The First Three Minutes Meeting 9

Peter Fisher

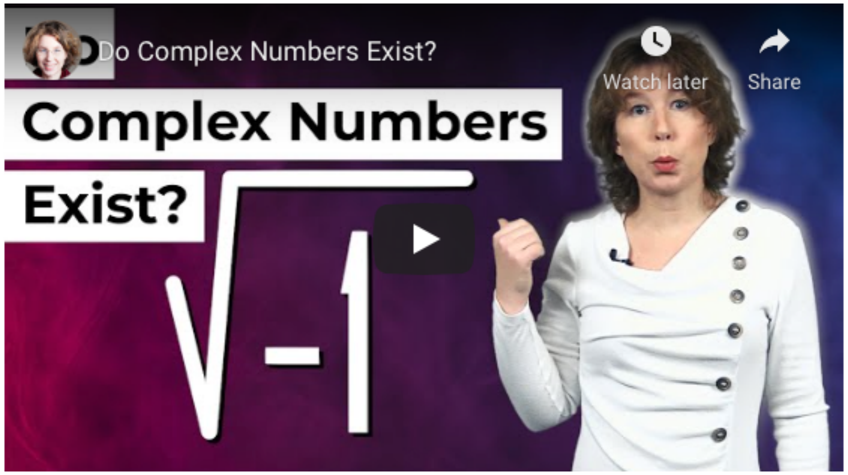
March 10, 2021

Meeting 8 – The First Three Minutes

- Announcements
- 30,000 ft
- Chapter VIII and Afterword
- **Break**
- Inflation

Announcements

- Notes, slides, etc. on website, tinyurl.com/firstthreeminutes
- Questions
  - Good science blogs:
    - physics buzz: http://physicsbuzz.physicscentral.com
    - Not even wrong: http://www.math.columbia.edu/~woit/wordpress/
    - Backreaction: http://backreaction.blogspot.com



SI Unit prefixes - https://www.nist.gov/pml/special-publication-811

Table 5. SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
$10^{24}=(10^3)^8$	yotta	Y	10^{-1}	deci	d
$10^{21}=(10^3)^7$	zetta	Z	10^{-2}	centi	c
$10^{18}=(10^3)^6$	exa	E	$10^{-3}=(10^3)^{-1}$	milli	m
$10^{15}=(10^3)^5$	peta	P	$10^{-6}=(10^3)^{-2}$	micro	µ
$10^{12}=(10^3)^4$	tera	T	$10^{-9}=(10^3)^{-3}$	nano	n
$10^{9}=(10^3)^3$	giga	G	$10^{-12}=(10^3)^{-4}$	pico	p
$10^{6}=(10^3)^2$	mega	M	$10^{-15}=(10^3)^{-5}$	femto	f
$10^{3}=(10^3)^1$	kilo	k	$10^{-18}=(10^3)^{-6}$	atto	a
10^{2}	hecto	h	$10^{-21}=(10^3)^{-7}$	zepto	z
10^{1}	deka	da	$10^{-24}=(10^3)^{-8}$	yocto	y

Note: Alternative definitions of the SI prefixes and their symbols are not permitted. For example, it is unacceptable to use kilo (k) to represent 2^{10} = 1024, mega (M) to represent 2^{20} = 1 048 576, or giga (G) to represent 2^{30} = 1 073 741 824. See the note to Ref. [5] on page 74 for the prefixes for binary powers adopted by the IEC.

30,000’ view

Galaxies are the “atoms” of the universe

When viewed on the 100 Mly scale, the universe is uniform and isotropic

Hubble’s redshift measurements showed all the galaxies are moving away from us. Their recession speed is proportional to how far away they are. H_o is the proportionality constant.

30,000’ (cont.)

The recession of the galaxies led to the idea that the space of the universe is expanding. The expansion is the same everywhere.

The numerical value of H_o implies the universe is 13.7 Gy old.

Penzias and Wilson’s observation of 2.7 K radiation led to the conclusion that neutral hydrogen formed from a plasma 377,000 y after the start of the universe.

30,000’ (cont.)

At 0.01 s, the recipe for a hot universe consists of

- Zero net charge
- Protons, neutrons, electrons at the 1 ppb level compared with photons (and neutrinos)
- T=100 G kelvin for black body photons
- Expansion as $t^{1/2}$

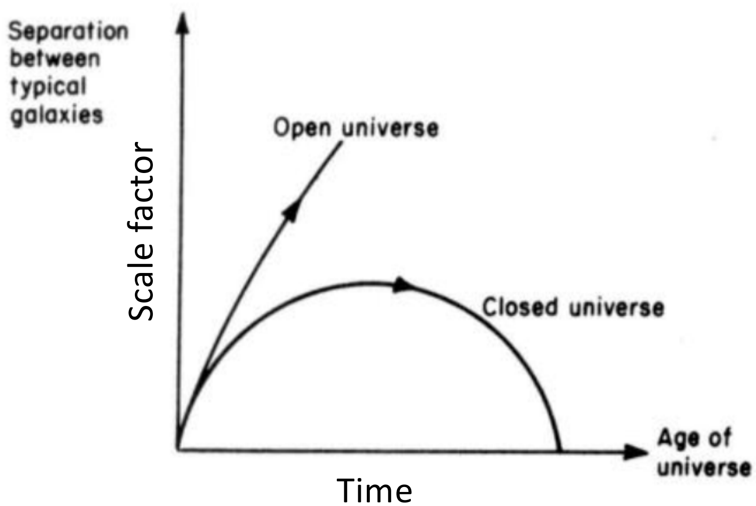
Synthesis of H, D, and He began at 0.01s as the proton-neutron imbalance developed, but was delayed to 3 min by the low binding energy and fragility of the deuteron.

Chapter VIII

Weinberg uses the Epilogue to discuss some open questions from 1977. He leaves a little list of problems…

- Open, flat or closed universe
- Quantum mechanics in the early universe
- Oscillating universe

Open, flat, or closed universe



Depends on density, dividing line is 8.5×10^{-27} kg/m^3 (8.5 mykg/m^3)

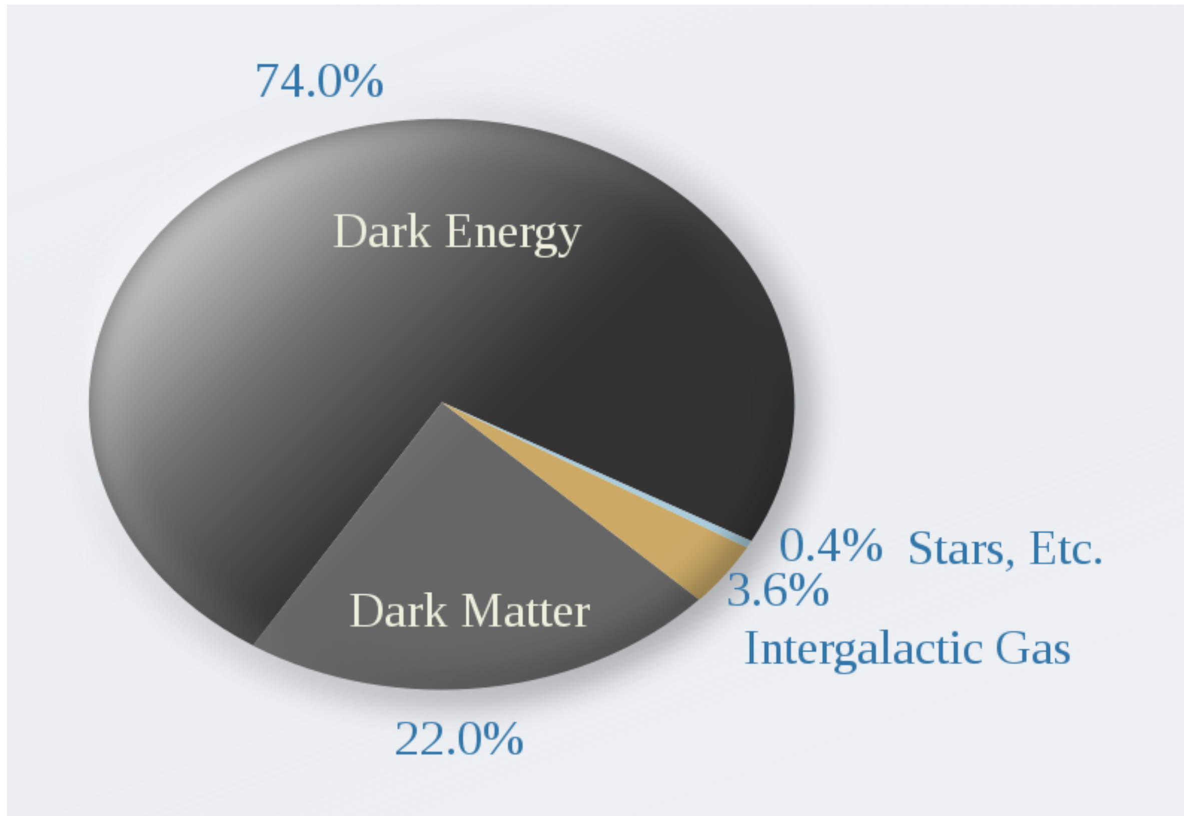
Sum of all kinds of matter. In Weinberg's time, the density was thought to be less than 1/10th the critical density based on several different observations.

Were the density to really be 0.1 ρ_c today, it would have had to be within 0.0001% of ρc at the time of the QGP

Critical density

Most astronomers assumed the real value was rc and we just did not count correctly.

It turned out that we *did* count correctly, but did not know about DE or DM.



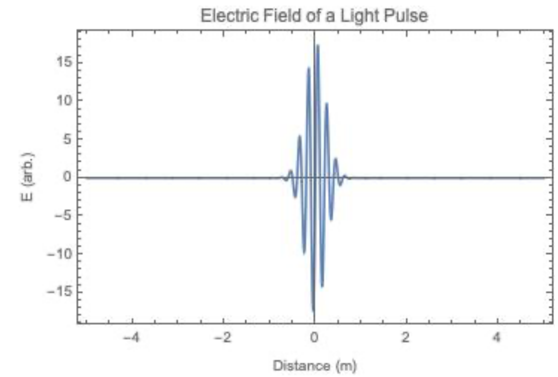
Gravity and QM

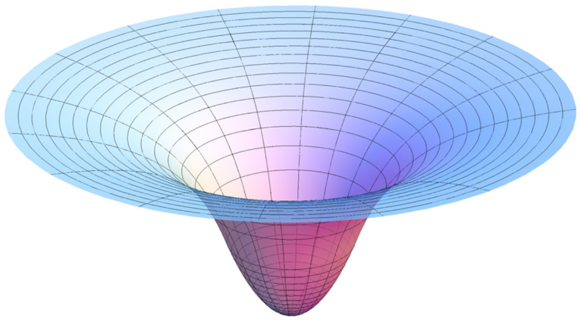
Particles have a wavelength λ.

Gravitational energy depends on 1/r

r becomes close to λ at Planck length 10^{-35}m (100 nym)

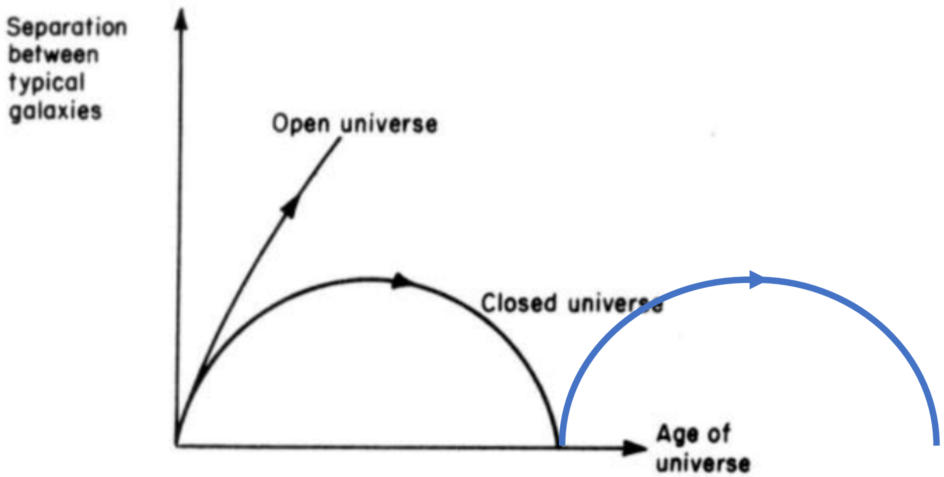
- Space and time in the Schwarzschild solution lose their meaning
- QM dominates over classical





At 10^{-104}s, the horizon is one planck length across

Oscillating universe



In the density were greater than critical (it isn't), the universe could collapse back on itself and start again.

Gets rid of "what was before start" problem.

Problem (aside from density): to date, 1 ppb of matter over antimatter was somehow created. Each cycle would create more. If the universe were infinitely old, should be 50/50…

Afterword – update 16 years later

Weinberg updates his laundry list of problems…

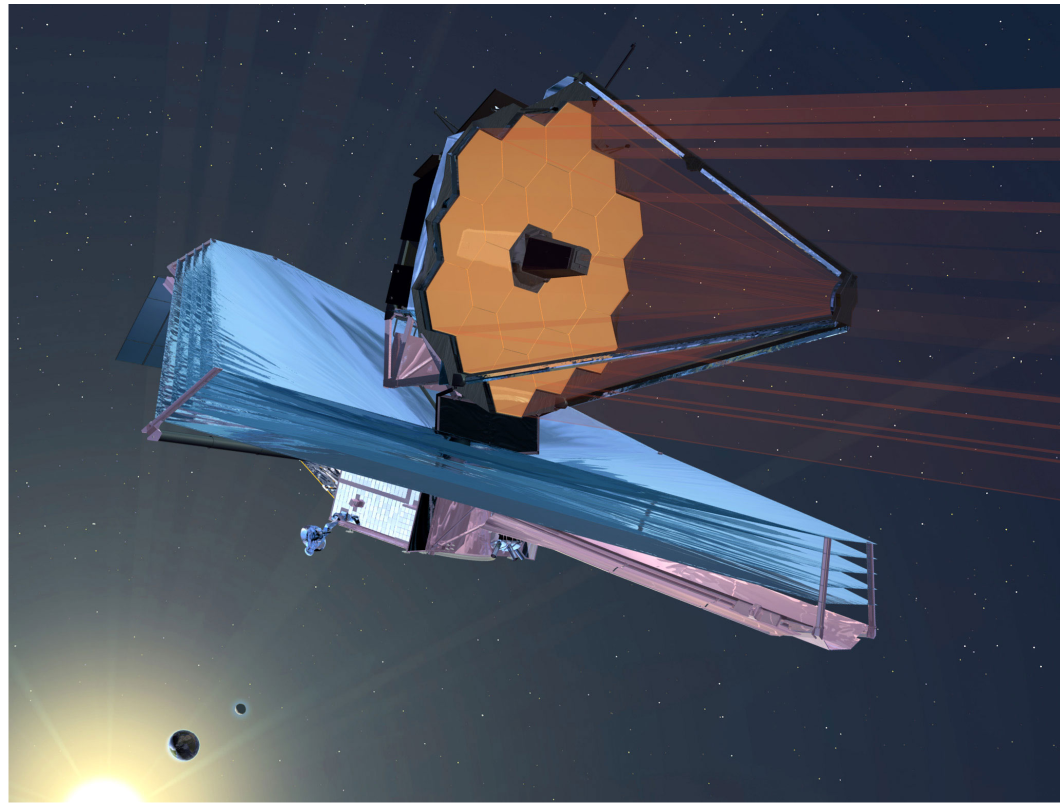
- Hubble/HST crisis
- COBE measurement of the CMB – Dark Matter next week
  - Earth dipole observed
  - Structure in the CMB
- Rotation curves – missing matter in galaxies - DM
- Density 2-4% of critical, theorists assume it is one - Inflation
- Horizon problem - Inflation

Hubble Space Telescope (HST)

although much of value has been learned with this telescope, scope, its notorious problems with excessive vibration and a distorted mirror have stood in the way of definitive measurements of galactic distances.

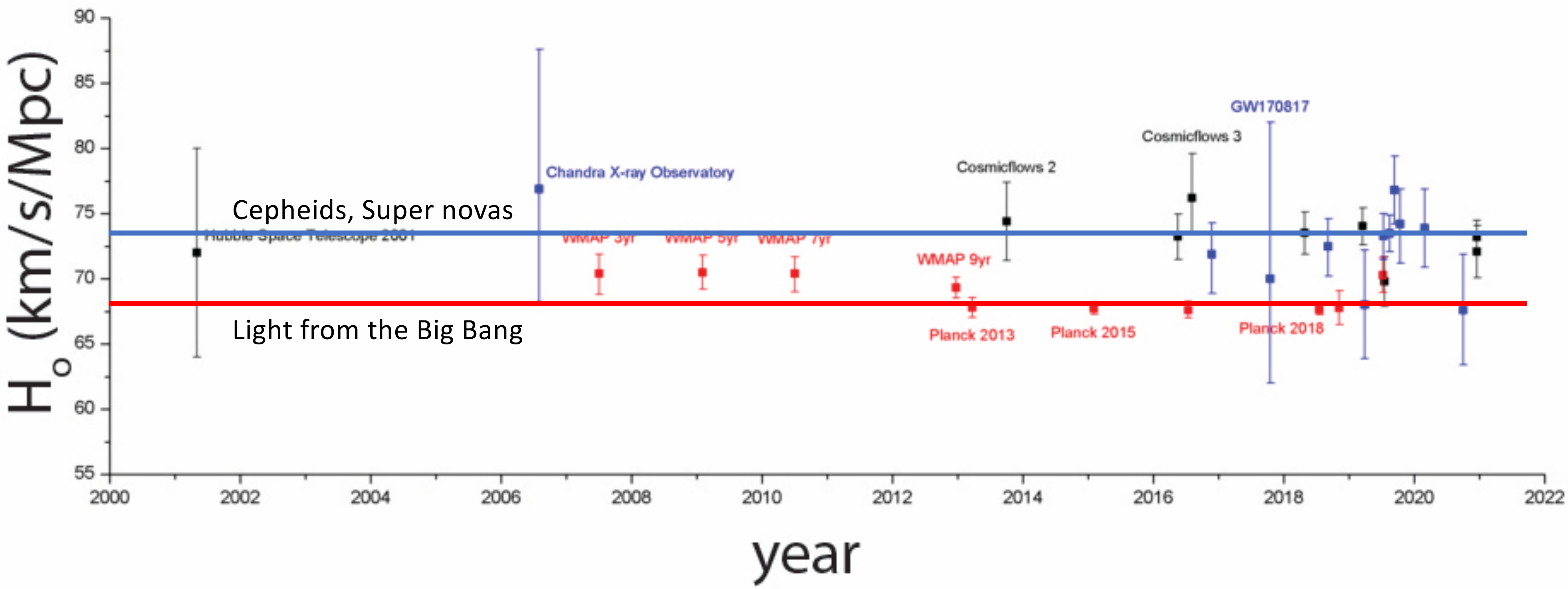
Steven Weinberg. The First Three Minutes: A Modern View Of The Origin Of The Universe (Kindle Locations 1869-1870). Kindle Edition.

Optics corrected in a servicing mission in 1993. Four other servicing missions took place. Every major instrument was upgraded. Still operating after 25 years, perhaps the most productive piece of scientific equipment ever.



James Webb Space Telescope

Hubble Constant



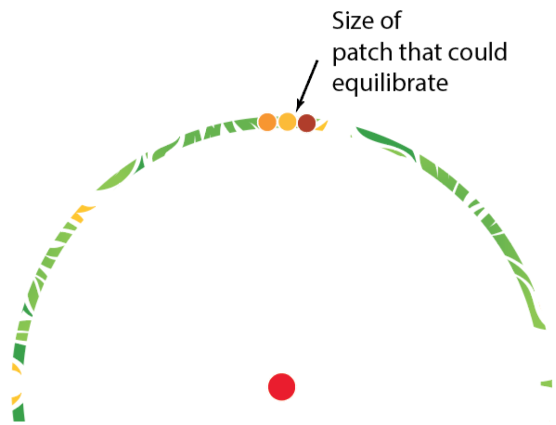
5 m Break

Inflation – Horizon problem

The CMB was emitted at 377,000 years and is uniform at the ppm level. At the emission of the CMB, light could only have travelled about 30 Mly in the age of the universe, about 2 degrees.

How could the universe be in thermal equilibrium?

Why isn't the CMB composed of little 2 degree patches at different temperatures?



Density

Also, how can the density be so close to the critical density in the early universe?

Earliest time we know about is 10 ps, the electroweak phase transition. Thermal equilibrium must have been established before then.

Inflaton field

Inflatons are particles, presumably very heavy, that make the universe expand very quickly for a time, then decay, eventually to Standard Model particles.

Necessary features:

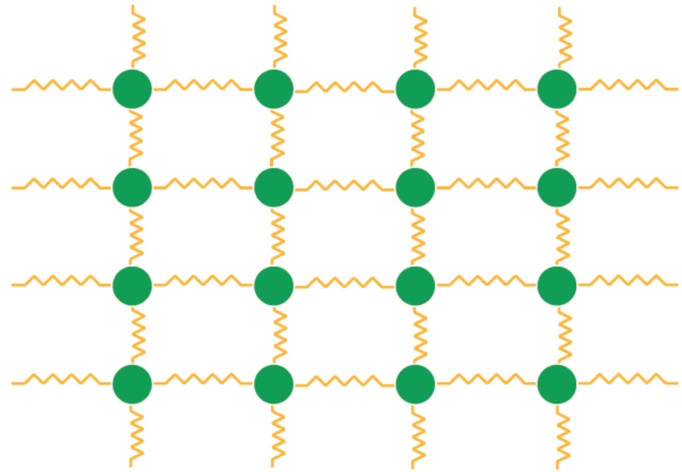
1. At start, 10^{-34} s (10 nys), the inflaton particles have large interaction energy
2. The interaction energy releases with time, arriving at a minimum, stable value
3. The pressure of the inflaton particles is proportional to their *negative* density

Interaction energy and pressure

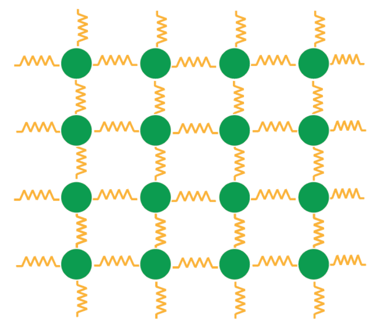
Masses on stretched springs

At start, masses stretched *out*, creating pressure to pull in, increasing density

High density of inflatons drives very rapid expansion of the universe, H increases with density



Stretched out



Relaxed – minimum energy

Inflation – how it works

Before 10^{-34} s – universe in equilibrium

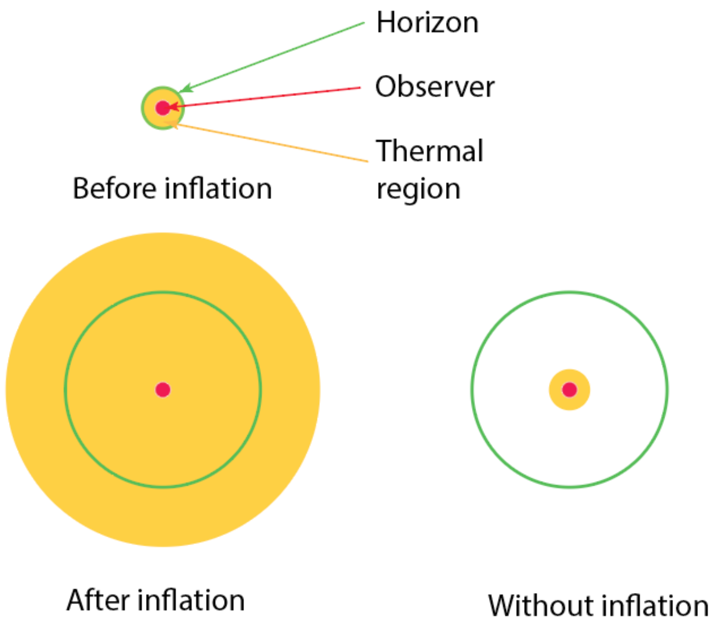
10^{-34} s – inflatons in stretched state, begins to contract or "roll"

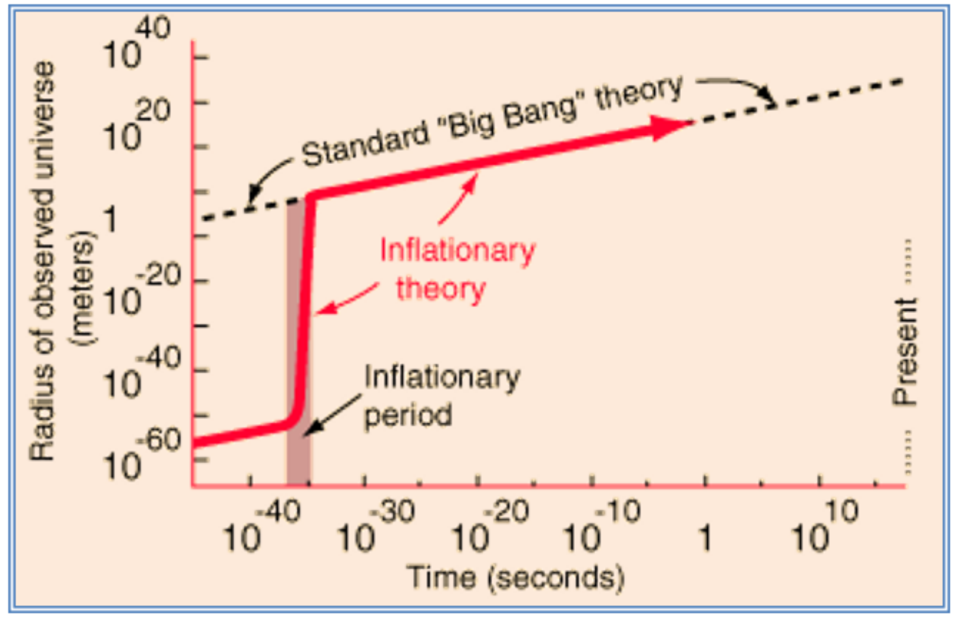
10^{-34} – 10^{-32} s – rolling, density increasing rapidly, causing expansion

10^{-32} s – Universe (scale factor) has doubled 86 times (10^{26}), inflatons reach minimum, stopping density increase

After 10^{-32} s – inflatons decay to precursors to SM particles

Result of Inflation





Also forces critical density

Inflation summary

Widely accepted idea, but not by everyone (no Nobel yet)

Makes several important predictions about dark matter we will discuss next week

Not really a theory, but an idea or class of theories.

- We do not know how the rolling works
- Do not know what the inflaton is