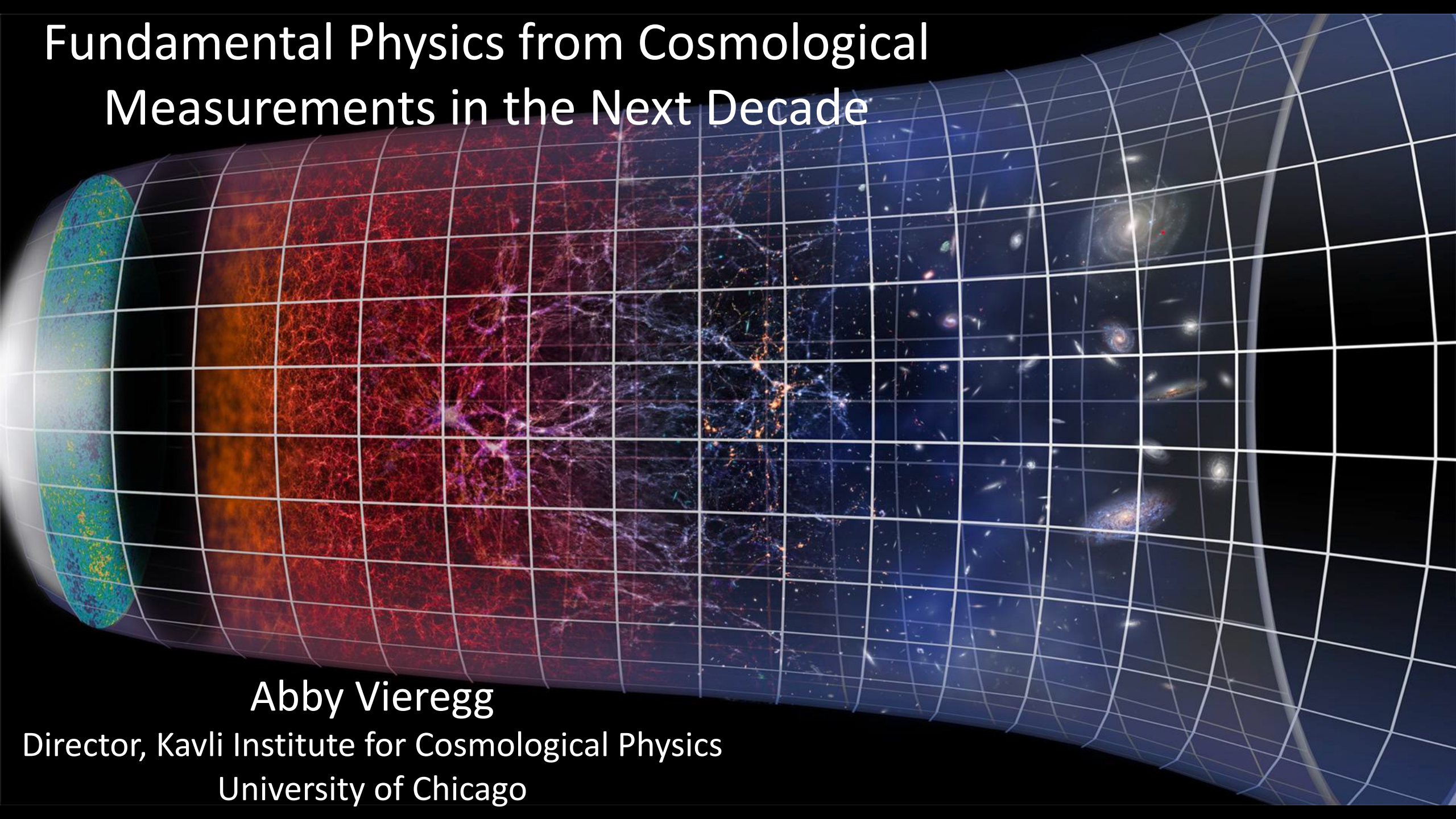
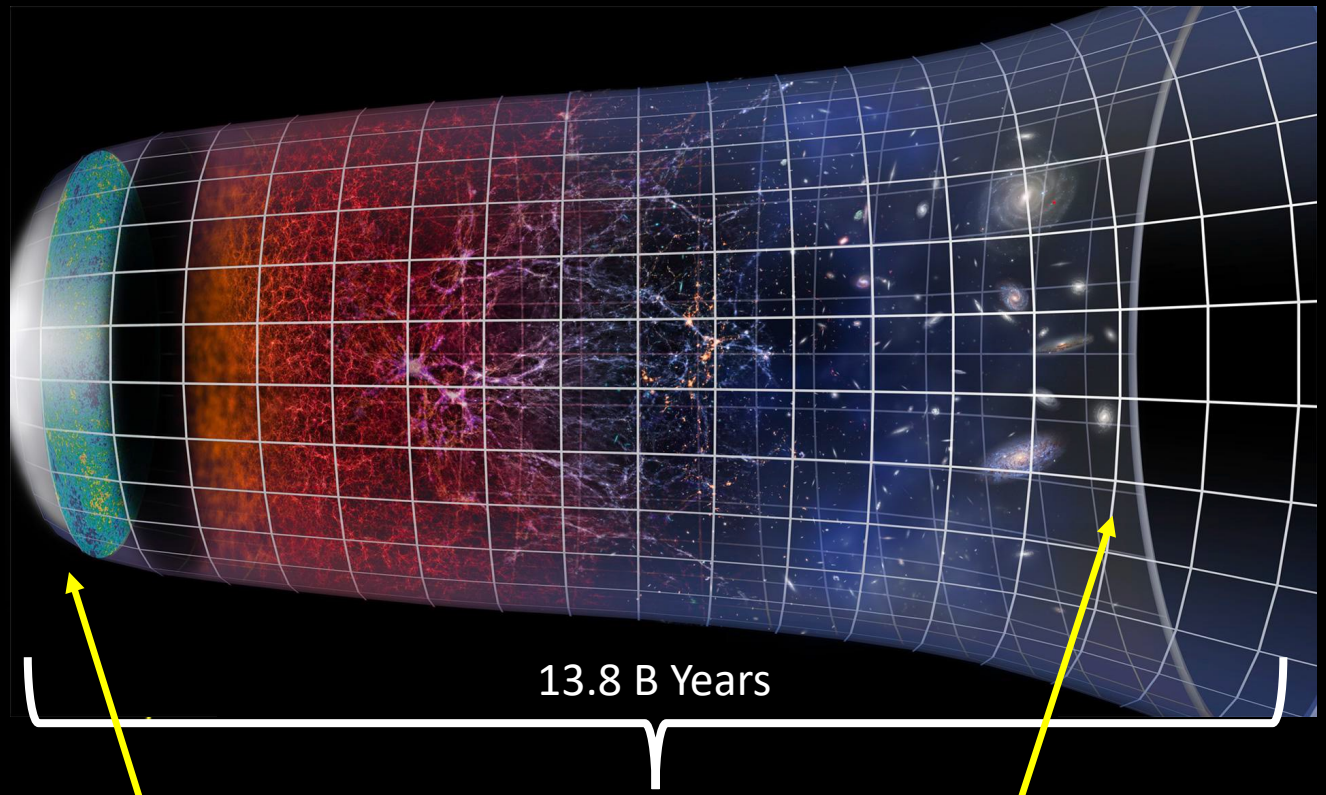
Fundamental Physics from Cosmological Measurements in the Next Decade



Abby Vieregg
Director, Kavli Institute for Cosmological Physics
University of Chicago

ΛCDM: The Standard Cosmological Paradigm

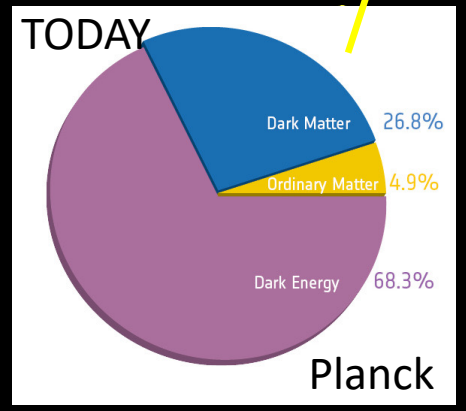


Quantum fluctuations expanded to macroscopic scales by inflation seed cosmic structure formation

The evolution of the Universe is governed by 6 free parameters in the Λ + Cold Dark Matter model

Ω_m density of matter
Ω_b density of atoms
H_0 expansion rate today
σ_8 amplitude of fluctuations
n_s scale dependence of fluctuations
(τ reionization optical depth)

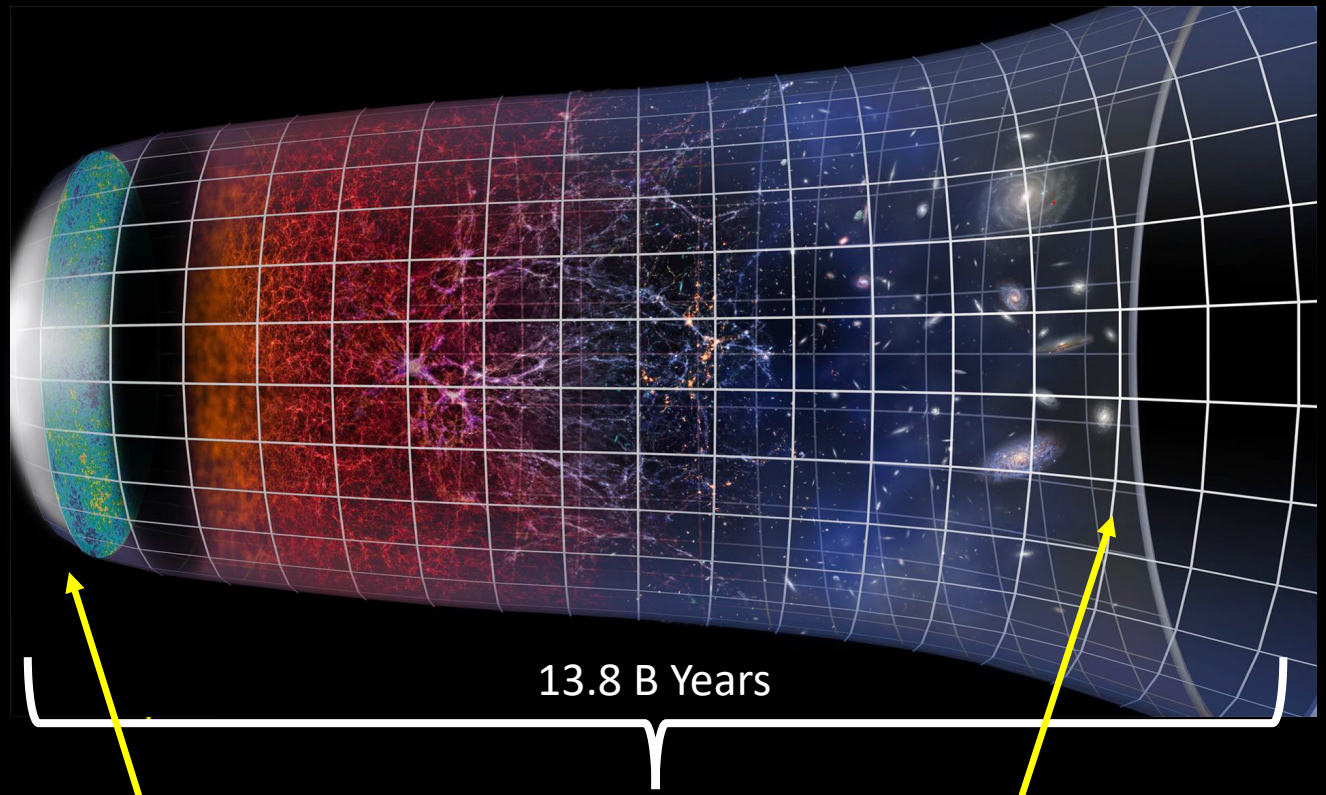
Physics at an energy scale of
$\sim 10^{16}$ GeV



Questions Remain:

What is the nature of **Dark Matter**?
What is the nature of **Dark Energy**?
How did **Inflation** happen?
What is the mass of the **Neutrino**?
How many **Light Relativistic Species** are there?

ΛCDM: The Standard Cosmological Paradigm



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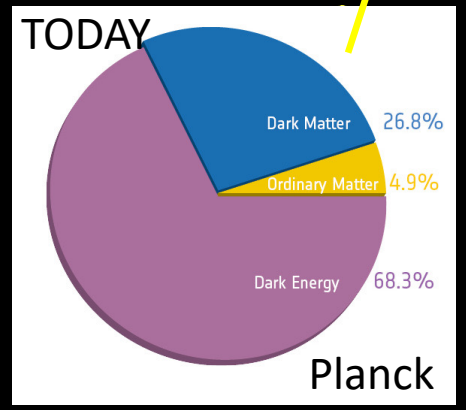

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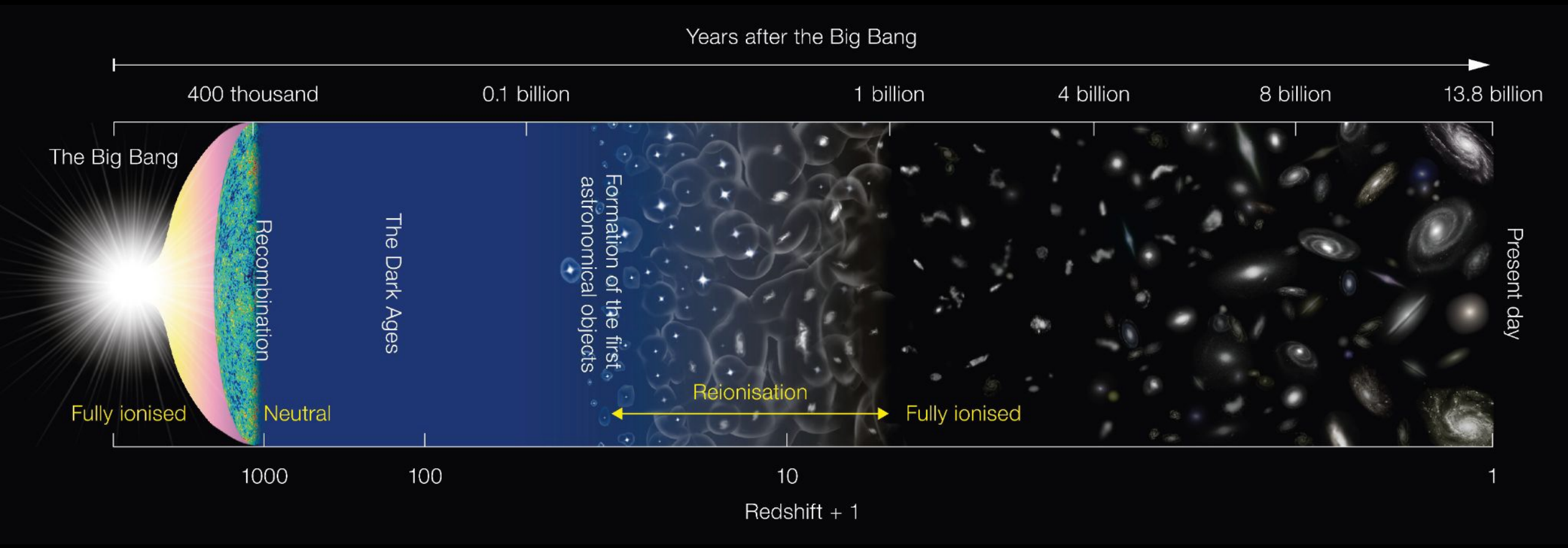
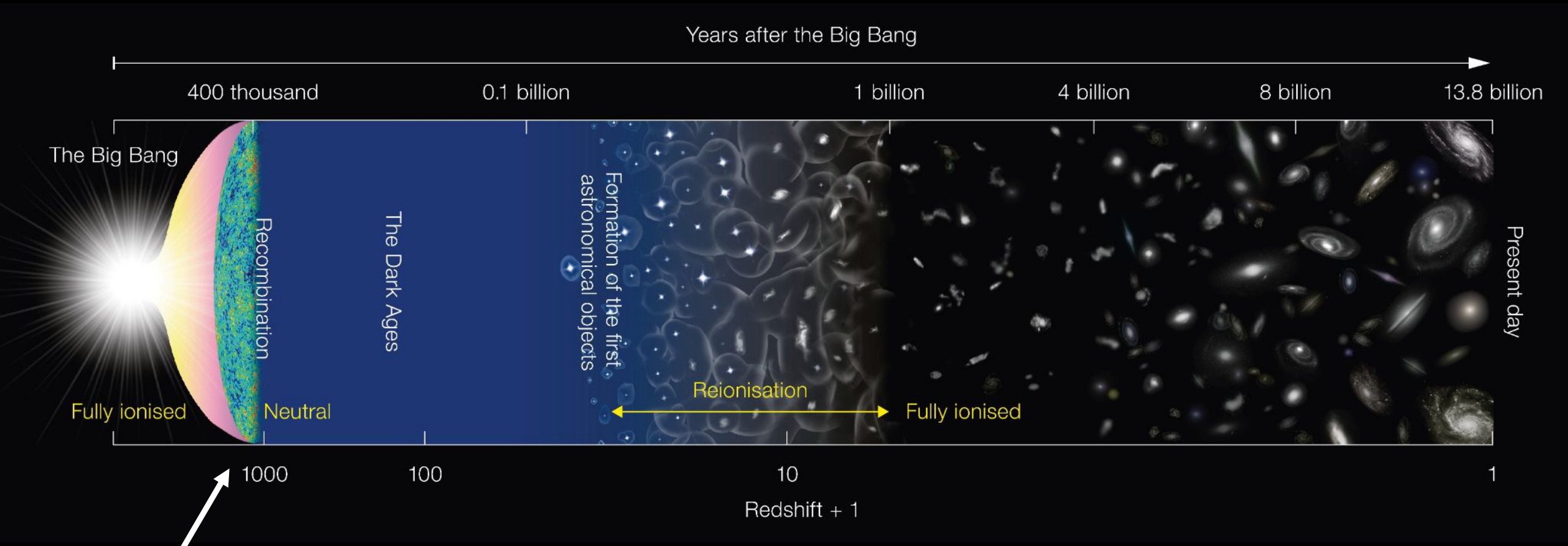
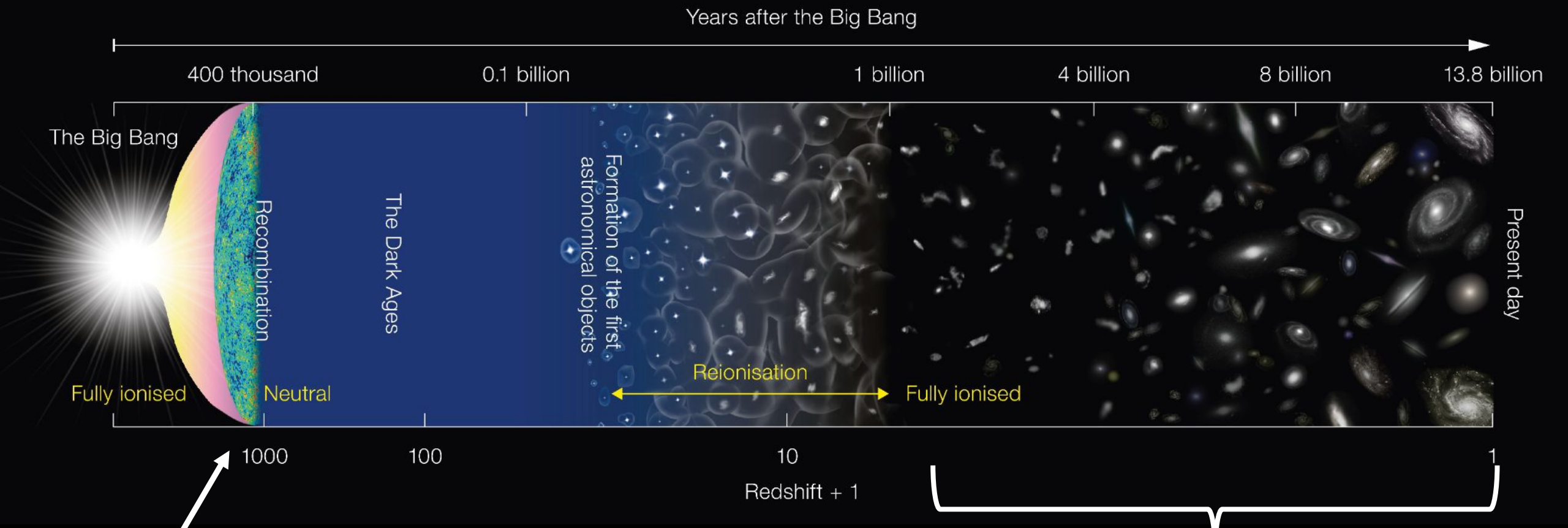

Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Reionisation
Present day
Fully ionised
Neutral
Fully ionised
1000
100
10
1
Redshift + 1



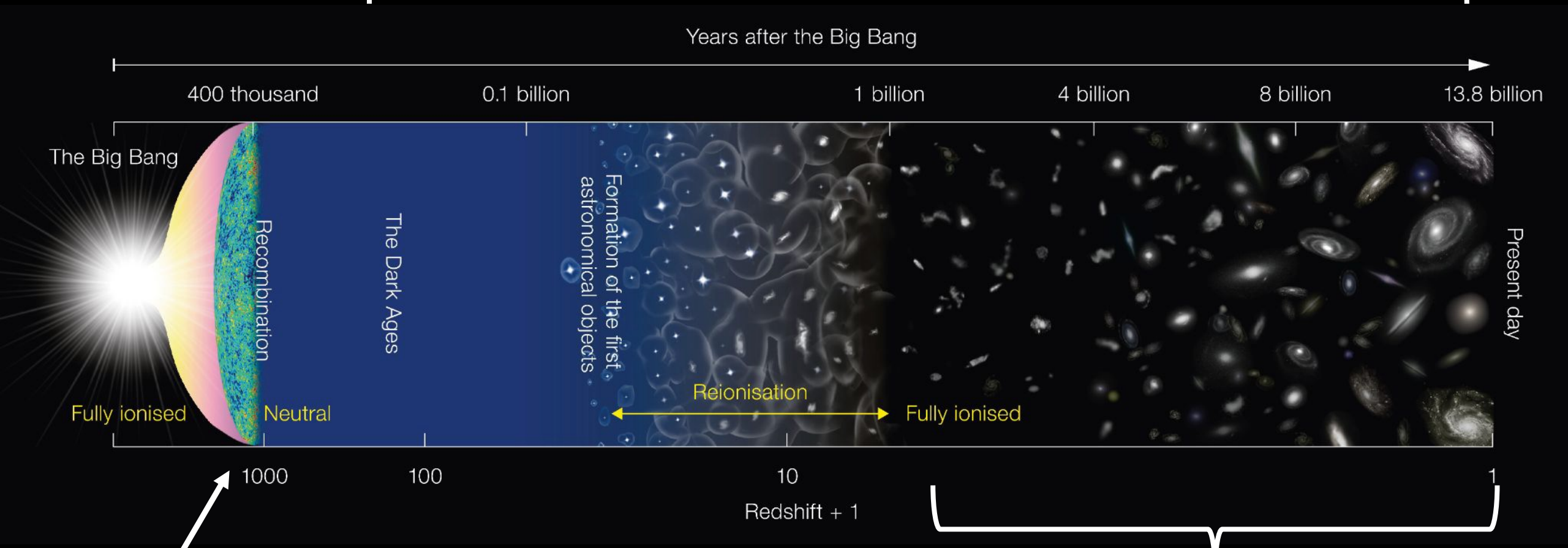
Cosmic Microwave Background (CMB)



Cosmic Microwave Background (CMB)

Galaxy Surveys (Imaging & Spectroscopic)

Line Intensity Mapping (LIM)



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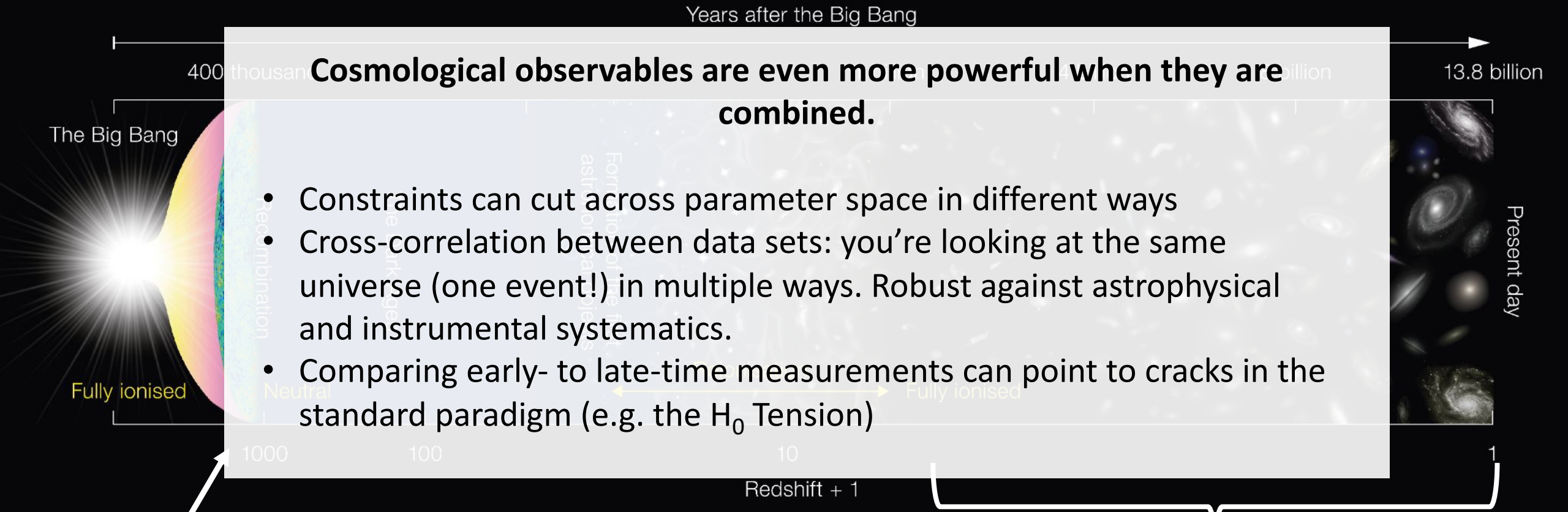


Cosmological observables are even more powerful when they are combined.

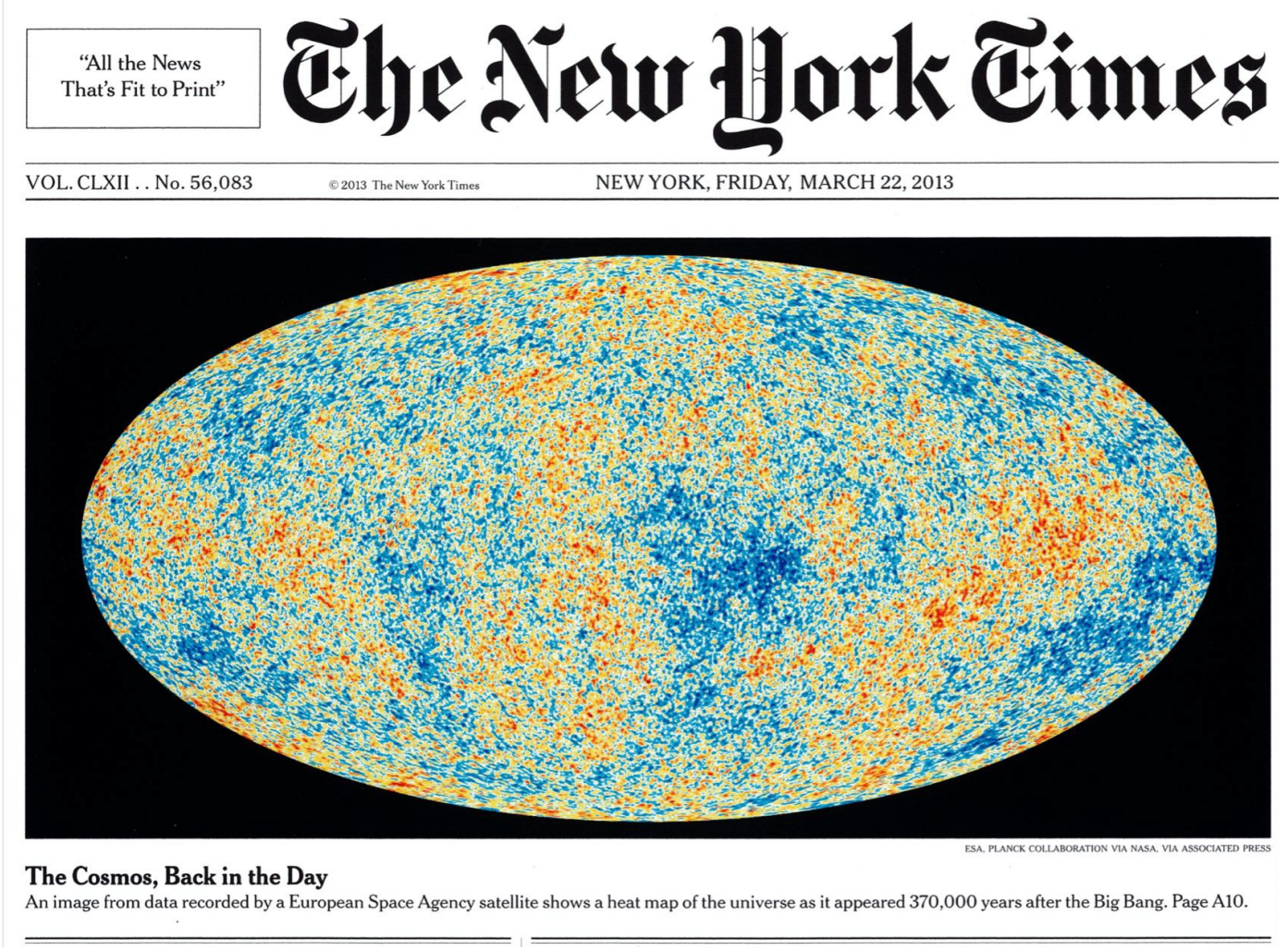
- Constraints can cut across parameter space in different ways
- Cross-correlation between data sets: you're looking at the same universe (one event!) in multiple ways. Robust against astrophysical and instrumental systematics.
- Comparing early- to late-time measurements can point to cracks in the standard paradigm (e.g. the H_0 Tension)

Cosmic Microwave Background (CMB)

Galaxy Surveys (Imaging & Spectroscopic)

The Story of Our Universe Told By Its Oldest Light: The CMB

- Universe initial conditions, the seeds of structure
- Age of the Universe: 13.8 Gyr
- Geometry of the Universe: Flat
- Baryon/Dark Matter/Dark Energy Composition (5%/27%/68%)
- Plus much more



"All the News That's Fit to Print"

The New York Times

VOL. CLXII . . No. 56,083 © 2013 The New York Times NEW YORK, FRIDAY, MARCH 22, 2013

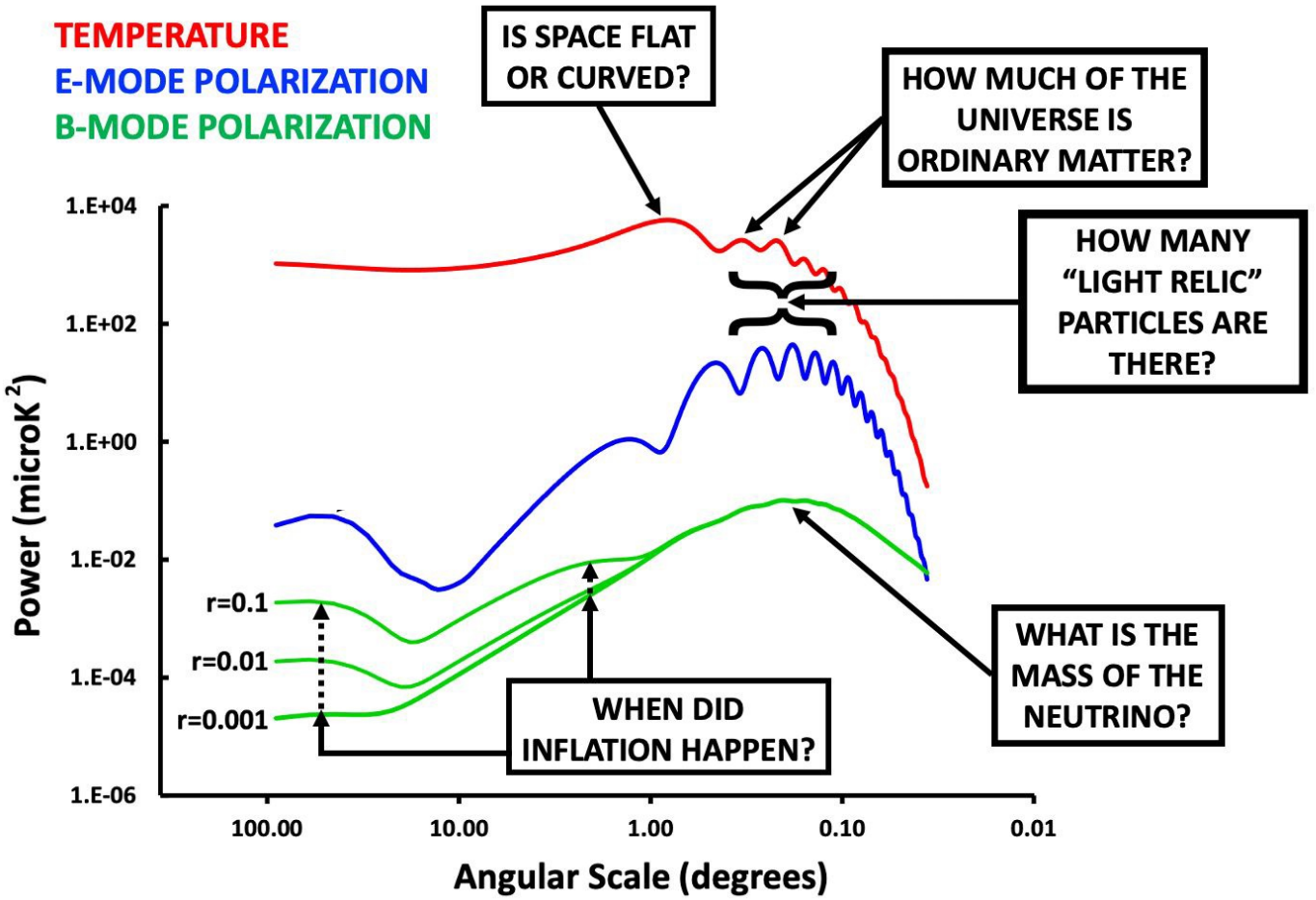
ESA, PLANCK COLLABORATION VIA NASA, VIA ASSOCIATED PRESS

The Cosmos, Back in the Day

An image from data recorded by a European Space Agency satellite shows a heat map of the universe as it appeared 370,000 years after the Big Bang. Page A10.

A Wealth of Information is Encoded in the CMB Power Spectrum

- Encoded in the weak anisotropy of the CMB intensity and polarization power is the story of the origin, evolution, and make up of the Universe.
- To extract it, we need to measure the anisotropy from angular scales of degrees to arcminutes with exquisite sensitivity and fidelity.



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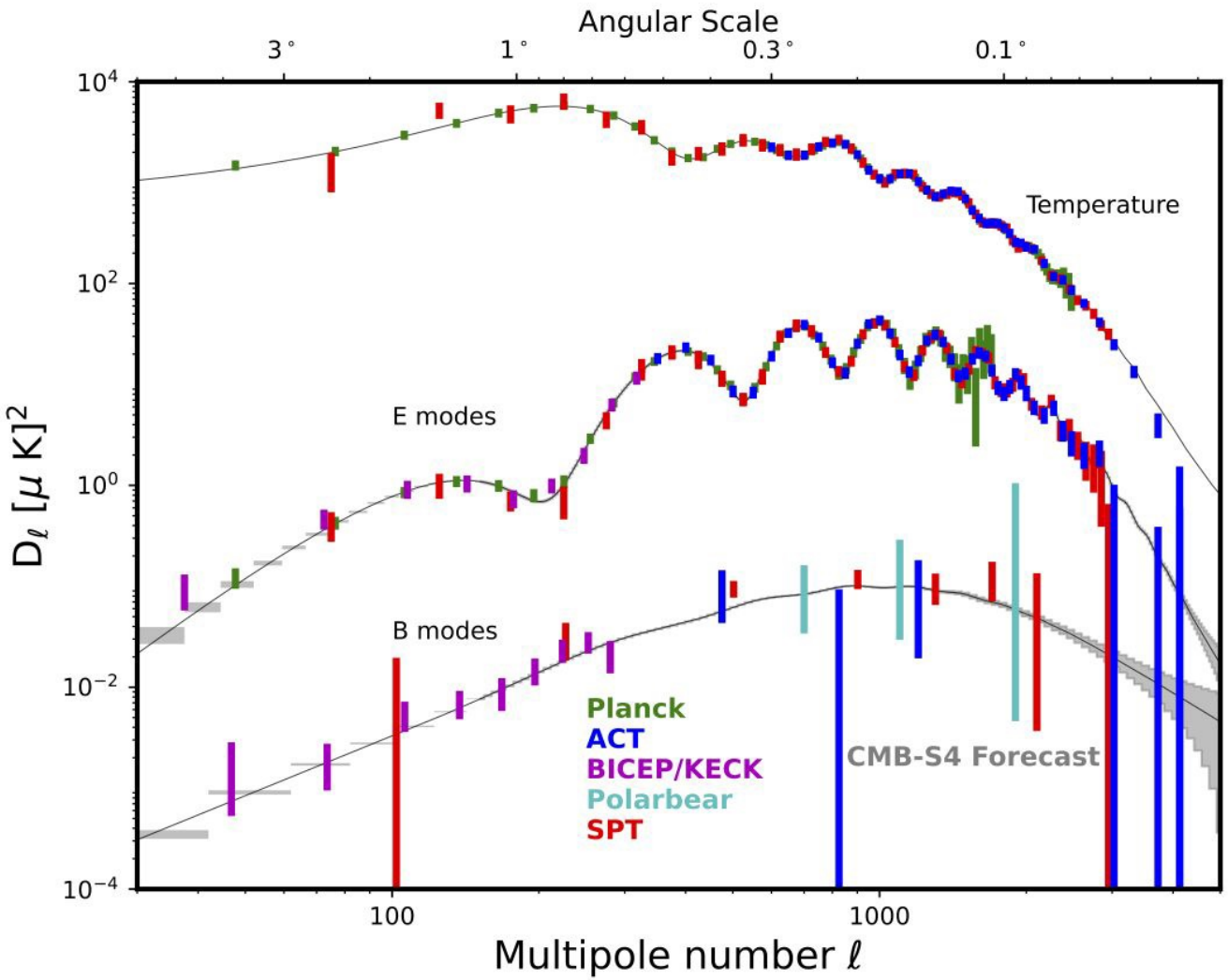
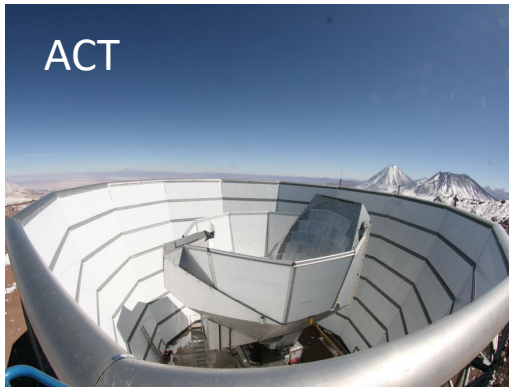


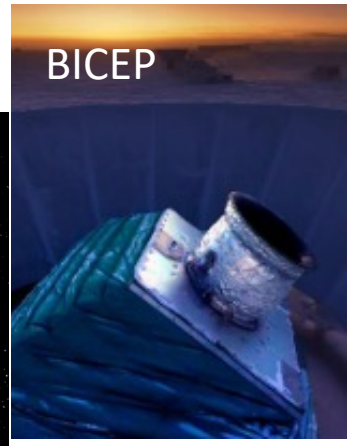
The current measurements are incredible. Measuring nanokelvin fluctuations on the 3K microwave background, in polarization.

But even more exciting fundamental science lies ahead, as sensitivity increases in the next decade.

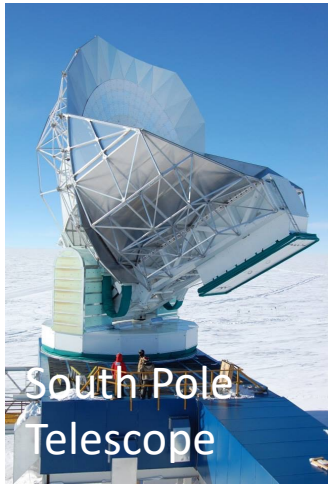
To Measure the CMB Across Angular Scales and Across the Sky, You Need Multiple Approaches

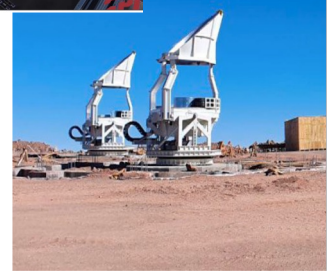
PAST



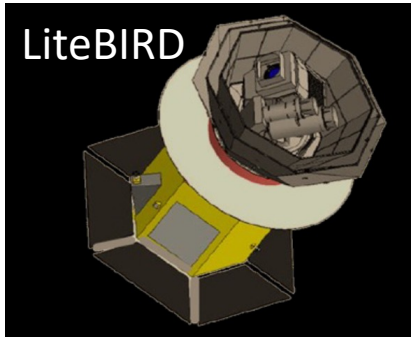


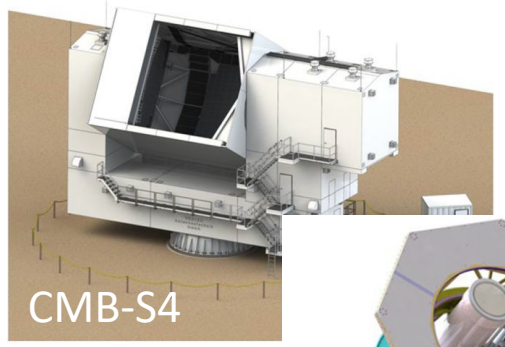
PRESENT

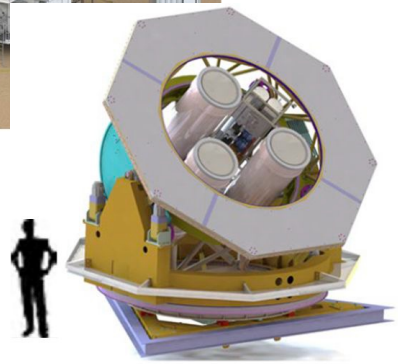




FUTURE





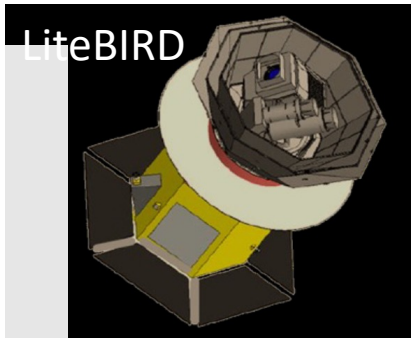


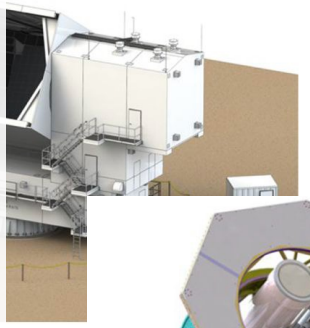
To Measure the CMB Across Angular Scales and Across the Sky, You Need Multiple Approaches

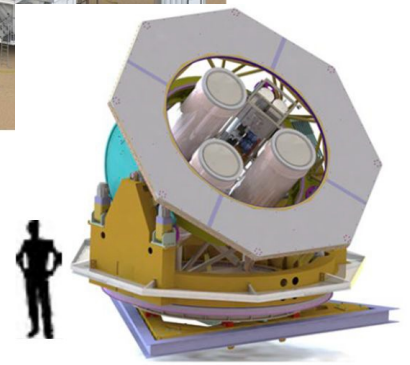
PAST

PRESENT

FUTURE







Space-based and ground-based experiments each have a unique place and excel at different measurements

Ground-based telescopes fall into ~2 categories: Small Aperture (large angular scales) and Large Aperture (smaller angular scales)

Name of the Game:

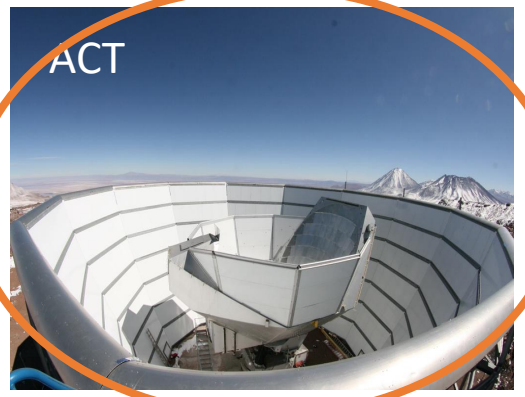
- Scale up number of detectors --> increased sensitivity
- Control instrumental systematics to not limit sensitivity

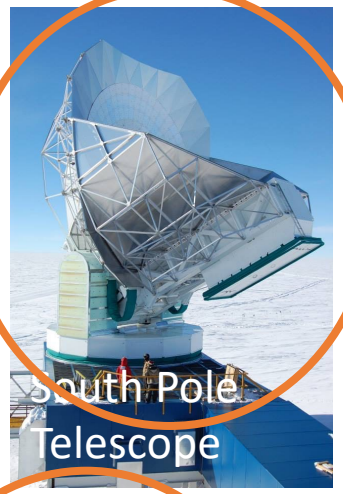
To Measure the CMB Across Angular Scales and Across the Sky, You Need Multiple Approaches

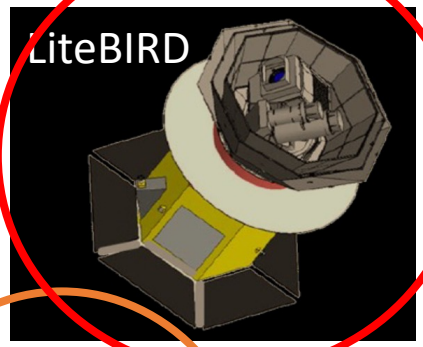
PAST

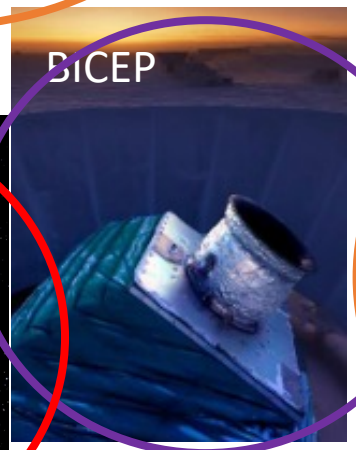
PRESENT

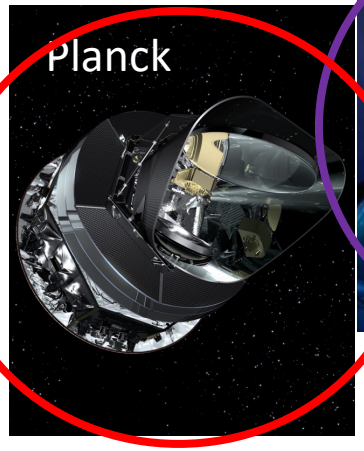
FUTURE

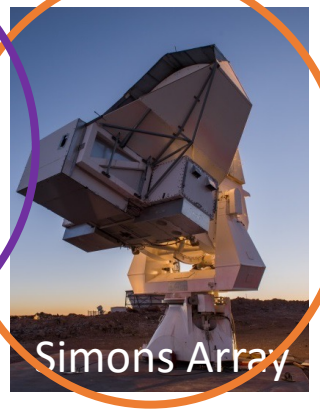


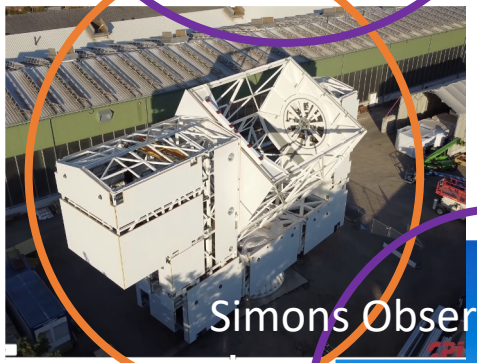


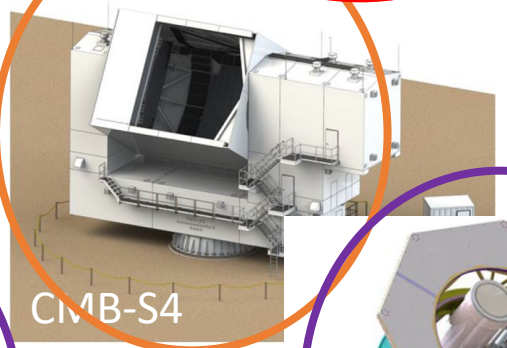


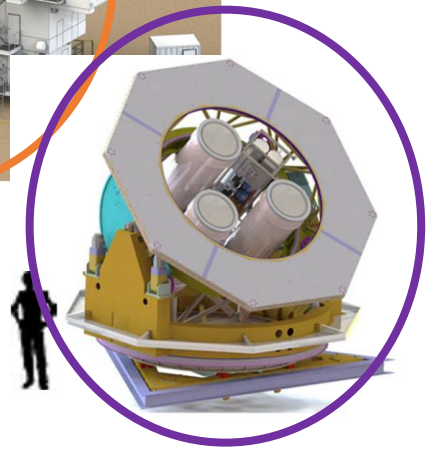












Small Aperture

Large Aperture

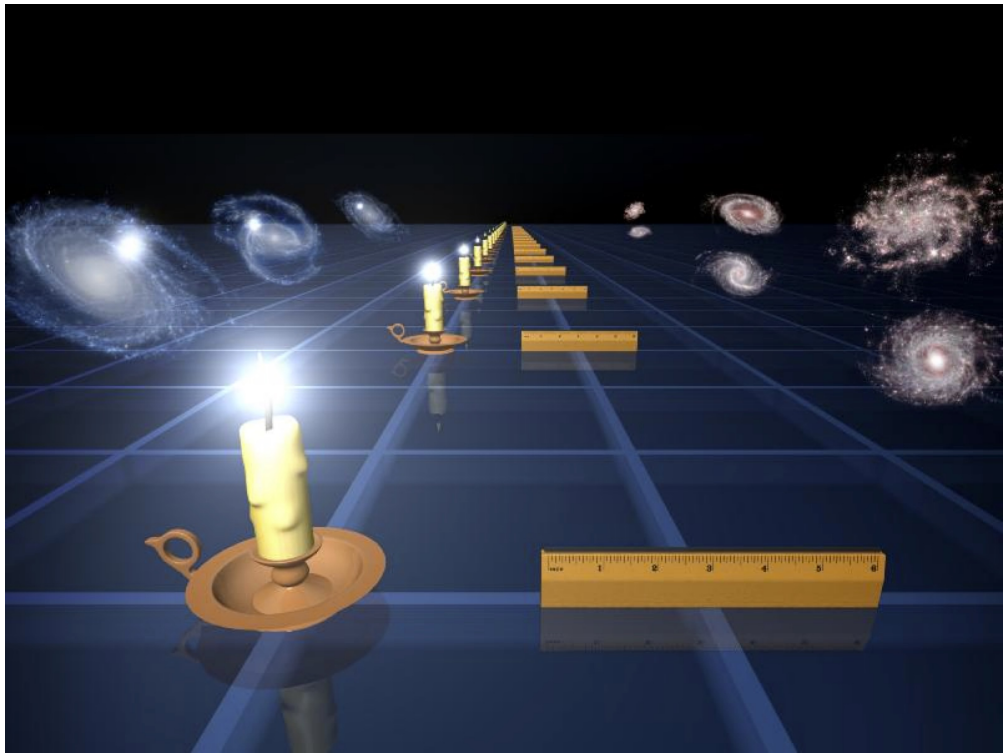
Space Based

The time evolution of the clumping of matter also contains a wealth of information

Geometric Probes

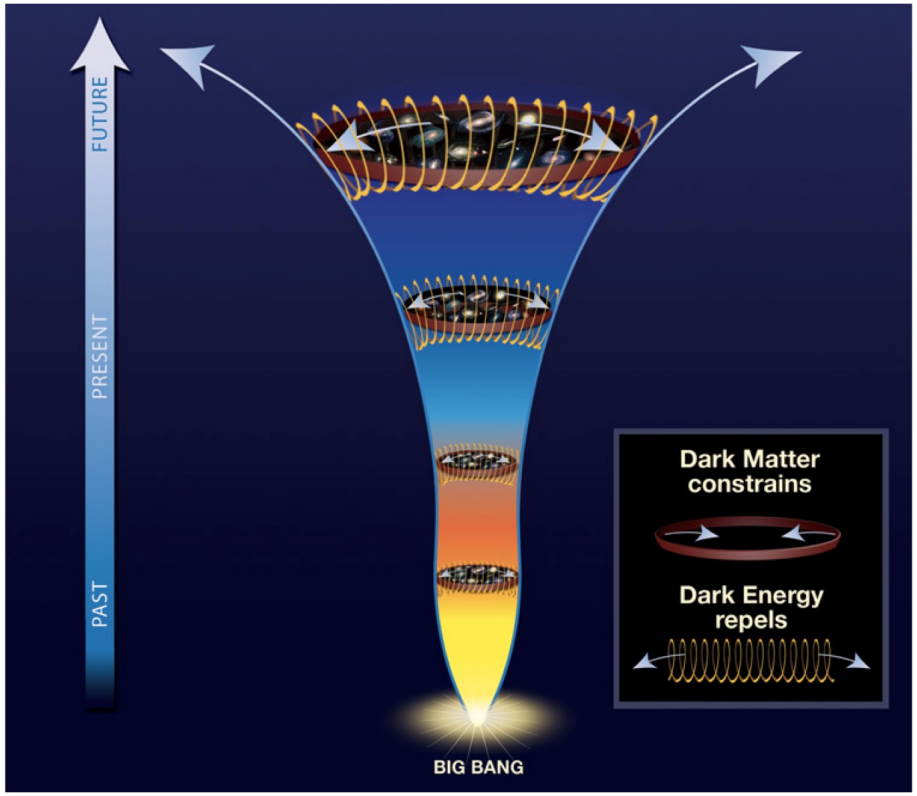
Standard Candles (e.g., supernova, gravitational waves)

Standard Rulers (e.g., baryon acoustic oscillations)



Growth of Structure

e.g., large-scale structure of galaxies, galaxy clusters, weak lensing



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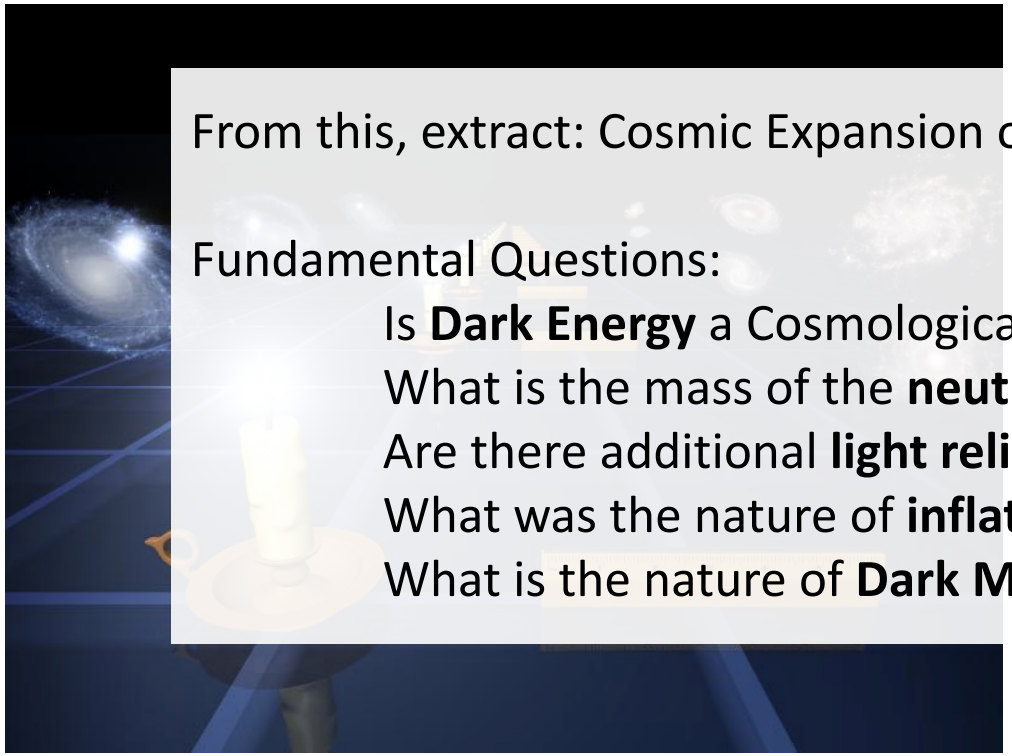

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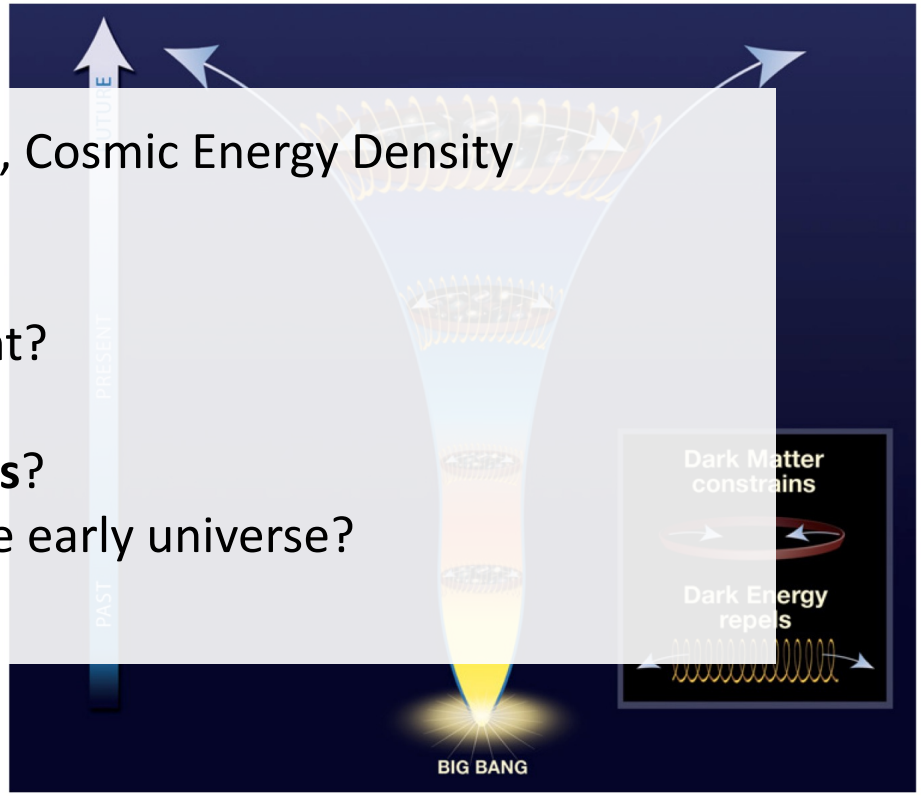


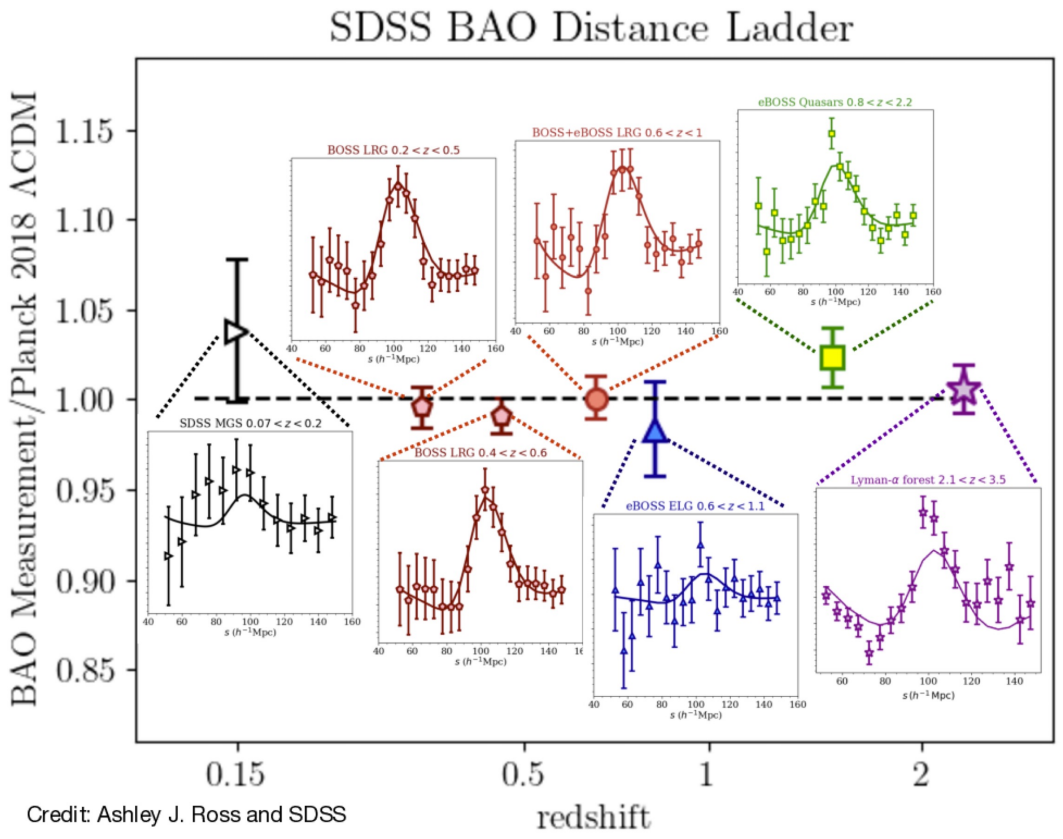
From this, extract: Cosmic Expansion over Time, Cosmic Energy Density

Fundamental Questions:

- Is **Dark Energy** a Cosmological Constant?
- What is the mass of the **neutrino**?
- Are there additional **light relic particles**?
- What was the nature of **inflation** in the early universe?
- What is the nature of **Dark Matter**?

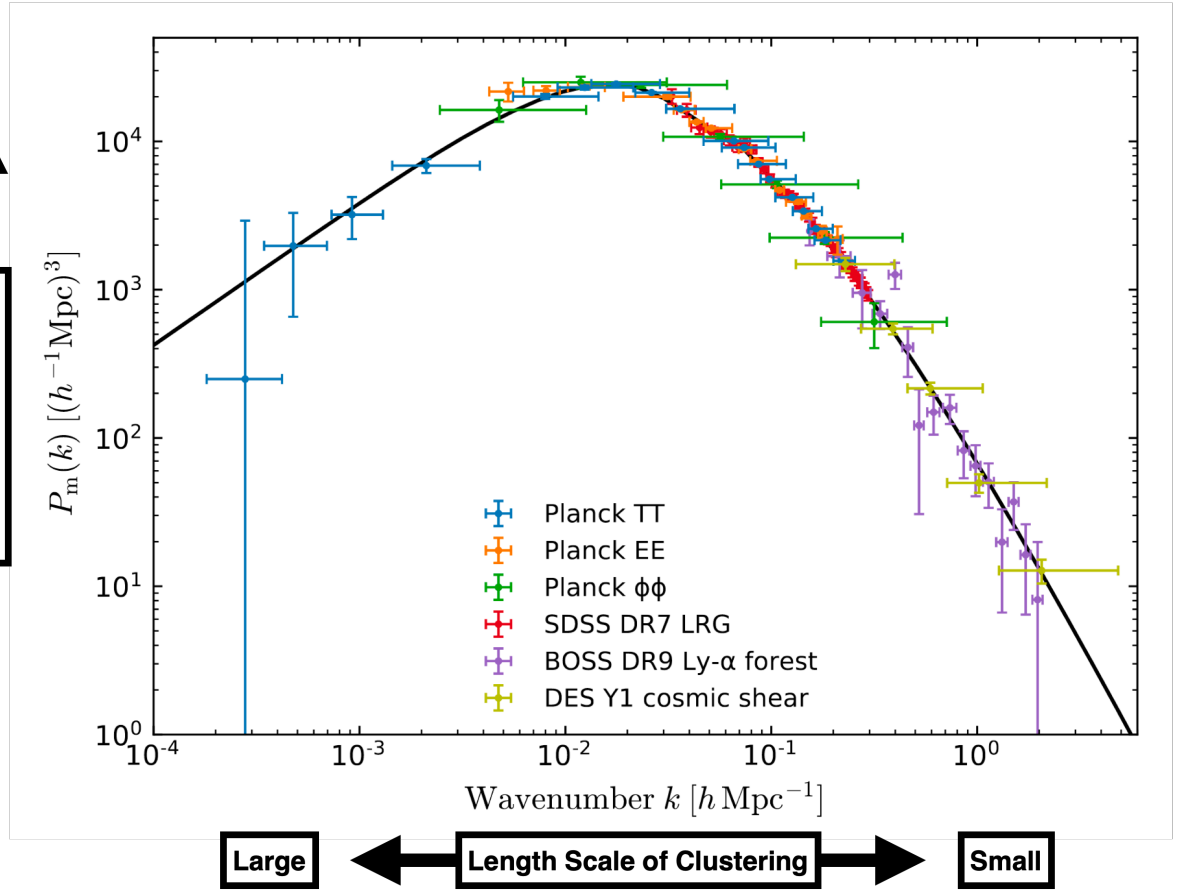
The time evolution of the clumping of matter also contains a wealth of information

Geometric Probes

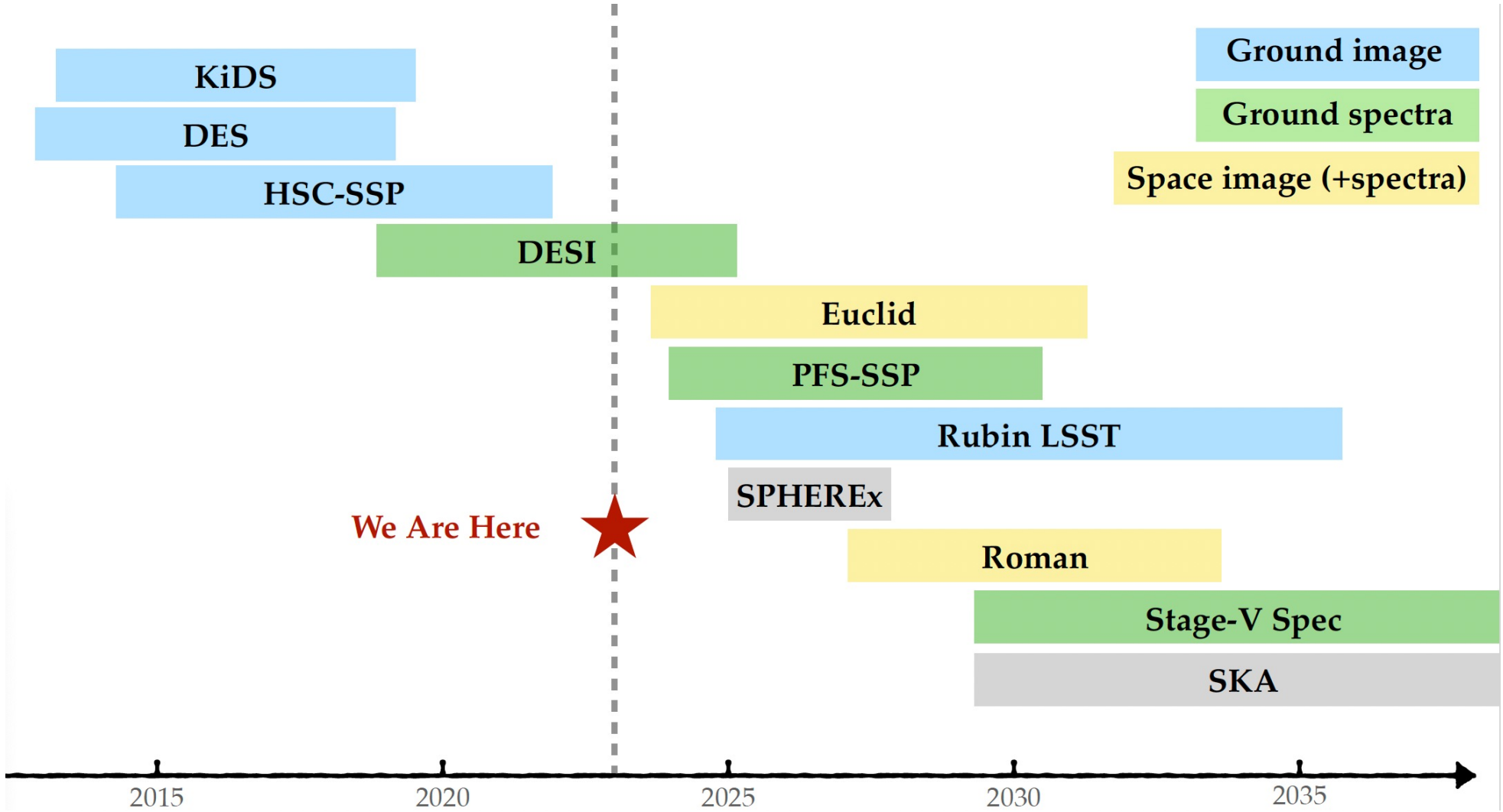


Credit: Ashley J. Ross and SDSS

Growth of Structure



Galaxy Surveys Come in Two Flavors: Imaging and Spectroscopic



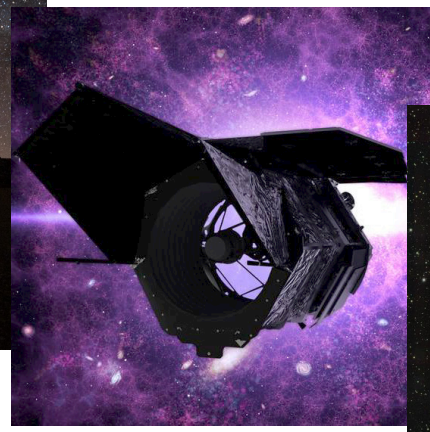
Galaxy Surveys Come in Two Flavors: Imaging and Spectroscopic

DESI/DESI-II

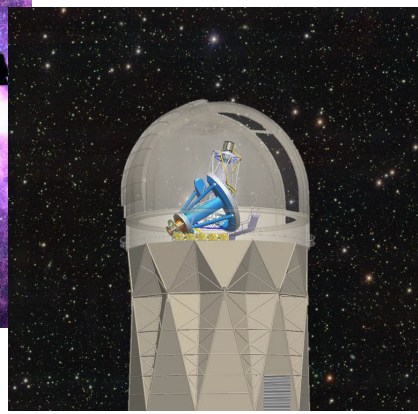
PFS@Subaru

Euclid

Rubin-LSST



Roman



Spec-S5

Need both to get lots of galaxies (statistics) and their redshifts (distances)

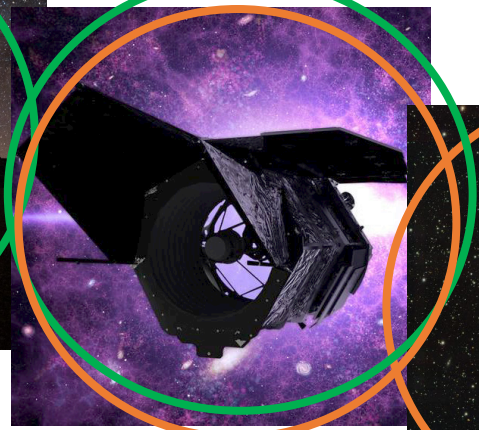
Galaxy Surveys Come in Two Flavors: Imaging and Spectroscopic

DESI/DESI-II

PFS@Subaru

Euclid

Rubin-LSST



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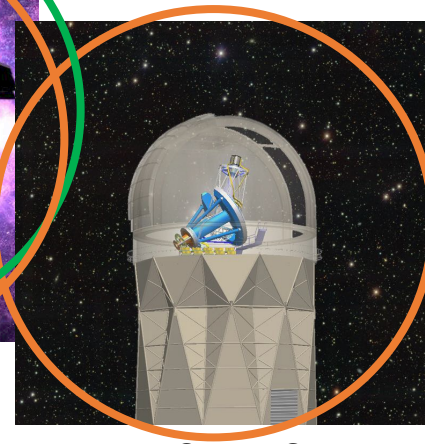


Spec-S5

Spectroscopic

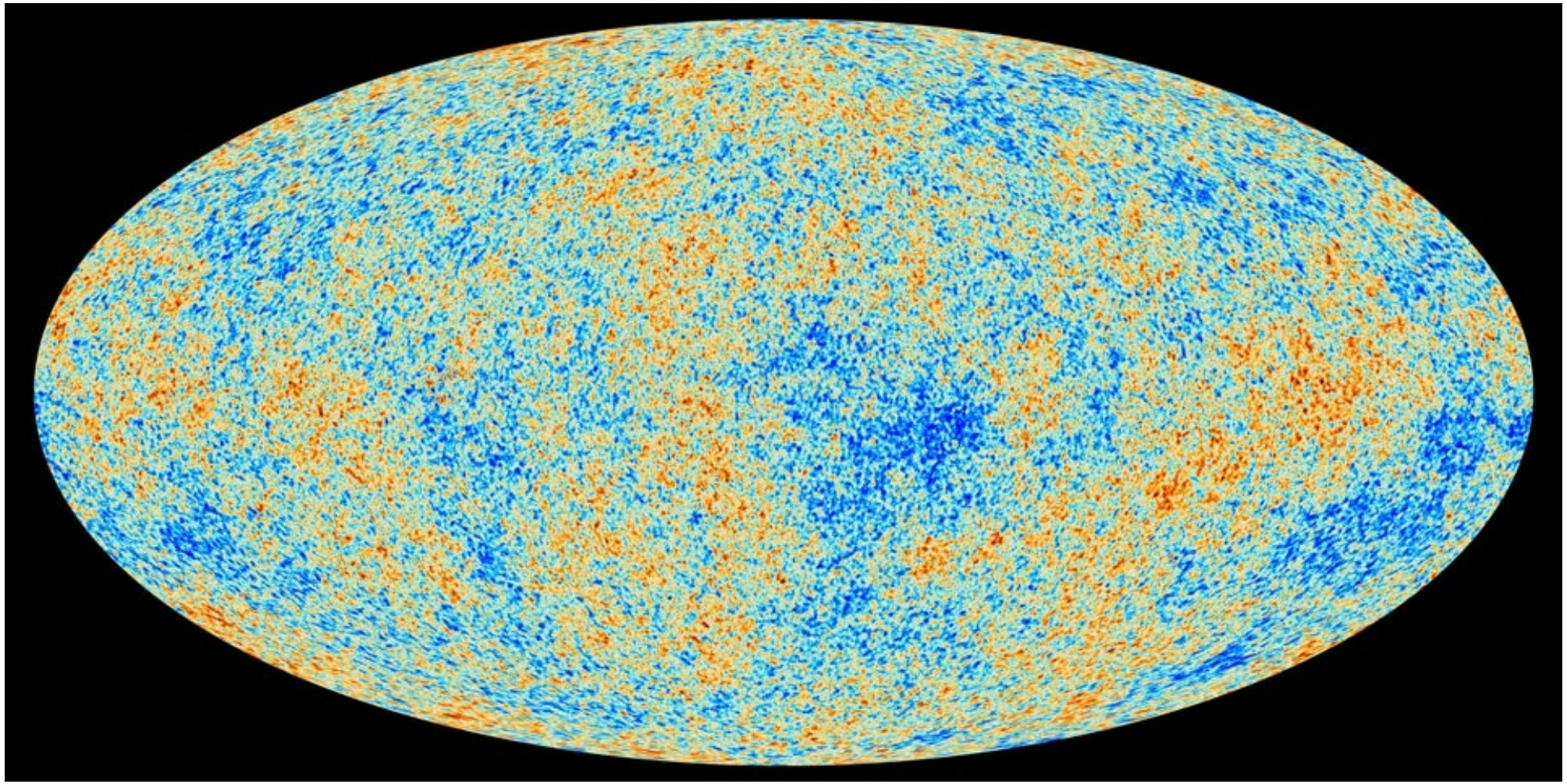
Imaging

Line Intensity Mapping: Mapping Line Emission from Matter Over Cosmic Time

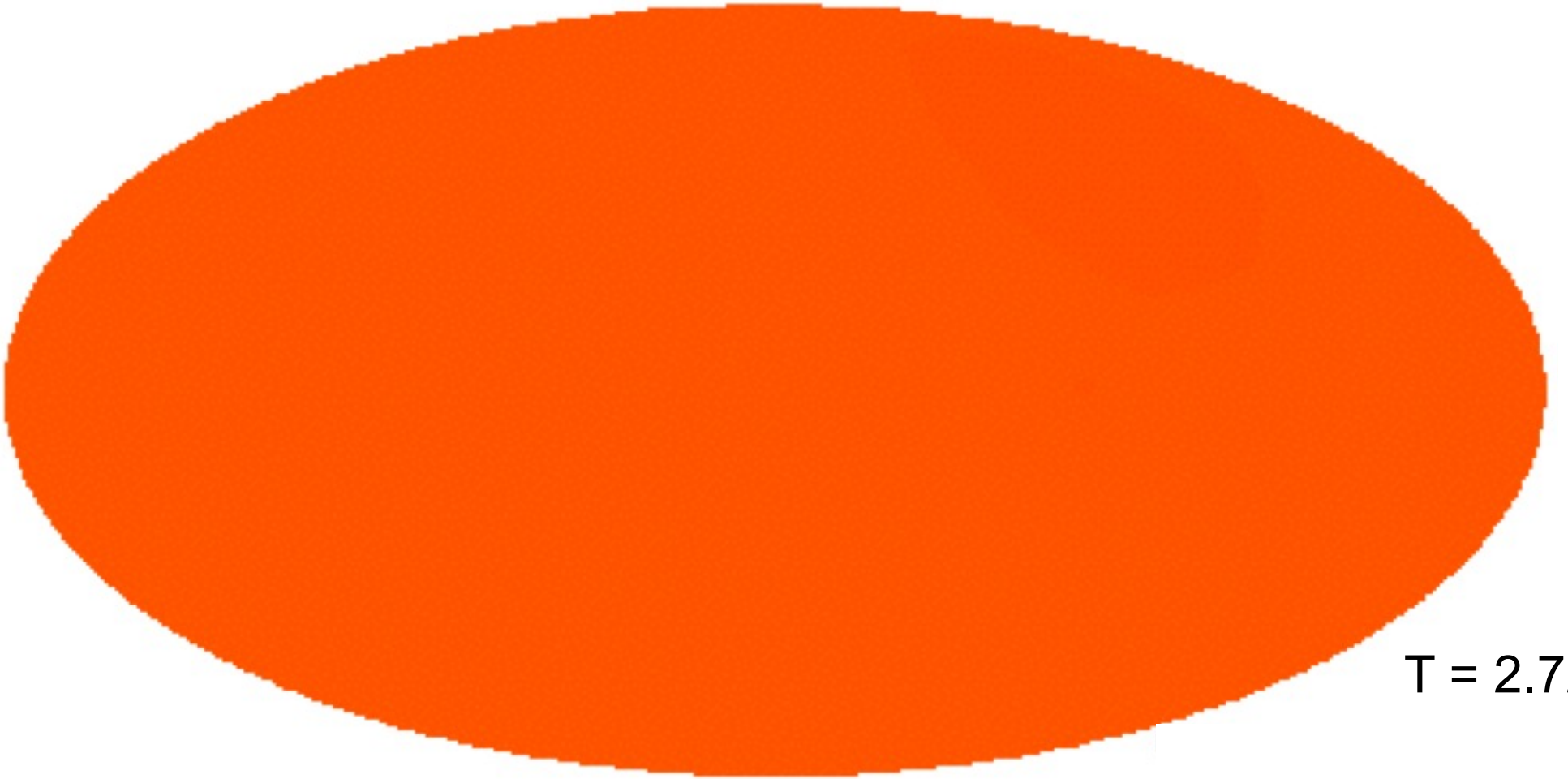
- A new technique for mapping matter v. time: map the abundance of some element (e.g. Neutral Hydrogen via 21cm emission, or CO/CII lines via millimeter or sub-mm emission) over time.
- Can get to higher redshifts → map much more volume, and when things were simpler in the universe.

A Deeper Dive into One Science Question:
What is the Nature of Inflation in the Early Universe?

Reminder



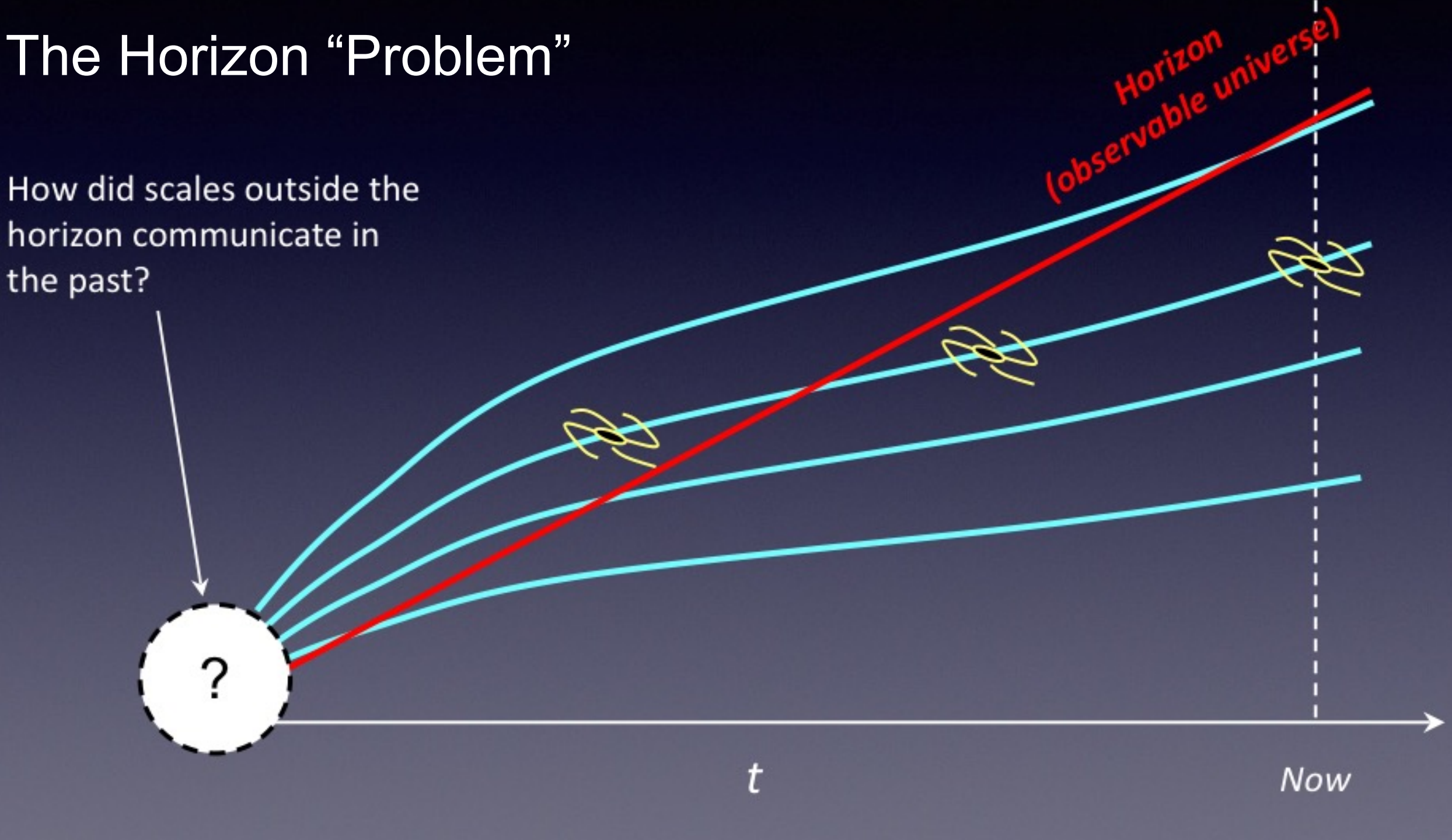
Reminder



T = 2.728 K

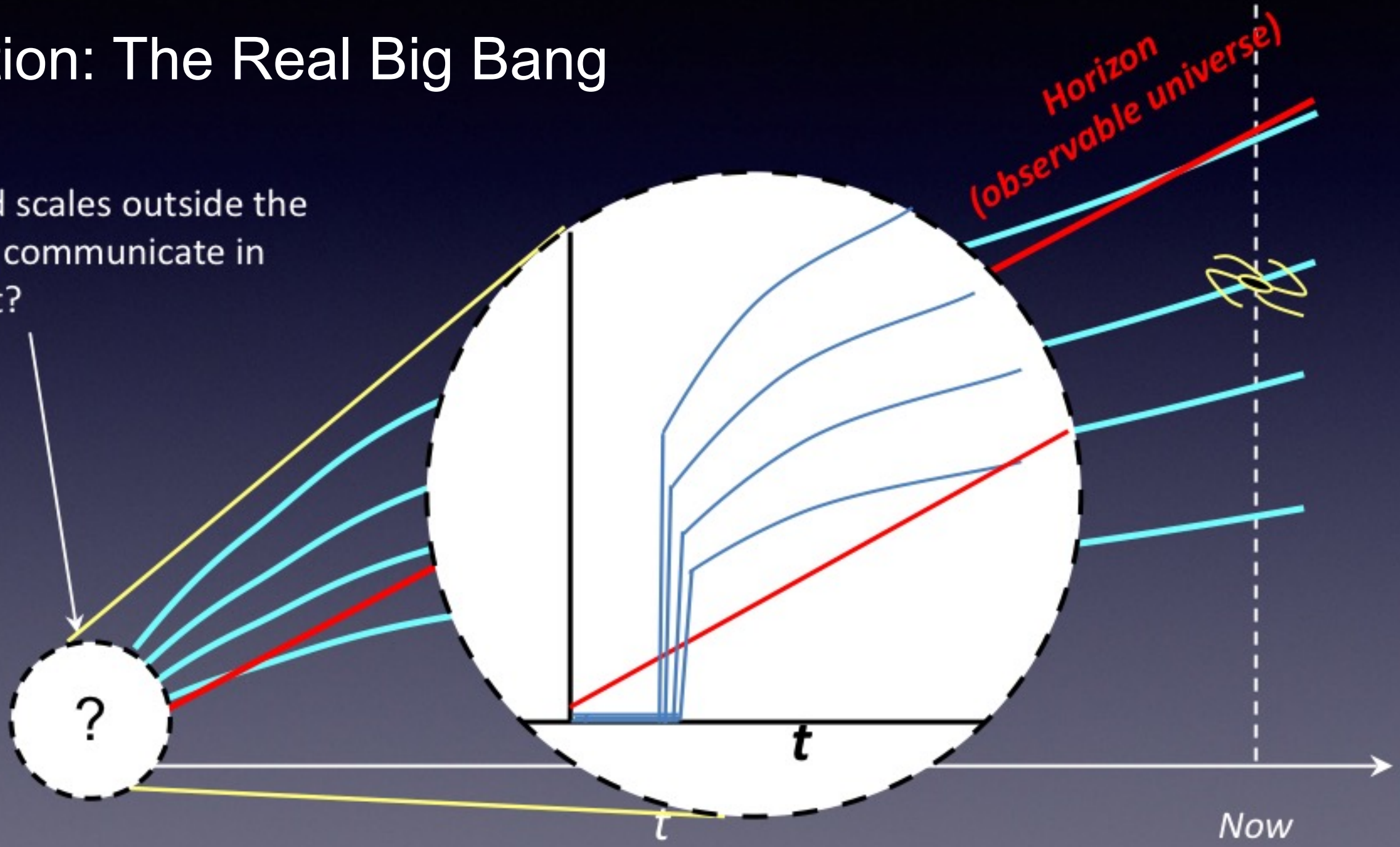
Homogeneous, isotropic, spatially flat, ….

The Horizon “Problem”

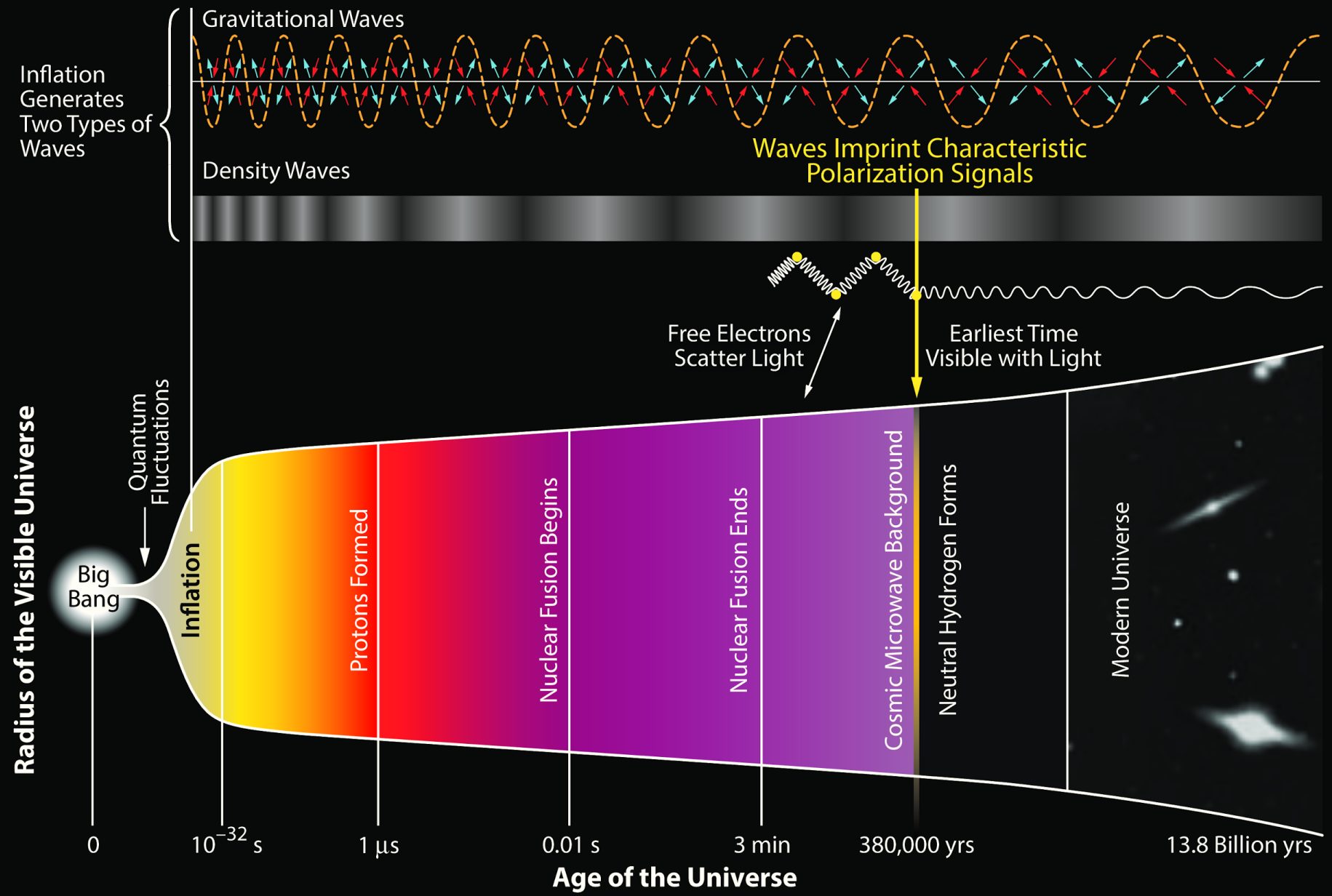


Inflation: The Real Big Bang

How did scales outside the horizon communicate in the past?



History of the Universe



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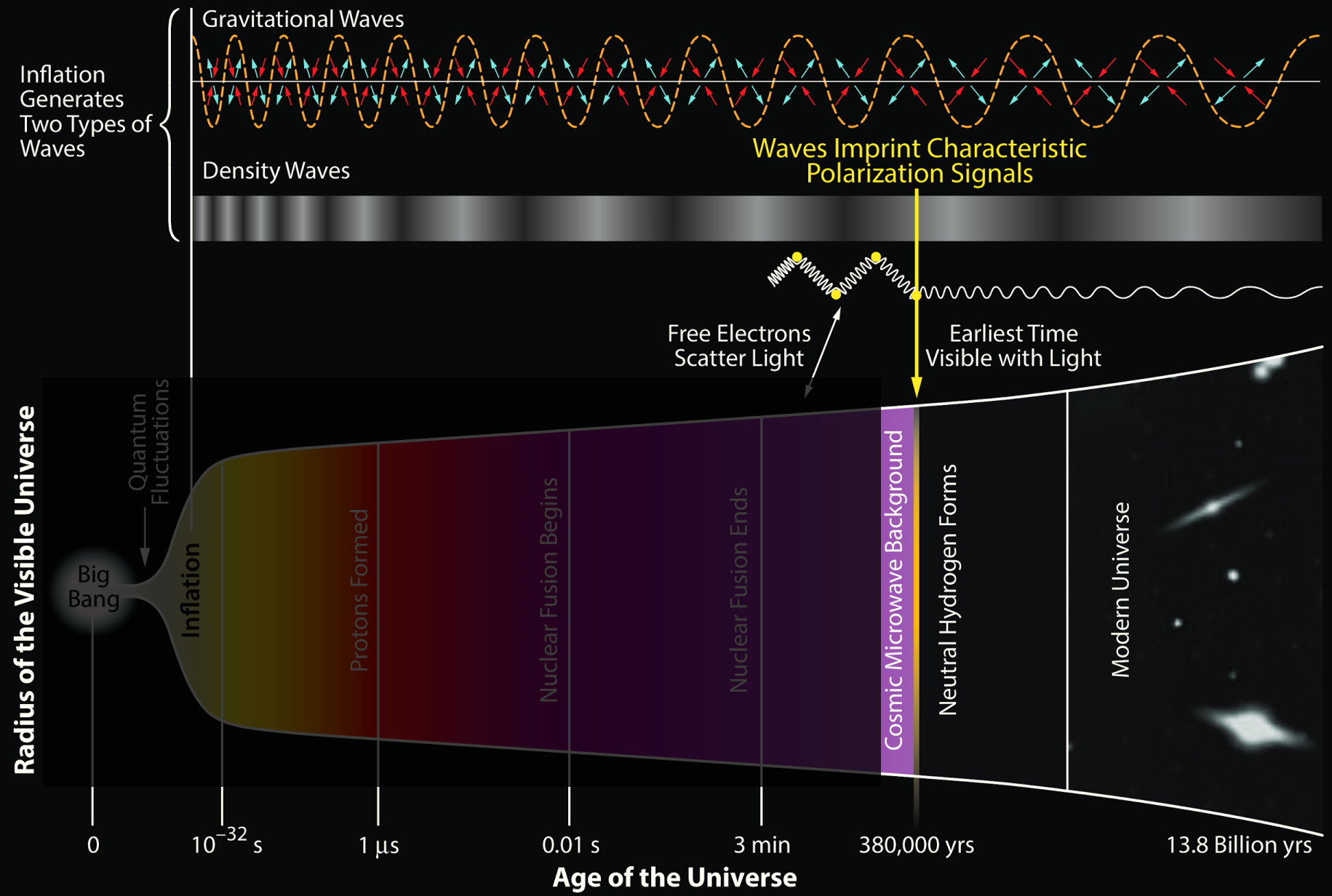
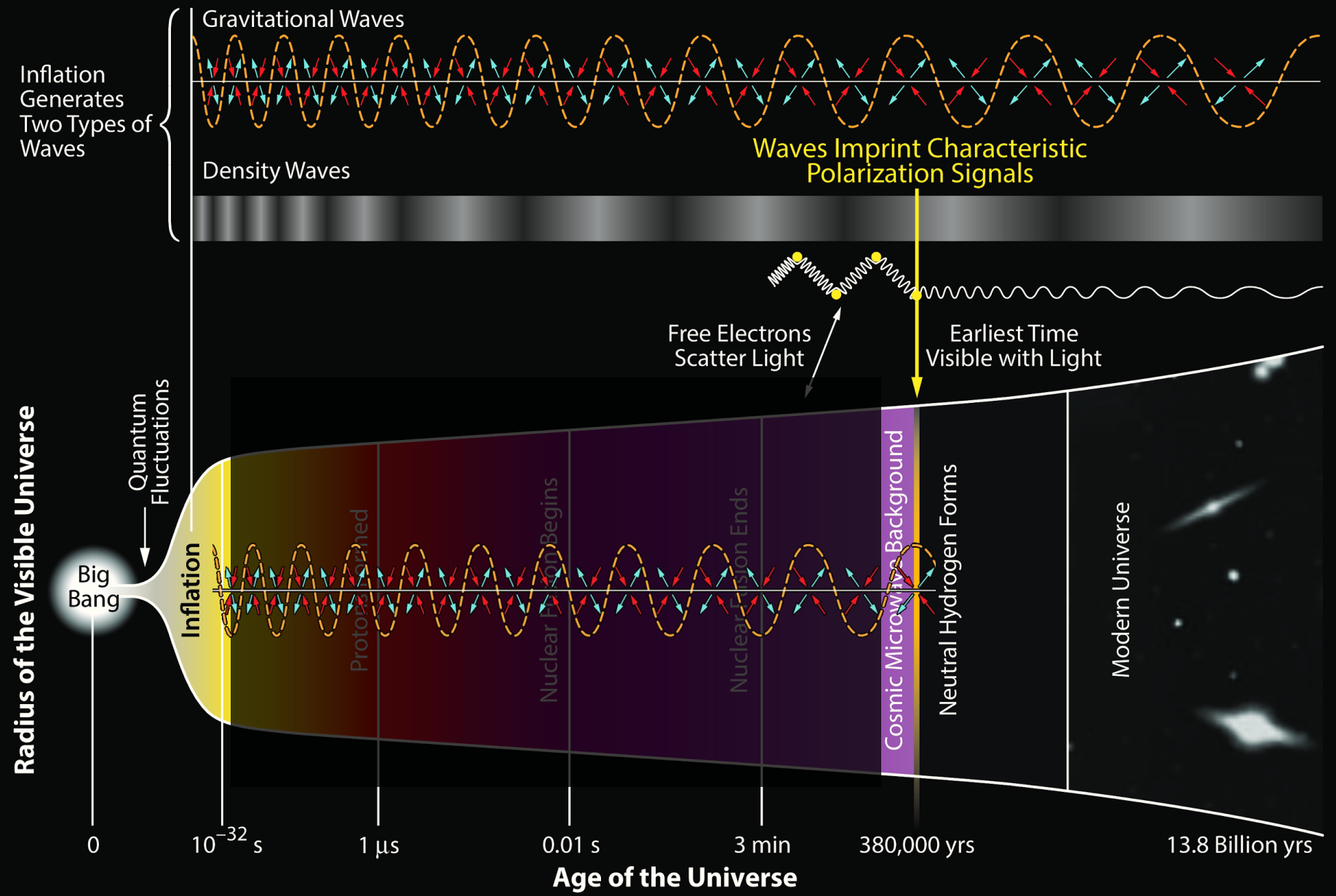
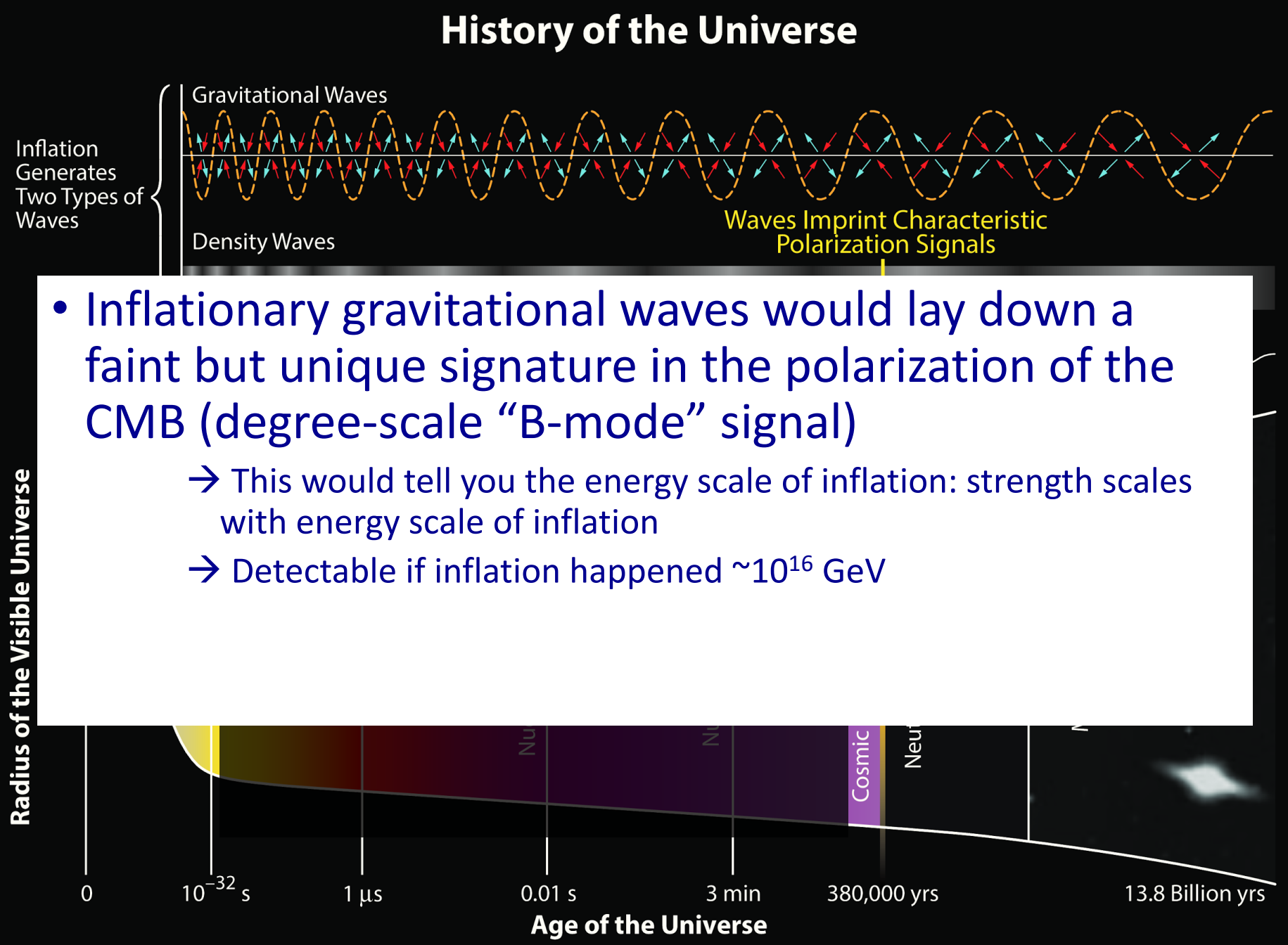


History of the Universe





- Inflationary gravitational waves would lay down a faint but unique signature in the polarization of the CMB (degree-scale "B-mode" signal)
  - → This would tell you the energy scale of inflation: strength scales with energy scale of inflation
  - → Detectable if inflation happened ~10^{16} GeV

Current constraints on the energy scale of inflation

Inflationary B-modes are a Big Deal!

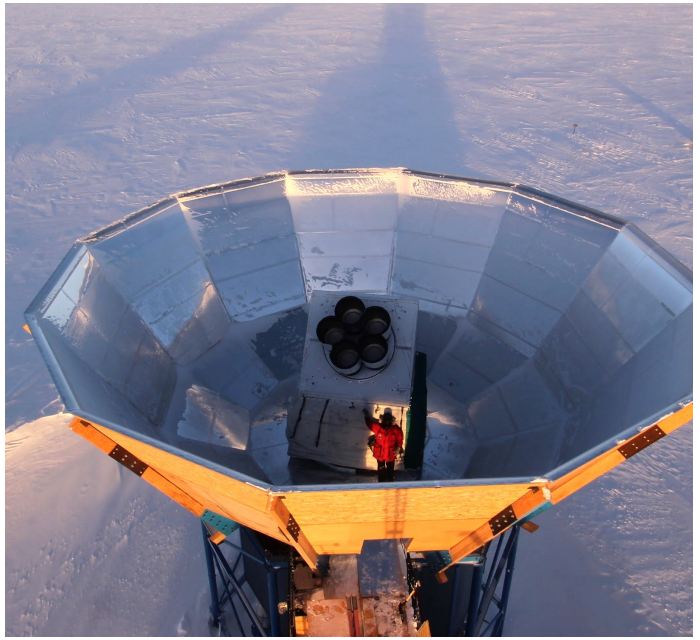
- A key test of inflation and our origins

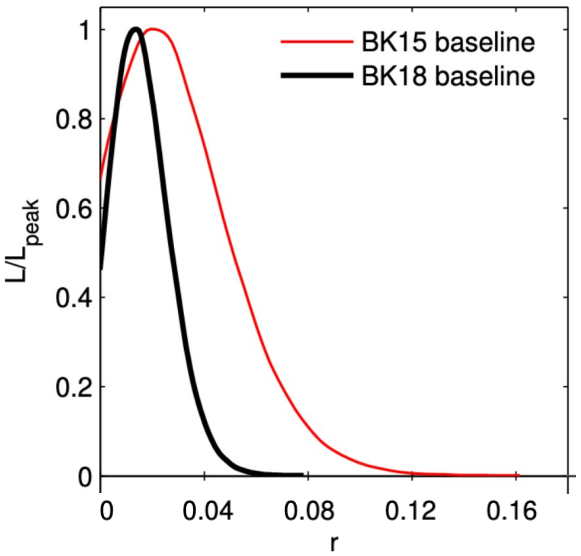
$$\text{time} = 10^{-36} \left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

- A relic from 10^{36} times earlier than the light elements created at t = 1 second.

$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

- Probing physics at the scale of superstring theory, a trillion times beyond the reach of the LHC.
- Insights into quantum gravity

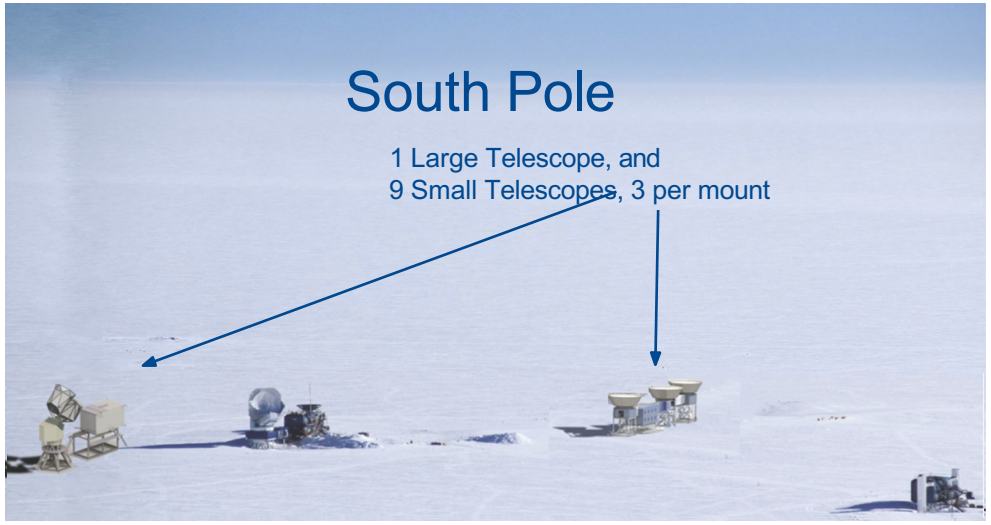


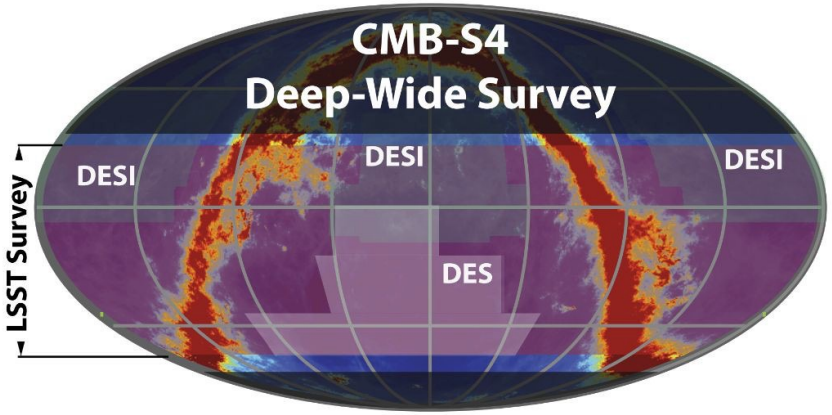


BICEP/Keck Array, PRL 2021

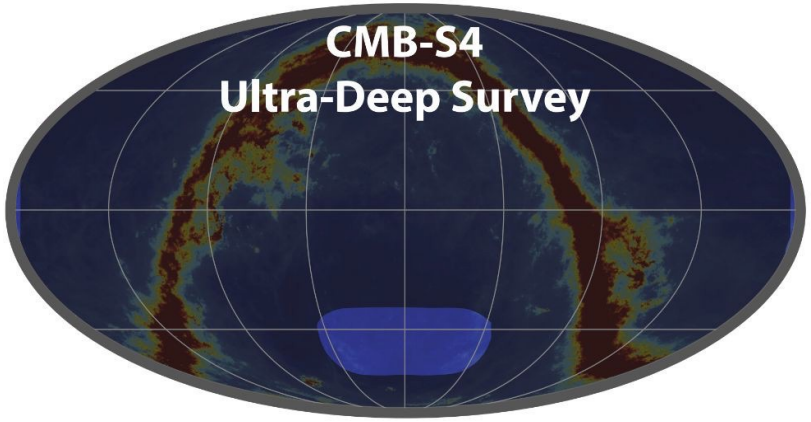
- Best constraint: BICEP/Keck Array, with WMAP and Planck Data
- $r < 0.03$ @95% confidence
- Improvements in the next 5 years will come from BICEP Array and Simons Observatory (one order of magnitude)

CMB-S4: A Powerhouse Ground-Based CMB Experiment with Multiple Science Drivers: Inflation, Light Relics, Neutrinos, Dark Energy





Observed from Chile



Observed from South Pole

Large area survey motivated by N_{eff}, matter mapping, and time domain science and enabled by the mid-latitude site

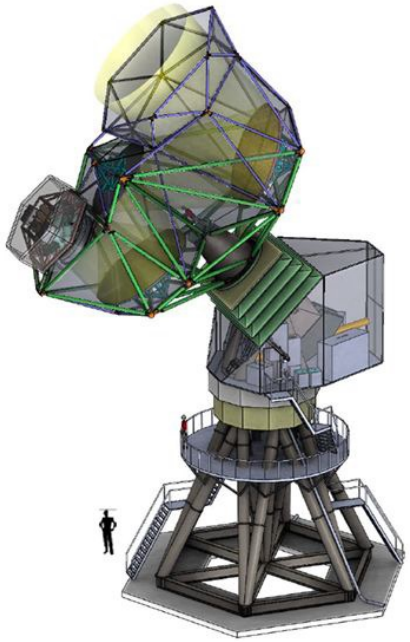
Small area survey primarily targeting inflationary gravitational waves, enabled by the sky coverage, low horizon blockage, and ultra stable atmosphere

Science Target on inflation, to cross critical theoretical thresholds:
$r < 0.0005$

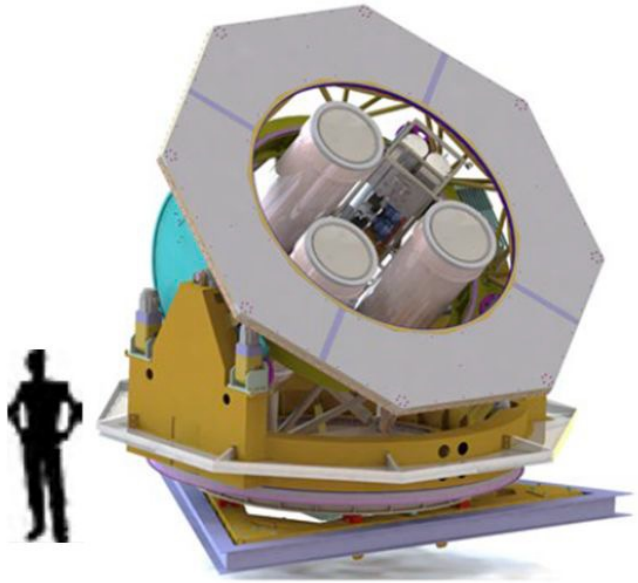
CMB-S4: A Powerhouse Ground-Based CMB Experiment

500,000 detectors across 12 telescopes and 2 sites

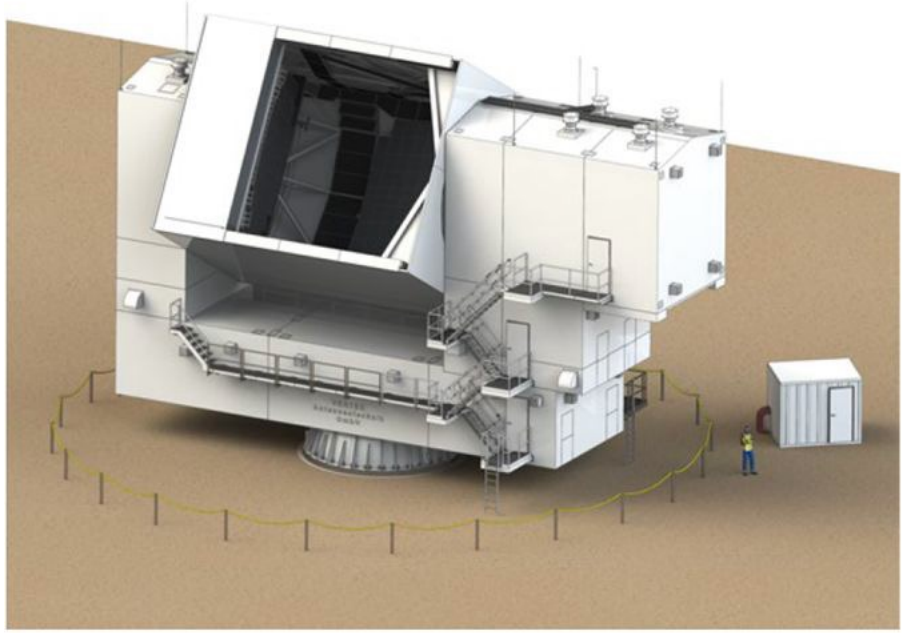
1 x Large Aperture Telescope at South Pole, Designed for high throughput and systematics control.



9 x Small Aperture Telescopes at South Pole, Designed for maximal sensitivity with exquisite systematics control.



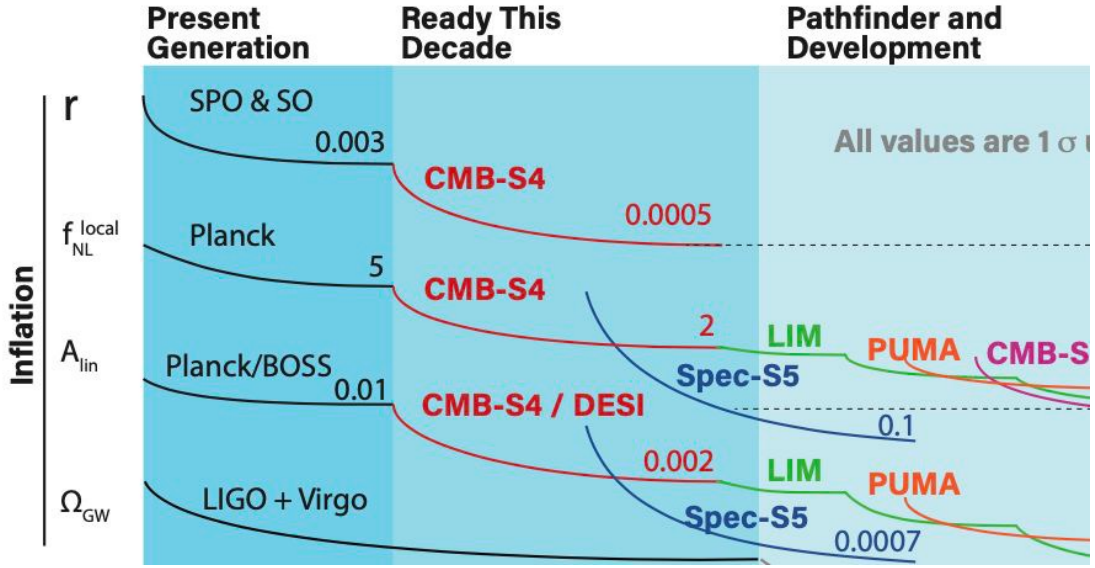
2 x Large Aperture Telescopes in Chile, Designed for sensitivity at smaller angular scales.



Inflation and Non-Gaussianity from Galaxy Surveys

- Simplest inflationary model predicts nearly Gaussian primordial fluctuations. Physics beyond single-field, slow roll inflation produces unique signatures:
  - Additional light field: primordial Non-Gaussianity (PNG) with local shape
  - Inflation self-interactions: equilateral/orthogonal PNG
  - Departure from scale invariance: power spectrum features

- Galaxy surveys, and later LIM, can measure two parameters that would help describe the physics of inflation: f_{NL} and A_{lin}



Summary

- Advances in our understanding of fundamental physics will come from cosmology in the next 10 years.
  - Including results from: South Pole Telescope, BICEP Array, Simons Observatory, LiteBIRD, DESI, Rubin-LSST, PFS, Euclid, and Roman.
- New projects also aim to begin construction.
  - Including: DESI-II, CMB-S4, Spec-S5