Cosmology

TUM WS 2019/2020

Lecture 12

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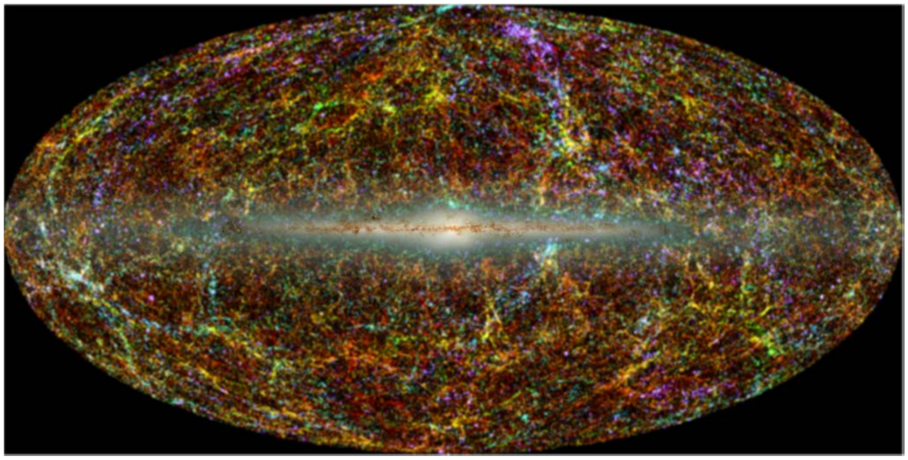
(http://www.eso.org/~bleibund/Cosmology)

Structure formation - Summary

- DM perturbations grow first ($a > a_{eq}$)
- Baryons gather in potential wells of the DM ($a > a_{dec}$)
- Small-scale perturbations in the DM grow first (and strongest): merge to form larger structures ("hierarchical clustering")

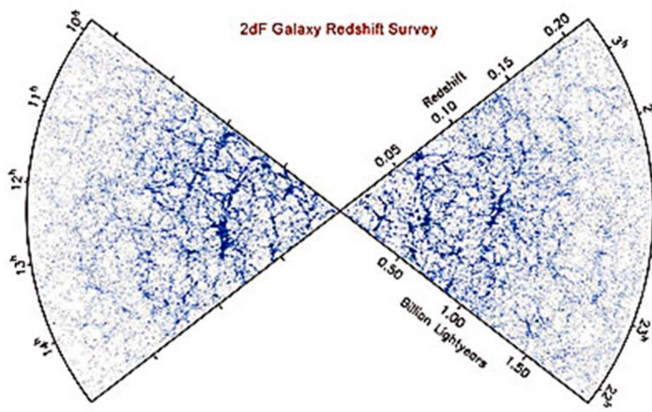
Matter distribution in todays universe

- 2MRS (CfA, infrared)



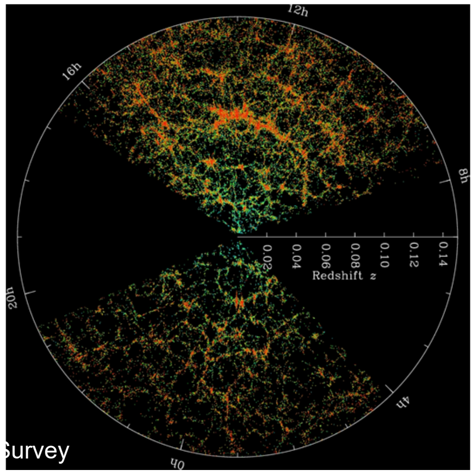
The spatial distribution of galaxies

- Galaxies are not randomly distributed but correlated
- Network of structures (filaments, sheets, walls) $\Rightarrow$ “cosmic web”



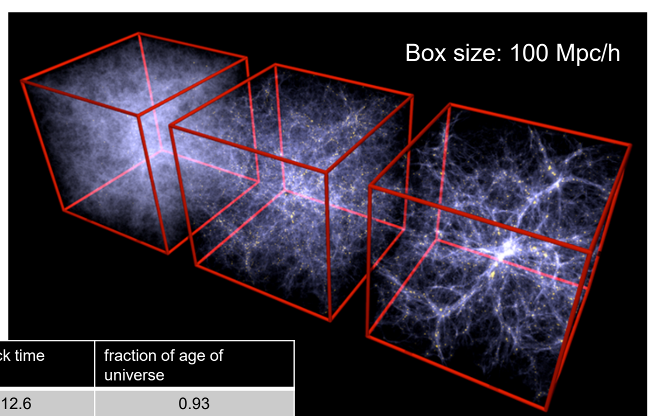
Matter distribution in todays universe

- SDSS galaxy map

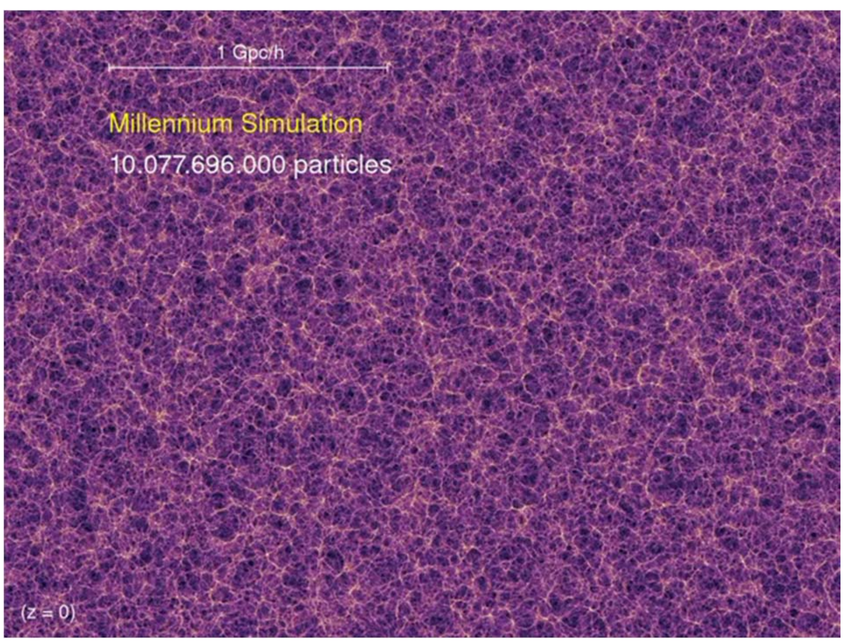


Example of a simulation

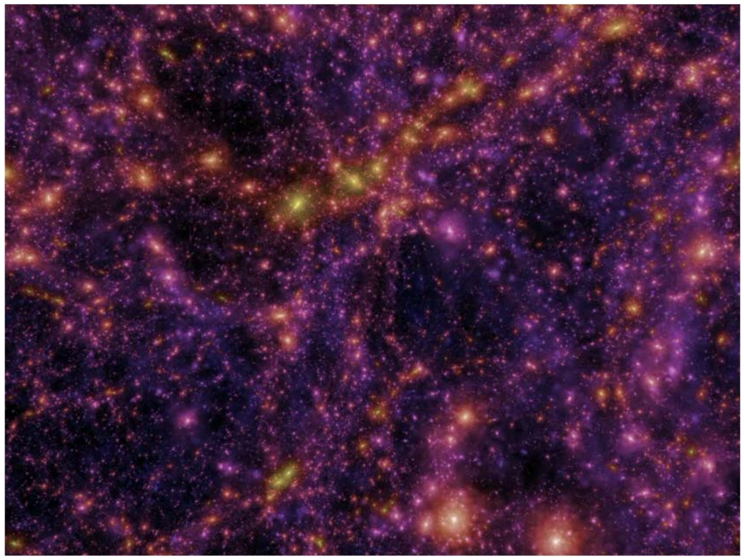
- Springel et al. (Virgo consortium)
  - snapshots at z=6, z=2, and z=0



redshift	lookback time (Gyr)	fraction of age of universe
6	12.6	0.93
2	10.2	0.76

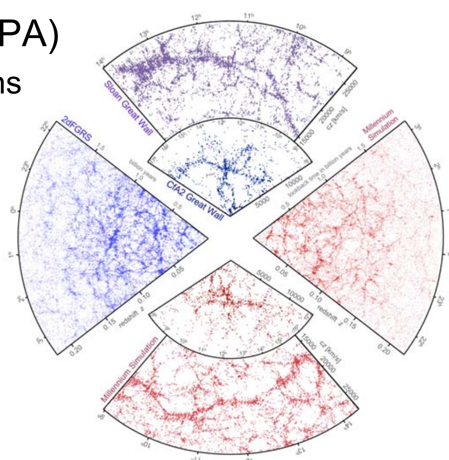

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

A voyage through a ΛCDM universe



Simulating the Universe

- Millenium simulation (MPA)
  - matching the observations extremely well
  - specific use of cosmological parameters
  - ΛCDM
  - Too many 'small' galaxies predicted?!

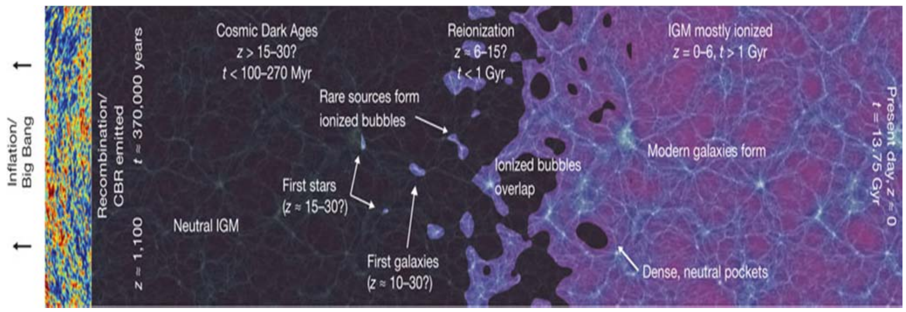


https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millenium/

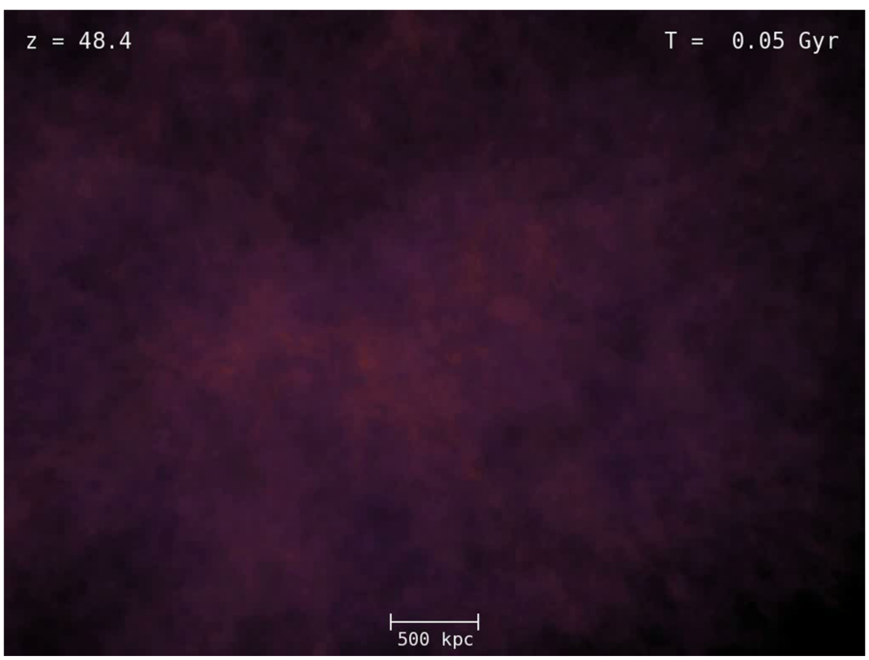
After recombination

- The only 'global' event is the reionization around z≈10

Robertson et al. (2010)



"Extragalactic Astrophysics"



Literature

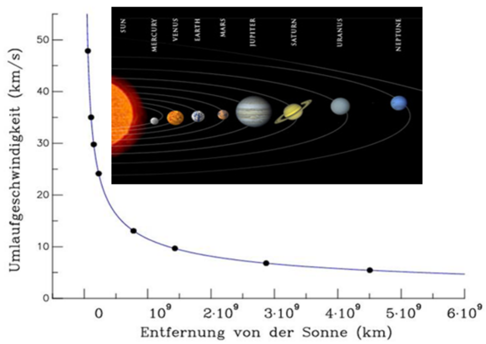
- Scott Dodelson, Modern Cosmology, Boston, Academic Press 2013 ISBN: 0122191412
- Malcolm S. Longair, Galaxy Formation, Astronomy and Astrophysics Library, Springer Verlag: ISBN 978-3-540-73477-2
- Bertschinger, E., Ann. Rev. Aston. Astrophys. **36**, 599 (1998)
- Springel, V., MNRAS **364** 1105 (2005)
- Springel, V., et al., Nature **435** 629 (2005)
- Springel, V., Frenk, C., White, S.D.M., Nature **440** 1137 (2006)
- Springel, V., 42rd Saas-Fee Course, arXiv:1412.5187v1 (2014)
- Hernquist, L., Bouchet, F.R., Suto, Y., Astrophys. J. Suppl. **75** 231 (1991)

Dark matter

- Evidence for its existence
- What is it ???

Gravity in the solar system

- Use Newton's law for gravity $F = G\frac{Mm}{r^2}$
- Centripetal force $F = \frac{mv^2}{r}$
- Hence the orbital velocity is $v = \sqrt{\frac{GM}{r}}$



99.9987% of the mass in the Solar System is in the Sun

Solar System

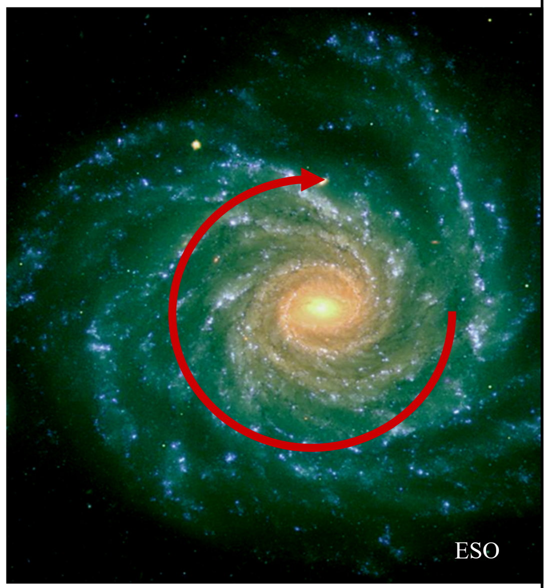
- Hence Kepler's Third Law

$$P = \frac{2\pi r}{v} = \frac{2\pi}{\sqrt{GM}} r^{3/2}$$

(which uses enclosed mass M)

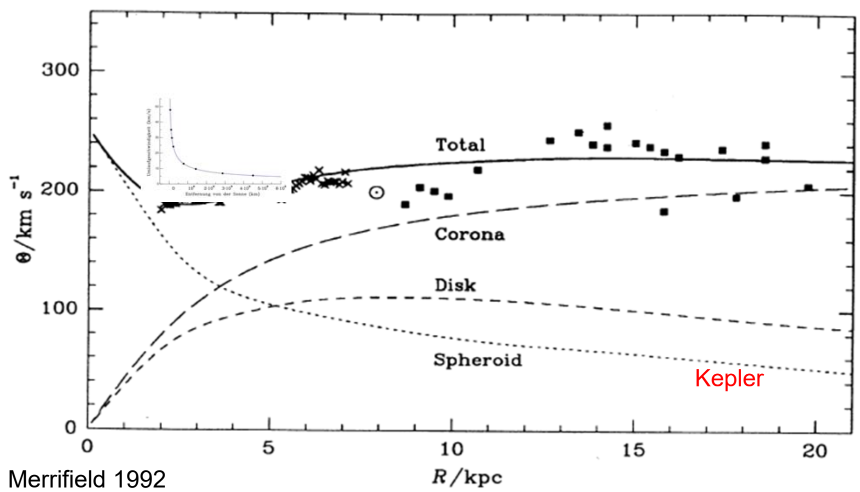
Solar Orbit in the Milky Way

- Sun orbits the Galactic Centre in 220 million years



Rotation curve of the Milky Way

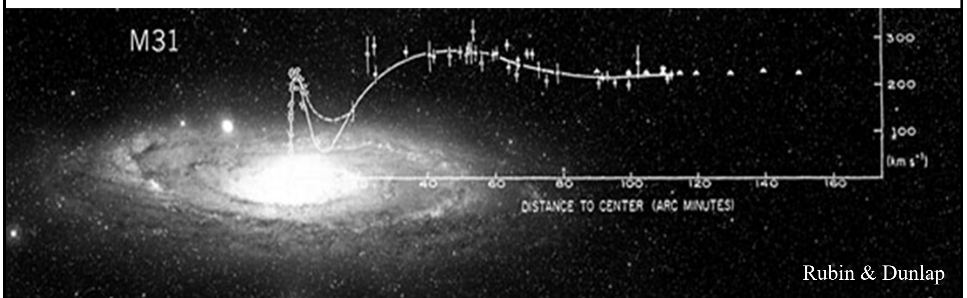
- Measure rotation curves like in the solar system (HI data)



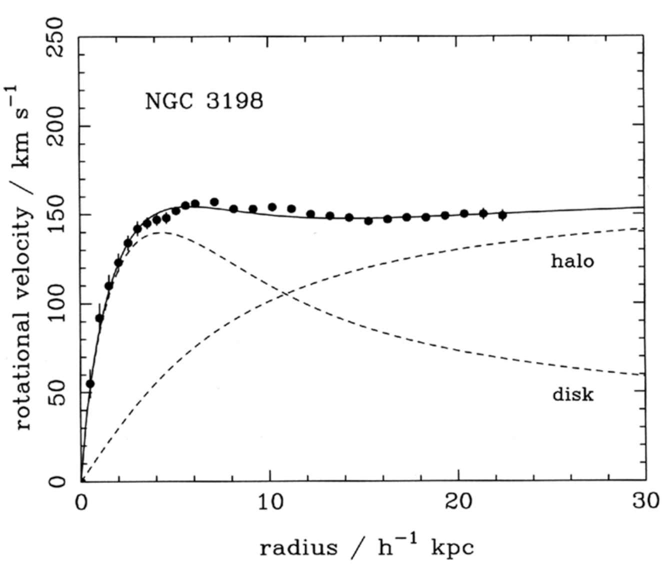
Merrifield 1992

How about other galaxies?

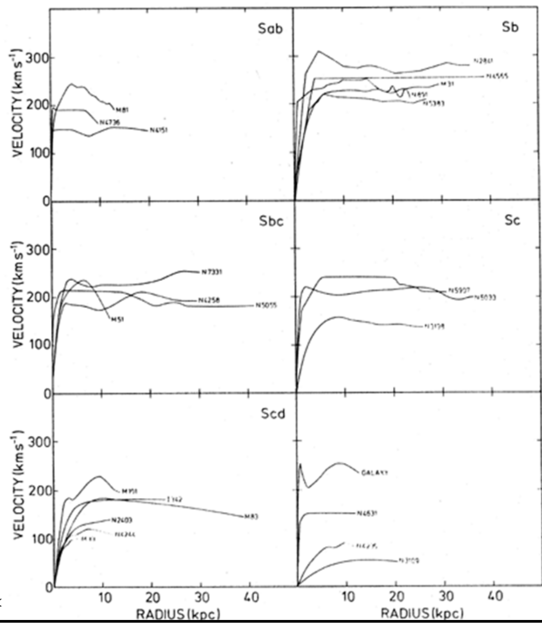
- Measure rotation curves like in the solar system
  - example: Andromeda Nebula (M31)



More rotation curves of galaxies



More rotation curves of galaxies



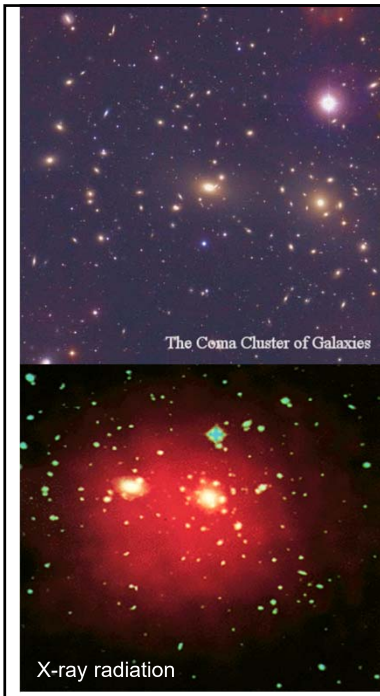
In general for (spiral) galaxies

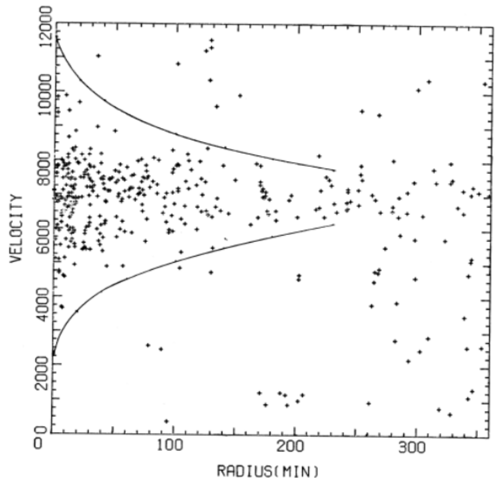
- Rotation curve increases beyond the observable light
  - can only happen if there is more enclose mass!
  - but there is no more light, i.e. no more (bright) stars
  - mostly diffuse matter, which is dark
- Alternative would be to change the law of gravity or the Newtonian force
  - Modified Newtonian Dynamics MOND

$$\boldsymbol{F_N} = m\mu\left(\frac{a}{a_0}\right)\text{a},\ a_0 \approx 1.2 \times 10^{-10}\ \text{ms}^{-2}$$

$$\mu\left(\frac{a}{a_0}\right) = 1/\sqrt{1+\left(\frac{a_0}{a}\right)^2} \qquad \text{(M. Milgrom, 1983)}$$

Galaxy Clusters





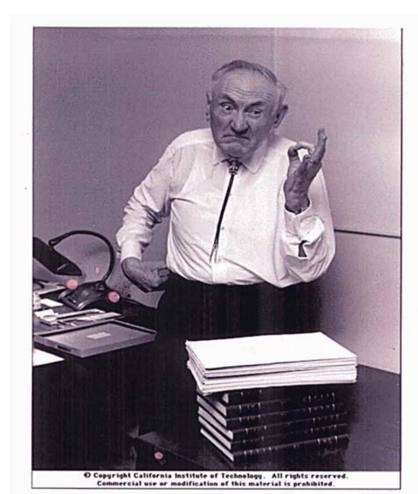
Coma cluster (Kent & Gunn 1982)

Galaxy Clusters

- First done by Fritz Zwicky for the Coma cluster in 1933.
- Use virial theorem

$$E_{kin} = -\frac{1}{2} E_{pot} \qquad M = \frac{\sigma^2 r}{G}$$

- Apparently 400 times more mass than seen in the stars



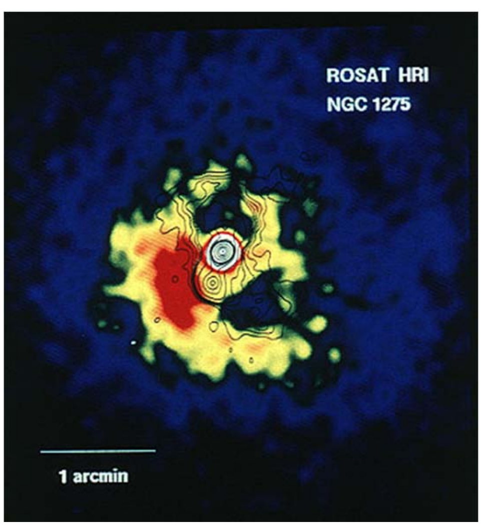
HELVETICA
PHYSICA ACTA

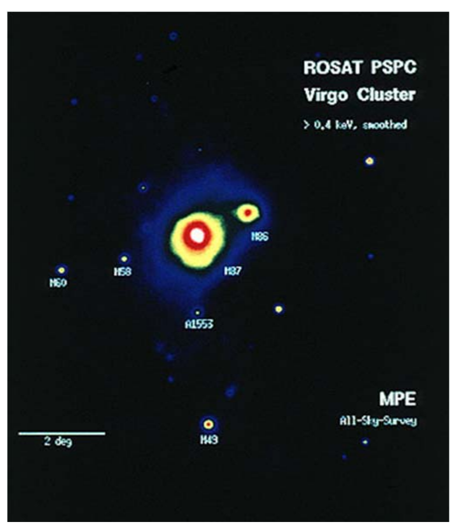
EDITA A SOCIETATE PHYSICA HELVETICA

Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.
(16. II. 33.)

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

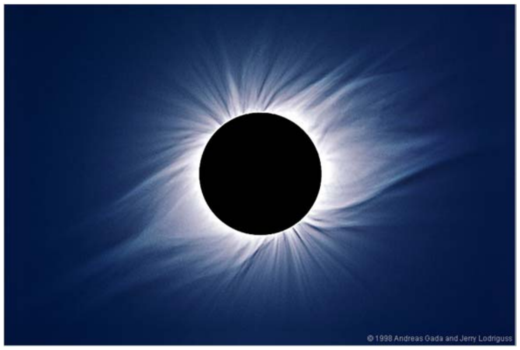
More evidence of dark matter: "X-ray clusters"

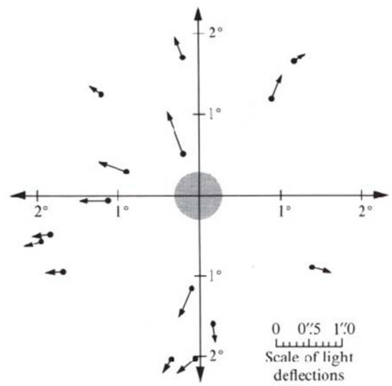




Gravitational lensing
(Solar eclipse 1919)

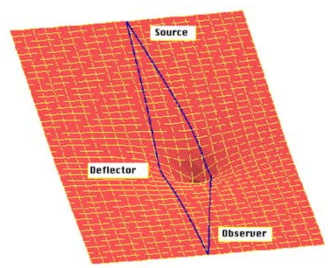
- Proof of General Relativity

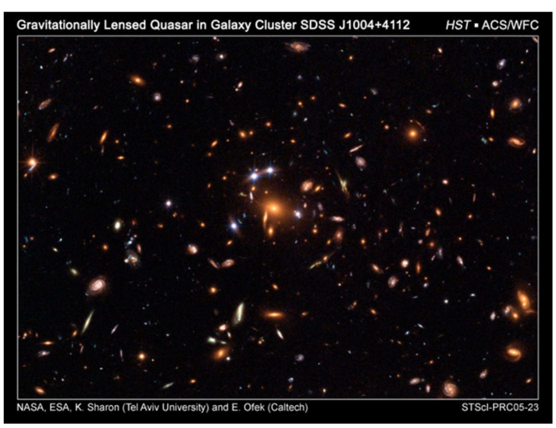


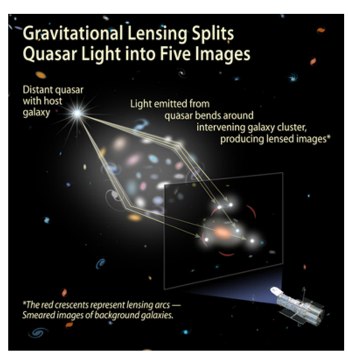


Gravitational lenses

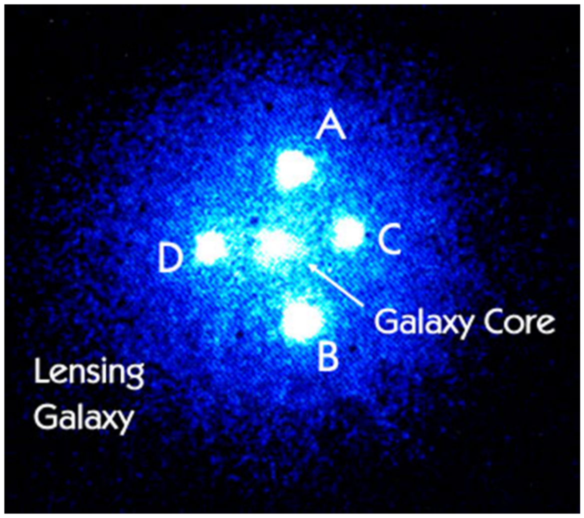
- Deflections of photons in the gravitational potential







Example for light bending



"Einstein Cross" - G2237+0305

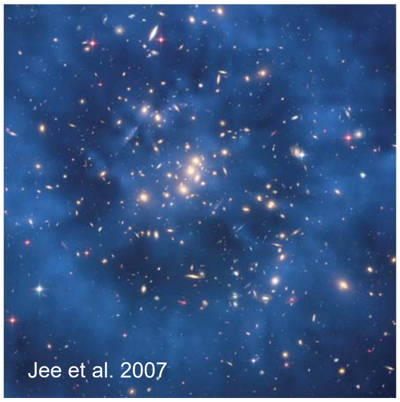
Gravitational lenses

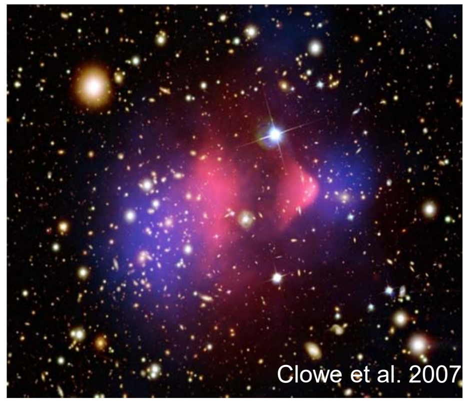
- The deflection scales with the total mass of the lens, i.e. galaxy cluster, although it really measures the gravitational potential.
- The measurement indicates that there are several times the visible mass in the clusters

➡ Dark Matter

Dark Matter maps

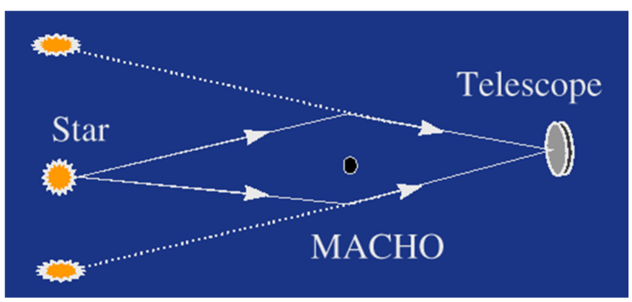
- By measuring the system of lensed images around a cluster a map of the dark matter density can be constructed





'Microlensing': Can we see MACHOs ?

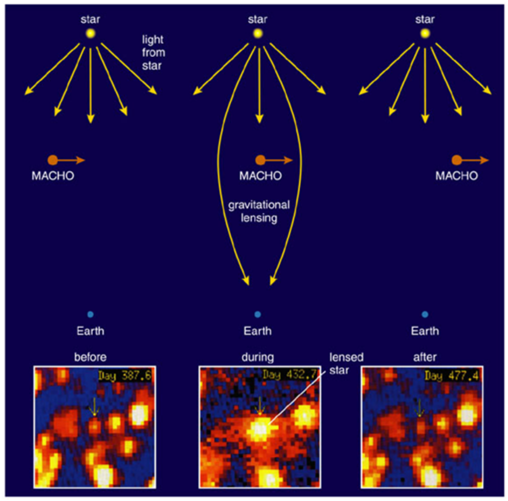
- Gravitational lensing:



- If foreground object has only little mass, the image split is too small to be observed
- But the amplification (brightening) is observable

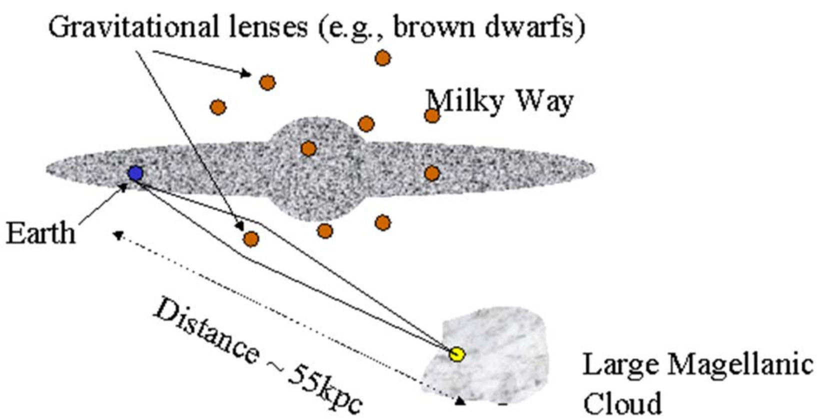
How can we see MACHOs ?

- How likely is it for a star in the Milky Way to get amplified ?
- Once every 10 million years !!!

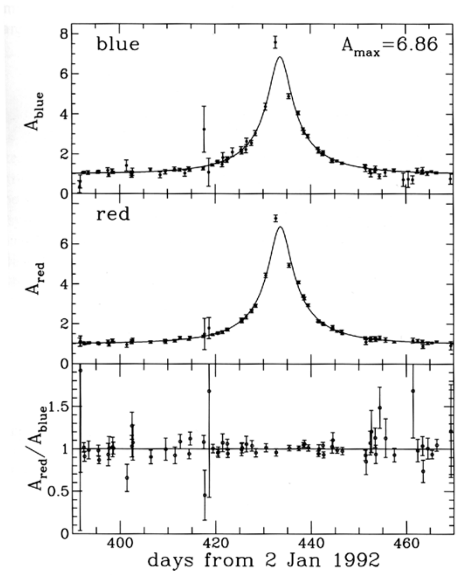


How did this work ?

- Monitor 10 million stars simultaneously !



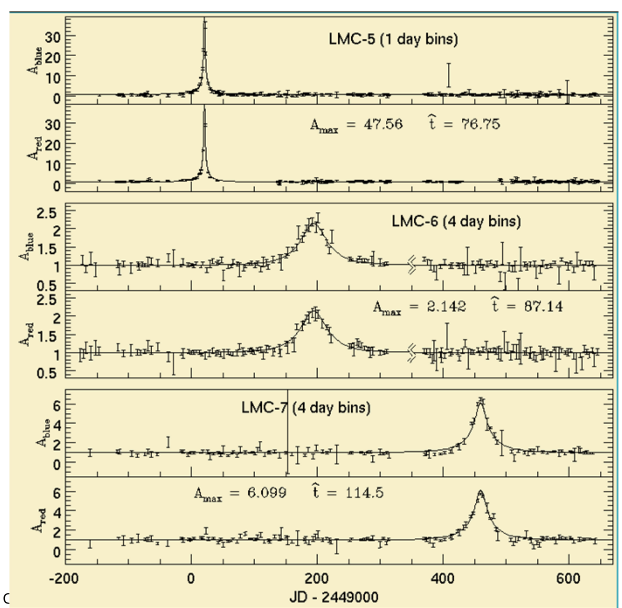
Light curve of a MACHO event



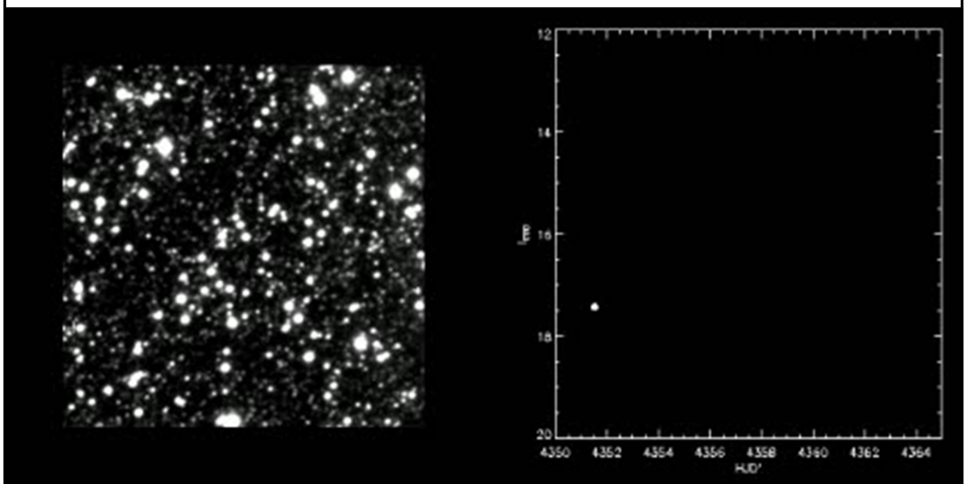
Achromatic (!) magnification due to gravitational lensing

There seem to be not enough brown dwarfs (or dark objects of similar mass) to account for the dark matter in the Milky Way !

Other MACHO candidates



An OGLE MACHO candidate



Data:

- Found (since 1990): ~ 1-3 candidates per year
- Most probable mass: $\approx 0.5\ (\pm\ 0.3)\ M_{sun}$!?
- Brown dwarfs are excluded
- Could make up for up to 0.3% of the critical density
- But: problems with stellar evolution

Dark Matter trouble

- Still a number of problems
- no direct detection of the dark matter particle

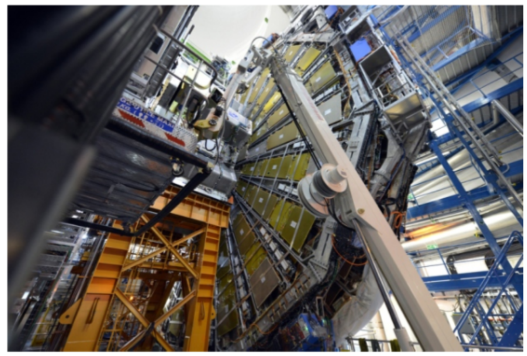
NATURE | NEWS

Crunch time for pet theory on dark matter

Thought to make up the Universe's missing matter, WIMPs are running out of places to hide.

Davide Castelvecchi

21 January 2015



Harold Cunningham/Getty Images

Scientists hope to create WIMPs when the Large Hadron Collider comes back online.

Dark Matter trouble?

- Indications of a new particle?
- Not confirmed!

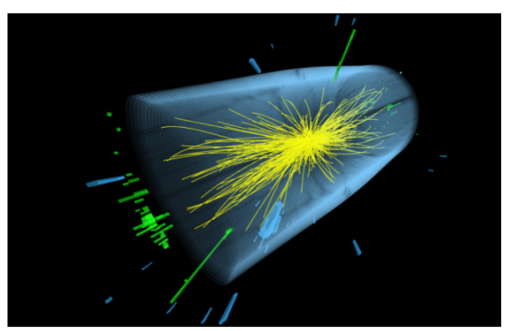
NATURE | NEWS

LHC sees hint of boson heavier than Higgs

Tantalizing results from upgraded collider will be followed up within a year.

Davide Castelvecchi

15 December 2015 Corrected: 16 December 2015

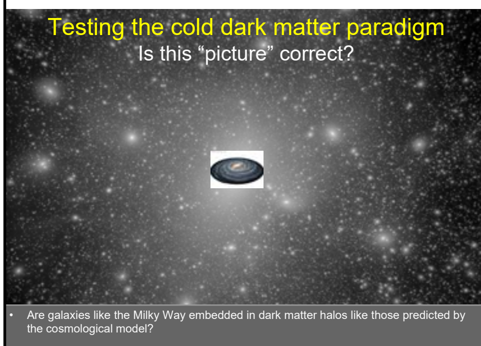


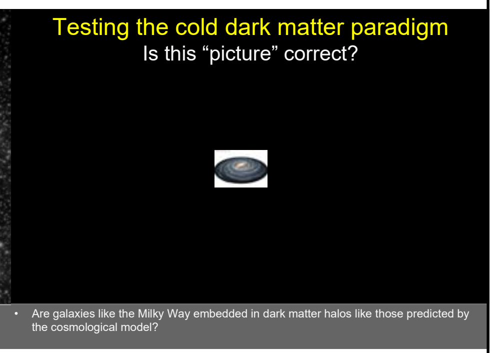
CMS/CERN

Pairs of photons (green) produced in LHC collisions suggest the existence of a boson with a mass of 750 gigaelectronvolts.

Dark Matter trouble

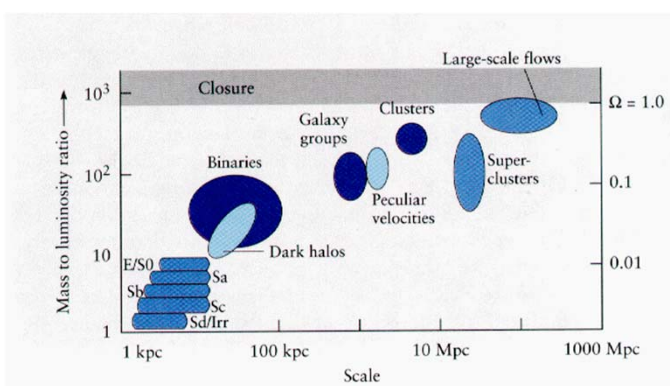
- Collision-less dark matter predicts too much structure at small scales





Summary

- Dark matter becomes more dominant with increasing mass scale
- Low-mass axions seem to be the best bet



Dark Energy - Background

- Discovered only in 1998
- 'Cosmological constant' added by Einstein (1917) to his equations to allow for a static solution

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

- Alternatively one could add a (constant) vacuum energy to the energy-momentum tensor $T_{\mu\nu}$

Dark Energy - Background

The corresponding Friedmann-Lemaître equation is

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

with the density summed over all components:

$$\rho(t) = \rho_M + \rho_R + \rho_{vac}$$

The vacuum density is related to the cosmological constant through

$$\rho_{vac} = \frac{\Lambda}{8\pi G}$$

Acceleration

The dynamics of the expansion is given by (Lectures 3 and 4)

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

(from the time part of the Einstein equations)

Acceleration ($\ddot{a} > 0$) means $(\rho c^2 + 3p) < 0$

– Negative pressure can lead to acceleration!

Equation of state

Using the equation of state formalism for a perfect fluid we have $\omega = \frac{p}{\rho c^2}$ and the density then relates to the scale parameter through $\frac{\dot{\rho}}{\rho} = -3(1+\omega)\frac{\dot{a}}{a}$, which leads to $\rho = const.\times a^{-3(1+\omega)}$

(Pressure-less) Matter: $\omega = 0$ and $\rho \propto a^{-3}$

Radiation: $\omega = 1/3$ and $\rho \propto a^{-4}$

Cosmological constant: $\omega = -1$ and $\rho = const.$

Equation of state

For full generality allow for a changing equation of state parameter $\omega \neq const$.

The distance then becomes

$$D_L = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_R(1+z')^4 + \Omega_k(1+z')^2 + \Omega_X f_X(z')}}\right)$$

As before $S = \begin{cases} \sin(x) & k > 1 \\ x & k = 1 \\ \sinh(x) & k < 1 \end{cases}$

and $f_X(z) = e^{3\int_0^z \frac{1+\omega_X(z')}{1+z'}dz'}$

Distances today

- Radiation density very low $\Omega_R < 10^{-5}$
- Curvature $\Omega_k \approx 0$ (flat space - from CMB)
- Assume cosmological constant
  - Mostly for simplicity

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

Dark Energy

- Measure the expansion rate of the universe to determine its content
- Luminosity distance (Lecture 4)

$$D_L = a_0 r_1 (1+z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{\Omega_{matter}(1+z')^3 + \Omega_{rad}(1+z')^4 + \Omega_\Lambda + \Omega_k (1+z')^2}}\right)$$

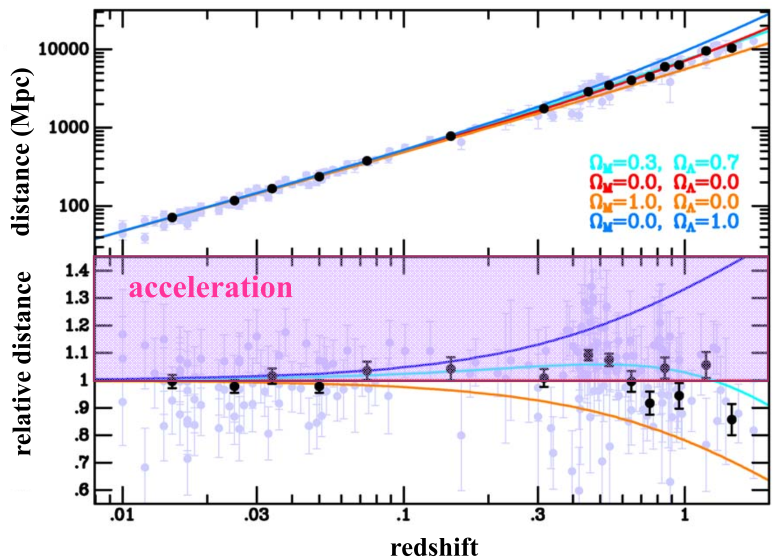
$$S = \begin{Bmatrix} \sin x & k>0 \\ x & k=0 \\ \sinh x & k<0 \end{Bmatrix}$$

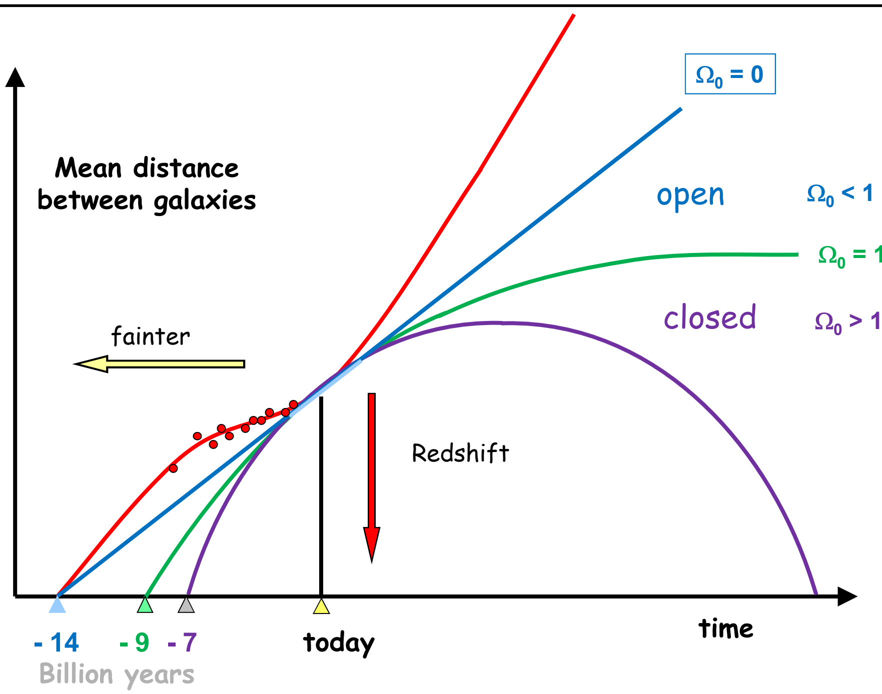
- Measure luminosity over several redshifts will give the combination of the densities

Measuring distances

- Type Ia Supernovae are the best cosmological distance indicators
- Measure them over a range of redshifts (out to z≈1) and then plot the Hubble diagrams

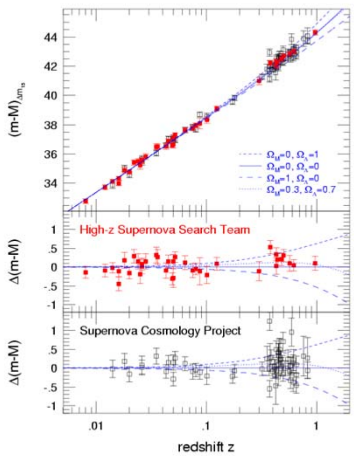
Measure acceleration





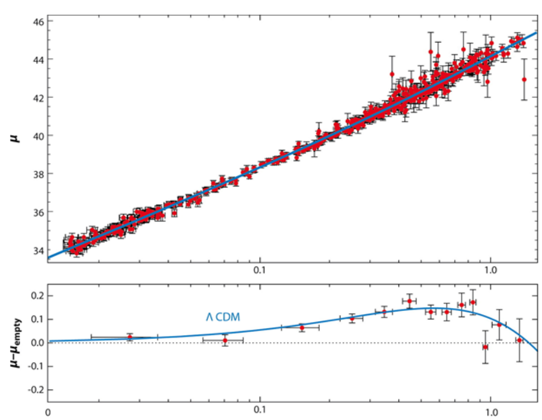
The Supernova Hubble diagram

- Two teams pursuing this research



The SN Ia Hubble diagram today

- Now over 700 SNe Ia measured
- Clear evidence of an additional late acceleration



Goobar A, Leibundgut B. 2011.
Annu Rev. Nucl. Part. Sci. 61:251–79

To be continued ....