Lecture 21
History of the Universe

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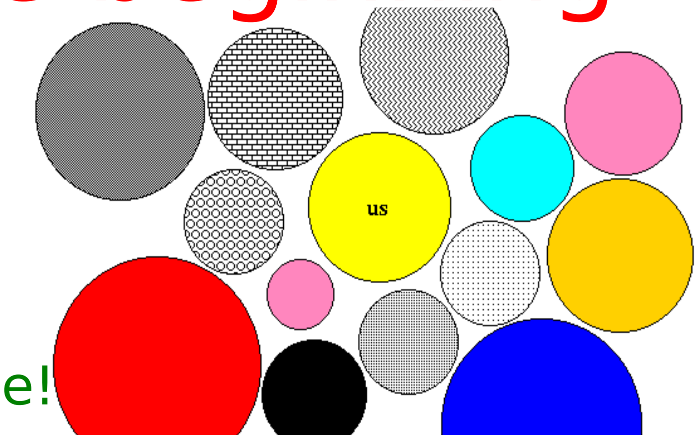
News

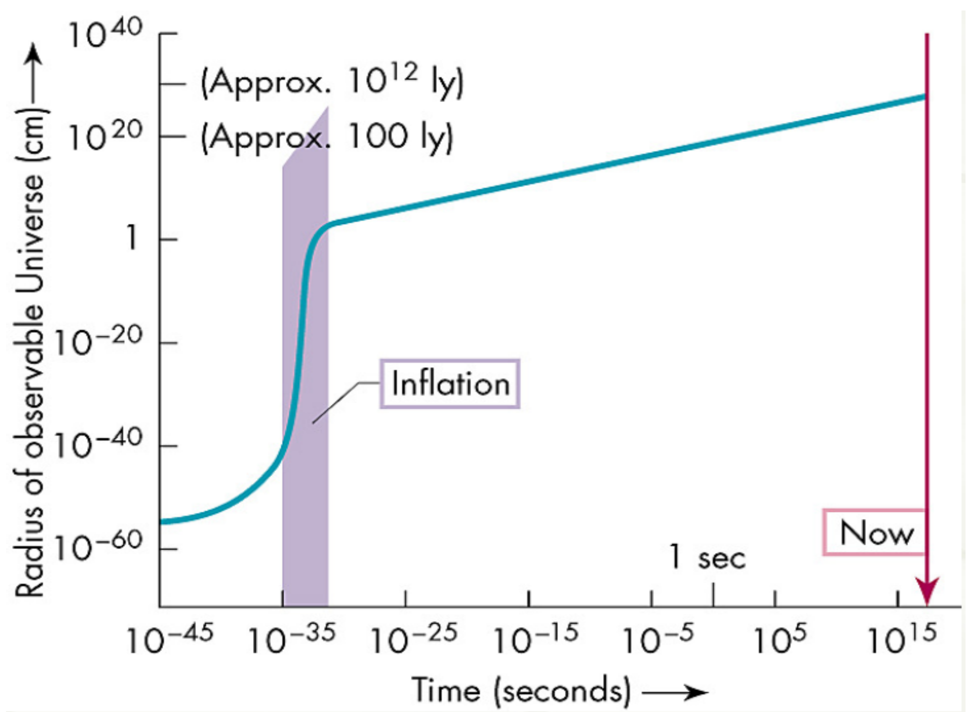
- Presentations
  - Apr. 14: Life of Galileo, Controlled fusion
  - Apr. 19: Nuclear power, Search for ET life
  - Apr. 21: Music, Nuclear terrorism
  - 2 per day 20 min+discussion/Q&A
  - Presentations will be evaluated by the audience
- Come see me if you need help or guidance on topics, and getting material

Your life... starting at the beginning



In the beginning there was...

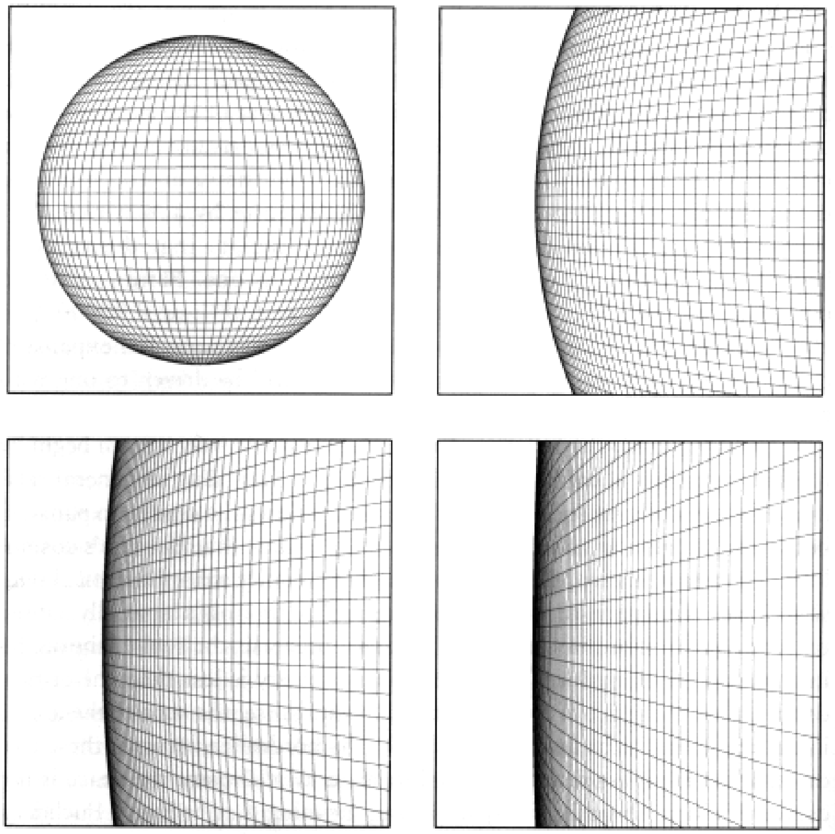
- **Space-time foam**
  - Not empty space
  - Quantum fluctuations can produce a Universe!
- **10^{-43} s: "Plank time"** Quantum limit of General Relativity
  - The shortest time we can know anything about in Physics
  - We don't know anything before this time
- **10^{-37} s: Inflation starts**
  - Universe is 10^{30} times smaller than the size of an atom
  - space is filled with an unstable "inflaton" field
  - Tremendous repulsive pressure
  - Exponential expansion



Inflation transforms the Universe

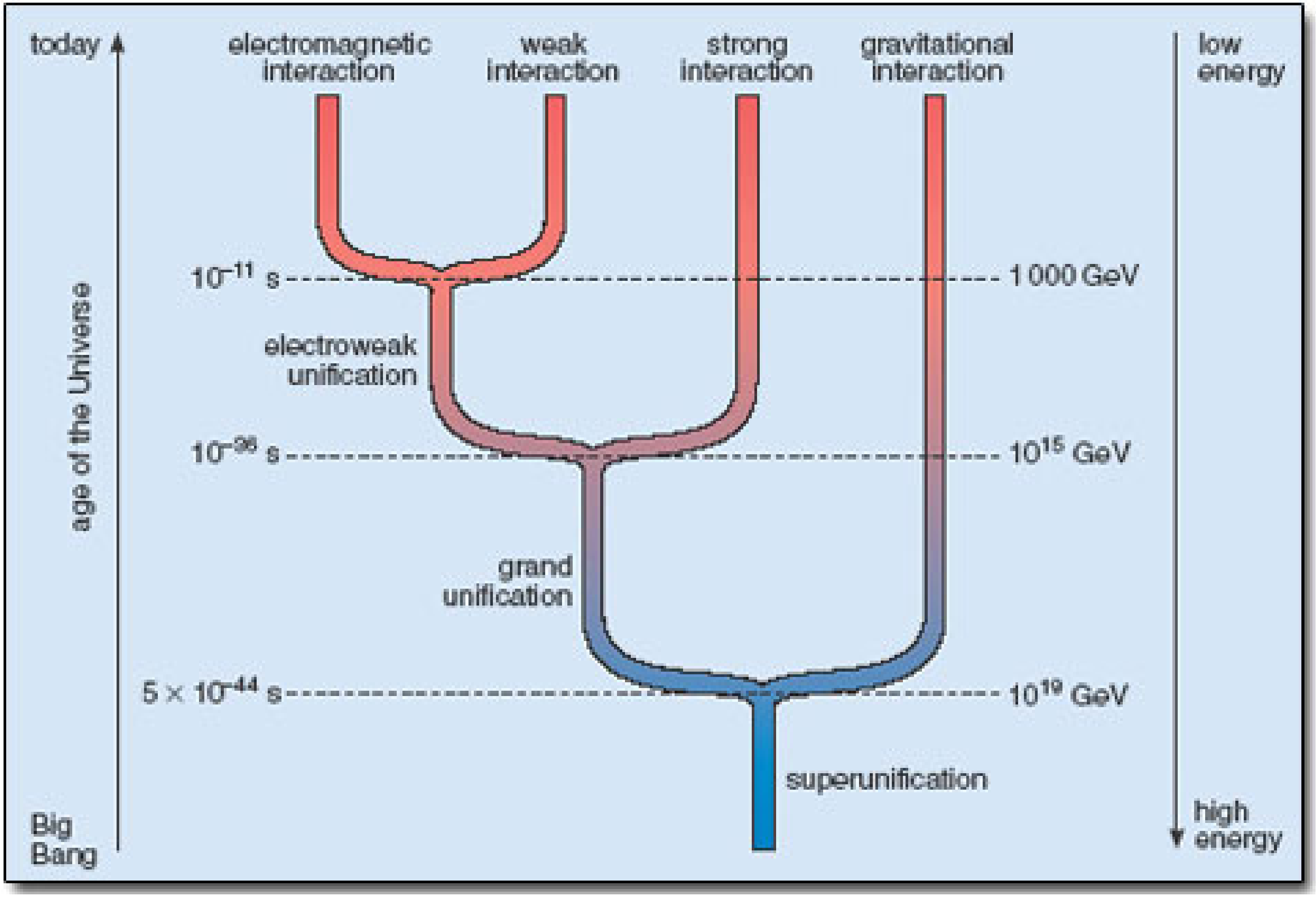
- The Universe expanded a factor 10^{40} to 10^{100} during inflation
- The universe went from a size $\sim 10^{-40}$ cm to the size of a marble
  - The Universe ended up much bigger (1 cm) than the observable universe then (at the time: $d = tc = (10^{-35}s)(3x10^{8}\ m/s) \sim 3x10^{-27}\ m$)

- What was curved, now is flat
  - Space is flat
  - Two parallel photons remain parallel
  - Sum of angles in triangle=180˚
- What was small, now is big
  - Quantum fluctuations become large density/energy fluctuations
  - Act as seeds for large scale structure formation: matter would condense in these fluctuations producing the super-clusters of galaxies and the filaments and voids that we observe today



Unification of forces

- Early in the history of the Universe, it wasn't possible to distinguish between the forces
- We still haven't proved the unification of Electroweak+Strong, much less the unification with gravity...

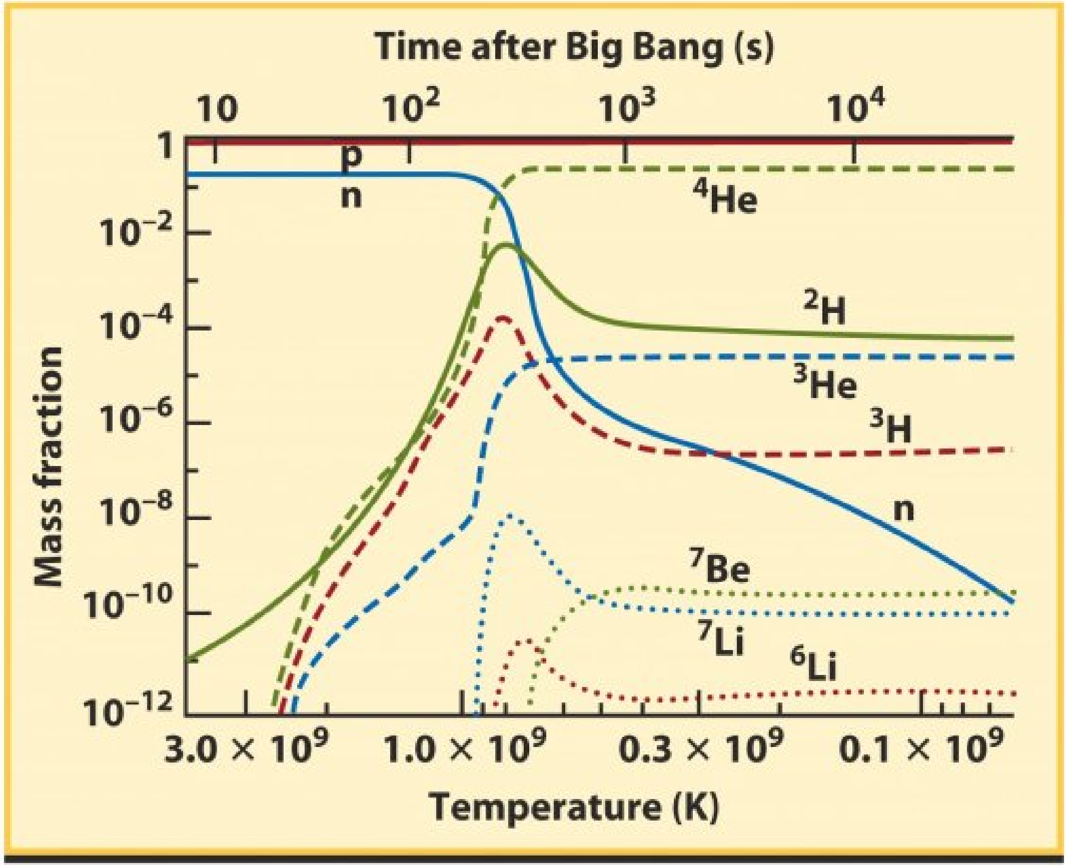


Timeline continued

- **10^{-35} s: End of Inflation**
  - Inflaton field is unstable, it "decays" ending inflation
  - Energy driving inflation is dumped into matter and radiation in early Universe, forming a hot, dense, "primordial soup"
- **10^{-35} s – 10^{-5} s: "Quark Gluon Plasma"**
  - At this point the universe is the size of a marble, and composed of subatomic particles: quarks, electrons, Z, W, gluons, photons at very high Temperature (~10^{27} K)
  - The Big Bang description takes over: Universe will keep expanding, but this time at "normal" rate ~80 km/s/Mpc
- **10^{-5} s: Bounded hadrons**
  - Quarks bound into baryons (protons, neutrons) and mesons
- **10^{-4} s: Matter-antimatter asymmetry**
  - The Universe has cooled to 1 trillion K: still too hot for nuclear fusion to occur, photons destroy any nuclei that forms
  - Protons and anti-protons annihilate, leaving 1 extra proton per billion
  - Photons are since then the most abundant particle: 10^9 photons for every baryon

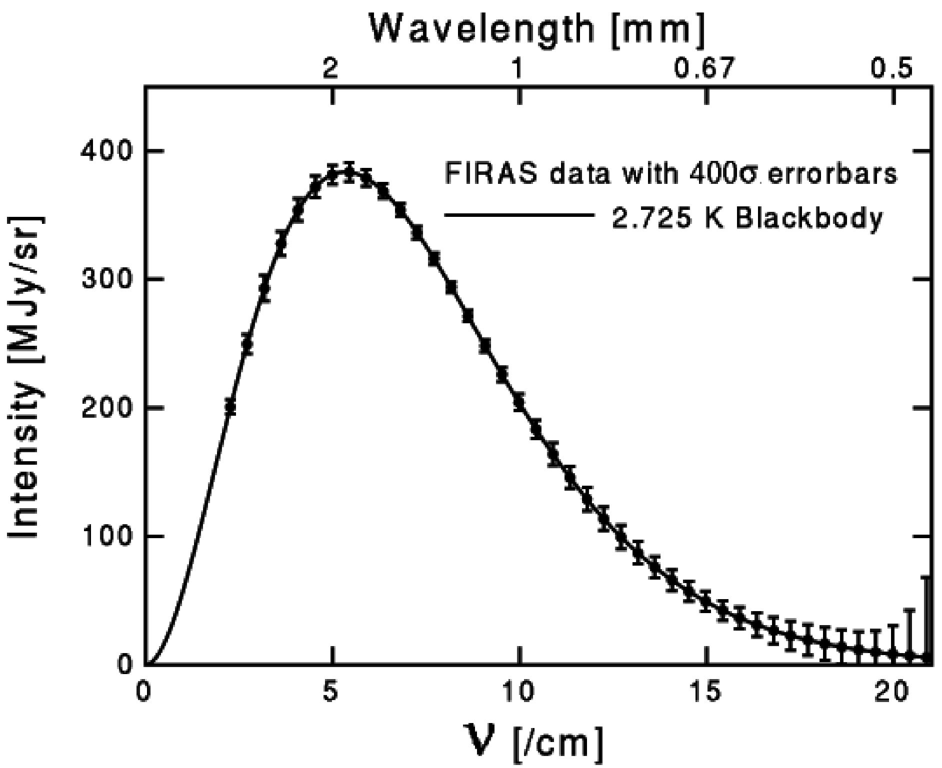
Light elements form

- **3 minutes: "Big Bang nucleosynthesis"**
  - It is cool enough (1 billion K) for light nuclei form: Deuterium, He, Li, Be
  - No heavier elements than Be could form
  - The abundance of H and He is set by the Temperature and density of normal matter between 3 and 30 minutes after the Big Bang
  - Abundance: H ~ 75%, He ~ 25%
  - Photons are too energetic to allow neutral atoms to form
  - Everything is ionized (electrons are not bound into atoms)
  - Light cannot travel through ionized gas
  - The Universe is opaque: its blackbody radiation trapped



Neutral atoms form

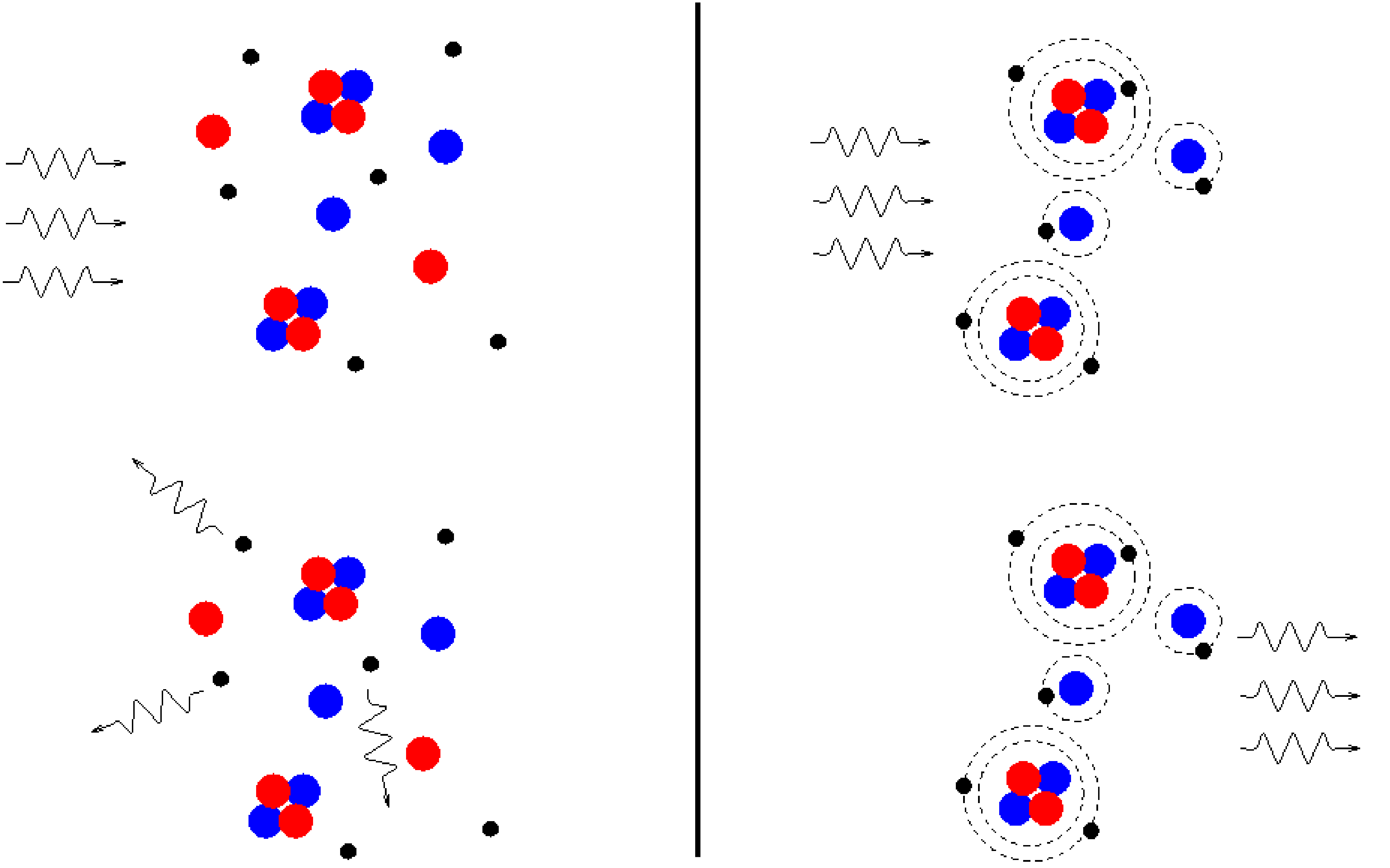
- **400,000 years: Neutral atoms form**
  - Cooled to 3,000 K: Hydrogen atoms can form
  - Universe becomes transparent, the 3,000K blackbody radiation travels freely
  - We see that radiation today, greatly redshifted to 3 K blackbody: Cosmic Microwave Background (→next page)
  - It is the farthest thing we can see
  - CMB discovered in 1964
  - "Almost" perfect blackbody radiation at 2.725 K
  - Isotropic: the same wherever you look in the sky
  - But not perfectly homogeneous: otherwise no galaxies!
  - Tiny fluctuations in temperature



Before/After recombination

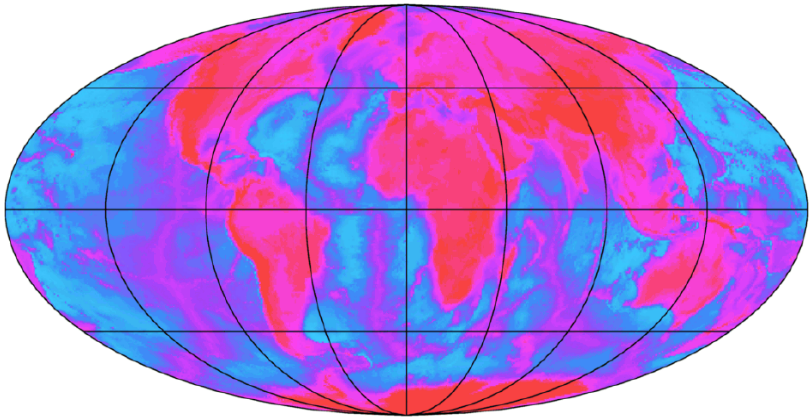
Before: Ionized = opaque

After: Neutral = transparent



The CMB map: anisotropies in T

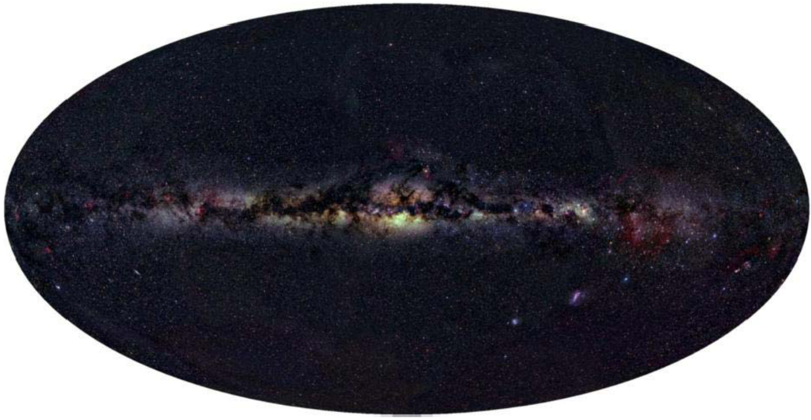
Map of the gravitational potential of Earth in the surface: red=high (~9.83m/s^2), blue=low (~9.76m/s^2)



All-sky map in galactic coordinates (map of sky unrolled), with visible light

The Milky Way is seen along the horizontal axis

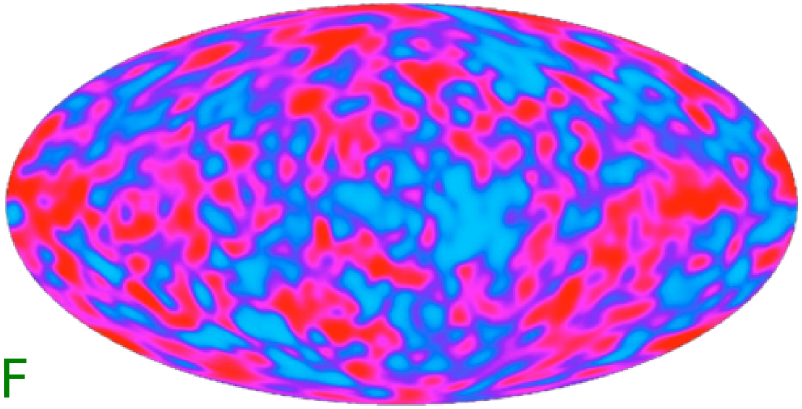
The same idea applies below, but now in Infrared



COBE map of the anisotropies in the CMB Temperature: Red areas are 30 μK hotter than average, and the blue areas are 30 μK colder than average

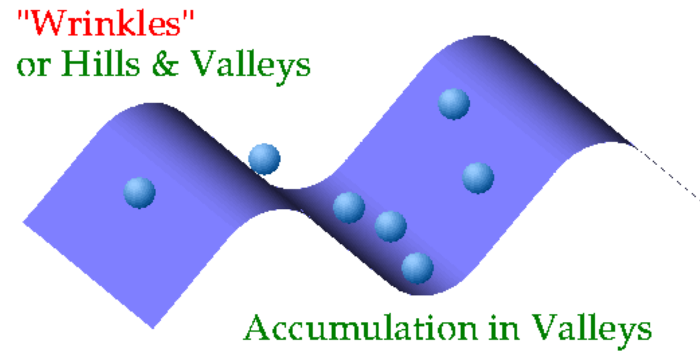
Remember: 1 μK = 10^{-6} K

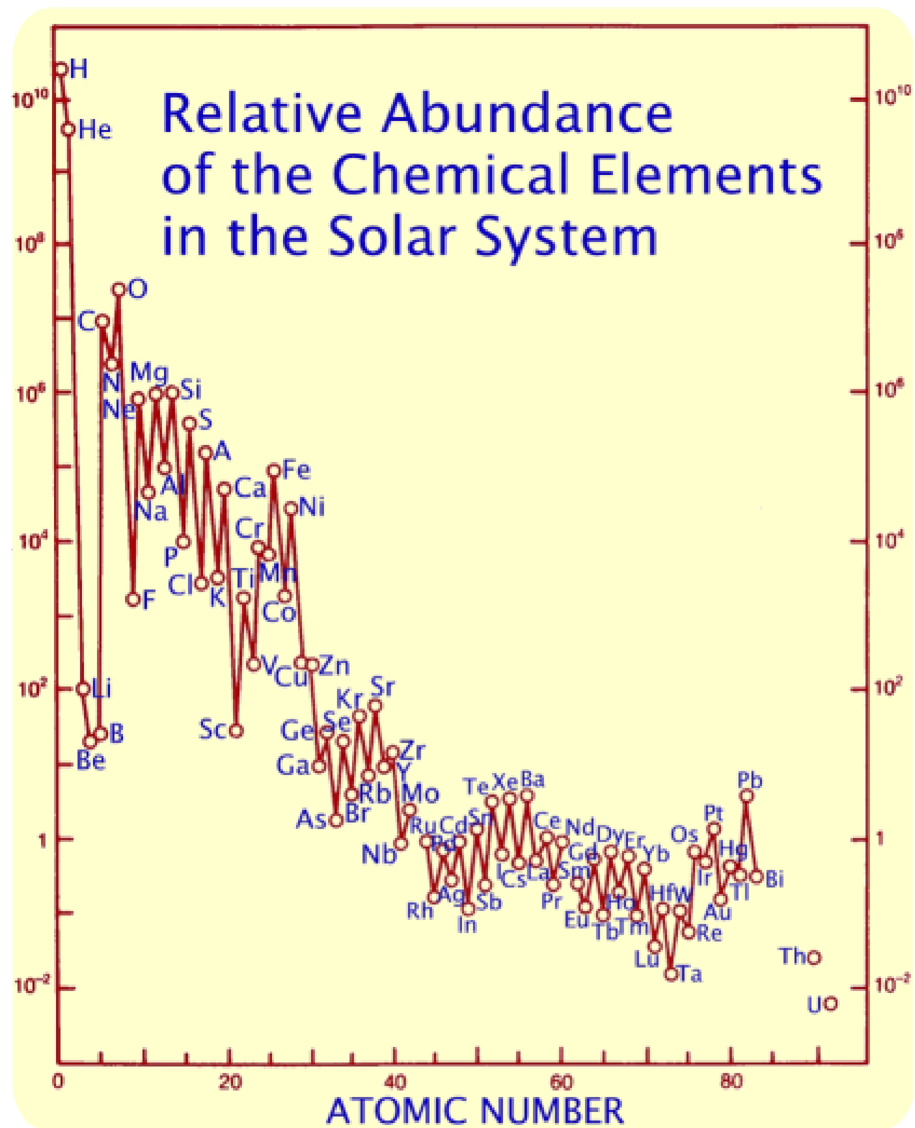
Average CMB temperature = 2.725 K = -454 °F



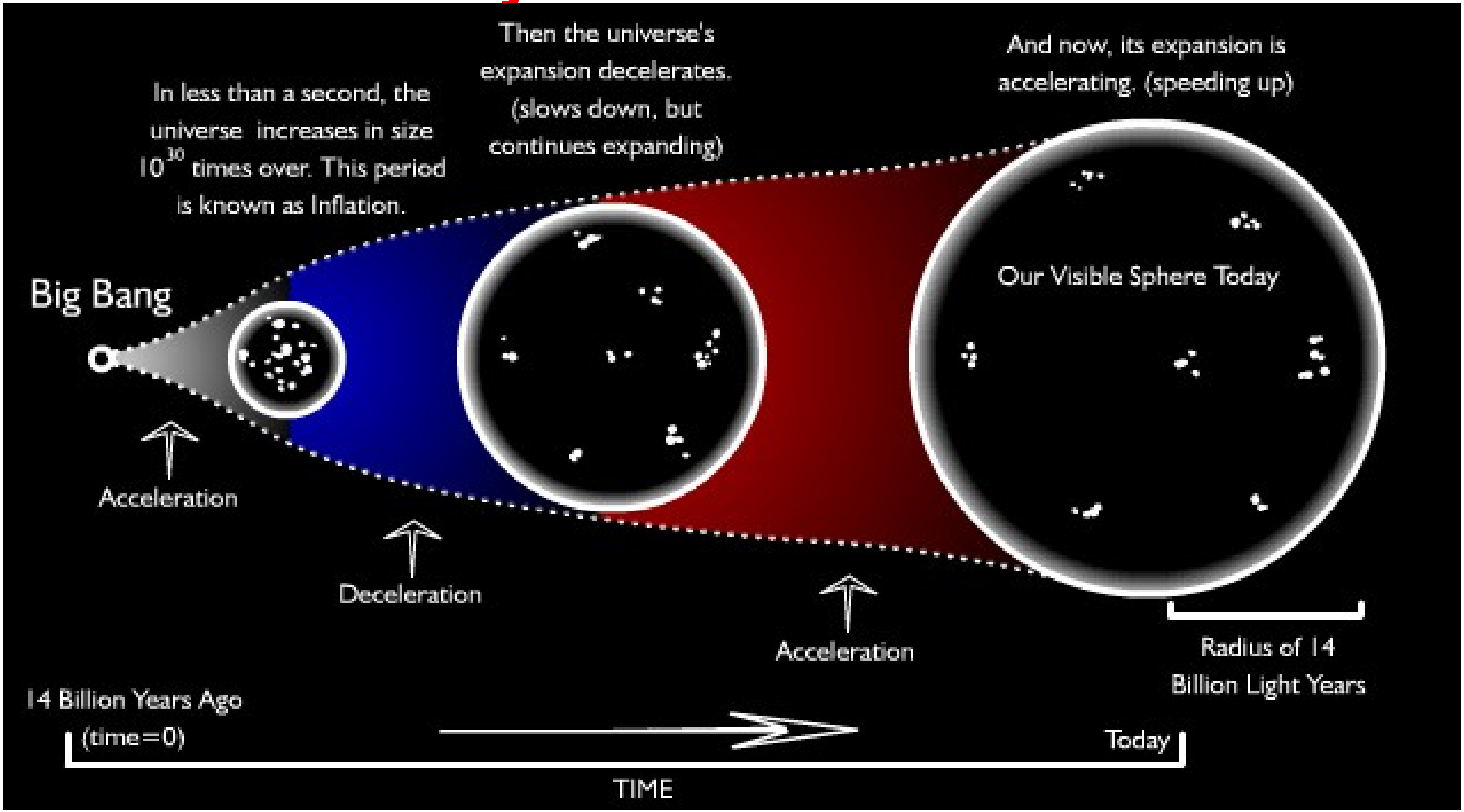
Timeline continued

- **400 million years: First stars**
  - Probably much more massive than today's stars
- **1 billion years: Galaxies**
  - Quasars have formed: very active galactic cores, around a super massive black hole
  - Globular clusters form in initial collapse that results in formation of galaxies
- **9 billion years: Solar System**
  - Large clouds of gas, from previous stars plus interstellar medium inside the Milky Way
- **13.7 billion years: Now**
  - Us, pondering about the universe
  - The expansion is accelerating

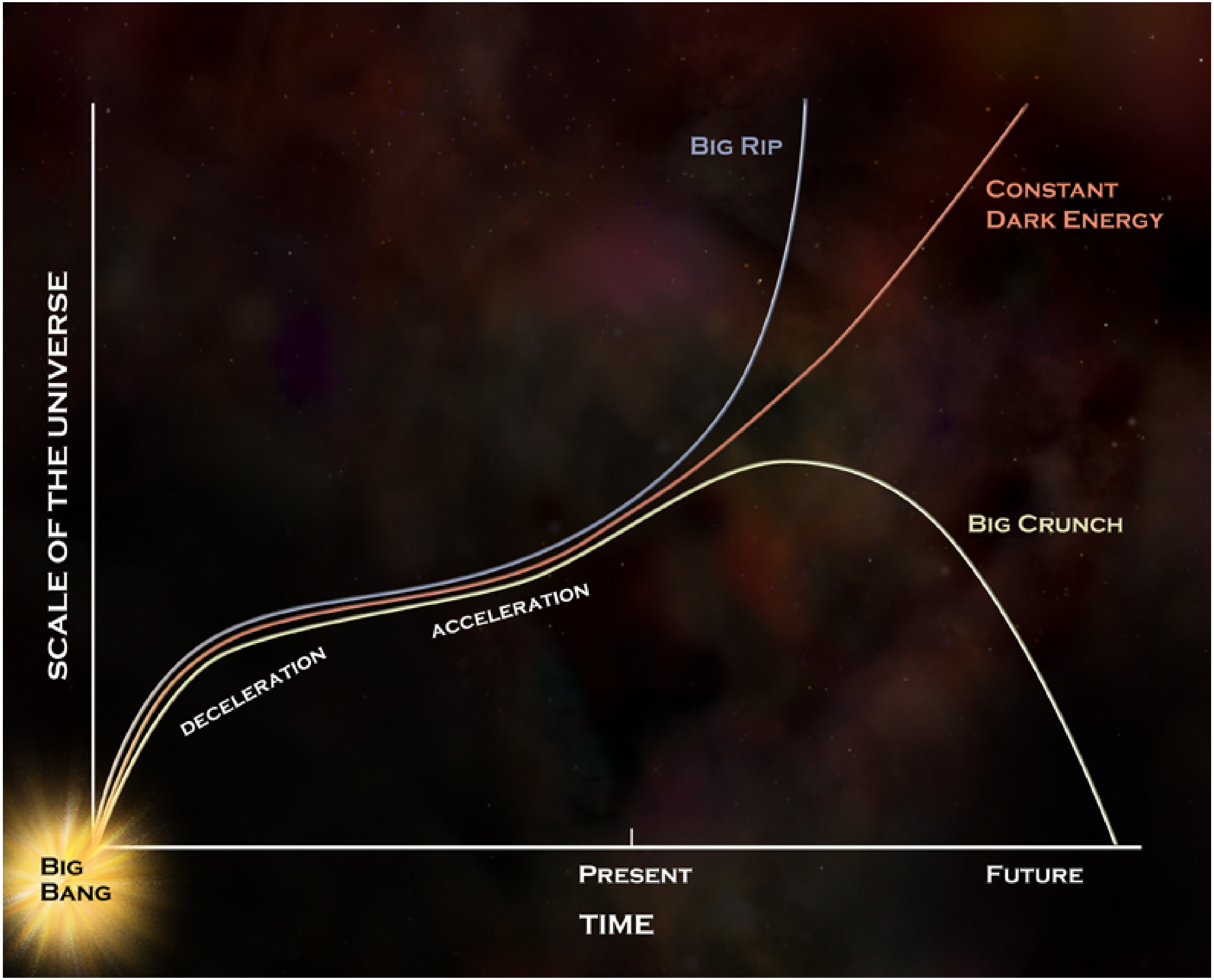




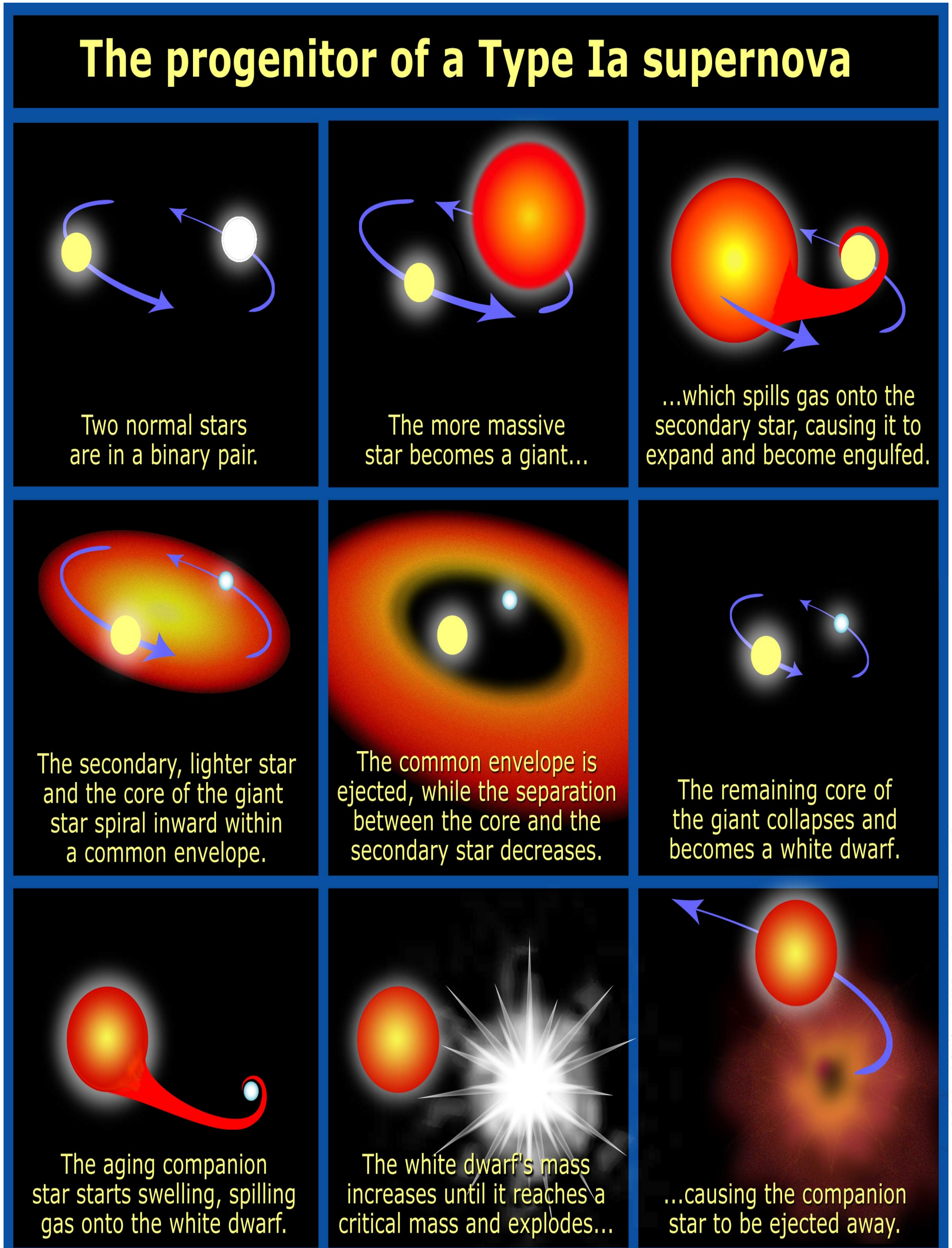
History of acceleration

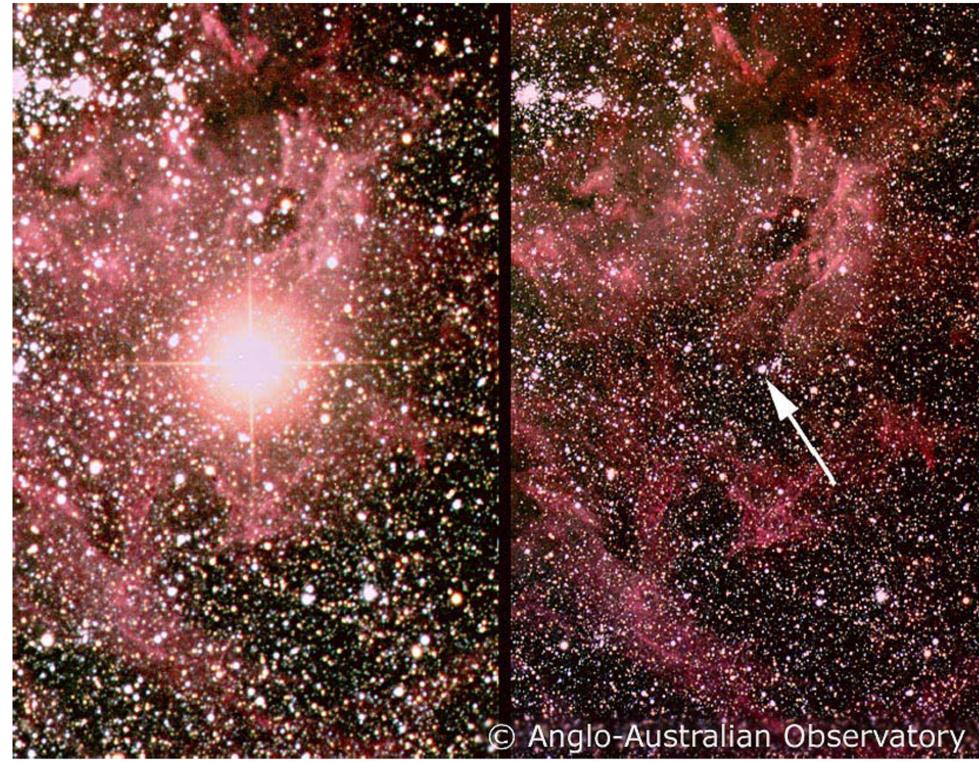


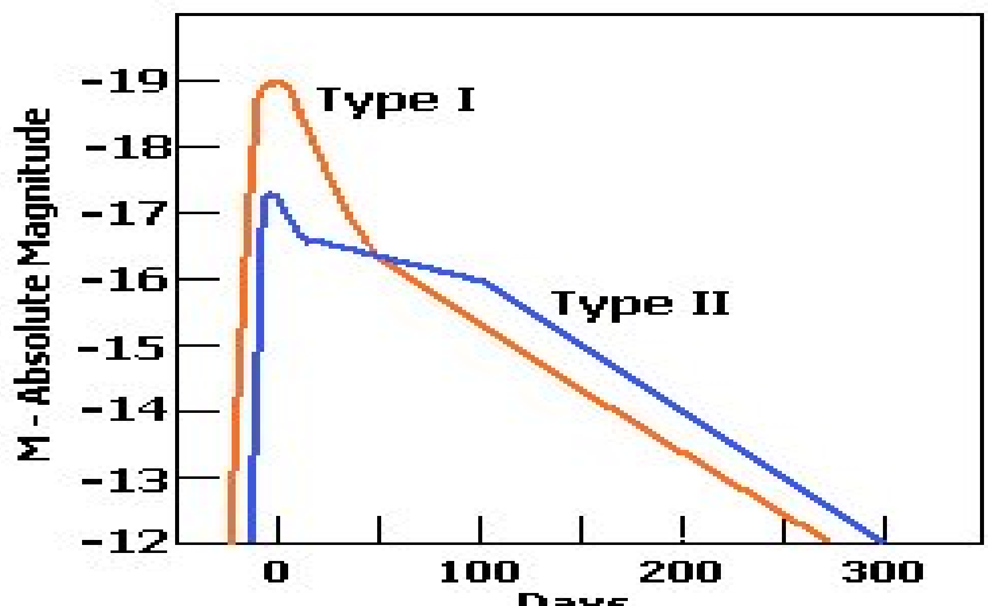
- Use supernovae to measure distances to galaxies: they shine with known brightness, so they are seen dimmer the further away they are
- Two groups discovered in the 1990's that supernovae were brighter than the distance (determined by the Hubble law) would suggest
- Together with CMB data, confirms that the Universe is now accelerating

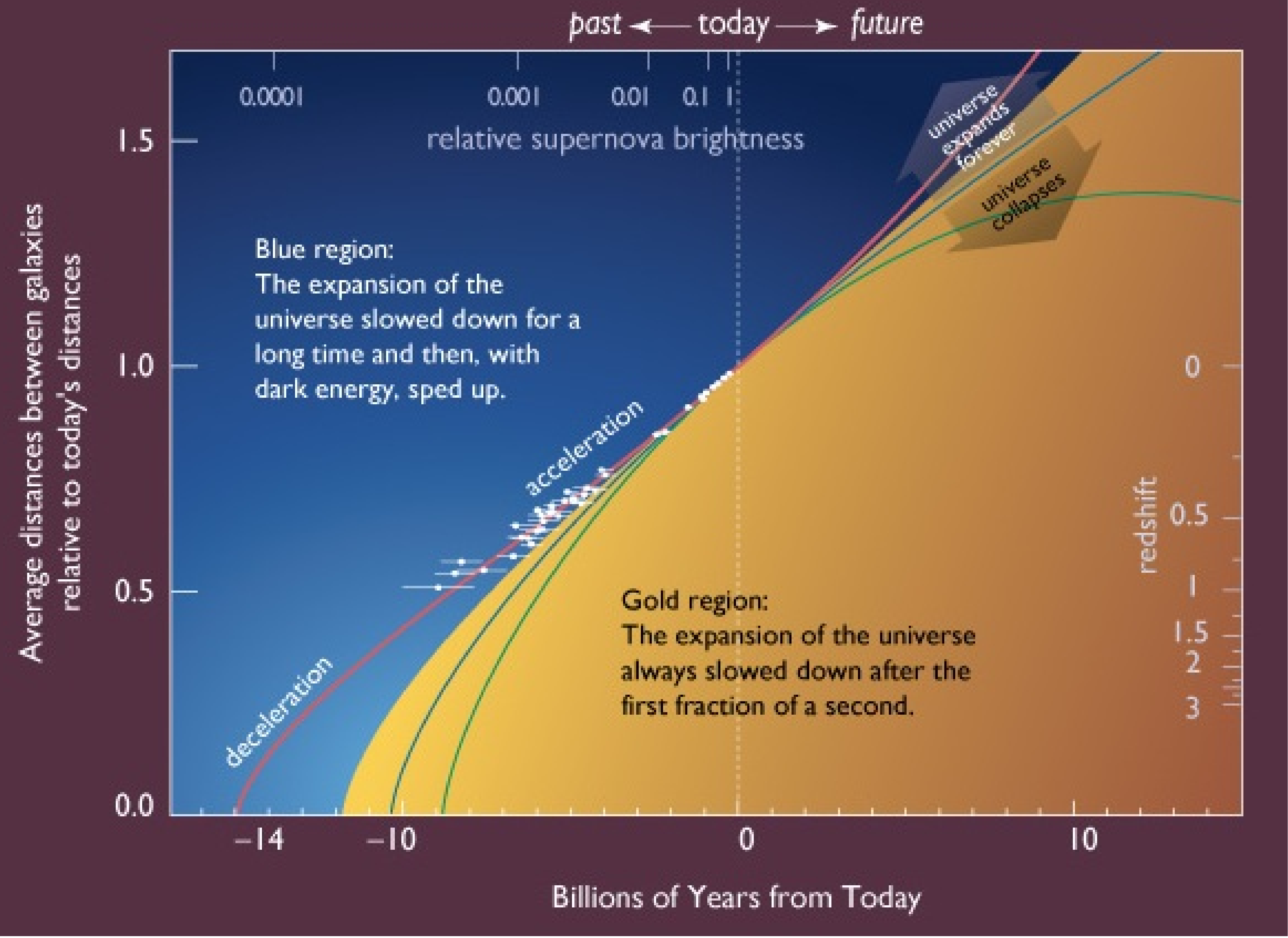

Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Acceleration
Deceleration
Big
Bang
Present
Future
Time

Supernovae as standard candles







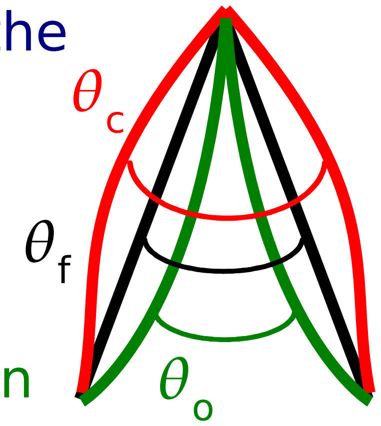

past ← today → future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
1.5
1.0
0.5
0.0
Average distances between galaxies relative to today's distances
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
0
0.5
1
1.5
2
3
redshift
−14
−10
0
10
Billions of Years from Today

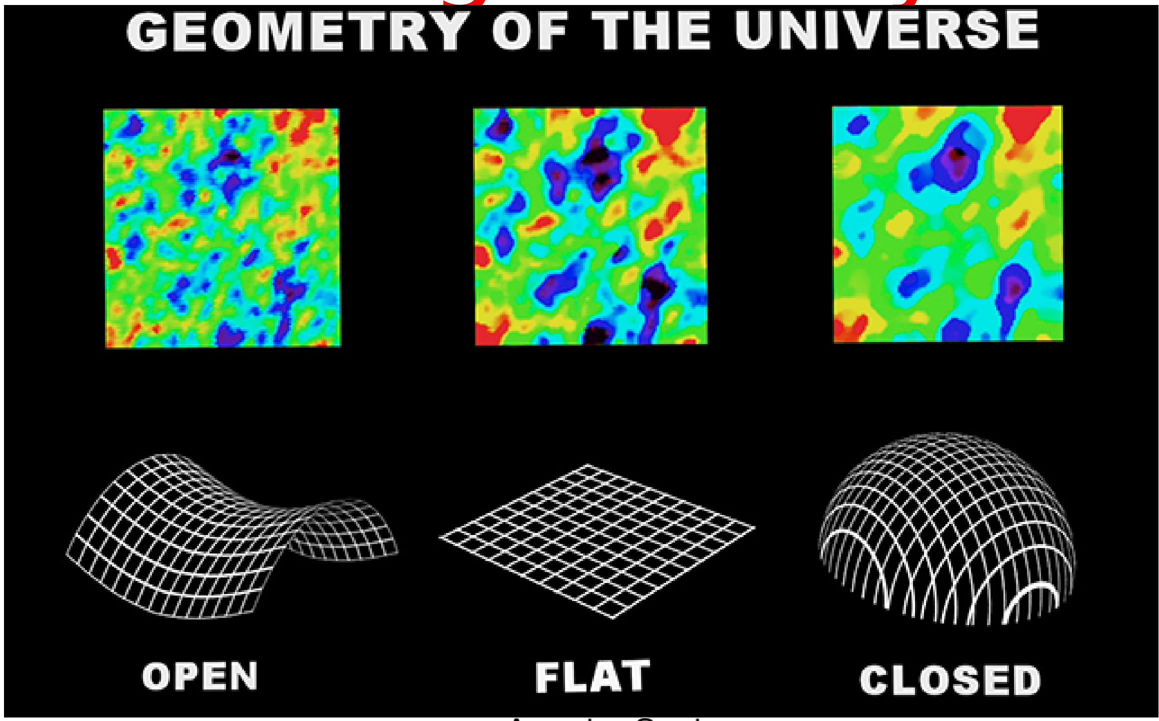
Size of fluctuations → geometry

- Angular Size of fluctuations/structure in CMB is sensitive to the geometry of the universe

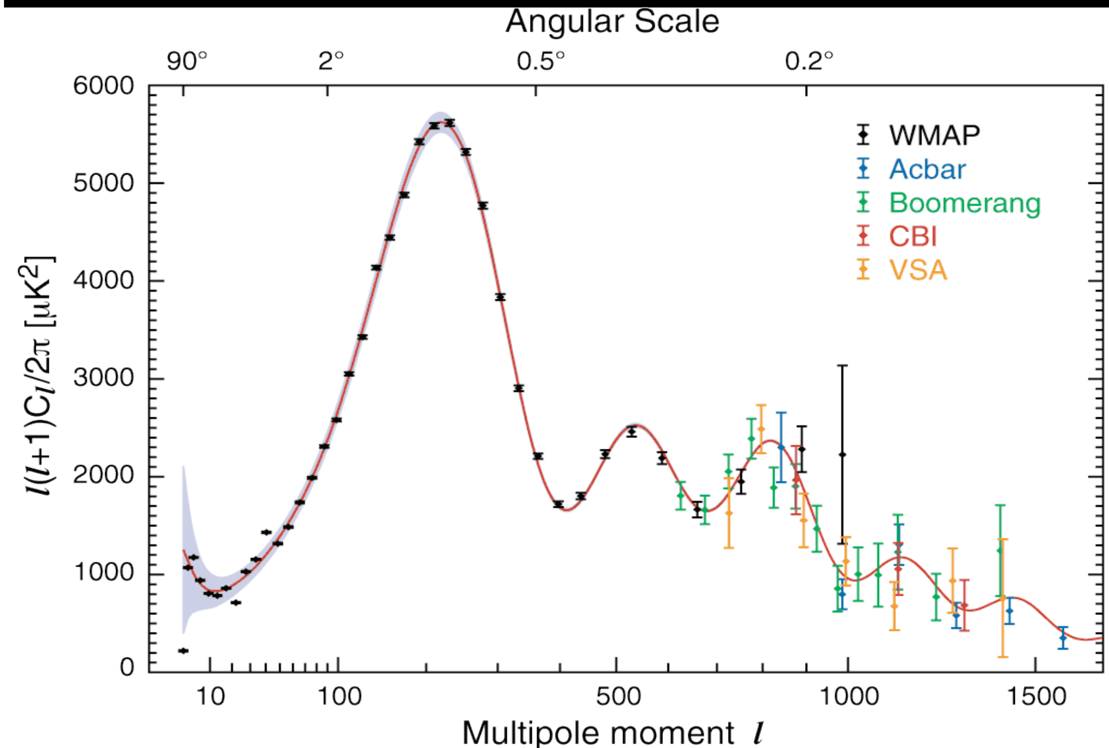
Measure:

- θ_f if space is flat
- θ_o if space is open
- θ_c if space is closed



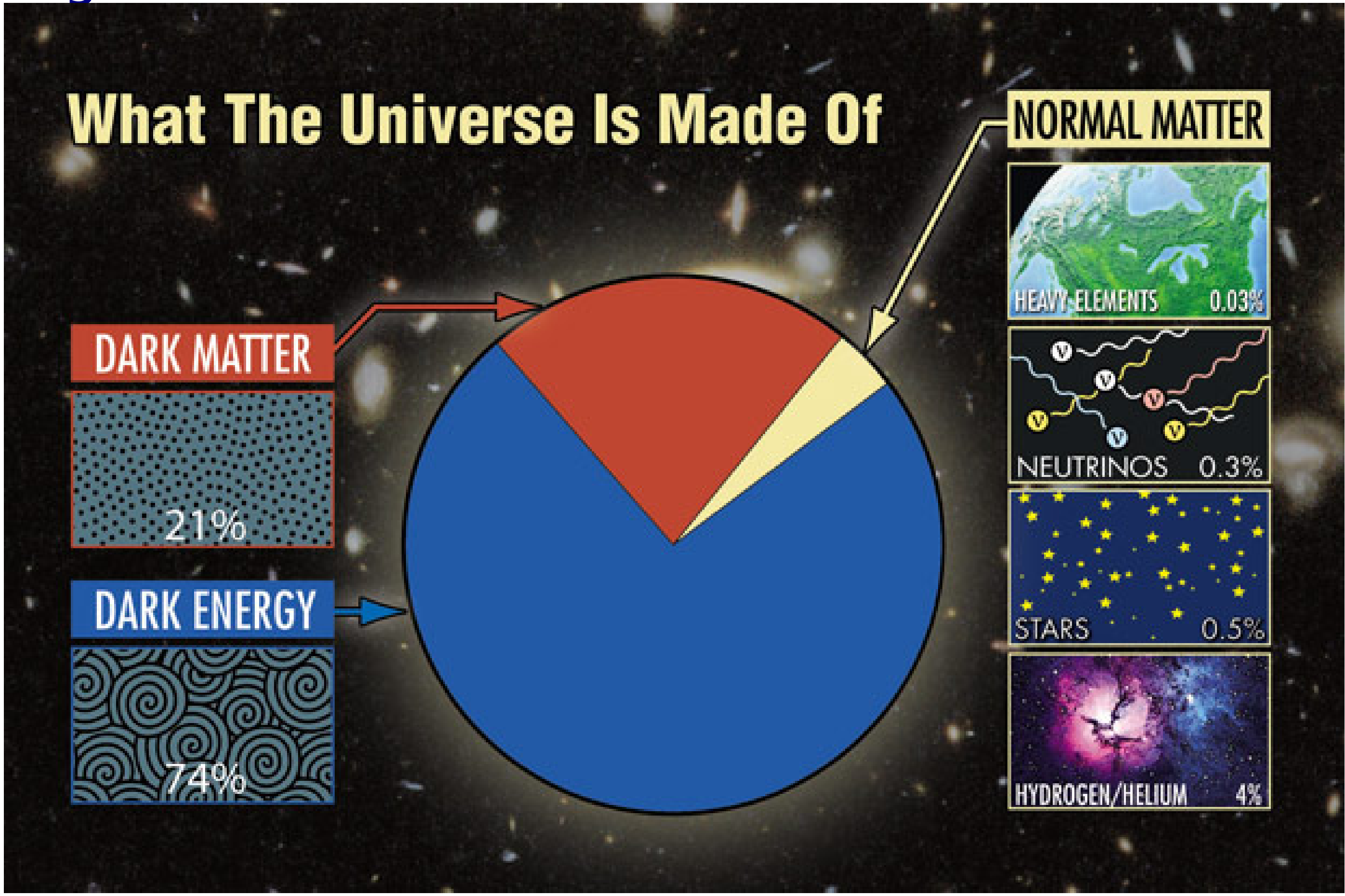


- Wiggles in the Cosmic Background represent density fluctuations in the early universe
- Higher density regions attract matter (especially dark matter) which makes the density higher, which attracts more matter
- Clumps of dark matter grew to form the structures we see



A consistent picture

- 13.7 Billion Years Old
- Flat (Euclidean) Spatial Geometry
- Critical Mass+Energy Density
- Expansion Accelerating



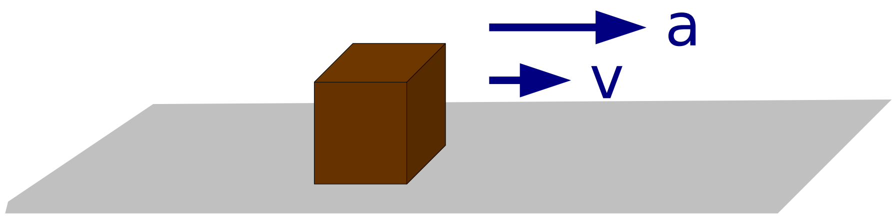
- Us: ~5%
- Dark matter ~25%
- Dark energy ~70%

95% of the universe is unknown!

Dark Energy

- If the universe is flat, then 70% of the mass/energy is not in the form of normal matter, dark matter, or photons. Then what is it?
- Dark energy provides a pressure to space increasing the rate of expansion, counteracting gravity
- The net effect is like a negative gravity

Analogy:



- See box accelerating down sidewalk
- We **know** there is a force + source of energy
- We have ideas, but we don't know for sure the nature of the force/energy:
  - property of space (a constant that doesn’t change as space expands)
  - A field/fluid/energy that dilutes as space expands
  - Einstein equations need modification

Dark energy connections

- We know from particle physics and quantum physics that the energy density of the vacuum is NOT zero
- We can try to calculate the vacuum energy density by adding the zero-point energies of all quantum oscillators that make up fields (see lecture 18):

  $\Omega_{vac} = 10^{122}$ (simplest calculation)

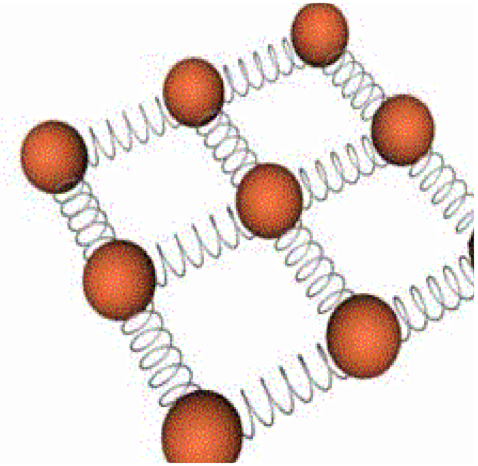
  $\Omega_{vac} = 10^{55}$ (improved calculation with supersymmetry)

  In reality, we measure:

  $\Omega_{vac} = 0.70$

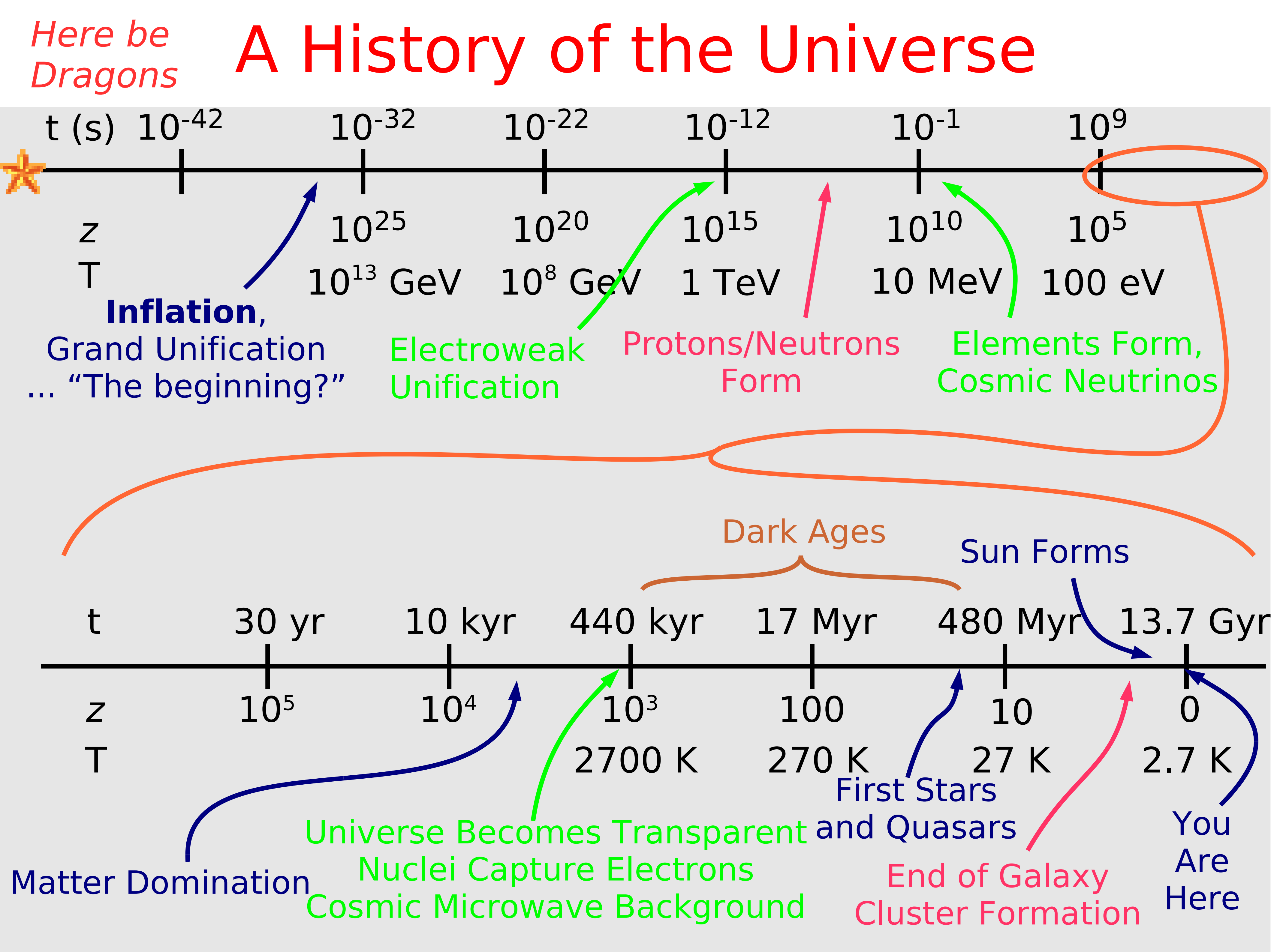
  (we expected $\Omega_{vac} = 0$ before 1998!)

This embarrassing inconsistency is probably THE biggest issue today in Physics



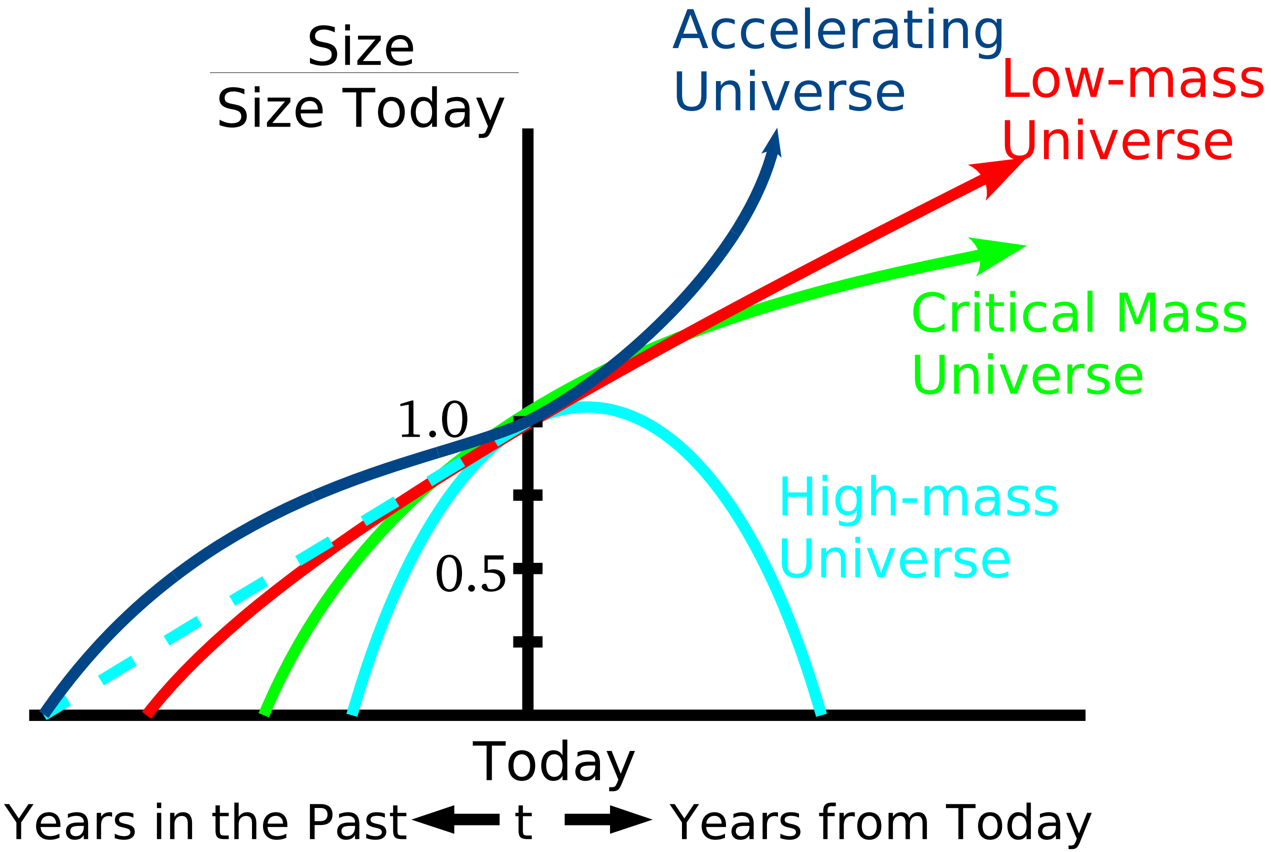
- Einstein could not find static solutions to his equations of General Relativity
- All solutions described a Universe either expanding or contracting
- He added a term corresponding to the energy of the vacuum, to counteract gravity and make the Universe static!
- His biggest blunder!
- But right after all!

A History of the Universe

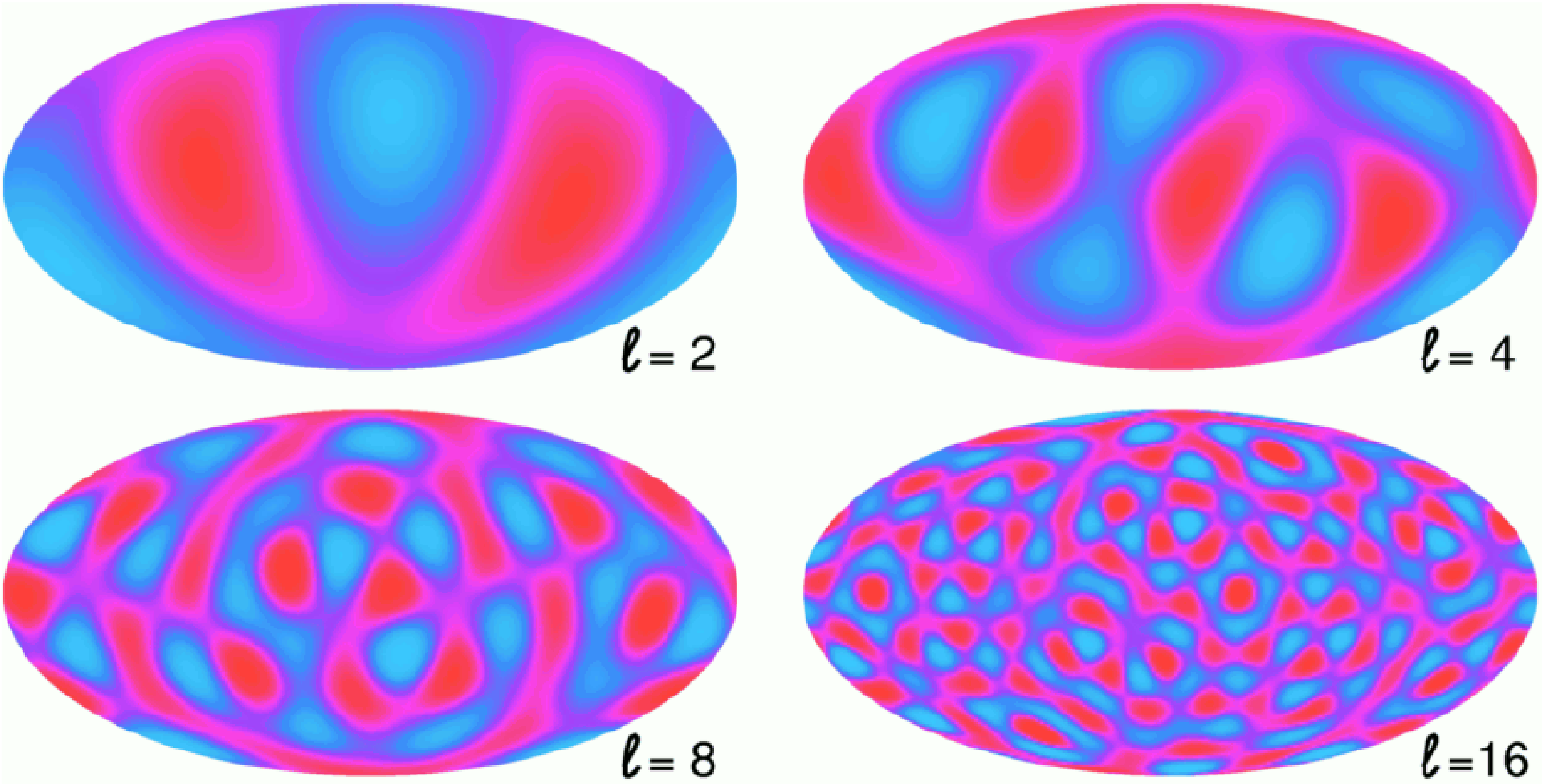


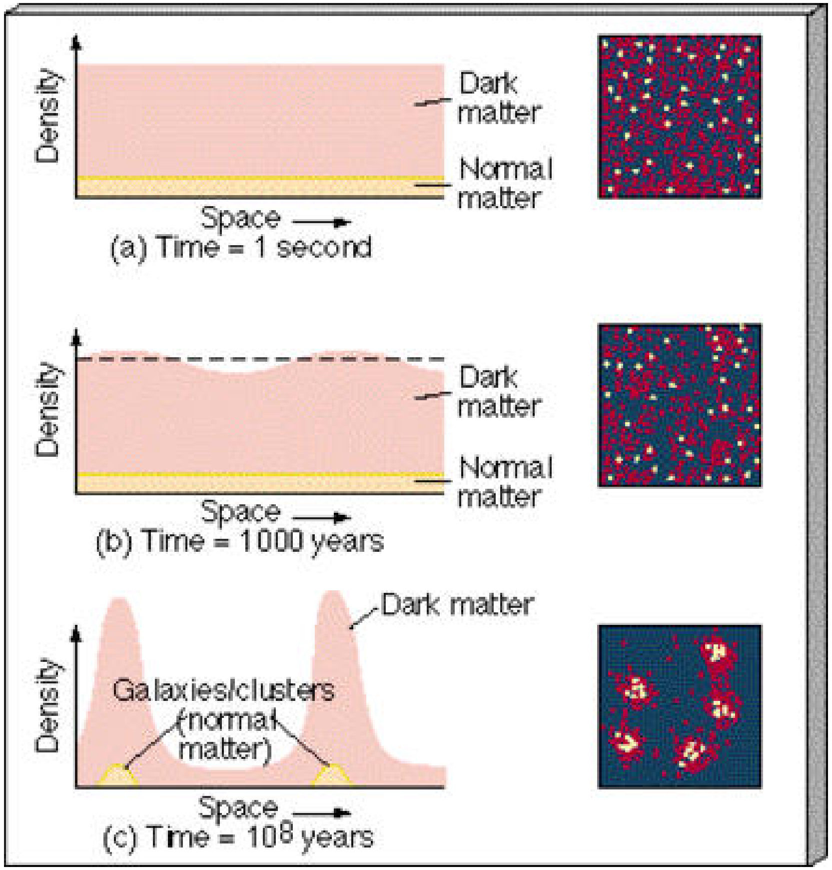
Extras

History of acceleration

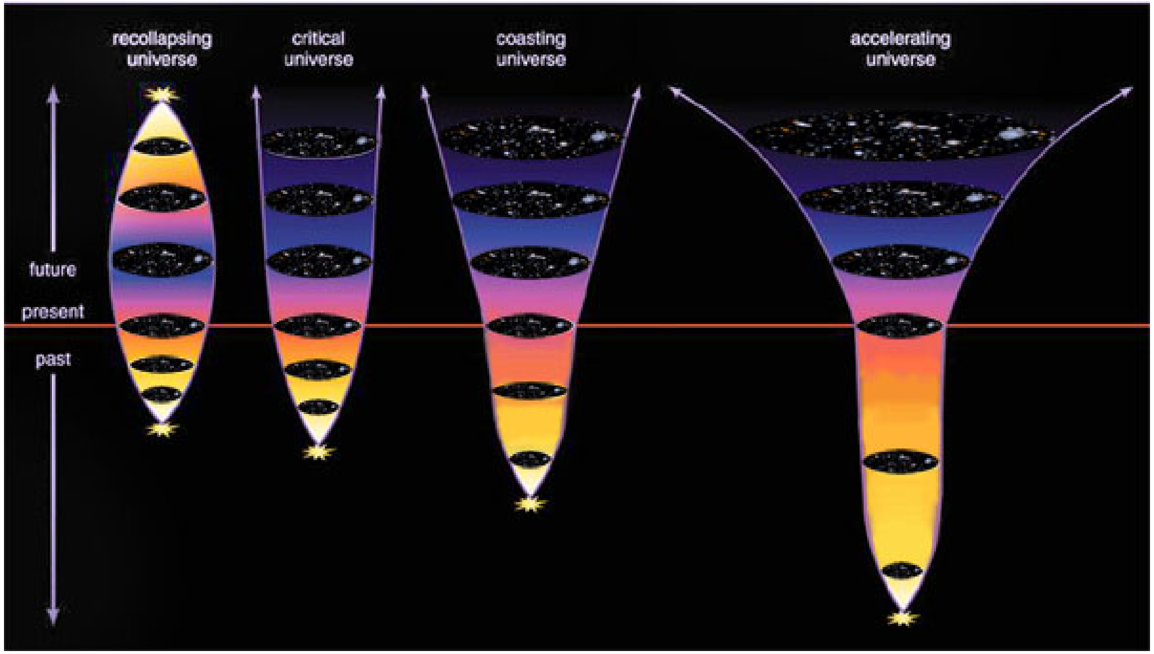


Spherical harmonic decomposition

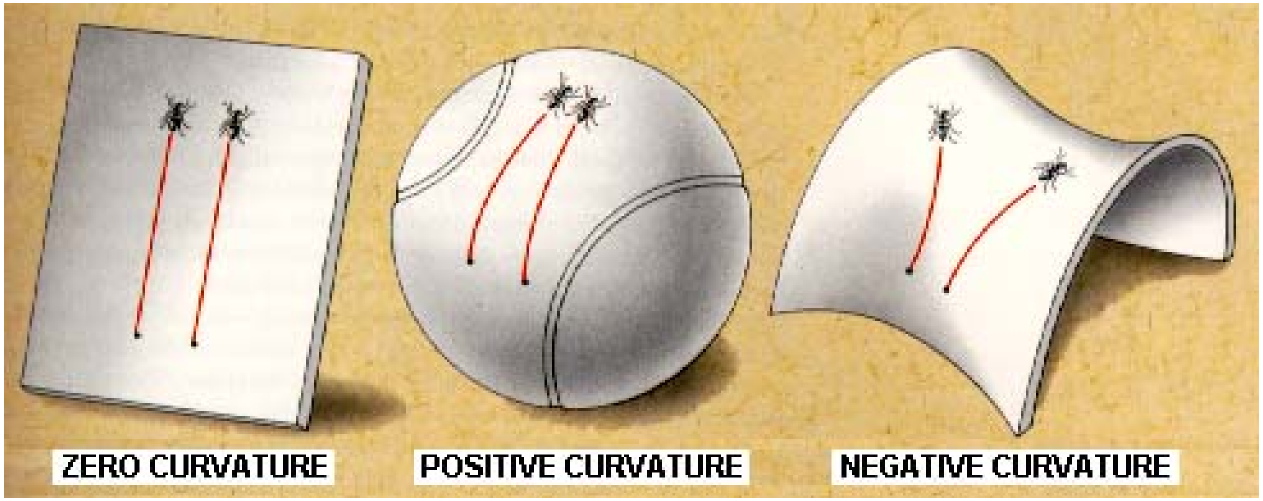




Density
Dark matter
Normal matter
Space
(a) Time = 1 second
Density
Dark matter
Normal matter
Space
(b) Time = 1000 years
Dark matter
Galaxies/clusters (normal matter)
Density
Space
(c) Time = 10^8 years



recollapsing universe
critical universe
coasting universe
accelerating universe
future
present
past



ZERO CURVATURE
POSITIVE CURVATURE
NEGATIVE CURVATURE