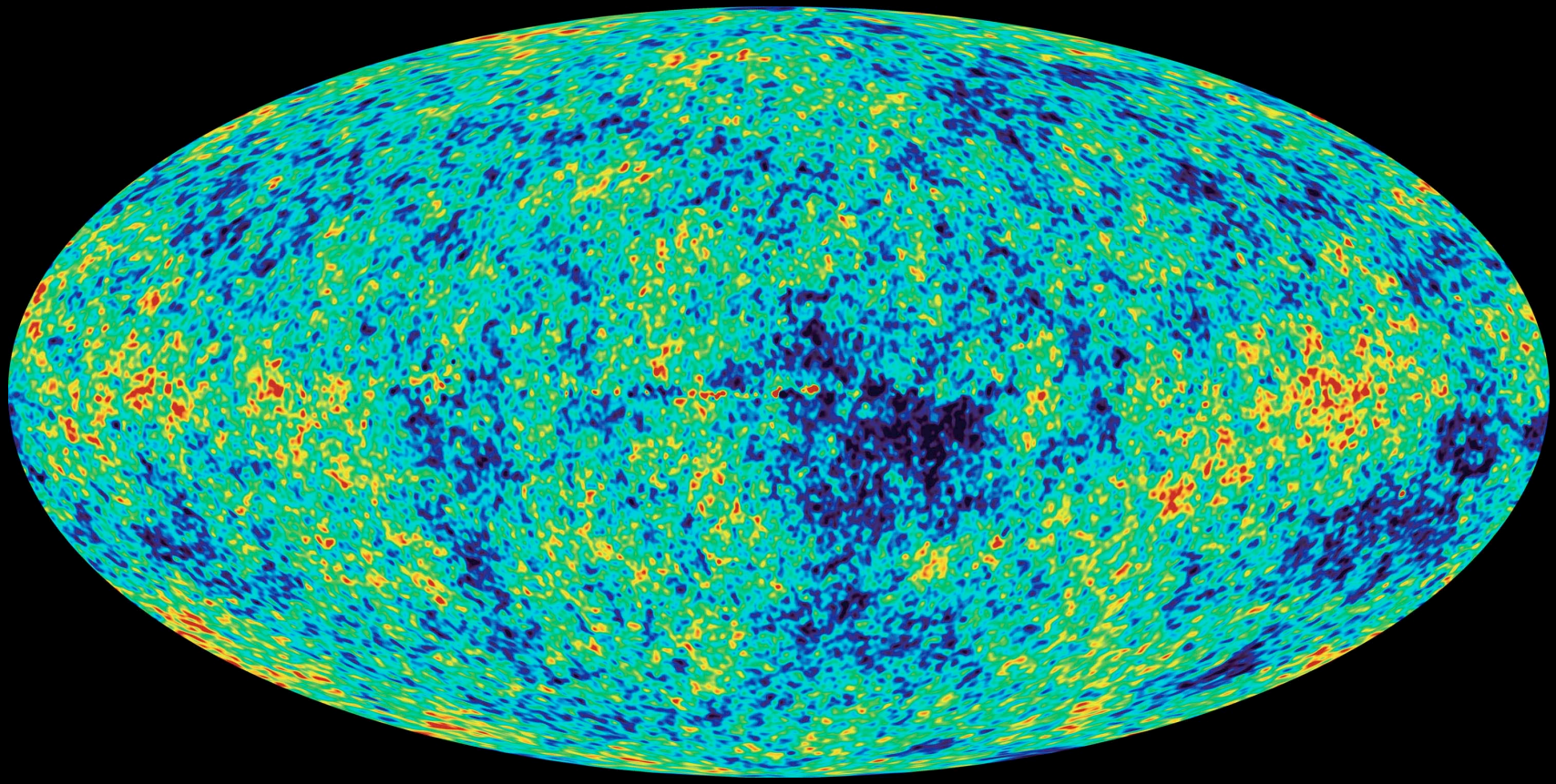


What we don't know about the Universe?

Dr Chris Pearson : RAL Space

Cosmology

- How did the Universe Begin ?
- How old is the Universe ?
- How big is the Universe ?
- What is the Universe made of ?
- Will the Universe end ?

Cosmology: A Tale of 3 Numbers

Hubble parameter

(how fast is Universe expanding)

Density parameter

(how much stuff is in the Universe)

Cosmological Constant

(is the Universe accelerating or decelerating)

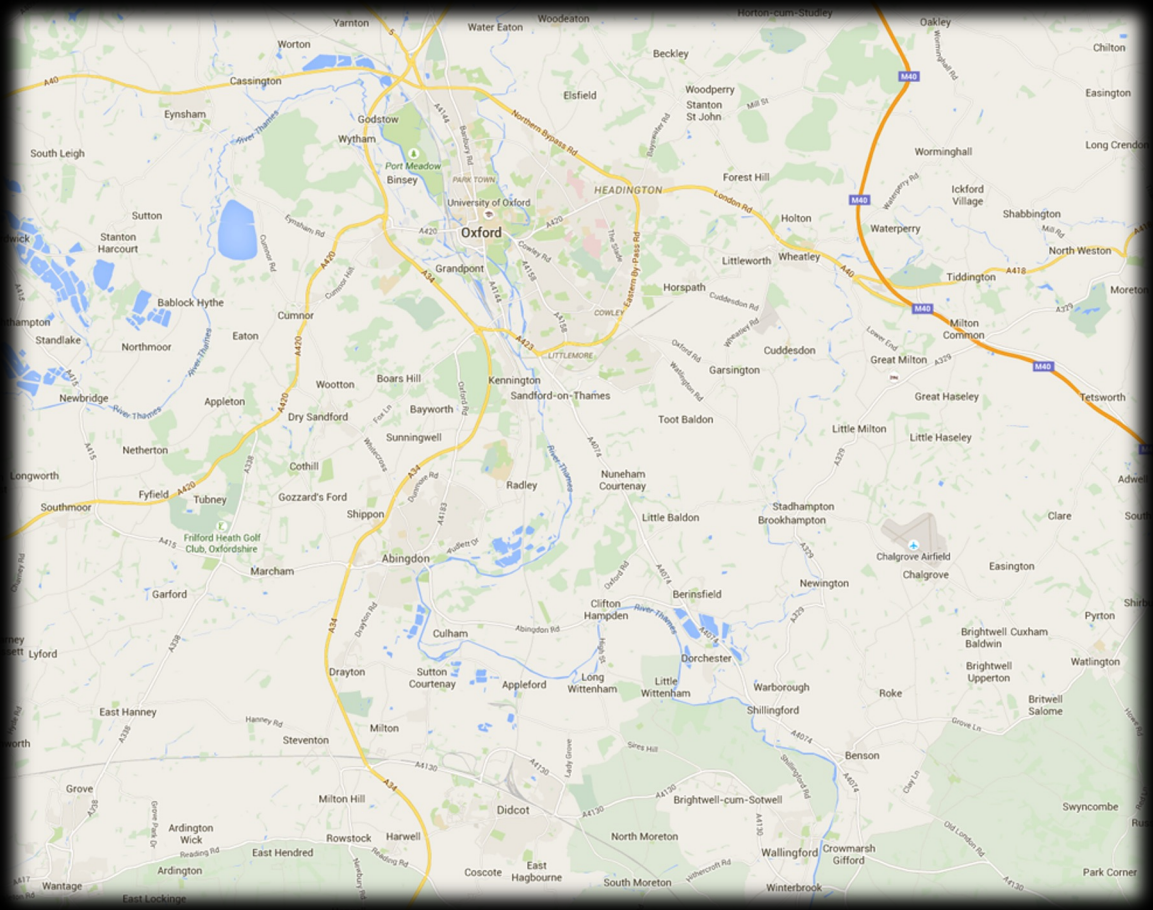
Our Place in the Universe

Rutherford Appleton Laboratory

Scale ~ 1 km

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire



Scale ~ 10 km

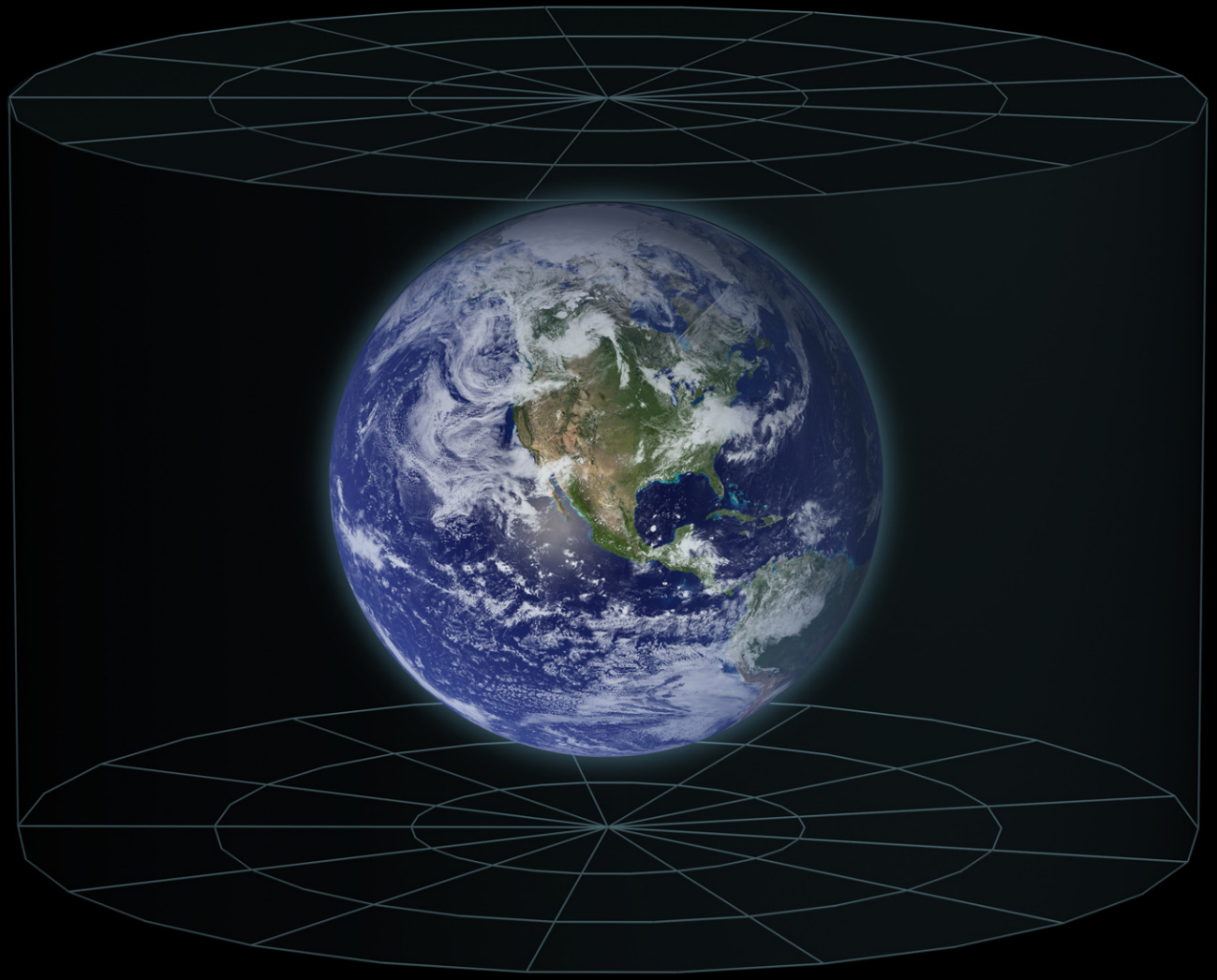
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom

Scale ~ 100 km

Our Place in the Universe

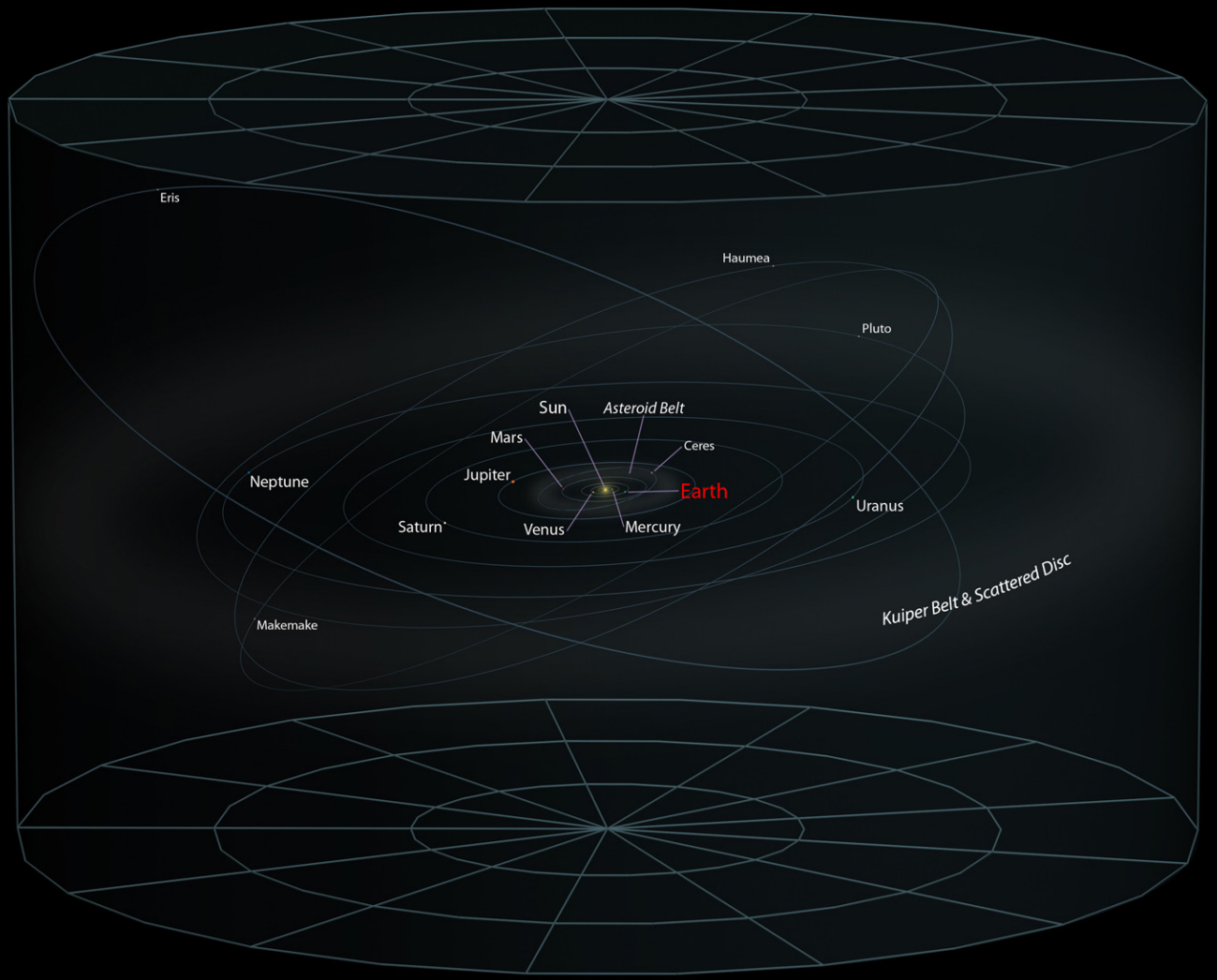
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth



Scale ~ 1000 km

Our Place in the Universe

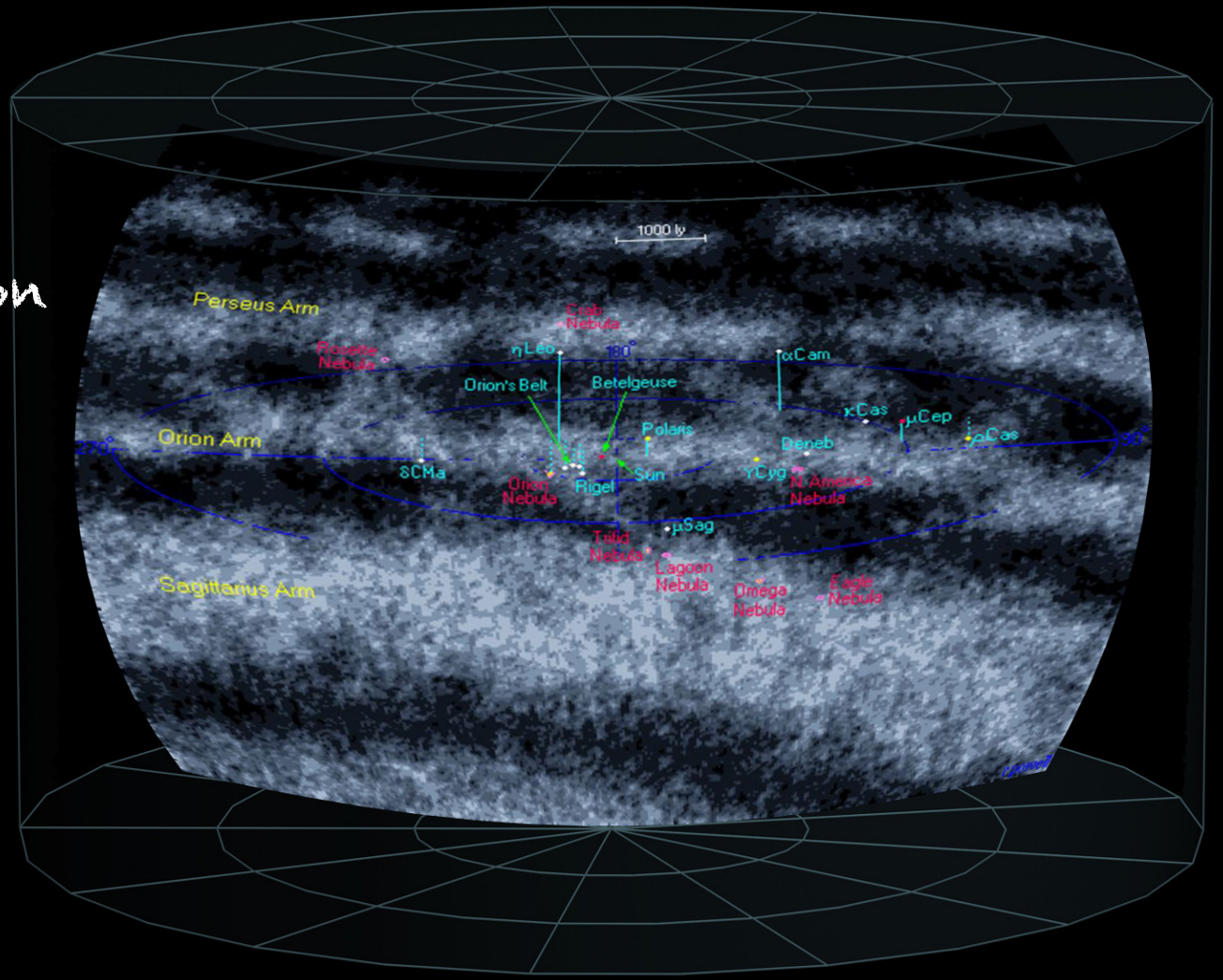
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System



Scale ~ 1 A.U. = 1.5×10^8 km or 7 lm

Our Place in the Universe

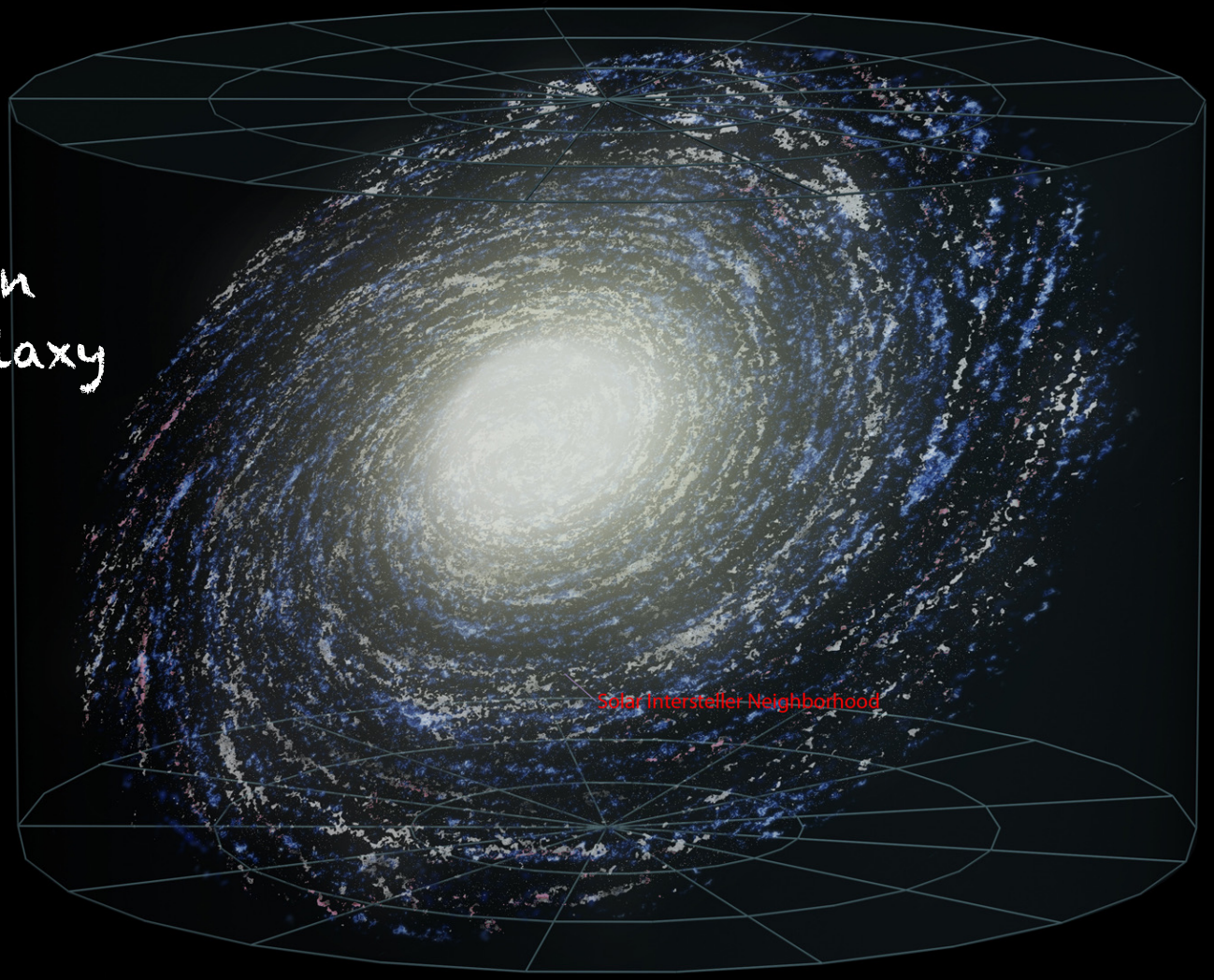
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion



Scale ~ 1000 light years = 9.5×10^{15} km

Our Place in the Universe

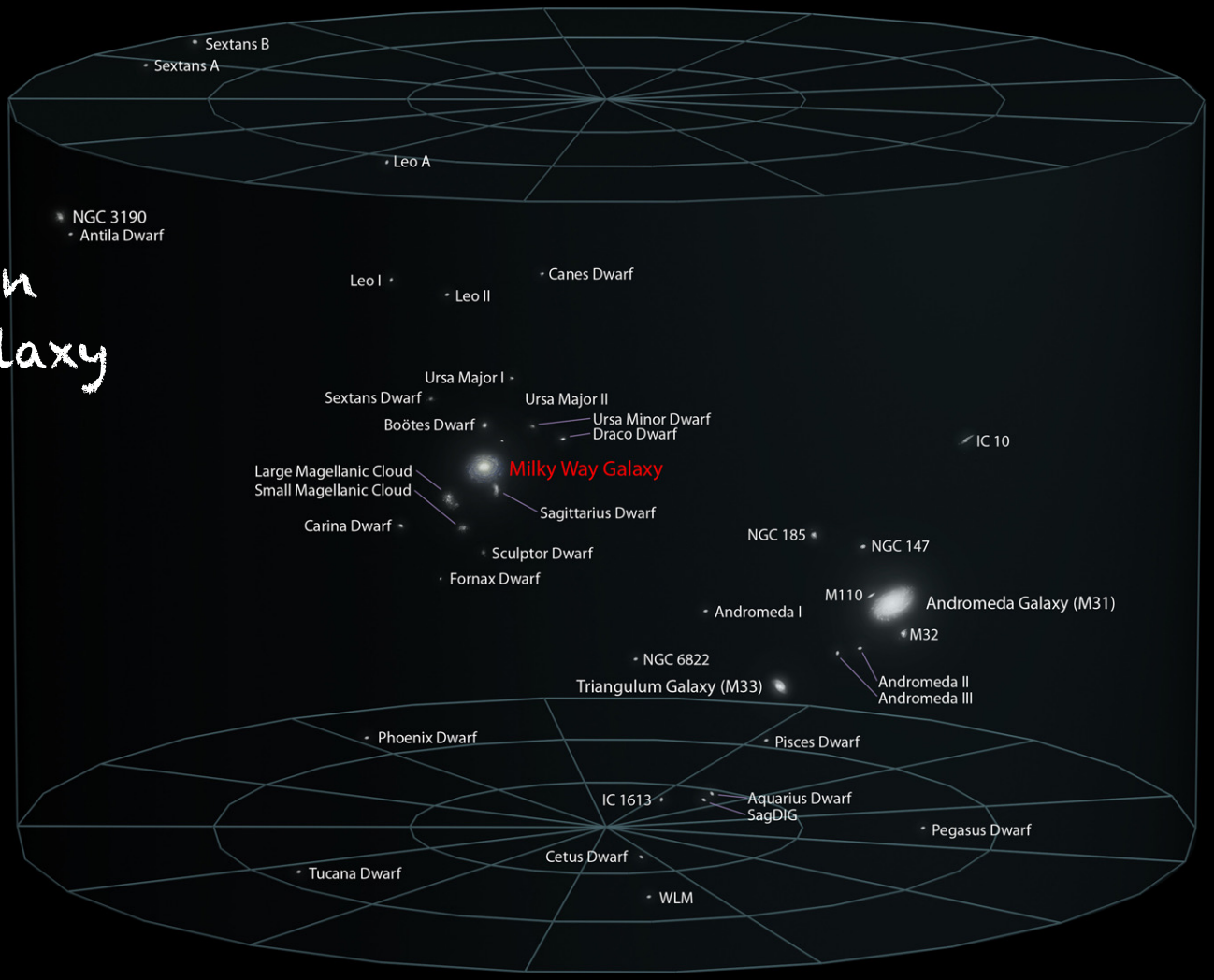
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy



Scale ~ 100,000 light years ~ 30 kpc

Our Place in the Universe

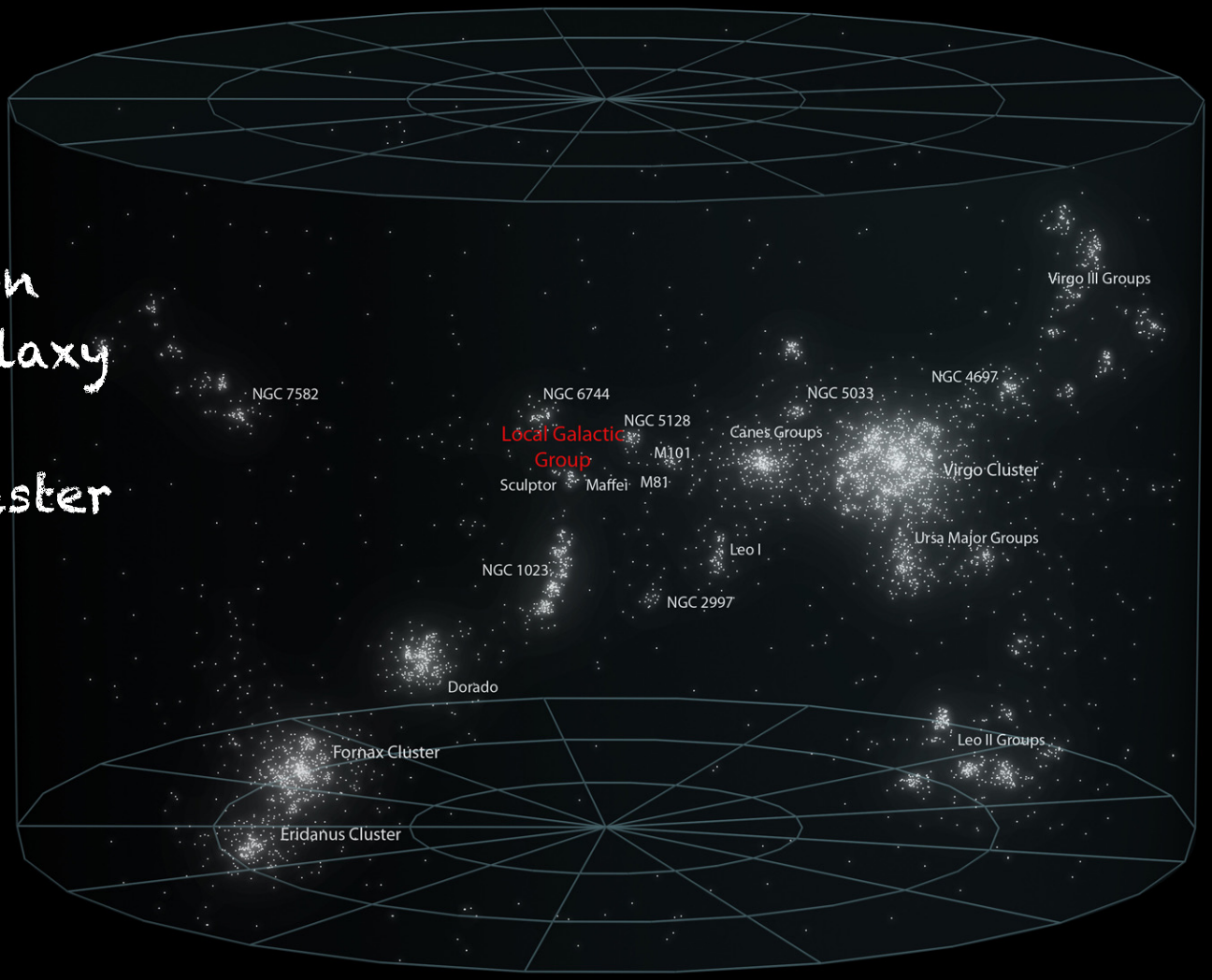
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group



Scale ~ 1 million light years ~ 0.5 Mpc

Our Place in the Universe

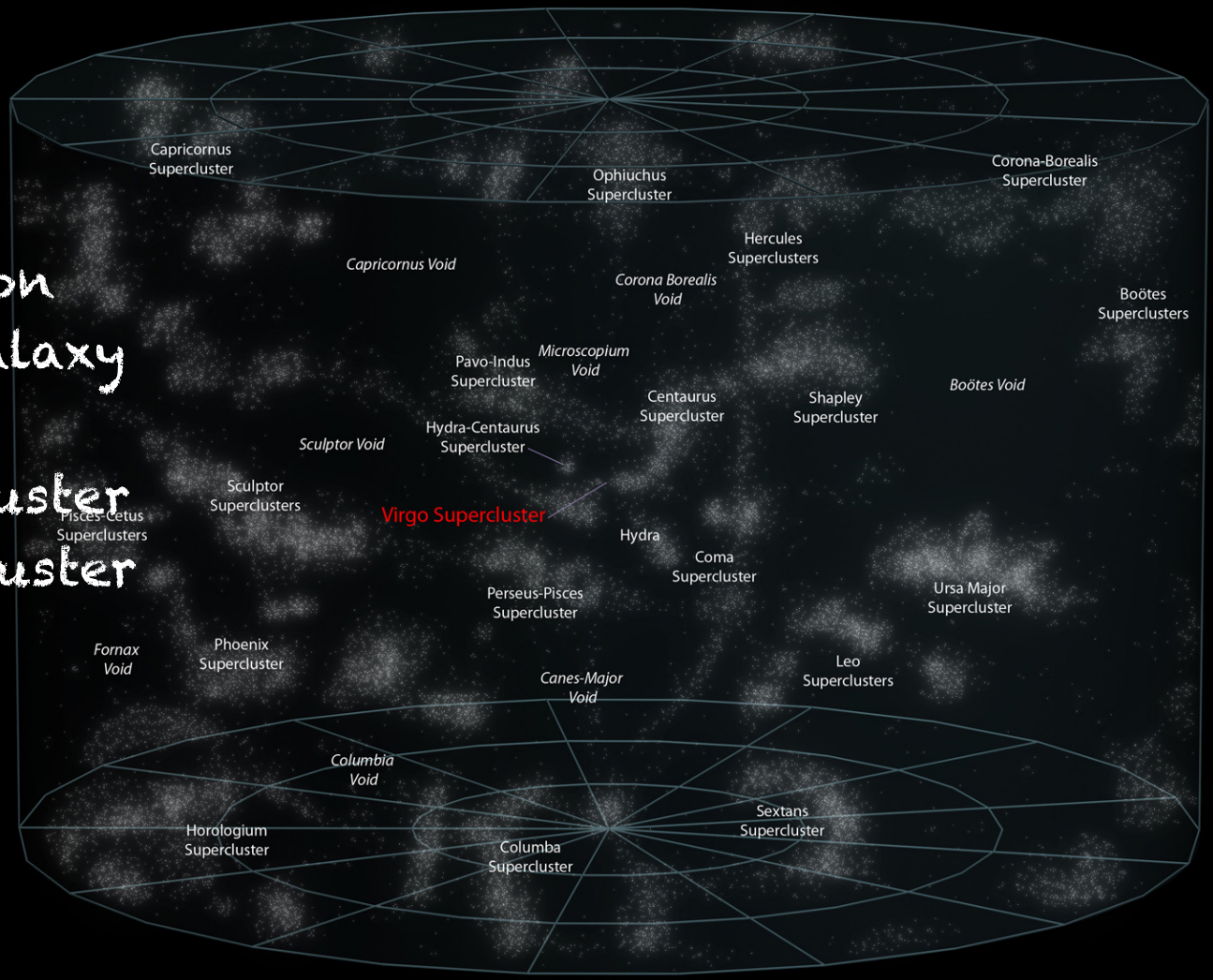
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
Near the Virgo Cluster



Scale ~ 50 million light years

Our Place in the Universe

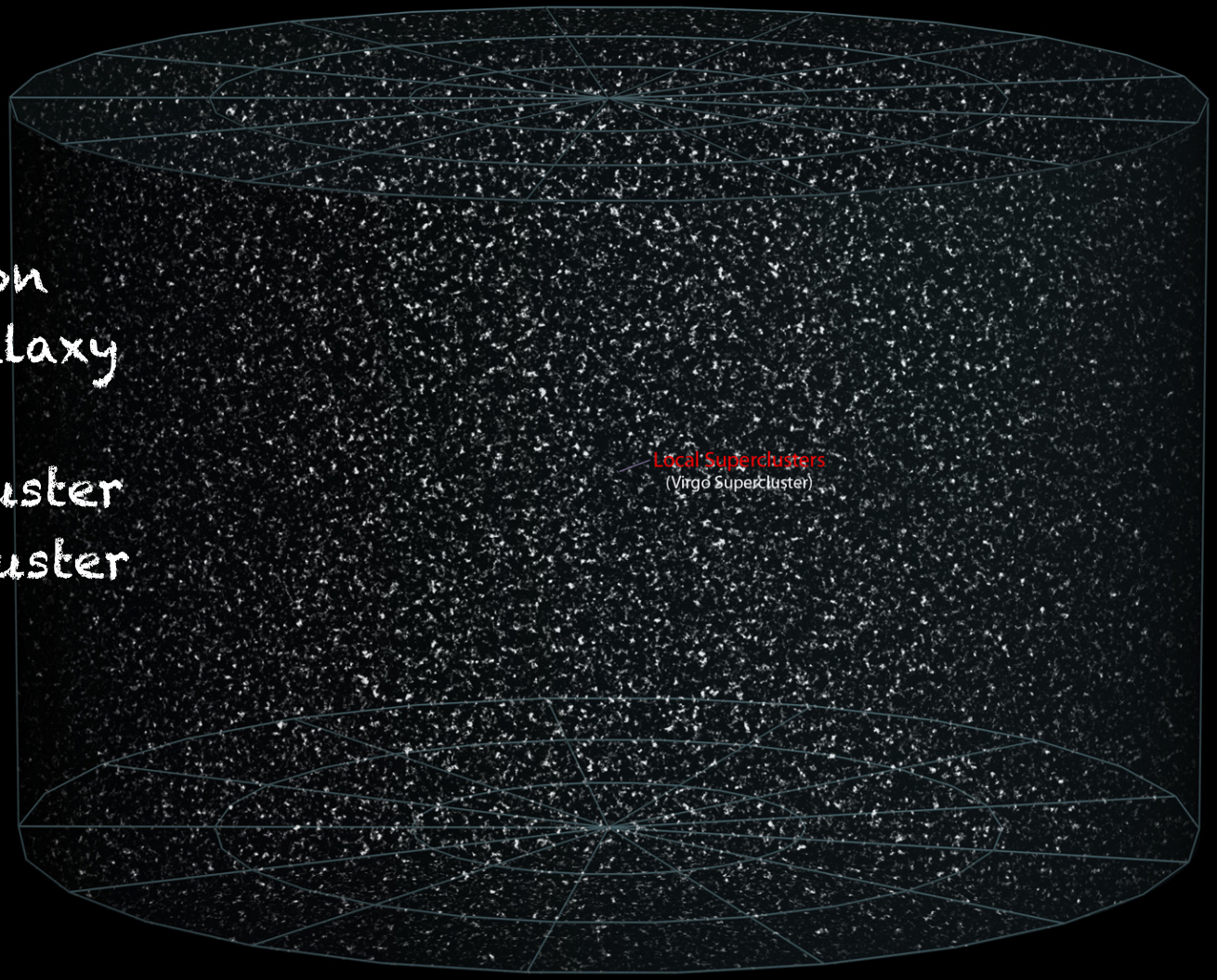
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
near the Virgo Cluster
The Local Supercluster



Scale ~ 100 million light years

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
near the Virgo Cluster
The Local Supercluster
The Universe



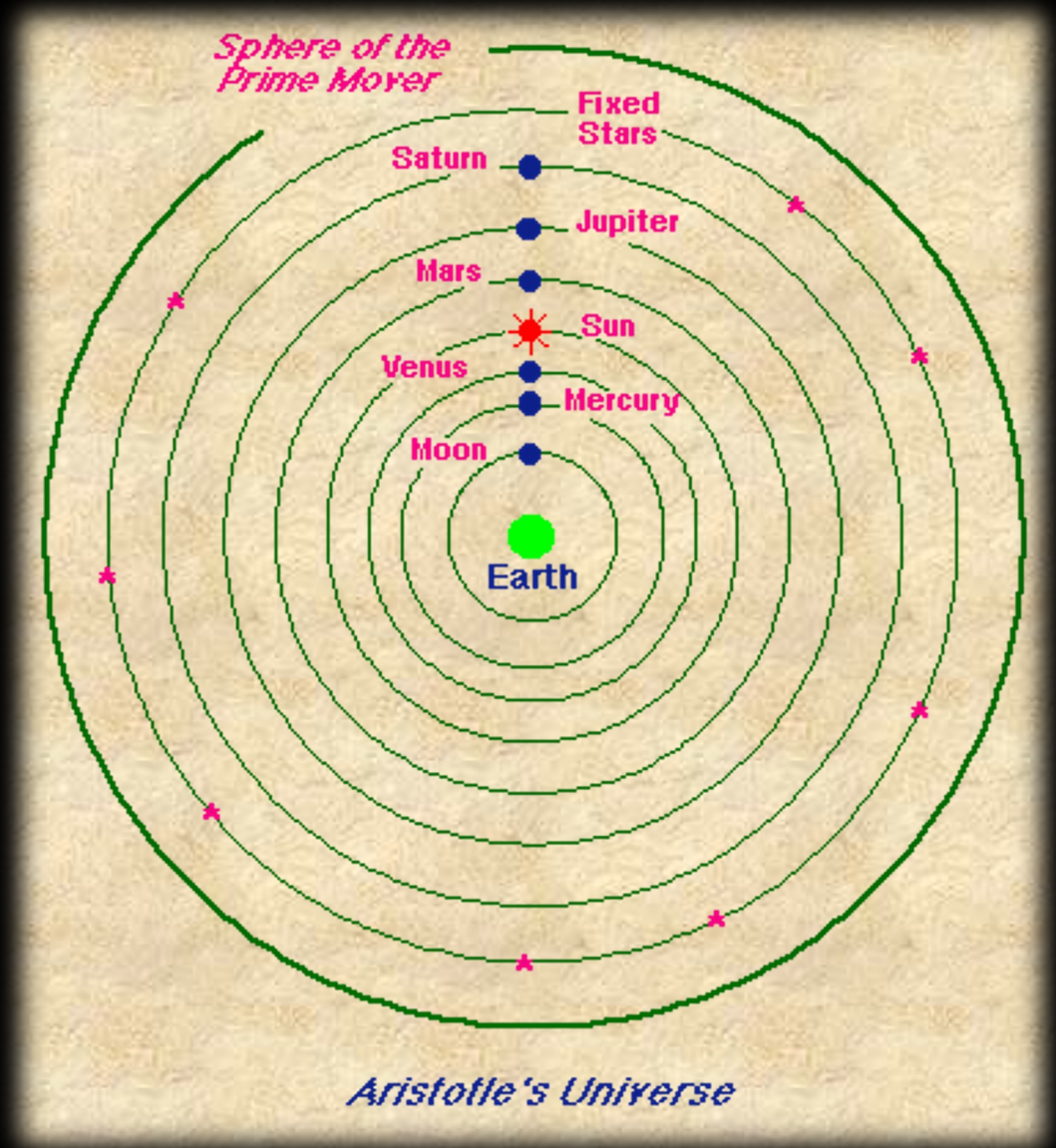
Scale ~ 90 billion light years ~ 28Gpc

The Birth of Cosmology

Ancient Greeks: The first cosmological model

Aristotle (384-322 B.C.)

Geocentric

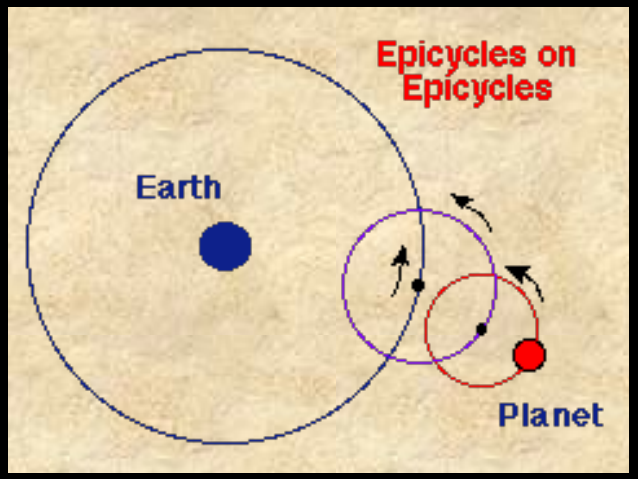


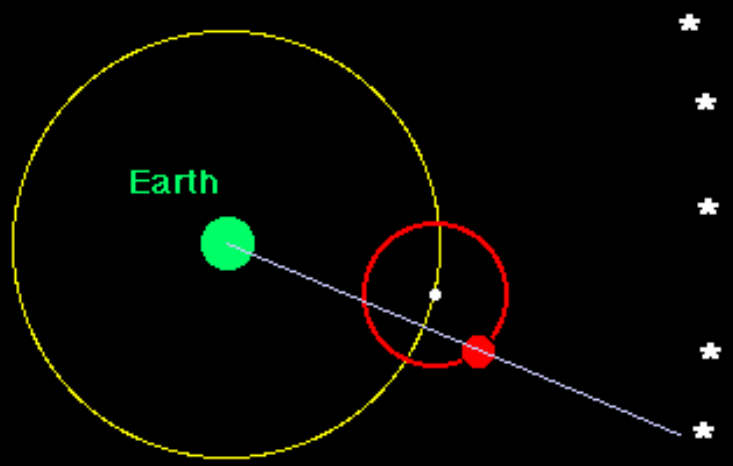
The Birth of Cosmology

Ptolemy (90-168 A.D.)

Geocentric

Perfect motion should be in circles,
so the stars and planets,
being heavenly objects, moved in circles.

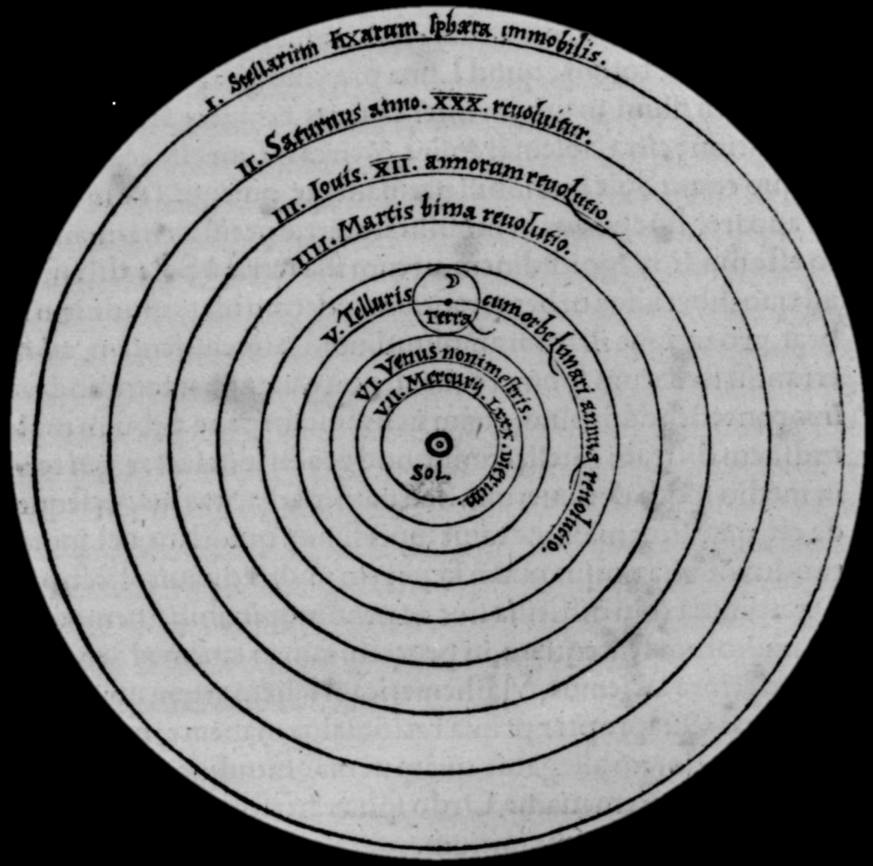


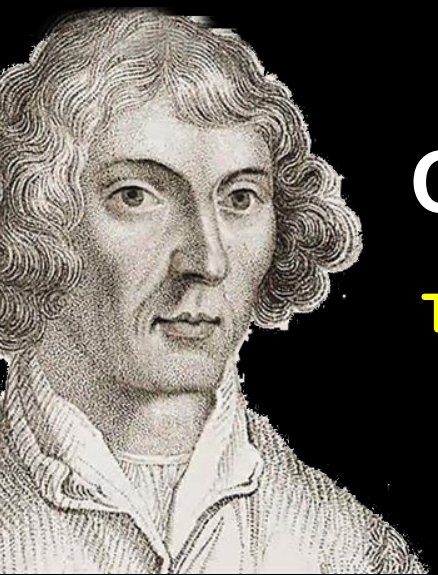


The Birth of Cosmology

Copernicus (1473-1543)

Heliocentric



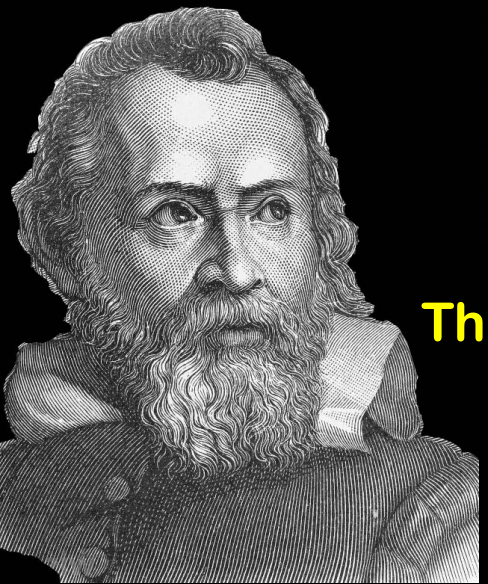


Copernican Cosmological Principle

The Earth does not occupy a special place in the Universe

The Birth of Cosmology

Galileo Galilei (1564-1642)
and the telescope



The Earth does not occupy a special place in the Universe

The Birth of Cosmology

Edwin Hubble (1929)

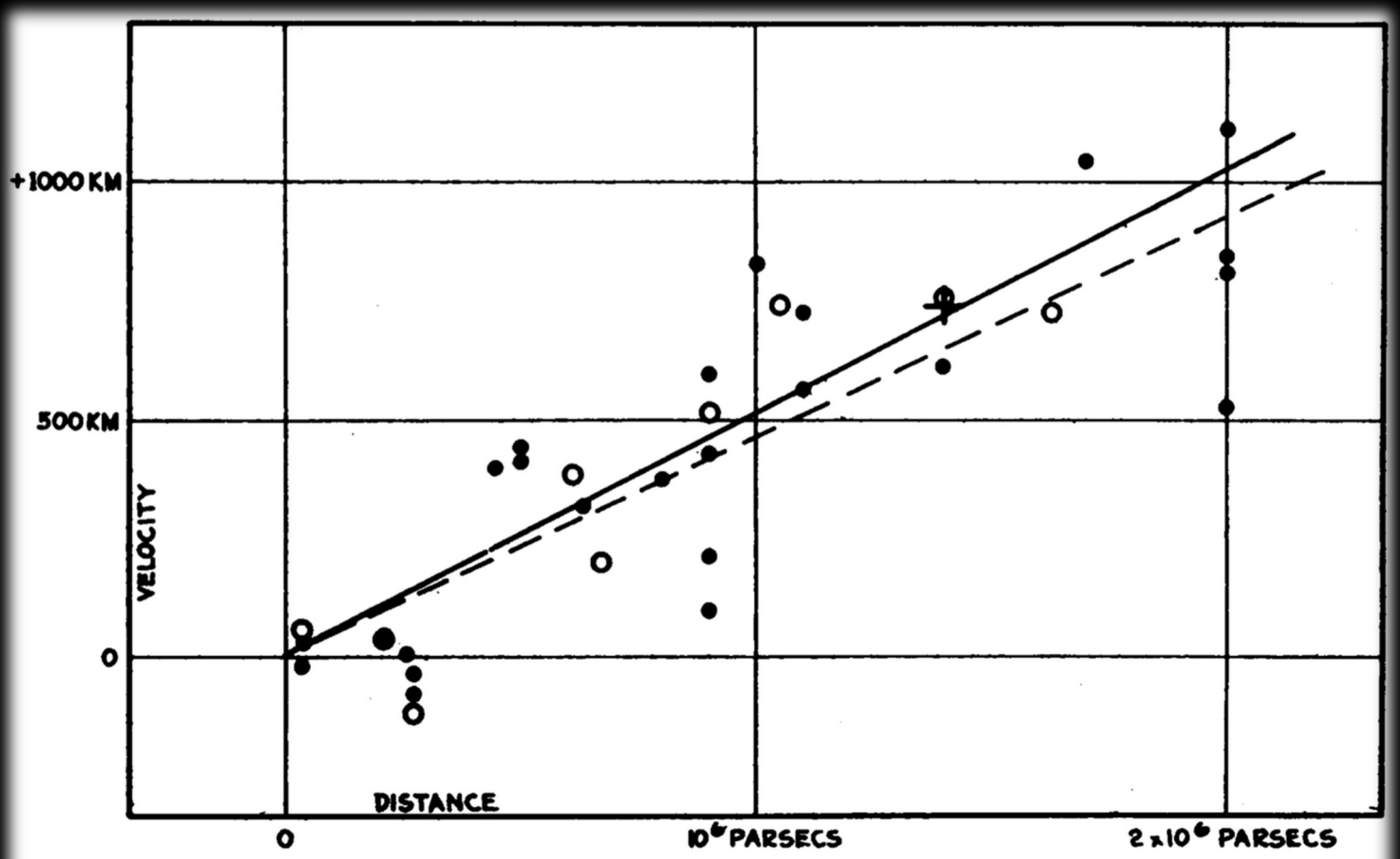
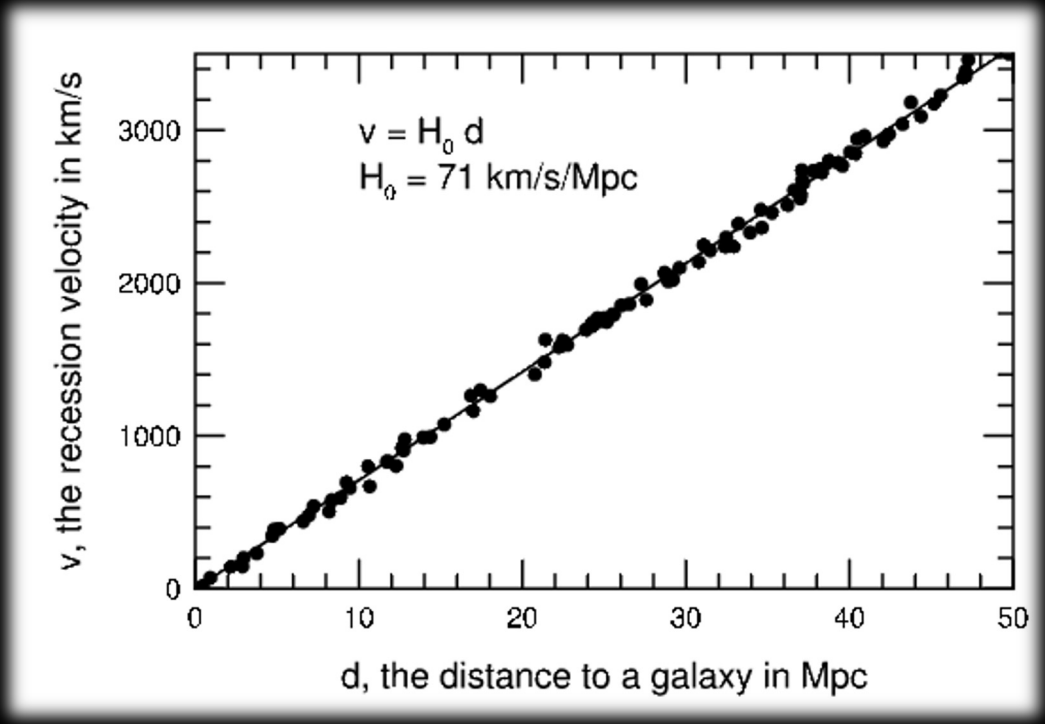


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

The Birth of Cosmology



1) (almost) all galaxies are moving *away* from us
2) More distant galaxies are moving away *faster*

$$v \propto d \qquad v = H_0 d$$

H_0 : The Hubble Constant

Cosmology: A Tale of 3 Numbers

Hubble parameter

(how fast is Universe expanding)

Ho = 67.3 km/s/Mpc

Density parameter

(how much stuff is in the Universe)

Cosmological Constant

(is the Universe accelerating or decelerating)

The Cosmological Principle

Copernican Cosmological Principle
The Earth does not occupy a special place in the Universe

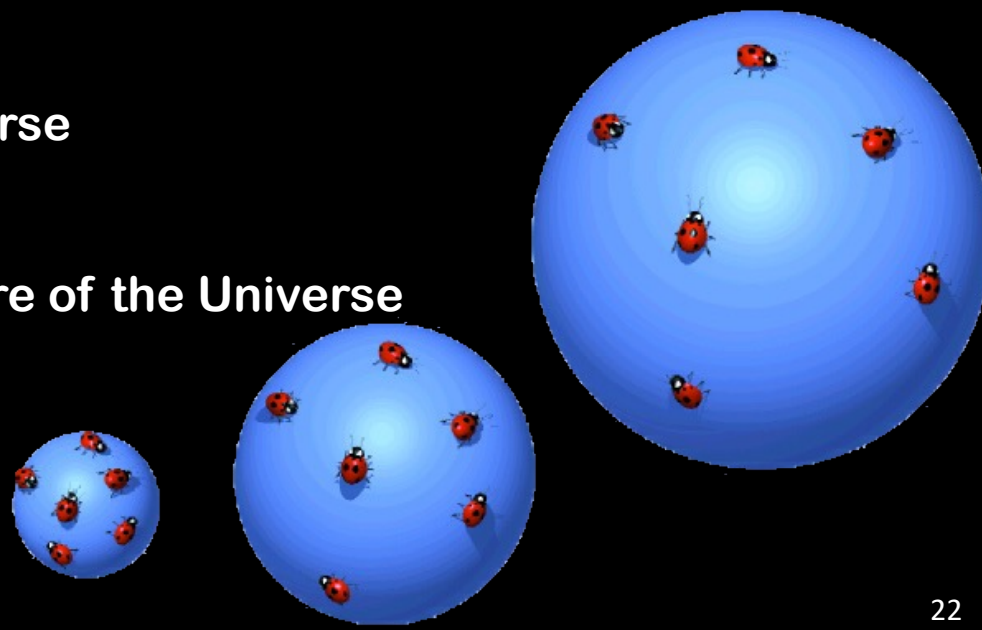
The Cosmological Principle
At any single time: the Universe appears homogeneous and isotropic to everyone

Homogeneity : *No preferred locations*
Same picture of Universe at any time seen by all observers.

Isotropy : *No preferred Directions*
The Universe looks the same in all directions to all observers.

There is no preferred place in the Universe

There is no centre to the Universe
…. or everyone thinks they are the centre of the Universe



The Big Bang

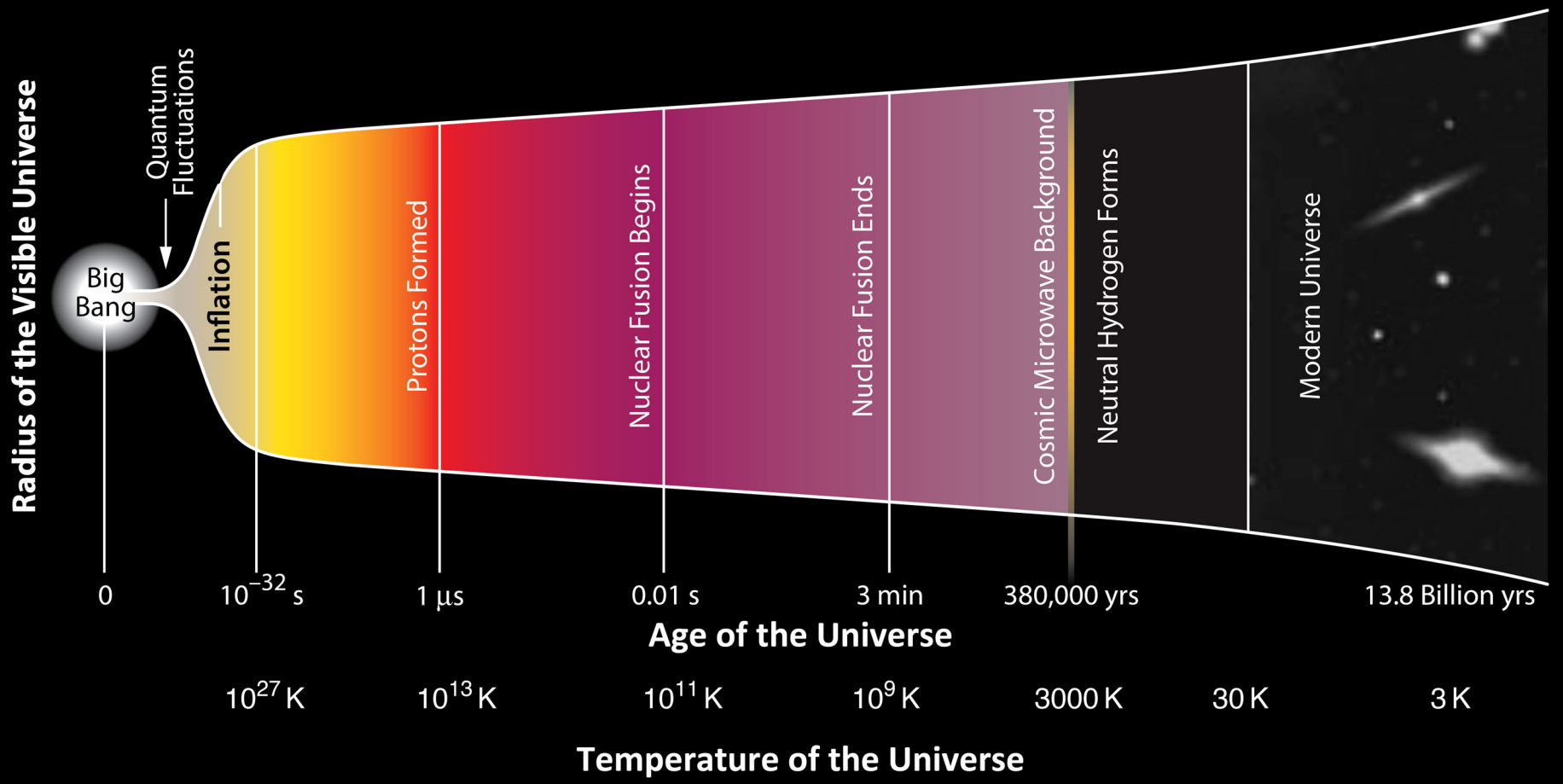
The Big Bang

Running Time backwards

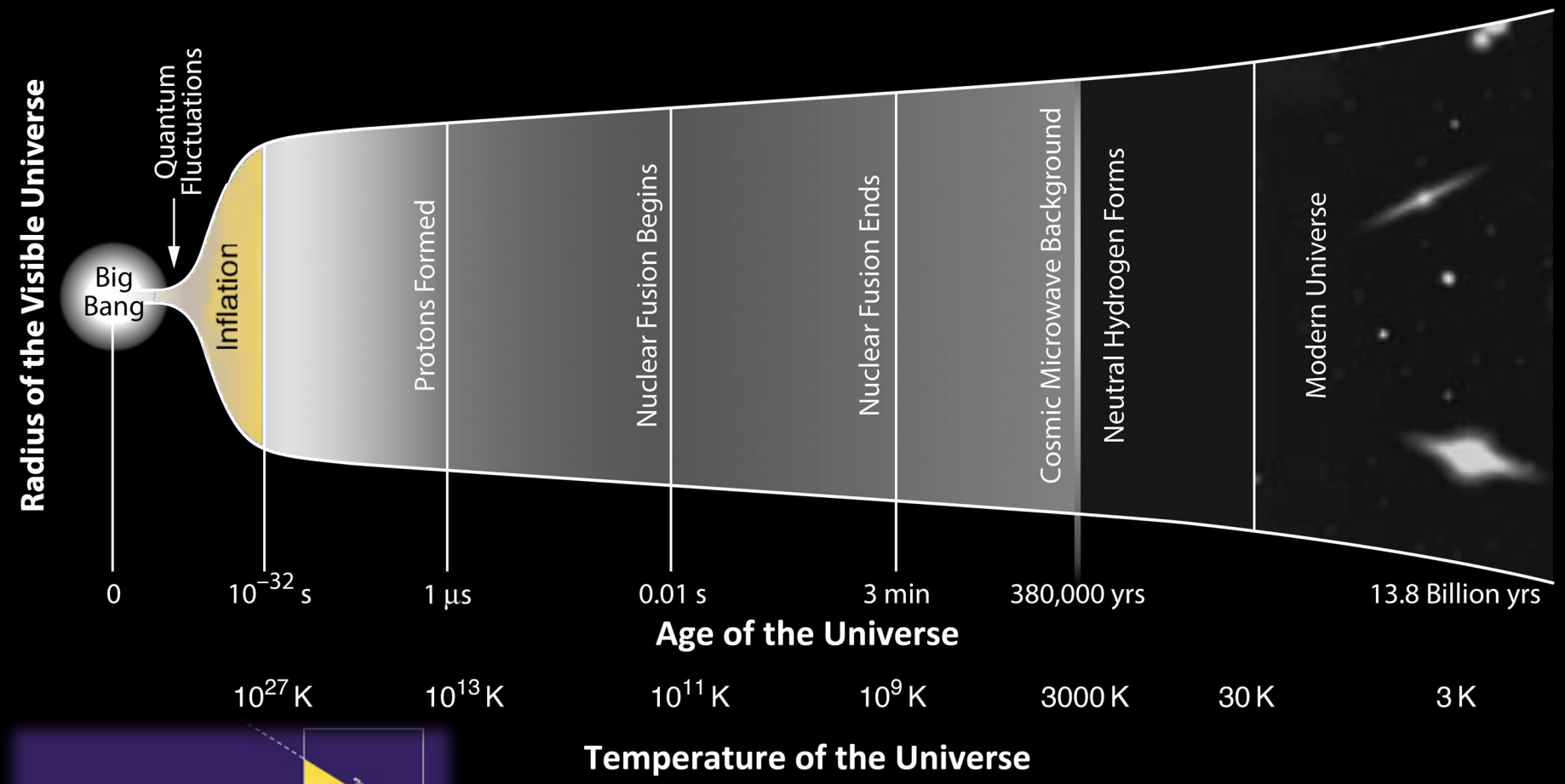
$$\begin{cases} t \to 0 \\ R \to 0 \\ T \to \infty \\ \rho \to \infty \end{cases}$$

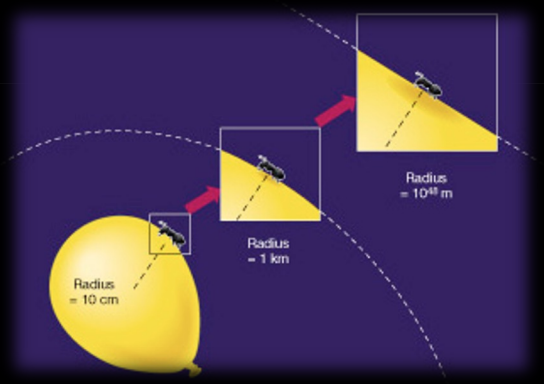
Initial singularity - The Creation Event

The Big Bang


Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe
10^{27} K
10^{13} K
10^{11} K
10^{9} K
3000 K
30 K
3 K
Temperature of the Universe

The Big Bang





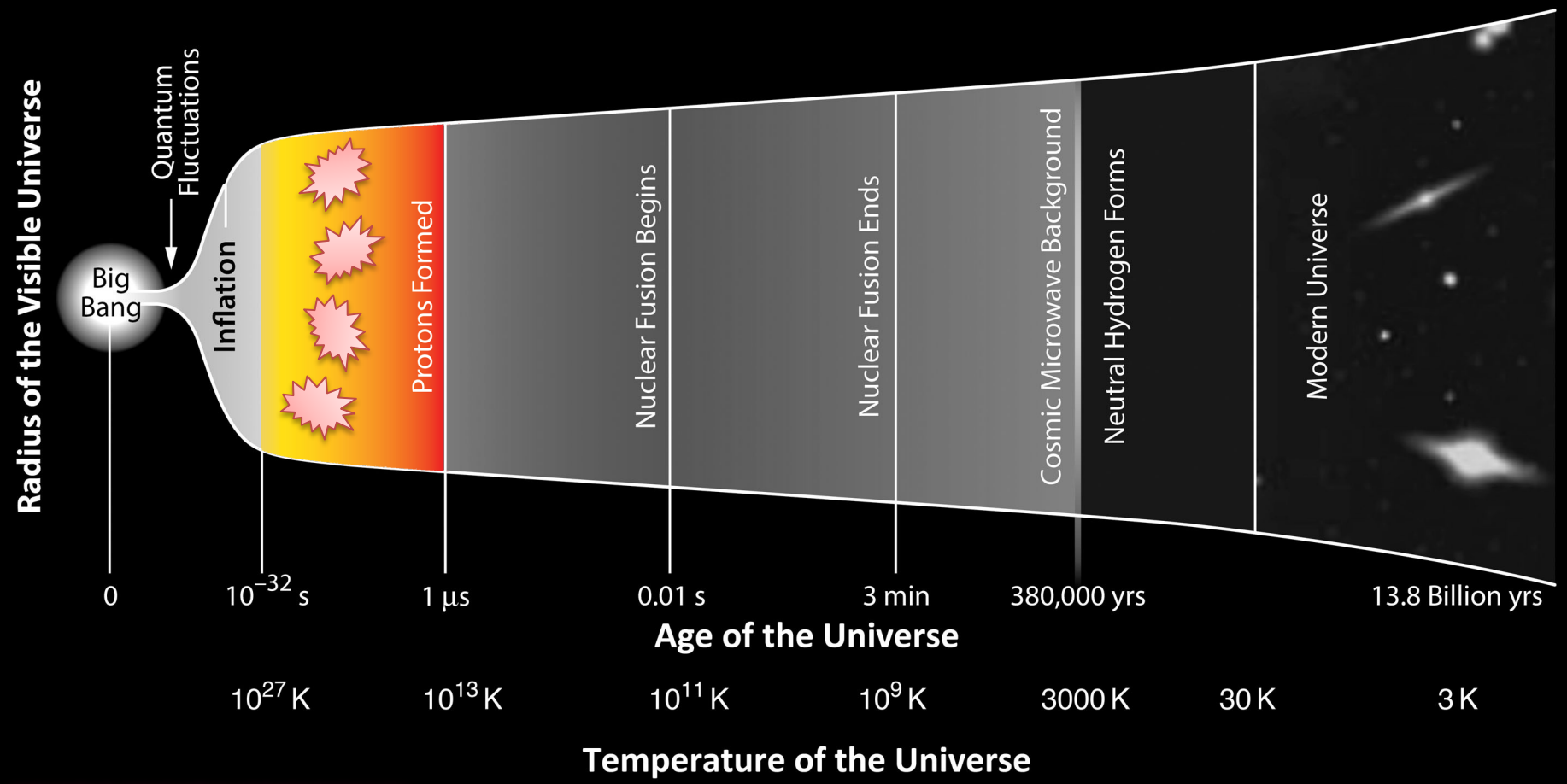
Inflation Period

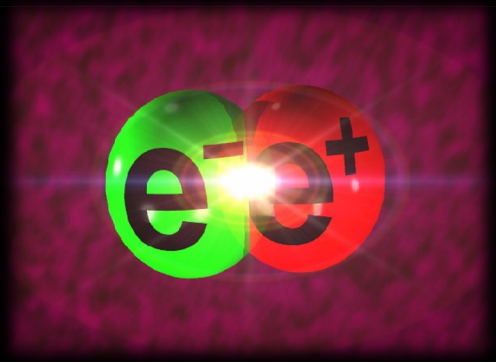
Universe expands exponentially

10^{-34} s to 10^{-32} s ~ 100 e foldings

Quantum fluctuations -> macroscopic scales -> seed Structure Formation

The Big Bang





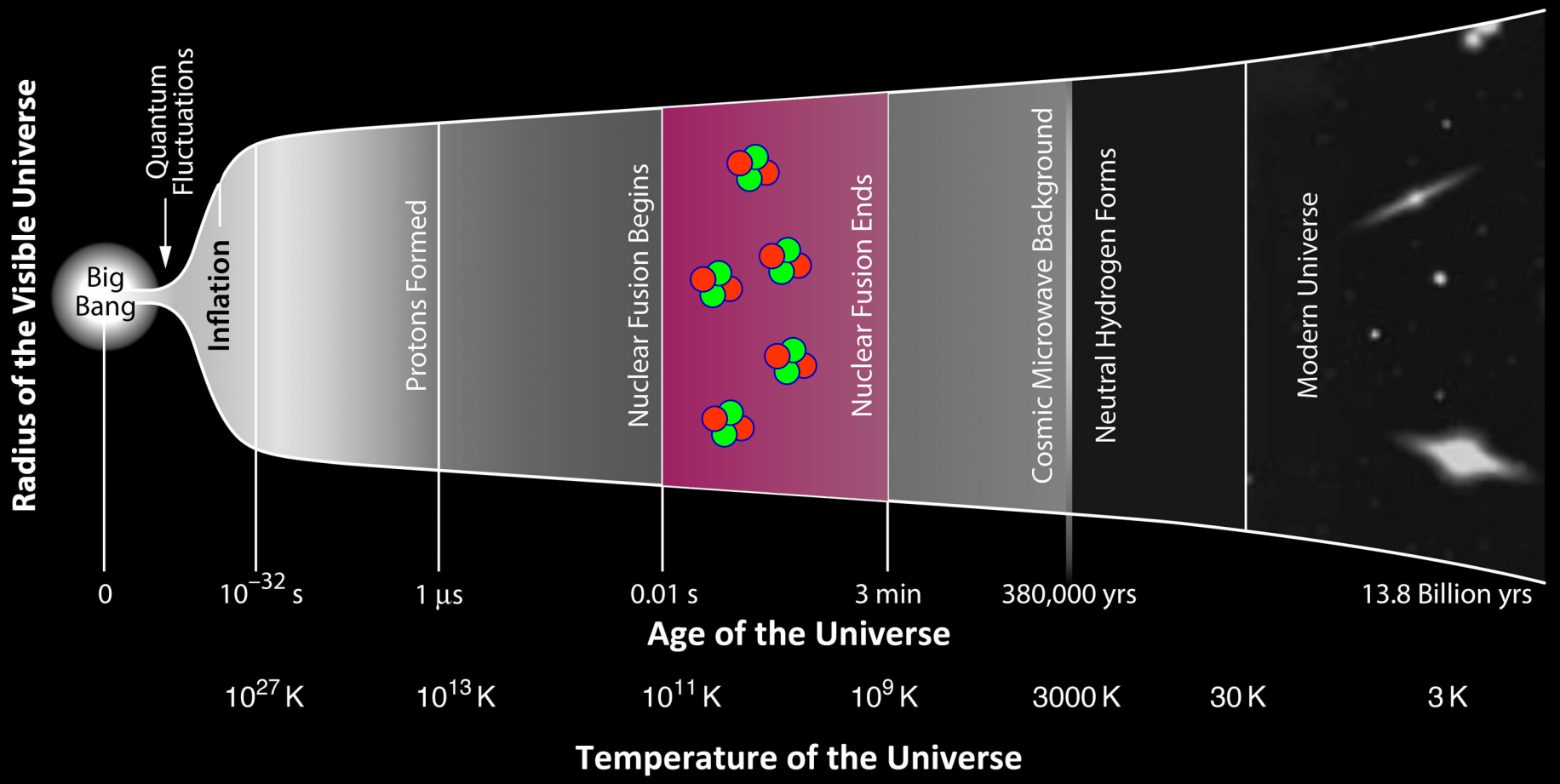
matter and antimatter annihilate

creates the photon background

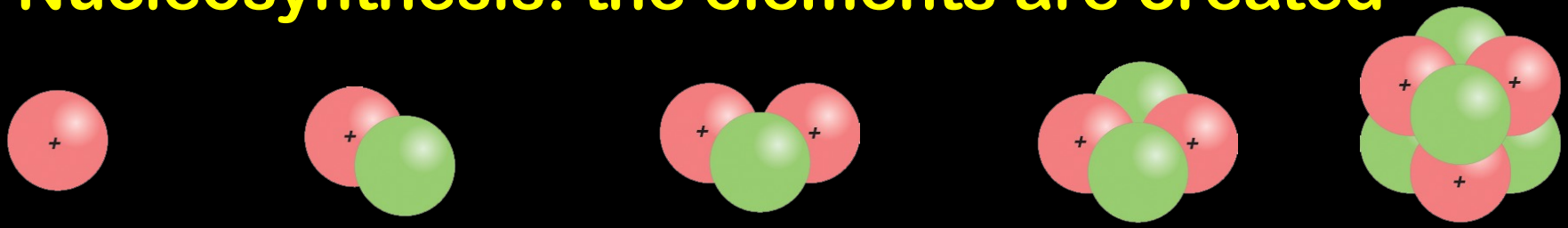
Small asymmetry in matter/antimatter

Small excess of matter remains

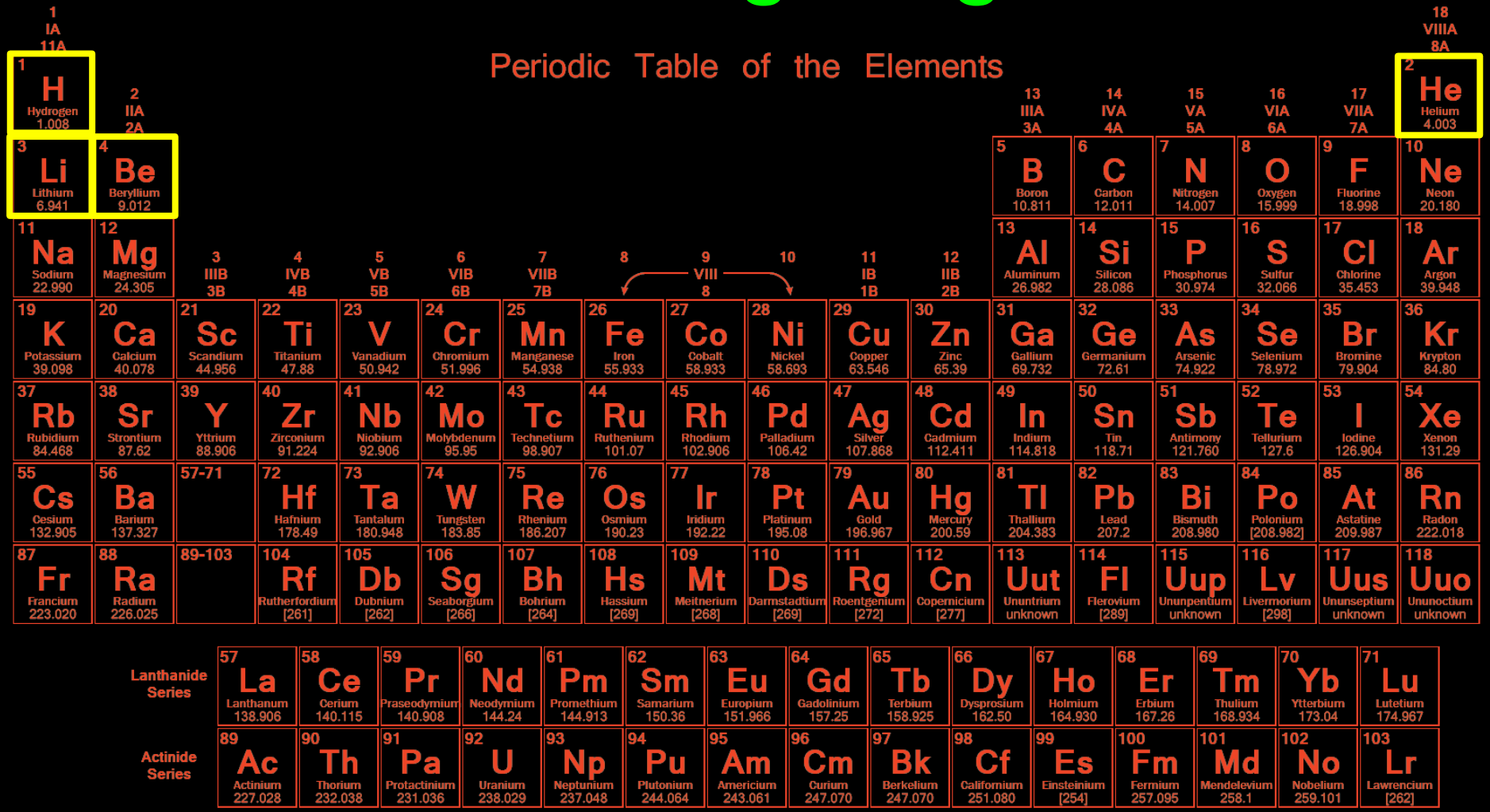
The Big Bang



Nucleosynthesis: the elements are created



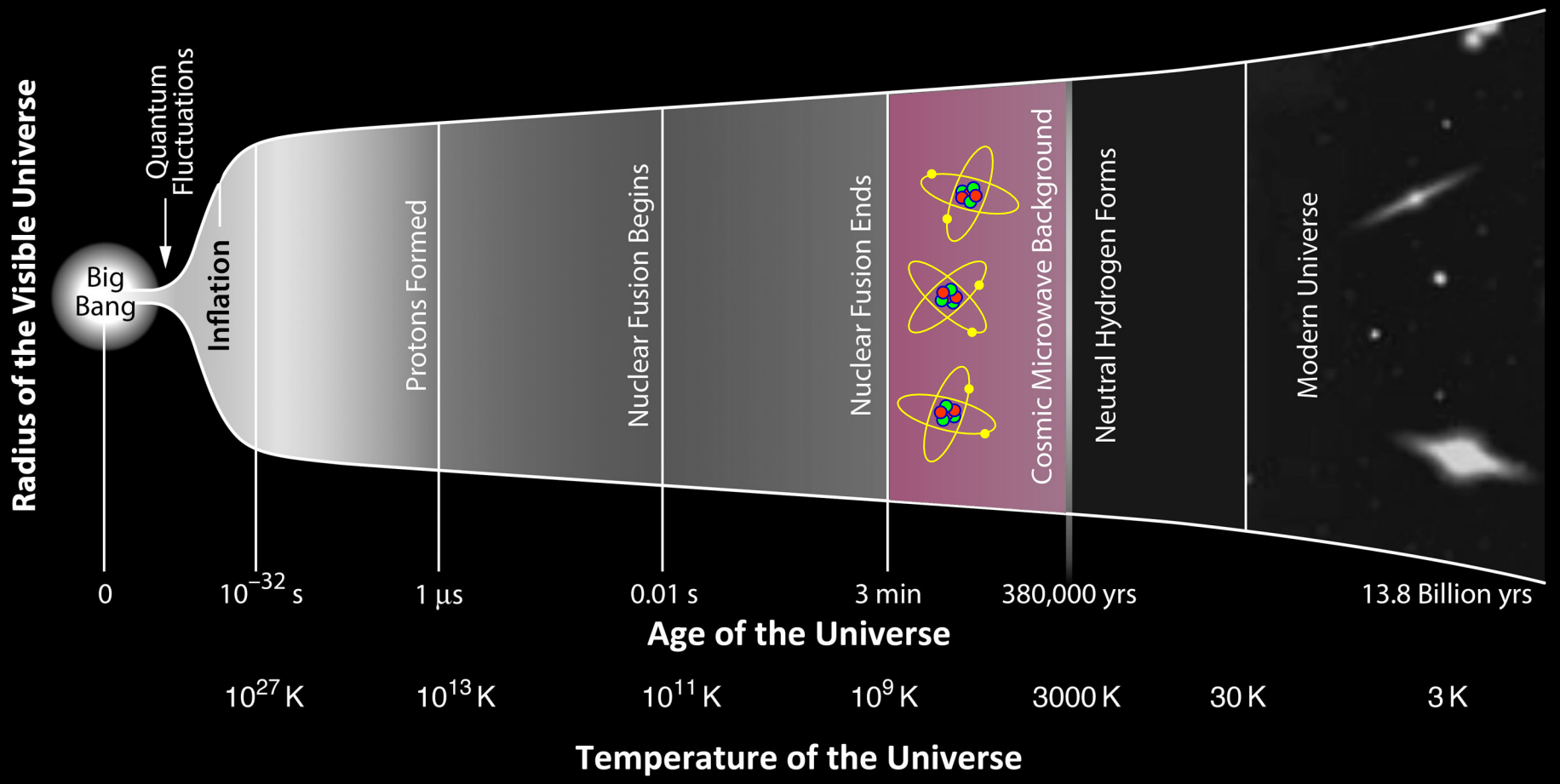
The Big Bang



Only the very lightest elements are created in the Big Bang

Everything else is made in Stars 10 -100 million years later !

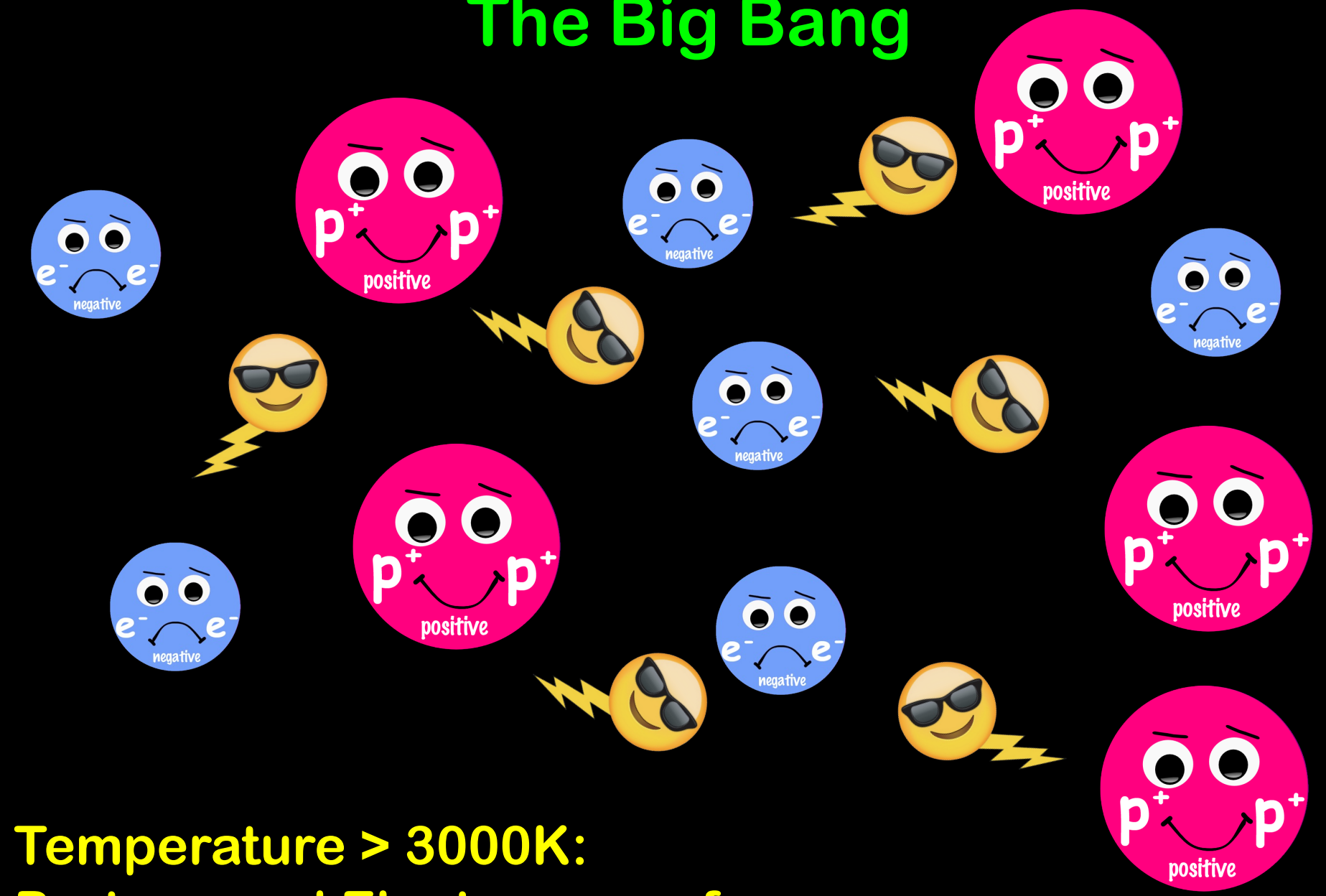
The Big Bang



Atoms are made: Protons can capture electrons

Atoms "recombine"

The Big Bang

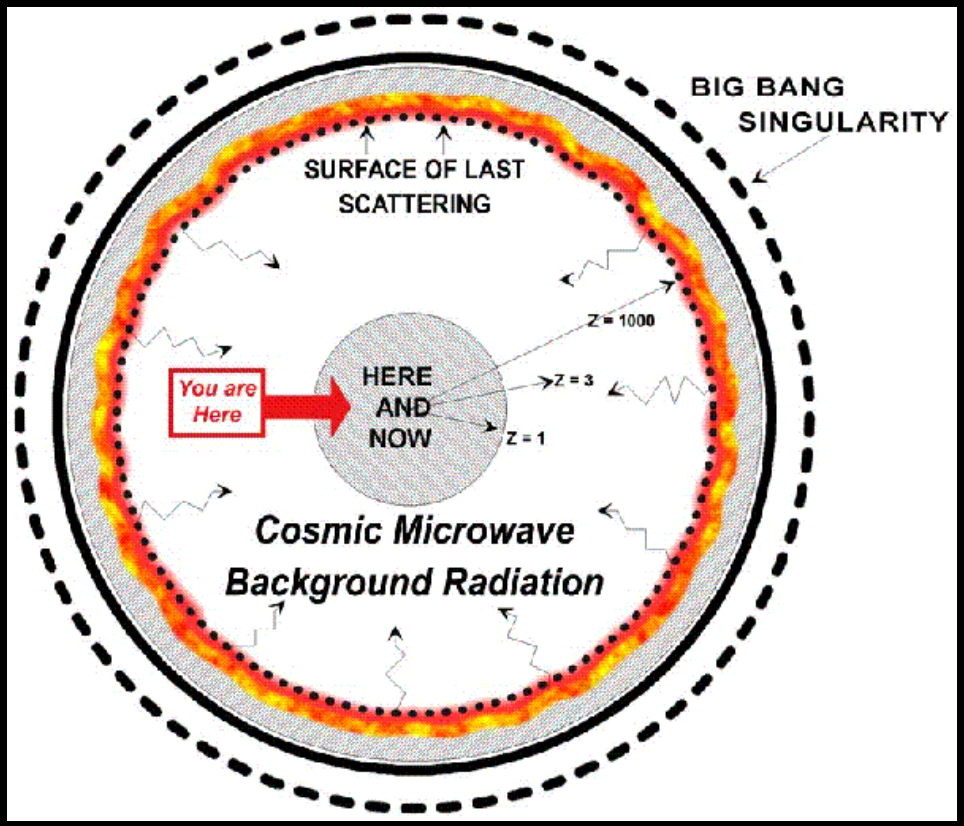


Temperature > 3000K:
Protons and Electrons are free
lots of electric charge means photons are trapped

The Big Bang

Temperature < 3000K:
Protons and Electrons recombine to make atoms
Atoms neutral means the photons (light) are free

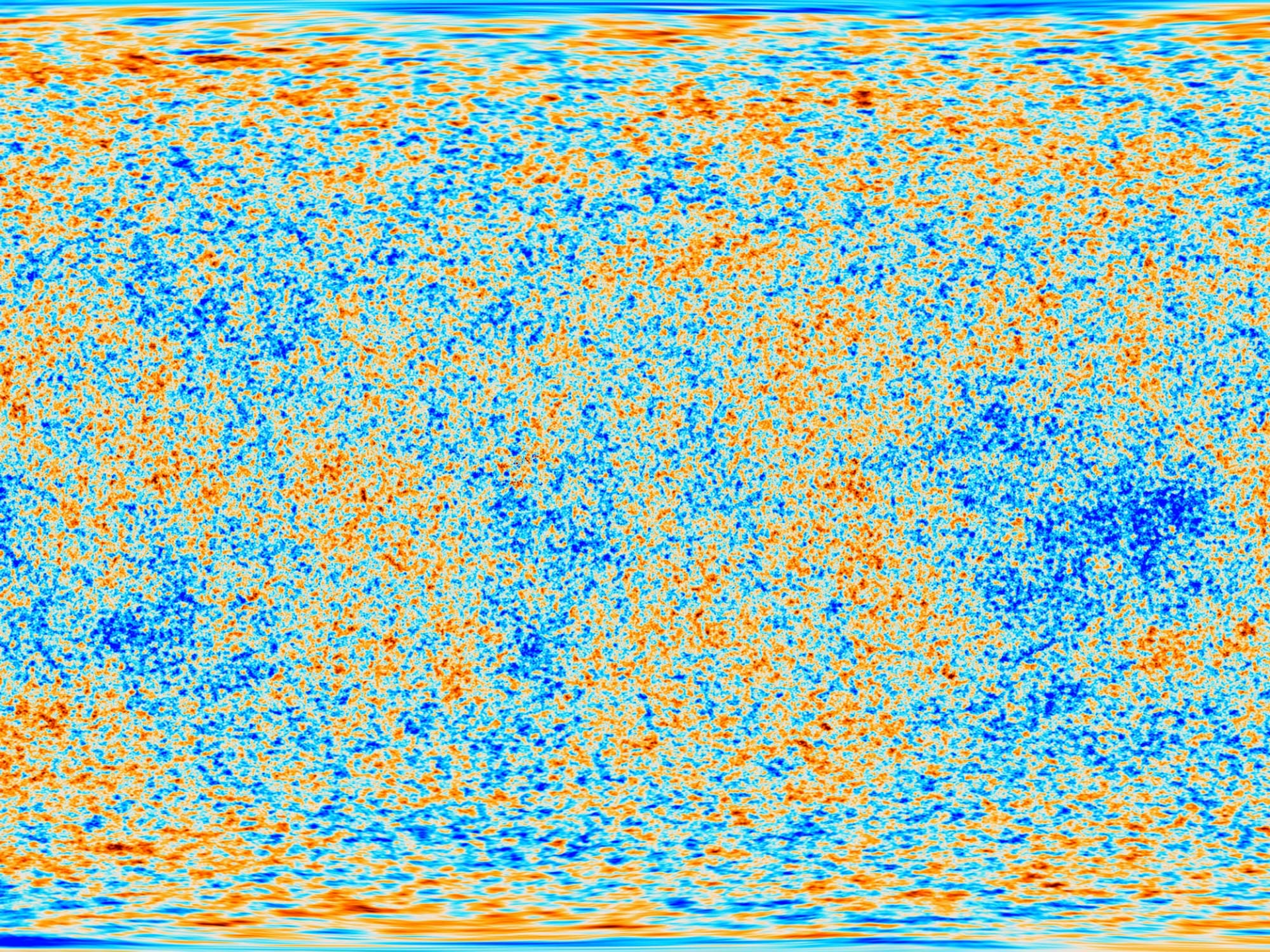
The Oldest Light in the Universe



These light particles have been travelling through space ever since and are 13.8 billion years old when they hit your eyes !

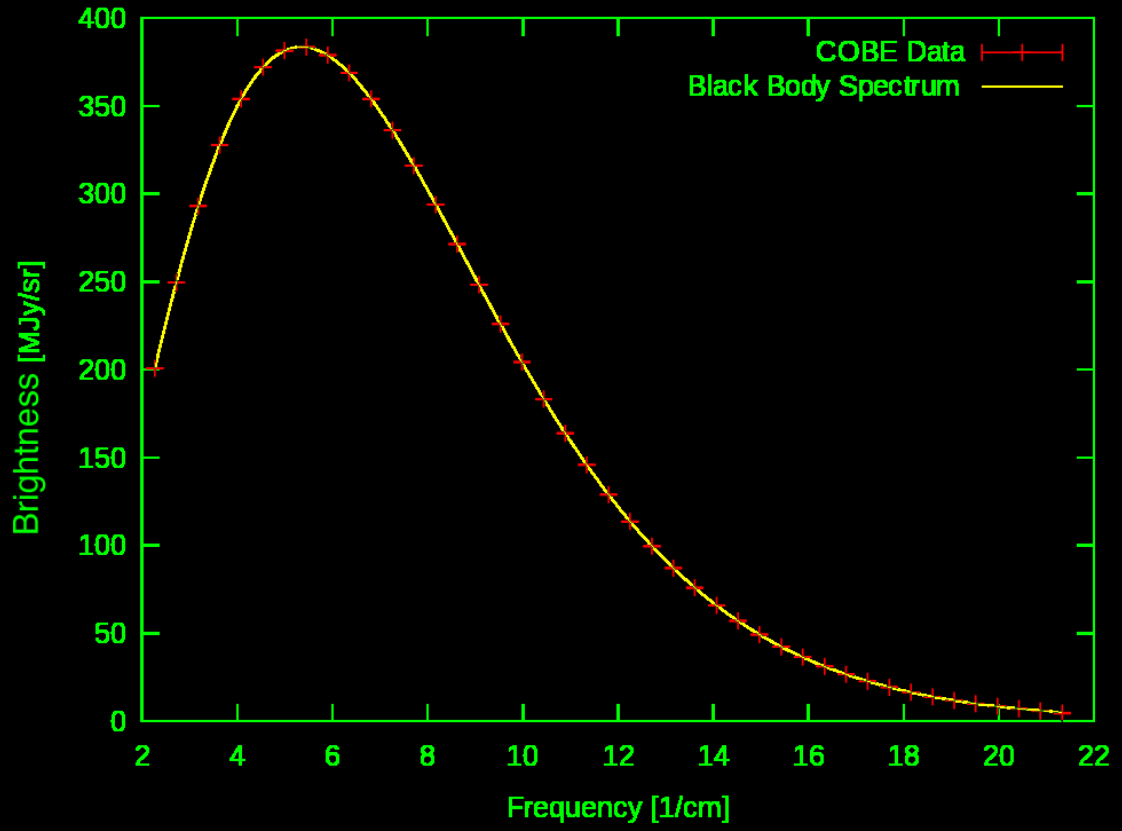
The Oldest Light in the Universe

The oldest photo of the universe



The Oldest Light in the Universe

Penzias and Wilson (1964)



The temperature of space
2.7K (~ - 270 Celsius)

The Future of the Universe

What is the fate of the Universe ?

Will it expand forever ?

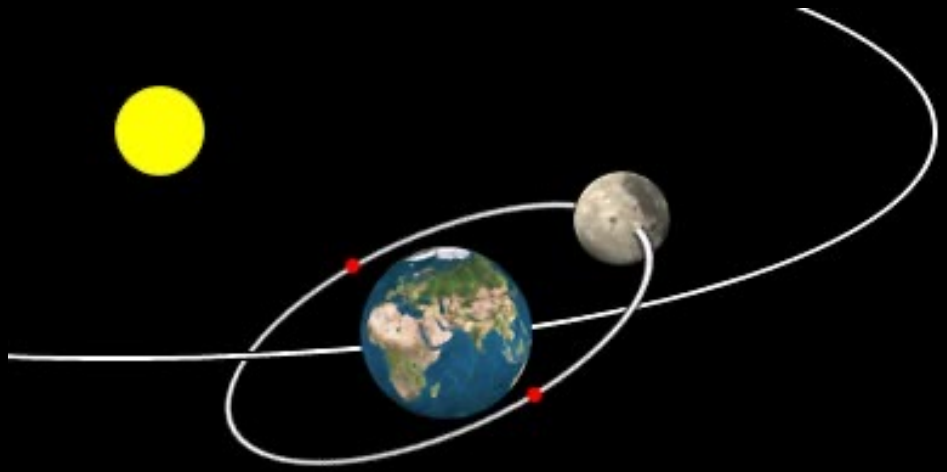
To understand what will happen to our Universe we must go back to school ☺

….. And talk about apples

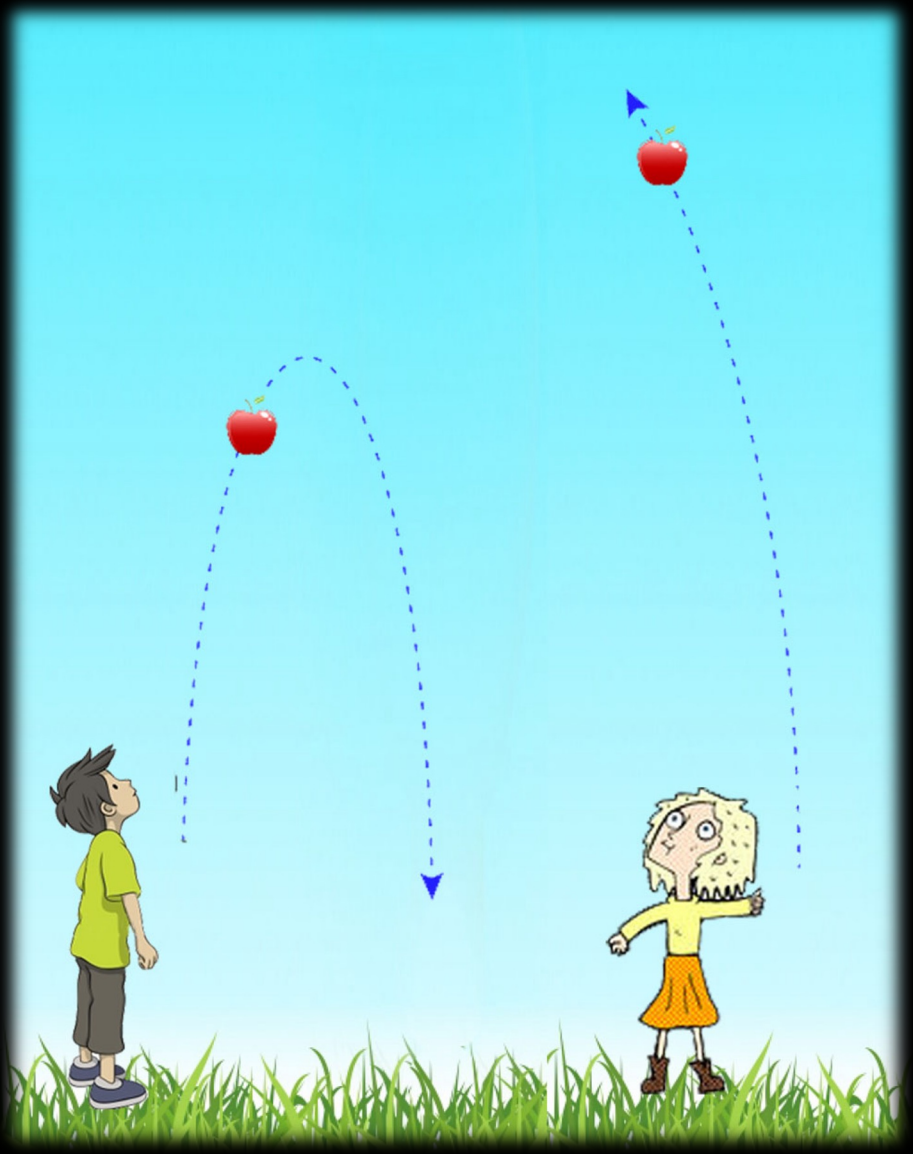
Gravity

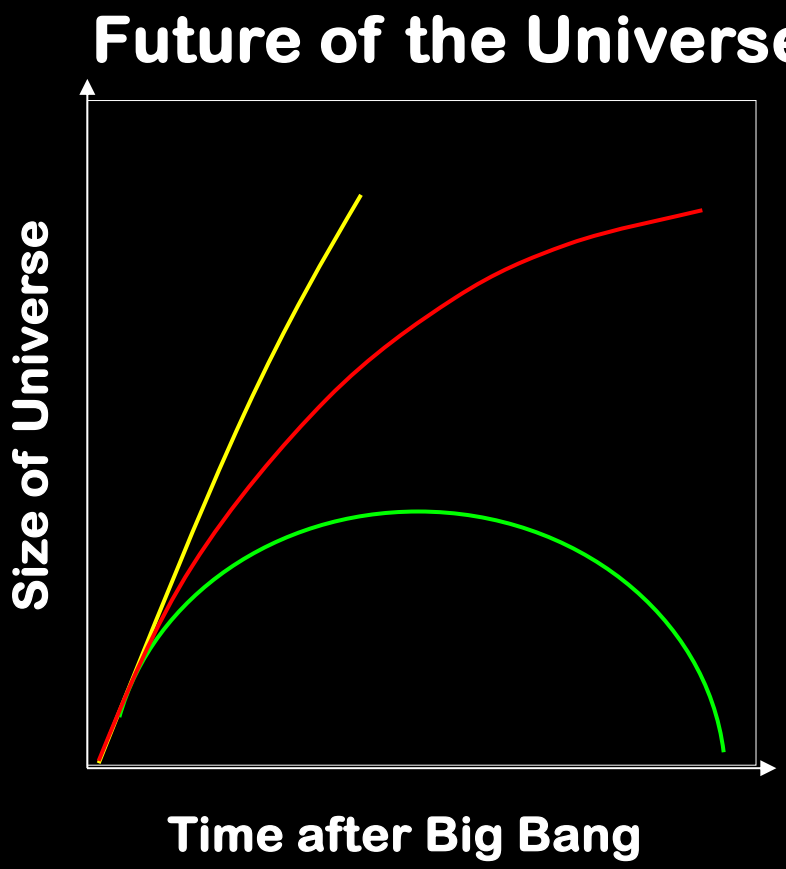
Sir Isaac Newton (1642-1727)

Laws of motion Universal gravitation



Gravity





The fate of the Universe has a lot to do with apples

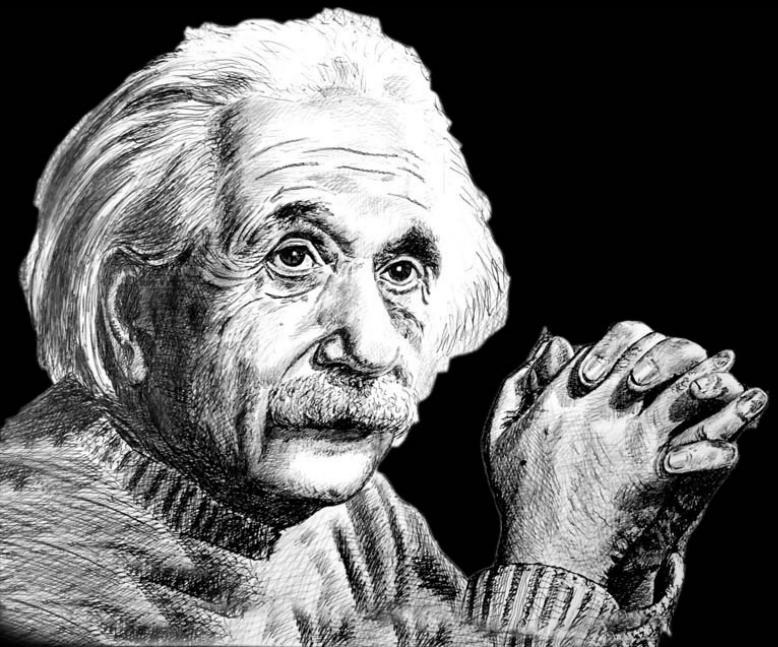
Einstein's Theory of Gravity

Albert Einstein (1879 – 1955)

The theory of General Relativity (1905-1915)

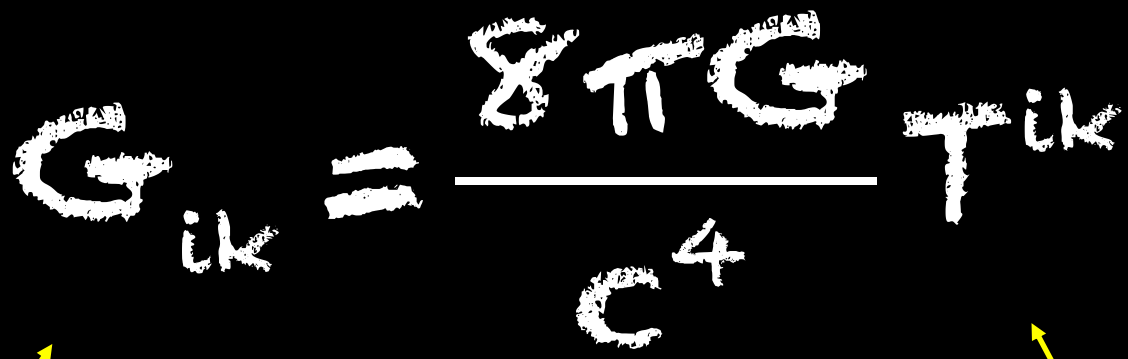
Space and Time are interwoven together

Gravity: not a force but a consequence of Geometry



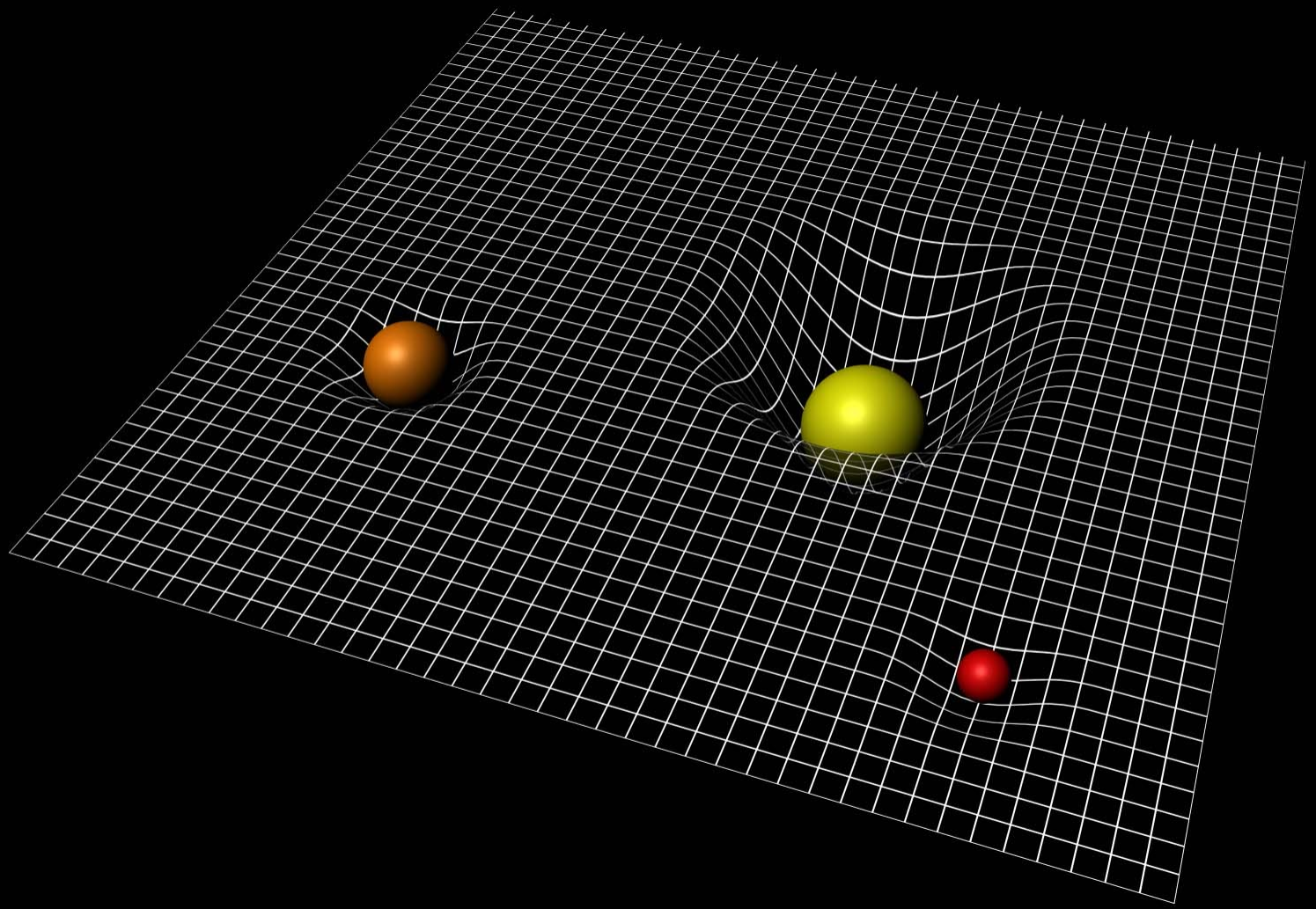
Einstein's Theory of Gravity

Einstein Equation:
Relates the Matter Energy to the Geometry of the Universe



Space tells Matter how to move
Matter tells Space how to curve

Einstein's Theory of Gravity

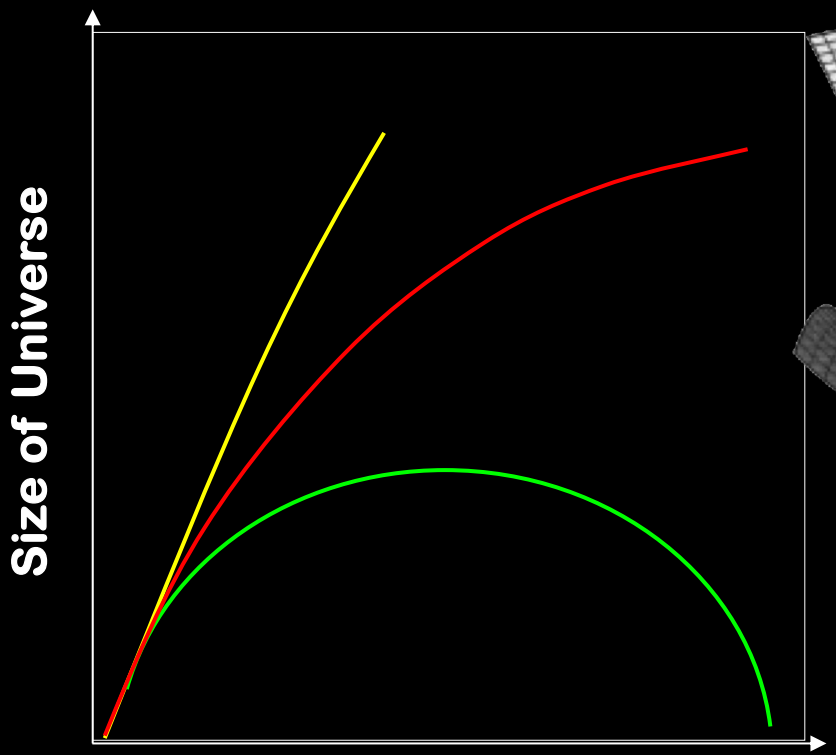


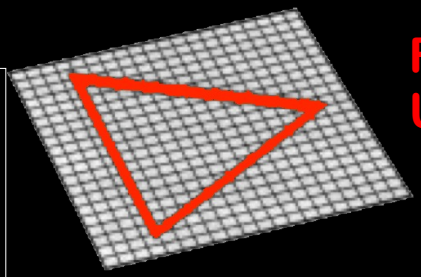
Space tells Matter how to move
Matter tells Space how to curve

What Universe do we live in ?

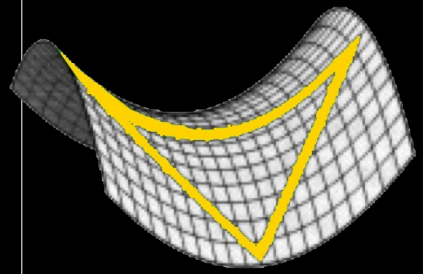
Shape (geometry) of Universe decides its fate

Amount of stuff in the Universe decides its shape

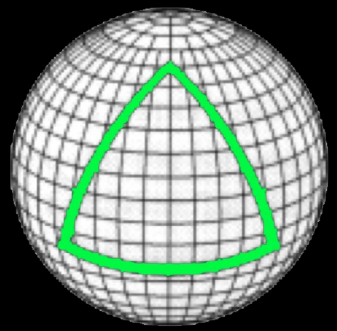




Flat space
Universe expands forever



Hyperbolic space
Universe expands forever



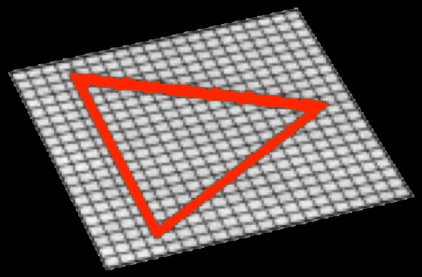
Spherical space
Universe eventually collapses

What Universe do we live in ?

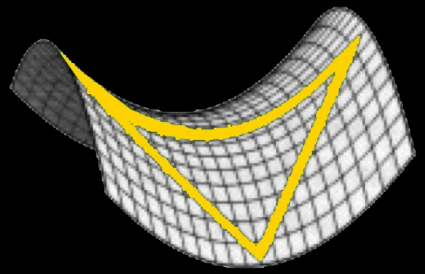
How much stuff do we need to STOP th Universe expanding?

define $\Omega = \dfrac{\rho}{\rho_{critcal}}$

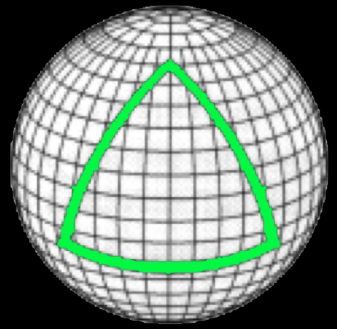
$\rho_{critical} \approx 10^{-26}\ kg / m^3$



$\Omega = 1 : \rho = \rho_{critical}$ **Critical value**



$\Omega < 1 : \rho < \rho_{critical}$ **Universe expands**

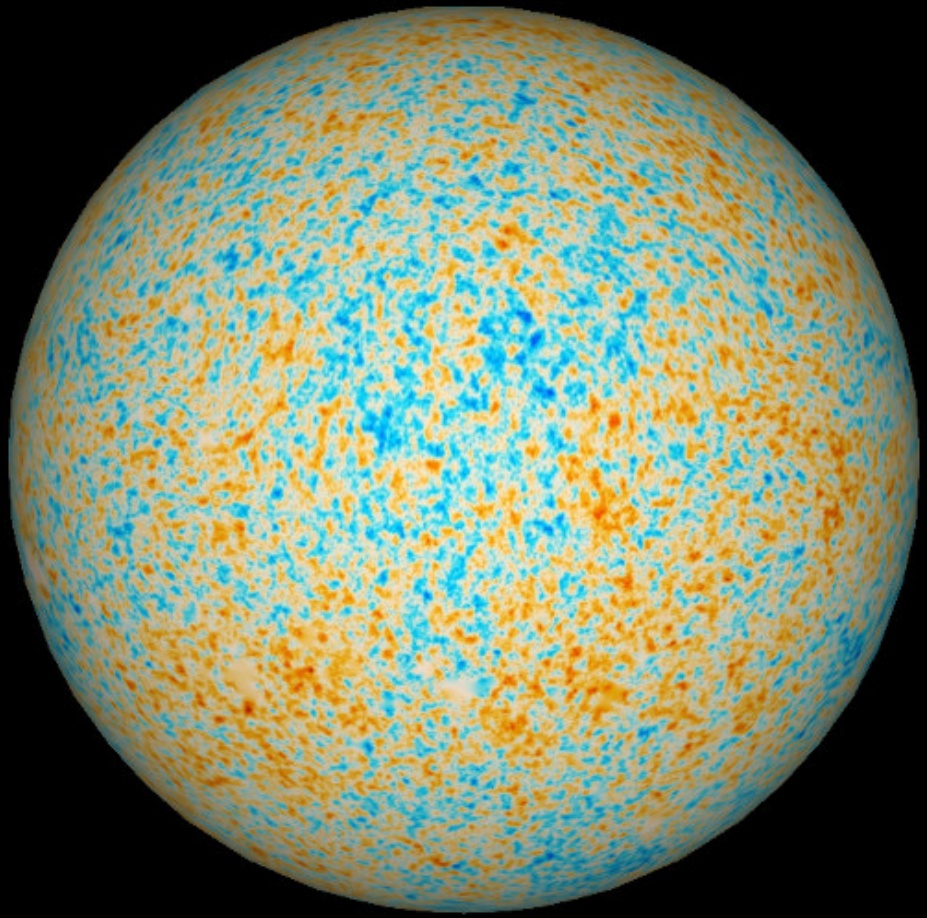


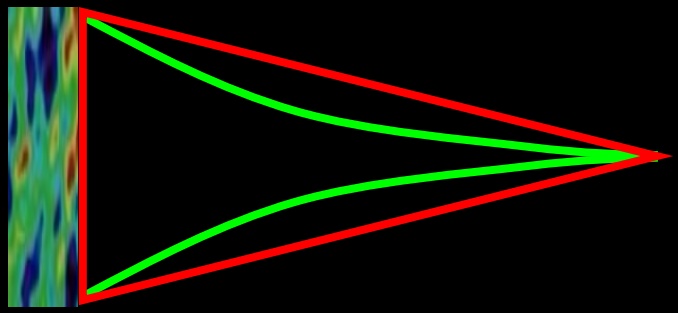
$\Omega > 1 : \rho > \rho_{critical}$ **Universe contracts**

What Universe do we live in ?

Shape (geometry) of Universe decides its fate

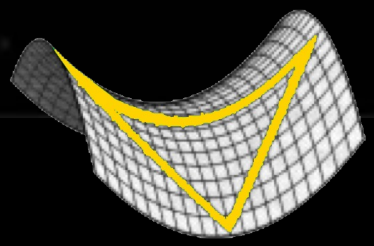
Amount of stuff in the Universe decides its shape

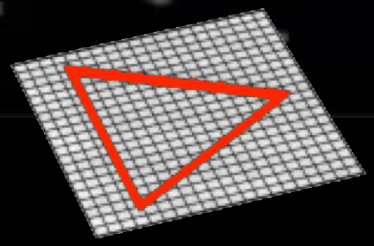


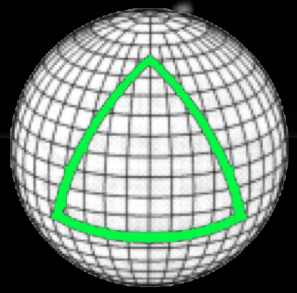


What Universe do we live in ?

We live in a Flat Universe







Cosmology: A Tale of 3 Numbers

Hubble parameter

(how fast is Universe expanding)

$H_o = 67.3$ km/s/Mpc

Density parameter

(how much stuff is in the Universe)

$\Omega_{total} = 1$

Cosmological Constant

(is the Universe accelerating or decelerating)

The Problem of Missing Mass

Recall from Big Bang Nucleosynthesis

Baryon density $\rho_{baryons} \sim 0.05 \times 10^{-26}\ kg/m^3$

BUT……

Inflation + Cosmic Background tells us the Universe is flat !

$\Omega = 1 : \rho = \rho_{critical} \approx 10^{-26}\ kg / m^3$

$\rho_{baryons} / \rho_{critical} = \Omega_{atoms} = 0.05$

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The Problem of Missing Mass

The End of the Story?

still many missing pieces

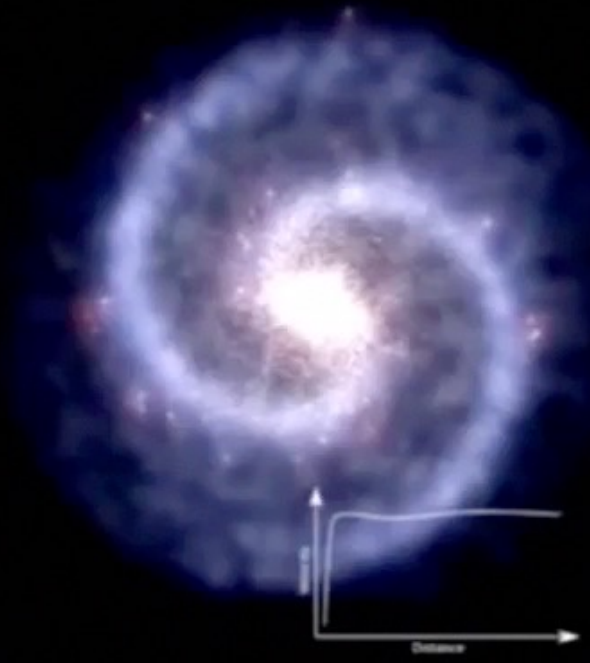
The Problem of Missing Mass

Fritz Zwicky 1933: weighed clusters of galaxies

The Problem of Missing Mass

Vera Rubin 1970s : Galaxy Rotation Curves

Galaxy Without Dark Matter



Galaxy With Dark Matter

The Problem of Missing Mass

Galaxies are surrounded by an enormous halo of nonluminous (dark) matter!

Luminous matter is concentrated at the center

The Problem of Missing Mass

The Problem of **MISSING MASS**

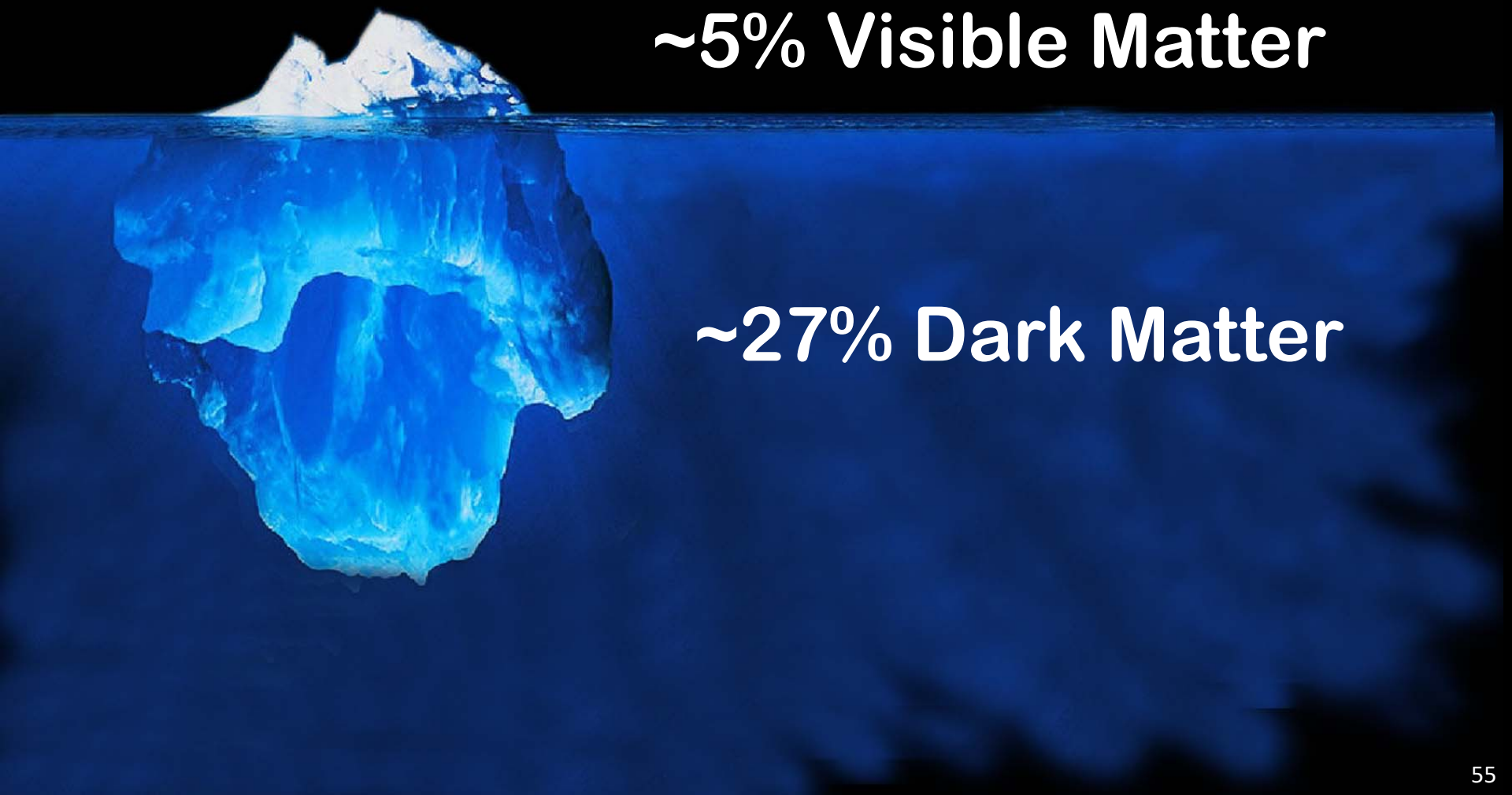
More accurately the problem of **MISSING LIGHT**

→ giant **Dark Matter** spherical halos

$$\Omega_{Dark\ Matter} \approx 0.27$$

The Problem of missing mass (or light)

Compared to what we observe; 5x the mass is missing !
Problem of **MISSING MASS ?** → rather **MISSING LIGHT !**



Non-Baryonic Dark Matter

To be born Dark, to become dark, to be made dark, to have darkness

COLD DARK MATTER	Non Relativistic at decoupling	Heavy Neutrino	WIMPs
		SUSY Particles	
		Axions	
HOT DARK MATTER	Relativistic at decoupling	Light Neutrino	
COSMIC RELICS	Symmetry Defects	Monopoles	
		Cosmic Strings	
		Cosmic Textures	

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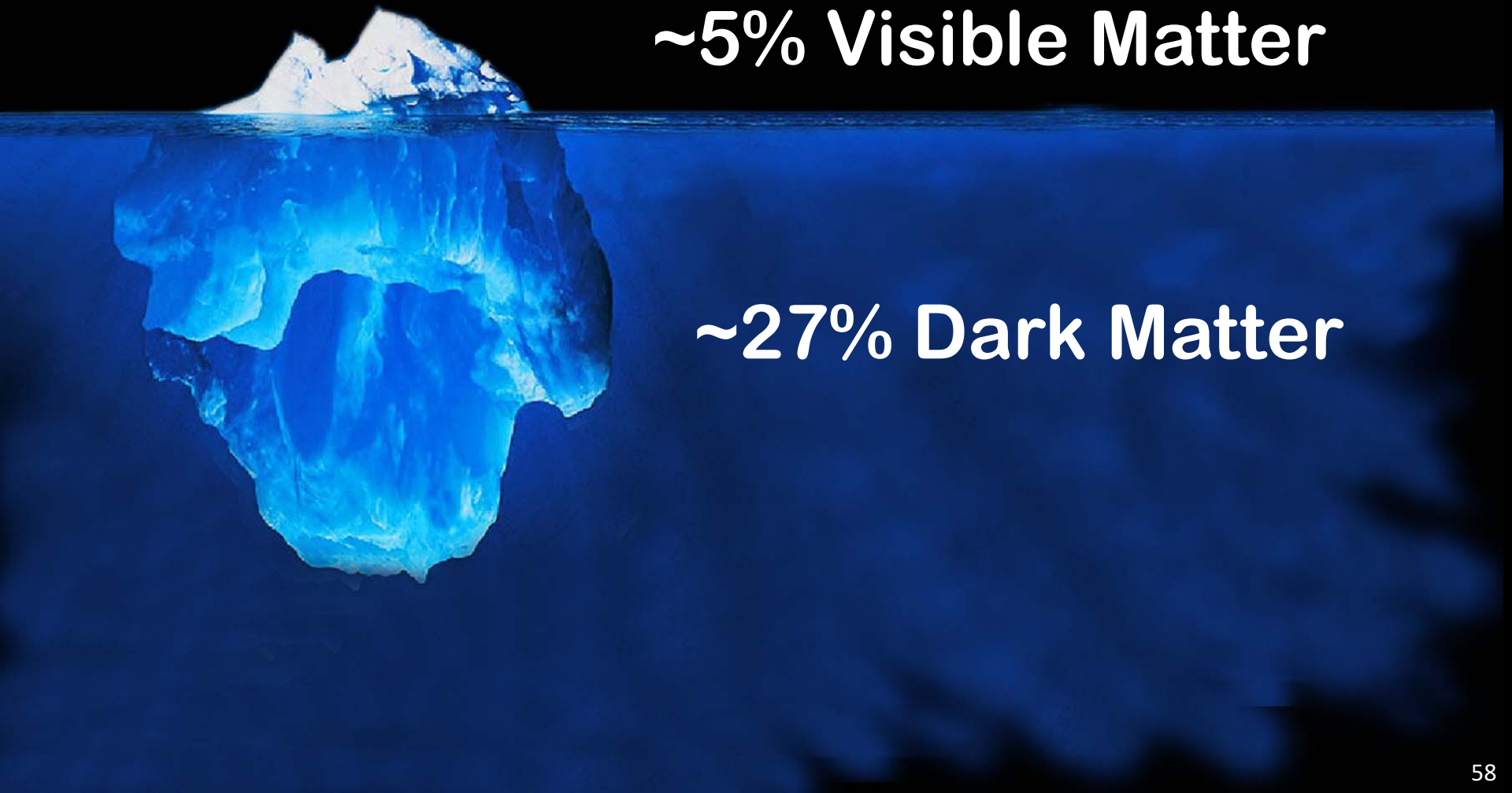
Cosmological Constant

(is the Universe accelerating or decelerating)

The Problem of missing mass (or light)

Still not enough to flatten the Universe

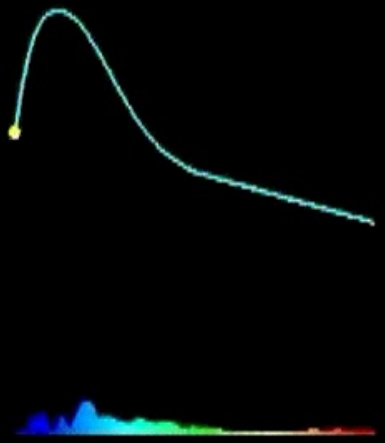


The End of the Story?

still many missing pieces

The Supernova Catastrophe

Saul Perlmutter 1998



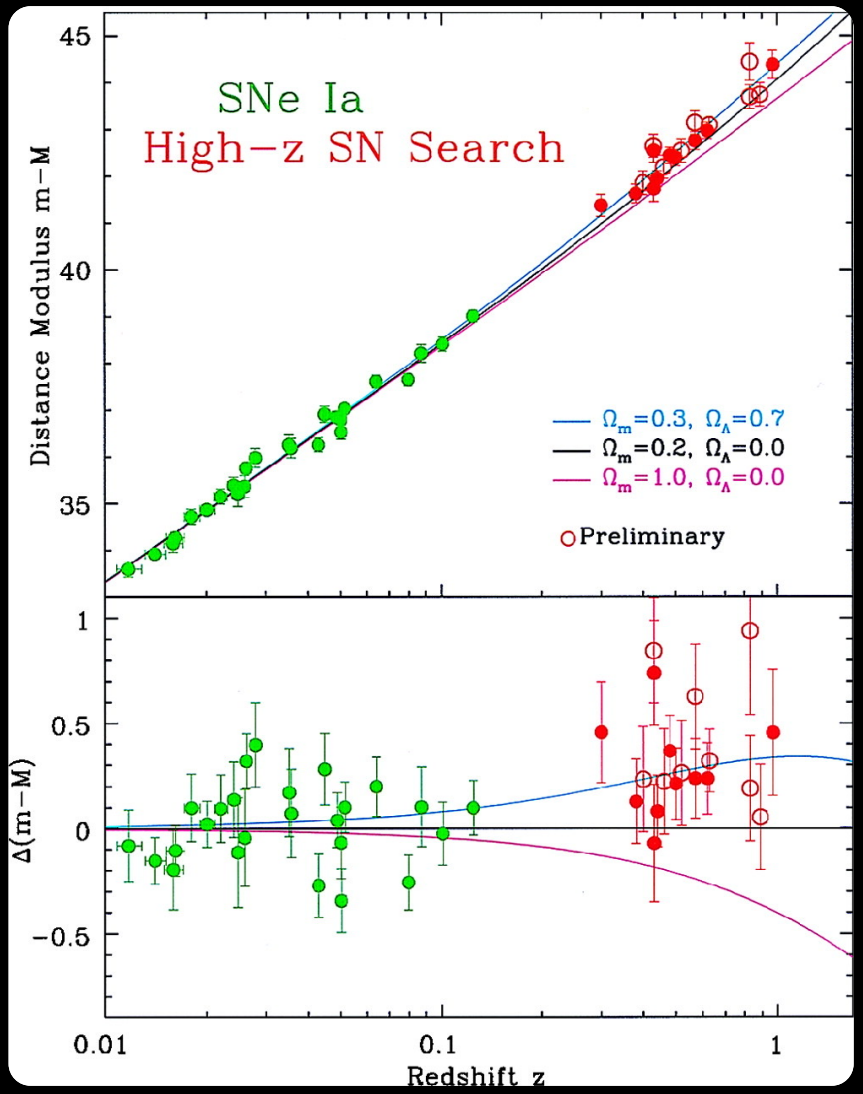
Measure distances in Cosmology using

- Standard Ruler: objects of known standard proper size.
- Standard Candles: objects of known luminosity.

can then calculate

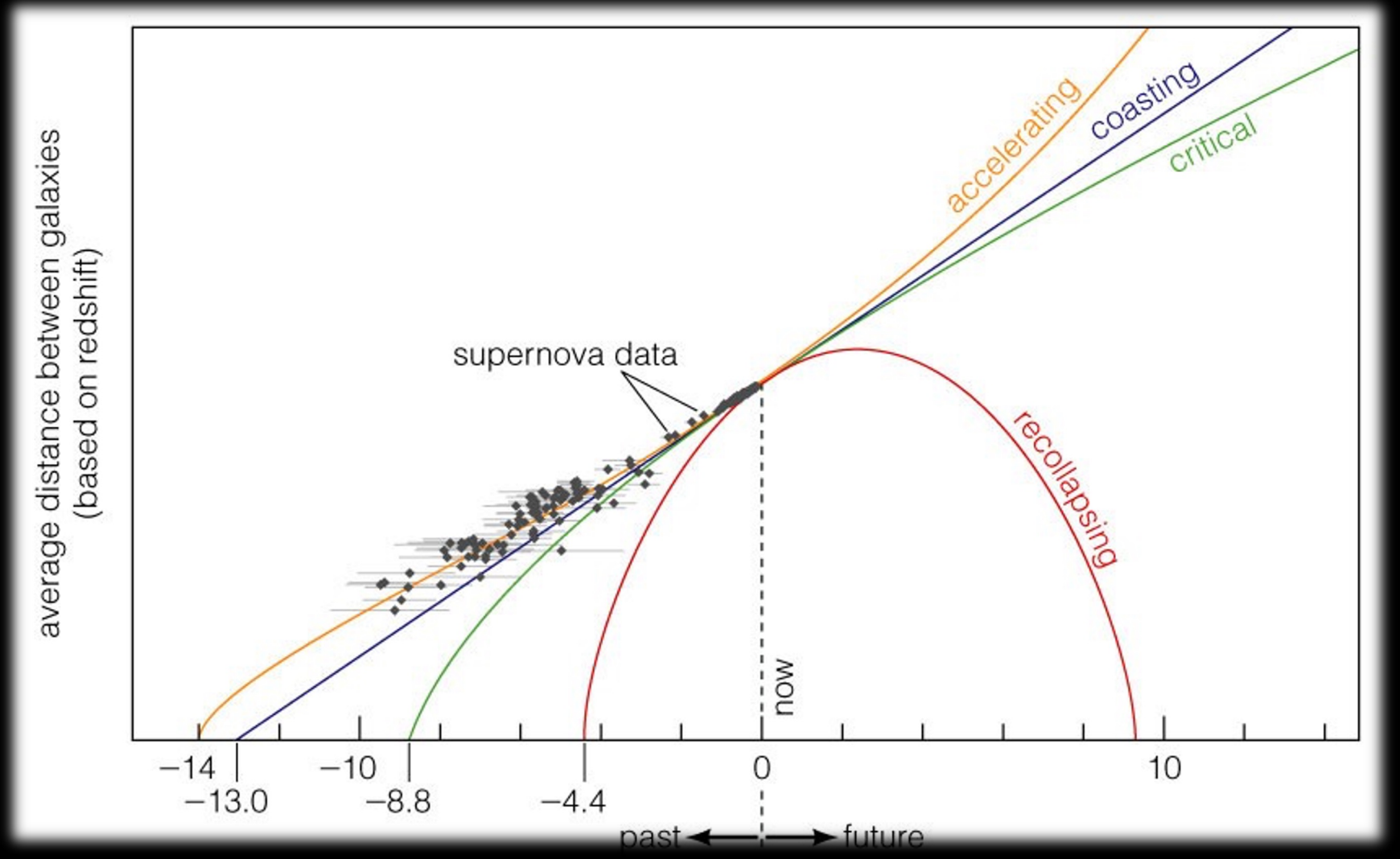
- Distance → cosmological parameters H_o Ω_m Ω_Λ

The Supernova Catastrophe



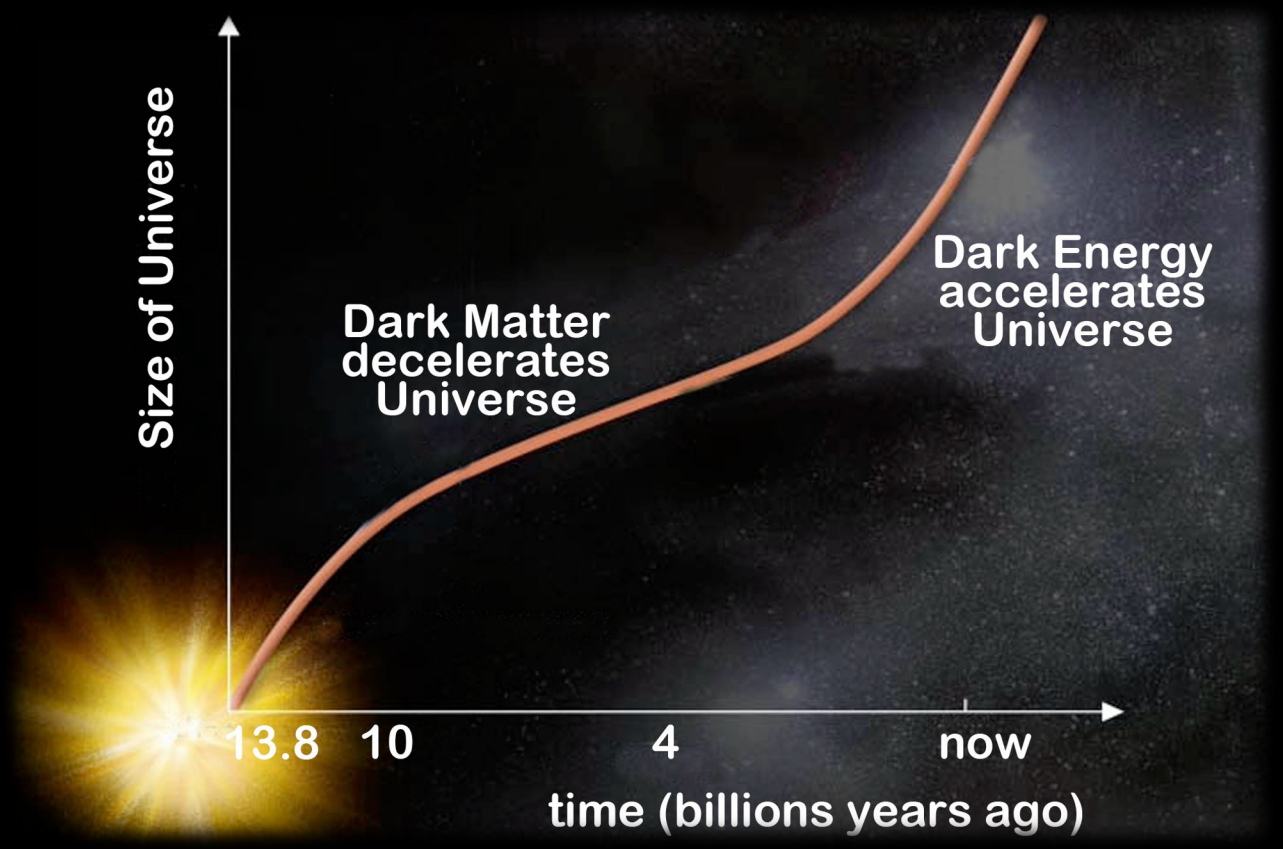
Universe is accelerating →standard candle of lower brightness.
Universe is decelerating →standard candle of higher brightness

The Supernova Catastrophe



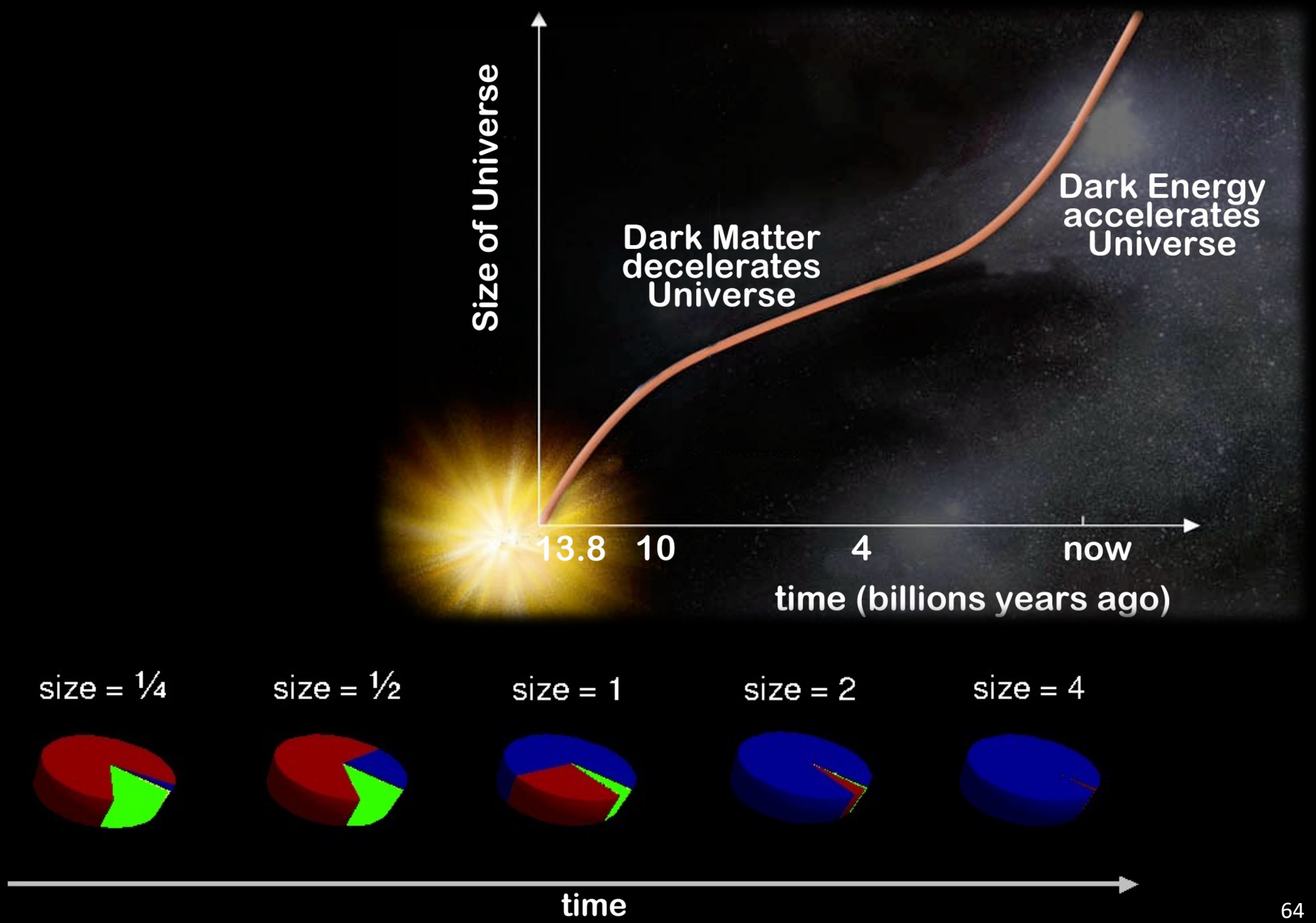
Supernova data show we are living in a Universe that is accelerating

A Universe Dominated by Dark Energy

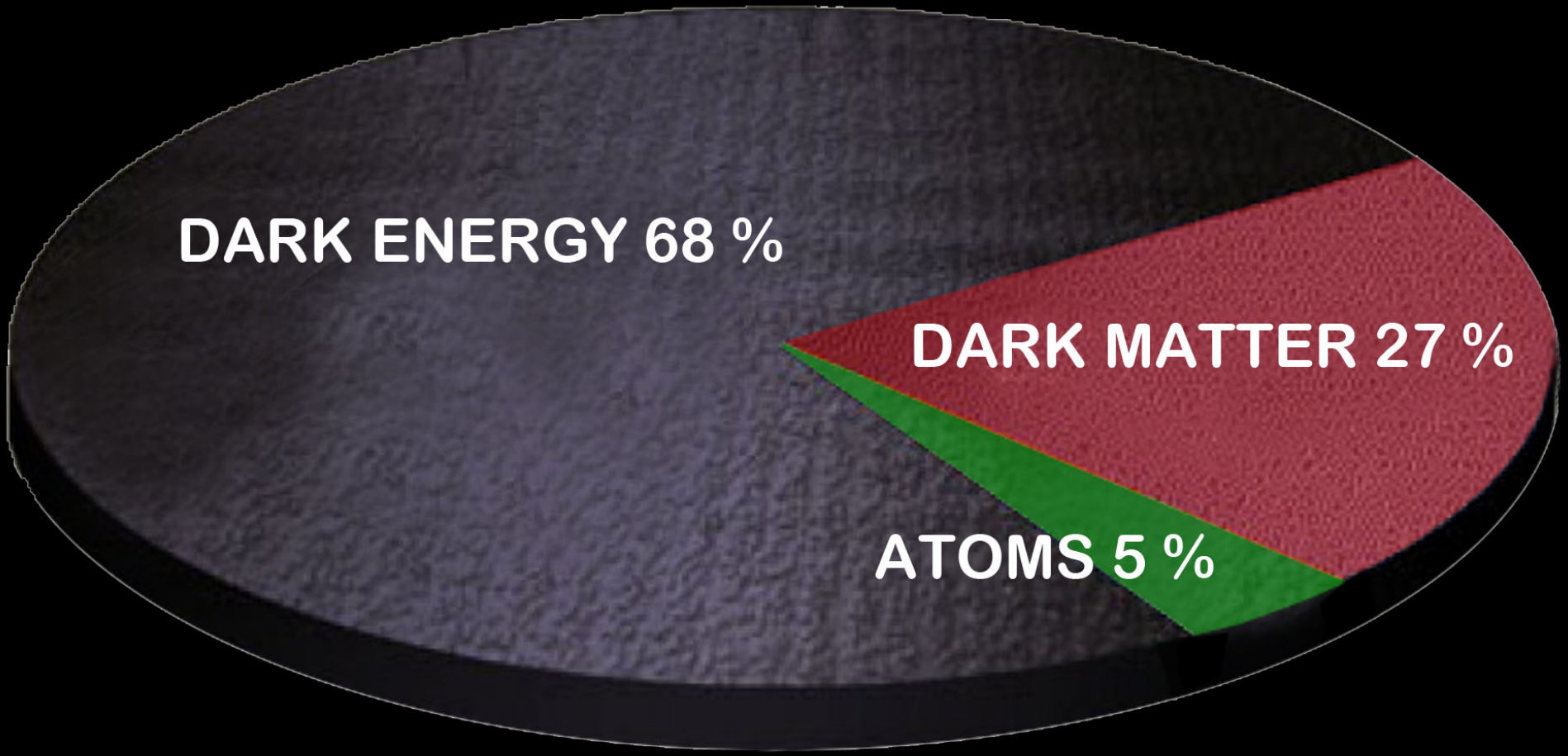


Our Universe is accelerating due to a repulsive force equivalent to $\Omega_\Lambda \sim 0.7$ Dark Energy

A Universe Dominated by Dark Energy

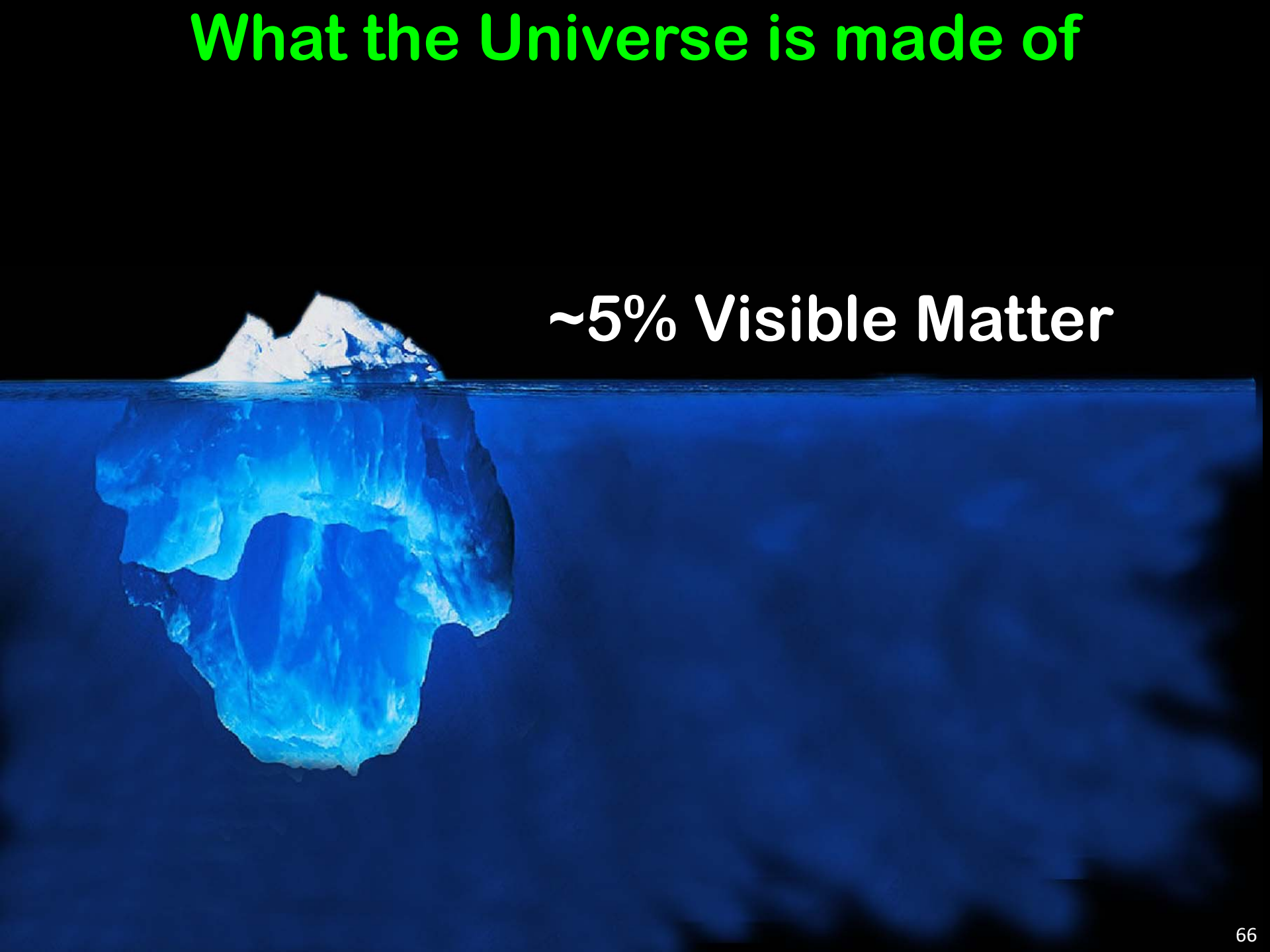


What the Universe is made of



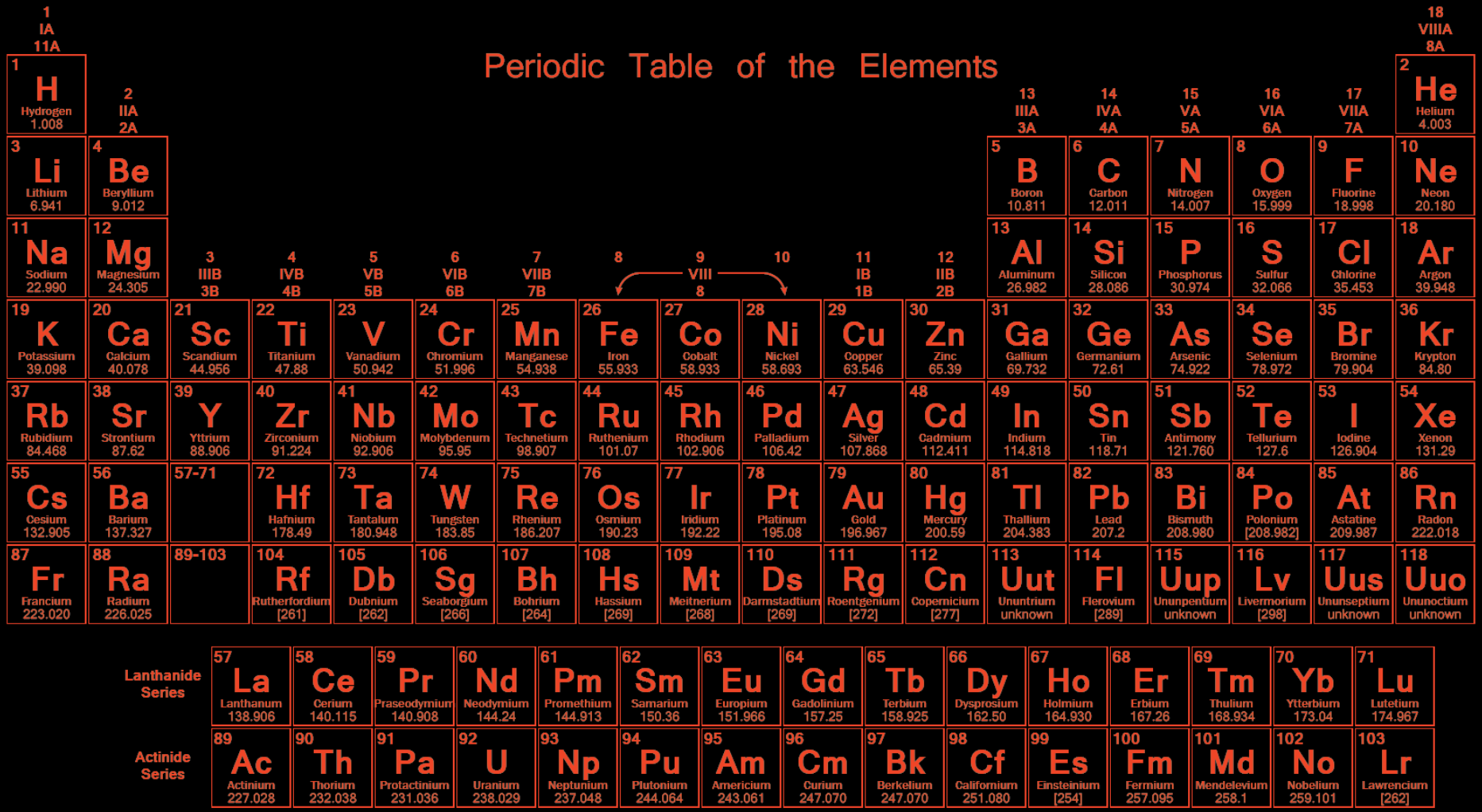
- Visible matter: atoms and stuff (we know what this is)
- Dark Matter (we don't know what this is)
- Dark Energy (we don't know what this is)

What the Universe is made of

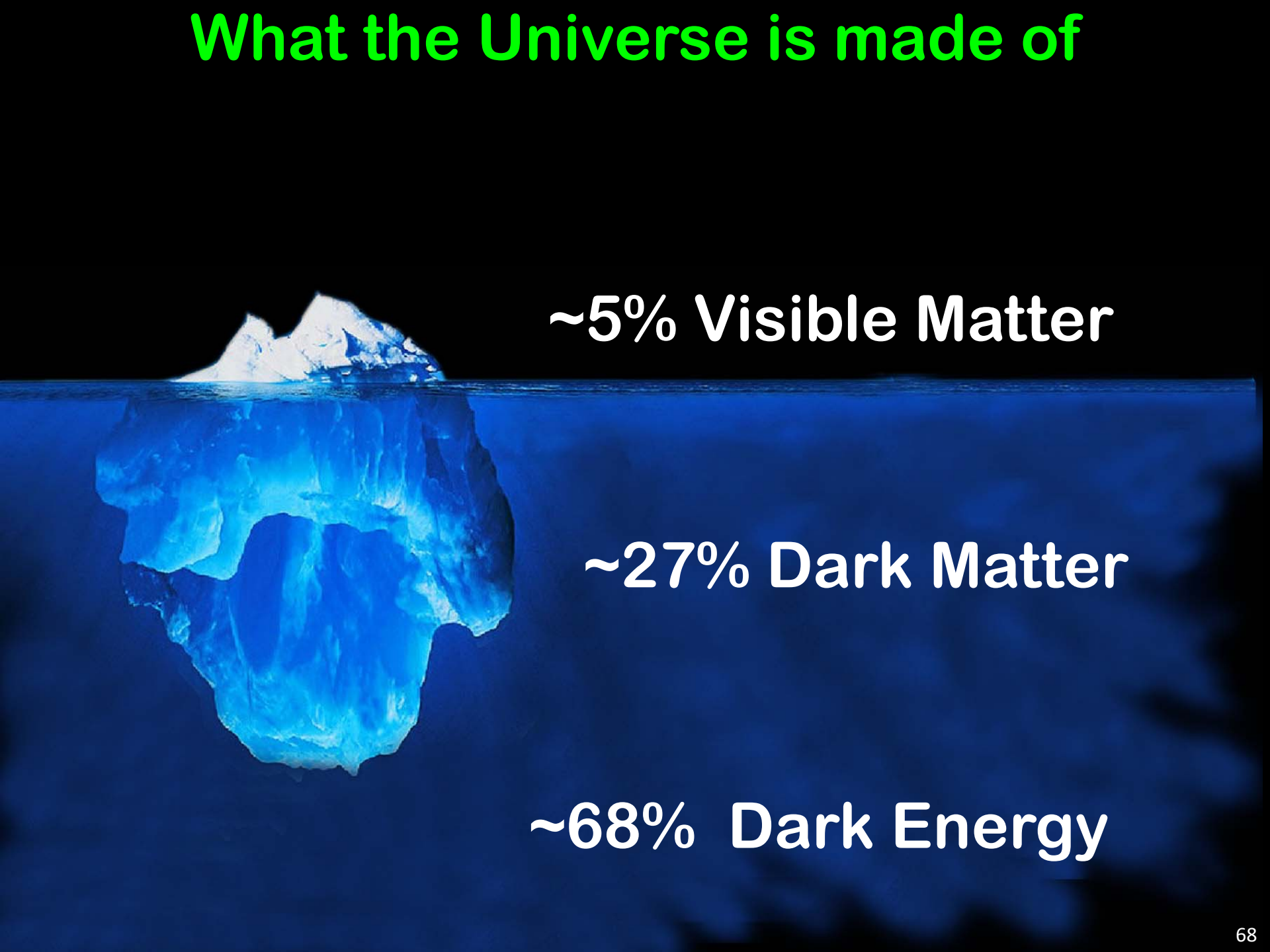


What the Universe is made of

~5% Visible Matter



What the Universe is made of



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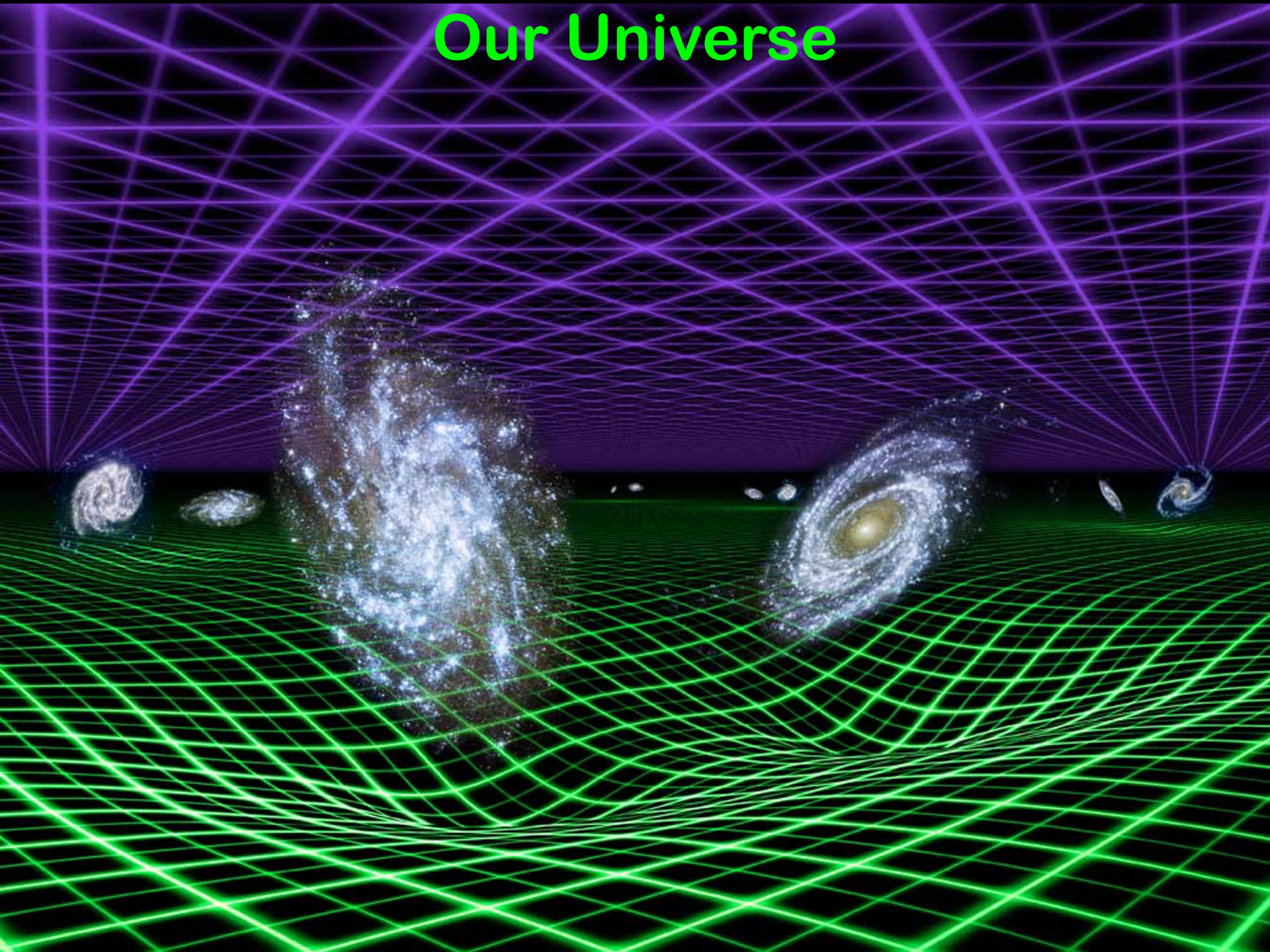
Cosmological Constant

(is the Universe accelerating or decelerating)

$\Omega_{total} = 1, \quad \Omega_{\Lambda} = 0.68$

Our Universe



Our Universe

- began in a Big Bang event ~ 13.8 Billion Years ago

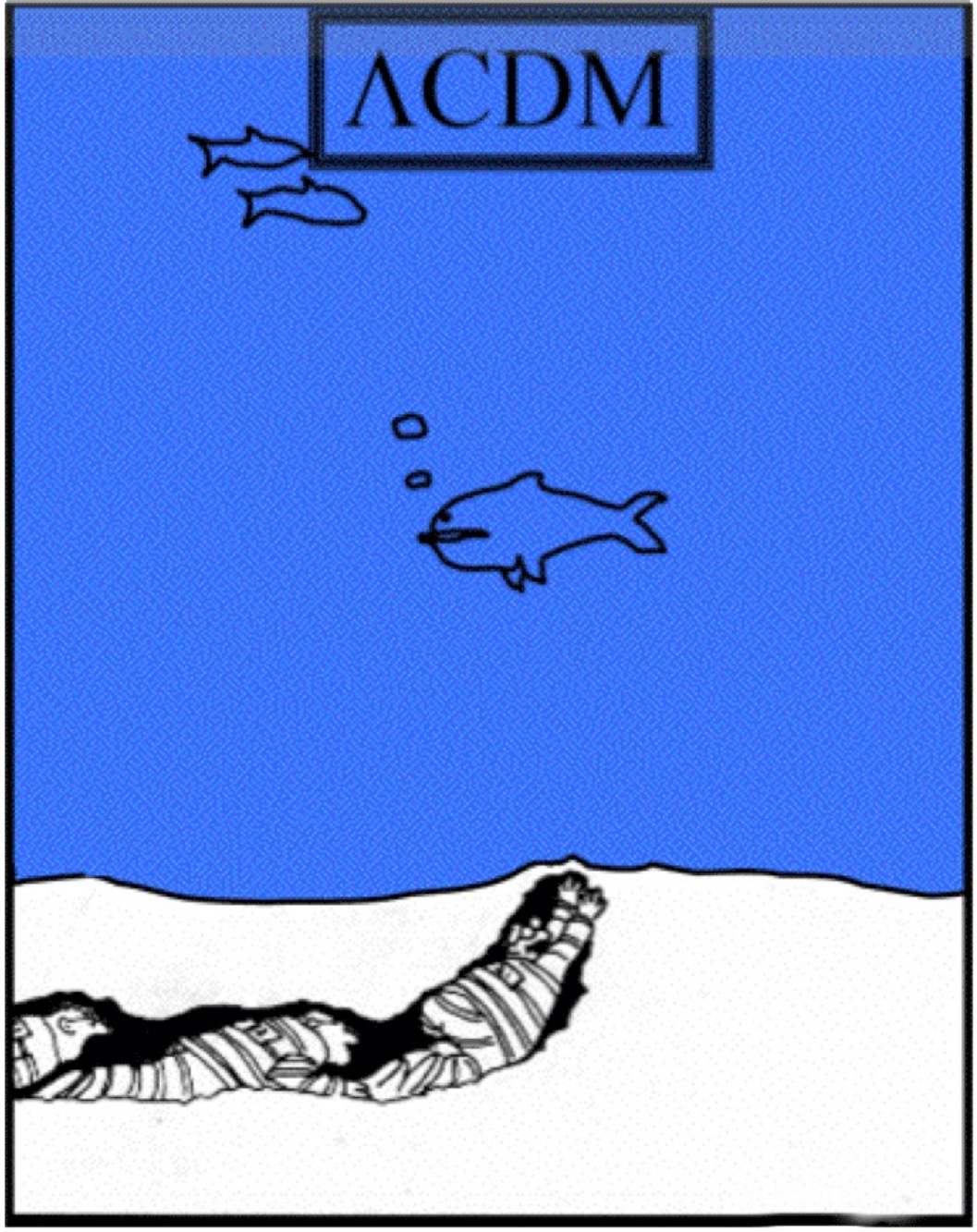
Big Bang Theory has had great success in predicting fine details of;

- The expanding Universe
- Primordial Nucleosynthesis and the light element abundances
- The Relic Radiation from the fireball
- The beginning of structure formation

Our Universe

- began in a Big Bang event ~ 13.8 Billion Years ago
- has been expanding ever since
- started accelerating about 4 billion years ago

- contains 6x as much Dark (non-baryonic) matter than normal matter
- and is dominated by a Dark Energy 3x greater than the dark matter
- so we don't really know what 95% of our Universe is made of



We're almost free, I just felt the first drops of rain

Thank you for Listening