# Uncovering our Cosmic Origins:
## What we know, what we can know, and what limits we may face.

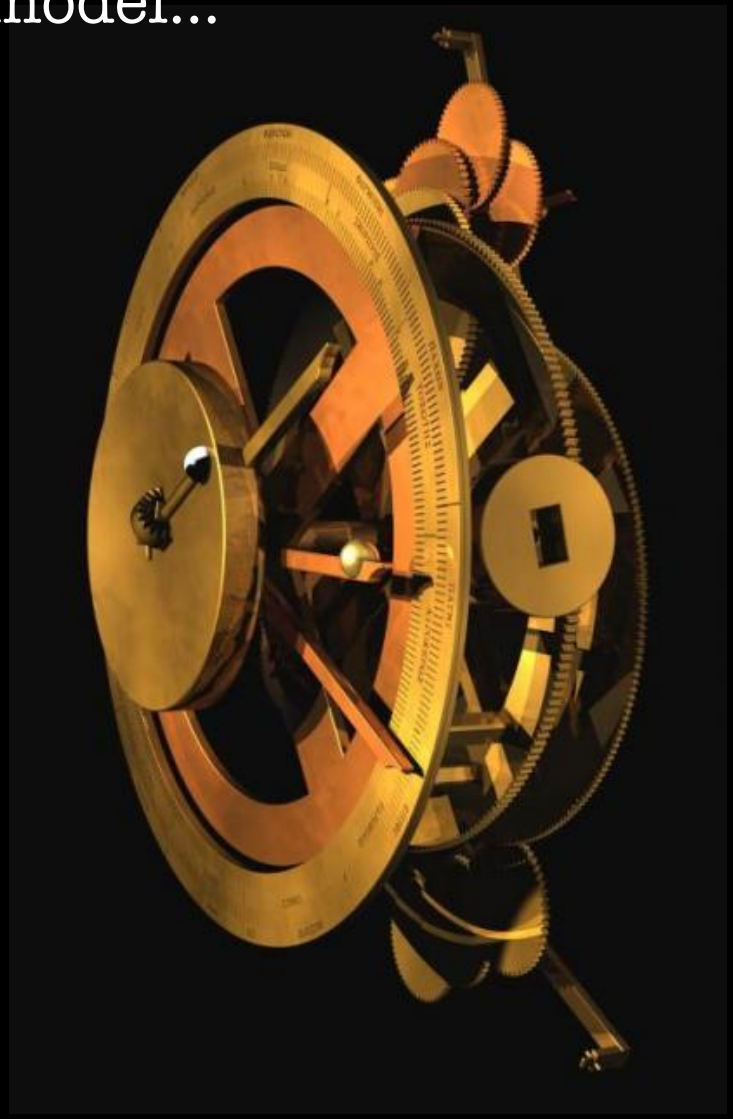
Science on Saturday
Princeton Plasma Physics Lab

William Jones
Princeton University
Physics Department

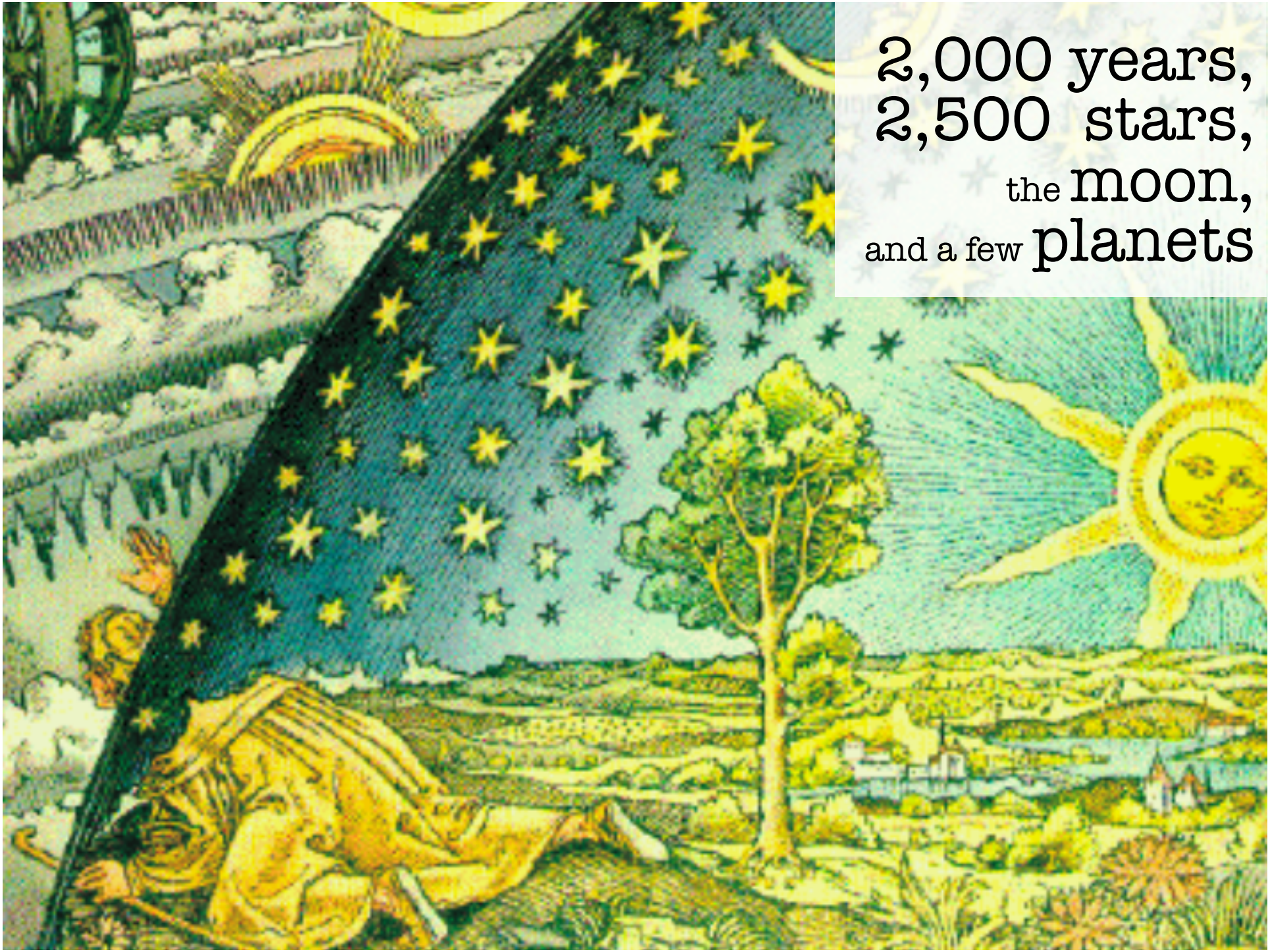
1500's :
2,500 stars,
the moon,
and a few planets

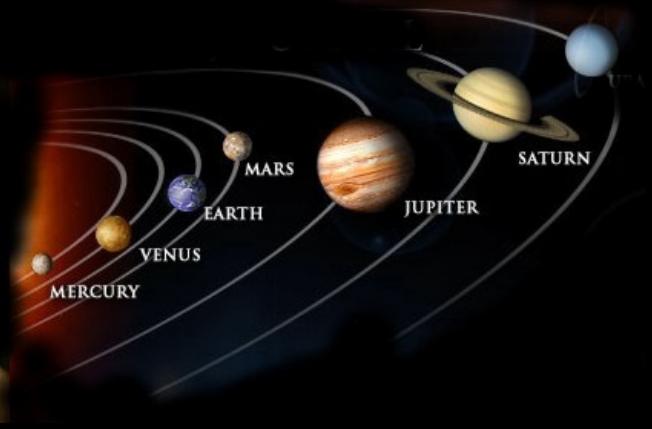
# Antikythera Mechanism: 1st century B.C.E.

Earliest (known) cosmological model...



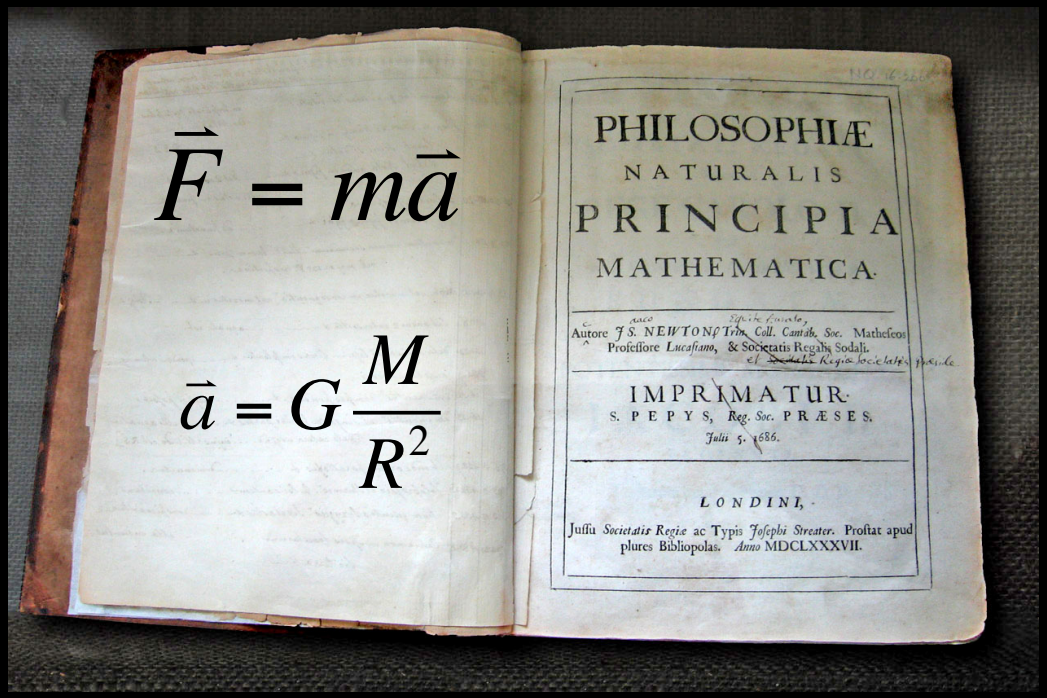
# The Wallingford clock: 15th century C.E.

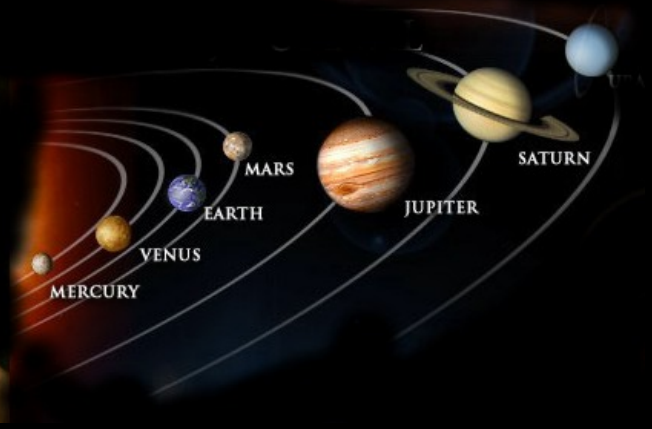

2,000 years,
2,500 stars,
the moon,
and a few planets



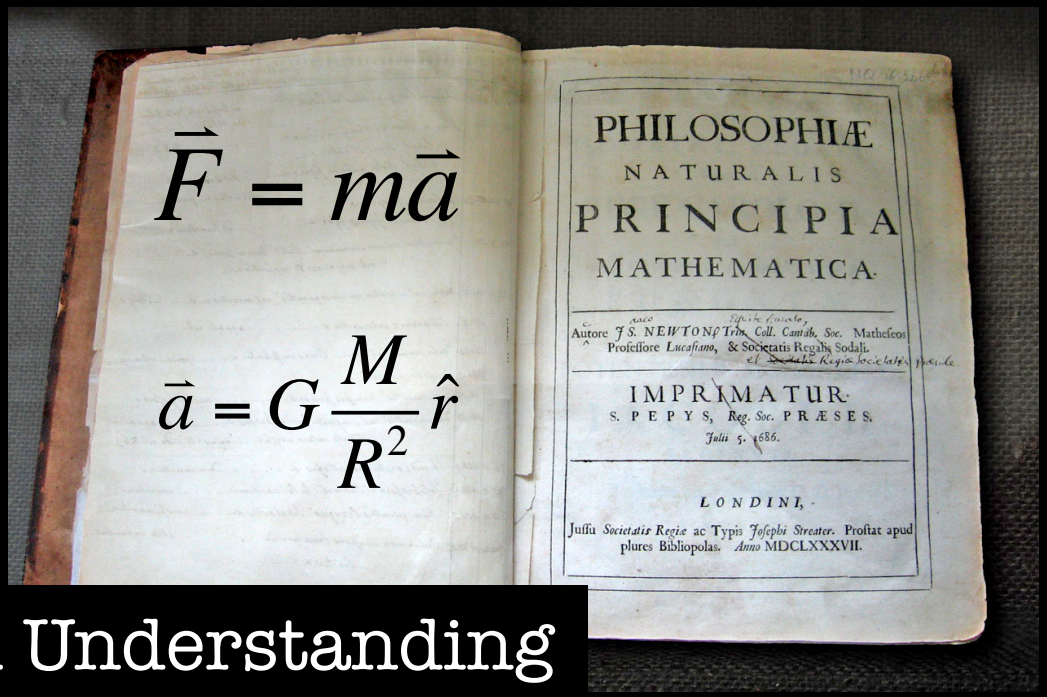

Tycho Brahe & Johannes Kepler, 1600

Issac Newton, 1686



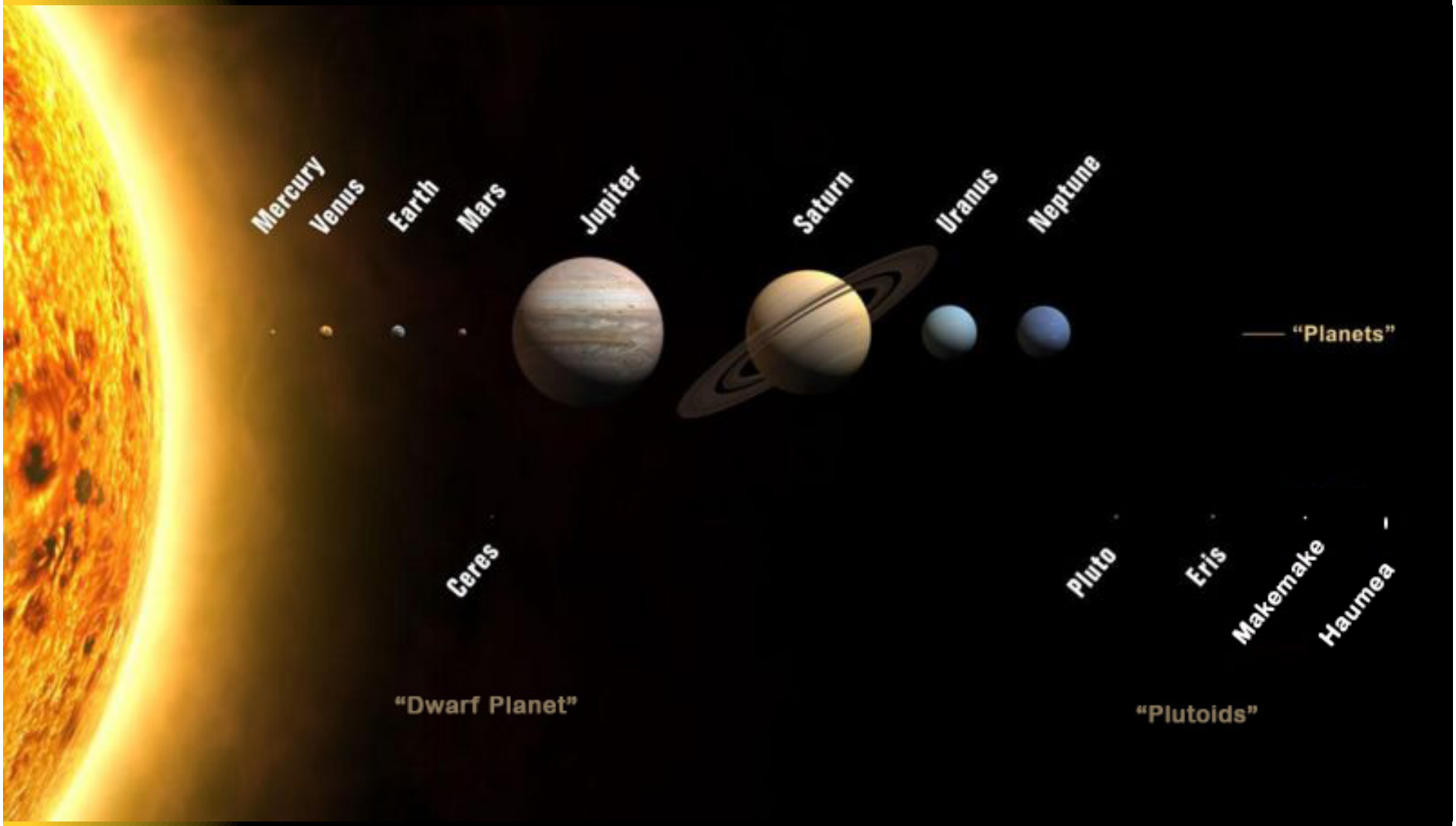



New Observational data → Empirical Laws

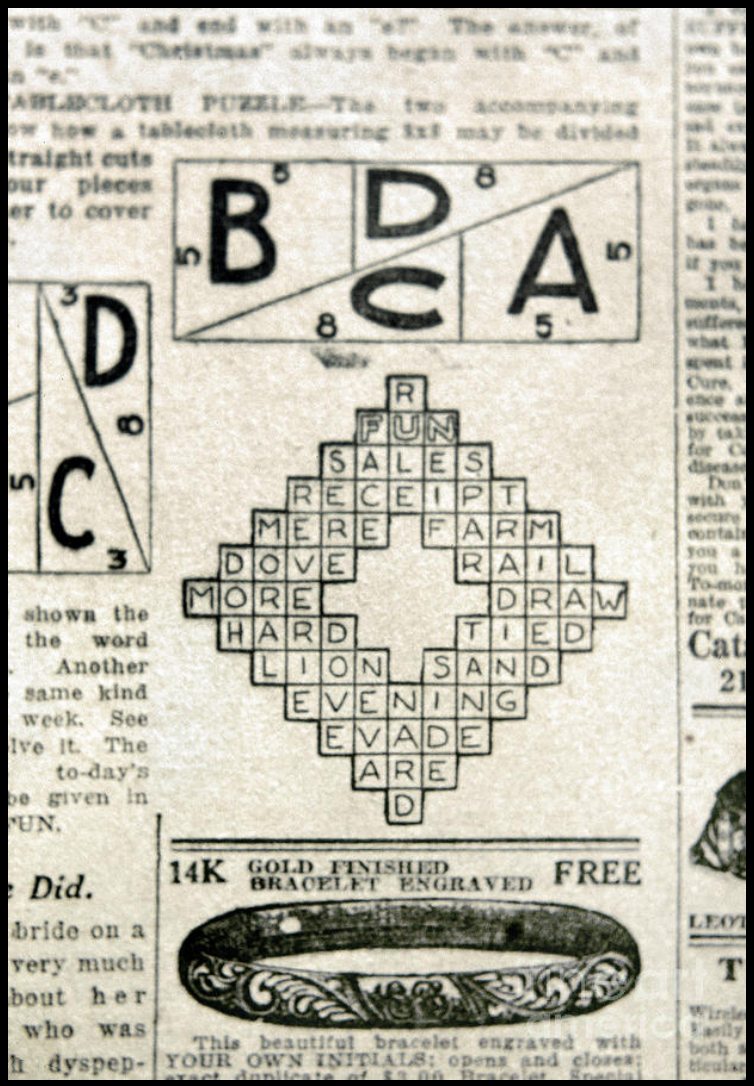



A More Fundamental Understanding

# A universal model of the Solar System




What about Everything Else?

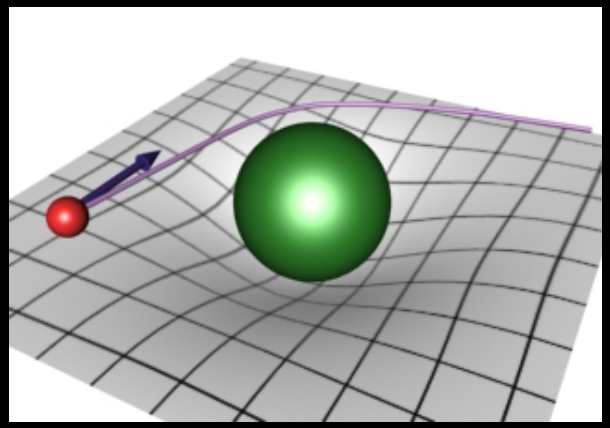



Arthur Wynne, December 1913

# 1905-1925:
# Two Remarkable Decades.

Crossword Puzzles
Fortune Cookies
Traffic lights
Television
Bras
...
General Relativity
Universal Expansion

# Albert Einstein, and his General Theory of Relativity



$$ds^2 = c^2 dt^2 - a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2(\theta) d\phi \right)$$

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

# Edwin Hubble, and his Diagram (+HST,SNe1a)

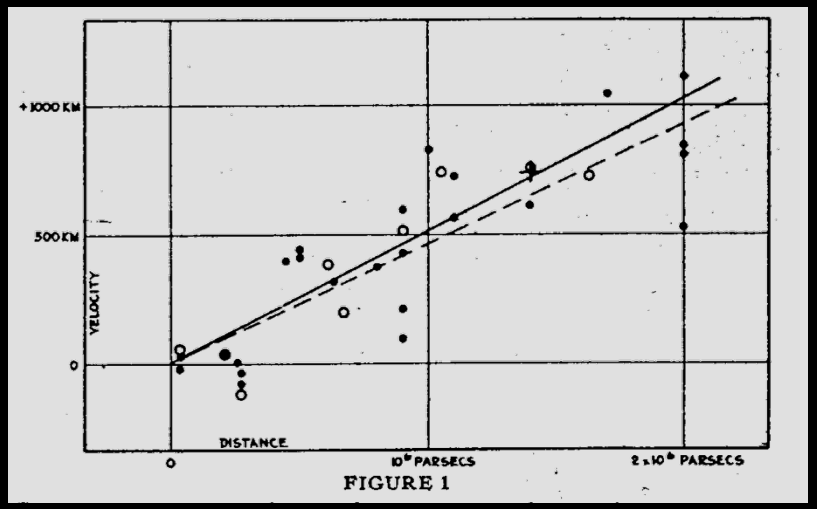


FIGURE 1

1920's

... and Hilbert, Lemaître, Friedman, Robertson, Walker, Henrietta Leavitt, et al.

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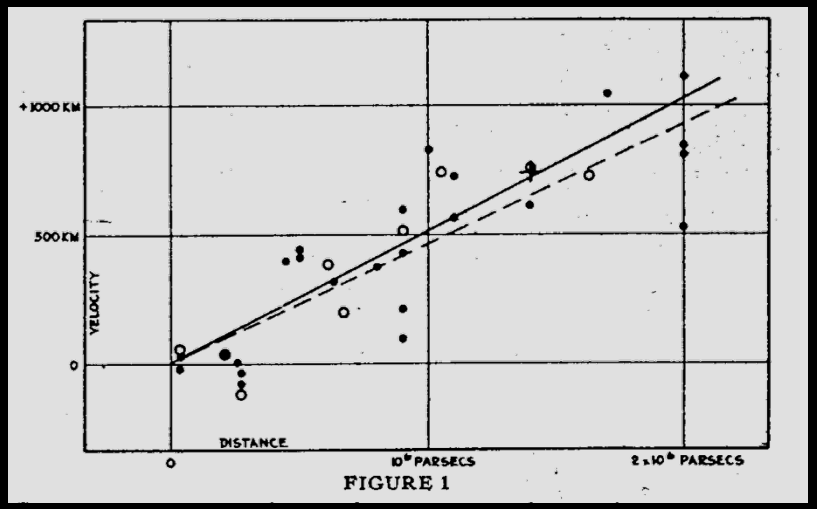
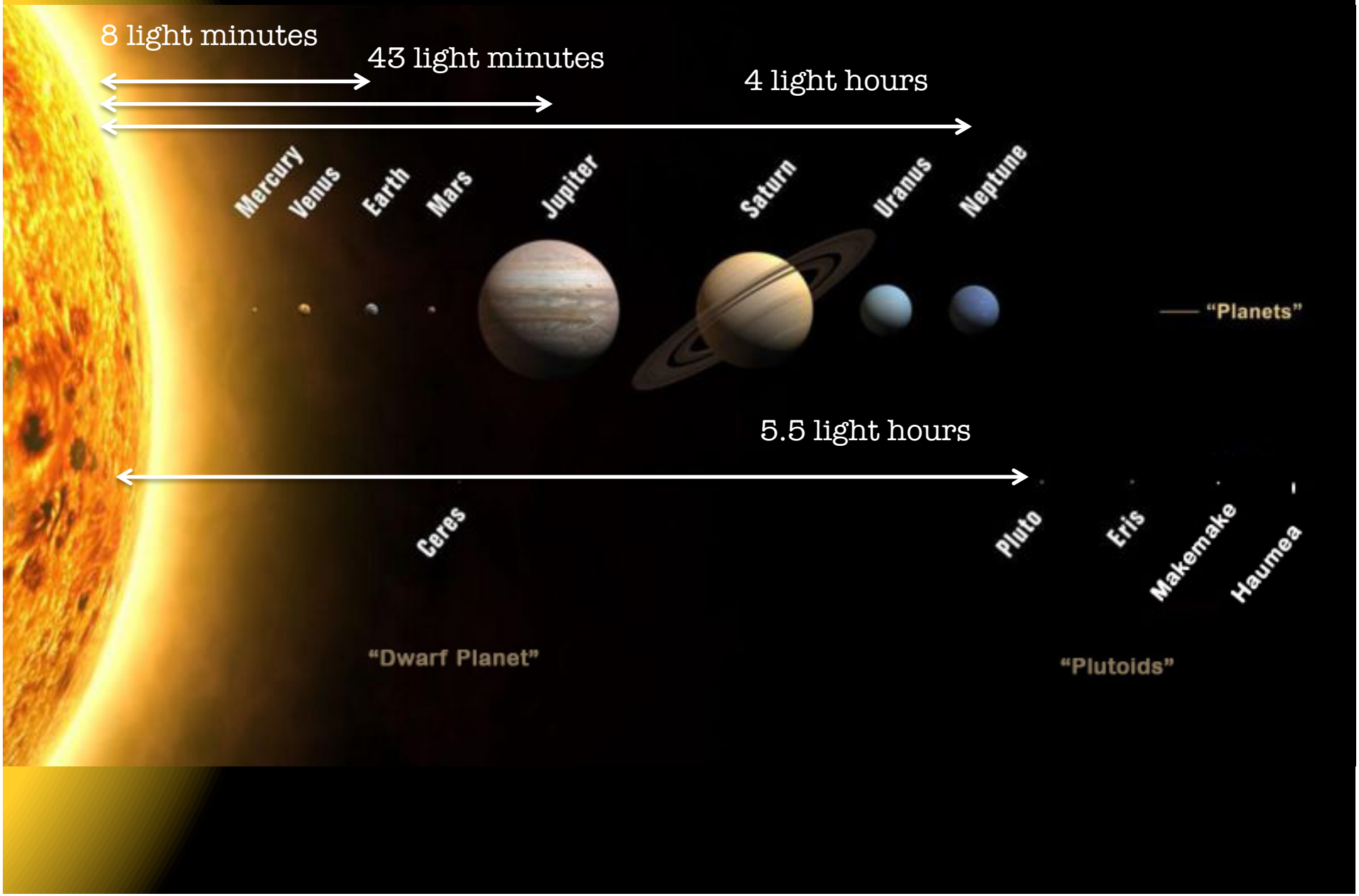


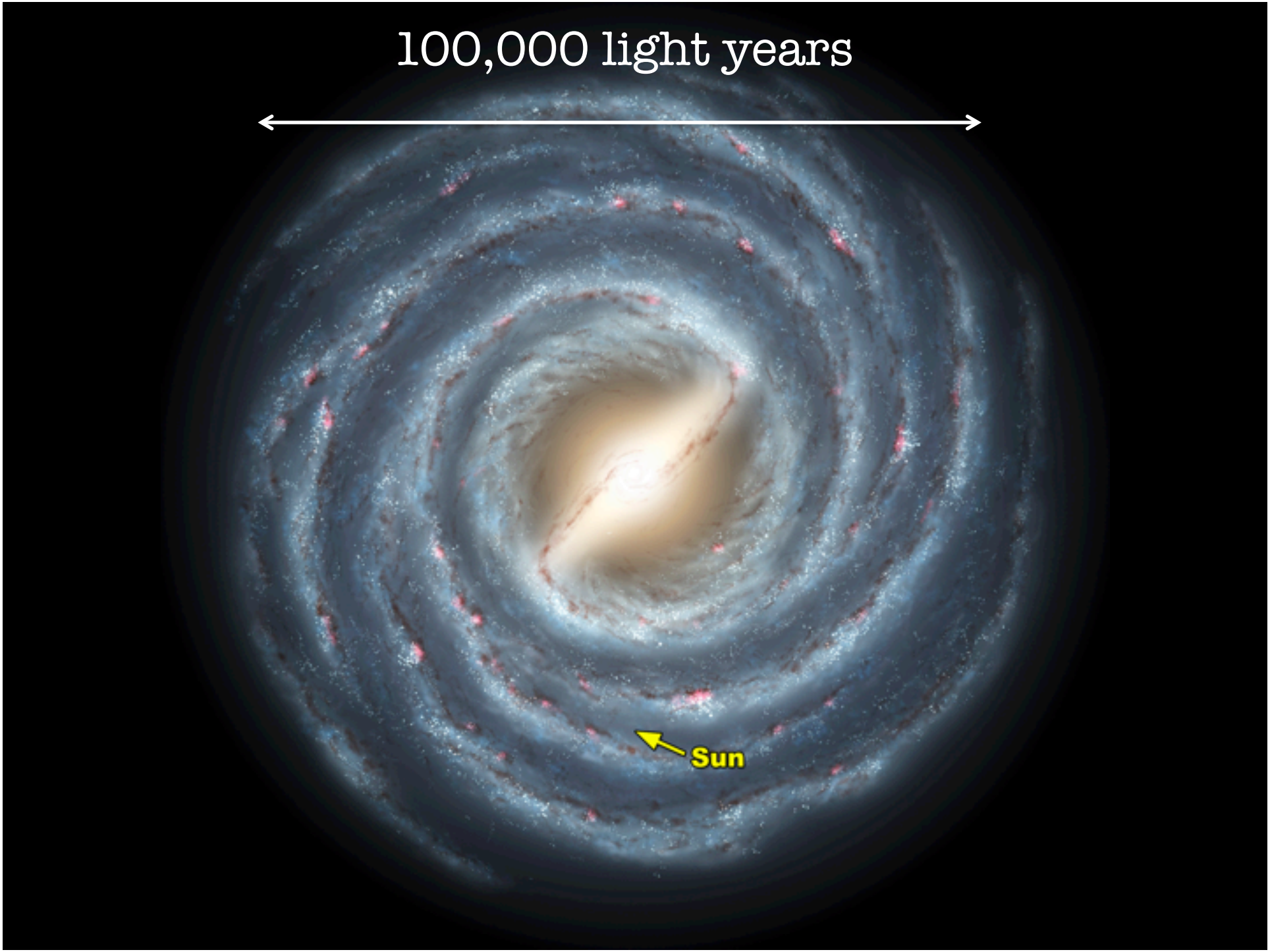
FIGURE 1

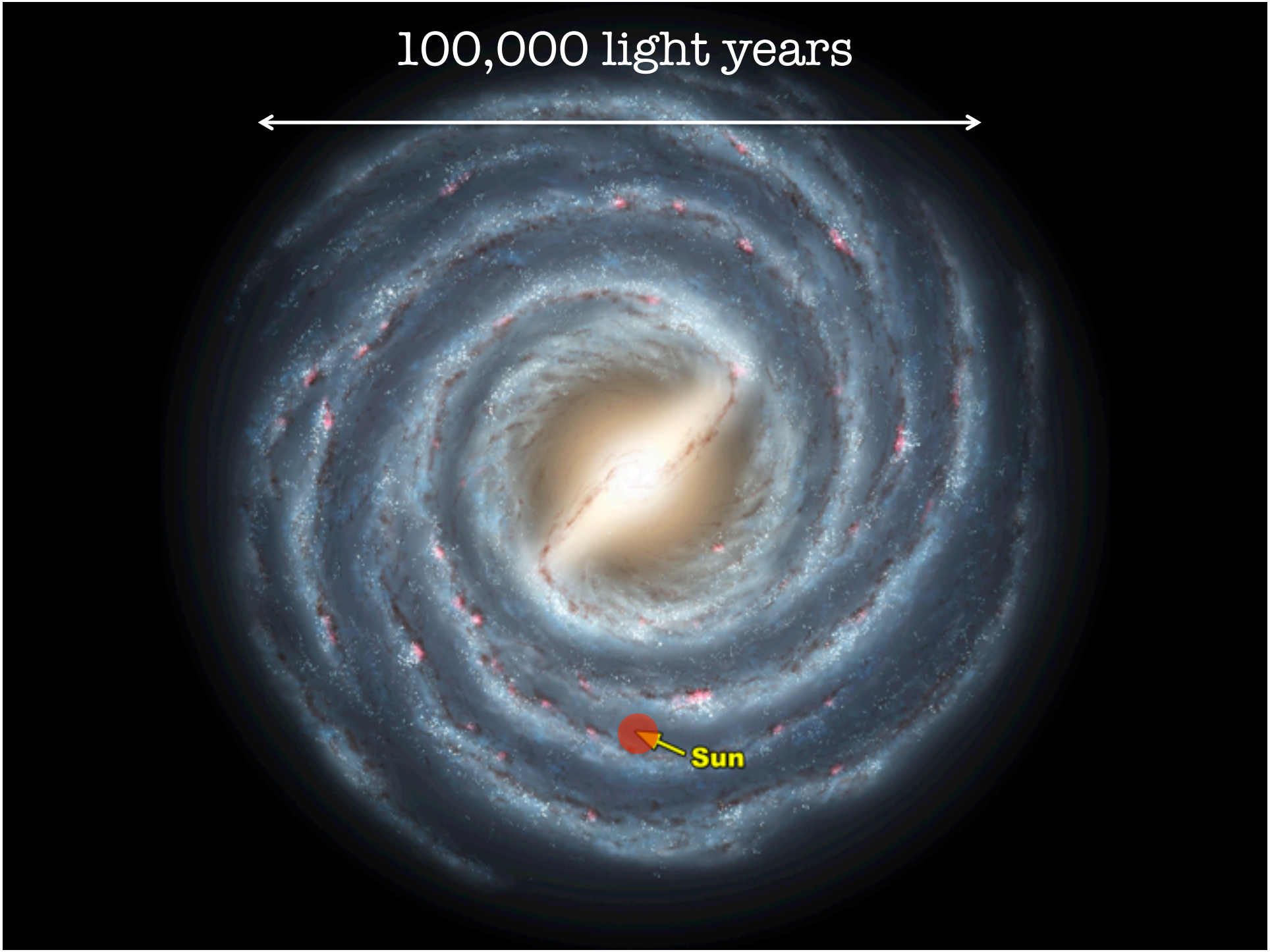
1920's

A More Fundamental Understanding

# Distance Scales in our Solar System




100,000 light years
Sun


100,000 light years
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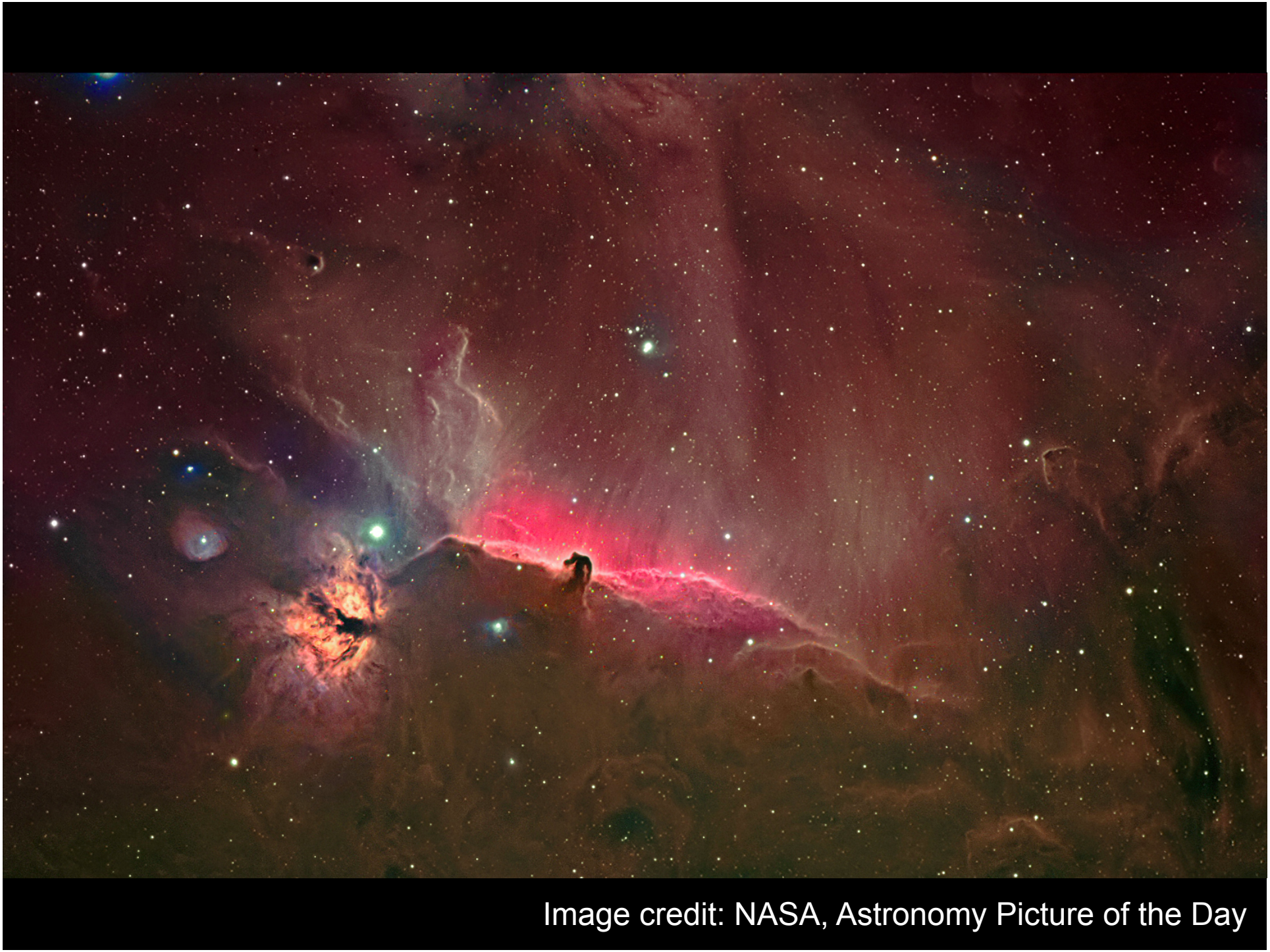


Image credit: NASA, Astronomy Picture of the Day

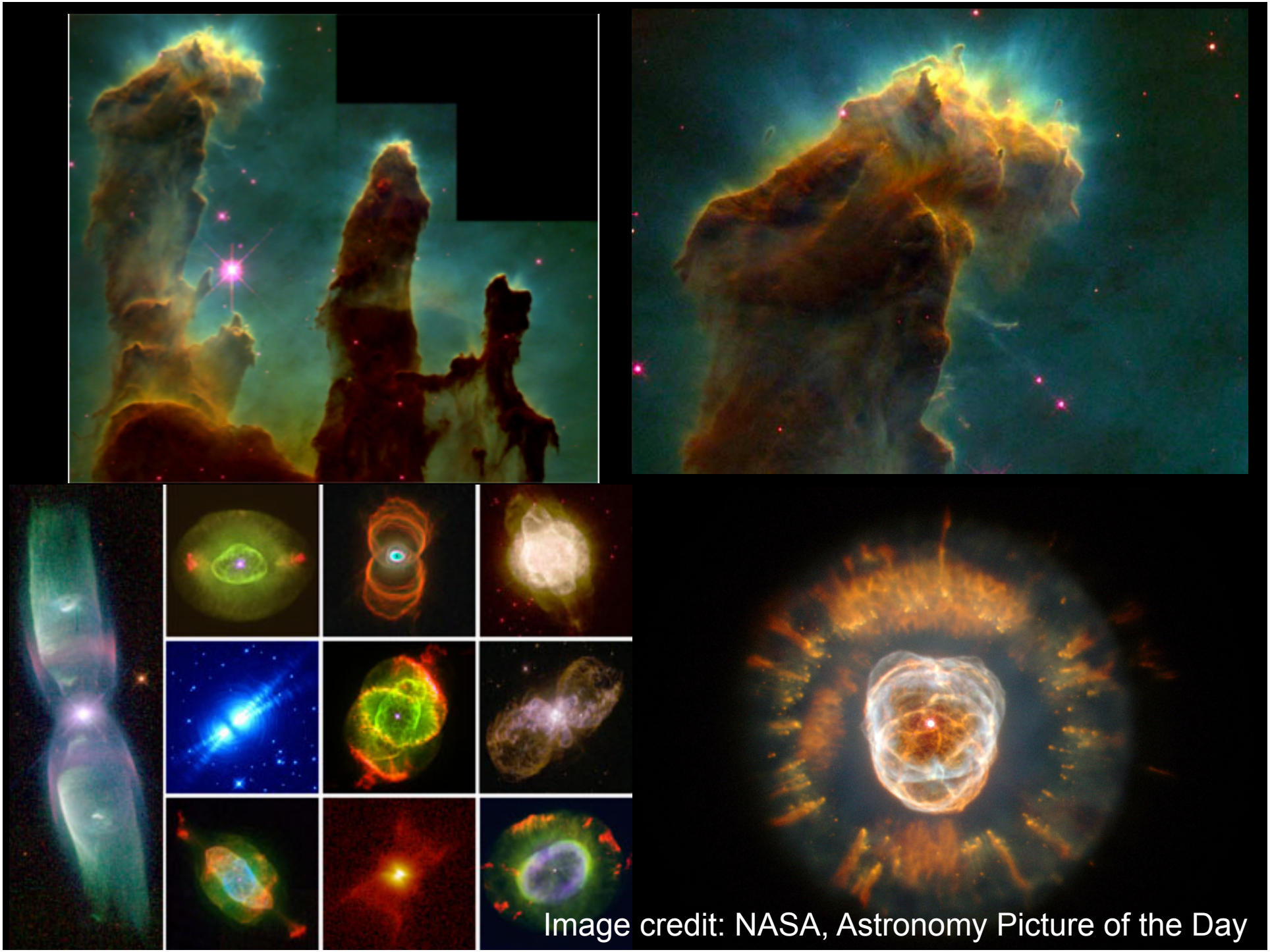


Image credit: NASA, Astronomy Picture of the Day

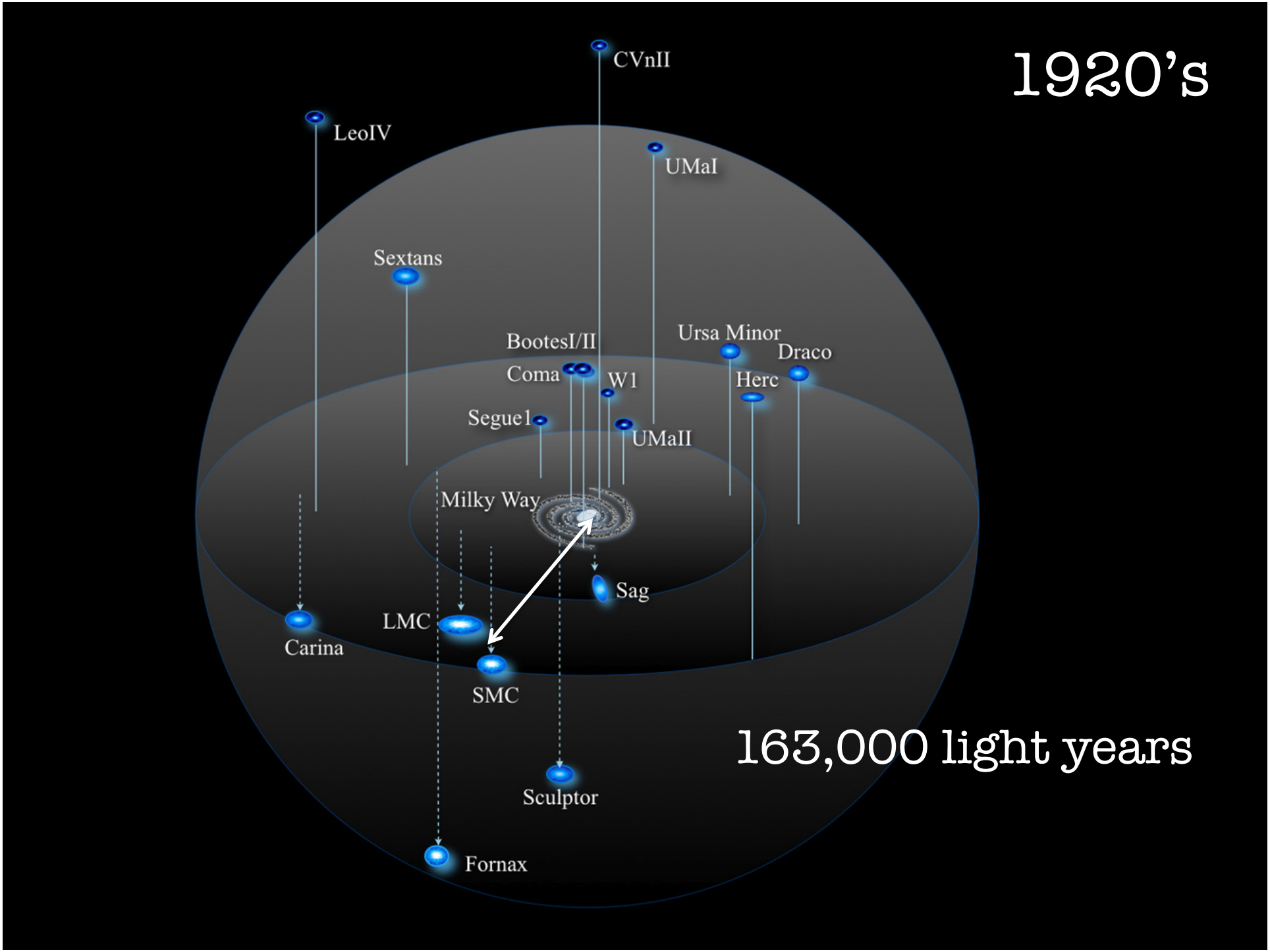
Distance to a typical “nice” star = 25 ly

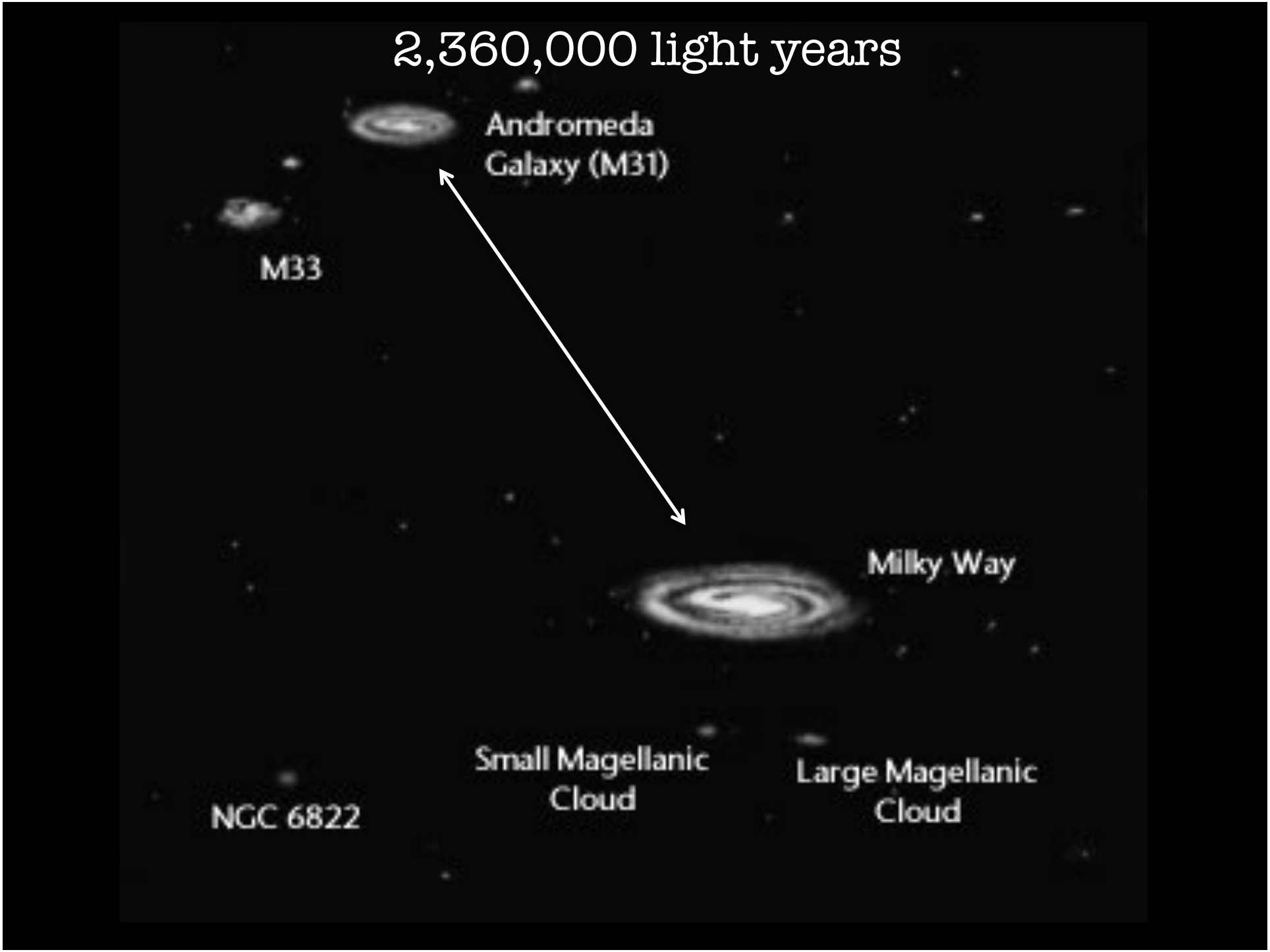
Suppose you figure a way to travel @ ¾ speed of light

It will take you 67 years to get there and back

Your twin will have aged 34 more years than you!

# I WANT TO BELIEVE


1920's
CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
163,000 light years


2,360,000 light years
Andromeda
Galaxy (M31)
M33
Milky Way
Small Magellanic
Cloud
Large Magellanic
Cloud
NGC 6822

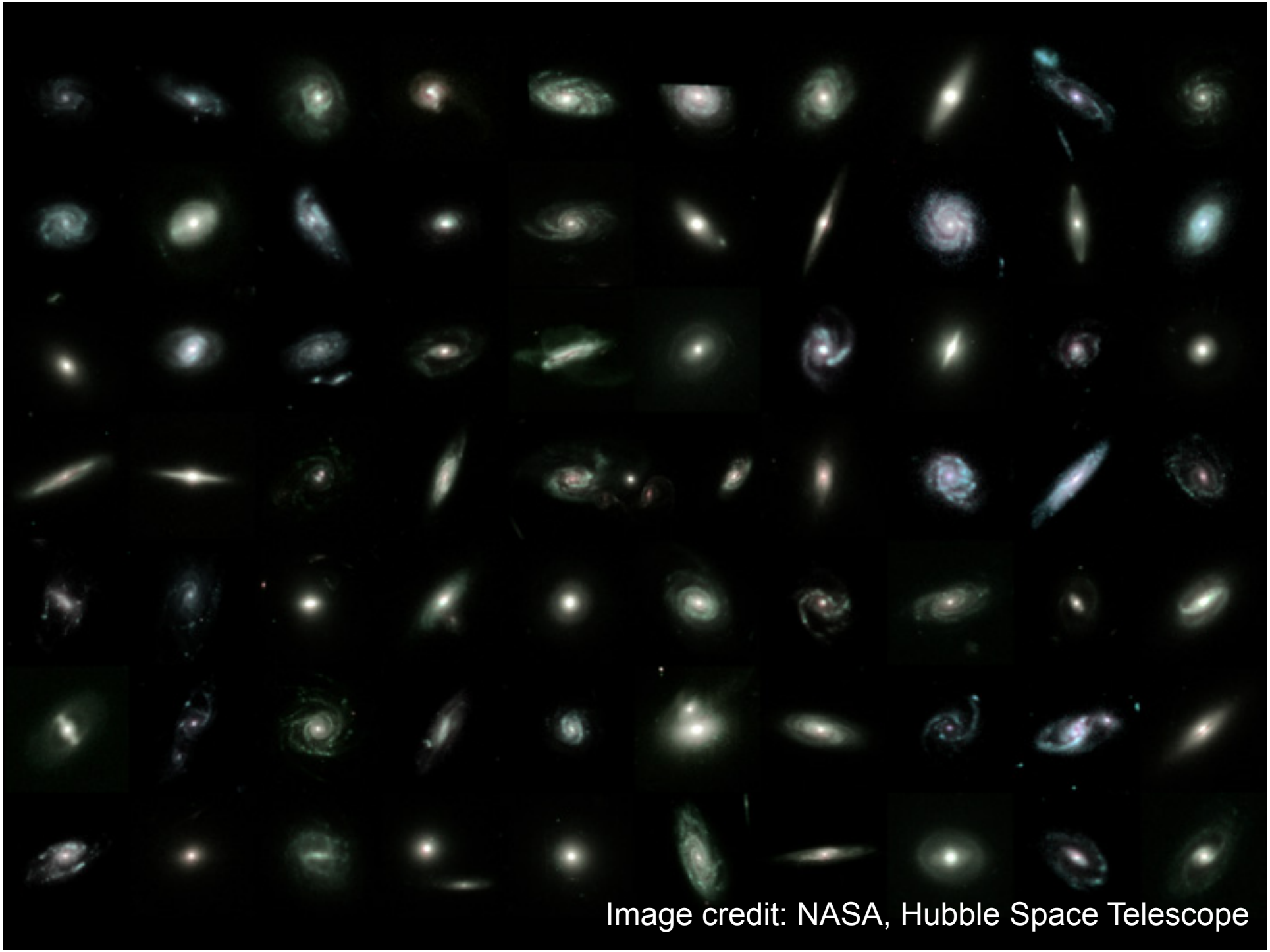


Image credit: NASA, Hubble Space Telescope

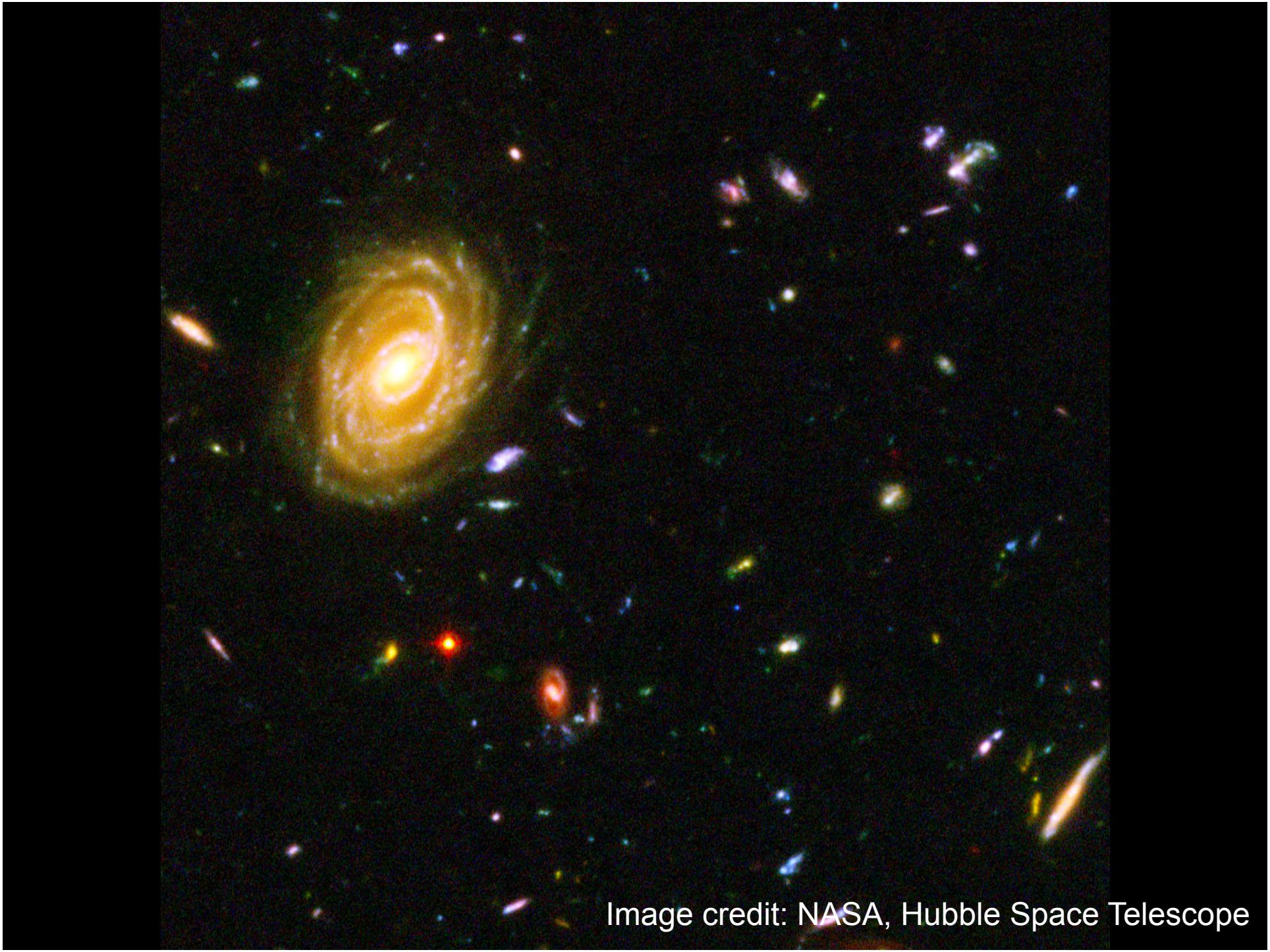
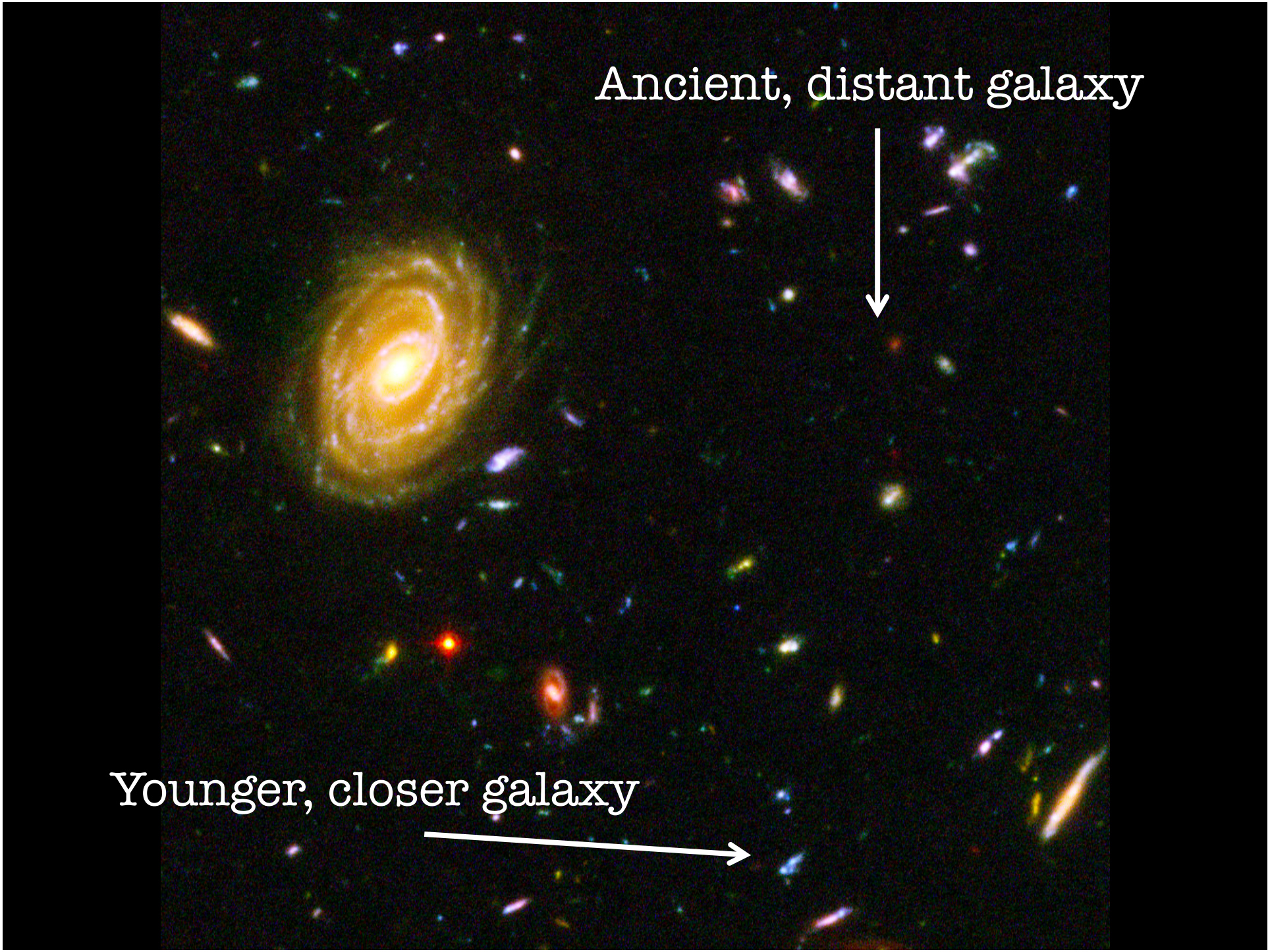


Image credit: NASA, Hubble Space Telescope


Ancient, distant galaxy
Younger, closer galaxy

# Summary:

- Our Universe is filled with galaxies like our own
- It looks the same in every direction
- It seems to be expanding
- We have a physical theory that
  - is (mostly) consistent with the data*
  - makes predictions that we can test

* we'll get to the "mostly" bit later

# Back to the Expansion of the Universe

$$ds^2 = c^2 dt^2 - a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2(\theta) d\phi \right)$$

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

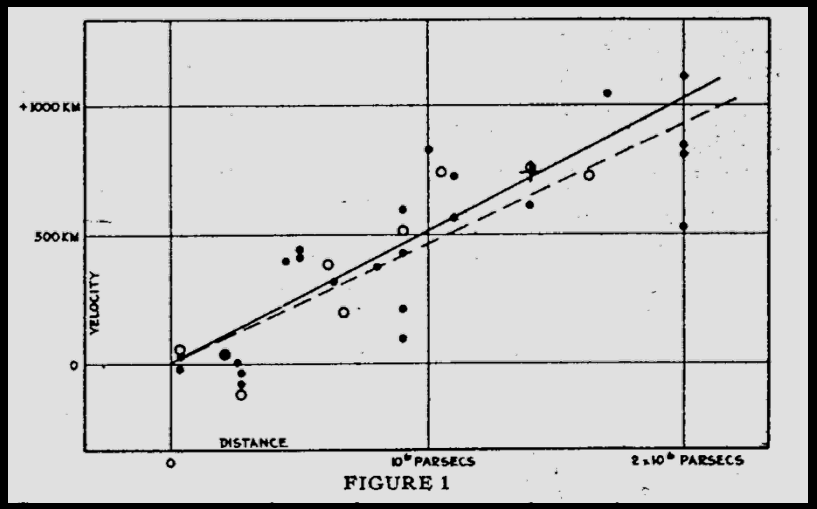
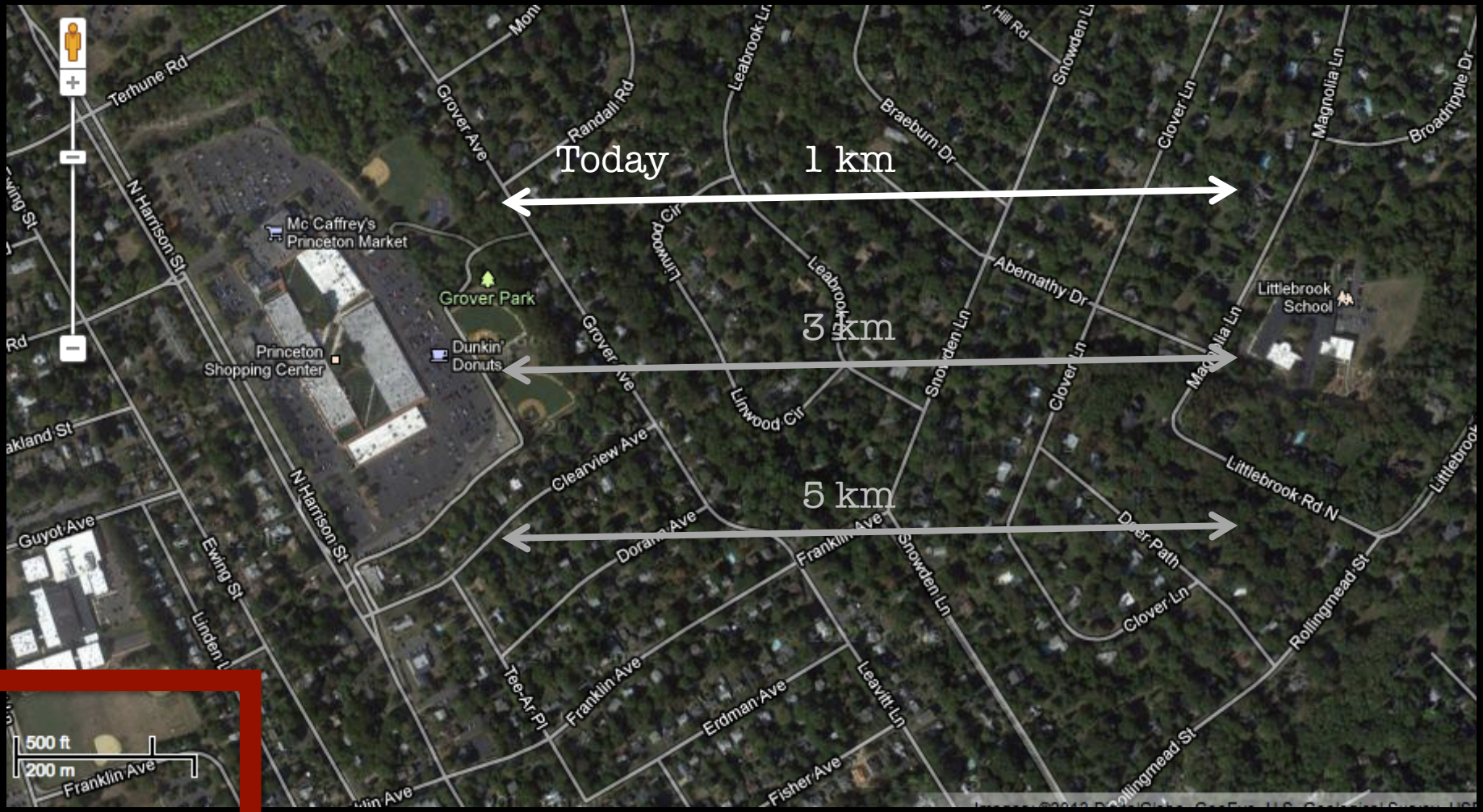


FIGURE 1

1920's

# Wait. What is expanding ?



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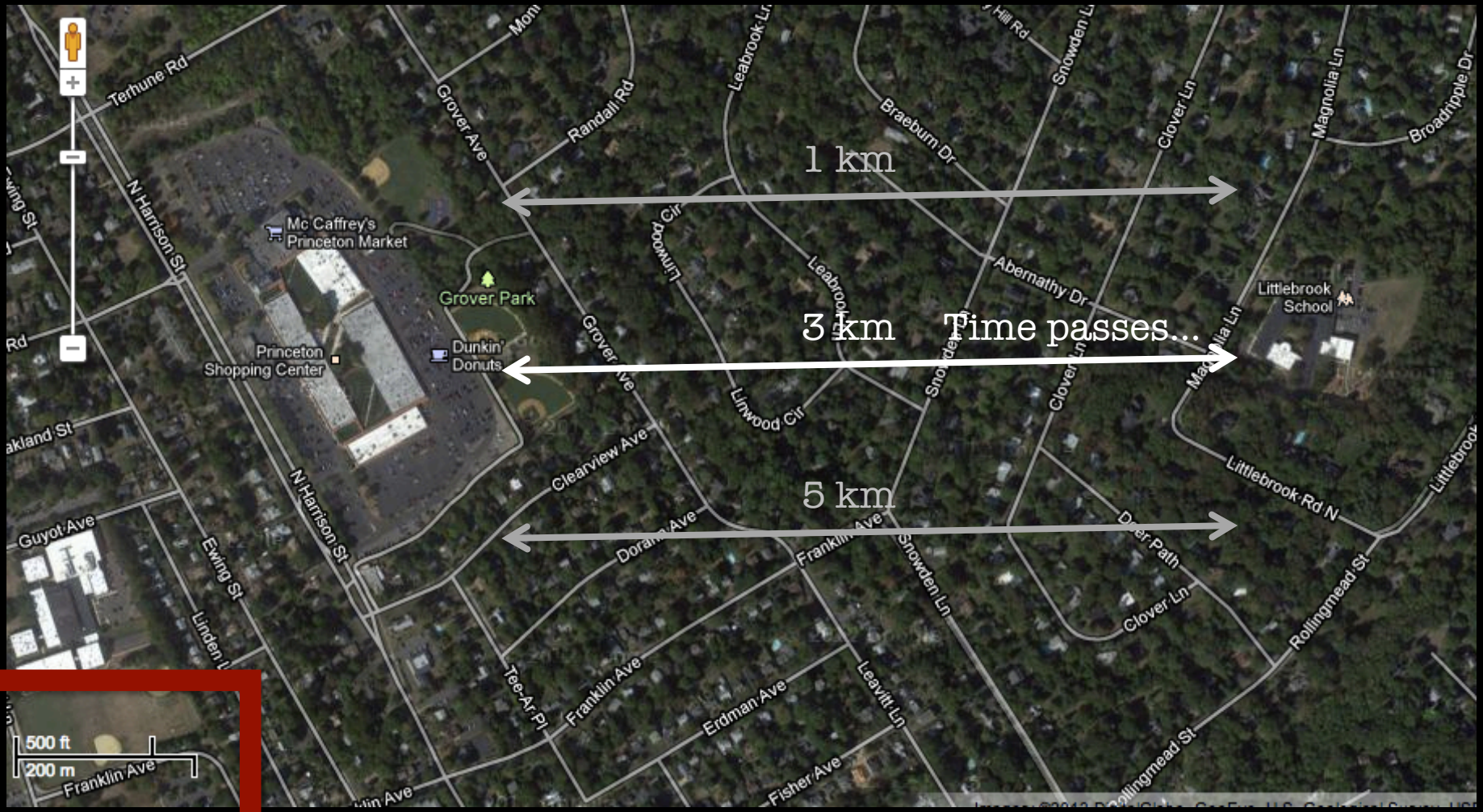

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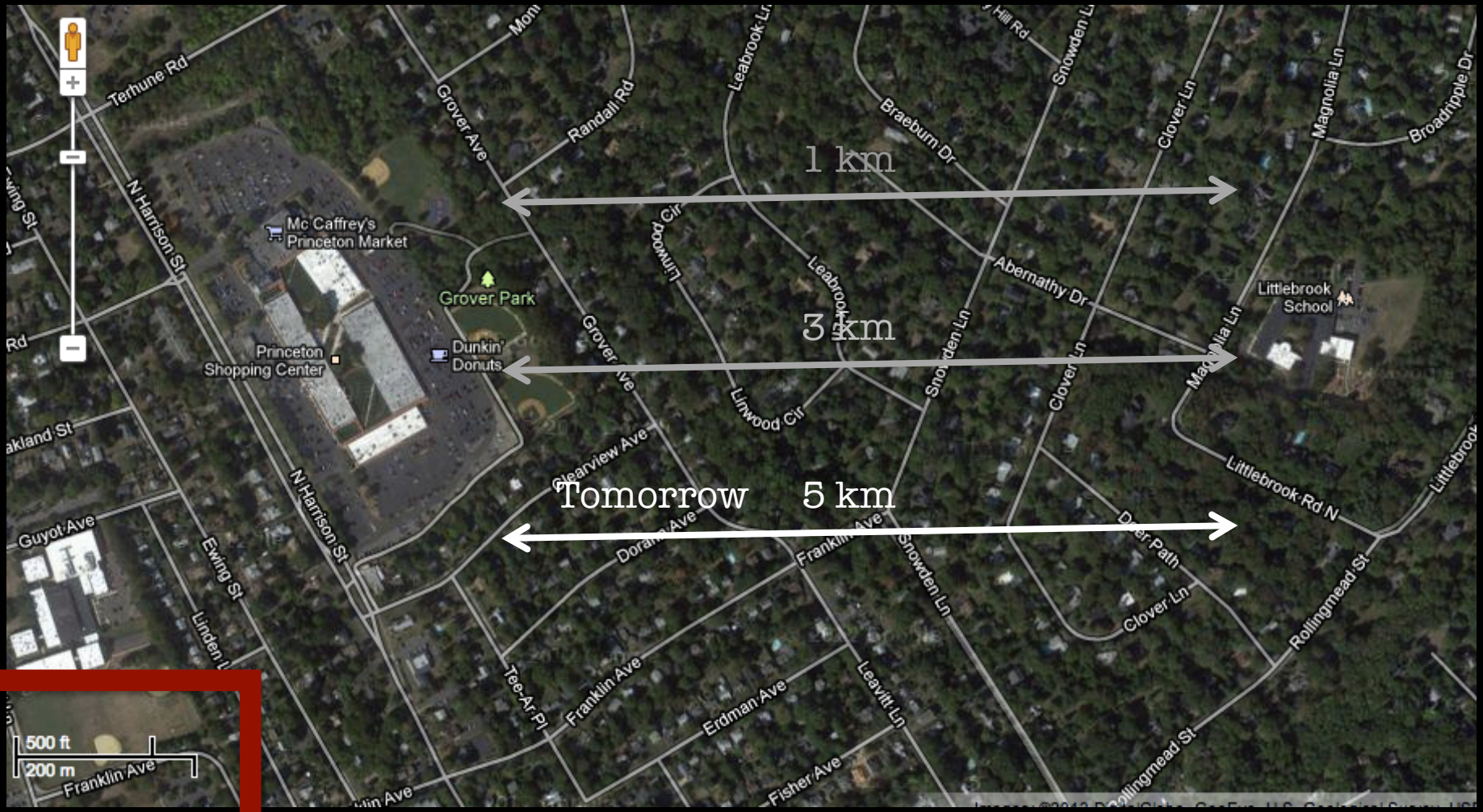
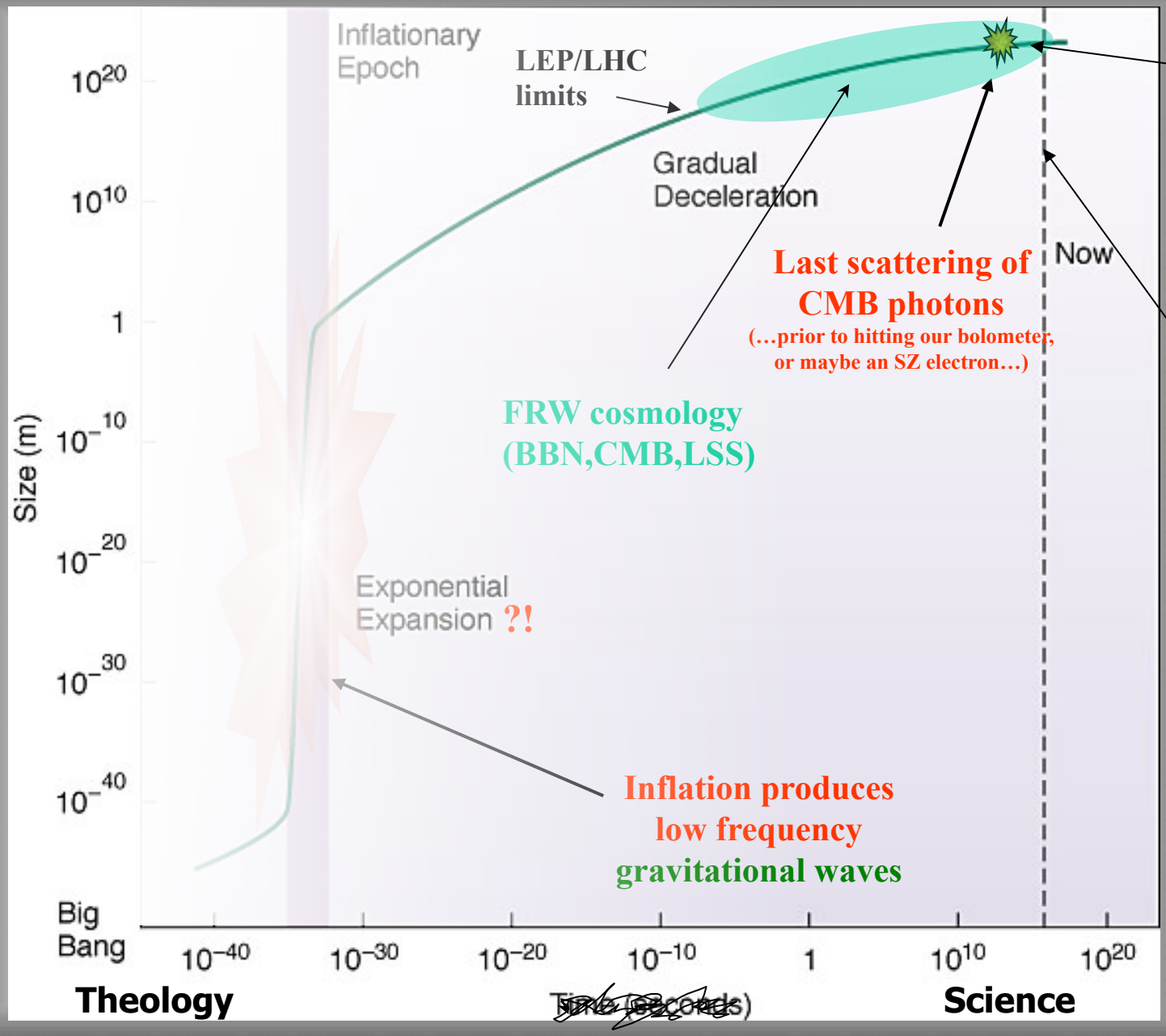





- non-linear evolution
- galaxy formation…

- Eukaryotes
- Fire
- Sliced-bread
- Latte…

# History of the Universe

Time

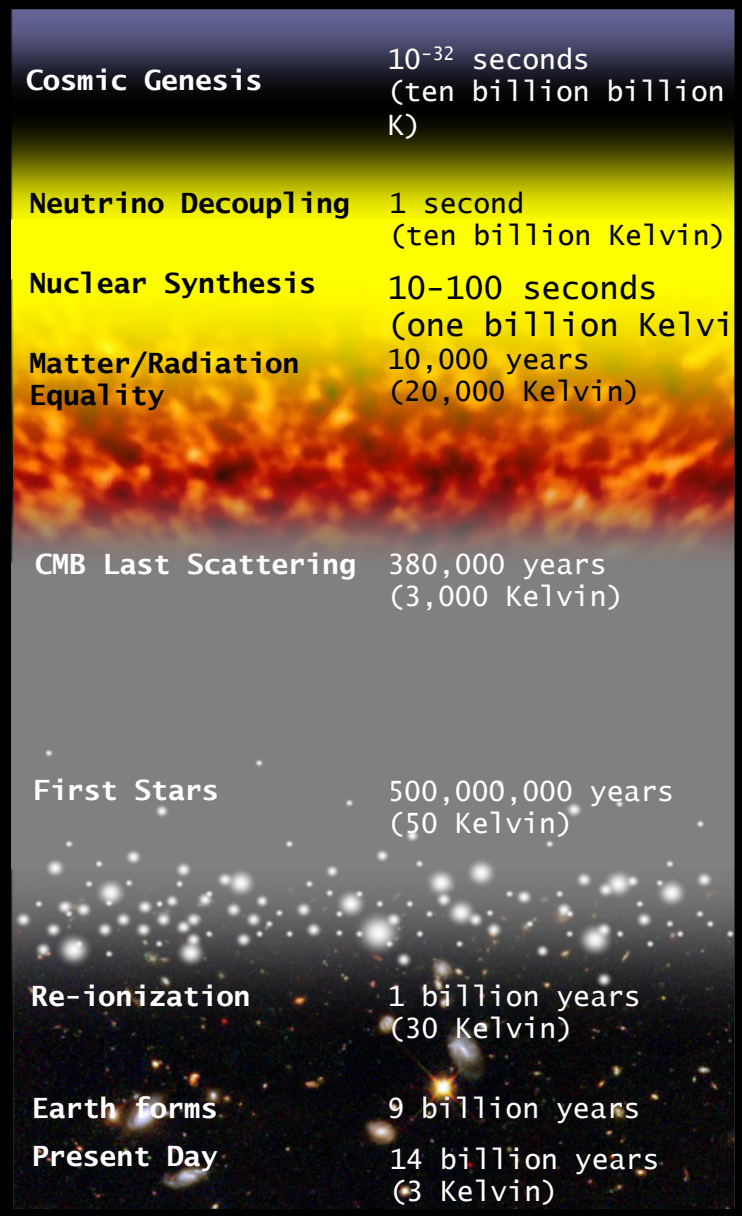
| | |
|---|---|
| Cosmic Genesis | $10^{-32}$ seconds (ten billion billion K) |
| Neutrino Decoupling | 1 second (ten billion Kelvin) |
| Nuclear Synthesis | 10-100 seconds (one billion Kelvi |
| Matter/Radiation Equality | 10,000 years (20,000 Kelvin) |
| CMB Last Scattering | 380,000 years (3,000 Kelvin) |
| First Stars | 500,000,000 years (50 Kelvin) |
| Re-ionization | 1 billion years (30 Kelvin) |
| Earth forms | 9 billion years |
| Present Day | 14 billion years (3 Kelvin) |

Size of the Universe

## Related Physics

- Quantum Gravity?
- Something having to do with strong/electroweak phase transition?
- Differentiation of electromagnetic and weak Interaction (Limit of LHC)
- Protons and Neutrons condense
- Nuclear Fusion
- [Nothing but neutral hydrogen gas]
- Chemistry
- Biology
- Politics

# History of the Universe




Size of the Universe

## The ΛCDM Cosmology: Only Six Parameters!

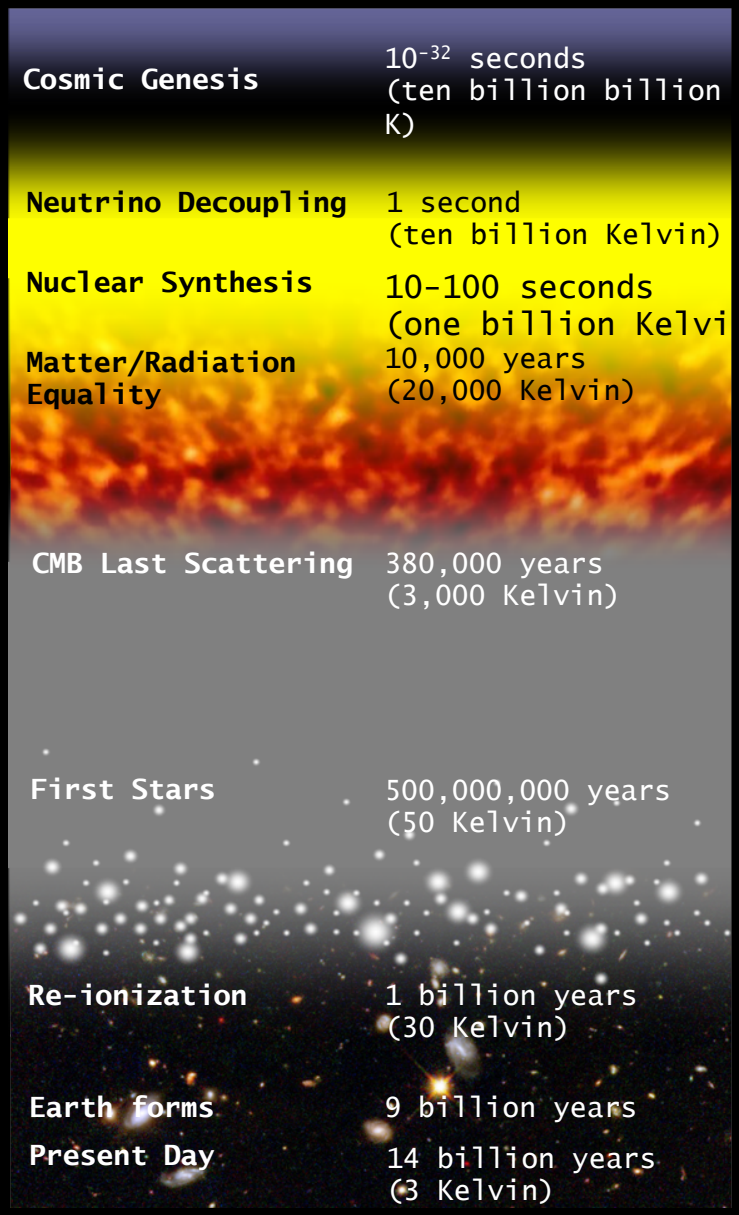
$A_s$, $n_s$

$\rho_b$ , $\rho_c$ , $\rho_\Lambda$

$\tau$

# History of the Universe

Time




Size of the Universe

## The ΛCDM Cosmology: Only Six Parameters!

$A_s$, $n_s$

Primordial fluctuations

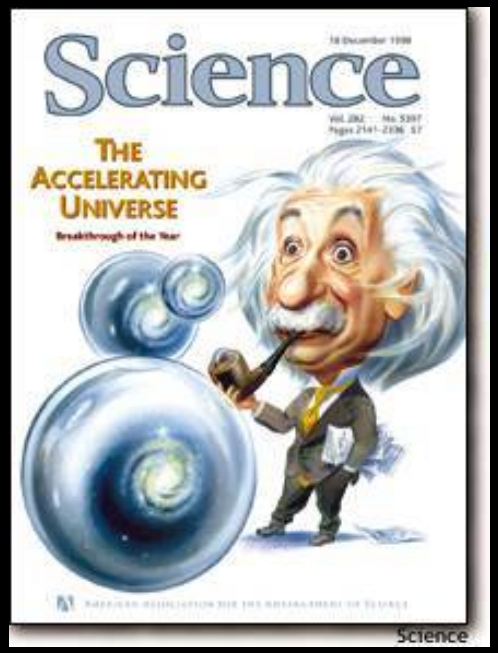
$\Omega_b h^2$ , $\Omega_c h^2$ , $\Omega_\Lambda h^2$

Dark Energy

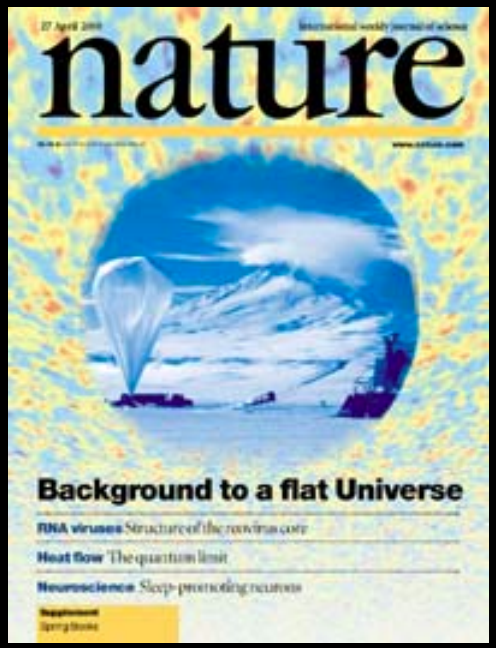
Dark Matter

Baryonic Matter
(usual stuff)

A measure of when the first stars began to form




Science

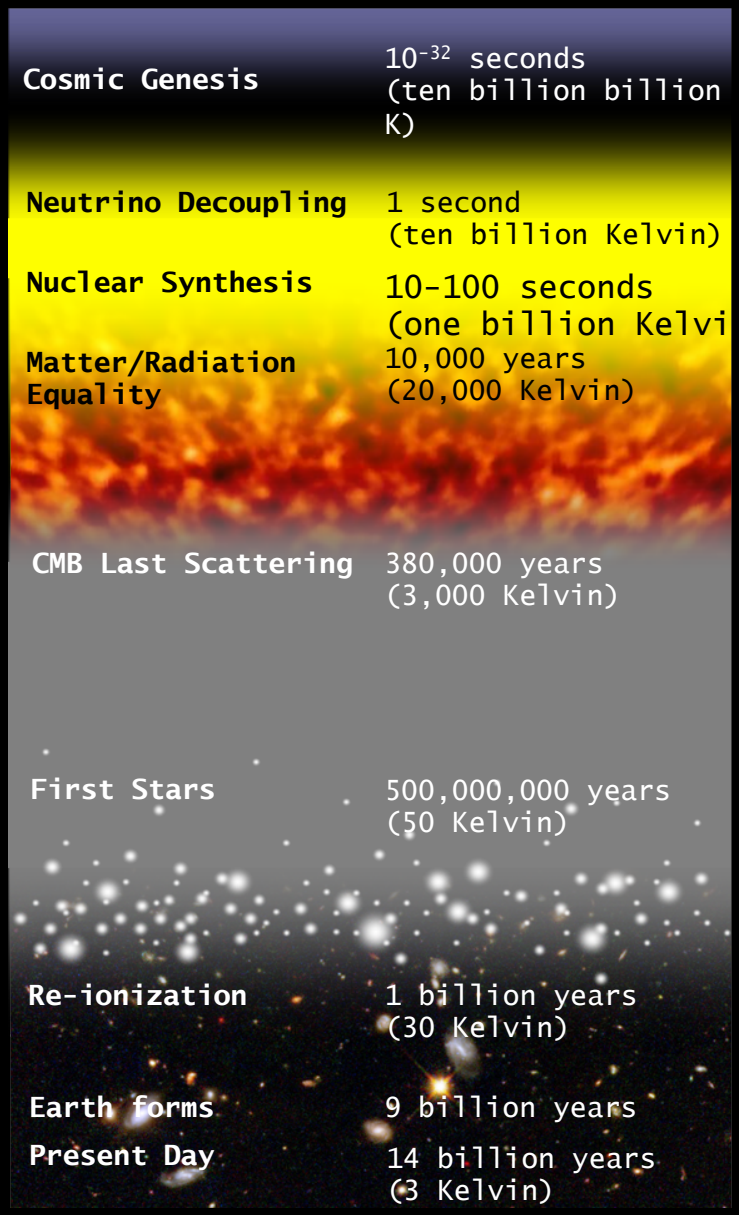



1998-2000:
Two Remarkable Years.

Google
Viagra
...
Dark Matter
Dark Energy
Neutrino Mass
The Universe is Flat
Universal Acceleration

# History of the Universe

Time




Size of the Universe

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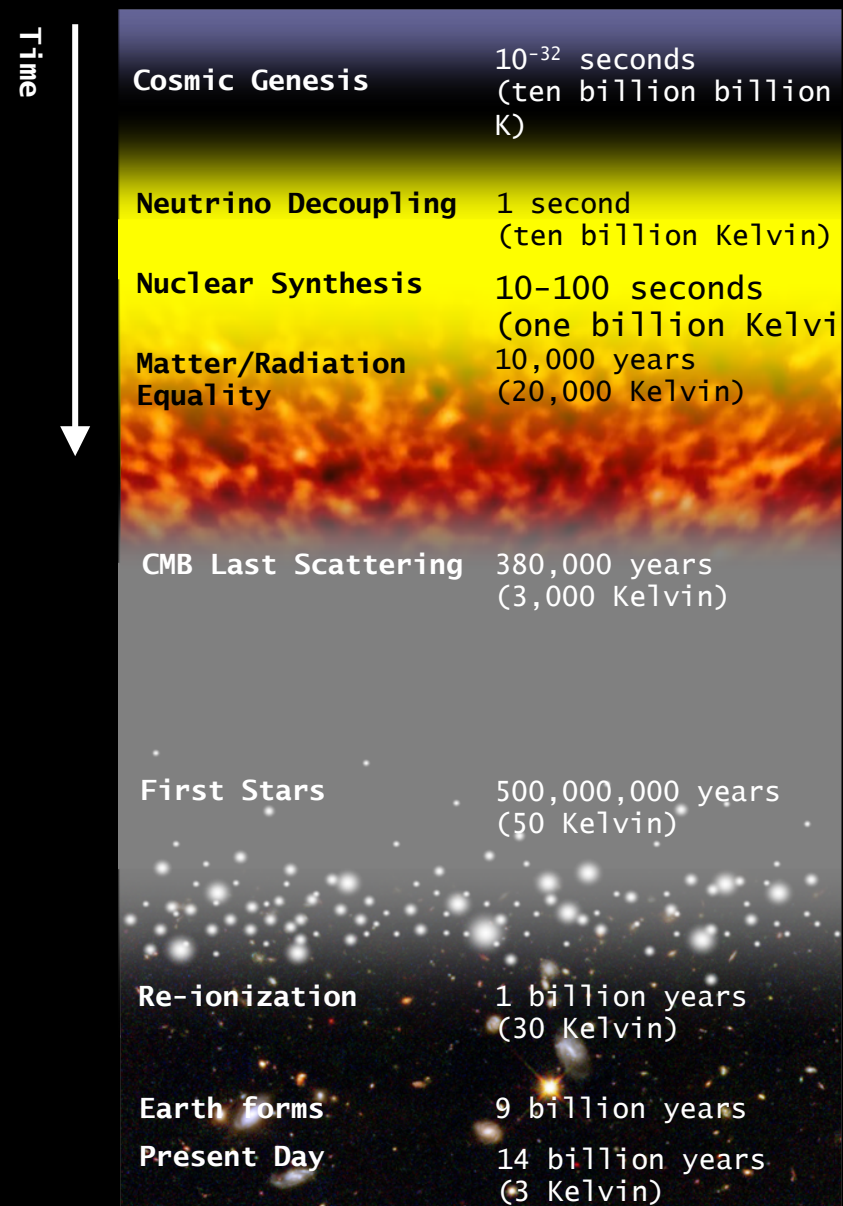
## History of the Universe




## The ΛCDM Cosmology: Only Six Parameters,

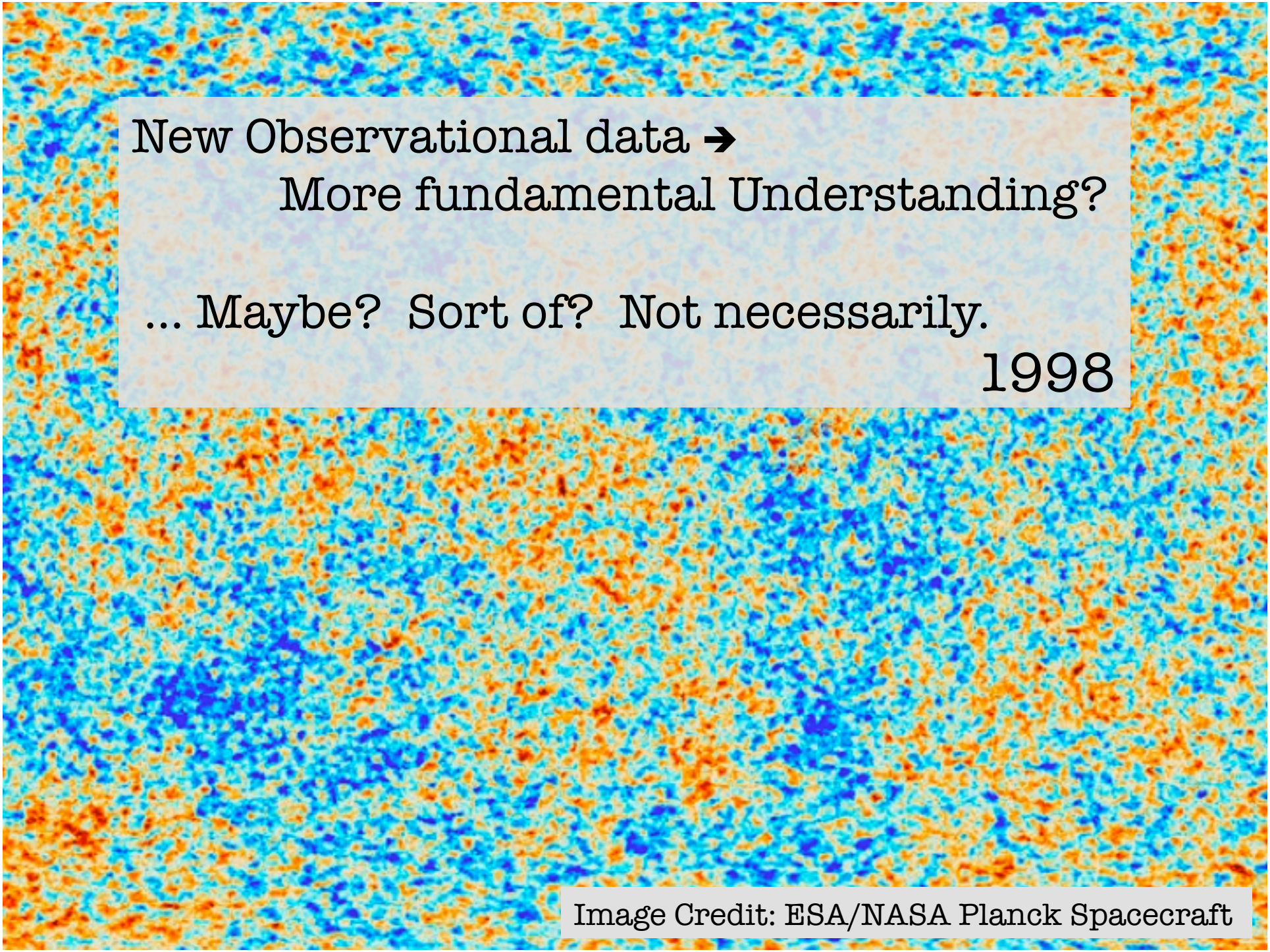
captures a huge amount of data!

Predictions:

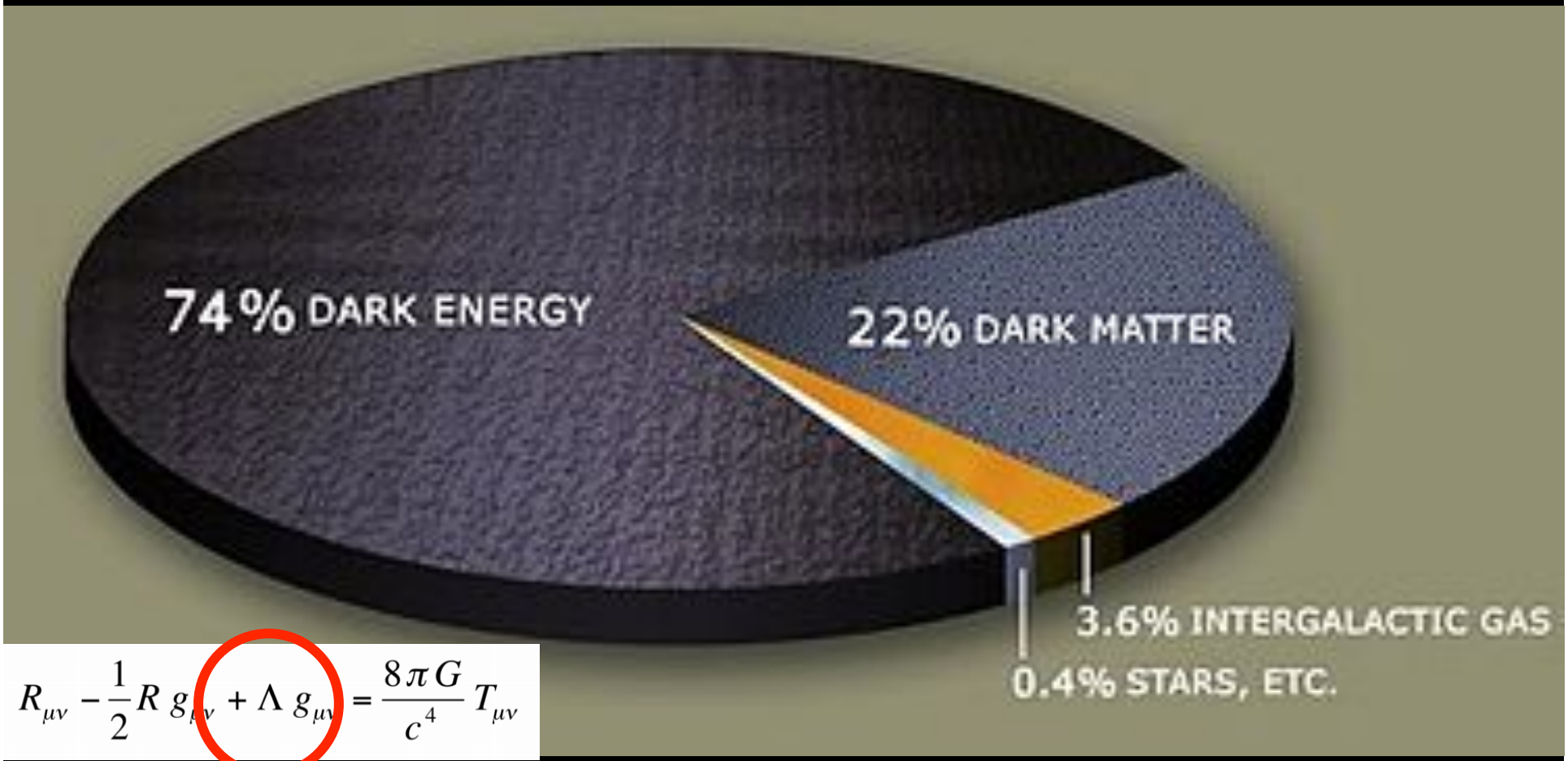
- Primordial Nucleosynthesis ✓
- Cosmic Microwave Background ✓
- Large scale distribution of matter ✓
- Expansion rate (Hubble parameter) ✓
- Dynamics of galaxies and clusters ✓

Physical Scales:

- temporal: <1 s to $10^{10}$ years
- thermal: 3 Kelvin to $10^{10}$ Kelvin
- spatial: subatomic to causal horizon

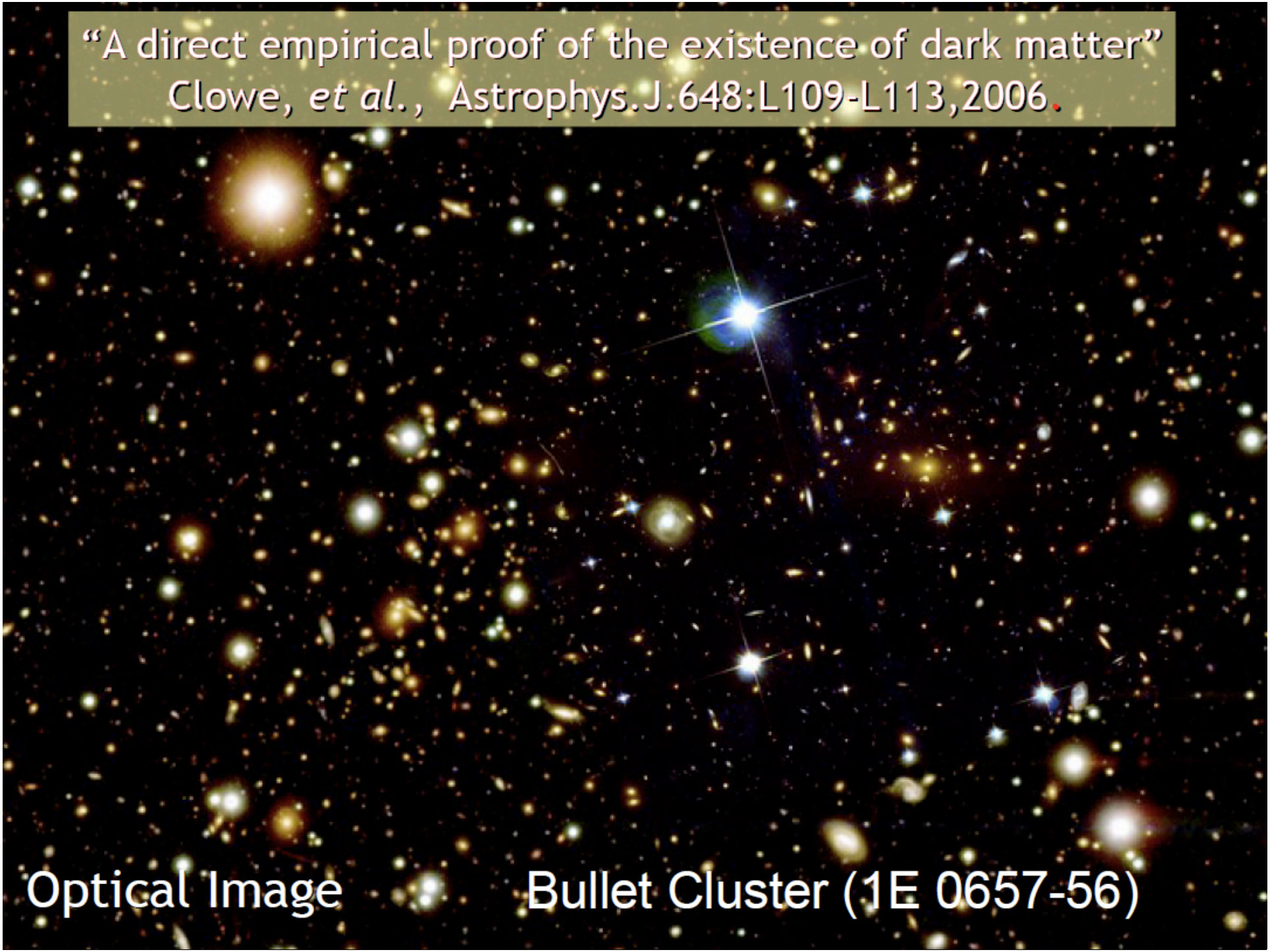

New Observational data ➔
More fundamental Understanding?
... Maybe? Sort of? Not necessarily.
1998
Image Credit: ESA/NASA Planck Spacecraft

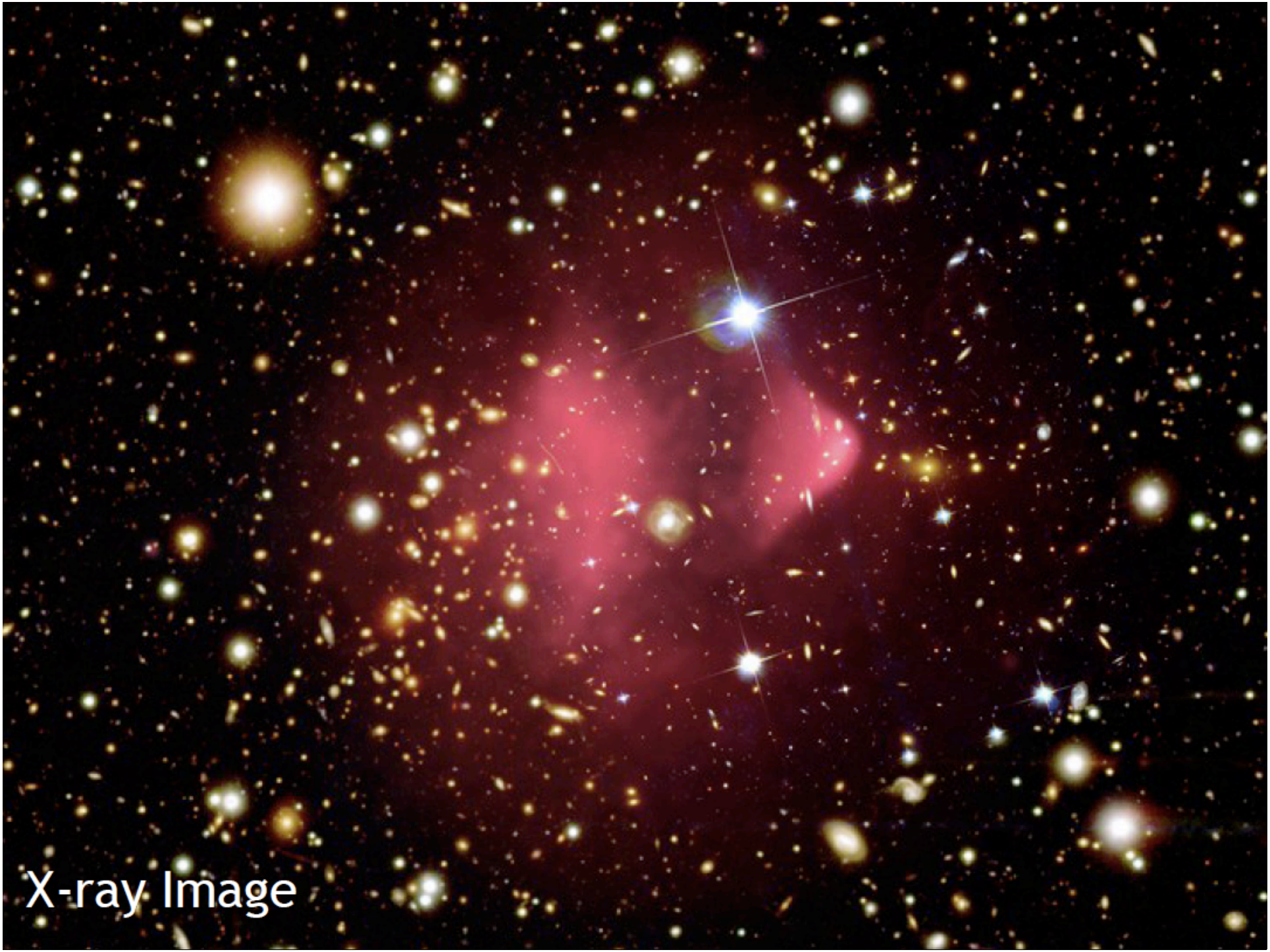
# What is Universe made of?



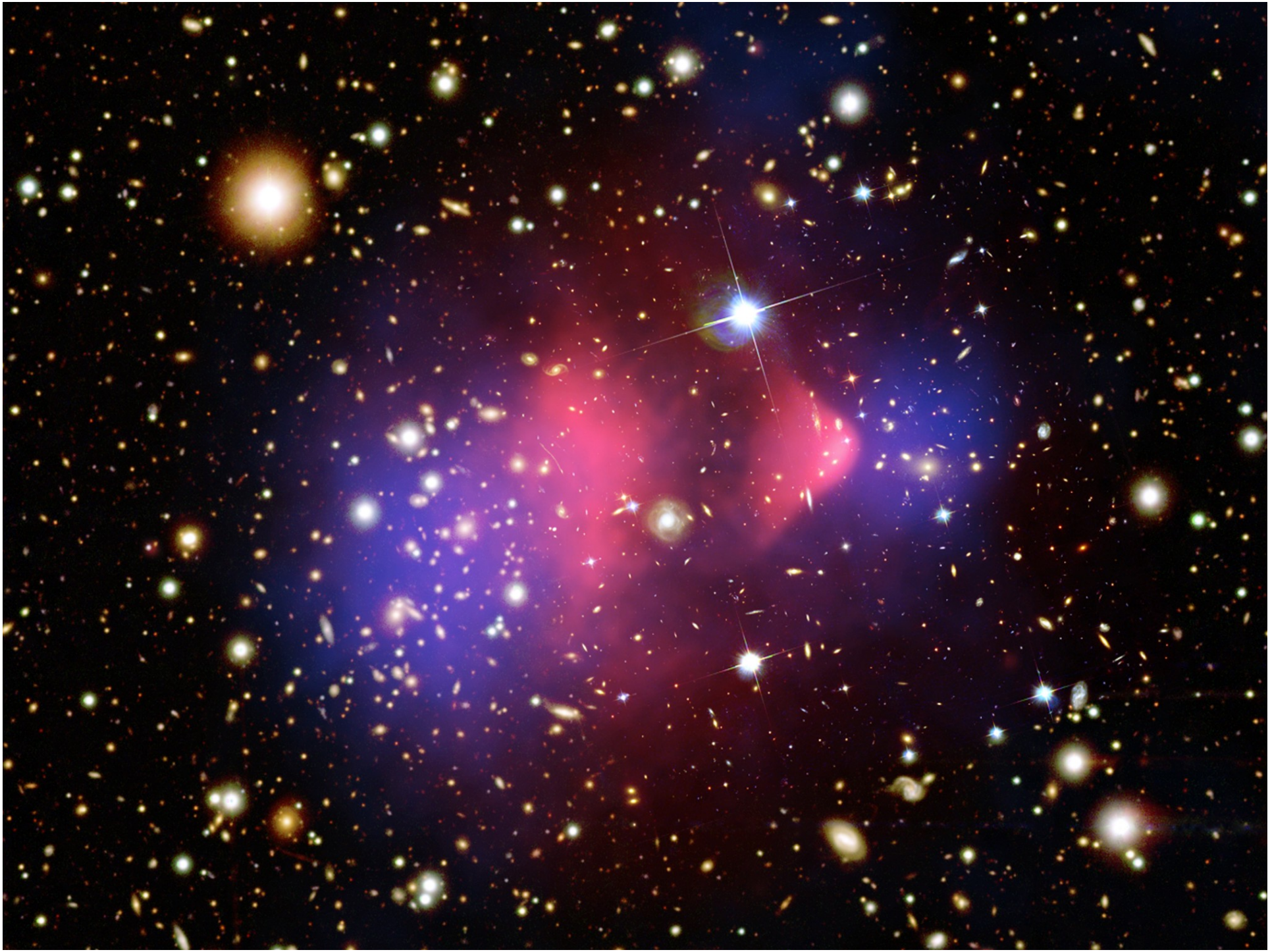

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

(we have no idea.)


"A direct empirical proof of the existence of dark matter"
Clowe, *et al.*, Astrophys.J.648:L109-L113,2006.
Optical Image
Bullet Cluster (1E 0657-56)


X-ray Image

Weak lensing Image



# Summary:

- Our Universe is filled with galaxies like our own
- It looks the same in every direction
- It seems to be expanding
- We have a physical theory that
  - is amazingly consistent with the data
  - makes predictions that we can test
- ... as long as we accept Dark Matter, Dark Energy, and an extremely unstable Universe (Cosmic Inflation)

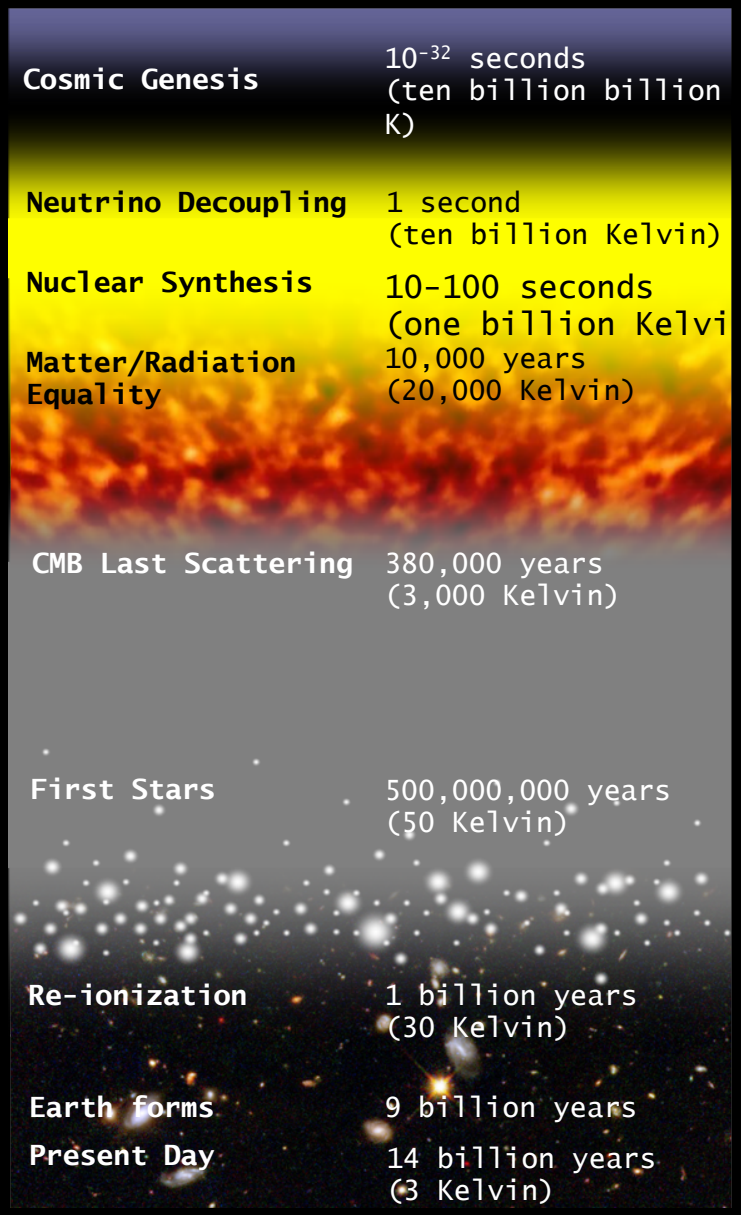
MORE DATA REQUIRED

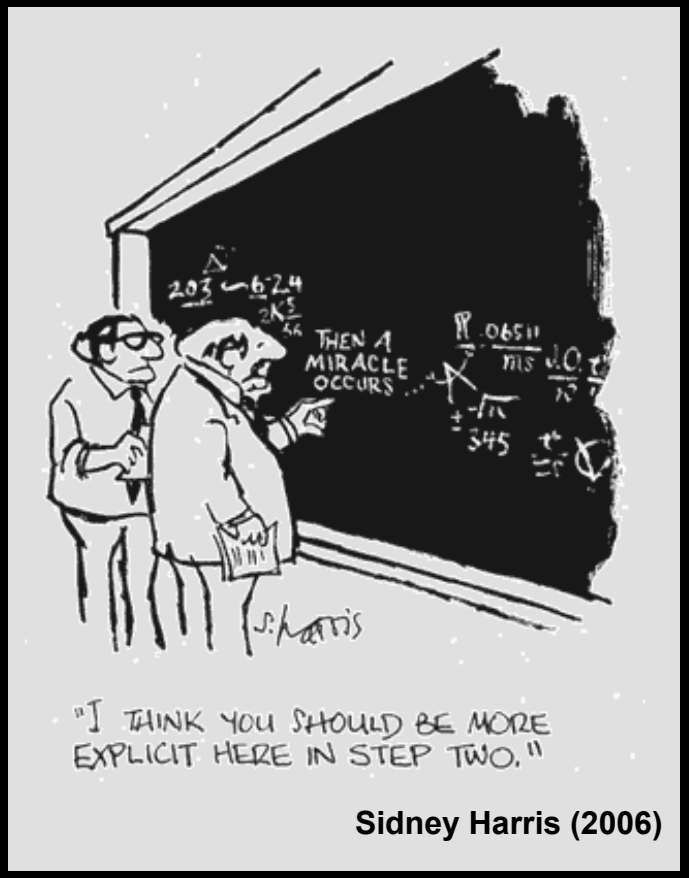
Where did this Universe come from?

# History of the Universe

Time

Size of the Universe



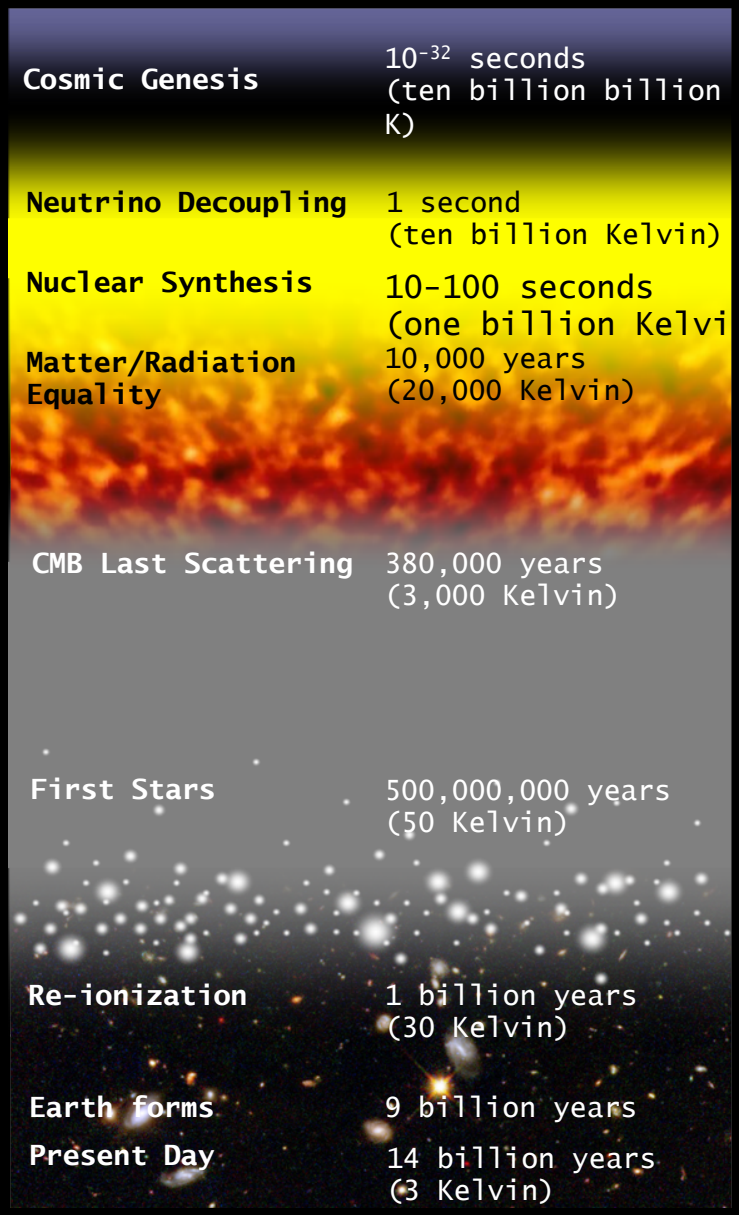

Sidney Harris (2006)

**Virtues of Inflation:**

- Lack of Magnetic monopoles
- Euclidean Geometry (flatness)
- Homogeneity and Isotropy
- Seeds of structure formation

# History of the Universe

Time




Size of the Universe

Violent expansion of space-time: potentially observable signatures on the cosmic microwave background

- Isotropy
- Gaussianity
- Polarization
- Primordial Power Spectrum

Virtues of Inflation:

- Lack of Magnetic monopoles
- Euclidean Geometry (flatness)
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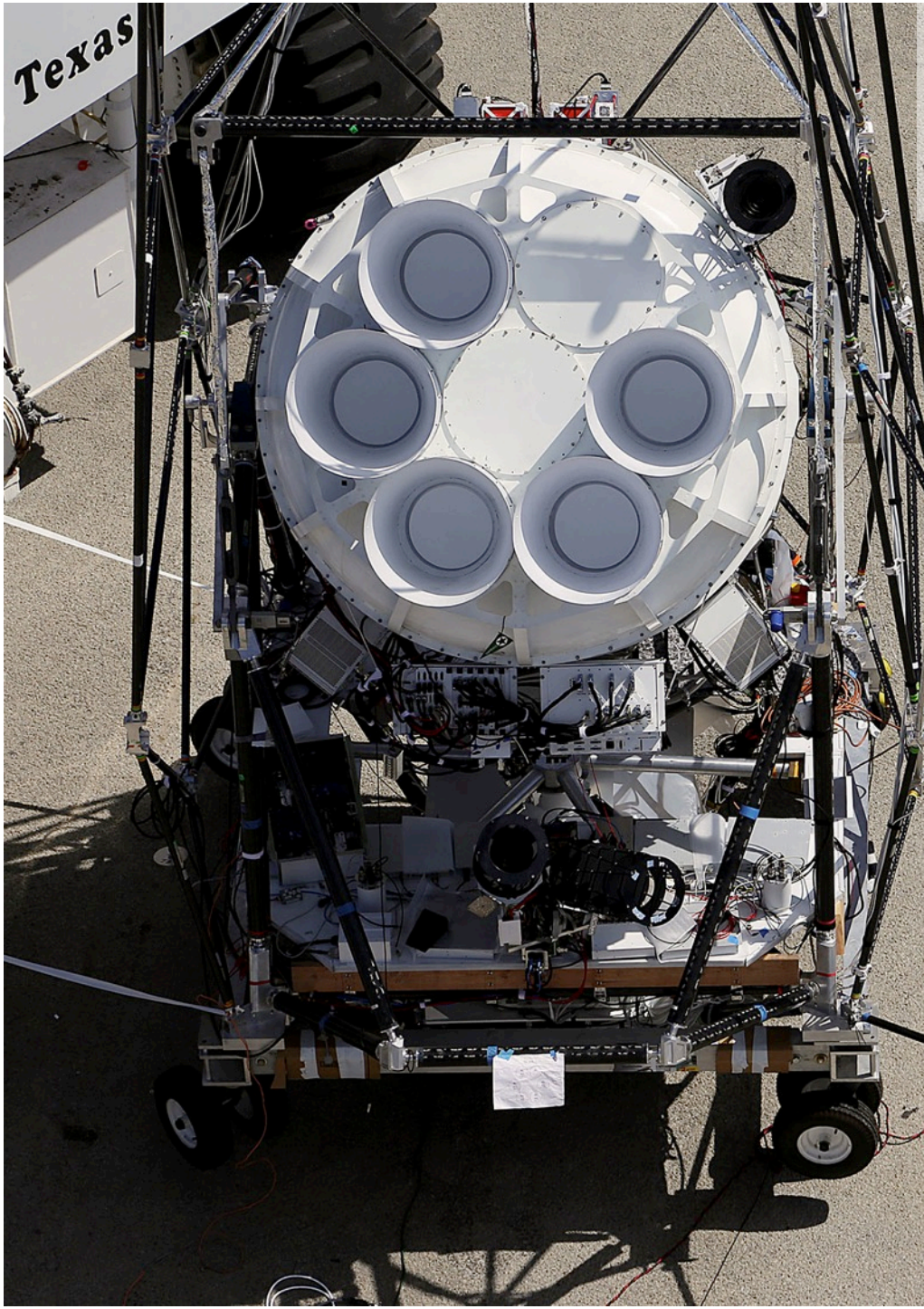
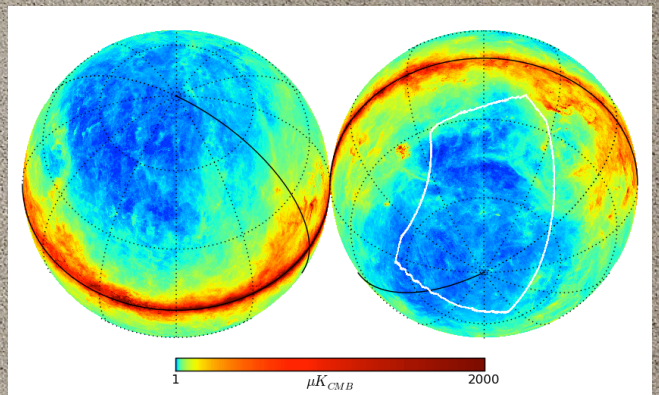
- Seeds of structure formation




# SPIDER

## Searching for the Echoes of Inflation




NASA · NSF · NIST · NSERC CRSNG · JPL

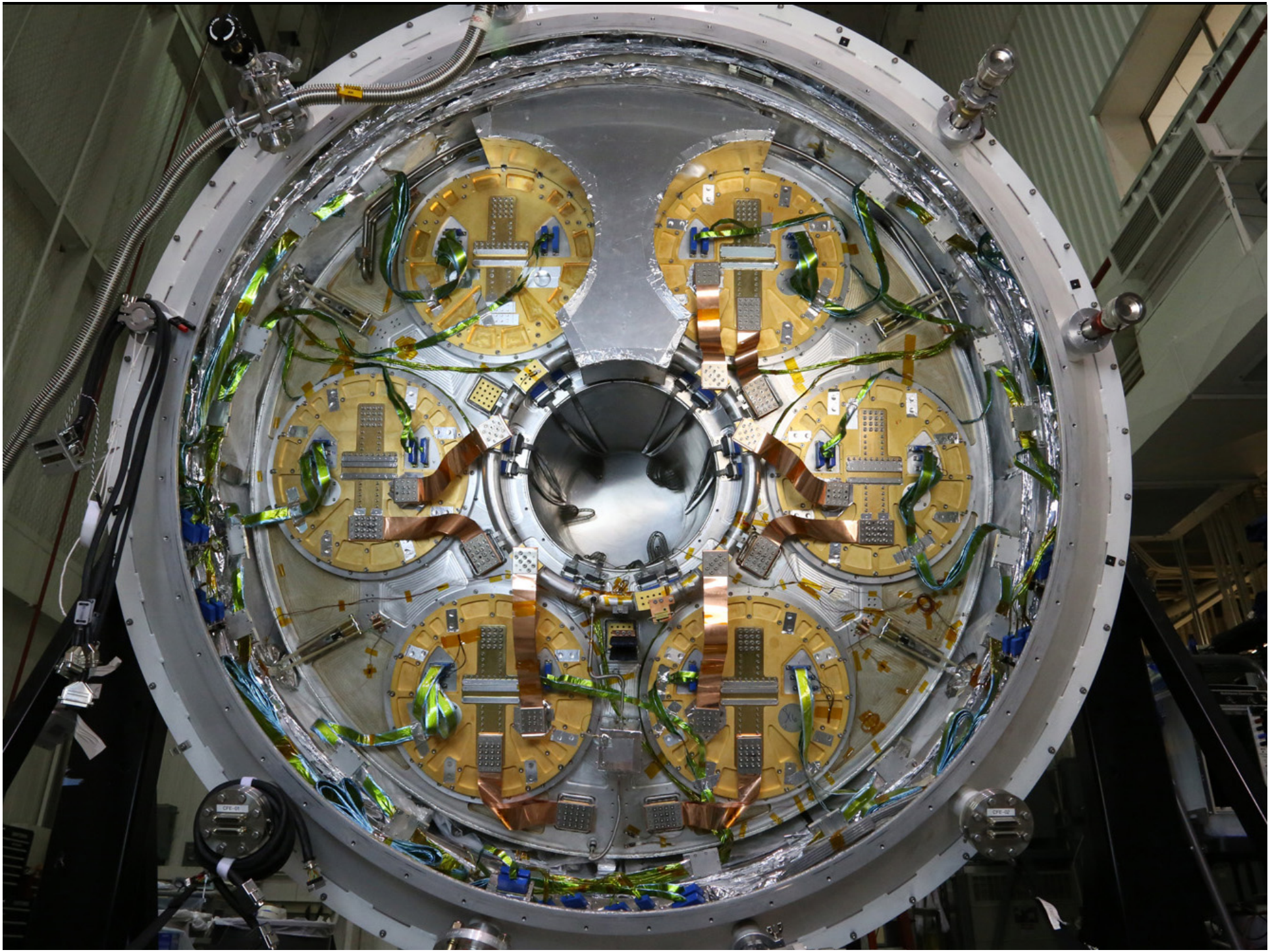
PRINCETON UNIVERSITY · CASE WESTERN RESERVE UNIVERSITY est. 1826

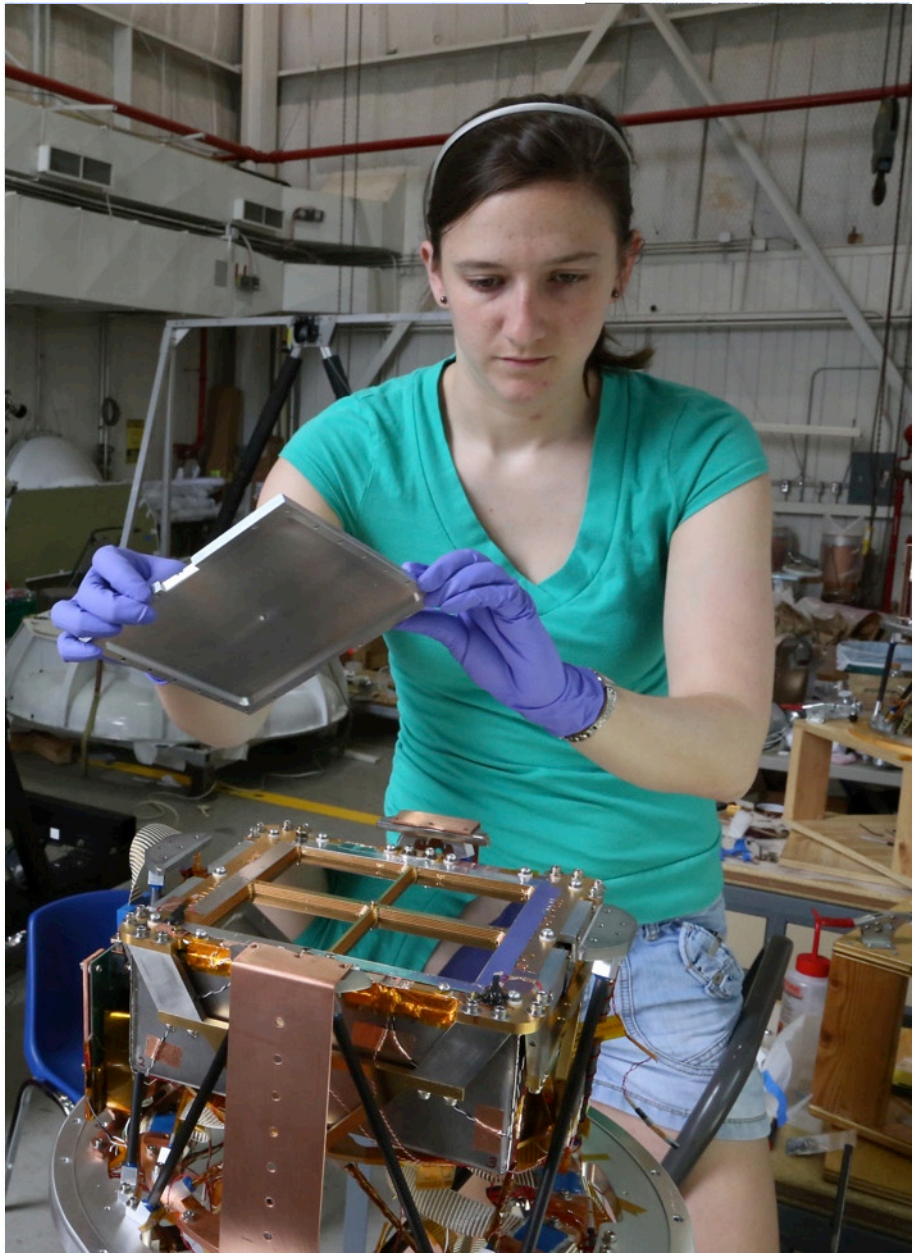
the David & Lucile Packard FOUNDATION · UNIVERSITY OF TORONTO

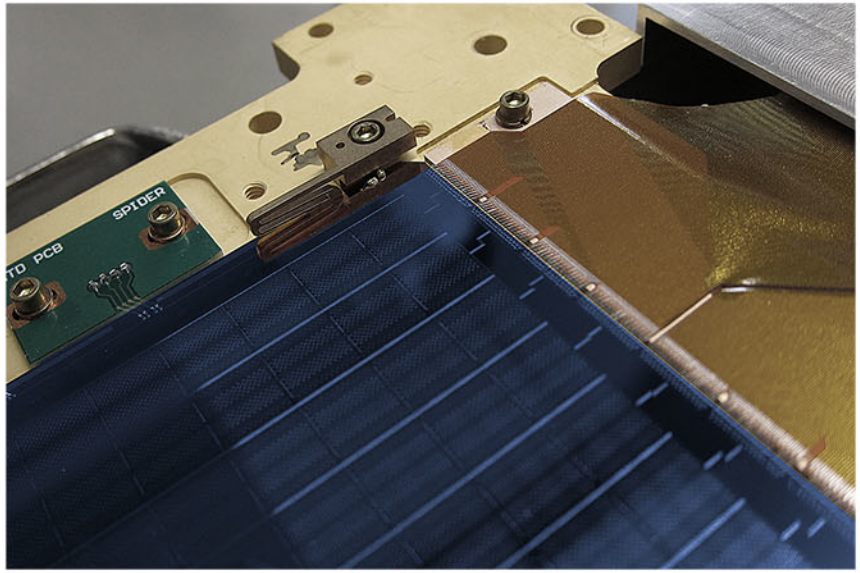
CITA ICAT Canadian Institute for Theoretical Astrophysics · Imperial College London

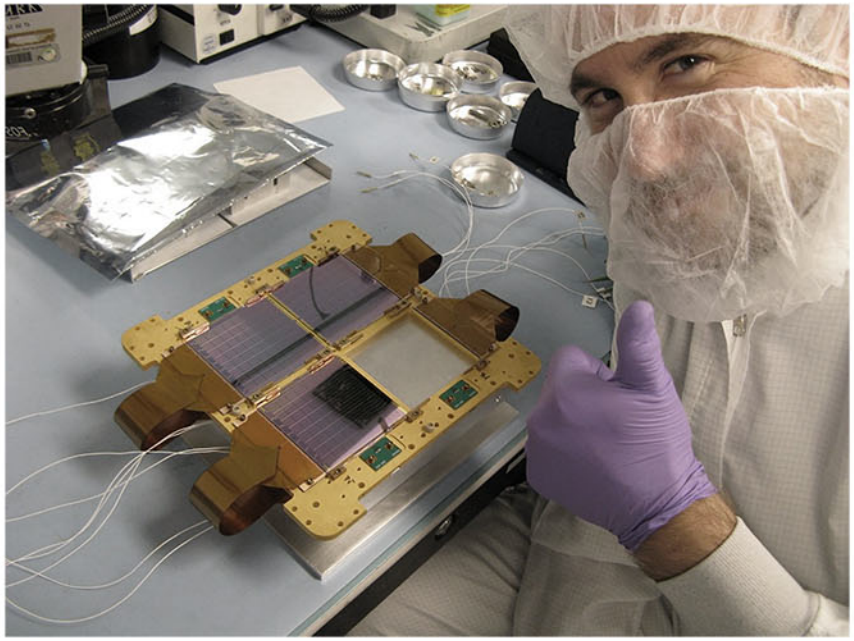
STANFORD UNIVERSITY · SLAC NATIONAL ACCELERATOR LABORATORY

UNIVERSITY OF KWAZULU-NATAL · UBC · CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD



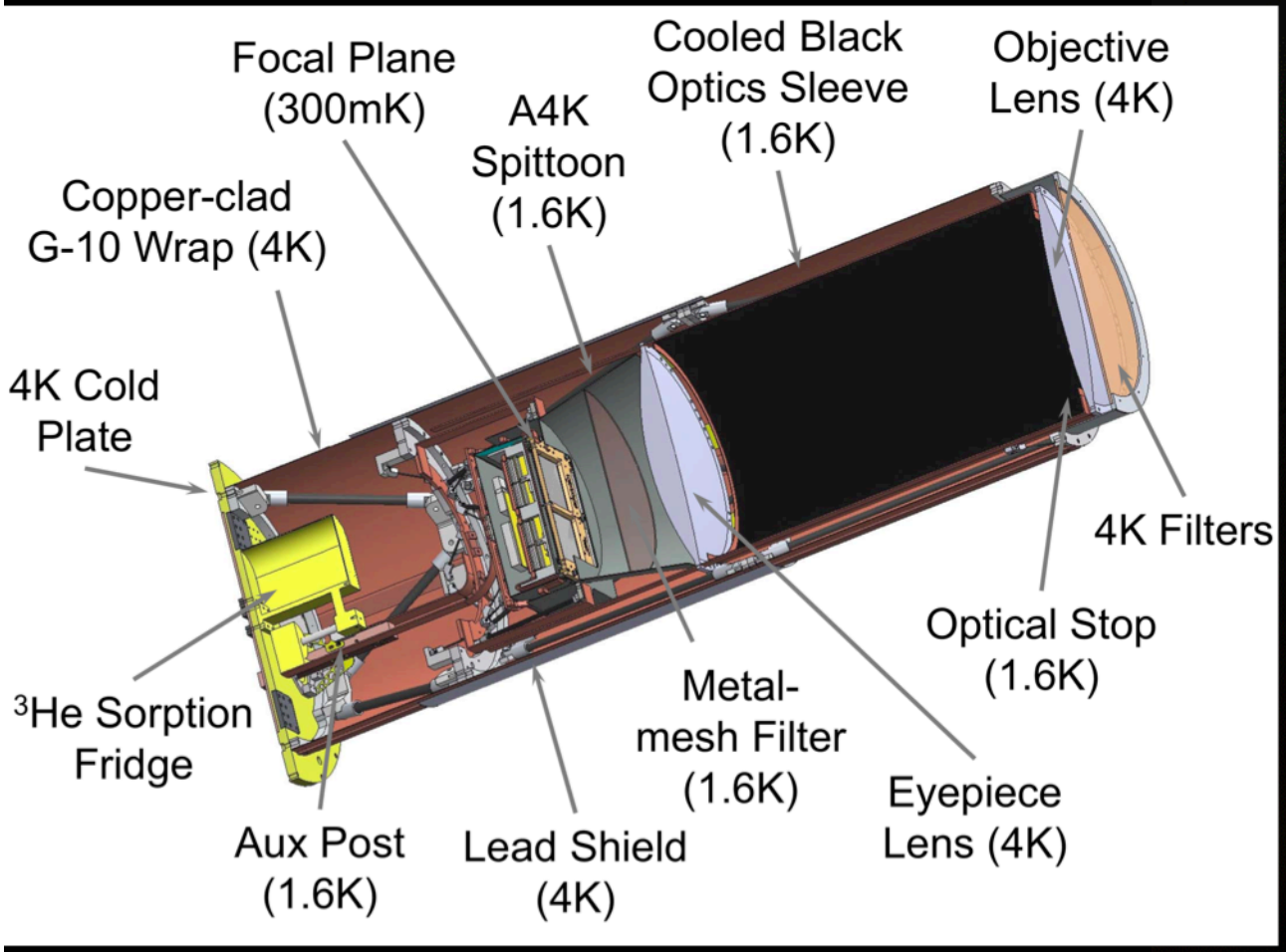
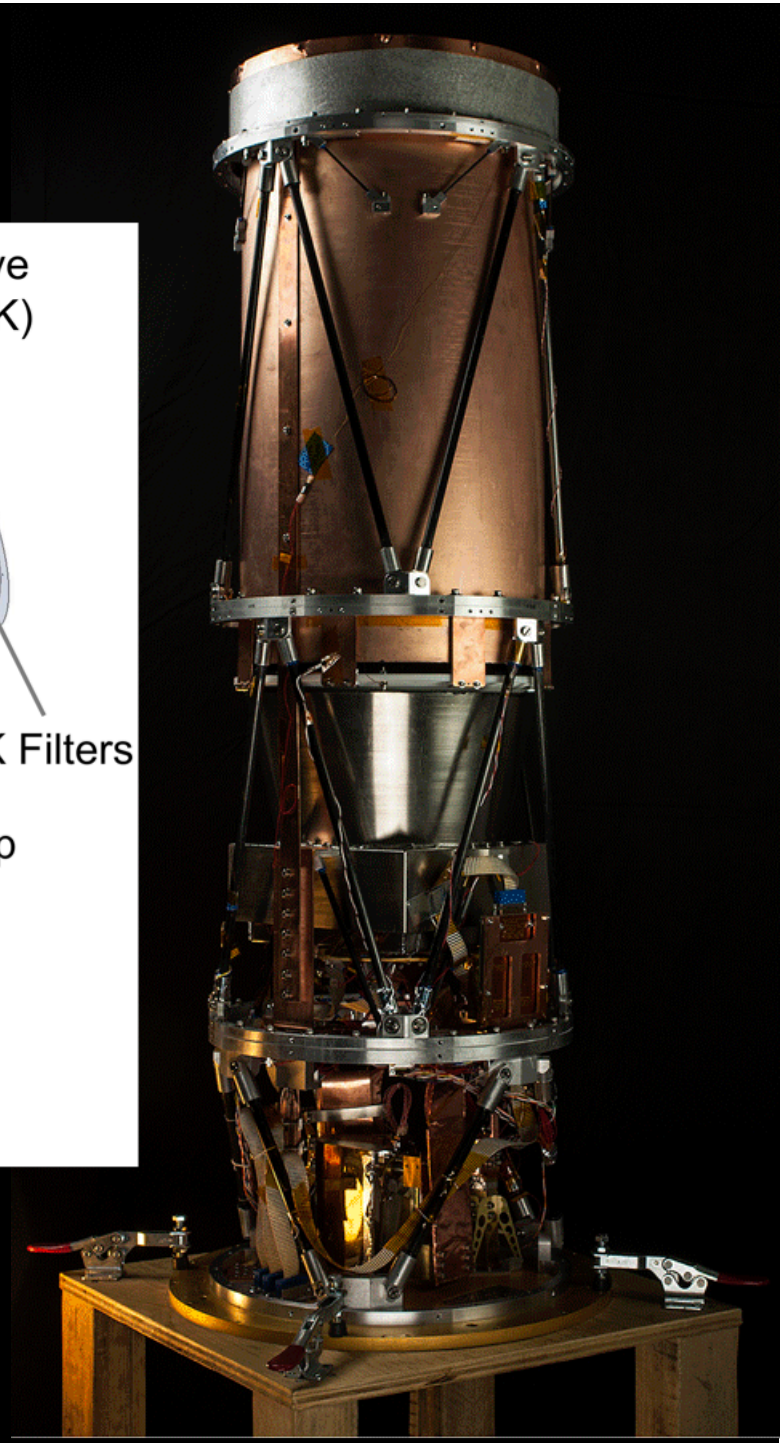



SPIDER
TD PCB



# Summary:

- Our Universe is filled with galaxies like our own
- It looks the same in every direction
- It seems to be expanding
- We have a physical theory that
  - is amazingly consistent with the data
  - makes predictions that we can test
- ... as long as we accept Dark Matter, Dark Energy, and an extremely unstable Universe (Cosmic Inflation)
- In the next 5 years:
  - observational data probing the Origin of the Cosmos


Focal Plane
(300mK)
Cooled Black
Optics Sleeve
(1.6K)
Objective
Lens (4K)
A4K
Spittoon
(1.6K)
Copper-clad
G-10 Wrap (4K)
4K Cold
Plate
4K Filters
Optical Stop
(1.6K)
$^3$He Sorption
Fridge
Metal-
mesh Filter
(1.6K)
Eyepiece
Lens (4K)
Aux Post
(1.6K)
Lead Shield
(4K)