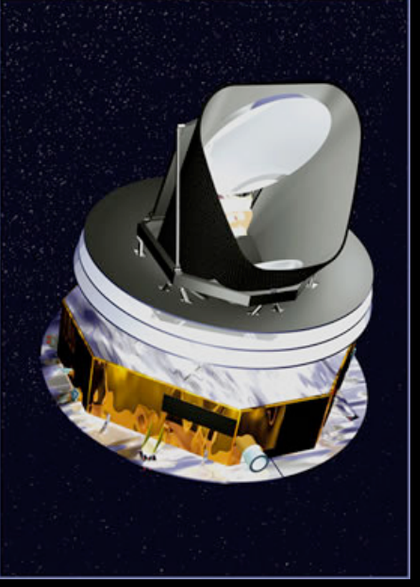
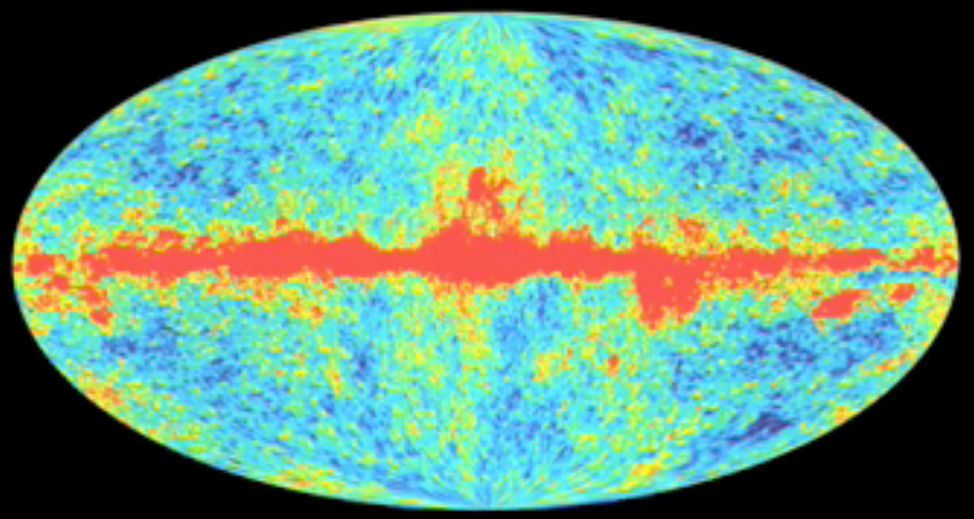
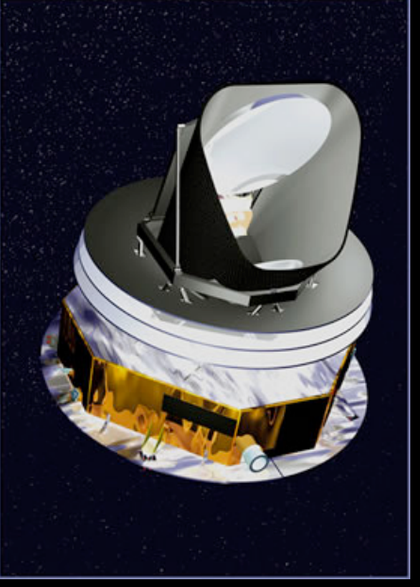
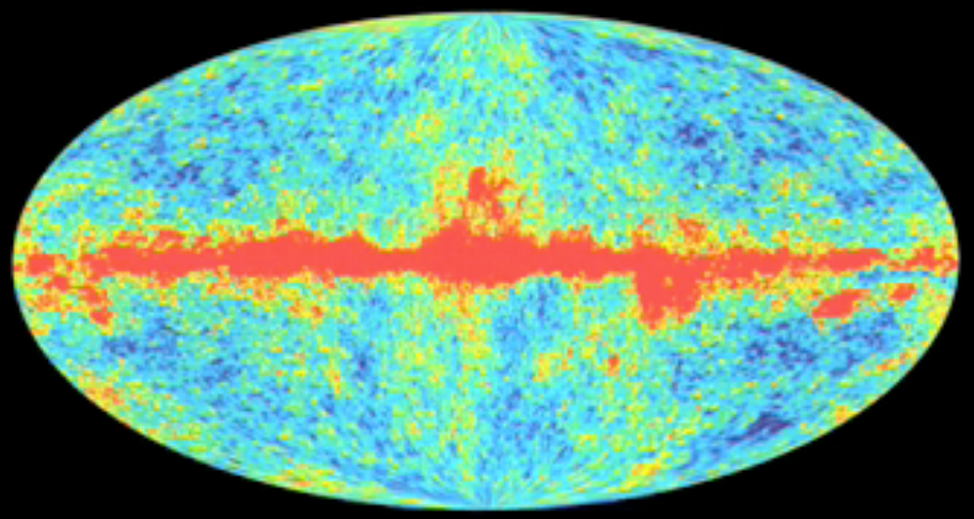




The big bang and the cosmic microwave background

Daniel Grin
University of Chicago





The big bang and the cosmic microwave background

Daniel Grin
University of Chicago

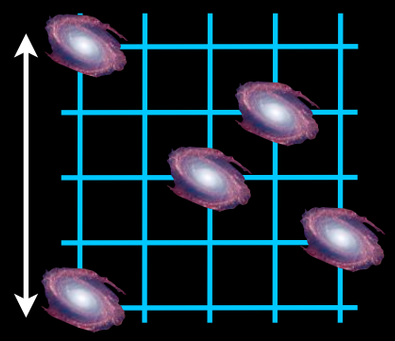
OUTLINE

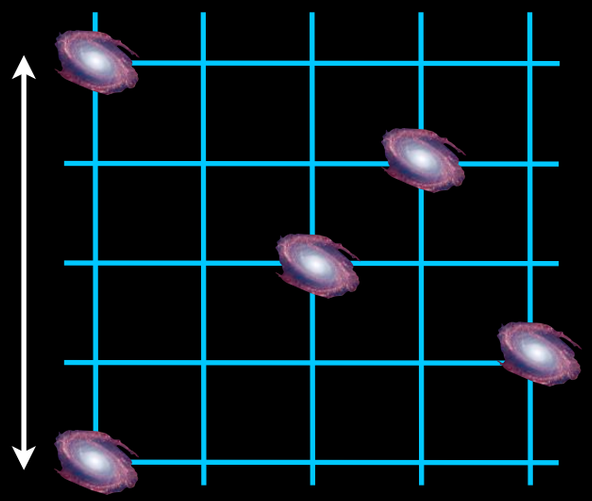
- The expanding universe
- The cosmic microwave background
- The cosmic energy budget
- Cosmic inflation

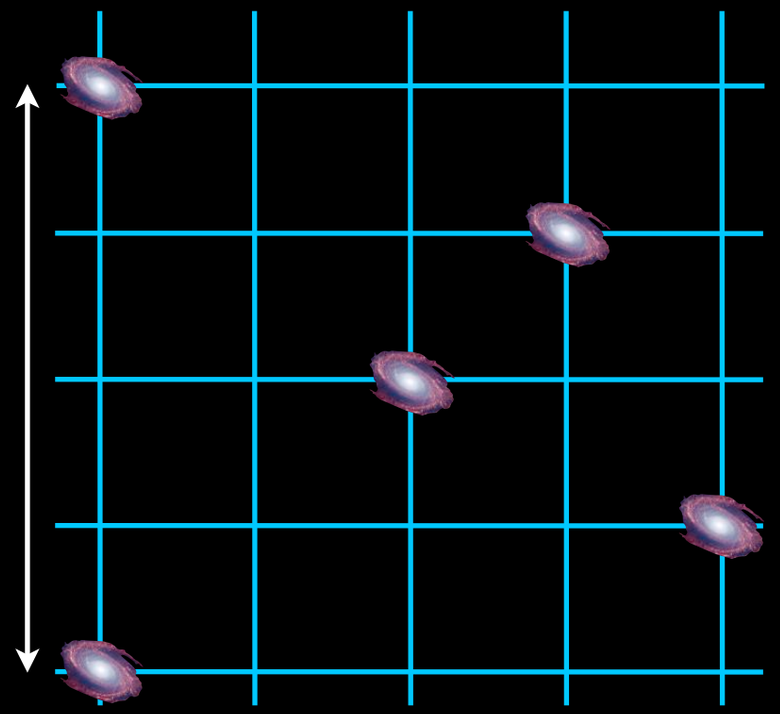
The Expanding Universe

Edwin Hubble - 1929

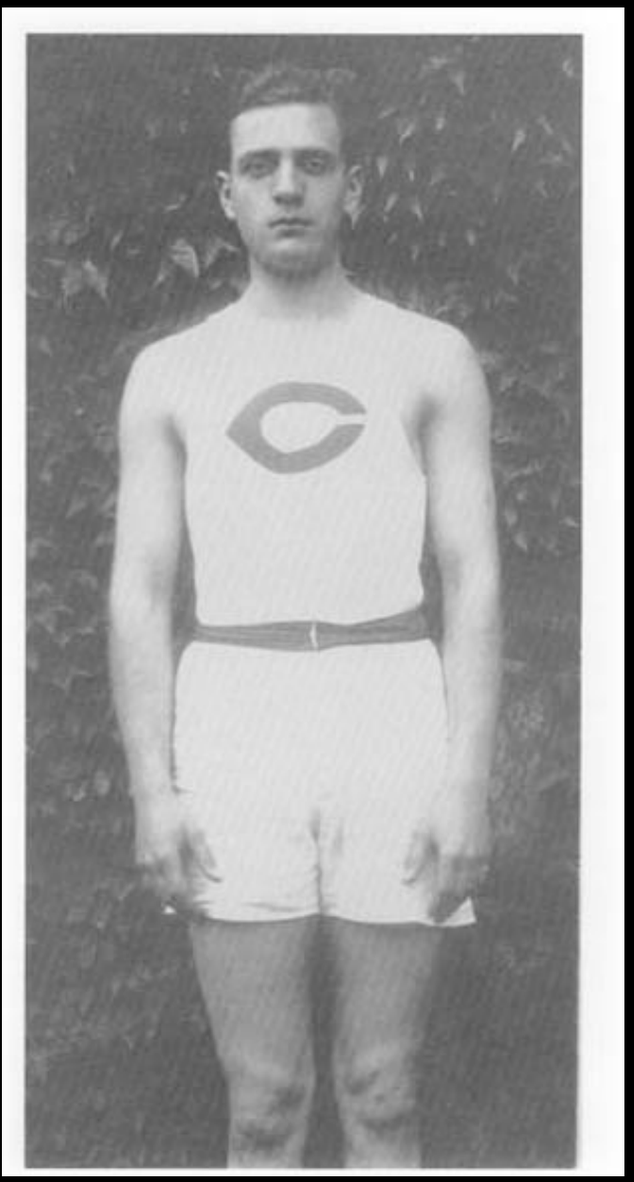
Galaxies are moving away from each other. The farther apart they are, the faster they recede!







The Expanding Universe



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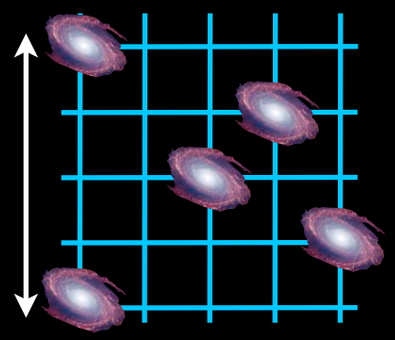
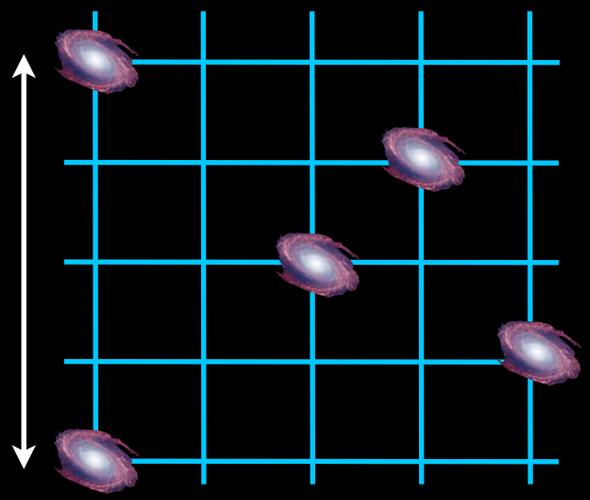
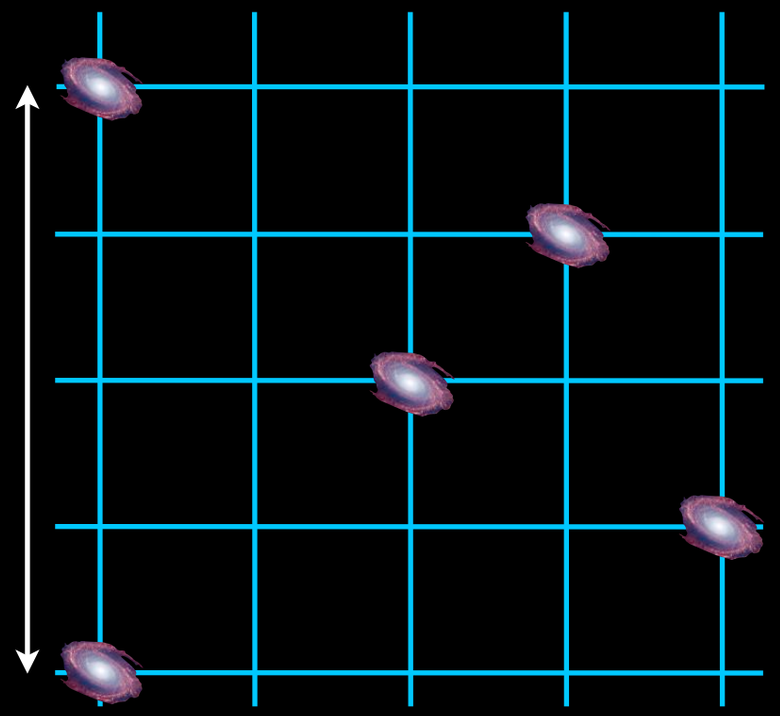


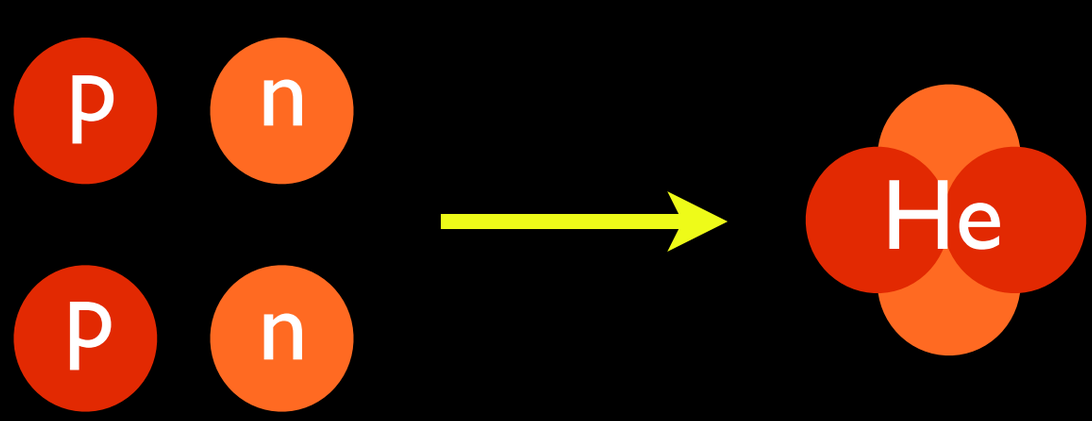




History of the Universe in One Year

- Recorded History: Last 15 seconds!
- Human Lifetime: ~0.18 seconds (on this scale)

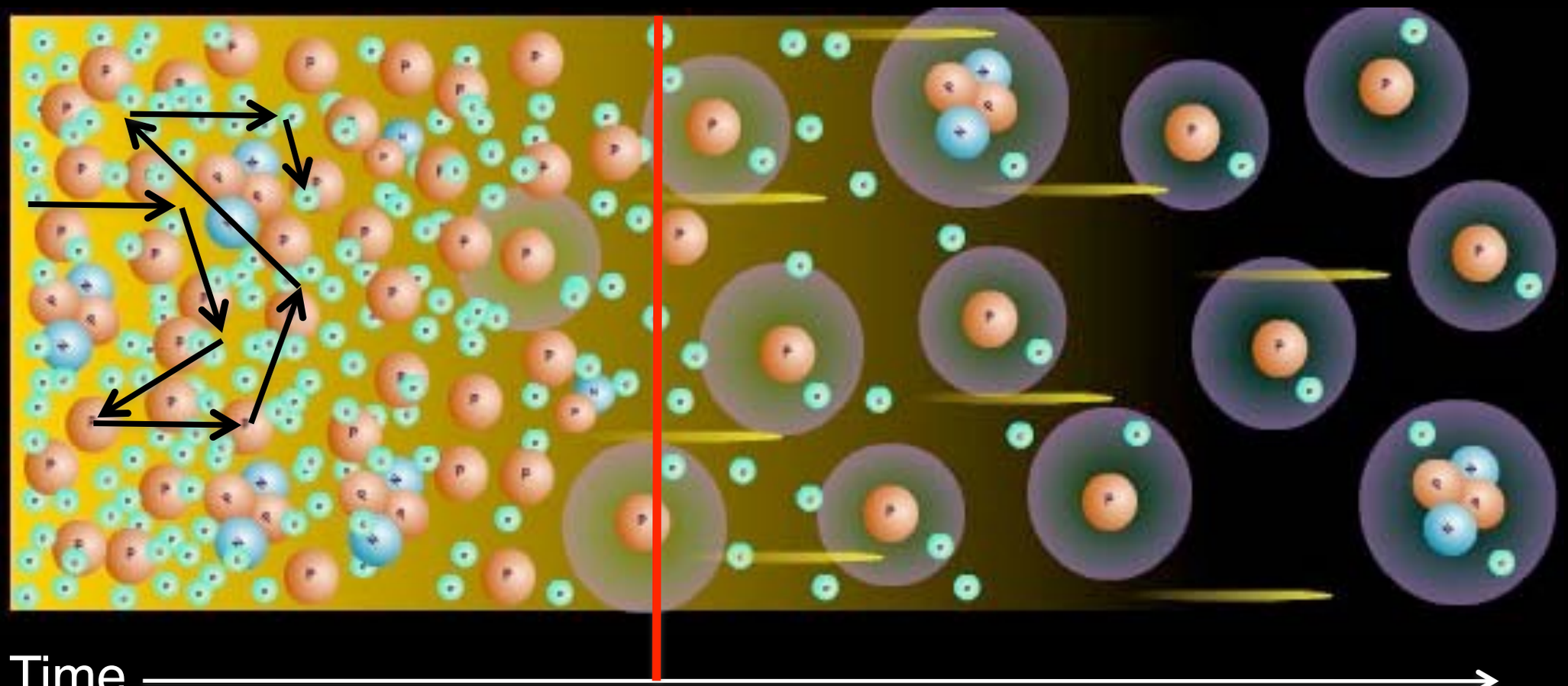
Big Bang Nucleosynthesis
2-3 minutes after the Big Bang
Temperature: 1 Billion Kelvin



A Foggy Universe

At first, just a soup of particles and light.

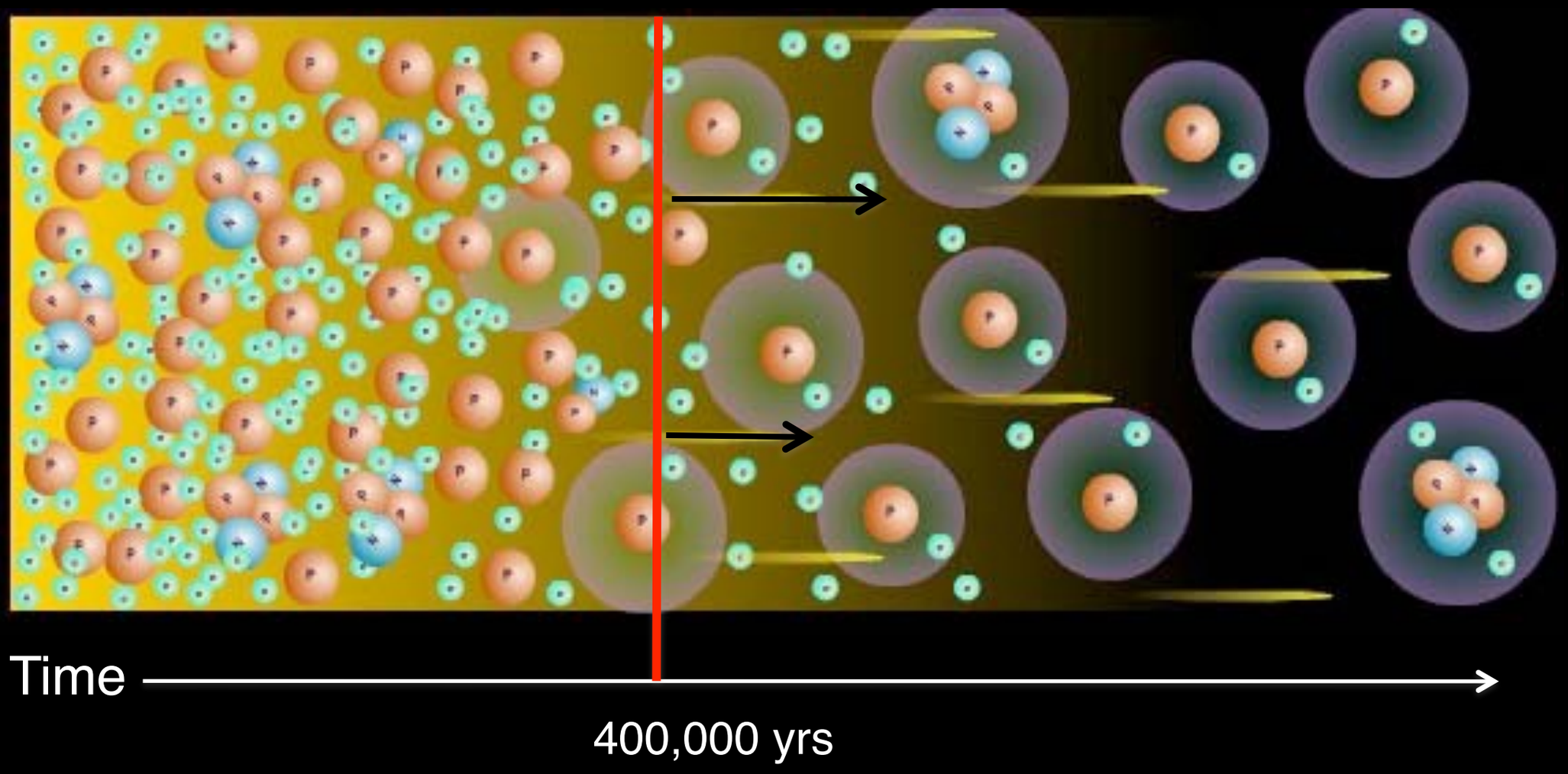
Like a foggy morning, like bounces around instead of traveling in a straight path.



Credit: Lawrence Berkeley National Laboratory Physics Division

The Fog Clears

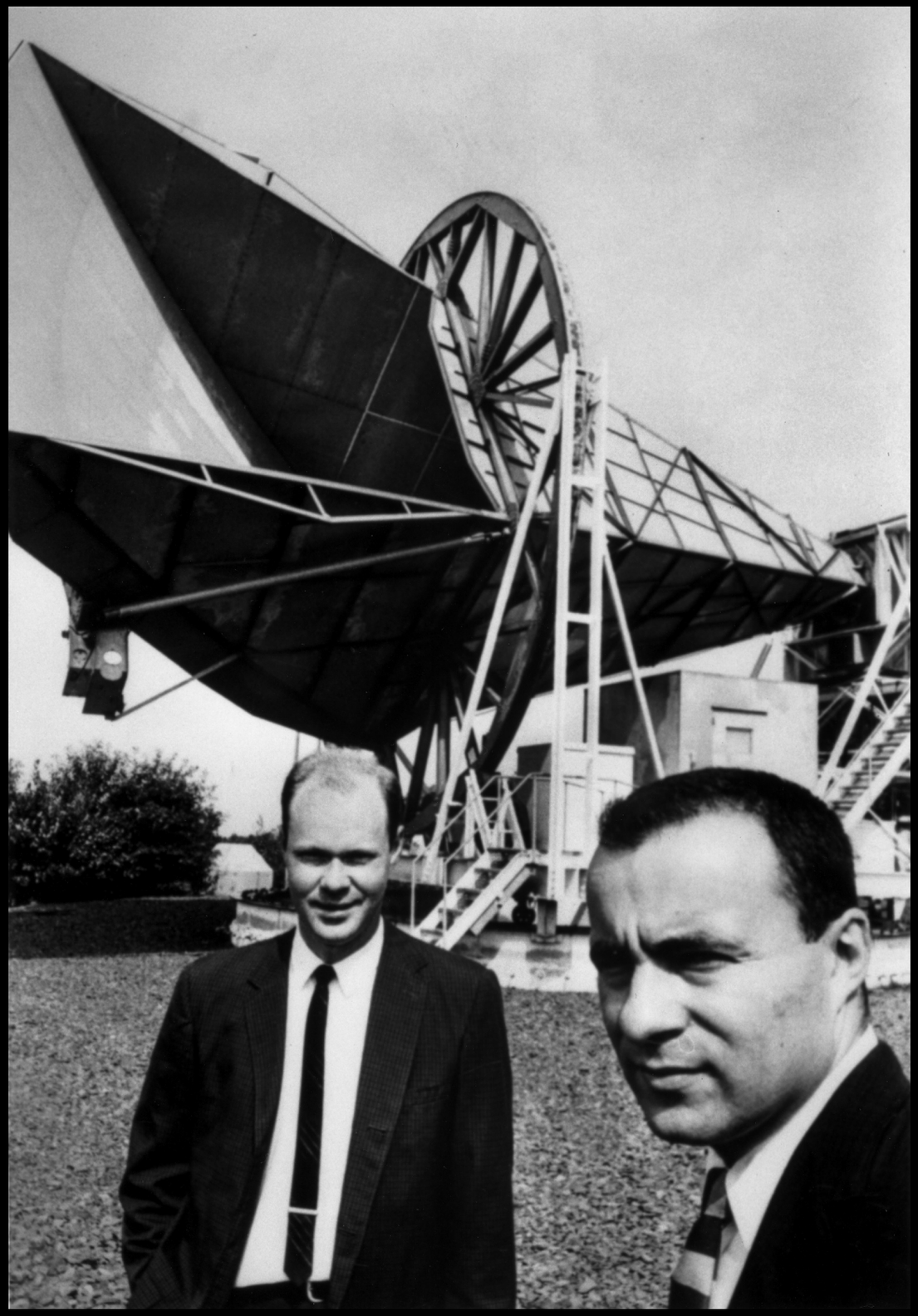
~400,000 years after the Big Bang, light escaped the dense fog. This light becomes the Cosmic Microwave Background (CMB).



Credit: Lawrence Berkeley National Laboratory Physics Division

So do we see this afterglow?

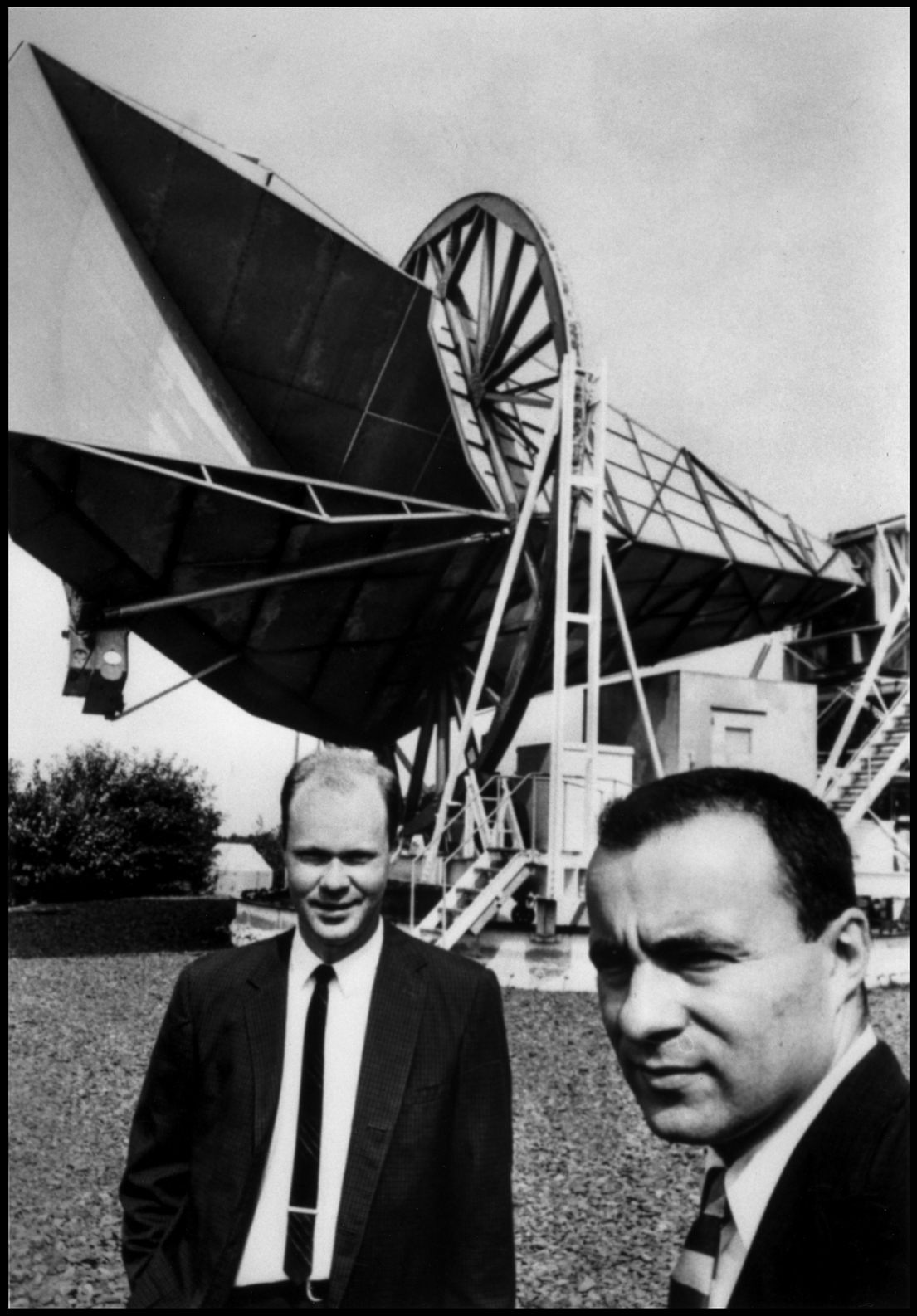
Penzias and Wilson



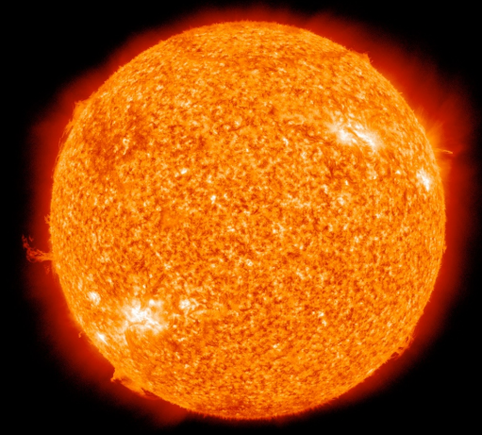
Bell Labs' Horn Antenna, NJ

Trying to measure
radio waves bouncing
off metalized
high-altitude balloons
…
but lots of excess "static"

Penzias and Wilson



Bell Labs' Horn Antenna, NJ



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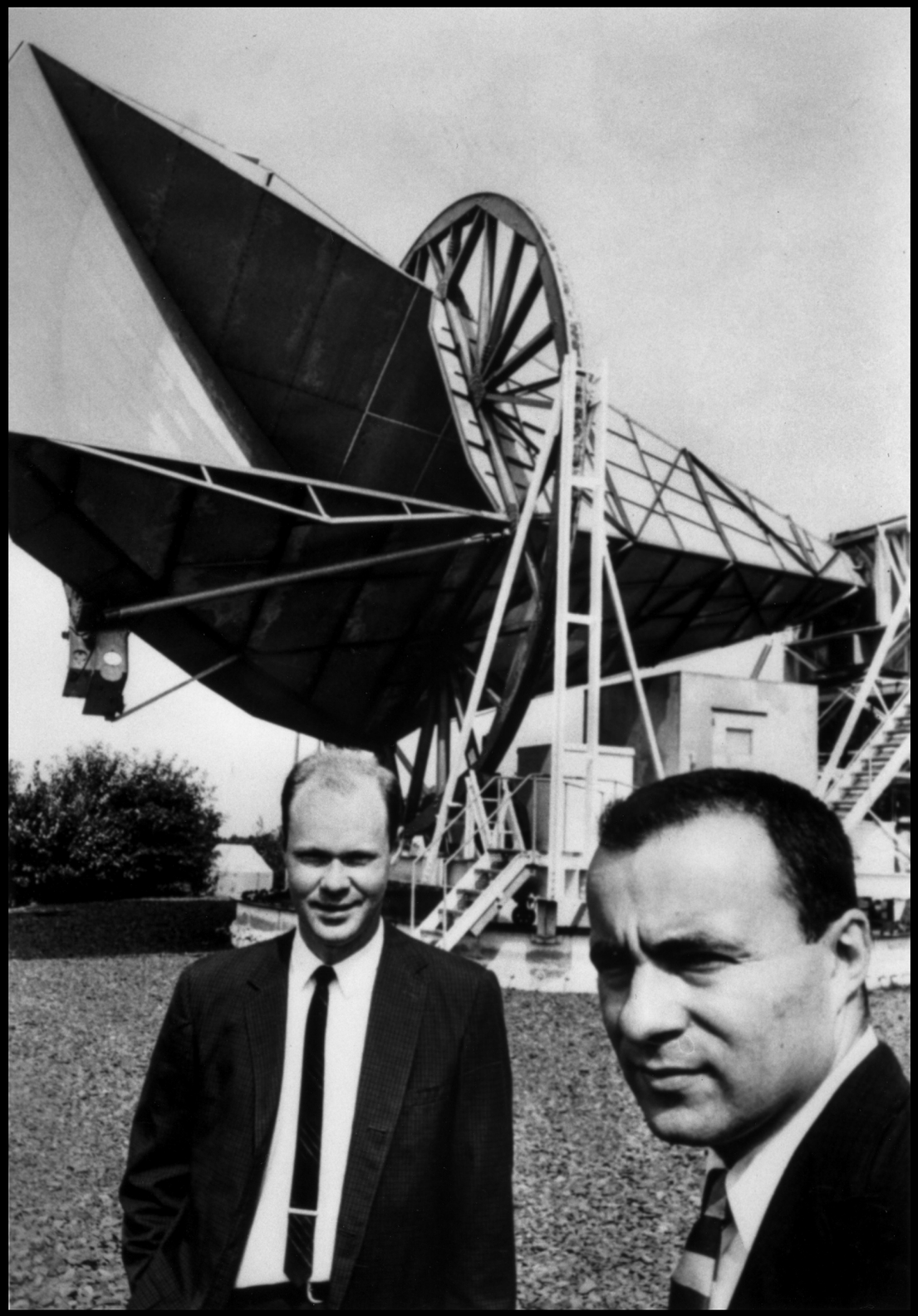

Bell Labs' Horn Antenna, NJ

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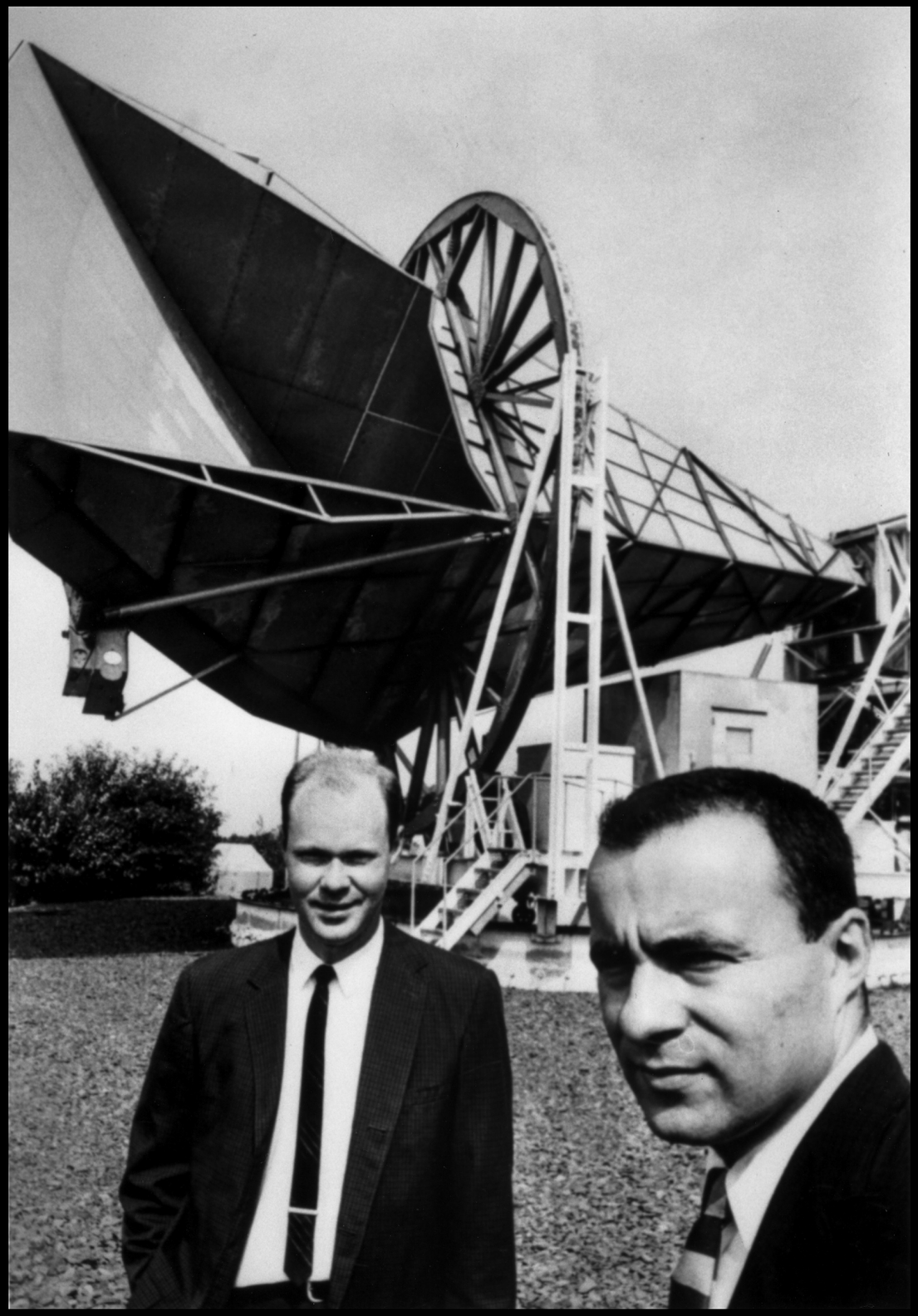
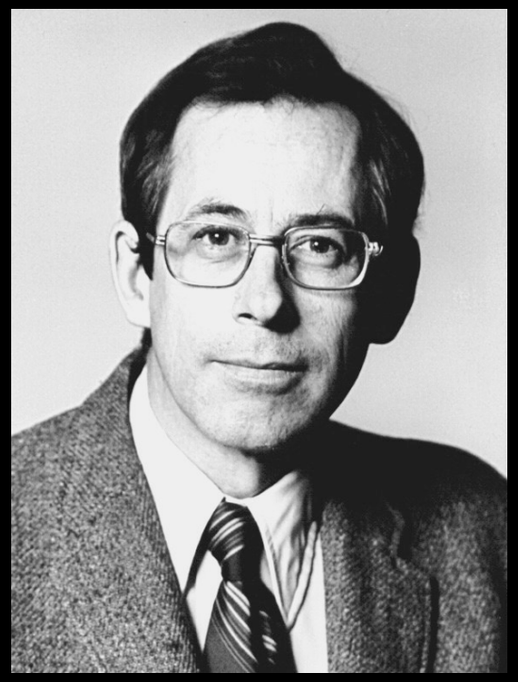


Bell Labs' Horn Antenna, NJ

Robert Dicke

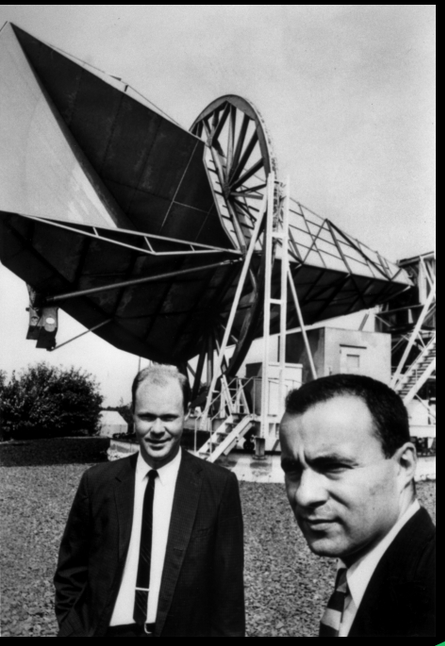


Jim Peebles

Dave Wilkinson

If you turn on an antenna TV, about 1% of the 'snow' comes from the CMBR

-270 Degrees Celsius!



Penzias and Wilson - 1965
(Nobel Prize - 1978!)

Uniform glow everywhere

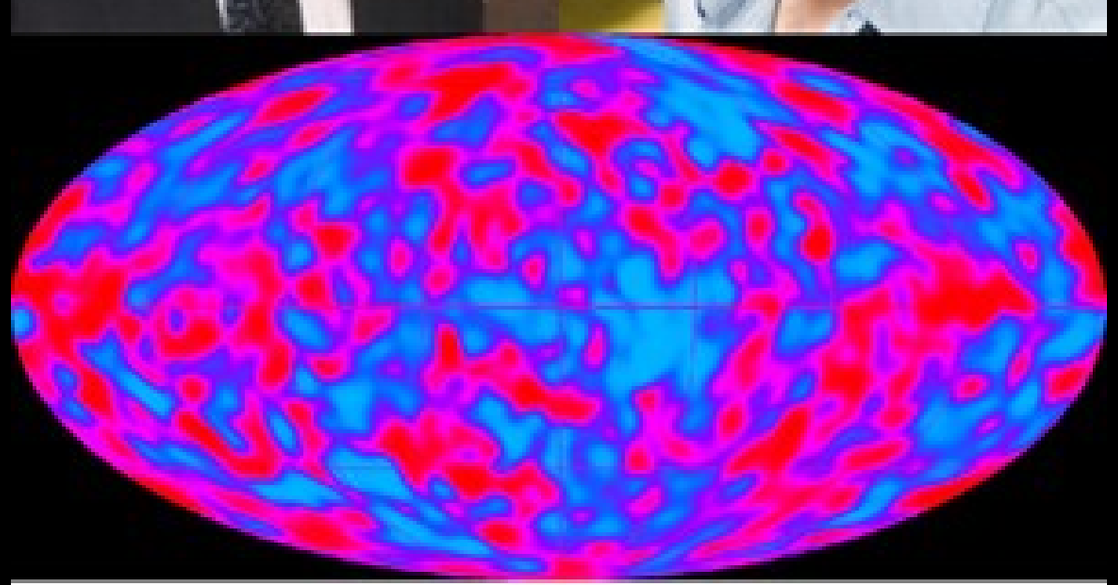
COBE Satellite - 1989
(Nobel Prize - 2006!)

Turn up contrast by 100,000x ...

2006 Nobel Prize for Physics

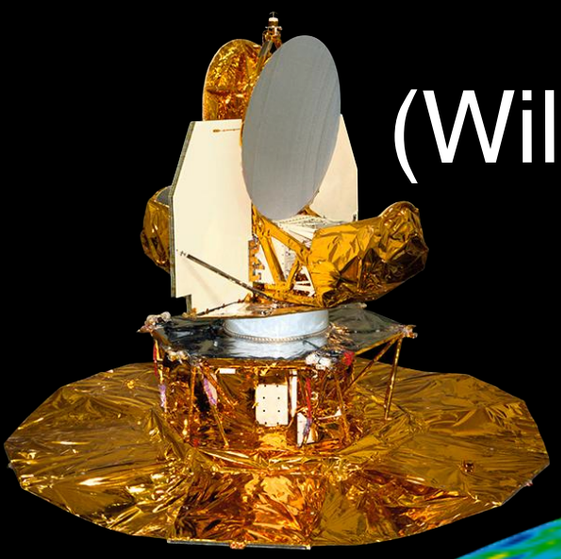
George F. Smoot

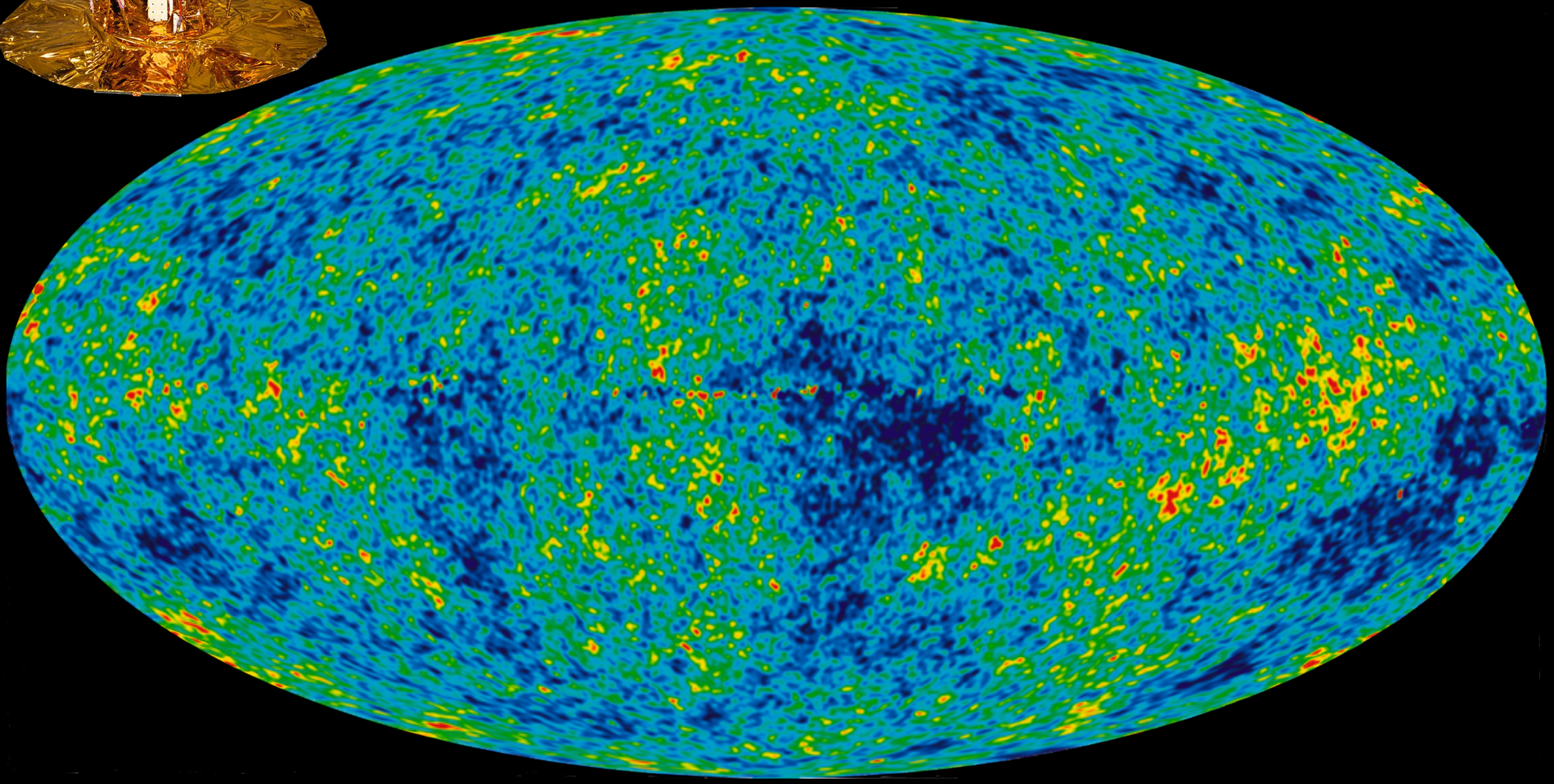
John C. Mather



Map of Cosmic Microwave Background radiation,
provided by NASA.
George F. Smoot photo provided by Wikipedia.
John C. Mather photo provided by NASA.

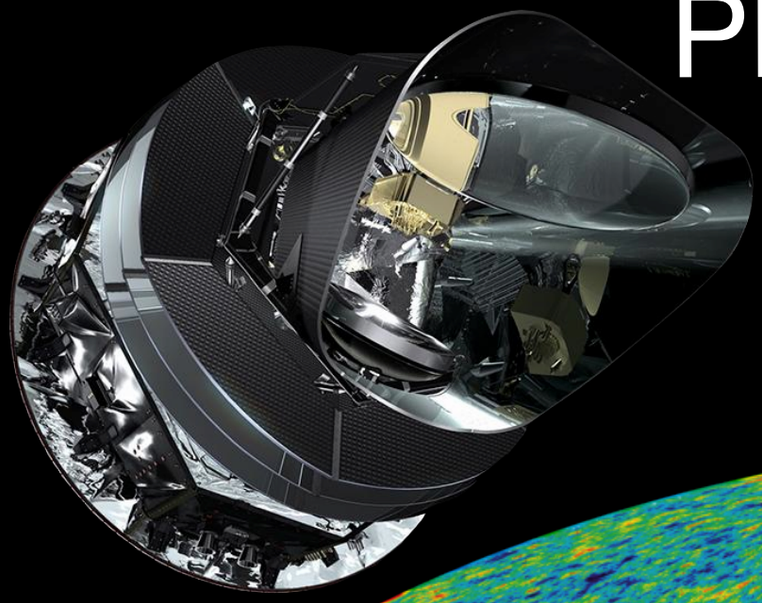
WMAP Satellite - 2001
(Wilkinson Microwave Anisotropy Probe)

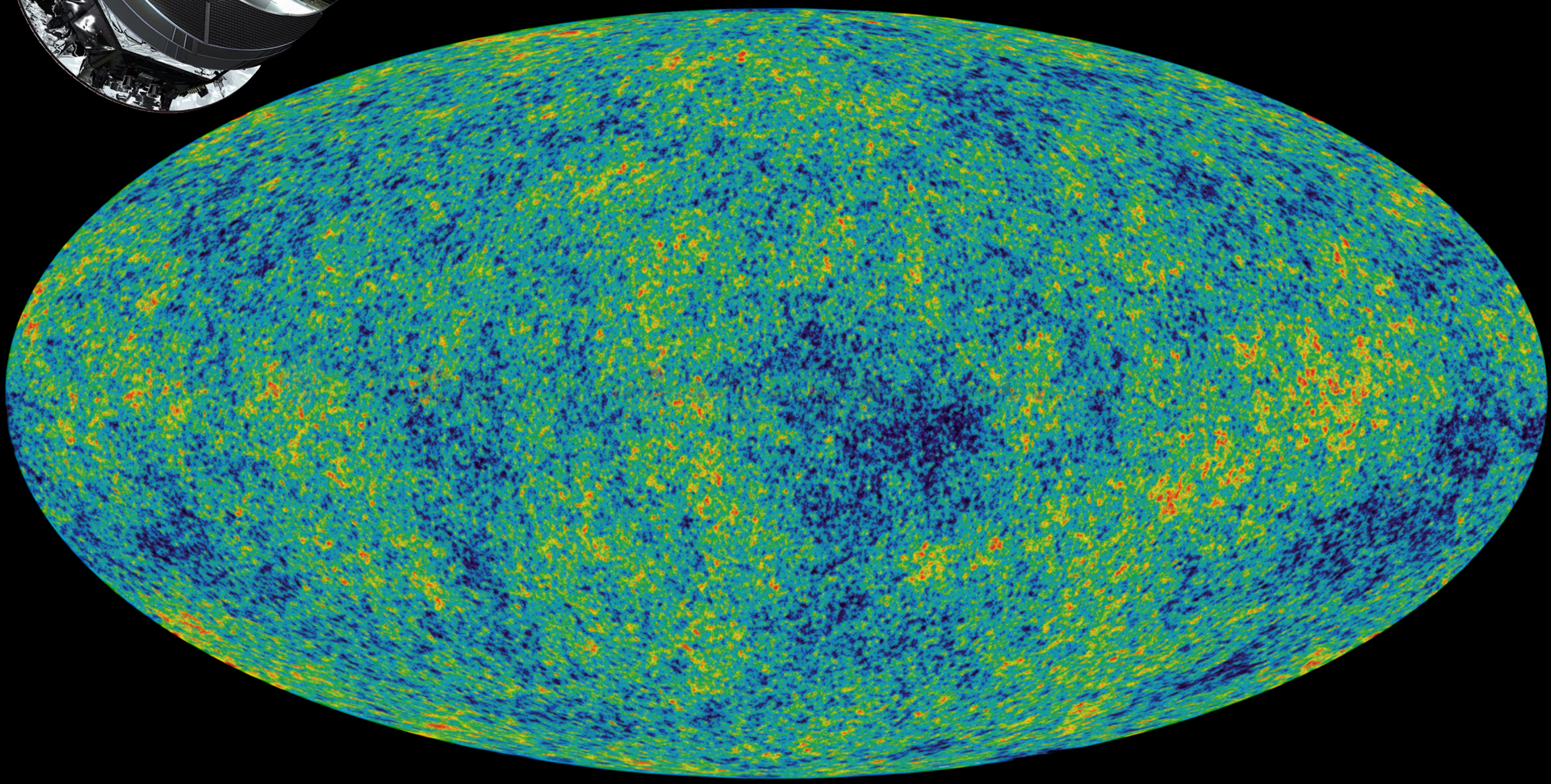




Higher resolution...

Planck Satellite - 2009

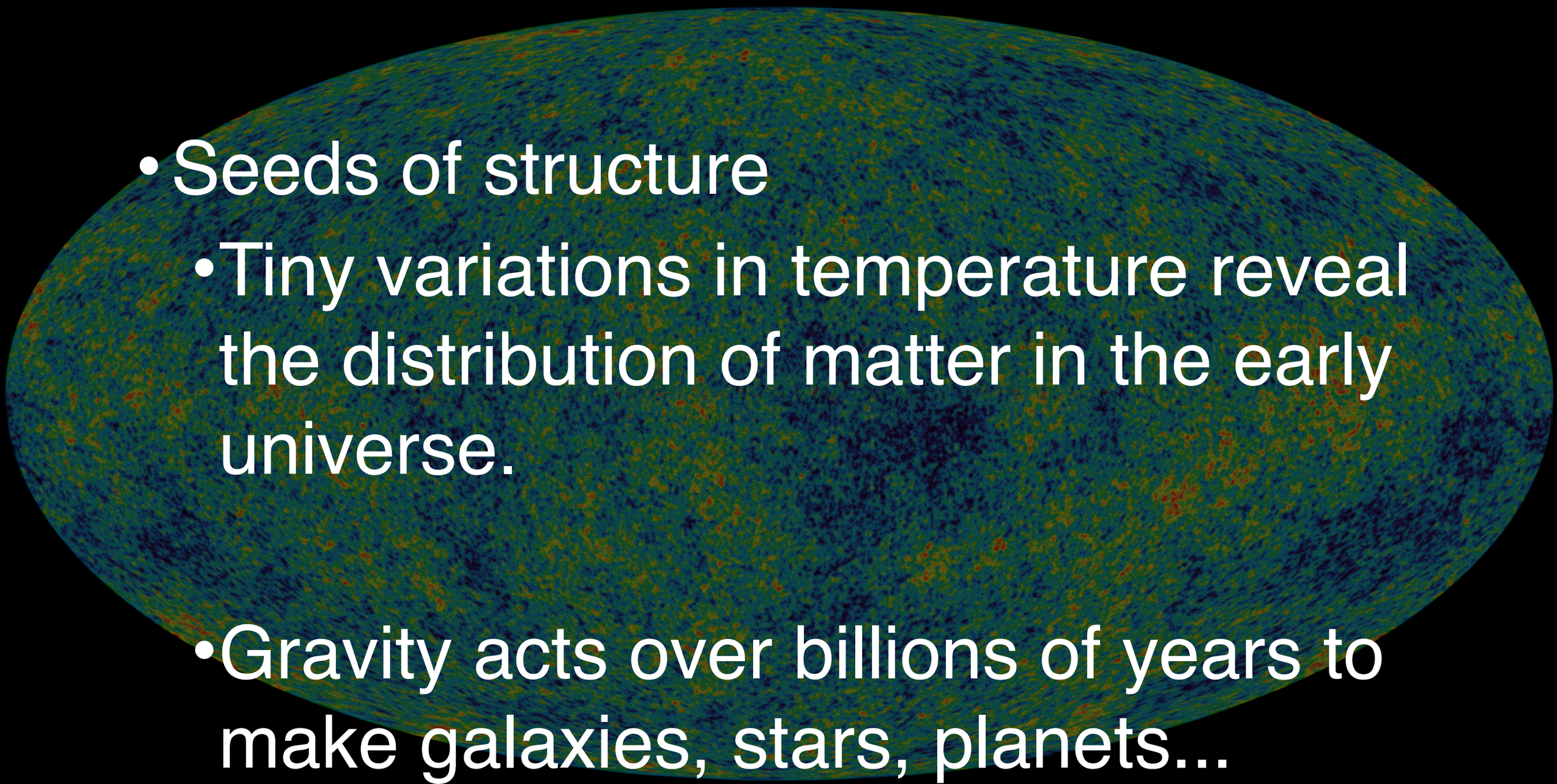




Even *higher* resolution...

The CMB is a Baby Picture Of the Universe

The CMB is a Baby Picture Of the Universe



- Seeds of structure
  - Tiny variations in temperature reveal the distribution of matter in the early universe.

- Gravity acts over billions of years to make galaxies, stars, planets...

z = 17.6

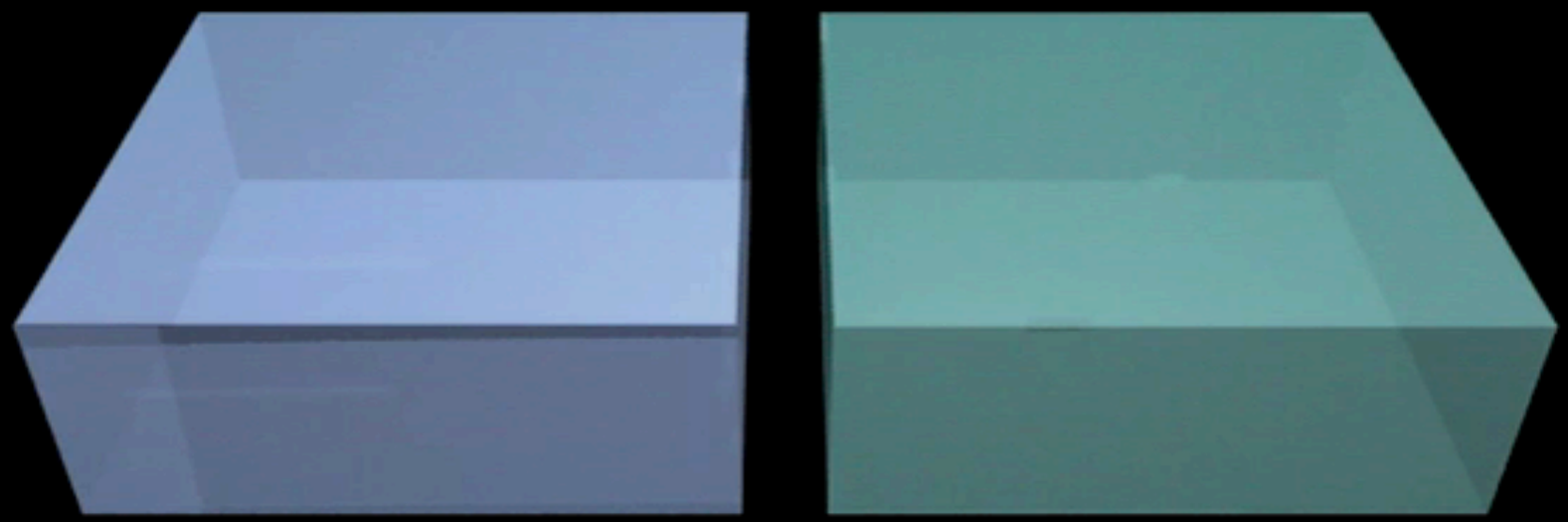
50 Mpc/h

z = 17.6

50 Mpc/h

Cosmic symphony

- Fluid of electrons and photons
- Pressure from photons (reflects amount of ordinary matter)
- Gravity from all matter (including dark matter)



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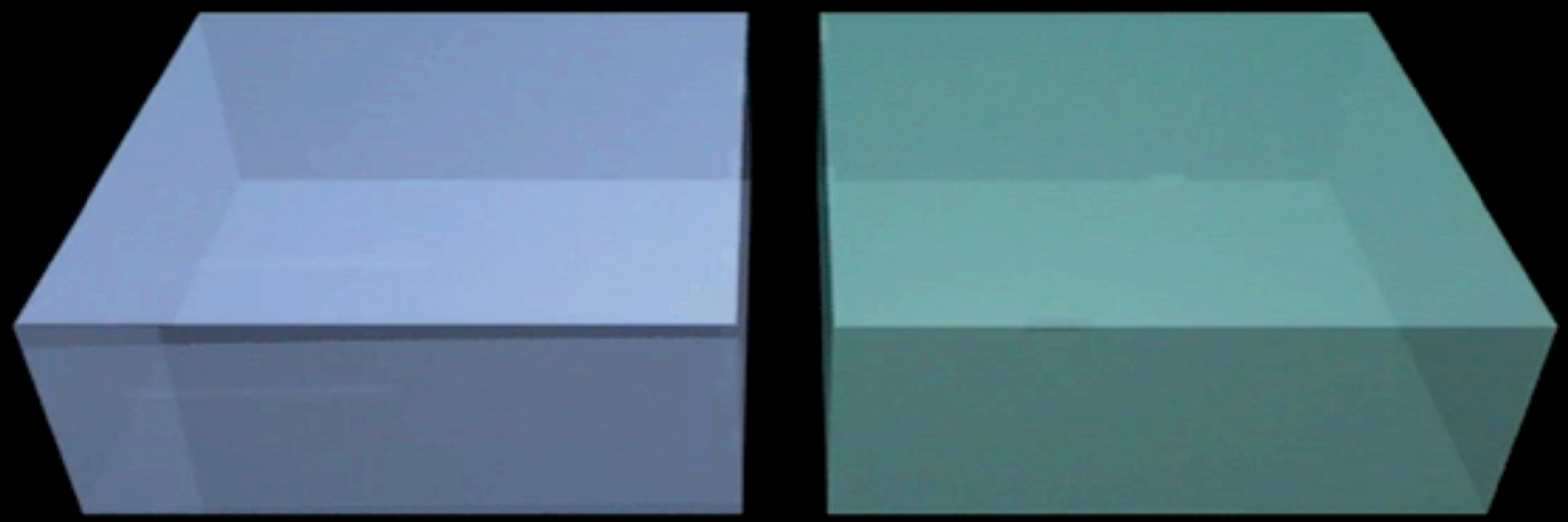

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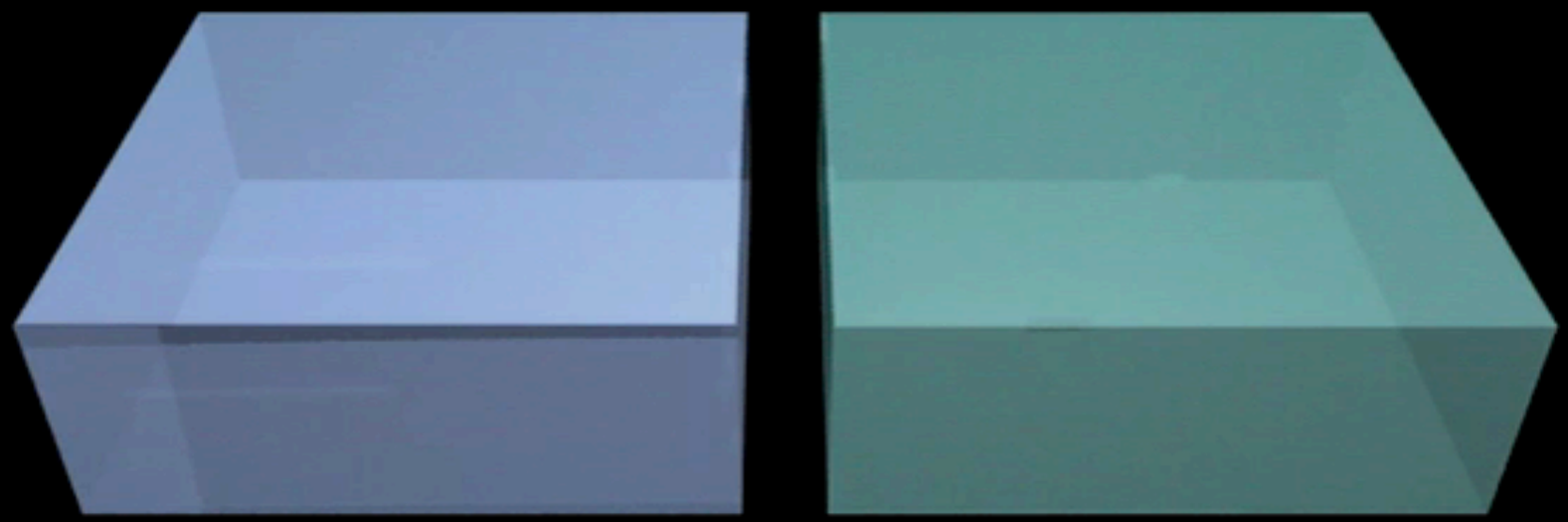
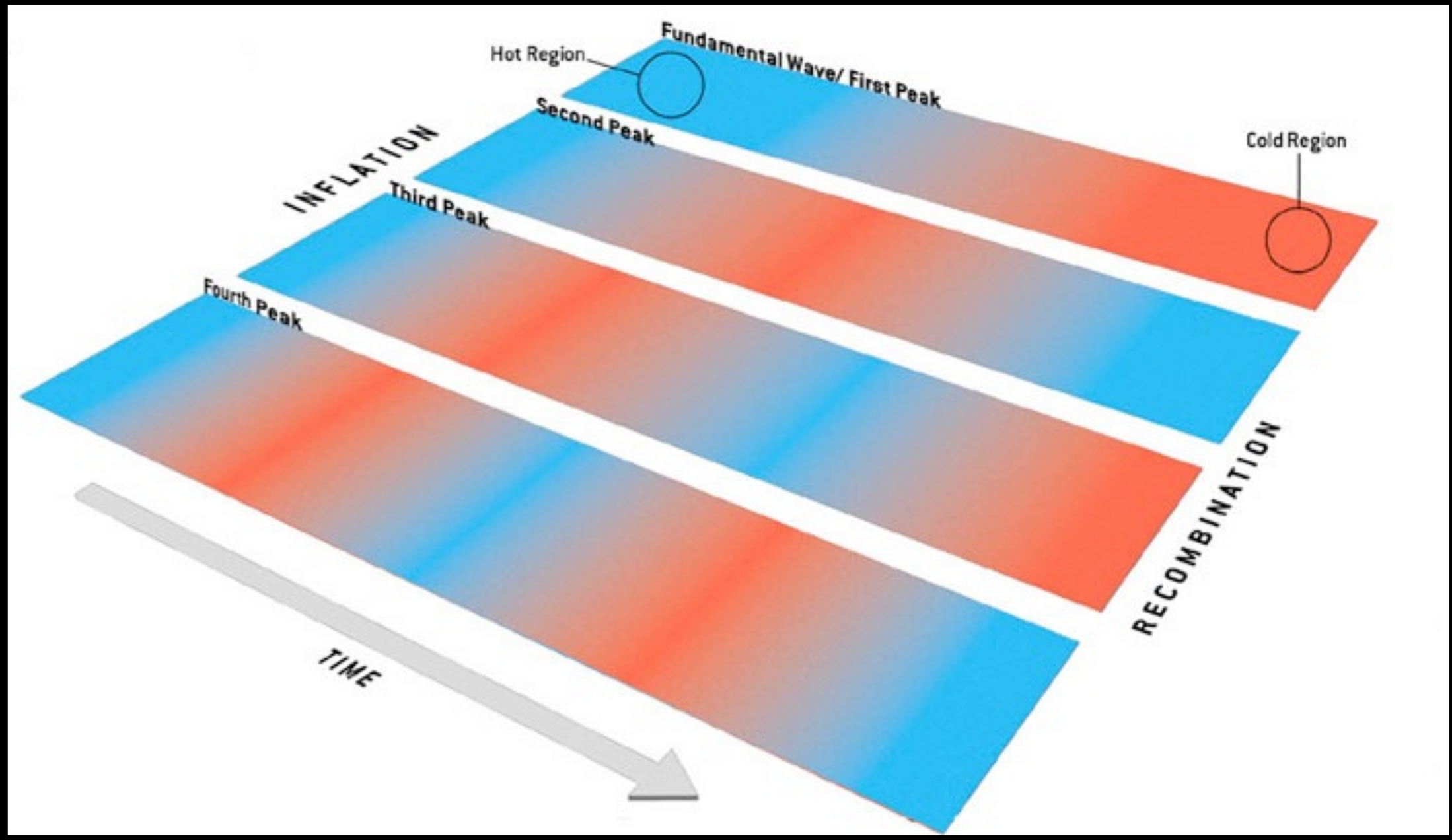
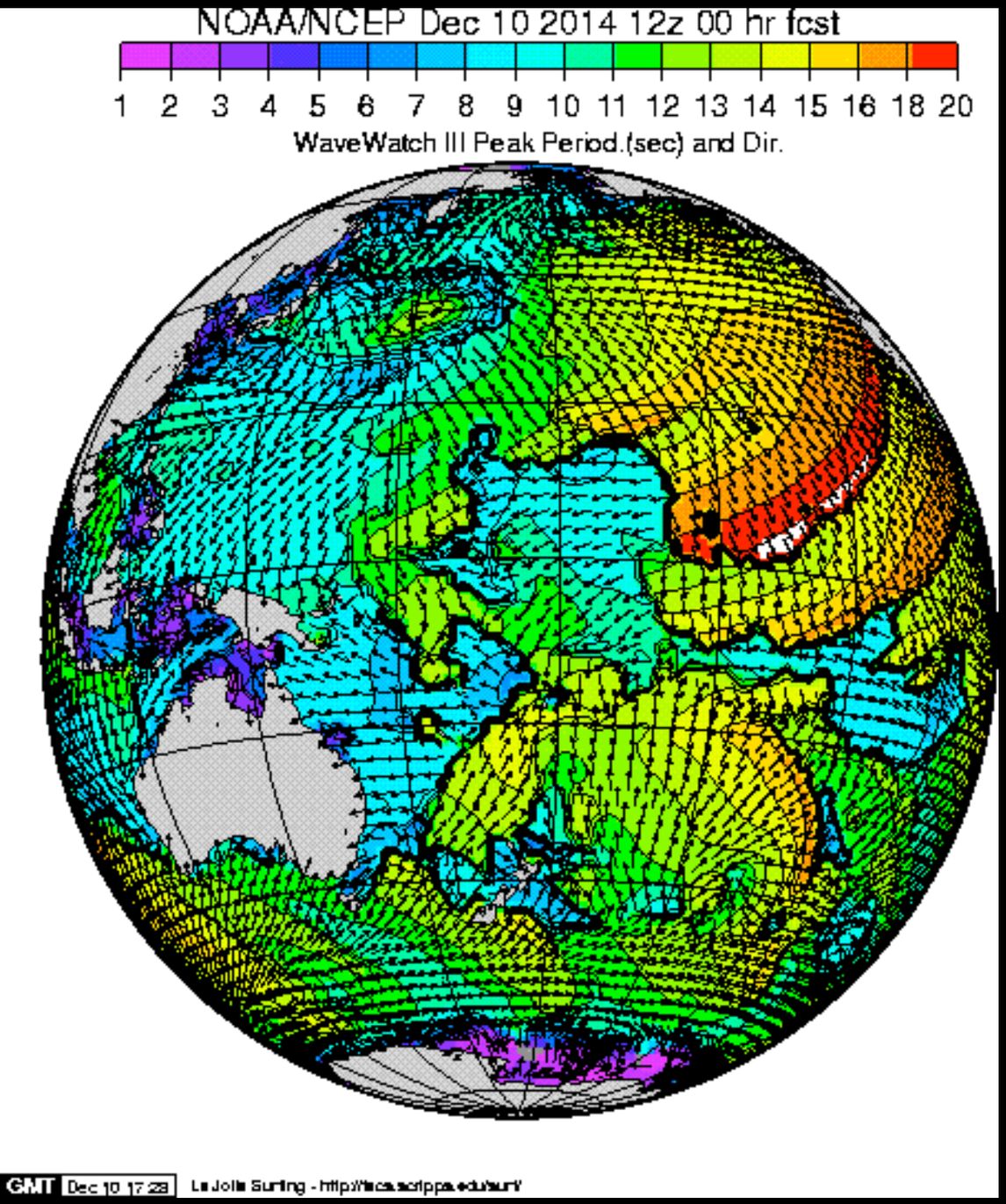


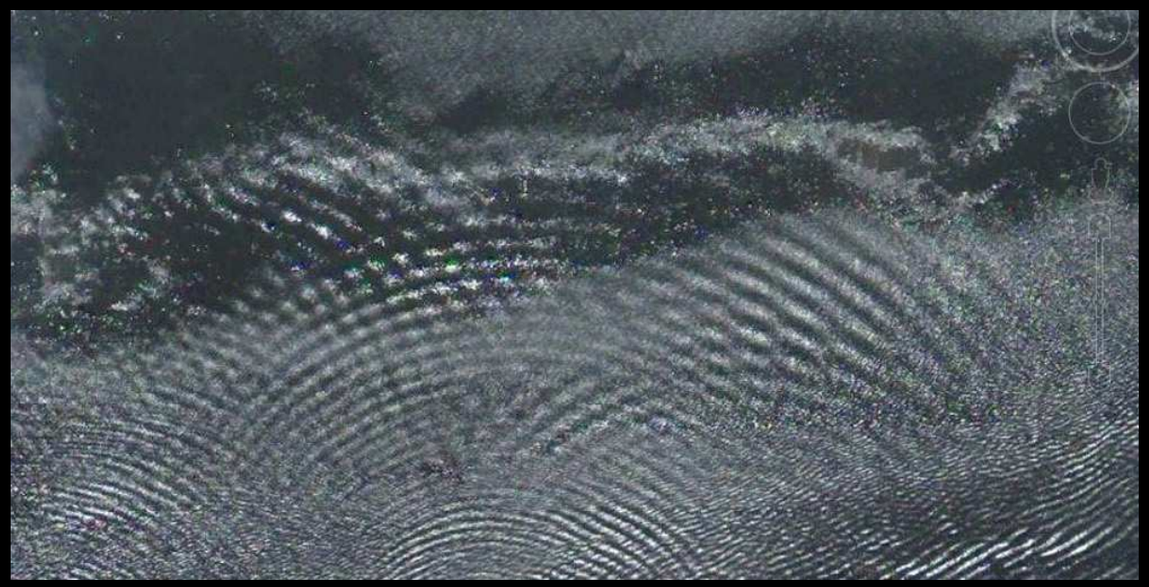
Cosmic symphony



From 2004 Scientific American Article by Wayne Hu and Martin White

Earth based analogy





Breakdown of Energy in the Universe:

5% baryonic matter: protons, electrons, atoms

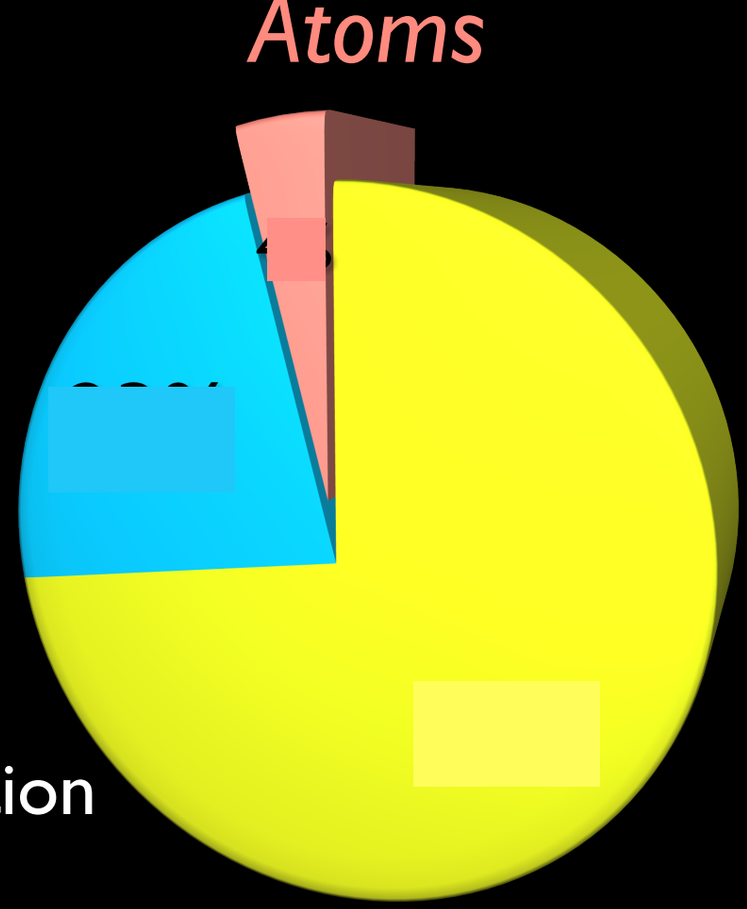
- "stuff we know"
- supported by He produced 3 min. after Big Bang

27% dark matter

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

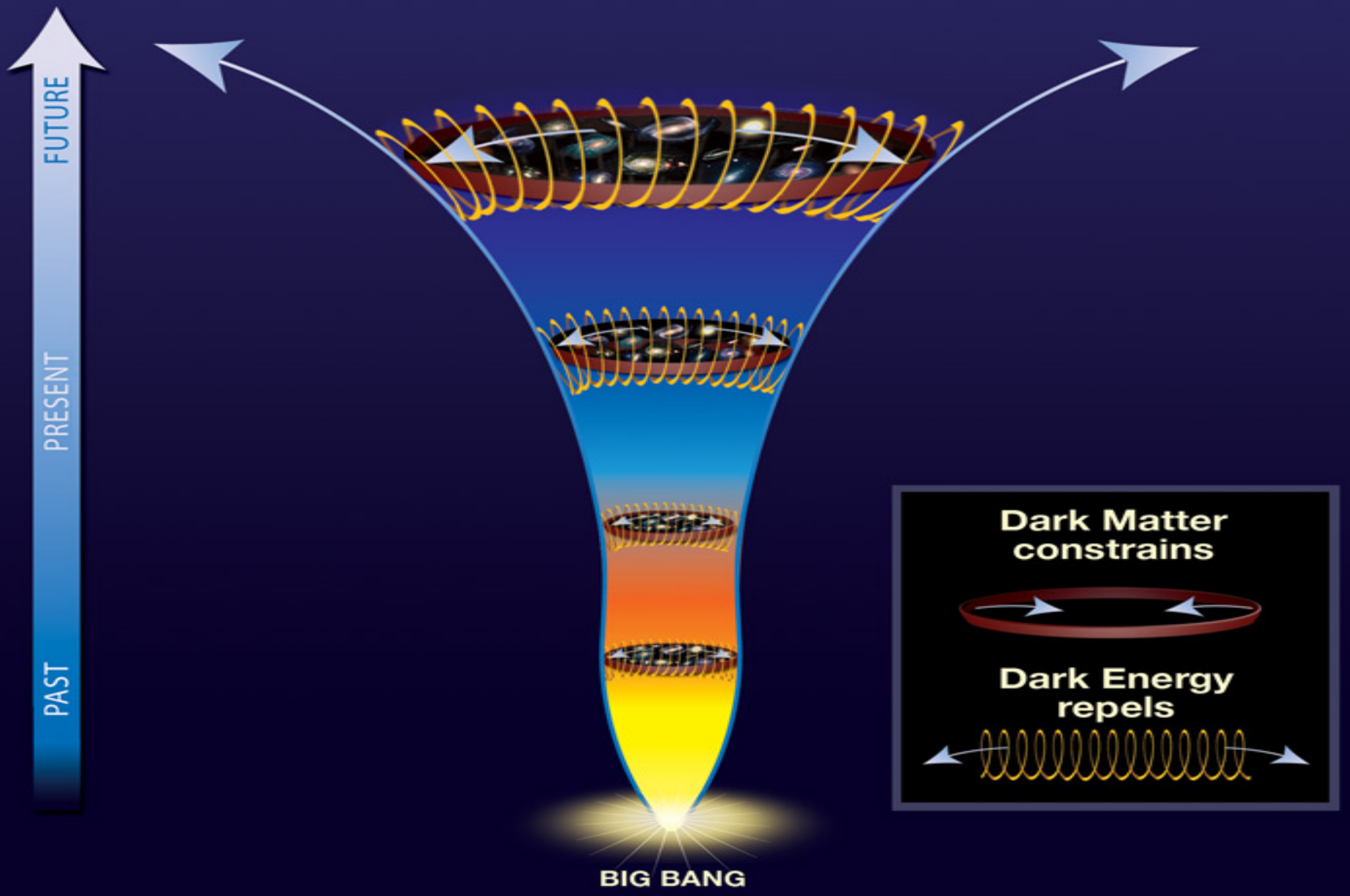
68% dark energy

- Anti-gravitating substance causes cosmic acceleration
- supported by supernova observations

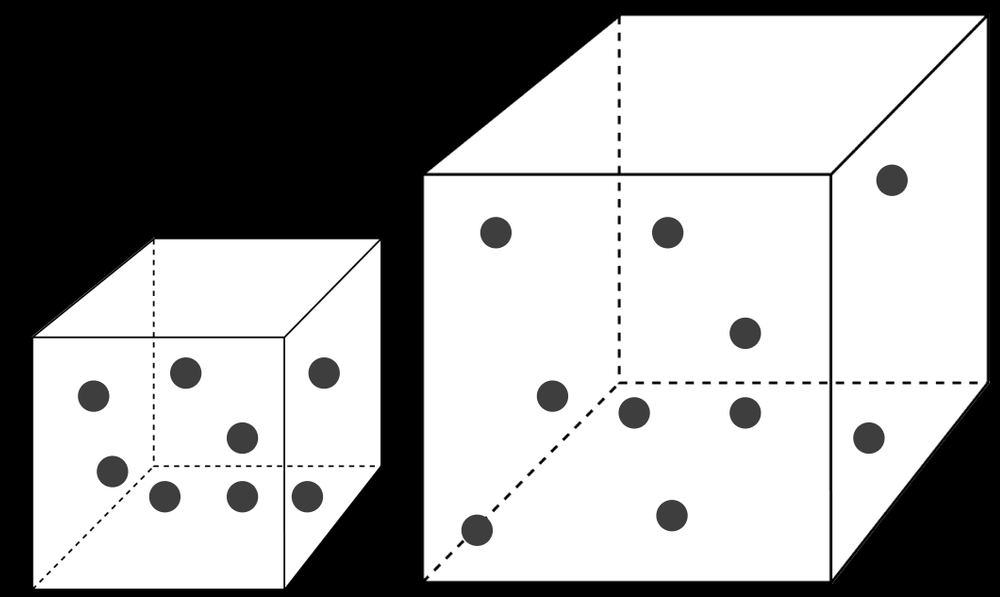


Cosmic tug of war

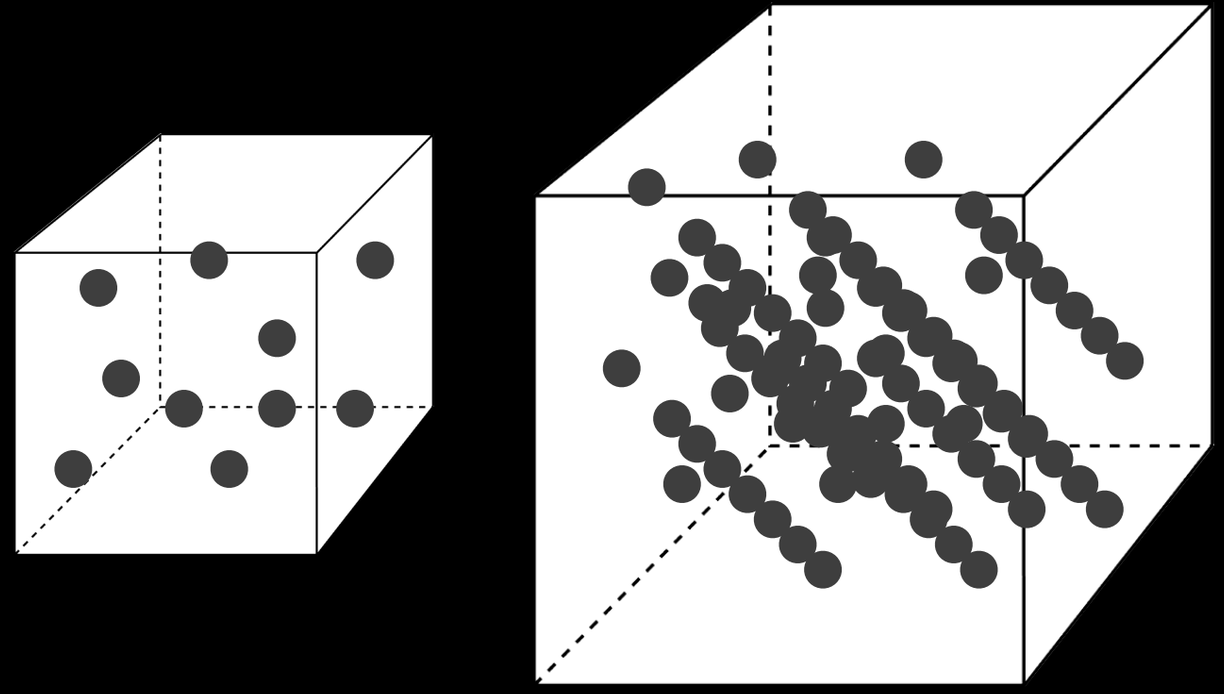
The force of dark energy surpasses
that of dark matter as time progresses.



DARK ENERGY?

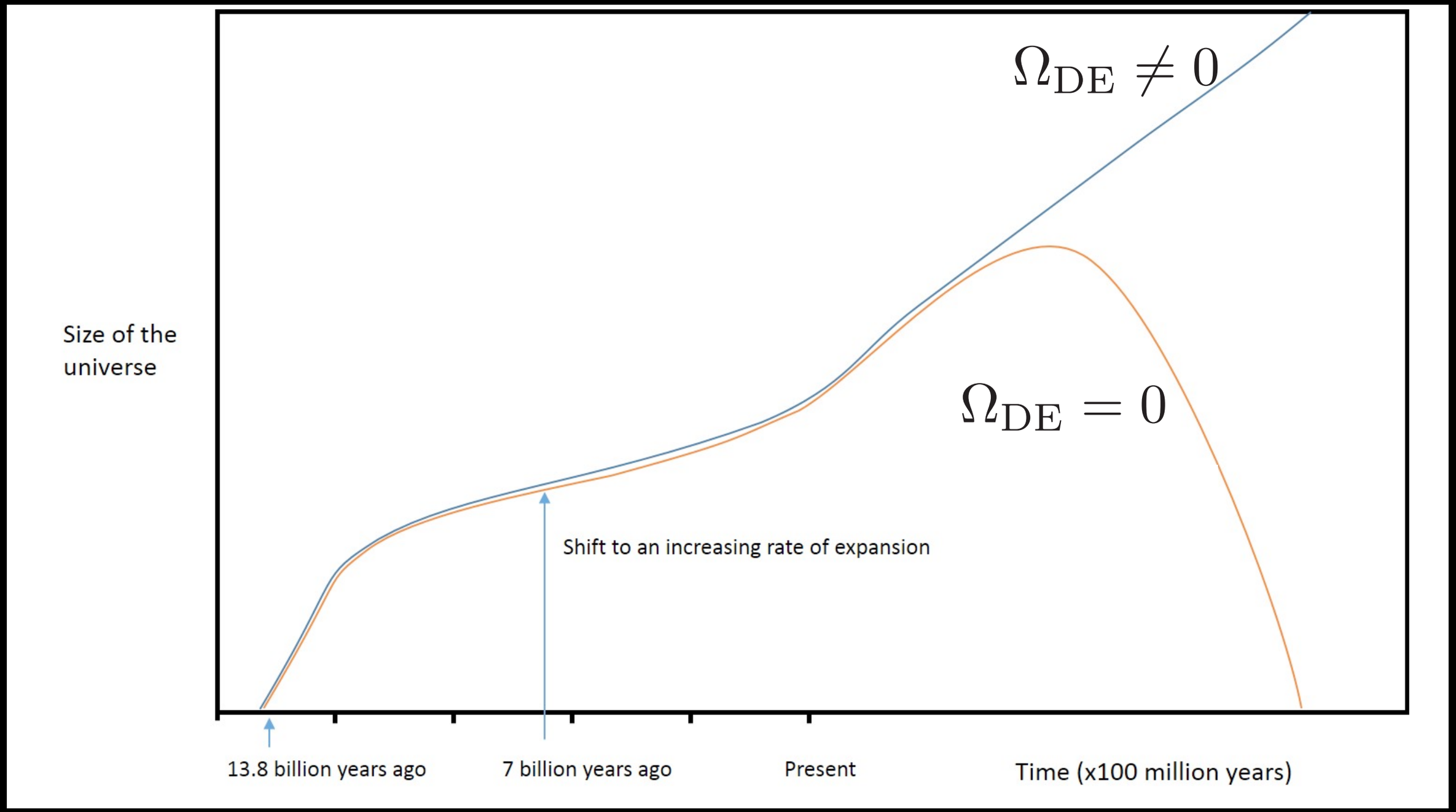


Ordinary or dark matter

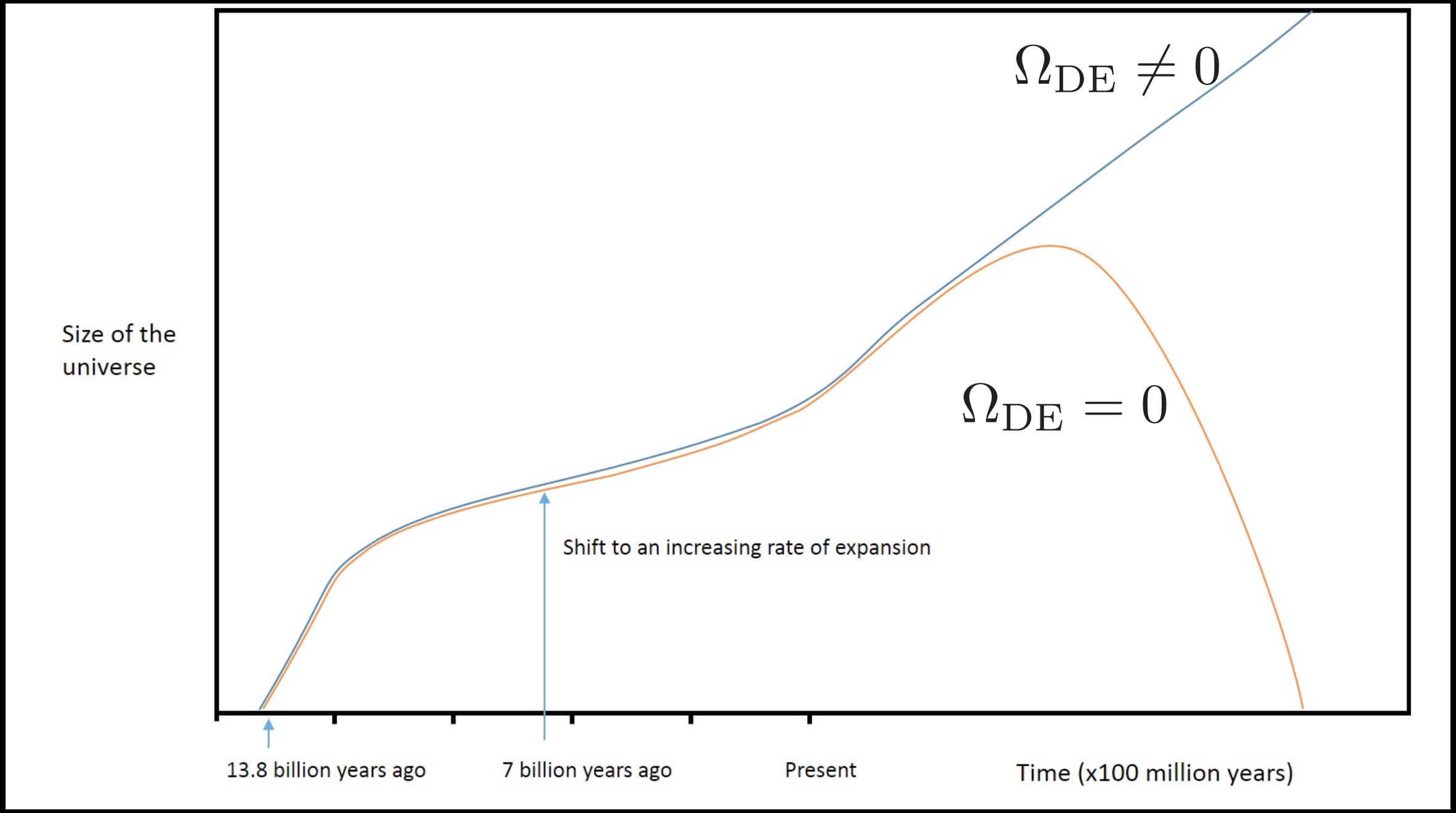


Dark energy

DARK ENERGY?


$\Omega_{\mathrm{DE}} \neq 0$
$\Omega_{\mathrm{DE}} = 0$
Size of the universe
Shift to an increasing rate of expansion
13.8 billion years ago
7 billion years ago
Present
Time (x100 million years)

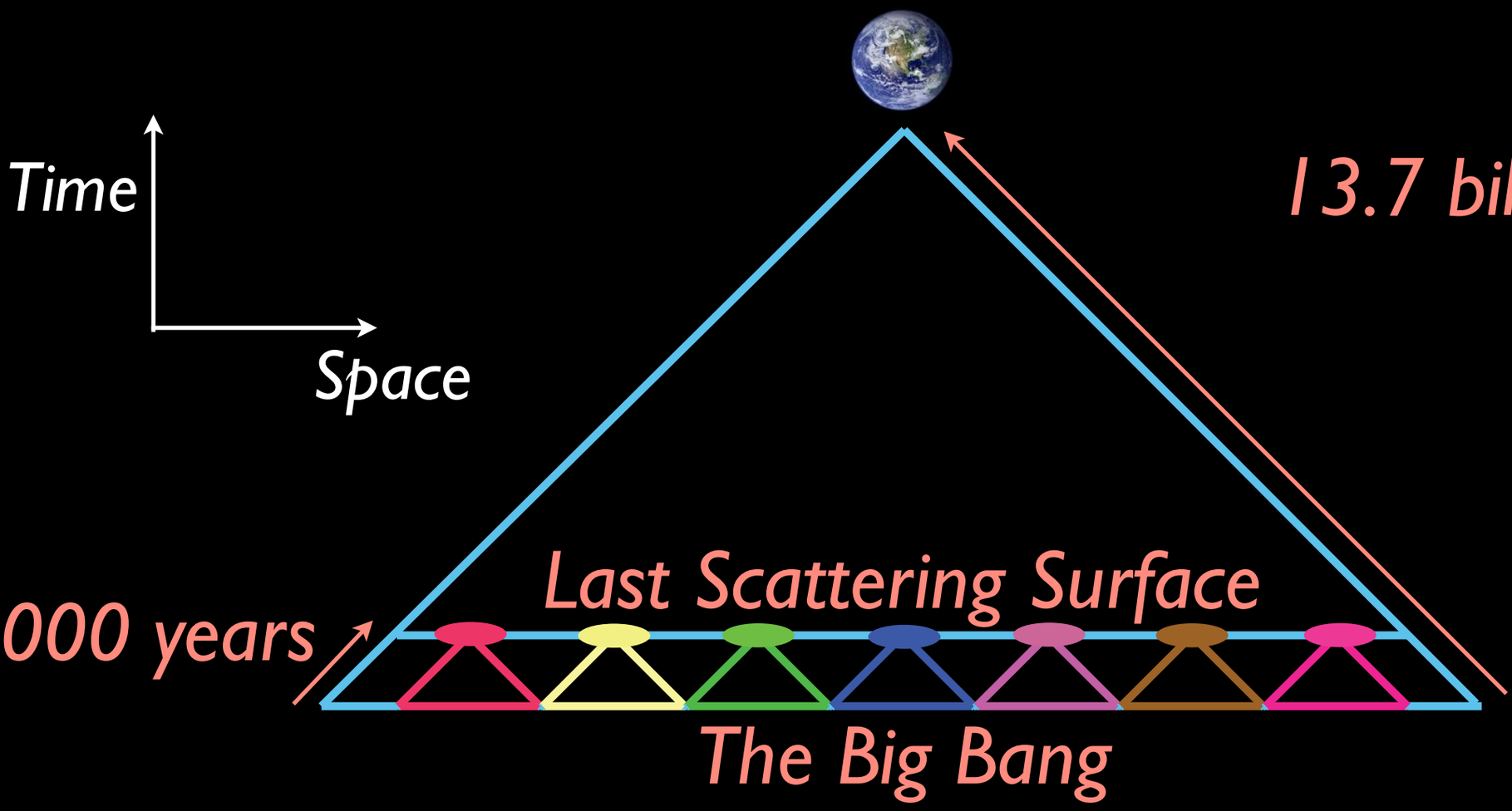
DARK ENERGY?



Standard Model Vacuum Energy $\Omega_\Lambda \sim 10^{120}$

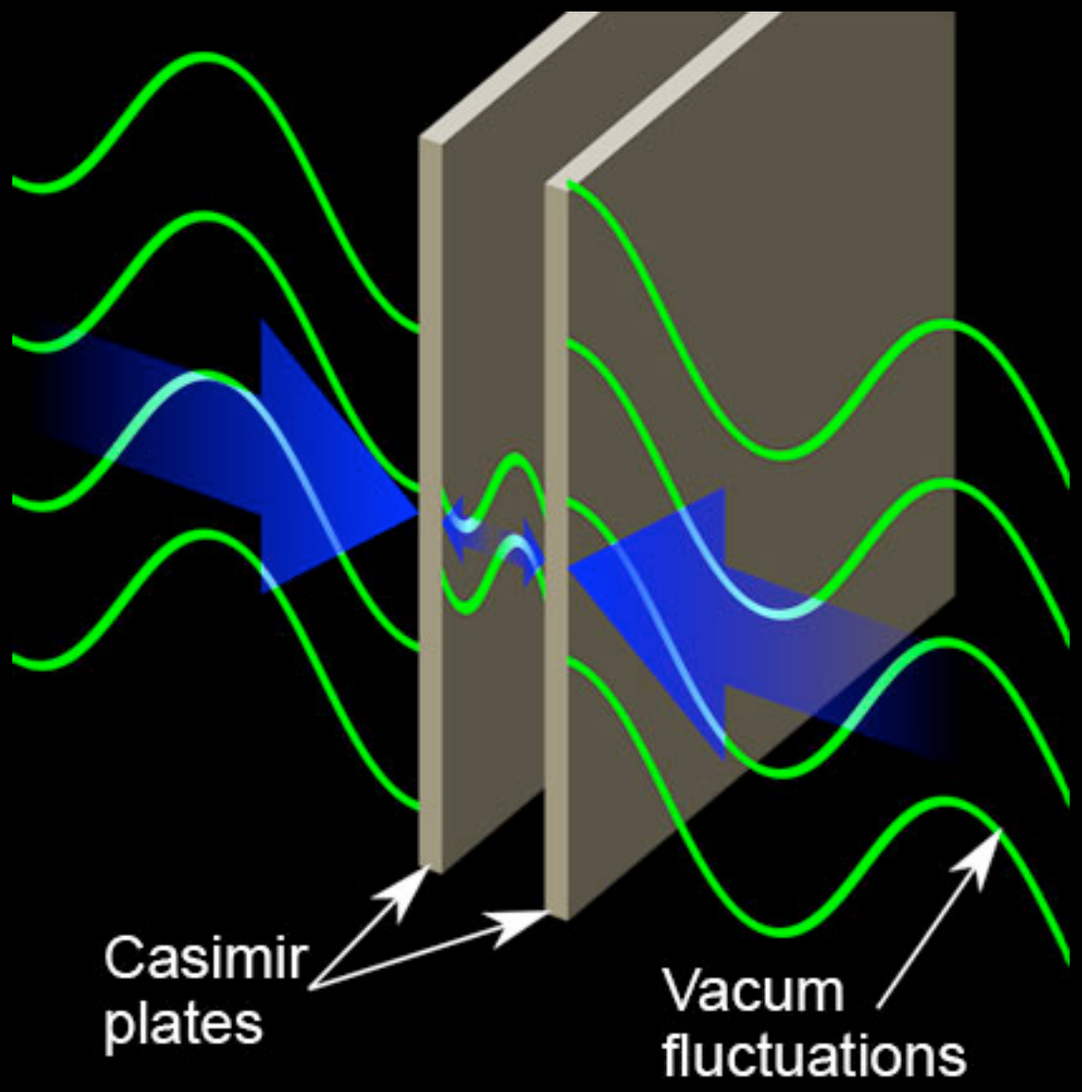
Mystery 1: The Horizon Problem

The CMB should not be so perfectly uniform!

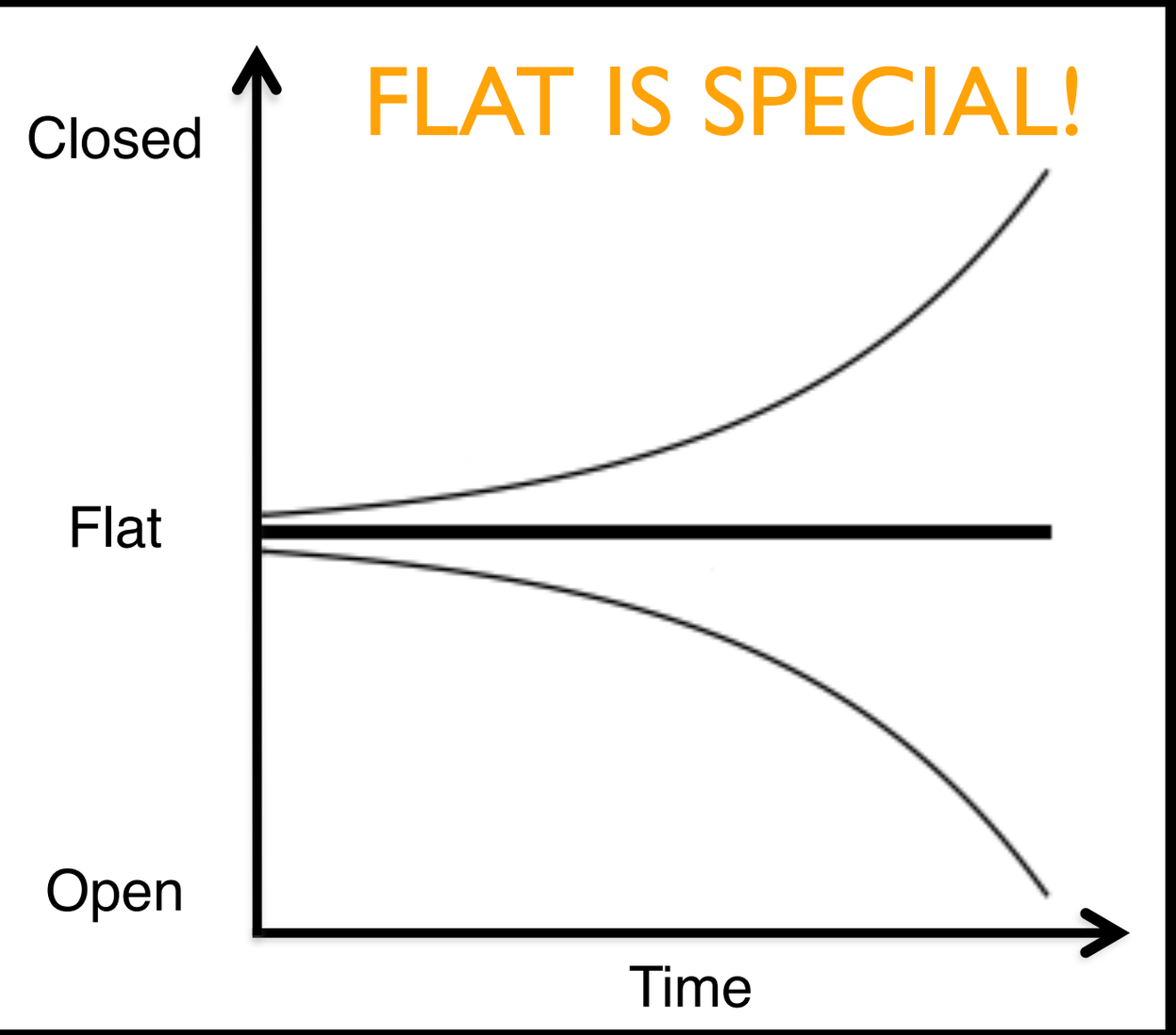


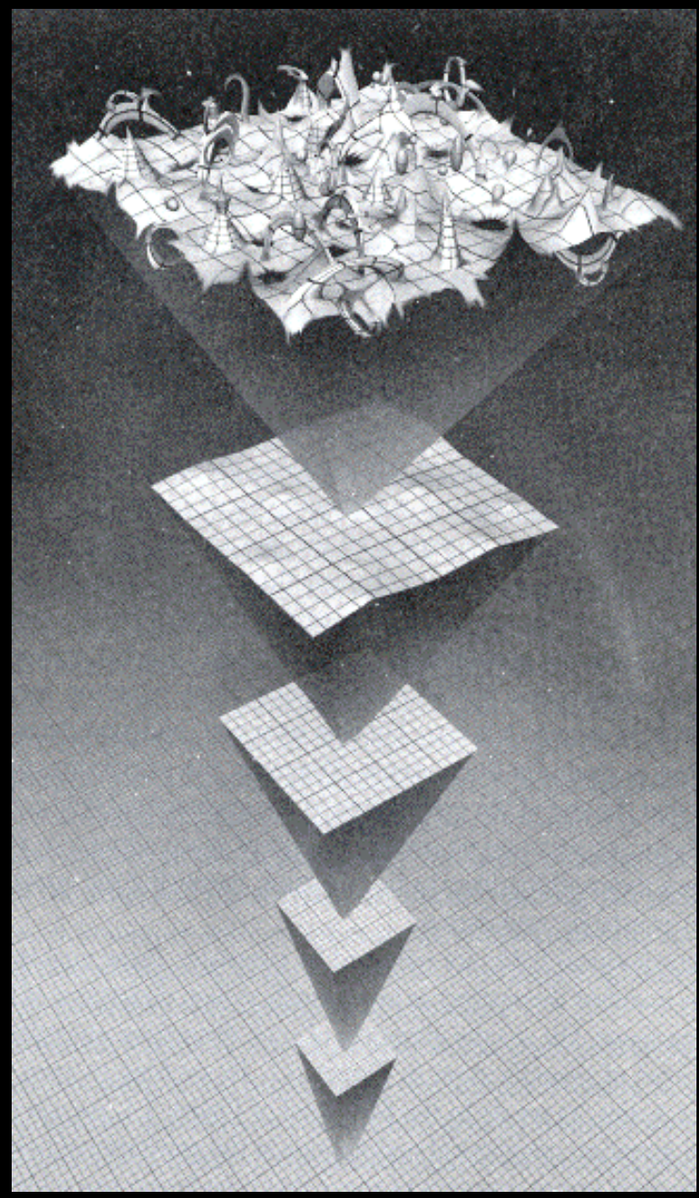
- At the last scattering surface, the horizon was 1° across.
- These different patches should not have the same temperature!

Empty space is not empty



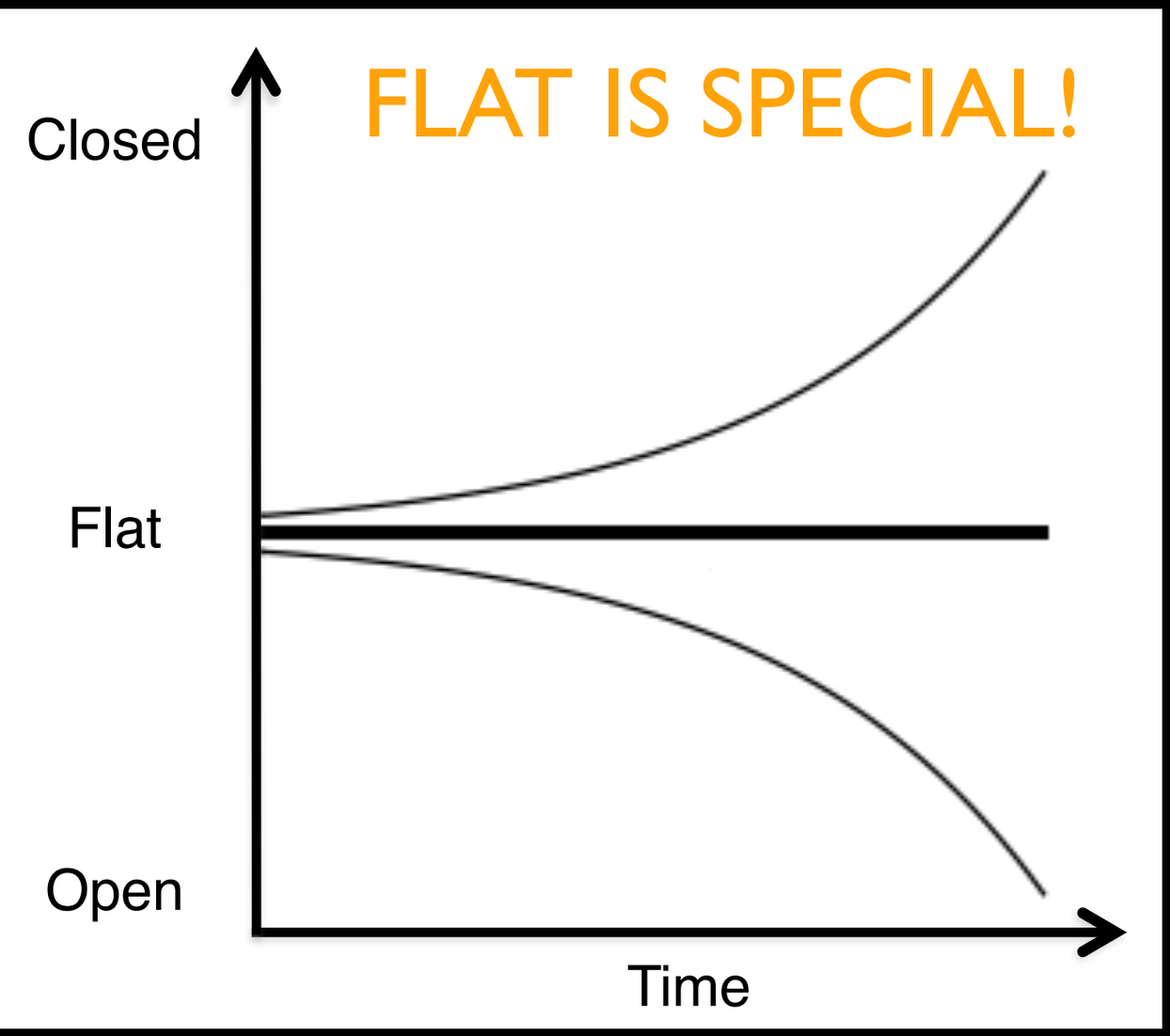
Mystery 2: The Flatness Problem

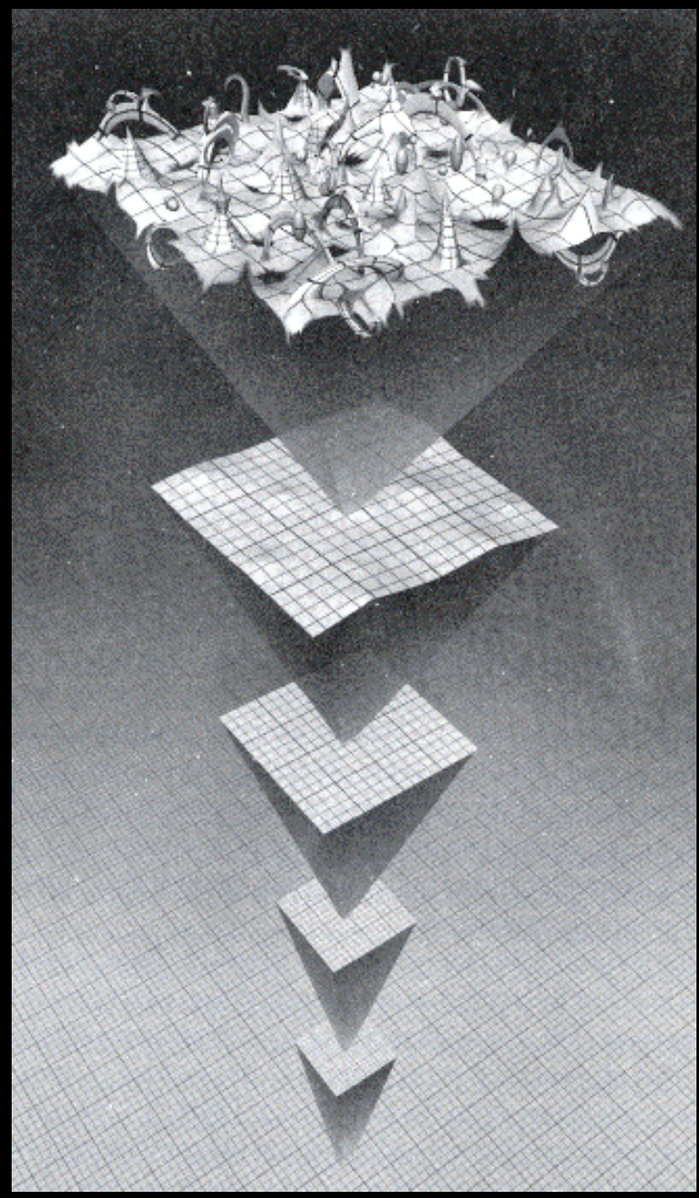




Mystery 2: The Flatness Problem

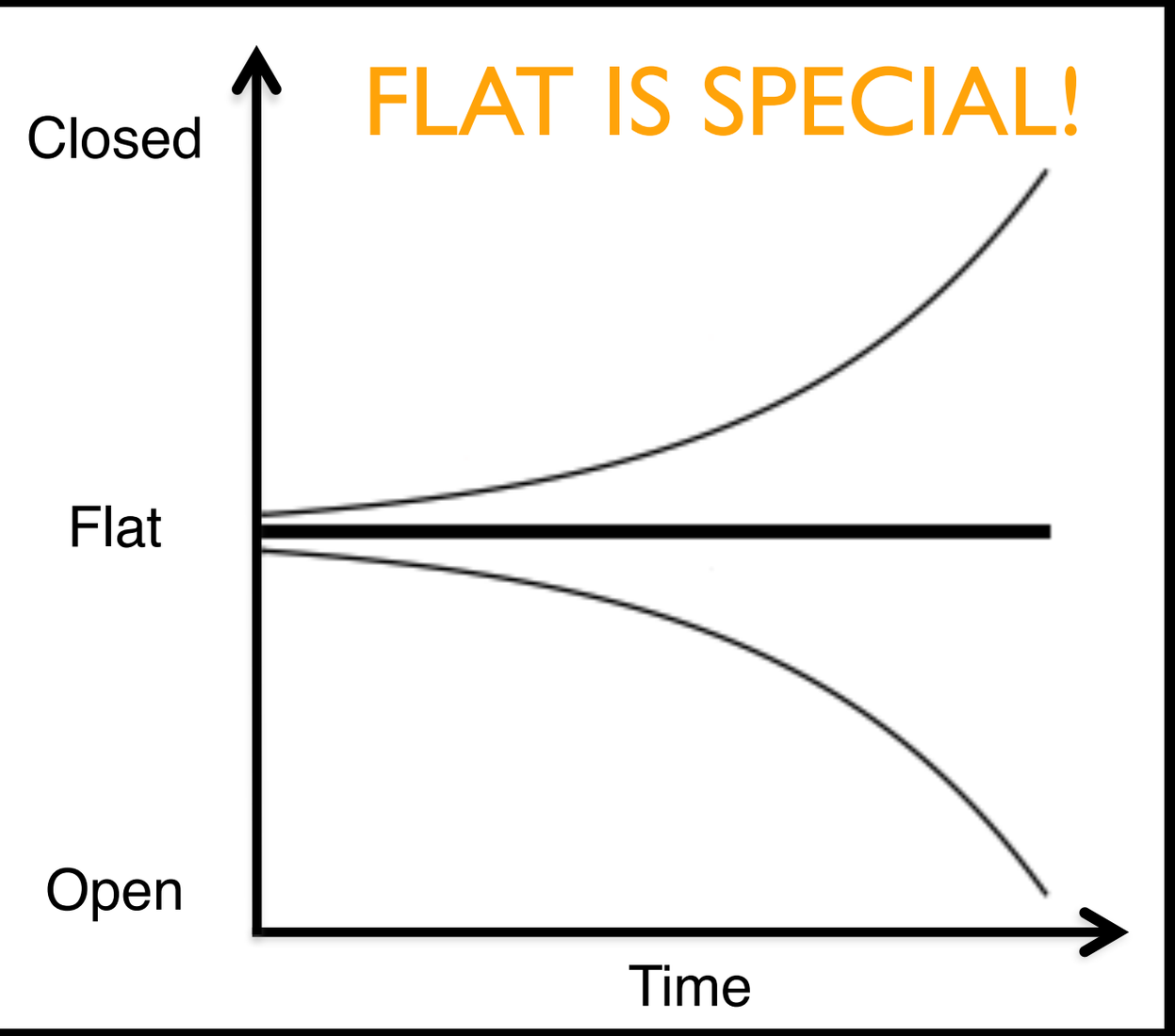
$$\Omega \equiv \frac{\textit{Energy in the Universe}}{\textit{Energy required for flatness}}$$

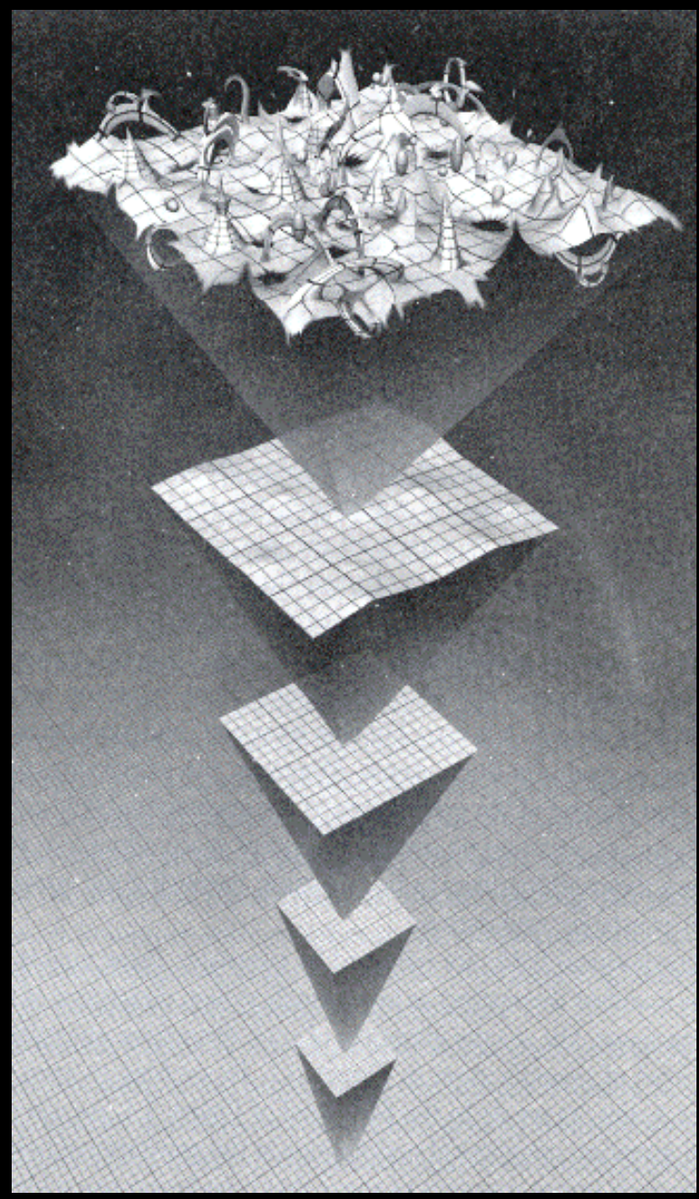




Mystery 2: The Flatness Problem

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

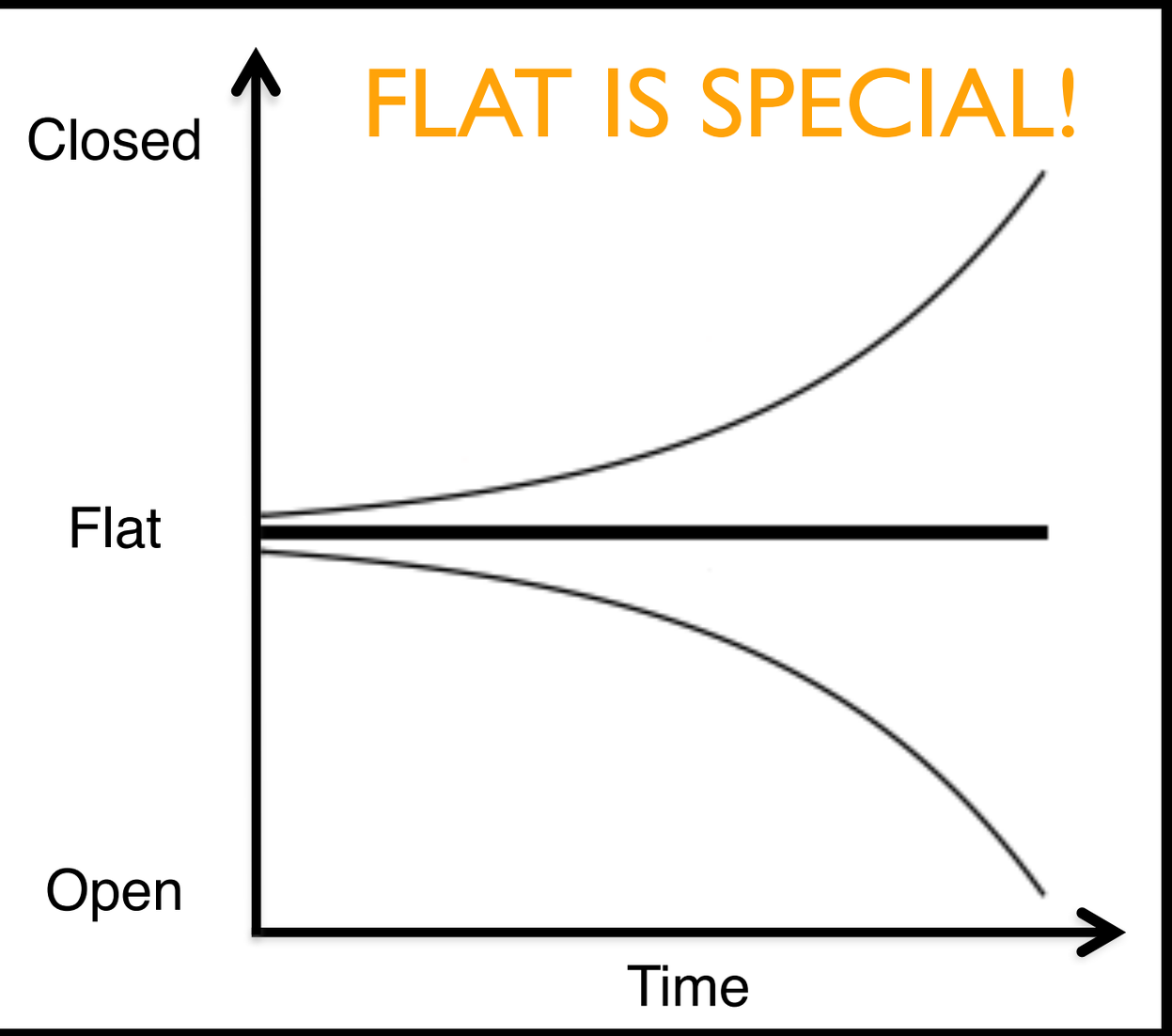




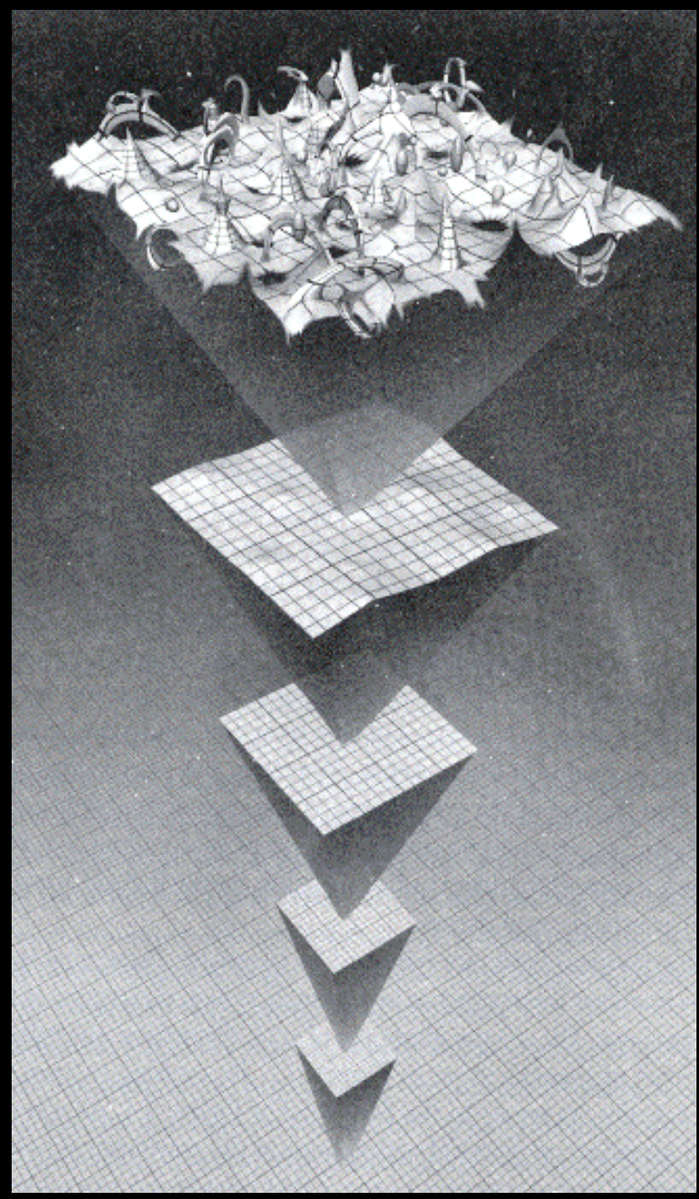
Mystery 2: The Flatness Problem

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

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



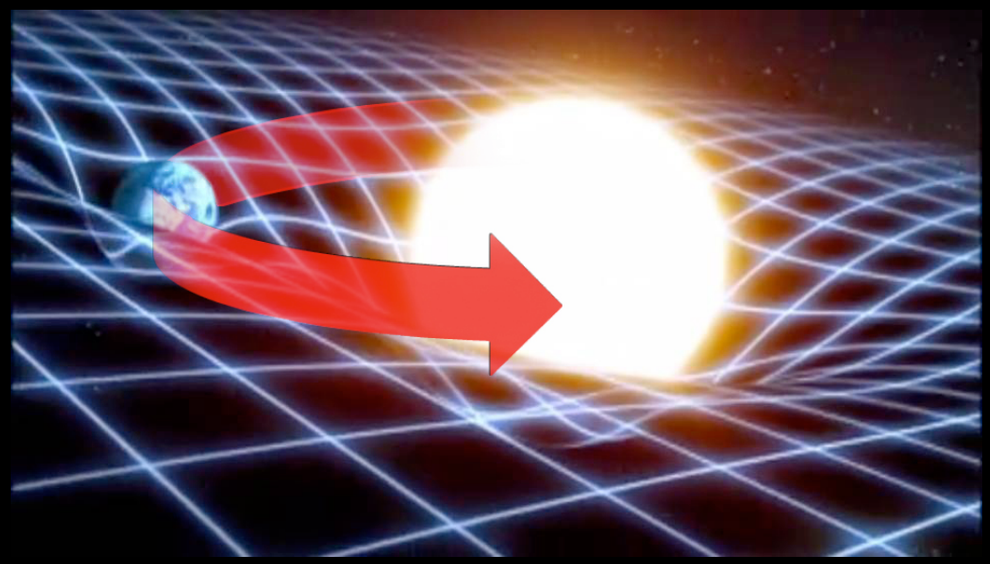
FLAT IS SPECIAL!

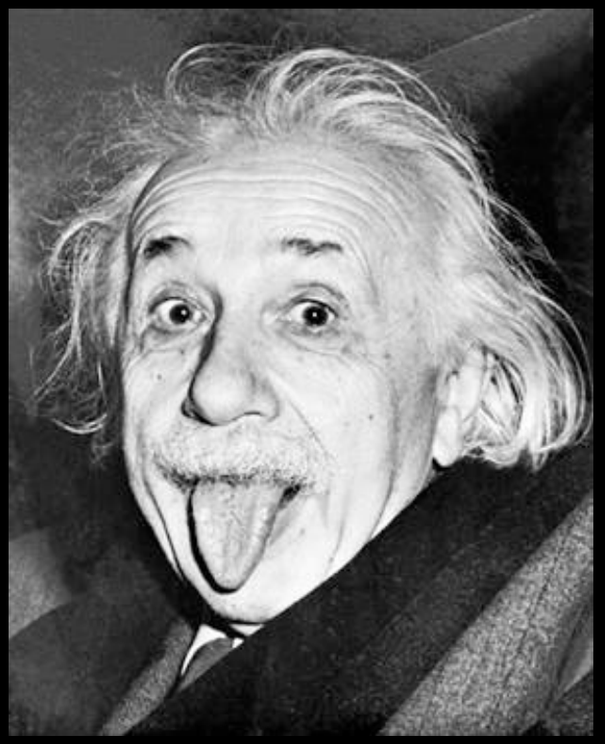


General Relativity Crash Course

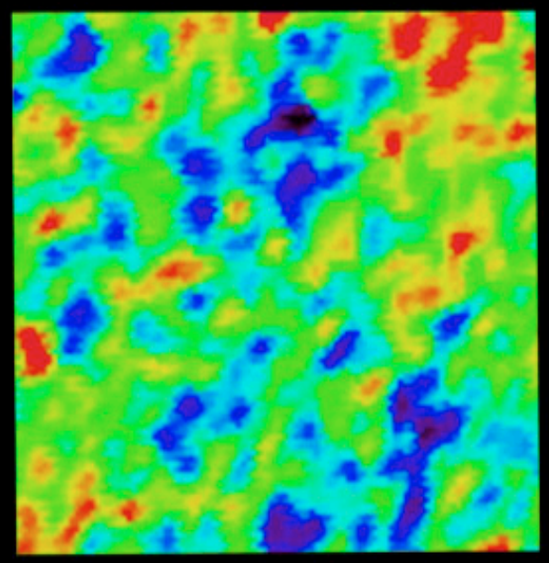
Mass curves spacetime.
Spacetime tells mass how to move.

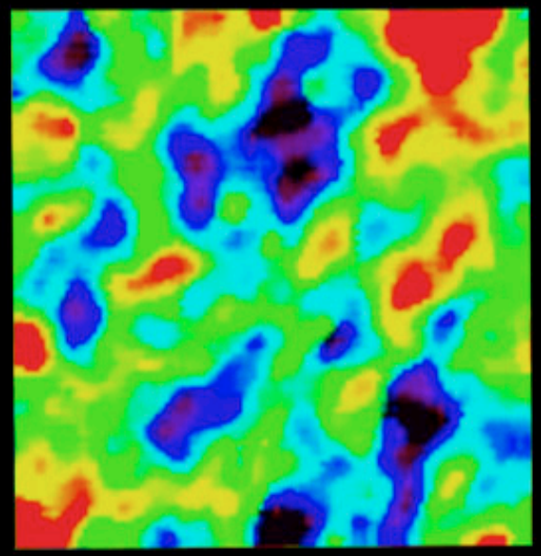
WGBH Boston

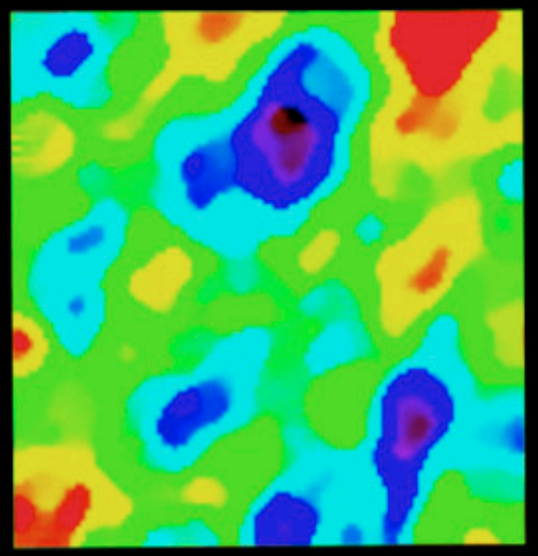


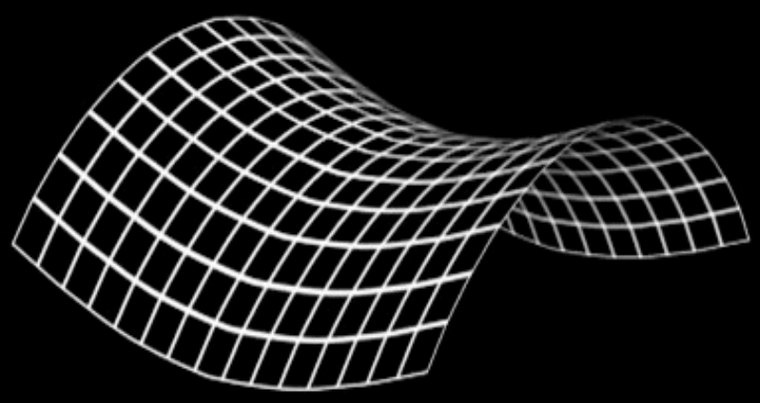


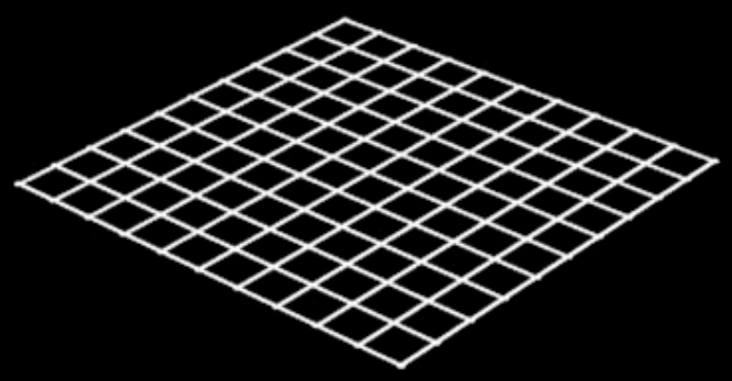
GEOMETRY OF THE UNIVERSE

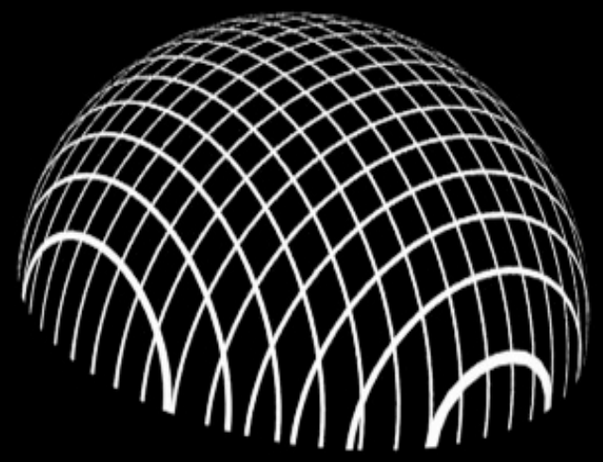










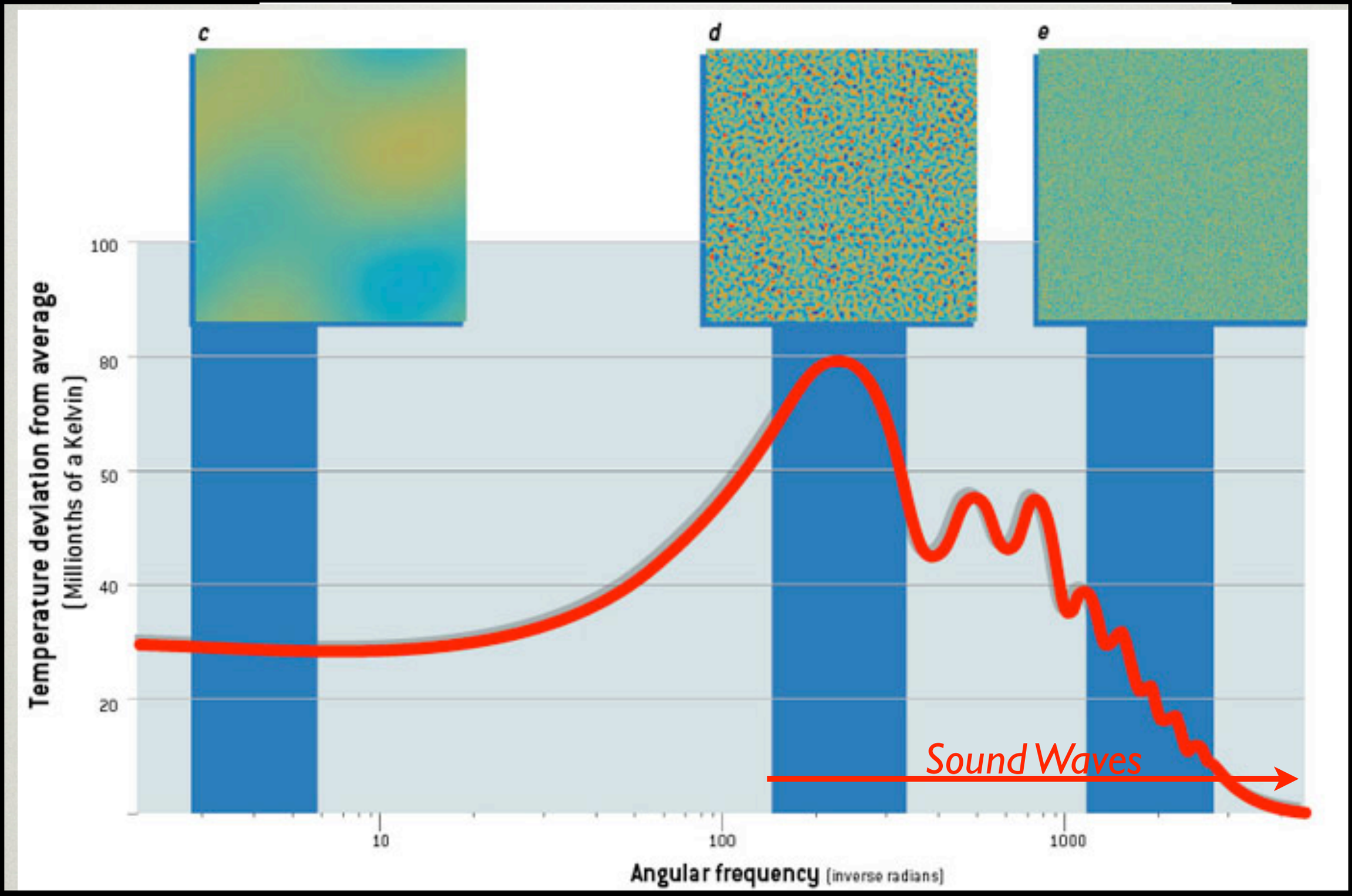


OPEN

FLAT

CLOSED

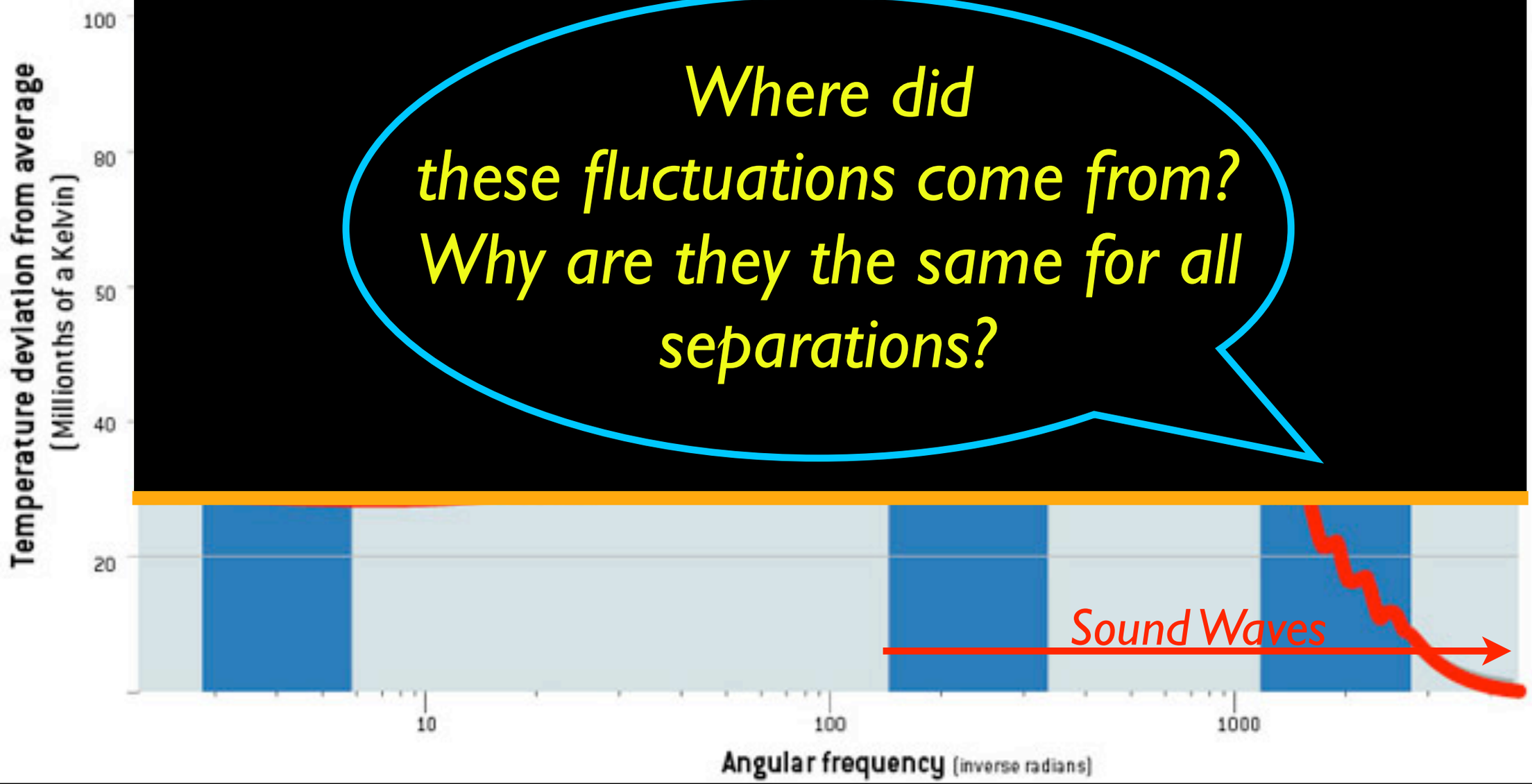
Mystery 3: Initial Fluctuations



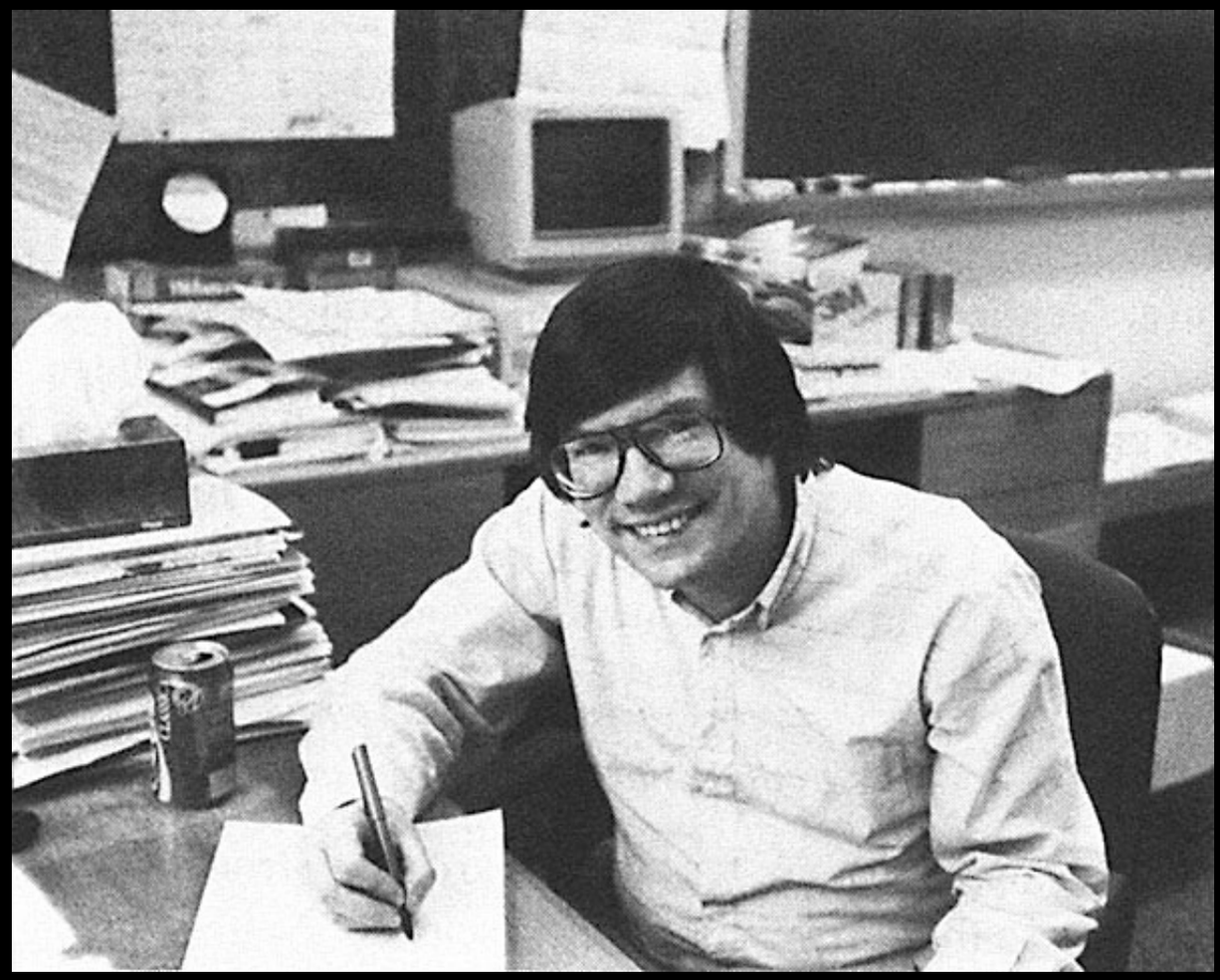
Mystery 3: Initial Fluctuations

Rewind the sound waves:
All notes are equally loud!

Where did these fluctuations come from? Why are they the same for all separations?



Problem: I need a job!



1980

Solution: Inflation

I have a job!

EV ⑤
Dec 7, 1979

SPECTACULAR REALIZATION:

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

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

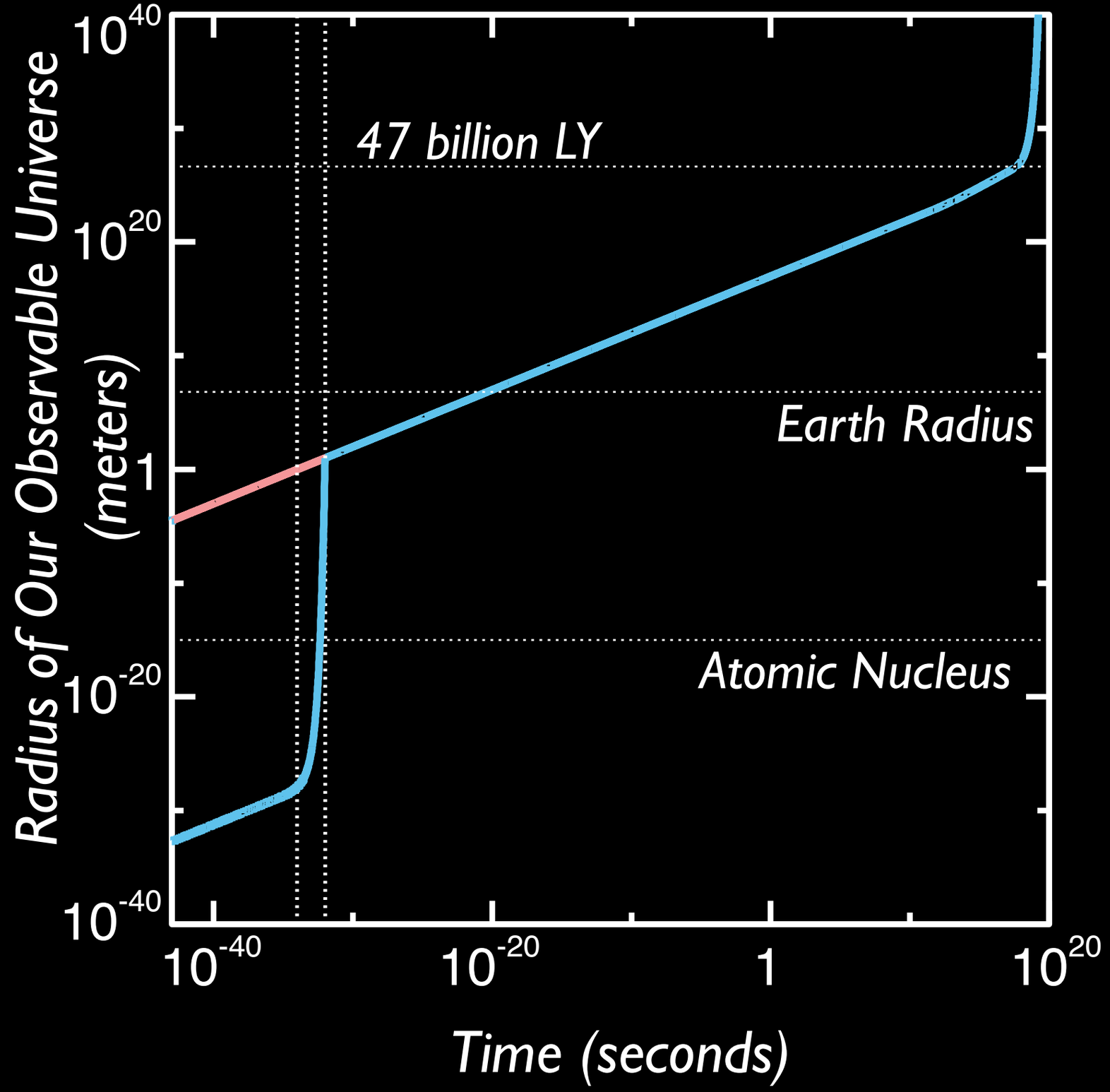
$$\frac{k}{R^2} = \frac{8\pi\rho}{3M_P^2} - H^2 \qquad G = \frac{1}{M_P^2} , \quad H = \frac{\dot{R}}{R}$$

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

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

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

Inflation: Accelerated Expansion

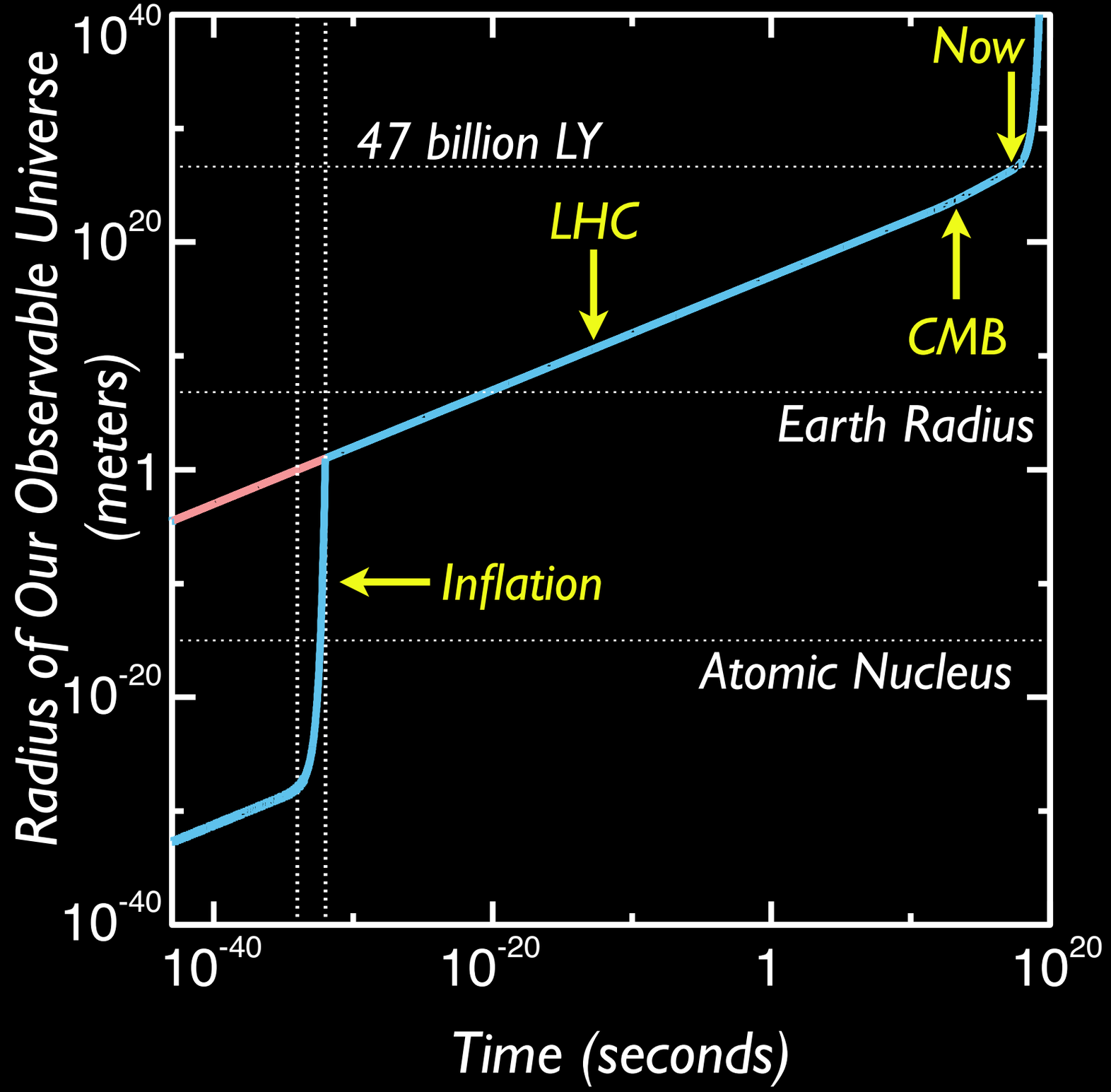


Inflation: Accelerated Expansion

INFLATION

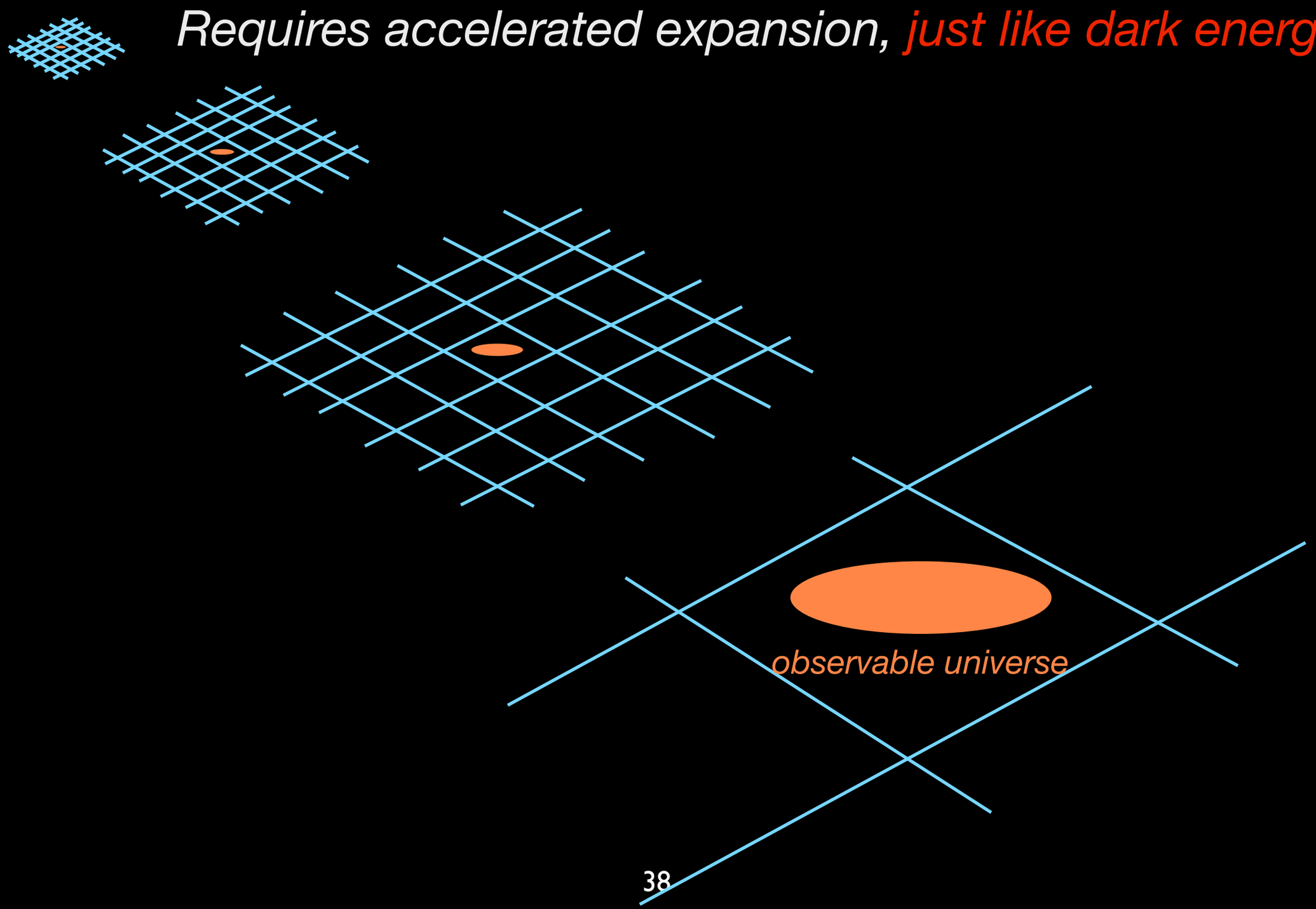
Alan Guth, 1981

The Universe's volume doubled at least 260 times *instantly* (proton to AU).



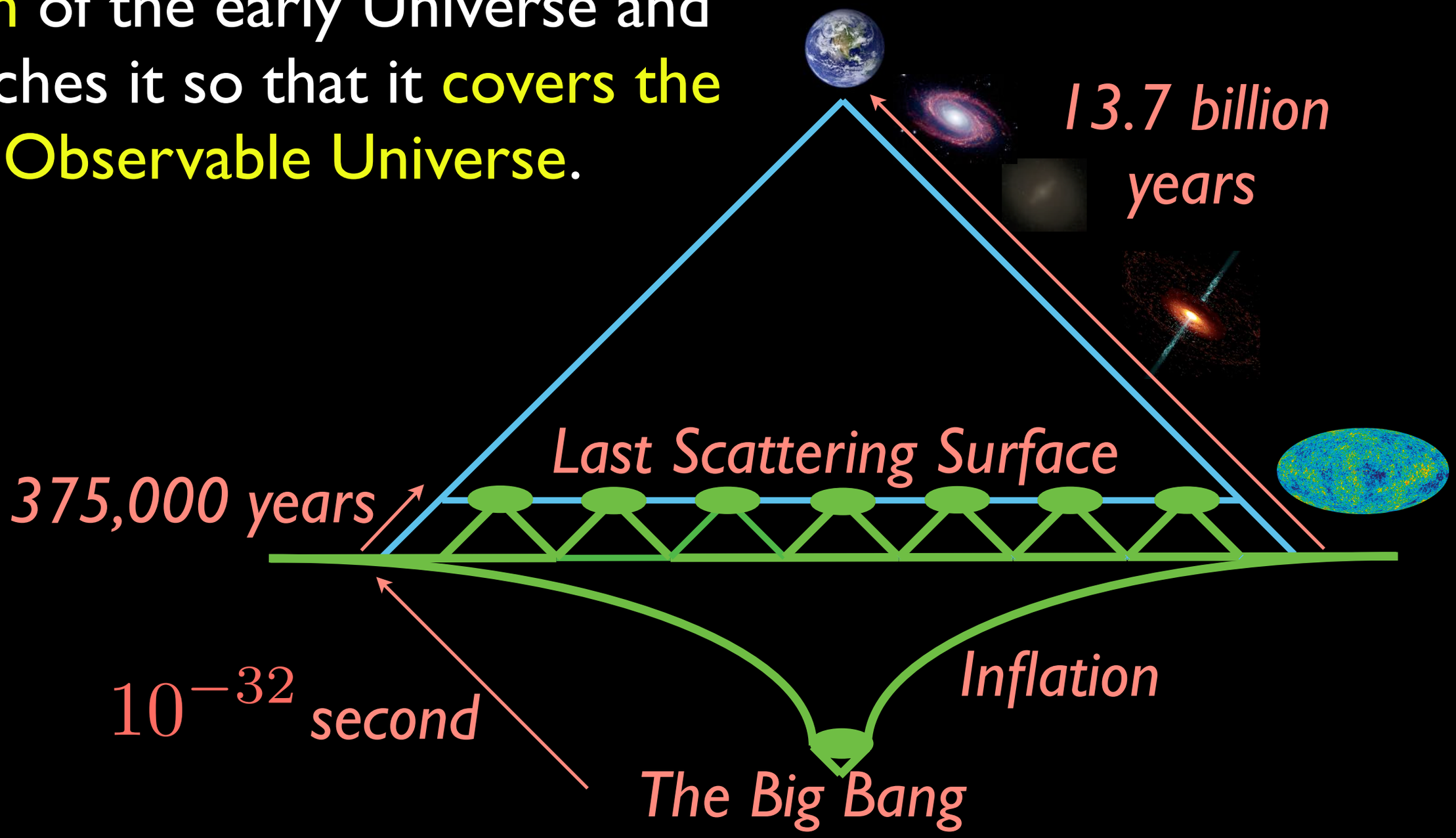
Inflation: Accelerated Expansion

A tiny patch of space becomes the entire observable universe:



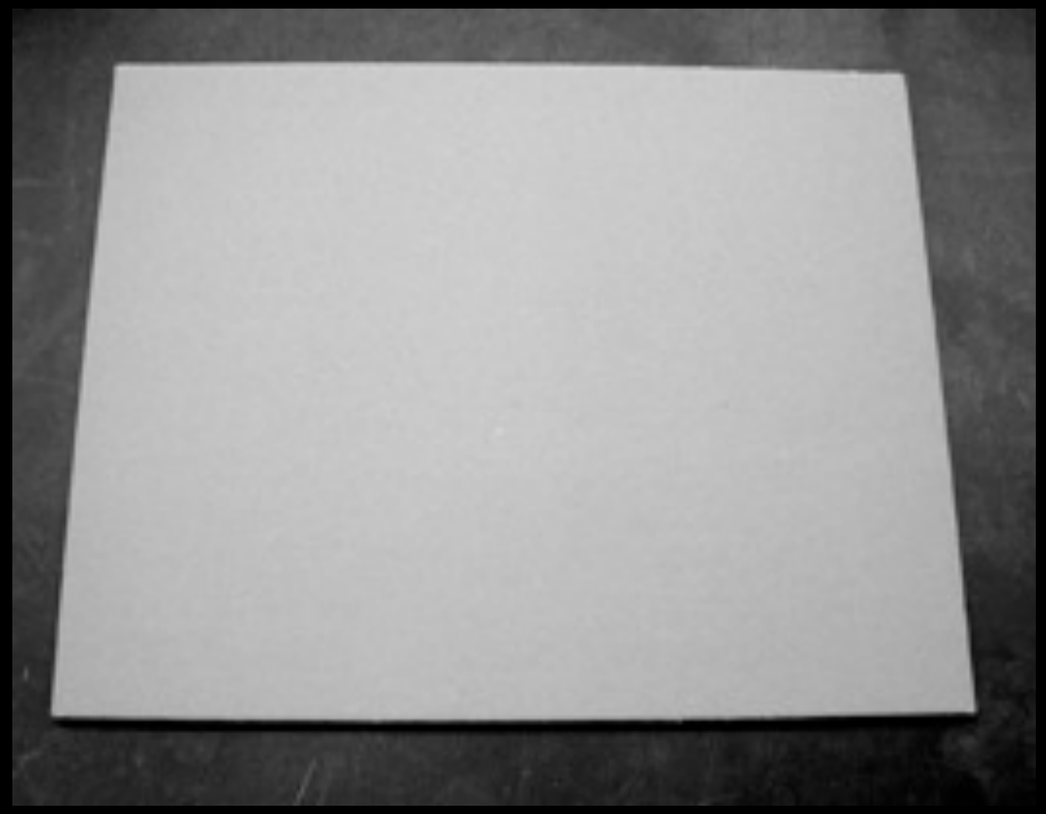
Inflation Solves the Horizon Problem

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

Stretch



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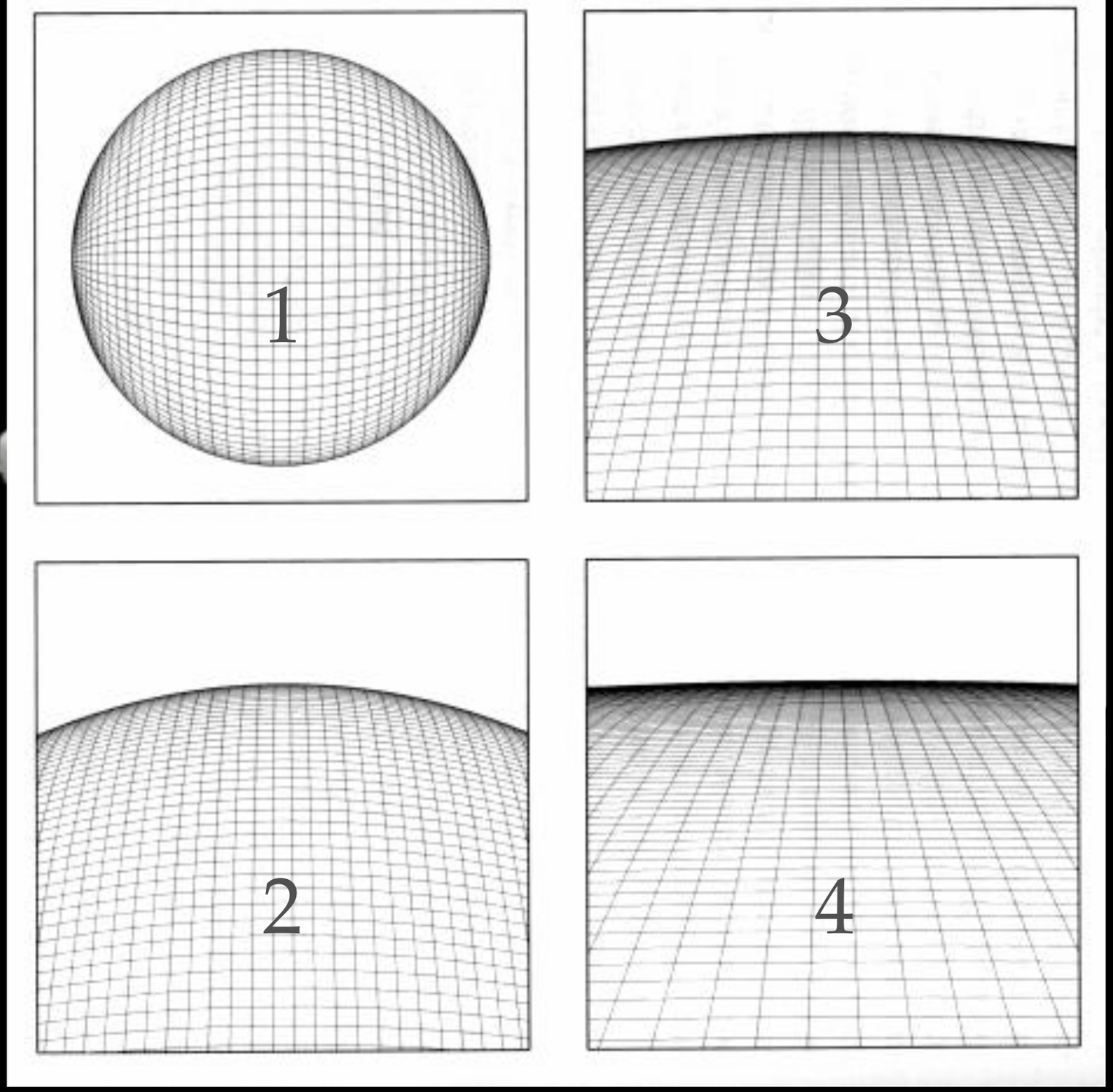
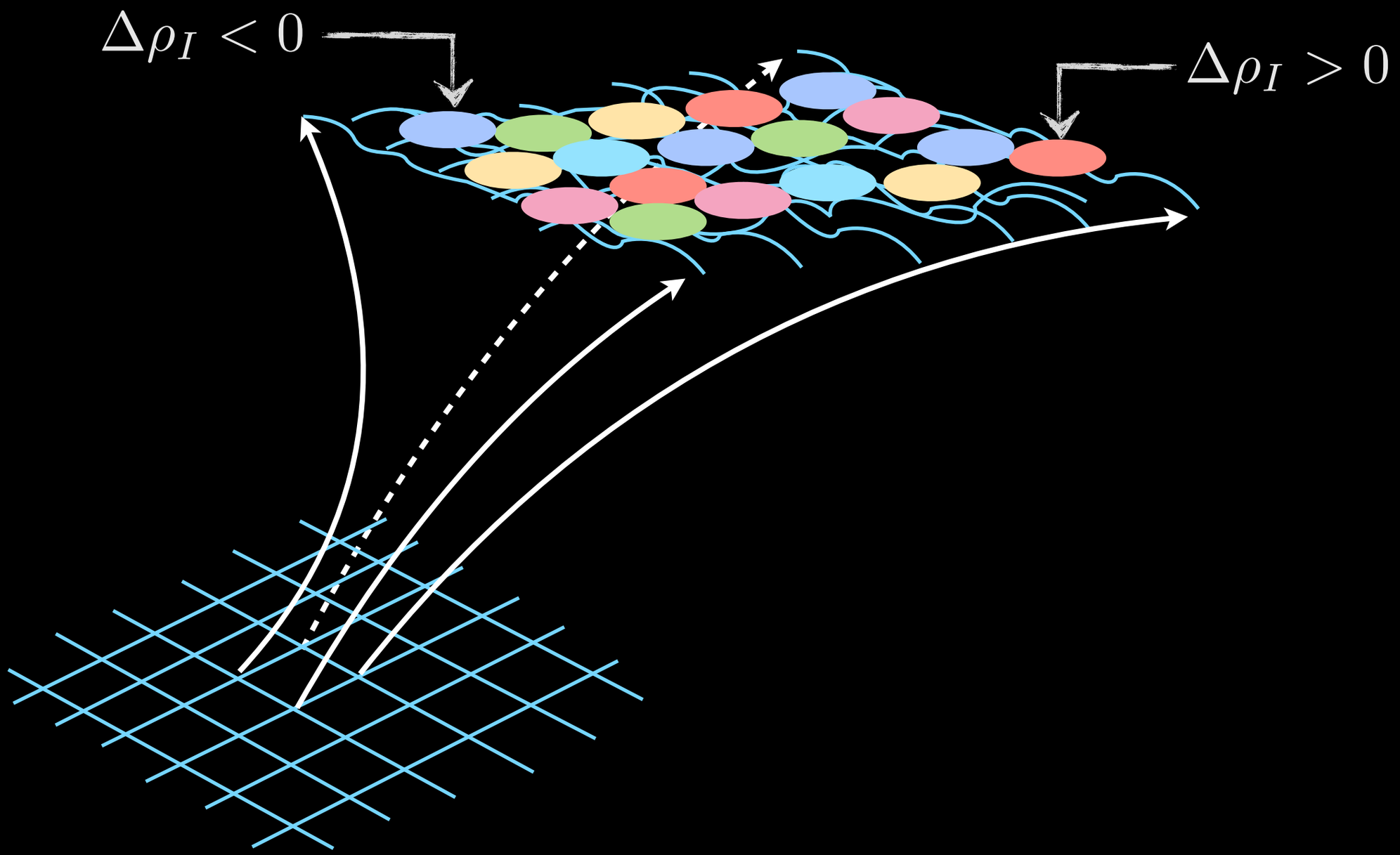


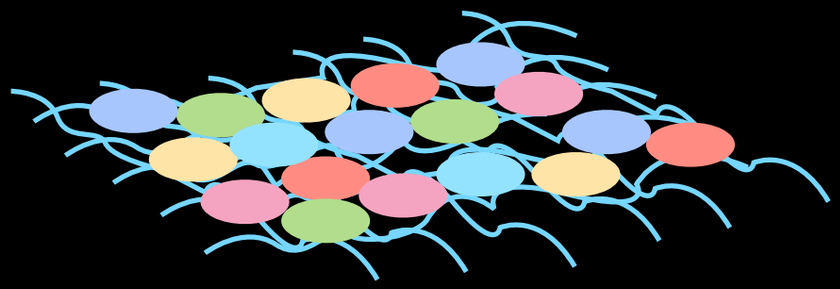
Inflation seeds the sound waves and all structure

Quantum fluctuations in the energy density during inflation get stretched to cosmological scales:

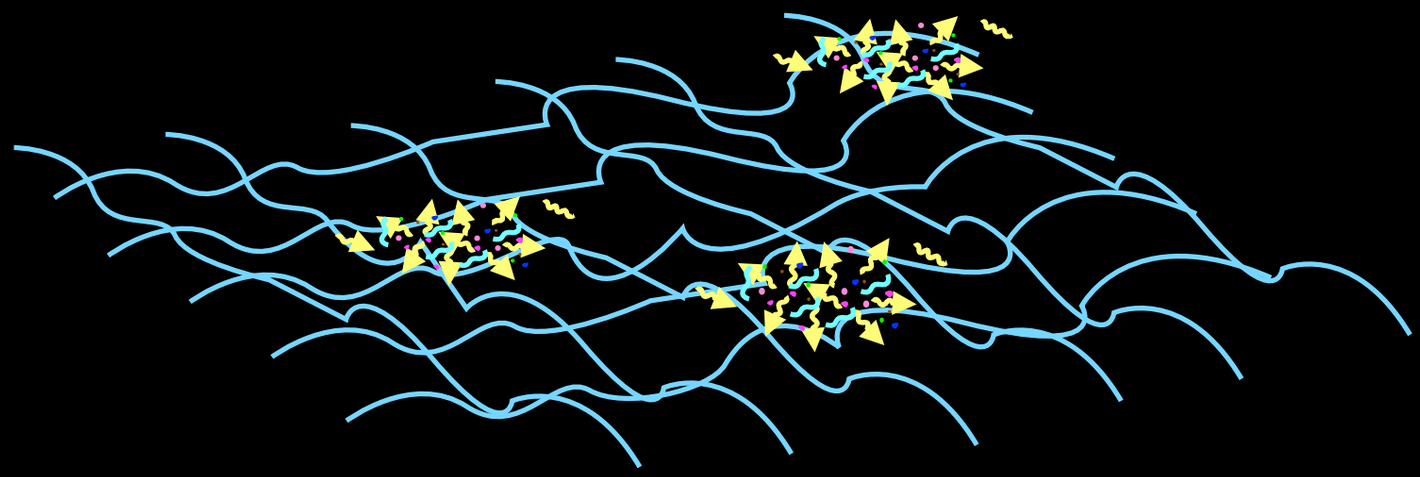


Inflation seeds the sound waves and all structure

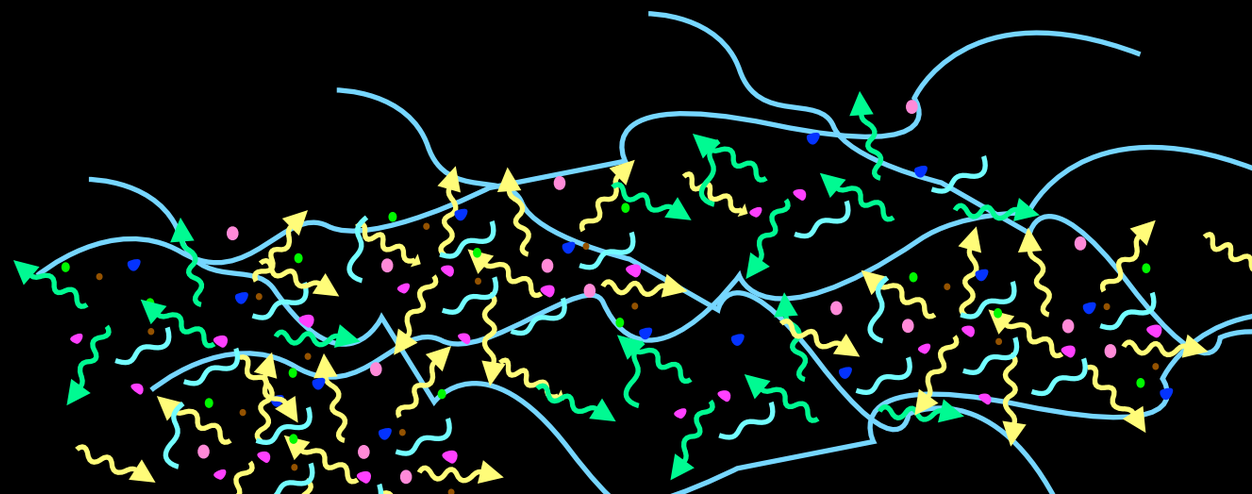
quantum fluctuations induce variations
in the inflationary energy density



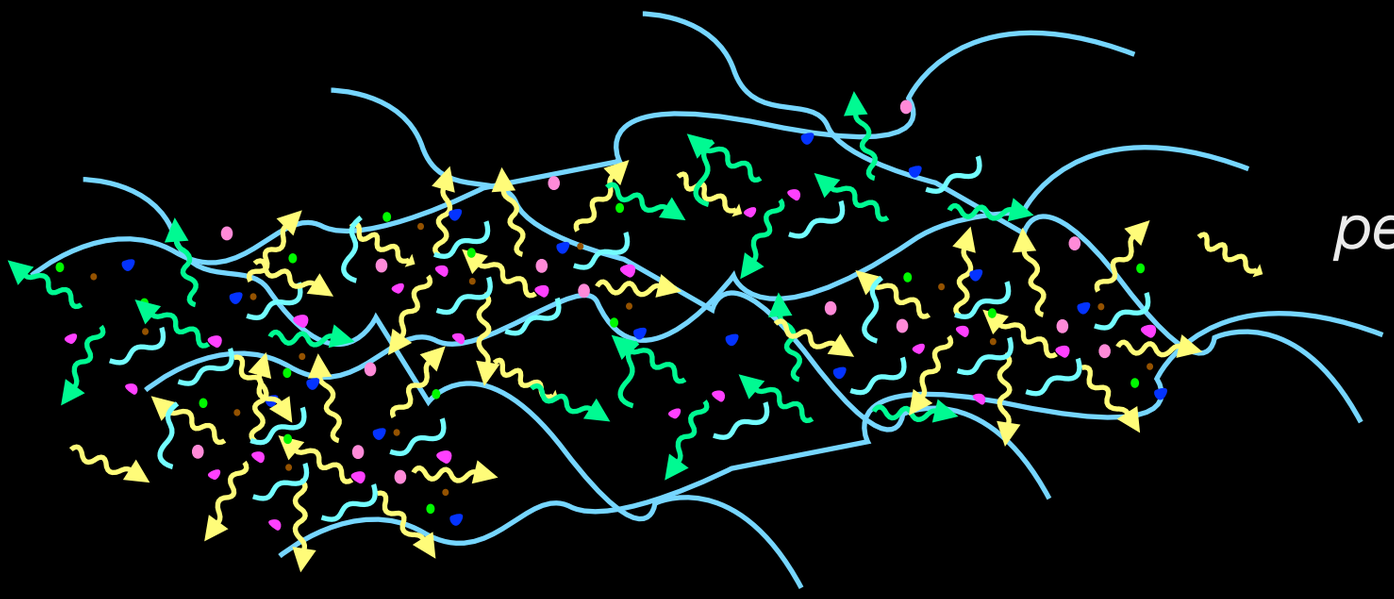
some patches of the universe stop inflating
first and start the hot big bang earlier



these patches of the universe will
have more time to expand and cool

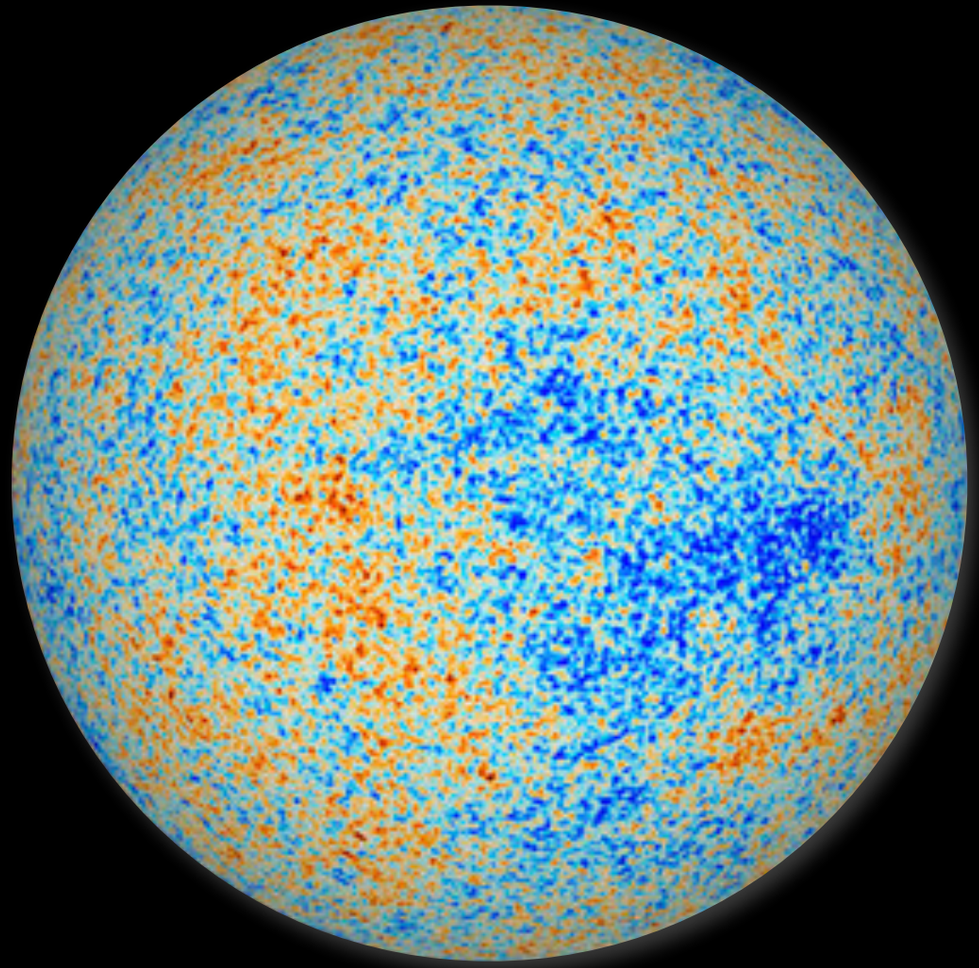


Inflation seeds the sound waves and all structure



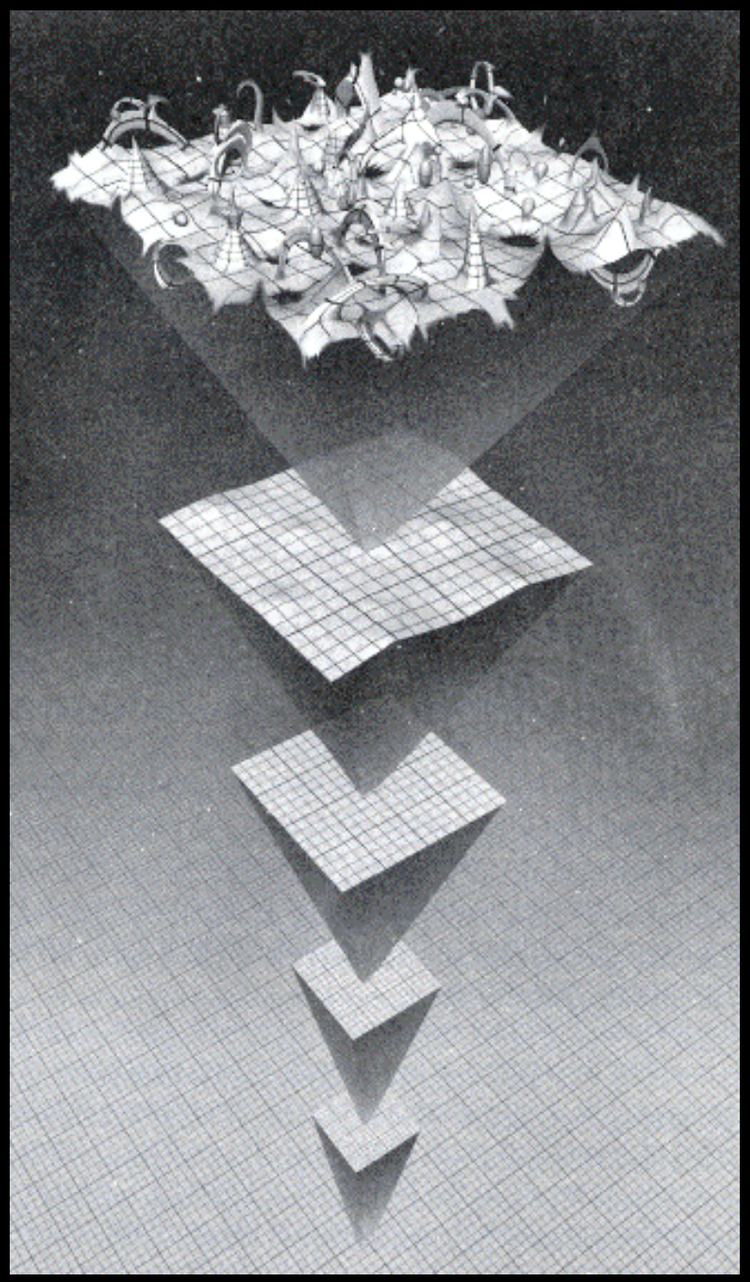
We end up with density perturbations after inflation.

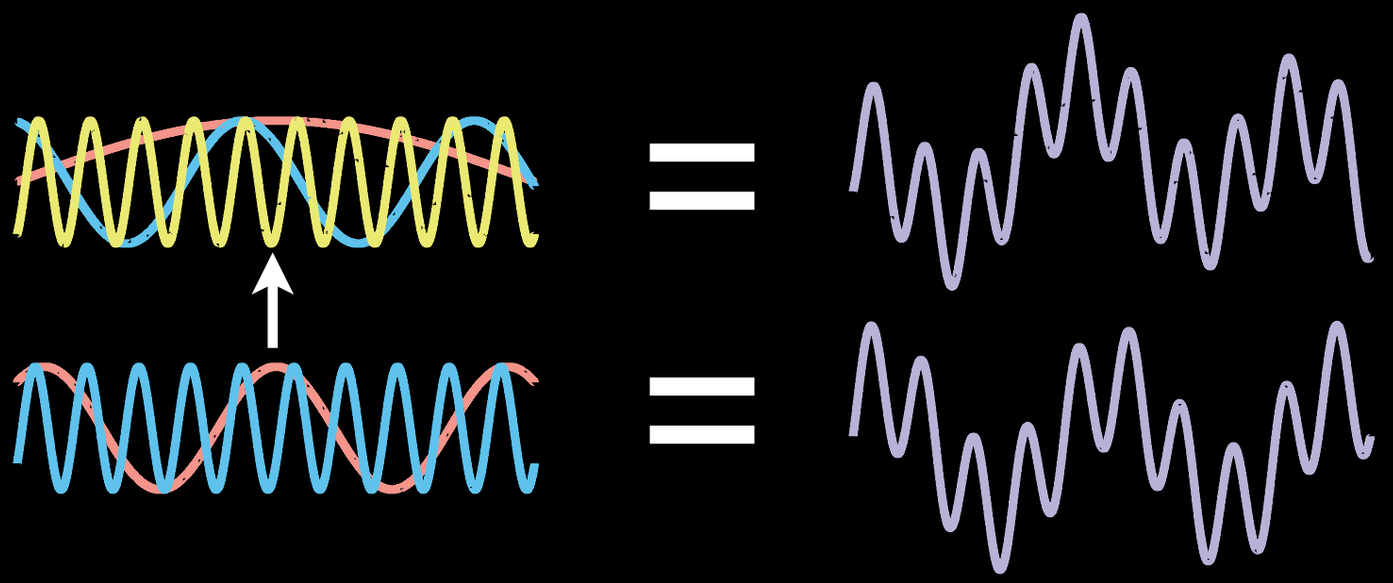
Eventually, these fluctuations become the CMB anisotropies.



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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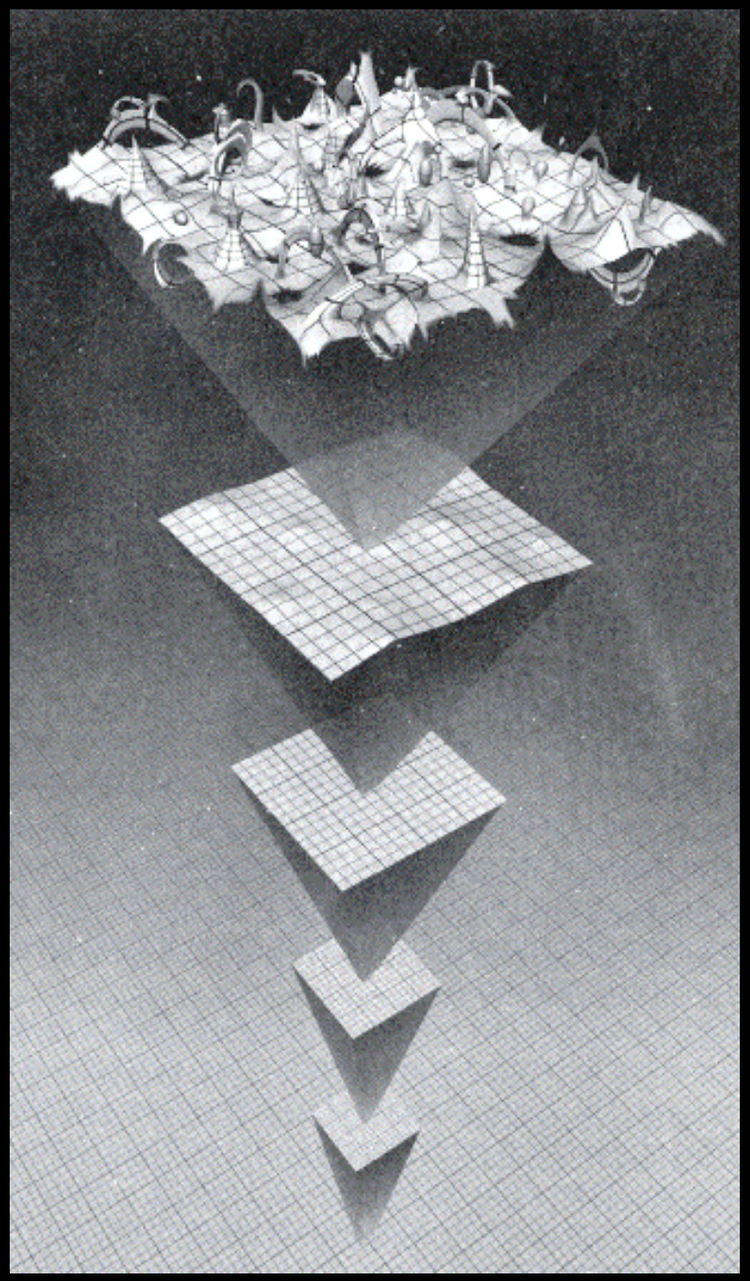
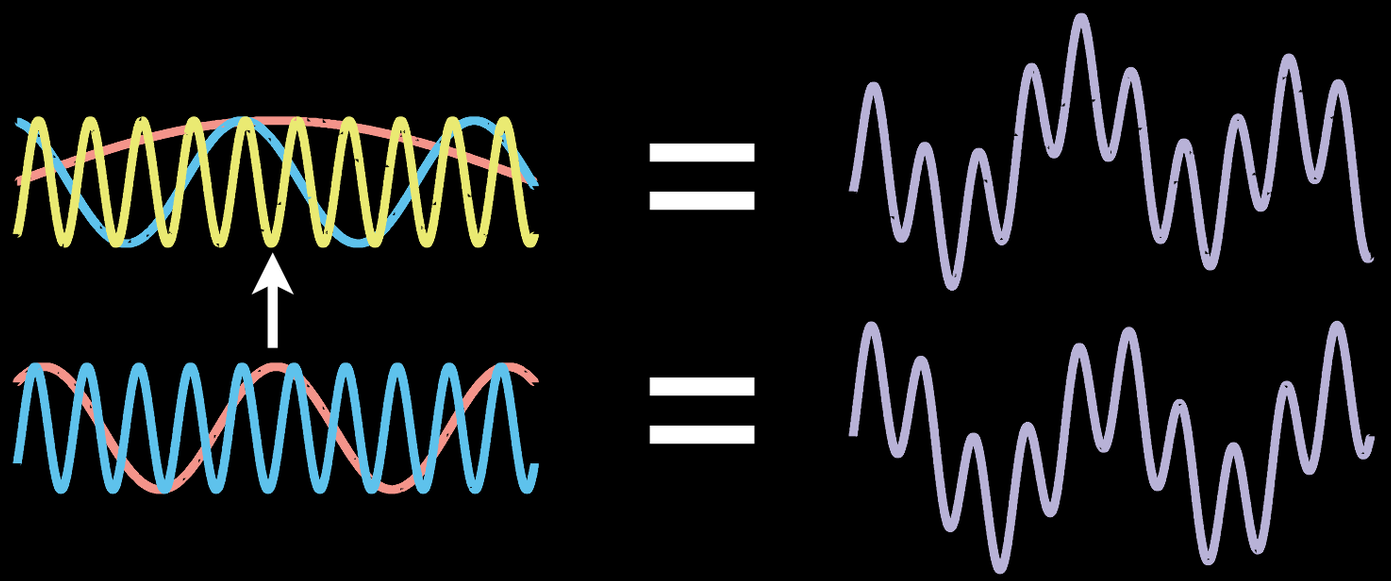


- During inflation, quantum fluctuations are stretched outside the horizon and are frozen.



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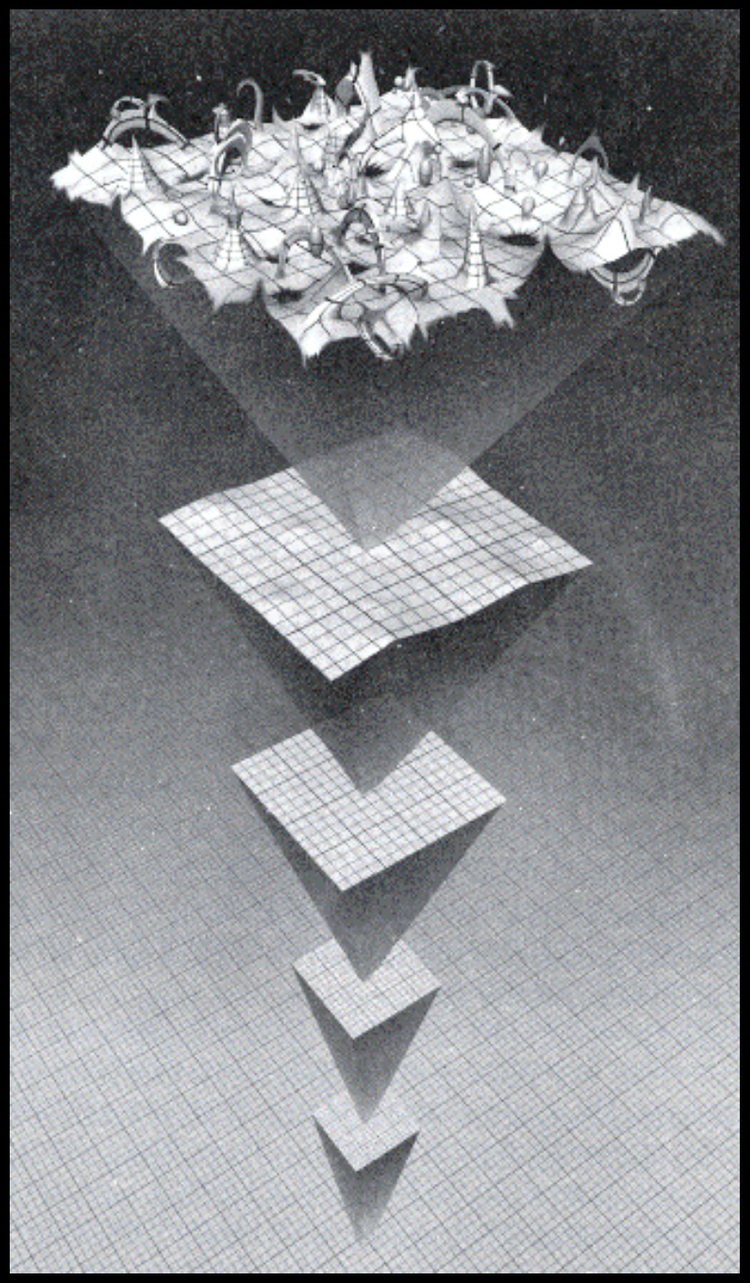

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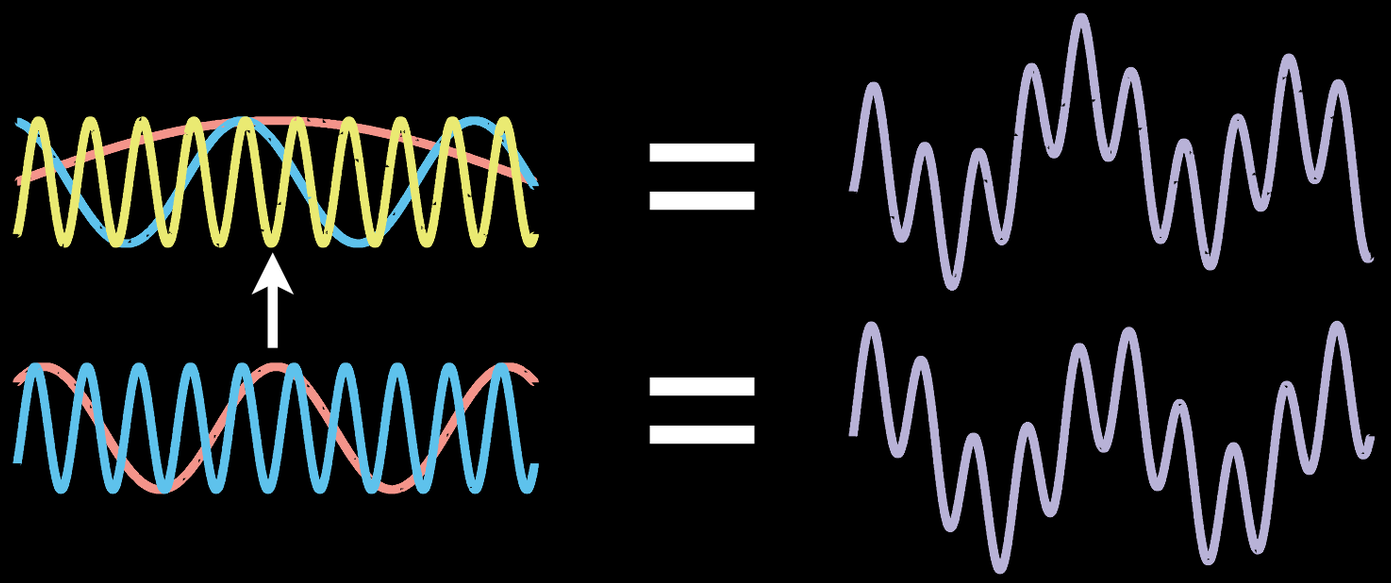


Inflation produces the same ripple height on all wavelengths!

Gravitational waves from inflation

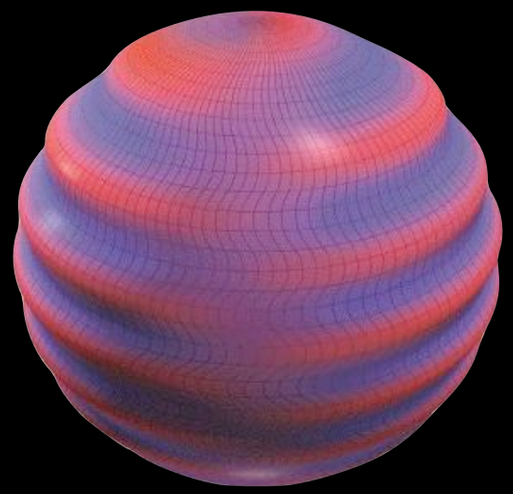
What is the energy scale?

These gravitational waves leave a special imprint on the CMB

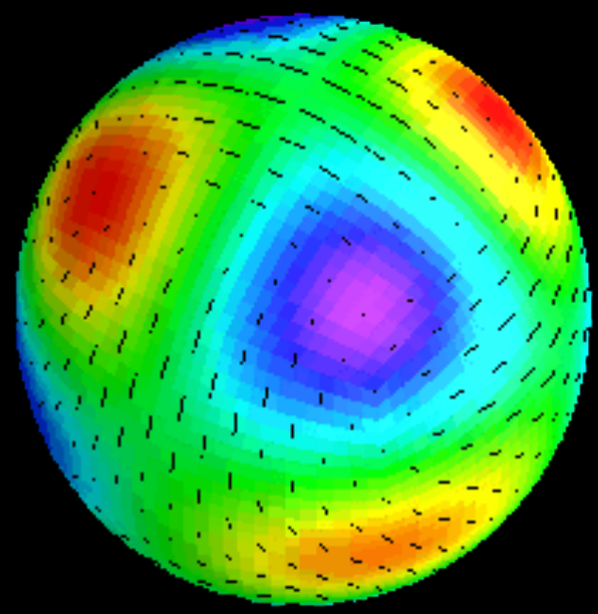
Gravitational waves from inflation

What is the energy scale?

During inflation, spacetime itself has fluctuations



These gravitational waves leave a special imprint on the CMB



Gravitational waves from inflation

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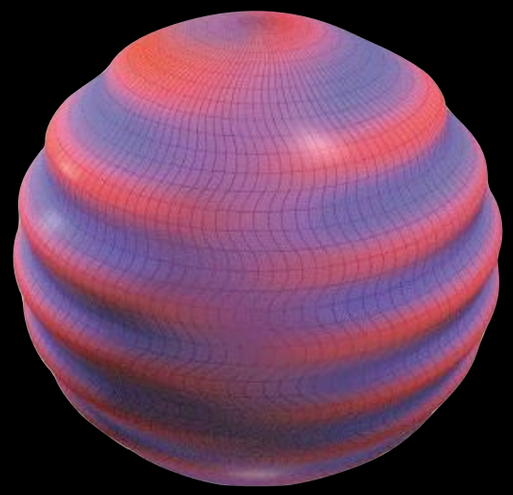

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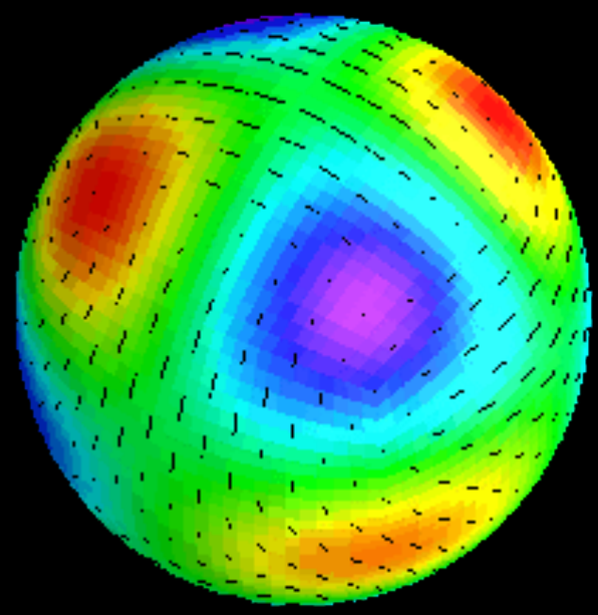


The search is on!

Compare to puny accelerators

$$E \sim 1000 \text{ protons } c^2$$

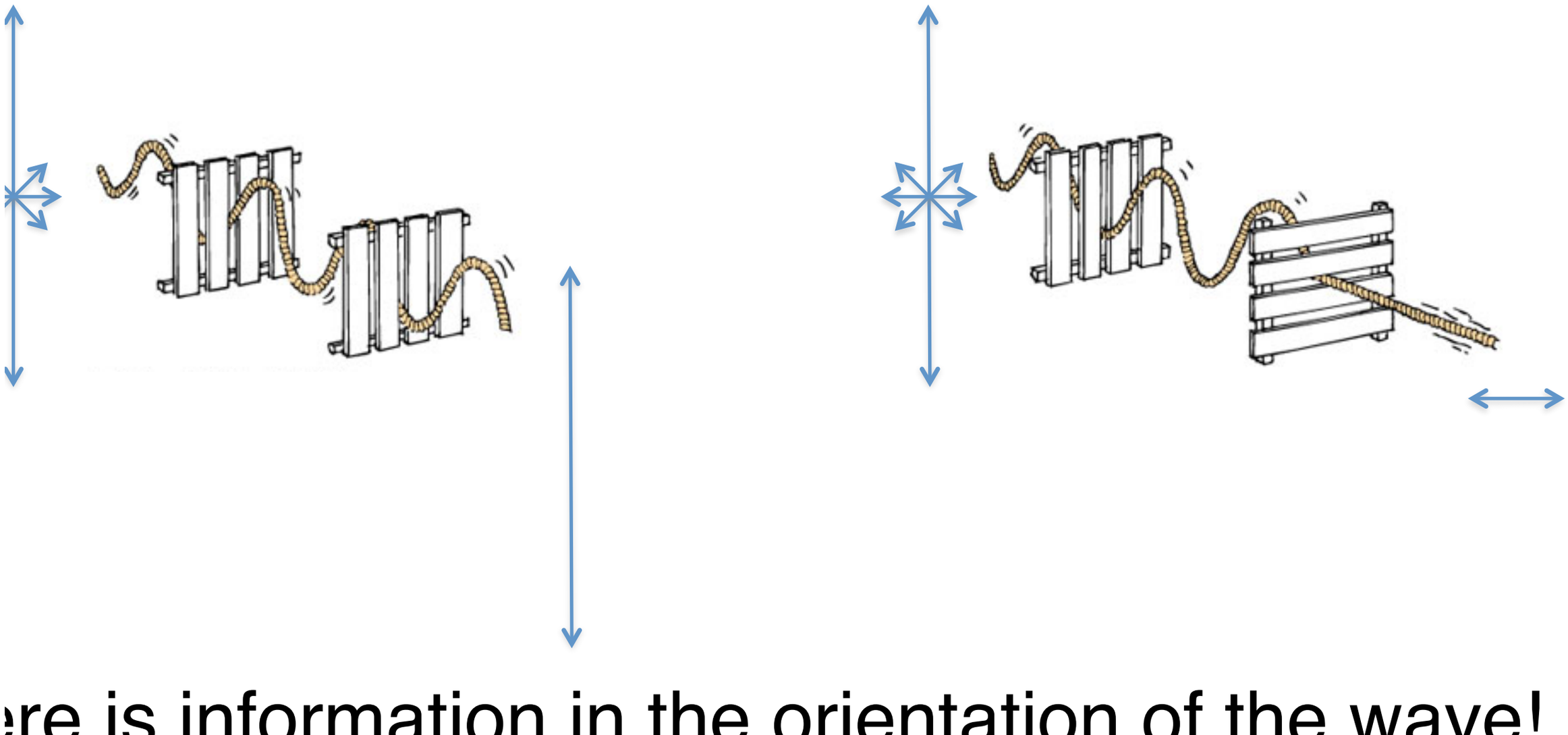
Large hadron collider

Remaining challenges

- Understand dark matter
- Understand dark energy
- Understand scale of universe at inflation

CMB is polarized

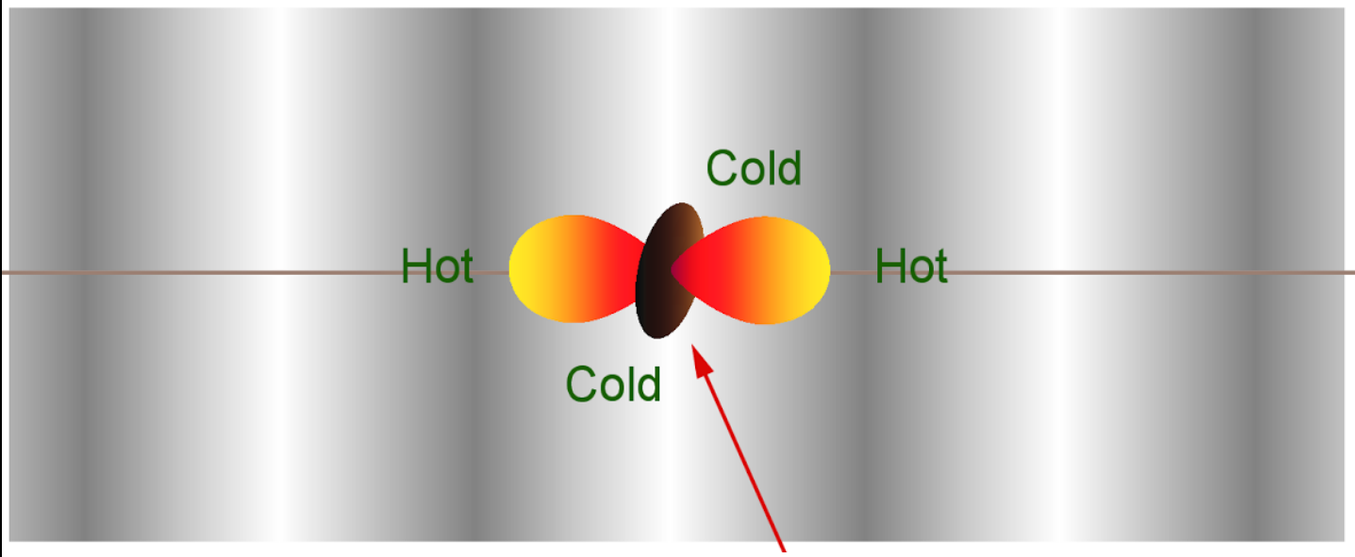
Light is a *wave*



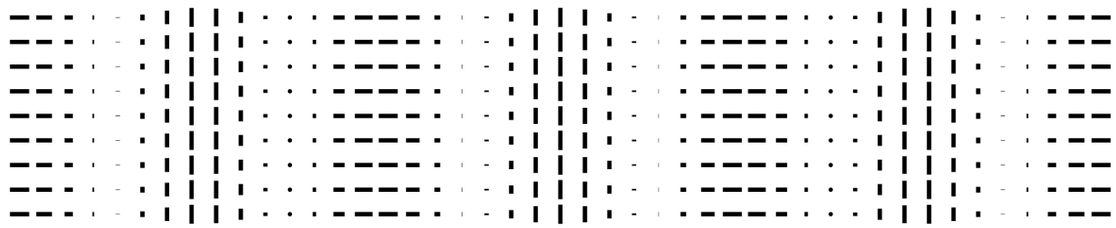
ere is information in the orientation of the wave!

Gravitational waves squeeze cosmic microwaves

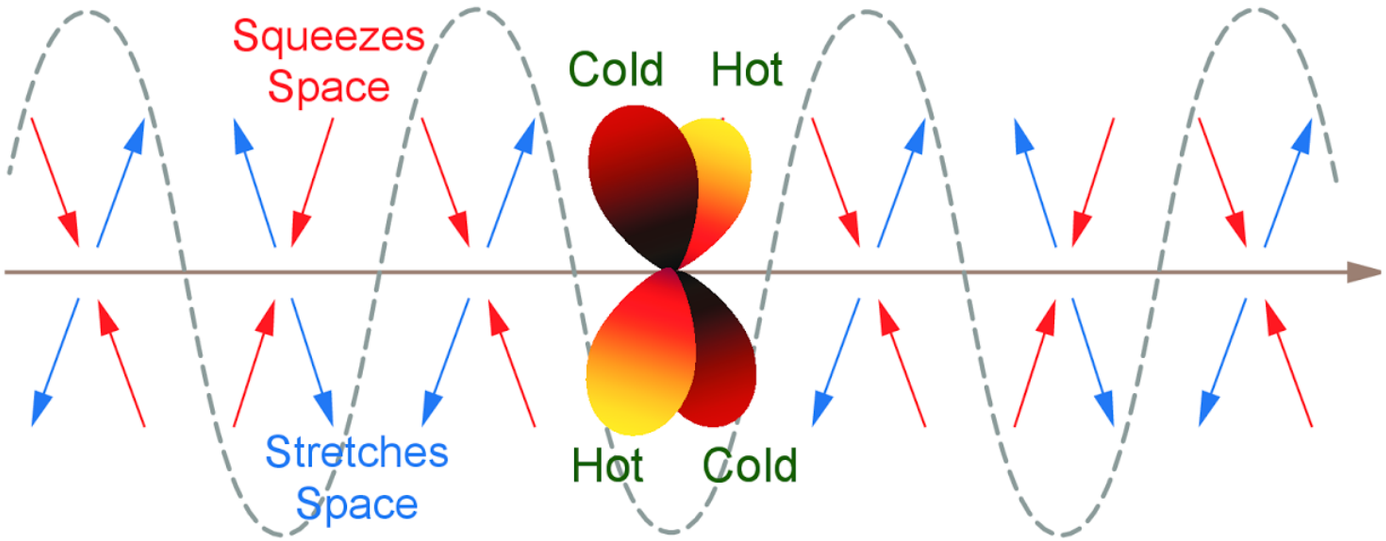
Sound Wave



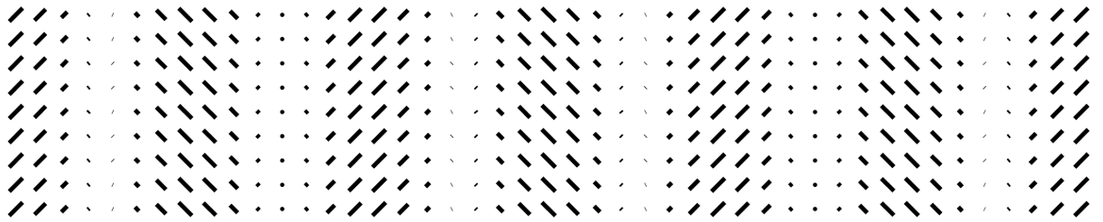
non-swirly

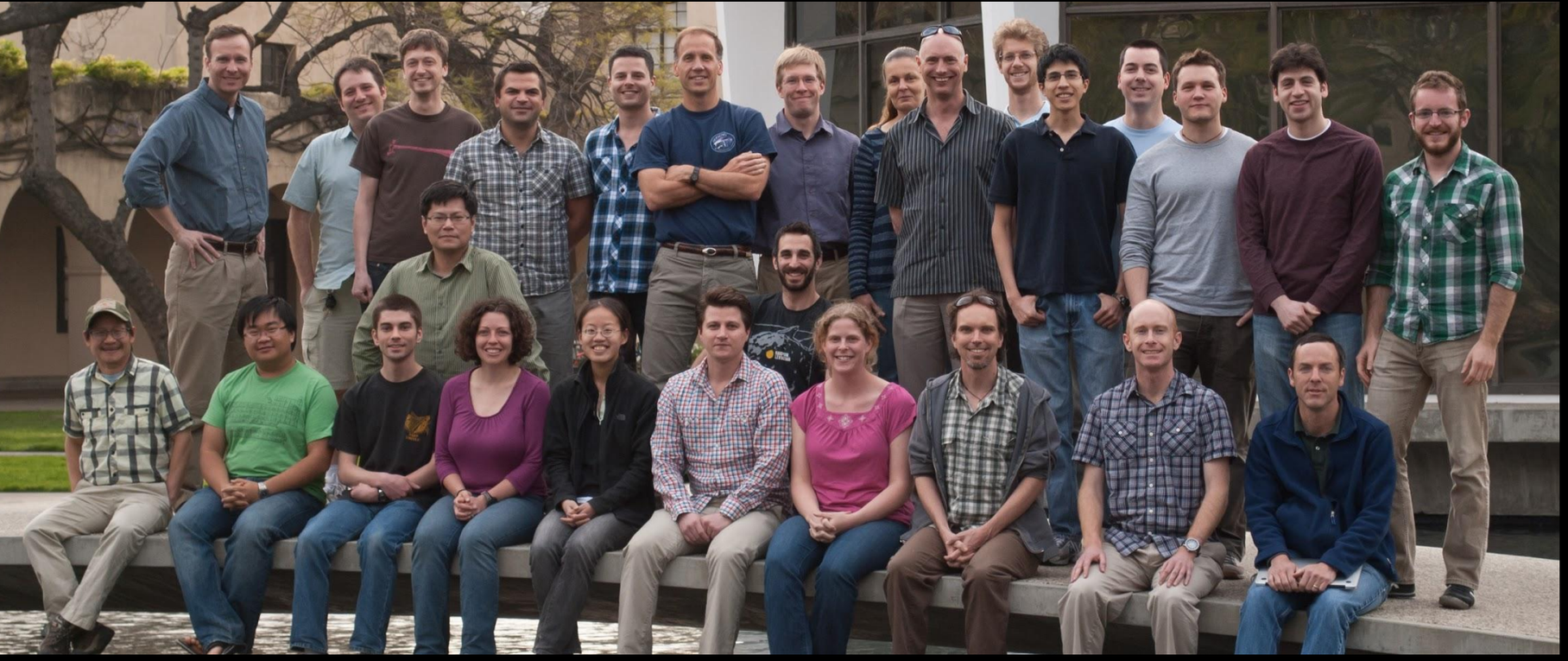


Gravitational wave



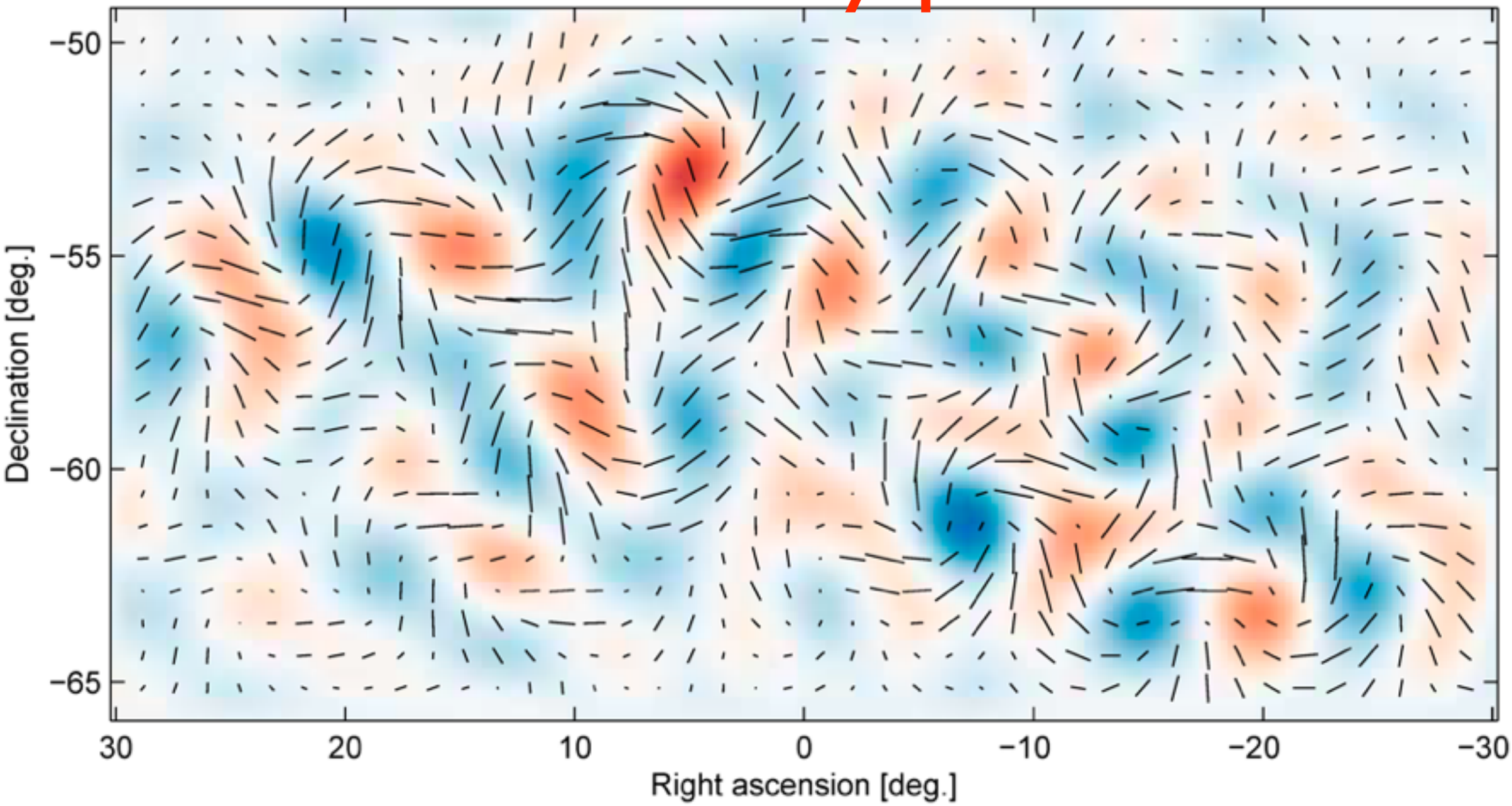
Swirly





BICEP2

Results: swirly patterns!



$$E \sim mc^2$$

$$E \sim 10000 \times \text{billion protons } c^2$$

The New York Times

West Steps Up Sanctions on Russia After Crimea Vote

By PETER BAKER 11:14 AM ET

"We're making it clear there are consequences for these actions," President Obama said in announcing sanctions on those deemed to be responsible for the seizing of Crimea.

Crimean Lawmakers Move Swiftly to Split From Ukraine

By DAVID M. HERSZENHORN and ALAN COWELL 9:17 AM ET

The Crimean Parliament declared its independence from Ukraine and formally asked to join Russia, and while Moscow embraced the result of Sunday's vote, the Kremlin has not declared its intent to annex Crimea.

260 Comments

TimesMinute

Steffen Richter/Associated Press

Ripples in Space-Time Support Big Bang

By DENNIS OVERBYE 10:46 AM ET

Astronomers found gravitational waves that buttress the theory of a universe wrenched violently apart around its inception. Above, the telescope used to detect the waves.

West's Drought and Growth Intensify Water Conflict

By MICHAEL WINES

The explosive growth of cities is raising the stakes for farmers and industry amid a series of fierce legal and political battles over water.

110 Comments

Low-Wage Workers Find Poverty Harder to Escape

By STEVEN GREENHOUSE

Climbing out of poverty has become more daunting as the work

The Opinion Pages

OP-ED CONTRIBUTOR

The Story of Bridie and Mo

By ROSEMARY MAHONEY

Two red-haired girls on the Dublin docks, at the end of an Irish boom.

- **Editorial: The Flute, the Flute Is Calling**

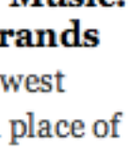
MORE IN OPINION

- **Op-Ed: The Ugandan Tabloid That Stole Our Pride**
- **Bittner: Is Crimea the Next Yugoslavia?**

THE GREAT DIVIDE

On the Wrong Side of Globalization

By JOSEPH E. STIGLITZ



Trade agreements like the Trans-Pacific Partnership would make our problems worse.

- **Editorial: A Hard Turn for De Blasio | Charter Schools**
- **Krugman: That Old-Time Whistle**
- **Taking Note: Metro-North Review**

MARKETS » At 1:05 PM ET

S.&P. 500	Dow	Nasdaq
1,859.38	16,247.12	4,292.29
+18.25	+181.45	+46.89
+0.99%	+1.13%	+1.10%

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MEDIA »

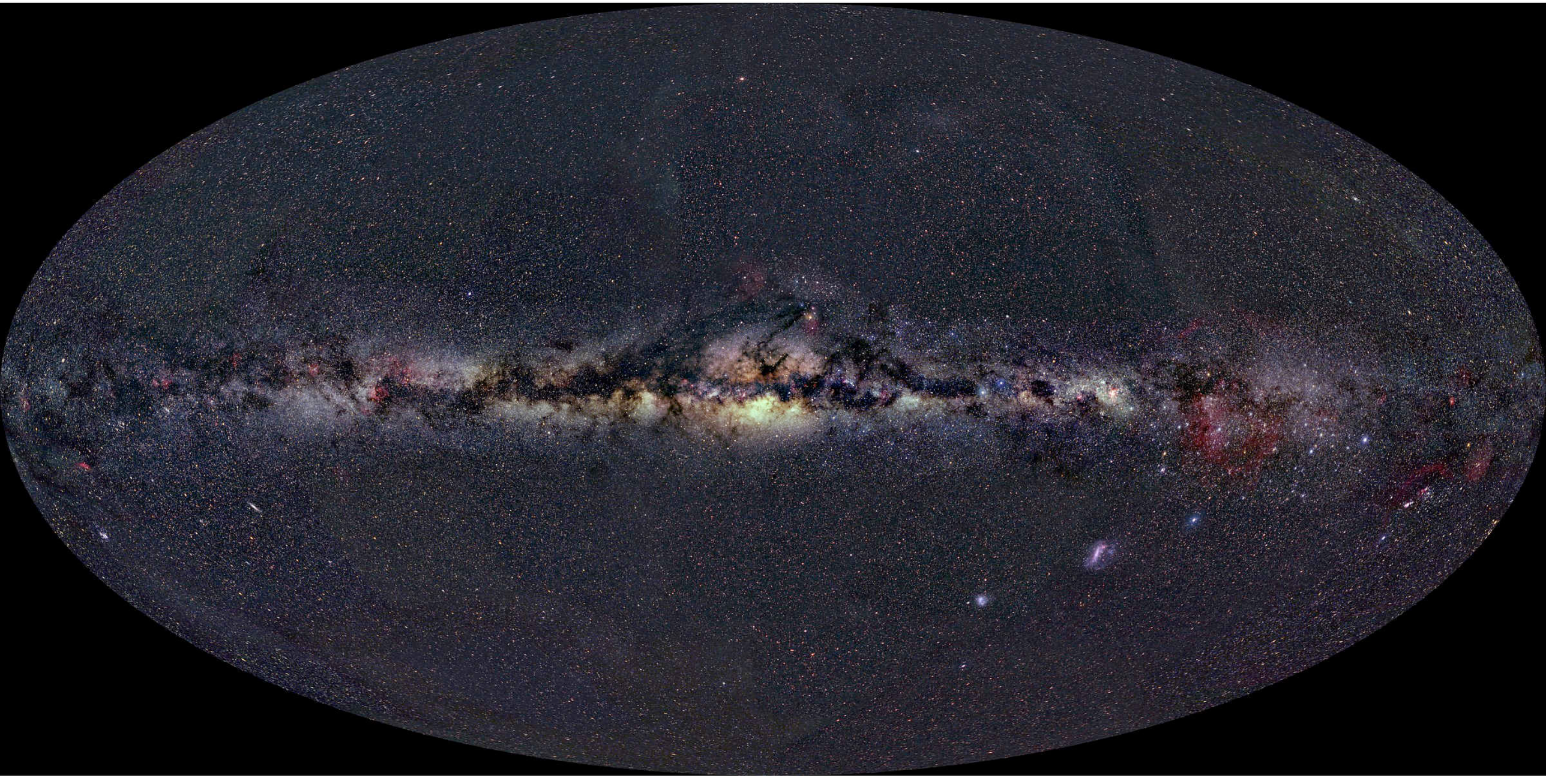
Marlo Thomas Carves a Niche on Internet TV

"Mondays With Marlo," a talk show hosted by Marlo Thomas, the actress and

A New Model for Music: Big Bands, Big Brands

At the South by Southwest festival, historically a place of artistic idiosyncrasy, music labels were an afterthought and corporate logos were

Dust in our own Galaxy also produces polarized microwaves:



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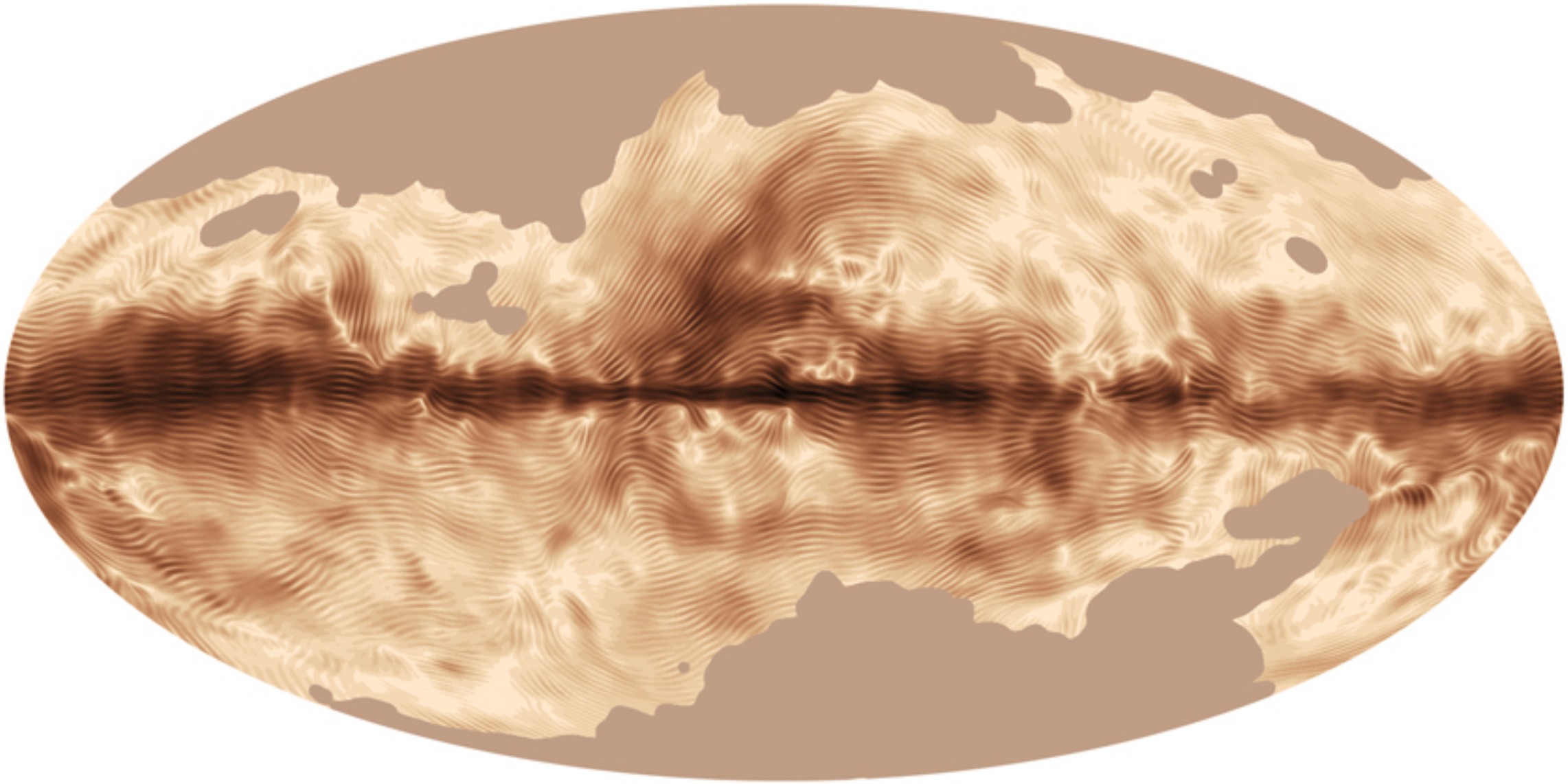

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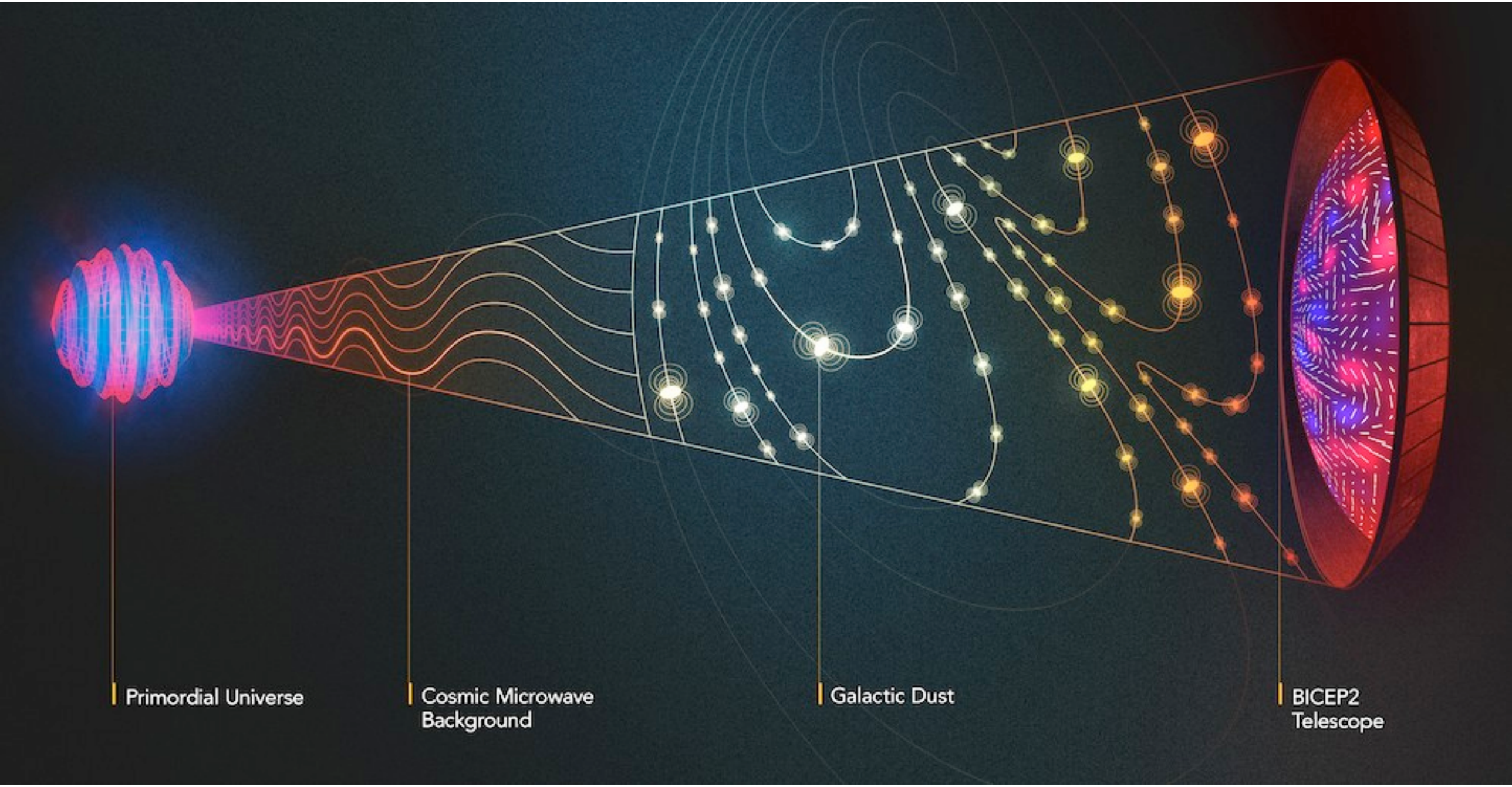

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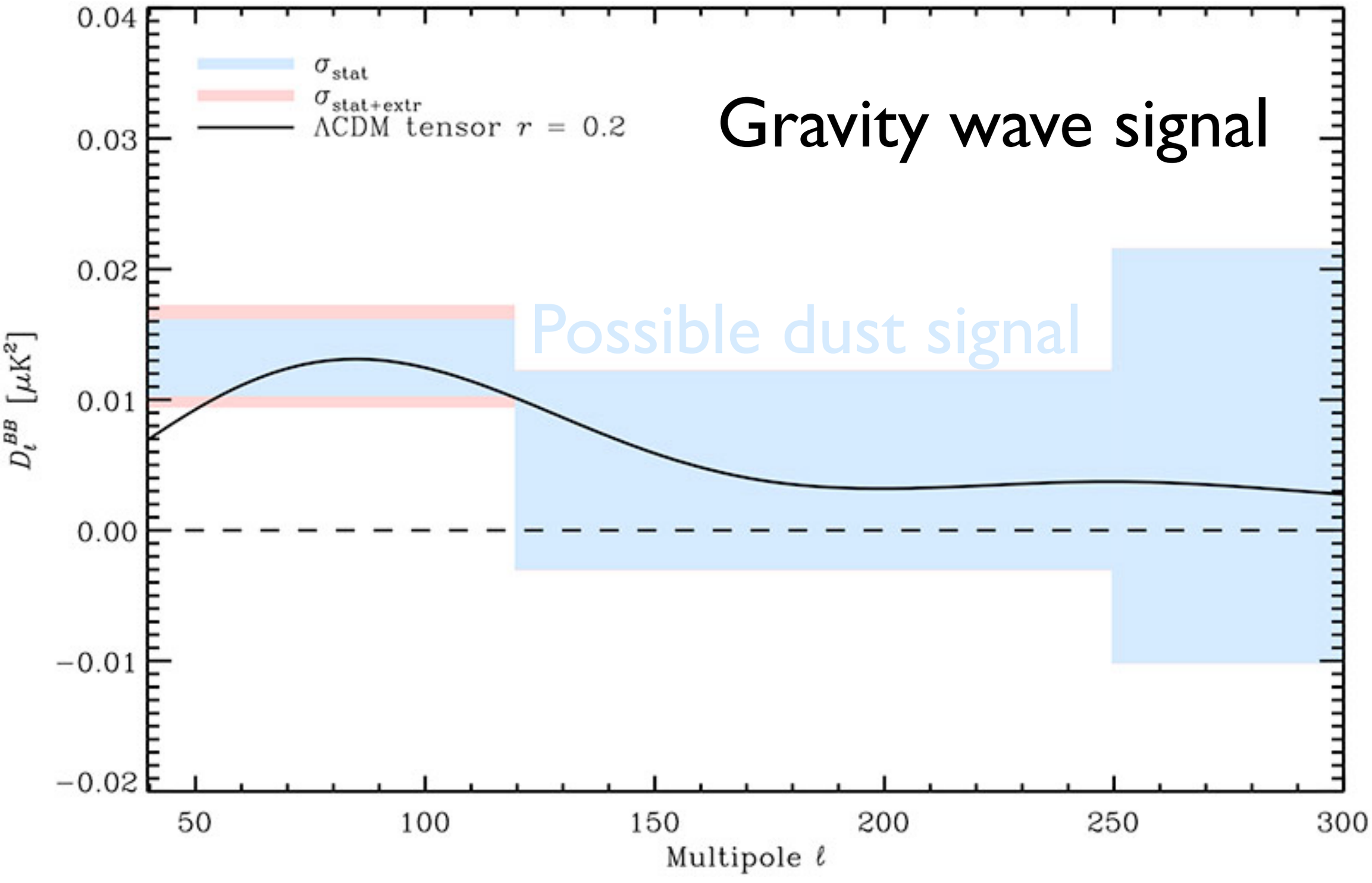
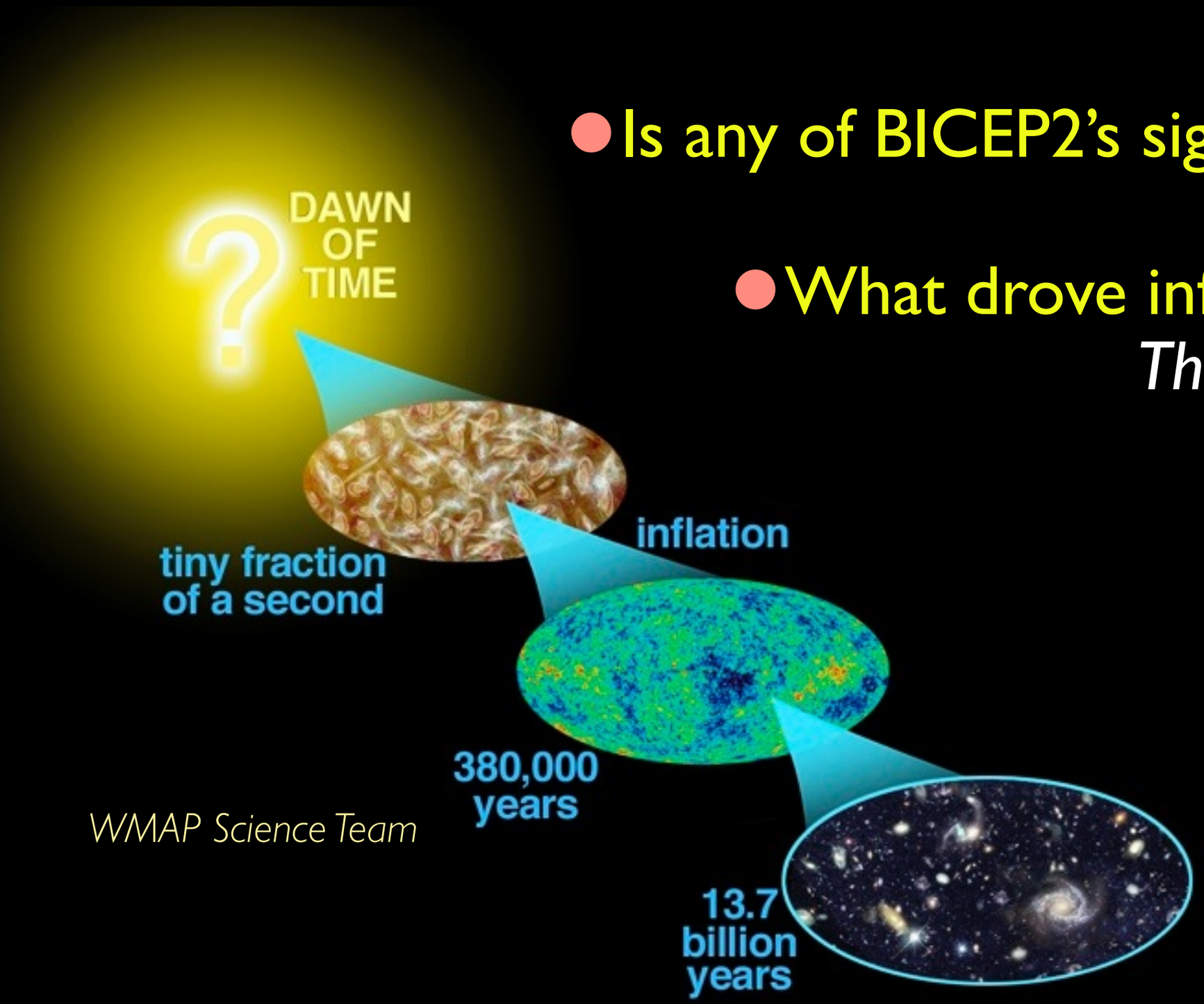


Unanswered Questions

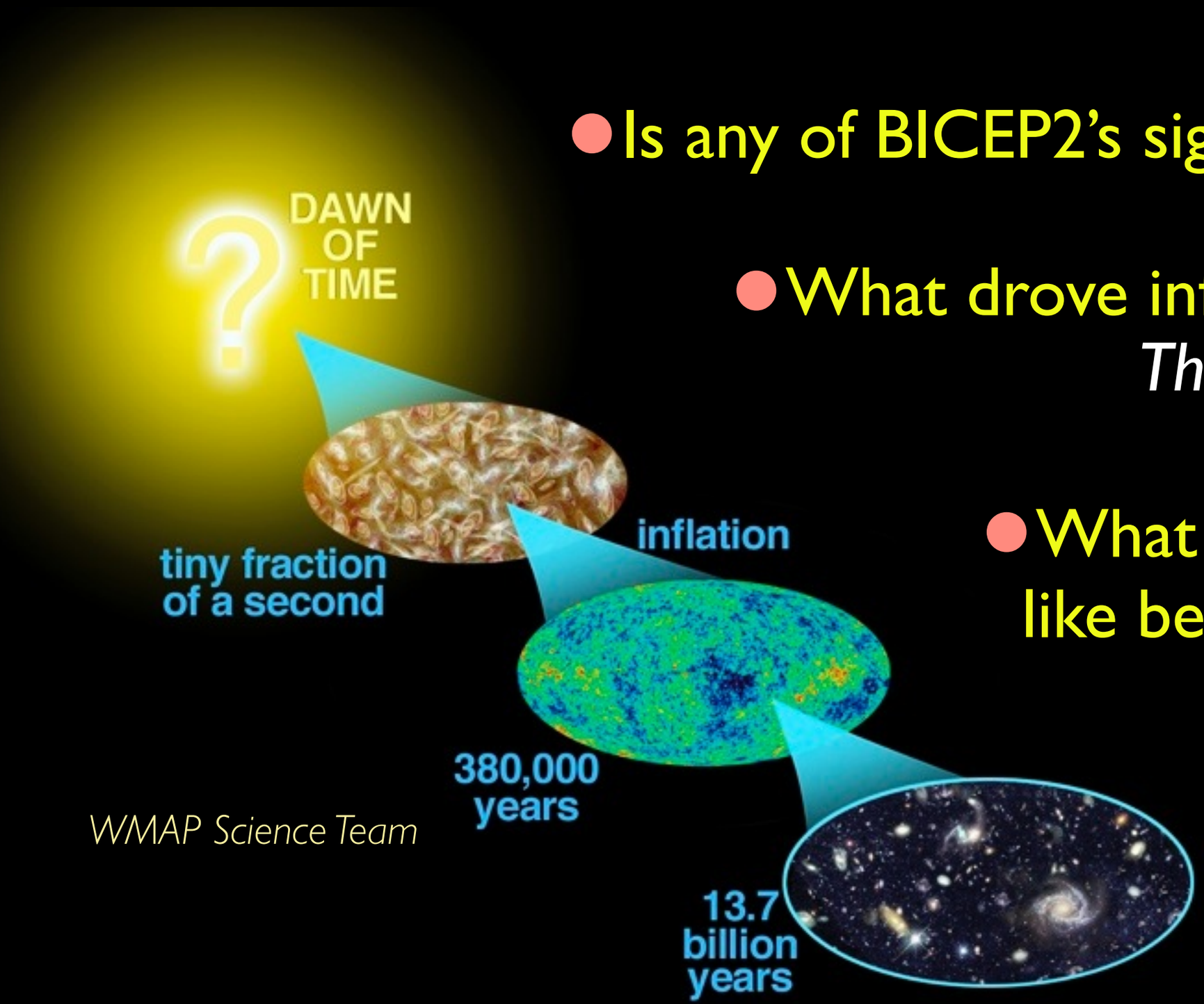


WMAP Science Team

- Is any of BICEP2's signal primordial?
- What drove inflation?

  The inflaton...
- How did inflation start?

Unanswered Questions



- Is any of BICEP2's signal primordial?
- What drove inflation?
  The inflaton...
- What was the Universe like before inflation?

?

- How did inflation start?