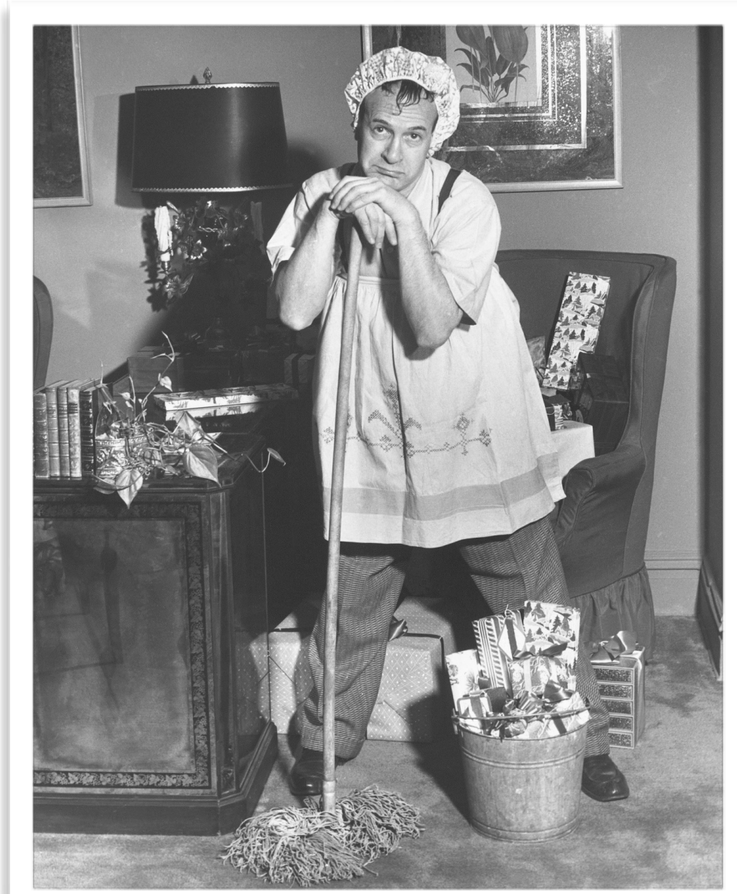
hi

Day LAST, 26.04.2018

Cosmology 5

housekeeping



The end game: next slide

Quiz was messed up. Fixed at 21:45 last night

so you may turn it in at the Final

Particle Physics:

Readings: Oerter, Cosmic Horizons, and Hobson

Hobson_quantum_fields.pdf is chapter 17

Homework #13 is: partly from MasteringPhysics - normal due date

partly on paper...see the blog

Feynman Diagram rules

3 movies in the lecture slide directory - you'll need them for homework and the final

they are: primitiveDiagrams_X. mp4 where X = 0,1,2

last ~~2~~ 1 weeks & final

Homework #13 will be assigned 4/21 and due 4/28 - normal rotation

On-line final exam will be assigned Sunday, 4/29 and due Tuesday night, May 1

will cover material since midterm plus the last week of class

There is 1 more 10 point quiz (stay tuned)…

~~only the shadow knows when~~…actually, watch the blog. Quiz up tomorrow, return Thursday in class.

Remember when I was sick?

been trying to catch up, but not going to make it. Hence:

Final Exam day:

1. You'll arrive at 0745 on May 4, here. I know.
2. I'll provide bagels. You supply liquids.
3. We'll have a quiz.
4. I'll finish with about a 1 hour grand finale, lalapalooza, mind-bending lecture
5. You'll do your Feynman Diagram Project
6. There will be no poster project this year

I'm did rethink this, do it by May 4th midnight , but no presentation

now hear this:

sirs@msu.edu <sirs@msu.edu> Inbox - Exchange April 16, 2018 at 7:34 AM

SIRS Online Forms

To: brockr@msu.edu <brockr@msu.edu>

To: RAYMOND L BROCK

From: sirs@msu.edu

Student Instruction Rating System (SIRS Online) collects student feedback on courses and instruction at MSU. Student Instructional Rating System (SIRS Online) forms will be available for your students to submit feedback during the dates indicated:

ISP 220 001: 4/16/2018 - 5/16/2018
ISP 220 002: 4/16/2018 - 5/16/2018

Direct students to https://sirsonline.msu.edu.

Students are required to complete the SIRS Online form OR indicate within that form that they decline to participate. Otherwise, final grades (for courses using SIRS Online) will be sequestered for seven days following the course grade submission deadline for this semester.

SIRS Online rating summaries are available to instructors and department chairs after 5/16/2018 at https://sirsonline.msu.edu. Instructors should provide copies of the rating summaries to graduate assistants who assisted in teaching their course(s). Rating information collected by SIRS Online is reported in summary form only and cannot be linked to individual student responses. Student anonymity is carefully protected.

If you have any questions, please contact Michelle Carlson, (mcarlson@msu.edu, (517)432-5936).

honors project ended

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

contains:

the first instructions: the plan & tutorial

the second instructions – v2 uploaded, added a missing student

the data, assigned by name in the second instructions - see next

dates:

complete first part, March 16

analyze data by April 24 and hand in complete writeup at the final exam

have

I need a Section 2

to test the Z-path uploading machinery and instructions

You should be able to do it now!

Physics and Astronomy Colloquium

4:10pm today...this room

Professor Alan Nathan
University of Illinois

Title: Recent Advances in the Physics of Baseball

After reading Bob Adair's classic book The Physics of Baseball over 20 years ago, I thought I knew everything there was to know about the subject. Since then I have learned much, much more, due in large part to some superb tools that are now available. These tools, which I will describe in the talk, allow detailed studies that were not available to Adair at the time he wrote his book. The advances have come in two broad

areas: The aerodynamics of a baseball in flight and the physics of the ball-bat collision. Not only have these advances furthered our understanding of the physics, but they have also had a practical application to the game itself. I will give several examples, including some of the following:

What is the role of the batter's grip during the ball-bat collision?
How do atmospheric conditions affect the flight of the baseball? Why the recent surge in home runs? What is the "launch angle revolution"?
What's the deal with the humidor?

I will sprinkle the talk with amusing high-speed videos and ancectotes about our national pastime. So, the talk should have something for everybody, whether your interest is primarily physics, baseball, or the intersection between them.

of particle physics

definite predictions

of Weinberg's model

0. The weak and electromagnetic interactions are two aspects of the same force

1. The *W* Boson should exist

2. An additional "*Z* Boson" should exist

Many physics reactions relate M_w to M_Z

3. This *Z* Boson and the γ are intimately related

any reaction with a photon, must also happen with a Z^0

4. The Higgs Boson should exist

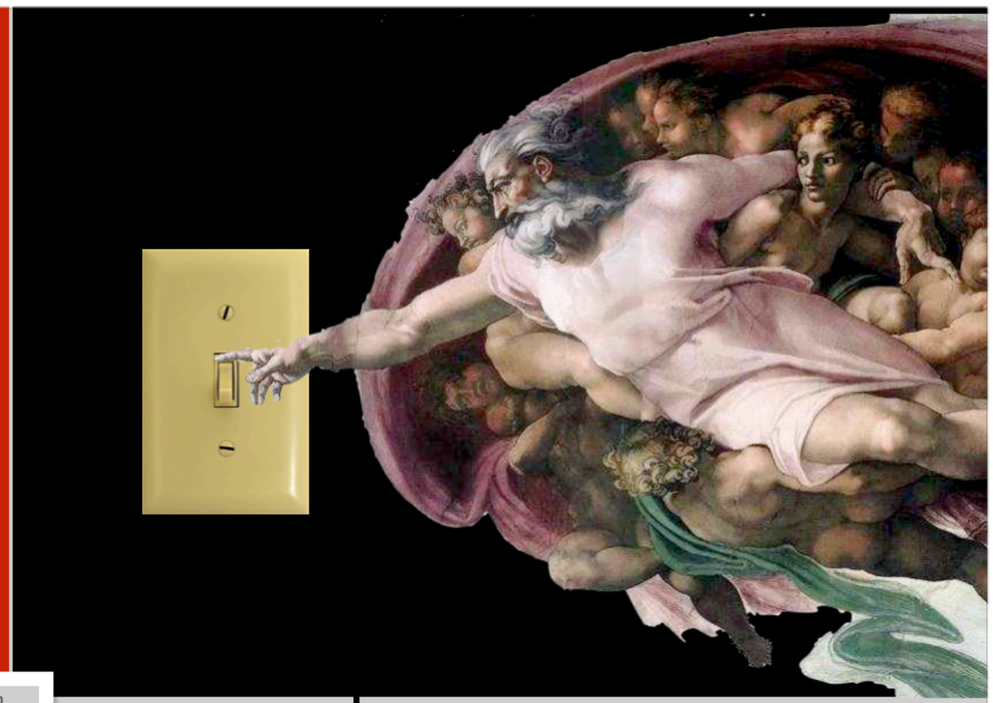
the Standard Model and Higgs

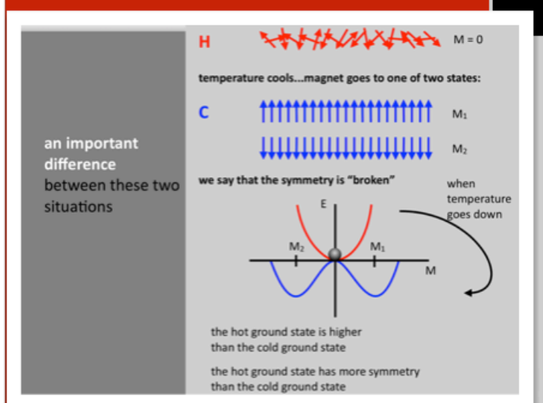
"symmetry breaking? Maybe points the way?

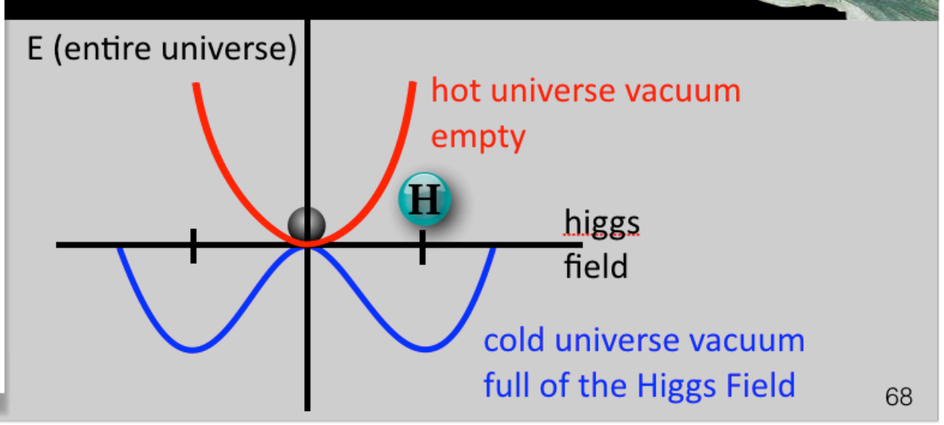
from a hot phase in the universe

cool it all at once

@ 10^{-12} seconds after the BB







and it worked.
Flawlessly

remember these energy-shapes

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

Share this:

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

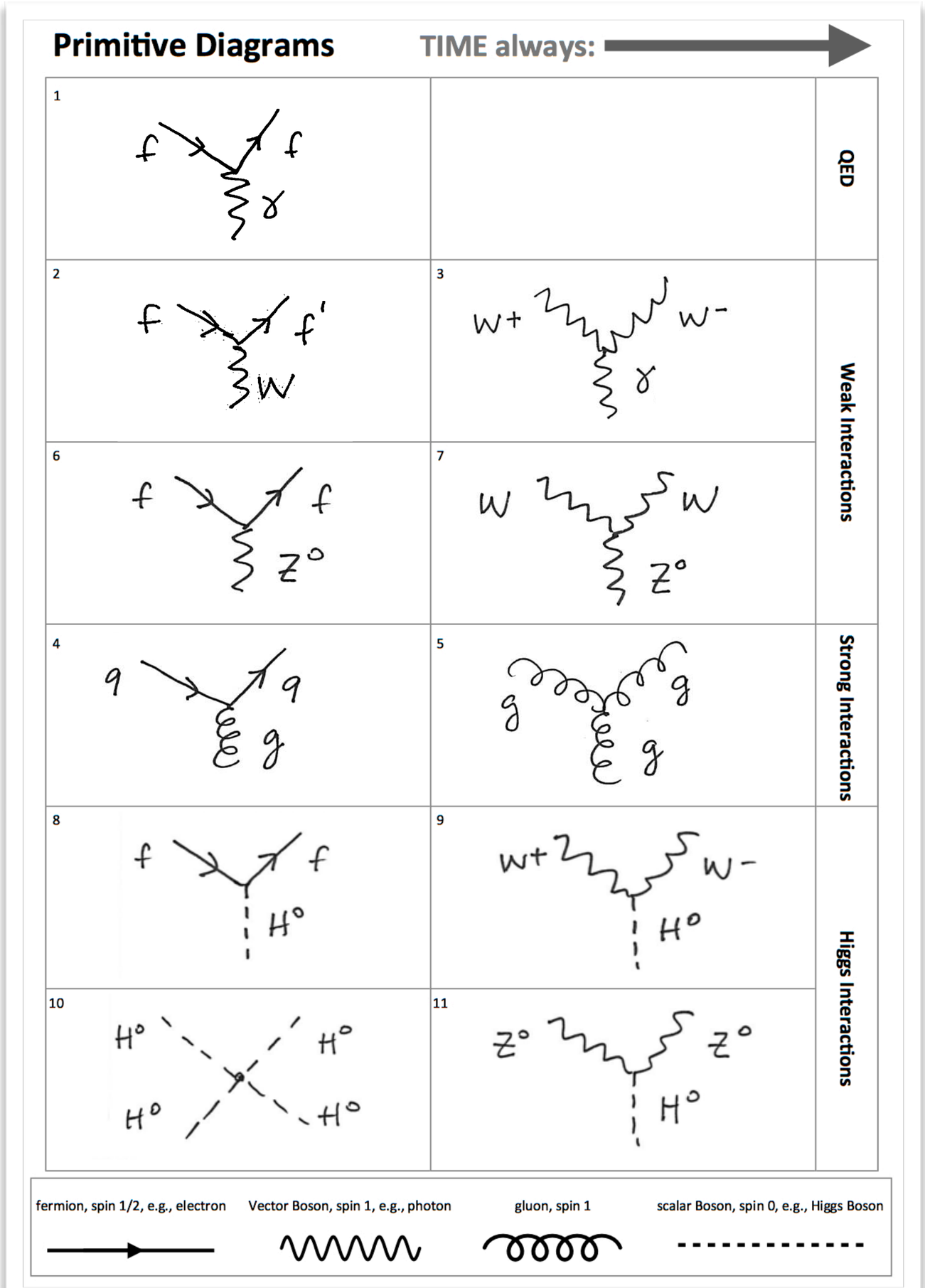
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

like any particle,

we predict and then search for its manifestation

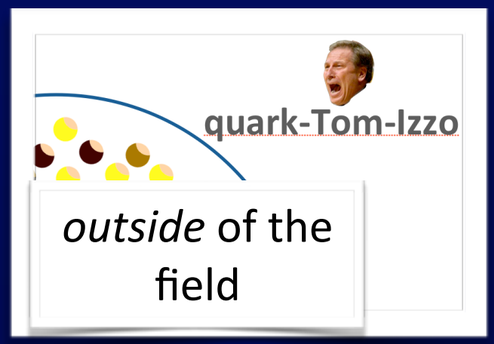
through its decays

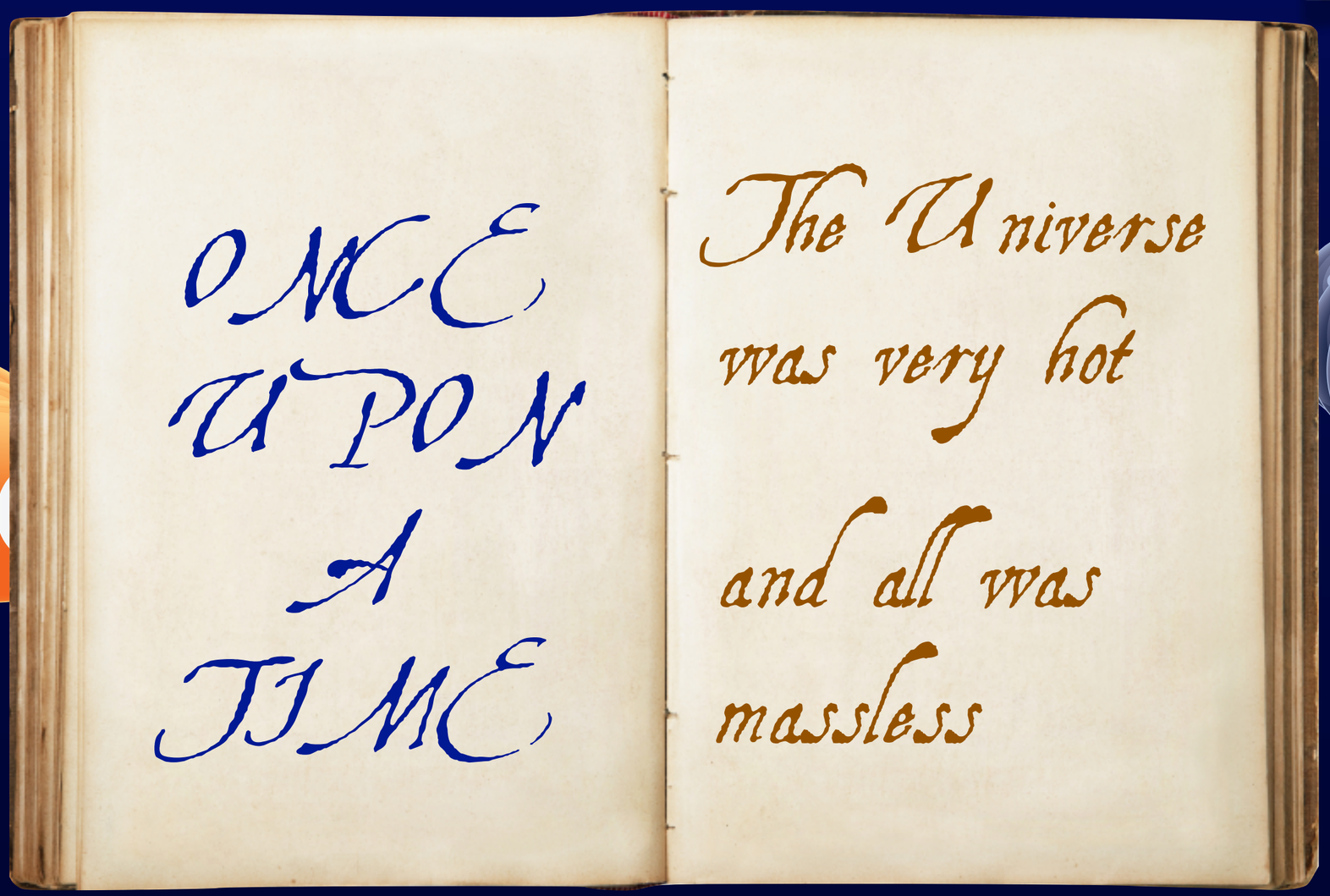
Your final entries into the Primitive Diagram collection

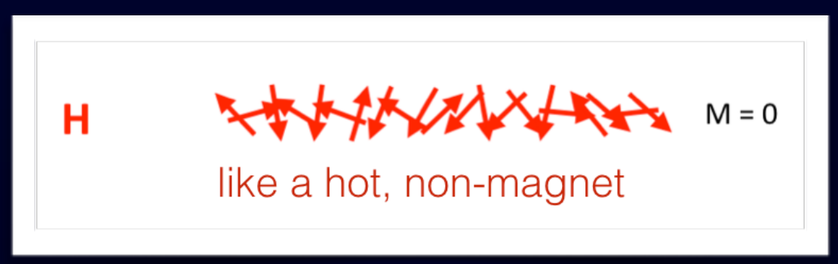


the big story of the Standard Model

is the story of mass.


quark-Tom-Izzo
outside of the field


ONCE UPON A TIME,
The Universe was very hot and all was massless

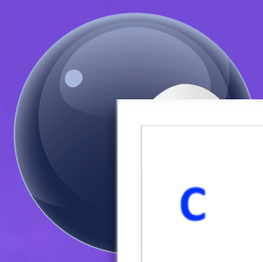

H
M = 0
like a hot, non-magnet

inside of the field

At a Magic Temperature

The Universe expanded and cooled and a

Higgs Field became manifest and all became heavy



C

$M_1 \neq 0$

like a regular magnet

mass

was born

in the Higgs Field

elementary particle epoch

$T_{Critical}$

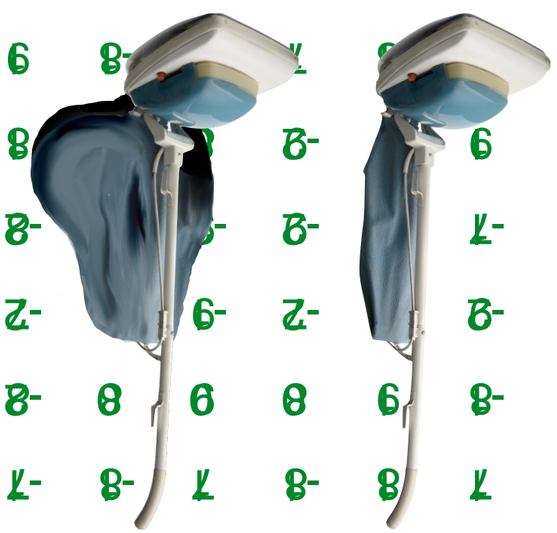
?

particle

particl

10^{-42}s 10^{-39}s 10^{-36}s 10^{-33}s 10^{-30}s 10^{-27}s 10^{-24}s 10^{-21}s 10^{-18}s 10^{-15}s 10^{-12}s 10^{-9}s 10^{-6}s

10^{22} K 10^{21} K 10^{18} K 10^{15} K



elementary particle epoch

$T_{Critical}$

?

No Higgs Field

particle

Higgs Field forever

10^{-42}s 10^{-39}s 10^{-36}s 10^{-33}s 10^{-30}s 10^{-27}s 10^{-24}s 10^{-21}s 10^{-18}s 10^{-15}s 10^{-12}s 10^{-9}s 10^{-6}s

10^{22} K 10^{21} K 10^{18} K 10^{15} K

vacuum

h[illegible] empty fields

now it's full of Higgs Fields

where’s

the antimatter?

what the heck

is dark matter?

watch the off-line movie:

https://qstbb.pa.msu.edu/storage/Extras_2017/DarkMatter/

Cosmology 5

Where we're going:

The Hot Big Bang Model

We:

will flesh it out

speculate beyond

of cosmology

And here's what you missed in COSMOLOGY

Einstein invented General Relativity and applied it to the whole universe.

geometry $G = T$ energy, pressure, mass

He didn't like what happened and so he added the Cosmological Constant to stop the Universe from expanding

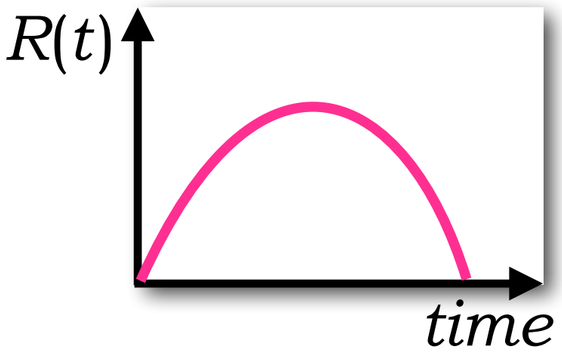
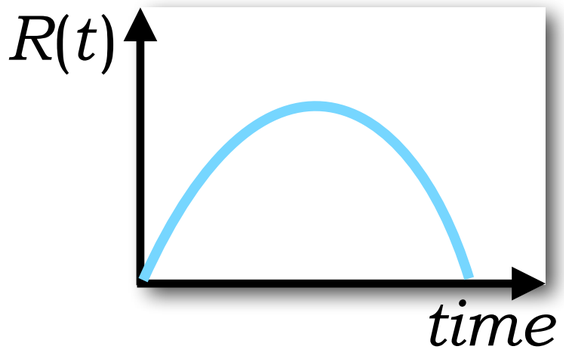
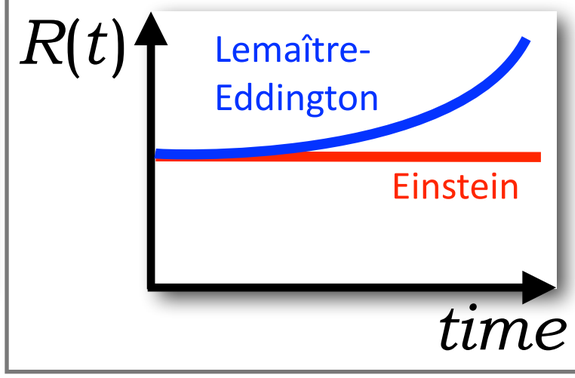
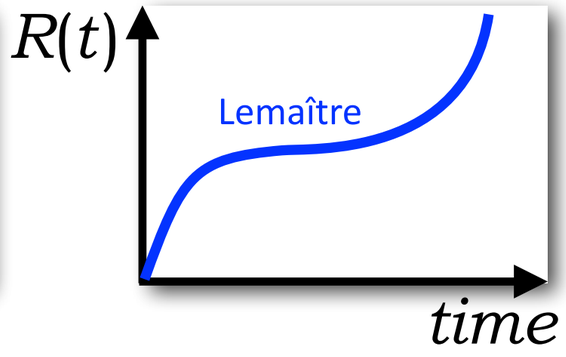
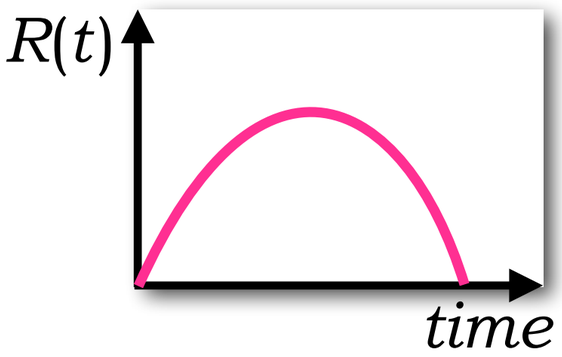
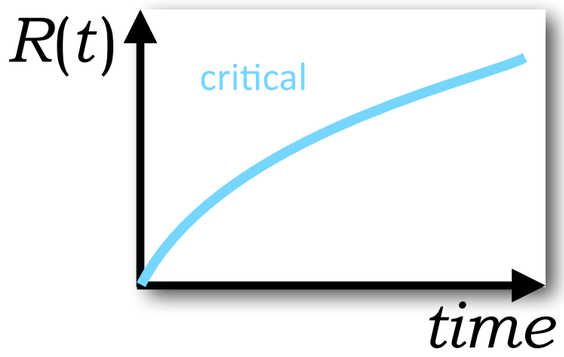
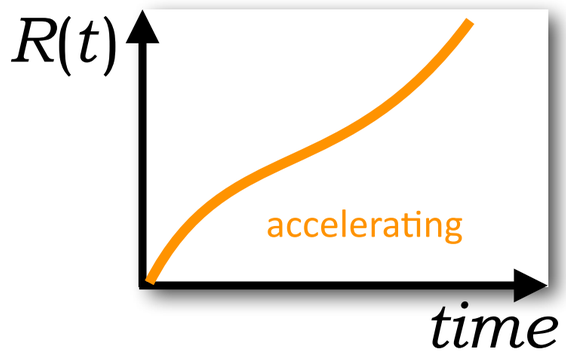
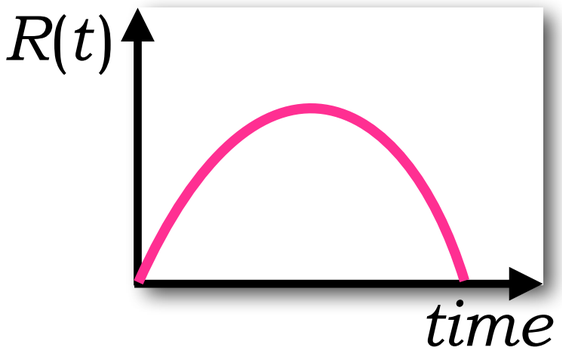
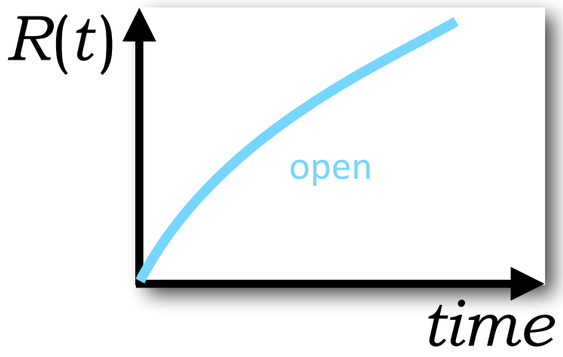
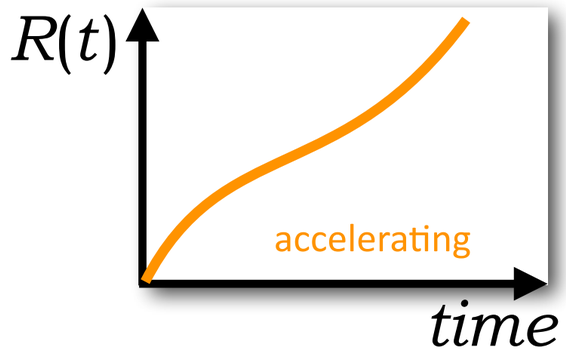
$$G + \Lambda = T$$

Hubble found that the Universe was expanding.

Lemaitre, Friedmann, Robertson, Walker, deSitter...and others solved his equations with and without the Cosmological Constant.

It became useful to describe the expansion of the Universe in terms of the Scale Factor, R(t).

FLRW catalogue of Universes

	$\Lambda < 0$	$\Lambda = 0$	$\Lambda > 0$	
			$\Lambda = \Lambda_E$	$\Lambda > \Lambda_E$
$k = +1$				
$k = 0$				
$k = -1$				

constant of nature:

Cosmological Constant, Λ

value: Einstein's original: $\Lambda = \frac{4\pi G\rho}{c^2}$

units: length^{-2}

usage: In the Friedman, Lemaître, Walker, Robertson models

relation alert: **Hubble's Law**

refers to: $$v = Hr$$

example: where v refers to the measured velocity of a galaxy (from the redshift) and r, the distance to the galaxy, originally from analysis of Cepheid Variable stars within the

constant of nature:

Hubble “Constant”

value: $H_0 = 67.8 \pm 0.9$

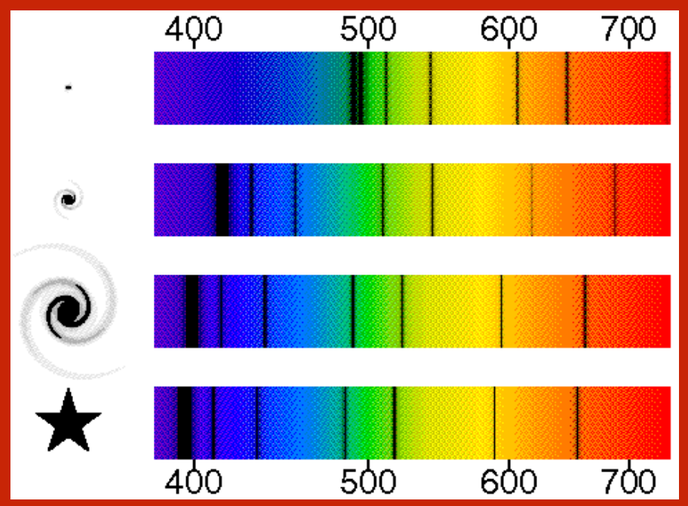
units: (km/s)/Mpc (1Mpc = 3 x 10^{22}m) so $H_0 = 2.46 \times 10^{-15}$ s^{-1}

usage: **fundamental** measurable in experimental cosmology

the “red shift”

isn’t a Doppler velocity

it’s geometry



close

late

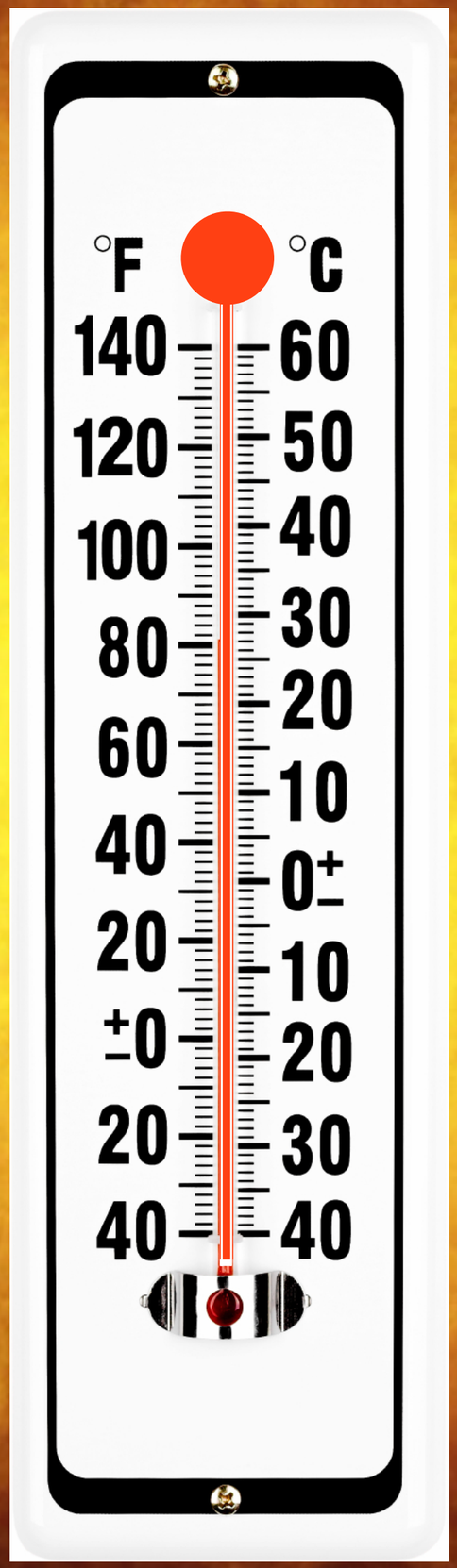
early

George Gamow

universe born

hot primordial soup

If not the Father of the Big Bang, at least the Crazy Uncle of the Big Bang.


°F
°C
140
120
100
80
60
40
20
±0
20
40
60
50
40
30
20
10
0±
10
20
30
40

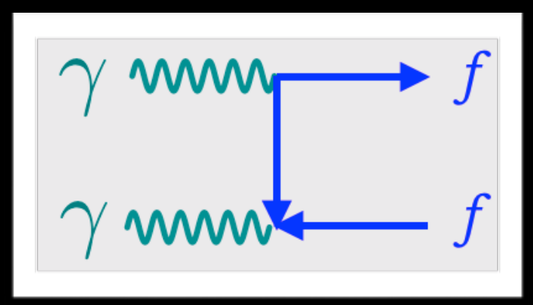
Mmmm, Mmmm Good....

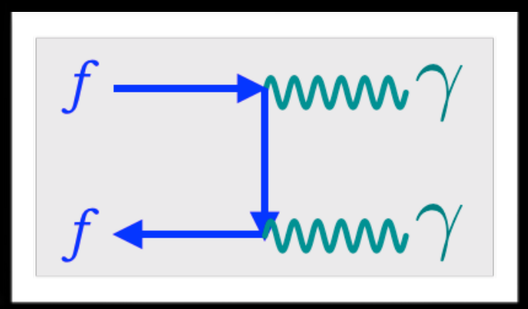
elementary particle epoch

"Quantum Foam"

?

presumed that processes are in equilibrium



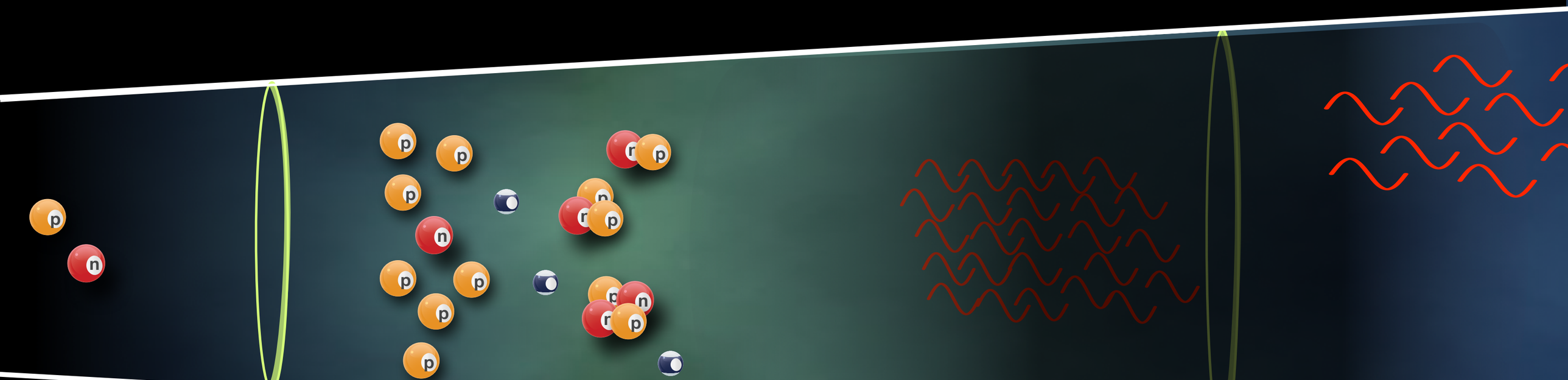


10^{-42}s 10^{-39}s 10^{-36}s 10^{-33}s 10^{-30}s 10^{-27}s 10^{-24}s 10^{-21}s 10^{-18}s 10^{-15}s 10^{-12}s 10^{-9}s 10^{-6}s

10^{22} K 10^{21} K 10^{18} K 10^{15} K

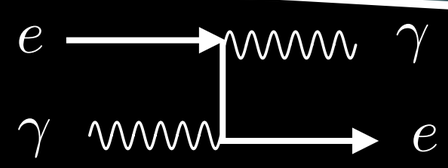
n u c l e o n e p o c h

opaque era



hadron era

nucleosynthesis era



10^{-6}s

10^{13} K

10^{-3}s

10^{12} K

10^{0}s

10^{10} K

10^{3}s

10^{8} K

10^{6}s

10^{7} K

10^{9}s

10^{6} K

10^{12}s

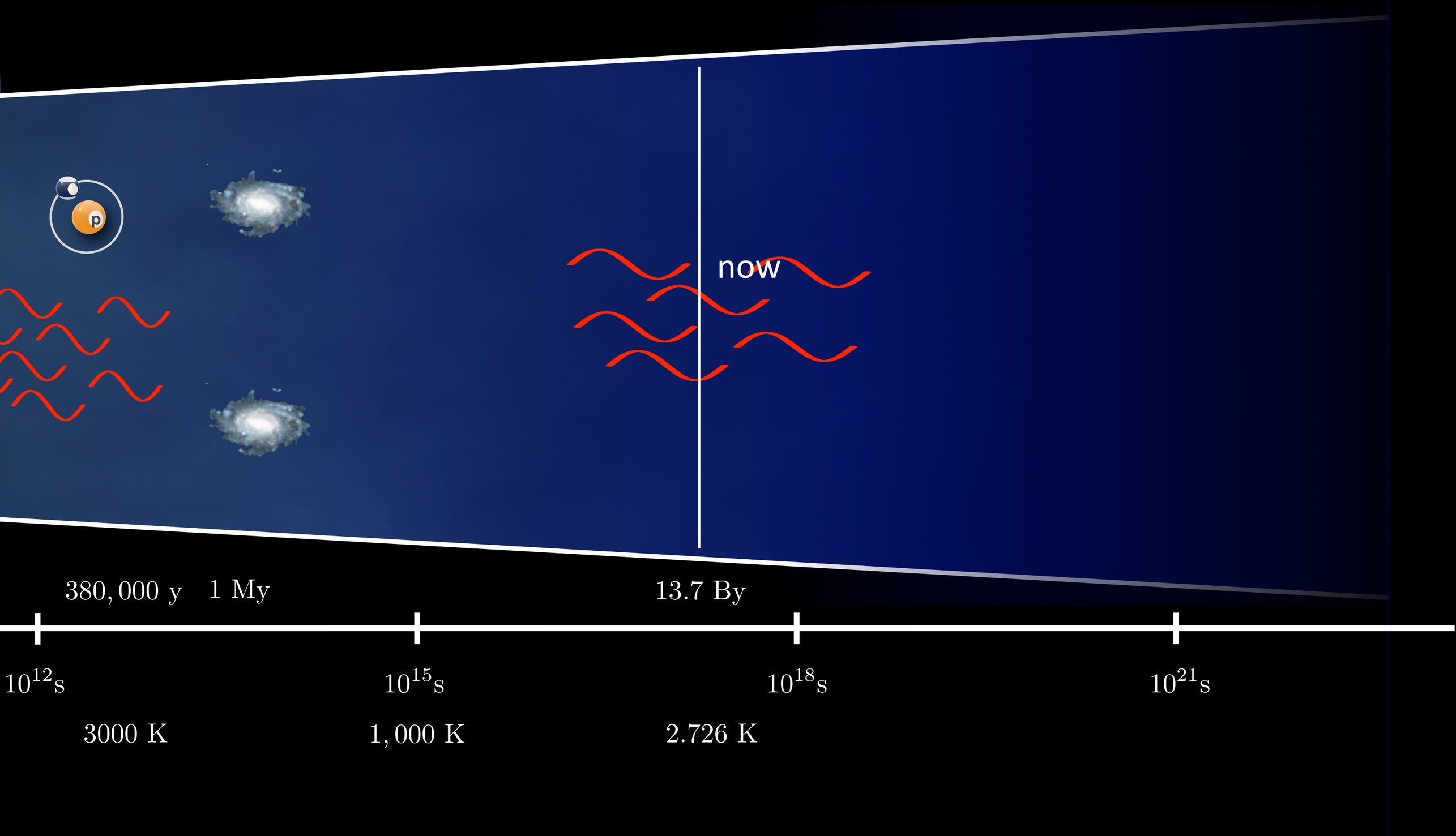
$10,000$ K

galactic epoch

light era

our era

dark era



380,000 y

1 My

13.7 By

10^{12}s

10^{15}s

10^{18}s

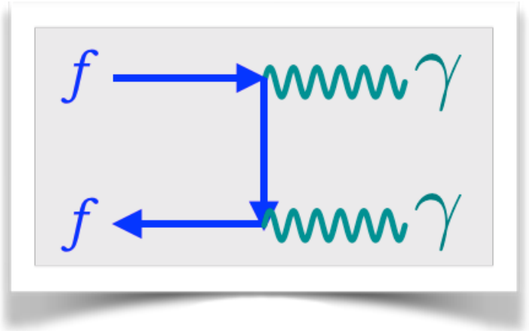
10^{21}s

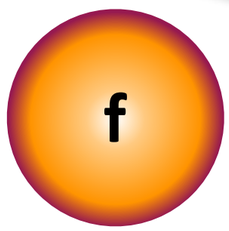
3000 K

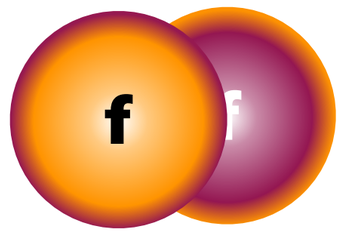
1,000 K

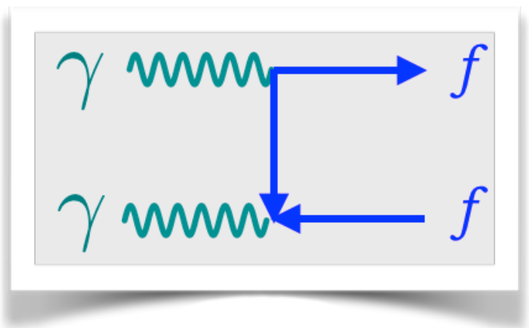
2.726 K

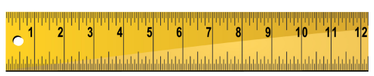
prior to 3 minutes: balance between radiation and particles.











Early moments: short wavelength photons = high frequency photons = high energy photons
lots of mc^2 available–can make heavy particles

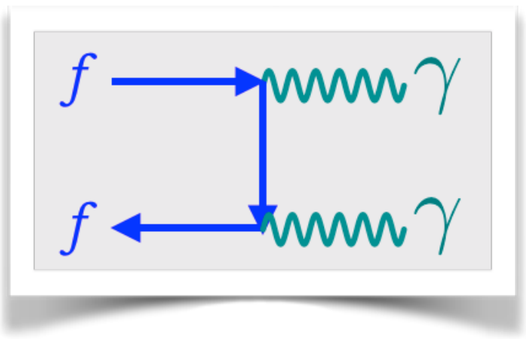
prior to 3 minutes: balance between radiation and particles.

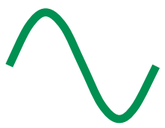
Later moments:

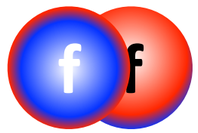
spacetime has stretched!

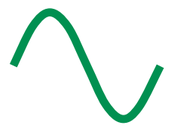
longer wavelength, lower frequency = less high energy photons

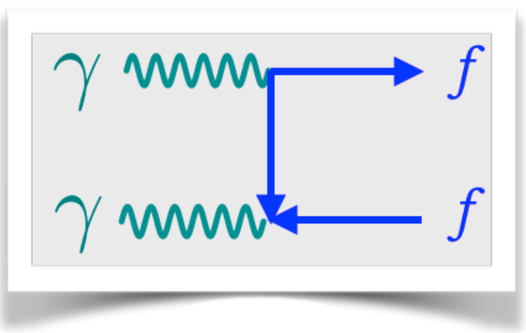
less mc^2 available–can't make heaviest particles





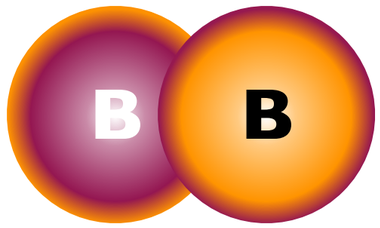




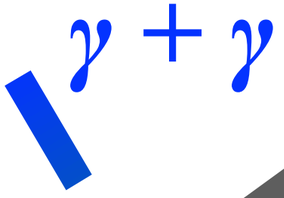


heavy species "freeze out": pairs cannot be created any more

energies

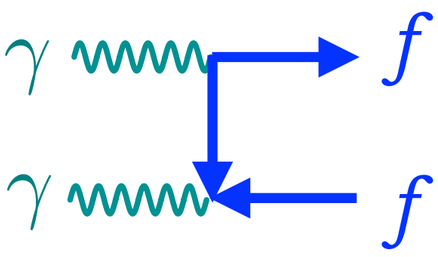


$2m_{really\ heavy}c^2$

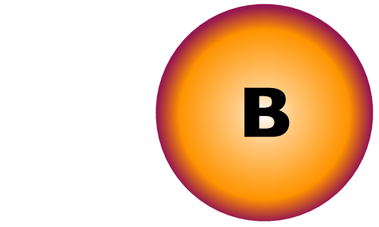


below this point:
can't make BB

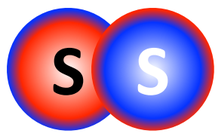
from:



wavelength stretching...
energy shrinking

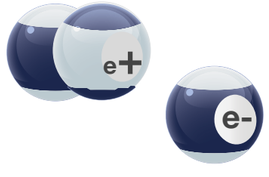


$m_{really\ heavy}c^2$



$2m_{heavy}c^2$

$m_{heavy}c^2$



$2m_{electron}c^2$

$m_{electron}c^2$

below this point:
can't make SS

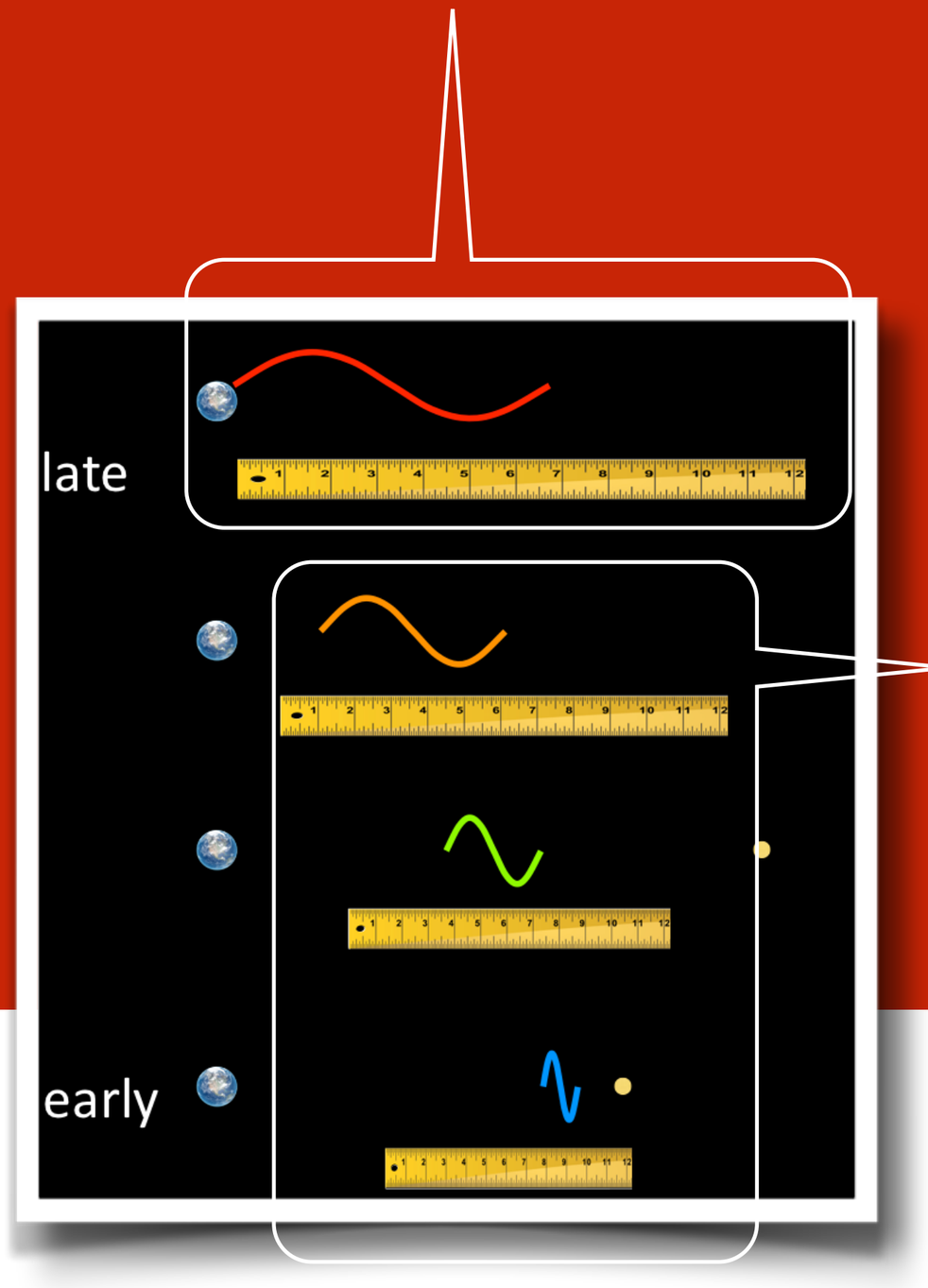
below this point:
can't make anything!

time →

space stretching →

at some point, they are too low in energy to do anything...they just hang around.
about 70,000 years after BB

remember



many high energy photons: create new particles, ionize atoms, disintegrate nuclei

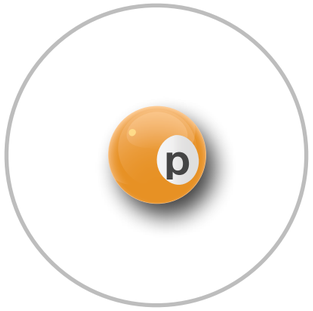
there is a magic point

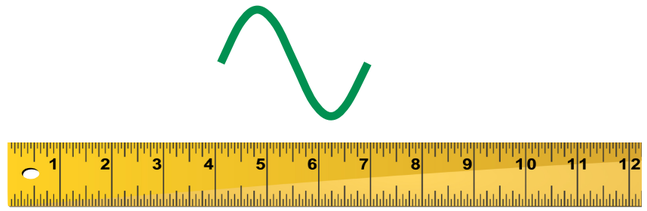
at which atoms can start to form

"recombination"

which is an odd name, since there wasn't a "combination" yet!

After protons, neutrons, and electrons are stable...





left-over photons ionize the baby Hydrogen atoms

The Universe consists of: a **plasma**...charged particles, unbound...freely moving around. Opaque.

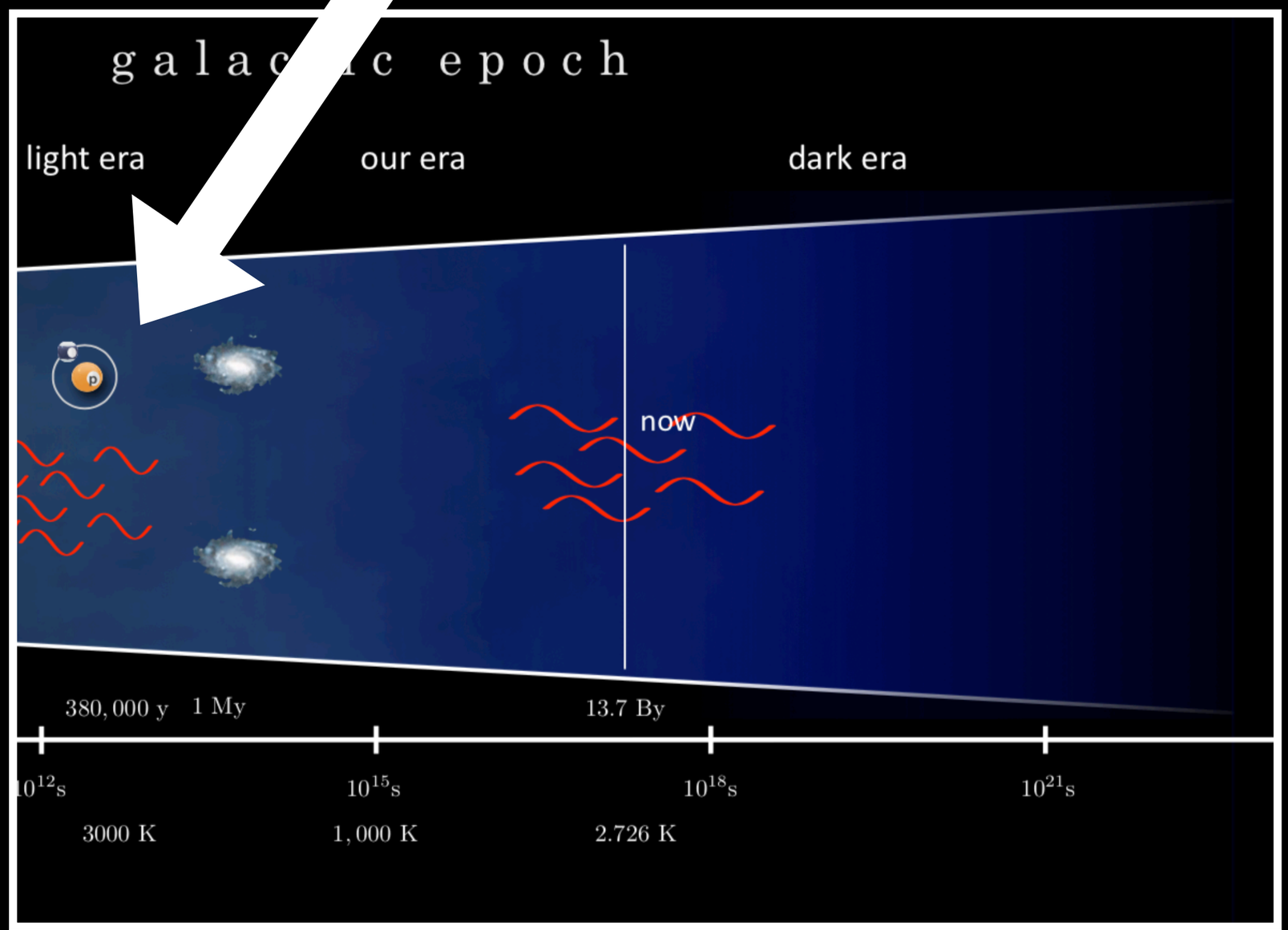
At one point...about $10^{12\text{-}13}$ s - 370,000 y:

Bingo.
We have H atoms (and He)

the photons don't have 13.6 eV of energy

There's nothing else for the photons to do!

The Universe has suddenly become transparent to photons


galactic epoch
light era
our era
dark era
p
now
380,000 y
1 My
13.7 By
10^{12}s
10^{15}s
10^{18}s
10^{21}s
3000 K
1,000 K
2.726 K

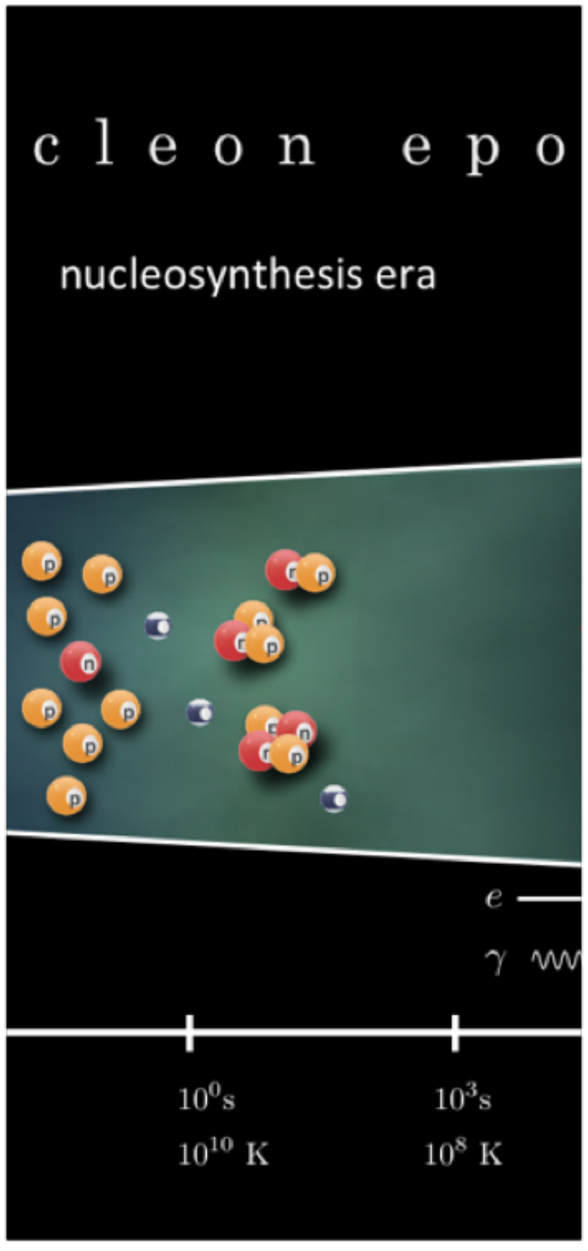
the photons that are left?

just hanging around

getting “longer,” **making trouble**, but not making new matter

There are two critical times

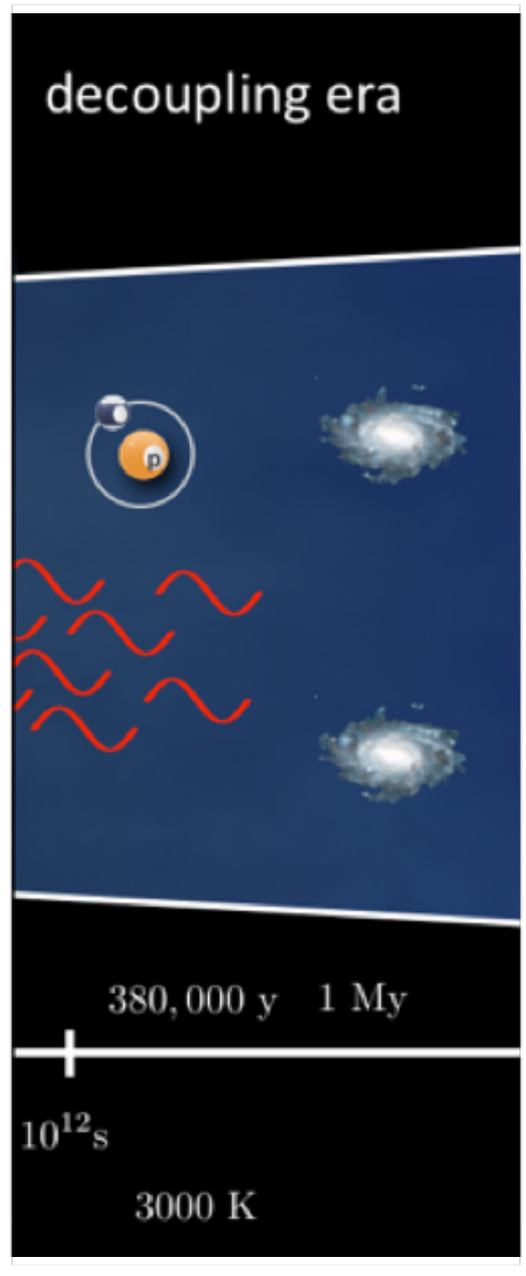
that confirm the Big Bang



3 minutes

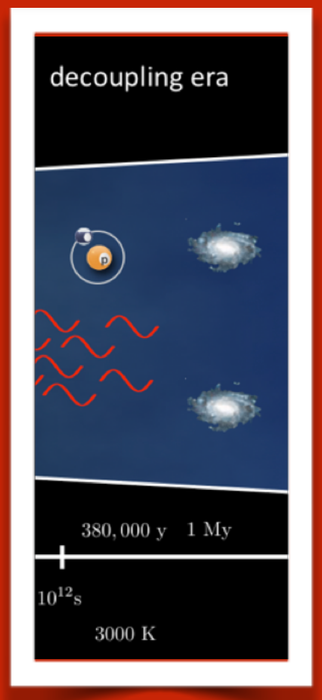
370,000 years

(all within the first 15 fake-minutes on my calendar)

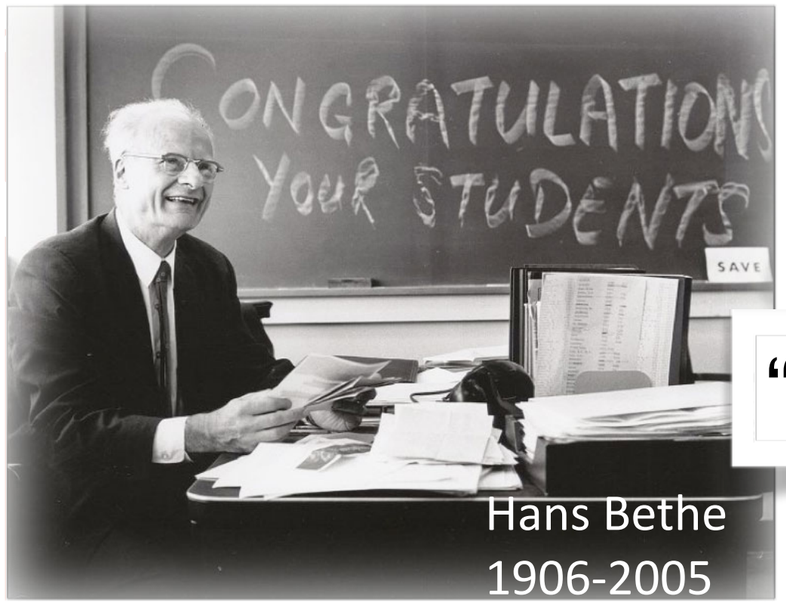


the Cosmic Microwave Background, CMB

about 370,000 y after BB



Ge
Ga

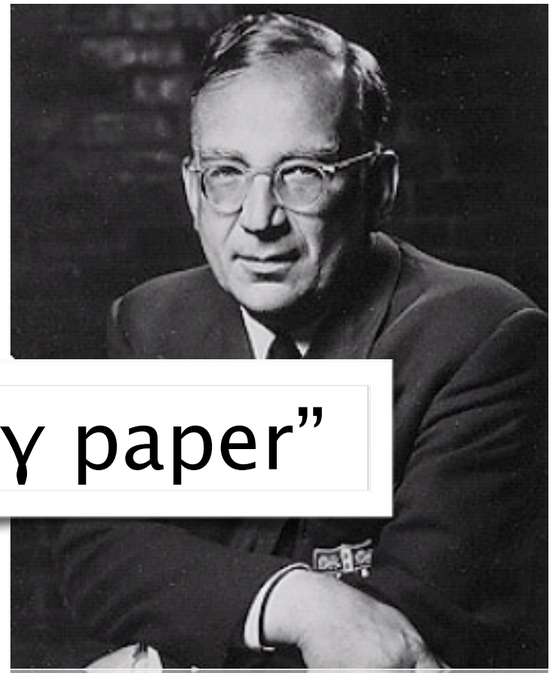


Hans Bethe
1906-2005

predicted this
left-over radiation

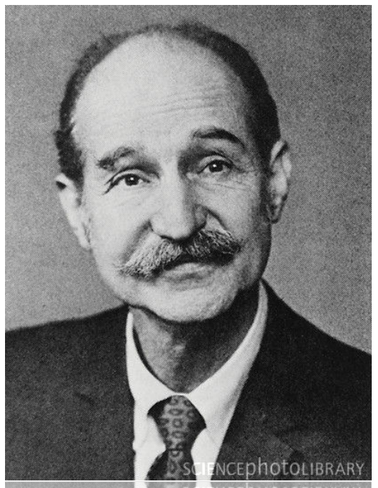
those left over
photons would have
started out hot...

*but cooled as the
Universe
expanded*



"αβγ paper"

Ralph Alpher
1921-2007



Robert Herman
1914 - 1997

1948 with collaborators Alpher and Herman:
predicted a left-over electromagnetic radiation

Alpher and Herman predicted it would be distributed across the Universe in a **Blackbody Spectrum** shape at a temperature of 5^0 K...microwaves

nobody paid attention...or remembered.

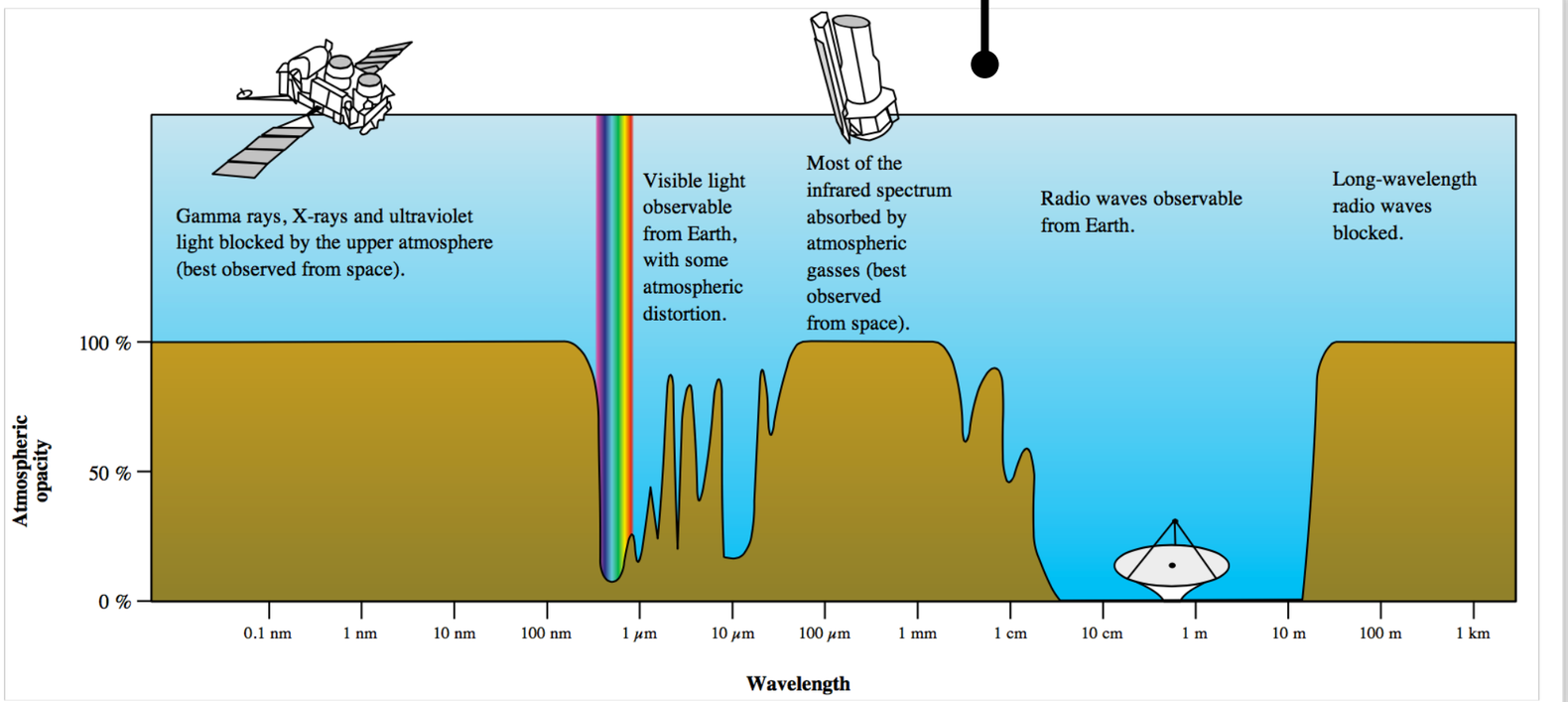
1993, the National Academy of Sciences gave
Alpher and Herman the Henry Draper Medal

so, all these cold photons left

the phone company was the hero

satellite communications are usually microwaves

where we're going

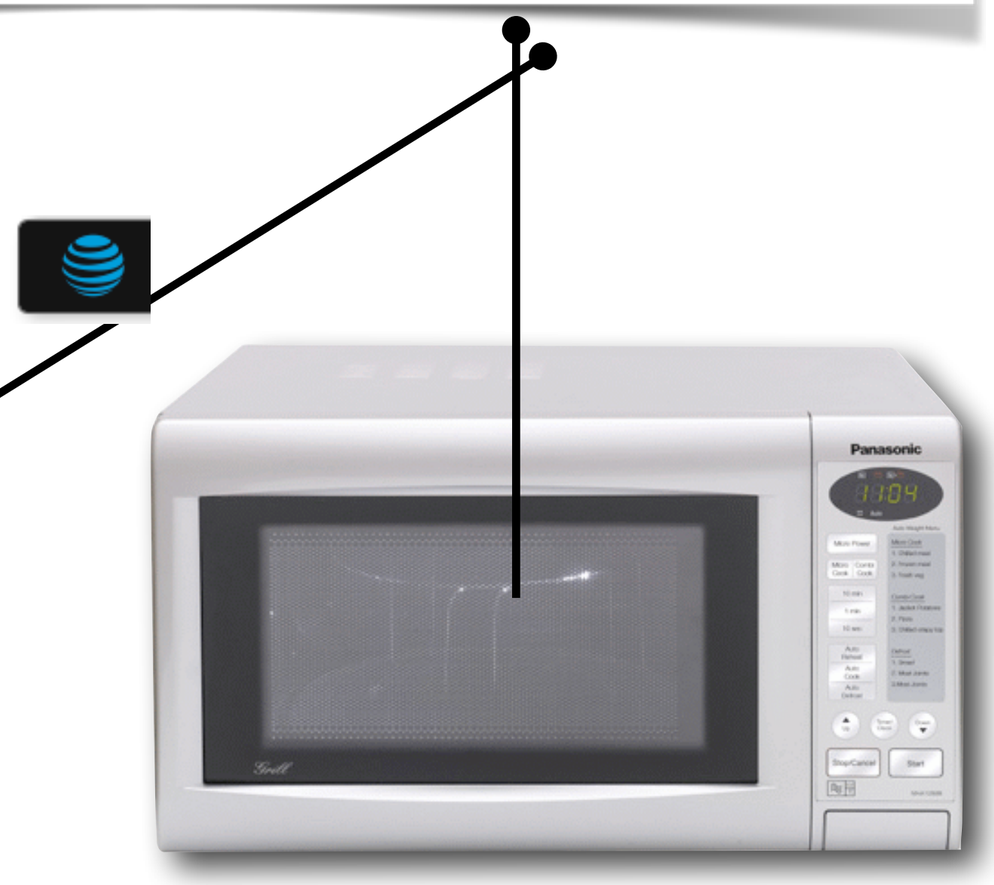


ATT cell phone frequencies of

~2 GHz

~15 cm

microwave ovens



the phone company

ATT Labs,
Crawford Hill, New Jersey

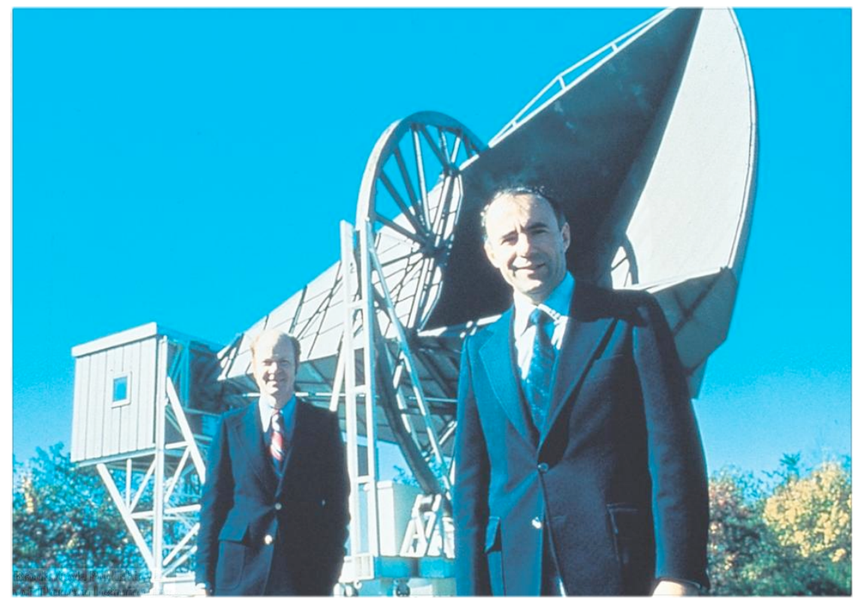
1963

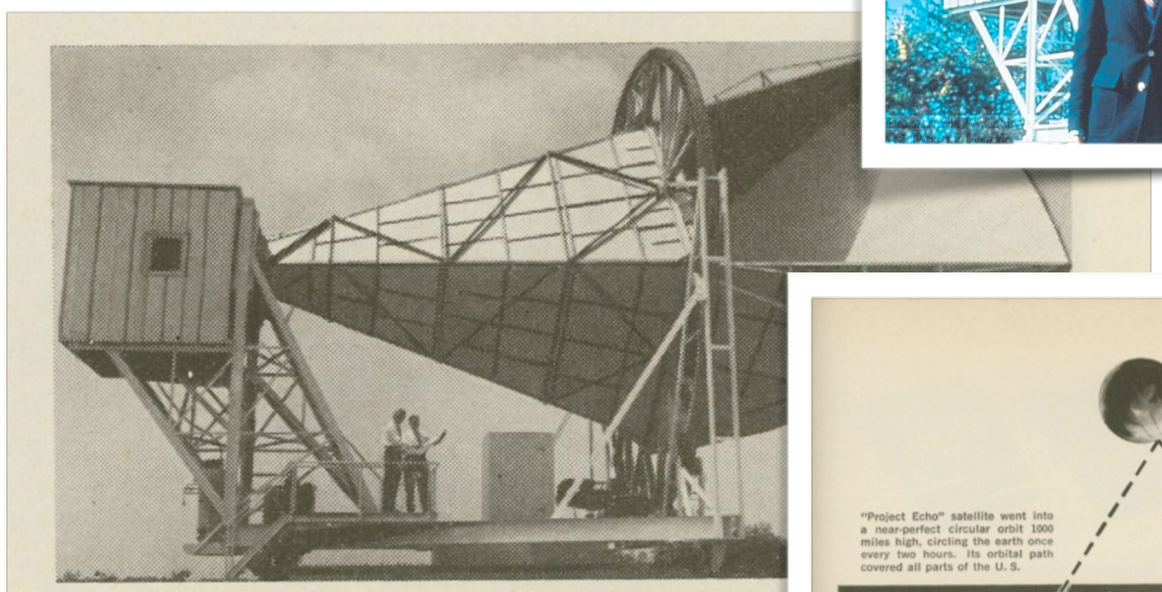
Arno Penzias

Robert Wilson

sensitive to wavelengths of 7.35 cm, 4000MHz

Echo





Giant ultra-sensitive horn-reflector antenna whic
bounced off the satellite. It is located at Bell Tele
Holmdel, New Jersey.

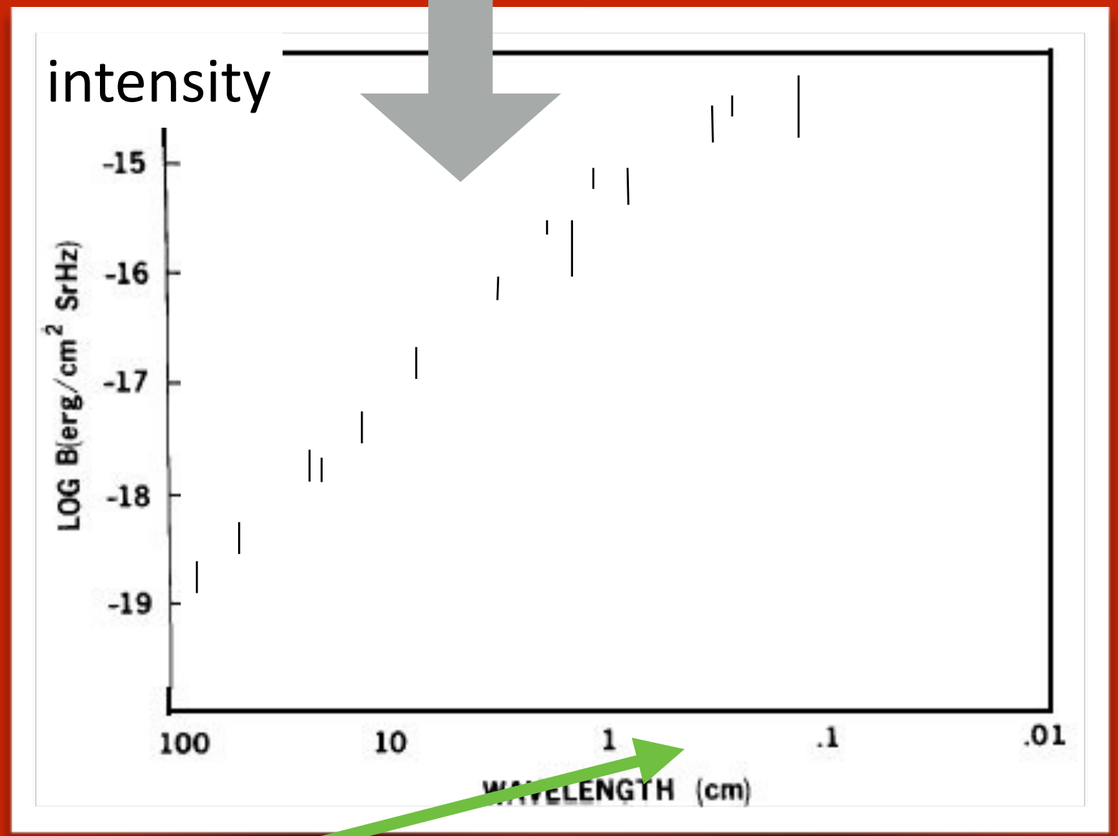
BELL TELEPHONE LAB
WORLD CENTER OF COMMUNICATIONS RESEA

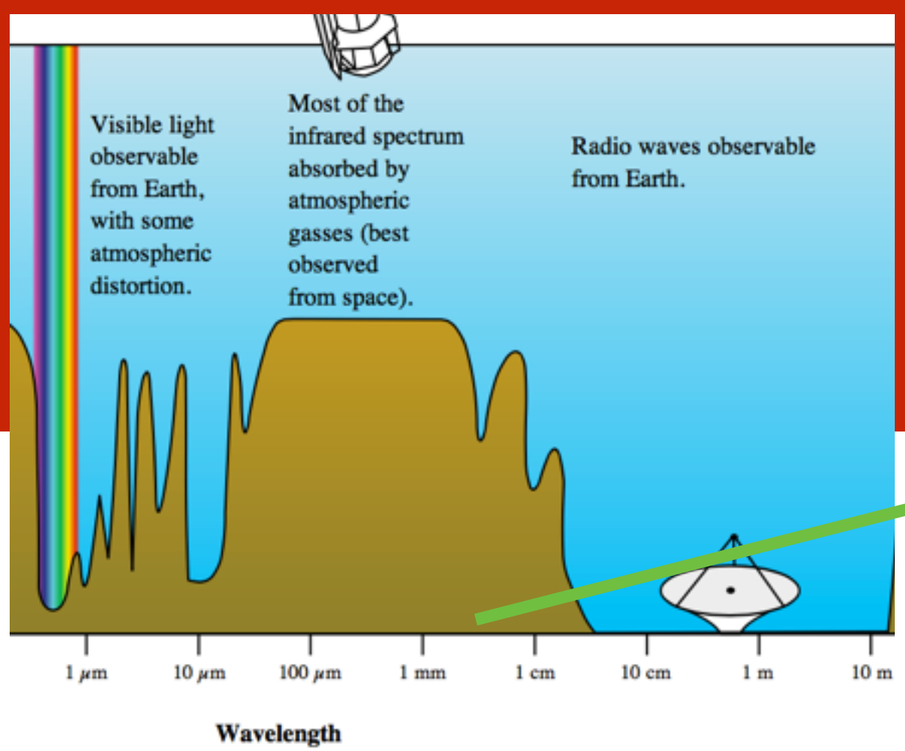
Penzias/Wilson wavelength

microwave hiss

everywhere...

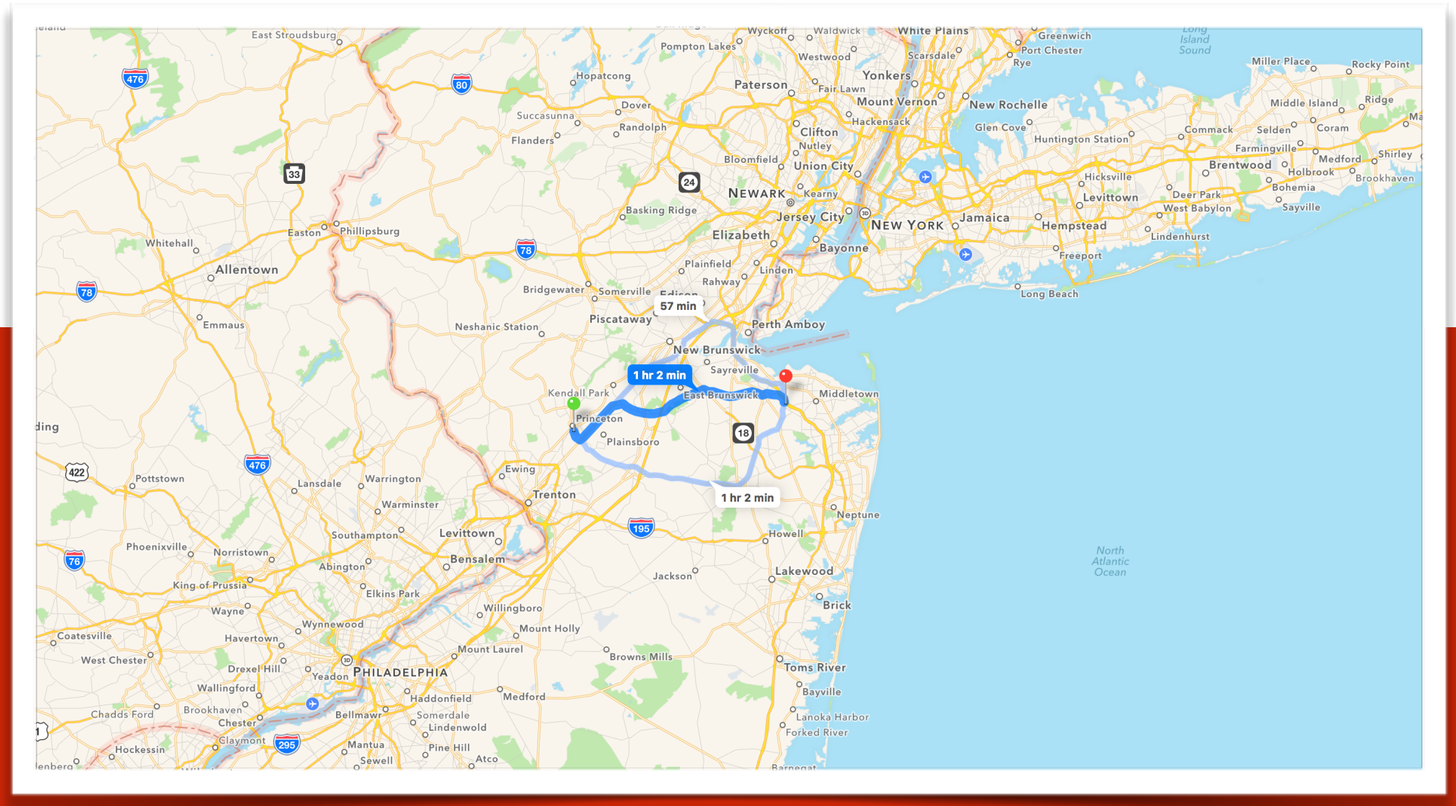
with a special frequency distribution





atmosphere becoming opaque

down the road



Jim Peebles and students, David Todd Wilkinson and Peter G. Roll

redid Gamow's calculation...forgetting that it had been done!

Robert Dicke was thinking of building a receiver

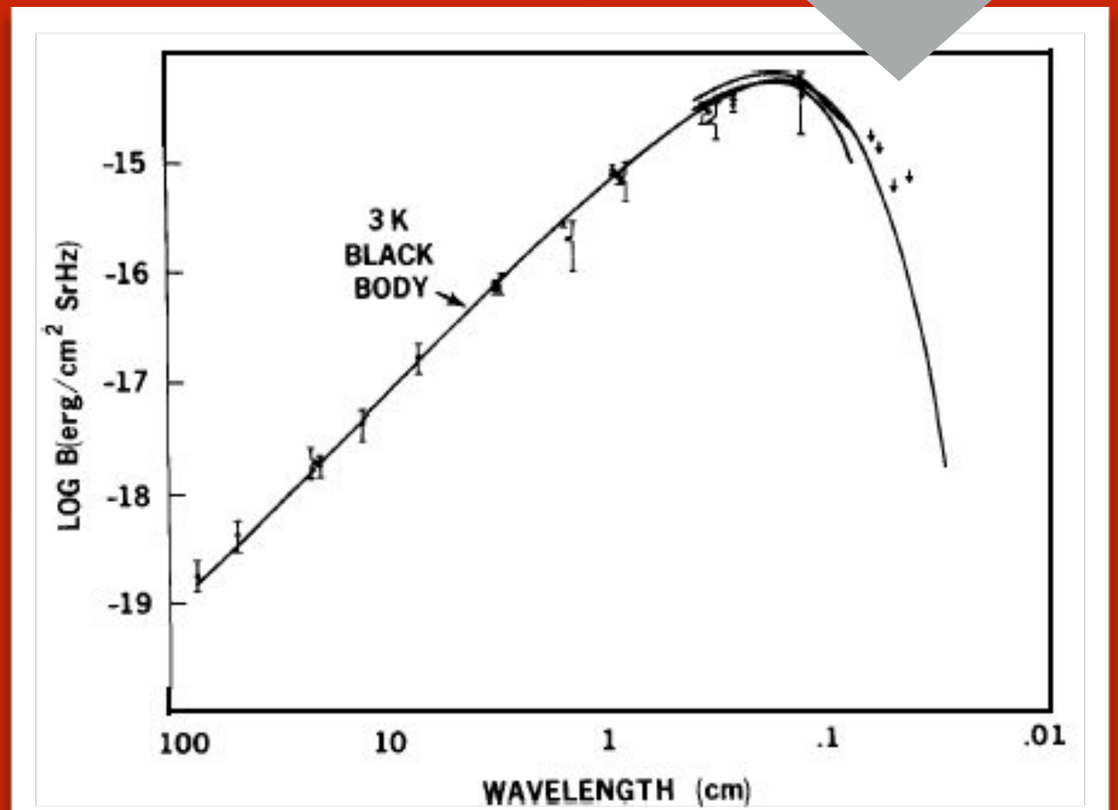
Penzias called Dicke...

balloons to get above atmosphere to measure infrared wavelengths

a blackbody spectrum

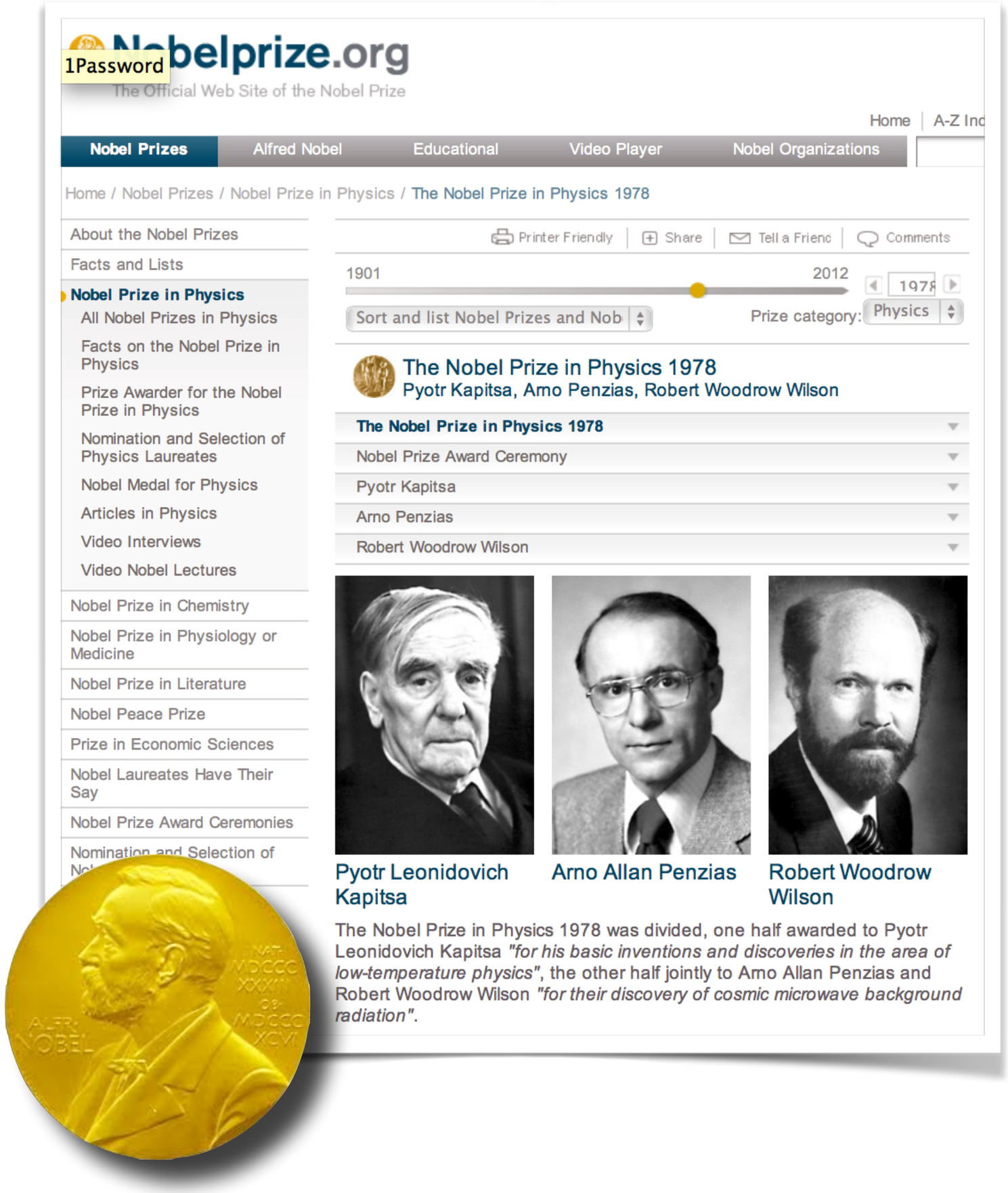
of ~3K above absolute zero

the peak is limited by the atmosphere



Penzias and Wilson 1978

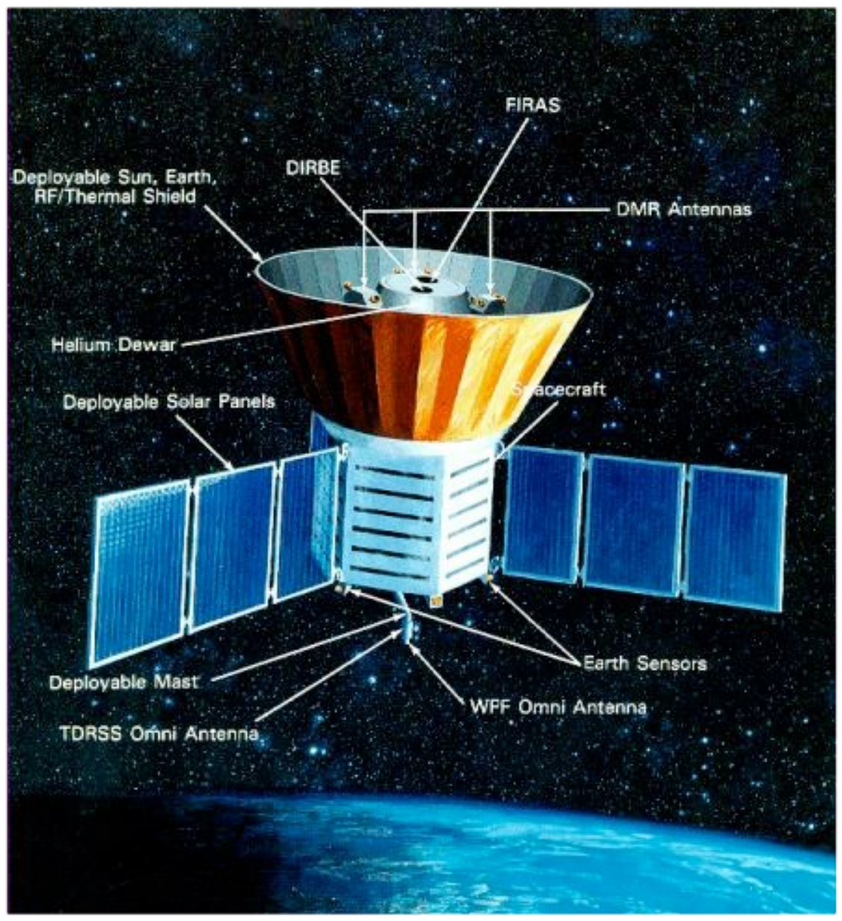
gave credit to the deceased George Gamow.



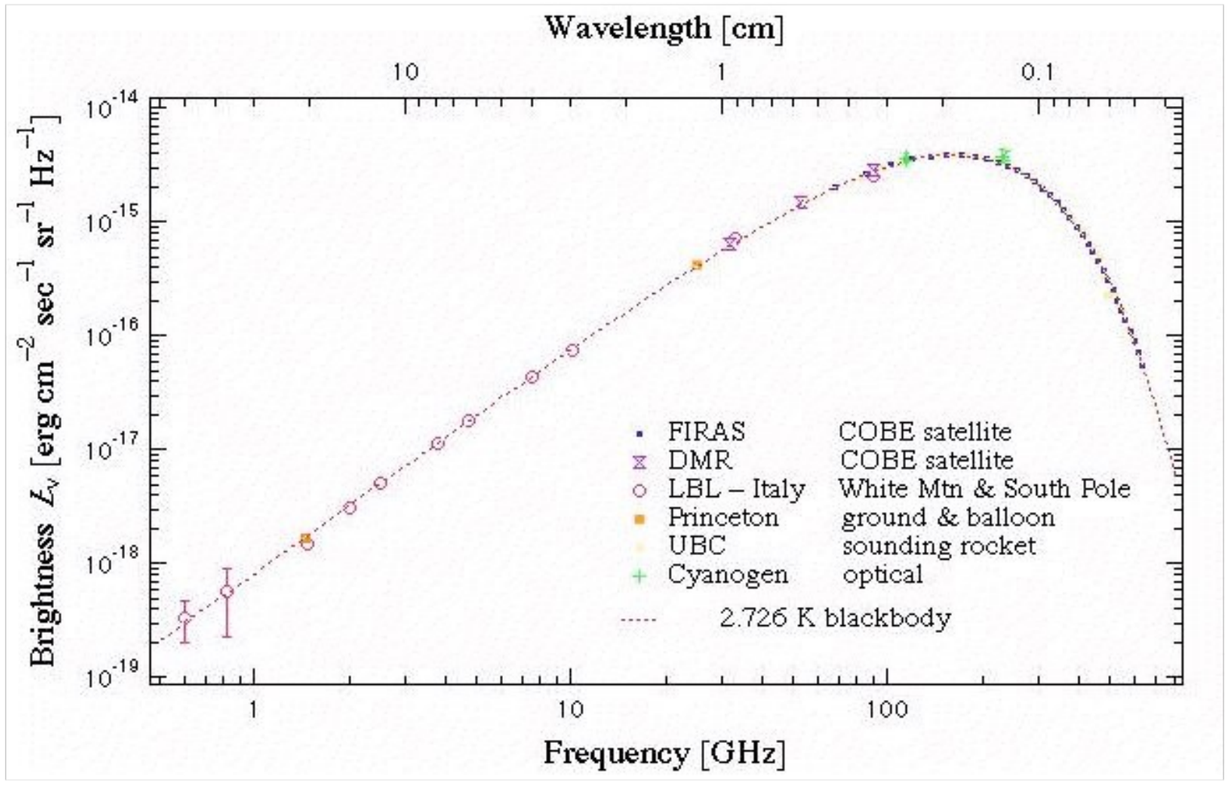
The Cosmic Background Explorer (COBE)

mission launched in 1989 to measure the CBM

COBE measured E&M radiation as a function of frequency outside of the earth's atmosphere



showing precisely the blackbody spectrum for a temperature of 2.726K



But they went further

and mapped the “sky” in various wavelengths — temperatures

and built “false-color” thermo-maps — pioneered a Method

This is the newest one

Planck...gives you the idea

gotten
better
and
better

An all-sky image (like a Mercator projection) of the sky…

John Mather and George Smoot

COBE principals

Nobelprize.org

The Official Web Site of the Nobel Prize

Home | A-Z Inc

Nobel Prizes | Alfred Nobel | Educational | Video Player | Nobel Organizations

Home / Nobel Prizes / Nobel Prize in Physics / The Nobel Prize in Physics 2006

About the Nobel Prizes
Facts and Lists
Nobel Prize in Physics
- All Nobel Prizes in Physics
- Facts on the Nobel Prize in Physics
- Prize Awarder for the Nobel Prize in Physics
- Nomination and Selection of Physics Laureates
- Nobel Medal for Physics
- Articles in Physics
- Video Interviews
- Video Nobel Lectures

Nobel Prize in Chemistry
Nobel Prize in Physiology or Medicine
Nobel Prize in Literature
Nobel Peace Prize
Prize in Economic Sciences
Nobel Laureates Have Their Say
Nobel Prize Award Ceremonies
…ion of

Printer Friendly | Share | Tell a Friend | Comments

1901 — 2012 — 2006

Sort and list Nobel Prizes and Nob… | Prize category: Physics

The Nobel Prize in Physics 2006
John C. Mather, George F. Smoot

The Nobel Prize in Physics 2006
Nobel Prize Award Ceremony
John C. Mather
George F. Smoot

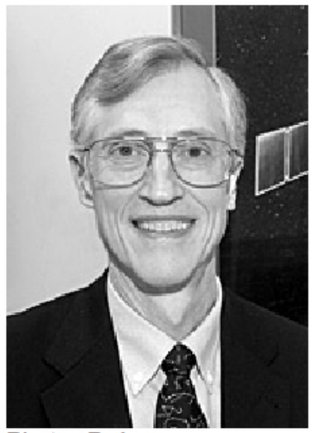


Photo: P. Izzo

John C. Mather

Photo: J. Bauer

George F. Smoot

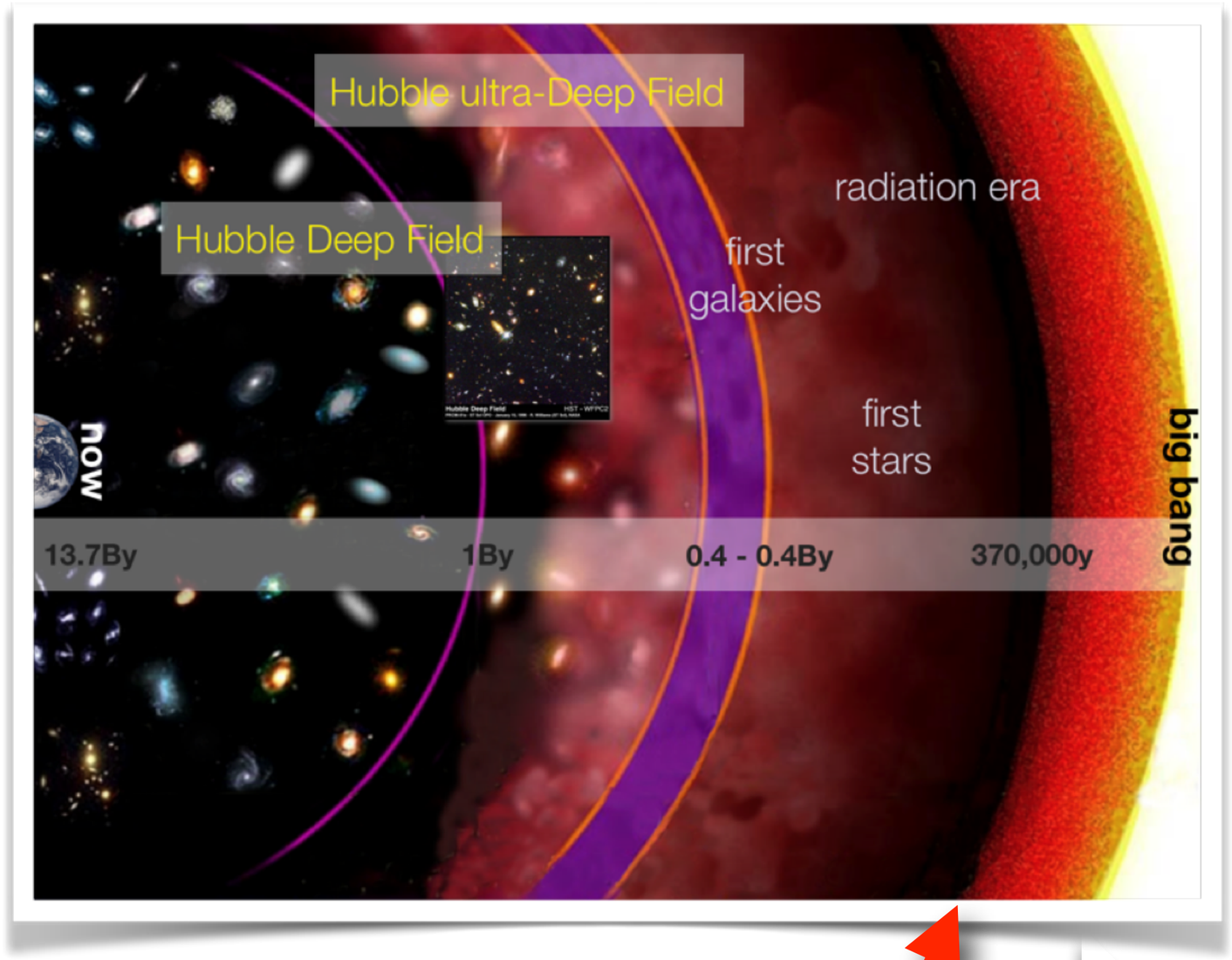
The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

this is very convincing

Heck. This is amazing!

We can see the left-over, cooled radiation from the BB

everywhere in the cosmos at the same temperature



can’t “see” any further back than this

now we know that the universe had a beginning

Stars are finite in number, and finite in lifetime - they have not been shining forever

you can comfirm that tonight.

the initial hot radiation...now cool and measured to be uniform

and everywhere

It’s smooth...

universe is isotropic and homogeneous

That’s good!

It’s smooth...

universe is isotropic and homogeneous

That’s bad! We’re here! Our Stuff is here!

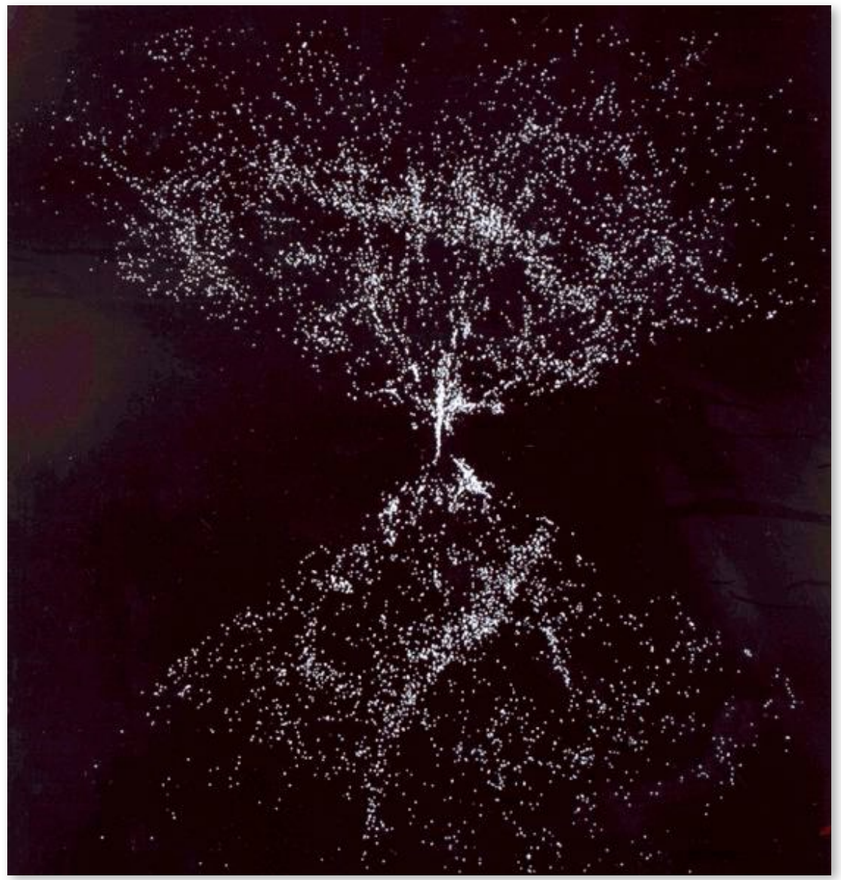
stay tuned.

There *is* structure in the universe

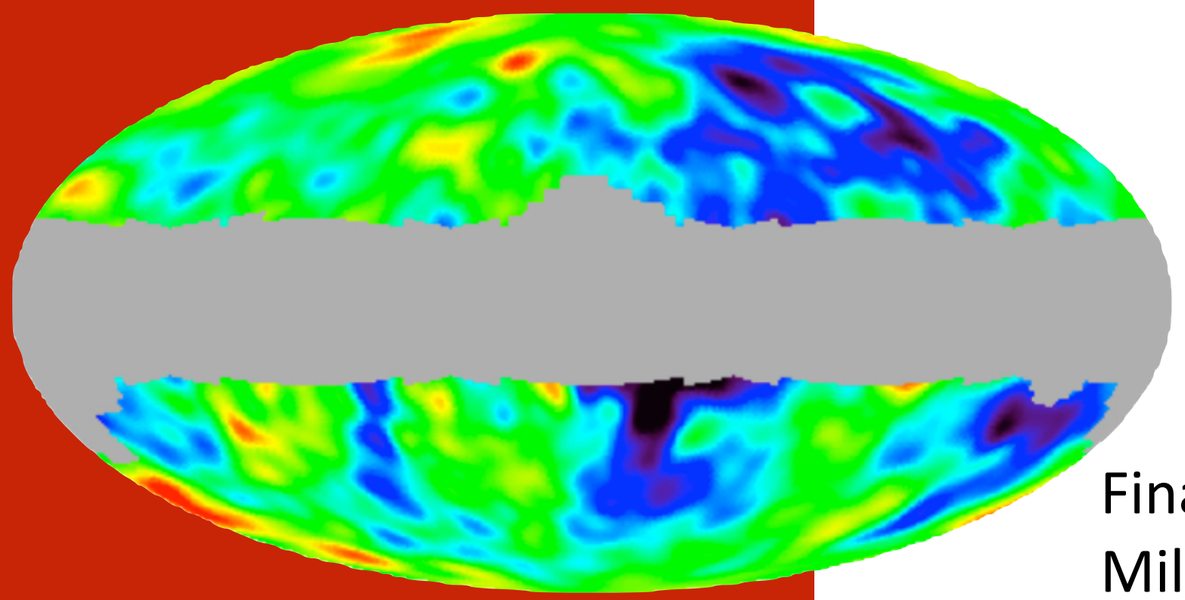
galaxies

planets

you, me



And, that's true. There is non-random structure: These filament-like strands are combinations of 11,000 galaxies (MW at the center).



Final 4 year exposure of COBE with a model of the Milky Way microwaves subtracted

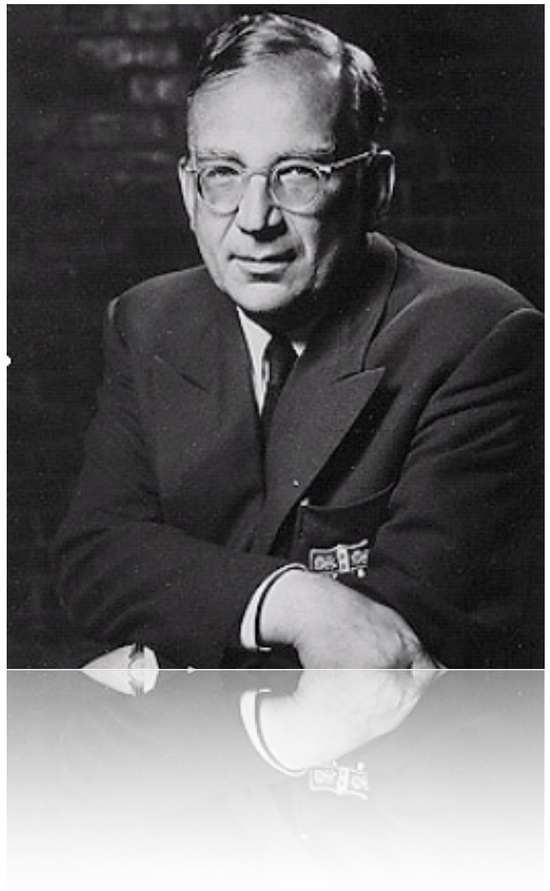
Helium.

about 3 minutes after BB

George Gamow

tried to make the Big Bang make elements

failed for all but H, its isotopes, and He



Remember the isotopes:

H 1 proton

D 1 proton + 1 neutron

Deuterium

^{3}He 2 protons + 1 neutron

“Helium three”

^{4}He 2 protons + 2 neutrons

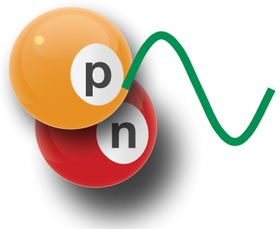
“Helium four” - regular He

very tightly bound together

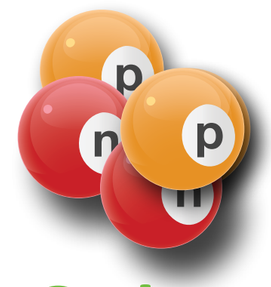
~3 min ABB, cool enough for protons & neutrons to fuse

$p + n \rightarrow$ deuterium $(np) + \gamma$

$(np) + (np) \rightarrow {}^3\mathrm{He} + n$



${}^3\mathrm{He} + (np) \rightarrow {}^4\mathrm{He} + p$



a delicate chain...correlated temperatures & densities

a critical test: it was all over within a minute.

All natural deuterium must have come from the Big Bang

* stay tuned

‘‘primordial Helium’’ and Deuterium

Accounting for the Big Bang production of light elements by mass-fractions:

H ~ 73%

He ~ 24% → cannot have come from stars

D ~0.01% cannot have come from stars

equal in all directions

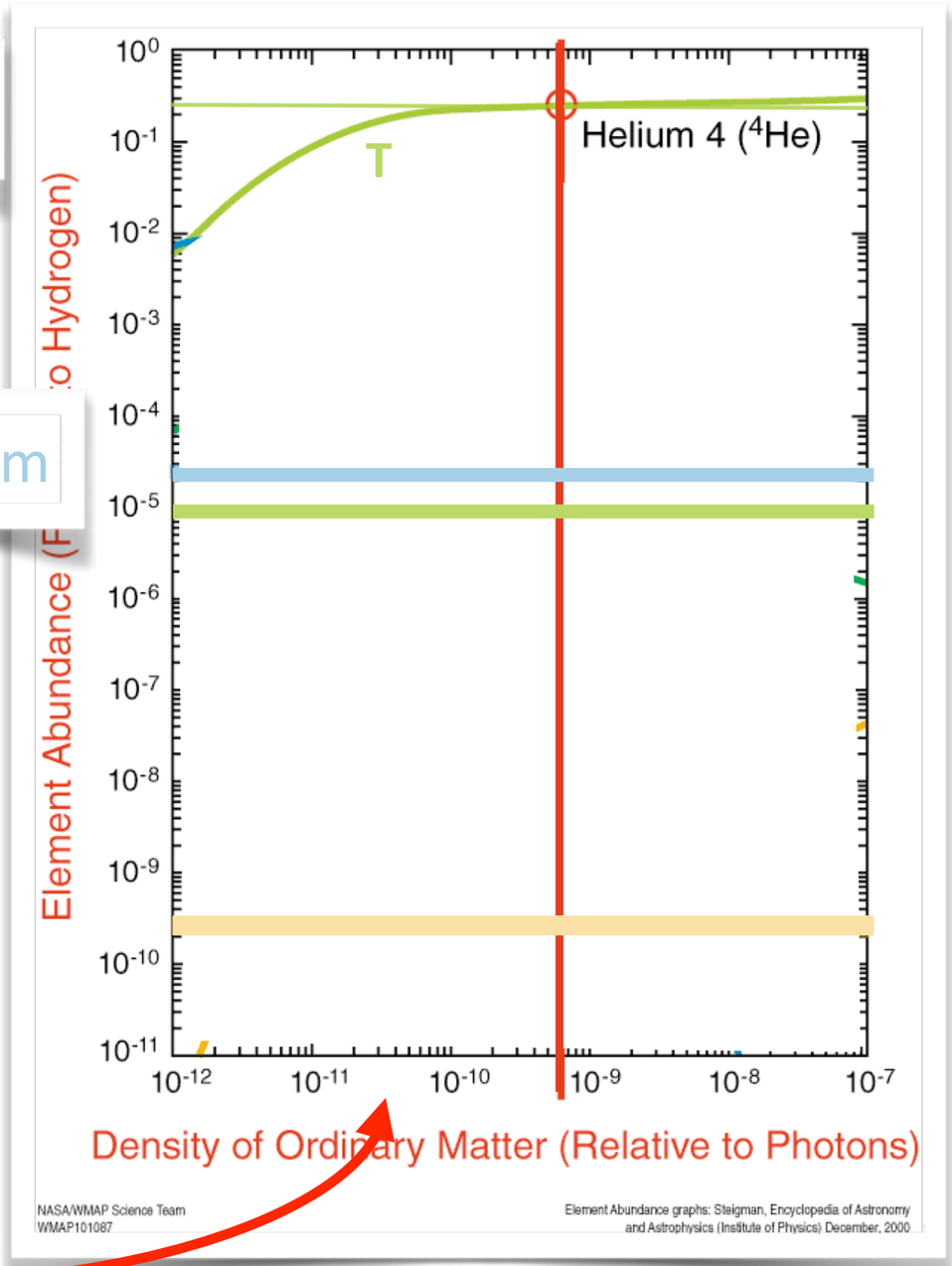
Theory Predictions

data, ^{4}He

data, Deuterium

data, ^{3}He

data, Li



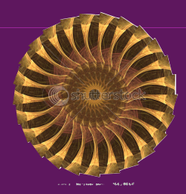
essentially: $\frac{\#\ \text{baryons}}{\#\ \text{photons}}$

The Hot Big Bang Model is very highly and precisely confirmed.

From 10^{-10} seconds after the BB

our understanding of the Universe is standard physics

particle: **the universe**

symbol:    $

charge: 0

mass: 6×10^{51} kg, size? ~46 BLy

spin: ?

category: the one we've got

so. about the Universe

How old is the Universe?

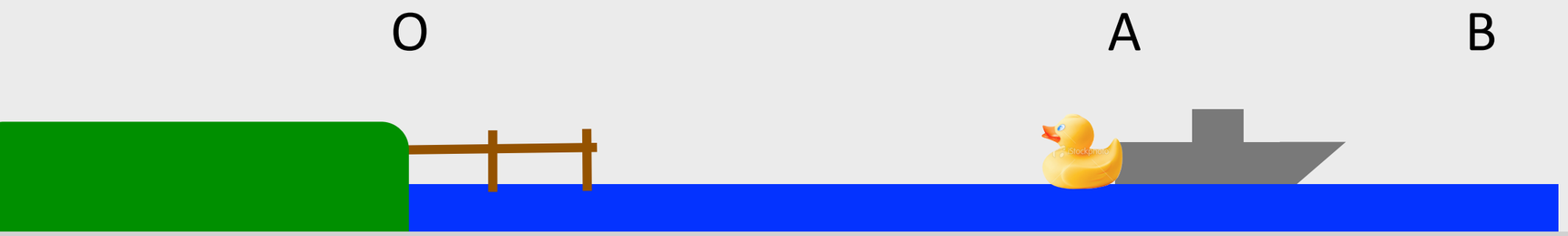
We're sure of that: 13.82 ±0.050 B years

How big is the Universe?

Thaaaat's a toughy: multiple answers depending on how you interpret it!

You could say "13.82 Light Years" in radius.

From this way of thinking:



How far away is the boat? OA? ...like the 13.82 B years number.

so. about the universe

How old is the universe?

We're sure of that: 13.82 ±0.050 B years

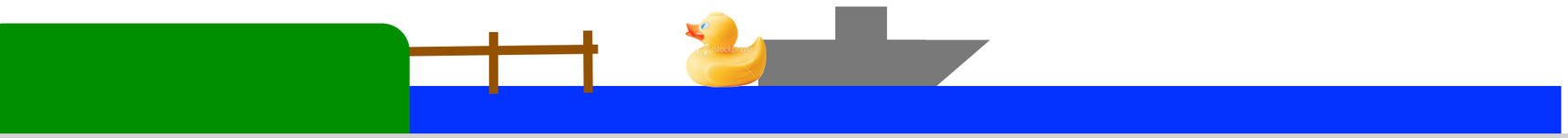
How big is the universe?

Thaaaat's a toughy: multiple answers depending on how you interpret it!

You could say "13.82 Light Years" in radius.

From this way of thinking:

O A B C



How far away is the boat? OA? ...like the 13.82 B years number.

OB? ...you know that the boat is at B when ducky comes home.

so. about the universe

How old is the universe?

We're sure of that: 13.799 ±0.050 B years

How big is the universe?

Thaaaat's a toughy: multiple answers depending on how you interpret it!

You could say "13.82 Light Years" in radius.

From this way of thinking:

How far away is the boat? OA? ...like the 13.82 B years number.

OB? ...you know that the boat is at B when ducky comes home.

If the ocean stretches over time...you might even say that it's OC away.

In these "co-moving coordinates"...the universe is about 46 BLy big.

I tend towards this one.

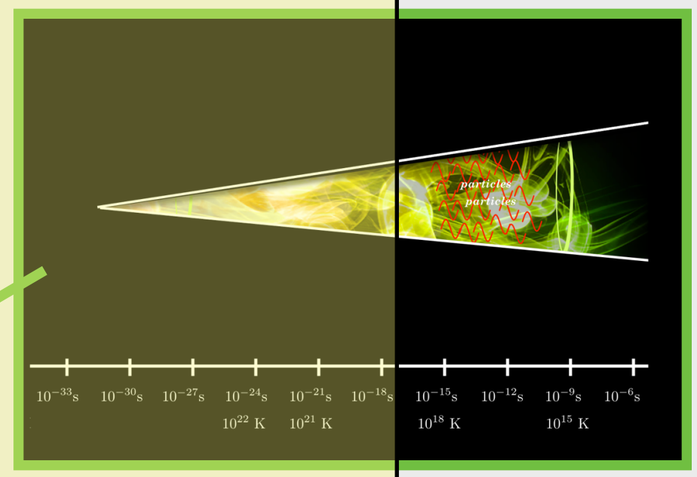
our observable patch might be only a small part of a larger universe

Size of the Observable Universe?

Radius of Observable Universe, meters

10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}

Hot Big Bang



10^{-40} 10^{-30} 10^{-20} 10^{-10} 1 10^{10}

Time, seconds

But. There are a few issues with the Standard Model of Cosmology

famously called:

1. The Horizon Problem (or: Smoothness Problem)
2. The Flatness Problem (or: Fine Tuning Problem ~ the Age problem)
3. The Structure Problem
4. The Antimatter Problem (or the Baryon Problem)
5. The Relic Problem (or the Monopole Problem)

a word of warning

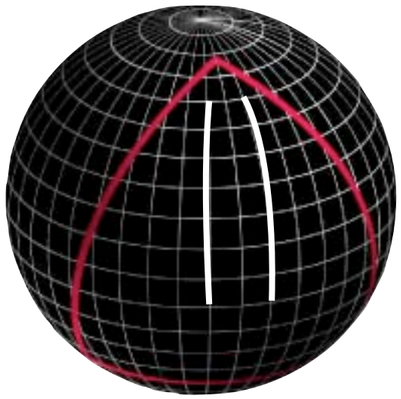
colloquially, we might refer to: “Why is X the way it is?”

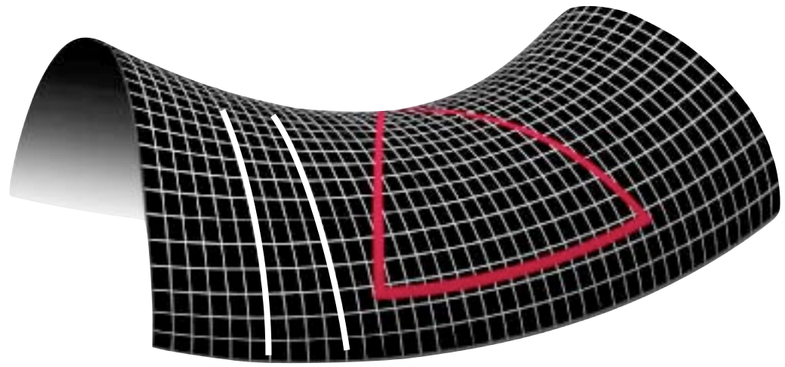
scientifically, we almost always mean: “How is X the way it is?”

Why questions are usually not physics questions.

curvature, "k" – hypervolumes

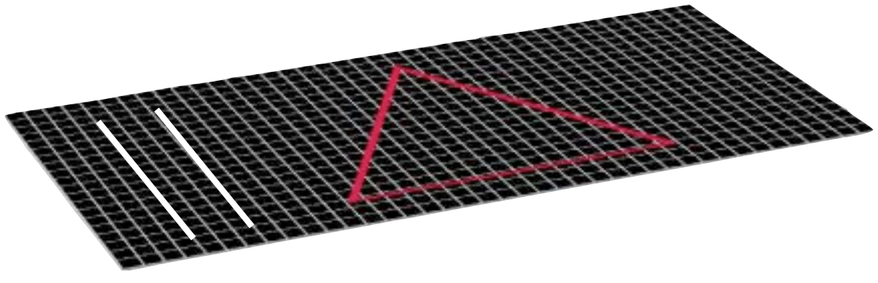
$k = +1$,
positive curvature
finite, unbounded





$k = -1$, negative curvature
infinite, unbounded

$k = 0$, no curvature
infinite, unbounded



These 3 are the only geometries that can be homogeneous and isotropic

want to know the curvature of the Universe

linked to the fate of the Universe

and to its origins

curvature of the universe

will be formed by the distribution of mass, energy, and pressure

curvature, k

would depend on:

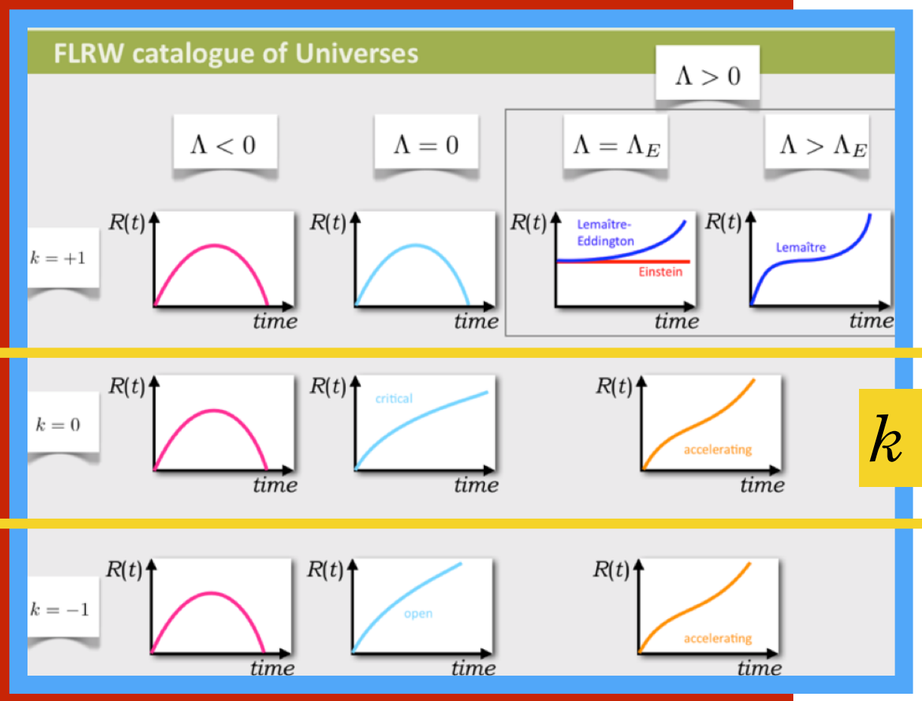
Hubble Constant, H

Mass density, ρ

Like Goldilocks:

if H and ρ are just right...

the universe will be flat



$k = 0$ ....would mean flat.

follow along:

The Friedman equation relates curvature of the universe to its density, ρ

$$\frac{kc^2}{R^2} \propto \_\_\_\_\_$$

A flat universe means that $k = \_\_\_$

So: $k = \frac{C\rho}{H^2} - 1 = 0$

Solve for ρ: $\rho = \rho_c = \_\_\_\_\_$ $\rho_c = \_\_\_\_\_$ H atoms/m^3

Now treat the density as a measurable parameter and relate it to that particular critical density

$\Omega_m(t) = \_\_\_\_\_$ $\frac{kc^2}{R^2} \propto H^2 (\quad)$

So a flat universe means that $\Omega_m(t) = \_\_\_\_\_$

from Friedman Equation

gathering constants...

$$\frac{kc^2}{R^2} \propto H^2 \left(\frac{C\rho}{H^2} - 1 \right) = H^2 \left(\Omega_m - 1 \right)$$

Want flat? $k = 0$ so: $\frac{C\rho}{H^2} - 1 = 0$

call $\rho_c = \frac{H^2}{C}$

"Critical density"...
for the current value of *H*...
$\rho_c \sim 10^{-26}\ \mathrm{kg\ m^{-3}}$

about 5 Hydrogen atoms per cubic meter

define the "density parameter:

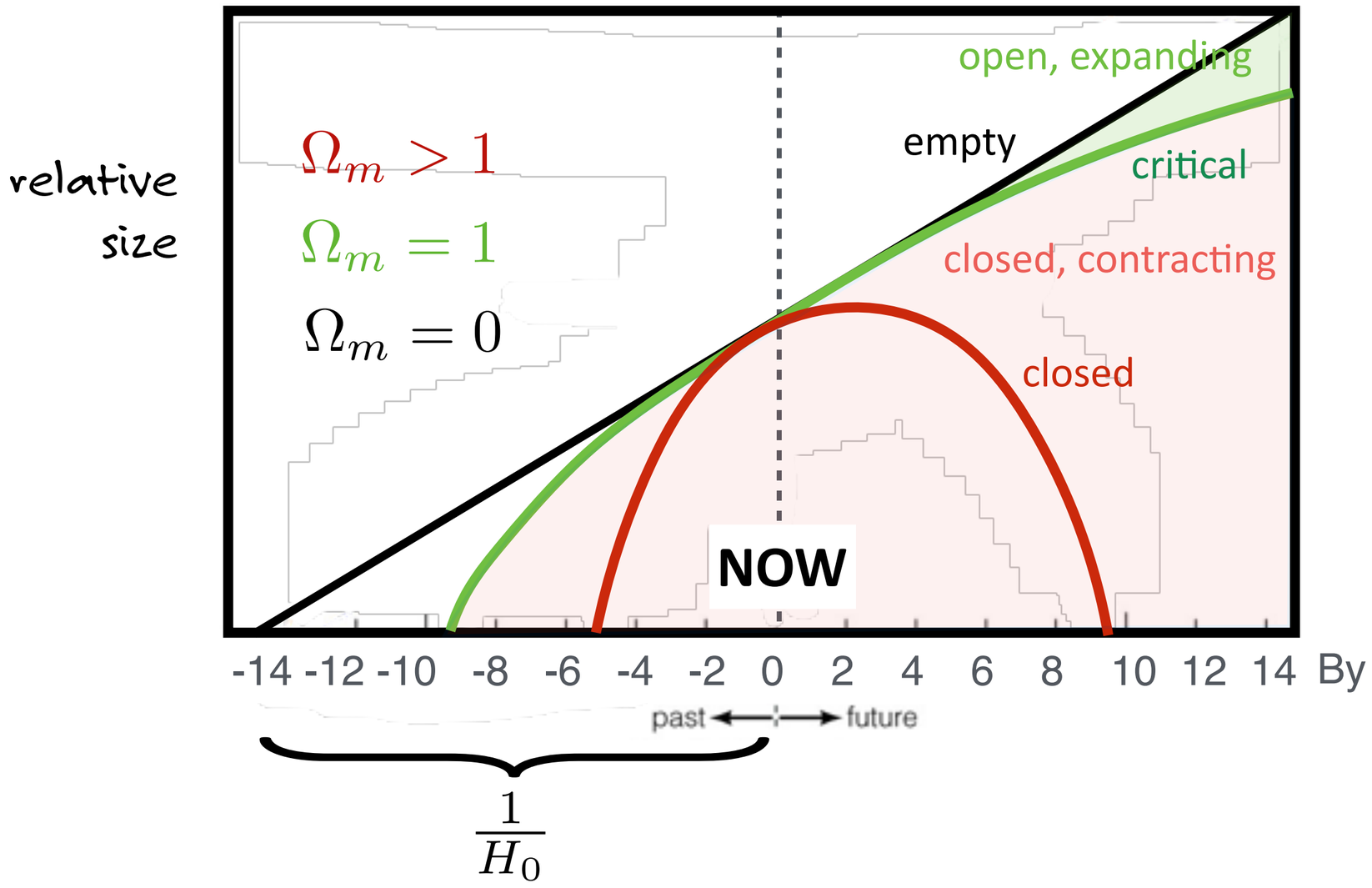
$$\Omega_m(t) = \frac{\rho}{\rho_c}$$ Density parameter for matter

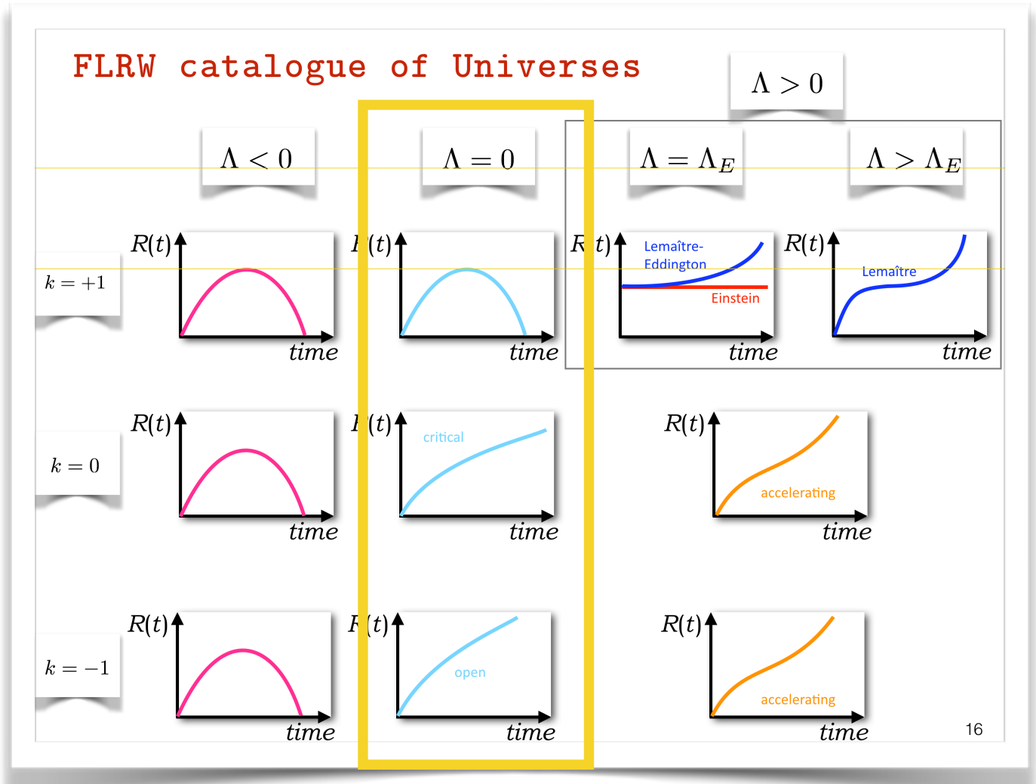
$\Omega_m(t) = 1$ is the boundary between flat and either closed or open geometries.

Competition

Between expansion (Hubble Parameter)

Gravitation (Density)





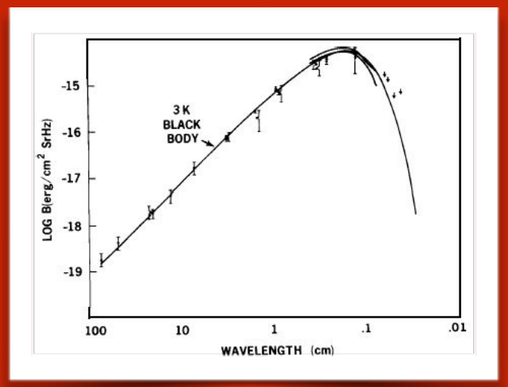
what can be measured?

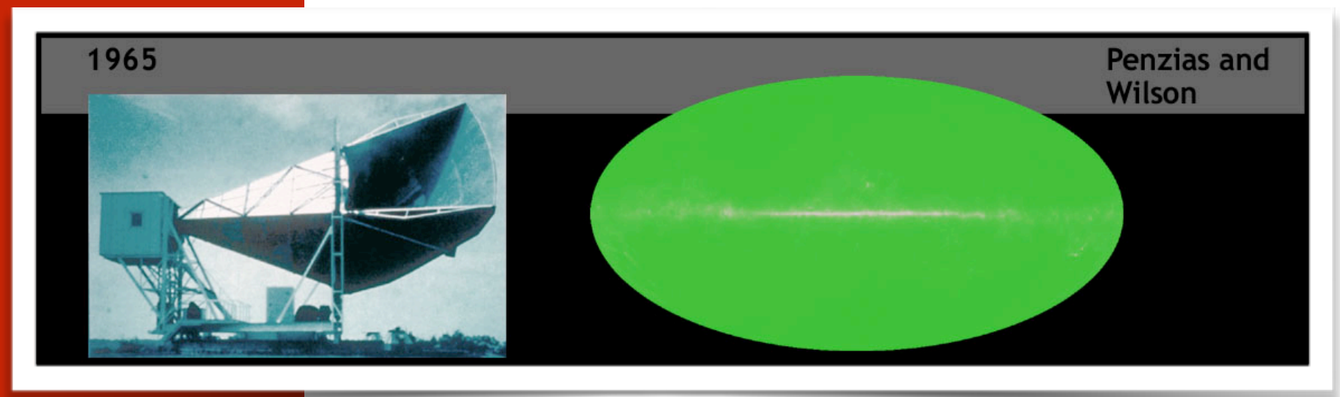
many quantities

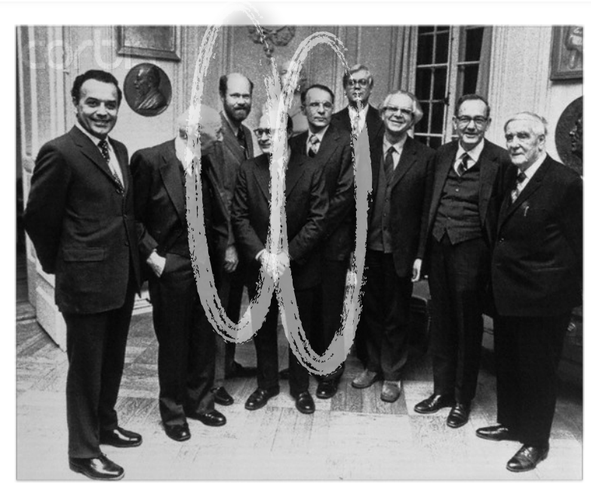
1. **Hubble Constant**
   from velocities of far-away galaxies

2. **large-scale densities**
   motions of galaxies
   the Cosmic Microwave Background, CMB

3. **“baryon densities”**
   survey of stuff that shines...mostly Hydrogen
   from the CMB







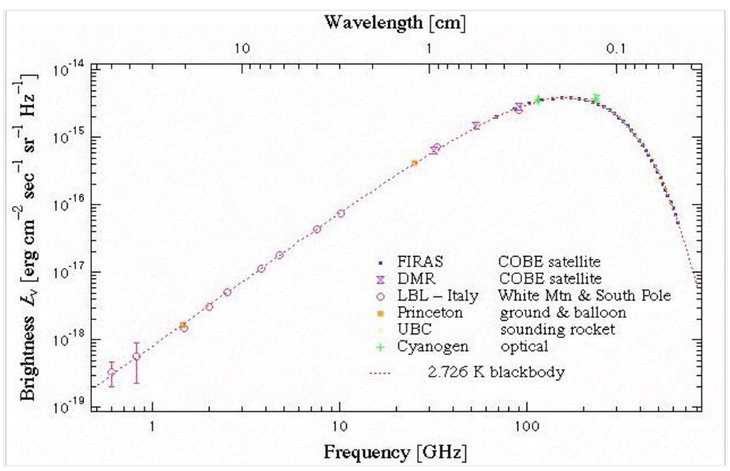
Robert Wilson Anro Penzias, 1978

CMB:

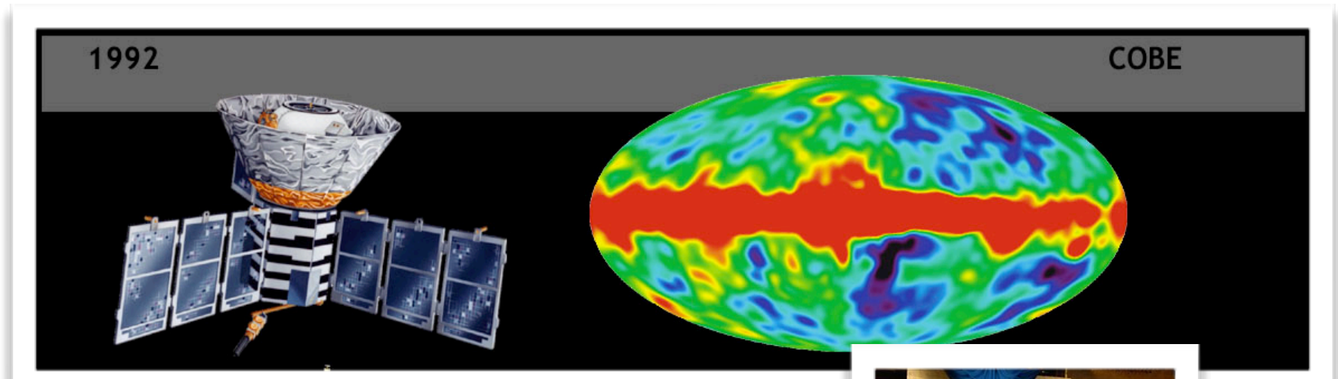
1965 - 1992

this is the point of "last scattering"

of the photons at 370,000 years ABB

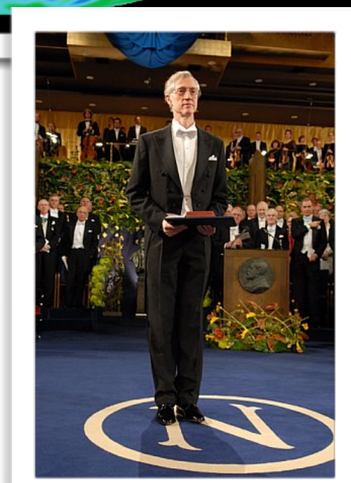


Penzias and Wilson, from the phone company.



could distinguish about 7°

COBE...



George Smoot and John Mather, 2006

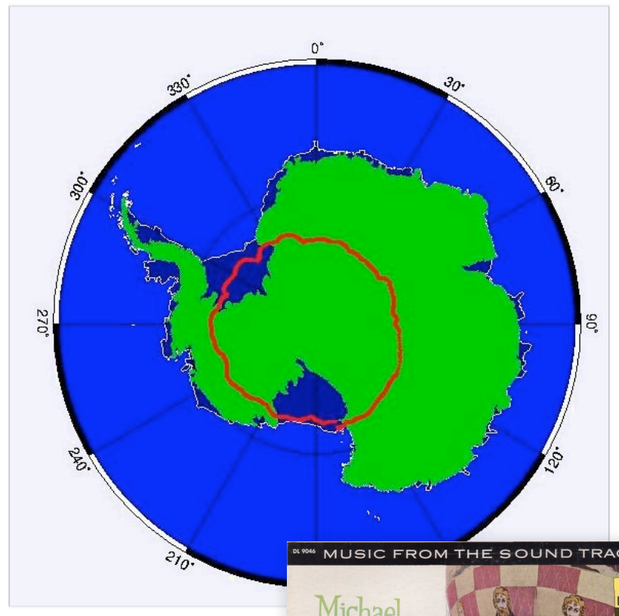
problem #1

the flatness problem.

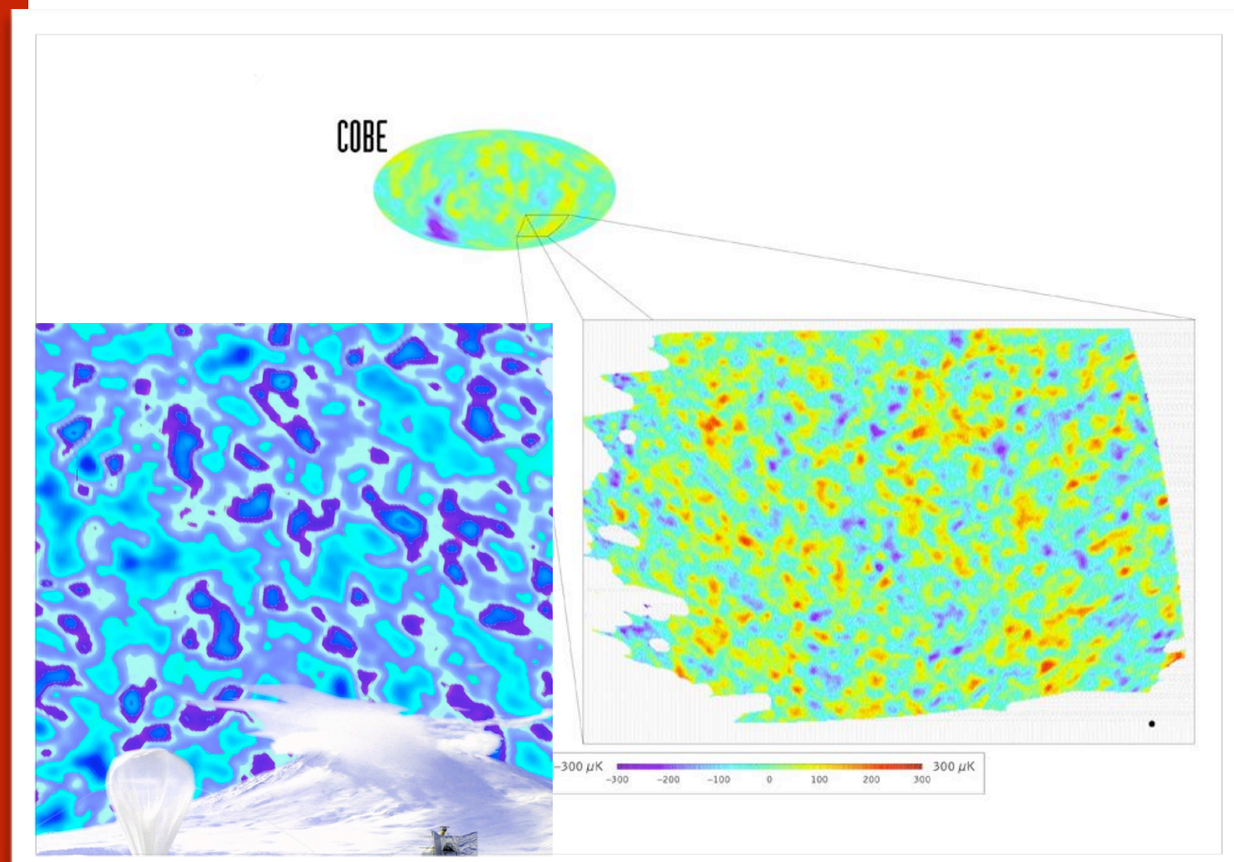
CMB, 1999

Balloon **O**bservations **O**f **M**illimetric **E**xtragalactic **R**adiation **ANI**sotropy and **G**eophysics...

BOOMERANG

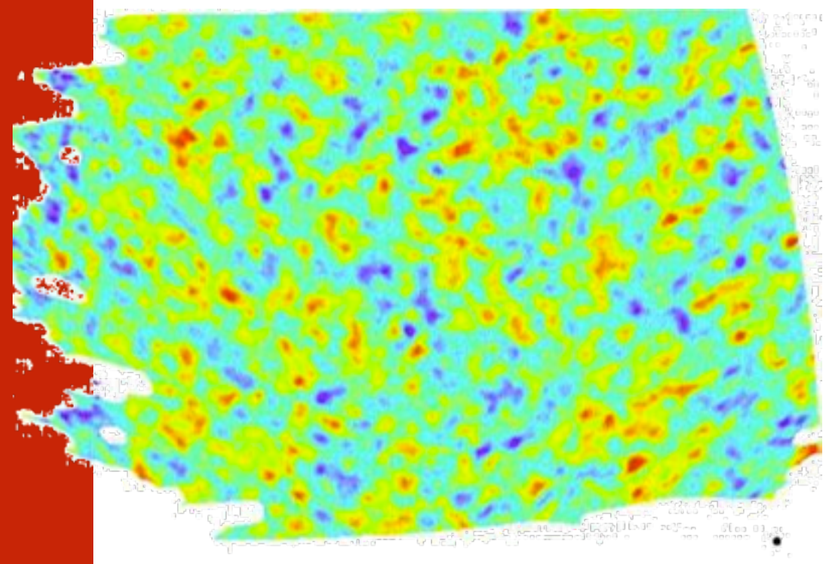


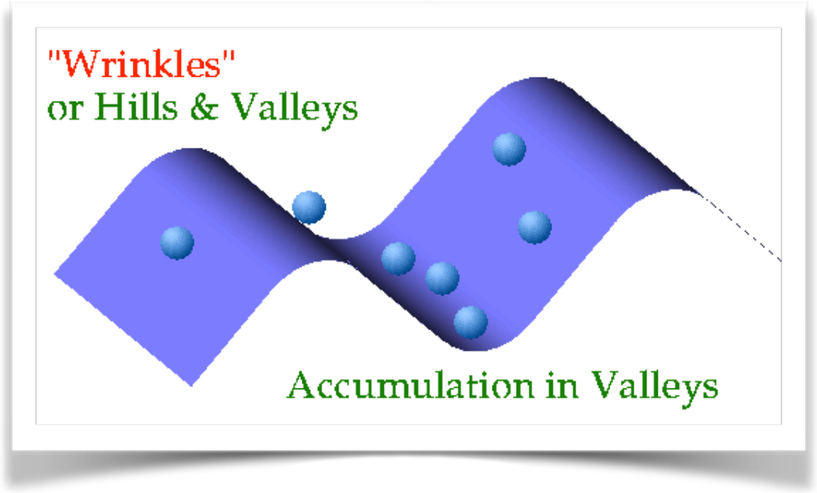
Around the world in 10 days...from Antarctica



could distinguish about 0.3°

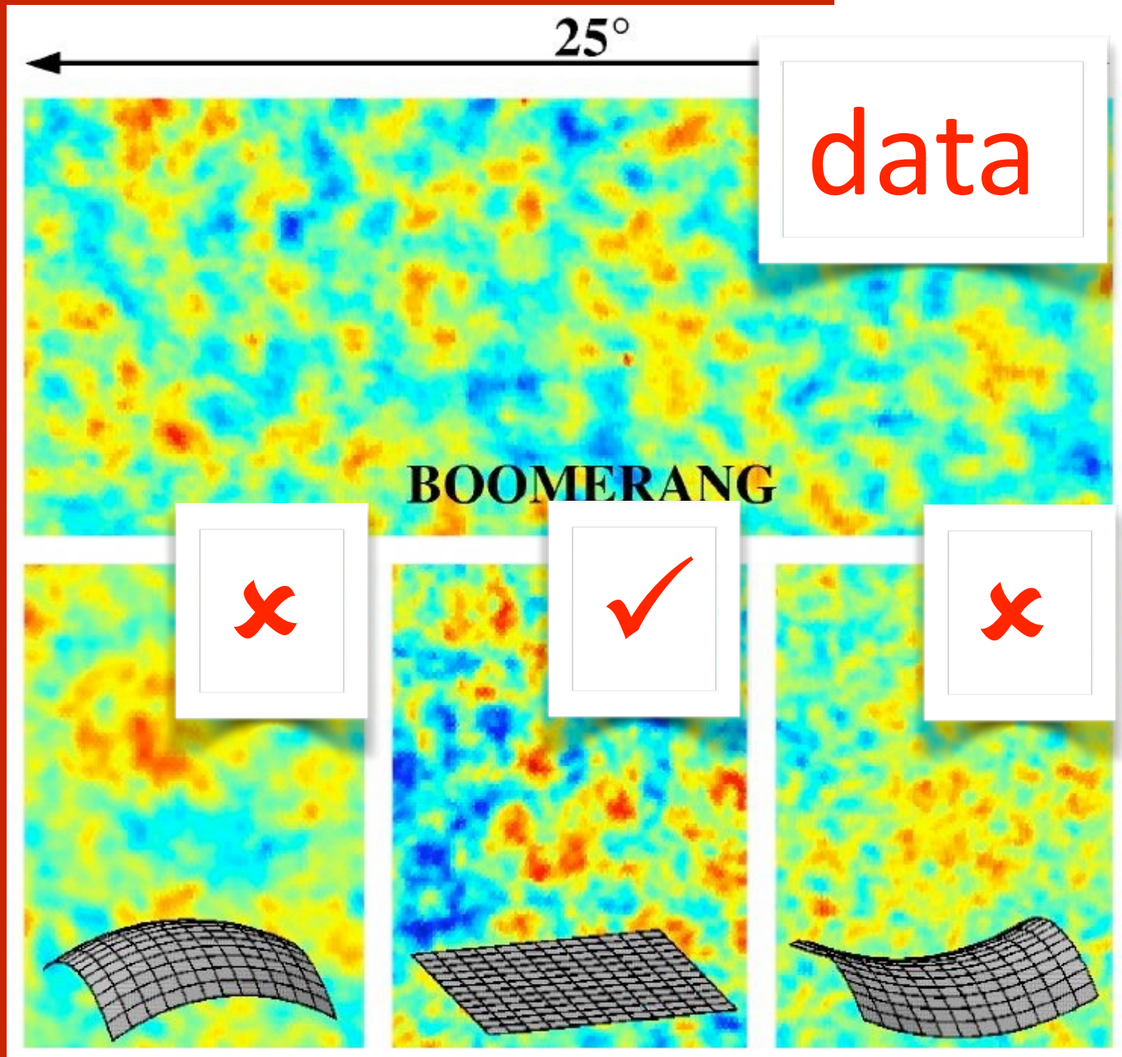
the temperature fluctutation pattern is a measurement of curvature

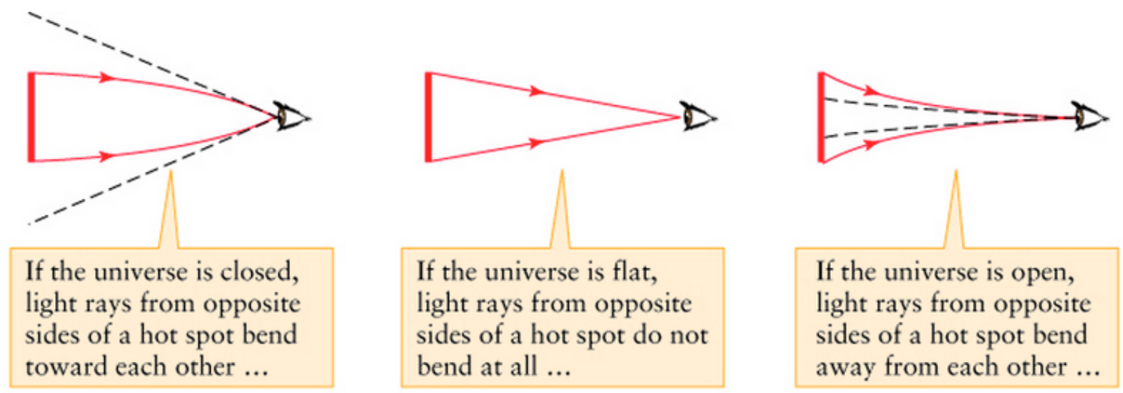




“high” temperature means high density regions
“low” temperature means low density regions

Red = Hotter than average by 300 microKelvin.
Blue = Cooler than average by 300 microKelvin.





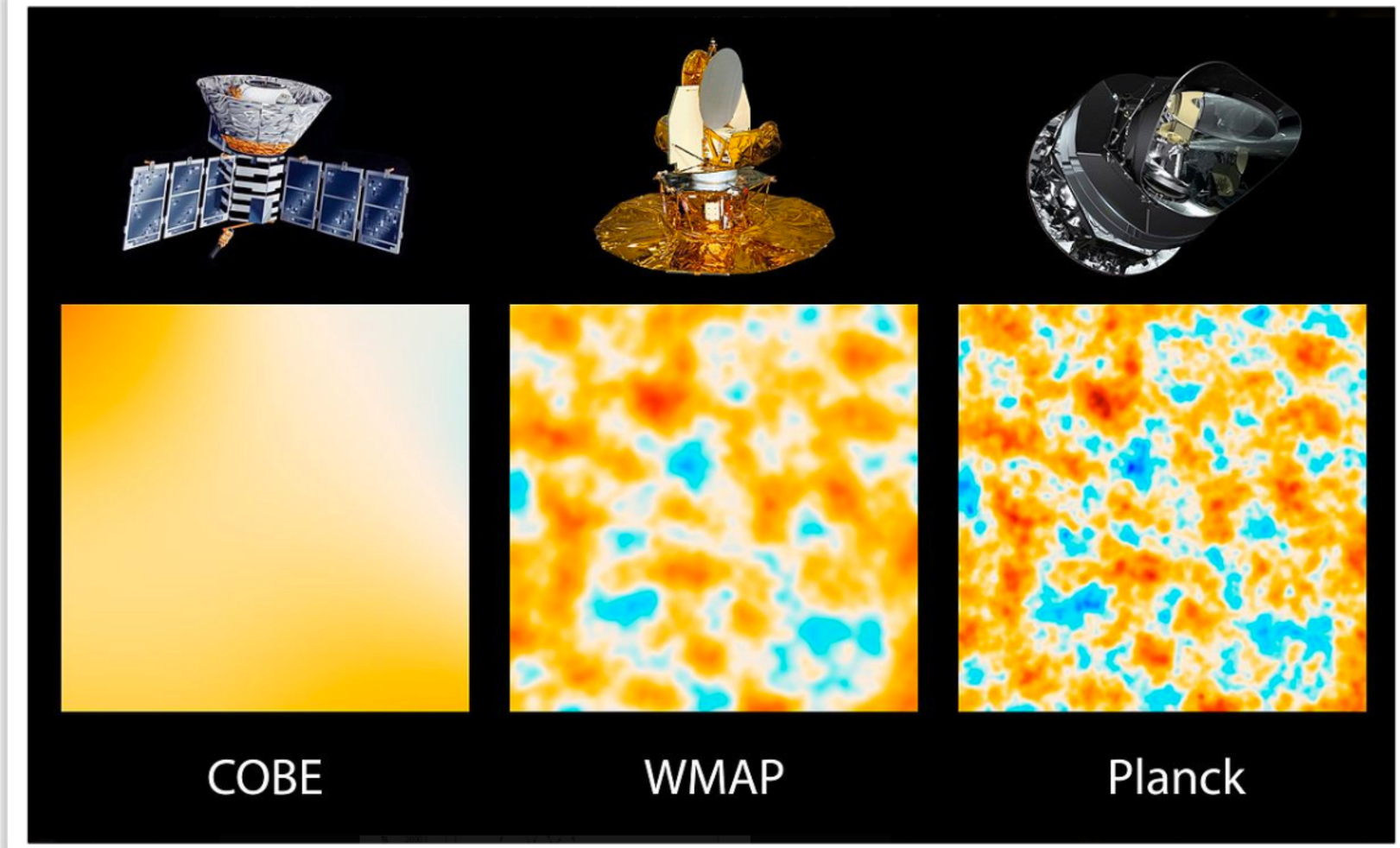
Can be modeled for that moment of last scattering...

The result? **A flat geometry was determined.**

So we’d better have: $\Omega_m(t) = 1$

This measurement has evolved

Cosmology is actually now a precision science.



COBE's resolution was 7 degrees.

Planck's resolution is roughly 1/12 of a degree

CMB measurements

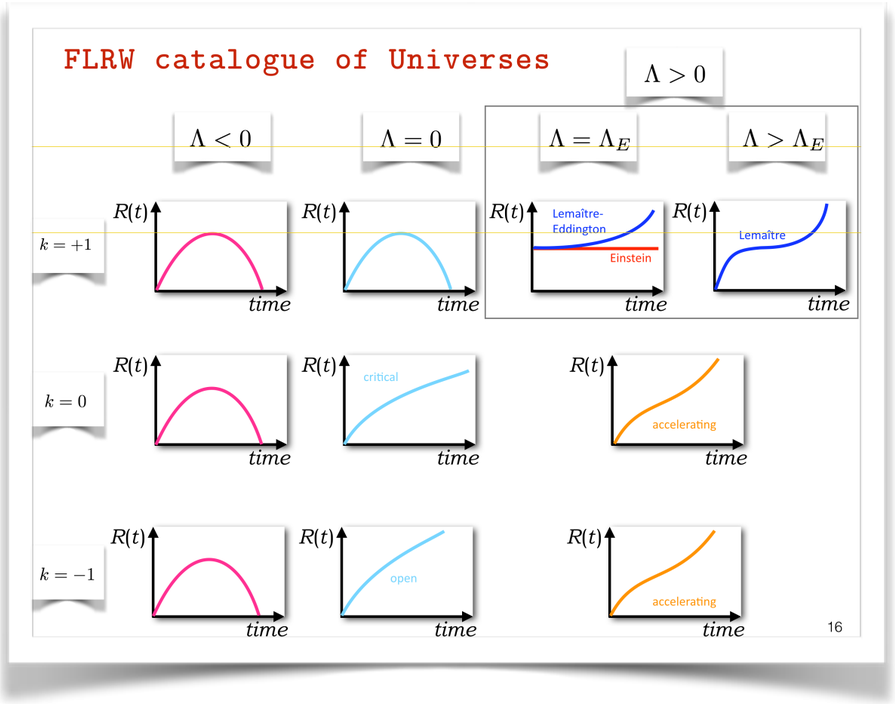
Remember: $\frac{kc^2}{R^2} \propto H^2 \left(\Omega_m - 1\right)$

The 1999 Boomerang South Pole measurements suggest: $\Omega_m(t) =$ _____

So, Boomerang data suggest: $k \quad < \quad > \quad \text{or} \quad \quad = 0?$

The 2013 Planck Satellite measurements suggest: $\Omega_m(t) =$ _____

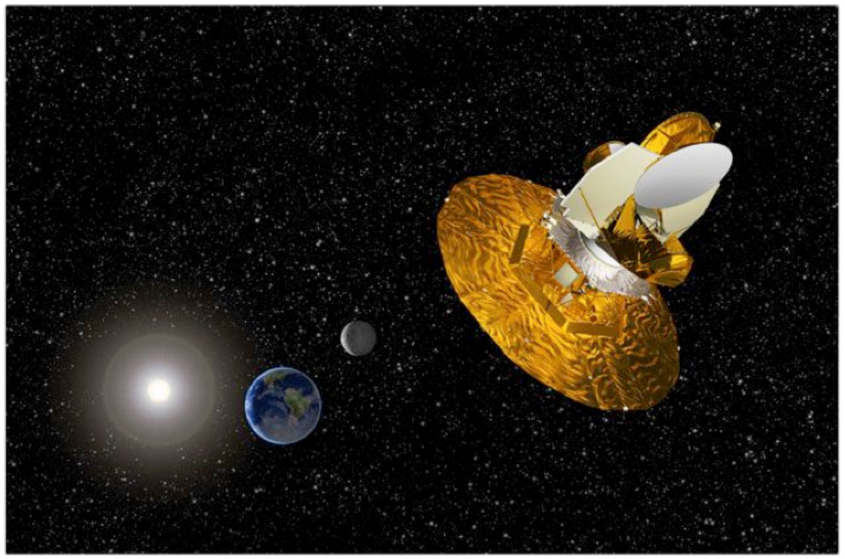
So, Planck data suggest: $k \quad < \quad > \quad \text{or} \quad \quad = 0?$



So, for no cosmological constant:

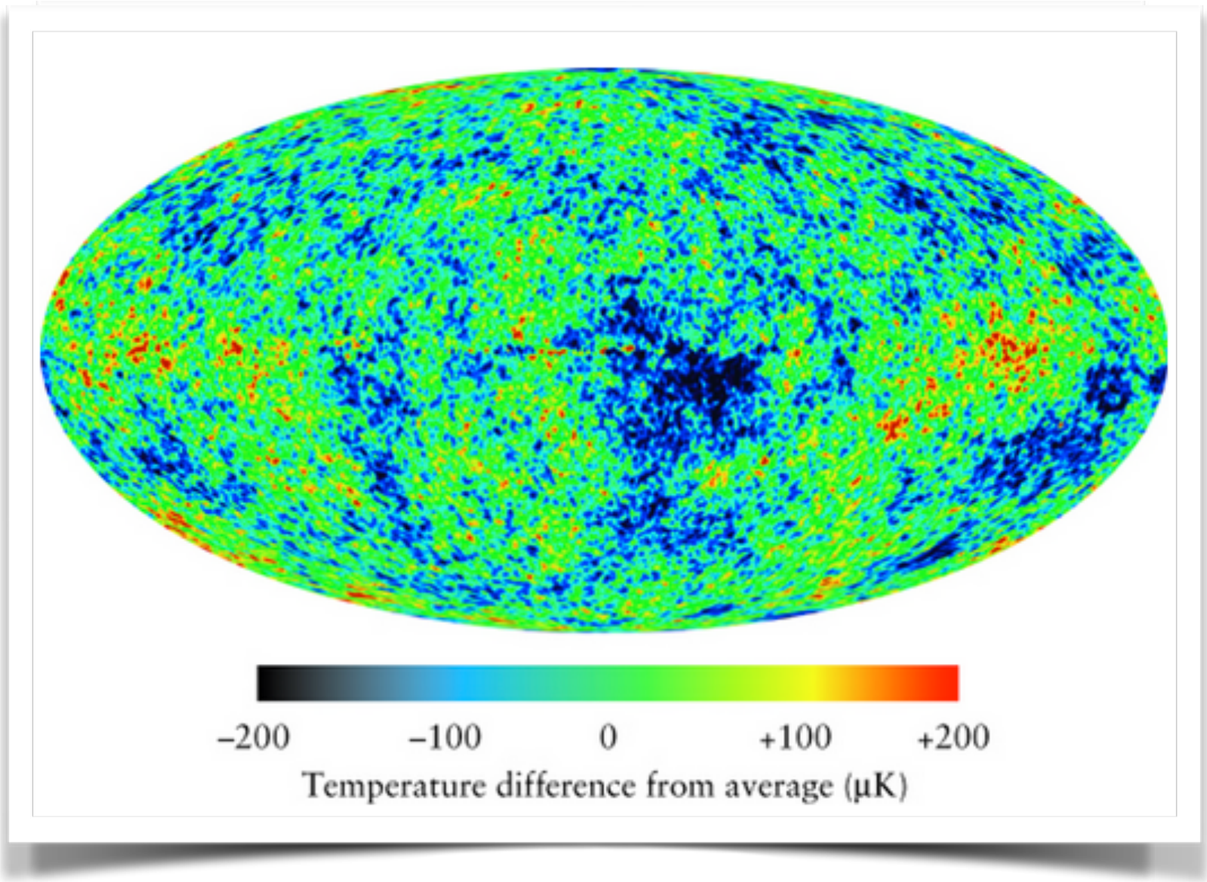
circle the Boomerang universe

square the Planck universe



WMAP… Wilkinson Microwave Anisotropy Probe

Planck just 2013!



From multiple, different kinds of measurements:

$$\Omega_m(t) = 0.27 \pm 0.04$$

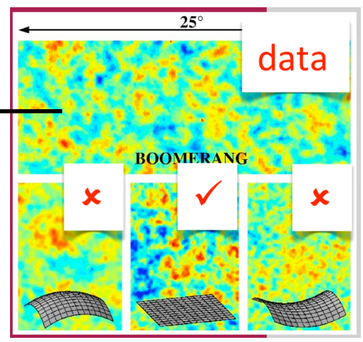
$$0.308 \pm \sim 0.010$$

$$\Omega_m(t) \neq 1\,!$$

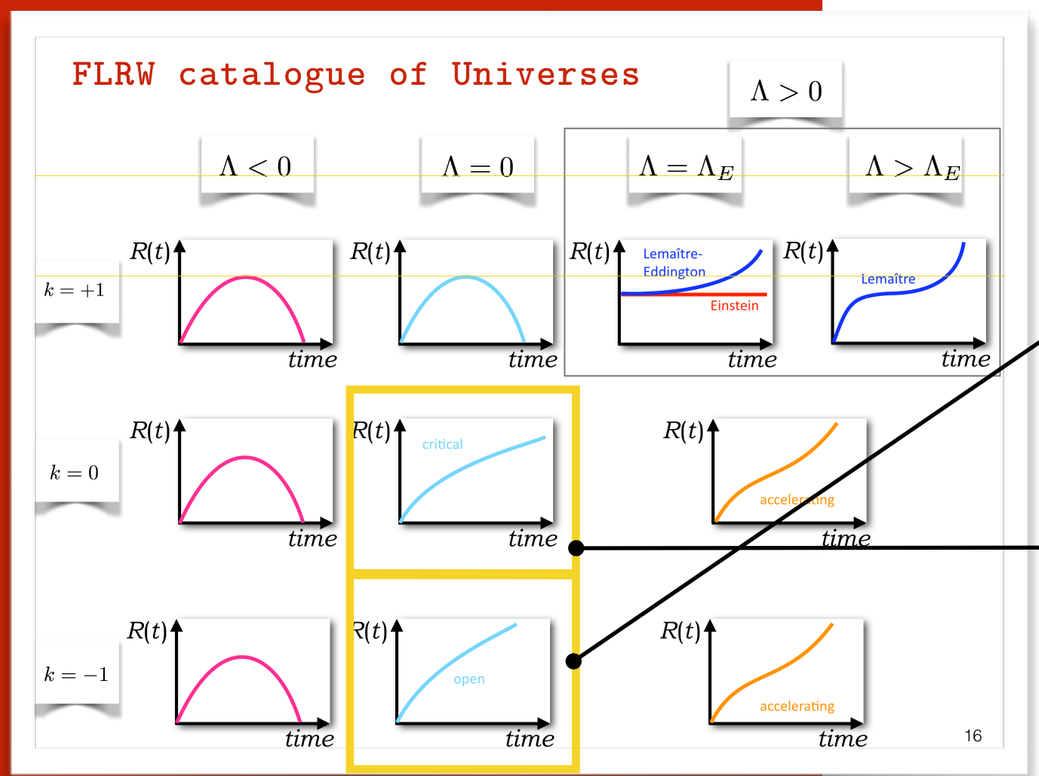
$$\frac{kc^2}{R^2} = H^2\left(\Omega_m - 1\right)$$

suggests k <0

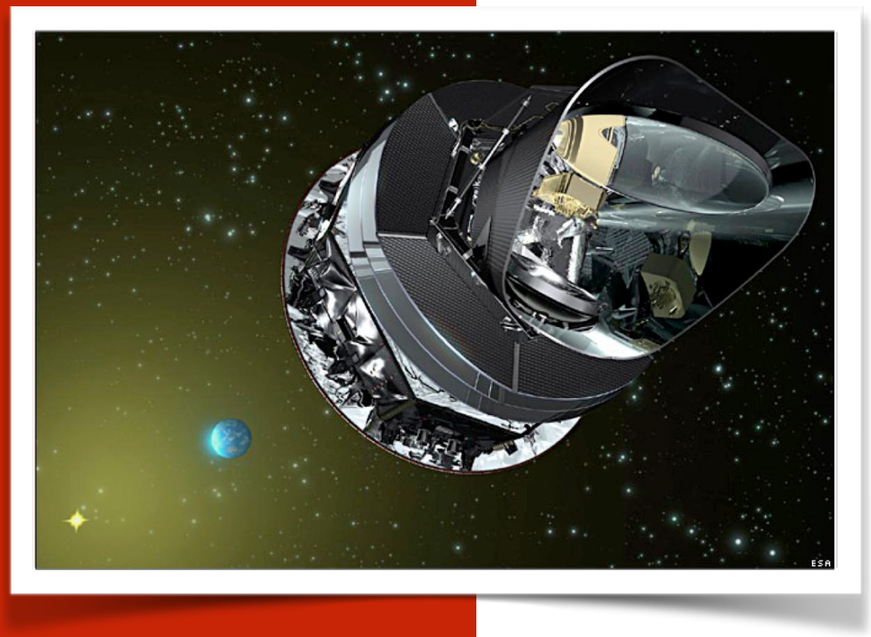
But:

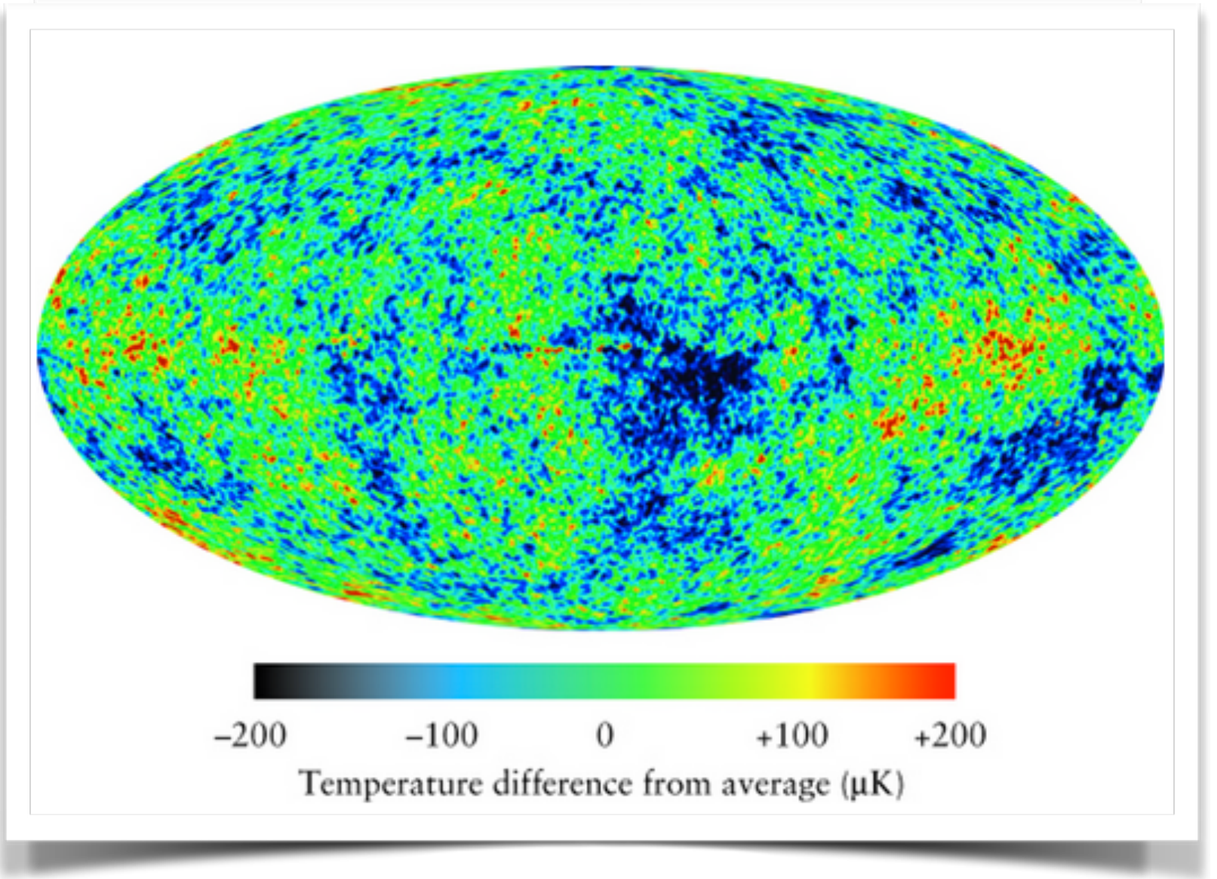


suggested that k = 0



CMB ,





now it's really precise

WMAP... Wilkinson Microwave Anisotropy Probe

Planck just 2013!

2. **large-scale densities**
   from motions of galaxies
   from the CMB

3. **"baryon densities"**
   survey of stuff that shines...mostly Hydrogen
   from the CMB

From multiple, different kinds of measurements:

$$\Omega_m(t) = 0.27 \pm 0.04$$

$$0.308 \pm \sim 0.010$$

$$\Omega_m(t) \neq 1\,!$$

Further, if Dark Matter is part of this...

$$\Omega_m(t) = \Omega_{\mathrm{DM}} + \Omega_b$$

From other...multiple, different kinds of measurements:

$$\Omega_b = 0.0412 \pm \sim 0.001$$

$$\Omega_{\mathrm{DM}} = \sim 0.3$$

everything that shines - Baryons -...4% of the critical density

Dark Matter? 30%...

Something missing in order to get to flat at 100%

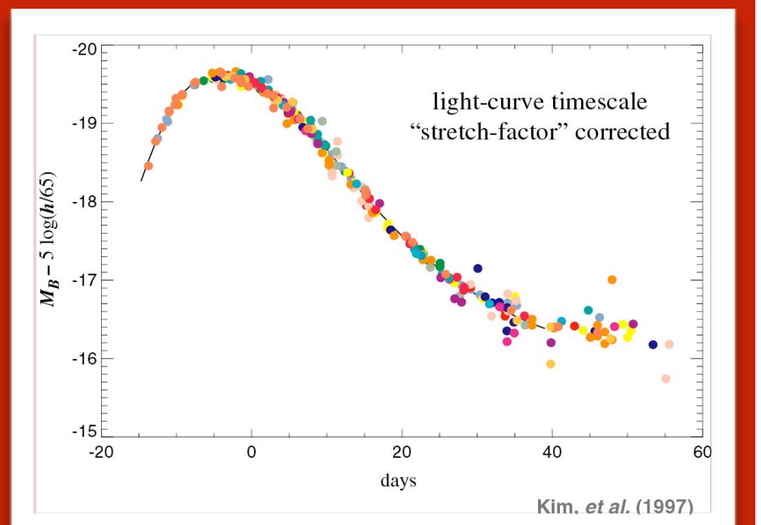
this is where we were in 1999

after the BOOMERANG results

by 1998, the Supernova Cosmology Project

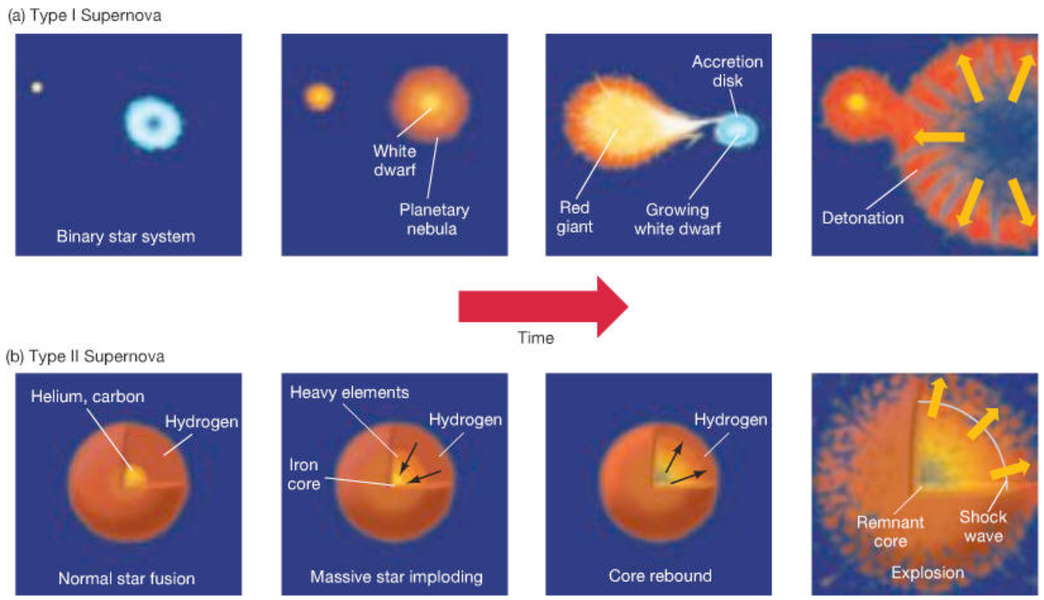
was concluding a decade-long experiment

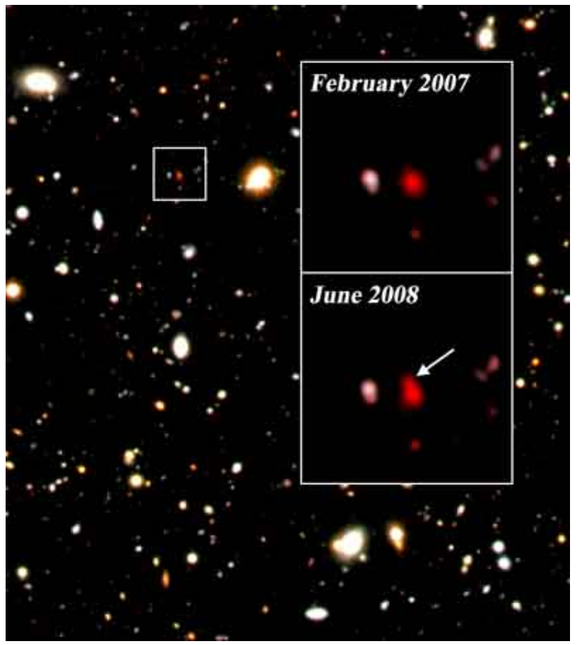
measure of brightness



Find and characterize a particular kind of Supernova, called "1a"

1a supernovae are different:
From stars not massive enough by themselves to nova





Remarkably reliable light output.

But in close proximity to another star which it siphons matter from, enough to cause a supernova explosion after all

or the other way around.

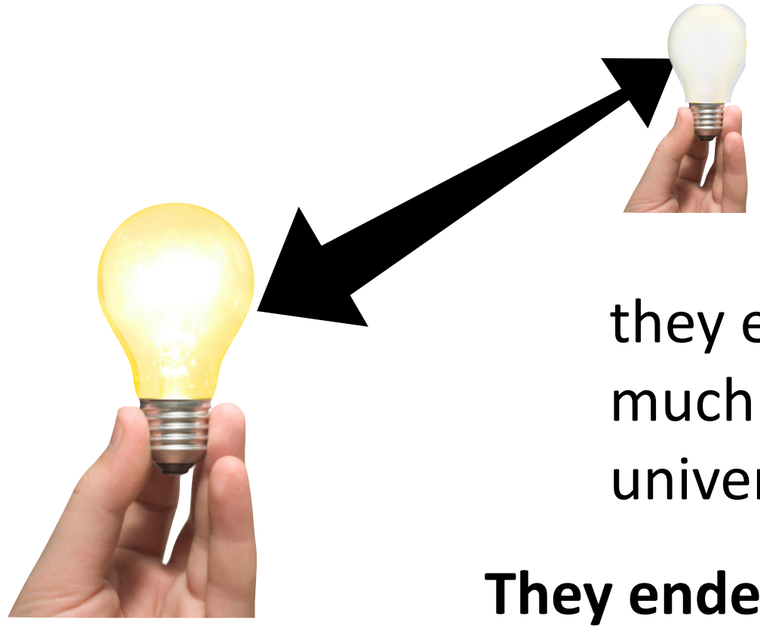
suppose you know how far away an identical bulb is...you could calculate how bright it should appear

so, the game was clear

do the Hubble-thing

use spectra to determine speed, distance

The far-away 1a supernovae appeared to be much too dim for the distances away!



? no...must be further away than expected

they expected to determine how much the expansion of the universe was slowing down.

They ended up showing the opposite!