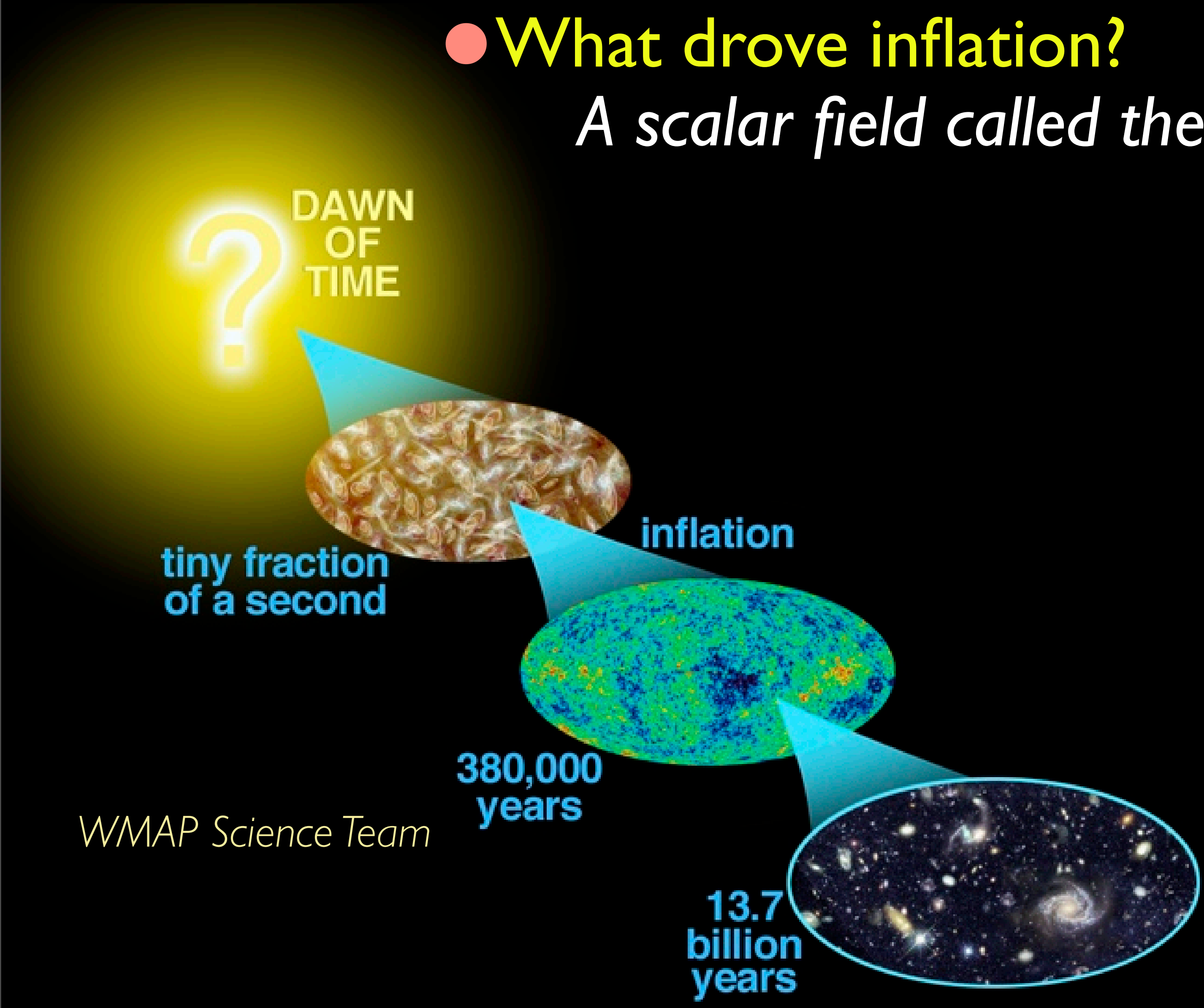


Inflation produces nearly scale-invariant fluctuations!

Unanswered Questions

- What drove inflation?

  A scalar field called the inflaton...



WMAP Science Team

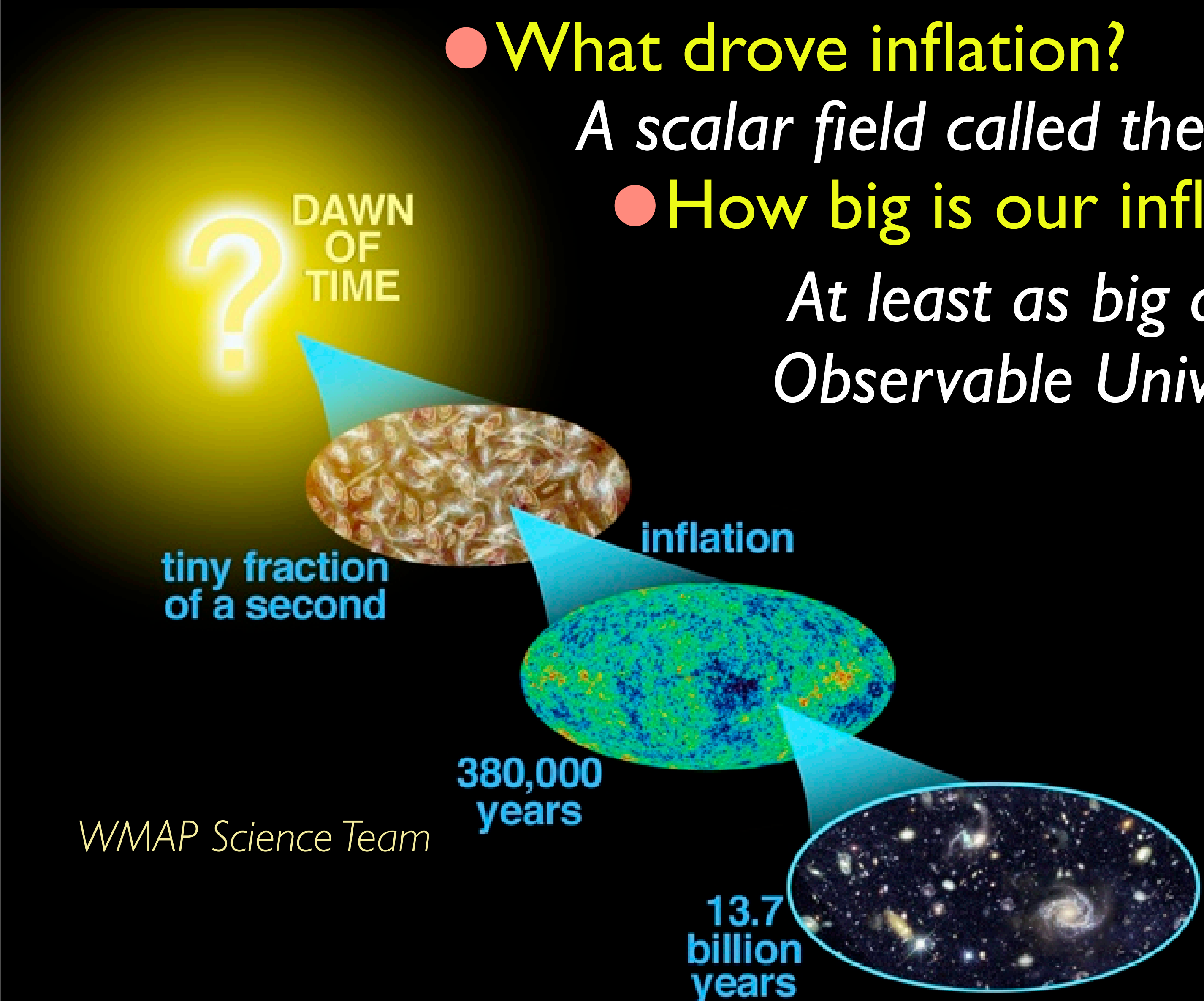
Unanswered Questions

- What drove inflation?

  A scalar field called the inflaton...

  - How big is our inflationary patch?

    At least as big as the Observable Universe...



WMAP Science Team

Unanswered Questions

- What drove inflation?

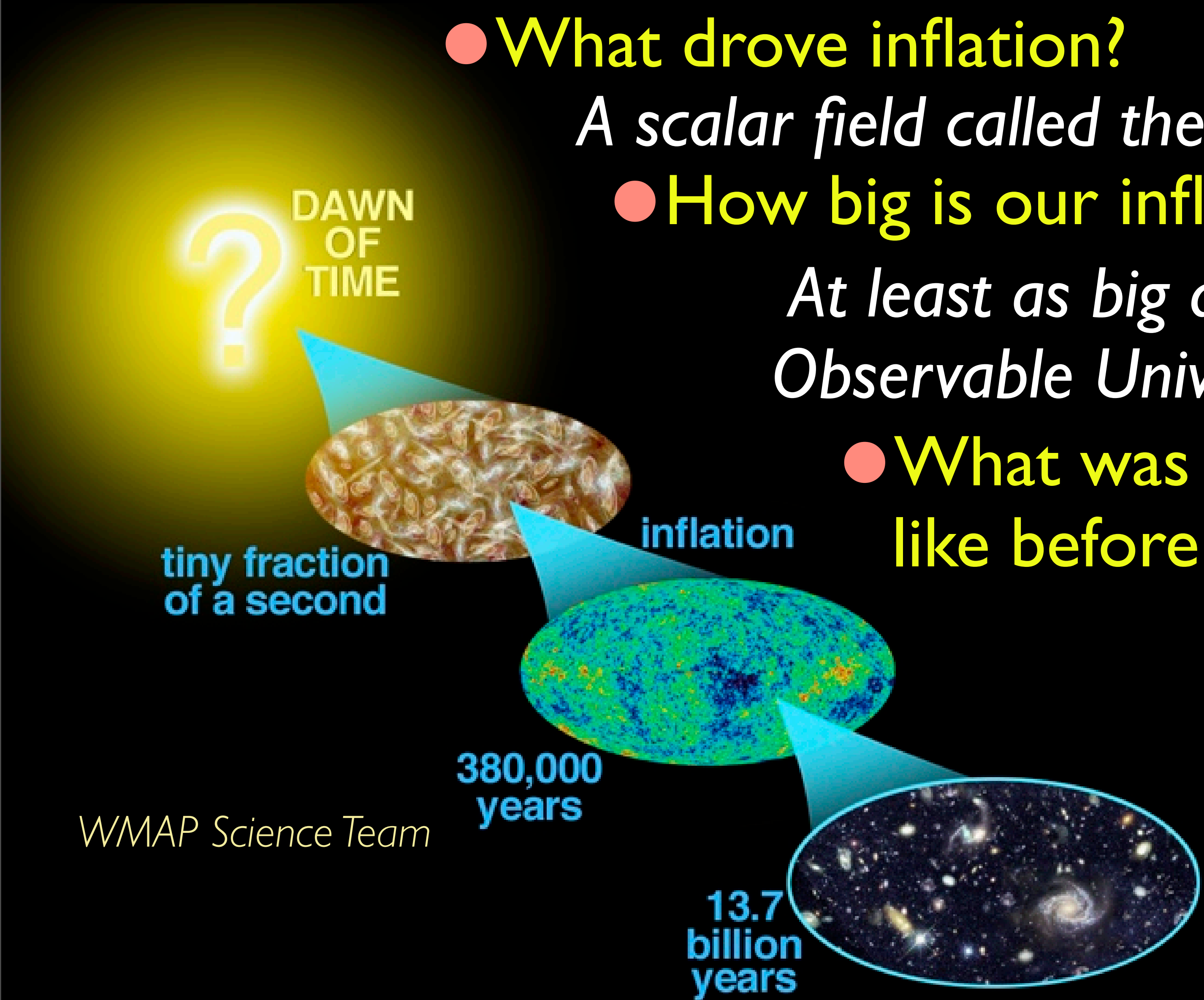
  A scalar field called the inflaton...

- How big is our inflationary patch?

  At least as big as the Observable Universe...

- What was the Universe like before inflation?

  ?



WMAP Science Team

Unanswered Questions

- What drove inflation?

  A scalar field called the inflaton...

- How big is our inflationary patch?

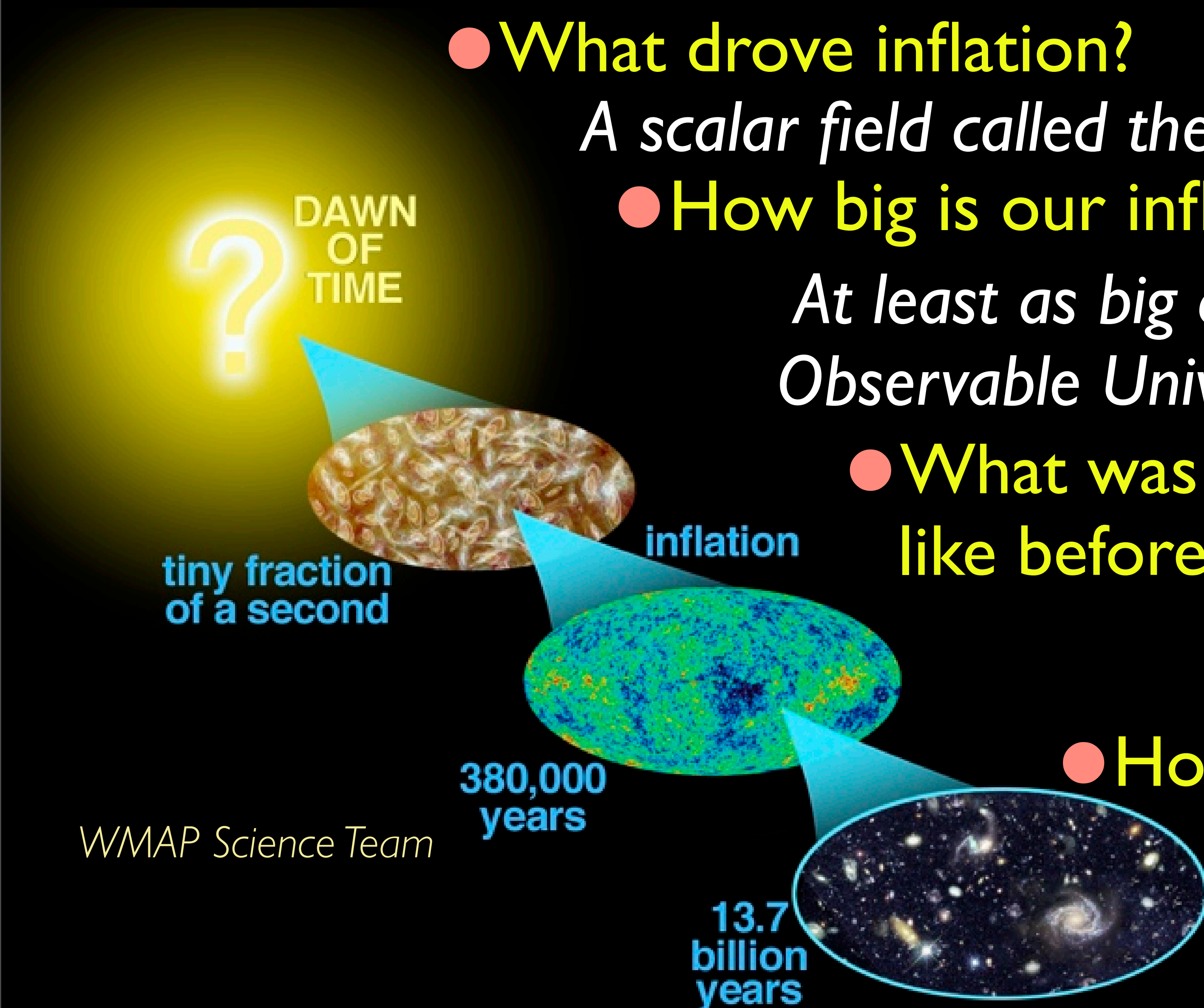
  At least as big as the Observable Universe...

- What was the Universe like before inflation?

  ?

- How did inflation start?

  The inflaton started nearly at rest at the top of a nearly flat potential slope



WMAP Science Team

Unanswered Questions

- What drove inflation?

  A scalar field called the inflaton...

- How big is our inflationary patch?

  At least as big as the Observable Universe...

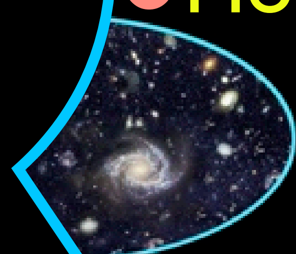
- What was the Universe like before inflation?

  ?

We need more information!

- How did inflation start?

  The inflaton started nearly at rest at the top of a nearly flat potential slope



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

General Relativity tells us

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

expansion rate of the Universe

energy density of the Universe

Quantum Fluctuations Revisited

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

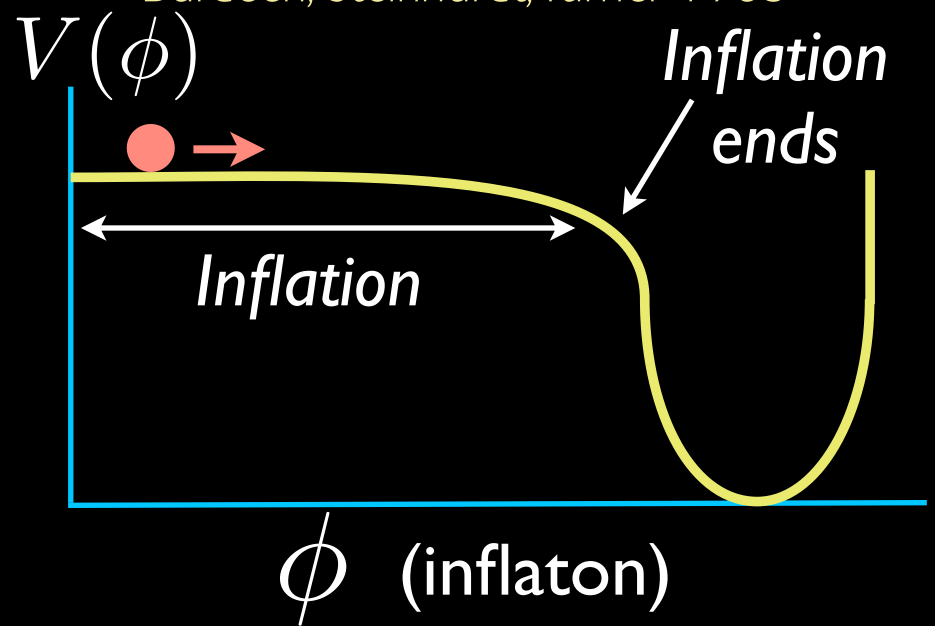
Hawking 1982; Starobinsky 1982; Guth 1982; Bardeen, Steinhardt, Turner 1983

General Relativity tells us

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

expansion rate of the Universe ($\dot{R}/R$); *energy density of the Universe* (ρ)

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



Quantum Fluctuations Revisited

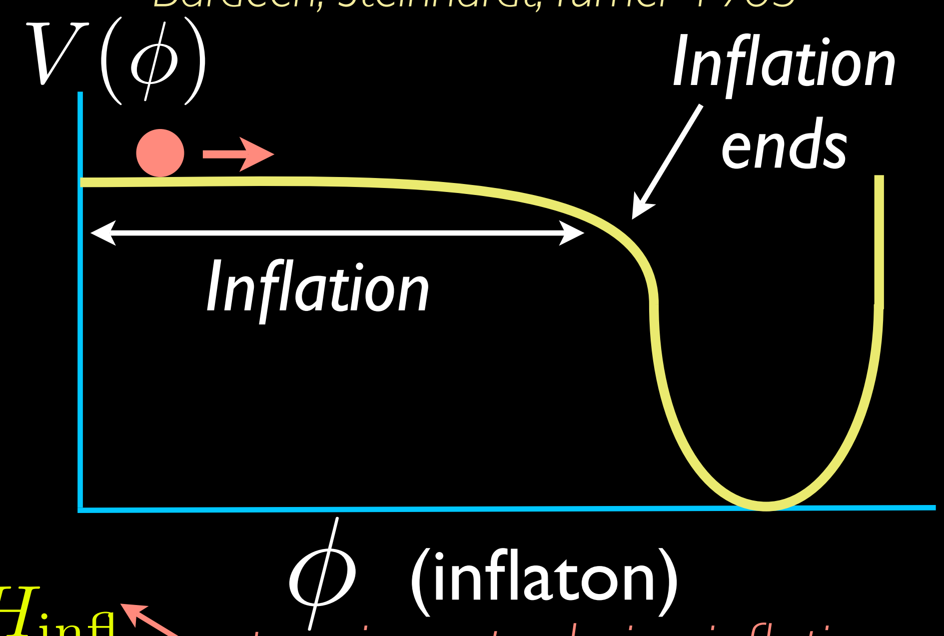
Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

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

General Relativity tells us

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

expansion rate of the Universe ($\dot{R}/R$); *energy density of the Universe* (ρ)



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

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

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

Quantum Fluctuations Revisited

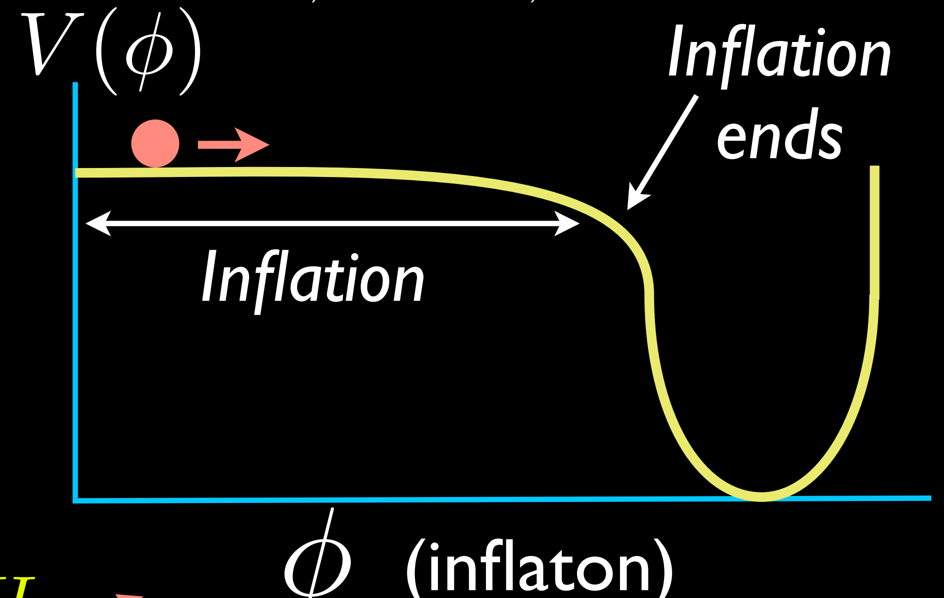
Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

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

General Relativity tells us

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

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: $\delta t = \frac{\delta\phi}{\dot{\phi}}$

$$\frac{\Delta T_{\mathrm{CMB}}}{T_{\mathrm{CMB}}} = -\frac{1}{5}\frac{\delta R}{R} = -\frac{1}{5}H\delta t$$

how much space has expanded

Quantum Fluctuations Revisited

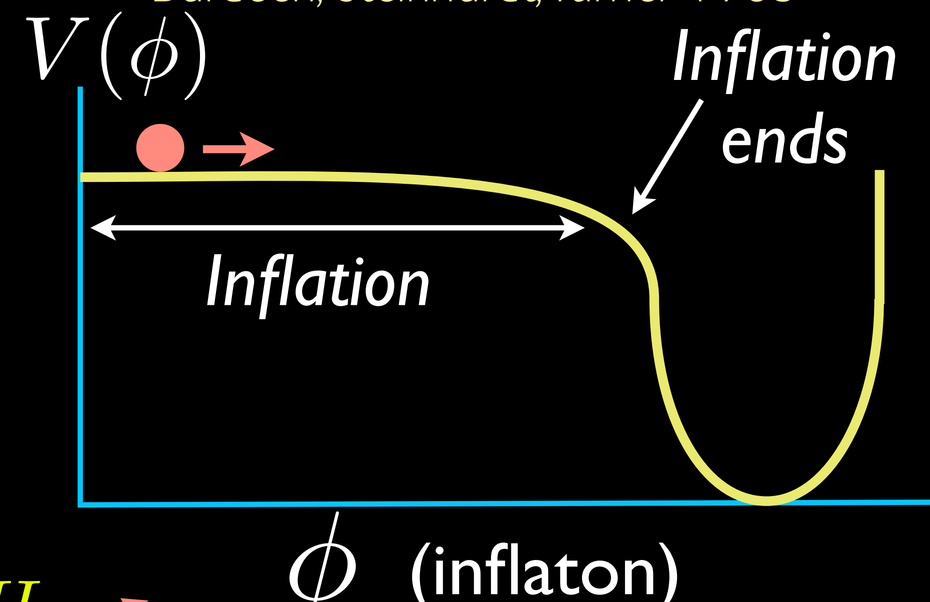
Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

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

General Relativity tells us

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

expansion rate of the Universe (H) — *energy density of the Universe* (ρ)



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

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

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

$$\left(\frac{\Delta T_{\mathrm{CMB}}}{T_{\mathrm{CMB}}} = -\frac{1}{5}\frac{\delta R}{R} = -\frac{1}{5}H\delta t\right)_{\mathrm{rms}}$$

how much space has expanded ($\frac{\delta R}{R}$)

Quantum Fluctuations Revisited

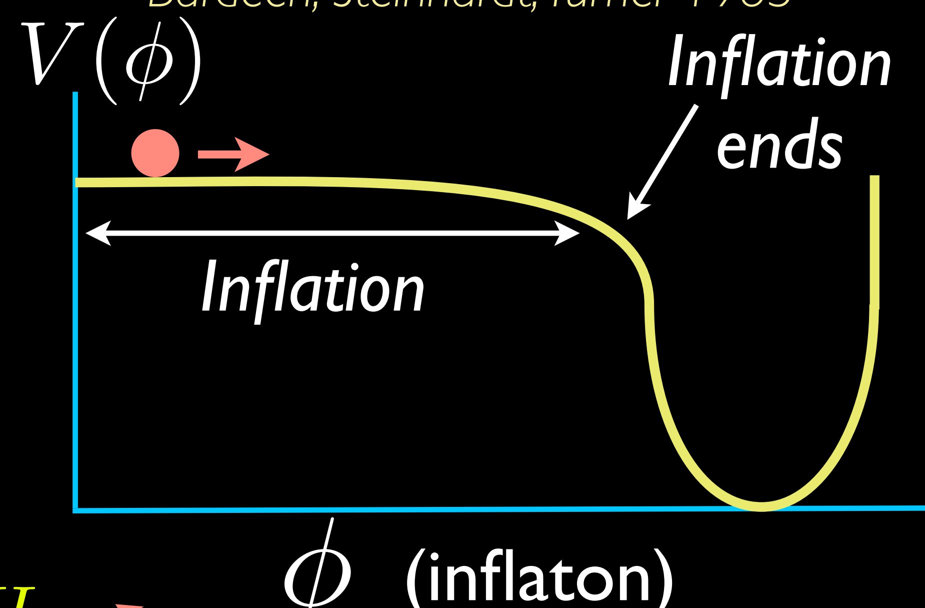
Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

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

General Relativity tells us

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

expansion rate of the Universe — *energy density of the Universe*



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

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

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

$$\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} = -\frac{1}{5}\frac{\delta R}{R} = -\frac{1}{5}H\delta t\right)_{\rm rms} = \frac{1}{5}\left(\frac{H_{\rm infl}^2}{2\pi\dot{\phi}}\right) = \frac{1}{5}\left(\frac{8G}{6\dot{\phi}}\right)V(\phi)$$

how much space has expanded — *connection to quantum fluctuations*

Gravitational waves from inflation

CMB temperature fluctuations give us some information about the inflaton: $$\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}}\right)_{\rm rms} \propto \frac{V(\phi)}{\dot{\phi}}$$

We really want to know $V(\phi)$: the energy scale of inflation.

Gravitational waves from inflation

CMB temperature fluctuations give us some information about the inflaton: $\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}}\right)_{\rm rms} \propto \frac{V(\phi)}{\dot{\phi}}$

We really want to know $V(\phi)$: the energy scale of inflation.

During inflation, quantum fluctuations are also imprinted on spacetime itself:

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

$$H^2 = \frac{8\pi G}{3} V(\phi)$$

Gravitational waves from inflation

CMB temperature fluctuations give us some information about the inflaton: $$\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}}\right)_{\rm rms} \propto \frac{V(\phi)}{\dot{\phi}}$$

We really want to know $V(\phi)$: the energy scale of inflation.

During inflation, quantum fluctuations are also imprinted on spacetime itself:

Quantum fluctuations: $$(\,h\,)_{\rm rms} = \frac{H_{\rm infl}}{2\pi}$$ ← *expansion rate during inflation*

spacetime fluctuation

$$H^2 = \frac{8\pi G}{3} V(\phi)$$

Gravitational waves from inflation

CMB temperature fluctuations give us some information about the inflaton: $\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}}\right)_{\rm rms} \propto \frac{V(\phi)}{\dot{\phi}}$

We really want to know $V(\phi)$: the energy scale of inflation.

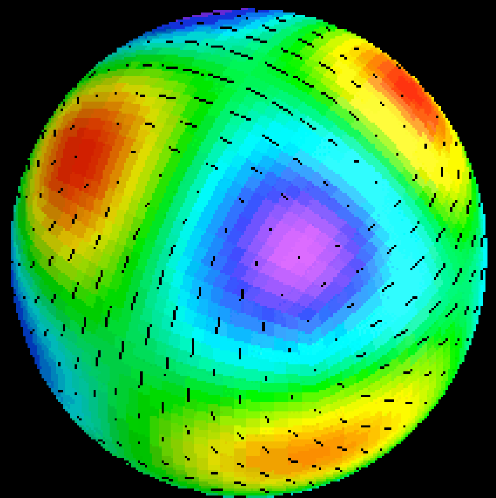
During inflation, quantum fluctuations are also imprinted on spacetime itself:

Quantum fluctuations: $(\ h\ )_{\rm rms} = \frac{H_{\rm infl}}{2\pi}$ ← *expansion rate during inflation*

spacetime fluctuation

$$H^2 = \frac{8\pi G}{3} V(\phi)$$

The gravitational waves leave a special imprint on the CMB polarization -- we can use this to measure $V(\phi)$.



Gravitational waves from inflation

CMB temperature fluctuations give us some information about the inflaton: $\left(\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}}\right)_{\rm rms} \propto \frac{V(\phi)}{\dot{\phi}}$

We really want to know $V(\phi)$: the energy scale of inflation.

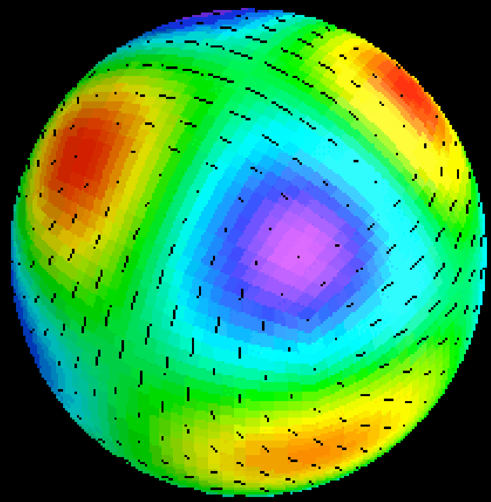
During inflation, quantum fluctuations are also imprinted on spacetime itself:

Quantum fluctuations: $(\,h\,)_{\rm rms} = \frac{H_{\rm infl}}{2\pi}$ ← *expansion rate during inflation*

spacetime fluctuation

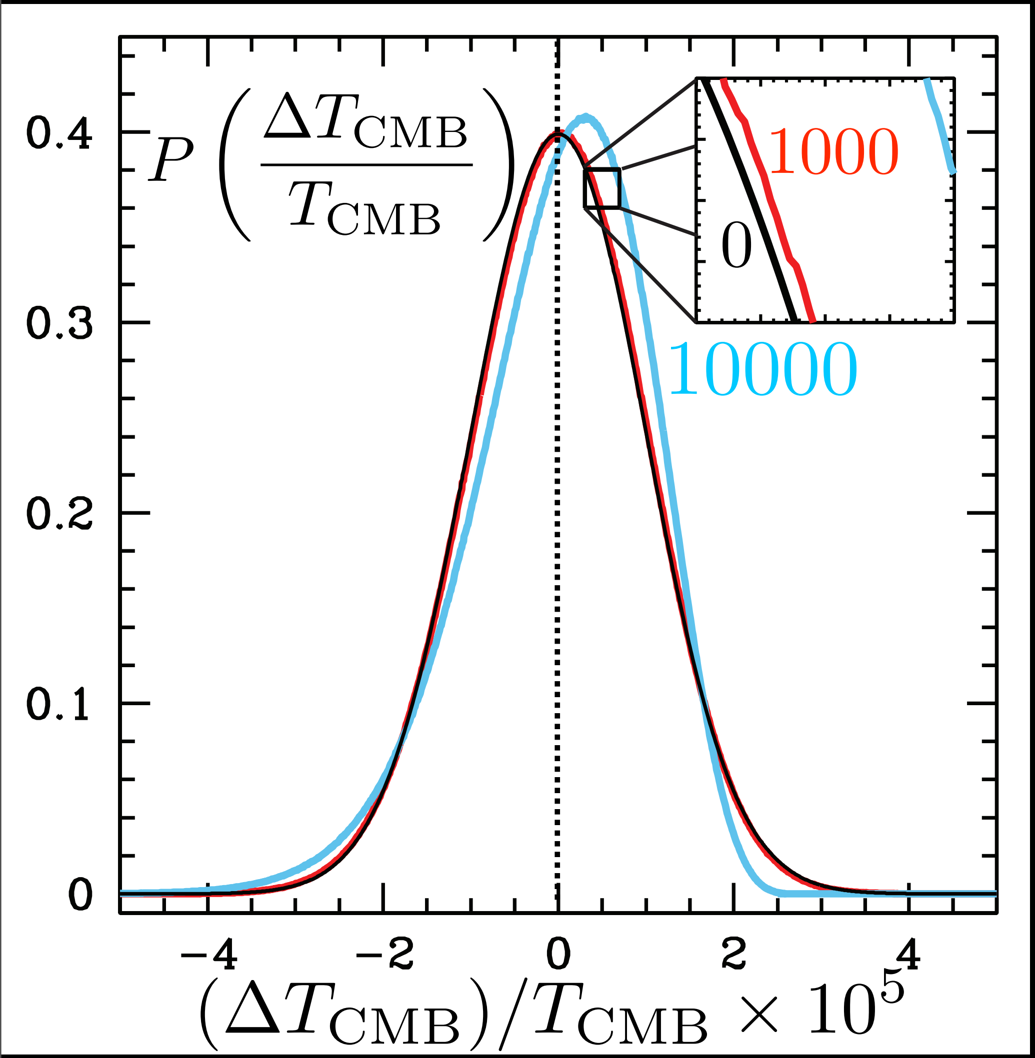
$$H^2 = \frac{8\pi G}{3} V(\phi)$$

The gravitational waves leave a special imprint on the CMB polarization -- we can use this to measure $V(\phi)$.



The search is on!

Are the perturbations Gaussian?

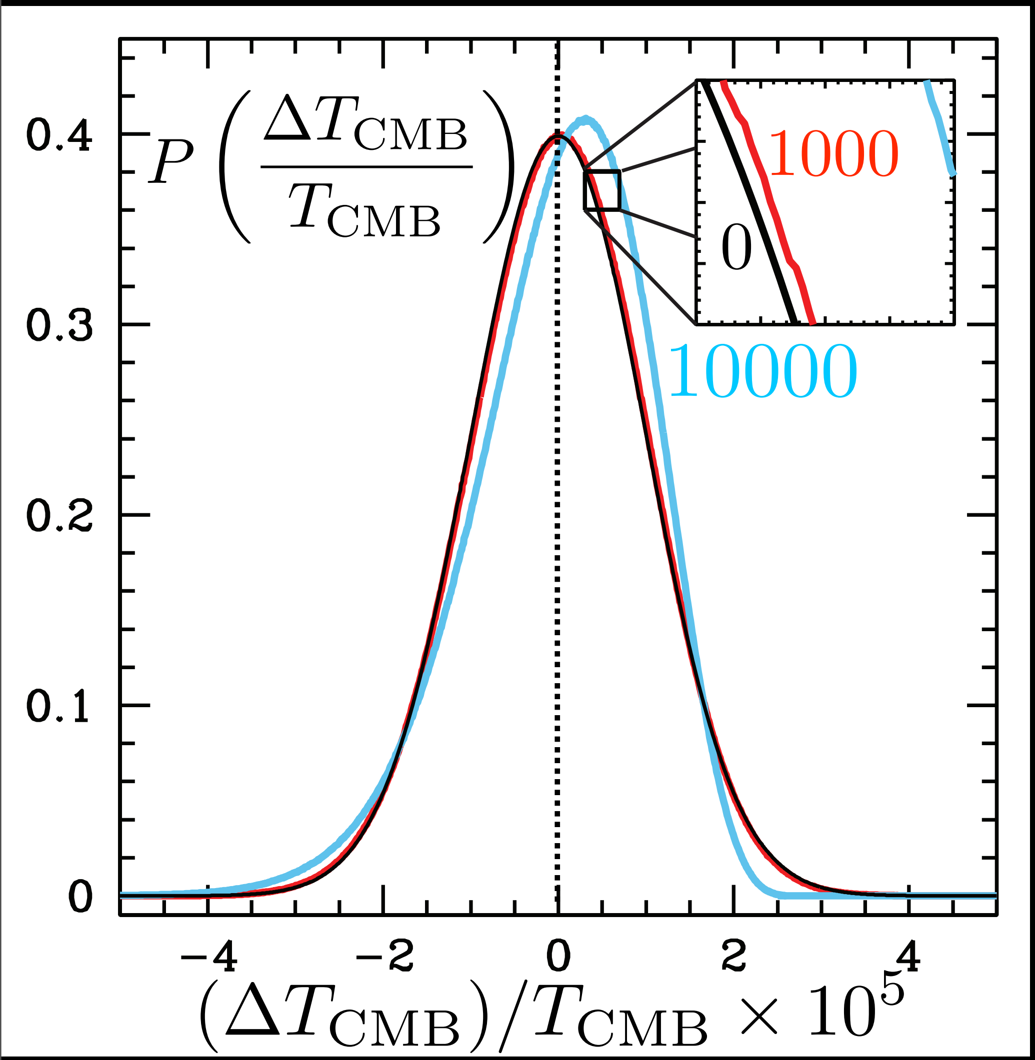


temperature fluctuation $\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} = \frac{\Psi}{3}$ *gravitational potential*

Parametrize:

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

Are the perturbations Gaussian?



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

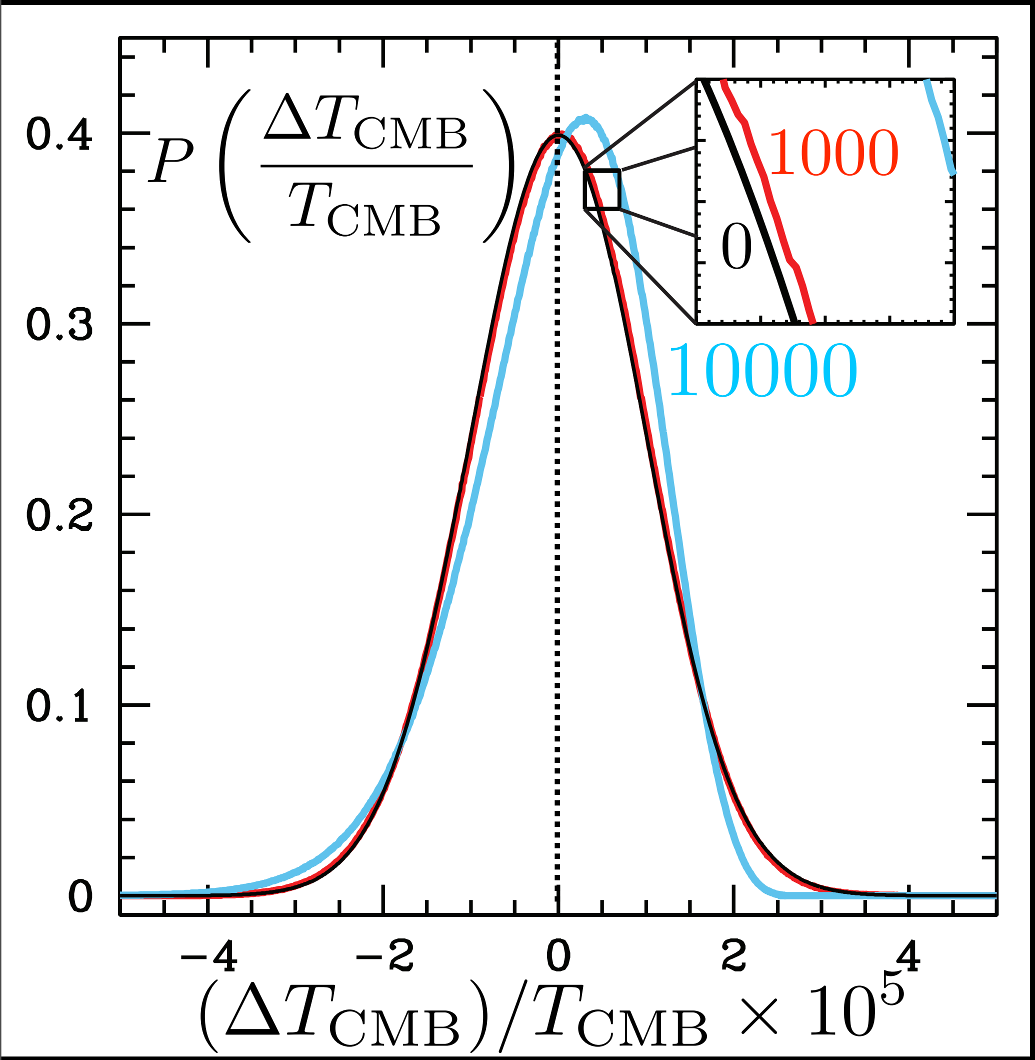
Parametrize:

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

Non-gaussianity tells us about field interactions during inflation.

- Single-field inflation predicts
$$f_{\rm NL} \simeq 1$$
- Multi-field inflation can produce larger values of $f_{\rm NL}$
- Current bounds: *Komatsu et al. 2010; WMAP7+SDSS*
$$-5 < f_{\rm NL} < 59$$

Are the perturbations Gaussian?



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

Parametrize:

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

Non-gaussianity tells us about field interactions during inflation.

- Single-field inflation predicts

$$f_{\rm NL} \simeq 1$$

- Multi-field inflation can produce larger values of $f_{\rm NL}$
- Current bounds:

Komatsu et al. 2010; WMAP7+SDSS

$$-5 < f_{\rm NL} < 59$$

The search is on!

Alternatives to Inflation

Alternatives to Inflation

The null hypothesis: the Big Bang just made it that way.

- Maybe homogeneous and flat is the natural starting point?
- And Gaussian, scale-invariant perturbations?
- It's not easy to start inflation -- did we make progress?

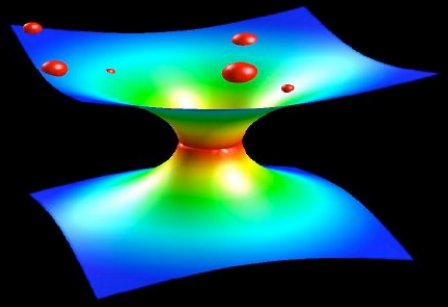
Alternatives to Inflation

The null hypothesis: the Big Bang just made it that way.

- Maybe homogeneous and flat is the natural starting point?
- And Gaussian, scale-invariant perturbations?
- It's not easy to start inflation -- did we make progress?

Cyclic Models and Ekpyrotic Models *Khoury, Ovrut, Steinhardt & Turok 2001, and many others followed*

- A slowly contracting Universe can make a flat, homogeneous universe with scale-invariant perturbations
- And then there's a bounce....



Alternatives to Inflation

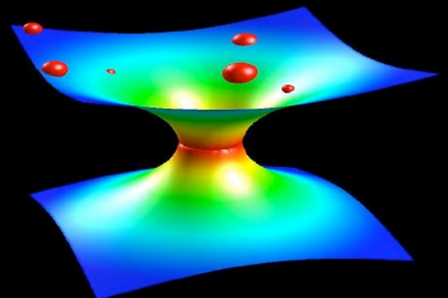
The null hypothesis: the Big Bang just made it that way.

- Maybe homogeneous and flat is the natural starting point?
- And Gaussian, scale-invariant perturbations?
- It's not easy to start inflation -- did we make progress?

Cyclic Models and Ekpyrotic Models

Khoury, Ovrut, Steinhardt & Turok 2001, and many others followed

- A slowly contracting Universe can make a flat, homogeneous universe with scale-invariant perturbations
- And then there's a bounce....



Eternal Inflation and the String Theory Landscape

- Maybe inflation is the Universe's natural state, and only little pockets ever stop inflating
- Welcome to the Multiverse....
- But watch out for bubble collisions!

Dark Matter: The Evidence

From nucleosynthesis: $\Omega_{\rm p+n} = 0.042 \pm 0.004$ *protons and neutrons*

From the CMB: $\Omega_b = 0.046 \pm 0.002$ *charged particles tightly coupled to photons*

$\Omega_{dm} = 0.227 \pm 0.014$

massive neutral particles that do not interact with photons

Dark Matter: The Evidence

From nucleosynthesis: $\Omega_{\rm p+n} = 0.042 \pm 0.004$ *protons and neutrons*

From the CMB: $\Omega_b = 0.046 \pm 0.002$ *charged particles tightly coupled to photons*

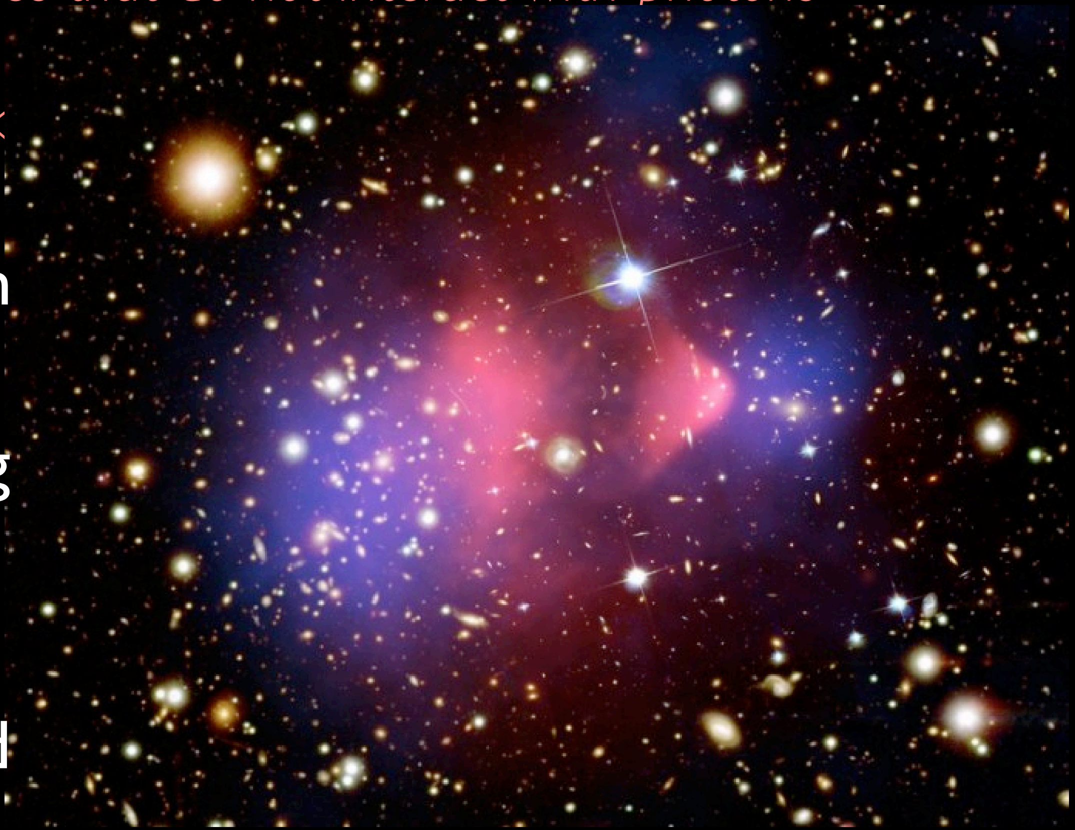
$$\Omega_{dm} = 0.227 \pm 0.014$$

massive neutral particles that do not interact with photons

From galaxies and clusters:

More details in Anne-Marie's talk next week

- the dynamical masses of galaxies and clusters are much larger than their luminous masses.
- confirmed by gravitational lensing
- $\Omega_m \simeq 0.3$ from counting the galaxies and clusters
- the dark matter can be separated from the luminous matter.



Bullet Cluster: NASA/CXC/CfA Markevitch et al.

Prime Suspect: the WIMP

WIMP = Weakly Interacting Massive Particle

WIMPS are the leading dark matter candidate for 2 reasons

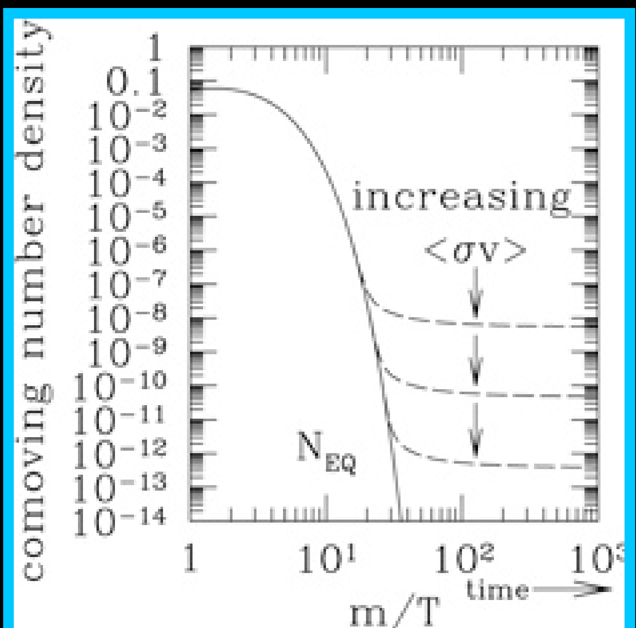
- Supersymmetry predicts a stable neutral particle with Weak interactions -- called the neutralino
- easily created in the early Universe via "the WIMP miracle"

Prime Suspect: the WIMP

WIMP = Weakly Interacting Massive Particle

WIMPS are the leading dark matter candidate for 2 reasons

- Supersymmetry predicts a stable neutral particle with Weak interactions -- called the neutralino
- easily created in the early Universe via "the WIMP miracle"



How to make WIMP dark matter

1. Start with hot photons: T > m

$$\text{hot photon}\ \gamma \longleftrightarrow \chi\chi\ \text{pair of WIMPs}$$

2. Allow the photons to cool: T < m

$$\chi\chi \longrightarrow \gamma$$

3. Self-annihilations stop because particles can't find each other: age of Universe < time between collisions

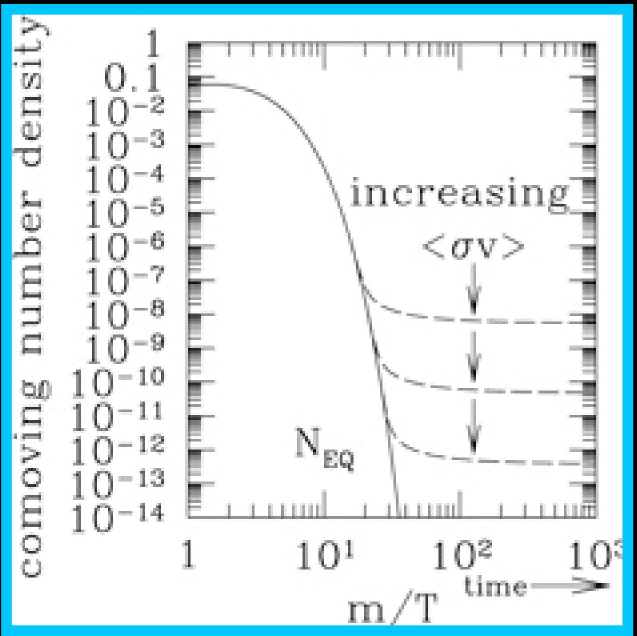
$$H > n\langle\sigma v\rangle$$

Prime Suspect: the WIMP

WIMP = Weakly Interacting Massive Particle

WIMPS are the leading dark matter candidate for 2 reasons

- Supersymmetry predicts a stable neutral particle with Weak interactions -- called the neutralino
- easily created in the early Universe via "the WIMP miracle"



How to make WIMP dark matter

1. Start with hot photons: T > m

$$\text{hot photon } \gamma \longleftrightarrow \chi\chi \text{ pair of WIMPs}$$

2. Allow the photons to cool: T < m

$$\chi\chi \longrightarrow \gamma$$

3. Self-annihilations stop because particles can't find each other: age of Universe < time between collisions

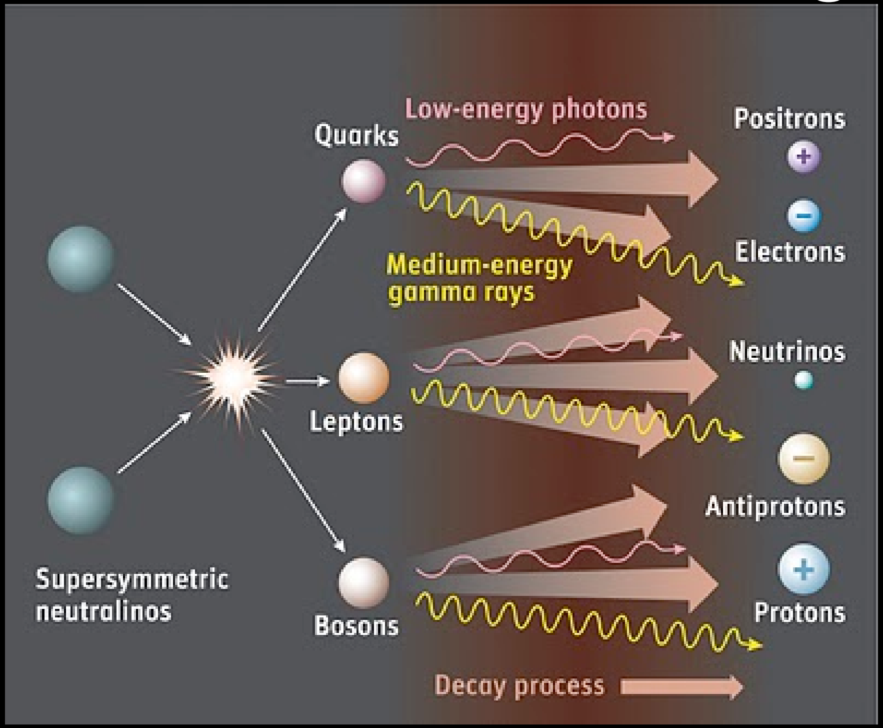
$$H > n\langle\sigma v\rangle$$

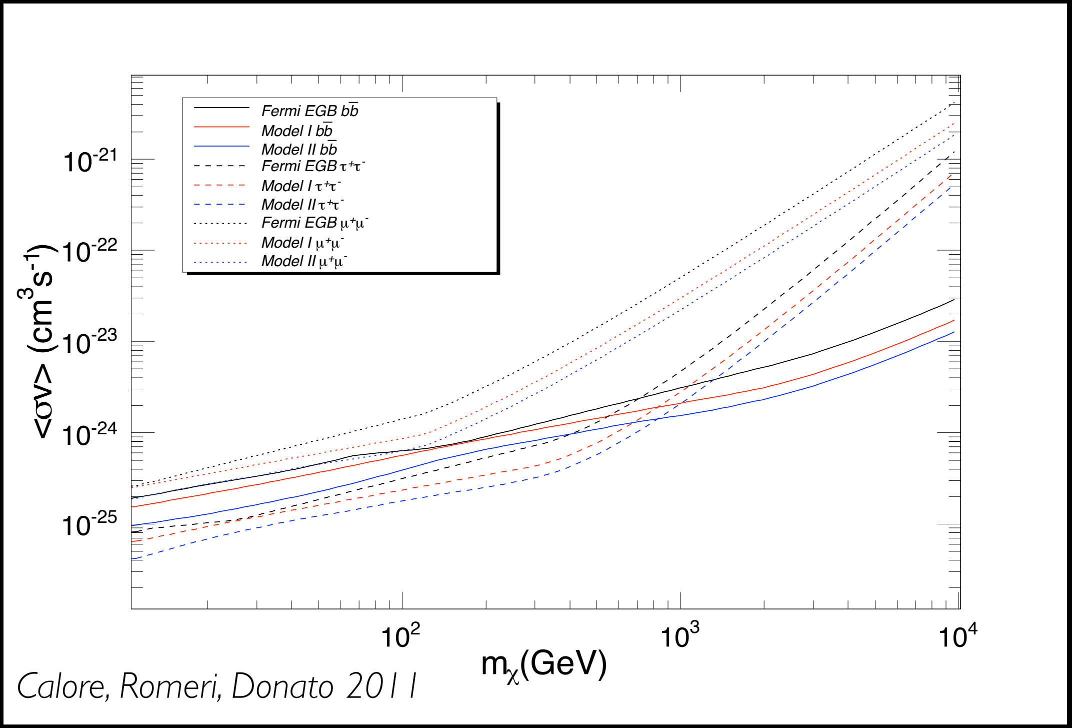
Remaining dark matter density matches observations if

$$\langle\sigma v\rangle \simeq 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \simeq (0.005/200\,\mathrm{GeV})^2$$

Searching for a WIMP Indirectly

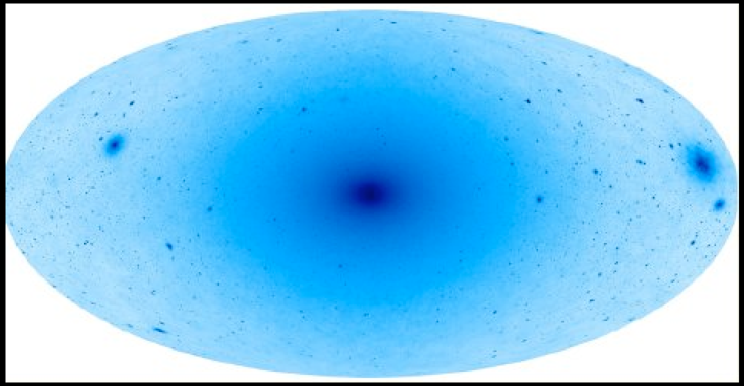
Indirect detection: signals from DM self-annihilation





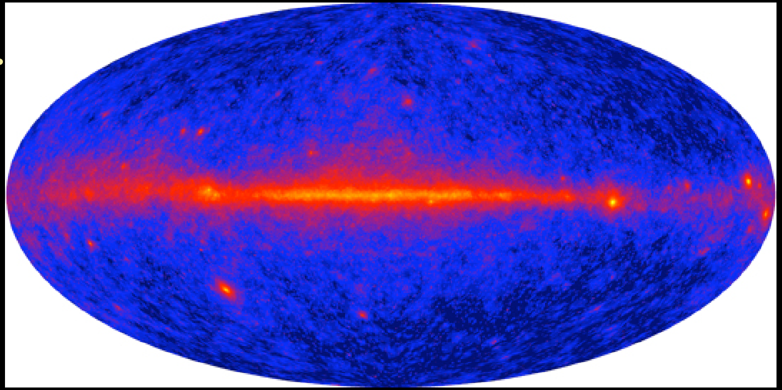
Calore, Romeri, Donato 2011

Predicted Gamma-Ray Sky



Kuhlen et al. 2009

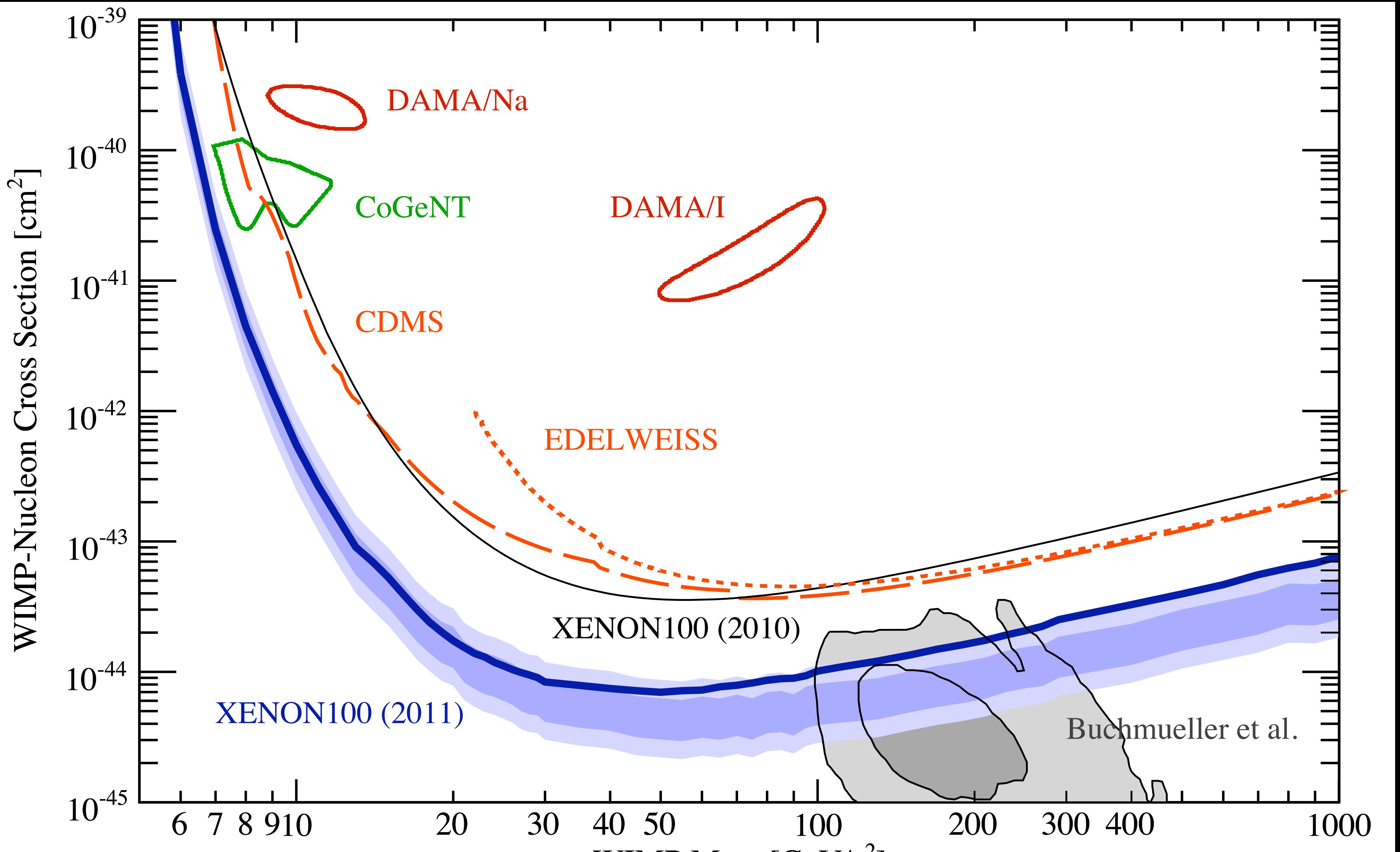
Observed Gamma-Ray Sky



NASA/DOE/ Fermi LAT team

Searching for a WIMP Directly

Direct detection: when WIMPS and atomic nuclei collide



Xenon100 Collaboration arXiv:1104.2549

Other Dark Matter Candidates

Other Dark Matter Candidates

1. Sterile Neutrinos

- Minimal extension to Standard Model required to give neutrino mass, as required by neutrino oscillations
- Non-interacting and very difficult to detect

Other Dark Matter Candidates

1. Sterile Neutrinos
   - Minimal extension to Standard Model required to give neutrino mass, as required by neutrino oscillations
   - Non-interacting and very difficult to detect
2. Axions
   - Particle that was invented to explain the absence of Strong CP violation in the Standard Model
   - Can decay into photons -- this leads to constraints

Other Dark Matter Candidates

1. Sterile Neutrinos
   - Minimal extension to Standard Model required to give neutrino mass, as required by neutrino oscillations
   - Non-interacting and very difficult to detect
2. Axions
   - Particle that was invented to explain the absence of Strong CP violation in the Standard Model
   - Can decay into photons -- this leads to constraints
3. Primordial Black Holes
   - Primordial black holes form when the initial density fluctuations on small scales are very large
   - Severely constrained by gravitational microlensing & evaporation

Other Dark Matter Candidates

1. Sterile Neutrinos
   - Minimal extension to Standard Model required to give neutrino mass, as required by neutrino oscillations
   - Non-interacting and very difficult to detect
2. Axions
   - Particle that was invented to explain the absence of Strong CP violation in the Standard Model
   - Can decay into photons -- this leads to constraints
3. Primordial Black Holes
   - Primordial black holes form when the initial density fluctuations on small scales are very large
   - Severely constrained by gravitational microlensing & evaporation
4. Asymmetric Dark matter
   - Establishes a link between baryon density and DM density
   - No anti-dark matter means no self-annihilation

Other Dark Matter Candidates

1. Sterile Neutrinos
   - Minimal extension to Standard Model required to give neutrino mass, as required by neutrino oscillations
   - Non-interacting and very difficult to detect
2. Axions
   - Particle that… …nce of Strong CP violation i…
   - Can dec… …ts
3. Primor…
   - Primordial … …nsity fluctuations on small scales are …
   - Severely constrained by gravitational microlensing & evaporation
4. Asymmetric Dark matter
   - Establishes a link between baryon density and DM density
   - No anti-dark matter means no self-annihilation

The only evidence for dark matter is gravitational. Maybe our theory of gravity is wrong?
MOND, TeVeS, and others

Dark Energy: The Evidence

From the CMB: missing energy

$$\Omega_r + \Omega_b + \Omega_{dm} + \Omega_? = 1$$

$$10^{-5} \quad 0.045 \quad 0.227 \quad 0.728$$

From Type Ia Supernovae:

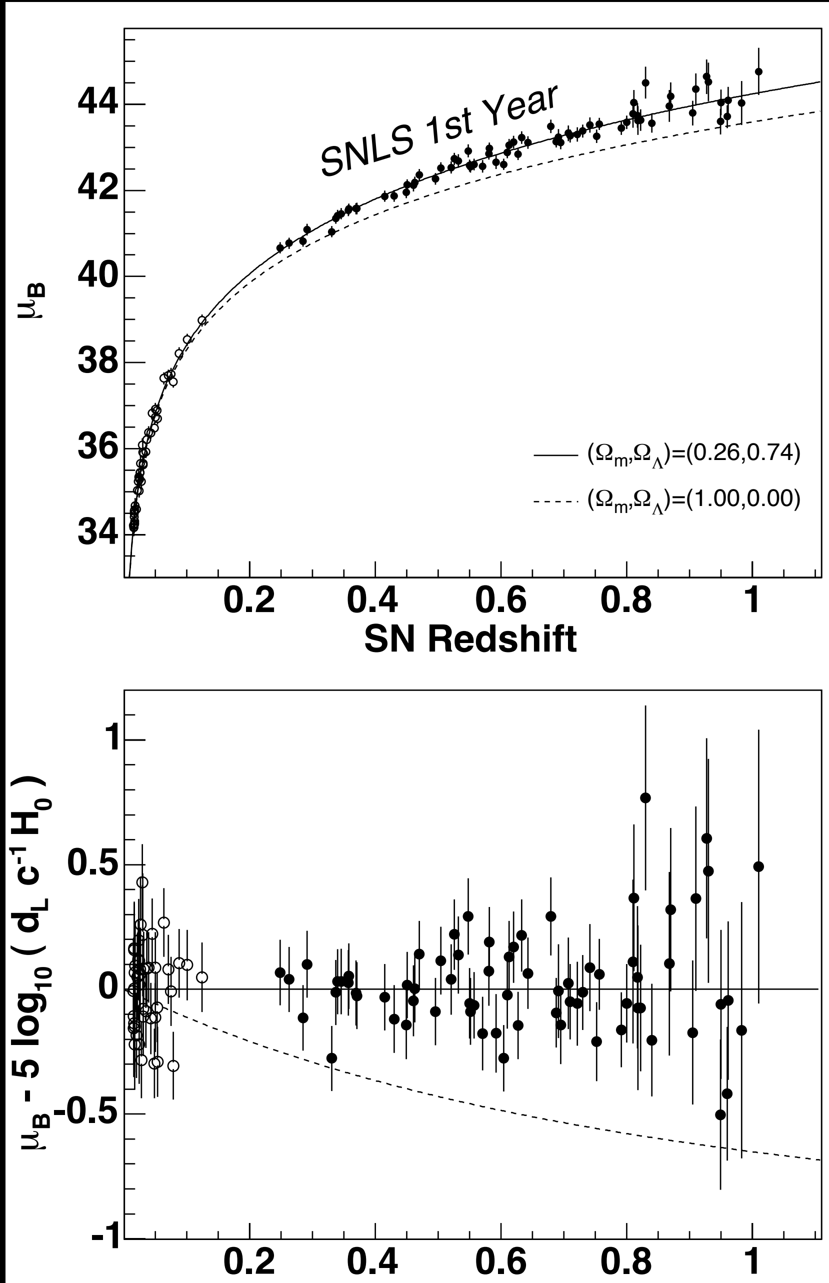
1998 Surprise:

Cosmic Expansion is Accelerating!

- Type Ia Supernova are "standard candles," so their apparent magnitude gives their distance
- distant supernovae are moving slower than expected in a matter-only universe
- the Hubble expansion used to be slower than it is today

SNLS 3rd Year, 2011

$$\Omega_{de} = 0.74 \pm 0.02$$



Astier et al. 2006

Dark Energy: What is it?

Basic information: $\text{pressure} = w \times \text{density}$

radiation: $w = 1/3$

matter: $w = 0$

acceleration: $w < -1/3$

Dark Energy: What is it?

Basic information: $\text{pressure} = w \times \text{density}$

radiation: $w = 1/3$

matter: $w = 0$

acceleration: $w < -1/3$

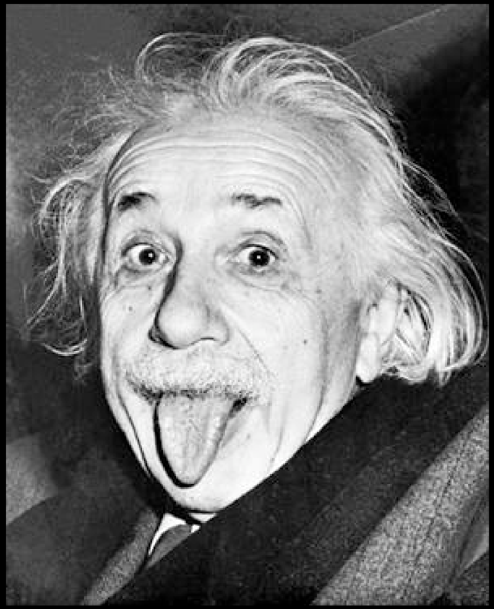
Option 1: A Cosmological Constant (Λ)

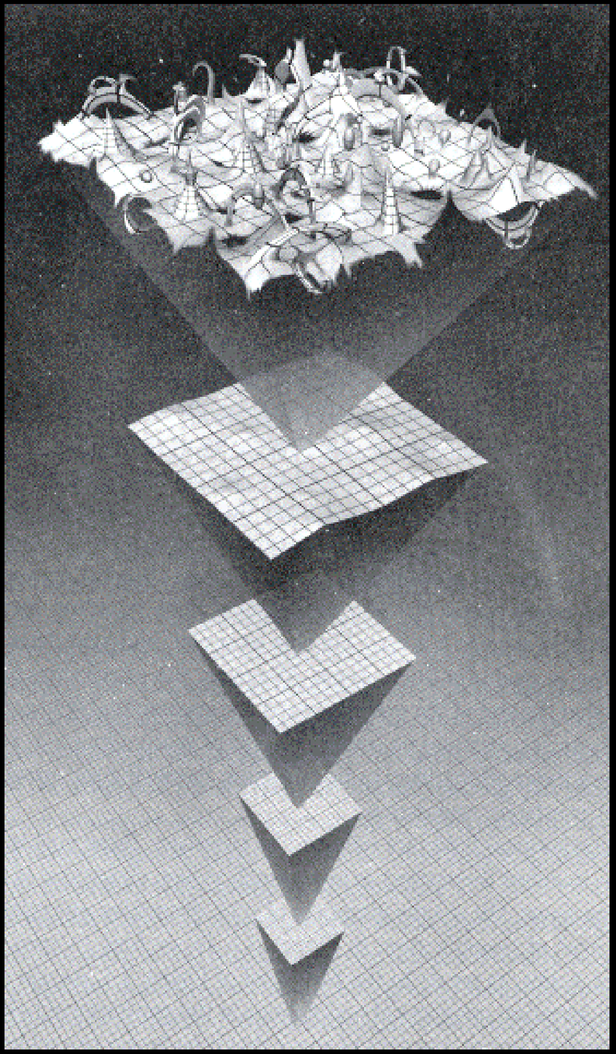
- Einstein's blunder -- it's back!
- $w = -1 \Rightarrow$ constant density
- interpret as "vacuum energy"
- quantum field theory predicts

$$\rho_\Lambda \simeq M_{\rm Pl}^4$$

- observed value

$$\rho_\Lambda \simeq 10^{-120} M_{\rm Pl}^4$$





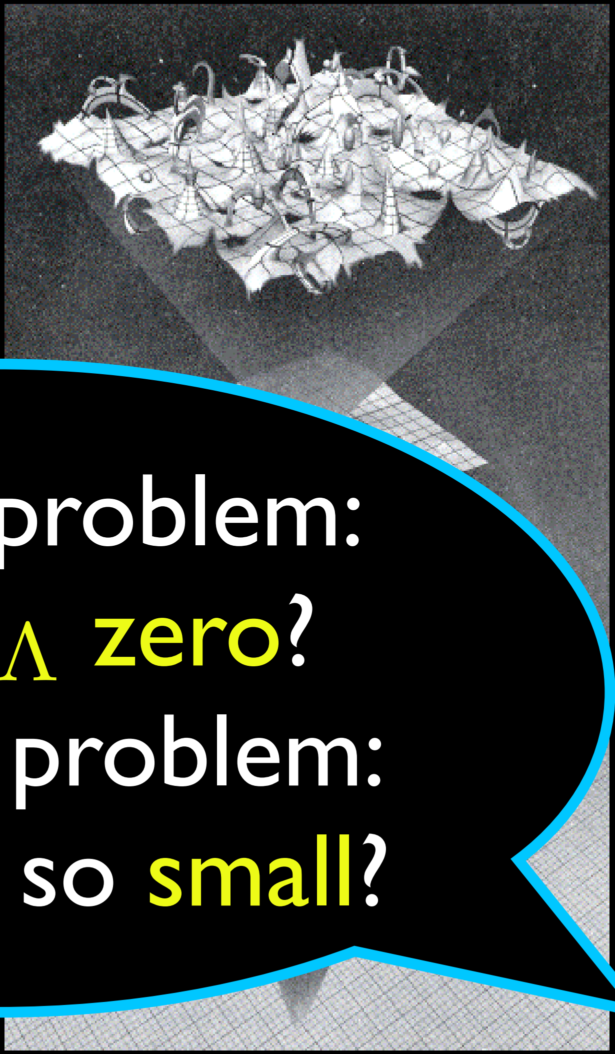
Dark Energy: What is it?

Basic information: $\text{pressure} = w \times \text{density}$

radiation: $w = 1/3$

matter: $w = 0$

acceleration: $w < -1/3$



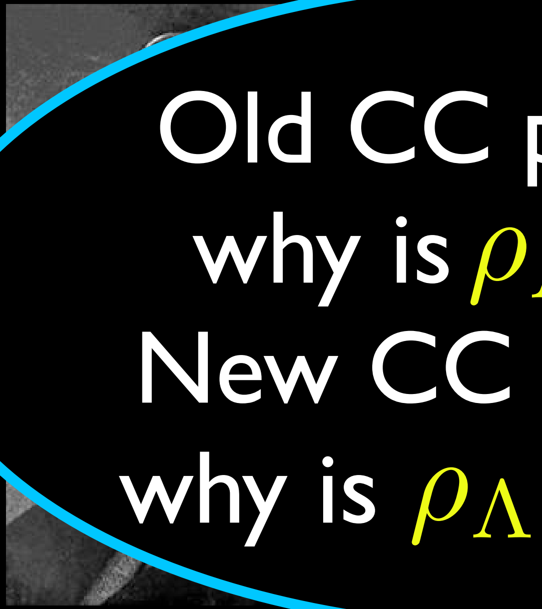
Option 1: A Cosmological Constant (Λ)

- Einstein's blunder -- it's back!
- $w = -1 \Rightarrow$ constant density
- interpret as "vacuum energy
- quantum field theory predic

$$\rho_\Lambda \simeq M_{\rm Pl}^4$$

- observed value

$$\rho_\Lambda \simeq 10^{-120} M_{\rm Pl}^4$$



Old CC problem:
why is ρ_Λ zero?
New CC problem:
why is ρ_Λ so small?

Dark Energy: What is it?

Basic information: $\mathrm{pressure} = w \times \mathrm{density}$

radiation: $w = 1/3$ acceleration: $w < -1/3$

matter: $w = 0$ cosmological constant: $w = -1$

Option 2: Quintessence (a scalar field)

- lesson from inflation: when you need cosmic acceleration, invent a scalar field
- like inflaton, we need a slowly varying scalar field with near-constant $V(\phi)$
- very different energy scales:
  $(10\,\mathrm{MeV})^4 \lesssim \rho_{\mathrm{infl}} \lesssim (10^{16}\mathrm{GeV})^4$
  $\rho_{de} = (0.002\,\mathrm{eV})^4$
- quintessence is dynamical: $w \gtrsim -1$

Data please?

Dark Energy: What is it?

Basic information: $\text{pressure} = w \times \text{density}$

radiation: $w = 1/3$ acceleration: $w < -1/3$

matter: $w = 0$ cosmological constant: $w = -1$

Option 2: Quintessence (a scalar field)

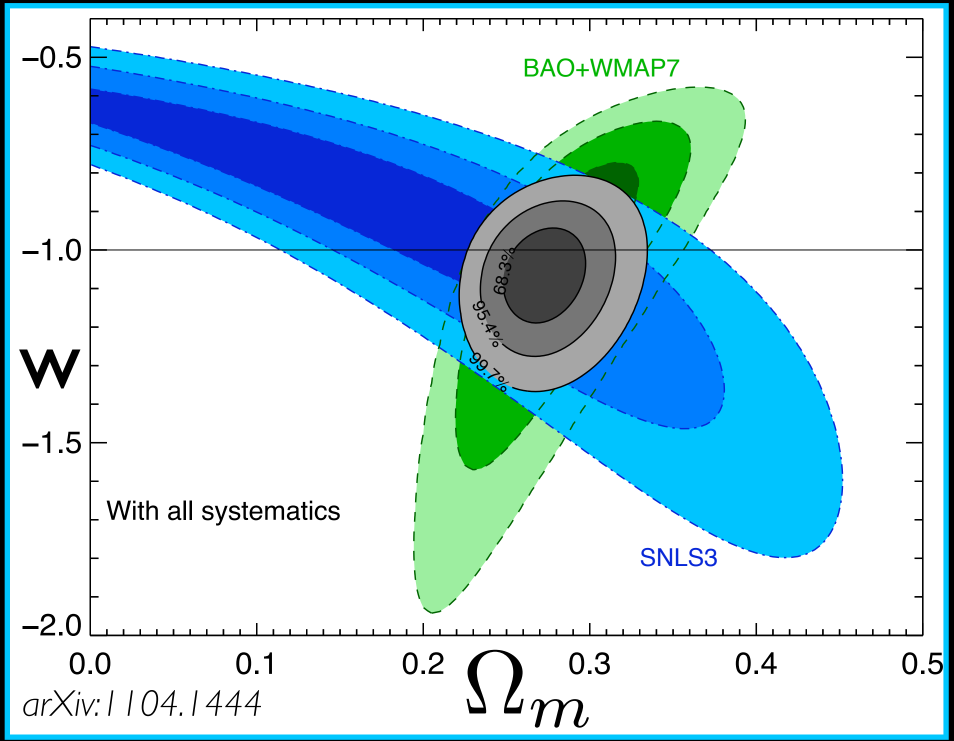
- lesson from inflation: when you need cosmic acceleration, invent a scalar field
- like inflaton, we need a slowly varying scalar field with near-constant $V(\phi)$
- very different energy scales:

  $(10\,\mathrm{MeV})^4 \lesssim \rho_{\mathrm{infl}} \lesssim (10^{16}\mathrm{GeV})^4$

  $\rho_{de} = (0.002\,\mathrm{eV})^4$
- quintessence is dynamical: $w \gtrsim -1$

Data please?

SNLS 3-yr Year



Maybe Gravity is the Problem?

General Relativity:

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

cosmic expansion rate

radiation and matter

dark energy

A different approach: change gravity

$$f(H) = \frac{8\pi G}{3}\left(\rho_m + \rho_r\right)$$

matter and radiation only

Maybe Gravity is the Problem?

General Relativity:

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

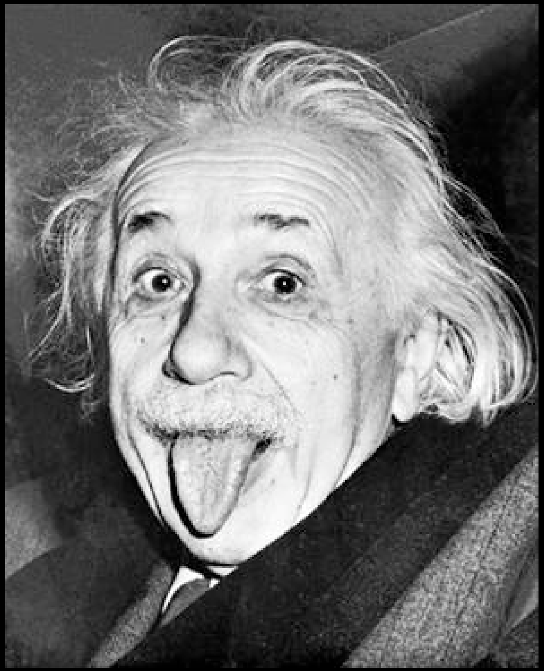
cosmic expansion rate; radiation and matter, dark energy

A different approach: change gravity

$$f(H) = \frac{8\pi G}{3}(\rho_m + \rho_r)$$

matter and radiation only

We have to change gravity between galaxies without changing it in the Solar System.

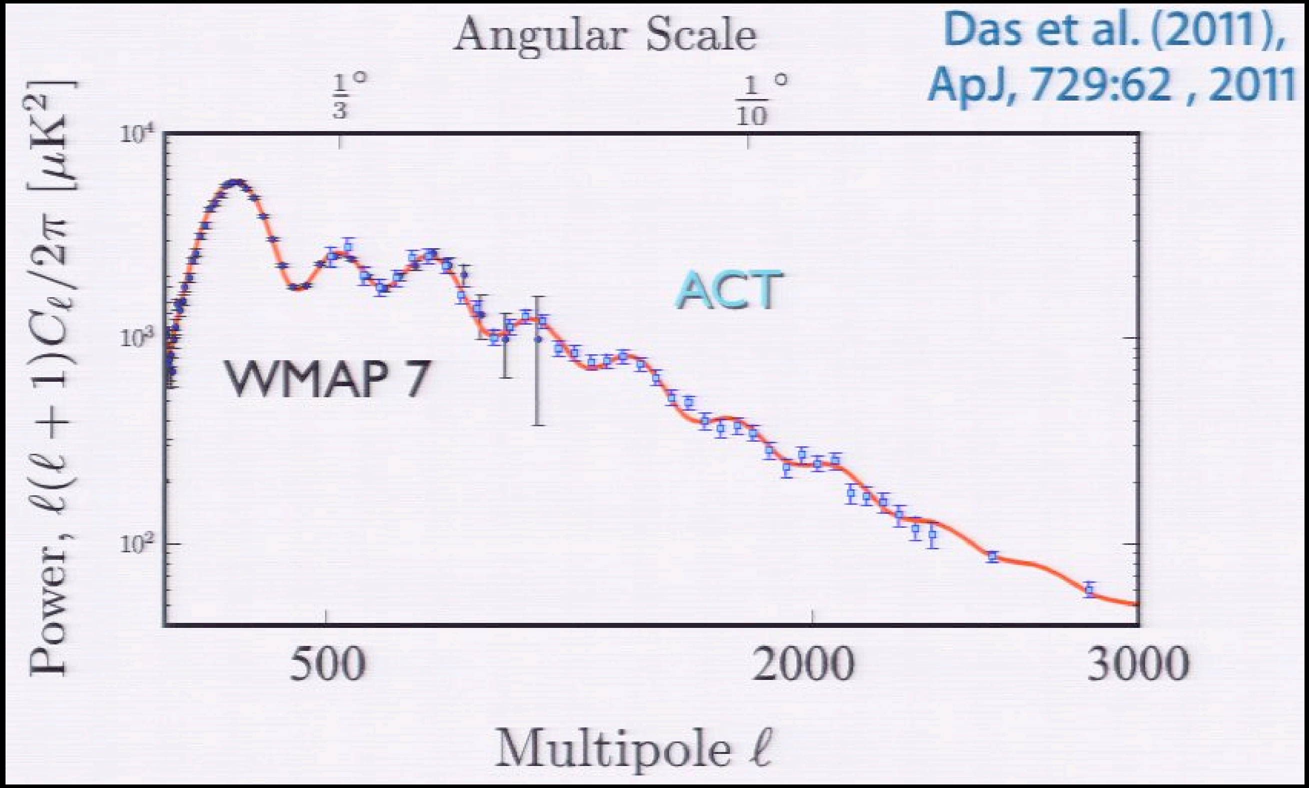


- time delay and lensing measurements around the Sun confirm General Relativity
- General Relativity is sensitive!
- Solution: chameleon gravity, higher dimensional gravity, massive gravity...

Summary: Where are we?

Cosmology's Standard Model: $\Lambda\mathrm{CDM}$ + Inflation

The Good

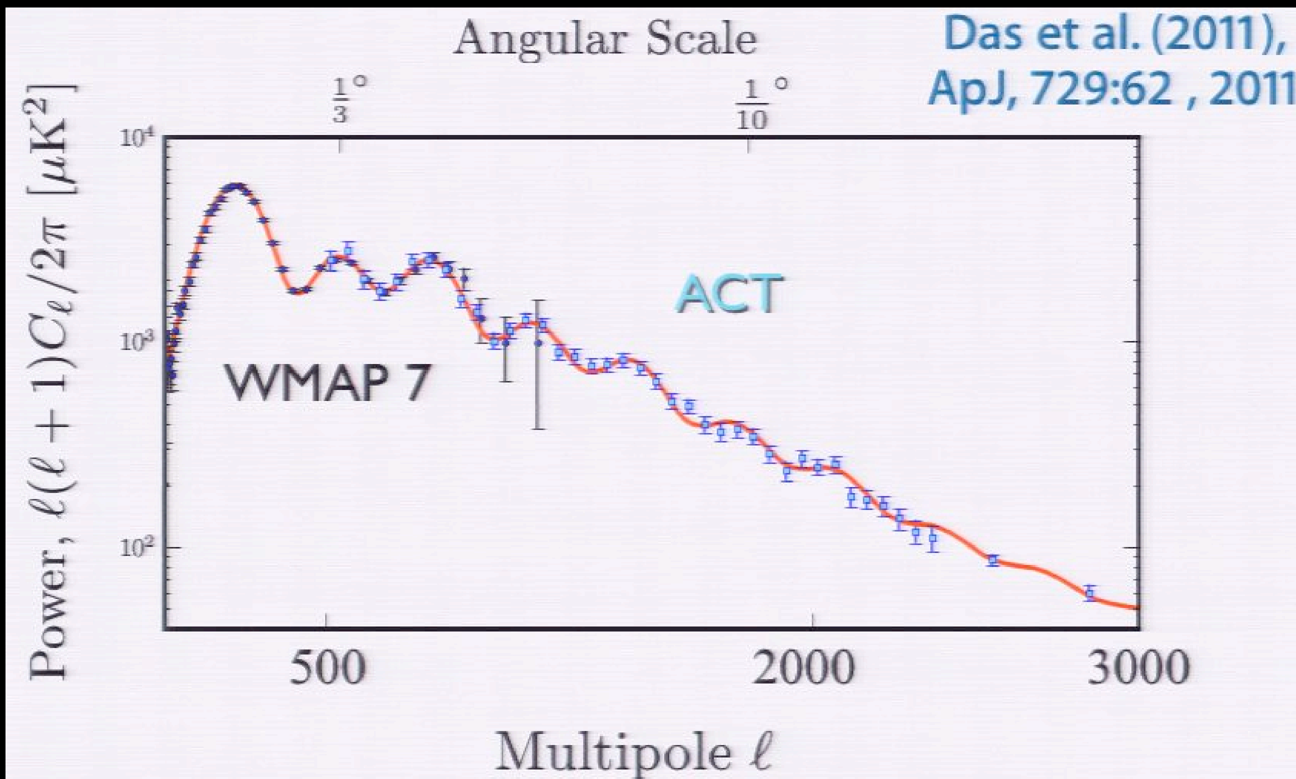


CMB, Supernovae, Galaxies, Clusters all in concordance

Summary: Where are we?

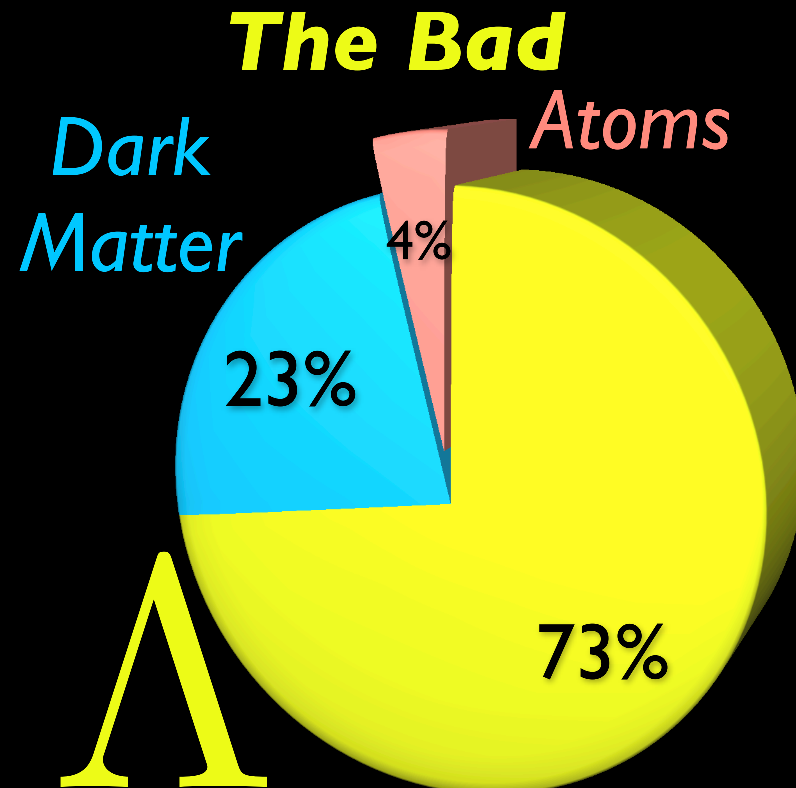
Cosmology's Standard Model: $\Lambda\mathrm{CDM}$ + Inflation

The Good



CMB, Supernovae, Galaxies, Clusters all in concordance

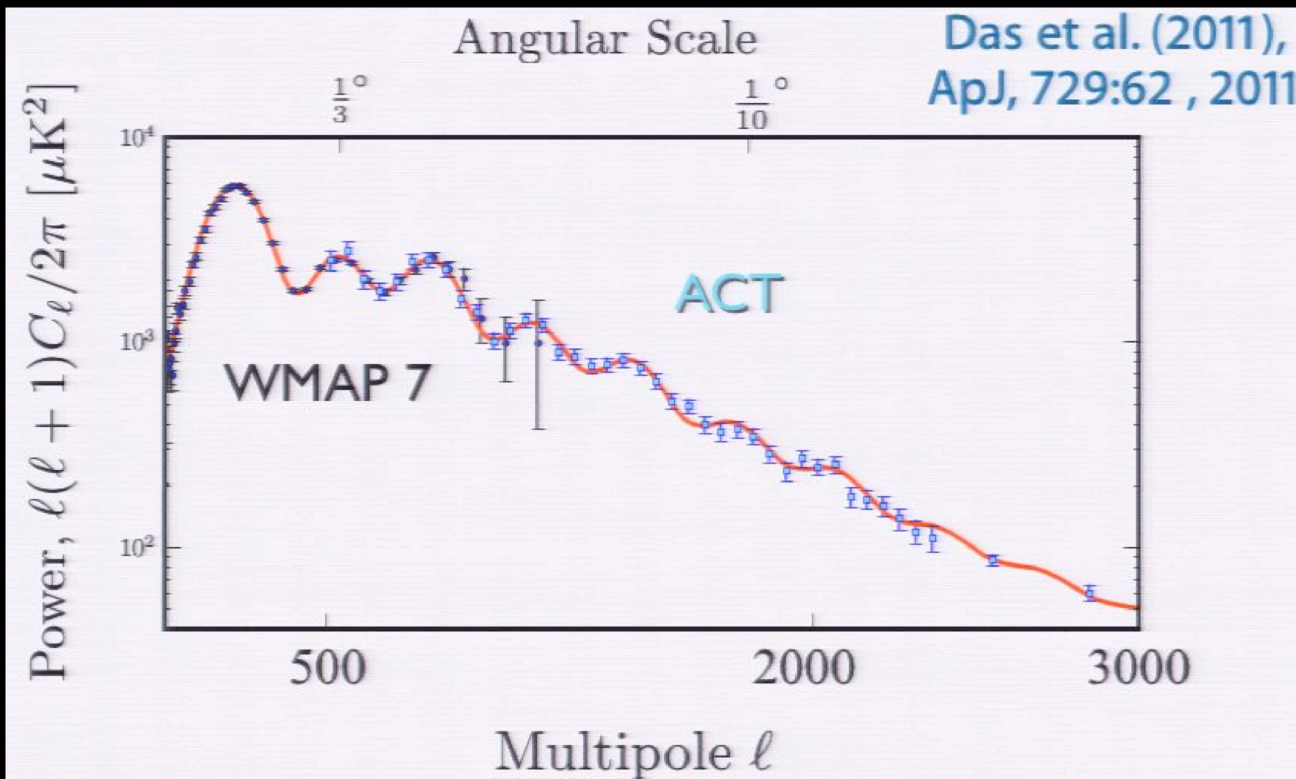
The Bad



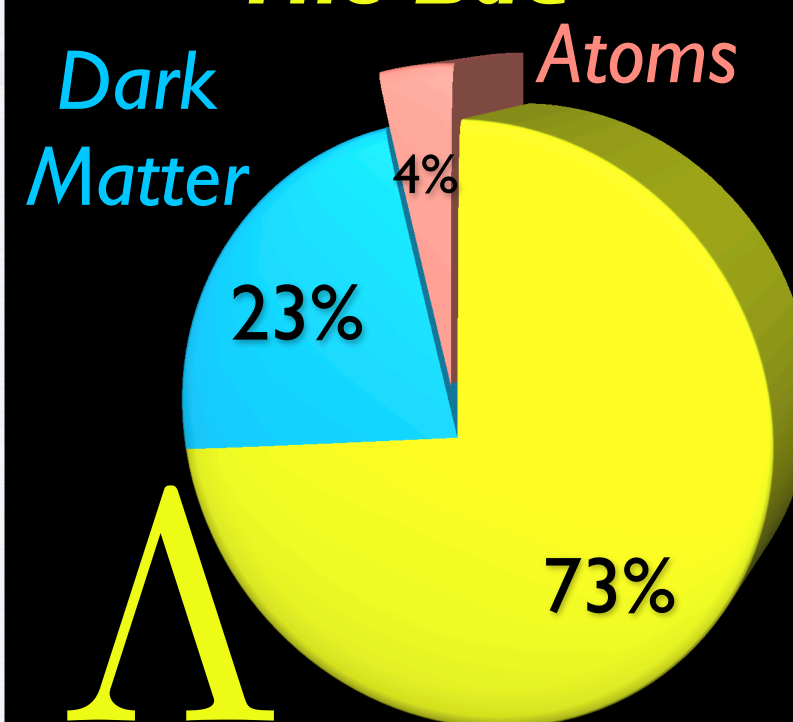
Summary: Where are we?

Cosmology's Standard Model: $\Lambda\mathrm{CDM}$ + Inflation

The Good



The Bad



CMB, Supernovae, Galaxies, Clusters
all in concordance

The Ugly: Will we ever understand the origin of Λ ?
Will we ever know what drove inflation?

Further Reading

On General Cosmology:

Modern Cosmology by Scott Dodelson (textbook, CMB focused)

Cosmology by Peter Coles & Francesco Lucchin (textbook)

Web Tutorials:

www.astro.ucla.edu/~wright/cosmolog.htm by Ned Wright

http://background.uchicago.edu/index.html by Wayne Hu

On inflation:

The Inflationary Universe by Alan Guth (popular science book)

"Lectures on Inflation and Cosmological Perturbations" by David Langlois http://arxiv.org/abs/1001.5259 (review article)

On dark matter and dark energy:

The 4% Universe by Richard Panek (popular science book)

"Dark Matter and Dark Energy" by Marc Kamionkowski http://arxiv.org/abs/0706.2986

"Particle Dark Matter: Evidence, Candidates & Constraints" by Bertone, Hooper & Silk http://arxiv.org/abs/hep-ph/0404175