
THE DARK ENERGY SURVEY

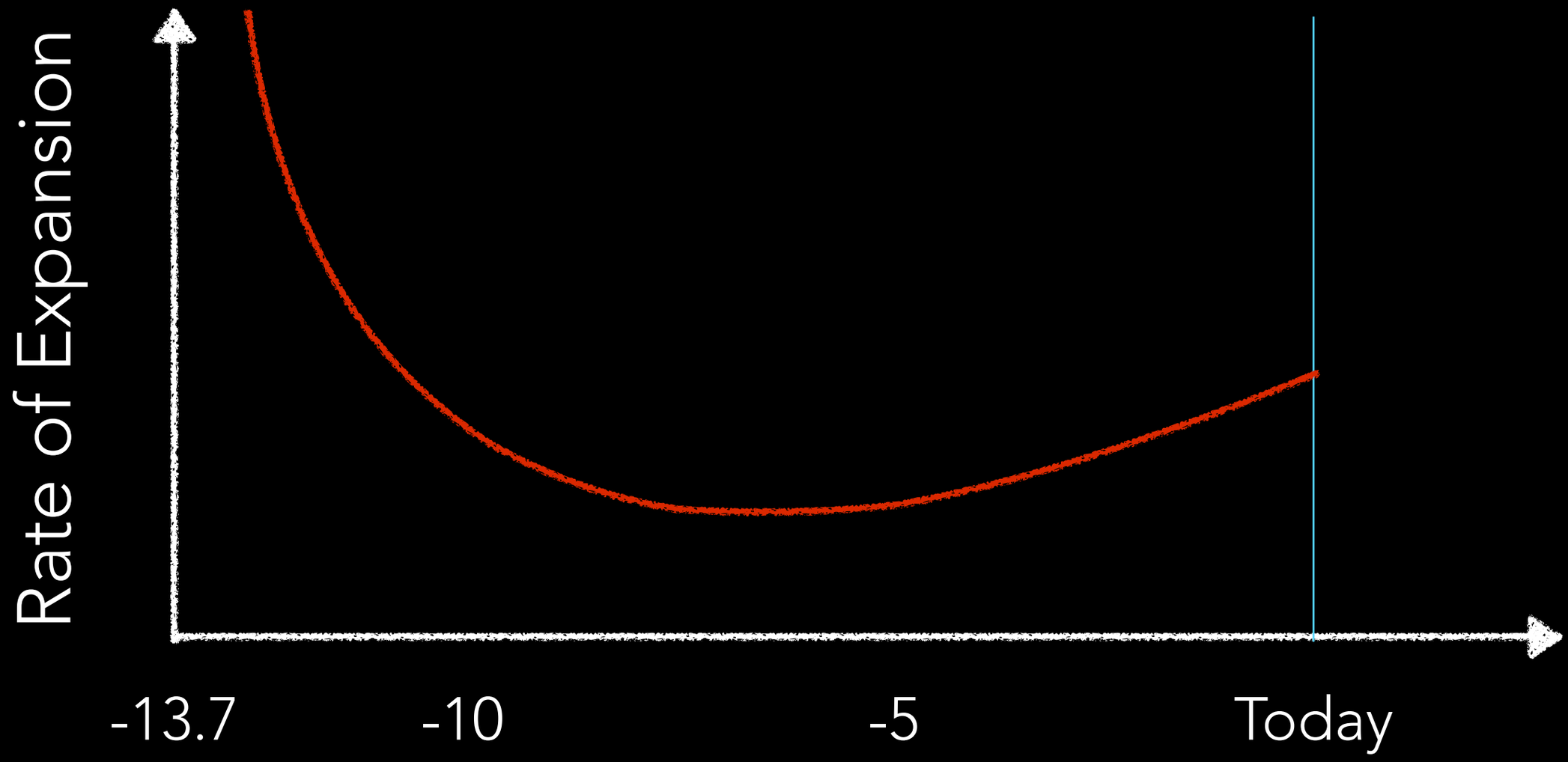
AN EXPERIMENTAL PERSPECTIVE

DARK ENERGY

Keith Bechtol
KICP Fellow, University of Chicago

DARK ENERGY

"Placeholder" name for the ***something*** causing space to expand at an ever increasing rate



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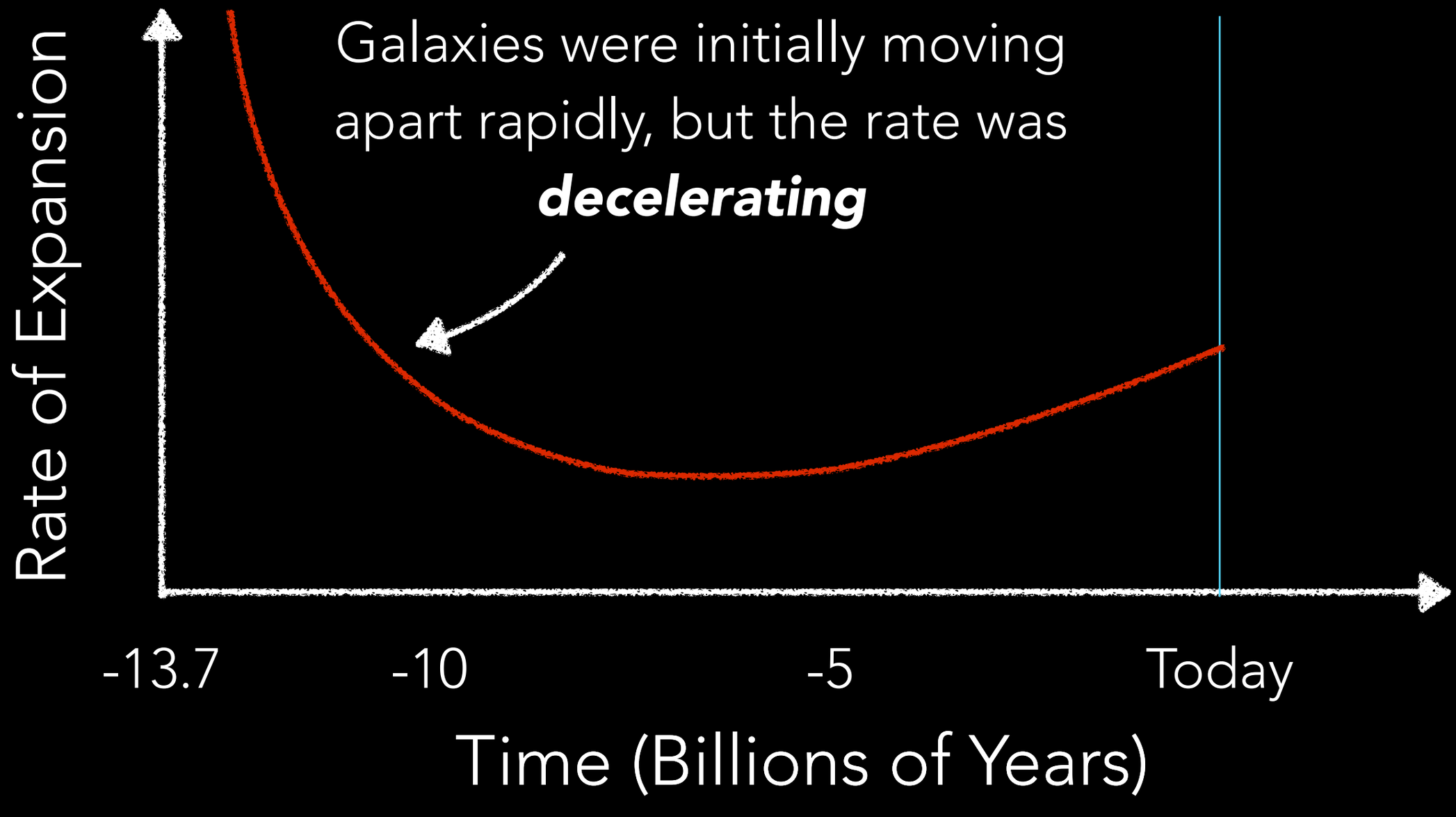

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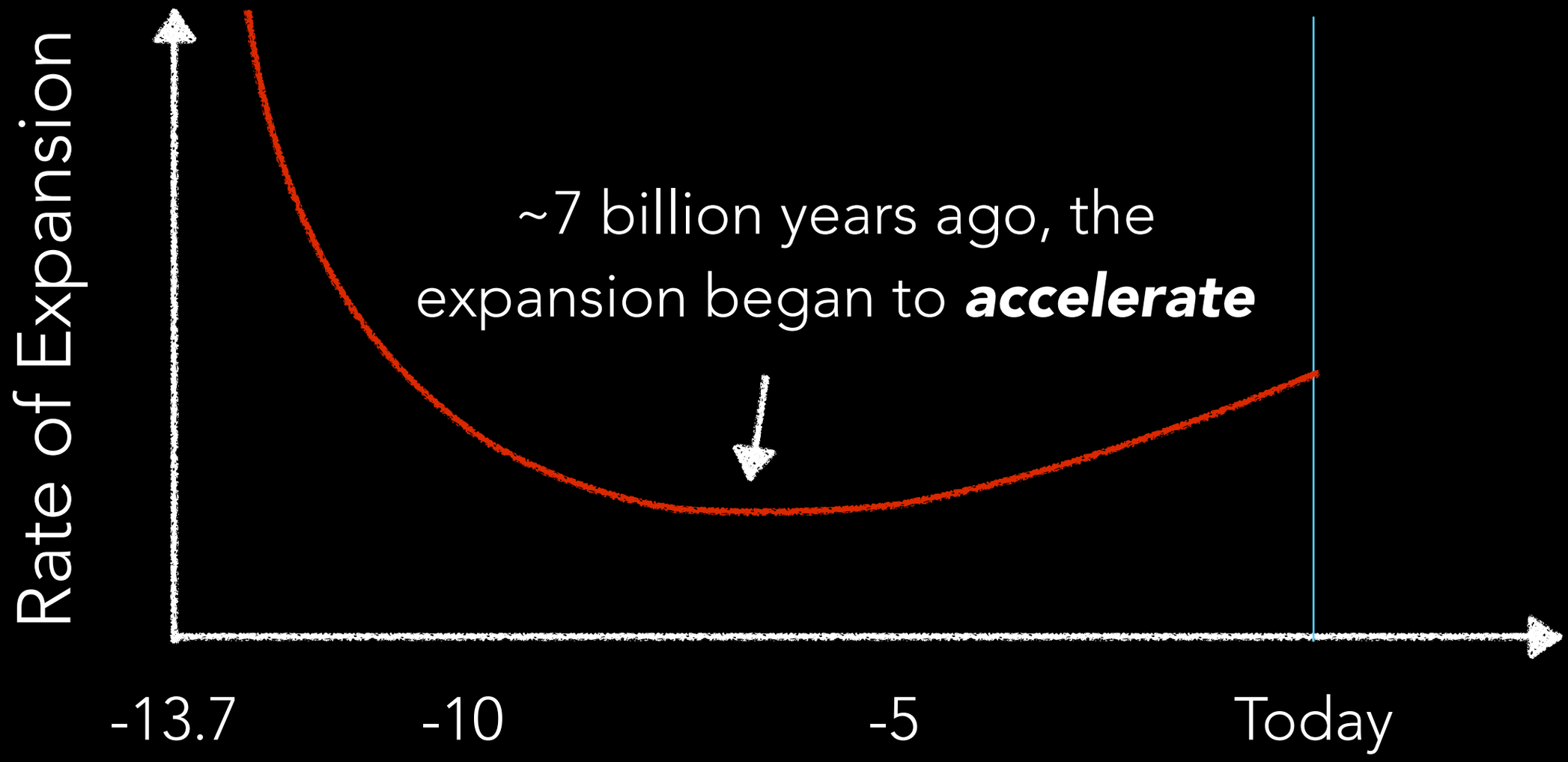

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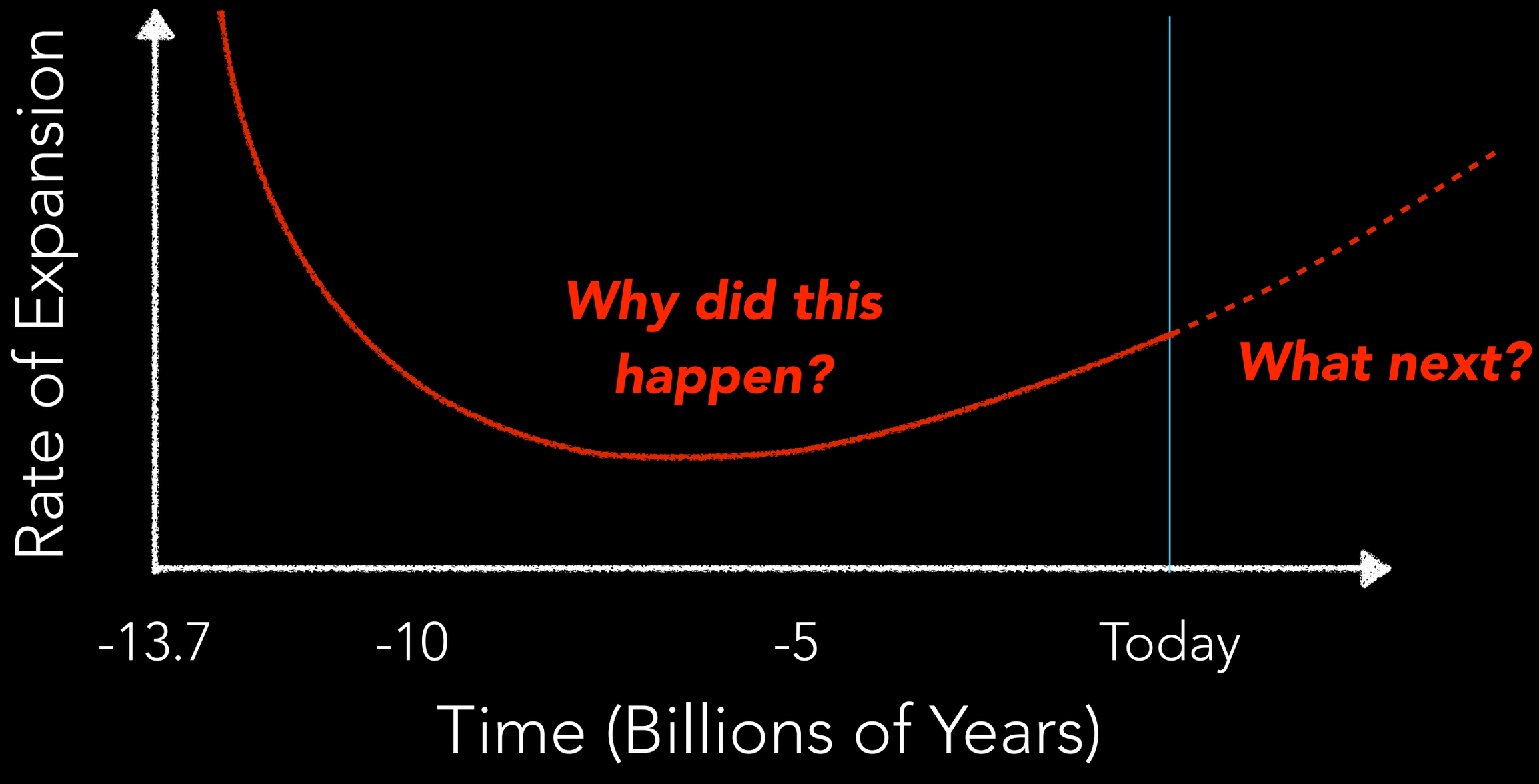
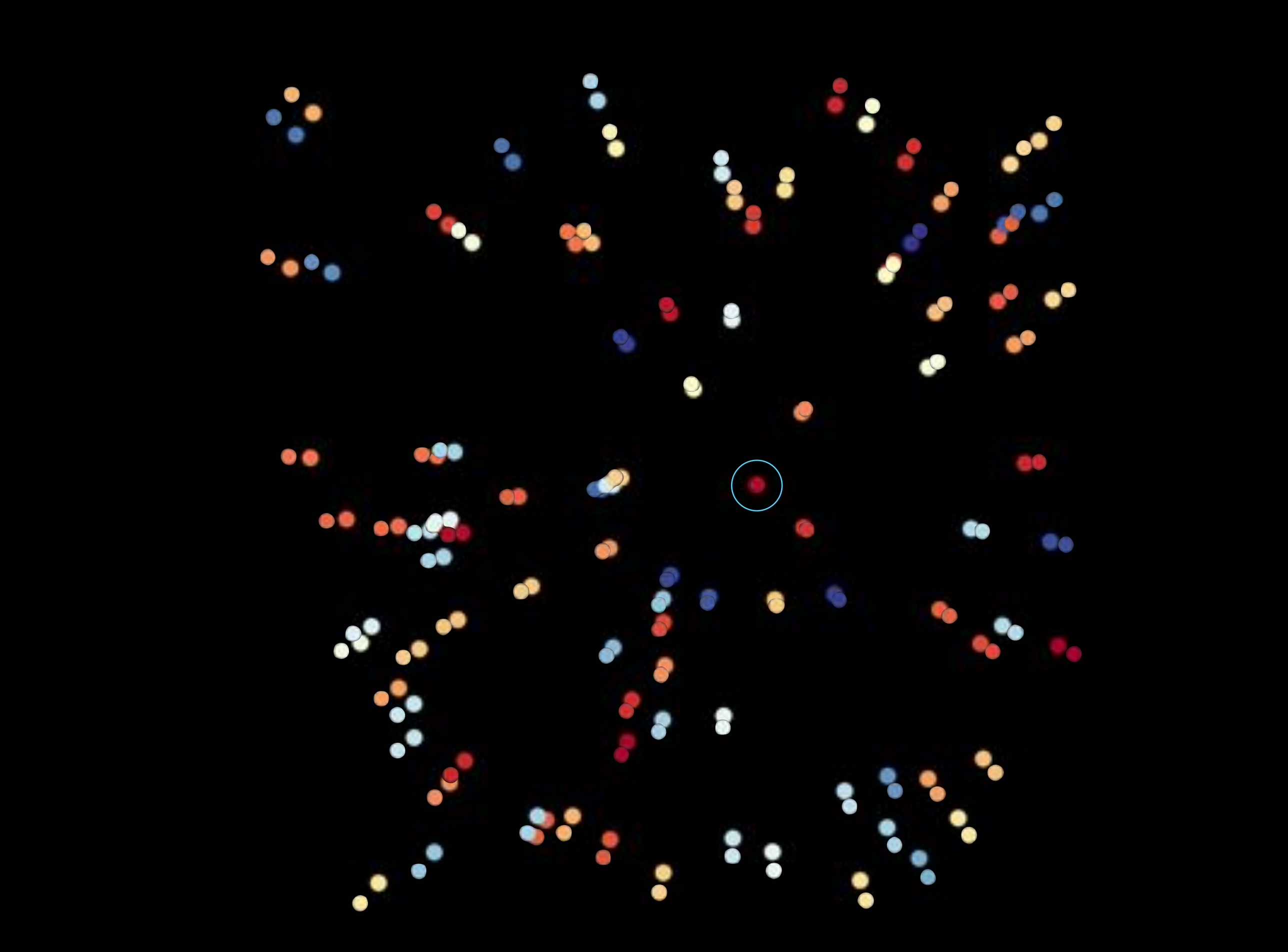
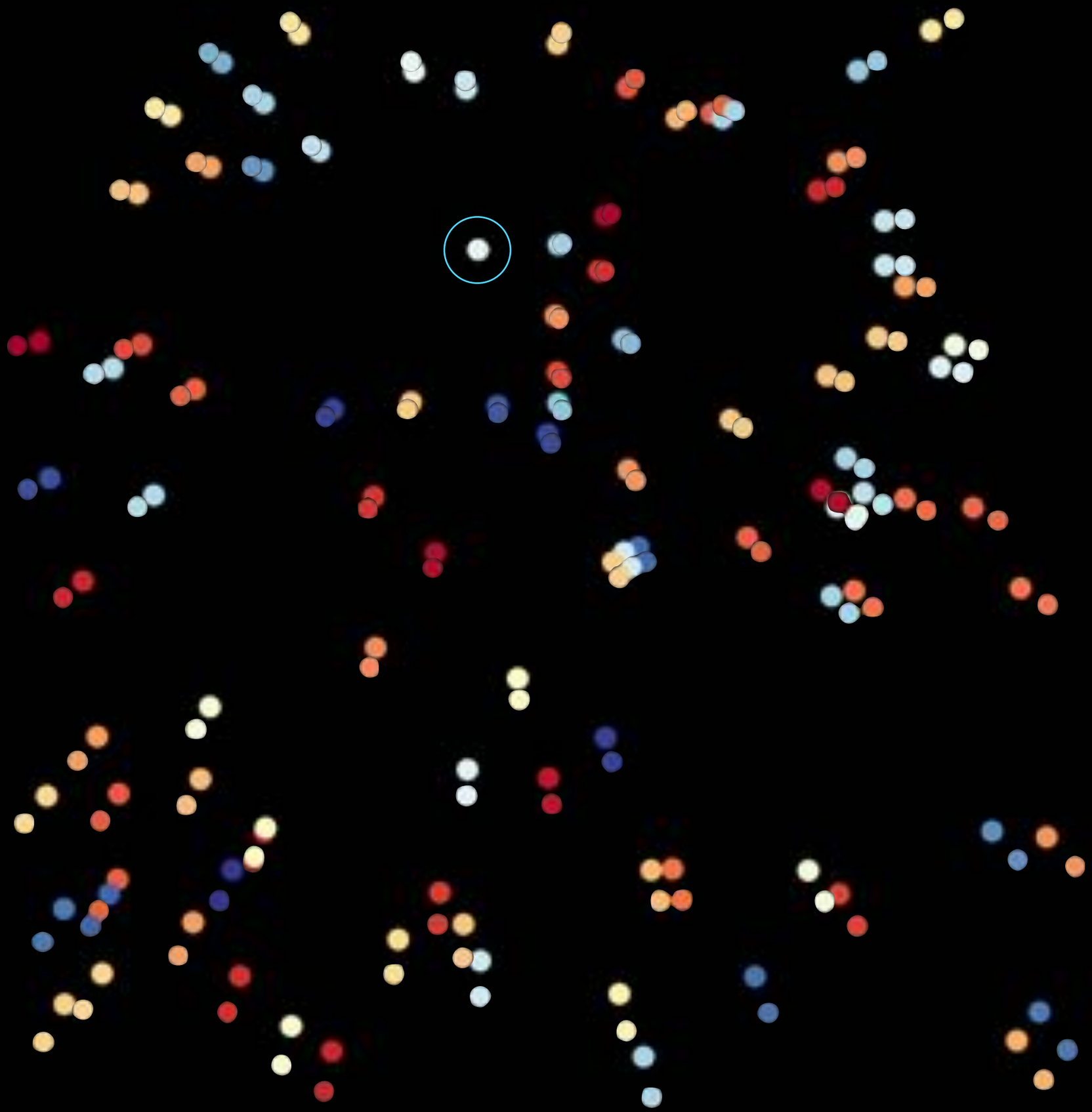
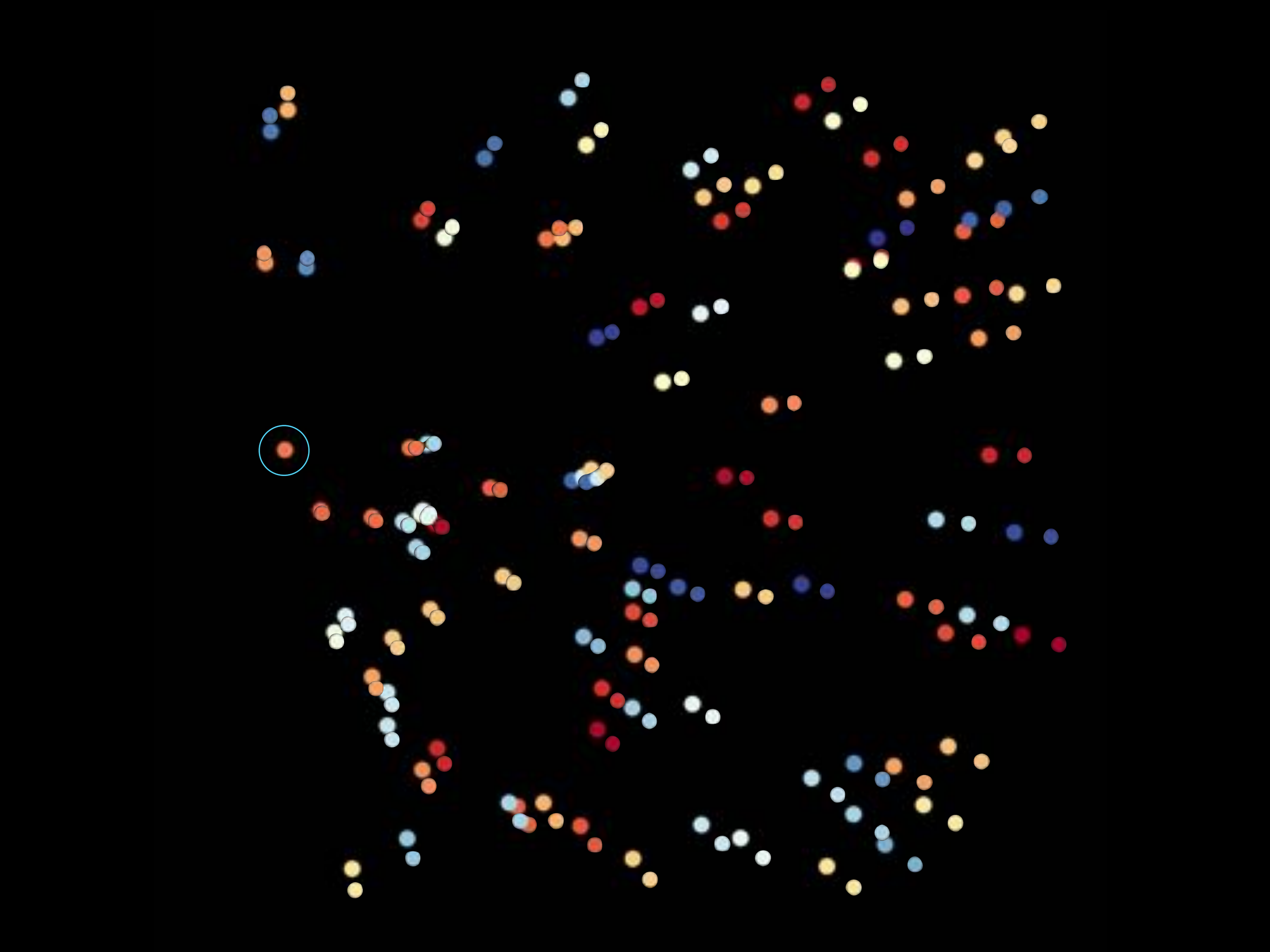
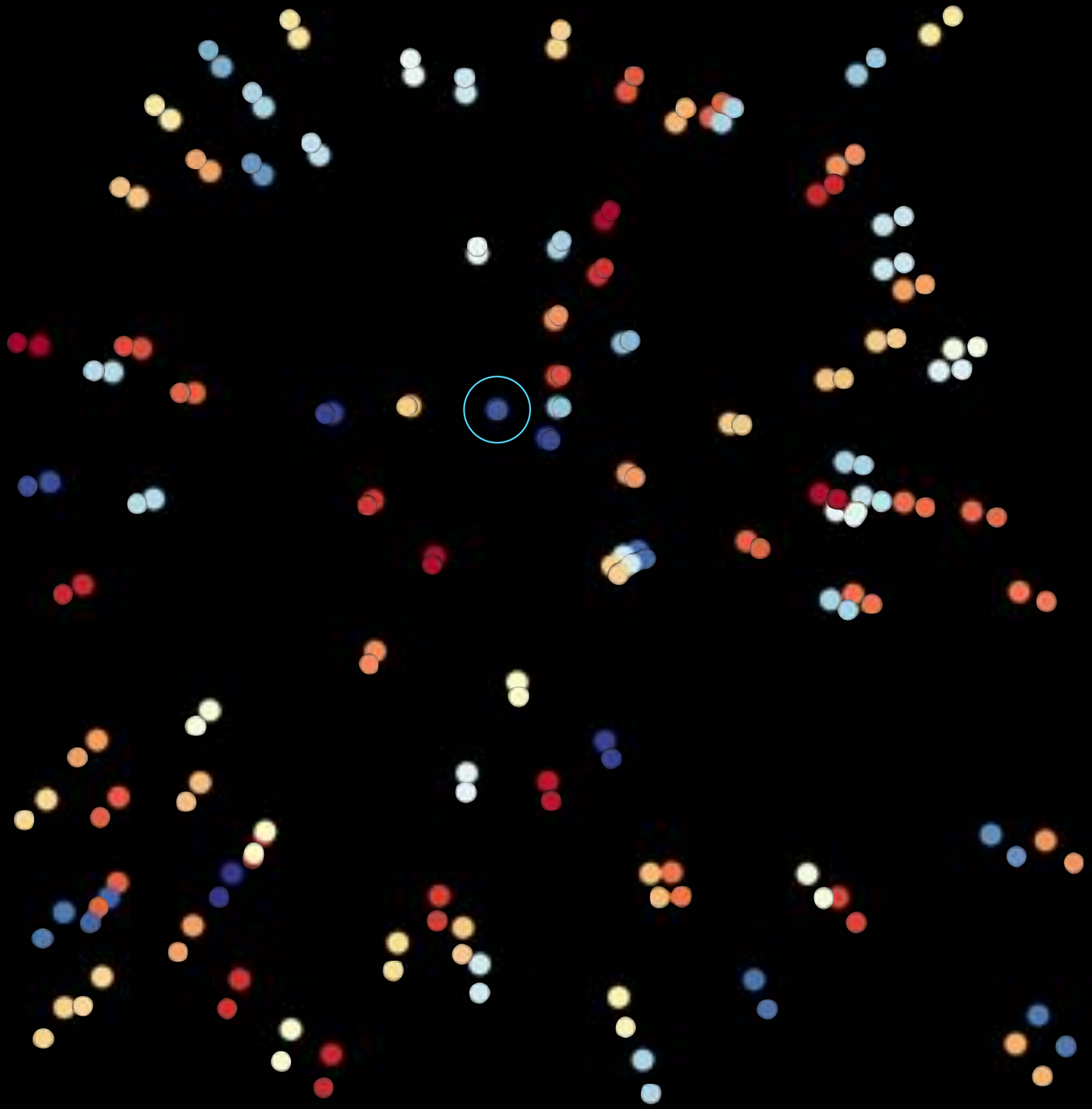
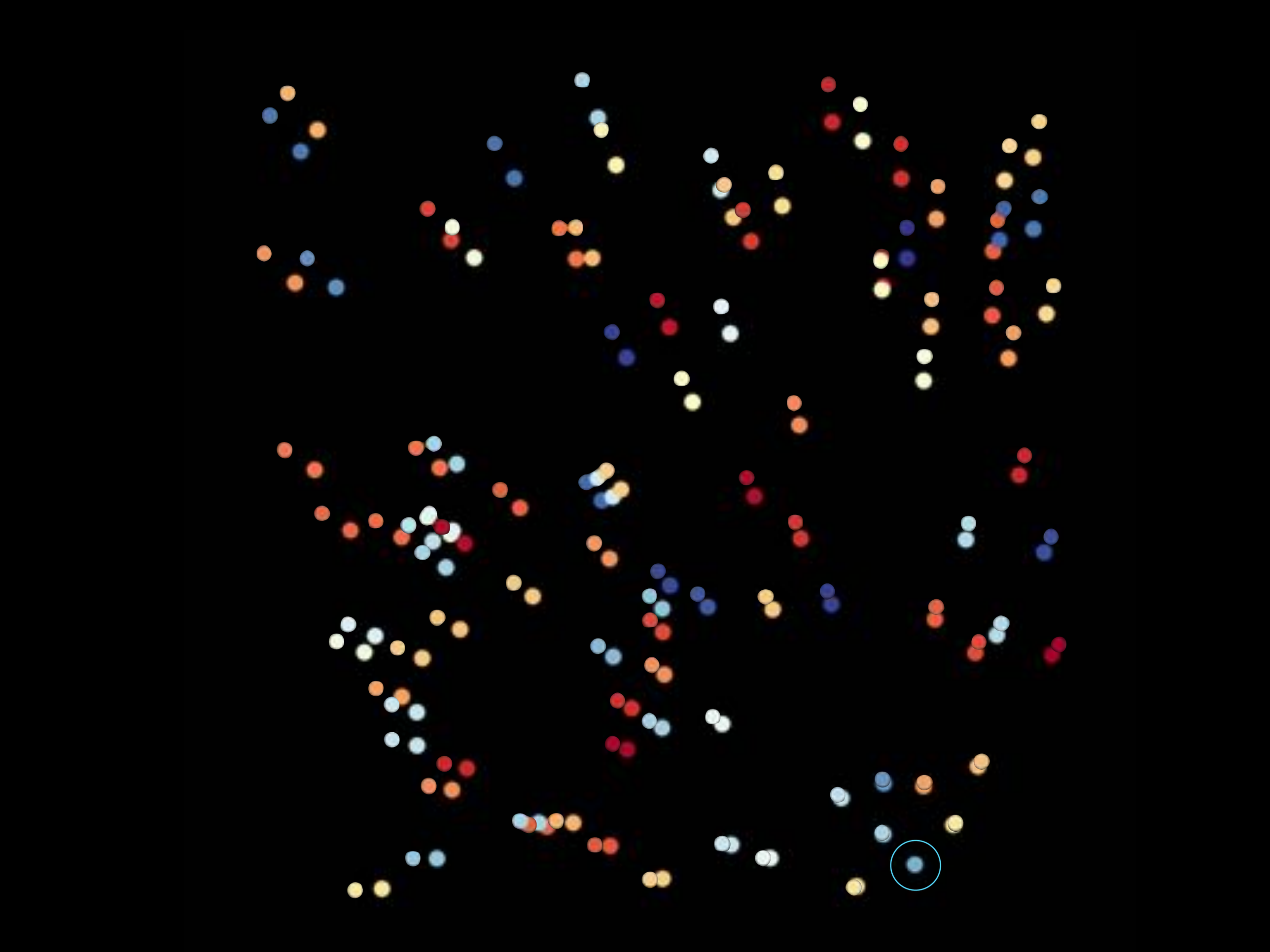


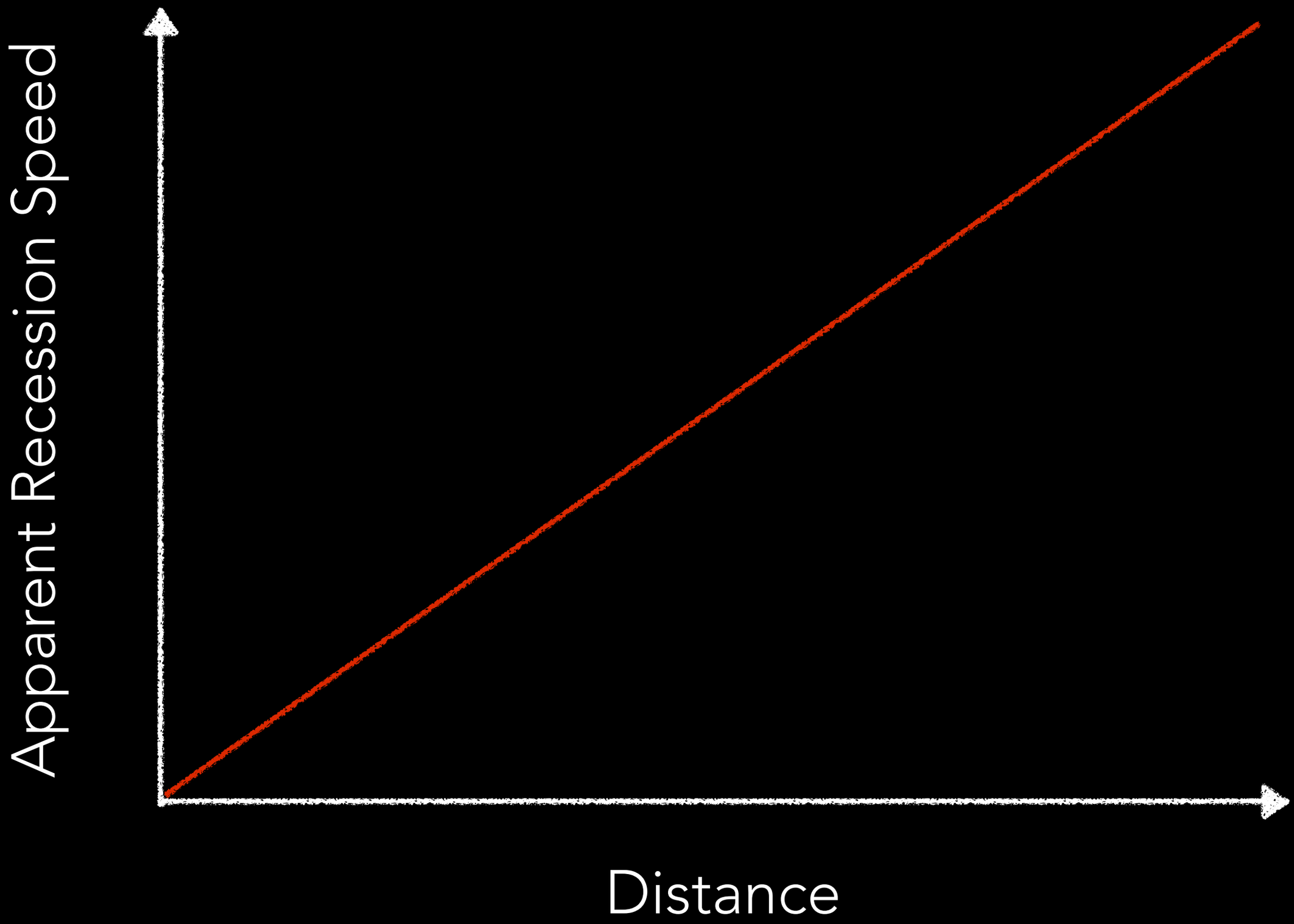











Apparent Recession Speed
Distance

The ORIGINAL Hubble Diagram (1929)

APPARENT RECESSION SPEED

RECENT SURPRISE:
THE RATE OF EXPANSION
IS *INCREASING!*

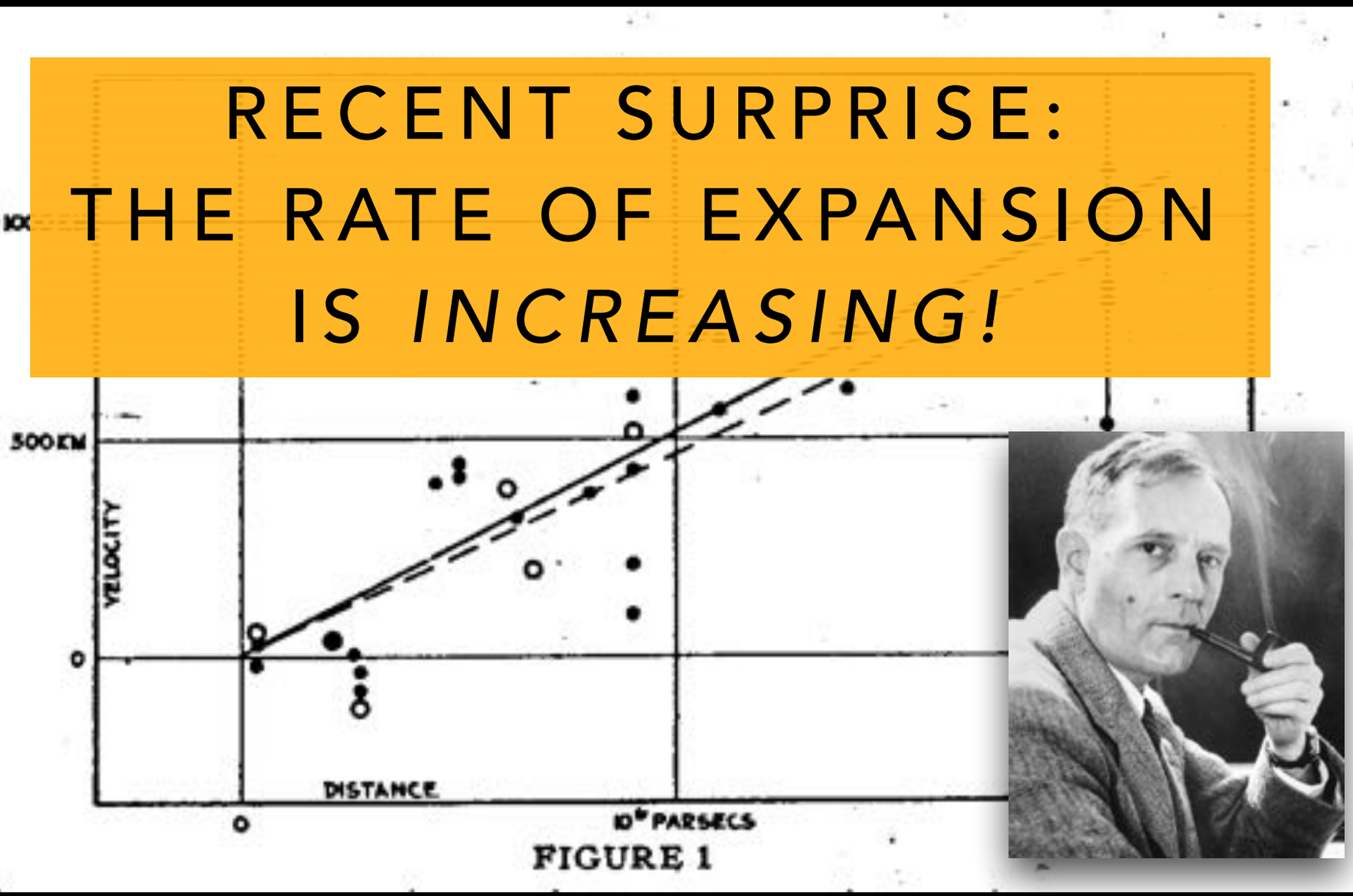
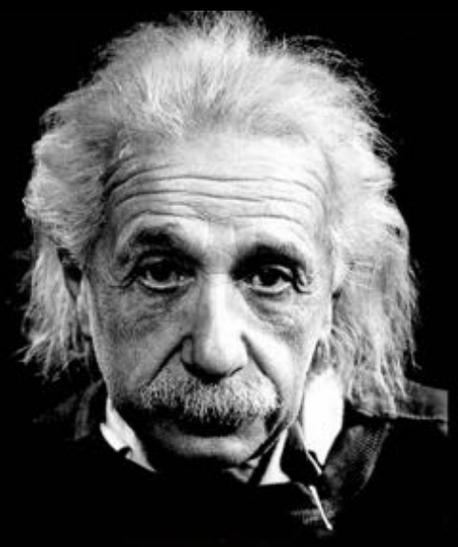
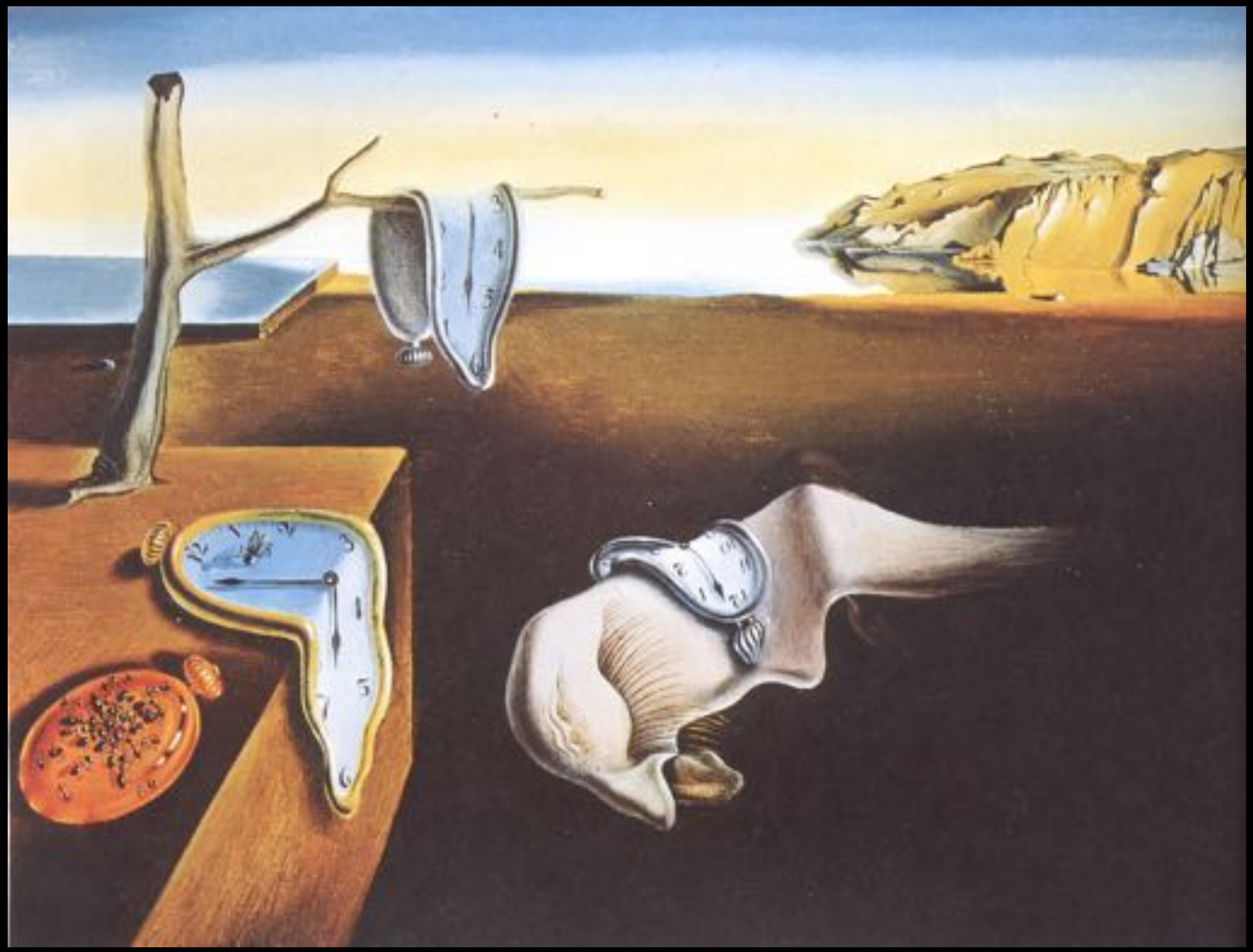


FIGURE 1

DISTANCE



Spacetime is *NOT* a passive stage,
it reacts to the "stuff" in it

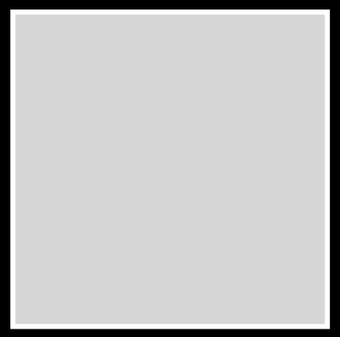


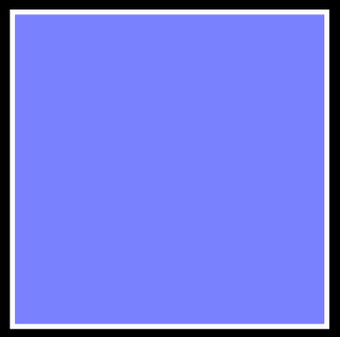
Matter

(Atoms + Dark Matter)

Dark Energy

(???)





Matter
(Atoms + Dark Matter)

Density diluted by same factor that volume increases

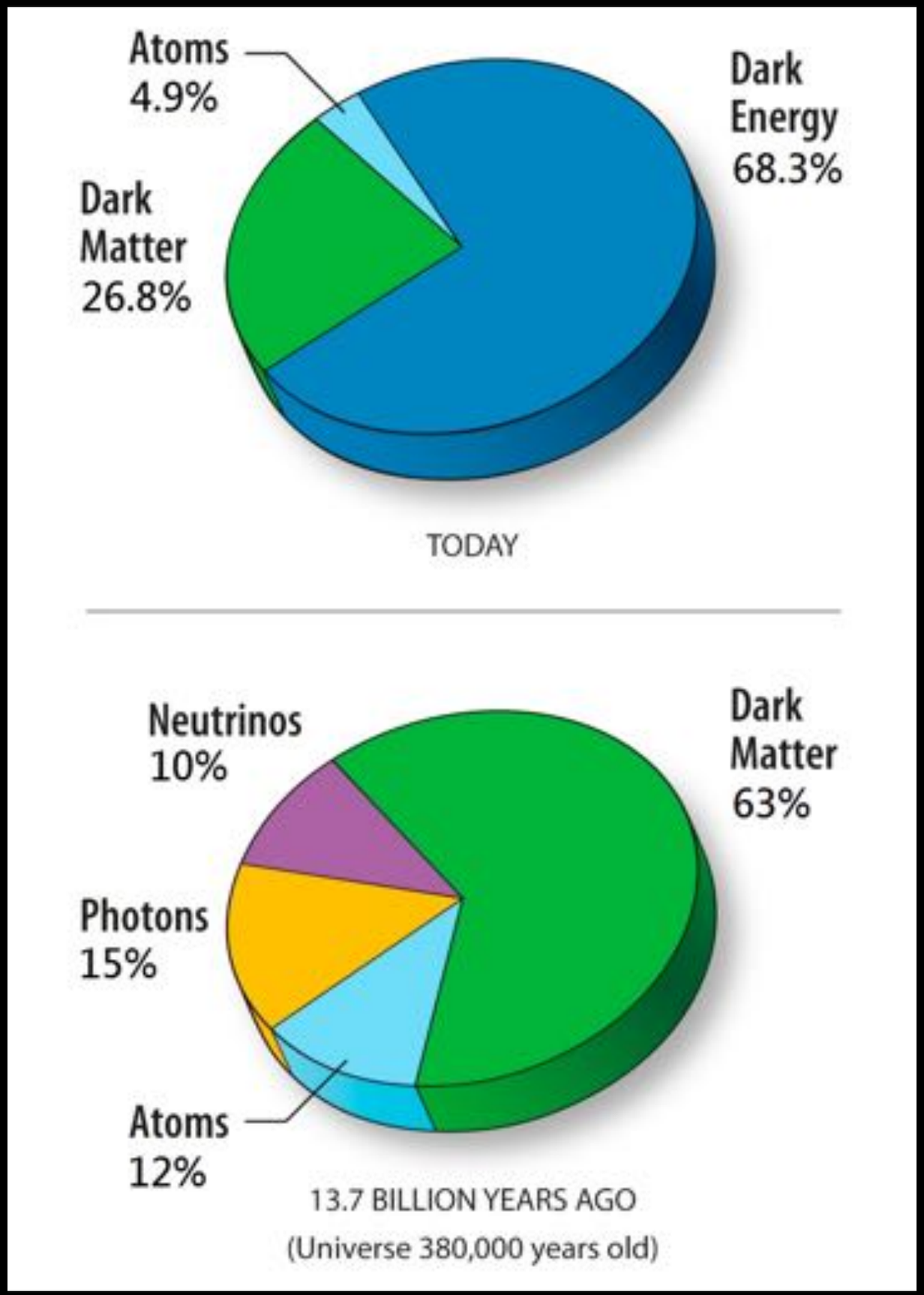
Dark Energy
(???)

Density remains ***constant***

→ ***negative*** pressure!

Today

13.7 billion years ago



Matter
(Atoms + Dark Matter)

Density diluted by same factor that volume increases

Dark Energy
(???)

Density remains ***constant***

→ ***negative*** pressure!

Dark Energy

(???)

What is this stuff?

We don't really know, but isn't "dark energy" a great name?

Density remains ***constant***

→***negative*** pressure!

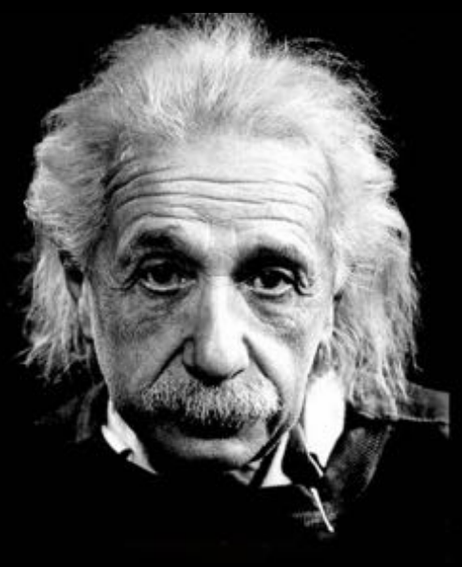
Dark Energy

(???)

What is this stuff?

Density remains ***constant***

→***negative*** pressure!



Cosmological constant??

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$$

"Energy" of empty space

Dark Energy

(???)

What is this stuff?

Modified gravity?

Quintessence?

Density remains ***constant***

→***negative*** pressure!

Dark Energy

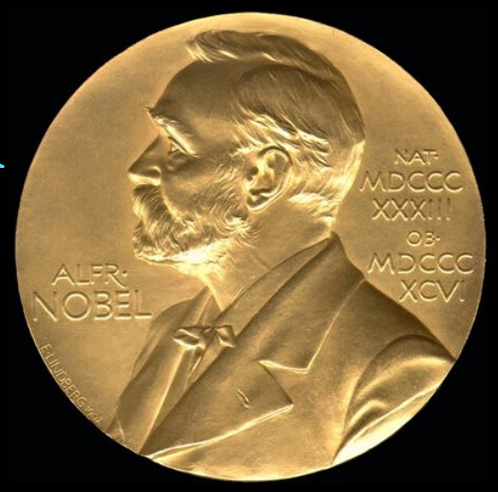
(???)

What is this stuff?

Density remains ***constant***

→***negative*** pressure!

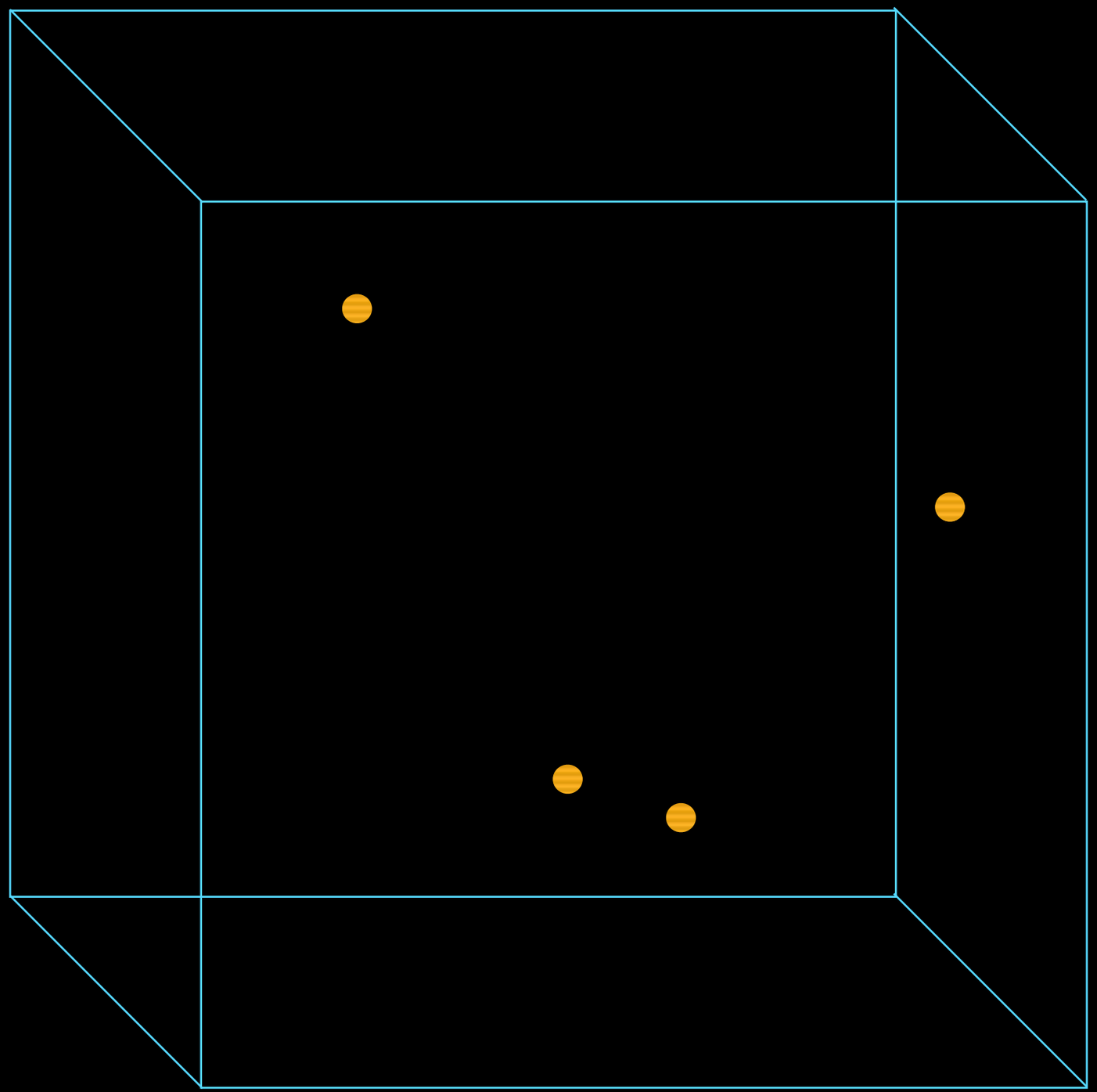
Swedish Gold!!



Great! You say we've discovered an ***unlimited*** energy source that is ***everywhere at all times***?

(= $$$$)

The density of dark energy corresponds to
~4 protons per cubic meter



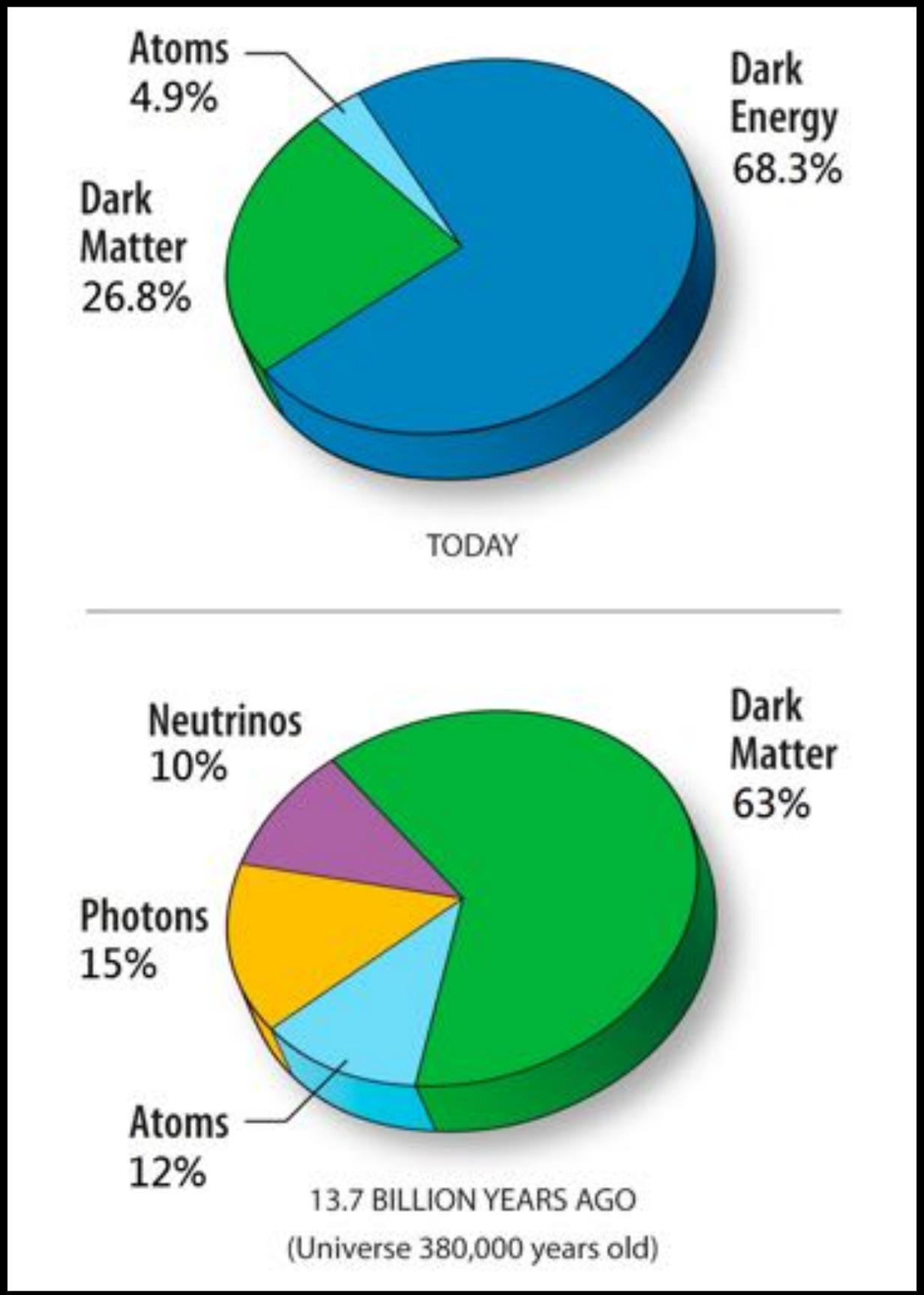
That density is a factor ~10^{120} smaller than what we would naively expect from the particles we already know

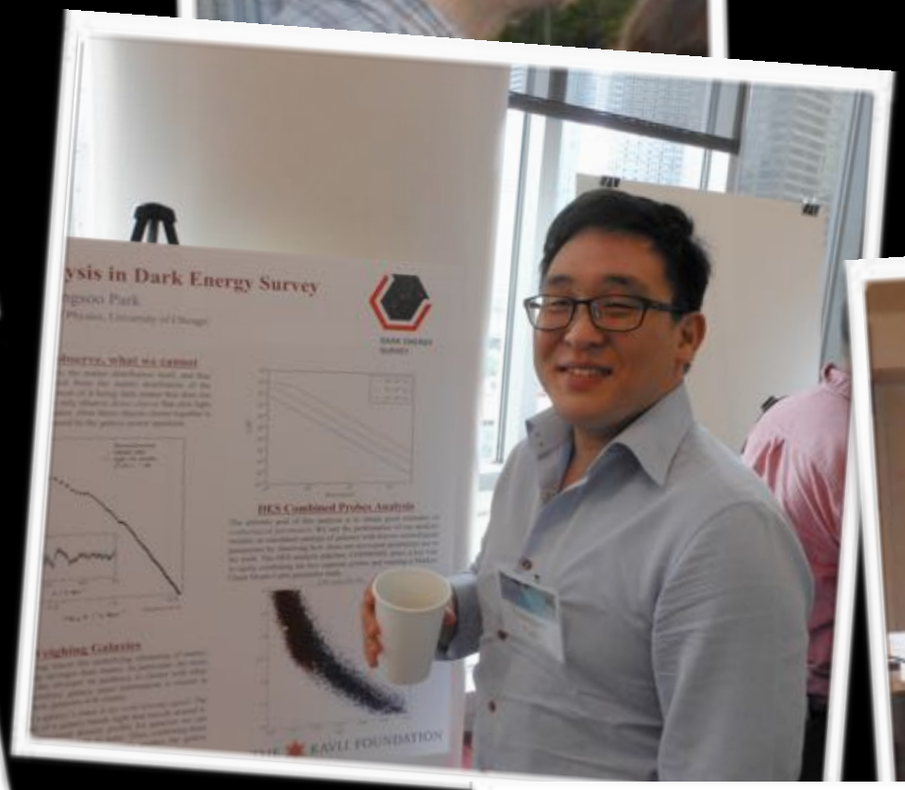
10^{-120} = 0.000000000000000000000000000000
000000000000000000000000000000
000000000000000000000000000000
000000000000000000000000000001

There is something ***important*** to understand here…

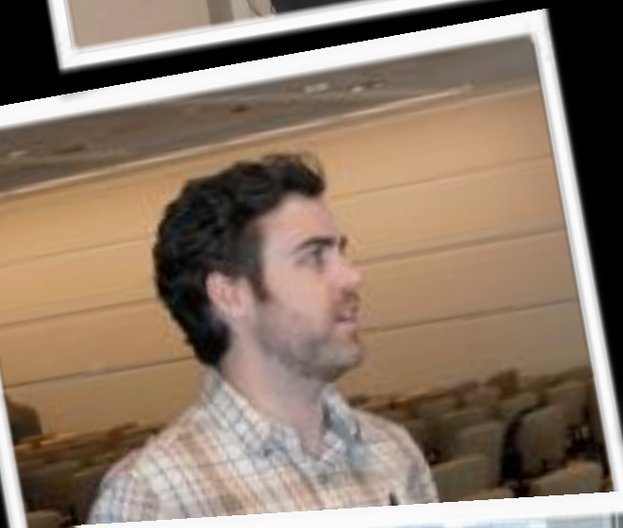
Today

13.7 billion years ago




ysis in Dark Energy Survey
gsoo Park
DES Combined Probes Analysis
KAVLI FOUNDATION


SUMMARY
EE
BB
ΦΦ
x B2

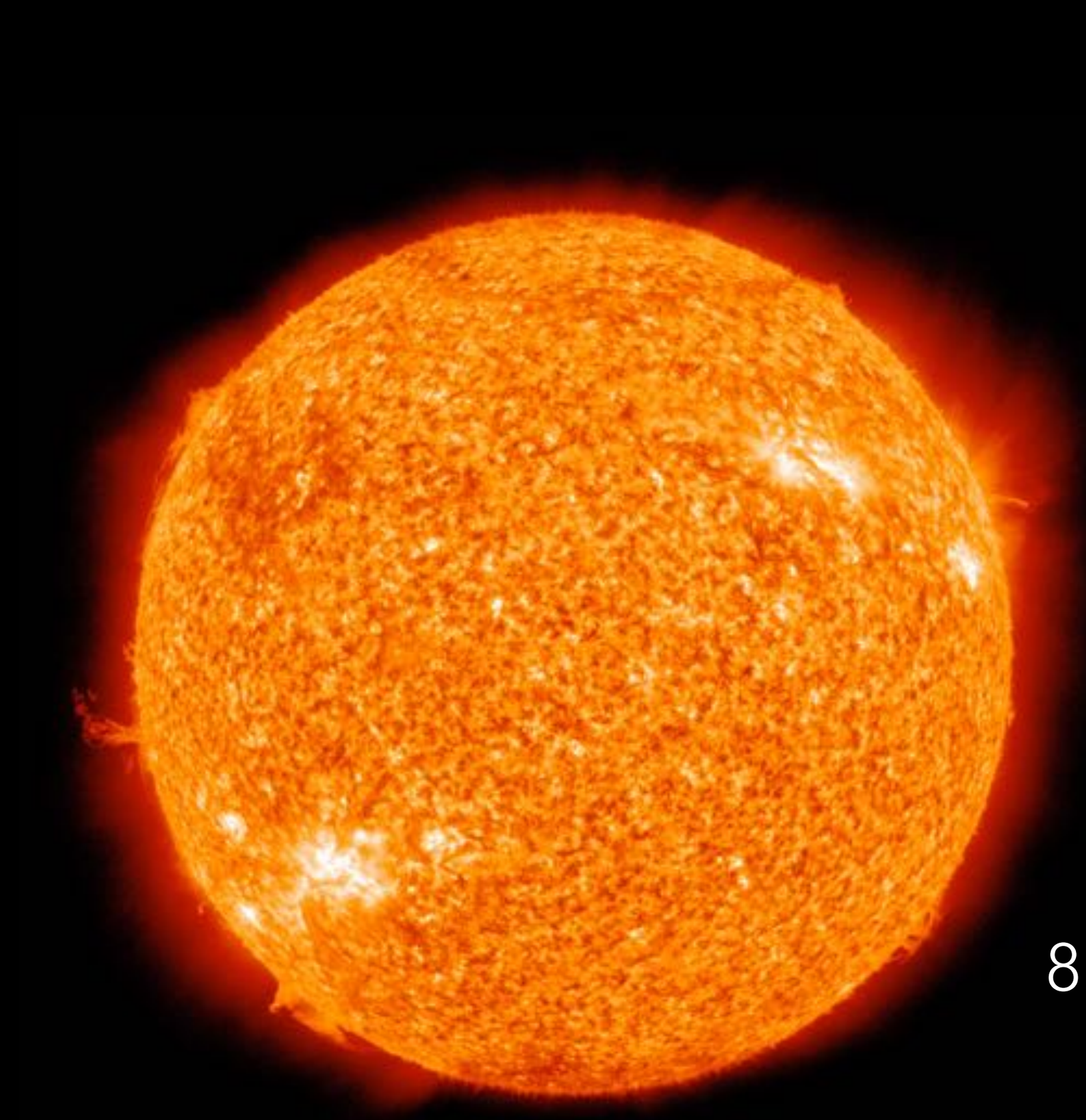


TELESCOPES ARE
TIME MACHINES

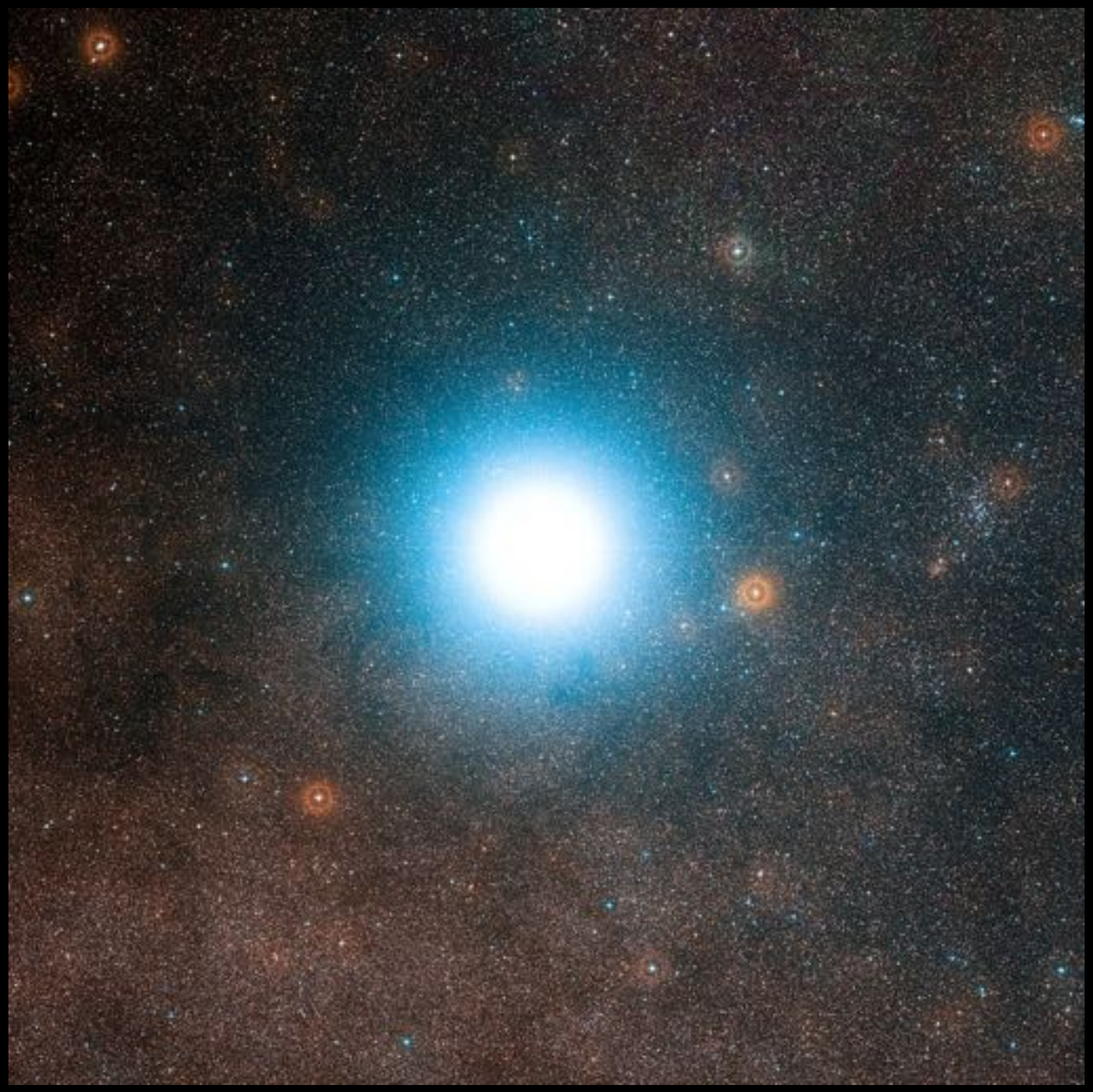
TELESCOPES ARE TIME MACHINES

SPEED LIMIT:
186,000 MILES PER SECOND

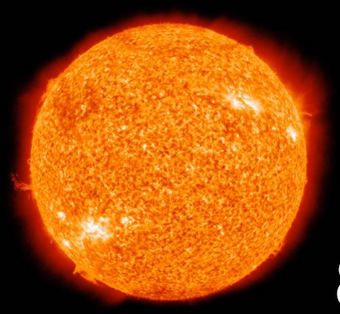
Rio 2016?



8.5 minutes

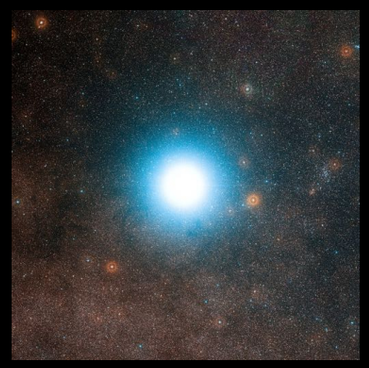


4 years

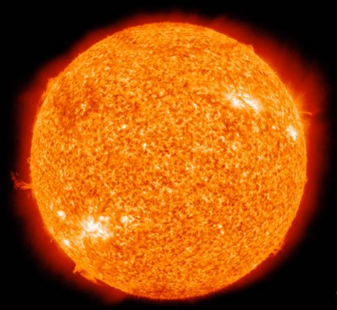


8.5 minutes

25K years



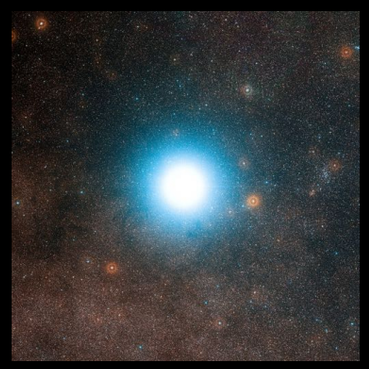
4 years



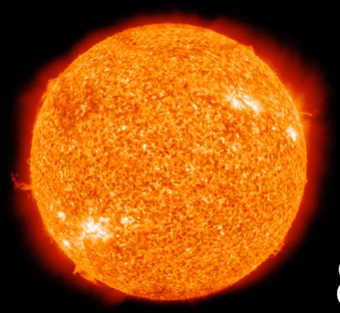
8.5 minutes

3M years

25K years



4 years



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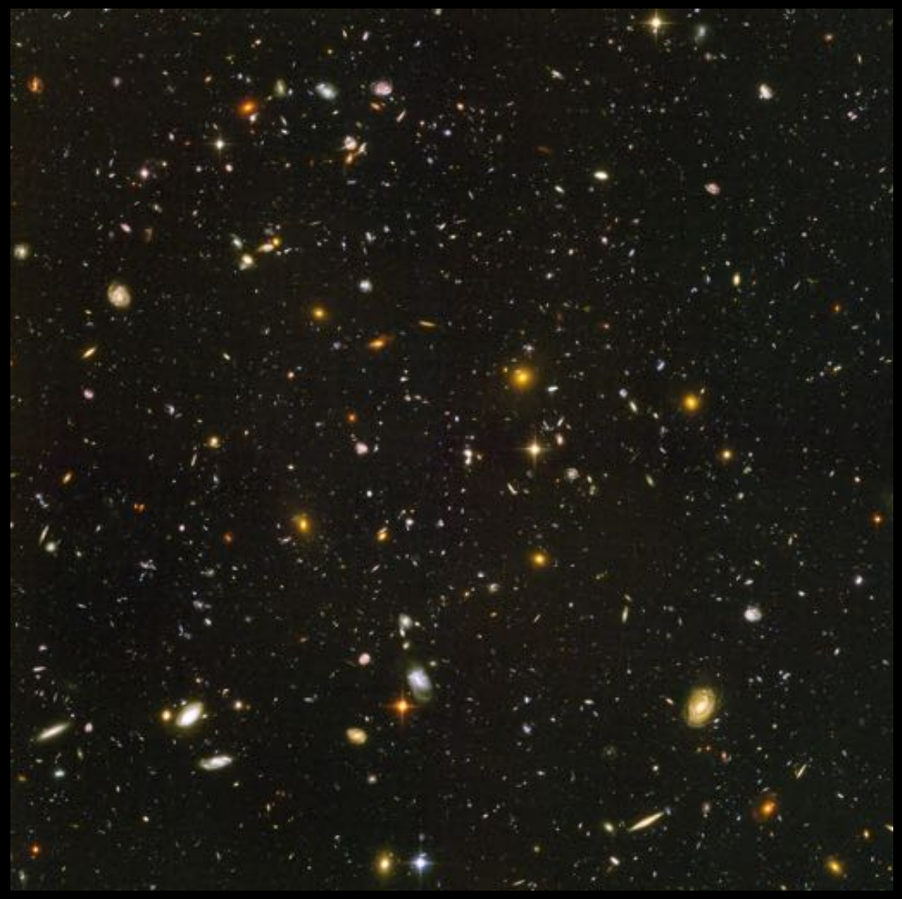
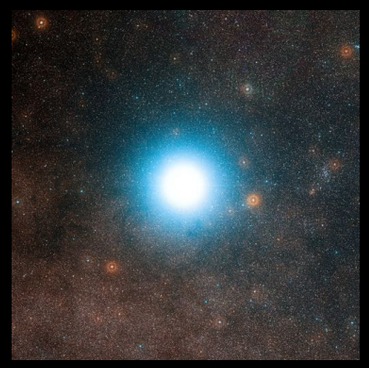


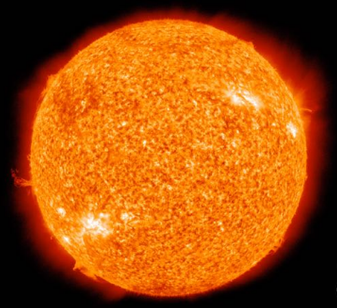
13B years

3M years

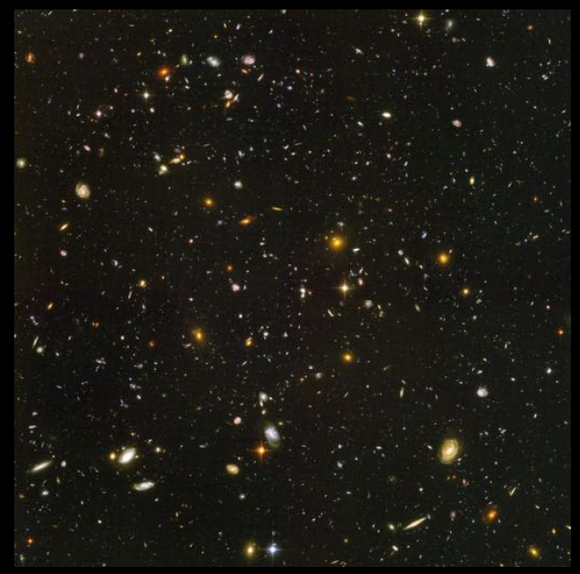
25K years



4 years



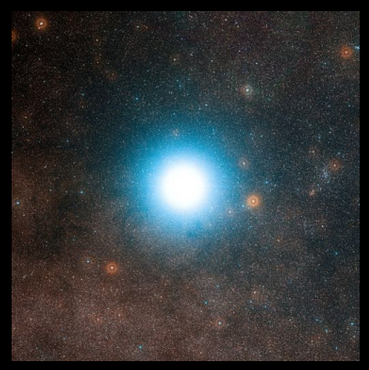
8.5 minutes



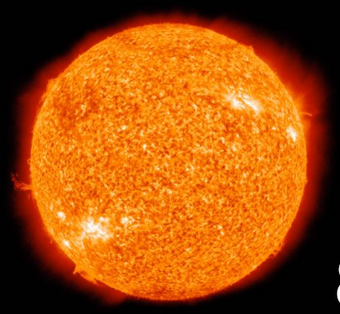
13B years

3M years

25K years



4 years



8.5 minutes

This photo covers roughly one thirteen-millionth of the full sky

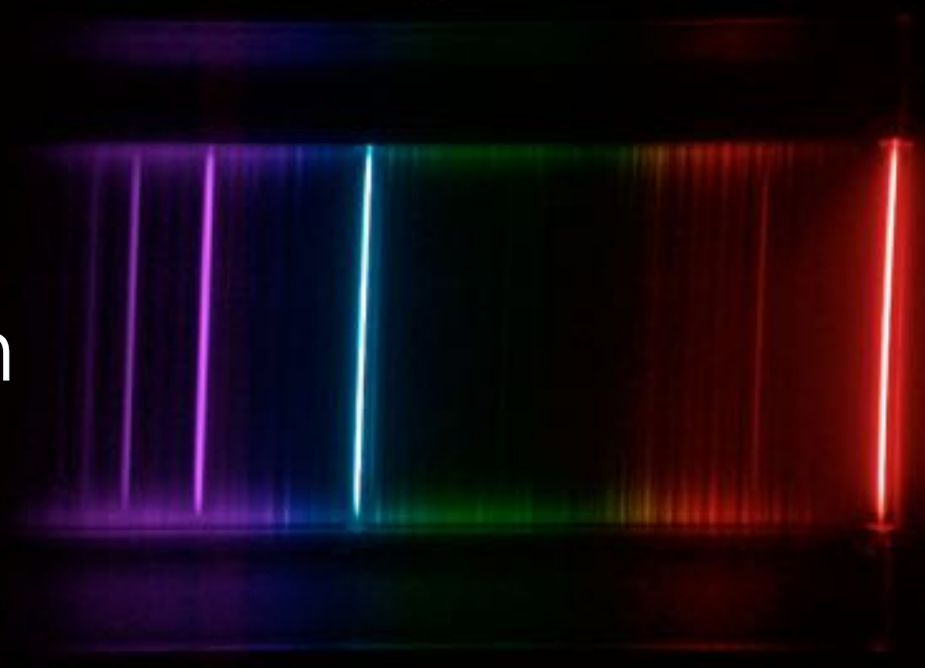
Each smudge of light is a galaxy

There are over 100 billion galaxies in the observable universe

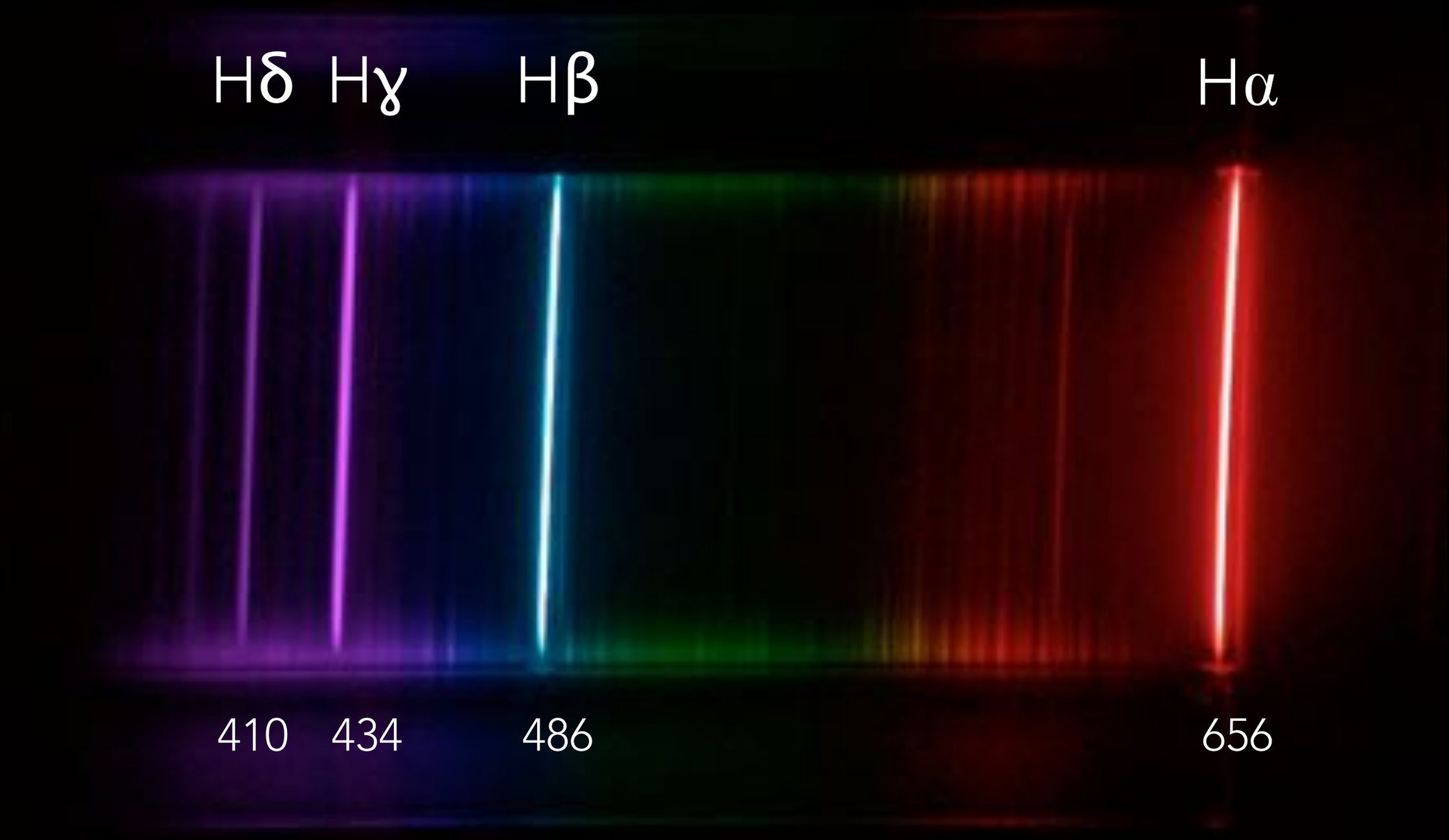
REDSHIFT MEASURES EXPANSION

Hydrogen discharge tube

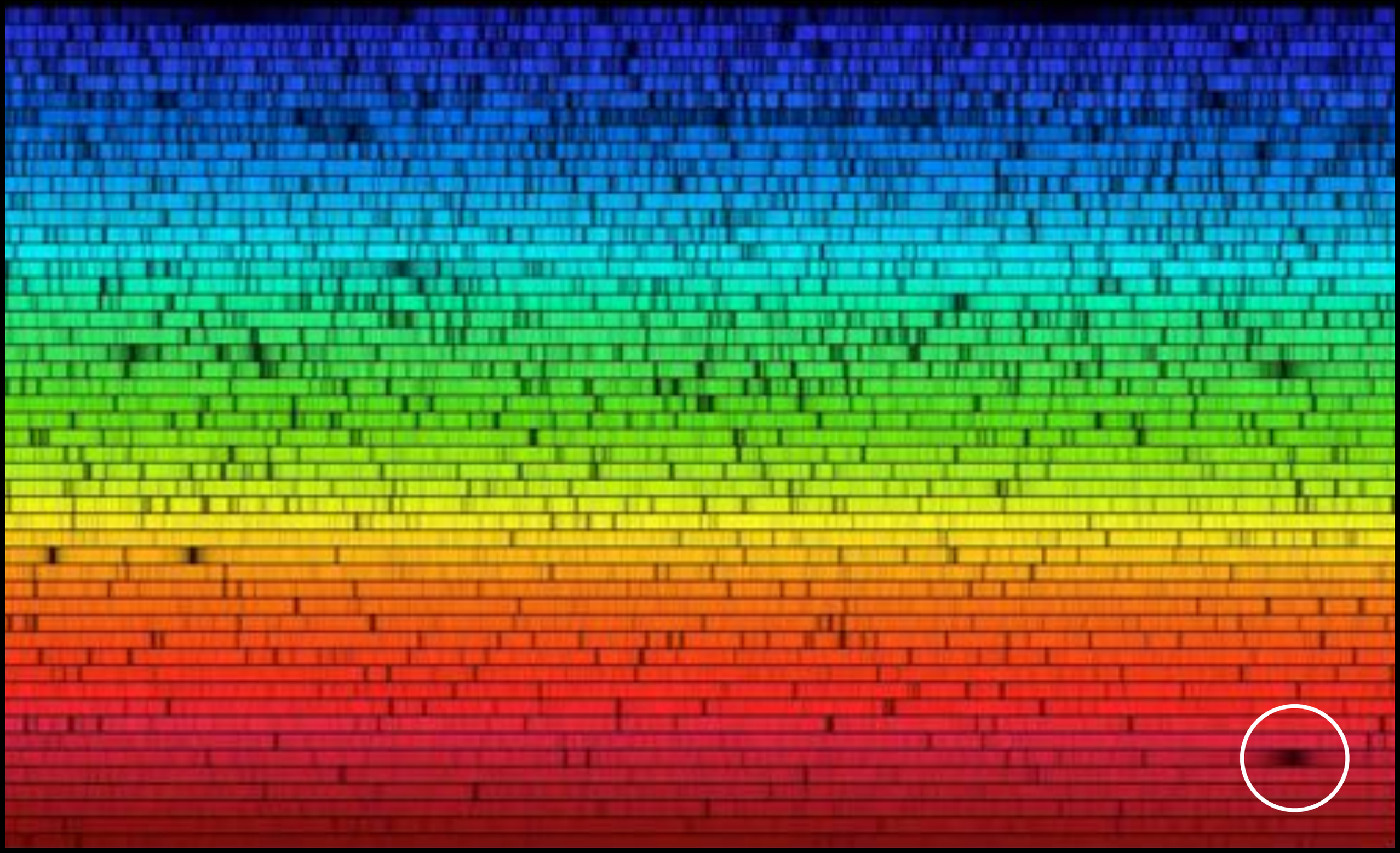
Spectrum



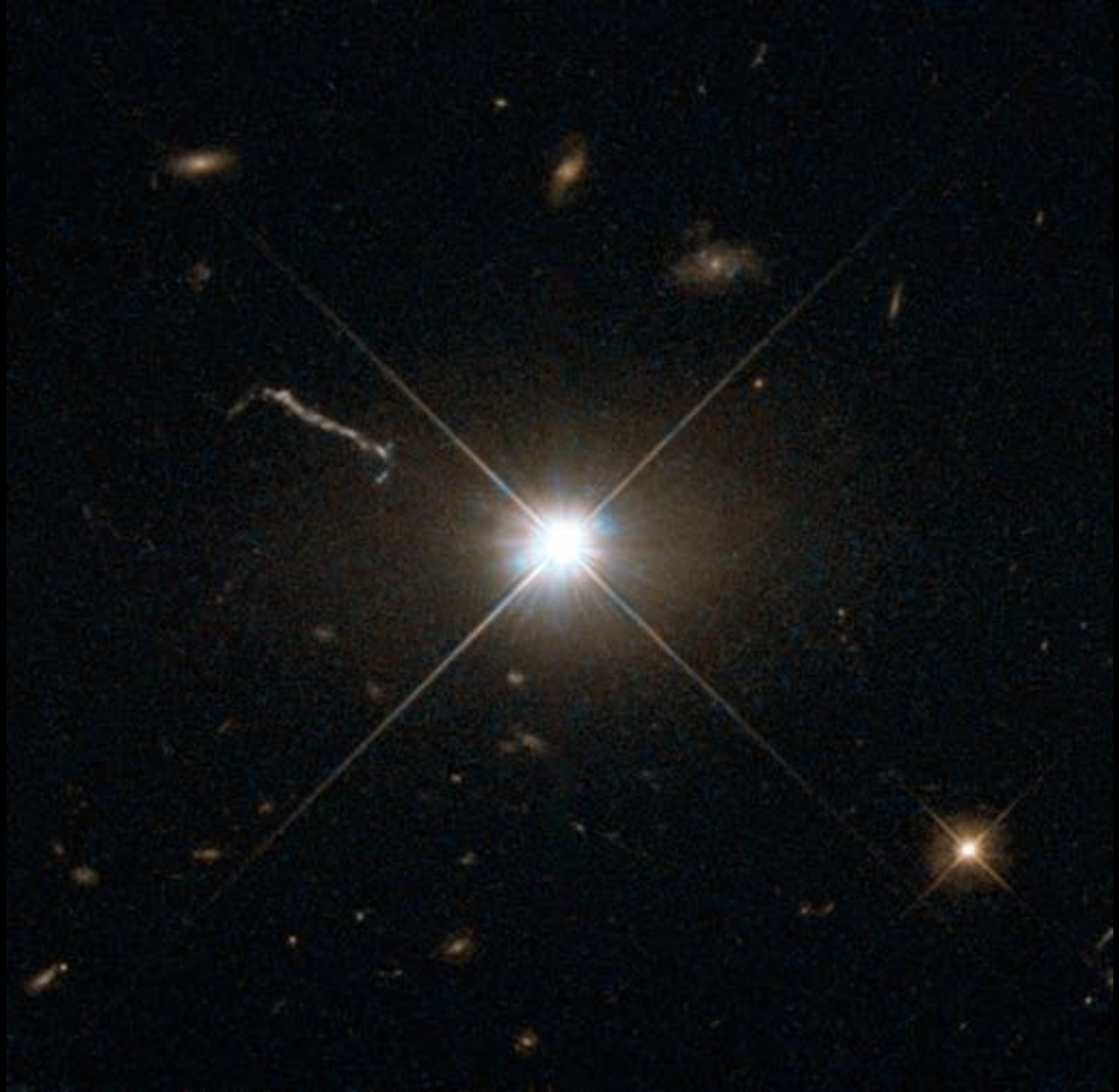
Emission Spectrum of Hydrogen



Wavelength (nanometers)



Spectrum of the Sun



3C 273 : A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

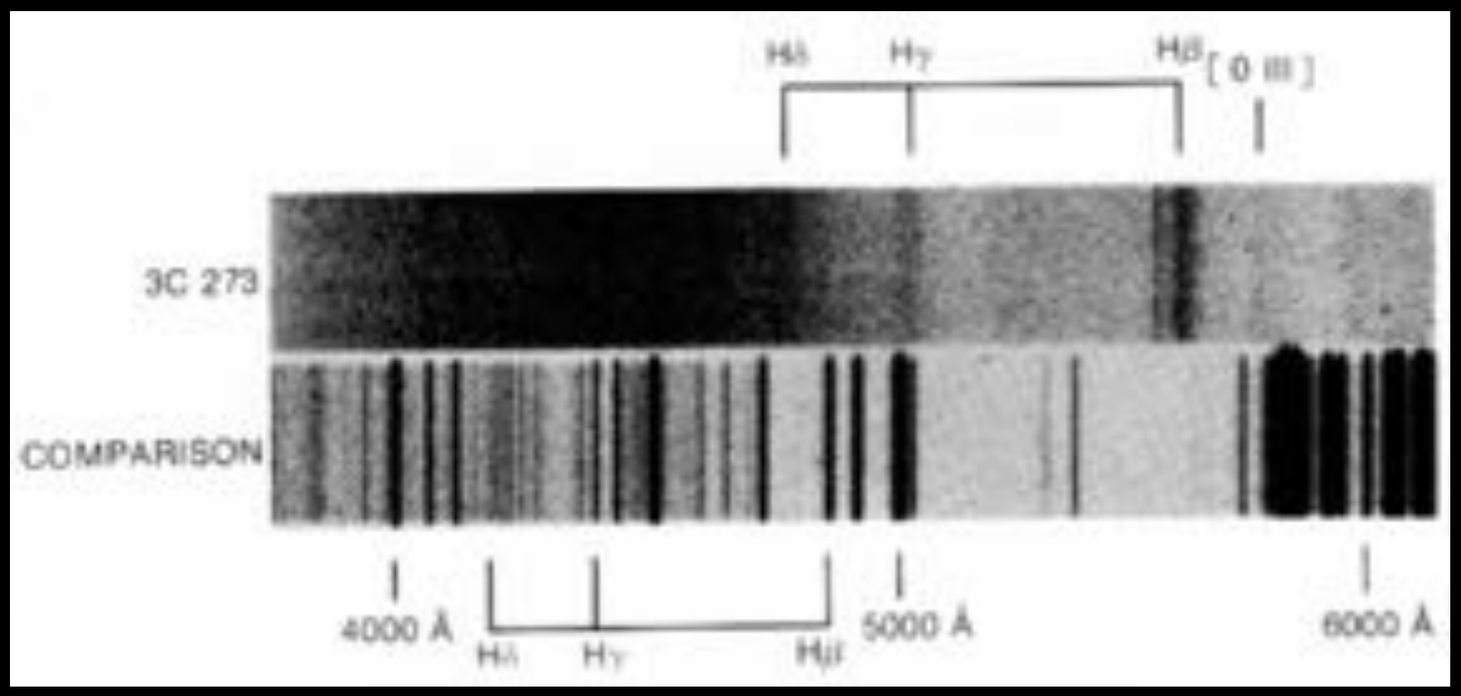
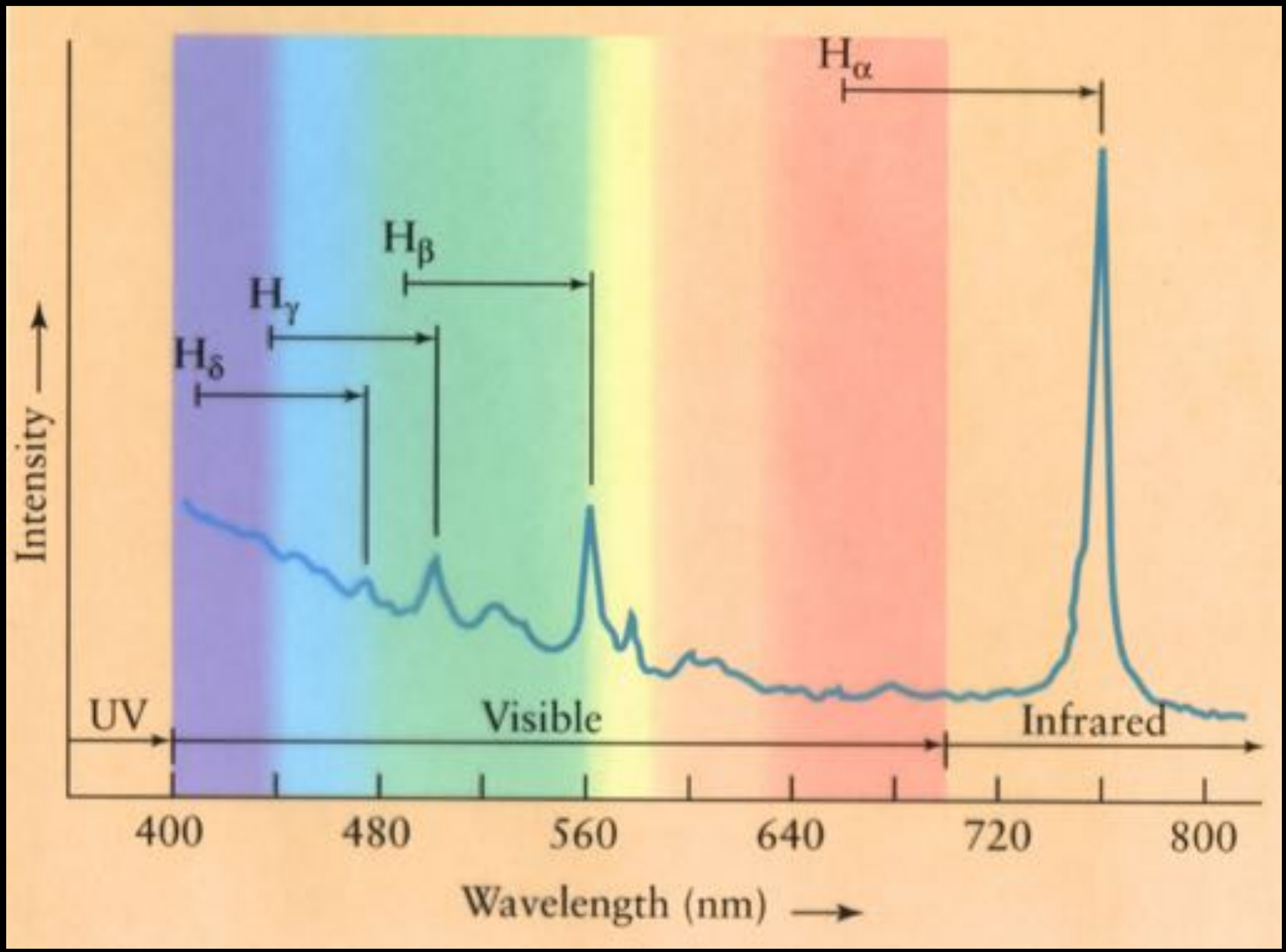


Table 1. Wave-lengths and Identifications

λ	λ/1·158	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hε
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

(2) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0·158, corresponding to an apparent velocity of 47,400 km/sec. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter optically than the luminous galaxies which have been identified with radio sources thus far. If the optical jet


H_α
H_β
H_γ
H_δ
Intensity
UV
Visible
Infrared
400
480
560
640
720
800
Wavelength (nm)

COSMOLOGICAL REDSHIFT

$$1 + z = \frac{\text{size of Universe today}}{\text{size of Universe at time of emission}}$$

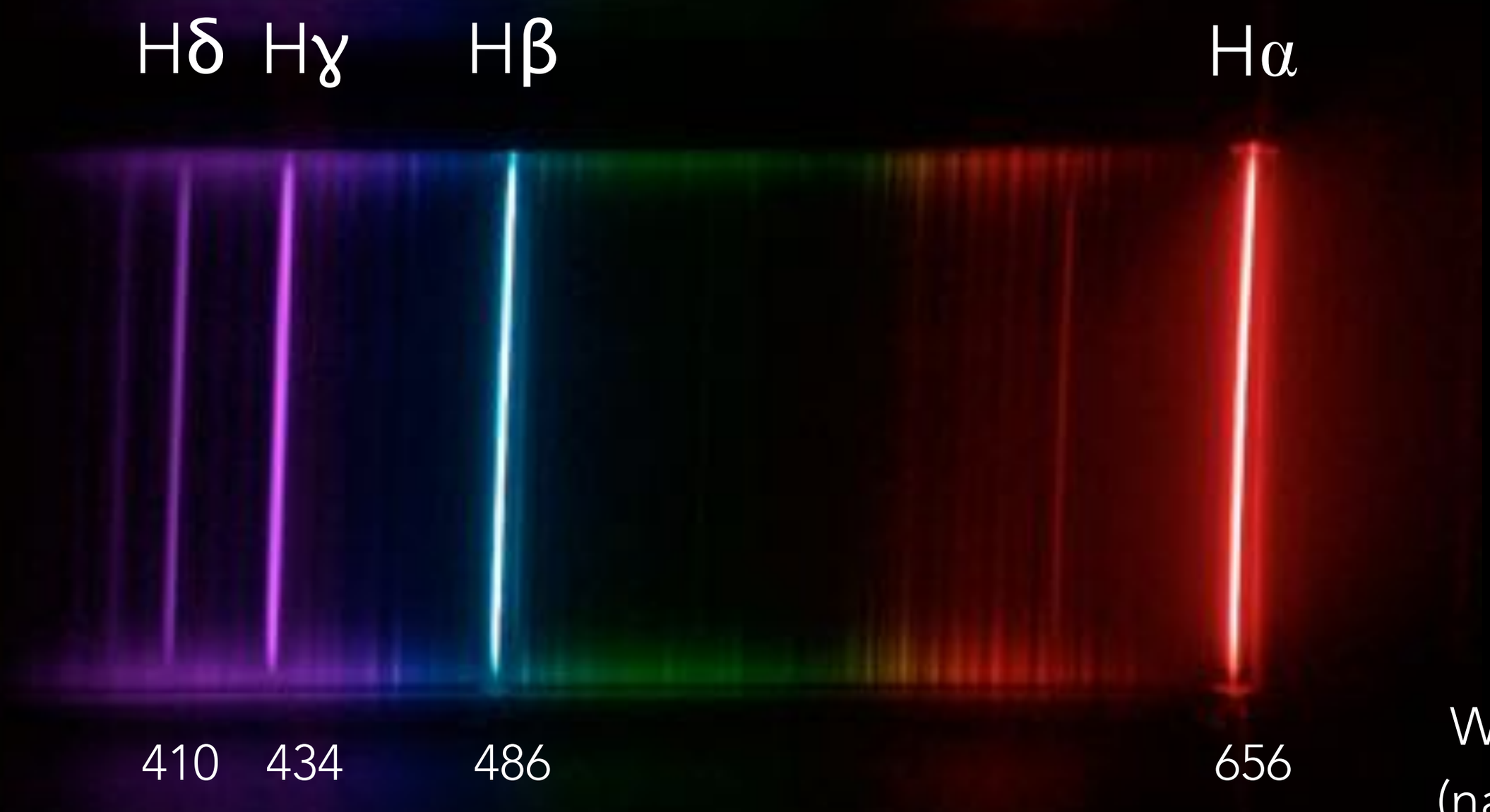
$$z = \frac{\text{wavelength observed}}{\text{wavelength emitted}} - 1$$

$$z = \frac{\text{frequency emitted}}{\text{frequency observed}} - 1$$

NOTE: The increase in wavelength does not depend on the rate of change of the size scale of the universe at the times of emission of absorption, but on the increase of the scale in the whole period

COSMOLOGICAL REDSHIFT

EXAMPLE: What was the relative size of the Universe when light was emitted from a source if the Hα line is observed with wavelength of 1300 nanometers?



LET'S REVIEW

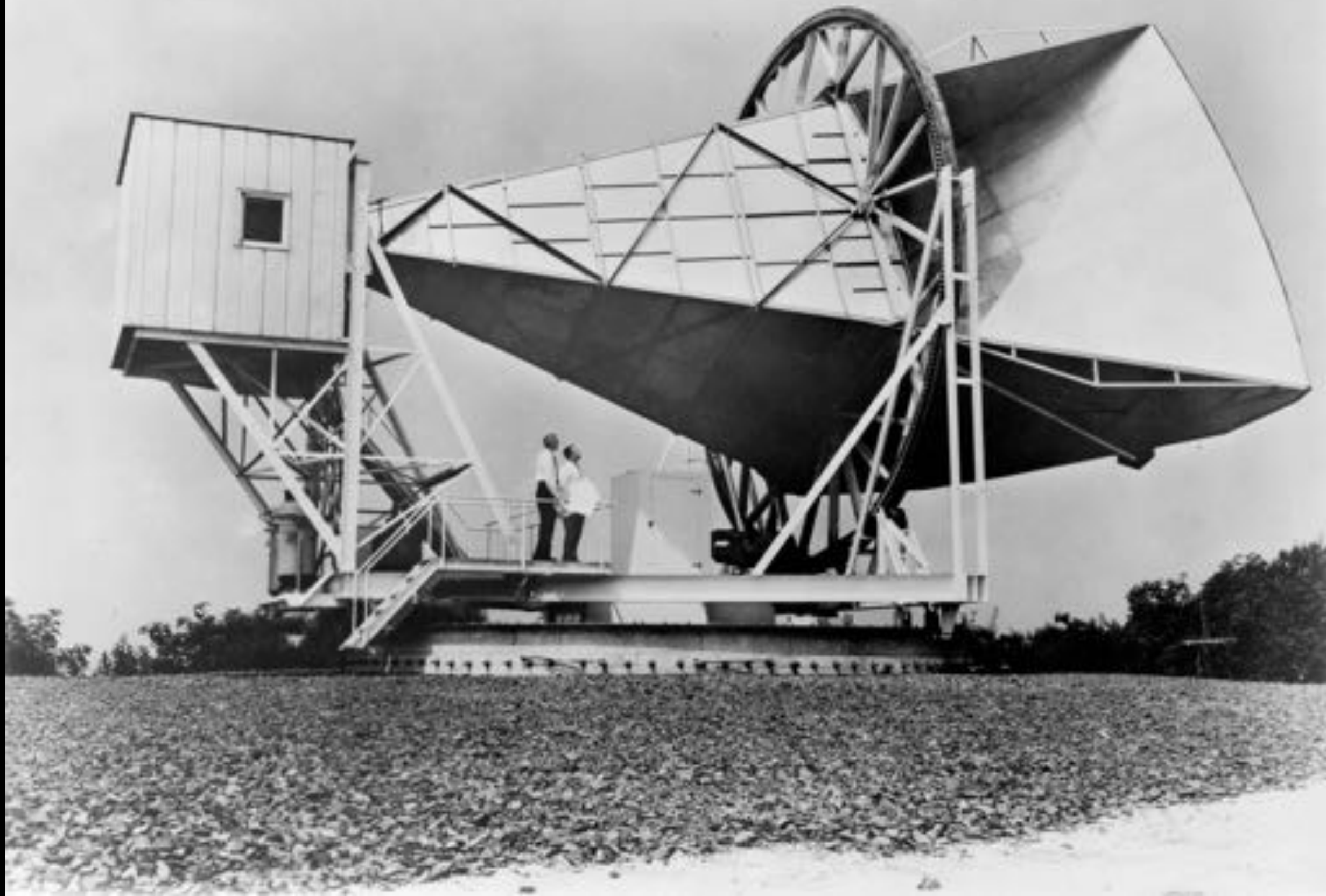
- **Redshift** tells us **relative size** of Universe when light was emitted

- **Distance** tells us light travel **time**

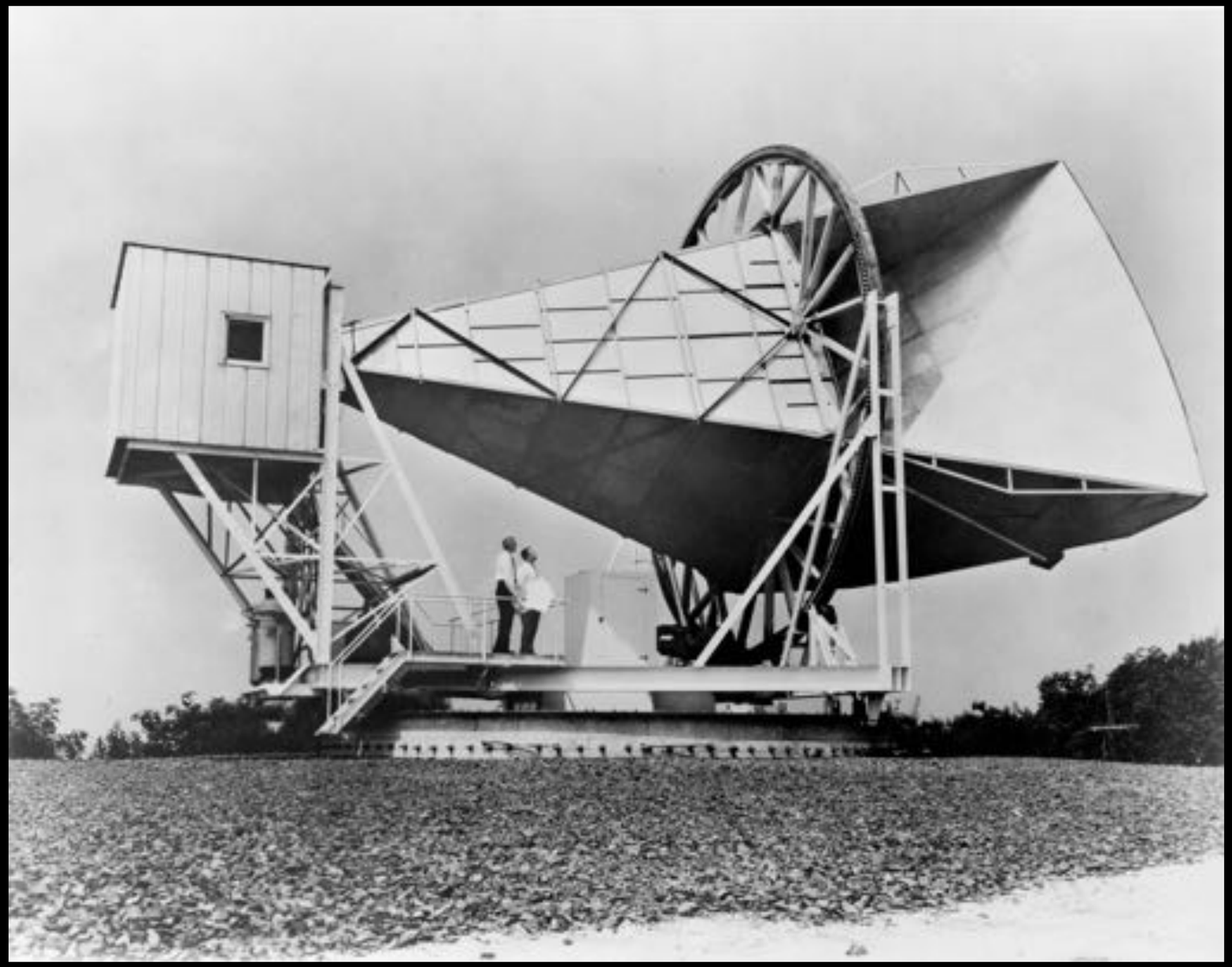
- Redshift + independent distance measurement tells us **expansion history** of Universe

Redshift Implications:

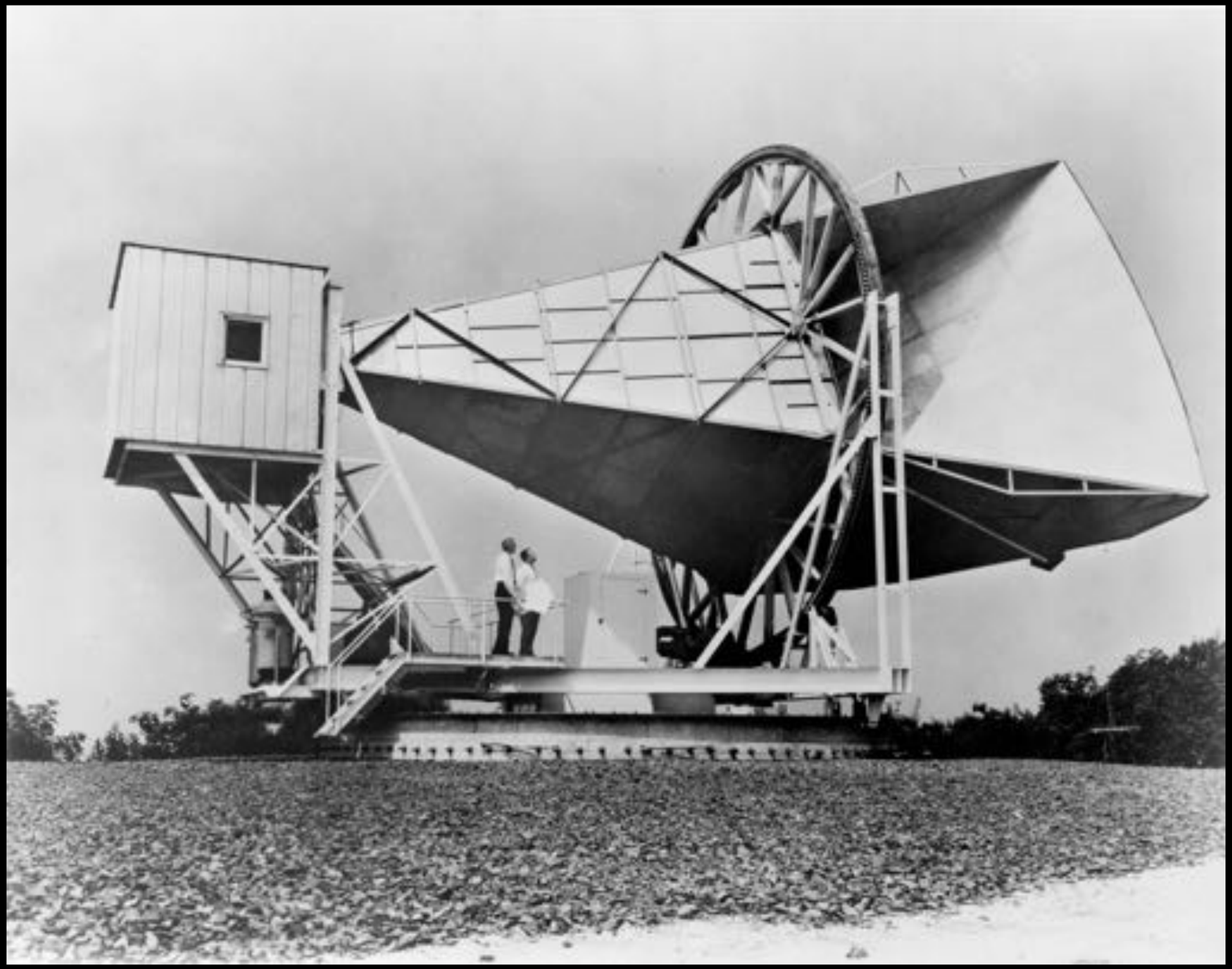
Discovery of the Cosmic Microwave Background, 1964

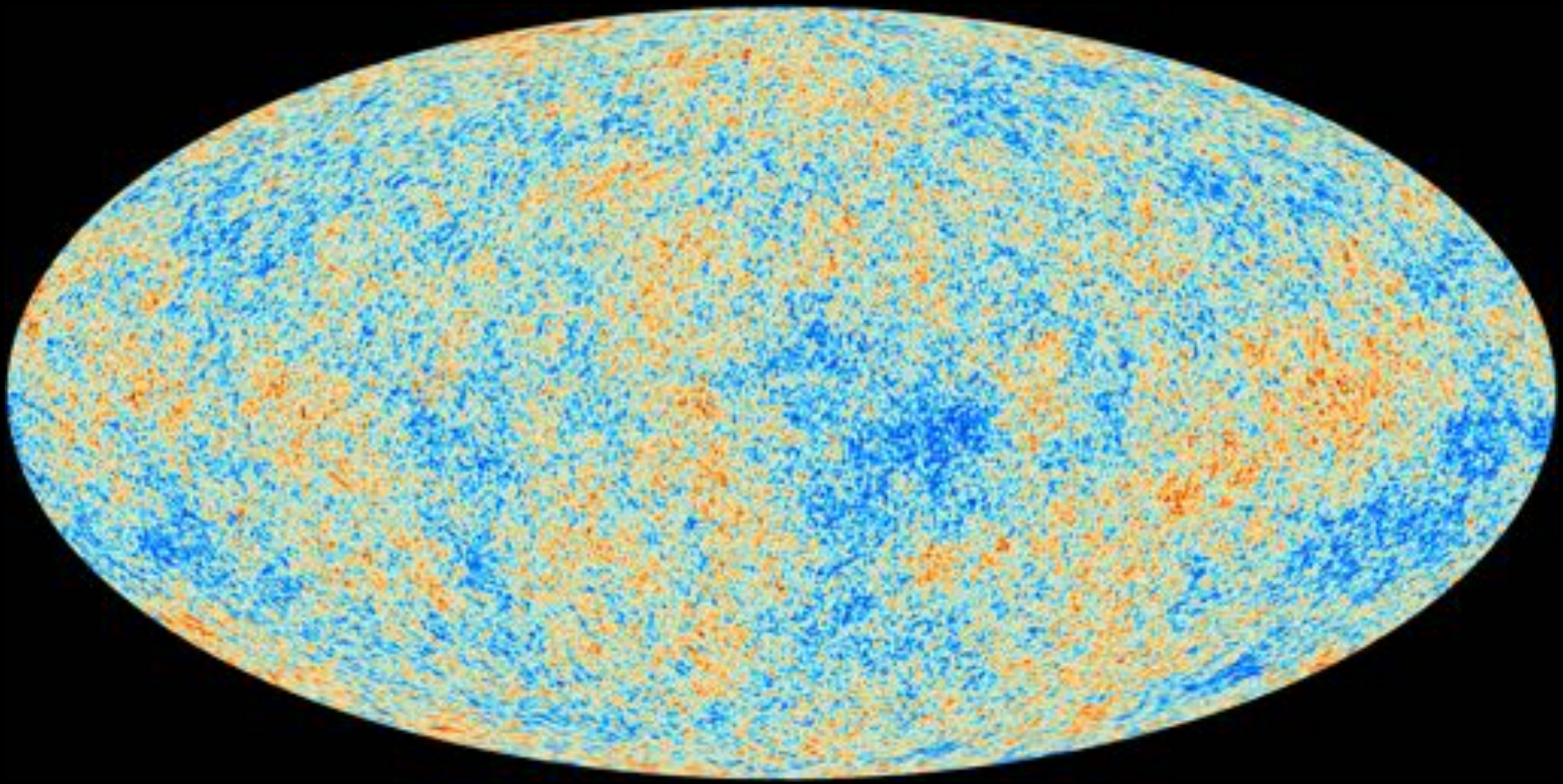


380,000 years after the Big Bang, the Universe was 1100 times smaller than it is today, and filled with glowing plasma as hot as the surface of the Sun

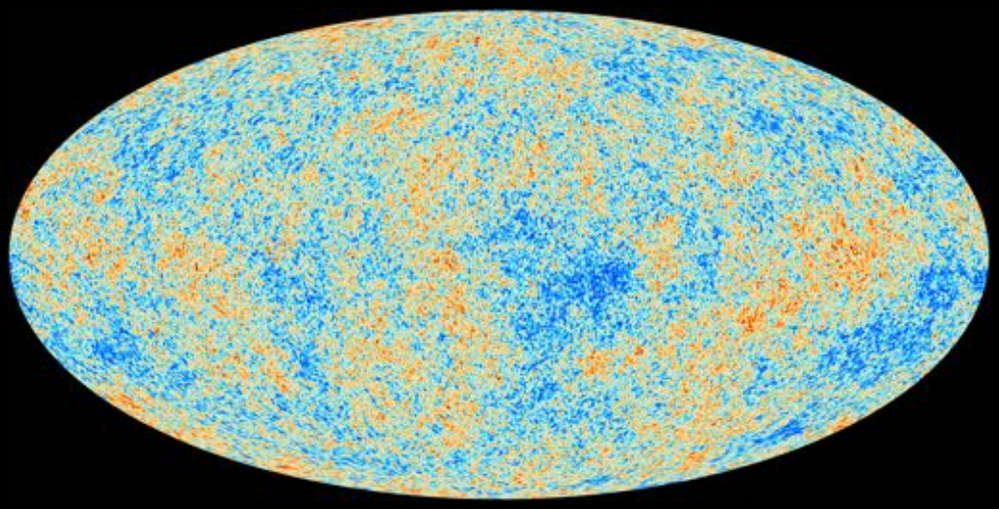


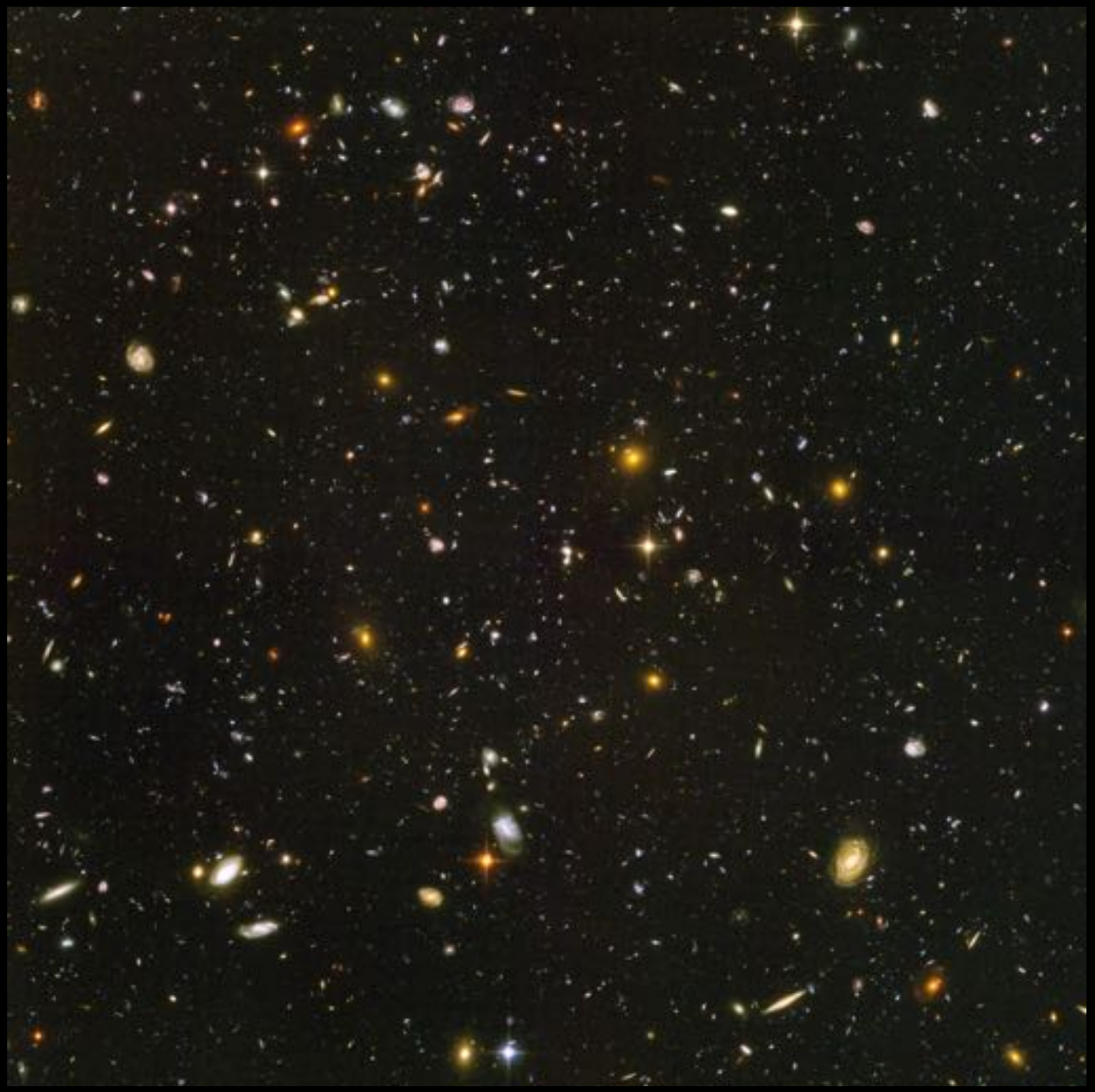
Due to redshifting, we now detect the primordial radiation from that time as a faint microwave hum…
the most highly redshifted light we can see



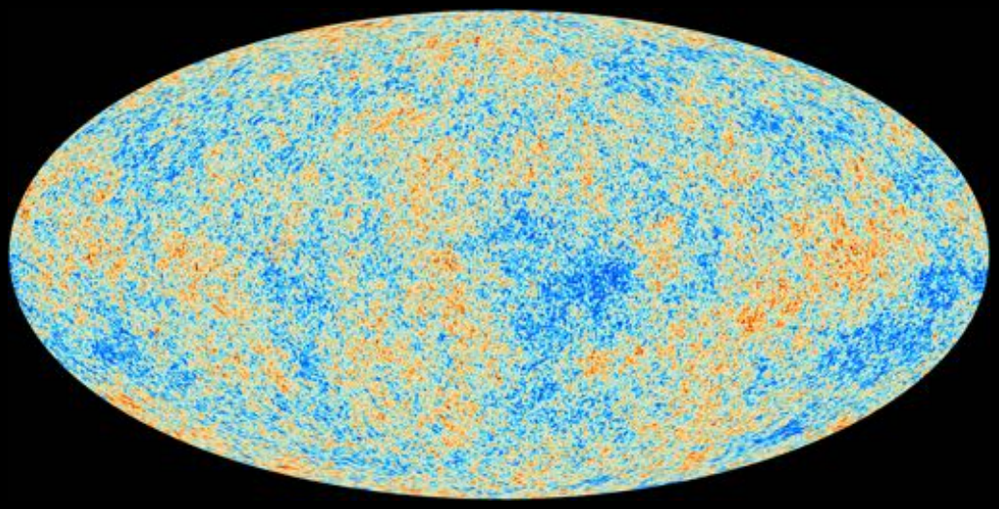


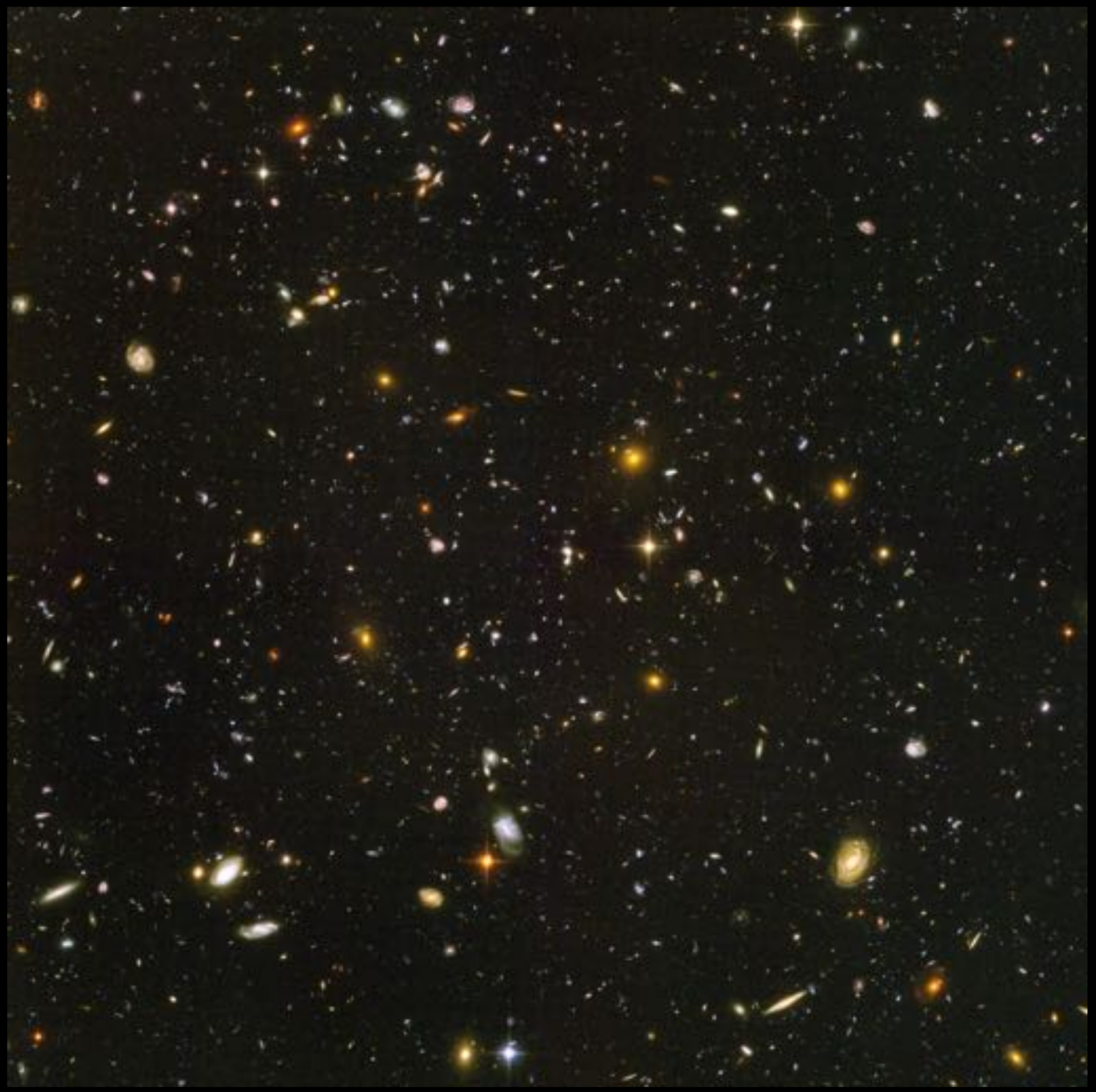
Maps of the Cosmic Microwave Background intensity
show that the Universe was uniform in density to
1 part in 100,000 at those early times





…and the slight over-dense regions grew to become the galaxies and clusters of galaxies we see today…





More on the Cosmic Microwave Background later…

DARK ENERGY SURVEY

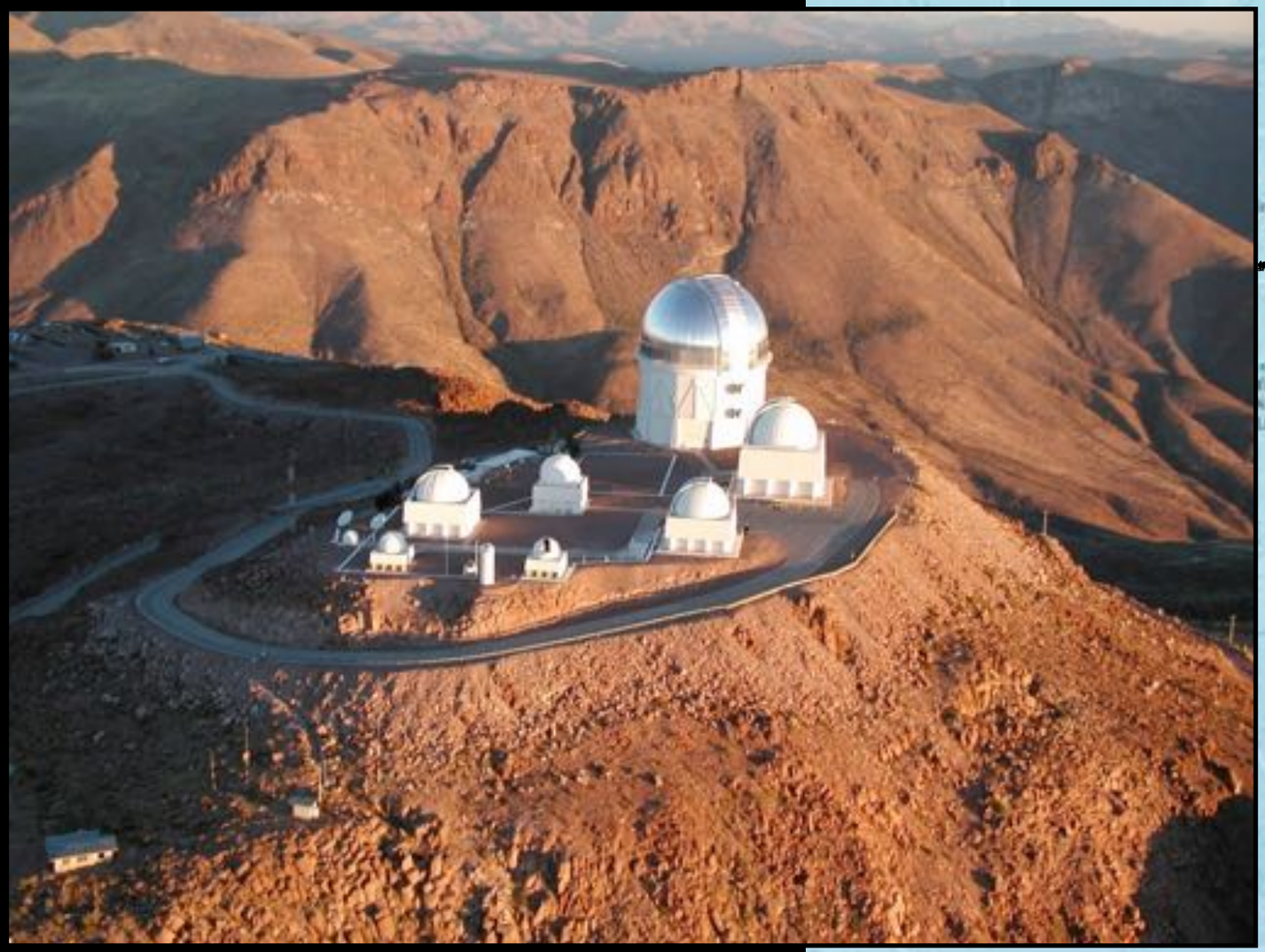
DARK ENERGY SURVEY

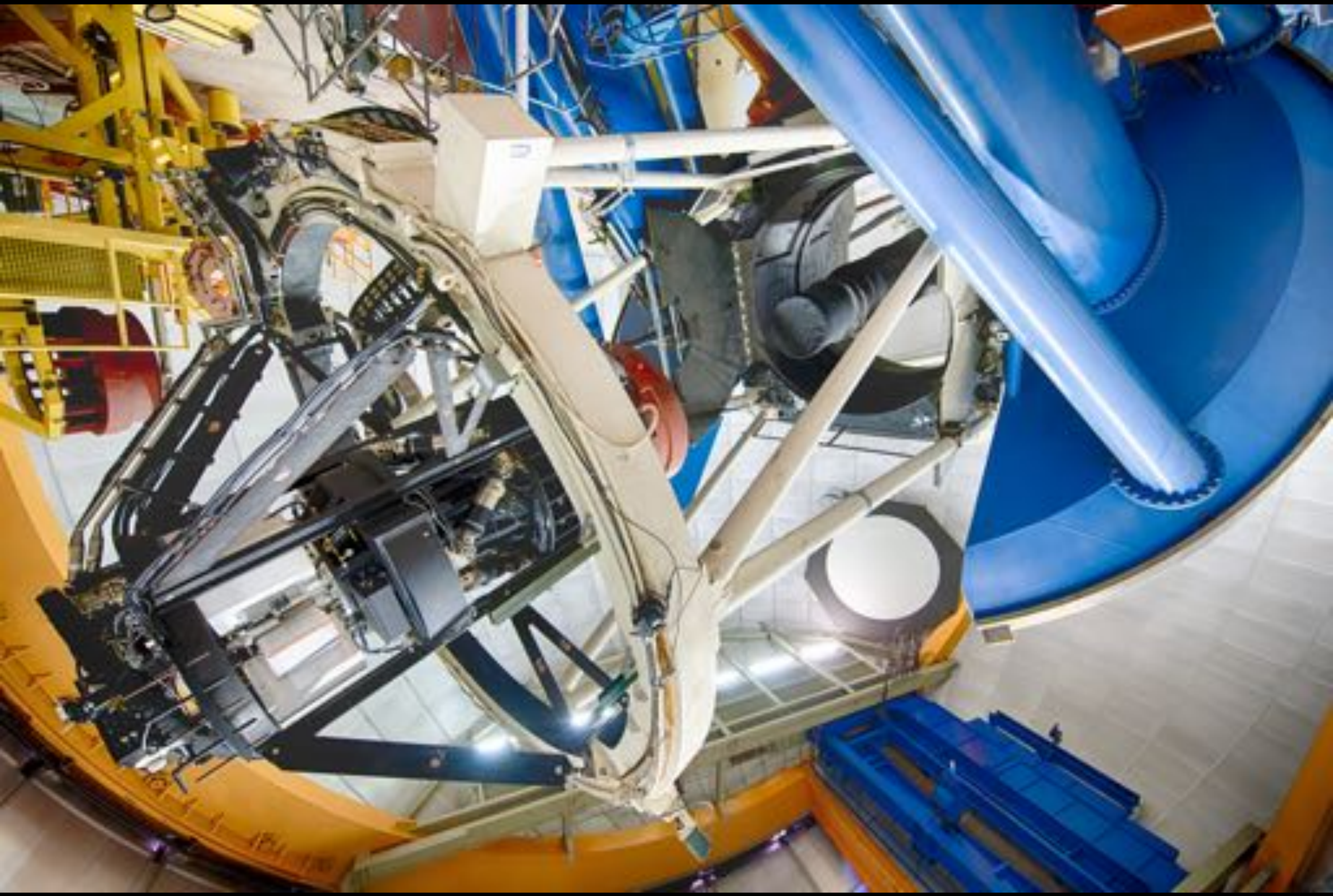
Mapping 300 million galaxies over one-eighth of the full sky over 10 billion years of cosmic history

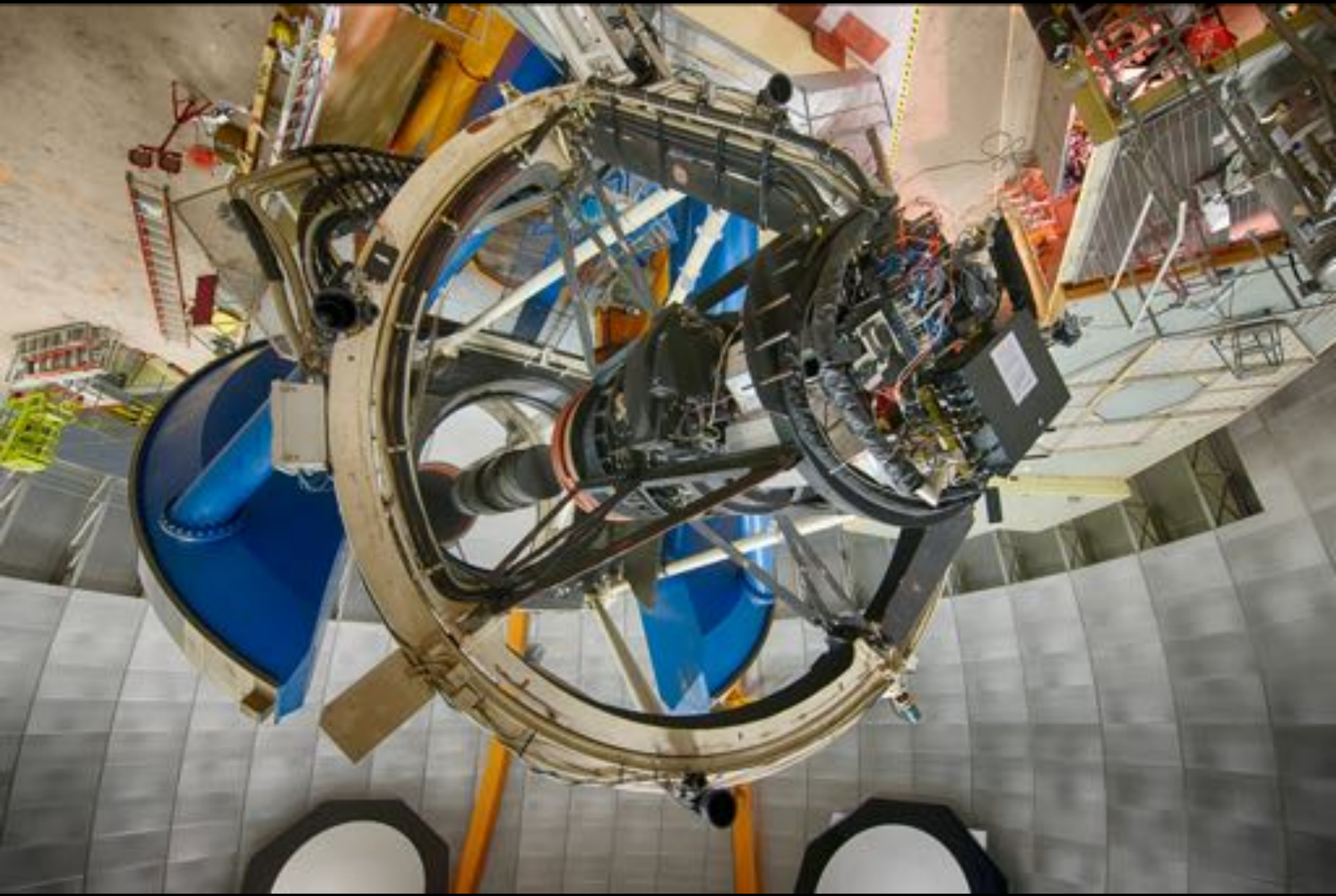
The first dedicated survey to study dark energy using four distinct and complementary techniques

Cerro Tololo Interamerican Observatory (CTIO)

near La Serena, Chile



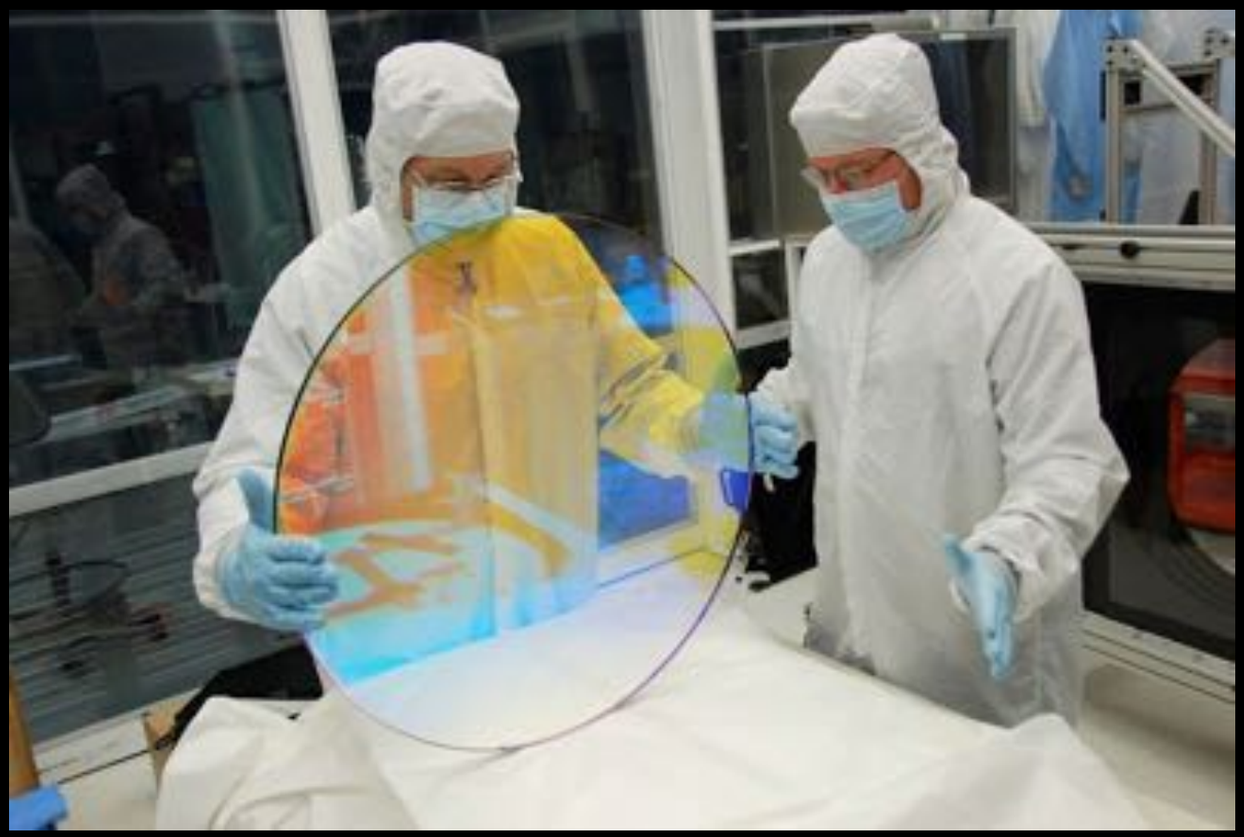




A focal plane the
size of a manhole

62 science CCDs with
enhanced red-sensitivity

5 color filters



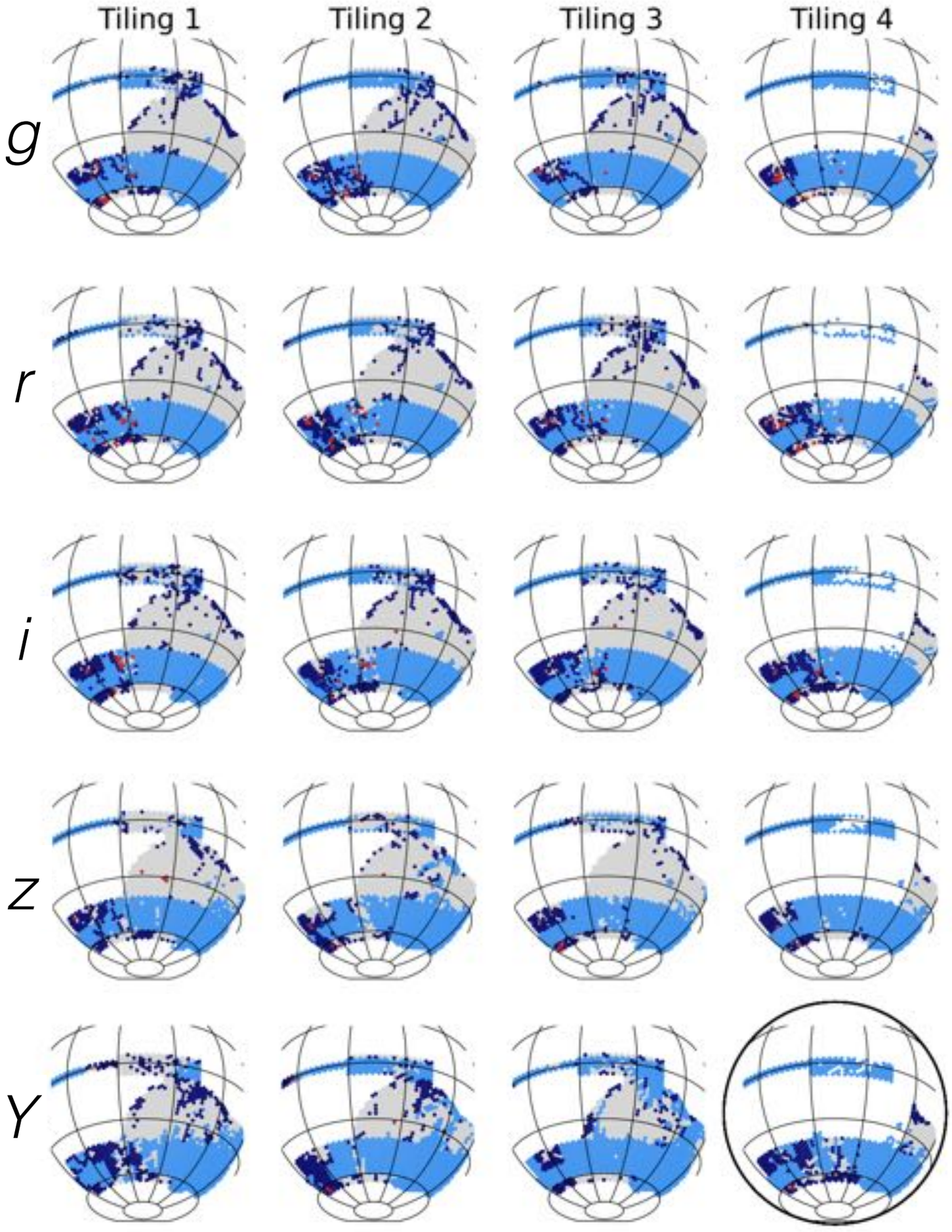
Most of the objects are galaxies a ***million*** times fainter than the limit of unaided human vision

"Nearby" Galaxy

Star in the Milky Way

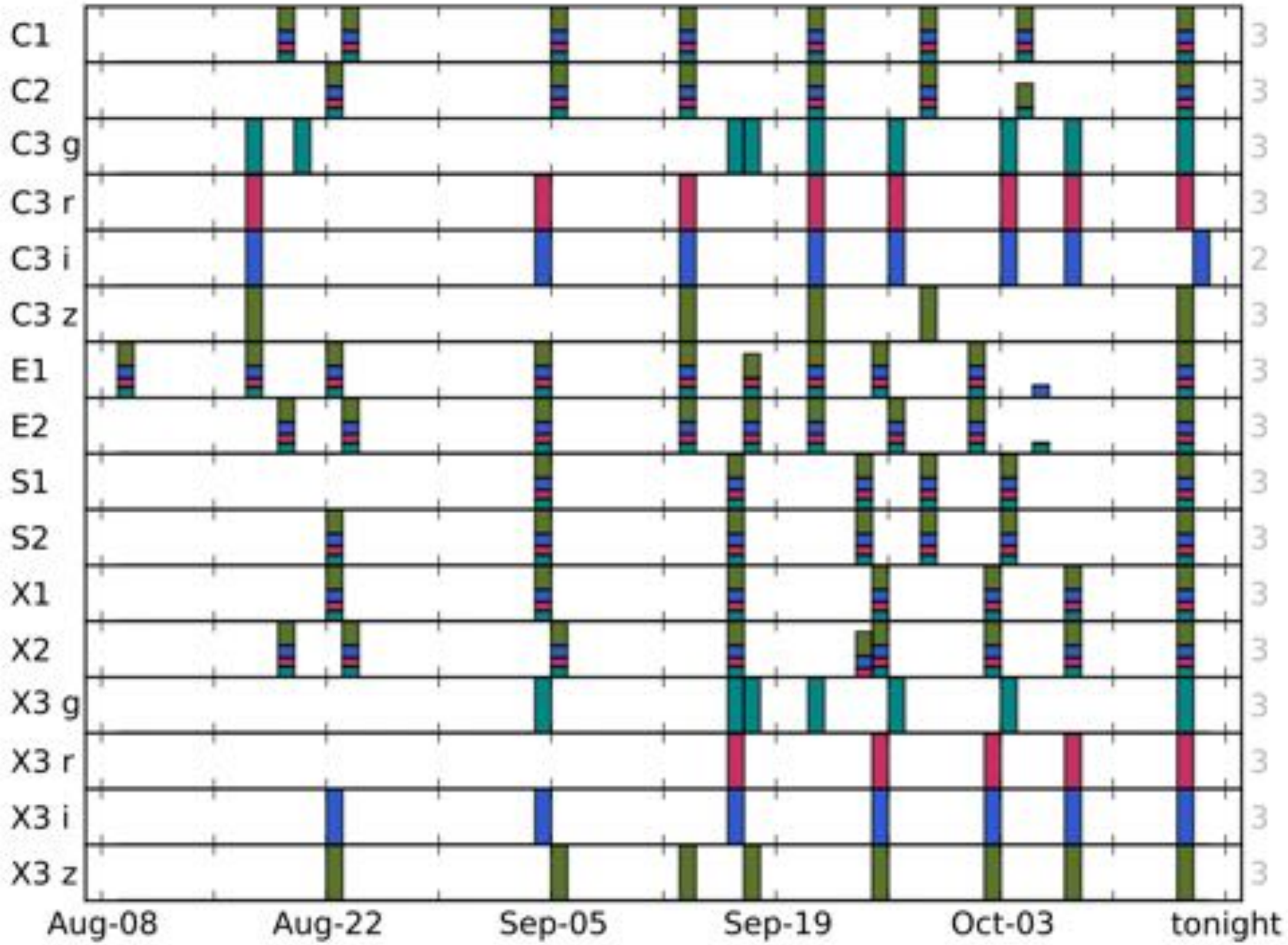

Distant
Galaxy
Cluster

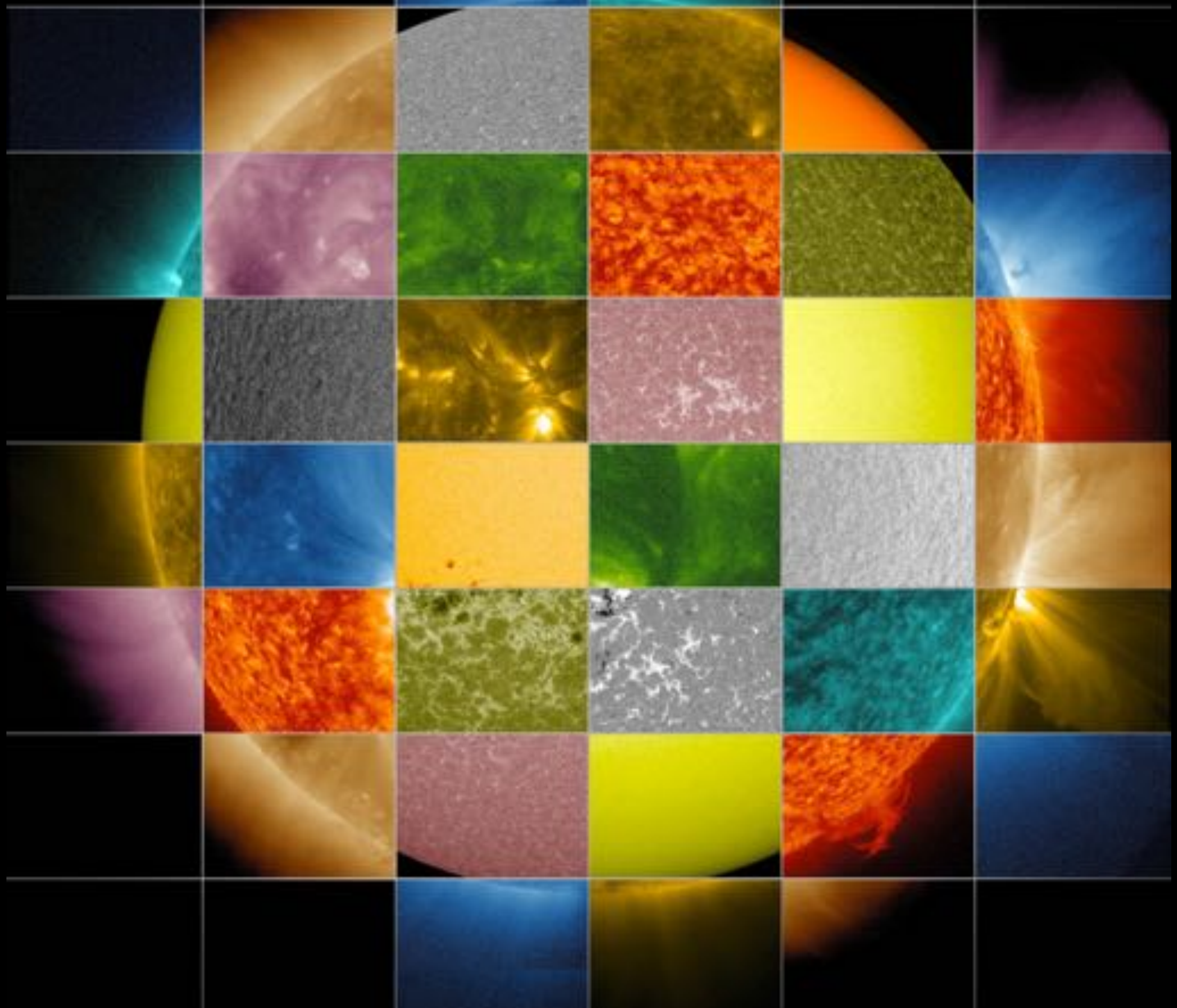
5 years
525 nights
A photo every 2 minutes



Total of 10 tilings in each patch of sky
Each “hex” = 3 deg^2

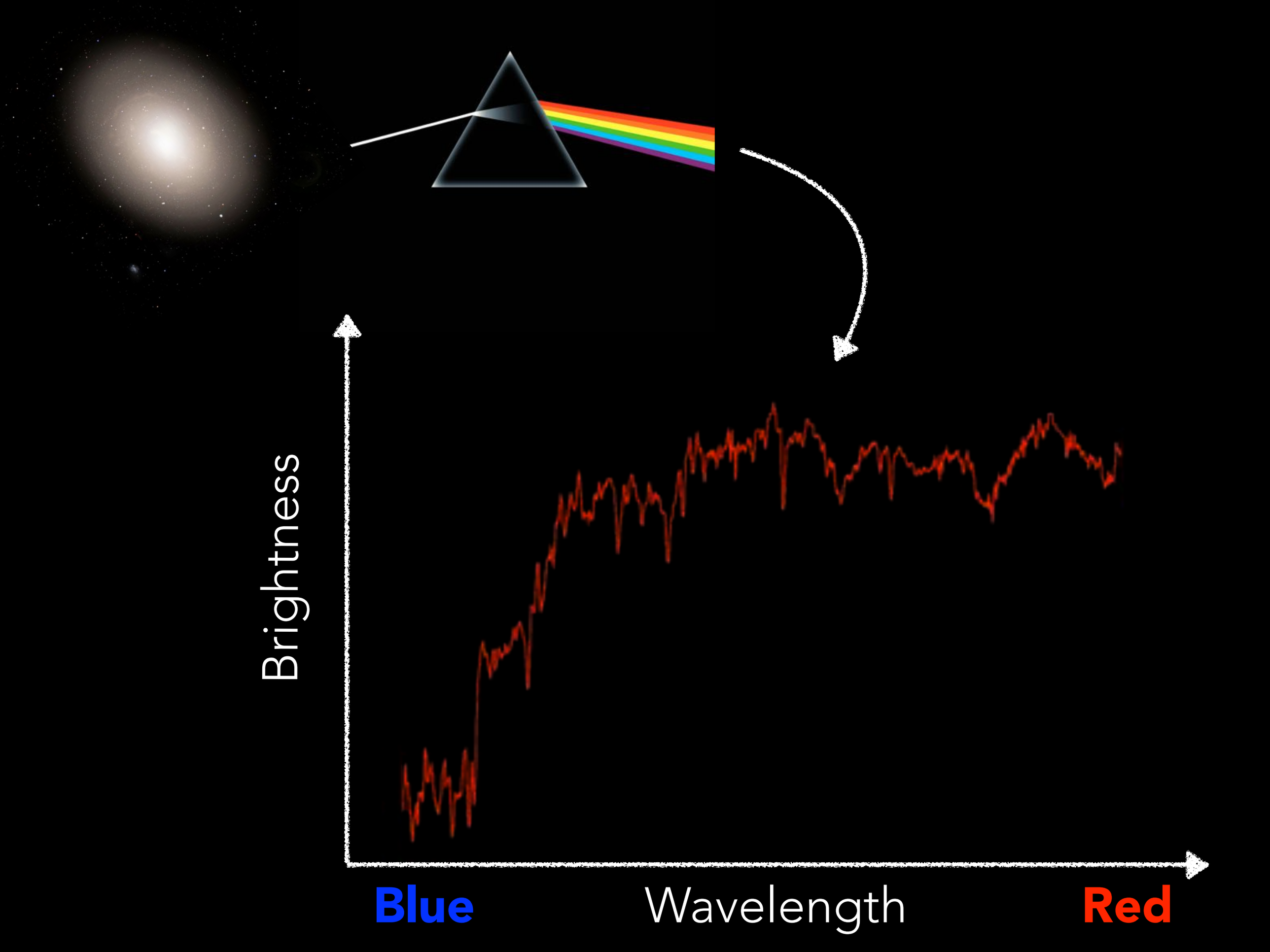
Survey footprint
1st Season
2nd Season
Last Night


C1
C2
C3 g
C3 r
C3 i
C3 z
E1
E2
S1
S2
X1
X2
X3 g
X3 r
X3 i
X3 z
3
3
3
3
2
3
3
3
3
3
3
3
3
3
3
3
Aug-08
Aug-22
Sep-05
Sep-19
Oct-03
tonight

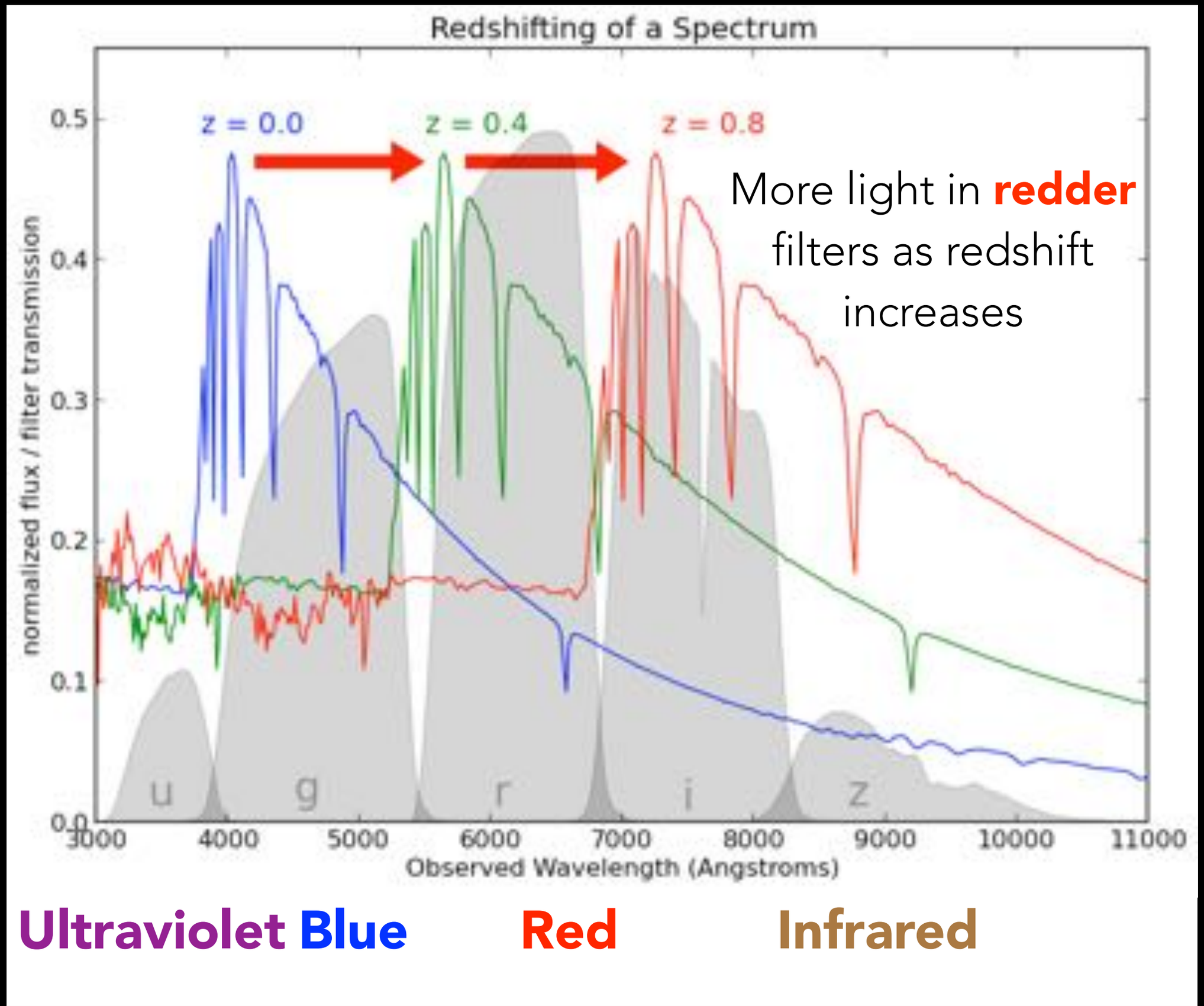


ULTRAVIOLET

INFRARED


Brightness
Blue
Wavelength
Red

Photometric Redshift



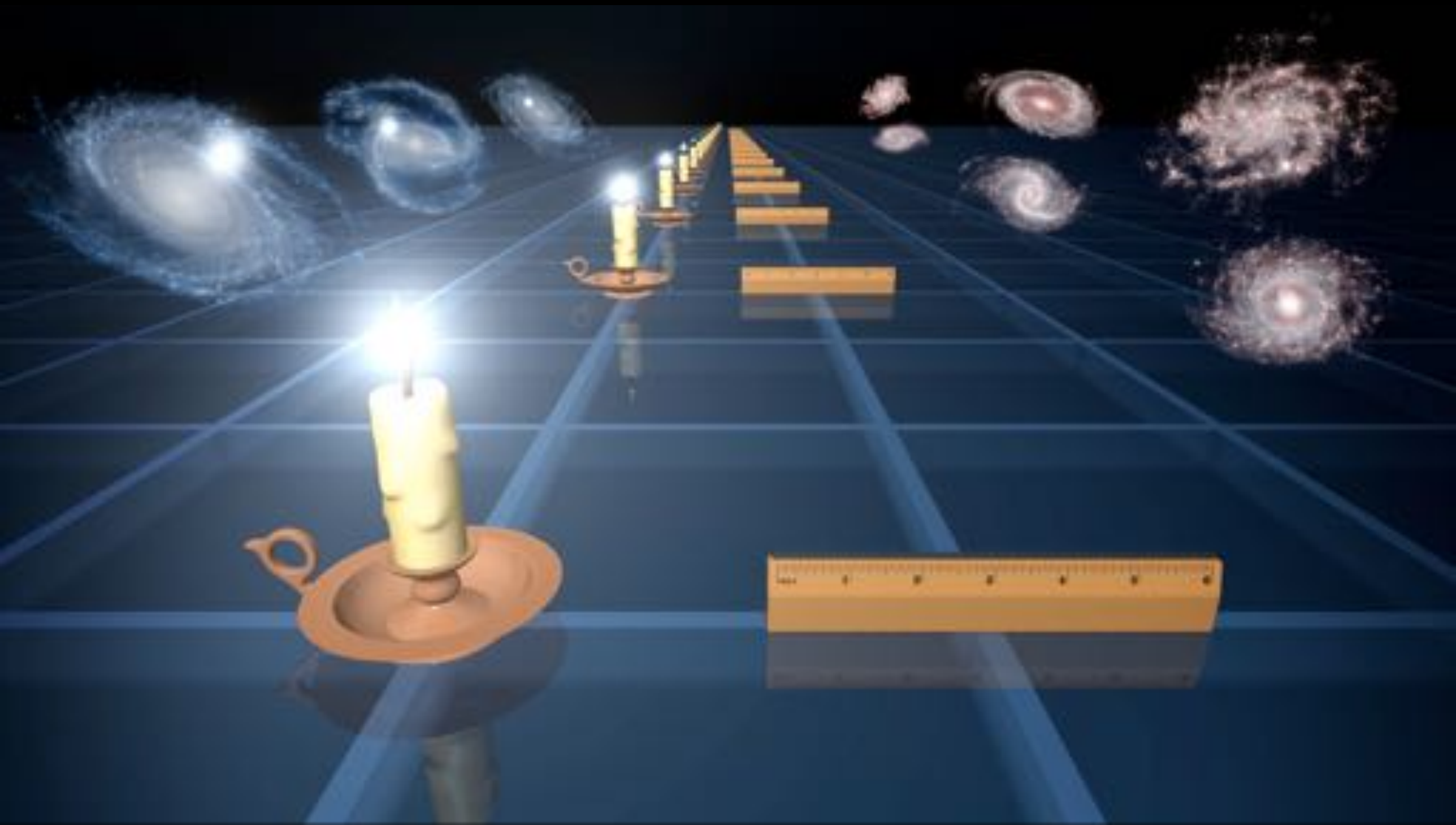
Ultraviolet **Blue** **Red** **Infrared**

MEASURING DISTANCES IN AN EXPANDING UNIVERSE

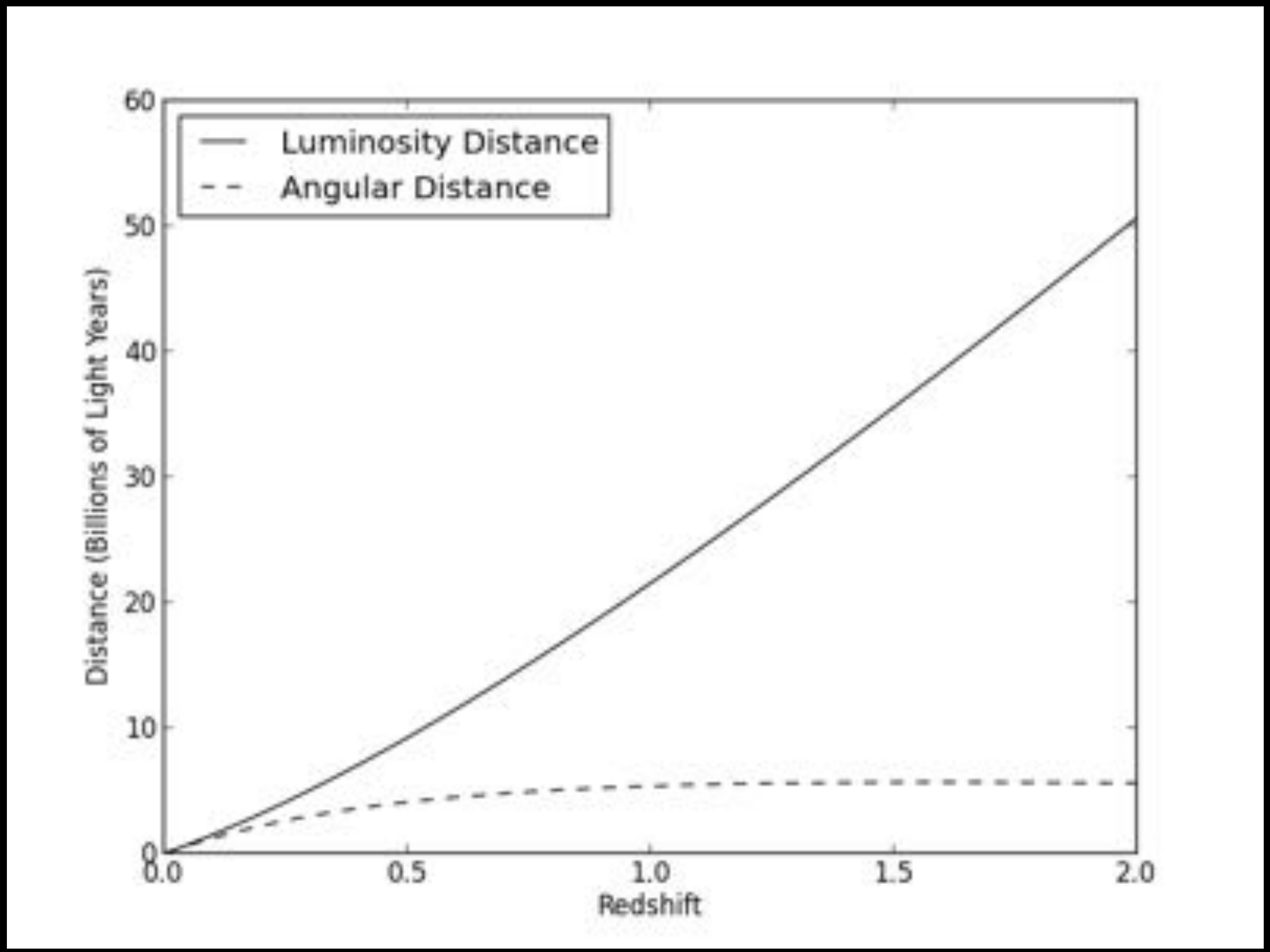
LUMINOSITY DISTANCE

ANGULAR DIAMETER DISTANCE

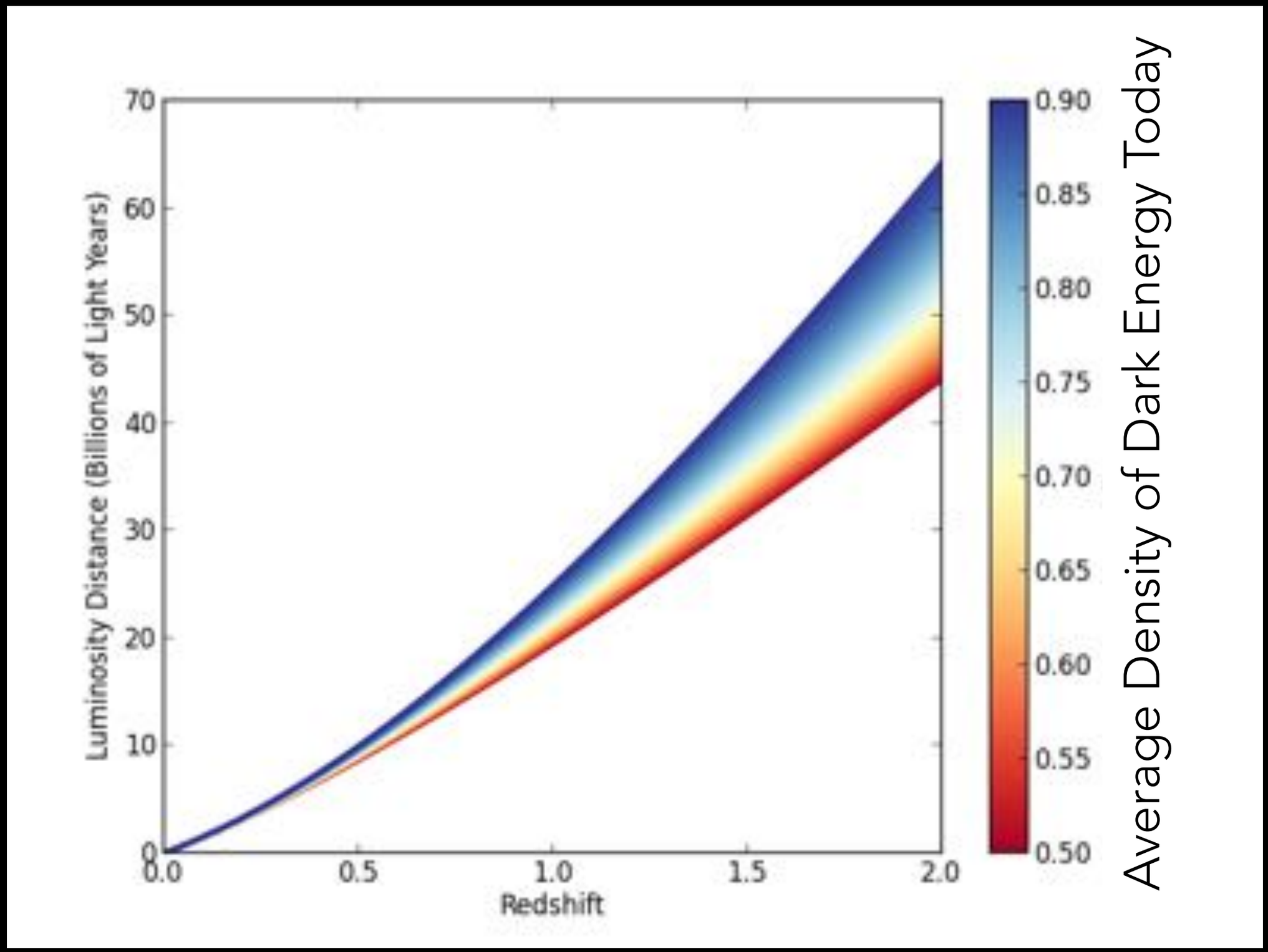
Preserving notion that distant objects appear **dimmer** and **smaller**



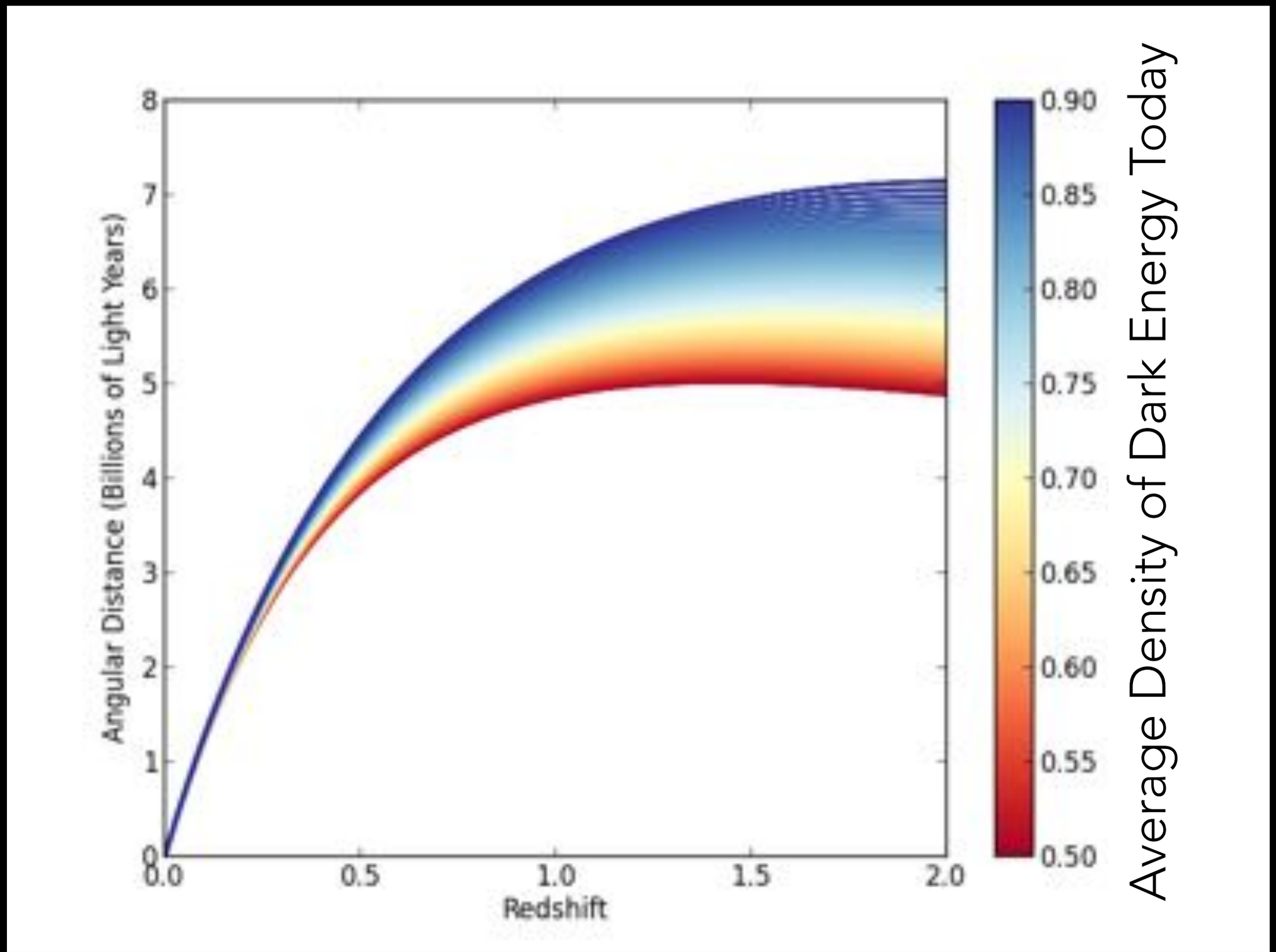
In general, luminosity and angular distance are NOT the same



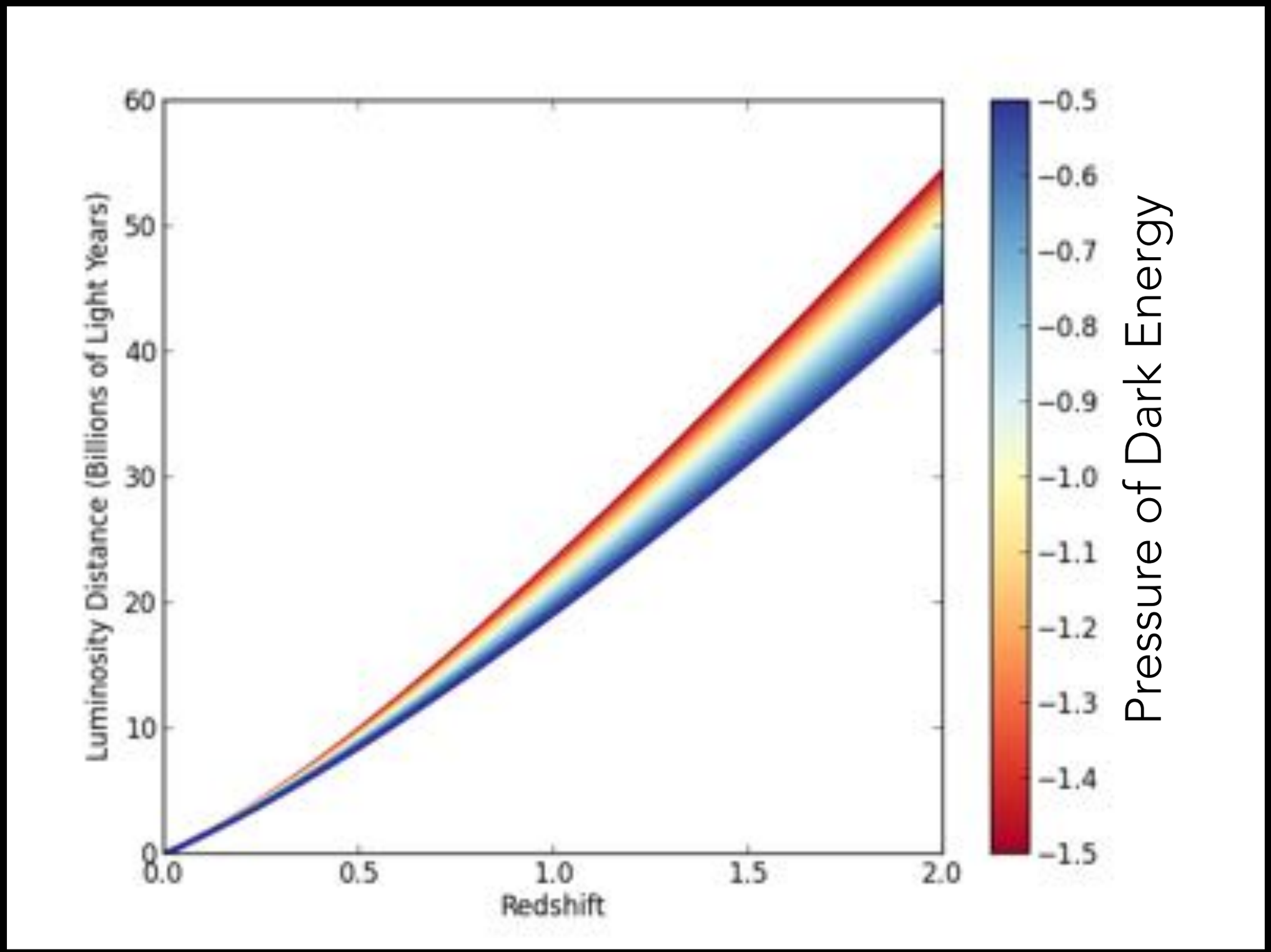
Luminosity distance vs. redshift for different amounts of dark energy in the Universe today



Angular distance vs. redshift for different amounts of dark energy in the Universe today

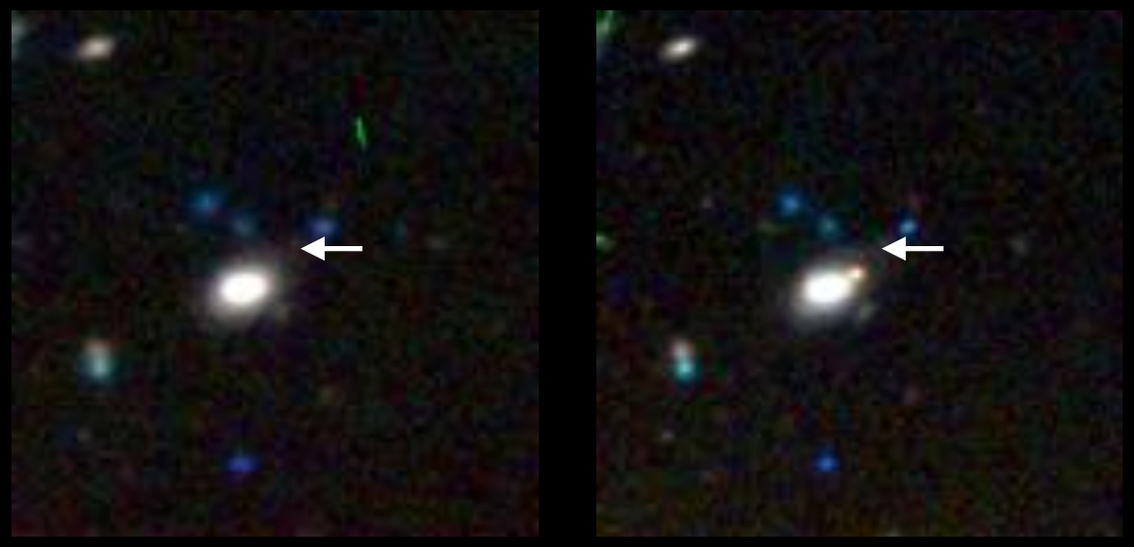


Luminosity distance vs. redshift for different properties of dark energy

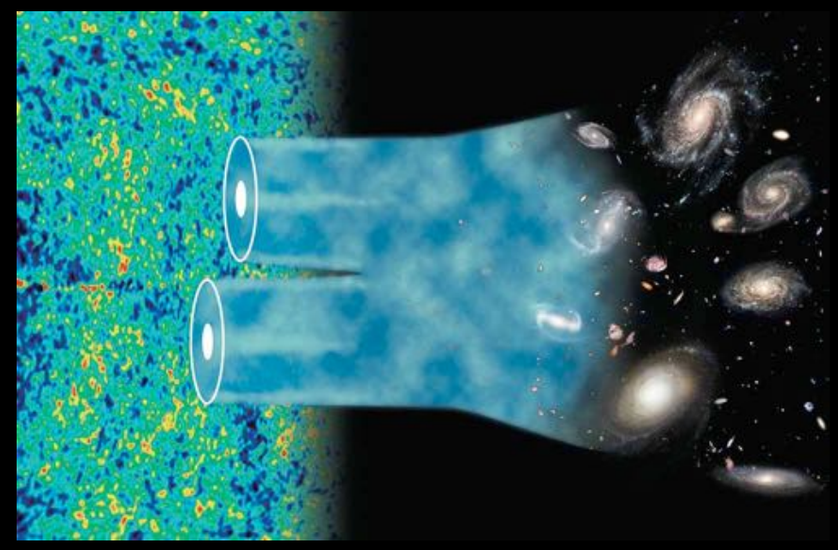


TESTS OF DARK ENERGY

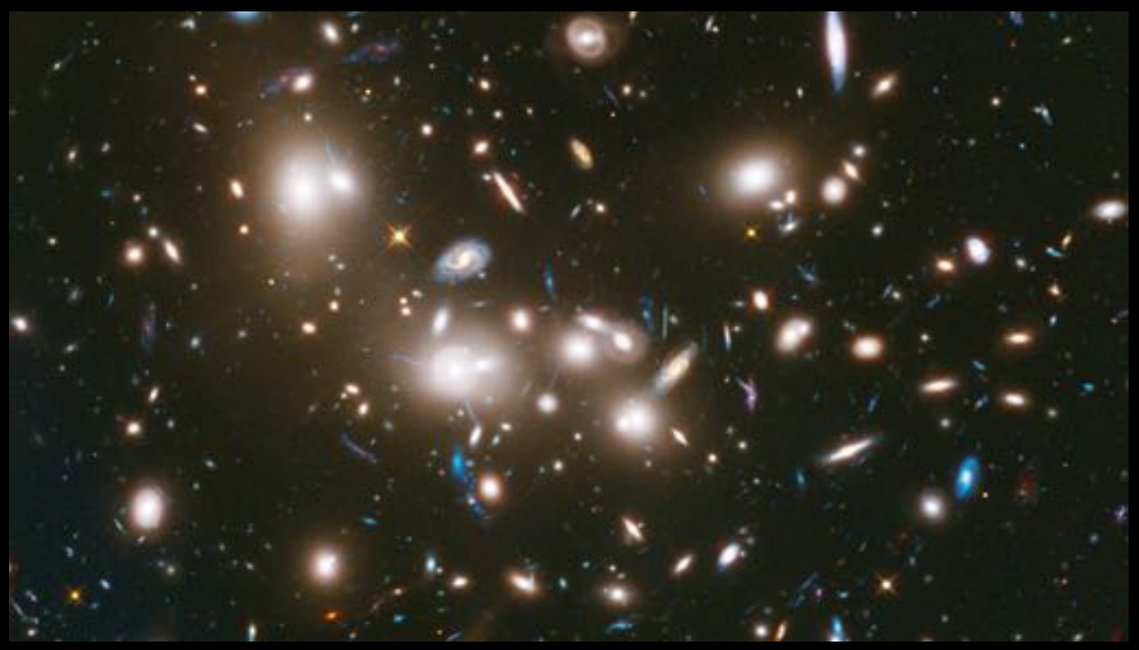
TESTS OF DARK ENERGY



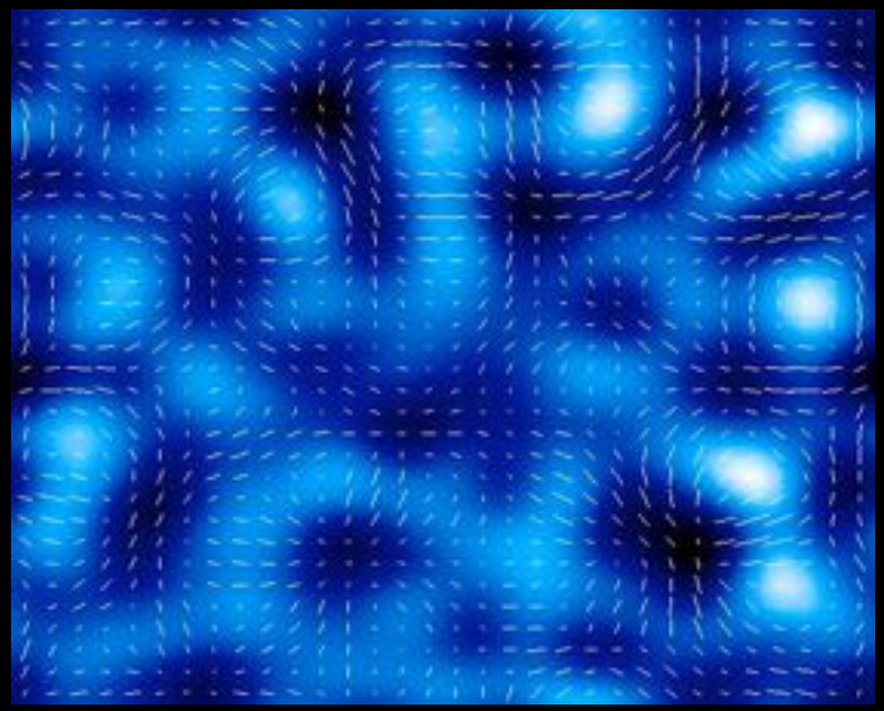
Type 1a Supernovae



Baryon Accoustic Oscillations

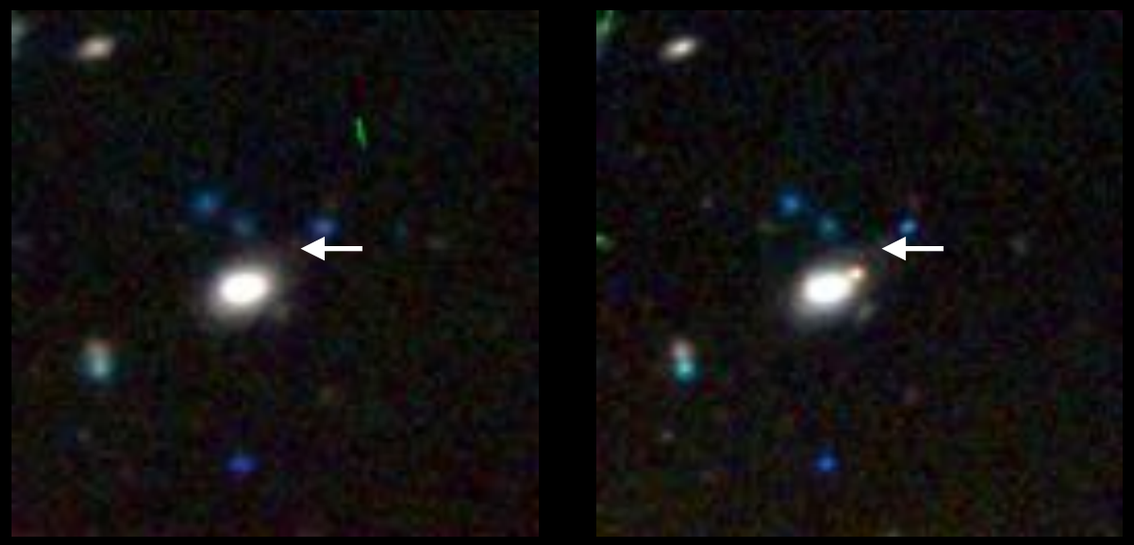


Galaxy Cluster Abundance



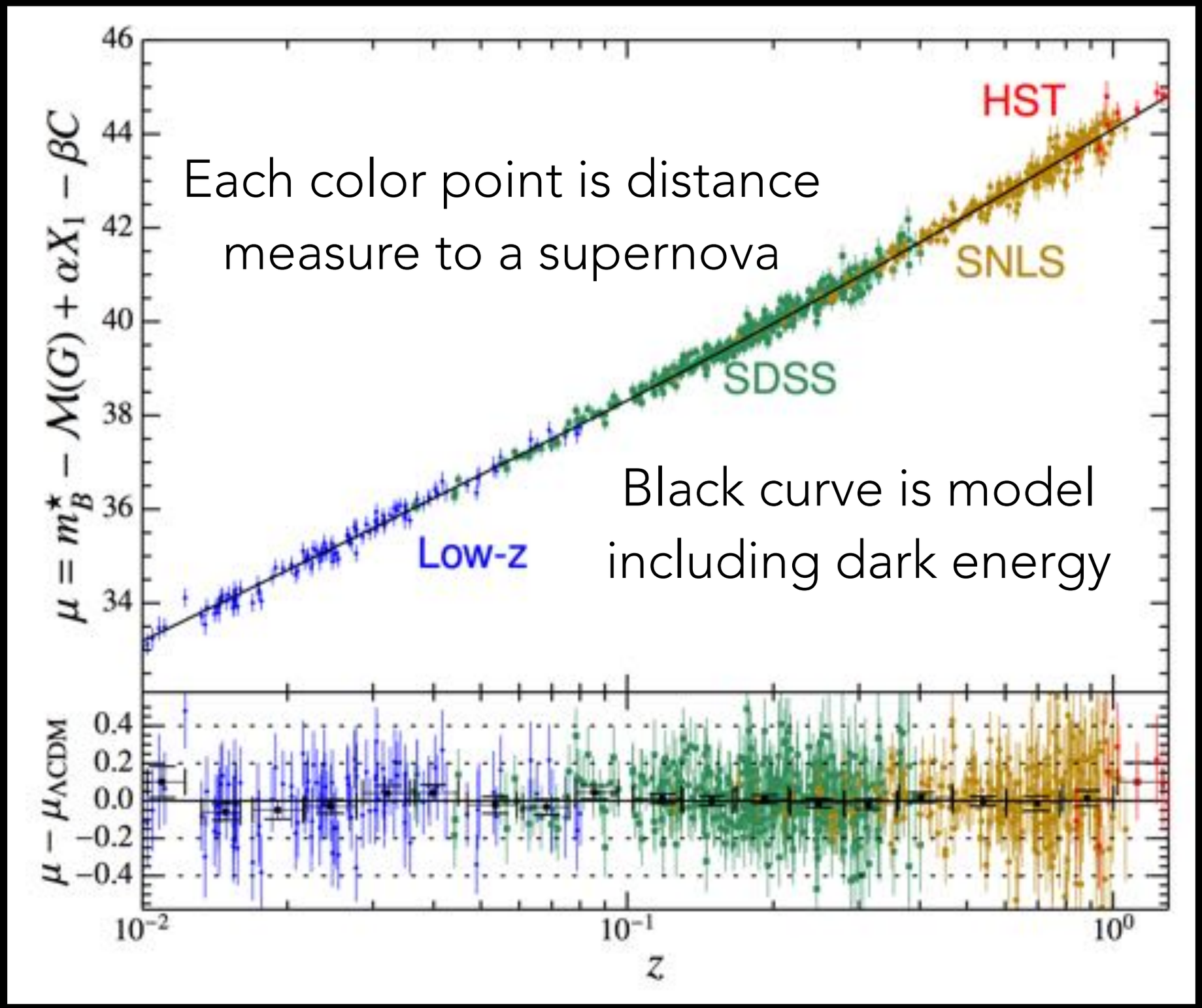
Weak Gravitational Lensing

TESTS OF DARK ENERGY



Type 1a Supernovae

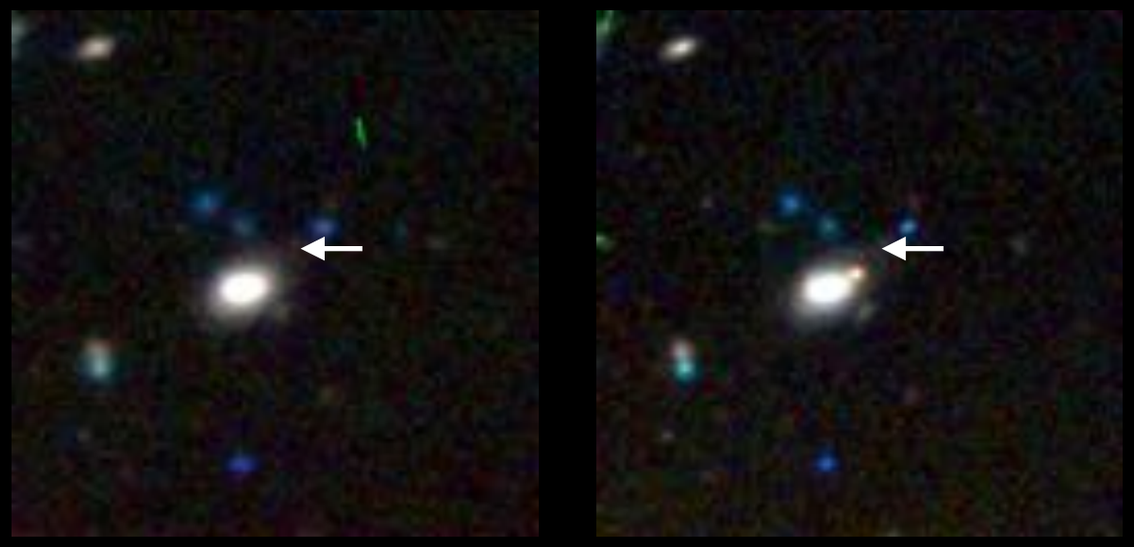
Extremely Good Agreement Between Model and Data



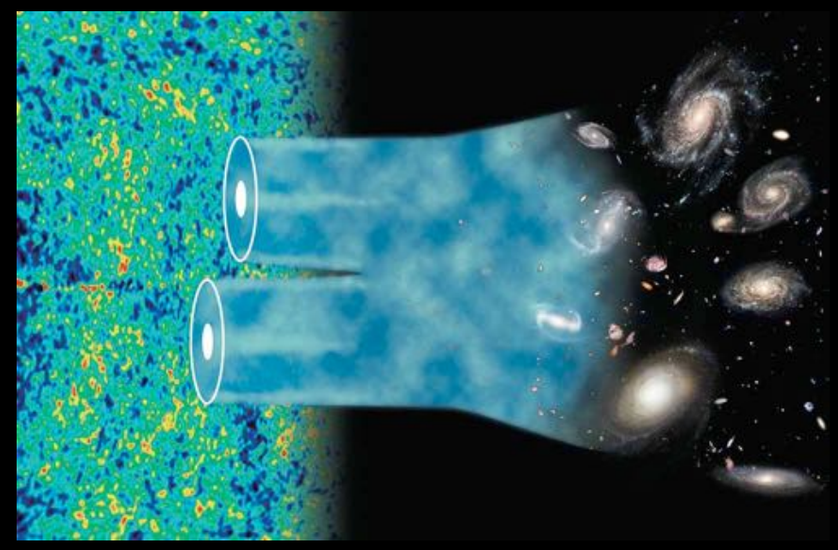
Residuals Luminosity Distance

Redshift

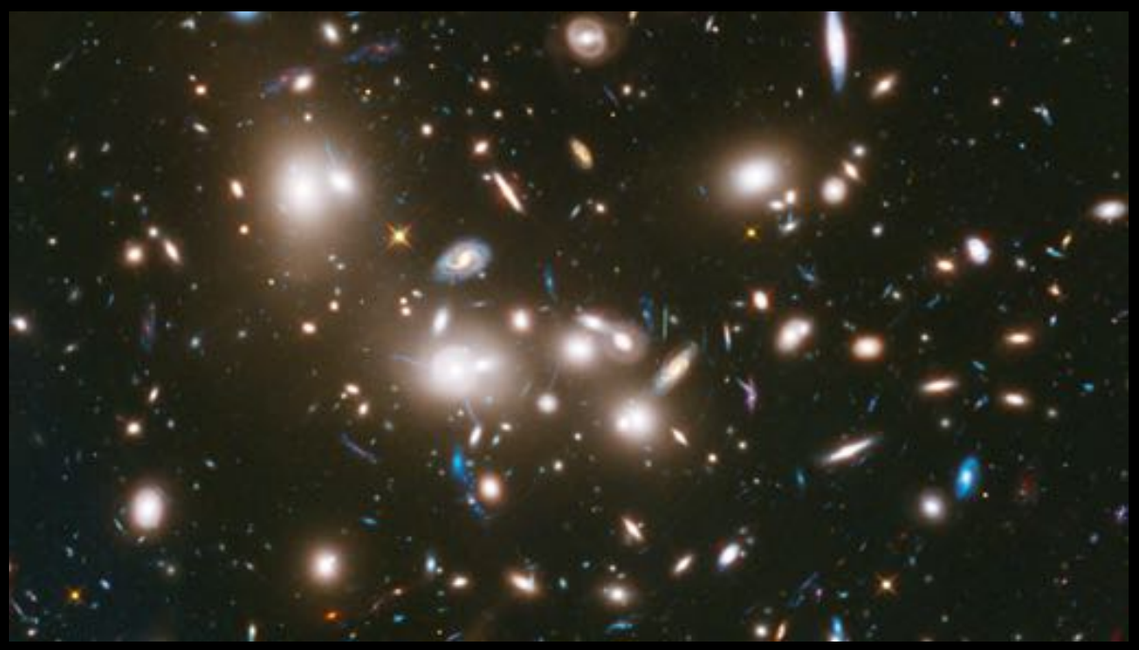
TESTS OF DARK ENERGY



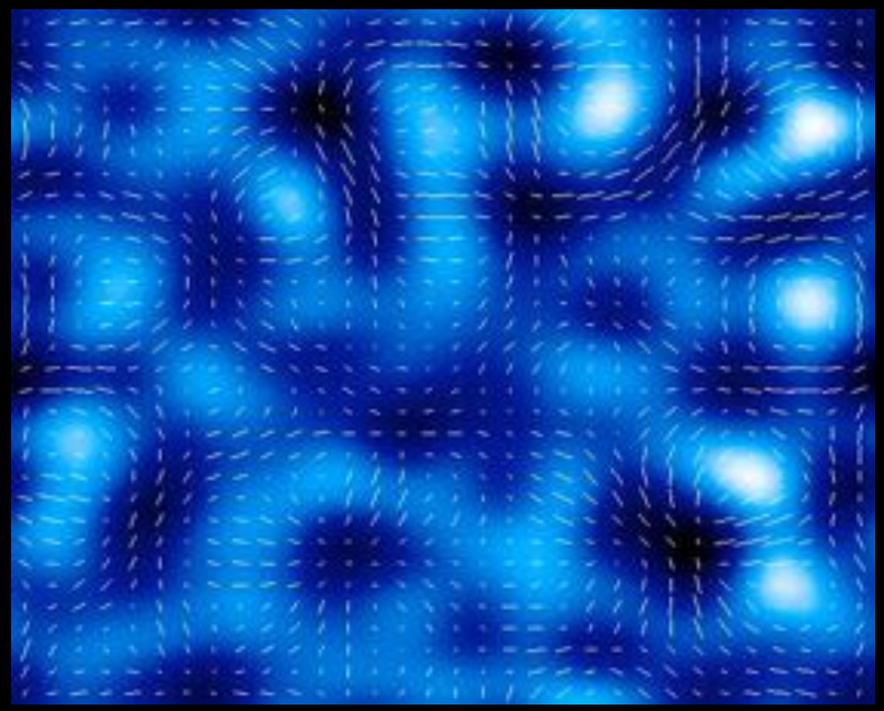
Type 1a Supernovae



Baryon Accoustic Oscillations

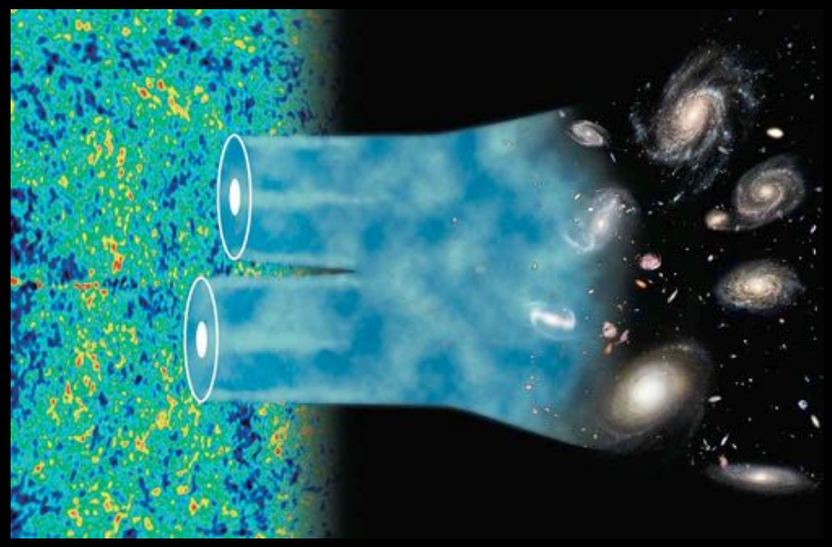


Galaxy Cluster Abundance



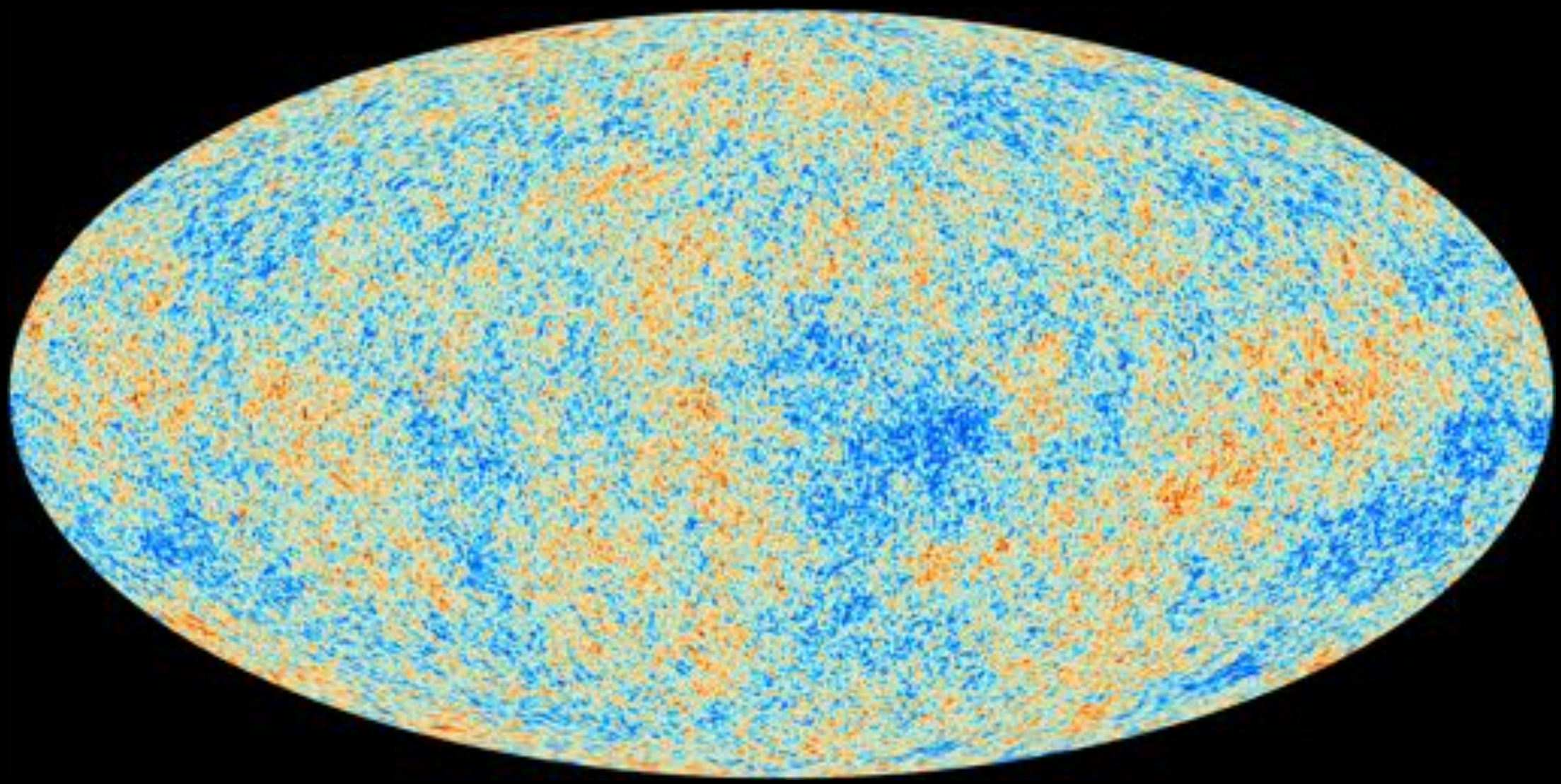
Weak Gravitational Lensing

TESTS OF DARK ENERGY



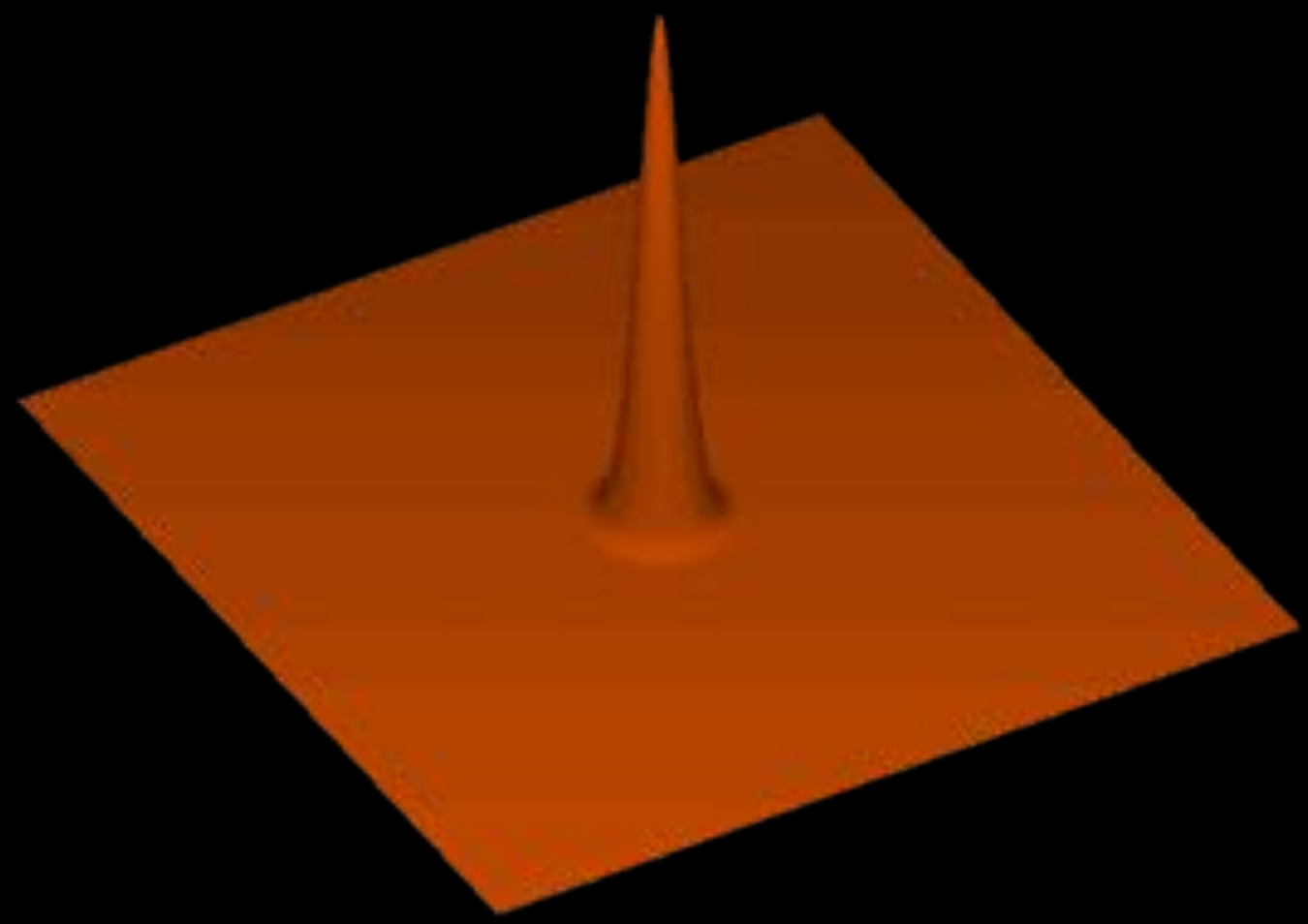
Baryon Accoustic Oscillations

Remember the Cosmic Microwave Background map?

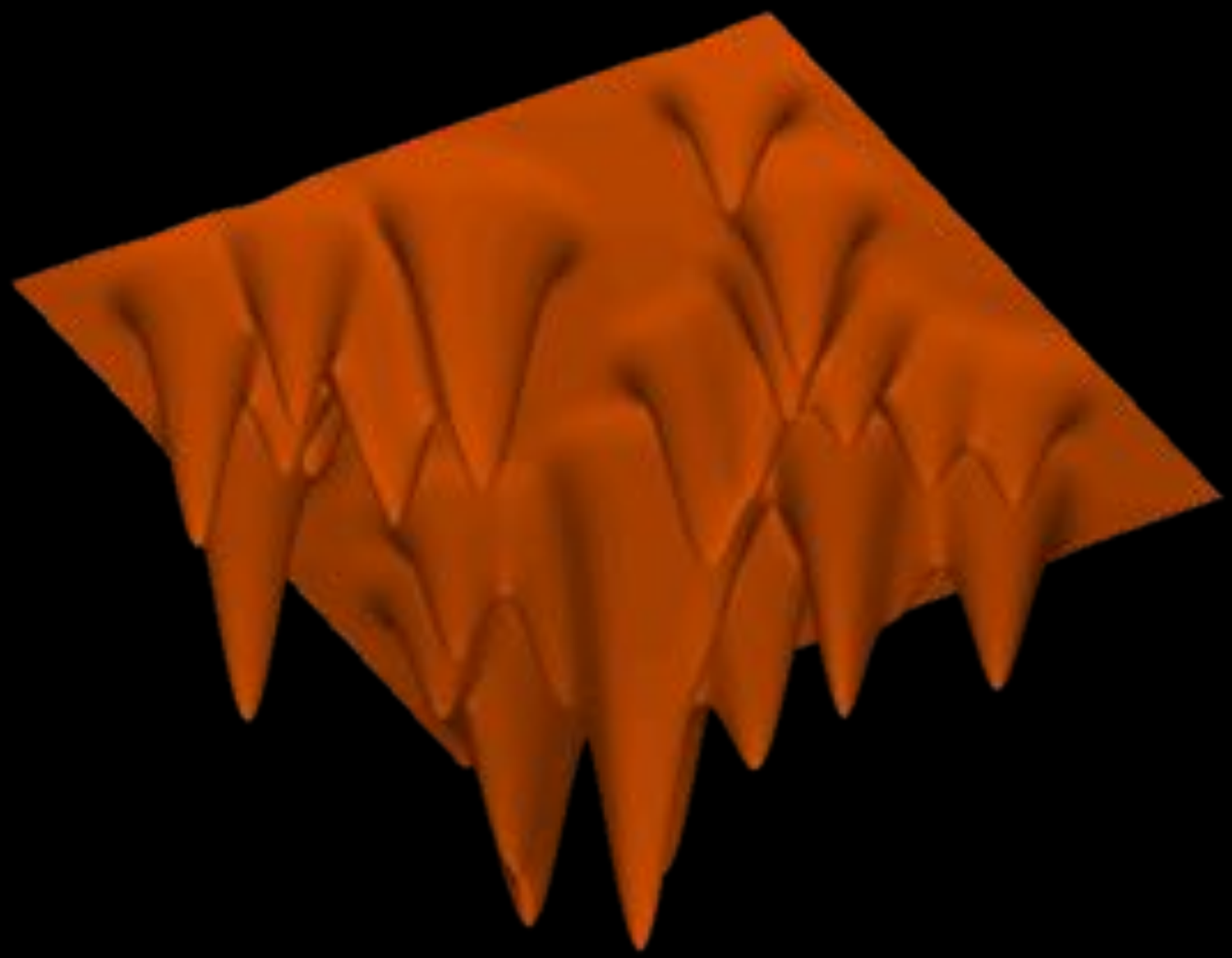


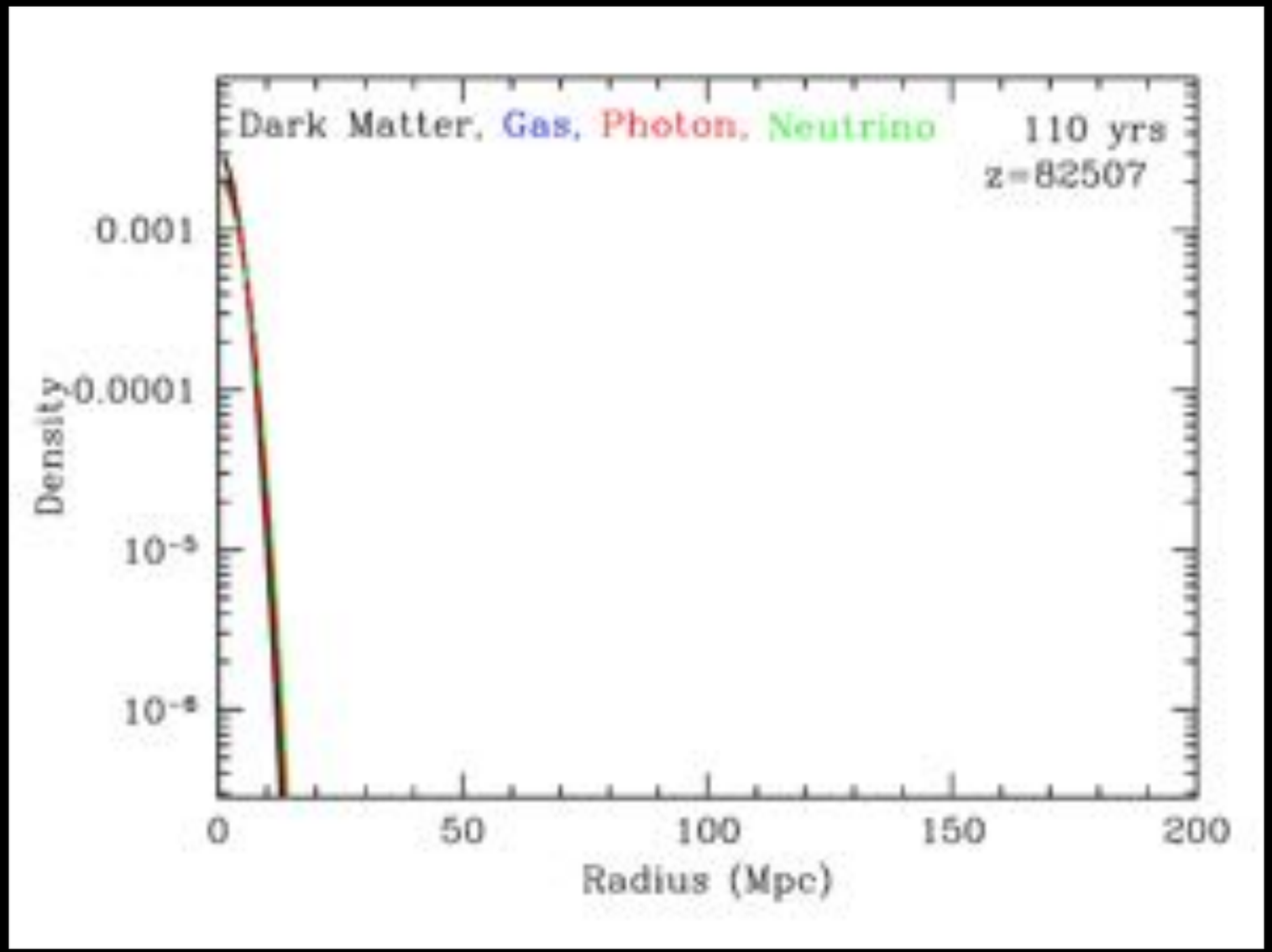
You may have noticed a characteristic size of the speckles indicating slightly over-dense and under dense regions

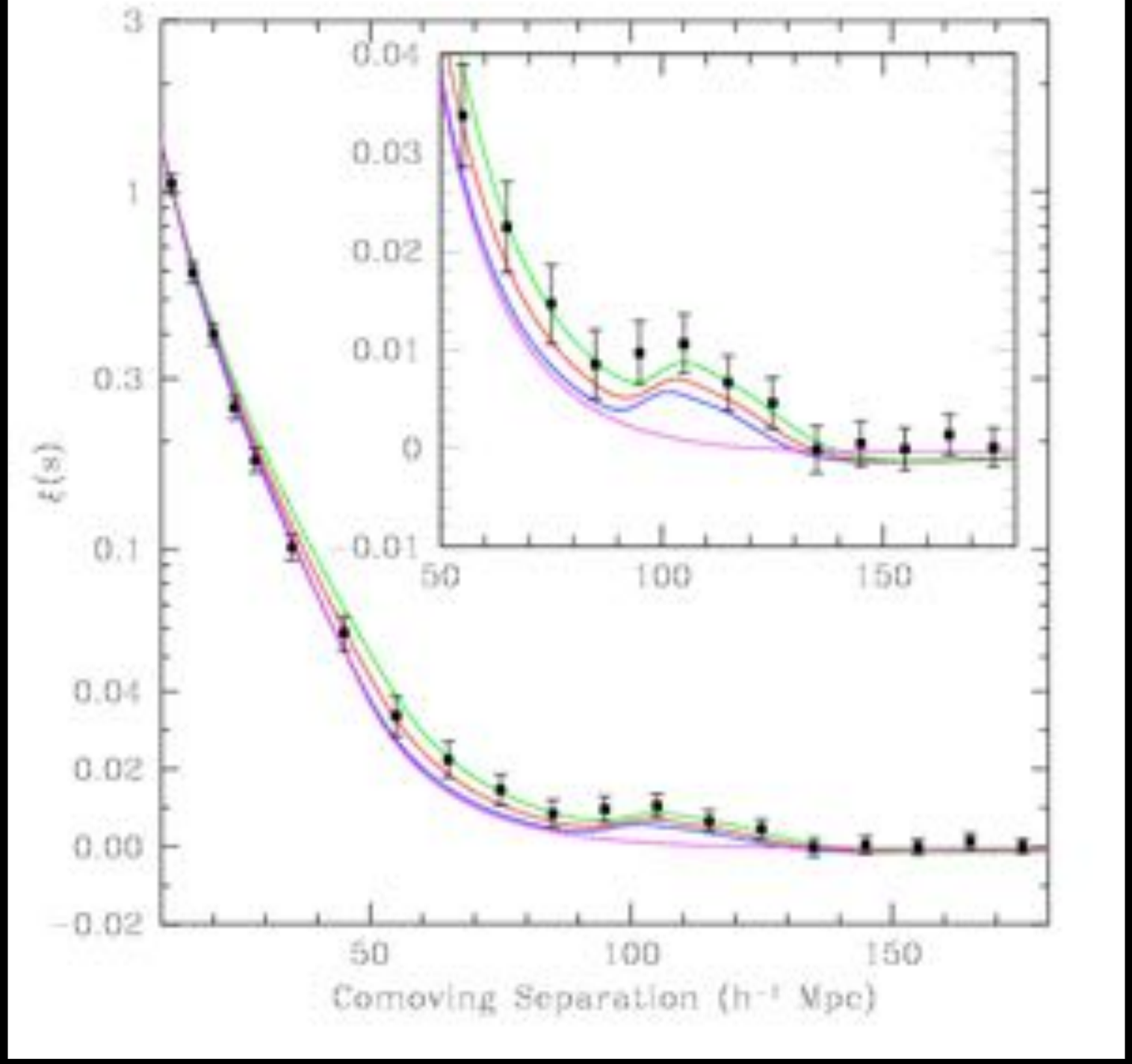
In early times , nuclei, electrons, and light interacted so often that they moved together as a single fluid



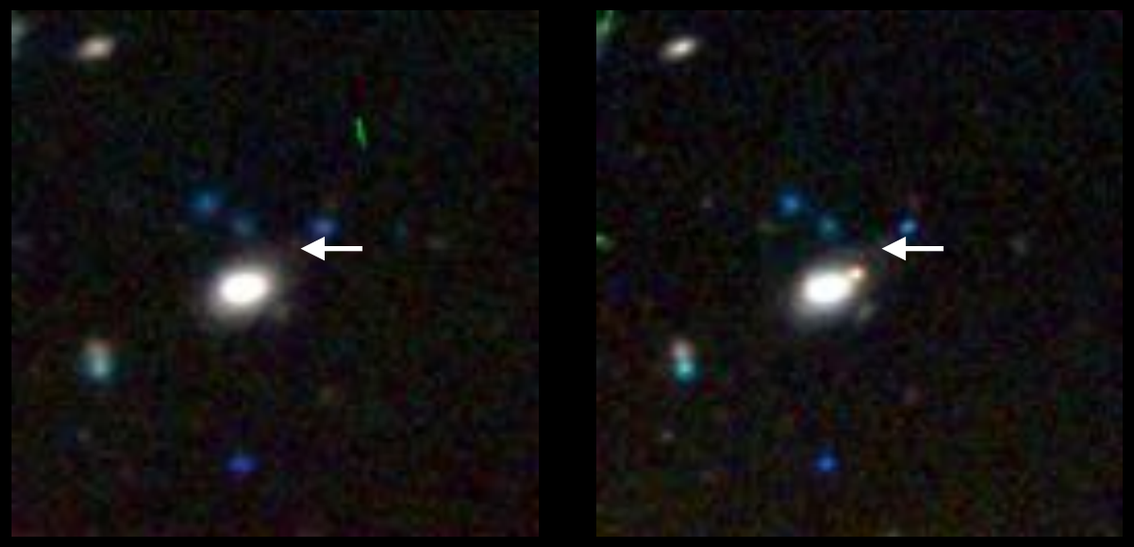
The size of the speckles in the microwave map is related to distance sound waves could travel before light separated from atoms 380,000 years after the Big Bang



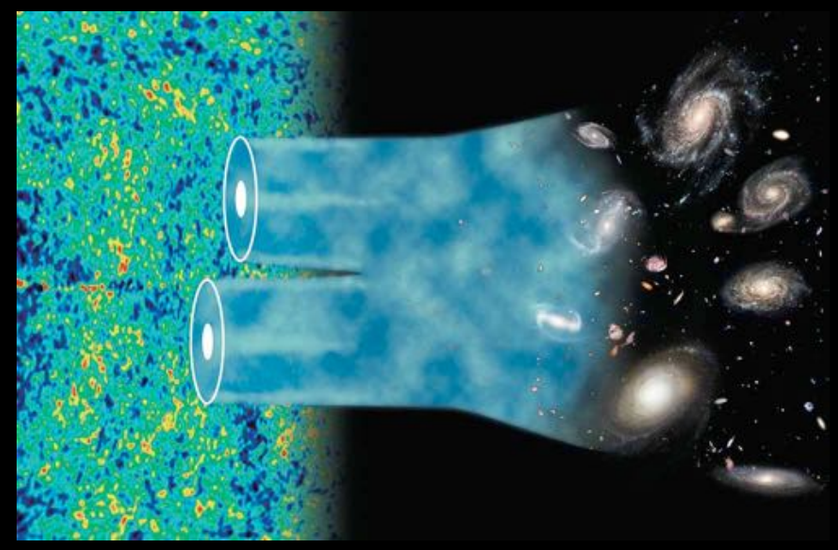

Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
0.001
0.0001
10⁻⁵
10⁻⁶
Density
0
50
100
150
200
Radius (Mpc)


3
1
0.3
0.1
0.04
0.02
0.00
-0.02
ξ(s)
0.04
0.03
0.02
0.01
0
-0.01
50
100
150
50
100
150
Comoving Separation (h⁻¹ Mpc)

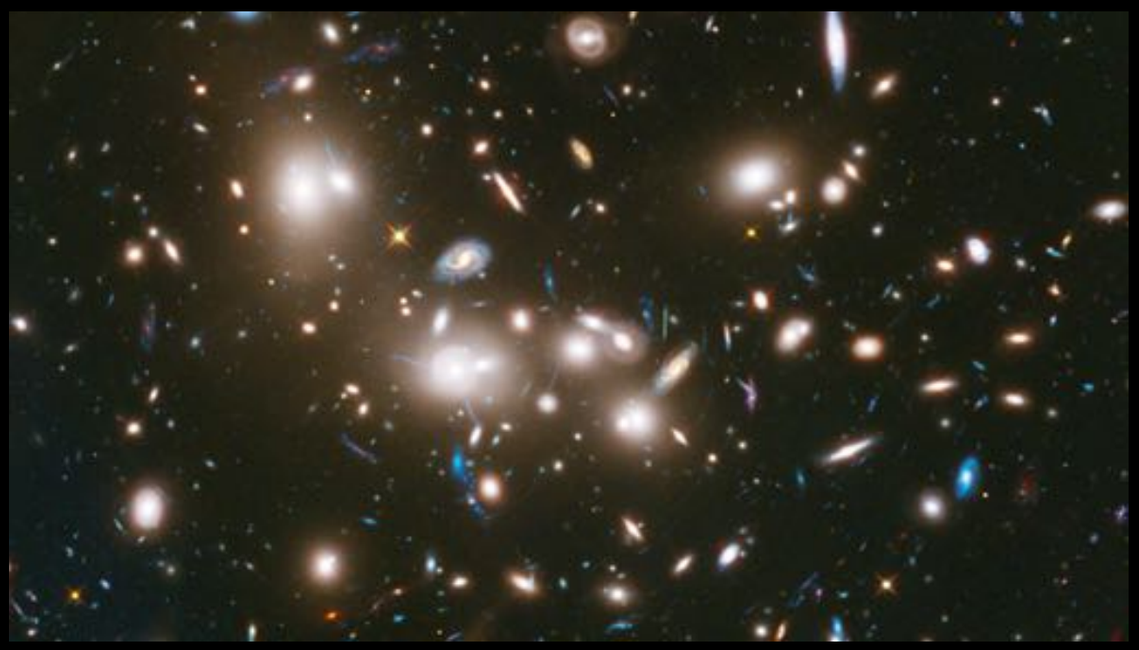
TESTS OF DARK ENERGY



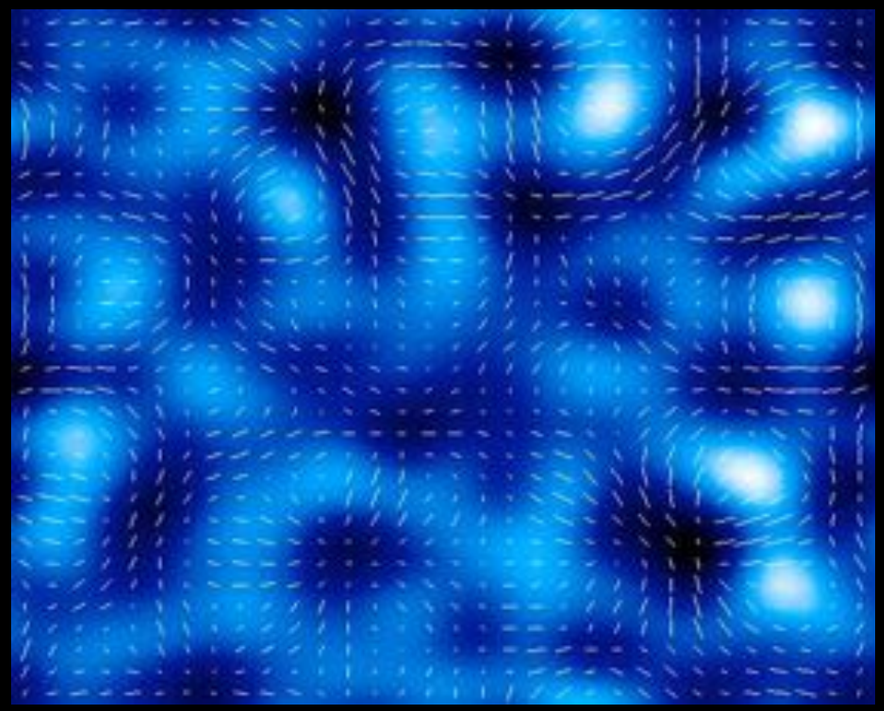
Type 1a Supernovae



Baryon Accoustic Oscillations

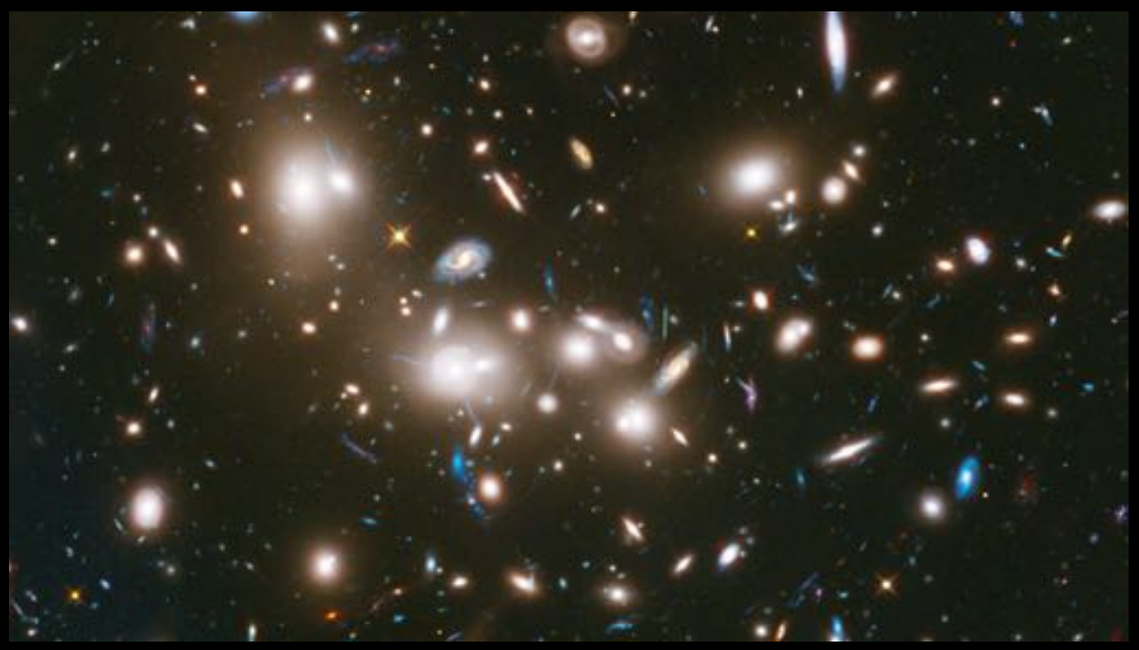


Galaxy Cluster Abundance



Weak Gravitational Lensing

TESTS OF DARK ENERGY



Galaxy Cluster Abundance

Computer
Simulation

Telescope
Observation

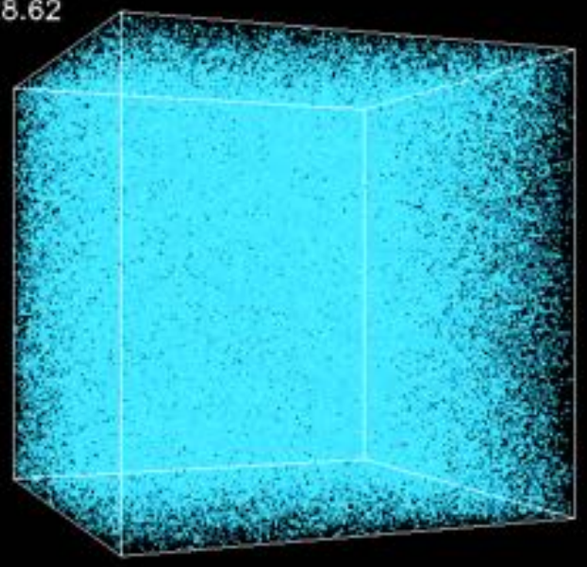
Galaxies live in dark matter “halos”

The luminous matter we see traces
the invisible dark matter

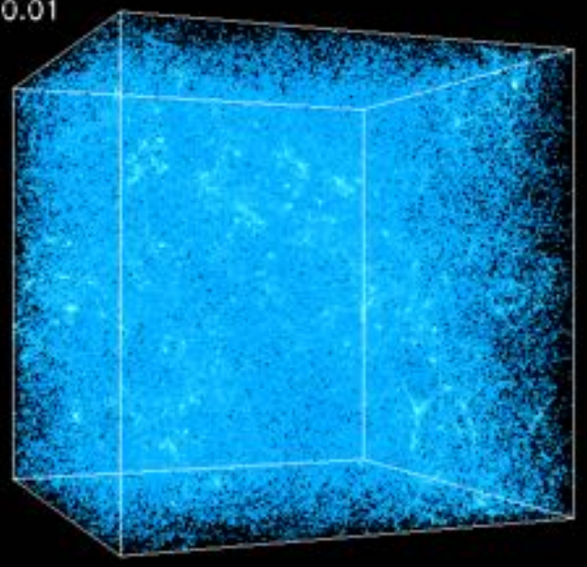
https://www.youtube.com/watch?v=xfgDoExbu_Q

https://www.youtube.com/watch?v=8C_dnP2fvxk

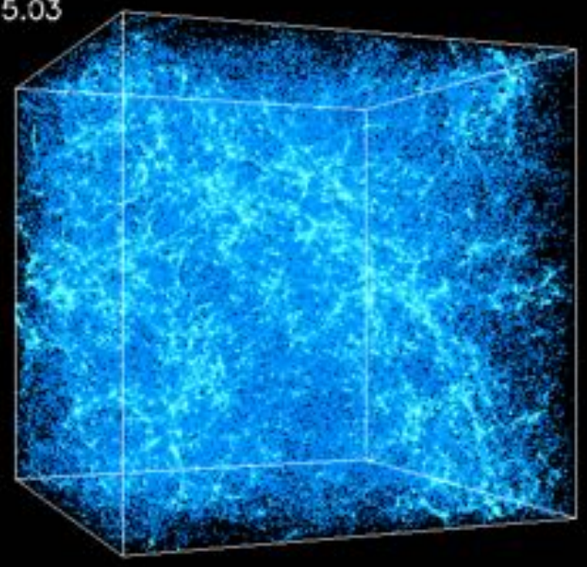
Z=28.62



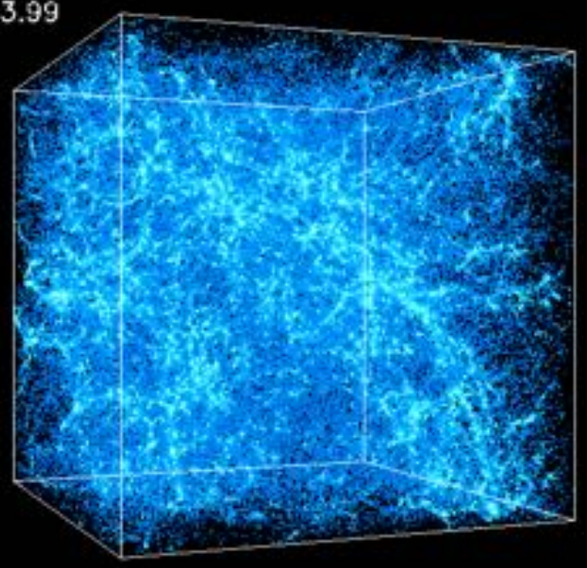
Z=10.01



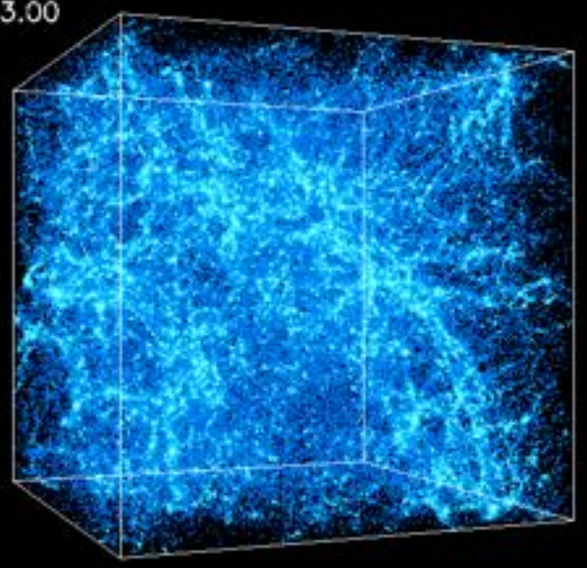
Z= 5.03



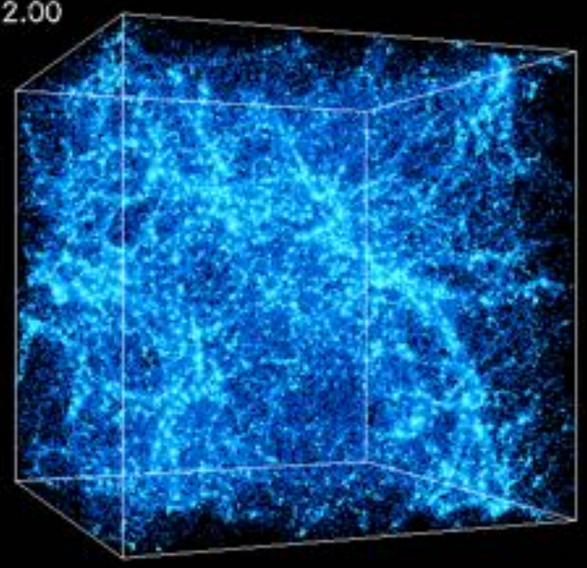
Z= 3.99



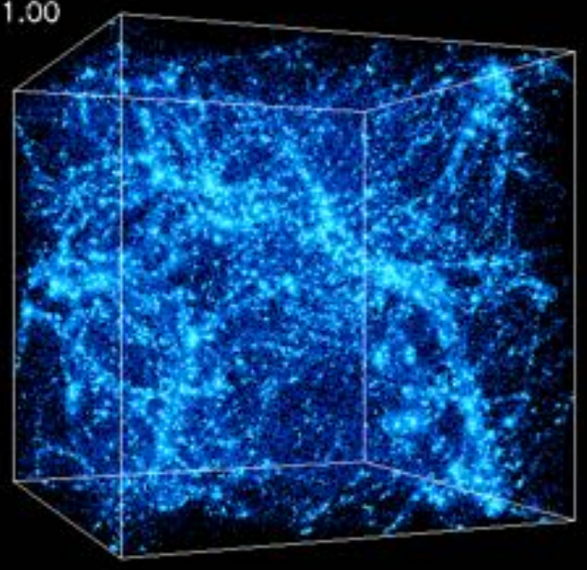
Z= 3.00



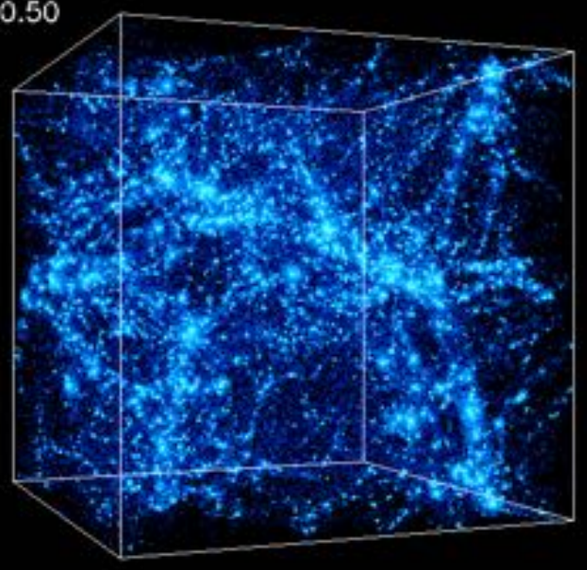
Z= 2.00



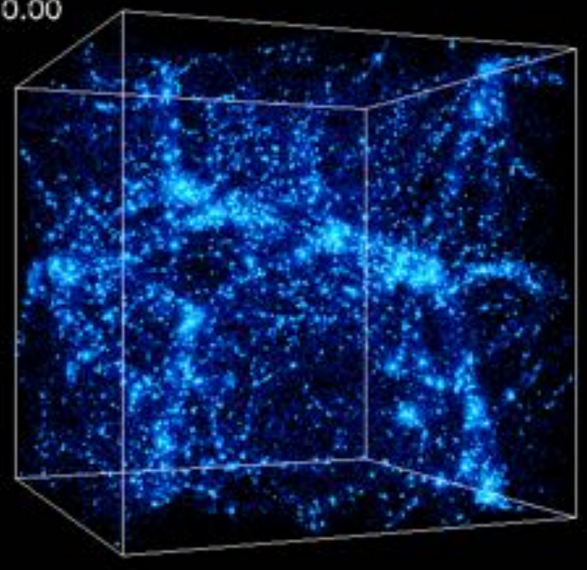
Z= 1.00



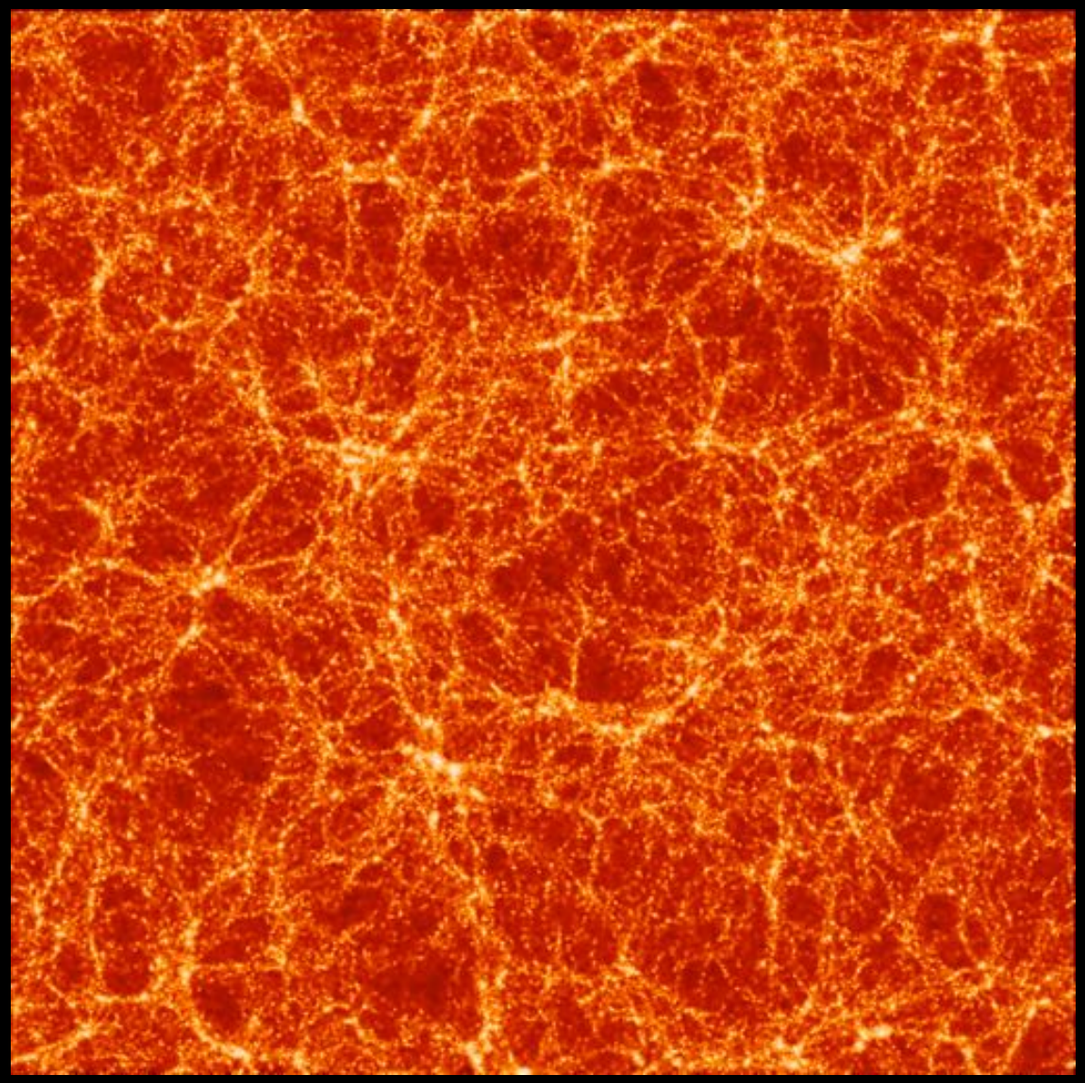
Z= 0.50



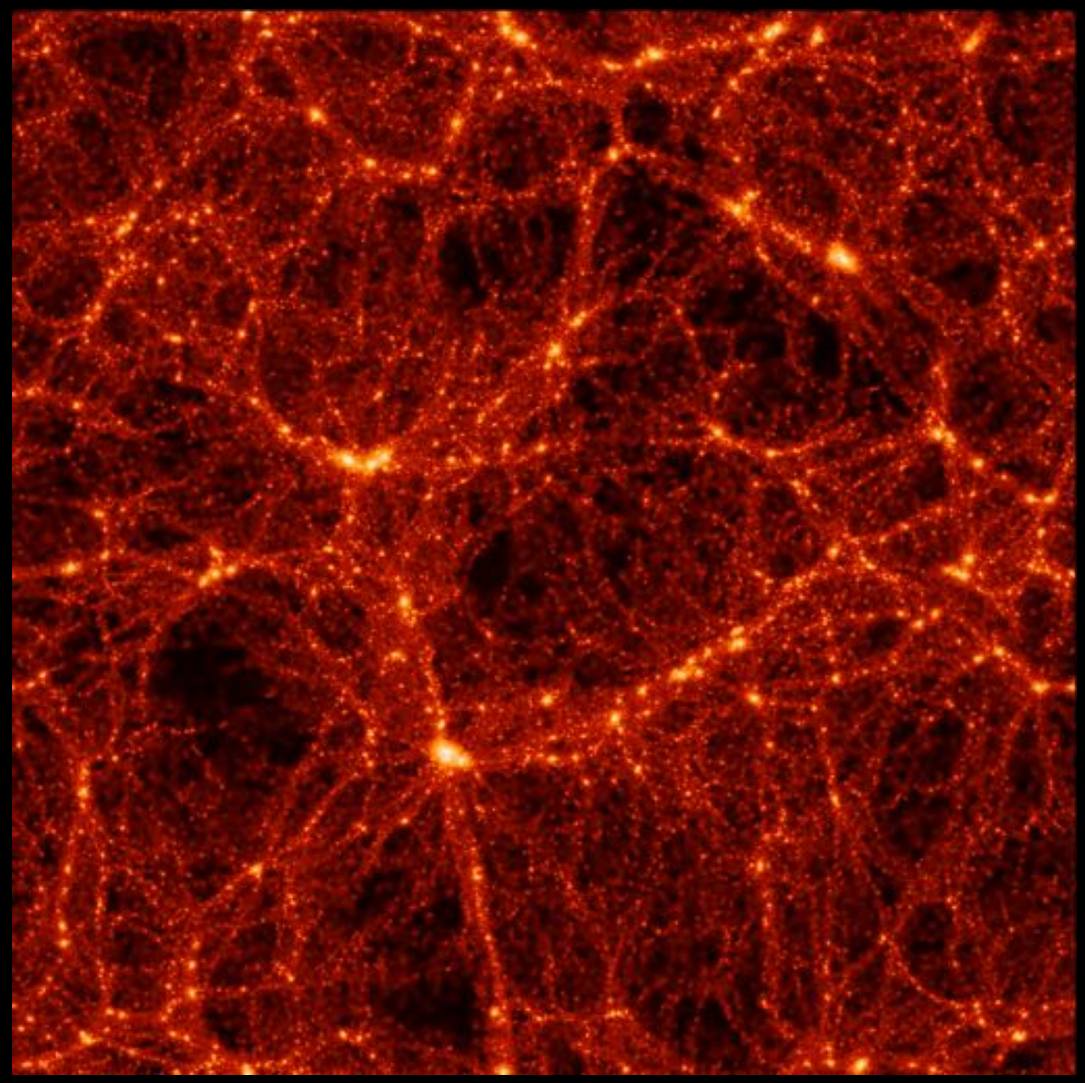
Z= 0.00



Growth of Structure

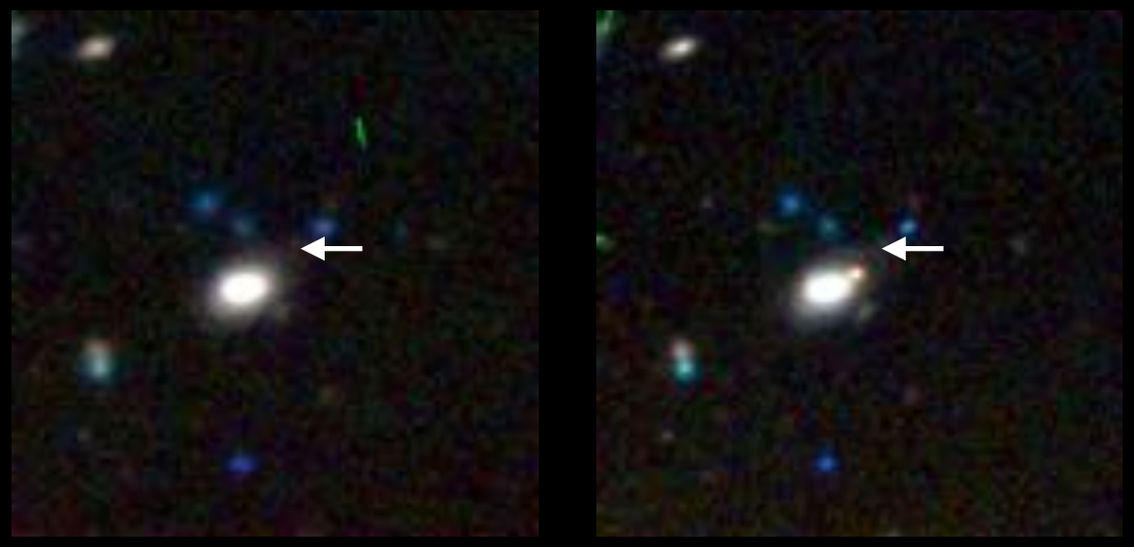


Matter Only

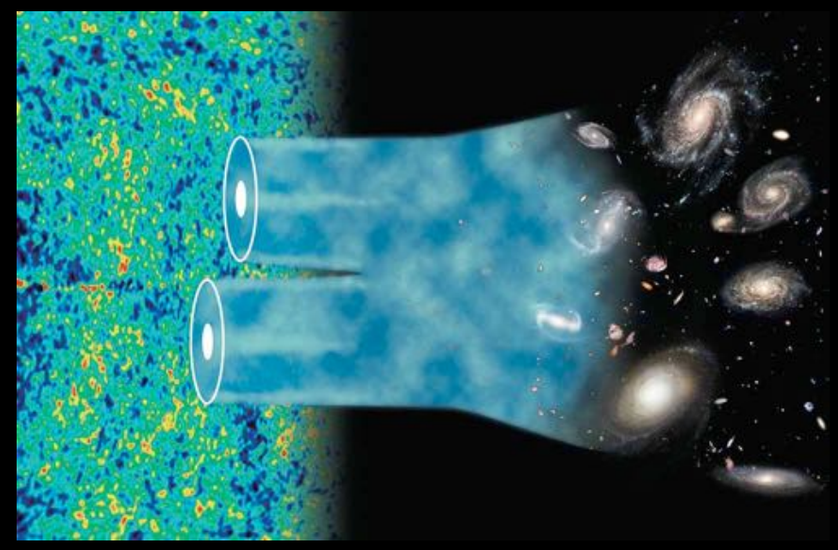


Matter + Dark Energy

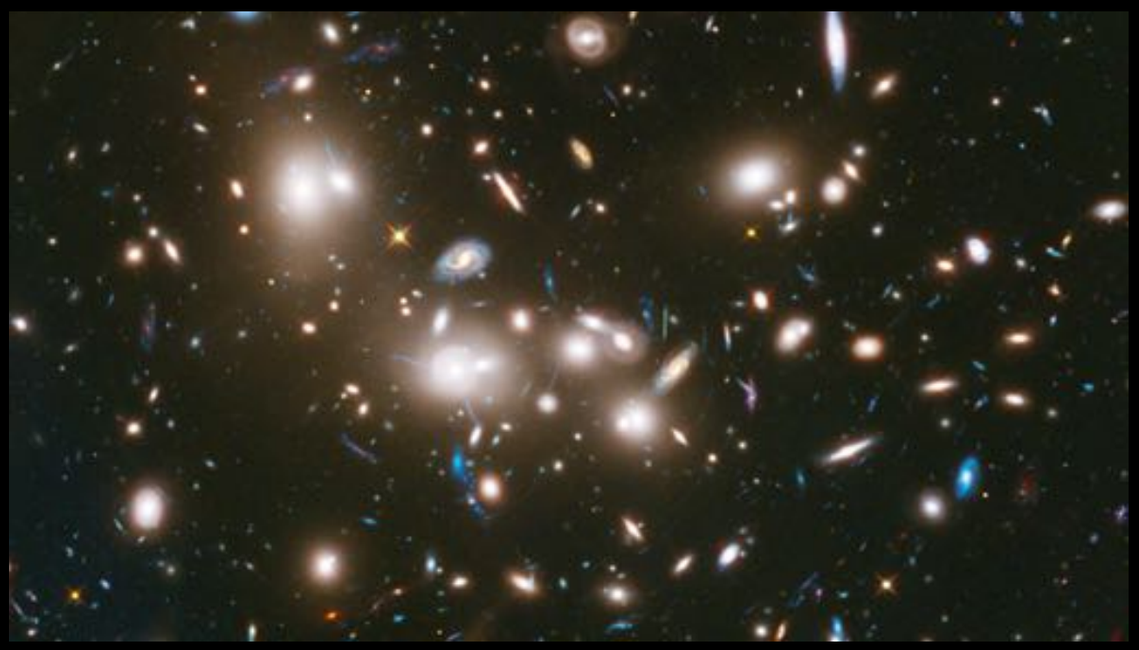
TESTS OF DARK ENERGY



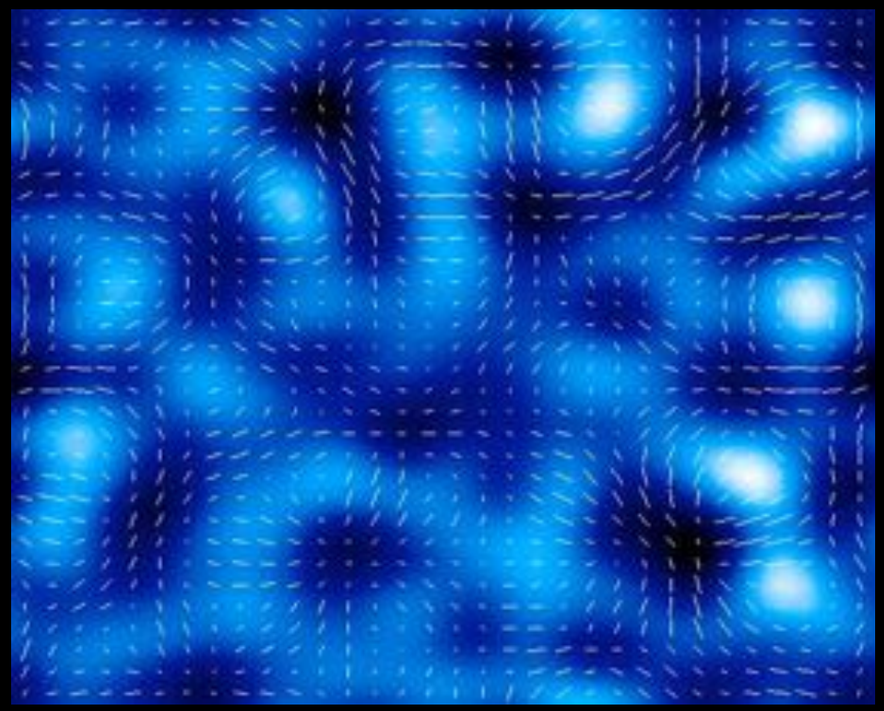
Type 1a Supernovae



Baryon Accoustic Oscillations

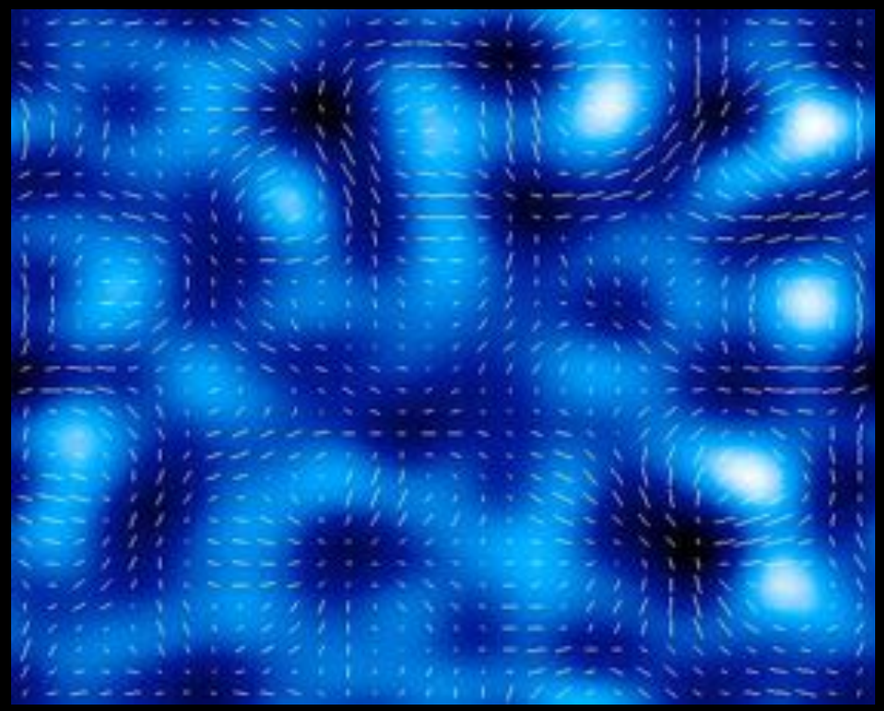


Galaxy Cluster Abundance

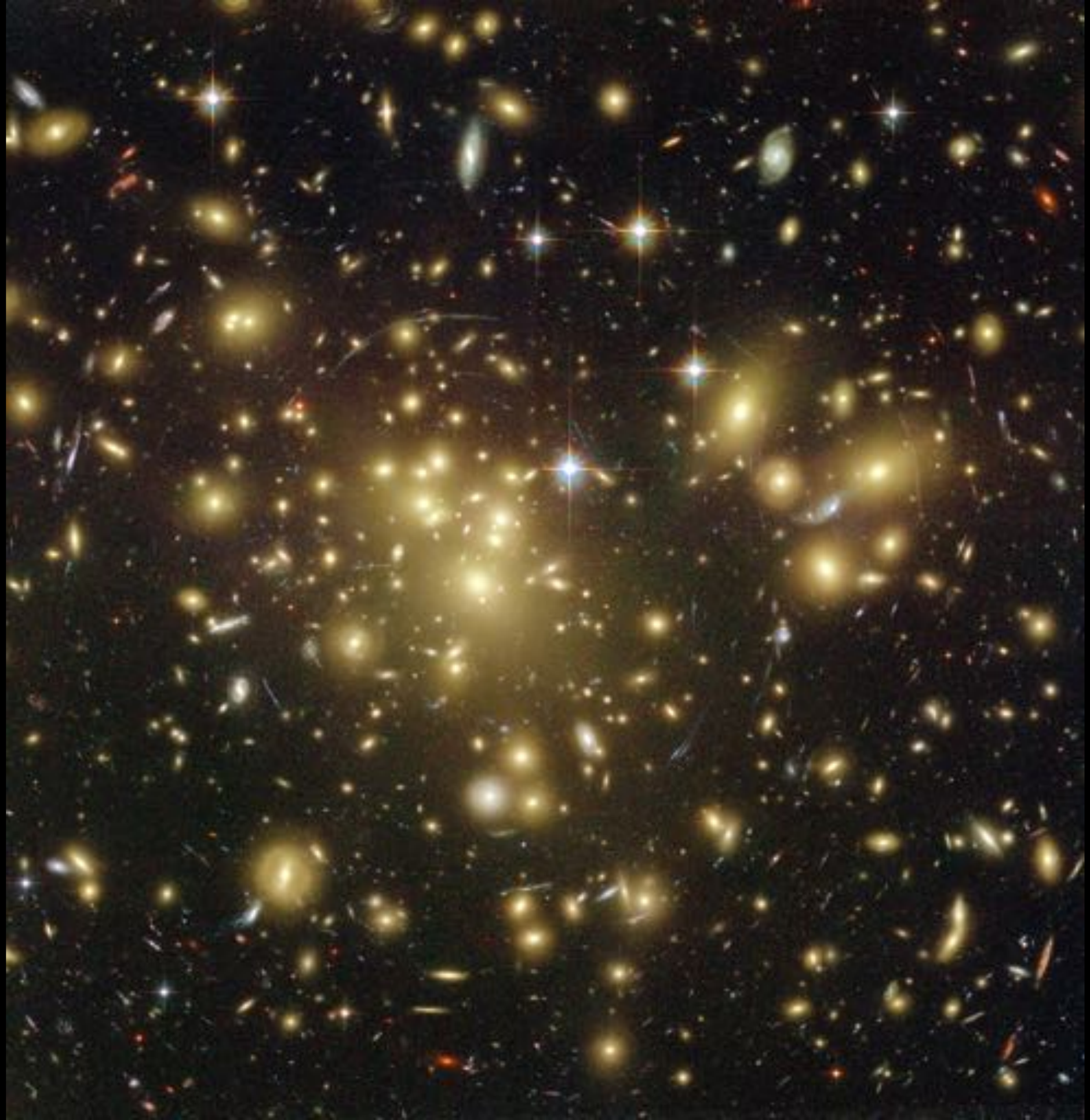


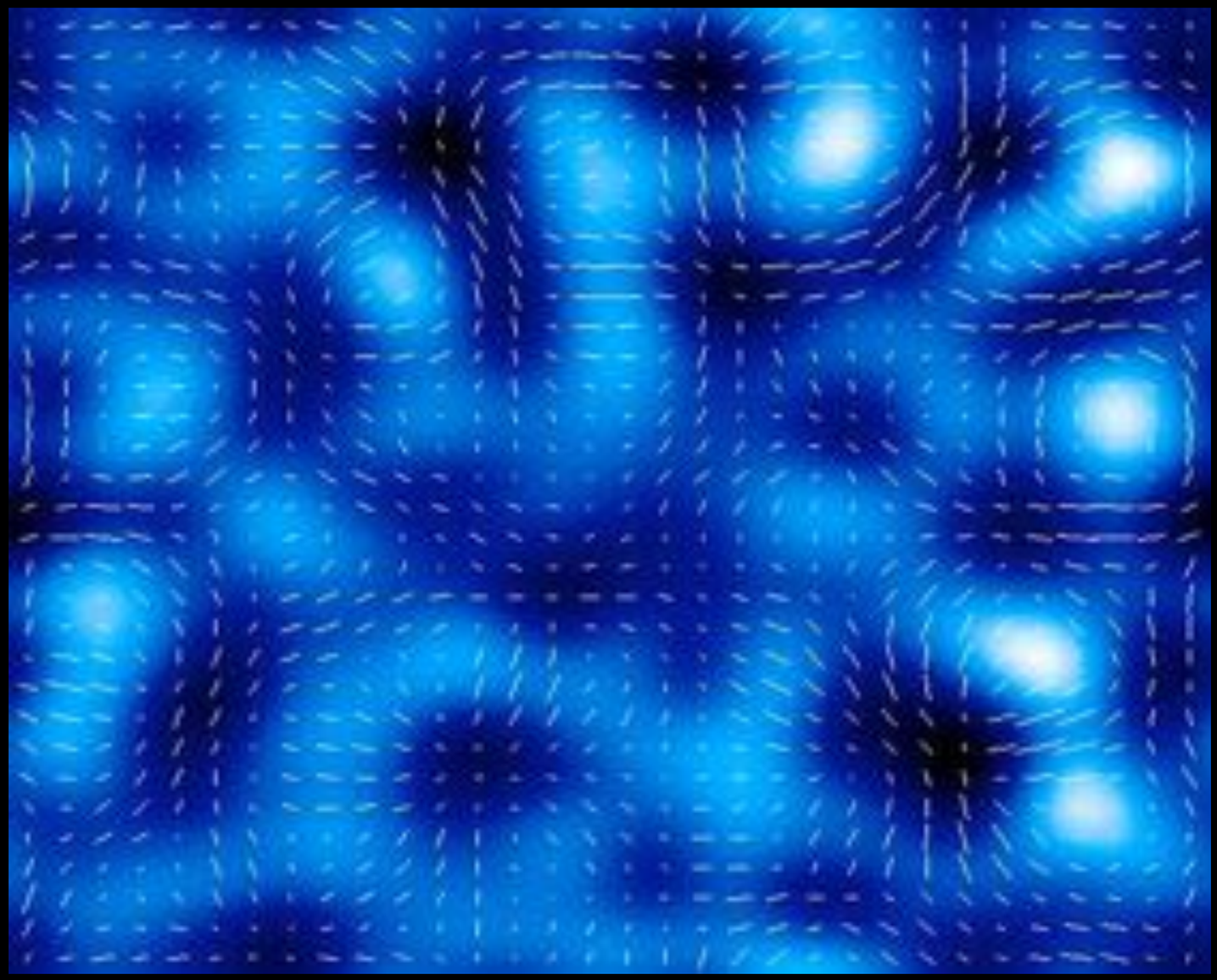
Weak Gravitational Lensing

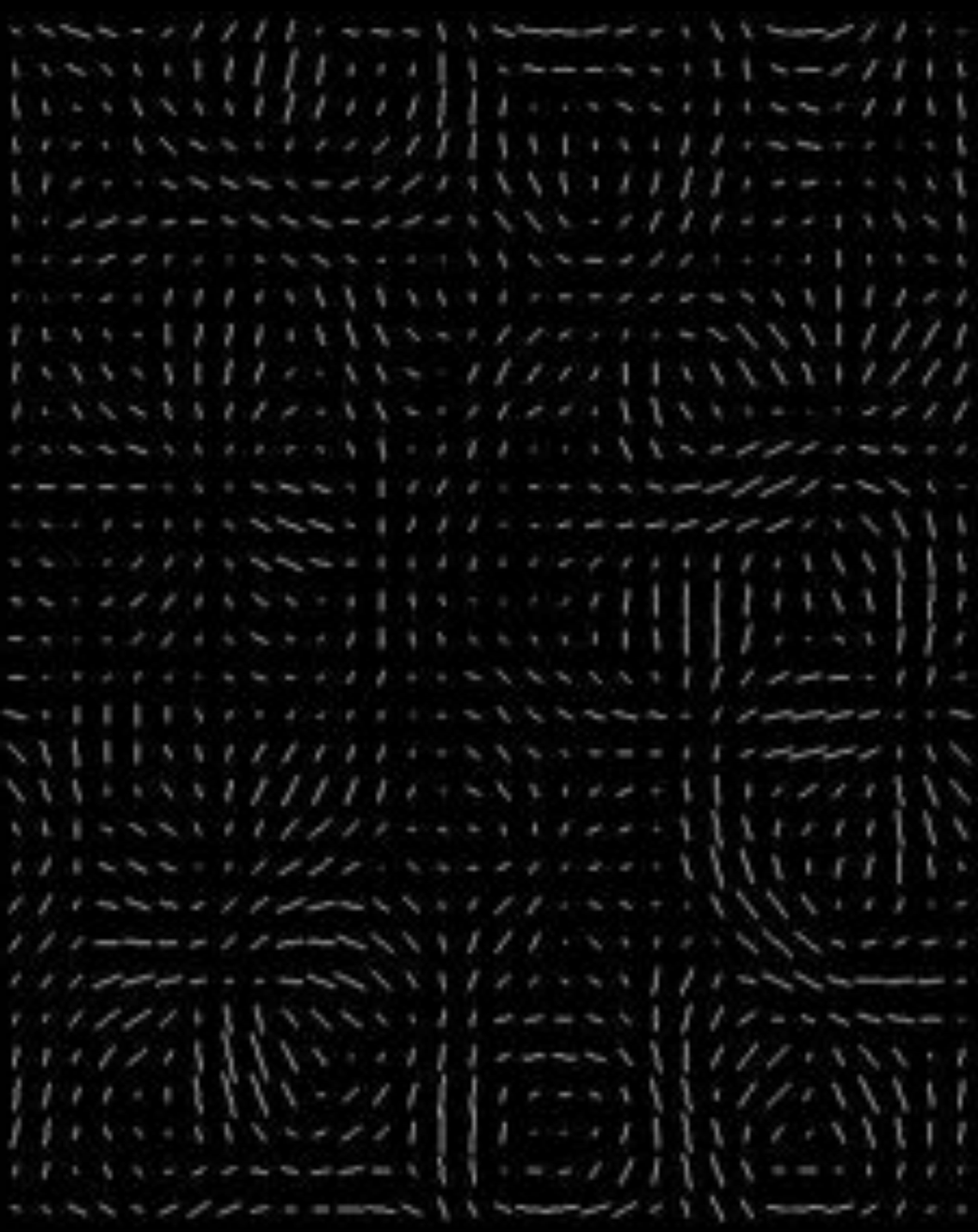
TESTS OF DARK ENERGY

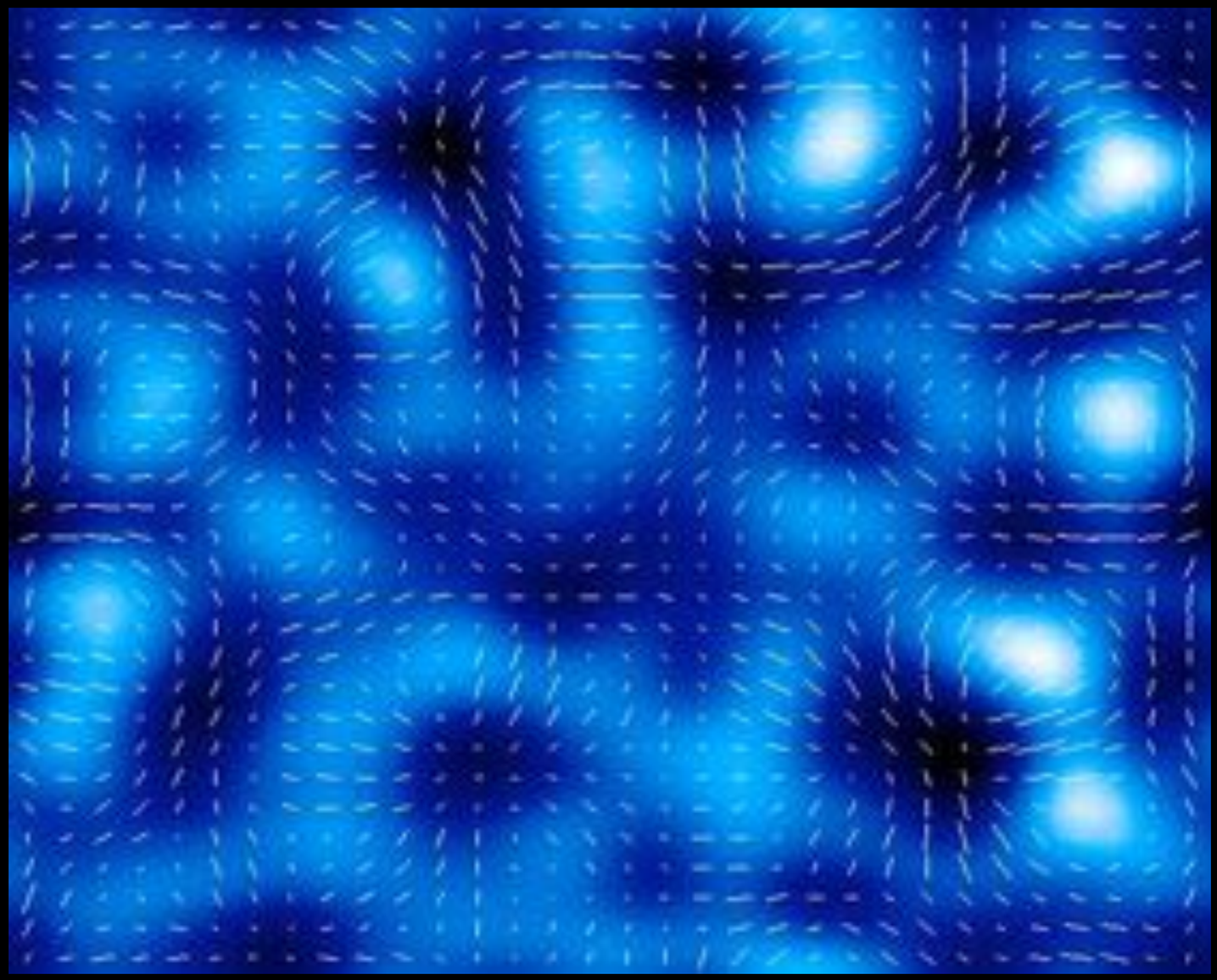


Weak Gravitational Lensing

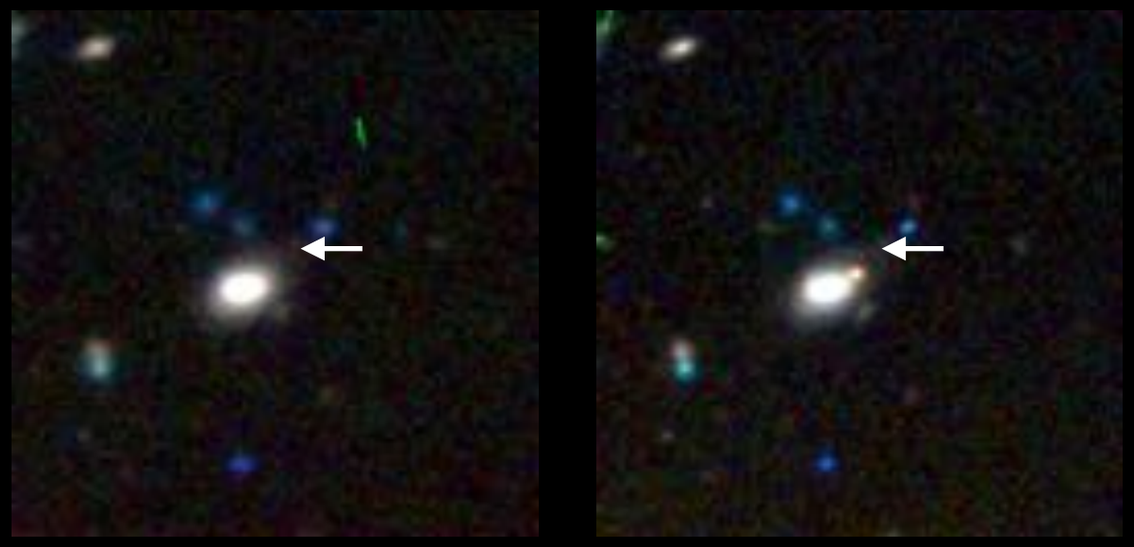




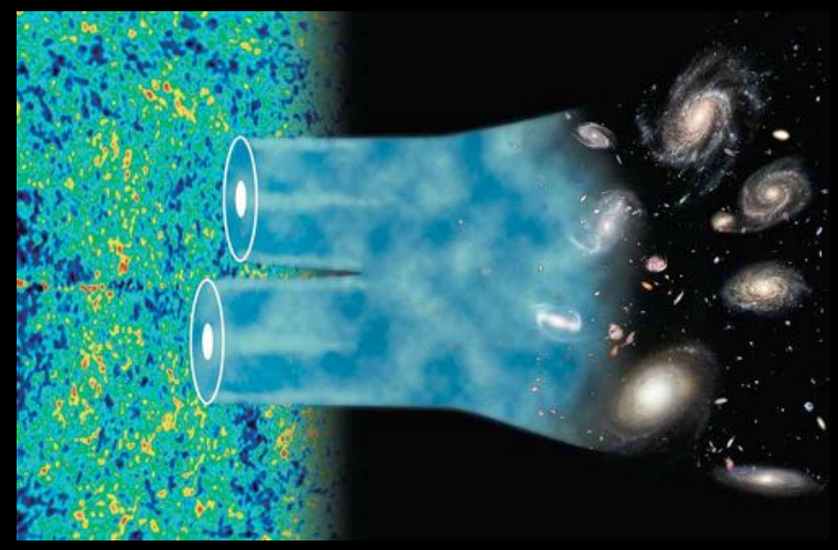




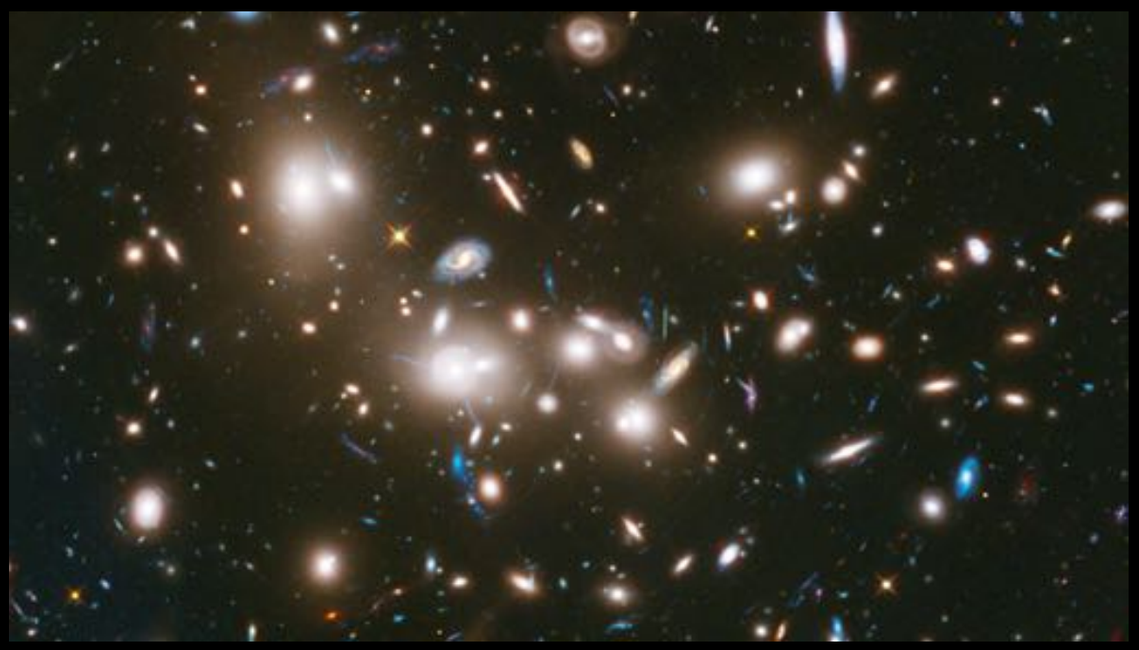
TESTS OF DARK ENERGY



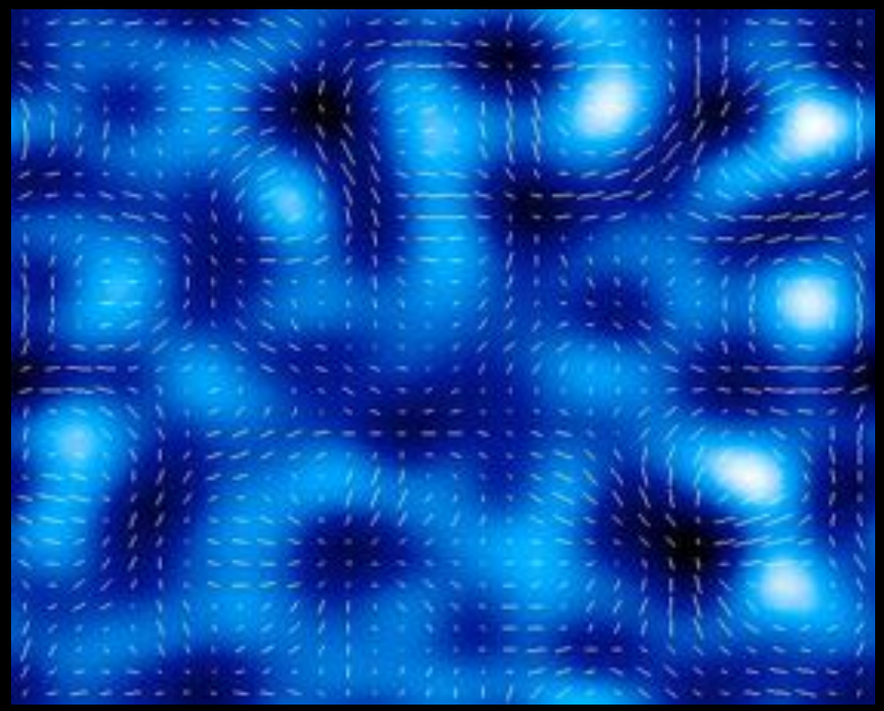
Type 1a Supernovae



Baryon Accoustic Oscillations

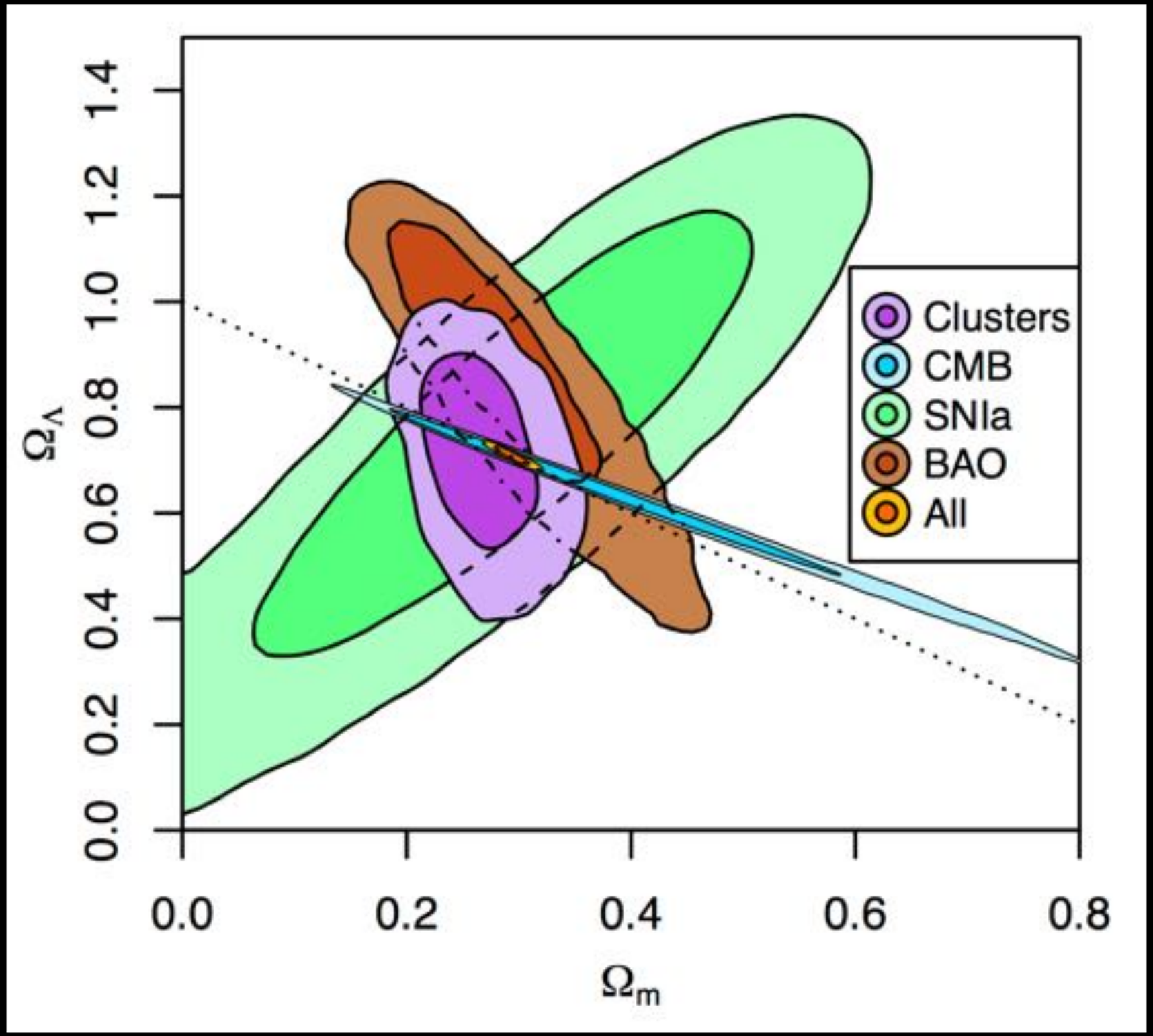


Galaxy Cluster Abundance



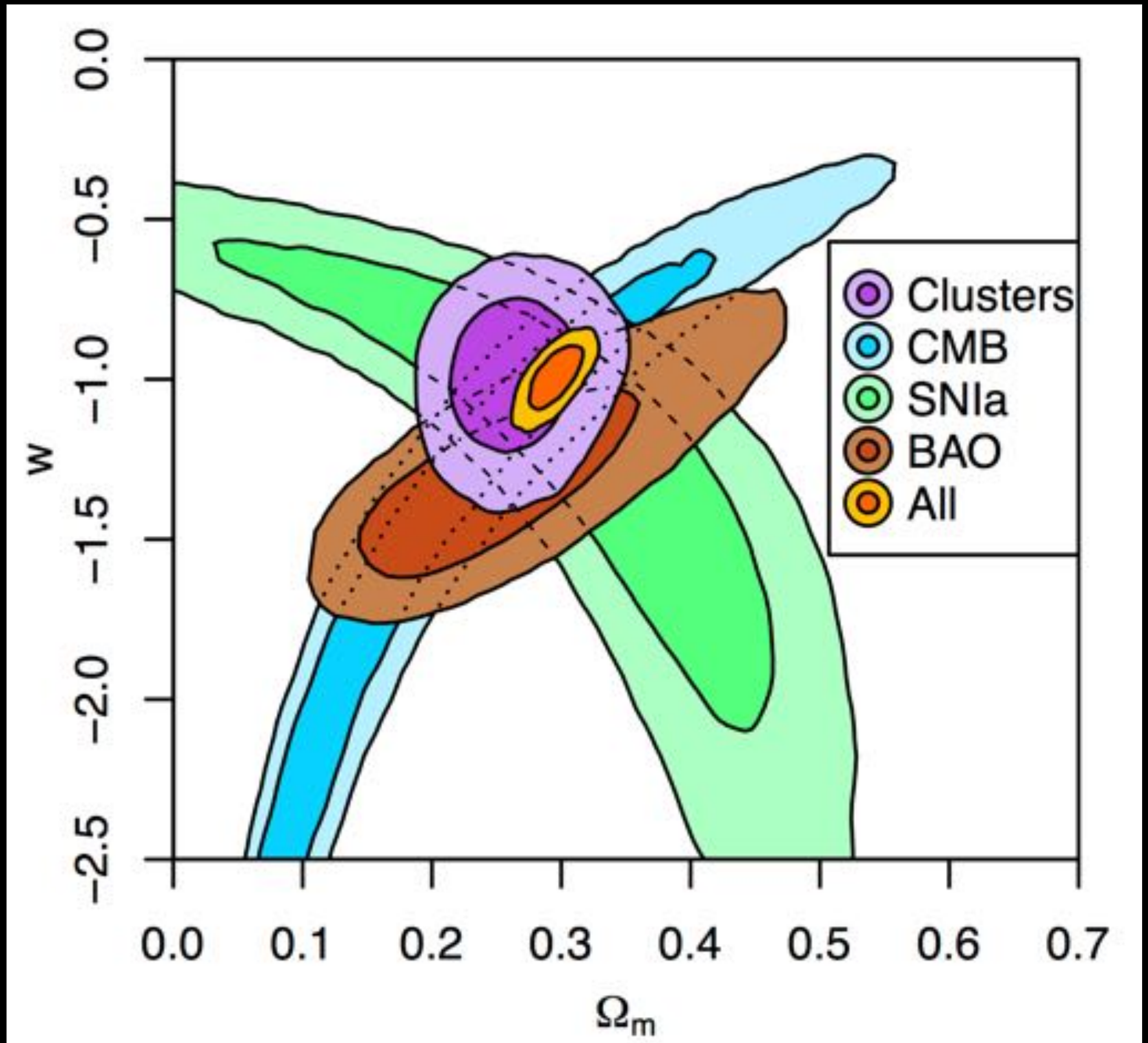
Weak Gravitational Lensing

Average Density of Dark Energy Today



Average Density of Matter Today

Pressure of Dark Energy Today



Average Density of Matter Today

Dark Energy is one of the outstanding scientific mysteries of our generation

There is not yet a compelling theory to explain its measured properties

Revealing its nature will require a global effort similar in scope to that which discovered the Higgs Boson

Many faculty, staff, and students at the University of Chicago are deeply involved in this effort

Thanks!

Questions?

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THE DARK ENERGY SURVEY

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for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO