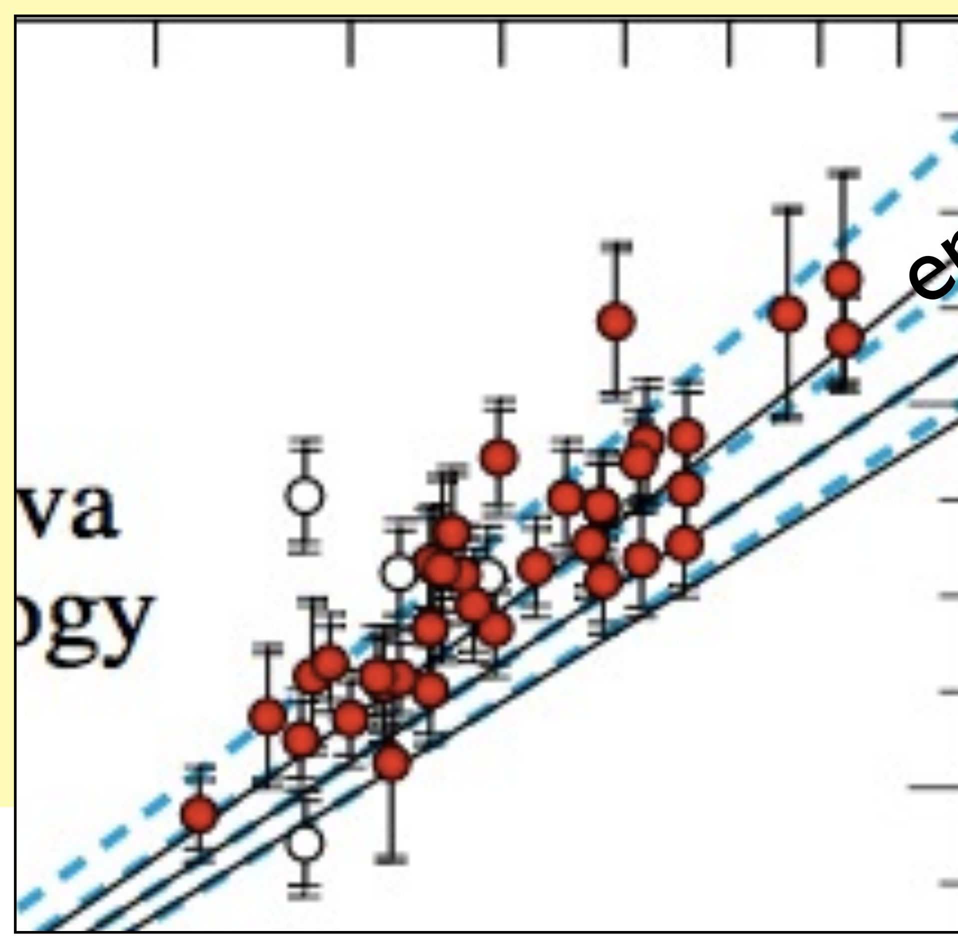
Nobel Prize

Physics 2011

How can the universe expand faster than an empty one?



high-z supernova are dimmer than they should be, even compared to an empty universe

Mistake here!
Dark energy solved
these two conflicts

Observations measure:

$\Omega_m = \varrho/\varrho_{crit} \sim 0.3$

Theory (using Friedmann eq.) then predicts

1) space is open

2) universe is 11.7 Gys old

Both predictions **conflict** with further observations:

1) space is flat

2) universe is at least 12.7 Gyrs old.

Where is the mistake?

Friedmann's equation for matter + dark energy universe

the classical analogue for this term will be pressure

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

before Hubble, universe is thought to be static

1920s, Einstein included the cosmological constant (an integration constant) in his field equations to produce a **static universe**: the cosmological constant acts as an anti-gravity to prevent contraction of universe.

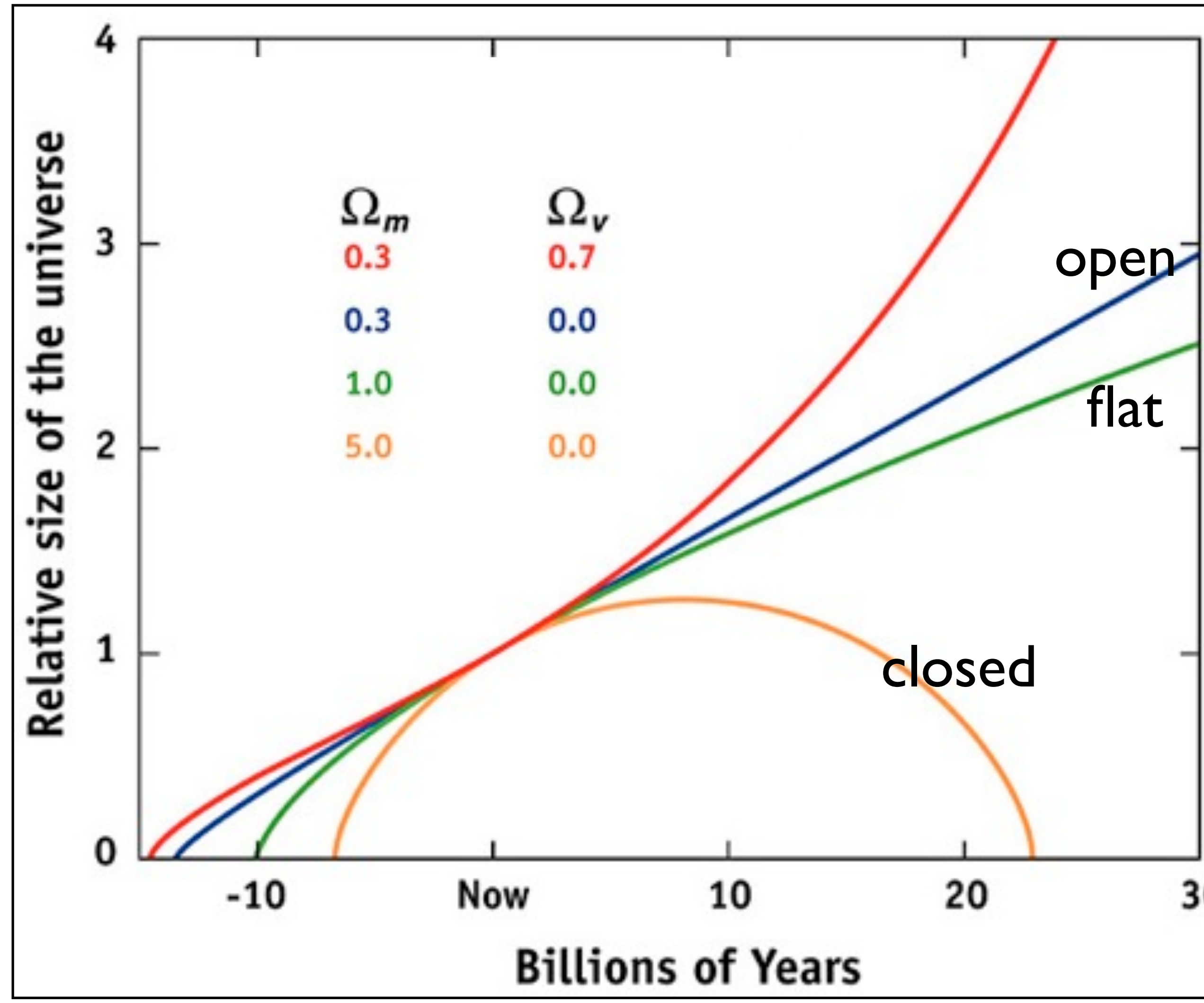
1929, Hubble discovered that the universe is expanding.

Einstein retracted this term, calling it his 'greatest blunder'

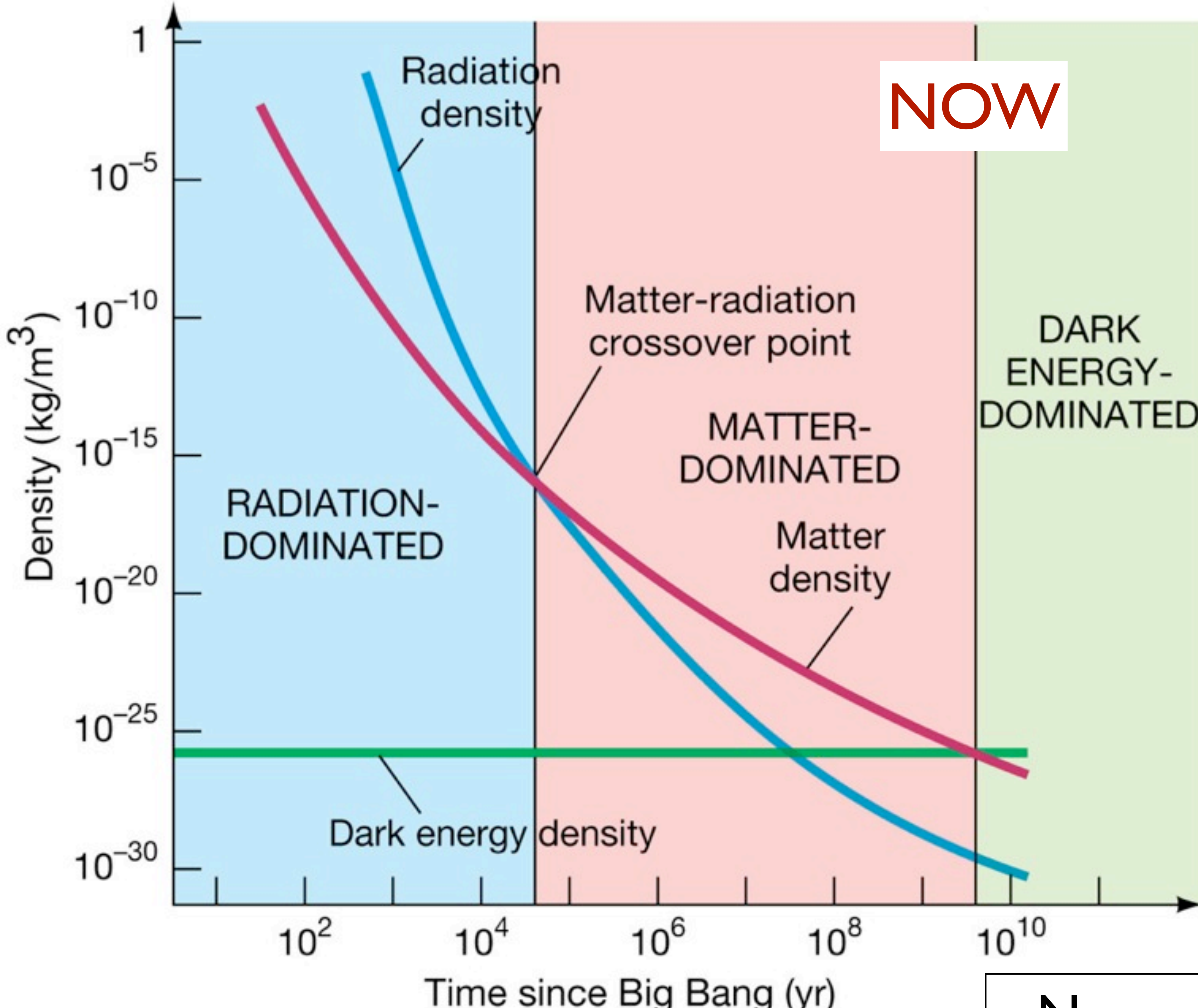
Current observations (late 1990s) revive the need for such a term. So, Einstein was right, in the end, but for the wrong reason.

What does this term do?

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$



- this term acts repulsively (pressure)
- it continuously adds energy into the universe.
- it dominates over gravity at late times
- interestingly, we are at the cross-road.



At current time, the effects of dark matter are measurable.

Now:

$\Omega_\Lambda = \Lambda\, c^2/3H^2 \sim 0.7$

$\Omega_m = 8\pi G\rho/3H^2 \sim 0.3$

Rees §7: 'The case for [dark energy] at the time of writing (Spring 2000) is strong but not overwhelming.'

View @ 2013:
dark energy seems in, as it explains 3 things in one go.

1) age determination of the universe

matter-only: $t \sim 11.2$ Gyrs , star age: $t > 12$ Gyrs
since expansion was slower in the past, it takes longer to get here (so age larger)

2) inferred acceleration from supernova data

matter-only: expansion should be decelerating with time
distance supernova: expansion in the past was slower than today
acceleration is related to the age problem

3) measured curvature of universe is flat (next lecture)

matter-only: universe should have a negative curvature (open)
cosmic microwave background: universe is nearly flat

the need for dark energy -- "dark saviour" -- is strong

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

What is dark energy?

a speculated form of energy that uniformly fills all space.

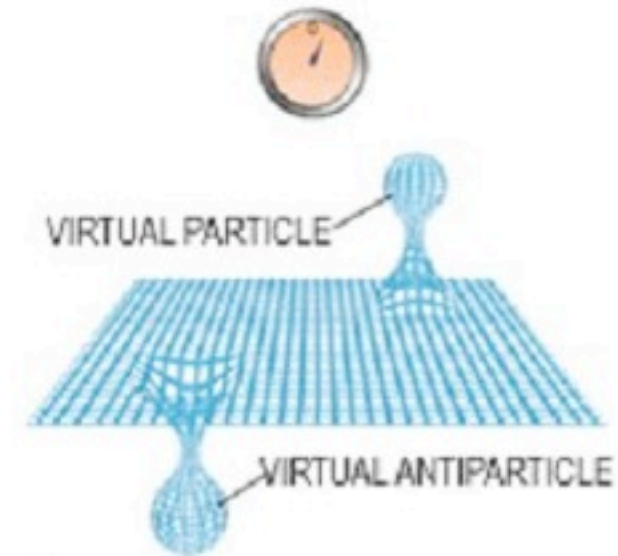
acting repulsively (pressure)

any reasonable guess to its nature (vacuum fluctuation energy, scalar fields) fails to give the right energy density

it came in different names: ‘dark energy’ = ‘cosmological parameter’ = ‘Λ’ = ‘vacuum energy’

Dark Energy as vacuum energy?

vacuum can not have zero energy, because "precisely zero" violates the uncertainty principle.



$$\boxed{\Delta E.\Delta t < \frac{\hbar}{2}}$$

Vacuum is a dynamic place, 'virtual particles' popping in and out on times short enough not to violate the uncertainty principle, giving an energy to the vacuum without messing up classical physics.

virtual photons created out of vacuum has been observed (the Casimir effect', 1997)

the so-called 'zero point energy' of vacuum behaves like dark energy (constant with time)

however, vacuum energy is some 10^{120} too strong compared to the observed acceleration. the universe would tear itself apart in microseconds.

Welcome to the forefront of physics!

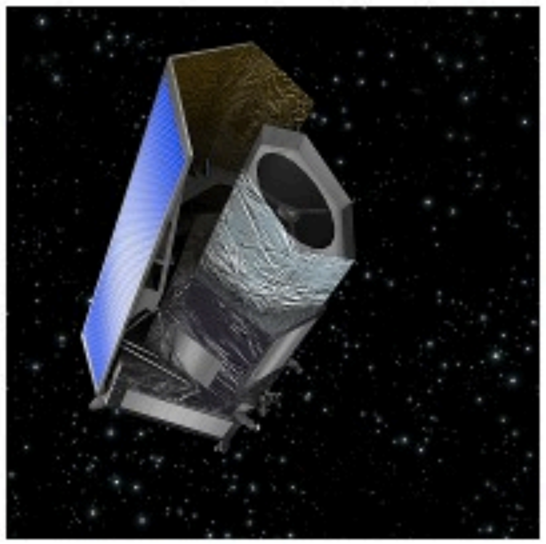
ESA/NASA Euclid Mission (2020)

Dark Universe mission blueprint complete

20 Jun 2012

ESA's Euclid mission to explore the hidden side of the Universe - dark energy and dark matter - reached an important milestone today that will see it head towards full construction.

Selected in October 2011 alongside Solar Orbiter as one of the first two medium-class missions of the Cosmic Vision 2015-25 plan, Euclid received final approval from ESA's Science Programme Committee to move into the full construction phase, leading to its launch in 2020.



Artist's impression of Euclid
Credit: ESA/C. Carreau

NASA joins European dark energy mission

Dark energy is especially intriguing, since many researchers believe it to be the strange force responsible for the accelerating expansion of the universe.

By Mike Wall, SPACE.com

Fri, Jan 25 2013 at 9:29 AM

+1 9 Like 11

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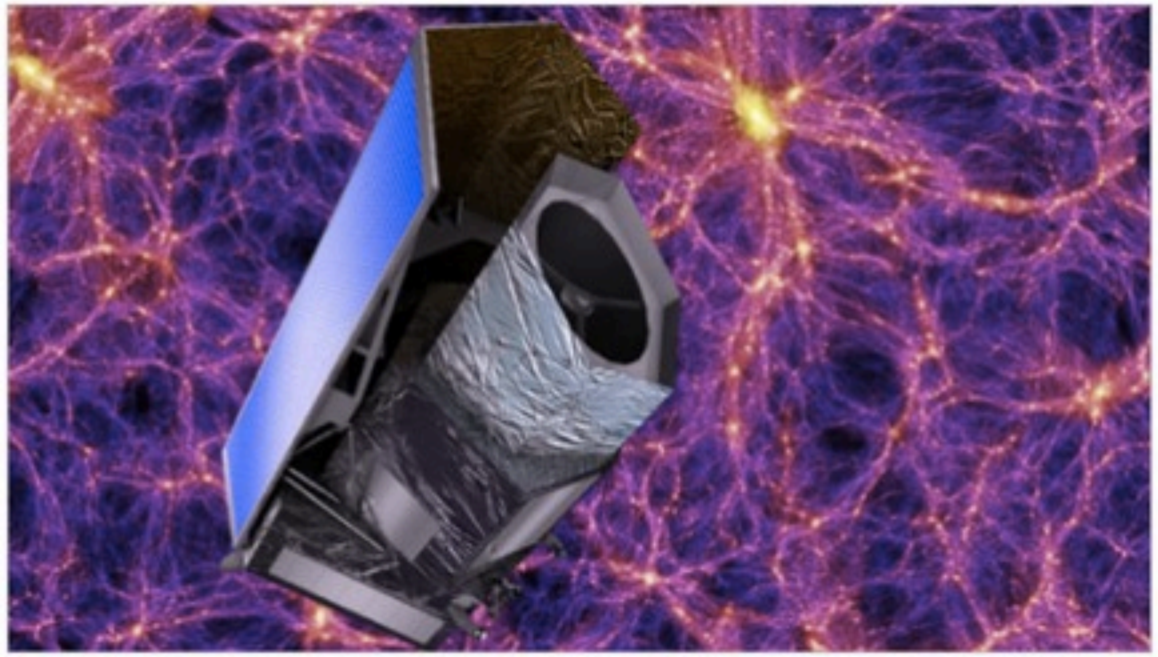
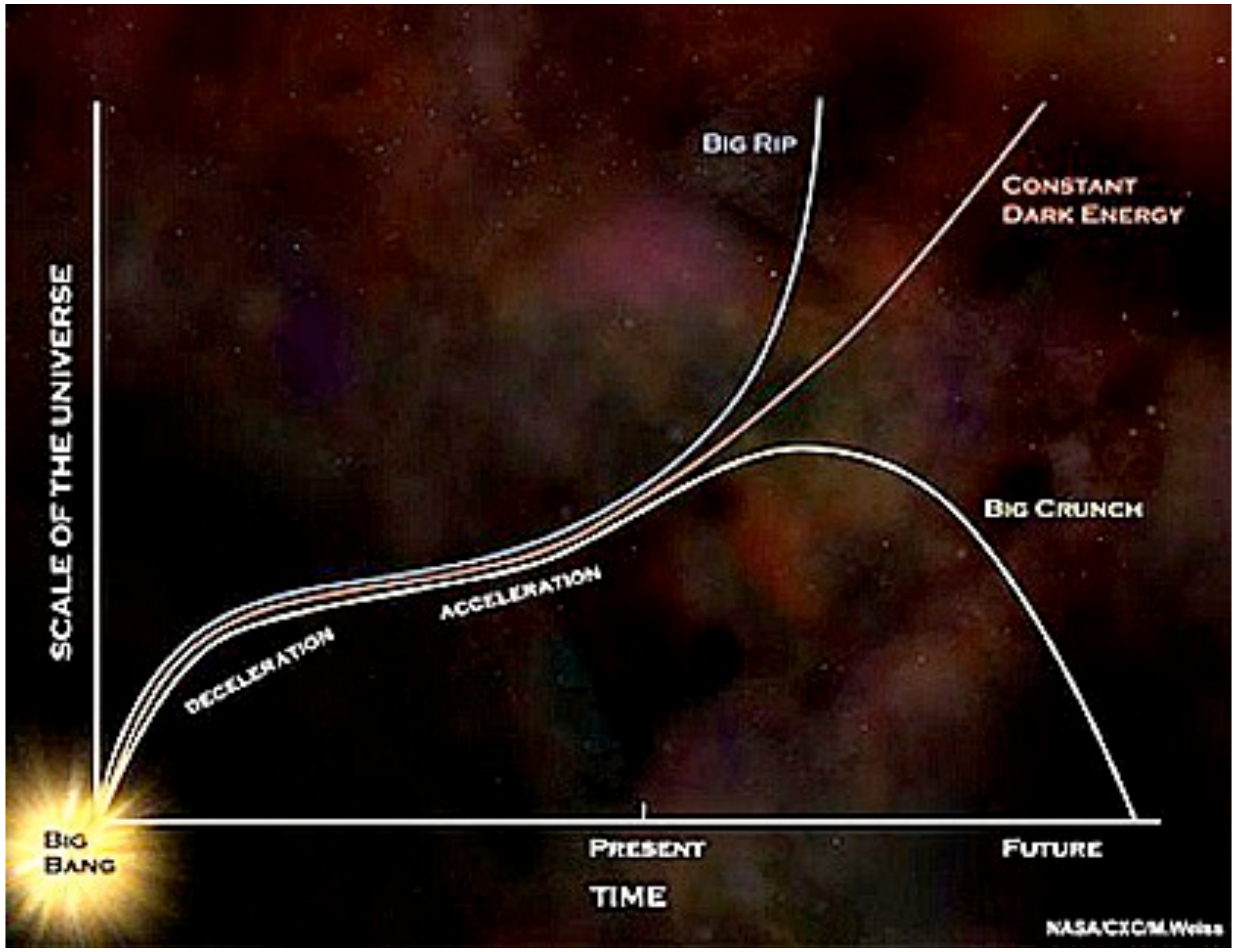


An artist's concept of the Euclid dark energytelescope in space. (Image: ESA)

NASA has officially joined the European Space Agency's Euclid mission, a space telescope that will launch in 2020 to study the mysterious dark matter and dark energy pervading the universe.

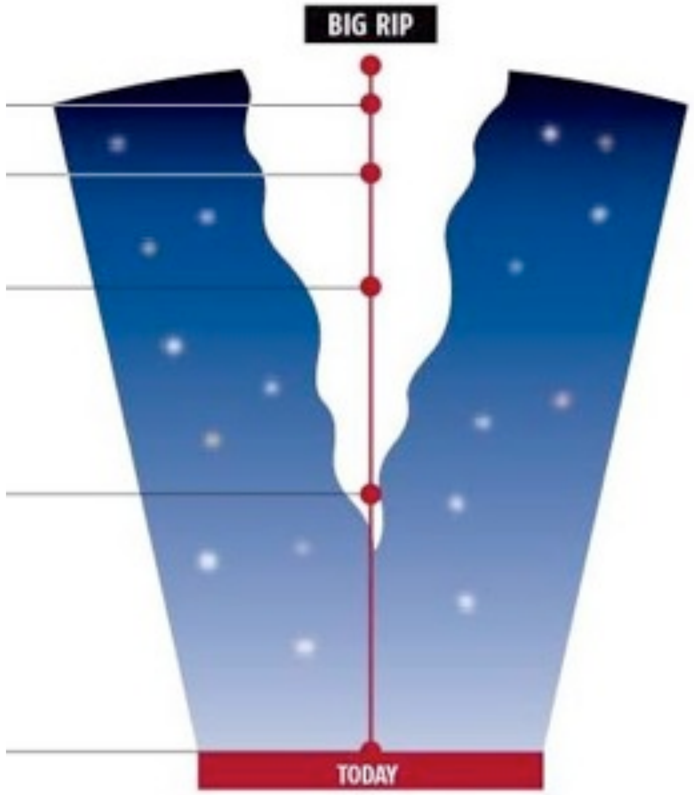
Dark Energy may change fate of the universe: BIG RIP?



as the universe expands ever faster, all of gravity's work may be undone.

if dark energy **increases** with time, expansion can accelerate so fast that, galaxies, the solar system, the Sun, planets, us, and even atomic particles may be shredded apart.

This is the exotic ‘BIG RIP’ scenario.



Summary: Expansion of the Universe & Dark Energy

•Universe is expanding. It was smaller yesterday...

•Universe's expansion is speeding up with time, opposite from what one expects from a ball decelerated by gravity.

•'dark energy', a form of pressure, can explain this acceleration, and age/curvature of universe.

•identifying dark energy with vacuum energy seems natural, but 120 orders of magnitude off. *if vacuum energy is important for universe, it will be ripped apart in split second*

•future of universe depends on how dark energy changes with time. and space missions are planned to find out.

Lecture 6: The Big Bang & the cosmic microwave background

Expansion and the big bang:

yesterday the universe was smaller, the day before even smaller... at some point in time, the entire observable universe may fit inside an atom...

Pillars of Big Bang Cosmology

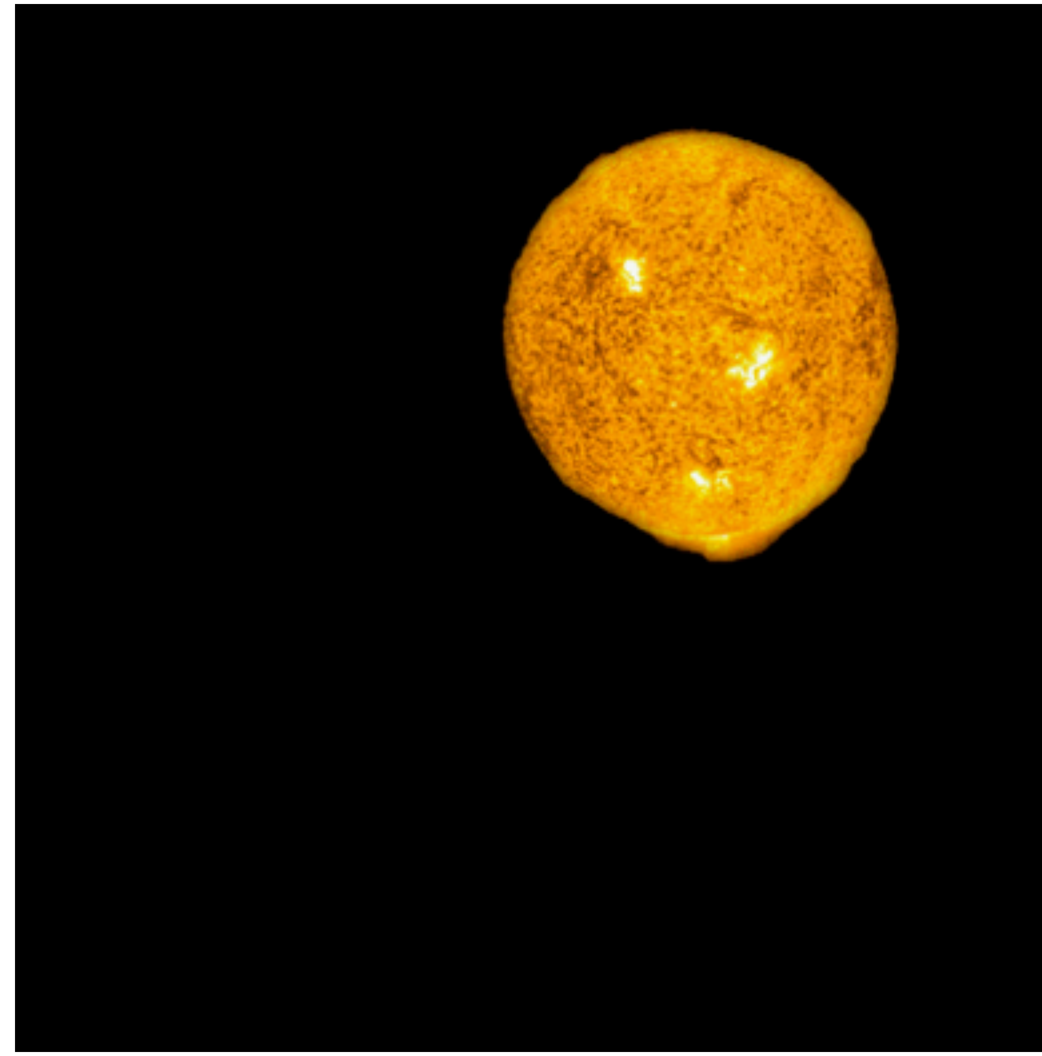
there was a beginning

- No stars older than 13 Gyrs
- Expansion of the universe -- something set it into motion.
- Olbers' paradox *(the oldest argument)*

& the beginning was hot

- Cosmic microwave background radiation (cmb)
- Observed helium and deuterium abundances.
- the fluctuations of matter density after a big bang explains the 'large scale structure' (galaxy cluster etc.)

A static, infinitely old universe seems aesthetically appealing, however...



Olbers' paradox

- Why is the sky dark at night?
- If the Universe is unchanging and has infinitely many stars, it shouldn't be.
  - Move the sun twice as far away and we'll receive 1/4 as many photons, but the sun will subtend 1/4 the angular area. So the areal intensity ("surface brightness" would stay the same.
  - With infinitely many stars, every angular element should interecept a star, and the sky should be as bright as the sun.
  - We'd have the impression of living in a hollow blackbody with a temperature of 6000K
- The paradox can be traced back to Kepler, and was rediscovered by Halley. But Olbers popularized it in the 19th century.

Possible Solutions to Olbers' Paradox

Won't work
- There is too much dust to see distant stars.

Trivial
- The Universe only has a finite amount of stars.

Unlikely
- The distribution of stars is highly-non uniform (ie. there could be an infinite number of them, but all lined up one behind another, so only a finite angular area is covered).

Yes! But not dominant
- The Universe is expanding, so distant stars are red-shifted into undetectability.

Yes! Dominant effect
- The Universe is young. Distant light hasn't even reached us yet (a "cosmological horizon" exists).

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

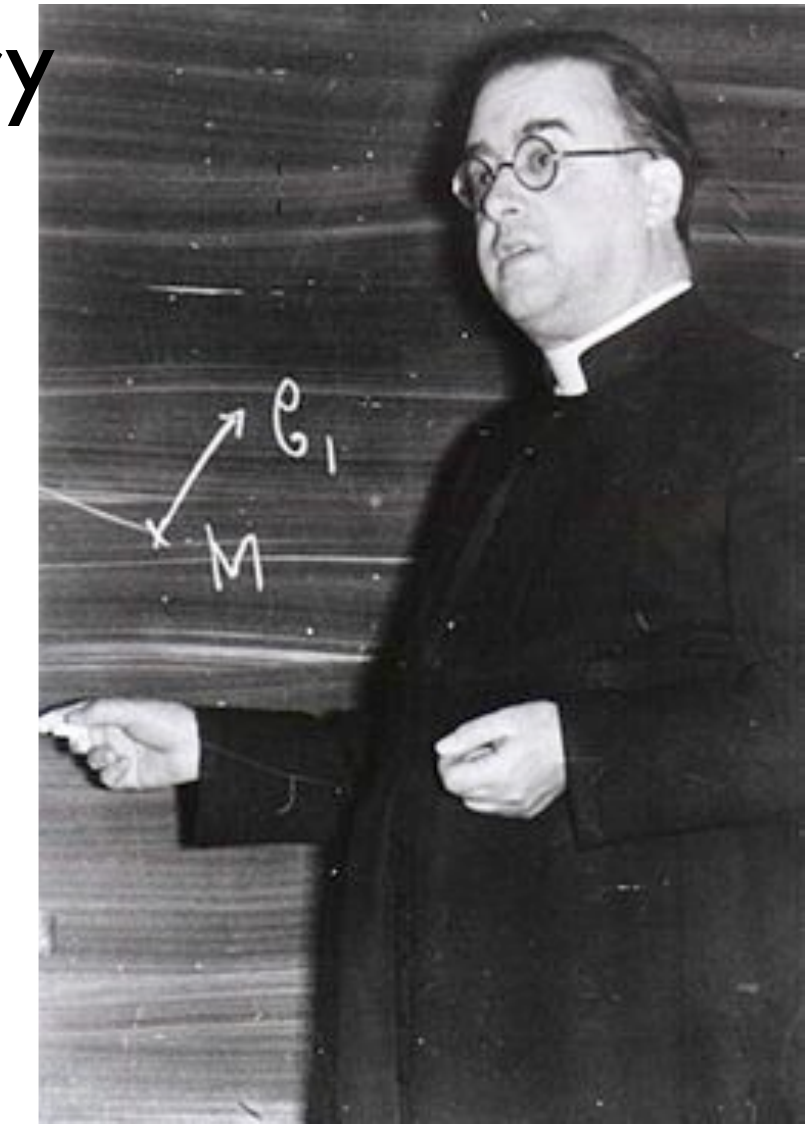
In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.

RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.

Lineweaver & Davis, Sci. American 2005

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

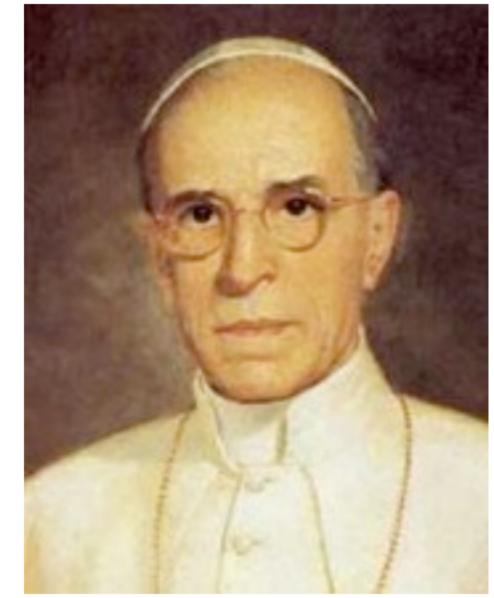
Einstein (1927): "Your math is correct, but your physics is abominable."

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."

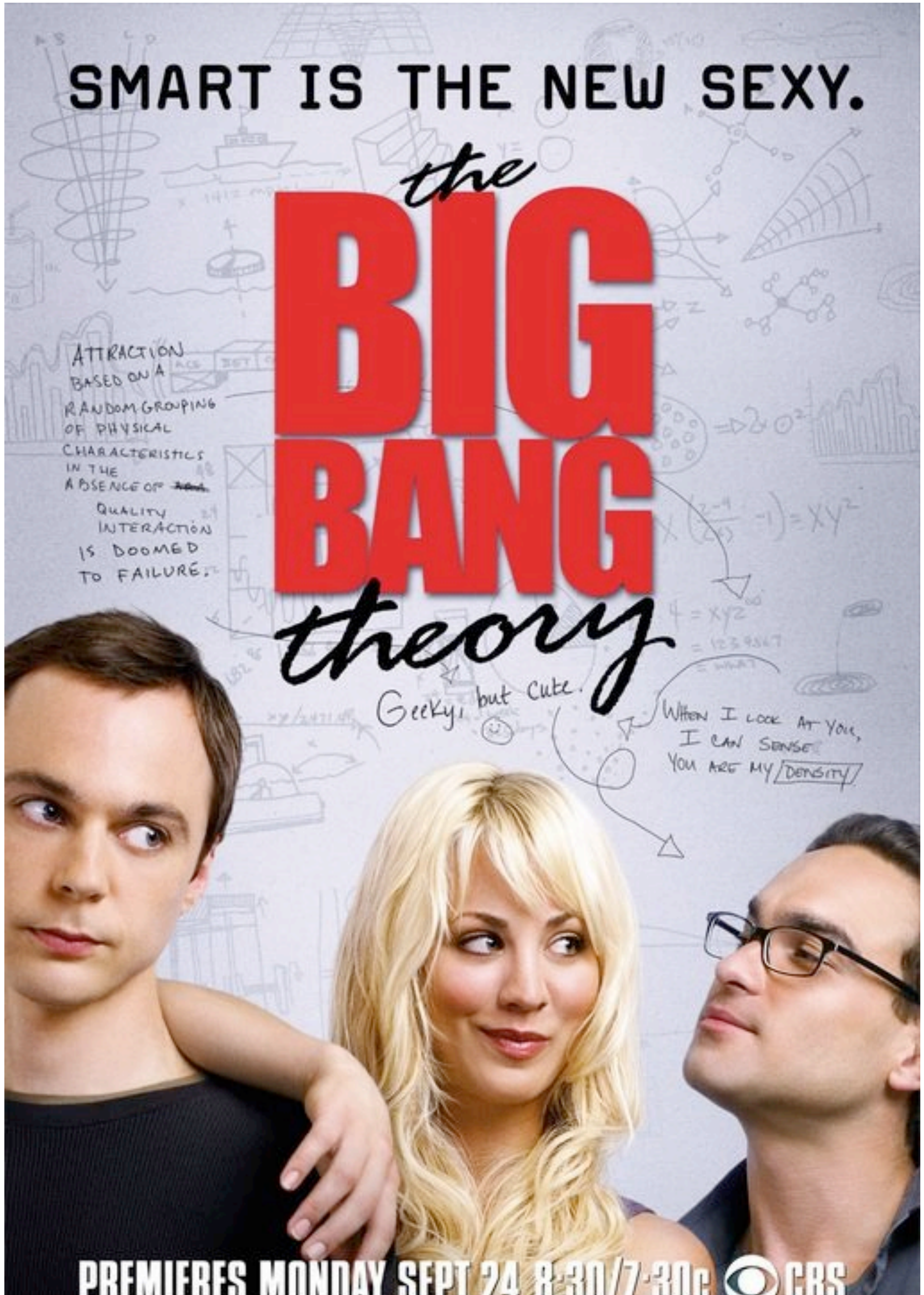
One of the earliest believers of the Big Bang theory:



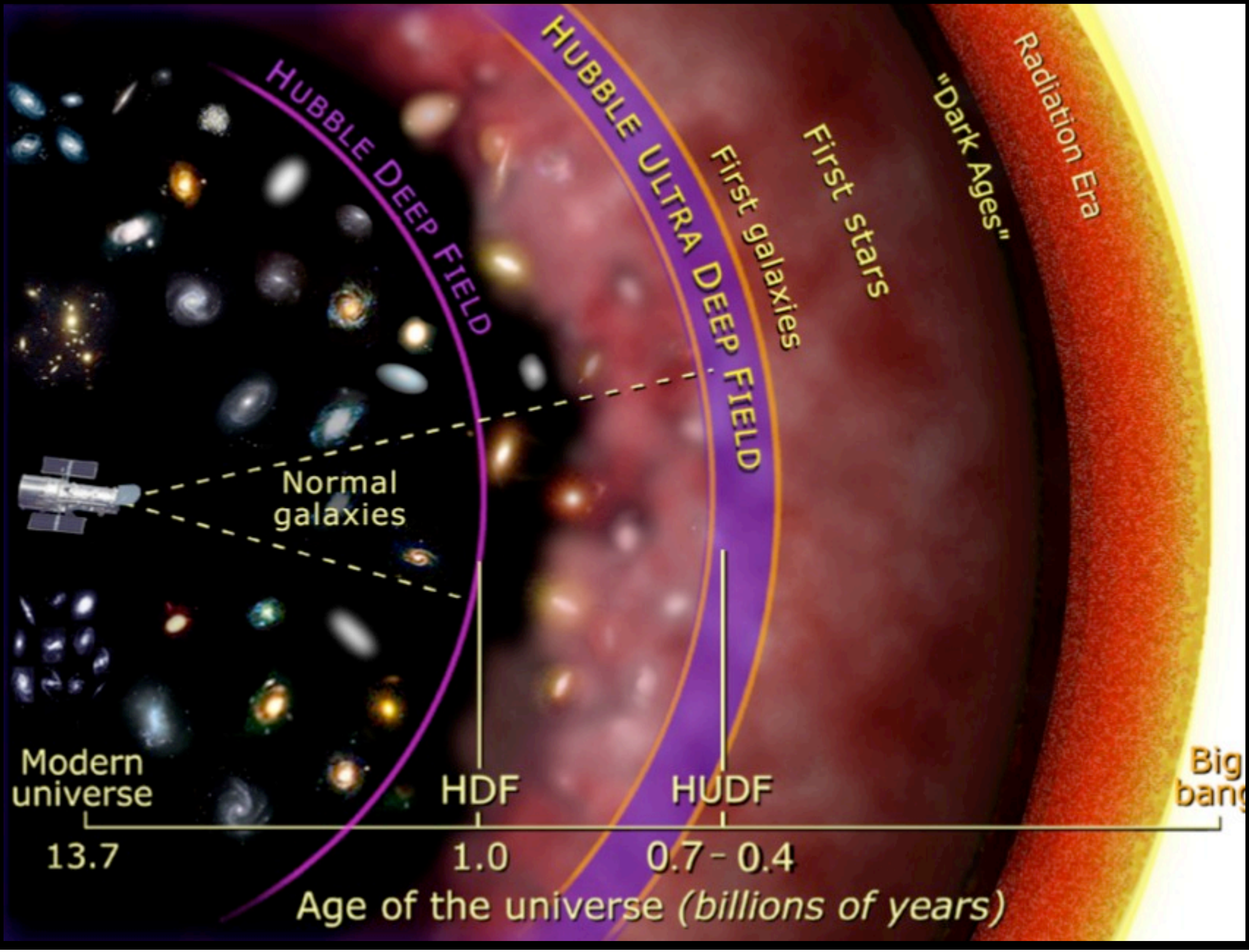
Pope Pius XII (1951)

"…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! "

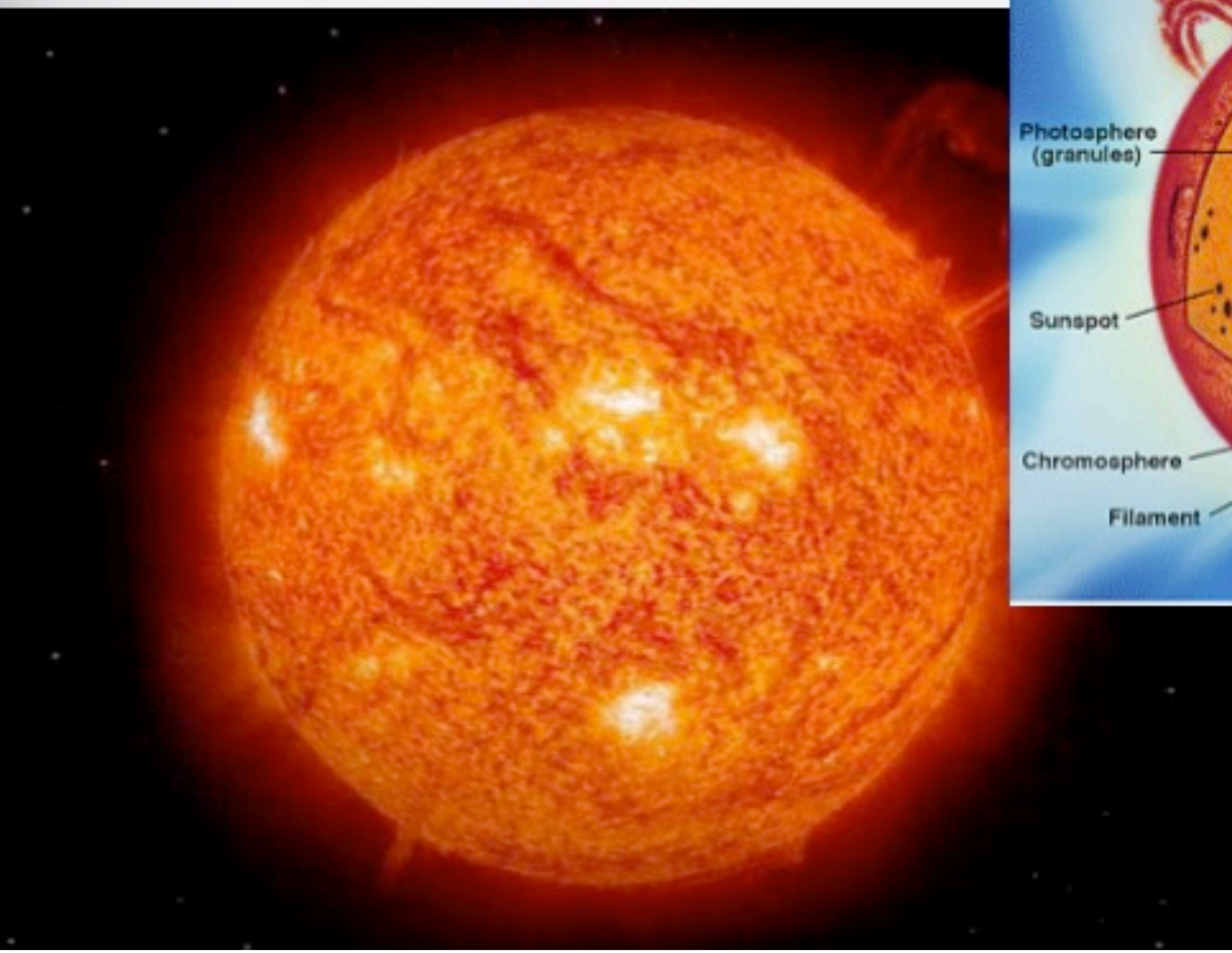

SMART IS THE NEW SEXY.
the BIG BANG theory
ATTRACTION BASED ON A RANDOM GROUPING OF PHYSICAL CHARACTERISTICS IN THE ABSENCE OF QUALITY INTERACTION IS DOOMED TO FAILURE.
Geeky, but cute.
WHEN I LOOK AT YOU, I CAN SENSE YOU ARE MY DENSITY
PREMIERES MONDAY SEPT 24 8:30/7:30c CBS

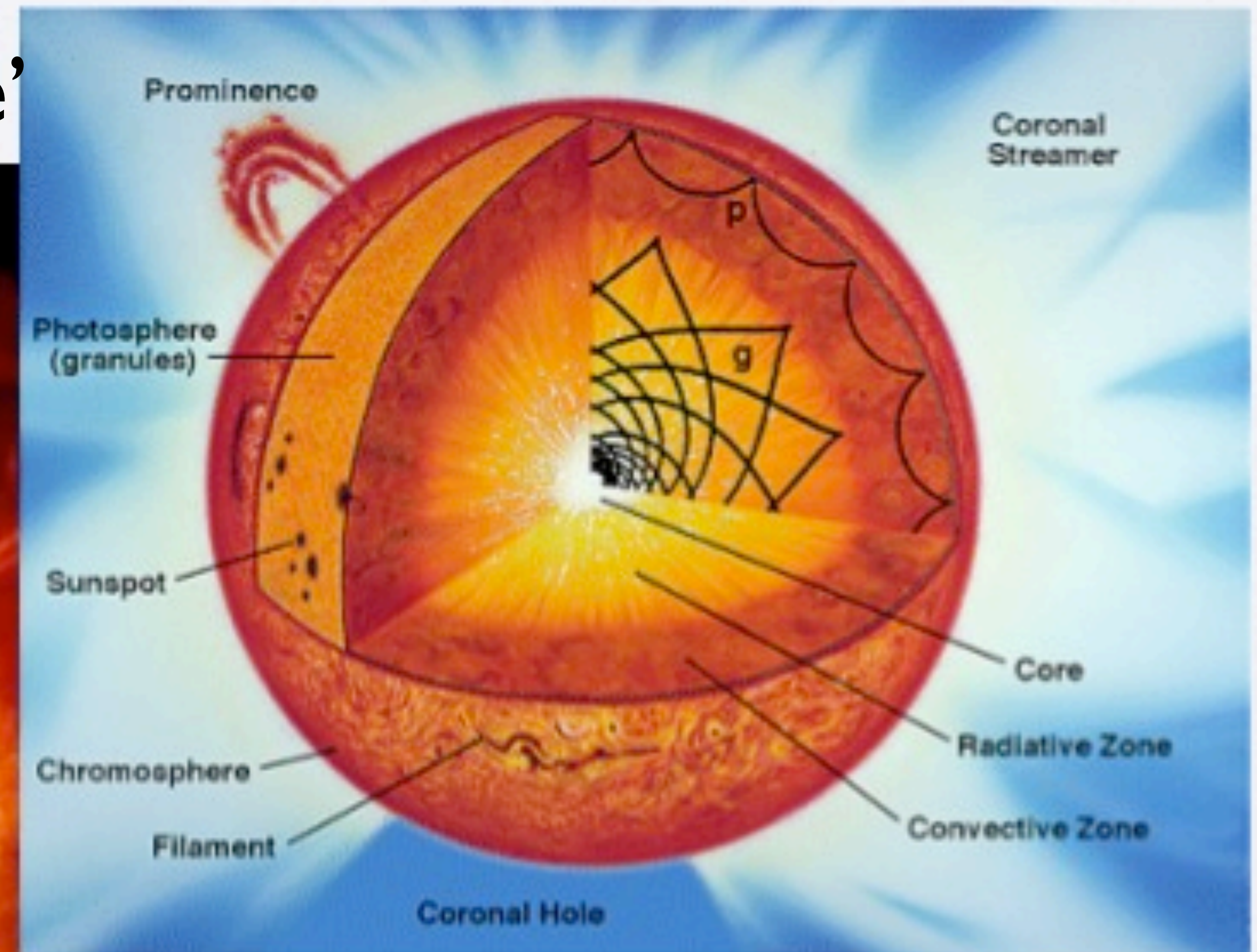
Unfortunately, the Cosmic Microwave Background (CMB, at redshift ~1100) is the closest we can see toward the Big Bang.



Why can’t you see into the Sun?

no direct view of the central hottest part; only the ‘photosphere’





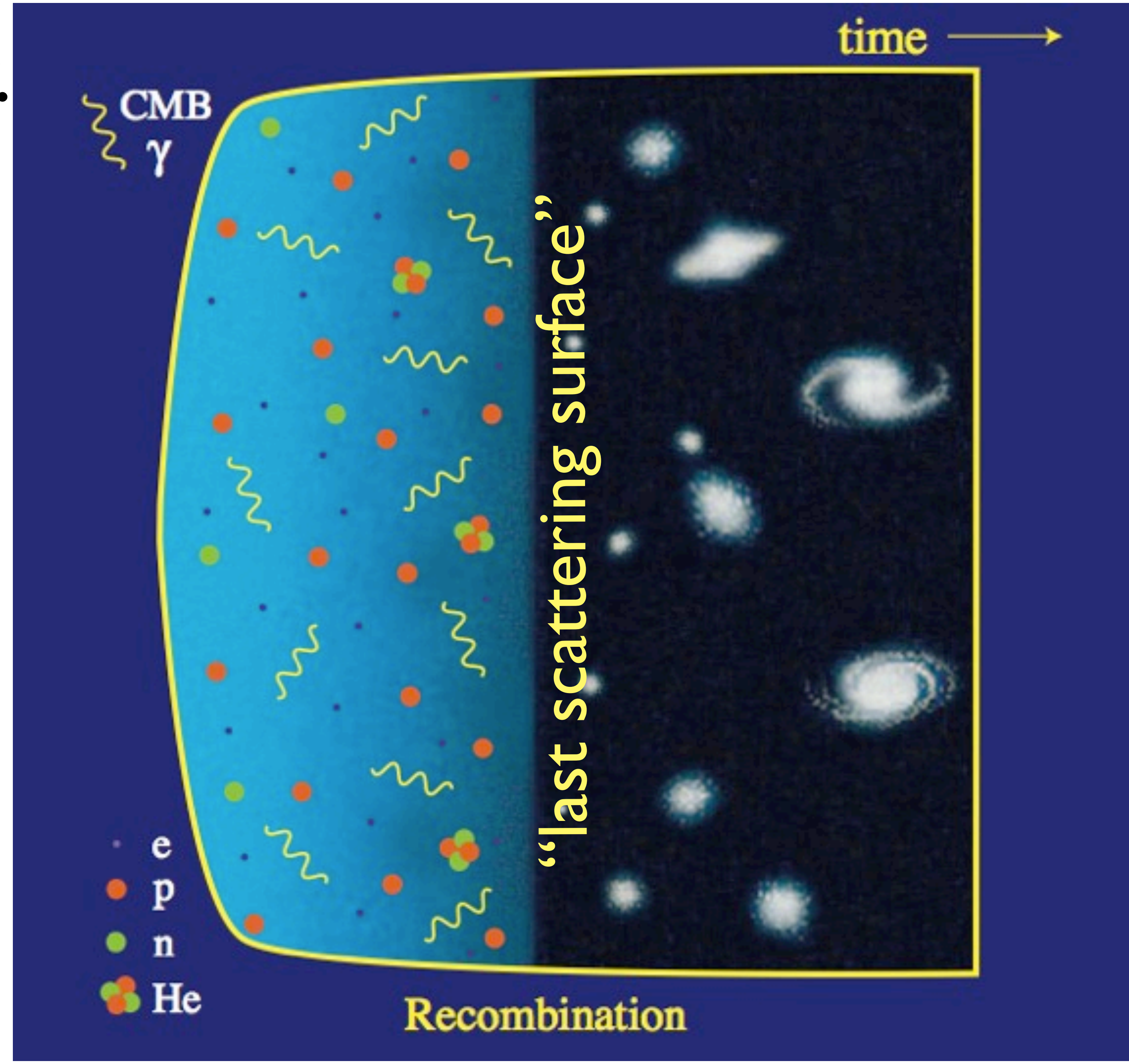
photons from the Sun embed information about the “last scattering layer”.

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



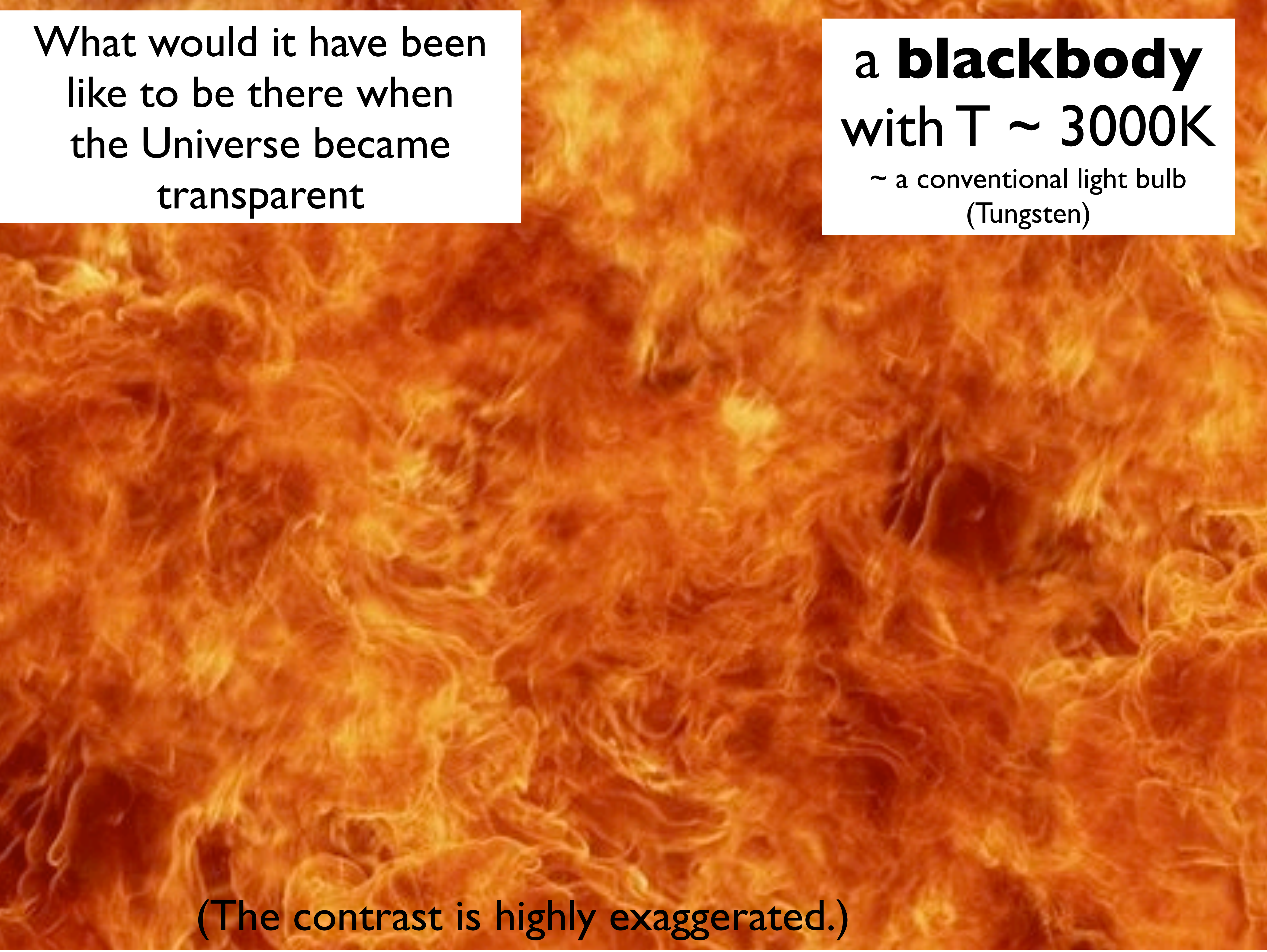
•as universe cools, electrons combine with hydrogen nuclei (recombination), most photons decoupled (electron orbits quantized, only interact with specific photons)

•'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

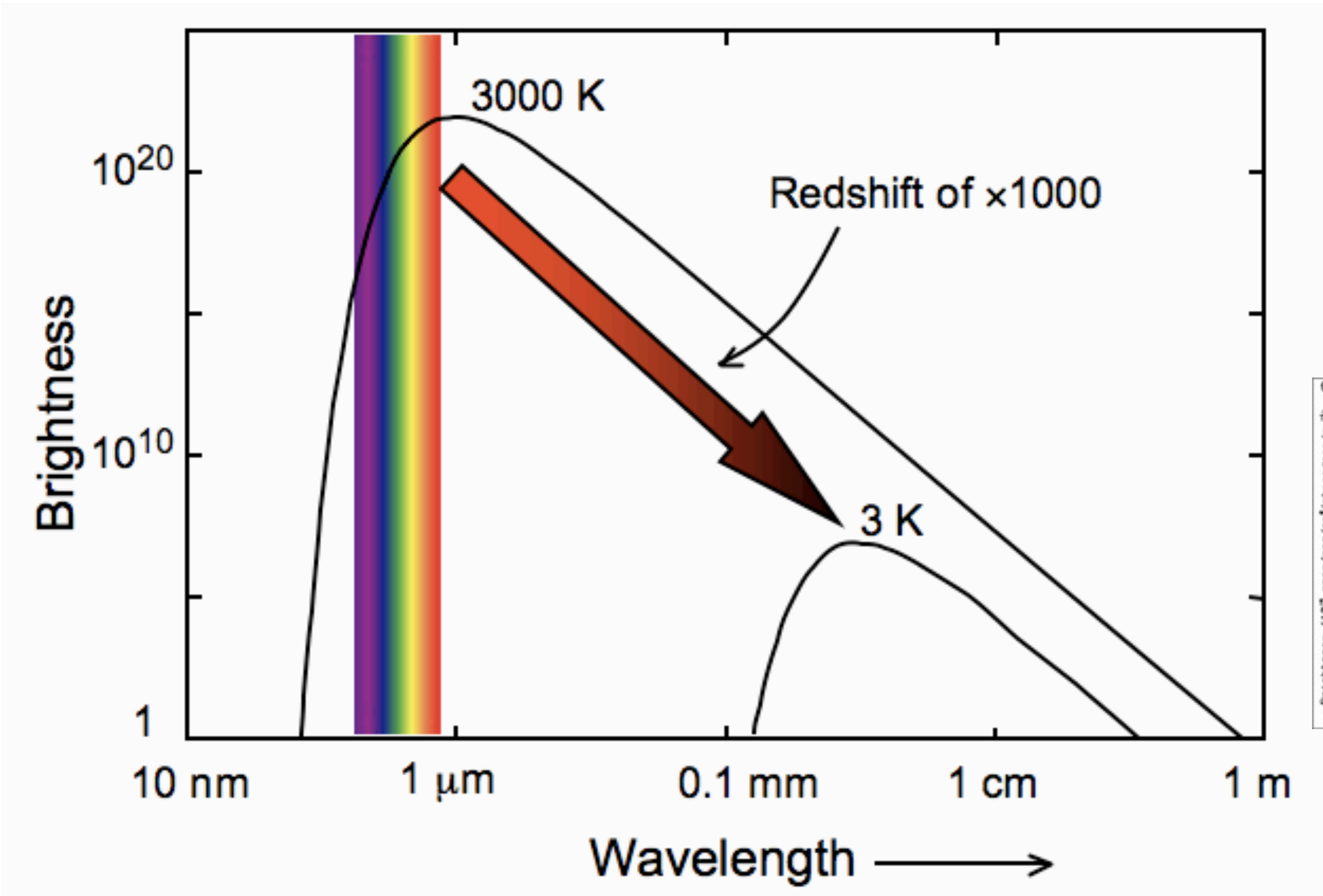
a **blackbody** with T ~ 3000K

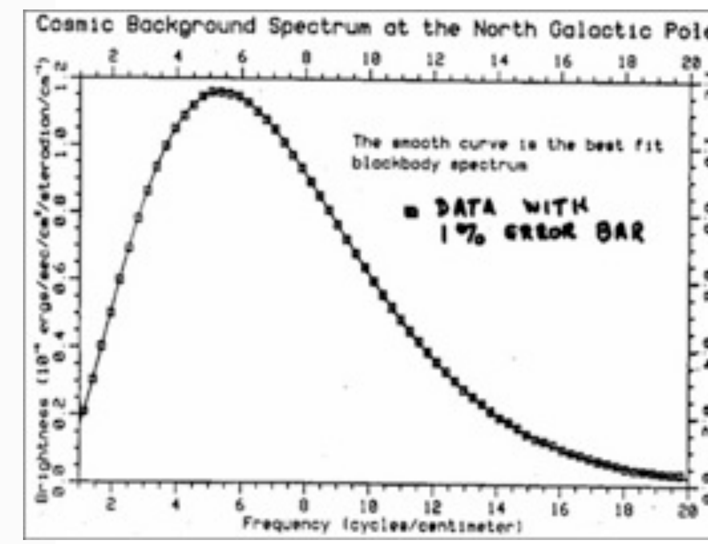
~ a conventional light bulb (Tungsten)



(The contrast is highly exaggerated.)

What does a redshifted blackbody spectrum look like?

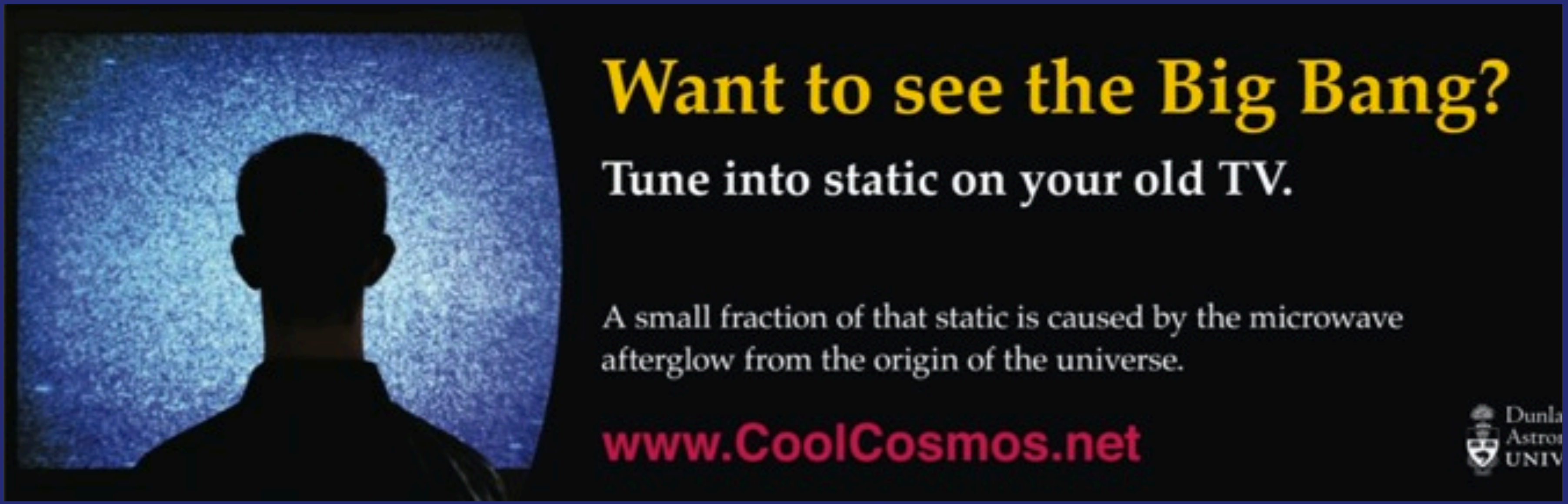




- $\lambda_{peak} = \lambda_{peak}(orig)*(1+z)$, shape invariant
- we get another blackbody with $T = T_{orig}/(1+z)$

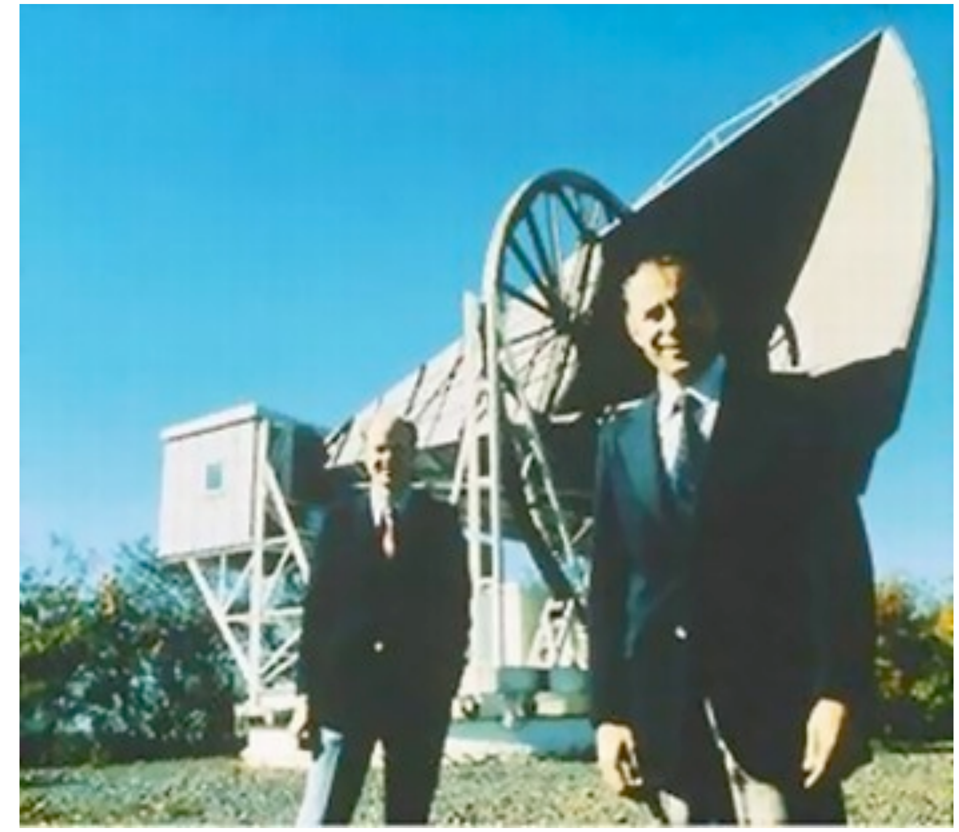
Now, ... redshifted to microwave (z ~ 1100)

- 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.

Serendipitous discovery of the Cosmic Microwave Background

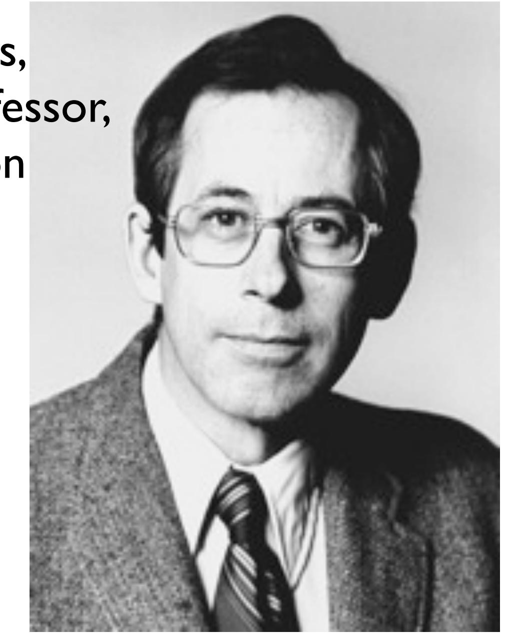


1965, Penzias & Wilson, radio astronomers at Bell Labs, discovered that we are immersed in a diffuse, isotropic (same everywhere) microwave radiation bath.

Spectrum of the radiation corresponds to a blackbody of 2.7 K.

They considered all possibilities for this background 'noise', including 'a white dielectric substance' (i.e., pigeon dropping) in the antenna horn.

J. Peebles,
Einstein Professor,
Princeton



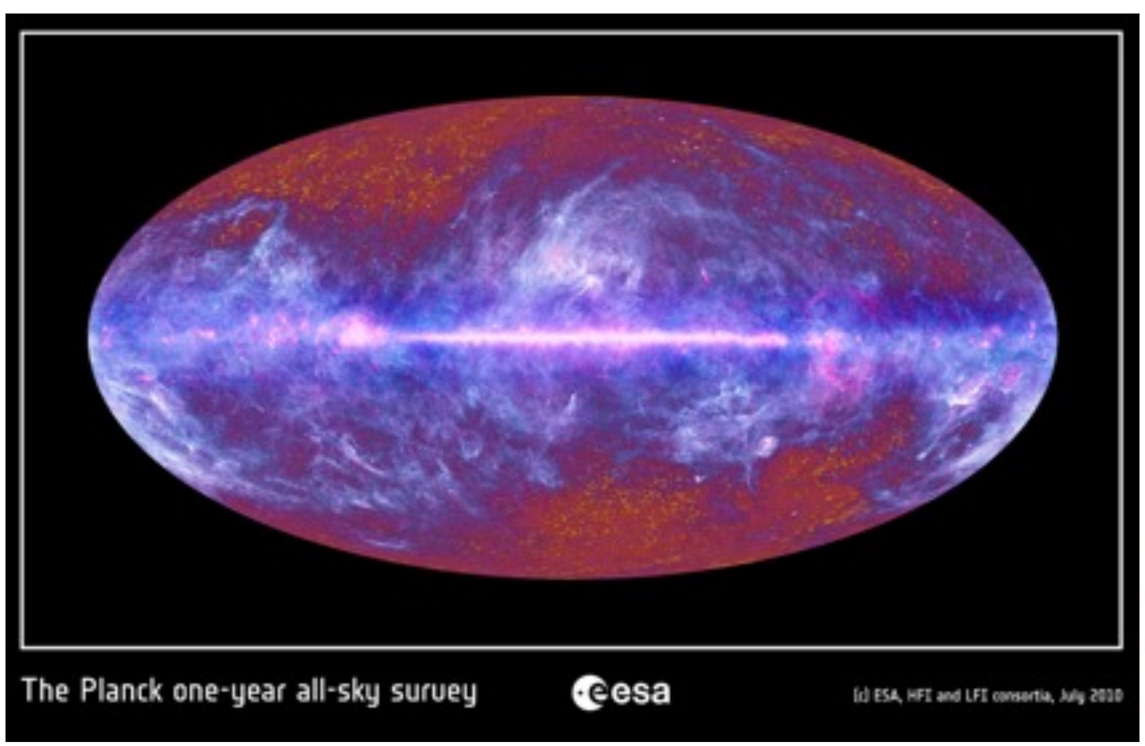
60 km away, Princeton astronomers (Peebles, Dicke..., and earlier, Russian scientists) predicted microwave signals from the initial fire-ball, were trying to build a telescope.

the groups soon found out about each other. Published two back-to-back papers in the Astrophysical Journal (one announcing the discovery, one explaining it).

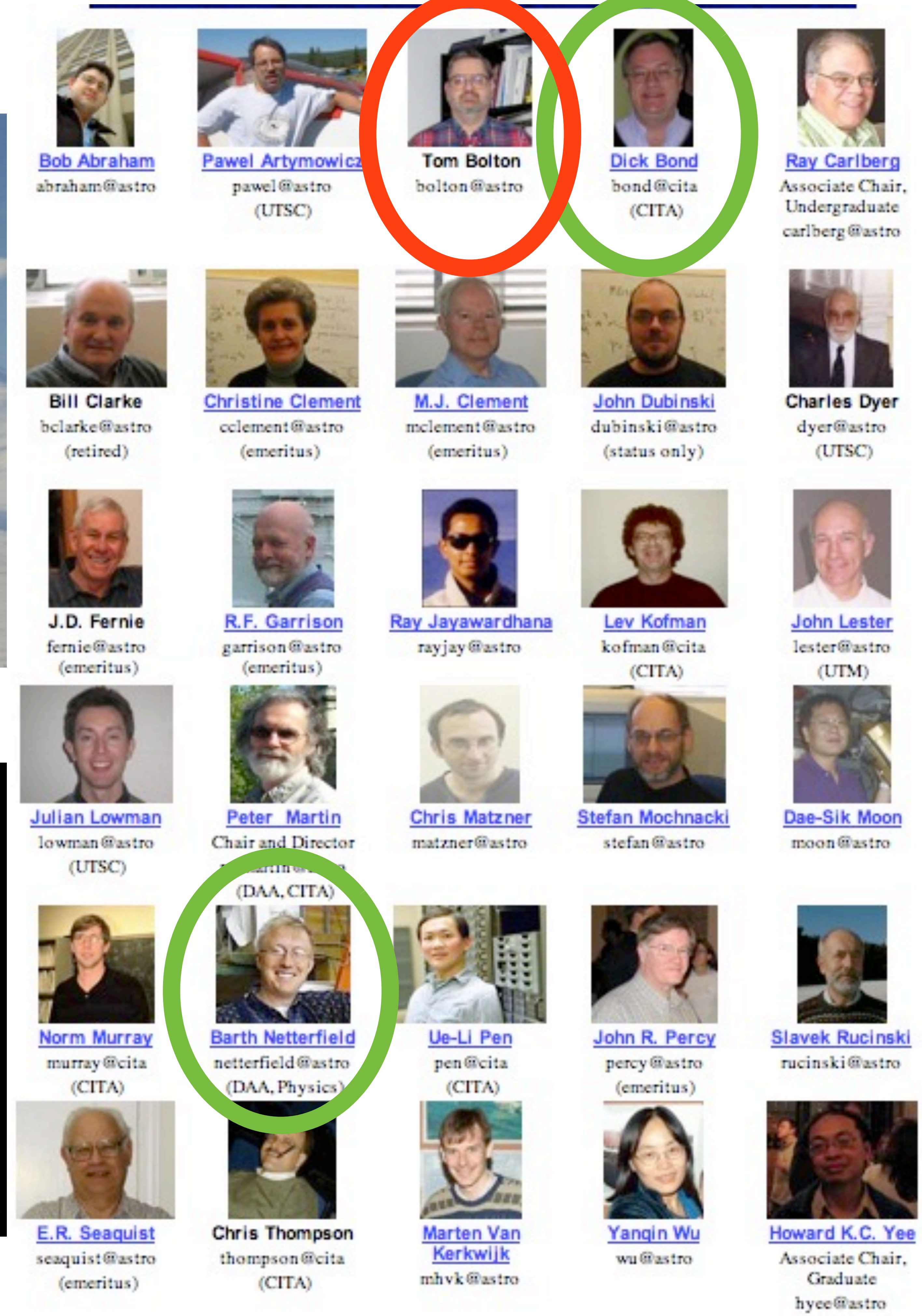
Penzias & Wilson shared the 1976 Nobel prize in Physics for this discovery.

CMB @ Toronto

Boomerang (Antarctica)



Planck mission (now in space)



Dr. Amir Hajian
Friday, CMB