Kavli IPMU Interdisciplinary Colloquium

An Introduction to Observational Cosmology I

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Speaker:	Naoki Yoshida (Department of Physics/Kavli IPMU, University of Tokyo)
Title:	Observational Cosmology: Evolution of the Universe over 13.7 billion years
Date:	Wed, Jul 25, 2012, 15:30 - 17:00
Place:	Lecture Hall
Abstract:	This is primarily an introduction to modern observational cosmology for mathematicians, string theorists, and all other non-cosmologists. Recent observations of the cosmic microwave background radiation, the large-scale structure, and distant supernovae established the so-called standard cosmological model. I explain how the data from these observations are used to infer the existence of dark matter and dark energy, and to measure the respective energy densities now and then. I will then describe the history of the universe, with focuses on several recent hot topics in astronomy and cosmology.

CONTENTS

1. Elements of modern cosmology

2. We don't know what they are,
but (we say) we know $\Omega_\Lambda + \Omega_{DM} = 0.96$??

3. Structure formation in a nutshell

4. The frontier of observational cosmology


Night Sky


The universe is filled with galaxies

To Study Structure Formation…

- The evolution of the universe as a whole:
  - Cosmic expansion history
  - Energy content
- The initial condition
  - Inflation and quantum fluctuations
  - Primordial density perturbations
- The perturbation evolution
  - Linear and nonlinear models

Pillars of Modern Cosmology

The Large-Scale Structure of the Universe

The Cosmic Microwave Background Radiation

Big Bang Nucleosynthesis

The Cosmic Expansion

These are all important in structure formation.

Let's begin.

Cosmological Principle

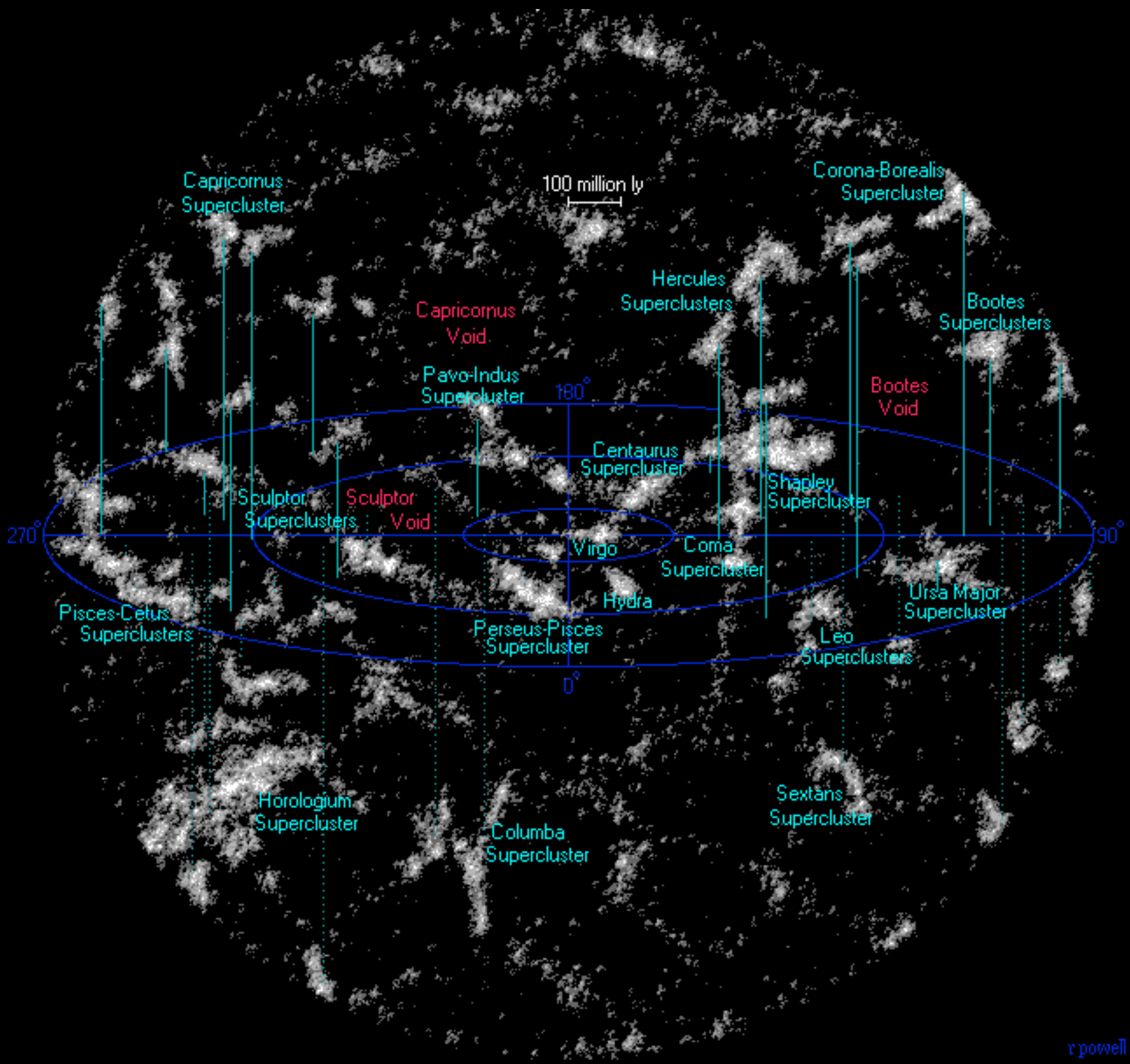
- The universe is homogeneous and isotropic
- This means that the universe does not possess any privileged positions and directions.

  - We are *not* in a special location.

Observationally this is true, or at least a very good approximation. There are galaxies, clusters of galaxies etc., but on very large-length scales, nearly homogeneous and isotropic.

But then another problem arises: in fact, our universe appears homogeneous on length scales much larger than the causal *horizon*.

The Universe within 100 Mpc

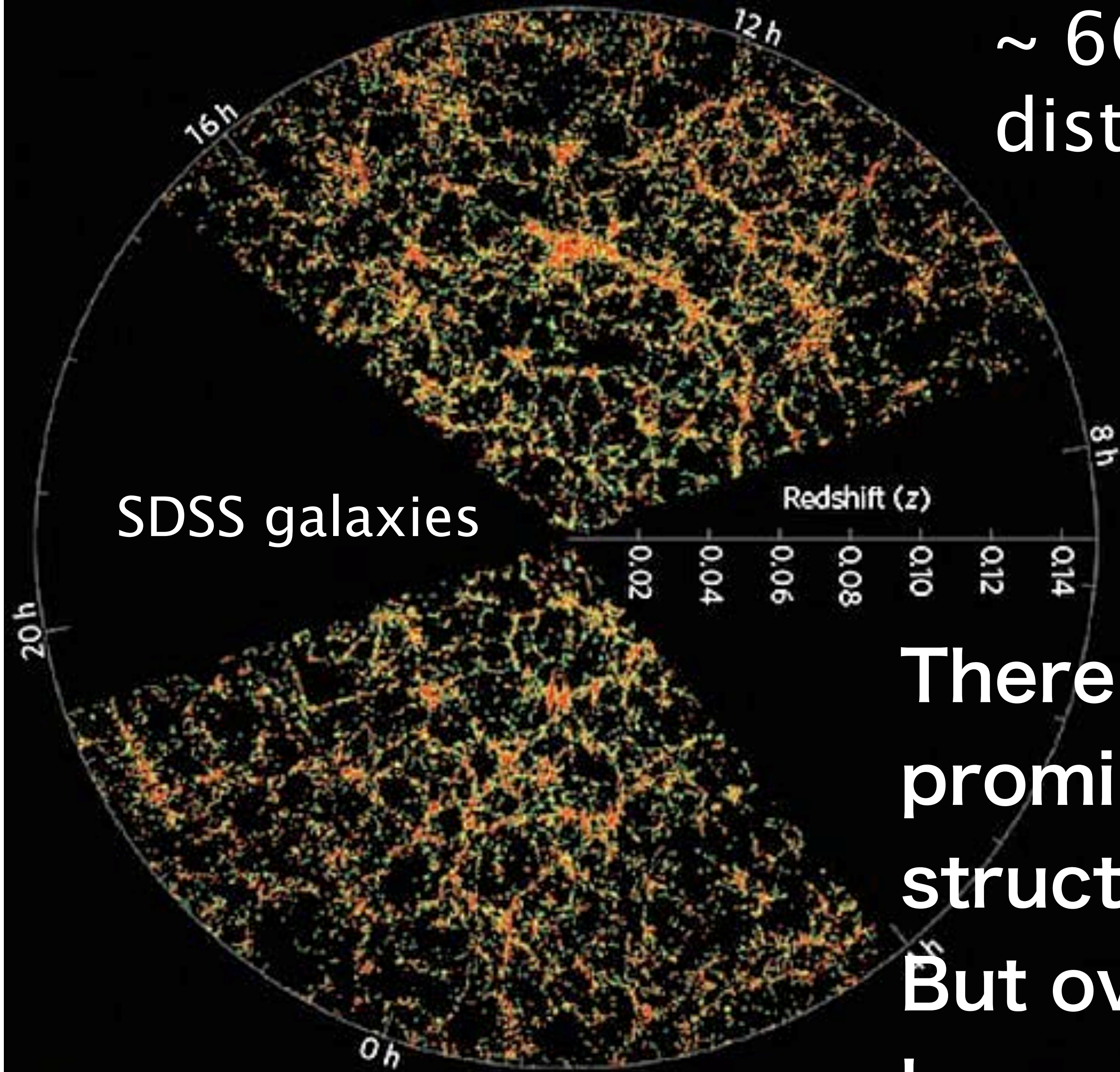


1 pc
= 3.24 lightyears
is the distance
over which
light travels
in 3.24 yrs.

1 Mpc = 10^6 pc
Roughly the
mean distance
between galaxies

~ 600Mpc
distance

SDSS galaxies



There are some prominent structures.
But overall, it looks homogeneous.

The Relativistic Universe

Describing the universe *as a whole.*

Einstein's field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

describe the interaction of gravity with space-time being curved by matter and energy.

This is a set of ten nonlinear equations for functions of four variables. Here, $R_{\mu\nu}$, R, $g_{\mu\nu}$ are the Ricci curvature tensor, the Ricci scalar, and the metric.

The Robertson-Walker Metric

Let us stand on the Cosmological Principle

The space-time of a homogeneous, isotropic universe can be described by a simple metric:

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta \, d\phi^2)\right]$$

t : time

Recall the polar coordinate *r*, *θ*, *Φ*

(note !) which has only one function,

the expansion parameter, and one constant,

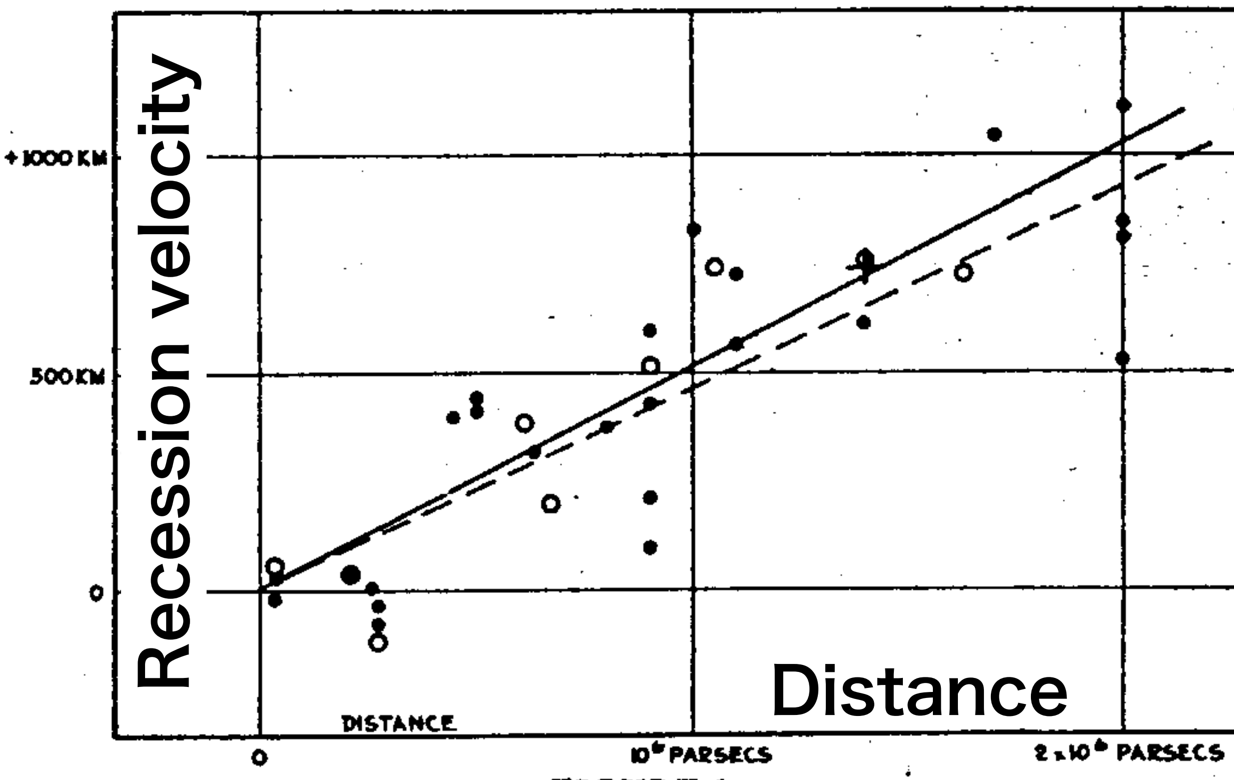
the curvature *K*.

a can be constant, or can increase, or decrease.

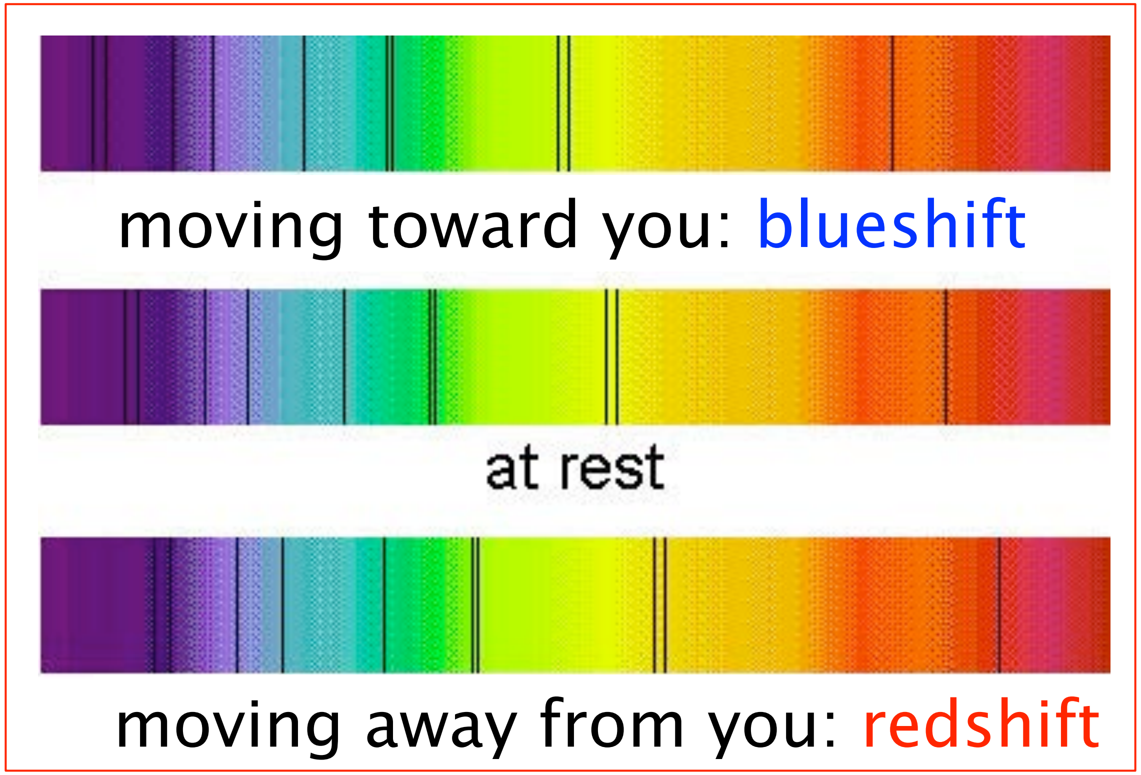
Essentially, only the evolution of *a(t)* is important.

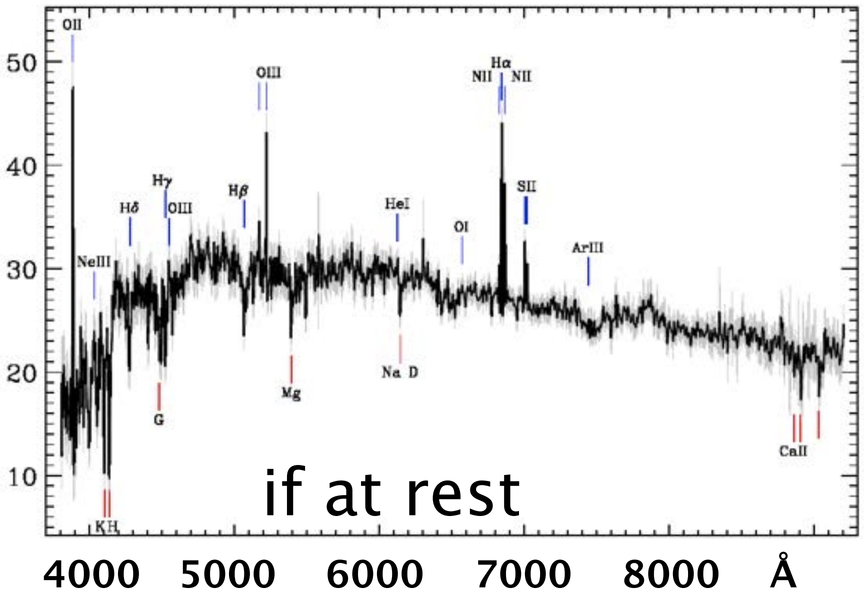
The Expanding Universe : Discovery

$V = H_0 d$



Nearly all the galaxies are receding from us. Furthermore, the recession velocities are greater for more distant galaxies.


moving toward you: blueshift
at rest
moving away from you: redshift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OIII
Hα
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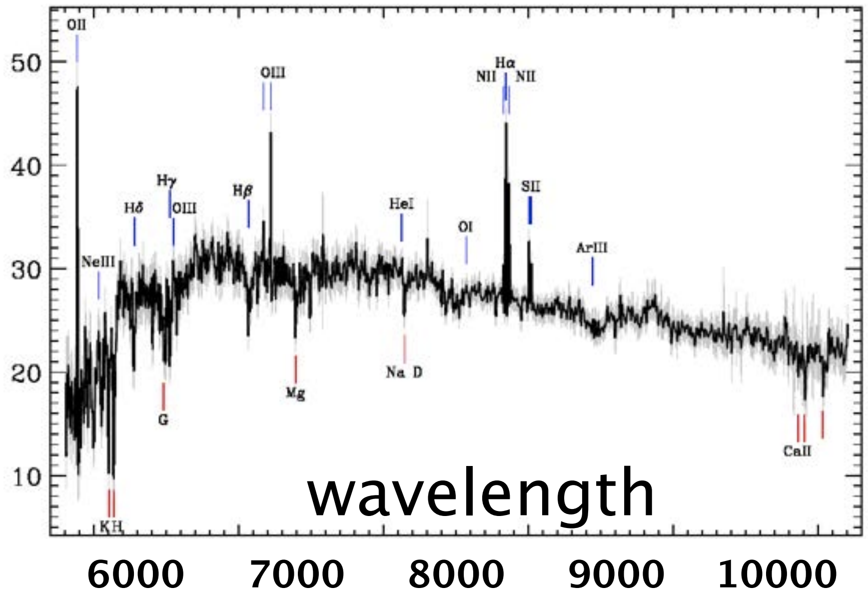
Hγ
Hδ
OIII
Hβ
HeI
OI
SII
ArIII
NeIII
Na D
Mg
G
CaII
KH
50
40
30
20
10
if at rest
4000 5000 6000 7000 8000 Å


OII
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SII
ArIII
NeIII
Na D
Mg
G
CaII
KH
50
40
30
20
10
wavelength
6000 7000 8000 9000 10000

Who discovered the expanding universe?

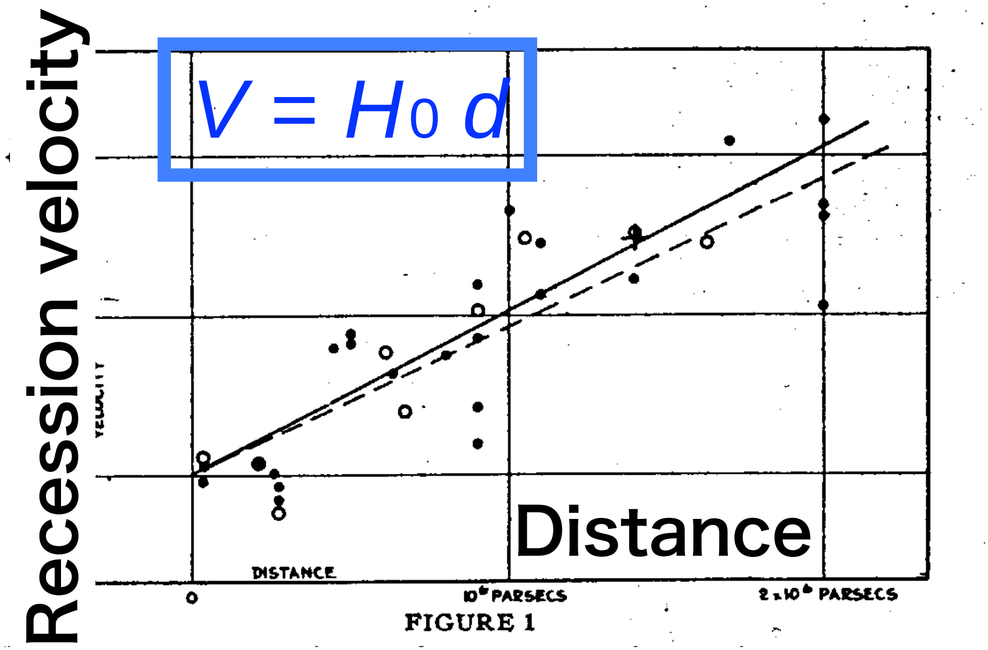
Harry Nussbaumer and Lydia Bieri

Does it really matter who discovered the expanding universe? Great discoveries are anyway never done single-handedly. This is a valid attitude. However, those interested in the evolution of our scientific culture are eager to know the intricate patterns that lead to new insights. As the expanding universe is one of the most important discoveries ever made, it is not astonishing that the question of how it happened is still widely discussed.

The debate on this topic has flared up again due to an article in *Nature View*, where Eugenie Reich highlighted two contributions by Sidney van den Bergh (2011) and David Block (2011). Their effect was to reanimate the discussion whether Hubble or Lemaître discovered the expanding universe, or whether it was simply a nearly predictable outcome of the normal scientific activity of those days. We have investigated this question in our book *Discovering the Expanding Universe* [7], where we reconstructed the discovery from original documents.

Arxiv:1107.2281

The Expanding Universe : Discovery



H_0, the so-called Hubble constant,
is the coefficient that relates the recession velocity and the distance. It actually
is the cosmic expansion rate at the present.
$H_0 \sim 70$ km/sec/Mpc.

The Expanding Universe : Theory

For the Robertson-Walker metric

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

Einstein equations reduce to two equations:

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

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p)$$

A rough derivation

Let us ignore Λ for now:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$R_{00} = \Gamma^{\alpha}{}_{00,\alpha} - \Gamma^{\alpha}{}_{0\alpha,0} + \Gamma^{\alpha}{}_{00}\Gamma^{\beta}{}_{\alpha\beta} - \Gamma^{\alpha}{}_{0\beta}\Gamma^{\beta}{}_{0\alpha}$$

where Christoffel symbols $\Gamma^{\alpha}{}_{\beta\gamma}$ are given by the combinations of the derivatives of $g_{\mu\nu}$

Namely, just algebra!

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

Note that the density depends implicitly on *a.*

(The rate of expansion)^2 coeffcient x density

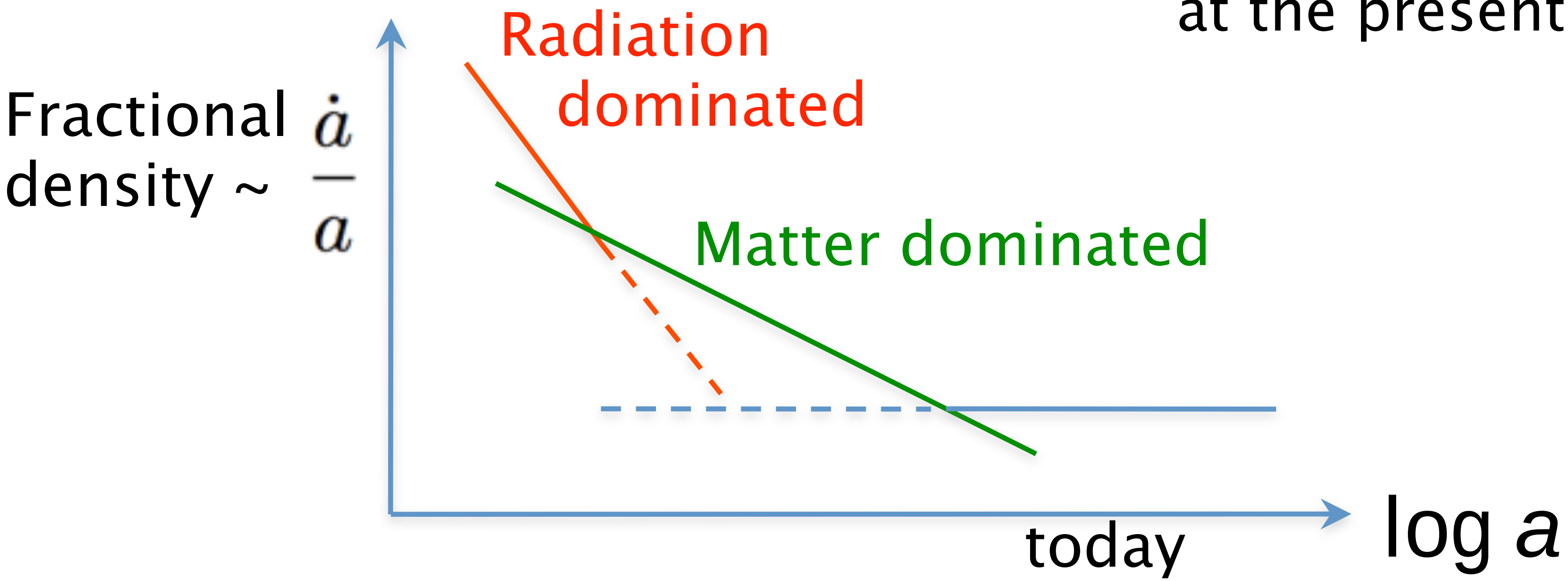
The Friedmann Equation

For a flat universe with matter, radiation and cosmological constant,

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\frac{\Omega_\mathrm{m}}{a^3} + \frac{\Omega_\mathrm{r}}{a^4} + \Omega_\Lambda\right]$$

Ω_m : matter density
Ω_r : radiation density
Ω_Λ : dark energy

at the present time



Quiz!

Solve the Friedmann equation for a universe dominated by dark matter and dark energy

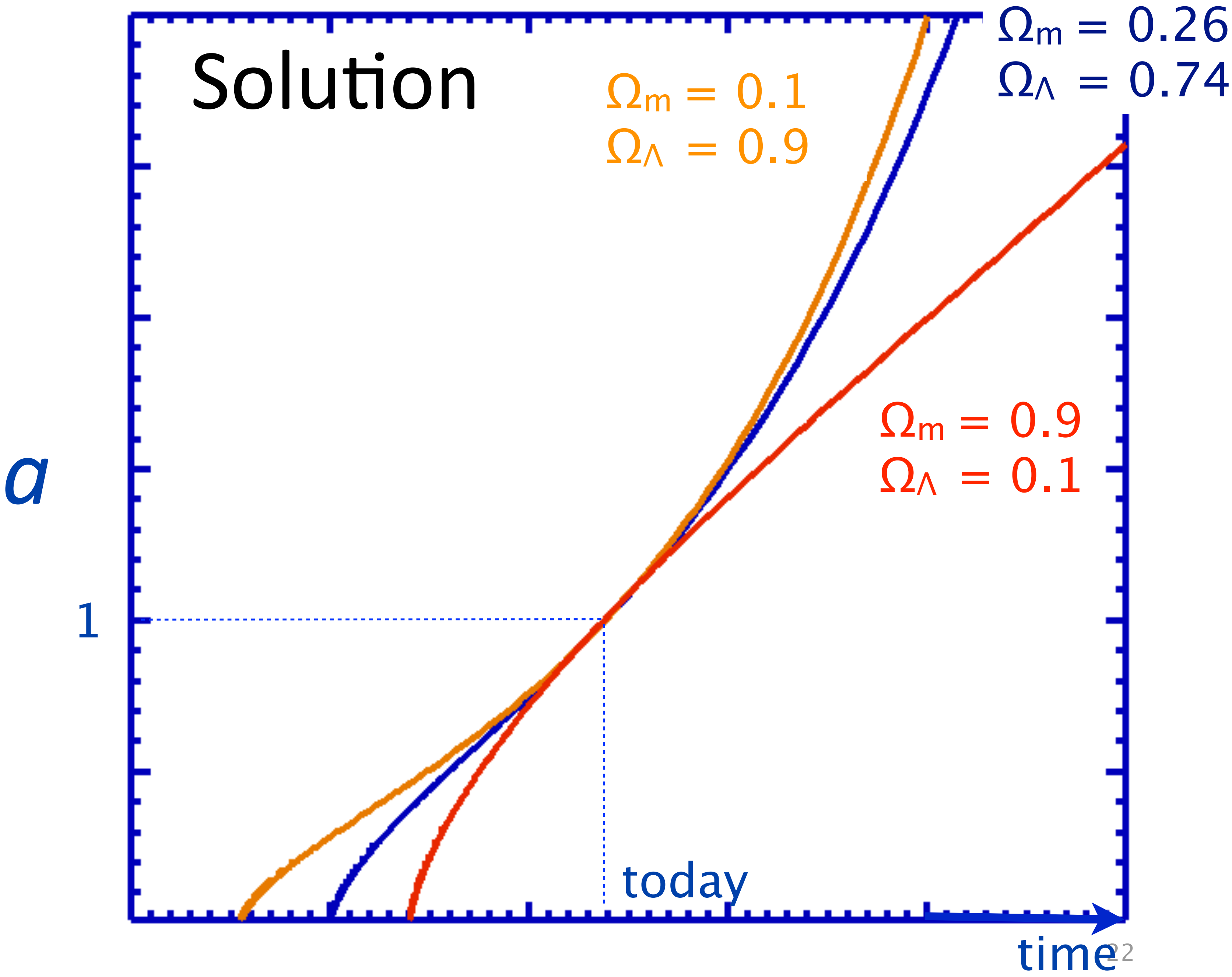
$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left[\frac{\Omega_{\rm m}}{a^3} + \Omega_\Lambda\right]$$

Express the expansion parameter a as a function of time.

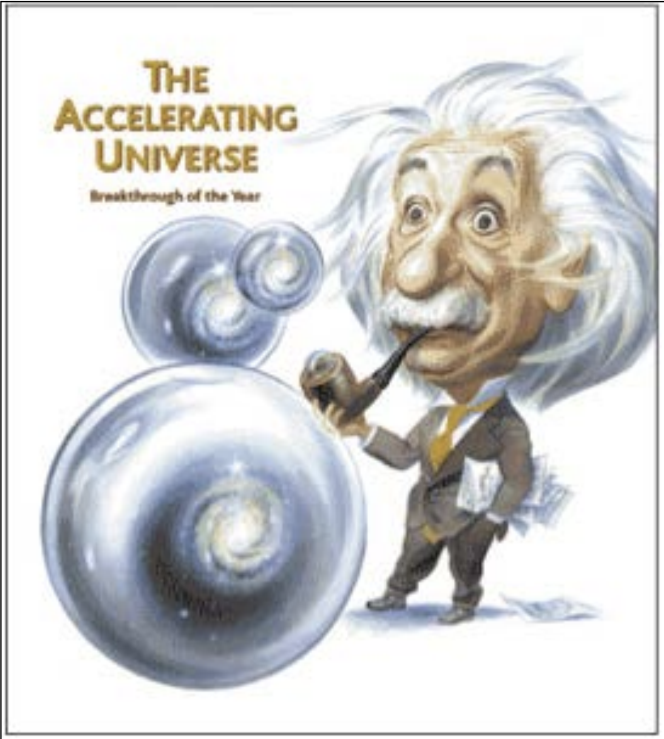
$$a = \left(\frac{\Omega_{\rm m}}{\Omega_\Lambda}\right)^{1/3} \sinh^{2/3} \frac{3\sqrt{\Omega_\Lambda}}{2} H_0 t.$$

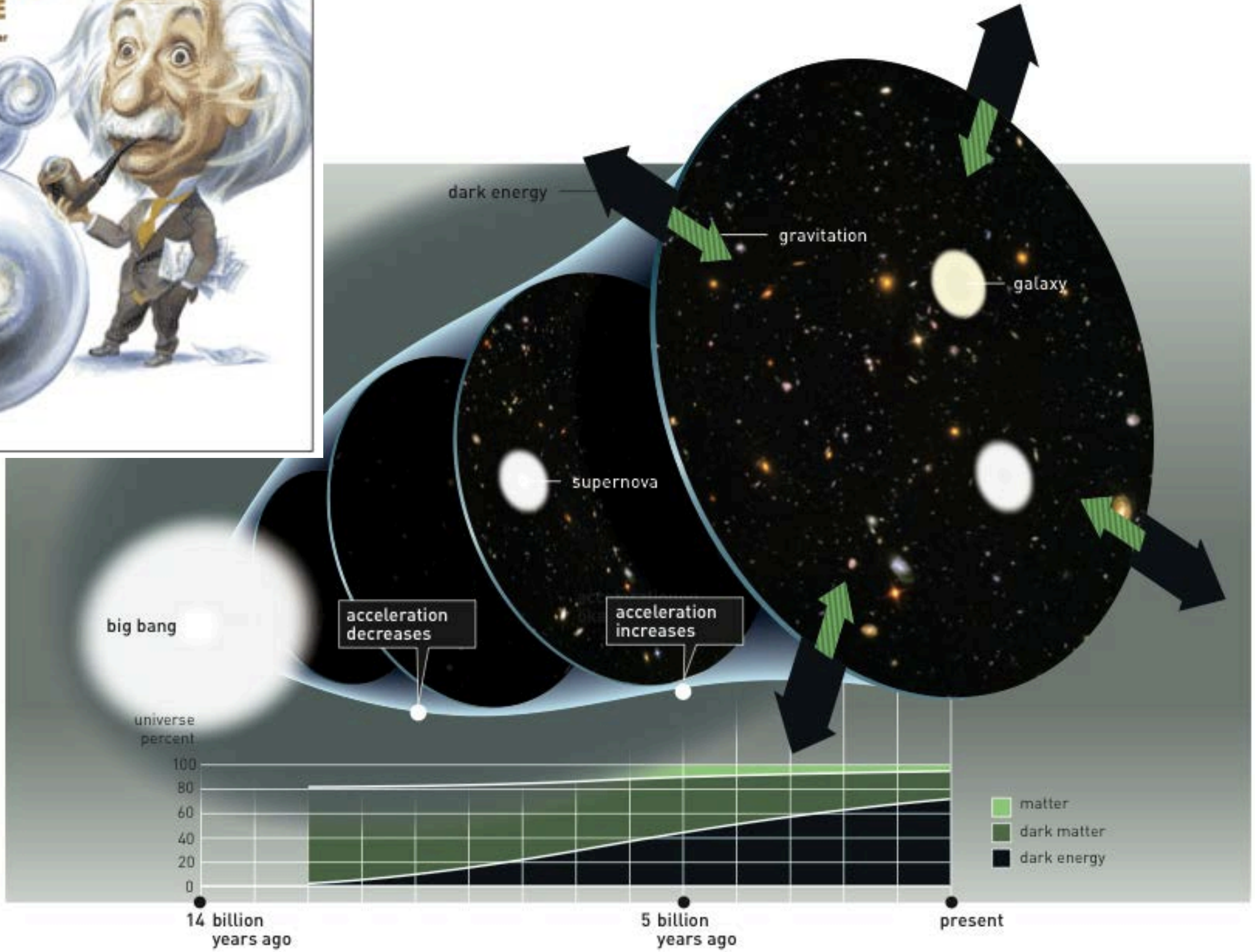
This will be a good exercise.

Solution



$\Omega_m = 0.26$
$\Omega_\Lambda = 0.74$
$\Omega_m = 0.1$
$\Omega_\Lambda = 0.9$
$\Omega_m = 0.9$
$\Omega_\Lambda = 0.1$
a
1
today
time


THE ACCELERATING UNIVERSE
Breakthrough of the Year


dark energy
gravitation
galaxy
supernova
big bang
acceleration decreases
acceleration increases
universe percent
100
80
60
40
20
0
matter
dark matter
dark energy
14 billion years ago
5 billion years ago
present

dation.

Nobel Prize in Physics 2011

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

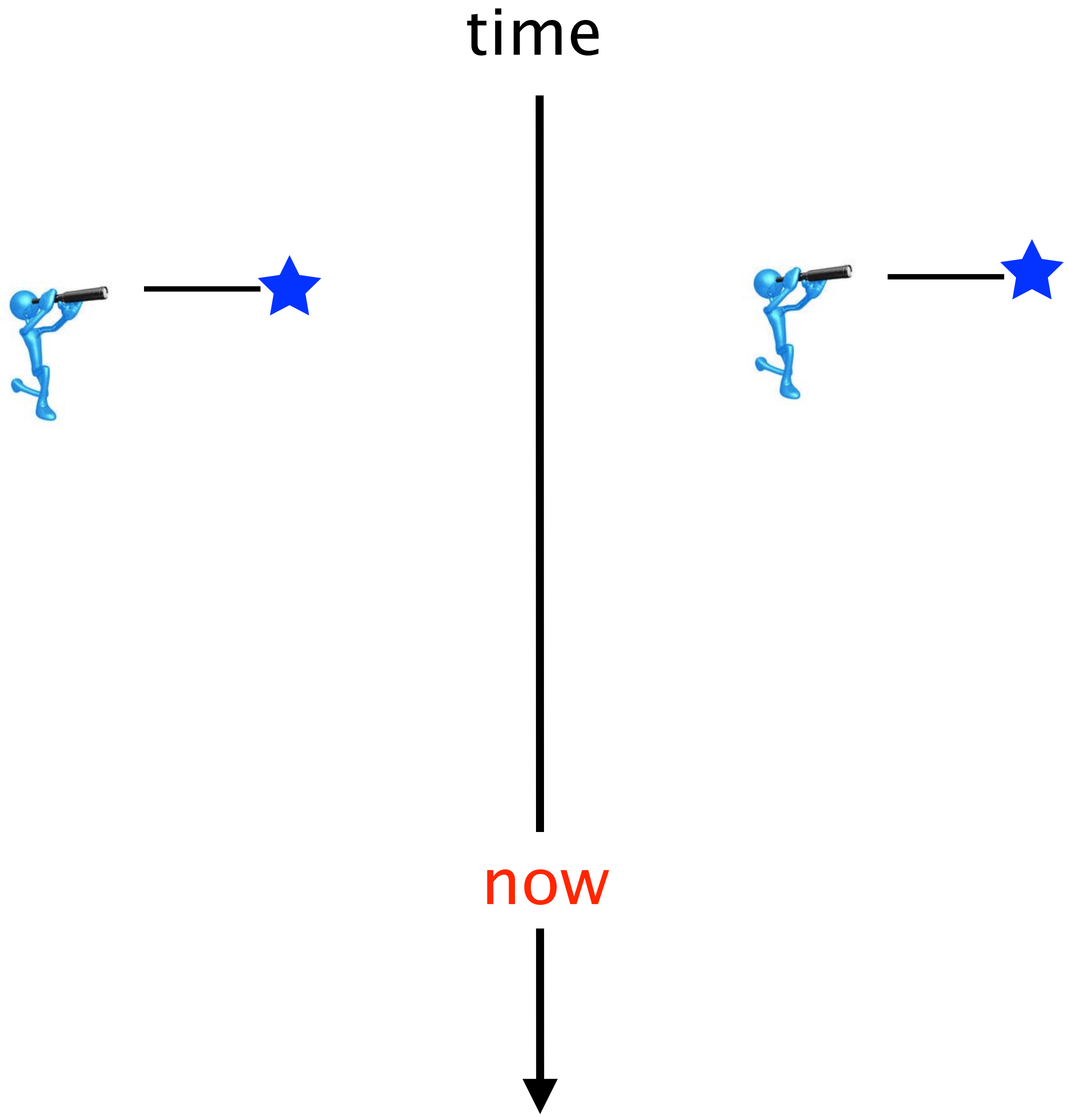
Brian P. Schmidt

Photo: Homewood Photography

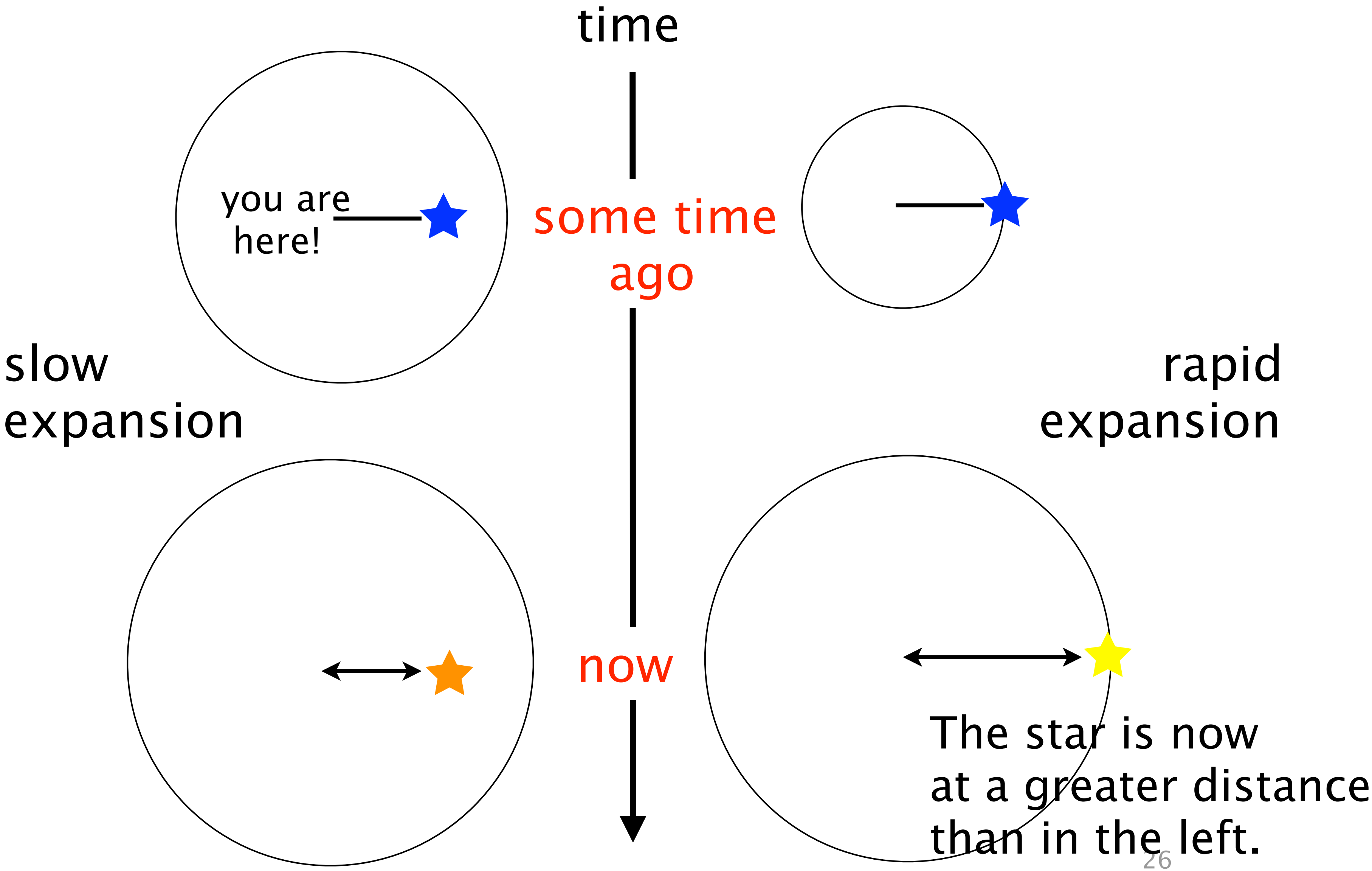
Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Expansion and the distance

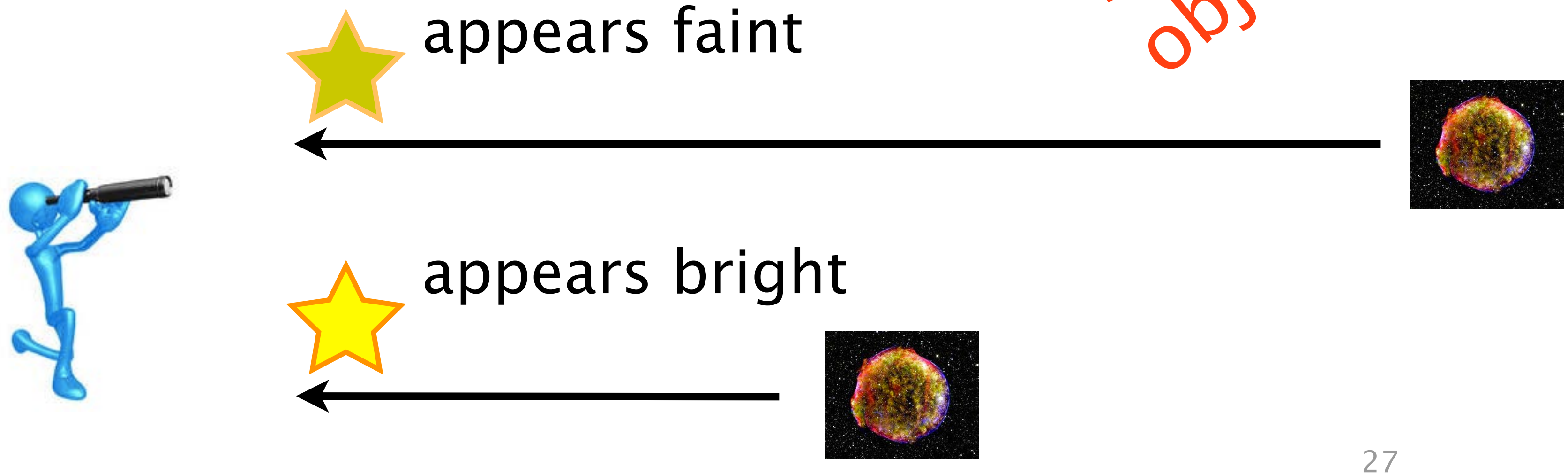


Expansion and the distance

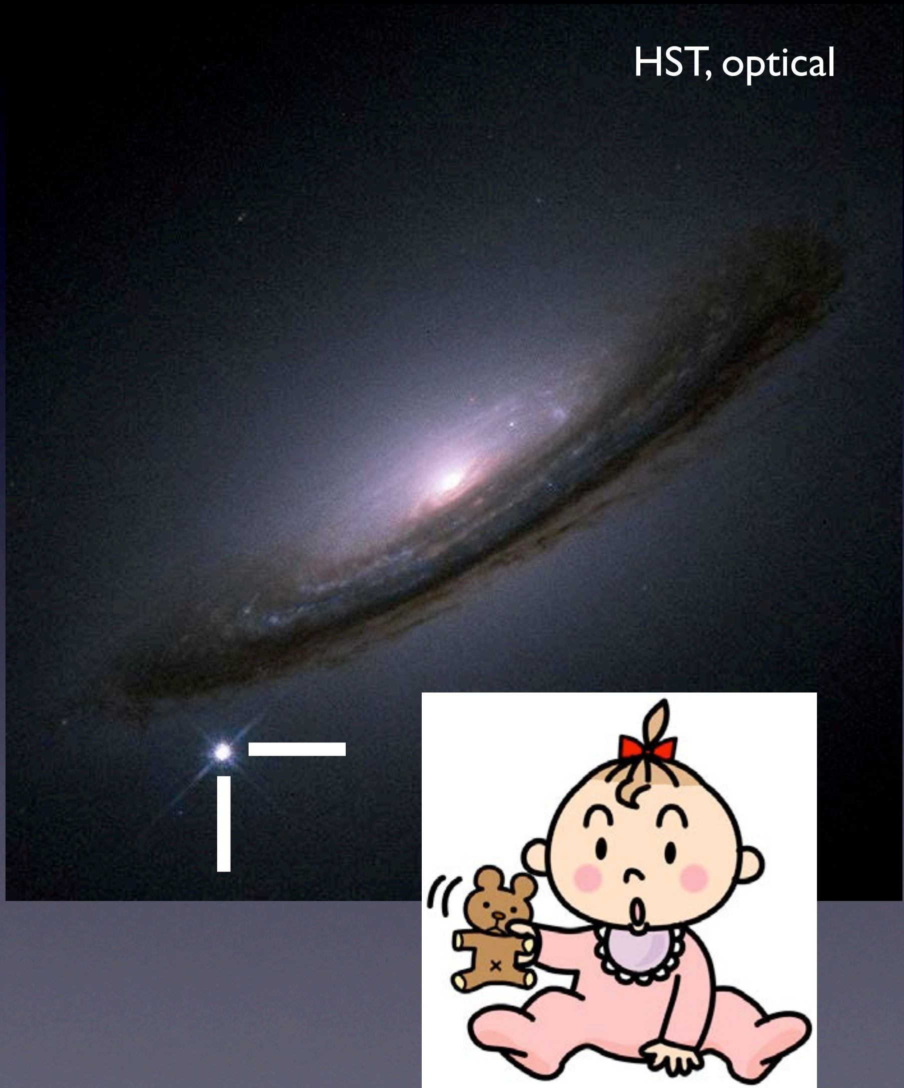


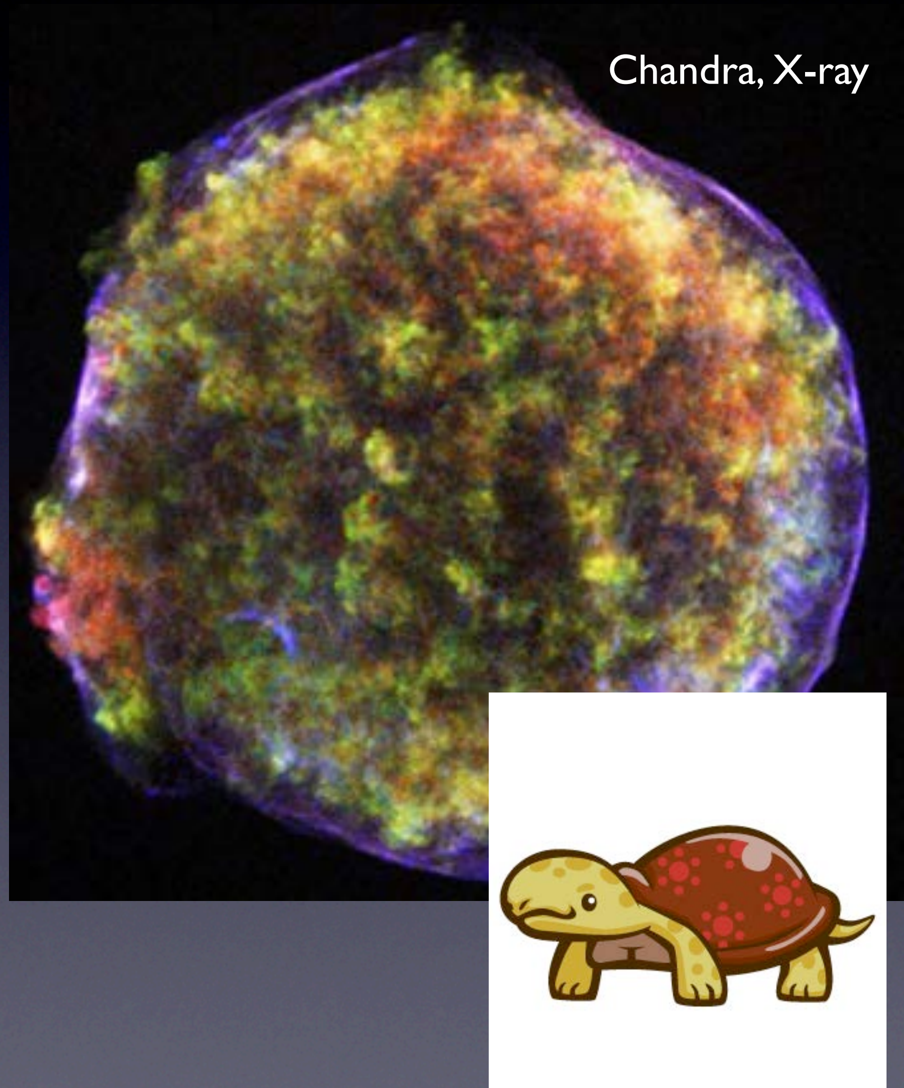
If there were
"standard candles"
that have the same luminosity
everywhere in the universe,
they could be used as
distance indicator.

All we need is
such convenient
objects.

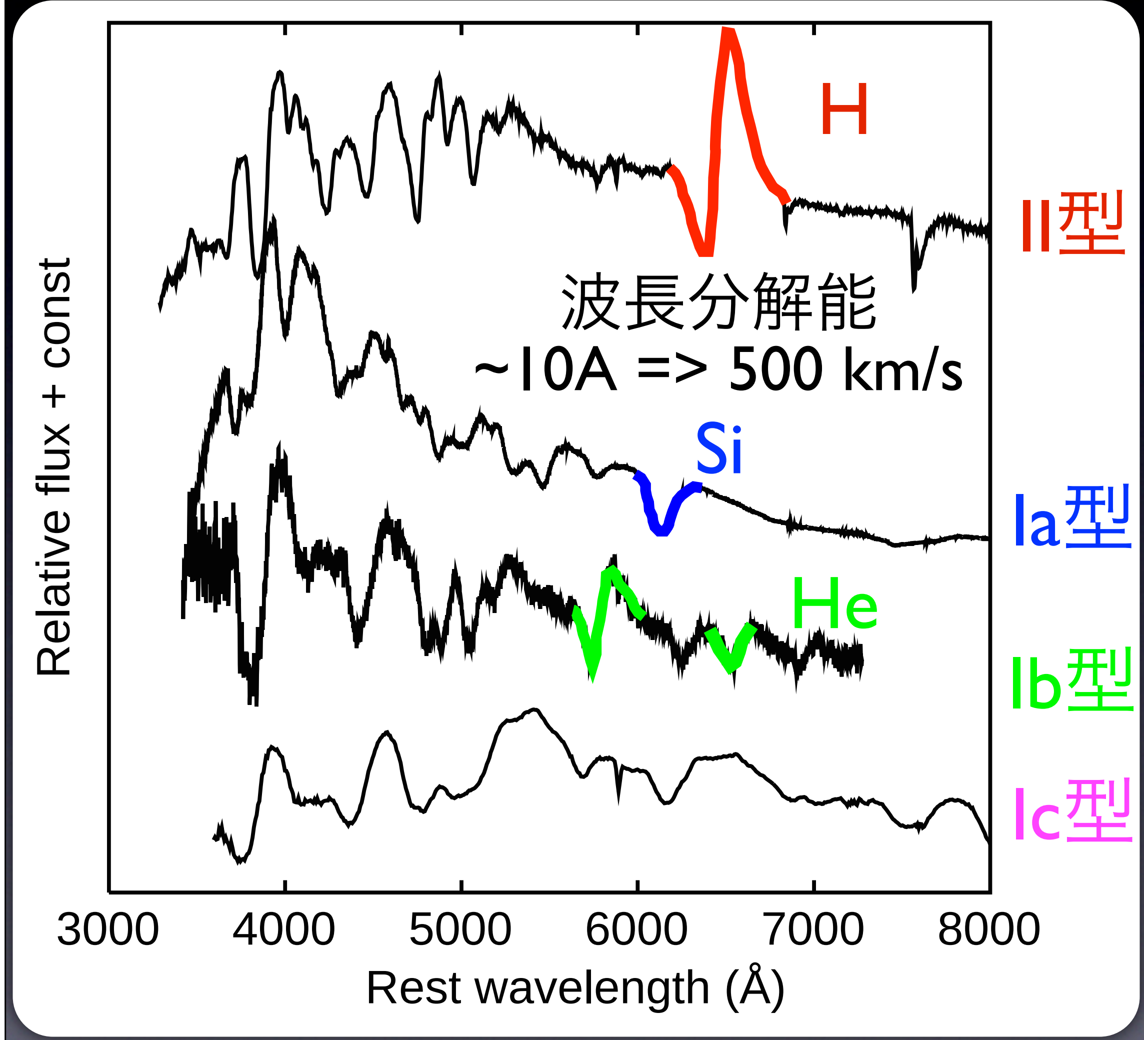


Supernova Type Ia

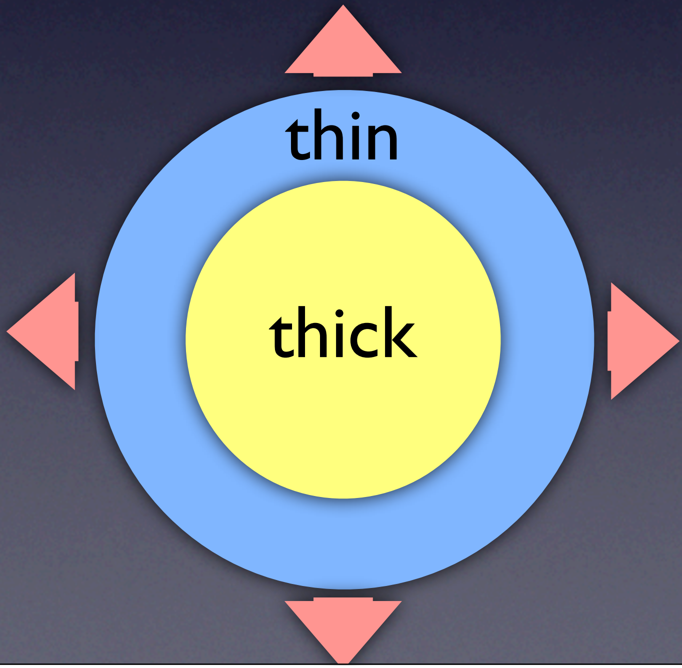




Spectral classification



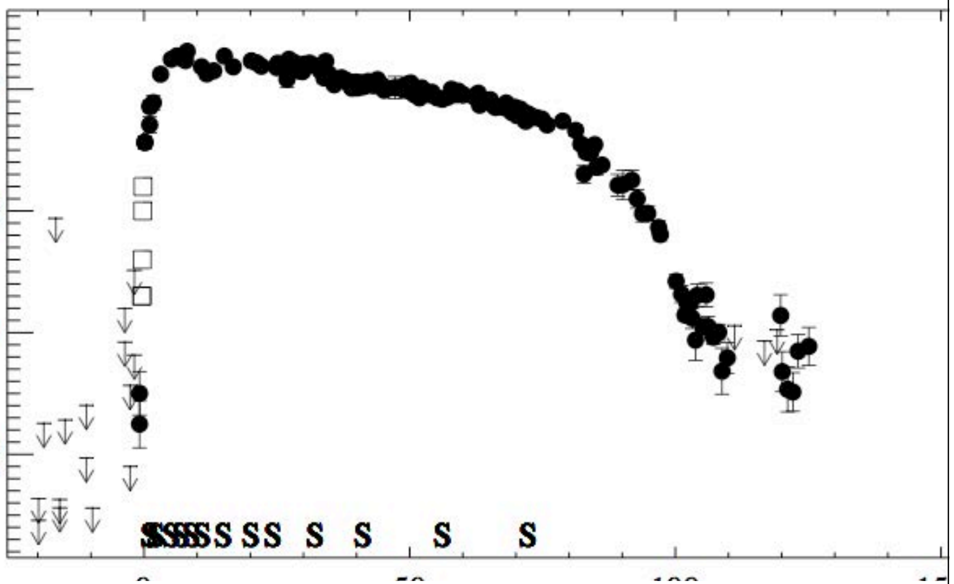
- optical
- spectra about 20days after the explosion



Supernova becomes bright, and then dim.

Light curve

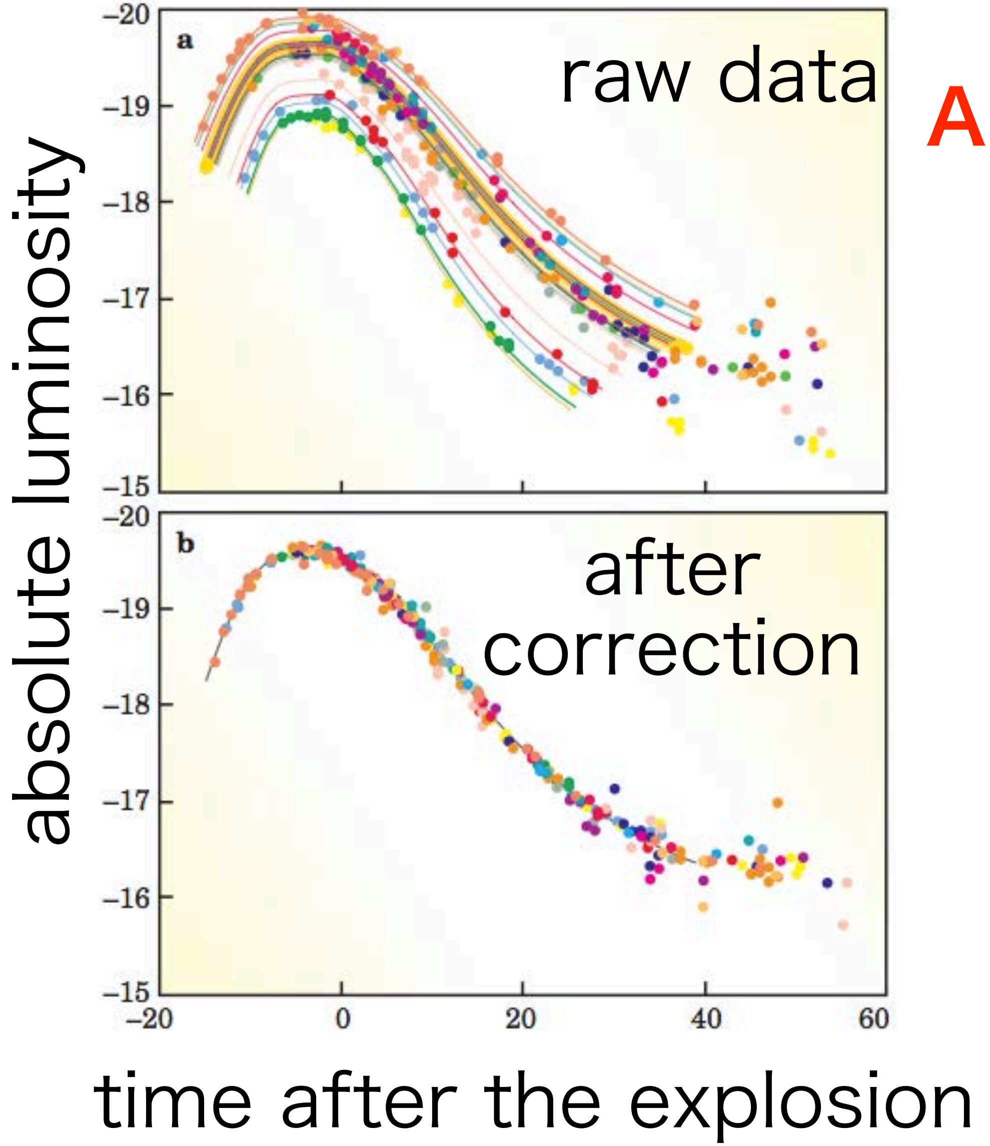
bright ↑



time →

Movie from Robert Quimby.

Type Ia's light curve



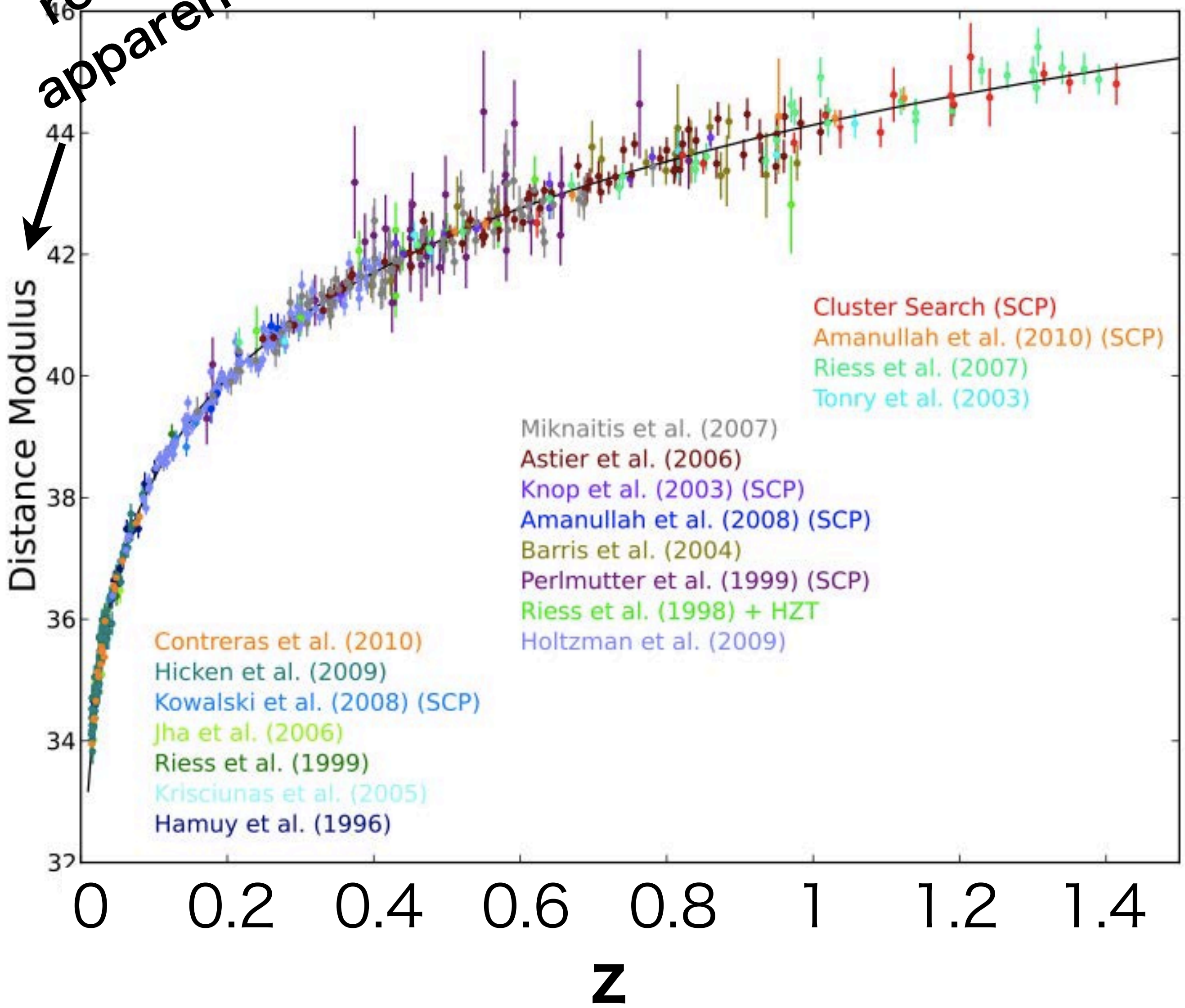
An astonishing feature

There exists a simple relation between the absolute brightness and the lightcurve “width”

They can be used as standard candles in the distant universe

redshift - distance

remember this is apparent brightness

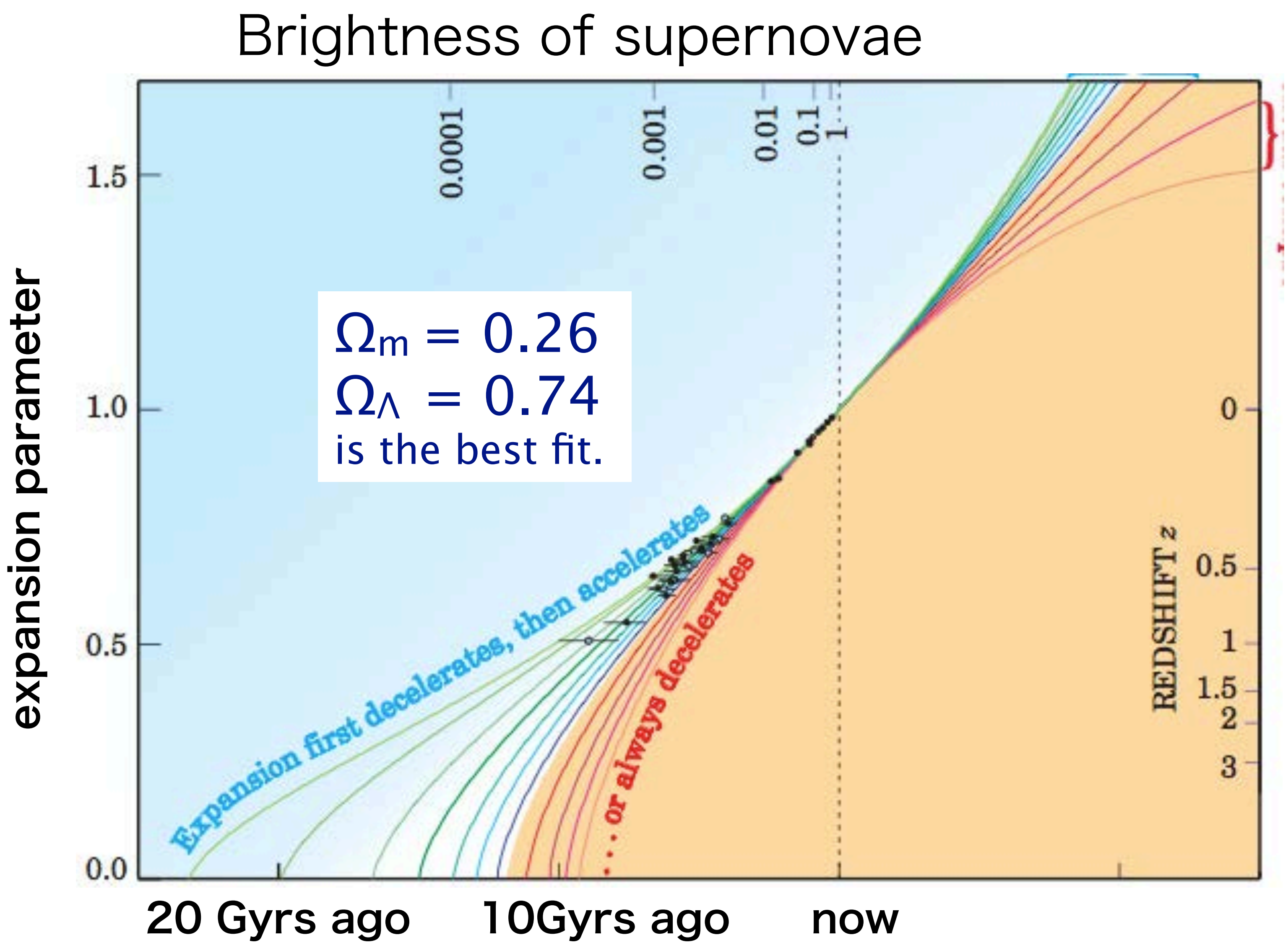


redshift z:

$1+z = 1/a$

z	a
0	1
1	0.5
4	0.4
99	~0.01
1000	~0.001

Measuring the expansion history



Summary Part 1

Did we actually weigh dark matter ?

No.

Did we measure the density of dark energy ?

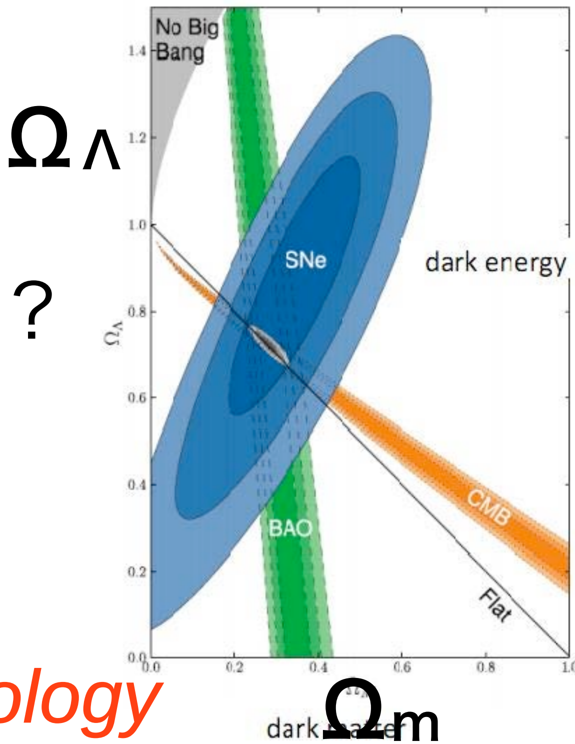
Not directly.

Do we know what they are ?

No.

Do we know the energy densities ?

YES! $\Omega_\Lambda = 0.74$, $\Omega_{matter} = 0.26$



How ?

The power of *observational cosmology*

The Large-Scale Structure

The Distribution of Galaxies

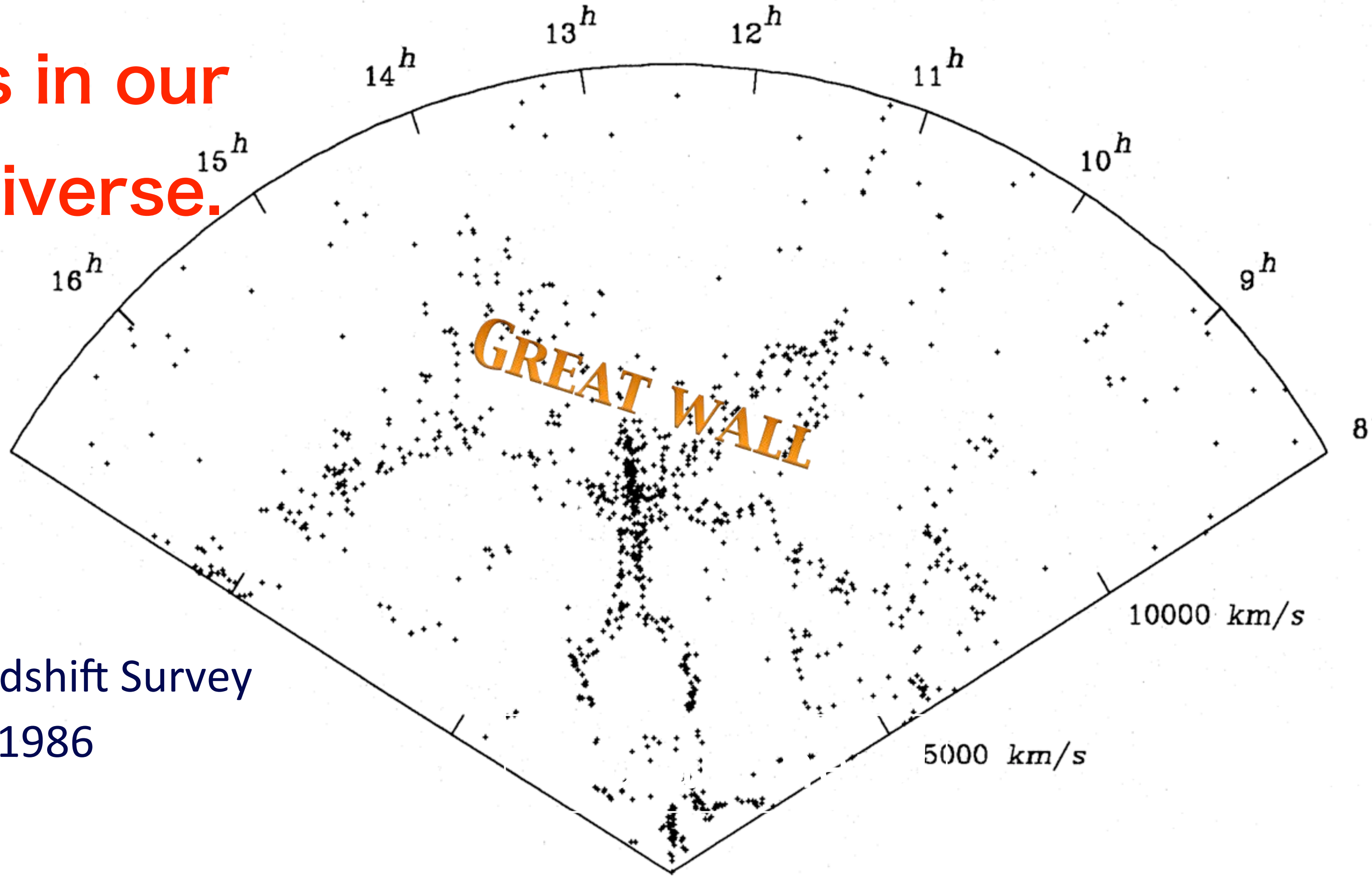
Lick Galaxy Catalogue (1970's)

showed the projected distribution of galaxies in the sky.

Galaxies are NOT distributed randomly

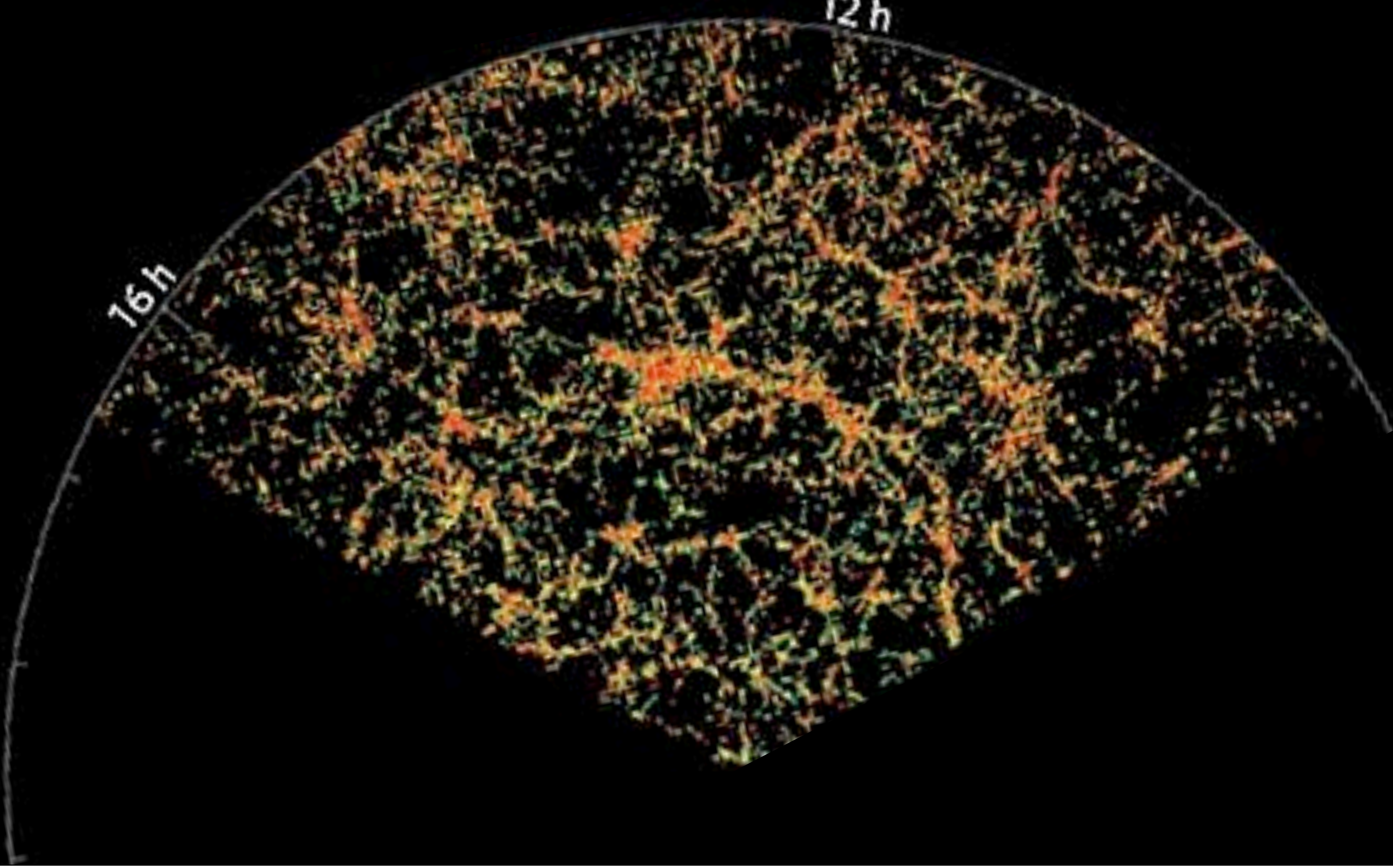
Galaxy Redshift Survey: 3D

The distribution of galaxies in our local universe.

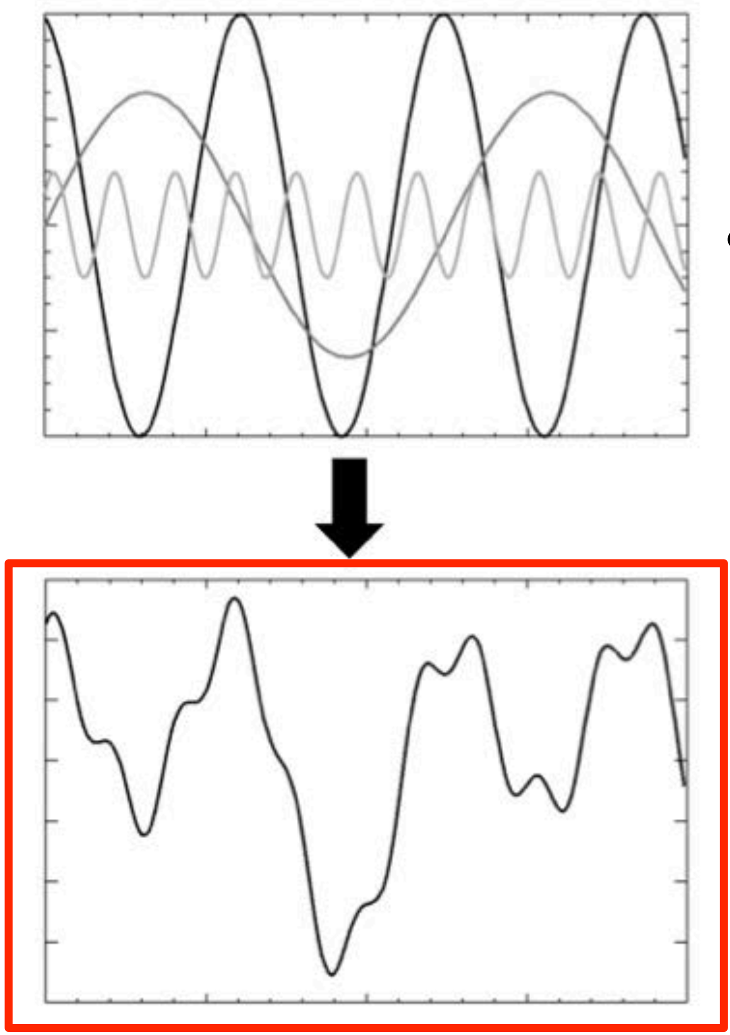


CfA Galaxy Redshift Survey completed in 1986

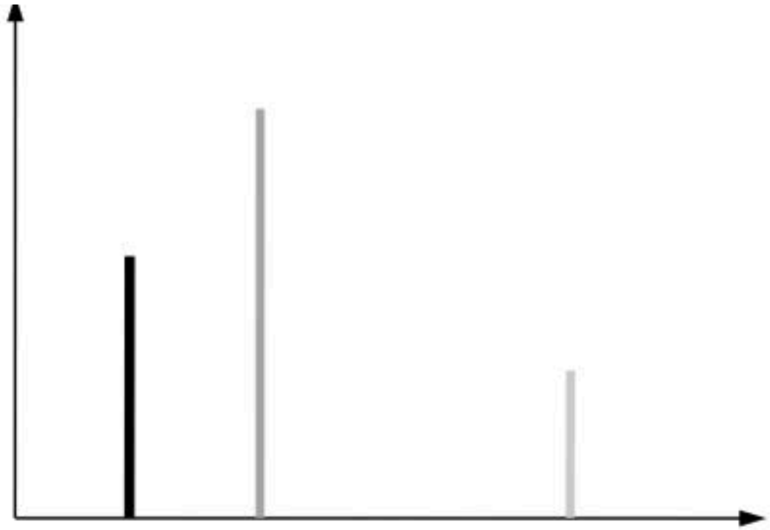
Cosmological information in the distribution of galaxies



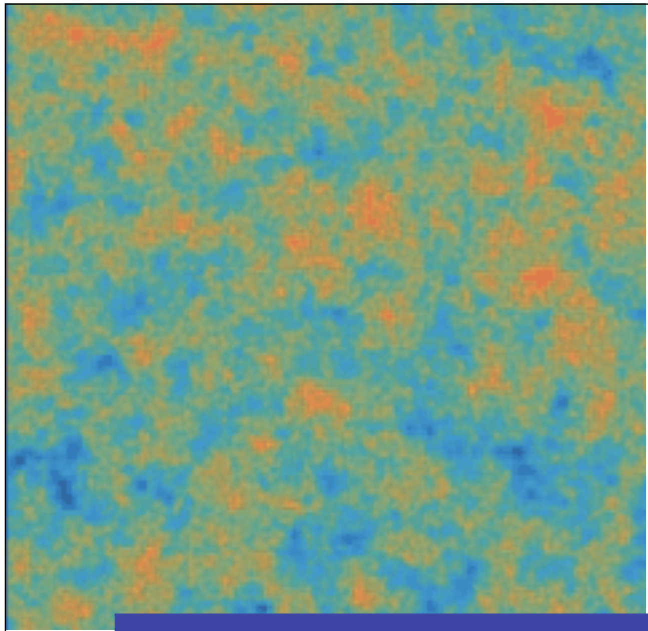
Fourier analysis and the power spectrum



real space density field (1D)

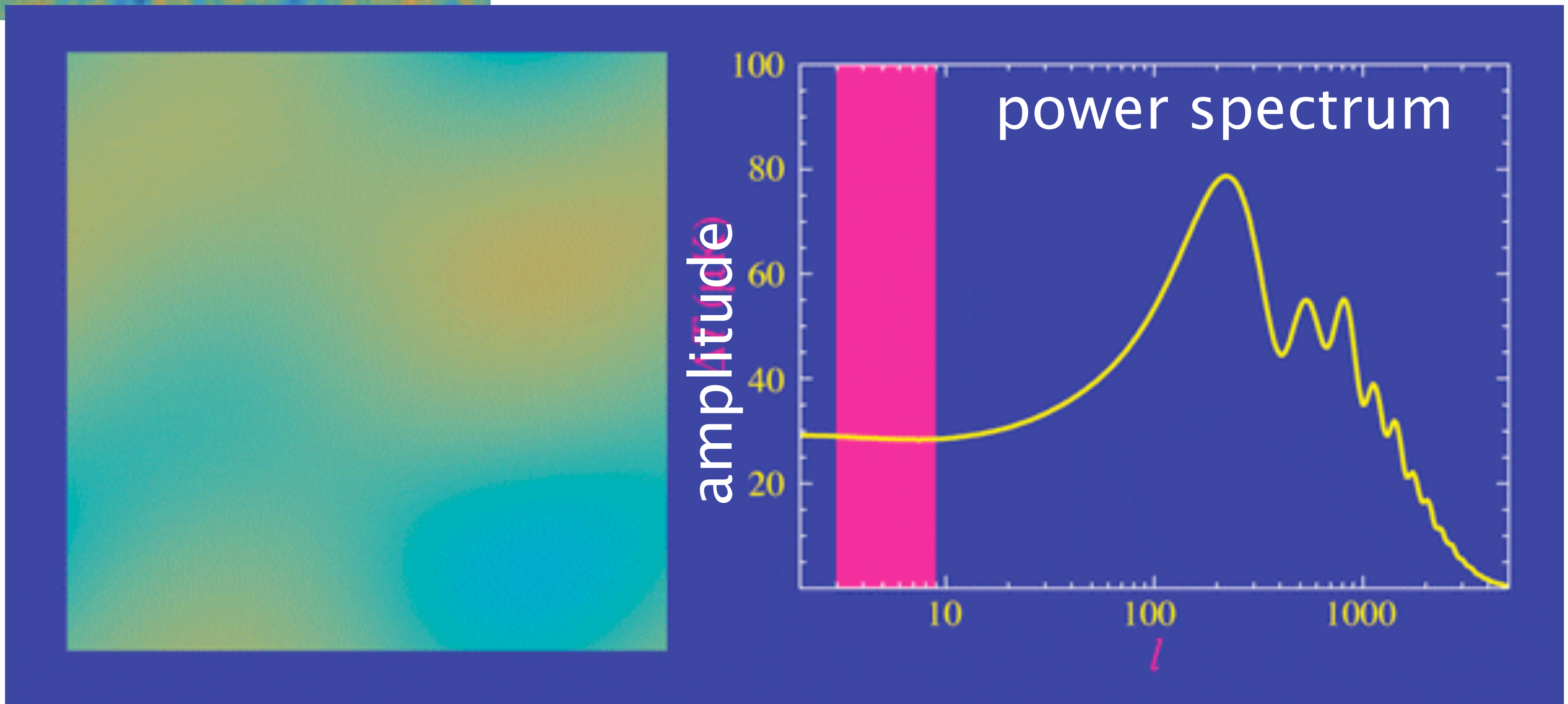


Simply imagine superposition of multiple sinusoidal waves.



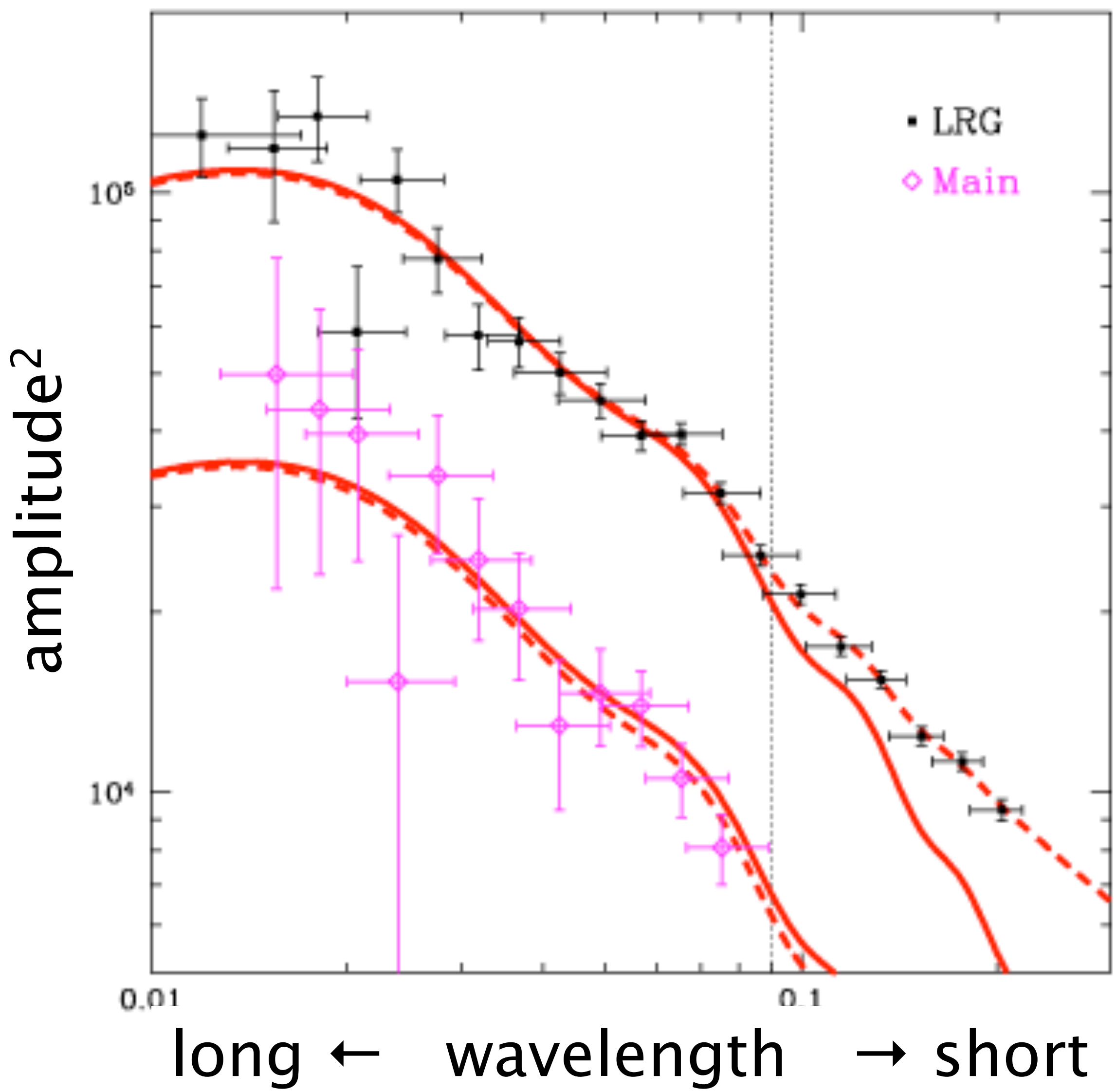
An example in 2D

Superposition of “ripples” with various sizes



from homepage of Wayne Hu

Galaxy power spectrum



Assume the galaxy distribution is described by

$$\delta(\mathbf{r}) = \frac{\rho(\mathbf{r}) - \bar{\rho}}{\bar{\rho}}$$

Fourier-transform it

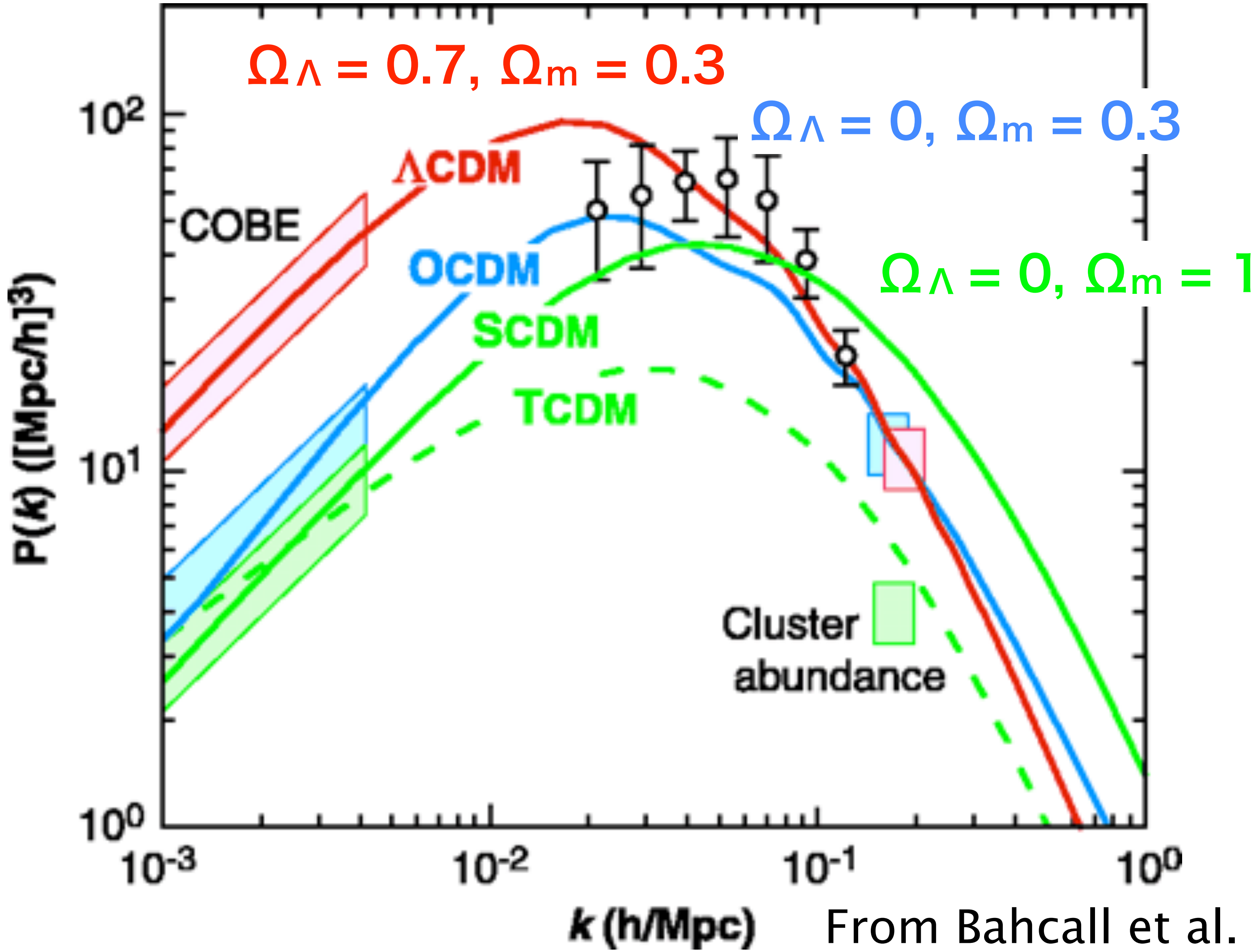
$$\delta(\mathbf{k}) = \int \mathrm{d}^3 r \; \delta(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}}$$

Then the power is essentially δ squared;

$$P(k) = \langle \delta(k)\, \delta^*(k) \rangle$$

i.e. $P \sim (\text{amplitude})^2$

P (k) as a cosmology probe



From Bahcall et al. 1998

Growth of linear perturbations in an expanding universe

But, consider that the background space is expanding as ***r = a(t) x***

The continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

(ρ fluid density, **u** fluid vel.)

The Euler equation

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \frac{\nabla P}{\rho} + \nabla \phi = 0$$

(P fluid pressure,
Φ grav. potential)

The Poisson equation

$$\nabla^2 \phi = 4 \pi G \rho$$

Find solutions of

$\rho = \rho_0 + \rho_1$

$u = u_0 + u_1$

$\Phi = \Phi_0 + \Phi_1$

The growing mode solution

The combined equations (continuity, Euler, and Poisson) lead to the second-order ordinary differential equations:

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\,\bar{\rho}\,\delta = 0$$

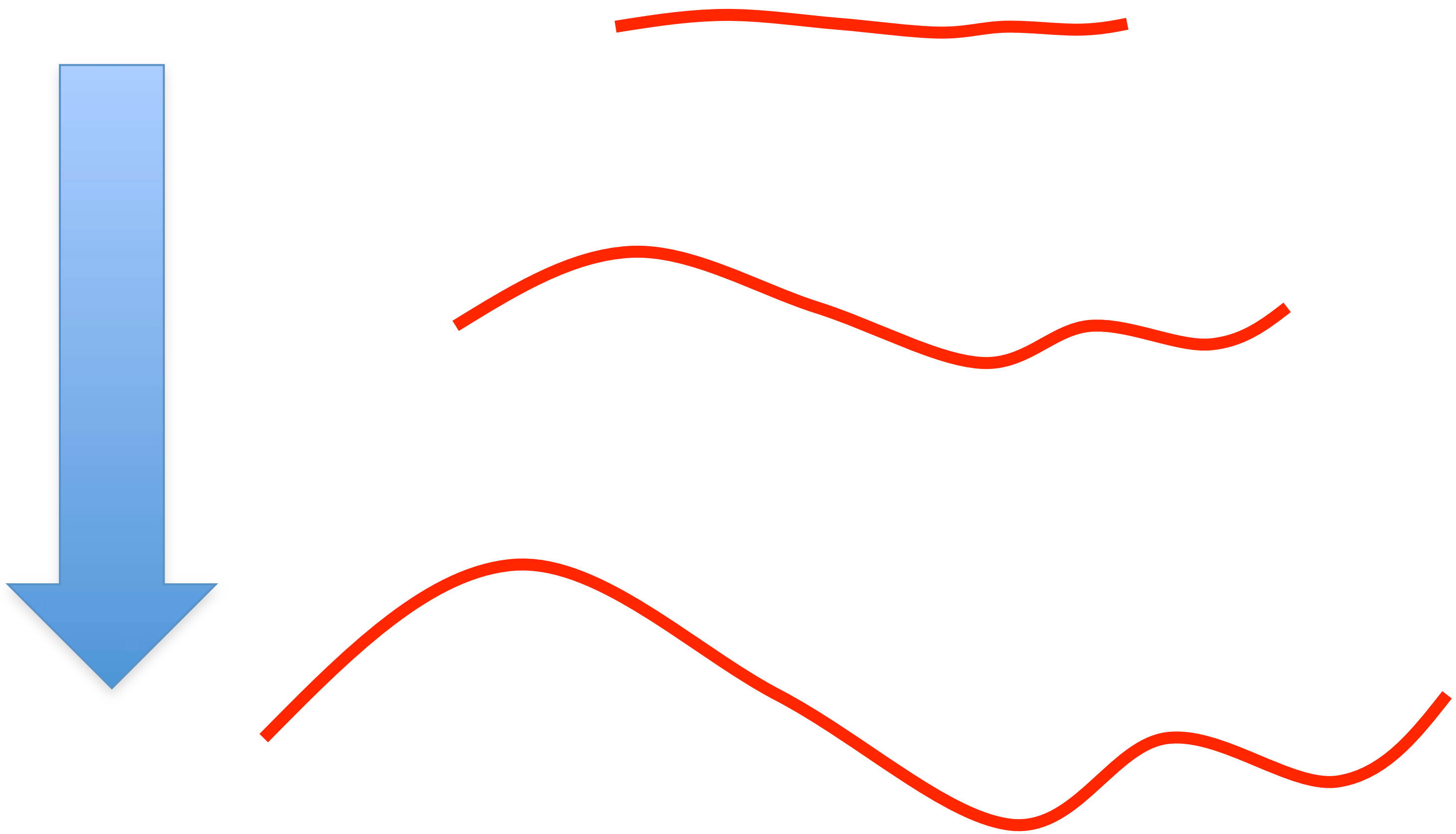
which has two solutions. (Derivation left for exercise.) The one we are interested in is the so-called "growing mode" which evolves as

$$\delta = D(t)\,\delta_{\text{initial}}$$

For a flat, matter-dominated universe, $D = a$ where a itself scales as $\sim t^{2/3}$

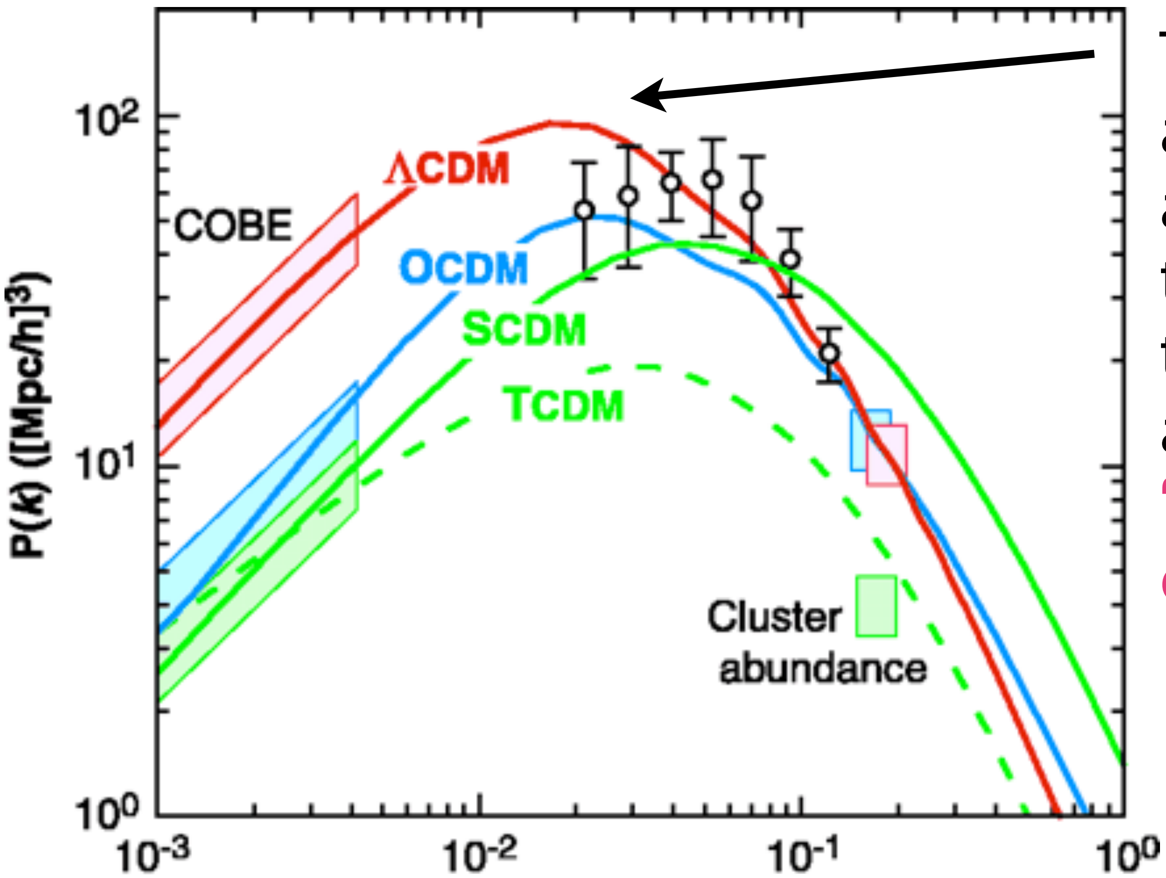
Density fluctuations grow with time in the early epoch.

The growing mode solution



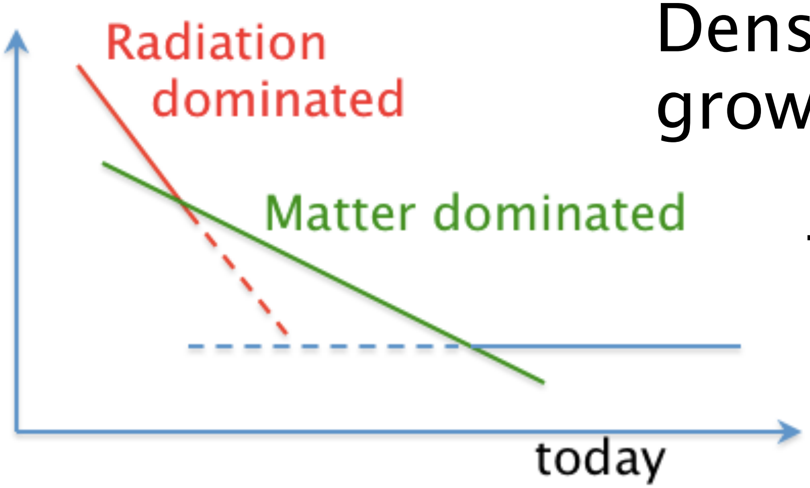
The initial density perturbations simply grow in time, as $\propto a$.

One can measure the matter density (Ωm) from P(k). How ?



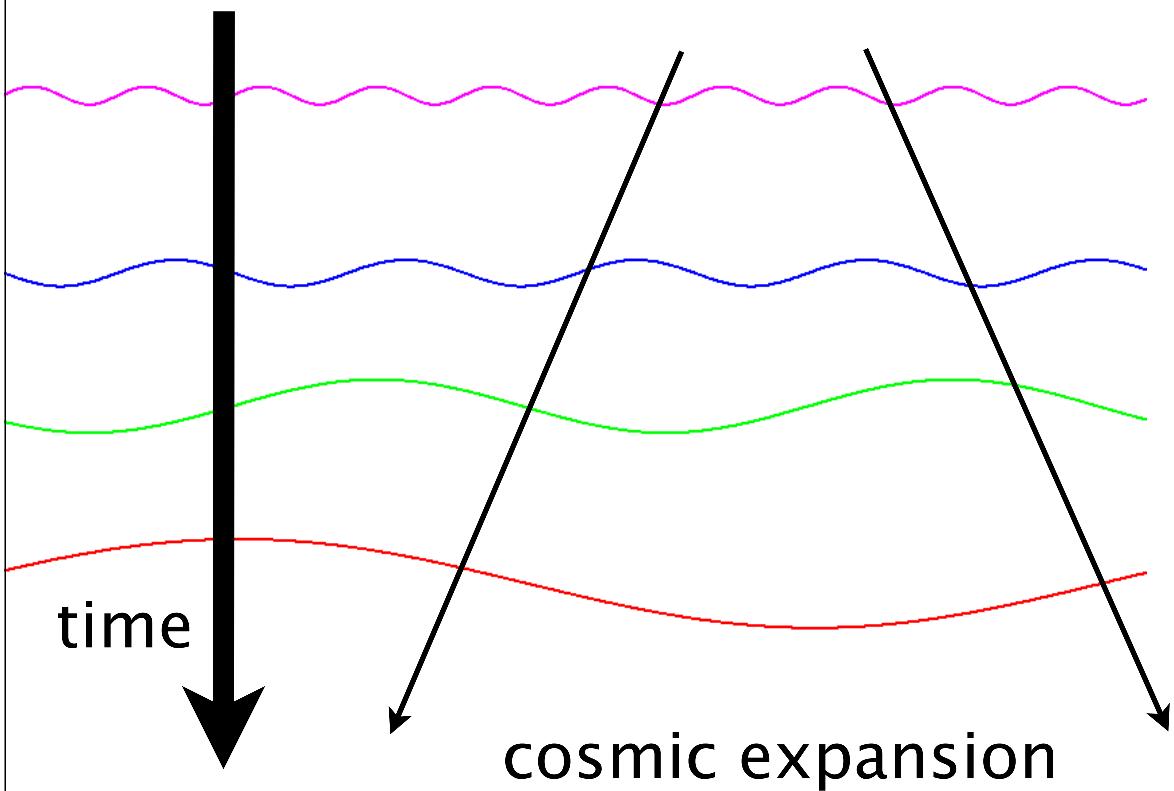
long ← wavelength → short

The break in the amplitude P(k) appears at a wavelength that correspond to the horizon size at "matter-radiation equality" epoch.

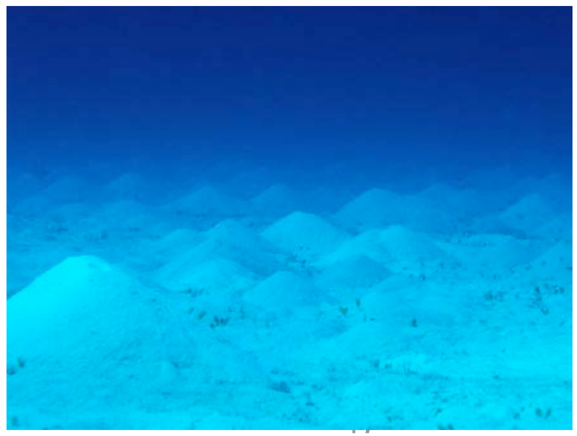


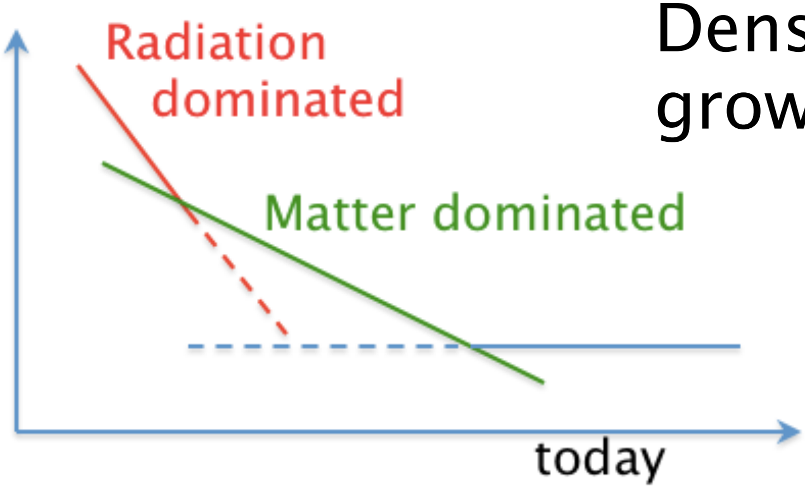
Density perturbations cannot grow in a sea of lots of photons.

There was a time when radiation energy dominated.



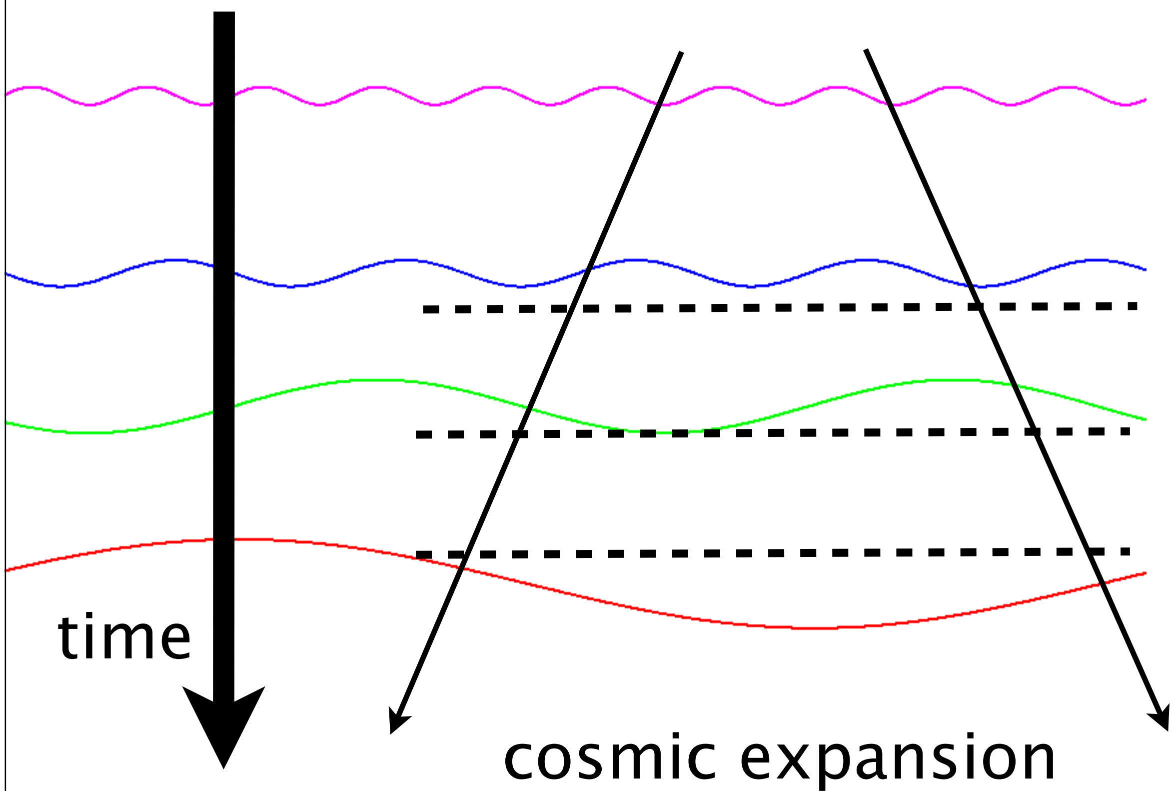
radiation dominated.





Density perturbations cannot grow in a sea of lots of photons.

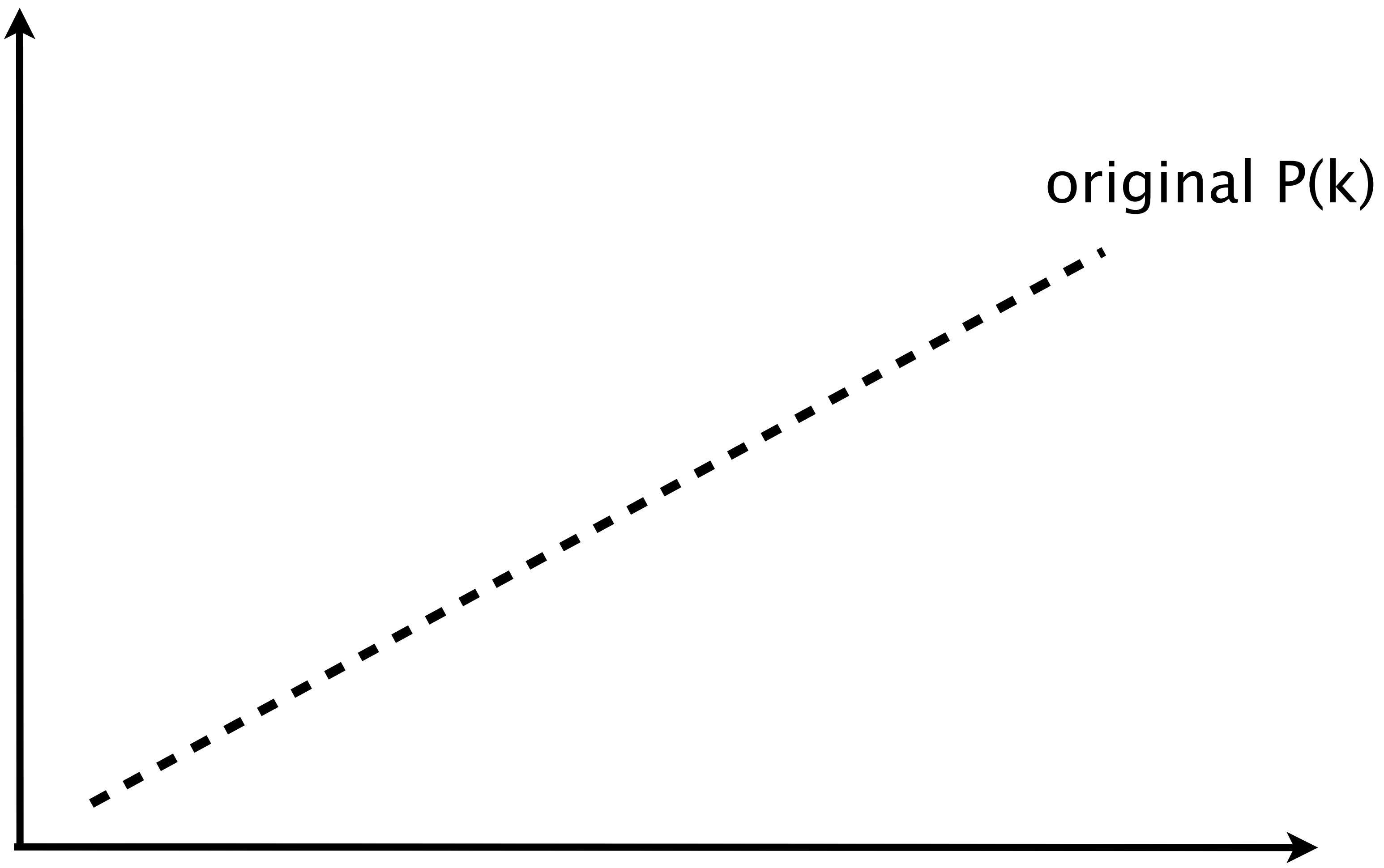
There was a time when radiation energy dominated.

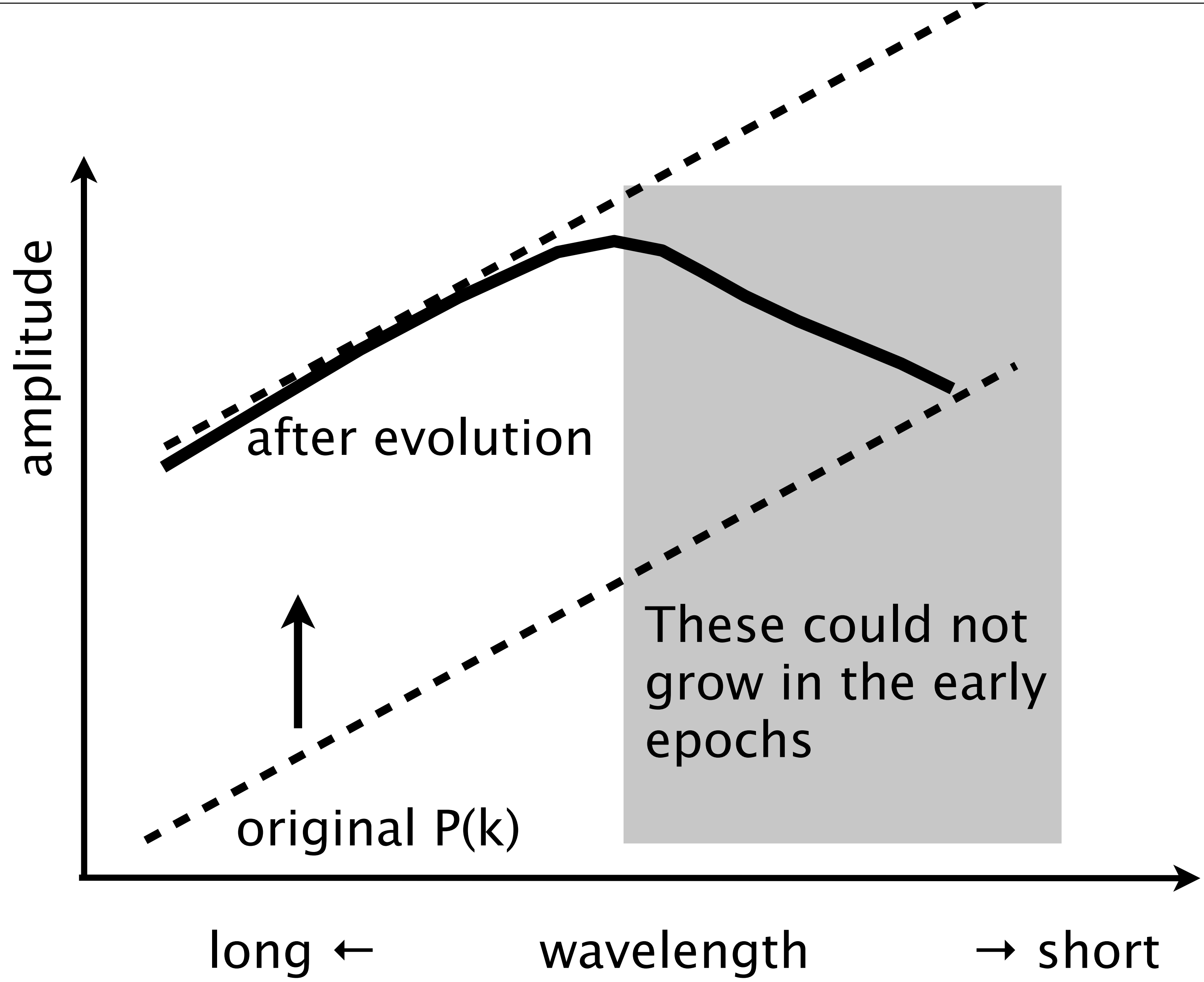


} radiation dominated.

Small Ωm
→ matter–radiation equality comes late.

Short wavelength modes could not grow.


original P(k)


amplitude
after evolution
These could not grow in the early epochs
original P(k)
long ←
wavelength
→ short

Summary Part 2

Did we actually weigh dark matter ?

No.

Did we measure the density of dark matter ?

Not directly.

Do we know what it is ?

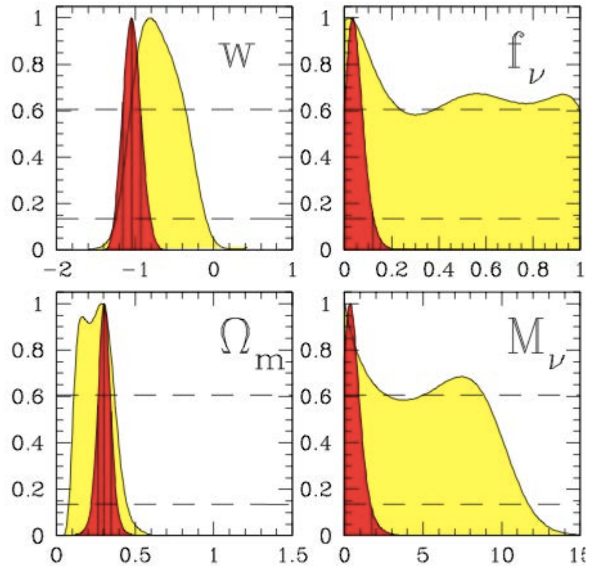
No.

Do we know the energy density ?

YES! $\Omega_{matter} = 0.26$

How ?

The actual procedures are more than that, but in principle...



The Cosmic Microwave Background
(perhaps time is up now).

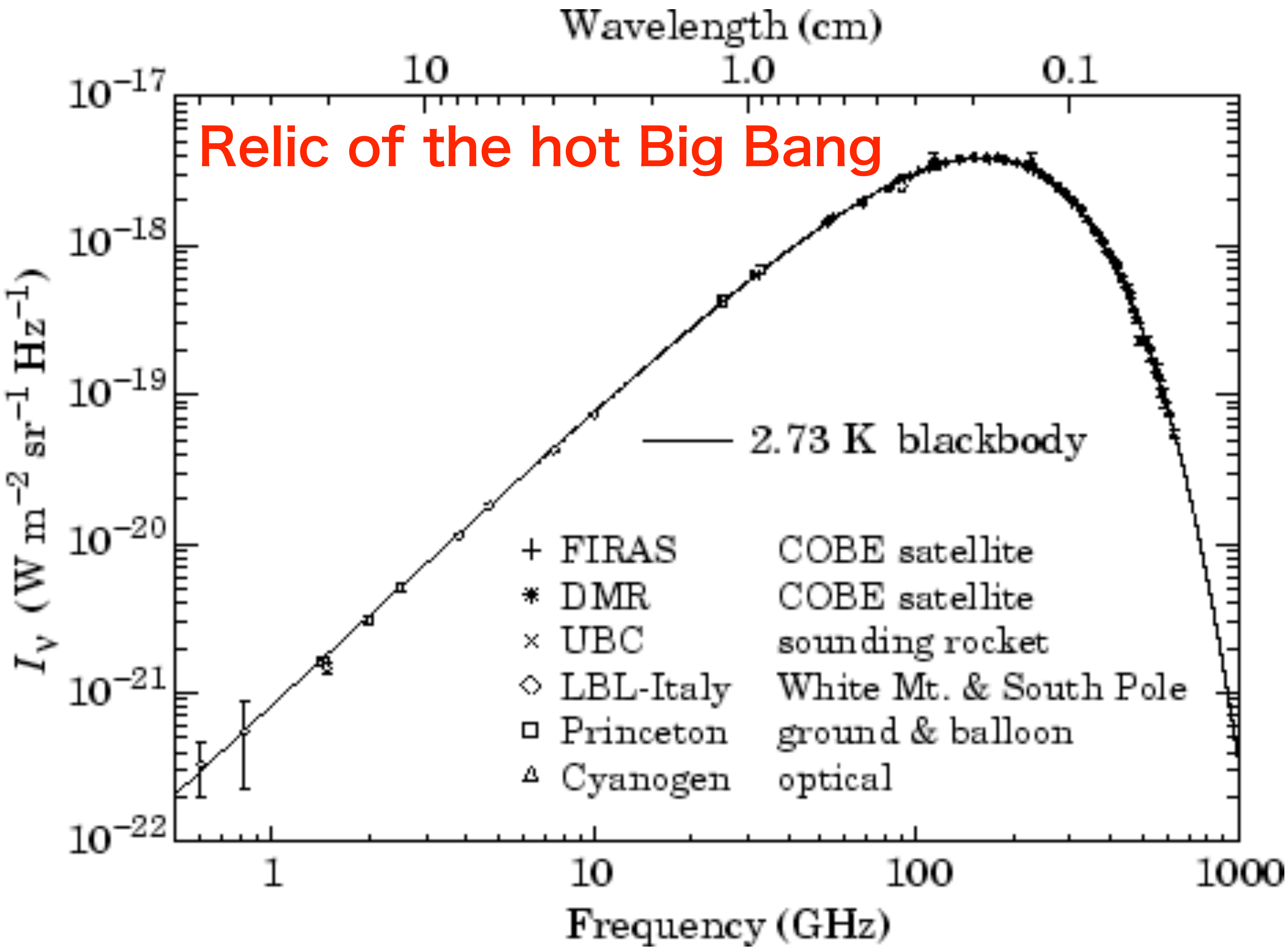
From the intensity ratio of the CN lines, a temperature of 2.3 K follows, which has of course only a very restricted meaning.
- G. Herzberg, 1950

This error estimate 2±1K is based on the temperature 'not otherwise accounted for' in previous experiments.
- E. A. Ohm, 1961

Measurements of the temperature have yielded a value about 3.5 K higher than expected. A possible explanation is given by Dicke et al.
- A. Penzias and R. Wilson, 1965

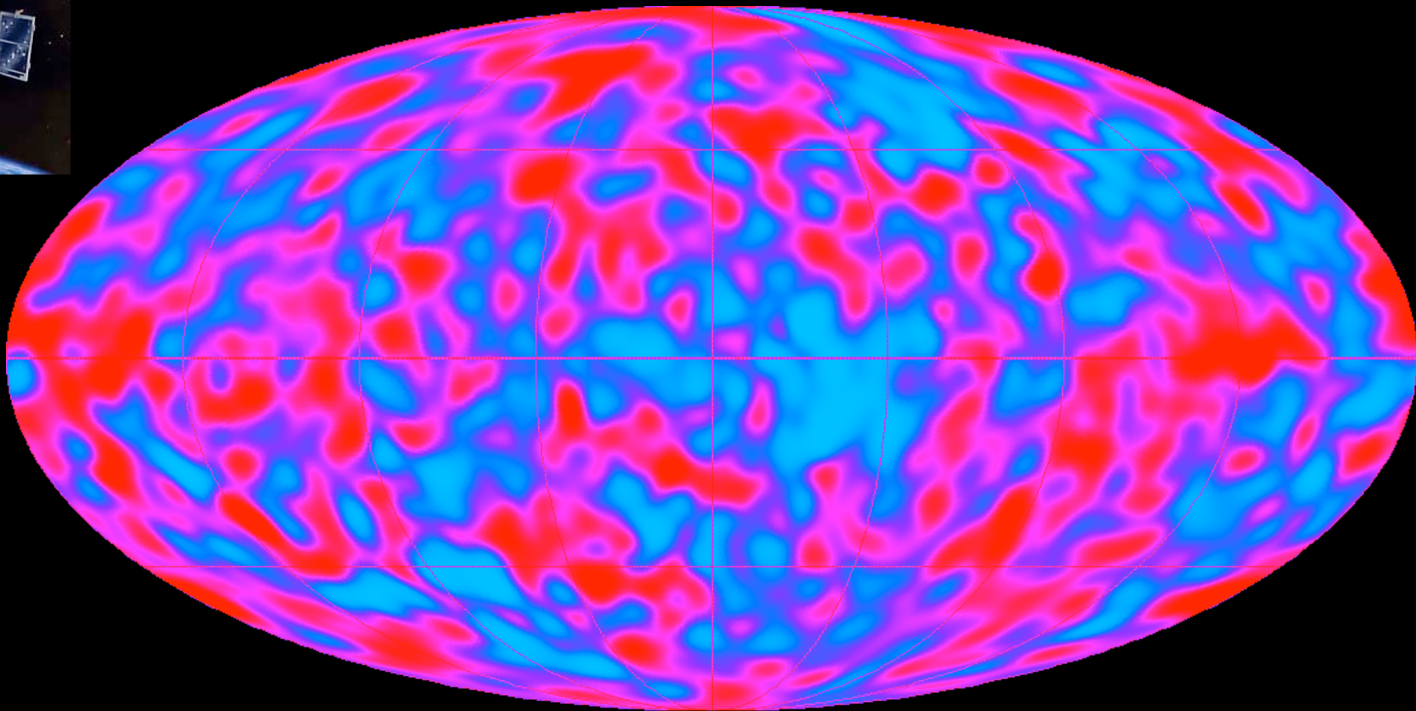
Penzias and Willson, with the horn telescope that discovered CMB

Cosmic blackbody radiation

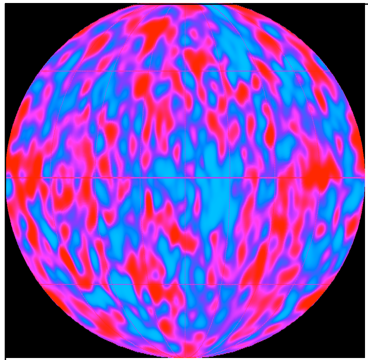


CMB anisotropies

Tiny density fluctuations left over from the Big Bang : Origin of the structure of the universe.



2006 Nobel Prize for Physics G. Smoot、J. Mather

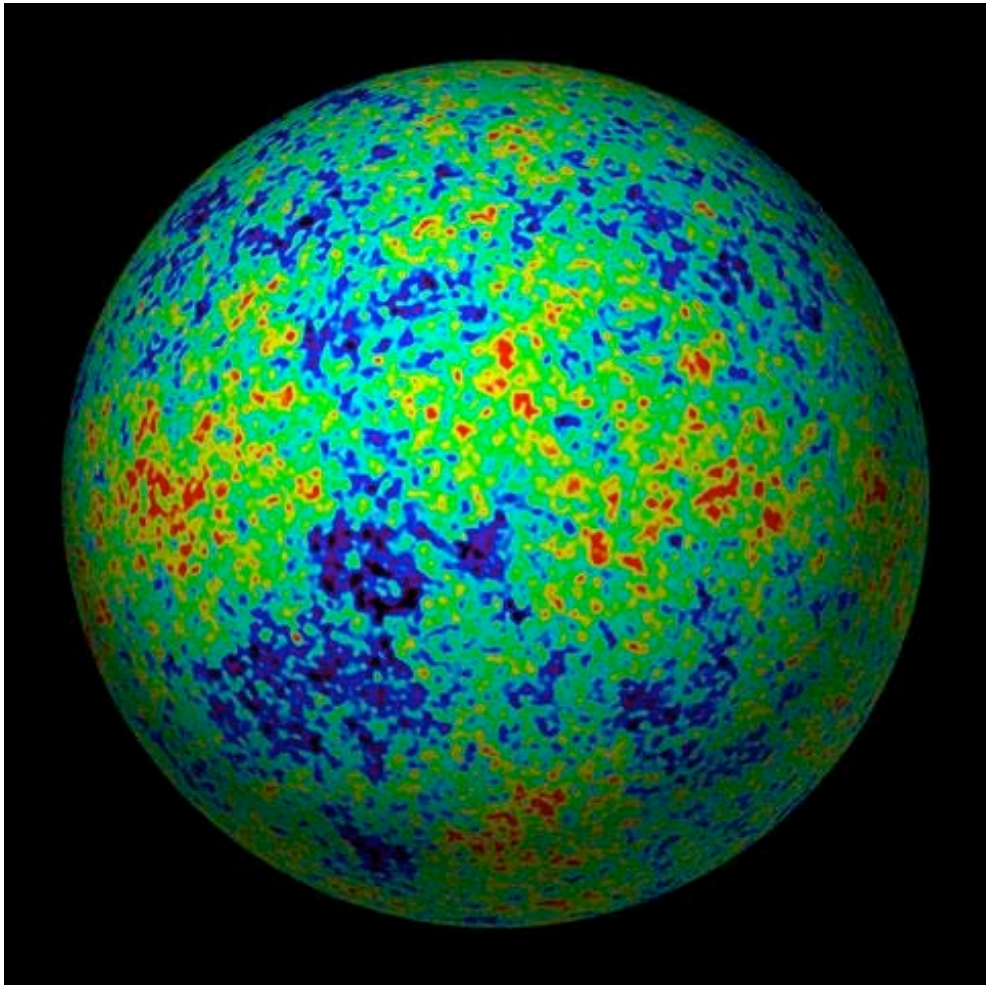


What we observe is temperature fluctuations.

But ΔT is almost directly Δρ. Why ?

- In an over-dense region, photons are slightly hotter, and thus the region appears “hot”.
- In an over-dense region, photons must climb up the gravitational potential which is slightly deeper. Thus the photons lose slightly more energy, hence the region appears “cold”.

Why are my colleagues so enthusiastic about just noises ?



Like hieroglyphics tell the ancient egypt, one can know much about the early universe by "reading" CMB.

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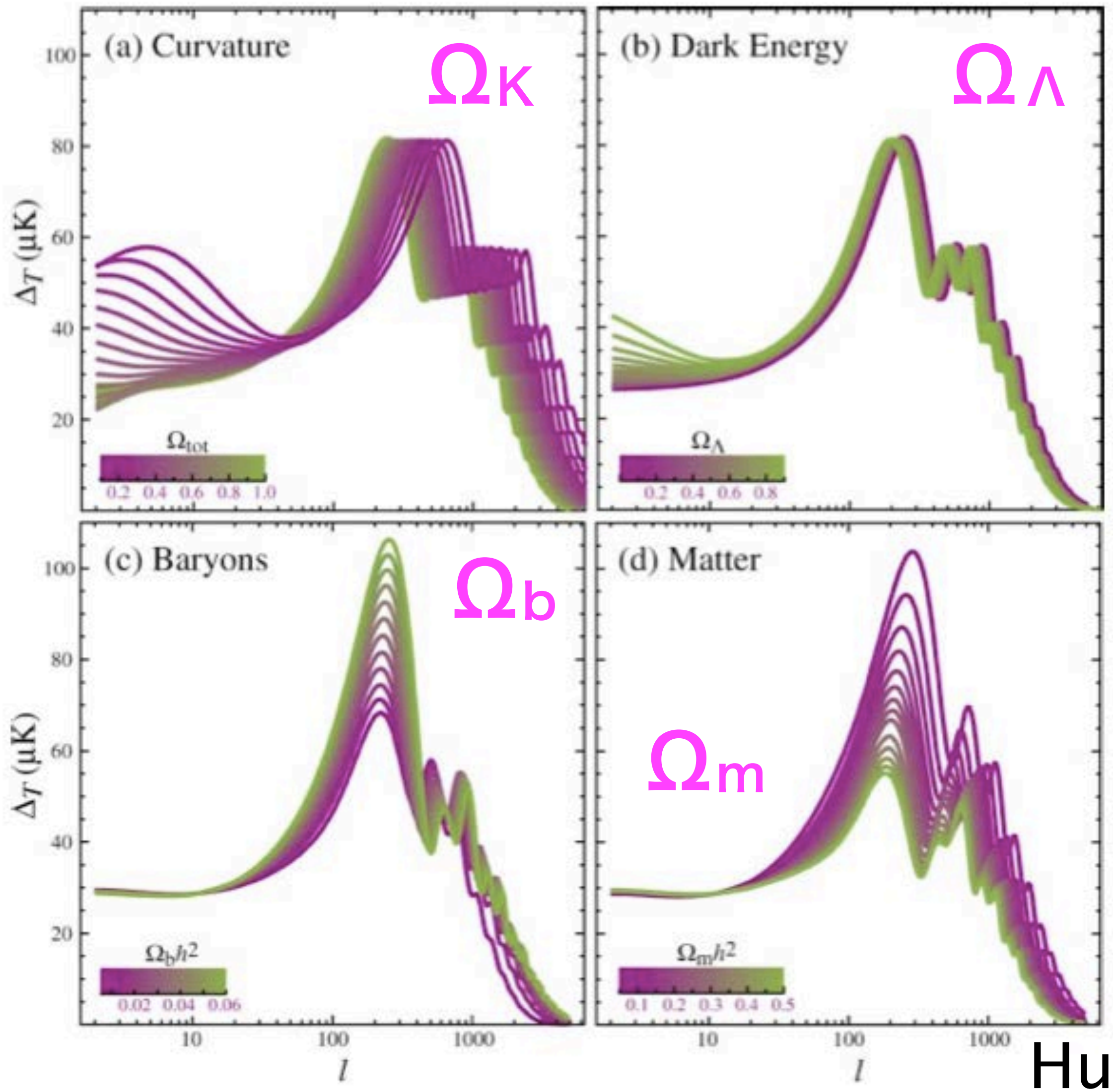
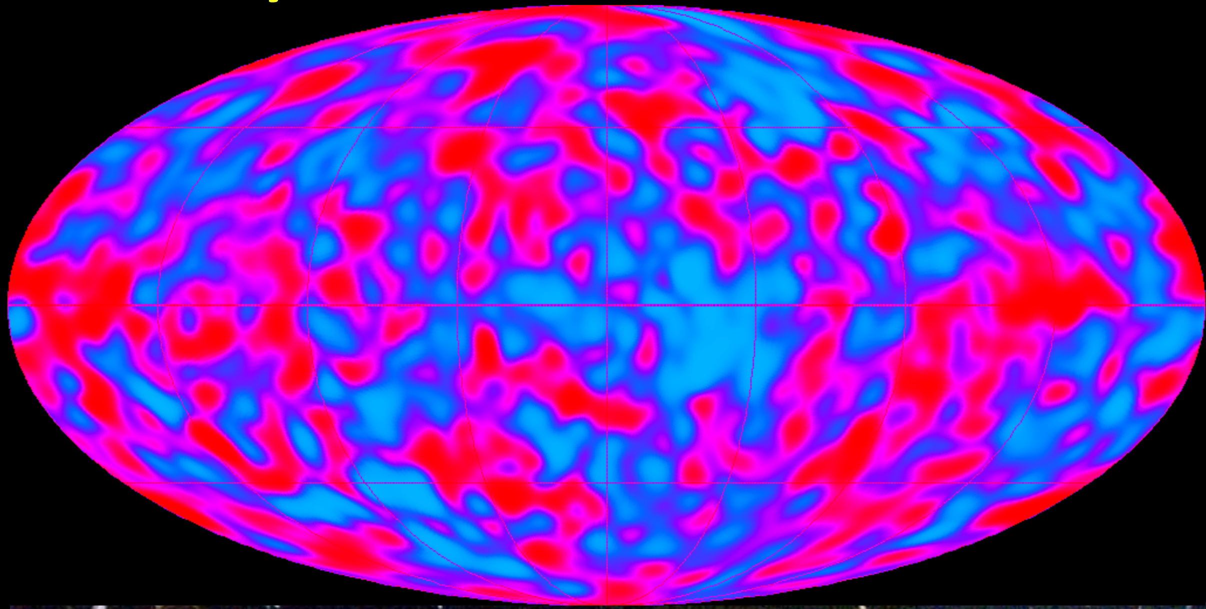


Like hieroglyphics tell the ancient egypt, one can know much about the early universe by “reading” CMB.

Hu & Dodelson, ARAA

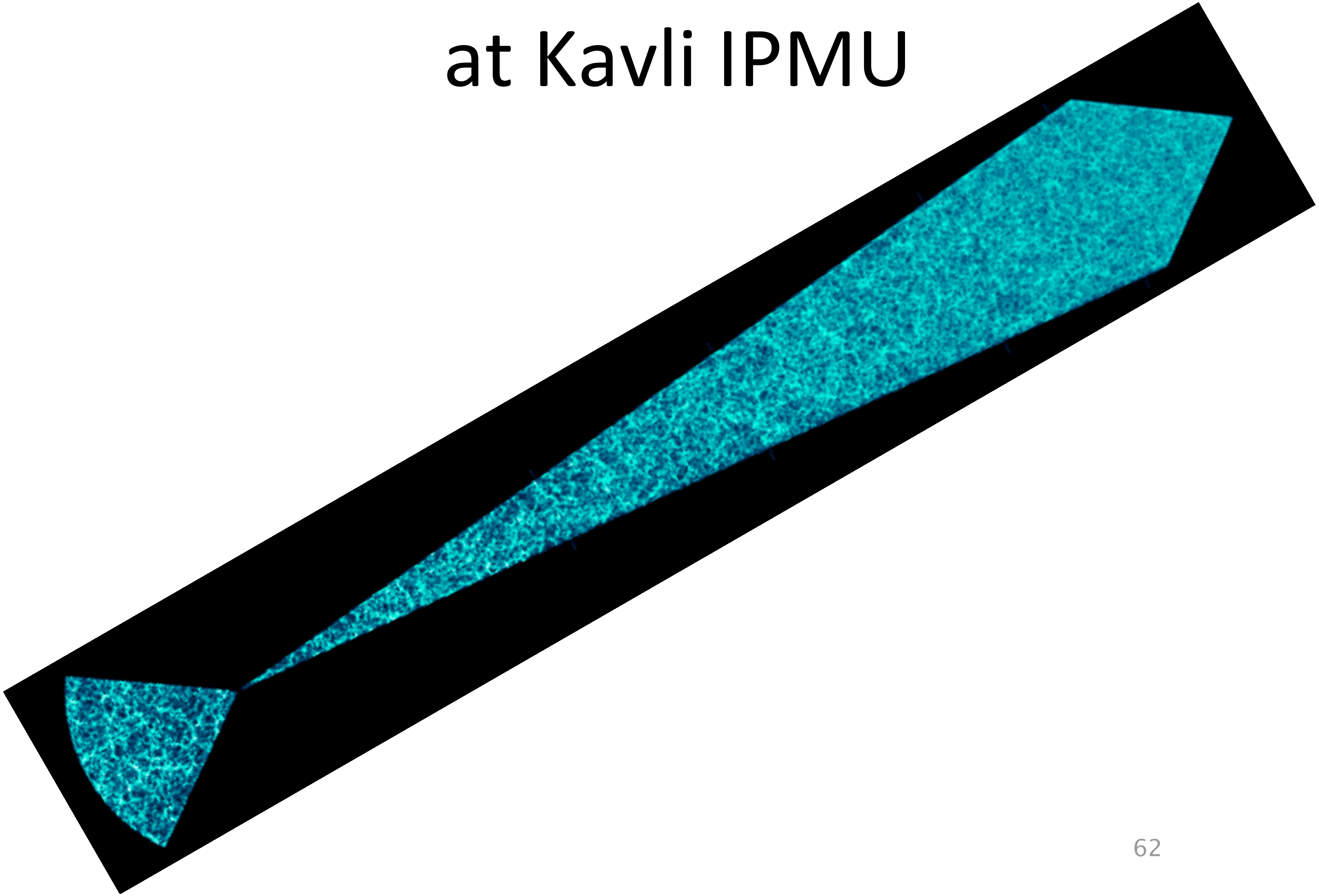

Present-day universe

Very smooth initial state

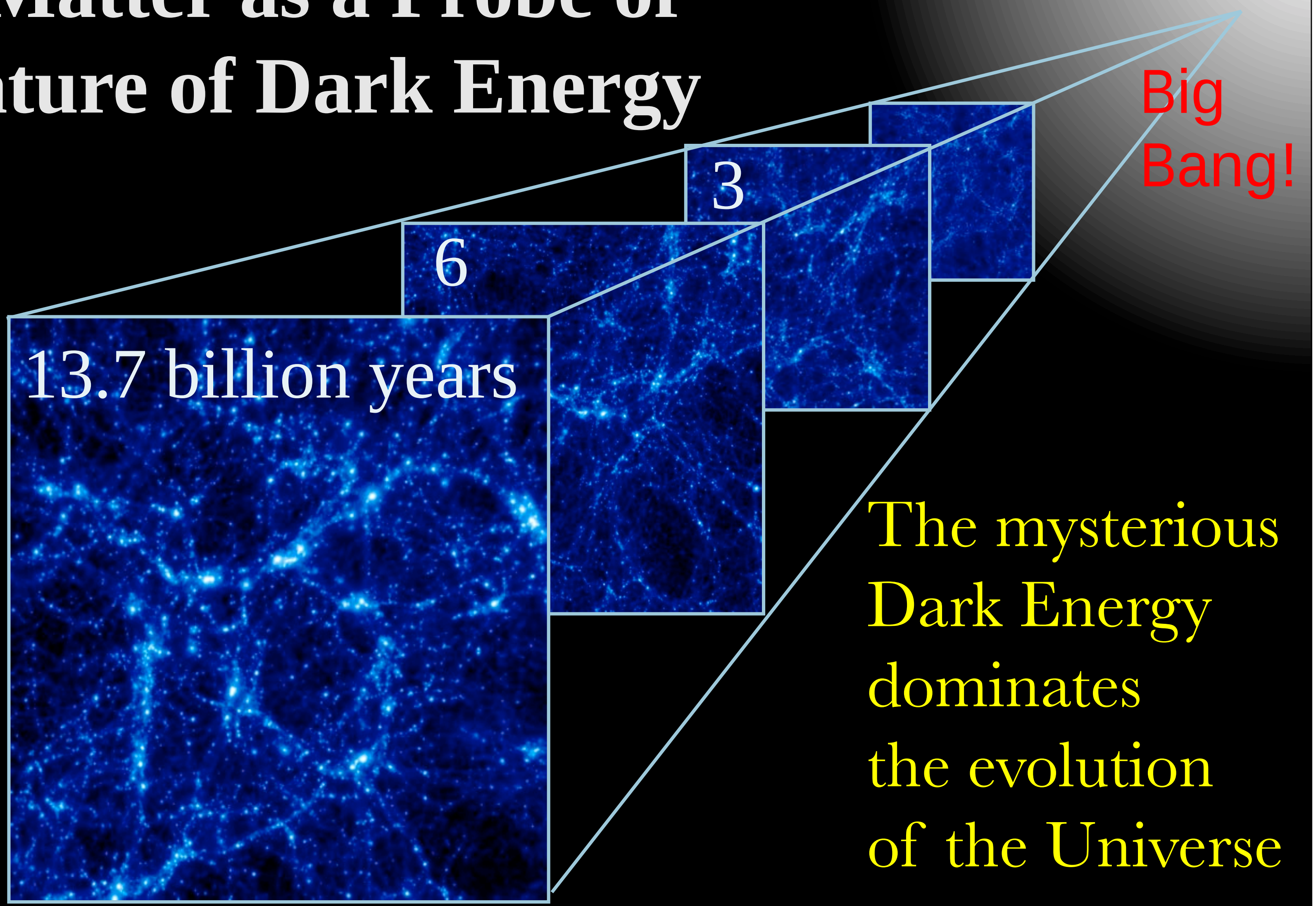


Ending as a clumpy universe

What is being done at Kavli IPMU



Dark Matter as a Probe of the Nature of Dark Energy



Imaging the shapes of millions galaxies in the sky

The mysterious Dark Energy dominates the evolution of the Universe

The new camera surveys 1000 times(!) larger area than the Hubble telescope

Summary

- Modern cosmology is based upon reasonable assumptions, reasonable and upon a wealth of data (in the future too).
- The outcomes of observations and surveys are often simple quantities, numbers (say Ω_Λ) but understanding the underlying physics and models is not always easy (for non-experts).
- But the results of cosmology should be shared with all of us, researchers, general public.

to be continued:

An Introduction to Observational Cosmology II