Friedmann with $\Lambda \neq 0$, I

$\Longrightarrow$ Need to study cosmology with $\Lambda \neq 0$.

Reviews: Carroll, Press & Turner (1992), Carroll (2001)

Friedmann equation with $\Lambda \neq 0$:

$$H^2(t) = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3} \tag{7.30}$$

And define the Ω's (Eqs. 4.58, 7.14):

$$\Omega_{\rm m} = \frac{8\pi G\rho_{\rm m}}{3H_0^2}, \qquad \Omega_\Lambda = \frac{\Lambda c^4}{3H_0^2}, \qquad \Omega_k = -\frac{kc^2}{R_0^2 H_0^2} \tag{8.50}$$

Because of Eq. (7.30),

$$\Omega_{\rm m} + \Omega_\Lambda + \Omega_k = \Omega + \Omega_k = 1 \tag{8.51}$$

Friedmann with $\Lambda \neq 0$, II

It is easier to set $c = 1$ and to work with the dimensionless scale factor,

$$a = \frac{R(t)}{R_0} \tag{4.29}$$

$\Longrightarrow$ Friedmann:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\frac{\rho_{\rm m,0}}{a^3} - \frac{k}{a^2 R_0^2} + \frac{\Lambda}{3} \tag{8.52}$$

since $\rho_{\rm m} = \rho_{\rm m,0} a^{-3}$ (Eq. 4.63).

Inserting the Ω's

$$\left(\frac{\dot{a}/H_0}{a}\right)^2 = \frac{\Omega_{\rm m}}{a^3} + \frac{1 - \Omega_{\rm m} - \Omega_\Lambda}{a^2} + \Omega_\Lambda \tag{8.53}$$

Substituting the time in units of todays Hubble time,

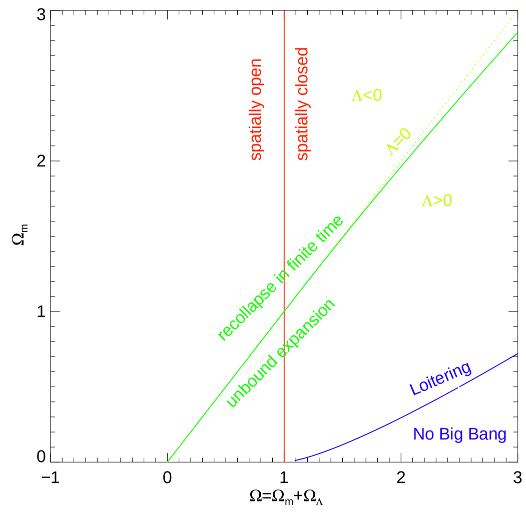
$$\tau = H_0 \cdot t \tag{8.54}$$

results in

$$\left(\frac{\mathrm{d}a}{\mathrm{d}\tau}\right)^2 = 1 + \Omega_{\rm m}\left(\frac{1}{a} - 1\right) + \Omega_\Lambda(a^2 - 1) \quad \text{where} \quad a(\tau = 1) = 1 \quad \text{and} \quad \left.\frac{\mathrm{d}a}{\mathrm{d}\tau}\right|_{\tau=1} = 1 \tag{8.55}$$

For most combinations of $\Omega_{\rm m}$ and Ω_Λ, need to solve numerically.

Friedmann with $\Lambda \neq 0$, III

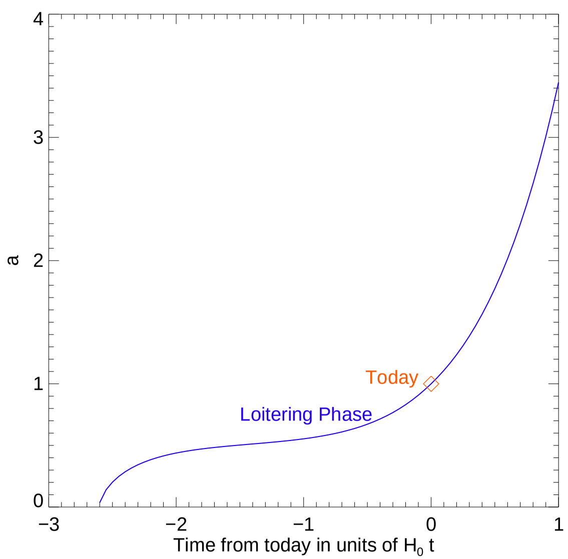


(after Carroll, Press & Turner, 1992, Fig. 1)

With Λ, evolution of universe is more complicated than without:

- unbound expansion possible for $\Omega < 1$,
- For Ω_Λ large: no big bang!
- For Ω_Λ large: possible "loitering phase"

$\Omega_\Lambda > 1$, I



For large Ω_Λ: contraction from $+\infty$ and reexpansion

$\Longrightarrow$ no big bang.

For slightly smaller Ω_Λ: phase where $\dot{a} \sim 0$ in the past

$\Longrightarrow$ loitering universe.

"Loitering universe" with $\Omega_{\rm m} = 0.55$, $\Omega_\Lambda = 2.055$

$\Omega_\Lambda > 1$, II

QSO at $z = 5.82$, courtesy SDSS

Threshold for presence of a turning-point (Carroll, Press & Turner, 1992, Eq. 12):

$$\Omega_\Lambda \geq \Omega_{\Lambda,\text{thresh}} = 4\Omega_\text{m}\left\{C_\kappa\left[\frac{1}{3}C_\kappa^{-1}\left(\frac{1-\Omega_\text{m}}{\Omega_\text{m}}\right)\right]\right\}^3 \quad (8.56)$$

where $\kappa = \text{sgn}(0.5 - \Omega_\text{m})$ and $C_\kappa(\theta)$ was defined in Eq. (4.24).

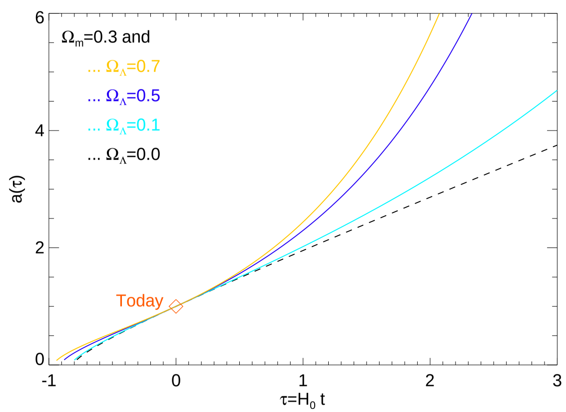
For $\Omega_\Lambda = \Omega_{\Lambda,\text{thresh}}$: turning-point, i.e., there is a minimal a.

Since $1 + z = 1/a$ (Eq. 4.40), existence of turning-point $\Longrightarrow$ maximal possible z:

$$z \leq 2C_\kappa\left(\frac{1}{3}C_\kappa^{-1}\left\{\frac{1-\Omega_\text{m}}{\Omega_\text{m}}\right\}\right) - 1 \quad (8.57)$$

(Carroll, Press & Turner, 1992, Eq. 14). Since quasars are observed with $z > 5.82$, this means that $\Omega_\text{m} < 0.007$, clearly not what is observed $\Longrightarrow \Omega_\Lambda < 1$.

$\Omega_\Lambda < 1$



For $\Omega_\Lambda < 1$ evolution has two parts:

- matter domination, similar to earlier results
- Λ domination, exponential rise.

Exponential rise called by some workers the "second inflationary phase"...

$\Omega_\Lambda < 1$

Calculation of age of universe is similar to $\Omega_\Lambda = 0$ case (see, e.g., Eq. 4.81), but generally only possible numerically.

Result:

Universes with $\Omega_\Lambda > 0$ are *older* than those with $\Omega_\Lambda = 0$.

This solves the **age problem**, that some globular clusters have age comparable to age of universe if $\Omega_\Lambda = 0$.

Analytical formula for age (Carroll, Press & Turner, 1992, Eq. 17):

$$t = \frac{2}{3H_0}\frac{\sinh^{-1}\left(\sqrt{(1-\Omega_a)/\Omega_a}\right)}{\sqrt{1-\Omega_a}} \quad (8.58)$$

for $\Omega_a < 1$, where

$$\Omega_a = 0.7\Omega_\text{m} + 0.3(1 - \Omega_\Lambda) \quad (8.59)$$

For $\Omega_\text{m} = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$: $t = 13.5\,\text{Gyr}$.

Remember that for $\Omega_\text{m} = 1$, $t = 3/2H_0$!

Luminosity Distance, I

Influence of Λ is most prominent at **large distances**!

$\Longrightarrow$ Expect influence on Hubble Diagram.

$\Longrightarrow$ Need to find relation between measured flux, emitted luminosity, and redshift.

Assume source with luminosity L at comoving coordinate r, emitting isotropically into 4π sr.

At time of detection today, photons are

- on sphere with proper radius $R_0 r$,
- redshifted by factor $1 + z$,
- spread in time by factor $1 + z$.

$\Longrightarrow$ observed flux is

$$F = \frac{L}{4\pi R_0^2 r^2 (1+z)^2} \quad (8.60)$$

Luminosity Distance, II

Because the observed flux is

$$F = \frac{L}{4\pi R_0^2 r^2 (1+z)^2} \tag{8.60}$$

in analogy to the inverse square law one defines the **luminosity distance** as

$$d_\mathrm{L} = R_0 \cdot r \cdot (1+z) \tag{8.61}$$

The calculation of d_L is somewhat technical, one can show that (Carroll, Press & Turner, 1992):

$$d_\mathrm{L} = \frac{c}{H_0} |\Omega_k|^{-1/2} \cdot S_{-\mathrm{sgn}(\Omega_k)} \left\{ |\Omega_k|^{1/2} \int_0^z \left[(1+z)^2 (1+\Omega_\mathrm{m} z) - z(2+z)\Omega_\Lambda \right]^{1/2} \mathrm{d}z \right\} \tag{8.62}$$

Supernovae

Best way to determine Ω_Λ:

Type Ia supernovae

Remember: SN Ia = CO WD collapse... (Hoyle, Fowler, Colgate, Wheeler,...)

The distance modulus is

$$m - M = 5 \log \left(\frac{d_\mathrm{L}}{1\,\mathrm{Mpc}} \right) + 25 \tag{8.63}$$

Use SNe as standard candles $\Longrightarrow$ Deviations from $d_\mathrm{L} \propto z$ indicative of Λ.

Two projects:

- High-z Supernova Team (STSCI, Riess et al.)
- Supernova Cosmology Project (LBNL, Perlmutter et al.)

Both find SNe out to $z \sim 1$.

Present mainly Perlmutter et al. results here, Riess et al. (1998) are similar.

Supernovae

Basic observations: easy:

- Detect SN in rise $\Longrightarrow$ CTIO 4 m
- Follow SN for $\sim$ 2–3 months with 2–4 m class telescopes, HST, Keck...

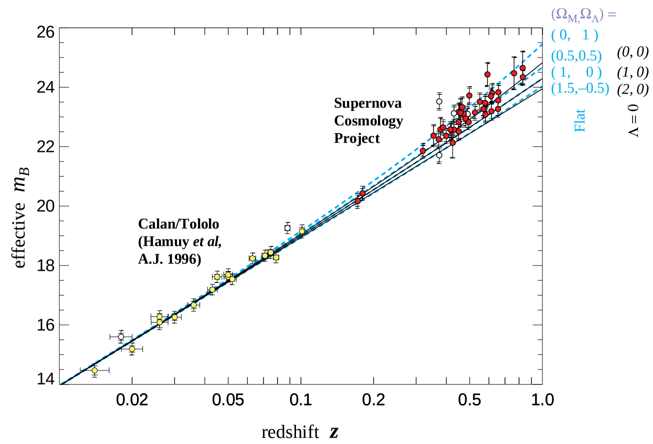
More technical problems in data analysis: Conversion into source frame:

- Correction of photometric flux for redshift: "K-correction"
- Correct for time dilatation in SN light curve

Further things to check

- SN internal extinction
- Galactic extinction
- Galactic reddening
- Photometric cross calibration
- Peculiar motion of SN

Supernovae

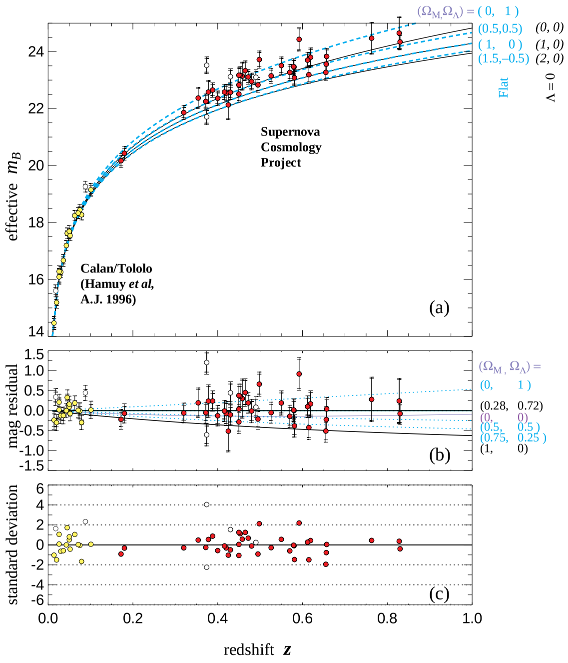


Vertical error bars: measurement uncertainty *plus* 0.17 mag intrinsic mag. dispersion

Horizontal error bars: 300 km s^{-1} peculiar velocity uncertainty

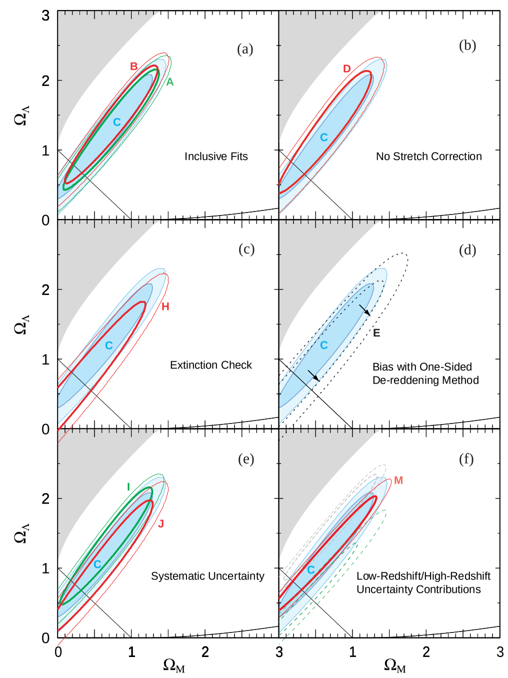
(Perlmutter et al., 1999, Fig. 1)

42 SNe from SCP, 18 low redshift from Calán/Tololo SN Survey

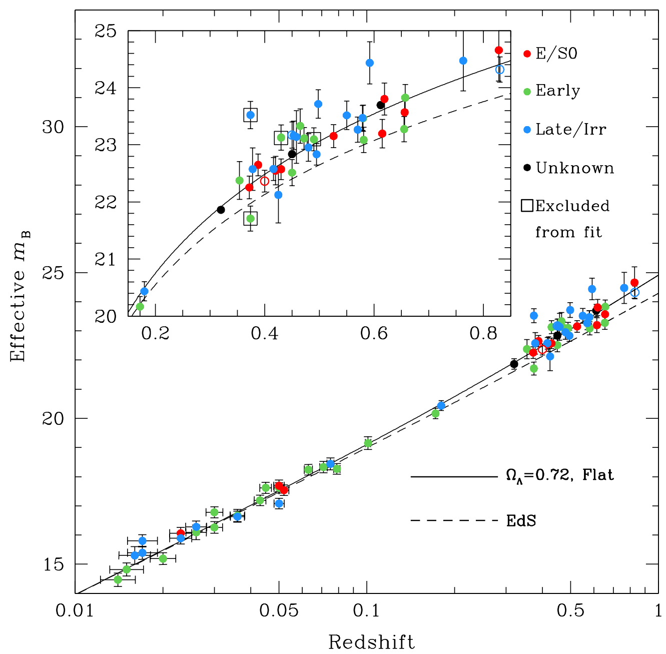


Best fit: $\Omega_{m,\,flat} = 0.28^{+0.09}_{-0.08}$,
$\chi^2/DOF = 56/50$
corresponding best free fit:
$(\Omega_m, \Omega_\Lambda) = (0.73, 1.32)$.

(Perlmutter et al., 1999, Fig. 2)

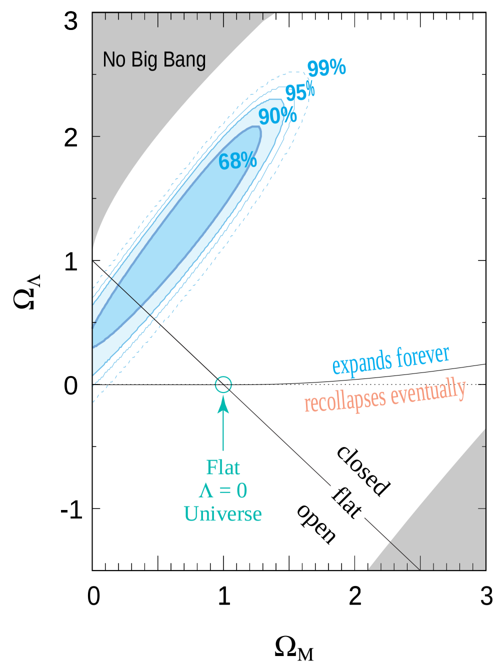


(68% and 90% confidence contours for sources of systematic error, Perlmutter et al., 1999, Fig. 5)

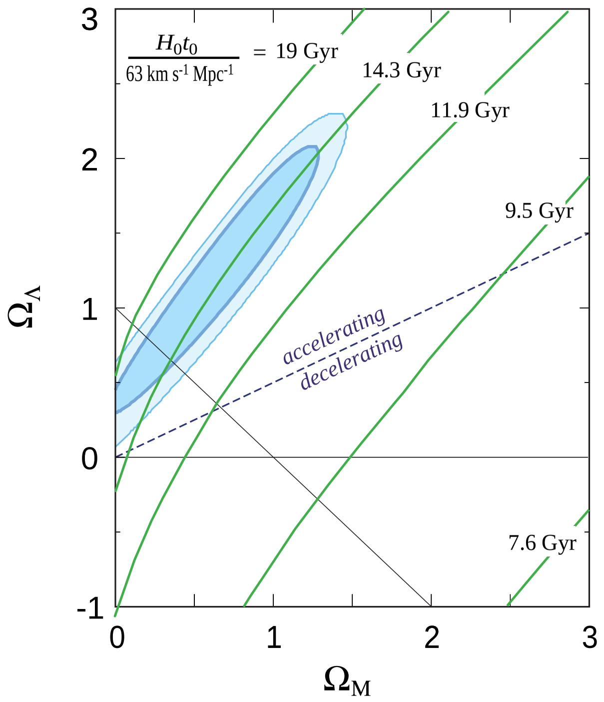


Updated 2002 Hubble diagram for SN Iae confirms Perlmutter 1999.

Sullivan et al., 2002



Combined confidence region (Perlmutter et al., 1999, Fig. 7; lower right: universes that are younger than oldest heavy elements)



Isochrones for age of universe for $H_0 = 63\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (for $h = 0.7$: age 10% smaller).
$\Longrightarrow$ Consistent with globular cluster ages!

(Perlmutter et al., 1999, Fig. 9)

Summary

For all practical purposes, currently the best values of Ω_m and Ω_Λ are

$\Omega_\mathrm{m} \sim 0.3$ and $\Omega_\Lambda = 0.7$

Even if $\Omega \neq 1$:

$\Omega_\Lambda \neq 0$

And therefore

Baryons are an energetically unimportant constituent of the universe.

"The dark side of the force. . . " :-)

Outlook

What is physical reason for $\Omega_\Lambda \neq 0$?

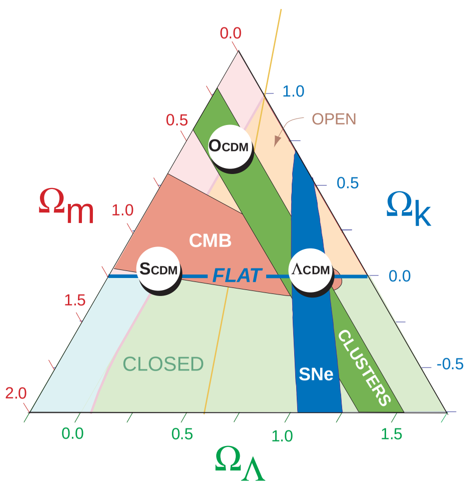
Currently discussed: quintessence: "rolling scalar field", corresponding to very lightweight particle ($\lambda_{\text{de Broglie}} \sim 1$ Mpc), looks like time varying cosmological "constant".

Why? $\Longrightarrow$ More naturally explains why Ω_Λ so close to 0 (i.e., why matter and vacuum have so similar energy densities)

Motivated by string theory and M theory. . .

Still VERY SPECULATIVE, decision Λ vs. quintessence should be possible in next 5. . . 10 years when new instruments become available.

Outlook



Bahcall et al.

Even better constraints come from combination of SNe data with structure formation.

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Large Scale Structures and Structure Formation

The Lumpy Universe

So far: treated universe as smooth universe.

In reality:

Universe contains structures!

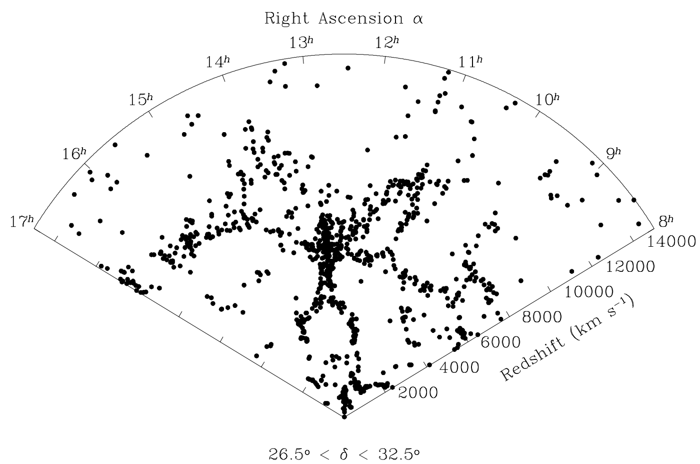
Last part of this class:

1. What are structures?
2. How can we quantify them?
3. How do structures form?
4. How do structures evolve?

Will see that all these questions are deeply connected with parameters of the universe seen so far:

1. H_0
2. Ω_0, Ω_b, Ω_m, $\Omega_\Lambda, \ldots$
3. Existence and Nature of Dark Matter

Introduction, I



(de Lapparent, Geller & Huchra, 1986, limiting mag $m_\mathrm{B} = 15.6$)

Lumpy universe: spatial distribution of galaxies and greater structures.

Introduction, II

How do we study the structure of the Universe?

⟹ We need distance information for many ($10^4 \dots 10^7$) objects

⟹ Large redshift surveys

Review: Strauss & Willick (1995)

Redshift survey: Survey of (patch of) sky determining galaxy z and position to predefined magnitude or z.

First larger survey: de Lapparent, Geller & Huchra (1986)

Classification:

1D-surveys: very deep exposures of small patch of sky, e.g. HST Deep Field, Lockman Hole Survey, Marano Field.

2D-surveys: cover long strip of sky, e.g., CfA-Survey ($1.5 \times 100^\circ$), 2dF-Survey ("2 degree Field").

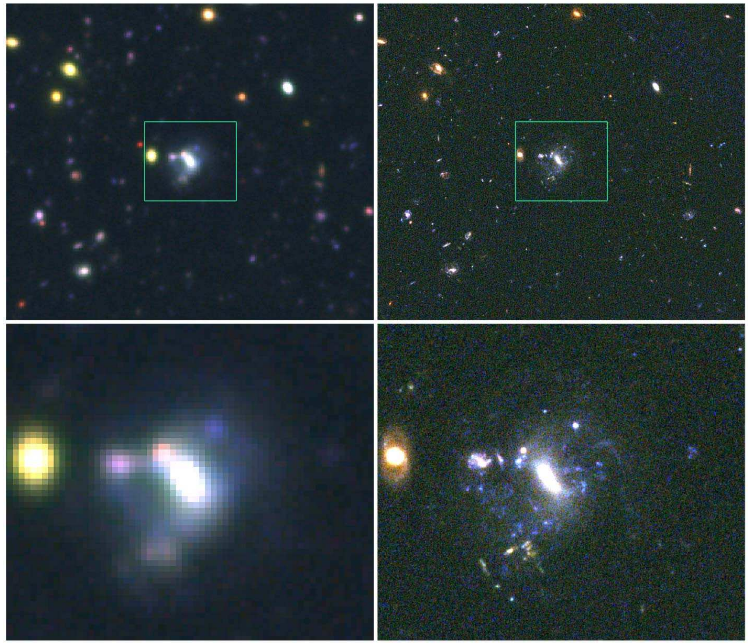
3D-surveys: cover part of the sky, e.g., Sloan Digital Sky Survey.

These surveys attempt to go to certain limit in z or m.

Other approaches: use pre-existing galaxy catalogues (e.g., QDOT Survey [IRAS galaxies], APM survey,...).

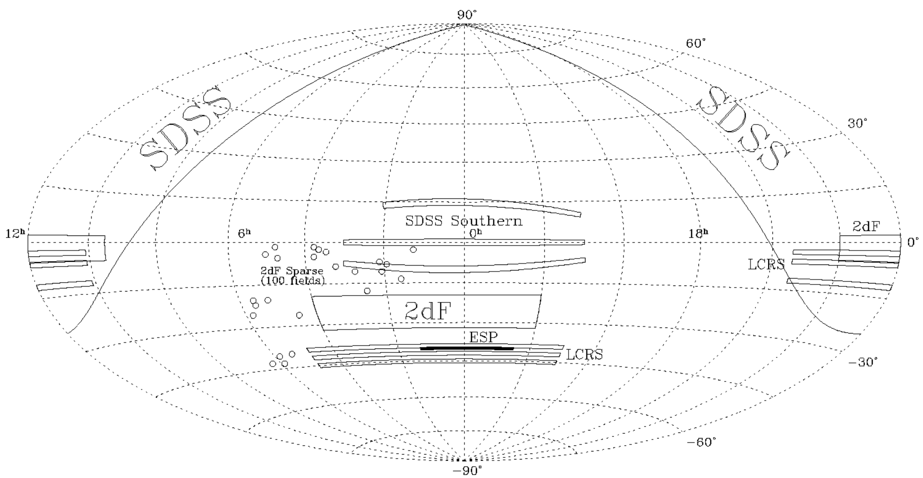
We will concentrate here on the larger surveys based on no other catalogue.

Ground: Subaru (8m) Space: *HST* (2.4m)

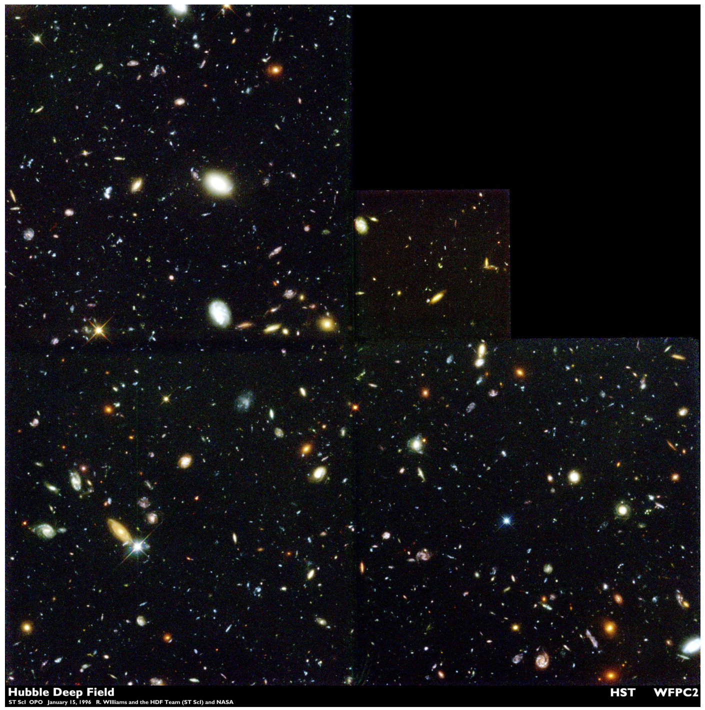


To go deep one needs to go to space

Introduction, III



(Strauss, 1999)

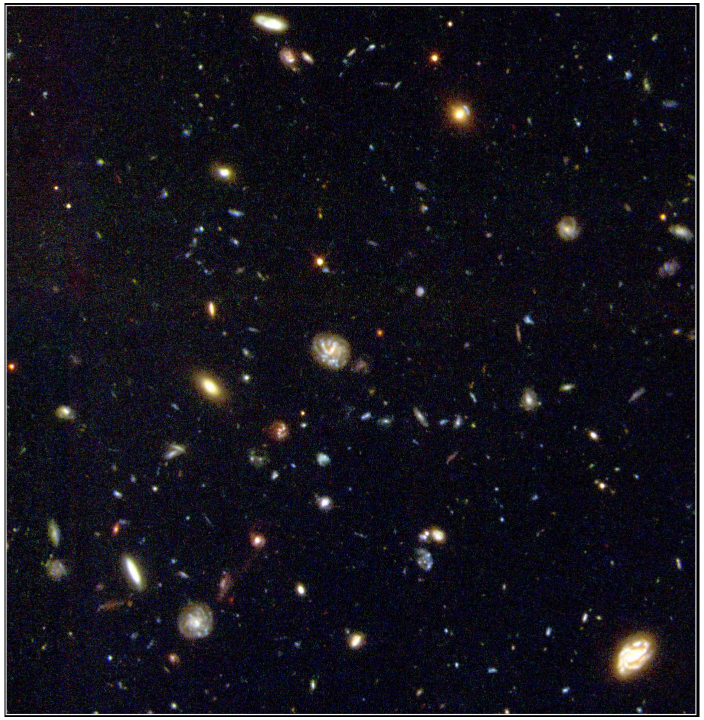


1995 December: Hubble Deep Field:

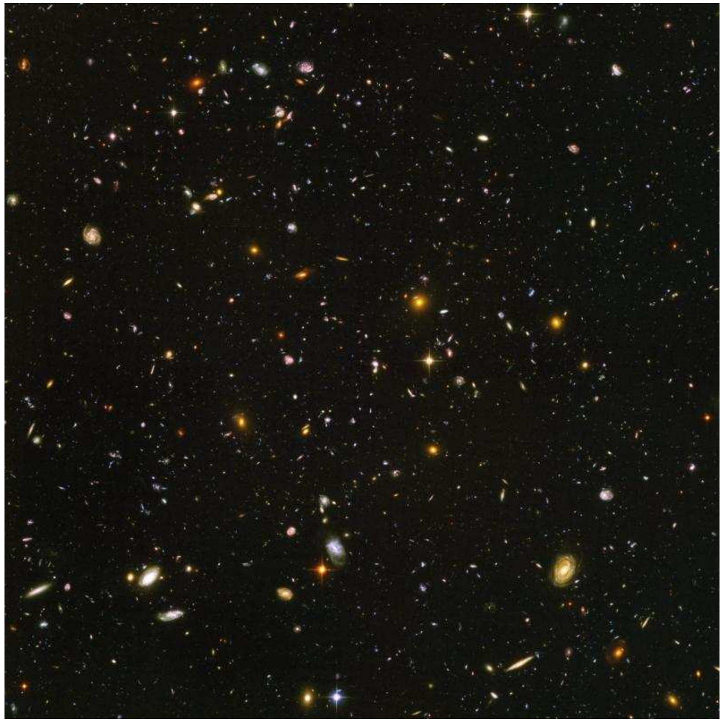
~ 150 ksec/Filter for four HST Filters

Many galaxies with weird shapes ⟹ protogalaxies!

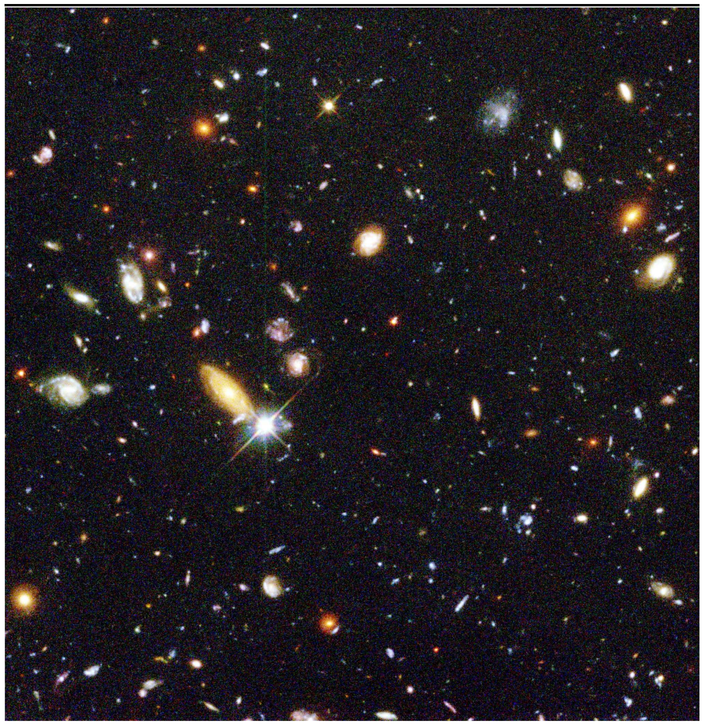
Redshifts: $z \in [0.5, 5.3]$ (Fernández-Soto et al., 1999)

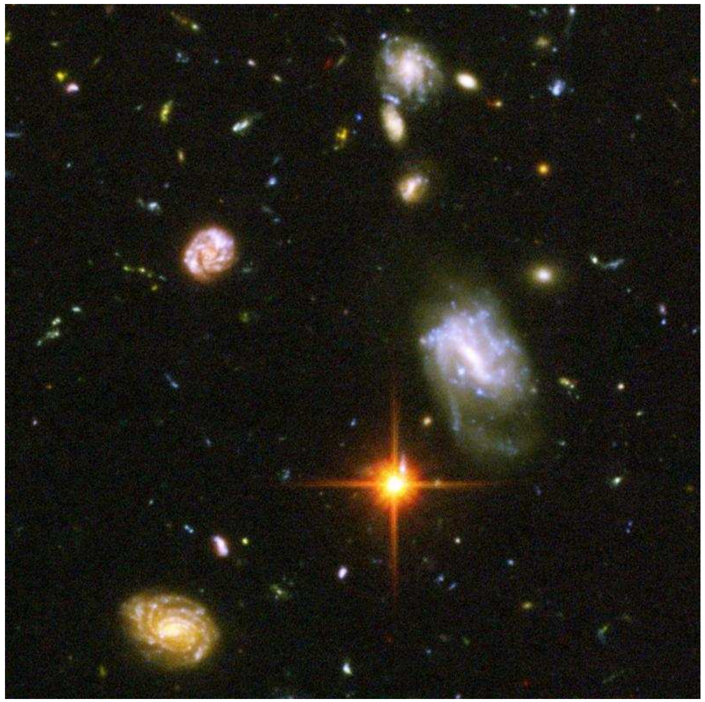


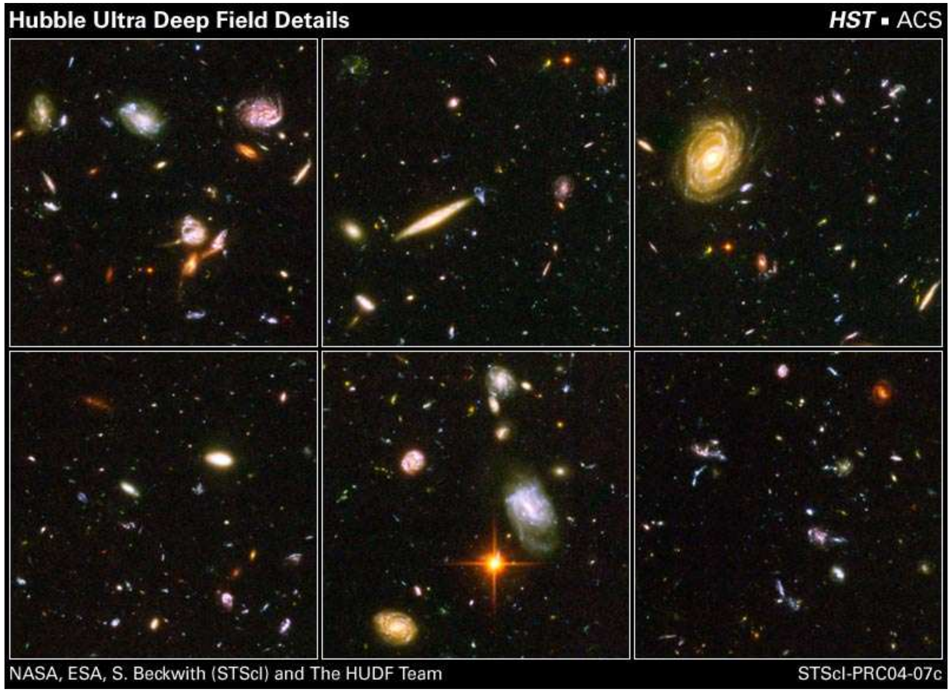
1998: Hubble Deep Field South, 10 d of total observing time!

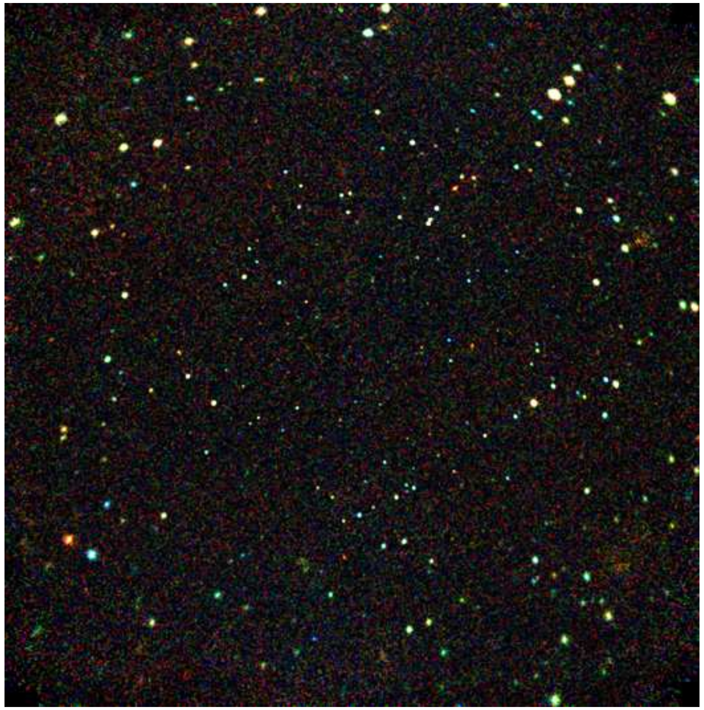


2004: Hubble Ultra Deep Field, 1 Msec long exposure of field in Fornax. Uses updated HST with Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS); diameter: 3′ (2× older HDF)
Limiting magnitude: 30 mag, ∼10000 galaxies visible, up to $z \gtrsim 7$
IR reveals many reddened objects



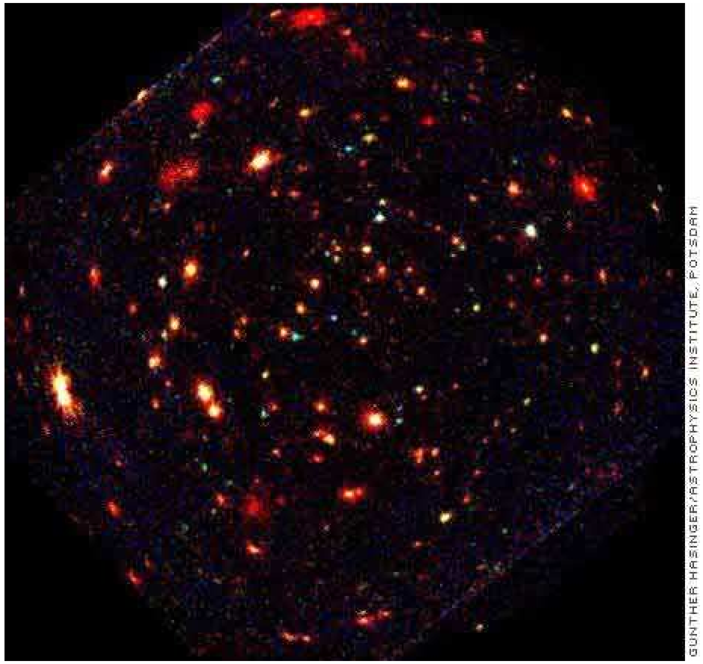






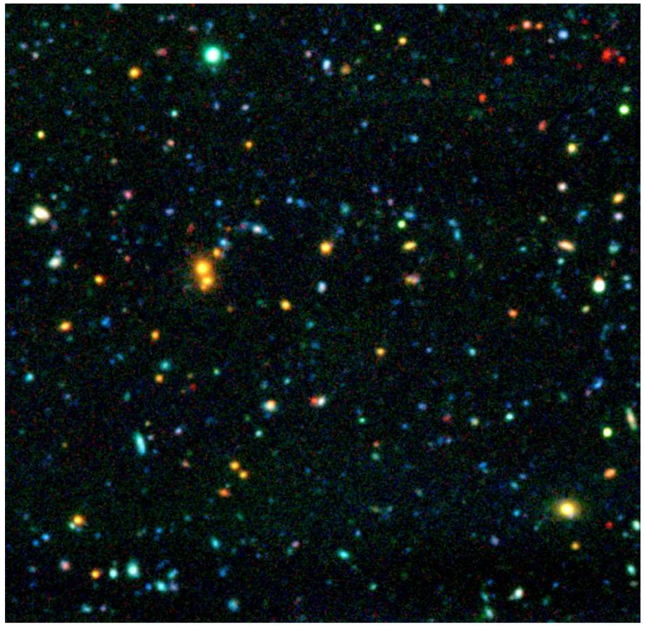
Chandra Deep Field South: 1 Msec (10.8 days) on one region in Fornax ($\alpha_{\mathrm{J2000.0}} = 3^{\mathrm{h}}32^{\mathrm{m}}28.0^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = -27^\circ 48' 30''$
Deepest X-ray field ever
color code: spectral hardness

scale: $15' \times 15'$; courtesy NASA/JHU/AUI/R.Giacconi et al.



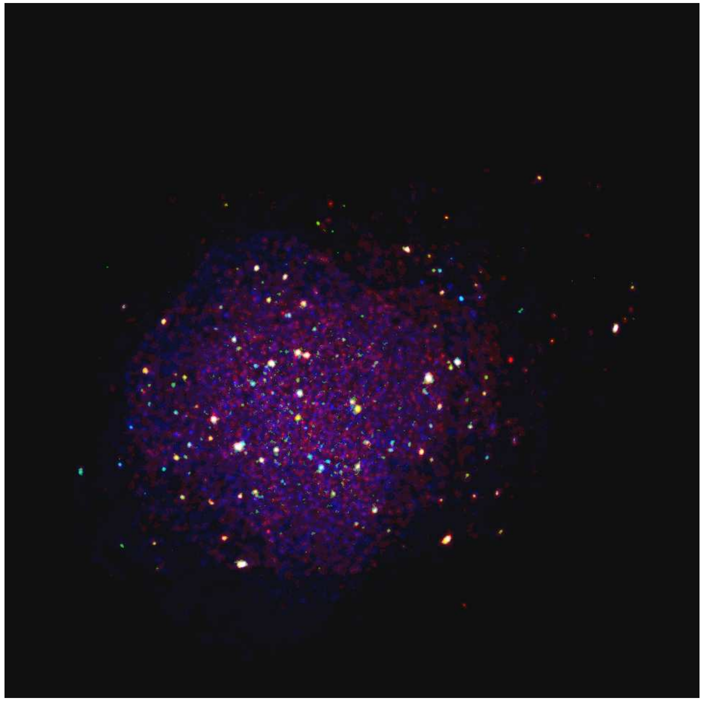
Lockman Hole: Northern Sky region with very low N_{H}
$\Longrightarrow$ low interstellar absorption
$\Longrightarrow$ "Window in the sky"
$\Longrightarrow$ X-rays: evolution of active galaxies with z!

XMM-Newton, Hasinger et al., 2001,
blue: hard X-ray spectrum,
red: soft X-ray spectrum



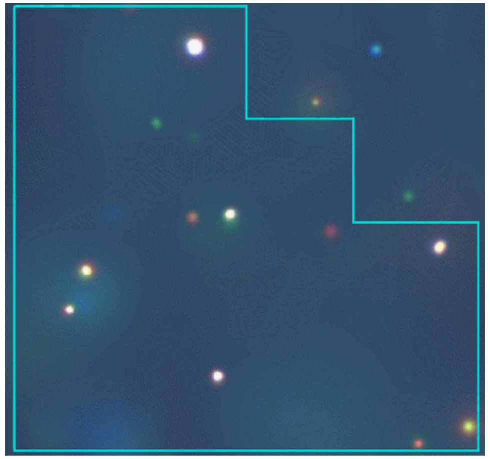
Distant Galaxies in "AXAF Deep Field" (VLT ANTU / ISAAC + NTT / SUSI-2)

ESO PR Photo 06b/00 (17 February 2000)



1D Surveys ("Deep Exposures") give snapshot of evolution of galaxies over large z.

Deep *XMM-Newton* image of the Marano Field (IAAT/AIP/MPE)



HST Chandra

Chandra/HST Image of Hubble Deep Field North; 500 ksec

Joint multi-wavelength campaigns allow the measurement of broad-band spectra of sources in the early universe!

$\Longrightarrow$ GOODS-Survey (Gread Observatories Origins Deep Survey)