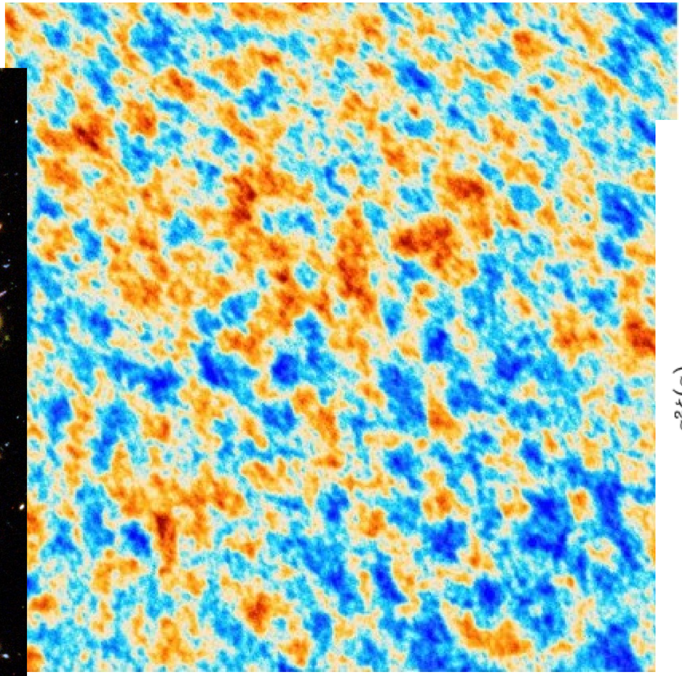
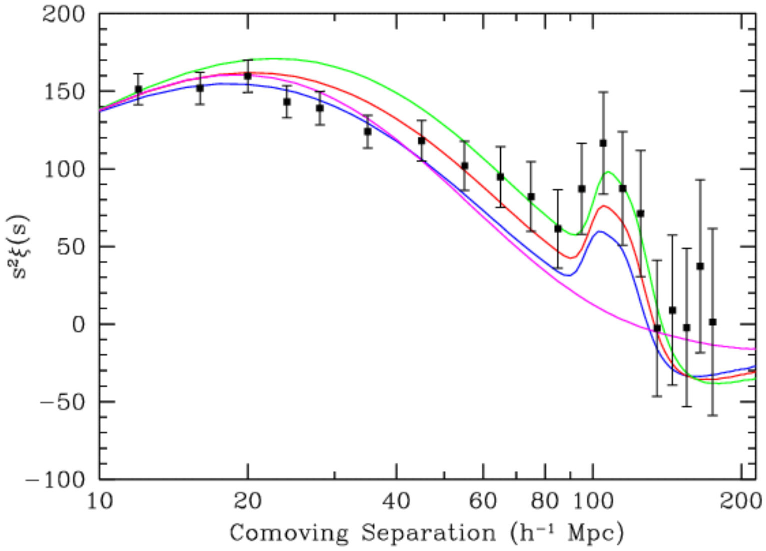
Cosmology (2)

Pierre Astier

LPNHE / IN2P3 / CNRS , Sorbonne Université.

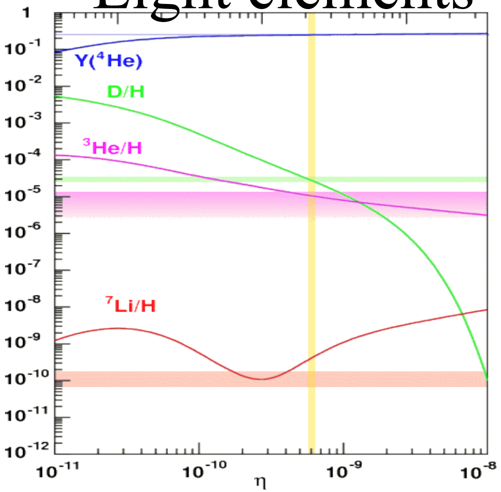
TES School - Bezmiechowa Górna, – July 2023.

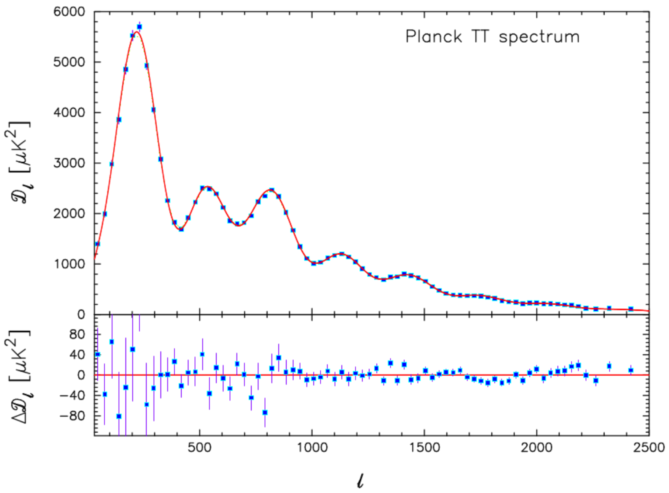


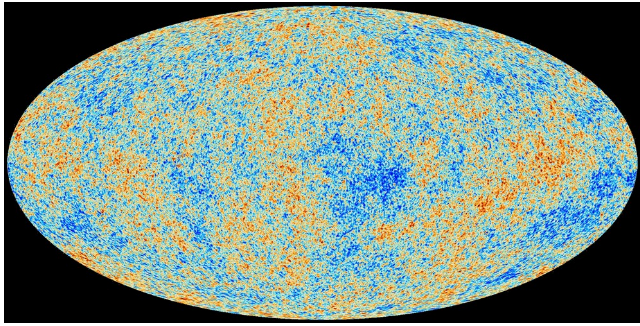


Previous lecture:
the Big Bang is not just a theory

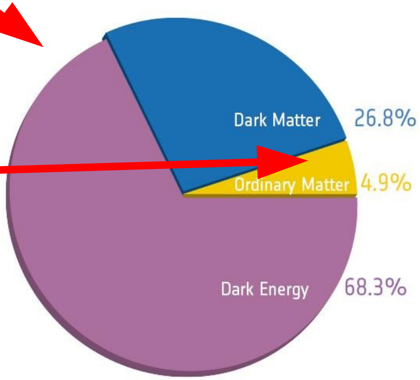
Abundance of Light elements







$\Omega_m \sim 0.3$



match

In our universe, there are about $2\ 10^9$ photons per nucleon

Outline

- Why and how we now measure the “expansion history”
- Hubble diagrams and “dark energy”
  - Supernovae
  - Baryon Acoustic Oscillations

Textbooks :

- James Rich : “Fundamentals of Cosmology”
- John Peacock : “Cosmological physics”
- Scott Dodelson : “Modern Cosmology”
-

Historical & Newtonian parenthesis

(

Our cosmological model :founding stones

1915 : Albert Einstein proposes General Relativity
1922 : Alexander Friedman proposes evolving universe models
1927 : Georges Lemaître proposes evidence for expansion
1929 : Edwin Hubble : “the faster, the fainter”

(Hubble, 1929)

Recession velocity
of nebulae (i.e. galaxies)
vs “distance”

velocity

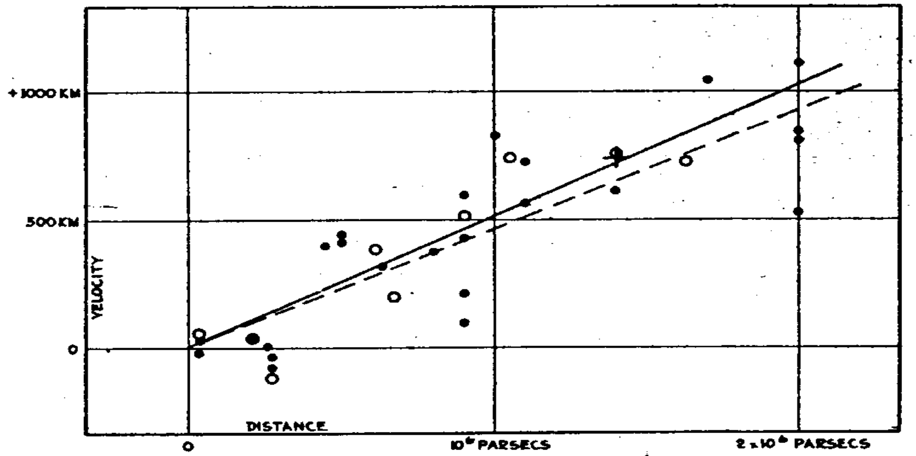
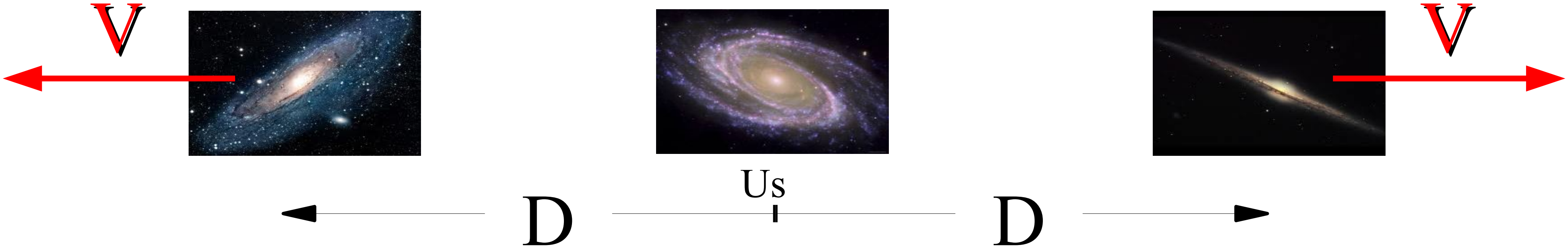


FIGURE 1

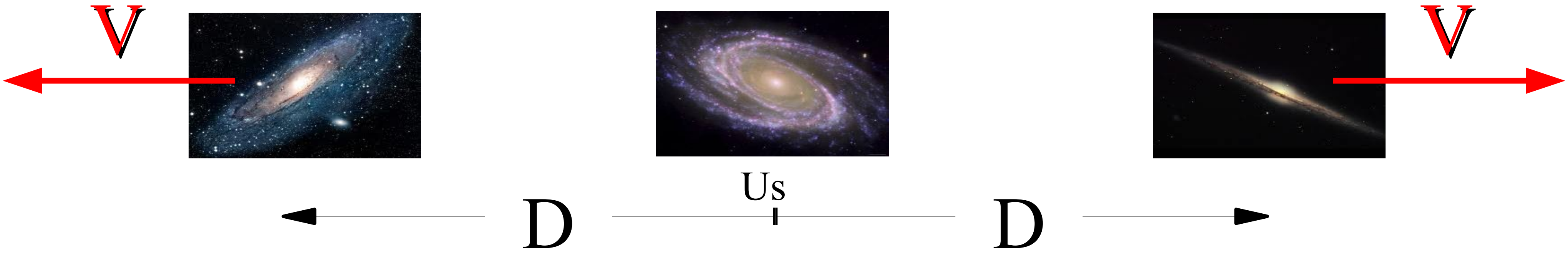
Distance (from flux)

Expansion



If we assume isotropy, the recession velocity has to be the same in all directions

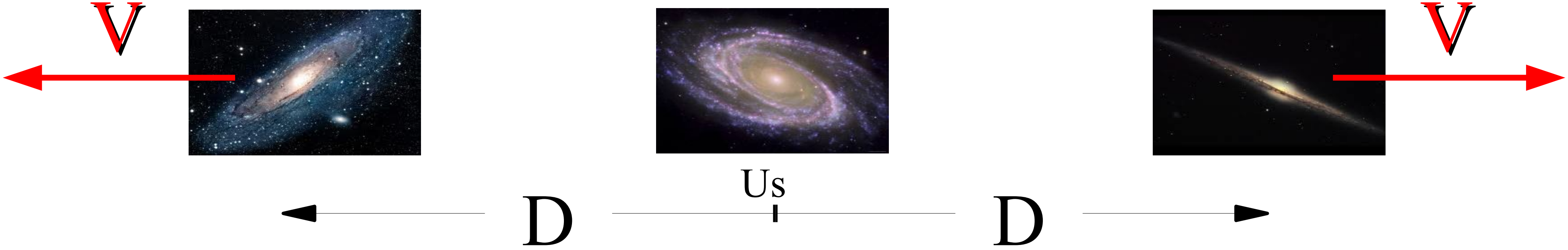
Expansion



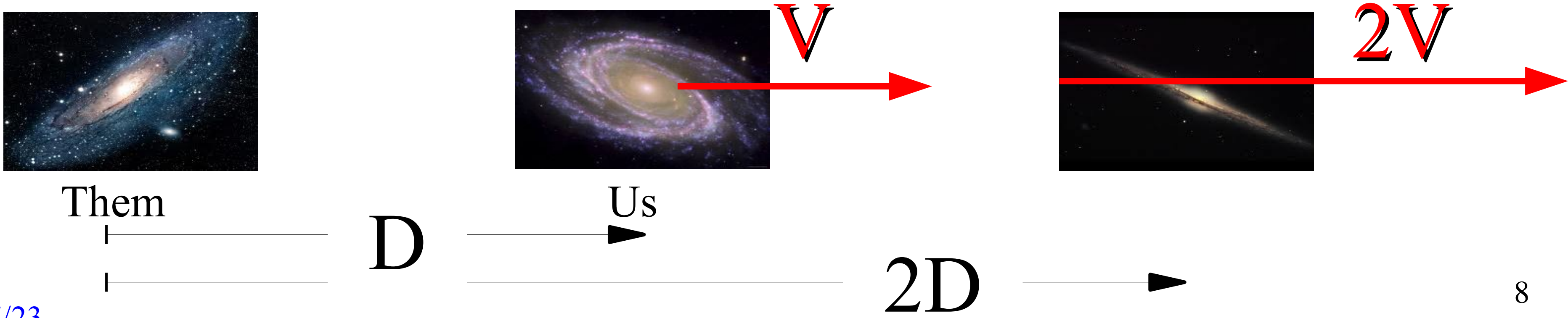
If we assume isotropy, the recession velocity has to be the same in all directions

If we assume homogeneity our place is just anywhere
(Just as claimed Copernic, some time ago)

Expansion



Let us change our view point



Expansion

Cosmological principle:

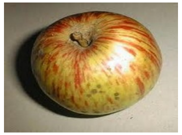
No favoured direction nor location

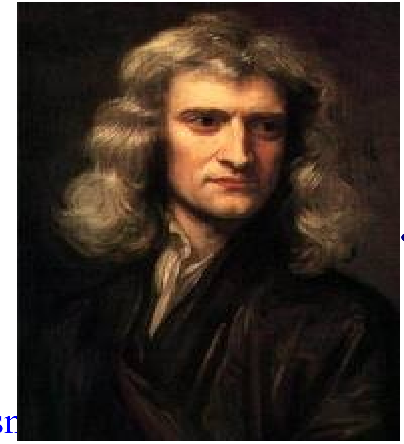
Velocity and distance are proportional

(to first order)

No expansion would be a particular case

Expansion : deceleration ?

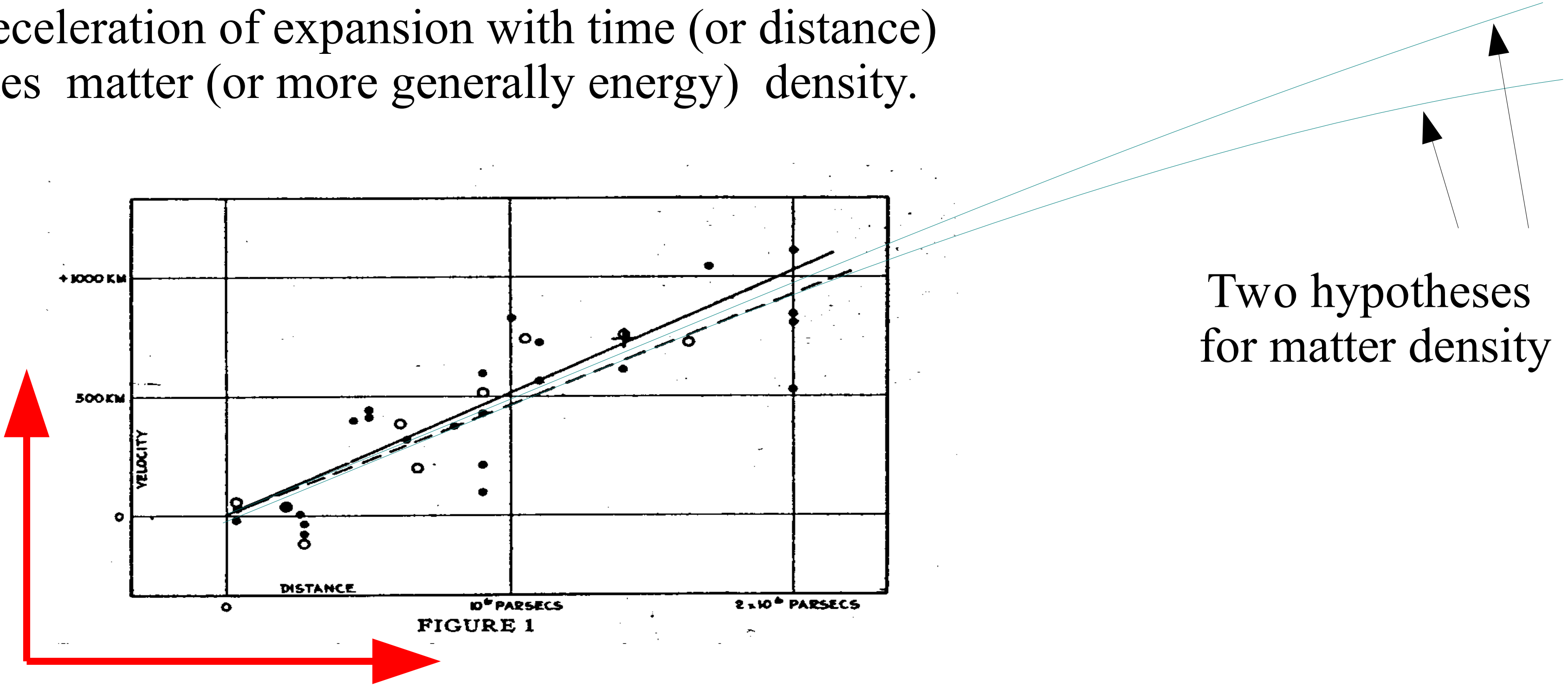




« universal attraction »
Galaxies attract each other:
relative velocities slow down

So

- V = H d   is a signature of the expansion of the universe
- The deceleration of expansion with time (or distance) encodes matter (or more generally energy) density.



Historical
& Newtonian
parenthesis

)

Cosmological principle

The universe is homogeneous and isotropic

- no special position (Copernic) or direction
- … but no time invariance
- .. and spatial curvature is not defined

-> Friedman-Lemaitre-Robertson-Walker metric:

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

Scale factor

Comoving coordinate

k = -1,0,1 (curvature sign)

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

Scale factor

Comoving coordinate

k = -1,0,1 (curvature sign)

Describes the relation to regular separations

Means that expansion does not change the coordinates of matter objects (galaxies, for example)

Between two galaxies : $D_{\text{physical}}(t) = a(t)\, d_{\text{comoving}}$

Friedman equation(s)

GR: Einstein Equations

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

FLRW metric

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

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

This is sufficient, once specified how density (ρ) depends on a(t).
Alternatively :

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

A negative pressure can accelerate expansion.

Densities in cosmology

Density means "energy density" (i.e. mass + kinetic energy)

$$H^2(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\rho_{crit} \equiv \frac{3H_0^2}{8\pi G}$$

Critical density: the one that makes the universe flat, i.e. k=0.

Dimensionless density (today):

$$\Omega_X \equiv \frac{\rho_X}{\rho_{\rm crit}} = \frac{8\pi G \rho_X}{3H_0^2}$$

"Physical" density:

$$\Omega_X h^2 = \frac{8\pi G \rho_X}{3H_{\rm ref}^2}$$

Common convention :

$$h \equiv \frac{H_0}{100\ \mathrm{km/s/Mpc}}$$

The fate of expansion ? It depends ...

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

"initial" conditions = present Conditions

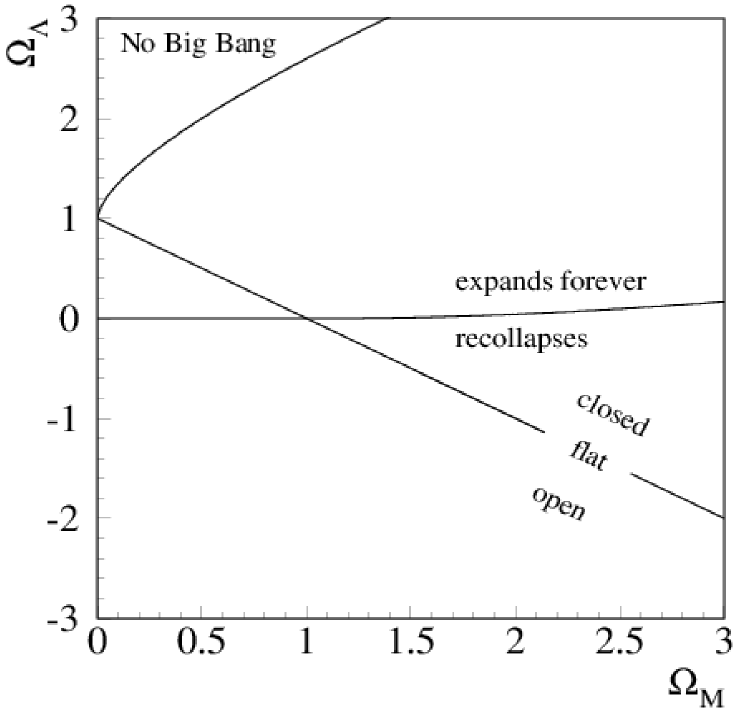
$$H_0 \equiv \left(\frac{\dot{a}}{a}\right)_0$$

$$\Omega_M \equiv \frac{8\pi G}{3H_0^2}\rho_{M,0}$$

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

$$\Omega_k \equiv -\frac{k}{a_0^2 H_0^2}$$

$$\Omega_M + \Omega_\Lambda = 1 - \Omega_k$$



The "equation of state"

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

To integrate this, you have to specify how ρ depends on a, or t .

$$d(\rho V) = -pdV = \rho dV + V d\rho$$

Definition of pressure

$$\dot{\rho} = -3H\rho(1+w)$$

w constant

Equation of state: $w \equiv \frac{p}{\rho}$

$$\rho = \rho_0 a^{-3(1+w)}$$

Simple solutions

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

Set k=0 (flat universe), Λ=0 (can be integrated into ρ)

ρ scales as $a^{-3(1+w)}$. w (assumed constant) is called "equation of state"

Radiation	Matter	Λ
w=1/3	w=0	w=-1
$\rho \propto a^{-4}$	$\rho \propto a^{-3}$	$\rho = C^{st}$
$a \propto t^{1/2}$	$a \propto t^{2/3}$	$a \propto \exp(t/\Lambda^{1/2})$

Differential equations for expansion

Friedman equation

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

Acceleration equation

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

"p" refers to the fluid whose density is ρ

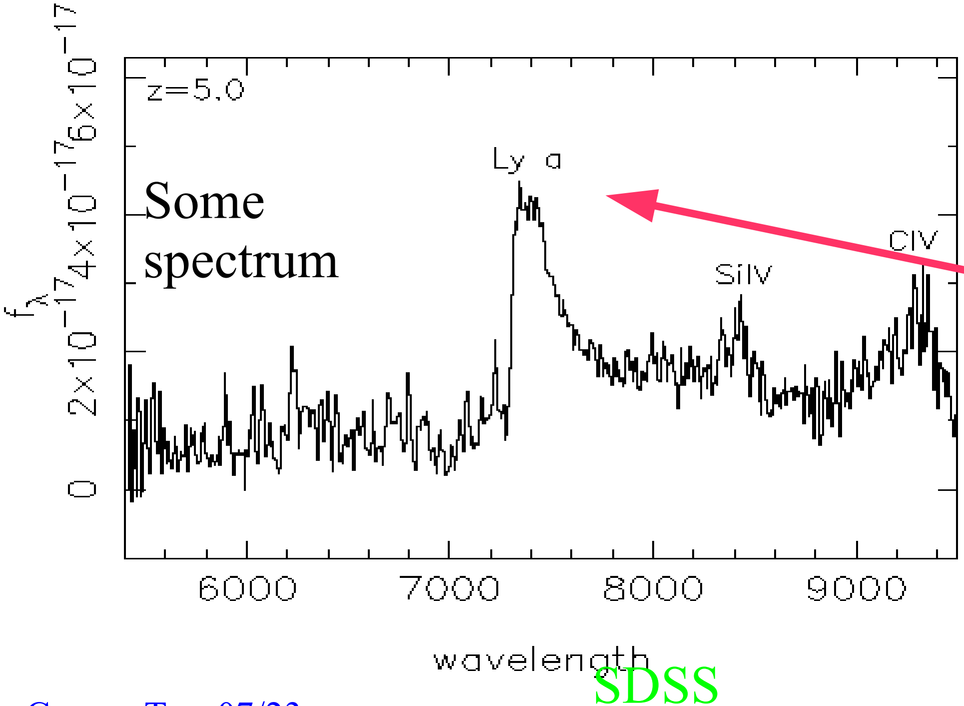
Energy conservation equation

$$\dot{\rho} = -3H(\rho + p)$$

Homework : show that these 3 equations are redundant

Redshift z

$$1 + z \equiv \frac{\lambda_{reception}}{\lambda_{emission}} = \frac{a(now)}{a(emission)}$$



Assumes that emitter and receiver are both comoving (i.e. "attached" to matter)

Redshift allows us to measure scale factors !

Ly α : 1216 Ang. In the lab

z = 7400/1216 - 1 =~ 5.0

Shift to the red:

- a(t) increases with t
- expansion !

From H(z) to content

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

Switch to z : one replaces t by z, the redshift of a source that emitted the light we observe at time t:

For an Ω_m Ω_Λ universe:

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2\right]$$

- One can then hope that the right-hand-side terms can be separated thanks to the different redshift (z) dependence.
- This requires a "sufficient" redshift lever arm

Framework

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(\sin^2\theta d\theta^2 + d\phi^2)\right)$$

We are at r=0. Physical distance to an object at coordinate r:

$$R(t_0 = now)r \equiv R_0 r$$

Compute r of a source at redshift z

Metric : $$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(\sin^2\theta d\theta^2 + d\phi^2)\right)$$

Eq. of motion for photons $ds = 0 \to dt = R(t)dr/\sqrt{1-kr^2}$

Expansion dynamics $$H(t) \equiv \frac{\dot{R}}{R} \quad \frac{R(t)}{R_0} = \frac{1}{1+z} \equiv a(t)$$

Switch to redshift $$\frac{dr}{\sqrt{1-kr^2}} = \frac{dt}{R(t)} = -\frac{dz}{R_0 H(z)}$$

Cosmological distances (2)

Switch to redshift

$$\frac{dr}{\sqrt{1-kr^2}} = \frac{dt}{R(t)} = -\frac{dz}{R_0 H(z)}$$

Comobile coordinate
Of an object observed at z

$$r(z) = Sin_k\left(\frac{1}{R_0 H_0}\int_0^z \frac{dz'}{H(z')/H_0}\right)$$

$$Sin_k(x) = \sin(x), x, \sinh(x) \quad \text{for } k = 1, 0, -1$$

$$\Omega_k = -\frac{k}{R_0^2 H_0^2} \qquad d_M \equiv R_0 r = \frac{H_0 R_0 r}{H_0} = \frac{r}{|\Omega_k|^{1/2} H_0}$$

$$H_0 d_M = \frac{1}{\sqrt{|\Omega_k|}} Sin_k\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{H(z')/H_0}\right)$$

Cosmological distances (summary)

$$Sin_k(x) = \sin(x), x, \sinh(x) \quad \text{for } k = -1, 0, 1$$

$$H_0 d_M = \frac{1}{\sqrt{|\Omega_k|}} Sin_k\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{H(z')/H_0}\right)$$

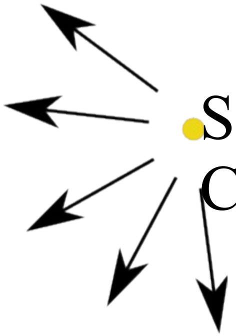
$$H(z)/H_0 = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$$

$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$

(assuming matter and cosmological constant only)

Luminosity distance : $d_L \equiv (1+z)d_M$

Luminosity distance



Source at comoving Coordinate r

$$Area = 4\pi(rR_0)^2$$

You are here

Proper energy luminosity

Observed energy flux

$$f = \frac{\mathcal{L}}{4\pi(1+z)(1+z)(rR_0)^2} = \frac{\mathcal{L}}{4\pi d_L^2}$$

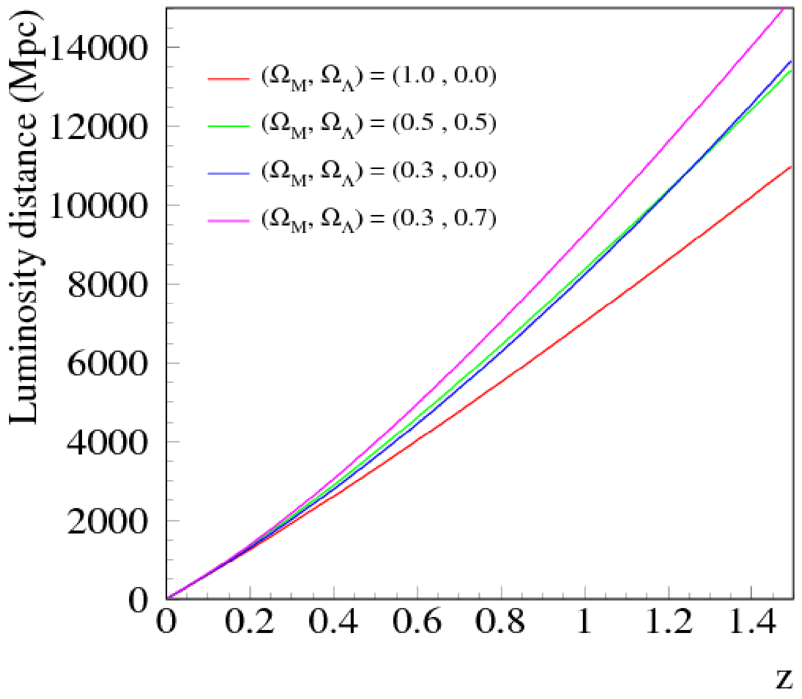
Time dilation

Radiation redshift

Definition of luminosity distance

The “physical” distance : $d_M \equiv rR_0 = d_L/(1+z)$

Evolution of d_L as a function of z



$$d_L \equiv (1+z) d_M$$

Evolution of distances with redshift is (indeed) sensitive to content

$$d_L = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} Sin\left(\sqrt{|\Omega_k|}\int_0^z [\Omega_M(1+z')^3 + \Omega_\Lambda + \Omega_k(1+z')^2]^{-\frac{1}{2}} dz'\right)$$

Testing the late-time energy content

- The distance-redshift relation is sensitive to the universe content.
- We hence need a way to observe and measure objects which are distance indicators.
- The difficult part is getting distances. Redshifts are “trivial” (with a big enough telescope), using spectroscopy.

Distances (summary 1)

Luminosity distance

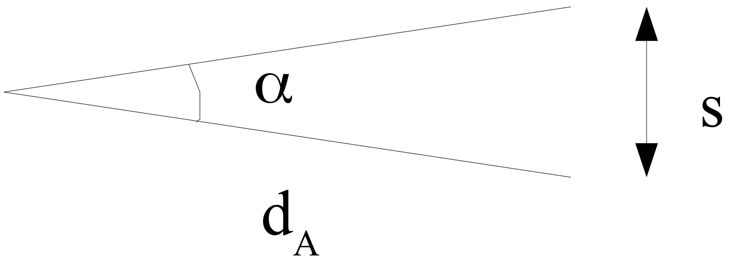
$$f \equiv \frac{\mathcal{L}}{d_{\rm L}^2}$$

Measured flux (observer) → f

Proper energy luminosity → $\mathcal{L}$

Angular distance

$$d_{\rm A} = (1+z)^2 d_{\rm L}$$



$$\alpha \equiv \frac{s}{d_{\rm A}}$$

s : proper size

Proper motion distance:

$$d_L \equiv (1+z) d_M$$

Distances (summary)

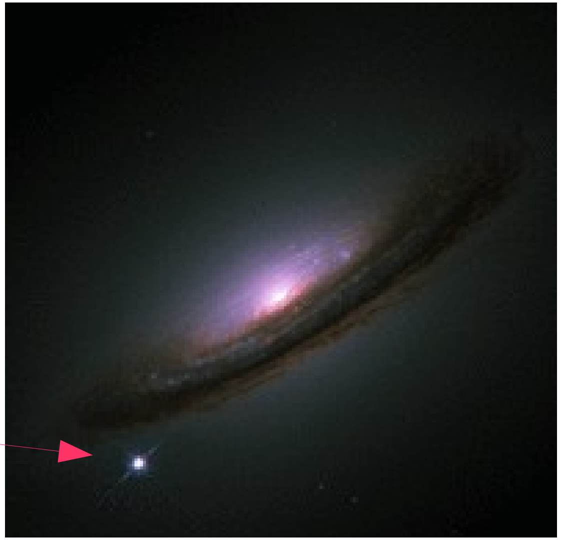
$$H_0 d_M = \frac{1}{\sqrt{|\Omega_k|}} Sin_k \left(\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')/H_0} \right)$$

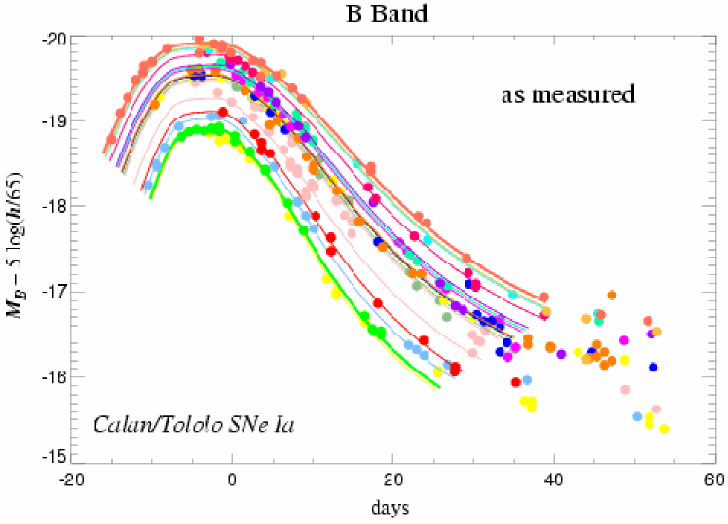
- The three distances differ by 1+z factors: they convey exactly the same cosmological constraints
- The constraints we get this way apply to $\int \frac{dz}{H(z)}$
- This is less direct than constraints on H
- One can get direct constraints on H(z) by measuring distances along the line of sight. BAO's allow that.

Type Ia supernovae

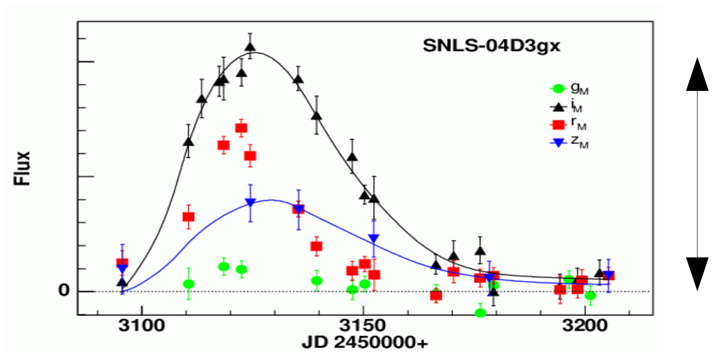
Thermonuclear explosions of stars which appear to be reproducible

- Very luminous
- Can be identified (spectroscopy)
- Transient (rise ~ 20 days)
- Scarce (~1 /galaxy/millennium)
- Fluctuations of the peak luminosity : 40 %
- With luminosity indicators :
  ~14 %

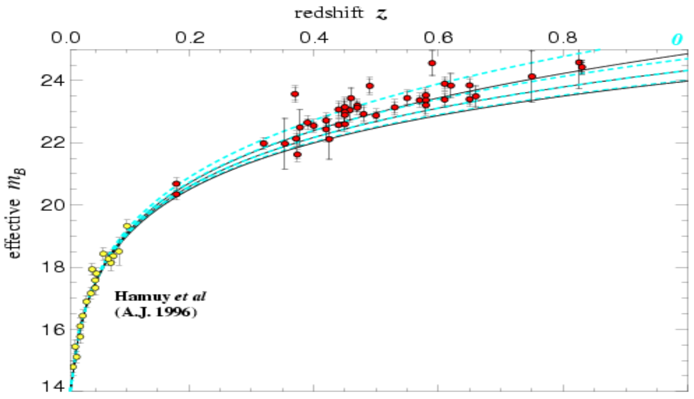




Hubble diagram : flux vs redshift

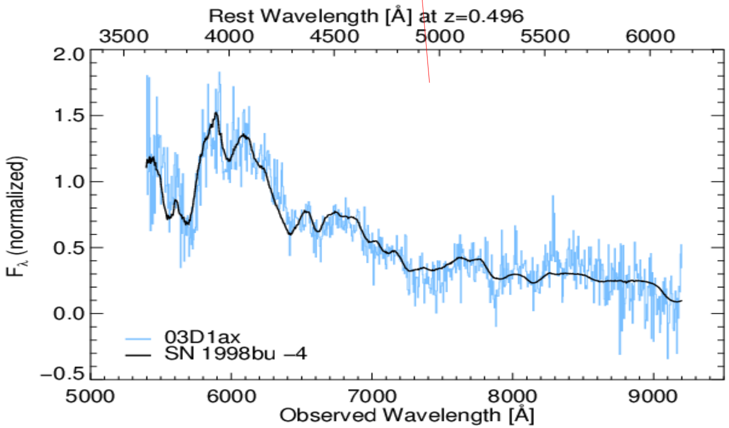


peak flux

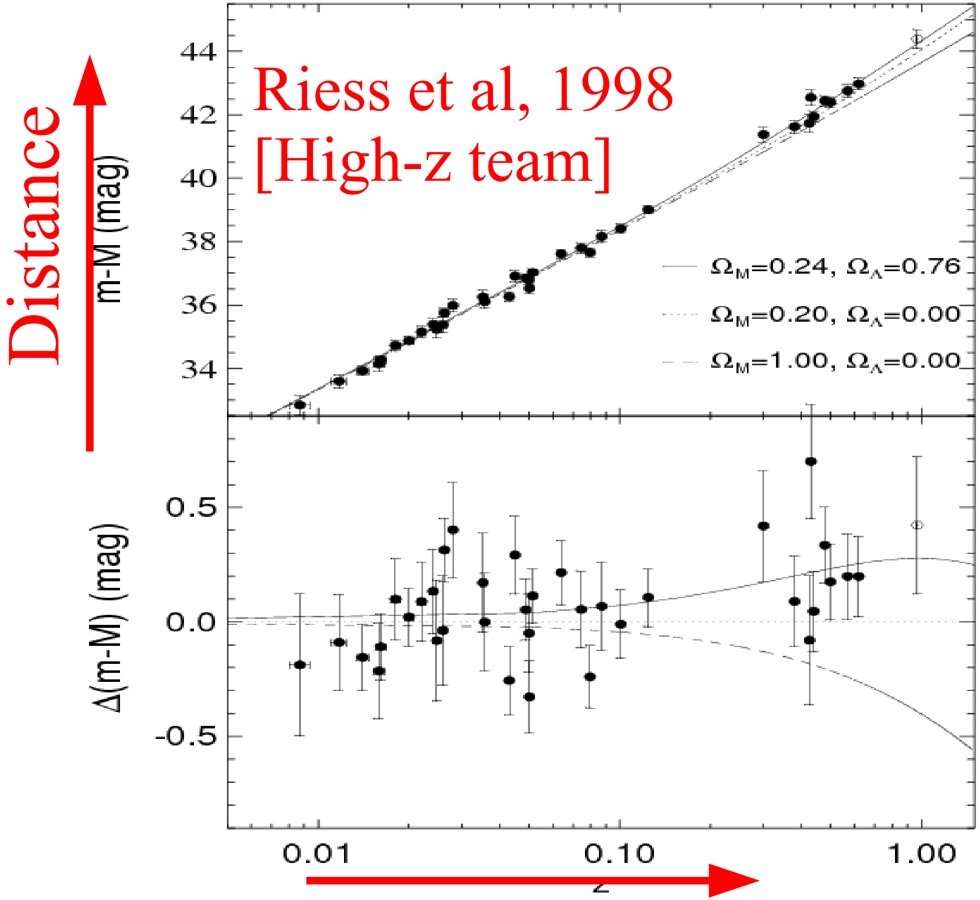


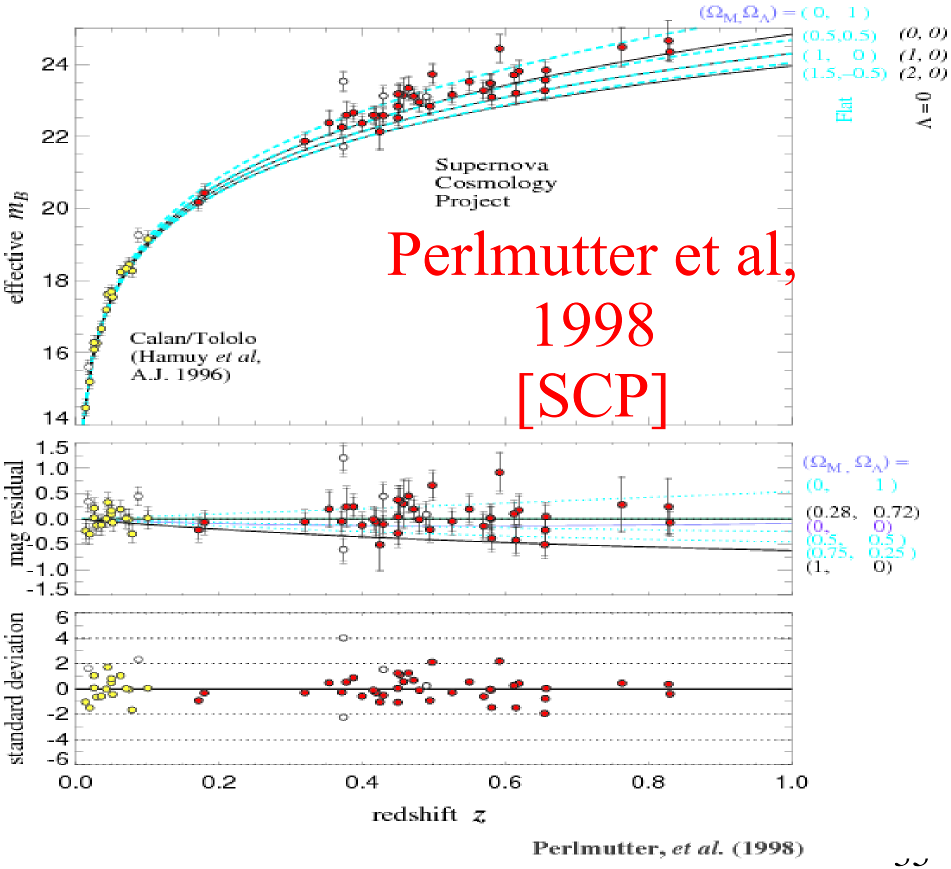
multi-band photometry
=> distance

spectroscopy:
- identification
- redshift

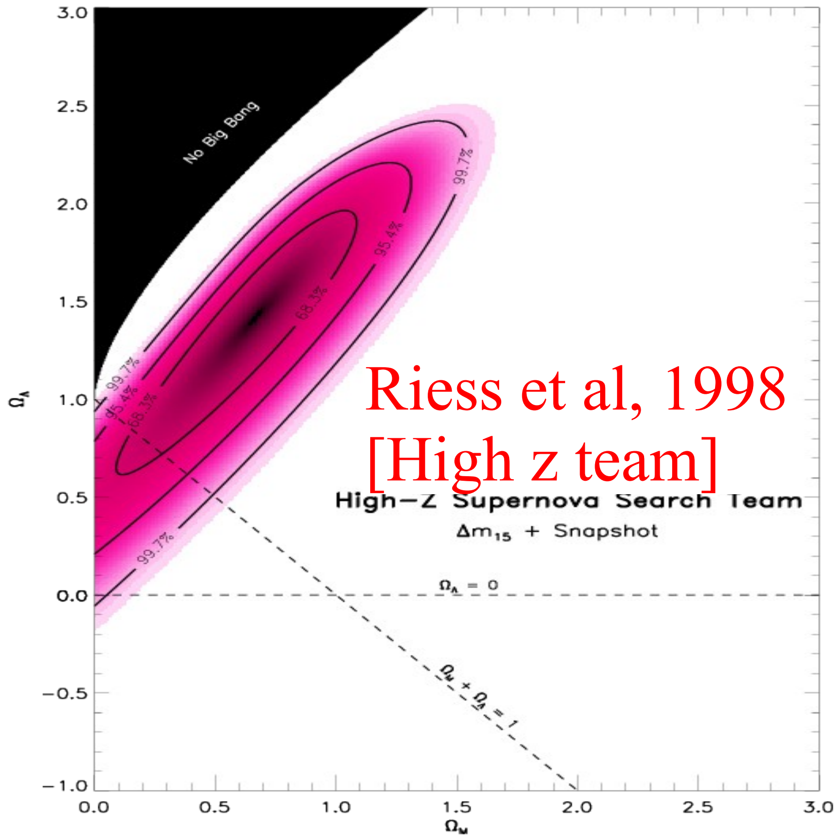


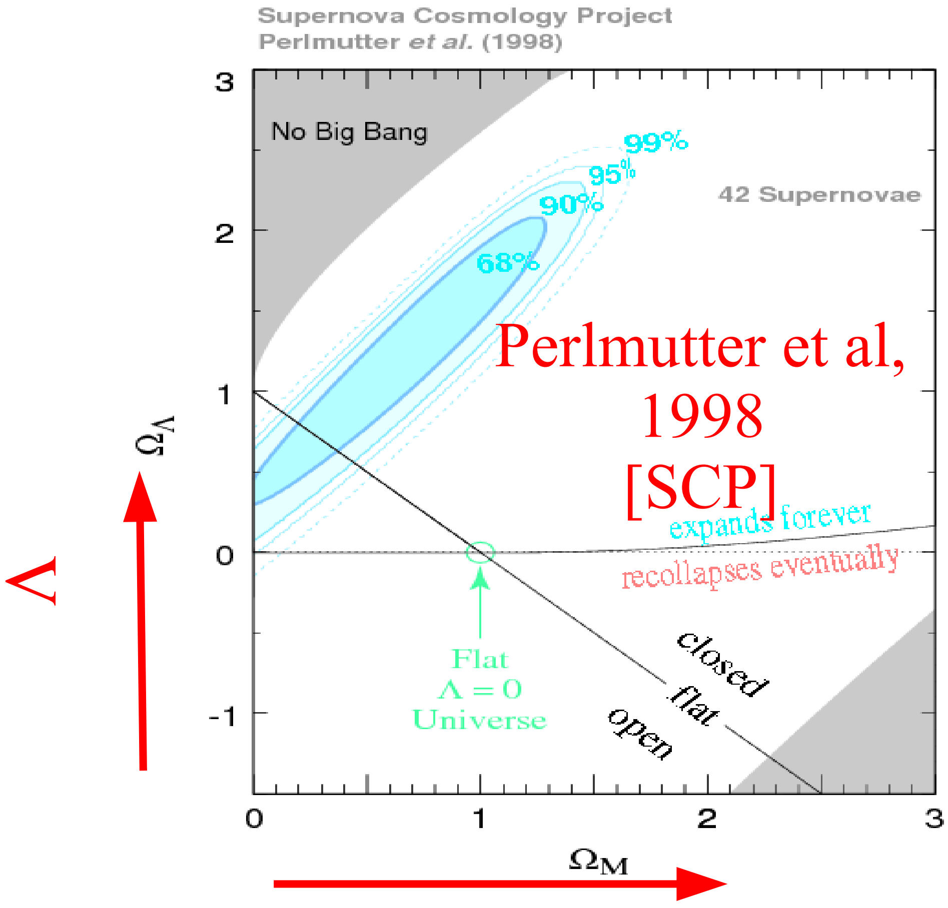
Fall 1998 : the twin papers





Fall 1998 : the twin papers





Matter

Cosmo-Tes 07/23

October 2011

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"*.

Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

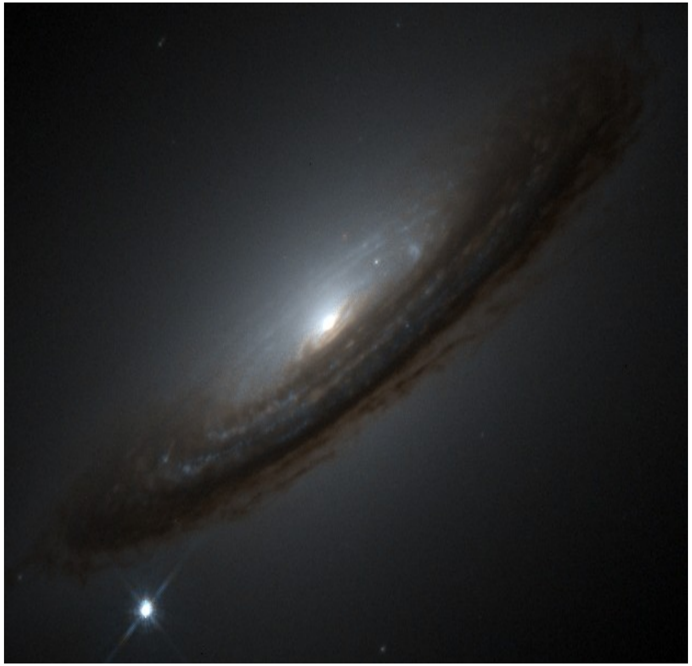
Adam G. Riess

Measuring supernovae : 3 steps

- Finding supernovae (rare events)
- Identifying them as SN Ia (spectroscopy)
- Measuring the light curves in 2 (spectral) bands or more.

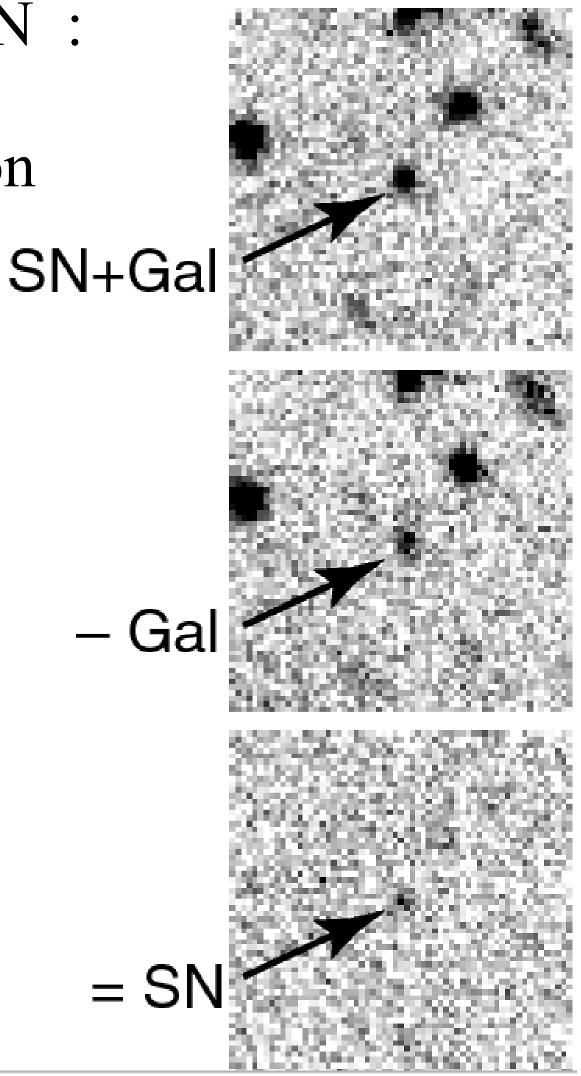
- (… go back to the telescope because you got bad weather....)

Finding supernovae



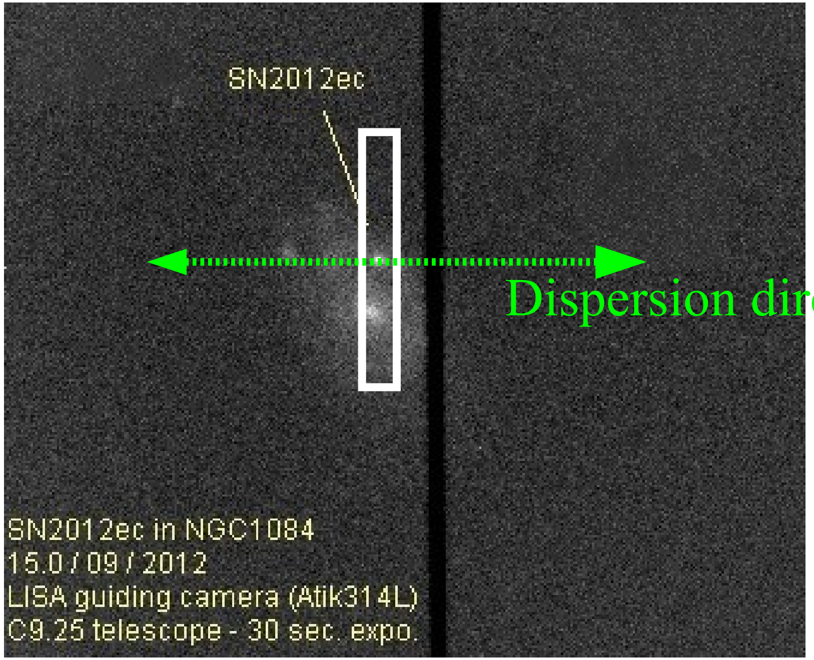
Nearby supernova

Distant SN : Image subtraction

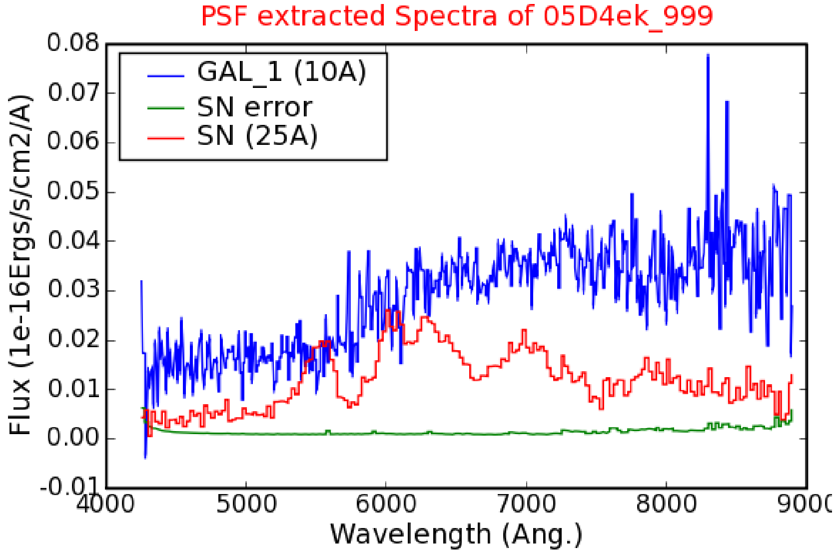


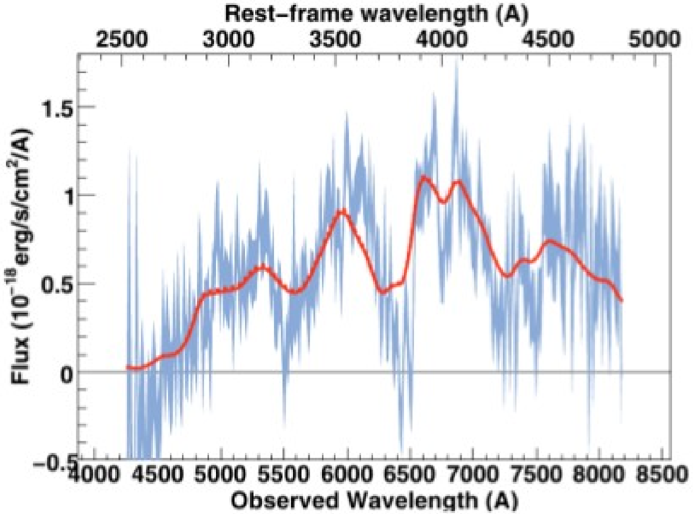
cfht/cfh12k (2000)

Spectroscopic Identification



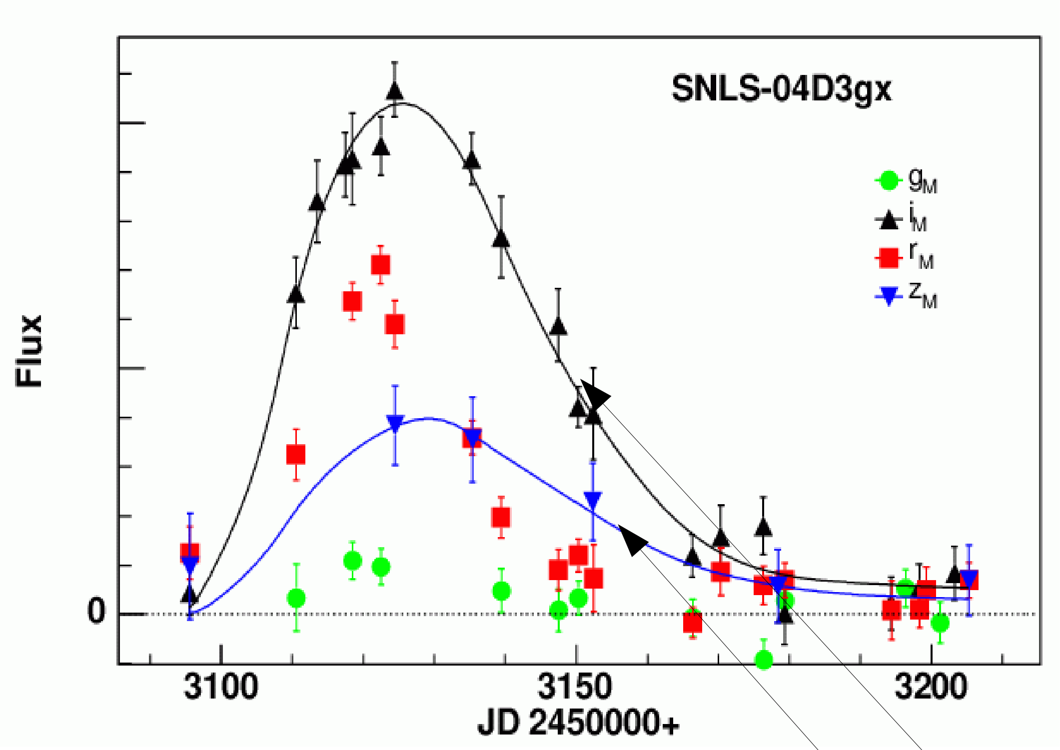
Dispersion direction





And one measures the redshift z, by the way

Measuring « light curves »



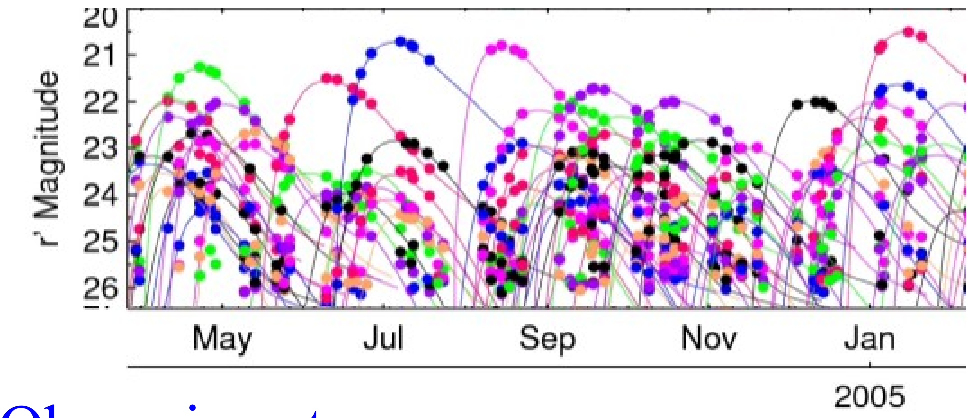
Measurement of the object flux as a function of time for about 2 (rest frame) months

One has to measure the « colour », i.e. measure light in at least two spectral bands

Fit of an empirical model which allows to summarise the data into a few parameters

Getting efficient: repeated imaging

Rolling searches on large CCD mosaics



Observing steps:

- Discovery in image subtraction
- Spectroscopic ID
- Measure light curves
- Get an image without the SN

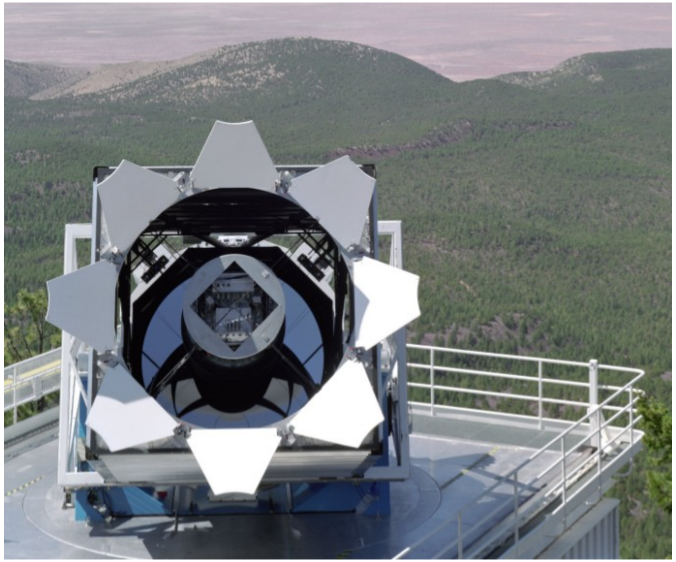
From the same images !

Implemented on 3 major surveys

… with "classical spectroscopy"

Major rolling searches by 2010

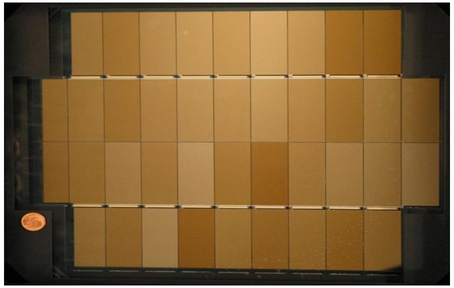
The SDSS SN Survey



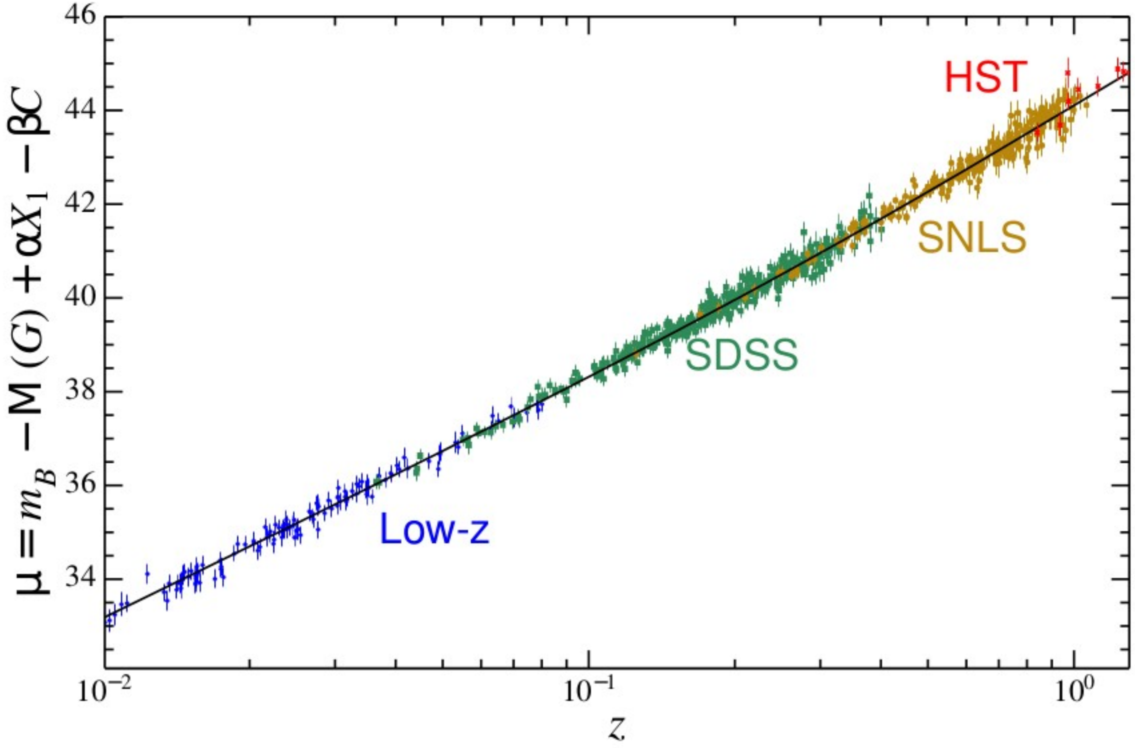
300 deg^2 x 3 years
0.1<z<0.45
~2000 SNe
~500 spectra

The SNLS survey @ CFHT

4 deg^2 x 5 years
0.3<z<1
~1000 SNe
~500 spectra



Supernova compilation (2014)

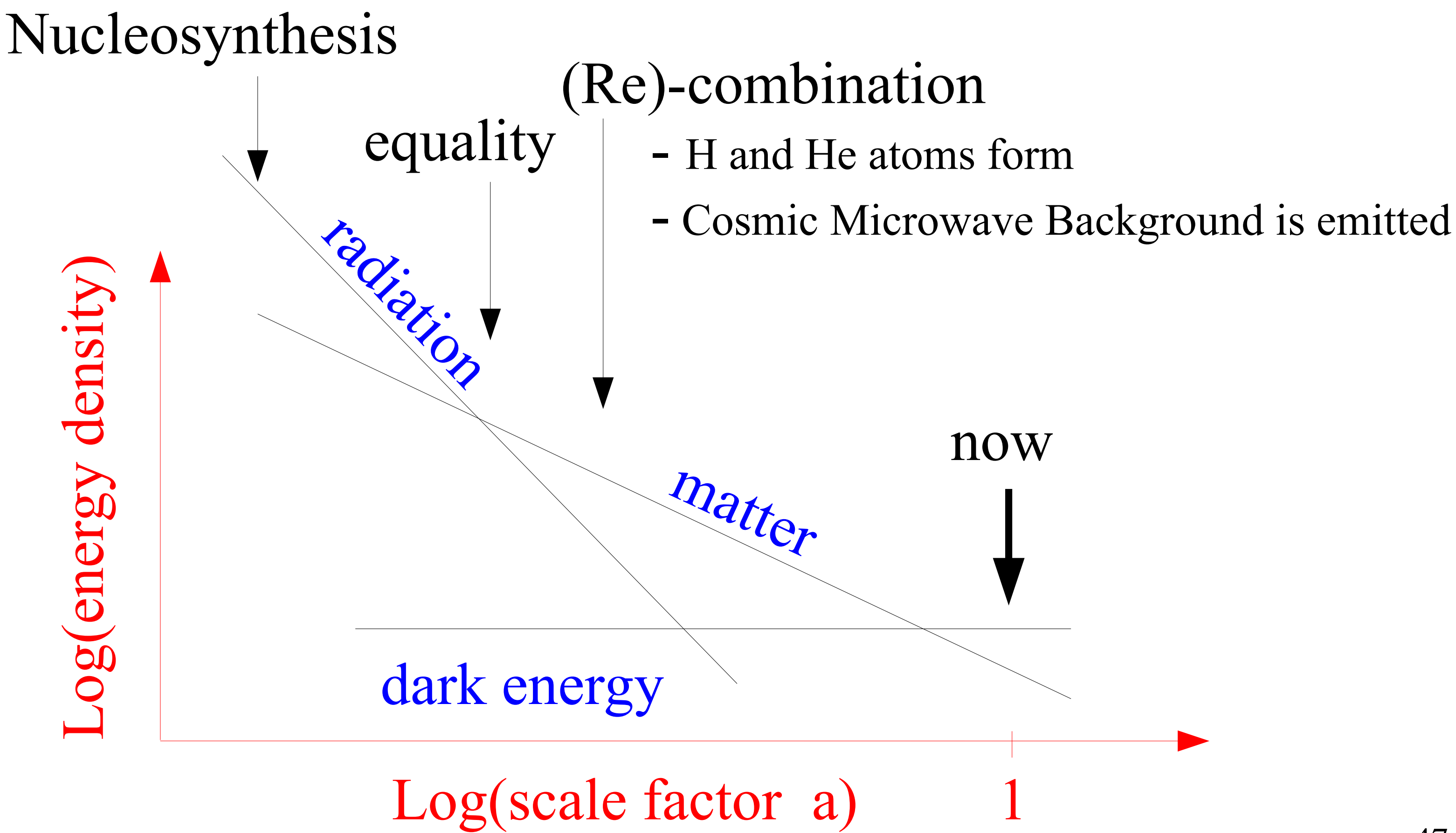


- 118 nearby SNe
- 366 SDSS
- 242 SNLS
- 14 HST

740 events in total

Betoule et al (2014)

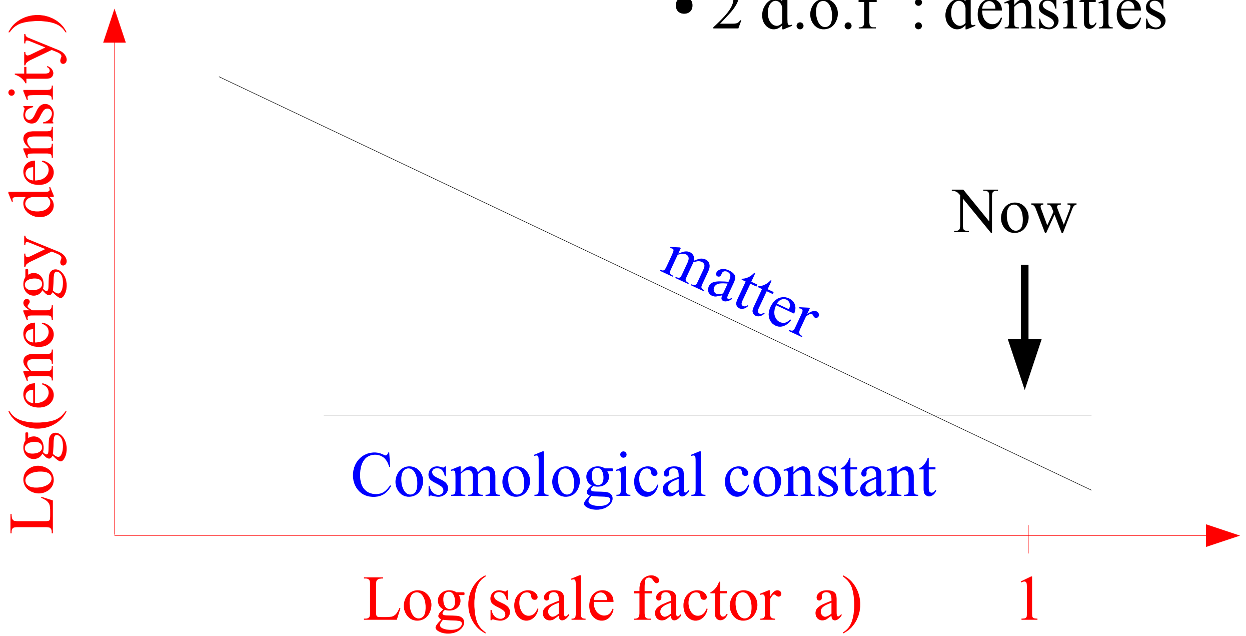
A sketch of the universe history



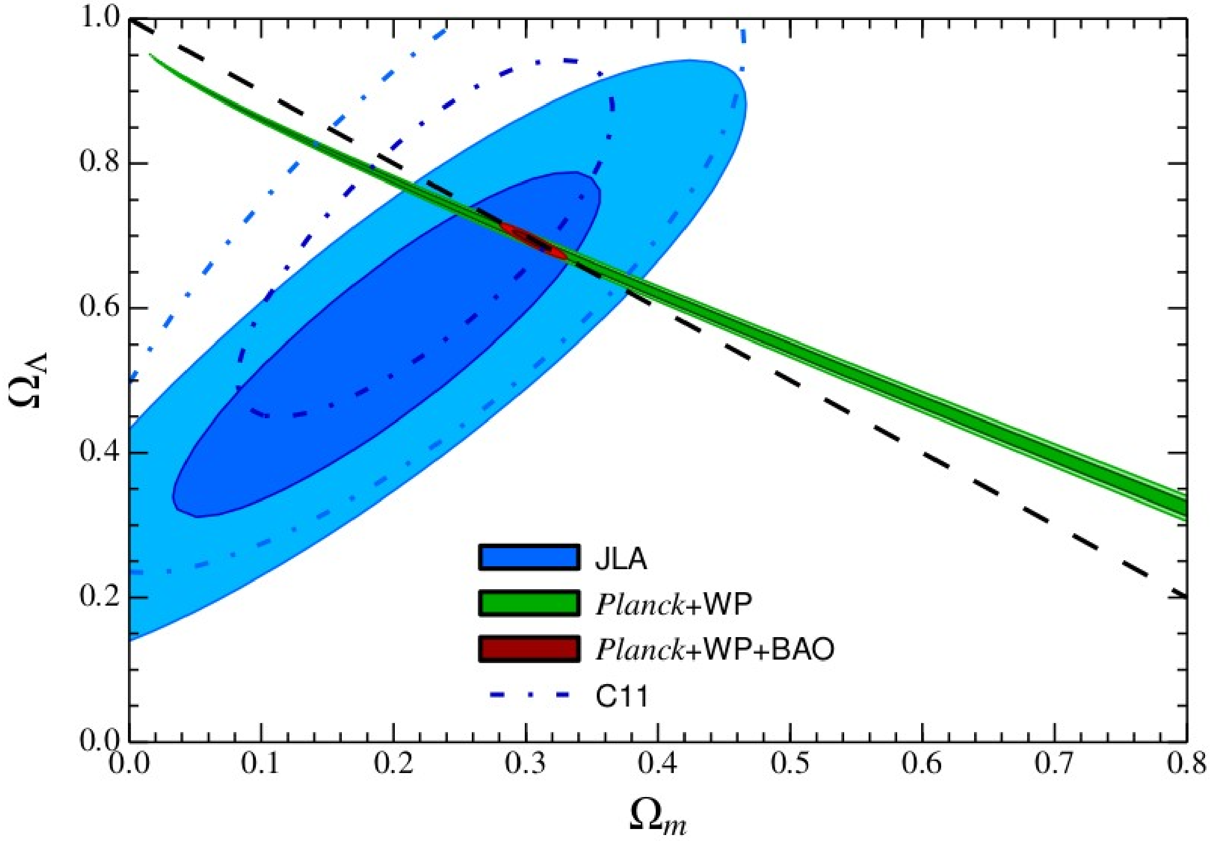
ΛCDM

A late-time simplification:

- 2 fluids
- Radiation is negligible
- 2 d.o.f : densities



Matter + cosmological constant : “ΛCDM”

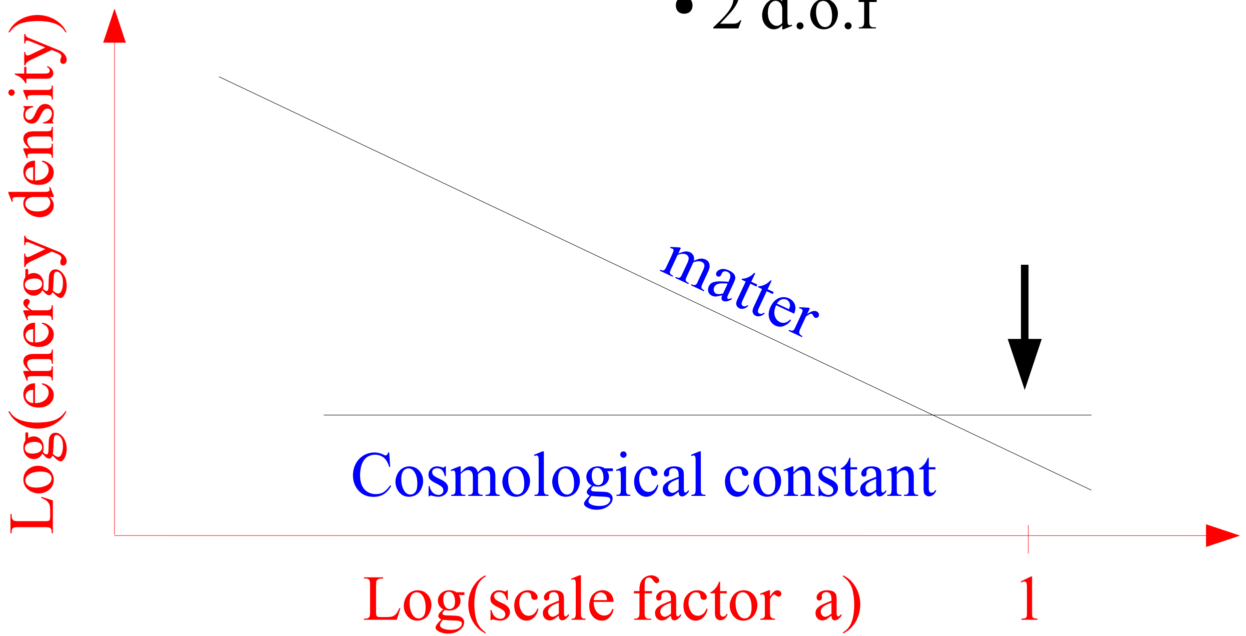


There is a positive cosmological constant

Compatible with a flat universe

ΛCDM

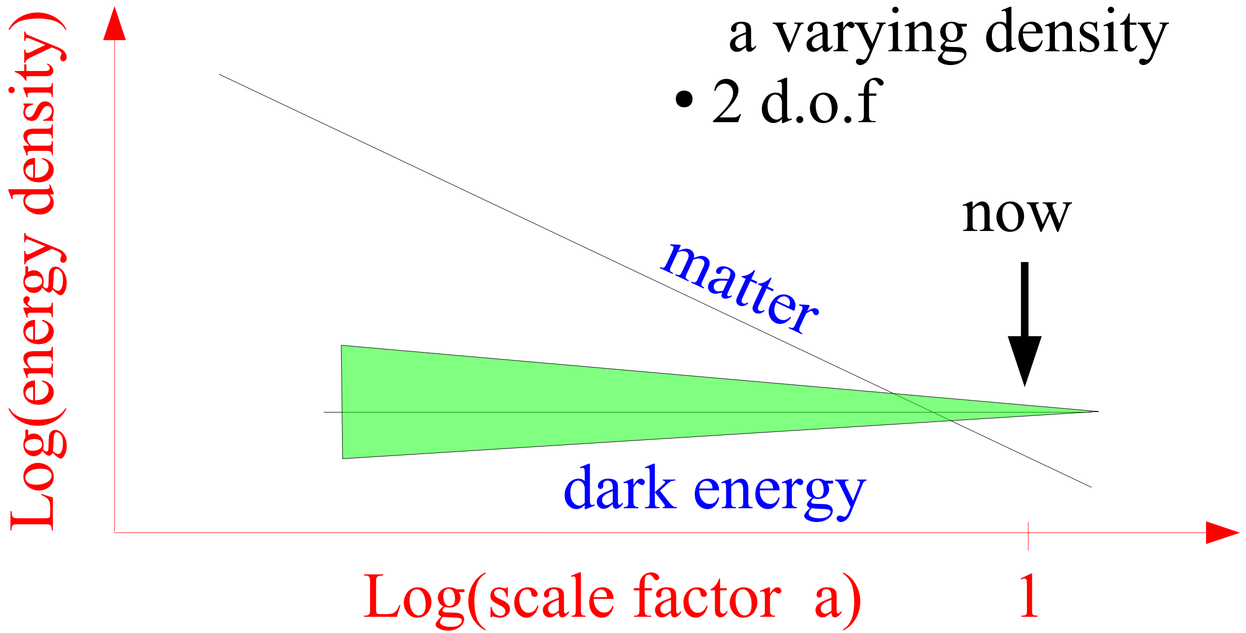
A late-time simplification:
- 2 fluids
- Radiation is negligible
- 2 d.o.f



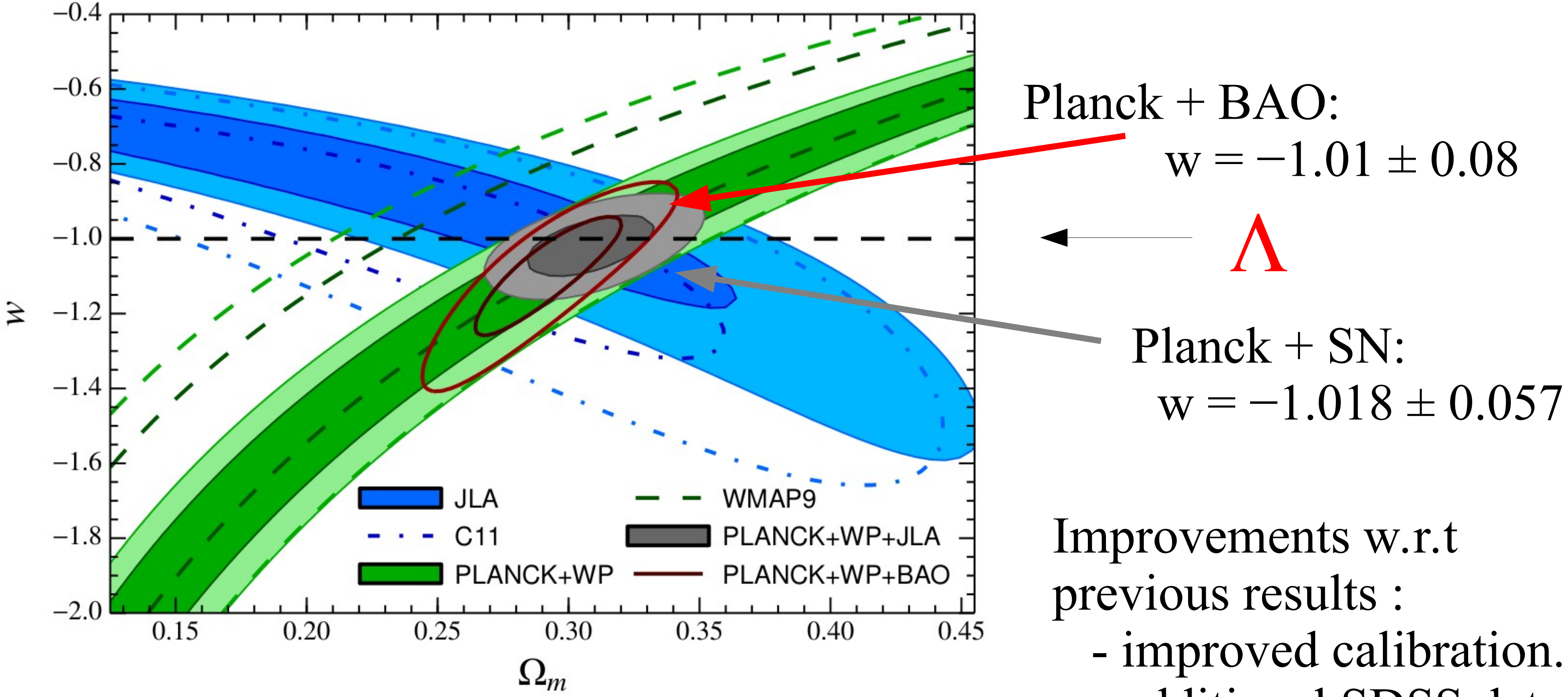
Flat wCDM

A late-time simplification:

- 2 fluids
- Flat universe
- Allow dark energy to have a varying density
- 2 d.o.f



Allow for a fluid with variable density :Flat wCDM



Improvements w.r.t previous results :
- improved calibration.
- additional SDSS data
- direct cross-calibration

Betoule et al (2014)

Current conclusions from observations

- Distant supernovae appear fainter than expected in a matter-dominated universe.

- Interpreted in a (Ω_m Ω_Λ) universe, this implies that the expansion is currently accelerated

Cosmological constant, acceleration and distances

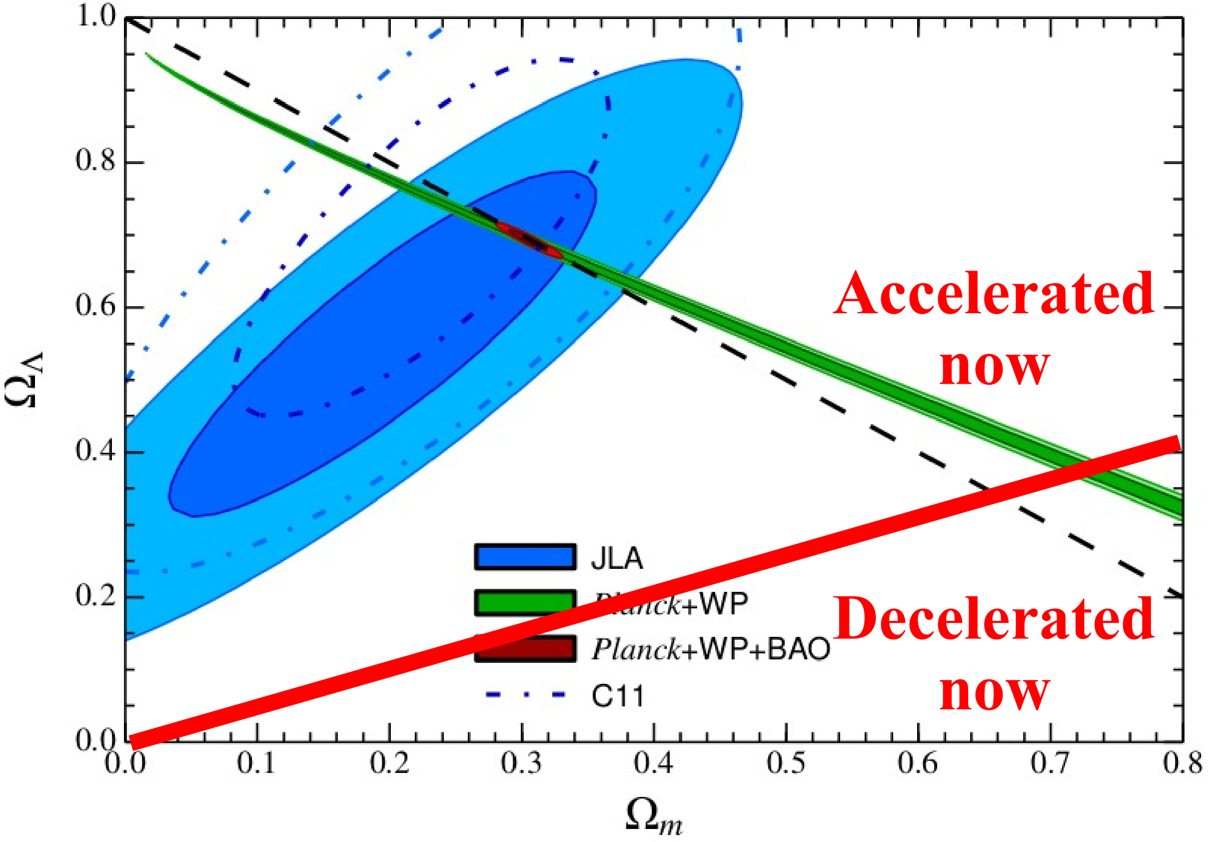
The core observation is that distance supernovae are fainter than expected with matter only . How to enlarge distances ?

Matter and CC, flat universe

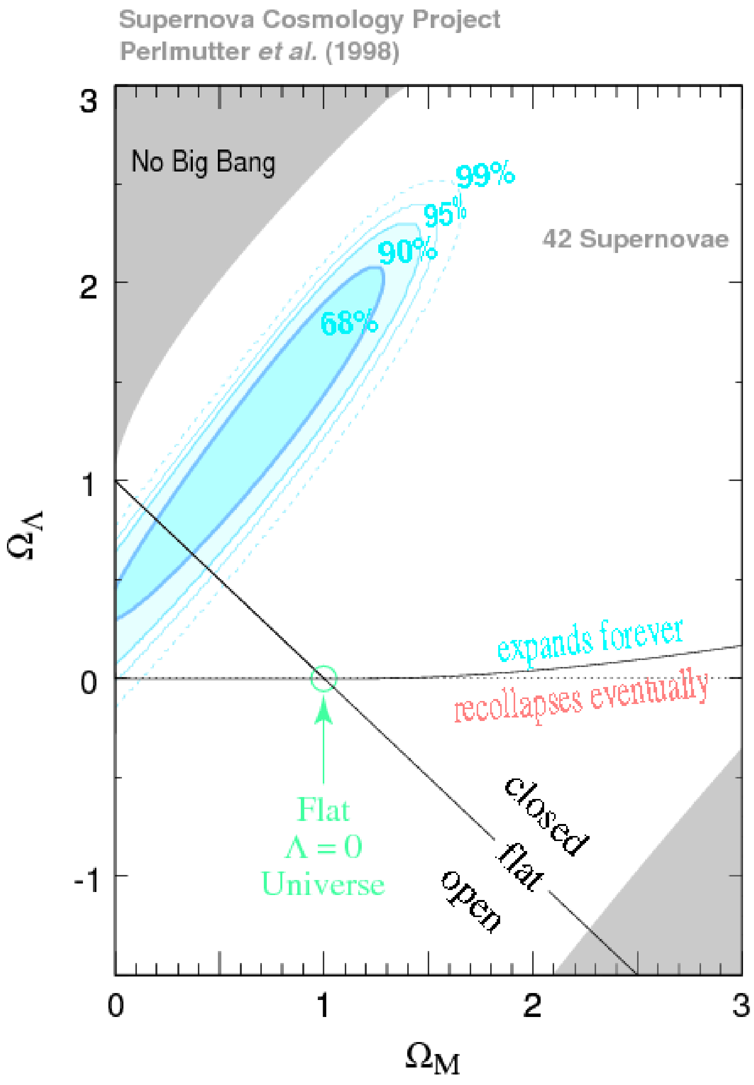
$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z)^3 + (1-\Omega_M)}}$$

The smaller Ω_M, the larger the distance !

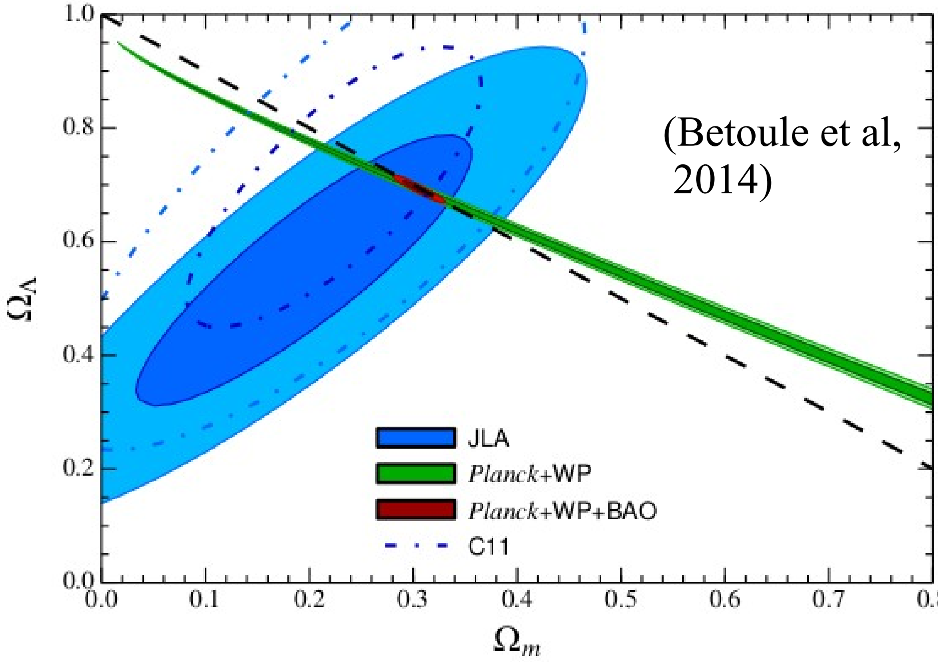
Why acceleration ? With a constant density, the expansion is exponential and hence accelerates. With a density decaying slowly, acceleration still happens.

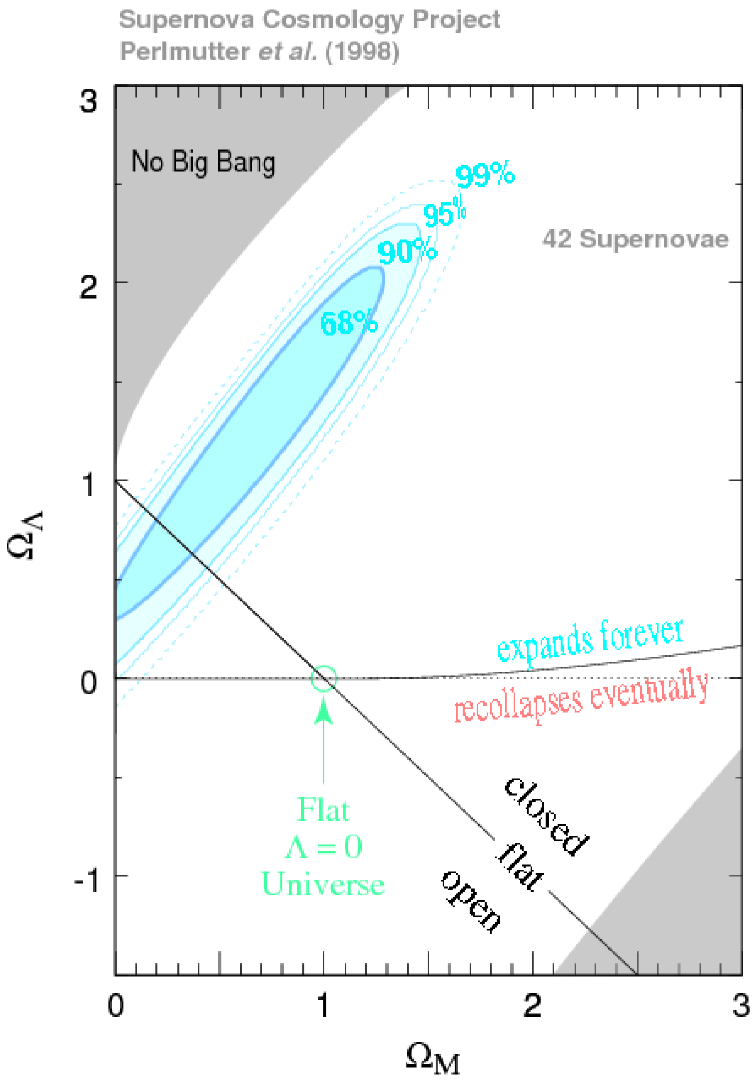


1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Ω_Λ
Ω_m
JLA
Planck+WP+BAO
C11
Accelerated now
Decelerated now

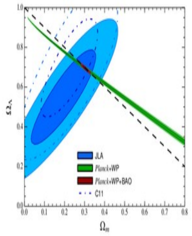


From the discovery of acceleration to 2014



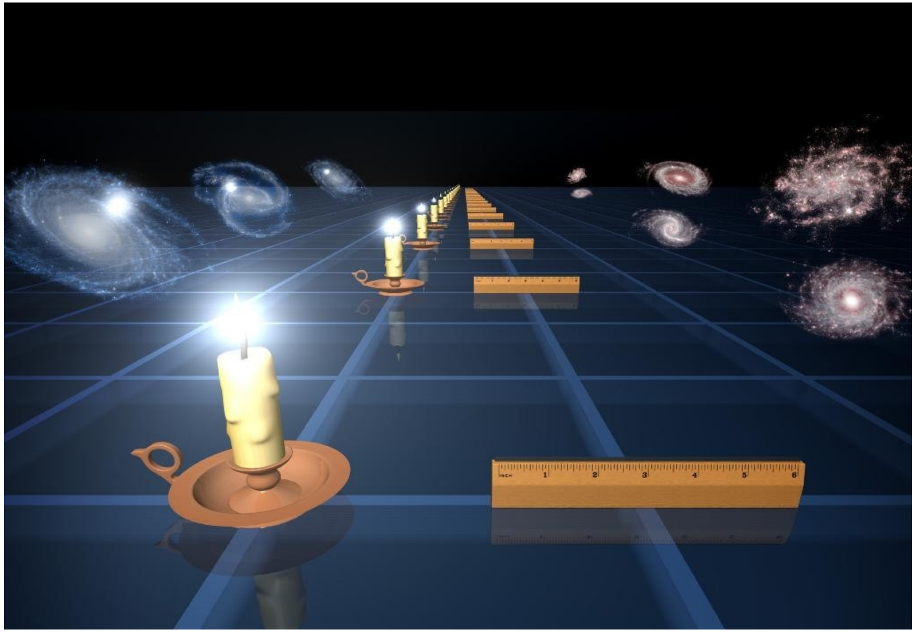


From the discovery of acceleration to 2014



(Betoule et al, 2014)

Yet another kind of Hubble diagram



Standard candles:
- reproducible
- redshift-independent
- luminosity
- Type Ia supernovae

They convey the same Cosmological information (except for one detail ...)

Standard rulers:
- Reproducible size
- (proper or comobile)

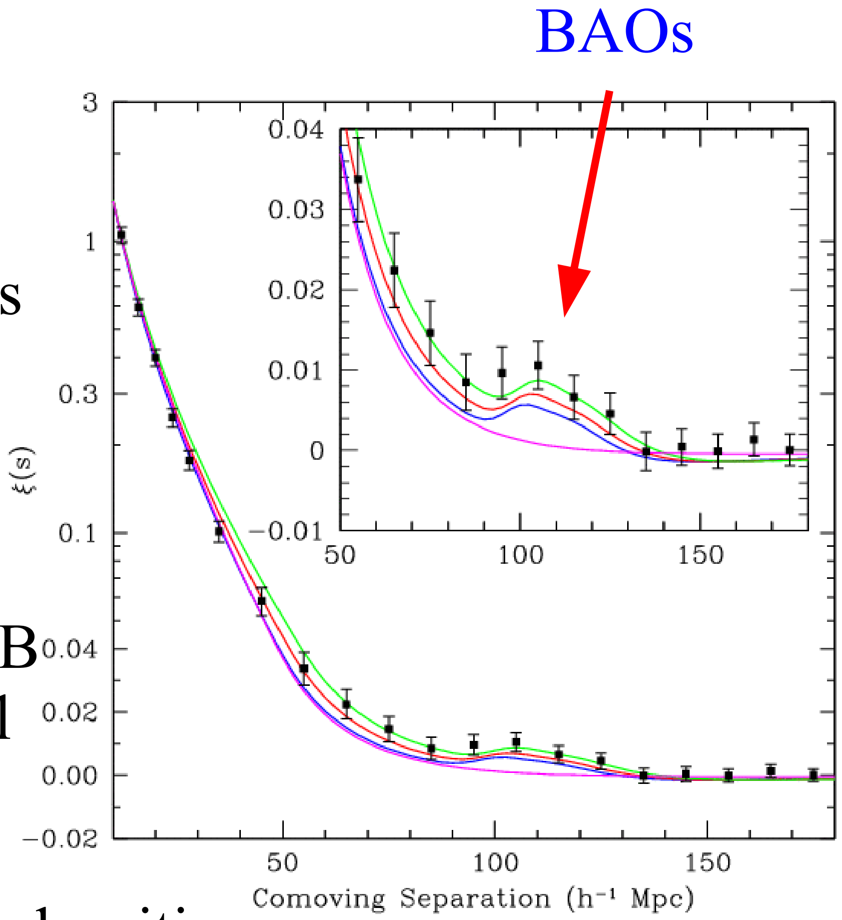
A standard ruler

(D.Eisenstein et al [SDSS Collab.] 2005)

Correlation function of galaxies
- histogram of (3-d) distances of galaxies

The peak is due to
Baryon Acoustic Oscillations (BAO)

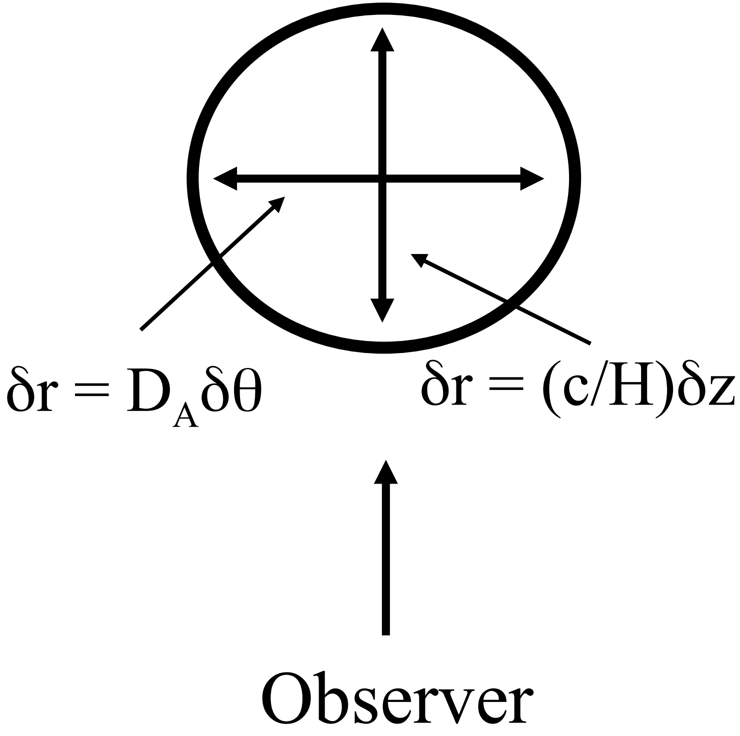
It reflects the correlations seen on the CMB that were imprinted on the baryons as well when CMB was emitted.



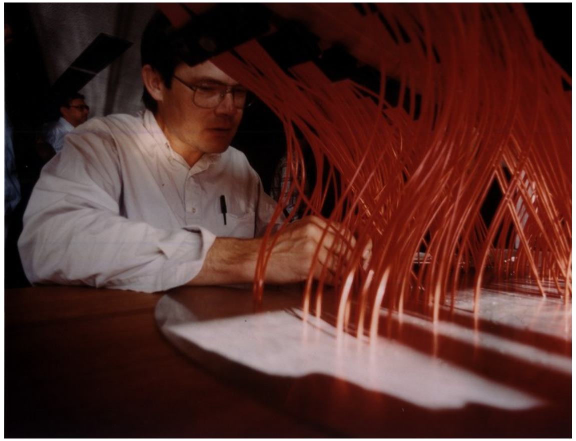
Galaxies have grown preferentially in overdensities

A standard ruler

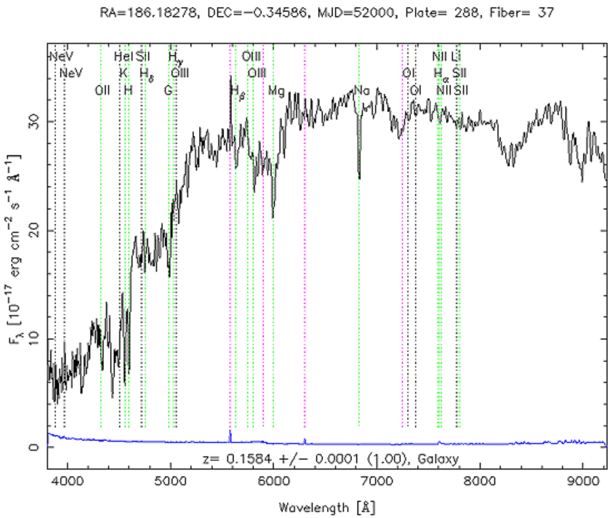
- Can be probed along and across the line of sight
- Hence probes both a distance and H(z)
  - Supernovae only probe a distance
- Requires 3-d coordinates : means measuring redshifts of very large numbers of galaxies.
- Requires multiplexed spectrographs (~hundreds to thousands of galaxies simultaneously)



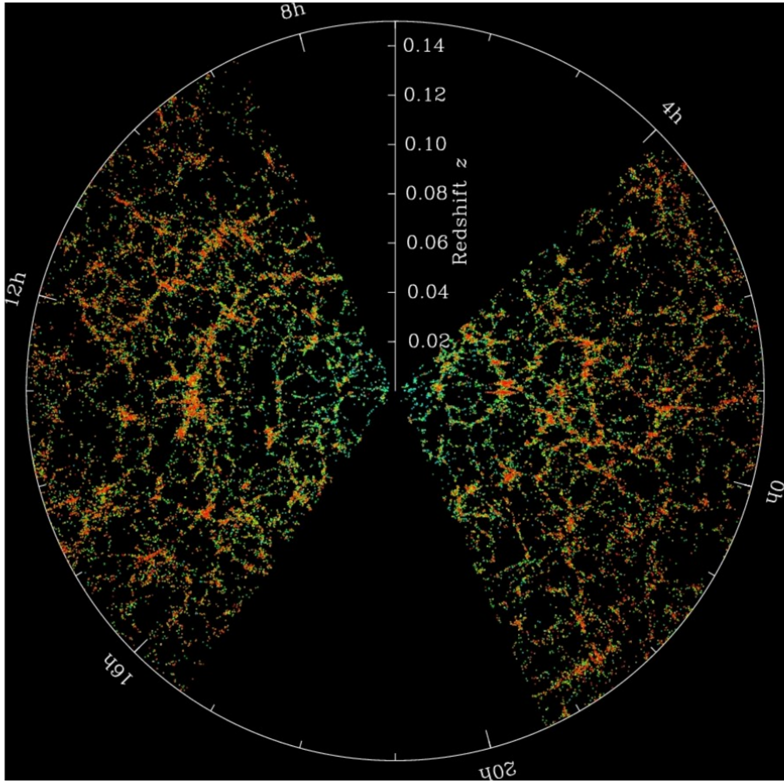
Sloan Digitized Sky Survey (SDSS), lasted from 2000 to 2020.



Plugging fibers in a drilled aluminium plate



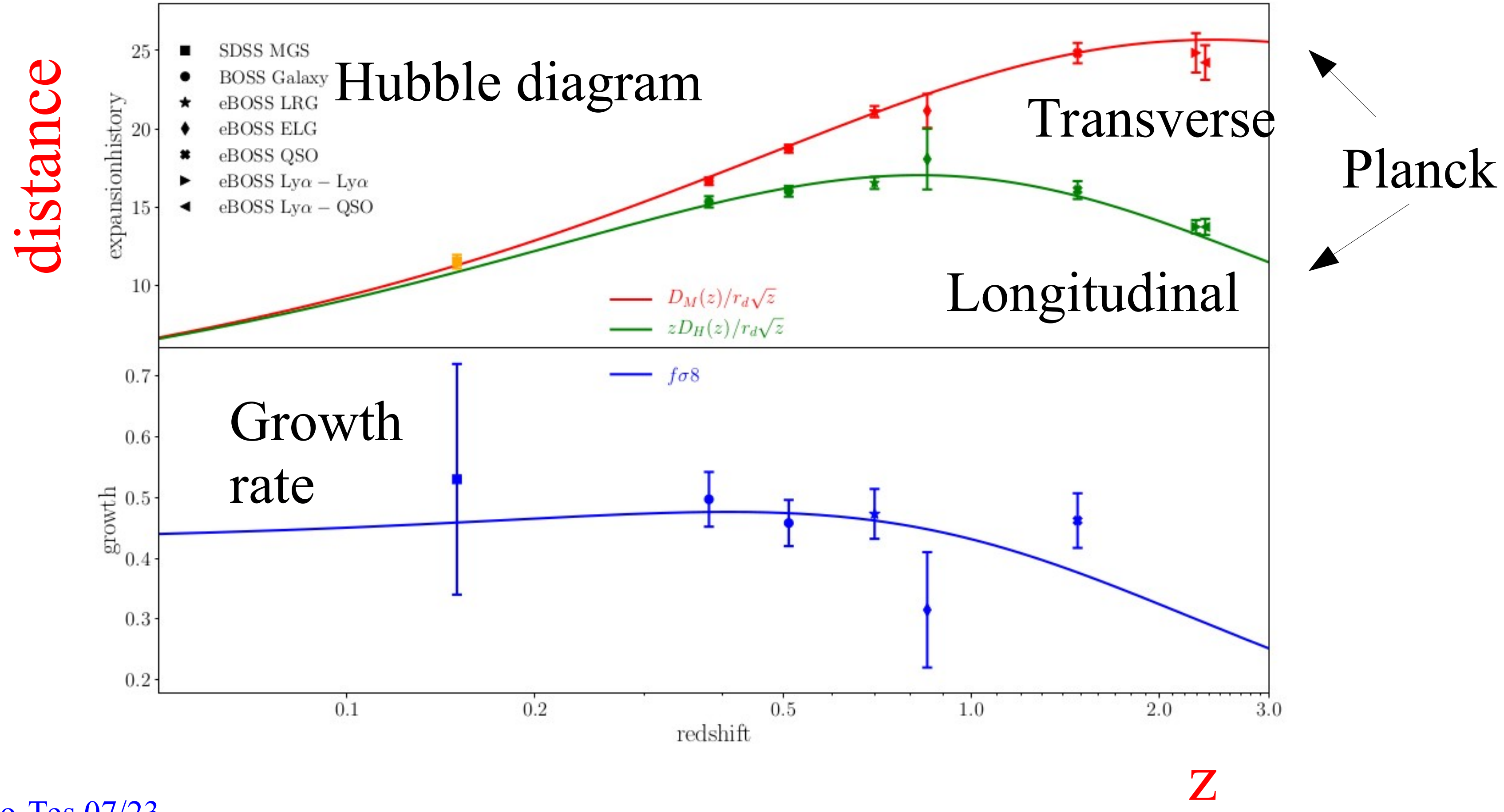
A spectrum

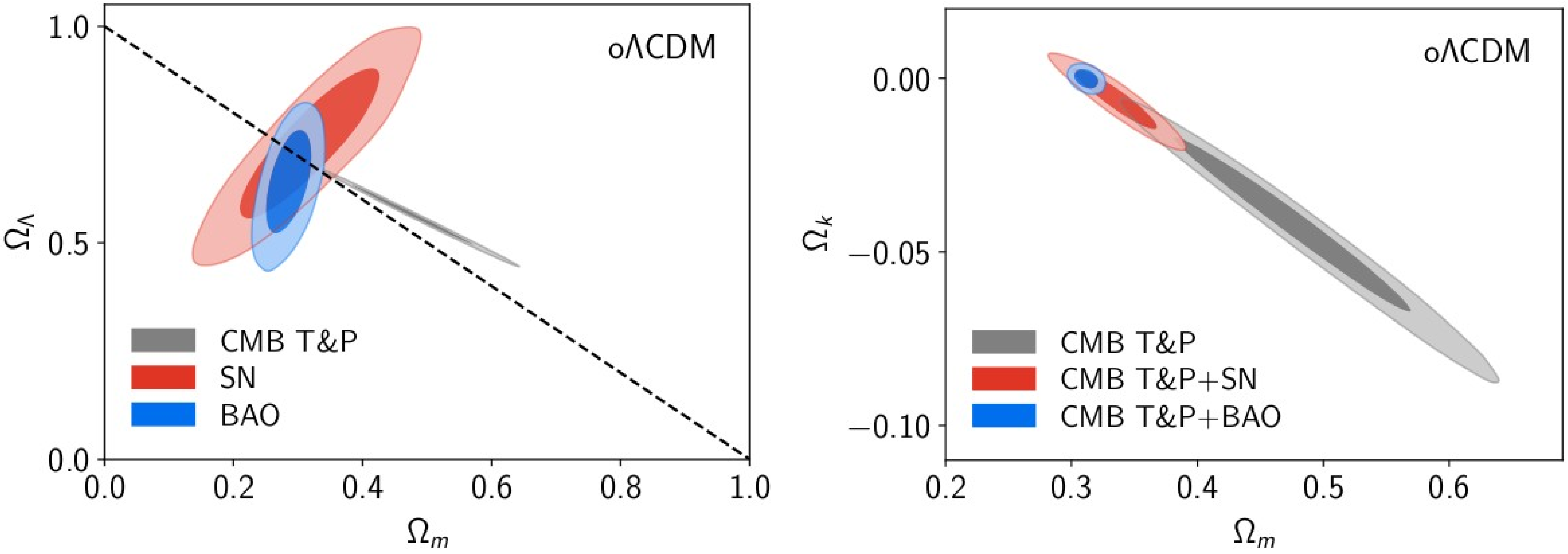


A slice of the nearby universe

2007.08991

BAO Hubble diagram





BAO describe the same expansion history as supernovae

Vacuum energy, cosmological constant, dark energy, negative pressure ?

Vacuum is invariant under a Lorentz transform :

Its energy-momentum tensor is proportional to the metric $T_{\mu\nu} \propto g_{\mu\nu}$

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

Vacuum is what is left when you have removed all particles:

- zero point of quantum mechanics oscillators
- minimum of the Higgs potential

THE problem of the cosmological constant (S. Weinberg, 1987)

- It has been noticed for decades that zero point of particle physics is way larger than anything cosmological.
- With naive expectations from particle physics, you could measure the universe curvature on table-top experiments.
- One often says that the cosmological constant is 120 orders of magnitude too small
- One possibility was that some unknown symmetry sets it to zero
  - SuperSymmetry does that (if exact…, which it is certainly not).
- In this respect, the discovery of accelerated expansion makes things worse, because you would need some (extremely) fine tuning.

So what ?

- We may be missing something fundamental about the source terms of gravitation, when quantum mechanics is involved.
- Inflation is an accelerated phase of expansion, driven by a scalar field, can we propose a similar scheme ?
- Yes, and this is called “quintessence” and many variants
- And usually relies on classical arguments

Quintessence: one more hypothetical scalar field (1)

$$\mathcal{L} = \Box\phi - V(\phi) \longrightarrow \ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

(KG)

Homogeneity: no spatial derivatives

$$\rho = \dot{\phi}^2/2 + V(\phi)$$

$$p = \dot{\phi}^2/2 - V(\phi)$$

As for inflation, if the field is quasi-static, the density is almost constant, and the pressure is negative

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

A moderate negative pressure can drive the second derivative positive

Quintessence: one more hypothetical scalar field (2)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

- The model is not very predictive: you can derive the potential that produces any plausible H(z)
- There are (as usual….) just no natural candidates from particle physics
  - This is related to the "problem of the cosmological constant": the energy density necessary to cause the observed acceleration is way smaller than anything particle physics can naturally propose.
- Anyhow, if something like quintessence drives acceleration, it is unlikely that its density is exactly constant with time, at variance with the cosmological constant.

Interpreting dark energy (or accelerated expansion)

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

THE cosmological constant (with its problem)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + T'_{\mu\nu} \right)$$

with $T'_{\mu\nu} \simeq C^{ste} g_{\mu\nu}$

Quintessence, ...

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \neq 8\pi G \, T_{\mu\nu}$$

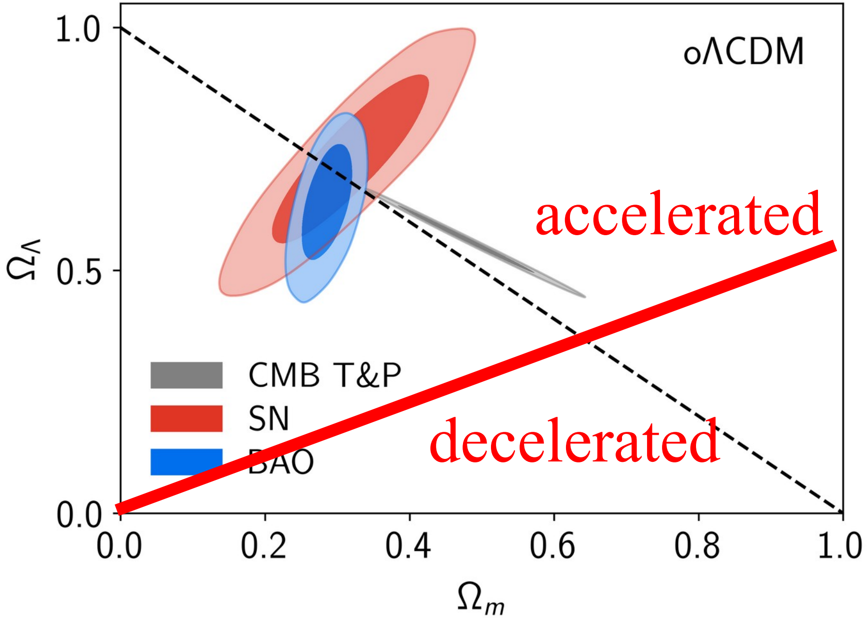
Einstein was wrong (but only on large scales)

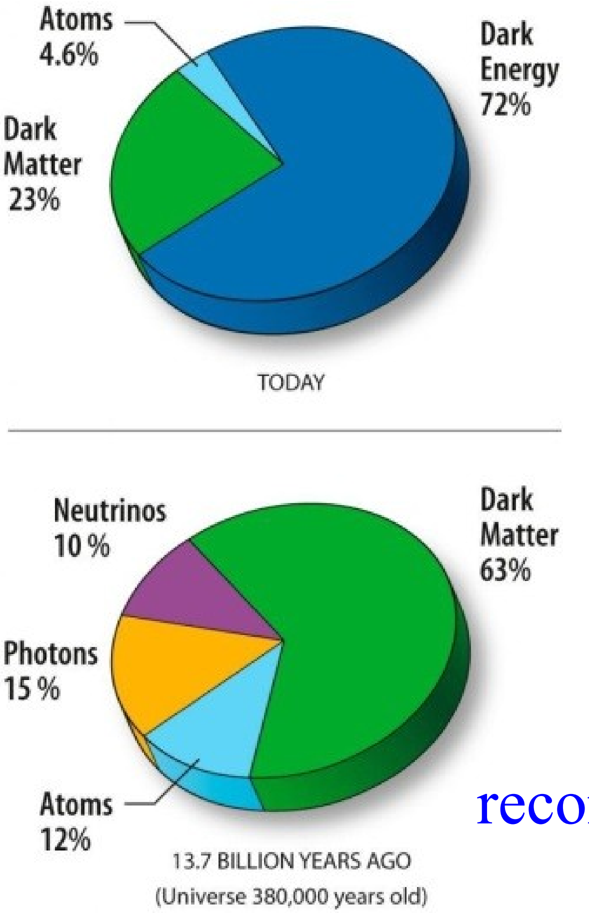
What comes next ?

- Separating Λ from quintessence or other variants goes through the measurements of the equation of state.
- Questioning General Relativity on large scales requires to test the GR predictions of the growth of structures, once the expansion history is measured.
- There are many large-scale projects that aim to carry out both:
  - Euclid : an European Space Agency mission (launched on July 1st)
  - LSST/Rubin: a ground-based large imaging telescope (2024)
  - DESI : a ground-based multi-object spectrograph collecting data since ~ two years.

Summary

Hubble diagrams:





Today

At recombination