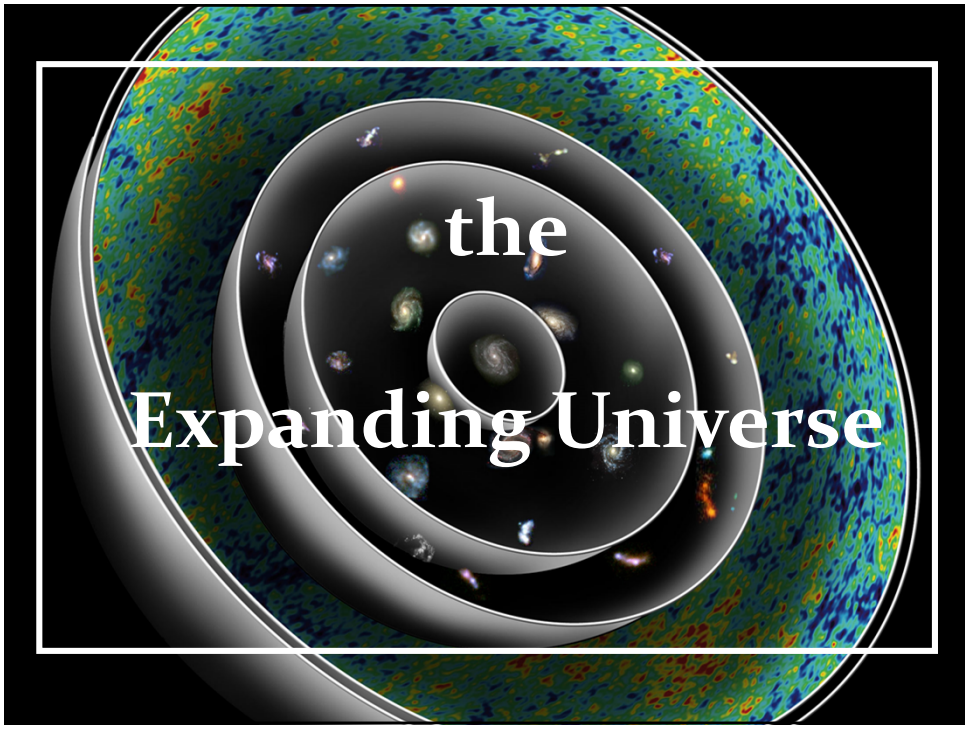



# Albert Einstein - 1915

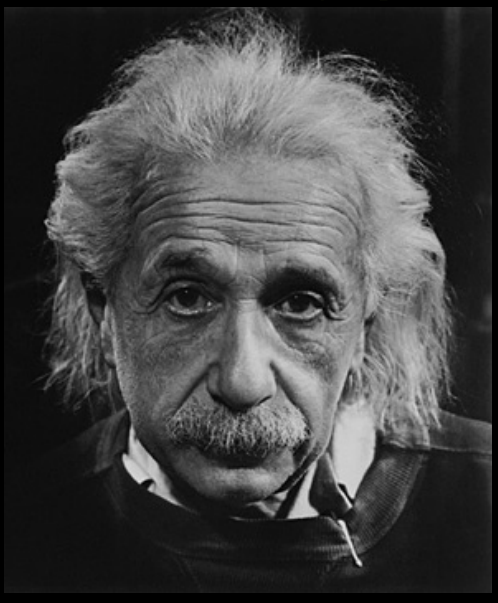
**Albert Einstein**
**(1879-1955; Ulm-Princeton)**

**father of theory of General Relativity (1915)**

**new theory of gravity opens road to Cosmology**

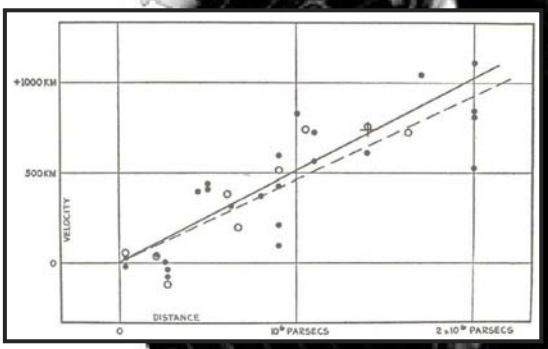
The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.

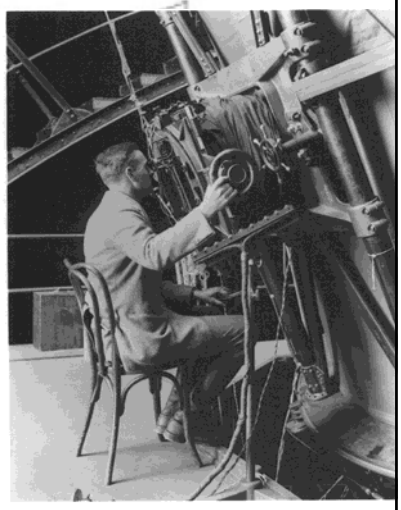
(Albert Einstein, 1954)



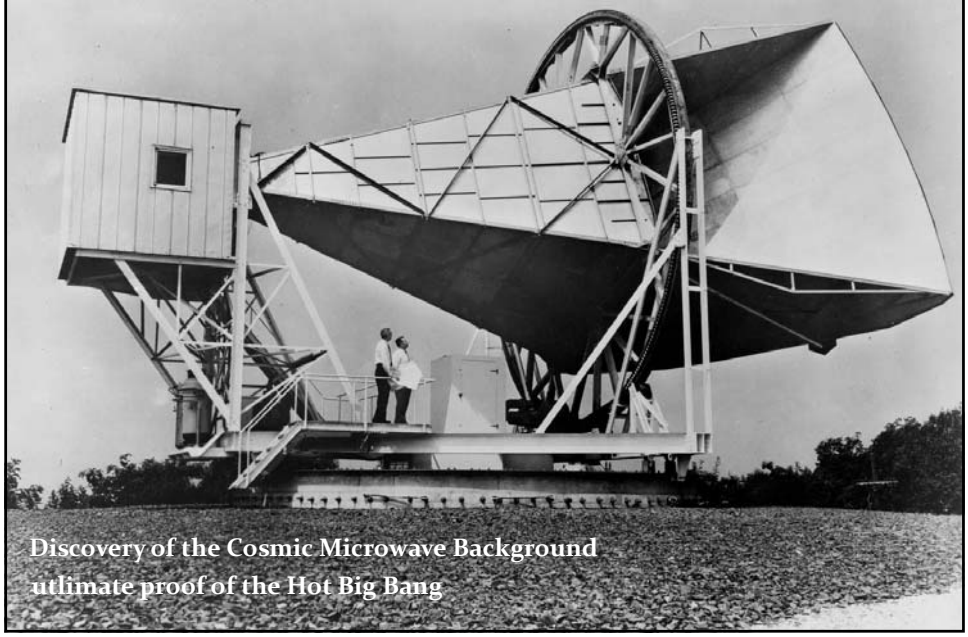
# Edwin Hubble - 1929

**Discovery of the Expanding Universe**



# Penzias & Wilson - 1965



**Discovery of the Cosmic Microwave Background**
**utlimate proof of the Hot Big Bang**

# Cosmology:

# Journey in Space & Time

## Velocity of Light

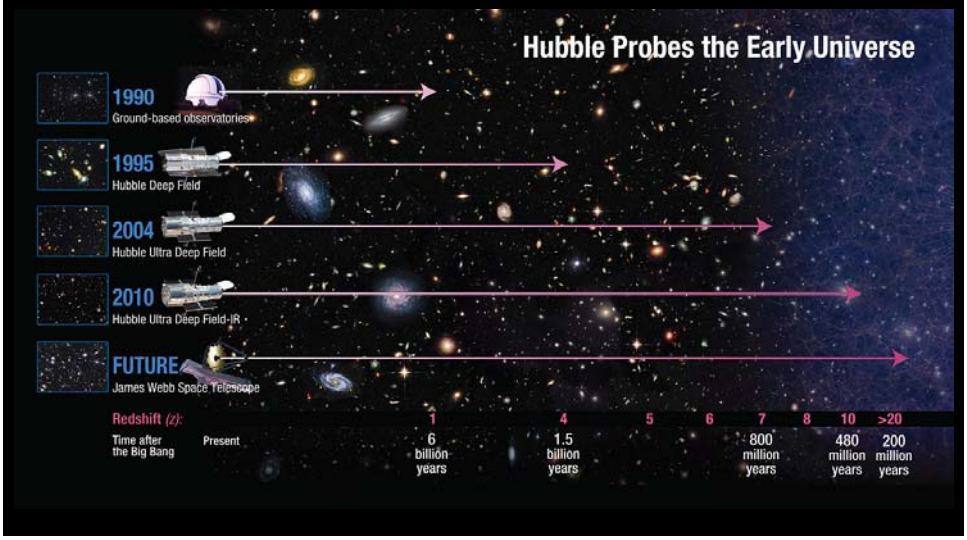
- The fastest way of communication in nature is by means of light.
- Light is an electromagnetic wave
  - and as quantum phenomenon: both a wave and particle nature:
  - light is the propagation of photons – light particles – which have a wave nature
- Einstein (1905):
  - the velocity of light propagation is CONSTANT, always, independent of from which system you look at it.
  - the velocity of light is the maximum velocity attainable in nature

$$c = 299792458\ m\,s^{-1}$$
$$= 1.080 \times 10^{9}\ km\ h^{-1}$$

# Cosmic Archaeology

- The finite velocity of light has highly interesting implications for the study of cosmology.
- Distances in the Universe are so vast – out to billions of lightyears - that the corresponding light travel time is in the order of billions of years:
  - this means that when receiving light from cosmological probes (galaxies at cosmological distances), the light was emitted billions of years ago.
  - hence, as we look deeper into space, we are looking back earlier and earlier in time
  - in other words, Cosmology is Archaeology !
- An additional consequence is that as cosmological timescales are in the order of billions of years, we see the universe change as we look further out into the Universe.

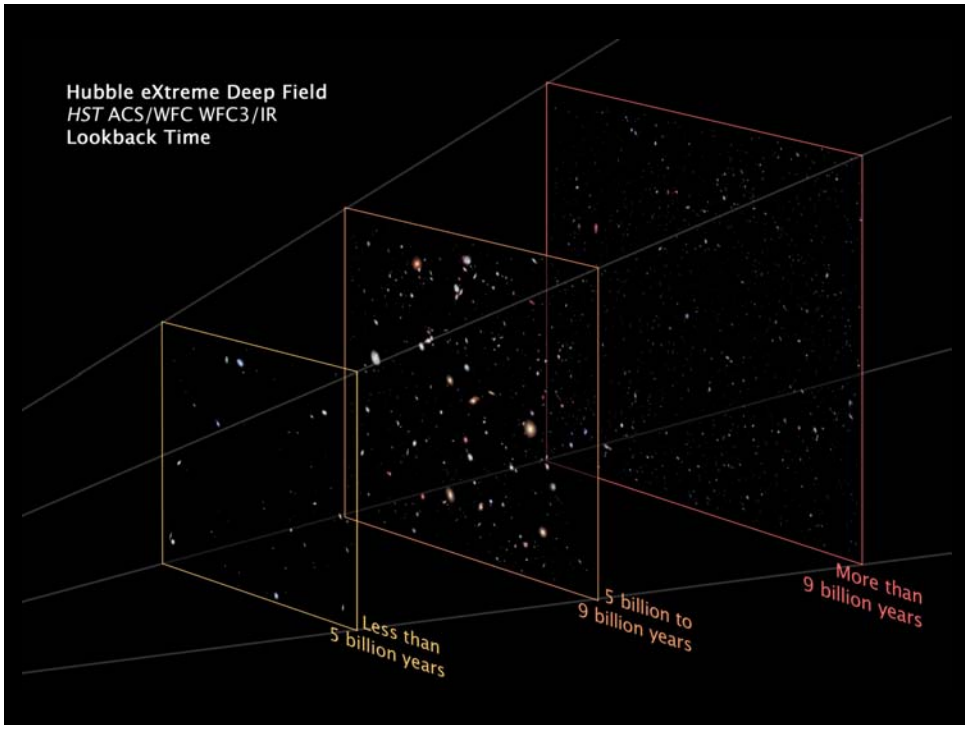
# Cosmic Depths & Time

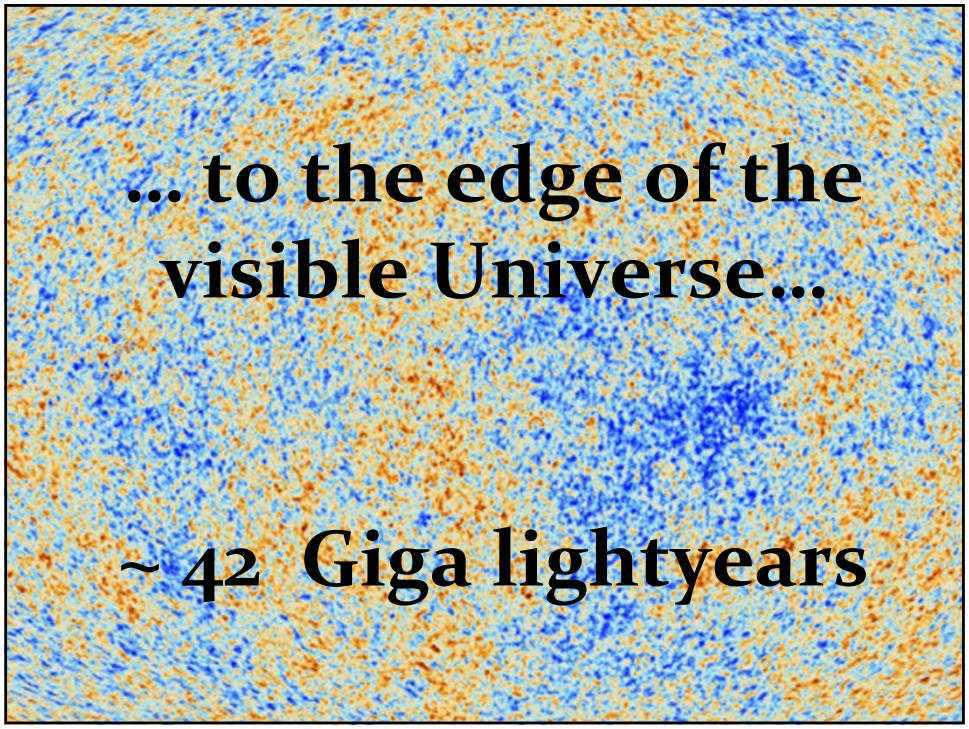


# to the depths of our Universe

Hubble Ultra Deep Field:

zwakste, roodste sterrenstelsels
~ 300-400 miljoen jaar
na de Big Bang (> 13 Gyr oud)



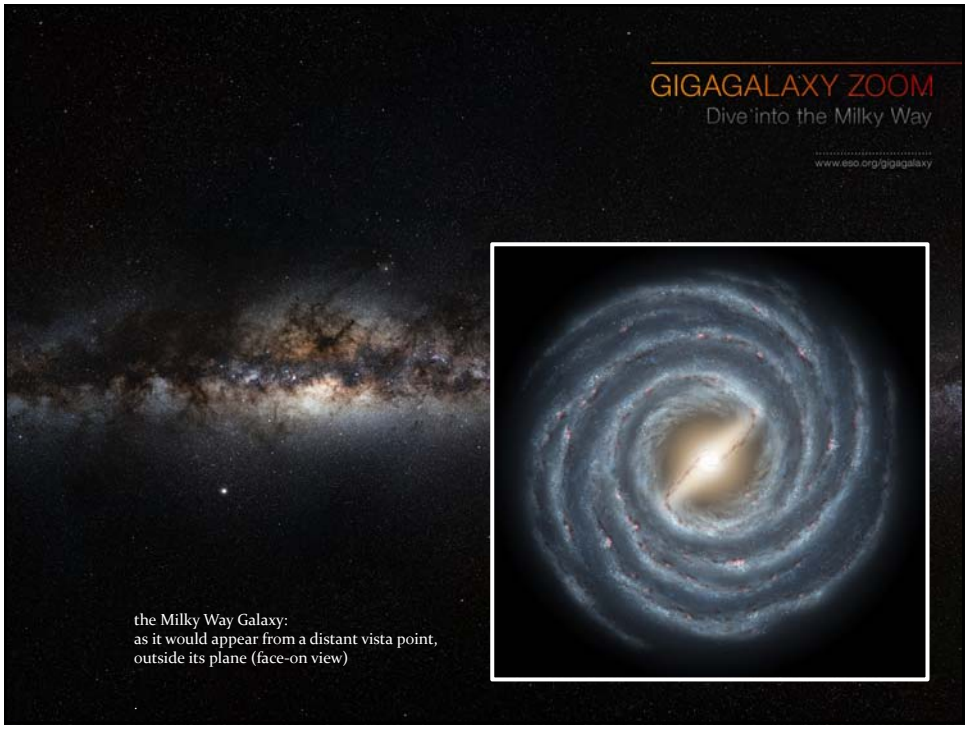


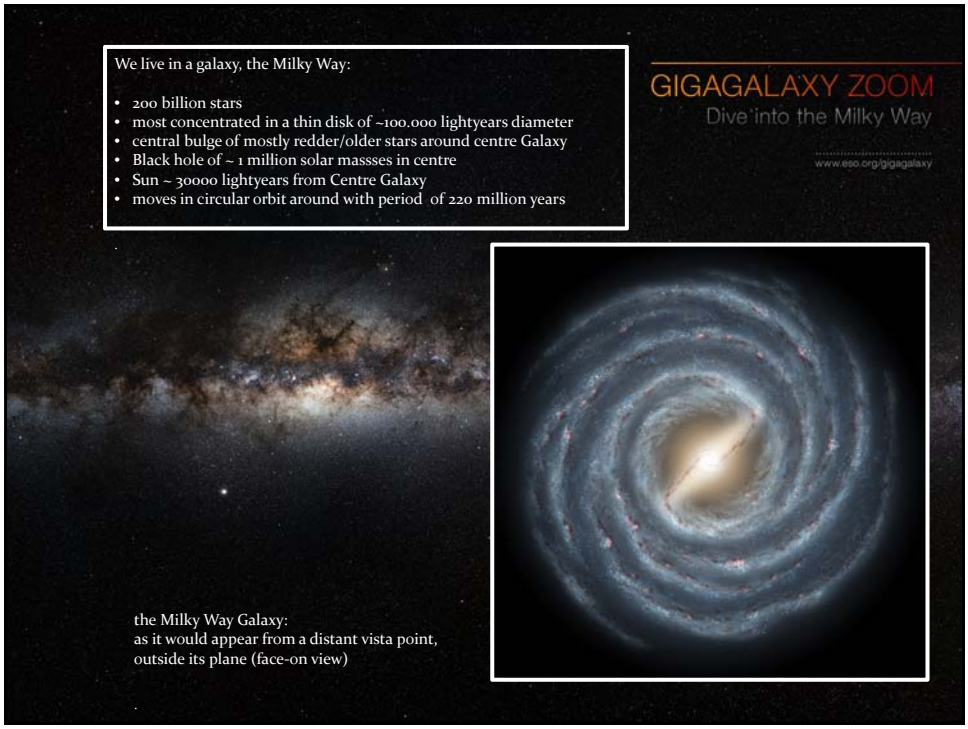

Universe
of
Galaxies

# a Universe of Galaxies

How to probe
the structure and dynamics
of the Universe ?

- Most mass not visible
- Galaxies as light beacons
- Use galaxies to map positions and motions of the galaxies


GIGAGALAXY ZOOM
Dive into the Milky Way
www.eso.org/gigagalaxy
the Milky Way Galaxy:
as it would appear from a distant vista point,
outside its plane (face-on view)


We live in a galaxy, the Milky Way:
• 200 billion stars
• most concentrated in a thin disk of ~100.000 lightyears diameter
• central bulge of mostly redder/older stars around centre Galaxy
• Black hole of ~ 1 million solar massses in centre
• Sun ~ 30000 lightyears from Centre Galaxy
• moves in circular orbit around with period of 220 million years
GIGAGALAXY ZOOM
Dive into the Milky Way
www.eso.org/gigagalaxy
the Milky Way Galaxy:
as it would appear from a distant vista point,
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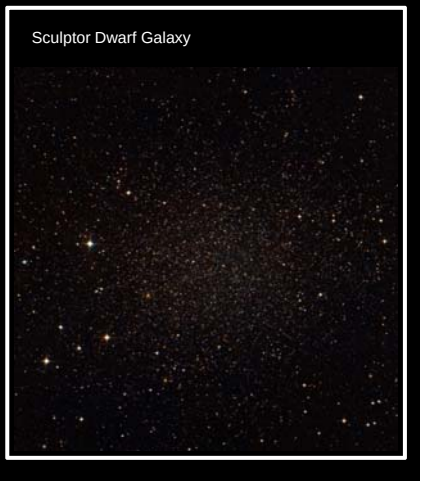
# Milky Way Satellites

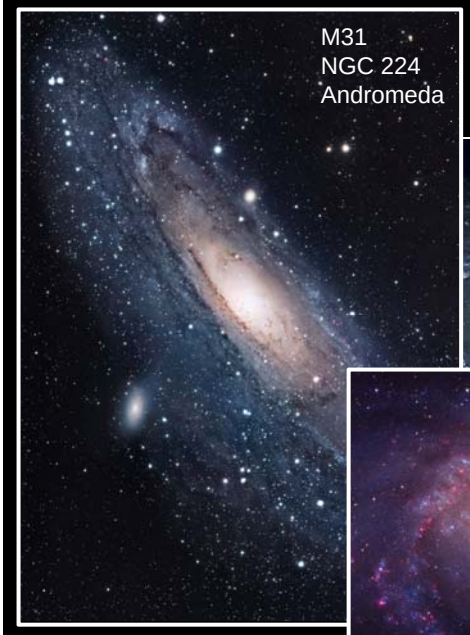

**The Milky Way has at least ~14 satellite galaxies.**

**Large & Small Magellanic Clouds: Irregular galaxies**

**all other satellite galaxies: Dwarf Spheroidal**

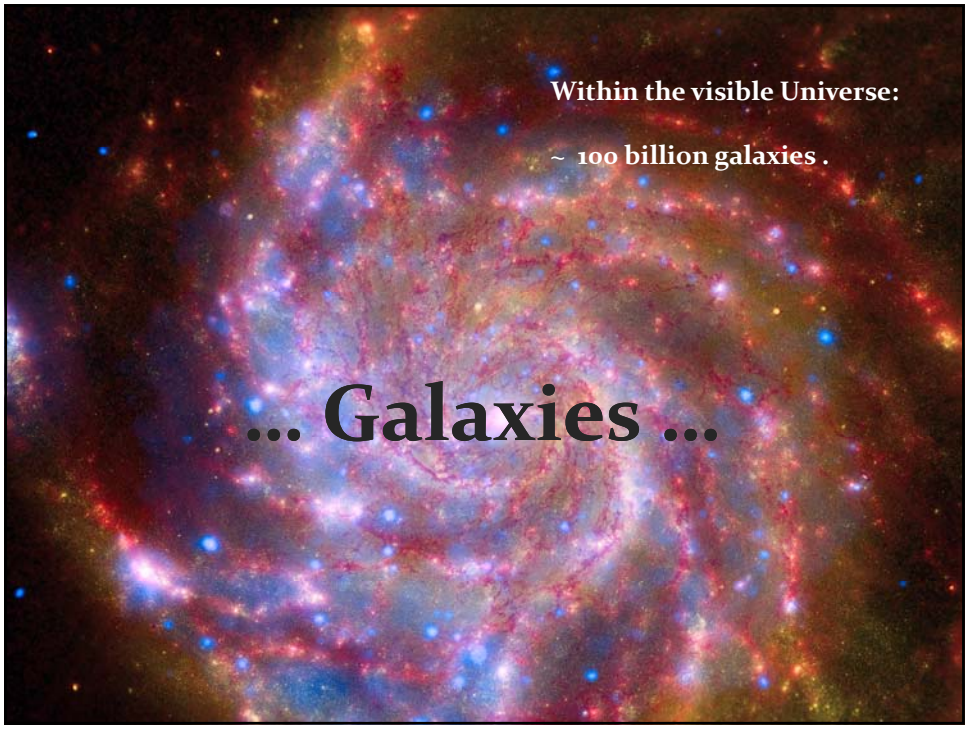
# Local Group

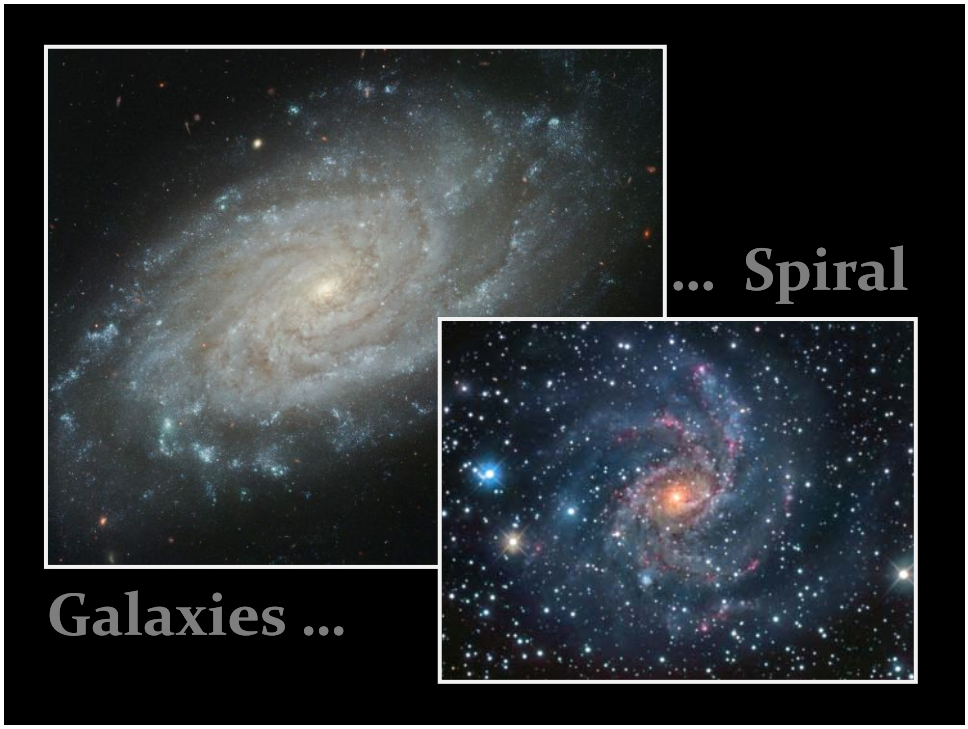
## Group Portrait



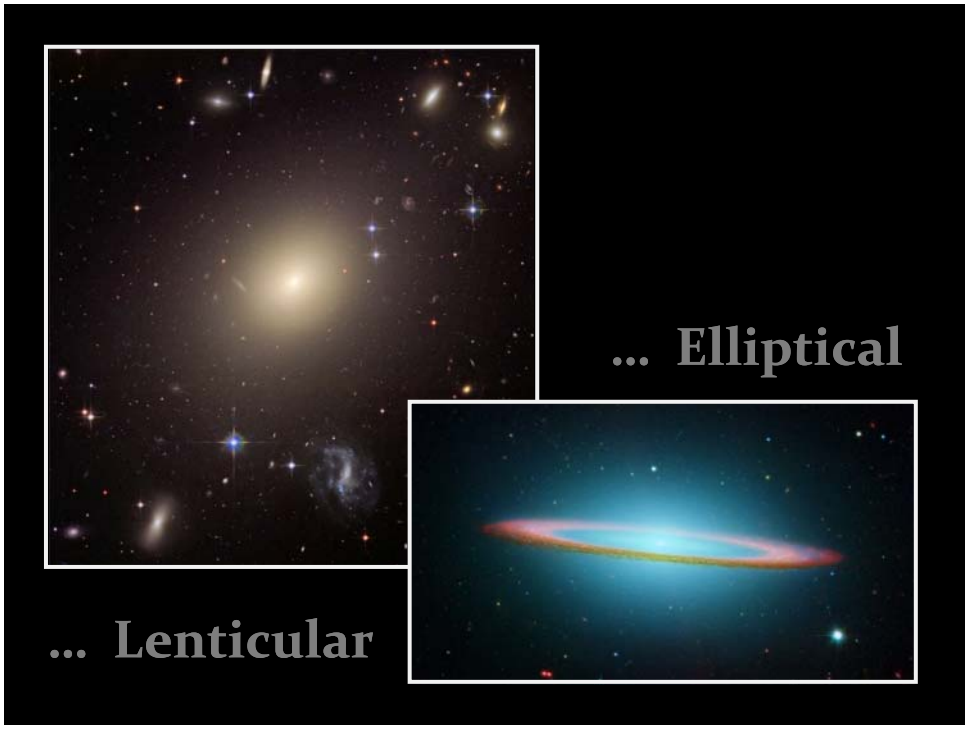


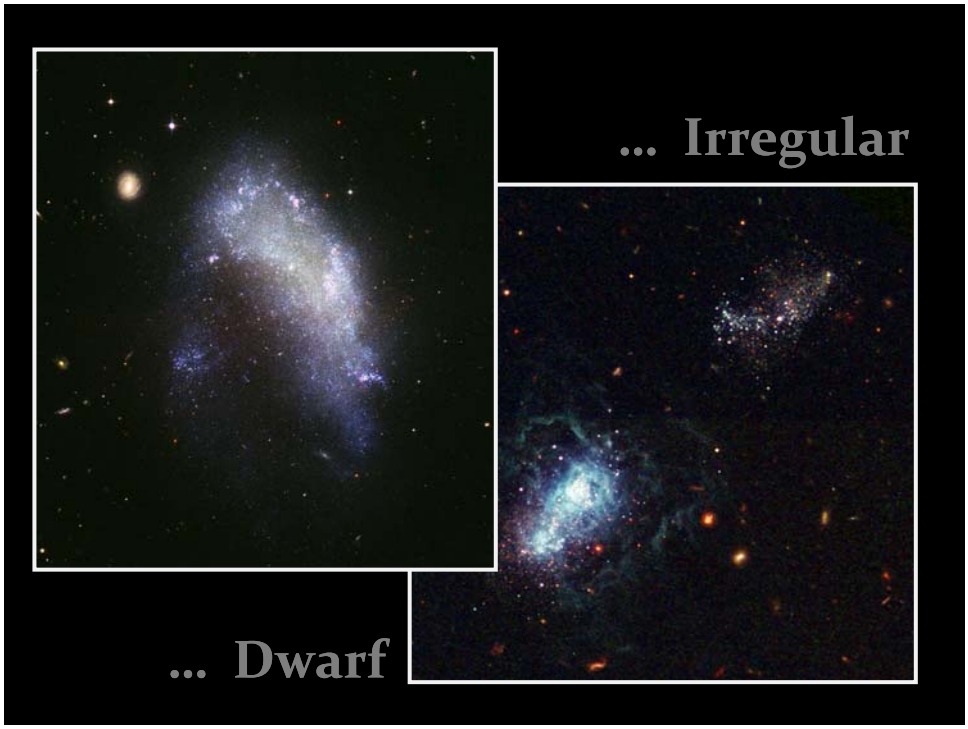

... Galaxies ...


Within the visible Universe:
~ 100 billion galaxies .
... Galaxies ...


... Spiral
Galaxies ...


NGC 1300:
a Milky Way look-alike ?


... Elliptical
... Lenticular


... Irregular
... Dwarf

# Galaxies & the Cosmos:

# Distances & Motions

# Distance Measurement

- Given the vast distances in the Universe, it is impossible to measure distances directly.
- Hence, we need to develop indirect methods that allow us to infer reliable estimates of the distances of objects.

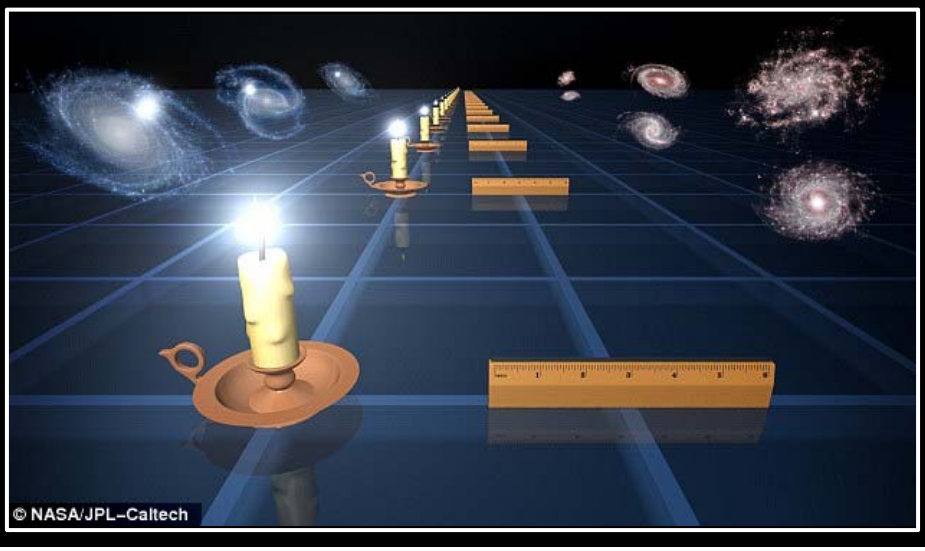
- One of the most practical means is based on the comparison between

  - observed brightness of an object
    ***(apparent brightness)***
  - intrinsic brightness of an object
    ***(absolute brightness)***

Compare this with distance of streetlights :


# Standard Candles

- To determine distances in the Universe, astronomers identify objects of which they know the intrinsic brightness: ***standard candles.***



# Standard Candles

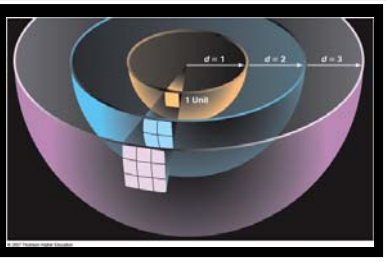
- To determine distances in the Universe, astronomers identify objects of which they know the intrinsic brightness:

***Standard Candles***

- Knowing the intrinsic luminosity/brightness $L_{abs}$ of a star/object, and measuring its apparent brightness, or flux S (light through per unit area),

the distance $D_L$ may simply be inferred from

$$S = \frac{L_{abs}}{4\pi D_L{}^2}$$




# Cepheids: Period-Luminosity

- **To be able to determine cosmological distances, the reference Standard Candles**

- need to be very bright objects/stars, whose intrinsic luminosity has been determined to high precision.

- It was **Henrietta Swan Leavitt (1868-1921)** who discovered that a particular type of variable stars, the Cepheid stars,
  - whose brightness varies as a result of their weeks long rhythmic pulsations –

  have a characteristic relation between

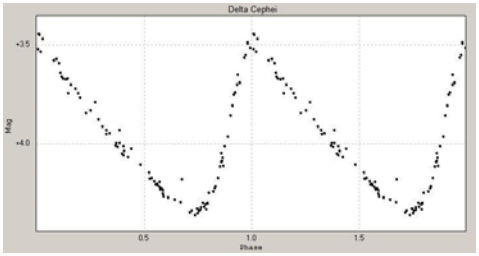
  - the period of their variation/pulsation
  - their intrinsic brightness
  - the socalled ***Period-Luminosity relation***

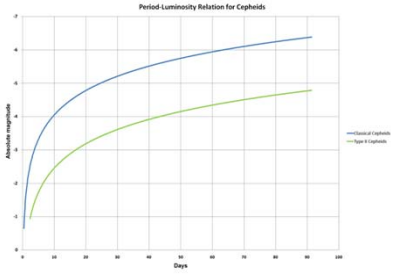
- As individual Cepheid stars are very bright
  - up to 100,000 times the Sun's luminosity, with masses in the order of 4-20 M⊙ -
  they can be identified in other galaxies

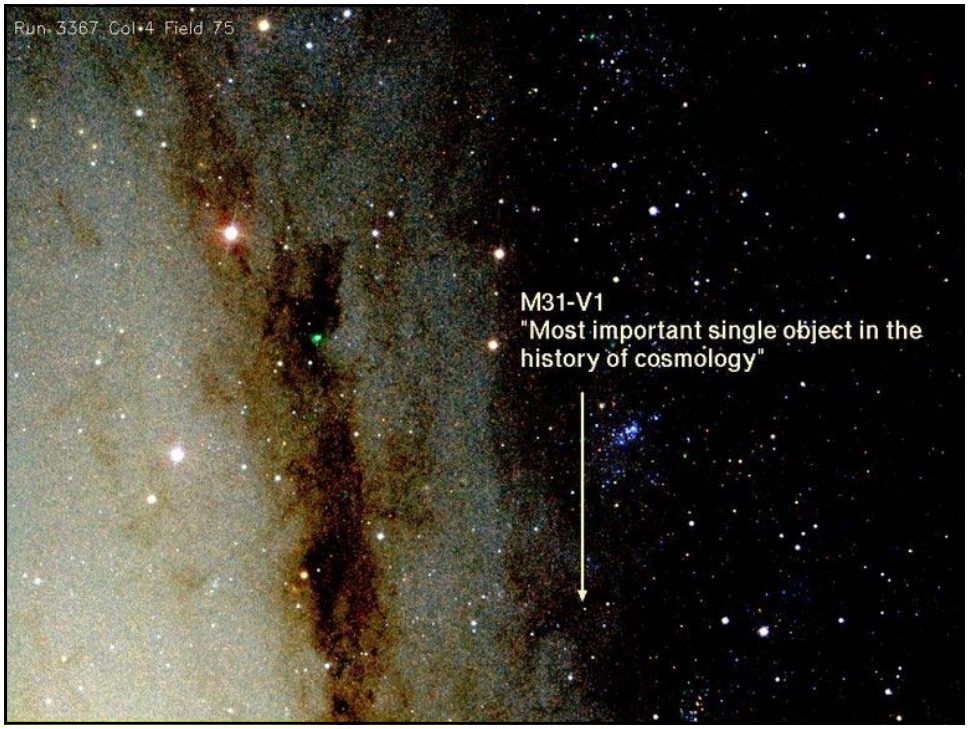
- and the distance to those galaxies determined.

# Henrietta Leavitt (1868-1921)

- Henrietta Swan-Leavitt started working in 1893 at Harvard College Observatory as one of the women human computers hired by Edward Pickering to measure and catalog brightness of stars on photographic plates.
- In this time, she made the fundamental discovery of the period-luminosity relation of Cepheid stars.
- During her lifetime she hardly got recognition for this discovery, which is one of astronomy's most significant ones as it allowed the measurement of extragalactic distances.
- Edwin Hubble used this relation to establish the distances to nearby galaxies and discover the expansion of the Universe.



# Andromeda-V1:

## the object that changed the Universe

- October 6, 1923:
  Edwin Hubble 45 minute exposure of
  the Andromeda galaxy M31 with the
  100 inch Hooker telescope at Mount Wilson
- Identifies 3 stars as N, thinking they are Novae
- Comparison with earlier plates of same region,
  he realizes one is a variable: VAR !
- And that it is a Cepheid variable, enabling the
  determination of the distance to M31
- finding it is ~ 1 million lightyears
- Virtually overnight,
  our perception of the Universe, and cosmic distances,
  changed radically !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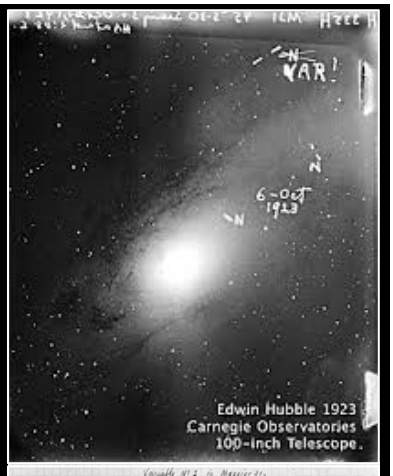
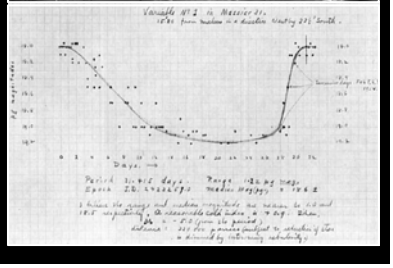
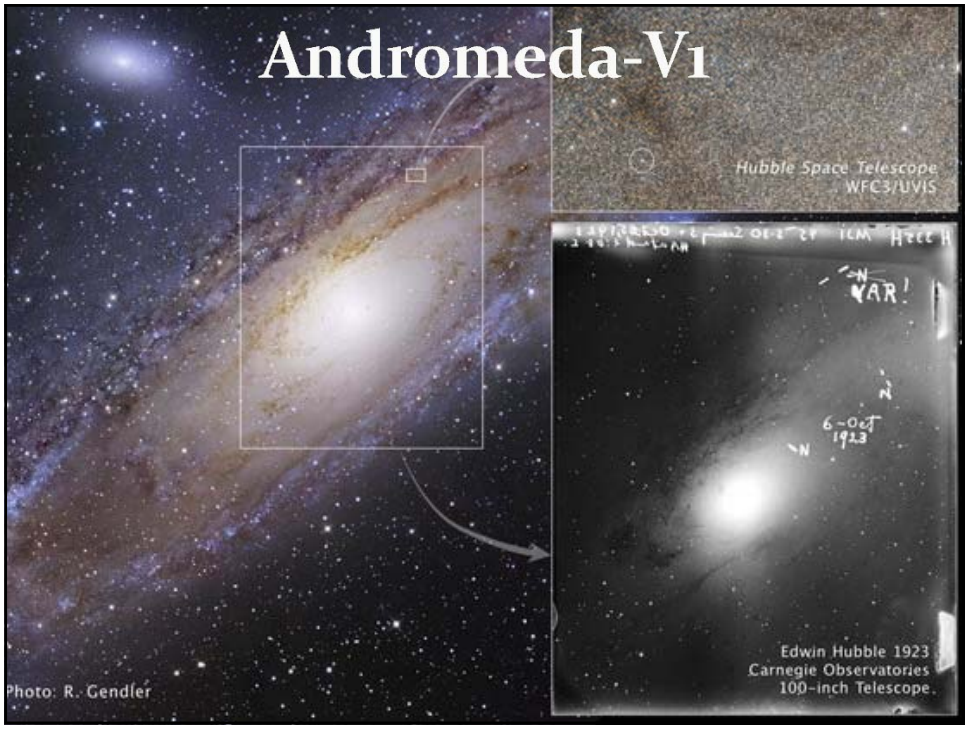
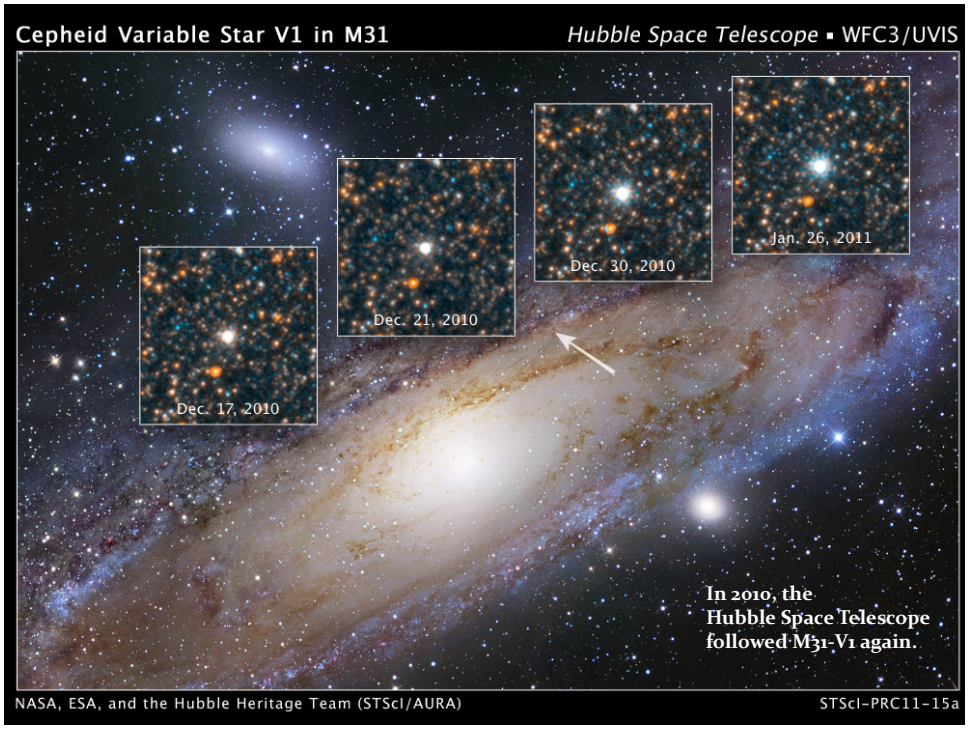
  our perception of the Universe,
  - of cosmic scales and distances -
  changed in a radical and revolutionary way !




Andromeda-V1
Hubble Space Telescope
WFC3/UVIS
VAR!
6 Oct 1923
Edwin Hubble 1923
Carnegie Observatories
100-inch Telescope.
Photo: R. Gendler


Cepheid Variable Star V1 in M31
Hubble Space Telescope ▪ WFC3/UVIS
Dec. 17, 2010
Dec. 21, 2010
Dec. 30, 2010
Jan. 26, 2011
In 2010, the
Hubble Space Telescope
followed M31-V1 again.
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
STScI-PRC11-15a

# Galaxy Velocities: Redshift

- Velocity measurement:

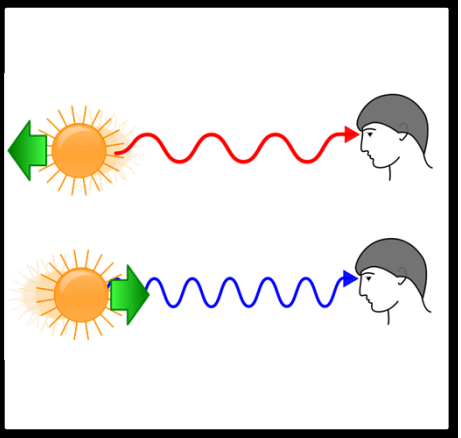
redshift/blueshift of radiation emitted by a source (galaxy, star)

- Comparable to Doppler shift:

the wavelength of radiation emitted by a source changes as it has a velocity towards or away from us:

towards us:
- towards shorter wavelength/higher frequency
- towards blue

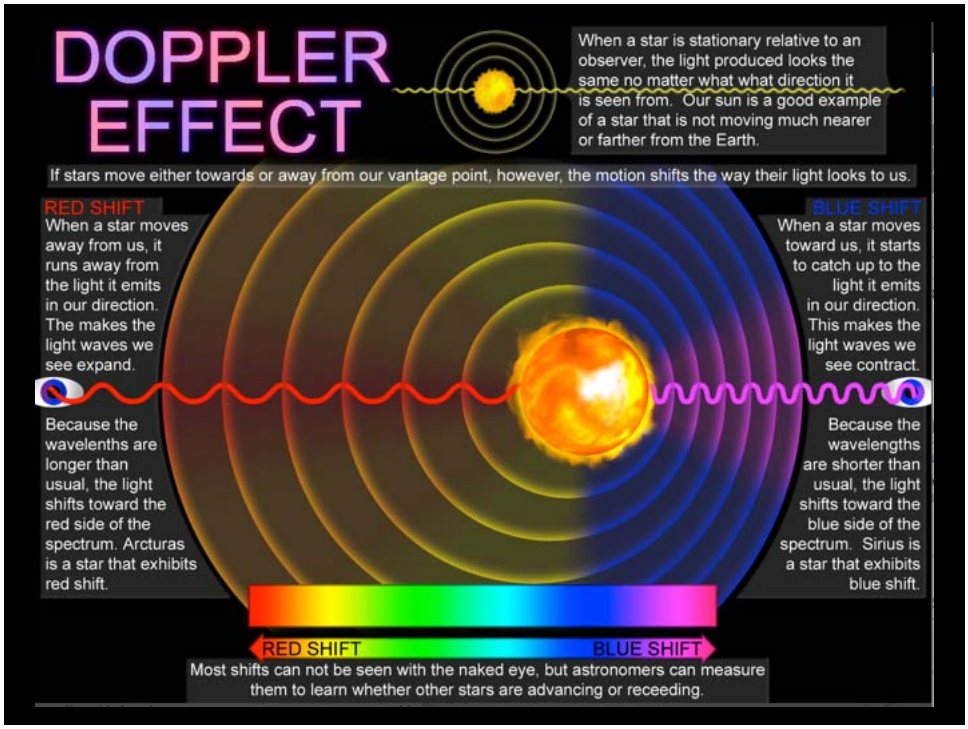
away from us:
- towards larger wavelength/lower frequence
- towards red

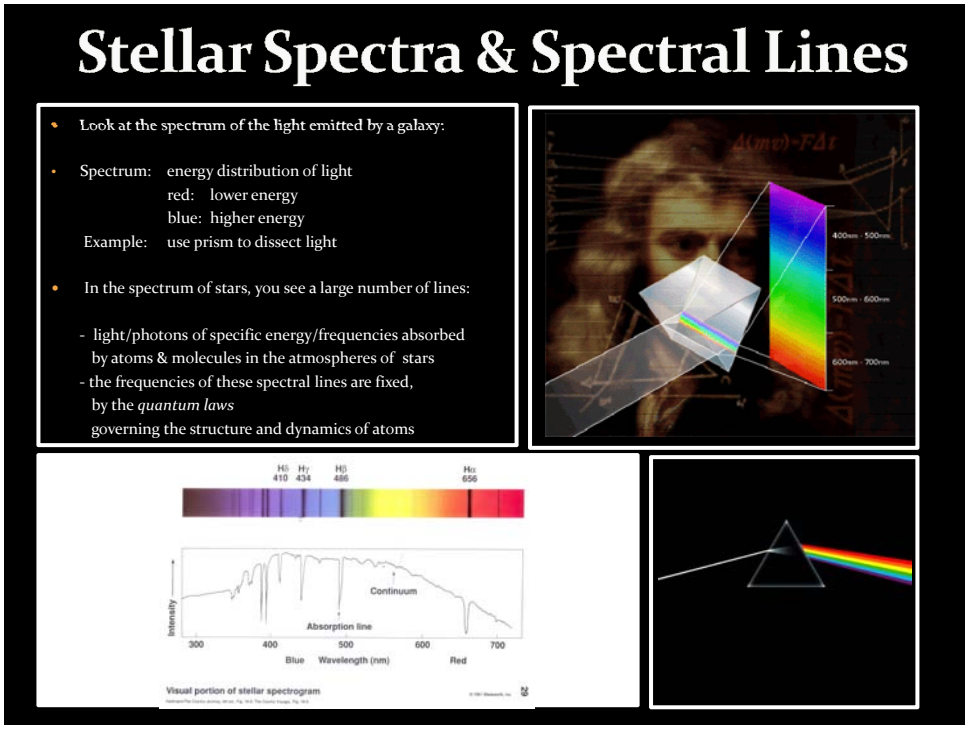


# Doppler Effect

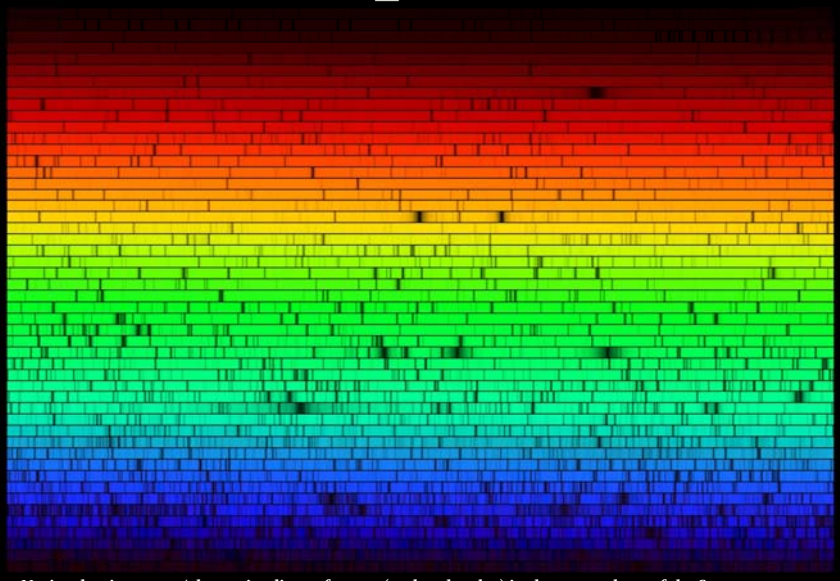

The Doppler effect explains why objects moving towards us or away from us at high speed appear to have their colours shifted either towards blue or red respectively.

When an object moves towards us, the crests of the light waves we see from it are compressed together, making the wavelength of the light shorter (and hence bluer), while for an object moving away the separation between crests is stretched, making the light's wavelength longer (and hence redder). In this simulation, the monochromatic source of light, as it moves right, would appear blue to an observer on the right-hand side, and red to an observer on the left.


DOPPLER EFFECT
When a star is stationary relative to an observer, the light produced looks the same no matter what what direction it is seen from. Our sun is a good example of a star that is not moving much nearer or farther from the Earth.
If stars move either towards or away from our vantage point, however, the motion shifts the way their light looks to us.
RED SHIFT
When a star moves away from us, it runs away from the light it emits in our direction. The makes the light waves we see expand.
BLUE SHIFT
When a star moves toward us, it starts to catch up to the light it emits in our direction. This makes the light waves we see contract.
Because the wavelenths are longer than usual, the light shifts toward the red side of the spectrum. Arcturas is a star that exhibits red shift.
Because the wavelengths are shorter than usual, the light shifts toward the blue side of the spectrum. Sirius is a star that exhibits blue shift.
RED SHIFT
BLUE SHIFT
Most shifts can not be seen with the naked eye, but astronomers can measure them to learn whether other stars are advancing or receeding.


Stellar Spectra & Spectral Lines
Look at the spectrum of the light emitted by a galaxy:
Spectrum: energy distribution of light
red: lower energy
blue: higher energy
Example: use prism to dissect light
In the spectrum of stars, you see a large number of lines:
- light/photons of specific energy/frequencies absorbed by atoms & molecules in the atmospheres of stars
- the frequencies of these spectral lines are fixed, by the quantum laws governing the structure and dynamics of atoms
Hδ 410
Hγ 434
Hβ 486
Hα 656
Continuum
Absorption line
Intensity
300
400
500
600
700
Blue
Wavelength (nm)
Red
Visual portion of stellar spectrogram

# Solar Spectrum



**Notice the signatures/absorption lines of atoms (and molecules) in the atmosphere of the Sun**

# Atoms & Spectral Lines

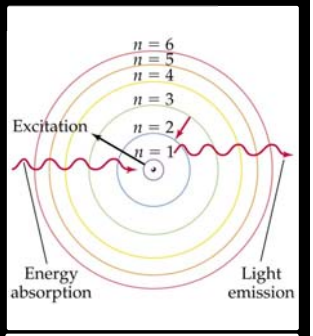
- Atoms (and molecules and other fundamental particles) are highly structured:

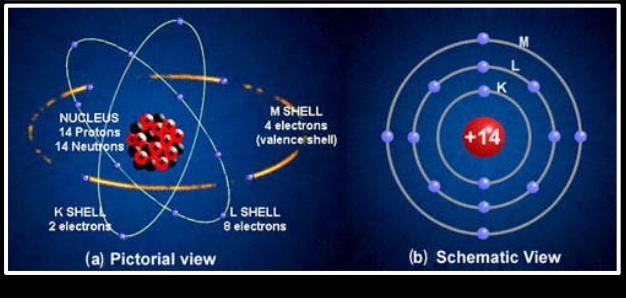
  - nucleus (consisting of protons and neutrons)
  - electron clouds, with electrons encircling the nucleus

- The precise structure is hard to imagine, and dictated by quantum physics (a world our visual imagination cannot fully grasp)

- From quantum physics we know that the electrons occupy a discrete set of orbits, with specific discrete energy levels (unlike the macroscopic world), entirely determined by the structure and dynamics of the atom.

- Energy transitions:
  discrete jumps between discrete atomic energy levels




The energy transitions go along with

- towards *higher level*:
  *absorption* of photon with that specific energy

- towards *lower* level:
  *emission* of photon with that specific energy

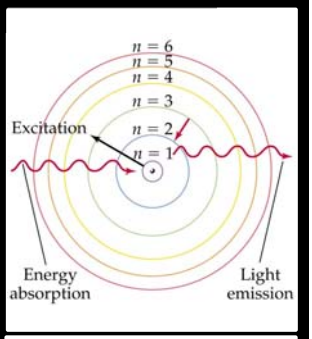
Energy of photon = frequency light

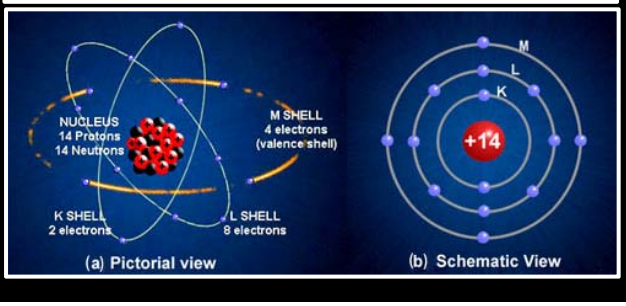
# Atoms & Spectral Lines

$$E = h\nu = \frac{hc}{\lambda}$$

**The energy of a photon is directly proportional to**
- **directly proporotional to its frequency (ie. colour)** $\nu$
- **inversely proportional to its wavelength** $\lambda$

**in this: c - velocity of light; h – Planck constant**




The energy transitions go along with

- towards *higher level*: *absorption* of photon with that specific energy
- towards *lower* level: *emission* of photon with that specific energy

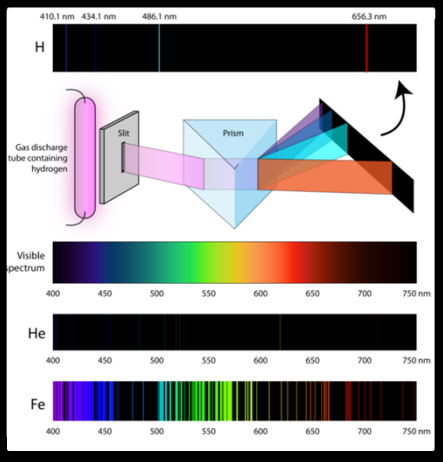
Energy of photon = frequency light

# Redshift Measurement & Spectral Lines

- When a star moves wrt. us, its light gets redshifted (away from us) or blueshifted (towards us)
- Also the spectral lines get shifted, ie. the frequency of the photons that were absorbed or emitted by the atoms in the stellar atmosphere.
- This provides the astronomer with a powerful tool:
  - find the spectral lines in a stellar spectrum
  - identify which atomic transition they correspond to
  - this always corresponds to very specific frequency / wavelength:

    the rest frequency $\nu_0$
    rest wavelength $\lambda_0$

    of the transition
  - compare this with the measured (redshifted or blueshifted) frequency $\nu$/ wavelength $\lambda$

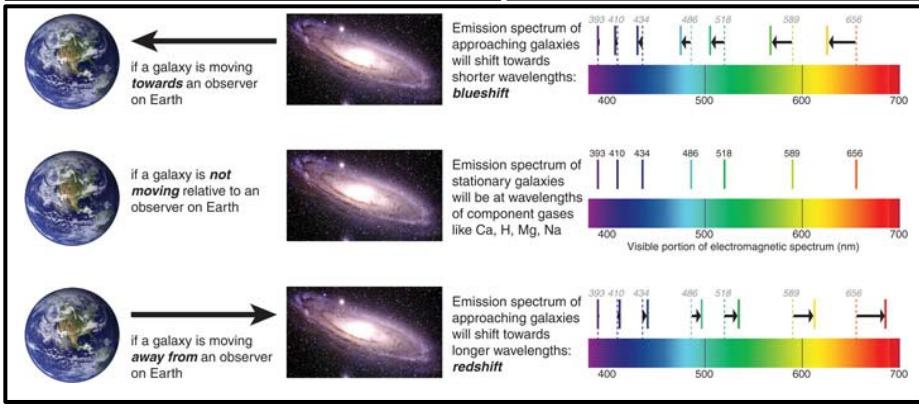



**Redshift:** $z = \frac{\lambda - \lambda_0}{\lambda_0}$

# Galaxy Spectra & Cosmic Redshift

- Galaxy spectra:
  - the combined light of 100s billions of stars
  - absorption lines mark the frequencies at which the atmospheres of the stars in the galaxy have absorbed light emitted by the stars
- Galaxy redshift determination:
  - identify (well-known and strong) spectral lines
  - compare to rest wavelength, then determine z

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$




# Redshifted Galaxy

# Slipher & Galaxy Redshifts

**Vesto Slipher (1875-1969)**

US astronomer who was the first to measure redshifts of galaxies

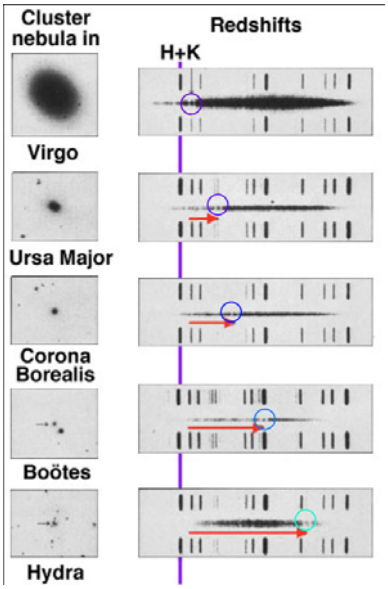
For a major part of his career he was director of

**Lowell Observatory, Flagstaff, Arizona, USA**

**1913:** Slipher finds that the spectrum of M31 is shifted to blue, corresponding to a velocity of ~ 300 km/s

Note: and, indeed, M31 is belonging with our Galaxy to a dense group of galaxies, the Local Group, and is moving towards us. M31 and the Galaxy will collide in 4.5 billion years

**1914:** additional redshifts of 14 spirals, some blueshifted (approaching), some redshifted (moving away)




# Slipher & Galaxy Redshifts

**Vesto Slipher (1875-1969)**

US astronomer who was the first to measure redshifts of galaxies

For a major part of his career he was director of

**Lowell Observatory, Flagstaff, Arizona, USA**

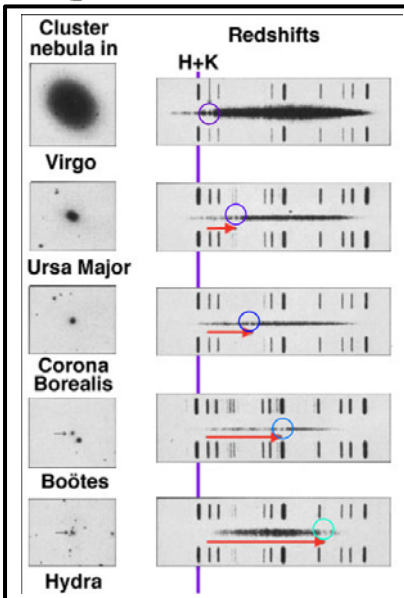
**1917:** Slipher measures more galaxy redshifts:

- more and more galaxies are redshifted
- proportion of redshifted galaxies such that it is no longer in accordance with random galaxy motions

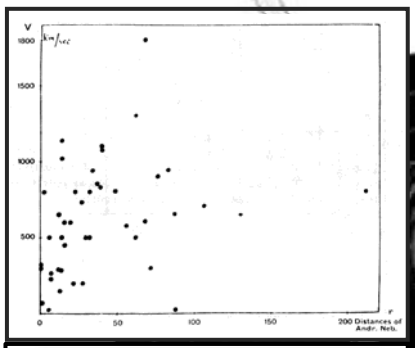
**AND**

- redshift on average larger as galaxy is smaller (ie. seems further away) !!!!!

***Is there a physical relationship between Radial Velocity and Distance of a galaxy ???***



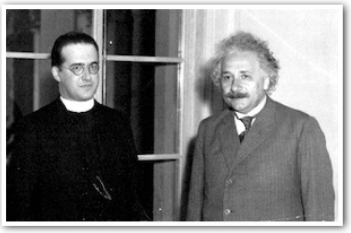
# Cosmic Expansion: first indications




**1925**: Lundmark, Swedish astronomer (1889-1958)

- radial velocity 44 galaxies
- rough distance estimates, comparing distances and brightnesses
- comparing to M31, estimated to be at 650,000 ly (in fact ~2,000,000 ly).

Lundmark concluded that there may be a relationship between galactic redshift and distance, but "not a very definitive one"



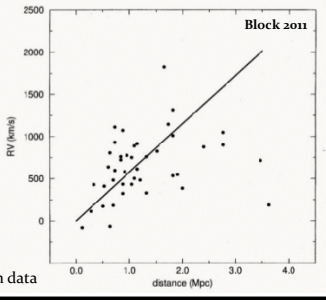
**1927**:
Georges Lemaitre (1894-1966)

Belgian priest

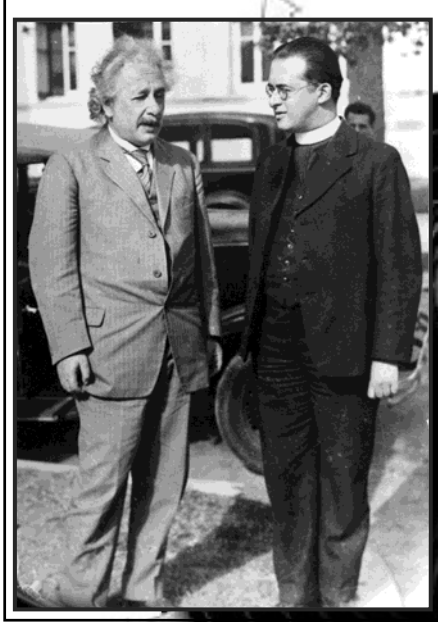
One of few who by 1920s understood General Relativity,

Predicted linear relationship redshift – distance

and … inferred it from data




# Lemaitre Expansion ?



**Georges Lemaitre (1894-1966)**

- On the basis of the General Theory of Relativity, Lemaitre derived the equations describing the expansion of the Universe:

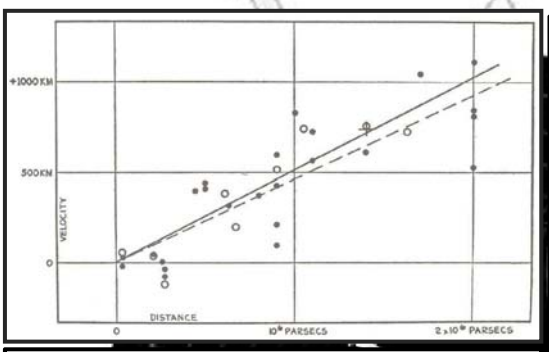
  Friedmann-Robertson-Walker-Lemaitre equations

- He then went on to show that this predicted a linear relation between redshift/recession velocity and distance.
- In a remarkable paper, in an "obscure" French-language journal,

  1927, Annales de la Societe Scientifique de Bruxelles, A47, 49

  he then used redshifts and distances of 42 galaxies to show that it seems indeed there is such a relation, and inferred the slope of the relation, now known as the ""Hubble constant"
- He assumed that the absolute brightness of galaxies can be used as standard candle, and thus inferred distances on the basis of galaxy brightnesses.
- Strangely enough, when the paper got later translated into English, the passage in which the expansion constant was determined got omitted.
- Had Hubble tried to cover up the earlier finding of expansion by Lemaitre ? A few years it was found Lemaitre himself who had tranlated the paper.
- Note: the scatter of the distance estimates on the basis of intrinsic brightness has a large scatter.. Significance of result was not very strong.

# Hubble Expansion – Hubble Law




Finally, the ultimate evidence for an expanding Universe follows in 1929, when Edwin Hubble (1889-1953) describes his finding of a

linear recession velocity – distance relation

This relation is now known as the **Hubble Law.**

*A relation between distance and radial velocity among extragalactic nebulae*
E. Hubble, Proc. Nat. Acad. Sciences, 1929, **15**, 168-173

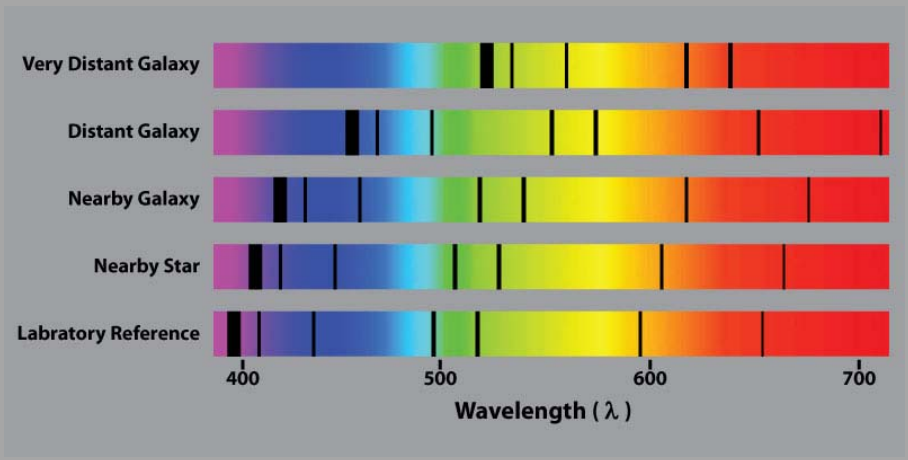
Note: Hubble himself never grasped that this was the evidence for an expanding Universe as described by the Friedmann-Lemaitre equations ie. as implied by Einstein's theory of General Relativity.

$$v_{rad} = cz = H_0 r$$

$H_0$ : **Hubble constant**

specifies expanssion rate of the Universe

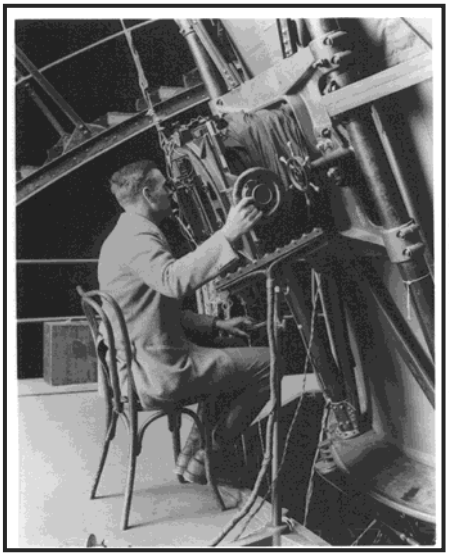
# Hubble Expansion & Galaxy Redshift




$$v_{rad} = cz = H_0 r$$

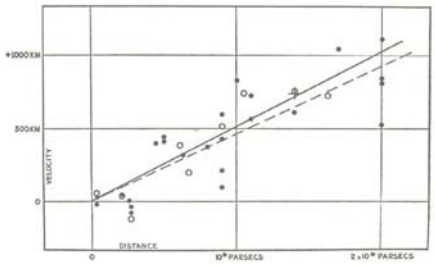
The Hubble law tells us that the further a galaxy is, the more redshifted it is.
Moreover, because this a linear relation, we can even estimate distances to galaxies once we know the value of the Hubble constant !

# Hubble Expansion



*Edwin Hubble*

*(1889-1953)*




$v = H\ r$

**Hubble Expansion**

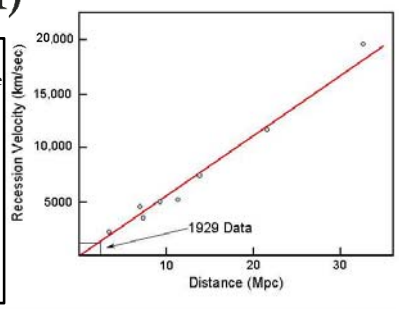
# Hubble – Humason (1931)

It was in the additional publication by Hubble & Humason (1931) that the linear Hubble relation was firmly established to far larger depths into the Universe:

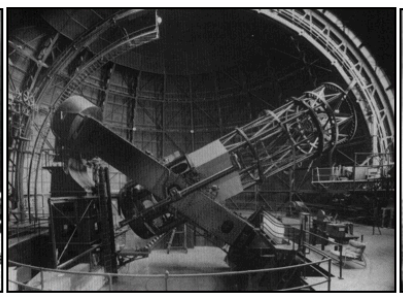
Hubble, Humason, 1931, Astrophys. J., **74**, 43

Humason (1891-1972) assisted Hubble, and did most of the work on world's most powerful telescope at the time, the 100 inch Mt. Wilson telescope.

Humason did not have a PhD, left school at 14, and was hired as janitor at Mt. Wilson Observatory.
His role in the discovery of the expansion of the Universe was seminal.



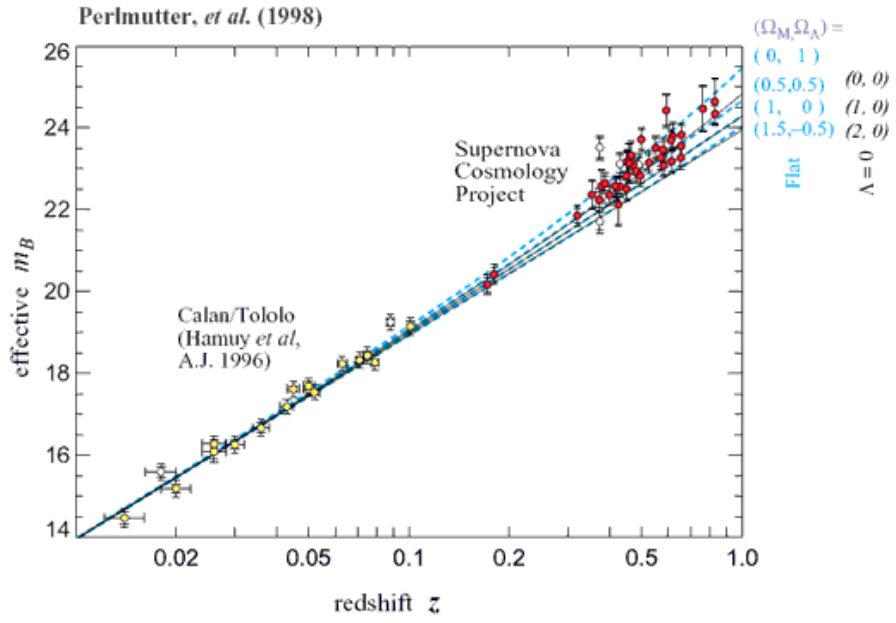

Edwin Hubble
1889 – 1953

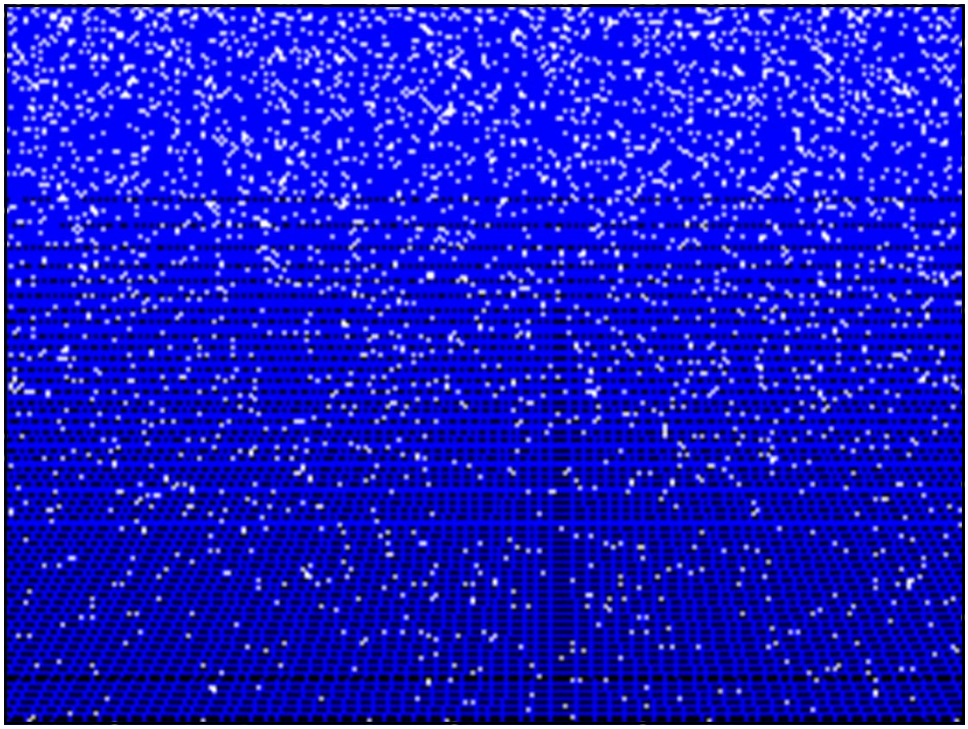


100 inch Mt Wilson Telescope

Milton Humason
1891 – 1972

# Hubble Diagram: end 20th Century



# Interpreting Hubble Expansion

- **Cosmic Expansion manifests itself in the in a recession velocity which linearly increases with distance**
- **this is the same for any galaxy within the Universe !**
- **There is no centre of the Universe: would be in conflict with the Cosmological Principle**

# Expanding Universe

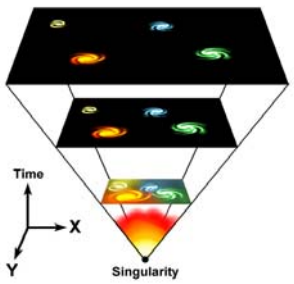
- Einstein, de Sitter, Friedmann and Lemaitre all realized that in General Relativity, there cannot be a stable and static Universe:
- The Universe either expands, or it contracts ...

- Expansion Universe encapsulated in a **GLOBAL expansion factor a(t)**
- All distances/dimensions of objects uniformly increase by a(t):

  at time t, the distance between two objects i and j has increased to

$$\vec{r}_i - \vec{r}_j = a(t)\left(\vec{r}_{i,0} - \vec{r}_{j,0}\right)$$

- Note: by definition we chose $a(t_o)=1$, i.e. the present-day expansion factor



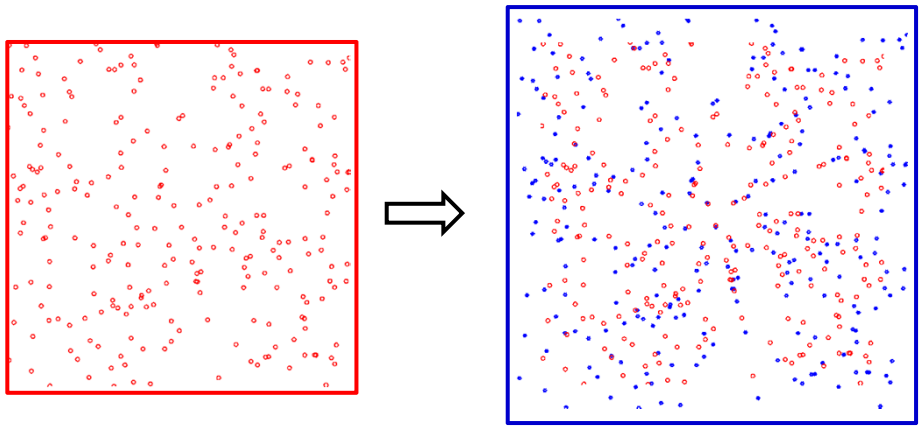
# Hubble Expansion

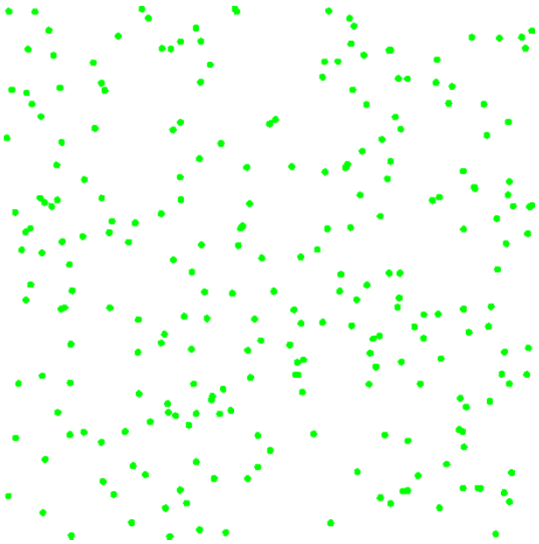
Space expands:

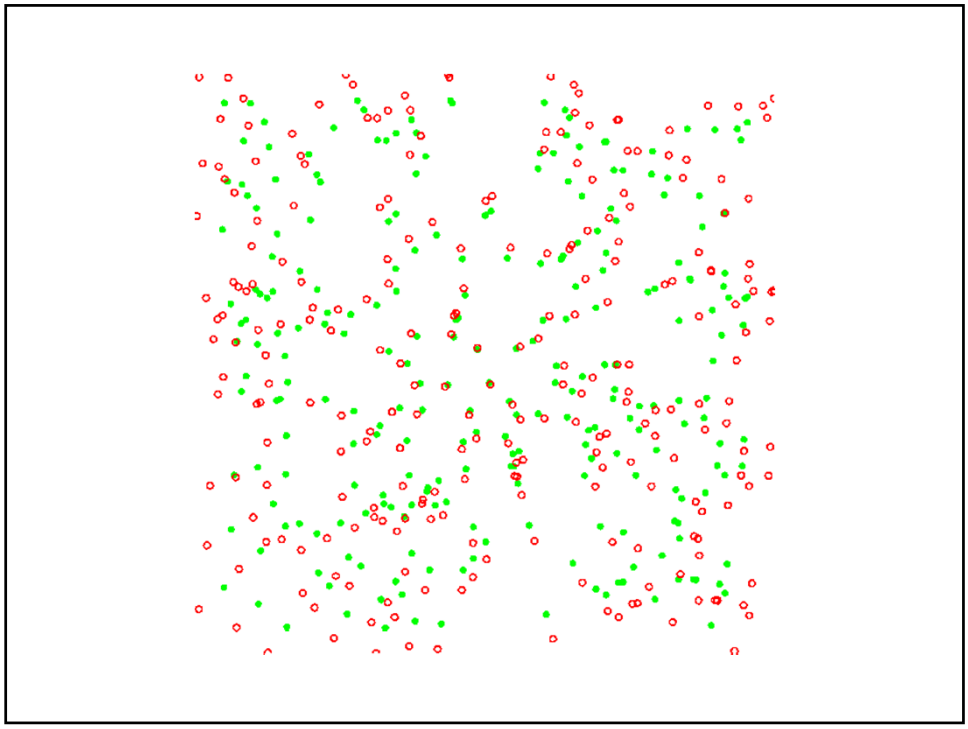
displacement - distance

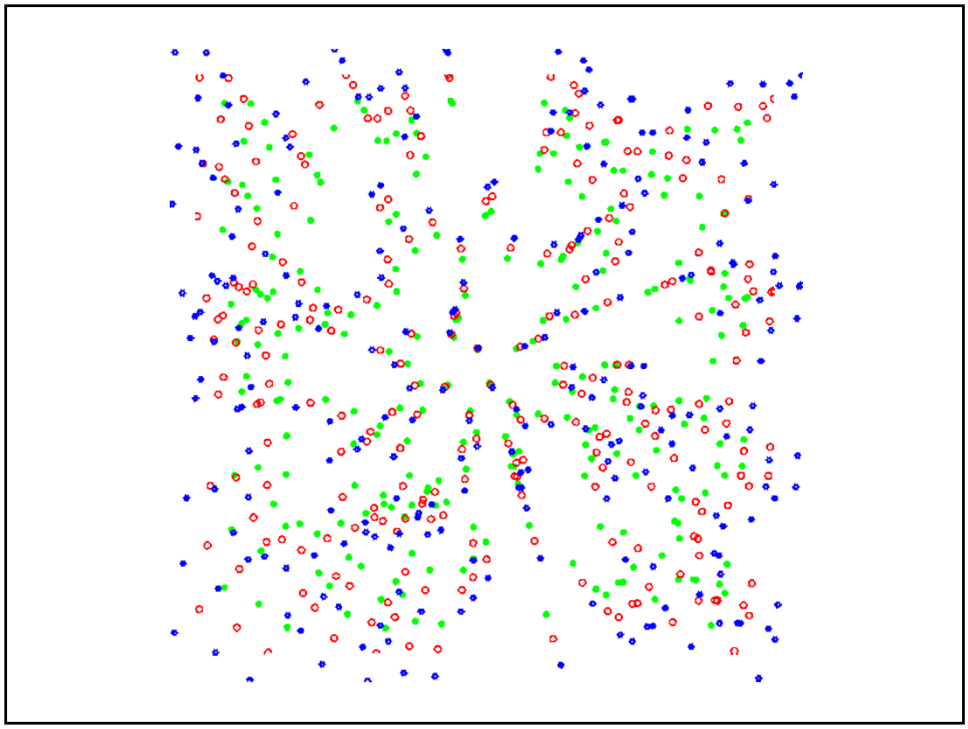
$$v = H\ r$$

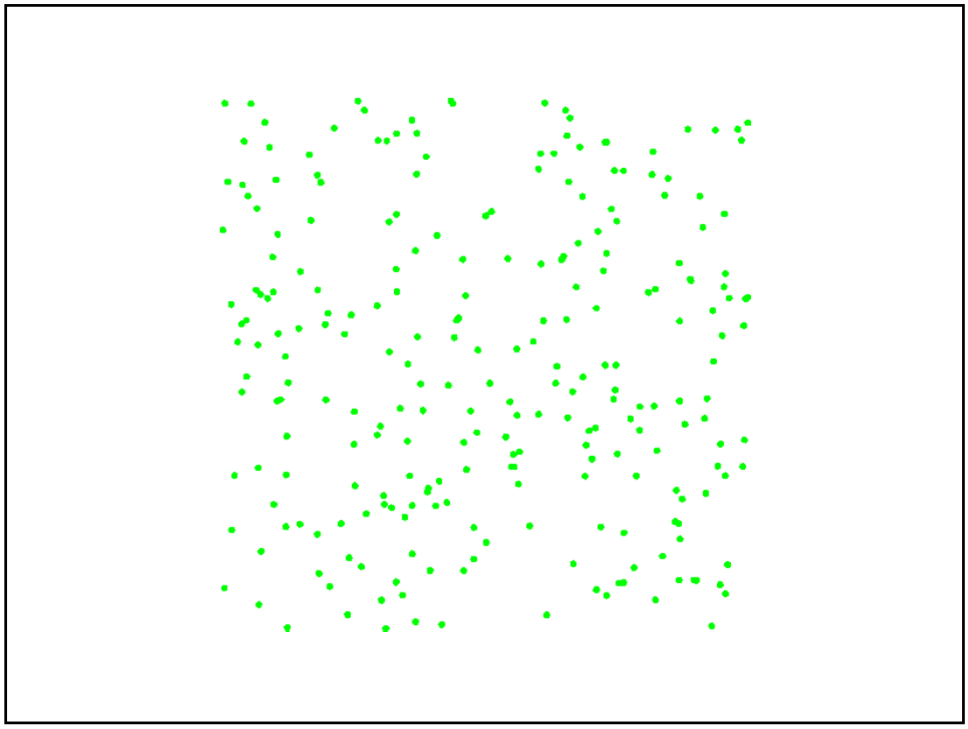
Hubble law: velocity - distance

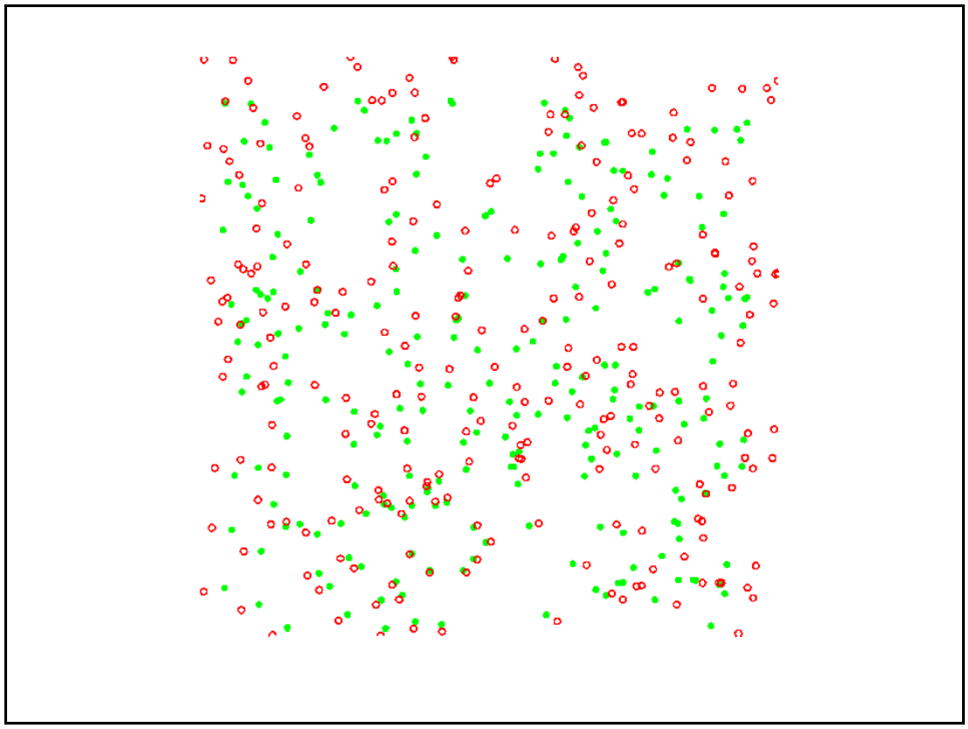


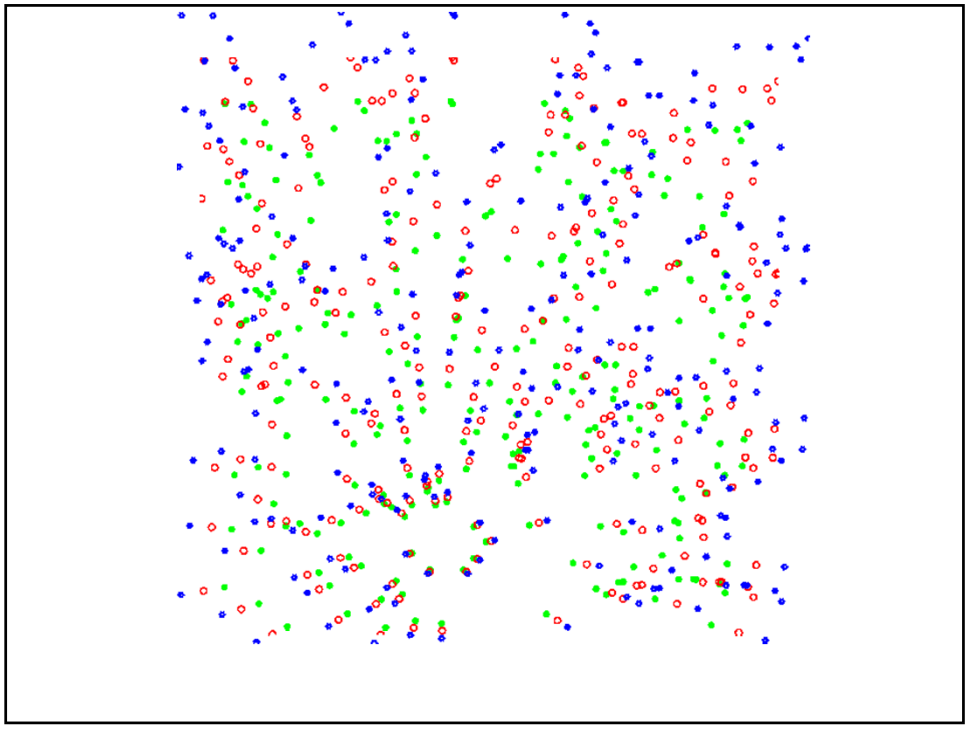












# Hubble Parameter

- For a long time, the correct value of the Hubble constant $H_o$ was a major unsettled issue:

  $H_o = 50$ km s$^{-1}$ Mpc$^{-1}$ ⟷ $H_o = 100$ km s$^{-1}$ Mpc$^{-1}$

- This meant distances and timescales in the Universe had to deal with uncertainties of a factor 2 !!!

- Following major programs, such as Hubble Key Project, the Supernova key projects and the WMAP CMB measurements,

$$H_0 = 71.9^{+2.6}_{-2.7}\ km\,s^{-1}Mpc^{-1}$$

# Hubble Time

- The repercussions of Hubble's discovery are truly tremendous: the inescapable conclusion is that the universe has a finite age !

- Just by simple extrapolation back in time we find that at some instant the objects will have touched upon each other, i.e. $r(t_H)=0$. If we assume for simplicity that the expansion rate did remain constant (which it did not !), we find a direct measure for the age of the universe, the

**Hubble Time:**

$$t_H = \frac{1}{H}$$

$$H_0 = 100h \ km\,s^{-1}Mpc^{-1}$$

$$\Downarrow$$

$$t_0 = 9.78h^{-1}\ Gyr$$

The Hubble parameter is usually stated in units of km/s/Mpc.
It's customary to express it in units of 100 km/s/Mpc, expressing the real value in terms of the dimensionless value $h=H_0/[100\ km/s/Mpc]$.
The best current estimate is $H_0=72$ km/s/Mpc. This sets $t_0 \sim 10$ Gyr.

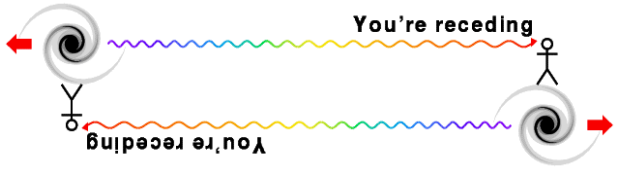
# Cosmic Redshift & Expansion

- As a result of the expansion of the Universe, not only distances get stretched:
- also the wavelength of light stretches along with the cosmic expansion
- Cosmic Redshift z: directly related to the expansion factor a(t) at which light gets emitted
- As a result, redshift z can be directly translated into:
  - distance of observed object
  - via its 1-1 relation with expansion factor a(t), alternative indication cosmic time t

# Cosmic Redshift

$$1 + z = \frac{1}{a} \Longleftarrow \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})}\,\lambda_0 \end{cases}$$

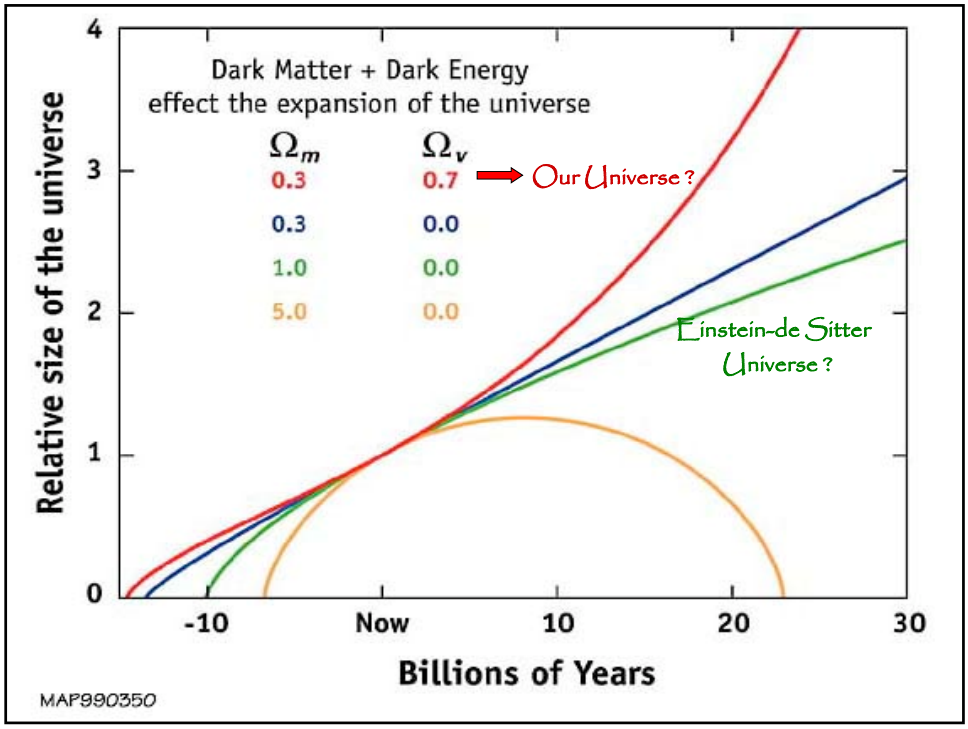
$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$




## Evolution & Fate Friedmann-Robertson-Walker-Lemaitre Universe

Completely determined by 3 factors:

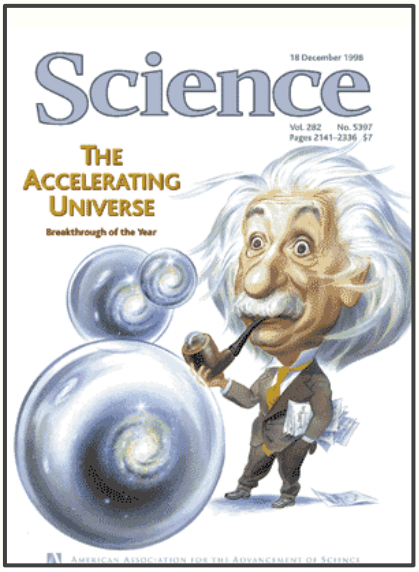
- energiy and matter content (density and pressure)
- geometry of the Universe (curvature)
- Cosmological Constant



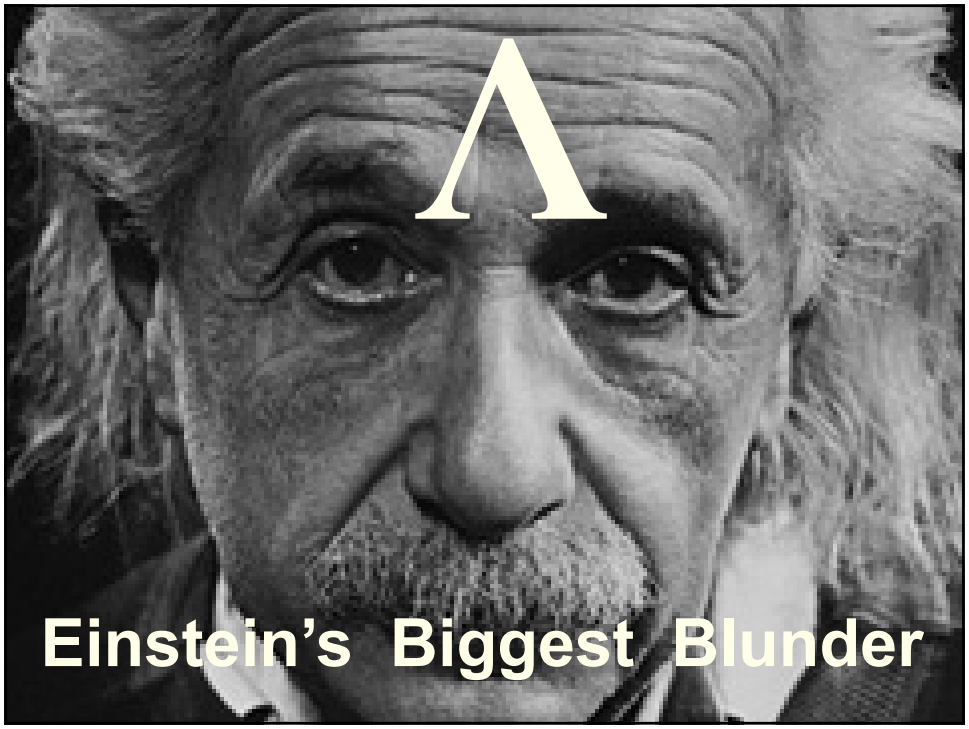

# Expansion

# Accelerates !

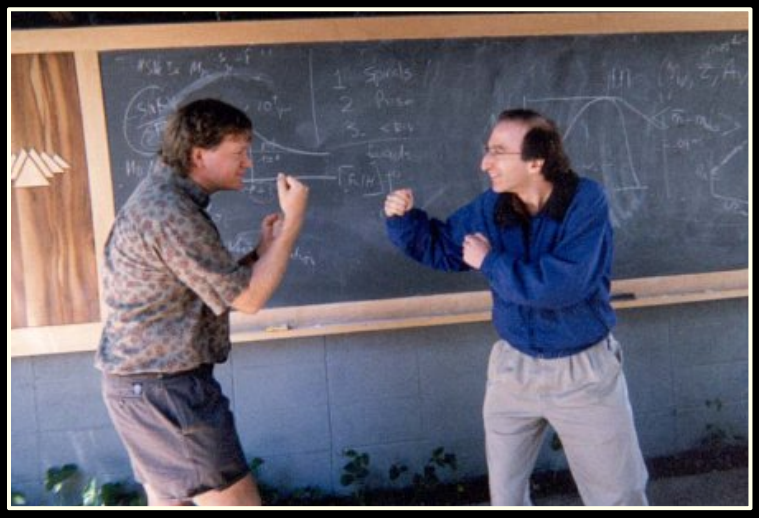
# Science Magazine 1998




**Science**
**Breakthrough of the Year**
**1998**



# Supernova Cosmology Project



## High-z Supernova Search Team

# Cosmic Fate

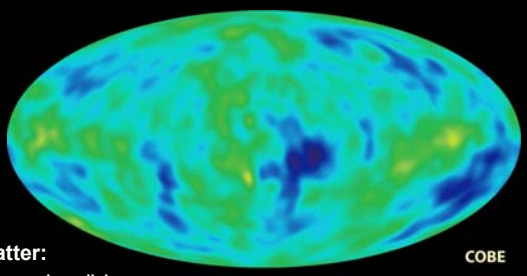
**100 Gigayears:**
**the end of Cosmology**

# 1990s:

# the Brewing Crisis

## Standard Cosmology ~ 1990

- FRW Universe
- augmented by Inflation
  - solved 4 fine-runing problems
  - accelerated expansion by
    factor $10^{60}$
    ~ $10^{-36}$-$10^{-34}$ sec after Big Bang
  - firm prediction:
    Universe flat: k=0, $\Omega_{tot}$=1



COBE

- Universe dominated by Dark Matter:
  - necessary to explain structure growth from primordial fluctuations, which COBE in 1992 had detected at $10^{-5}$ level
  - would have to make up 96% of matter density Universe
  - SCDM: "standard Cold Dark Matter", $\Omega_m$=1.0
- Succesfully explained large range of astronomical observations
  (or was made to explain these: "bias")

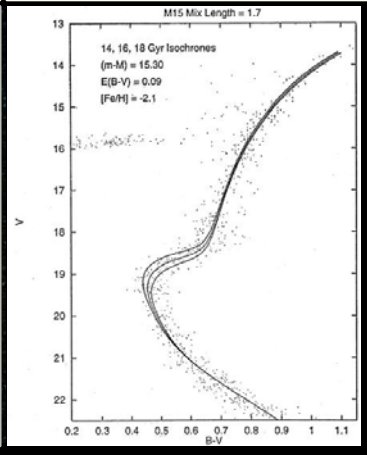
# Cosmic Age Crisis

**estimated age of the oldest stars in Universe far in excess of estimated age of matter-dominated FRW Universe:**

**Globular cluster stars: 13-15 Gyr**
**Universe: 10-12 Gyr**

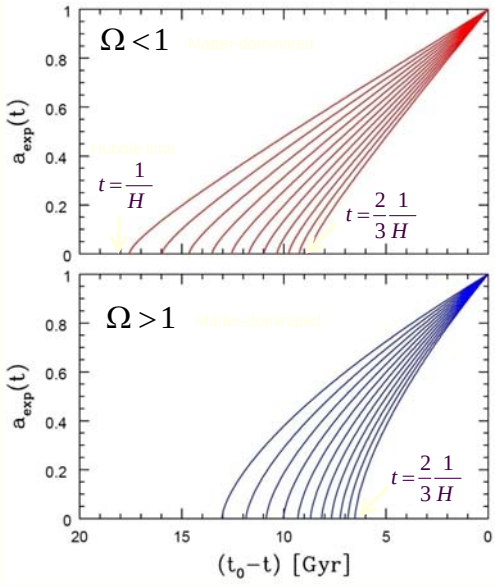
Globular Clusters

- Roughly spherical assemblies of 100,000-200,000 stars
- Radius ~ 20-50 pc: extremely high star density
- Globulars are very old, amongst oldest objects in local Universe
- Stars formed around same time: old, red, population
- Colour-magnitude diagram characteristic: accurate age determination on the basis of stellar evolution theories.


Typical 1980-1990s isochrone fit

# Age of the Universe




Age of a FRW universe at Expansion factor a(t)

$$H\,t = \int_0^a \frac{da}{\sqrt{\frac{\Omega_{rad}}{a^2} + \frac{\Omega_m}{a} + \Omega_\Lambda a^2 + (1-\Omega\ )}}$$

# Cosmic Age Crisis

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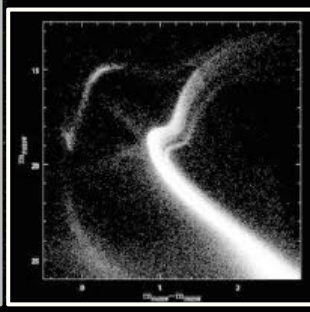
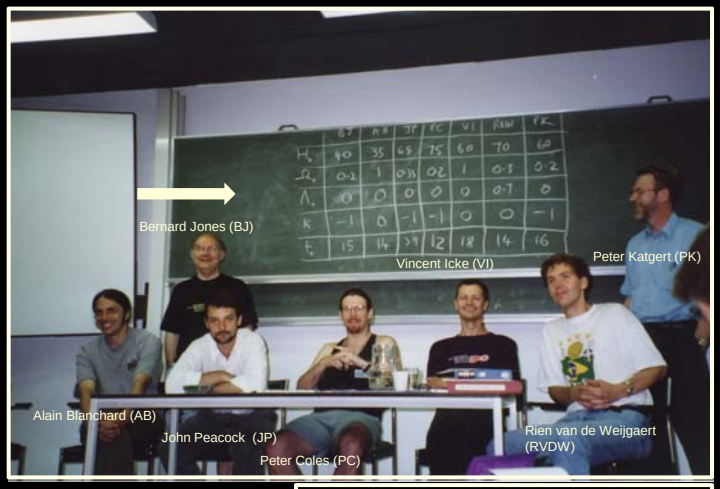


Typical 21st century colour-magnitude diagram:

multiple populations in Omega Centauri

# 1995: Cosmic Confusion

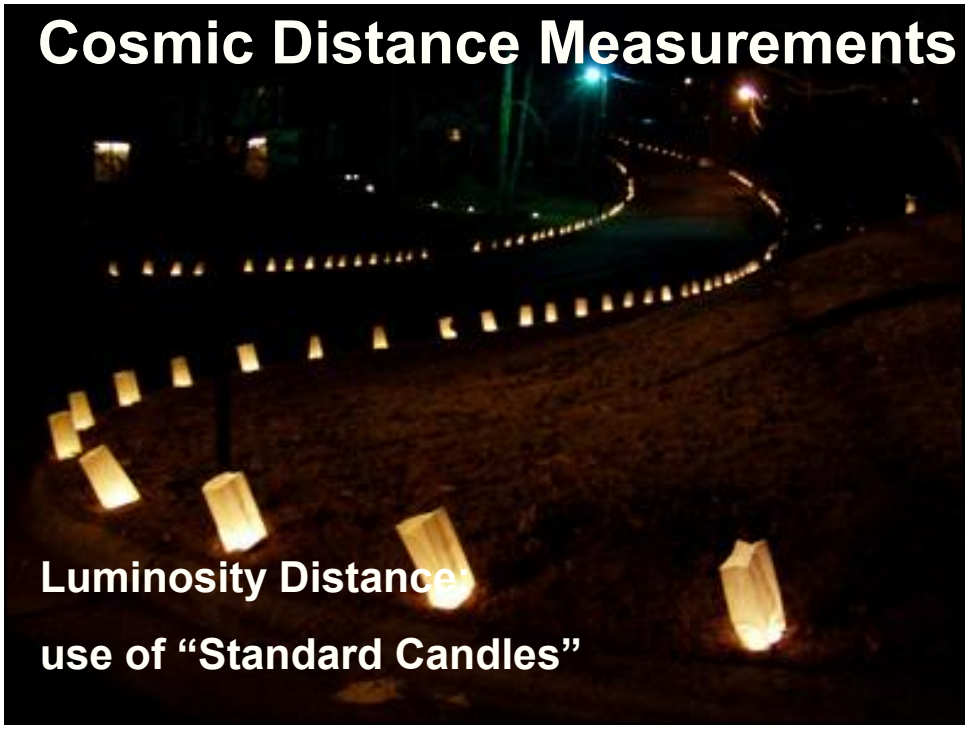
**EADN Summerschool, July 1995, Leiden**




**"Rien, be real … "**
**John Peacock**

# Standard Candle & Cosmic Distances

## Cosmic Distance Measurements



Luminosity Distance:

use of “Standard Candles”


# Standard Candles in Cosmology

# Luminosity Distance

Definition cosmological luminosity distance:

$$l = \frac{L}{4\pi D_L^{\,2}}$$

for a source with INTRINSIC luminosity L
OBSERVED brightness l

In a Robertson-Walker geometry, luminosity distance is

$$D_L = (1+z)D(z)$$

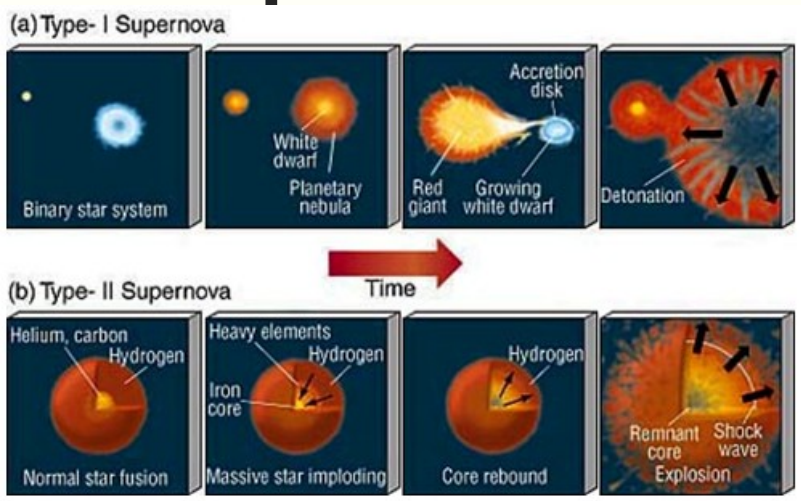
where D(z) is the cosmological distance measure

# Type Ia Supernovae

## Supernova Explosion & Host Galaxy


M51 supernovae

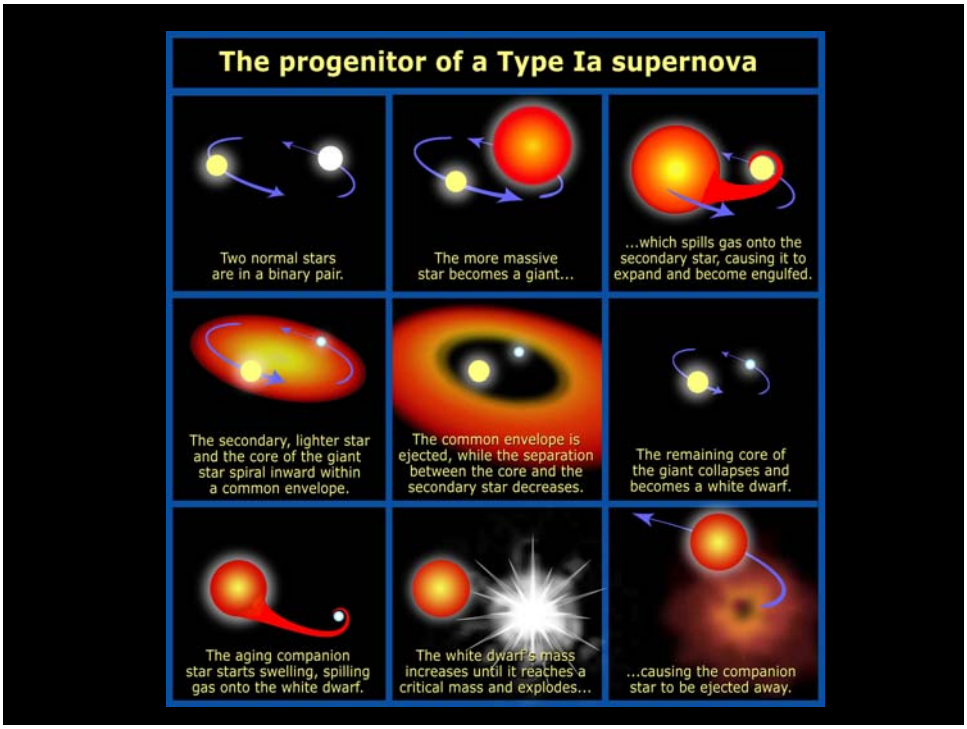
# Supernovae




**Supernovae:**
- gigantic stellar explosions
- within few months more radiation than Sun over entire lifetime
- shockwaves 5,000-30,000 km/s
- enrichment interstellar medium
- triggers star formation in surrounding ISM

**Supernovae, 4 types (spectral absorption lines):**
- SN II
- SN Ia - no hydrogen
- SN Ib
- SN Ic - no helium

# Type Ia Supernova Explosion




# Type Ia Supernova

- Amongst the most energetic explosions in our Universe:
  E ~ $10^{54}$ ergs
- During explosion the star is as bright as entire galaxy ! (ie. $10^{11}$ stars)

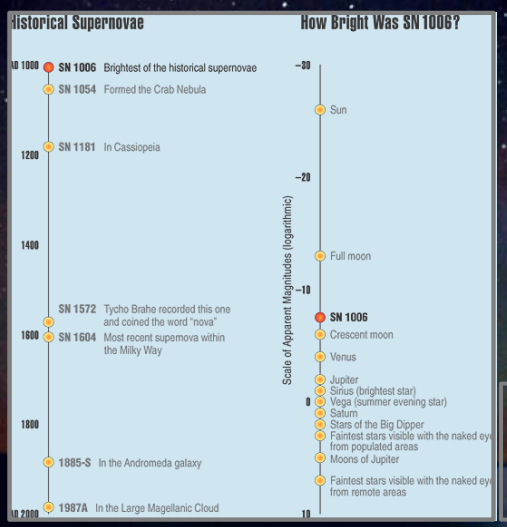
- Violent explosion Carbon-Oxygen white dwarfs:
- Embedded in binary, mass accretion from companion star
- When nearing Chandrasekhar Limit (1.38 $M_\odot$), electron degeneracy pressure
- can no longer sustain star.
- while contracting under its weight, carbon fusion sets in, powering a
- catastrophic deflagration or detonation wave,
- leading to a violent explosion, ripping apart entire star

- Because exploding stars have nearly uniform progenitor (~1.38 $M_\odot$ white dwarf), their luminosity is almost the same: M ~ -19.3
  Standard Candle

# SN1006

Supernova SN1006:
brightest stellar event recorded in history

# SN1006




Supernova SN1006:

- brightness: m = -7.5
- distance: d=2.2 kpc
- recorded: China, Egypt, Iraq, Japan, Switzerland, North America

Supernova SN1006:
brightest stellar event recorded in history

# SN1006

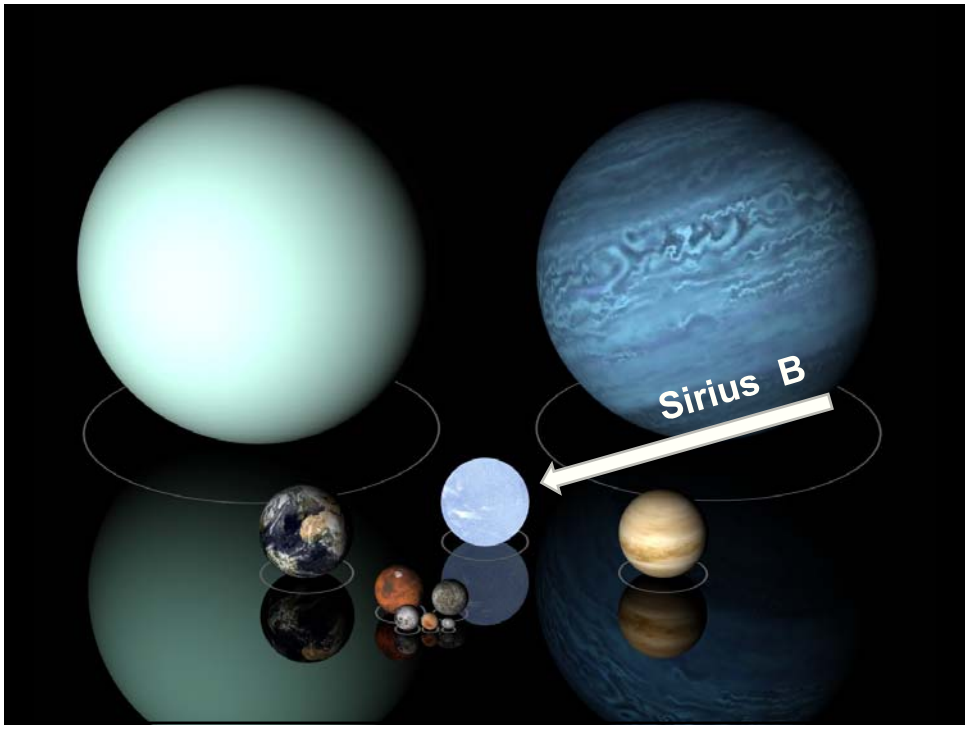

present-day
Supernova Remnant

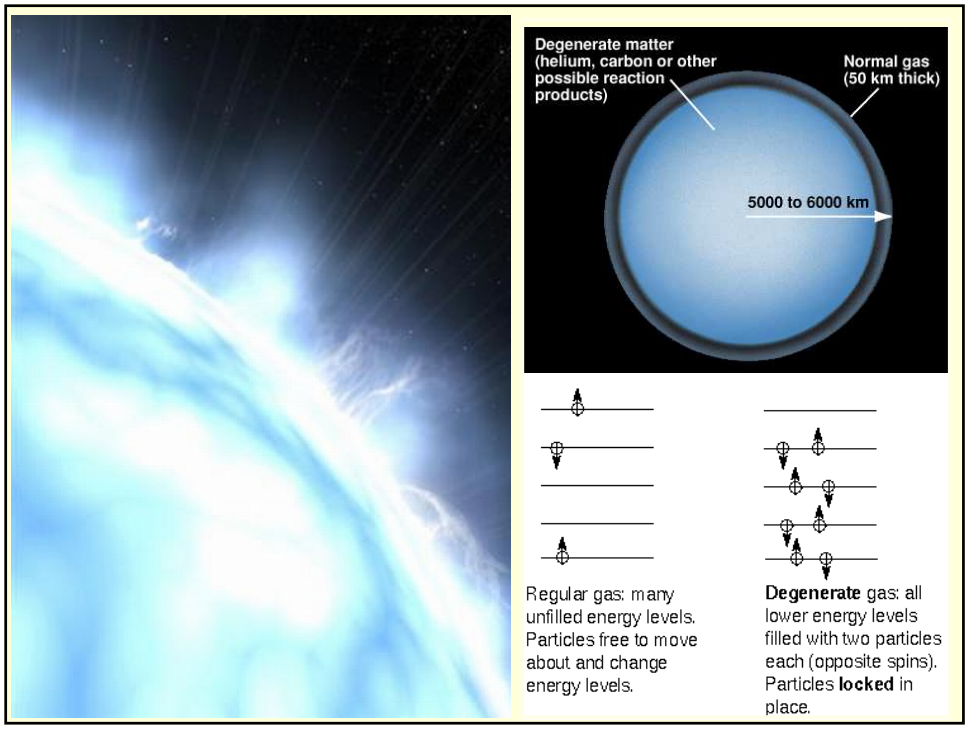
Supernova SN1006:

- brightness: m = -7.5
- distance: d=2.2 kpc
- recorded: China, Egypt, Iraq, Japan, Switzerland, North America

Supernova SN1006:
brightest stellar event recorded in history

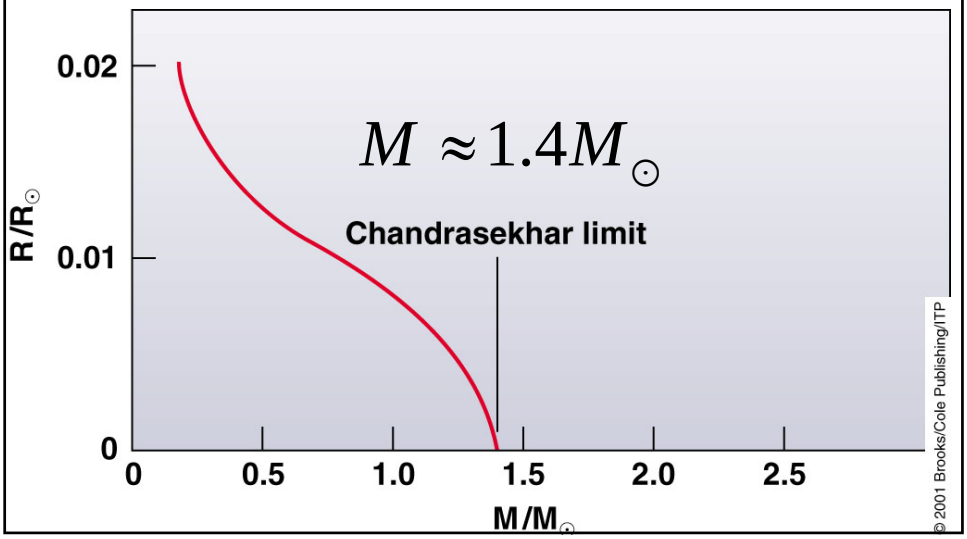
# White Dwarfs


Sirius B


Degenerate matter (helium, carbon or other possible reaction products)
Normal gas (50 km thick)
5000 to 6000 km
Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.
Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles locked in place.

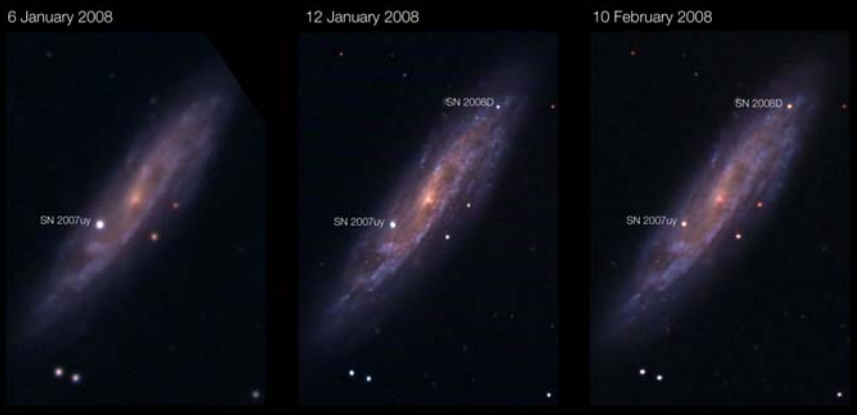
# Chandrasekhar Mass Limit

What is the maximum mass that can be supported by the dense compact material of a white dwarf star?




## Supernova Lightcurves

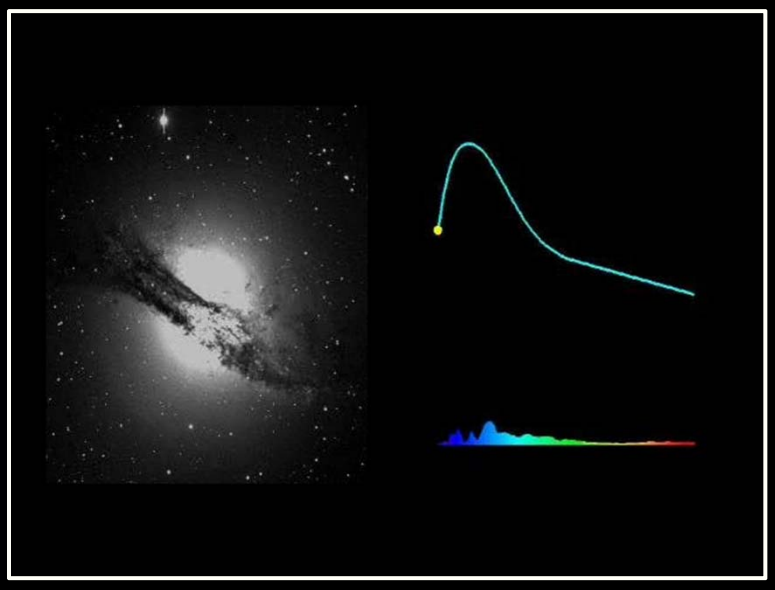
# SN 2007uy



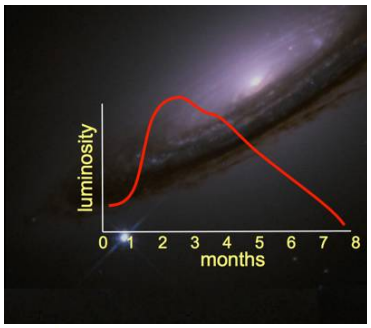

Supernova SN 2007uy in NGC2770

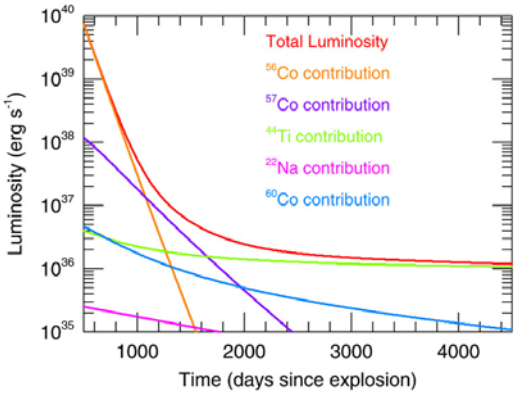
while fading, another supernova, SN2008D, went off in same galaxy

# Supernova Lightcurve & Spectrum



# Supernova Lightcurve



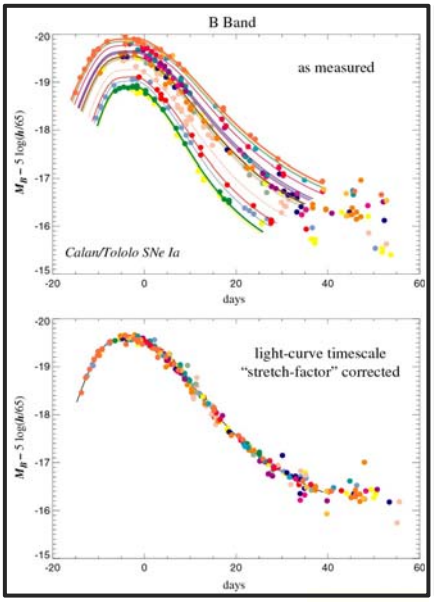




Type Ia supernovae follow a characteristic light curve
—the graph of luminosity as a function of time—after the explosion.

This luminosity is generated by the radioactive decay of Nickel-56 through Cobalt-56 to Iron-56.

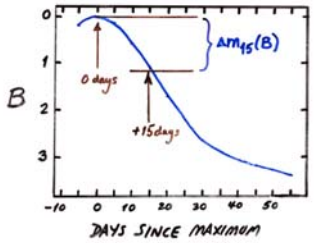
Maximum absolute magnitude of about -19.3.

# the Phillips Relation




**Relationship between**

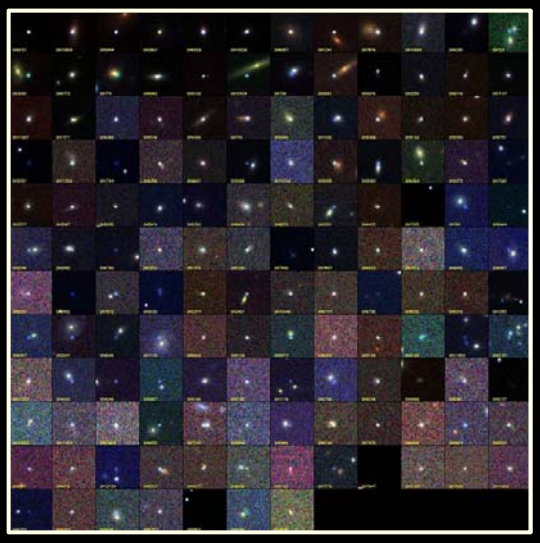
- **peak luminosity of a Type Ia supernova**
- **speed of luminosity evolution after maximum light.**




**Mark Phillips (1993):**

- **on the basis of Calan/Tololo Supernova Survey**
- **the faster a supernova fades after peak,**
- **the fainter its intrinsic peak luminosity**
- **reduces scatter in Hubble diagram to $\sigma$<0.2 mag**
- **heuristic relationship, as yet not theoretically "understood"**

## Supernova Cosmology Project

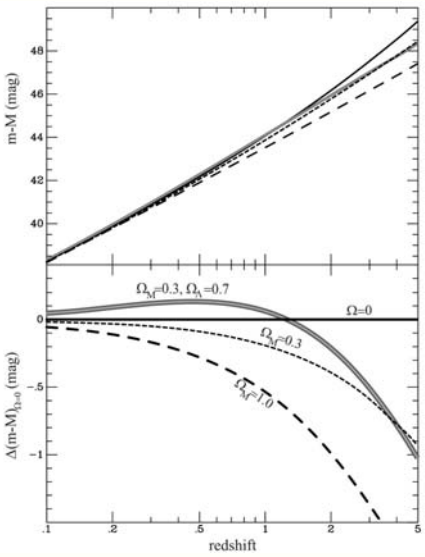


diligently monitoring millions of galaxies, in search for that one explosion …

## High-z Supernova Search Team

## Cosmic Acceleration

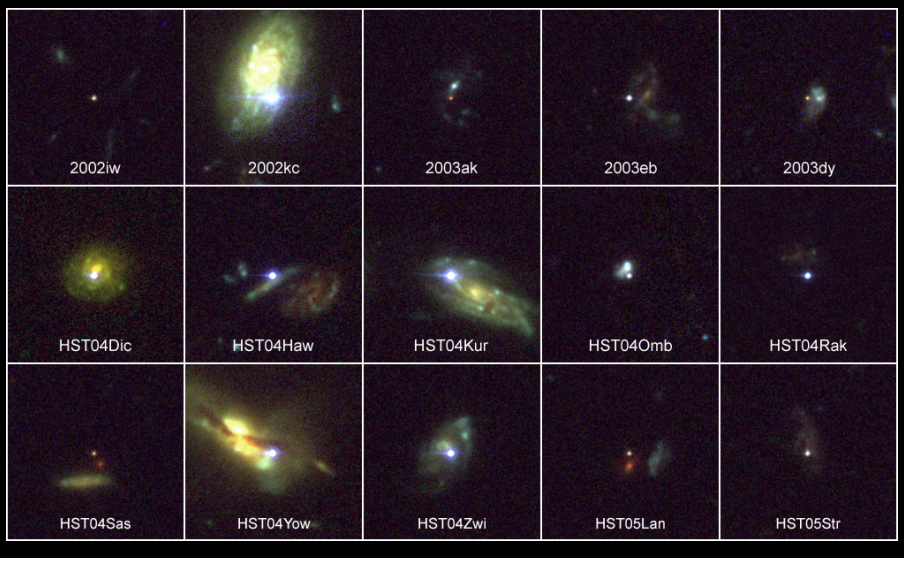
# Cosmic Acceleration



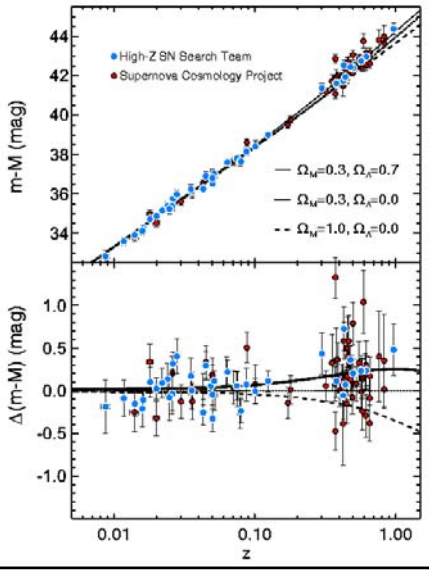

**Hubble Diagram high-z SNIa**

- distance vs. redshift z
  m-M vs. redshift z
- determine:
  - absolute brightness of supernova Ia
  - from dimming rate (Phillips relation)
- measure:
  - apparent brightness of explosion
- translates into:
  - luminosity distance of supernova
  - dependent on acceleration parm. q

# High-z SNIa: sample



# Cosmic Acceleration

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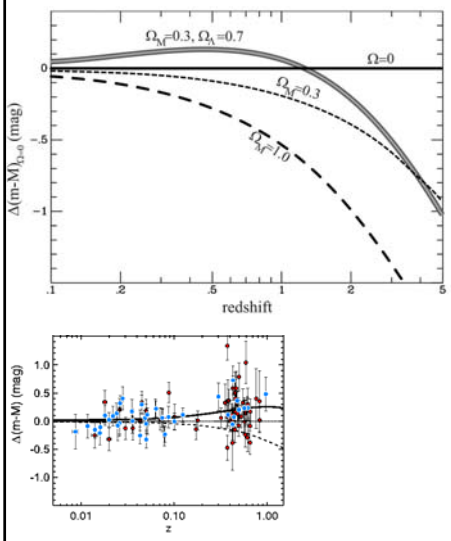
# Cosmic Acceleration




**Relative Hubble Diagram**

**Δ(m-M) vs. Redshift z**

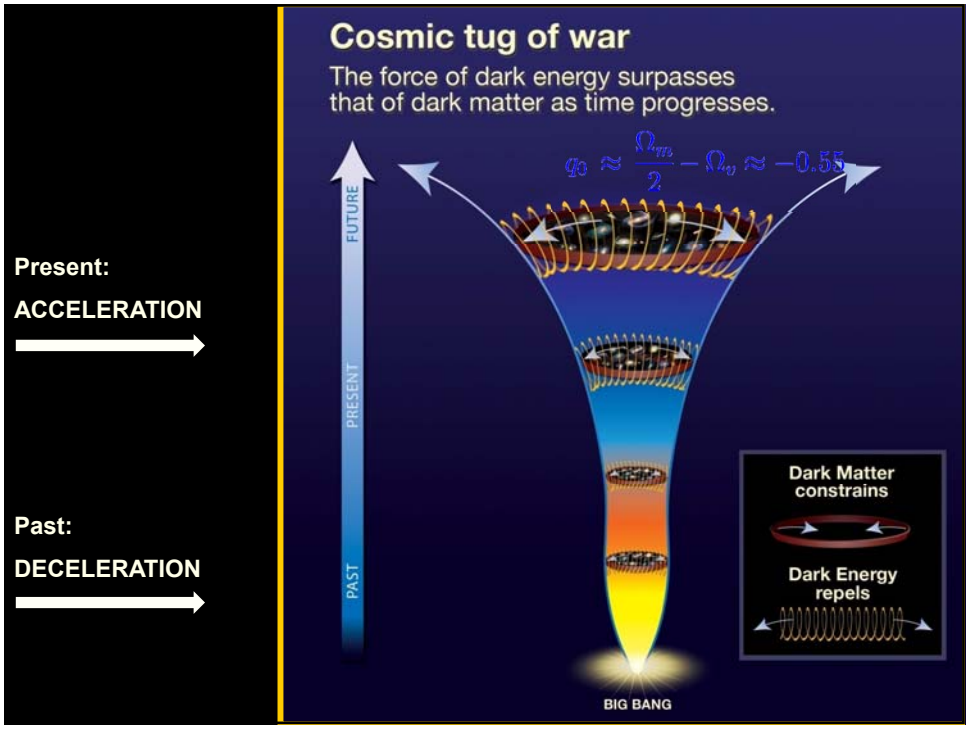
**with Hubble diagram for empty Universe**

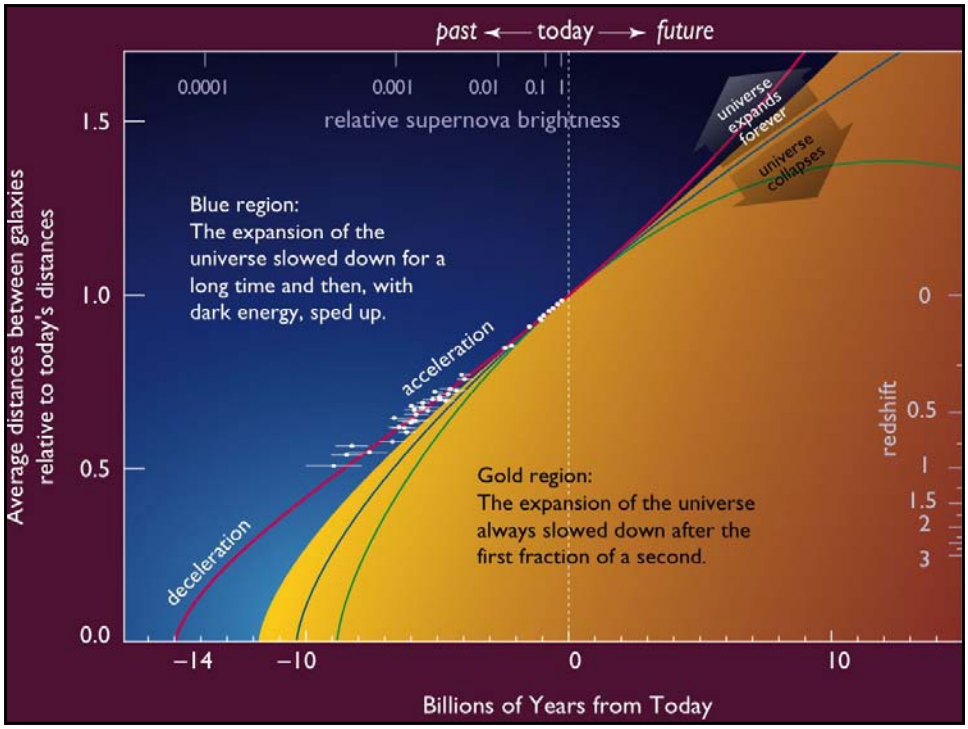
**$\Omega_m$=0.0, $\Omega_\Lambda$=0.0**

**as reference.**

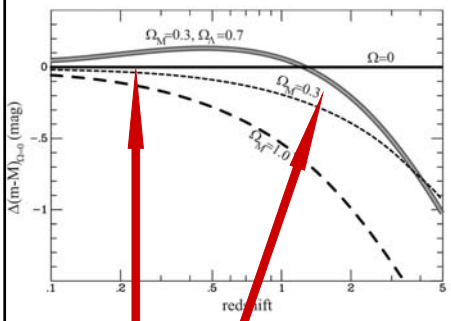
**Acceleration of the Universe:**

$$q_0 \approx \frac{\Omega_m}{2} - \Omega_v \approx -0.55$$


Present:
ACCELERATION
Past:
DECELERATION
Cosmic tug of war
The force of dark energy surpasses that of dark matter as time progresses.
$q_0 \approx \frac{\Omega_m}{2} - \Omega_\nu \approx -0.55$
FUTURE
PRESENT
PAST
Dark Matter constrains
Dark Energy repels
BIG BANG


past ← today → future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
redshift
0
0.5
1
1.5
2
3
−14
−10
0
10
Billions of Years from Today

# Cosmic Deceleration




Cosmic deceleration:
SNIa brighter

Cosmic acceleration:
SNIa fainter

Before current Dark Energy epoch

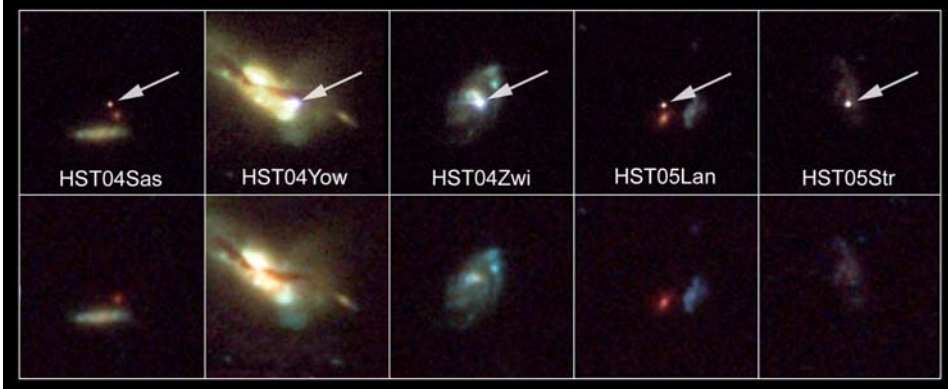
- Universe dominated by matter:

  Decelerating Expansion

- Observable in SNIa at very high z:

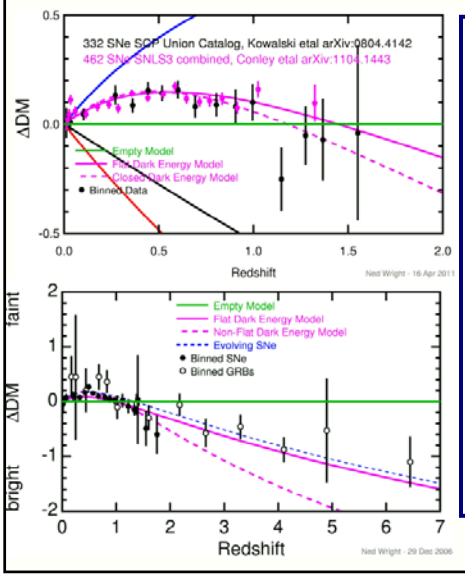
  z > 0.73

# Beyond Acceleration: SNe Ia at z > 0.7




Five high-z SNIa, images HST-ACS camera
SNIa and host galaxies lower panel: before
top panel: after explosion)

# Cosmic Deceleration




**Before current Dark Energy epoch**

- **Universe dominated by matter:**

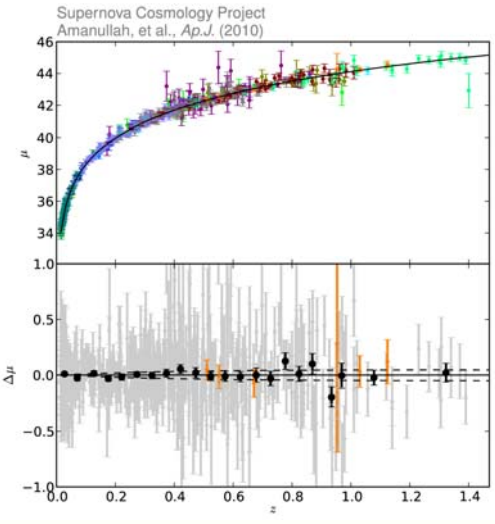
  **Decelerating Expansion**

- **Observable in SNIa at very high z:**

  **z > 0.73**

# Union2:

## state-of-the-art SNIa compilation




**SCP Union2.1 SN Ia compilation:**

**719 SNe, 17 datasets (557 used)**
**6 z>1 SN Ia**

**Amanullah et al. 2010**

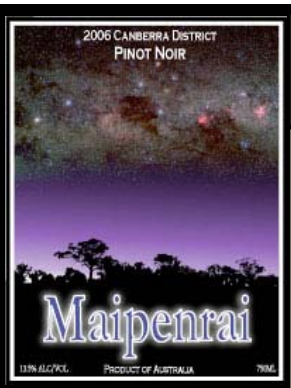
# Nobel Prize Laureates



Adam Riess


Saul Perlmutter


Brian Schmidt





Maipenrai

"I was shocked by my discovery, I just assumed we made a mistake"

Brian Schmidt