In Search of Dark Matter

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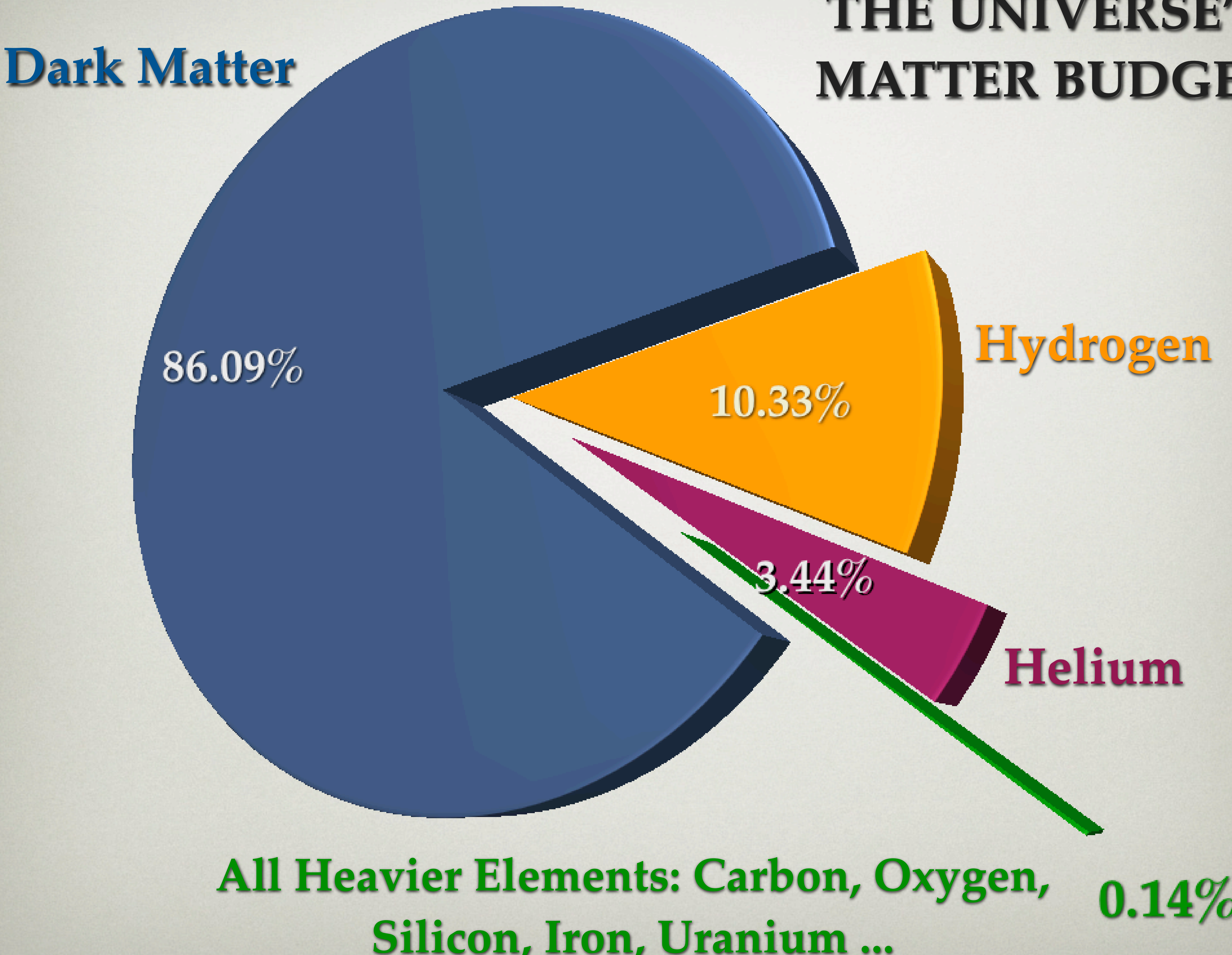
THE UNIVERSE'S MATTER BUDGET



Outline

- Eighty Years of Evidence for Dark Matter: Five Big Reasons
- Efforts to Detect Dark Matter
- The Next Ten Years

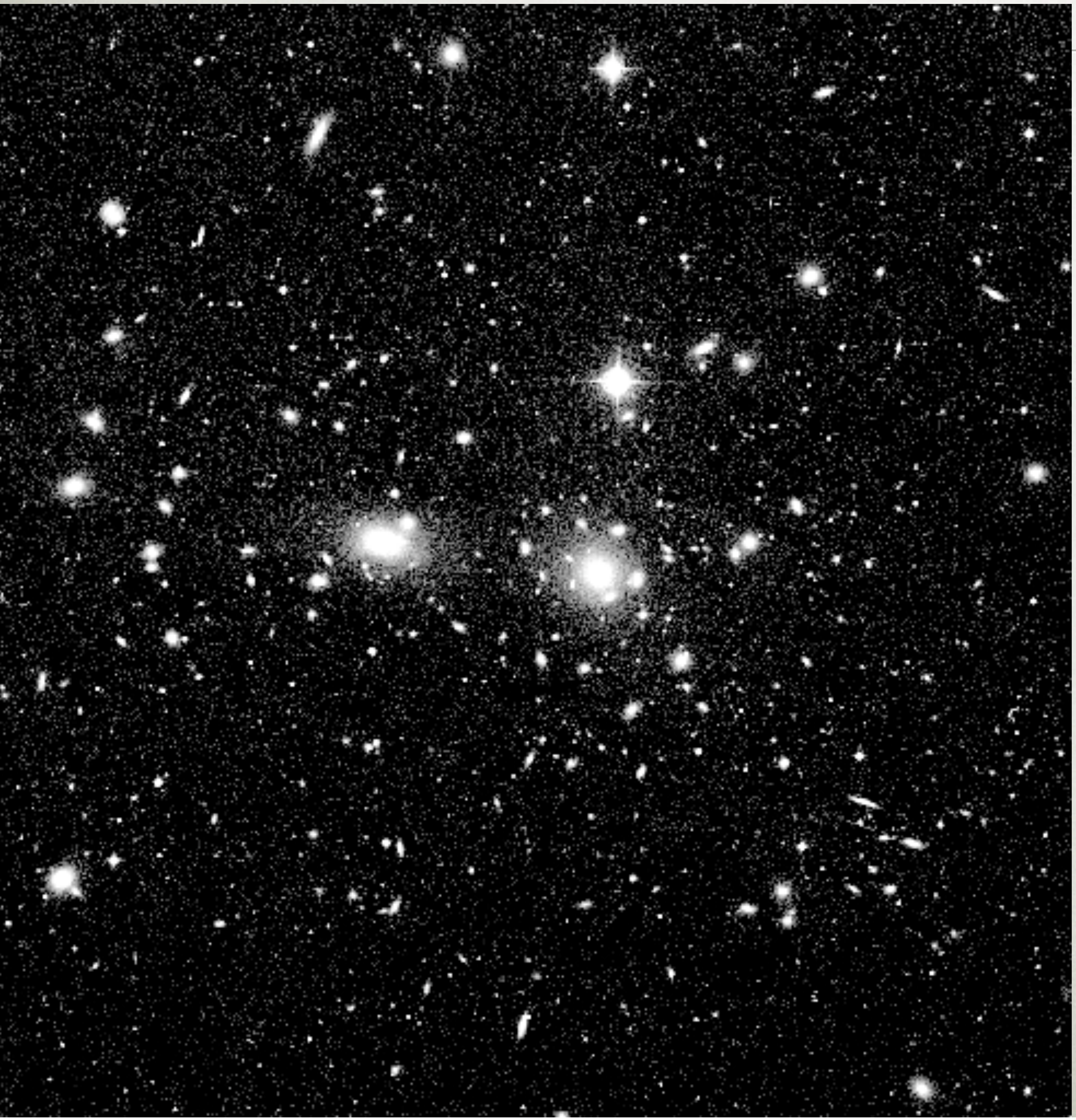
Evidence Part I:

Motions of Galaxies (1933)

Early Evidence

- Swiss Astronomer Fritz Zwicky is usually credited with providing the first indications of a large component of dark matter in the universe in two papers in 1933 and 1937
- Zwicky studied the velocities of galaxies in the nearby Coma Cluster of galaxies

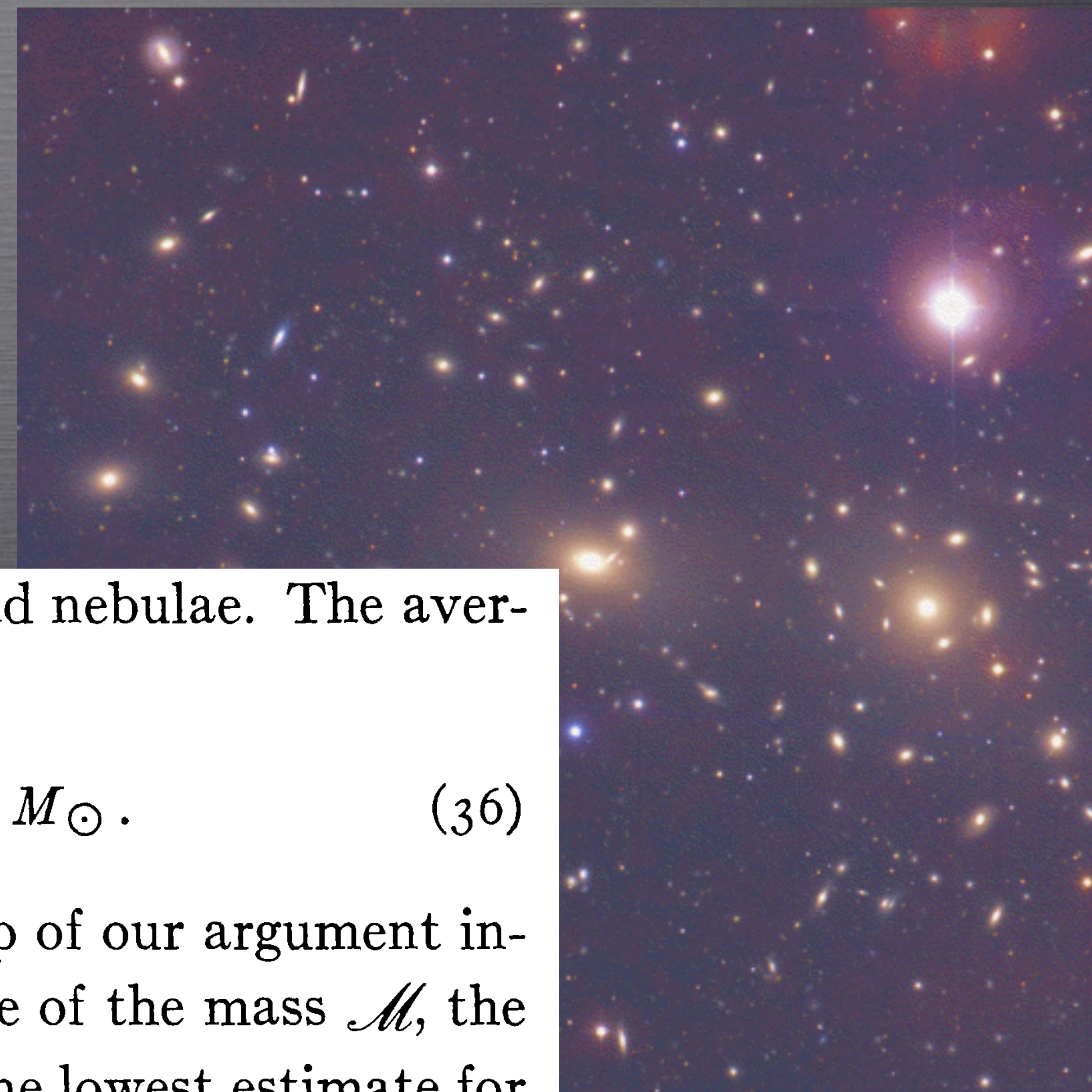
The Coma Cluster



Distance: 300 Million lightyears
Diameter: 12 Million lightyears
Apparent Size: 10 times bigger than the full moon on the sky

Dark Matter in the Coma Cluster of Galaxies

Dark Matter in the Coma Cluster of Galaxies



The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot . \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

Zwicky 1937

"If this result is confirmed, we would arrive at the astonishing conclusion that dark matter is present in Coma with a much greater density than luminous matter."

-Zwicky 1933

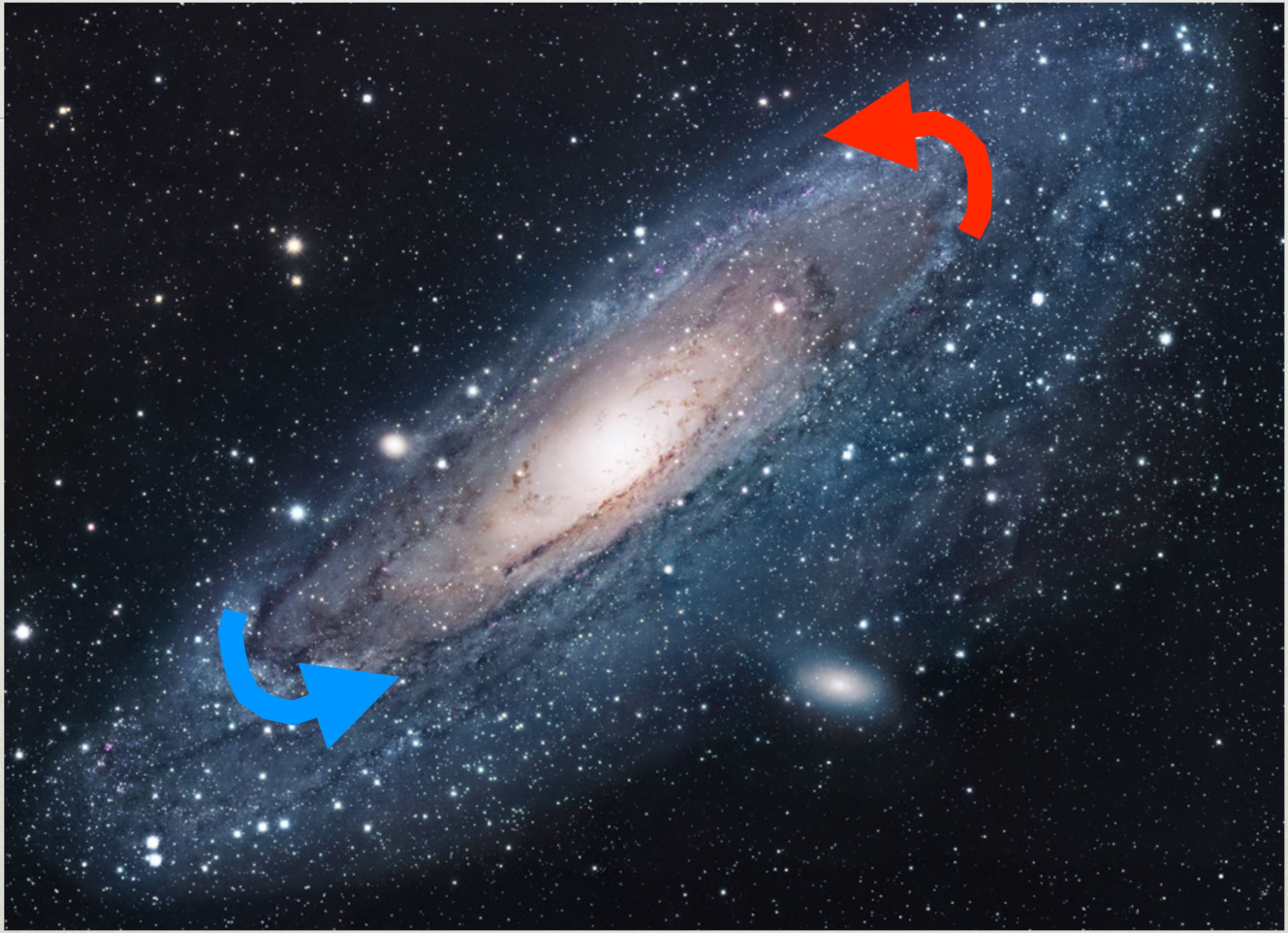
Evidence Part II:

Motions Within Galaxies (1970)

Rubin & Ford

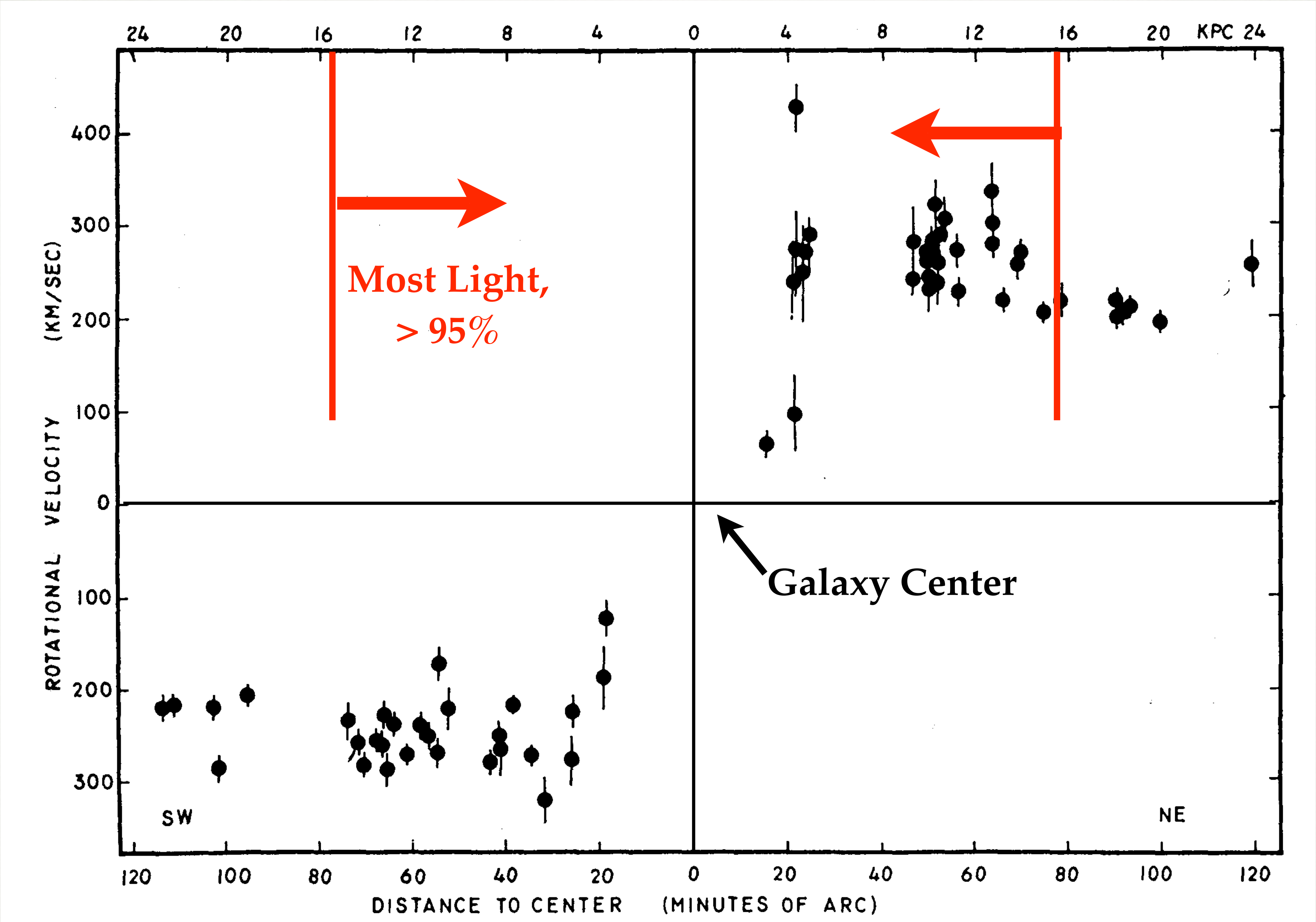
- Rubin & Ford (1970) reported on the "**rotation curve**" of the **Andromeda galaxy**

Andromeda



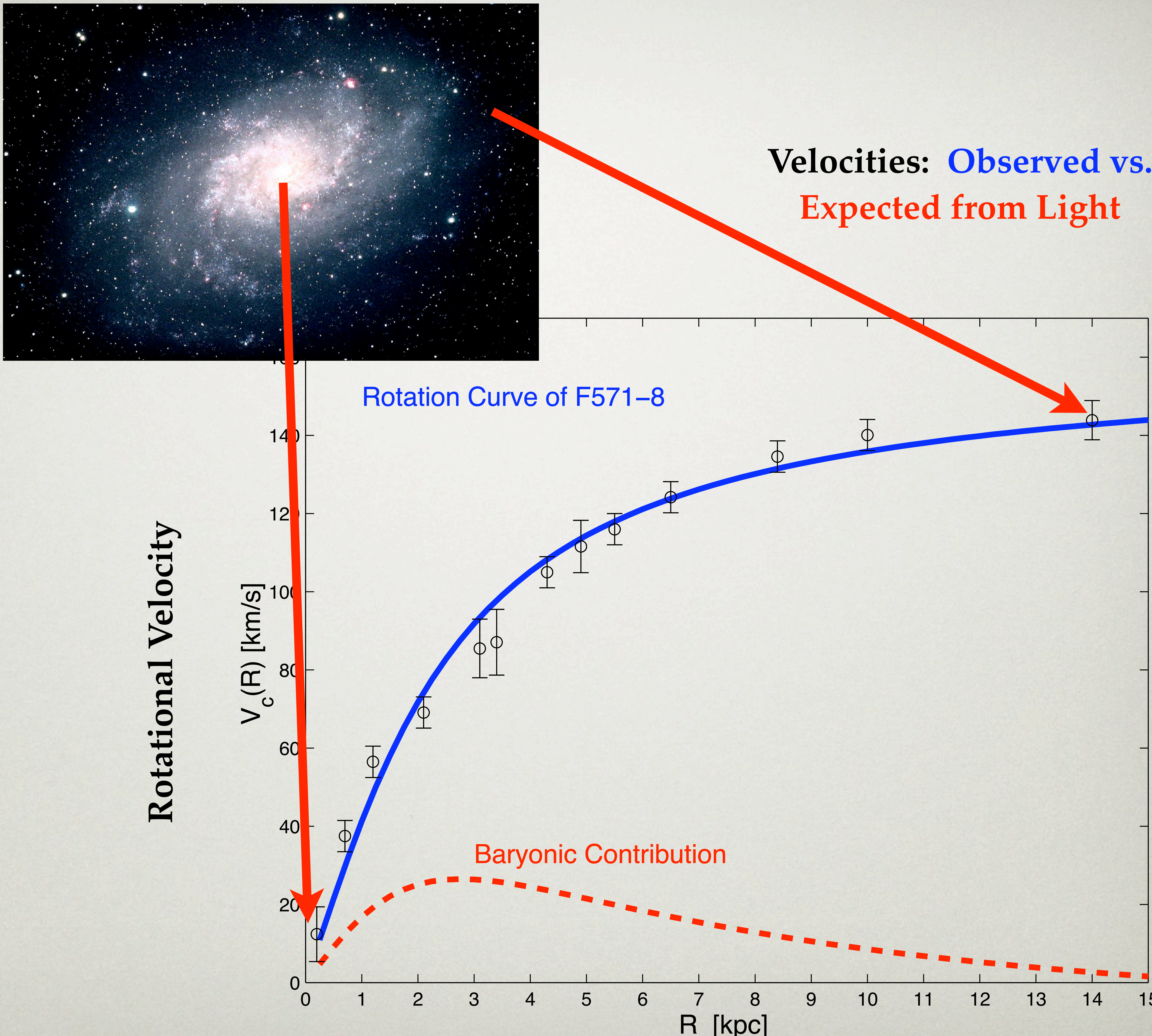
- about **750 kpc (2.4 Million lightyears)** distant
- About the size of the **Milky Way**

Andromeda



- Rubin & Ford's Rotation Curve

DARK MATTER



Velocities: Observed vs.
Expected from Light
Rotation Curve of F571−8
Baryonic Contribution
Rotational Velocity
$V_c(R)$ [km/s]
0
20
40
60
80
100
120
140
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
R [kpc]
Distance from Galactic Center

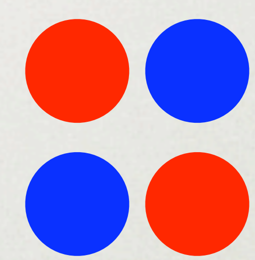
The material in galaxies moves too Fast to be explained only by the mass contained in stars and interstellar gas.

Evidence Part III: Light Element Nucleosynthesis (1964-2001)

Element/Isotope	Abundance	Made in...
Hydrogen	73%	Early Universe
Helium	24.5%	Early Universe
Oxygen	1%	Stars
Carbon	0.4%	Stars
Iron	0.1%	Stars
Silicon	0.06%	Stars
Deuterium	0.002%	Early Universe
Lithium	0.0000001%	Early Universe

Hydrogen and Helium

- **The Universe is 75% Hydrogen, 24% Helium, and 1% other stuff.**

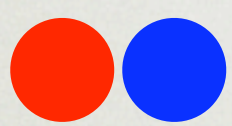


Helium (^{4}He): 2 protons, 2 neutrons, very strongly held together

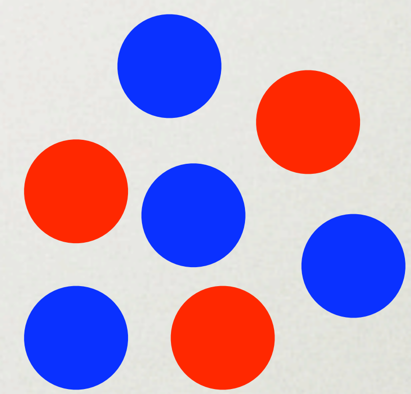
Hydrogen (H): 1 proton

Deuterium and Lithium

- **The Universe contains trace amounts of Deuterium and Lithium, which are destroyed rather than produced within stars**



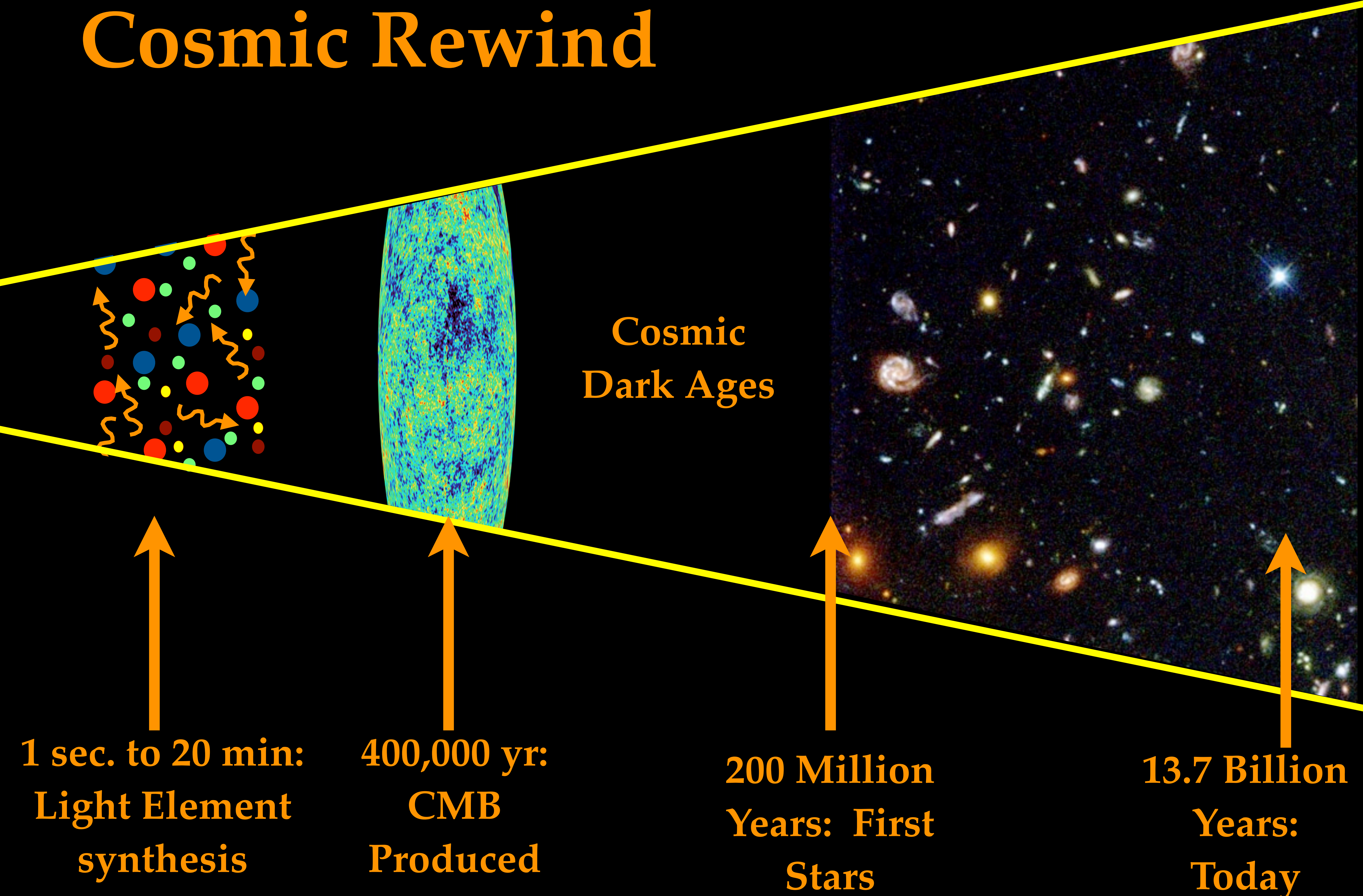
Deuterium (D): Hydrogen Isotope with one Proton and one Neutron, loosely bound together



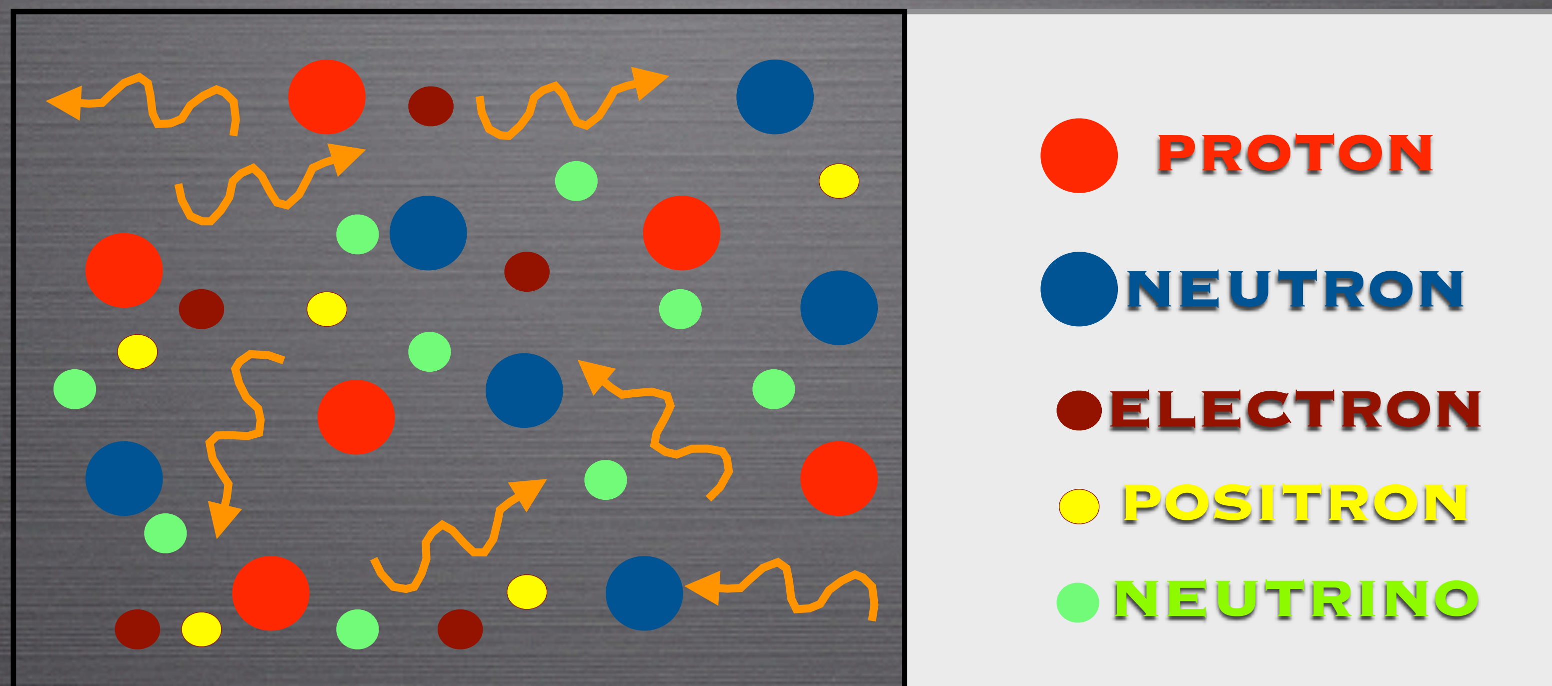
Lithium (^{7}Li): 3 **protons**, 4 **neutrons**, loosely bound together


Dr. Seuss's

Cosmic Rewind



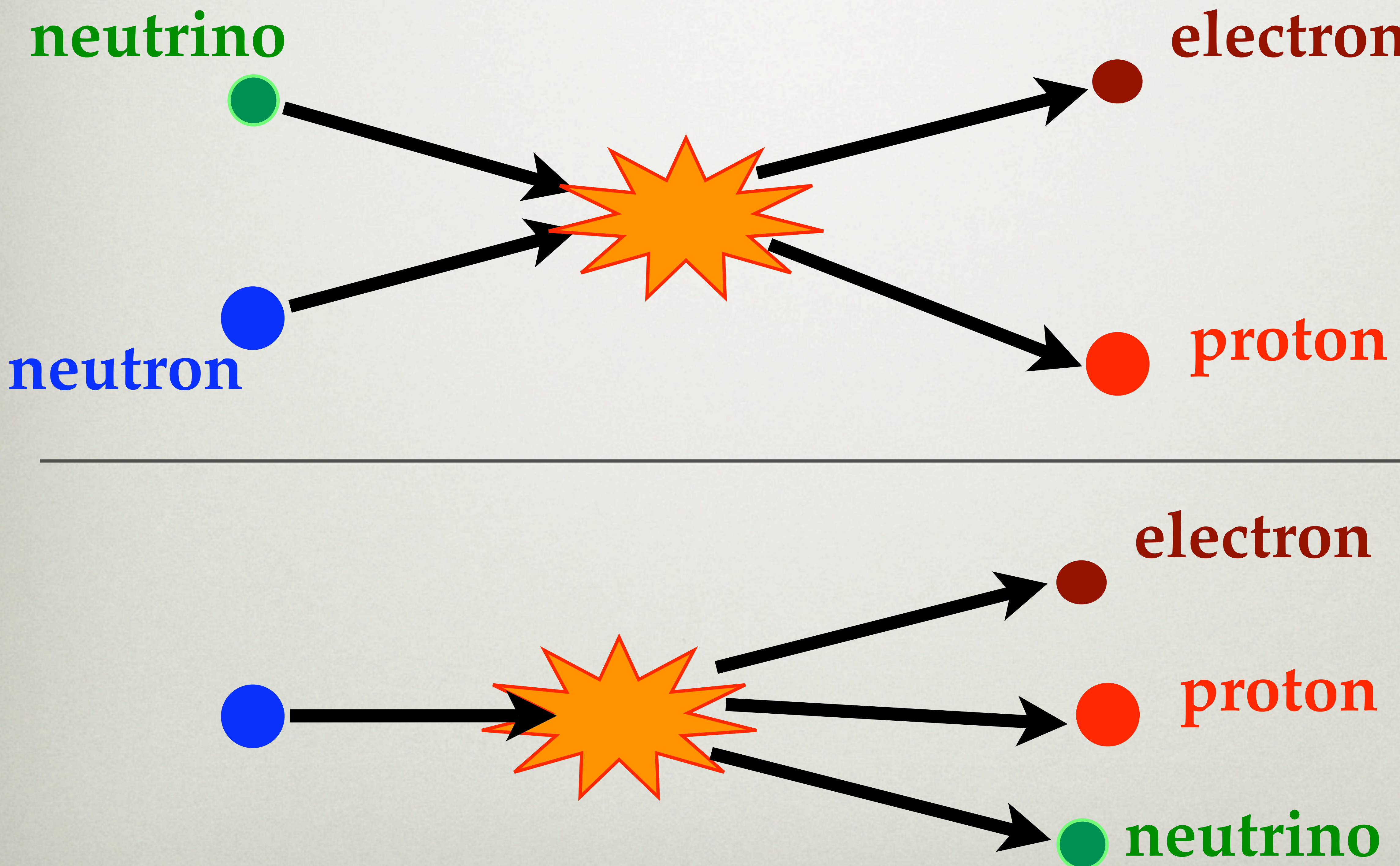
Synthesis of the Light Nuclei



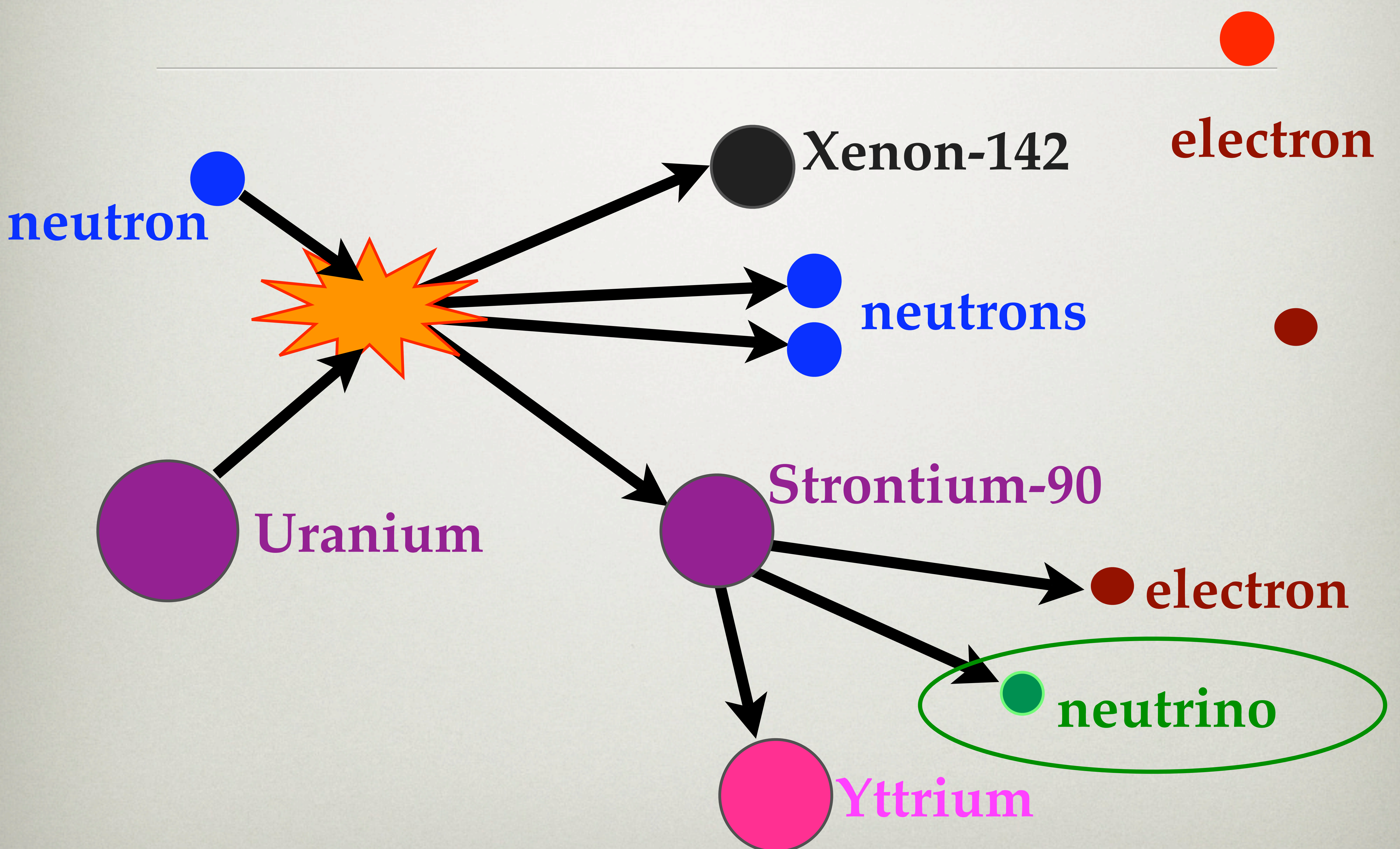
In the very early universe (t < 1 second):

- Densities are very high & interactions happen very quickly because interaction rates increase with temperature and density
- The weak interactions interconvert protons and neutrons
- Equilibrium is maintained while interactions are rapid

Neutrinos


neutrino
electron
neutron
proton
electron
proton
neutrino

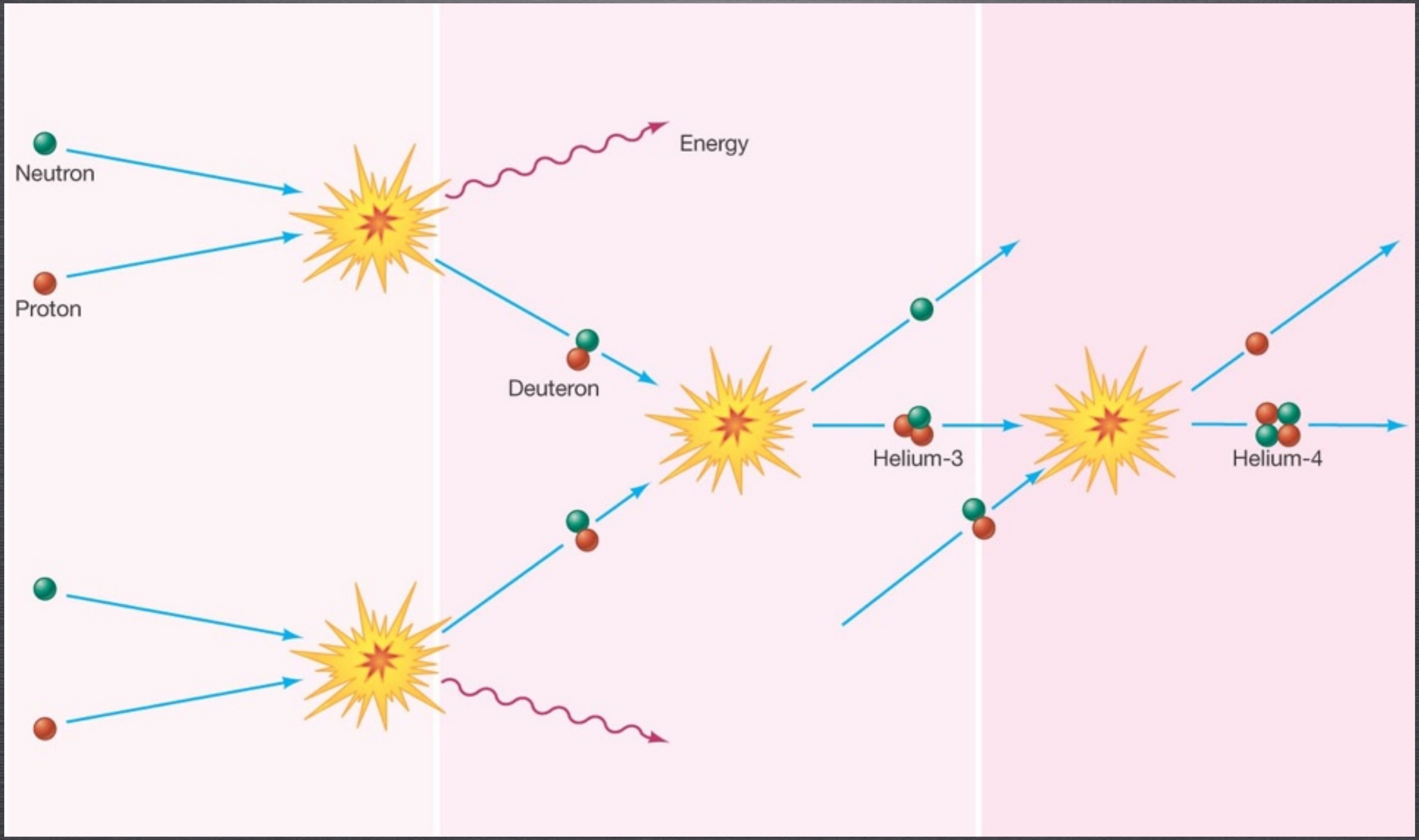
Neutrinos


proton
electron
Xenon-142
neutron
neutrons
Uranium
Strontium-90
electron
neutrino
Yttrium

Neutrinos

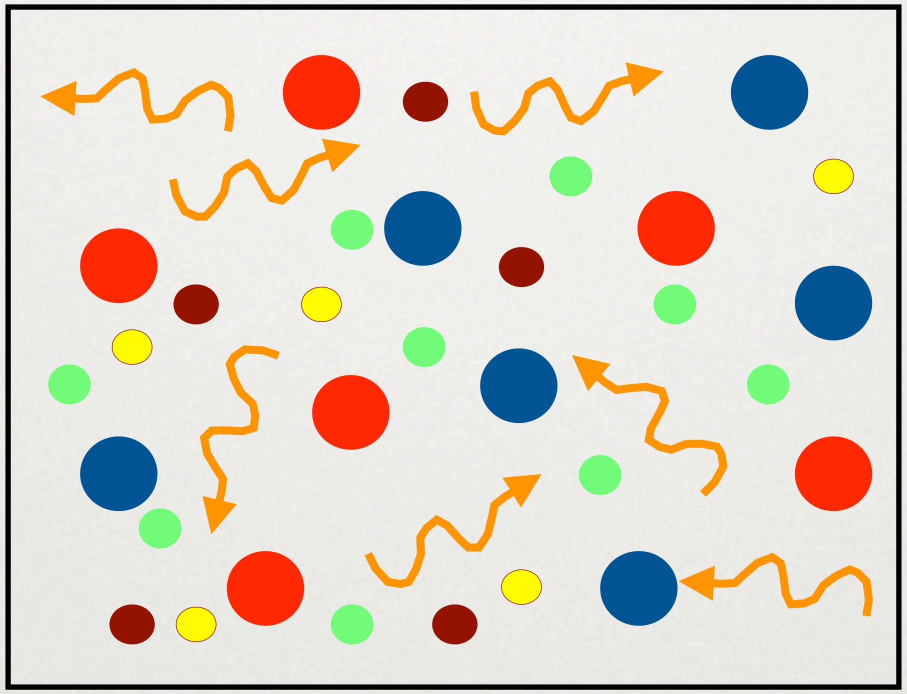
- Electrically neutral, therefore:
  - they do not interact with or emit light
  - they are unnoticed by us under most circumstances
- Interact via the Weak Nuclear Force only, so
  - four light-years of solid lead (24 trillion miles) would be required to have a 50% chance of "catching" a neutrino.
- Much lighter than protons, neutrons, or electrons so they move fast when produced

Synthesis of the Light Nuclei



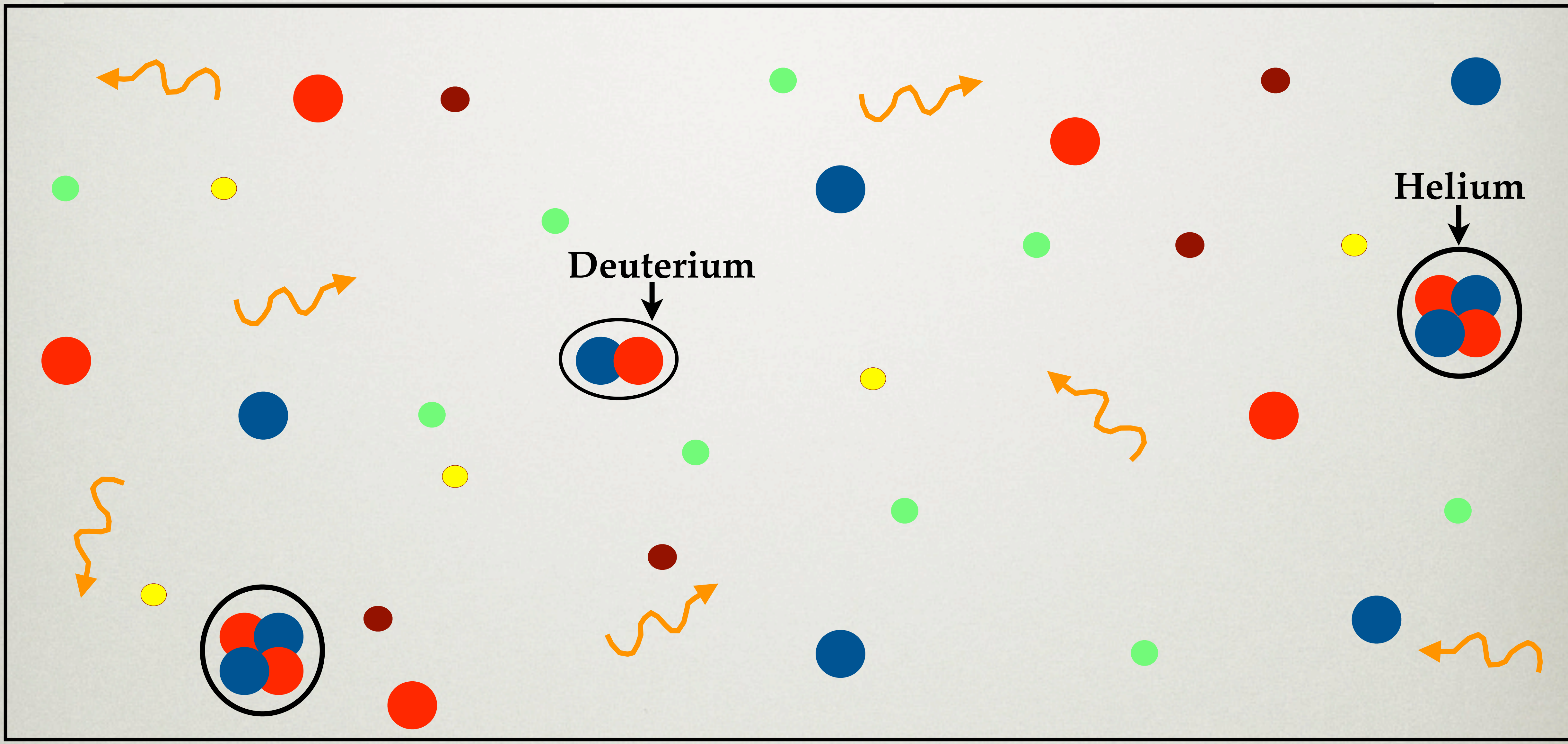
Fusion processes like the above, allow larger nuclei to form from the constituent protons and neutrons

Synthesis of the Light Nuclei



- The Universe expands, cools, and interactions "freeze out"
- Equilibrium is lost and residual neutrons are incorporated into Deuterium, Helium, & Lithium by t=20 minutes

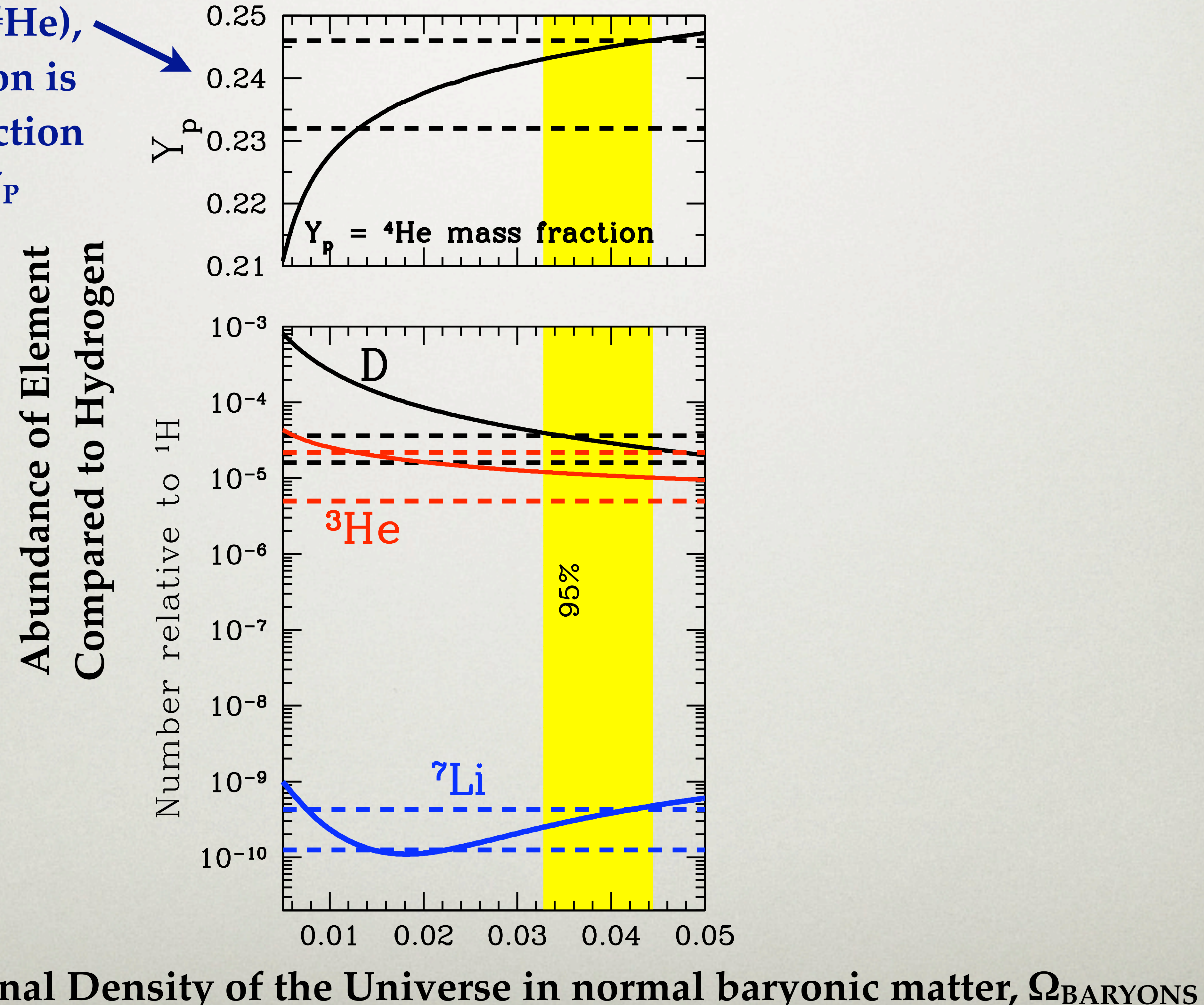
Synthesis of the Light Nuclei



- The Universe expands, cools, and interactions "freeze out"
- Equilibrium is lost and residual neutrons are incorporated into Deuterium, Helium, & Lithium by t=20 minutes

Light Element/Isotope Abundances

For Helium (^4He), the convention is to use the fraction by mass Y_P



Light Element/Isotope Abundances

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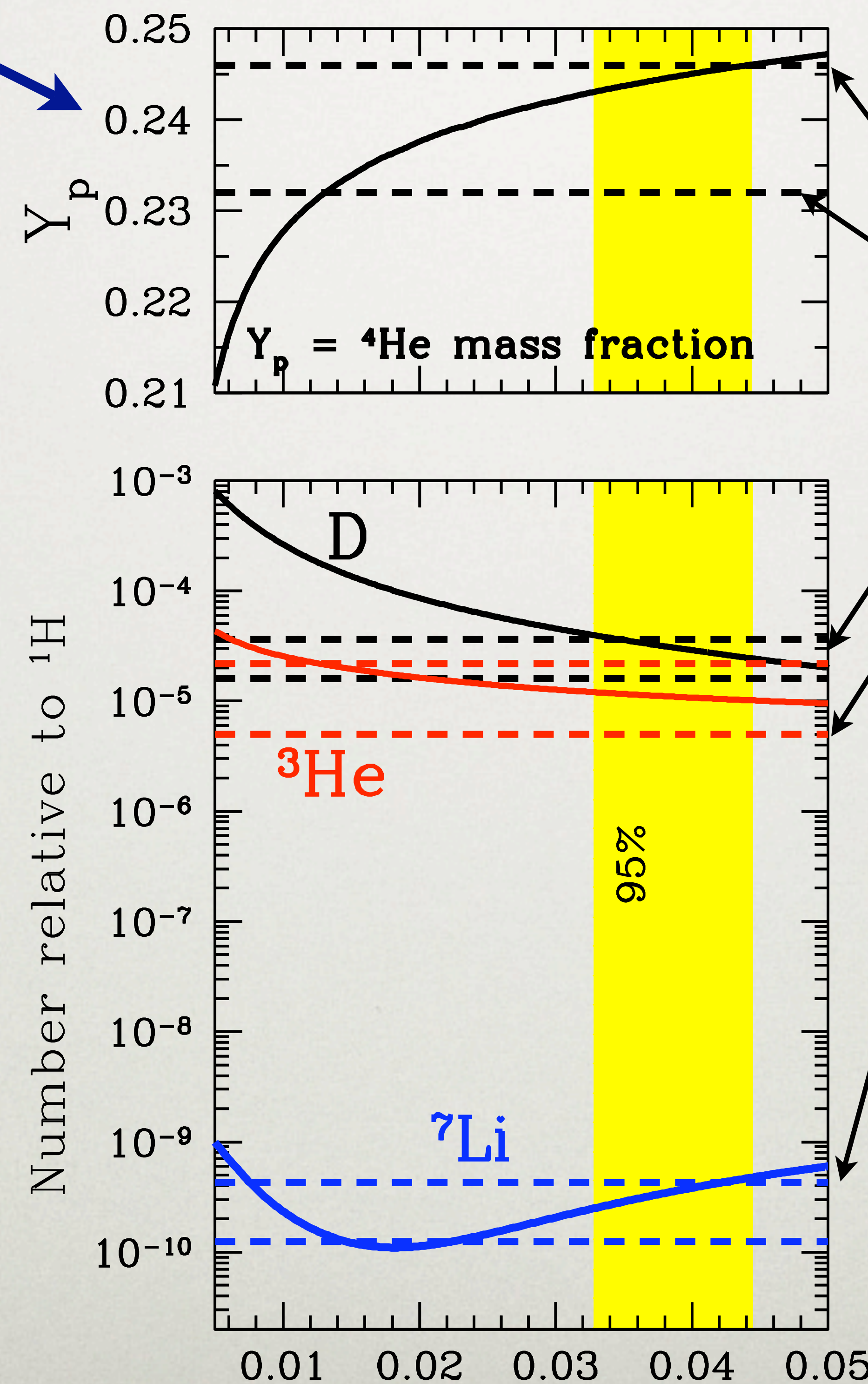
Abundance of Element Compared to Hydrogen



Dashed lines show range of observed values

Fractional Density of the Universe in normal baryonic matter, $\Omega_{BARYONS}$

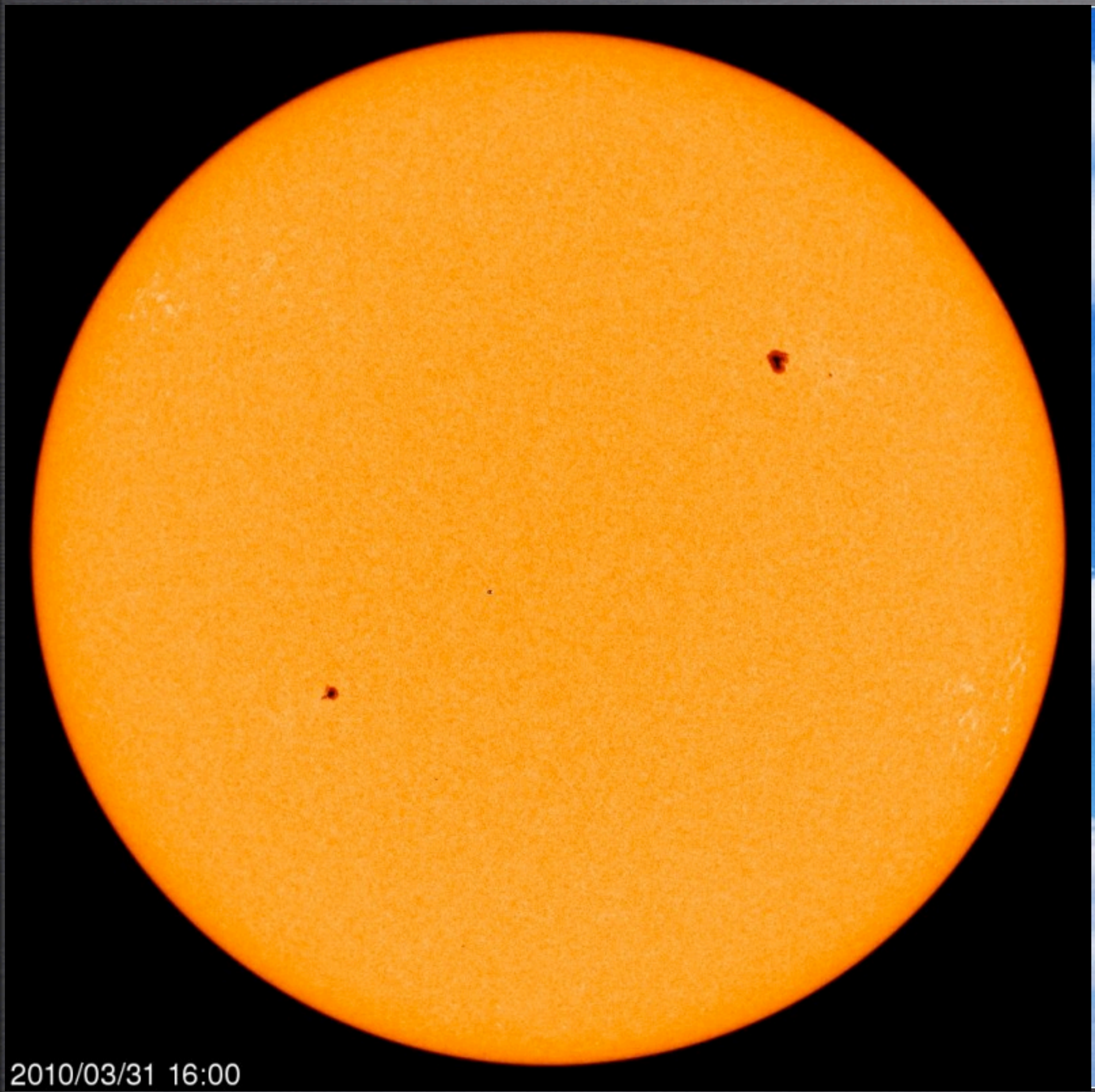
Production of light elements in the Early Universe is consistent with observations, only if 4% of the entire Universe is in the form of normal “baryonic” matter!

Note: This is also astounding because it says that we know how all of the elements in the Universe were produced!

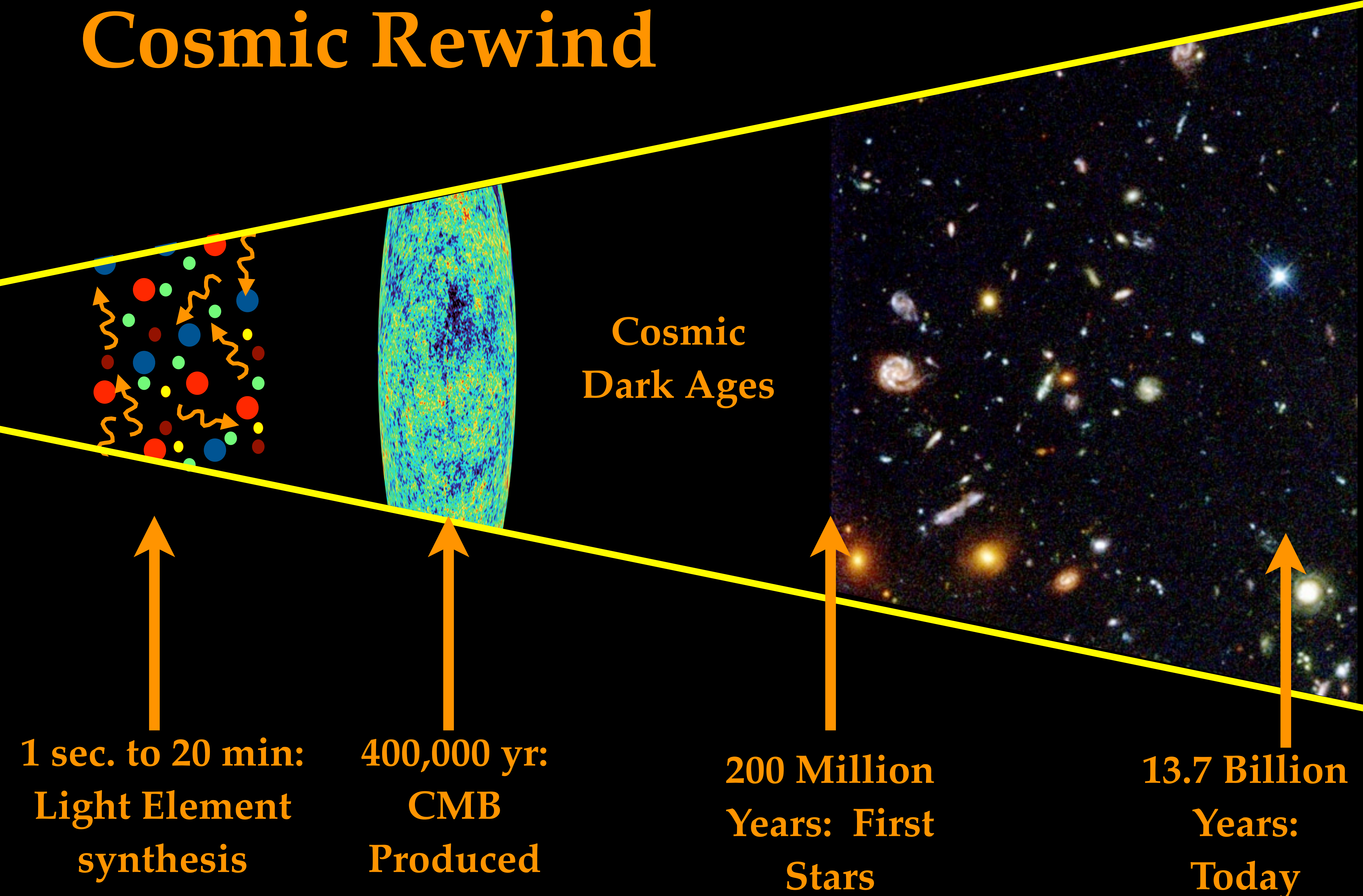
Evidence Part IV:

The Growth of Cosmic Structure (1970-2003)

Why do we see surfaces of clouds, the Sun, or Anything?

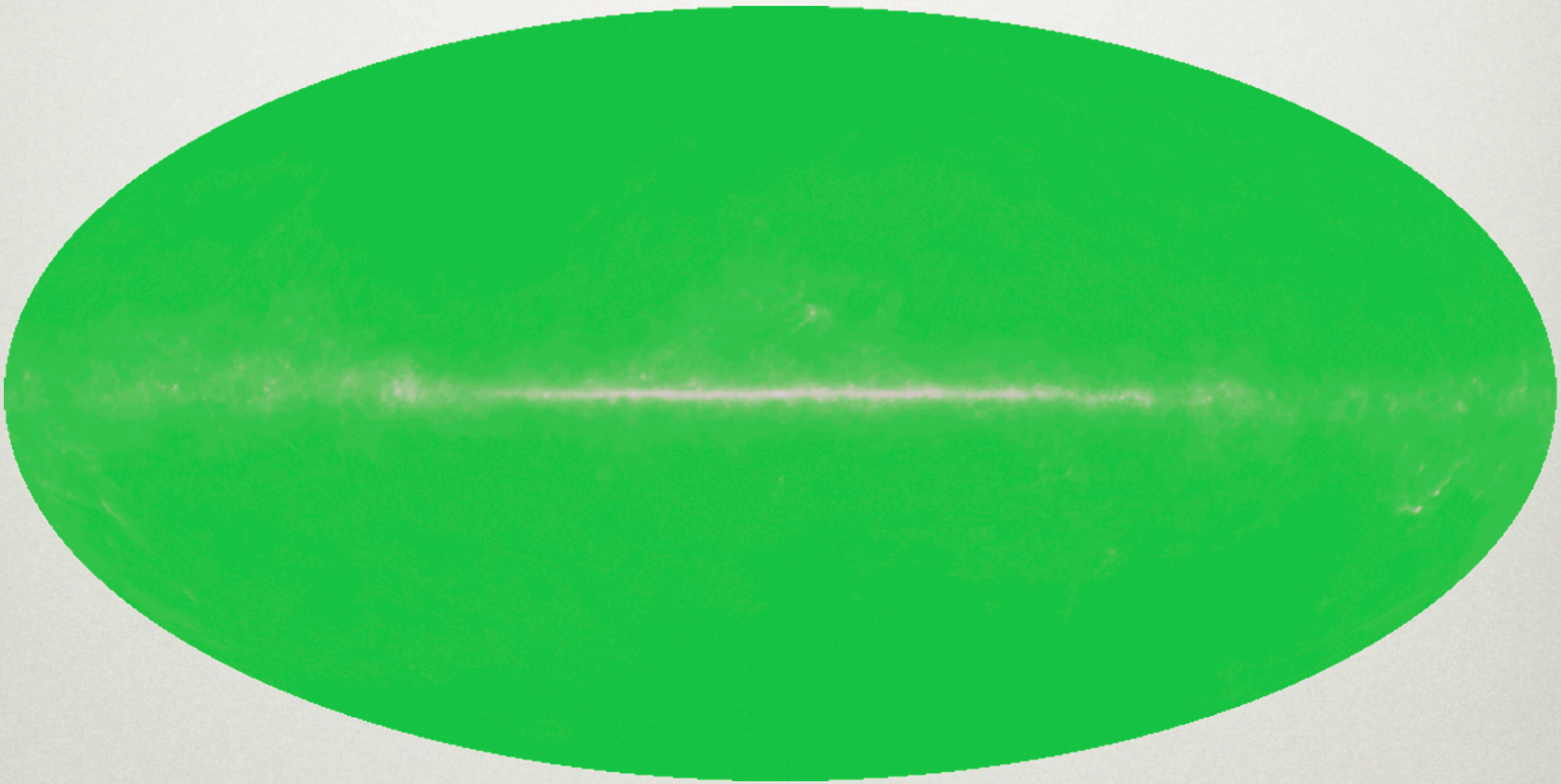


Cosmic Rewind



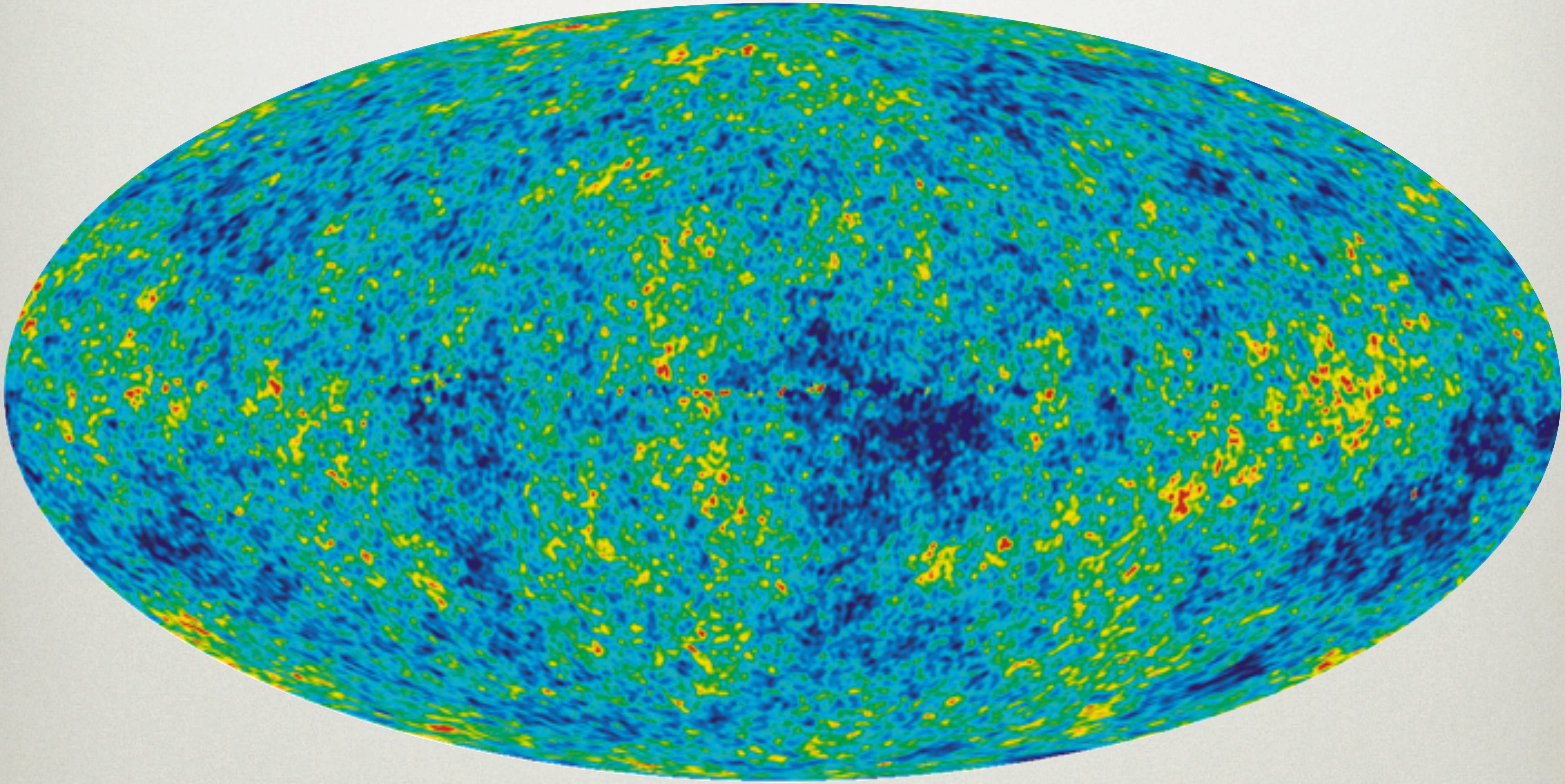
Our View of the Big Bang

The Universe's Baby Picture



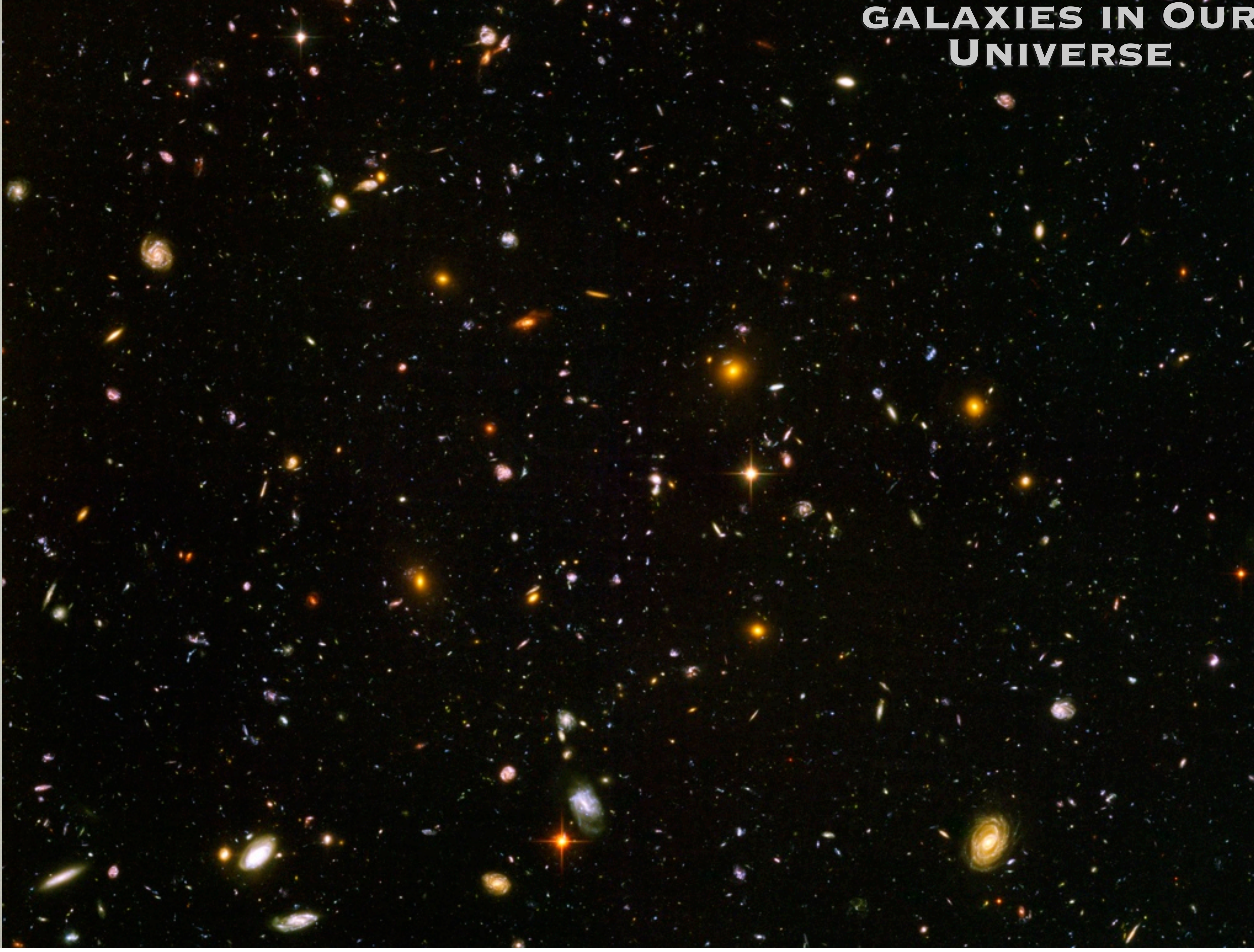
- Measured by the Wilkinson Microwave Anisotropy Probe

The Universe's Baby Picture



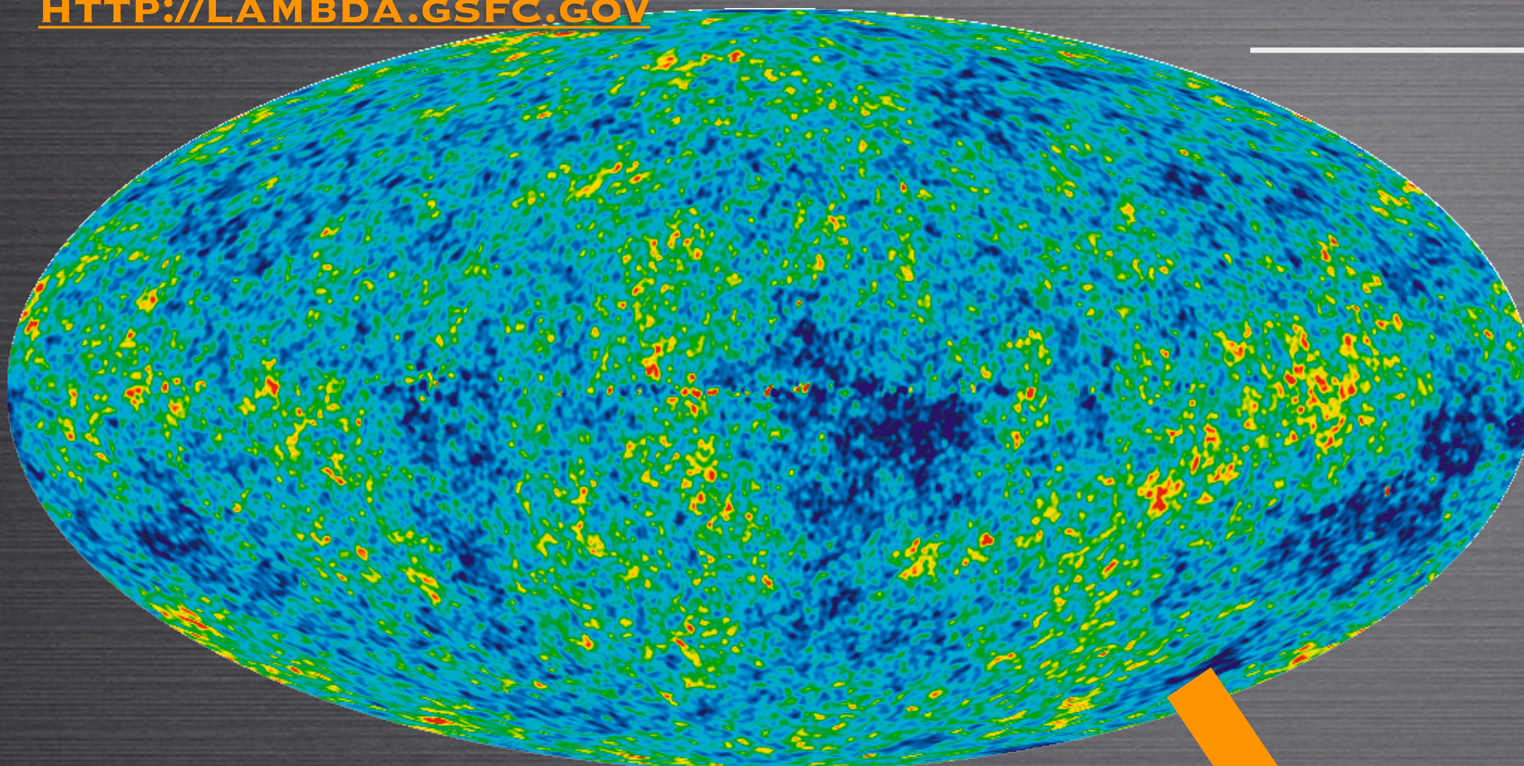
- Measured by the Wilkinson Microwave Anisotropy Probe

GALAXIES IN OUR UNIVERSE



Dark Matter

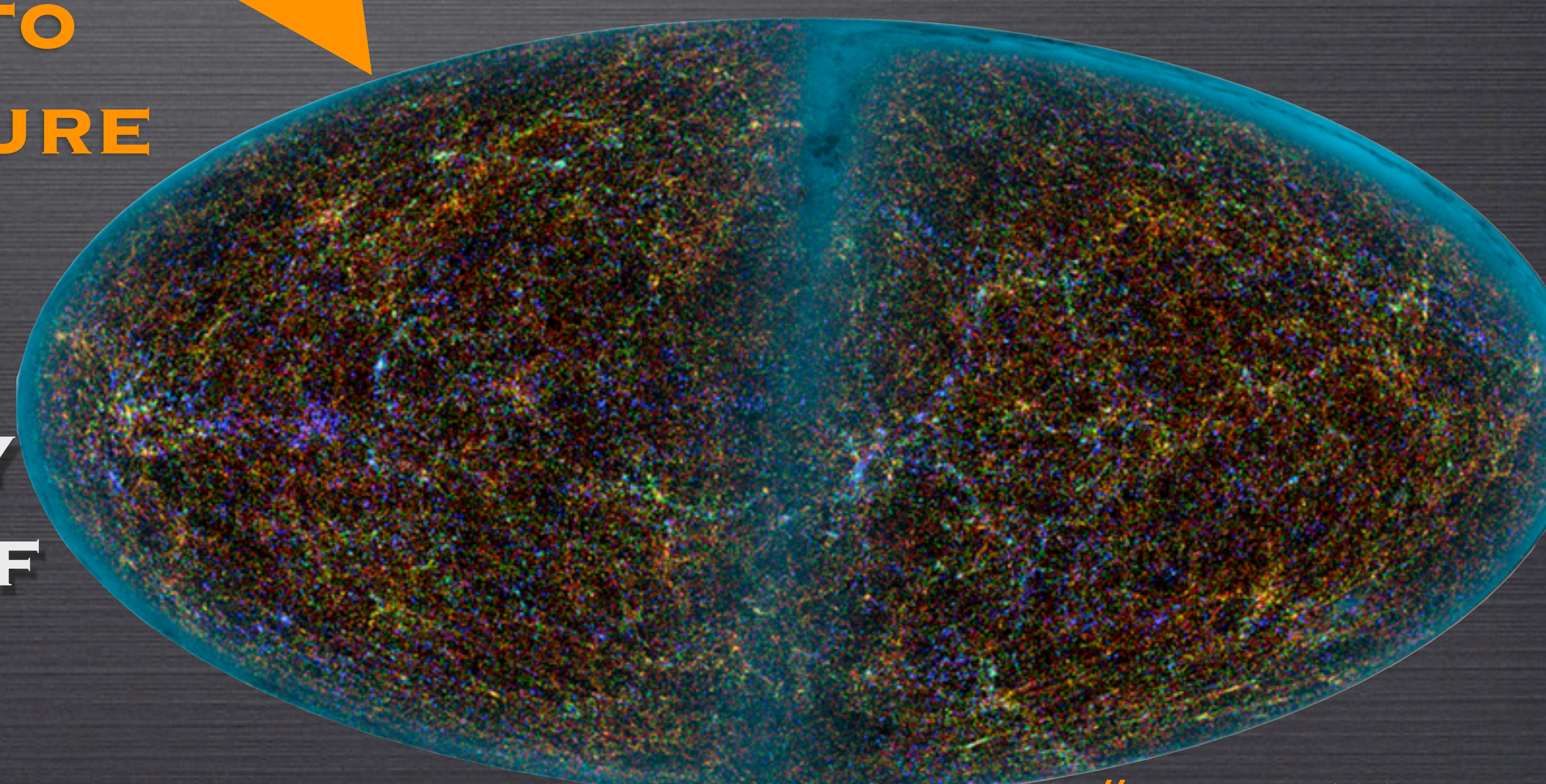
http://lambda.gsfc.gov



Microwave Background Image of the Universe 13 Billion Years Ago

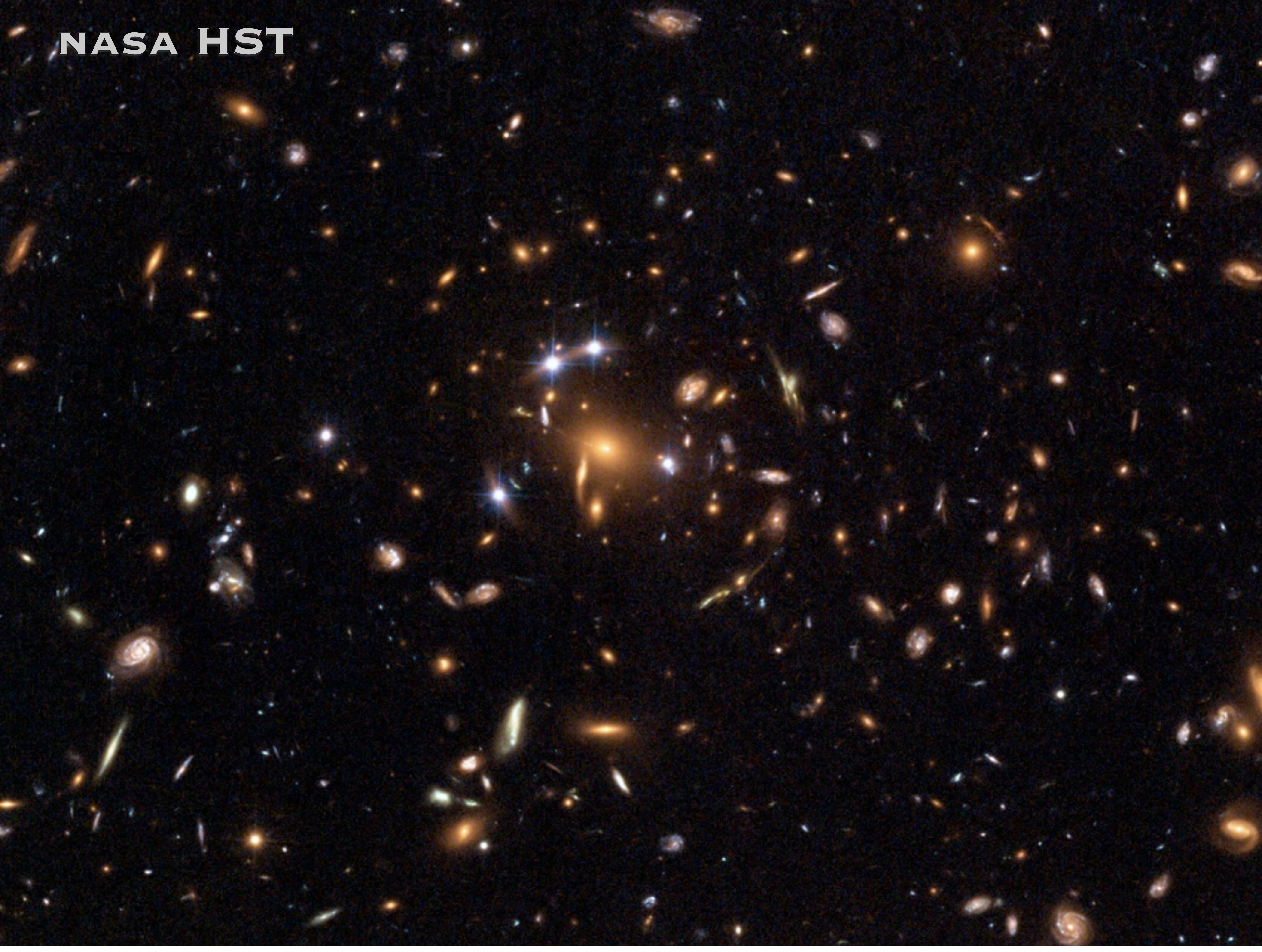
Dark Matter is Necessary to Grow Structure

Contemporary Distribution of Galaxies



http://ipac.caltech.edu

Evidence Part V: Gravitational Lensing


nasa HST

Dark Matter Candidates

Neutrinos

- Electrically neutral, therefore:
  - they do not interact with or emit light
  - they are unnoticed by us under most circumstances
- Interact via the Weak Nuclear Force only, so
- Much lighter than protons, neutrons, or electrons so they move fast when produced
- Like dark matter in that they are, dark, but they are much too light to be the dark matter!

Top Two Candidates

- Weakly-Interacting, Massive Particles (WIMPs):
  - Analogous to very heavy neutrinos
  - Can be produced in the Early Universe in processes analogous to light element nucleosynthesis
  - Are natural parts of theories that were developed to explain other phenomena

Top Two Candidates

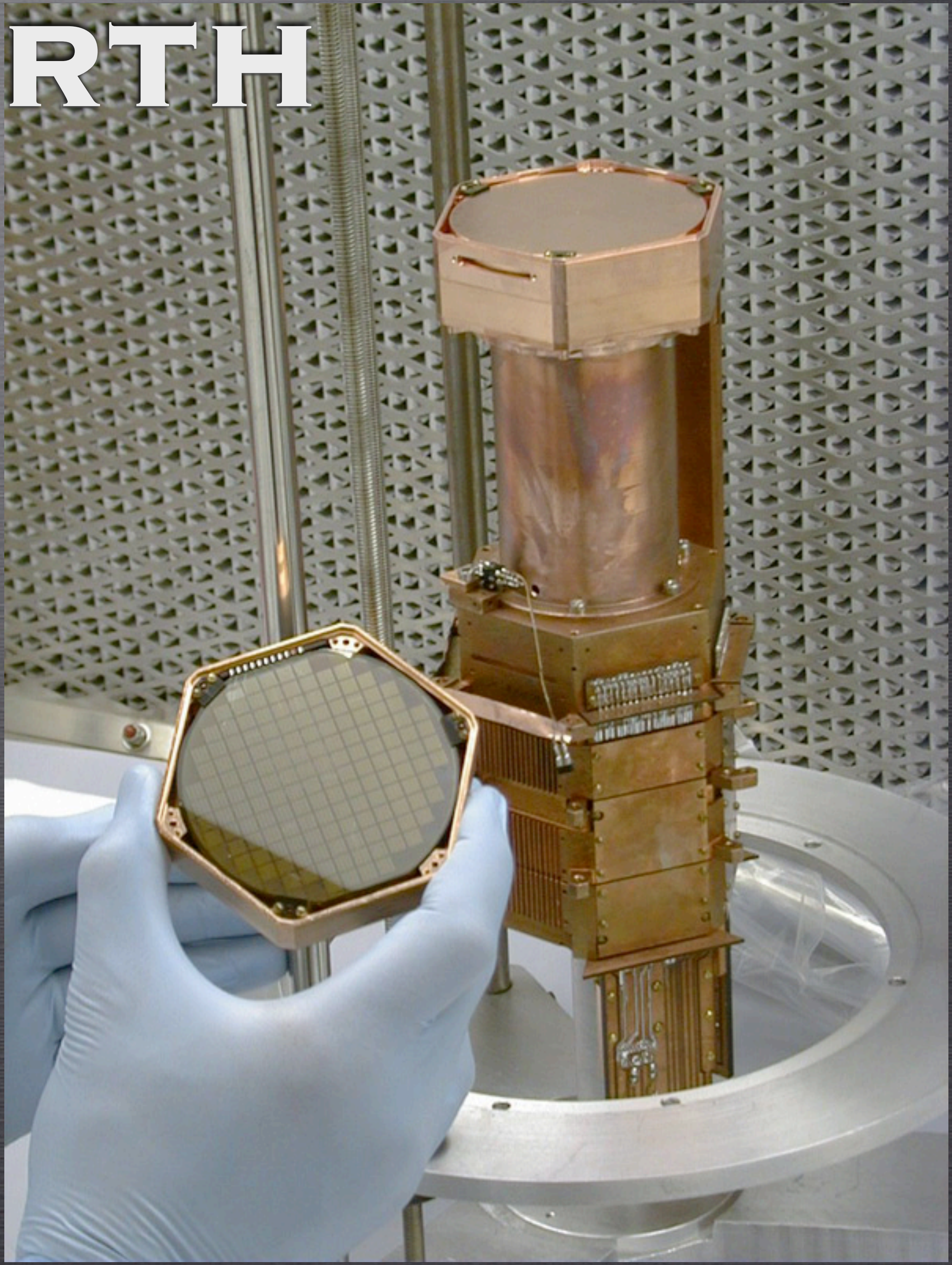
- Axions:
    - New particle invented to explain other aspects of the strong nuclear force.
    - Very difficult to detect.

Detecting Dark Matter Without Gravity

Detecting WIMPs

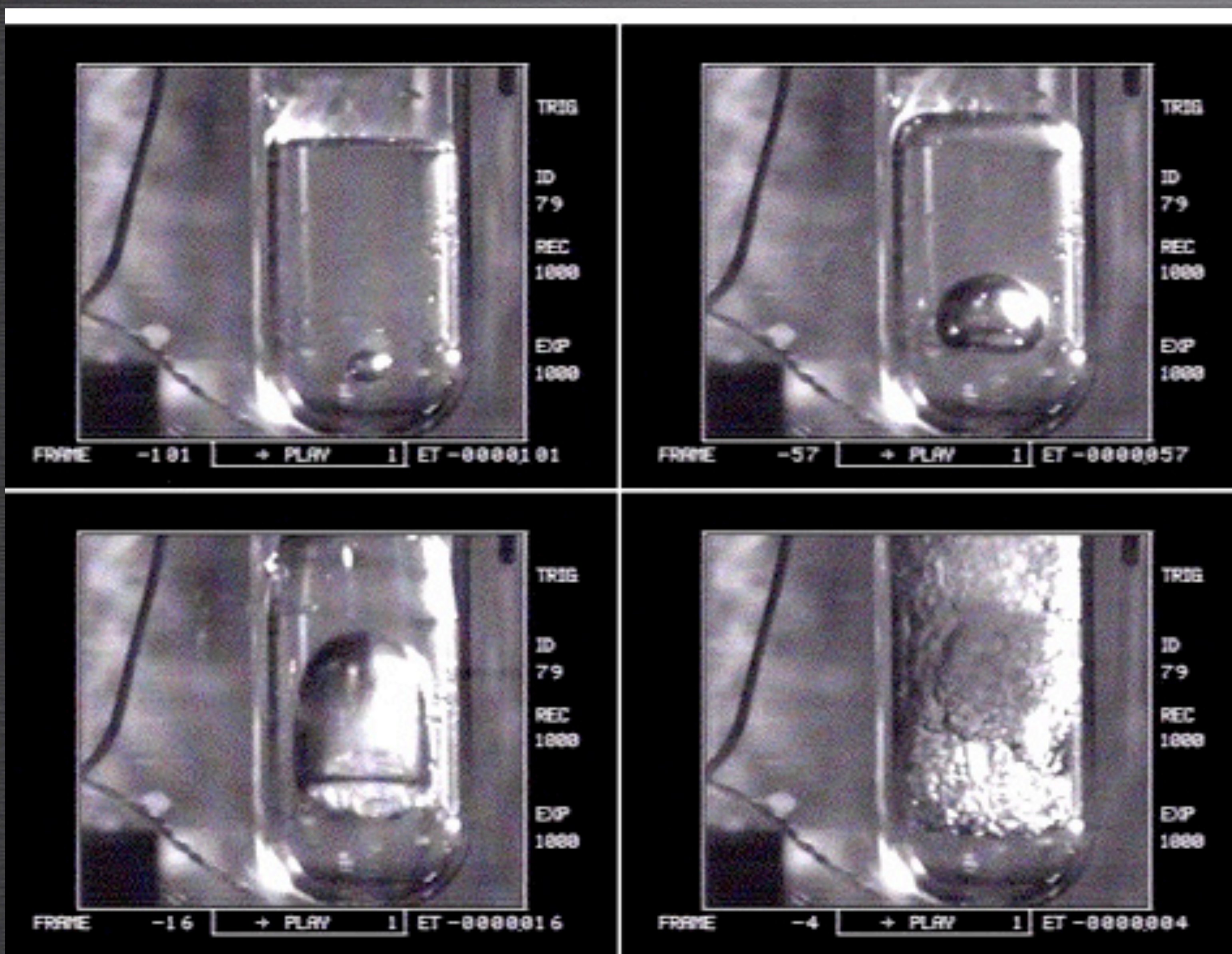
WIMPs Hit The Earth

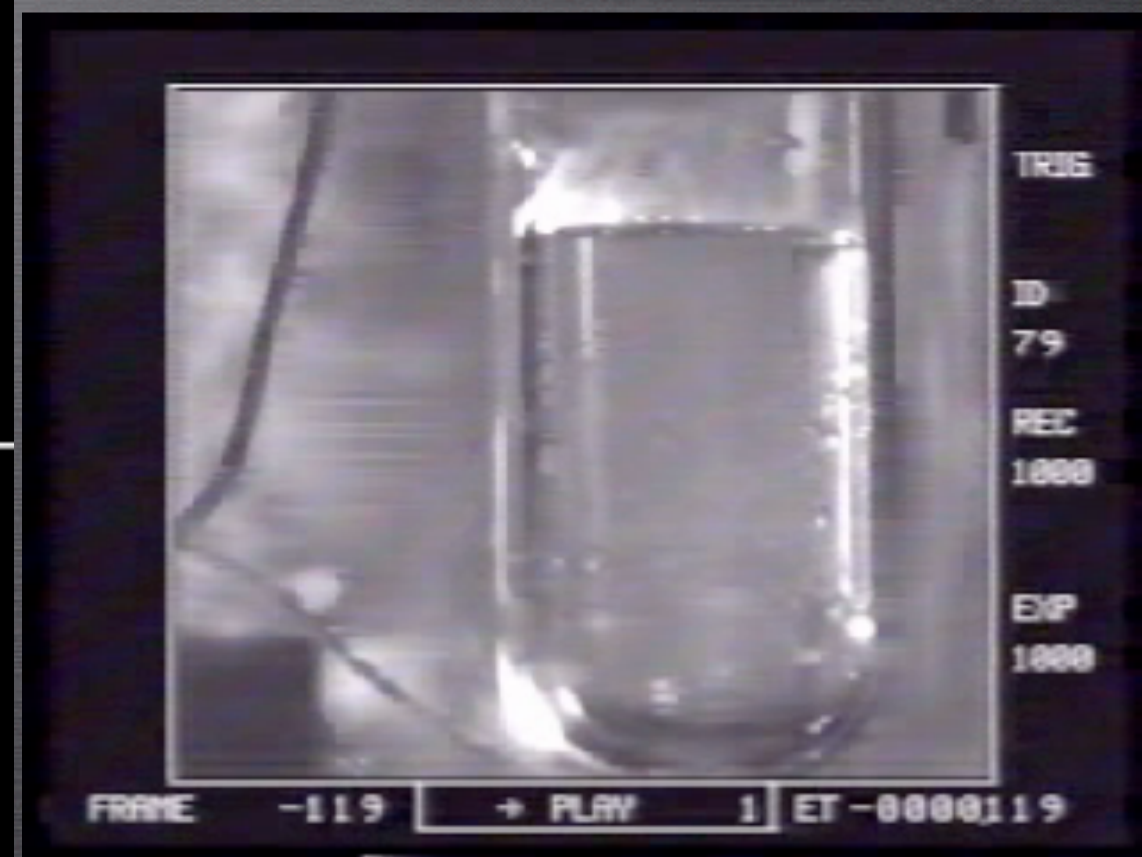
Directly On the Earth



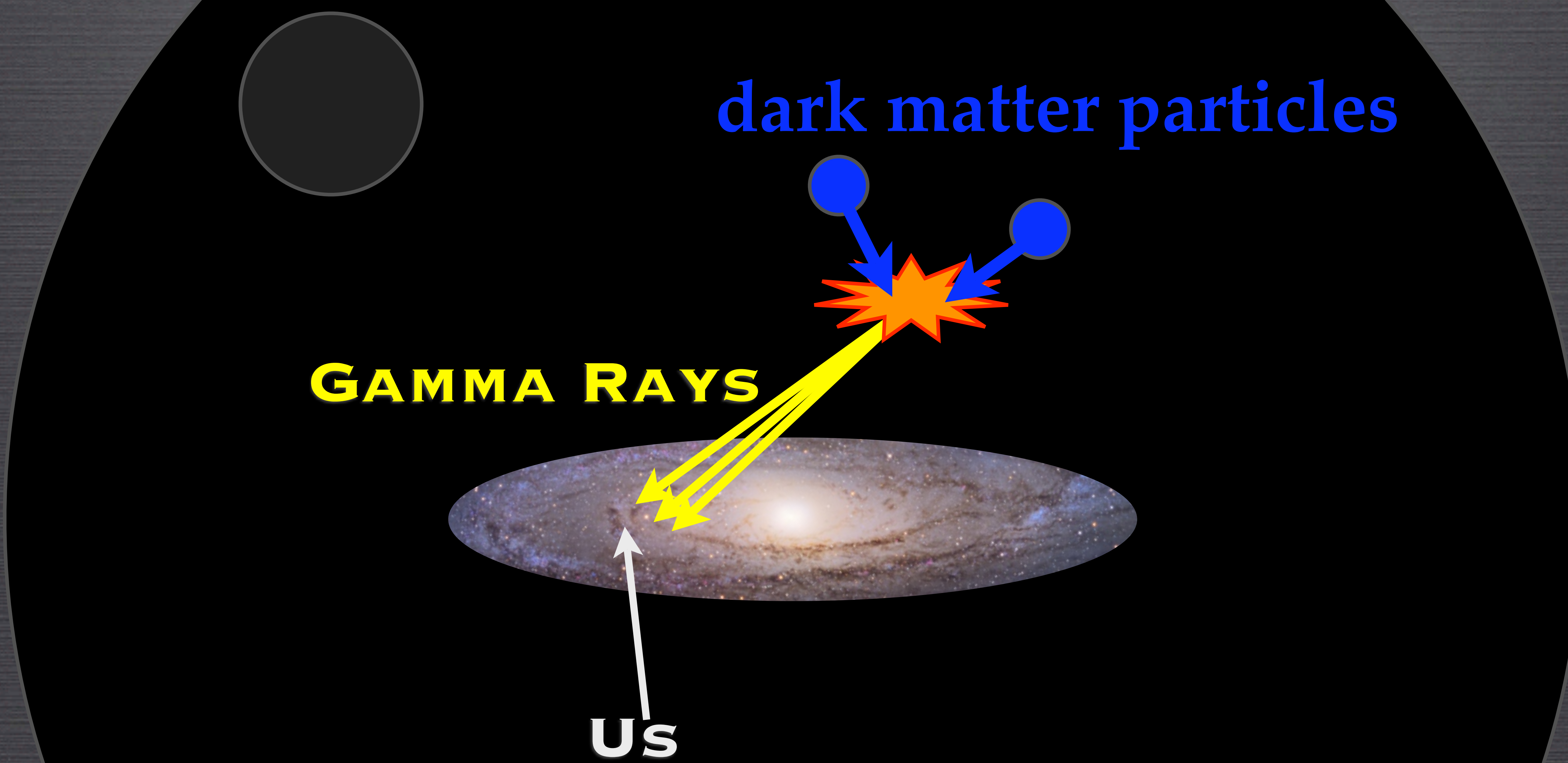
Depositing Heat on a Cold, Semi-Conductor Crystal

COUPP Detector





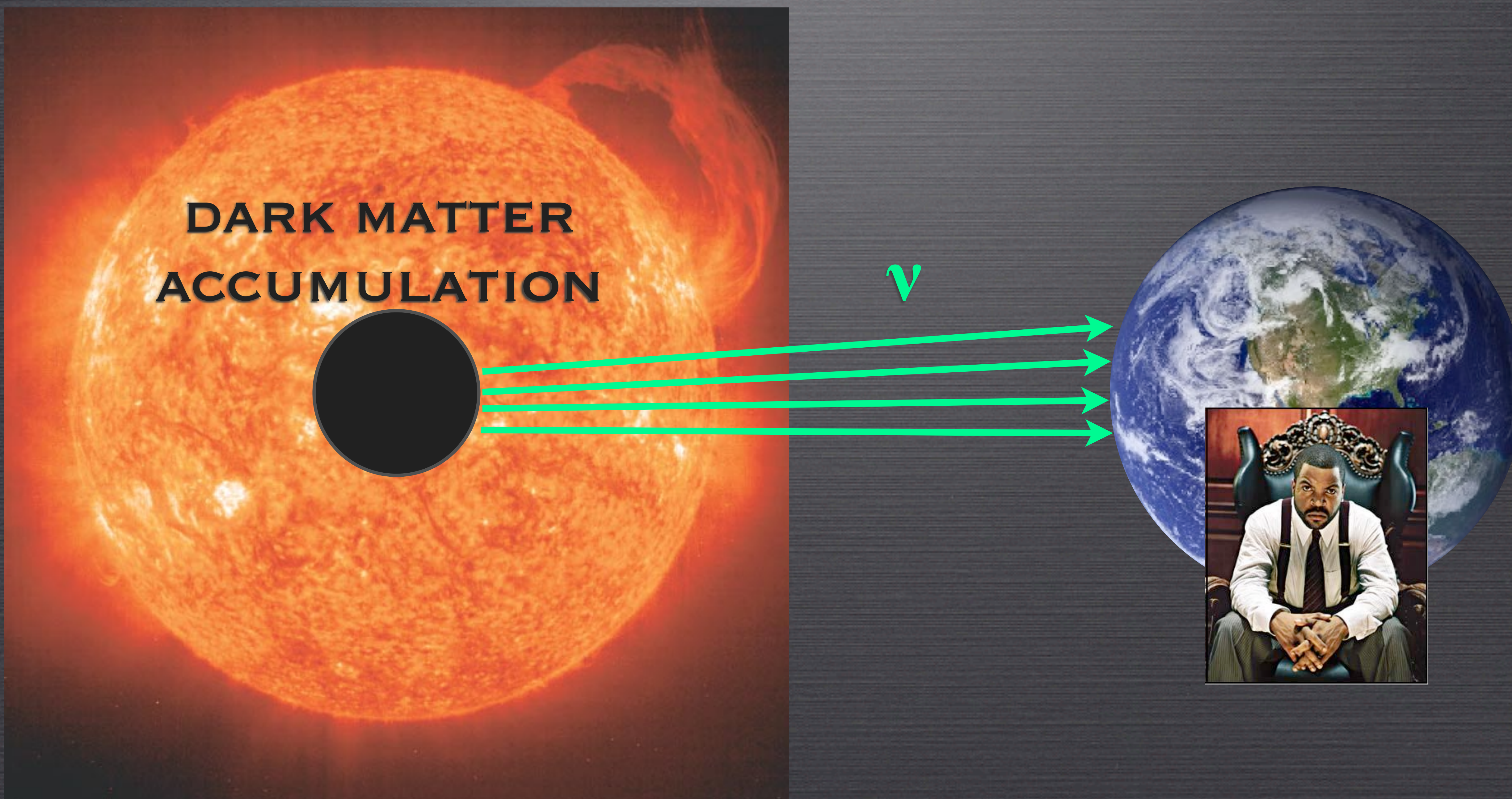
Annihilation Products



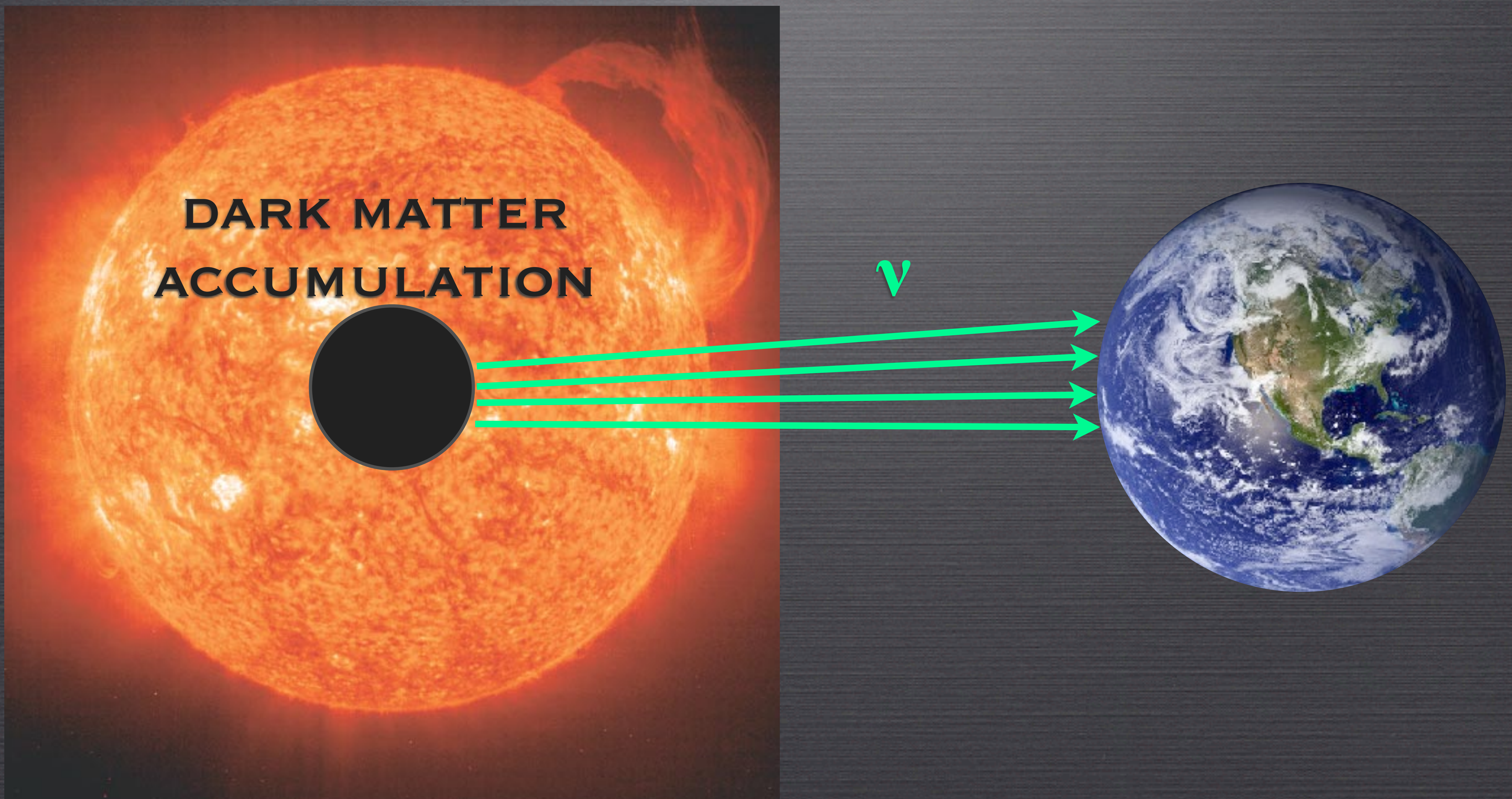
Annihilation Products

Annihilation Products

Accumulation of Dark Matter in the Sun

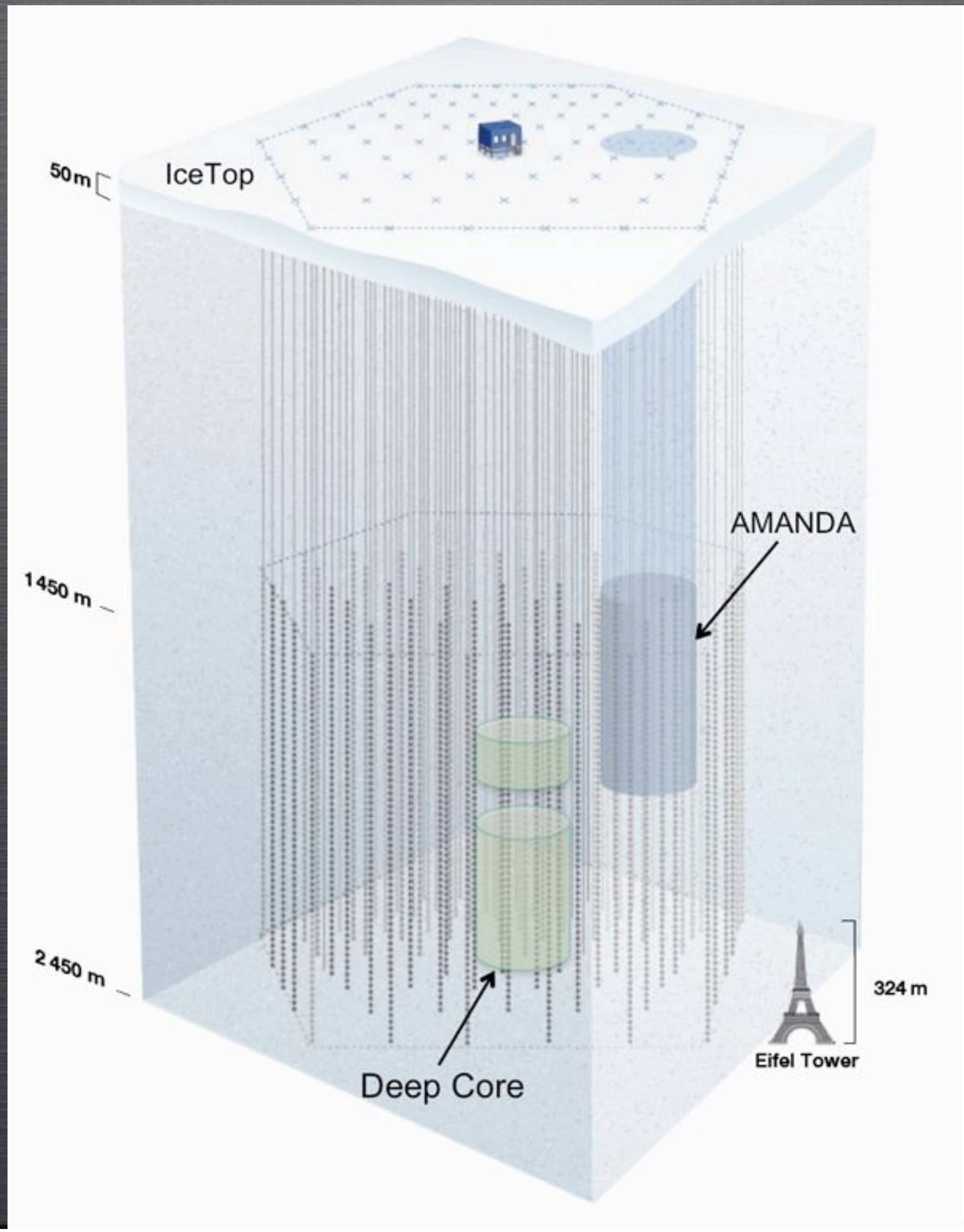


Accumulation of Dark Matter in the Sun



Ice Cube Neutrino Detector

Ice Cube Neutrino Detector



Ice Cube Neutrino Detector

Status Report

- To Date, there are no unambiguous detections of signal attributable to dark matter; however, ...
- We are just achieving the technologies that should be capable of seeing WIMP candidate particles
- The WIMP hypothesis could well be excluded or confirmed within the next decade.
- If dark matter is not a WIMP (an axion, say), the search could continue for quite some time