hi

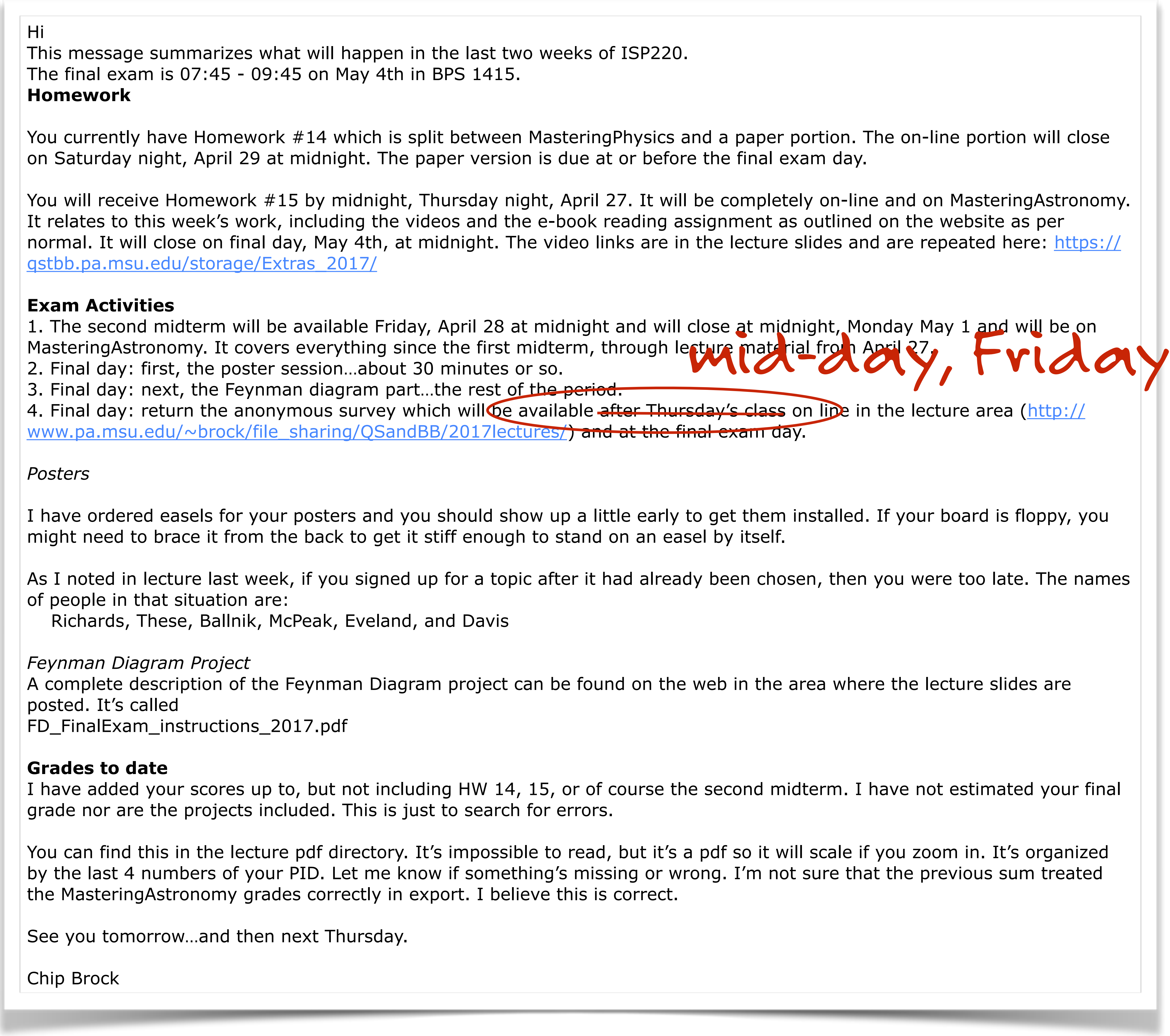
Lecture last, 04.27.2017

Cosmology 5

housekeeping

Read the mail message I sent to you all on Wednesday ;)

well, okay. Here it is.



Hi
This message summarizes what will happen in the last two weeks of ISP220.
The final exam is 07:45 - 09:45 on May 4th in BPS 1415.

Homework

You currently have Homework #14 which is split between MasteringPhysics and a paper portion. The on-line portion will close on Saturday night, April 29 at midnight. The paper version is due at or before the final exam day.

You will receive Homework #15 by midnight, Thursday night, April 27. It will be completely on-line and on MasteringAstronomy. It relates to this week's work, including the videos and the e-book reading assignment as outlined on the website as per normal. It will close on final day, May 4th, at midnight. The video links are in the lecture slides and are repeated here: https://qstbb.pa.msu.edu/storage/Extras_2017/

Exam Activities

1. The second midterm will be available Friday, April 28 at midnight and will close at midnight, Monday May 1 and will be on MasteringAstronomy. It covers everything since the first midterm, through lecture material from April 27.
2. Final day: first, the poster session…about 30 minutes or so.
3. Final day: next, the Feynman diagram part…the rest of the period.
4. Final day: return the anonymous survey which will be available ~~after Thursday's class~~ on line in the lecture area (http://www.pa.msu.edu/~brock/file_sharing/QSandBB/2017lectures/) ~~and at the final exam~~ day.

mid-day, Friday, April 28

Posters

I have ordered easels for your posters and you should show up a little early to get them installed. If your board is floppy, you might need to brace it from the back to get it stiff enough to stand on an easel by itself.

As I noted in lecture last week, if you signed up for a topic after it had already been chosen, then you were too late. The names of people in that situation are:
Richards, These, Ballnik, McPeak, Eveland, and Davis

Feynman Diagram Project
A complete description of the Feynman Diagram project can be found on the web in the area where the lecture slides are posted. It's called
FD_FinalExam_instructions_2017.pdf

Grades to date

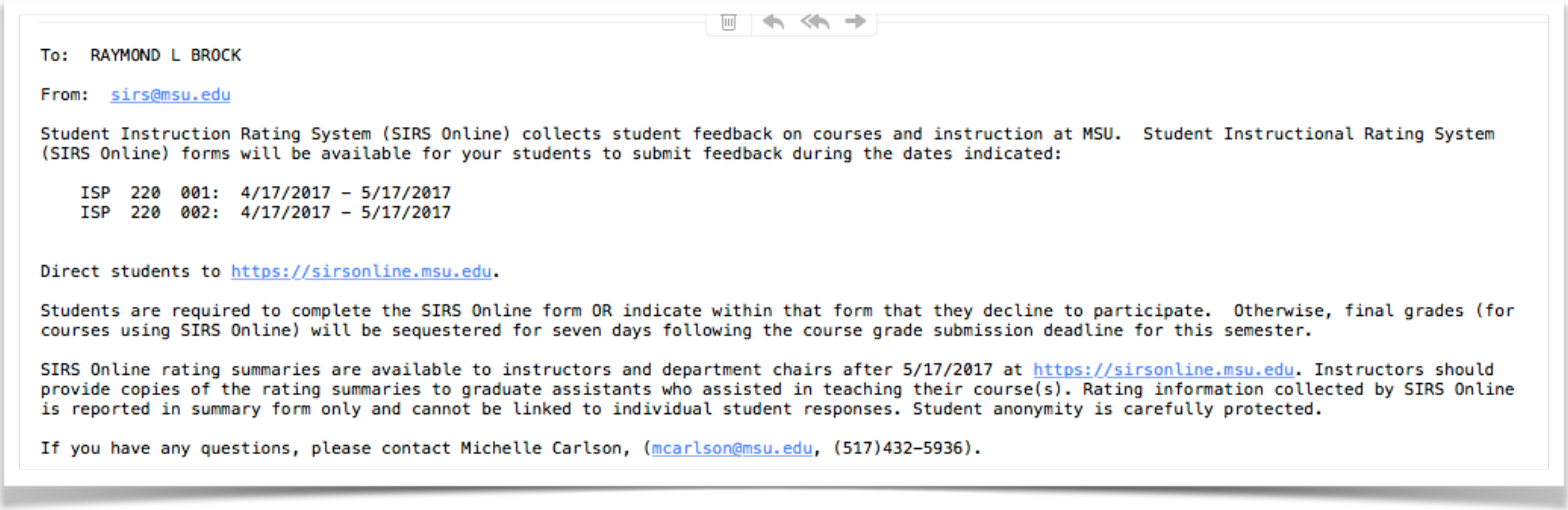
I have added your scores up to, but not including HW 14, 15, or of course the second midterm. I have not estimated your final grade nor are the projects included. This is just to search for errors.

You can find this in the lecture pdf directory. It's impossible to read, but it's a pdf so it will scale if you zoom in. It's organized by the last 4 numbers of your PID. Let me know if something's missing or wrong. I'm not sure that the previous sum treated the MasteringAstronomy grades correctly in export. I believe this is correct.

See you tomorrow…and then next Thursday.

Chip Brock

now hear this



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: 4/17/2017 - 5/17/2017
ISP 220 002: 4/17/2017 - 5/17/2017

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 5/17/2017 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).

also:

I’ll have an optional anonymous course review with points

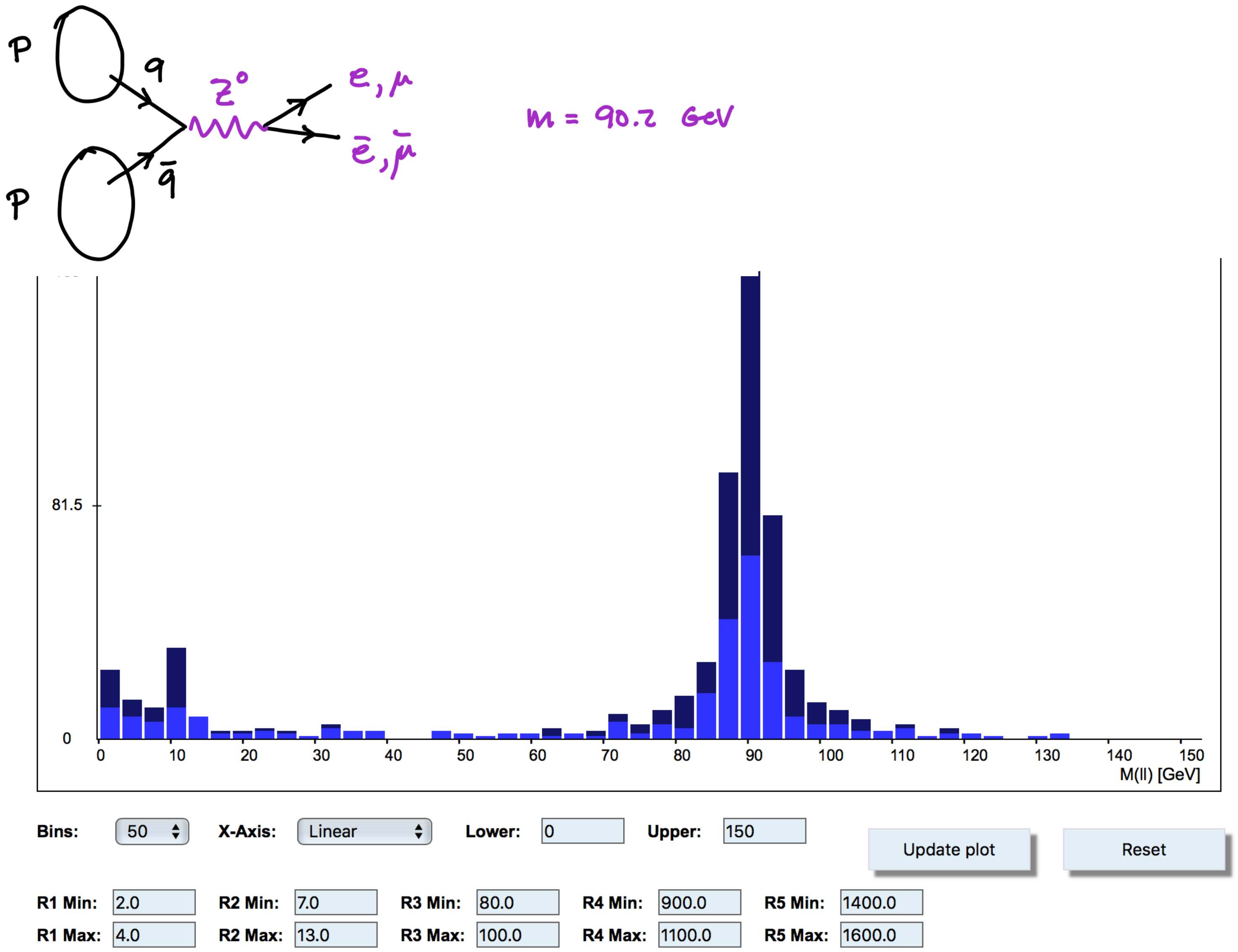
Honors Project

Data were due April 22. Paper due on May 4 (final day).

upload instructions:

http://www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/honors_project_2017/UploadInstructions

results:

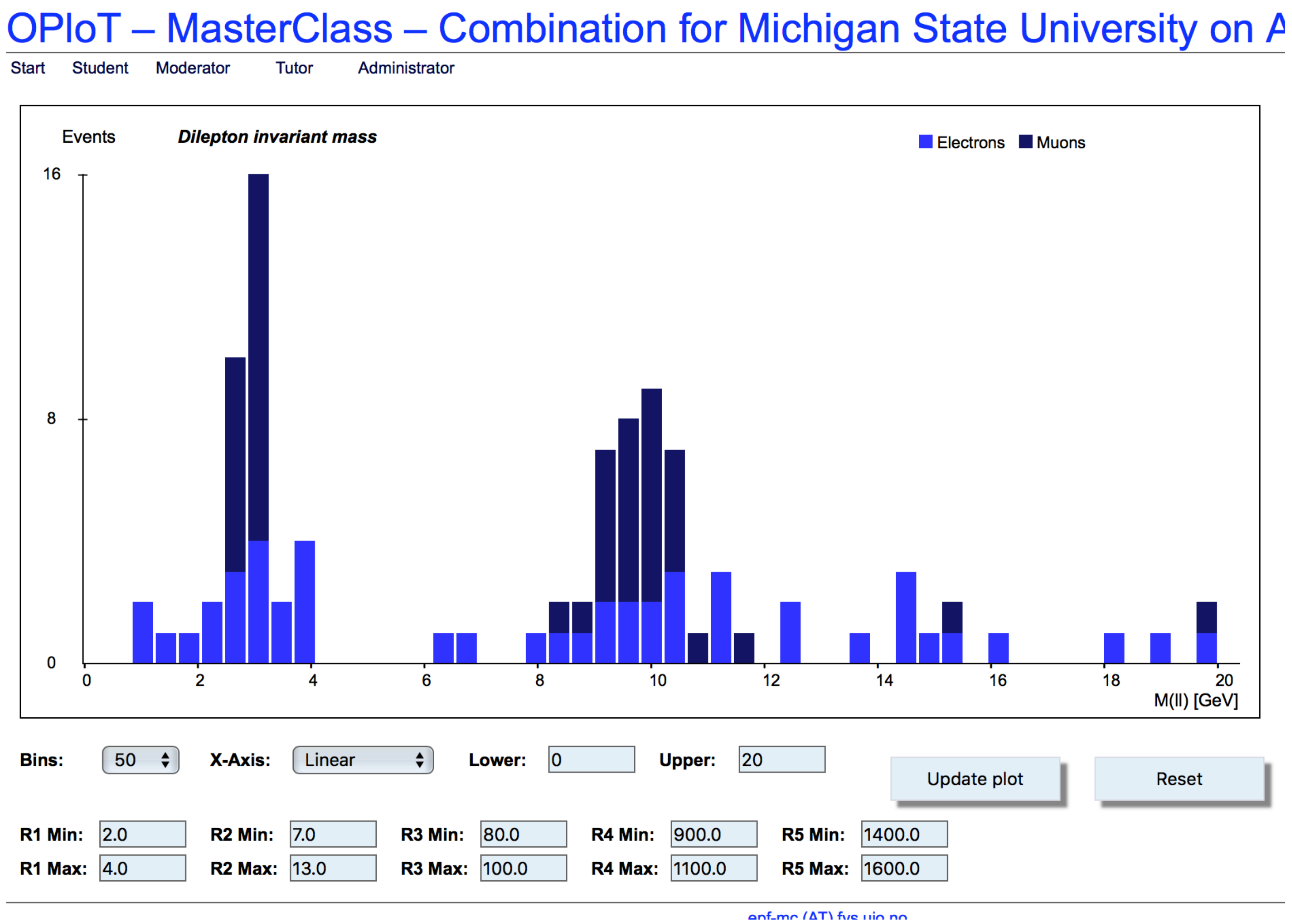


m = 90.2 GeV

Bins: 50 **X-Axis:** Linear **Lower:** 0 **Upper:** 150

R1 Min: 2.0 **R2 Min:** 7.0 **R3 Min:** 80.0 **R4 Min:** 900.0 **R5 Min:** 1400.0

R1 Max: 4.0 **R2 Max:** 13.0 **R3 Max:** 100.0 **R4 Max:** 1100.0 **R5 Max:** 1600.0

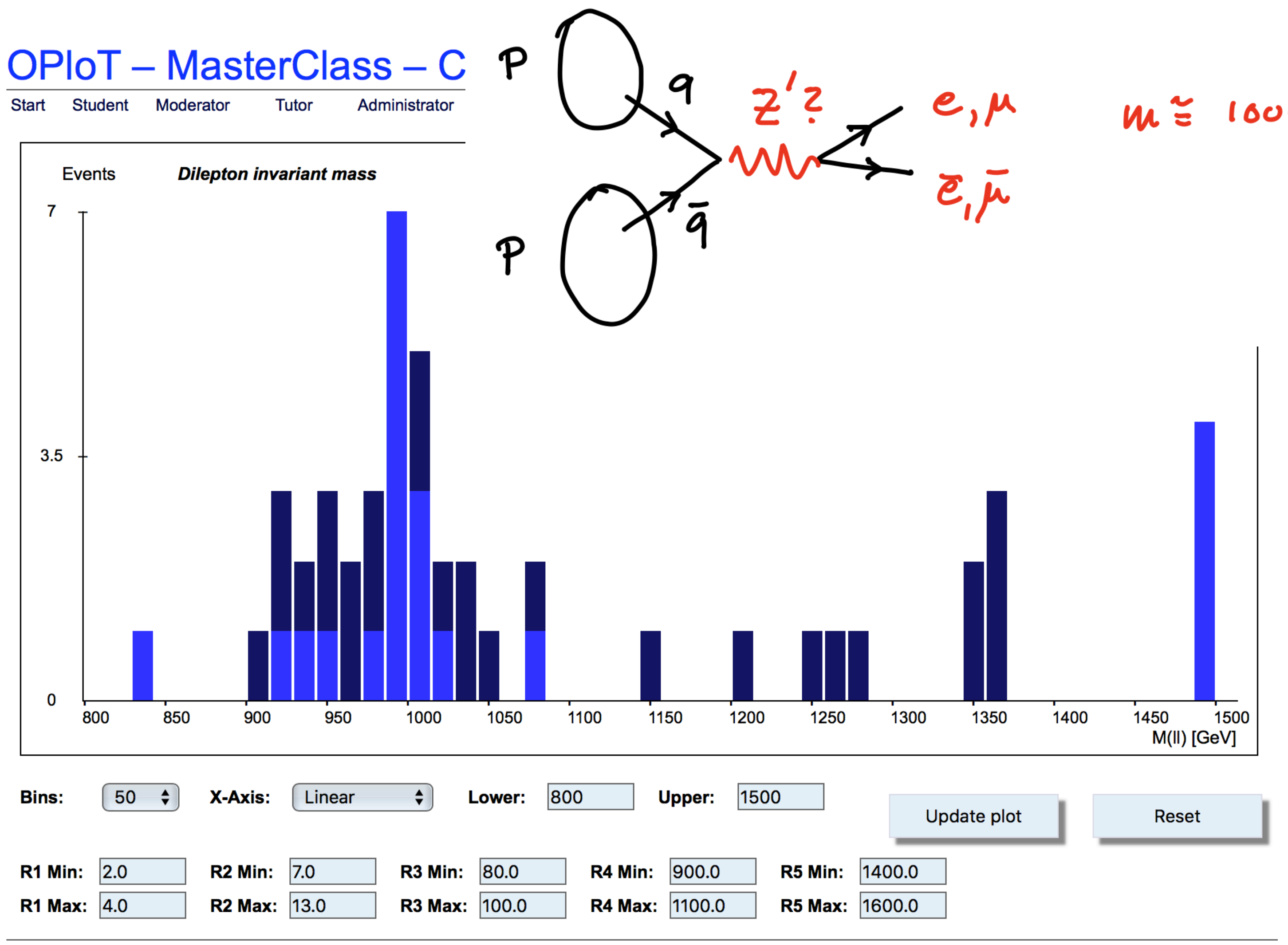


OPloT – MasterClass – Combination for Michigan State University on A

Bins: 50 **X-Axis:** Linear **Lower:** 0 **Upper:** 20

R1 Min: 2.0 **R2 Min:** 7.0 **R3 Min:** 80.0 **R4 Min:** 900.0 **R5 Min:** 1400.0

R1 Max: 4.0 **R2 Max:** 13.0 **R3 Max:** 100.0 **R4 Max:** 1100.0 **R5 Max:** 1600.0



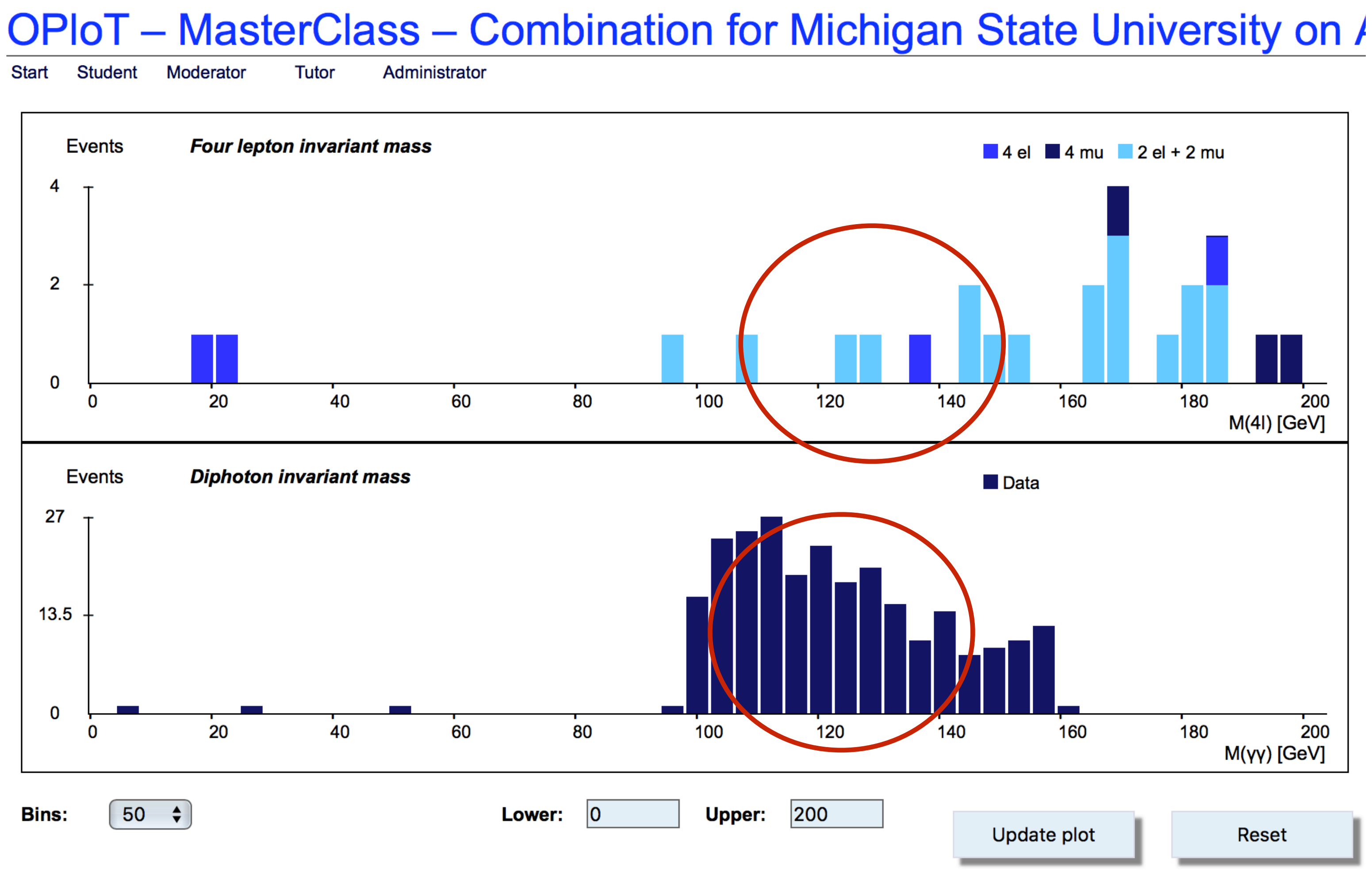
OPloT – MasterClass – C

Bins: 50 **X-Axis:** Linear **Lower:** 800 **Upper:** 1500

R1 Min: 2.0 **R2 Min:** 7.0 **R3 Min:** 80.0 **R4 Min:** 900.0 **R5 Min:** 1400.0

R1 Max: 4.0 **R2 Max:** 13.0 **R3 Max:** 100.0 **R4 Max:** 1100.0 **R5 Max:** 1600.0

m ≅ 1000 GeV ?



OPloT – MasterClass – Combination for Michigan State University on A

Bins: 50 **Lower:** 0 **Upper:** 200

0.00000000000000000000000000000000001 s

0.5m

1,000,000,000,000,000,000,000,000°

0.000000000001 s

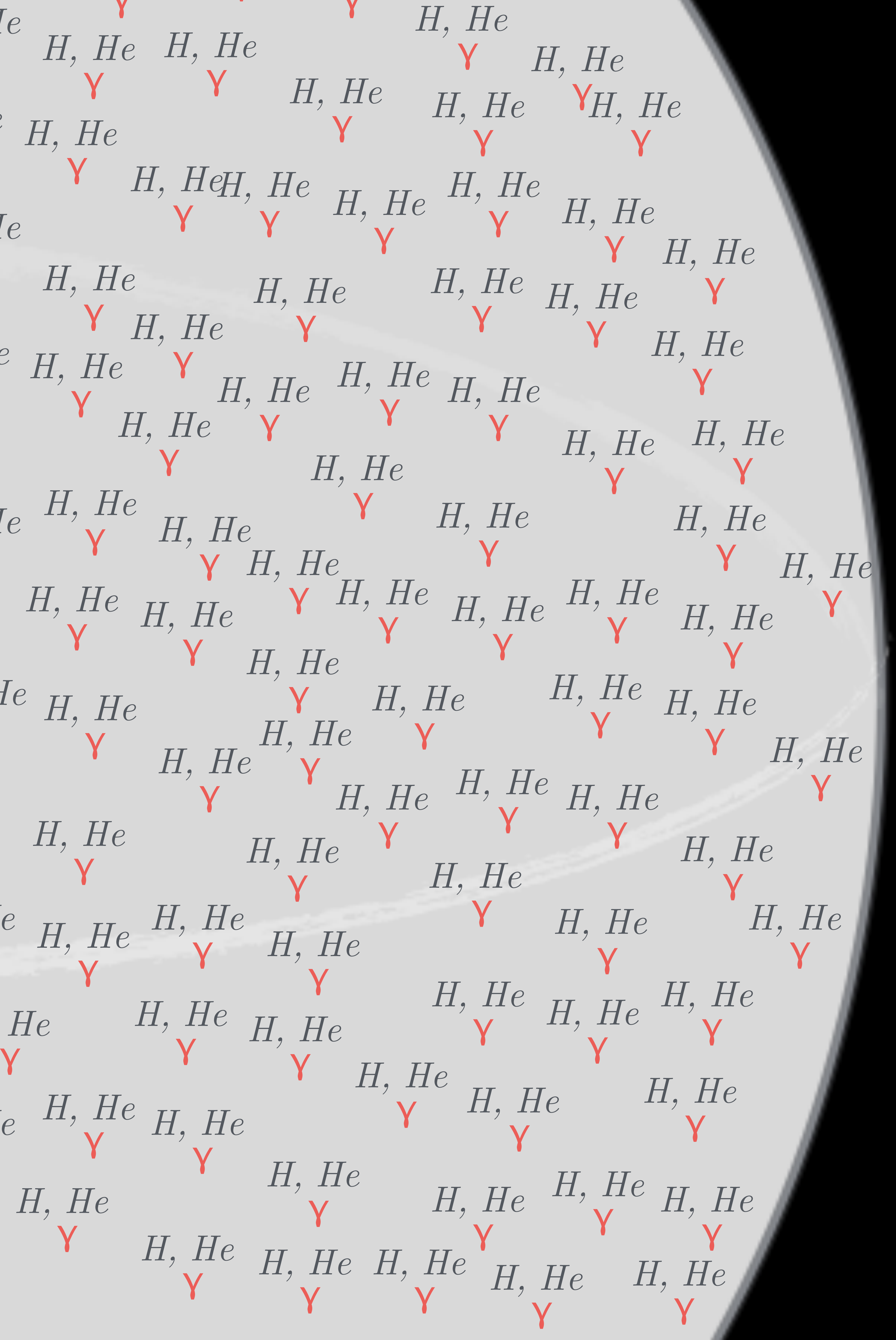
10,000,000,000m

100,000,000,000,000,000°

0.000001 s

1,000,000,000,000m

100,000,000,000,000°



370,000 y

100,000,000,000,000,000,000m

10,000 light years

100,000,000,000°

13,800,000,000 y

46,000,000,000 light years

3°

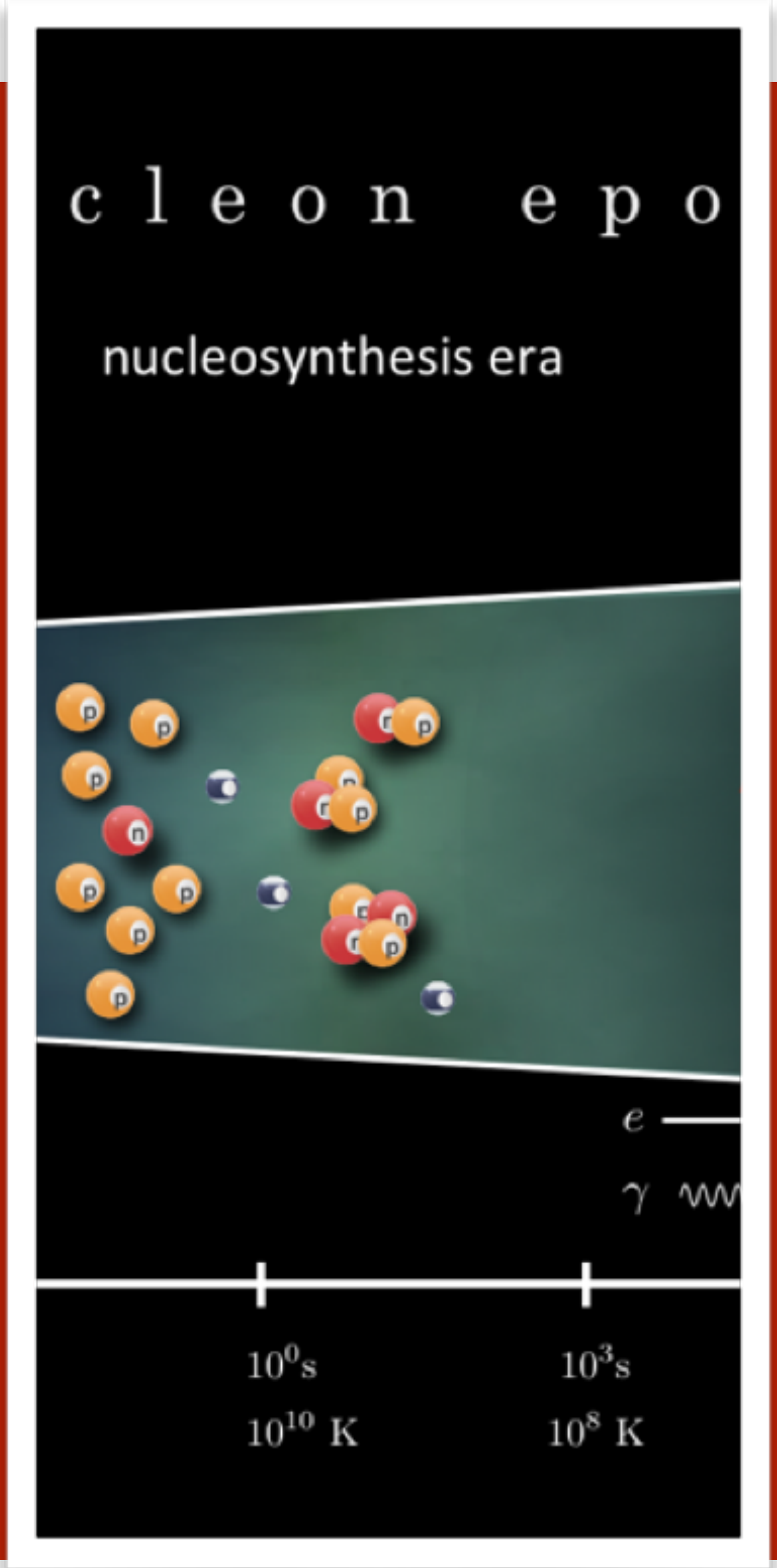
the photons that are left?

just hanging around

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

There are two critical times

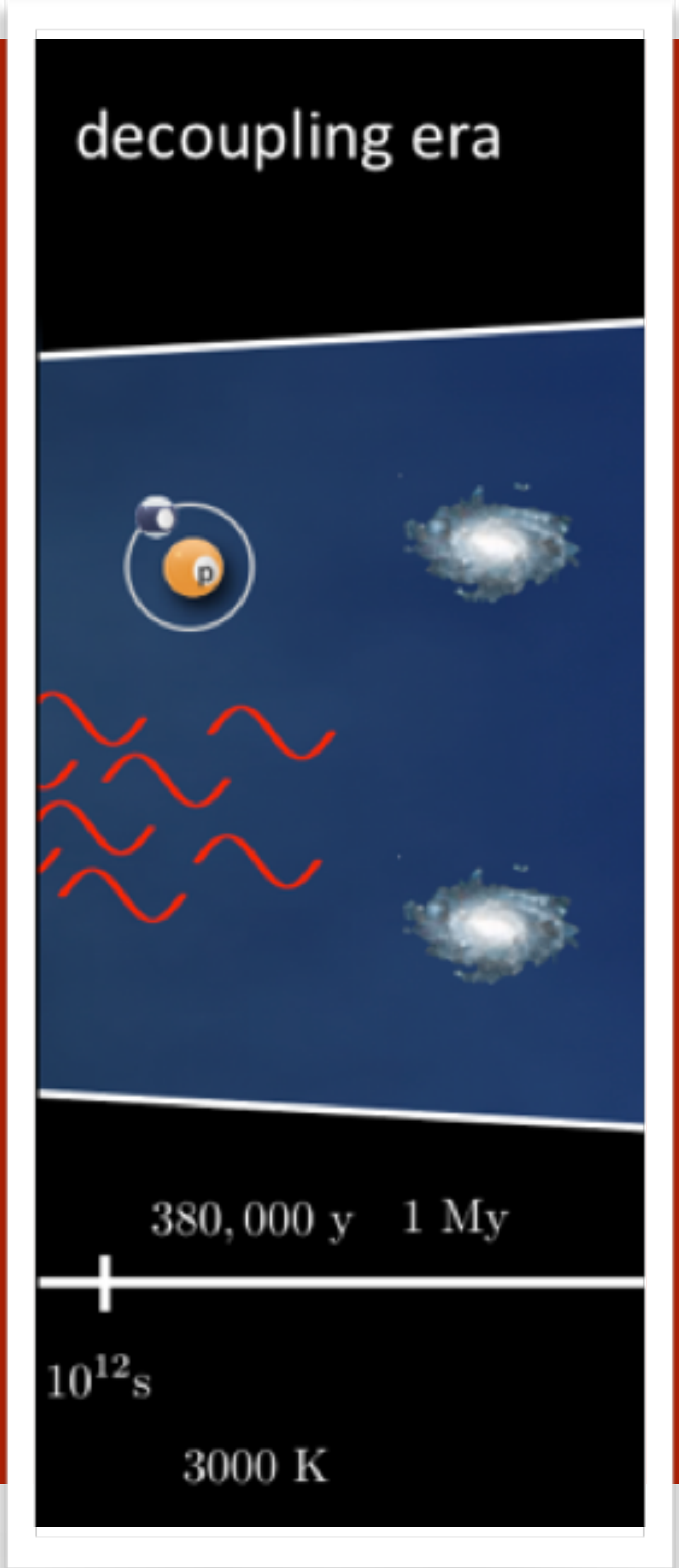
that confirm the Big Bang



3 minutes

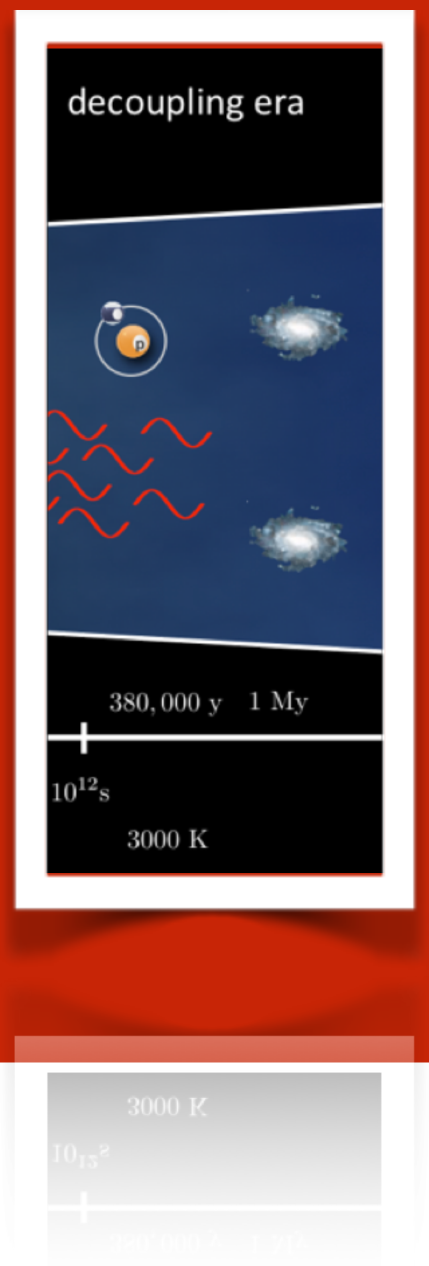
370,000 years

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

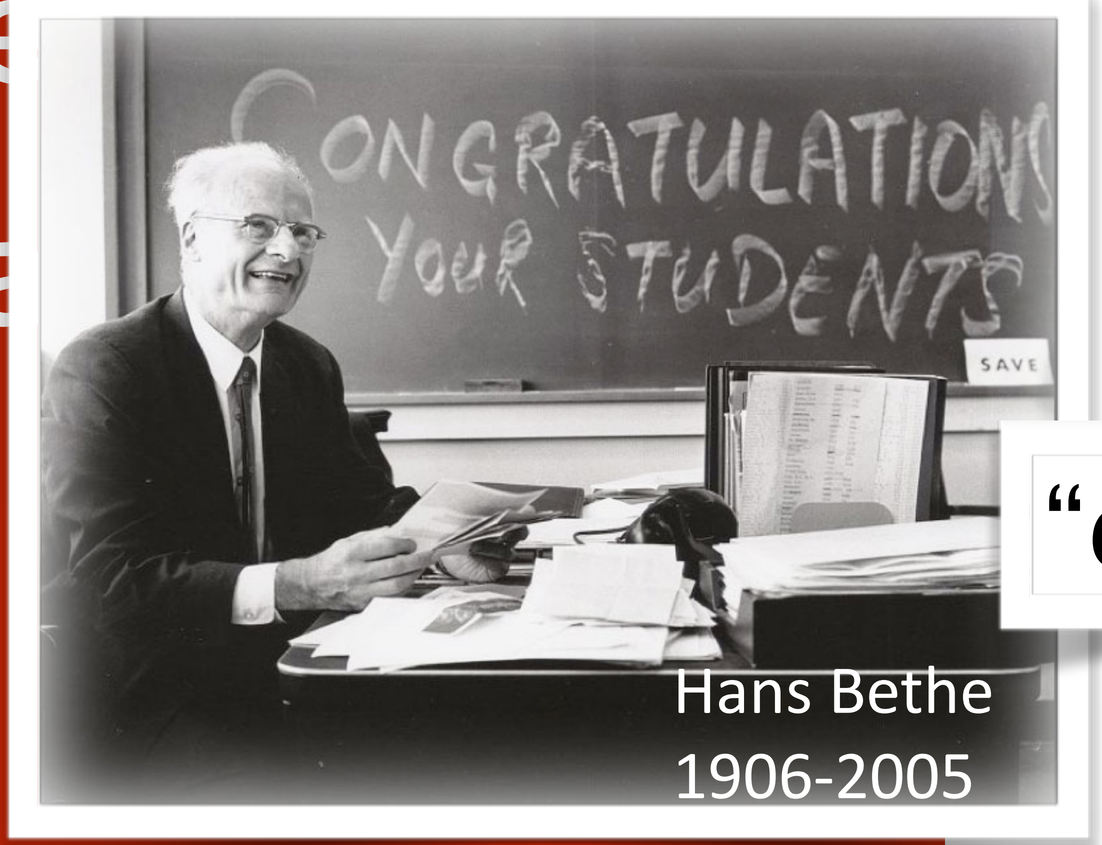


the Cosmic Microwave Background, CMB

about 370,000 y after BB

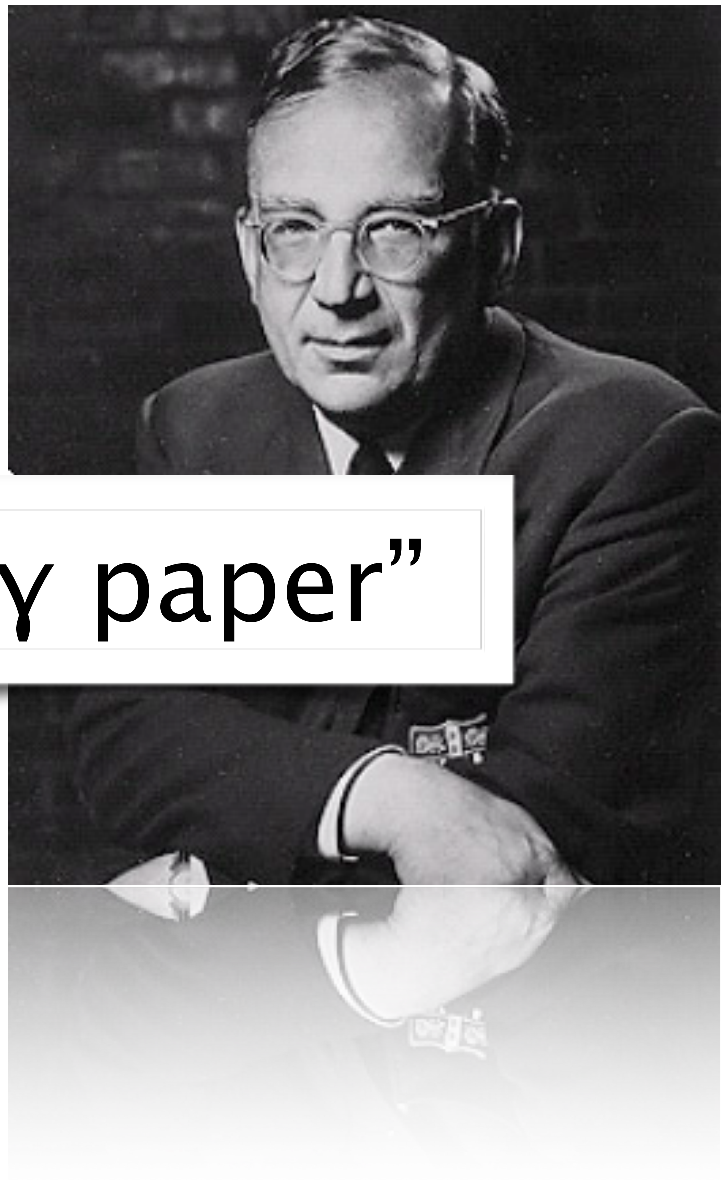


Ge
Ga

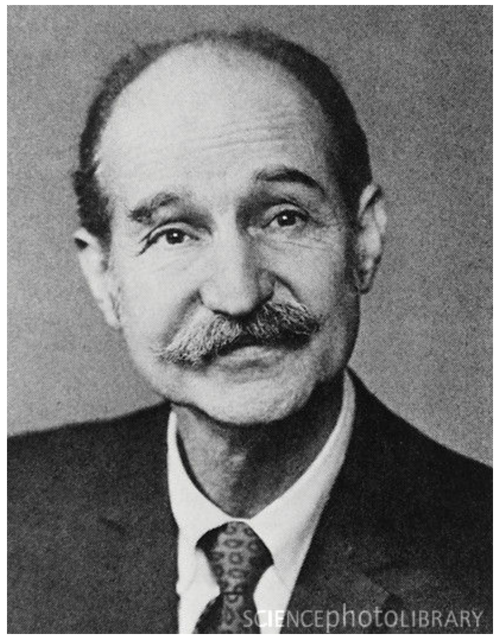


Hans Bethe
1906-2005

“αβγ paper”



Ralph Alpher
1921-2007



Robert Herman
1914 - 1997

predicted this left-over radiation

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

but cooled as the Universe expanded

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.

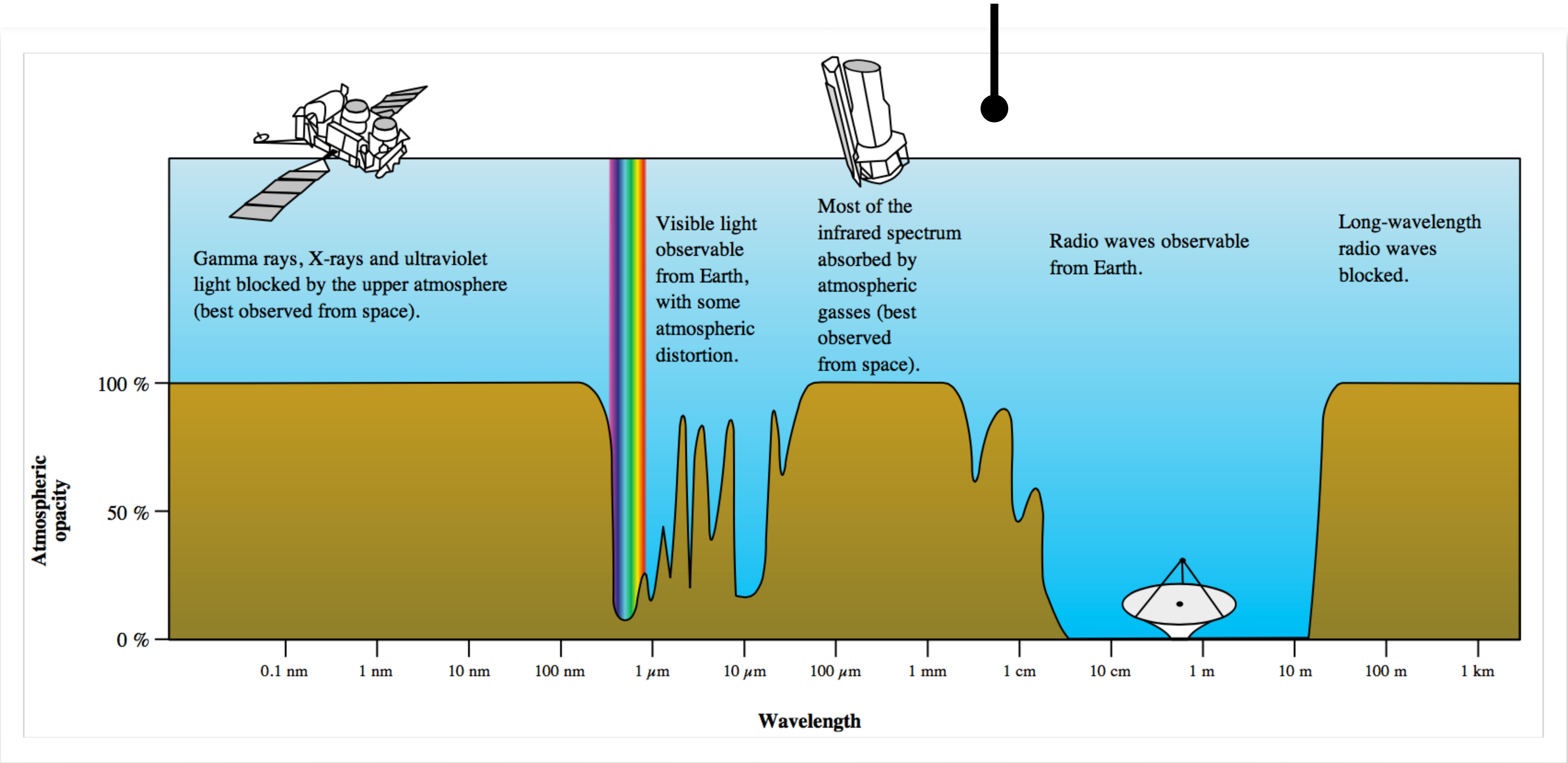
1993, the National Academy of Sciences gave Alpher and Herman the Henry Draper Medal

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

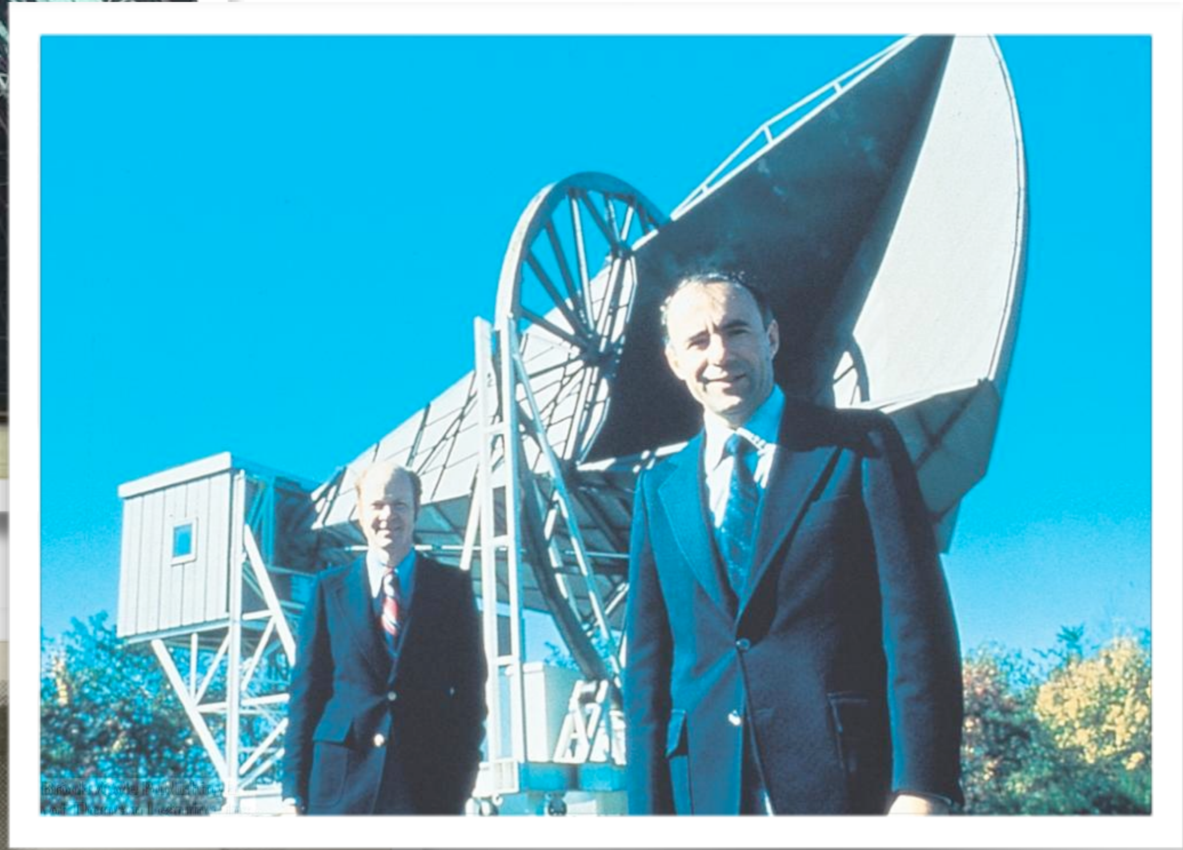
1963

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

FIRST PHONE CALL VIA MAN-MADE SATELLITE!

"Project Echo" satellite went into a near-perfect circular orbit 1000 miles high, circling the earth once every two hours. Its orbital path covered all parts of the U. S.

BELL TELEPHONE LABORATORIES BOUNCES VOICE OFF SPHERE PLACED IN ORBIT A THOUSAND MILES ABOVE THE EARTH

Think of watching a royal wedding in Europe by live TV, or telephoning to Singapore or Calcutta—*by way of outer-space satellites!* A mere dream a few years ago, this idea is now a giant step closer to reality.

Bell Telephone Laboratories recently took the step by

"Project Echo" foreshadows the day when numerous man-made satellites might be in orbit all around the earth, acting as 24-hour-a-day relay stations for TV programs and phone calls between all nations.

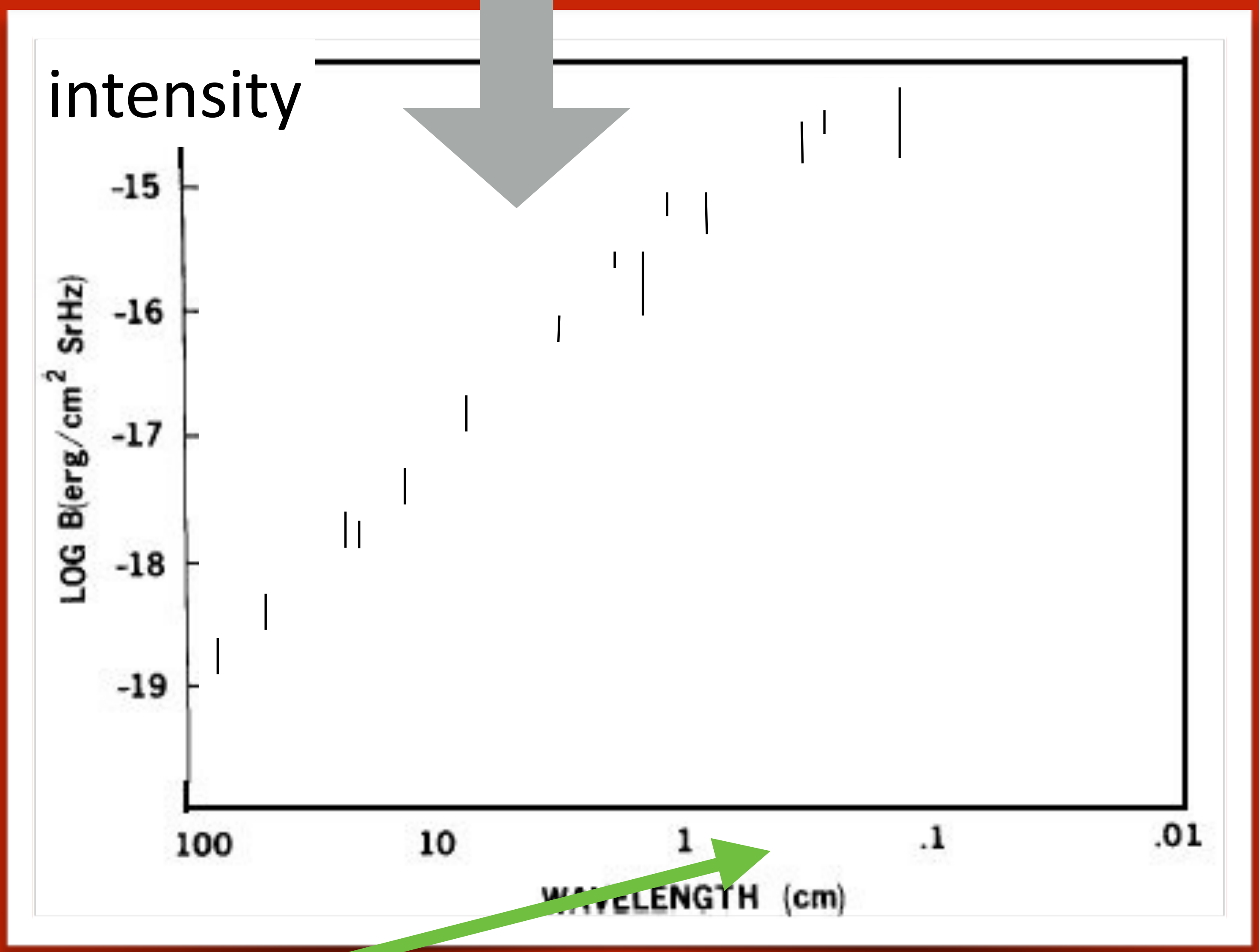
This experiment shows how Bell Laboratories, as part

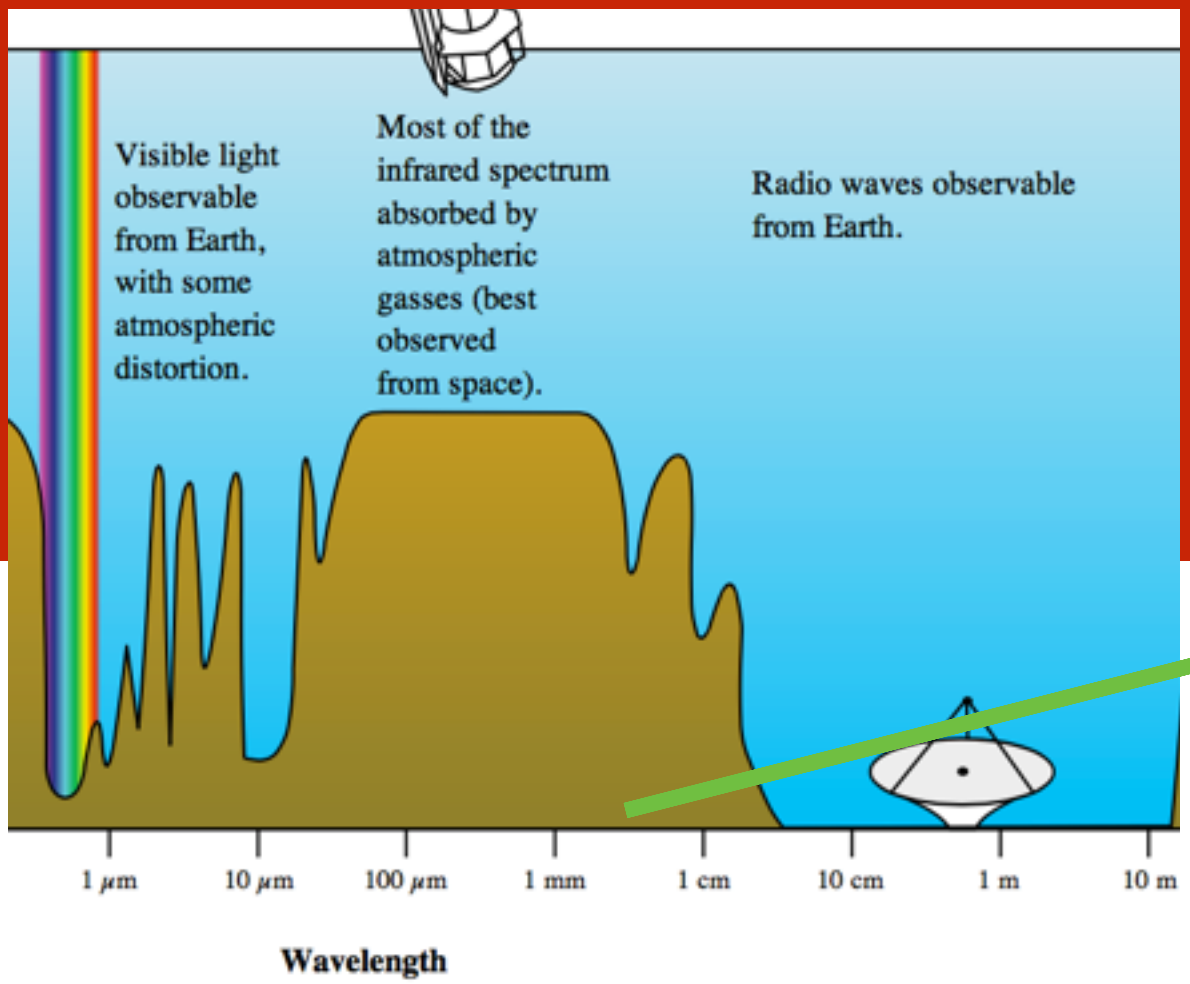
microwave hiss

everywhere…

with a special frequency distribution

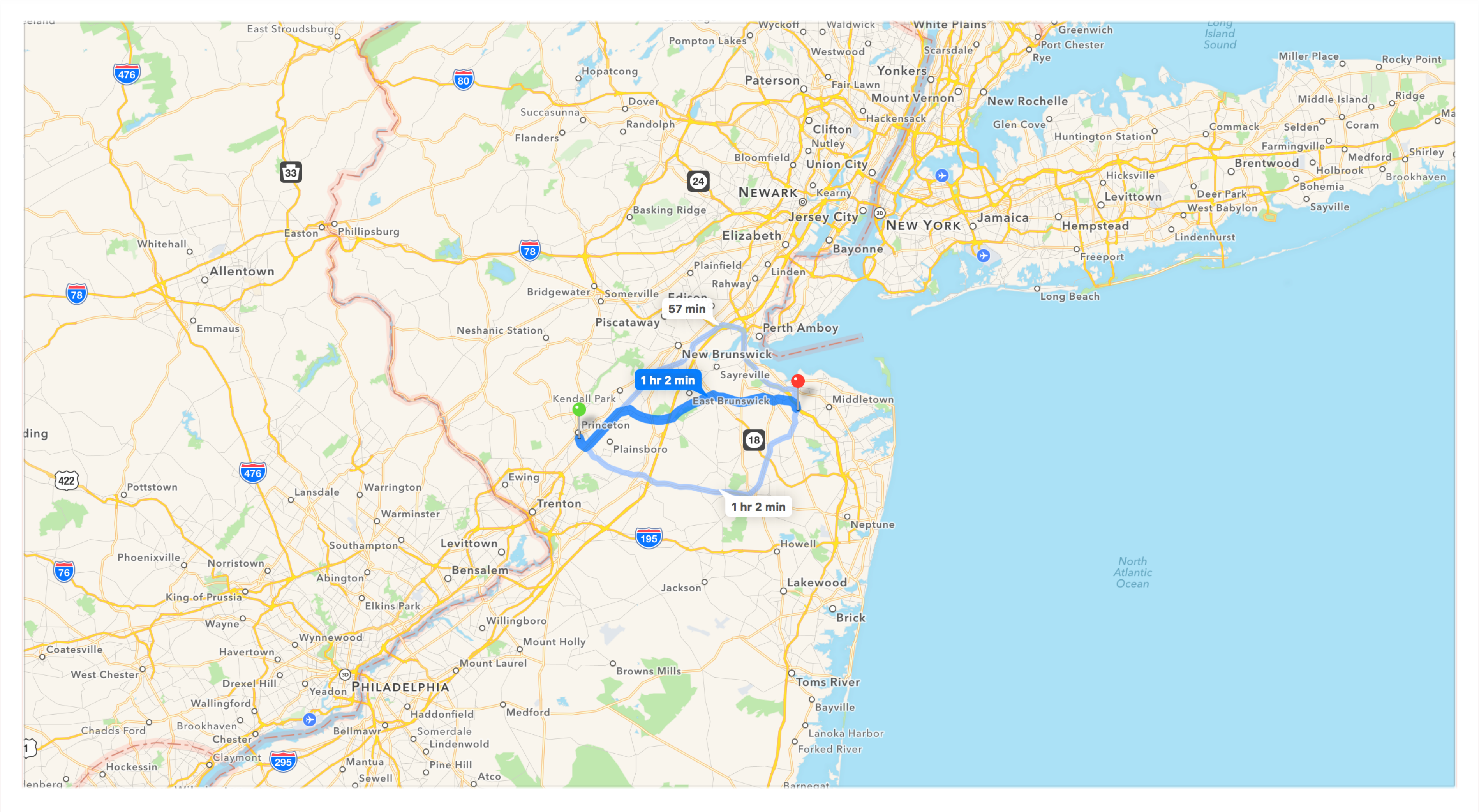
Penzias/Wilson wavelength





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!

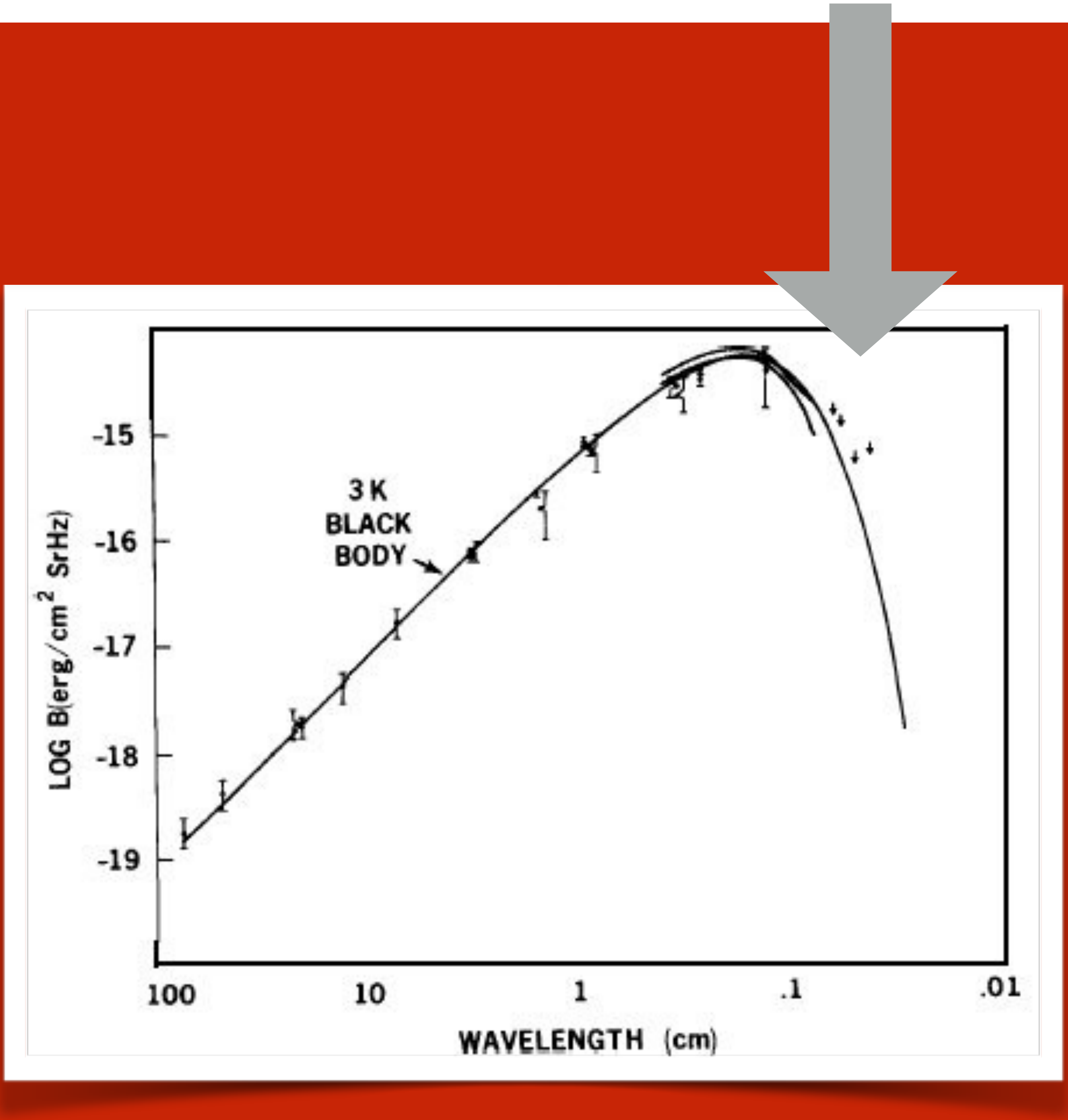
Robert Dicke was thinking of building a receiver

Penzias called Dicke…

a blackbody spectrum

of ~3K above absolute zero

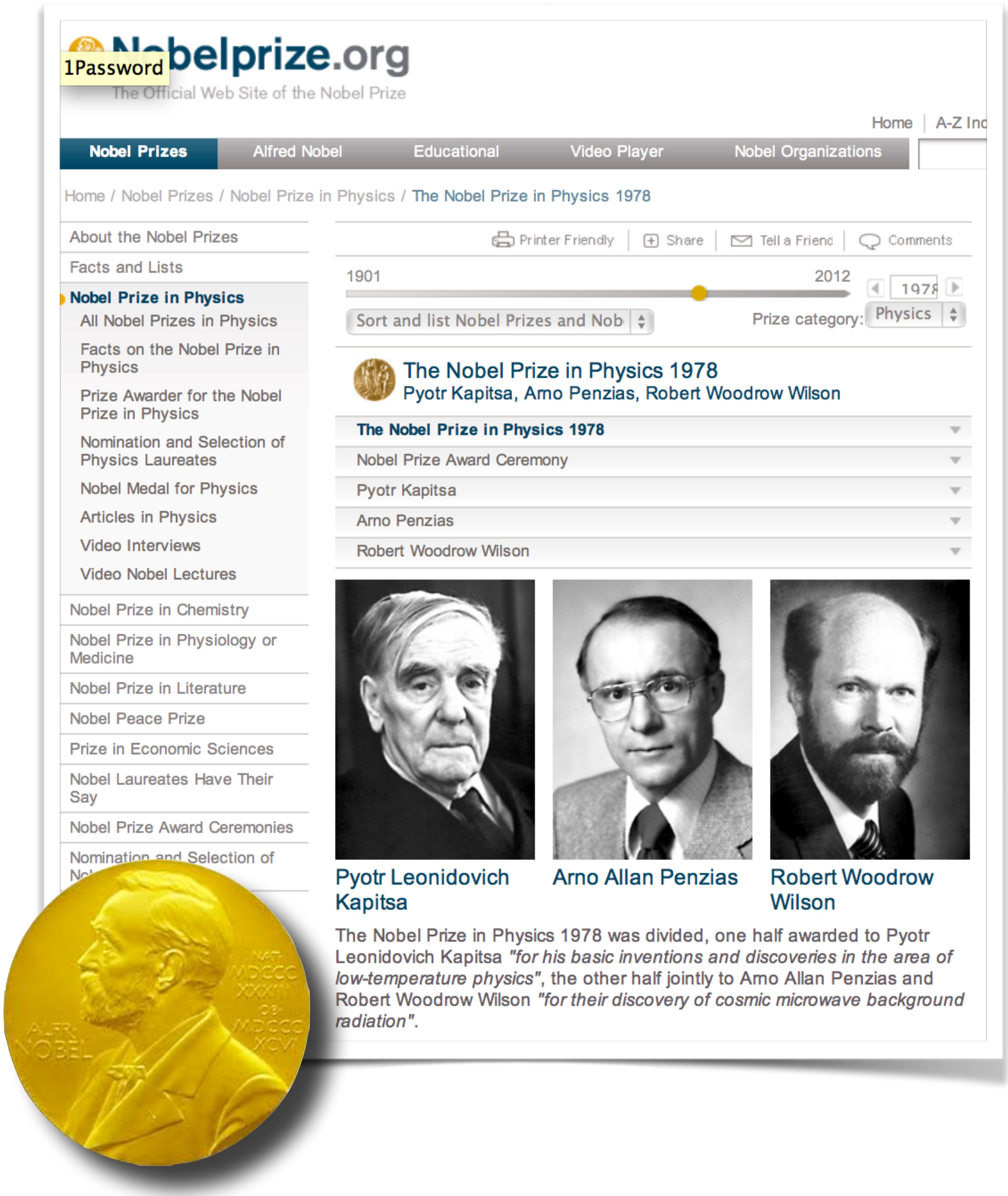
the peak is limited by the atmosphere



balloons to get above atmosphere to measure infrared wavelengths

Penzias and Wilson 1978

gave credit to the deceased George Gamow.



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The Nobel Prize in Physics 1978
Pyotr Kapitsa, Arno Penzias, Robert Woodrow Wilson

- **The Nobel Prize in Physics 1978**
- Nobel Prize Award Ceremony
- Pyotr Kapitsa
- Arno Penzias
- Robert Woodrow Wilson

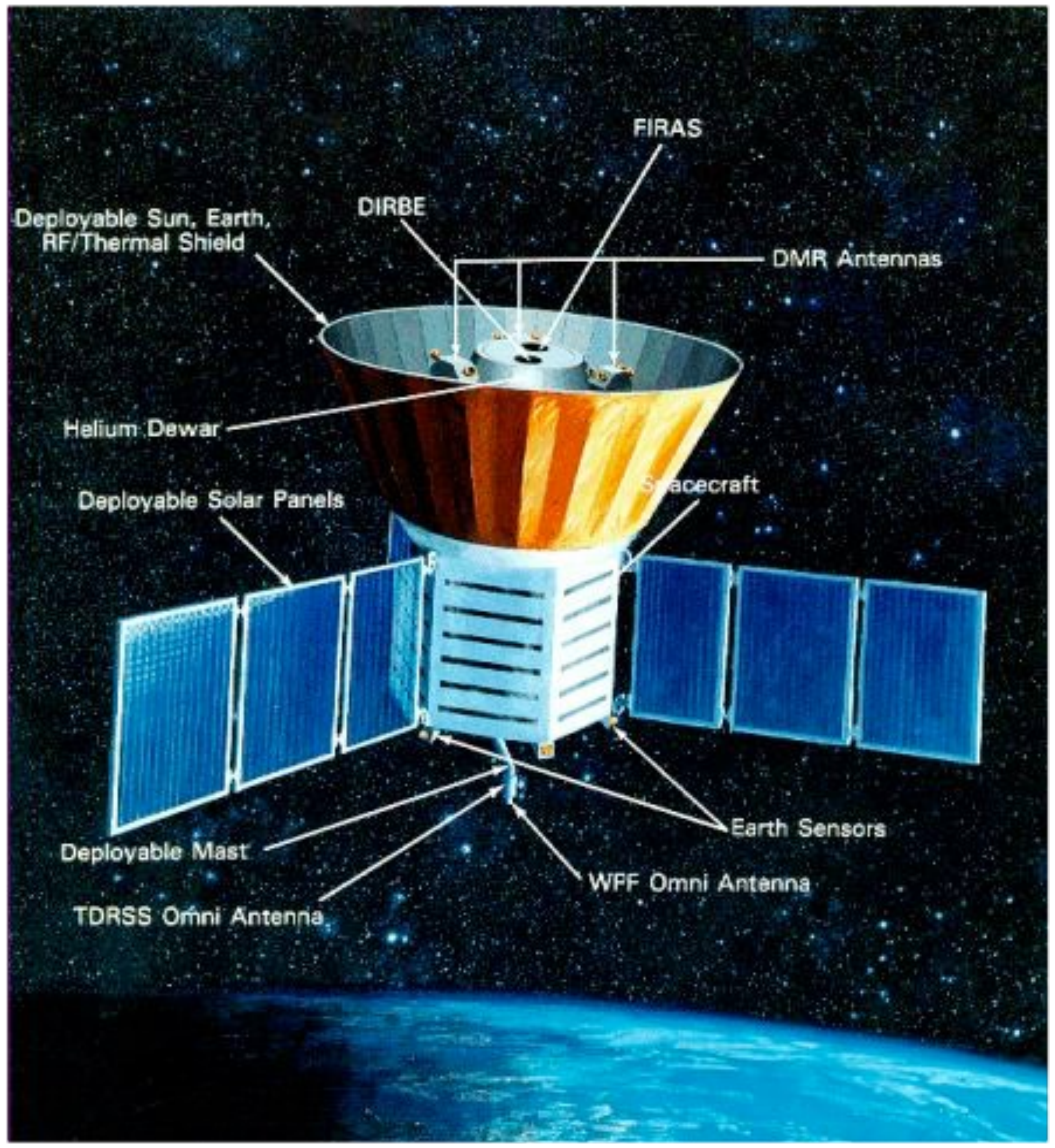
Pyotr Leonidovich Kapitsa
Arno Allan Penzias
Robert Woodrow Wilson

The Nobel Prize in Physics 1978 was divided, one half awarded to Pyotr Leonidovich Kapitsa *"for his basic inventions and discoveries in the area of low-temperature physics"*, the other half jointly to Arno Allan Penzias and Robert Woodrow Wilson *"for their discovery of cosmic microwave background radiation"*.

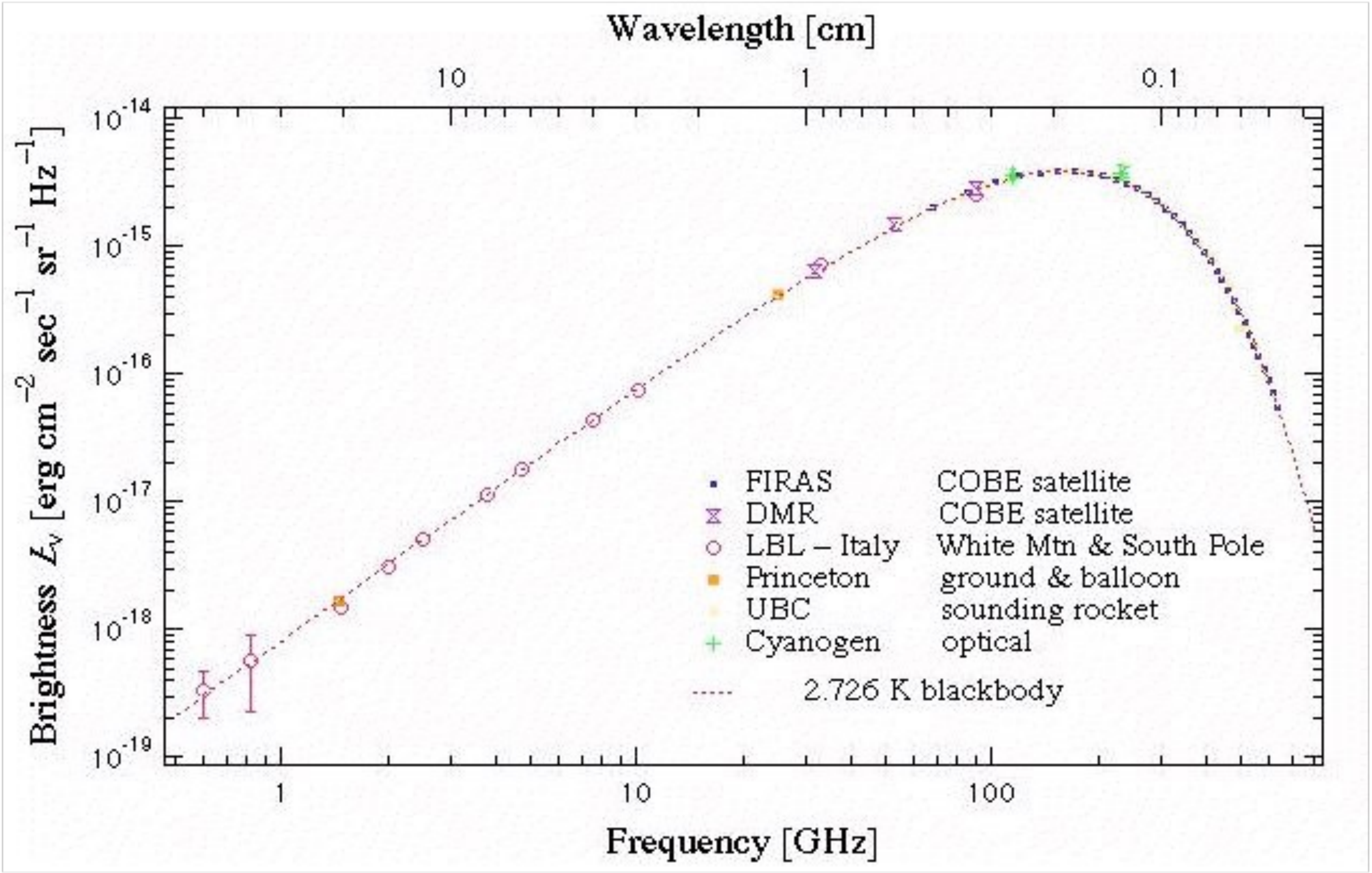
The Cosmic Background Explorer (COBE)

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



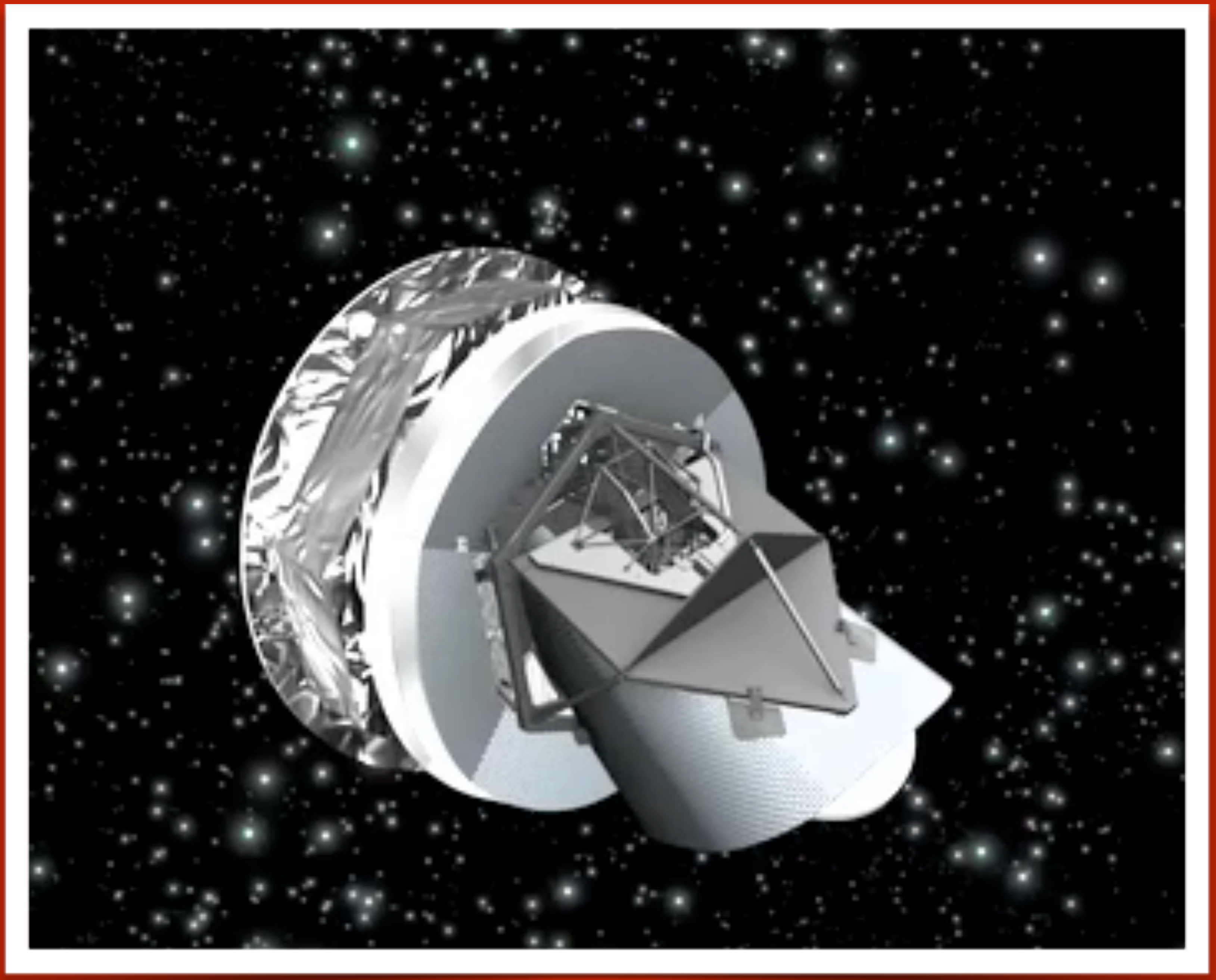
But they went further

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

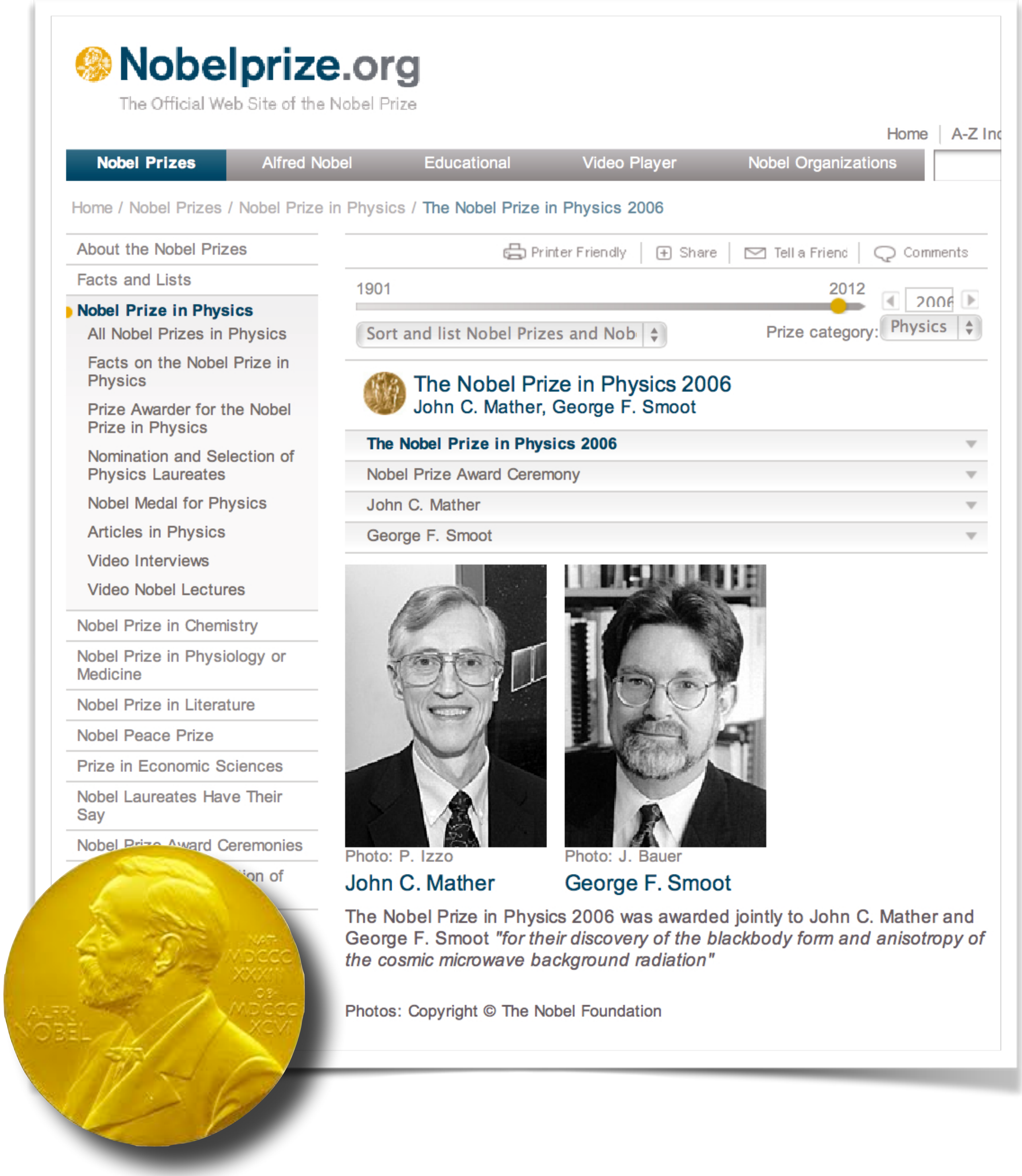


gotten better and better

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

John Mather and George Smoot

COBE principals



The Nobel Prize in Physics 2006
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"*

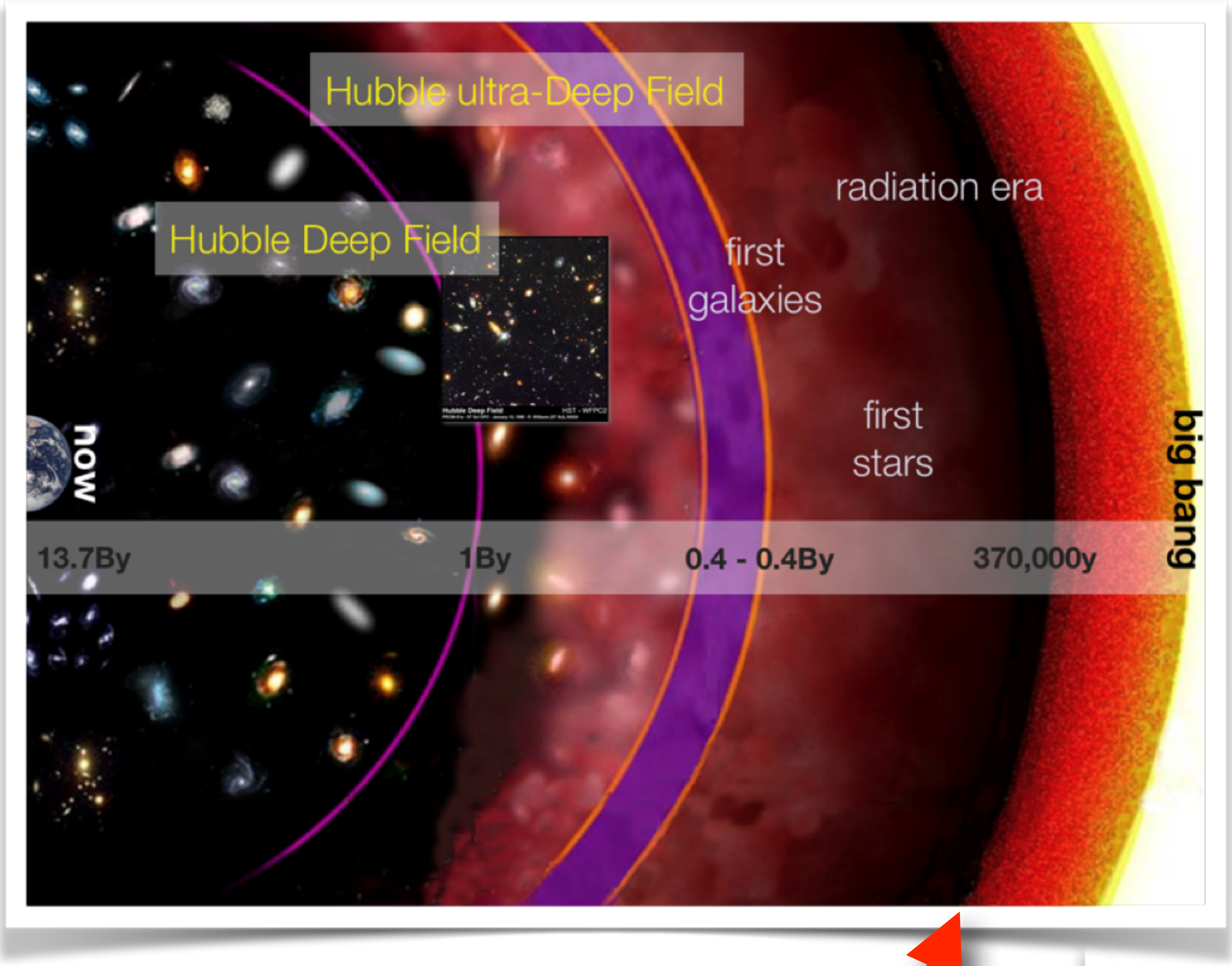
Photos: Copyright © The Nobel Foundation

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



opaque

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!

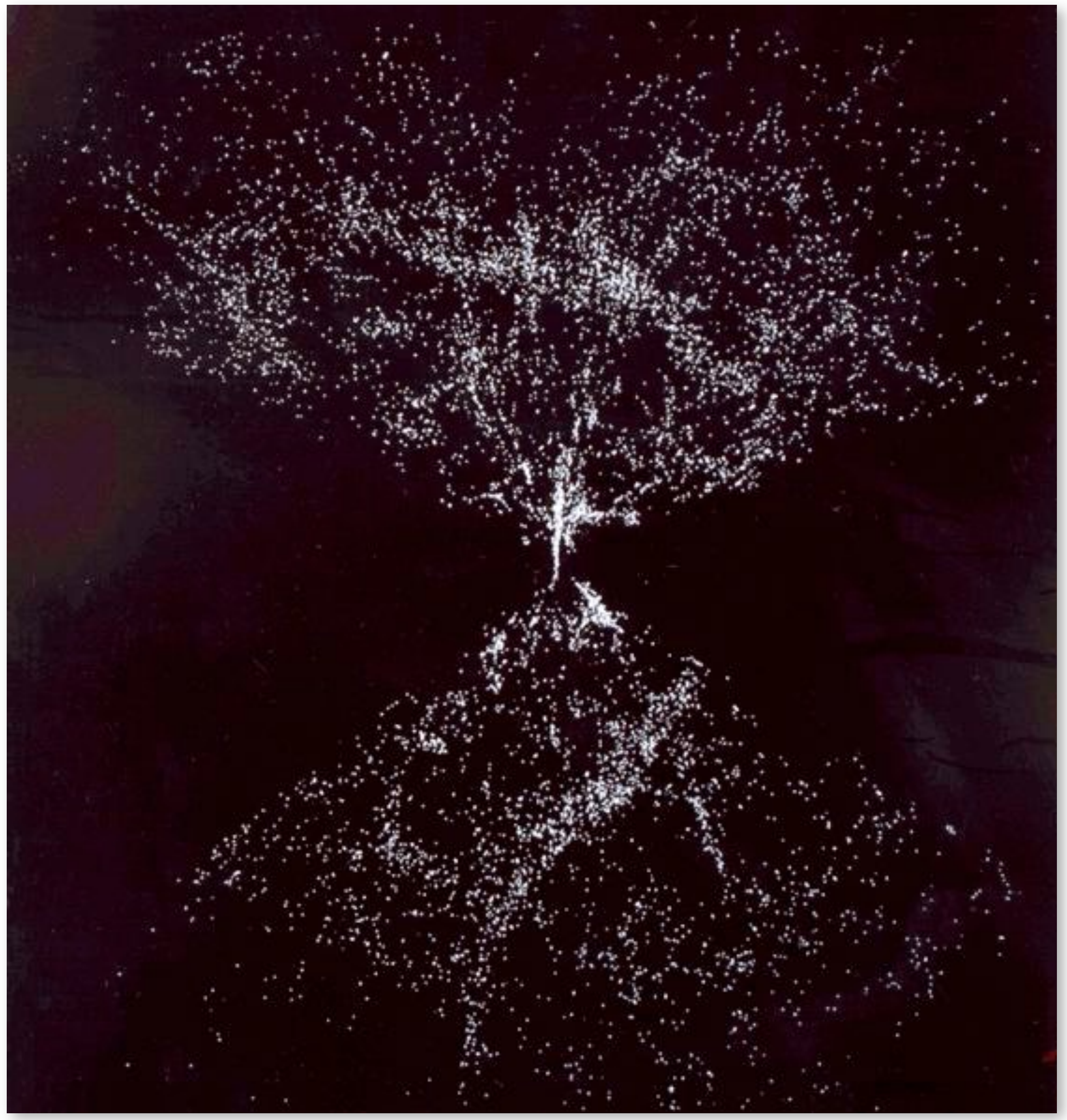
stay tuned.

There *is* structure in the universe

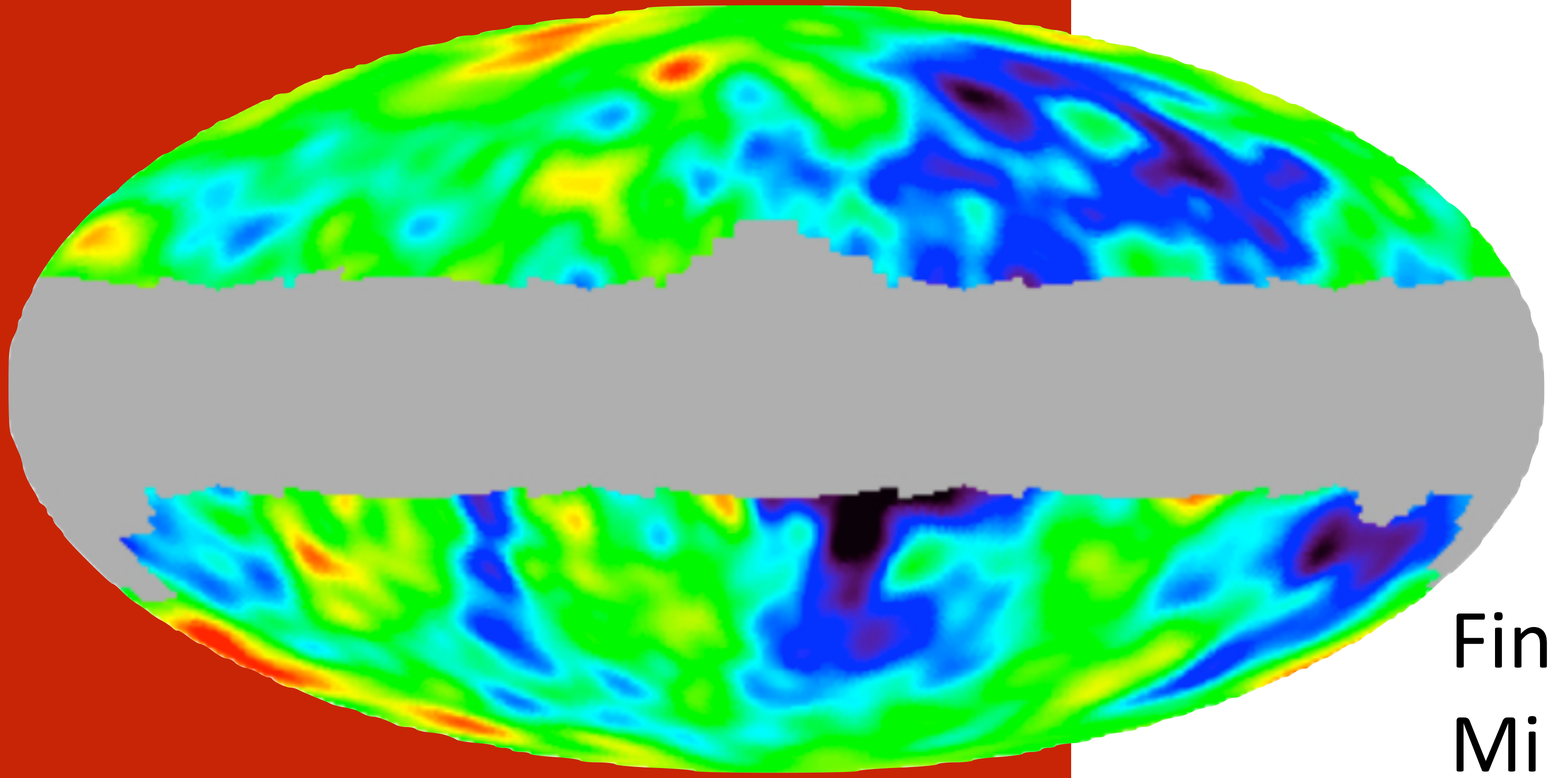
galaxies

planets

you, me



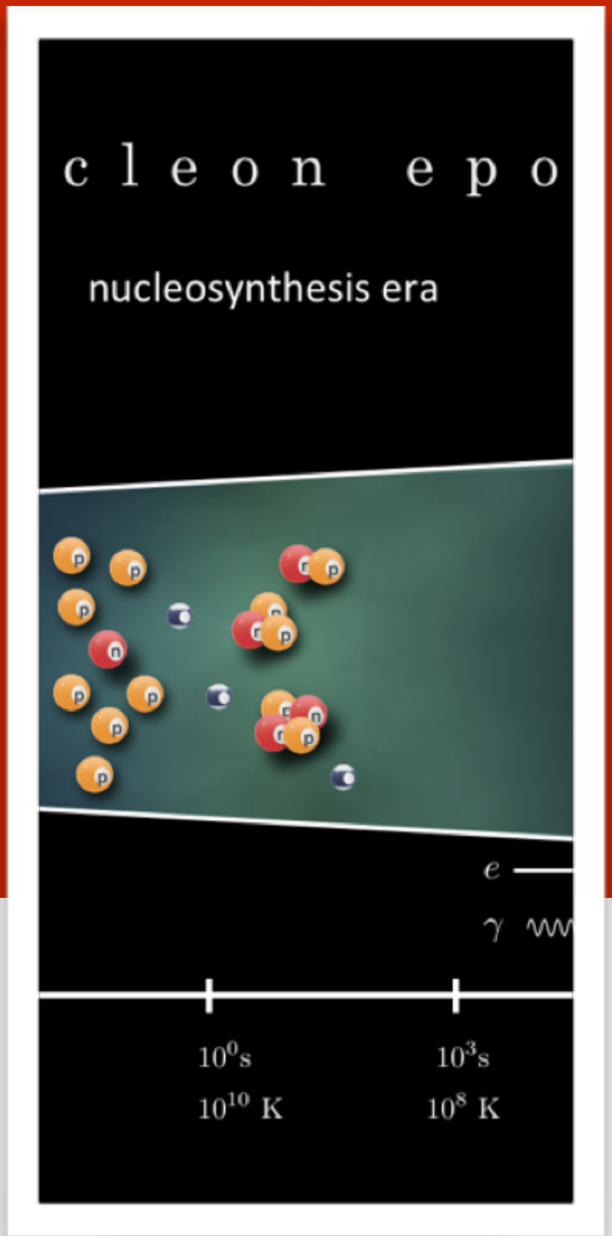
And, that's true. There is non-random structure: These filament-like strands are combinations of 11,000 galaxies (MW at the center).



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

Helium.

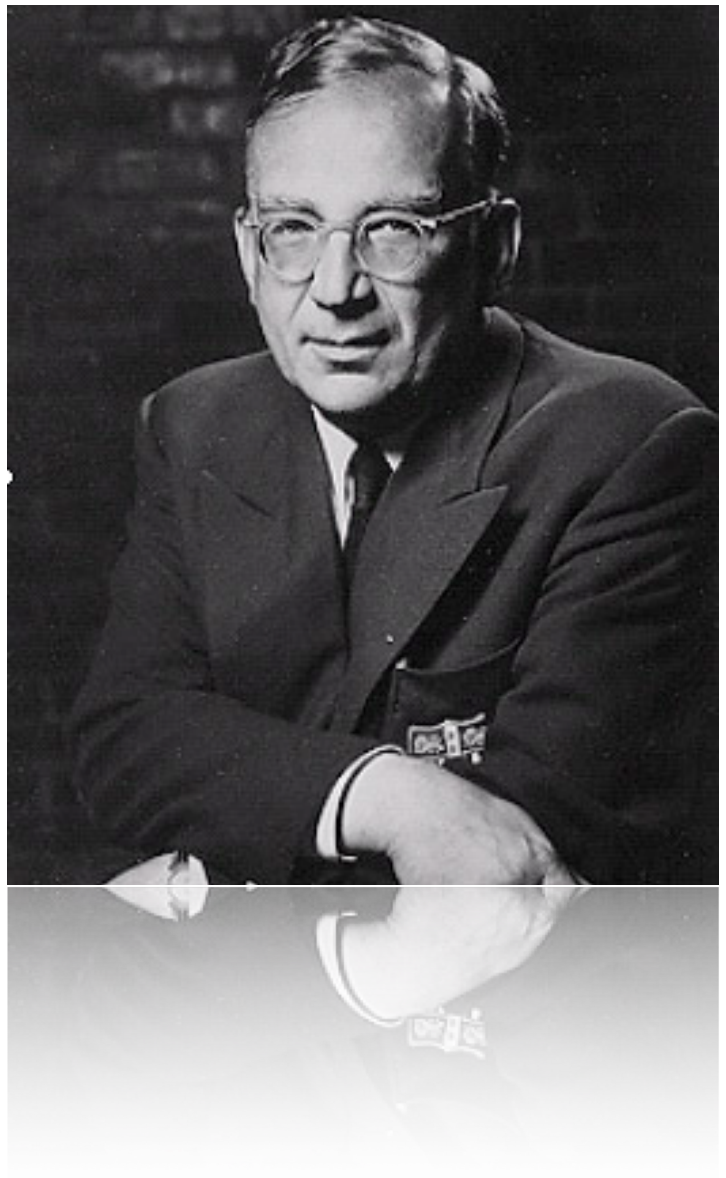
about 3 minutes after BB



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

''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

🟩 🟦 🟩 🟧

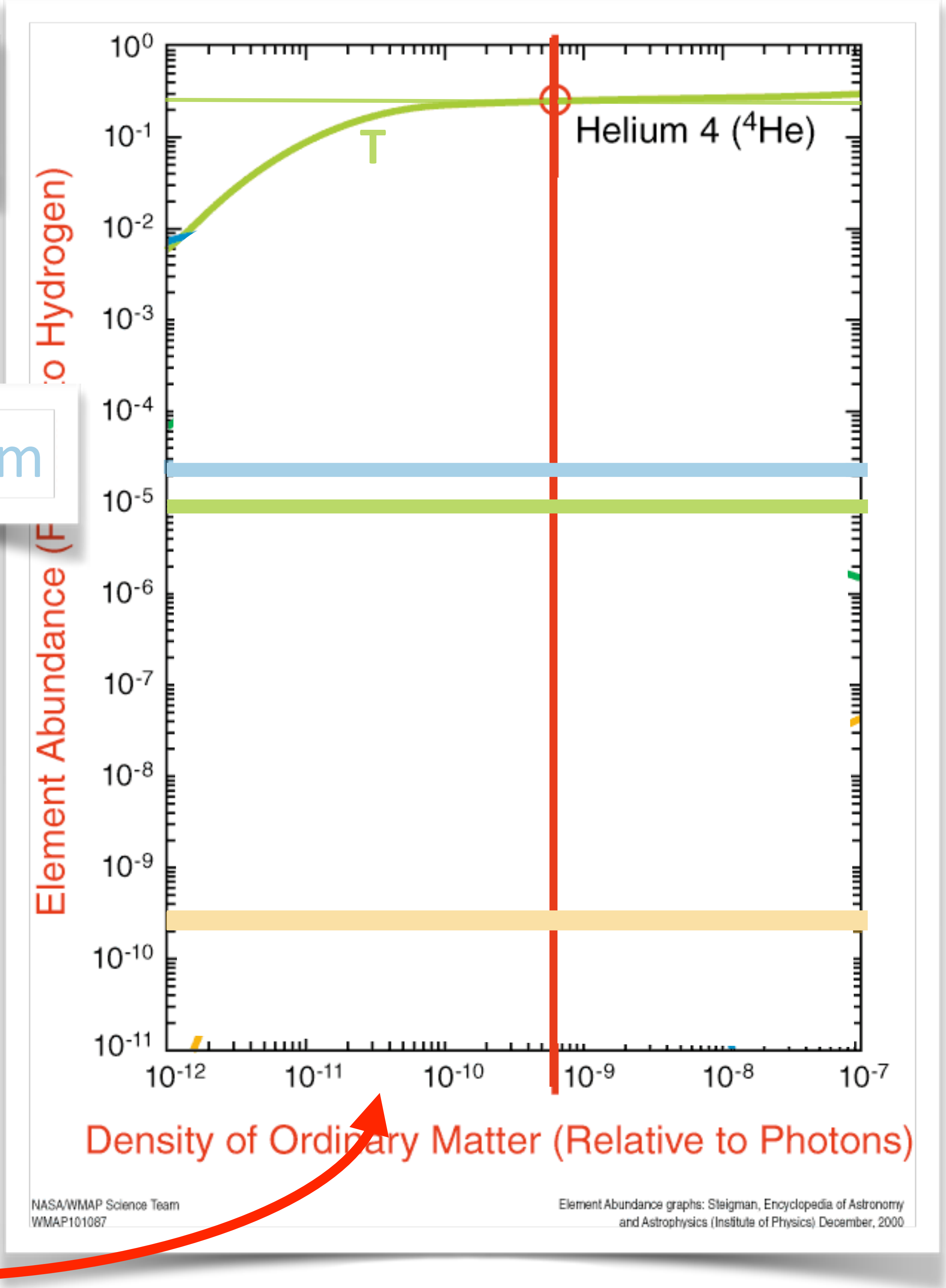
data, ^{4}He

data, Deuterium

data, ^{3}He

data, Li

data



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

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 x 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

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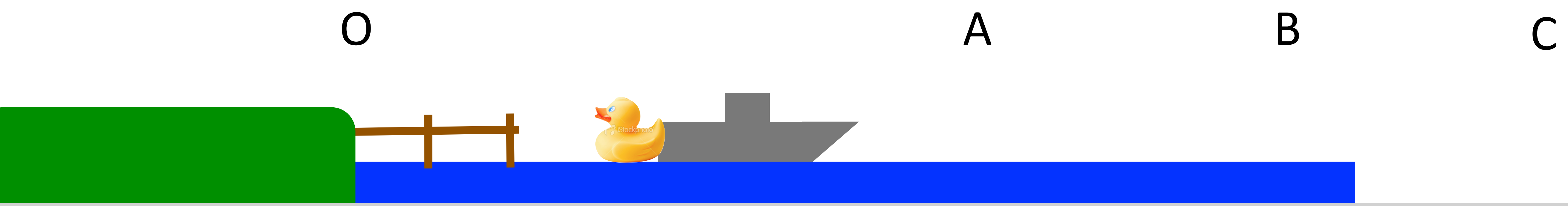


How far away is the boat? OA? ...like the 13.82 B years number.

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.

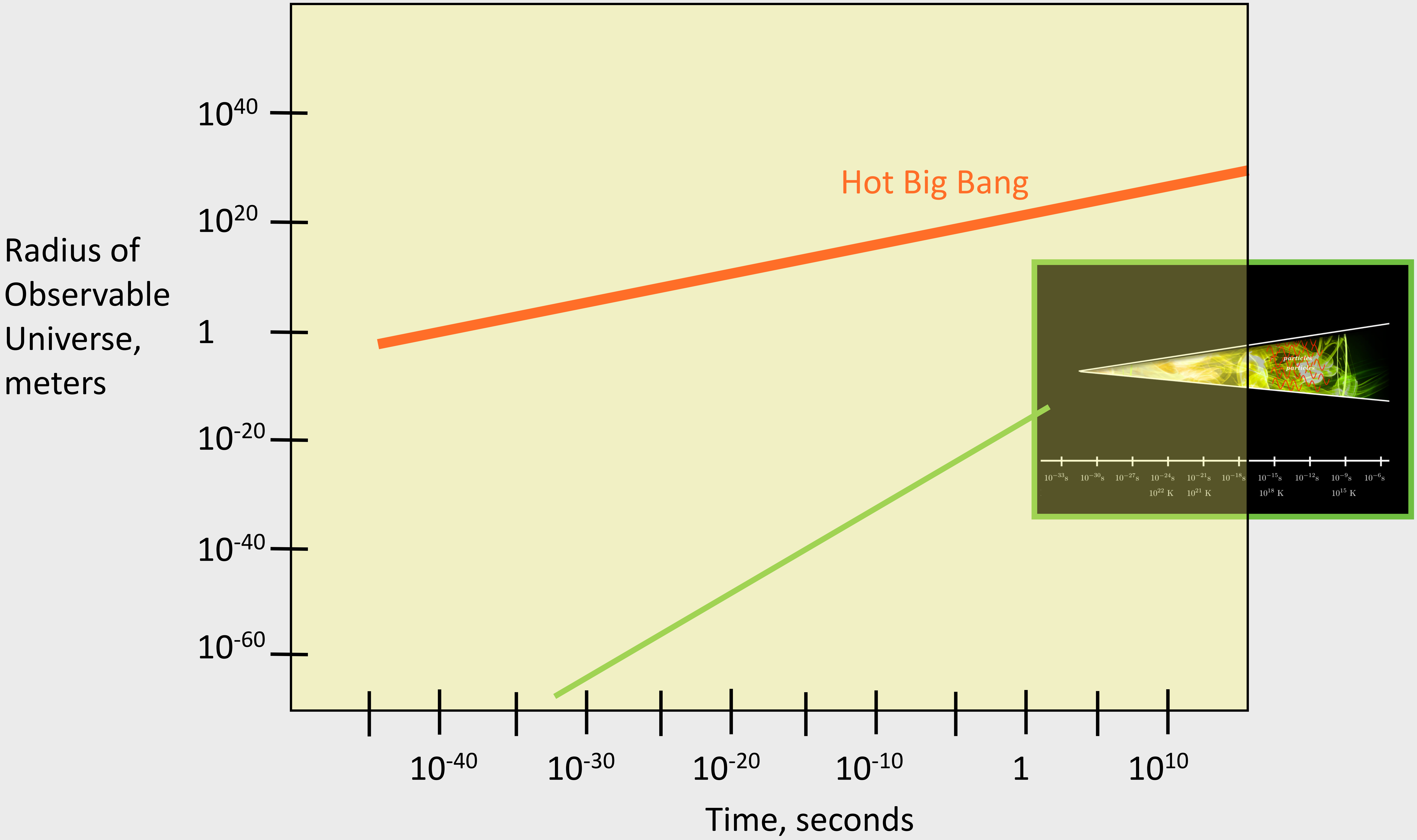
If the ocean stretches over time...you might even say that it’s OC away.

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?



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

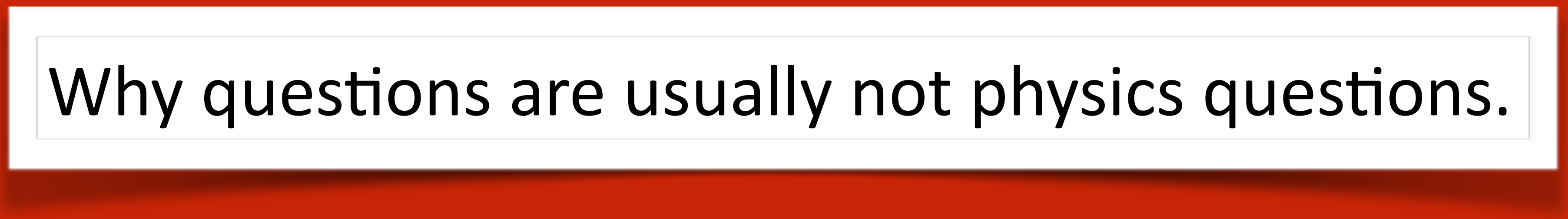
famously called:

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?”

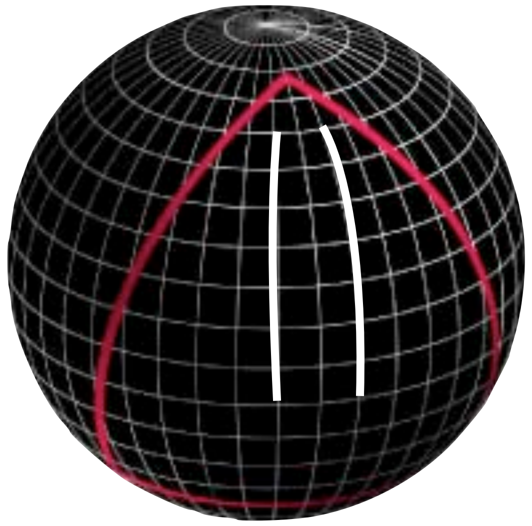
scientifically, we almost always mean: “How is X the way it is?”

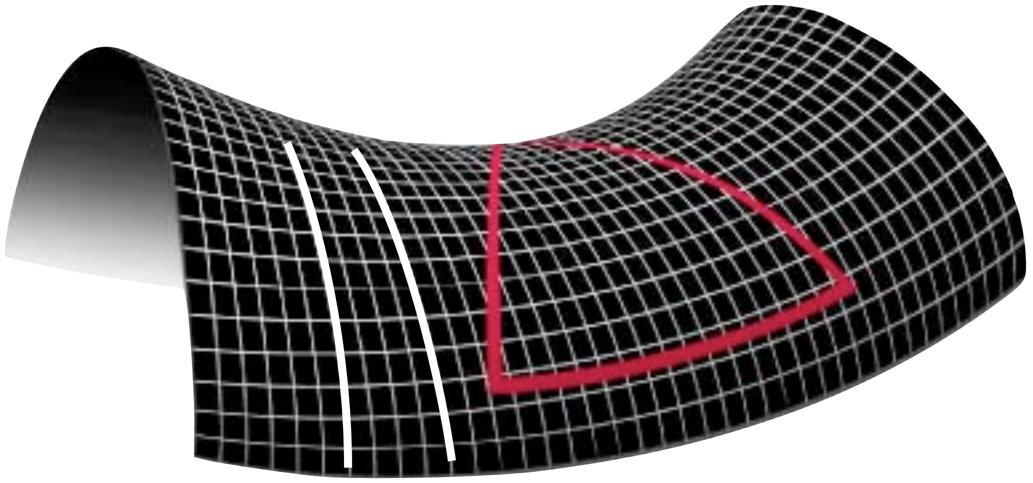


Why questions are usually not physics questions.

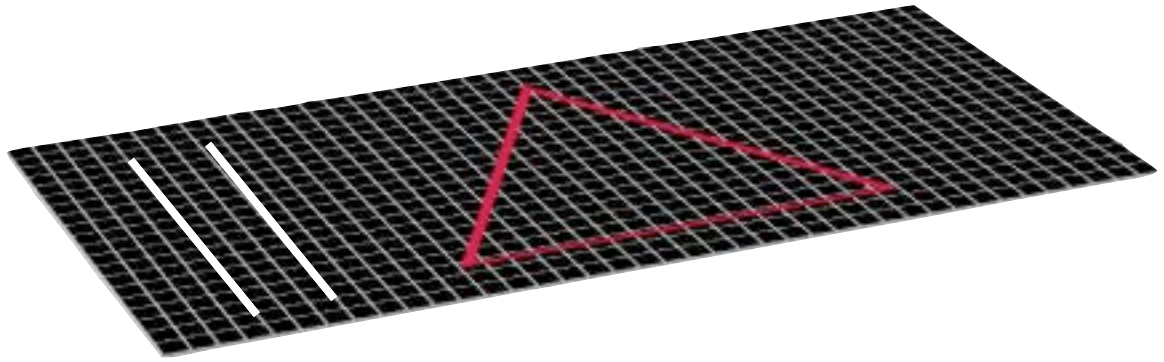
curvature, “k” – hypervolumes

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





$k = 0$, no curvature
infinite, unbounded



$k = -1$, negative 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:

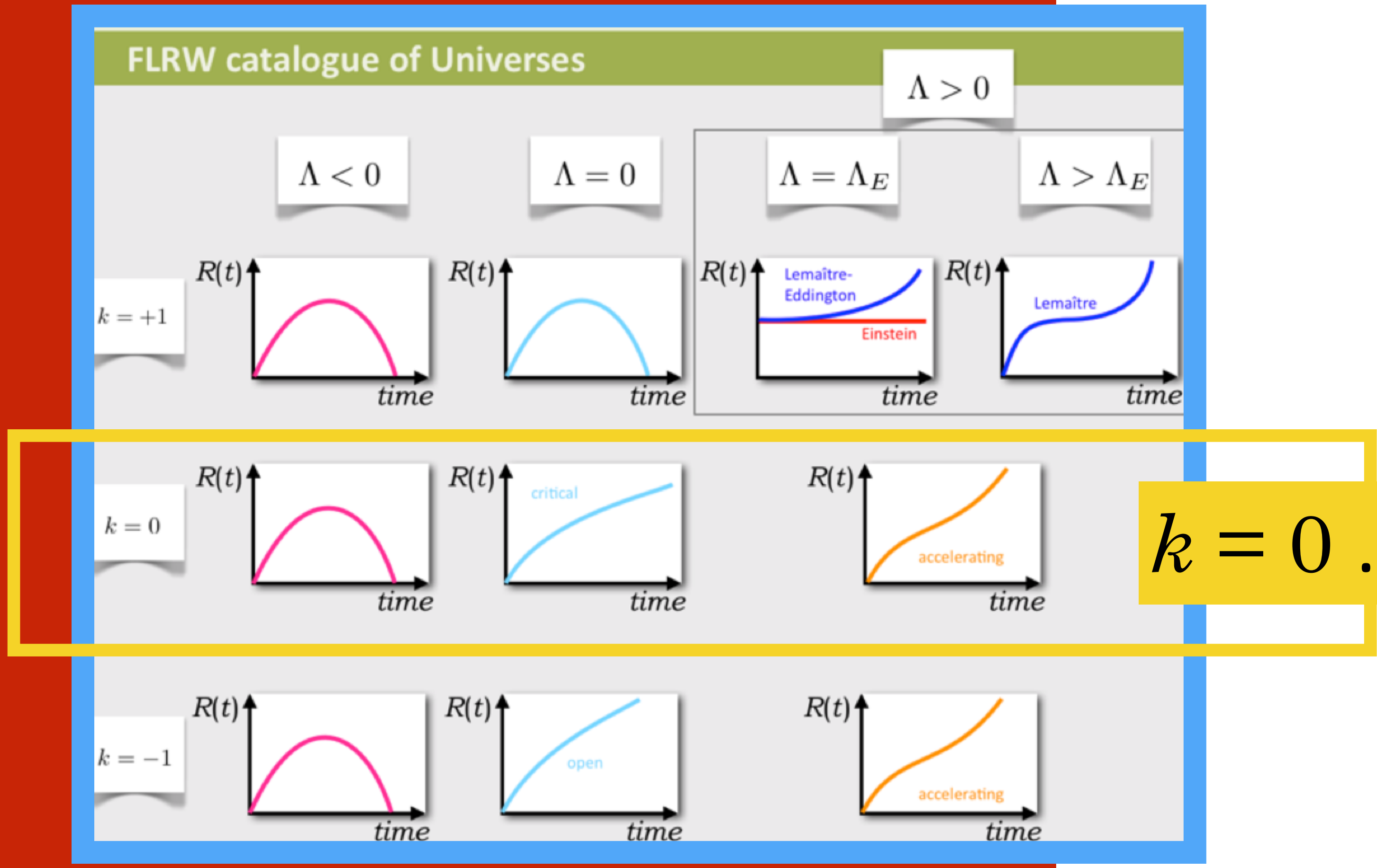
Hubble Constant, H

Mass density, ρ

Like Goldilocks:

if H and ρ are just right...

the universe will be flat



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

from Friedman Equation

gathering constants...

$$k \propto H^2(\frac{C\rho}{H^2} - 1)$$ $$\boxed{= H^2\,(\Omega_m - 1)}$$

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*...
$\rho_c \sim 10^{-26}\ \mathrm{kg\ m}^{-3}$

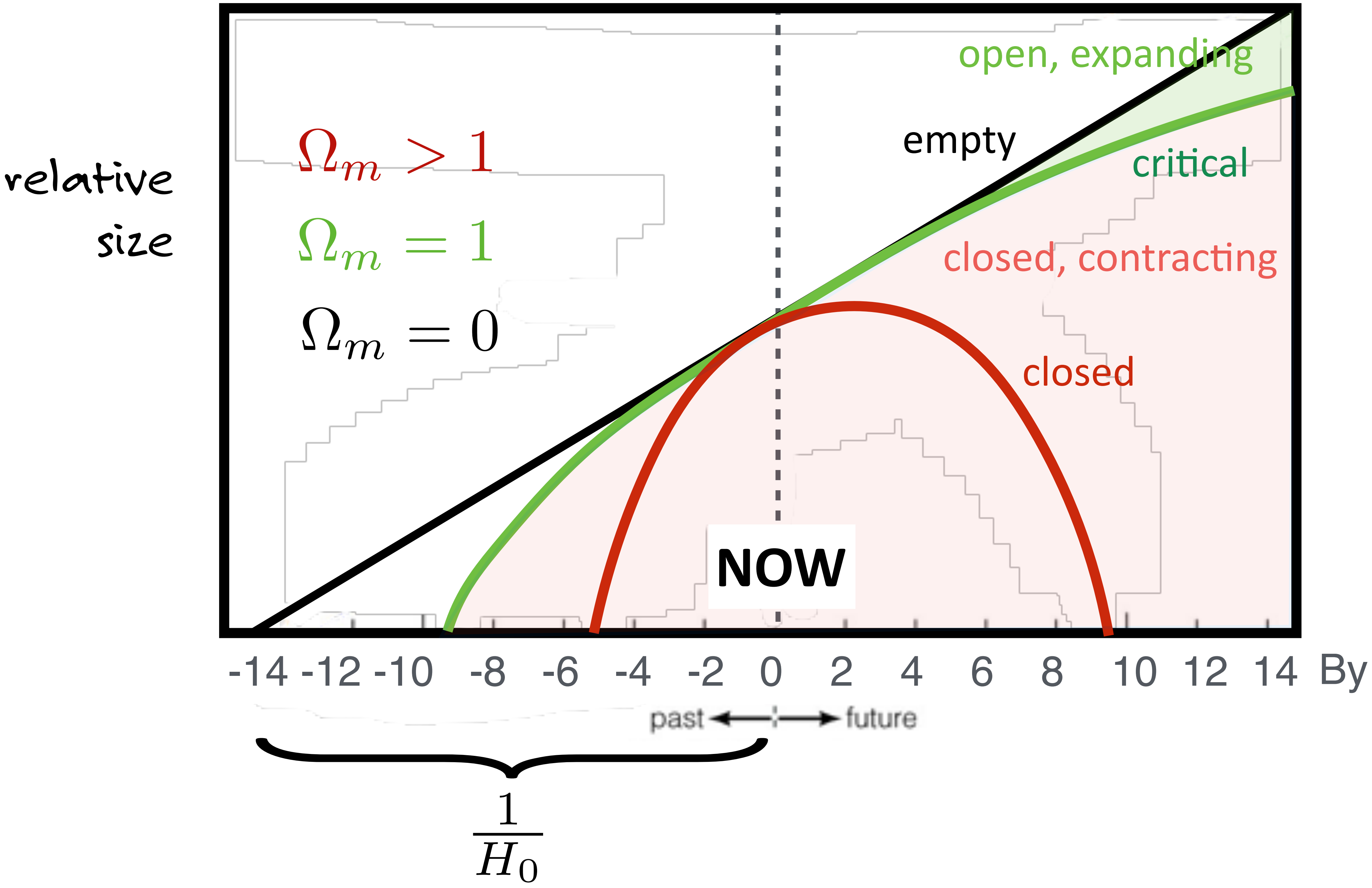
about 5 Hydrogen atoms per cubic meter

define the “density parameter:

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

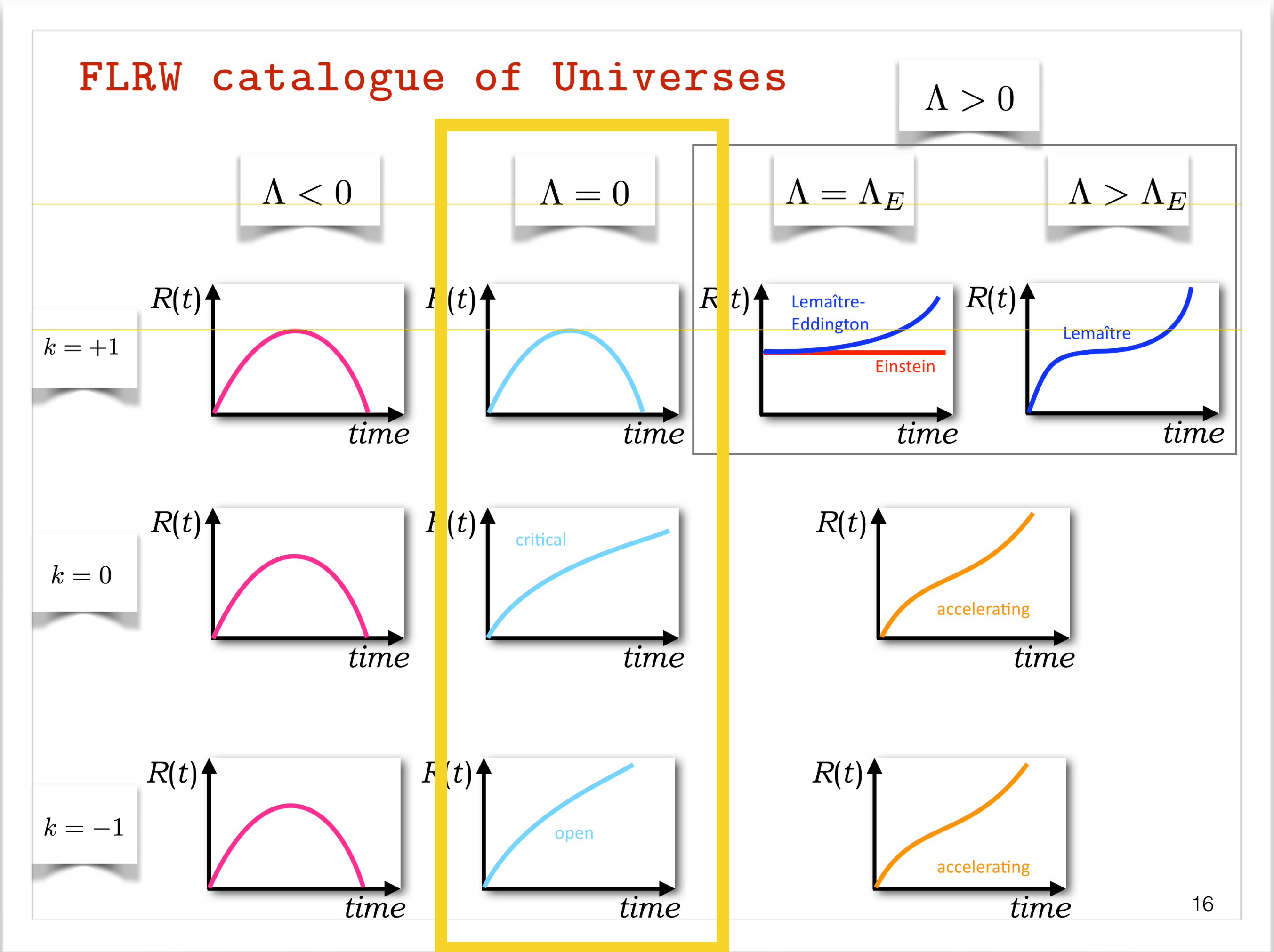
$\Omega_m(t) = 1$ is the boundary between flat and either closed or open geometries.

Competition



Between expansion (Hubble Parameter)

Gravitation (Density)



FLRW catalogue of Universes

$\Lambda > 0$

	$\Lambda < 0$	$\Lambda = 0$	$\Lambda = \Lambda_E$	$\Lambda > \Lambda_E$
$k = +1$			Lemaître-Eddington Einstein	Lemaître
$k = 0$		critical	accelerating	
$k = -1$		open	accelerating	

what can be measured?

many quantities

1. **Hubble Constant**

   from velocities of far-away galaxies

2. **large-scale densities**

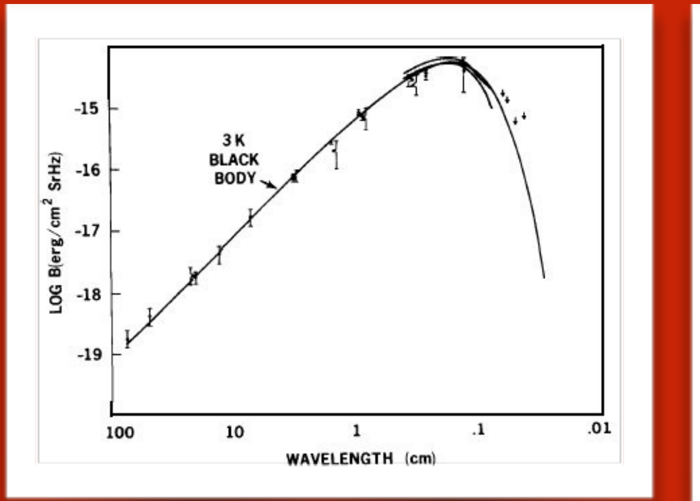
   motions of galaxies

   the Cosmic Microwave Background, CMB

3. **“baryon densities”**

   survey of stuff that shines...mostly Hydrogen

   from the CMB

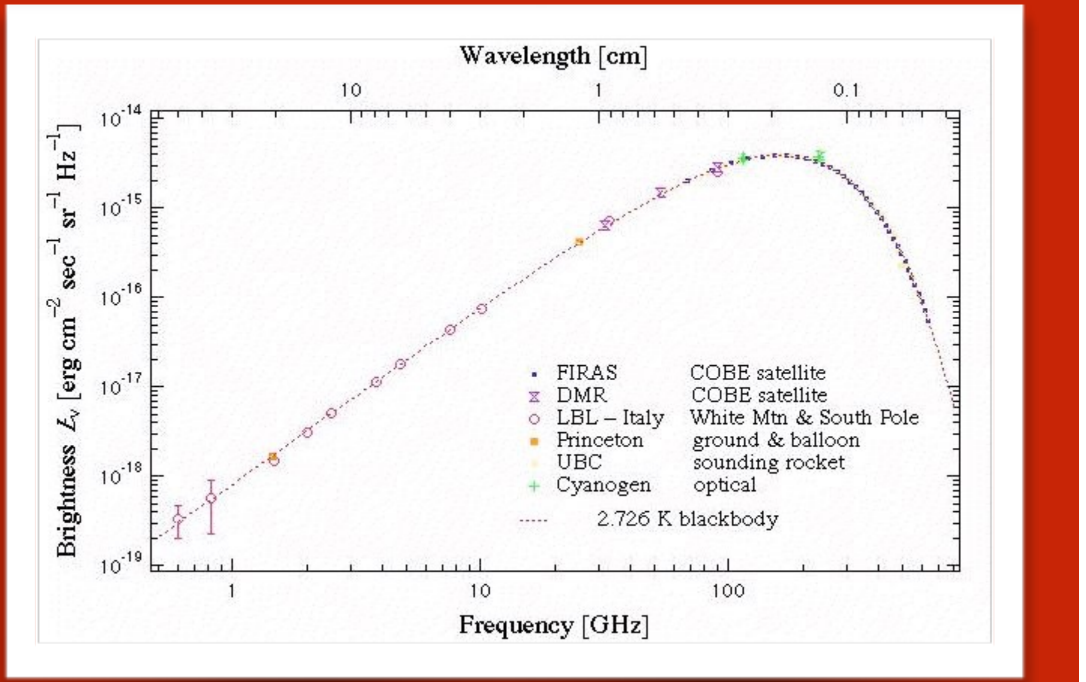


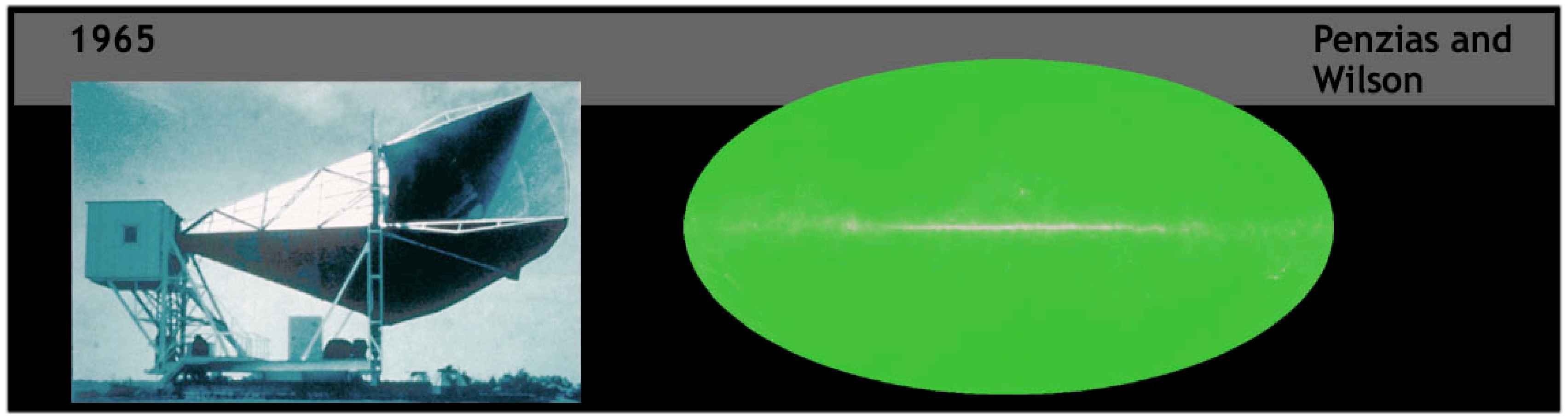
CMB:

1965 - 1992

this is the point of "last scattering"

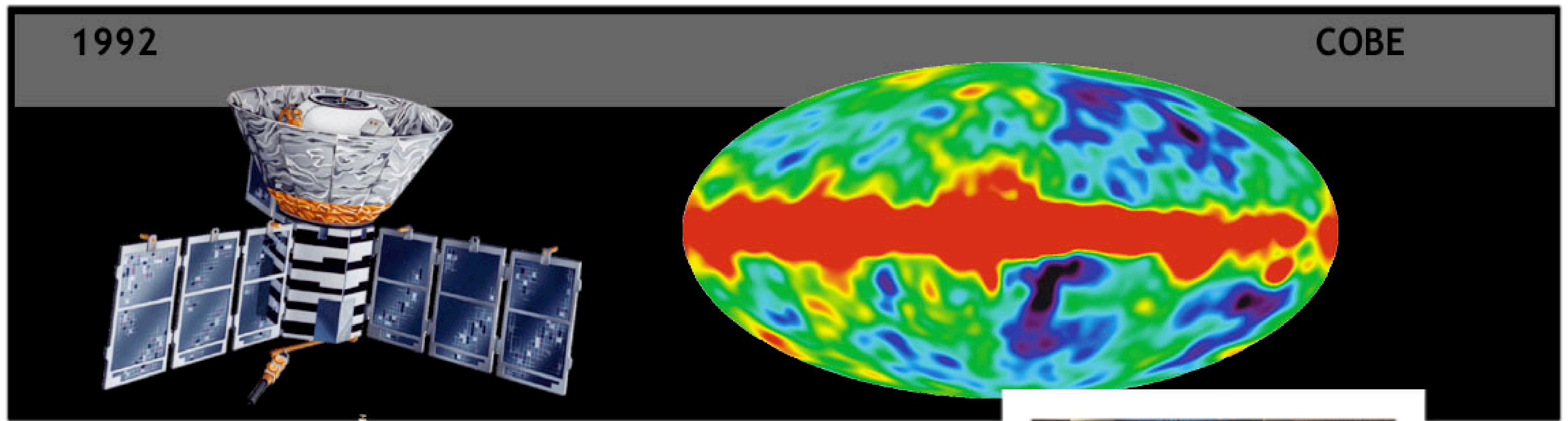
of the photons at 370,000 years ABB





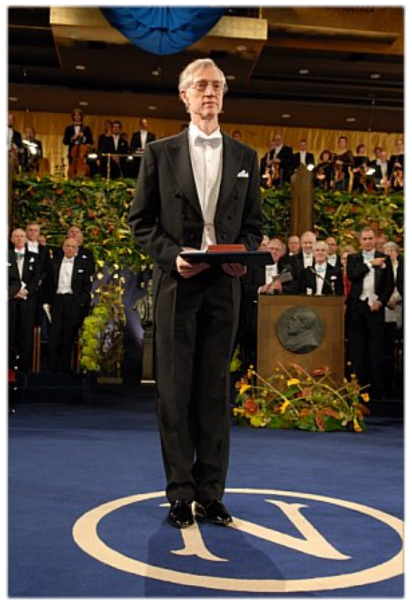
Penzias and Wilson, from the phone company.

Robert Wilson Anro Penzias, 1978



could distinguish about 7°

COBE...

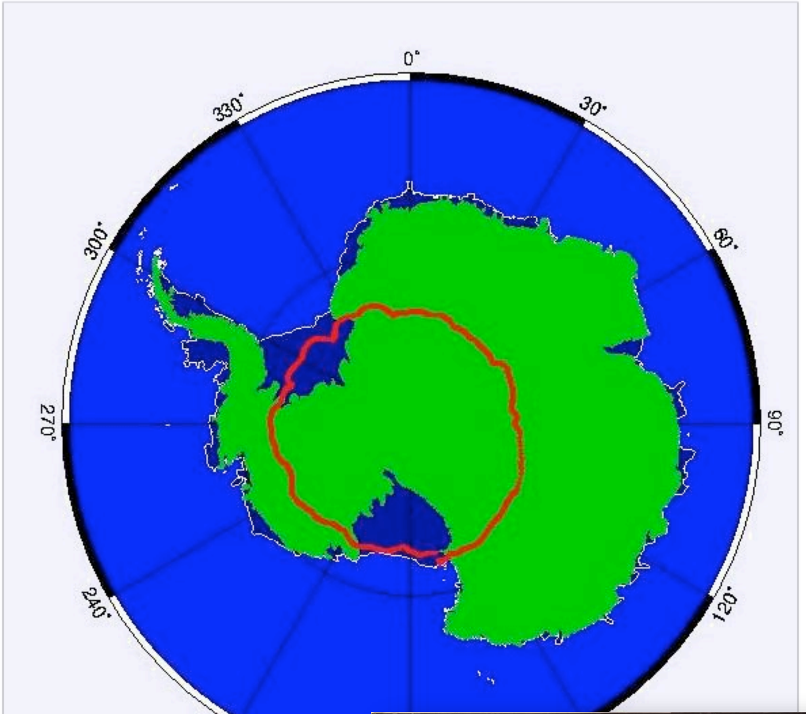


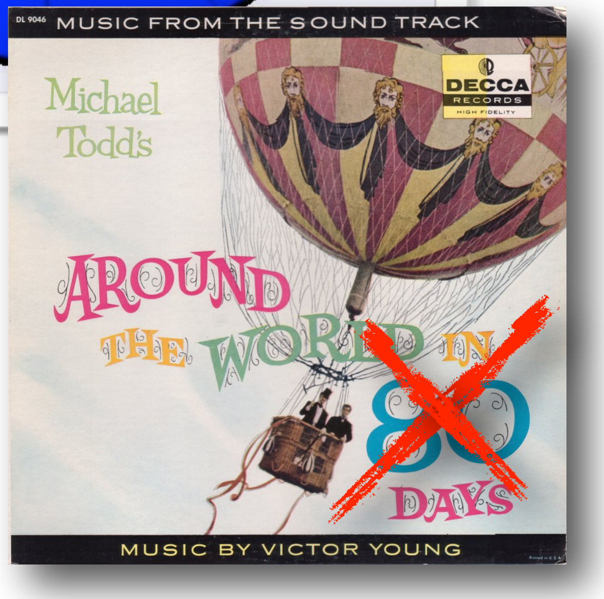
George Smoot and John Mather, 2006

problem #1

the flatness problem.

CMB, 1999

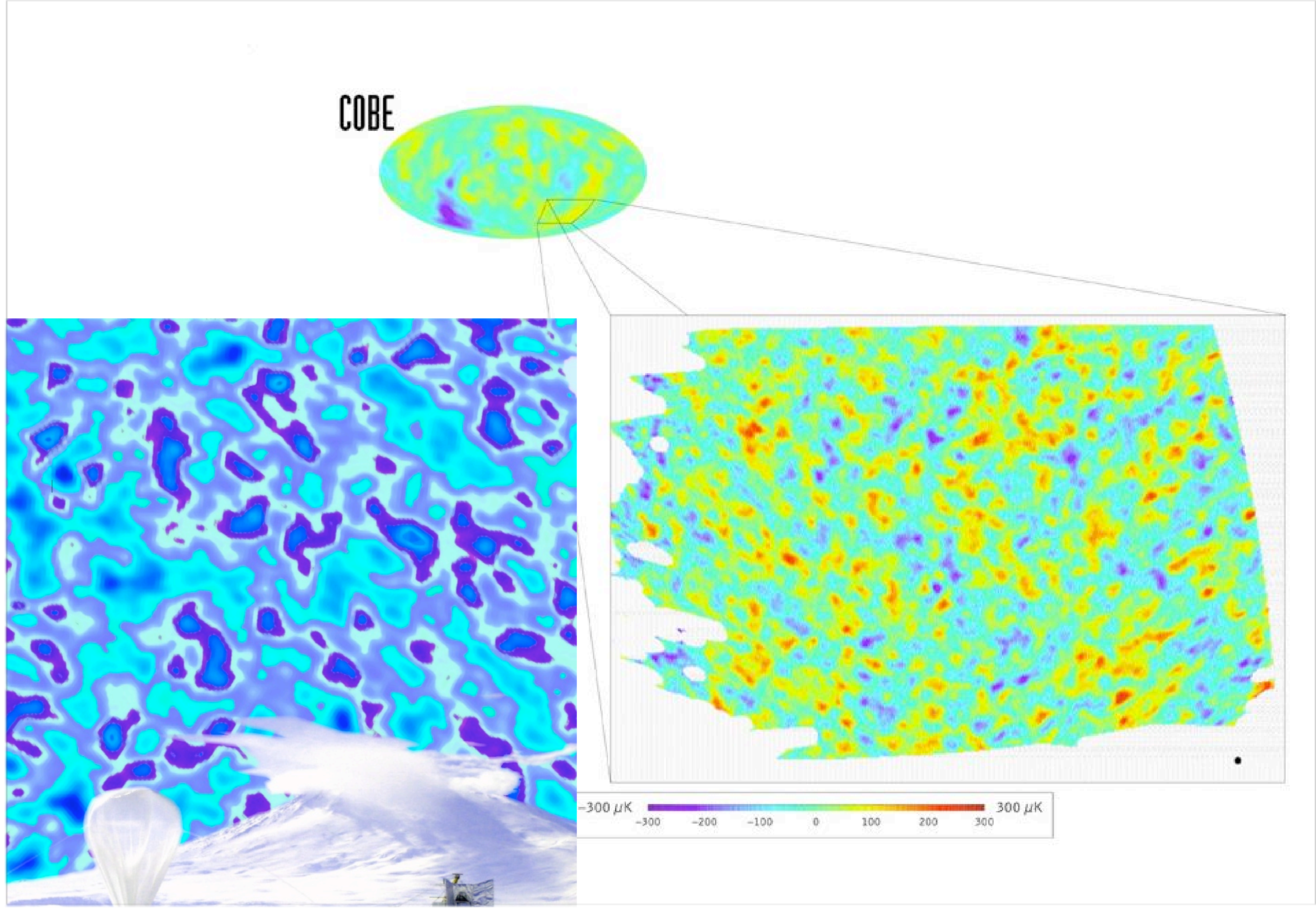




Around the world in 10 days...from Antarctica

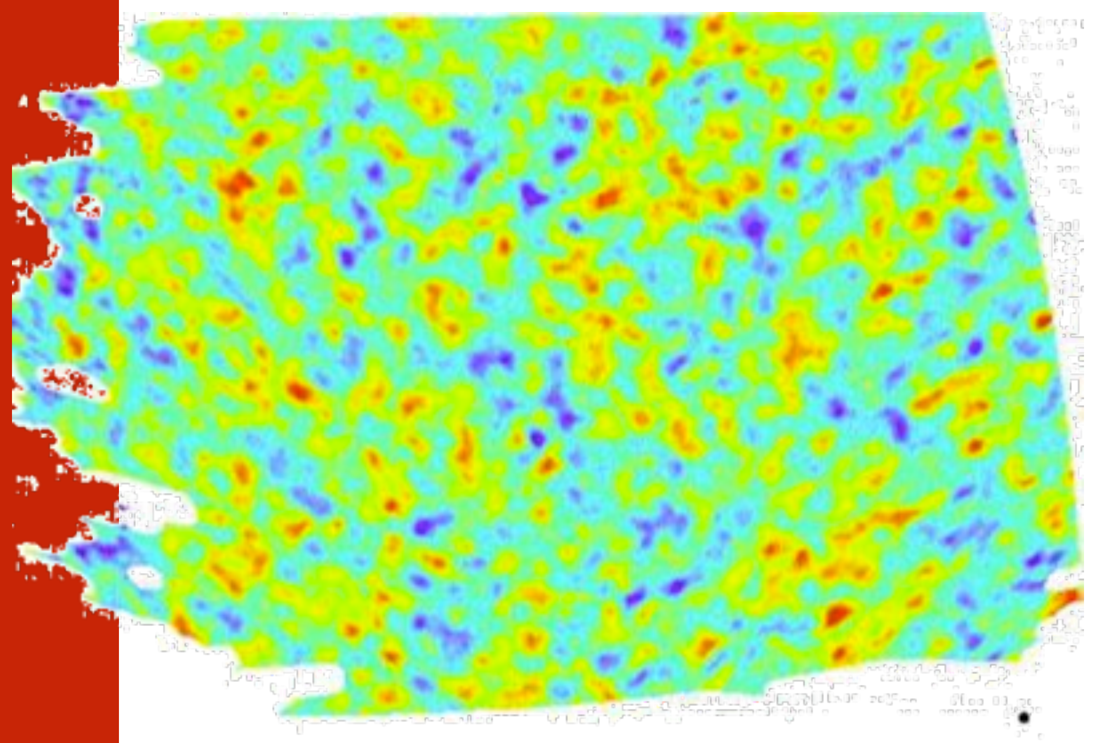
Balloon **O**bservations
Of **M**illimetric
Extragalactic
Radiation **AN**isotropy
and **G**eophysics...

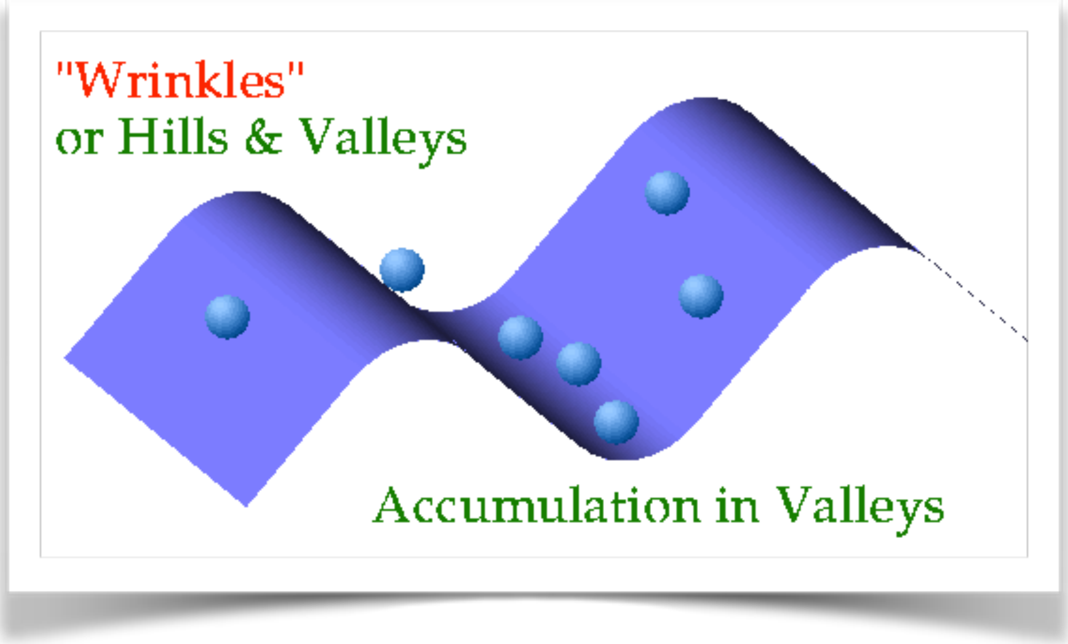
BOOMERANG



could distinguish about 0.3°

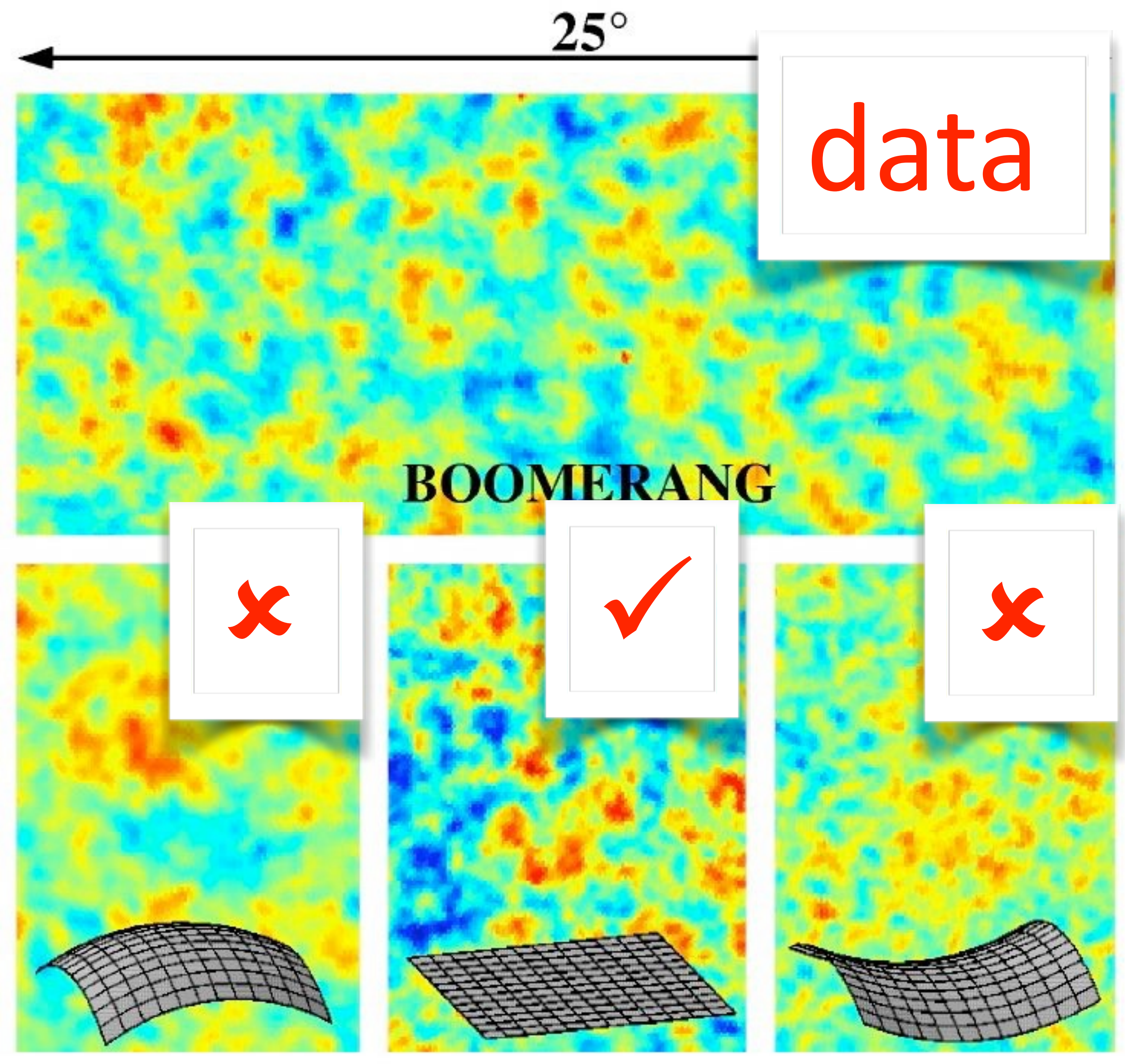
the temperature fluctutation pattern is a measurement of curvature

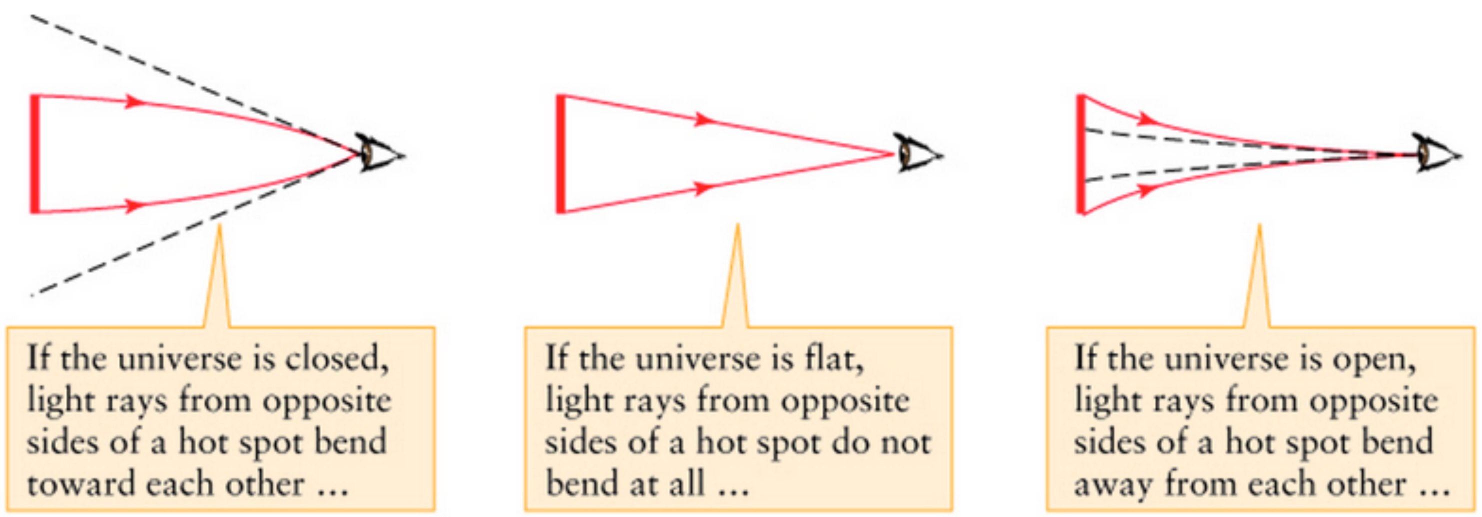




“high” temperature means high density regions
“low” temperature means low density regions

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





If the universe is closed, light rays from opposite sides of a hot spot bend toward each other ...

If the universe is flat, light rays from opposite sides of a hot spot do not bend at all ...

If the universe is open, light rays from opposite sides of a hot spot bend away from each other ...

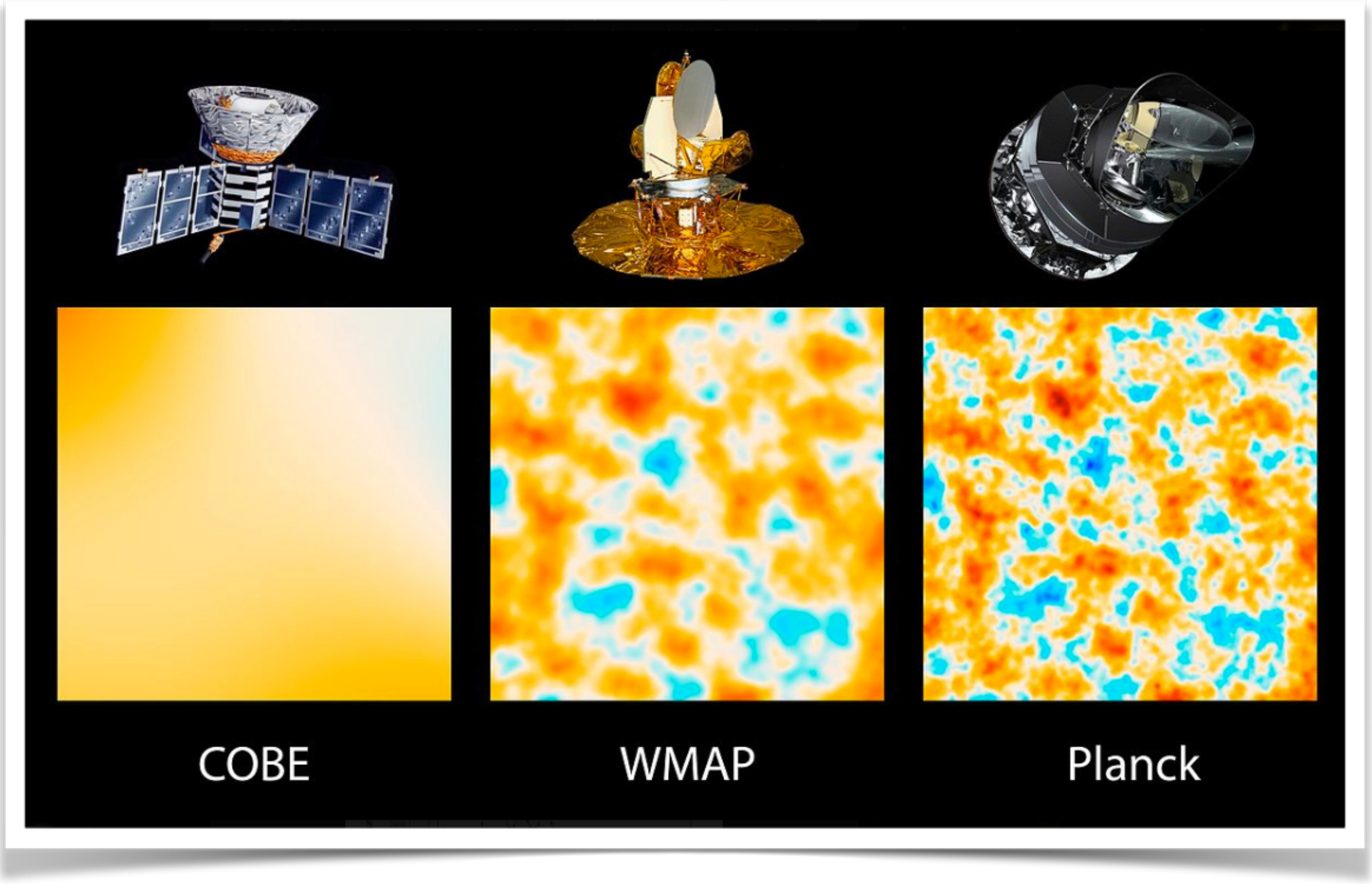
Can be modeled for that moment of last scattering...

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

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

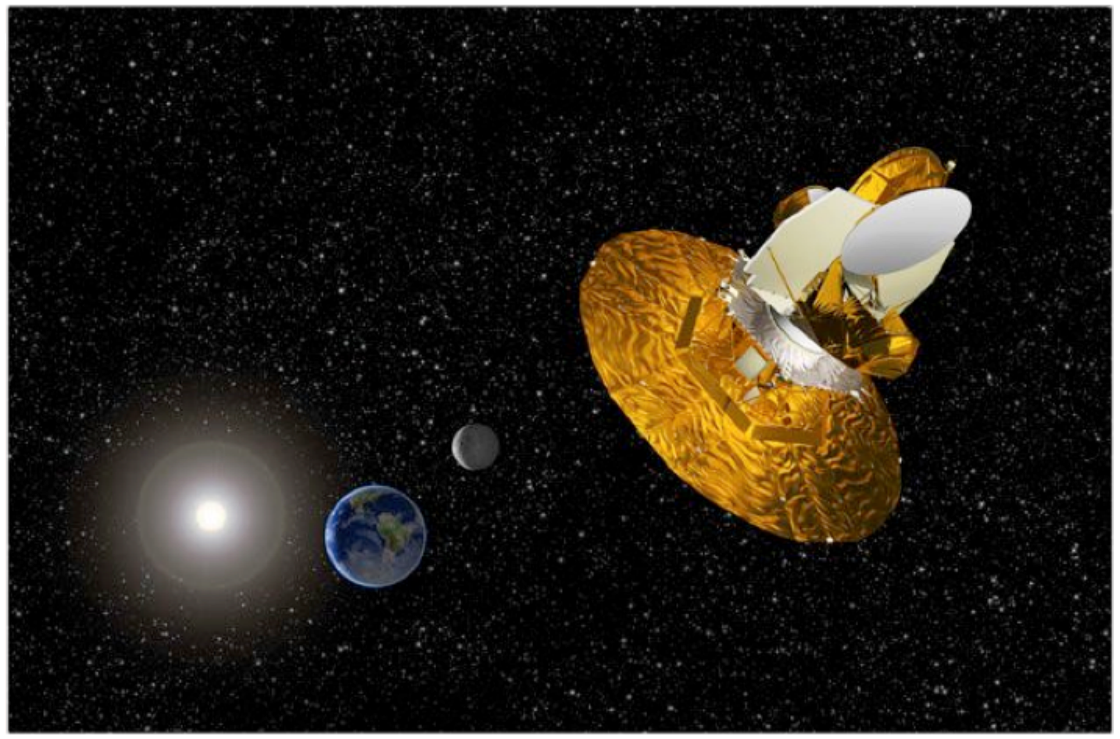
This measurement has evolved

Cosmology is actually now a precision science.



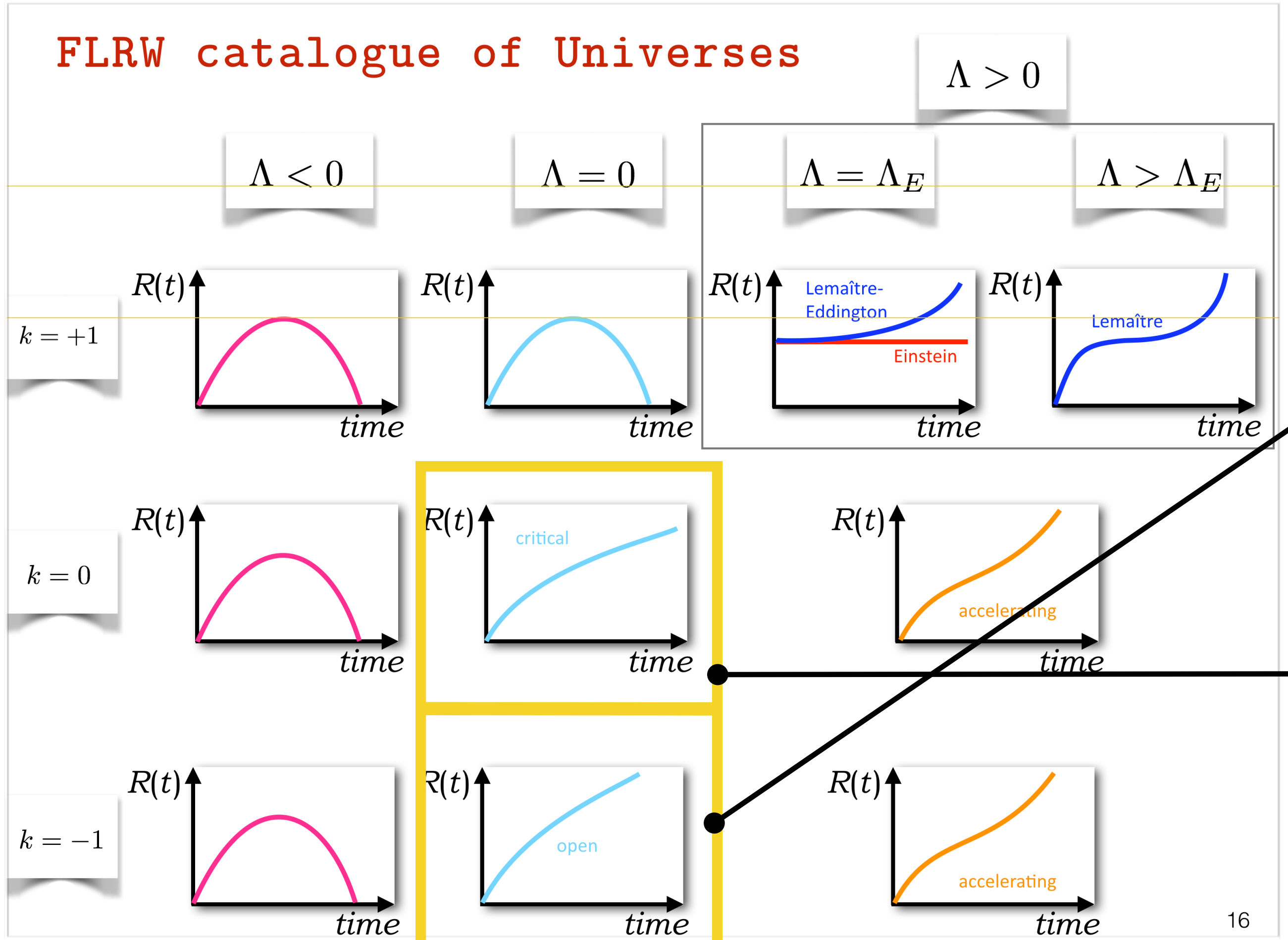
COBE’s resolution was 7 degrees.

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

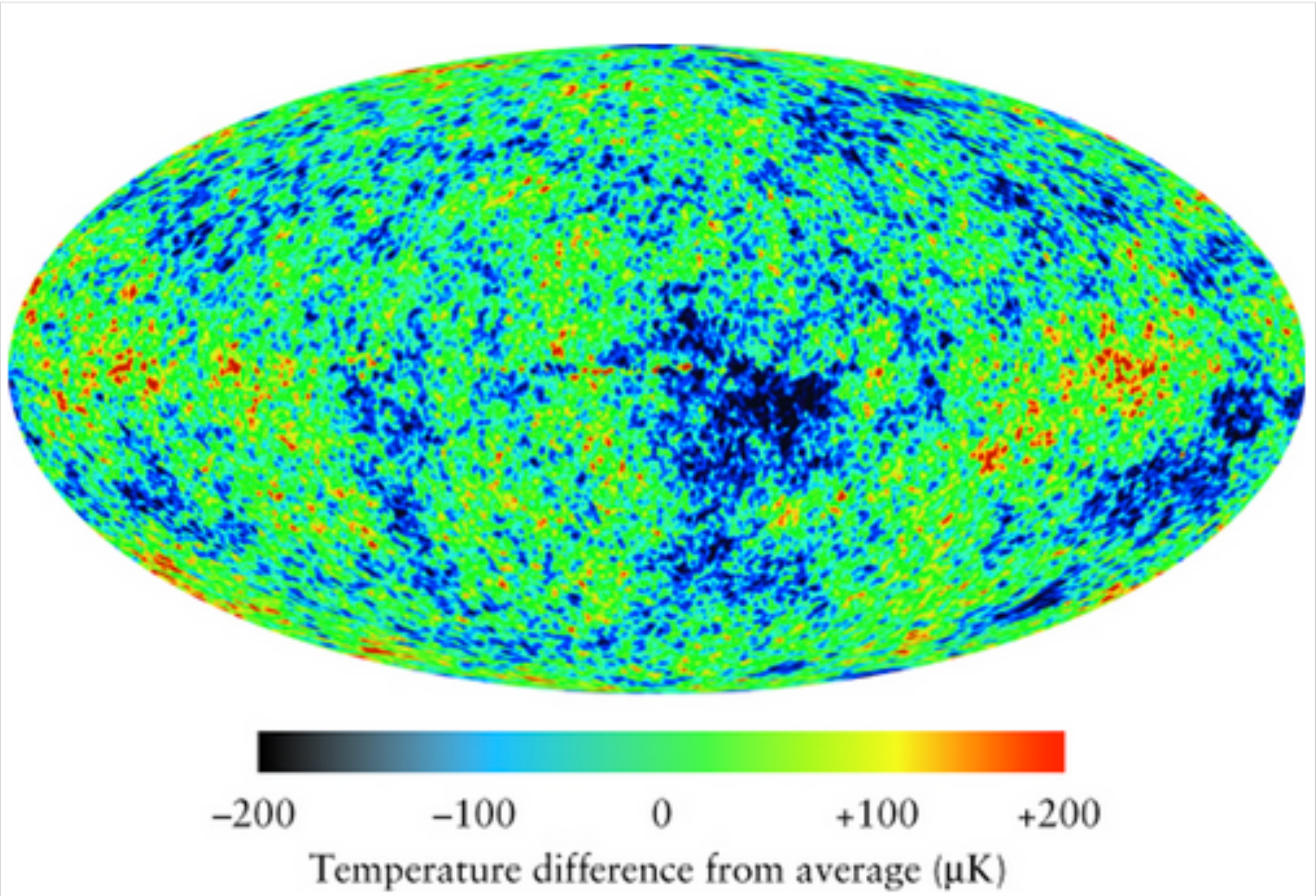


WMAP... Wilkinson Microwave Anisotropy Probe

Planck just 2013!



FLRW catalogue of Universes



From multiple, different kinds of measurements:

$$\Omega_m(t) = \cancel{0.27 \pm 0.04}$$

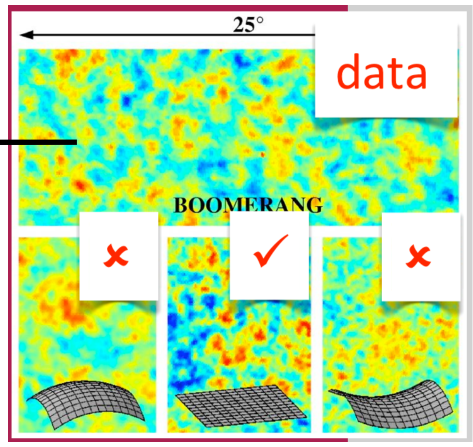
0.308 ± ~0.010

$$\Omega_m(t) \neq 1 \text{ !}$$

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

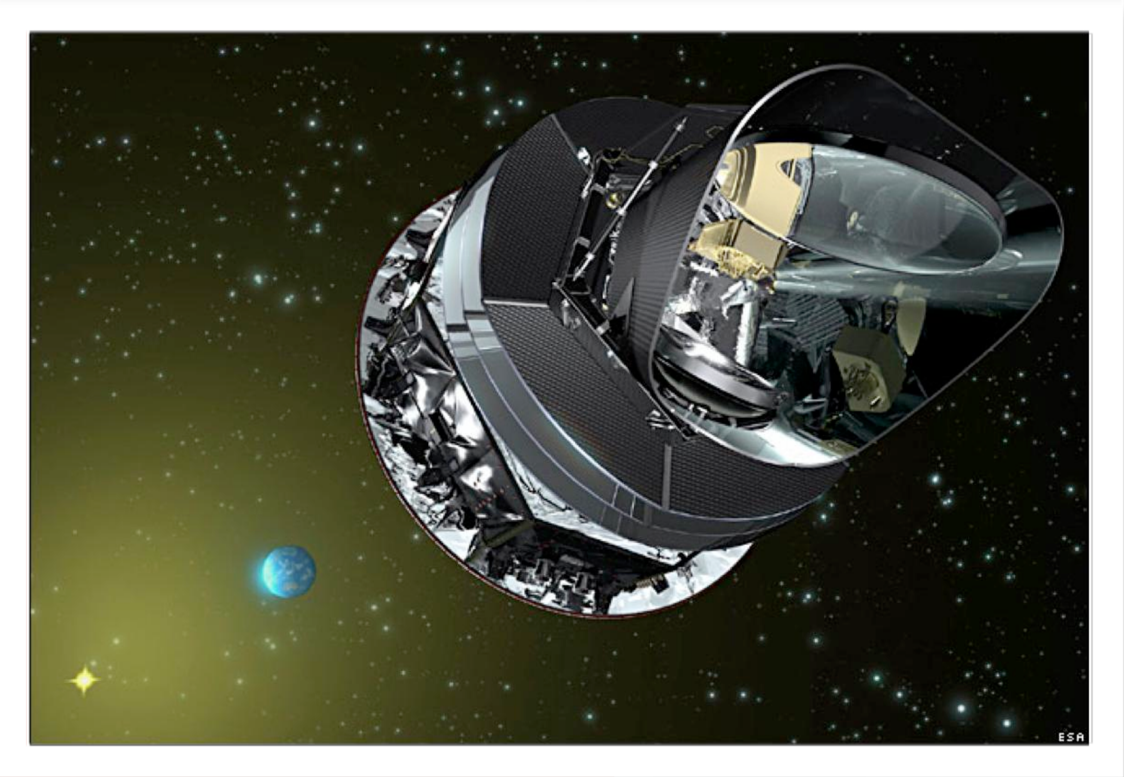
suggests k <1

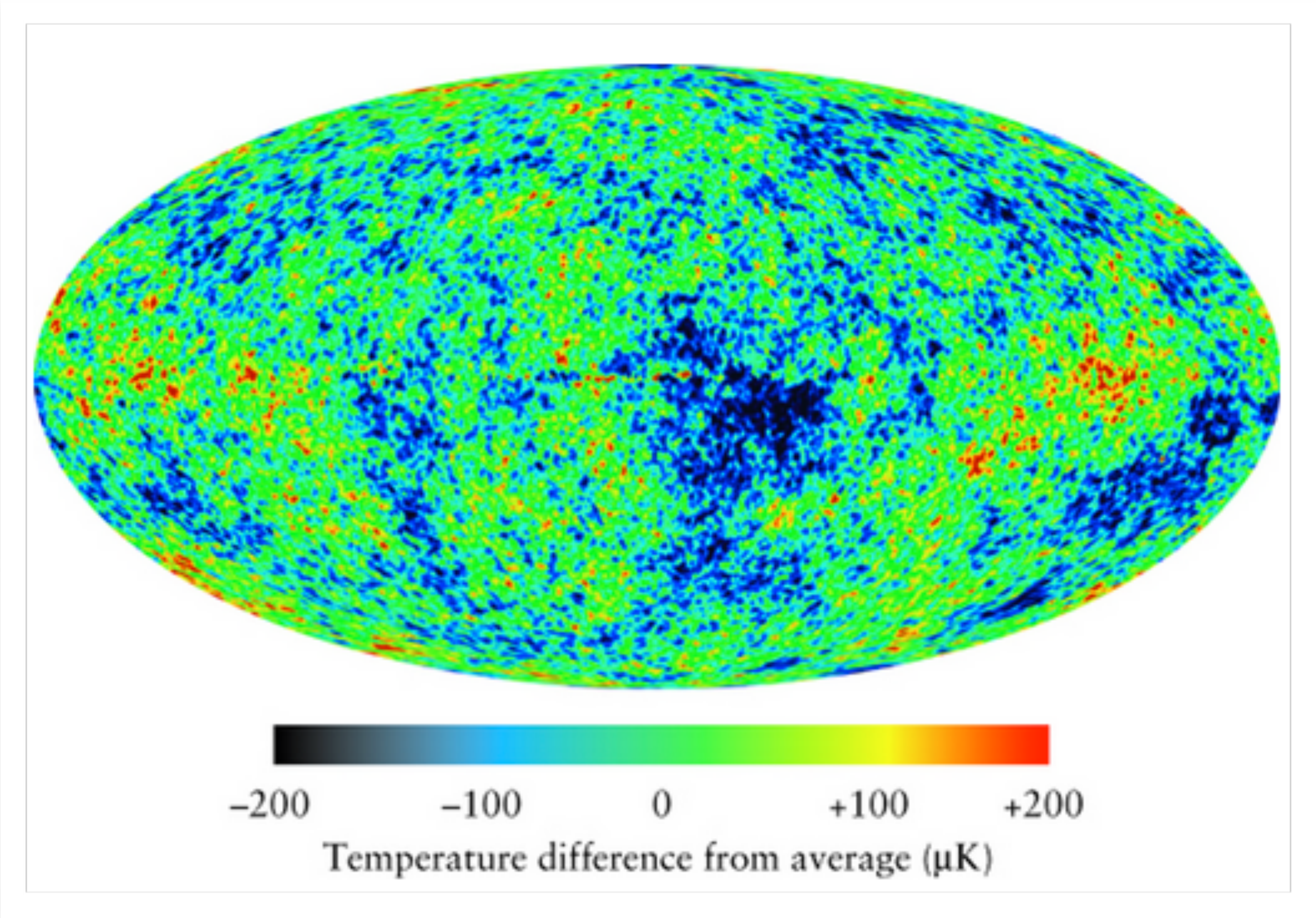
But:



suggested that k = 0

CMB,

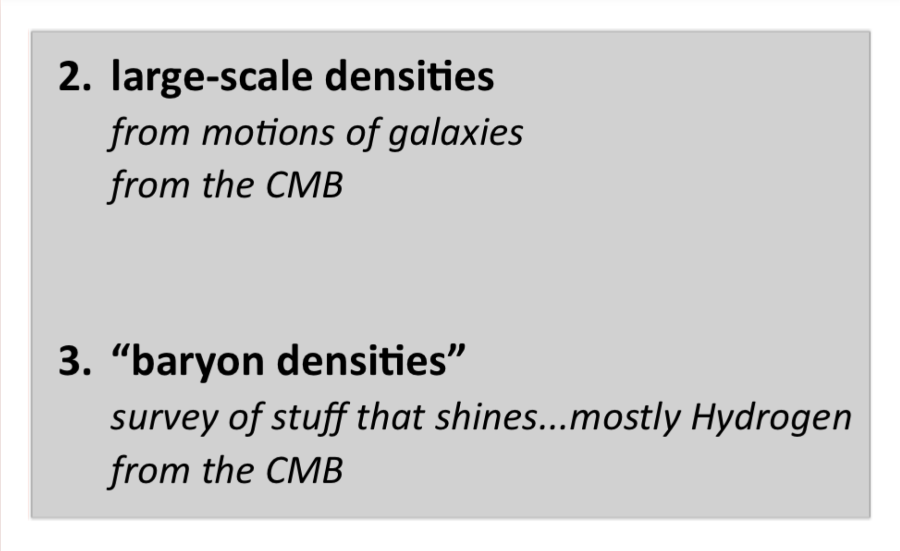




now it's really precise

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:

$$\Omega_m(t) = \cancel{0.27 \pm 0.04}$$

$$0.308 \pm \sim 0.010$$

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

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%...

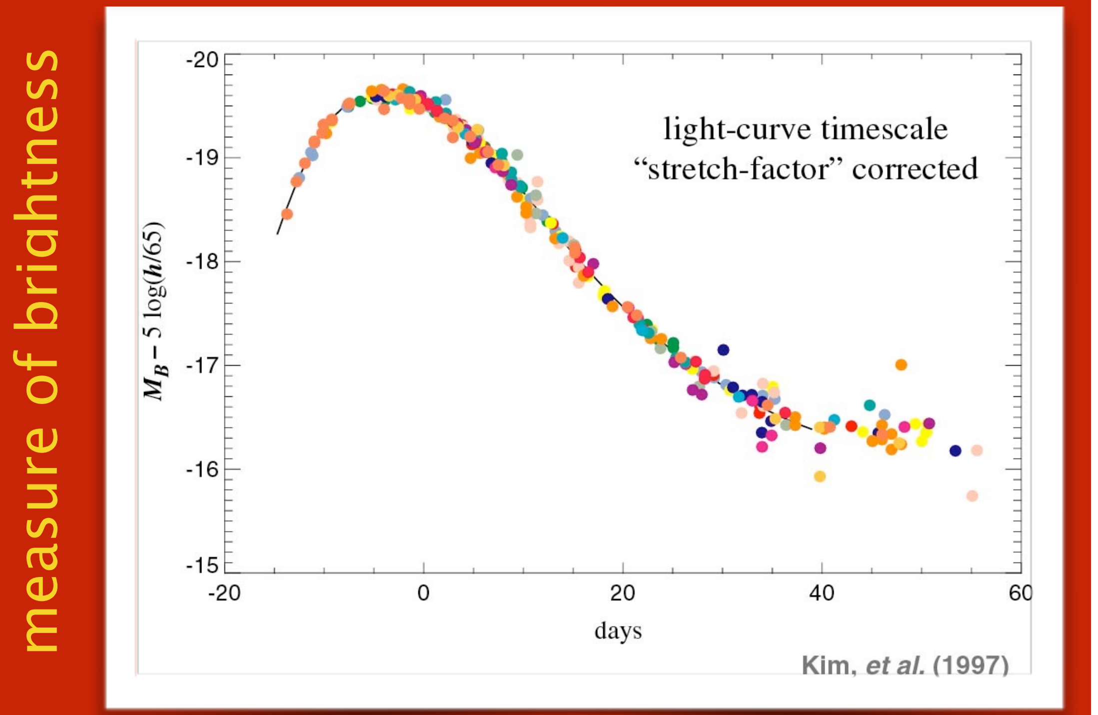
Something missing in order to get to flat at 100%

this is where we were in 1999

after the BOOMERANG results

by 1998, the Supernova Cosmology Project

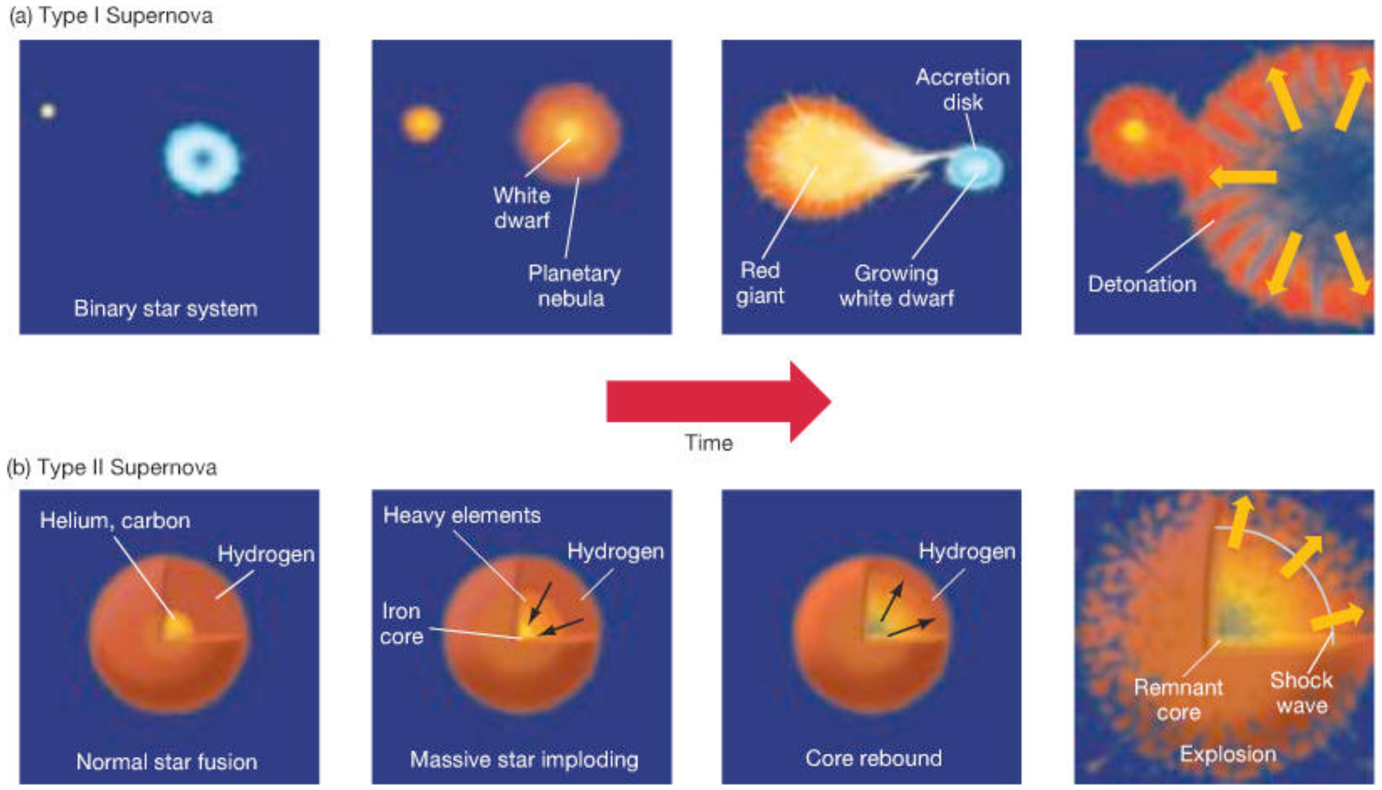
was concluding a decade-long experiment



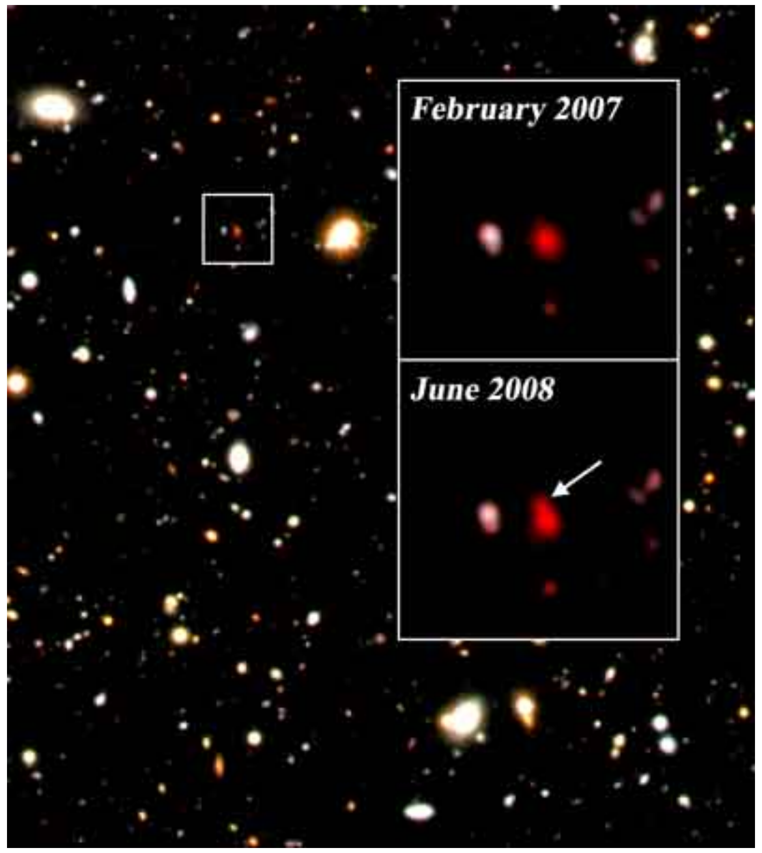
Kim, *et al.* (1997)

Find and characterize a particular kind of Supernova, called “1a”

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



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



Remarkably reliable light output.

or the other way around.

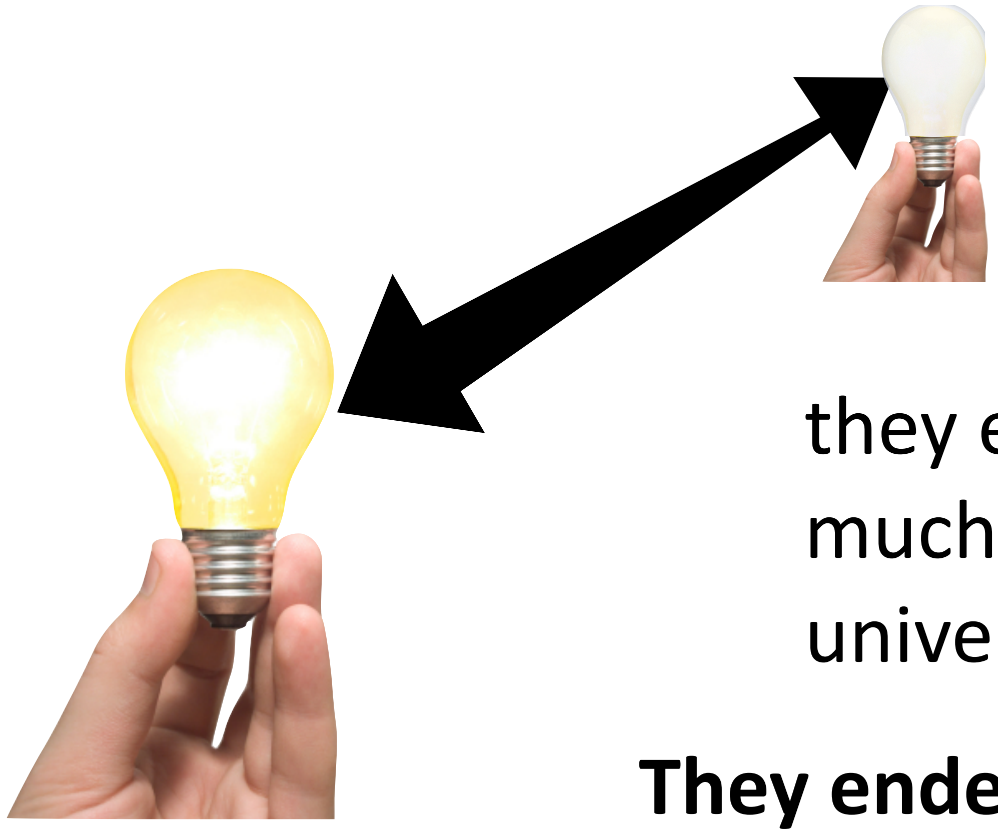
suppose you know how far away an identical bulb is...you could calculate how bright it should appear

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

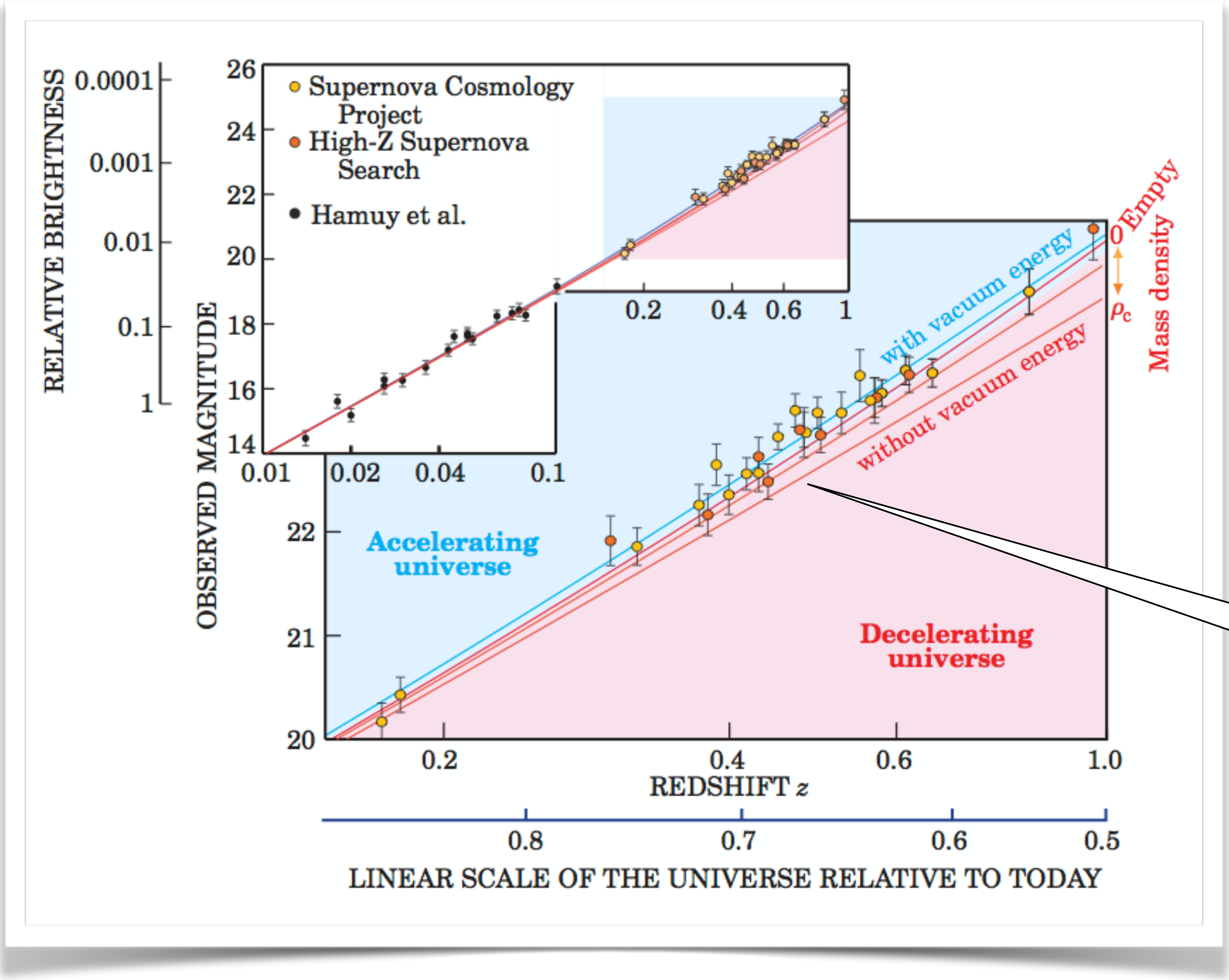
they expected to determine how much the expansion of the universe was slowing down.

They ended up showing the opposite!

enough of these type 1a SN to have one about per second in deep galaxies

many, quite far away...at very "large redshifts"

An amazing thing happens:



matter-dominated, decelerating universe

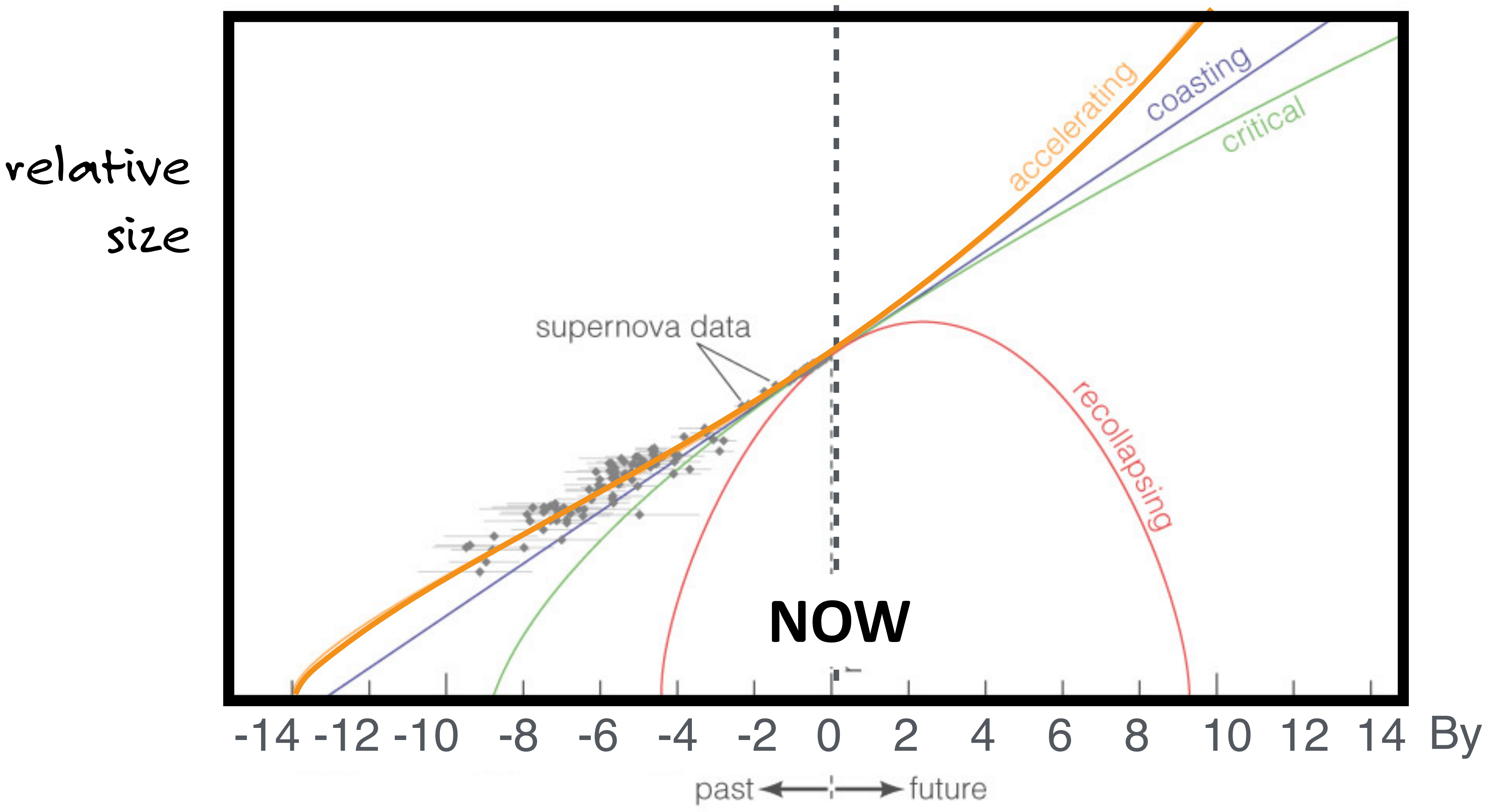
Georg Raffelt, Max-Planck-Institut fur Physik

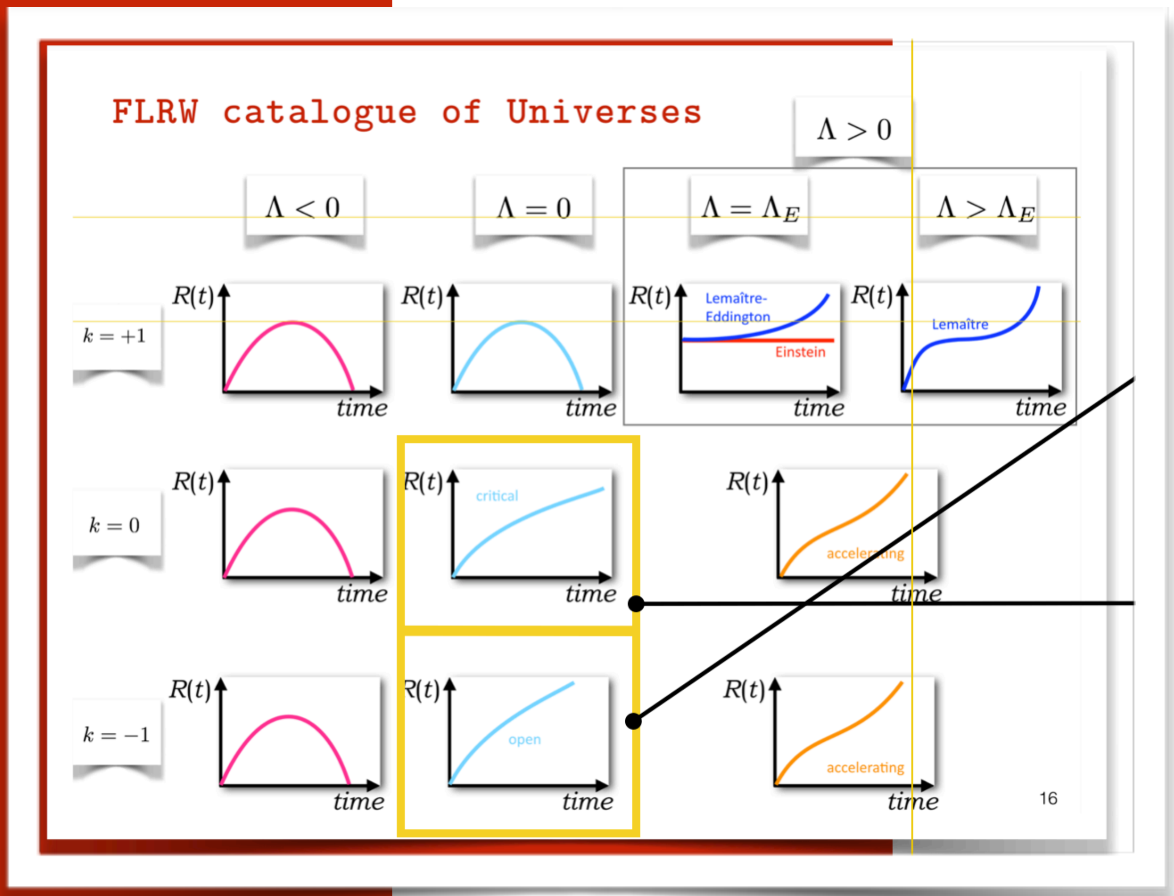
Competition

Between expansion (Hubble Parameter)

Gravitation (Density)

before, assumed no cosmological constant





FLRW catalogue of Universes

$\Lambda > 0$

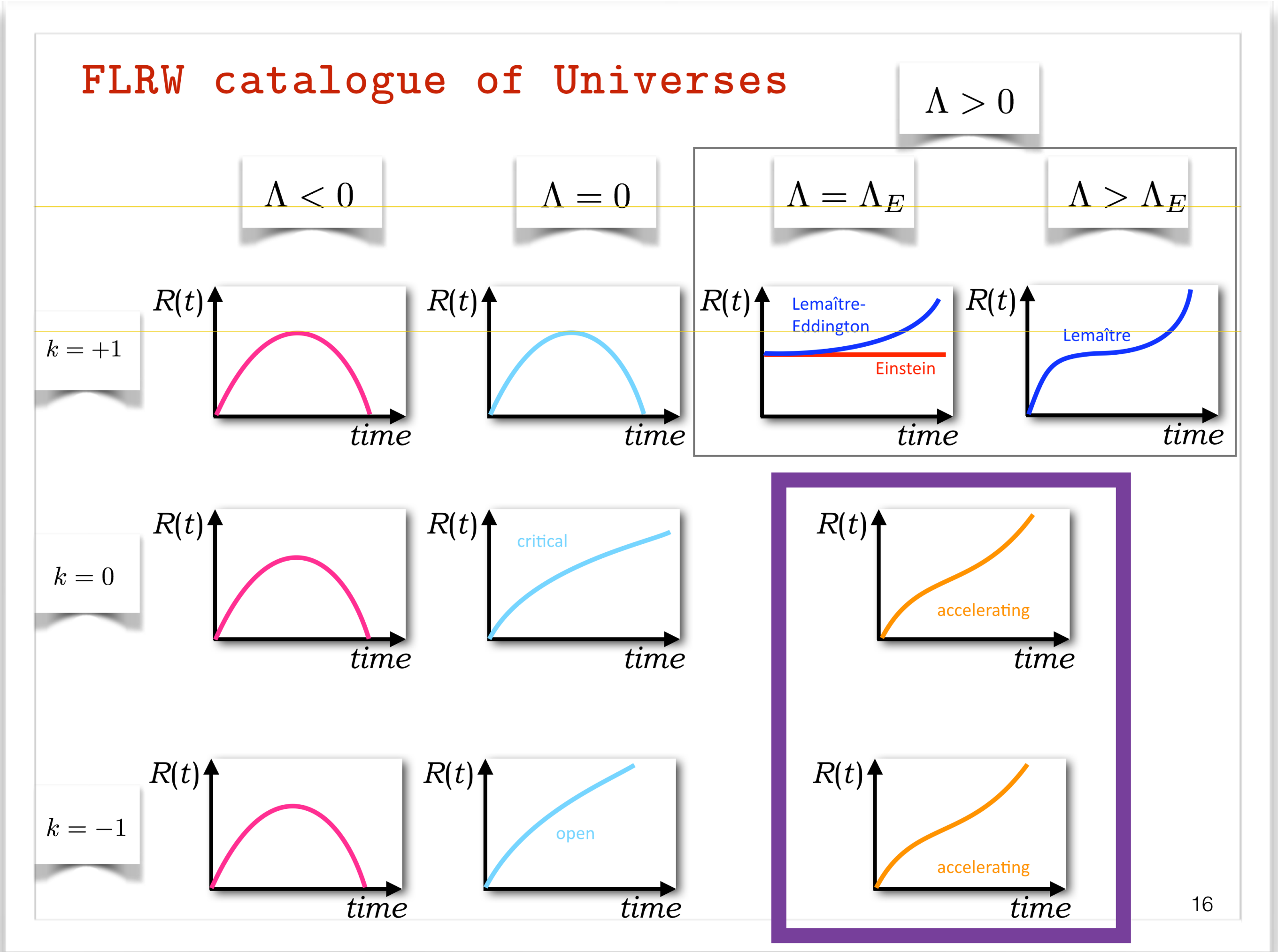
$\Lambda < 0$ | $\Lambda = 0$ | $\Lambda = \Lambda_E$ | $\Lambda > \Lambda_E$

$k = +1$

$k = 0$

$k = -1$

16



FLRW catalogue of Universes

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$k = +1$

$k = 0$

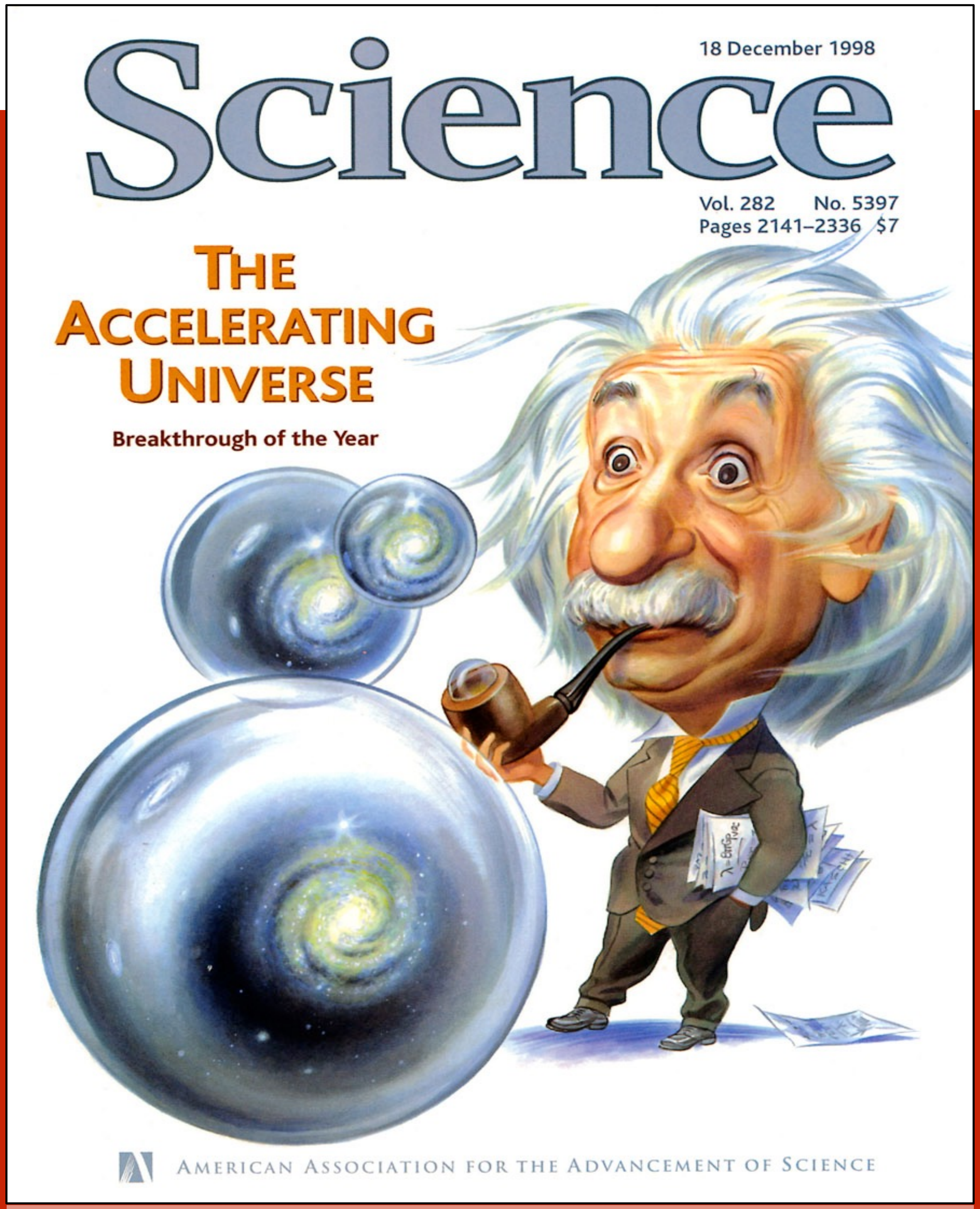
$k = -1$

16

The data require an interpretation

that the Universe's expansion is

Accelerating



Science

18 December 1998

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

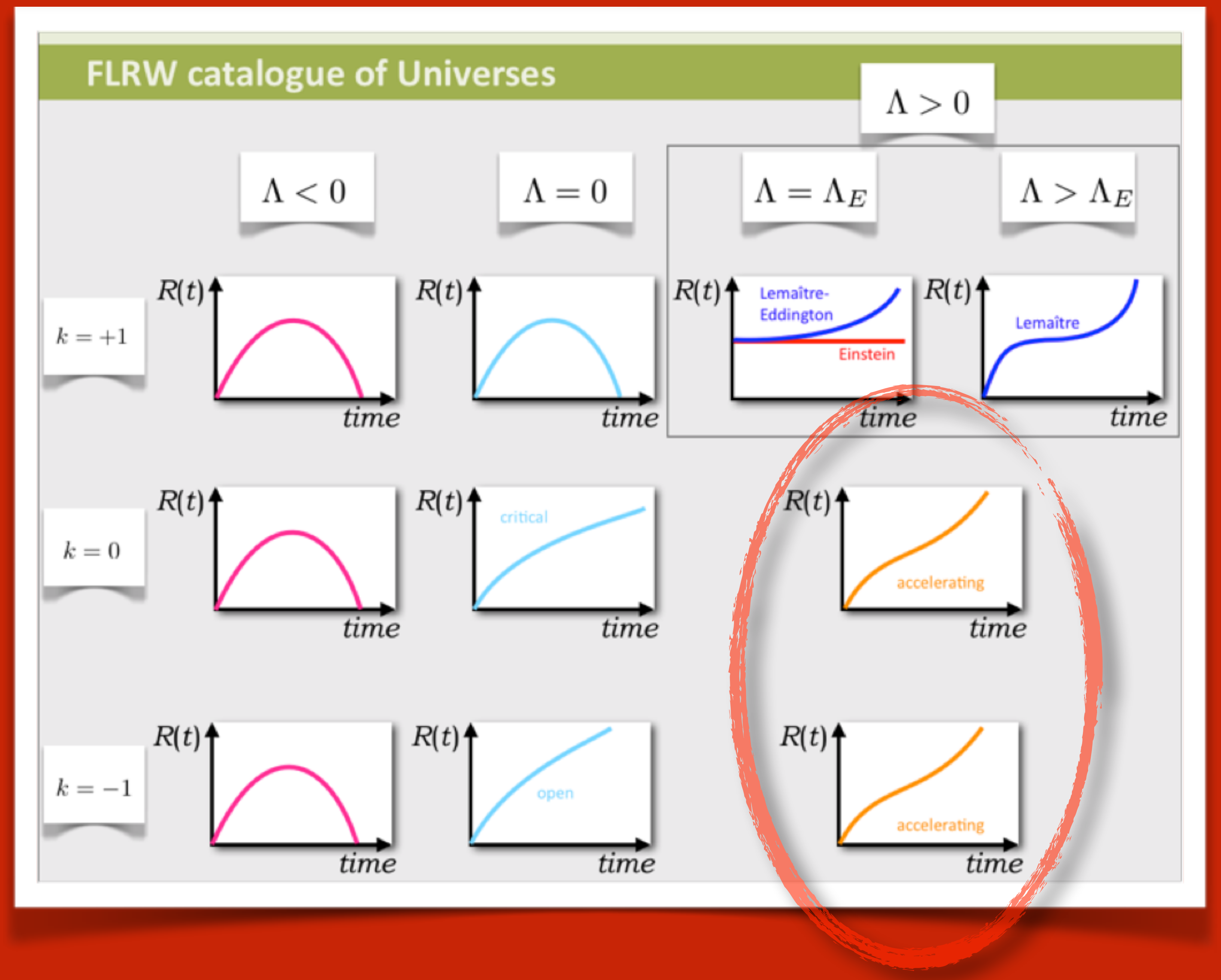
Breakthrough of the Year

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Saul Perlmutter, Brian P. Schmidt and Adam G. Riess, 2011 only one way to accomplish that

within the Friedman equations

the Cosmological Constant is back


FLRW catalogue of Universes

interpreting dark energy

as a vacuum energy:

$$G + \Lambda \quad = T$$

back to the Friedman Equation

$$k \propto H^2(\frac{C\rho}{H^2} - 1) = H^2(\Omega_m - 1)$$

$$\Omega_m(t) = \frac{\rho}{\rho_c} \quad \text{and} \quad \Omega_\Lambda(t) = \frac{``\rho_\Lambda"}{\rho_c}$$

with the addition of a Cosmological Constant

one that's different from Einstein's

$$k \propto H^2(\frac{C\rho}{H^2} - 1) = H^2(\Omega_m + \Omega_\Lambda - 1)$$

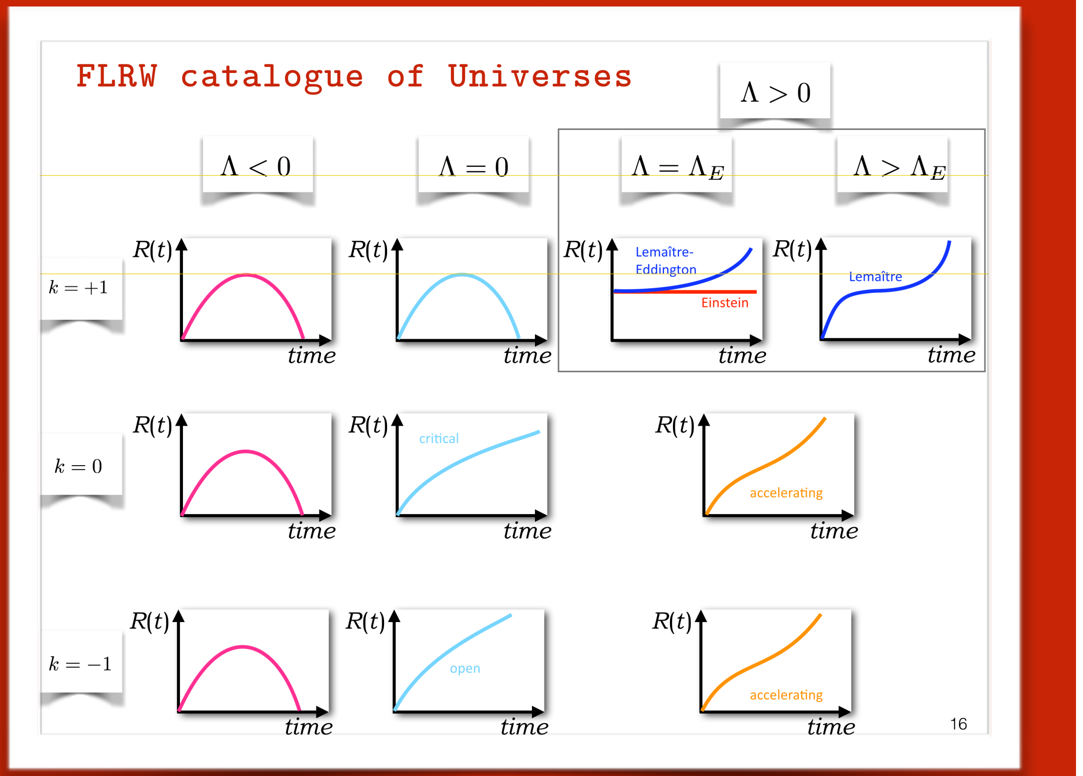
Measure it:

$$\Omega_\Lambda = 0.705 \pm {\sim}0.040$$

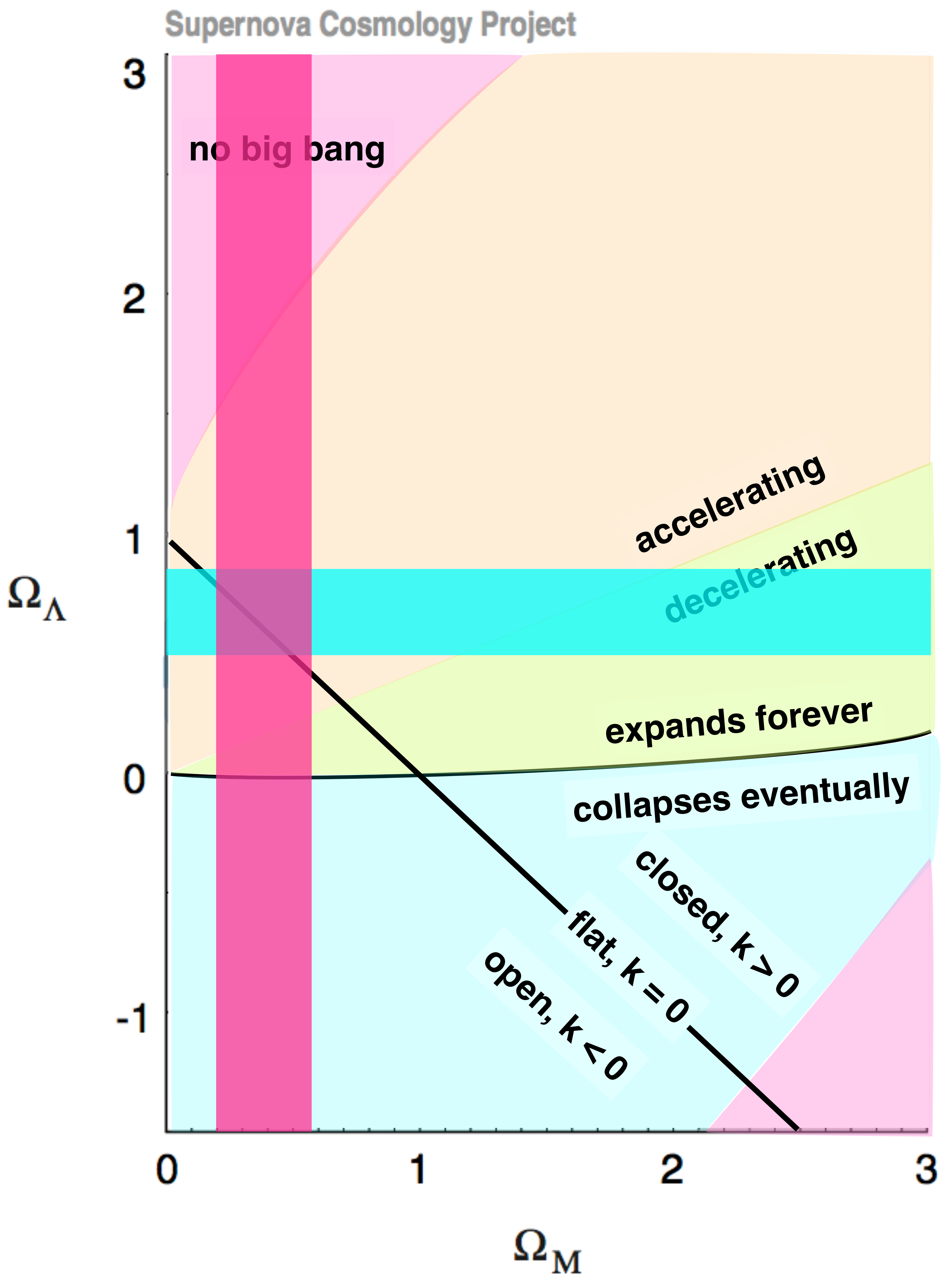
this doesn't say what it is!

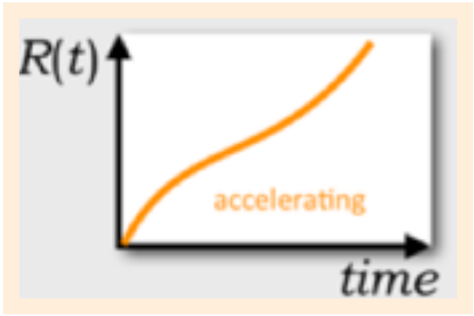
but it is a parameter that can be used to fit observations

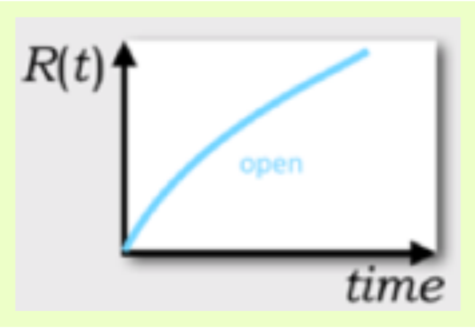
and model universes

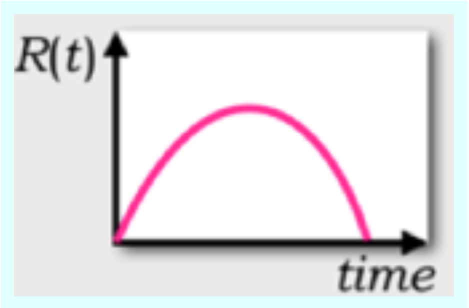


$$k \propto H^2(\Omega_m + \Omega_\Lambda - 1)$$





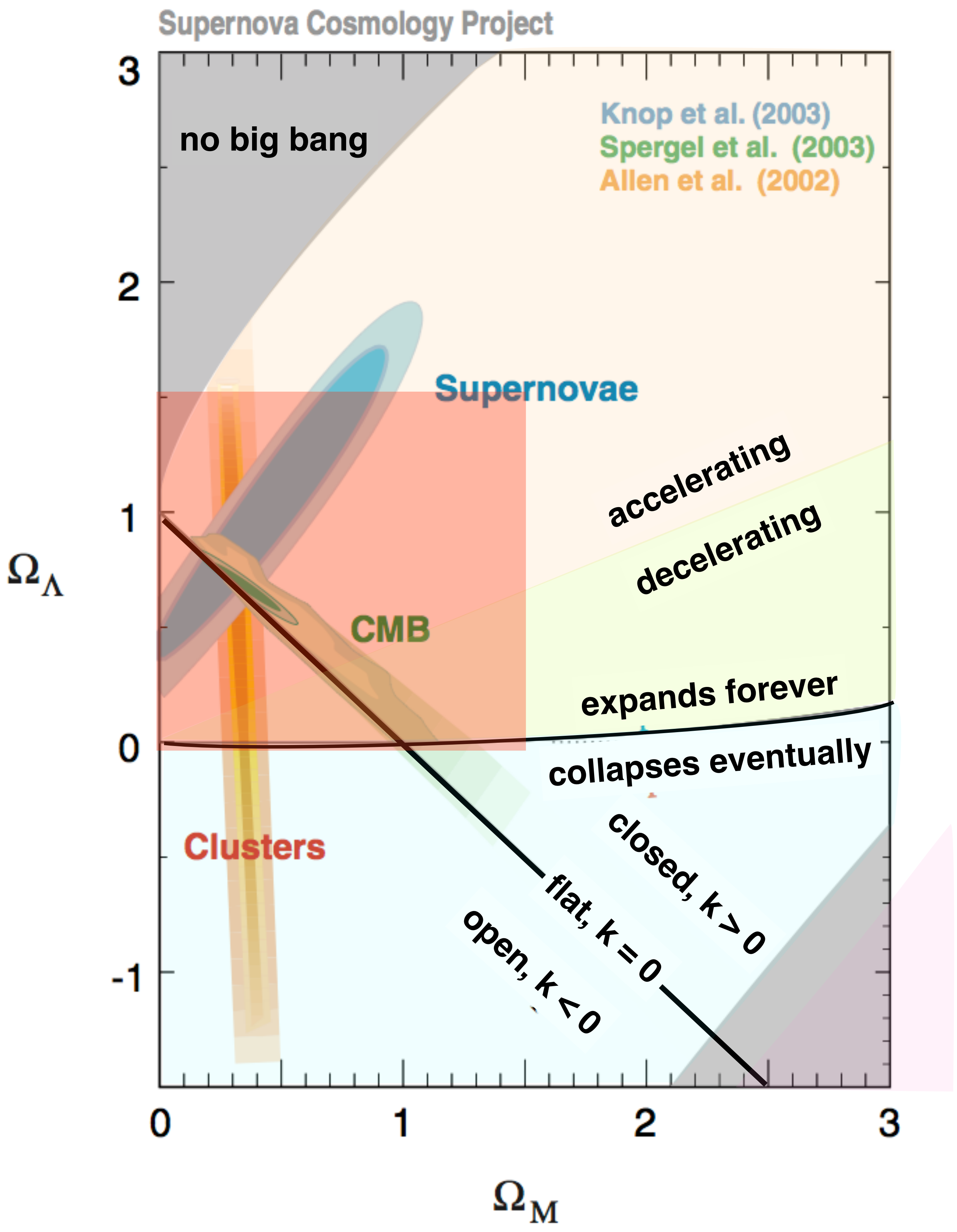


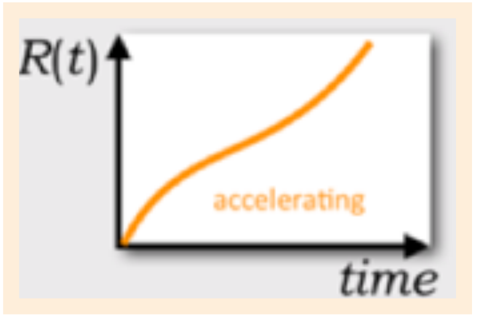


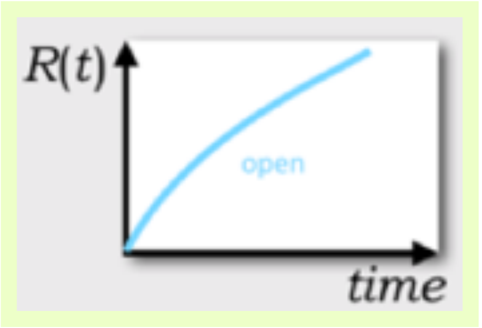
$$\left.\begin{array}{l} \Omega_\Lambda = 0.705 \pm \sim 0.040 \\ \Omega_m = 0.308 \pm \sim 0.010 \end{array}\right\} \sim 1.0!$$

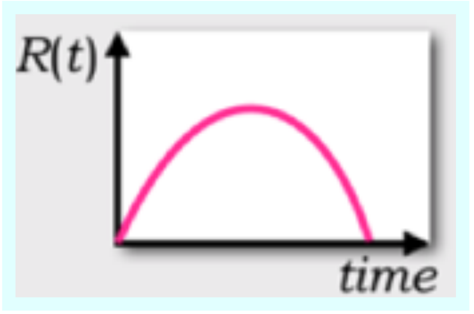
FLAT re-emerges

2003


Supernova Cosmology Project
no big bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
accelerating
decelerating
CMB
expands forever
collapses eventually
closed, k > 0
flat, k = 0
open, k < 0
Clusters
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

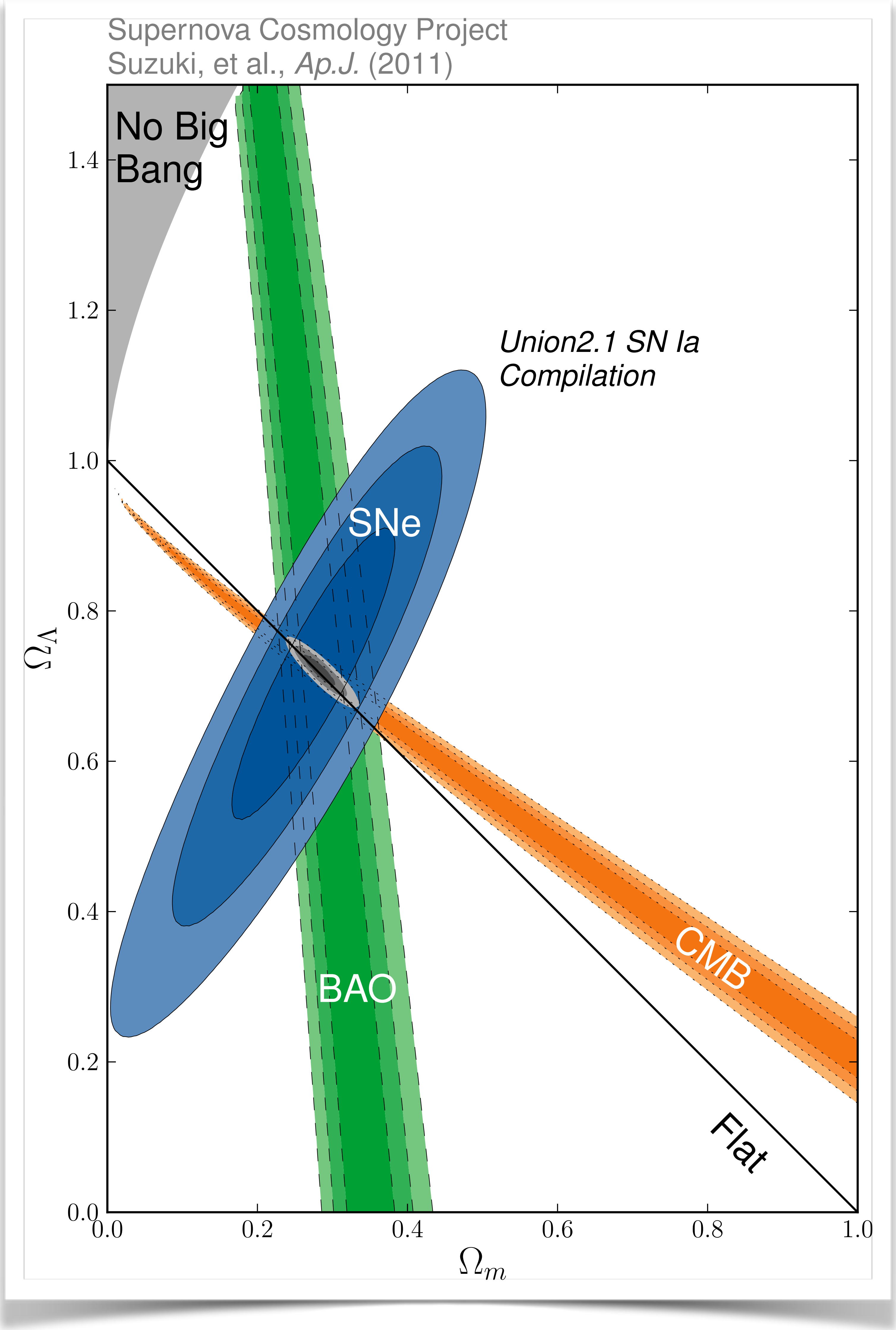

$R(t)$
accelerating
time


$R(t)$
open
time


$R(t)$
time

more precise, combined data

2011



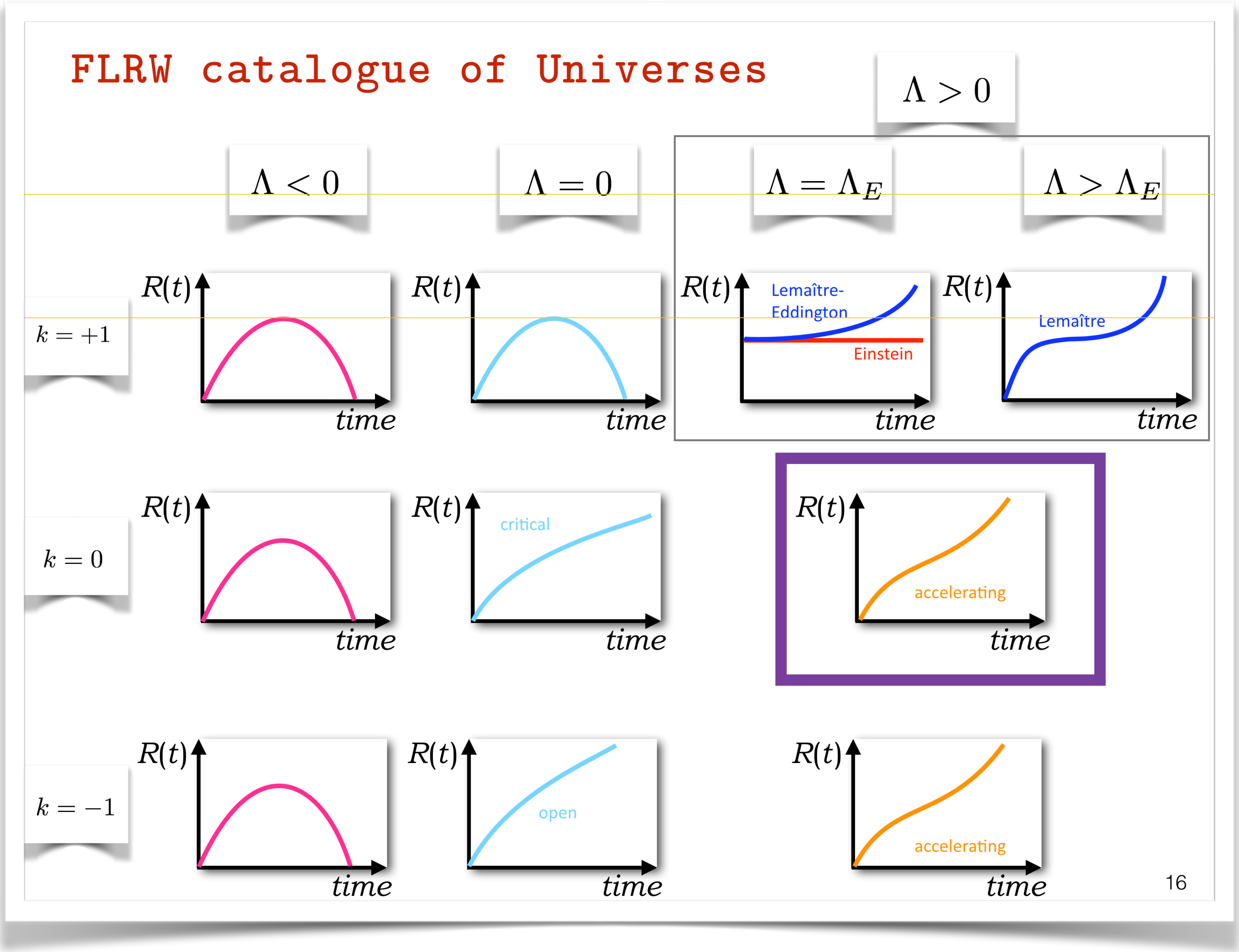
Bingo. Flat.

Didn’t have to be this way.

flat

seems to be our universe...

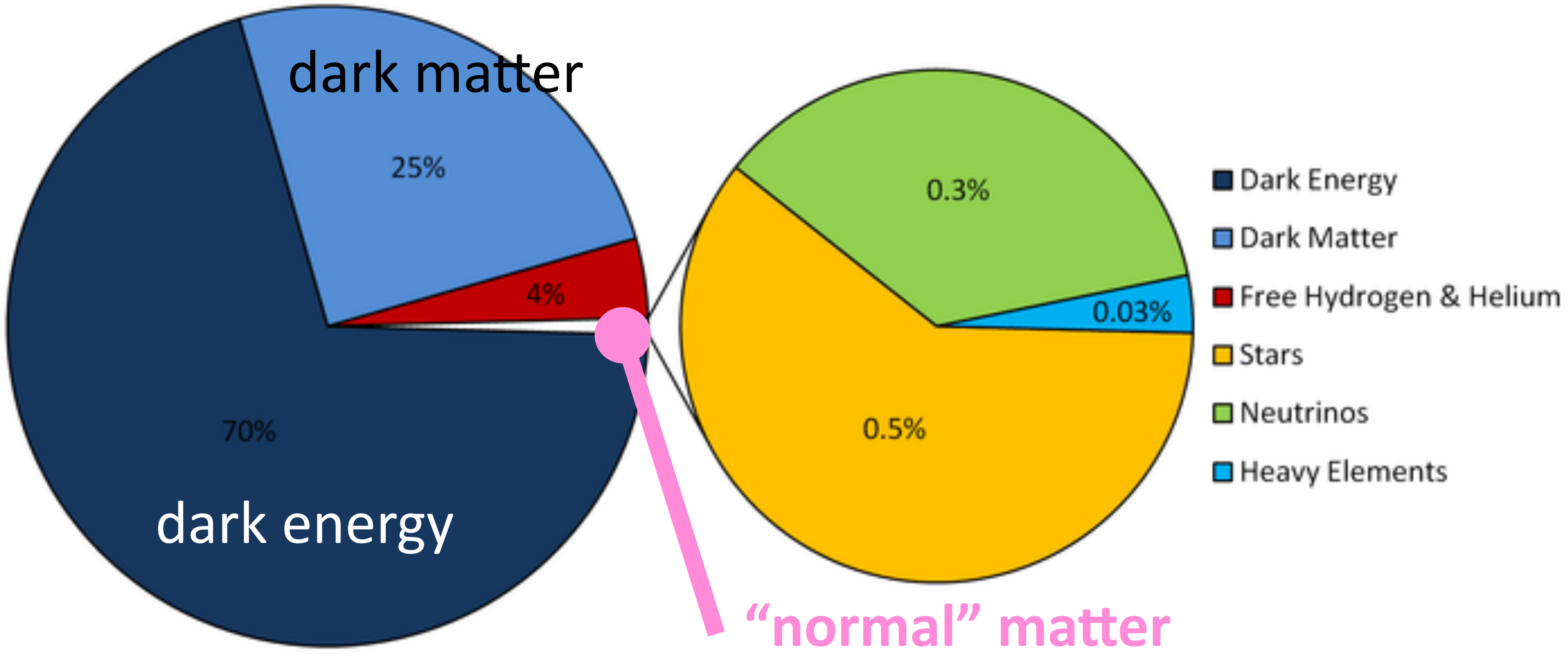
and our bleak fate!



FLRW catalogue of Universes

we don’t know much!!

This “dark energy” is a huge part of the energy density of the Universe!



interpretation for Λ?

Energy of the vacuum

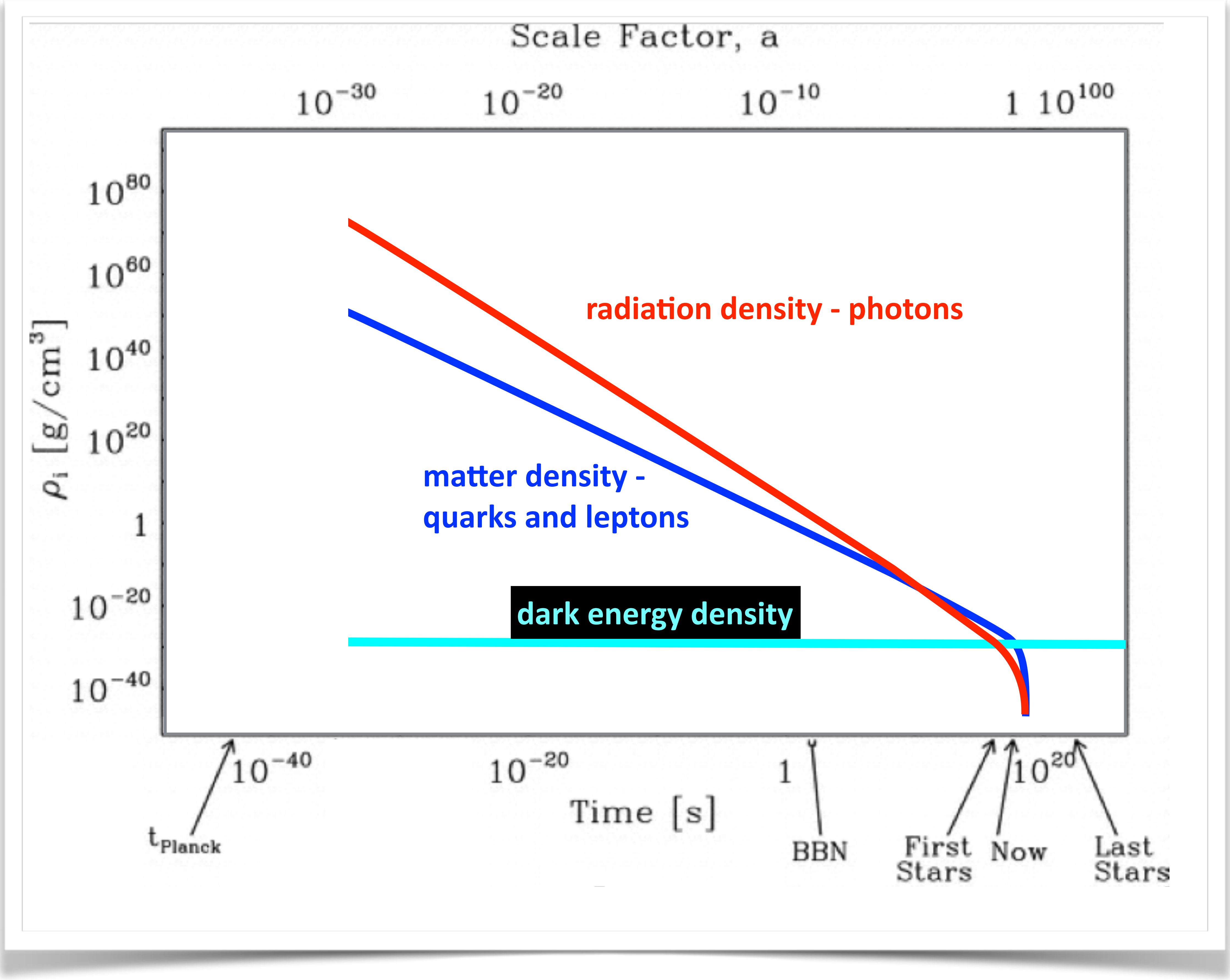
a negative pressure

um…

accelerating??

This stuff is called "Dark Energy"...we've no real understanding of what it actually is.

It has the characteristics of a constant **energy of the vacuum.**

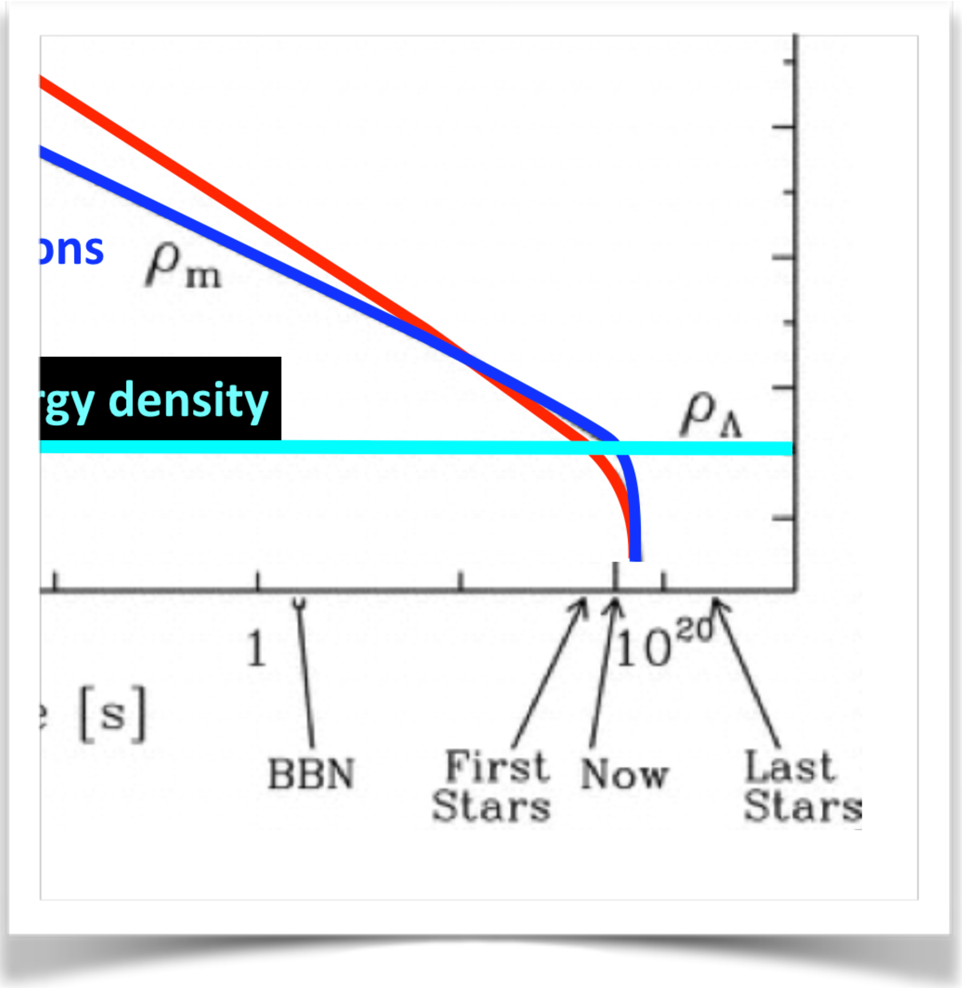


There has to be some "antigravity" kind of force at work to do this

What's more, there has to be a lot of it

why

now?

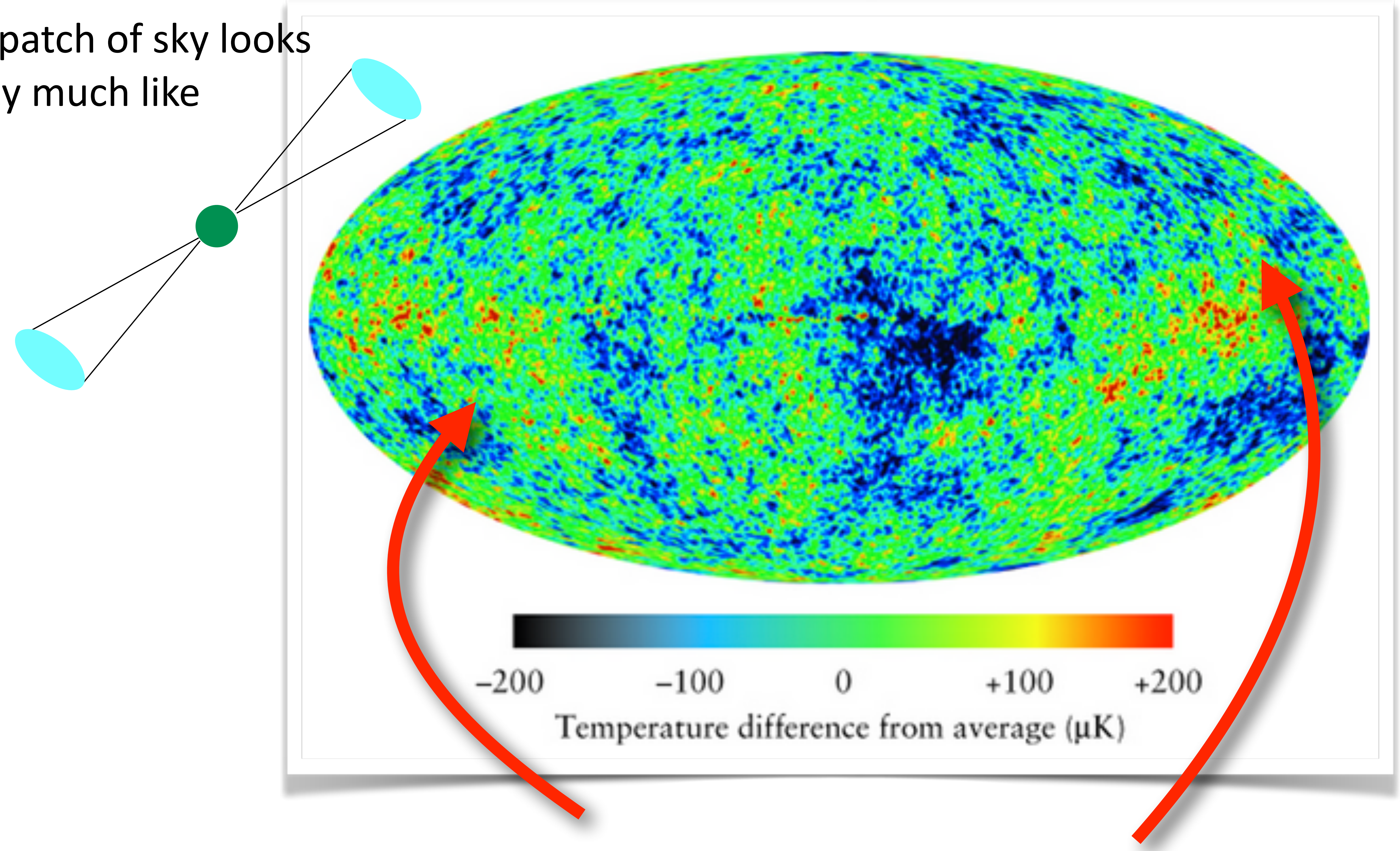

ons
ρ_m
gy density
ρ_Λ
1
10^{20}
[s]
BBN
First Stars
Now
Last Stars

problem #2

the horizon problem.

how could the sky be so uniform?

that patch of sky looks pretty much like



yet the amazing uniformity of the temperatures in the CMB – all over the sky – at recombination...

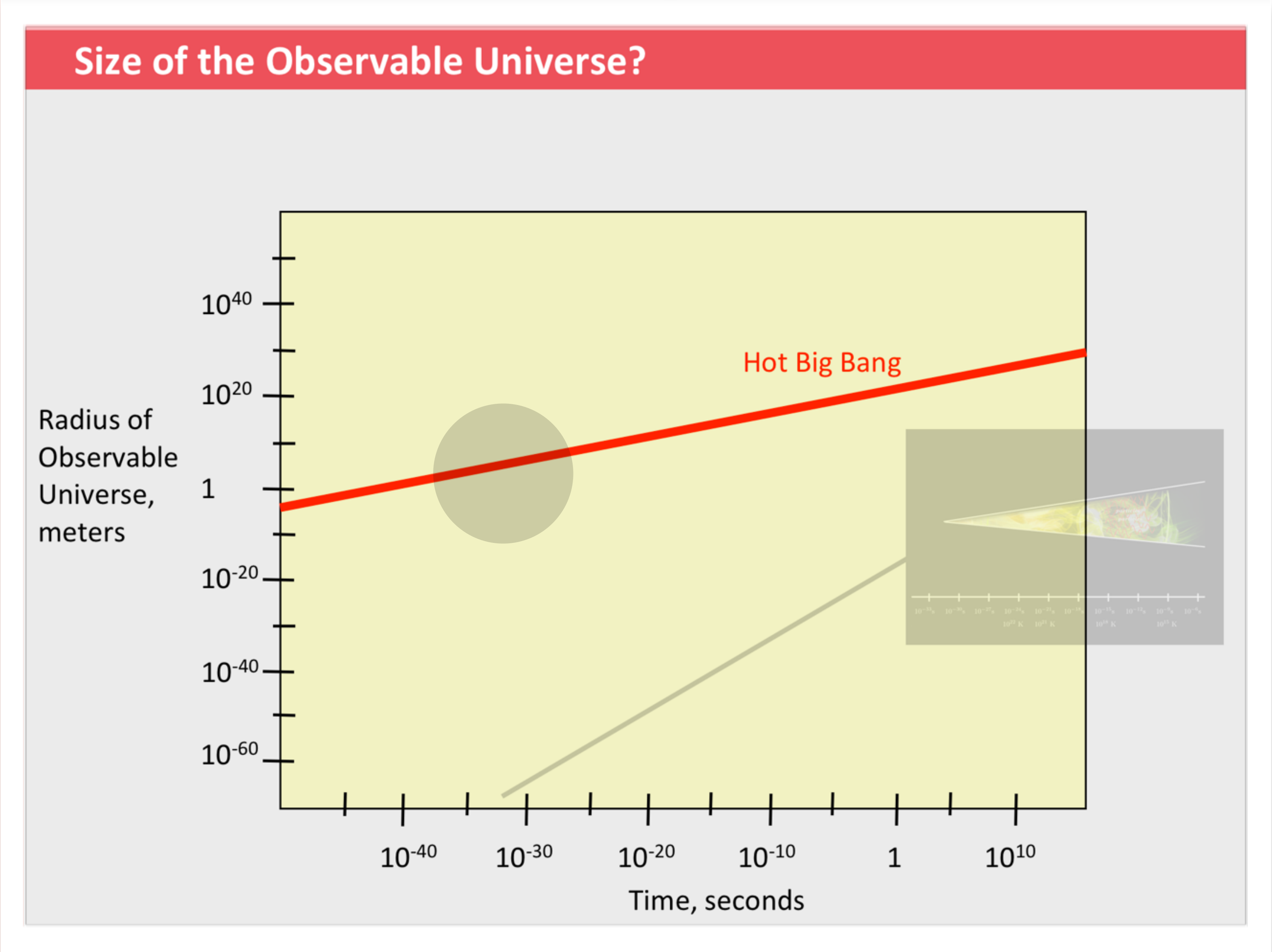
can't have happened causally

when would the two sides ‘‘talk’’?

In the hot big bang scenario...
at about 10^{-32} s, the universe is about a meter in radius

How far could light travel in that time?

$$\begin{aligned} d(\gamma) &= c \times 10^{-32}\mathrm{s} \\ &= (3 \times 10^{8}\mathrm{m/s}) \times 10^{-32}\mathrm{s} \end{aligned}$$

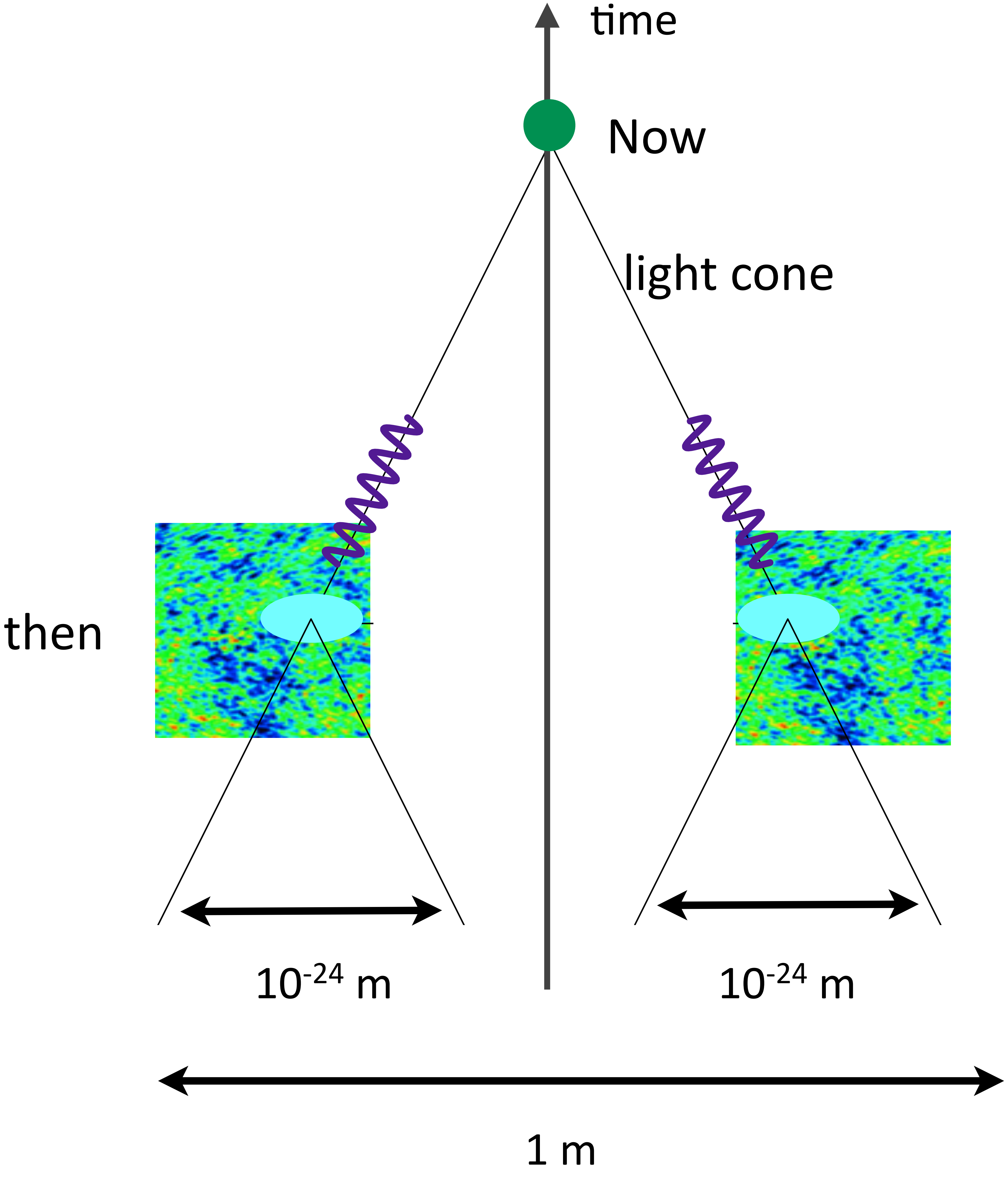


Size of the Observable Universe?

That’s the **Horizon** at that time.

Waaaay too short a time for one part of the universe to come to equilibrium with another part!

no thermal communication

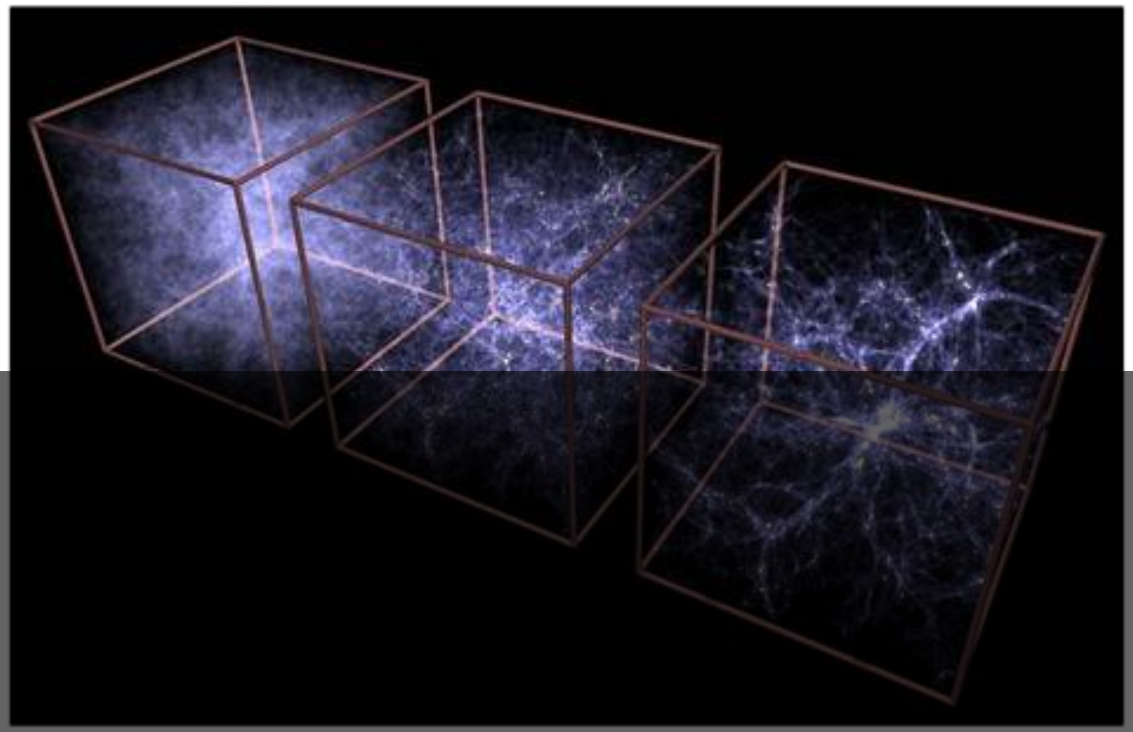


`problem #3`

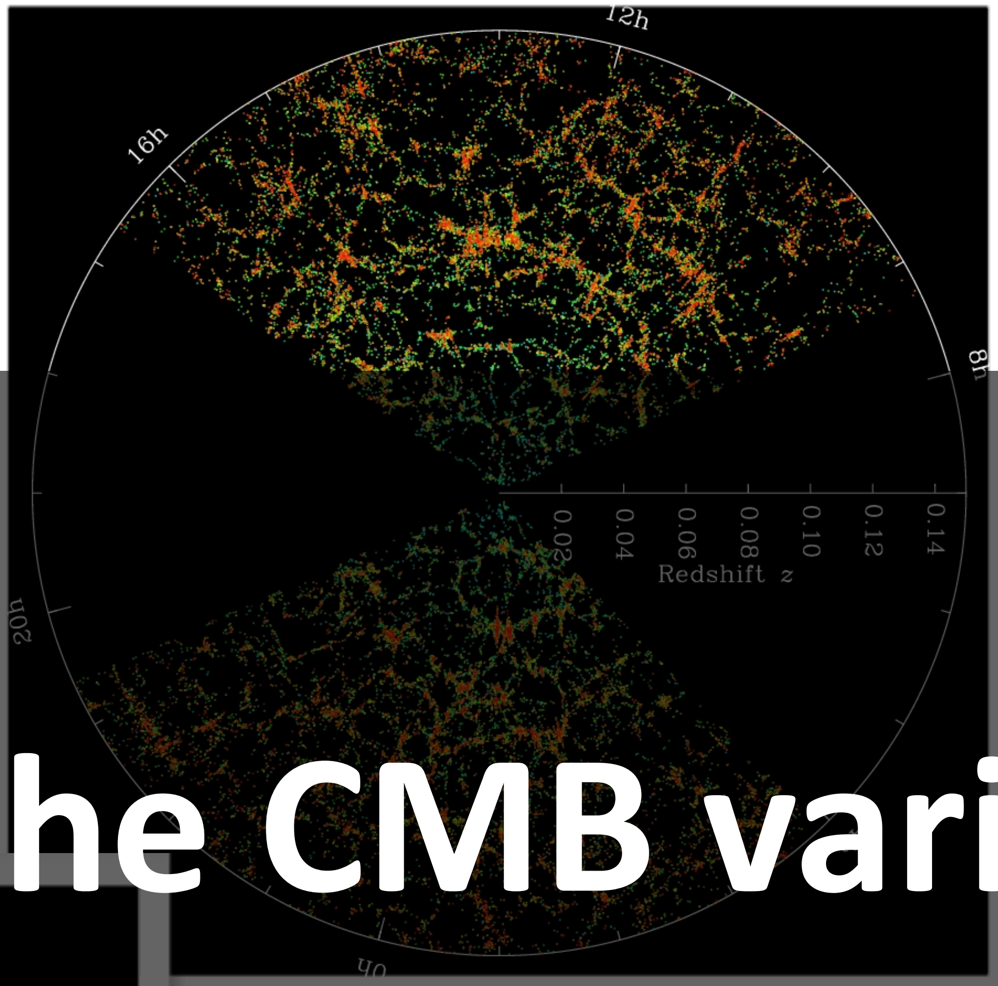
the structure problem.

simulation of galaxy clusters and superclusters is in hand

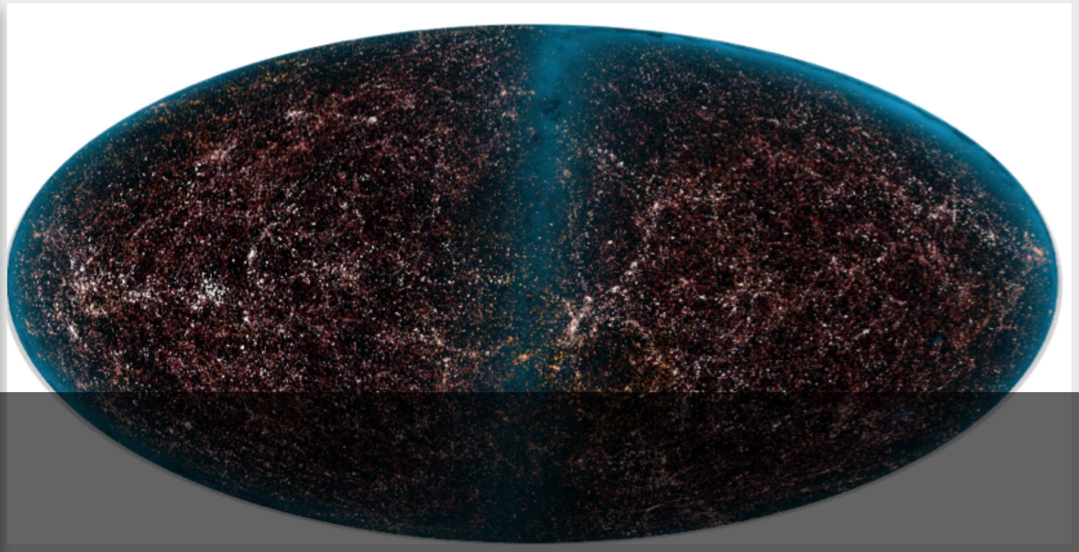
"Millennium Simulation"



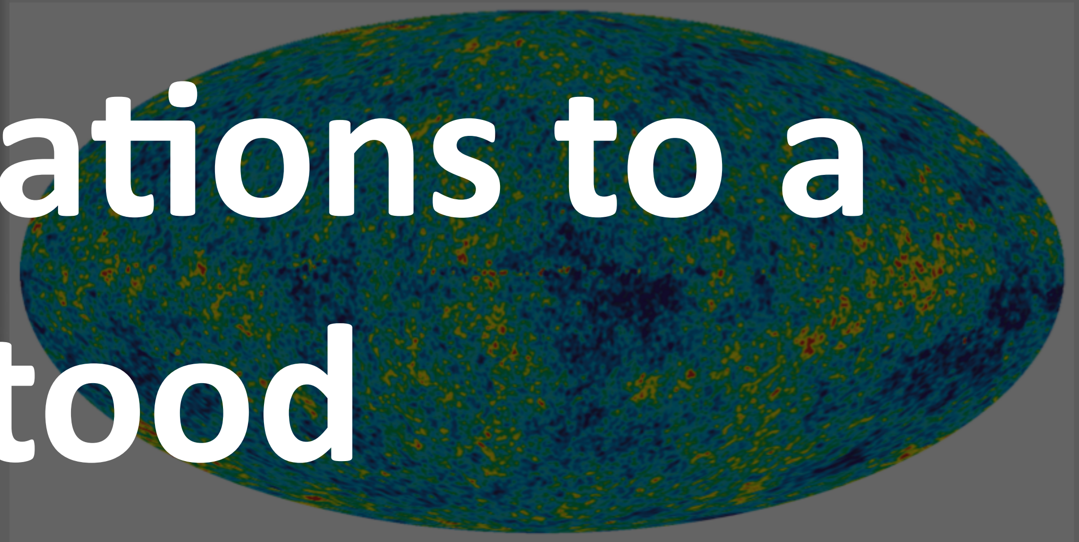
Data: Sloan Digital Sky Survey



Data: the 2MASS survey

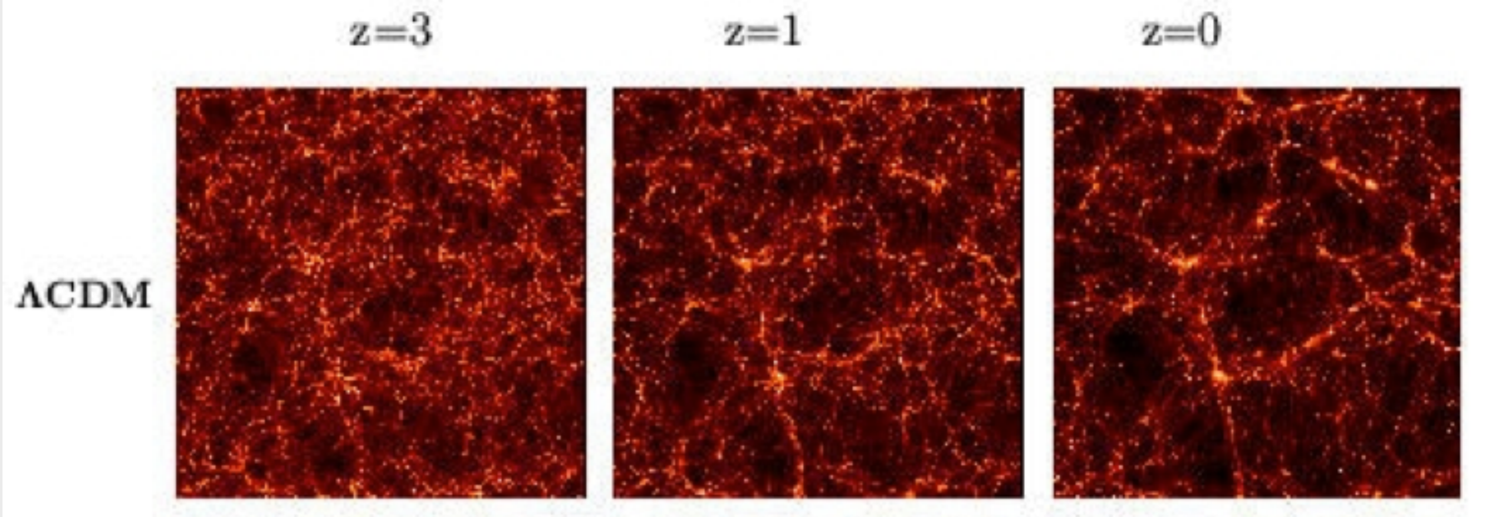


Data: WMAP



going from the CMB variations to a universe is understood

Simulation: Virgo Collaboration



Bolshoi Simulation compared with Sloan

All use data-based assumptions about Dark Matter and the CMB data as a starting point

`the problem is`

what’s the source of the CMB structure?

problem #4

the antimatter problem.

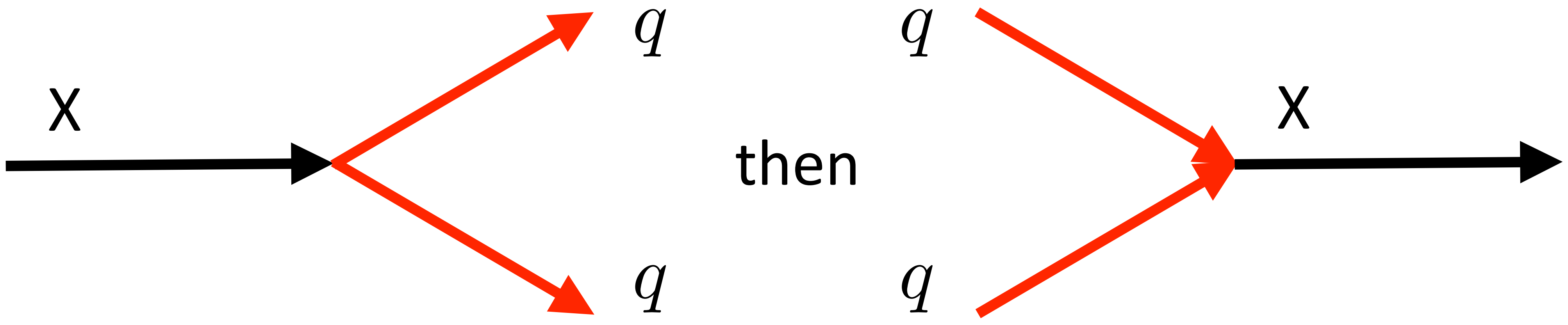
we have only a few ideas about this

all involve **new forces** of nature

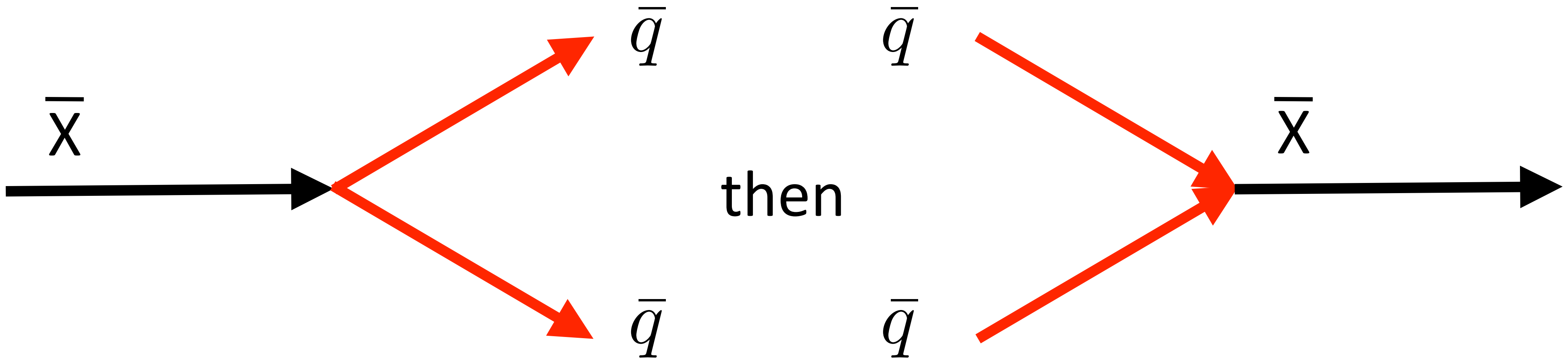
some new particles, X

In the very early universe:

This back-and-forth reaction has to go slightly faster



than this one:



and X has to be very heavy

A feature of most "Grand Unified Theories" GUTs

And a target of intense experimental searching!

likewise a new force of nature

to provide a quantum for Dark Matter fields

a particle to be found.

BTW:

What Banged?

`there is a favored solution to`

Horizon, Flatness, Structure...and indirectly, antimatter problems

another phase transition...**the Mother of All Phase Transitions!**

Inflation

supercooling and superheating

taken something out of the microwave and had it explode?

or

taken a bottle of water out of the freezer and had it suddenly freeze?

Called Superheating and Supercooling...

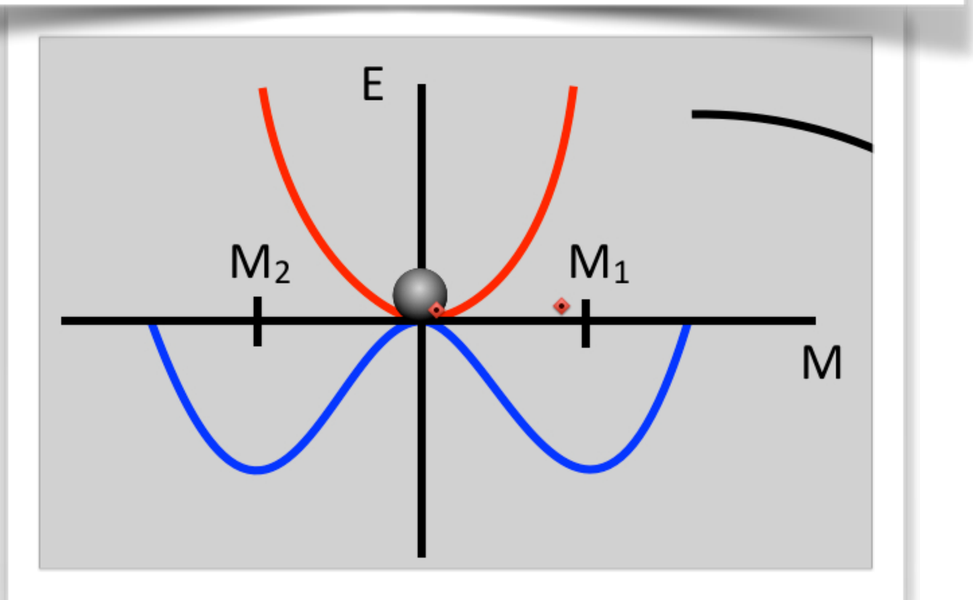
A substance above its boiling point...and not boiling

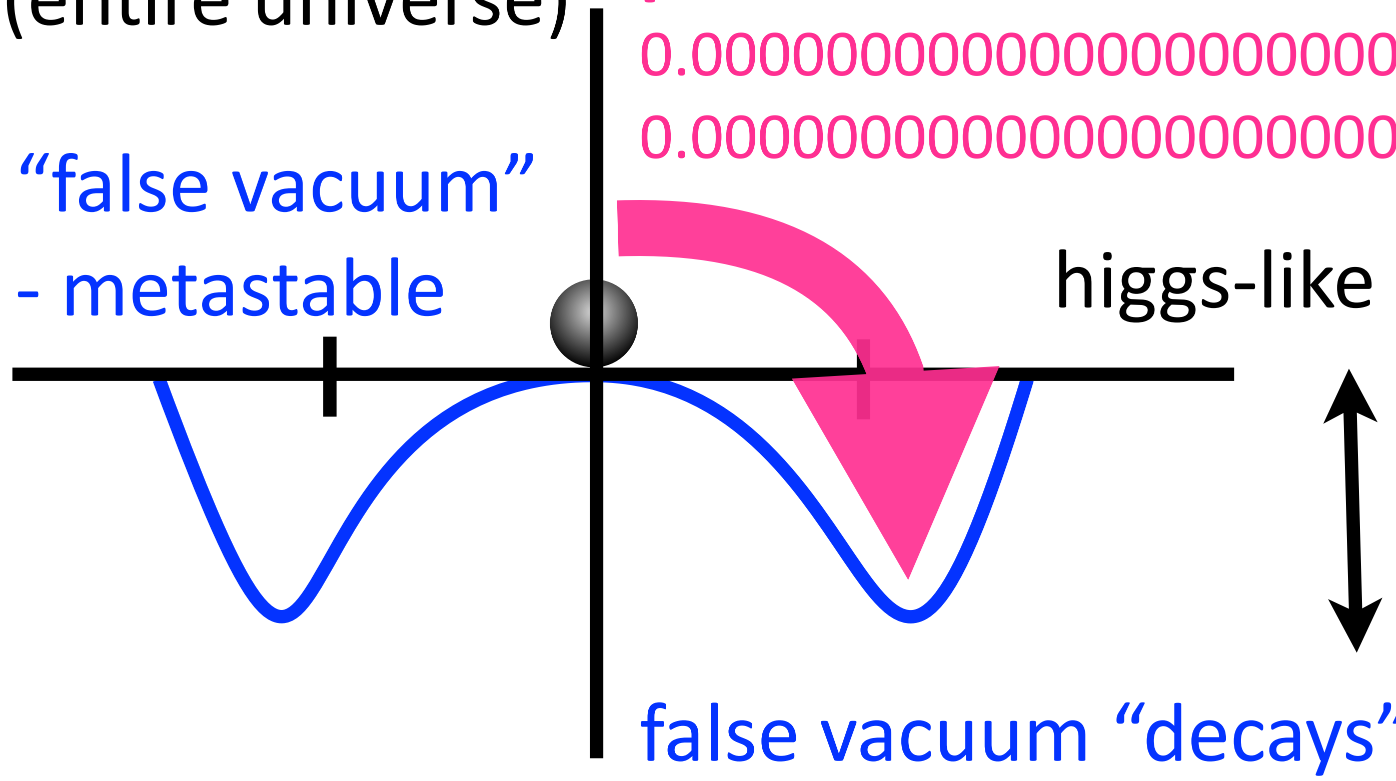
or below its freezing point...and not freezing.

like the magnet!

like the Higgs!...but 1st order

gives up energy





E (entire universe)

period of inflation

0.00000000000000000000000000000000000001 to
0.00000000000000000000000000000000001 s

“false vacuum”
- metastable

higgs-like field...the “Inflaton”

energy is

released --> Λ!

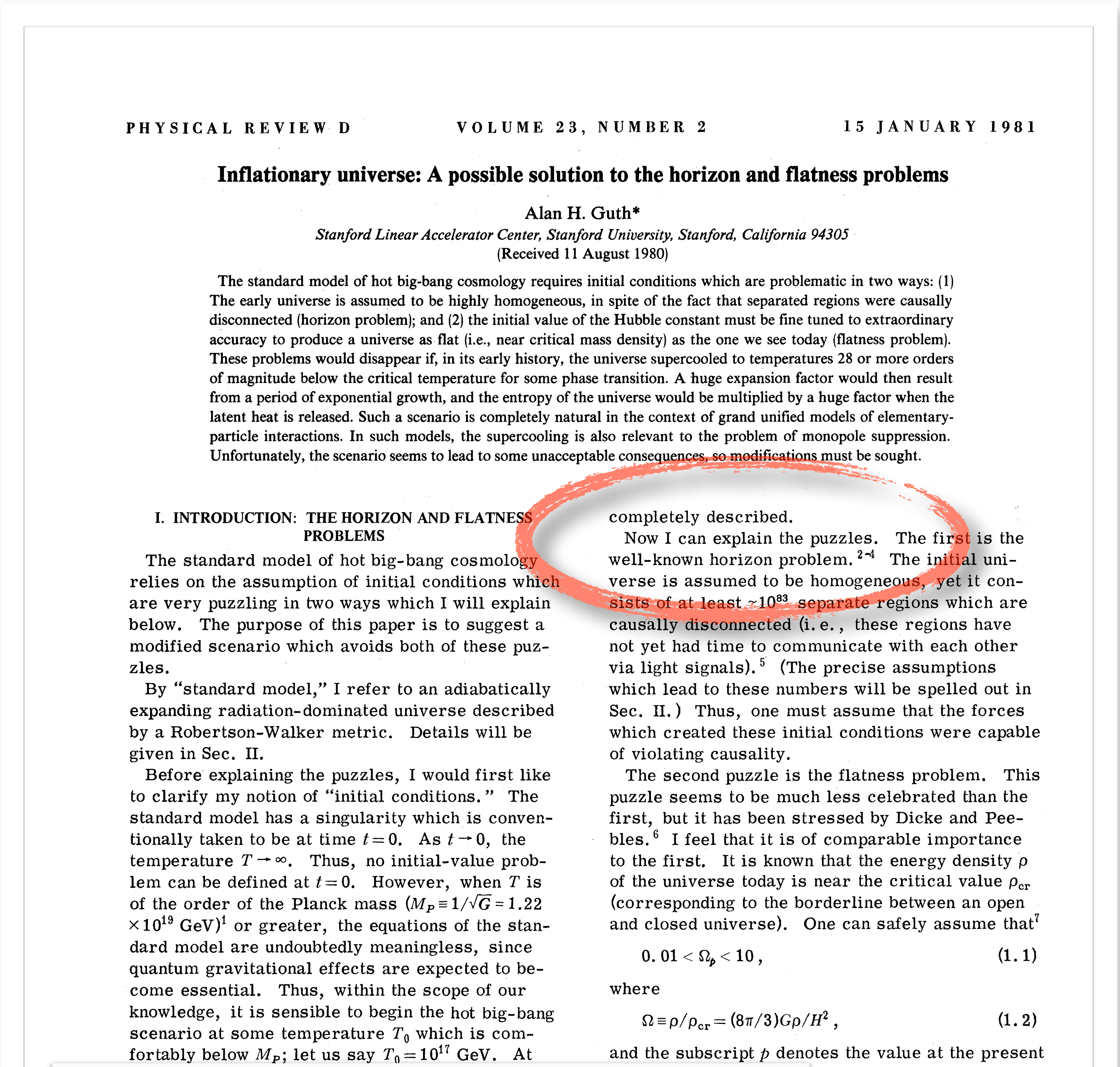
false vacuum “decays” into a cold universe
vacuum full of the Inflaton Field

negative pressure

like anti-gravity

ENORMOUS expansion of the universe

“Inflation”...idea of post doc Alan Guth 1980



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Inflationary universe: A possible solution to the horizon and flatness problems

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The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

I. INTRODUCTION: THE HORIZON AND FLATNESS PROBLEMS

The standard model of hot big-bang cosmology relies on the assumption of initial conditions which are very puzzling in two ways which I will explain below. The purpose of this paper is to suggest a modified scenario which avoids both of these puzzles.

By “standard model,” I refer to an adiabatically expanding radiation-dominated universe described by a Robertson-Walker metric. Details will be given in Sec. II.

Before explaining the puzzles, I would first like to clarify my notion of “initial conditions.” The standard model has a singularity which is conventionally taken to be at time $t=0$. As $t \rightarrow 0$, the temperature $T \rightarrow \infty$. Thus, no initial-value problem can be defined at $t=0$. However, when T is of the order of the Planck mass ($M_P \equiv 1/\sqrt{G} = 1.22 \times 10^{19}$ GeV)[1] or greater, the equations of the standard model are undoubtedly meaningless, since quantum gravitational effects are expected to become essential. Thus, within the scope of our knowledge, it is sensible to begin the hot big-bang scenario at some temperature T_0 which is comfortably below M_P; let us say $T_0 = 10^{17}$ GeV. At

completely described.

Now I can explain the puzzles. The first is the well-known horizon problem.[2-4] The initial universe is assumed to be homogeneous, yet it consists of at least ~10^{83} separate regions which are causally disconnected (i.e., these regions have not yet had time to communicate with each other via light signals).[5] (The precise assumptions which lead to these numbers will be spelled out in Sec. II.) Thus, one must assume that the forces which created these initial conditions were capable of violating causality.

The second puzzle is the flatness problem. This puzzle seems to be much less celebrated than the first, but it has been stressed by Dicke and Peebles.[6] I feel that it is of comparable importance to the first. It is known that the energy density ρ of the universe today is near the critical value ρ_{cr} (corresponding to the borderline between an open and closed universe). One can safely assume that[7]

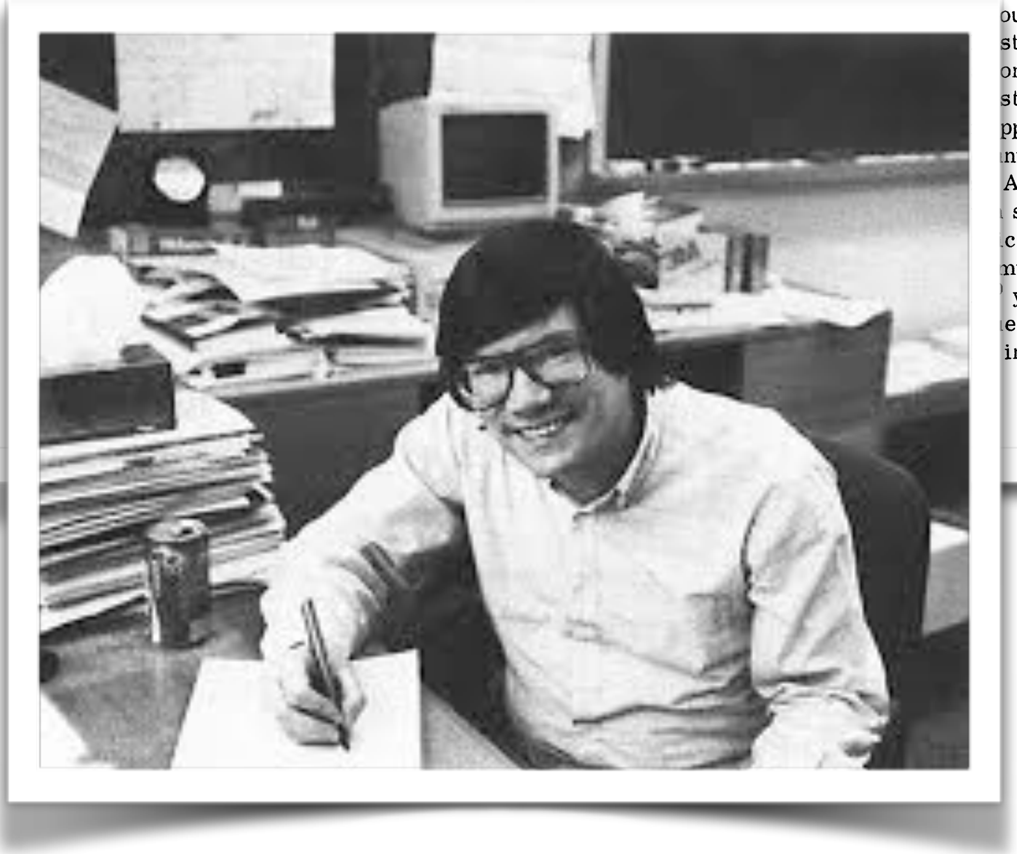
$$0.01 < \Omega_p < 10\,, \qquad (1.1)$$

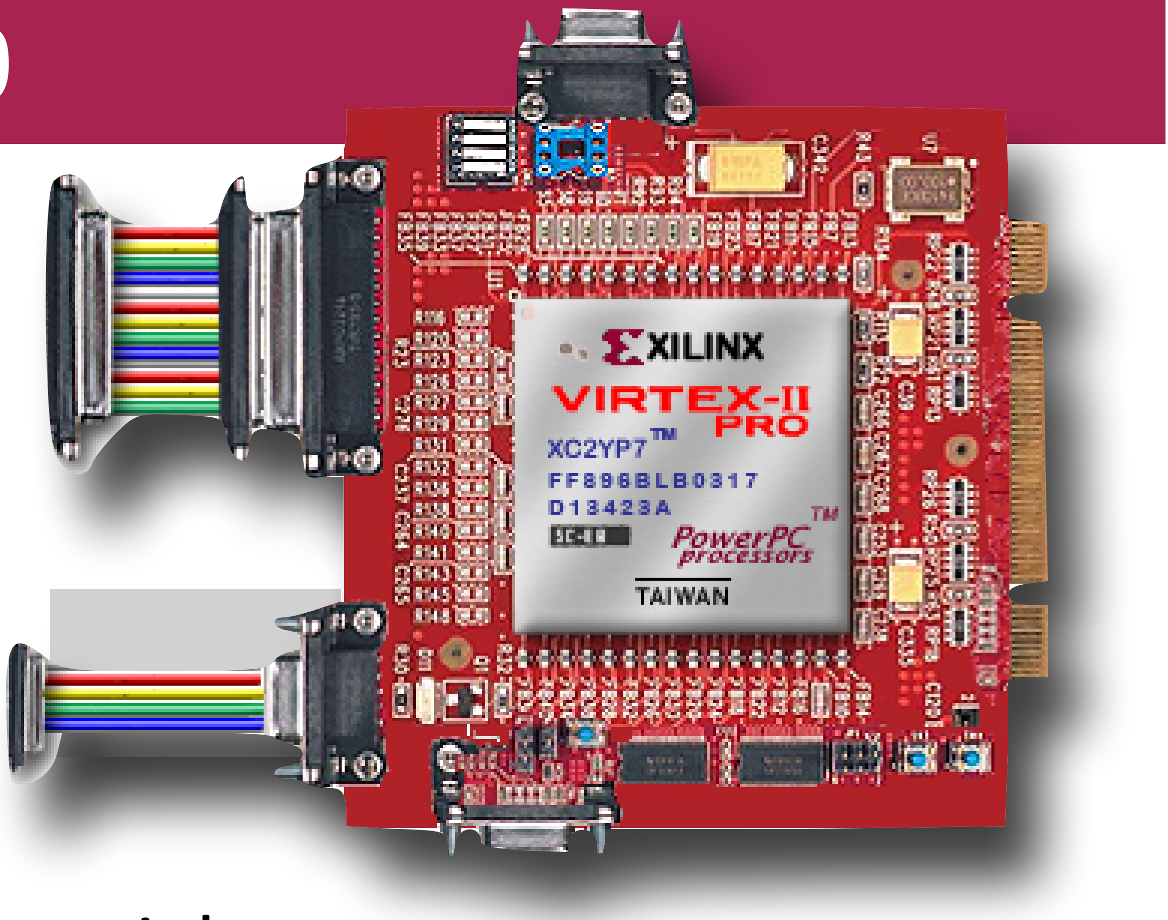
where

$$\Omega \equiv \rho/\rho_{cr} = (8\pi/3)G\rho/H^2\,, \qquad (1.2)$$

and the subscript p denotes the value at the present

ounds do not appear at first
stringent, they, in fact,
ons. The key point is that
stable. Furthermore, the
ppears in the equations for
niverse is the Planck time,
A typical closed universe
size on the order of this
cal open universe will
much less than ρ_{cr}. A uni-
years only by extreme fine
es of ρ and H, so that ρ is
initial conditions taken at





Expansion is exponential:

Size of observable universe increases by 10^{50} times

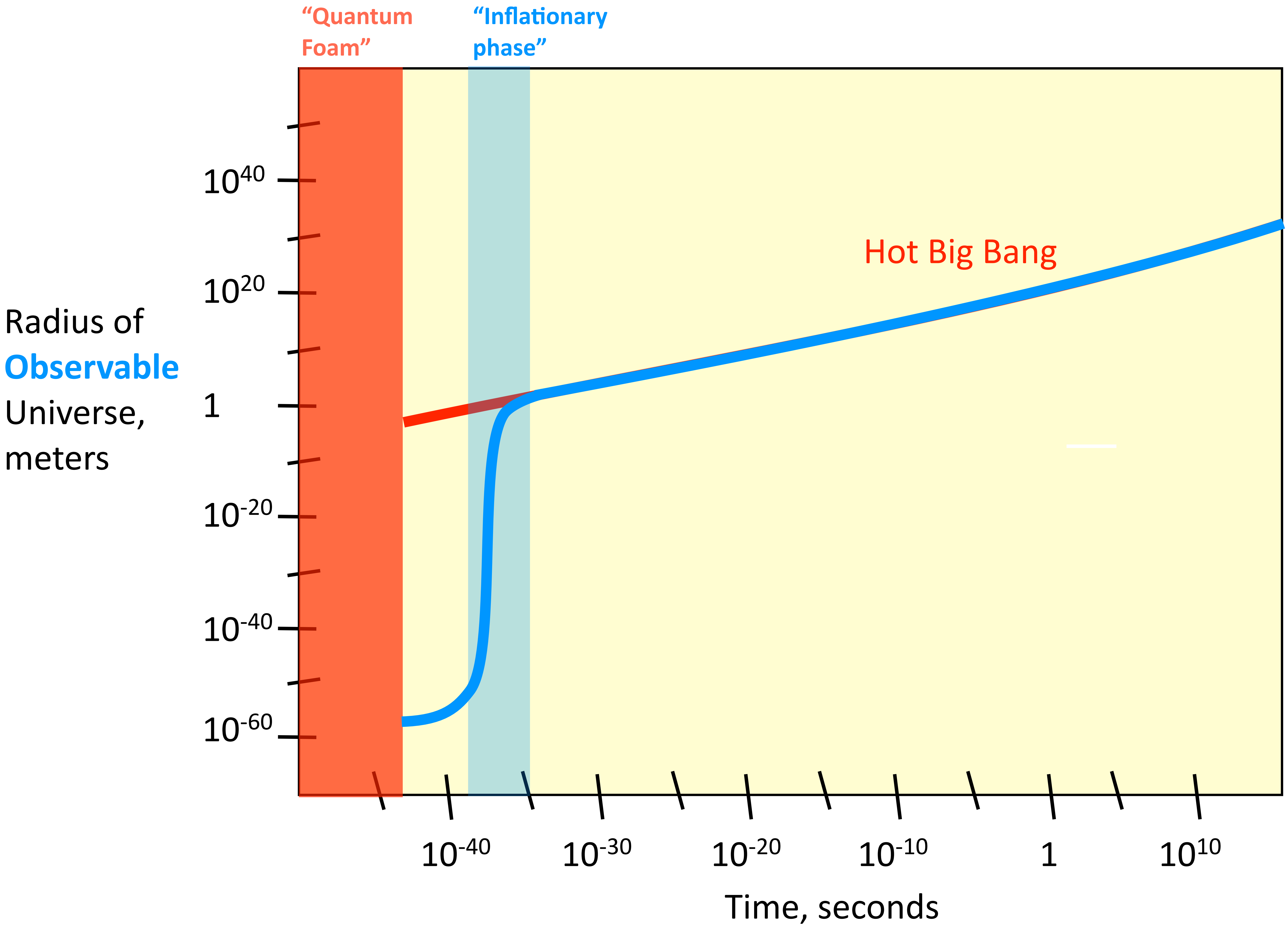
All by considering the universe to have undergone a 1st order phase transition.

What happens to the Inflaton?

It decays into the positive energy particles that begin the Hot Big Bang...reheating the universe... in the GUT phase

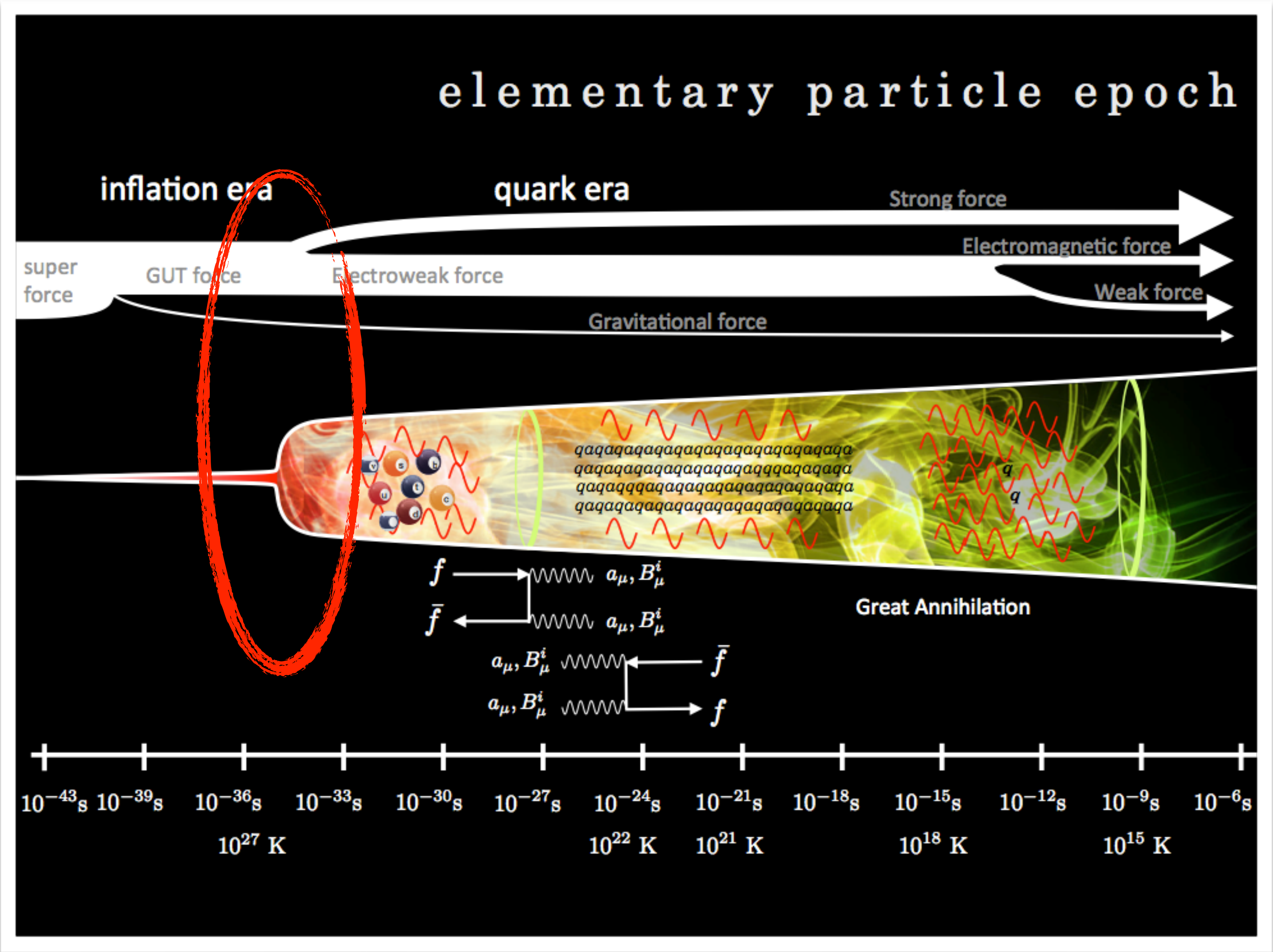
Remember the name: Alan Guth.

Size of the Observable Universe? take 2.



Inflation

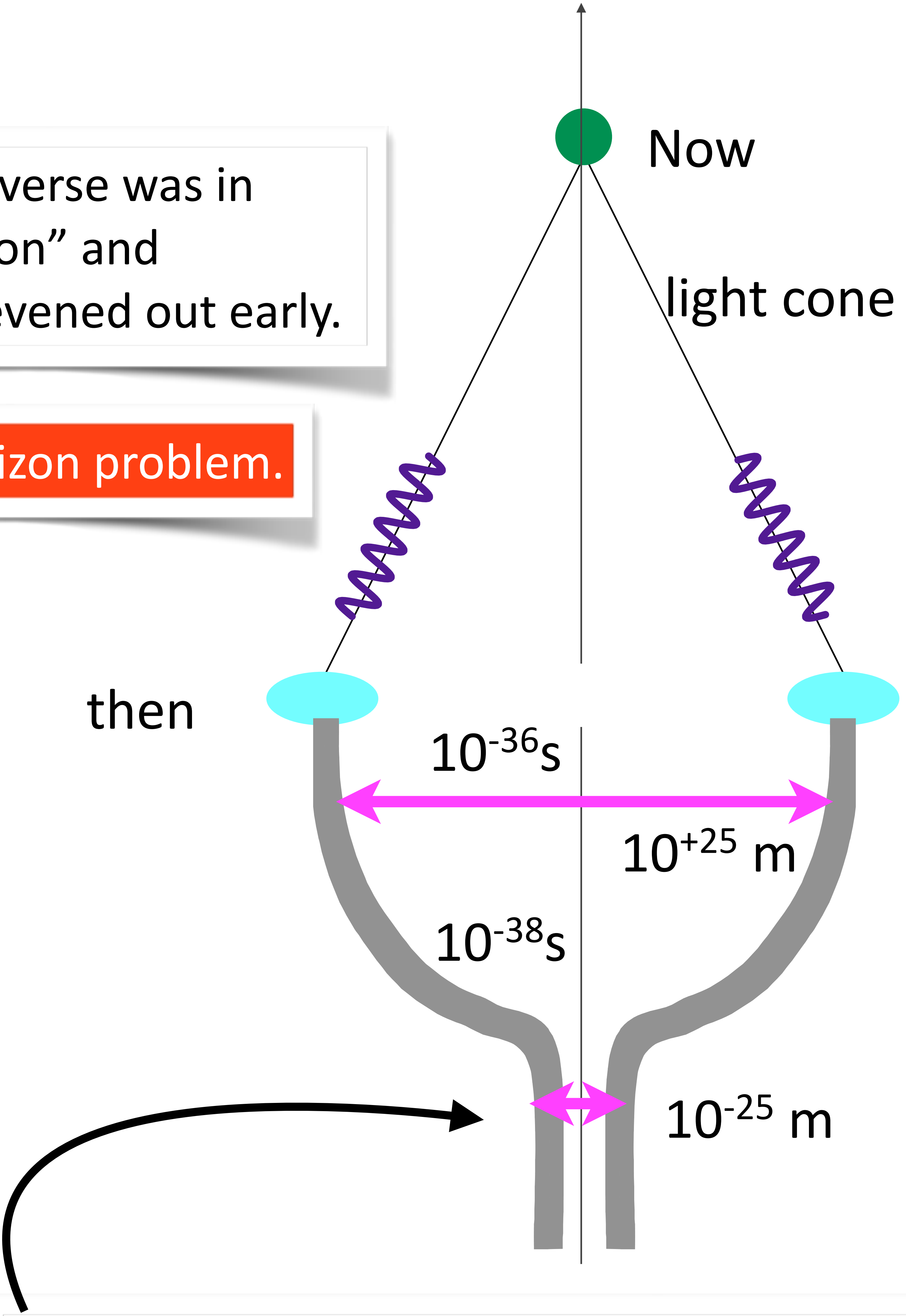
the phase transition that was responsible for separating the strong from the electroweak, fueled the inflationary phase?



‘‘Inflation’’

The whole universe was in “communication” and temperature evened out early.

solves the horizon problem.



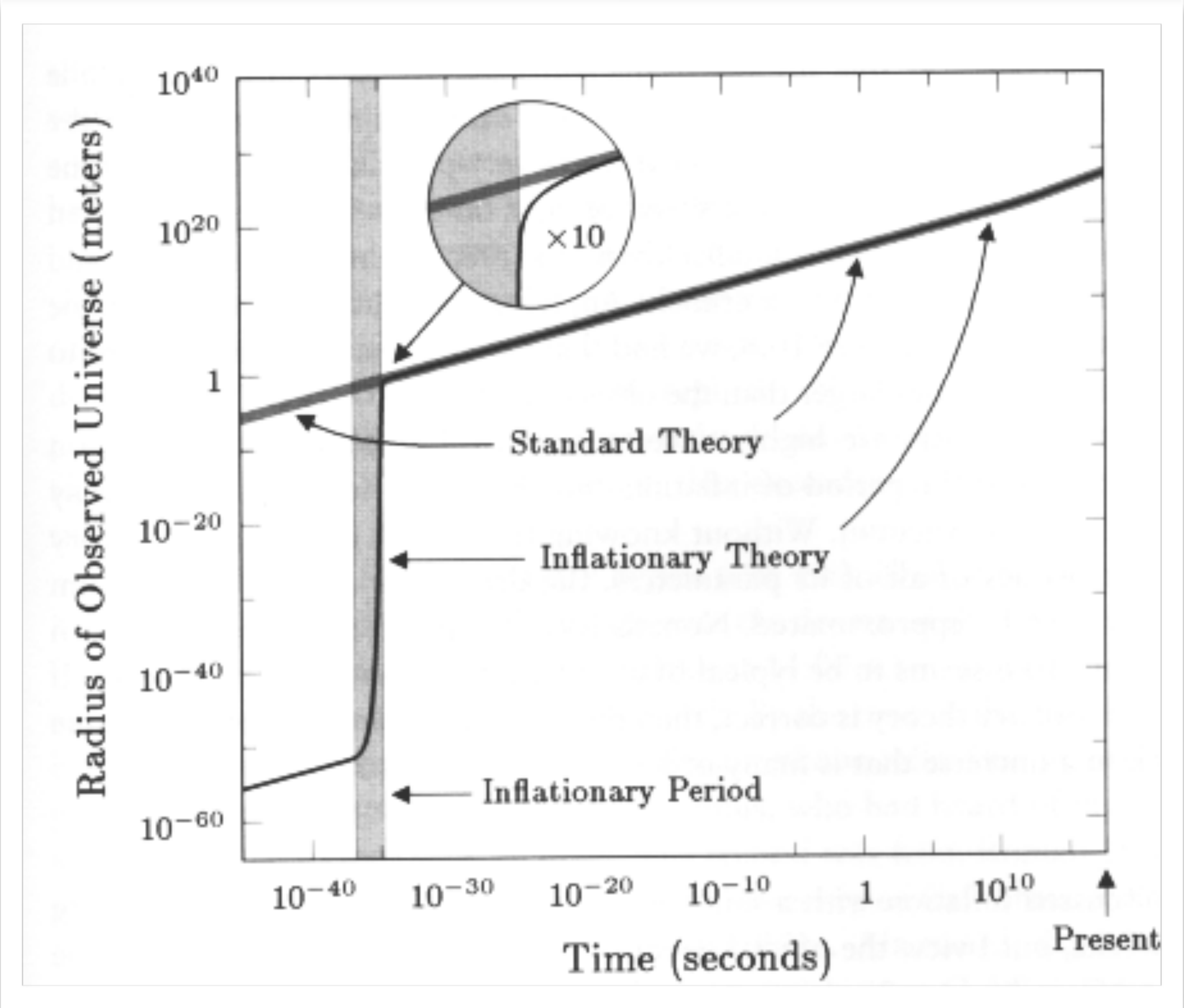
expands the size of the universe over 50 orders of magnitude

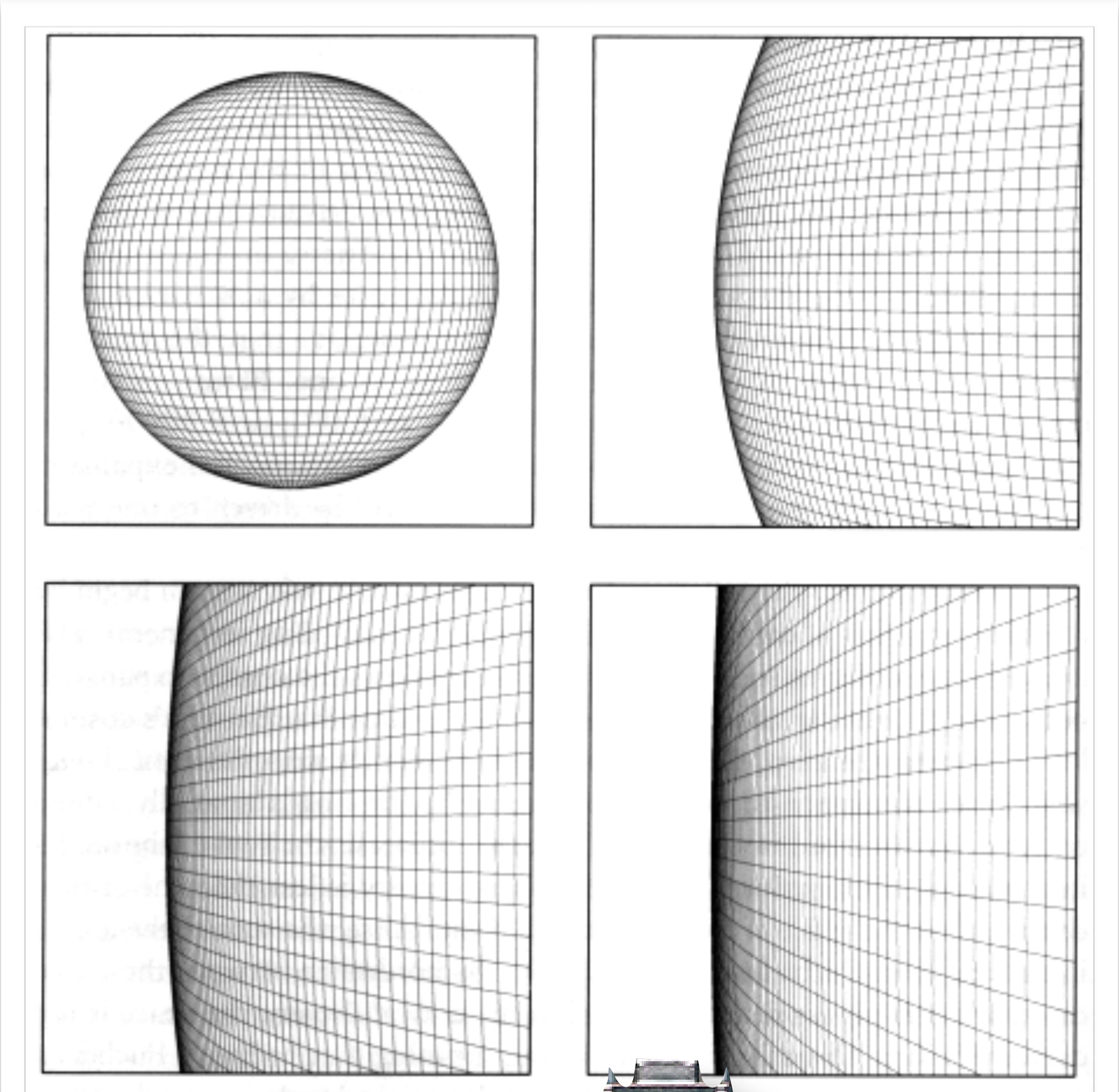
in fraction of a second

Quantum fluctuations are frozen as they inflate to macroscopic size

solves the structure problem.

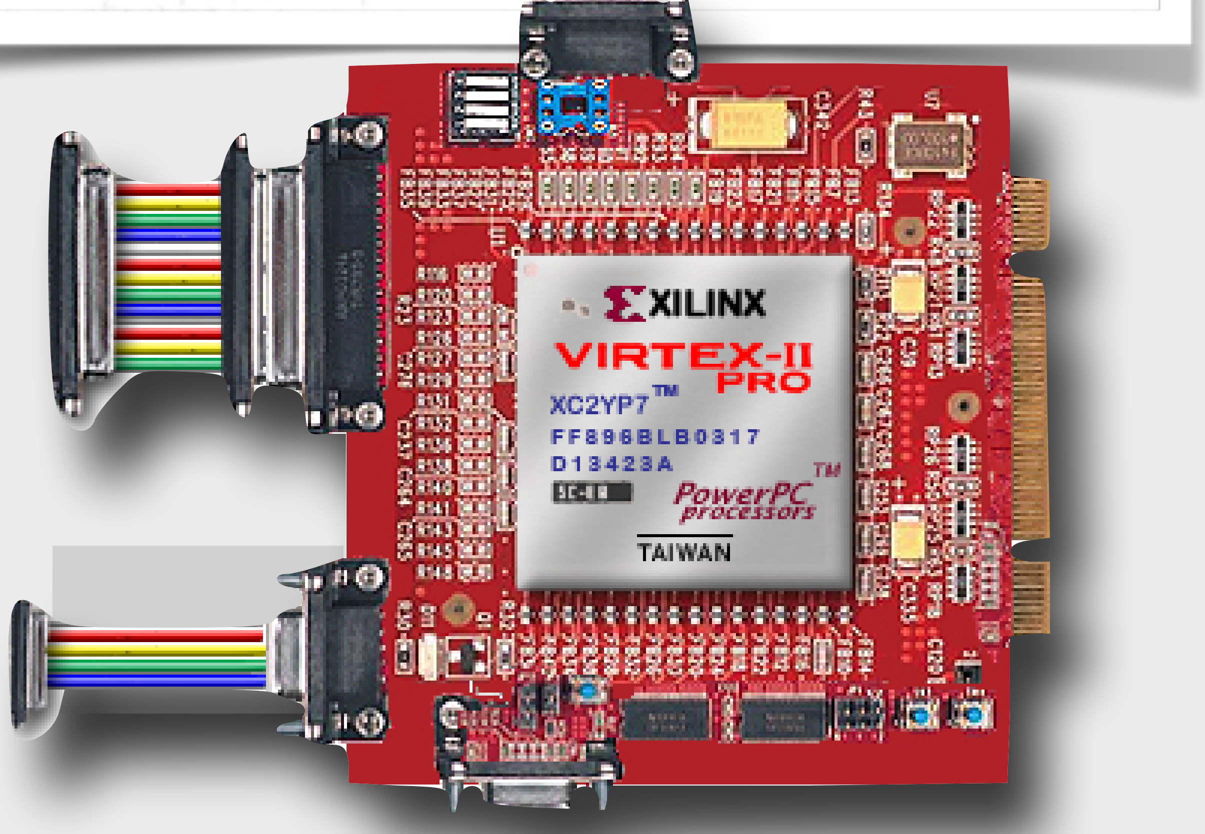
inflated so fast, as to make our neighborhood locally flat to 10^{-50}





solves the flatness problem.

In fact, inflation drives Ω = 1.000000000000000000000000



Relic problem?

solves the relic problem.

no problem...they are produced in the GUT phase

but they're so diluted that we'd never expect to see them all of that energy that's given up

during the inflation stage - inflated by factor of 10^{5}

comes from the vacuum

and creates all matter and energy, leaving negative gravitational energy

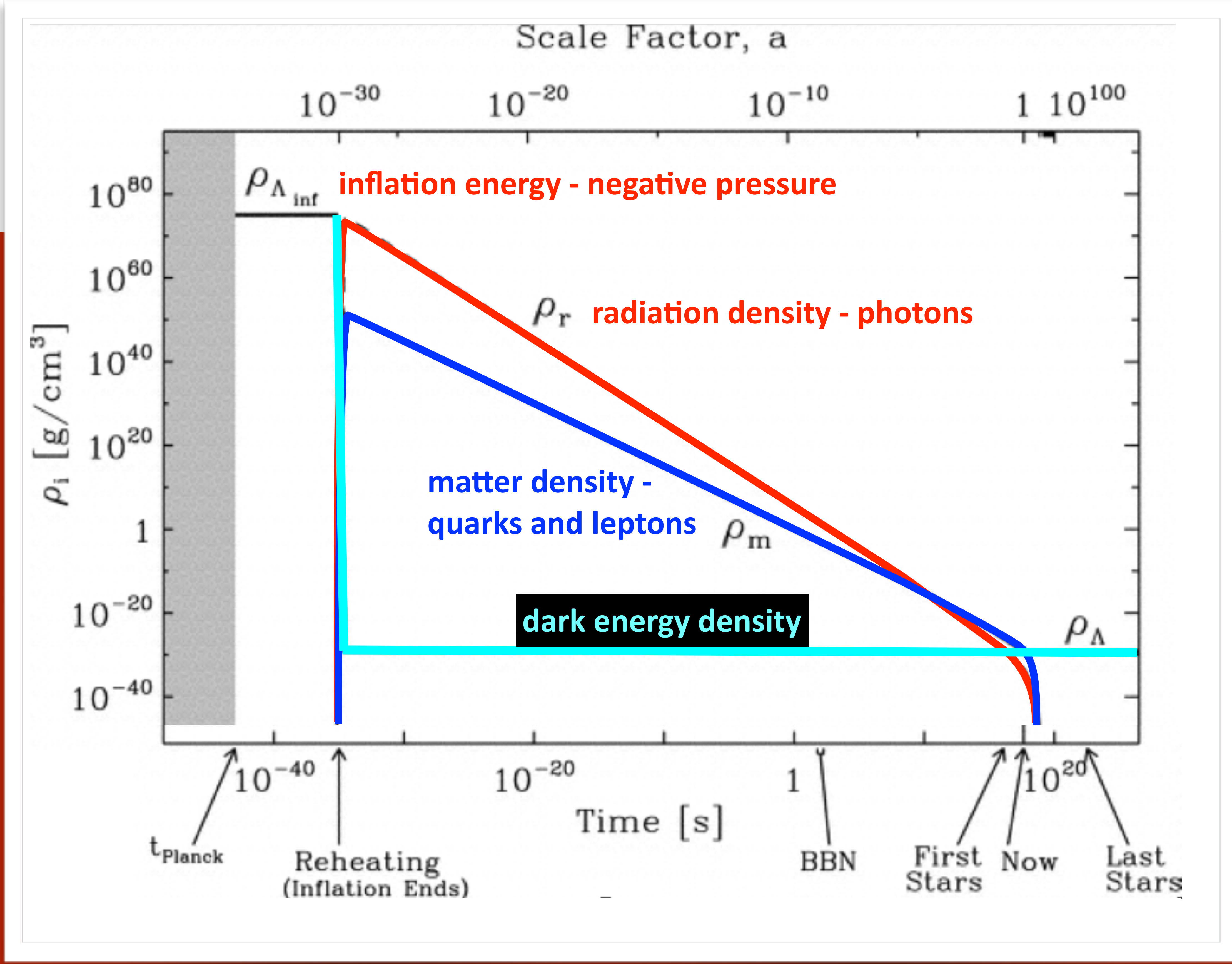
The total energy of the system? Zero.

the Universe might not have needed anything to start... except nothing

"Free lunch theorem"

what banged?

nothing.



Inflation even accounts for the “Bang” in Big Bang!

Inflation

Solves all of the problems with the Standard Big Bang model

except the antimatter problem...

but requires GUTS, which usually does solve the antimatter problem

Provides a reason for the "bang"

Uses primordial phase transitions, ala Higgs in particle physics

quantum fluctuations as the means of getting it all started

Of course the issue is: Is Inflation the case?

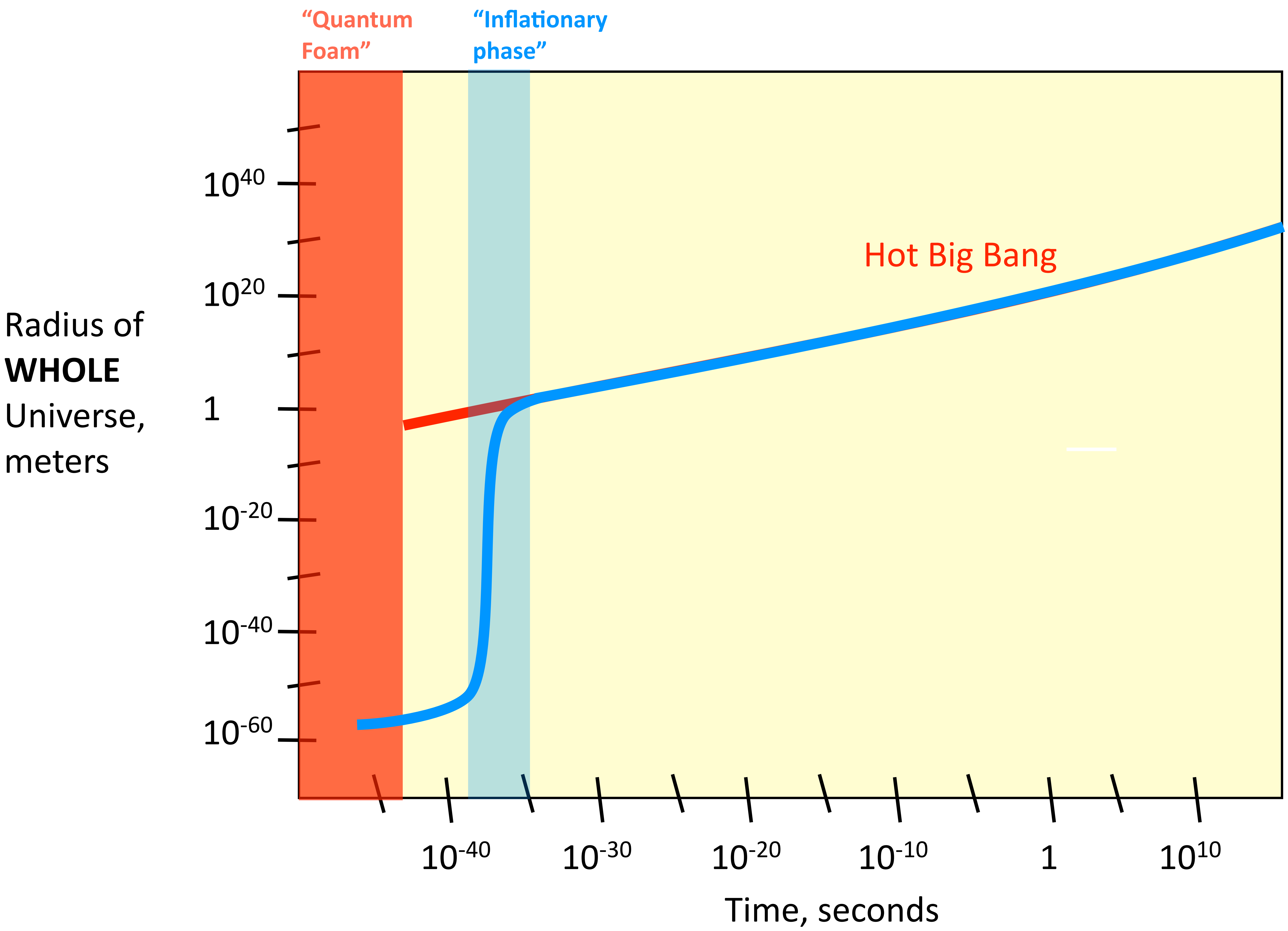
another

blessing-curse thingy

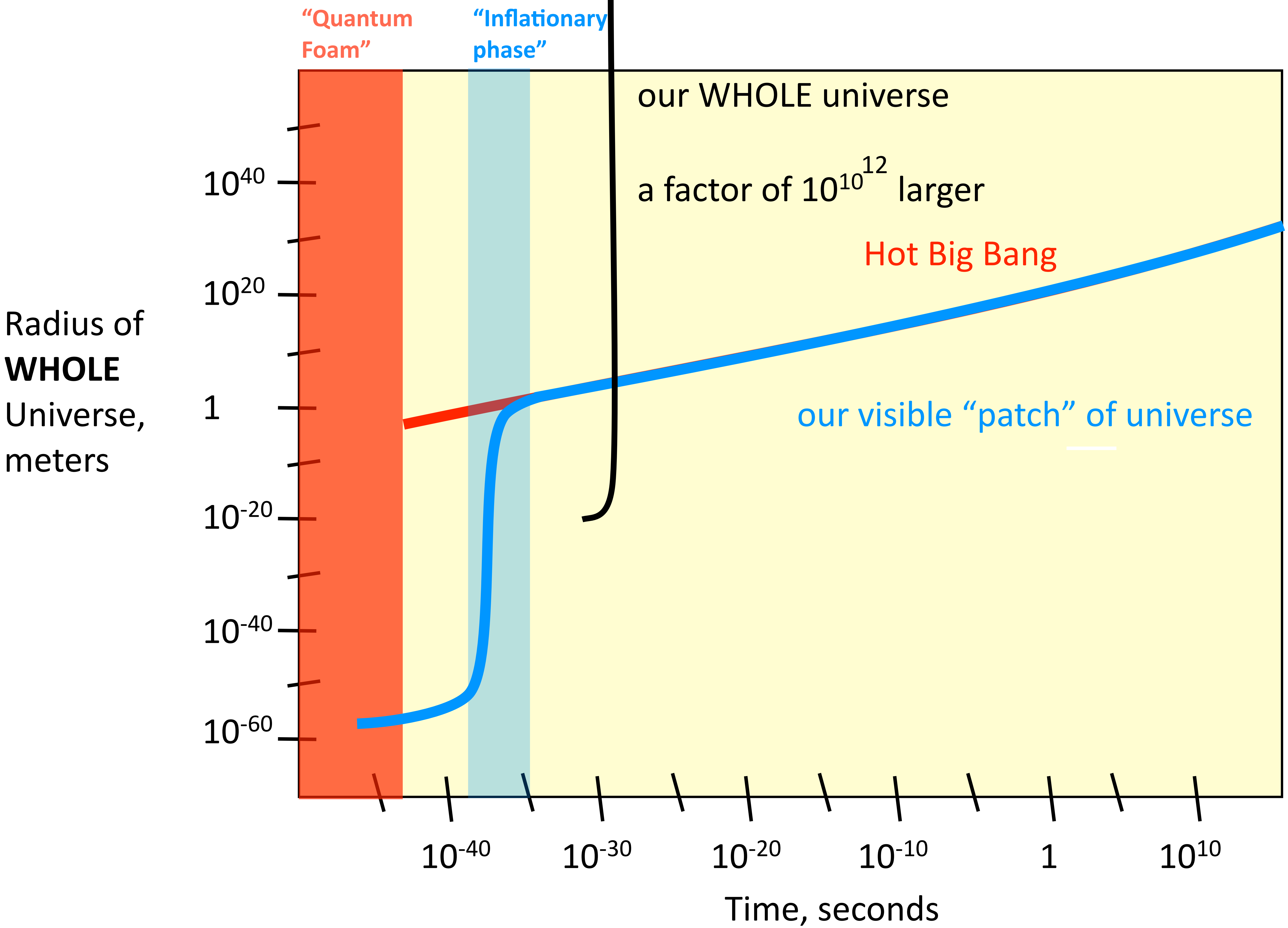
the actual universe must be huge

our visible part a tiny fraction

Size of the **WHOLE** Universe? take 3.



Size of the **WHOLE** Universe? take 3.



`another`

blessing-curse thingy

can’t stop inflation

from happening all the time, randomly, forever

lemons and lemonade

also have particle physics issues:

why are the constants of nature so precise?

and yet so apparently random?

remember string theories?

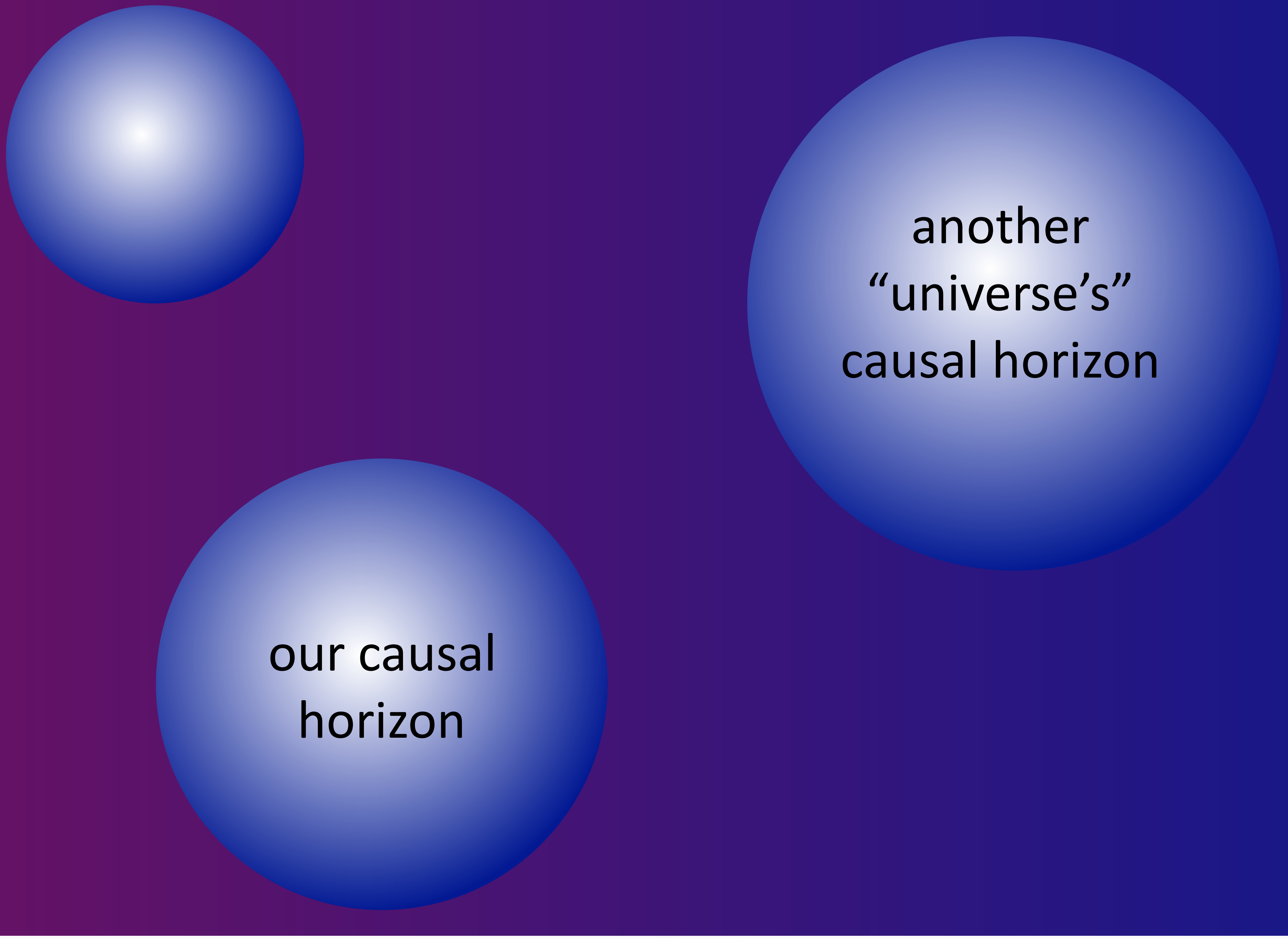
there are conservatively 10^{500} different vacuum solutions

WOO-HOO!

that's good!

for some

The “multiverse idea”



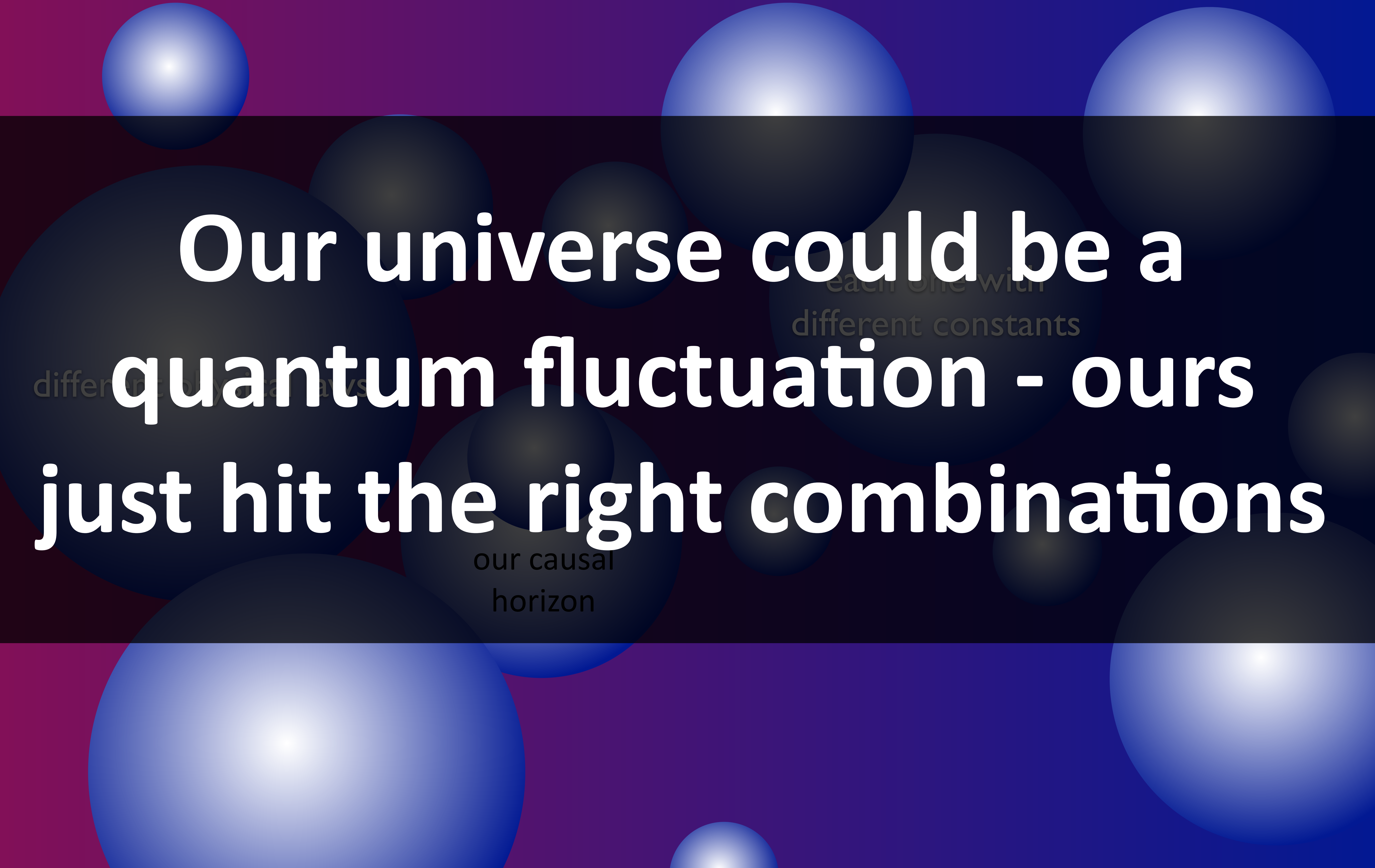
Other “universes” might have different physics

Is this how (not why) our universe supports us...? Could we be a random event?

The enormous number of others would be randomly produced with physics that couldn’t.

inflation is a quantum mechanical theory

quantum mechanically random



Our universe could be a quantum fluctuation - ours just hit the right combinations

Steven Weinberg:

particle: **the universe**

symbol:  $

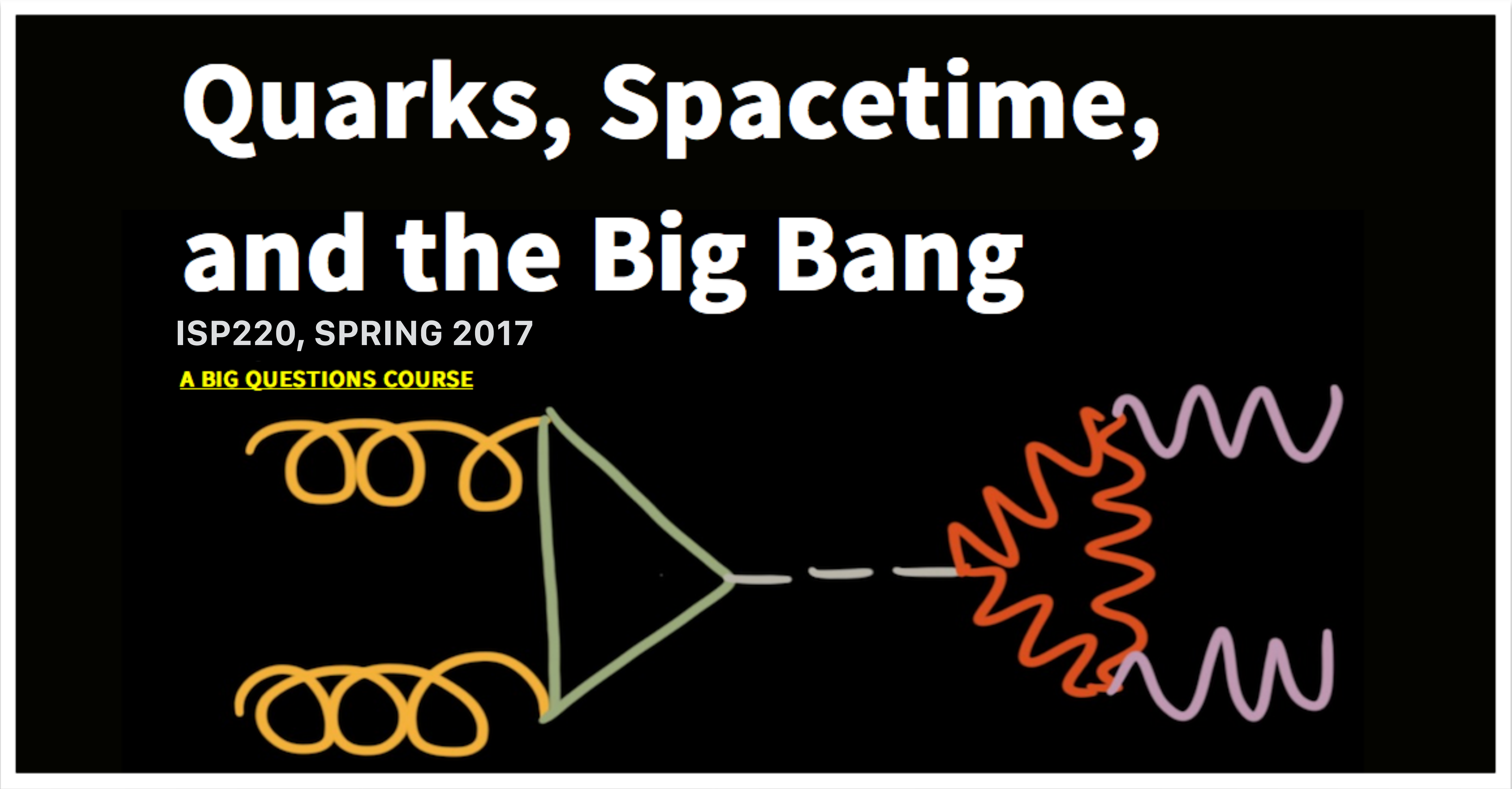
charge: 0

mass: 6 x 10^{51} kg

spin: ?

category: the one we've got

`bye`



Quarks, Spacetime, and the Big Bang

ISP220, SPRING 2017

A BIG QUESTIONS COURSE

after ISP220 you know a lot now.

our universe continues to surprise.

you’ve seen how the unimaginable

becomes acceptable

scratch any of us hard-boiled physicists

we’re pretty impressed with ourselves

But mostly...we’re in awe...every day

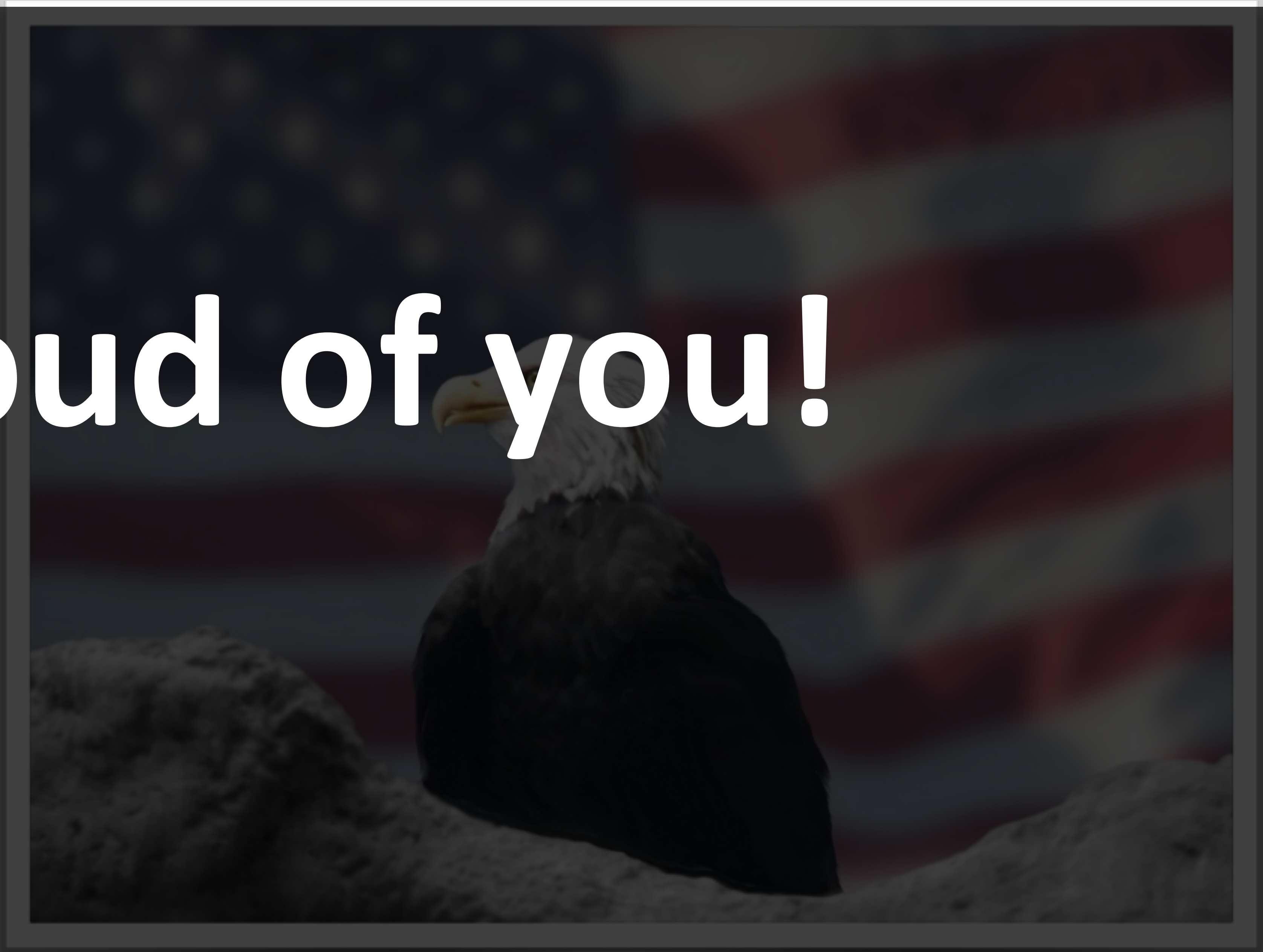
how incredibly gorgeous is our Universe

and what a privilege it is to study it.

you’re not physicists, so I know that you’re

brave and fearless to take this course.

I’m proud of you!



were

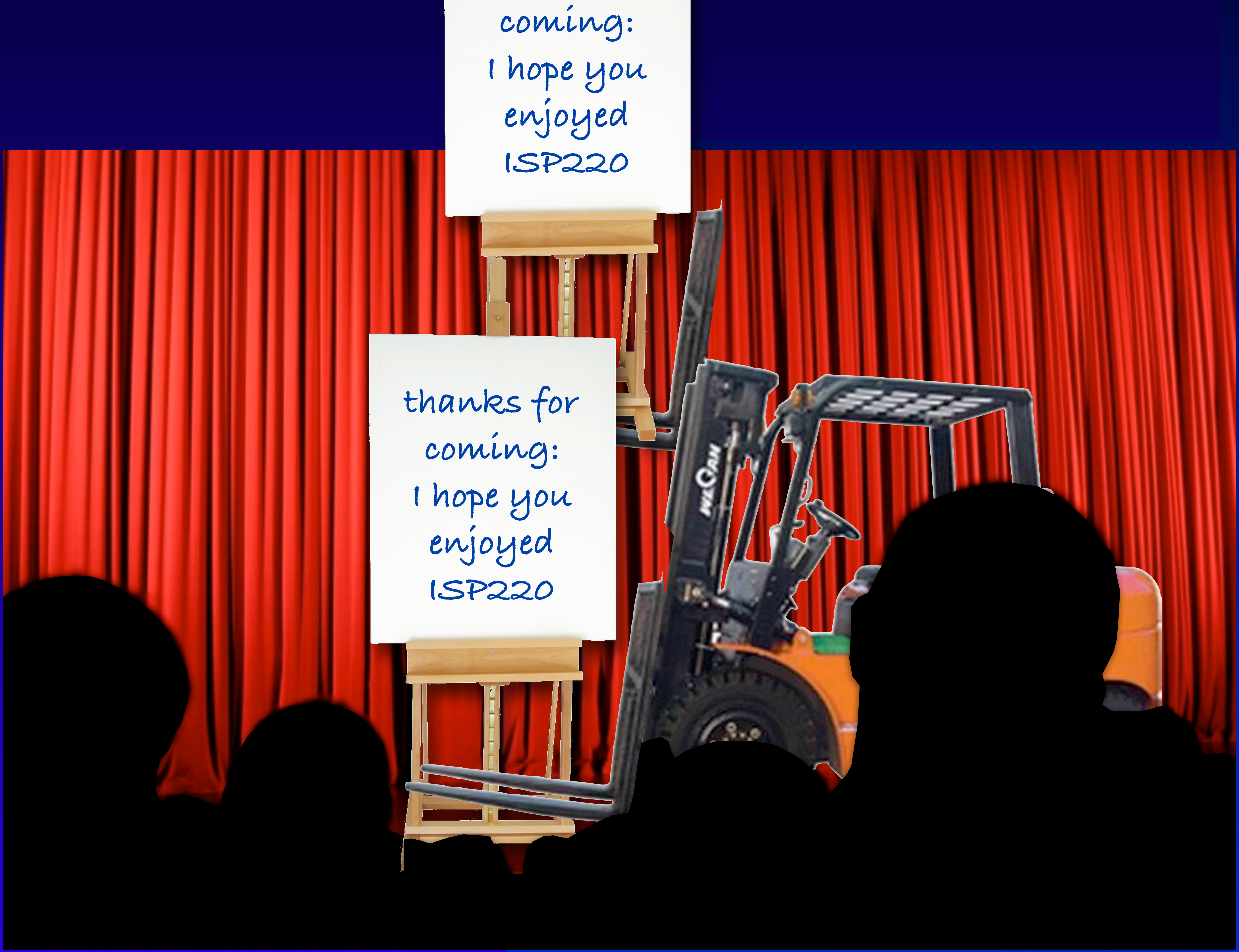
here ~~are~~ my goals

1. to learn some facts and theories about particle physics and cosmology.

2. to learn some tools and apply them in order to understand some experimental and theoretical techniques.

3. To meet some of the historical and contemporary physicists who have made important discoveries in these fields.

...and to immerse you in Science for 4 months.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