Welcome to…

The Dark Side of the Universe

Prof. Scott Watson (Syracuse University)

This talk will be available at:

https://gswatson.expressions.syr.edu

My research would not be possible without the financial support of:

NASA

U.S. DEPARTMENT OF ENERGY

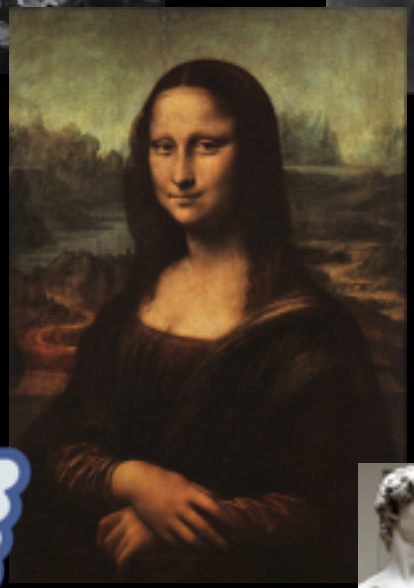
SYRACUSE UNIVERSITY FOUNDED AD 1870

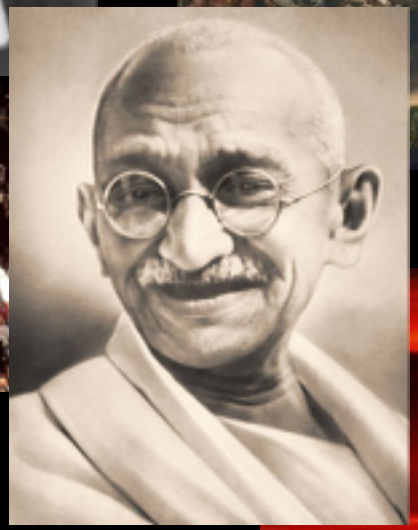
I am a theoretical cosmologist.


This is what our lab looks like
Stephen is still working hard!

The images we see shapes our lives in a dramatic way.














“Seeing is believing”

However, most of the stuff in the universe looks like this:

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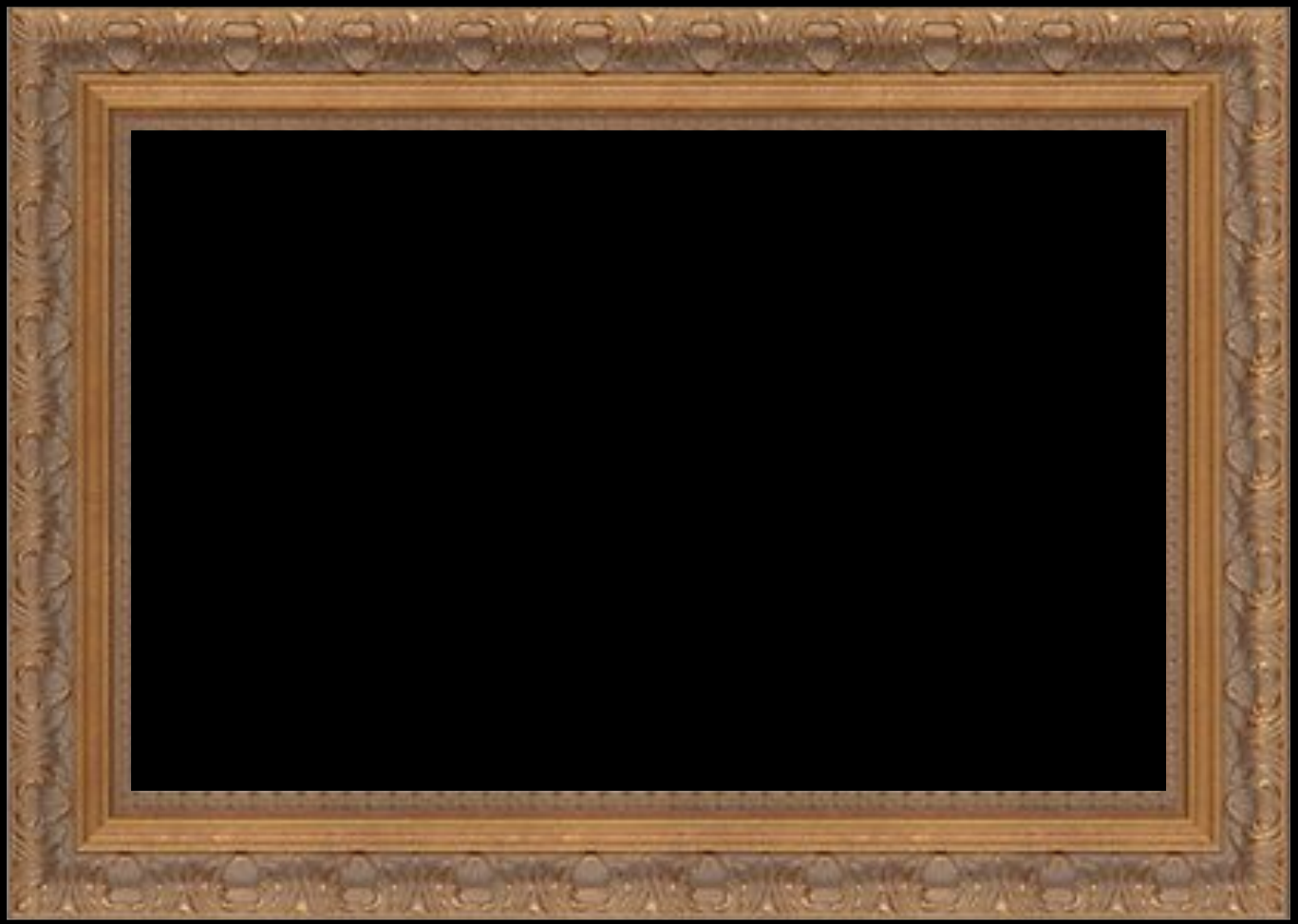


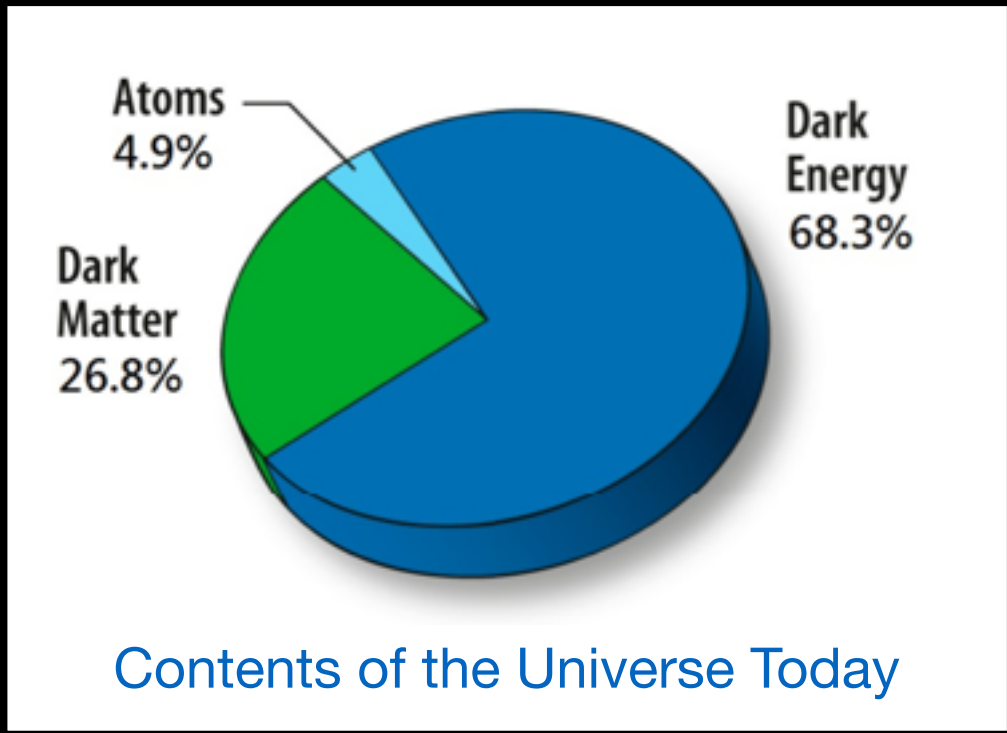
However, most of the stuff in the universe looks like this:

There are some stars and galaxies, maybe some aliens

Most of the universe is invisible to us

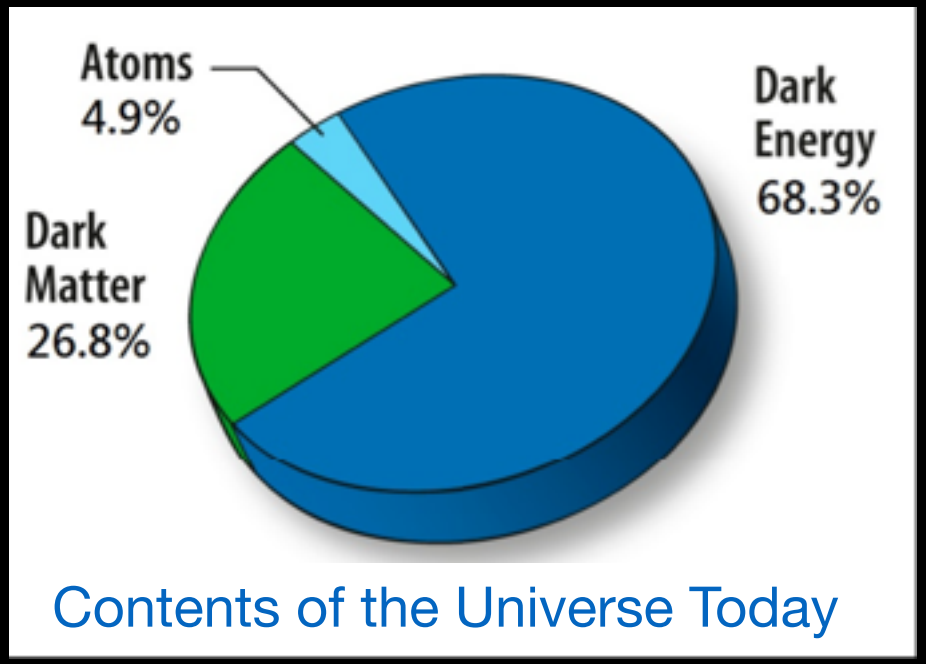
There are some stars, galaxies, and maybe some aliens

But most of the universe is invisible to our eyes!



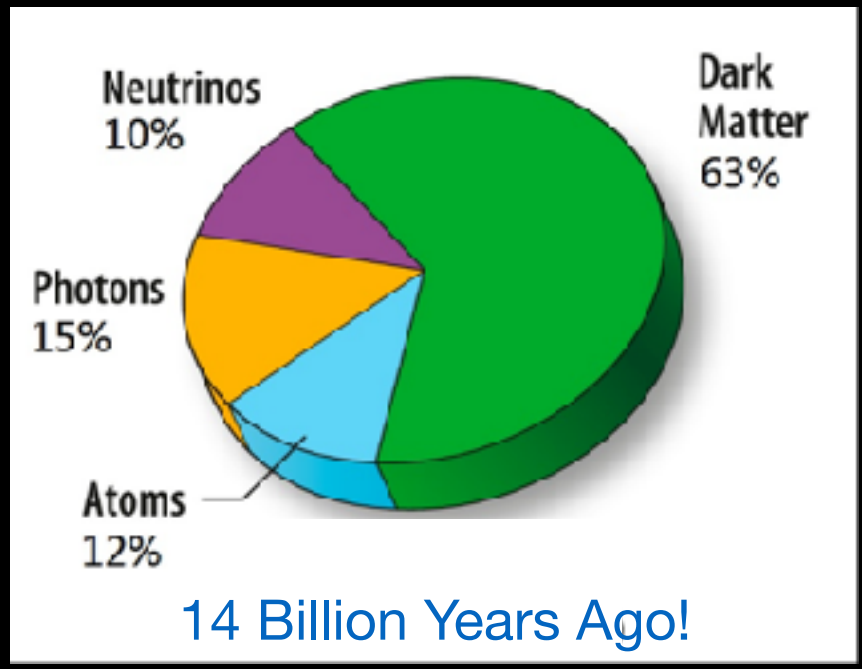
Contents of the Universe Today

Most of the universe is invisible to us



Contents of the Universe Today

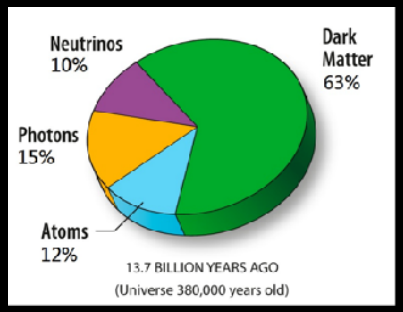
And the dark side is growing!

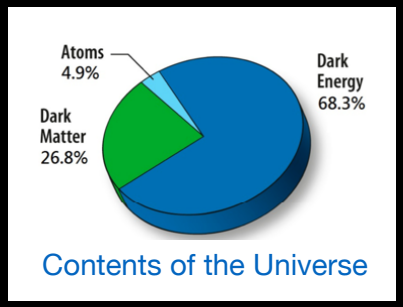


14 Billion Years Ago!

Questions we will address today:

- How do we know the composition of the universe?



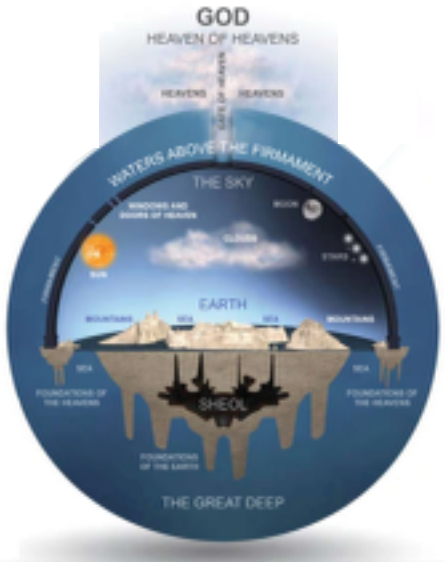


- What is Dark Matter?

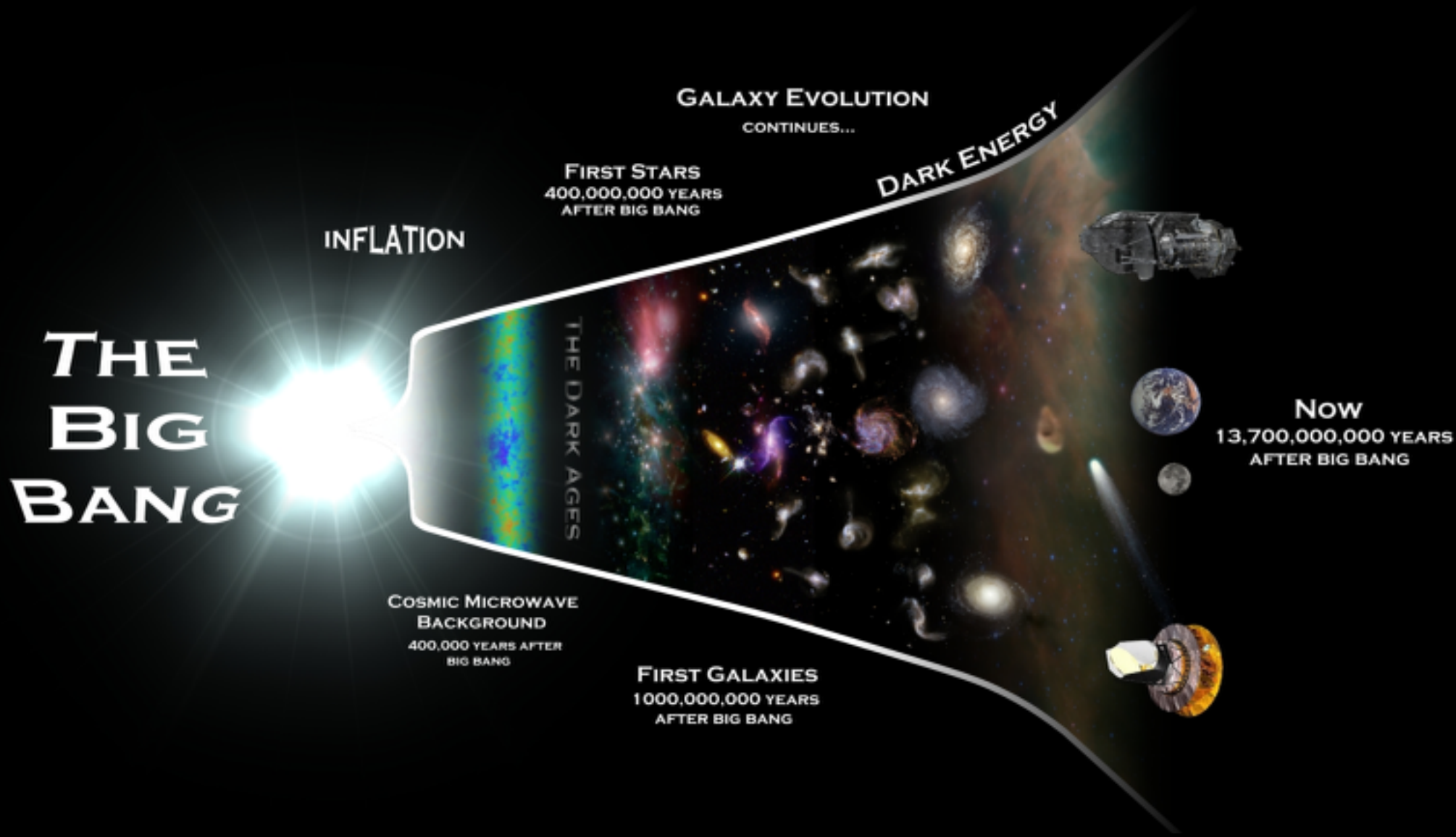
- What is Dark Energy?

- What is our final destiny?

Early Days of Cosmology



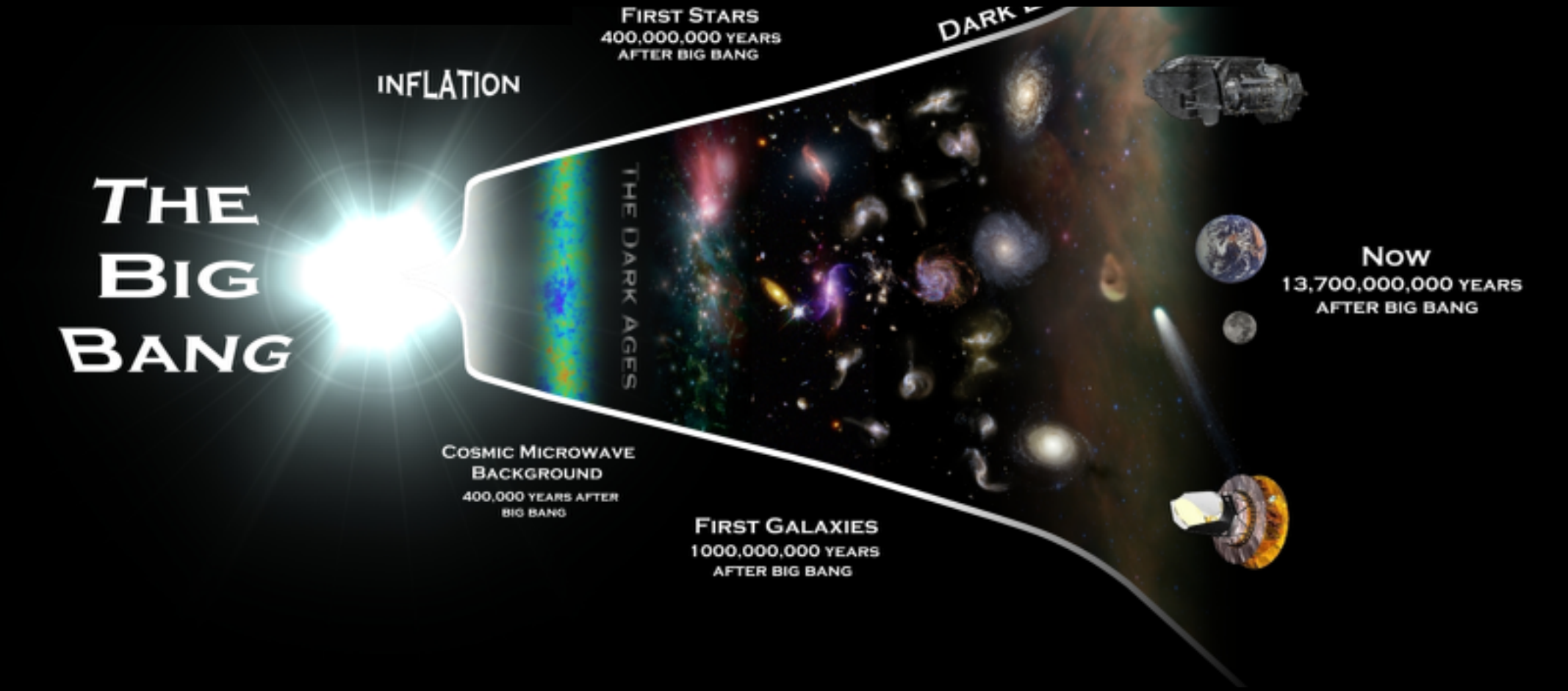
Today's Cosmological Standard Model

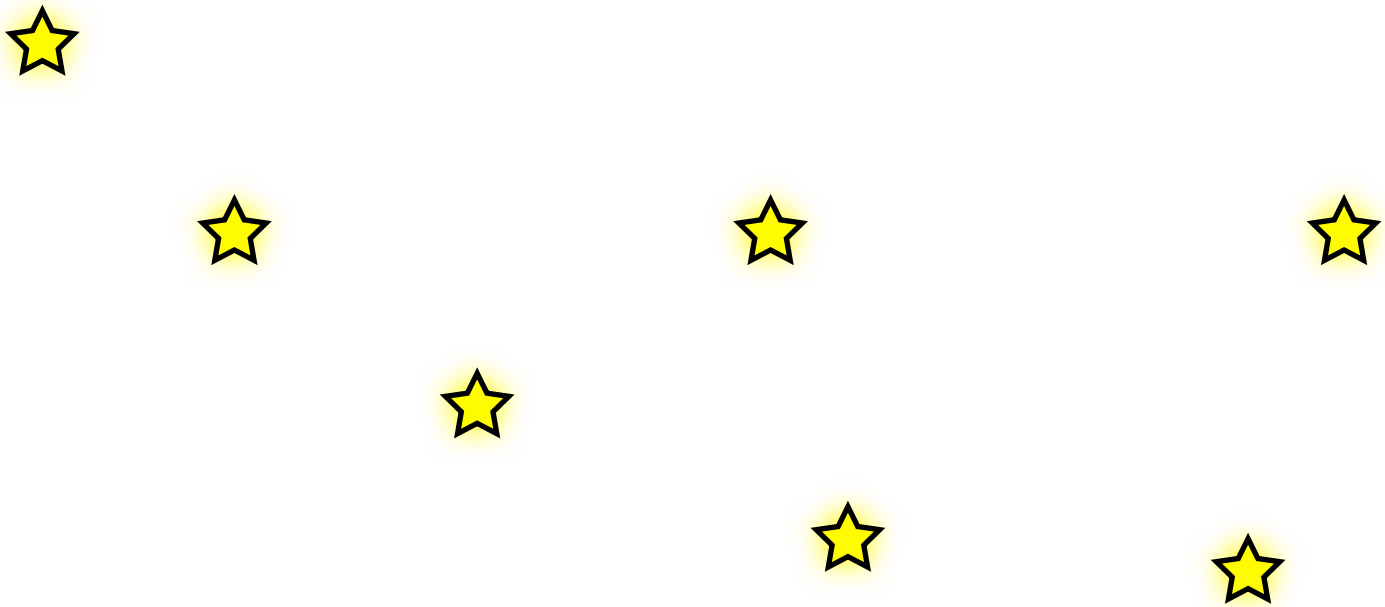


The Universe is expanding.

As it expanded it cooled.

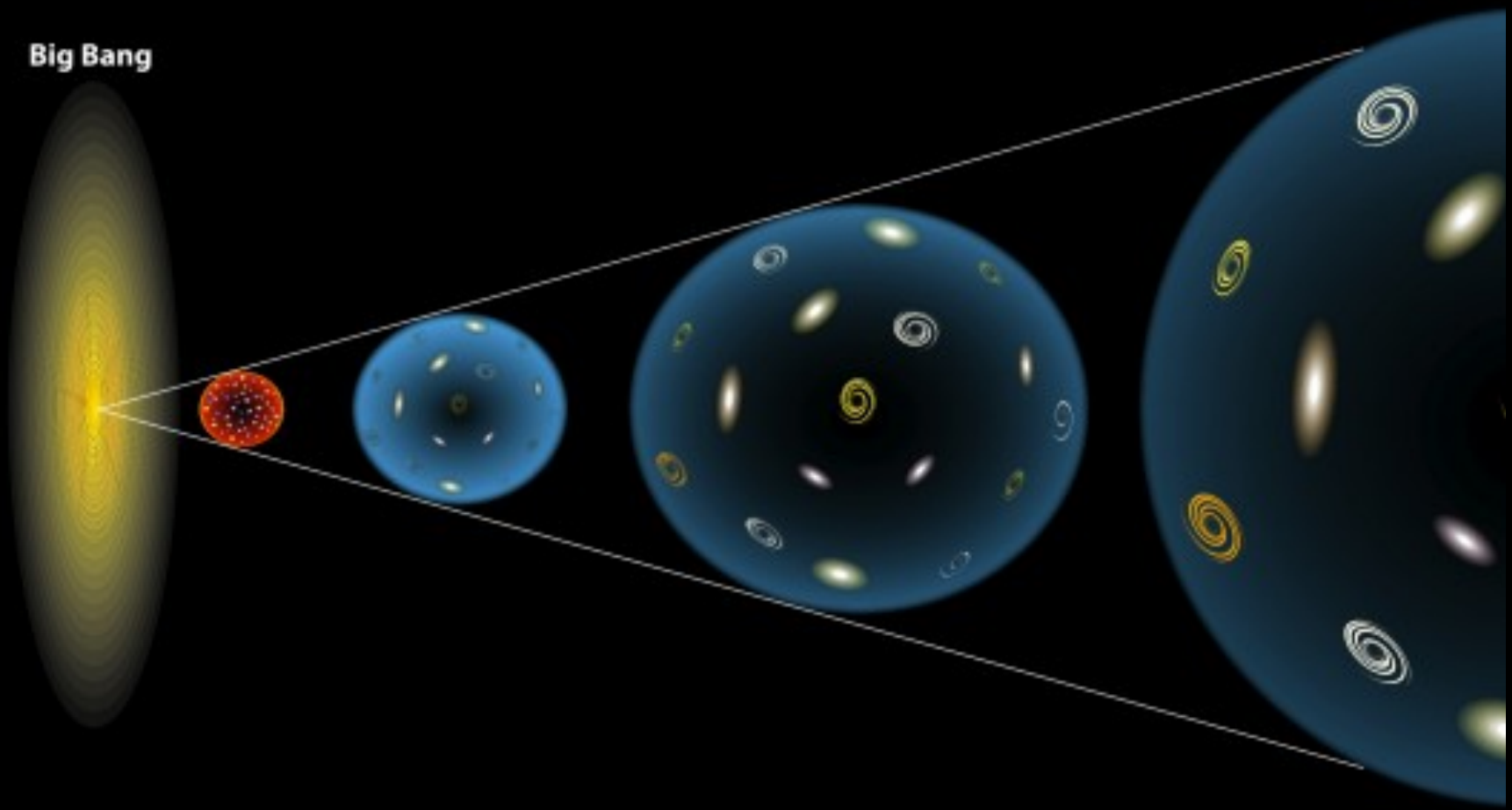
This results in observational implications that allow us to verify the Big Bang Theory





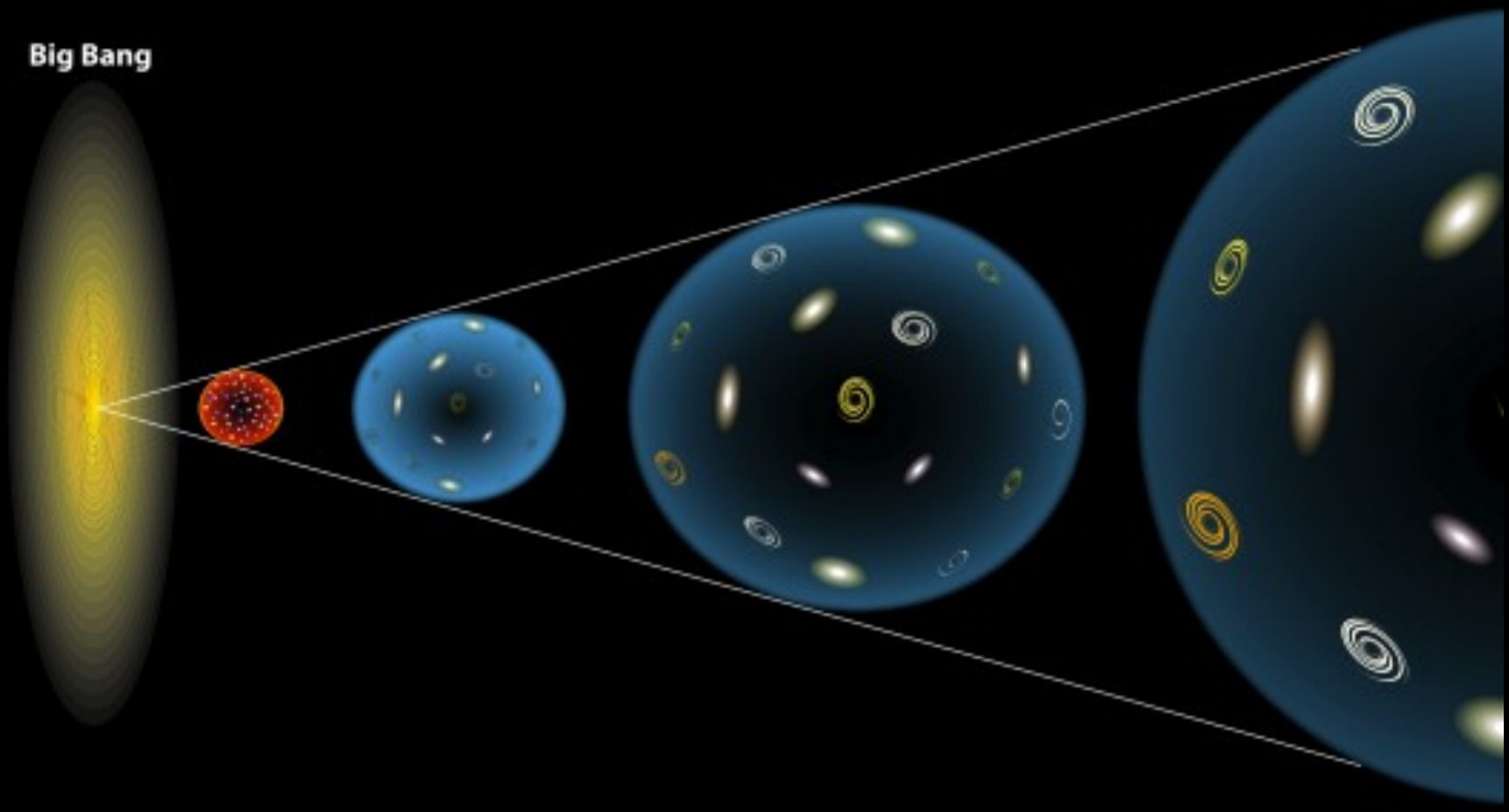
Why is the sky dark at night?

Question: Why is the night sky dark?



The universe is expanding!

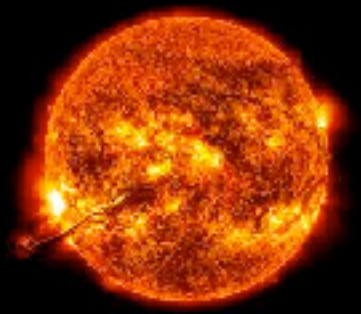
Question: Why is the night sky dark?



The expansion implies the universe had a beginning, and so the stars are not infinitely old.

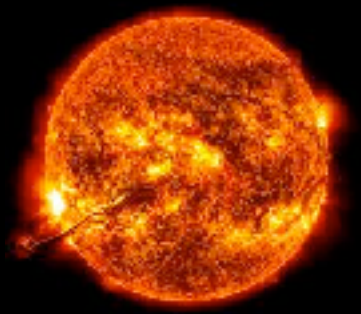
The universe changes in time.

It takes time for light to travel to us!



8 minutes

It takes time for light to travel to us!

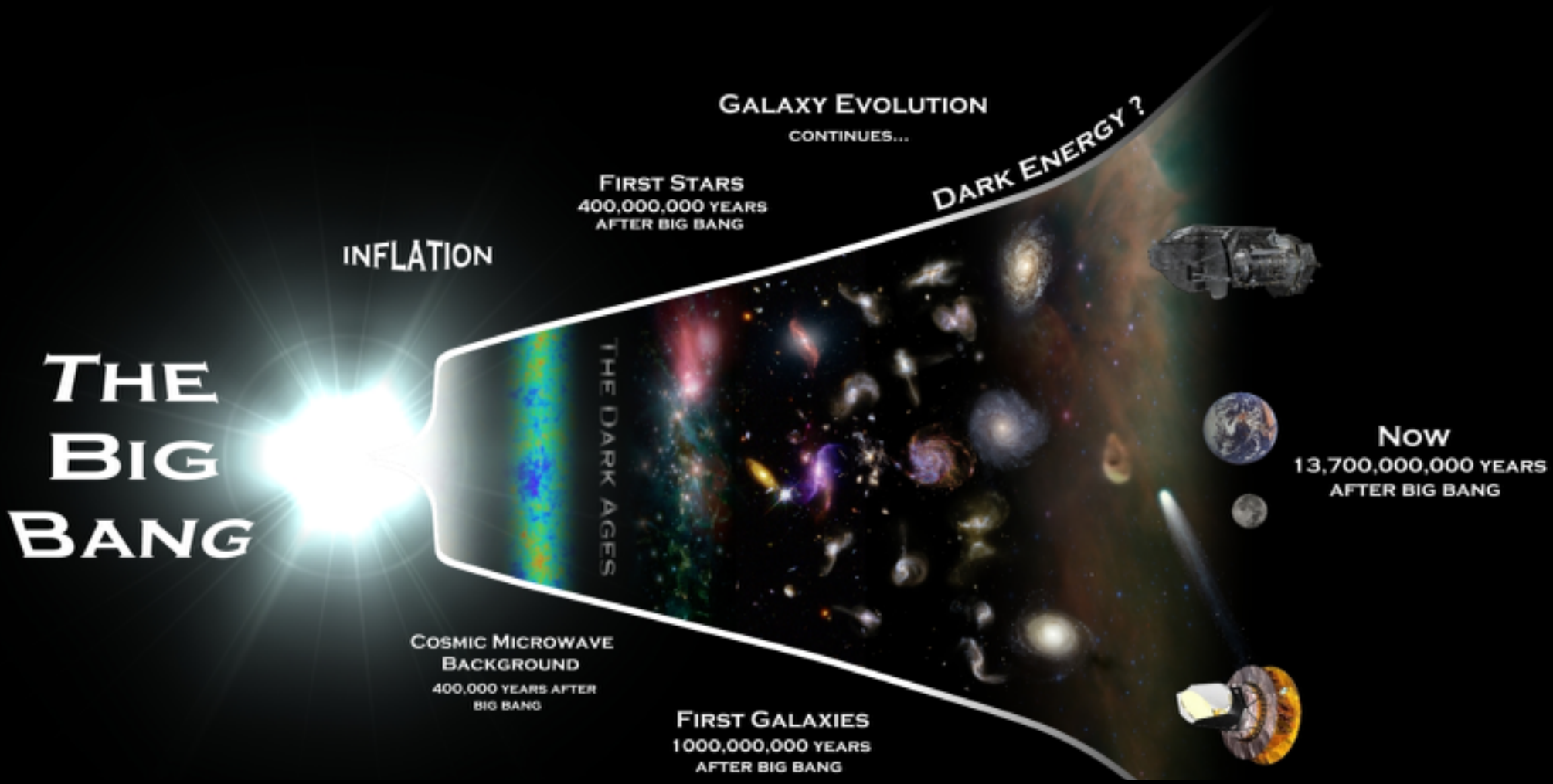


8 minutes

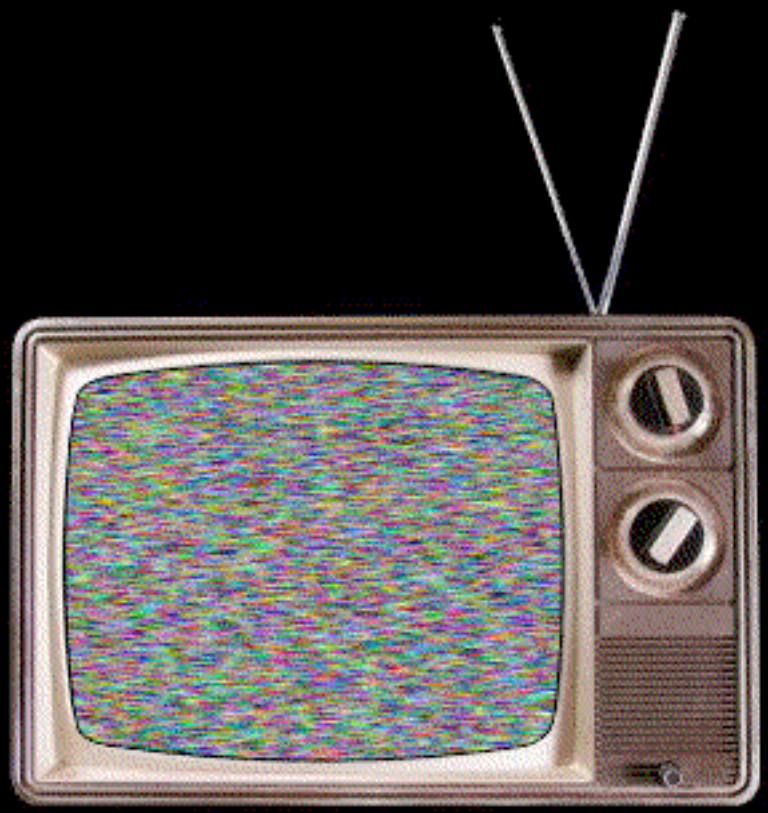
2.5 Million Years!

Andromeda
(nearest galaxy)

It took around 14 Billion years for the light from the Big Bang to reach us!

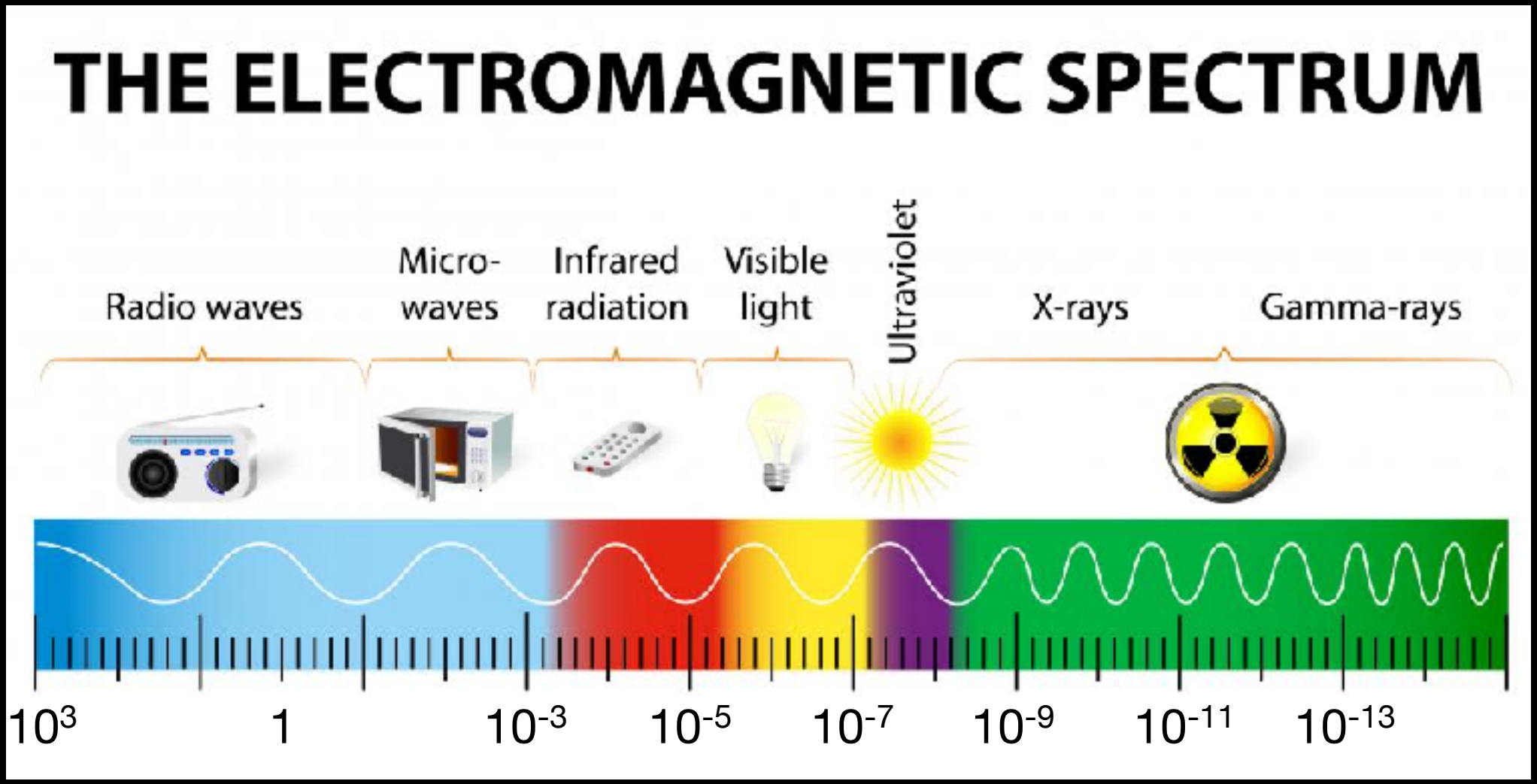


You can see it on your TV! (well, in the old days)



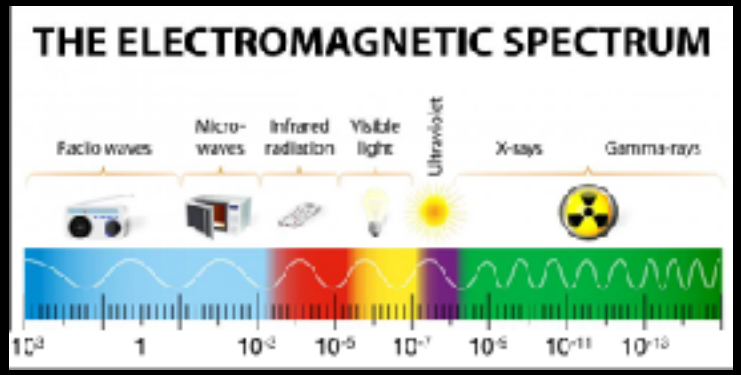
The Cosmic Microwave Background (CMB)

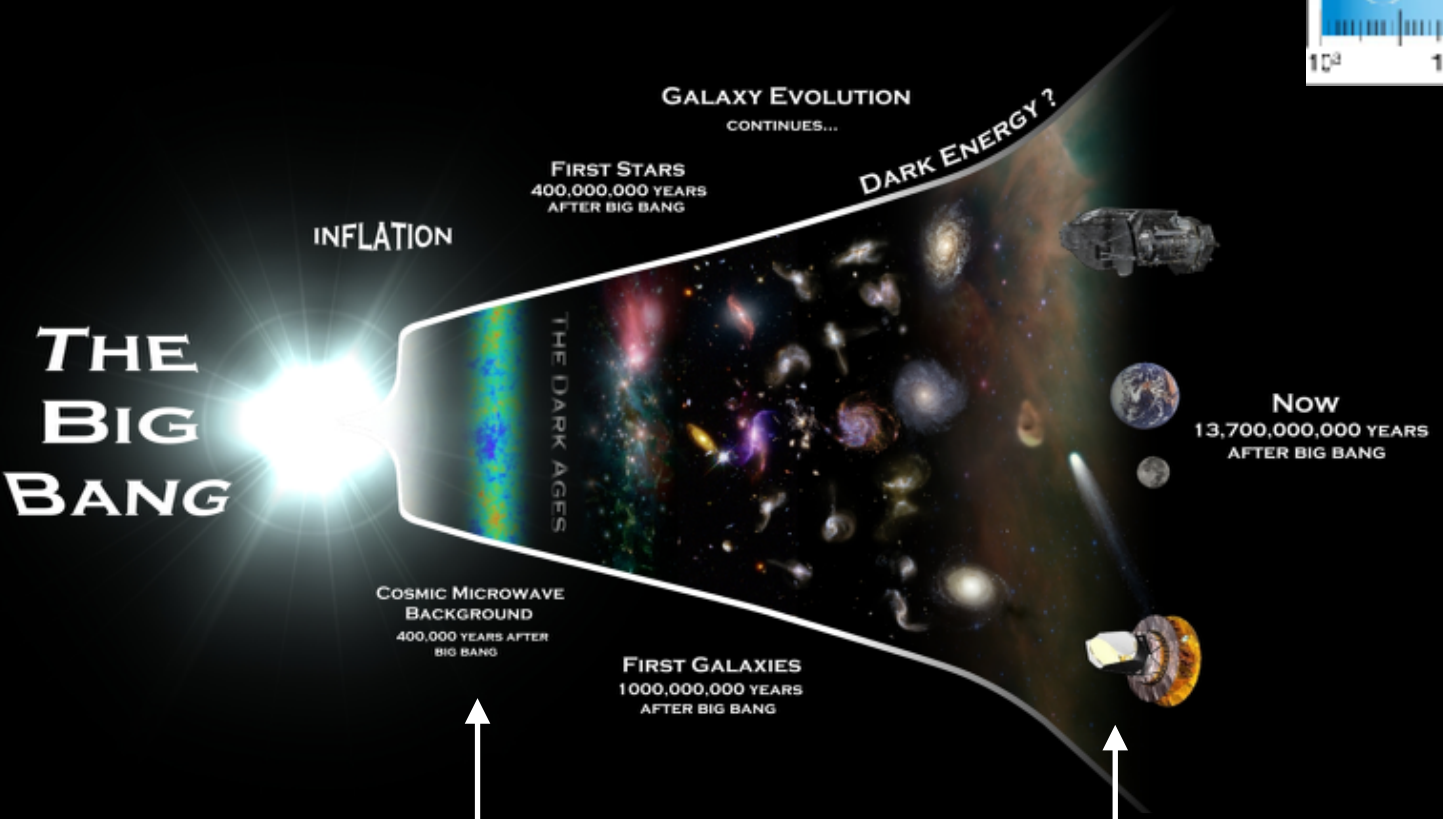
What is Microwave Radiation?



As the universe cooled, so did the CMB.

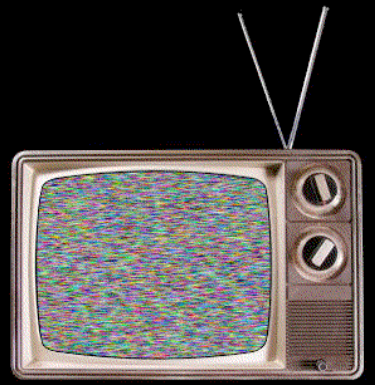
As the universe cooled,
so did the CMB.



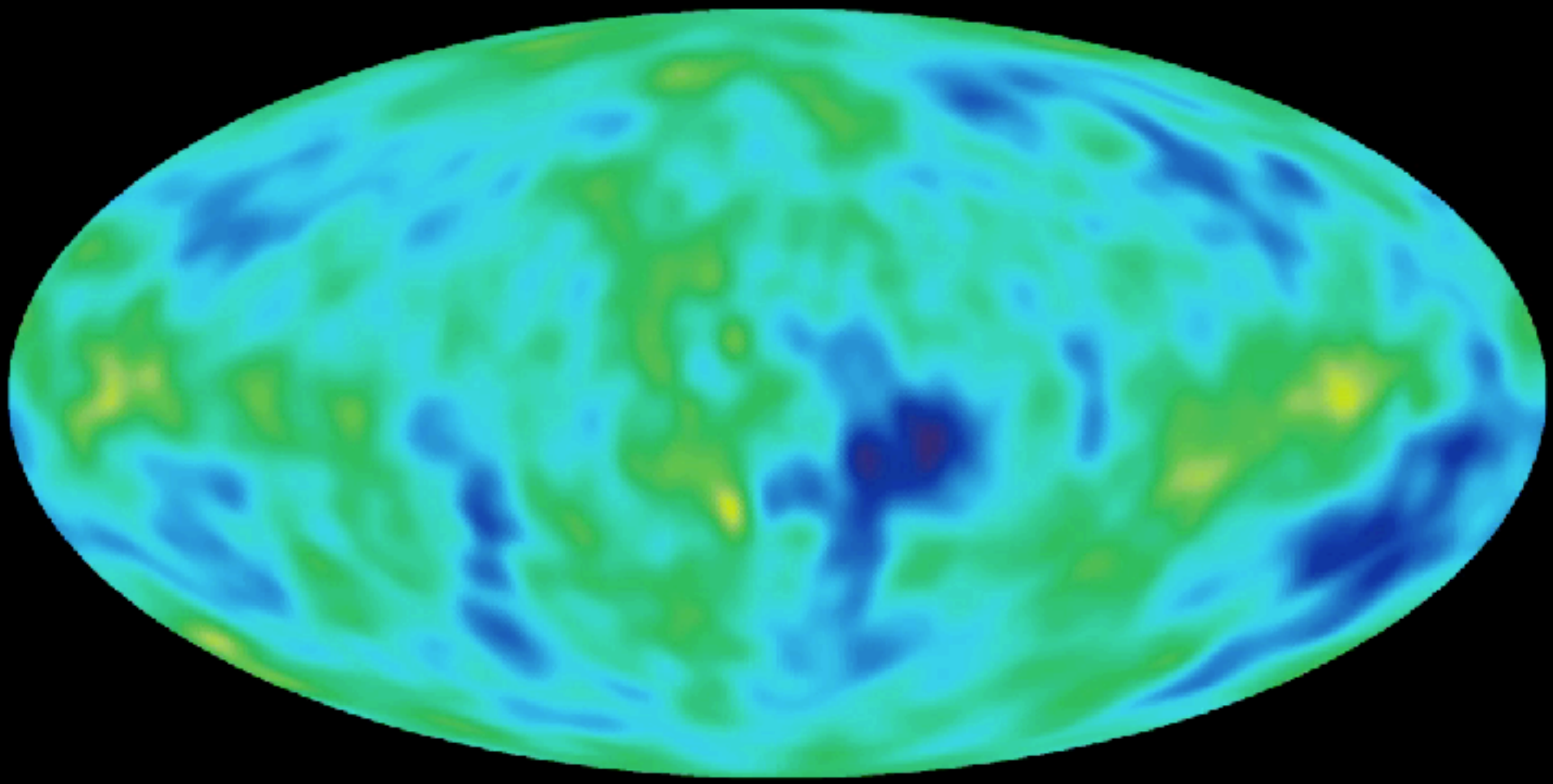


5000 F
(visible light)

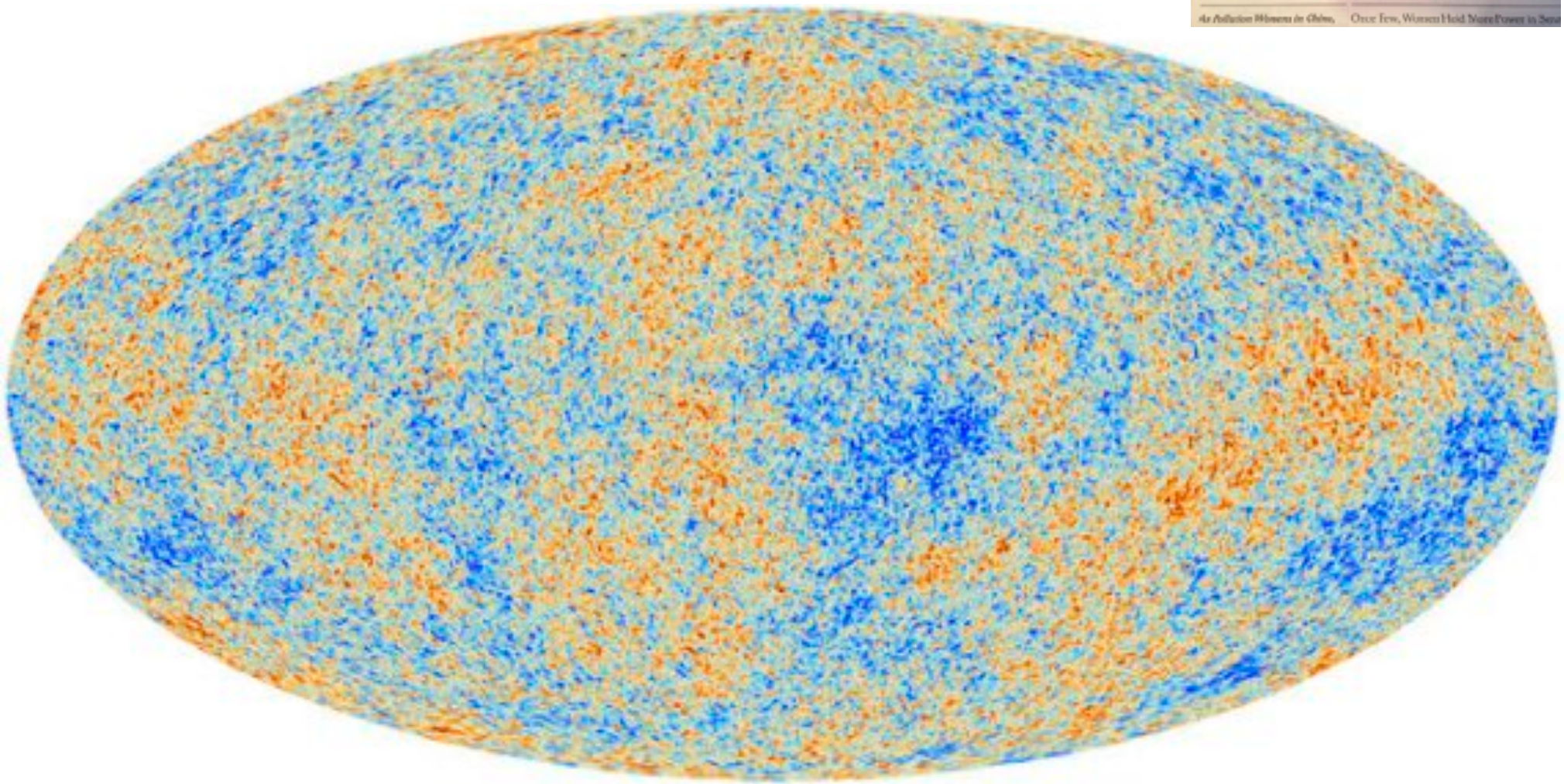
-454 F
(Microwave light)



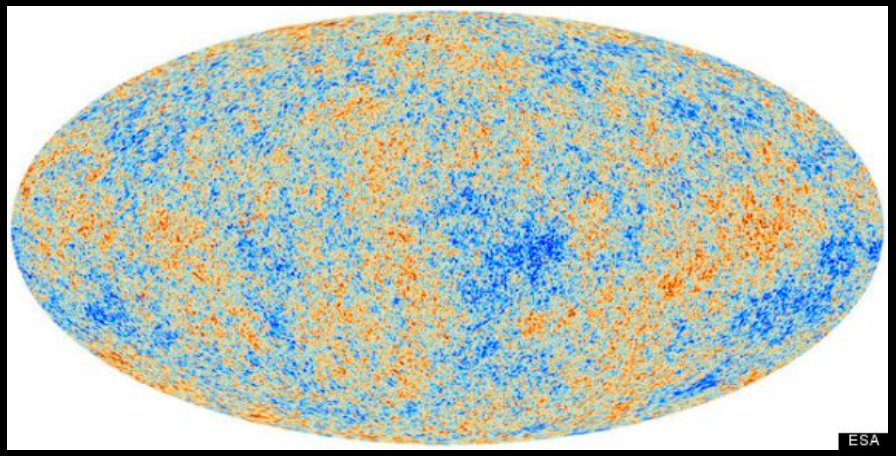
The CMB is not exactly - 454 F



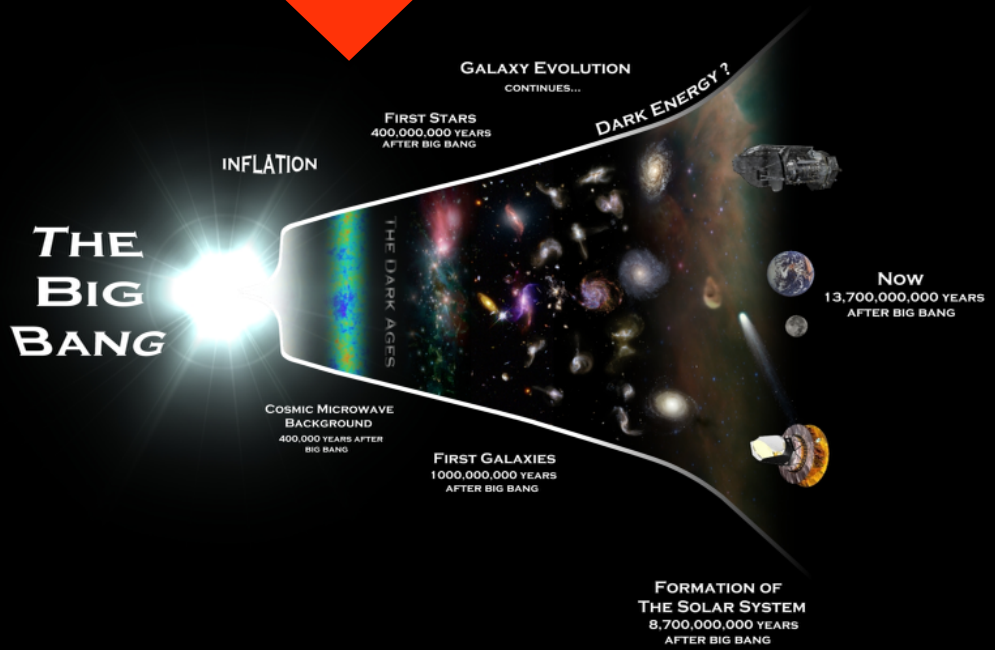
The CMB (as seen by the Planck Satellite)



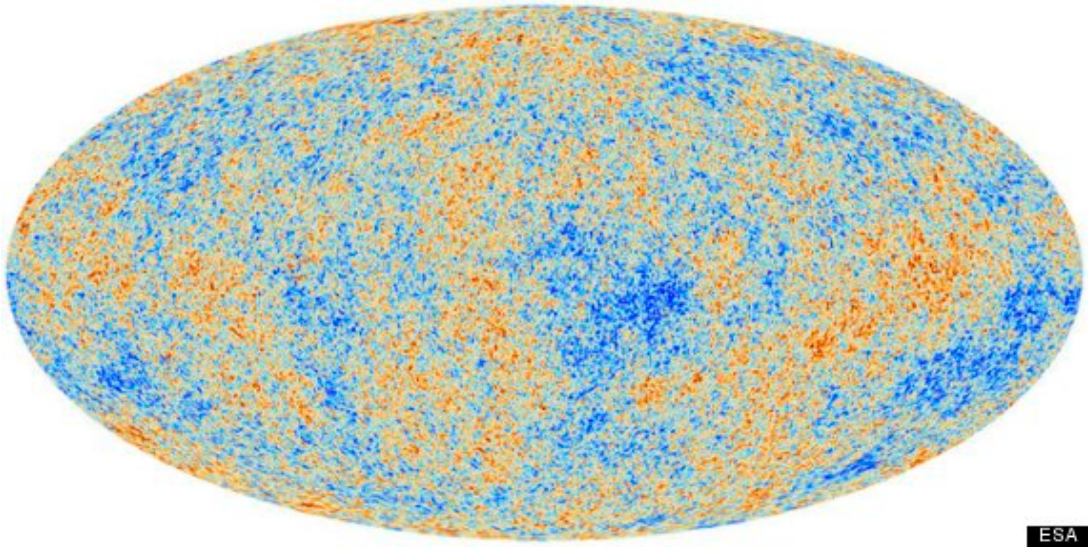
Red = hot **Blue = cold**



This photo is telling us the state of the universe about 13 Billion years ago!



The differences in temperature teach us about the contents back then.



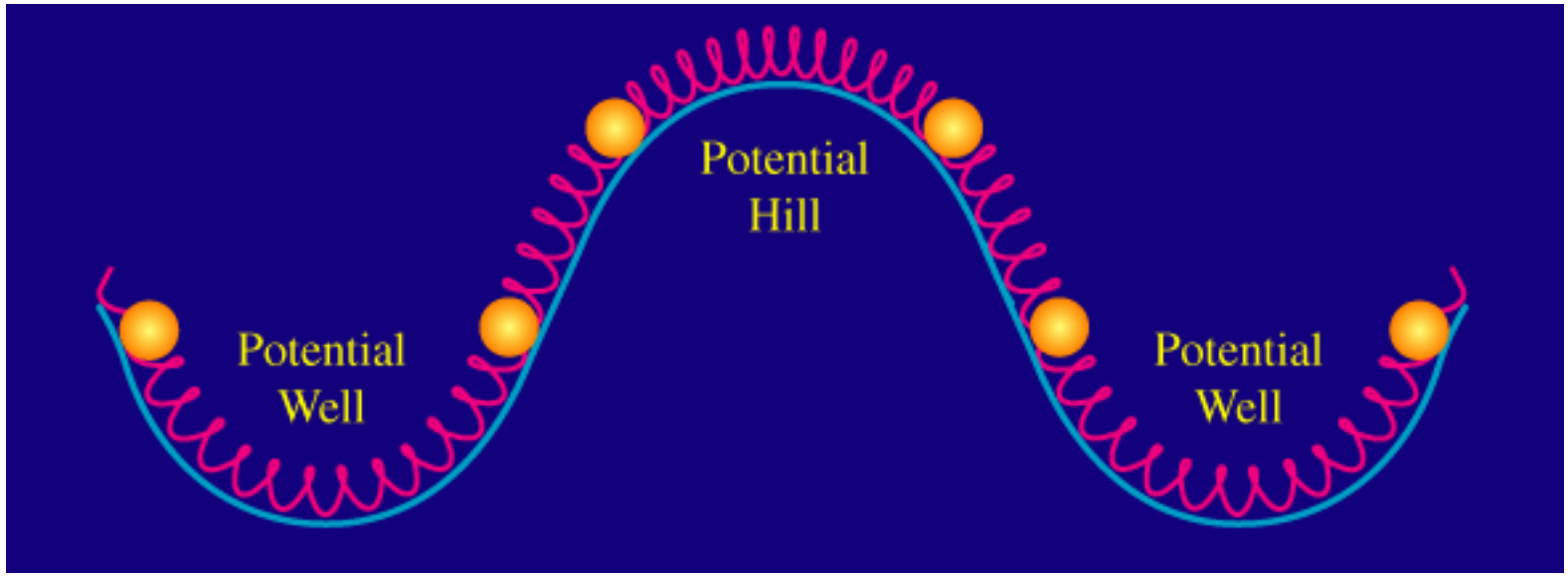
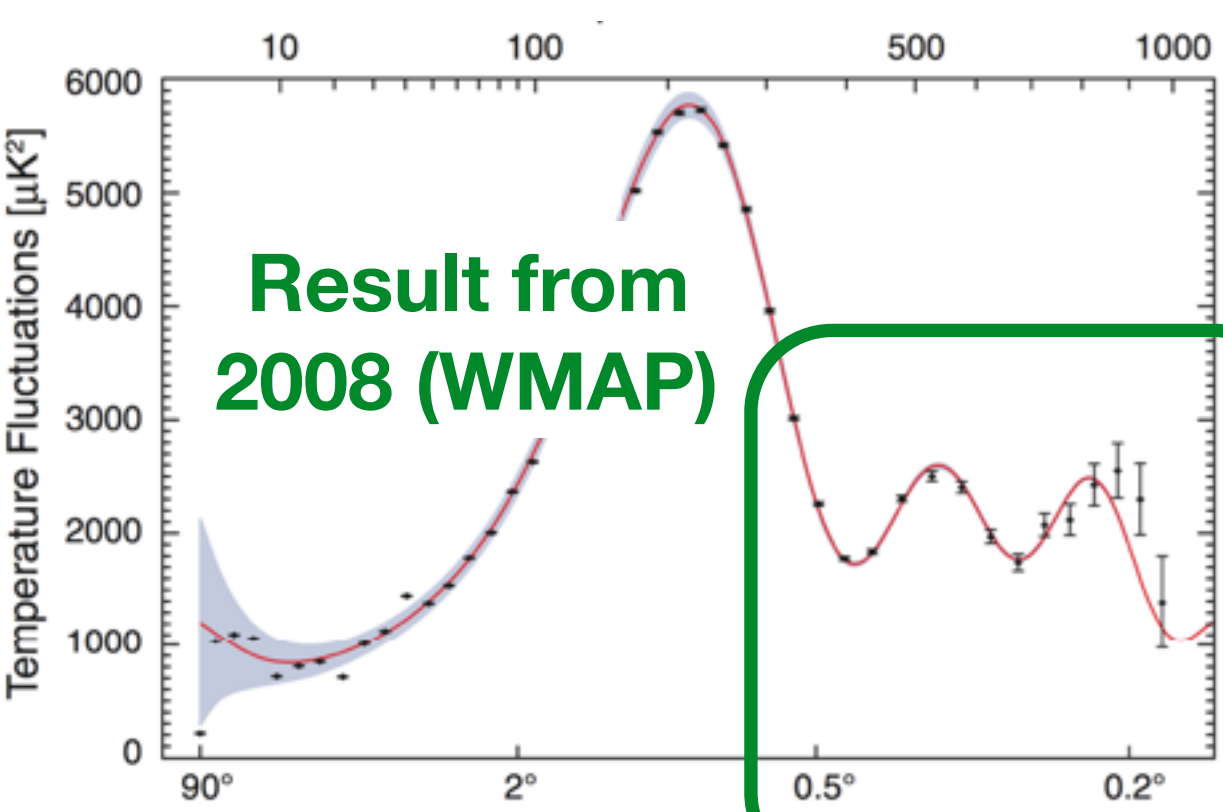
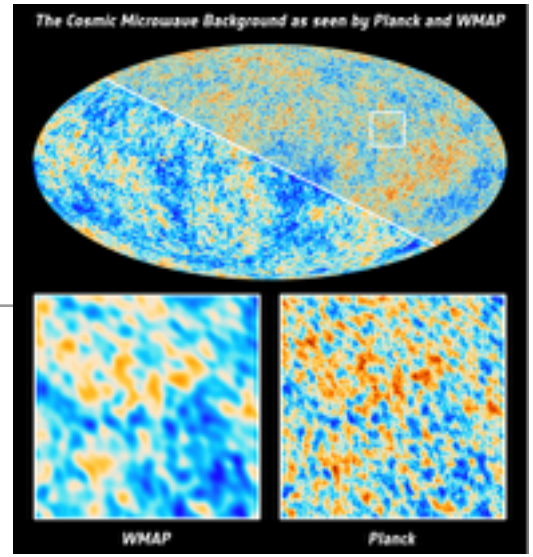


Image courtesy of Wayne Hu:
http://background.uchicago.edu/~whu

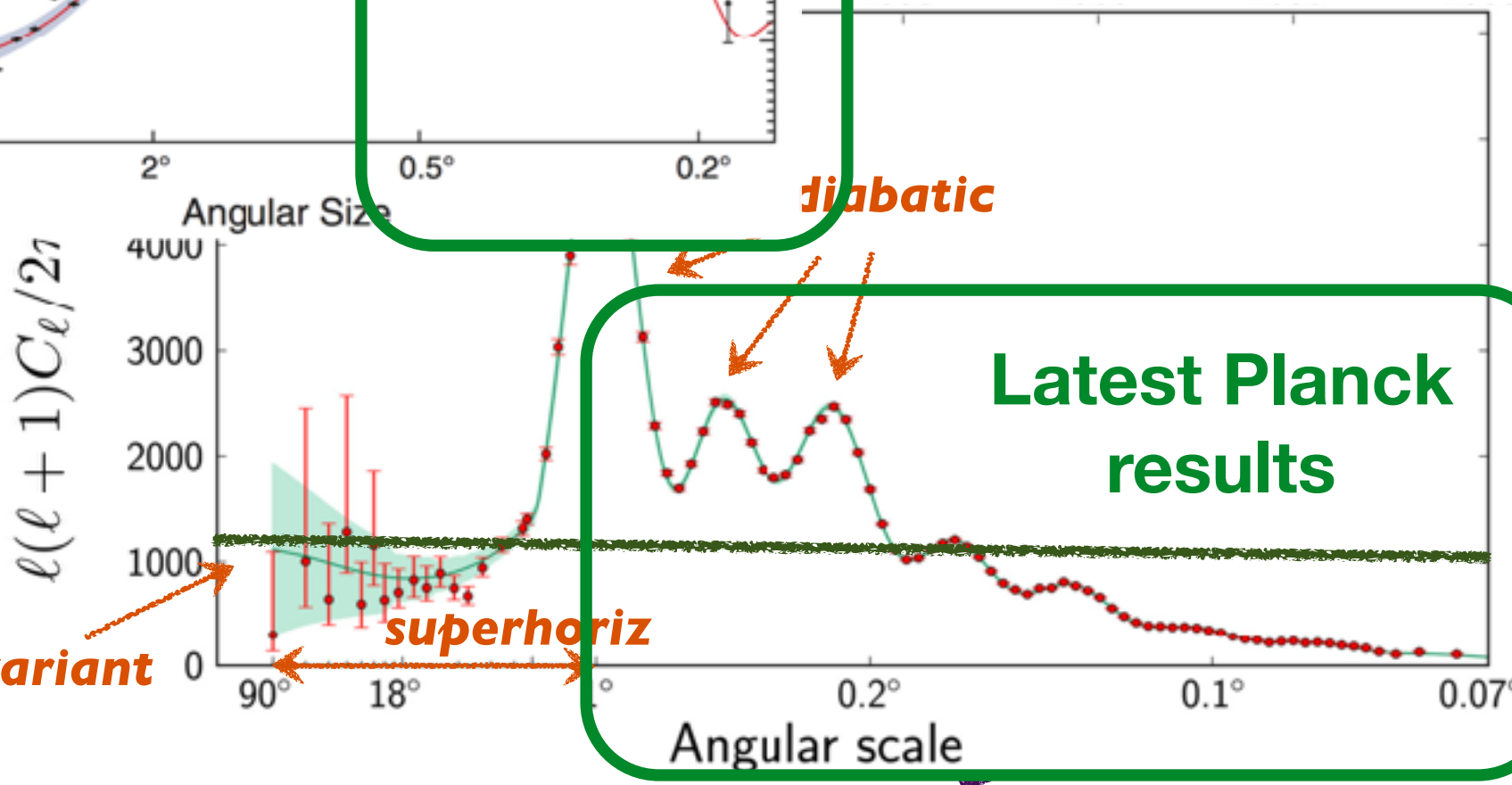


Result from 2008 (WMAP)



diabatic

Gaussian



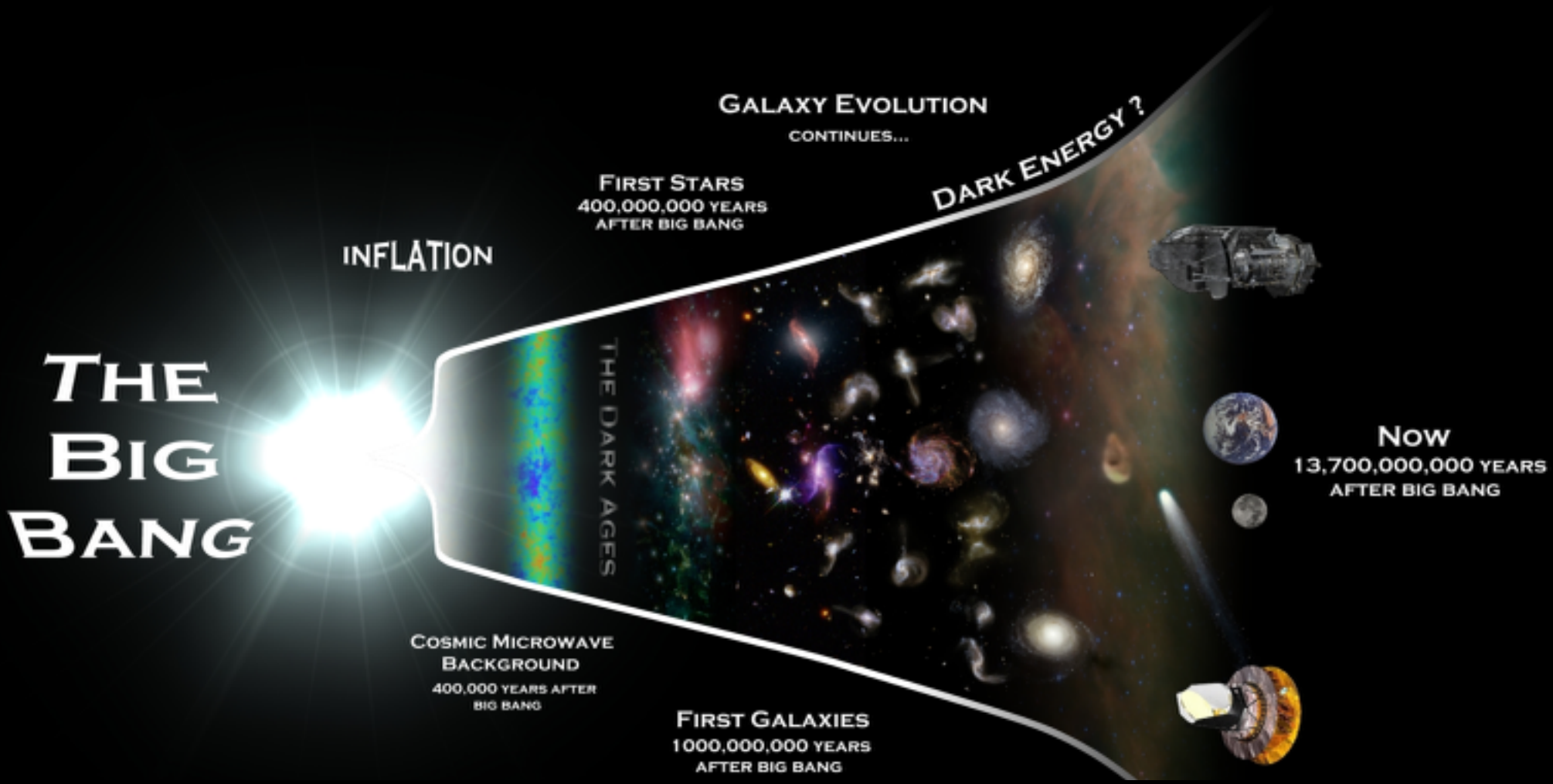
Latest Planck results

superhoriz

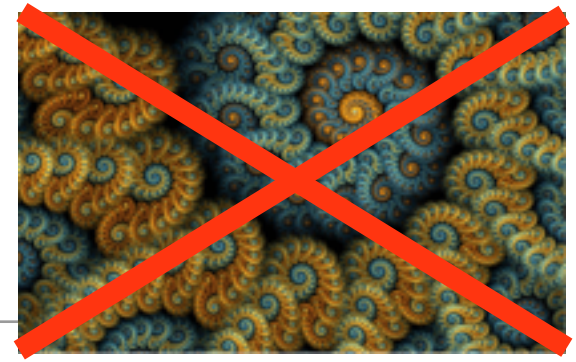
scale-invariant

isotropic

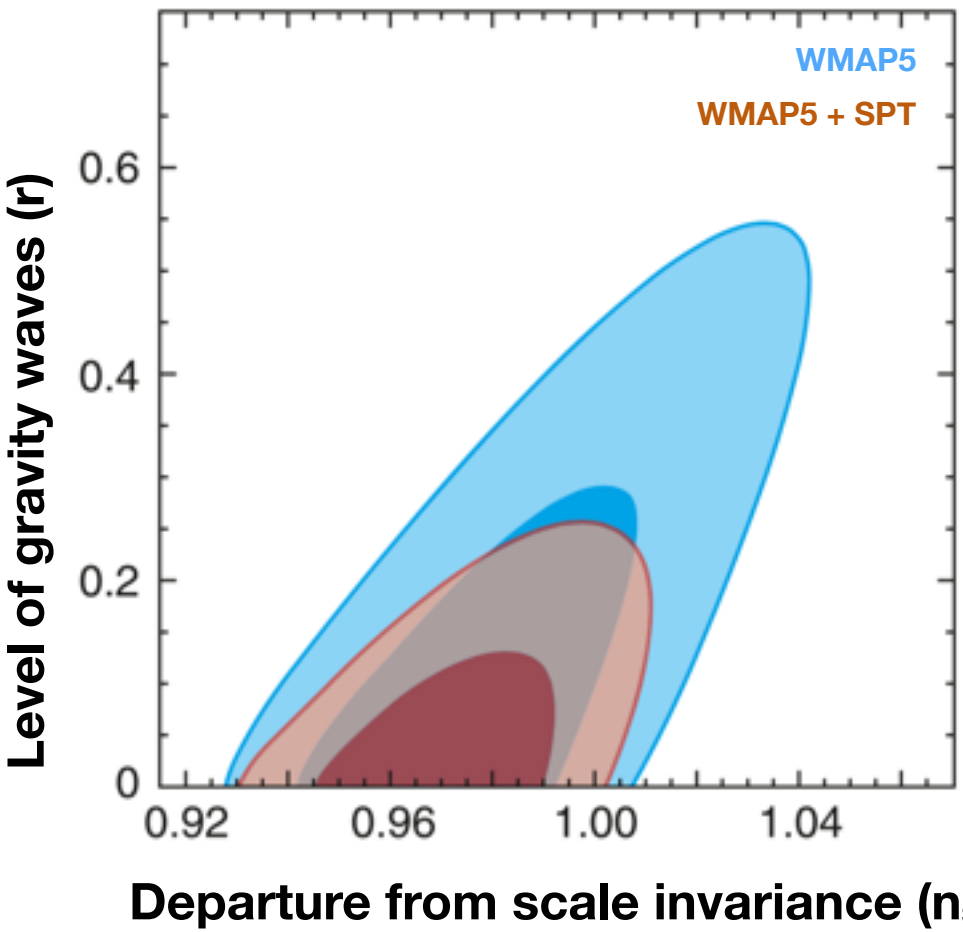
Inflation (early accelerated expansion) provides an origin for the fluctuations



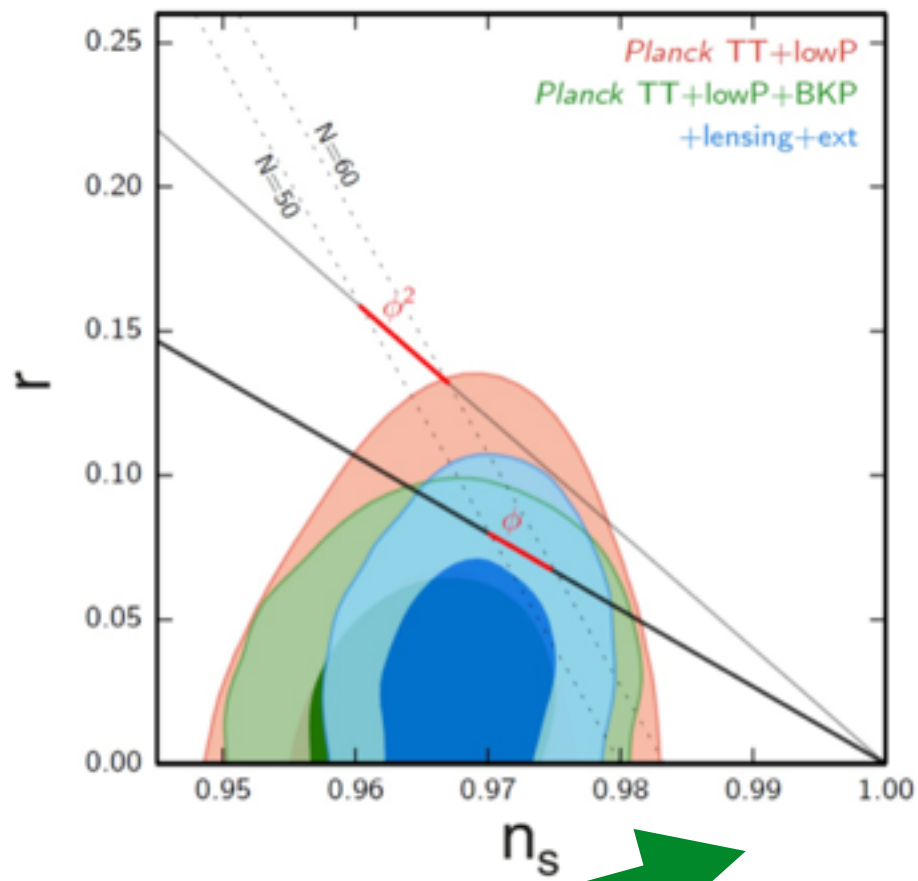
Improved understanding of Inflation



Data as of 2009

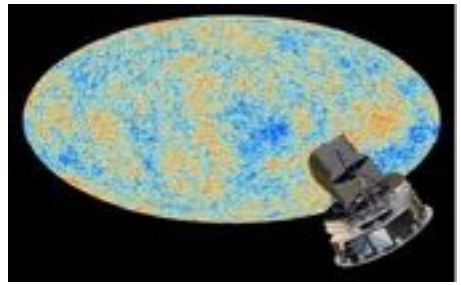


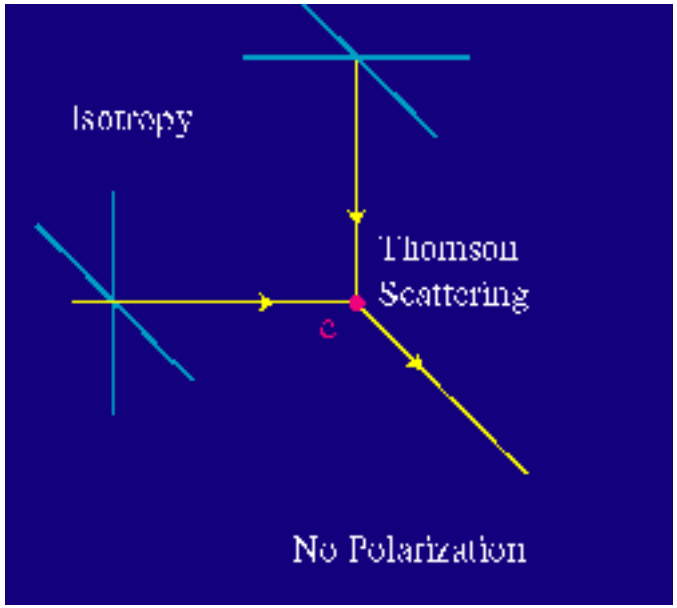
Data today

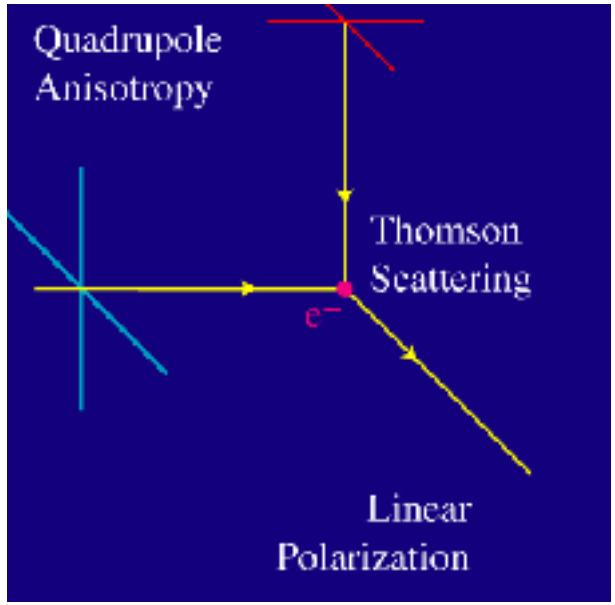


The **new result** $n_s < 1$ is **very important** theoretically.

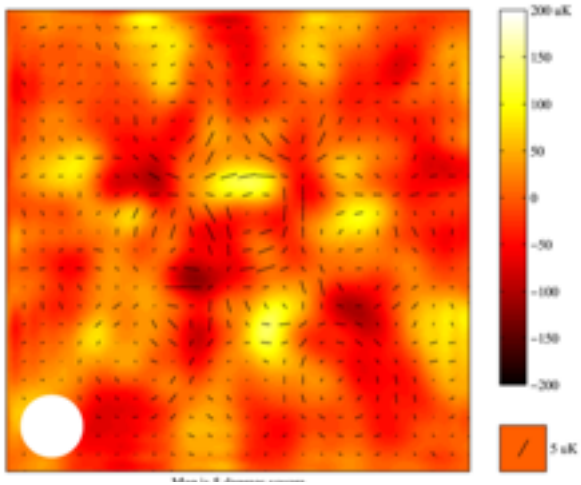
CMB Polarization and Primordial Gravity Waves

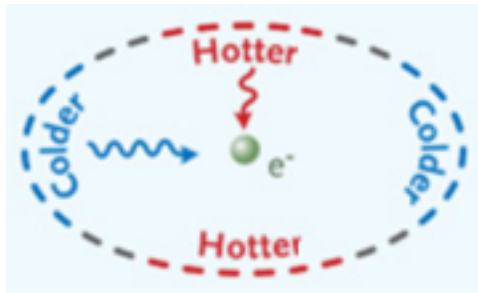




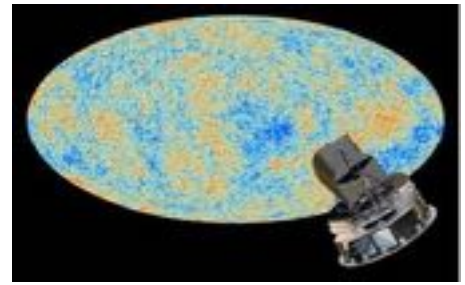


E-mode Polarization (DASI — 2002)

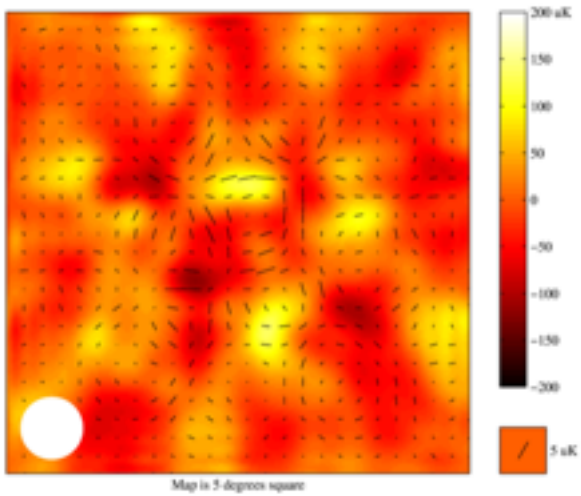


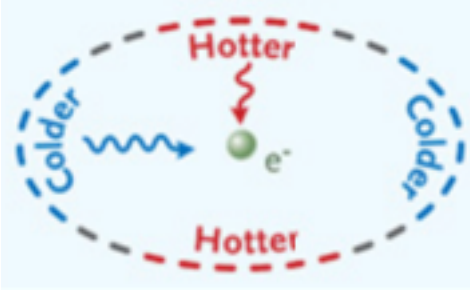


CMB Polarization and Primordial Gravity Waves

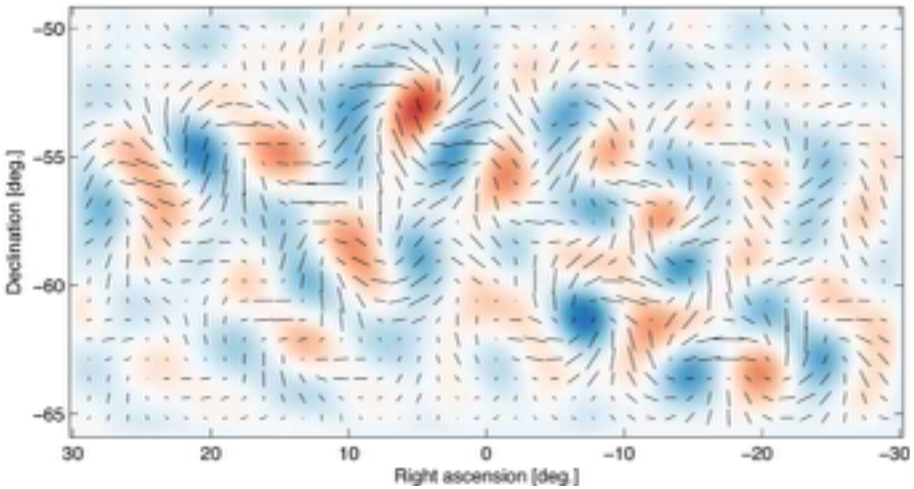


E-mode Polarization (DASI — 2002)



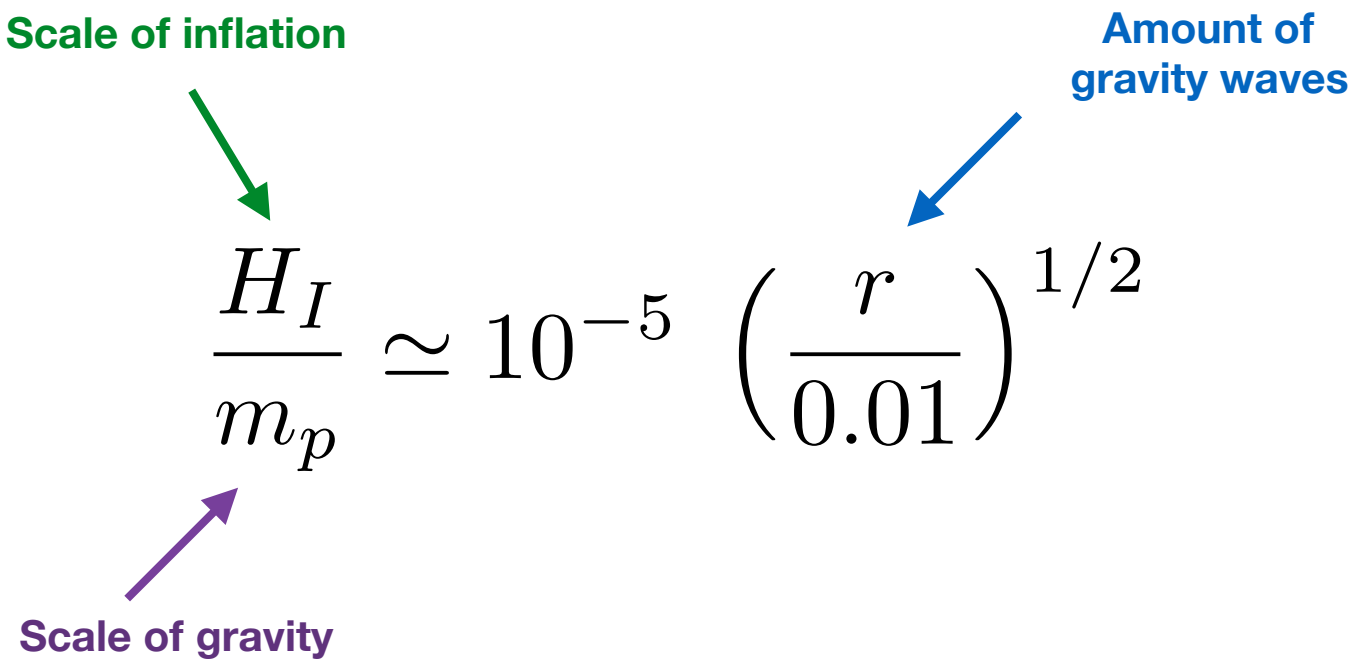


Gravity Waves can also produce B-mode Polarization

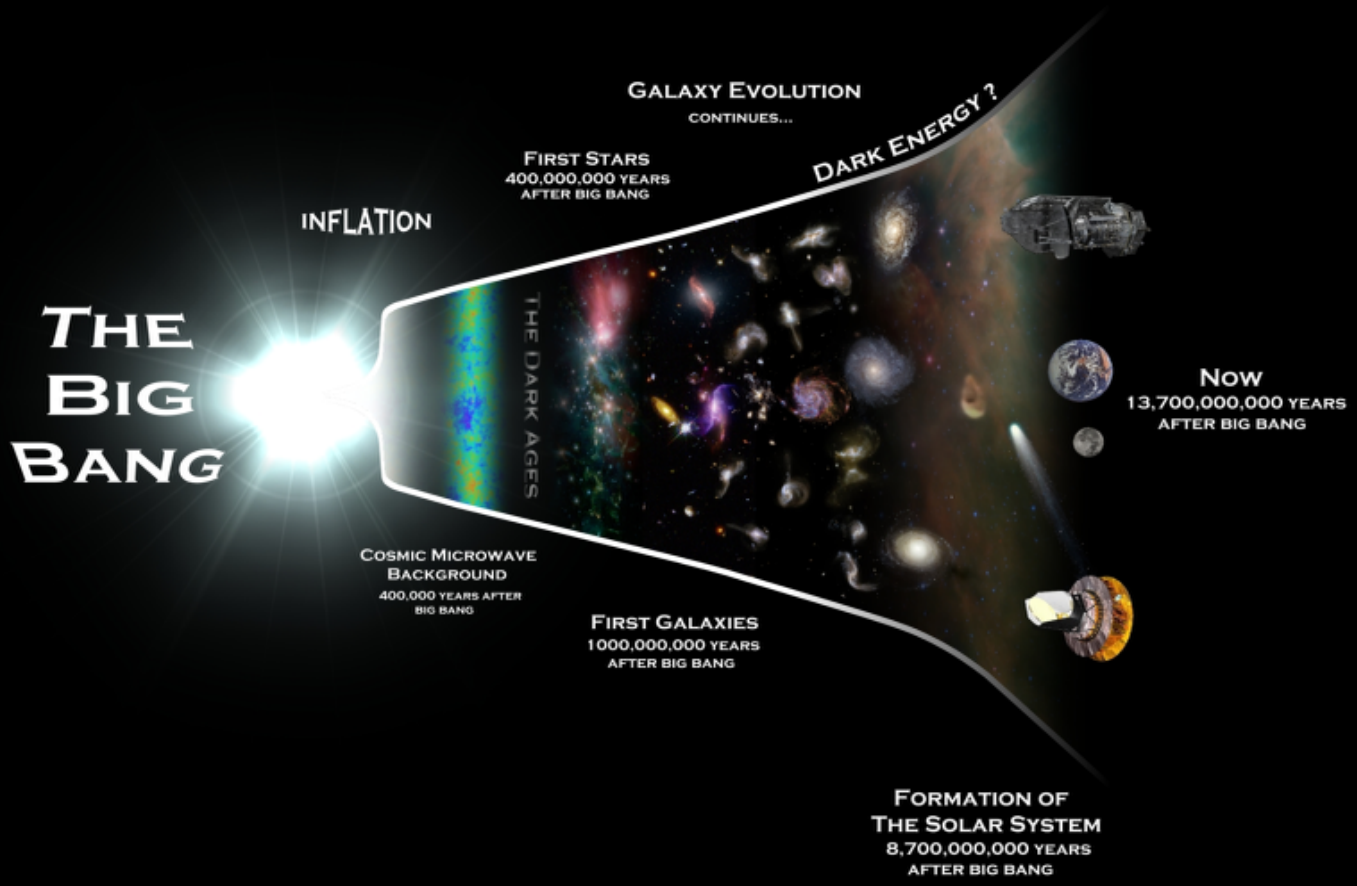


The Inflaton Hierarchy Problem

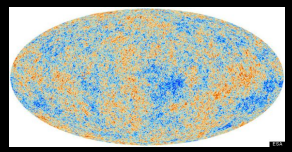
with O. Ozsoy and K. Sinha, Phys. Rev. D91 (2015)



What happened next?



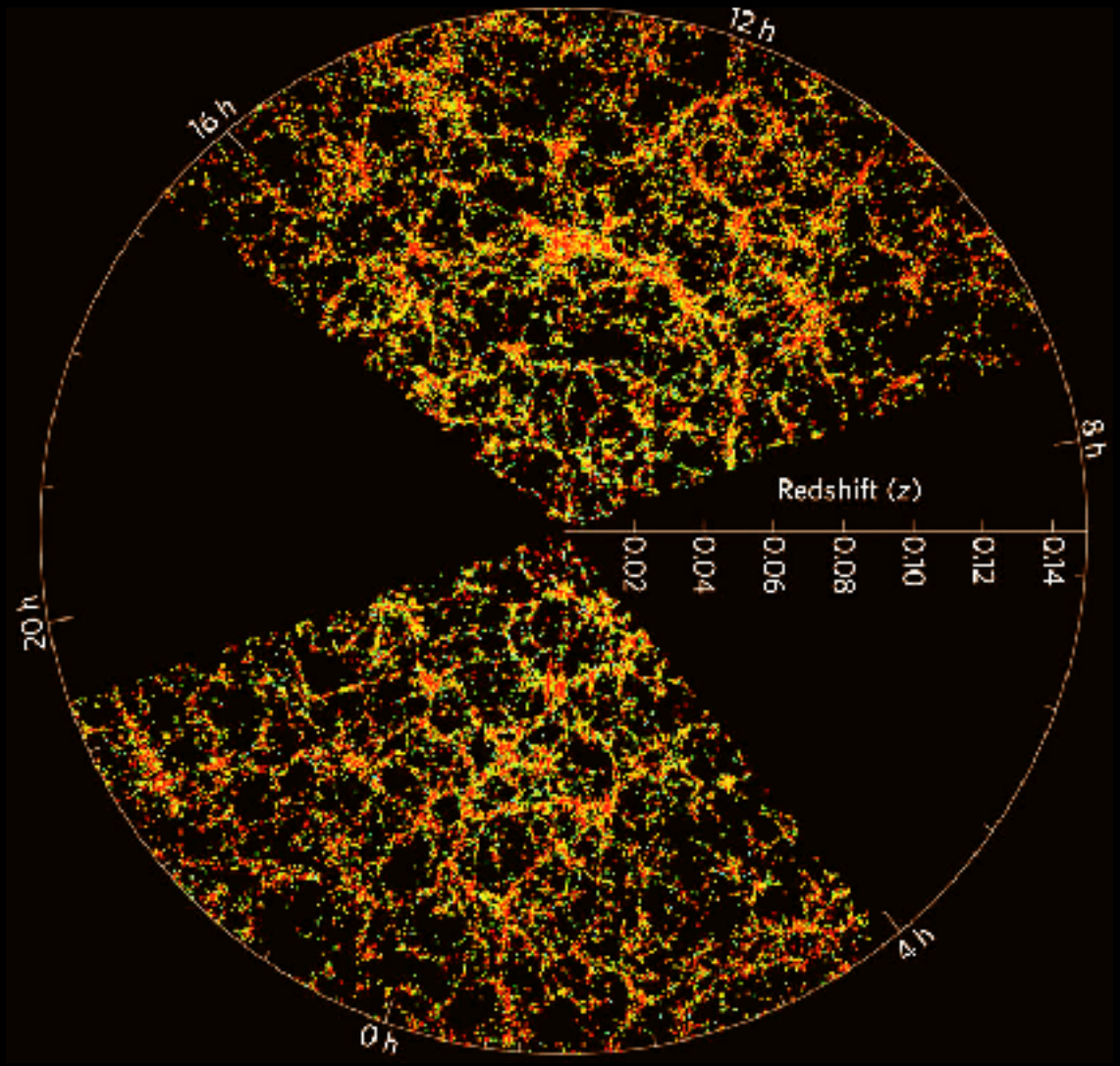
Using theory and experiments we can compare the universe then to the universe now!



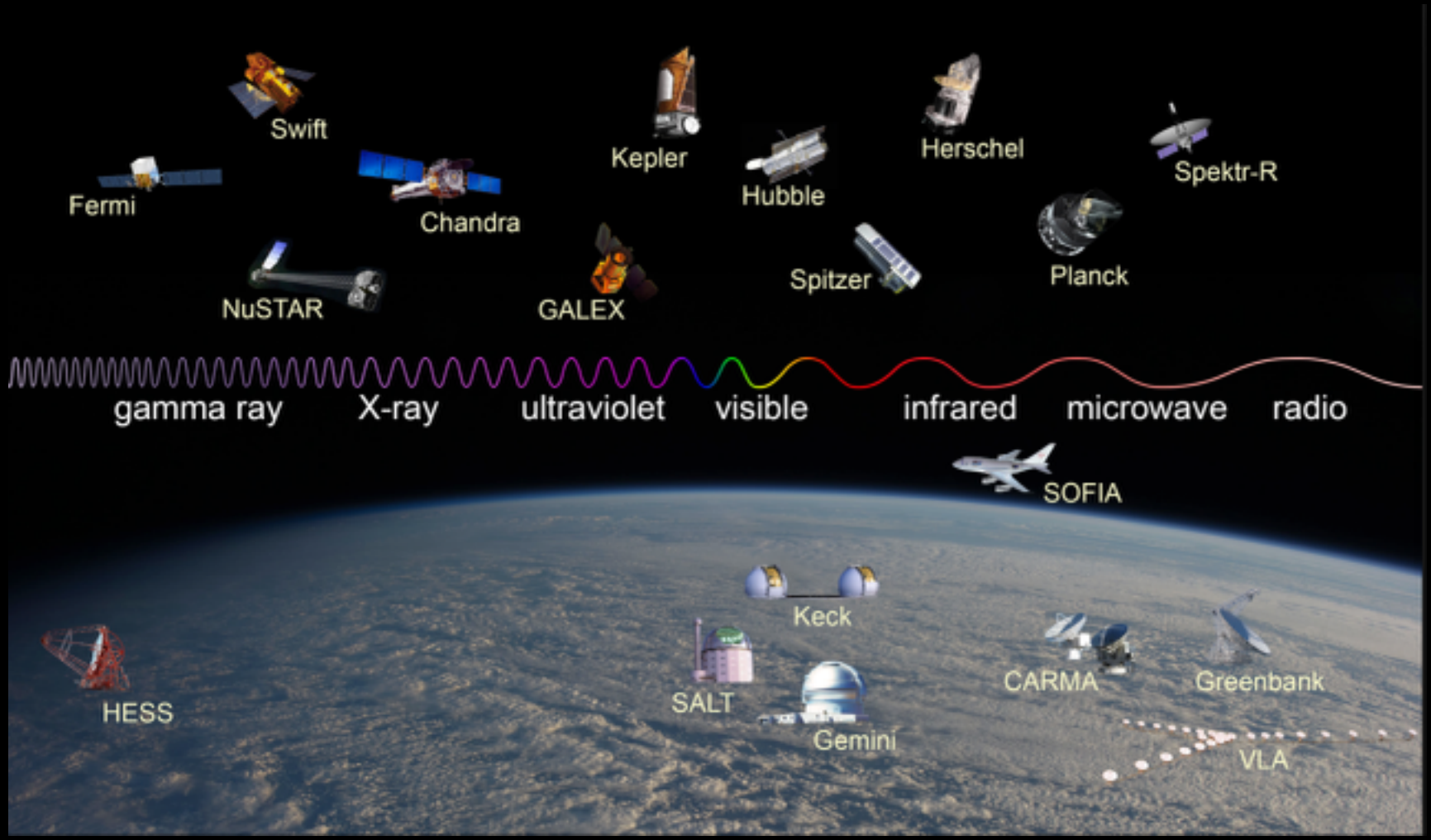
planck

INAF TV

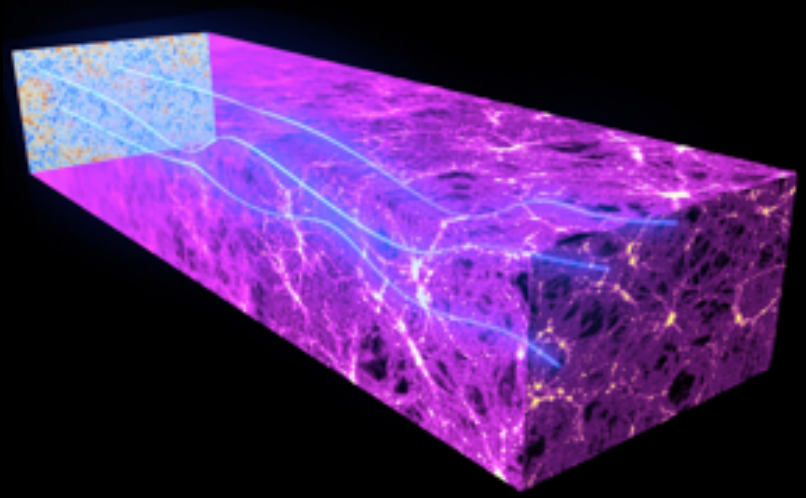
Observing galaxies teaches us about how they formed and what was around at that time.

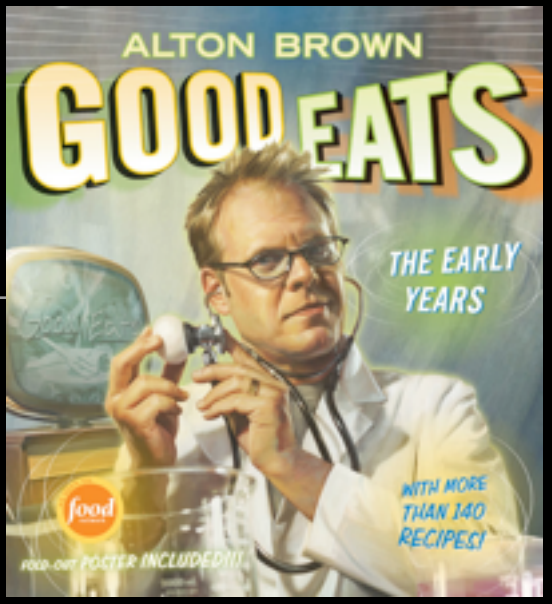


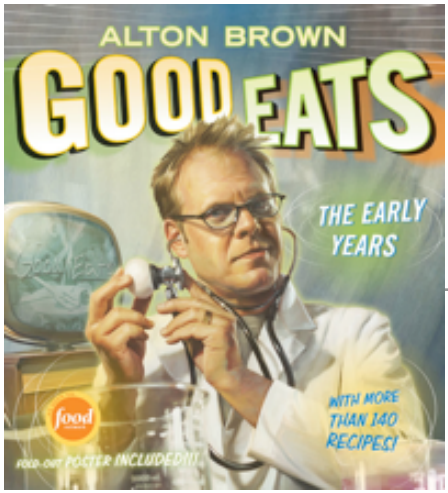
We make these observations beyond only visible light!



Different ingredients cook differently.







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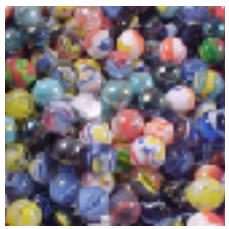
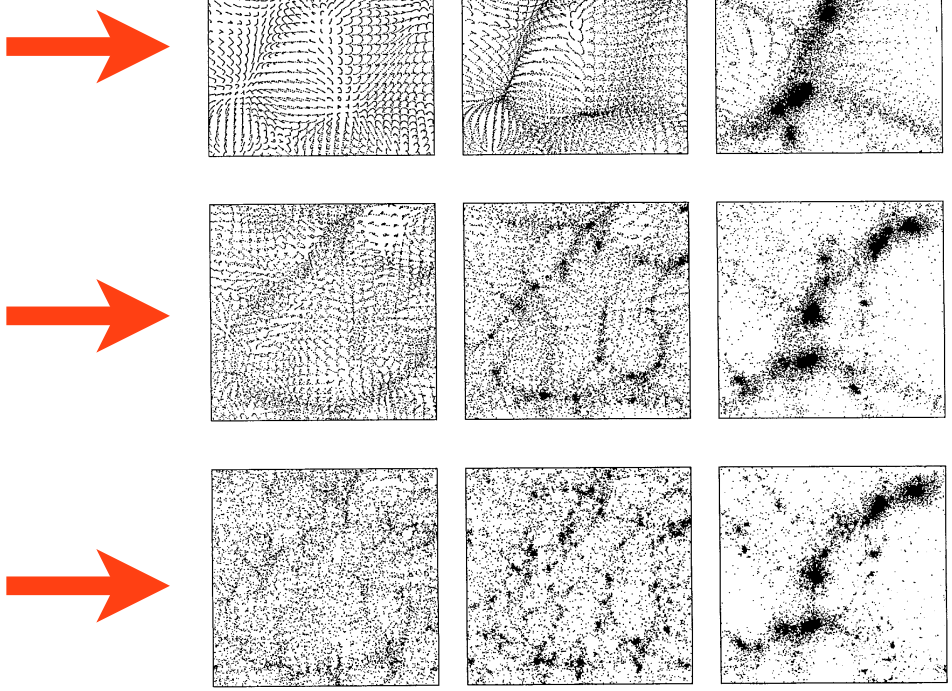
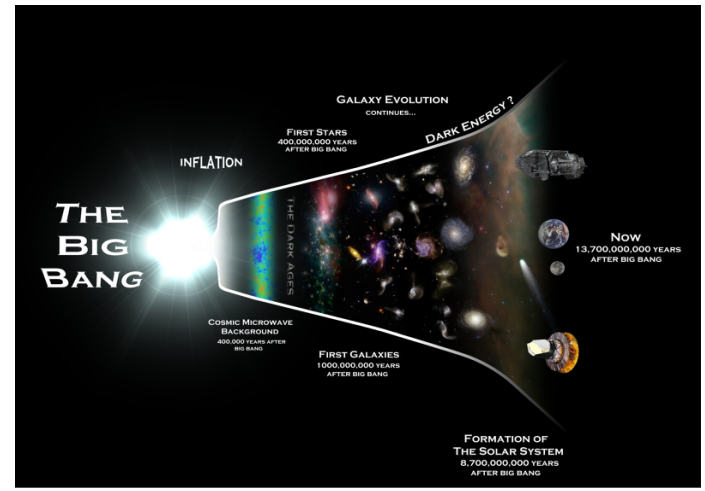
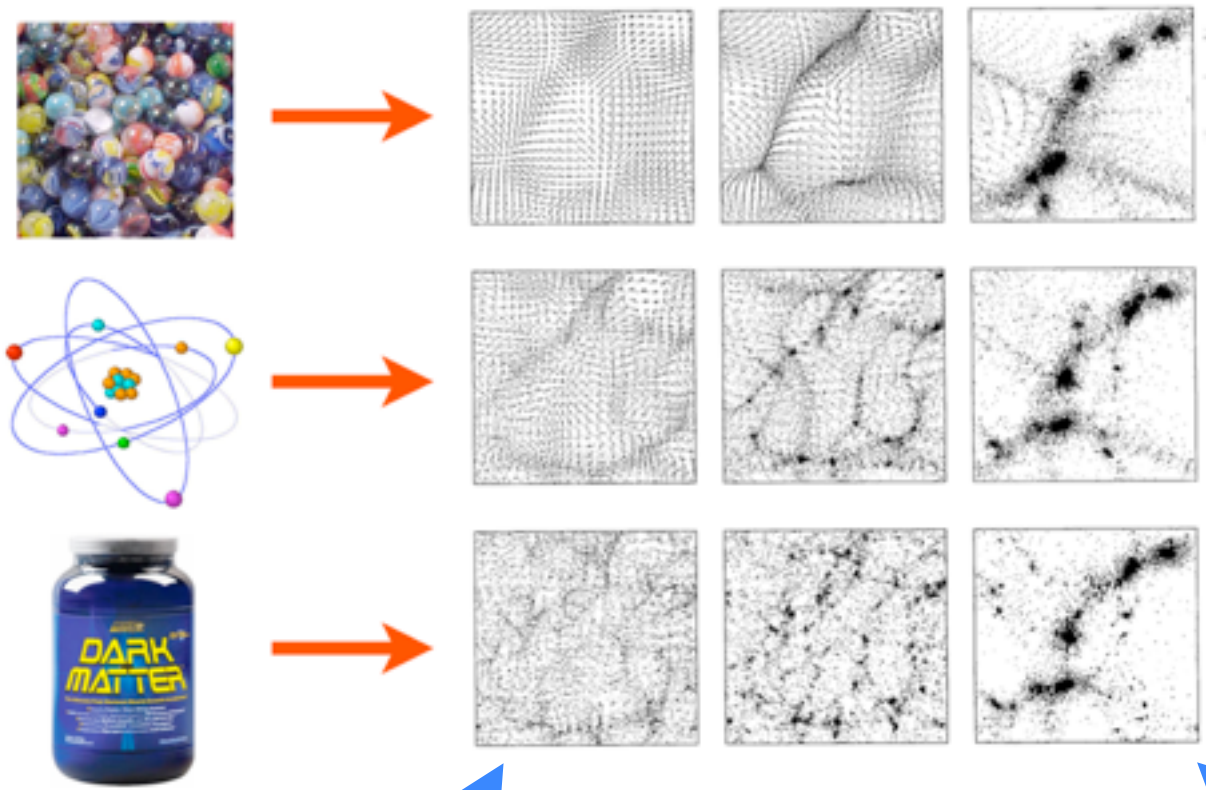




Time

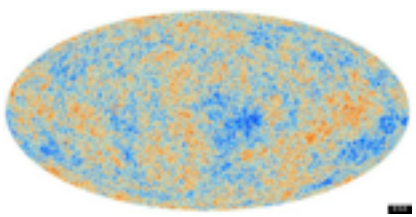


Different ingredients give us different universes!

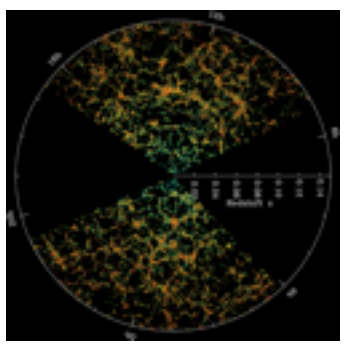


Time

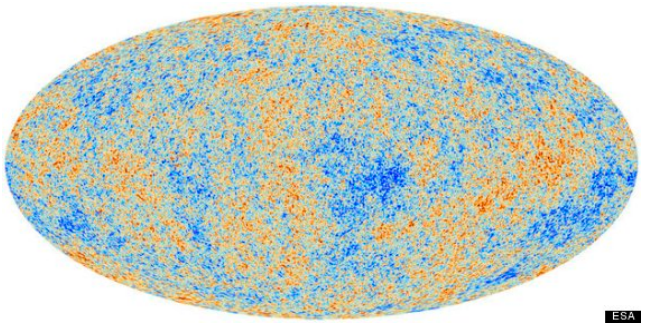
CMB pic (400,000 years)



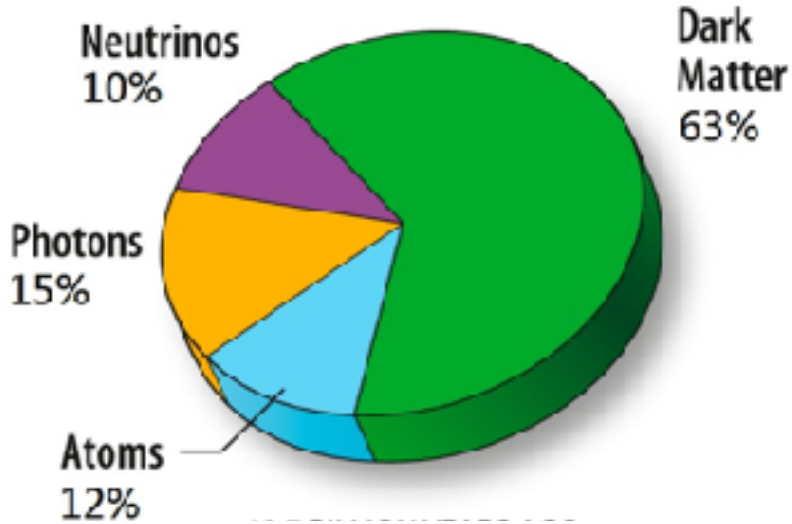
Galaxy Observations today



We learn from these observations the ingredients of the universe 14 Billion years ago.



CMB pic (400,000 years)

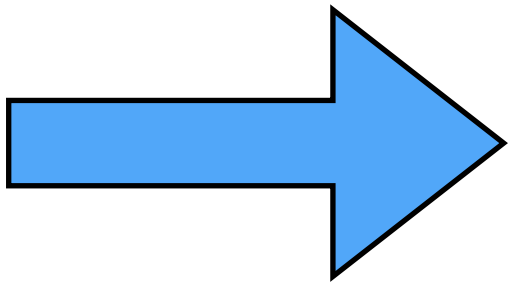


14 Billion Years Ago!

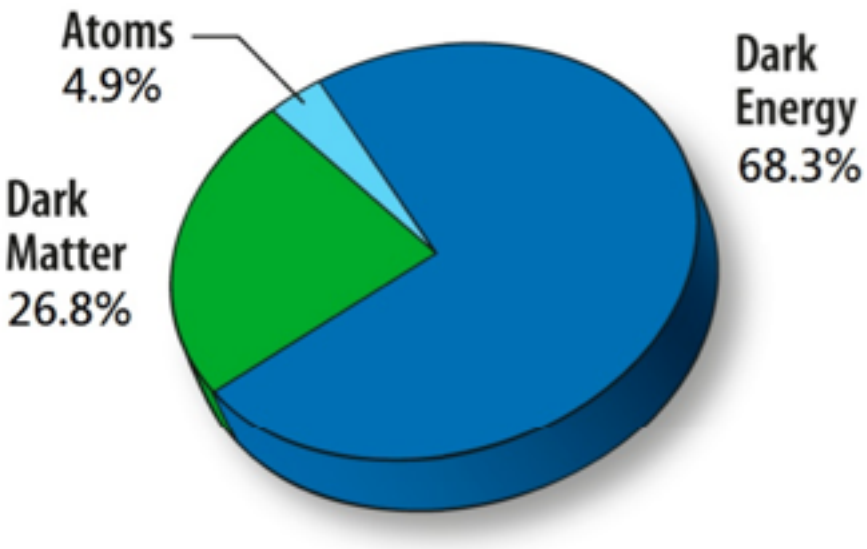
Most of the Universe had to be Dark Matter

(No marbles, sorry!)

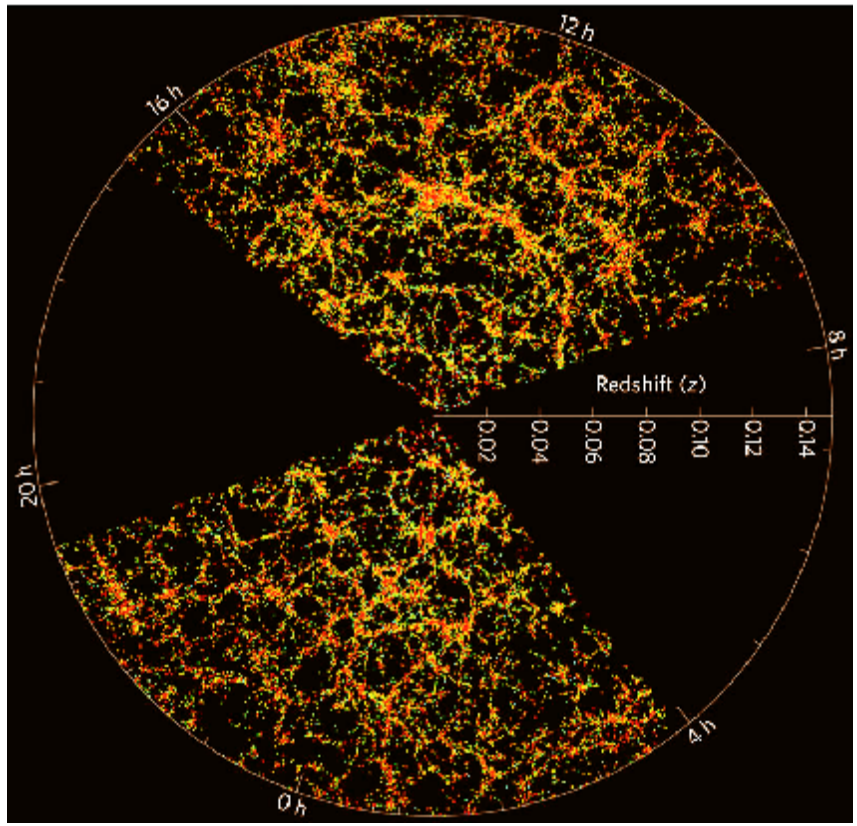
After 14 Billion years of cooking, the universe has changed!



After 14 Billion years of cooking, the universe has changed!

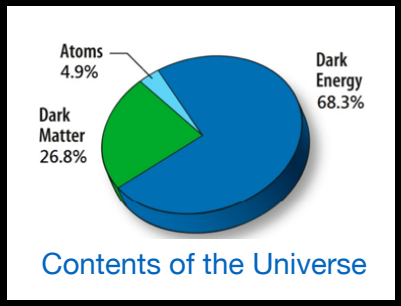


Contents of the Universe Today



Questions we will address today:

- How do we know the composition of the universe?



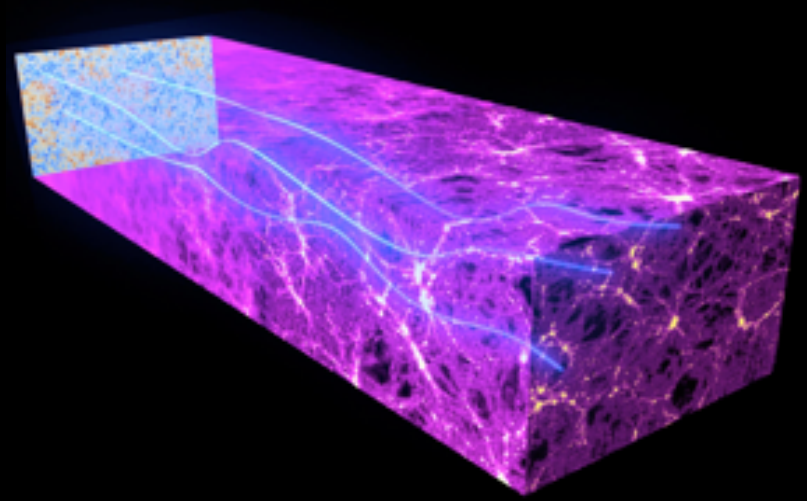
Contents of the Universe

- What is Dark Matter?

- What is Dark Energy?

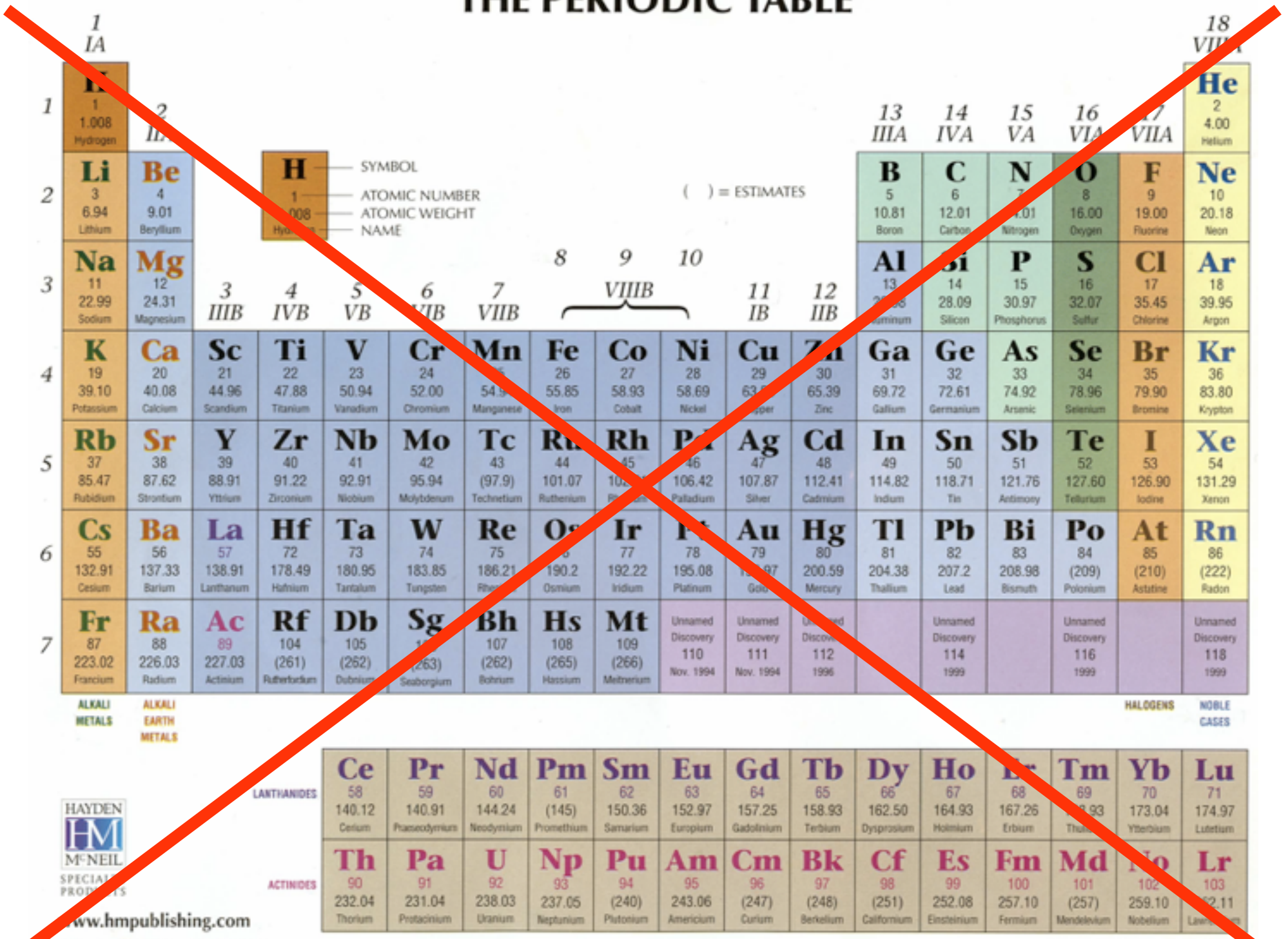
What is Dark Matter?

Its dark and its matter



So far we have observed it indirectly.

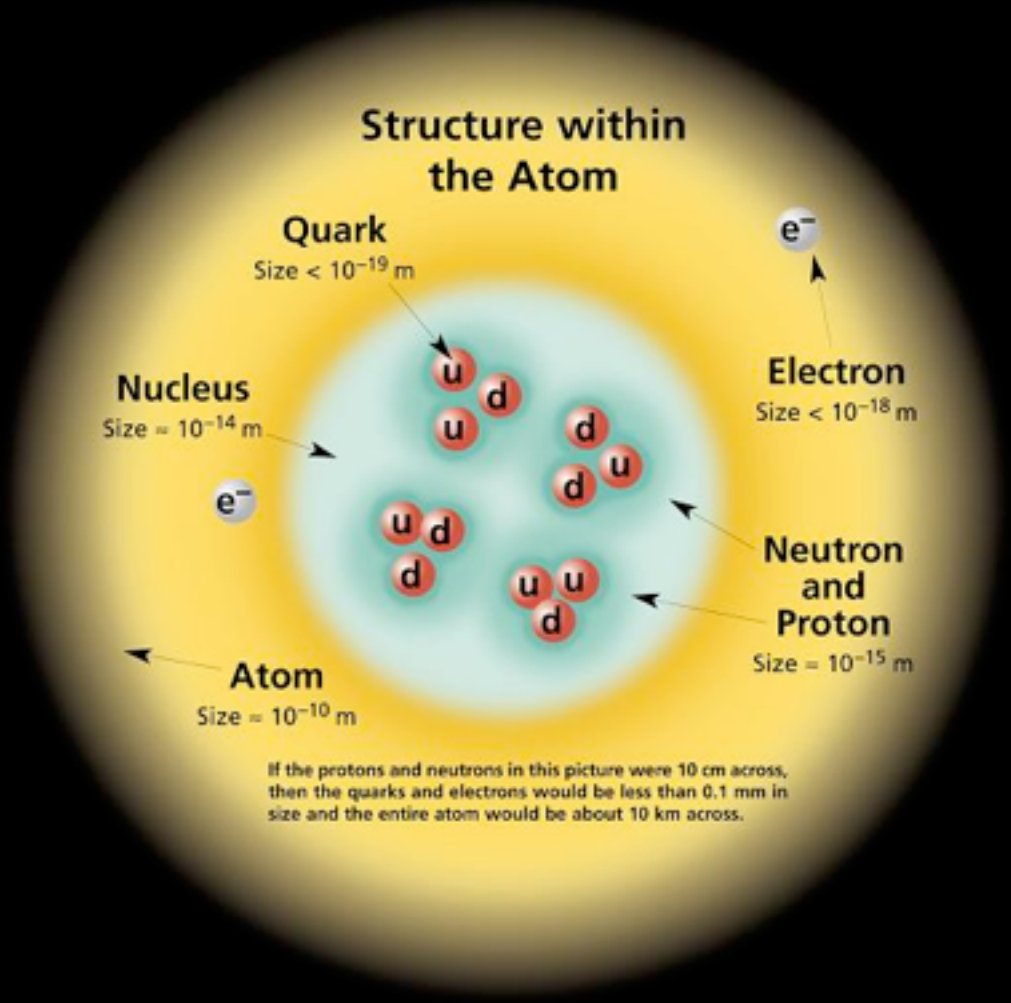
THE PERIODIC TABLE



HAYDEN McNEIL SPECIALTY PRODUCTS

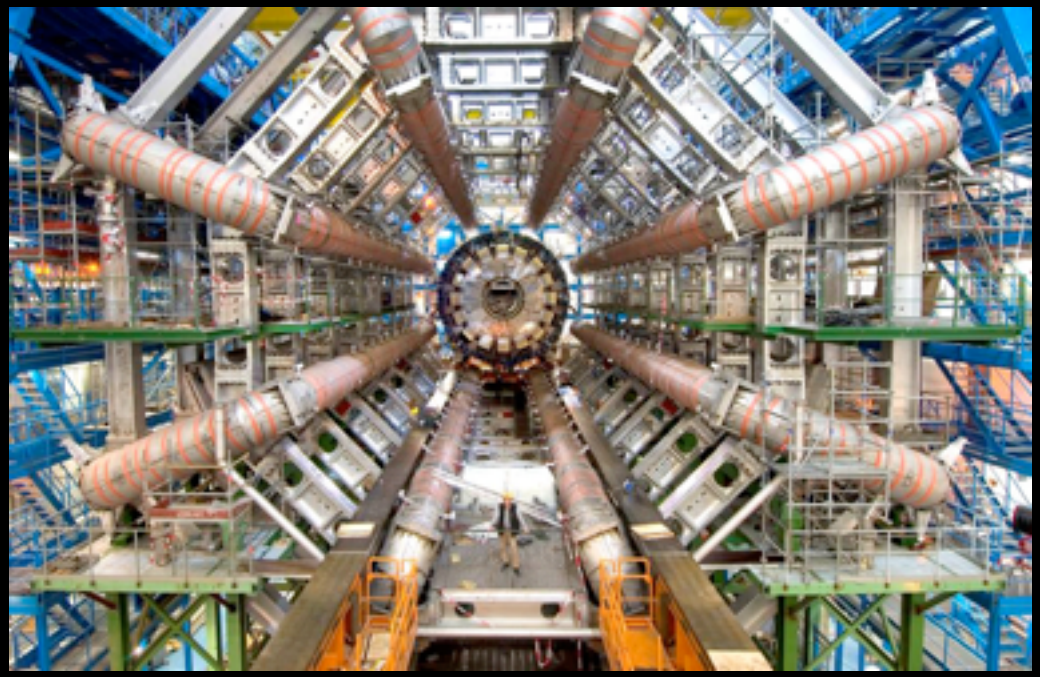
www.hmpublishing.com

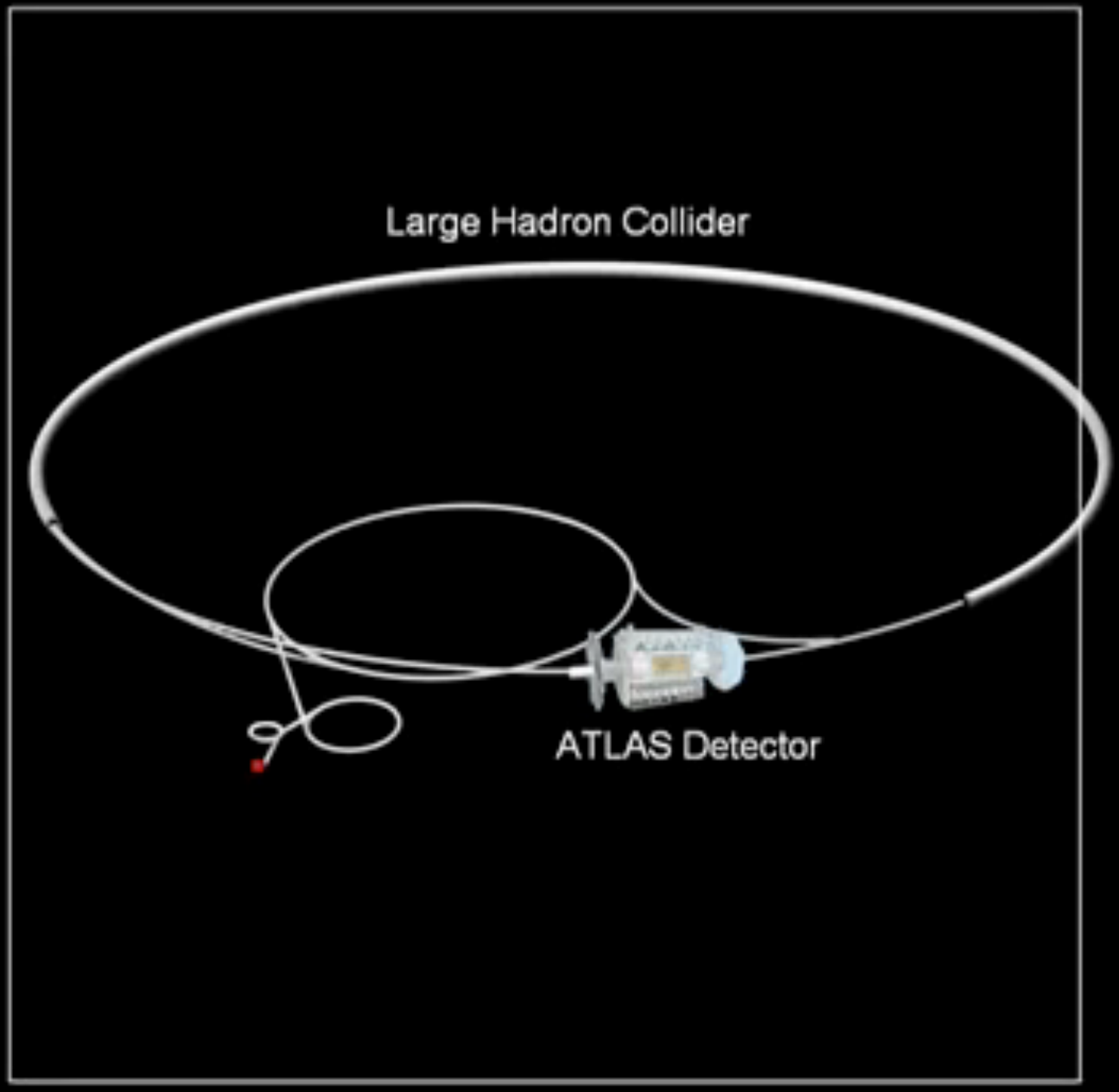
10^{-10}
meters



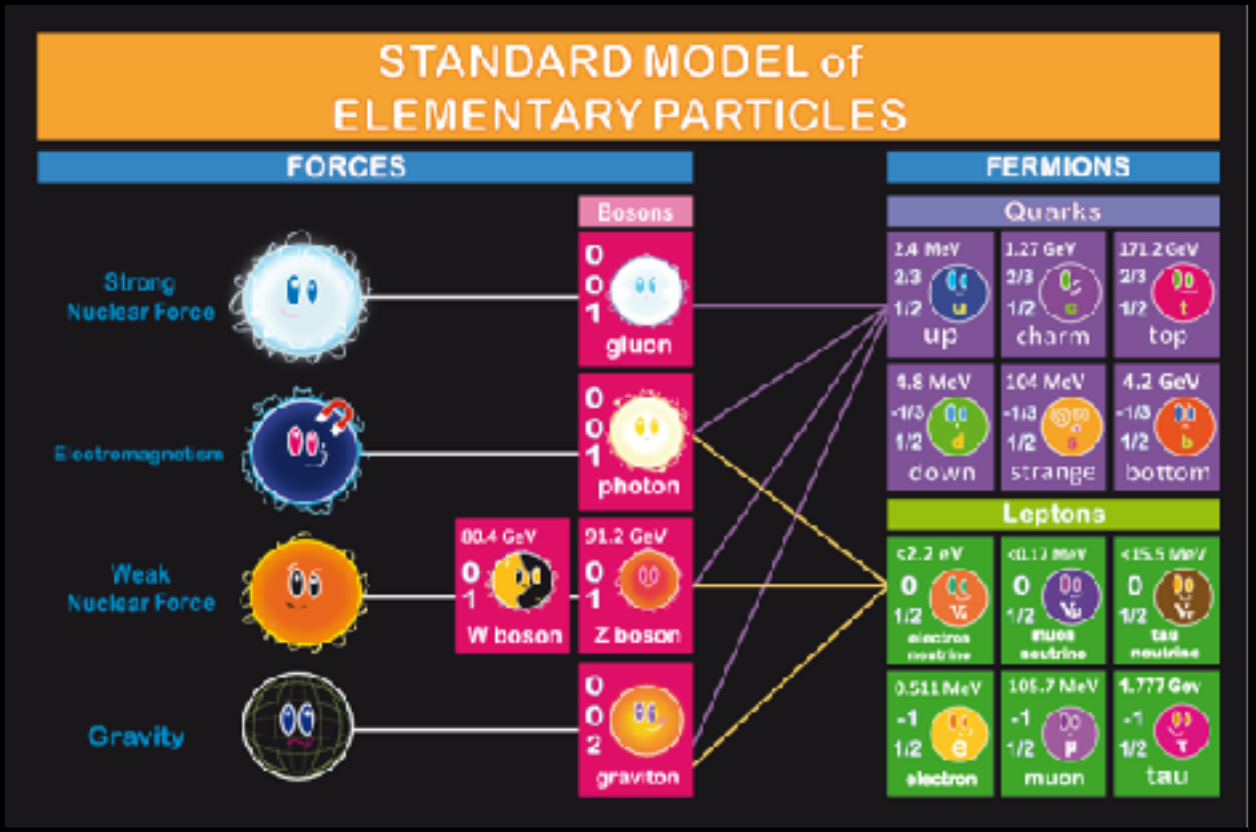
Atoms are not fundamental

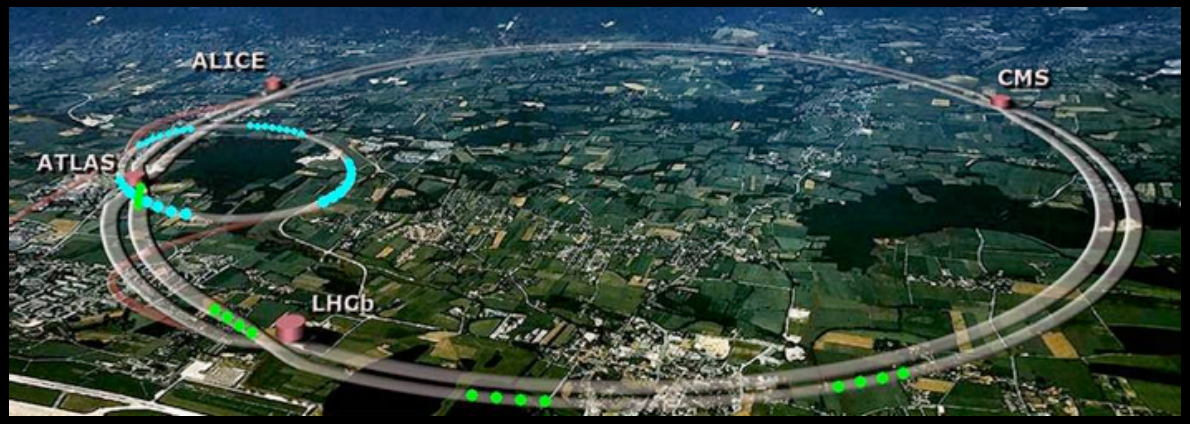
We probe inside the Atom using particle colliders




Large Hadron Collider
ATLAS Detector

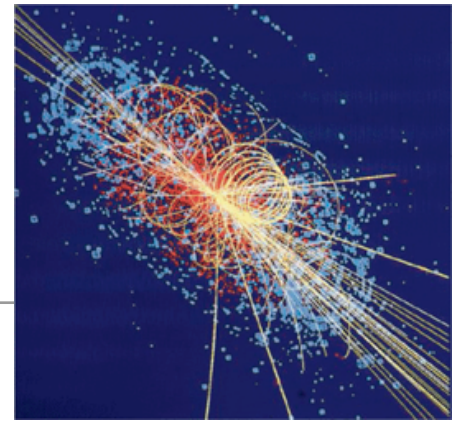
Many successful discoveries, but no Dark Matter yet!



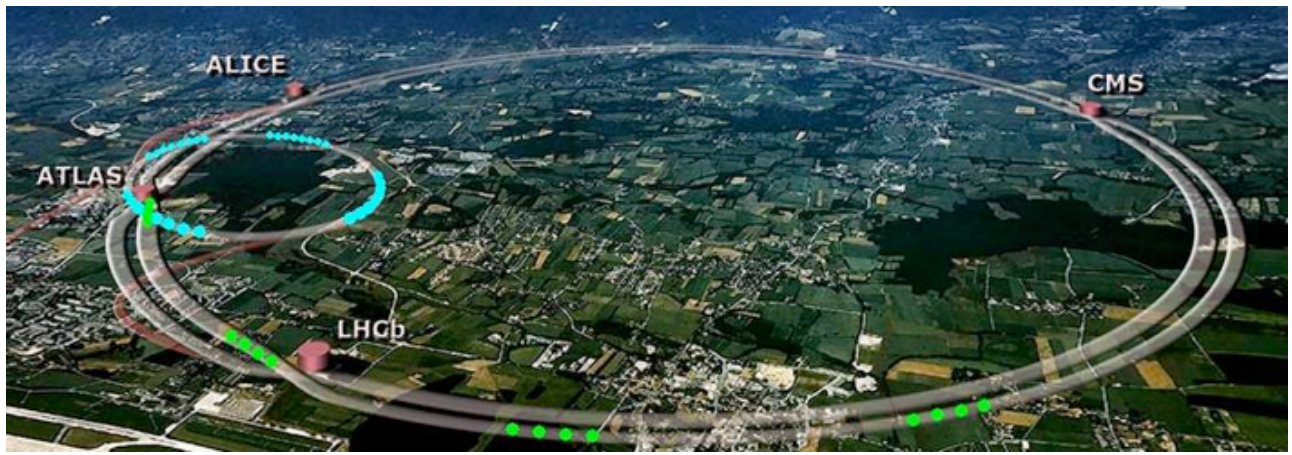


We discovered the Higgs particle!

Could there be more particles?



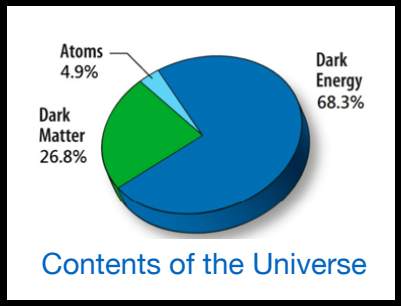
Supersymmetry theories suggest new particles that could be the Dark Matter



Stay Tuned!!!!!!

Questions we will address today:

- How do we know the composition of the universe?



Contents of the Universe

- What is Dark Matter?

- What is Dark Energy?

Thank you for coming.

2011 Nobel Prize

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

andard

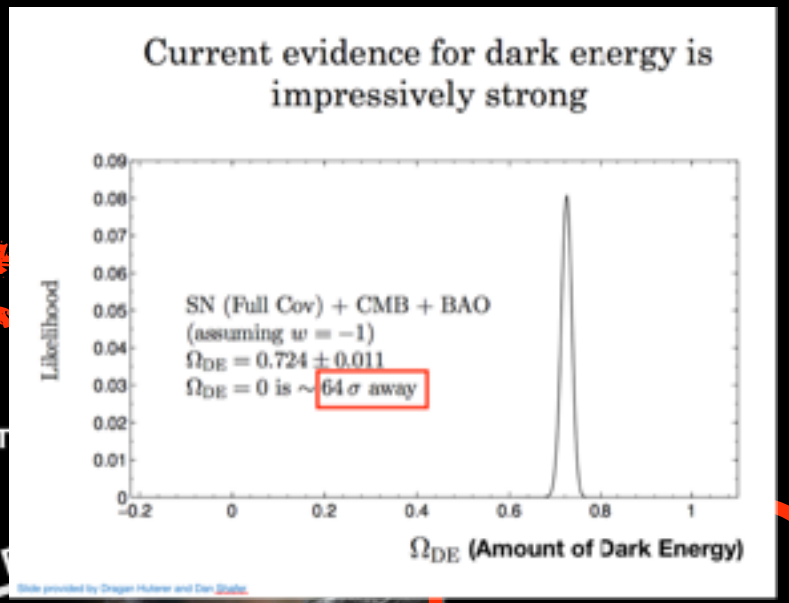
GALAXY EVOLUT

CONTINUES...

ARS

YEARS

AFTER BIG BANG



INFLATION

THE BIG BANG

THE DARK AGES

COSMIC MICROWAVE BACKGROUND

400,000 YEARS AFTER BIG BANG

FIRST GALAXIES

1000,000,000 YEARS AFTER BIG BANG

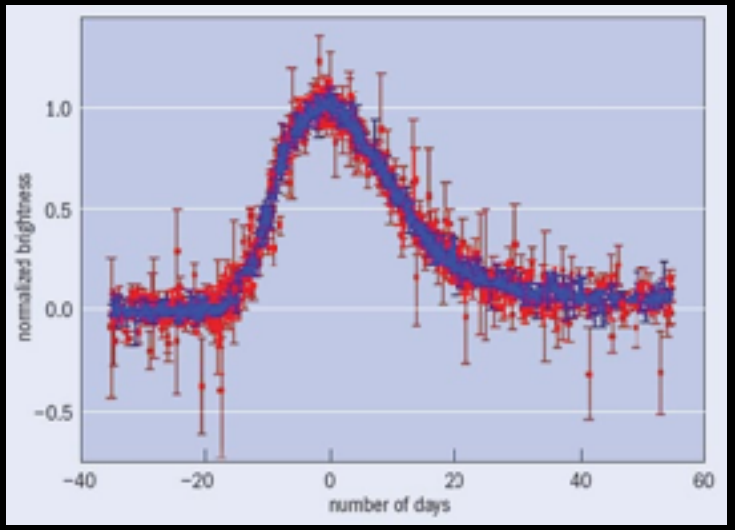
NOW

13,700,000,000 YEARS AFTER BIG BANG

The Universe is accelerating today!

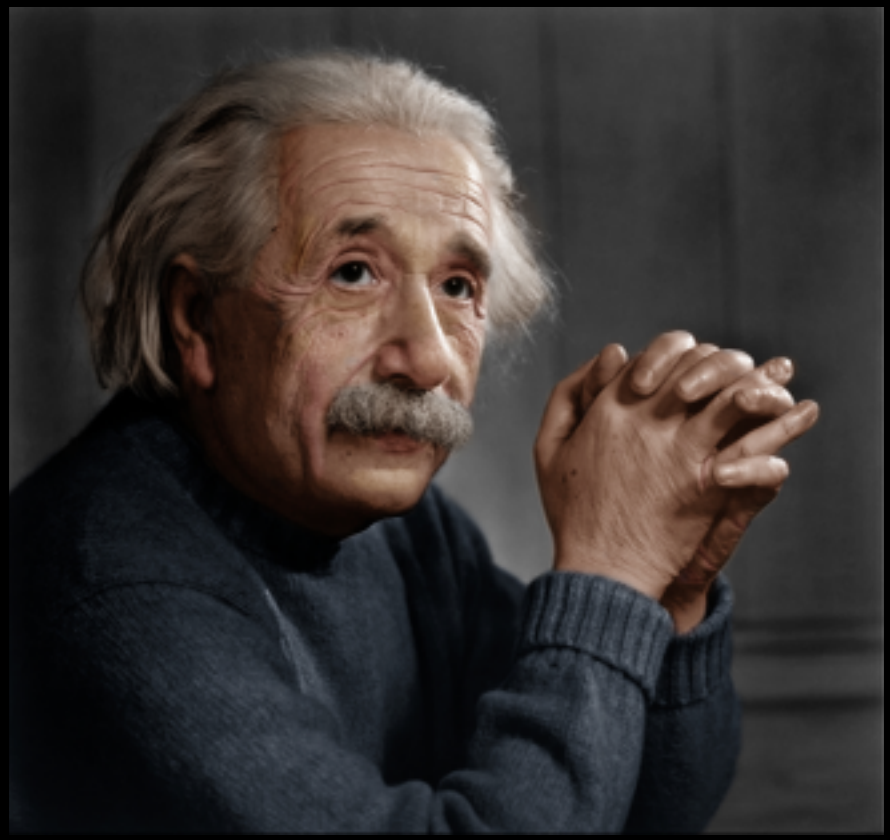
Today

The Universe is Accelerating today!
We call the stuff driving the acceleration, "Dark Energy"

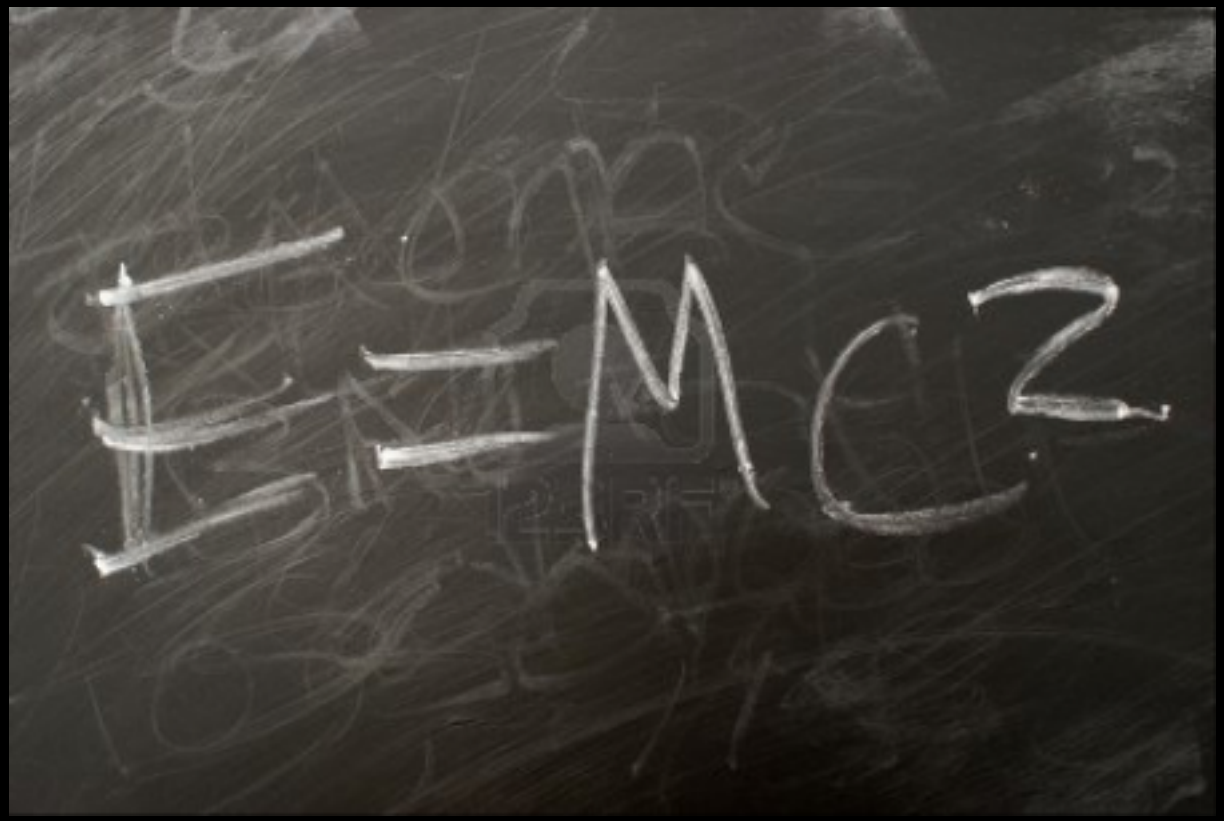


But again, this observation is indirect.

Einstein's legacy and Dark Energy



Einstein's Greatest Accomplishment



?

Einstein's Greatest Accomplishment

?

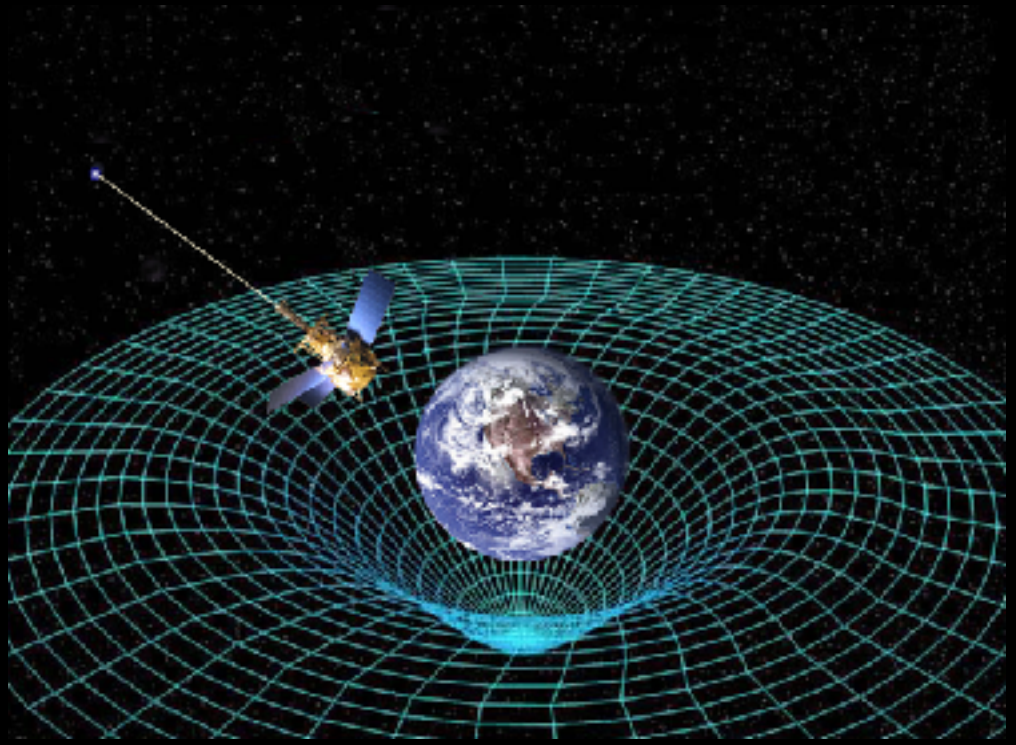
Einstein's Greatest Accomplishment

General Relativity

$$R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$

Einstein's Greatest Accomplishment

General Relativity



$$R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$

Curvature of Space (and time)

Energy and Matter
(planets, atoms, toothbrushes)

Einstein's Greatest Accomplishment

General Relativity

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Einstein's Greatest Accomplishment

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$$R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

Curvature of Space (and time)

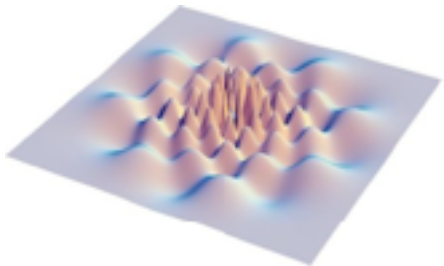
Energy and Matter
(planets, atoms, toothbrushes)

$$+\Lambda g_{\mu\nu}$$

This new term causes the universe to accelerate!

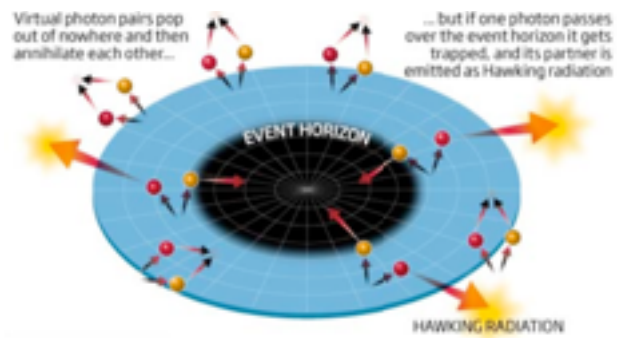
Is the Dark Energy a Cosmological Constant?

We expect space-time to contain quantum fluctuations



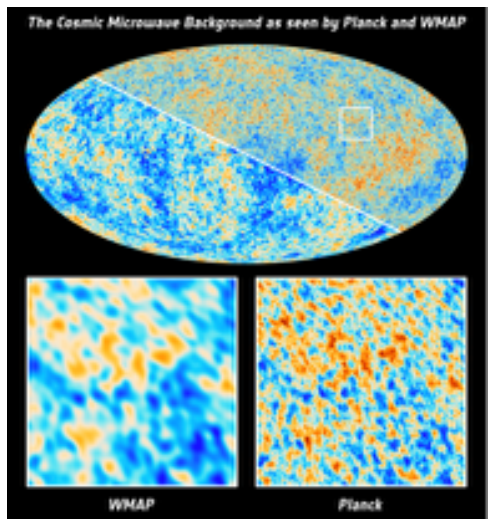
Stephen is still at work!

Hawking radiation from Black Holes



Our "Lab"

Inflationary Fluctuations

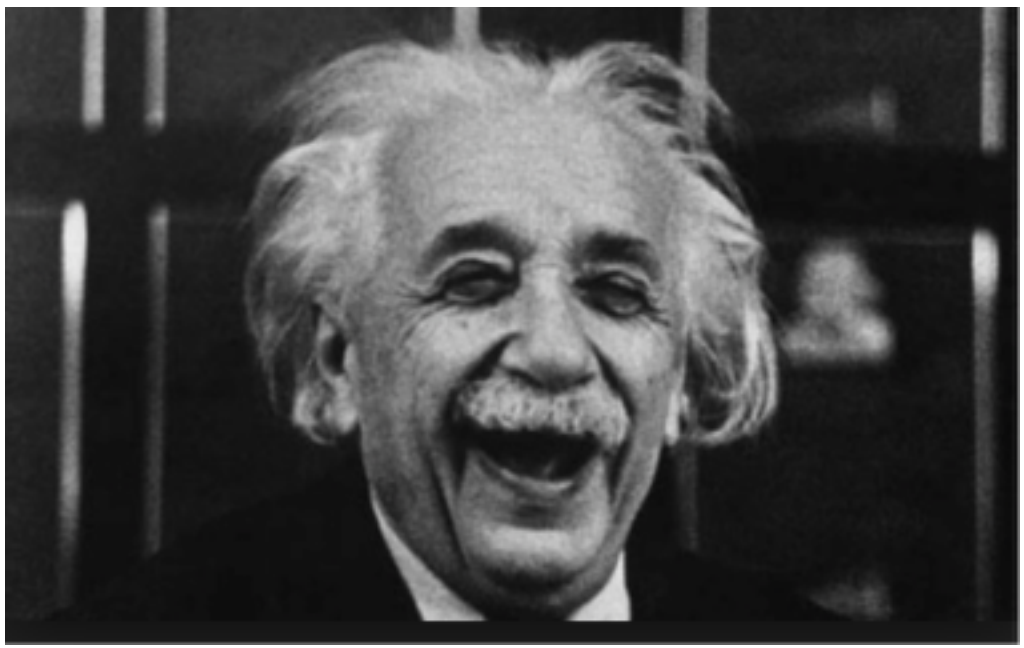


Could vacuum fluctuations be causing the acceleration?

The Cosmological Constant Problem

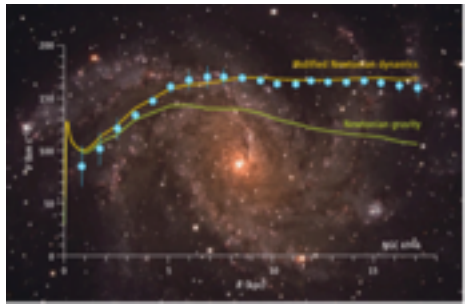
$$\left(\frac{\Lambda_{\rm observed}}{m_p}\right)^4 \simeq 10^{-120}$$

Could vacuum fluctuations be causing the acceleration?

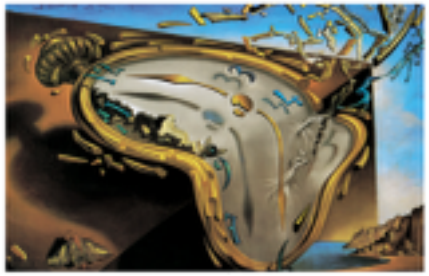


If Dark Energy is not a Cosmological Constant then what is it?

If Dark Energy is not a Cosmological Constant then what is it?



Modified Gravity?



Time varying constants?

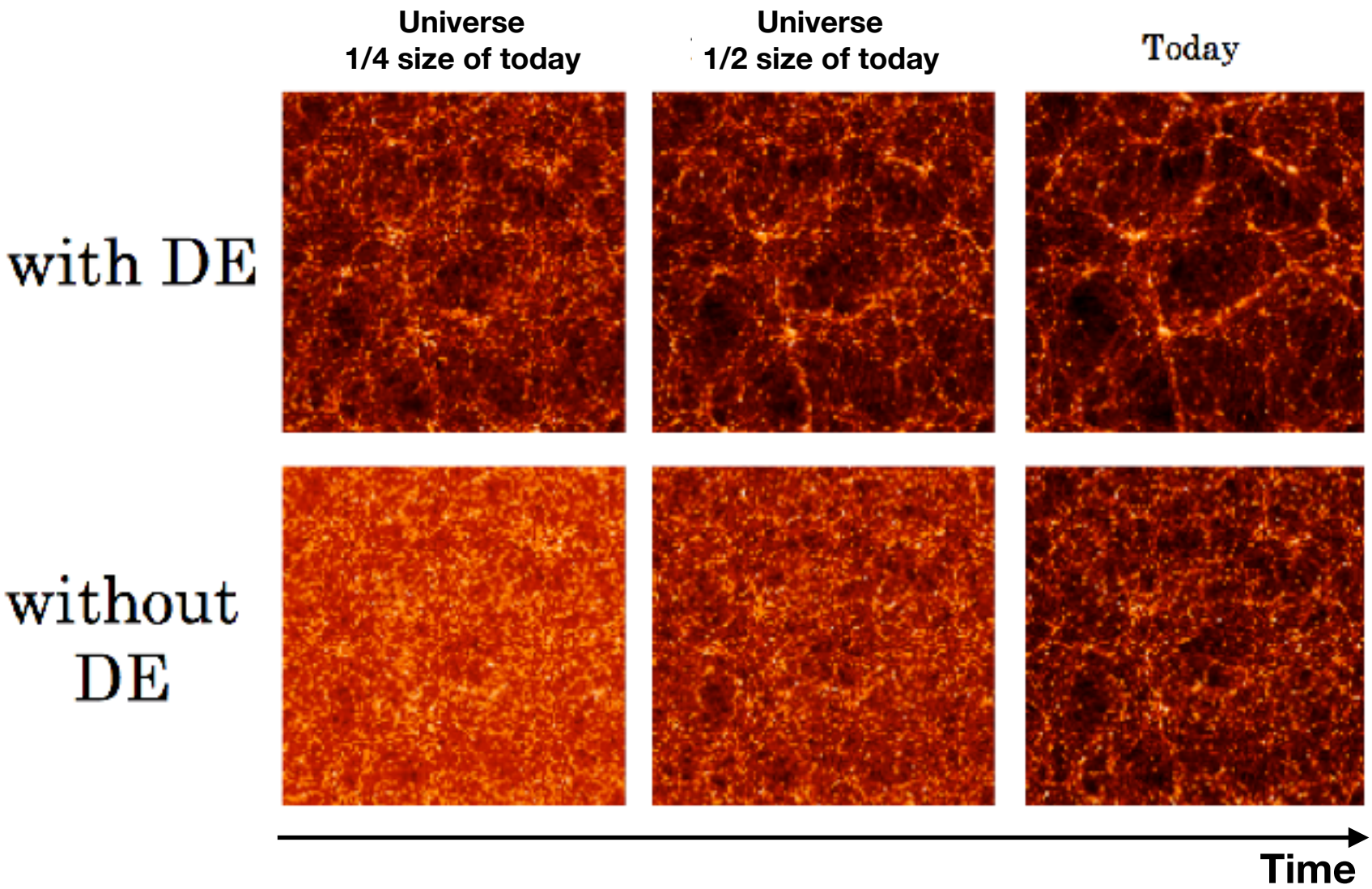
New forms of matter or energy?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_{\rm N}\, T_{\mu\nu}$$

Space-time evolution **Matter and Energy**

Λ ?

Dark Energy suppresses the growth of density fluctuations



Huterer et al, Snowmass report, 1309.5385

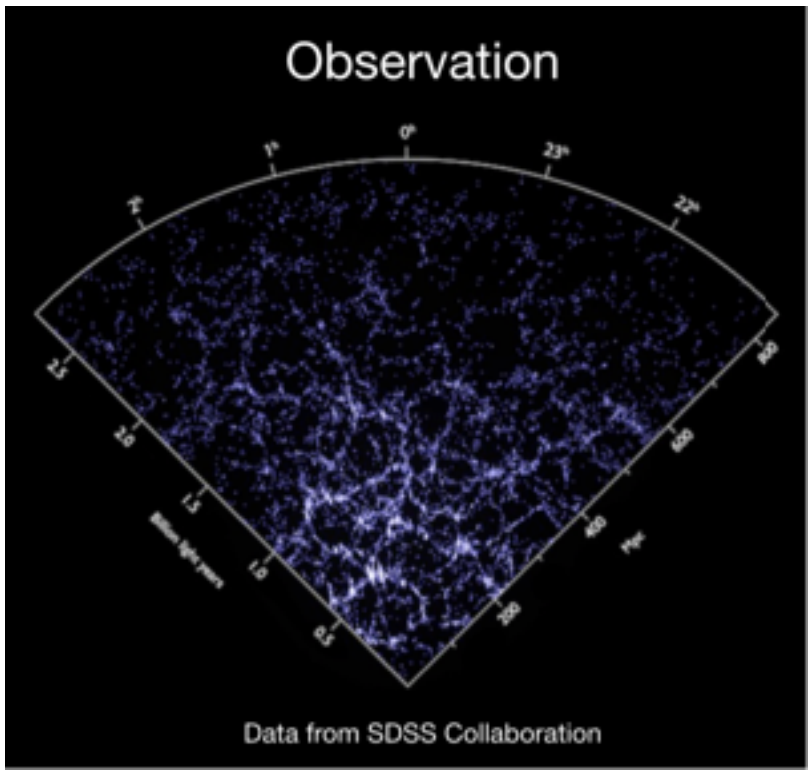
The Virgo Consortium (1996)

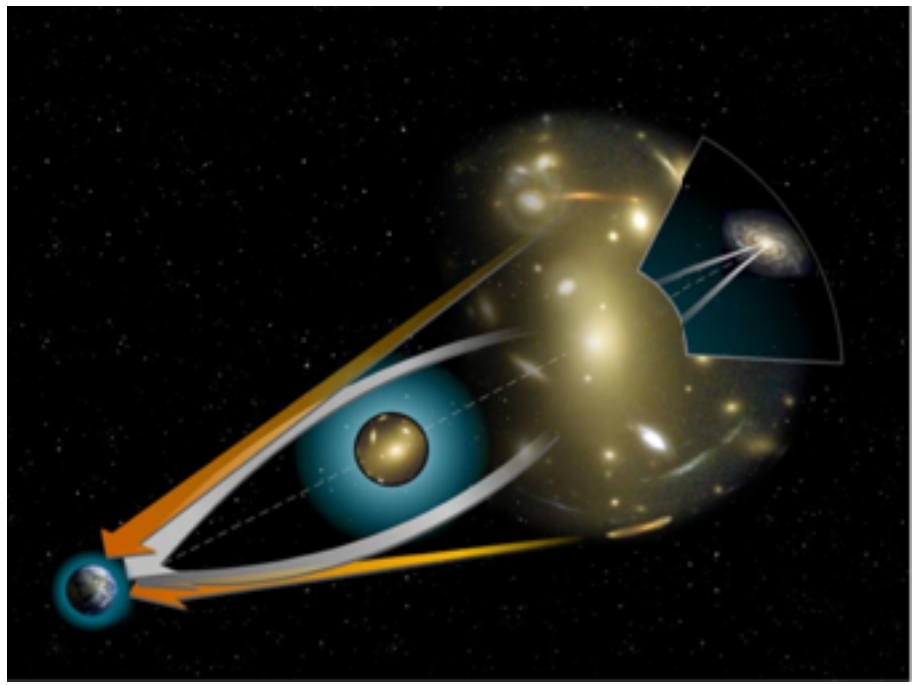
Constraints on the EFT of Cosmic Acceleration

$$ds^2 = -\left(1+2\Phi\right)dt^2 + a^2\left(1-2\Psi\right)d\vec{x}^2$$

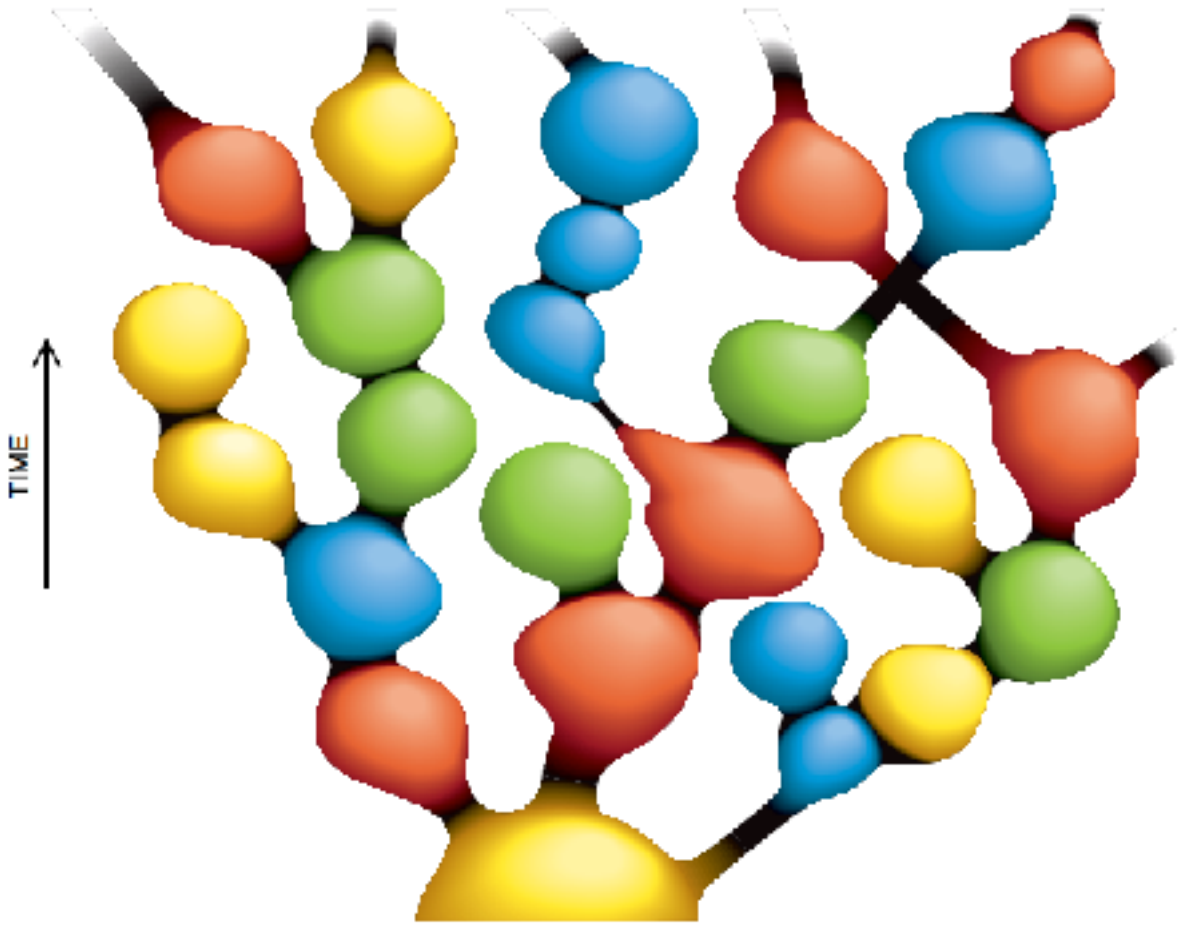
Φ Growth of Structure

$\Phi + \Psi$ Gravitational Lensing





Welcome to the Metaverse

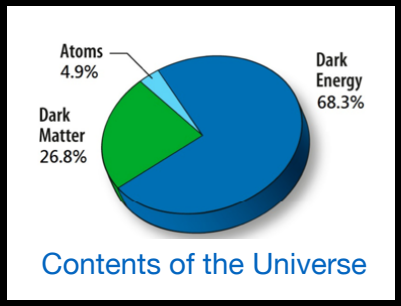


Is our universe the only one?


String Landscape?
visualparadox.com

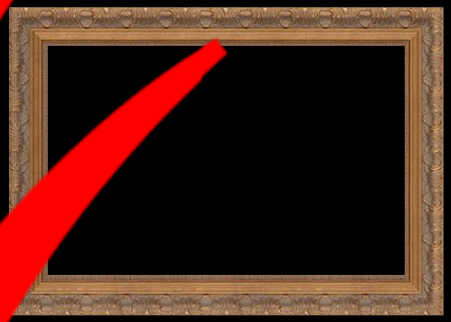
Questions we will address today:

- How do we know the composition of the universe?



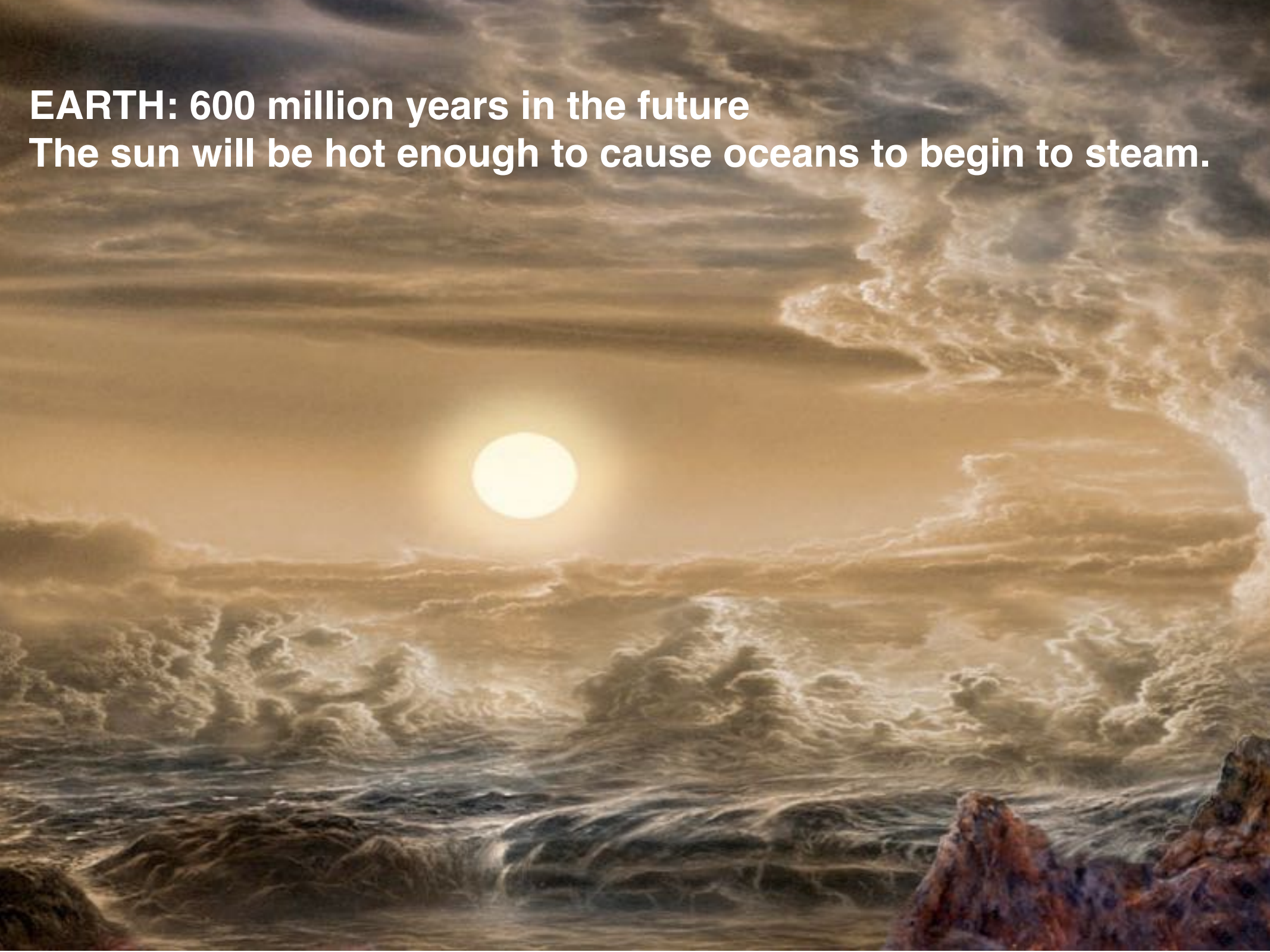
Contents of the Universe

- What is Dark Matter?



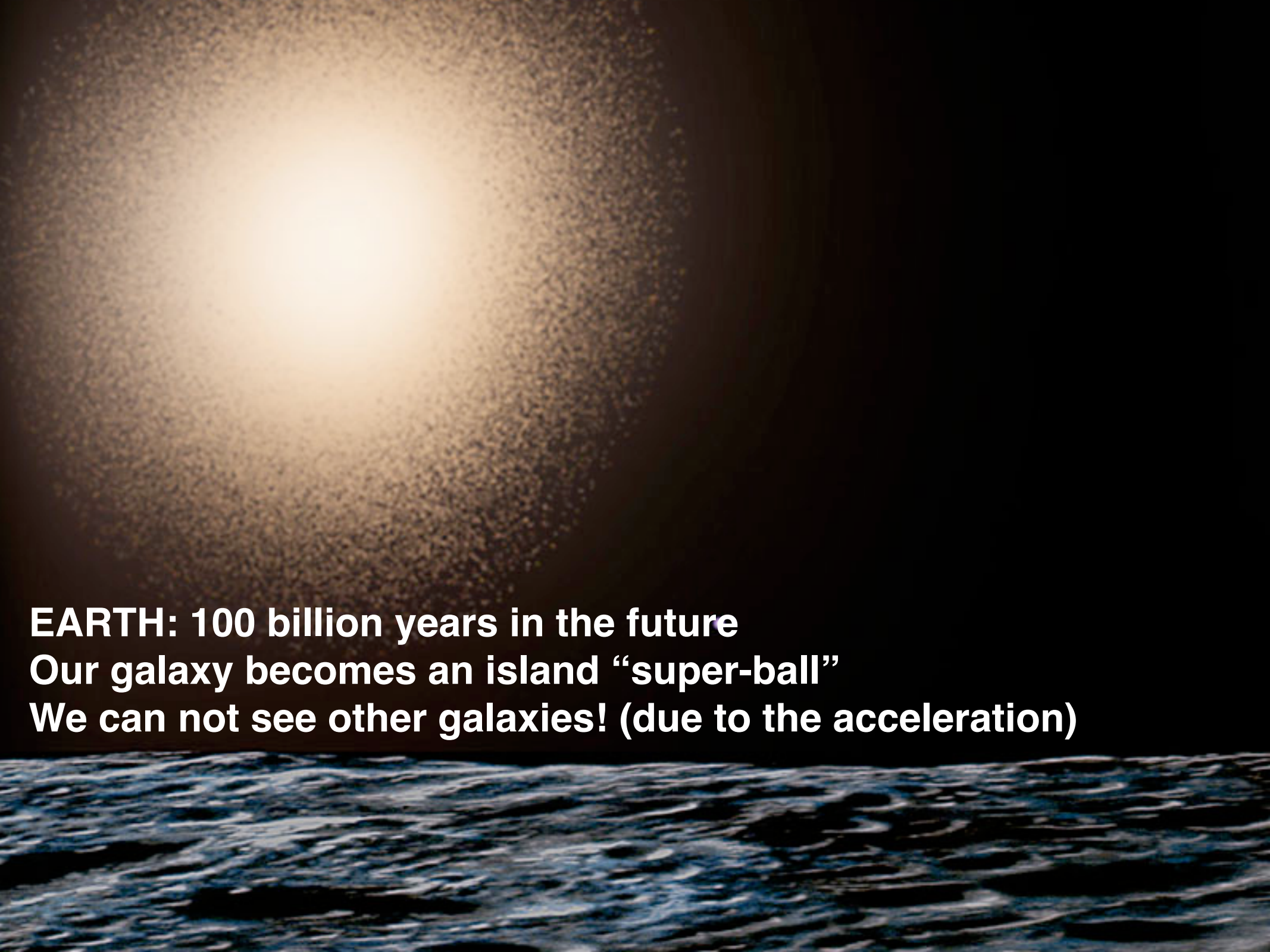
- What is Dark Energy?

- What is our final destiny?


EARTH: 600 million years in the future
The sun will be hot enough to cause oceans to begin to steam.

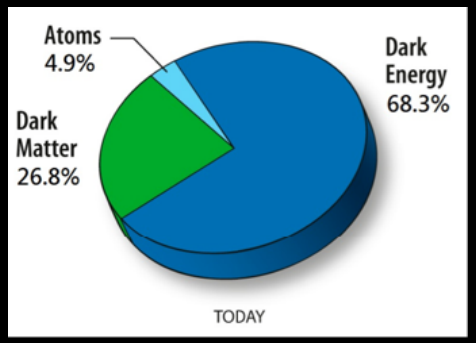
EARTH: 4.5 billion years in the future
Oceans are gone, sun is beginning to swell...

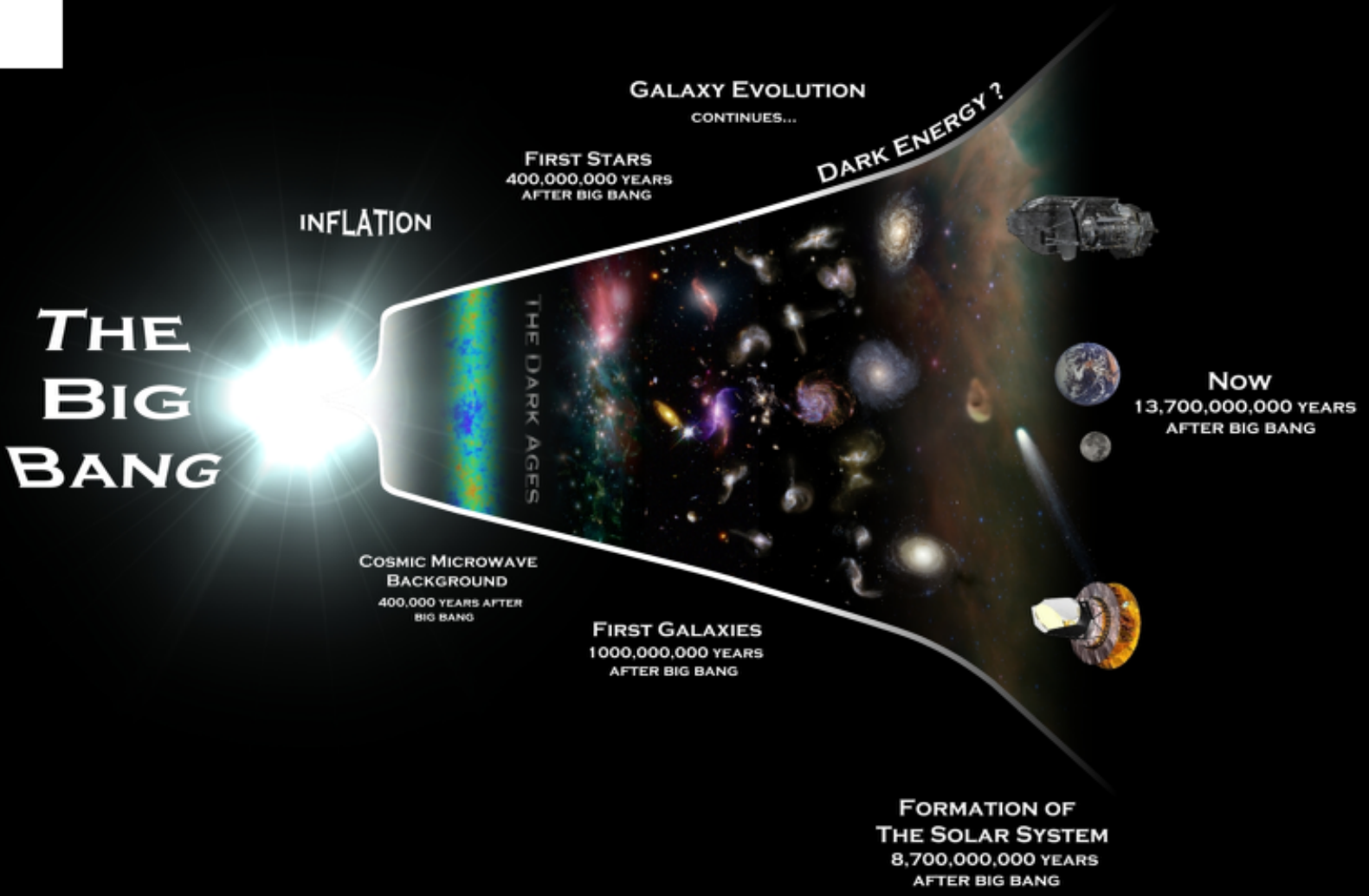

EARTH: 5 billion years in the future
Andromeda galaxy will collide with ours at 20 billion yrs.


EARTH: 100 billion years in the future
Our galaxy becomes an island “super-ball”
We can not see other galaxies! (due to the acceleration)

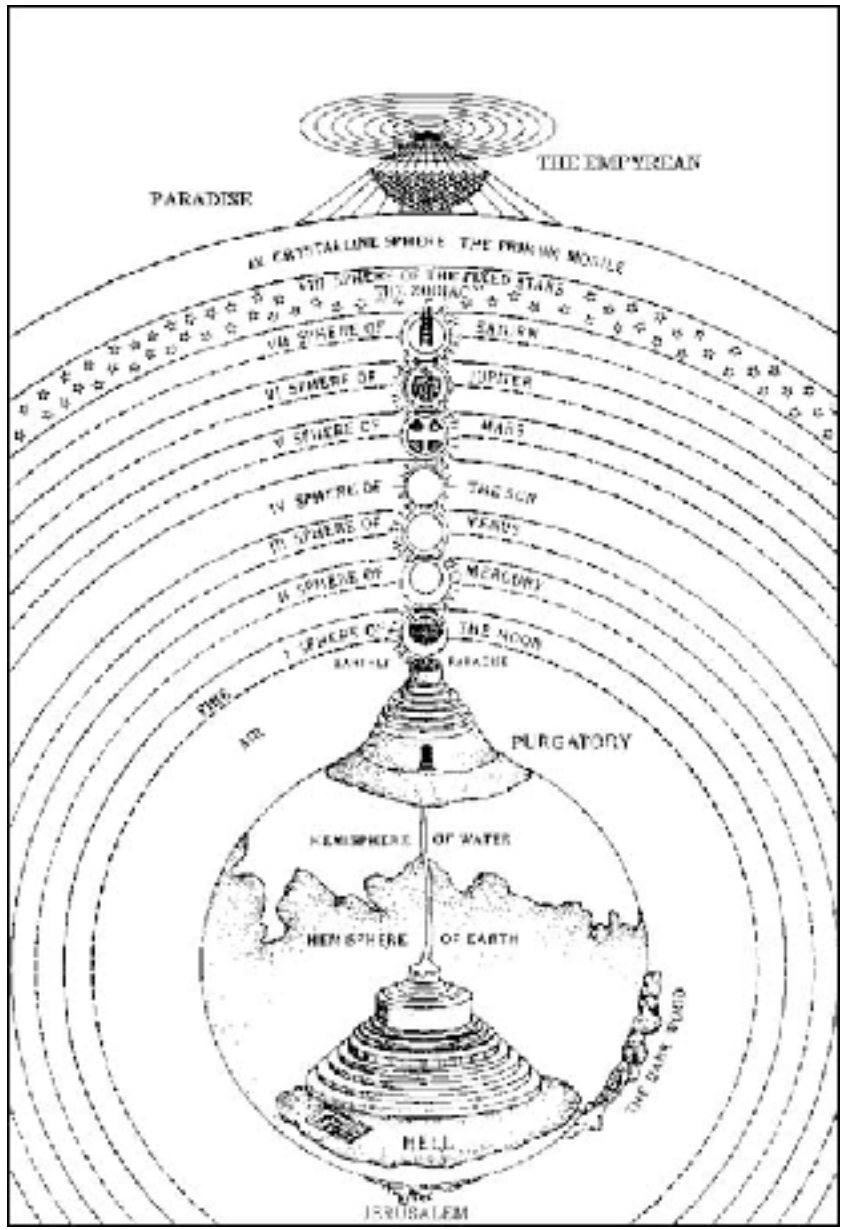

EARTH: 100 trillion years in the future
Stars have burned out, all proofs of our cosmic history are lost!
The universe goes out with a whimper...

The future depends on the fate of Dark Energy!



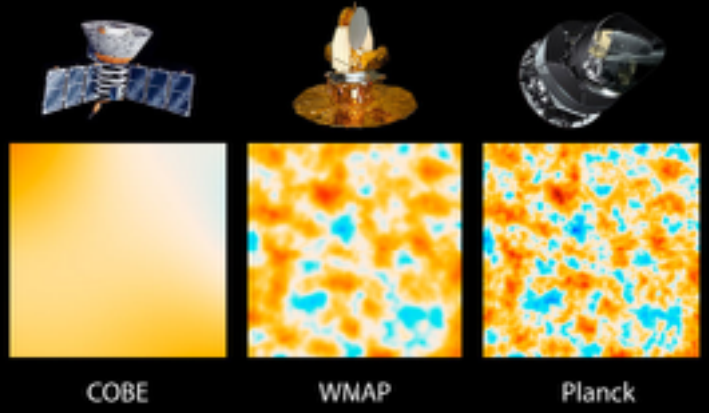


Cosmology has come a long way…

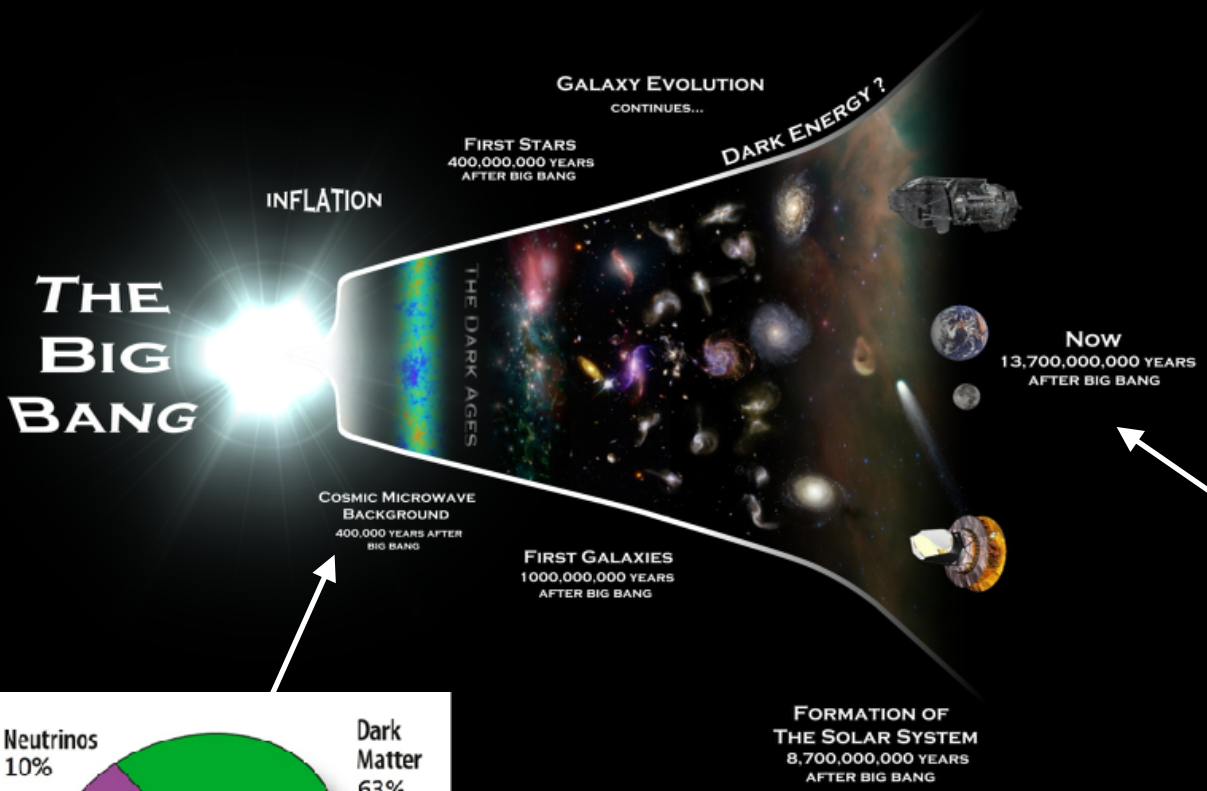


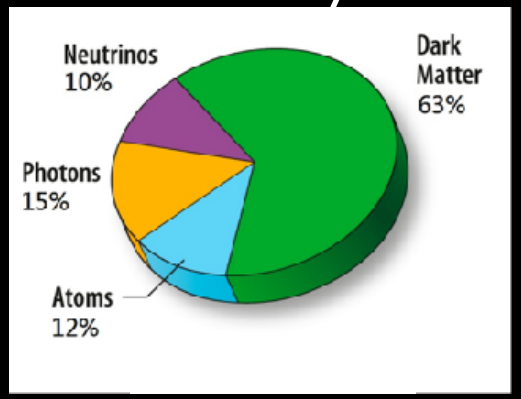
It has developed into a precision science!

The Big Bang Theory confirmed



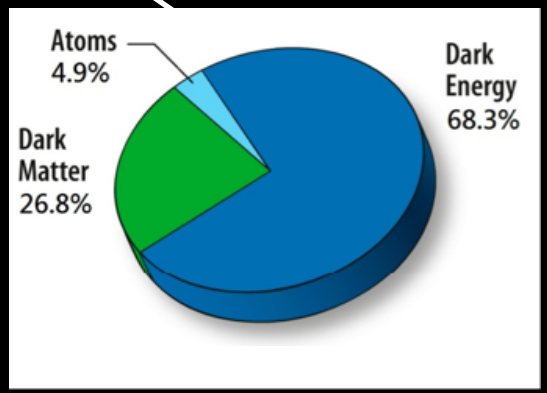
Precision experiments





Mostly Dark Matter then
(13.7 Billion years ago)

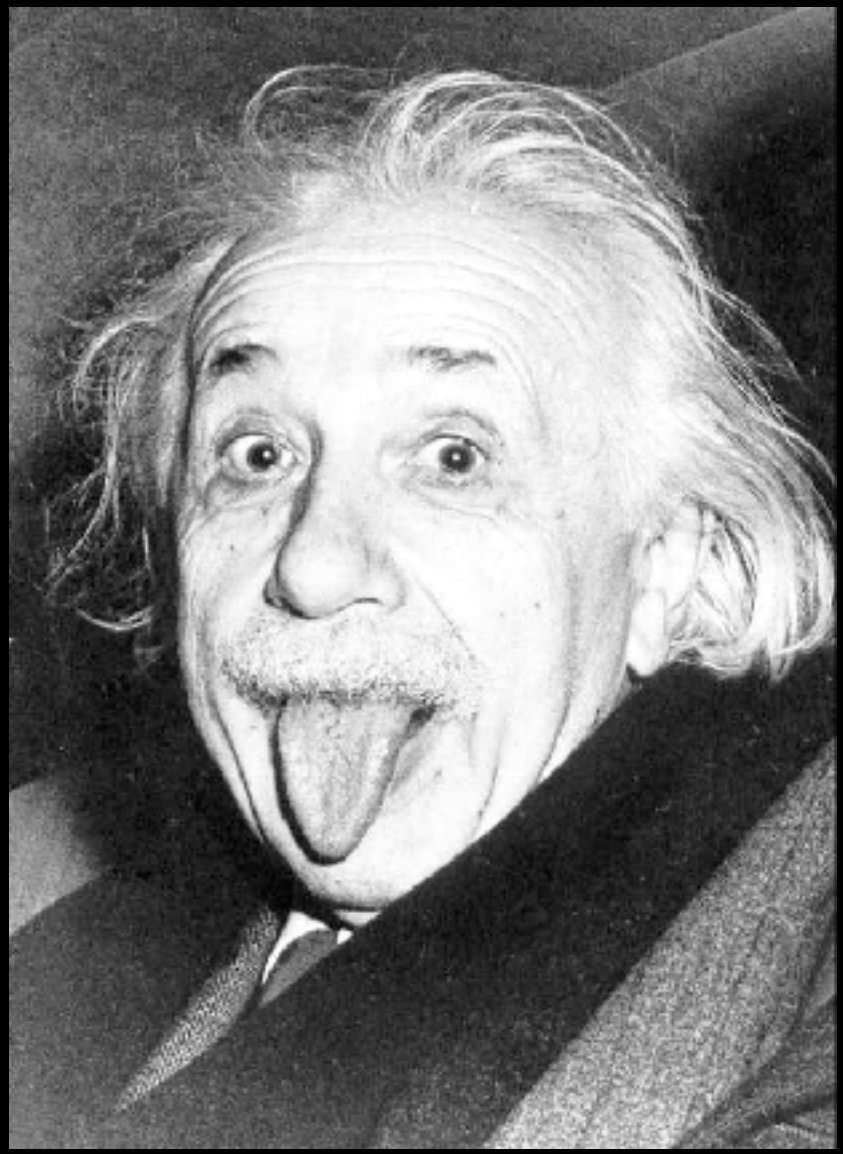
Ingredients known



Mostly Dark Energy now
(13.7 Billion years later)

What is our place in the Universe?

Scene from “Men in Black”



Thank you for listening.