

**Marco Drewes, Université catholique de Louvain**

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# INTRODUCTION TO COSMOLOGY

**11. 09. - 13. 09. 2019**

**BND Summer School**

**Spa, Belgium**

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# Lecture I

## Historical Overview and Basics of GR



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# Where Does the World Come From?

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# Where Does the World Come From?

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*And the lord stood upon Tiamat's hinder parts,  
And with his merciless club he smashed her skull.  
He cut through the channels of her blood,  
And he made the North wind bear it away into  
secret places.*

*[...]*

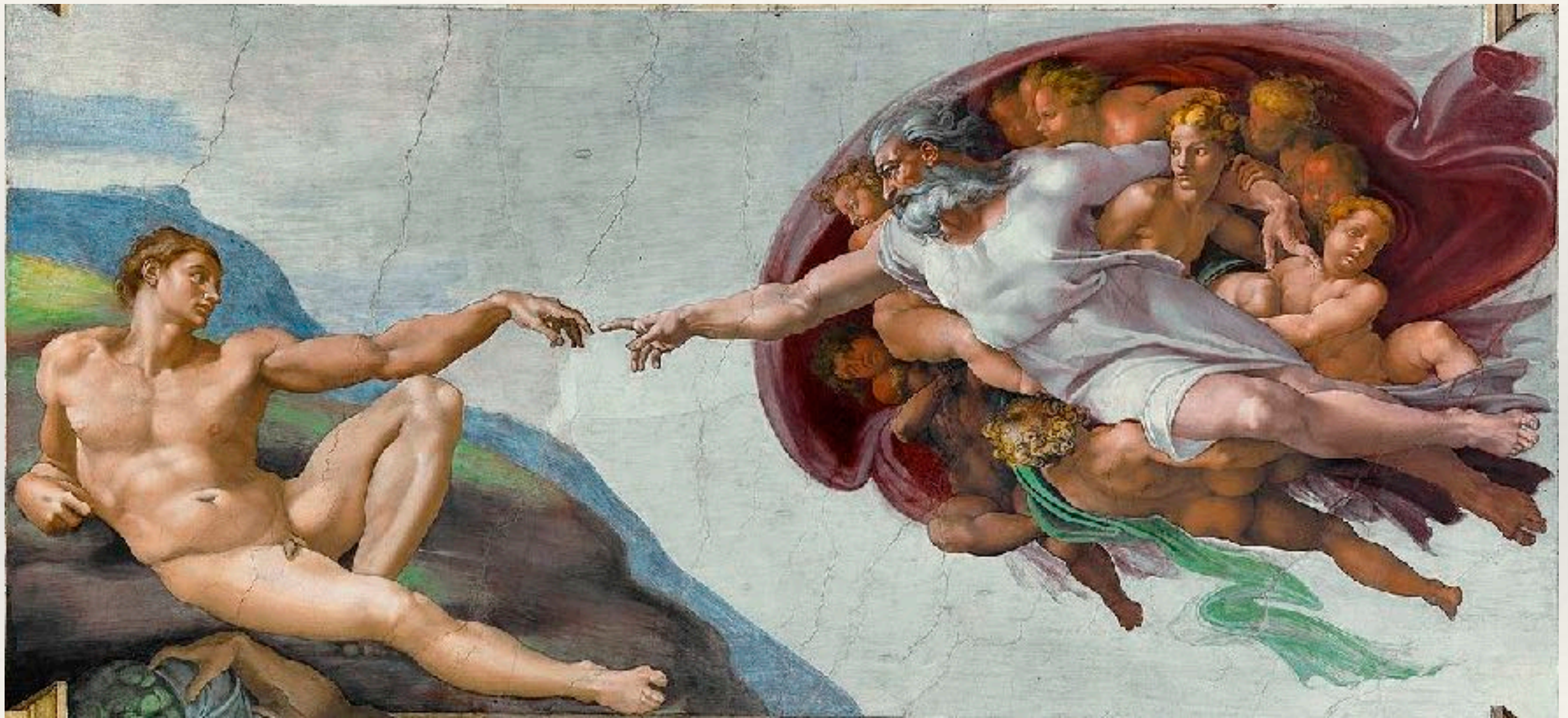
*Slicing Tiamat in half, he made from her ribs the  
vault of heaven and earth.  
Her weeping eyes became the source of the Tigris  
and the Euphrates,  
her tail became the Milky Way.*



Babylonian Enûma Eliš



# Where Does the World Come From?

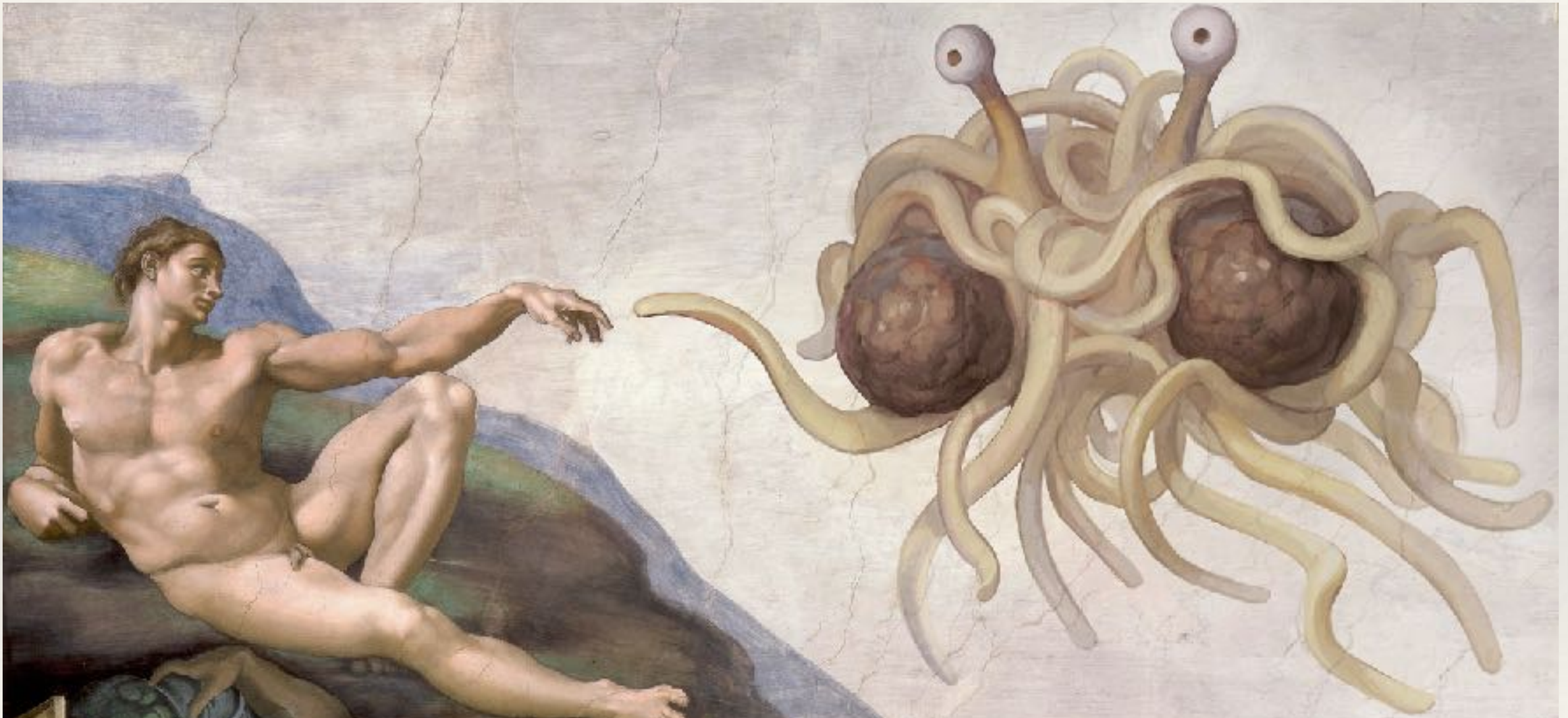




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# Where Does the World Come From?

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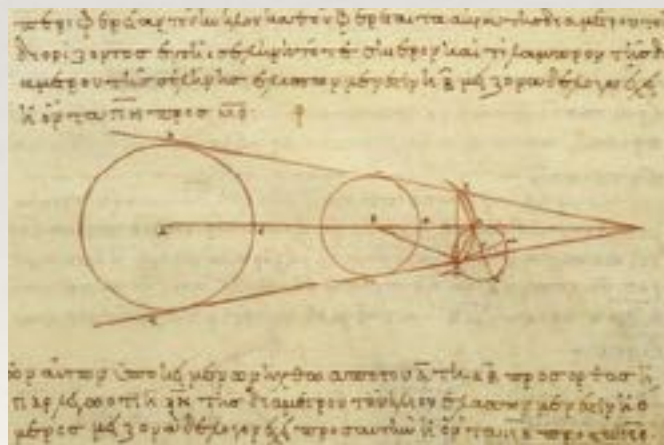
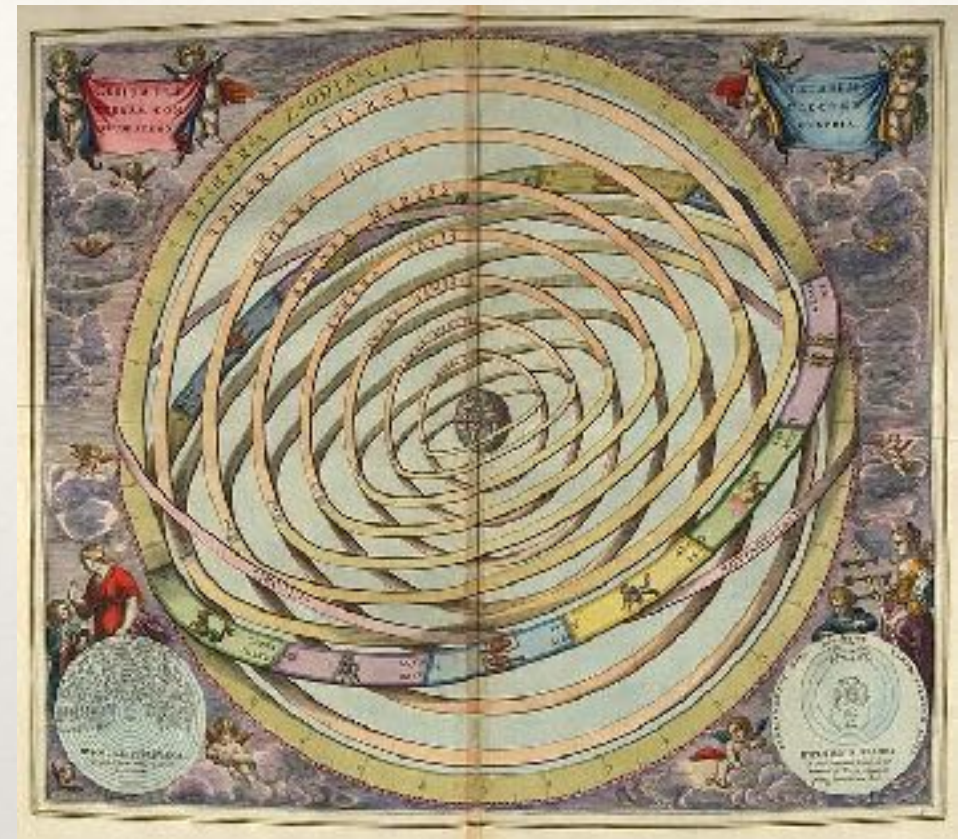


# Early Quantitative Models

**Aristotle** (384 - 322 BC) argued that Earth and Moon are spheres, based on lunar eclipses

**Eratosthenes** (276-194 BC) computed the radius of the Earth to be 6800 km

...but both assumed geocentric universes



**Aristarchus** (310 - 230 BC) correctly computed the ratios between the size and distance of the Moon and Sun...

...and computed the distance to the Sun (wrong by a factor 20), concluding that **the Universe is much bigger than Earth, and the Sun is the centre**

# Mapping the Solar System

In the renaissance age, many astronomers explored the dimensions of the solar system, including **Galileo**, **Copernicus**, **Brahe**, **Kepler**...

...but a quantitative understanding of the laws that govern it had to wait until **Newton's** *Philosophiae Naturalis Principia Mathematica* (1687), which paved the way for

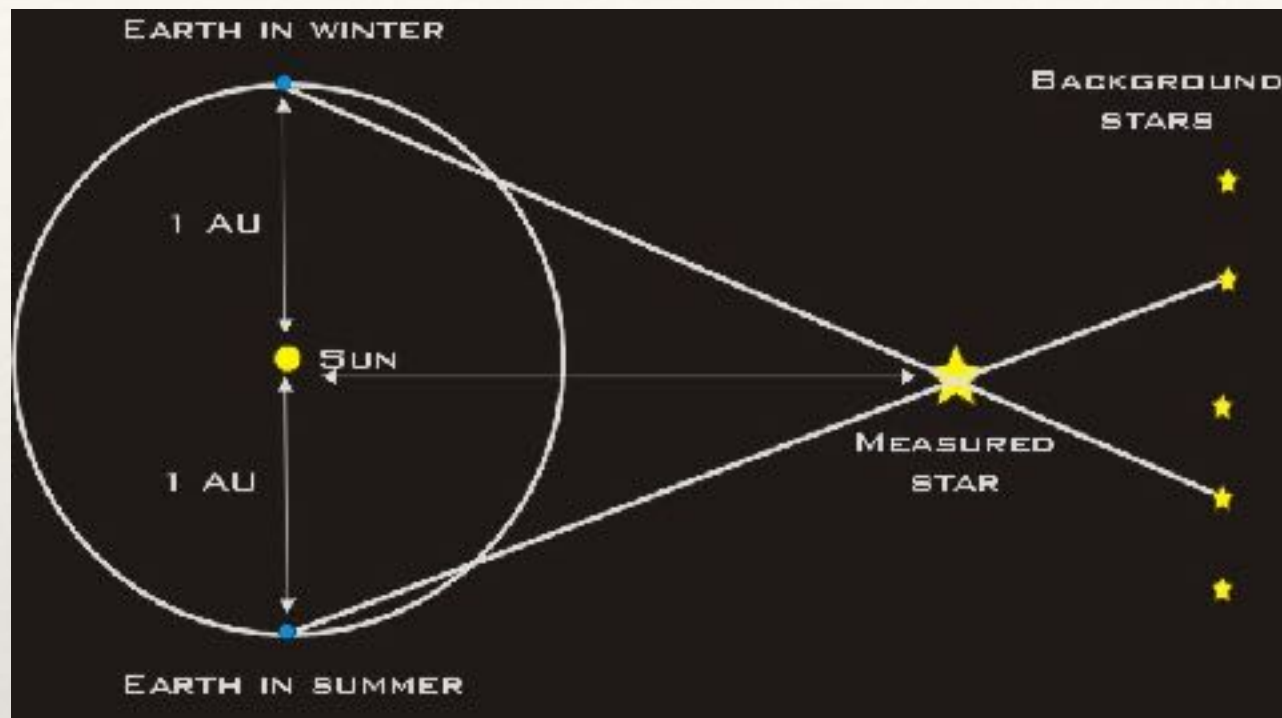
**connecting cosmology to fundamental physics!**



Around the same time **Rømer** (1644-1710) and **Huygens** (1629-1695) first measured the speed of light, using modulations in the period of Jupiter's moons orbit



# To the Stars!



In 1838 **Bessel** first measured the distance to other stars, using the parallax method...

...making the “universe”  
almost a million times larger!

Fun fact: Greek scholars rejected Aristarchus heliocentric model over 2000yrs before because they did not see parallaxes.

# To the Stars!

In the early 20th century **Hertzsprung** and **Russel** discovered a relation between colour and luminosity of stars, while **Leavitt** discovered a relation between the period and brightness of variable cepheid stars in 1912.

**The cosmic distance ladder was born!**

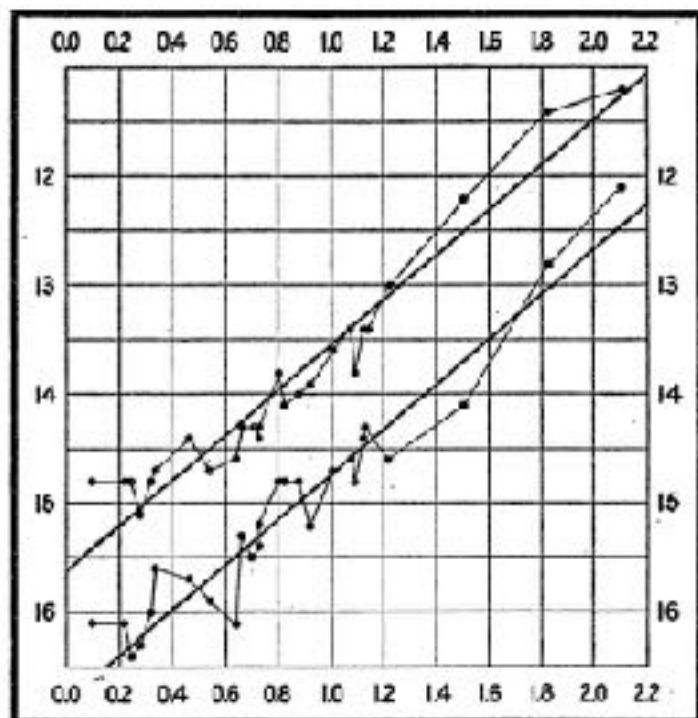
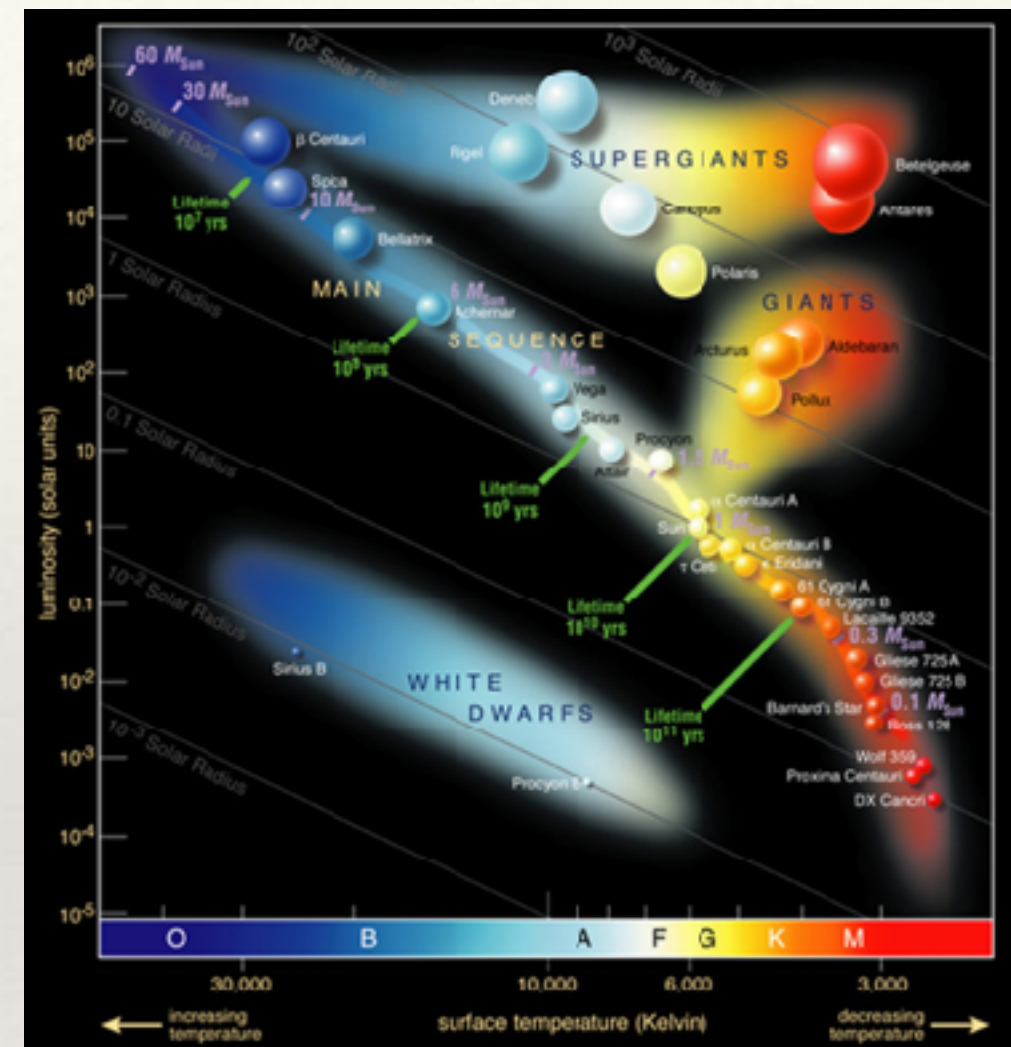


FIG. 2.

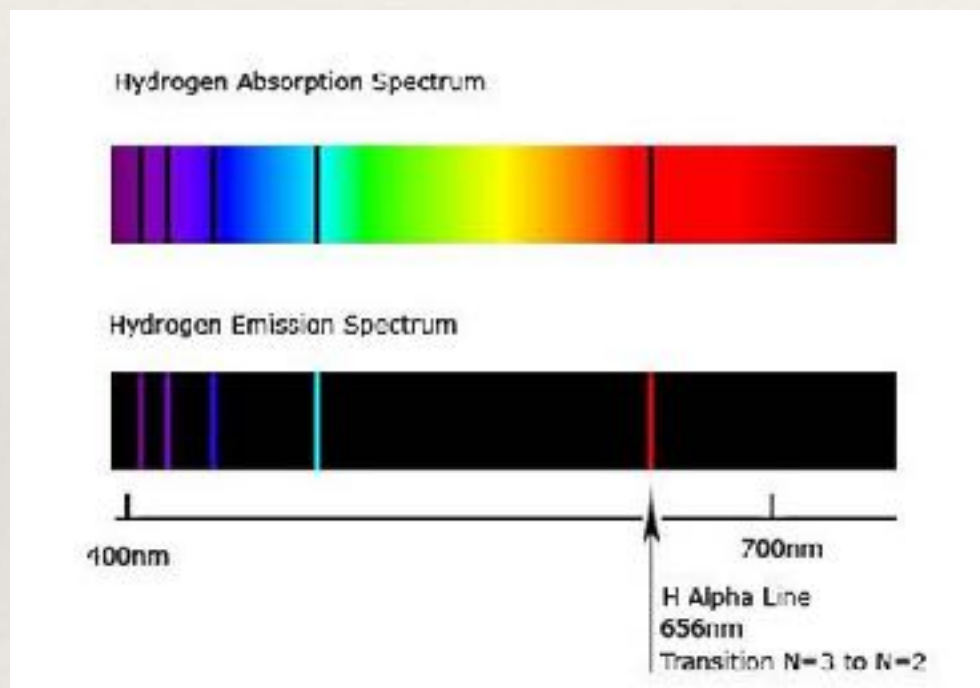


This allows to estimate the distance of far away stars, using distance measurements of nearby ones



# The Golden Age of Physics

In 1915 **Einstein** and **Hilbert** developed General Relativity, the mathematical framework to describe the Universe on large scales



The detailed mapping of **atomic spectra** and their understanding in **quantum mechanics** proved that

**other stars are made of the same atoms that we find on Earth**

and

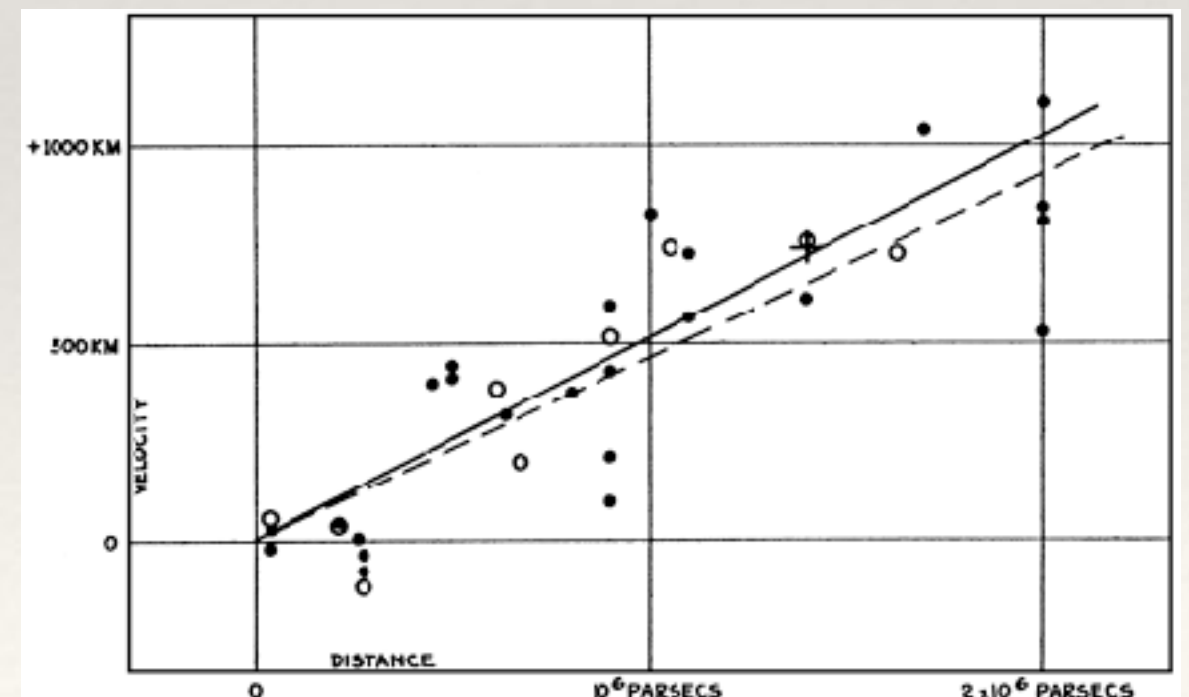
**allows to measure their velocity via the Doppler effect**

# The Big Bang

Between 1922 and 1924 **Friedmann** developed the first cosmological models in General Relativity based on the **cosmological principle**, concluding that the universe expands. **Lemaitre** derived this independently and proposed the “primeval atom”, marking the **birth of the Big Bang theory!**

In 1924 **Hubble** discovered that many “nebulae” are in fact distant galaxies... **making the universe millions of times bigger!**

In 1929 he found that the galaxies move away from us with a “velocity” that is proportional to their distance (“**Hubble-Lemaitre law**”)...  
...meaning that we are either the centre of the world of Friedmann and Lemaitre were right!

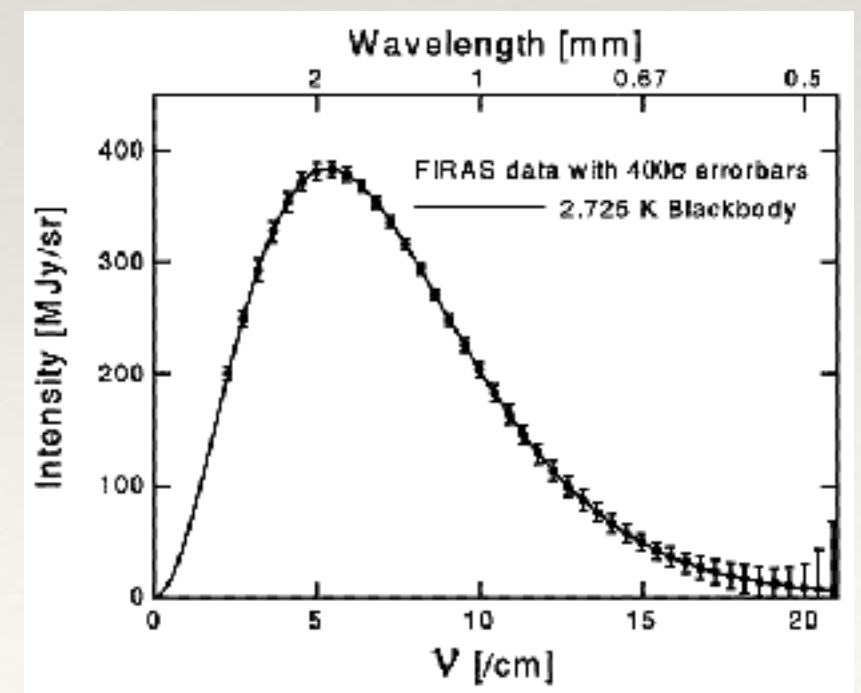
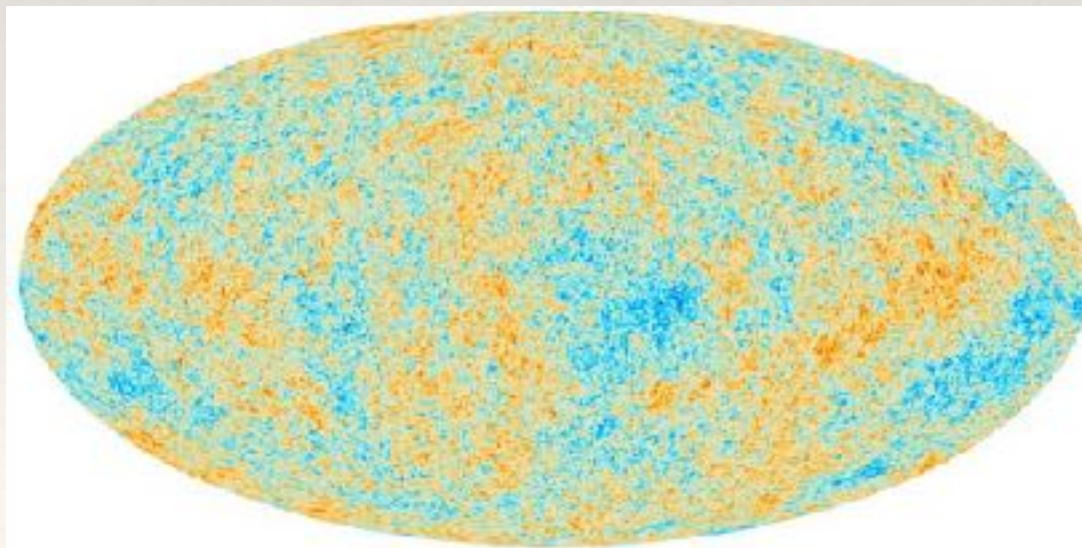




# The Primordial Plasma

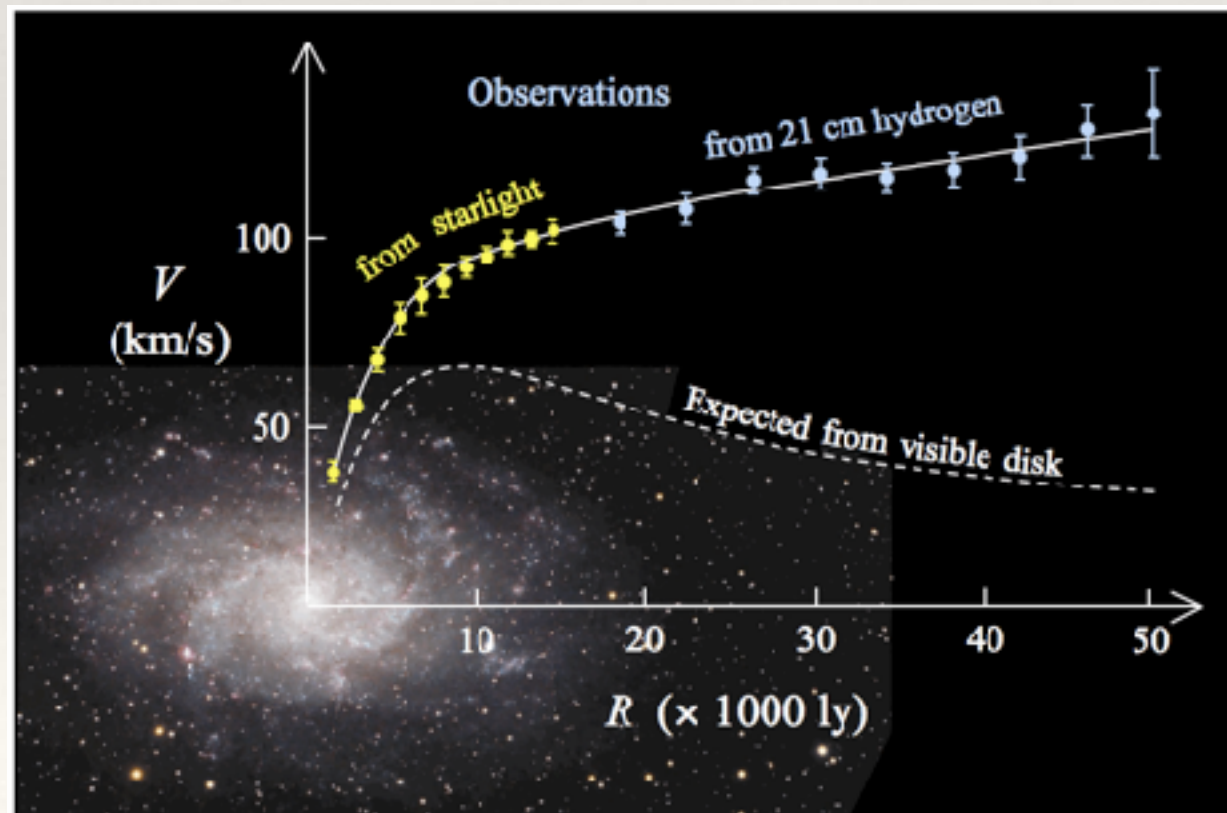
In the 1940s **Gamov, Alpher, Herman, Bethe** and others explored the implication of the high pressure, density and temperature in the infant universe predicted by Friedmann and Lemaitre., concluding that

- The temperature was so high that thermonuclear reactions would occur, giving rise to **Big Bang Nucleosynthesis**
- Redshifted photons from the hot plasma should still be present as a **Cosmic Background Radiation**



# Dark Matter

In 1933 **Zwicky** found that the Coma galaxy cluster cannot be bound together by the gravity of its visible constituents, suggesting that there is extra **Dark Matter**, but was largely ignored....

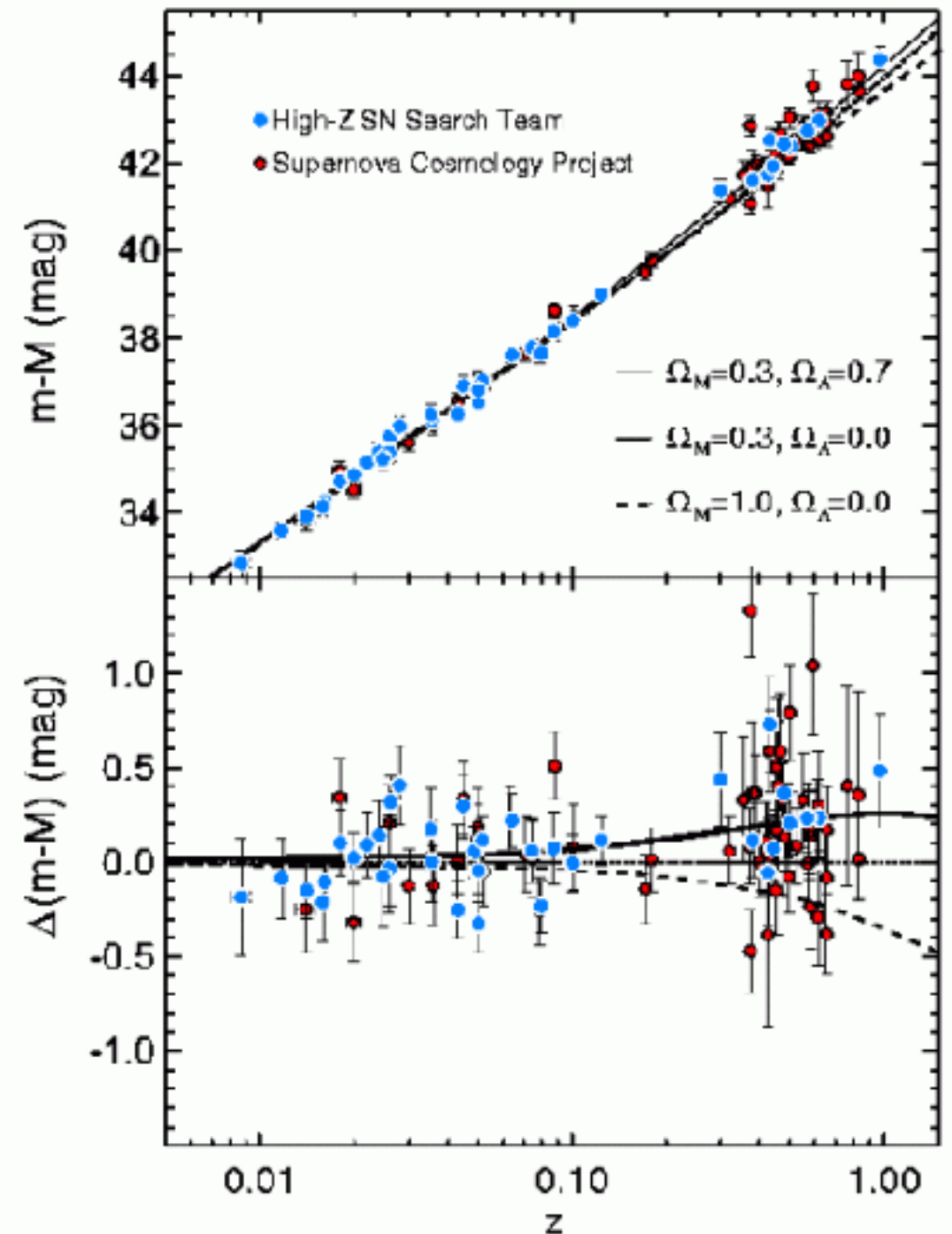


...until **Rubin** provided convincing evidence based on galaxy rotation curves and proved that Dark Matter makes up most of the mass in the universe

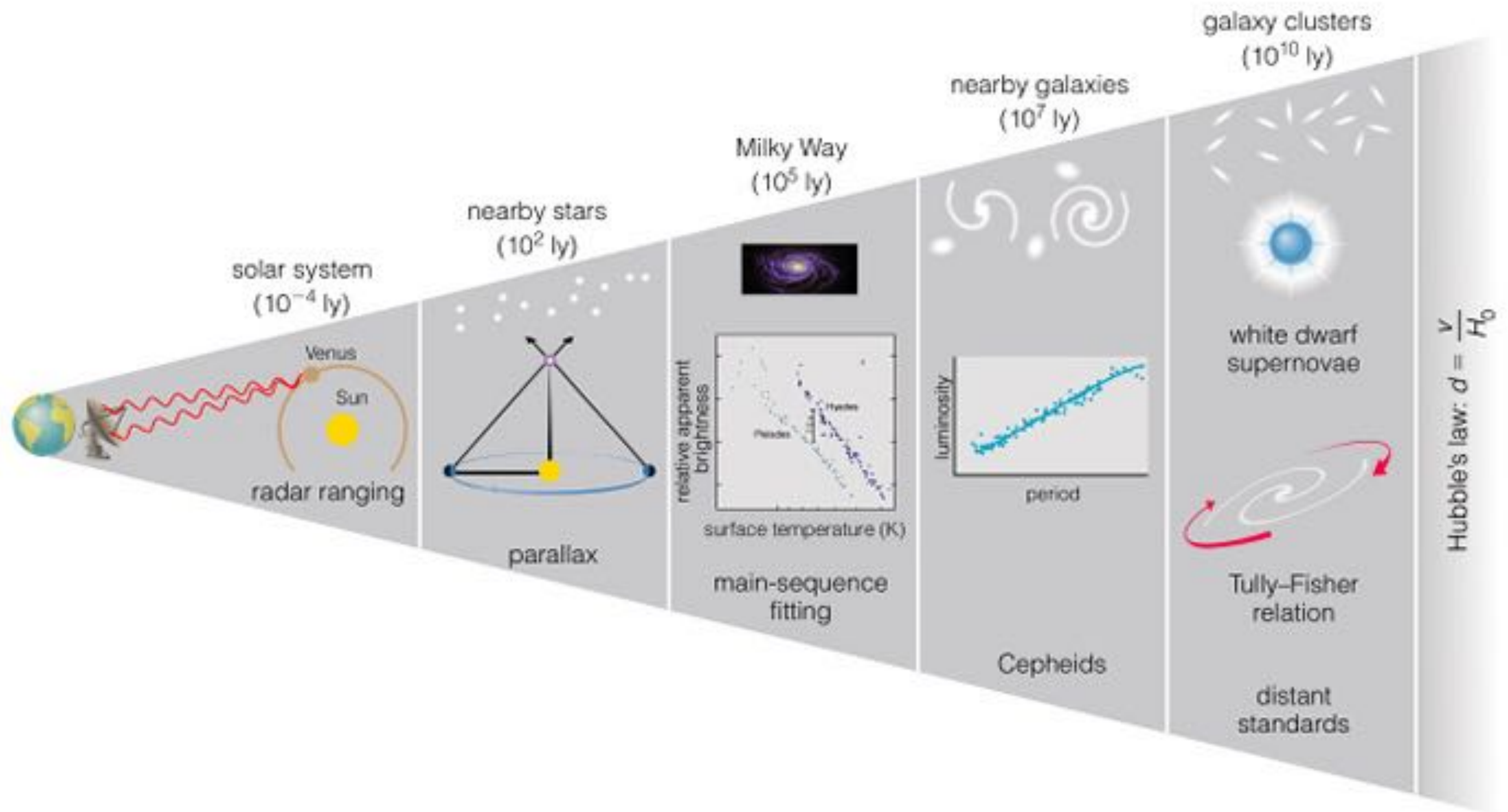


# Dark Energy

In 1998 and 1999 two teams of astronomers independently found deviations from Hubble's law in the “wrong direction”, indicating that the **universe is accelerating!**

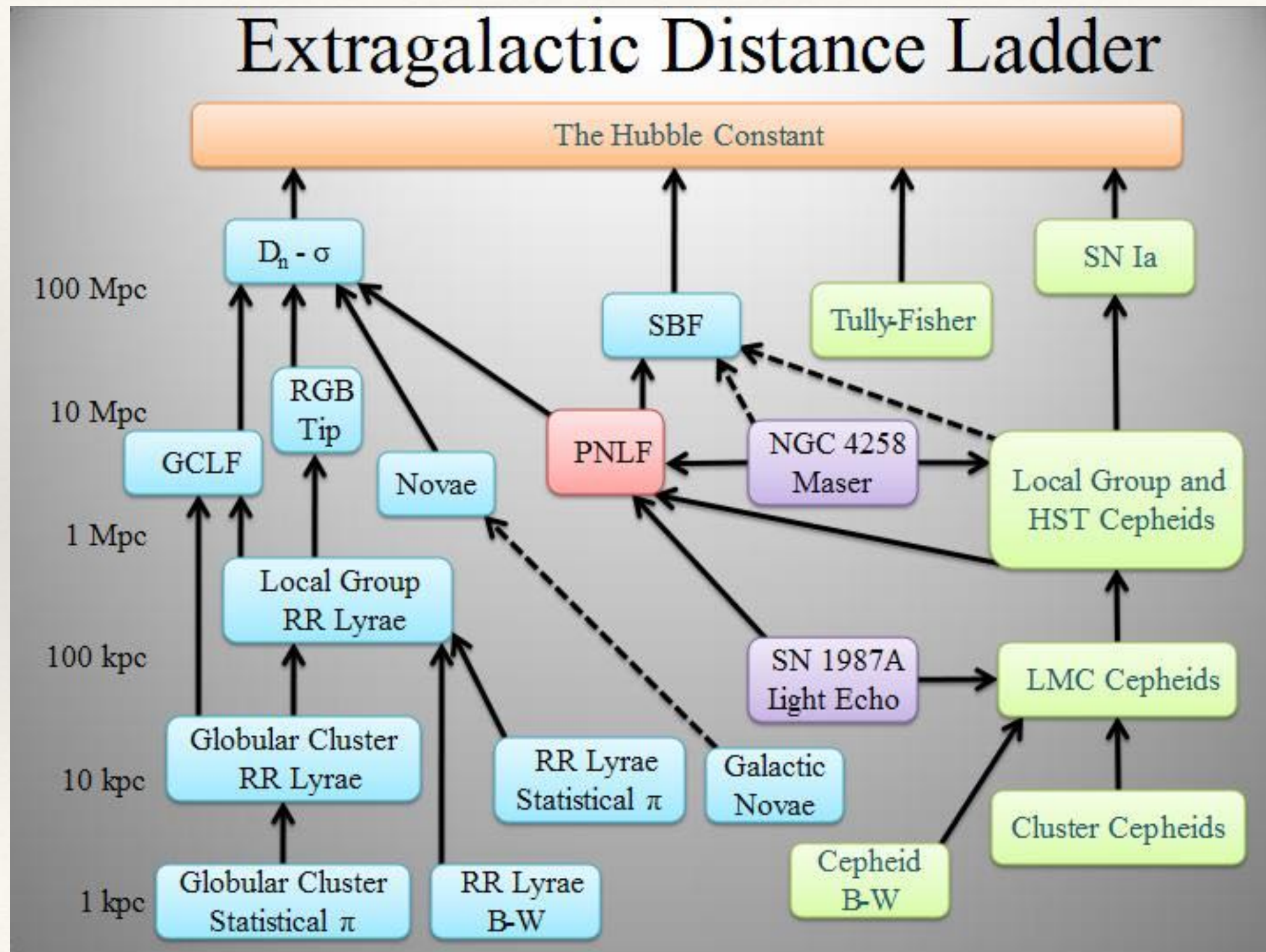


# Cosmic Distance Ladder





# Actual Cosmic Distance Ladder



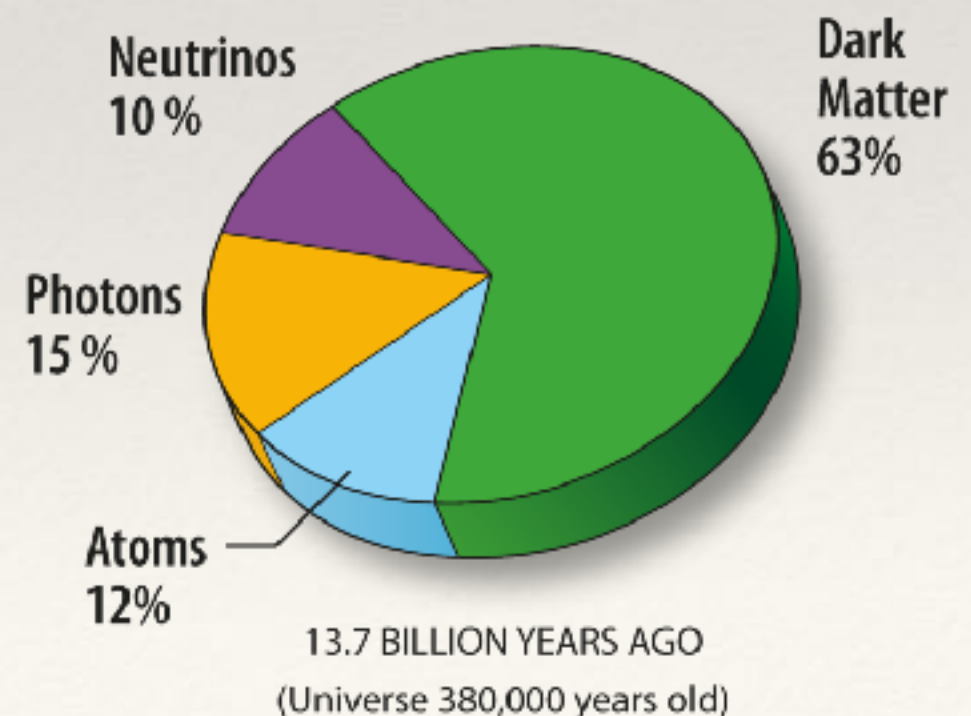
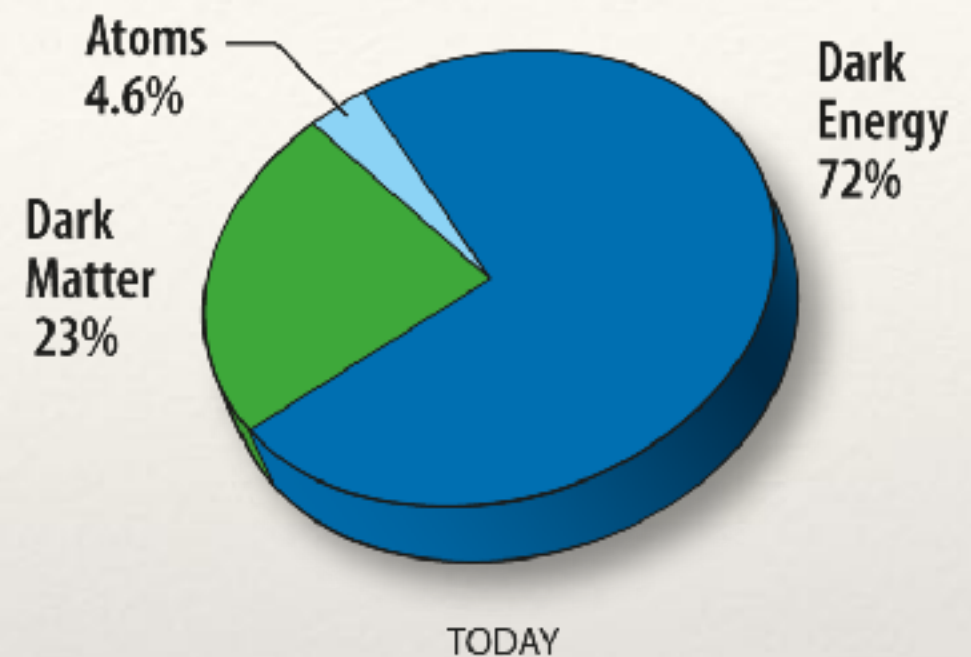
# Standard Model of Cosmology

The universe is largely homogeneous and isotropic.

It seems to have vanishing overall spacial curvature.

It is expanding and originated from a high temperature early phase known as “big bang”.

The visible constituents are well described by the Standard Model of particle physics, but there is a lot of dark stuff that we do not understand...





The basics of GR part was based on a combination of different books lecture notes. The main results (geodesic equation, Einstein field equations...) can be found in any textbook of GR

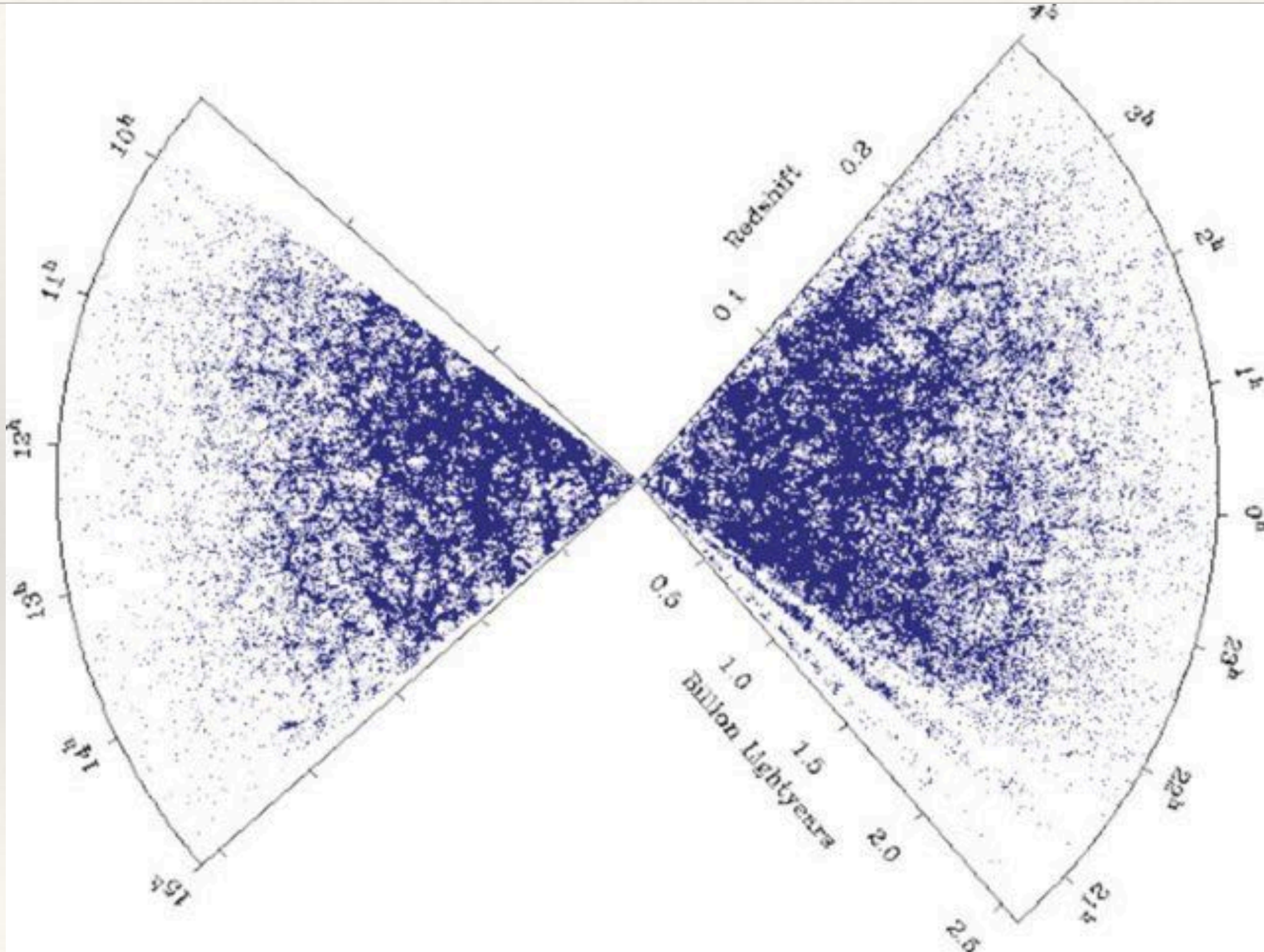
# Lecture II

## The Friedmann - Lemaitre - Robertson - Walter Metric

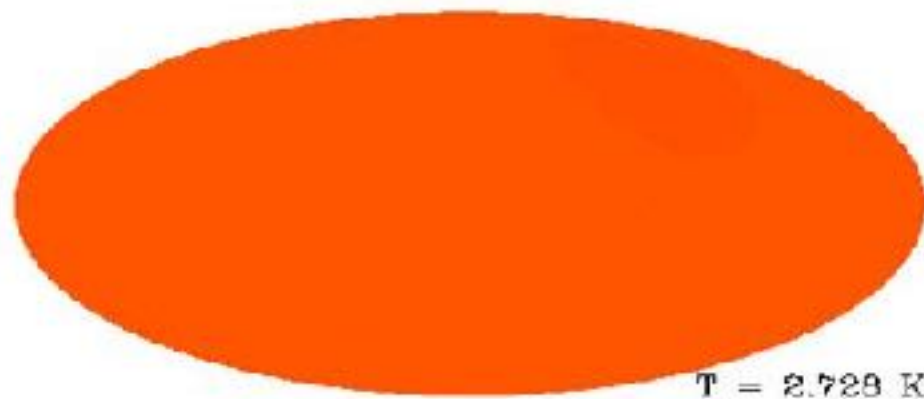
This part was closely following chapter 2 in the book “The Early Universe” by Kolb and Turner.



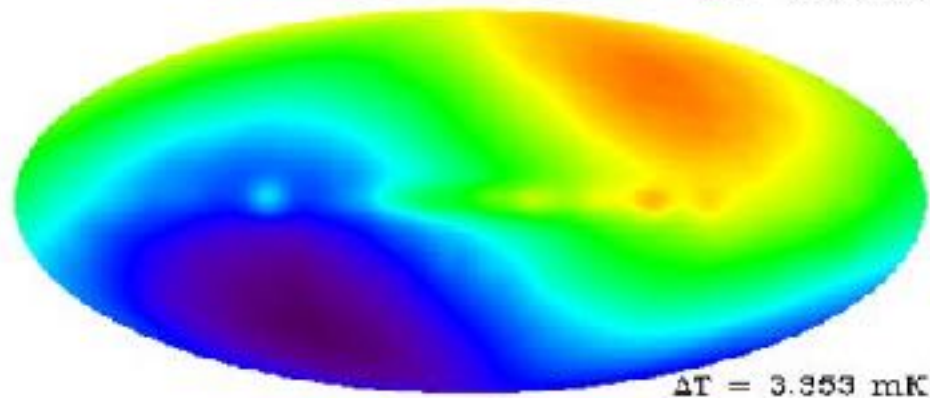
# Cosmological Principle Tested



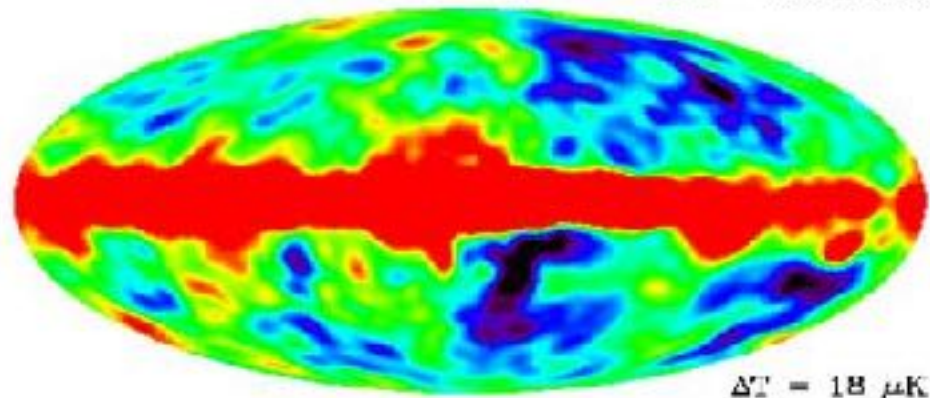
# Cosmological Principle Tested



Isotropic 3K background.  
The most perfect blackbody  
we know



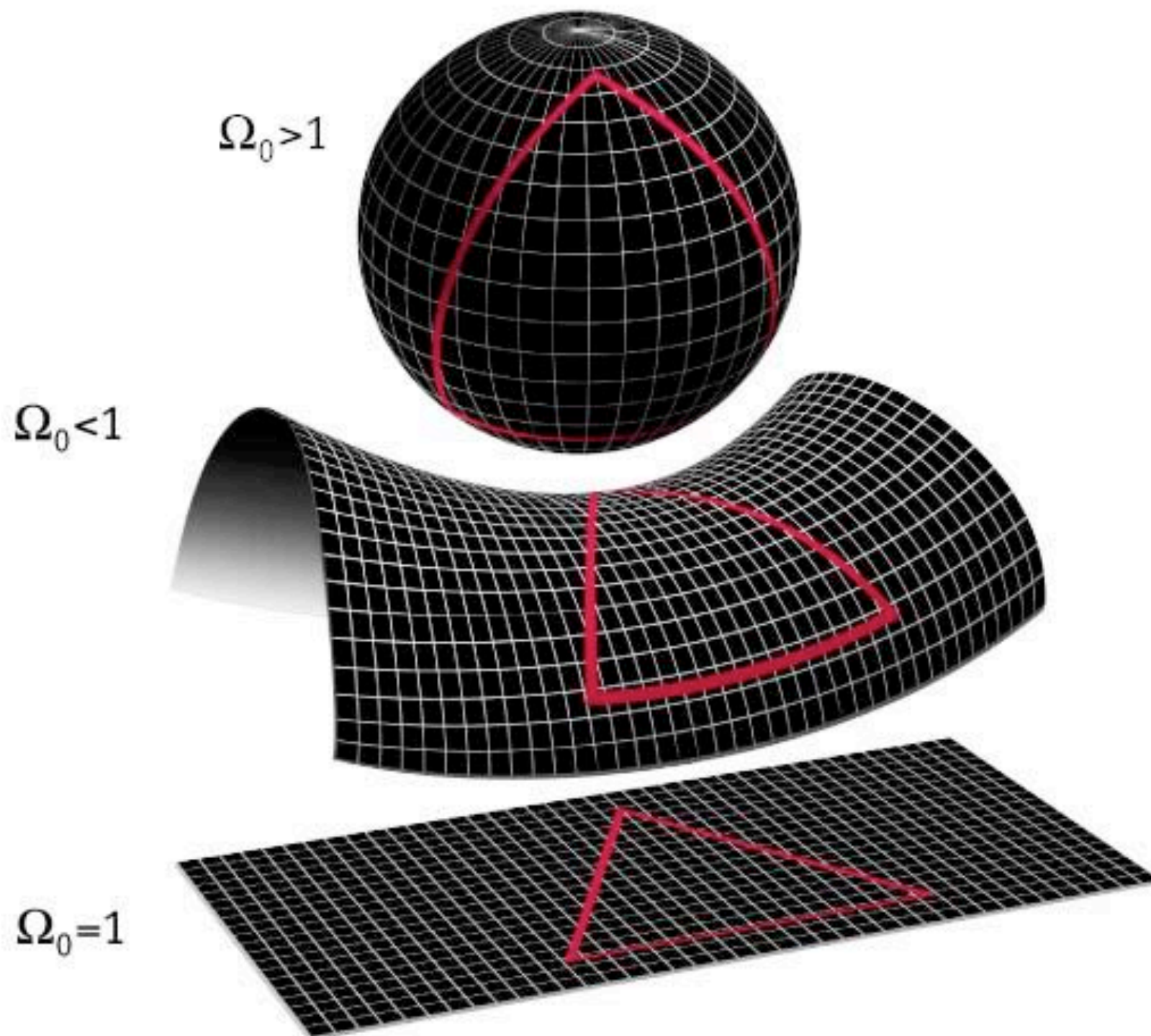
Dipole (3.4 mK).  
Our motion relative to CMB



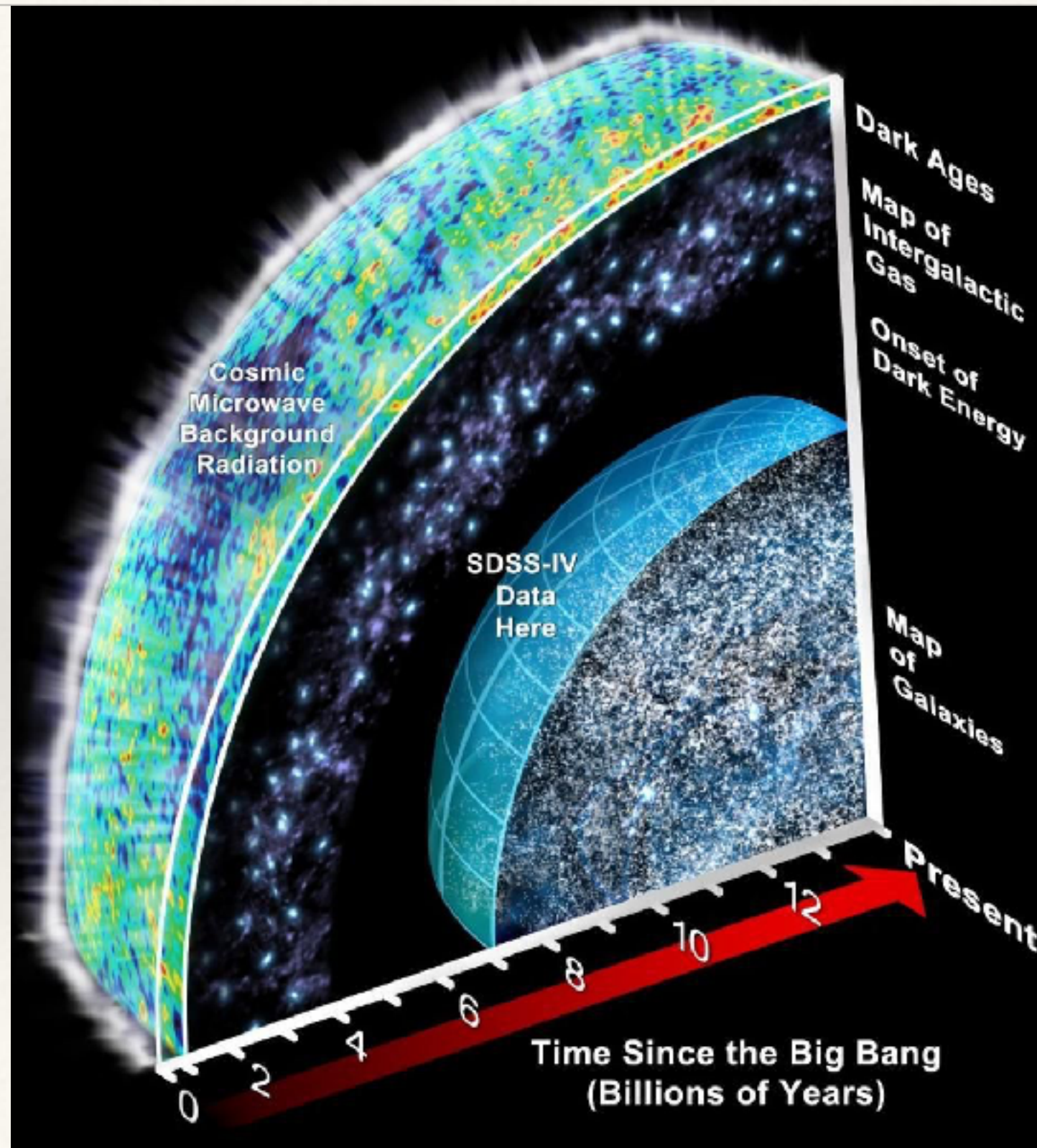
Primordial fluctuations  
 $20 \text{ } \mu\text{K}$



# FLRW Universes

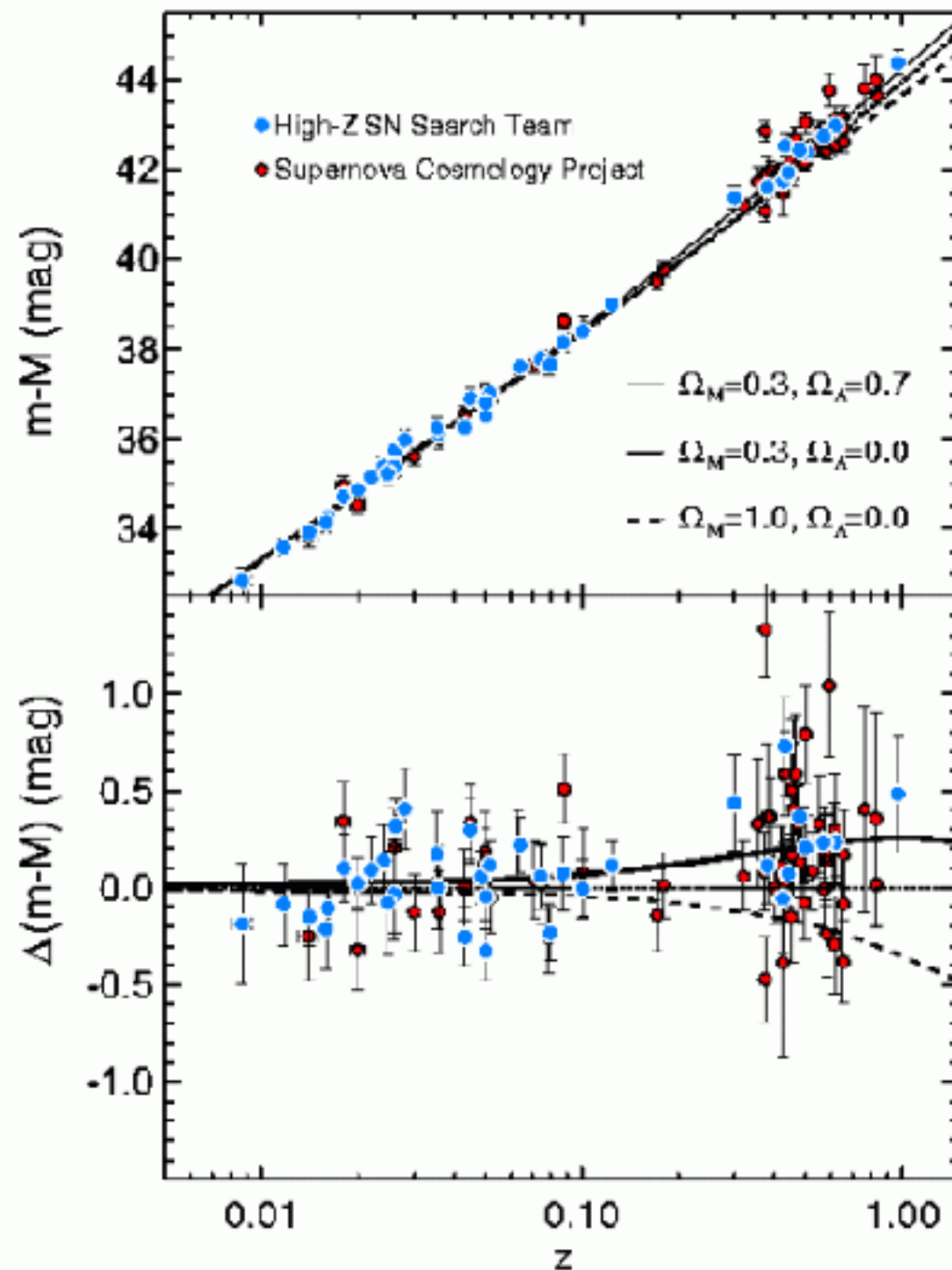


# Observable Universe

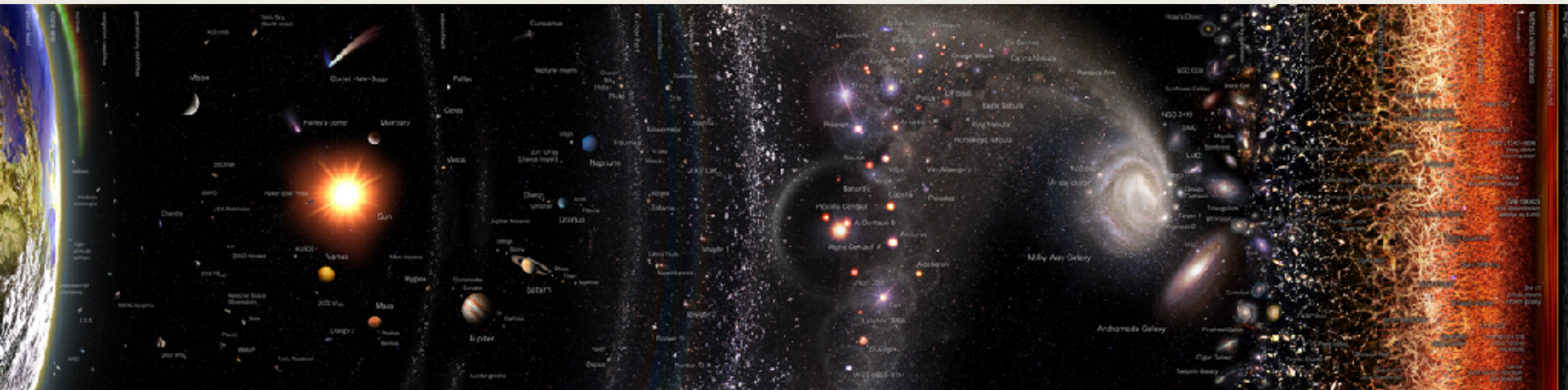




# Redshift - Distance Relation



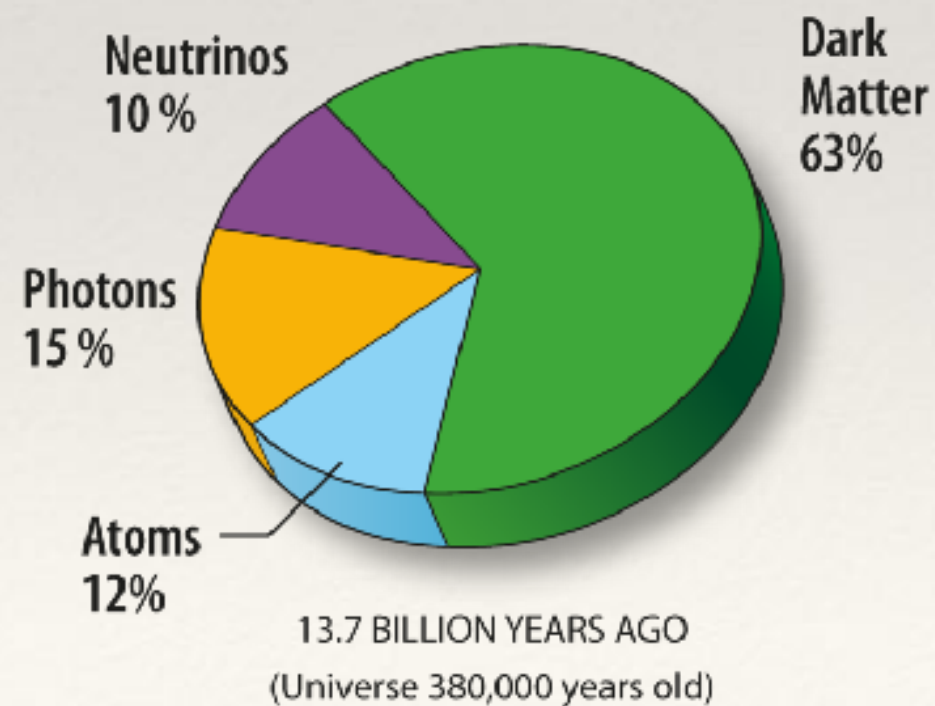
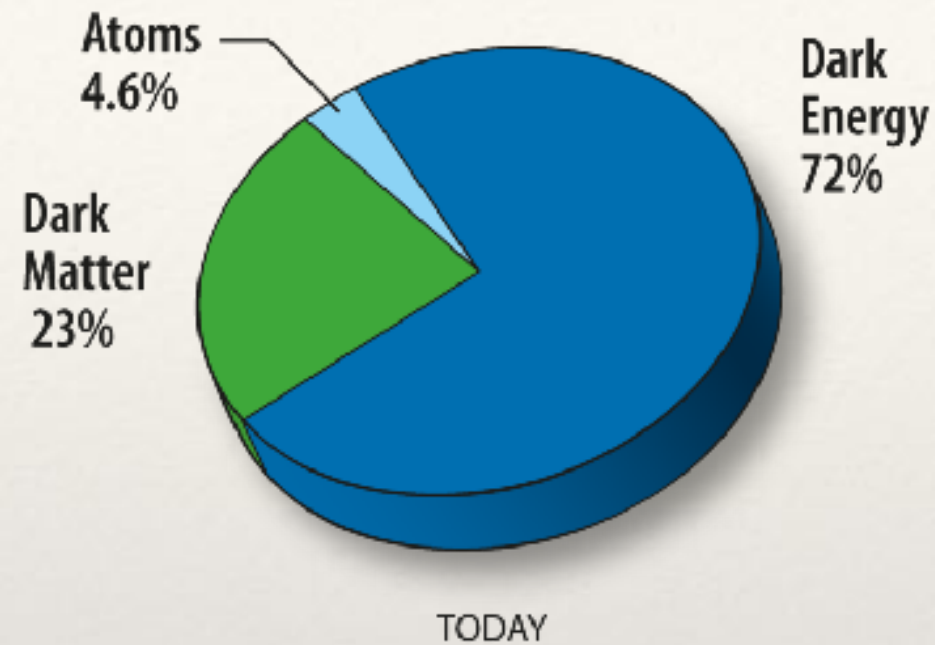
# Observable Universe



Size: 46.5 billion light-years



# Changing Energy Content



# Lecture III

Standard Model of Cosmology...

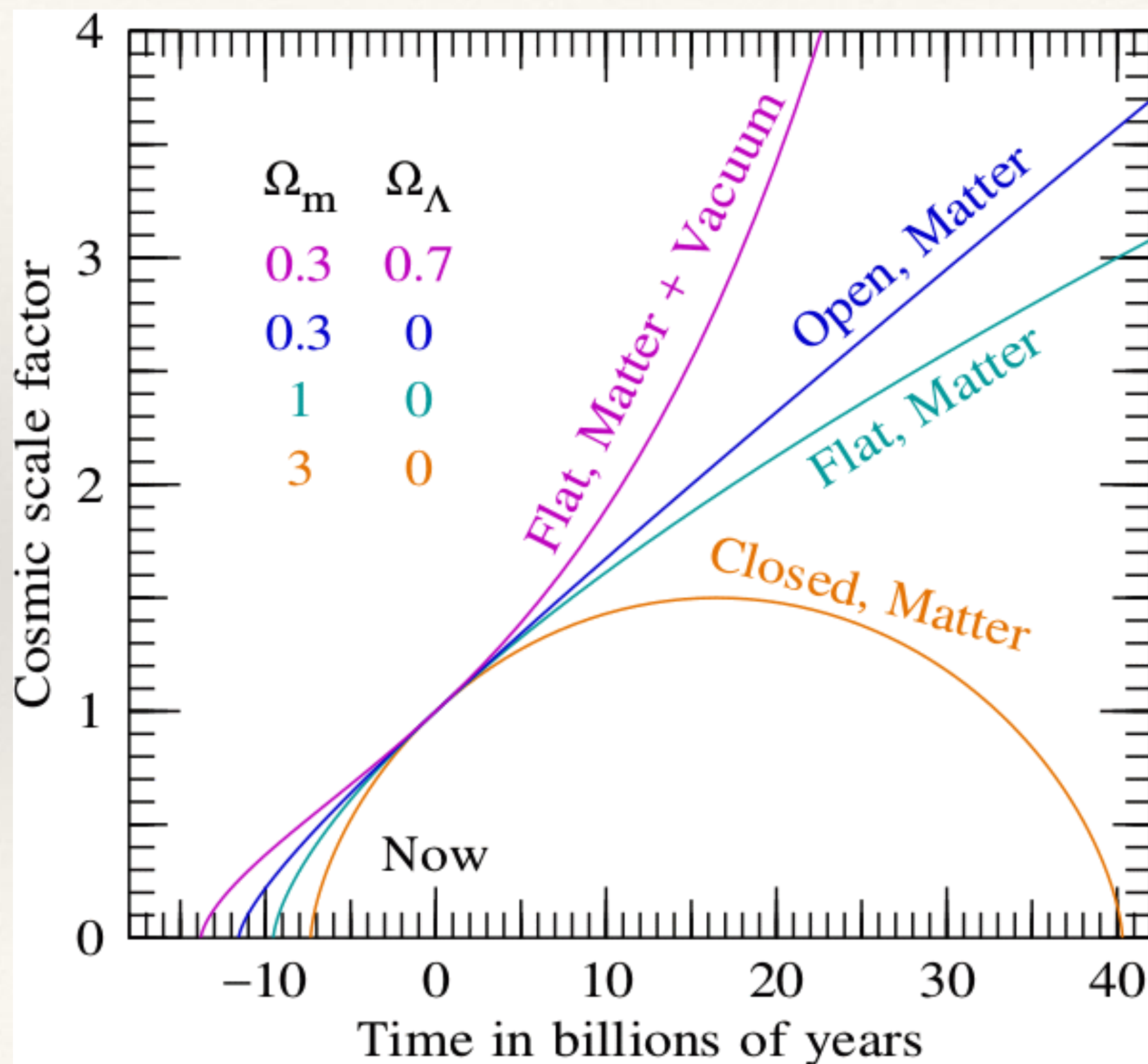
...and its Limits



# History of the Universe

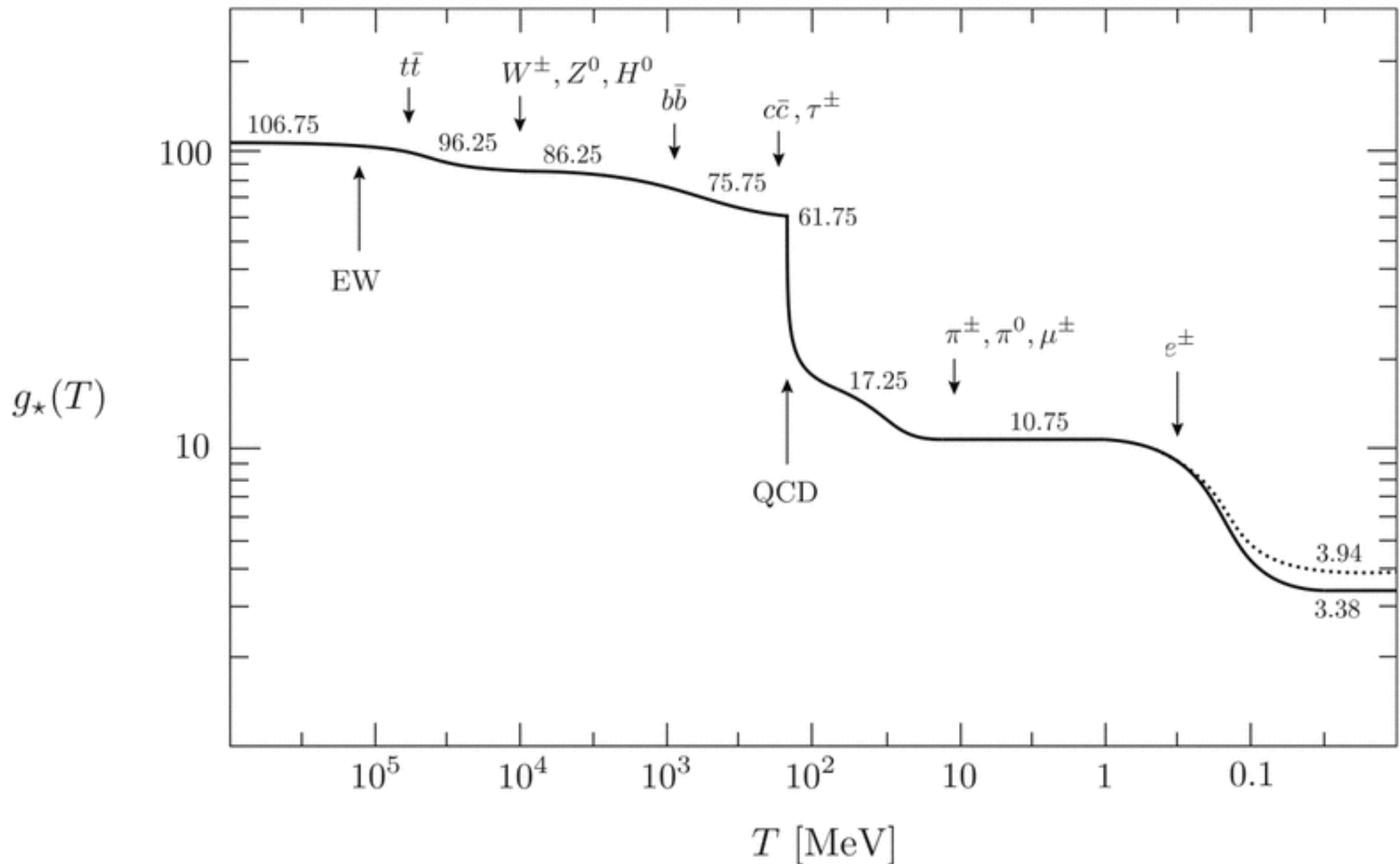
This part is closely following chapter 3 in the book  
“The Early Universe” by Kolb and Turner.

# Expansion History

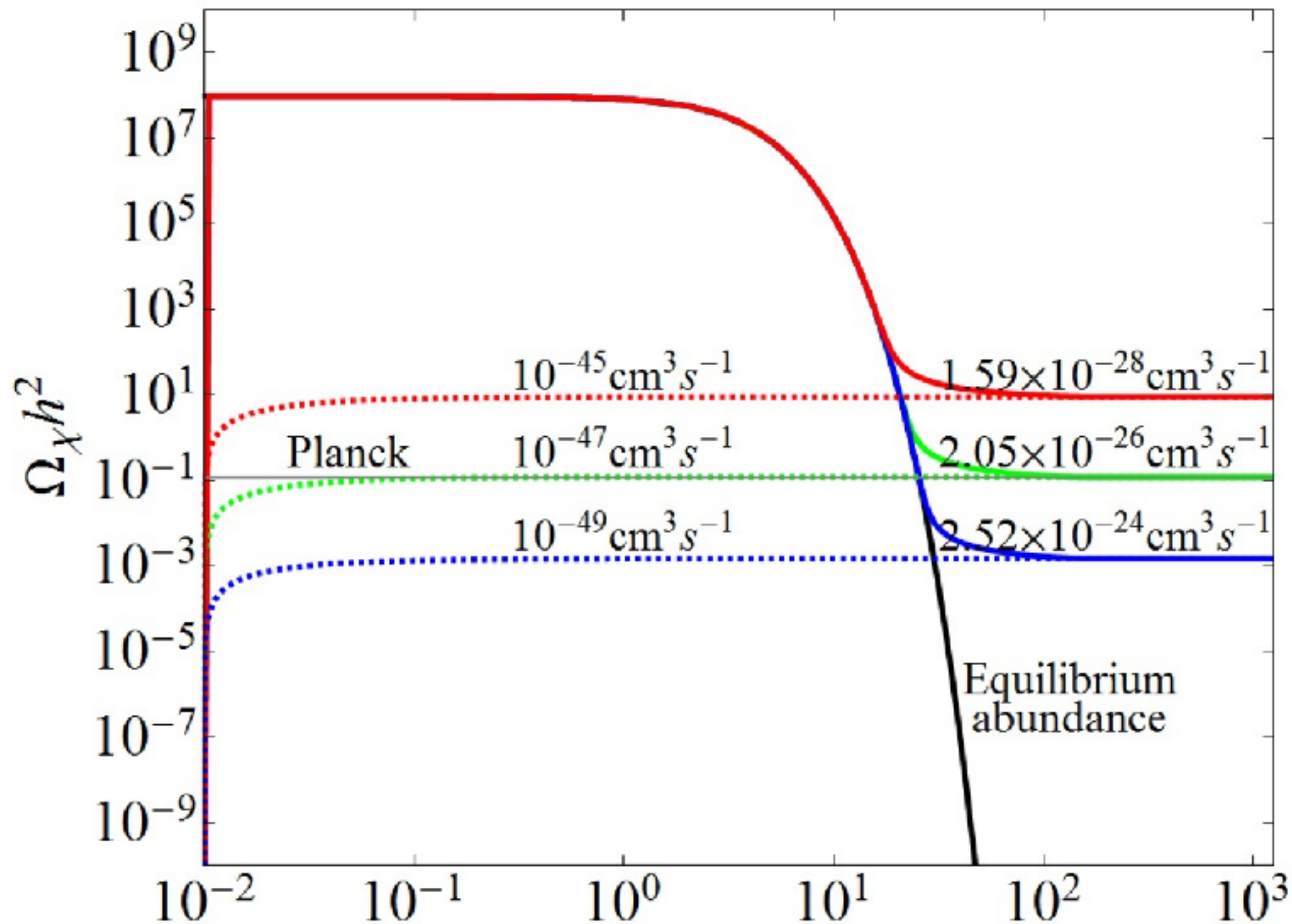




# Effective Number of Relativistic Degrees of Freedom

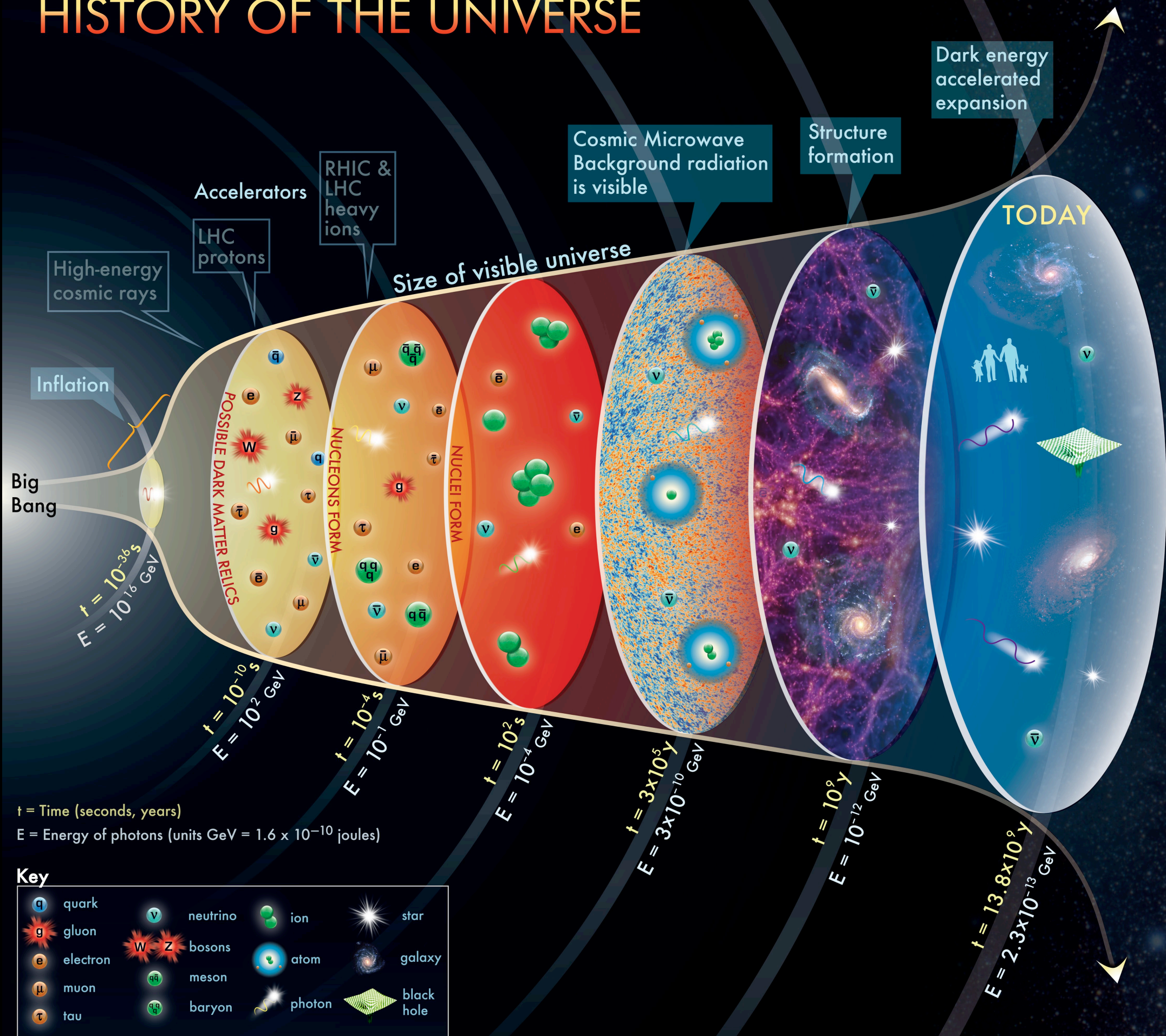


# Freeze Out and Freeze In





# HISTORY OF THE UNIVERSE



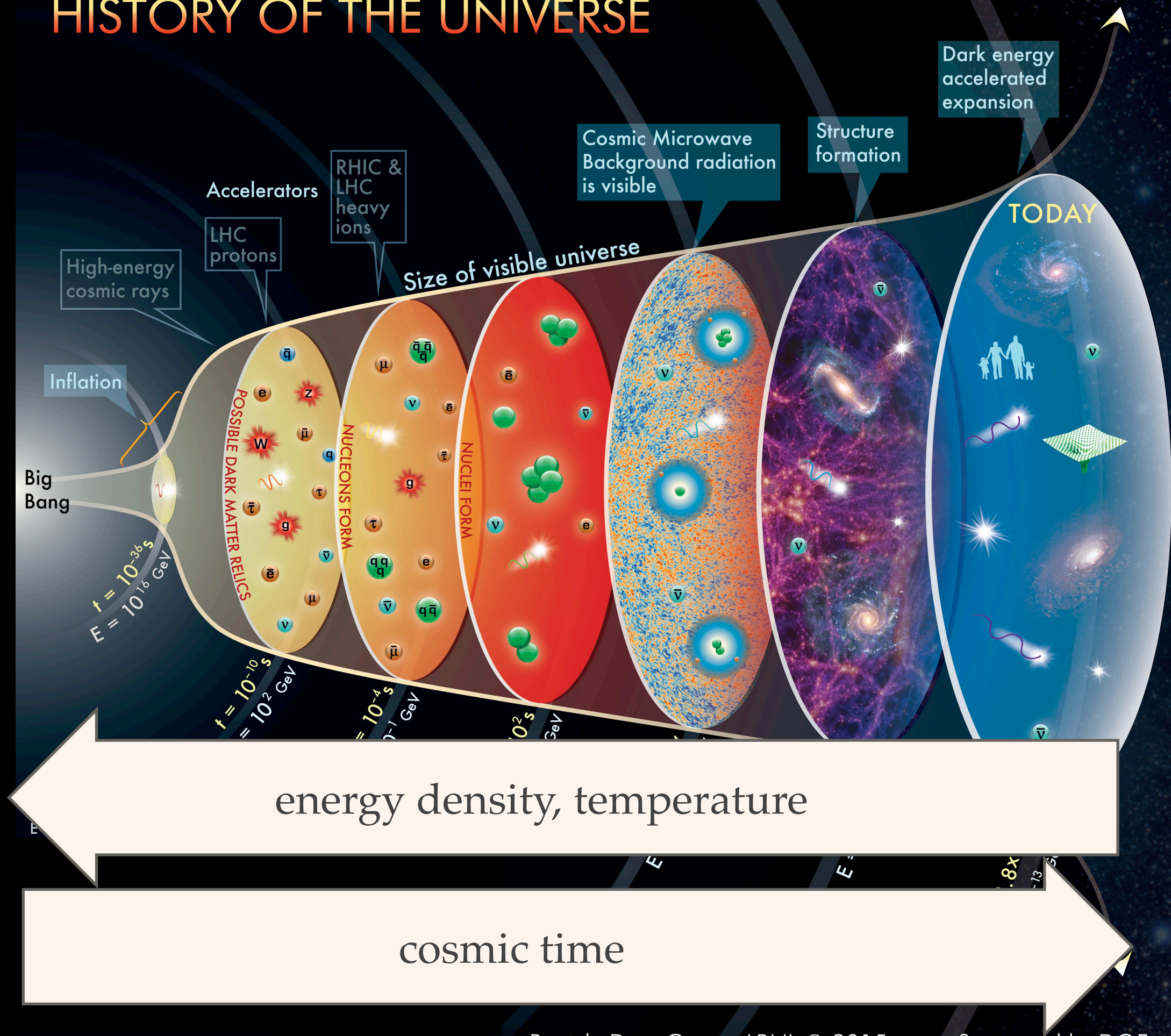
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE



# HISTORY OF THE UNIVERSE



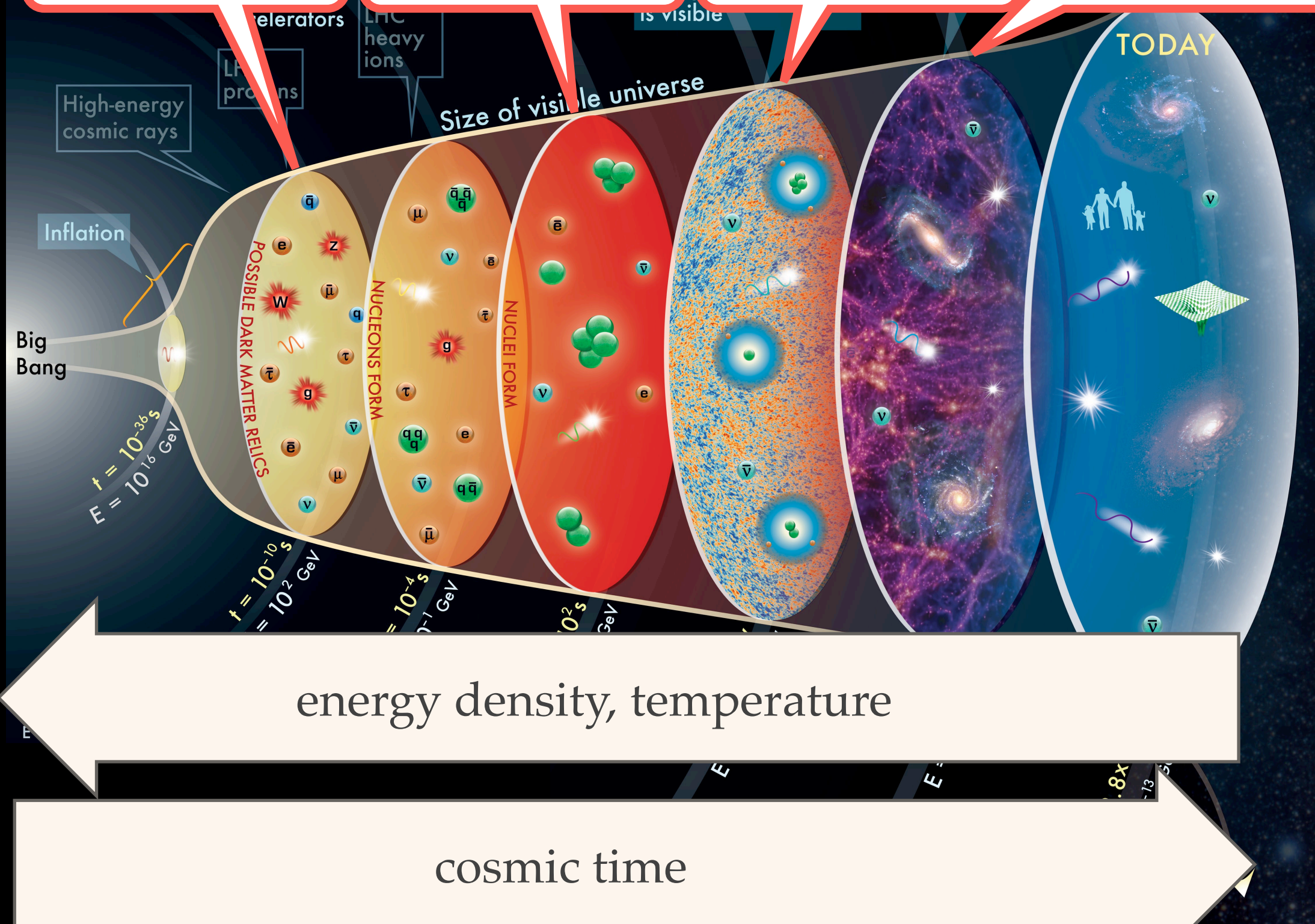


Large  
Hadron  
Collider

light  
element  
abundances

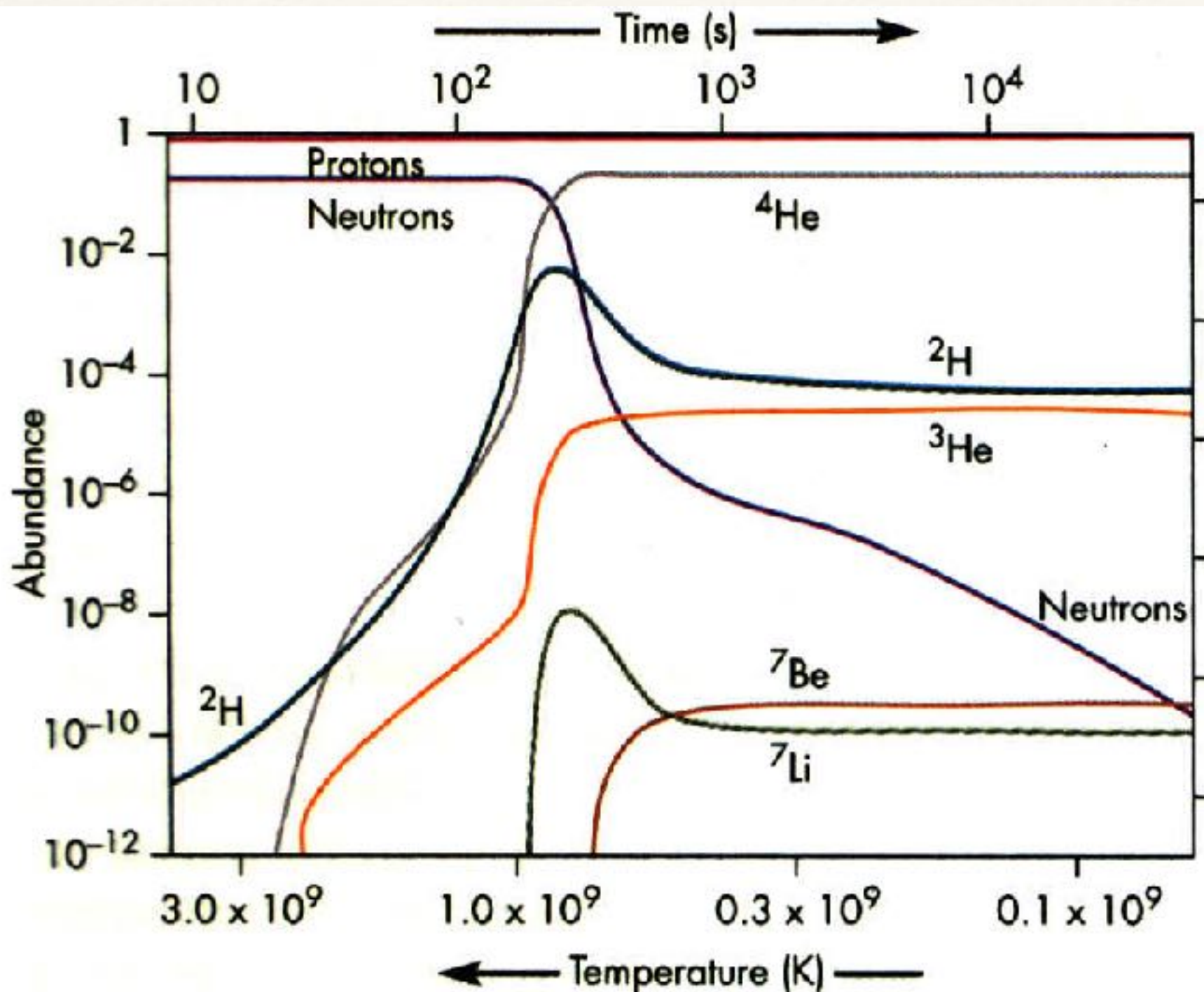
Cosmic  
Microwave  
Background

optical  
astronomy





# Big Bang Nucleosynthesis



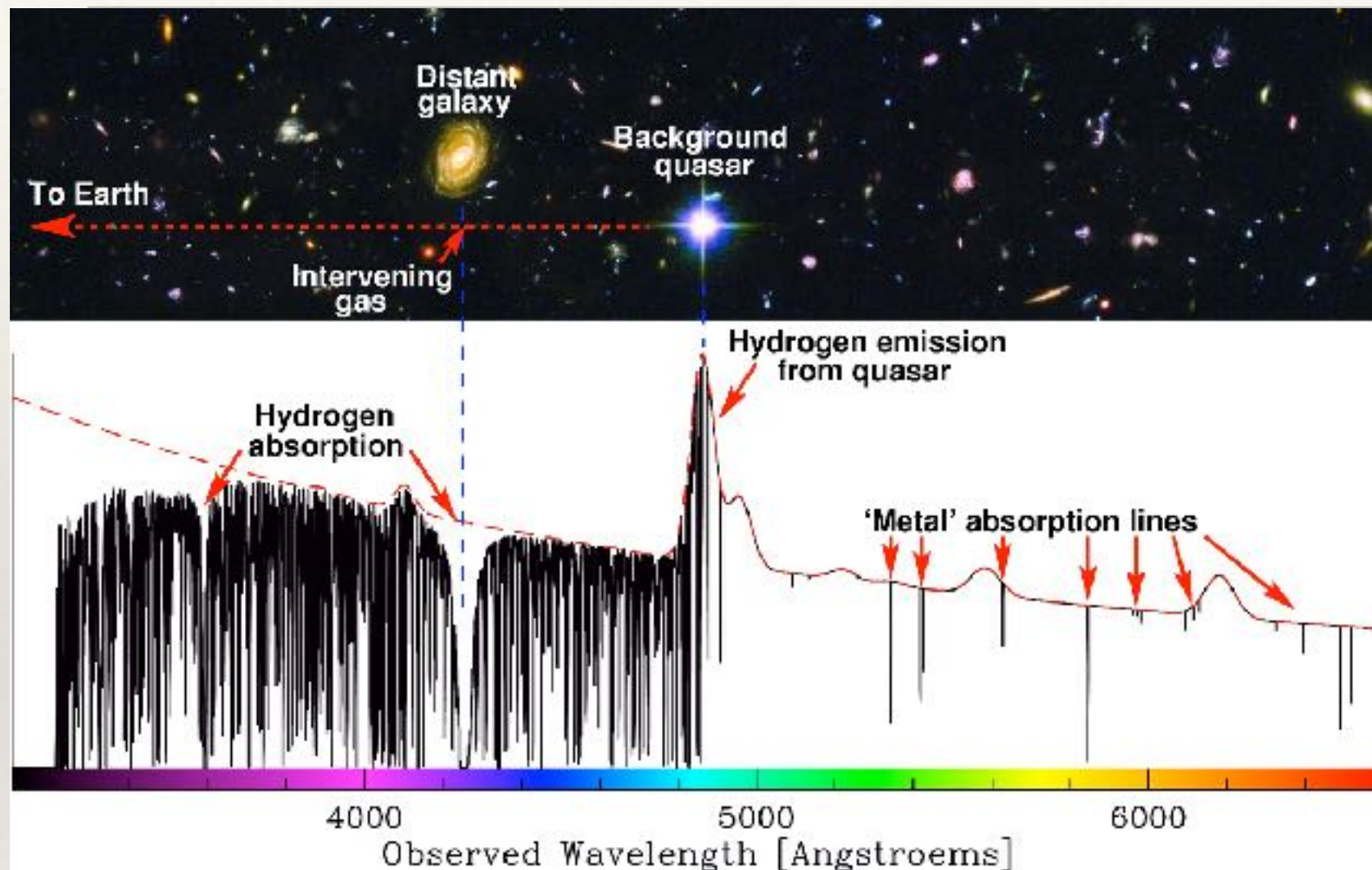
Light elements are produced in a chain of nuclear reactions.

The only unknown parameter is the baryon-to-photon ratio

**Primordial light element abundances measure the baryon asymmetry!**



# Big Bang Nucleosynthesis

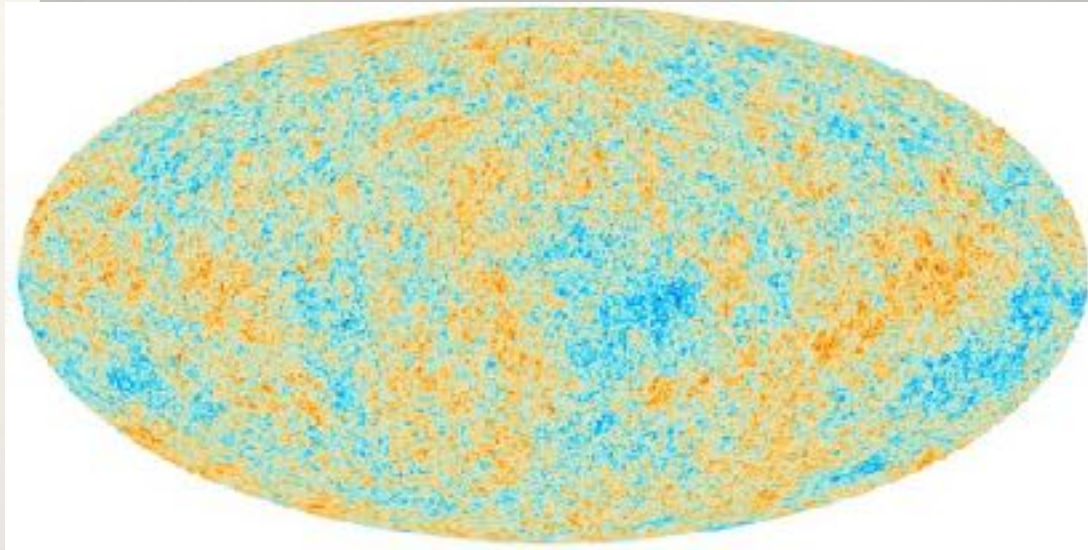


- ❖ light element abundances in intergalactic medium can be measured in quasar spectra
- ❖ Deuterium is sensitive to baryon asymmetry and not produced in stars

**Constraint on baryon-to-photon ratio  $\eta$ :**

$$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10} \quad \text{PDG 2016}$$

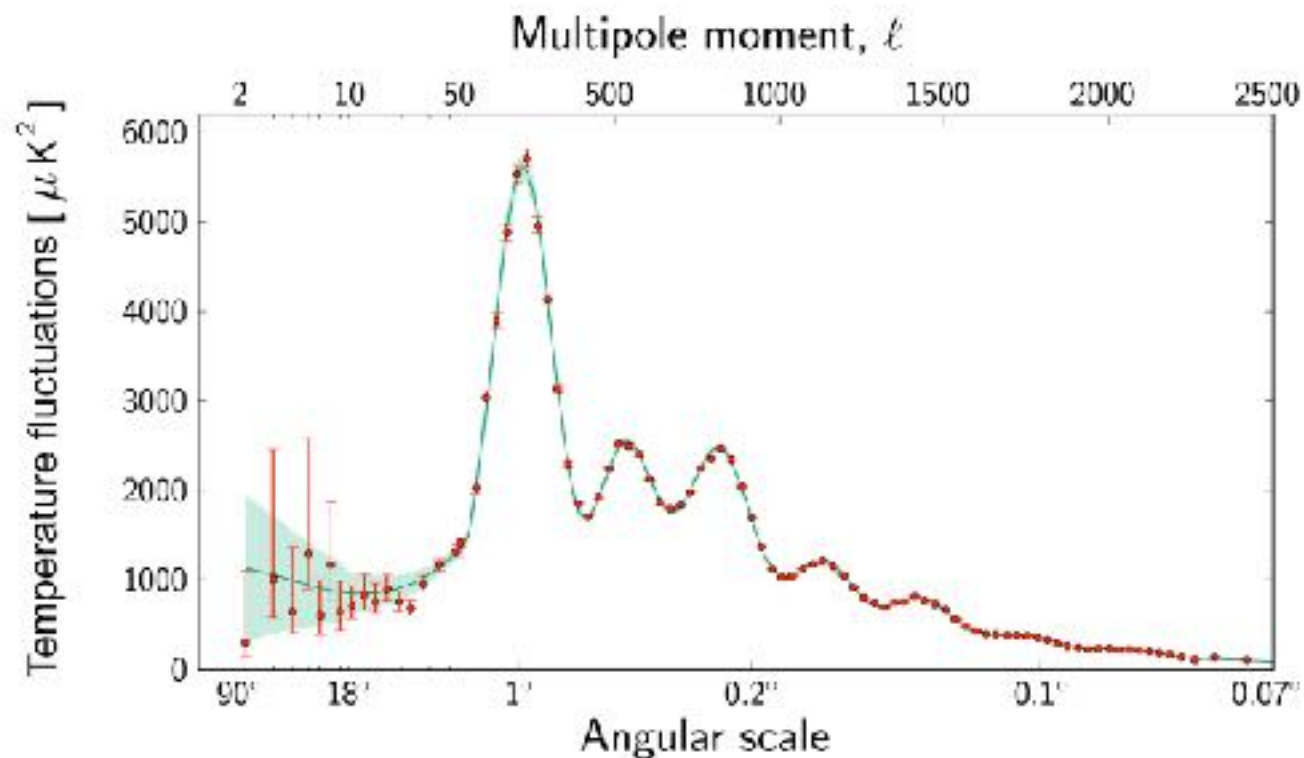
# Cosmic Microwave Background



**Constraint on  
baryon-to-photon ratio  $\eta$ :**

$$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$$

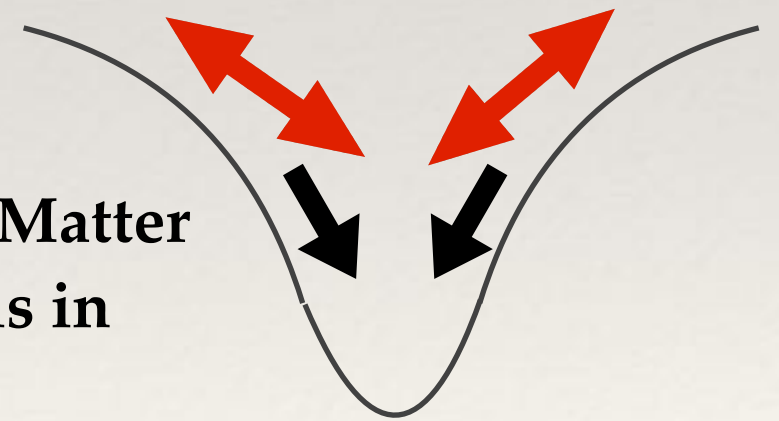
PDG 2016



**ordinary matter/radiation oscillates  
due to radiation pressure**

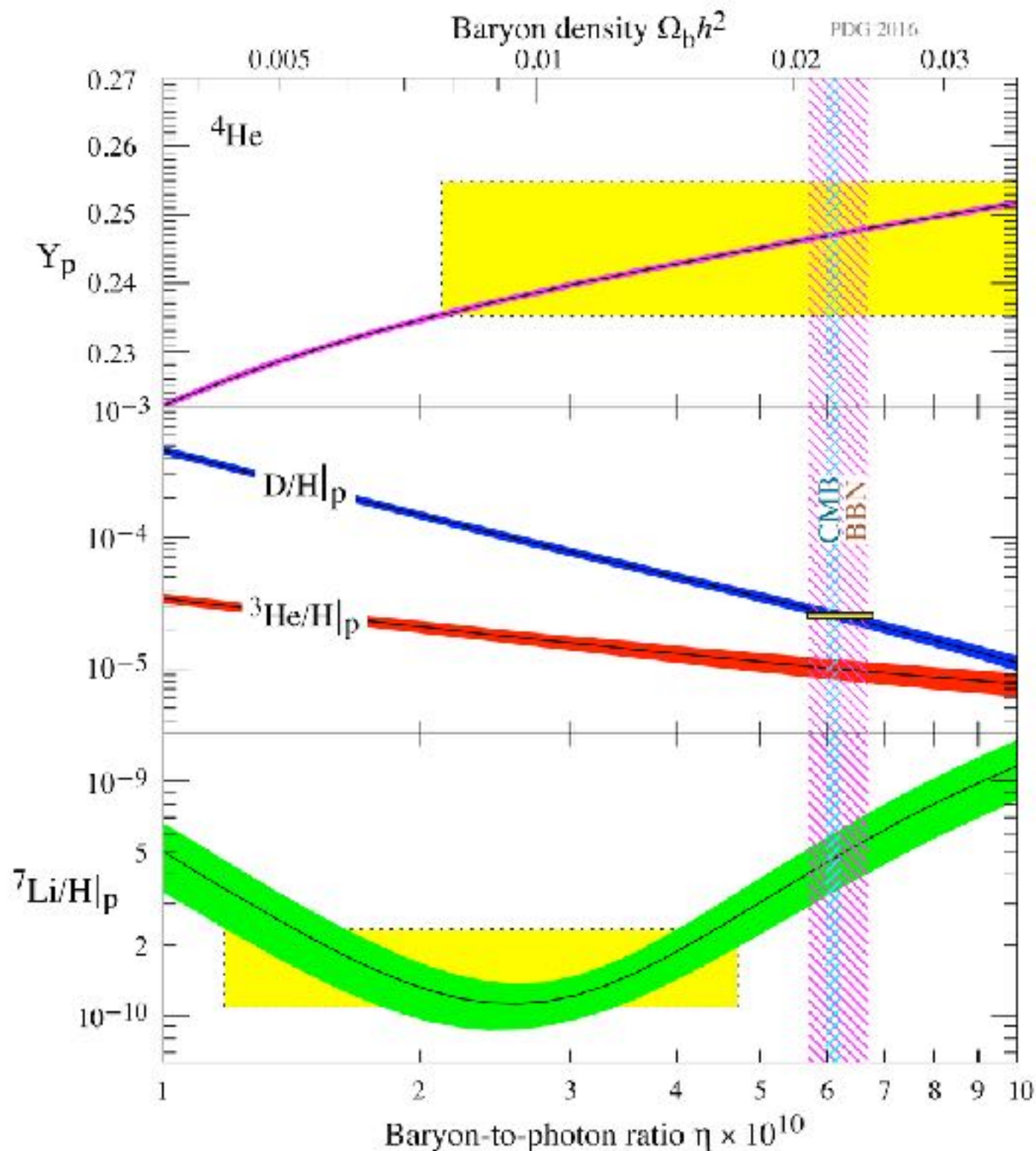
**Dark Matter  
falls in**

**gravitational potential well**





# Cosmic Microwave Background

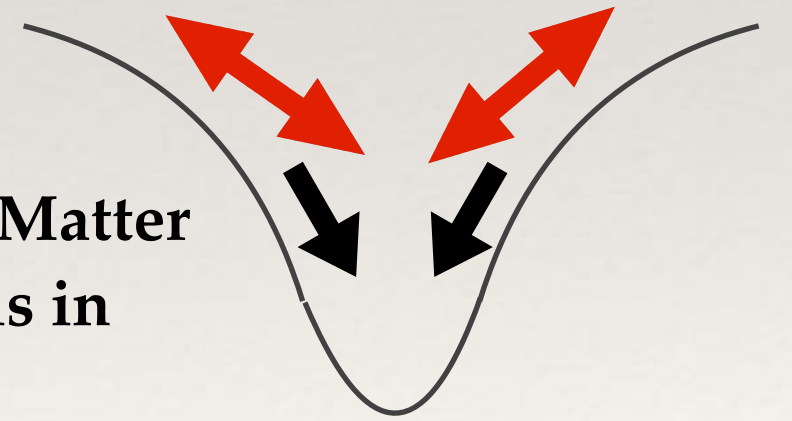


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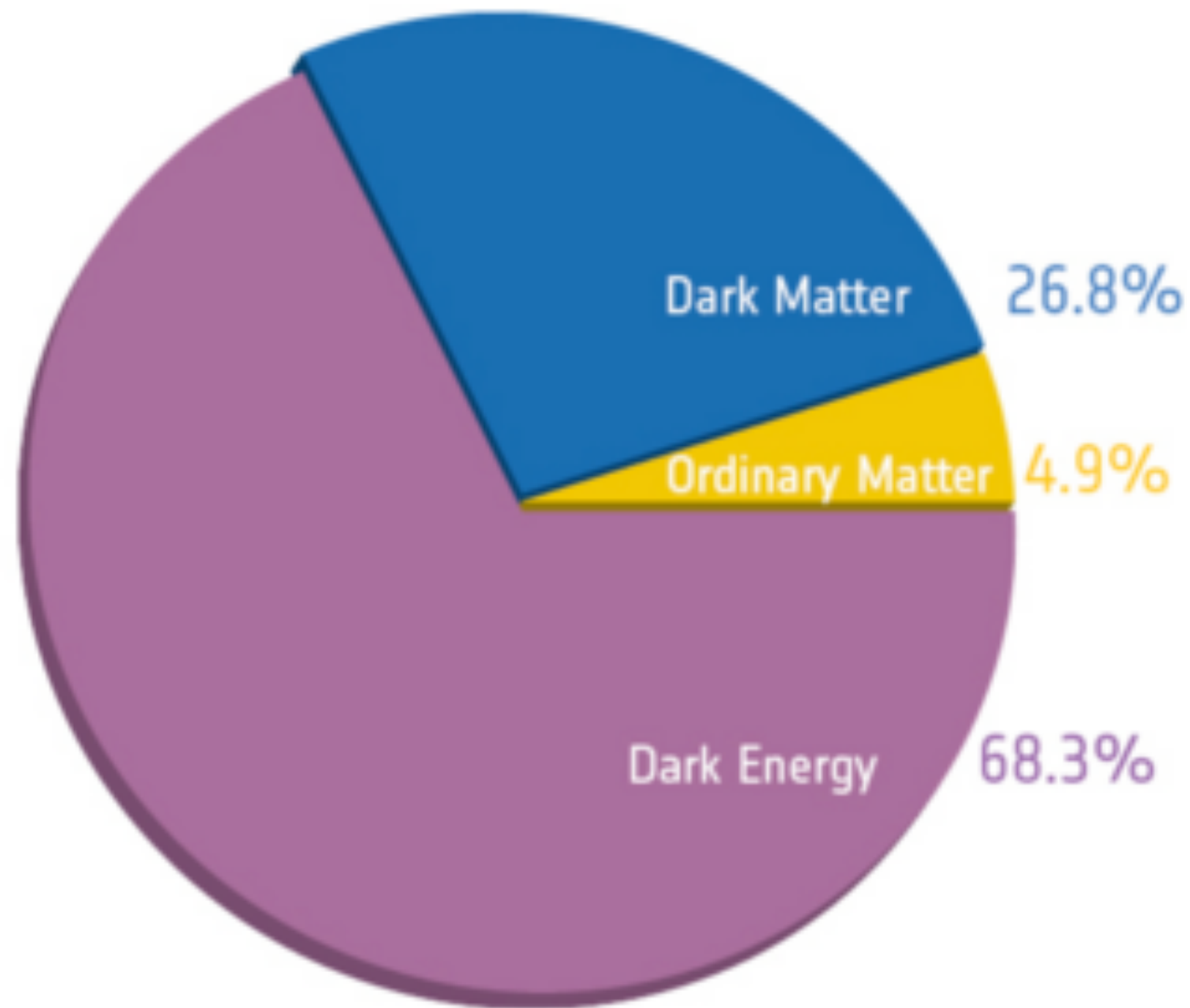
**gravitational potential well**



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# Energy Content of the Universe

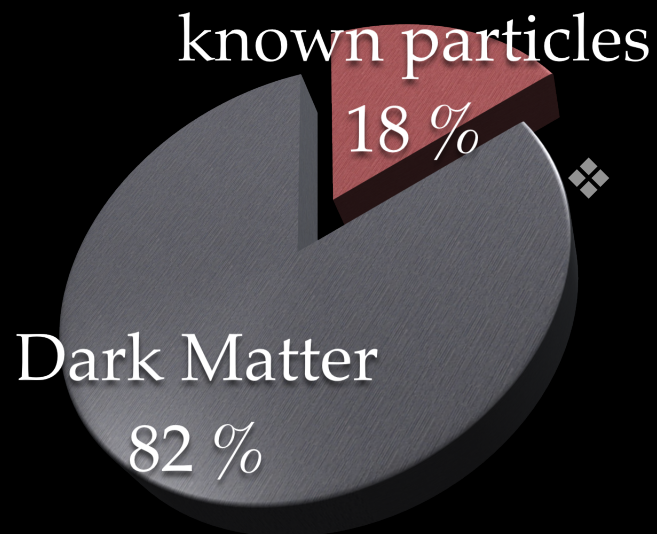
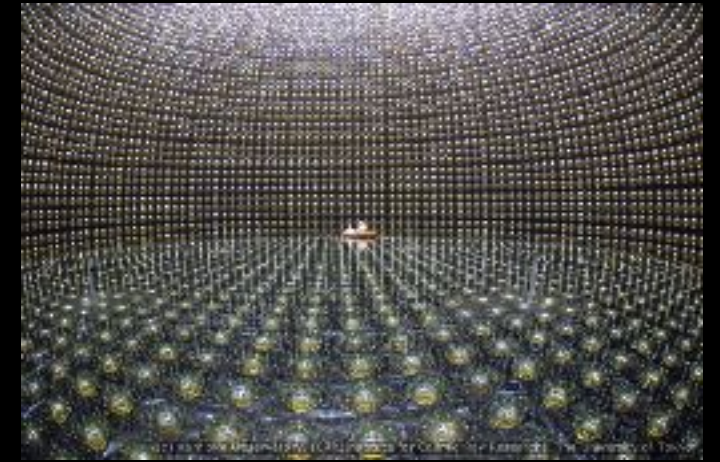
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# ❖ What is the origin of neutrino mass?

Possible key to embed Standard Model  
in a more fundamental theory of Nature



## ❖ What is the Dark Matter made of?

It makes up most of the mass in the universe.

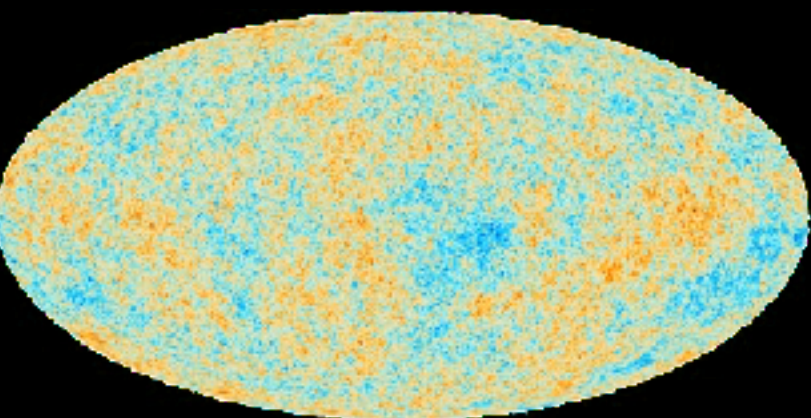
## ❖ Why was there more matter than antimatter in the early universe?

...so that some matter survived the mutual annihilation to form galaxies, stars etc.



## ❖ What set the initial conditions for the “hot big bang”?

Cosmic inflation? How did the transition to the radiation dominated epoch happen?



# The Initial Conditions Problem



# Flatness Problem

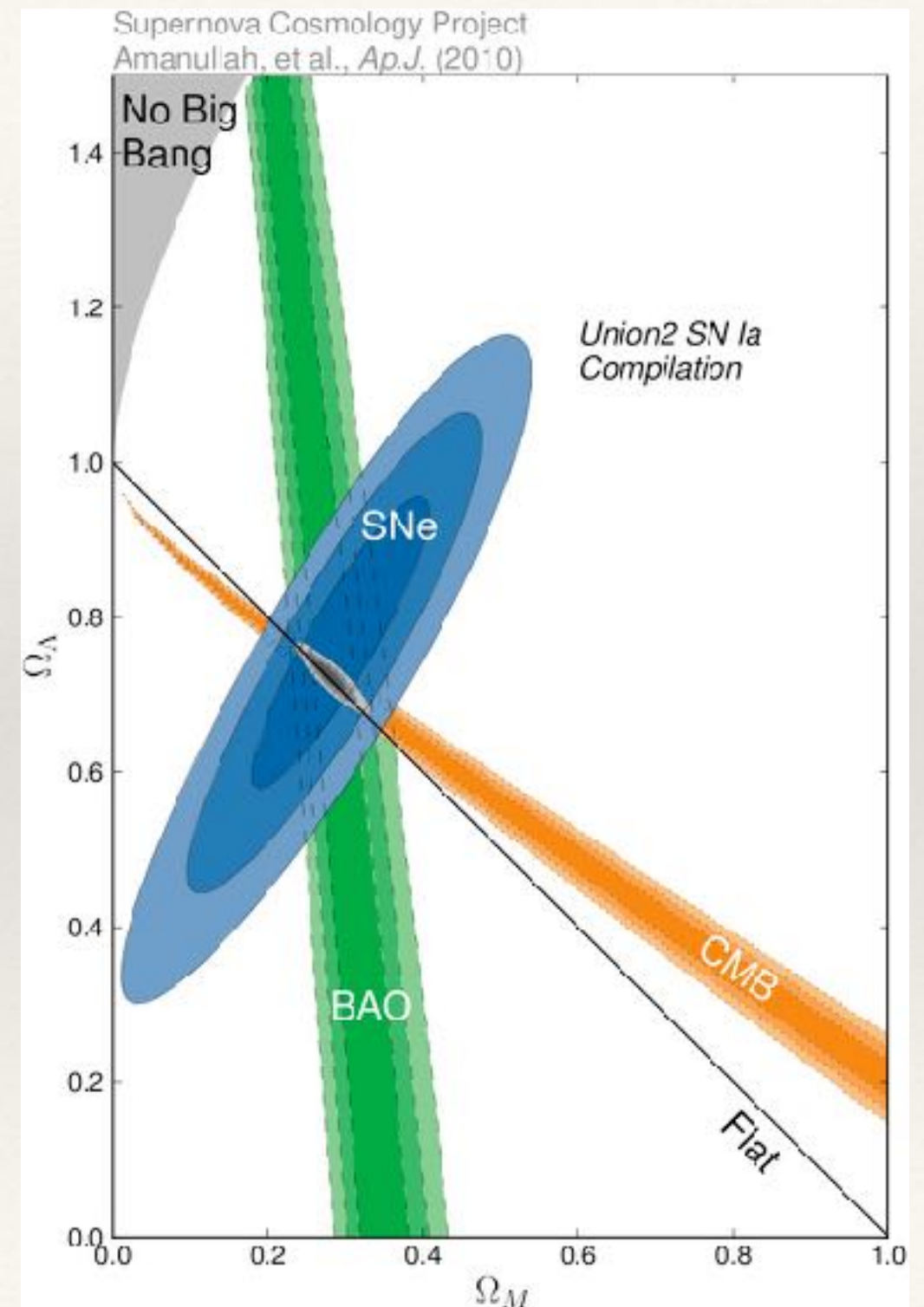
Flatness: Recall that the 3-dimensional curvature is

$${}^3R = 6k/a^2$$

Observationally we know  $(\Omega - 1) = k/(Ha)^2$

is small...

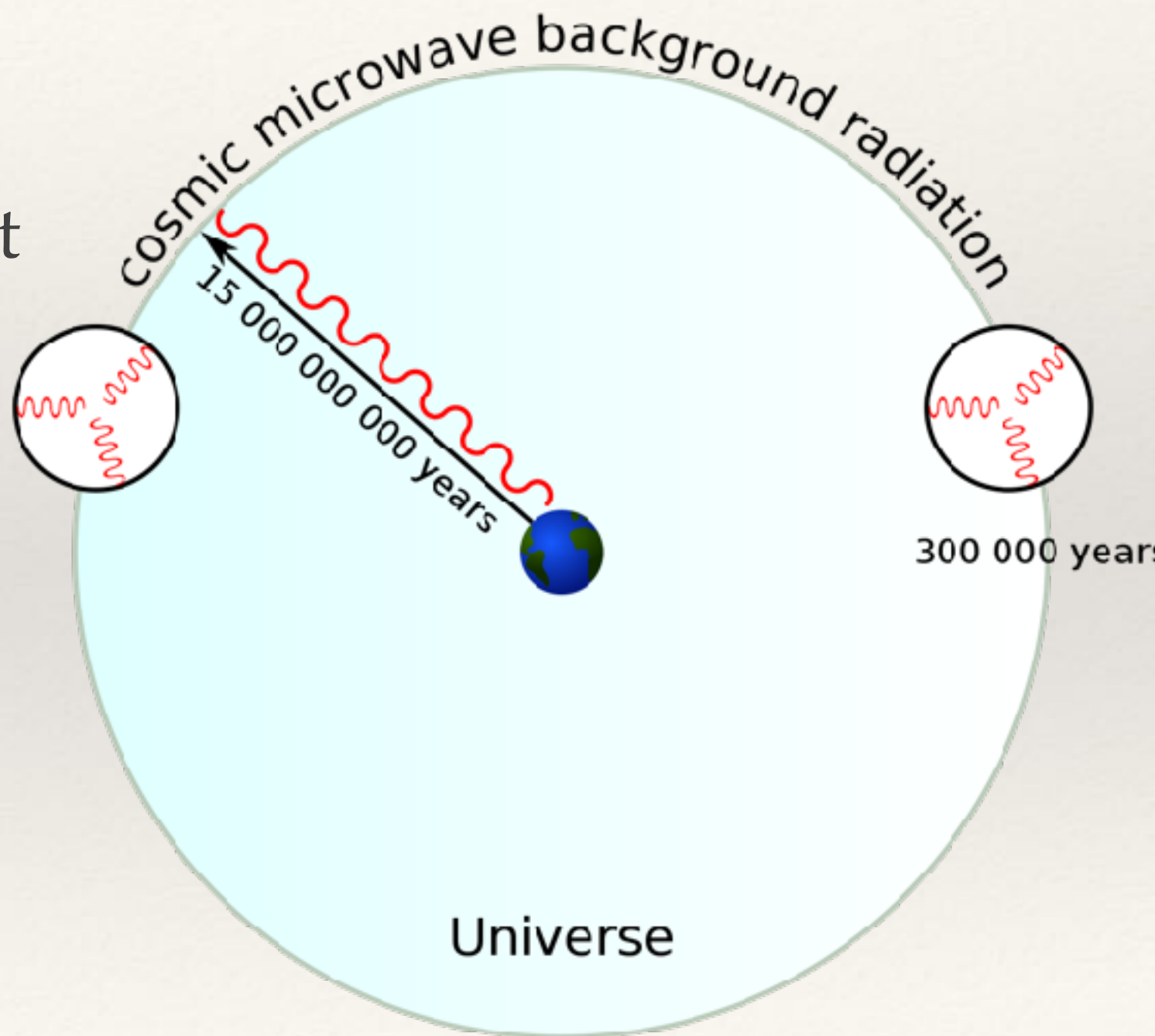
**...curvature must have been super tiny in the past!!!**



# Horizon Problem

Comoving particle horizon at CMB decoupling was much smaller than the comoving distance that light has travelled to us (i.e., the patch that we know to be in equilibrium because we see the same temperature in opposite directions)

**Why do we see the same temperature in causally disconnected patches???**

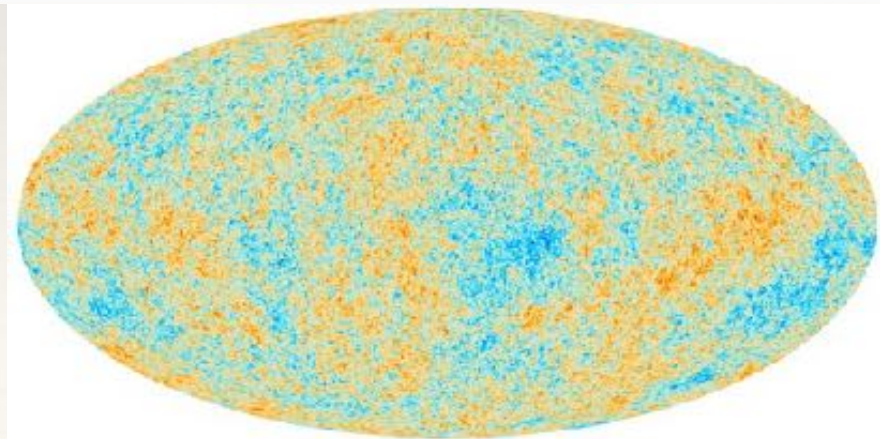
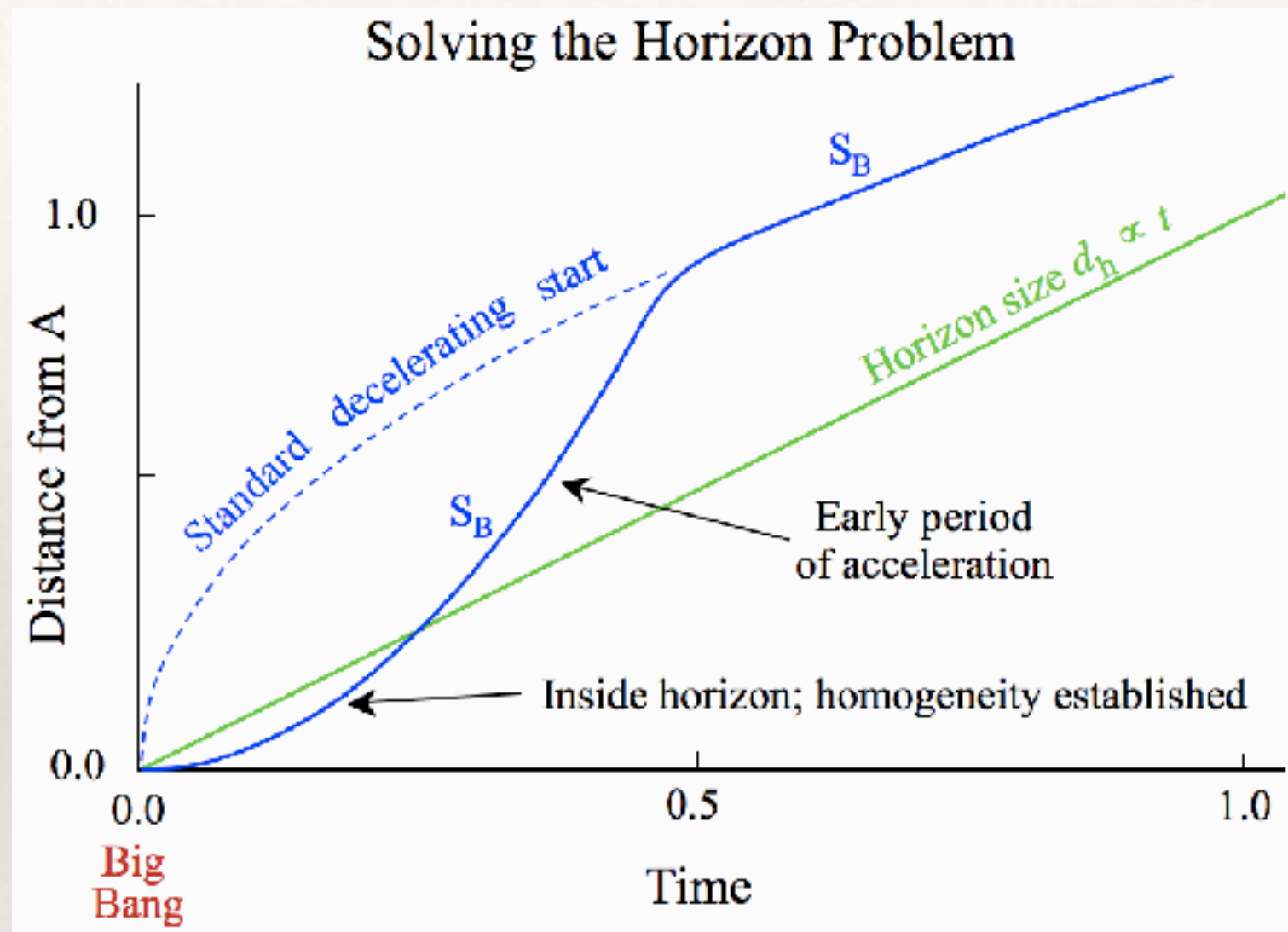




# Inflation

Both problems (and some others) can be solved if the universe underwent a period of exponential growth... **inflation**!

This explains the CMB anisotropies as “blown up” quantum fluctuations and correctly predicted their properties (Gaussian, spectral index)



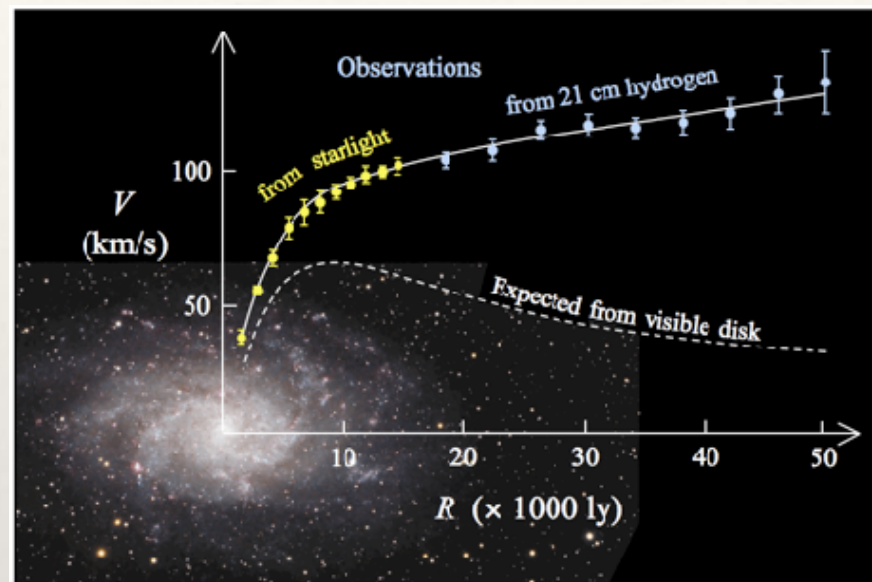
# The Dark Matter Puzzle



# Summary

There is compelling evidence that  $\sim 80\%$  of the mass in the universe is made of particles that are

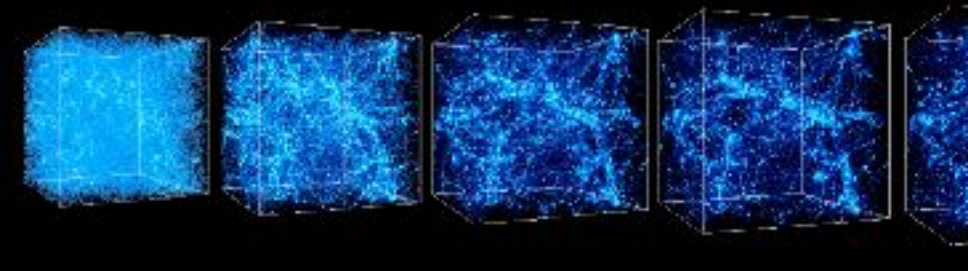
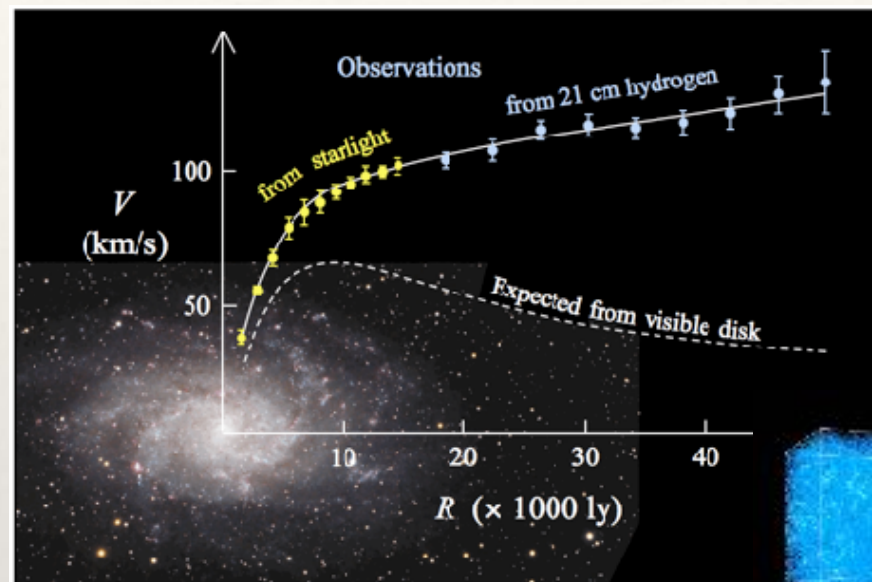
- neutral (“dark”)
- massive
- non-baryonic
- collisionless
- cold



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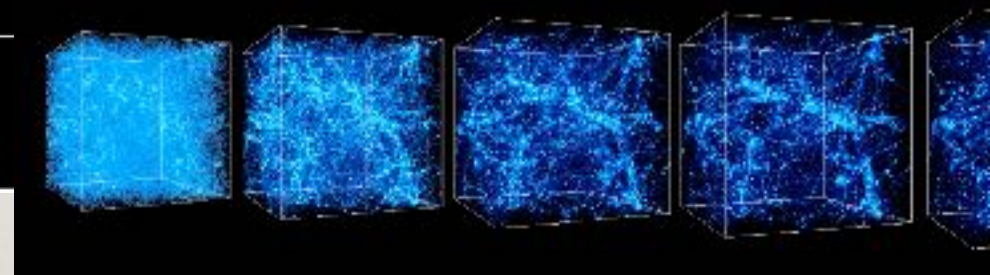
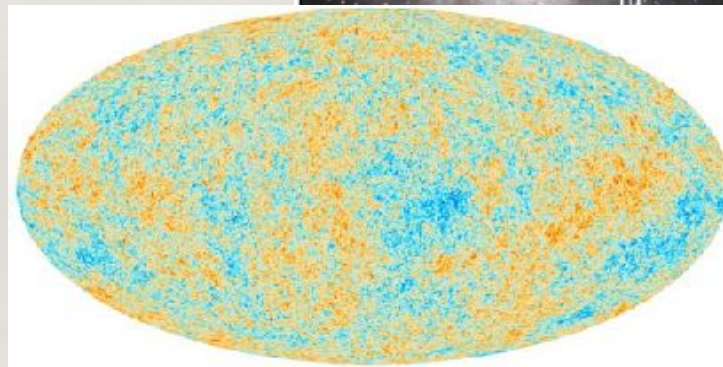
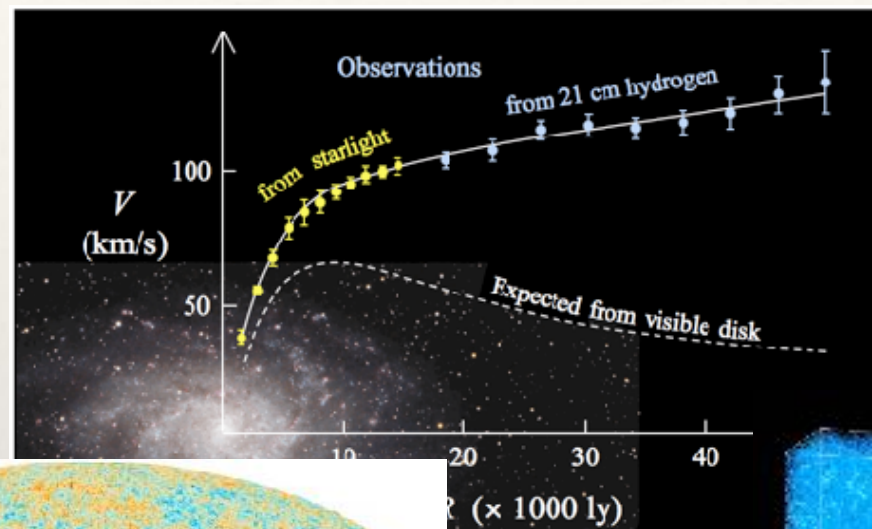




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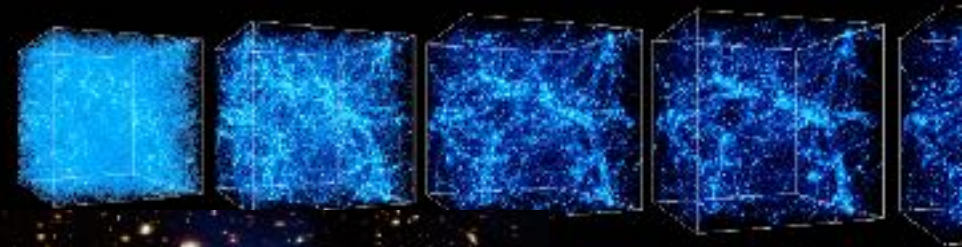
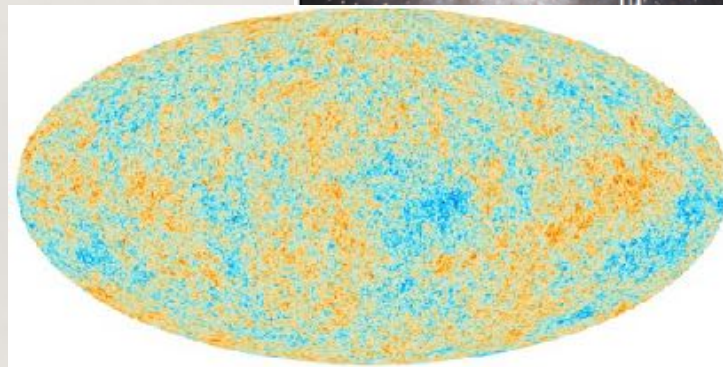
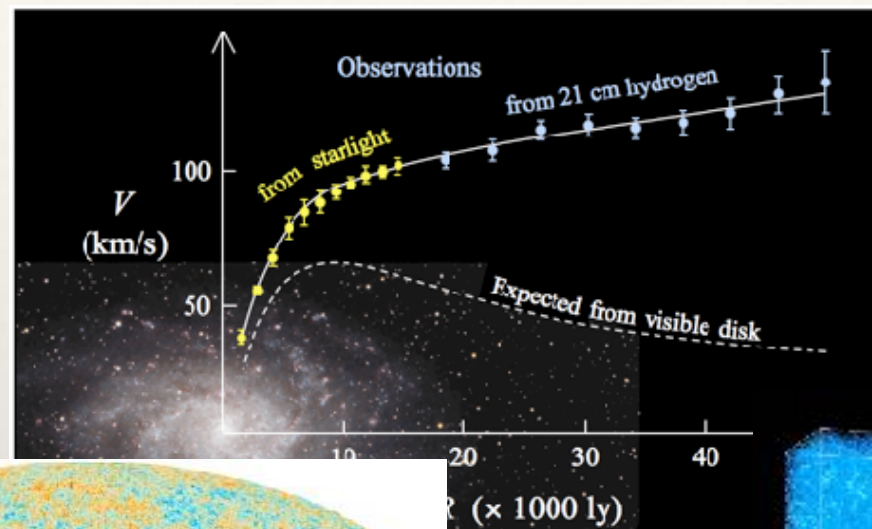
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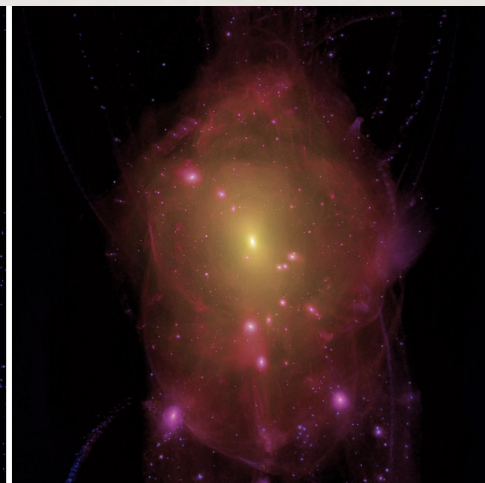
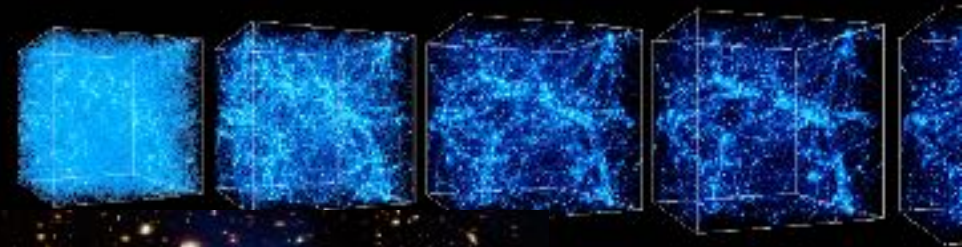
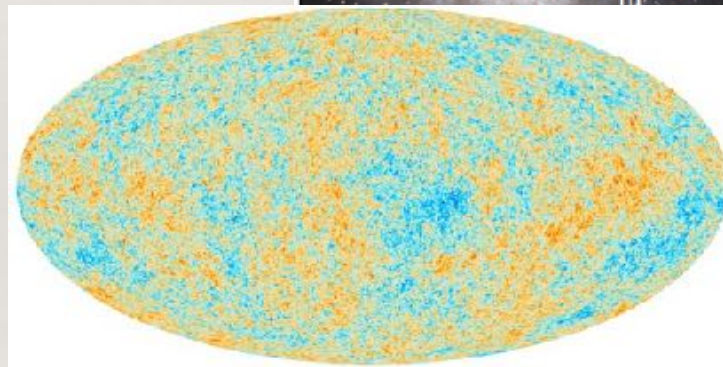
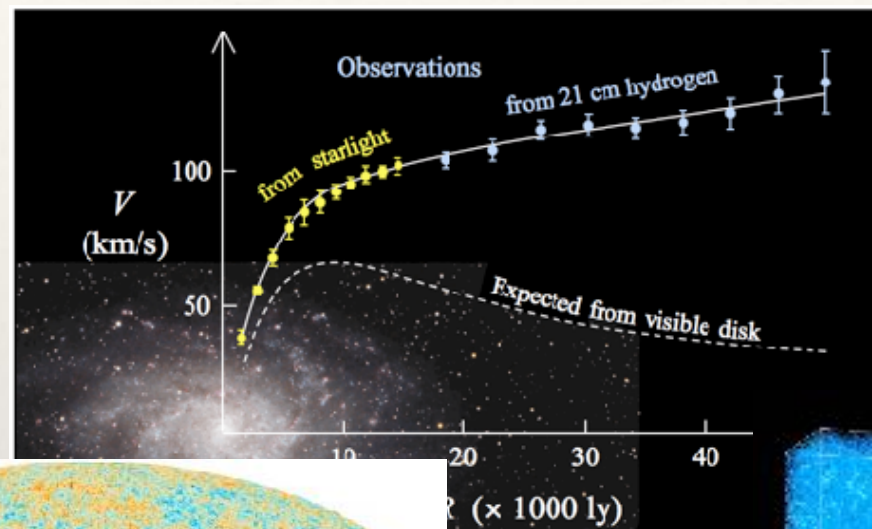




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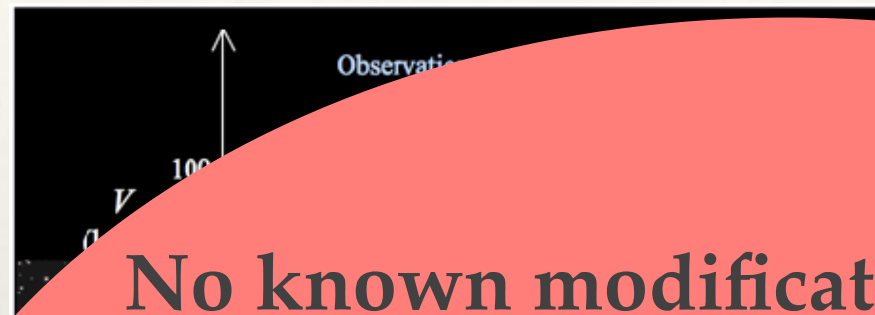
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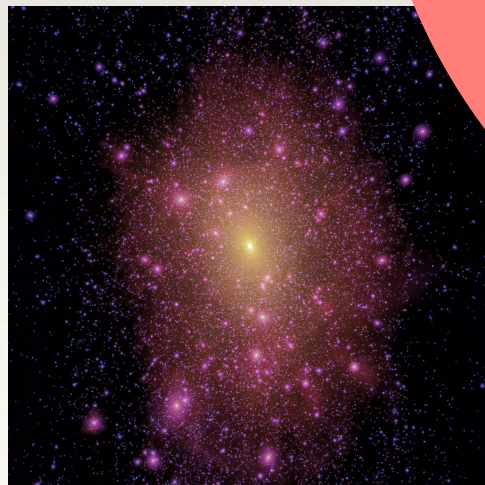


No known modification of gravity can explain all of this.

The Standard Model cannot, either.

A simple extension by one (or several) new “Dark Matter” particles could do the job.

...but no such “Dark Matter” particle has been seen yet

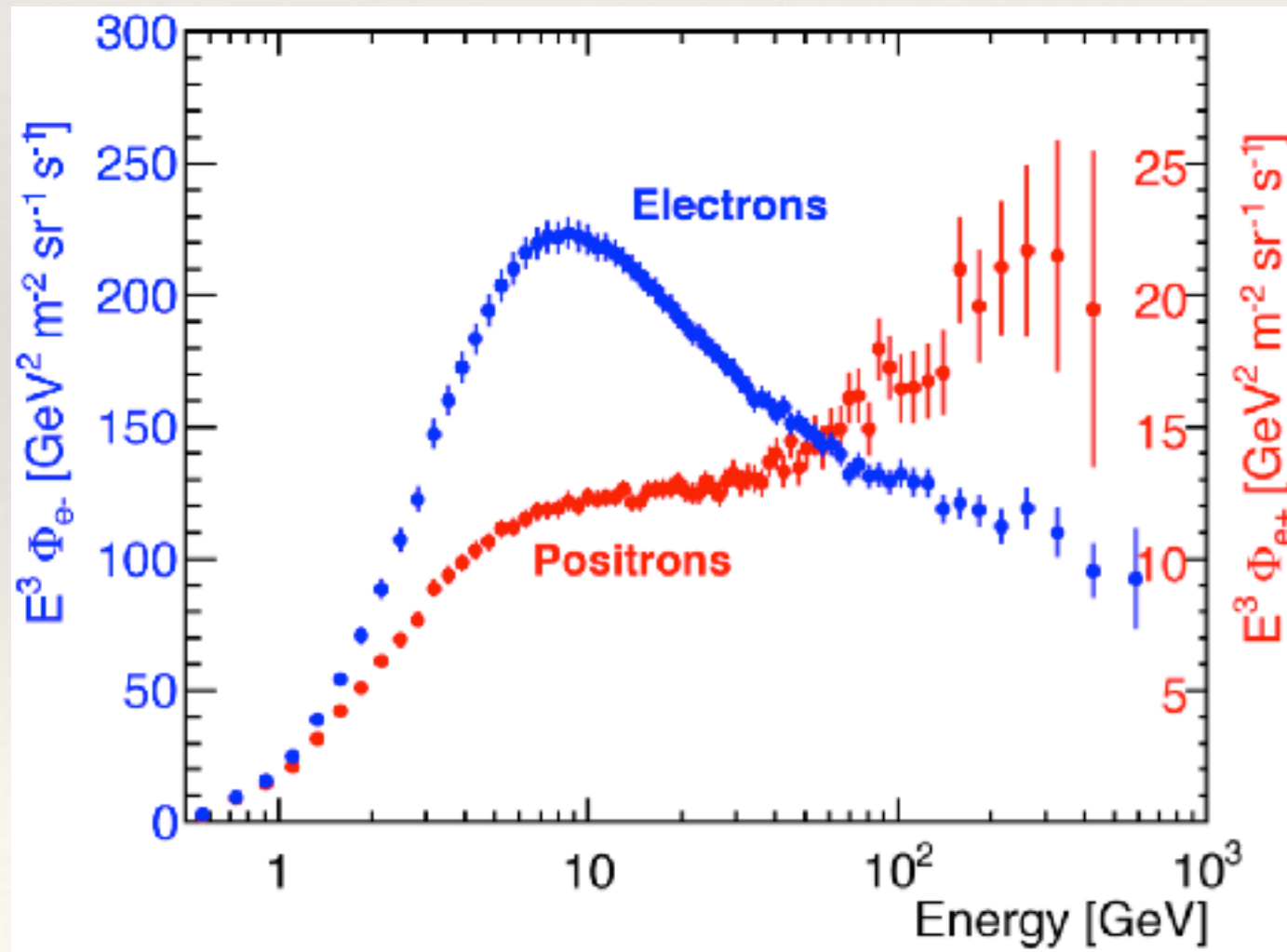




# The Origin on (Baryonic) Matter

# Antimatter in the Universe

- ❖ Is there any antimatter in the present universe? **Yes. But little.**





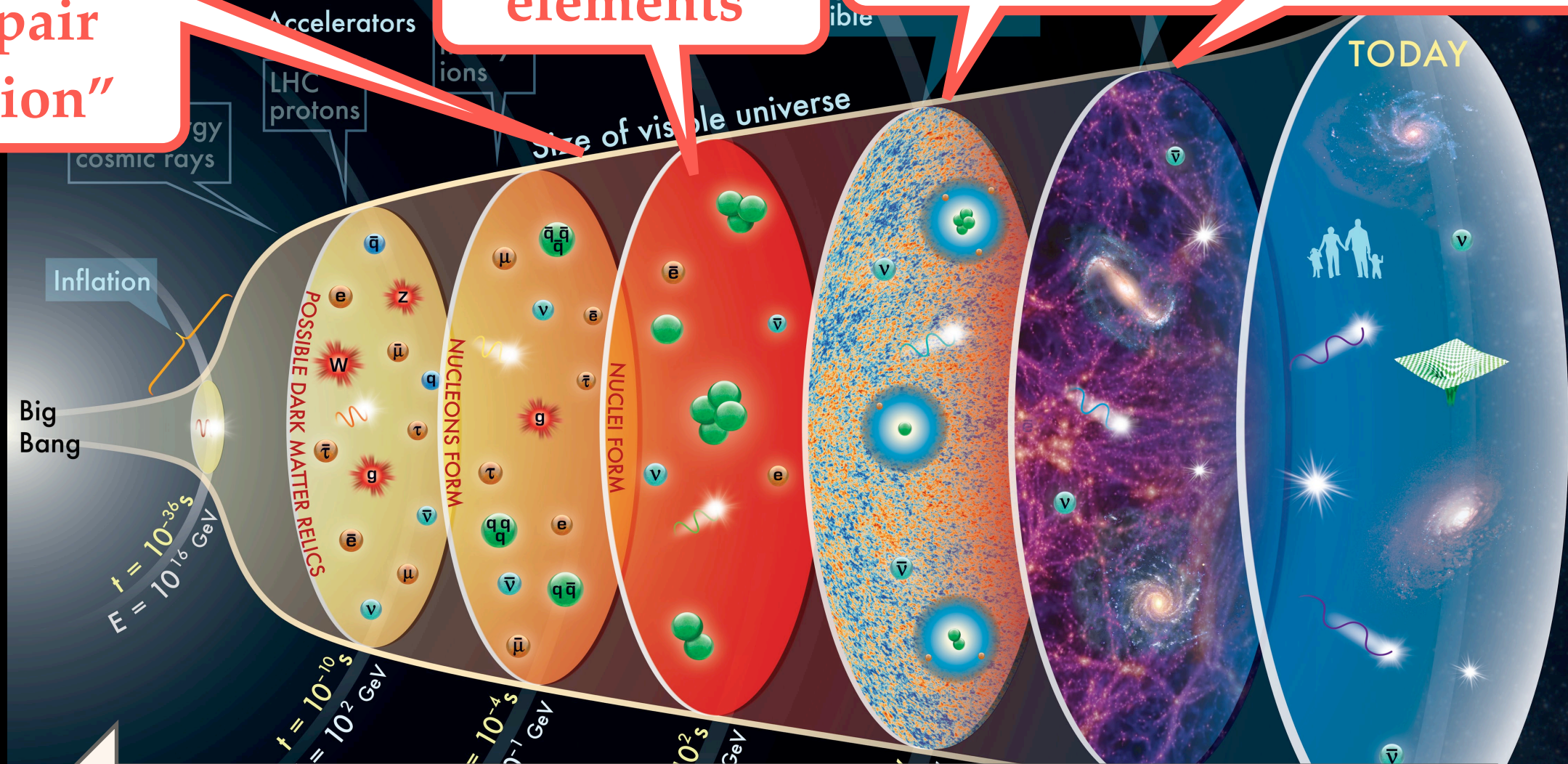
# COSMOLOGY OF

Hot enough  
to produce  
antimatter  
in “pair  
creation”

nuclear  
reactions  
form light  
elements

Cosmic  
Microwave  
Background

optical  
astronomy



energy density, temperature

cosmic time

---

# Baryon Asymmetry of the Universe

---

**The observable universe contains almost no antimatter and a lot more photons than baryons.**

e.g. Canetti/MaD/Shaposhnikov  
[arXiv:1204.4186](https://arxiv.org/abs/1204.4186)

**CMB constraint on  
baryon-to-photon ratio  $\eta$ :**  
$$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$$

(Planck Collaboration)

**BBN constraint on baryon-to-  
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$$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$$

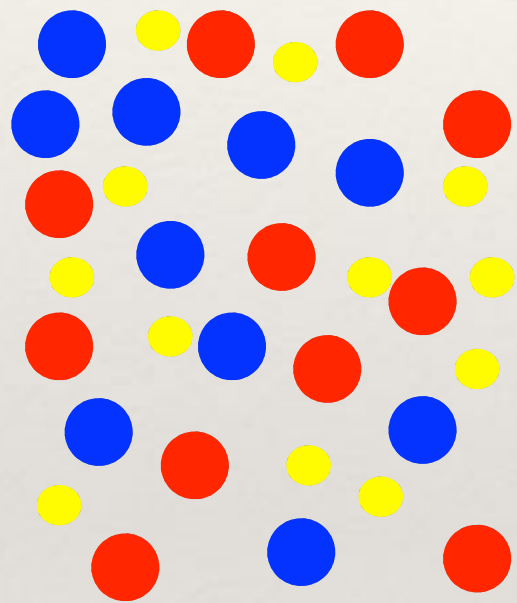
(PDG)



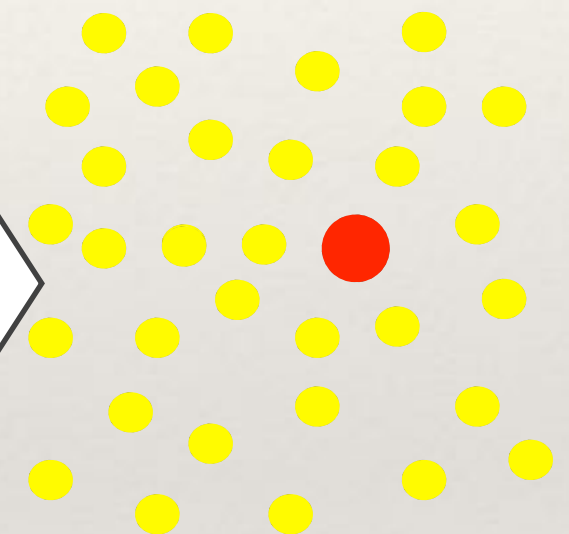
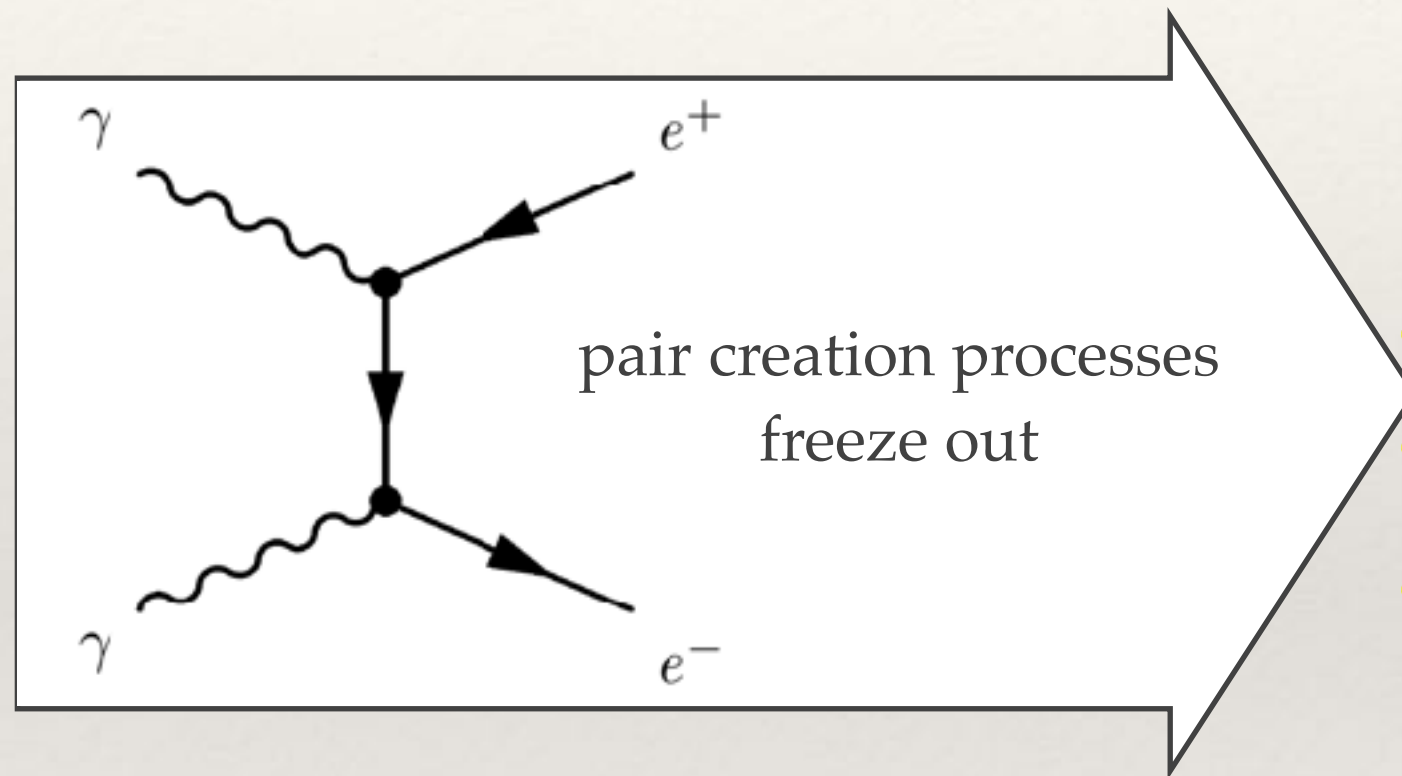
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$$T > 2 mc^2$$



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# Baryon-to-Photon Ratio

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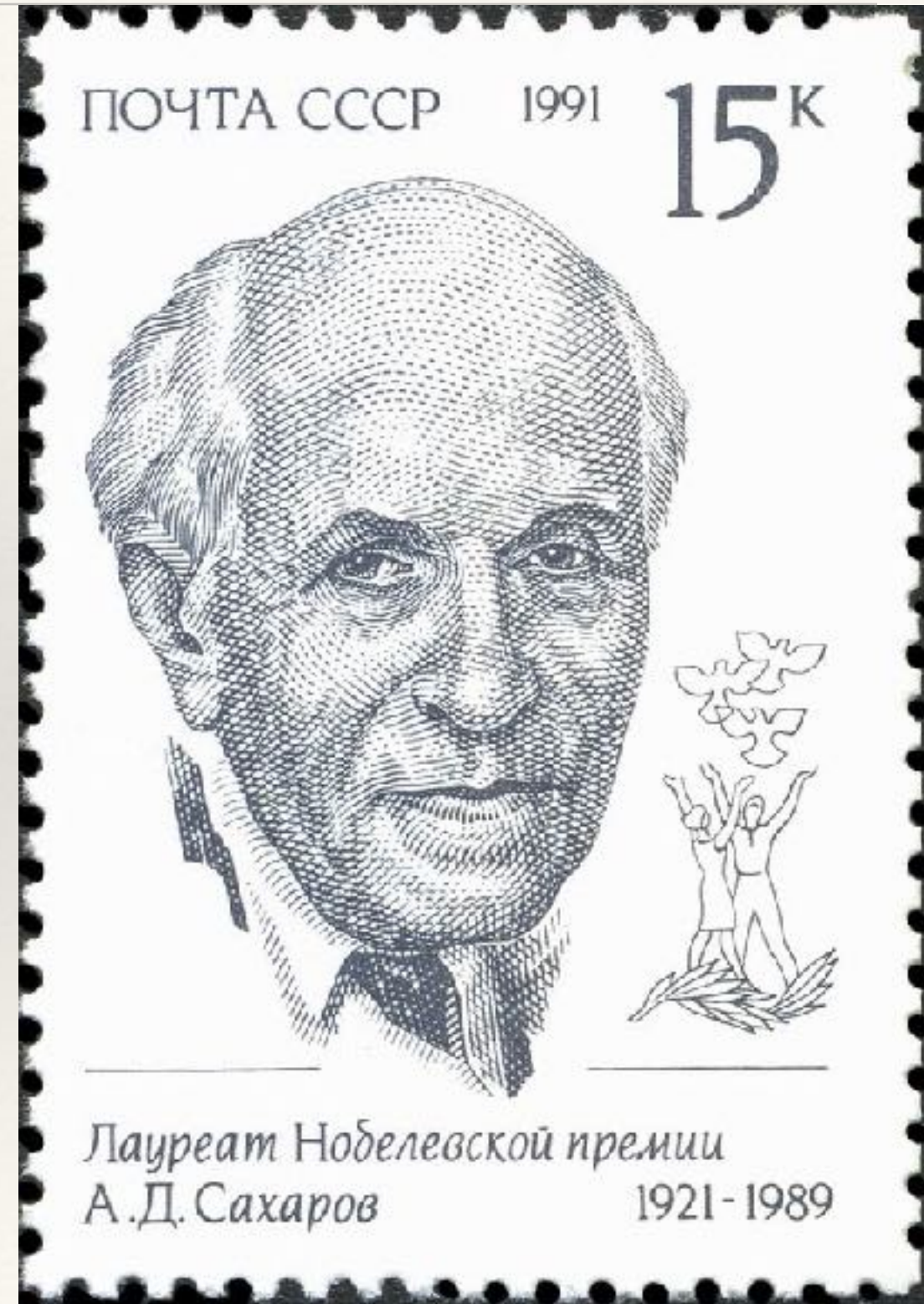
- ❖ When the temperature was very high, **pair creation processes were in equilibrium.**
- ❖ When the temperature dropped below the positron mass, no new antiparticles could be produced, and **all antiparticles were annihilated.**
- ❖ Obviously, some matter survived - so **there was more matter than antimatter in the early universe!**
- ❖ This “baryon asymmetry of the universe” was very small, it corresponds to today’s “**baryon-to-photon ratio**”  
 $\# \text{nucleons} / \# \text{photons} : \sim 1 / 10.000.000.000$



# Where does the asymmetry come from?

## Sakharov Conditions (1967)

- ❖ Baryon number violation
- ❖ C and CP violation
- ❖ Deviation from thermal equilibrium



# Where does the asymmetry come from?

## Sakharov Conditions (1967)

❖ Baryon number violation

Exists in Standard Model  
at  $T > 130 \text{ GeV}$   
(sphaleron)

❖ C and CP violation

Exists in Standard Model  
(weak interaction, CKM phase)  
...but Jarlskog invariant too small!

❖ Deviation from thermal  
equilibrium

Exists in Standard Model  
(Hubble expansion of the universe)  
...but deviation too small!



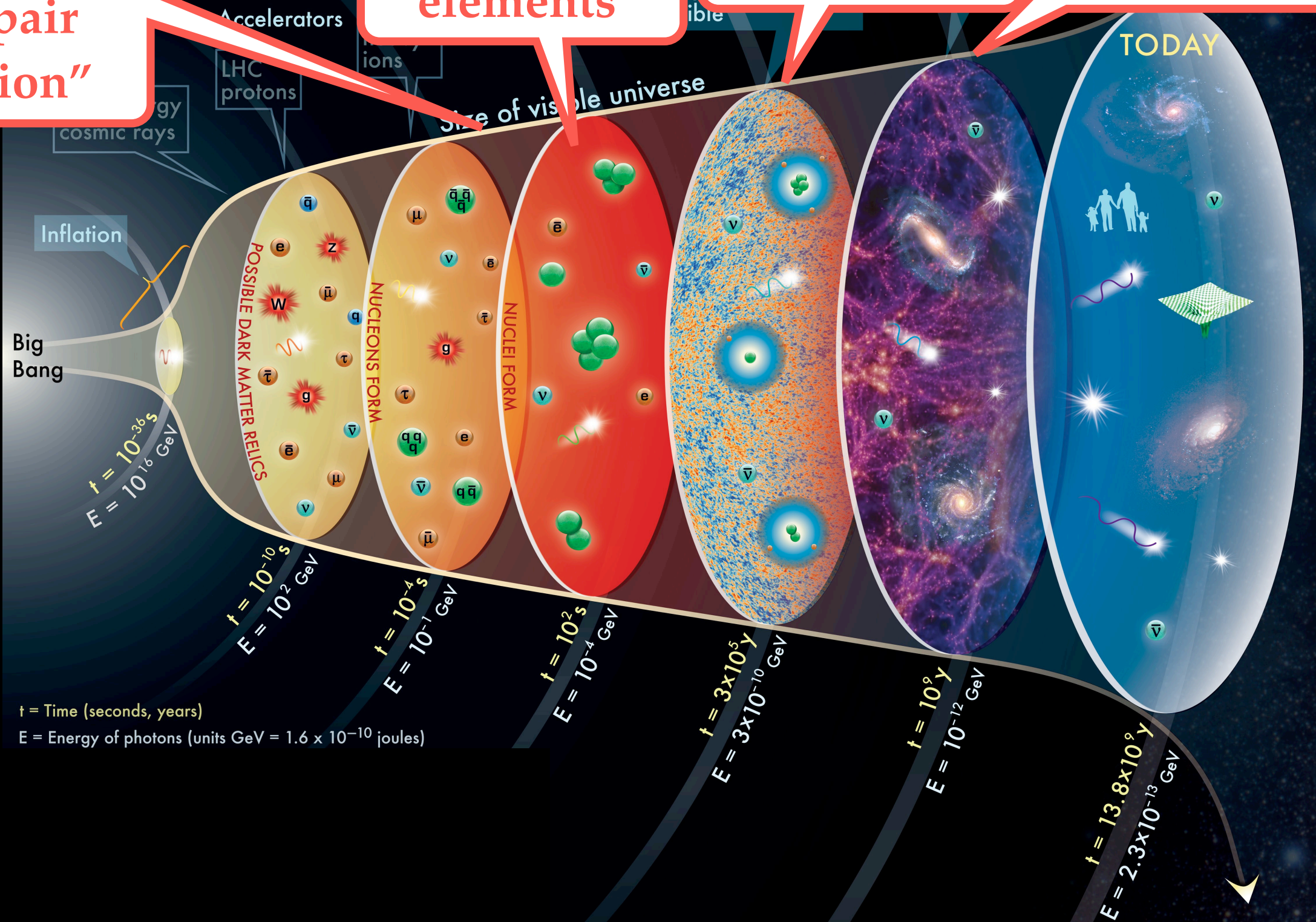
# COSMOLOGY OF

Hot enough  
to produce  
antimatter  
in “pair  
creation”

nuclear  
reactions  
form light  
elements

Cosmic  
Microwave  
Background

optical  
astronomy



$t$  = Time (seconds, years)

$E$  = Energy of photons (units  $\text{GeV} = 1.6 \times 10^{-10}$  joules)



# LORY OF

# Cosmic Microwave Background

# optical astronomy

# Sphaleron freezeout

$t = 3 \times 10^5 \text{ y}$   
 $E = 3 \times 10^{-10} \text{ GeV}$

$t = 10^9 \text{ Y}$   
 $E = 10^{-12} \text{ GeV}$

$$t = 13.8 \times 10^9 \text{ y}$$
$$E = 2.3 \times 10^{-13} \text{ GeV}$$

Supported by DOE



# ORY OF

Hot enough  
to produce  
antimatter  
in "pair  
creation"

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Microwave  
Background

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**Baryon  
number  
diluted  
by inflation**

**Baryon number conserved**

Cosmic  
Inflation  
dilutes pre-  
existing  
asymmetry

Sphaleron  
freezeout



ORY OF

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Microwave  
Background

optical  
astronomy

**Baryon  
number  
diluted  
by inflation**

Accelerators  
LHC  
protons

Size of visible universe

TODAY

**Baryon number conserved**

$t = 10^{-10}$  s  
 $E = 10^{16}$  GeV

Cosmic  
Inflation  
dilutes pre-  
existing  
asymmetry

**Baryon asymmetry generated  
("Baryogenesis")**



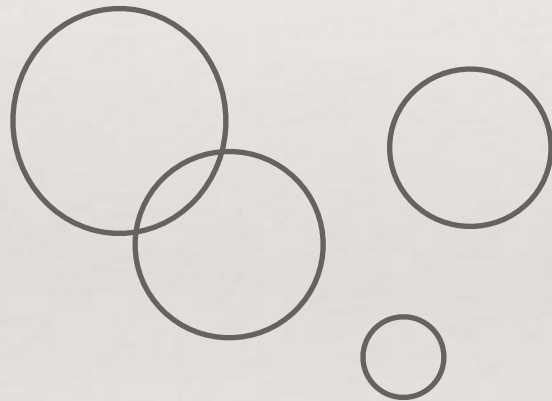
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# Where does the asymmetry come from?

---

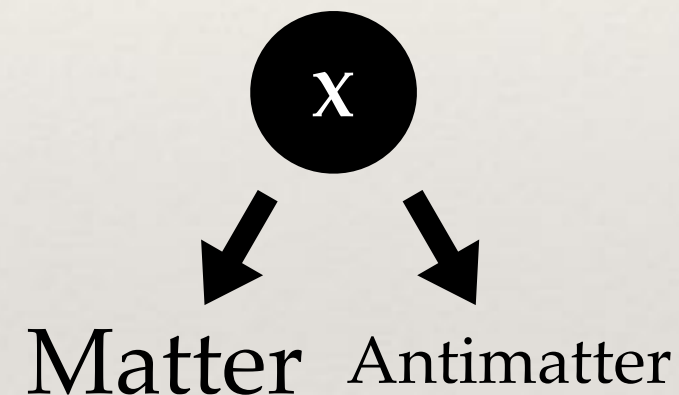
## Baryogenesis requires New Physics!

Cosmic phase transition?



Electroweak baryogenesis,  
...

Decay of a heavy particle?



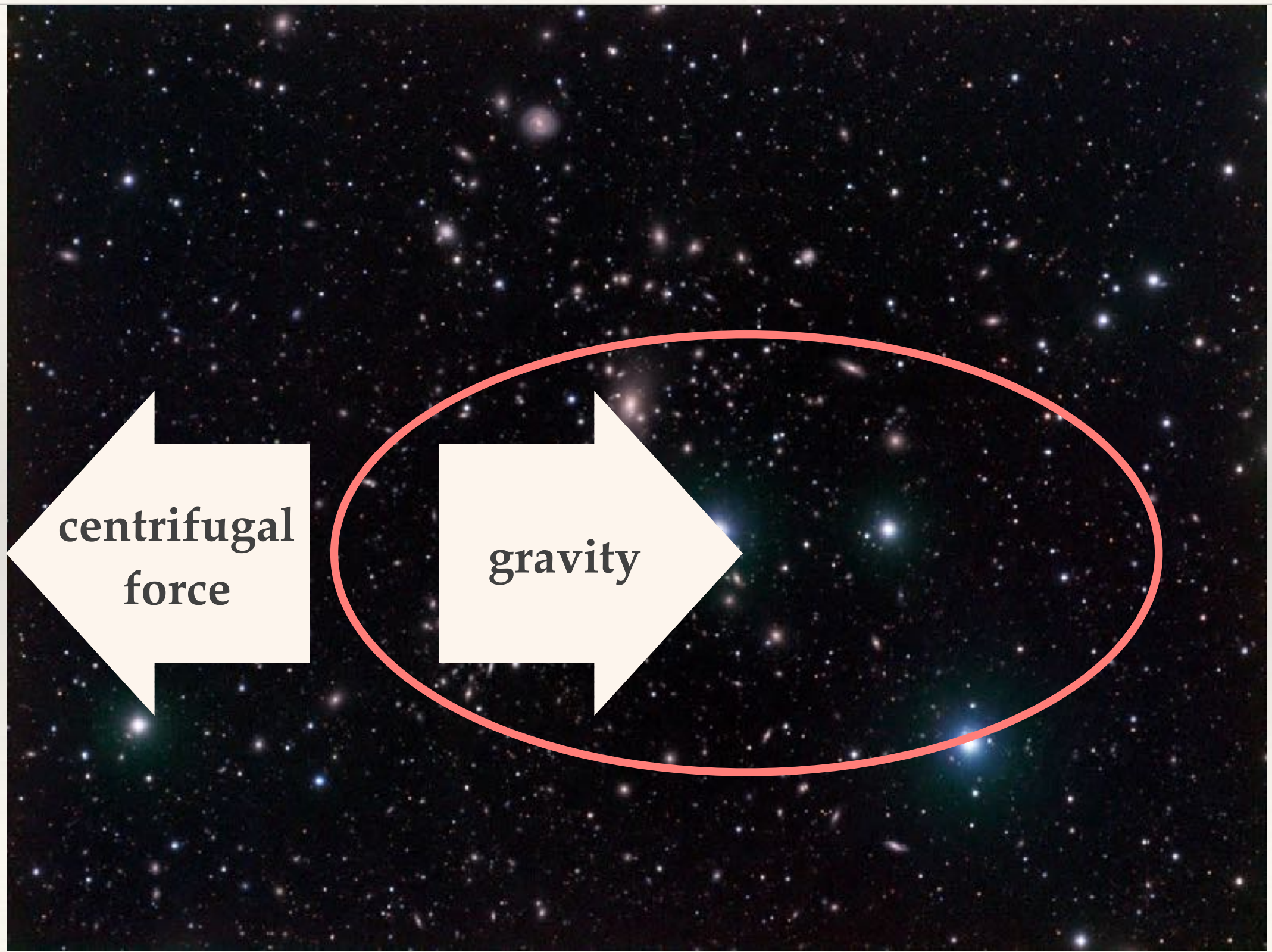
GUT baryogenesis,  
leptogenesis,  
...

# Appendix:

## Dark Matter vs Modified Gravity



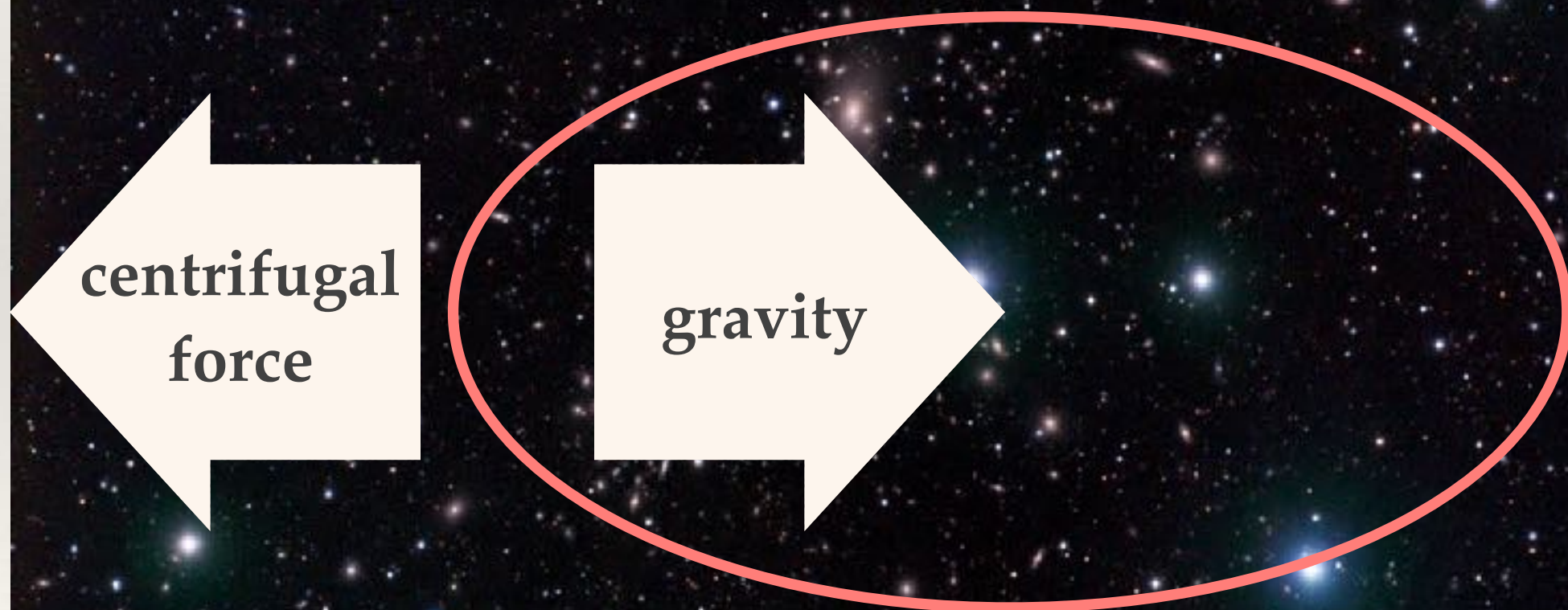
# 1) Galaxy Clusters





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The mass of all the stars and dust is not enough to explain the gravitational force that is needed to keep the cluster together!





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centrifugal  
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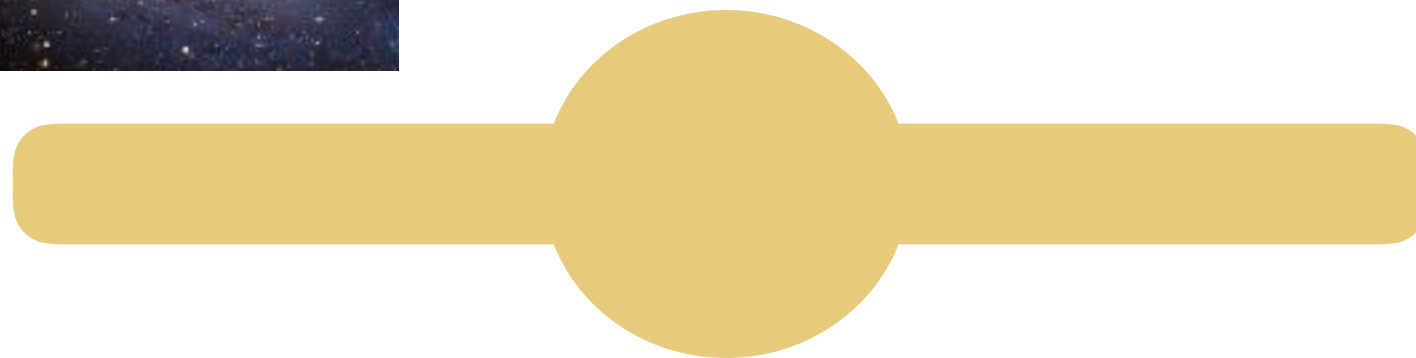
And if 2), it could be anything that doesn't shine or absorb too much



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## 2) Galaxy Rotation Curves

---

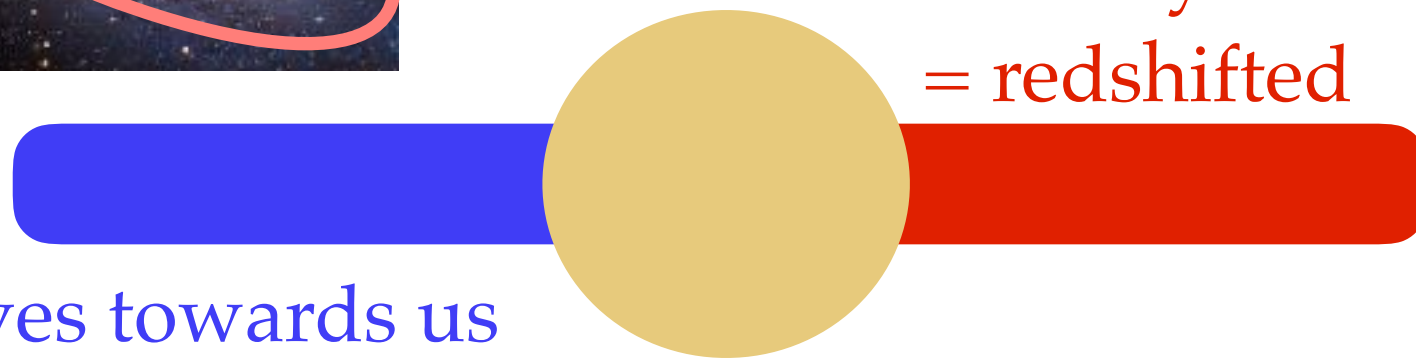


## 2) Galaxy Rotation Curves



moves towards us  
= blueshifted

moves away from us  
= redshifted





## 2) Galaxy Rotation Curves

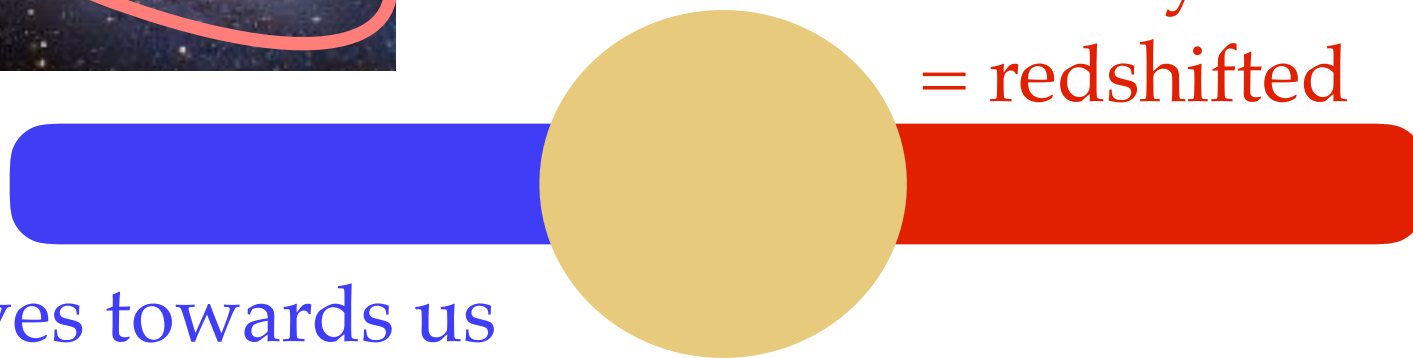


$$\frac{m}{r^2} M(r) G = \frac{m}{r} v^2(r)$$

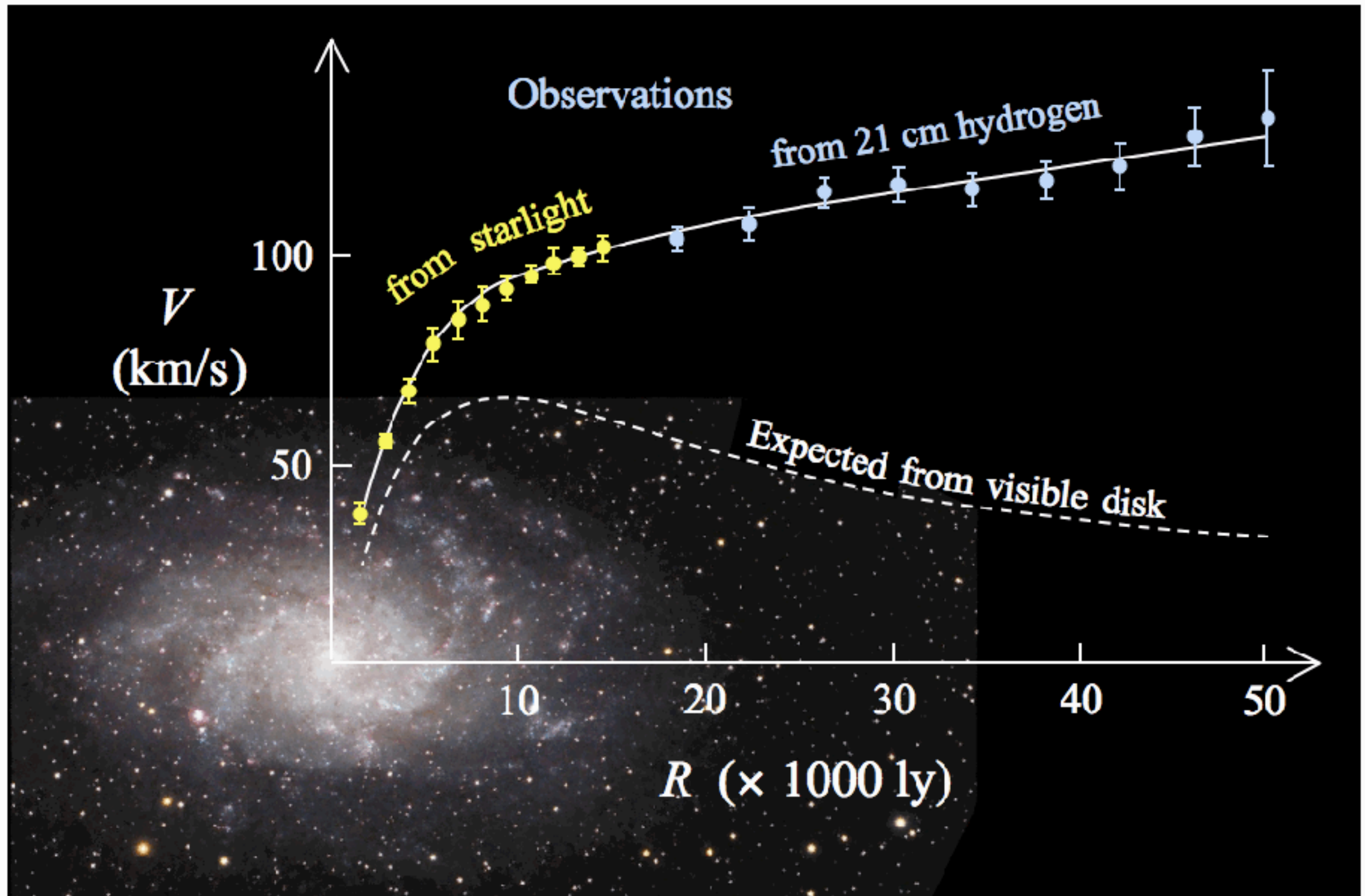
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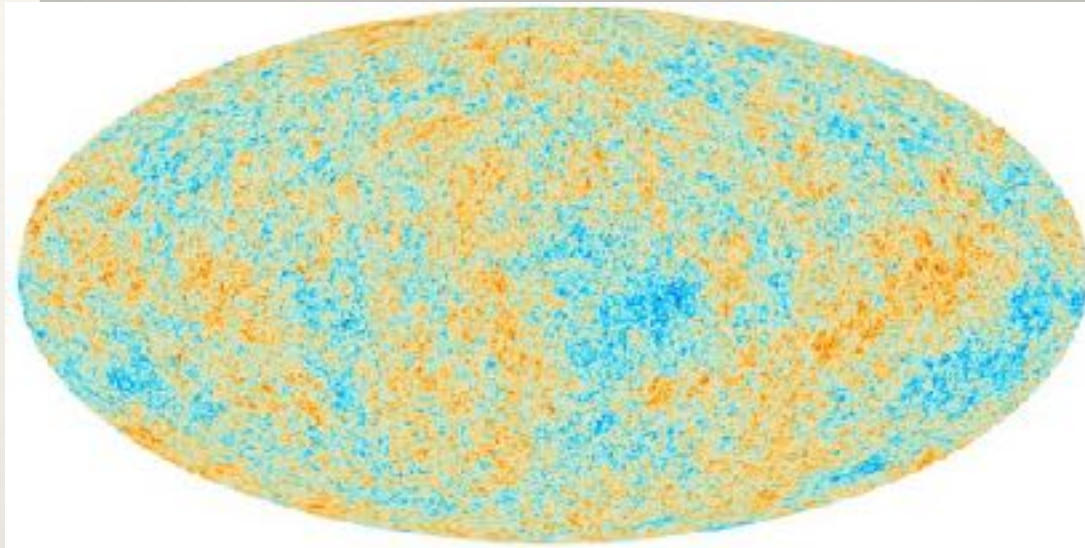
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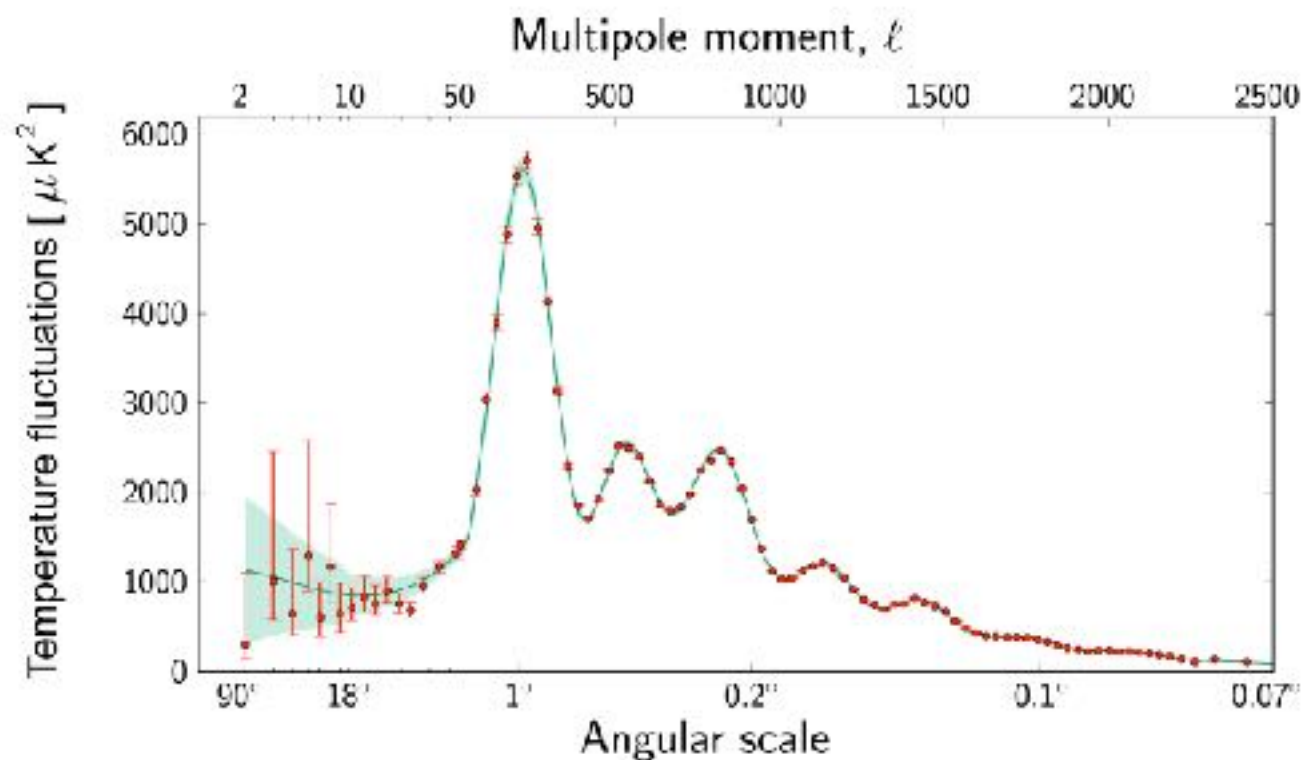
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# 3) Cosmic Microwave Background



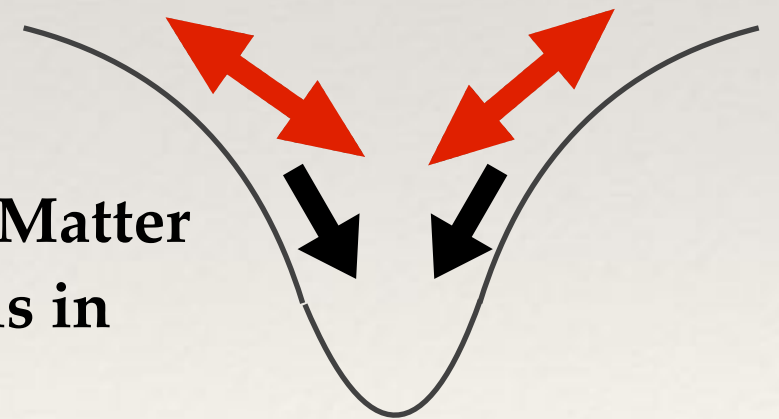
Radiation, baryons and Dark Matter affect the acoustic oscillations in the primordial plasma in different ways...



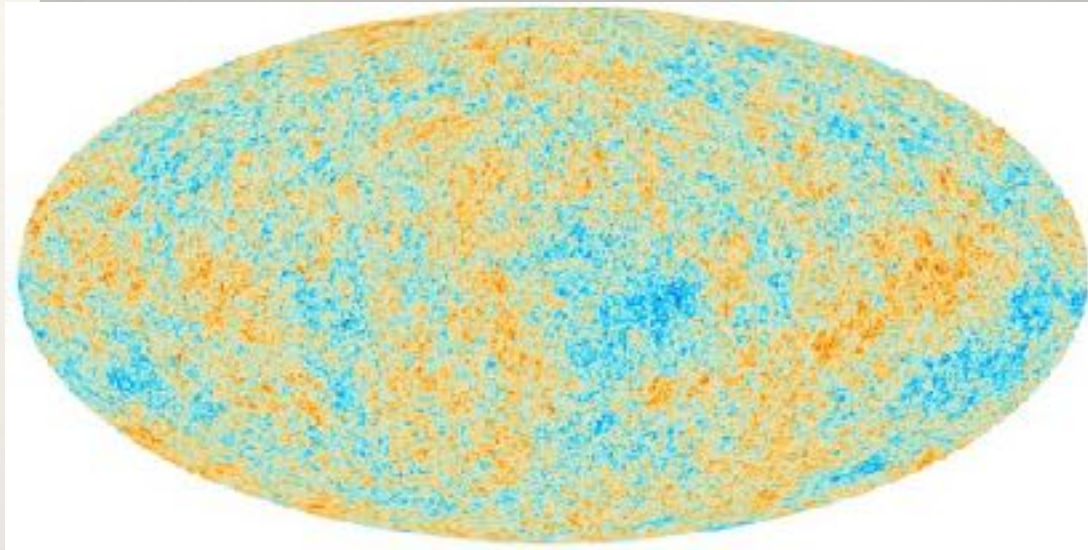
**ordinary matter/radiation oscillates  
due to radiation pressure**

**Dark Matter  
falls in**

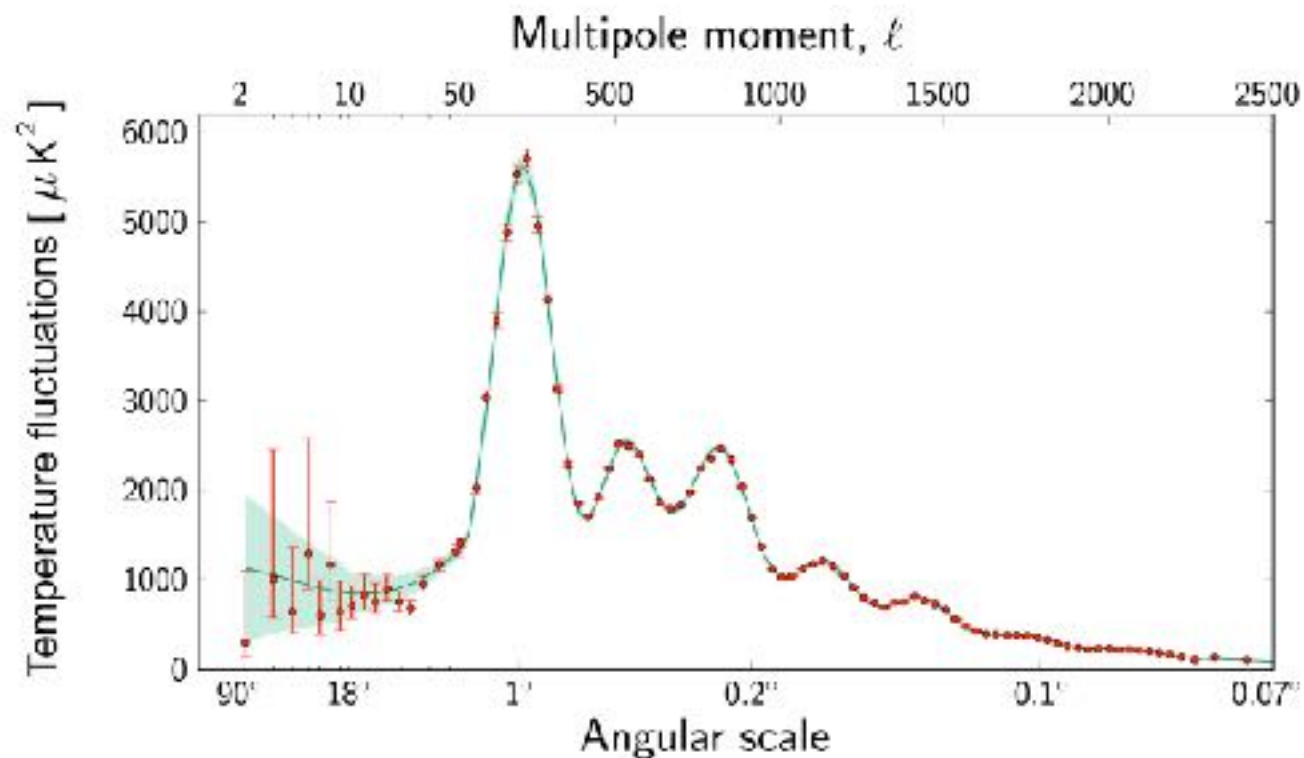
**gravitational potential well**



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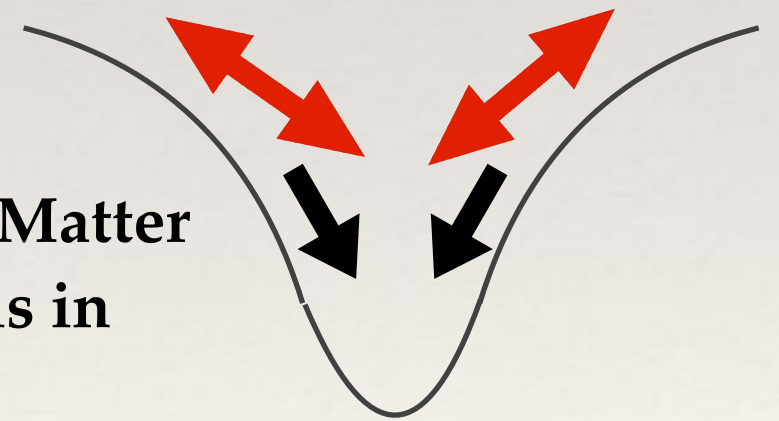
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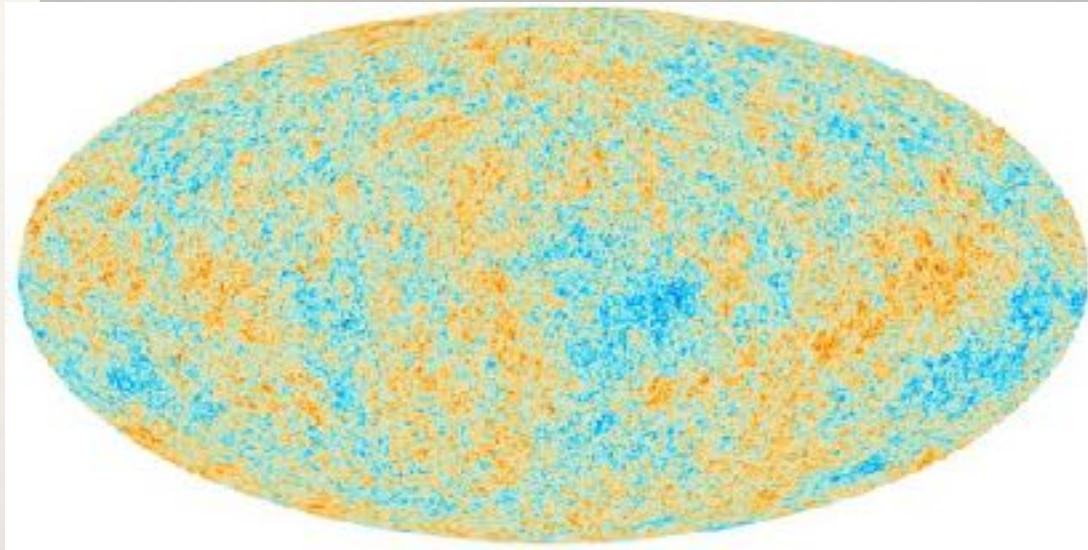
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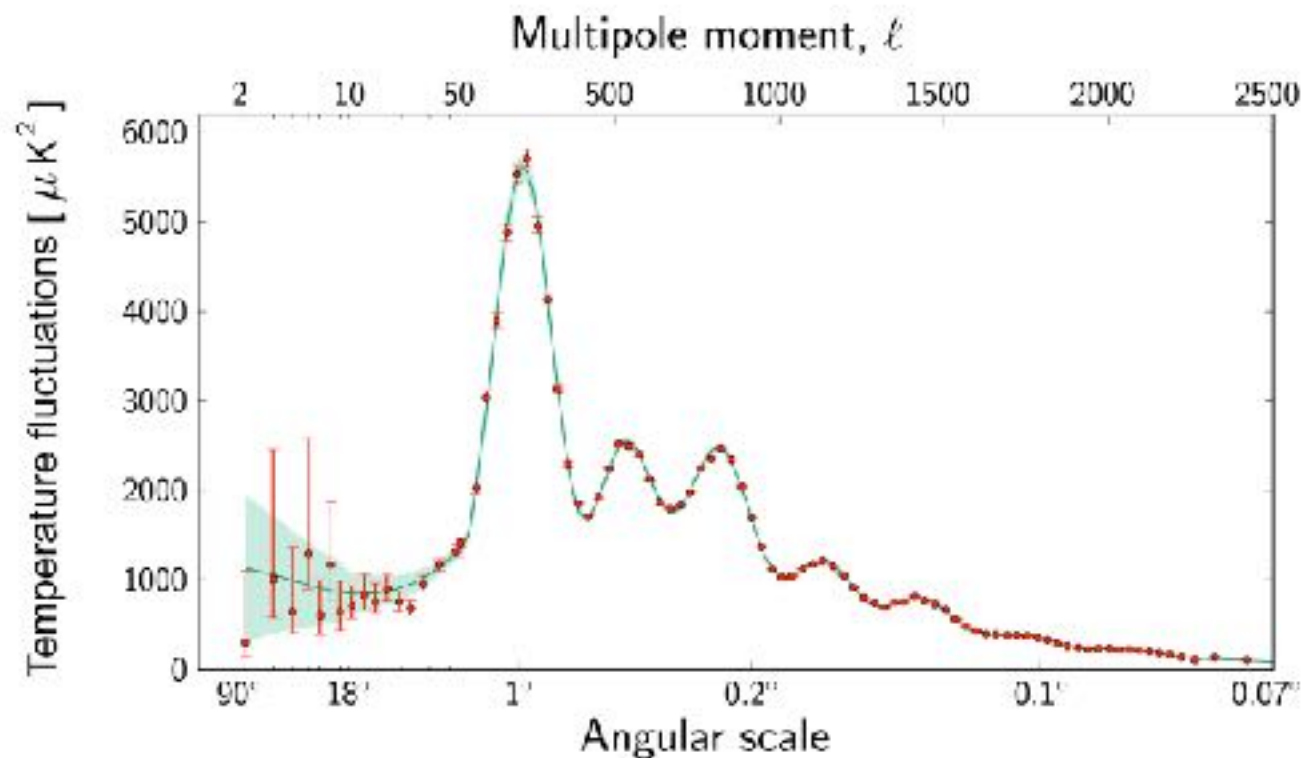


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Very difficult to explain with modified gravity.

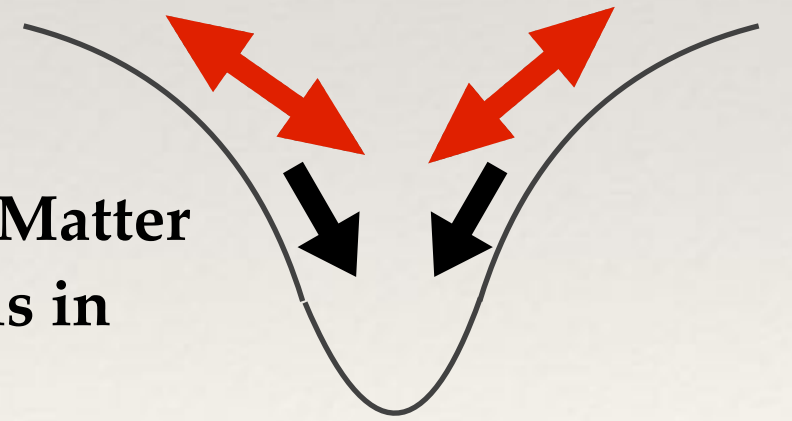
Shows that DM is not made of lumps of baryons.



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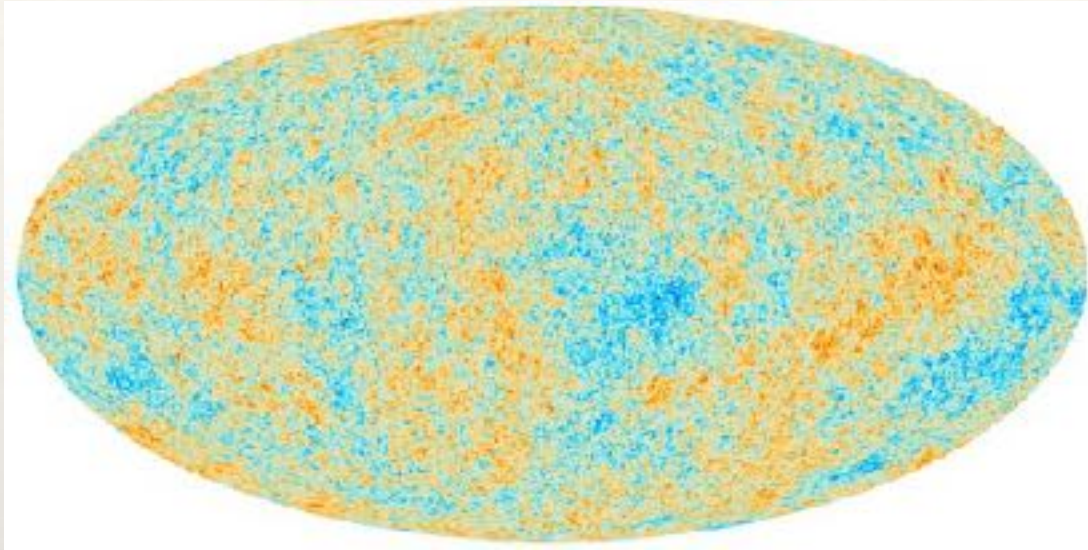
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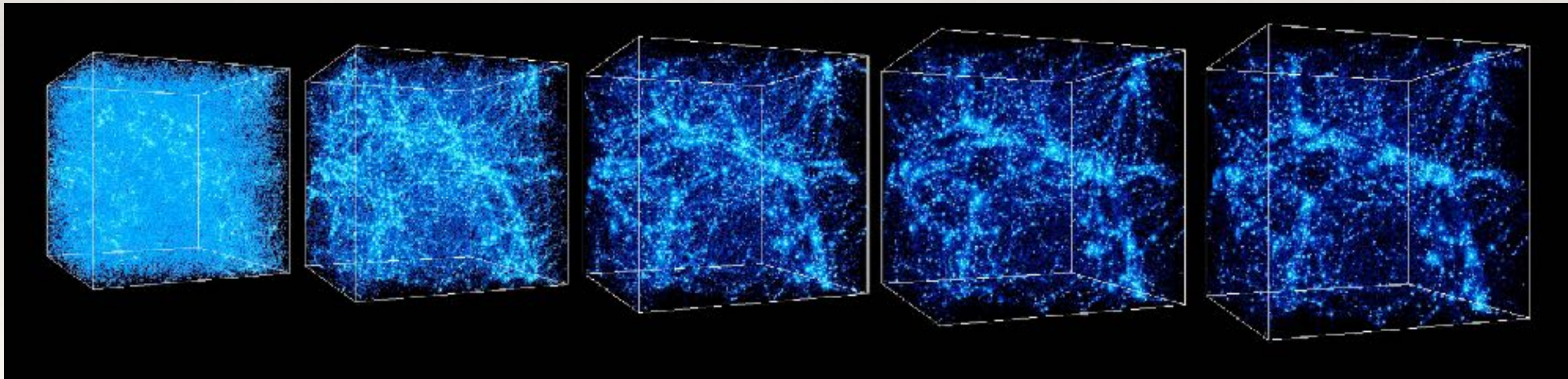


# 4) Structure Formation



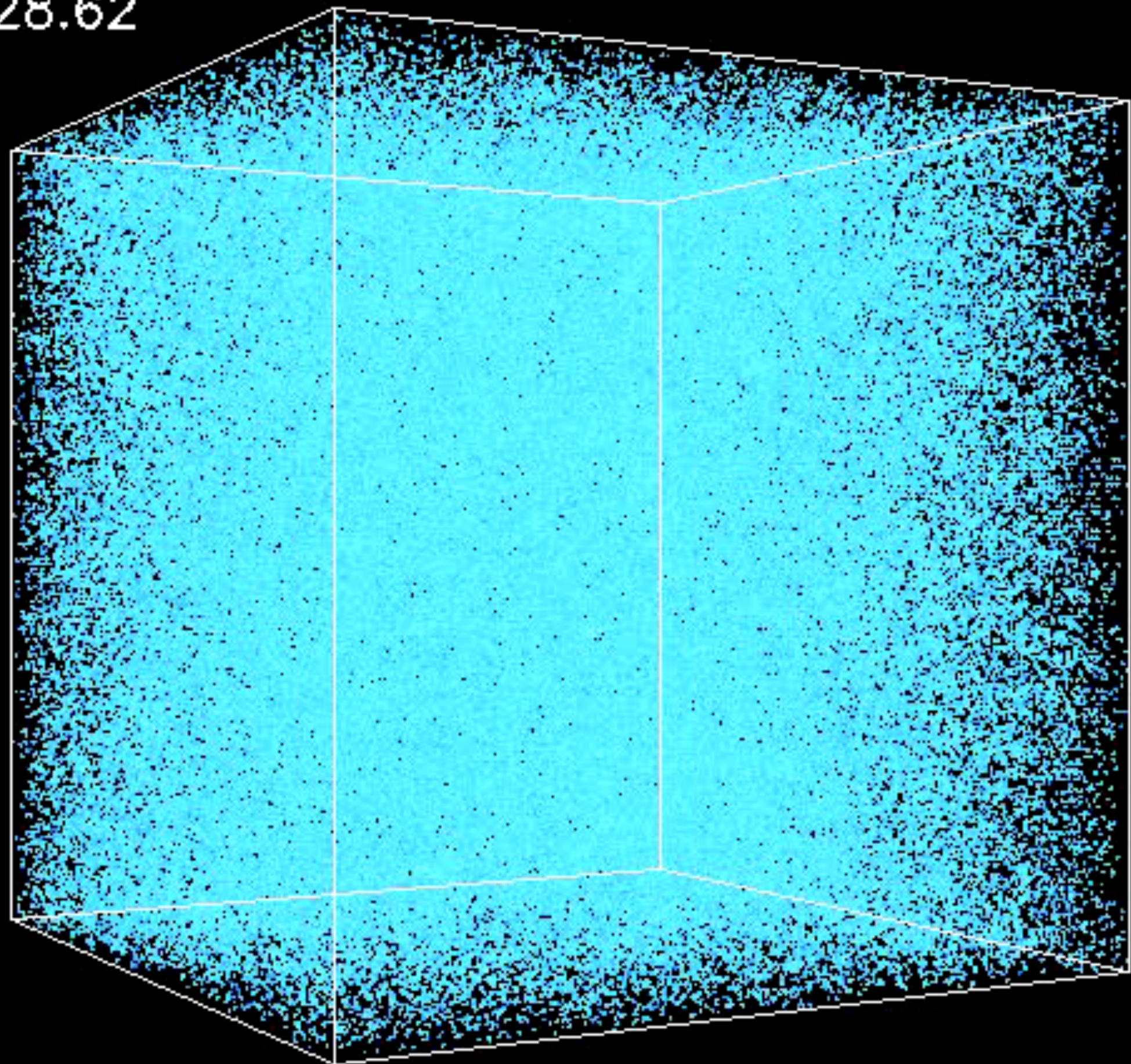
The early universe was very homogeneous and isotropic...

... structure formed by gravitational collapse of small inhomogeneities  $\sim 1 / 100.000$



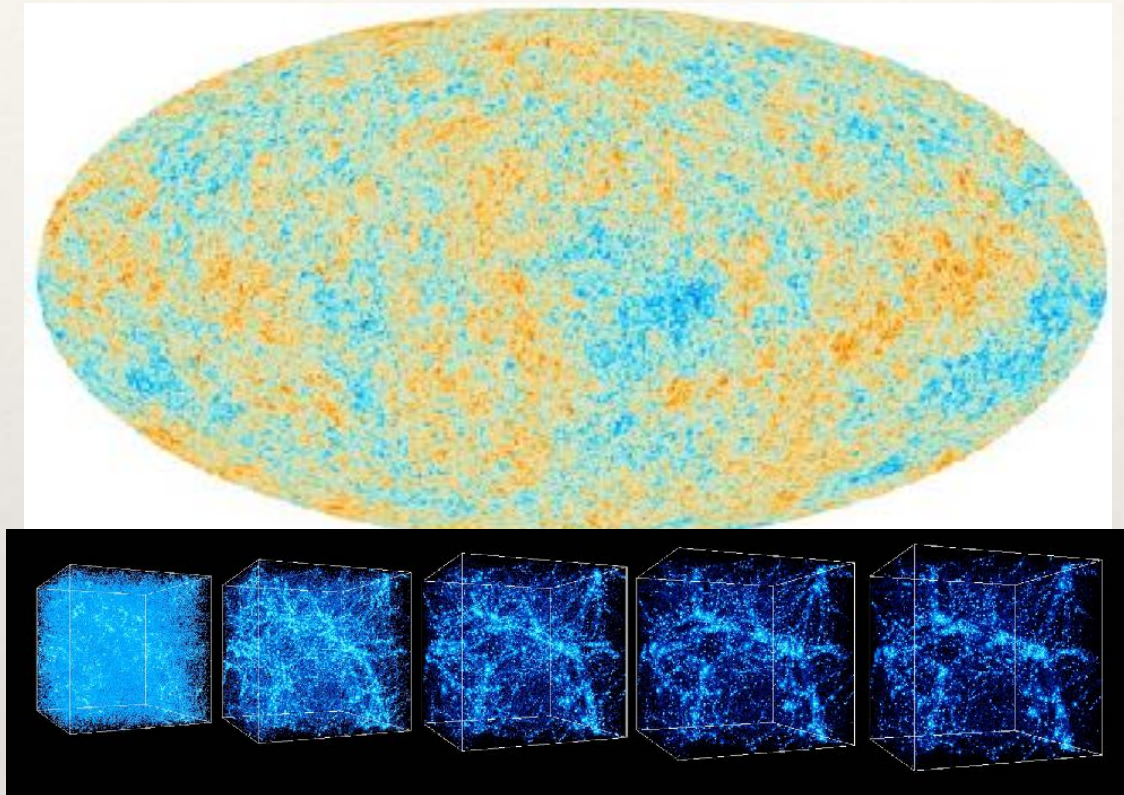


$z=28.62$





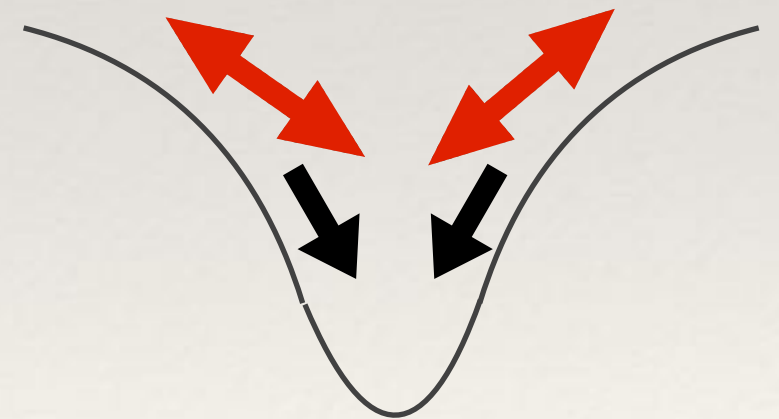
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gravitational potential well

Simulations only agree with observation if this process starts before the CMB decoupled

**Must be driven by particles that do not feel the radiation pressure!**



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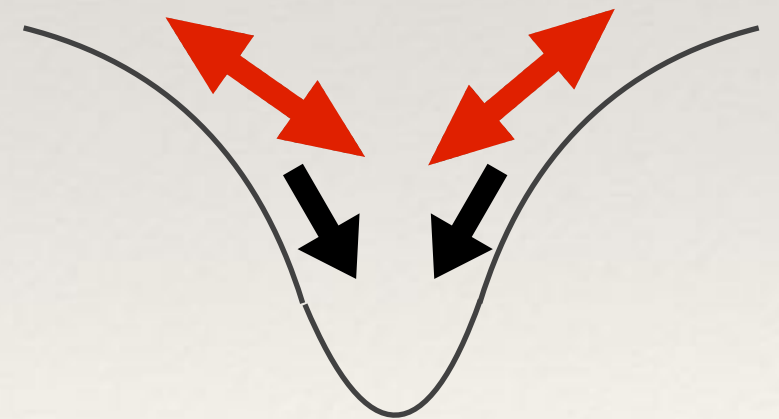
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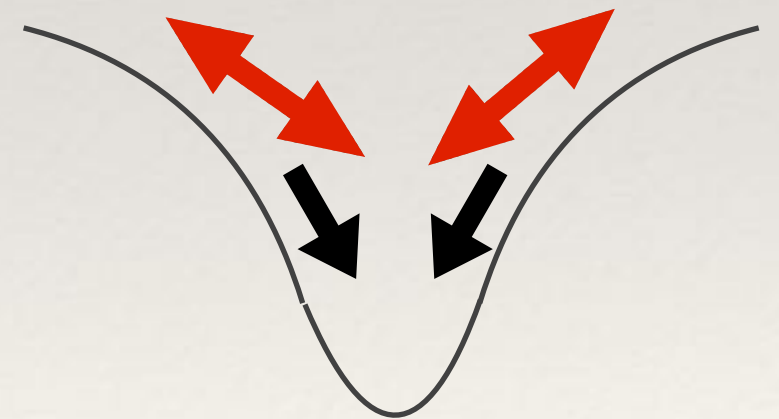
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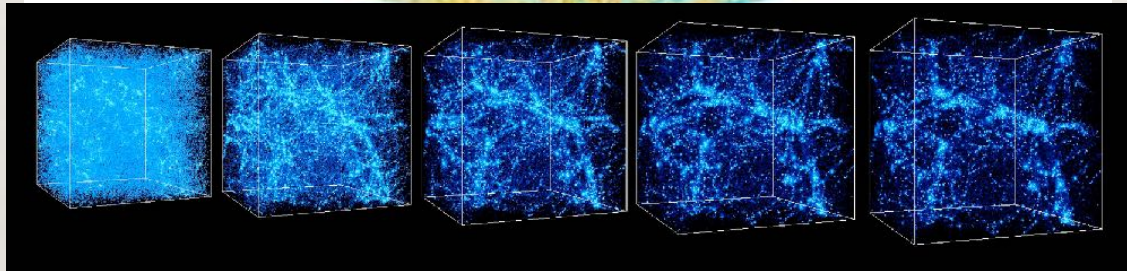
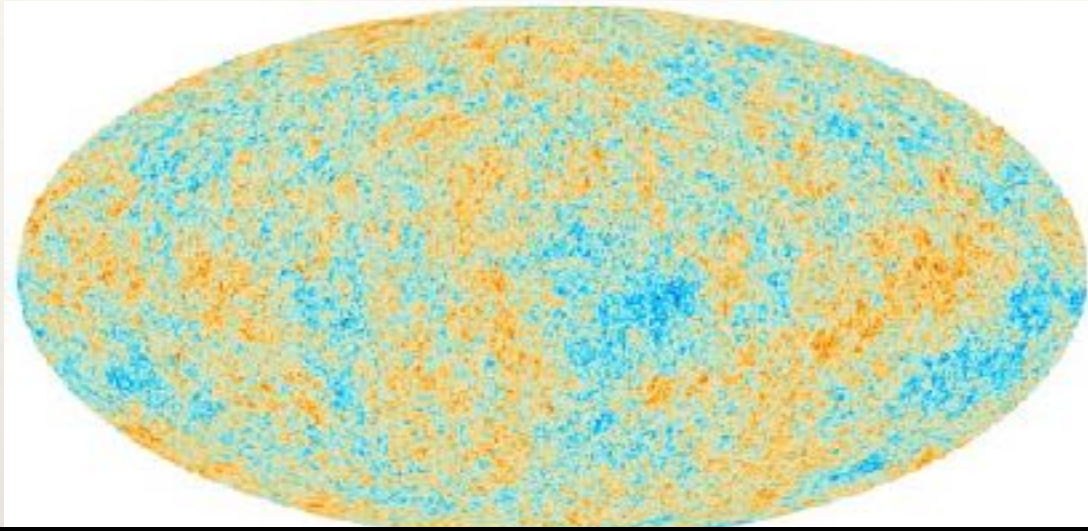
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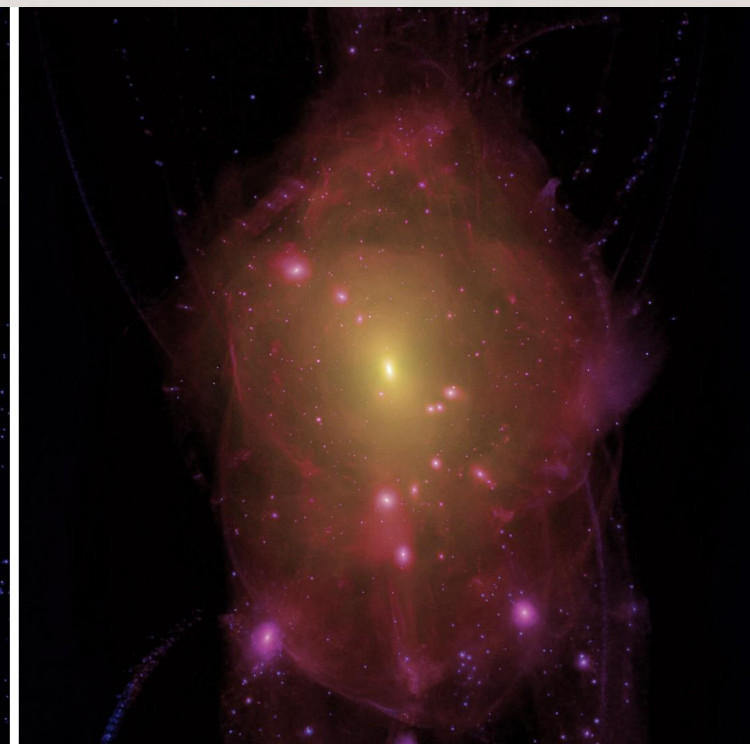


Movement of Dark Matter particles during structure formation “smears out” the inhomogeneities...

... which leads to a suppression of small scale structures in the universe!

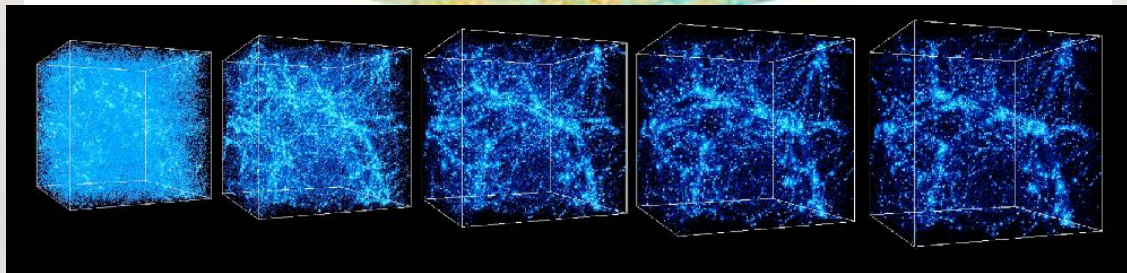
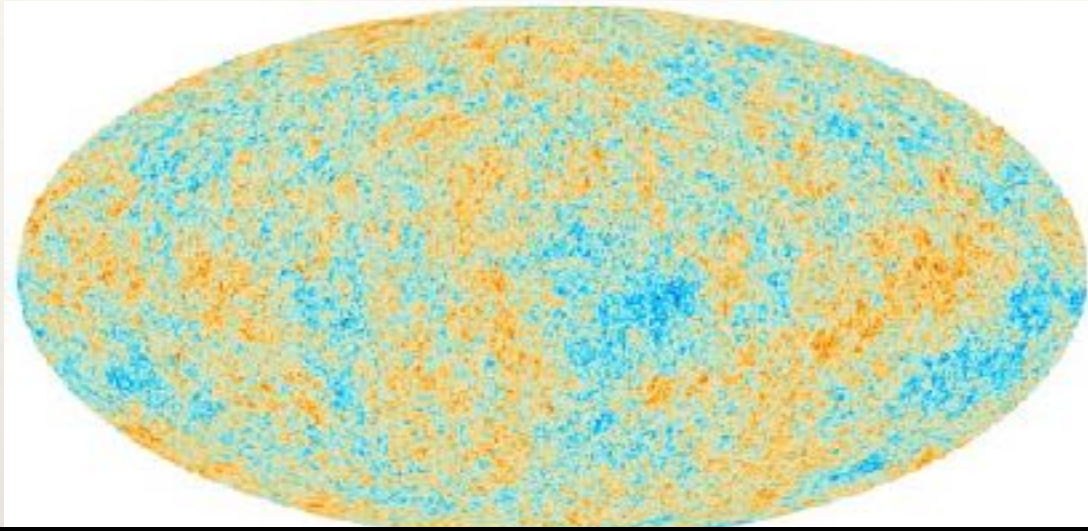
“cold” DM

“warm” DM





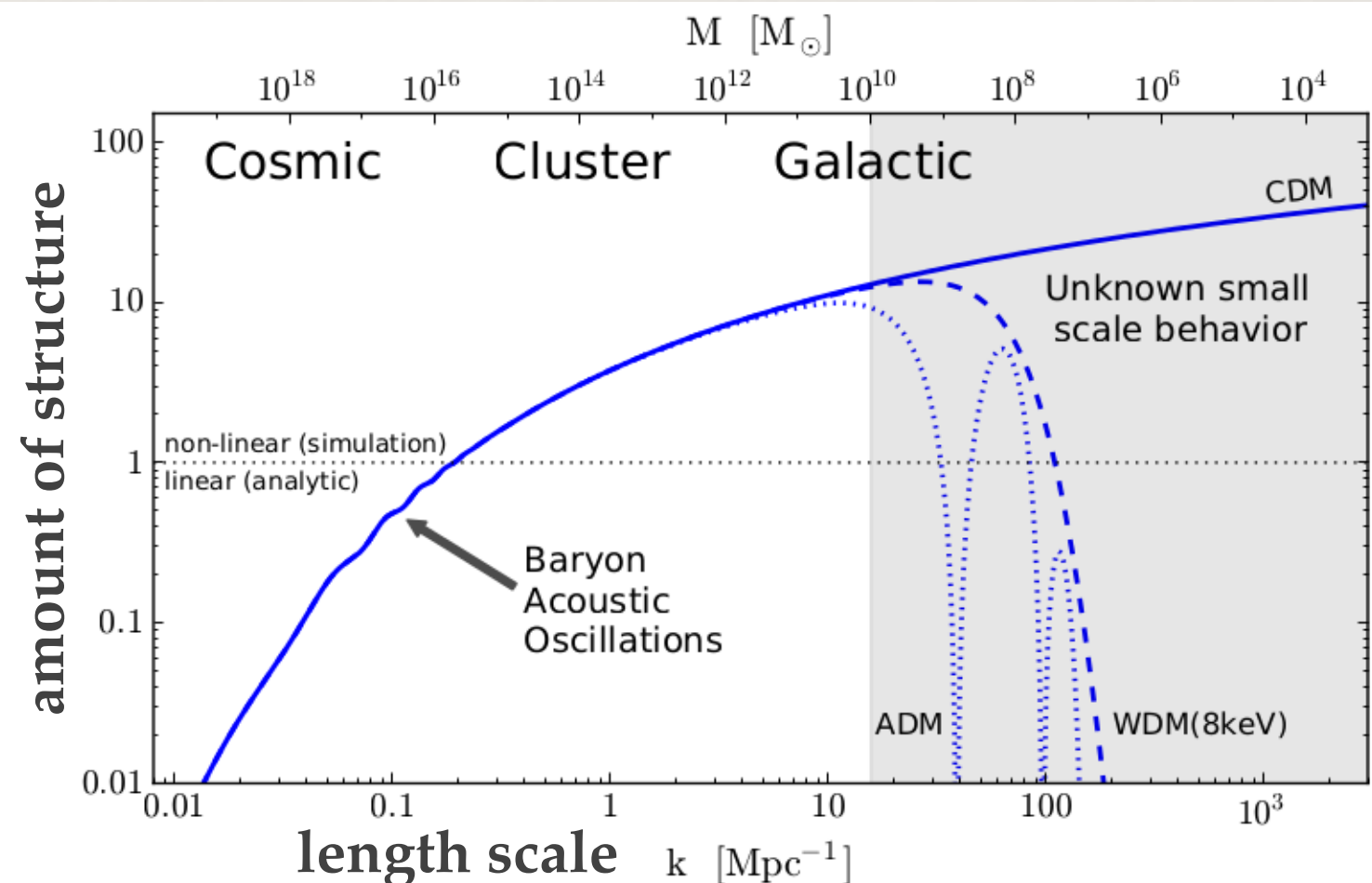
# 4) Structure Formation



This can be quantified in terms of the **matter power spectrum**

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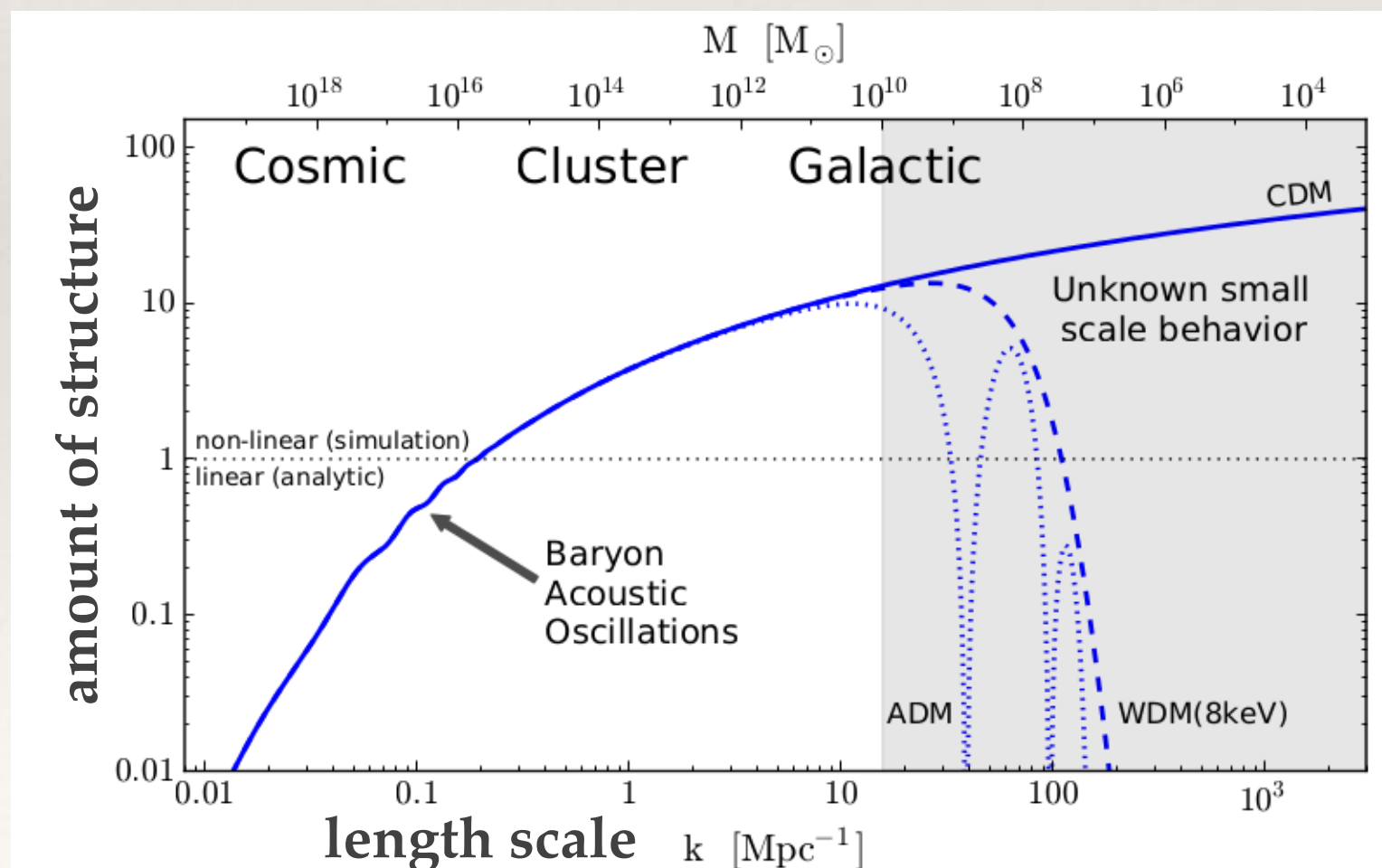
# 4) Structure Formation

Dark Matter must be (relatively) “cold”, i.e., non-relativistic at the time of structure formation

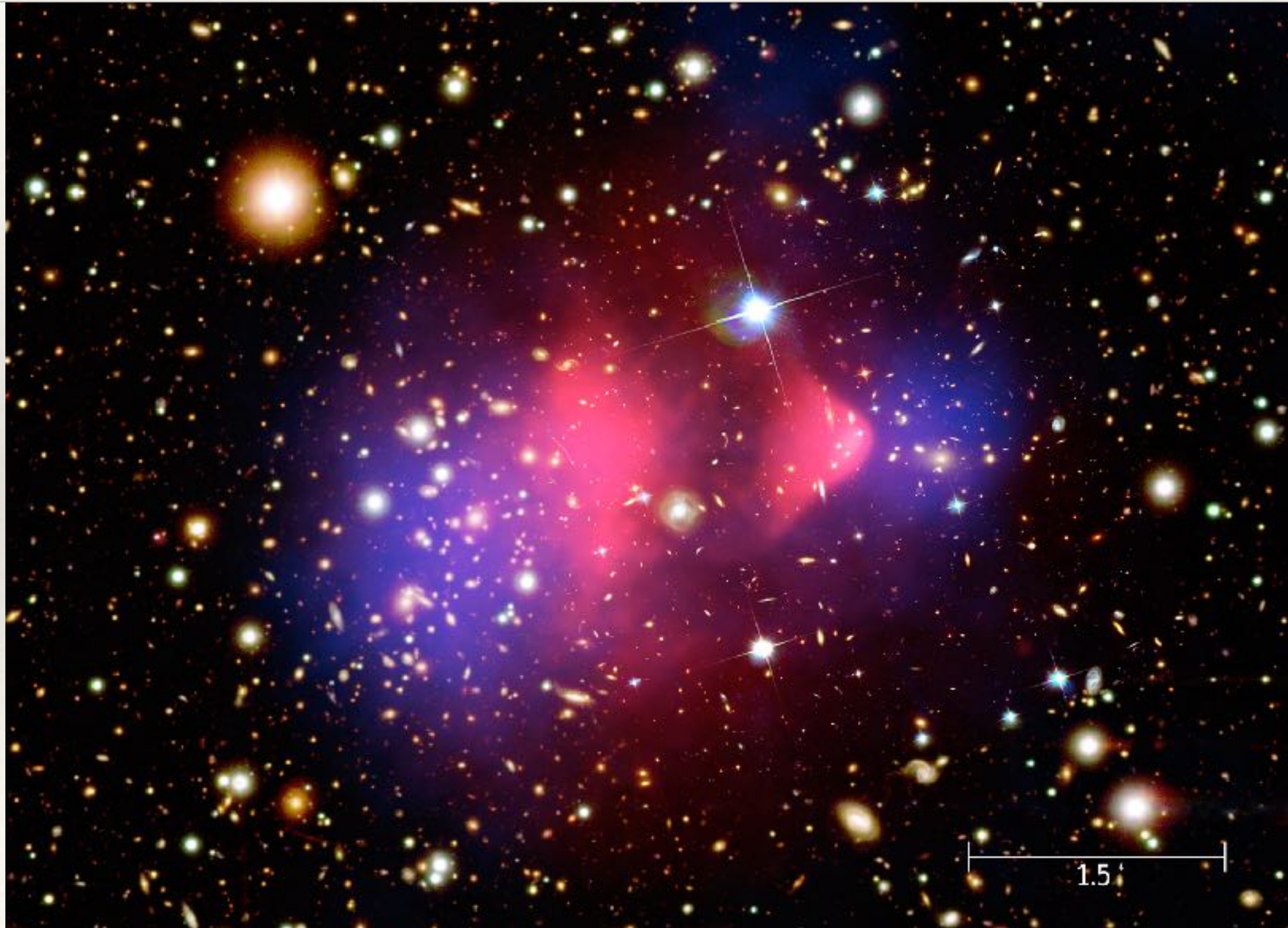
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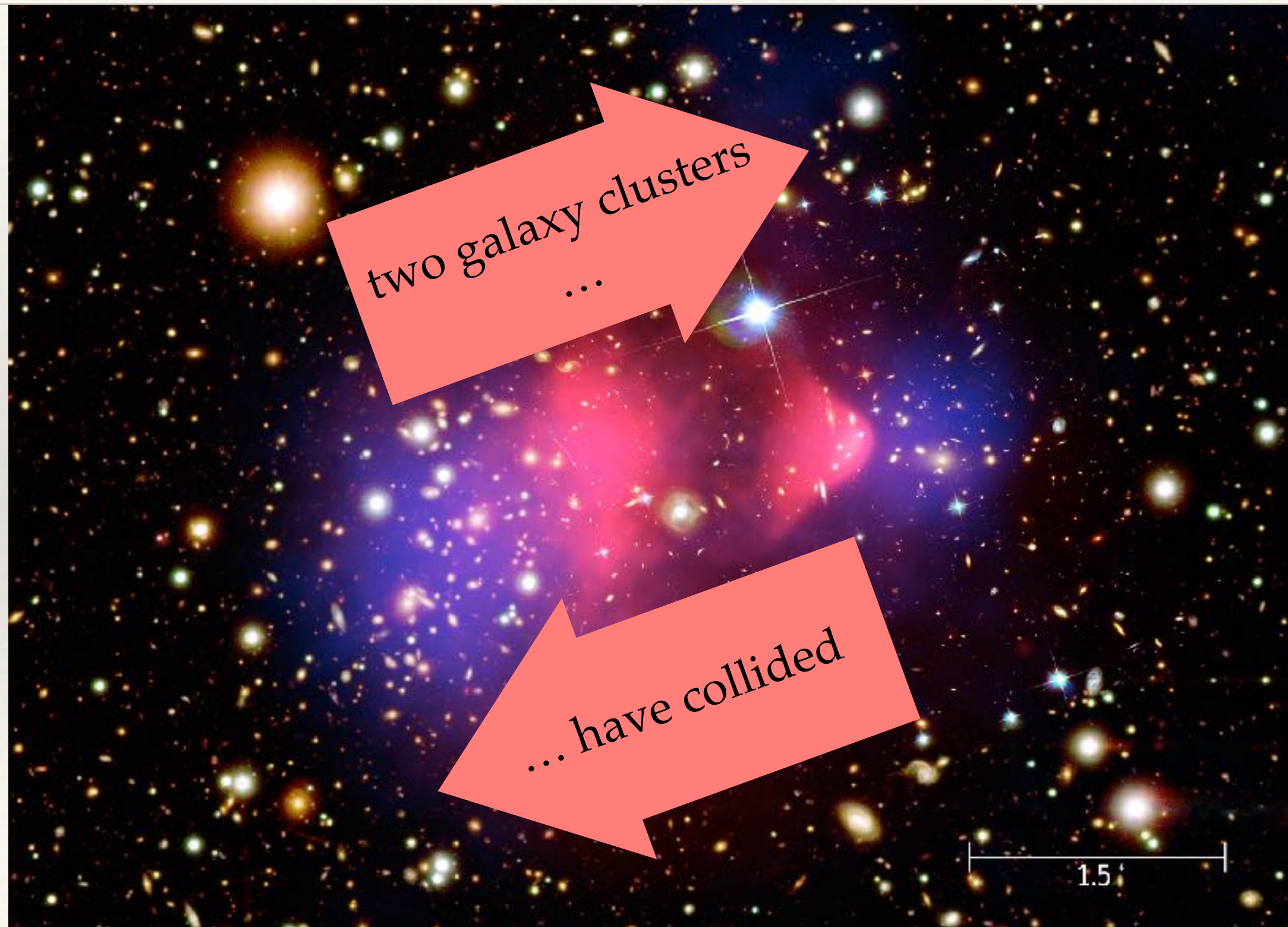


## 5) Bullet Cluster (and friends)



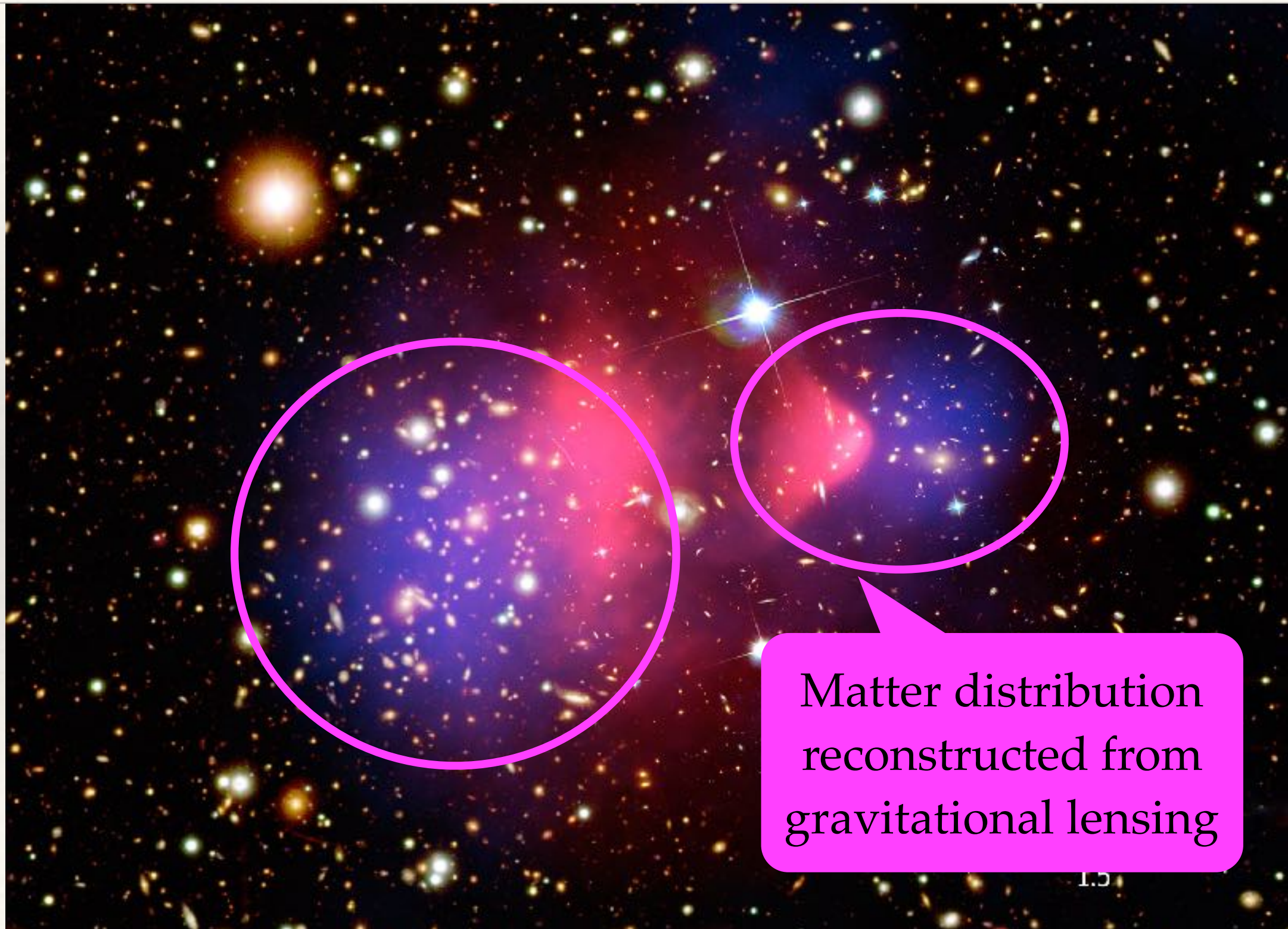


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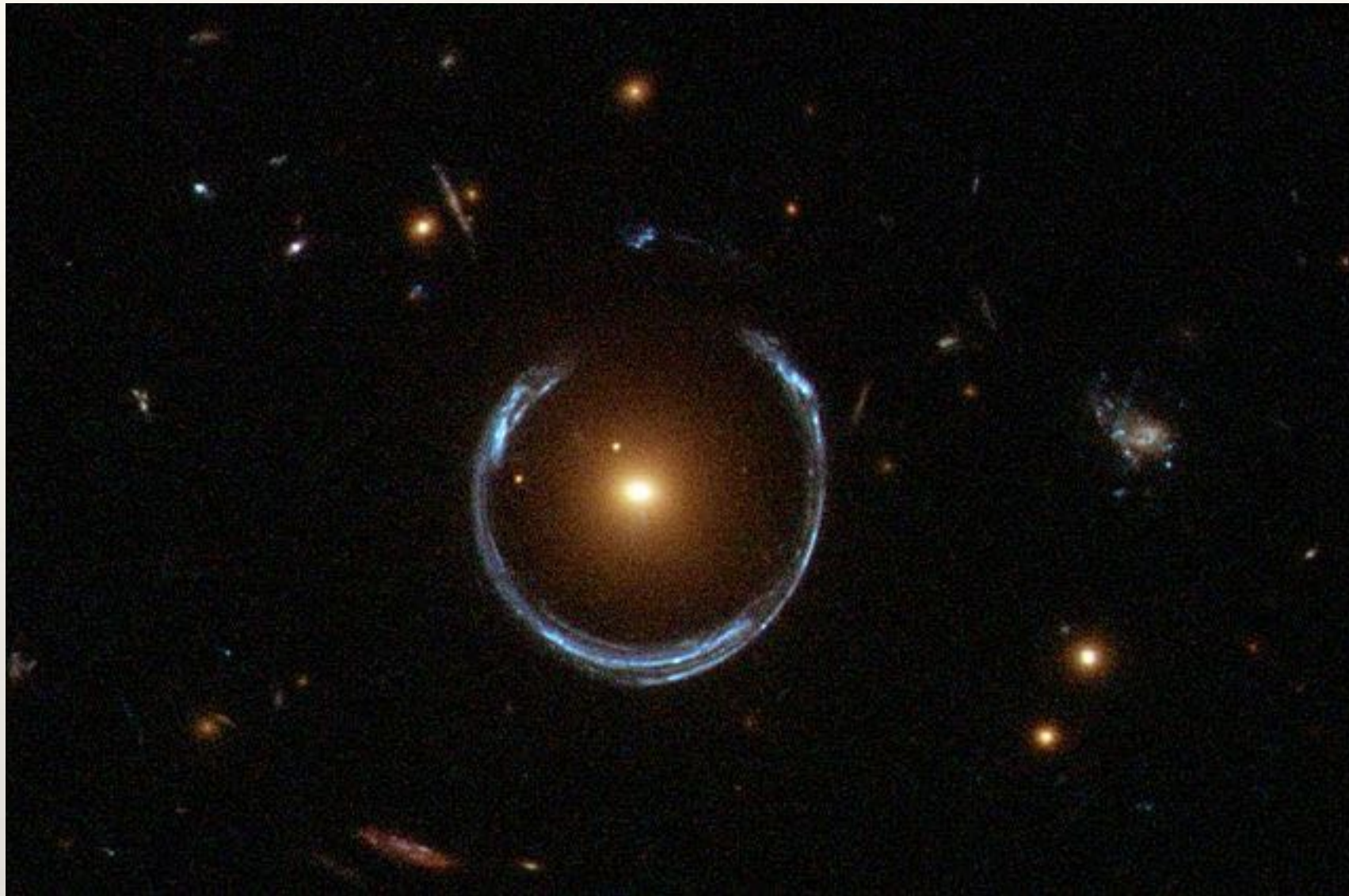


## 5) Bullet Cluster (and friends)





d friends)



Matter distribution  
reconstructed from  
gravitational lensing



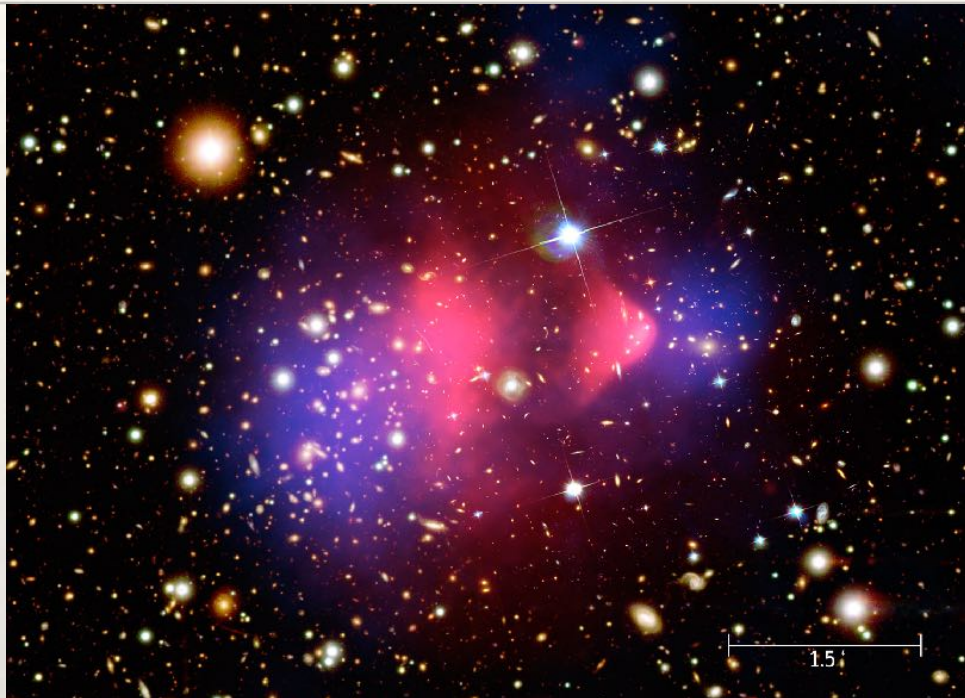
# 5) Bullet Cluster (and friends)

Matter distribution  
seen in X-ray  
observations

Matter distribution  
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# 5) Bullet Cluster (and friends)

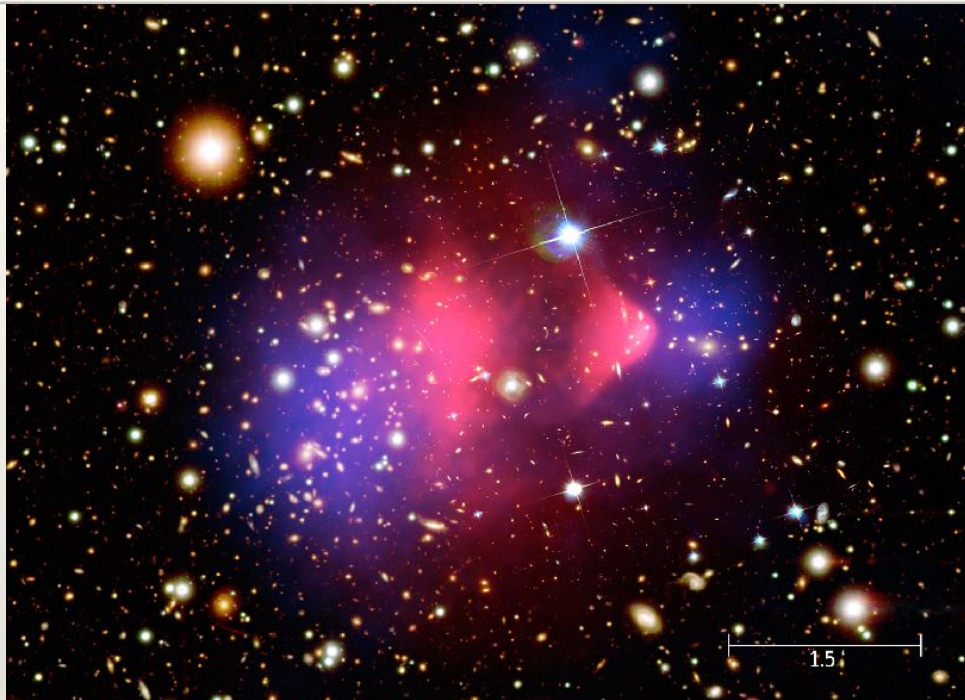


## **Interpretation:**

The visible matter scatters and undergoes a merger.

The Dark Matter is collision free and passes.

# 5) Bullet Cluster (and friends)



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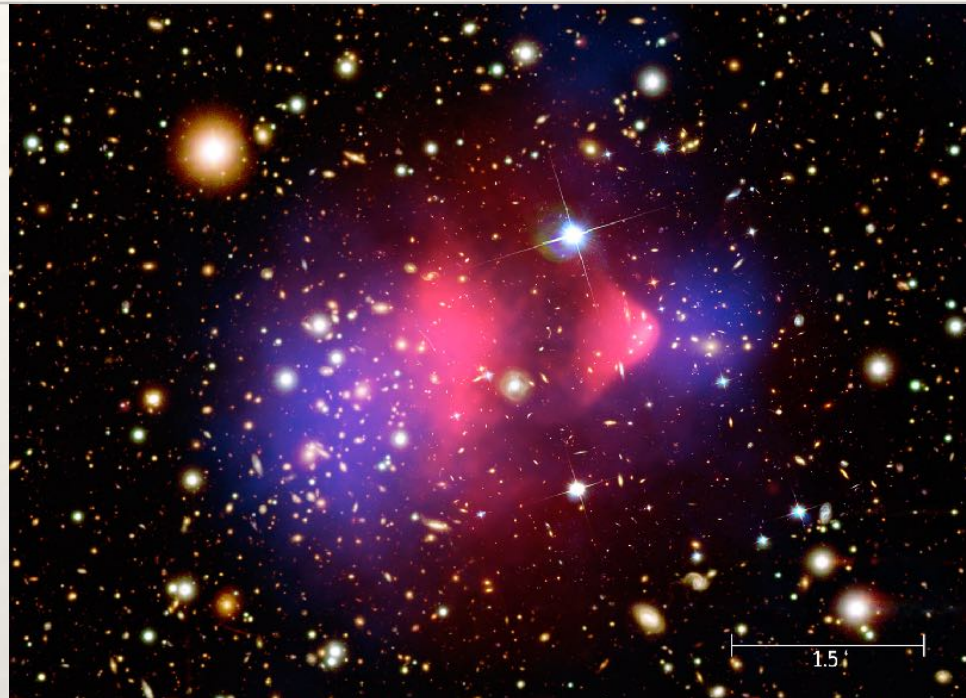
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# 5) Bullet Cluster (and friends)



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