



# Quarks and the Cosmos

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**100 years of General Relativity**

**90 years of Big Bang**

**50 years of Hot Big Bang**

**40 years of Quarks & Cosmos**

deep connections between the very big & the very small

**100 years of QM & atoms**

**50 years of the “Standard Model”**



The Universe is very big (billions and  
billions of everything) and often  
beyond the reach of our minds and  
instruments

Big ideas and powerful instruments  
have enabled revolutionary progress

The image features a central funnel-like structure that narrows from left to right. The left side of the funnel is filled with a dense, glowing network of orange and purple filaments, representing a quark-gluon plasma. The right side of the funnel is filled with a dark space containing numerous colorful galaxies, representing the cosmos. The text "a very big idea" is positioned at the top center, and "connections between quarks & the cosmos" is at the bottom center.

a very big idea

connections between  
quarks & the cosmos

# big telescopes on the ground



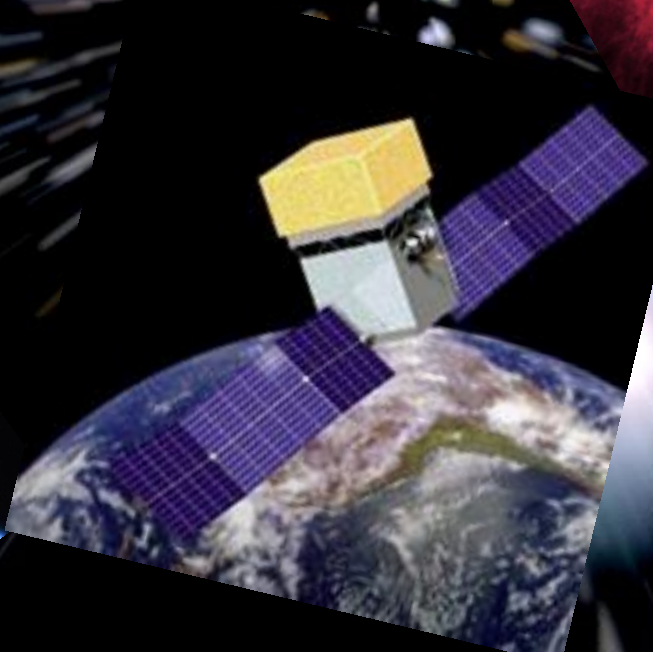
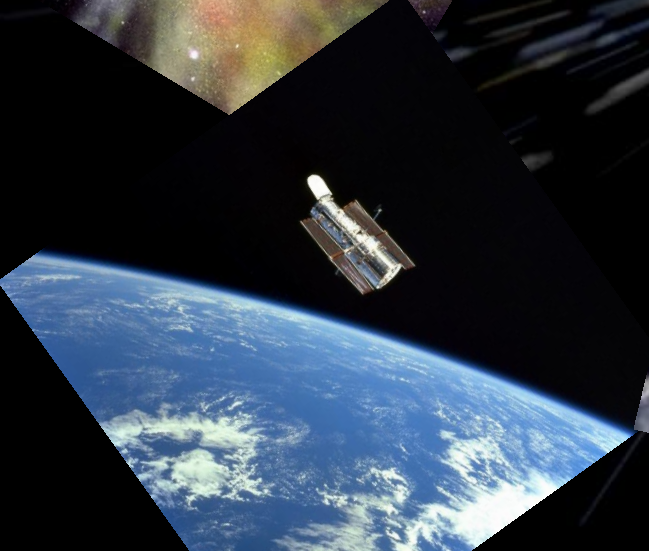
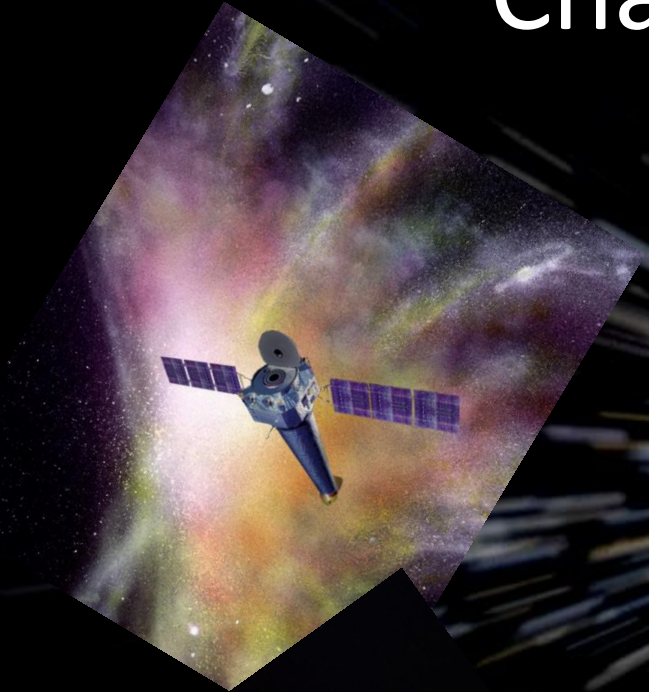
Hawaii



Chile



and in space: Hubble, Spitzer,  
Chandra, and Fermi



at the South Pole

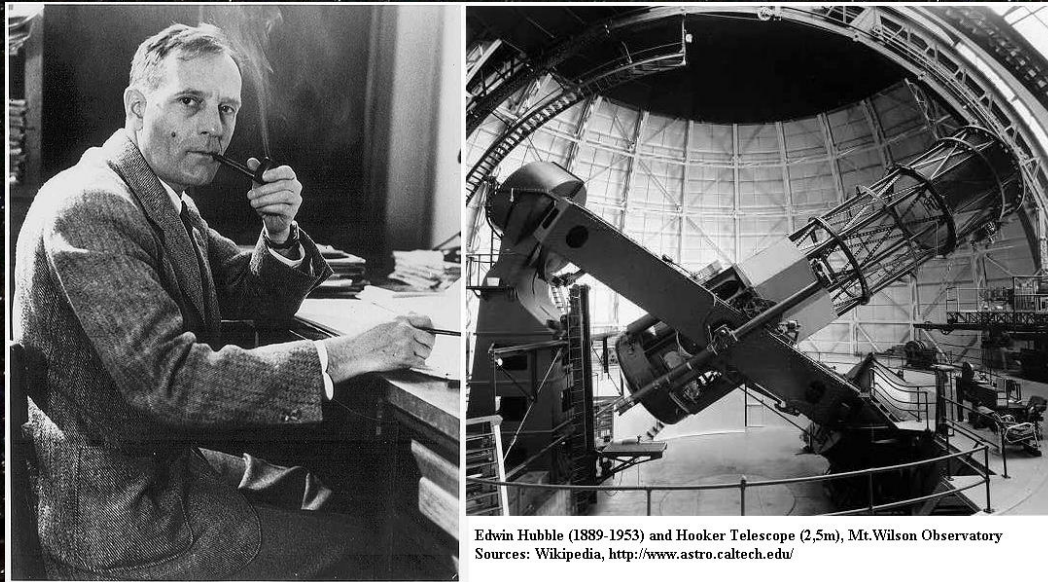


# basics of our Universe

- 100 billion galaxies
- each lit with the light of 100 billion stars
  - carried away from each other by expanding space from a
- big bang beginning 14 billion yrs ago



Hubble (1925): nebulae are “island Universes” → Universe comprised of billions of galaxies

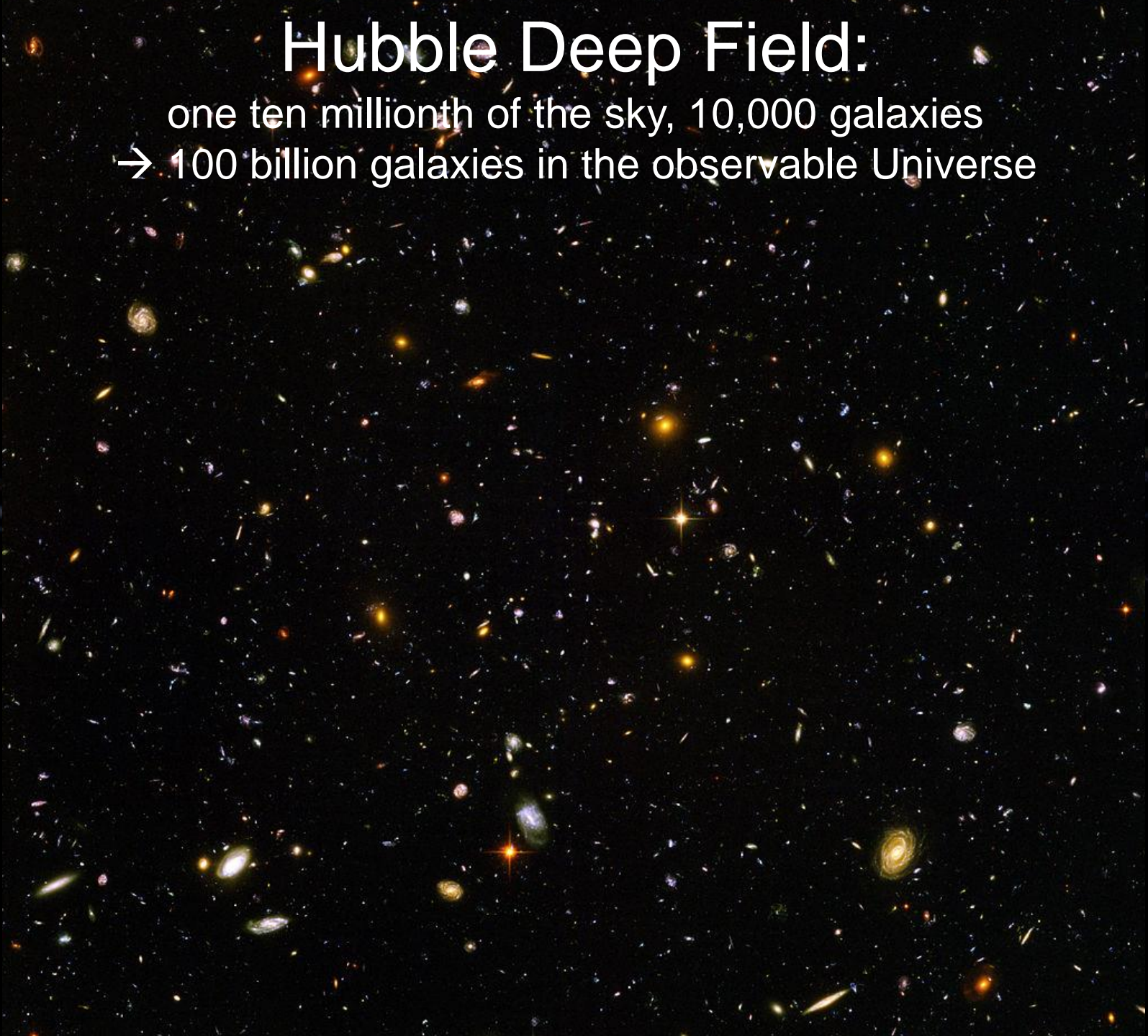


Edwin Hubble (1889-1953) and Hooker Telescope (2,5m), Mt. Wilson Observatory  
Sources: Wikipedia, <http://www.astro.caltech.edu/>

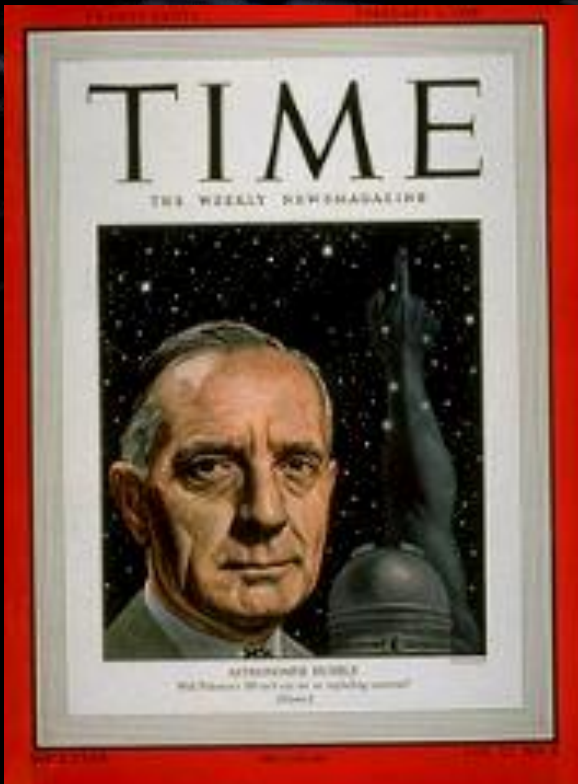
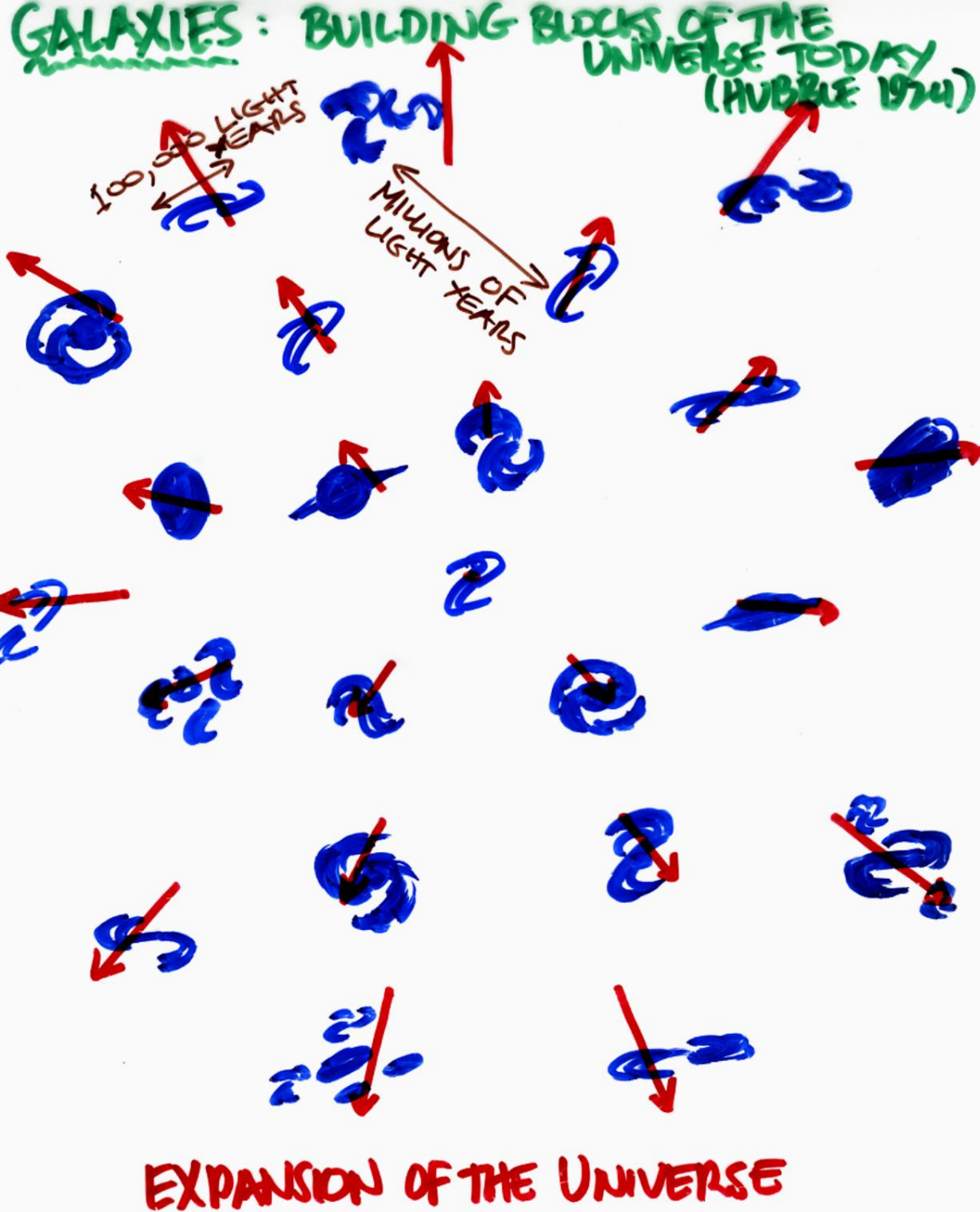
# Hubble Deep Field:

one ten millionth of the sky, 10,000 galaxies

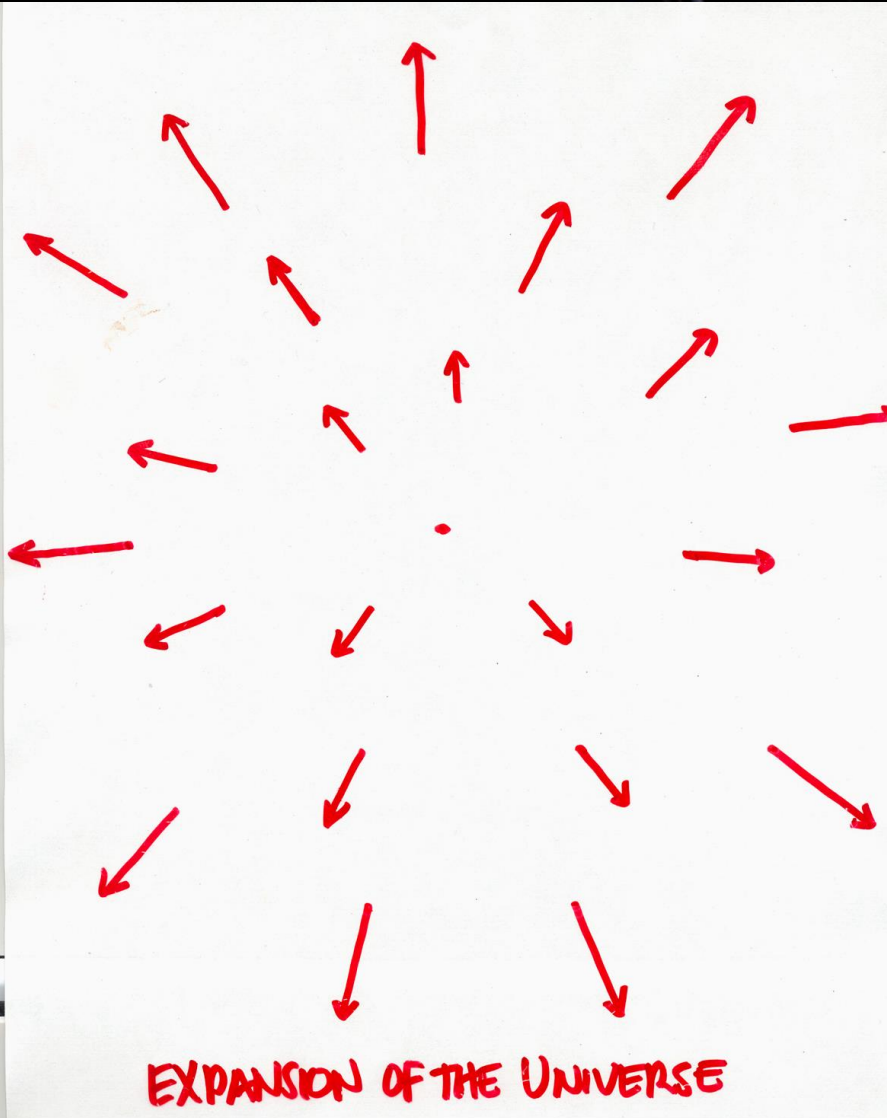
→ 100 billion galaxies in the observable Universe



Universe  
is expanding and  
had a beginning  
... Hubble, 1929



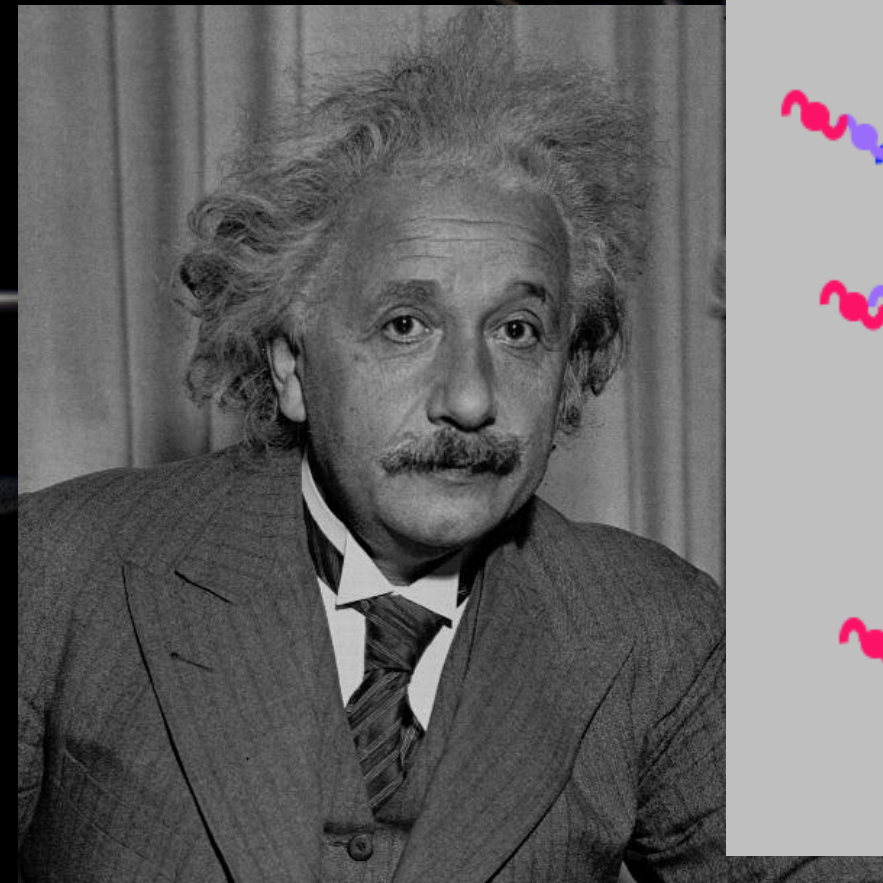
# Signature of big bang beginning



... GOING BACK IN TIME



Einstein: Big Bang = explosion of space with galaxies carried along

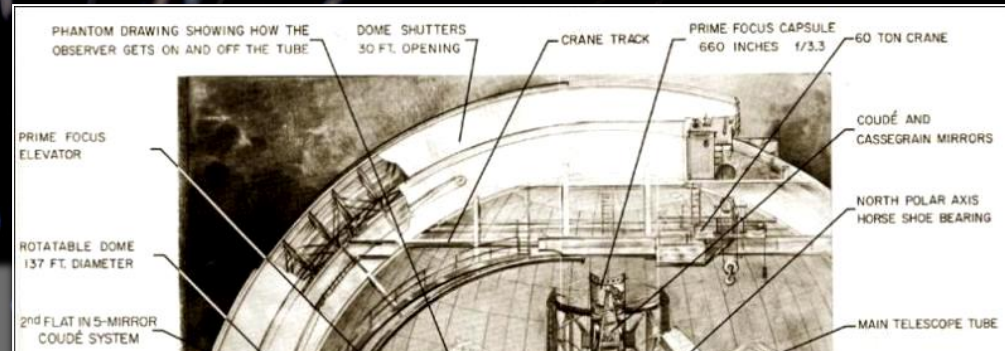
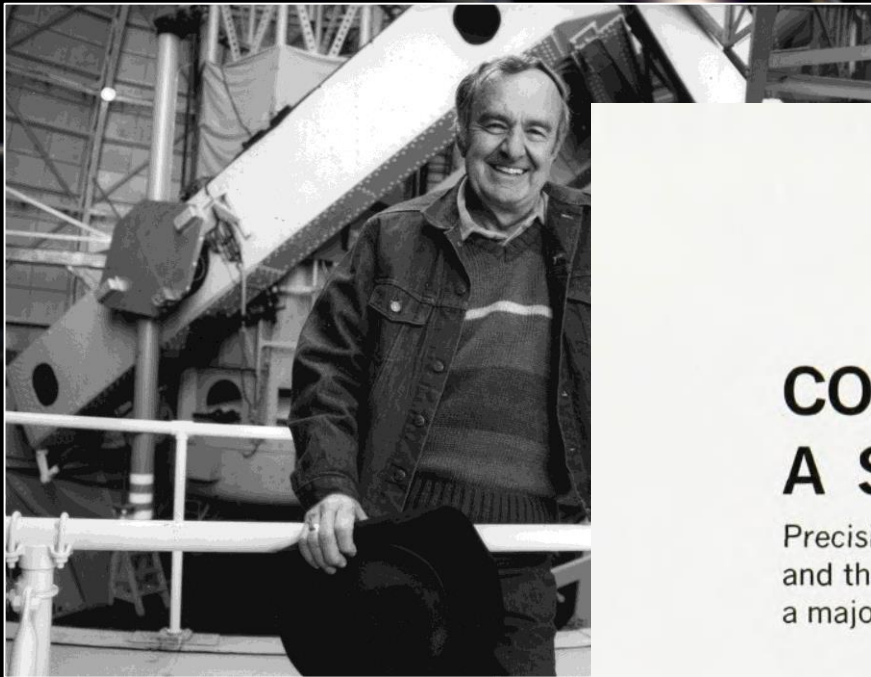




The big questions circa 1978

# just two numbers: $H_0$ and $q_0$

Allan Sandage,  
Hubble's "student"



## COSMOLOGY: A SEARCH FOR TWO NUMBERS

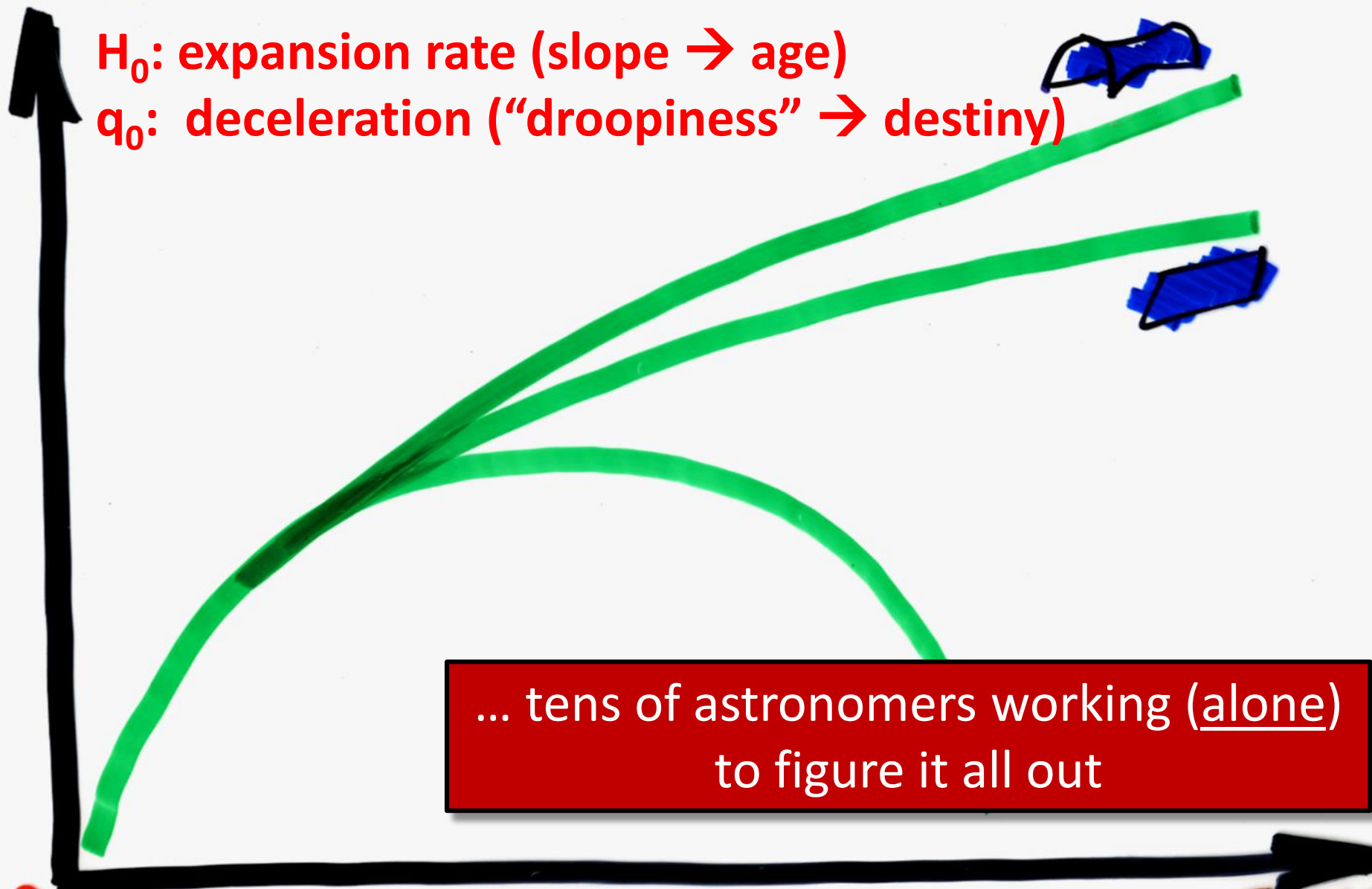
Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

ALLAN R. SANDAGE

SIZE

$H_0$ : expansion rate (slope  $\rightarrow$  age)

$q_0$ : deceleration ("droopiness"  $\rightarrow$  destiny)

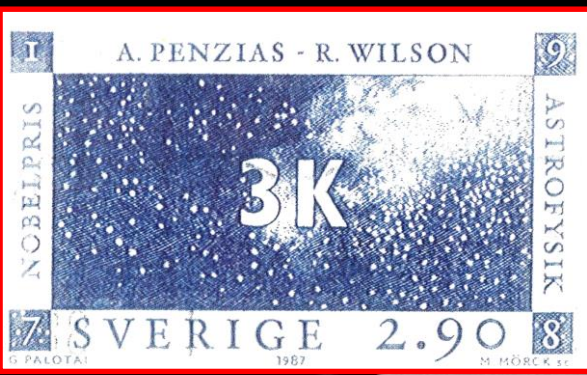


... tens of astronomers working (alone)  
to figure it all out

BIG BANG

TIME

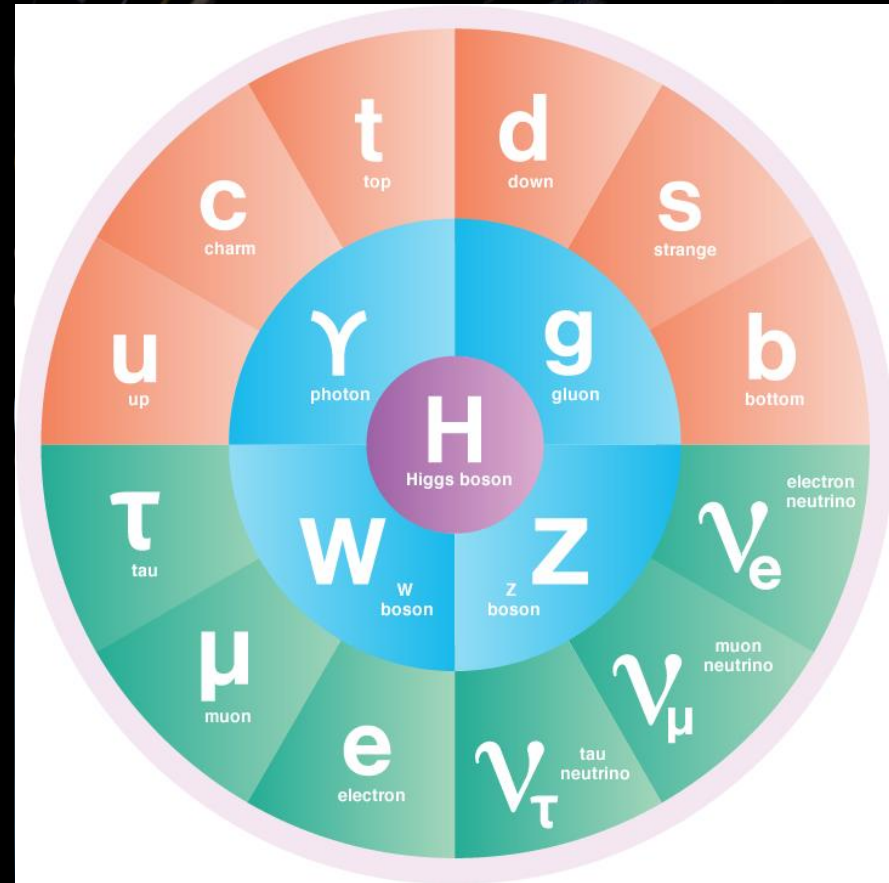




Microwave echo of the big bang →

**Hot Big Bang**

# Circa 1980: quark soup revolution



# ORDINARY MATTER: FROM QUARKS TO US

INFLATION  
BARYOGENESIS



$10^{-5}$  SEC

TRANSITION FROM  
QUARKS  $\rightarrow$  NEUTRONS, PROTONS



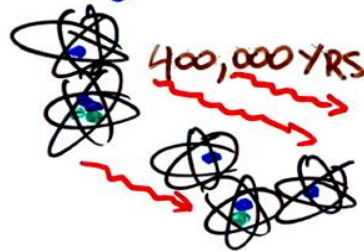
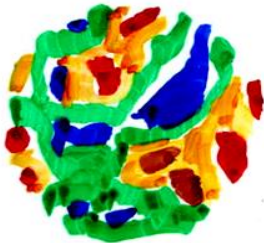
BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

BIG-BANG  
NUCLEOSYNTHESIS  
Formation of H, D,  
He, He-3, Li

FORMATION OF ATOMS  
COSMIC MICROWAVE  
BACKGROUND

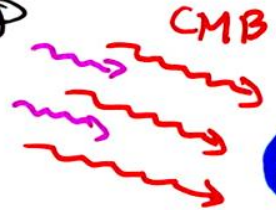


400,000 YRS



QSO LIGHT

1 BILLION YRS  
FIRST QUASARS



CMB

CMB

RATIO OF FIRST-TO-  
SECOND PEAKS:  $2/1$



$\Omega_B = 0.045 \pm 0.003$

INTERGALACTIC GAS

ABSORPTION OF  
QUASAR LIGHT  
BY HYDROGEN

$\Omega_B \geq 0.04$

HERE & NOW  
44 Billion YRS  
stars, gas,  
dust, ...

Quark Soup

**Dark Matter**

Elementary particles as Dark Matter

WIMPs

**Inflation**

Early burst of enormous expansion

Baryogenesis

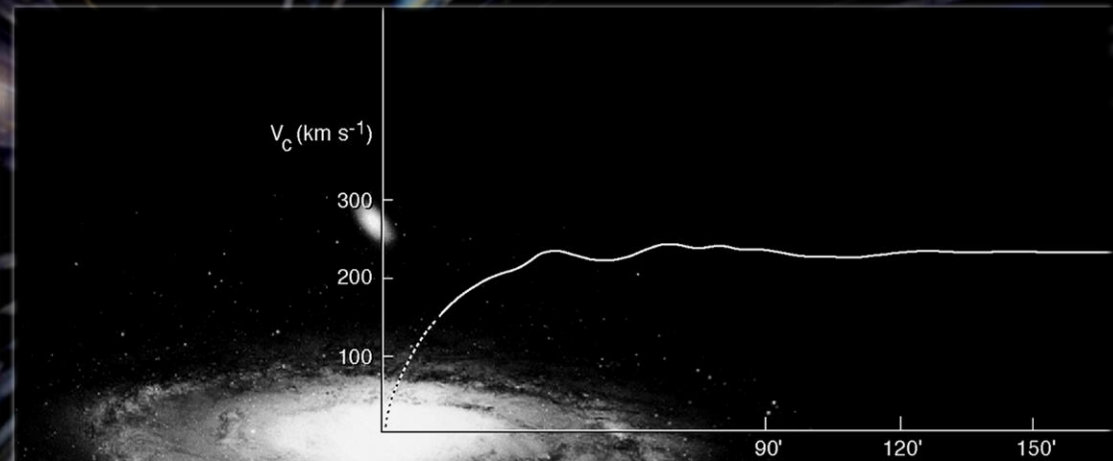
**Dark Energy**

Repulsive vacuum energy!

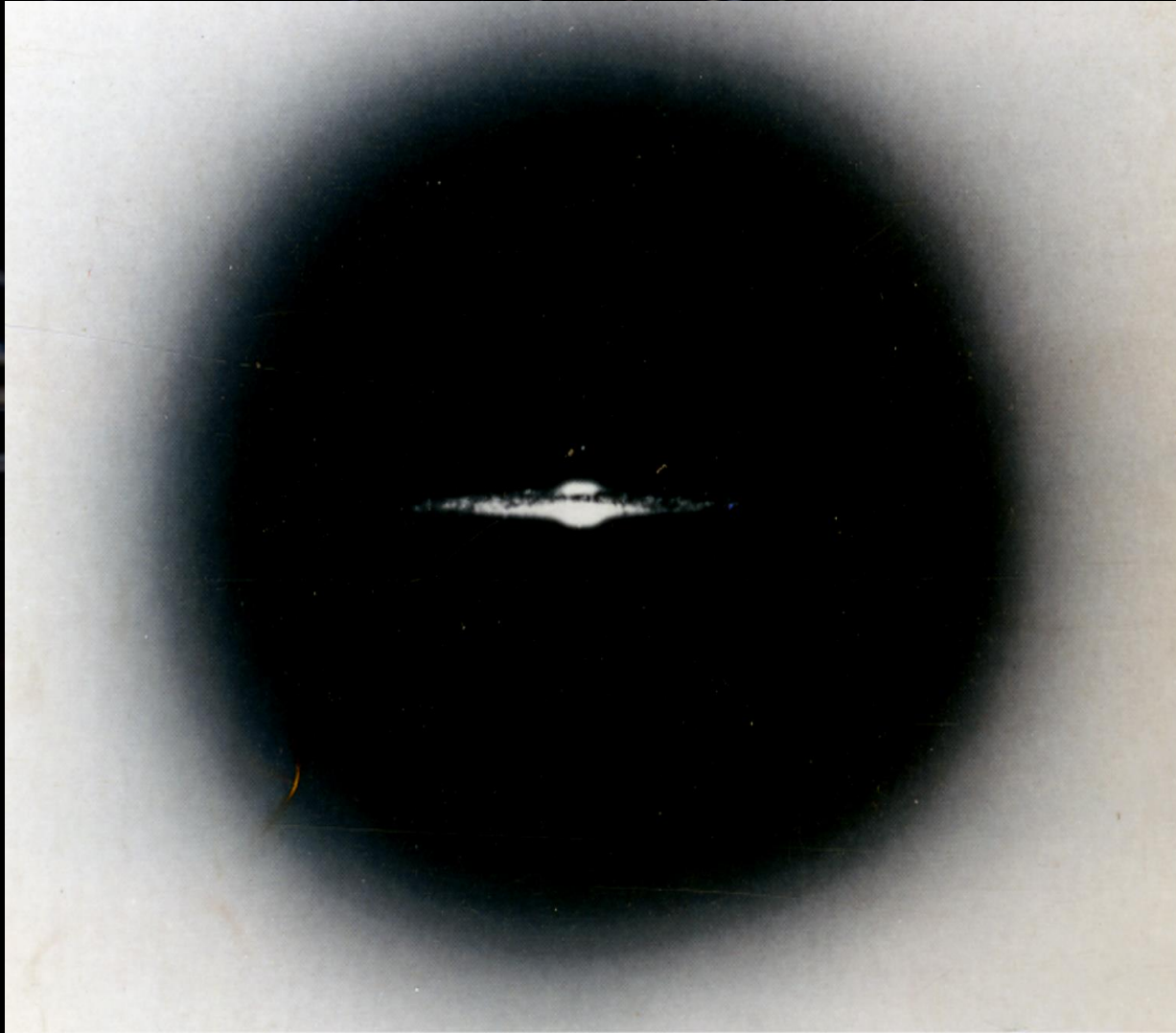
CDM

# 1970s: Vera Rubin

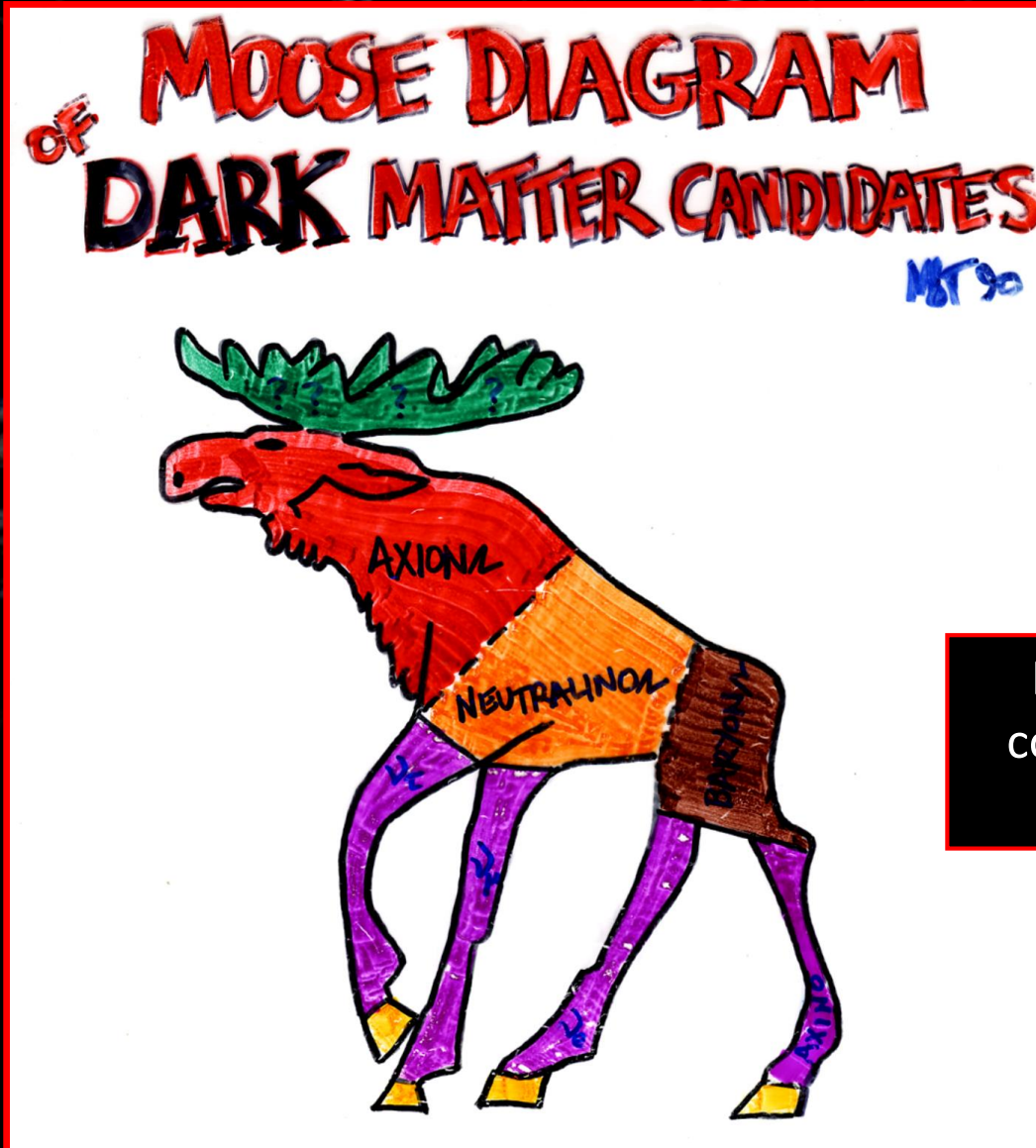
## Flat rotation curves reveal dark matter



Galaxy = dark matter halo + starry nugget

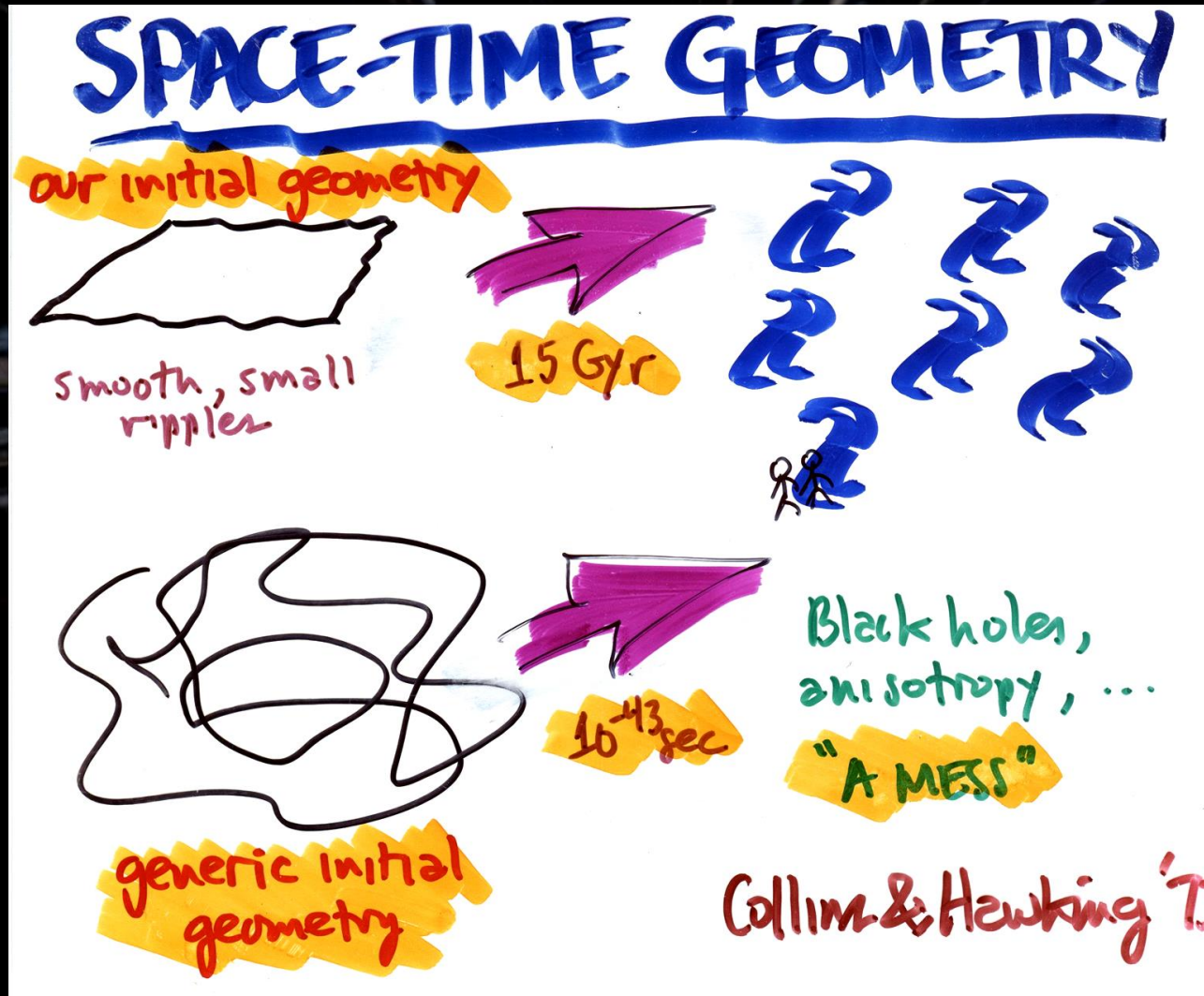


Dark matter is a new form of matter  
(predicted to exist in unified particle theories)



Neutrinos  
contribute a  
few 0.1%

# apparent special beginning





# explained by cosmic inflation



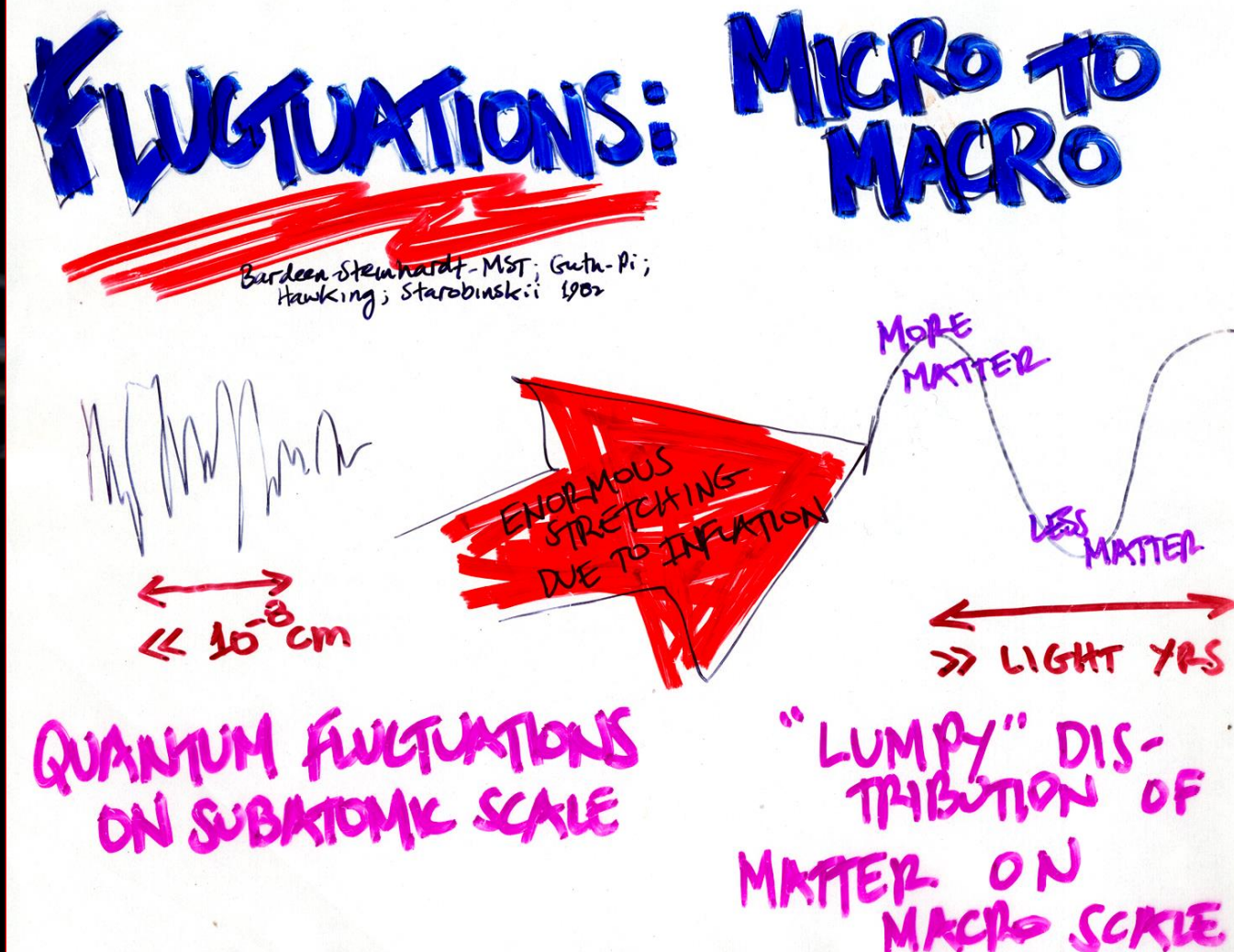
TINY ( $\lll 1\text{cm}$ ) BIT  
OF UNIVERSE IS FLAT  
& SMOOTH (but too  
small to contain all we  
see today)



ALL THAT  
WE CAN  
SEE TODAY  
  
(STILL SMOOTH  
& FLAT)

Explains the smoothness and heat of the Big Bang and predicts a flat Universe

# and more: quantum fluctuations become seeds for galaxies



"inflaton field"  $\phi$



EARLY EPOCH OF TREMENDOUS EXPANSION DRIVEN BY VACUUM ENERGY

$10^{-32}$  sec  $\gg 10^{40}$

SCALAR FIELD ENERGY

ACCOUNTS FOR:

SMOOTHNESS, HEAT OF BIG-BANG & ABSENCE OF MONOPOLES

& PREDICTS:

Robust Predictions

- ★ "FLAT UNIVERSE" ( $\Omega_0 = \frac{\rho_{TOT}}{\rho_{CRIT}} \approx 1.0$ )
- ★ NEARLY SCALE-INVARIANT DENSITY PERTURBATIONS
- ★ NEARLY SCALE-INVARIANT GRAVITY WAVES

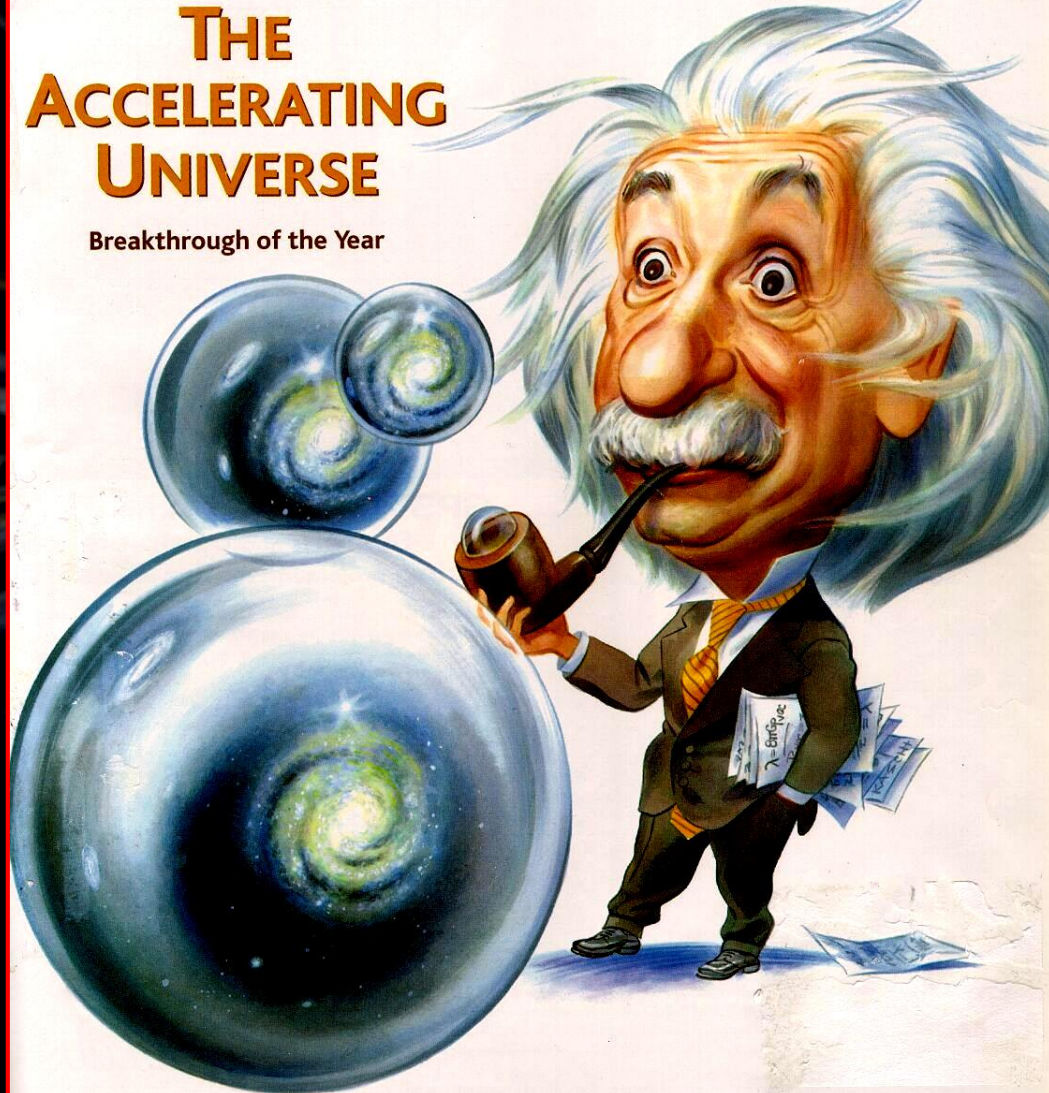
18 December 1998

# Science

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Pages 2141-2336 \$7

## THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

REPULSIVE GRAVITY  
IS A FEATURE NOT A  
BUG!

OF EINSTEIN'S  
THEORY

... but only really weird  
stuff has repulsive gravity

"DARK ENERGY"

QUANTUM NOTHINGNESS  
HAS REPULSIVE GRAVITY!



How REPULSIVE?

JUST ABOUT RIGHT --- GIVE OR  
TAKE  $10^{55}$

So, cosmic acceleration is  
caused by the repulsive gravity  
of quantum nothingness  
aka Einstein's  $\Lambda$

any questions?

# $\Lambda$ CDM: how we got here

- a jiffy\* after the beginning: tremendous burst of expansion (inflation) that smoothed spacetime, created hot quark soup, and turned subatomic quantum fluctuations into seeds for galaxies
- until 0.00001 sec: quark soup era during which ordinary matter and dark matter arose
- 0.00001 to 300 sec: neutrons and protons, then nuclei of the lightest elements were created
- 100,000 years to 5 billion years: gravity of dark matter builds cosmic structure from quantum seeds
- 5 billion years on: Dark energy takes over and speeds up the expansion

\*a jiffy =  $10^{-40}$ ish sec



# ORDINARY MATTER: FROM QUARKS TO US

## INFLATION BARYOGENESIS



TRANSITION FROM QUARKS  $\rightarrow$  NEUTRONS, PROTONS



BBN

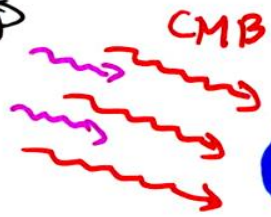
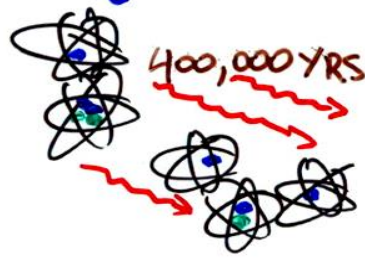
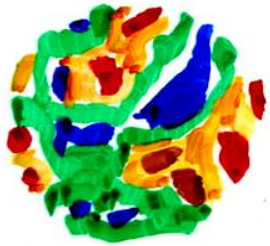
$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

inflation, origin of dark matter and ordinary matter

BIG-BANG NUCLEOSYNTHESIS  
Formation of H, D, He, He-3, Li

## FORMATION OF ATOMS COSMIC MICROWAVE BACKGROUND



## CMB

RATIO OF FIRST-TO-SECOND PEAKS:  $2/1$

$\Omega_B = 0.045 \pm 0.003$

## INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN

$\Omega_B \geq 0.04$

HERE & NOW  
14 Billion YRS  
stars, gas, dust, ...

# Inflation + Cold Dark Matter

cosmic structure  
forms "bottom up":

Stars ( $z \sim 10$ )

Galaxies ( $z \sim 2 - 5$ )

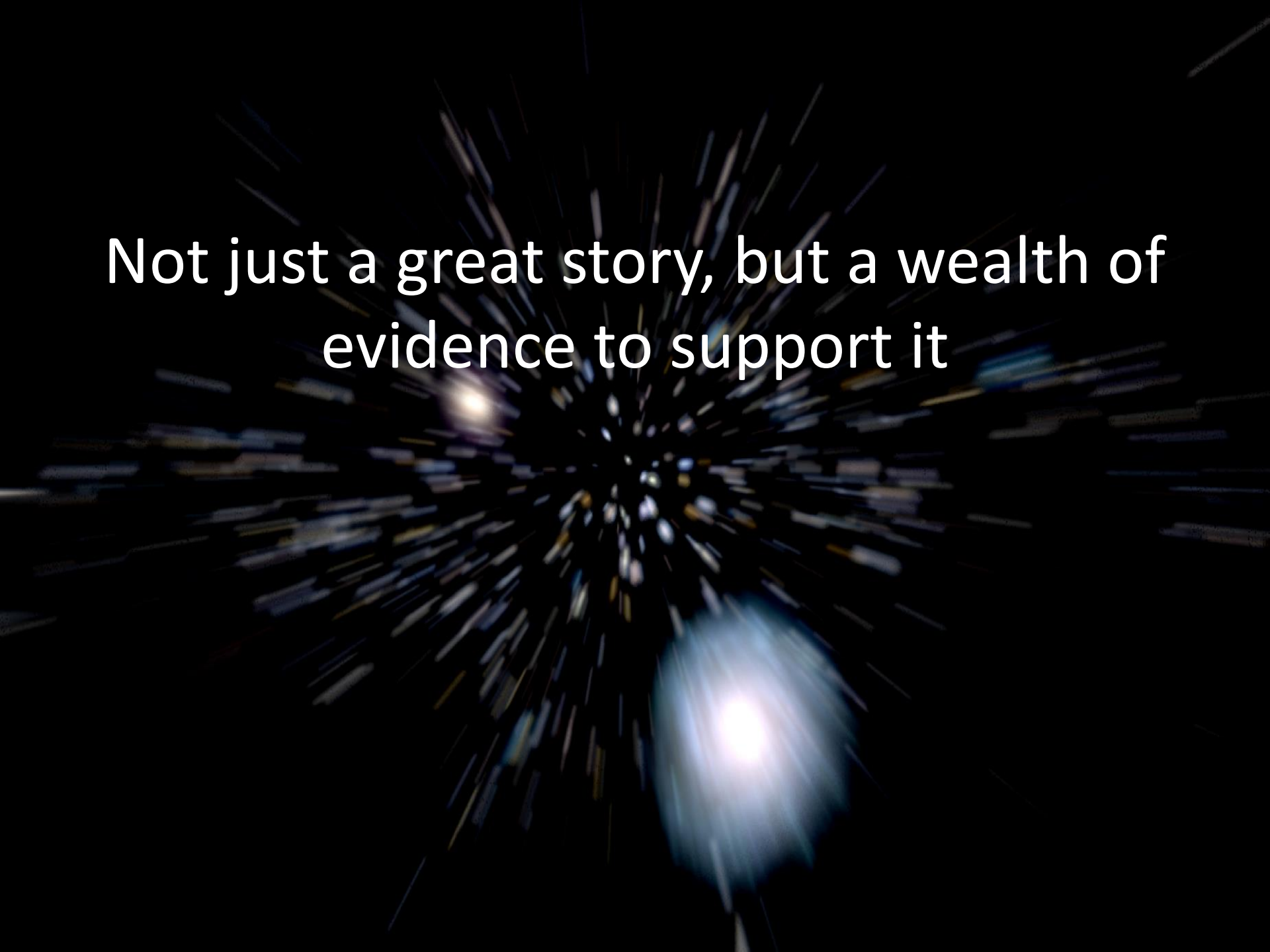
Clusters ( $z \sim 0 - 2$ )

Superclusters ( $z \sim 0$ )

EQ:  
 $R \sim 3 \times 10^5$   
 $t \sim 100 \text{ yr}$   
 $\rho \sim 10^{-25}$

$R \sim 1/3 - 1/2$   
 $t \sim \text{few Gyr}$   
GALAXIES FORM  
Dark halos, baryons  
dissipate

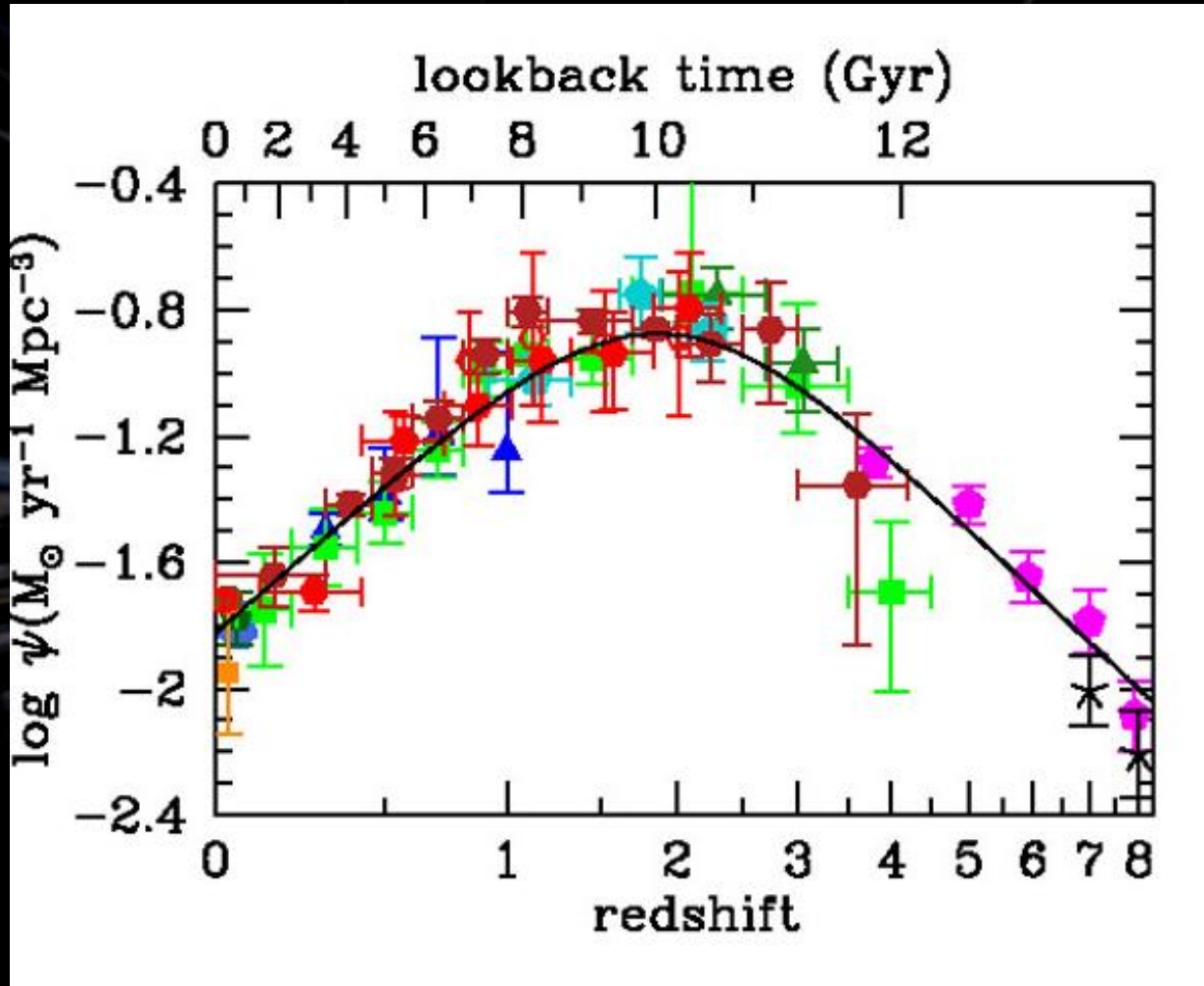
TODAY  
Formation of  
larger structures (superclusters) continues...



Not just a great story, but a wealth of  
evidence to support it

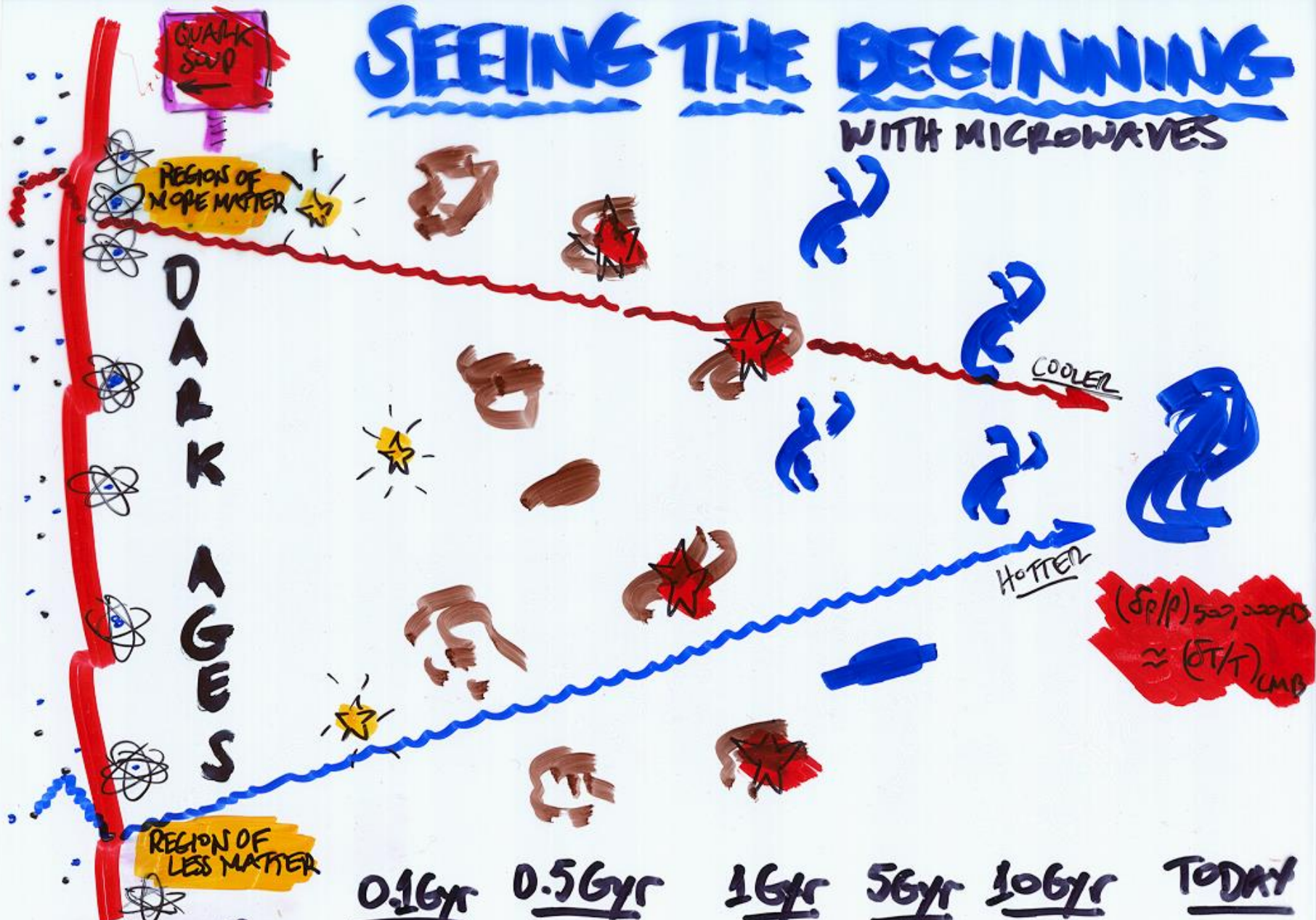
# assembly of stars and galaxies

Stellar birth rate



now <----- time ----- big bang

# SEEING THE BEGINNING WITH MICROWAVES



QUARK SOUP

REGION OF MORE MATTER

DARK AGES

REGION OF LESS MATTER

$$\left(\frac{\delta P}{P}\right)_{500,000} \approx \left(\frac{\delta T}{T}\right)_{CMB}$$

50,000 yrs

Last scattering formation of atoms

0.16 Gyr

First Stars

0.56 Gyr

Proto galaxies

1 Gyr

First Quasars

56 Gyr

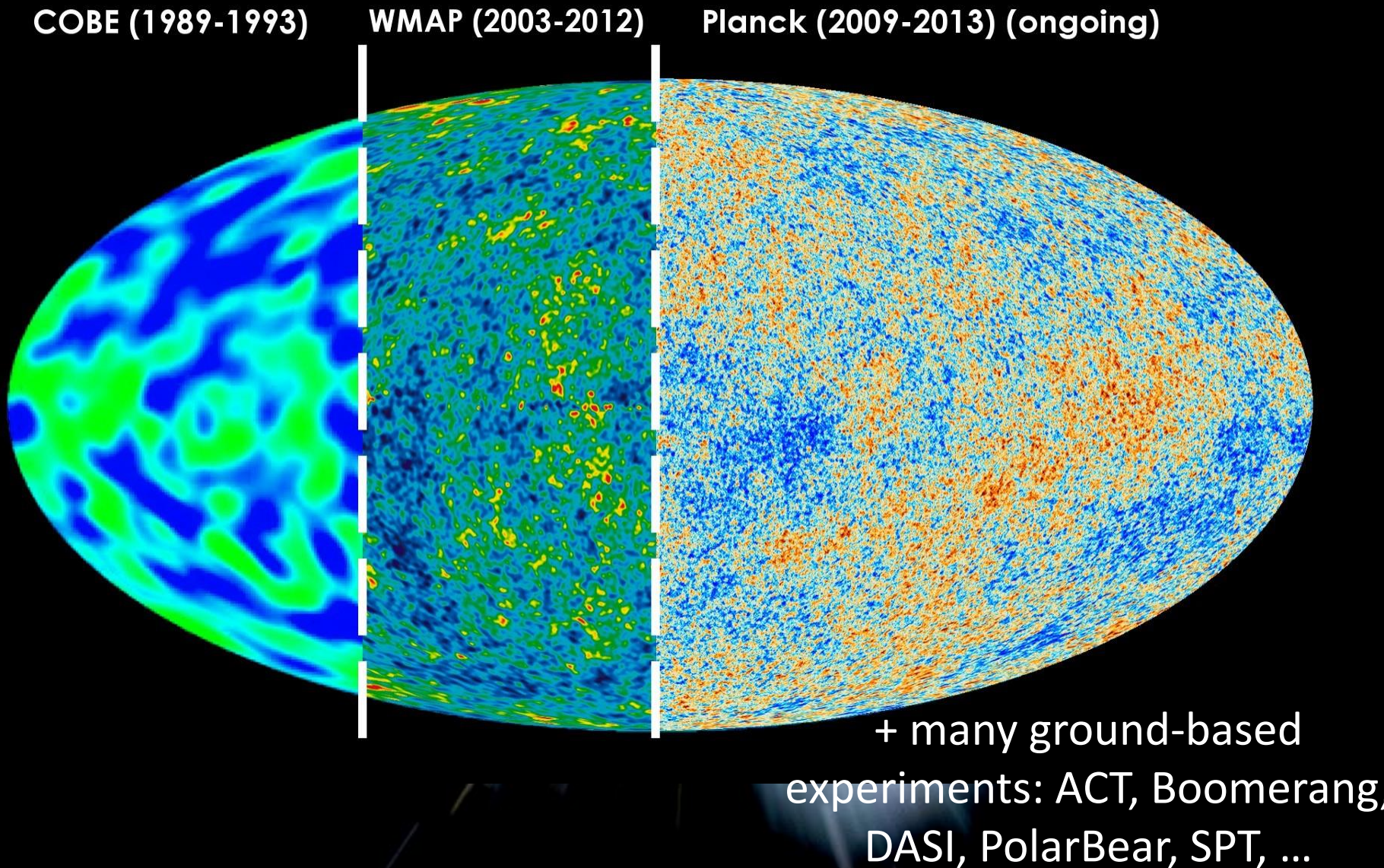
Peak of Galaxy formation

106 Gyr

Solar System forms

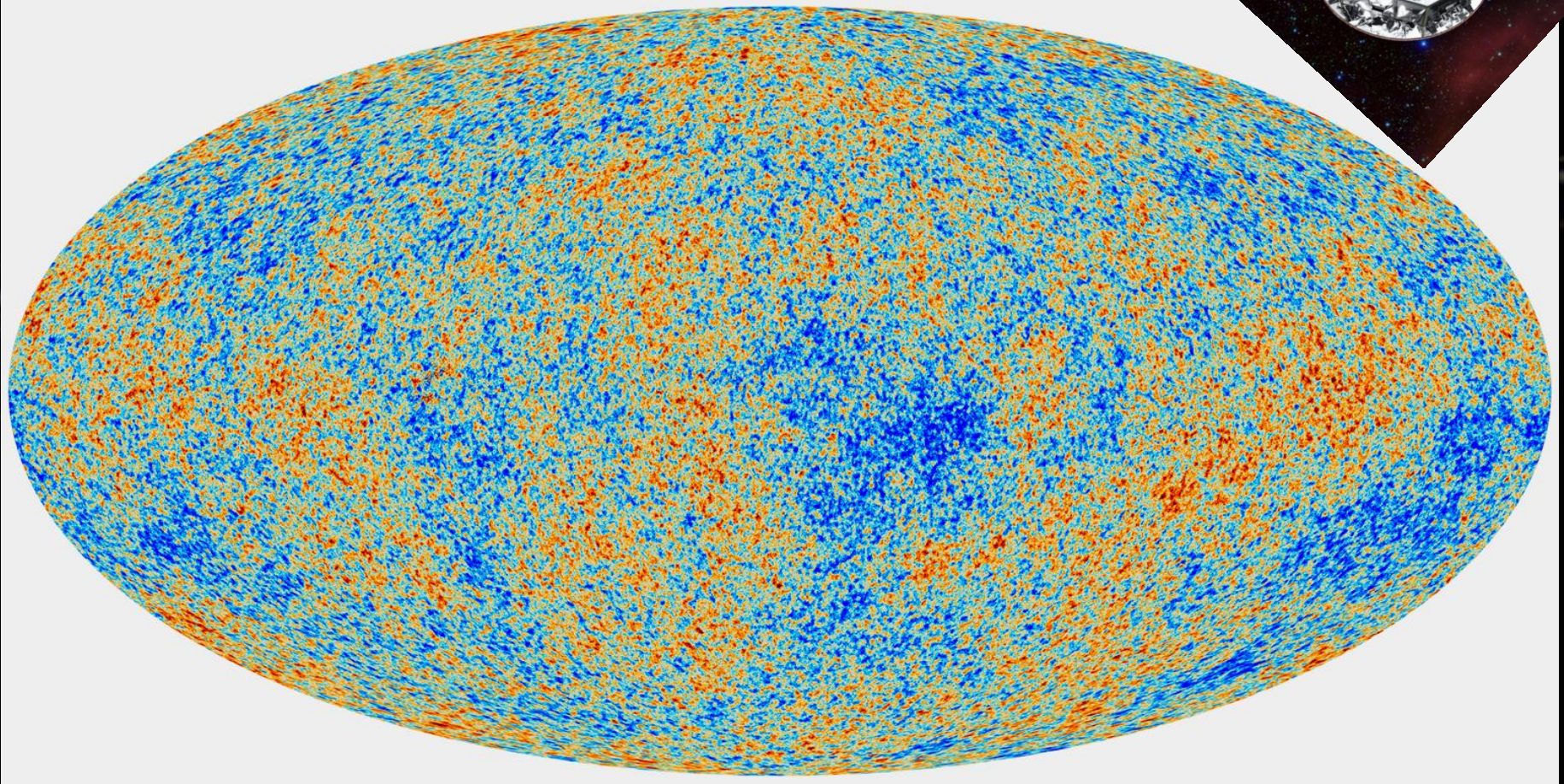
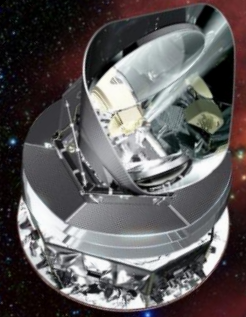
Today

# The Universe circa 380,000 yrs



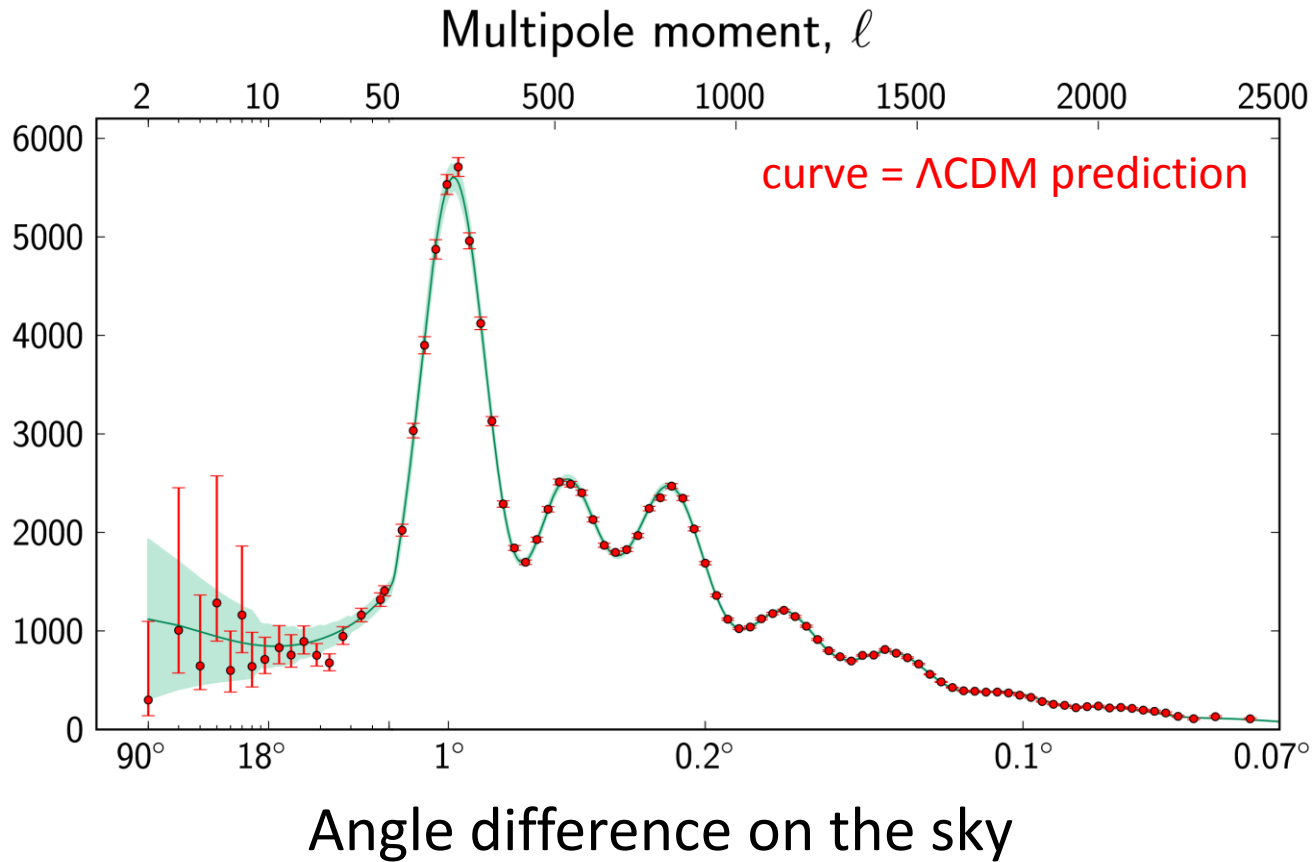
# Planck CMB Sky

9 frequencies



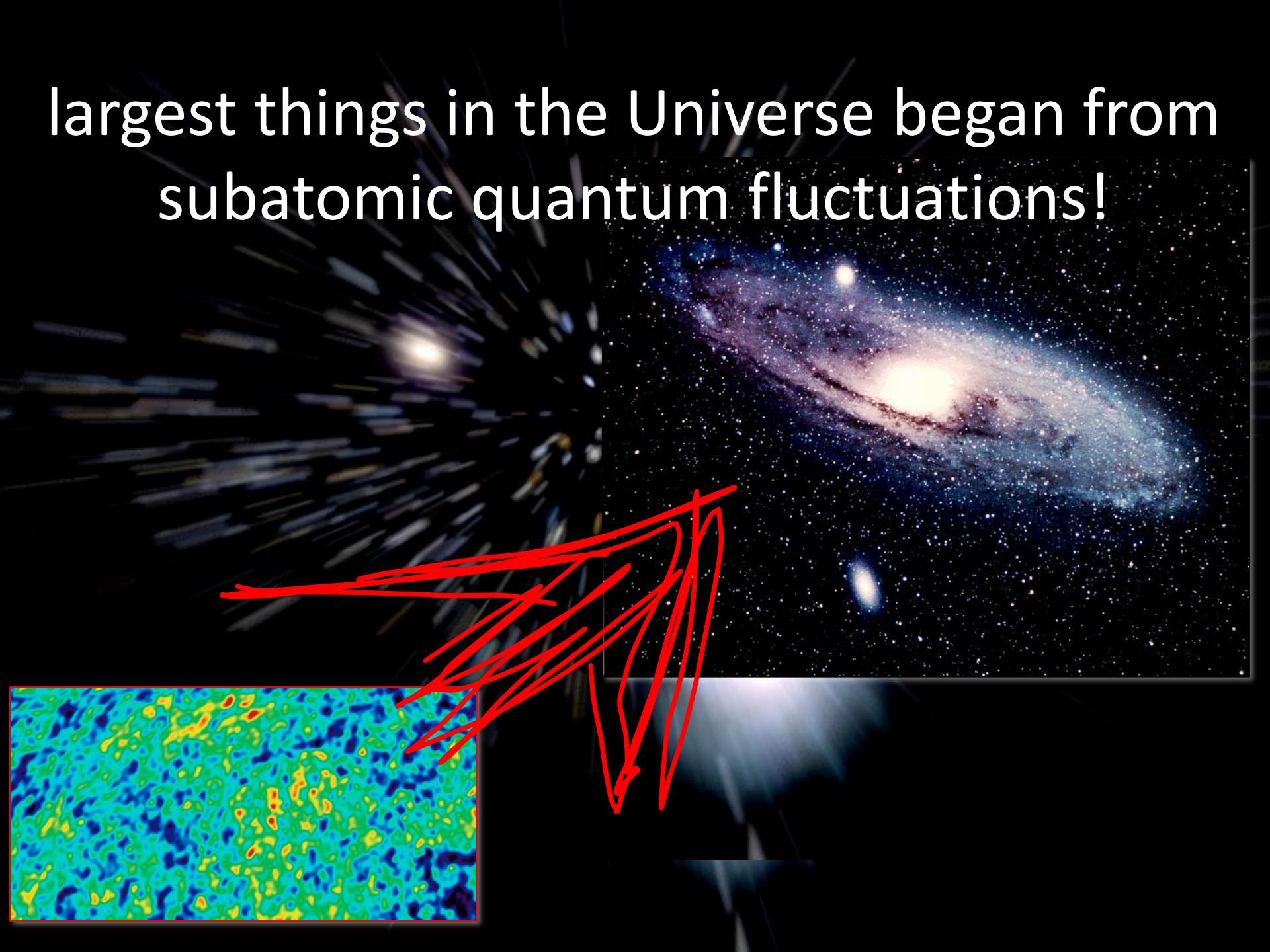
# $\Lambda$ CDM: just six numbers describe our Universe!

Temperature difference squared





largest things in the Universe began from  
subatomic quantum fluctuations!

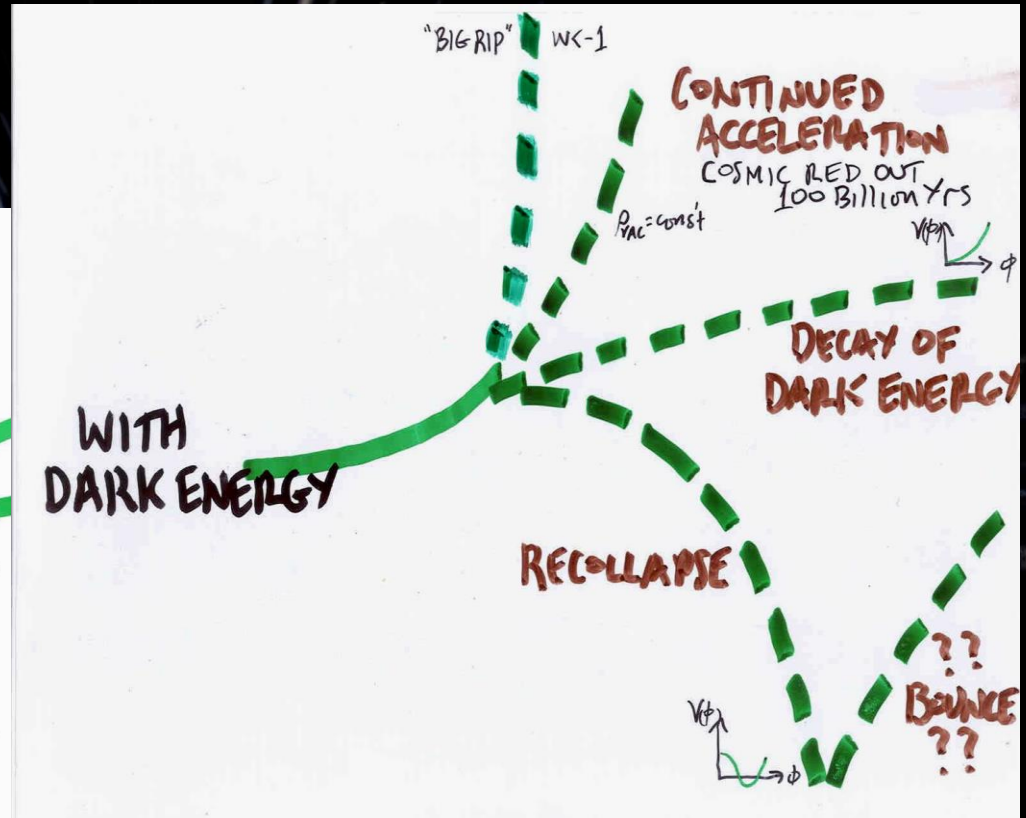


# for my friend Allan

- $H_0 = 70 \text{ km/s/Mpc}$
  - $q_0 = -0.6$
- 14 Byr old accelerating Universe



In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!



Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

# $\Lambda$ CDM



Built upon three mysterious pillars

# even bigger questions about the very small and the very big

- What is the dark matter particle? or is that even the right question?
- What is the nature of dark energy and what is our cosmic destiny?
- When did inflation take place and what is the cause of it?
- How did ordinary matter originate?
- What happened before the big bang and where did space-time come from?



## Full Court Press!!

- Produce at LHC
- Detect particles in our halo
- Detect annihilation products



# Gran Sasso Abruzzo, Italy Xenon1T



**HARD NEUTRALINO**  
 $KE = \frac{1}{2}mv^2$   
 $\approx 10^{16}m^2$   
 $\approx 10^6 keV$

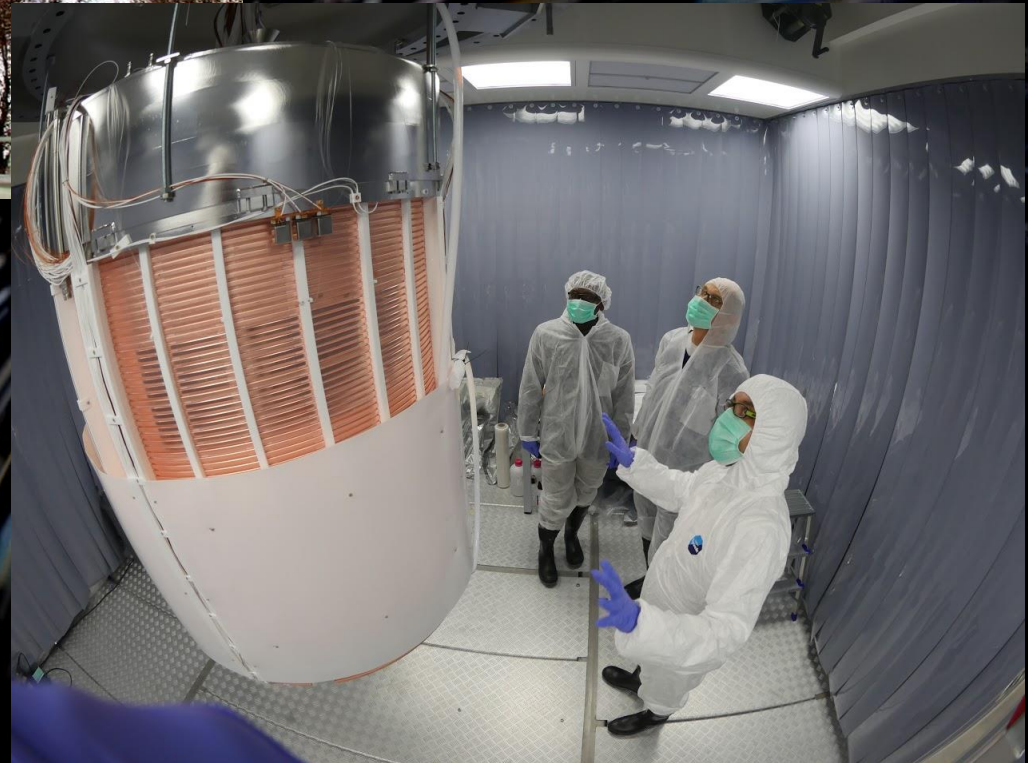
**TO DETECT A NEUTRALINO**

$\approx 10^4 kg$   
low background detector

Rate  $\propto (\sigma_{el})_{elastic} \sim (10^{-41}-1) da^2 kg^{-1}$   
 $\approx 0(10^{-31}cm^2)$  fixed by  $\Omega_{\tilde{\chi}_1^0} \frac{1}{\langle \sigma v \rangle_{ann}} = 1$

**NEED LARGE LOW-BACKGROUND, LOW-THRESHOLD DETECTORS**  
ESPECIALLY NEUTRALINO!

E.g.: 10 mK bolometers, LN NaI scintillators, Superheated Fizeau, TPC, LHe, ...







# before the Big Bang

Three ideas – all probably wrong

Question is now within the realm of science

# EINSTEIN'S BIG BANG

neat & tidy  
... but did  
Einstein  
get the last  
word  
on gravity?

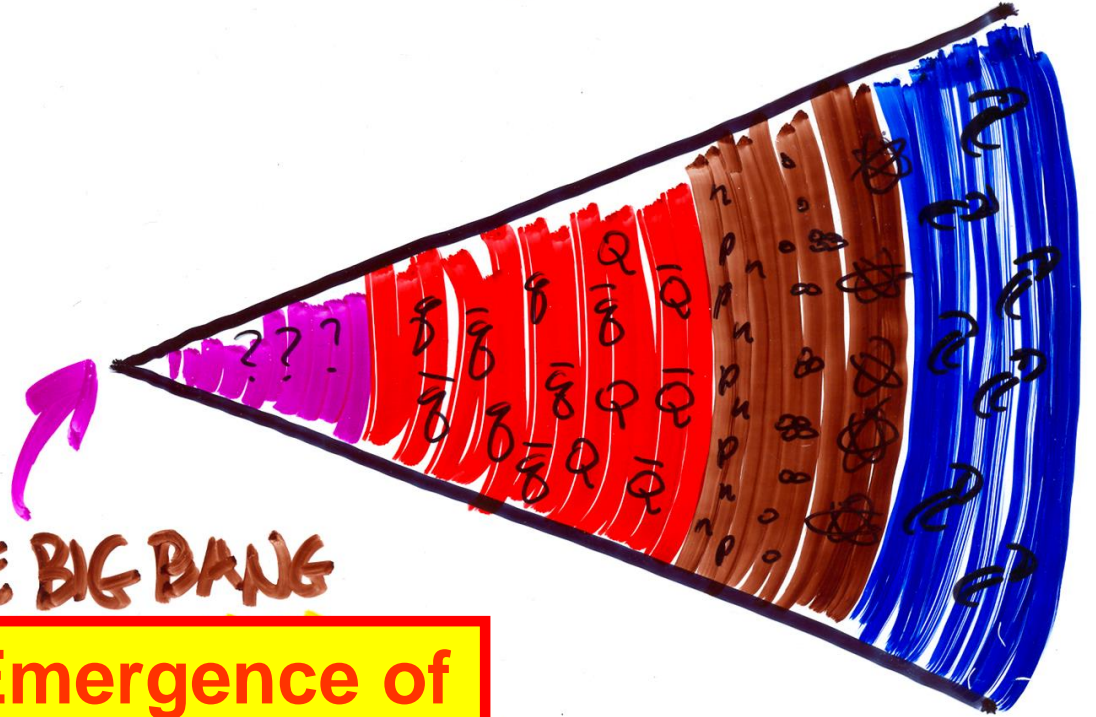


THE BIG BANG

CREATION OF  
SPACE, TIME, MATTER  
& ENERGY

• NO BEFORE THE BIG BANG

# EINSTEIN'S BIG BANG



THE BIG BANG

= Emergence of  
space and time

• NO BEFORE THE BIG BANG

String Theory  
to the rescue:  
Einstein got  
the right  
answer for  
the wrong  
reason



the multiverse: an infinity of disconnected pieces



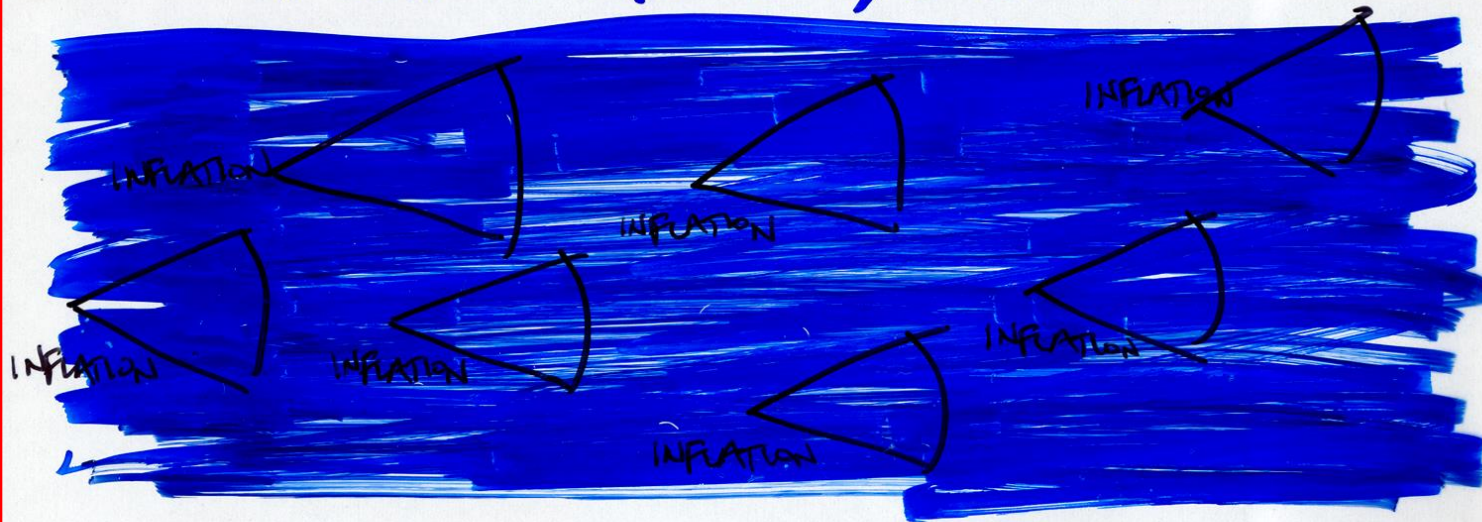
multiverse dilemma: is it science if it isn't testable?

# THE INFLATIONARY MULTIVERSE

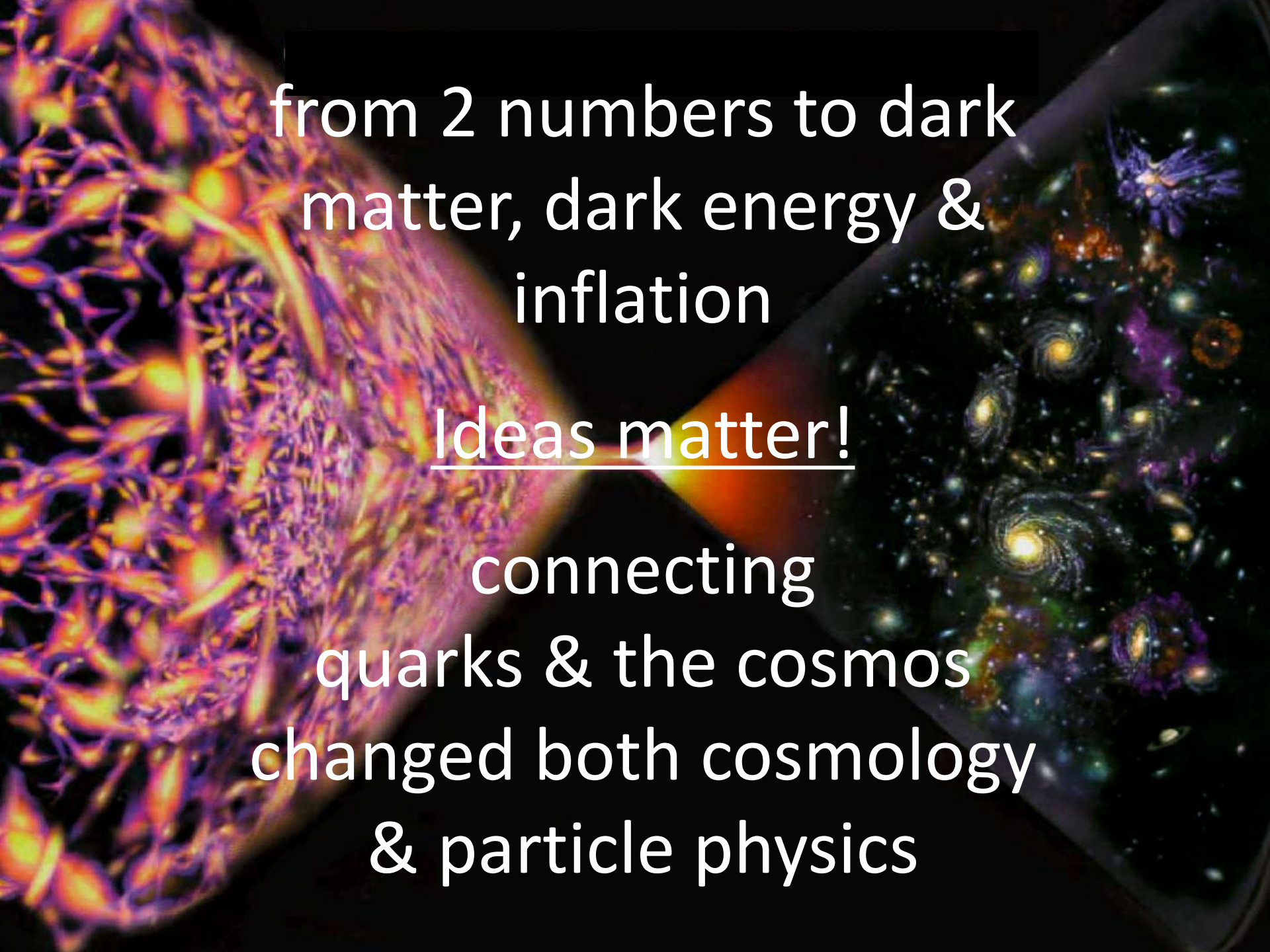
INFINITE NUMBER OF big bangs

ISSUE of a beginning is made moot

...we are but one of an infinite number of distinct inflationary bubbles!



"RIVER OF COSMIC TIME"



from 2 numbers to dark  
matter, dark energy &  
inflation

Ideas matter!

connecting  
quarks & the cosmos  
changed both cosmology  
& particle physics