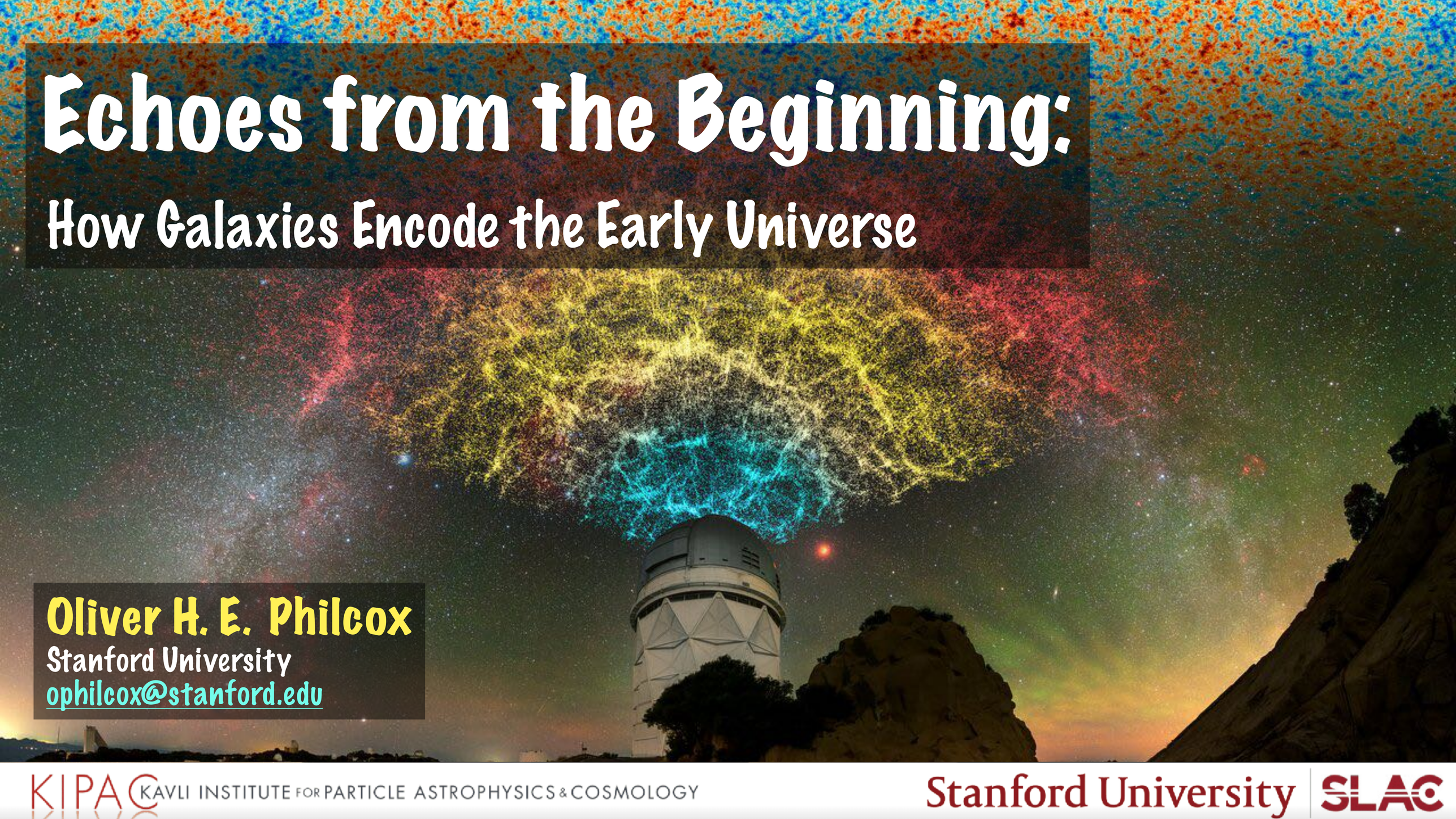
Echoes from the Beginning:

How Galaxies Encode the Early Universe



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KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Stanford University | SLAC


1964, New Jersey
Bell Telephone Labs
New York Times

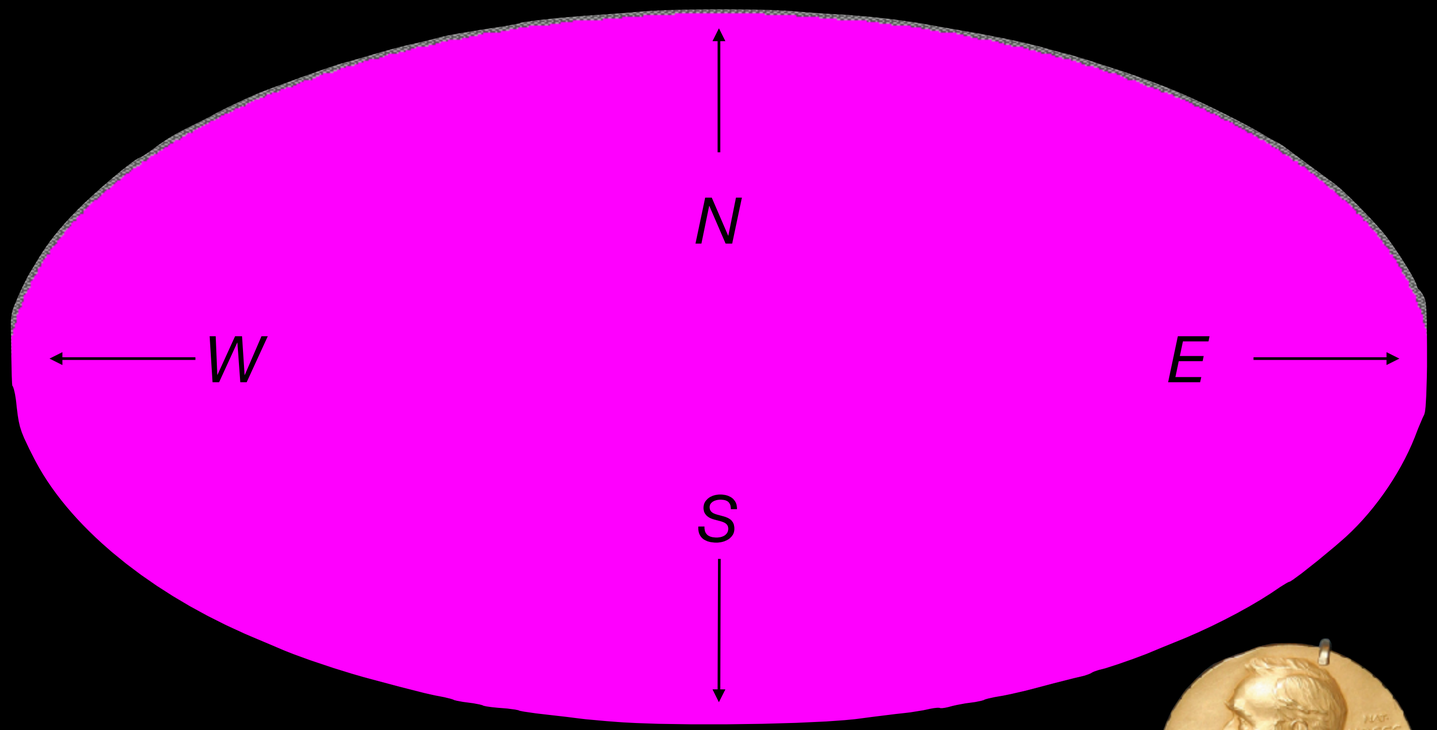
A cosmic mystery

In 1964, Arno Penzias & Robert Wilson found a **glow** of radio waves from all directions

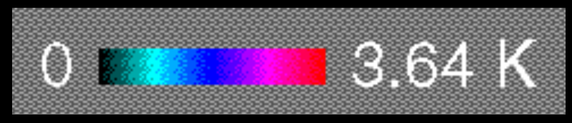
Wavelength: 3 inches (7 cm)

Equivalent **temperature**: 2.7 Kelvin

($\approx -455^{\circ}\mathrm{F}$)



This is the **Cosmic Microwave Background (CMB)**



Nobel Prize, 1978

COBE DMR

A brief history of the Universe

Today

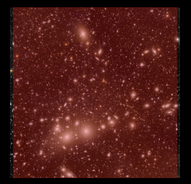
Age: 14 billion years

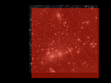
Size: 46 billion light-years

Euclid

A brief history of the Universe

Today → *14 bilion years ago*





Age: 14 billion years

Size: 46 billion light-years

Age: 6 billion years

Size: 23 billion light-years

Age: 2 billion years

Size: 12 billion light-years

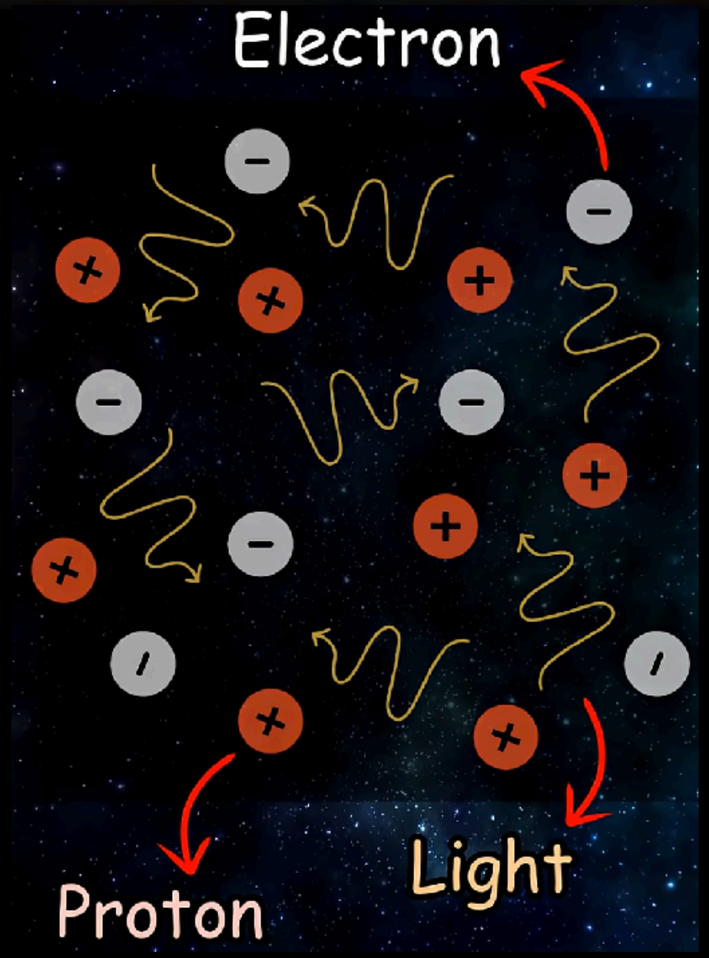
Age: 700 million years

Size: 6 billion light-years

Looking back in time, the Universe gets **hotter** and **denser**

Euclid

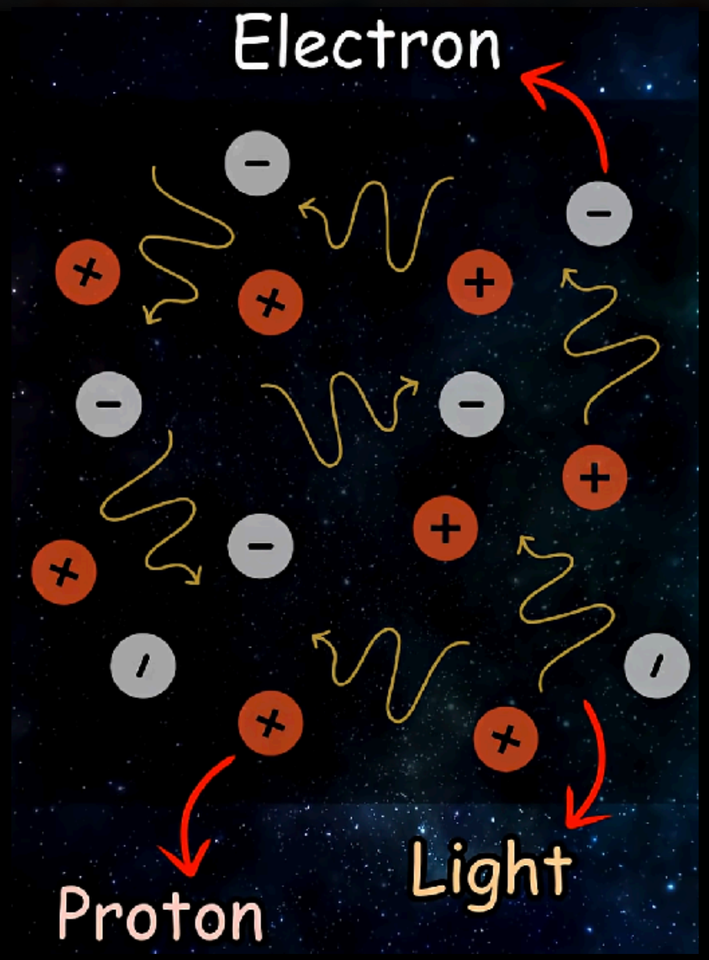
The early Universe was a particle soup...



Age: < 380,000 years

$T > 3000\text{K}\ (5000^{\circ}\text{F})$

...until it wasn't



Age: < 380,000 years

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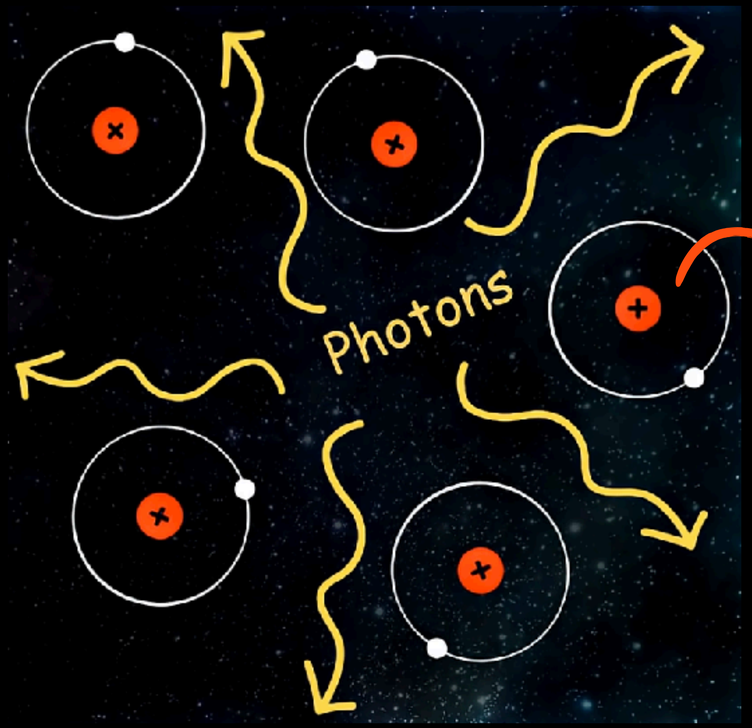
$$p^+ + e^- \rightarrow H + \gamma$$

RECOMBINATION!

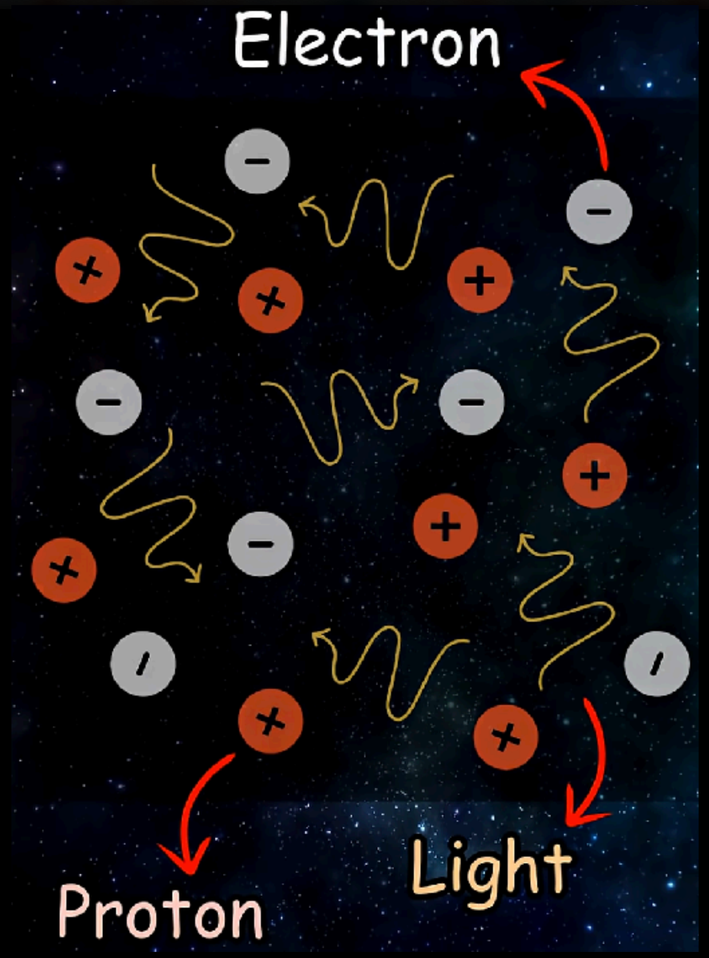


Age: > 380,000 years

$T < 3000\text{K}\ (5000^\circ\text{F})$

TronicXD

The CMB is photons from the early Universe



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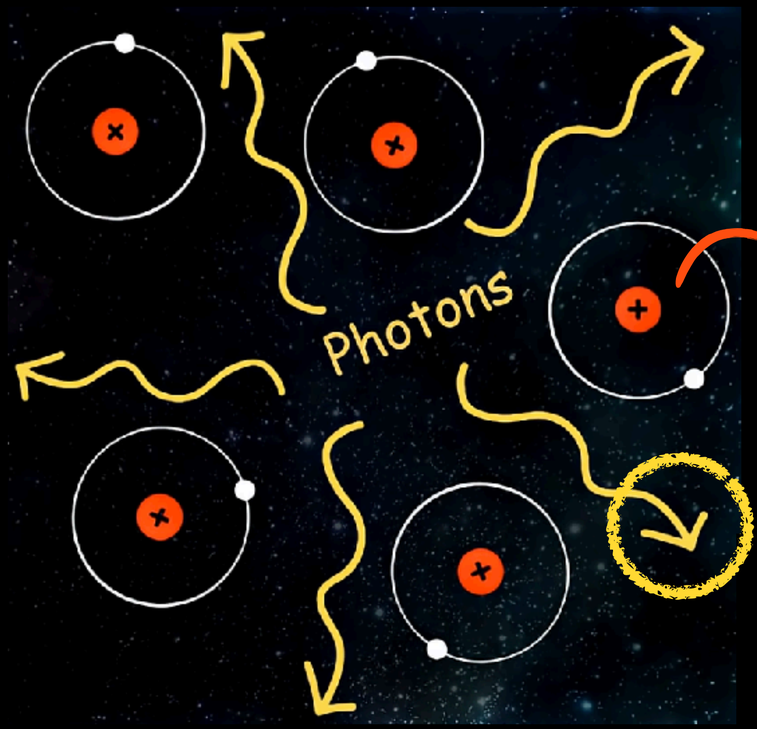


These form the CMB!

Age: < 380,000 years

$T > 3000\text{K}$ (5000°F)

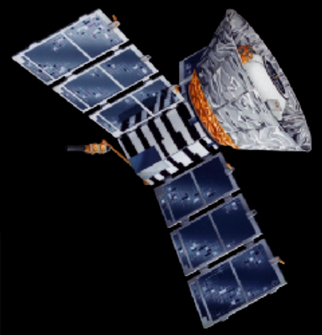
Age: > 380,000 years

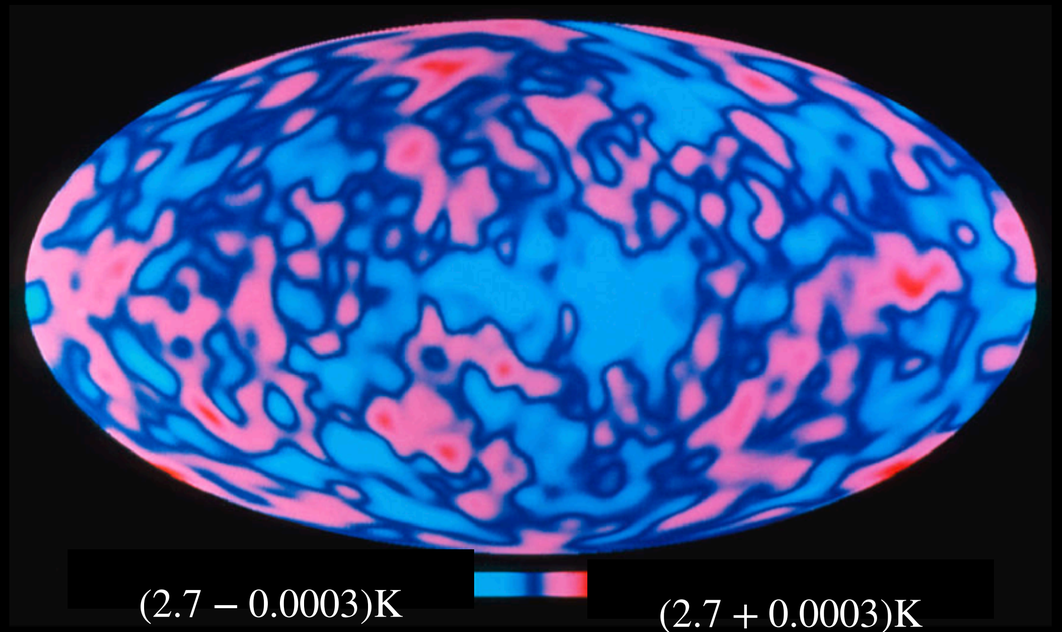
$T < 3000\text{K}$ (5000°F)

TronicXD

The COBE satellite confirmed the model

The Cosmic Background Explorer (COBE)

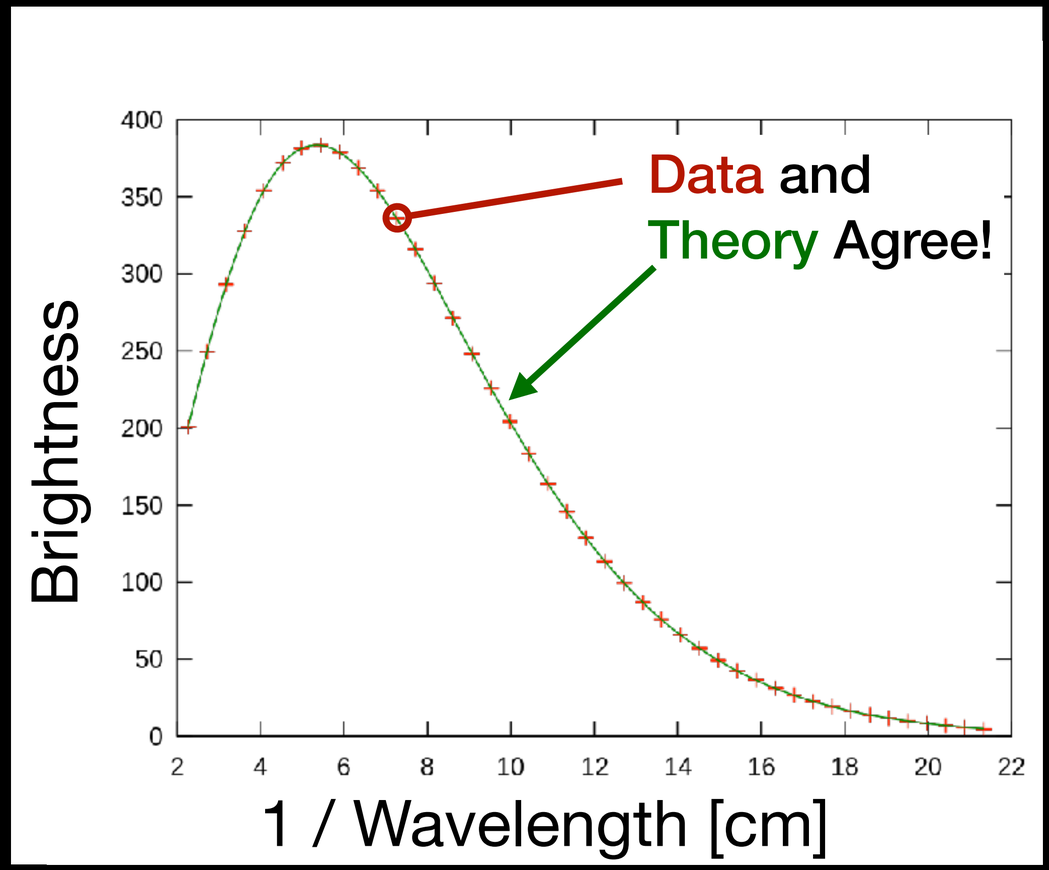




The CMB (c. 1990s)

COBE DMR

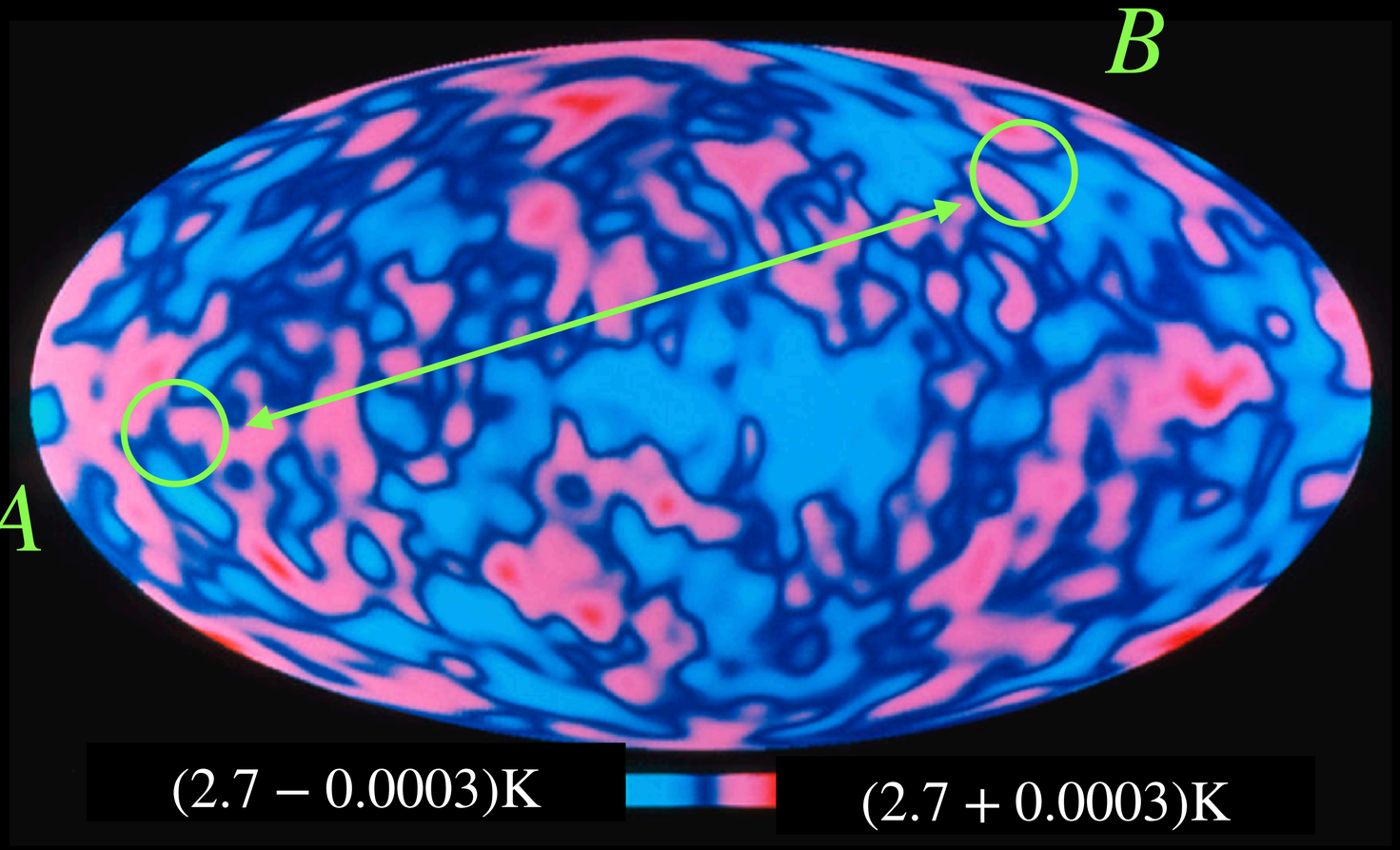
Nobel Prize, 2006



Frequency Spectrum

Why is the CMB so uniform?

The CMB (c. 1990s)



The temperature of the CMB is **extremely** similar across the sky

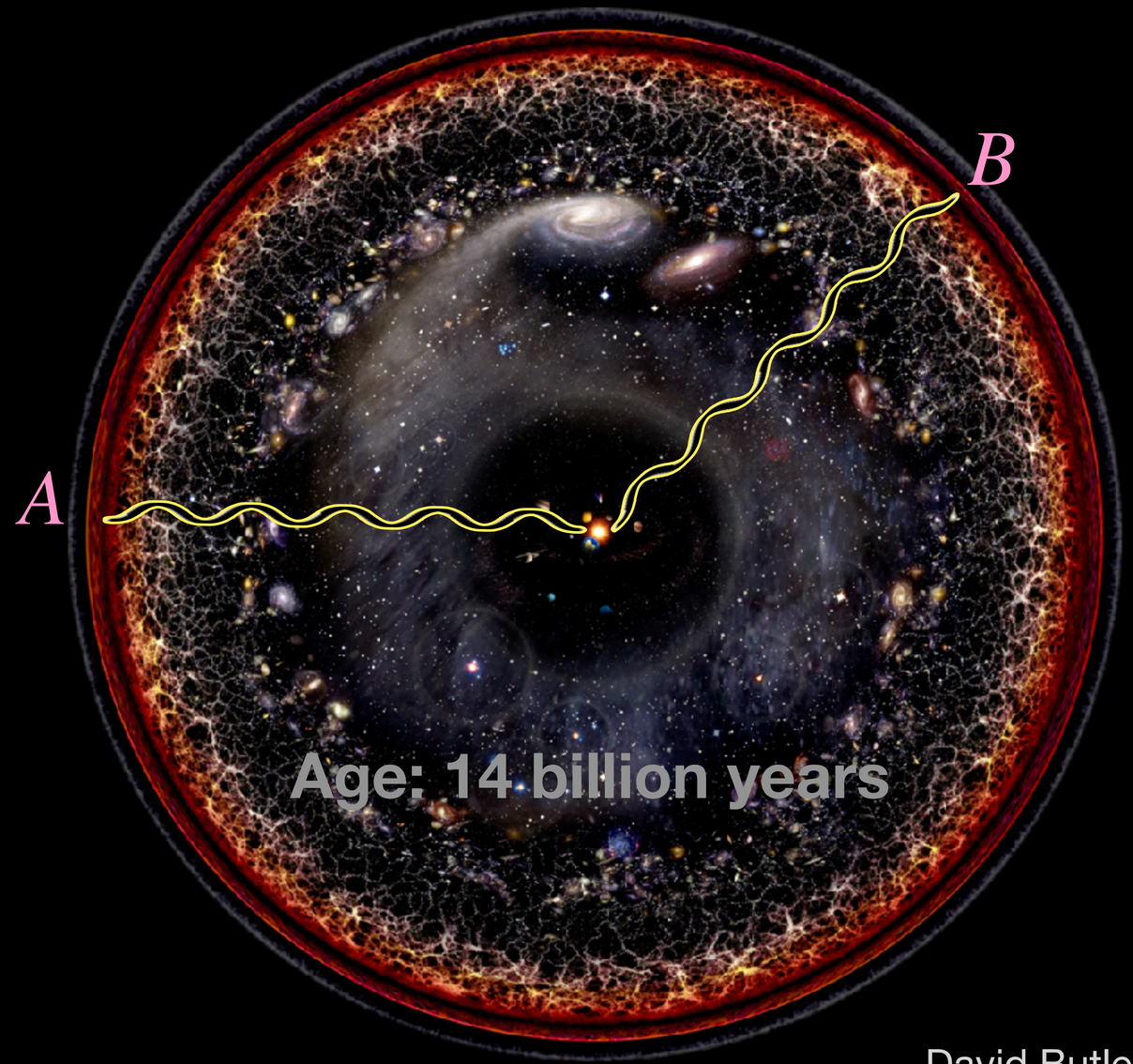
$$\frac{\Delta T}{T} \sim 10^{-5}$$

This is a surprising result!

COBE DMR

Why is the CMB so uniform?

Photons from A and B have travelled for **billions** of light-years to reach us today



David Butler

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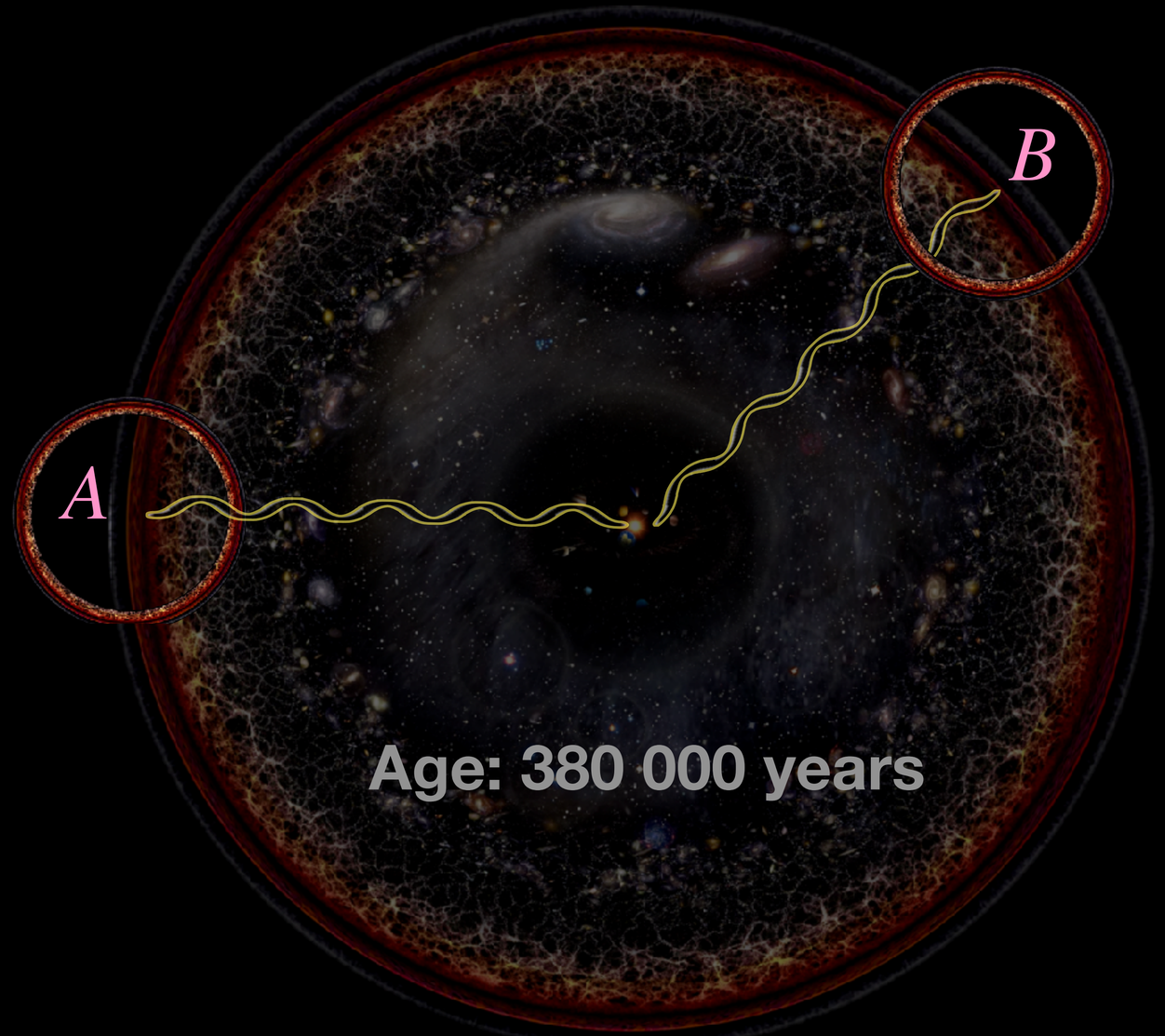
Photons from A and B have travelled for **billions** of light-years to reach us today

When they started out the Universe was **much** smaller



David Butler

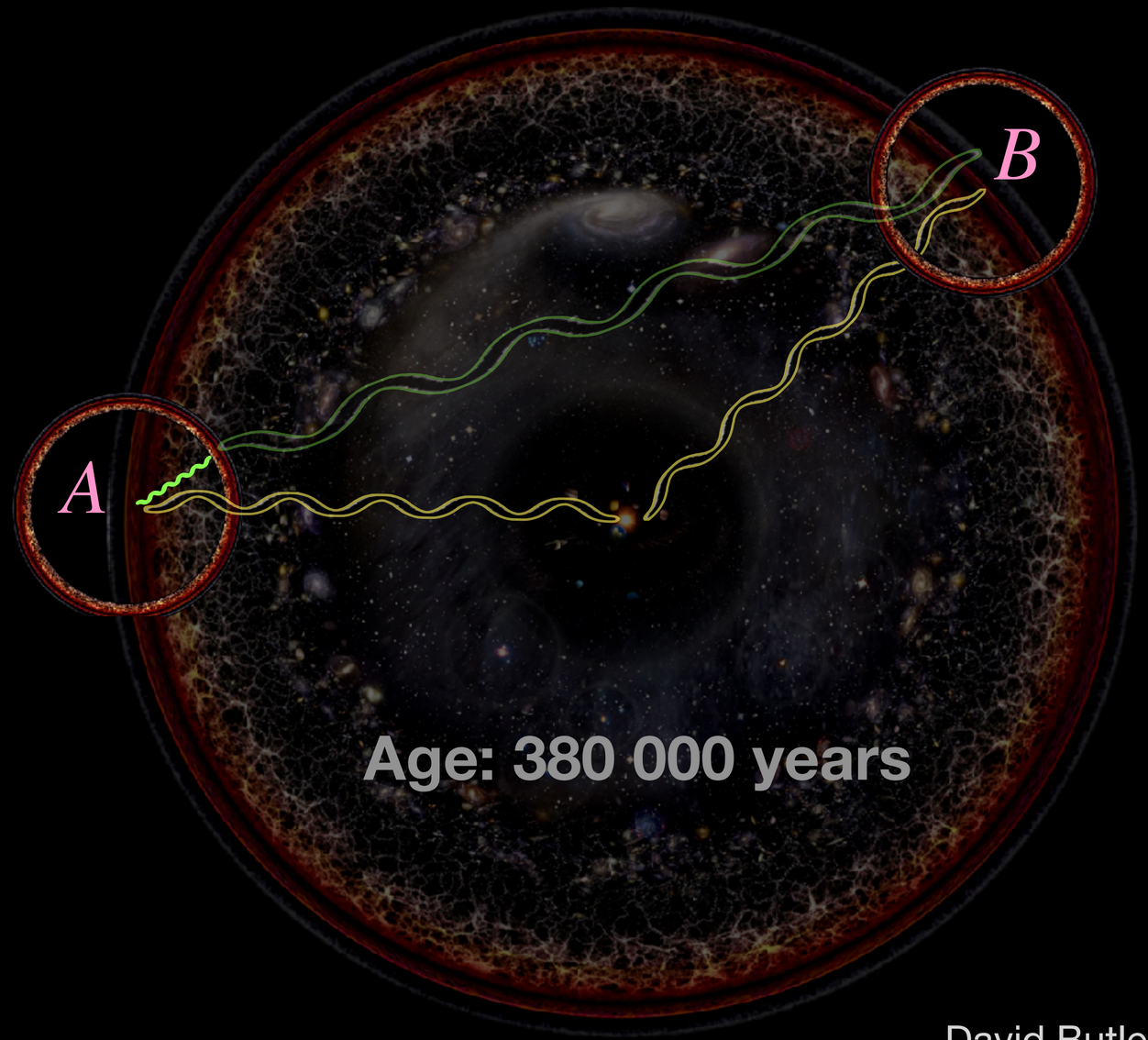
Why is the CMB so uniform?

Photons from A and B have travelled for **billions** of light-years to reach us today

When they started out the Universe was **much** smaller

There was **no way** to send information from A to B

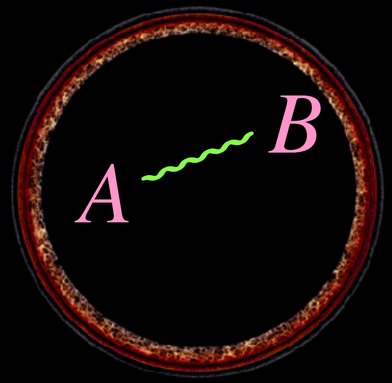
Why do they have the same temperature???



David Butler

Inflation explains the Universe's uniformity

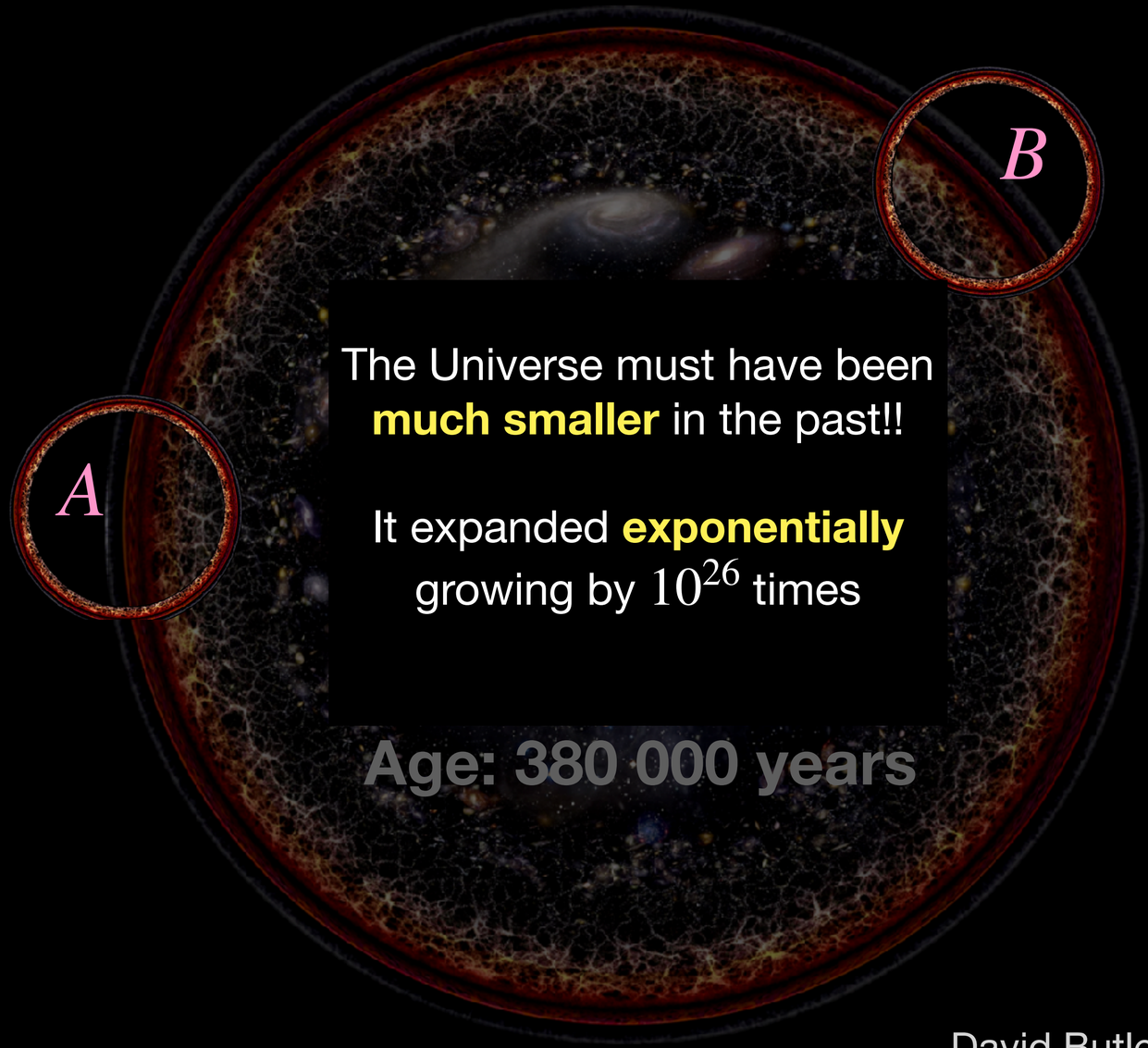
A and B are in contact initially!



INFLATION

INFLATION

Age: 10^{-35} seconds



The Universe must have been **much smaller** in the past!!

It expanded **exponentially** growing by 10^{26} times

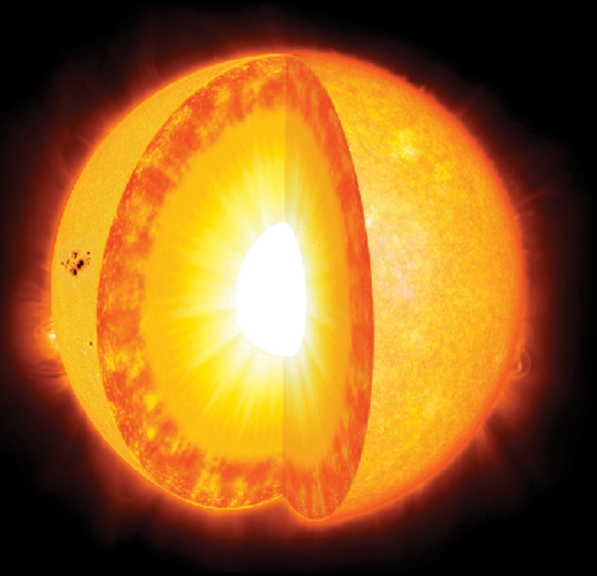
Age: 380 000 years

Andrei Linde (Stanford)

David Butler

In inflation, the Universe was hot and dense

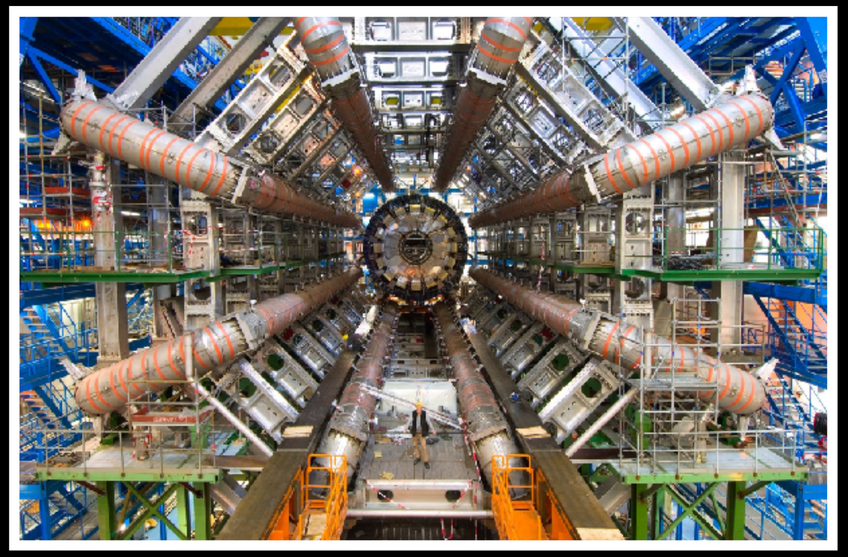
The Sun



15 million K

27 million ˚F

The Large Hadron Collider



1 billion billion K

2 billion billion ˚F

INFLATION

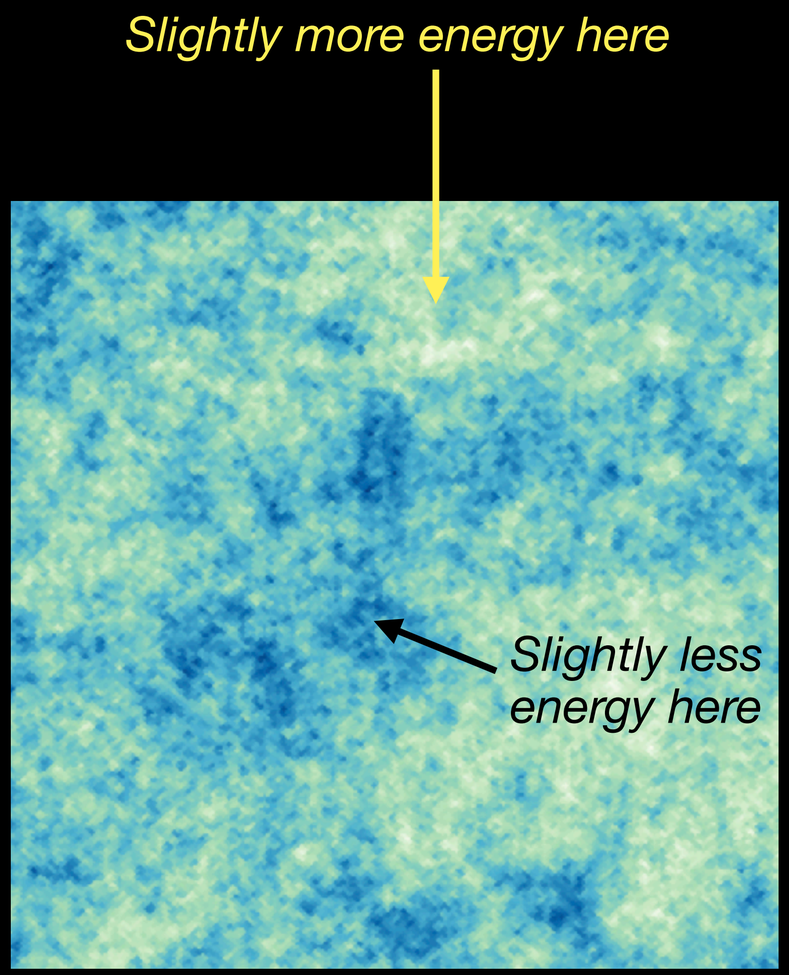
100 million billion billion K

200 million billion billion˚F

This is a ***quantum regime***

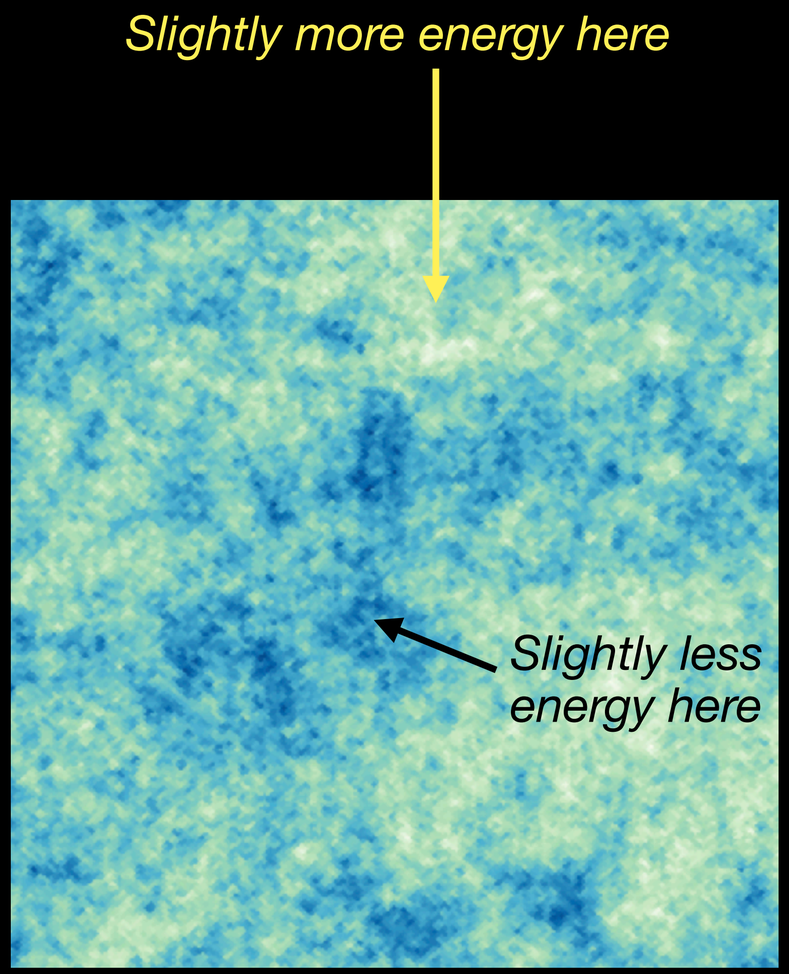
EOS, CERN, NASA/WMAP

Quantum fluctuations explain the Universe's structure



The Quantum Universe

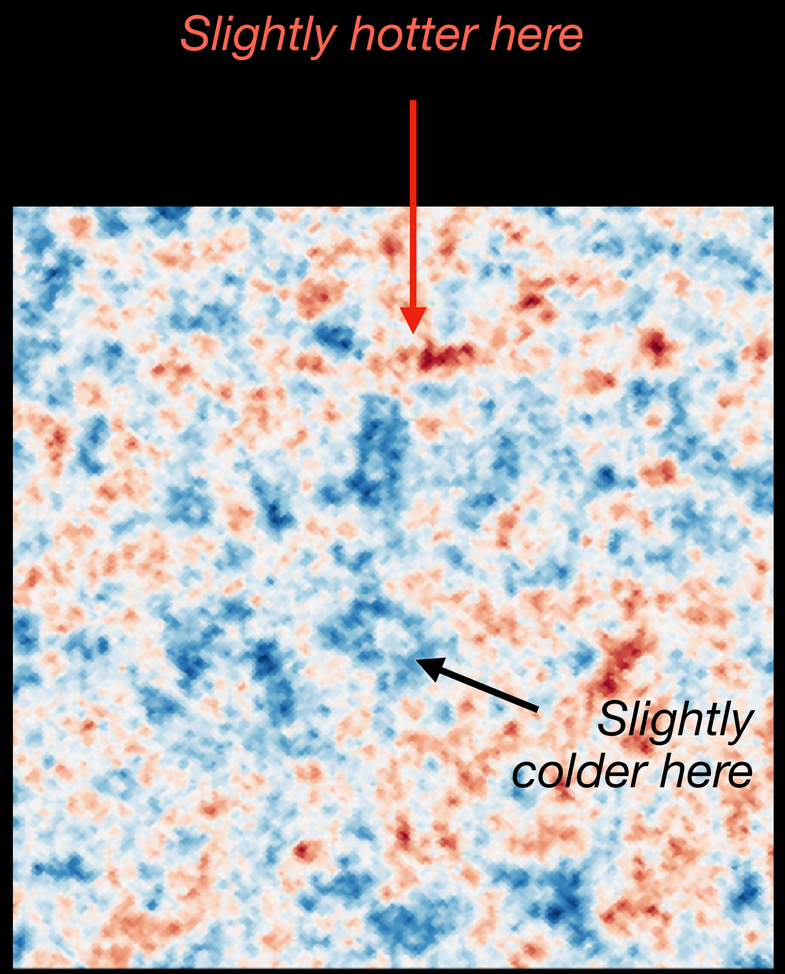
Quantum fluctuations explain the Universe's structure



The Quantum Universe

INFLATION

INFLATION

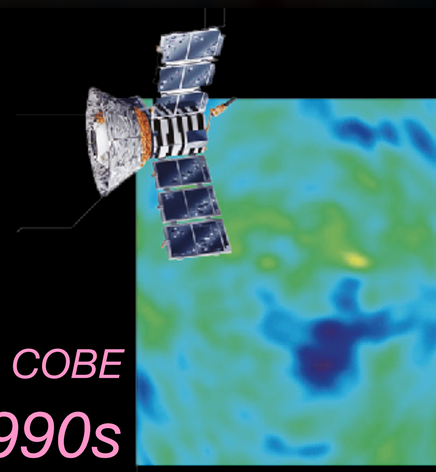


The CMB

Inflation matches the data

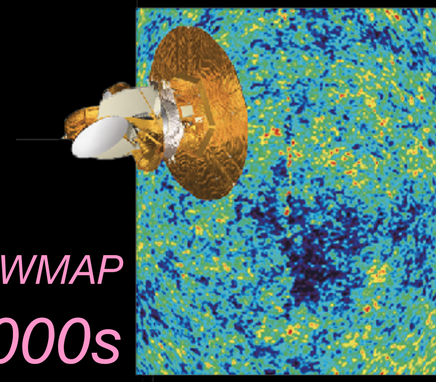
Just by knowing that inflation was a **quantum process**, we can **predict** the CMB fluctuations

$$T_{\mathrm{CMB}} = f[\text{Atomic Physics}] \times \text{Inflation}$$



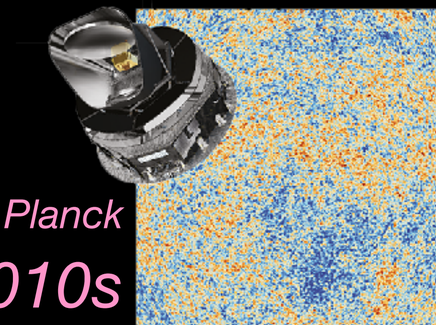
COBE

1990s



WMAP

2000s



Planck

2010s

BBC / COBE / WMAP / Planck

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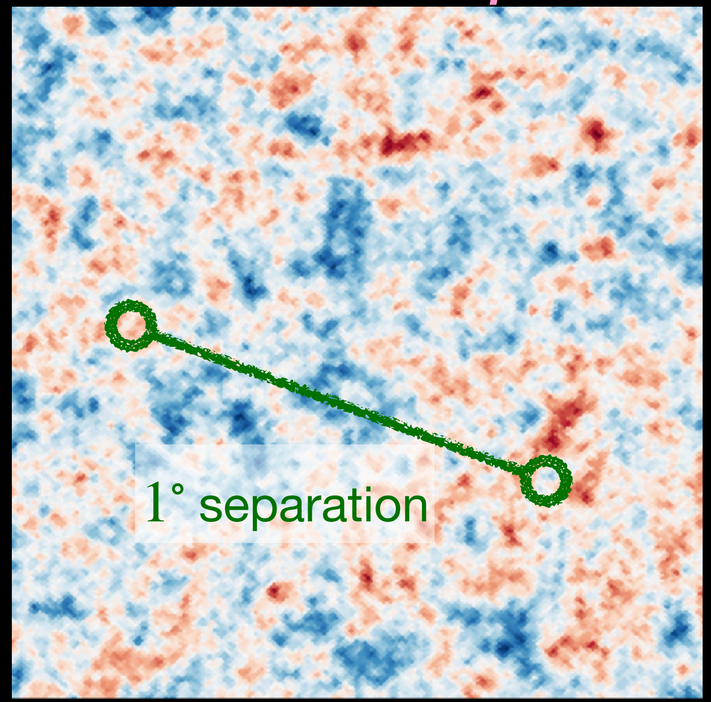
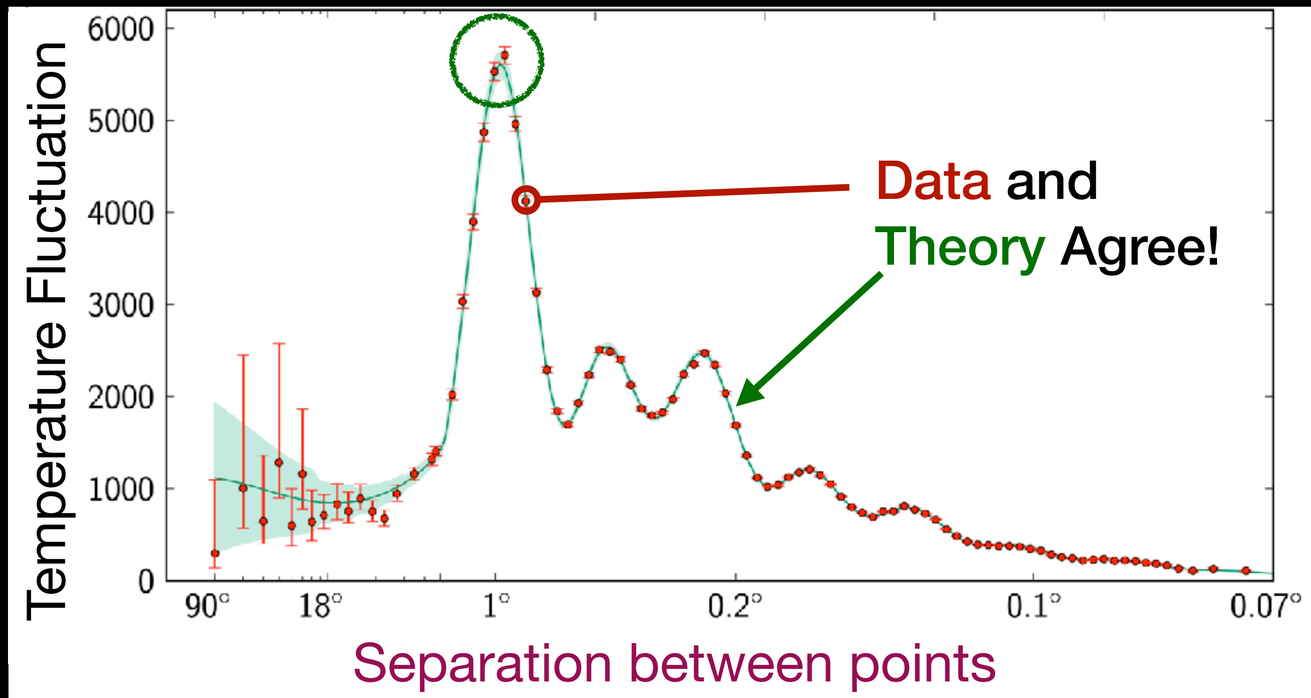
The CMB Map



Statistics of the CMB

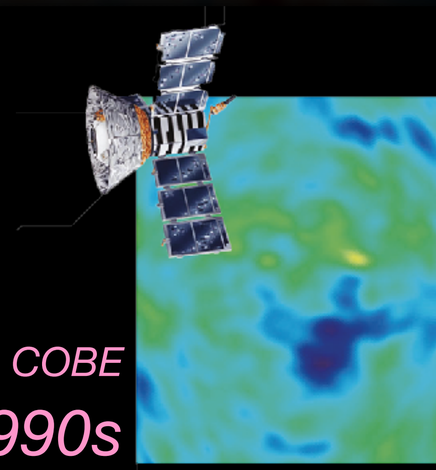


BBC / COBE / WMAP / Planck

Inflation has a lot of mysteries

Many models have been proposed to explain the early Universe

⇒ **Inflation fits the data the best!**



COBE

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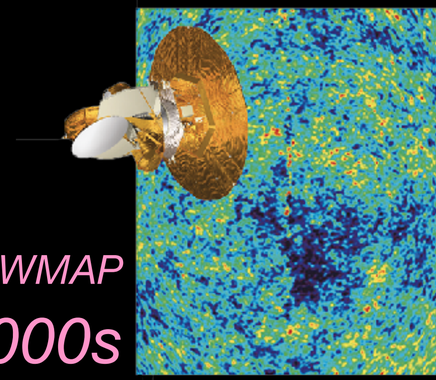
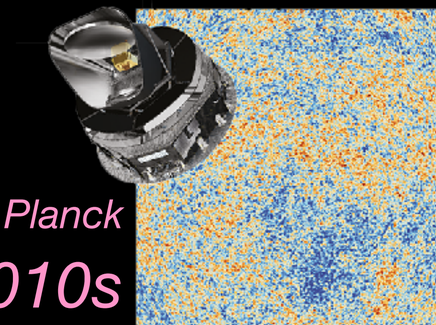


WMAP

2000s



Planck

2010s

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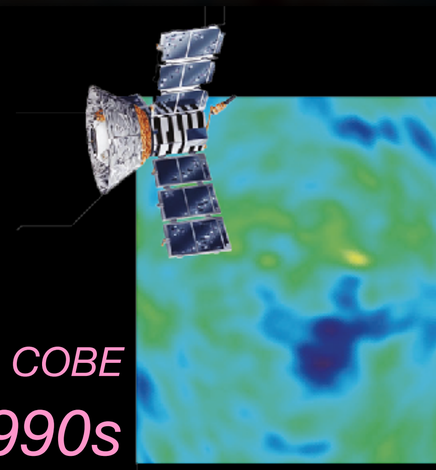
Things we know about inflation

- The Universe expanded **exponentially**
- There were **quantum fluctuations**



COBE

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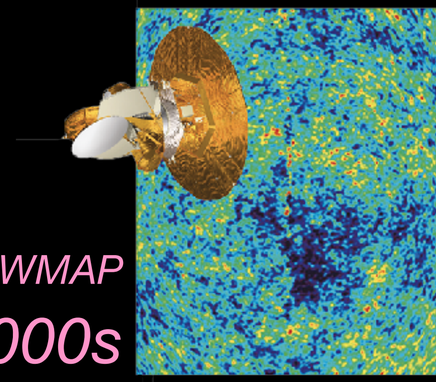
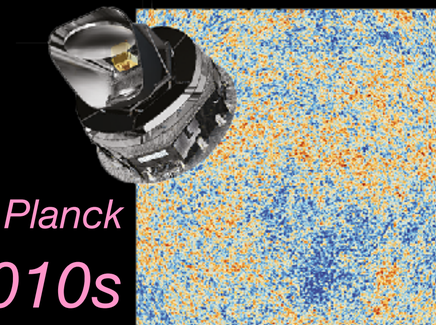


WMAP

2000s



Planck

2010s

BBC / COBE / WMAP / Planck

BBC / COBE / WMAP / Planck

Inflation has a lot of mysteries

Many models have been proposed to explain the early Universe

⇒ **Inflation fits the data the best!**

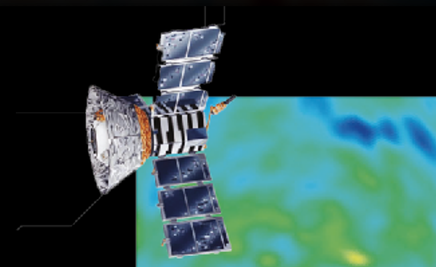
Things we know about inflation

- The Universe expanded **exponentially**
- There were **quantum fluctuations**

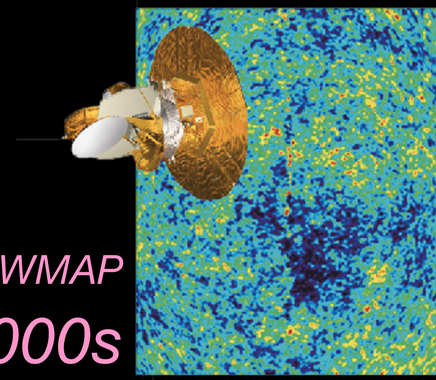
Things we don't know about inflation

- How did it begin?
- What caused the expansion?
- **What are the laws of physics in inflation?**

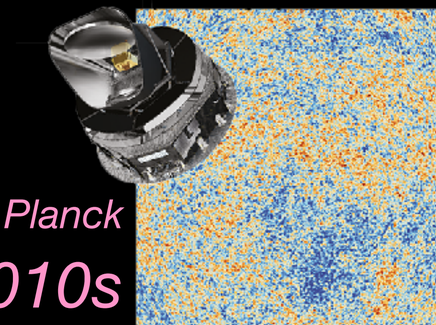
Inflation is a unique probe of physics at the *highest* energies



COBE
1990s



WMAP
2000s



Planck
2010s

What are the laws of physics in inflation?

The Standard Model

Lots of Particles
(Electrons, Quarks, Neutrinos, …)

Four Ways to Interact
(Strong, Weak, Gravity, Electromagnetism)

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The Standard Model

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(Electrons, Quarks, Neutrinos, …)

Four Ways to Interact
(Strong, Weak, Gravity, Electromagnetism)

Inflation

How Many Particles?
(At least one)

How Many Interactions?
(At least one)

Symmetry makes this much more concrete!

How to learn about inflation

Guess The Laws of Physics

How many particles?

How many interactions?

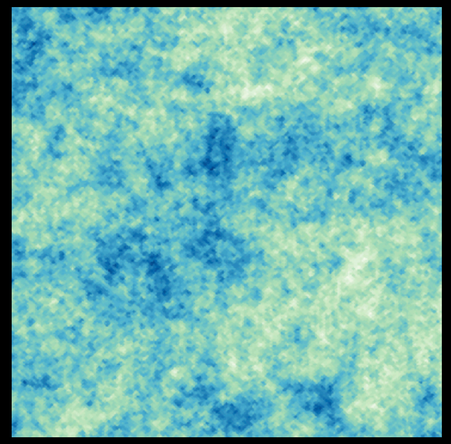
BBC / Planck

How to learn about inflation

Guess The Laws of Physics → *Predict Inflation*

How many particles?

How many interactions?



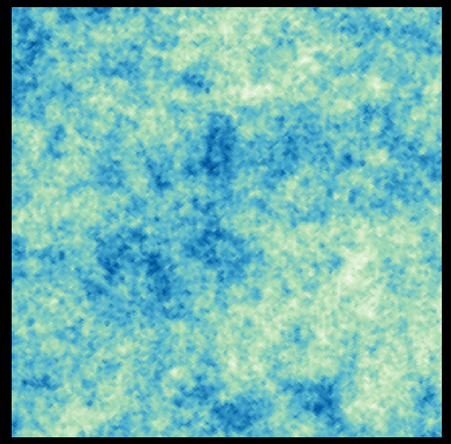
BBC / Planck

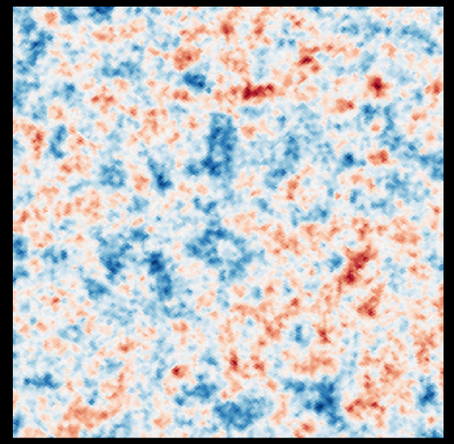
How to learn about inflation

Guess The Laws of Physics → *Predict Inflation* → *Predict the Cosmic Microwave Background*

How many particles?

How many interactions?





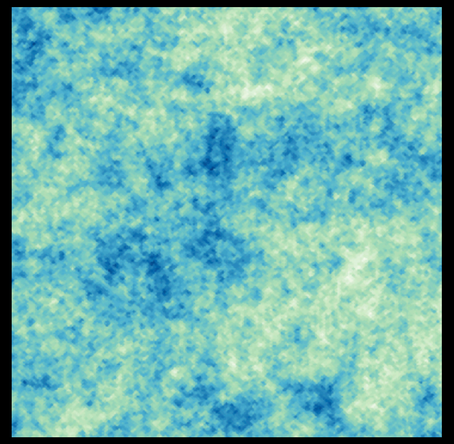
BBC / Planck

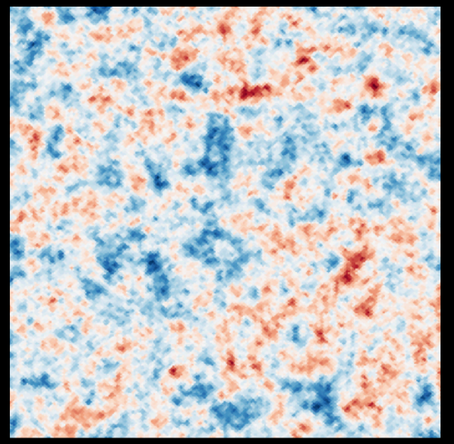
How to learn about inflation

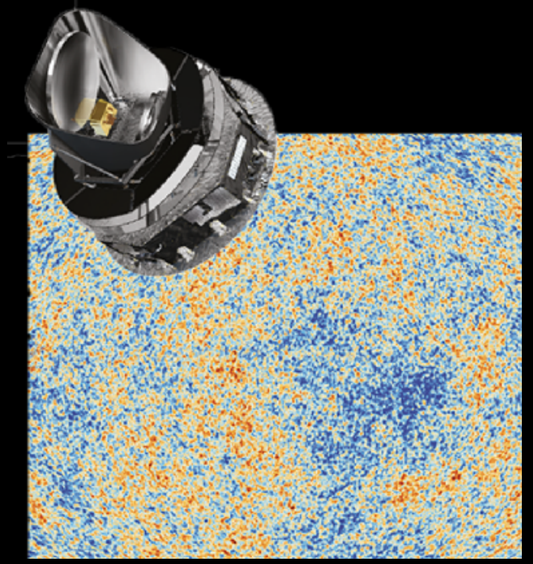
Guess The Laws of Physics → *Predict Inflation* → *Predict the Cosmic Microwave Background* → *Compare to Data*

How many particles?

How many interactions?



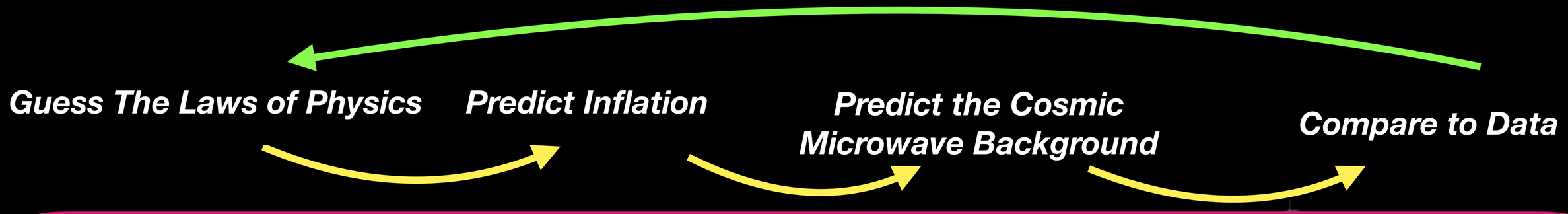




This is a **particle physics** experiment the size of the **whole Universe**

BBC / Planck

How to learn about inflation



At Stanford we're learning a lot from the CMB!

The **initial energy** was $\lesssim 10^{26}\,\mathrm{K}\,(200\,\text{trillion trillion}\,^\circ\mathrm{F})$

Inflation was *probably* controlled by just **one type of particle**

The particles **didn't interact with themselves** *too strongly*

BBC / Planck

How can we learn more?

Experiments have improved a lot since 2010

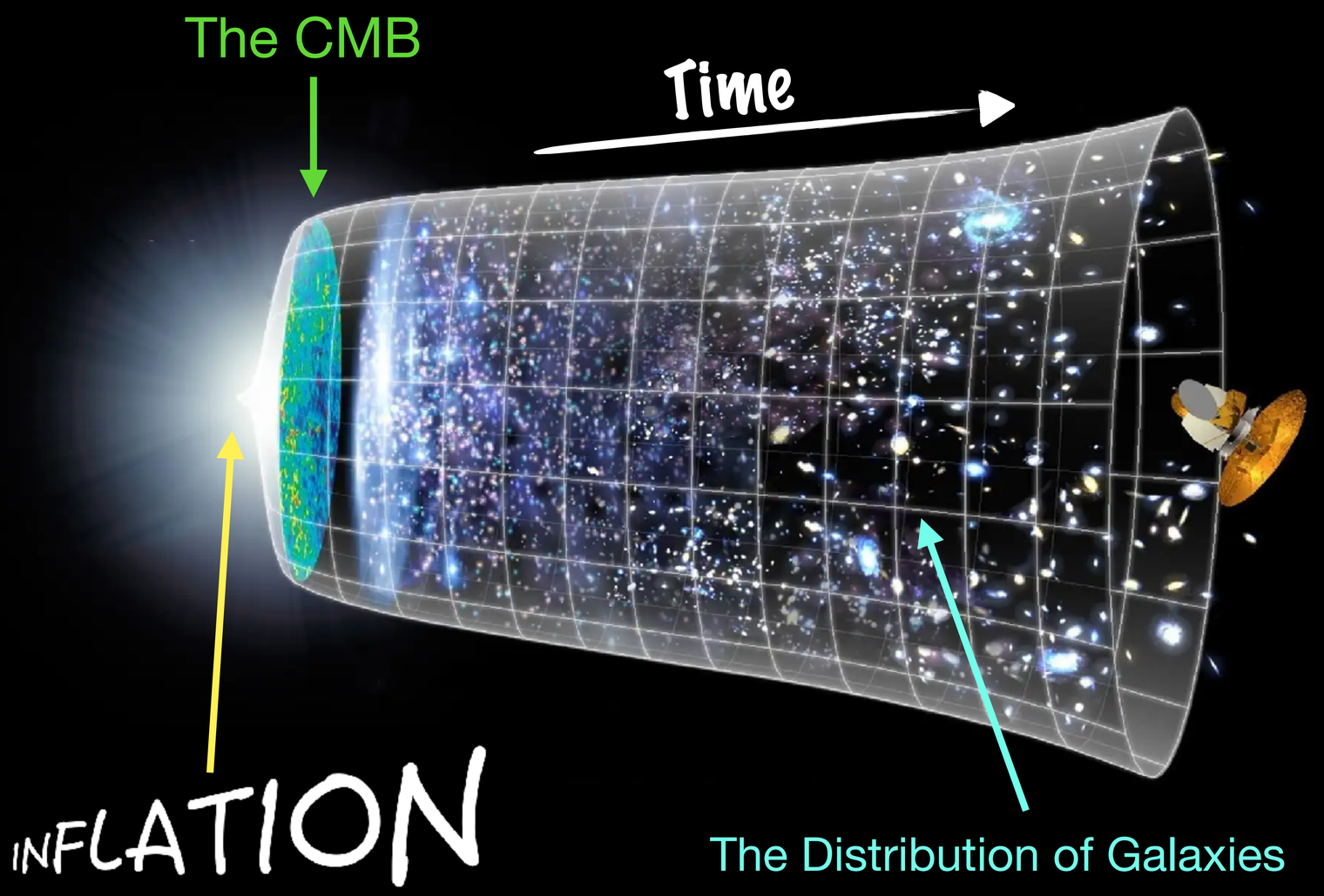
The new experiments go to **small scales** which are great for astronomy but bad for particle physics

We need a new probe!

Simons Foundation

The next-generation inflation experiment

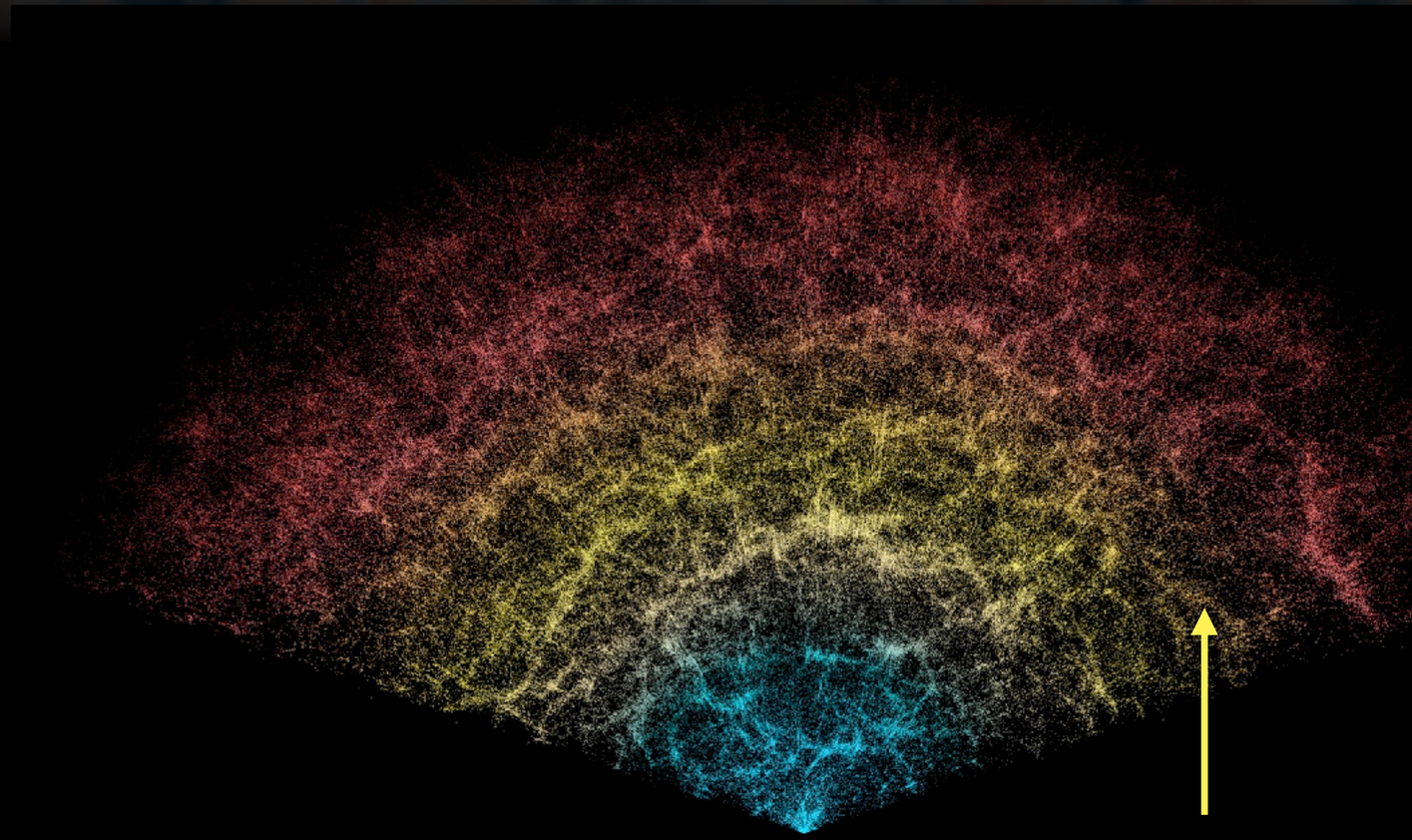
We can **also** probe inflation by looking at the nearby Universe!



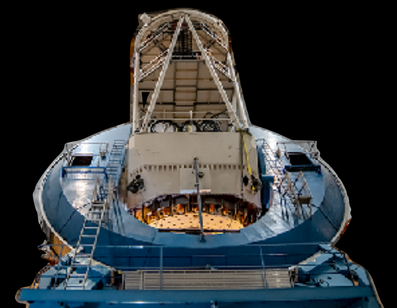
NASA/WMAP

The next-generation inflation experiment

Modern surveys (including **DESI**) map the 3D positions of **millions of galaxies**



Each dot is 1 galaxy!

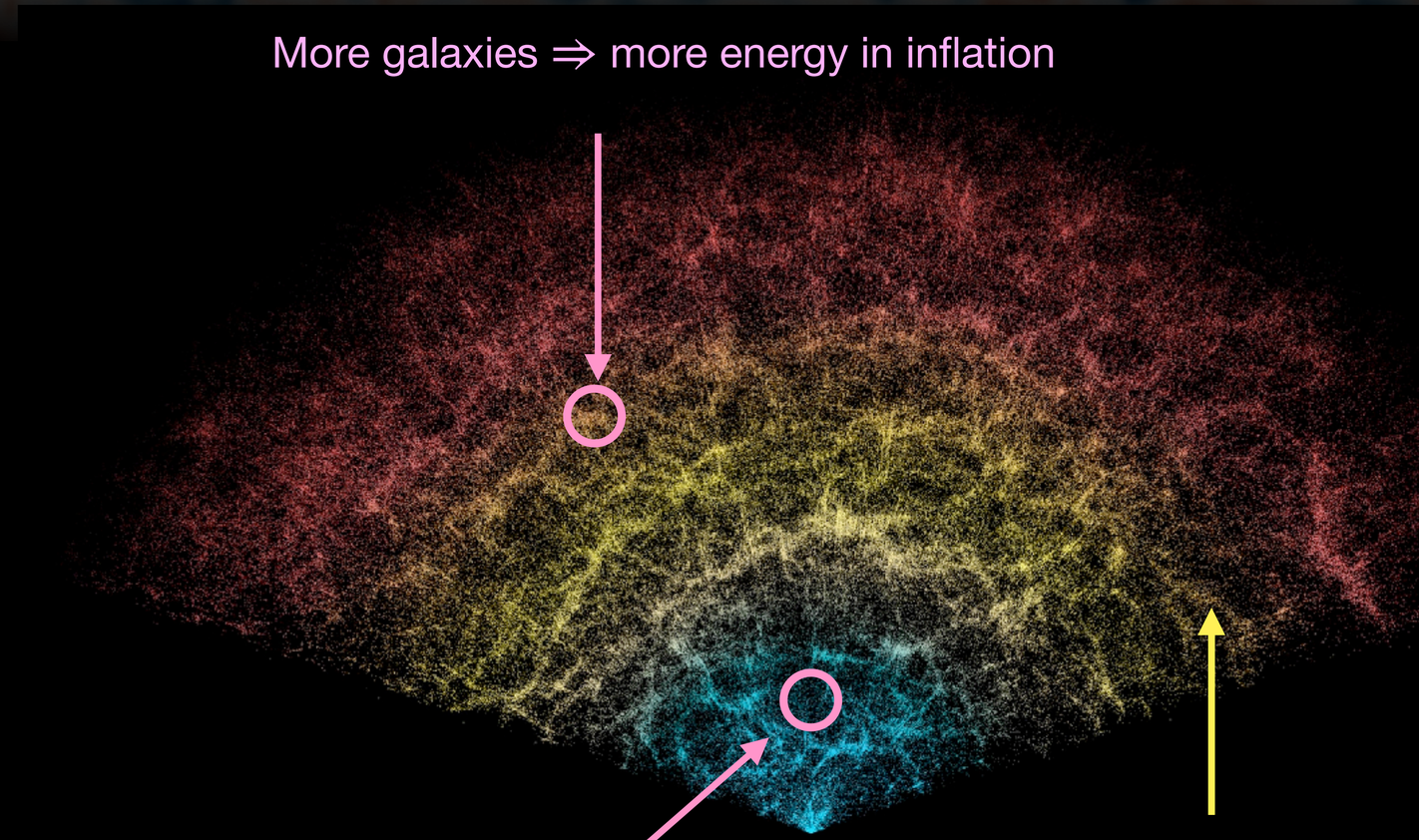


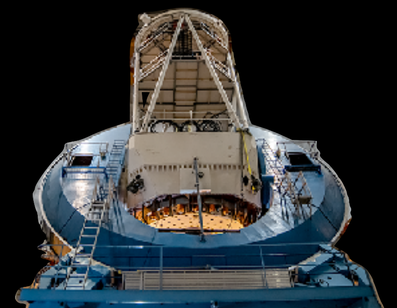
DESI

The next-generation inflation experiment

Modern surveys (including **DESI**) map the 3D positions of **millions of galaxies**

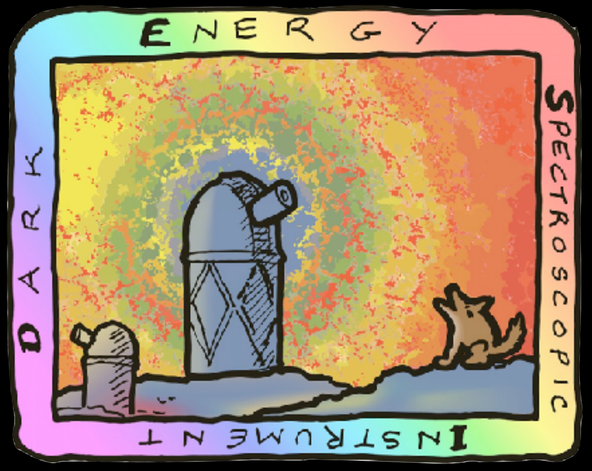
The distribution of galaxies tells us about quantum fluctuations in inflation!





DESI

Collecting this data is a HUGE community effort

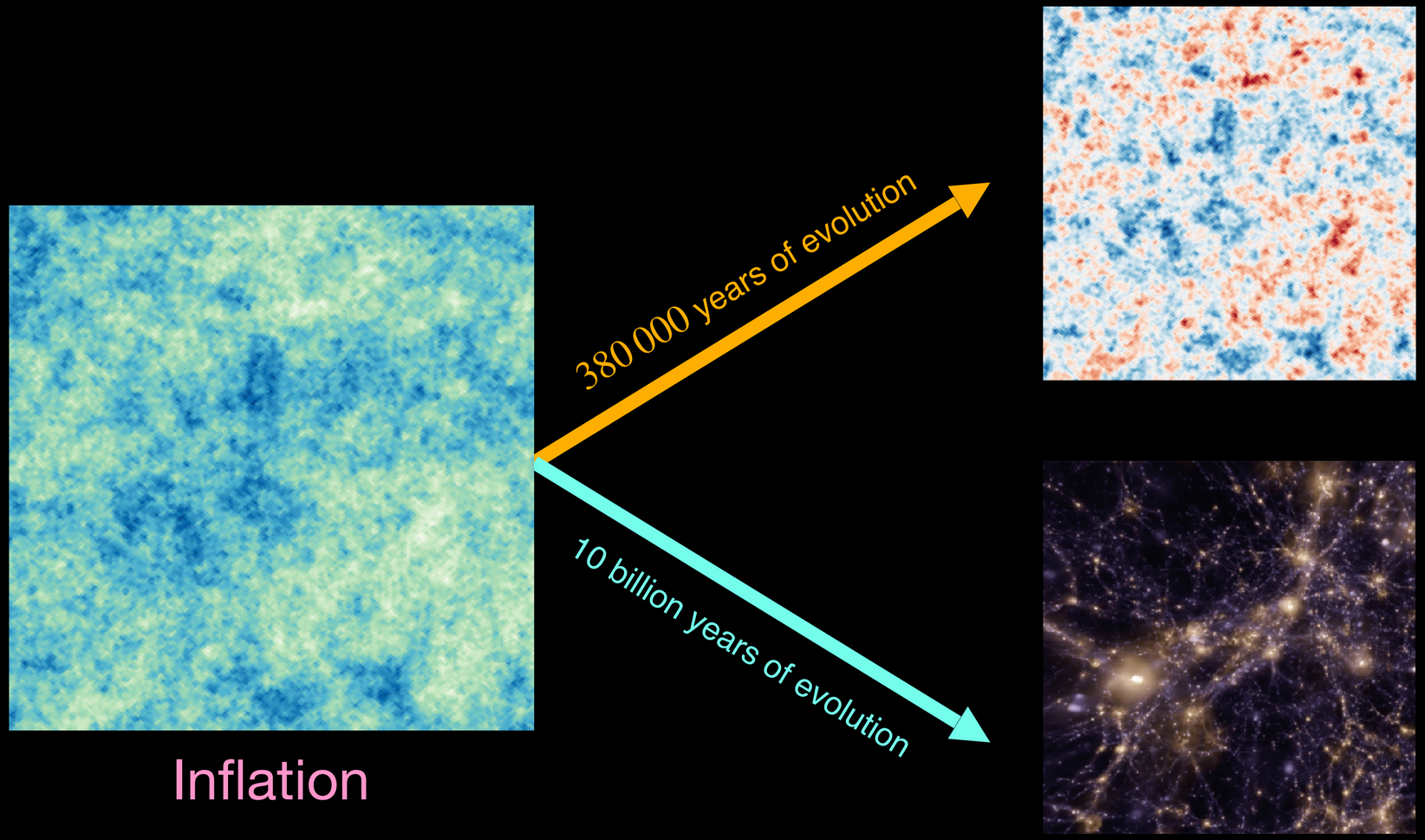


DESI collaboration, December 2025

... and the data has now been publicly released!

Modeling galaxies is challenging...

The CMB



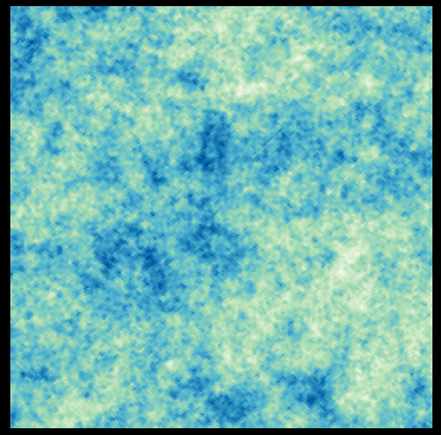
... but possible on large-scales!

At Stanford, we predict the distribution of galaxies on a blackboard!

$$\rho_{\text{galaxies}} = f[\text{Physics}] \times \text{Inflation} + g[\text{Physics}] \times \text{Inflation}^2 + \cdots$$

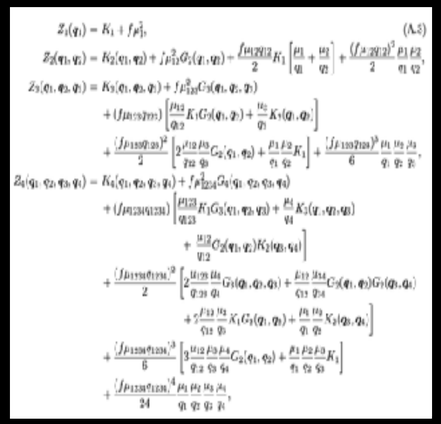
This can be done **robustly** using tools borrowed from Quantum Field Theory

Inflation



⇒

Theory



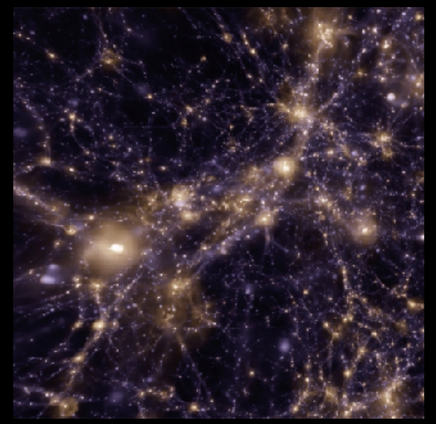
$$\begin{aligned}
Z_1(q_1) &= K_1 + f\mu_1^2, \qquad (A.5)\\
Z_2(q_1,q_2) &= K_2(q_1,q_2) + f\mu_{12}^2 G_2(q_1,q_2) + \frac{f\mu_{123}q_{123}}{2}K_1\left[\frac{\mu_1}{q_1}+\frac{\mu_2}{q_2}\right] + \frac{(f\mu_{123}q_{123})^2}{2}\frac{\mu_1\mu_2}{q_1\,q_2},\\
Z_3(q_1,q_2,q_3) &= K_3(q_1,q_2,q_3) + f\mu_{123}^2 G_3(q_1,q_2,q_3)\\
&\quad + (f\mu_{123}q_{123})\left[\frac{\mu_{12}}{q_{12}}K_1 G_2(q_1,q_2) + \frac{u_3}{q_3}K_3(q_1,q_2)\right]\\
&\quad + \frac{(f\mu_{123}q_{123})^2}{2}\left[2\frac{\mu_{12}\mu_3}{q_{12}\,q_3}G_2(q_1,q_2) + \frac{\mu_1\mu_2}{q_1\,q_2}K_1\right] + \frac{(f\mu_{123}q_{123})^3}{6}\frac{\mu_1\,u_2\,\mu_3}{q_1\,q_2\,q_3},\\
Z_4(q_1,q_2,q_3,q_4) &= K_4(q_1,q_2,q_3,q_4) + f^2\mu_{1234}^2 G_4(q_1,q_2,q_3,q_4)\\
&\quad + (f\mu_{1234}q_{1234})\left[\frac{\mu_{123}}{q_{123}}K_1 G_3(q_1,q_2,q_3) + \frac{\mu_4}{q_4}K_3(q_1,q_2,q_3)\right.\\
&\qquad \left. + \frac{u_{12}}{q_{12}}G_2(q_1,q_2)K_2(q_3,q_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^2}{2}\left[2\frac{\mu_{123}\,\mu_4}{q_{123}\,q_4}G_3(q_1,q_2,q_3) + \frac{\mu_{12}\,\mu_{34}}{q_{12}\,q_{34}}G_2(q_1,q_2)G_2(q_3,q_4)\right.\\
&\qquad \left. + 2\frac{\mu_{12}\,\mu_3}{q_{12}\,q_3}K_1 G_2(q_1,q_2) + \frac{\mu_1\,\mu_2}{q_1\,q_2}K_2(q_3,q_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^3}{6}\left[3\frac{\mu_{12}\,\mu_3\,\mu_4}{q_{12}\,q_3\,q_4}G_2(q_1,q_2) + \frac{\mu_1\,\mu_2\,\mu_3}{q_1\,q_2\,q_3}K_1\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^4}{24}\frac{\mu_1\,\mu_2\,\mu_3\,\mu_4}{q_1\,q_2\,q_3\,q_4},
\end{aligned}$$

⇒

Computation

⇒

Galaxies



(Our toolkit: the Effective Field Theory of Large Scale Structure)

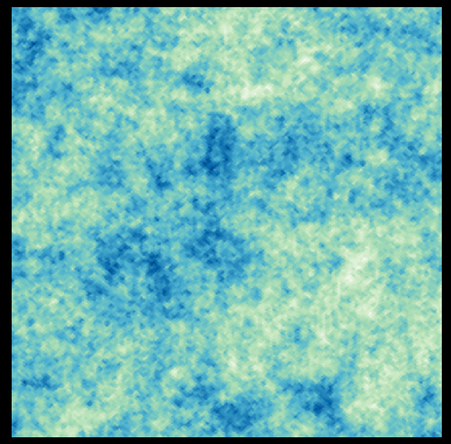
IllustrisTNG

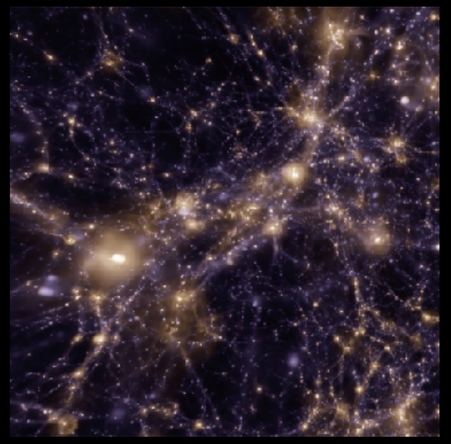
How to learn more about inflation

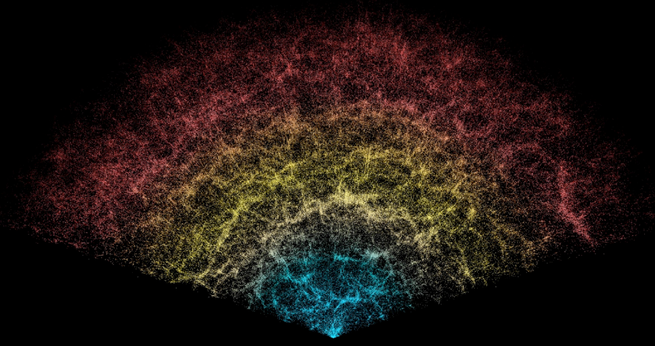
Guess The Laws of Physics → *Predict Inflation* → *Predict the Distribution of Galaxies* → *Compare to Data*

How many particles?

How many interactions?



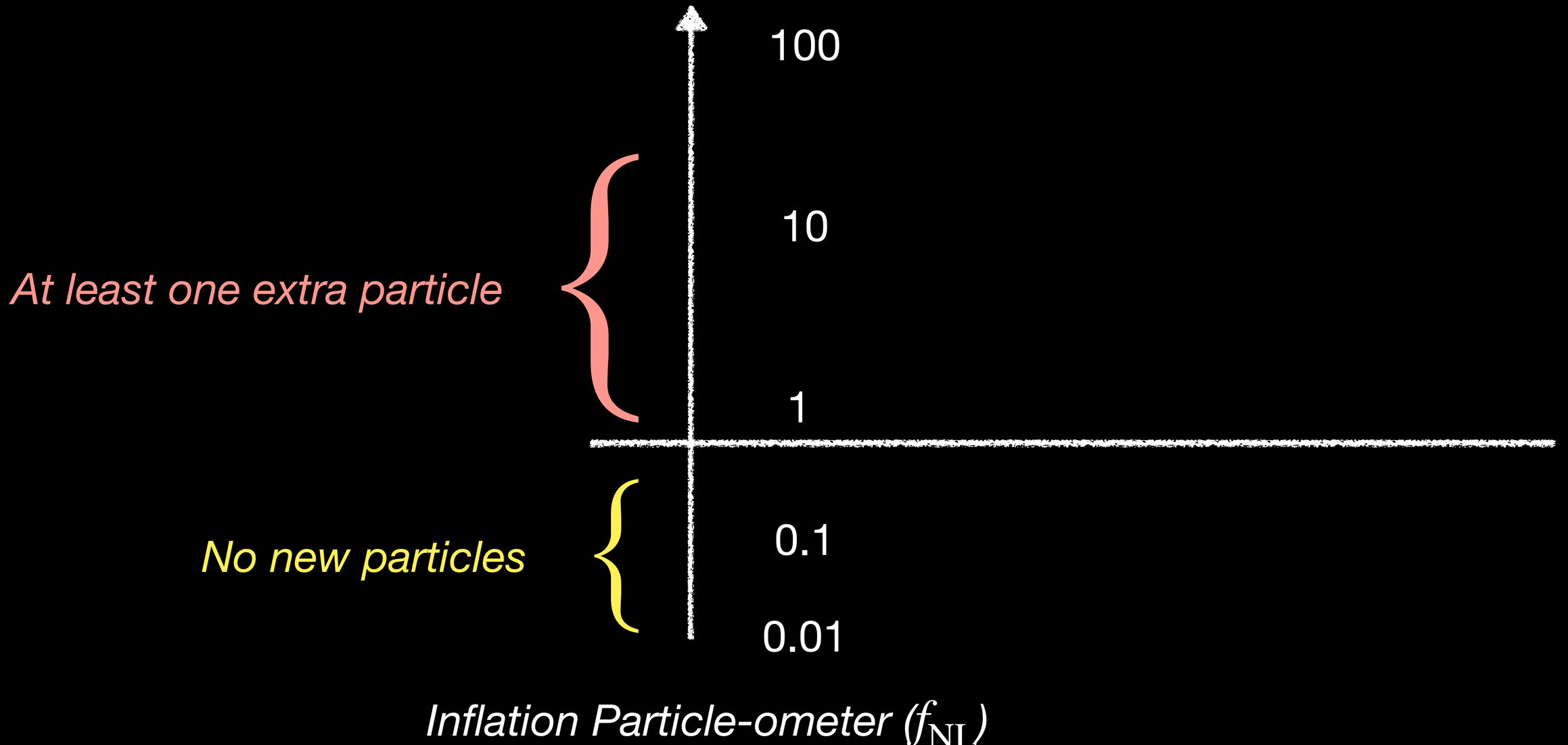




Learning about inflation with galaxies is an **ongoing** and **exciting** program!

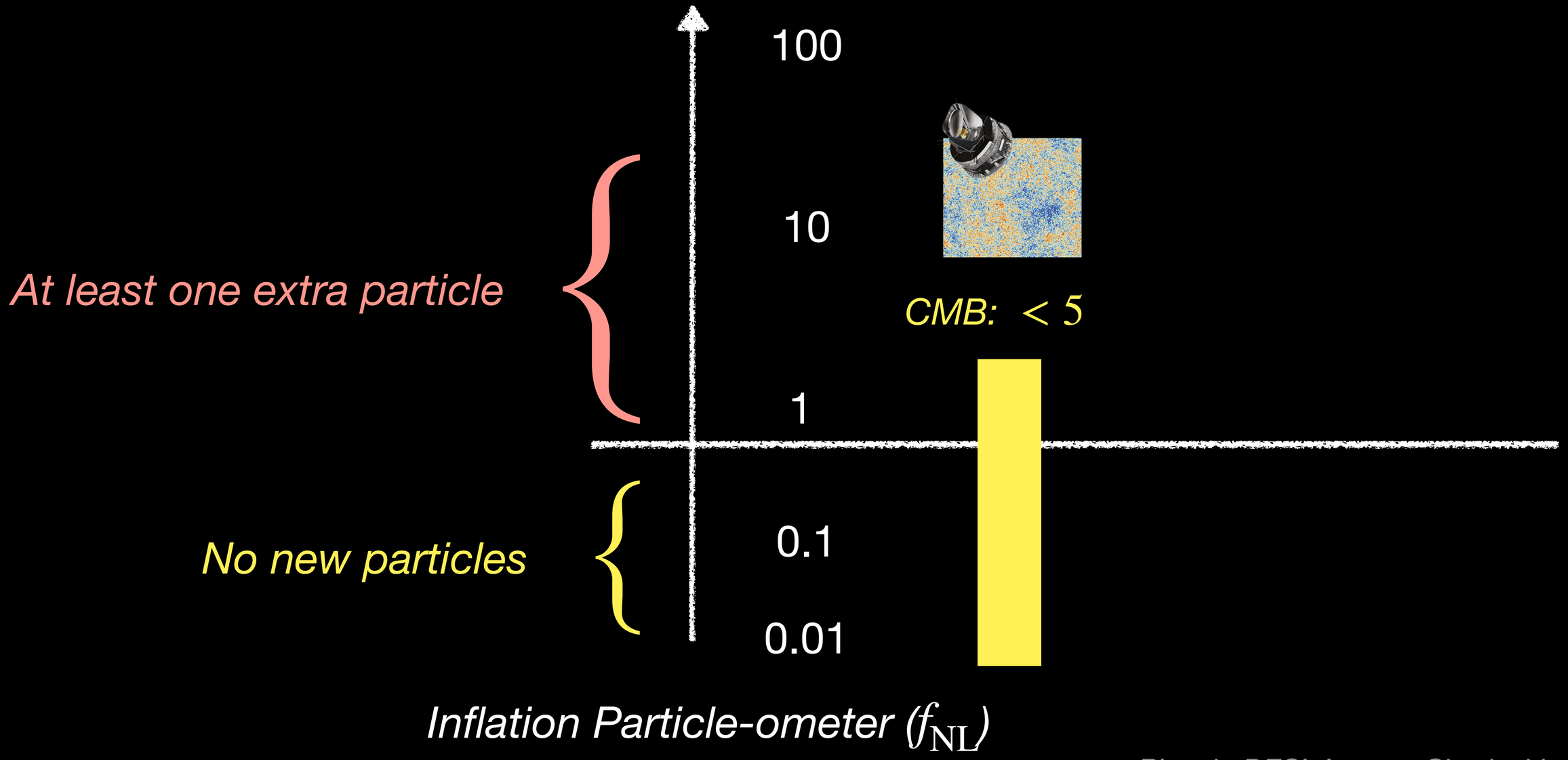
DESI

How many particles were in inflation?



Planck, DESI, Ivanov, Chudaykin, Philcox

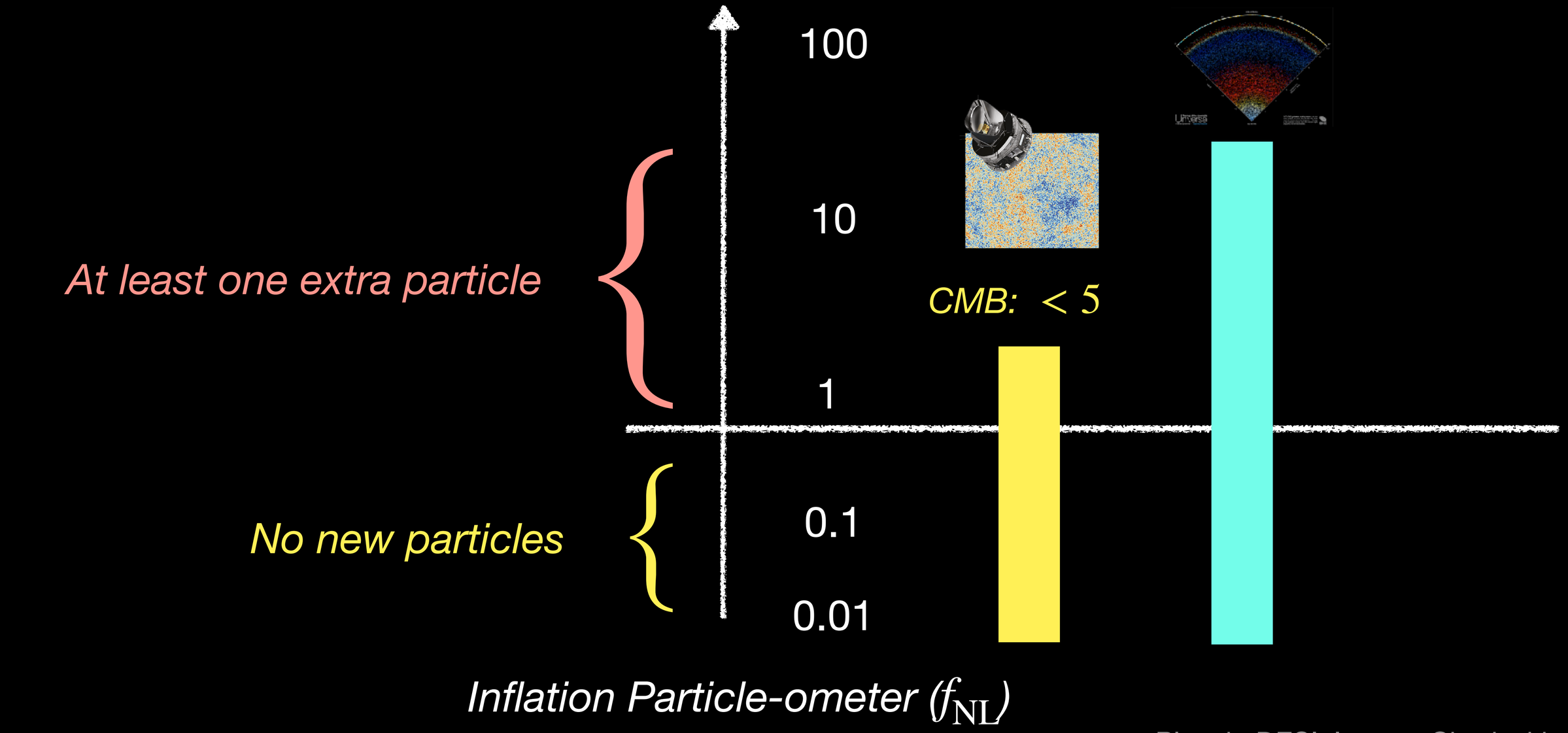
How many particles were in inflation?



Planck, DESI, Ivanov, Chudaykin, Philcox

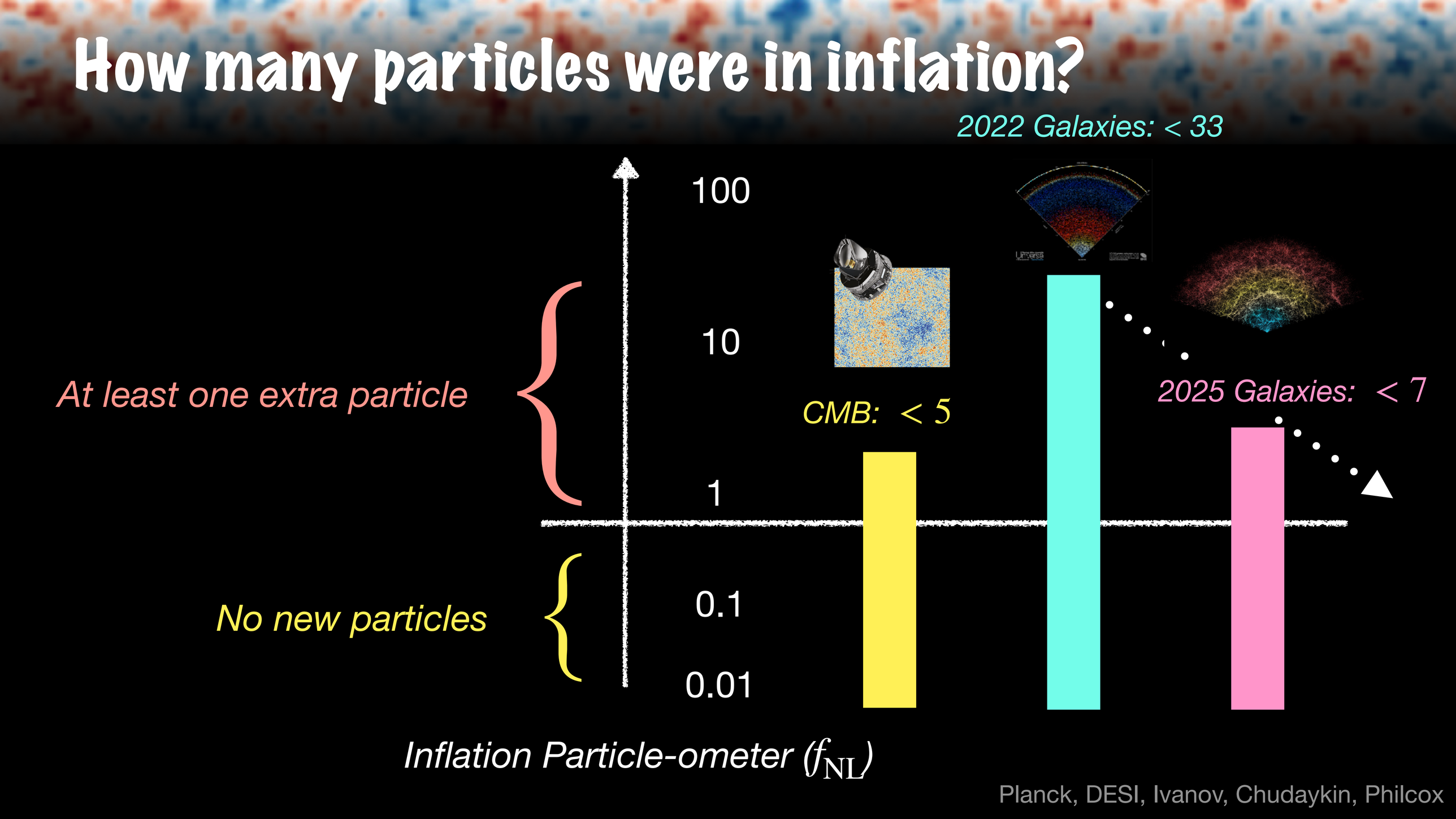
How many particles were in inflation?

2022 Galaxies: < 33



Planck, DESI, Ivanov, Chudaykin, Philcox

How many particles were in inflation?

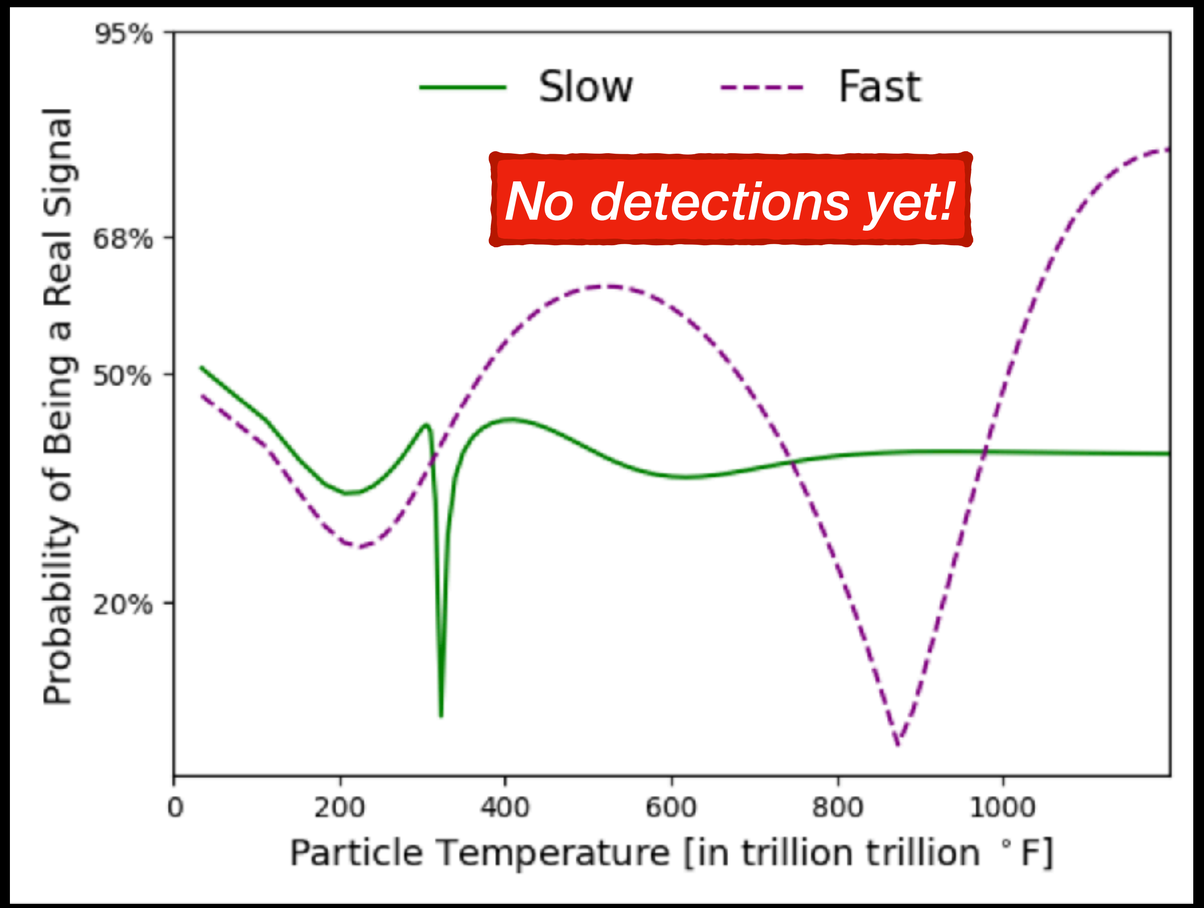


Planck, DESI, Ivanov, Chudaykin, Philcox

There's lots more to explore

- How strongly did particles *interact*?
- What *mass* did particles have?
- What *spin* did particles have?
- What *speed* did particles have?

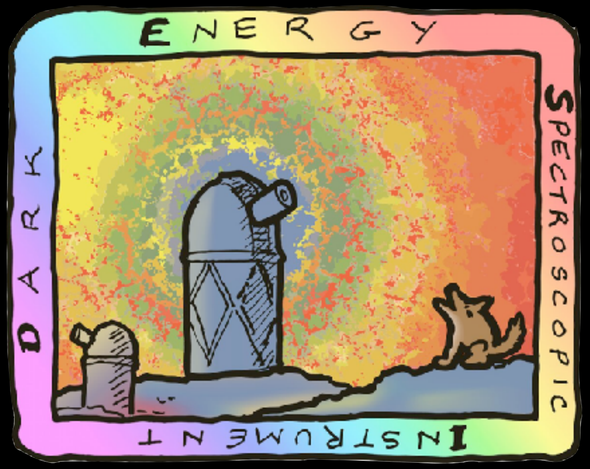
State-of-the-art measurements from the CMB at Stanford!



Planck, DESI, Ivanov, Chudaykin, Philcox

Bigger surveys are on the way...

DESI (2021—2029)



40 million galaxies!

Looking back ~6 billion years

Euclid (2024—2030)

30 million galaxies!

Looking back ~9 billion years

Spec-S5 (2030s?)

> 100 million galaxies!

Looking back ~12 billion years

Stay tuned for new results!

Also: Rubin, Roman, SphereX, CSST…

Summary

- **Inflation** explains our observations of the **Cosmic Microwave Background**
- Studying inflation allows us to probe **particle physics** at **huge** energies
- By combining **theory** and **data**, we can use **galaxy surveys** to learn about the earliest moments of the Universe!

More Questions?
ophilcox@stanford.edu

Discover our Universe

Echoes from the Beginning:

How Galaxies Encode the Early Universe

Prof. Oliver Philcox
(Stanford/KIPAC)

Wednesday, February 11 | 7-8pm PST

Science Teaching and Learning Center 111 & YouTube

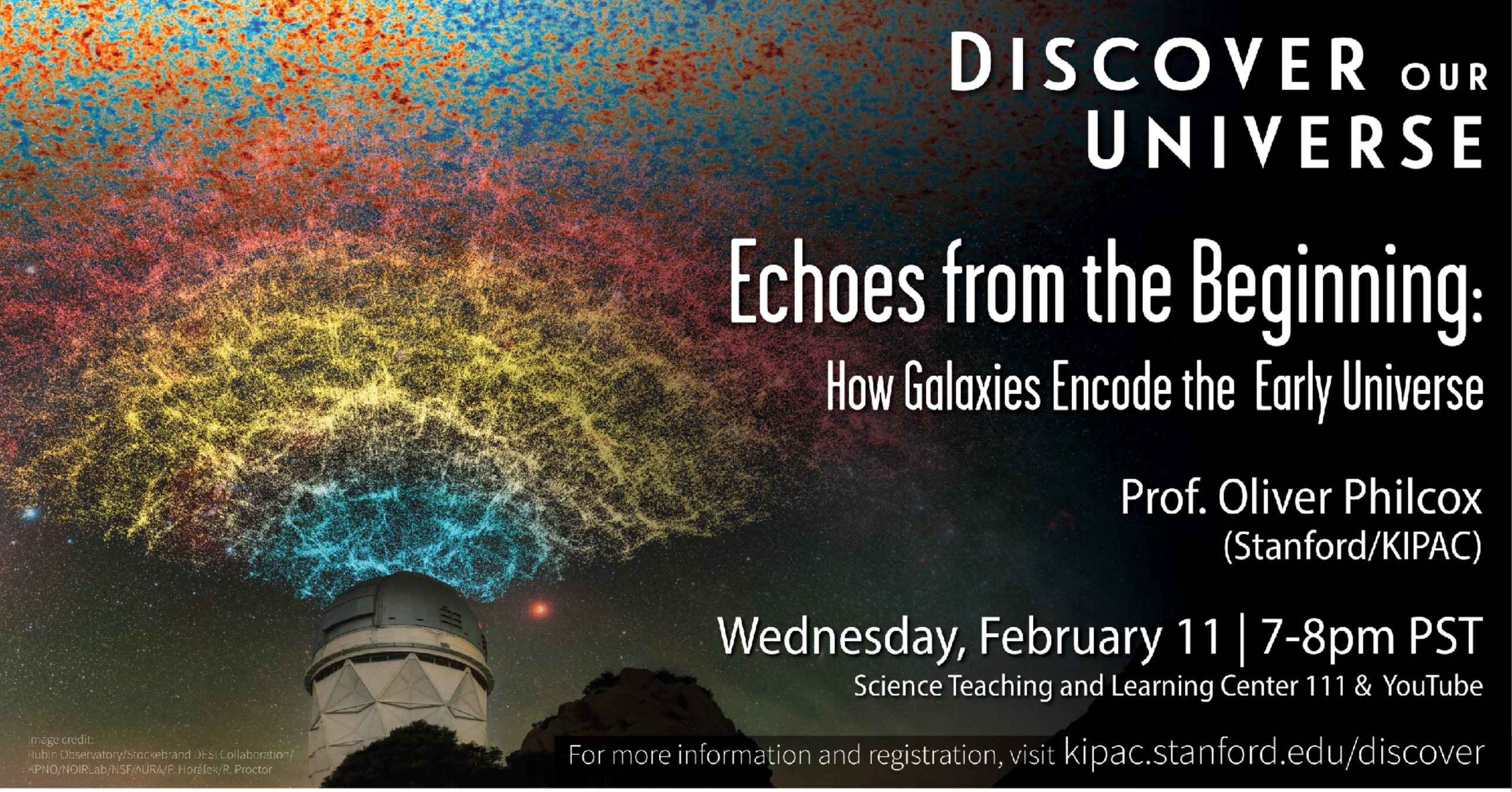


Image credit:
Rubin Observatory/Stockebrand DESI Collaboration/
KPNO/NOIRLab/NSF/AURA/P. Horálek/R. Proctor

For more information and registration, visit kipac.stanford.edu/discover

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