

TODAY

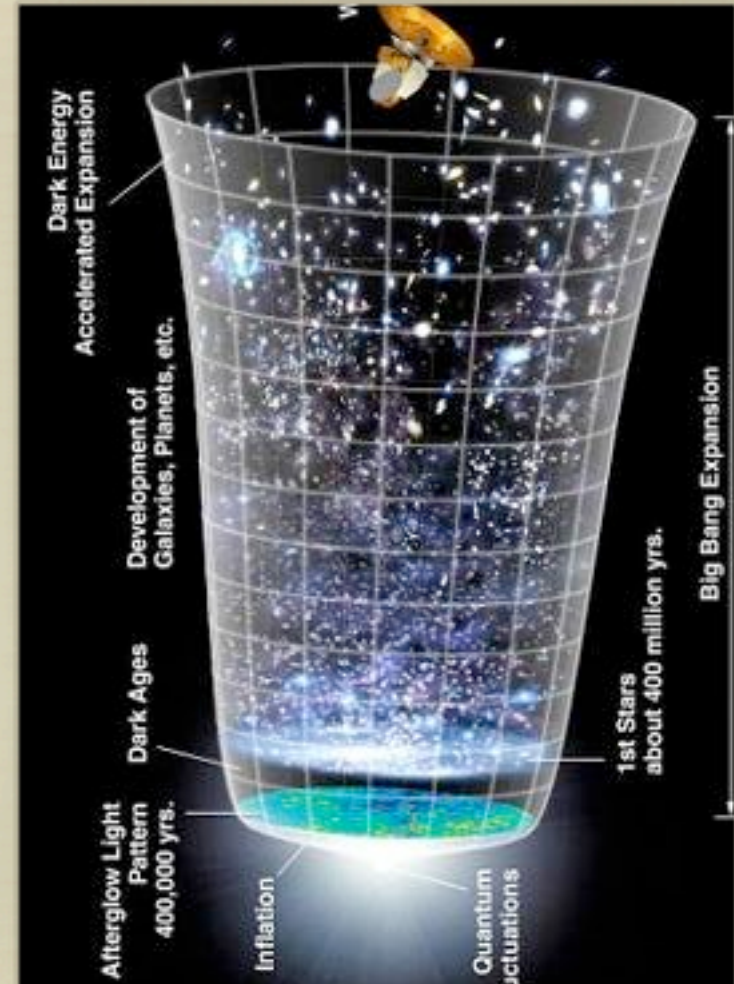
■ MODERN COSMOLOGY

- BIG BANG
NUCLEOSYNTHESIS
- DARK MATTER
- DARK ENERGY

LAST HOMEWORK
DUE NEXT TIME
FINAL EXAM:

8:00 AM TUE DEC. 14

COURSE EVALUATIONS OPEN

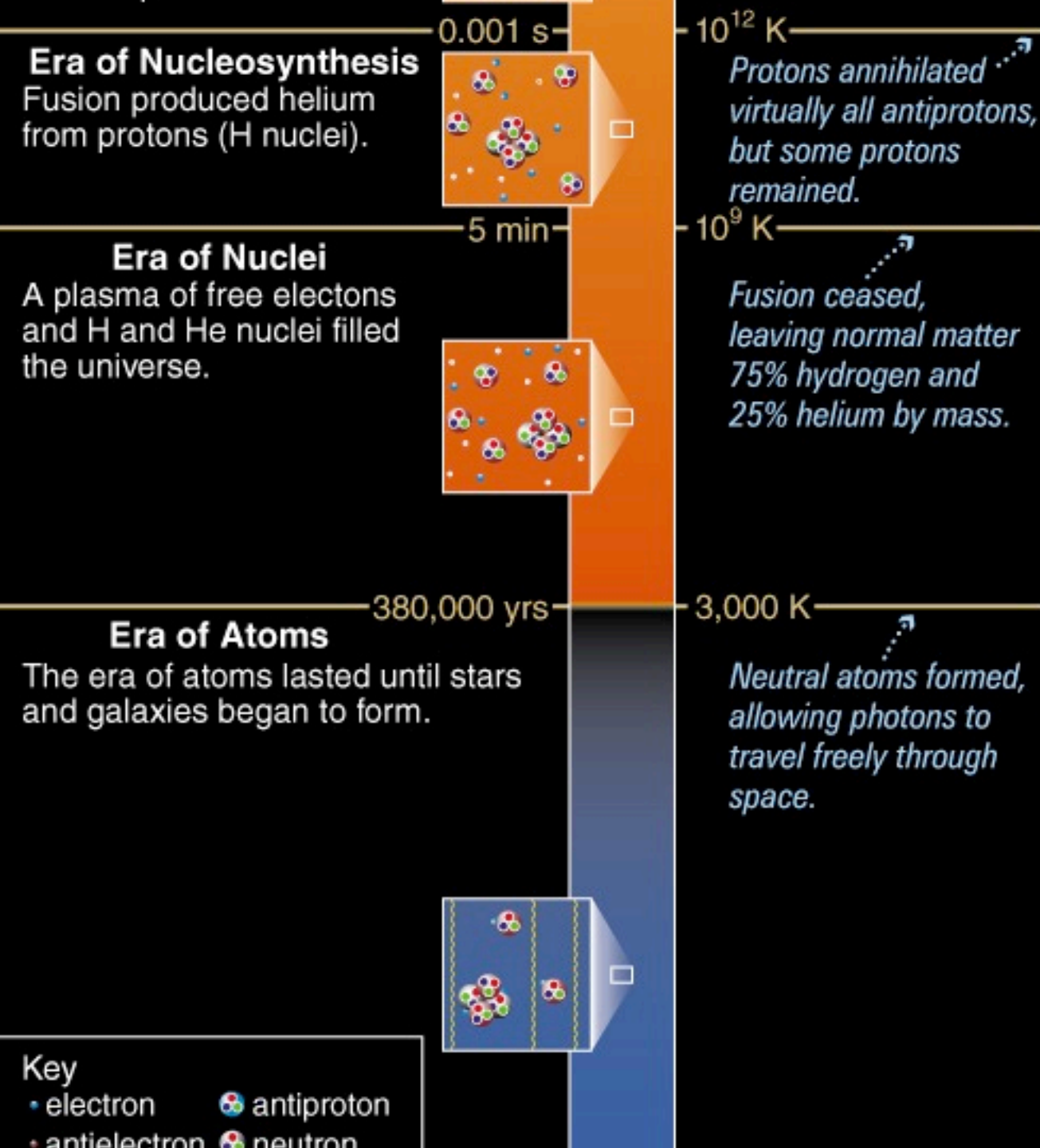


Elements of Modern Cosmology

1. Expanding Universe ✓
2. Finite Age ✓
3. Density & Geometry ✓
4. Thermal History ✓
5. Big Bang Nucleosynthesis ✓
6. Dark Matter ?
7. Dark Energy ?

5. Big Bang Nucleosynthesis

- When the universe was just a few minutes old, the density and temperature were like the core of a star. The whole universe was one big fusion reactor.
- This event, known as **Big Bang Nucleosynthesis**, made the 3/4 Hydrogen and 1/4 Helium mix seen in all stars.
- A small amount of other light elements (like Lithium) were also made at this time.



nucleosynthesis

~ 3 minutes

$T \sim 10^{10}$ K

recombination

~300,000 year

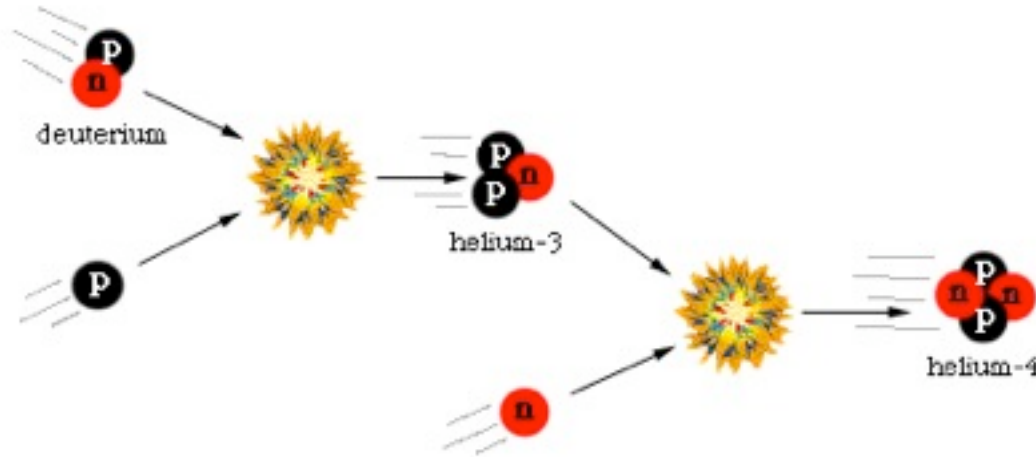
$T \sim 3000$ K

Primordial Nucleosynthesis:

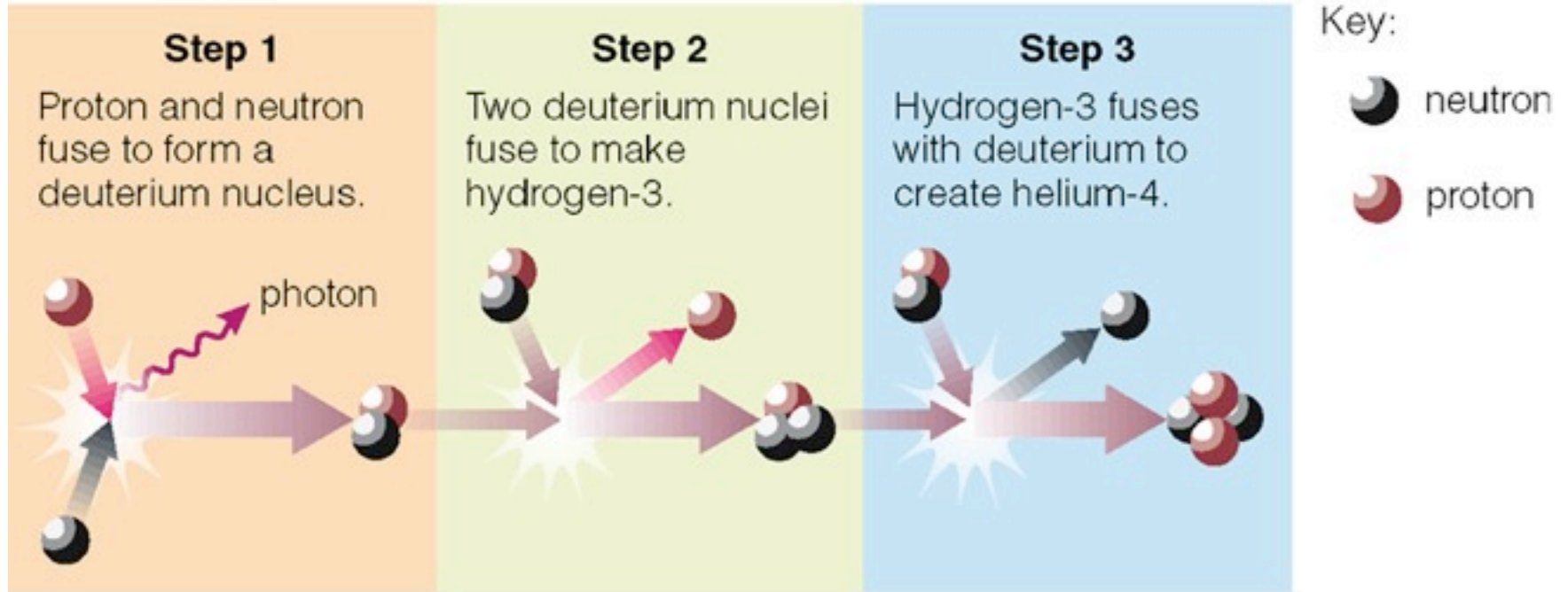


Gamow

When the universe is just a few minutes old, the Temperature and Density are just right for it to be one Big Nuclear Furnace:

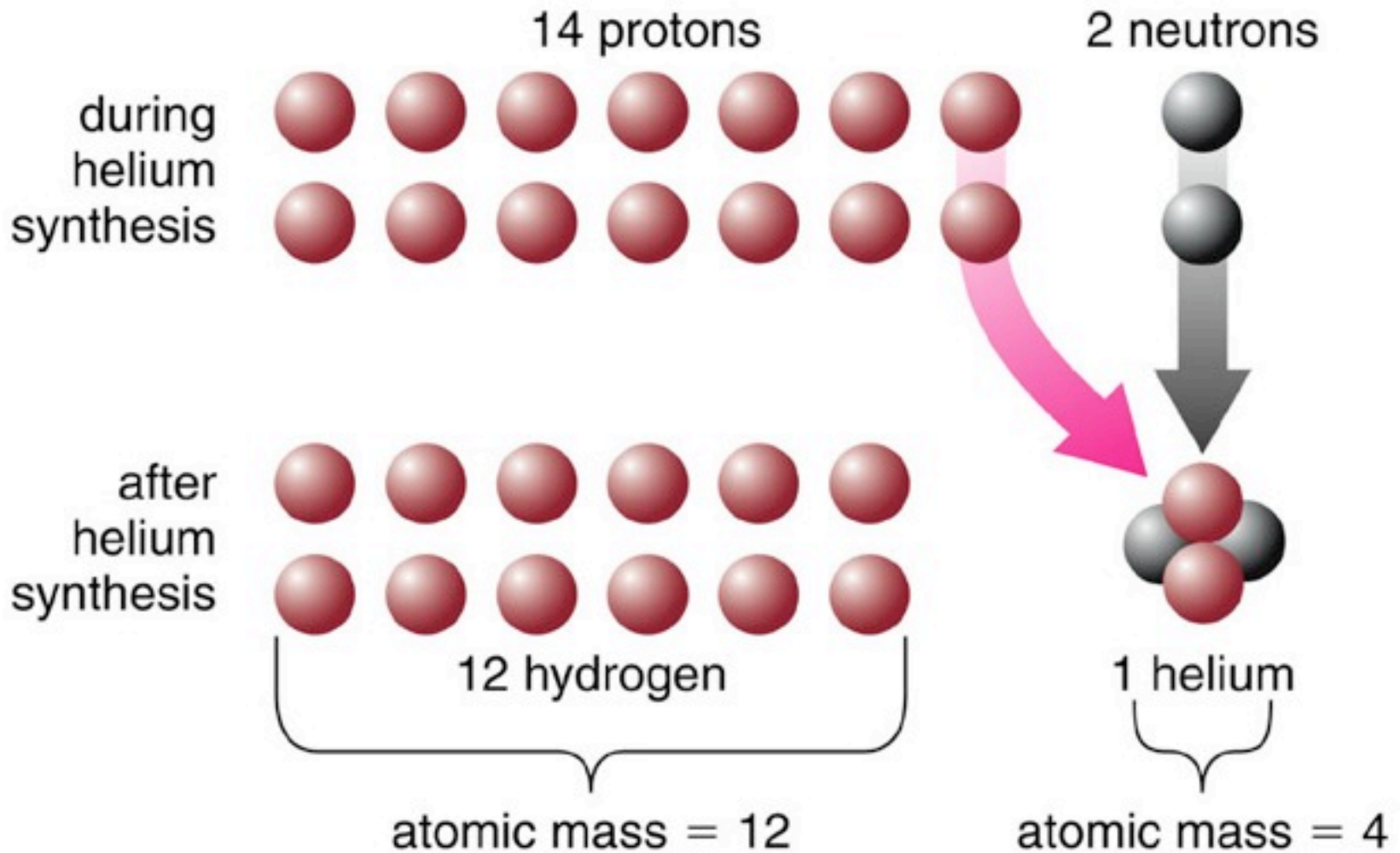


The light elements
Hydrogen, Helium, and Lithium
are made at this time.



Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~3 minutes old.

The proton-proton chain was enhanced by the presence of free neutrons, making the creation of deuterium easier.



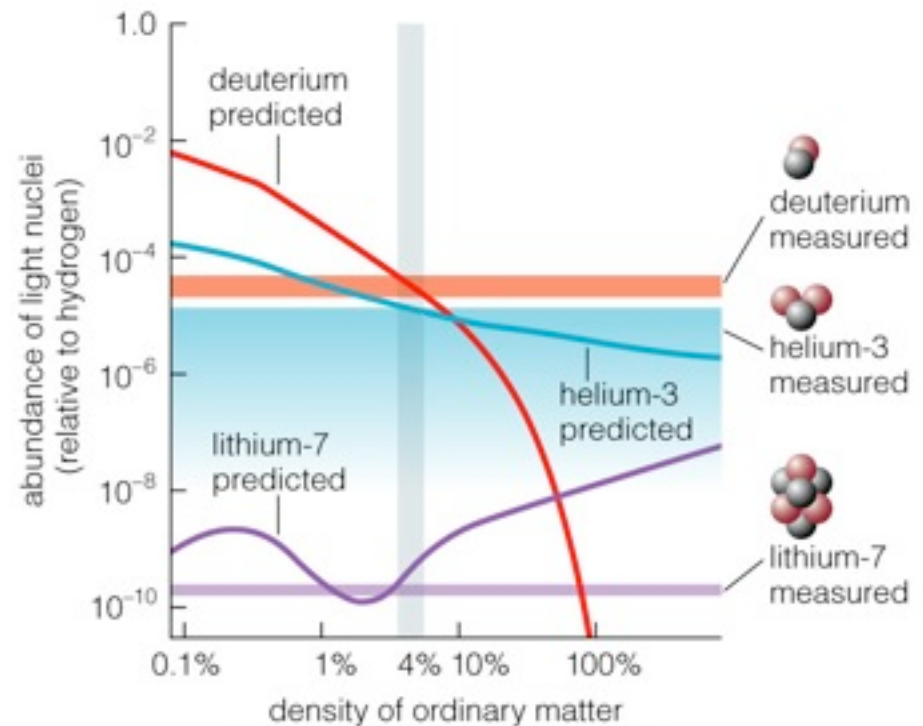
Big Bang theory prediction: 75% H, 25% He (by mass)

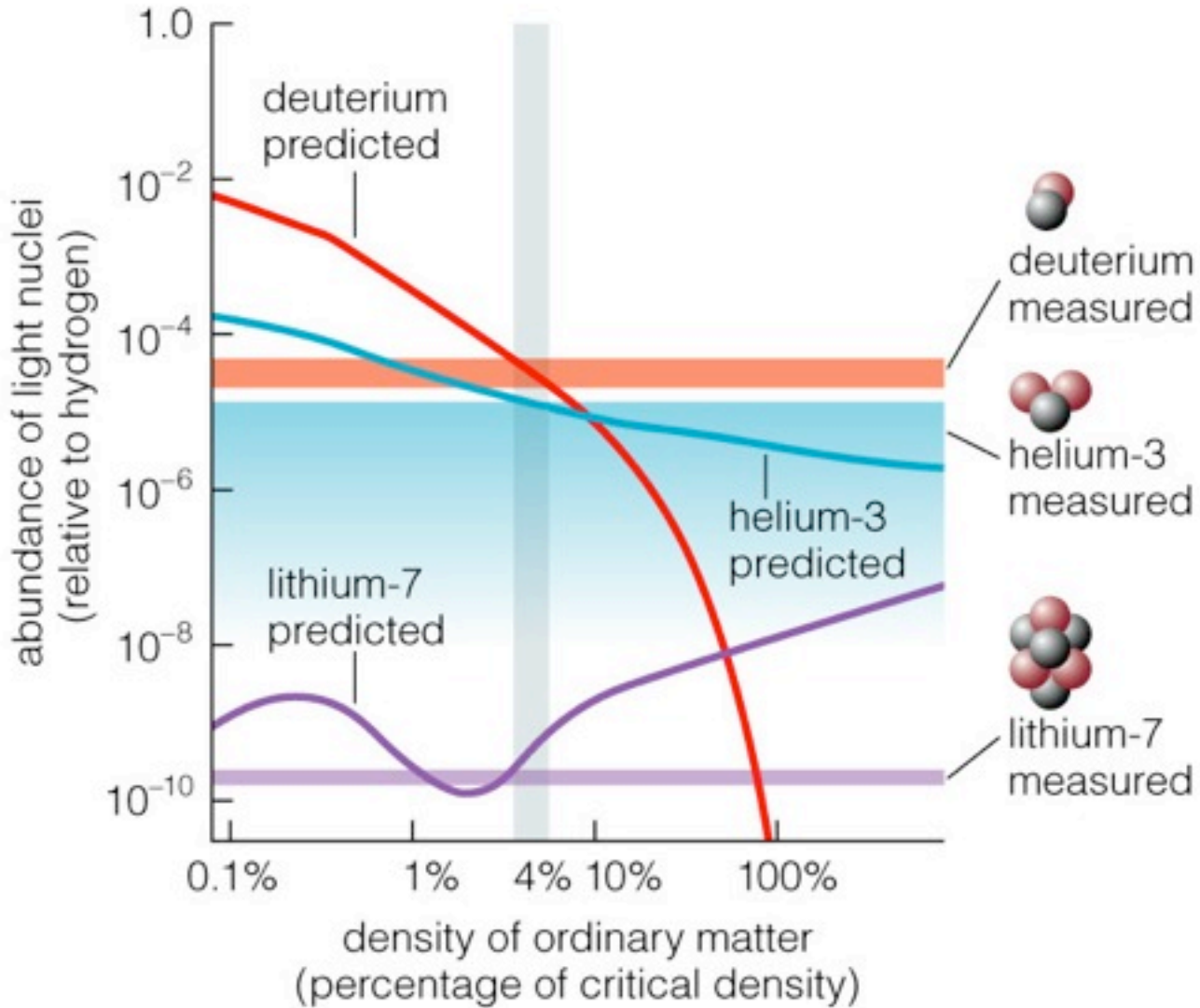
Matches observations of nearly primordial gases

BBN products:

- 3/4 Hydrogen
- 1/4 Helium
- Traces of
 - deuterium
 - tritium
 - helium 3
 - lithium
 - beryllium

Abundances depend on the density of matter. The higher the density parameter (Ω), the more helium.





$$\Omega$$

BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

Made in Early Universe

Made in Stars

Made in Supernovae

Made in the laboratory

1 H Hydrogen	2 He Helium																
3 Li Lithium	4 Be Beryllium	5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon										
11 Na Sodium	12 Mg Magnesium	13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon										
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111	112	113	114	115	116	117	118
57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium				
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium				

Big Bang Nucleosynthesis

- Explains bulk composition of the Universe
 - 3/4 hydrogen, 1/4 helium by mass
- Matches multiple independent abundance observations
 - over-constrained by abundances of
 - deuterium, helium, lithium
- Constrains the density to $\Omega = 0.04$

6. Dark Matter

- We can estimate the density parameter via gravity. How much gravitating mass is out there?

$$\Omega = 0.2 \text{ to } 0.3$$

- That's a lot more than allowed by big bang nucleosynthesis:

$$\Omega = 0.04$$

- There is more mass than meets the eye!

Evidence for dark matter

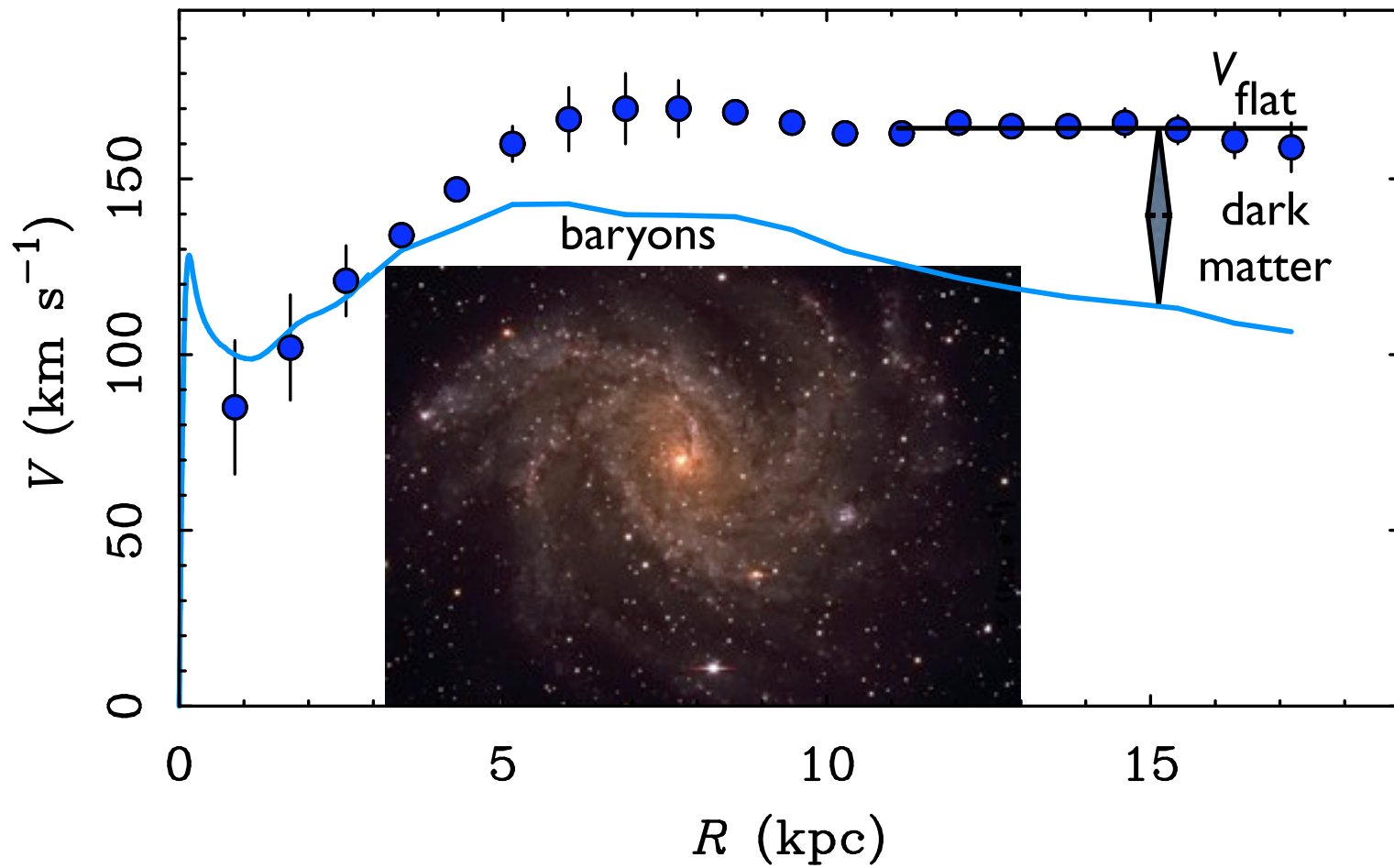
- Many systems exhibit mass discrepancies:

- Spiral galaxies
- Dwarf Galaxies
- Clusters of Galaxies
 - dynamics
 - gas temperature
 - gravitational lensing

Applying Newton's Law of Universal Gravitation to observed galaxy systems does not work.

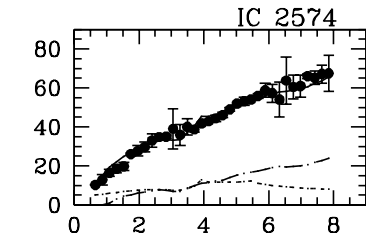
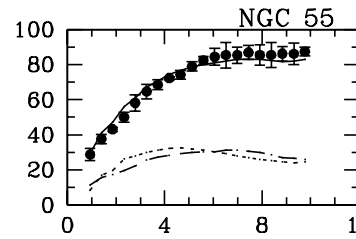
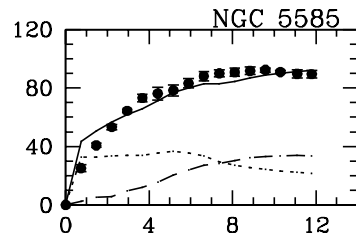
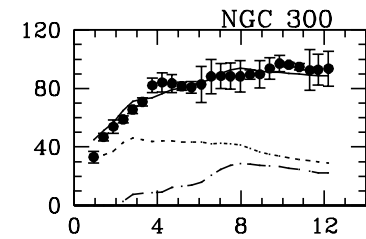
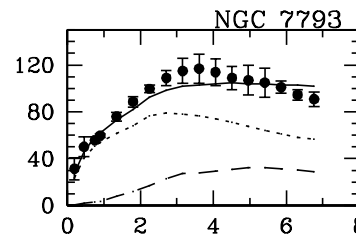
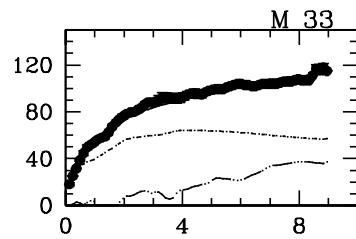
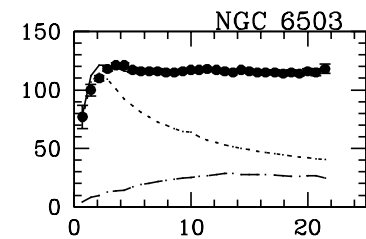
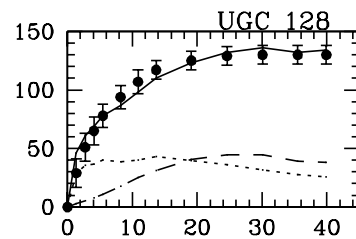
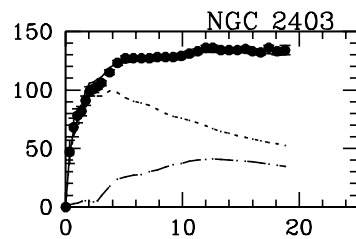
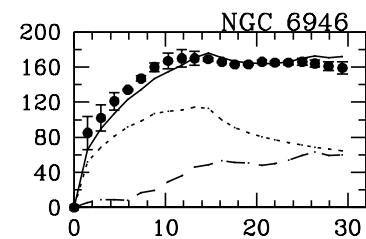
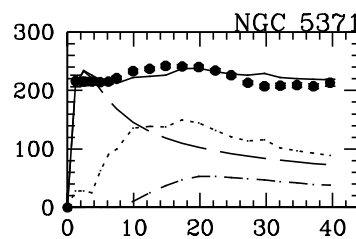
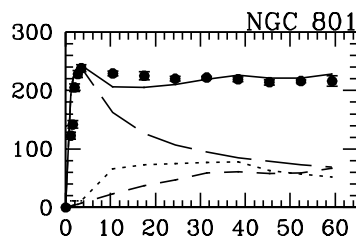
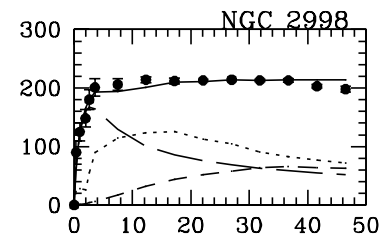
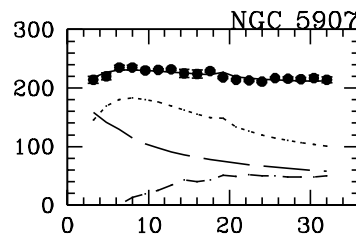
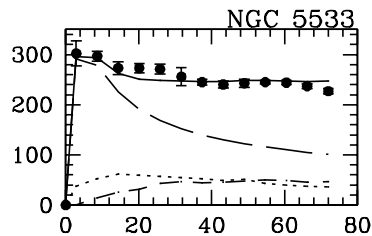
$$V^2 = \frac{GM}{R}$$

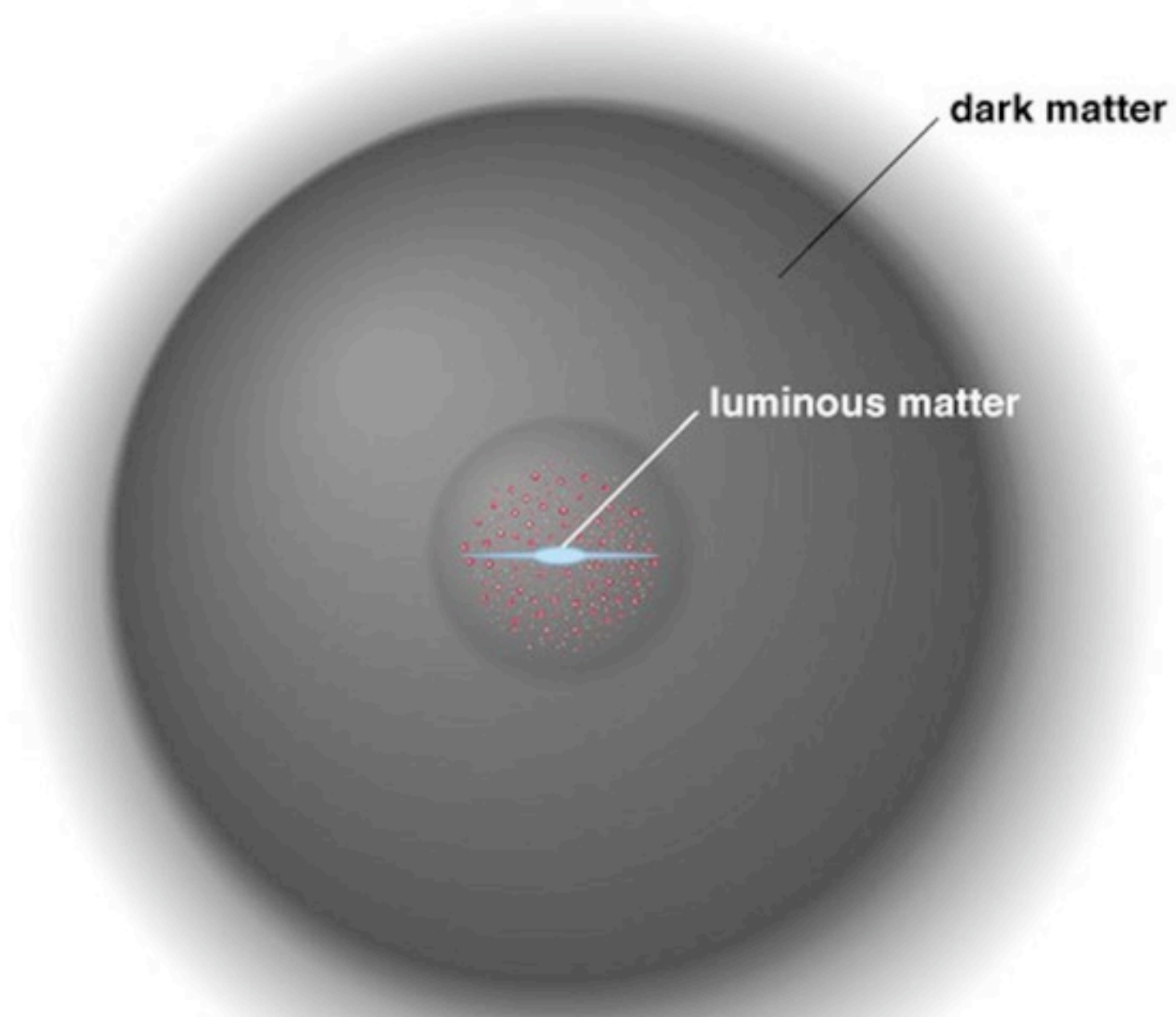
NGC 6946



The rotation curves of spiral galaxies are flat when they should be declining.

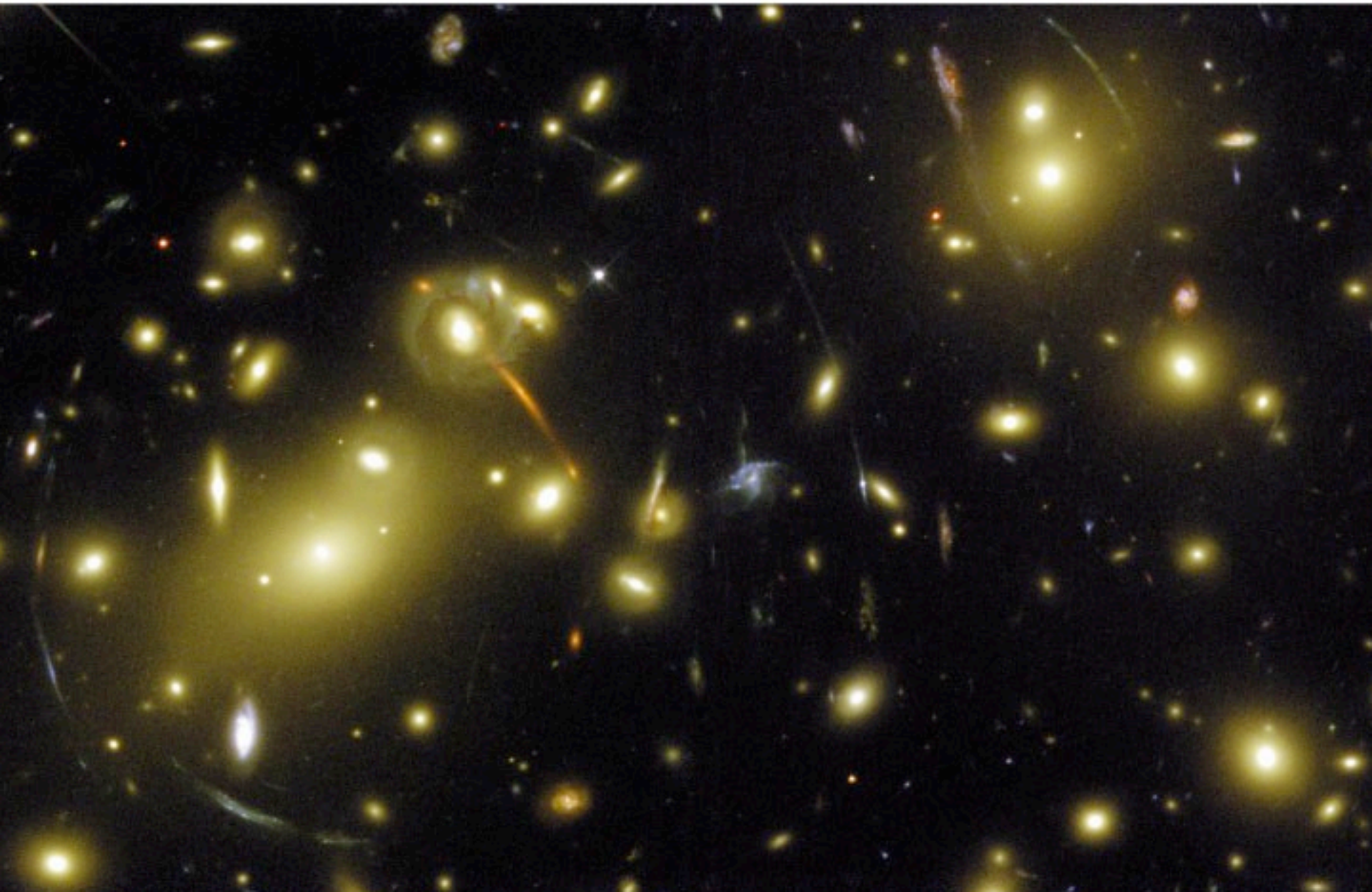
$$V^2 = \frac{GM}{R}$$

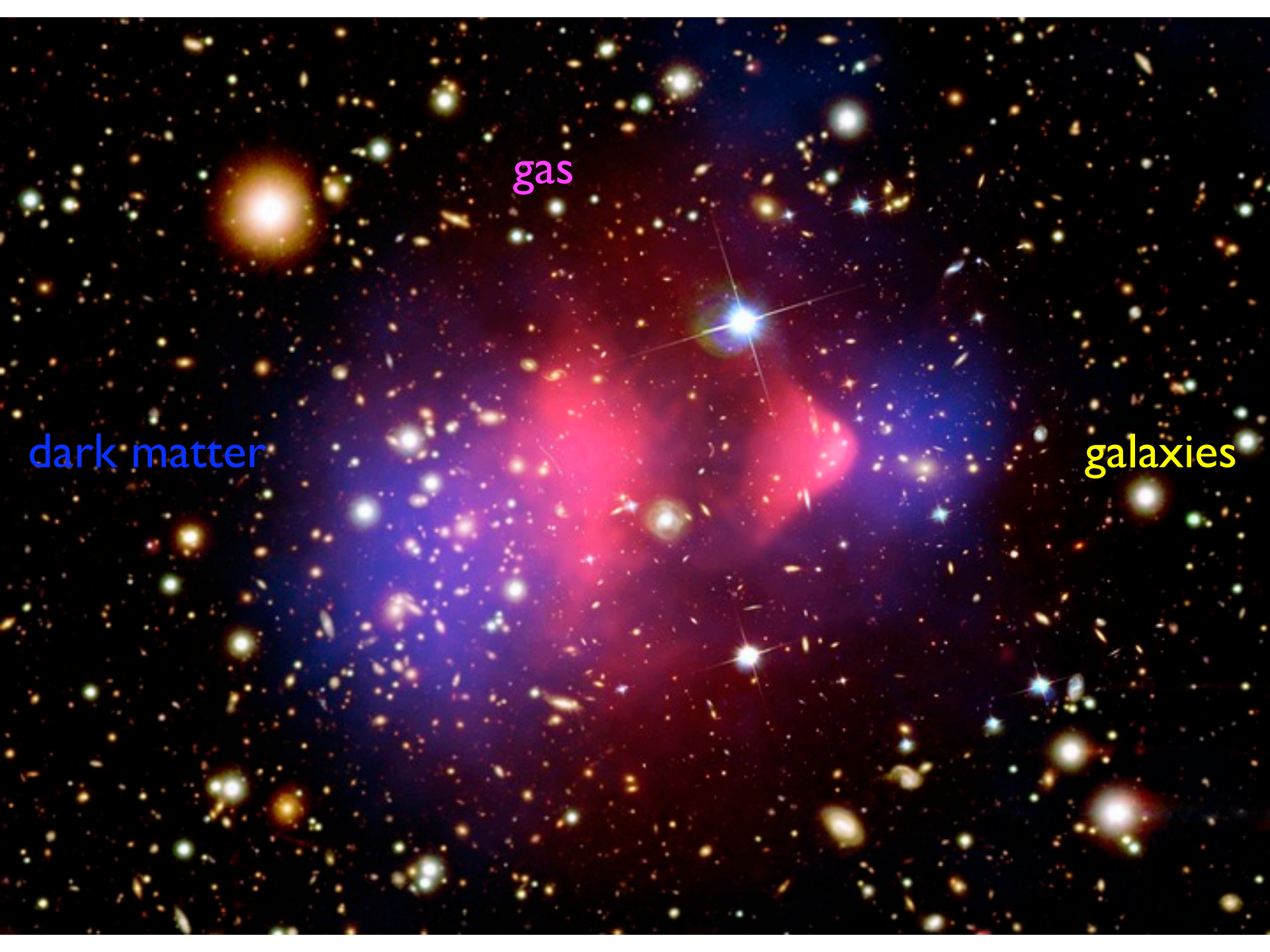




Galaxies seem to be embedded in larger dark matter halos

Also need dark matter in clusters of galaxies:





dark matter

gas

galaxies

What is the Dark Matter?

Baryonic Dark Matter

Normal things:

very faint stars, brown dwarfs

other hard-to-see objects (planets, gas)

Hot Dark Matter

neutrinos - got mass, but not enough

Cold Dark Matter

Some new fundamental particle

doesn't interact with light, so quite invisible.

Two big motivations:

- 1) total mass outweighs normal mass from BBN
- 2) needed to grow cosmic structure

(I)

Normal baryonic mass = 4% of total
from Primordial Nucleosynthesis

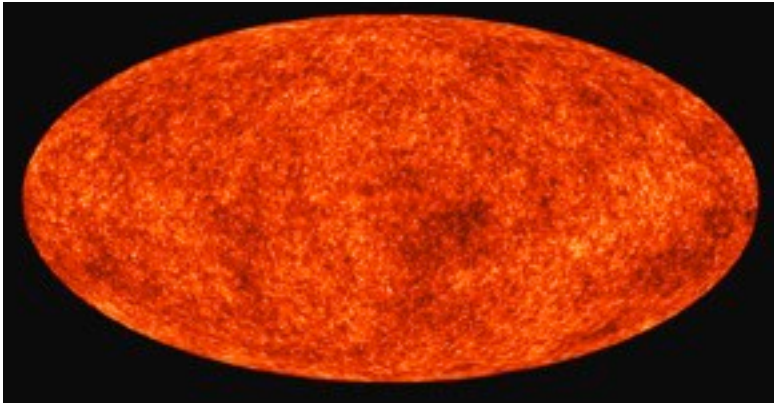
Total mass density = 27% of total
from gravity

gravitating mass \gg normal mass

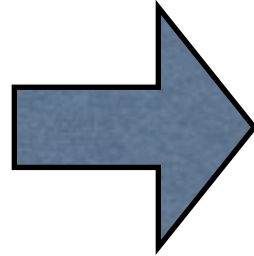
Most of the mass needs to be
in some brand new form!

(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5 \text{ yr}$



very smooth: $\delta\rho/\rho \sim 10^{-5}$



$t = 1.4 \times 10^{10} \text{ yr}$



very lumpy: $\delta\rho/\rho \sim 1$

$$\delta\rho/\rho \propto t^{2/3}$$

Time in billions of years

0.5

2.2

5.9

8.6

13.7

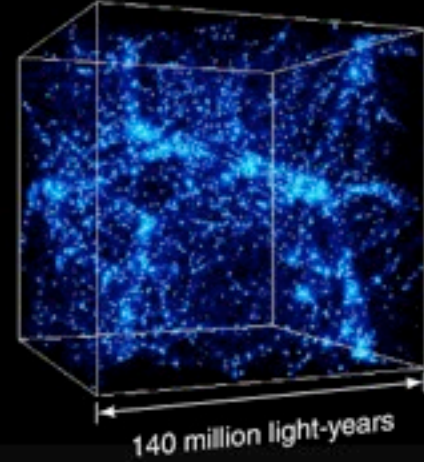
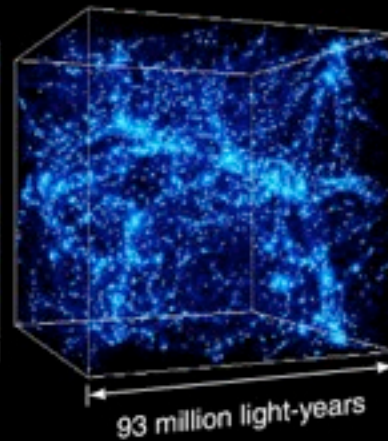
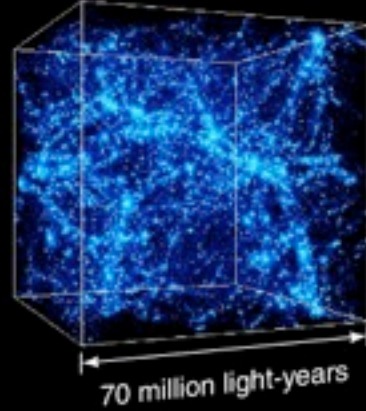
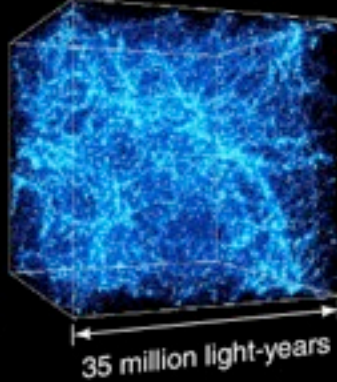
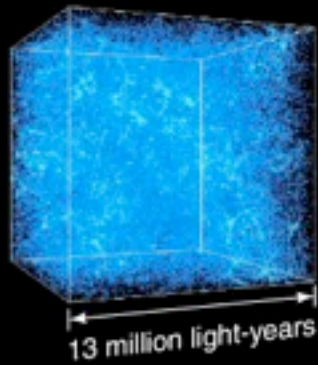
0.5 billion years

2.2 billion years

5.9 billion years

8.6 billion years

13.7 billion years



13

35

70

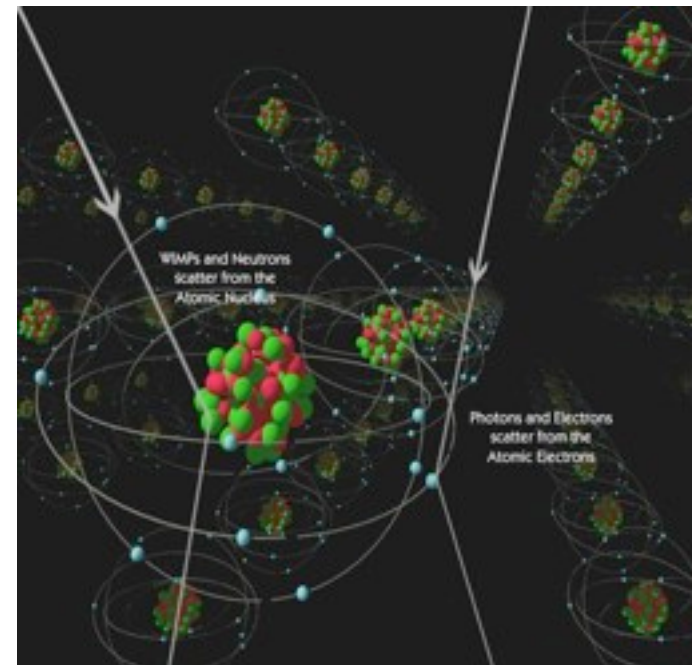
93

140

Size of expanding box in millions of light-years

The gravity of dark matter pulls mass into denser regions — universe grows lumpier with time.

Particle physicists' best guess is that the **Cold Dark Matter** needed in astronomy is a new form of fundamental particle called the **WIMP** (Weakly Interacting Massive Particle). There are ambitious projects to detect WIMPS as they pass by the earth.



7. Dark Energy

- Does some mysterious something act like anti-gravity?

The Expanding Universe

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} = 8\pi GT_{\mu\nu}$$

A homogenous, isotropic universe evolving according to Einstein's field equation must either expand or contract. It can not be static.

Philosophically, Einstein assumed something like the Perfect Cosmological Principle. The Universe had to have been around forever. Didn't it?

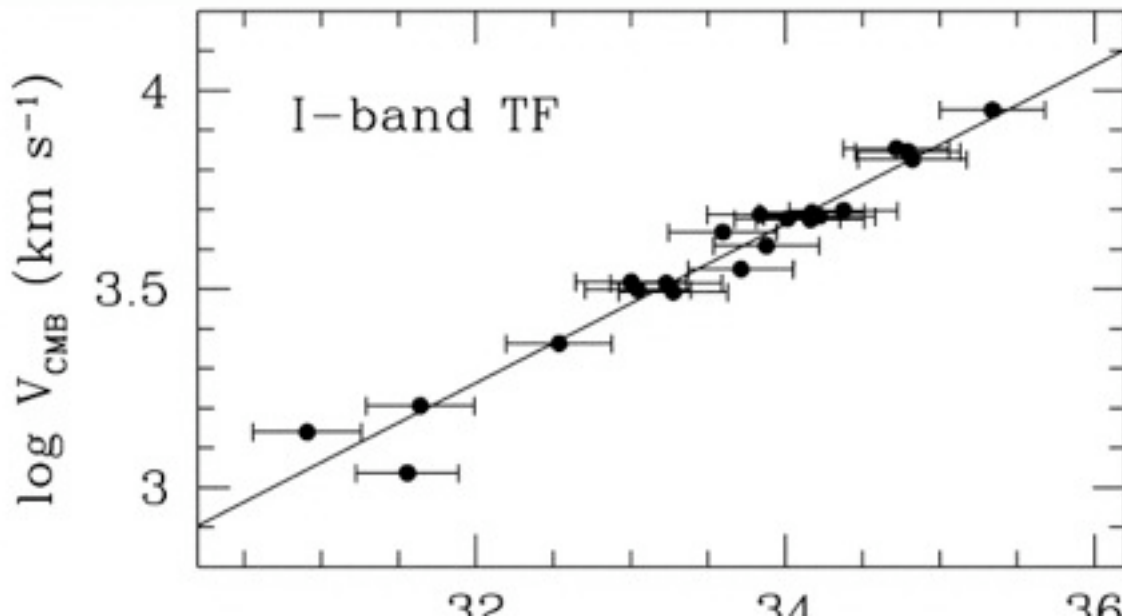


Dark Energy

Einstein's greatest blunder?

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} = 8\pi GT_{\mu\nu} + \Lambda g_{\mu\nu}$$

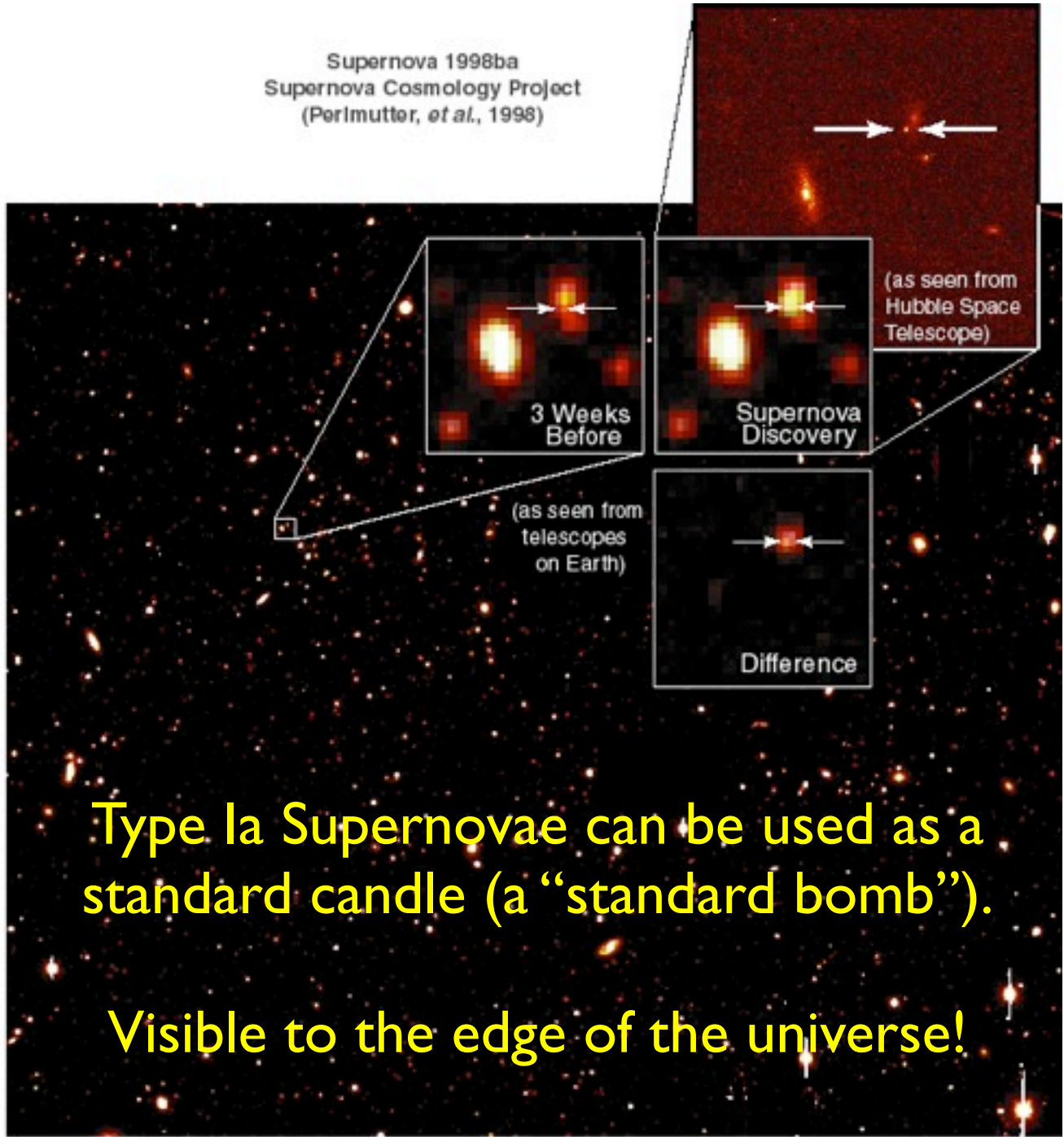
Einstein's intention was to keep the universe static. But it does expand!



Type Ia Supernovae can be used as a standard candle (a “standard bomb”).

Visible to the edge of the universe!

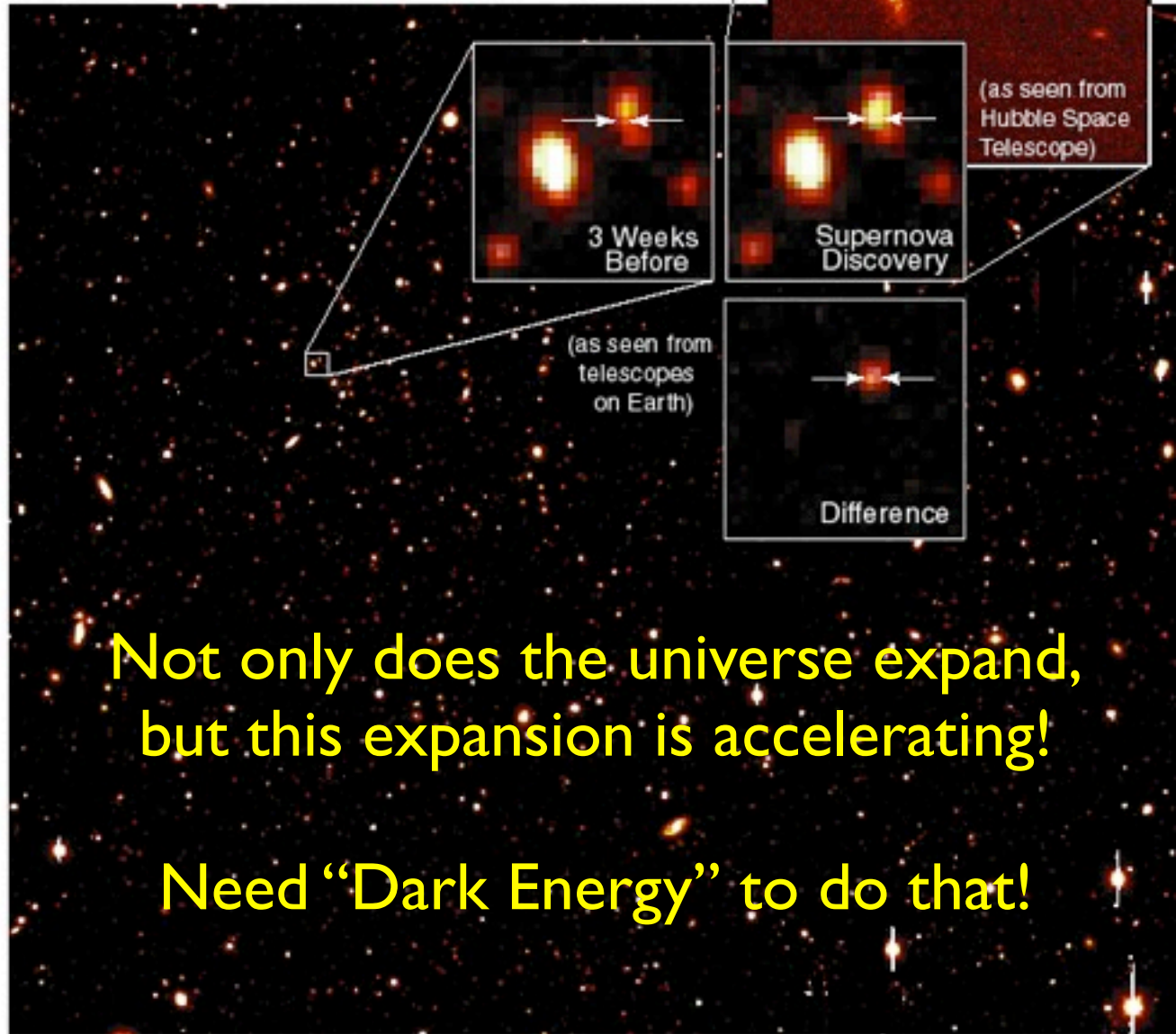
Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

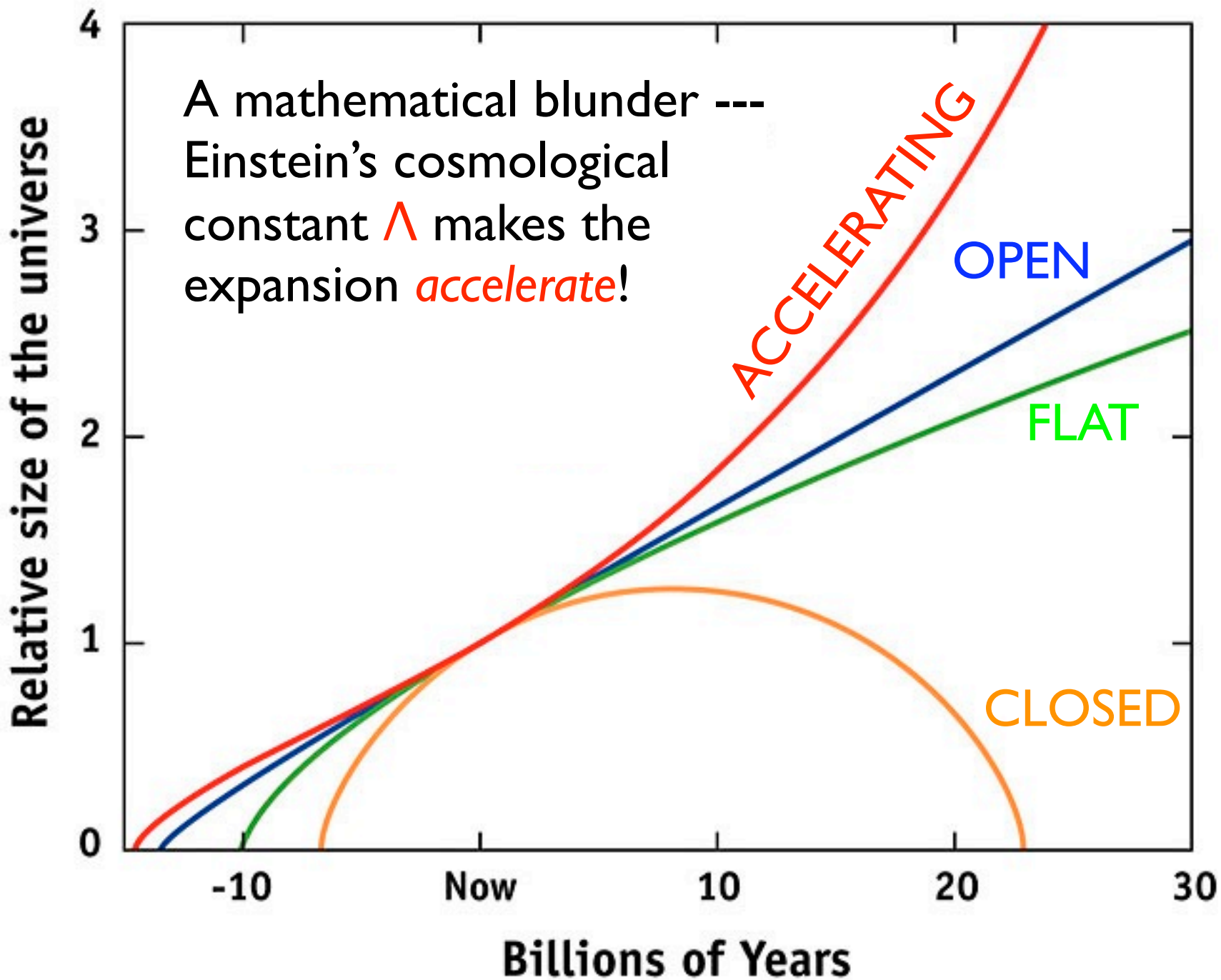


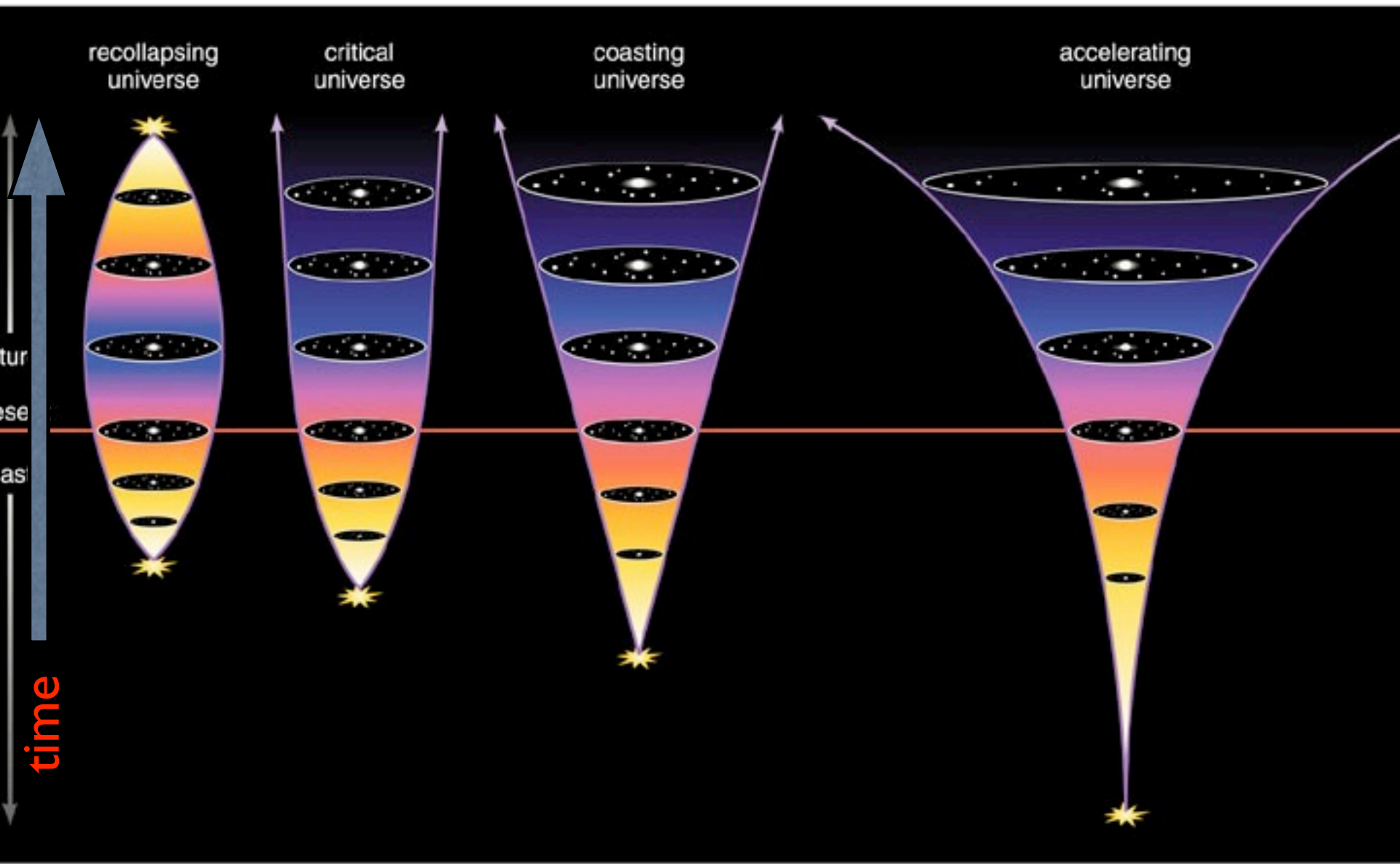
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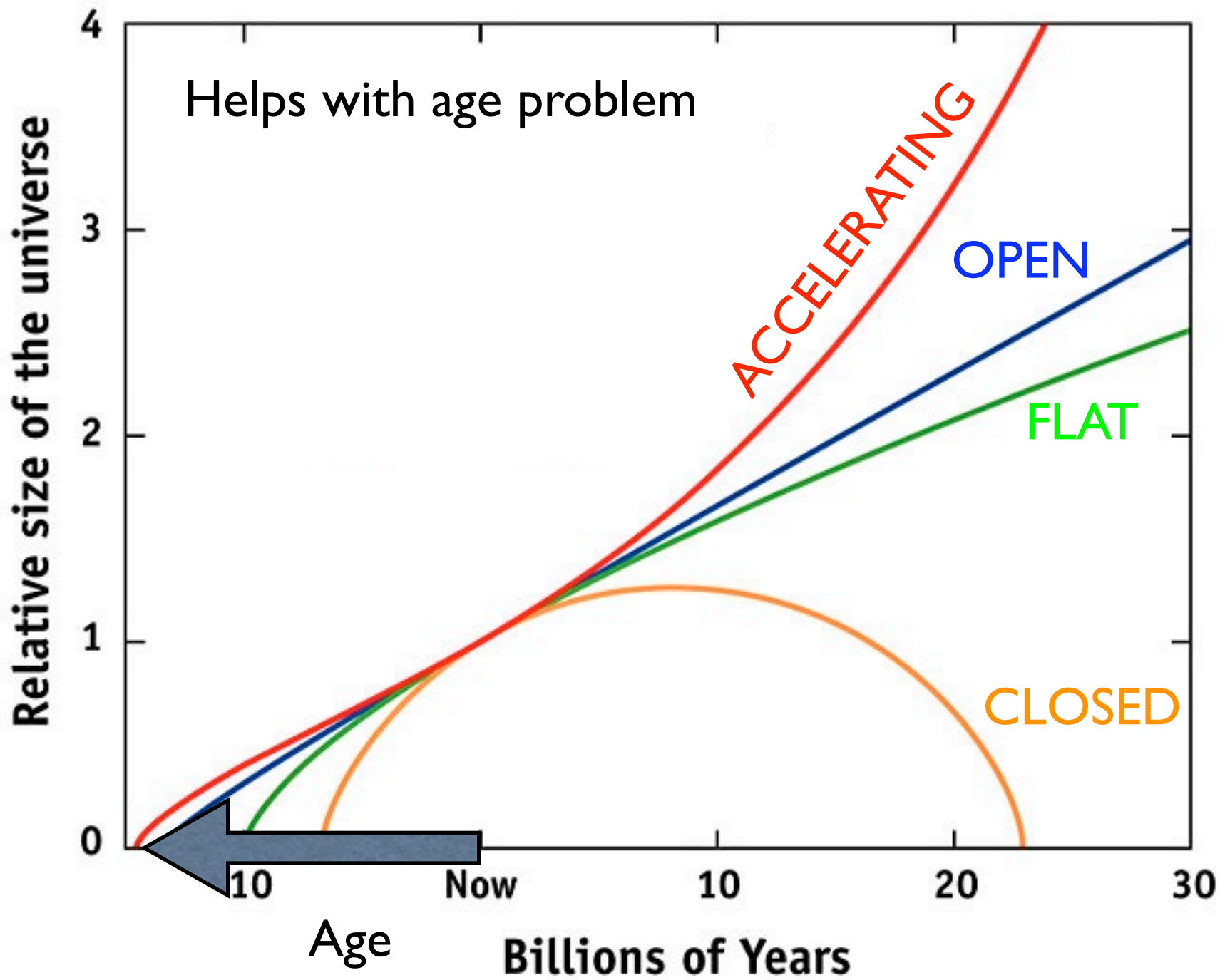
recollapsing universe

critical universe

coasting universe

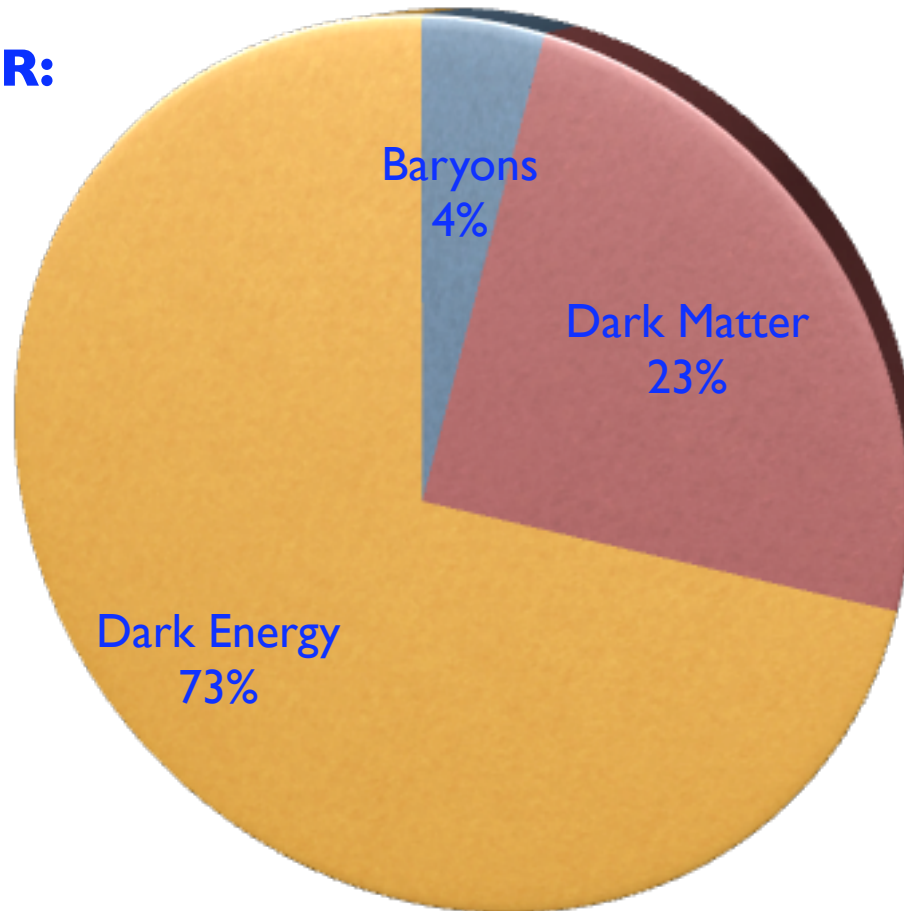
accelerating universe

time



Contents of the Universe

THE ANSWER:



Hot Big Bang
+
Dark Energy
+
Dark Matter
is now called

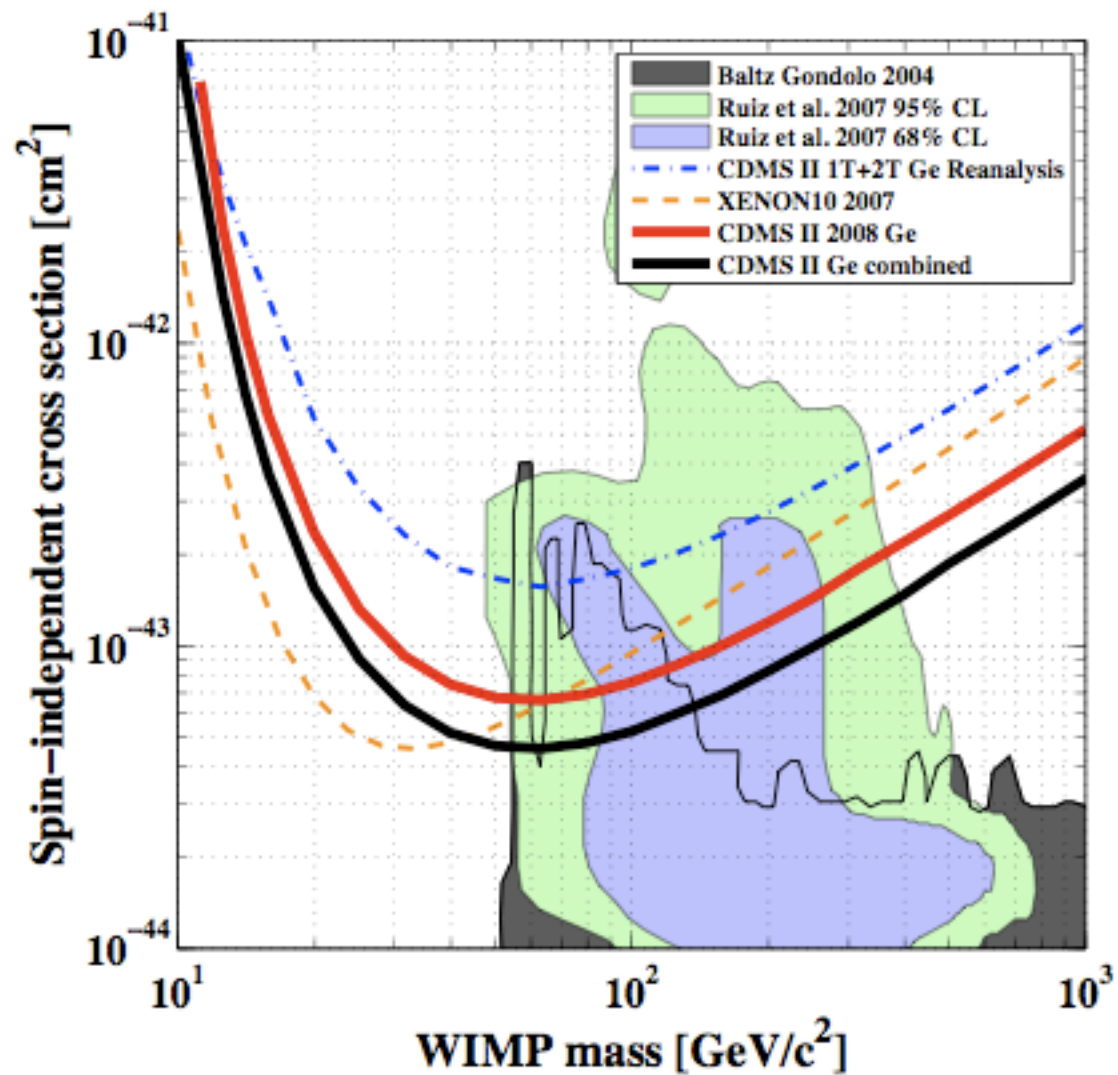
“ Λ CDM”

Elements of Modern Cosmology

- | | | |
|-----------------------------|---|----------------------|
| 1. Expanding Universe | ✓ | |
| 2. Finite Age | ✓ | Hubble's Law |
| 3. Density & Geometry | ✓ | |
| 4. Thermal History | ✓ | Microwave Background |
| 5. Big Bang Nucleosynthesis | ✓ | Light Elements |
| 6. Dark Matter | ? | Really there? |
| 7. Dark Energy | ? | |

Works well. But only holds true if dark matter and dark energy really exist.

What if we don't find WIMPs?



Dark Matter or Gravity?

Competing hypothesis called MOND
(for Modified Newtonian Dynamics)

