CMB -- summary

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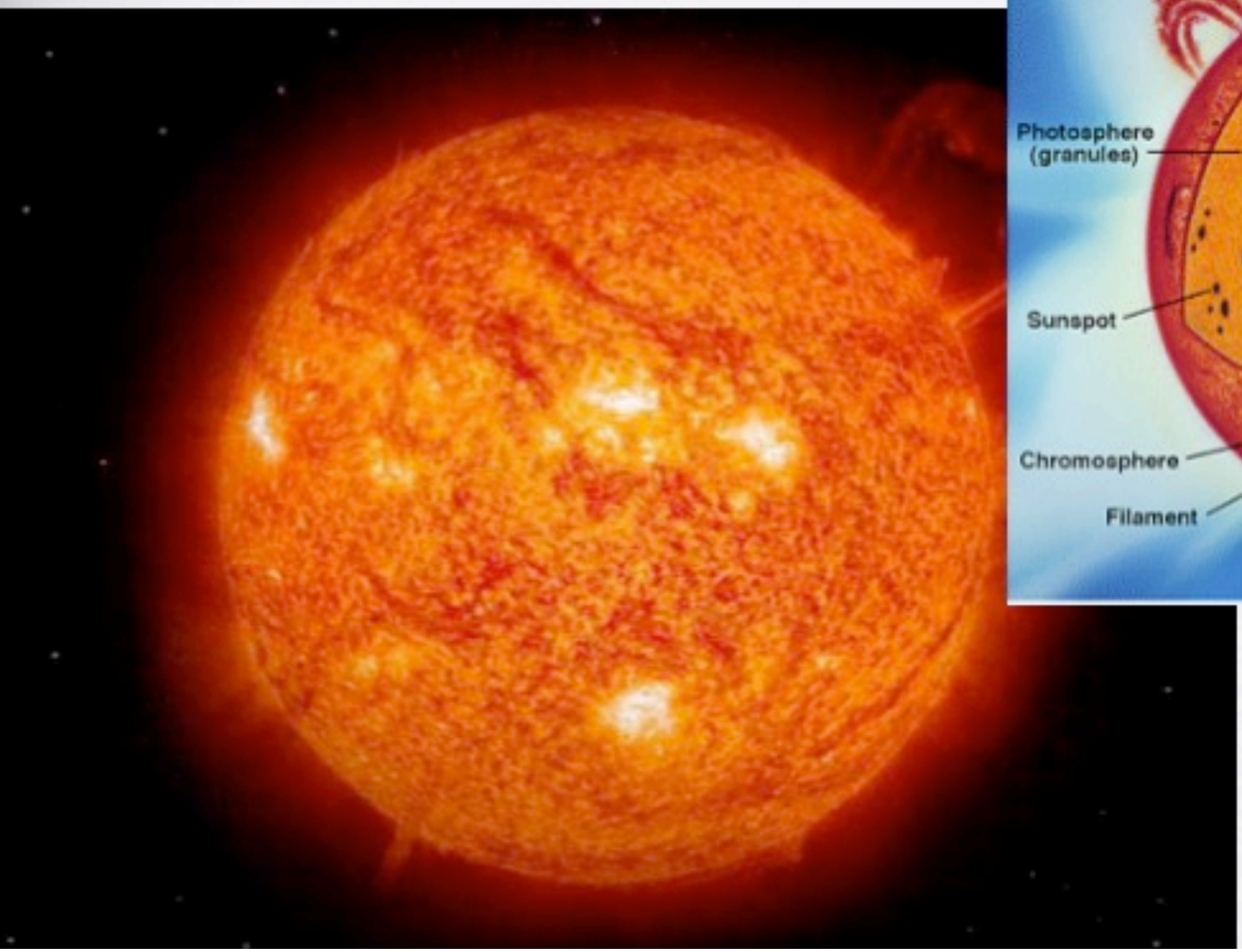
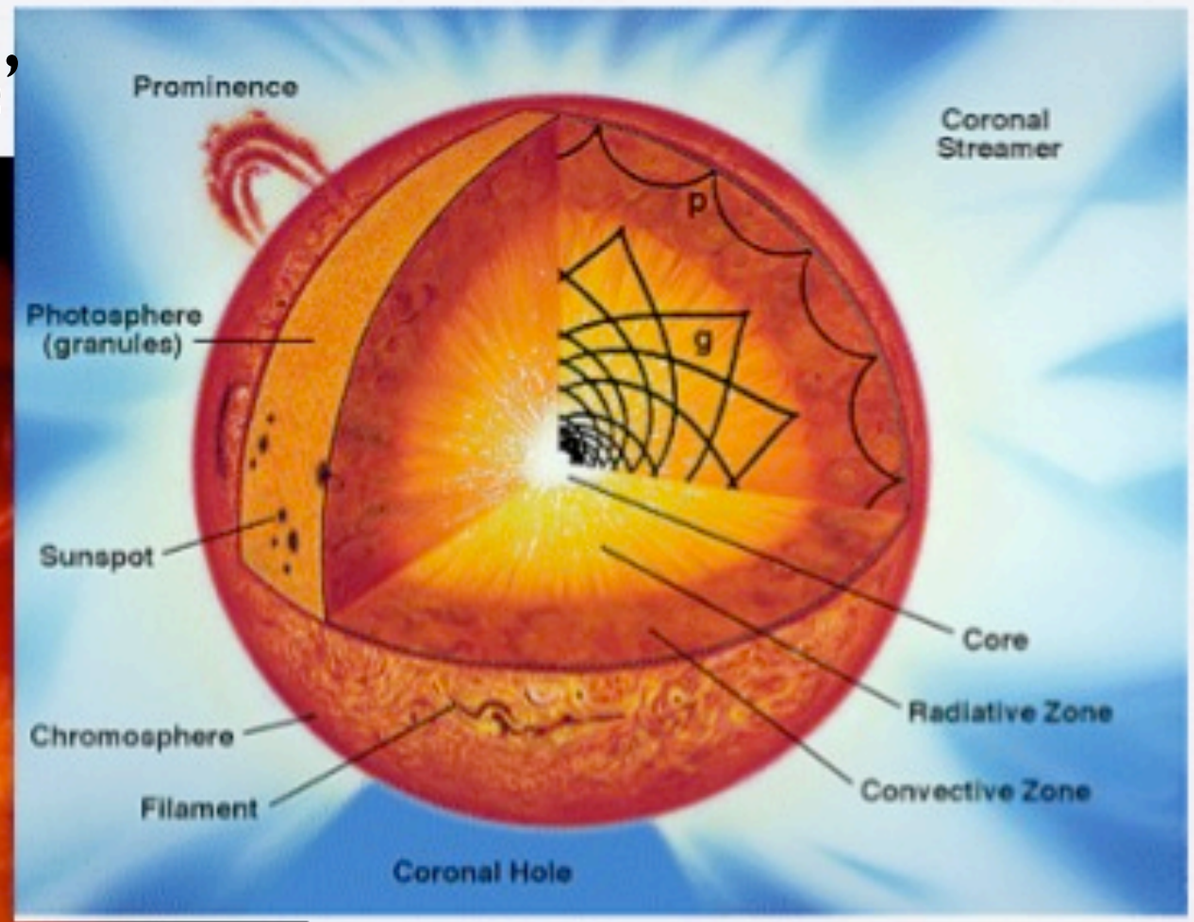
Why can't you see into the Sun?

no direct view of the central hottest part; only the 'photosphere'





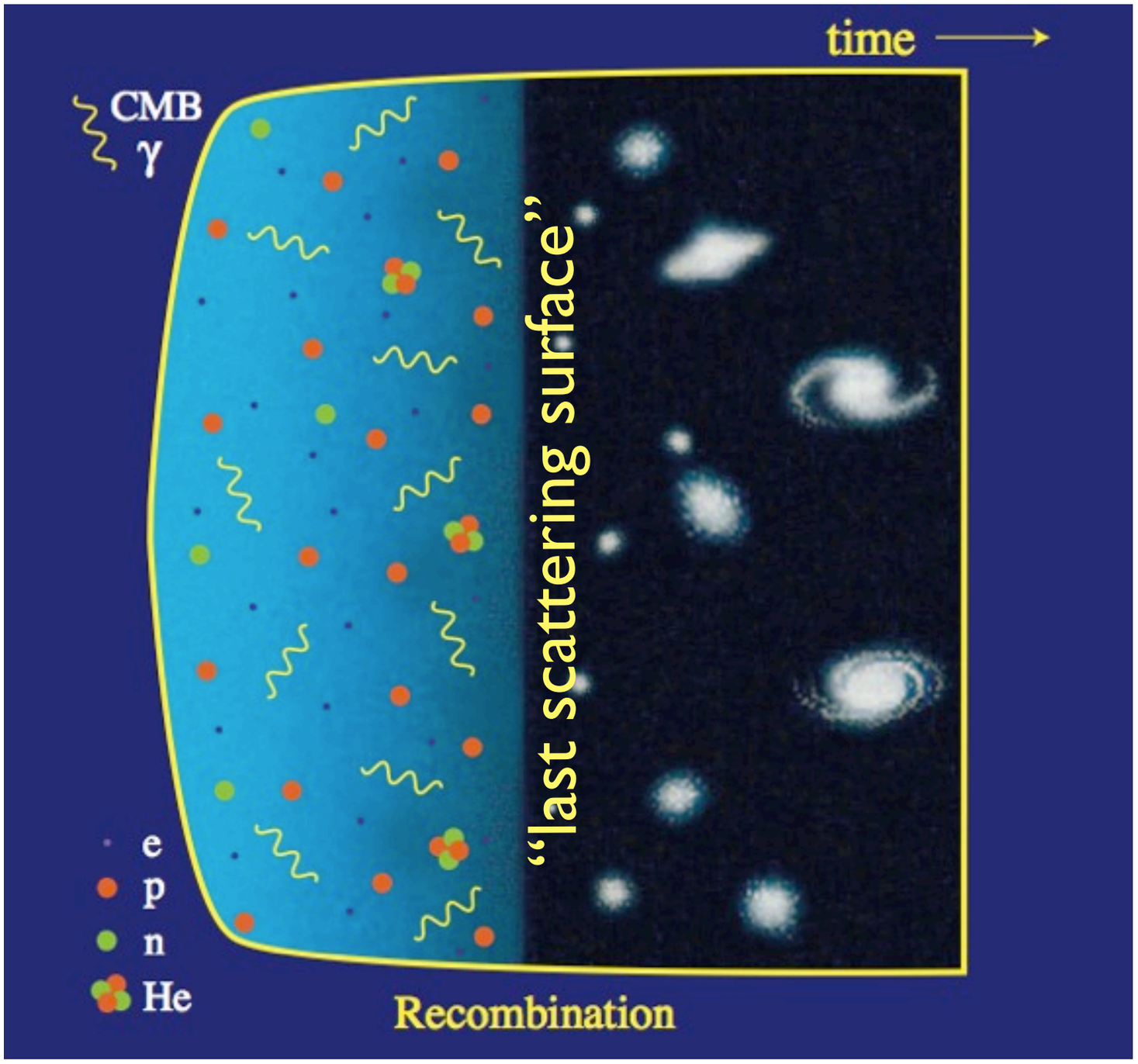
photons from the Sun embed information about the "last scattering layer".

Light started its journey.

- early universe, hot plasma + intense radiation

- photons are EM force carriers; interact strongly with charged particles (e.g., electrons)

- this gives a ‘fog’ in the direction of the big bang



- as universe cools, electrons combine with hydrogen nuclei (recombination), most photons decoupled (electron orbits quantized, only interact with specific photons)

- ‘fog’ lifted; this is the last scattering surface; the universe was 300,000 yrs old

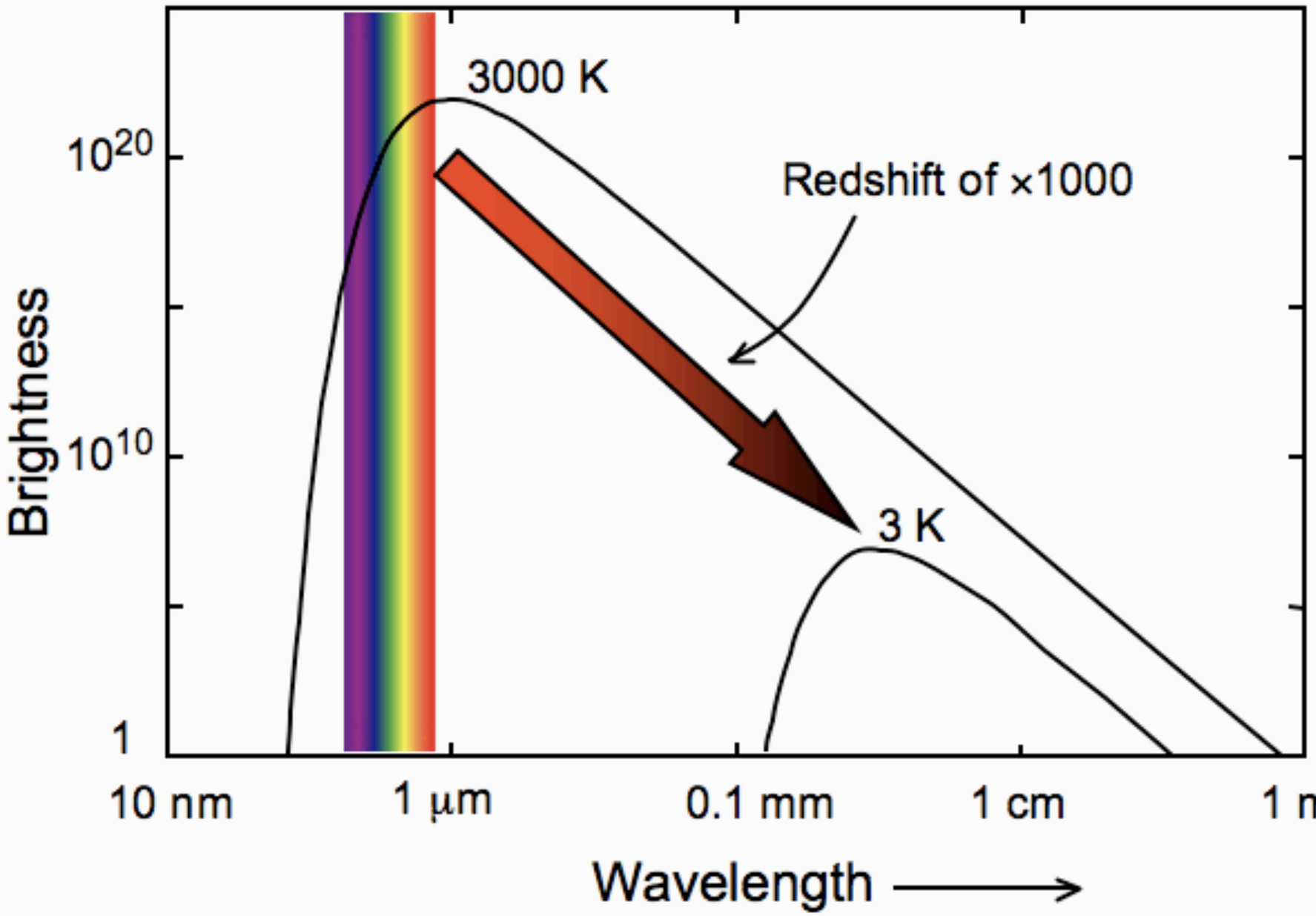
What would it have been like to be there when the Universe became transparent

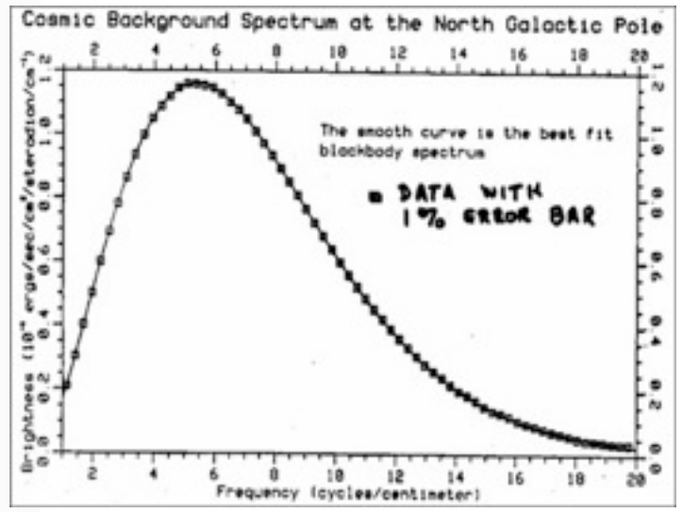
a **blackbody** with T ~ 3000K

~ a conventional light bulb (Tungsten)

(The contrast is highly exaggerated.)

What does a redshifted blackbody spectrum look like?



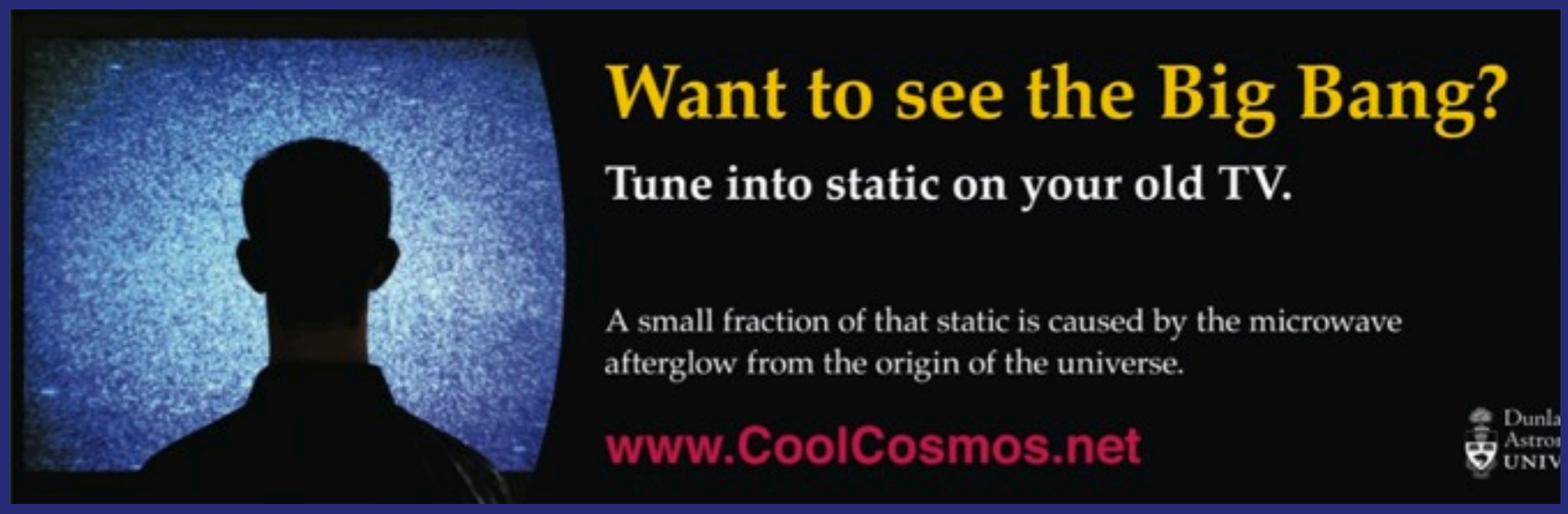


. $\lambda_{peak} = \lambda_{peak}$ (orig)*(1+z), shape invariant

. we get another blackbody with $T = T_{orig}/(1+z)$

Now, ... redshifted to microwave (z ~ 1100)

- CMB photons have dropped out of the visible spectrum into the microwaves; a temperature 3 degrees above absolute zero
- Wavelengths in the mm-cm regime, comparable to radio and TV wavelengths



- Tune a TV between channels and about 1% of the static is from the CMB
- Tune a microwave receiver to the peak frequency of CMB photons and they dominate the night sky and come from everywhere at a rate of 10 trillion photons per second per square cm.

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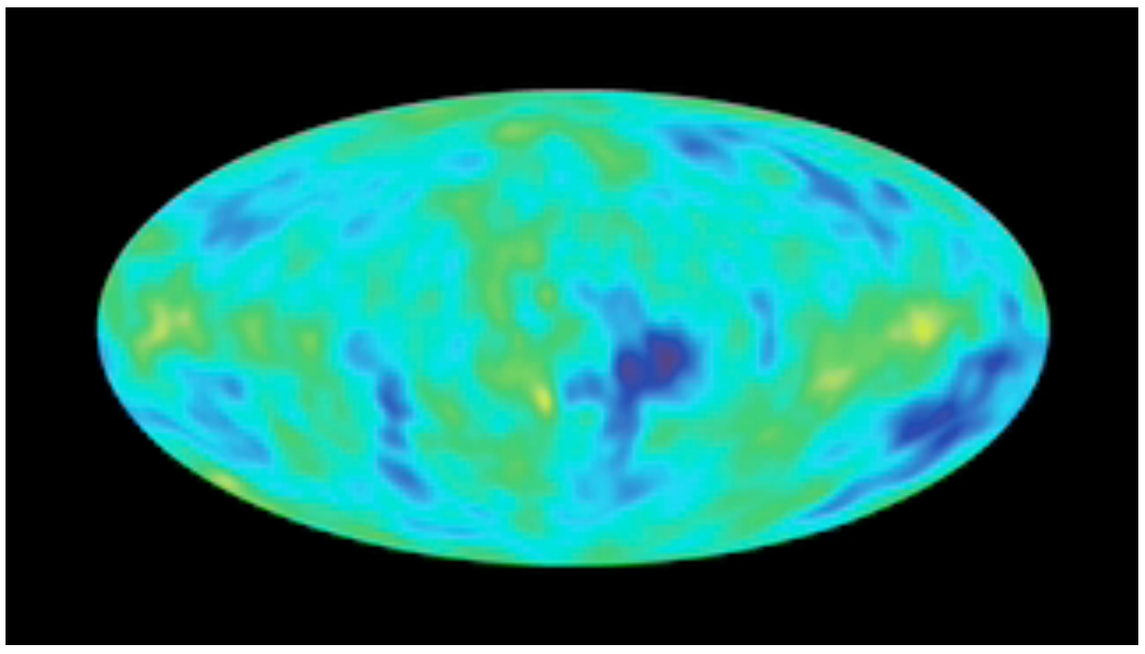
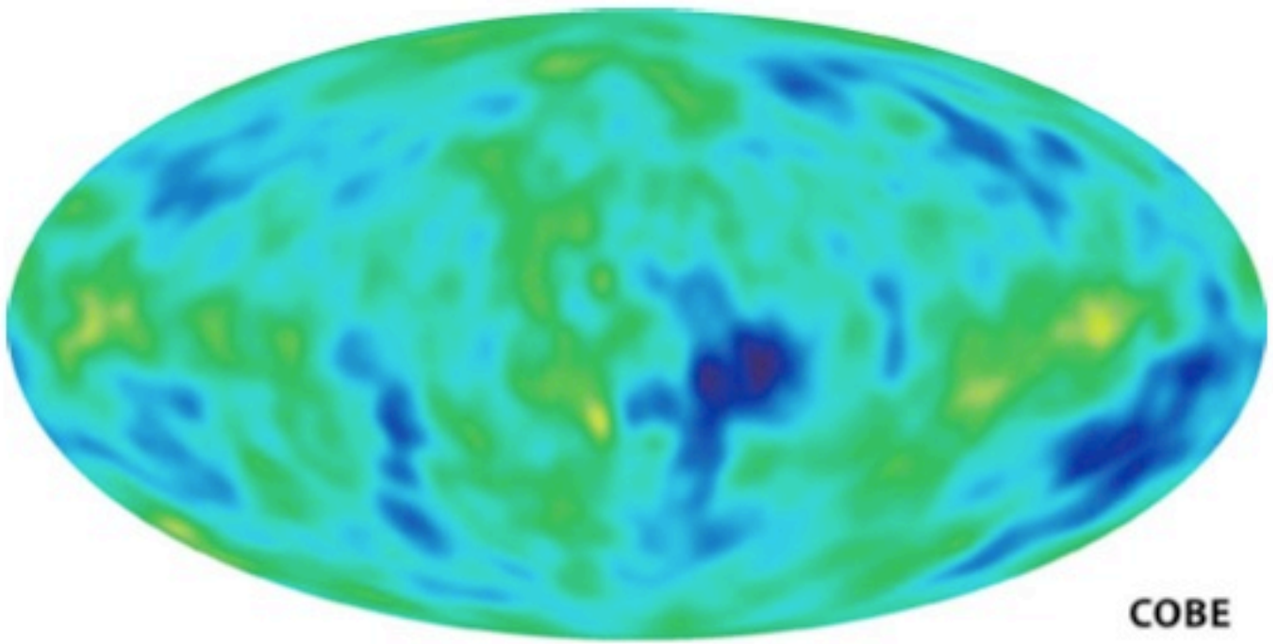
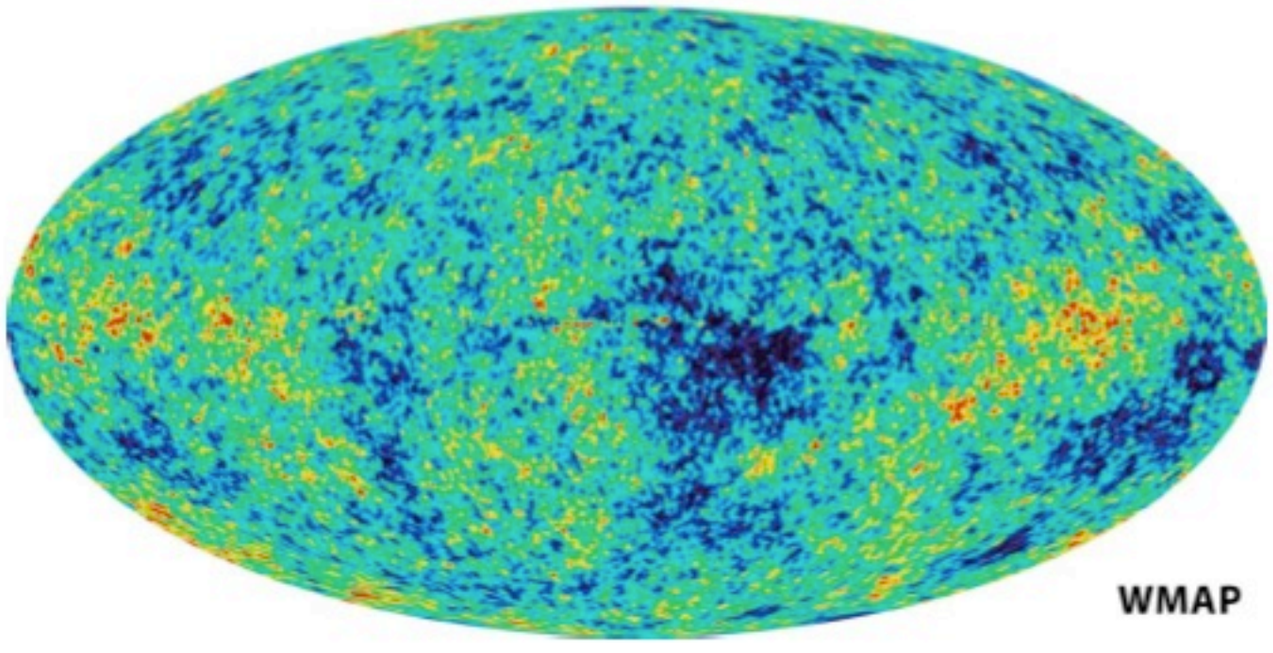
How does our CMB sky look?

COBE 1992 vs. WMAP 2008







CMB & galaxies

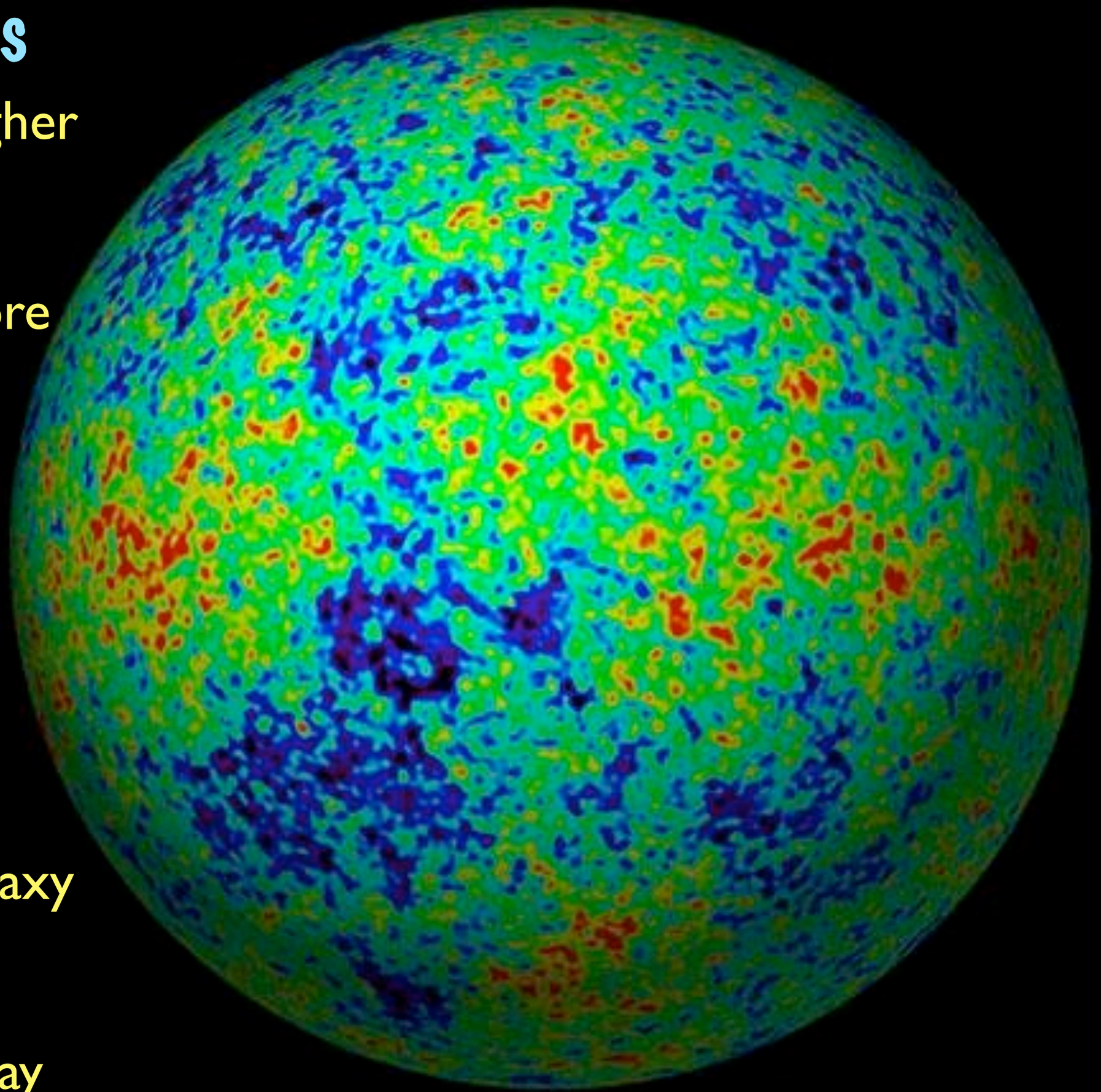
Hot spots: ~10^{-5} higher than average

denser (and therefore hotter) places

gravity is relatively stronger, can resist expansion of the universe better, collapse.

forming galaxies, galaxy clusters...

cold spots: void today



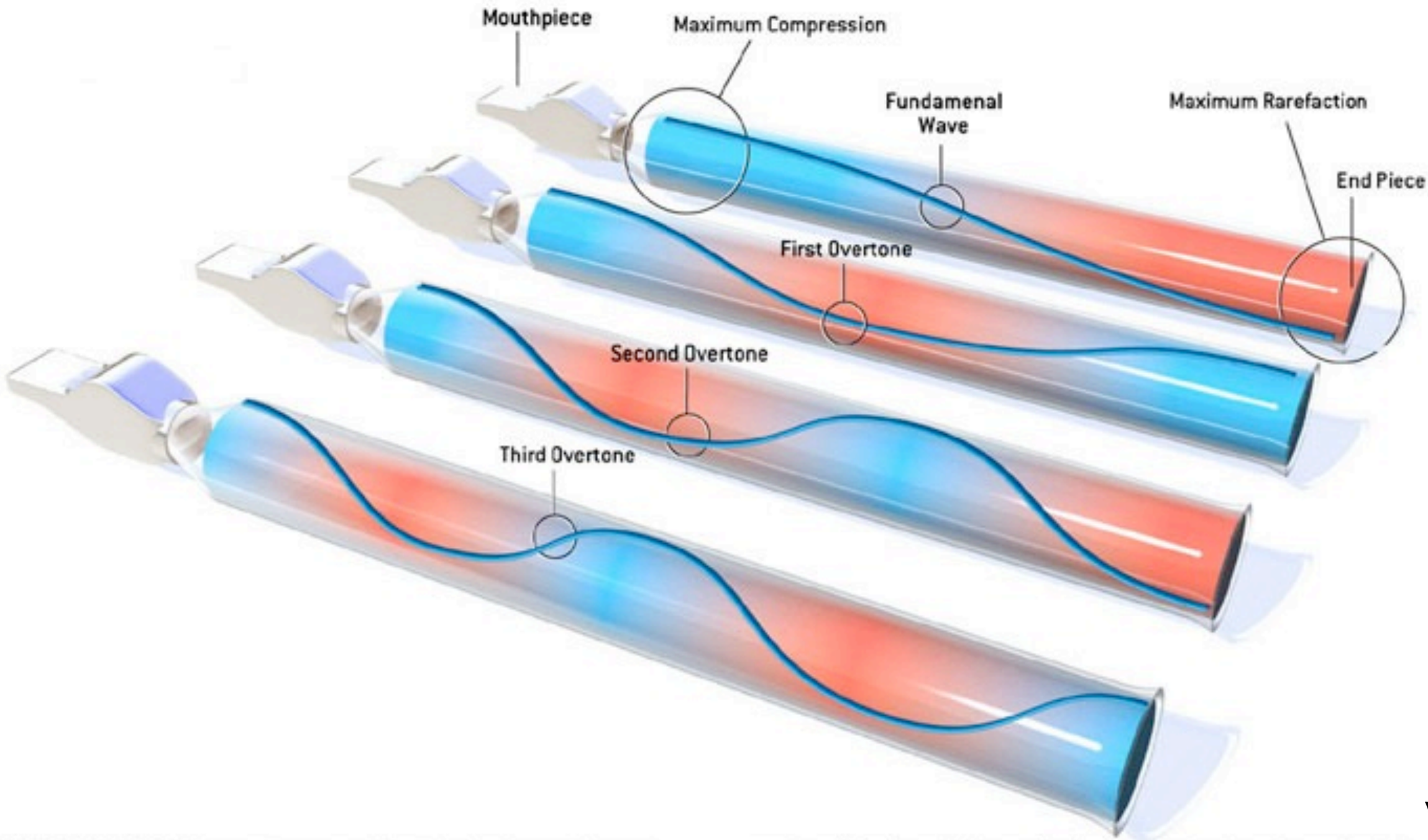
- If you blow into a pipe (no note), one note gets picked up.

  pipe blower: quantum fluctuations @ very early universe

- wavelength of the note equals the pipe length

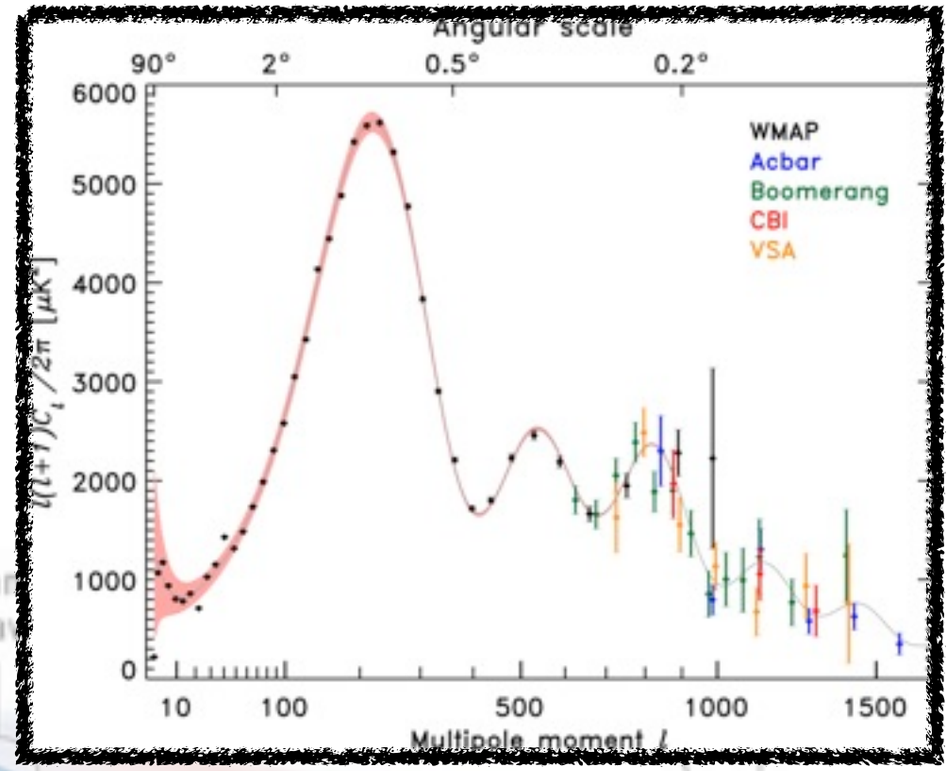
  pipe length $\approx c \times t$ (size of horizon)

- harmonics also produced



W. Hu

Why Horizon size at CMB special?



Before last scattering surface, photons coupled to matter; both matter and photon respond to sound compression

After last scattering surface, sound waves compress matter and matter heated up; but photons couldn't care less....

So only sound waves that are ~horizon size (or integer fractions of) at z ~ 1100 get picked up by CMB photons, appear as hot and cold spots, of angular size ~ 1 deg

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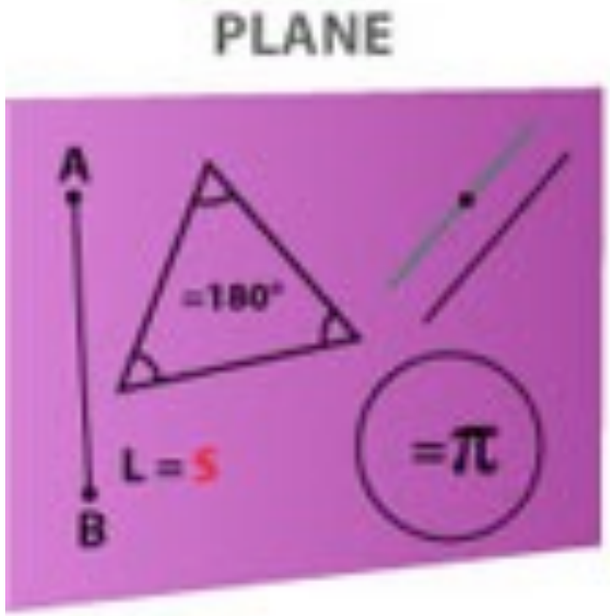
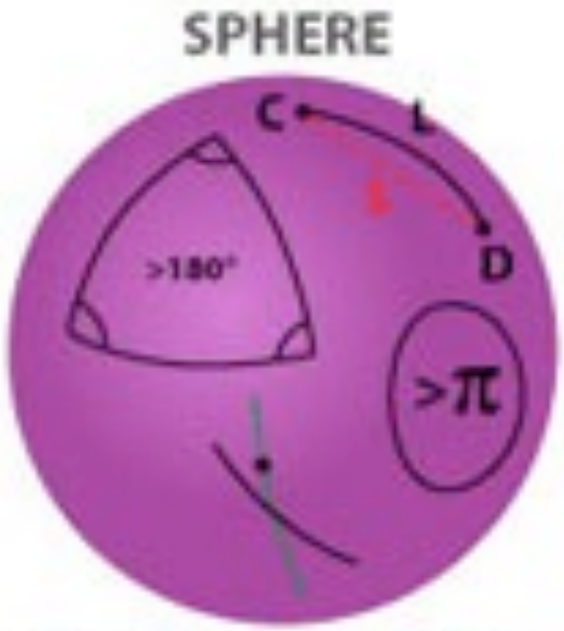
What is curvature of your space?



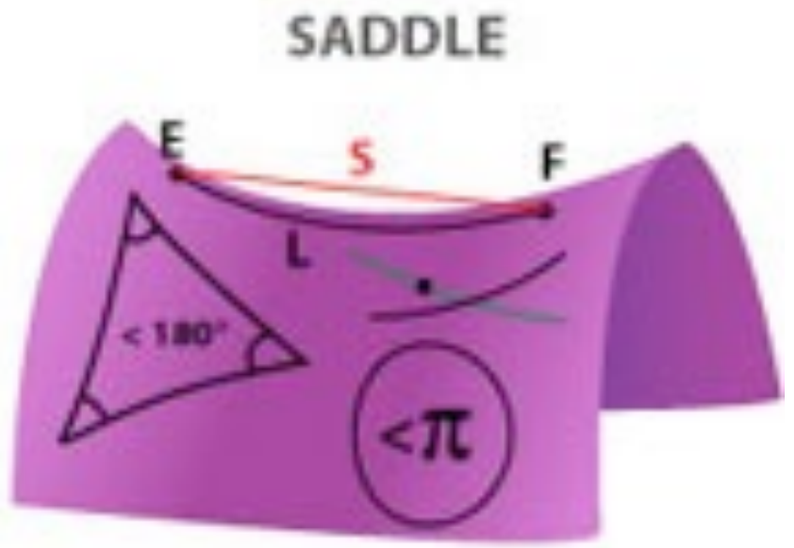
Zero Curvature

Euclidian geometry



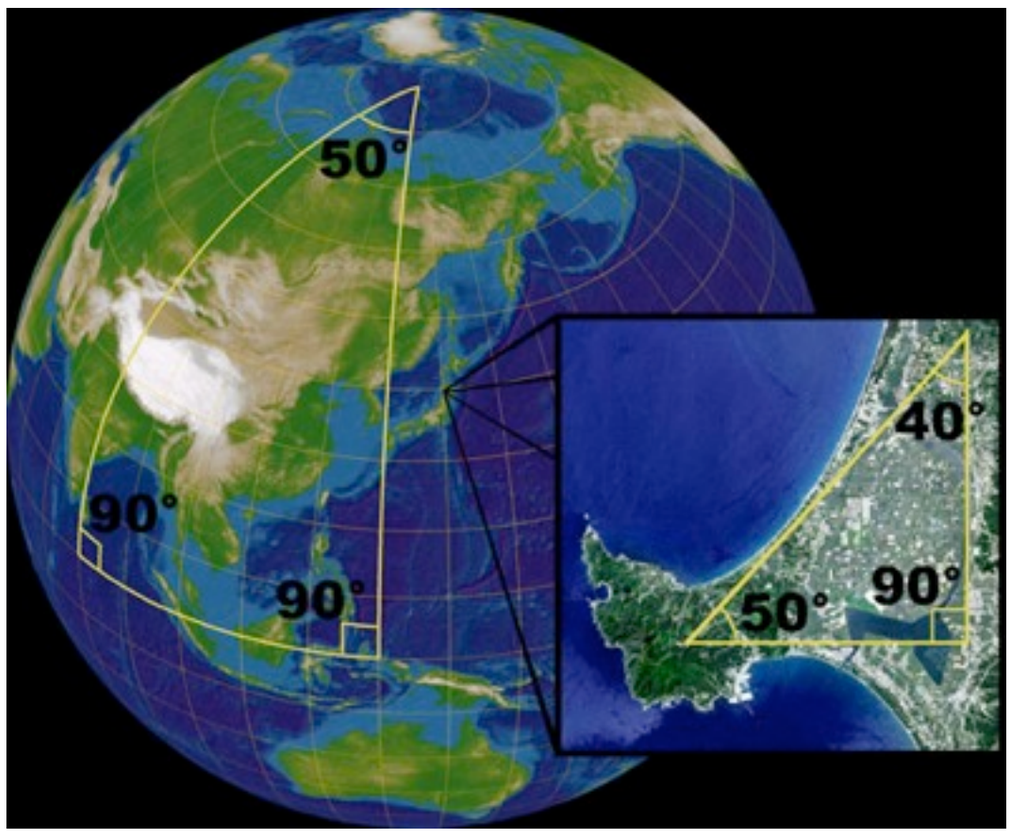
Positive Curvature

Elliptic geometry



Negative Curvature

Hyperbolic geometry



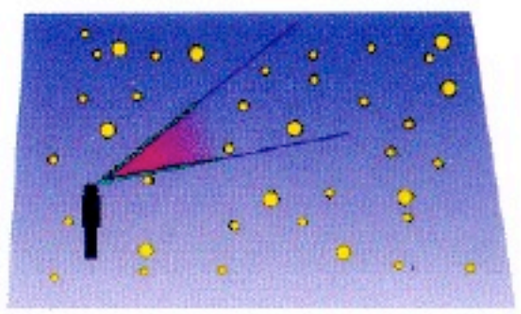
We live in 2D positive curvature.

Angle sum in a triangle > 180 deg

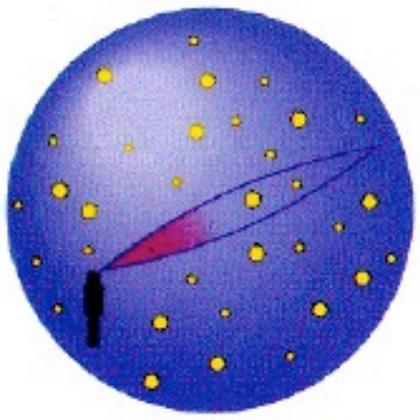
two parallel lines intercept

So, let us draw two ‘straight’ lines in the universe...

And, this musical note lets us measure curvature, for free



Flat universe

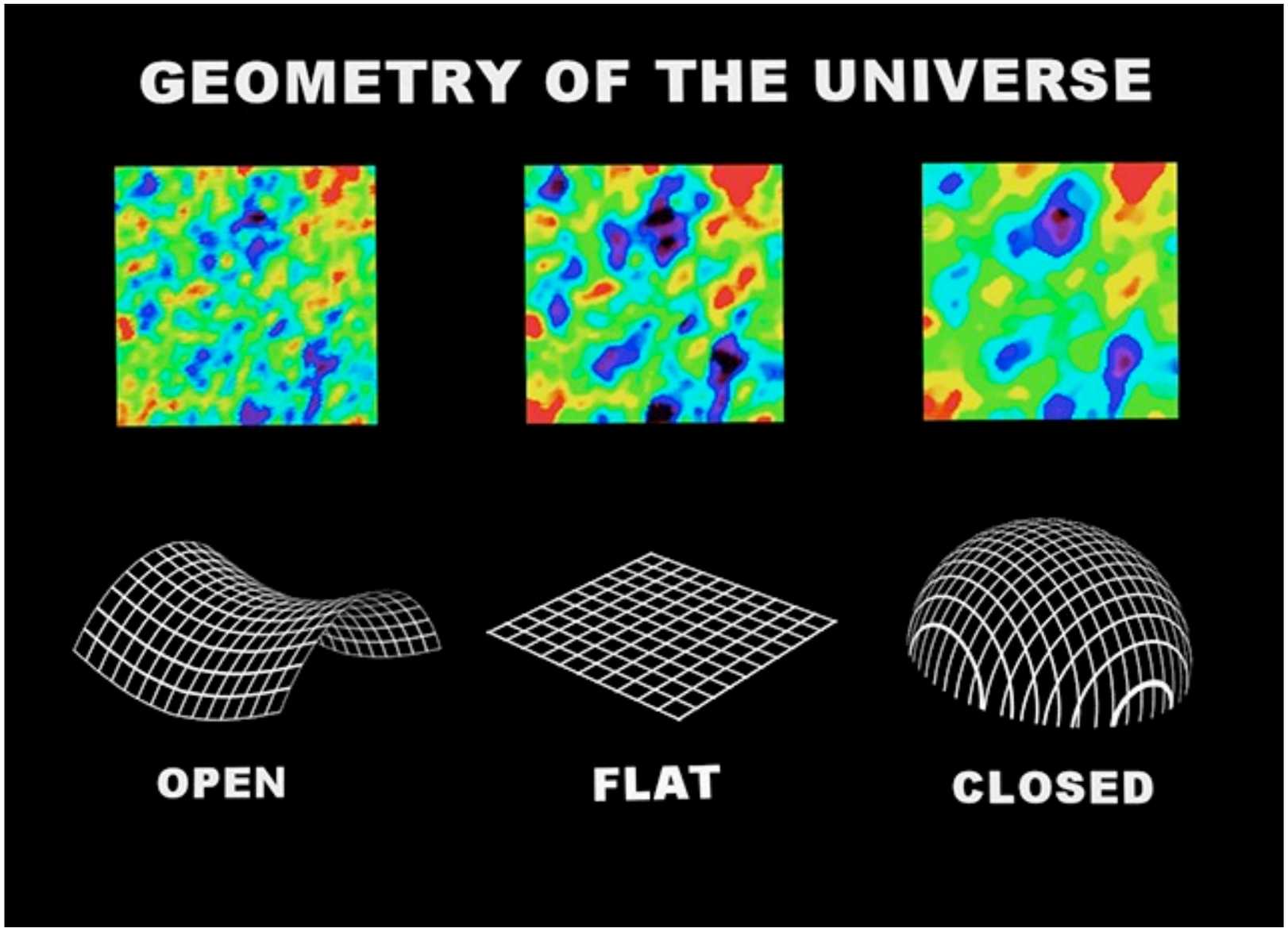


Positively curved universe

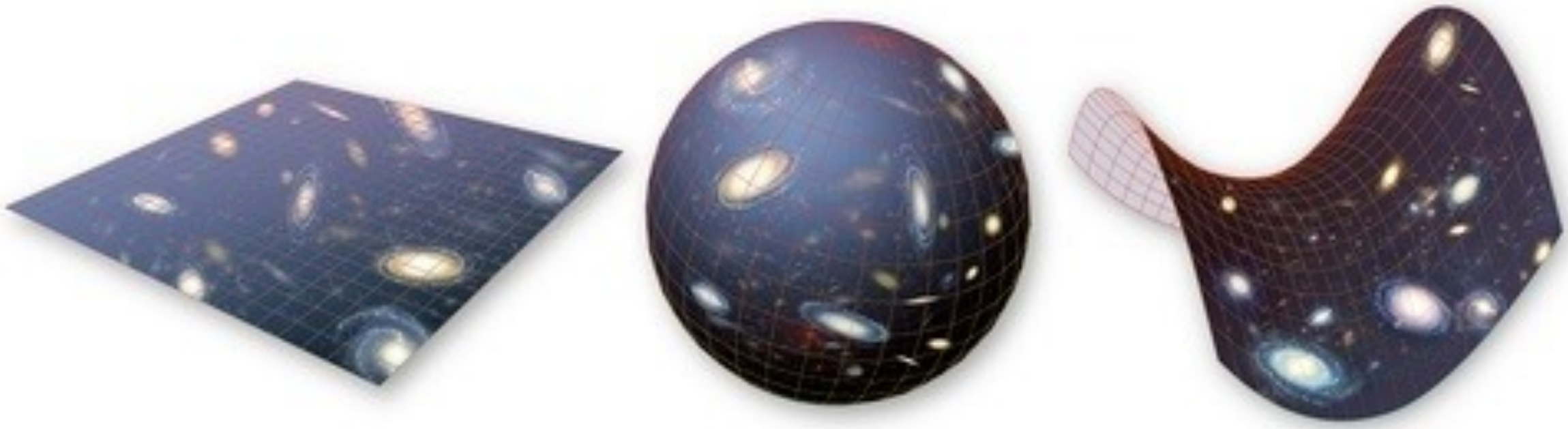
Negatively curved universe

- Spot size on CMB is a "standard ruler"

- if universe is flat, angular size of spot = horizon (cmb)/distance

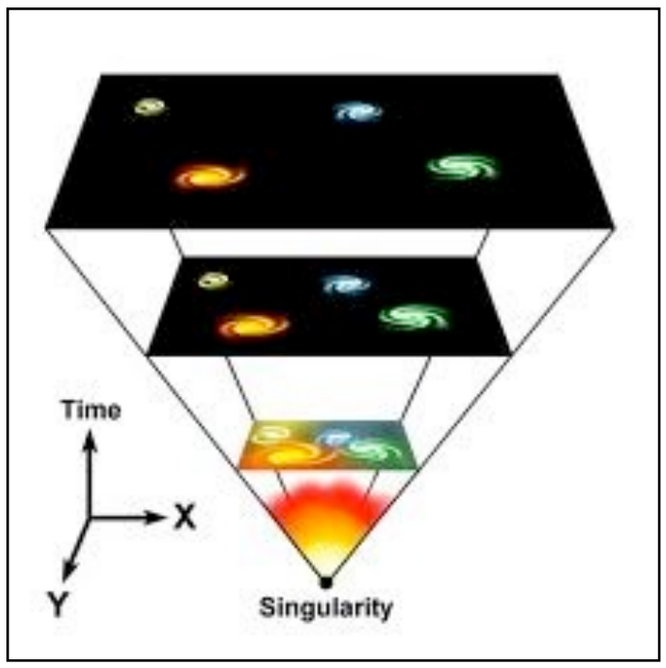


the universe looks.... flat



matter + dark energy
$\Omega=\Omega_m+\Omega_\Lambda=1$
(a conclusion independently reached by supernova groups)

matter only
$\Omega m = \rho/\rho_{crit} \sim 0.3$



clarifications on dark energy:

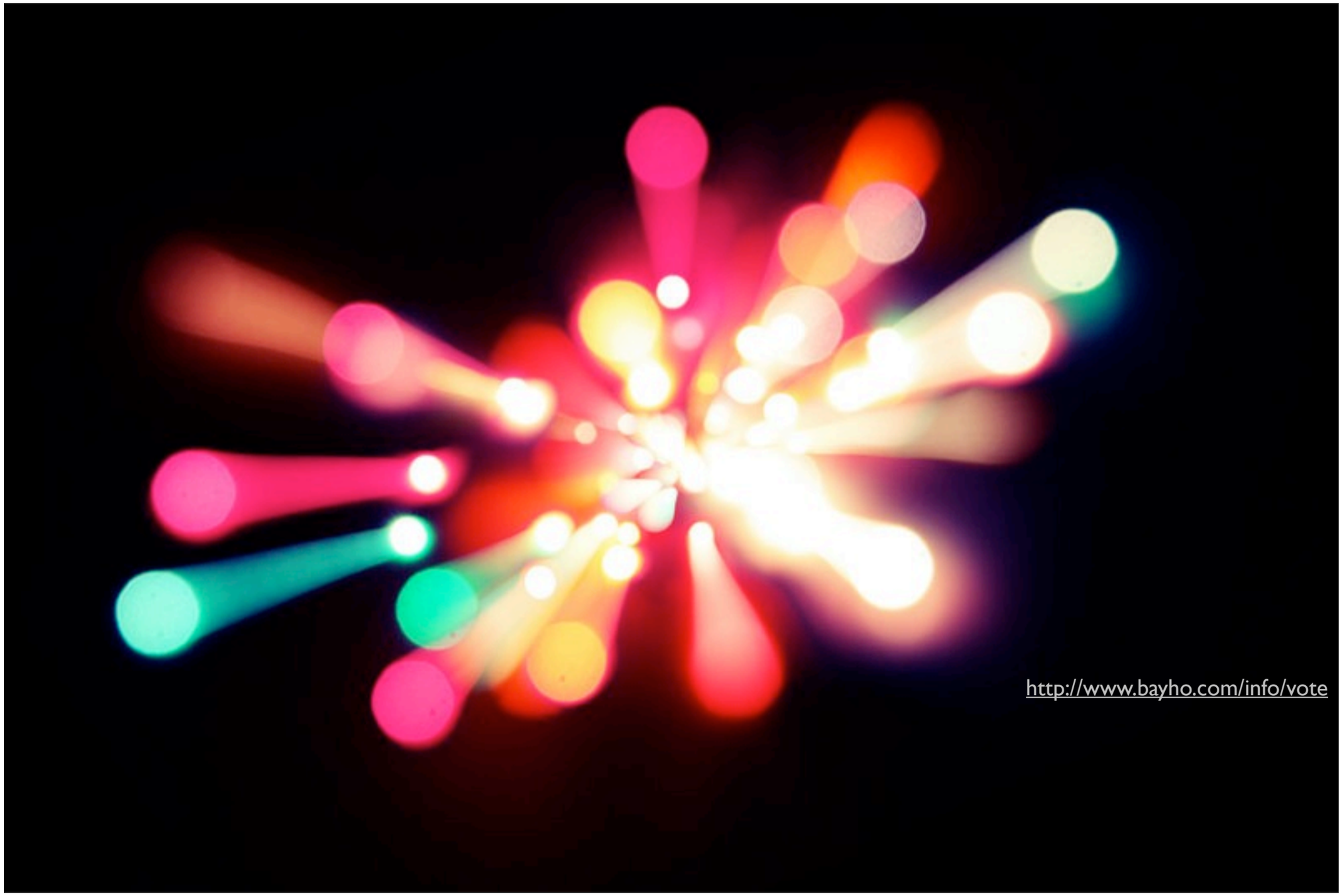
We don't know what is dark energy, but we know that

1) dark energy acts as pressure, causing expansion to accelerate

2) dark energy acts as energy density, curving the space

3) if universe is flat at some point, it will always remain flat

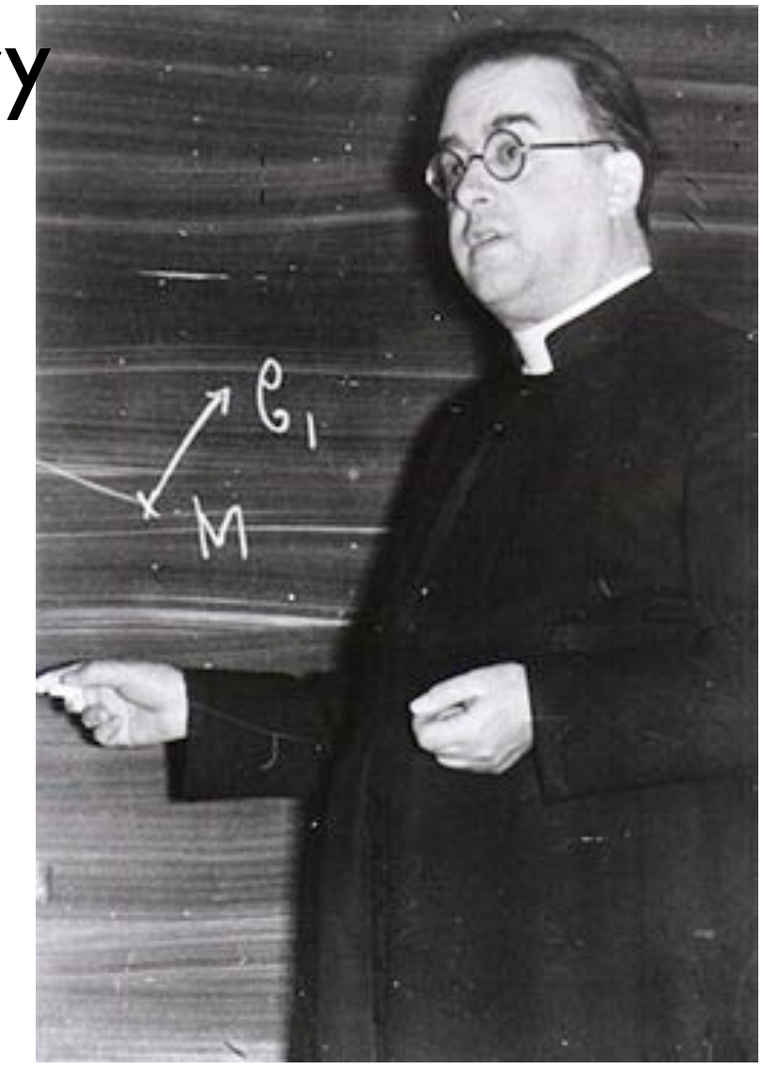
The Hot Big Bang



The first proponent of the Big Bang Theory

Georges Lemaitre (1894-1966)

Belgian Jesuit priest and physicist



he began graduate study in Cambridge same year he was ordained as a priest.

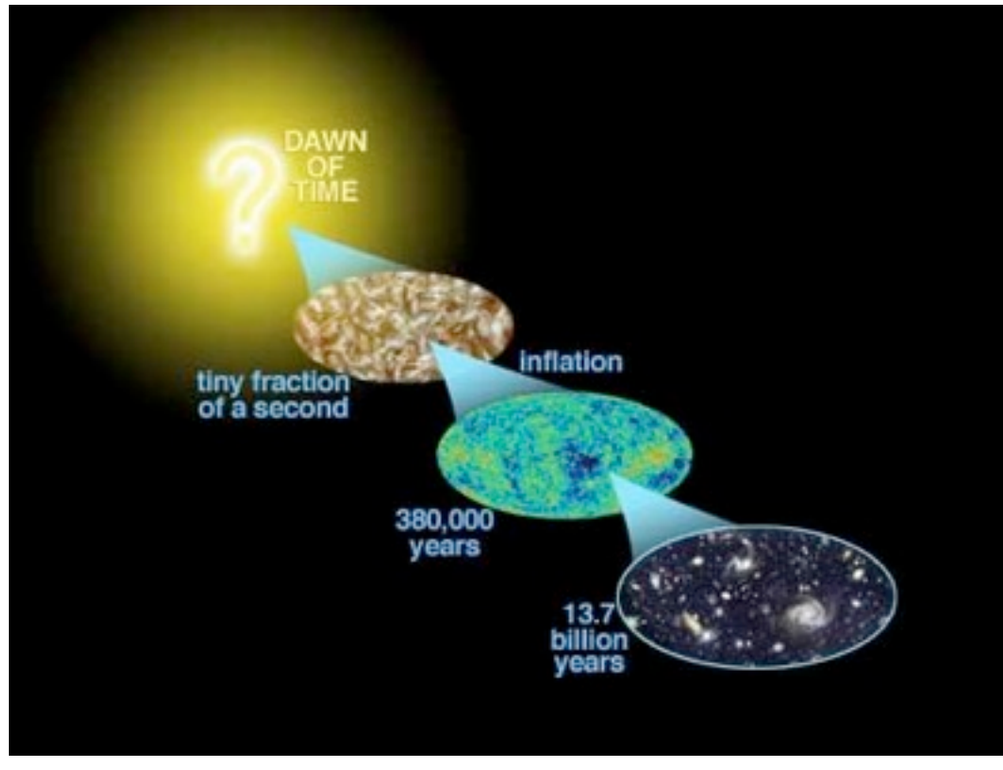
1927, he worked out the cosmic expansion

Einstein (1927): "Your math is correct, but your physics is abominable."

1931, he came up with a theory of ‘primeval atom’, or "the Cosmic Egg exploding at the moment of the creation"; "Big Bang theory" coined by Fred Holye, believer of static universe.

the big bang: the universe developed from an initial point at t = 0: a time of extreme density and temperature, lots of yet-to-be-understood processes give rise to the universe today

Einstein (1935): “This is the most beautiful and satisfactory explanation of creation to which I have ever listened.”



One of the earliest believers of the Big Bang theory:

Pope Pius XII (1951)

"…it would seem that present-day science... has succeeded in bearing witness to the august instant of the primordial Fiat Lux [Let there be Light], when along with matter, there burst forth from nothing a sea of light and radiation, and the elements split and churned and formed into millions of galaxies."

"Thus, **with that concreteness which is characteristic of physical proofs**, [science] has confirmed the contingency of the universe and also the well-founded deduction as to the epoch when the world came forth from the hands of the Creator. Hence, creation took place. We say: **therefore**, there is a Creator. Therefore, God exists! "

universe @ the big bang was dense

assuming no inflation

at the Planck time (t ~ 10^{-43} sec)

- our visible universe was ~ 0.01 cm across (10^{30} smaller)
- but any observer only sees a tiny fraction of this (horizon ~ 10^{-33} cm)
- density of matter ~ 10^{63} g/cm^3

  -- nuclear density ~ 10^{14}g/cm^3

  -- not describable with current physics

  *-- no atom, nuclei, proton, neutron **persist**, not even quarks and leptons*

- but there is an even larger energy density than matter

universe @ the big bang was 'empty' of matter

(relatively speaking)

importantly, the early universe was hot

'hot' means high in temperature, but also means photons dominate the energy density (temperature in very massive stars so hot that most energy in the stars is in photons, not matter, we call it 'radiation dominated')

1) going back in time, photons 'blue-shifted' up in energy; while matter density $\propto a^{-3}$, photon energy density $\propto a^{-4}$, (# of photons conserved; # of photons/unit volume $\propto a^{-3}$; energy per photon $\propto a^{-1}$; so energy density of photon $\propto a^{-4}$)

radiation energy density >> matter energy density @ early times

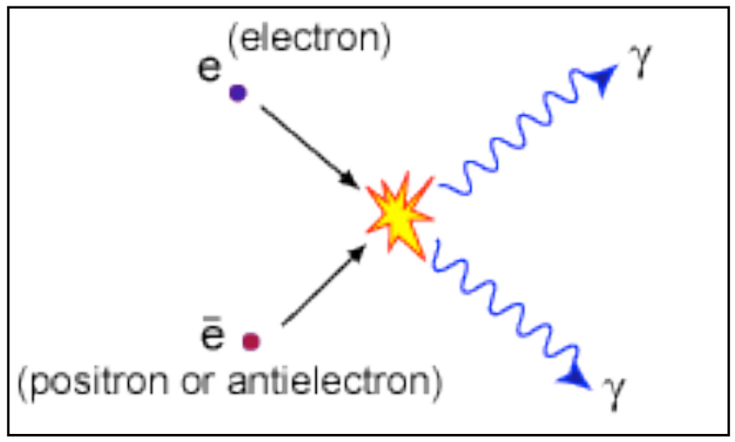
2) energy density of a blackbody radiation $\propto T^4$, so $T \propto a^{-1}$

3) a higher blackbody temperature means a typical photon have higher energy: $E = h\nu \propto T$

4) photons are so energetic, they can produce pairs of heavy particles --- out of 'nothing'.

$E=Mc^2$

photons constantly undergo pair creation
Pair creation: 2 photons ===> matter + anti-matter particles



annihilation (reverse process of pair creation)

5) the matter-anti-matter particles quickly annihilate back to photons. a radiation soup bubbling with particles/anti-particles.

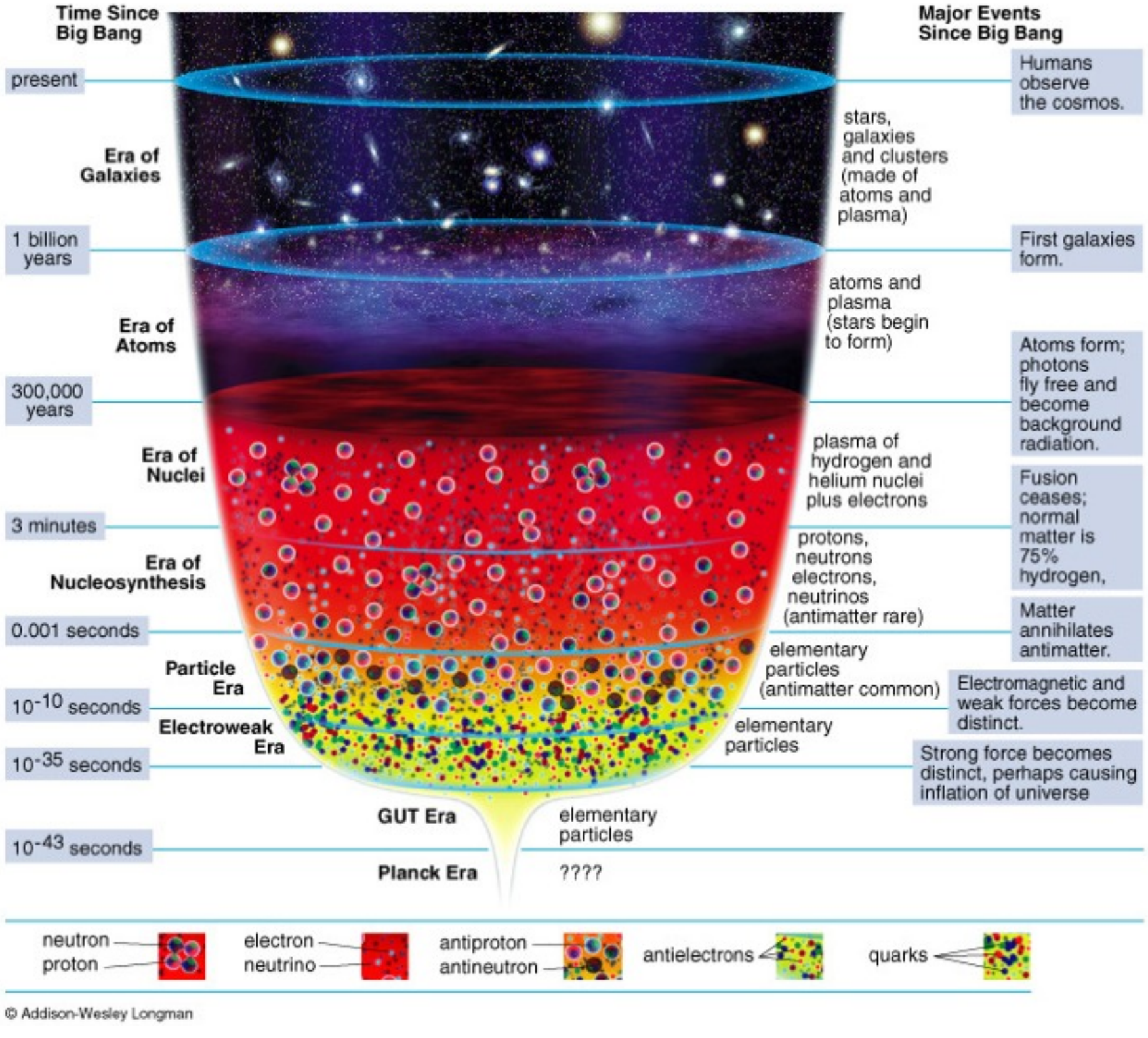
6) as the universe cools (why?), more and more limited in what particles can be pair-created. Earlier productions frozen-in.

7) the early universe was separated into different epochs based on what particles can be pair-created. Many properties of our universe were determined here.

Photon "fog" at CMB (~300,000 yrs), how do we know what happened before that?

Safe physics

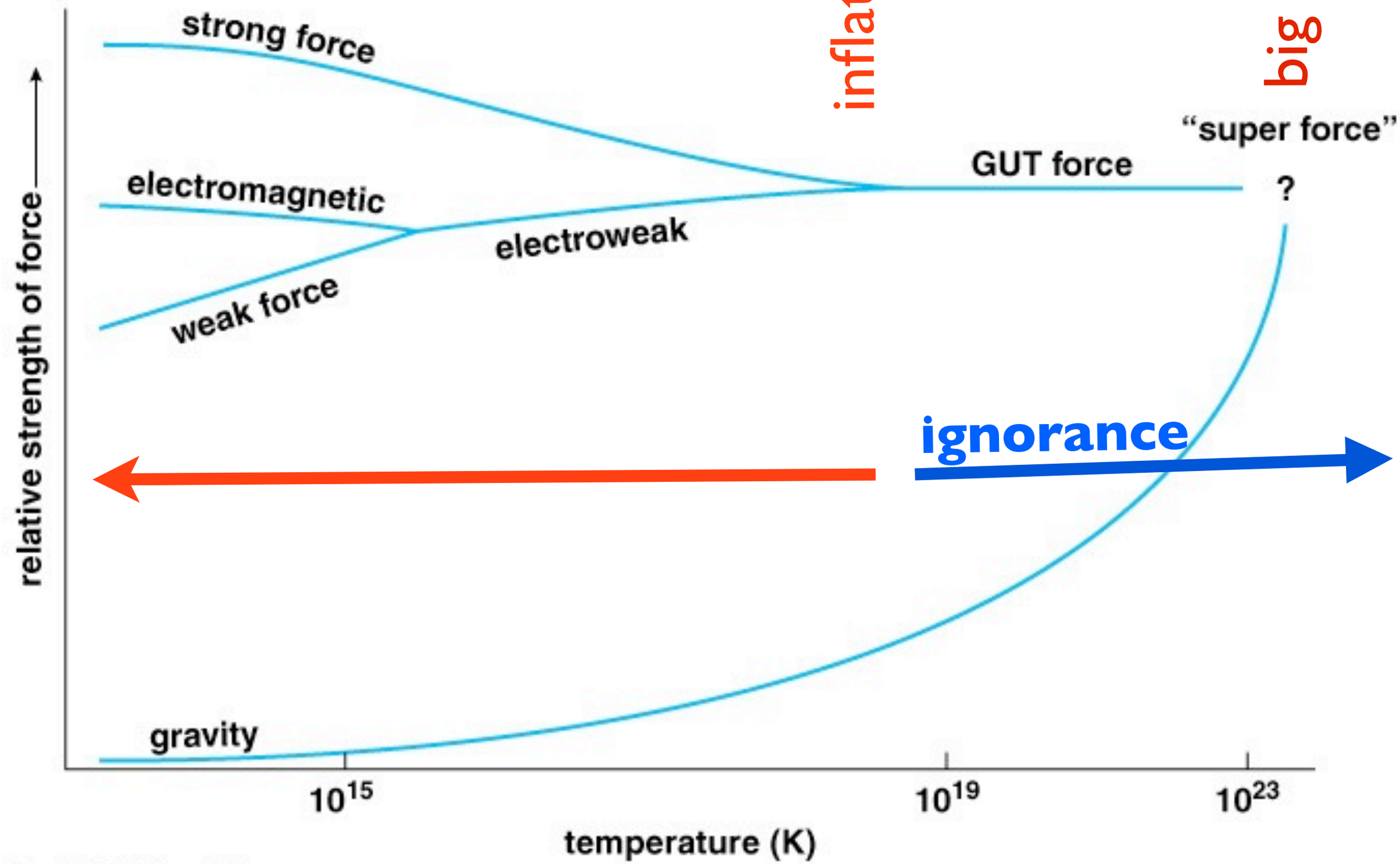
Unsafe physics



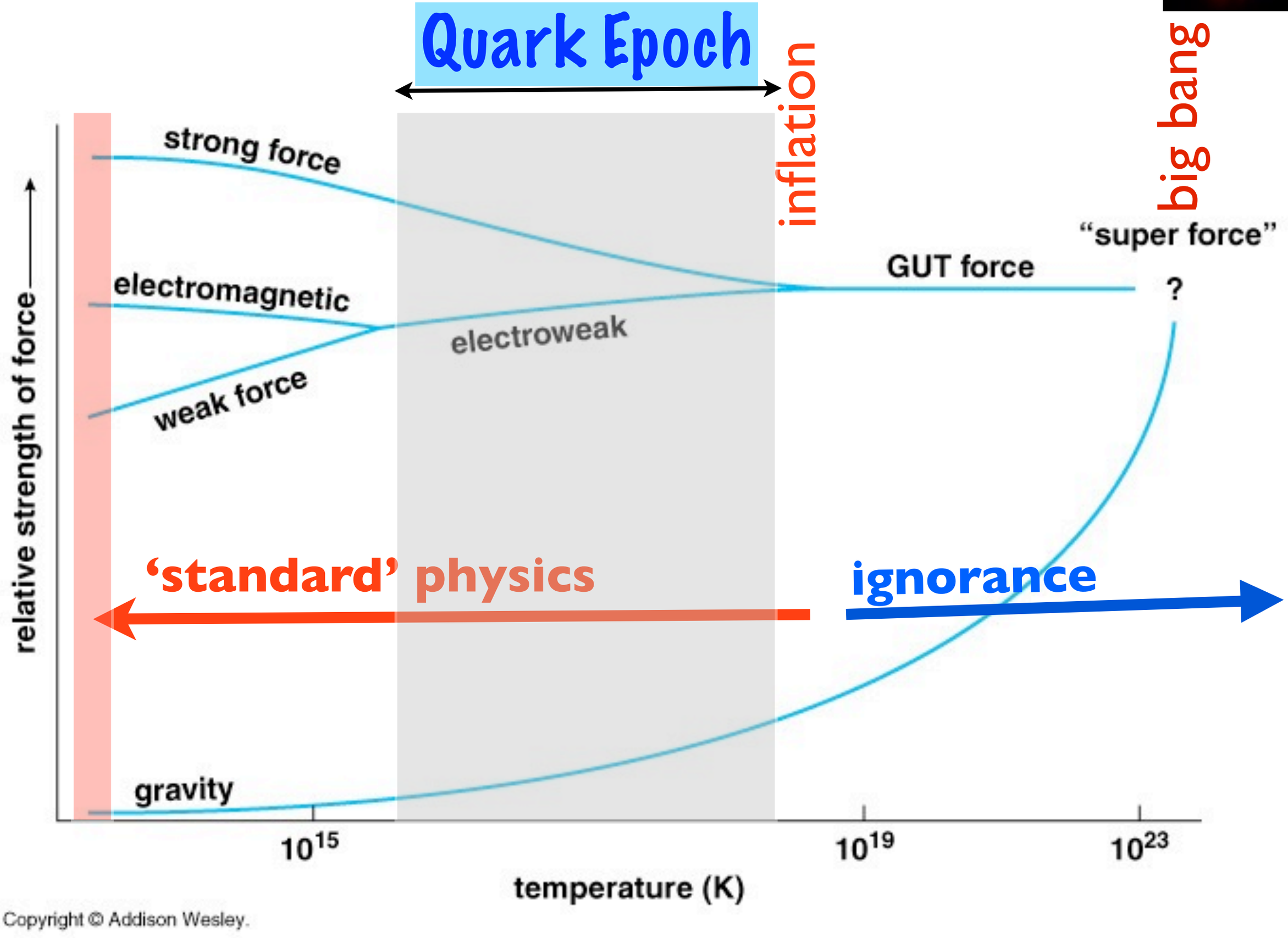
EM opaque

transparent to gravitational waves

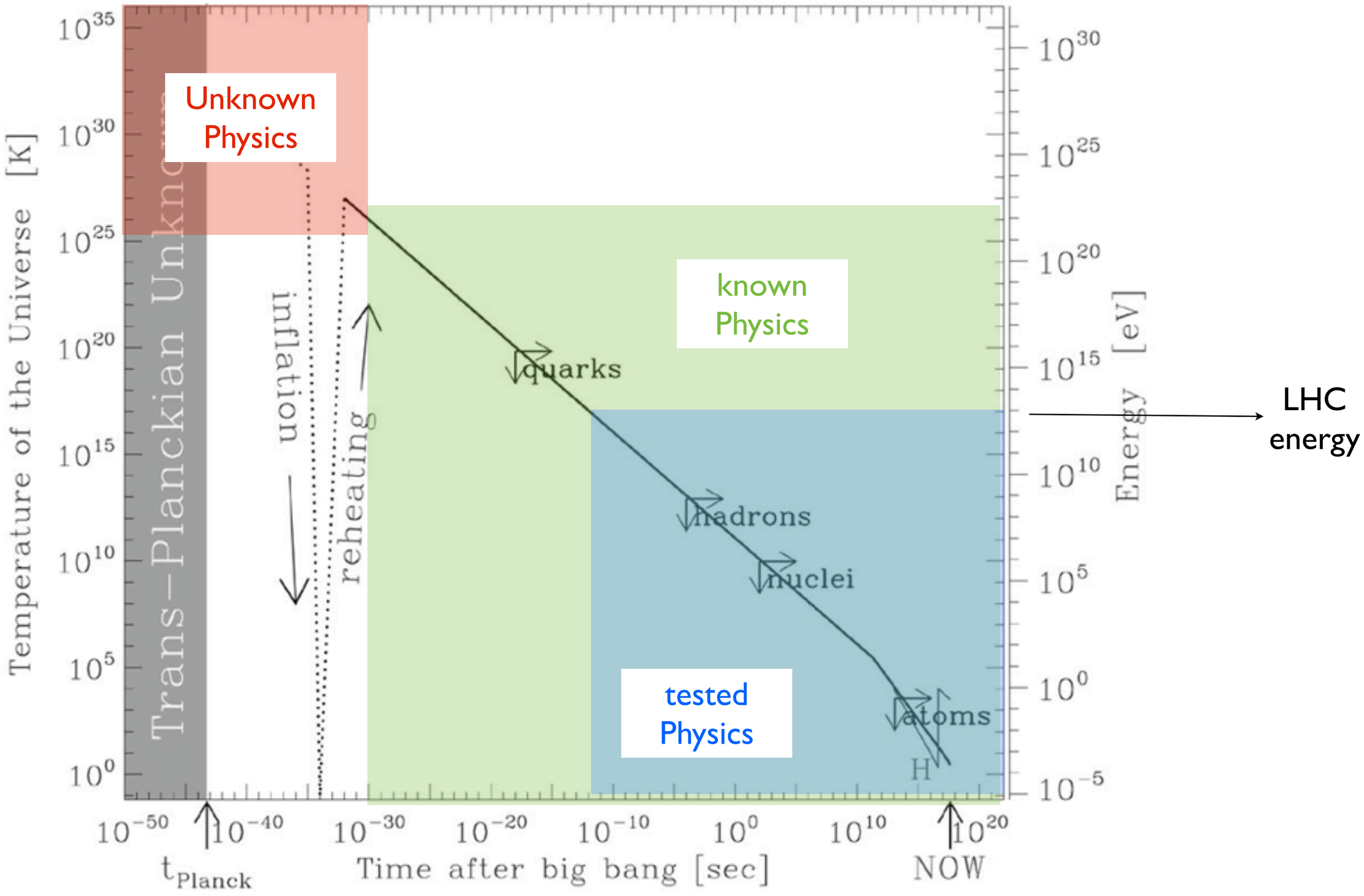
rapid curvature variation emits gravitational waves



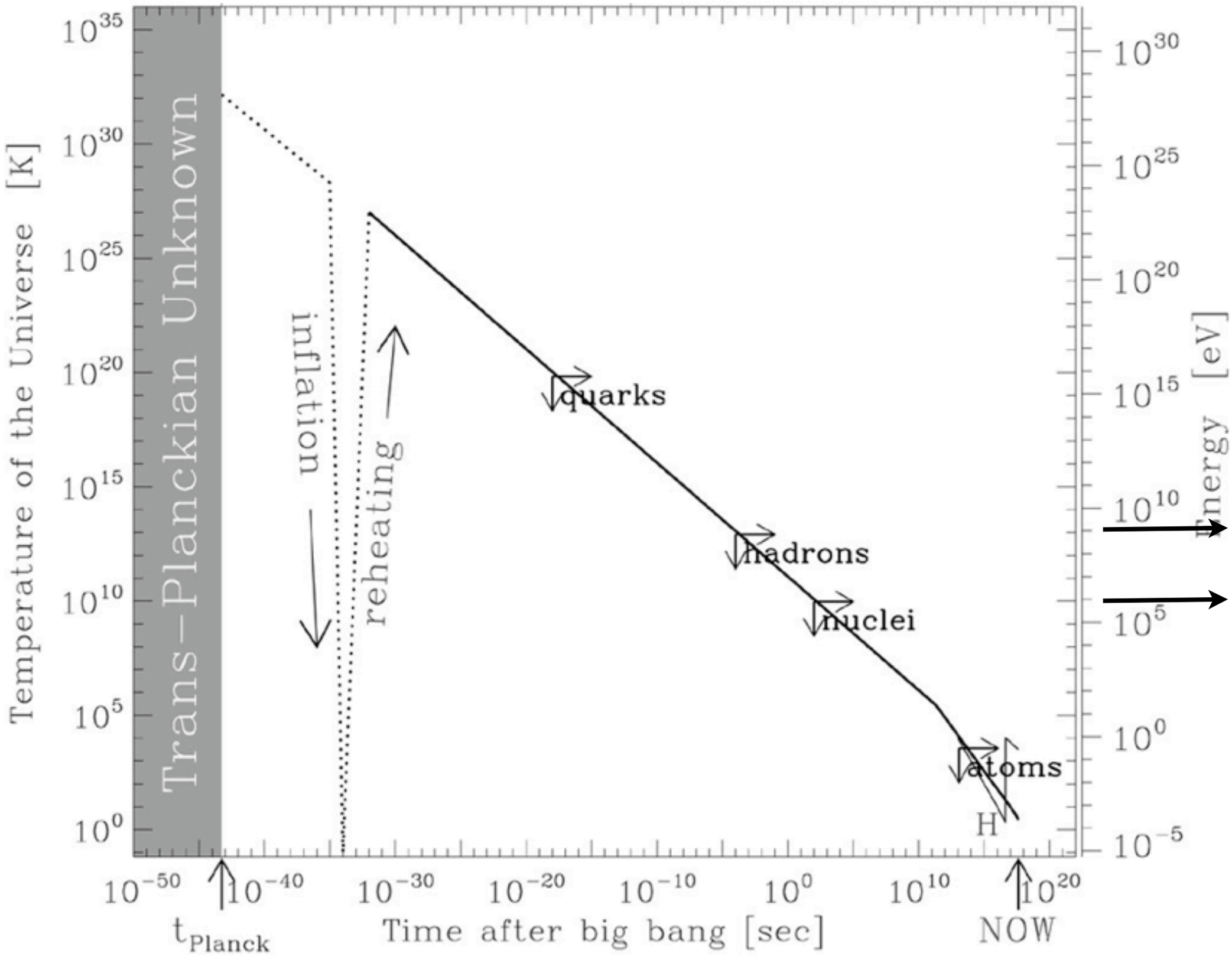
No quarks till strong force separates.
Temperature too high for confinement.



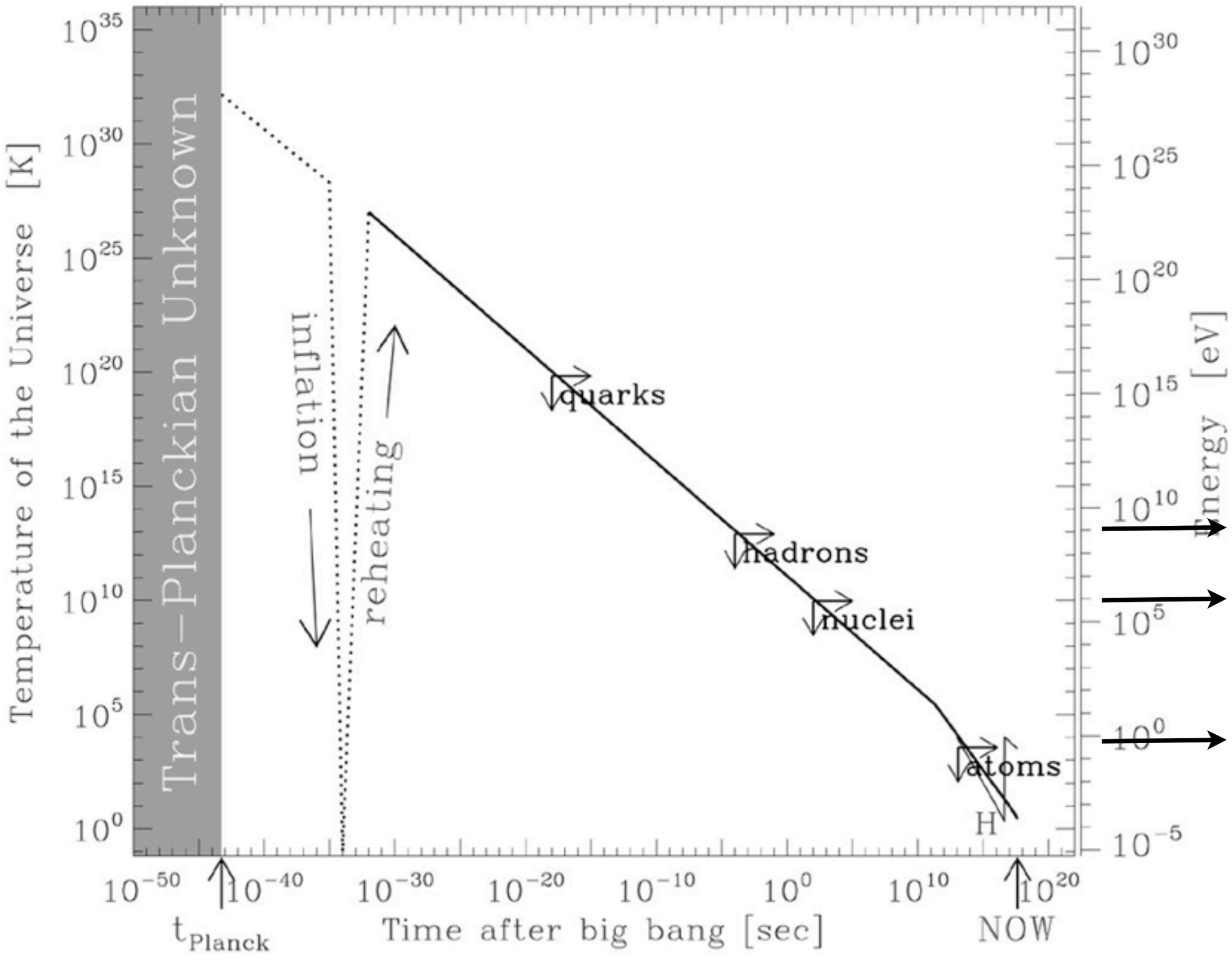
When photon mean energy drops below mc^2 pair creation/annihilation freezes out -- era of particles



When photon mean energy drops below ~1 Mev $=10^6$ ev, nuclear fusion/fission freezes out -- era of nuclei



When photon mean energy drops below ~1 ev, electrons bound to nuclei --- era of atoms



$m_{proton}\ c^2$

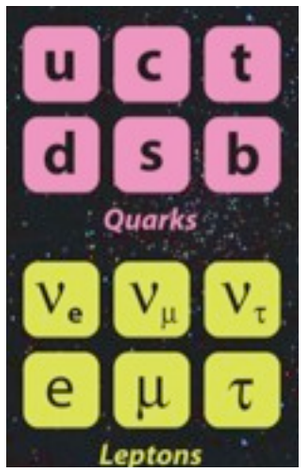
nuclear binding energy, ~ 1Mev

electron binding energy to nuclei ~ 1ev, CMB

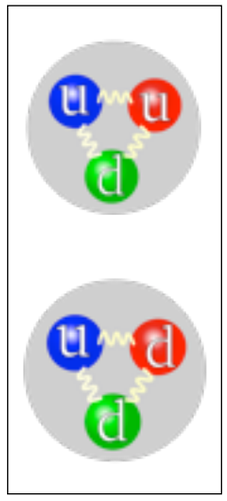
early universe

In the beginning, there is light.

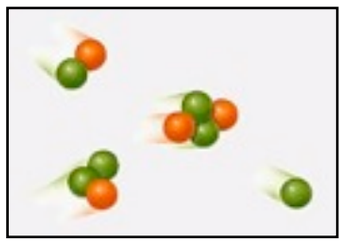
particles
~10^{-10} sec



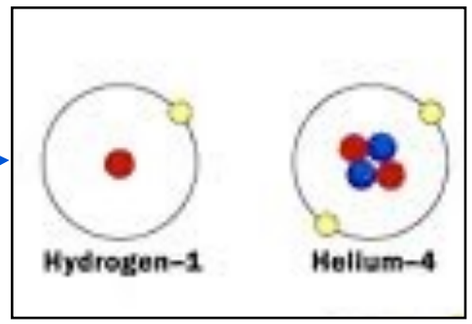
proton & neutron
0.001 sec



nuclei
3 min.



atom
300,000 yrs



accelerators