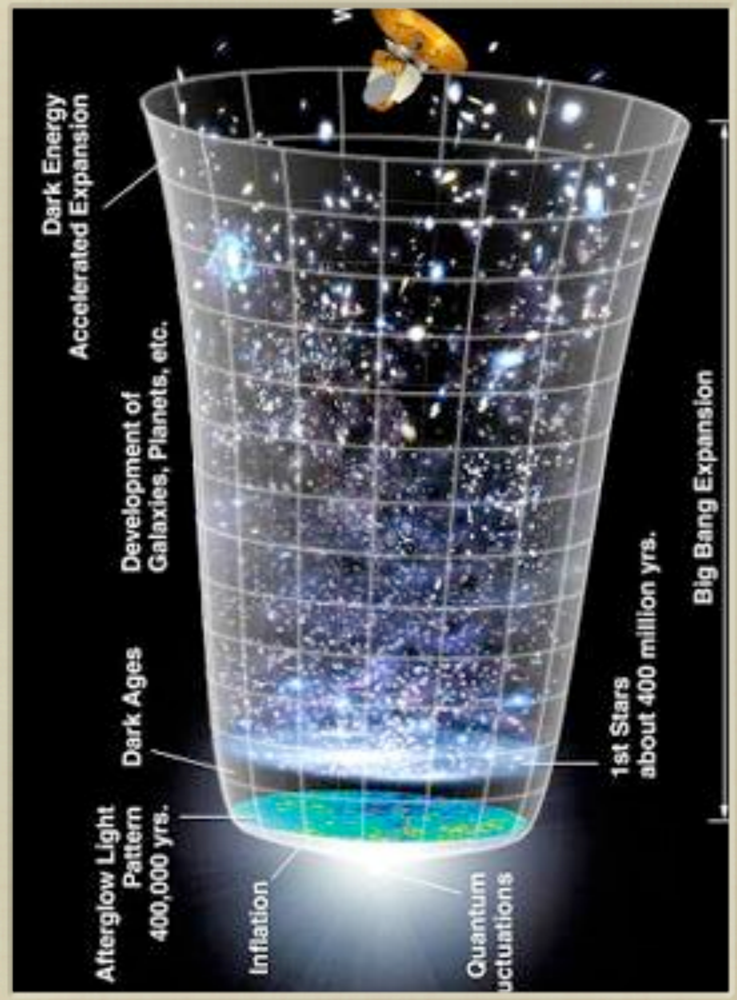
Today

- Modern Cosmology
  - Big Bang Nucleosynthesis
  - Dark Matter
  - Dark Energy



Last homework
Due next time
FINAL EXAM:
8:00 AM FRI Dec. 16

Course Evaluations Open

Extra credit
(2 points)

- Relative to the critical density, what does the average density of the universe have to be if the universe is closed (i.e., less, more, or equal to the critical density)?

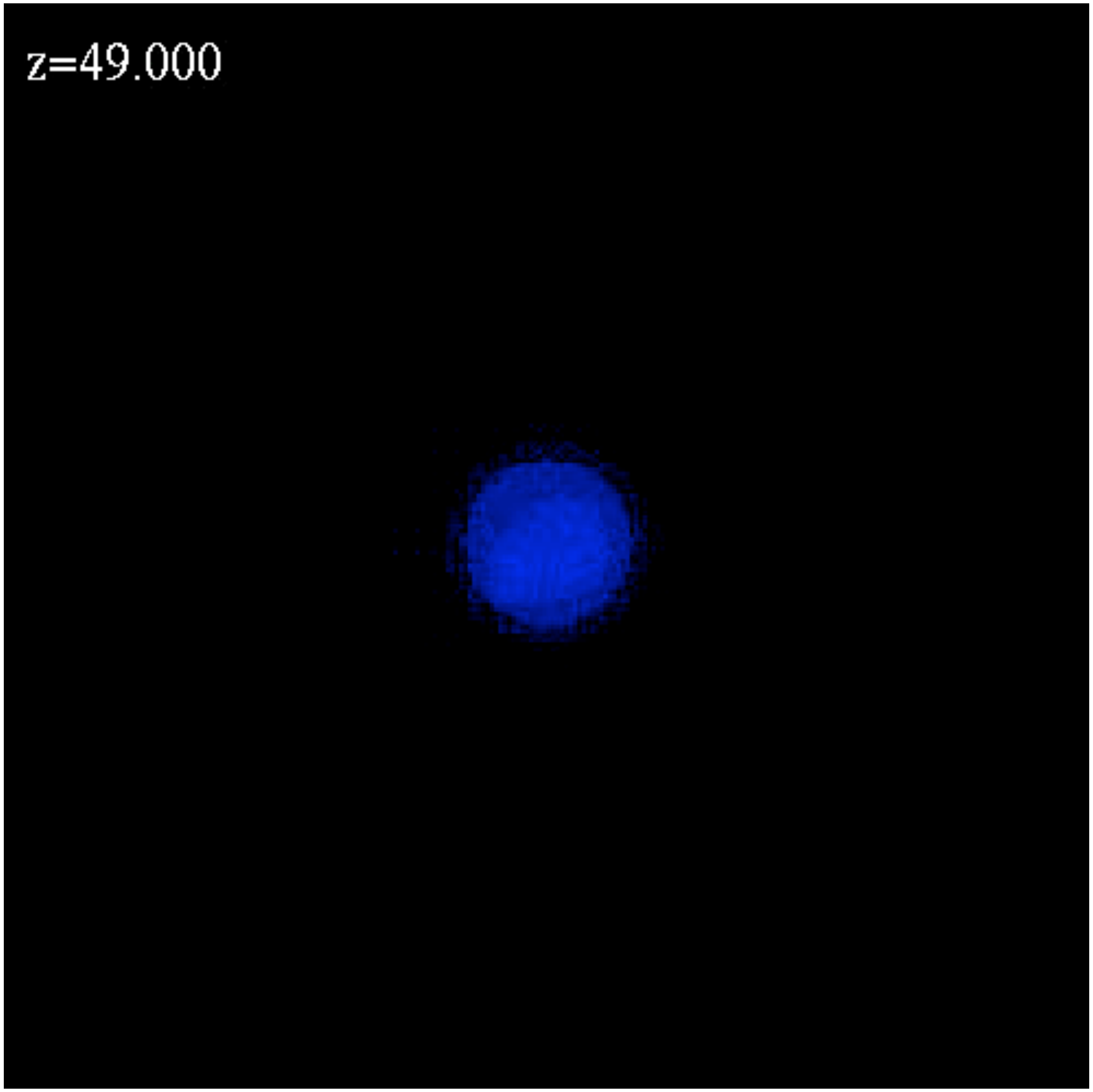
- Be sure to include your name and section number

- You may consult your notes, but do not communicate with anyone else

Reminders about final exam

- This room, 8-10 AM, Friday, Dec 16
- Cumulative: all material in whole class!
  But greater emphasis on stuff since 2nd exam
- Format same as before, but more questions
- Review: 6-8 PM, Tues, Dec 13, PHYS 1410
- For short answer questions, can put critical information in bullet form; full credit if you have the right answers
  Don't need to waste time writing long essay!

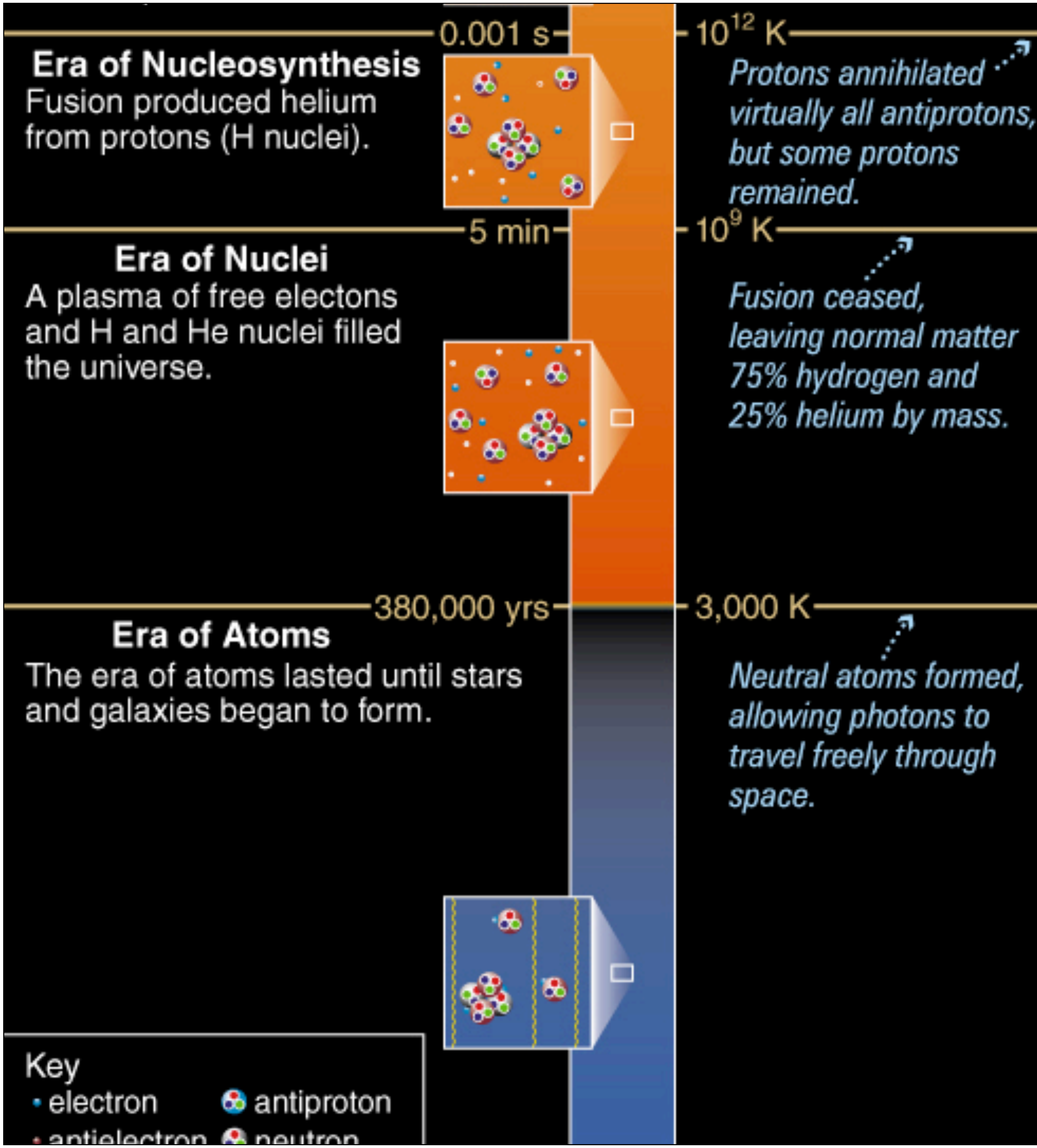
Formation of Structure



Ben Moore "Virgo" simulation

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	?



nucleosynthesis

~ 3 minutes

T ~ 10^{10} K

recombination

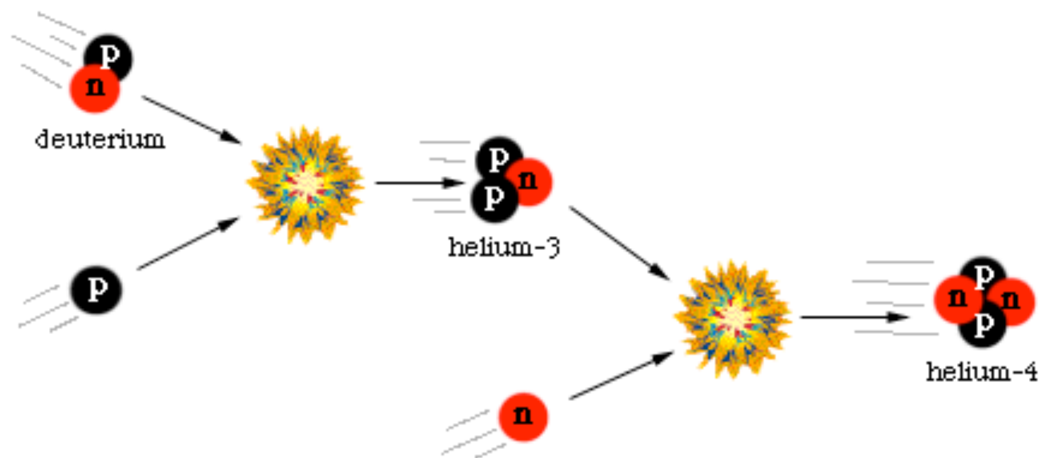
~300,000 year

T ~ 3000 K

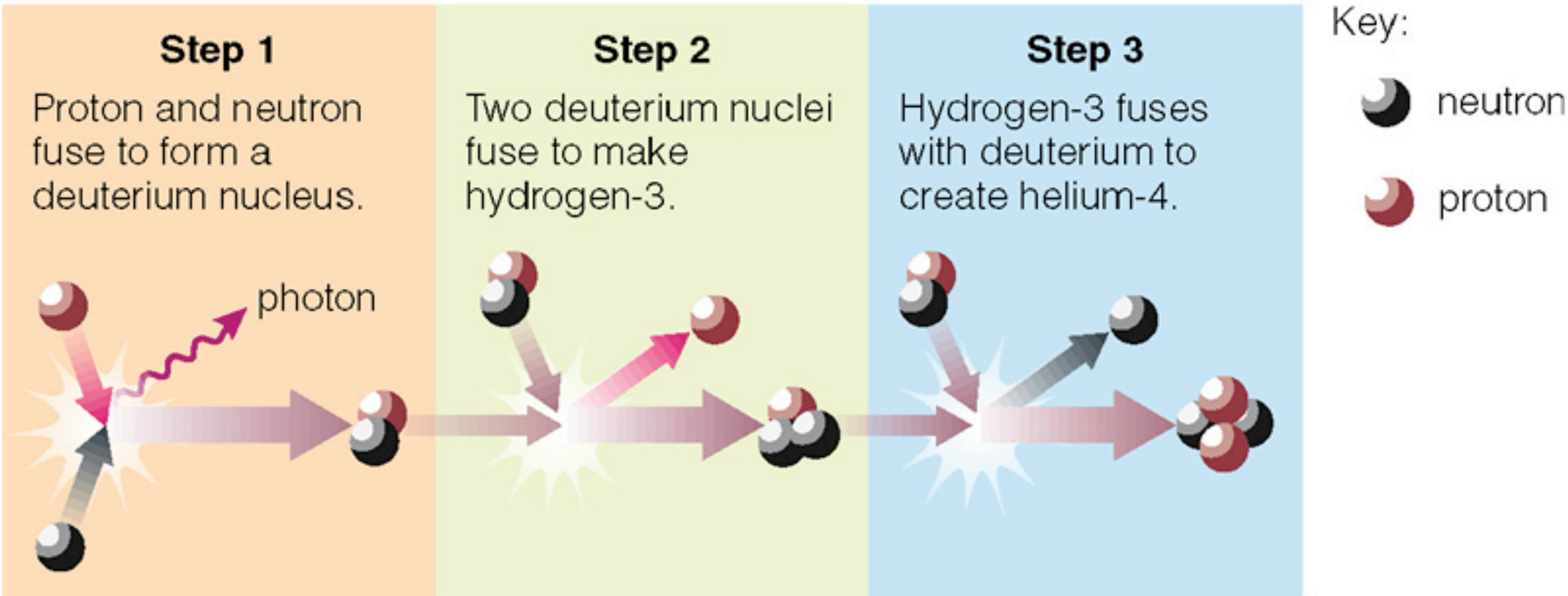
Primordial Nucleosynthesis:

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:

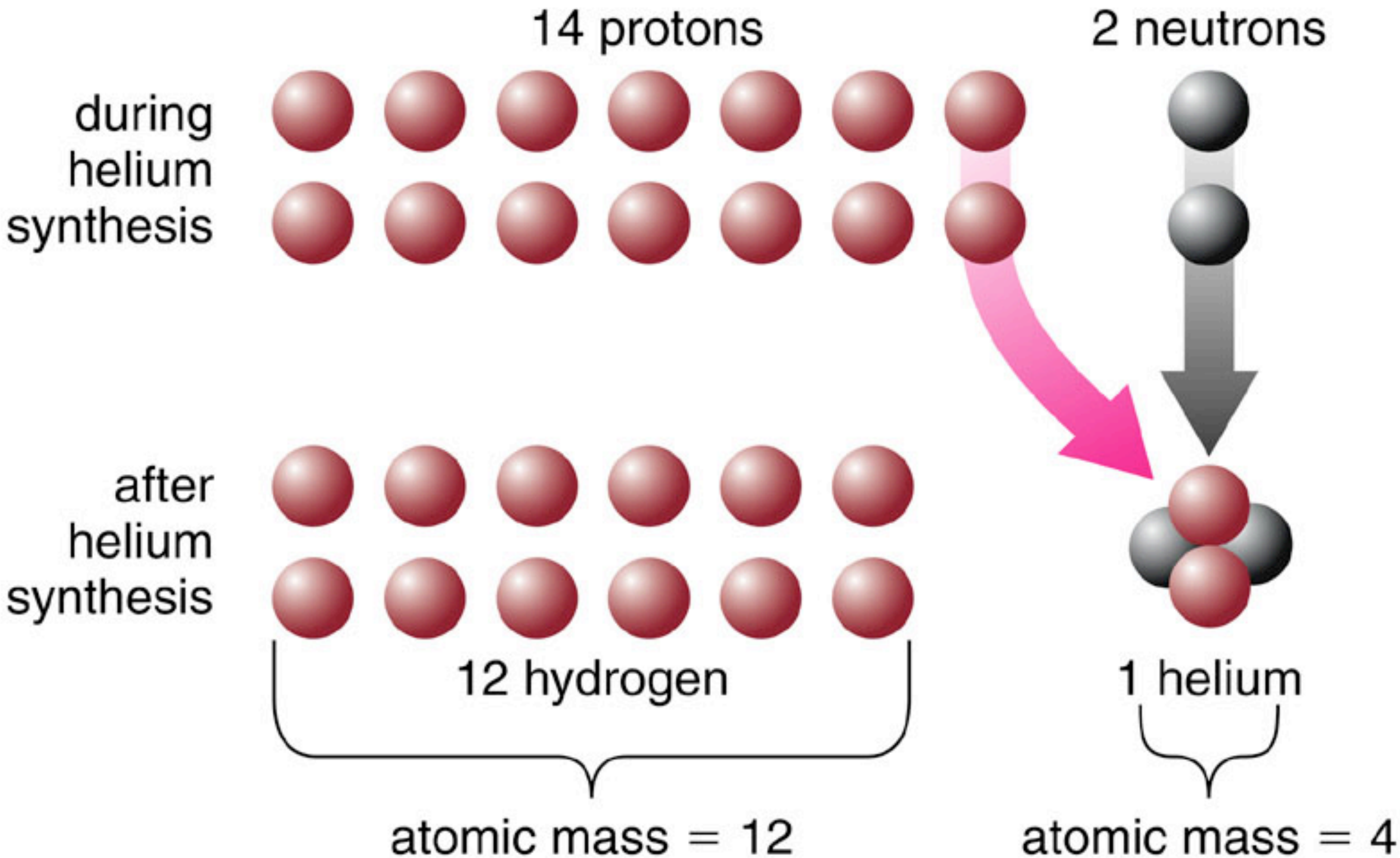


The light elements
Hydrogen, Helium, and Lithium
are made at this time.



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.



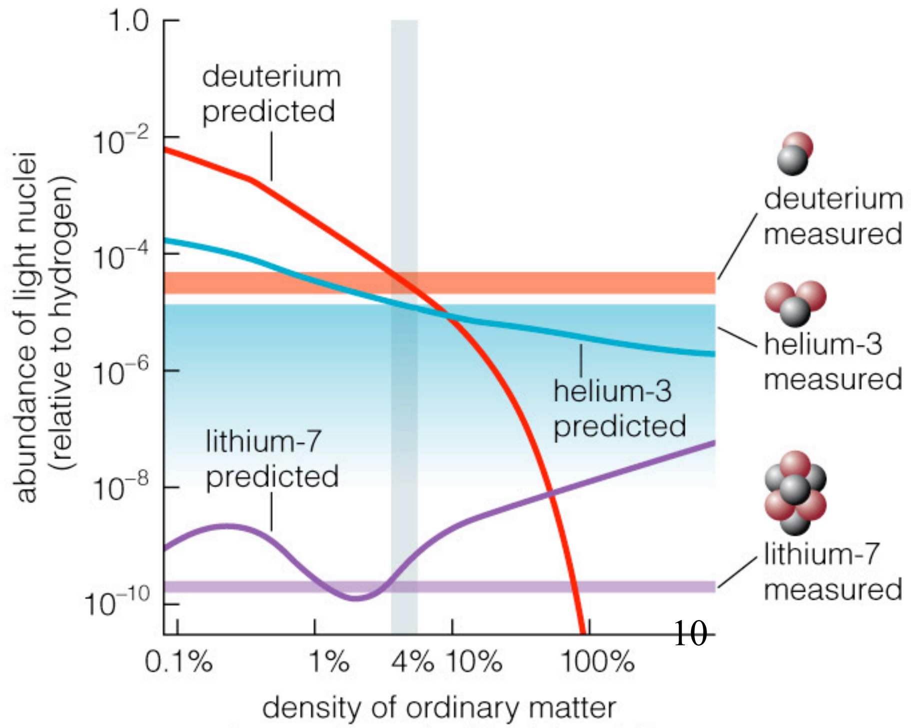
Big Bang theory prediction: 75% H, 25% He (by mass)

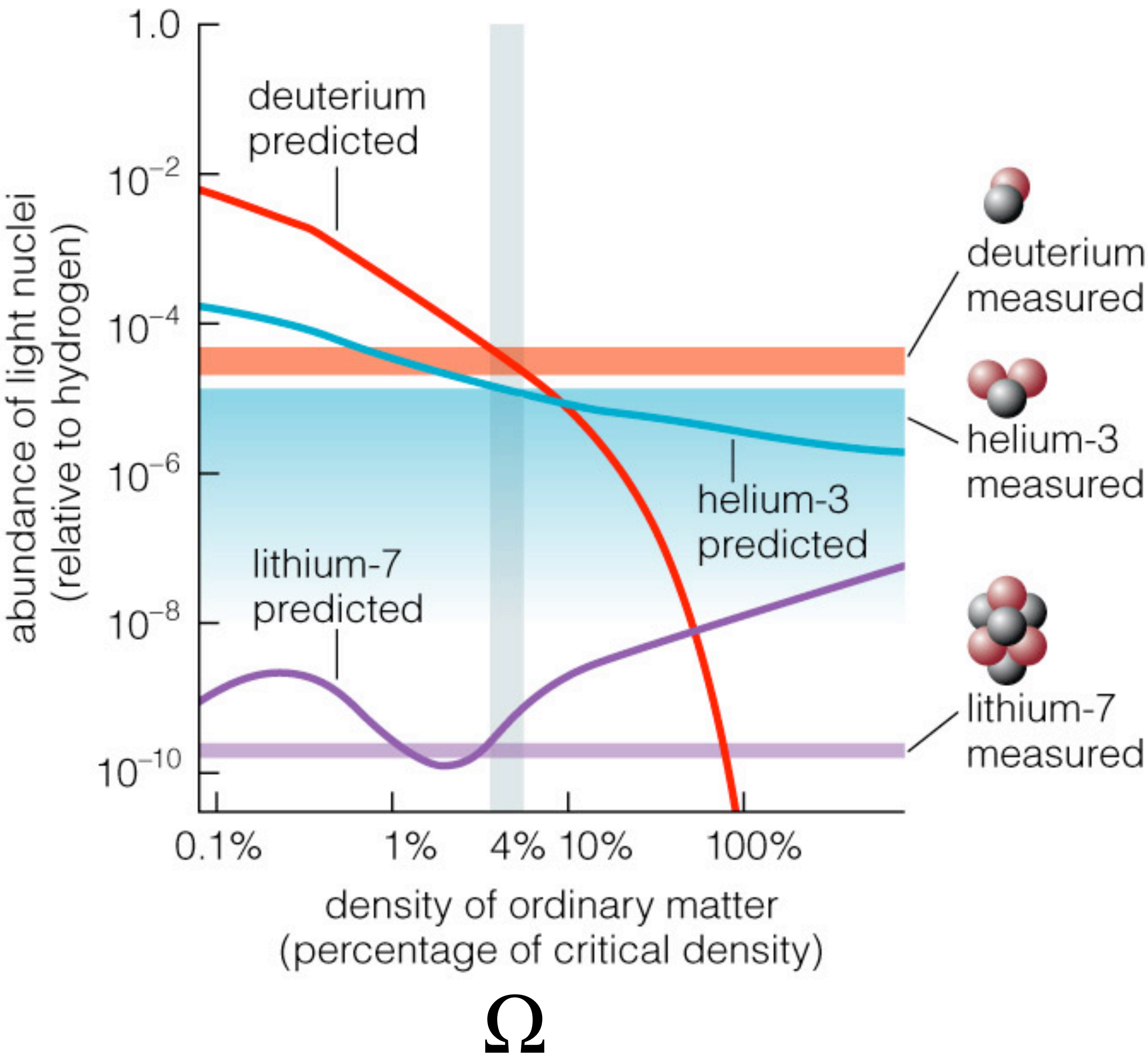
Matches observations of nearly primordial gases

BBN products:

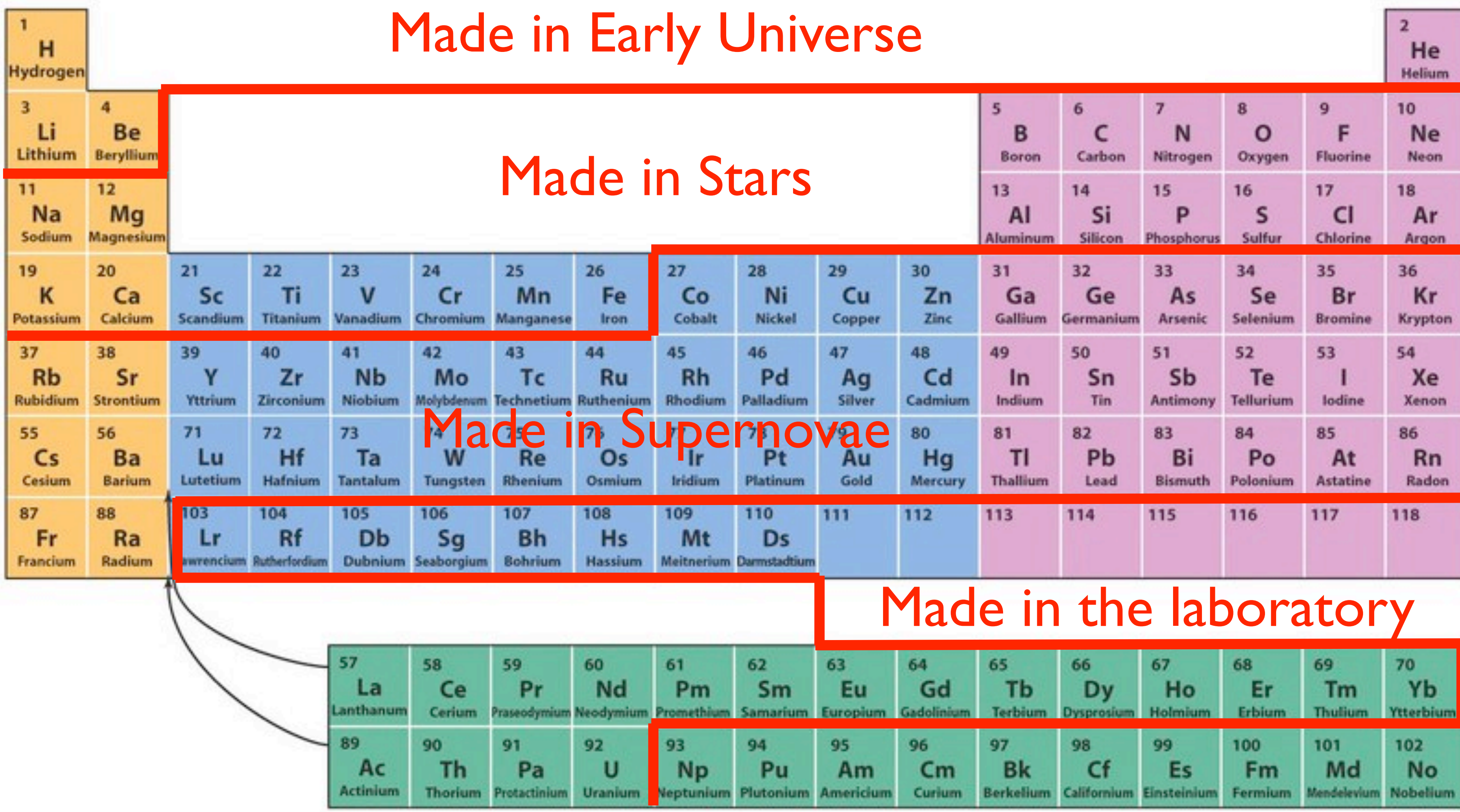
- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - beryllium

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





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
W Tungsten
Re Rhenium
Os Osmium
Ir Iridium
Pt Platinum
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 of atoms and anything formed from neutrons, protons to

$$\Omega = 0.04$$

To really blow your minds: inflation

- Remember the puzzle that the CMB is so uniform when it couldn't have been in contact with itself?
- This, and other cosmological problems, was solved by the idea of *inflation*; at a very early time ($<10^{-32}$ seconds after BB!!) the universe expanded much faster than light (???)

  No, doesn't violate Einstein; spacetime can expand, but no matter moves faster than light relative to the spacetime

To really blow your minds: inflation

- Thus all the stuff we see *did* interact with itself before inflation, so it was smooth and uniform by the time of the CMB
- Bizarre? Counterintuitive? Unsatisfactory? Yes! But, also supported by data and new discoveries. Sometimes that happens...
- Now back to a much more solid and tangible subject...

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!

What could Dark Matter be?

If Ω=0.27 and Ω_b (baryons) = 0.04, what could the rest be?

A. Planets (don't shine by their own light)

B. Neutron stars (small, therefore dim)

C. Cold gas spread throughout space

D. A new particle no one has discovered

E. I don't know

Evidence for dark matter

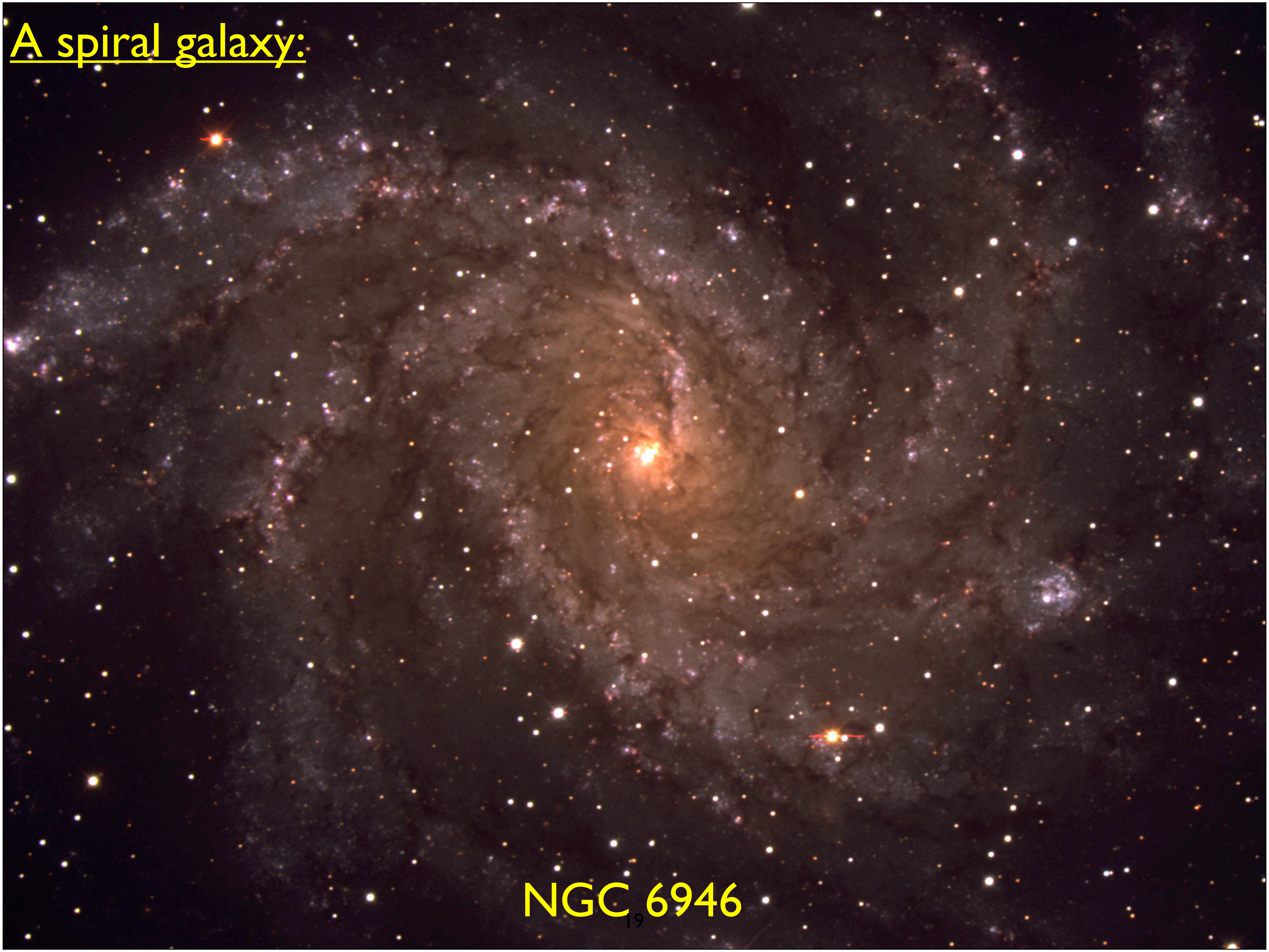
DM video

- Many systems exhibit mass discrepancies:

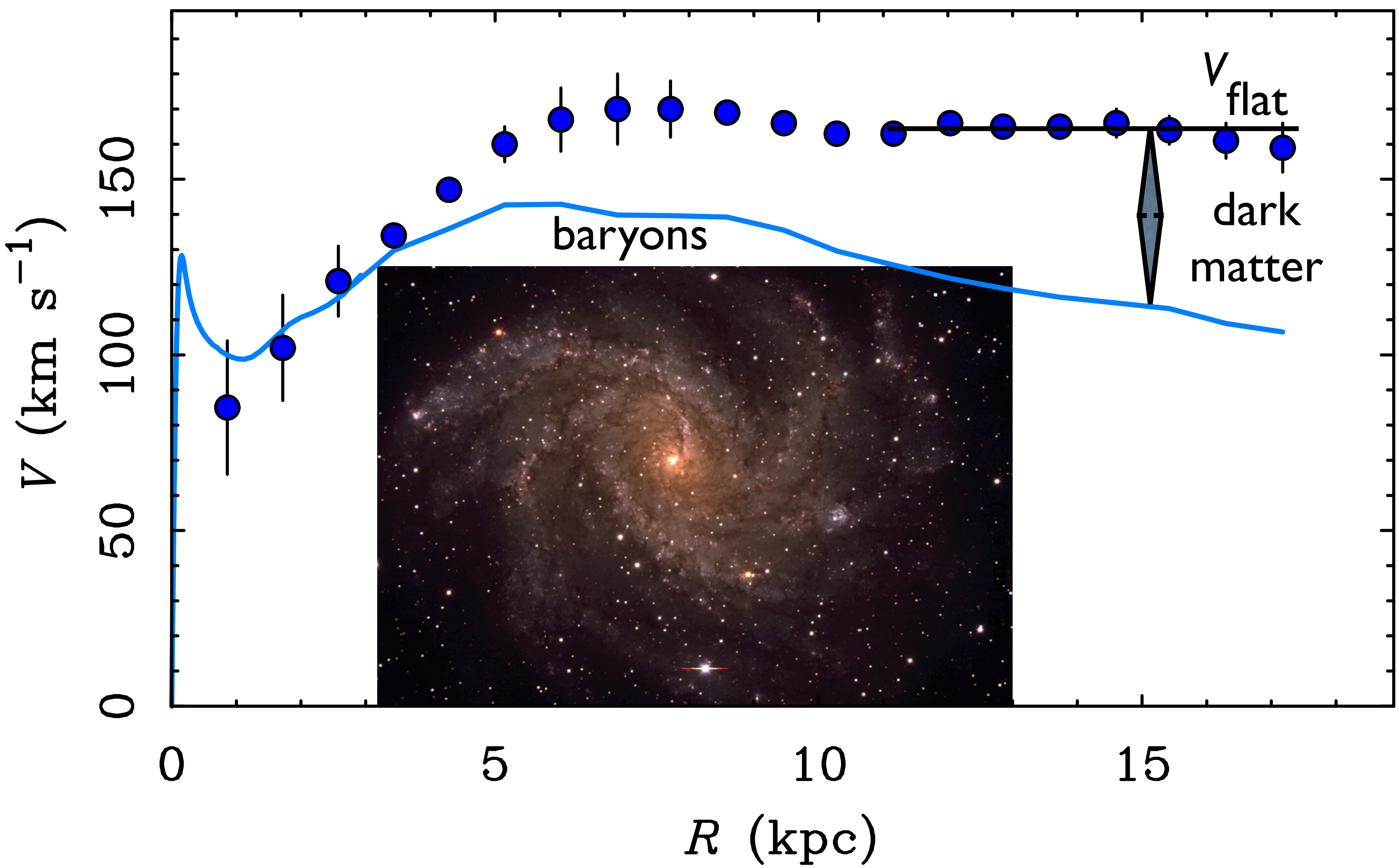
- Spiral galaxies
- Dwarf Galaxies
- Clusters of Galaxies
  - dynamics
  - gas temperature
  - gravitational lensing

Applying Newton's Law of Universal Gravitation to observed galaxy systems does not give observed masses!

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

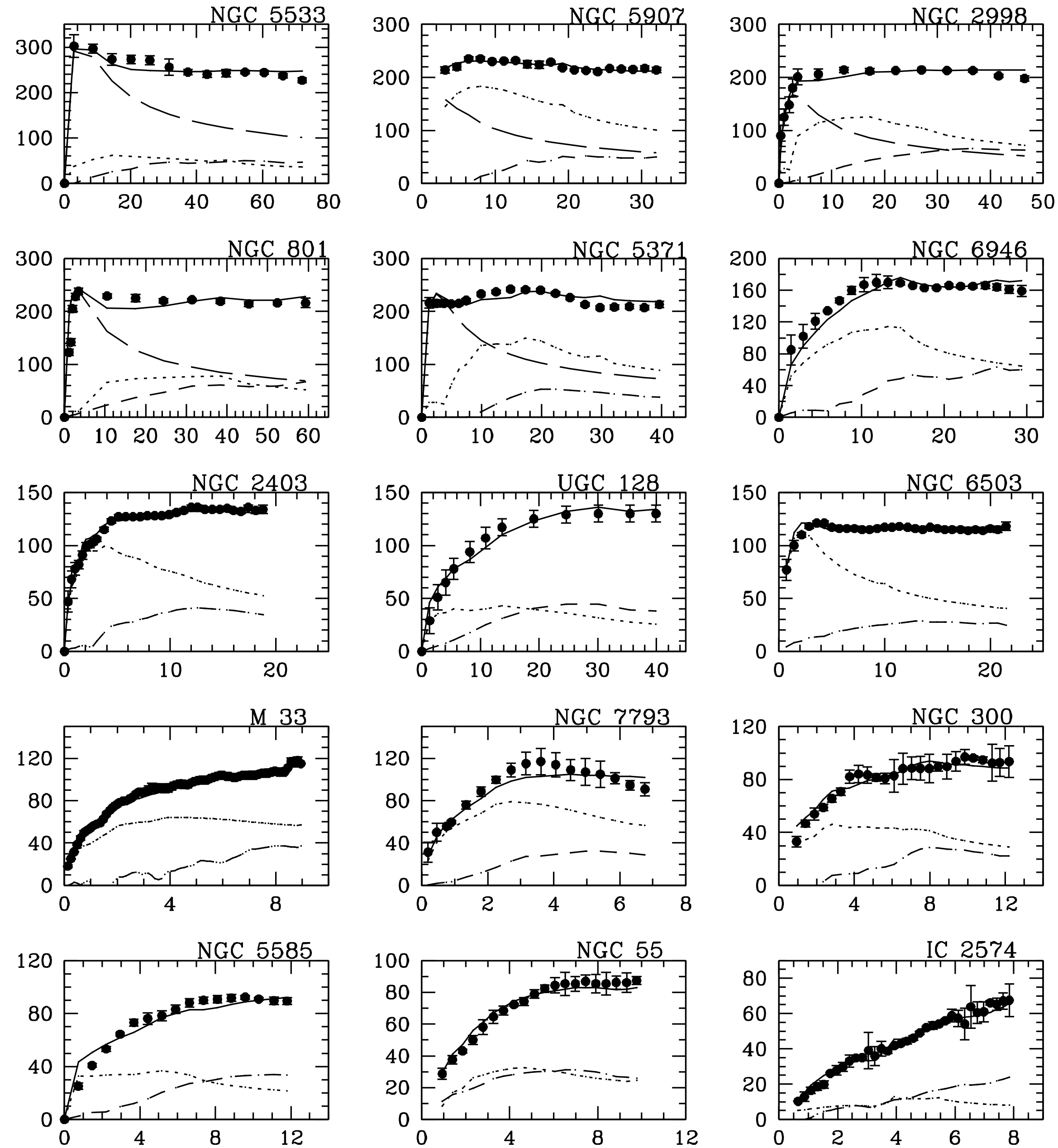

A spiral galaxy:
NGC 6946

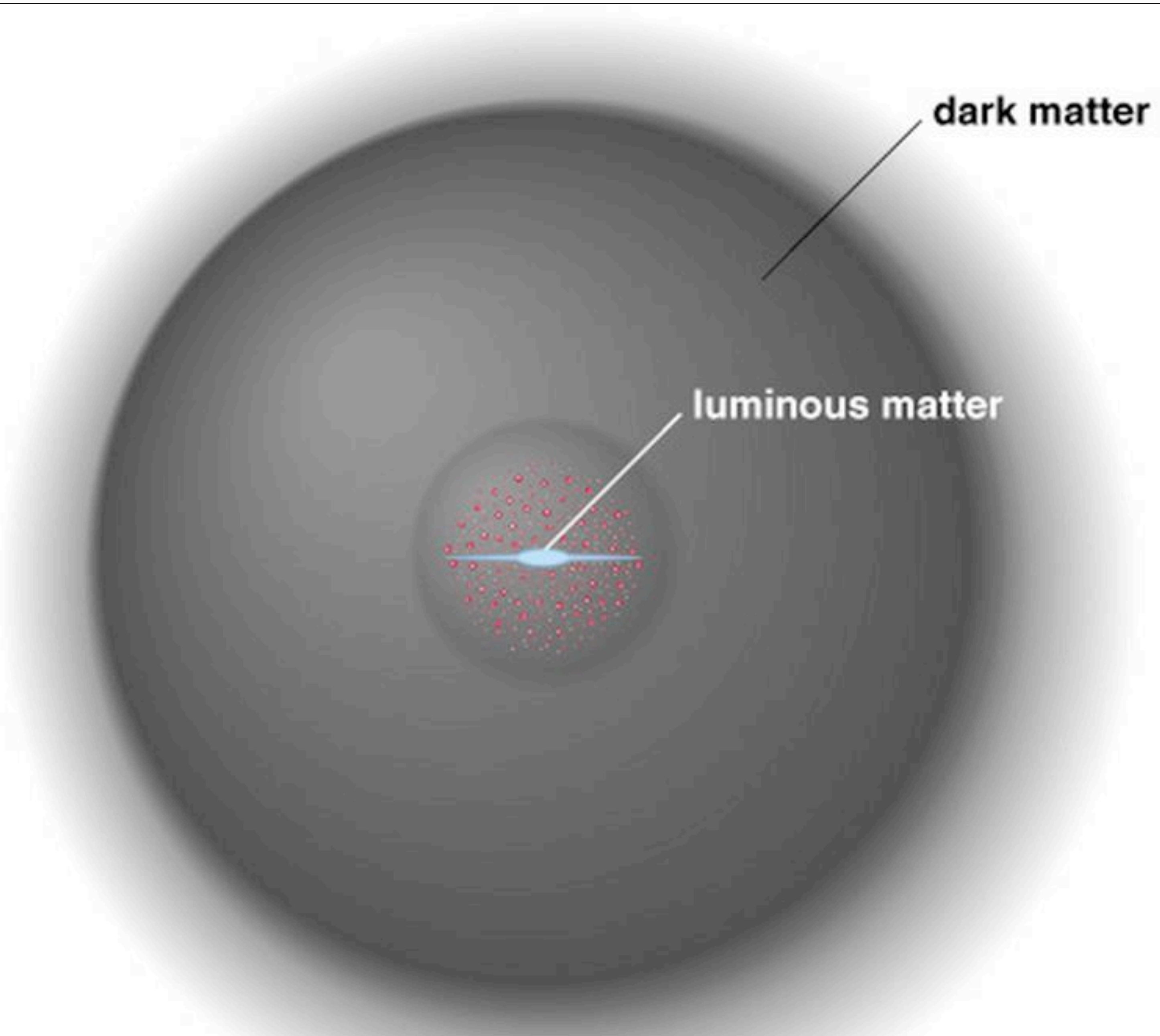
NGC 6946



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

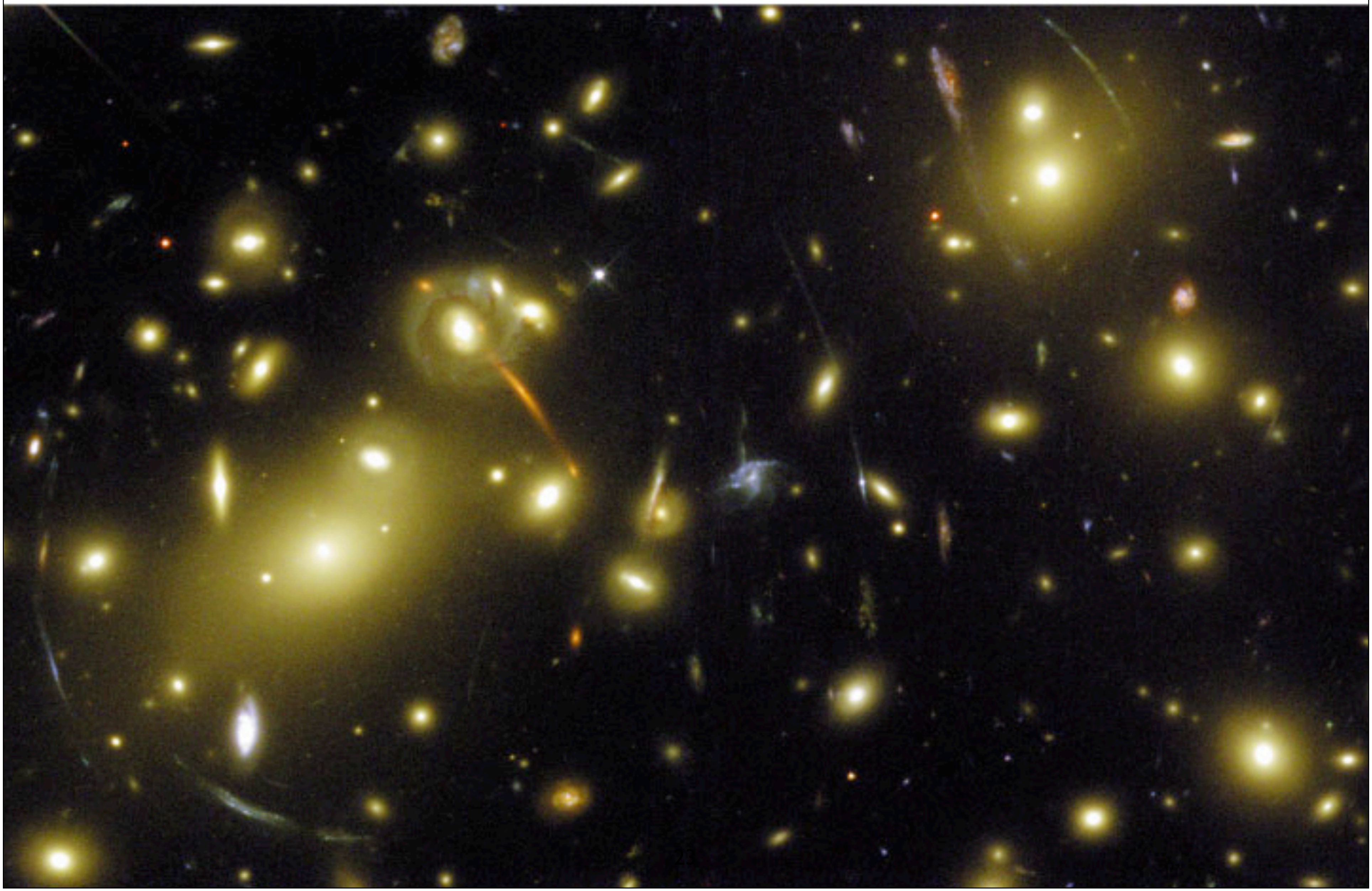
$$V^2 = \frac{GM}{R}$$

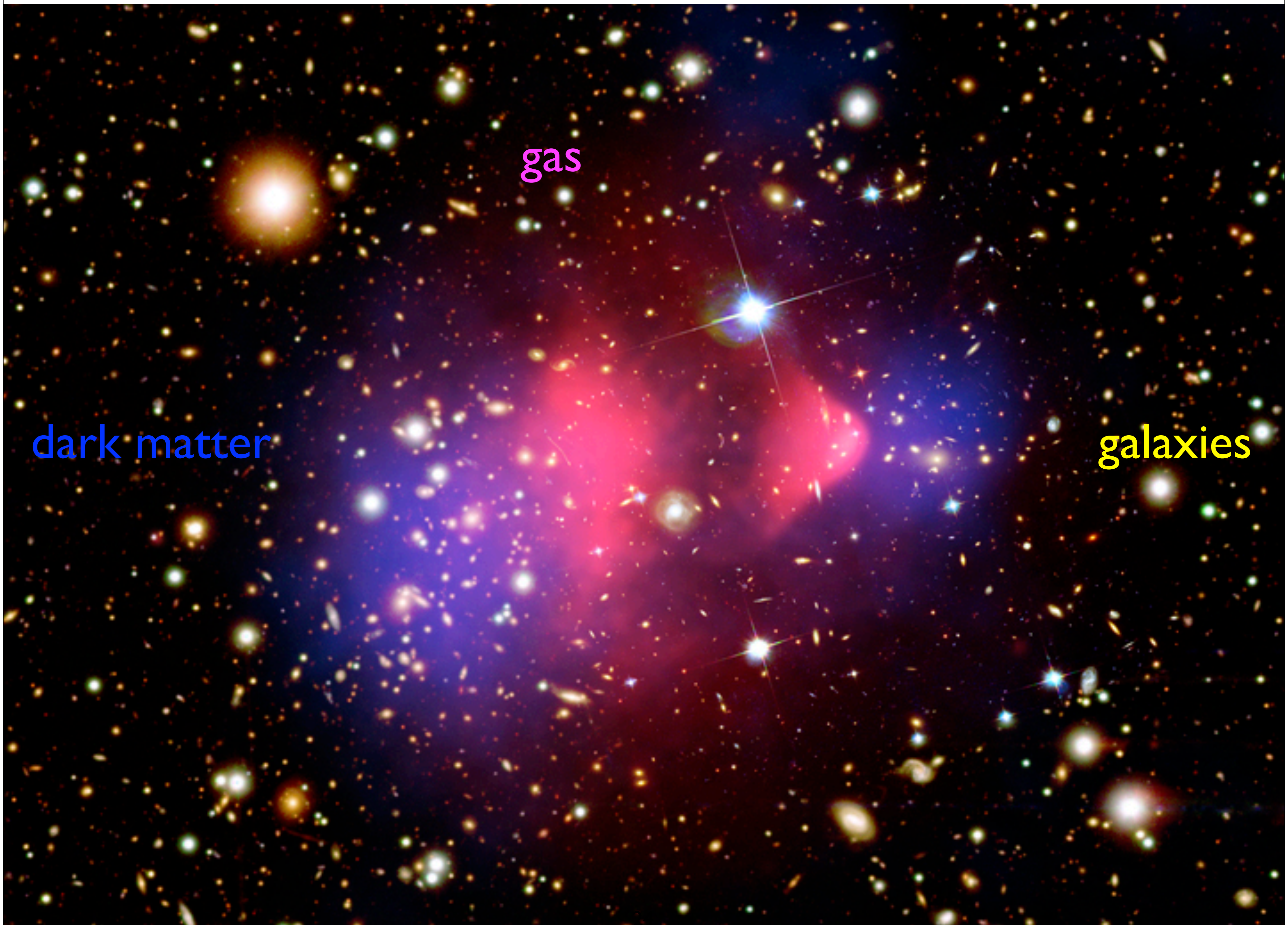




Galaxies seem to be embedded in larger dark matter halos

Also need dark matter in clusters of galaxies:




gas
dark matter
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

(1)

Normal baryonic mass = 4% of total

from Primordial Nucleosynthesis

Total mass density = 27% of total

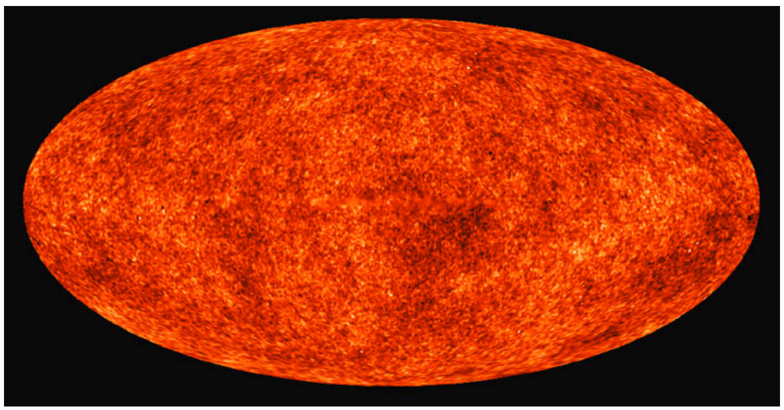
from gravity

gravitating mass >> normal mass

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

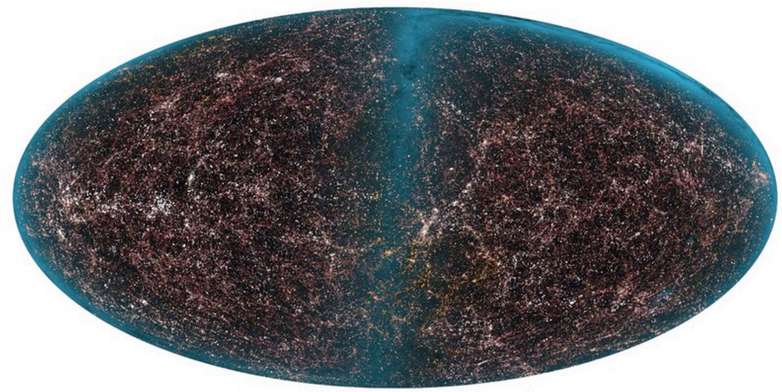
(2) There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



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

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

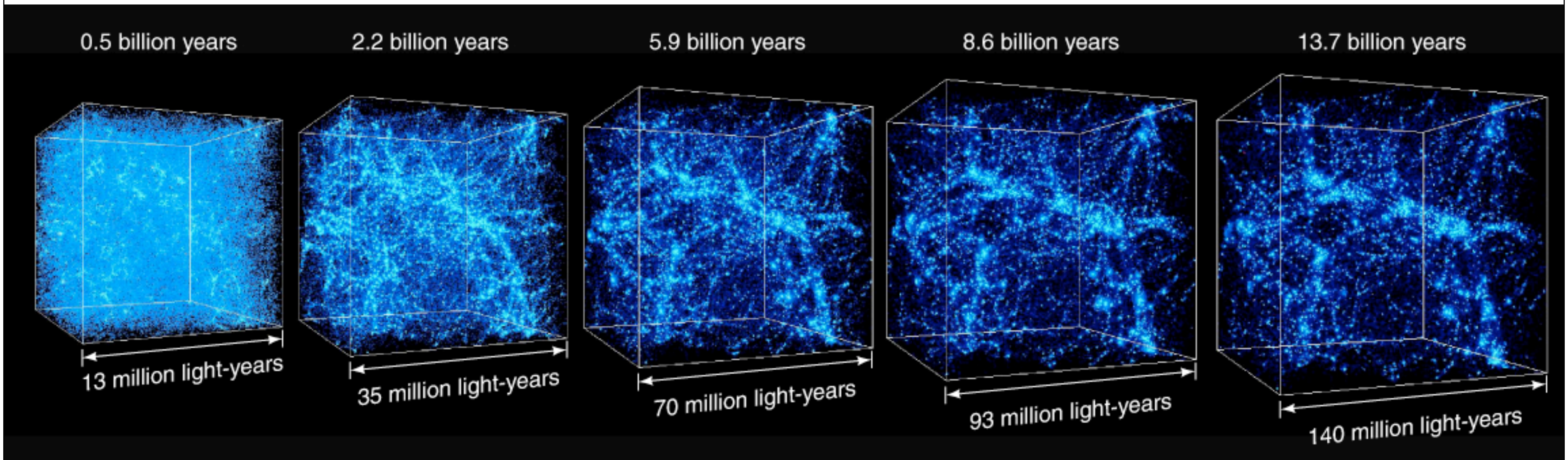


very lumpy: $\delta\rho/\rho \sim 1$

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

Time in billions of years

0.5 2.2 5.9 8.6 13.7

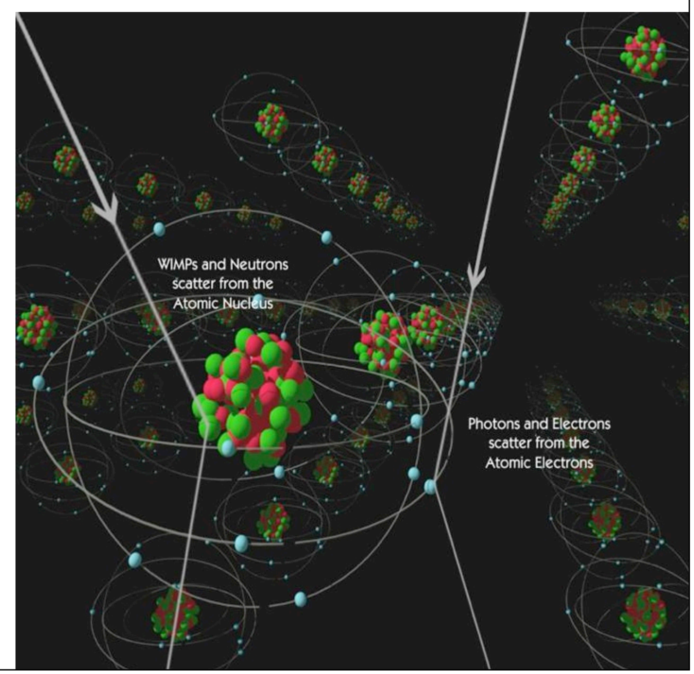


13 35 70 93 140

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?

DE video

The Expanding Universe

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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

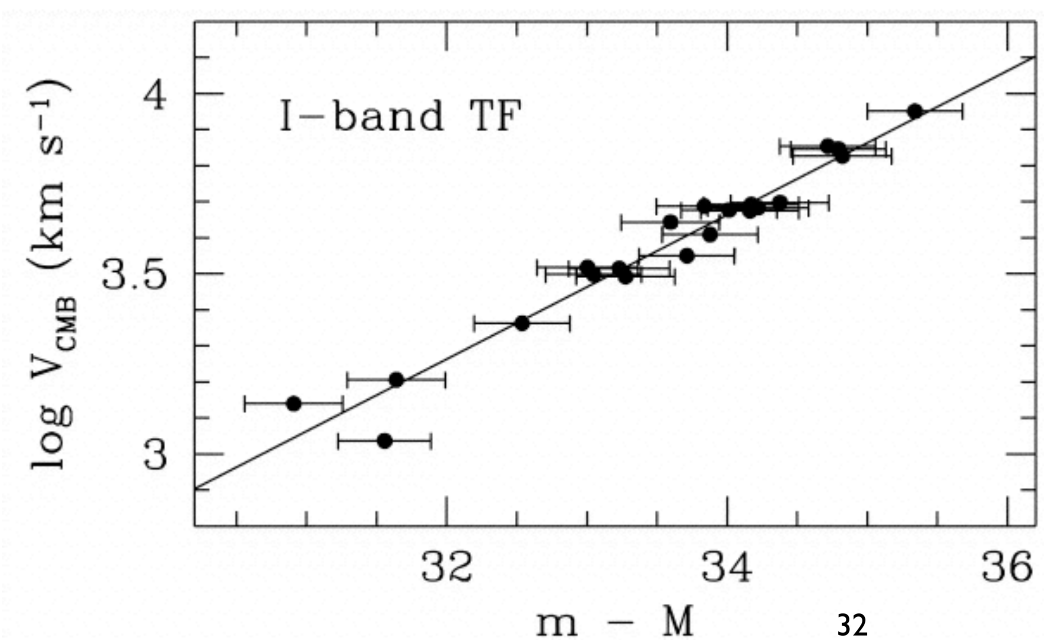
Philosophically, Einstein assumed something like the Perfect Cosmological Principle. The Universe had to have been around forever. Didn't it?

Dark Energy

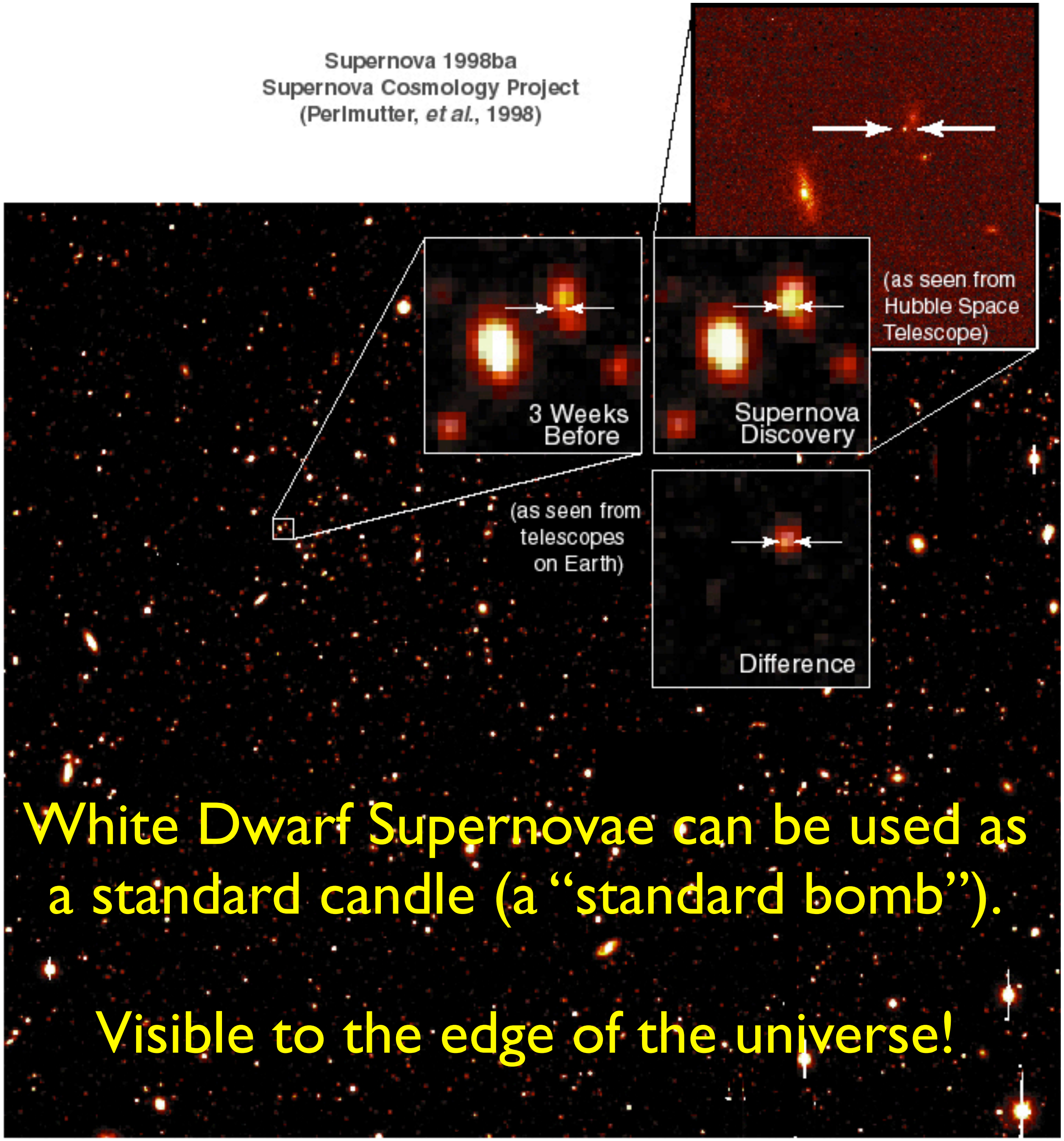
Einstein's greatest blunder?

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

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

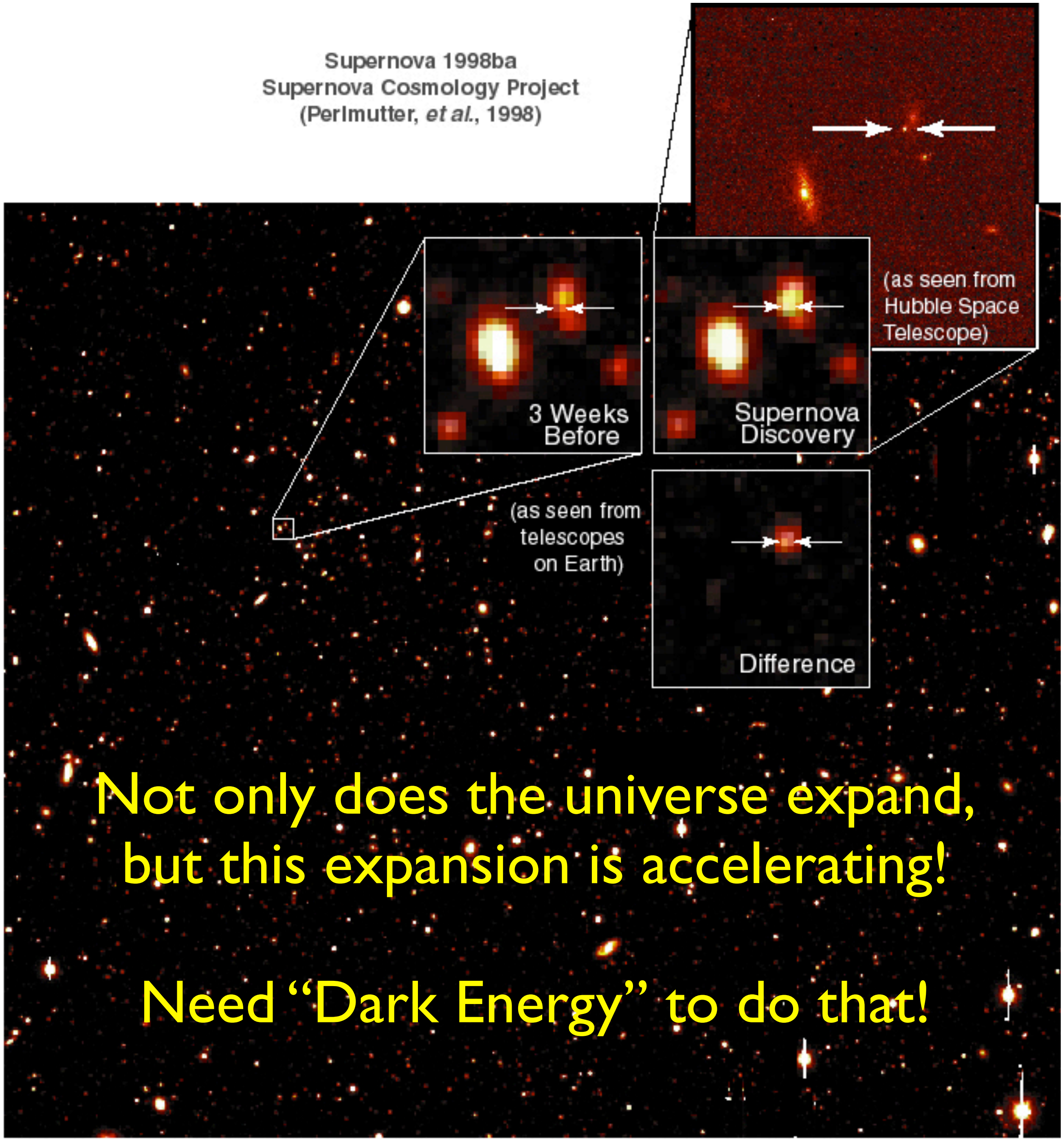


Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



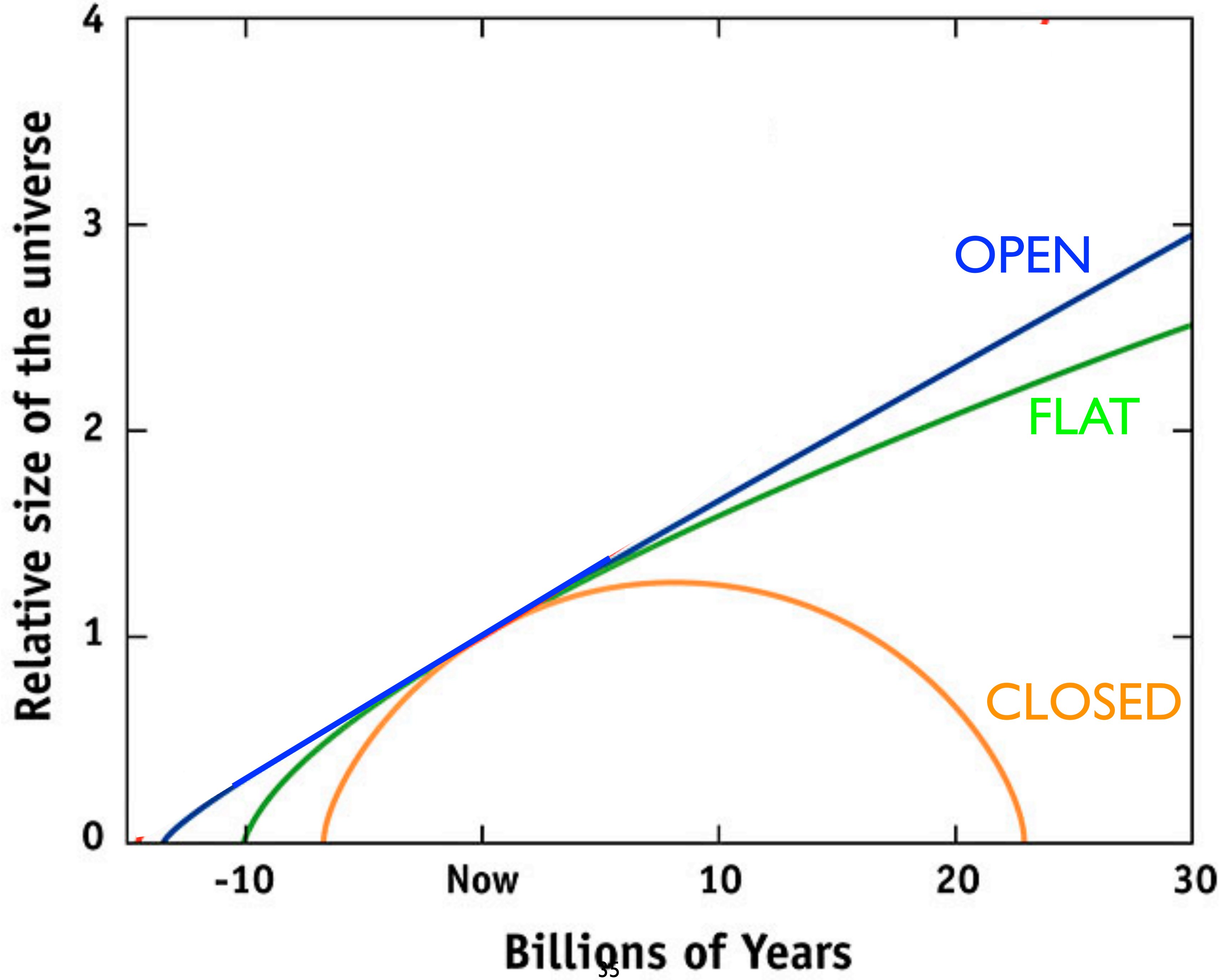
White Dwarf Supernovae can be used as a standard candle (a “standard bomb”).

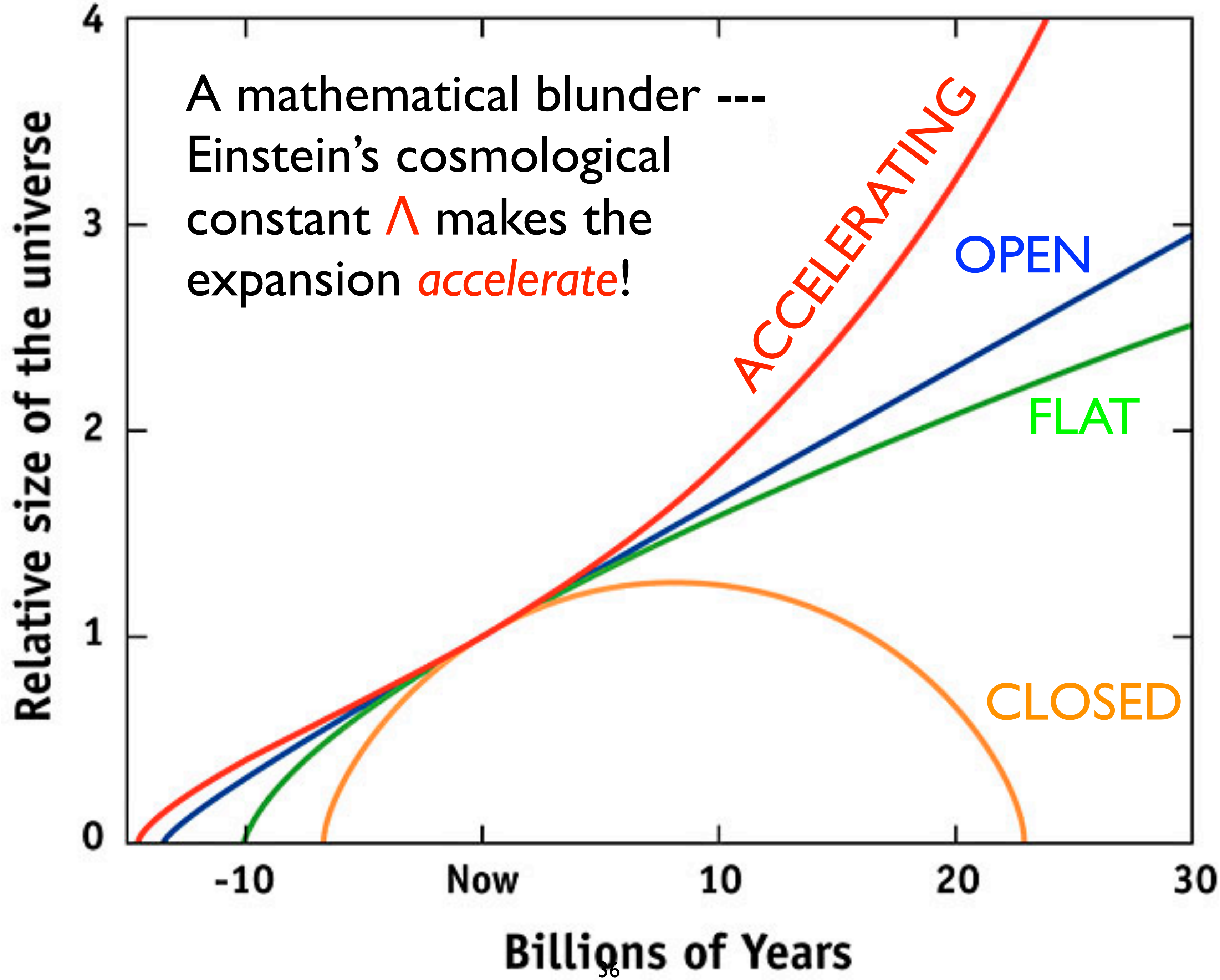
Visible to the edge of the universe!

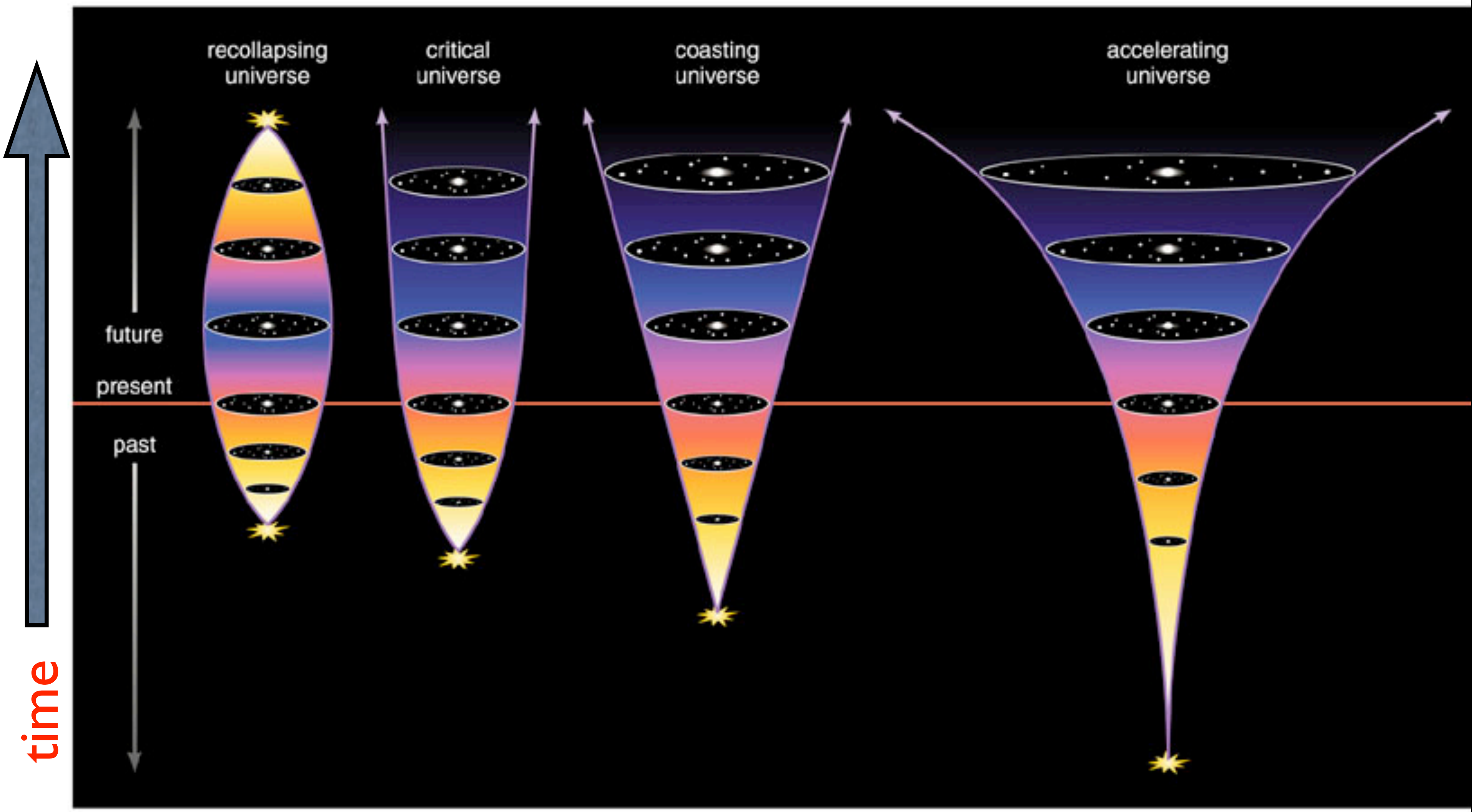


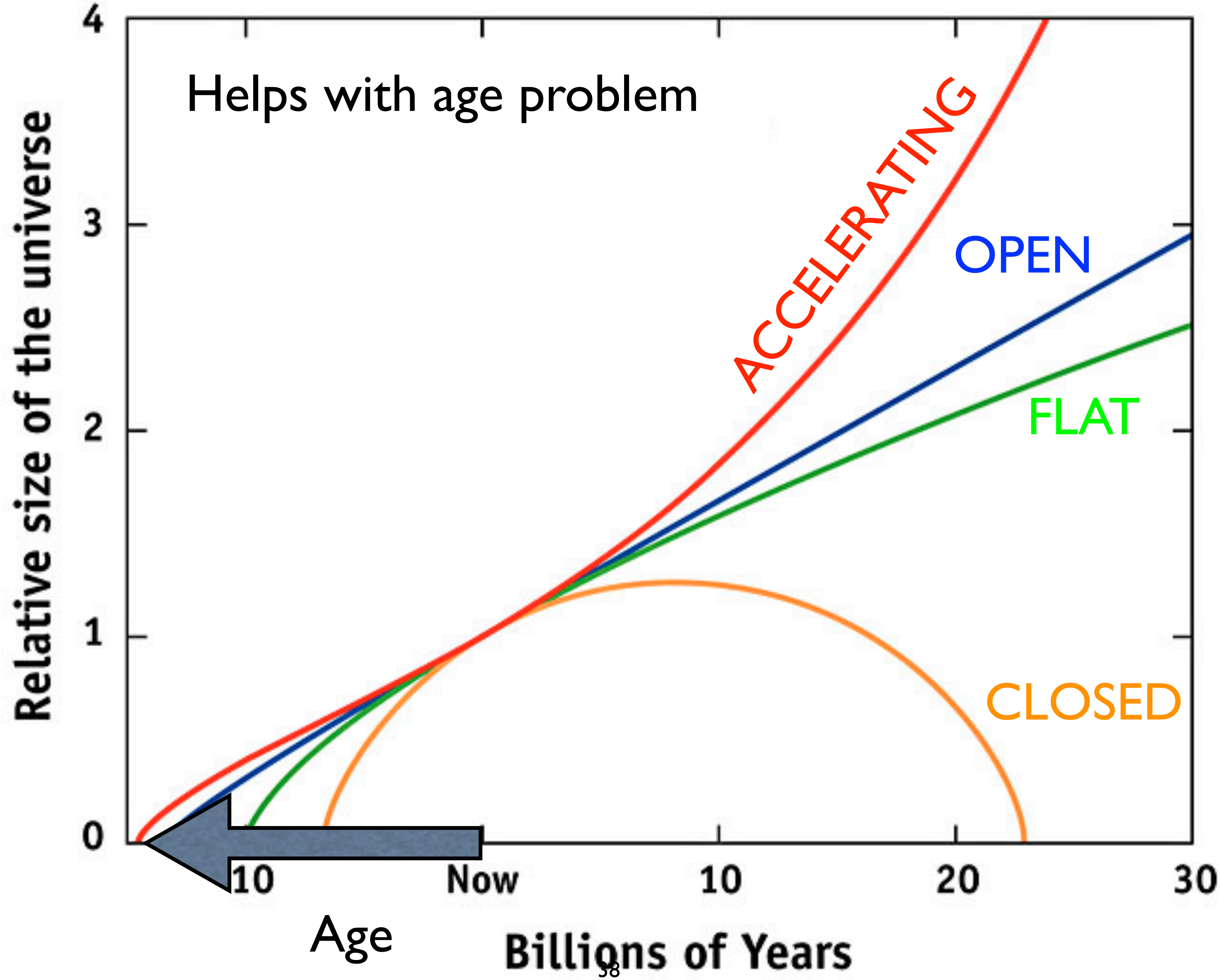
Not only does the universe expand, but this expansion is accelerating!

Need "Dark Energy" to do that!


Relative size of the universe
4
3
2
1
0
OPEN
FLAT
CLOSED
-10
Now
10
20
30
Billions of Years


A mathematical blunder ---
Einstein's cosmological
constant Λ makes the
expansion *accelerate*!
ACCELERATING
OPEN
FLAT
CLOSED
Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years


time
recollapsing universe
critical universe
coasting universe
accelerating universe
future
present
past


Helps with age problem
ACCELERATING
OPEN
FLAT
CLOSED
Relative size of the universe
4
3
2
1
0
10
Now
10
20
30
Age
Billions of Years