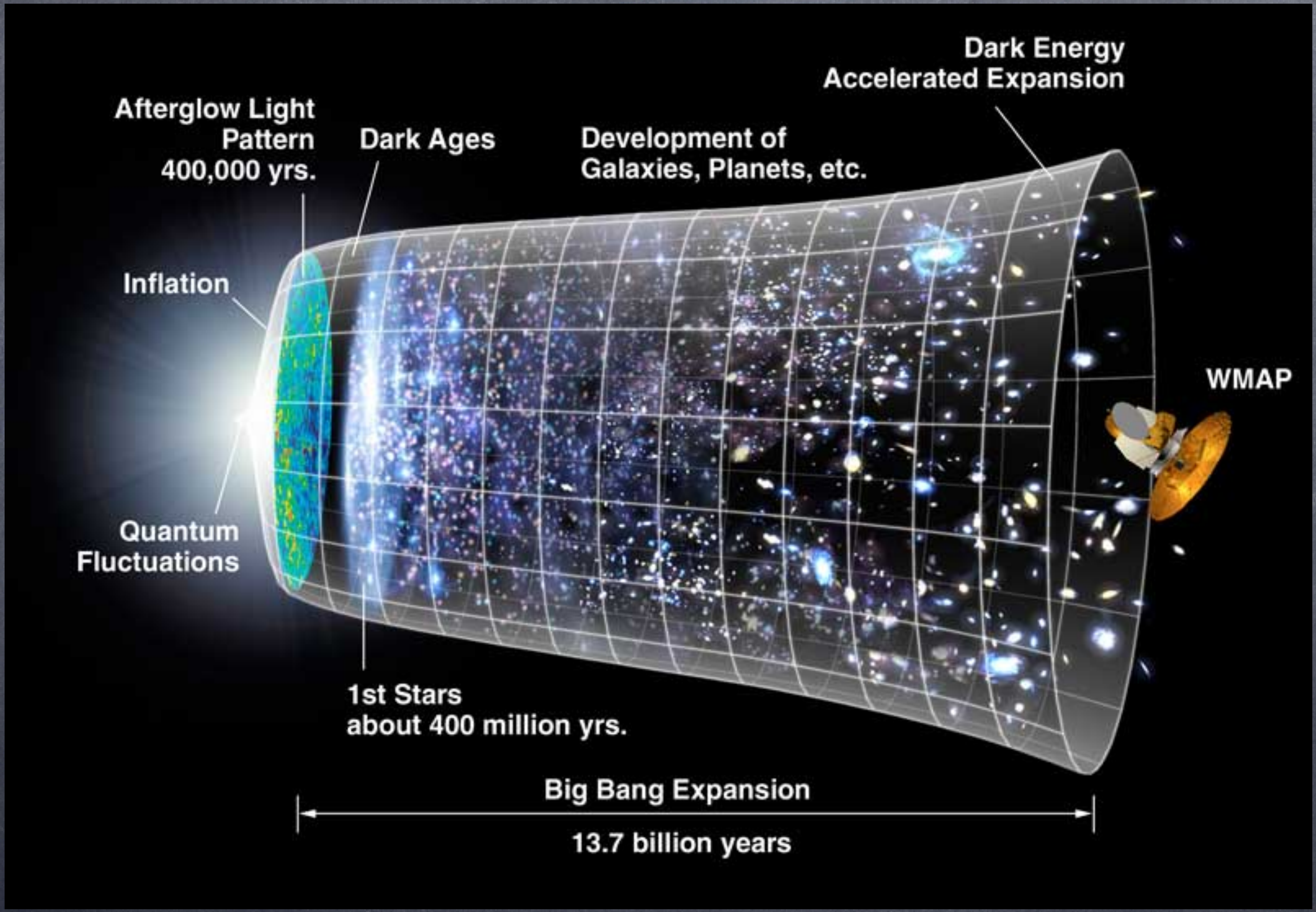
Cosmology

What is Cosmology?

- It is the "ology" of the cosmos, the everything we consider our universe.
- It is not, in my opinion, a quest for primal causes.
  - It is a search to go back in time as far as science can then run the clock forward and see if we can tell how the universe evolved and where it is going.

Cosmology

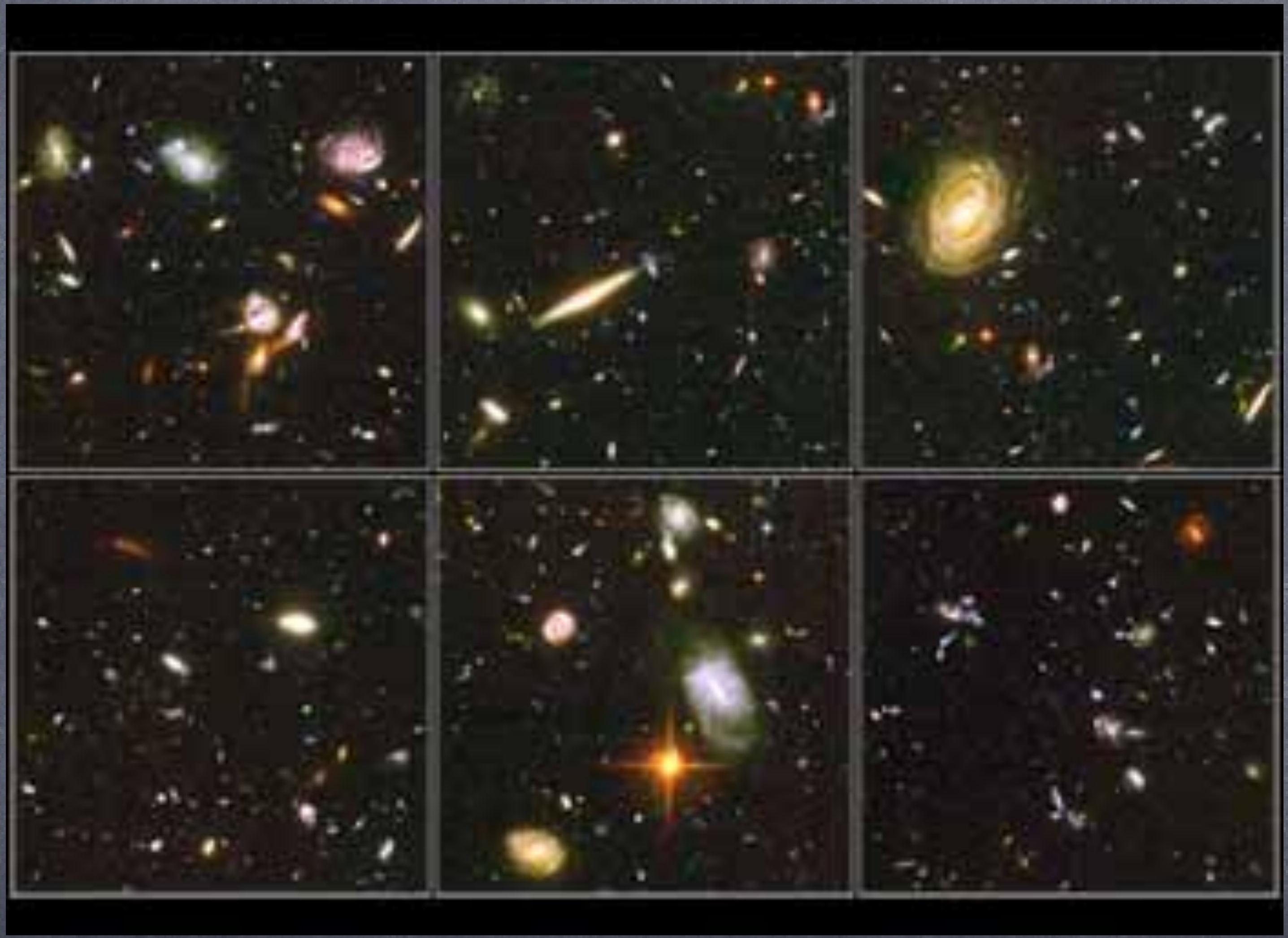

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

A brief interlude

- The Hubble Ultra Deep Field
- Point the Hubble Telescope at a particularly dark section of the sky in the constellation Fornax.
- Look at an area with approximately the height and width of a tenth of a fingernail and record light for 400 orbits.

- This is the area covered by a 1 sq mm piece of paper held a meter away.
- Looked at for about 200 hours.
- Looking back to 600 million years after the beginning of the Big Bang.
- We see 10,000 galaxies
- This made me start over with a psychology degree and become an astrophysicist.

How did they/us all get there/here?



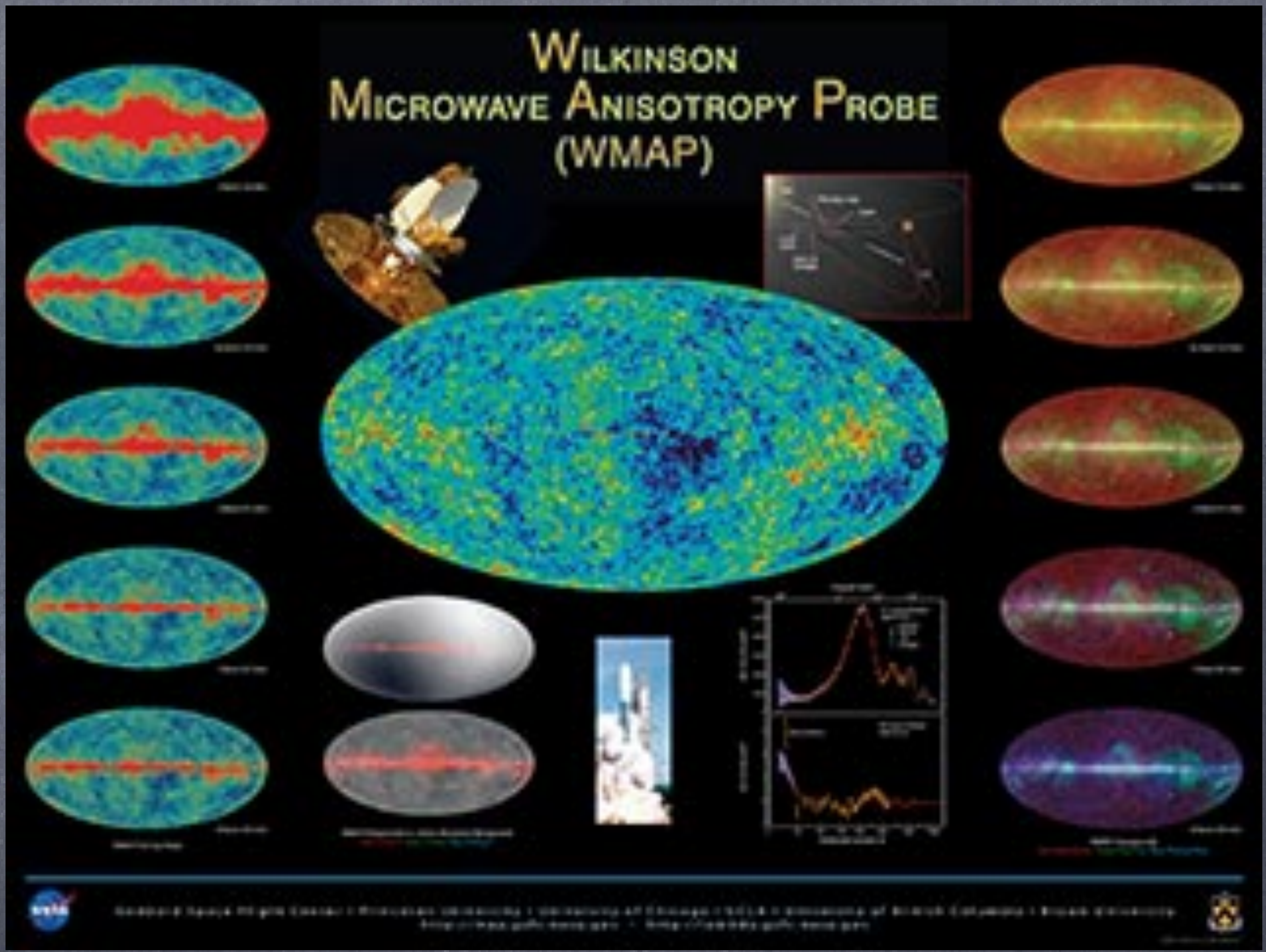
- And what is going to happen to them/us?

A brief history

- Ptolemy, 2nd century ad - Geocentric Universe
- Copernicus, 1500s - Sun Centered Universe
- Newtonian, 1600s - Static, Uniform Universe
- Shapley, 1900s, Galaxy is huge but other galaxies are not island universes, they are part of our universe
- Hubble, 1929, Our galaxy is one of many that are far away and receding from us - An Expanding Universe
- Steady State vs Big Bang arguments

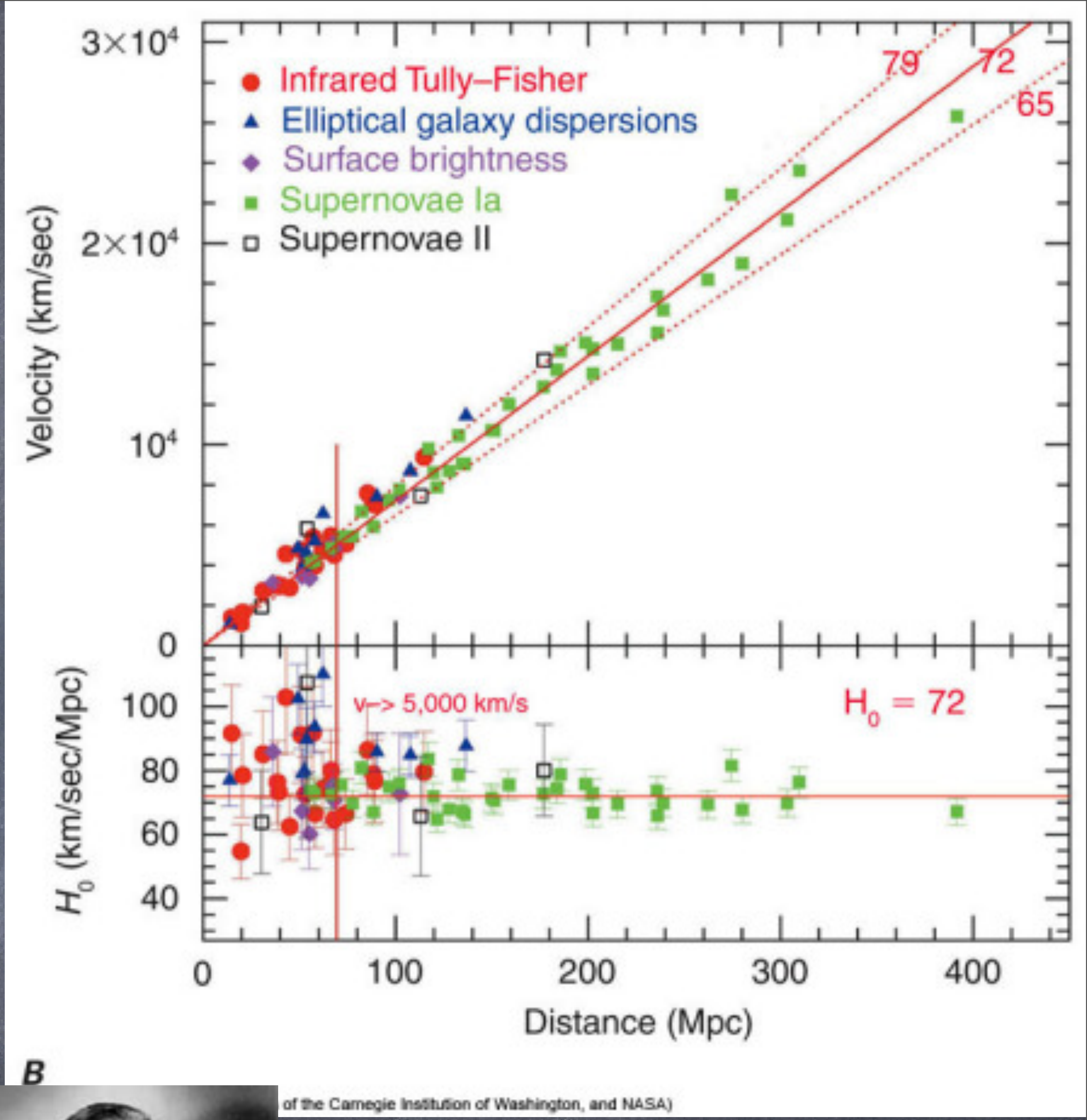
Continued

- In 1948 Gamow proposed we should see the embers from the early universe
- In 1963 Penzias and Wilson found them, the Cosmic Microwave Background Radiation. 1% of static on old projection tube tvs is a signal from the early universe.

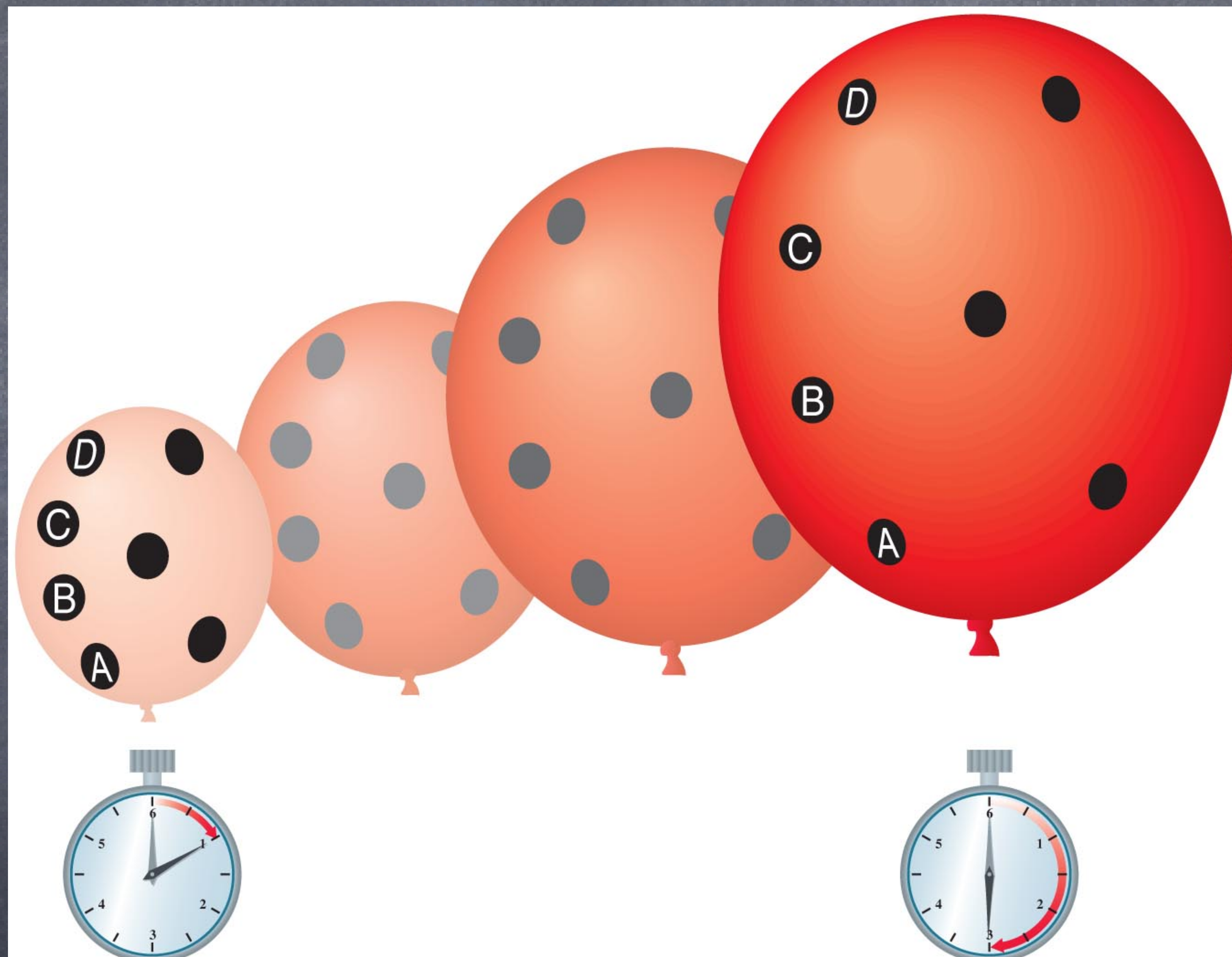


We'll start with Hubble

- The universe is expanding radially away from us in every direction we look
- The expansion velocity increases with distance from us.
- Hubble's Law $v = H_0 D$
- The Hubble Telescope was put up to measure the distance to Cepheid Variables, distance measurements pin down the Hubble Constant.
- $H_0 = 74.3 \pm 2.1$ (km/s)/Mpc
- $1/H_0$ ~ age of universe ~ 14 billion Years

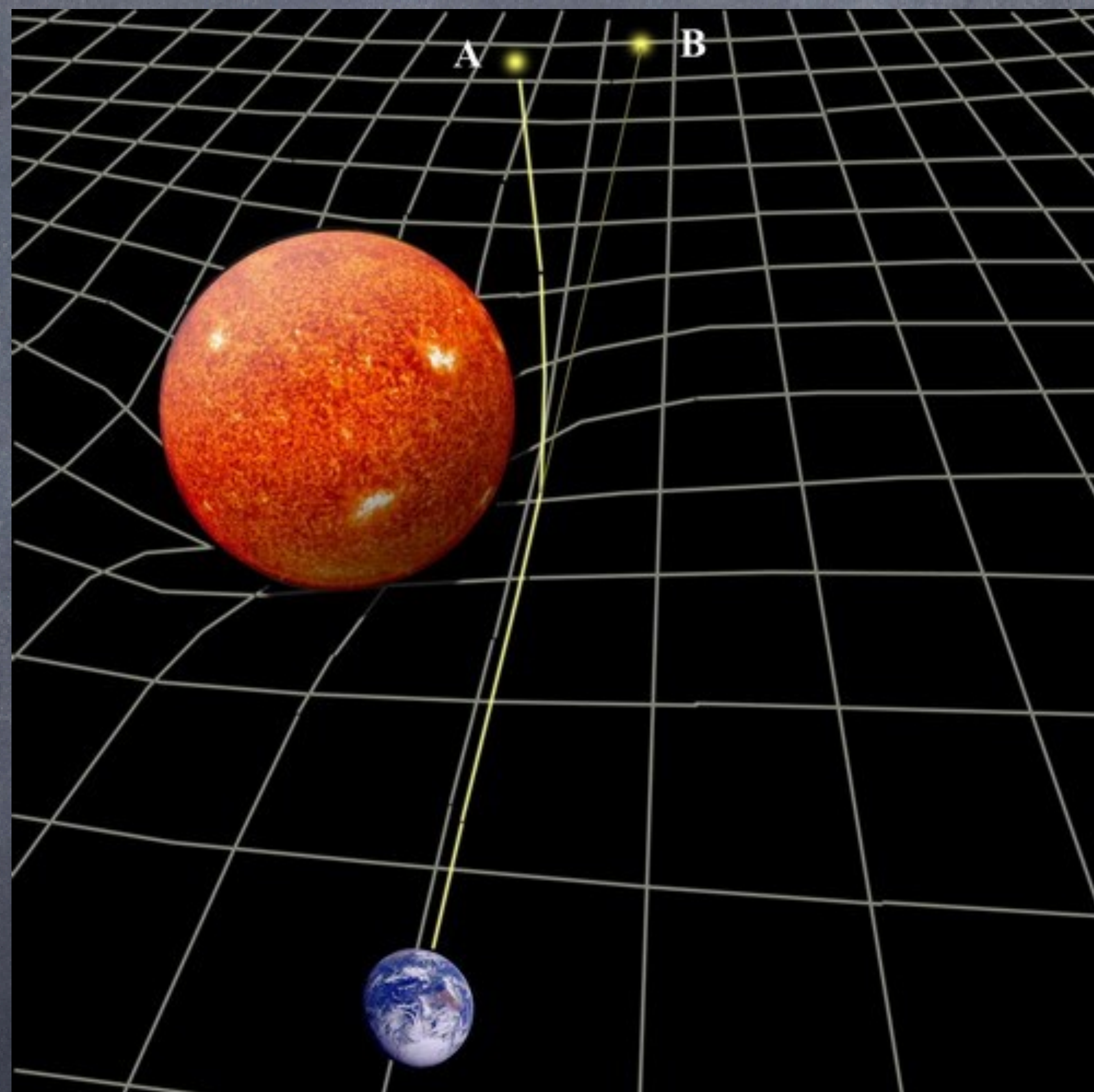


Thursday, March 14, 13


D
C
B
A
D
C
B
A

Today

- The current paradigm is that we live in a ΛCDM universe.
- A universe with cold dark matter (CDM) and dark energy (Λ)
- The evolution of the universe is governed by Einstein's field equations.
  - Matter tells space-time how to bend, space-time tells matter how to move.


A
B

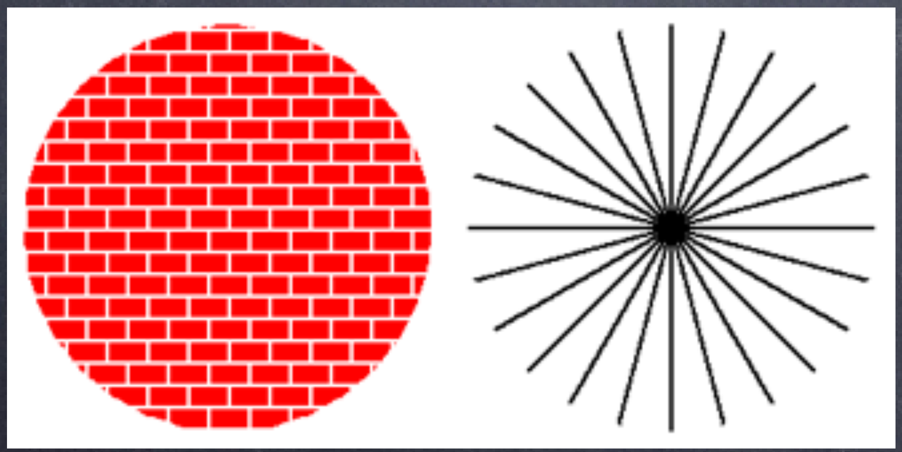
How do we tell what is going to happen?

- Friedmann Equations, derived by assuming a homogenous and isotropic universe and sticking matter and energy density into Einstein's equation for general relativity - means we need to stick in all the stuff, dark or not

$$(\frac{\dot{R}}{R})^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{R^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P) + \frac{\Lambda}{3}$$

$$\dot{\rho}c^2 = -3\frac{\dot{R}}{R}(\rho c^2 + P)$$



k is curvature

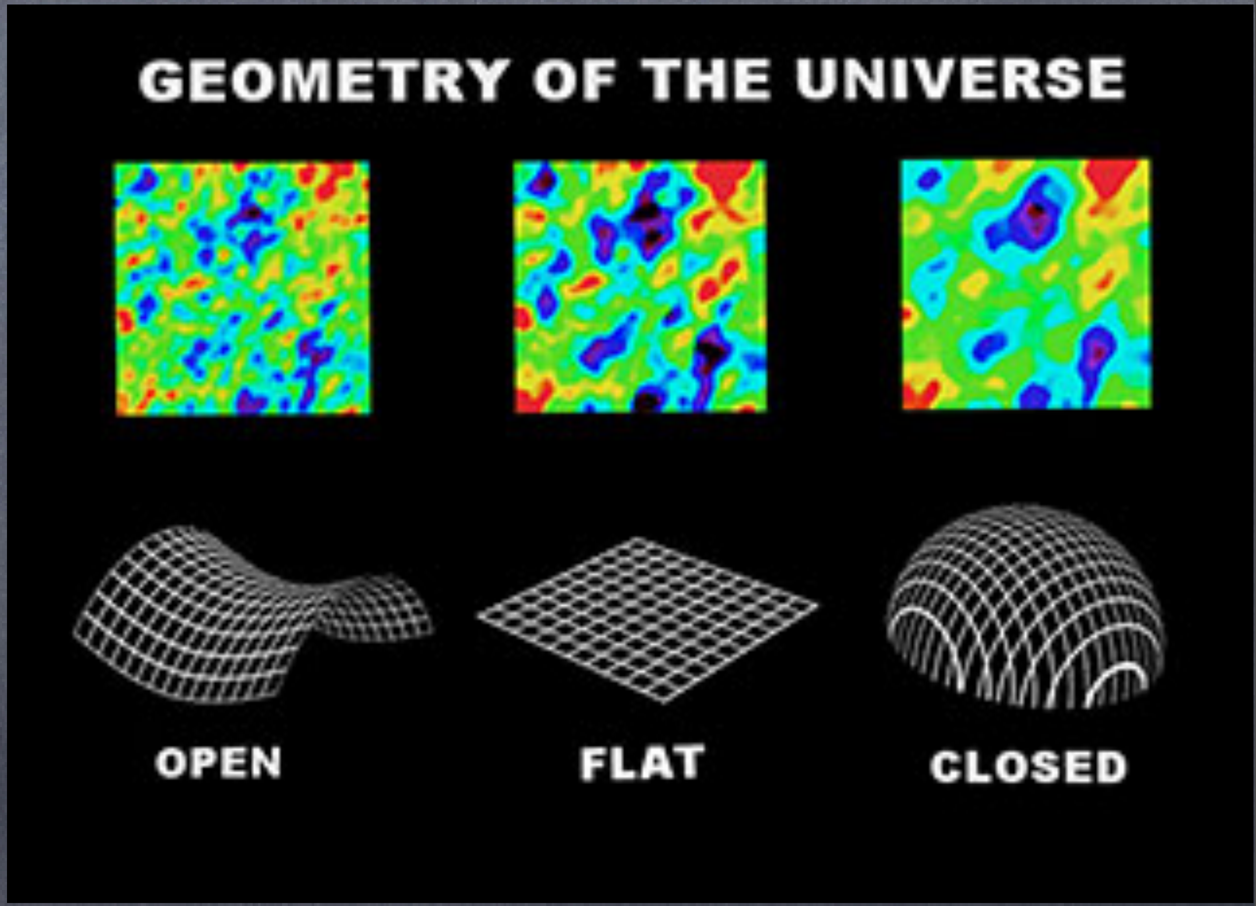
$$R(t) \propto t^{2/(3*(1+w))}, w = [\frac{1}{3}, 0], \propto t^{[\frac{1}{2}, \frac{2}{3}]}$$

$$w = -1, R(t) \propto E^{Ht}$$

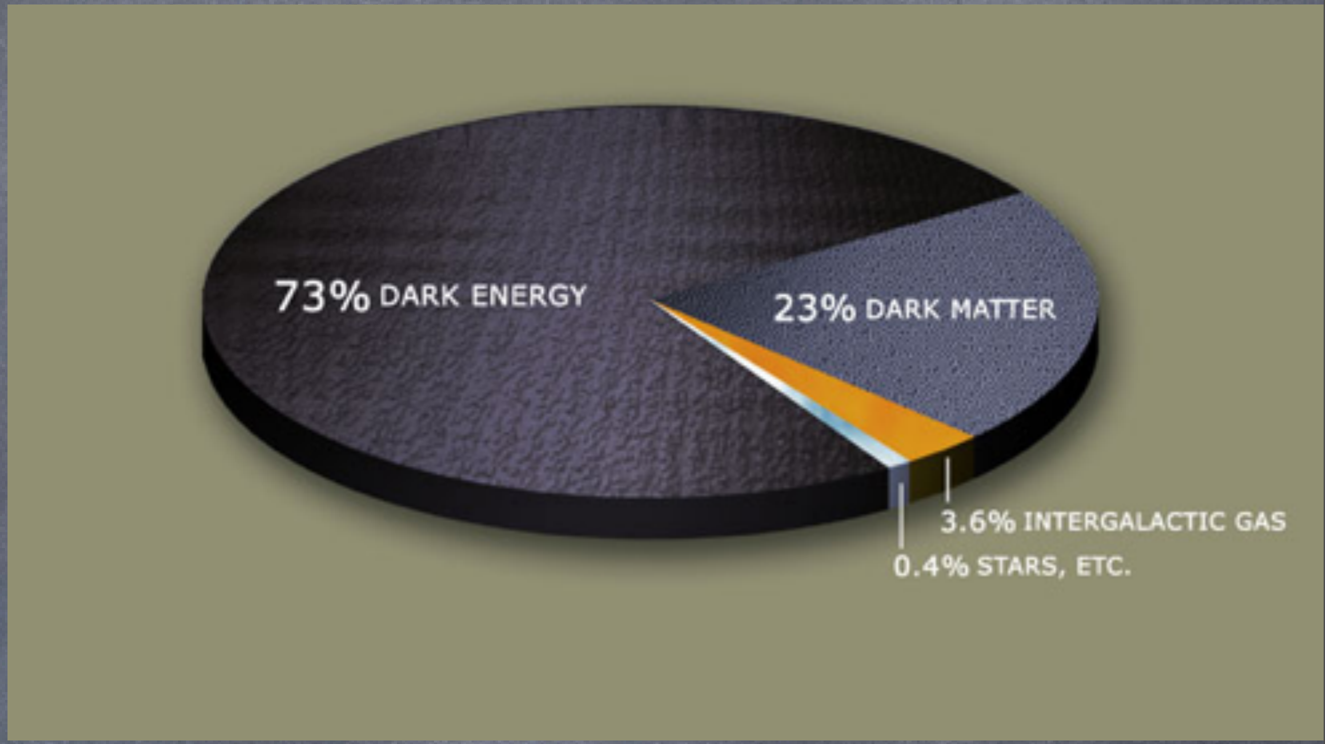
What will happen to the universe?

- It will continue to expand forever or recollapse.

- We must measure the matter and energy budget in the universe and stick it into Friedmann's equations to tell what's going to happen
- Critical Density $\rho_c = \frac{3H_0^2}{8\pi G}$ $\Omega = \frac{\rho}{\rho_c}$
- if $\Omega = 1$ $k = 0$ flat
- if $\Omega > 1$ $k = +1$, closed universe
- if $\Omega < 1$ $k = -1$, open, expanding universe
- Coincidentally, the critical density is
  - 9.2×10^{-30} g cm^{-3}
  - Toss an electron into every 10 cm^{-3}



We add up all the "stuff" in the universe to see what's going to happen to it



As fractions of density

photons - $5*10^{-5}$

neutrinos - $3.4*10^{-5}$

baryonic matter - .04

dark matter -.26

dark energy - .7

Ω = 1 k = 0 flat, almost perfectly

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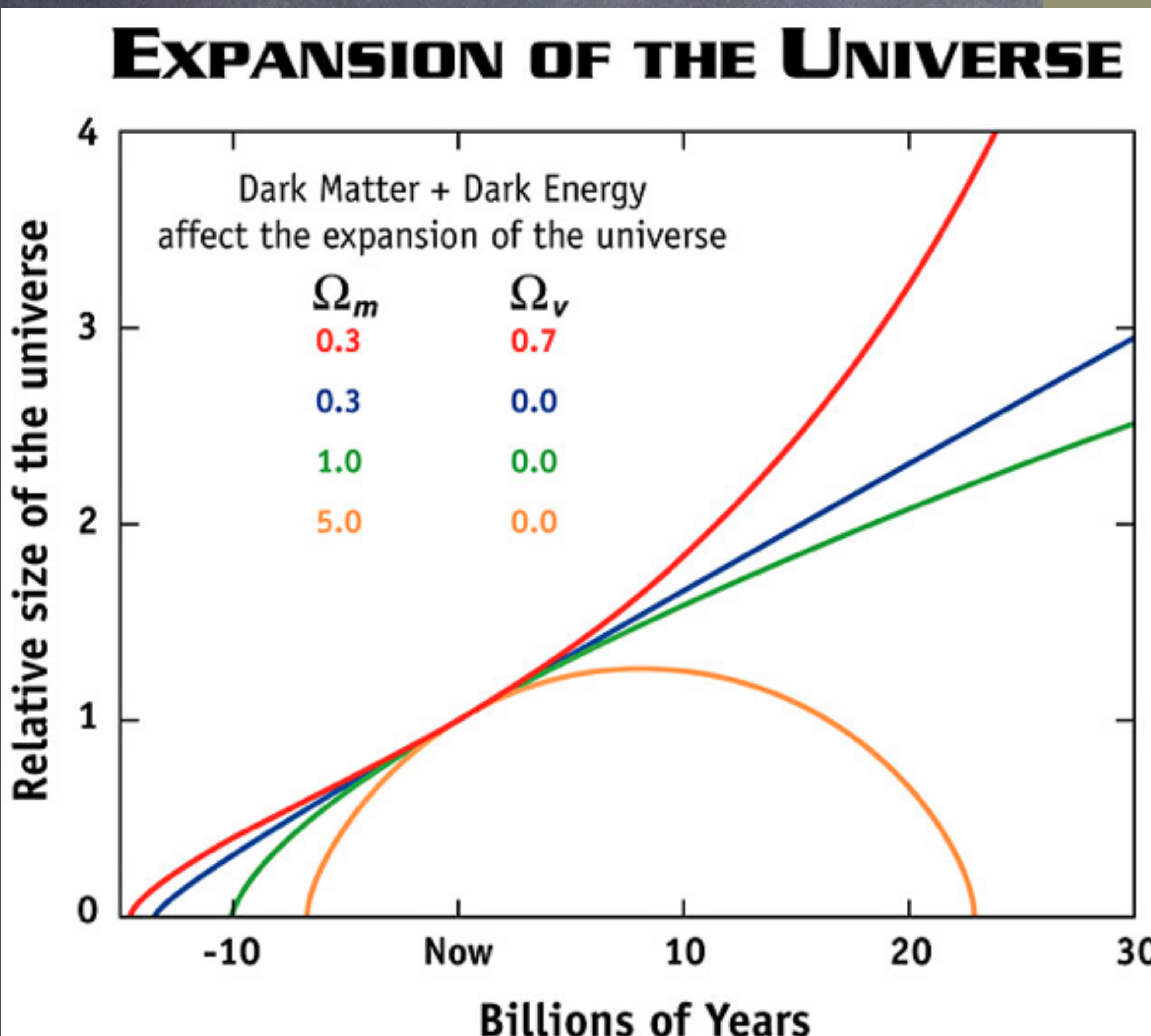

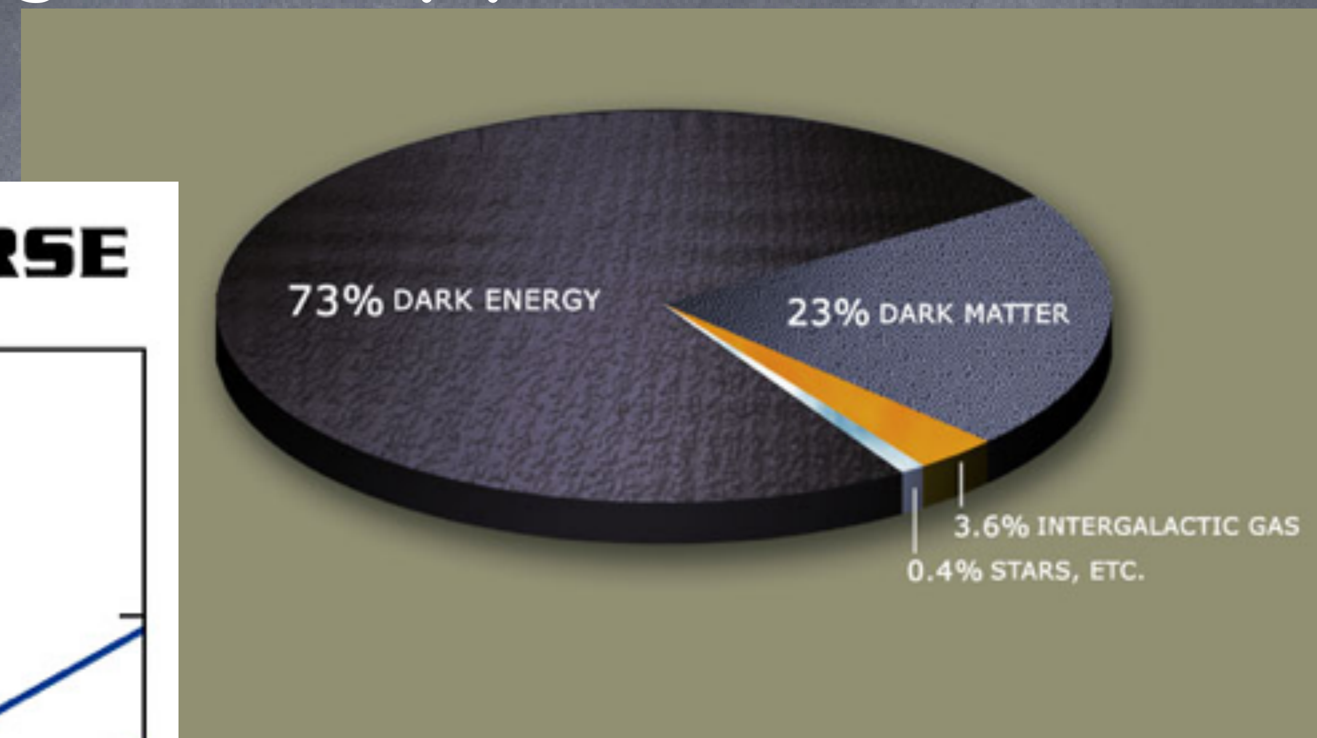

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Let's Back Up

- Its pretty arrogant to make a claim about the future without looking backward to see if any of this stuff is self-consistent.

Enter The Big Bang

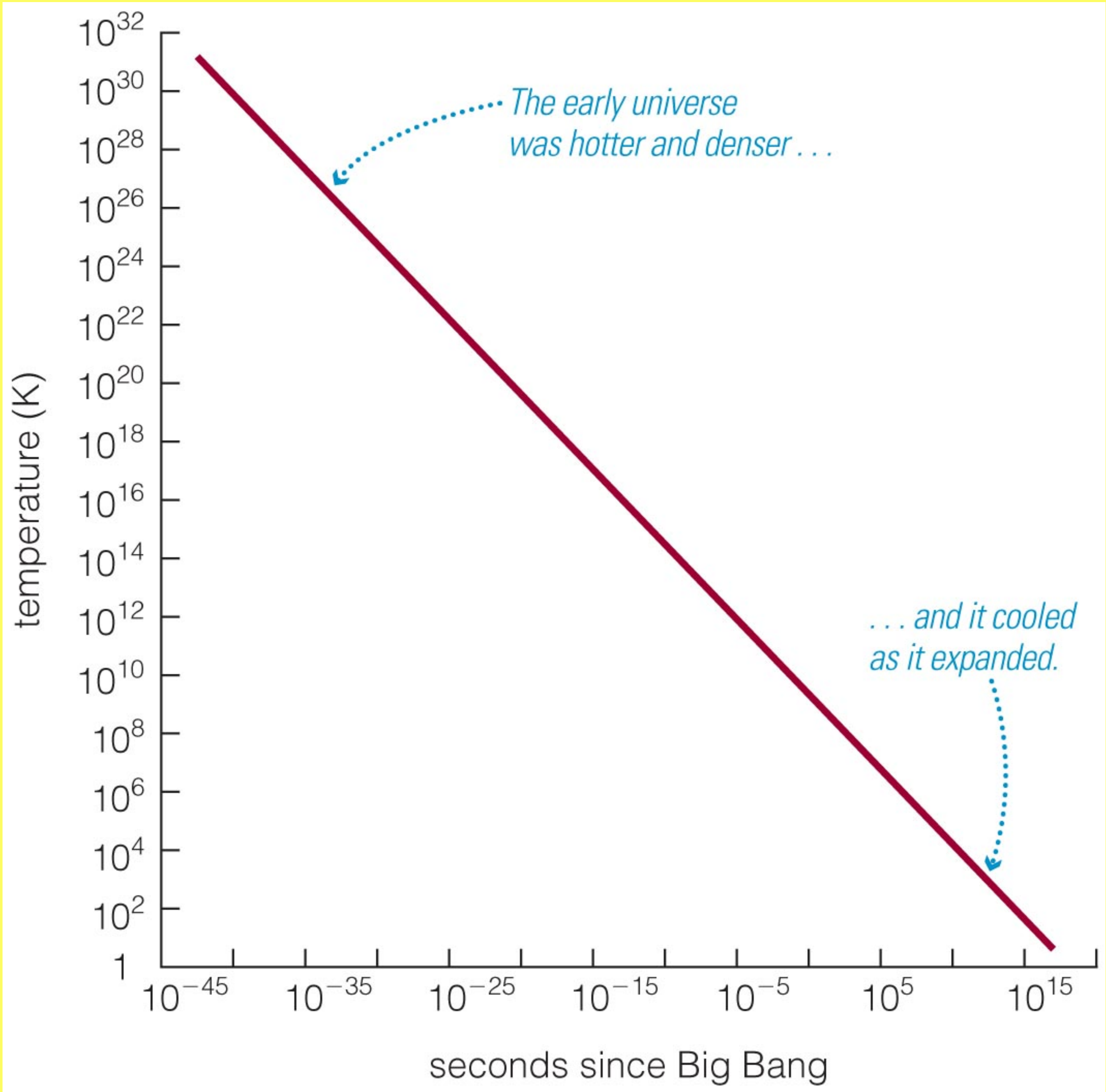
- The Big Bang says
  - The universe started out much smaller
  - It started out much denser and hotter
  - Space has been expanding since the beginning, hence the "bang"
- It does not say there was a huge explosion

If the Friedman Equations are correct

- We should be able to run the clock backwards.
- We should reverse time and make the expansion into a contraction.
- We should be able to go back and say what we should see today if we understand how the universe evolved.
- We should then be able to run it forward and see if what we get is correct.

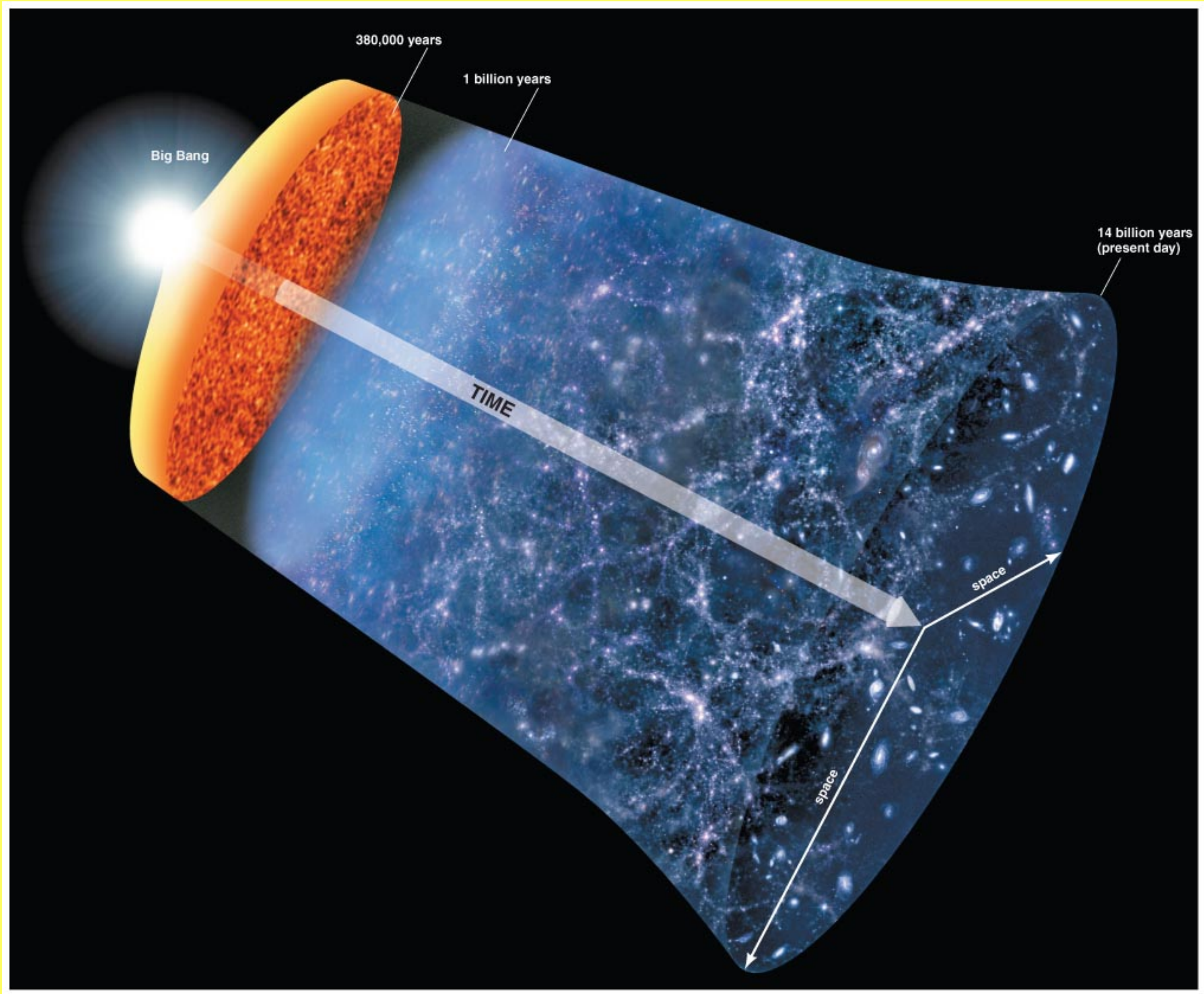
Key Predictions

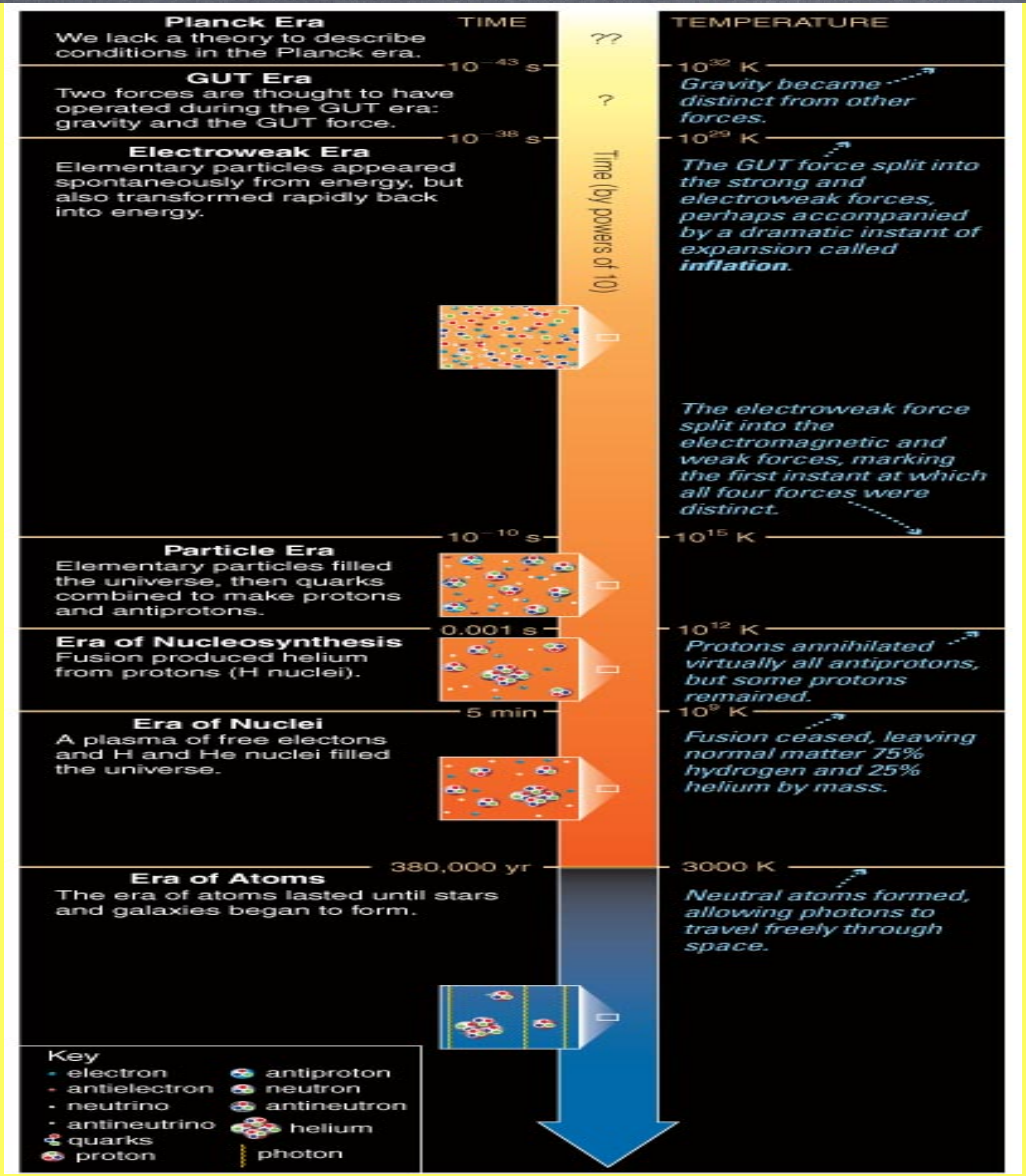
- Elemental Abundances
- Cosmic Microwave Background radiation
- Age of structures and structure formation in the universe
- The universe should be expanding



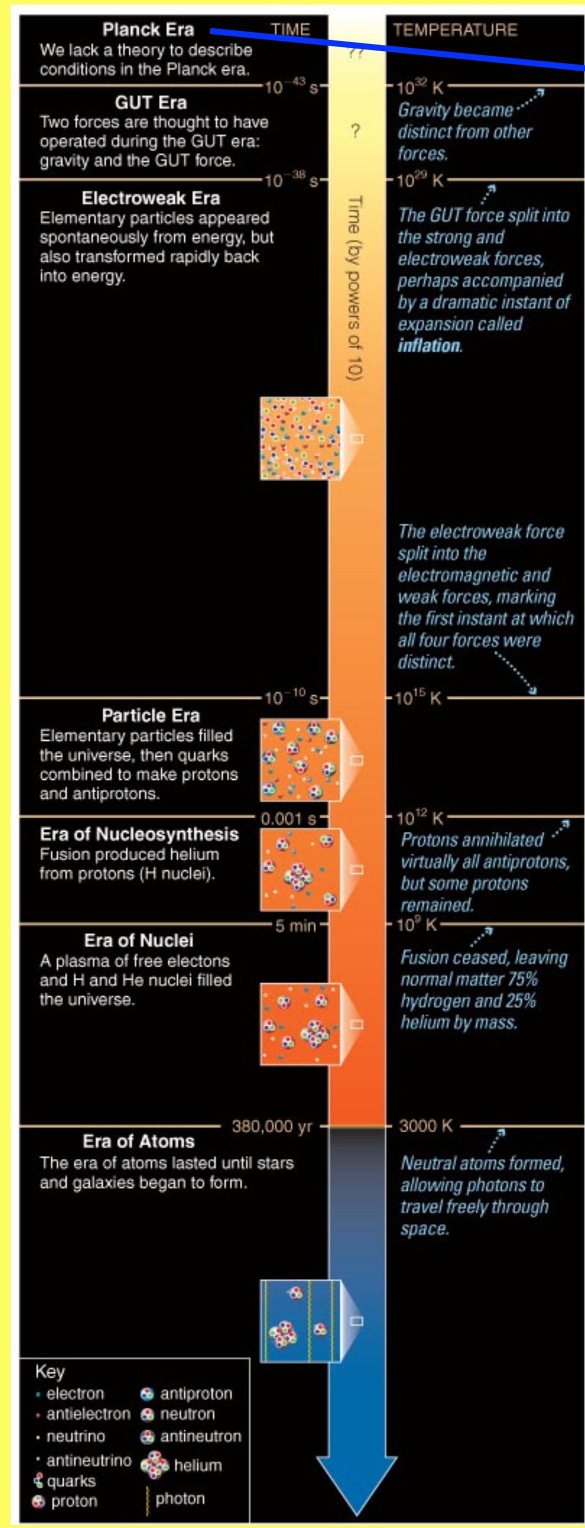
The early universe must have been extremely hot and dense.

What is the history of the universe according to the Big Bang theory?





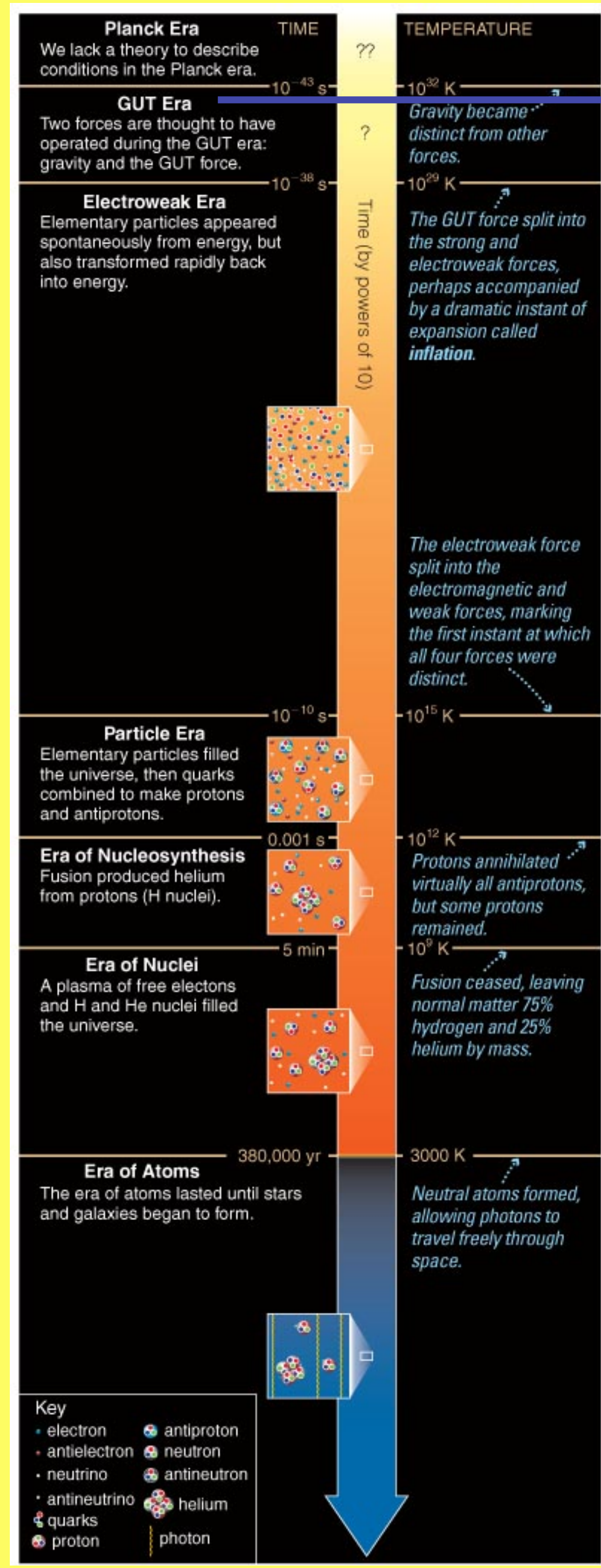
Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
??
TEMPERATURE
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
?
Gravity became distinct from other forces.
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
Time (by powers of 10)
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called **inflation**.
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon



Planck era

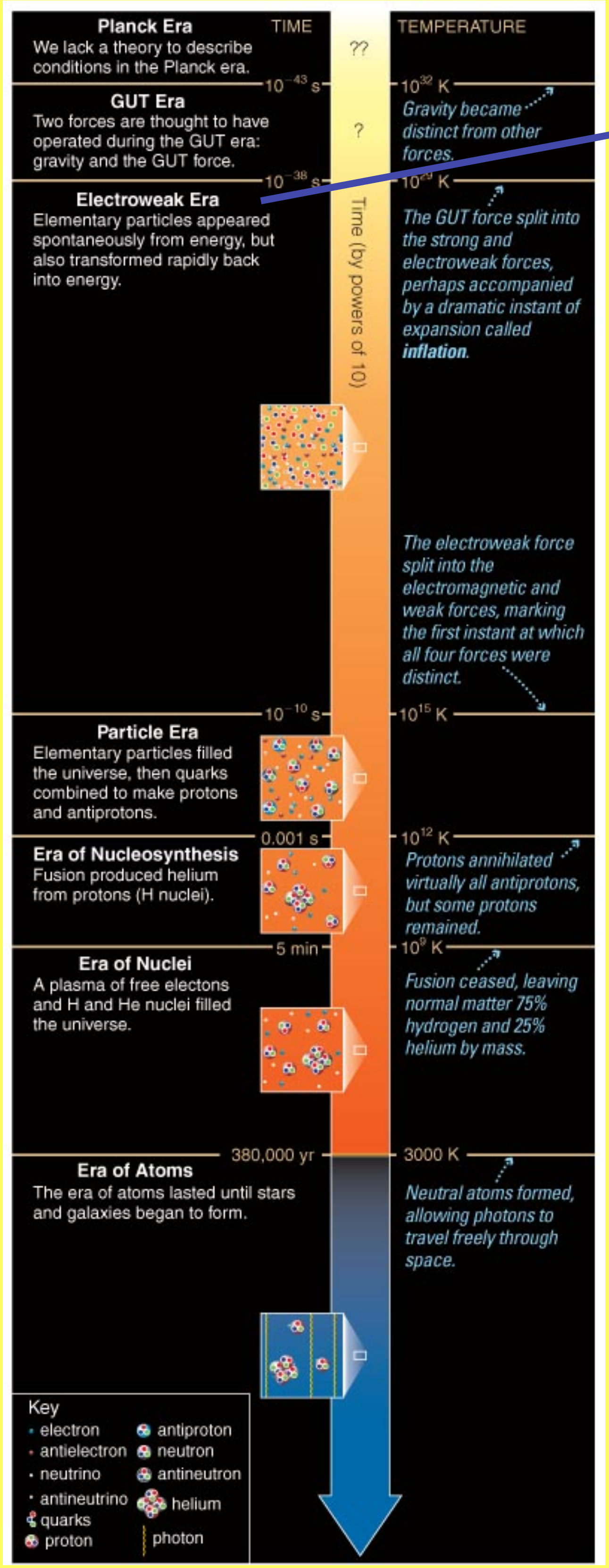
Before Planck time ($\sim 10^{-43}$ second)

No theory of quantum gravity



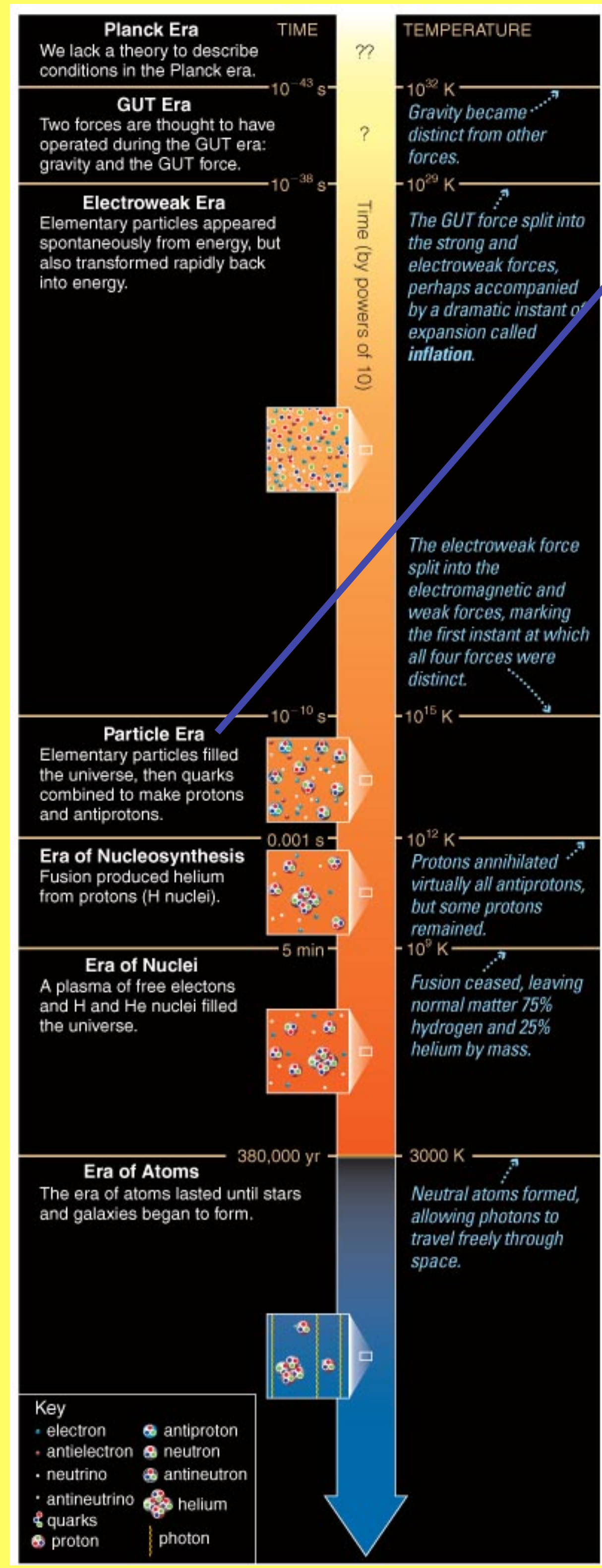
GUT era

Lasts from Planck time ($\sim 10^{-43}$ second) to end of GUT force ($\sim 10^{-38}$ second)



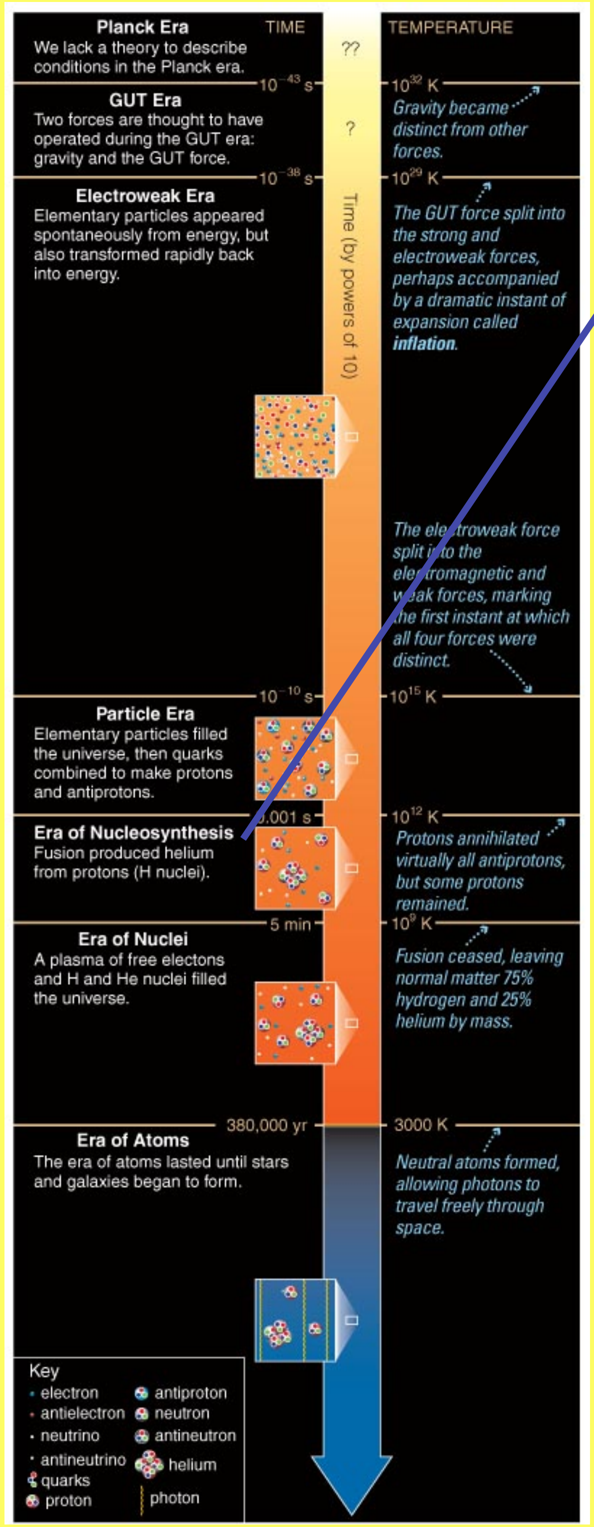
Electroweak era

Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second).



Particle era

Amounts of matter and antimatter nearly equal (roughly 1 extra proton for every 10^9 proton–antiproton pairs!)

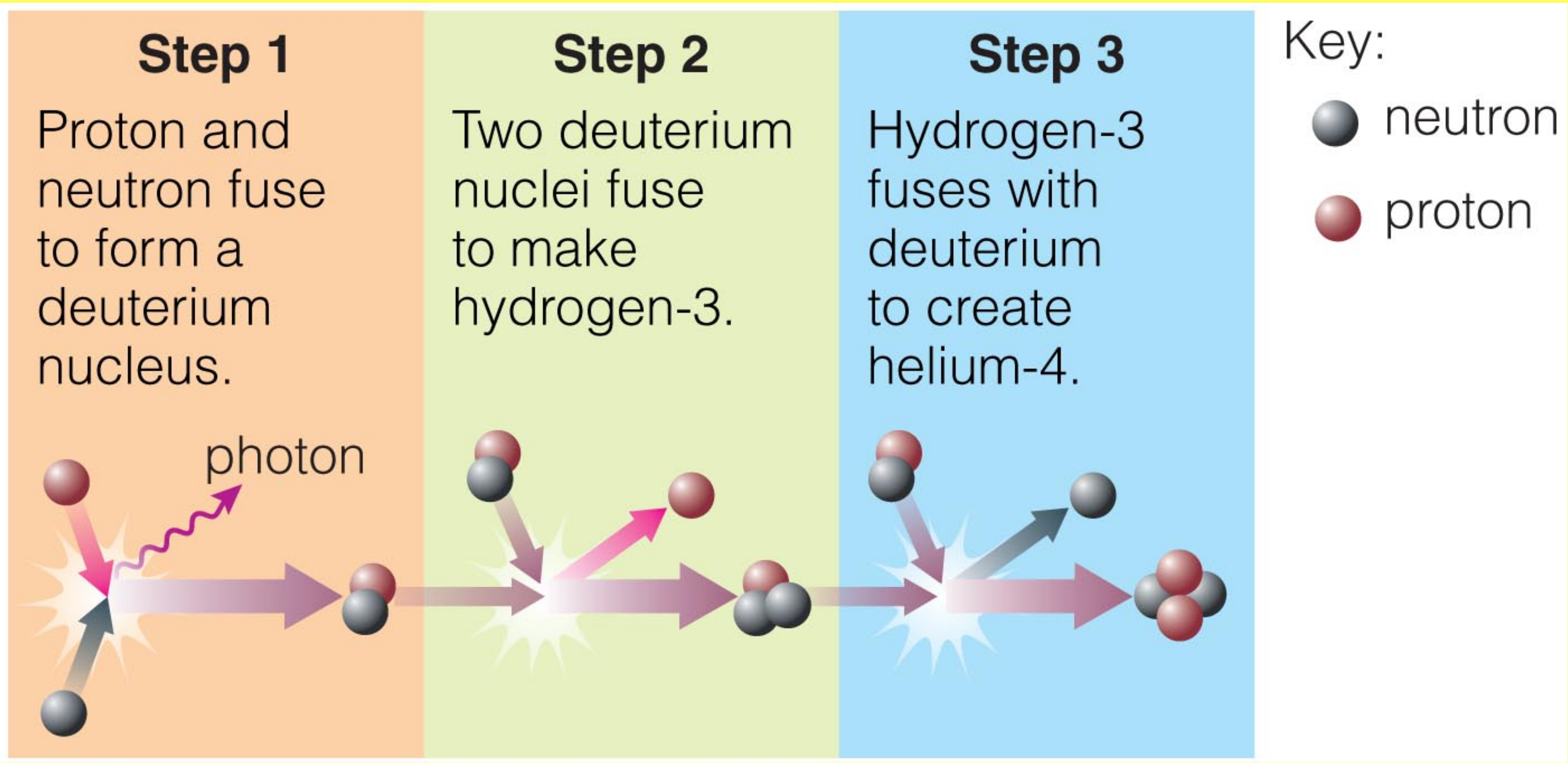


Era of nucleosynthesis

Begins when matter annihilates remaining antimatter at ~ 0.001 second.

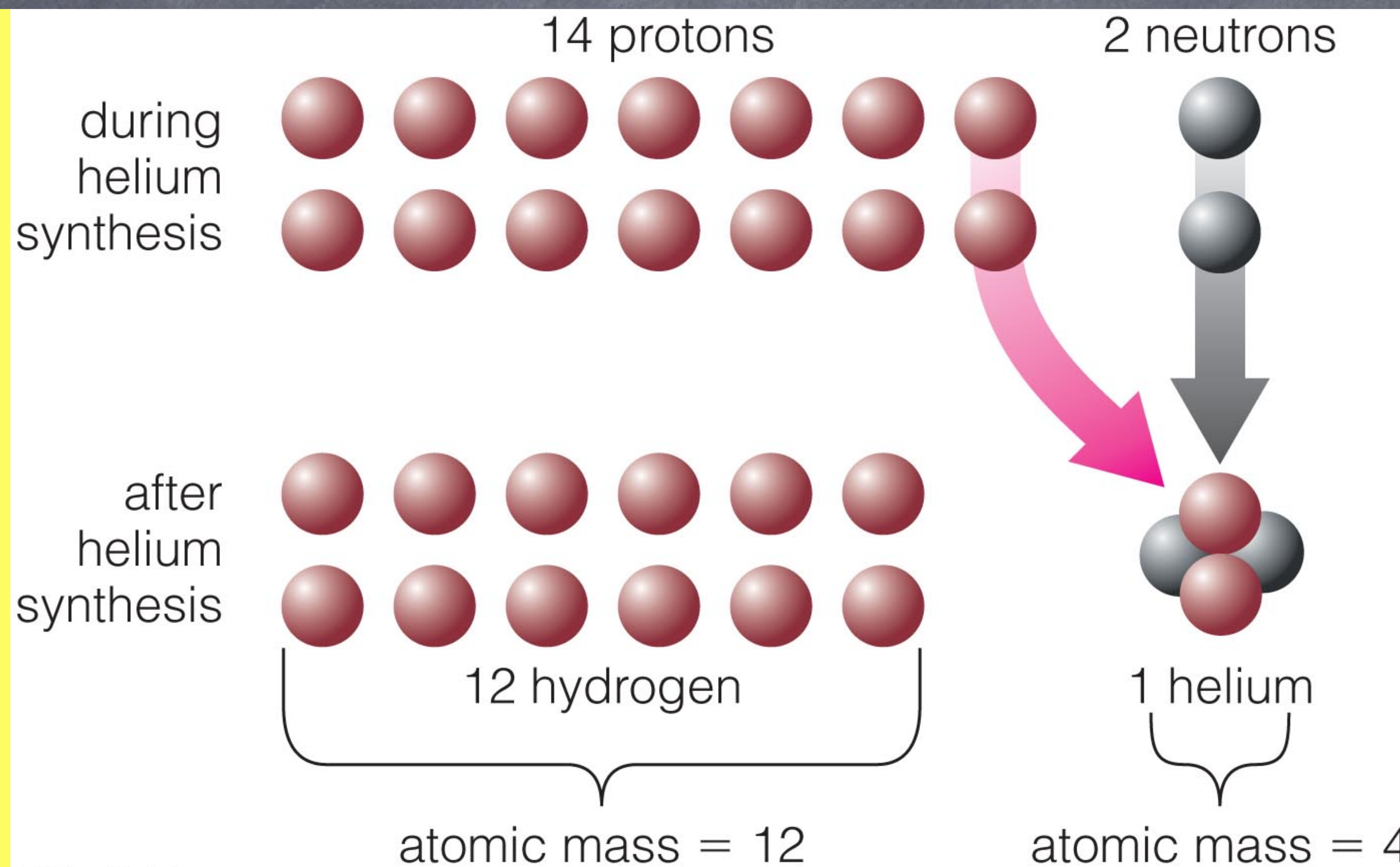
Nuclei begin to fuse.

Prediction 1 Elemental Abundances

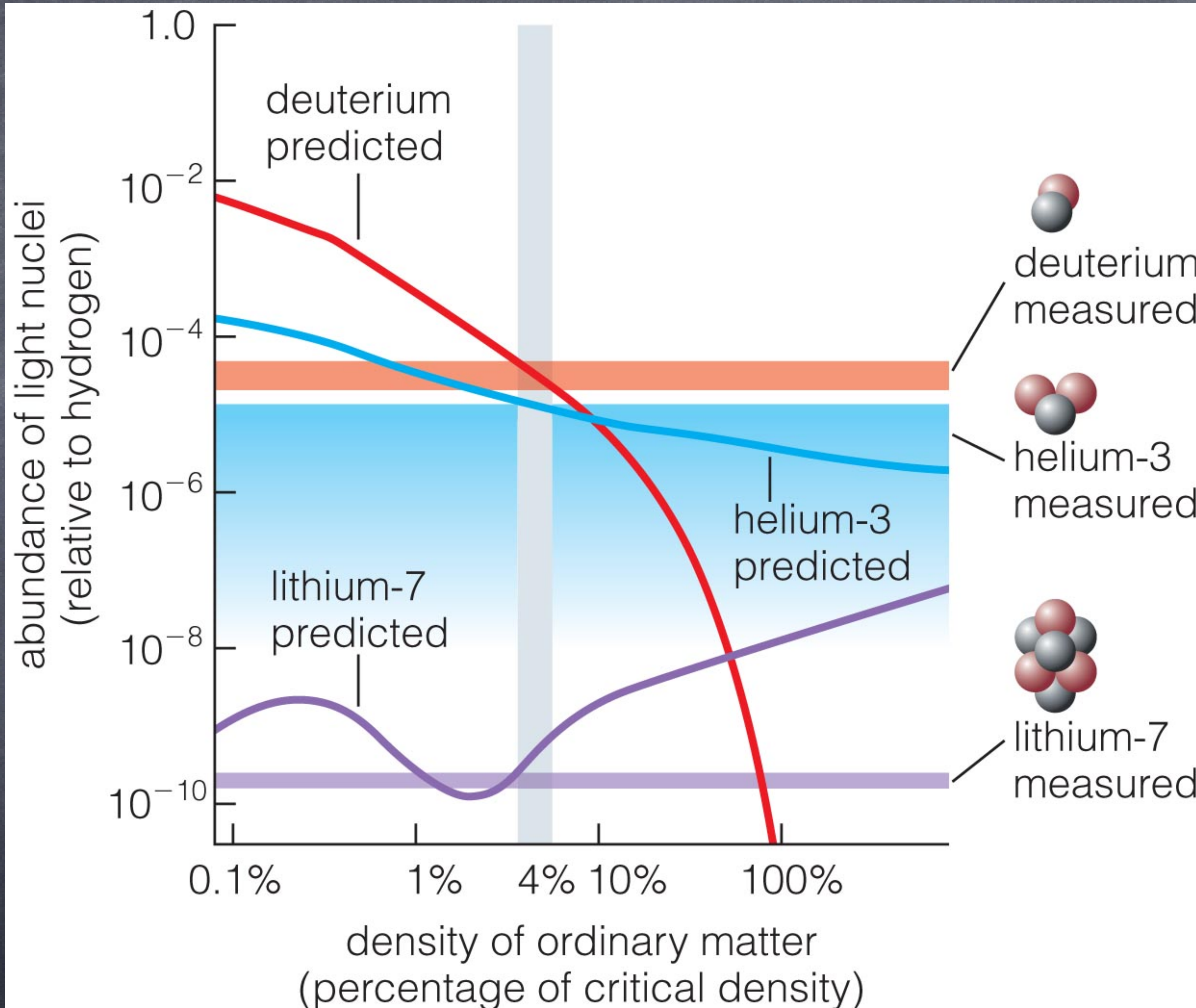


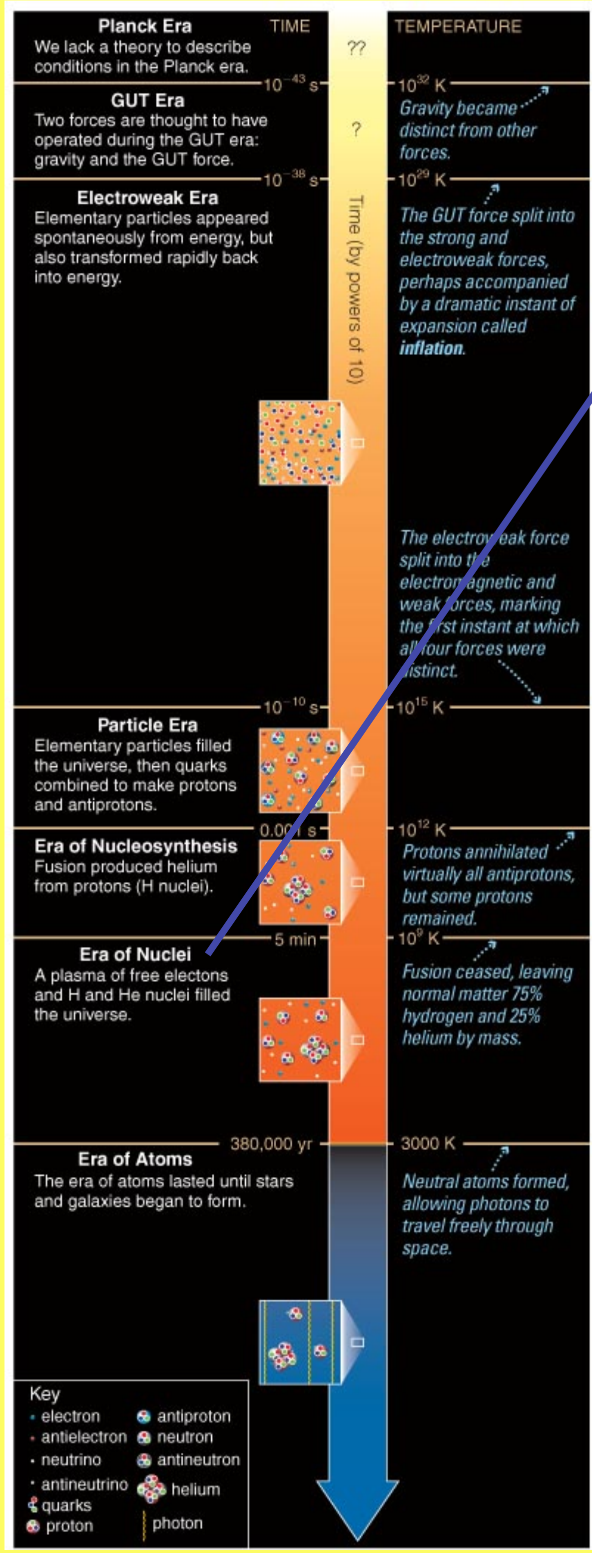
Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old.

Hydrogen and Helium



Big Bang theory prediction: 75% H, 25% He (by mass).
This prediction matches observations of primordial gases.


1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
abundance of light nuclei
(relative to hydrogen)
deuterium
predicted
helium-3
predicted
lithium-7
predicted
deuterium
measured
helium-3
measured
lithium-7
measured
0.1%
1%
4%
10%
100%
density of ordinary matter
(percentage of critical density)



Era of nuclei

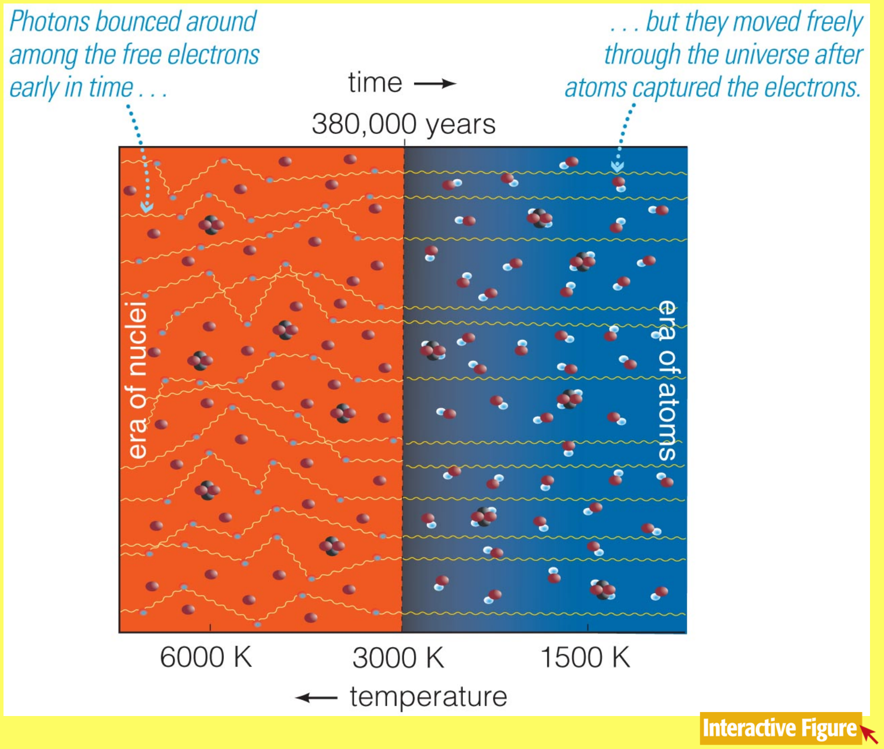
Helium nuclei form at age ~ 3 minutes.

Universe became too cool to blast helium apart.

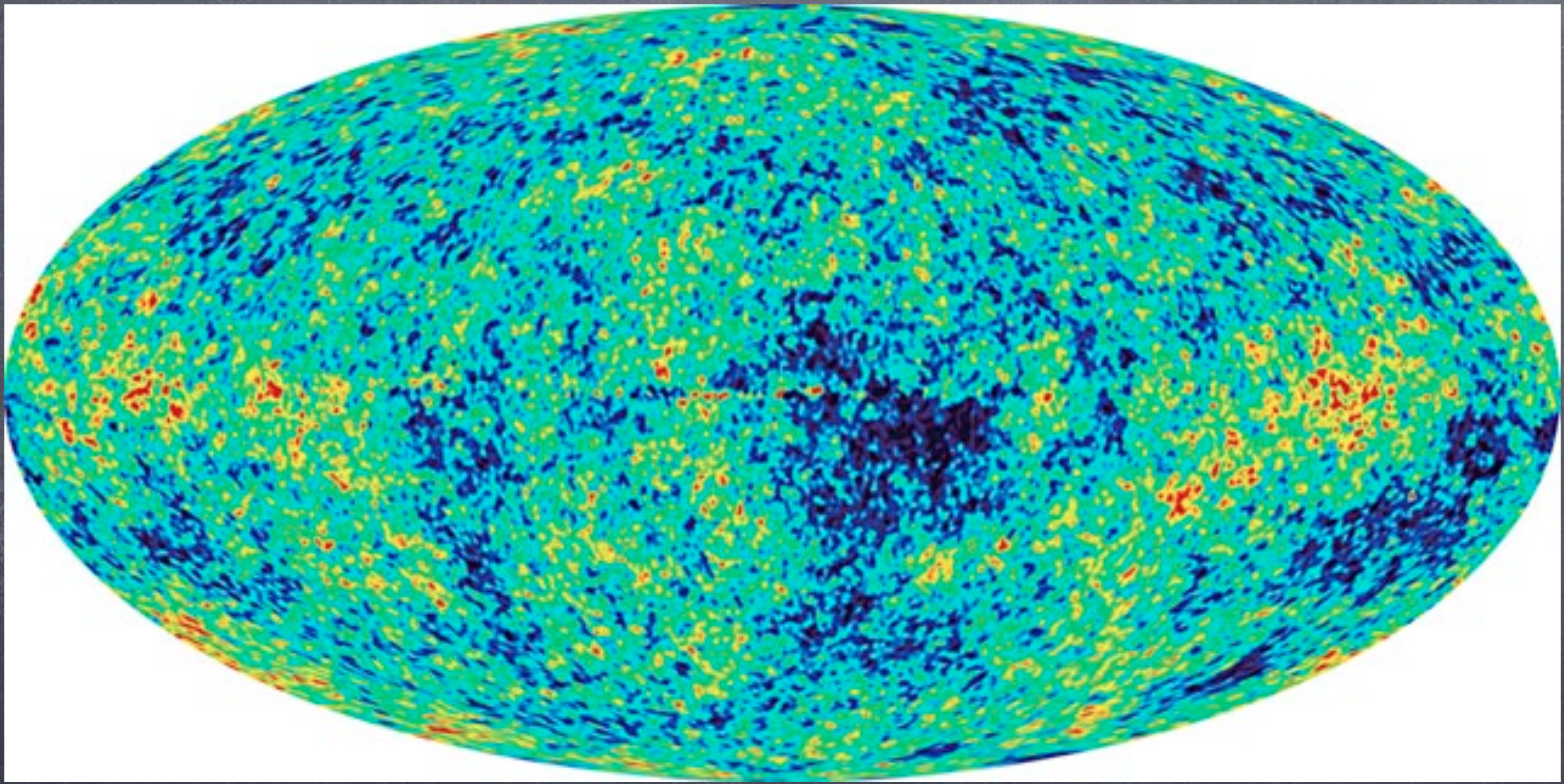
Prediction 2 CMB

Cosmic Microwave Back Ground Radiation

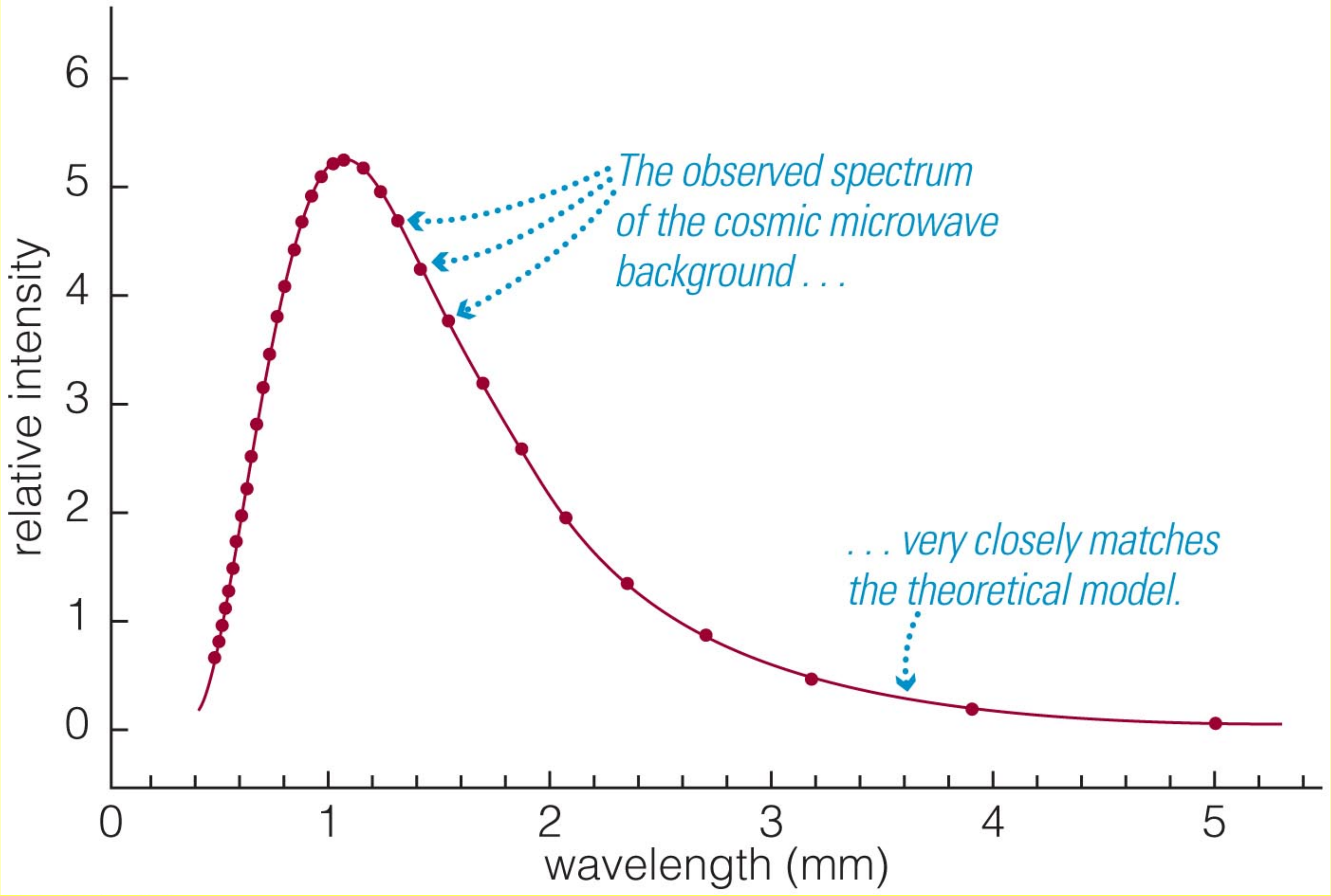
- If we knew how hot it was then we know how much it should have cooled to by now.



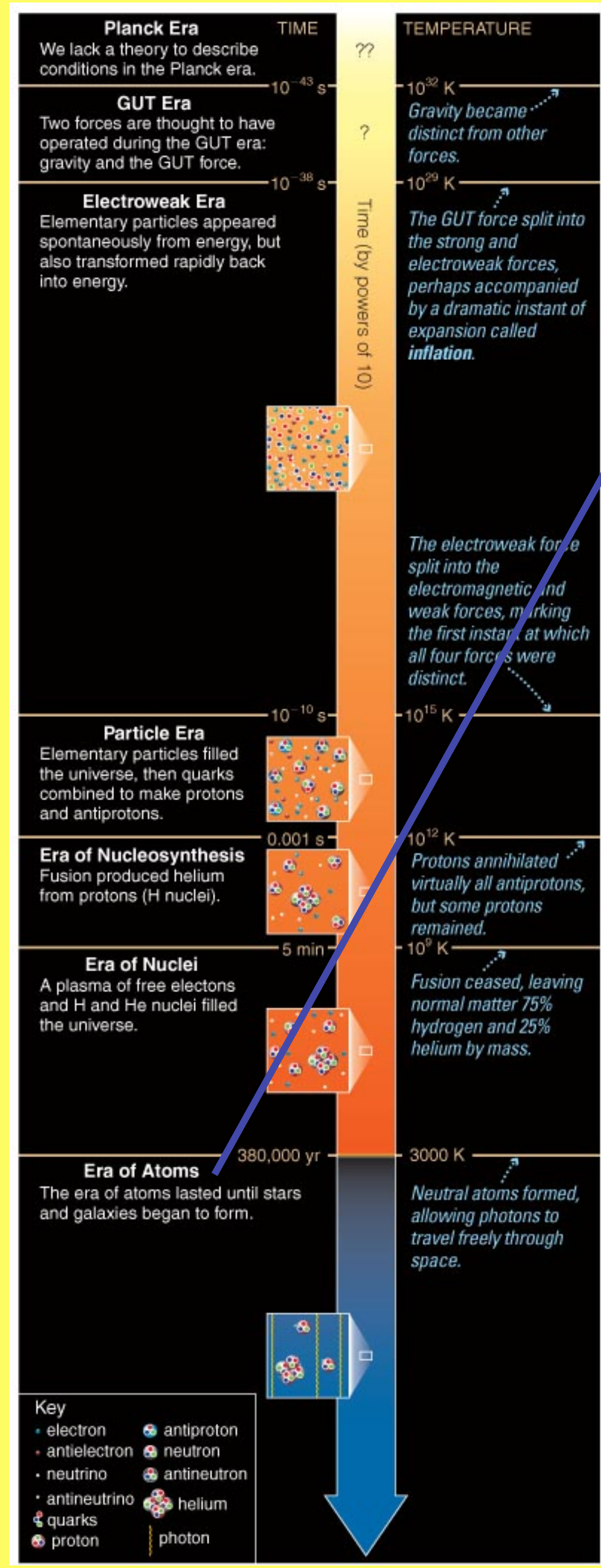
Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3000 K: *visible/IR.*



Background has perfect thermal radiation spectrum at temperature 2.73 K.



Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves.*



Era of atoms

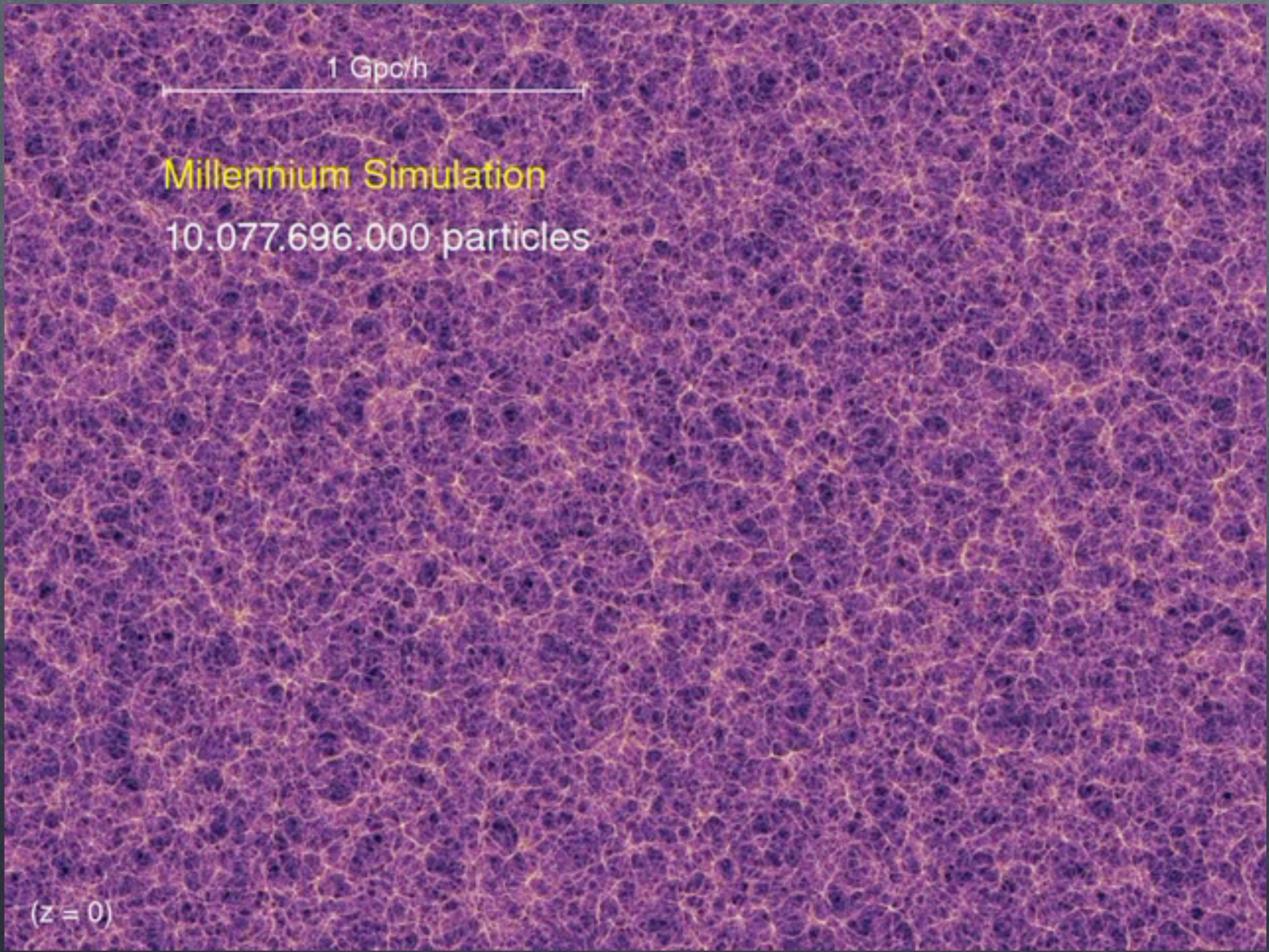
Atoms form at age ~ 380,000 years.

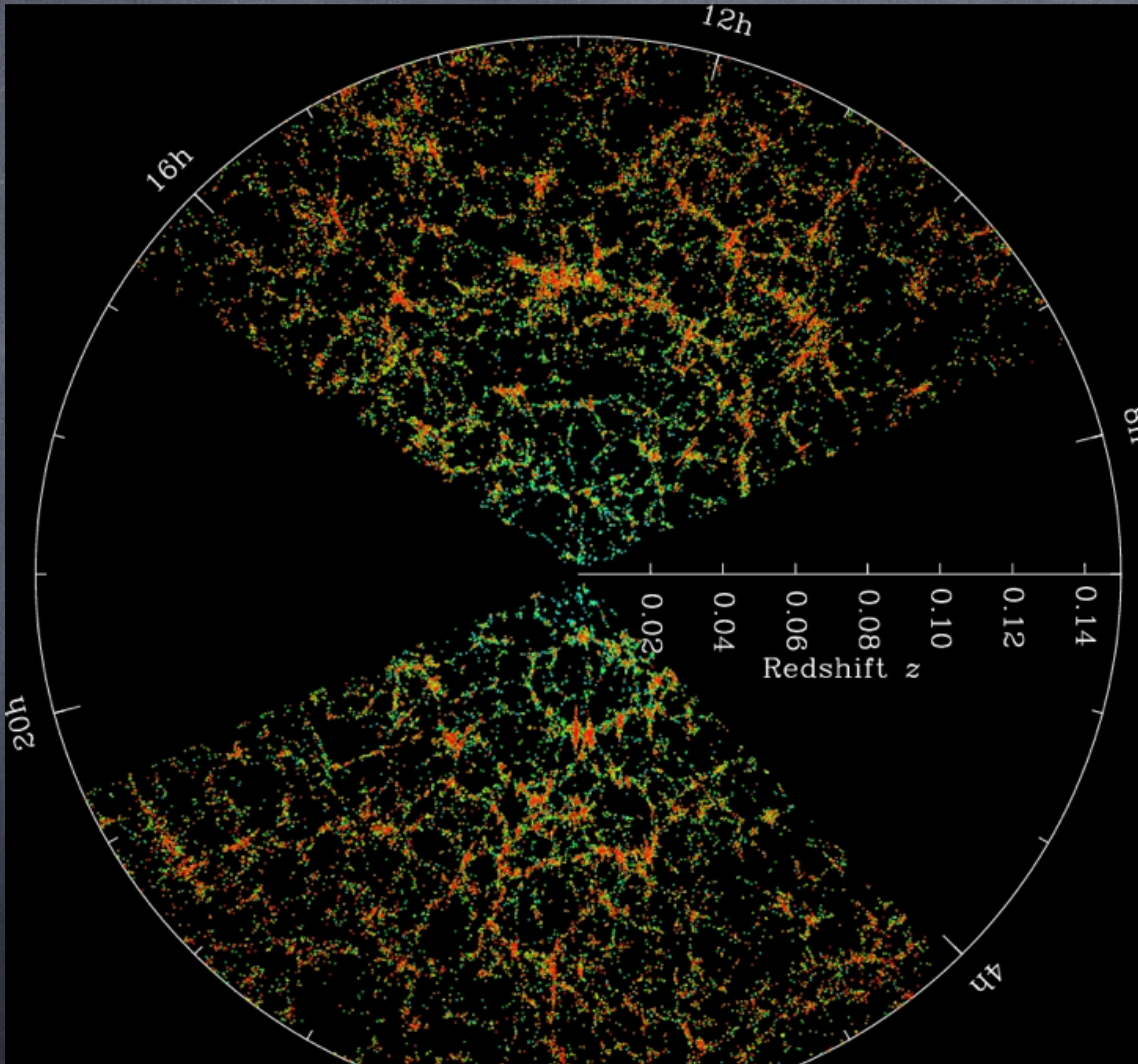
Background radiation released.

Then All Was Dark

- Until, reionization, the first stars start to form, the universe lights back up.
- Structure forms.

Prediction 3 Structure Formation

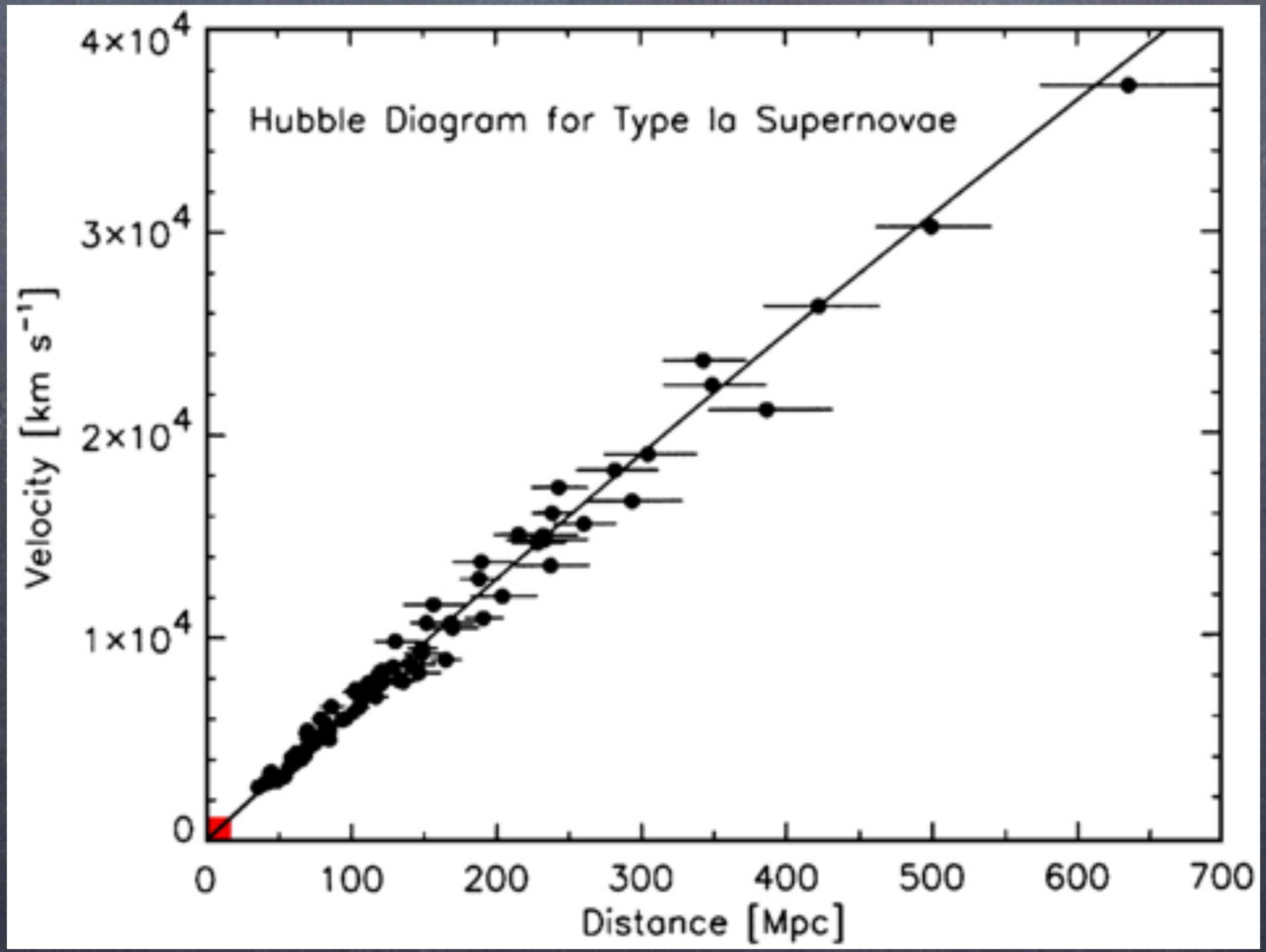

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)


12h
16h
8h
20h
4h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Prediction 4 - Expansion

And we see expansion

- Redshift of all distant things, Hubble's Law



There are problems with the big bang

- They are fixed by something called inflation

Mysteries Needing Explanation

1) **Where does structure come from?**

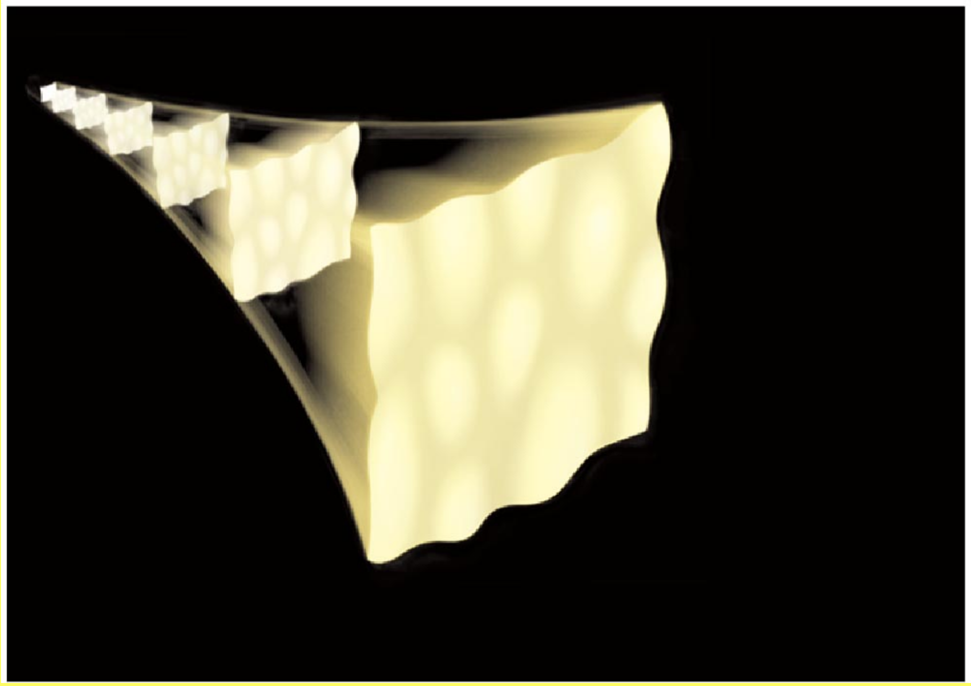
2) **Why is the overall distribution of matter so uniform?**

3) **Why is the density of the universe so close to the critical density?**

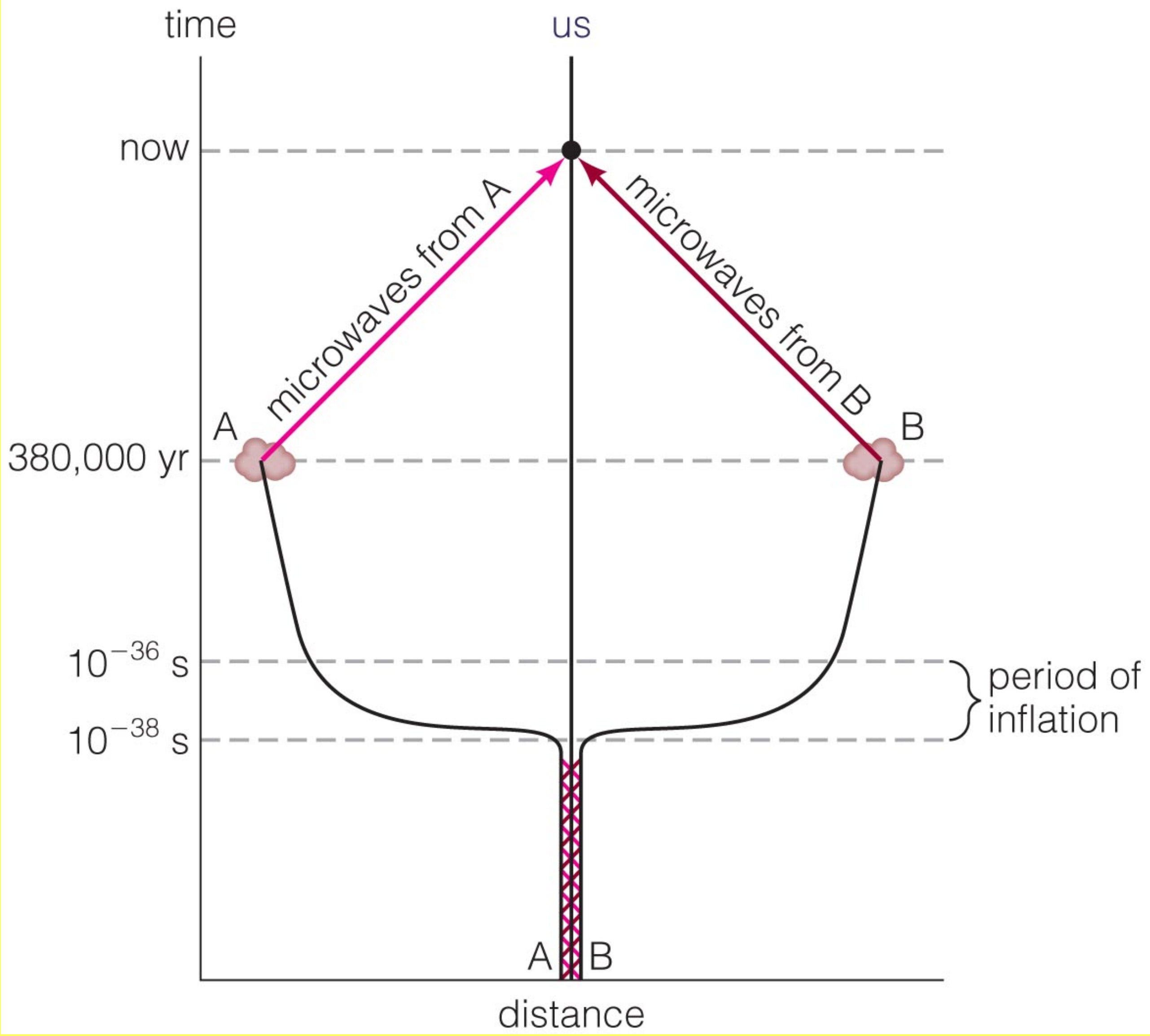
An early episode of rapid inflation can solve all three mysteries!

Solution

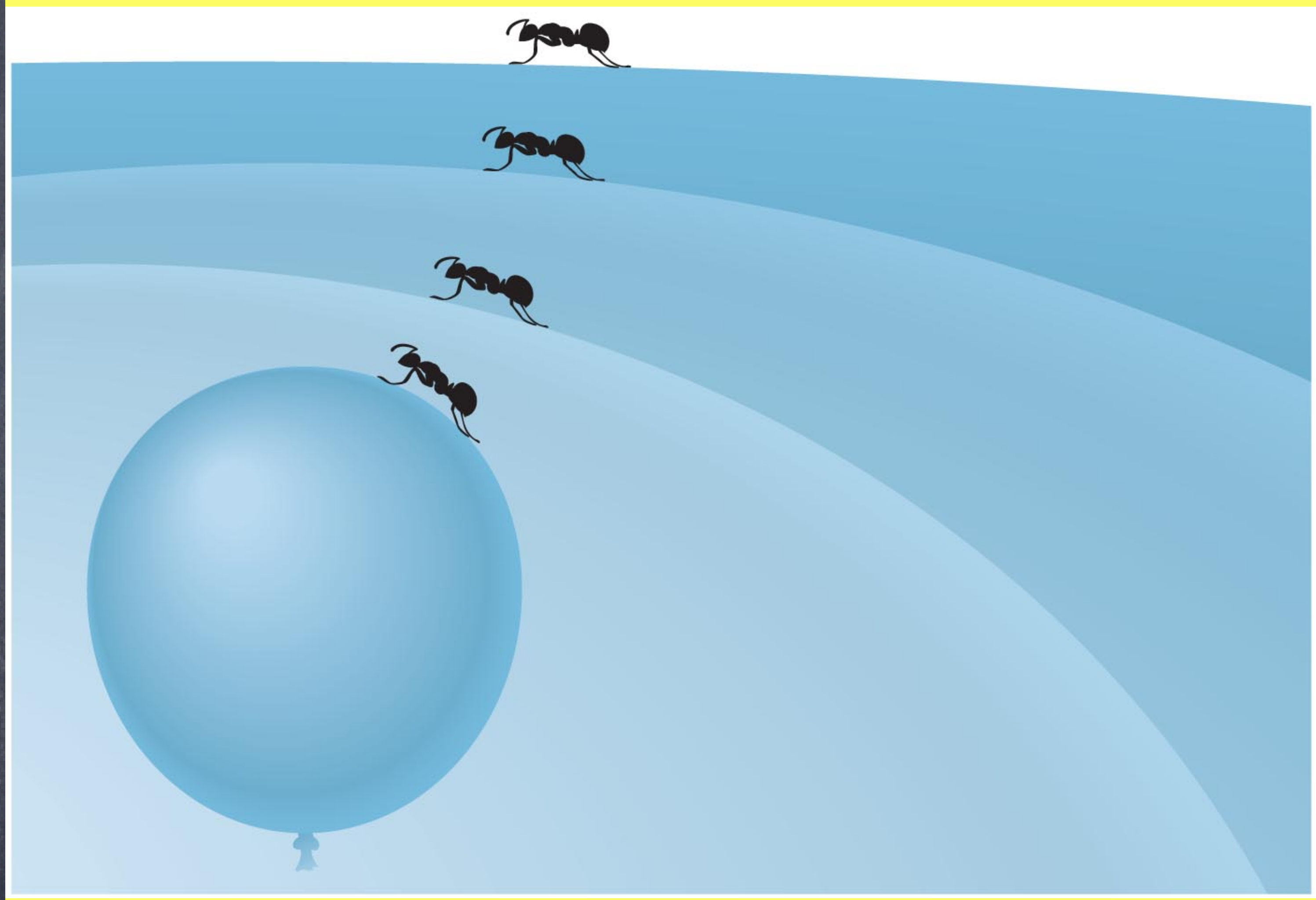
- Inflation
- Universe grew by 10^{78} in volume between 10^{-36} and 10^{-33} seconds



Inflation can make all the structure by stretching tiny quantum ripples to enormous size.
These ripples in density then become the seeds for all structures in the universe.



Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

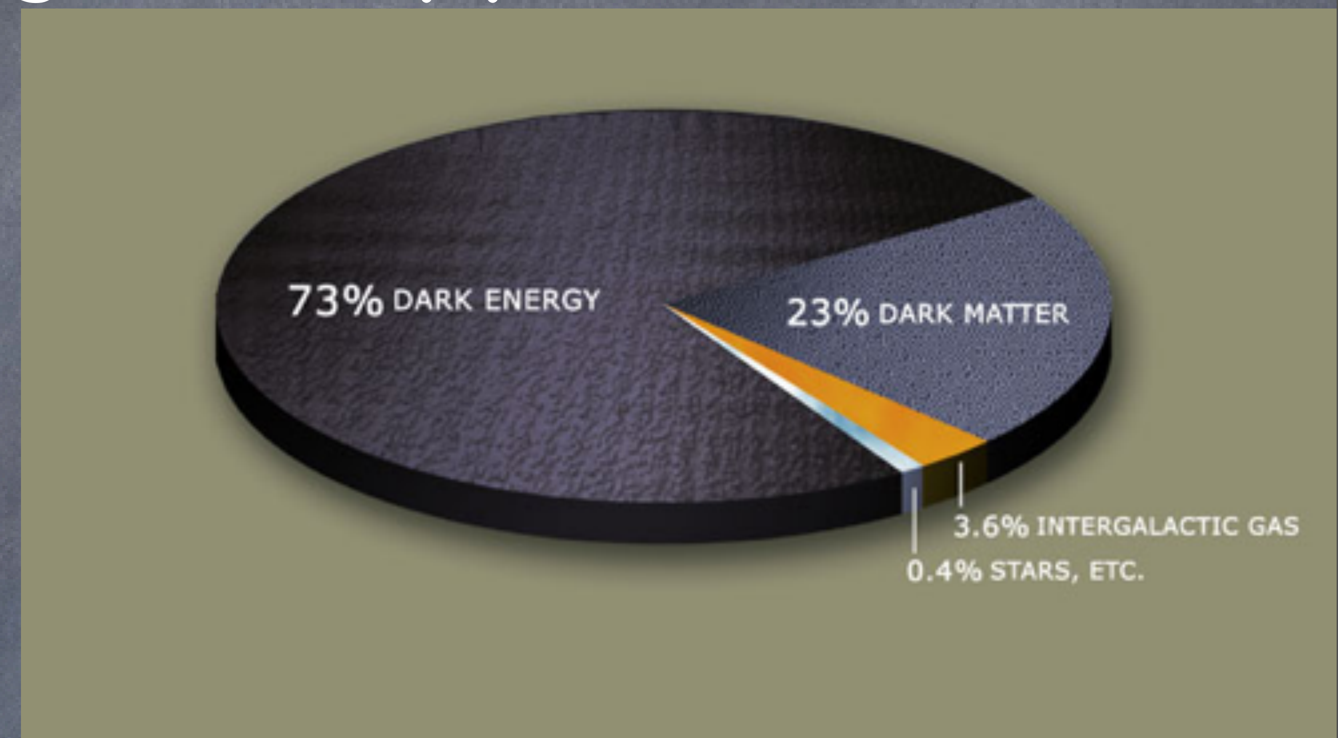


Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

So what's next?

- Add up all the mass and energy in the universe and run the clock forward.

We add up all the "stuff" in the universe to see what's going to happen to it



As fractions of density

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$\Omega = 1$ $k = 0$ flat, almost perfectly

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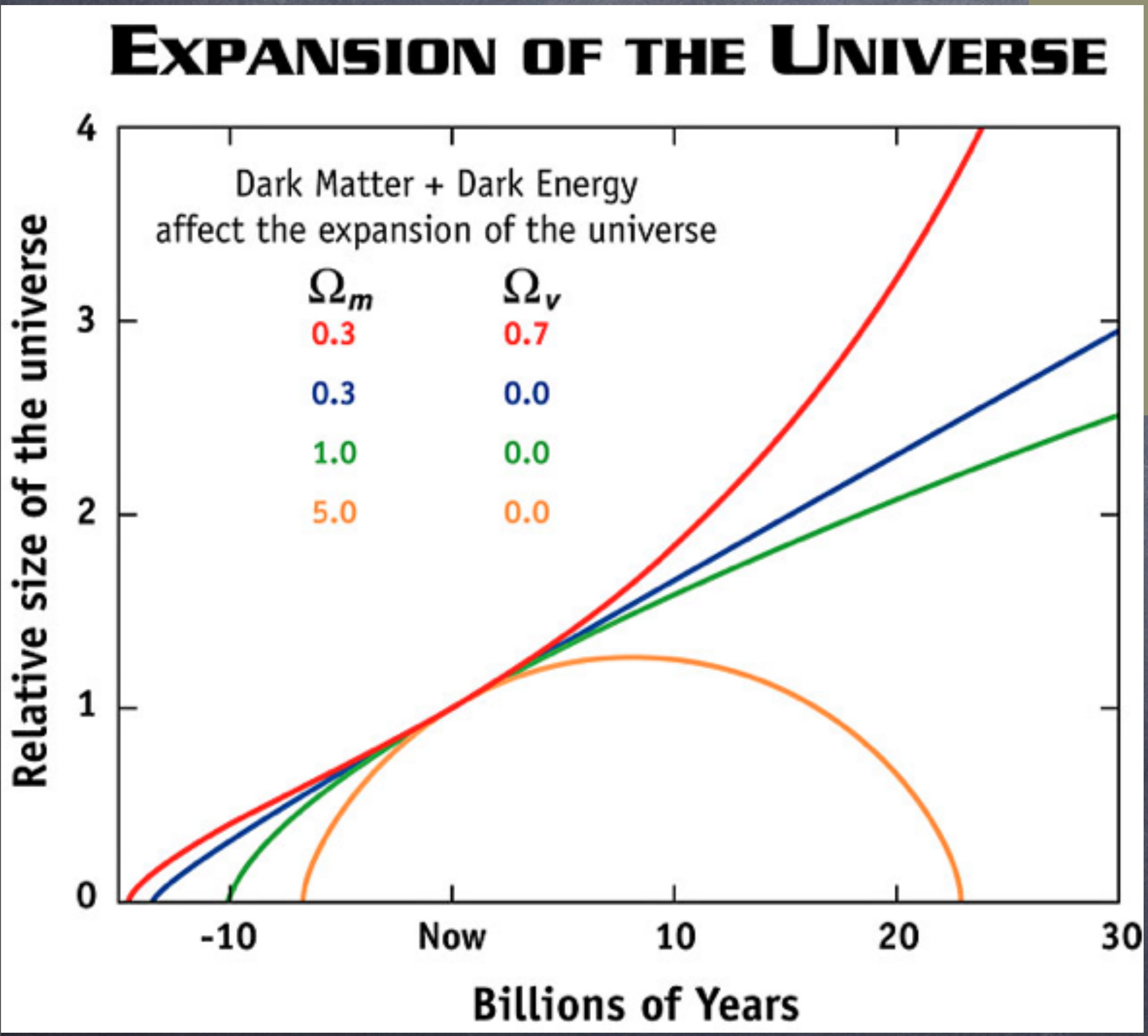

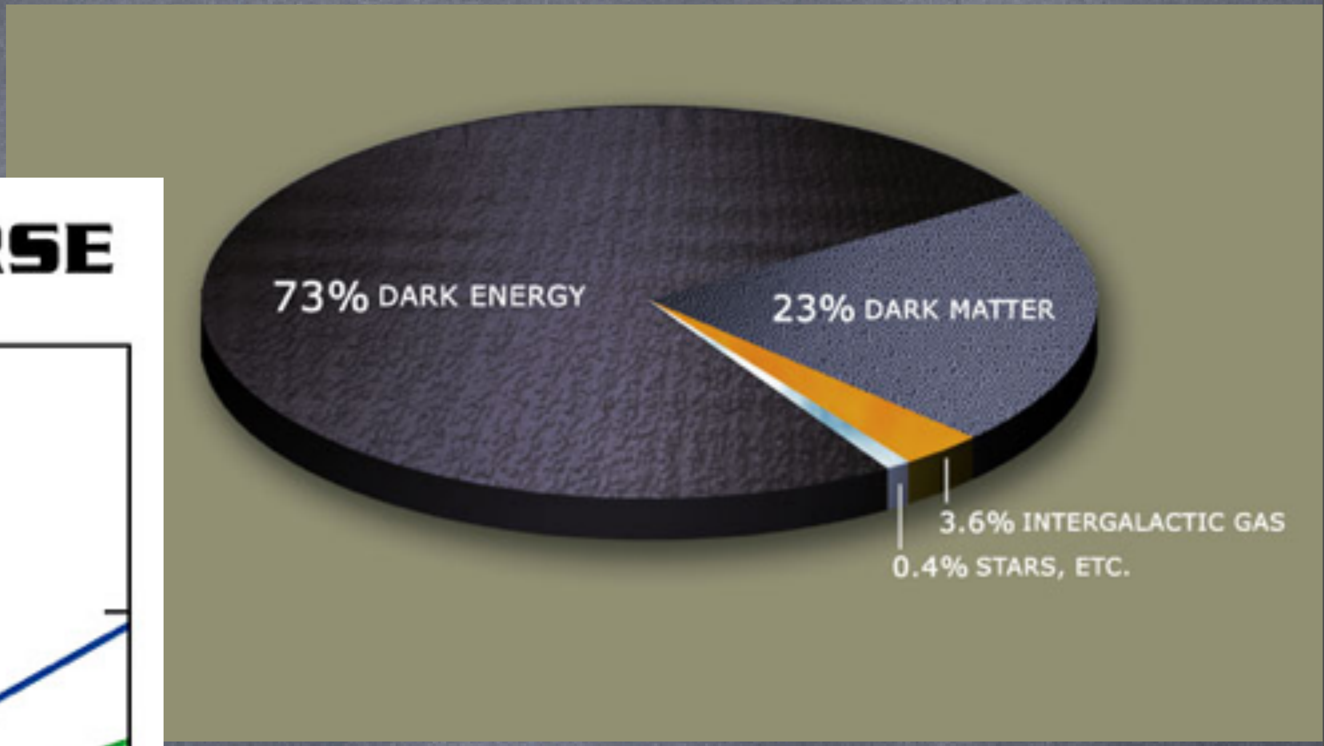

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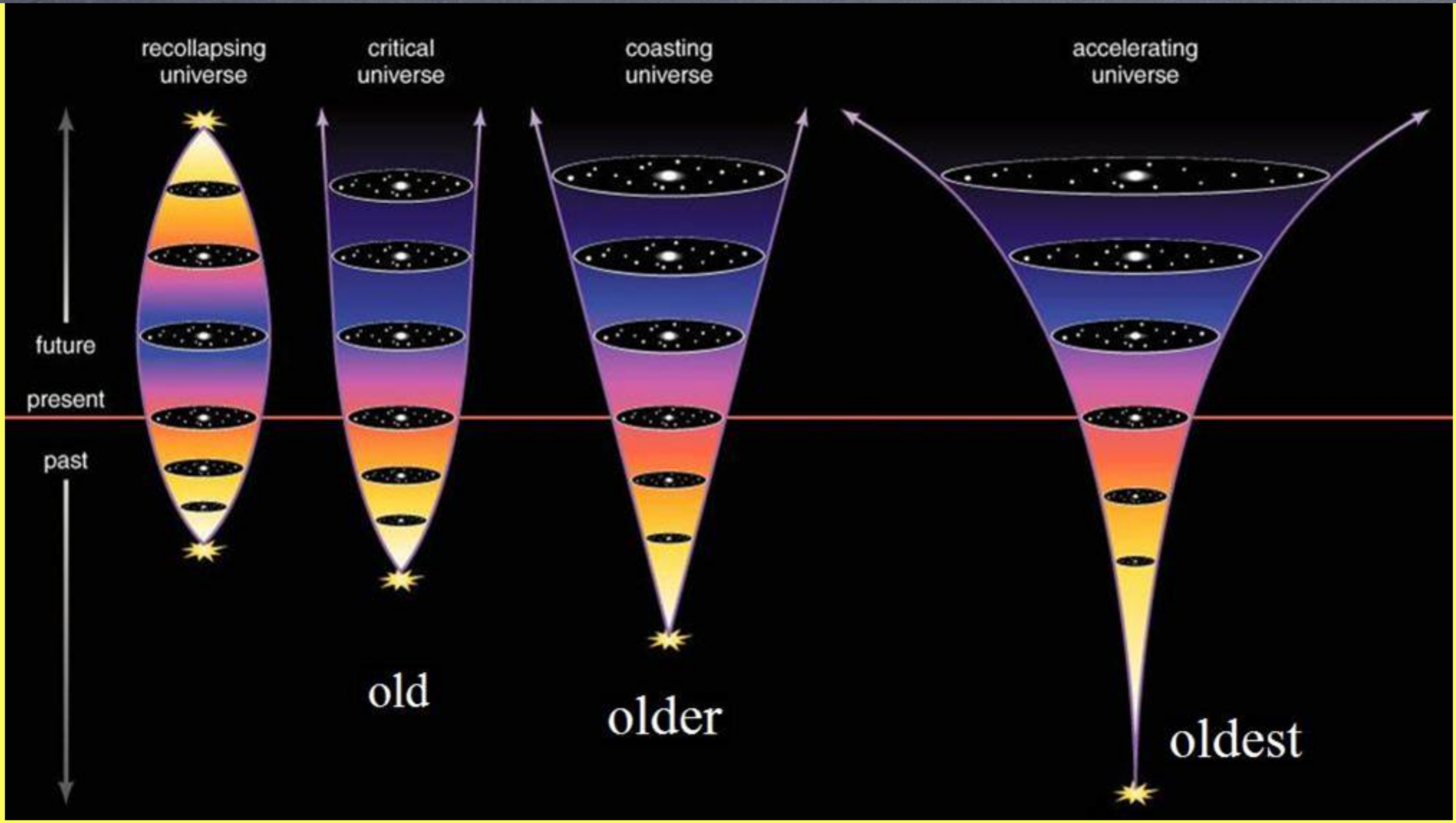

Fate depends on amount of stuff in the universe

Strange new things

Galaxy Rotation Curves

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- If galactic mass follows light then most material would orbit with a Keplerian velocity $v \simeq r^{-1/2}$, we see $v \simeq$ constant

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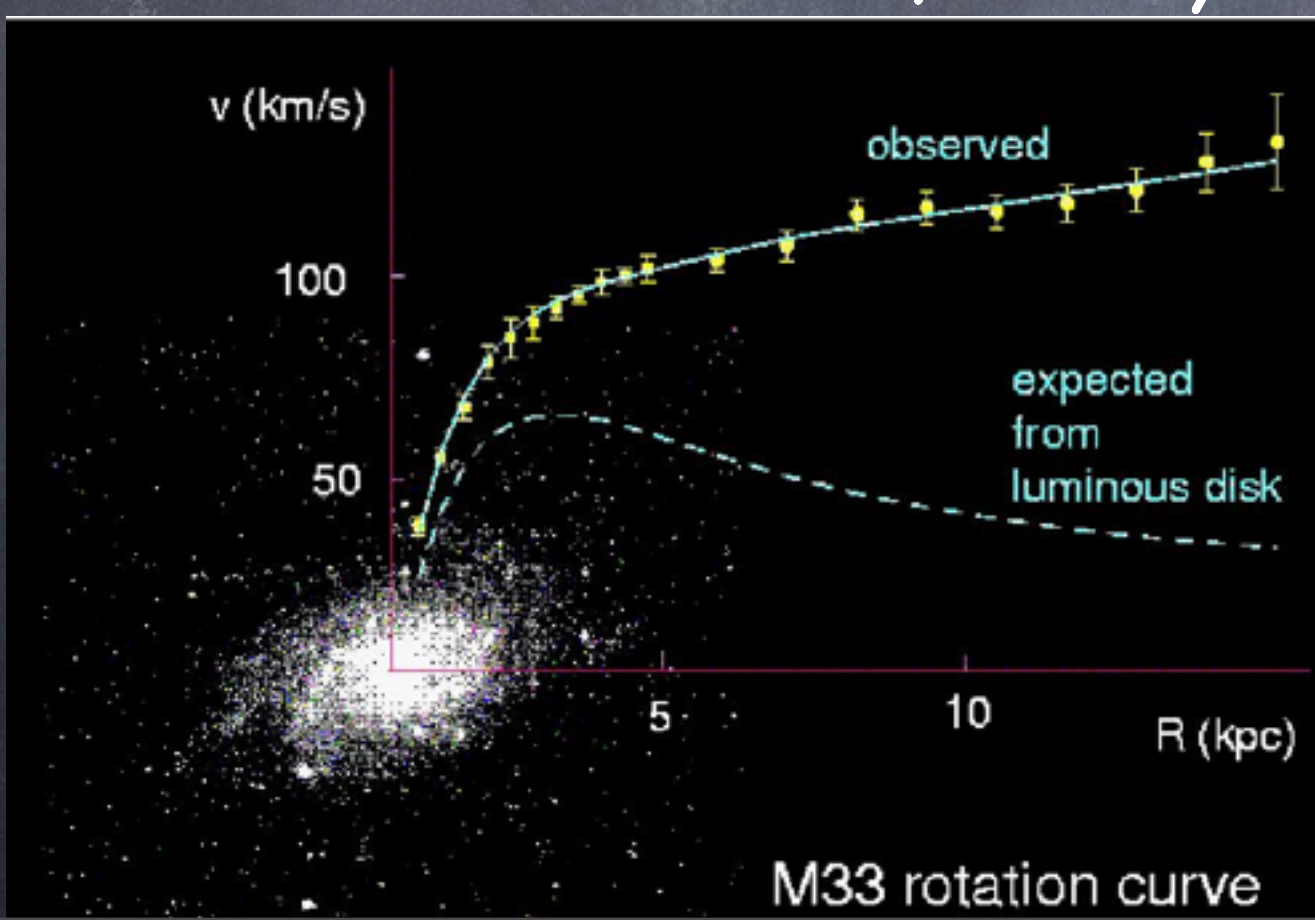

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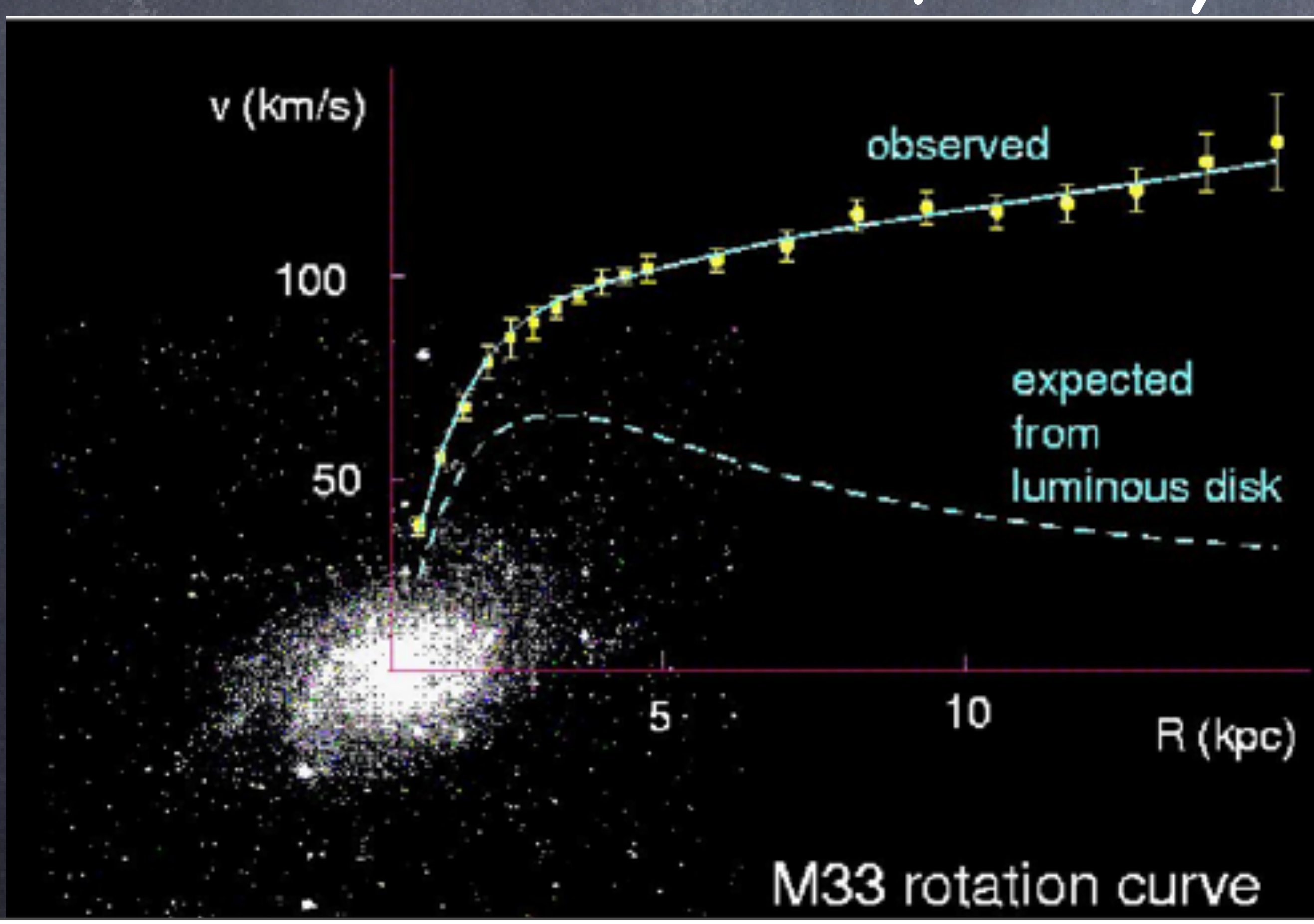
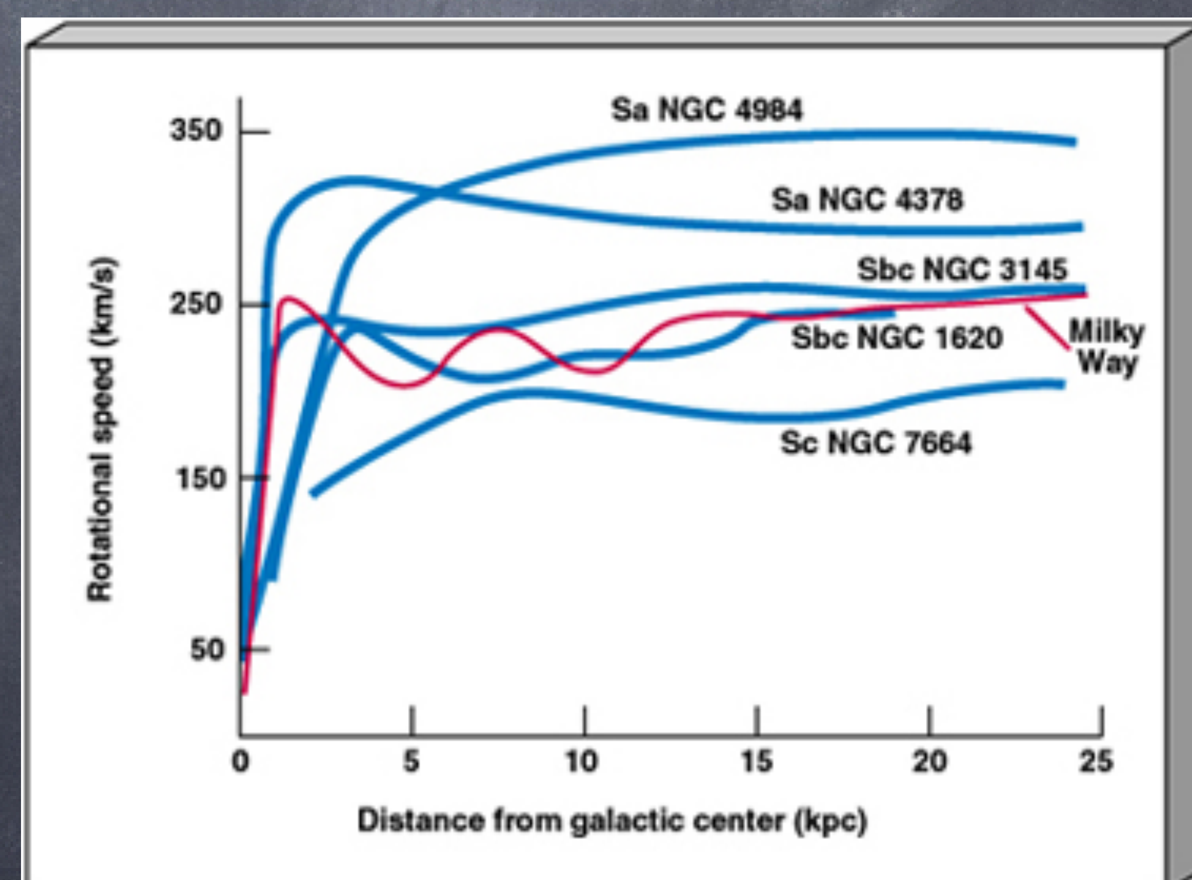
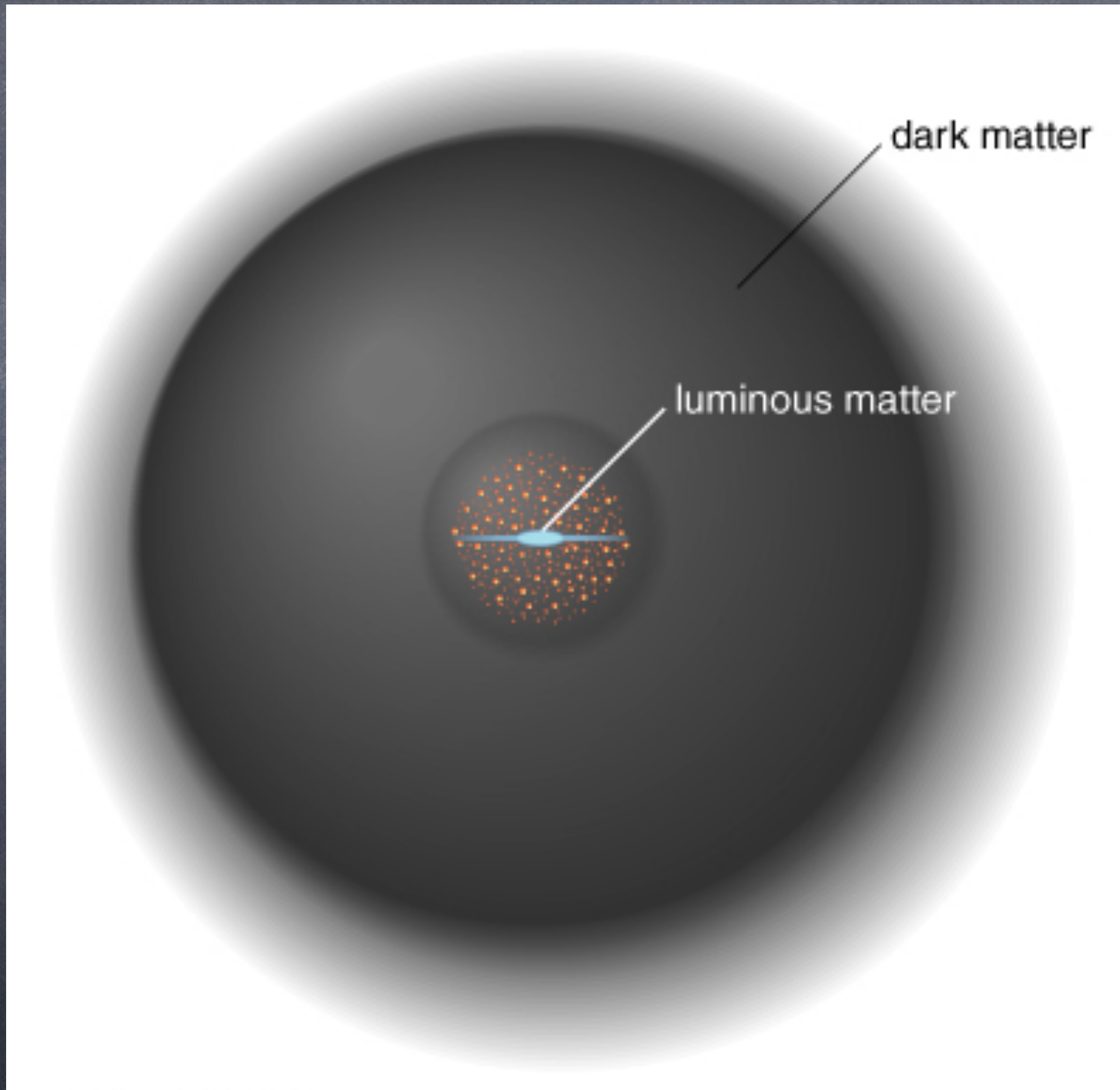





dark matter
luminous matter

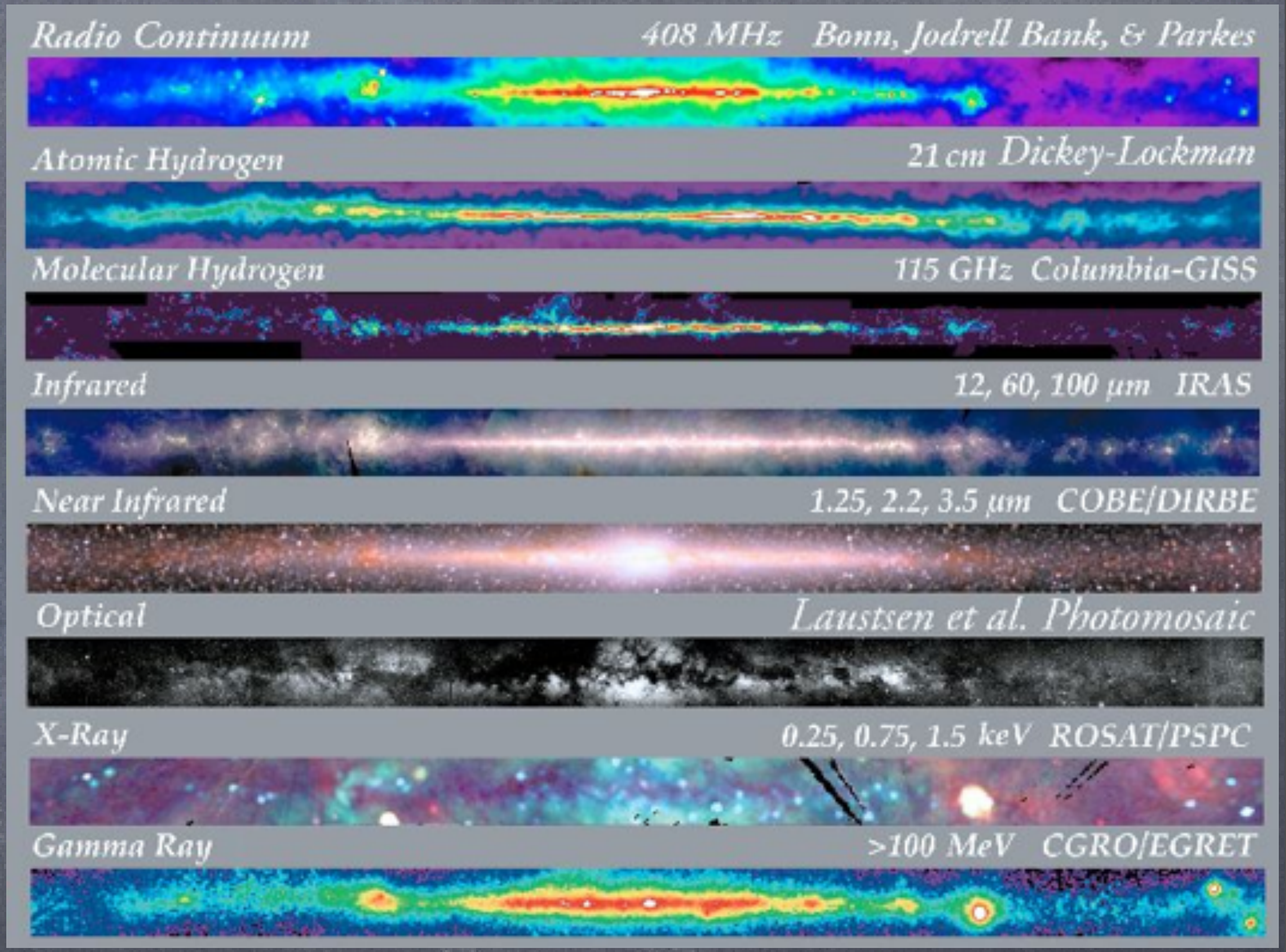
CONVERGENT EVIDENCE

- Newtonian Gravity
- Einstienian Gravity
- Virial Equilibrium
- Thermodynamics
- Structure Formation
- CMB power spectrum

- Coming to the same answer from several different starting points is what we want in science
  - DM **almost** universally accepted in astrophysics

Dark Matter is just

- Some form of matter that is too dim to see, too fast/weakly interacting to see, or simply does not interact with the electromagnetic force
- No problem with option three, leptons do not participate in strong interactions, not all matter interacts with all forces (except gravity)

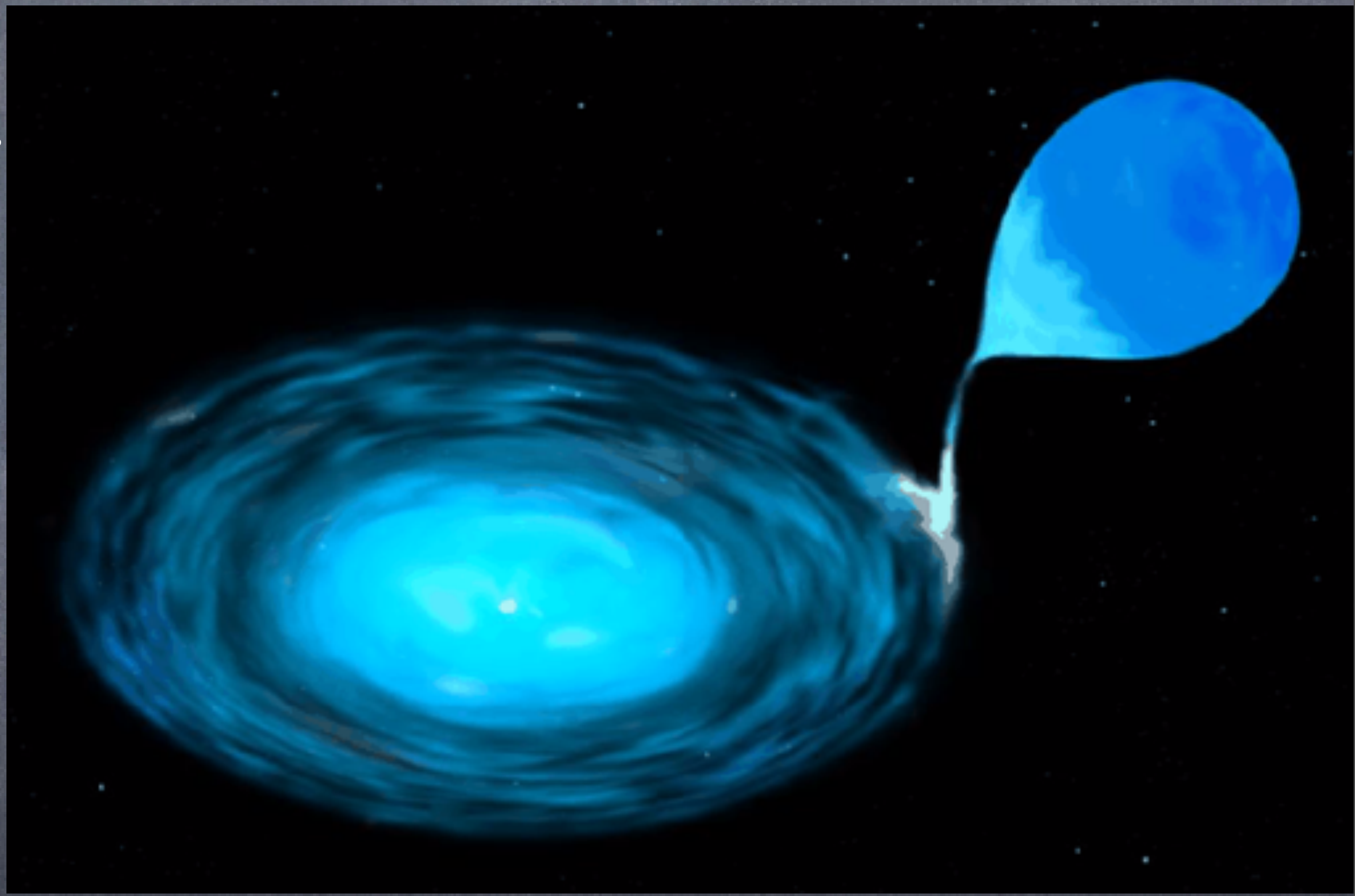


Not Dark Matter ☝

Even weirder, Dark Energy

Standard Candles

- Astrophysical phenomenon used to determine distance
- Type 1a supernovae are very good, very luminous, probe the farthest distances well and relate distance to recessional velocity to confirm Hubble's Law.



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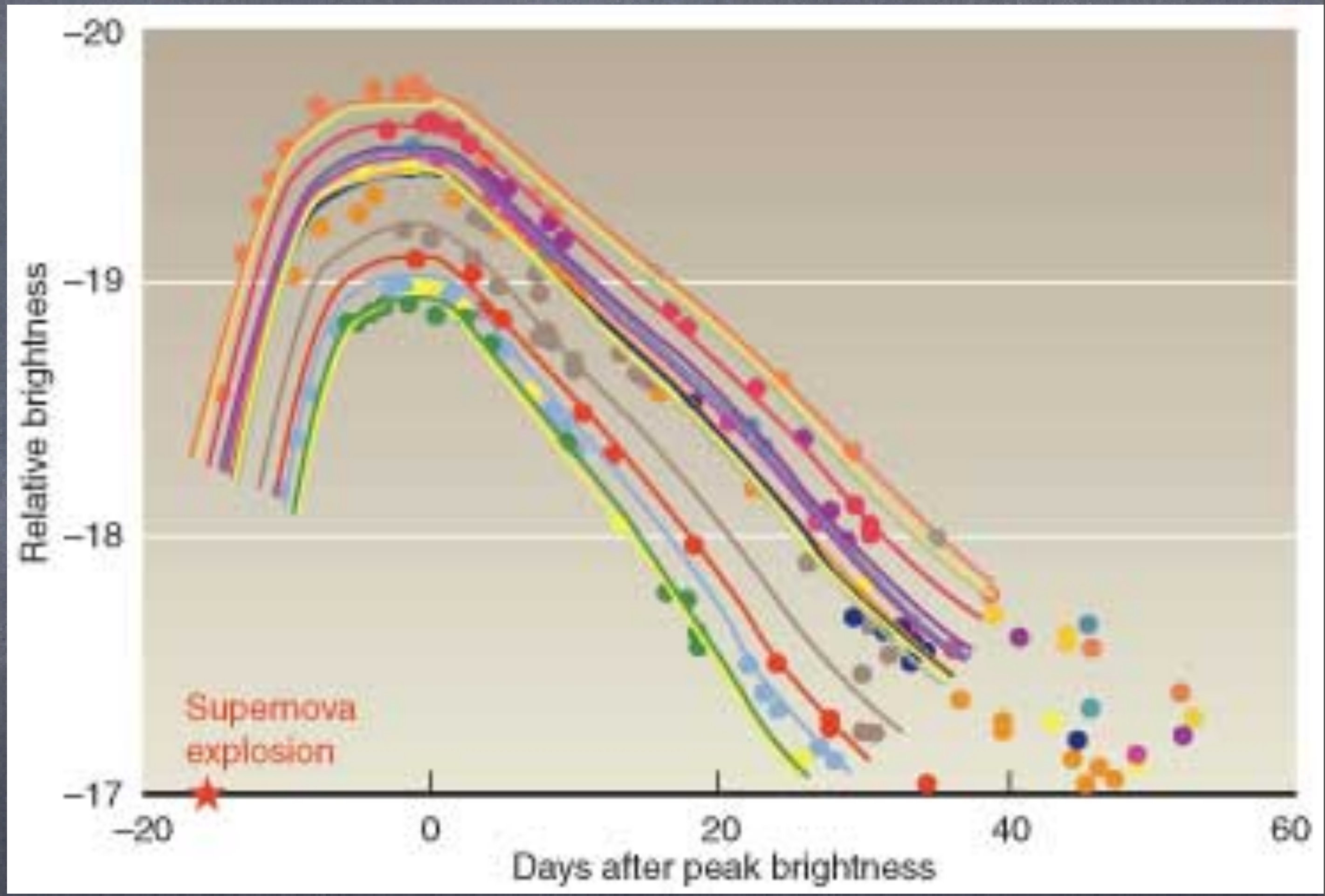

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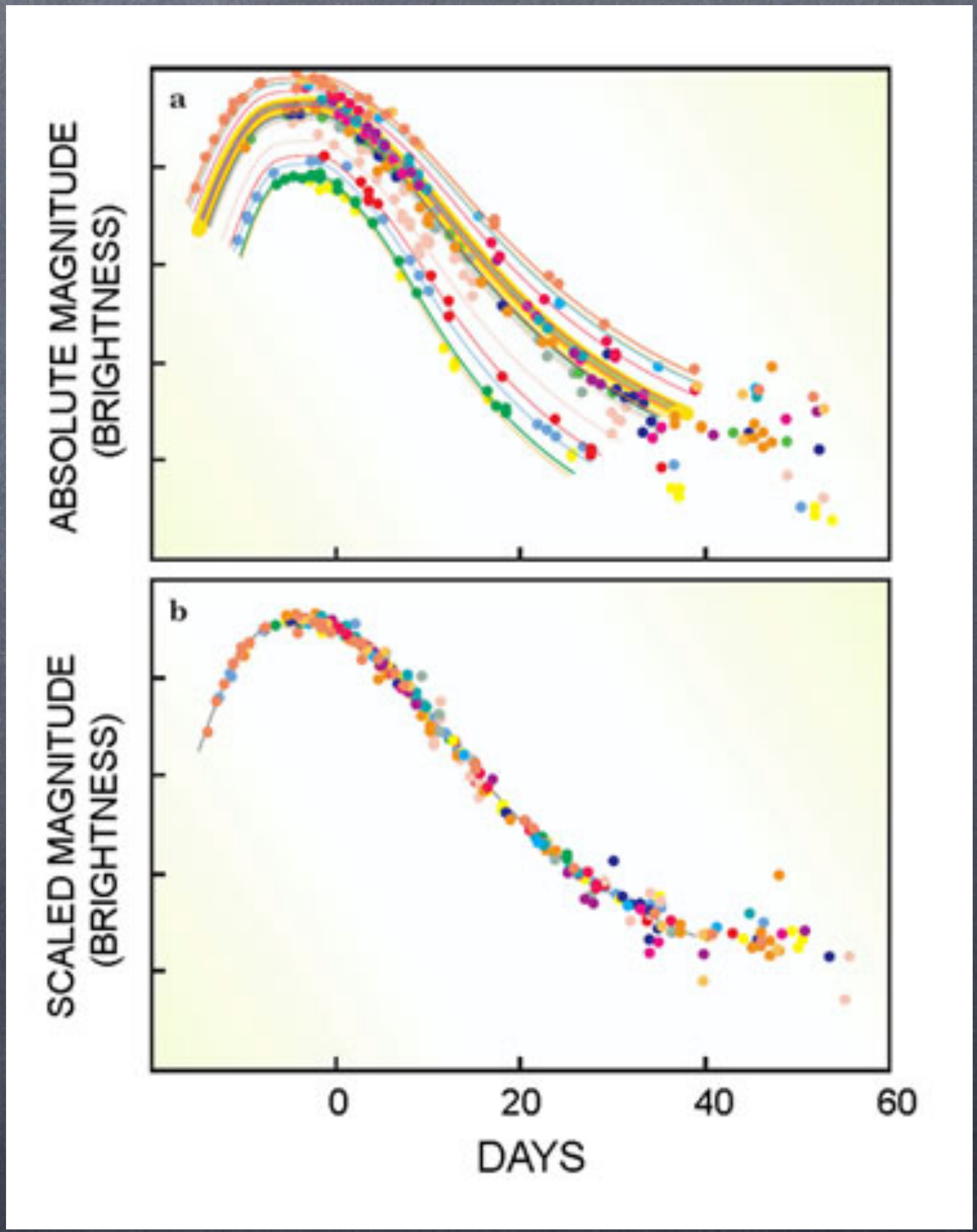

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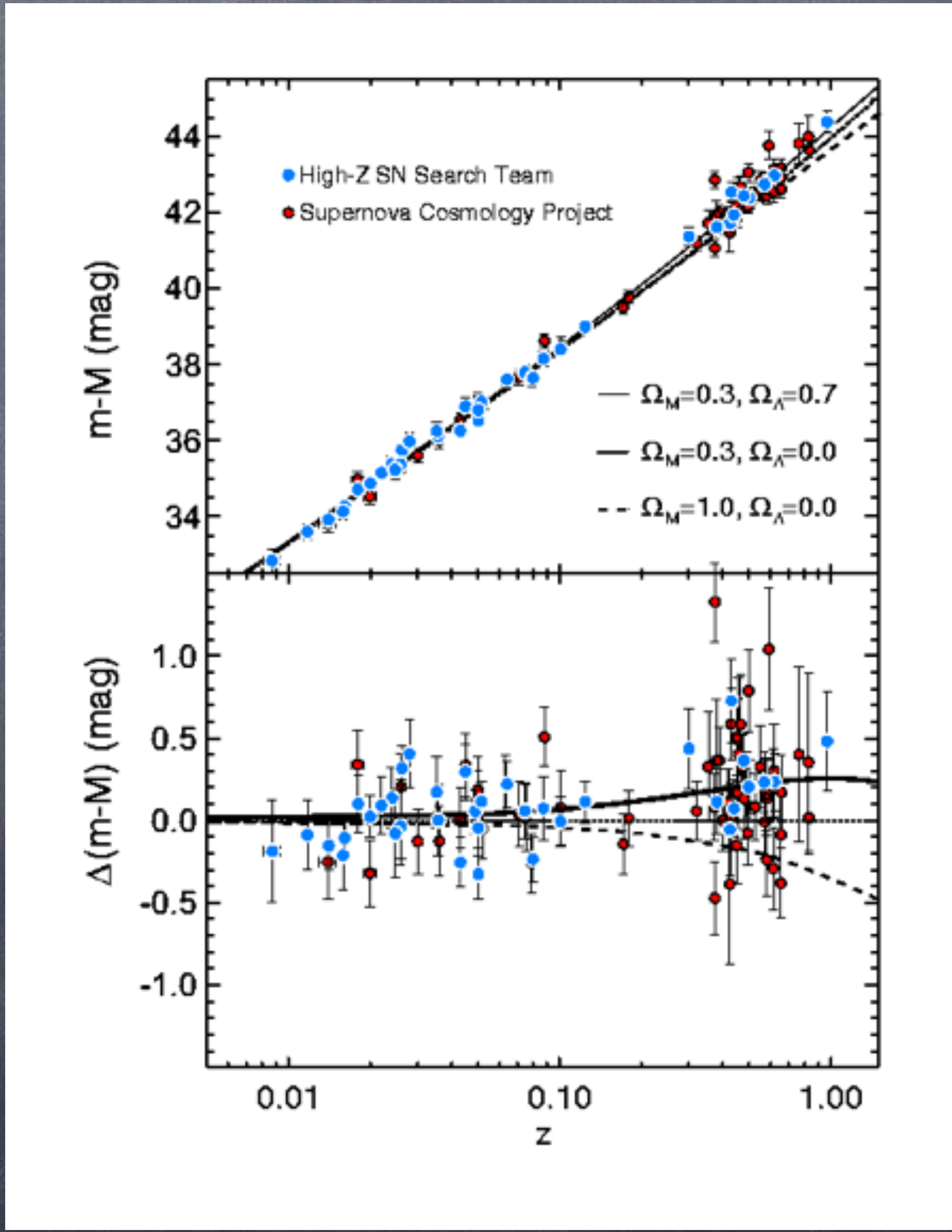

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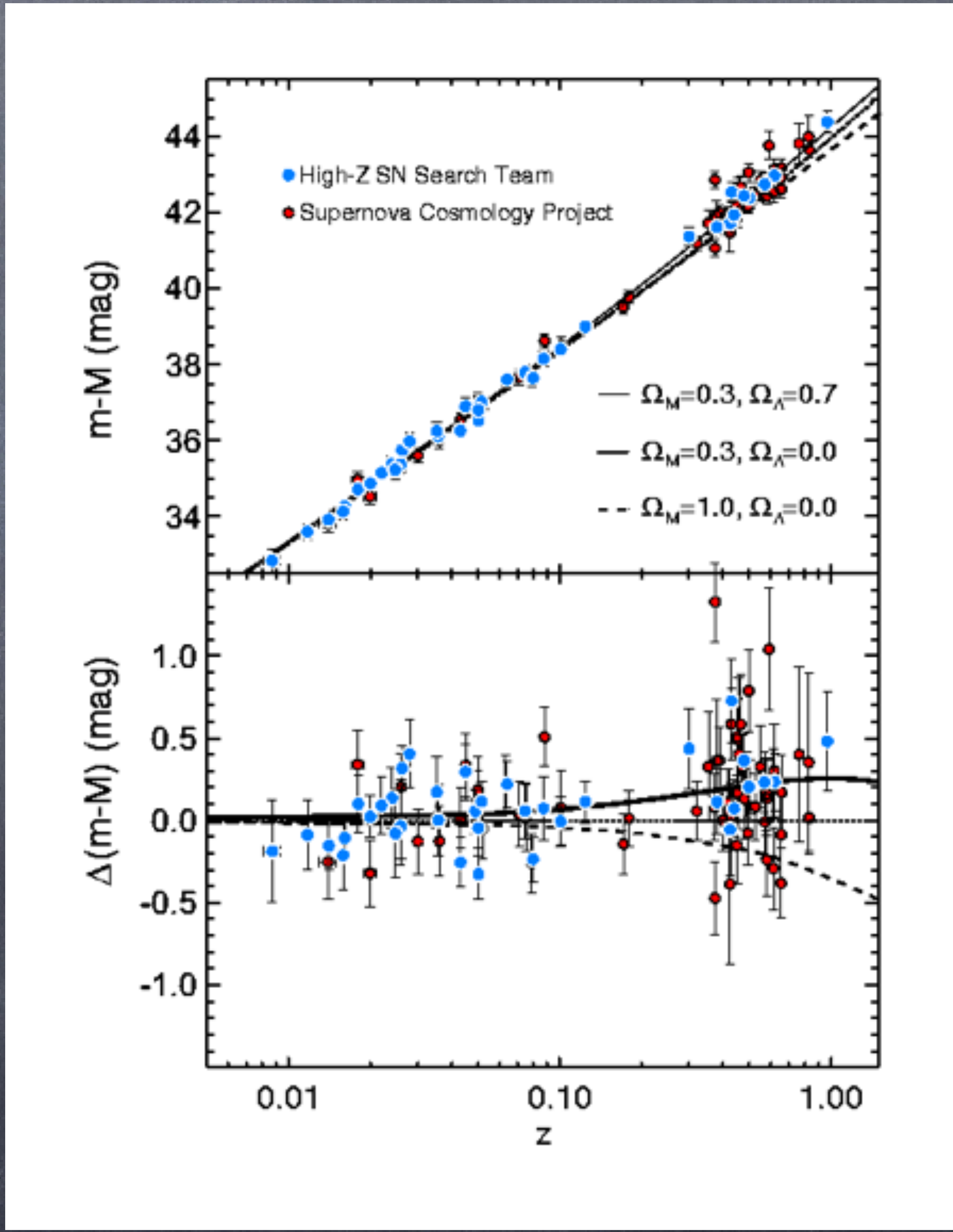

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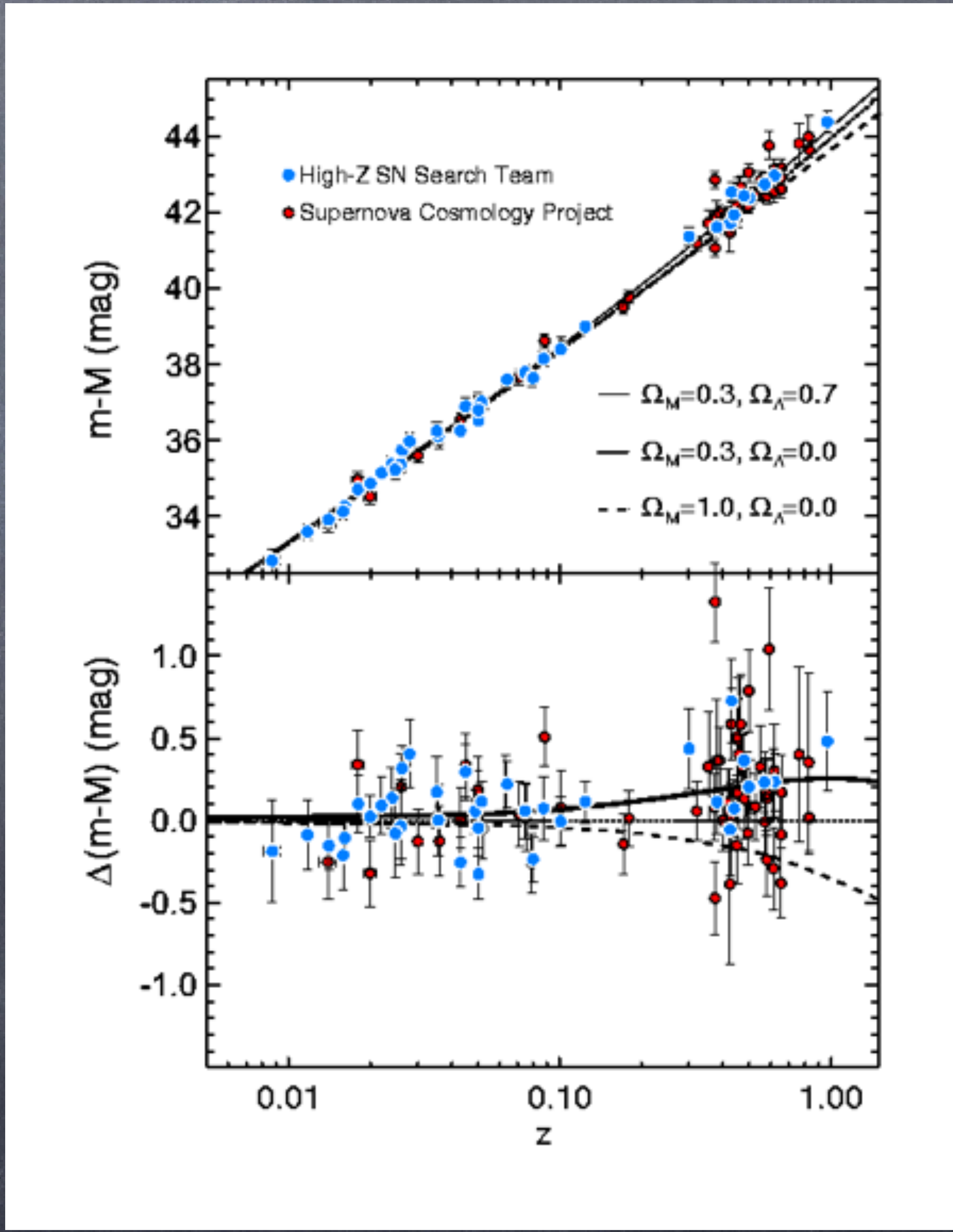

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- Universe appears to be accelerating at the farthest observable edges
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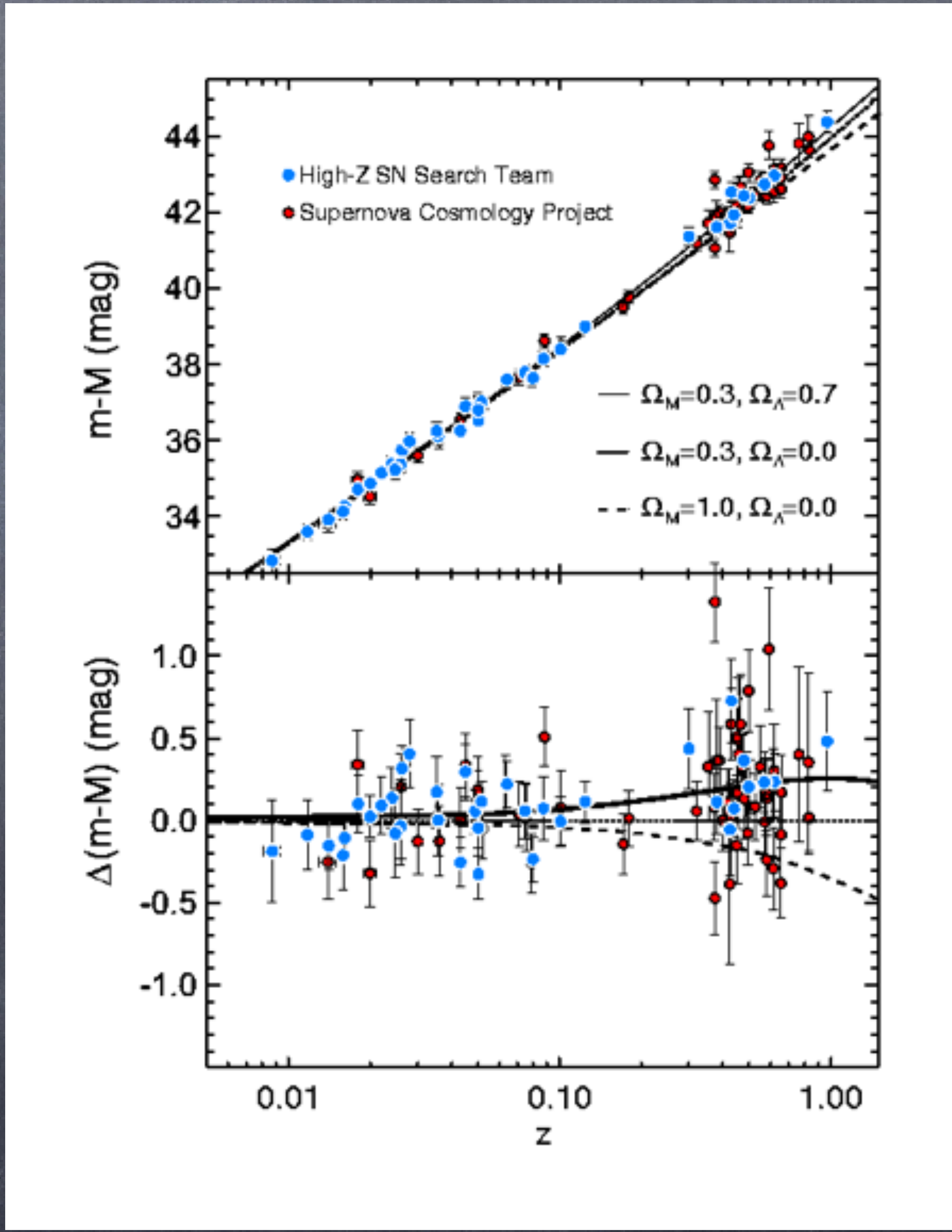
- Or some other reason space at its observable edges appears to be accelerating



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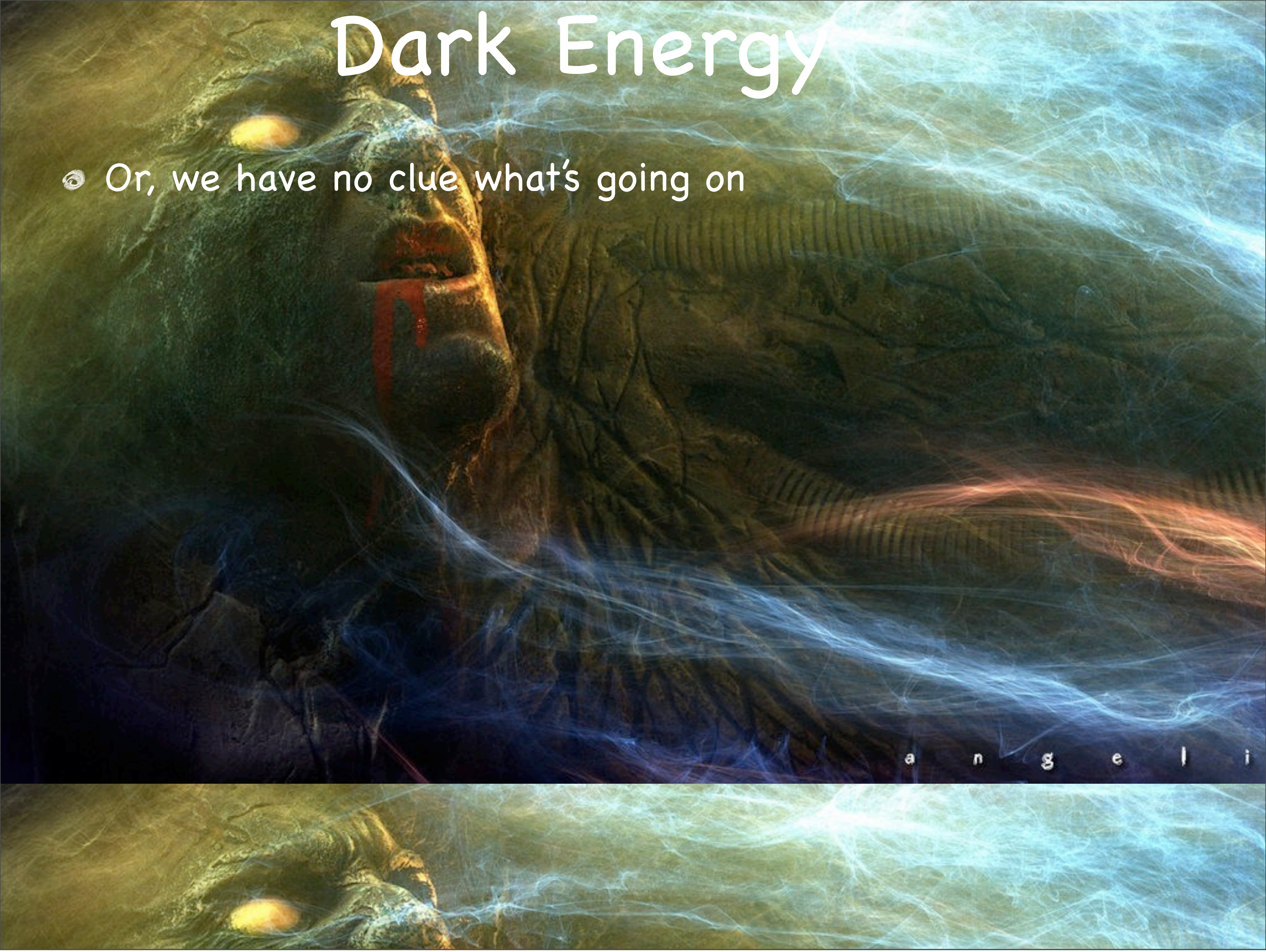

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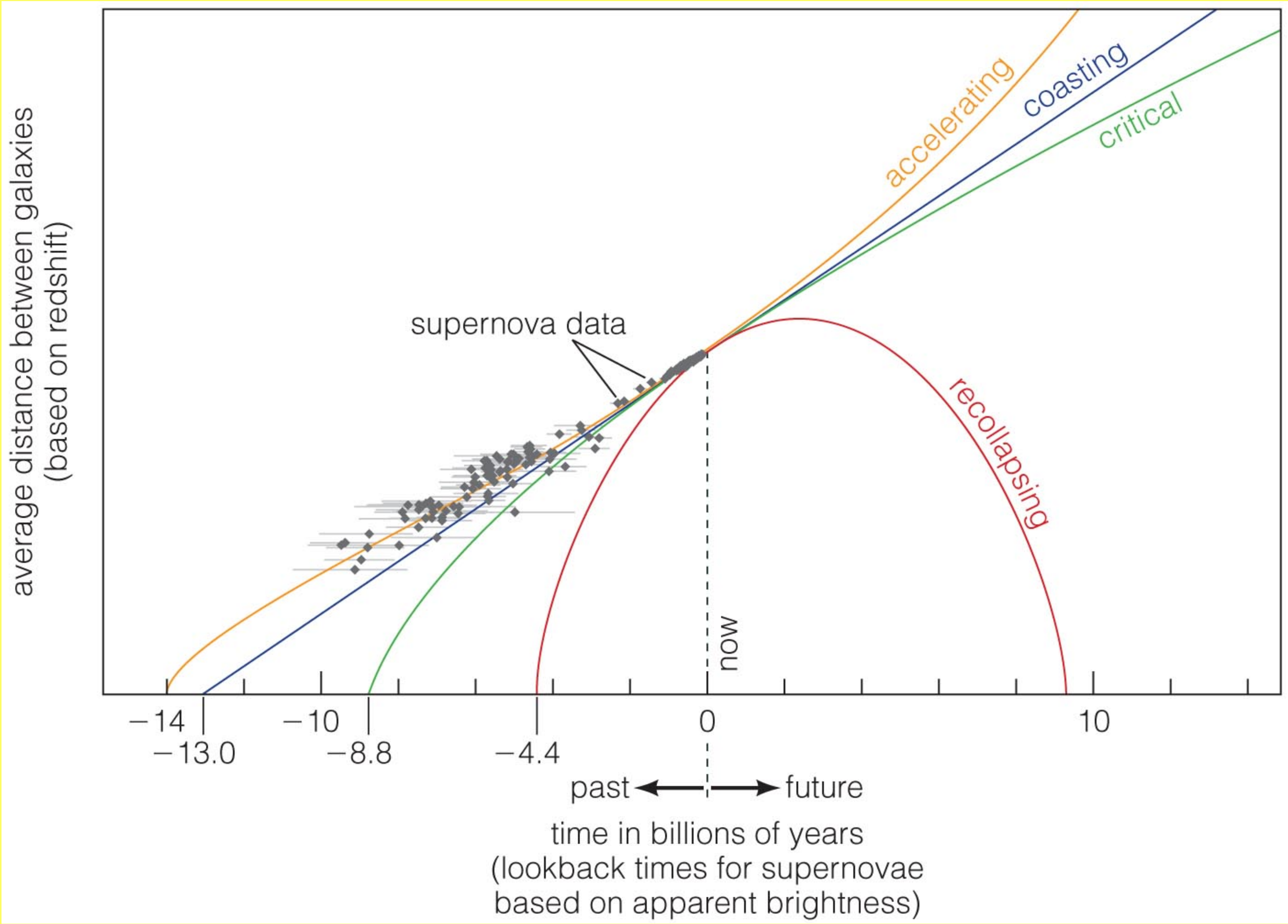
- At least in an entirely unimportant except for philosophically sort of way



An accelerating universe best fits the supernova data.

Back to the drawing board

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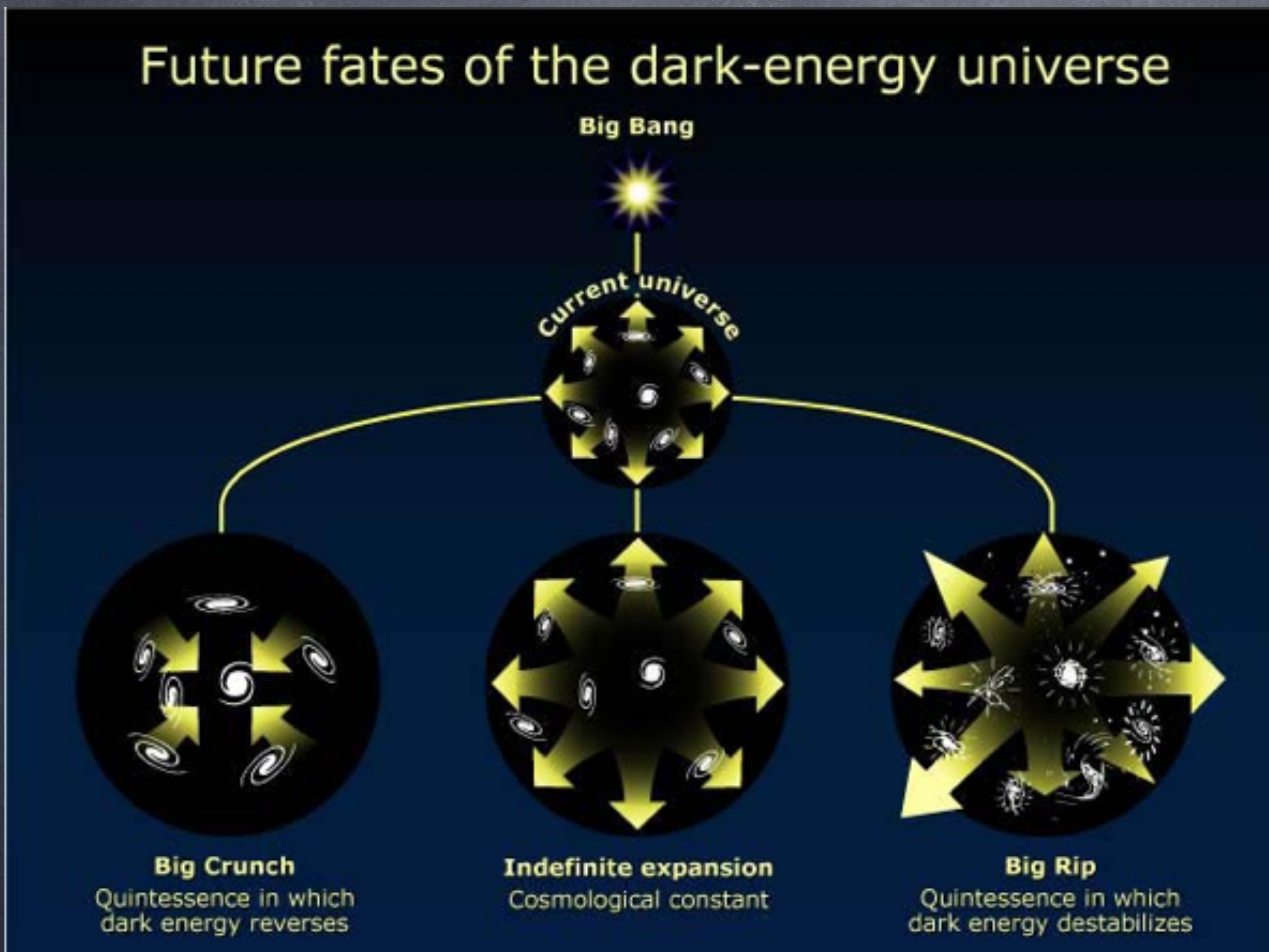

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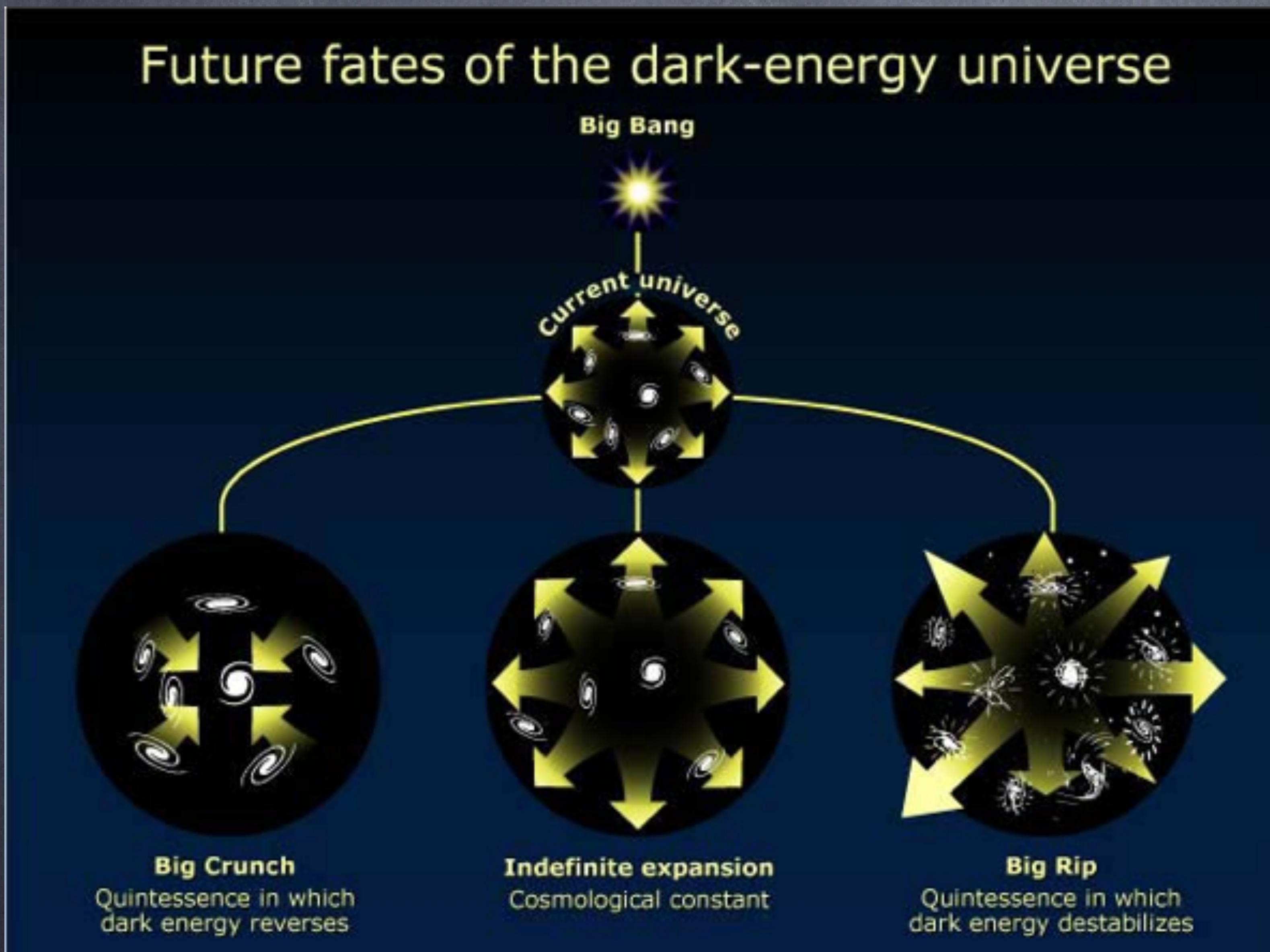


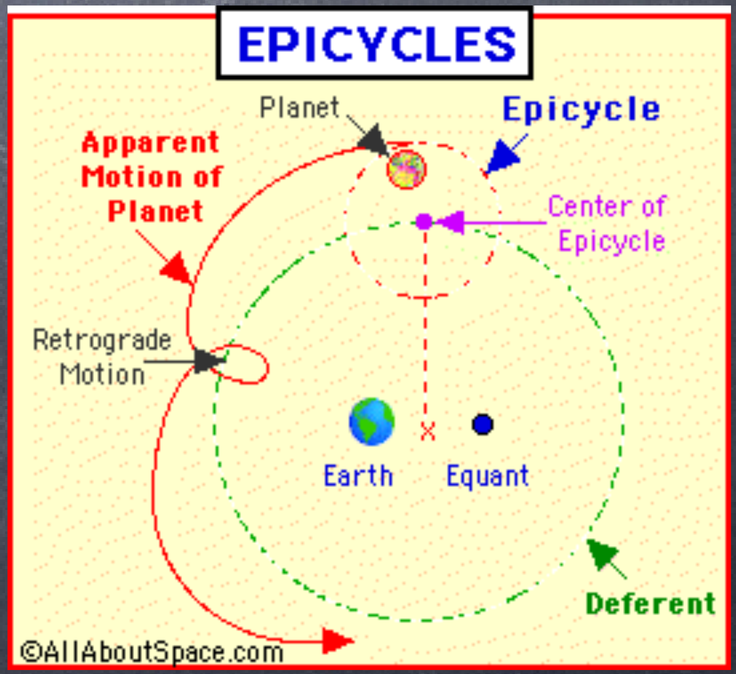
- Depending on what this energy is and how it behaves we may either
  - expand forever - everything dies
  - expand too quickly - the universe rips itself apart, the big rip
  - eventually contract - big crunch

We're at the point

- Where we are relatively certain we know where we came from
- We are quite uncertain as to where we are going

Dark Energy or Retrograde Motion and Epicycles?

- MOND?
- Dark Flow
- $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi\frac{G}{c^4}T_{\mu\nu}$ wrong?
- One way or another, inflation, dark matter and dark energy, are our present day "deus ex machina" fixes in cosmology
  - Either they are correct or cosmology sits on the precipice of a Coppernican revolution
    - Hopefully we don't have to wait 1400 years this time



So pretty much

- Pick your fate
- We don't know at this point
- How long until we do is not known
- Right now some models from the standard model suggest collapse, new cylce
- Here is what I like to think is going to happen

Thank You