
the
Expanding Universe

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

$$c = 299792458 \; m\,s^{-1}$$

$$= 1.080 \times 10^{9} \;\; km \;\; h^{-1}$$

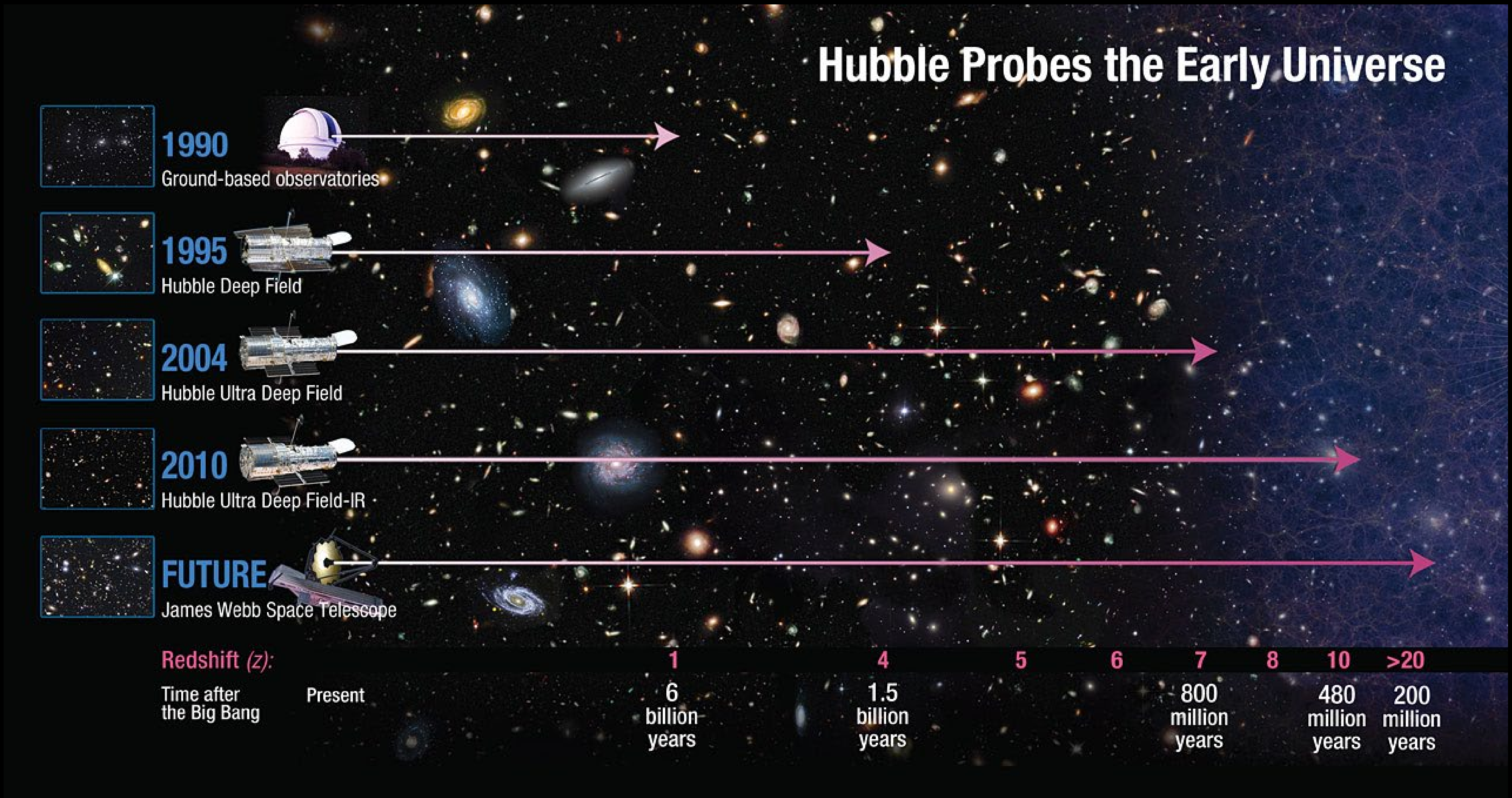
Cosmic Archaeology

- The finite velocity of light has highly interesting implications for the study of cosmology.

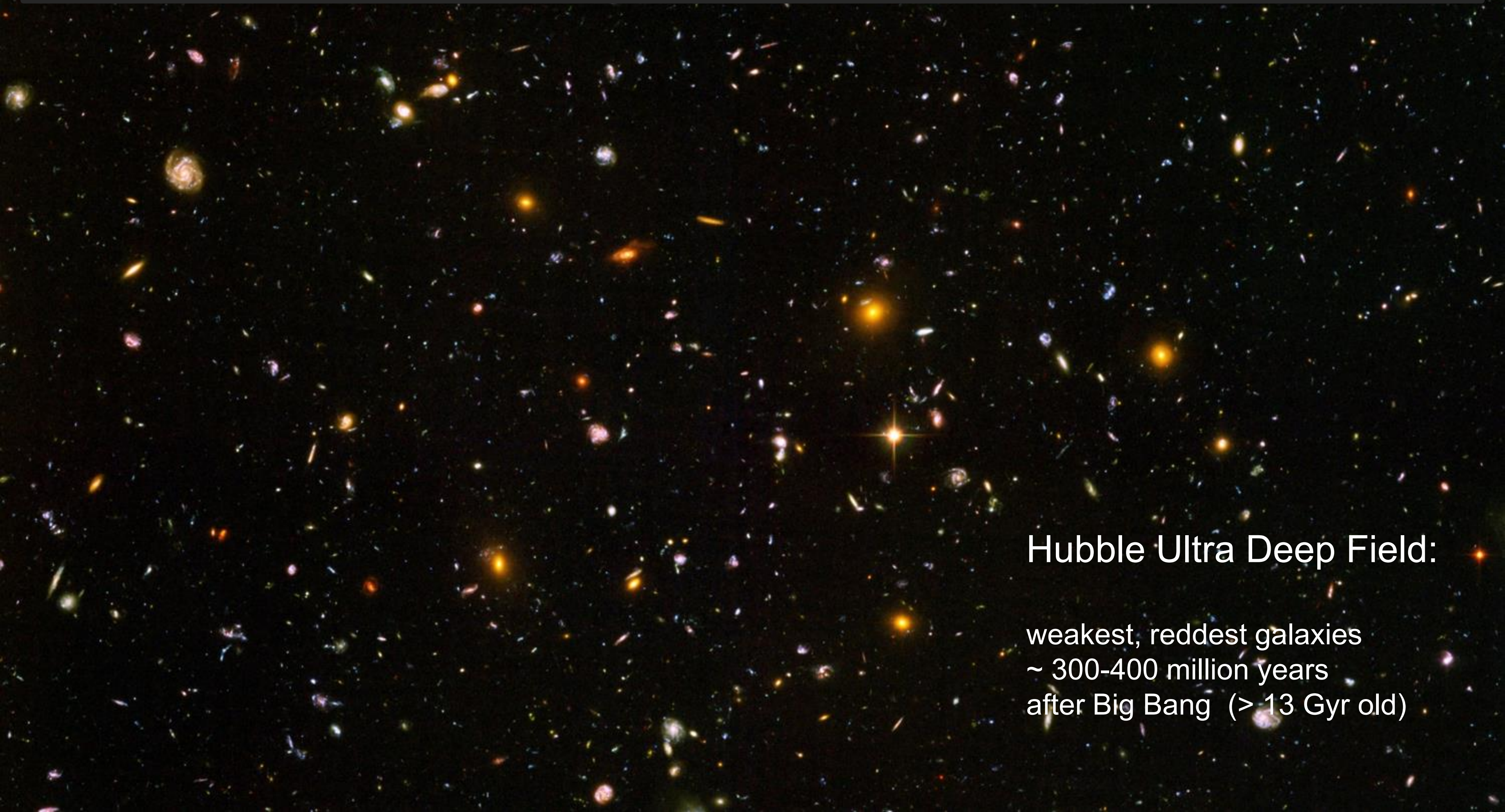
- Distances in the Universe are so vast – out to billions of lightyears - that the corresponding light travel time is in the order of billions of years:
  - this means that when receiving light from cosmological probes (galaxies at cosmological distances), the light was emitted billions of years ago.
  - 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.

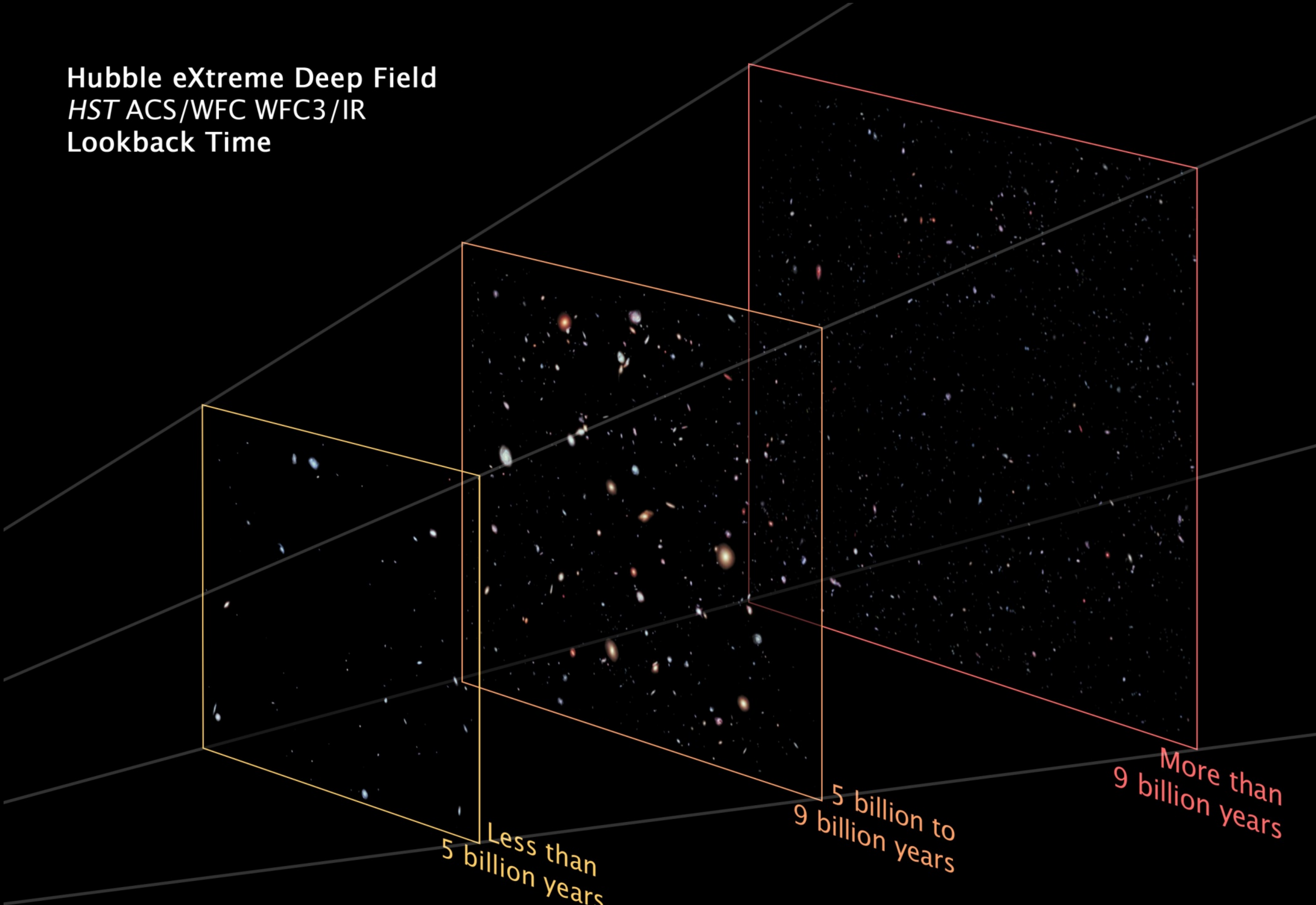
Cosmic Depths & Time



to the depths of our Universe



Hubble eXtreme Deep Field
HST ACS/WFC WFC3/IR
Lookback Time



… to the edge of the visible Universe…

~ 42 Giga lightyears

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


the Galaxy

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

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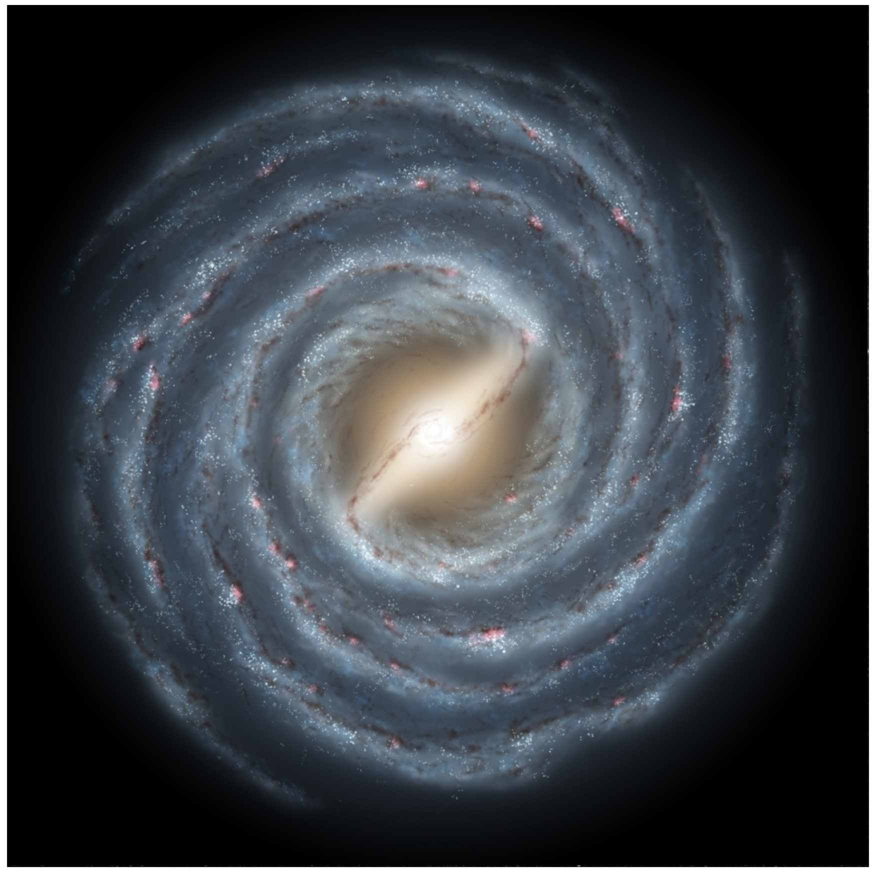


the Milky Way Galaxy:
as it would appear from a distant vista point,
outside its plane (face-on view)

Milky Way Satellites

Sculptor Dwarf Galaxy

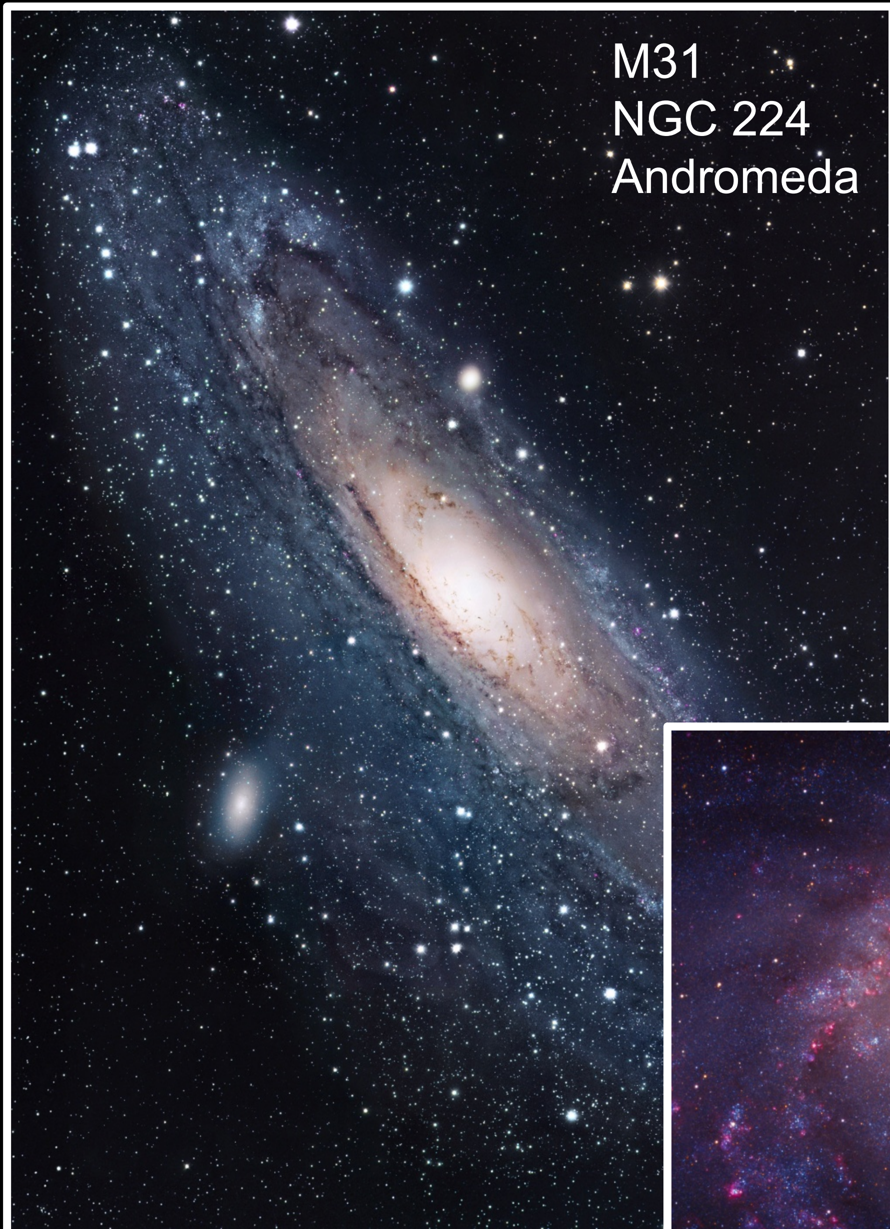
The Milky Way has at least ~14 satellite galaxies.

Large & Small Magellanic Clouds: Irregular galaxies

all other satellite galaxies: Dwarf Spheroidal

Local Group

Group Portrait



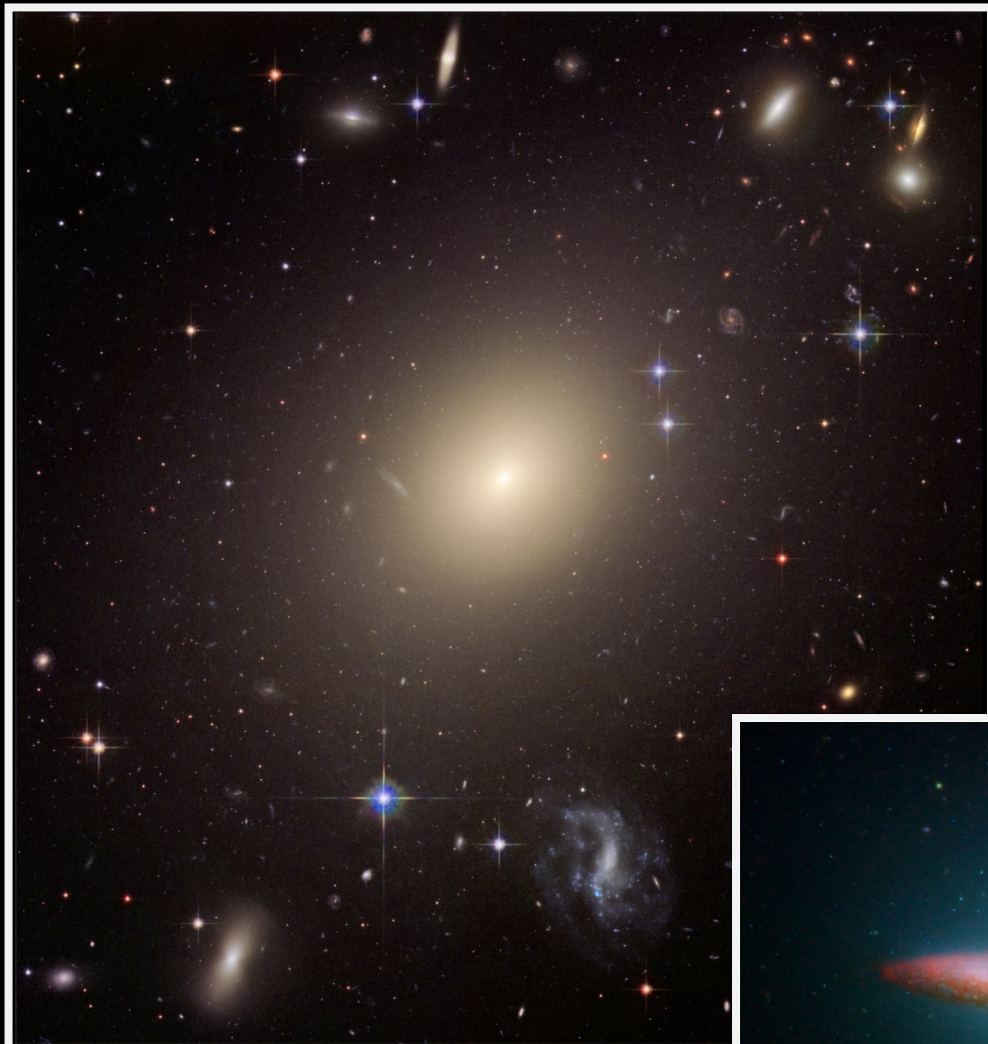

... Galaxies ...


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

... Spiral

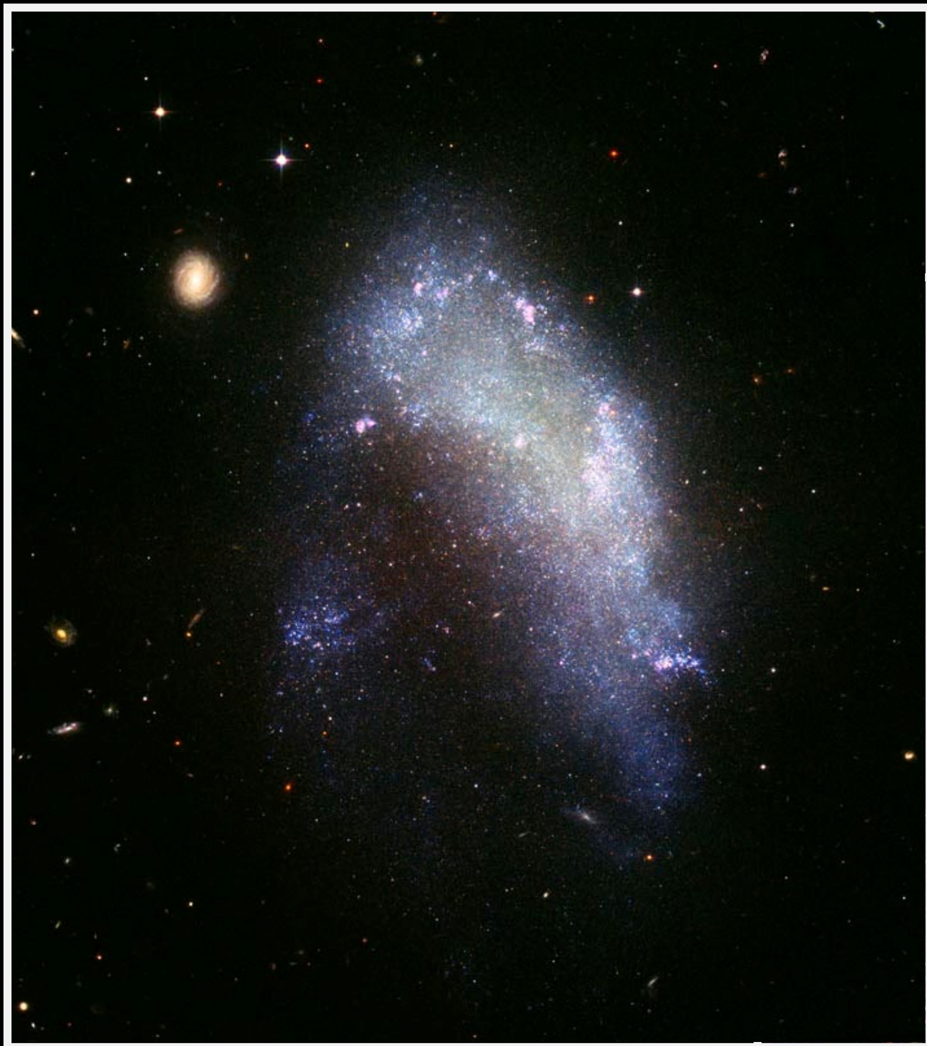
Galaxies ...

NGC 1300:
a Milky Way look-alike ?

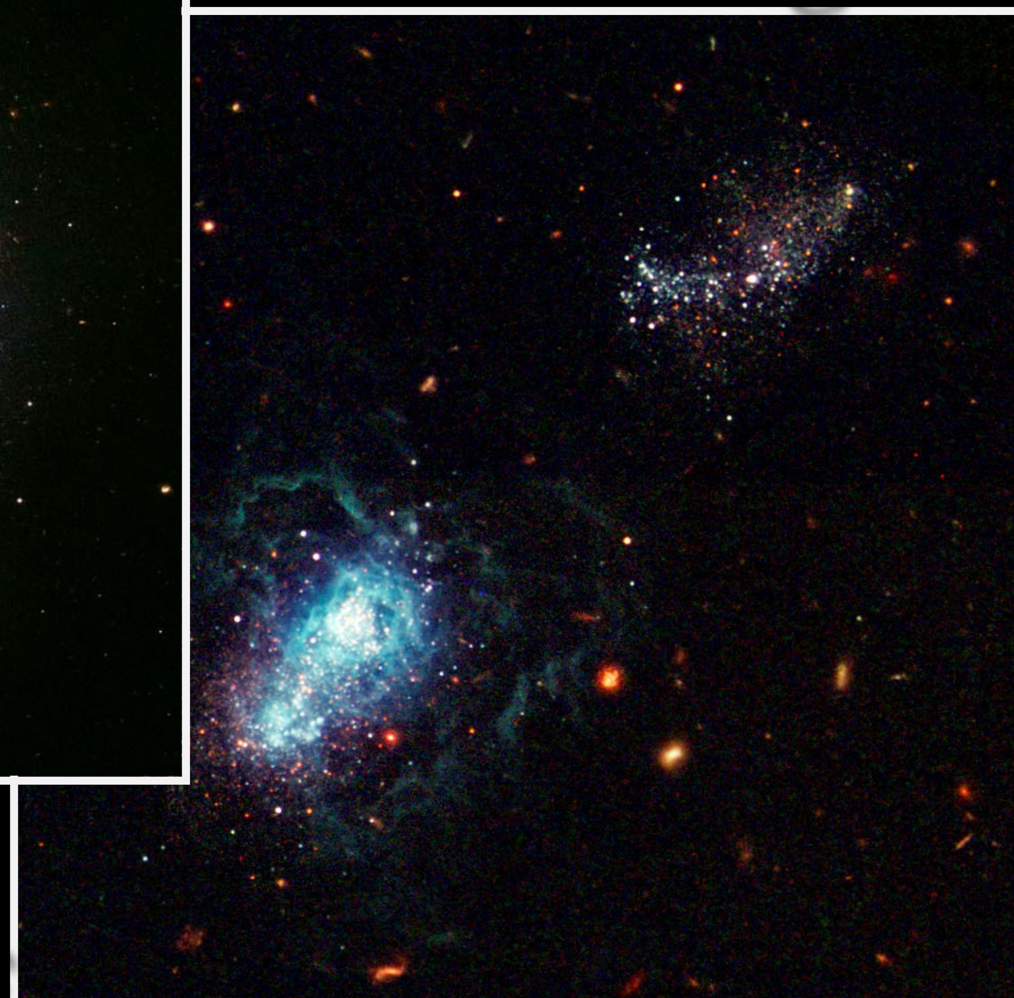


... Elliptical

... 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.

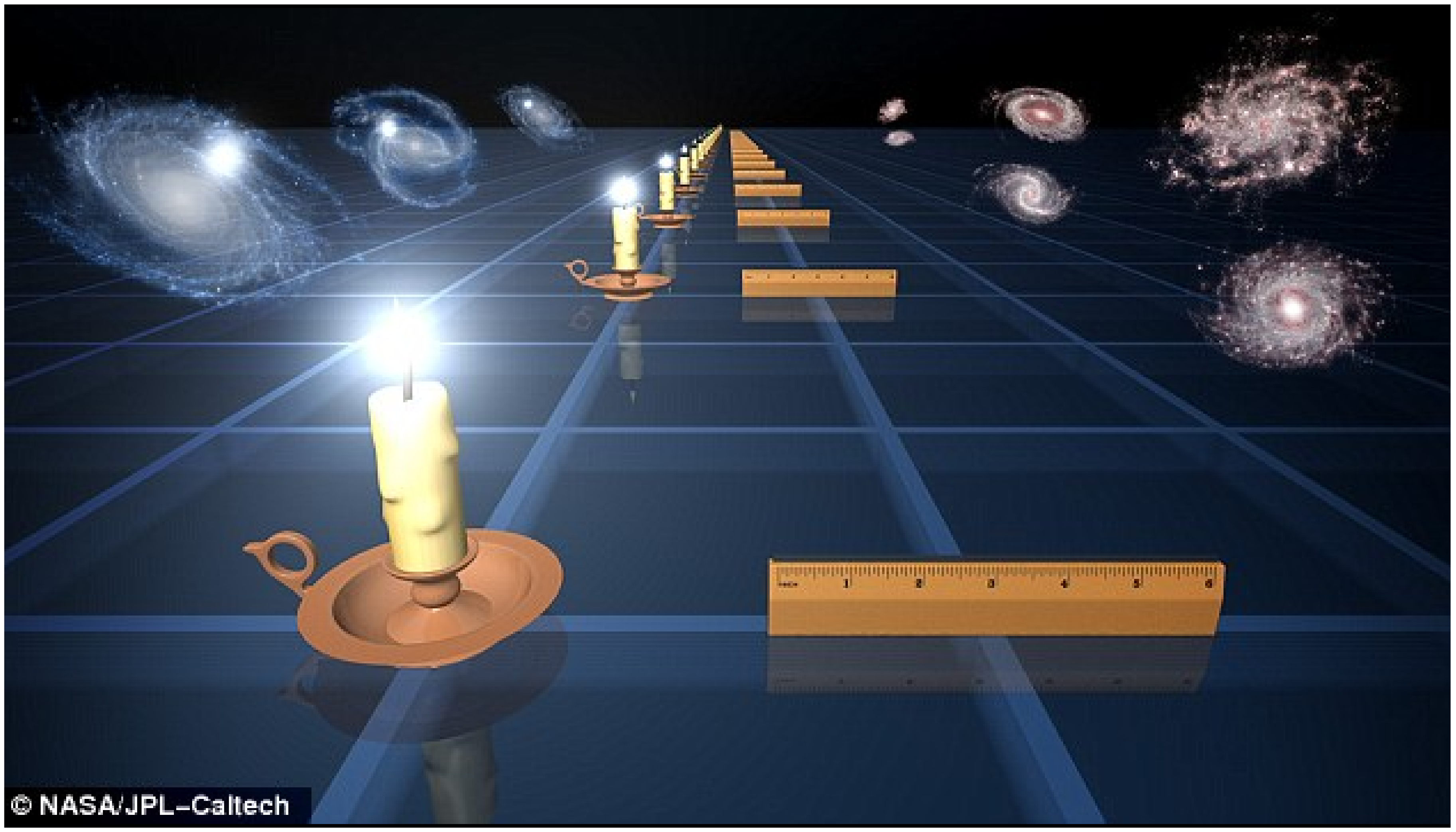
- One of the most practical means is based on the comparison between

  - 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

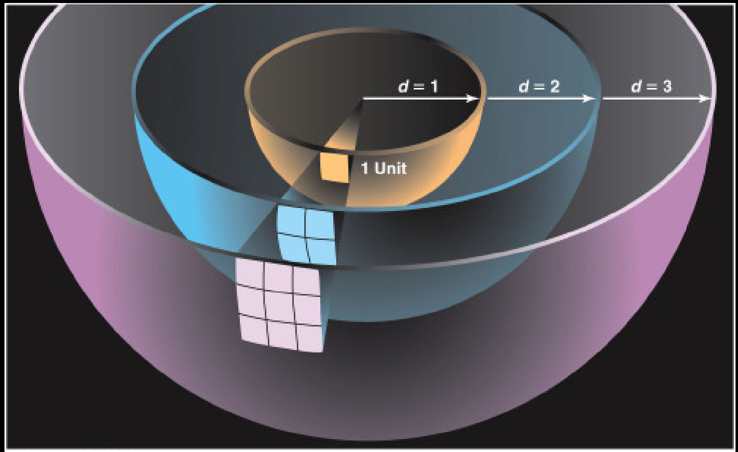
- To determine distances in the Universe, astronomers identify objects of which they know the intrinsic brightness:

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

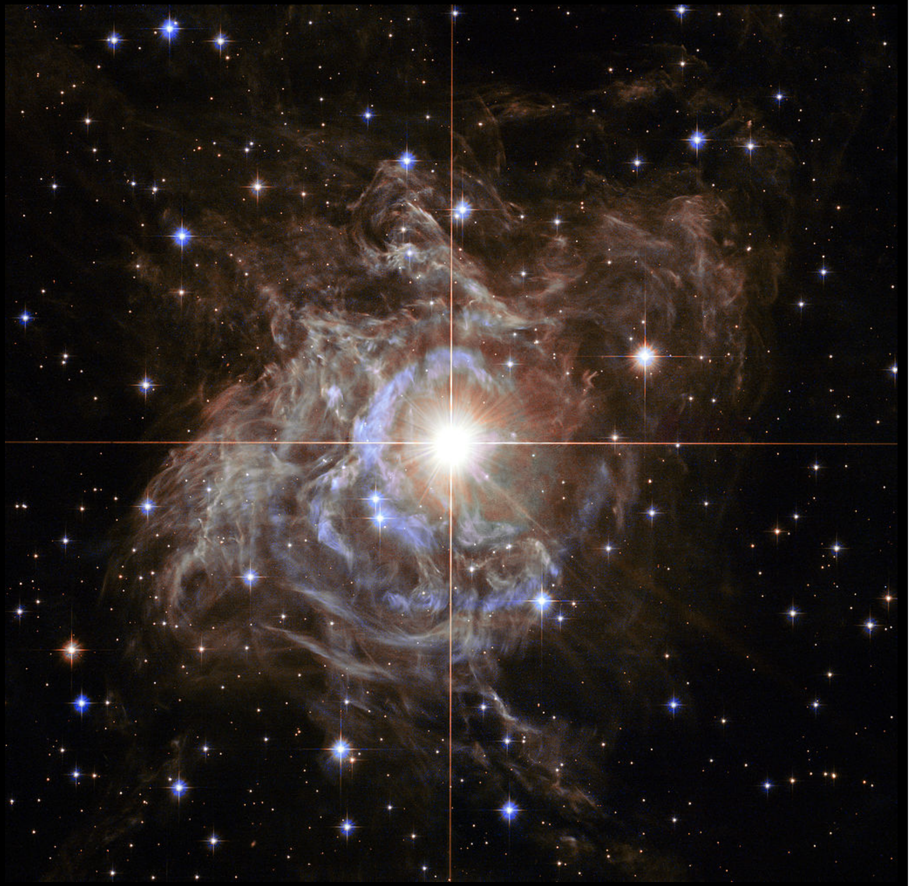
- To be able to determine cosmological distances, the reference Standard Candles

- 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***



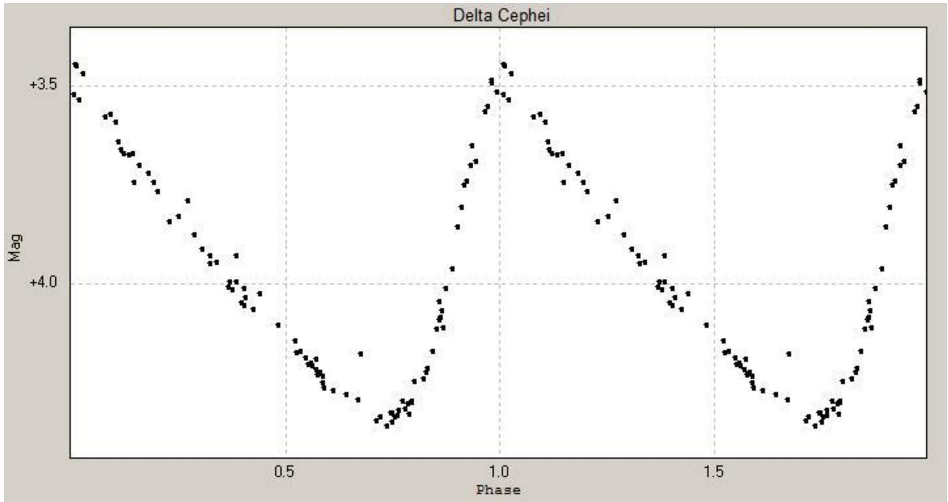
- As individual Cepheid stars are very bright
  - up to 100,000 times the Sun's luminosity, with masses in the order of 4-20 M⊙ -

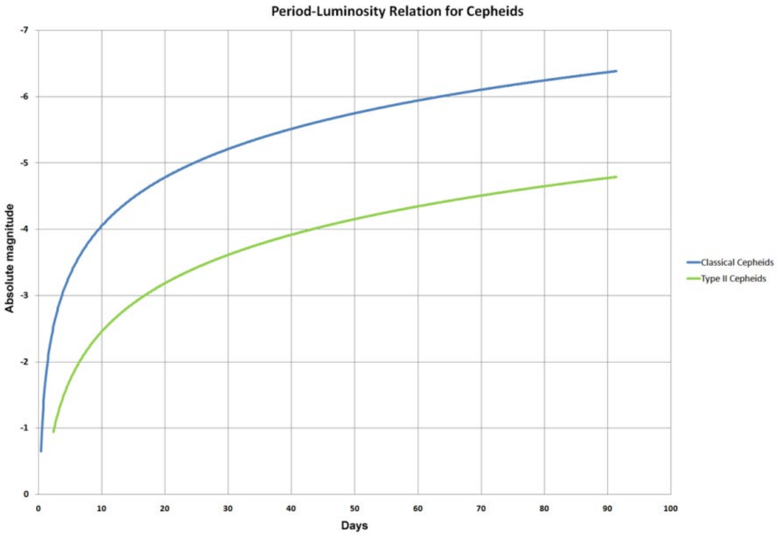
  they can be identified in other galaxies

- 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.





Run 3367 Col 4 Field 75
M31-V1
"Most important single object in the history of cosmology"

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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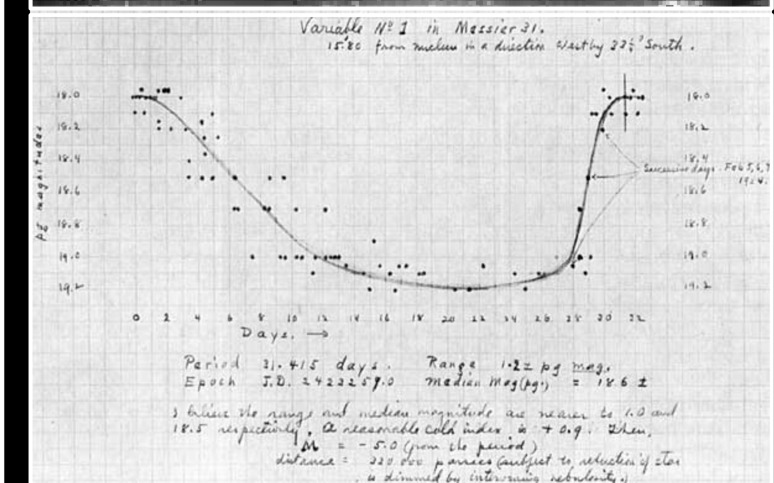
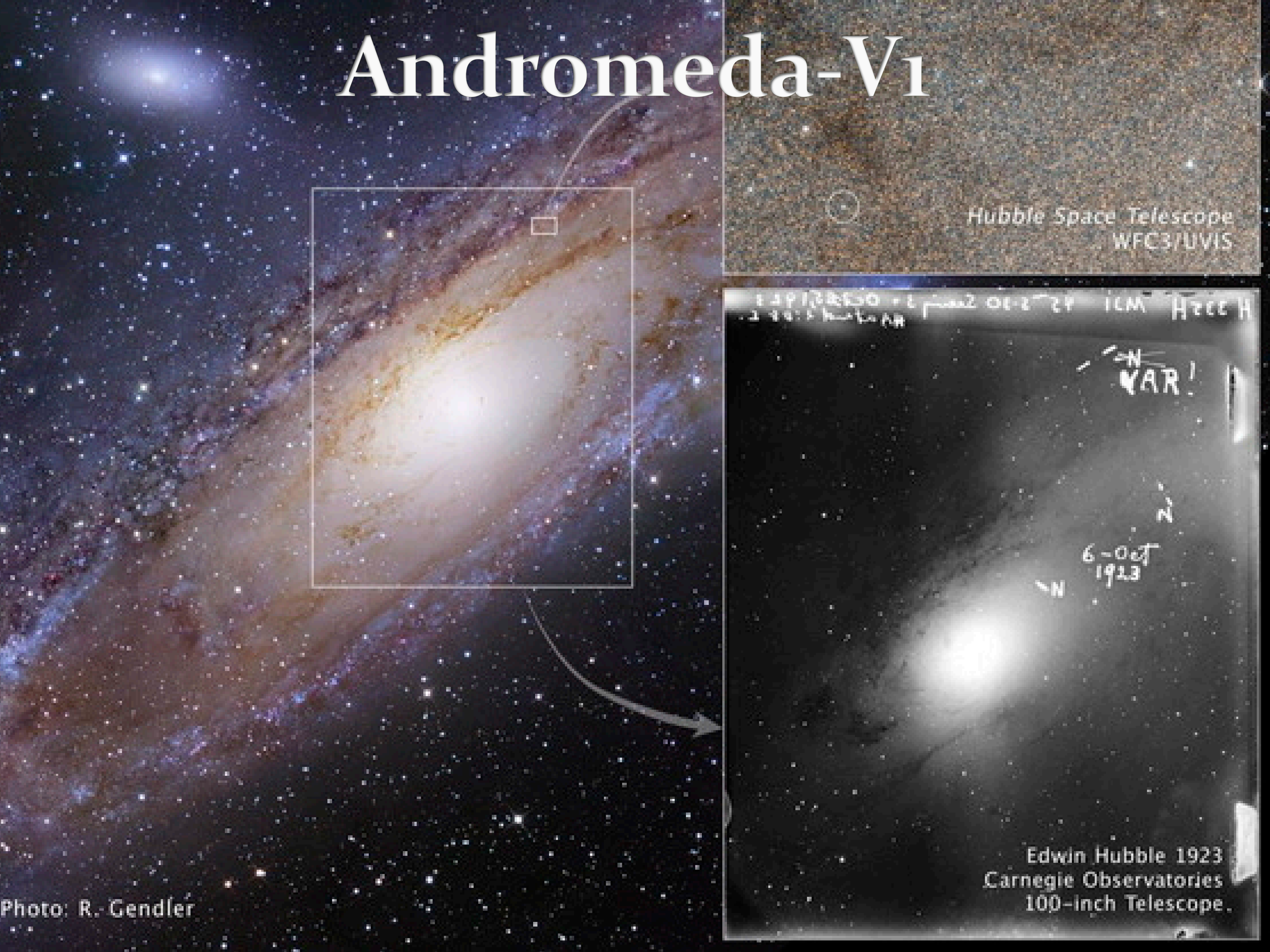
  determination of the distance to M31
- finding it is ~ 1 million lightyears
- Virtually overnight,
  our perception of the Universe,
  - of cosmic scales and distances -
  changed in a radical and revolutionary way !

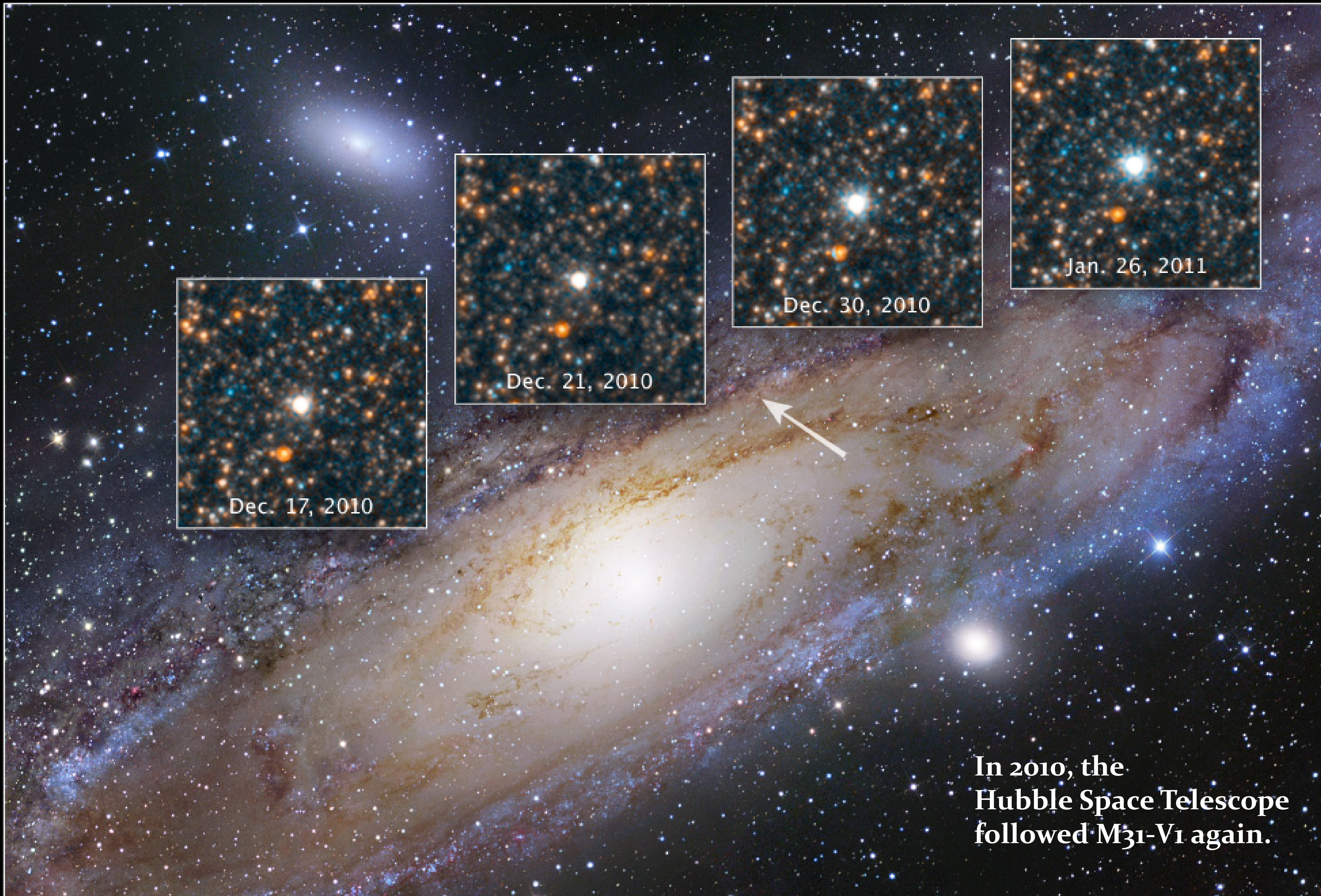


Andromeda-V1



Cepheid Variable Star V1 in M31

Hubble Space Telescope ▪ WFC3/UVIS



NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

STScI-PRC11-15a

Galaxy Velocities: Redshift

- Velocity measurement:

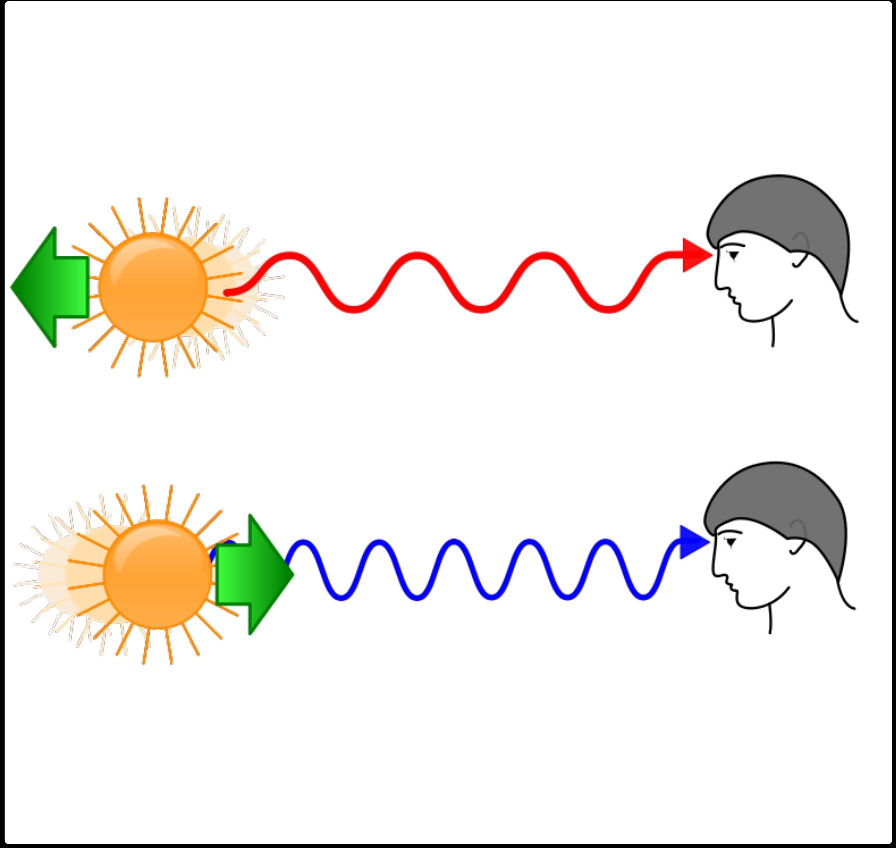
  redshift/blueshift of radiation emitted by a source (galaxy, star)

- 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

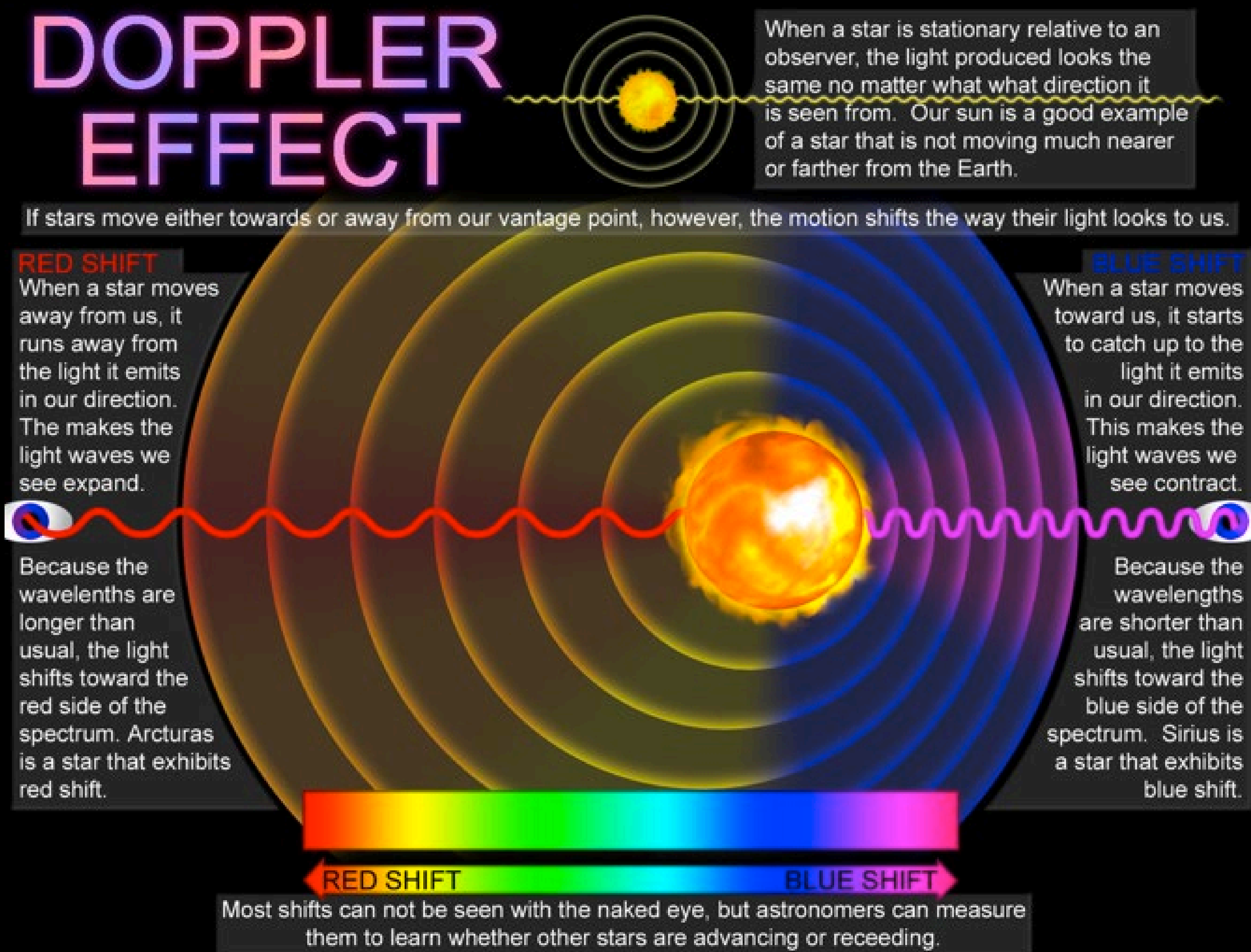
  away from us:
  - towards larger wavelength/lower frequence
  - towards red



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.
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.
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 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

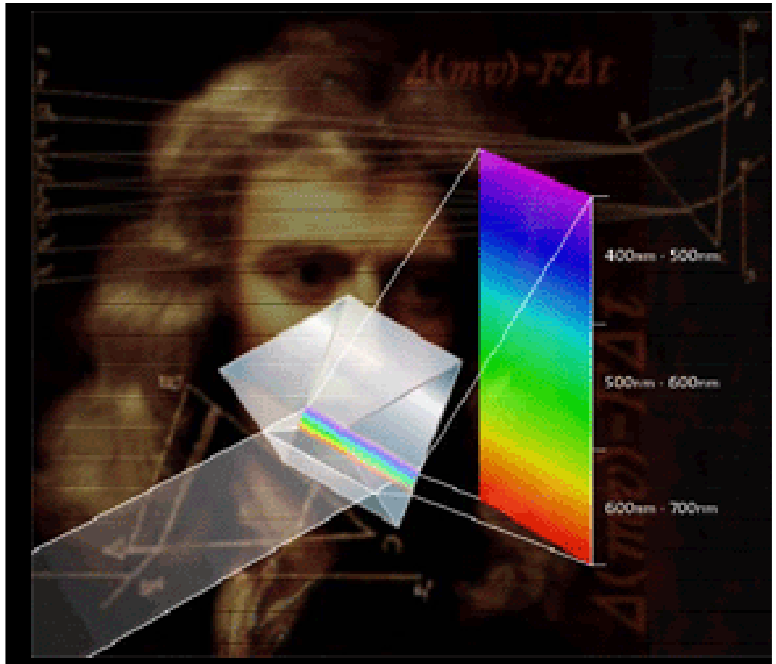
- Look at the spectrum of the light emitted by a galaxy:

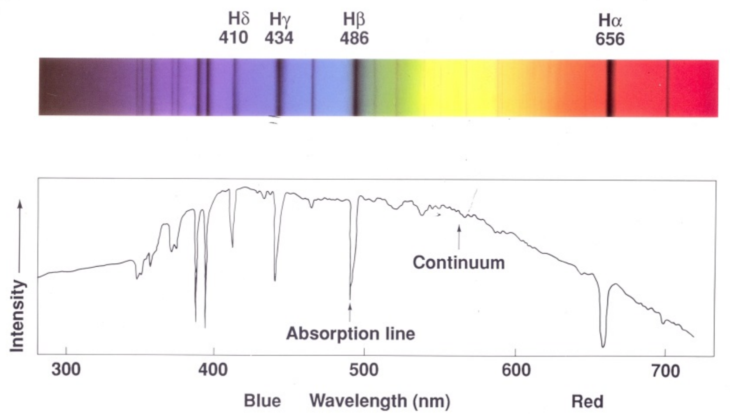
- Spectrum: energy distribution of light
  red: lower energy
  blue: higher energy

  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





Visual portion of stellar spectrogram

Hartmann/The Cosmic Journey, 4th ed., Fig. 16-5; The Cosmic Voyage, Fig. 16-3

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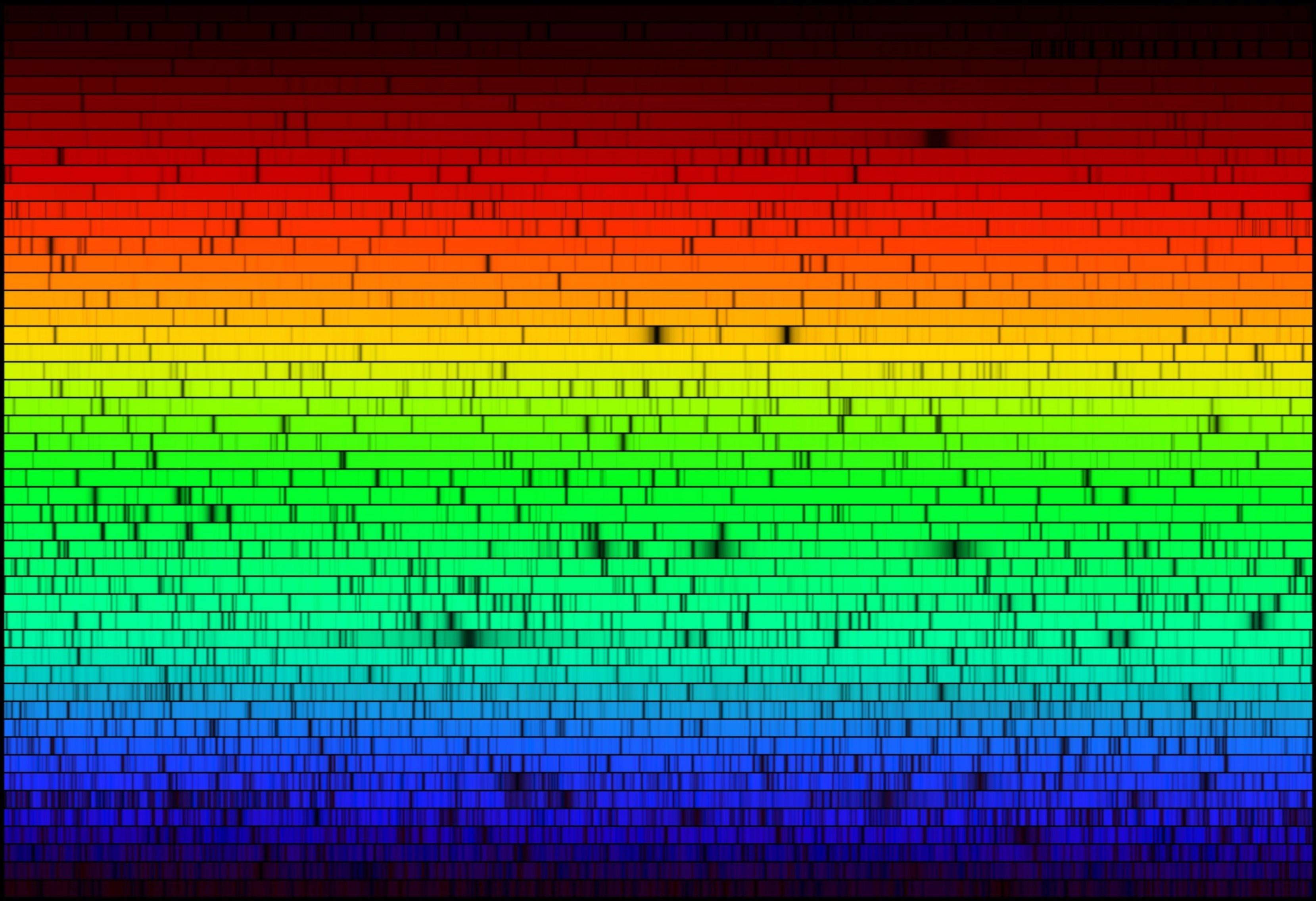
Solar Spectrum



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

Atoms & Spectral Lines

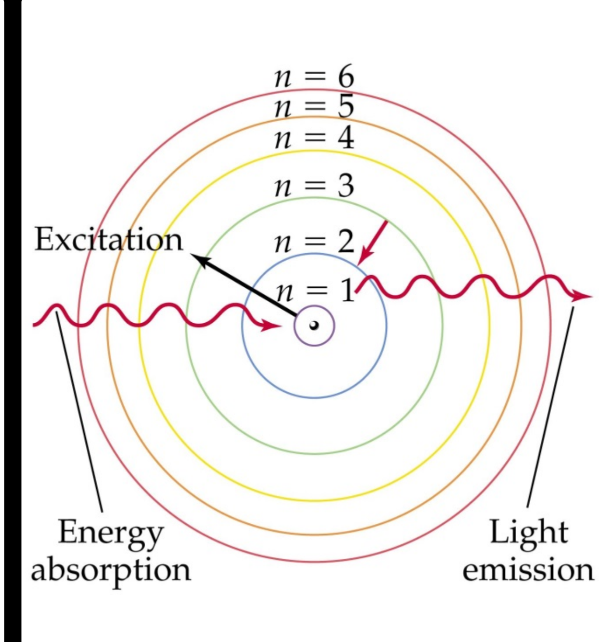
- Atoms (and molecules and other fundamental particles) are highly structured:

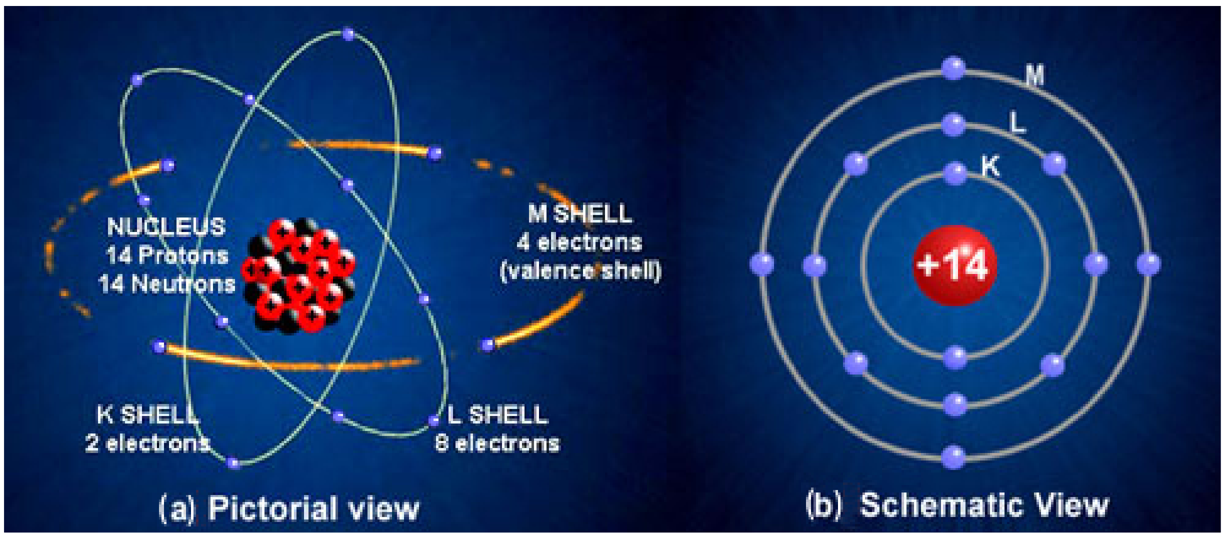
  - nucleus (consisting of protons and neutrons)
  - electron clouds, with electrons encircling the nucleus

- 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

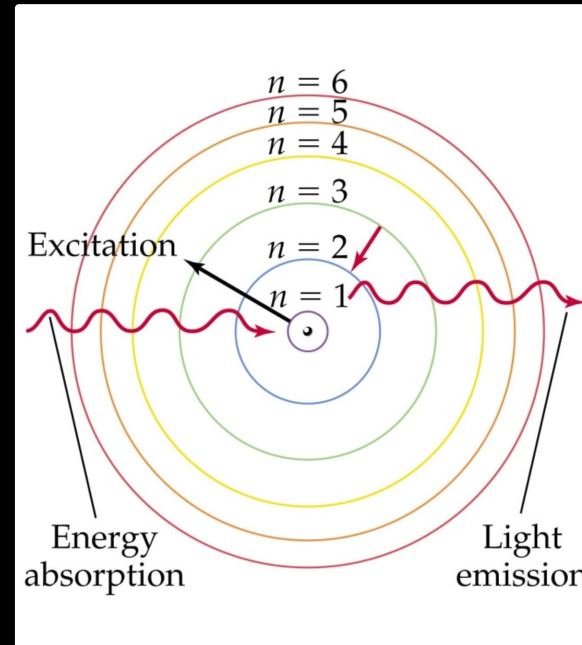
Energy of photon = frequency light

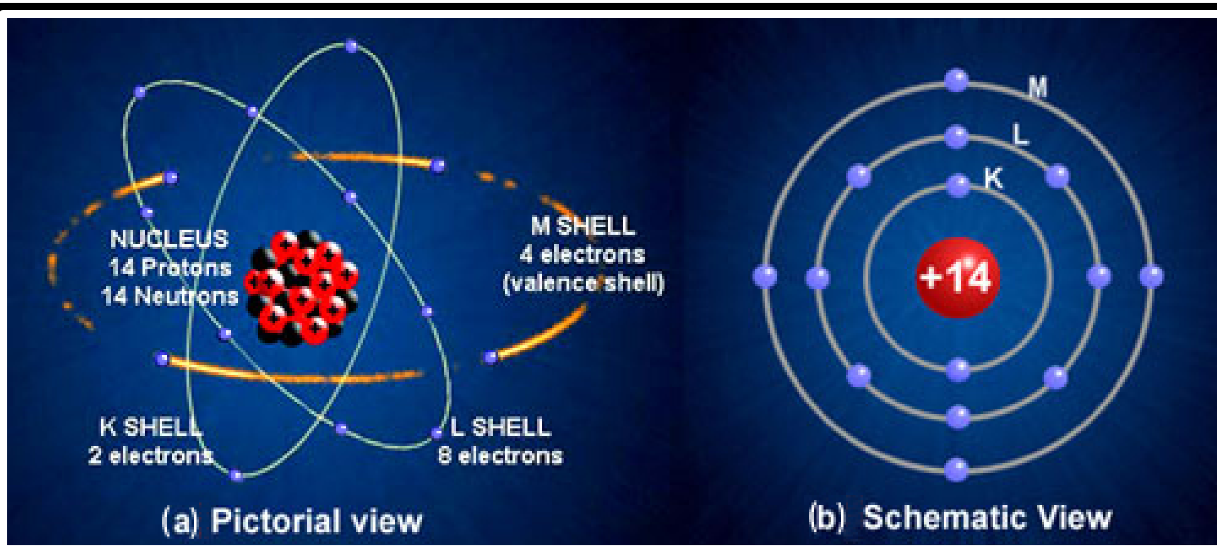
Atoms & Spectral Lines

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

The energy of a photon is directly proportional to
- directly proporotional to its frequency (ie. colour) ?
- inversely proportional to its wavelength ?

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:

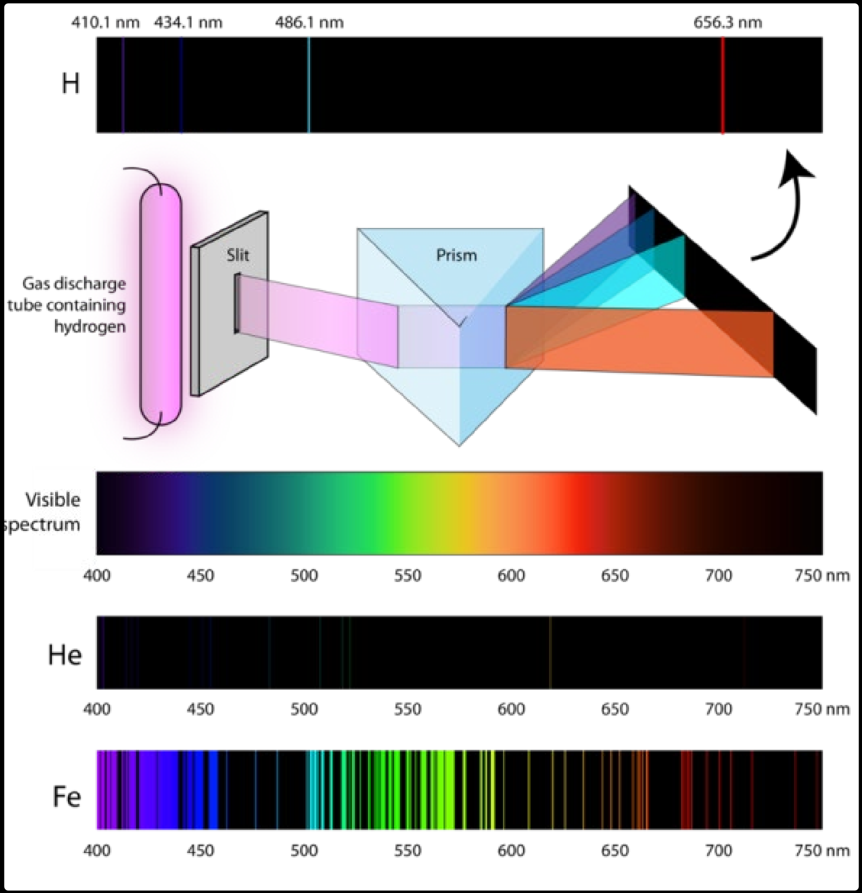
  - find the spectral lines in a stellar spectrum
  - identify which atomic transition they correspond to

  - this always corresponds to very specific frequency / wavelength:

    the rest frequency ν_o
    rest wavelength λ_o

    of the transition

  - compare this with the measured (redshifted or blueshifted) frequency ν/ wavelength λ



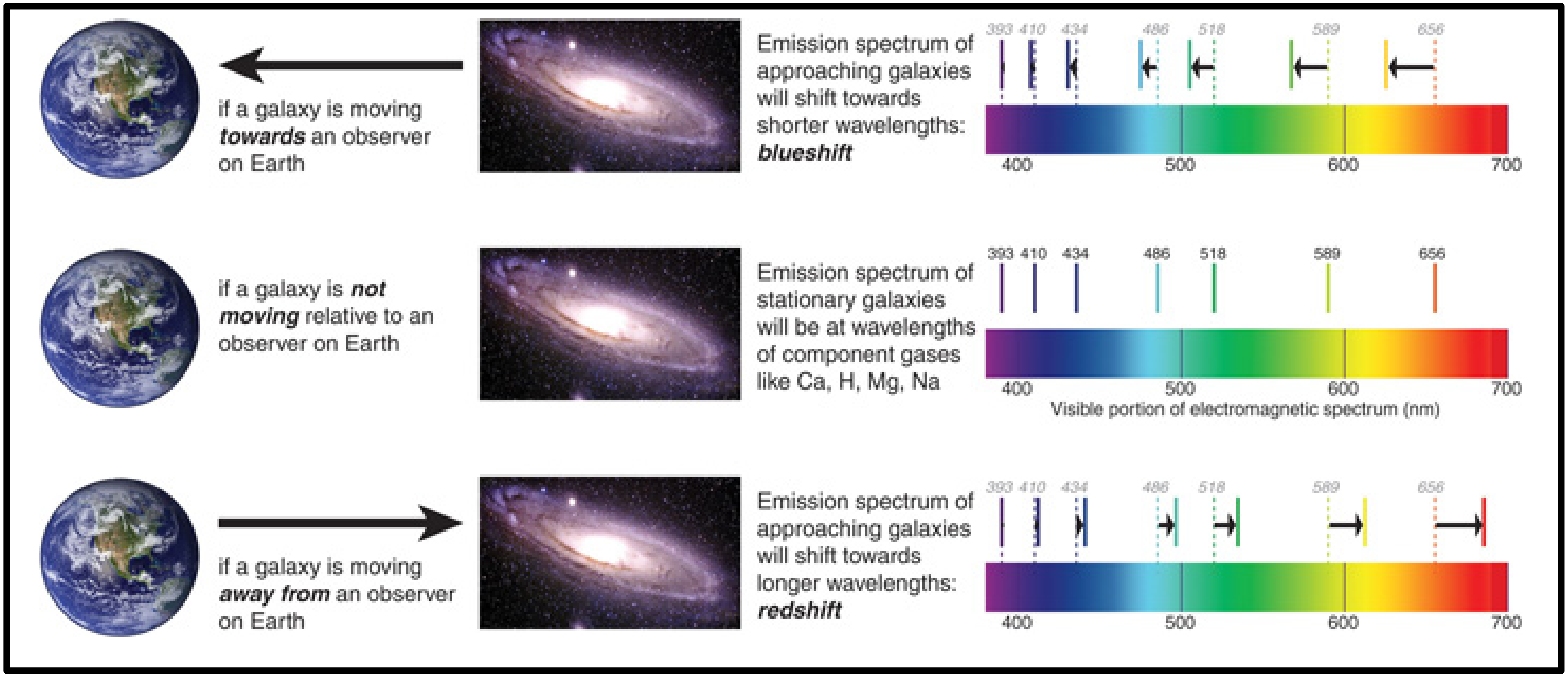
Redshift: $$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

Galaxy Spectra & Cosmic Redshift

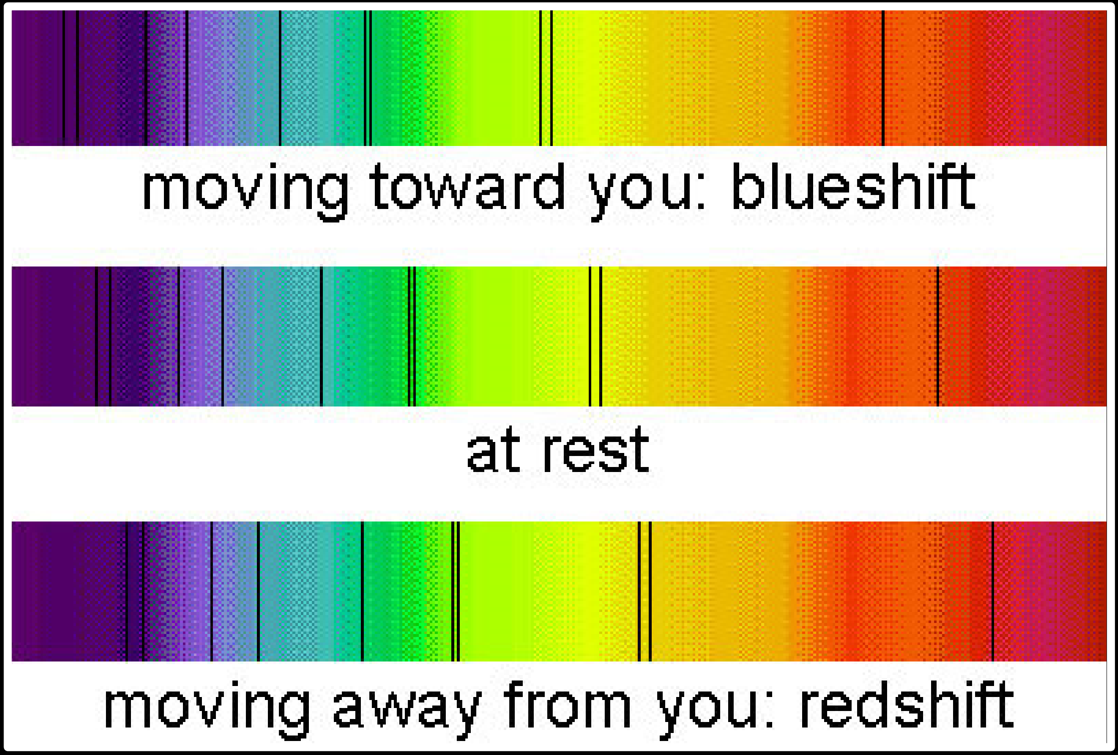
- **Galaxy spectra:**
  - **the combined light of 100s billions of stars**
  - **absorption lines mark the frequencies at which the atmospheres of the stars in the galaxy have absorbed light emitted by the stars**

- **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

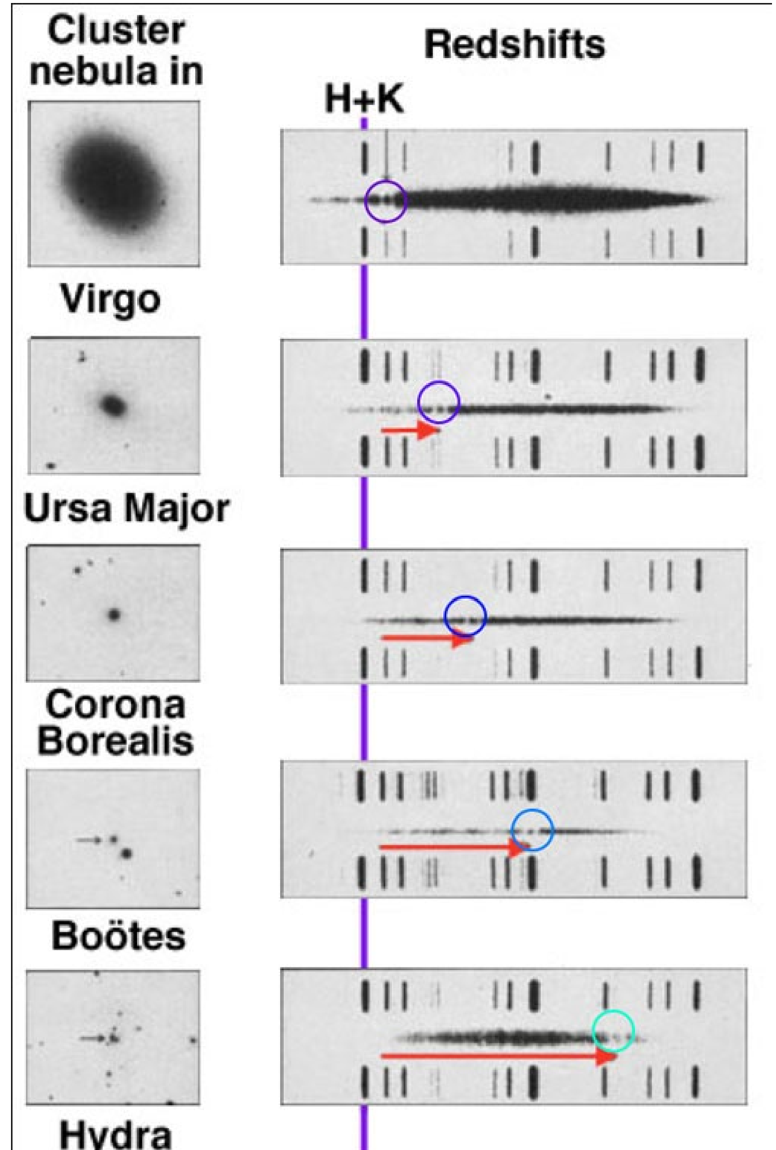
For a major part of his career he was director of

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)



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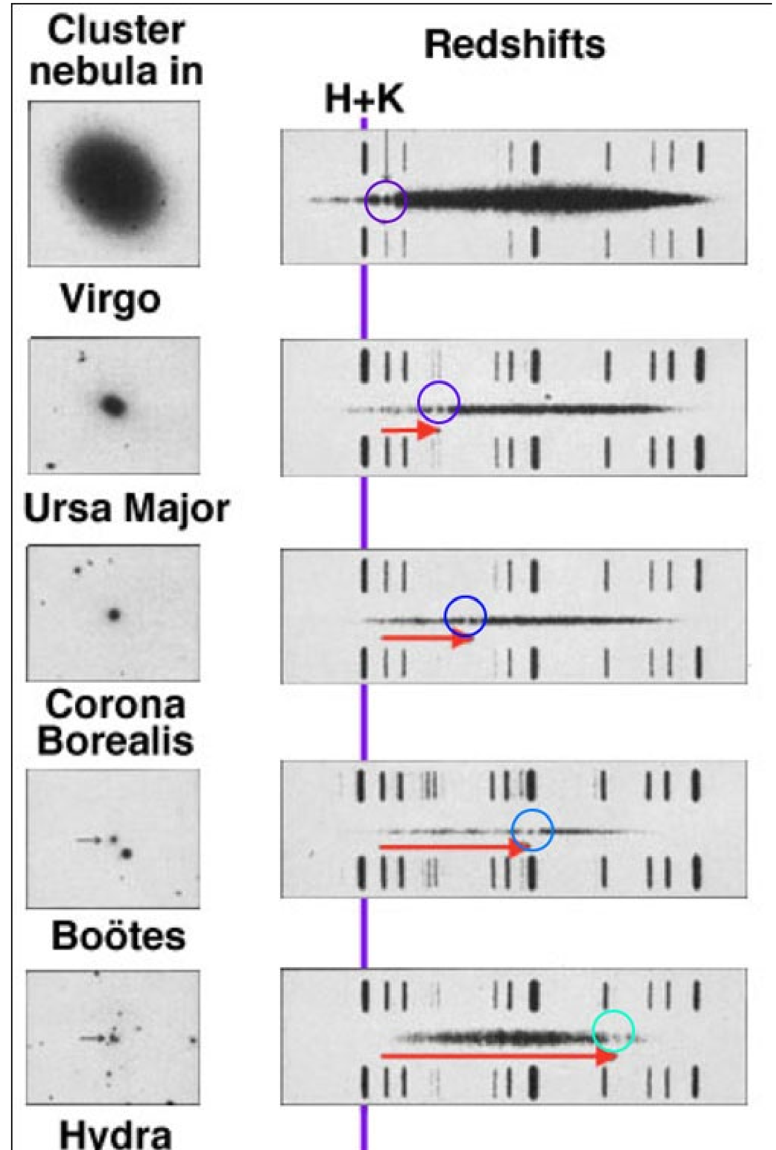


1917: Slipher measures more galaxy redshifts:

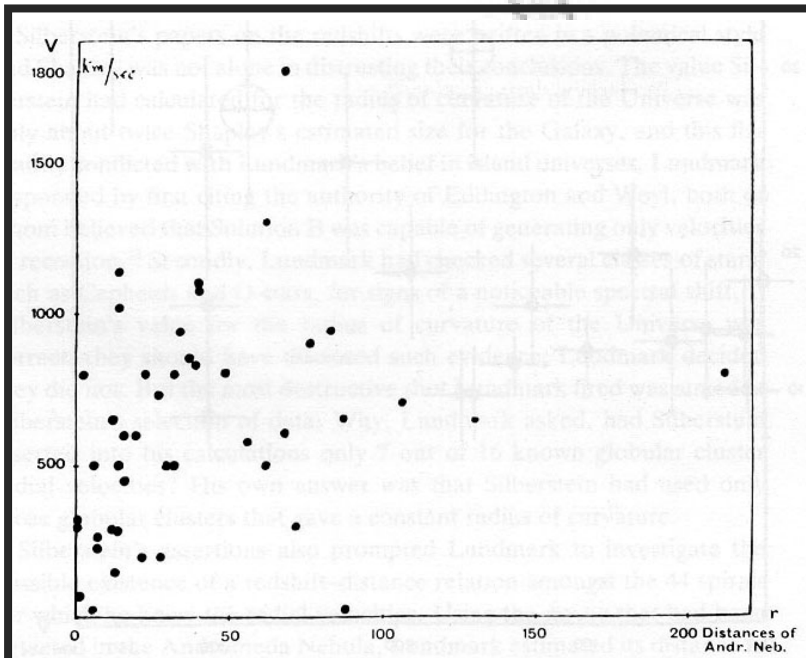
- more and more galaxies are redshifted
- proportion of redshifted galaxies such that it is no longer in accordance with random galaxy motions

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 ???

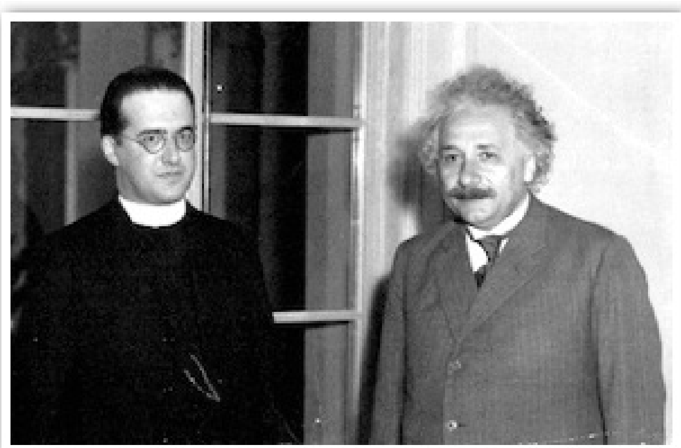
Cosmic Expansion: first indications



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"



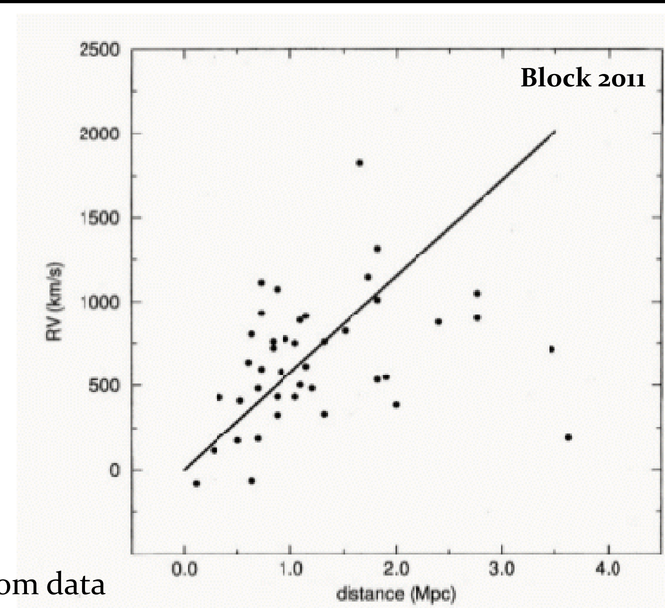
1927:
Georges Lemaitre (1894-1966)

Belgian priest

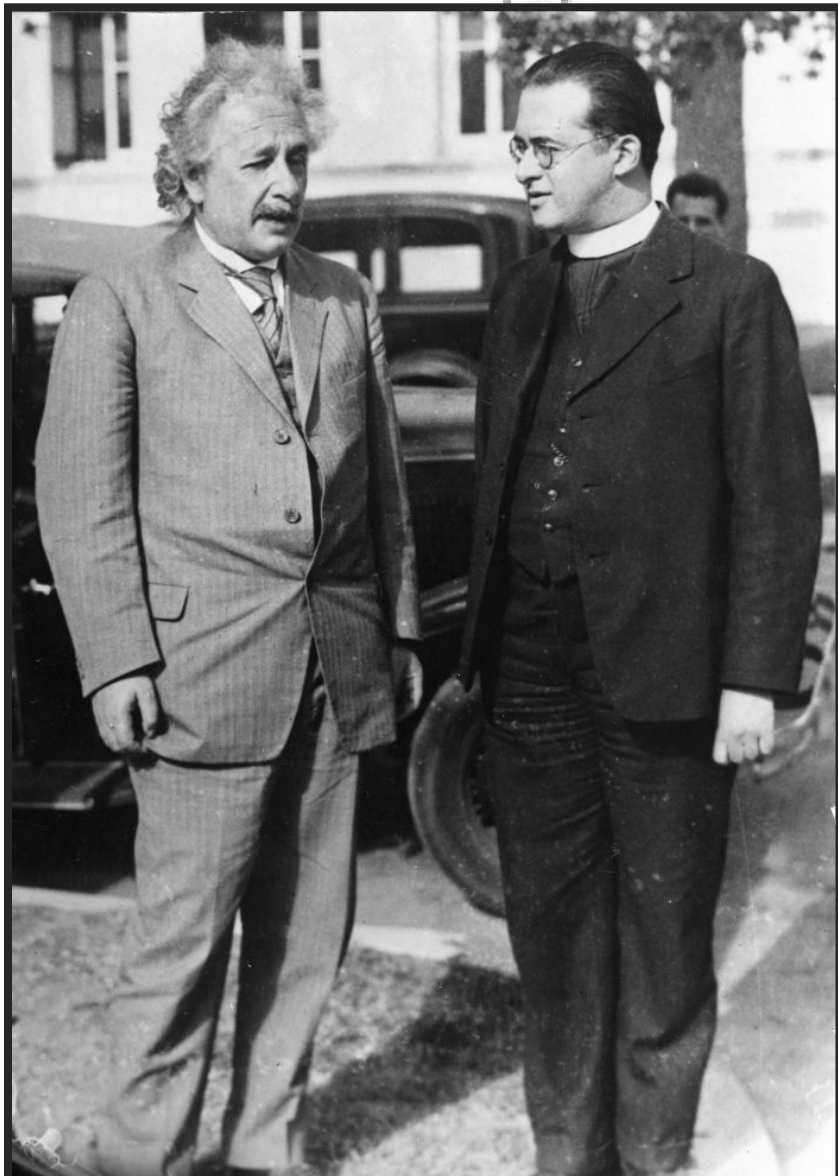
One of few who by 1920s understood General Relativity,

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”

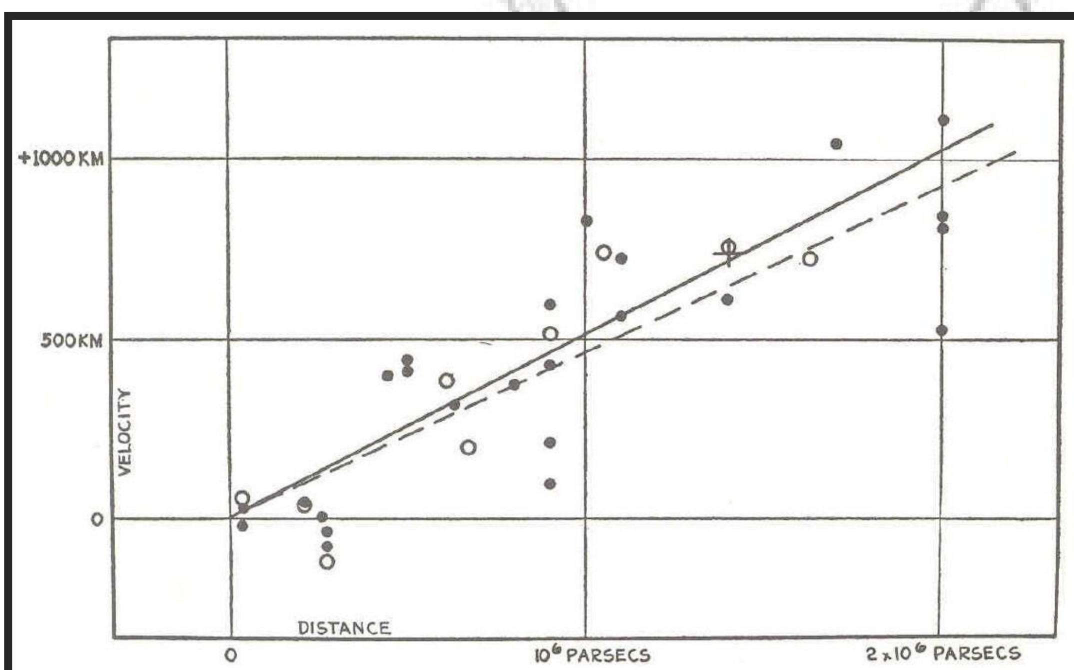
- He assumed that the absolute brightness of galaxies can be used as standard candle, and thus inferred distances on the basis of galaxy brightnesses.

- 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

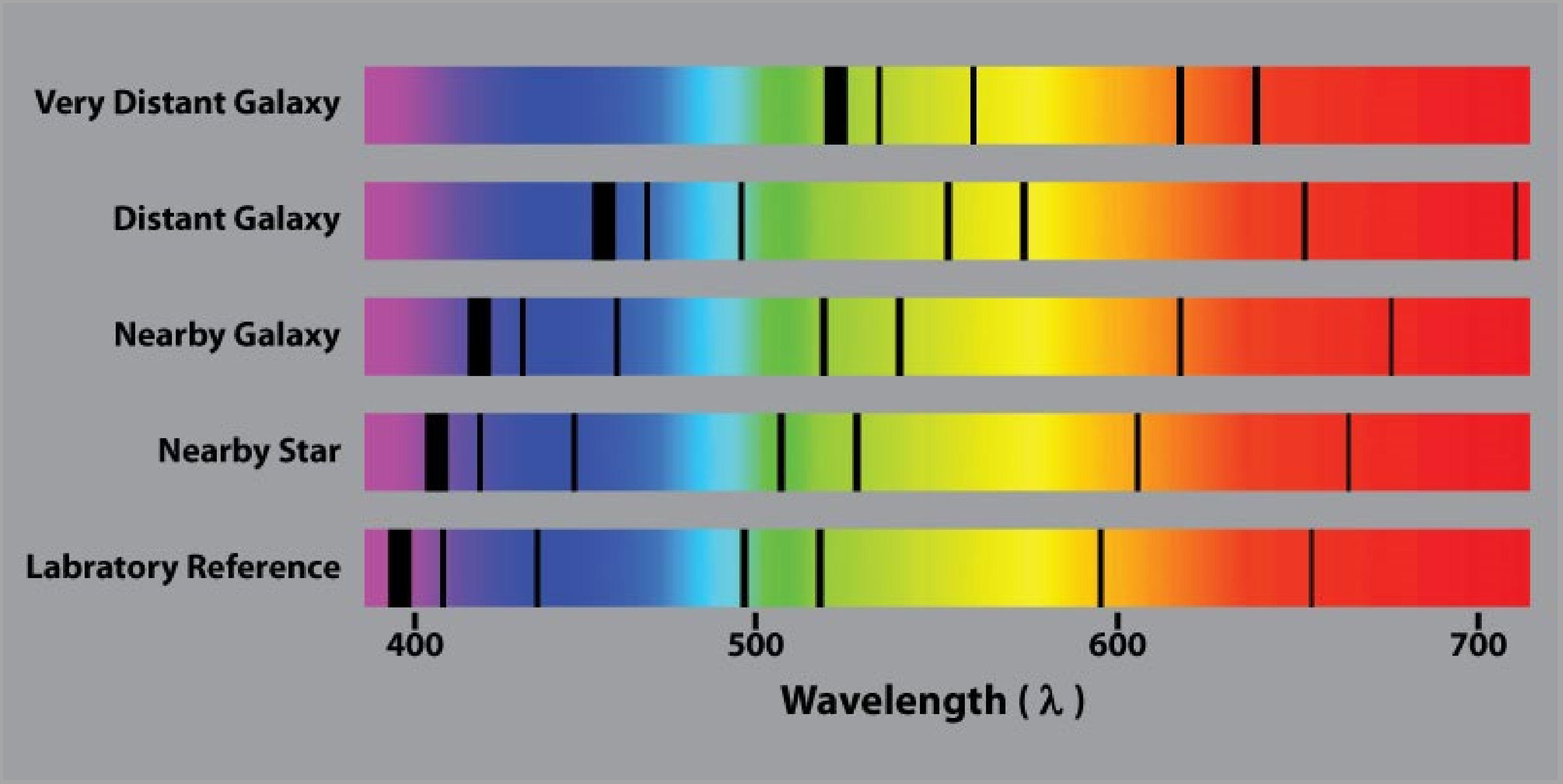
Note: Hubble himself never grasped that this was the evidence for an expanding Universe as described by the Friedmann-Lemaitre equations ie. as implied by Einstein's theory of General Relativity.

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

H_0 : **Hubble constant**

specifies expanssion rate of the Universe

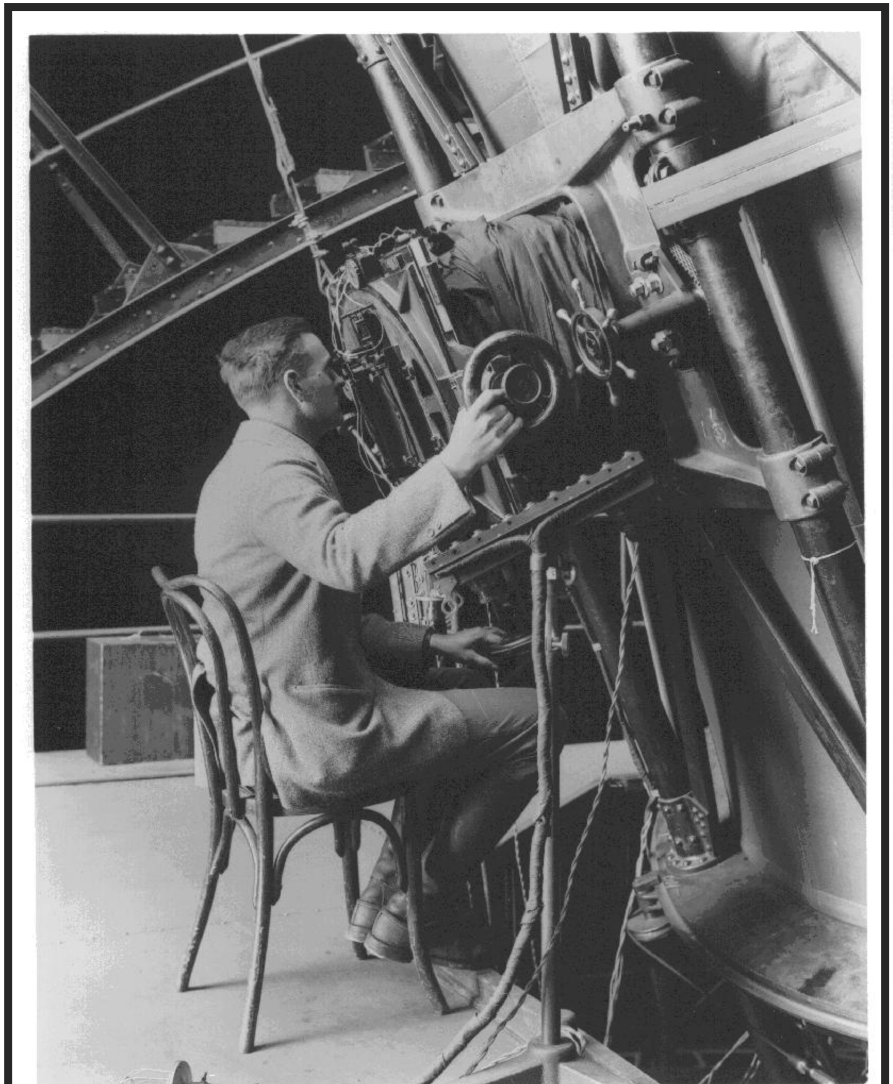
Hubble Expansion & Galaxy Redshift



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

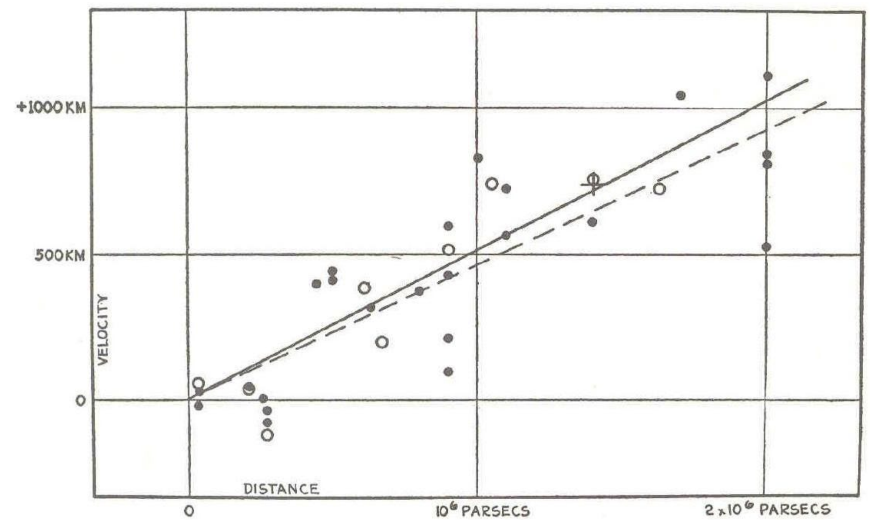
The Hubble law tells us that the further a galaxy is, the more redshifted it is.
Moreover, because this a linear relation, we can even estimate distances to galaxies once we know the value of the Hubble constant !

Hubble Expansion



Edwin Hubble

(1889-1953)



v = H r

Hubble Expansion

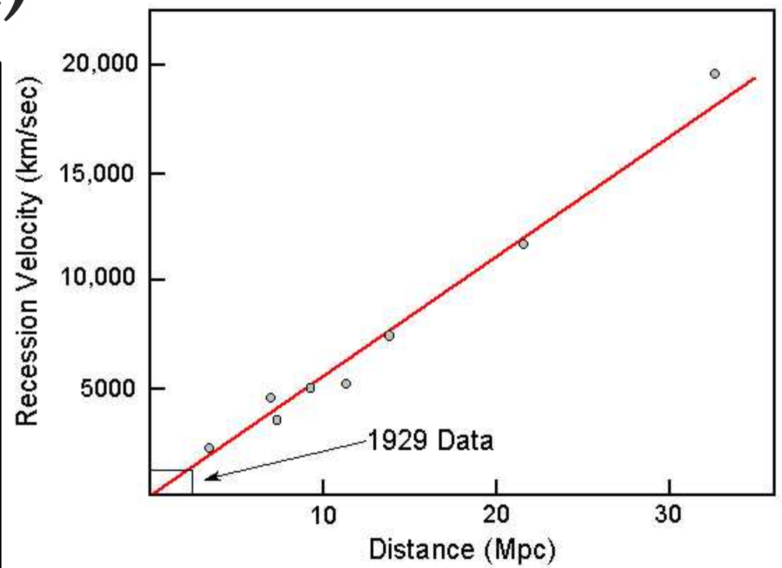
Hubble – Humason (1931)

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:

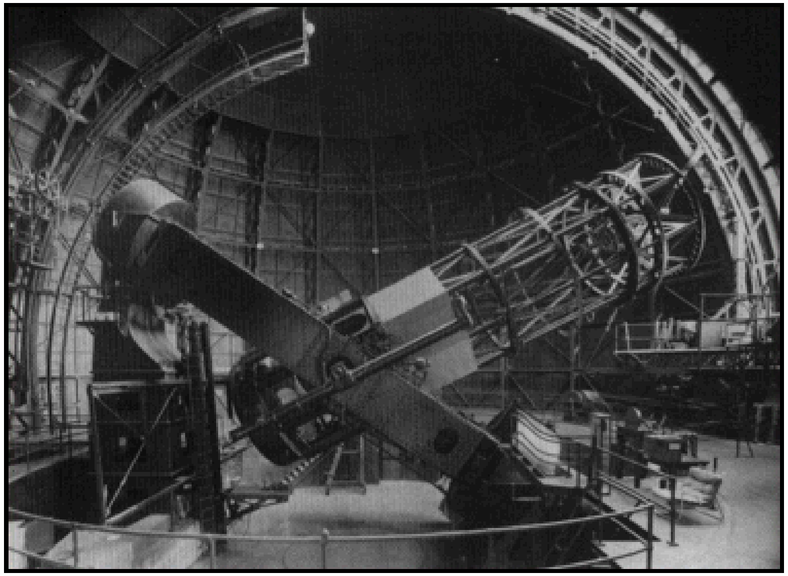
Hubble, Humason, 1931, Astrophys. J., **74**, 43

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.



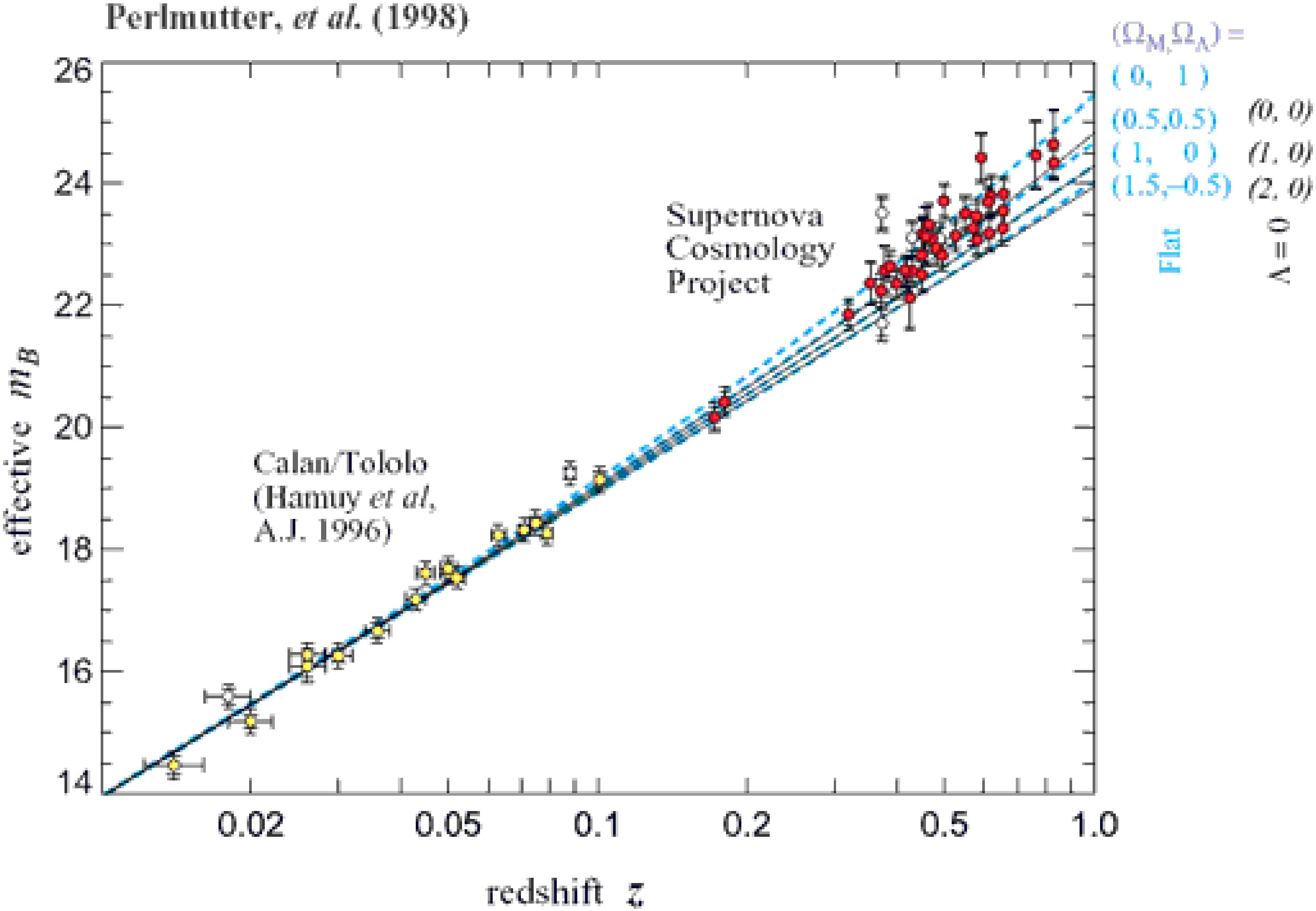
Edwin Hubble
1889 – 1953



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

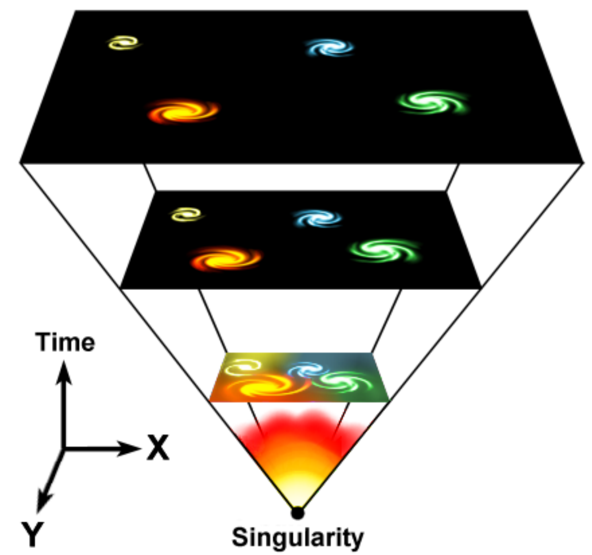
GLOBAL expansion factor a(t)

- 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 $a(t_0)=1$, i.e. the present-day expansion factor



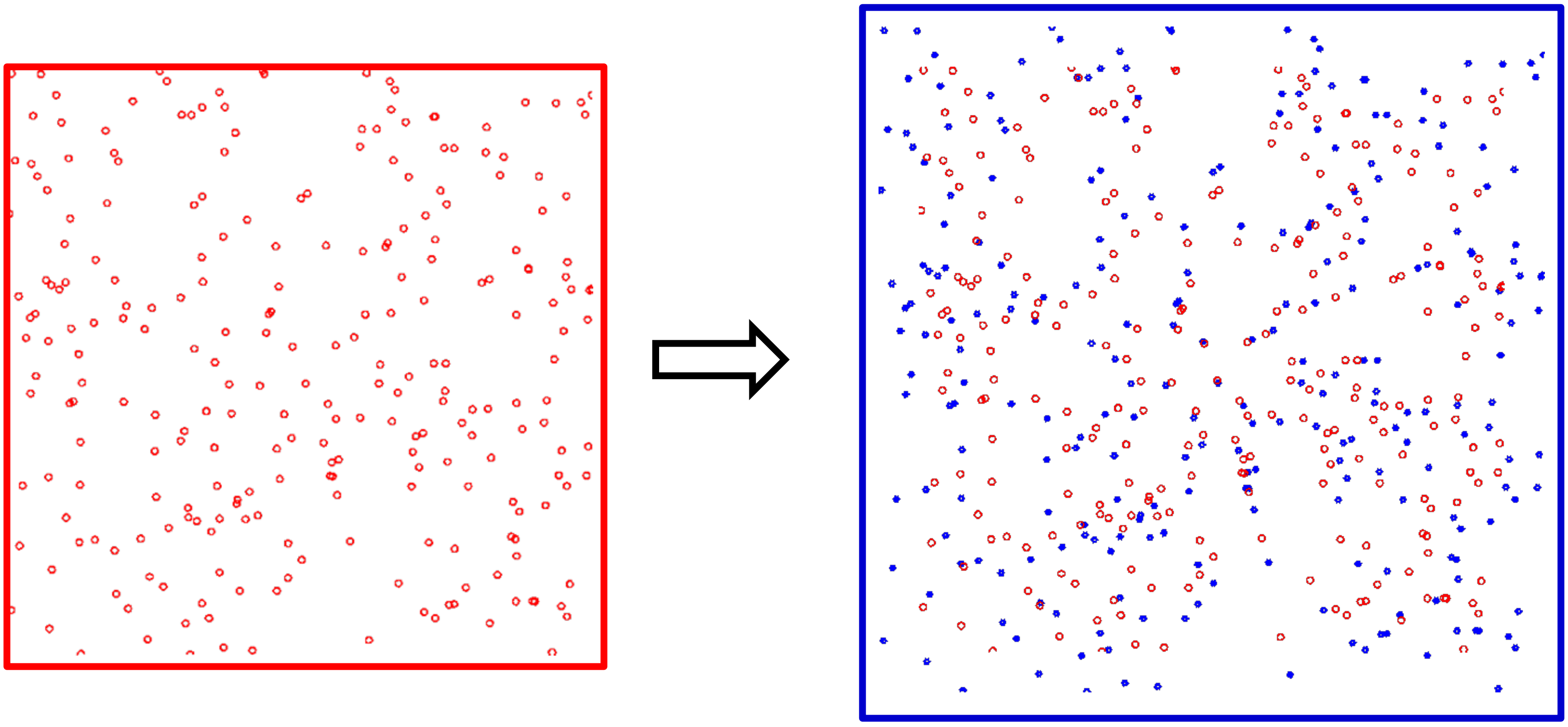
Hubble Expansion

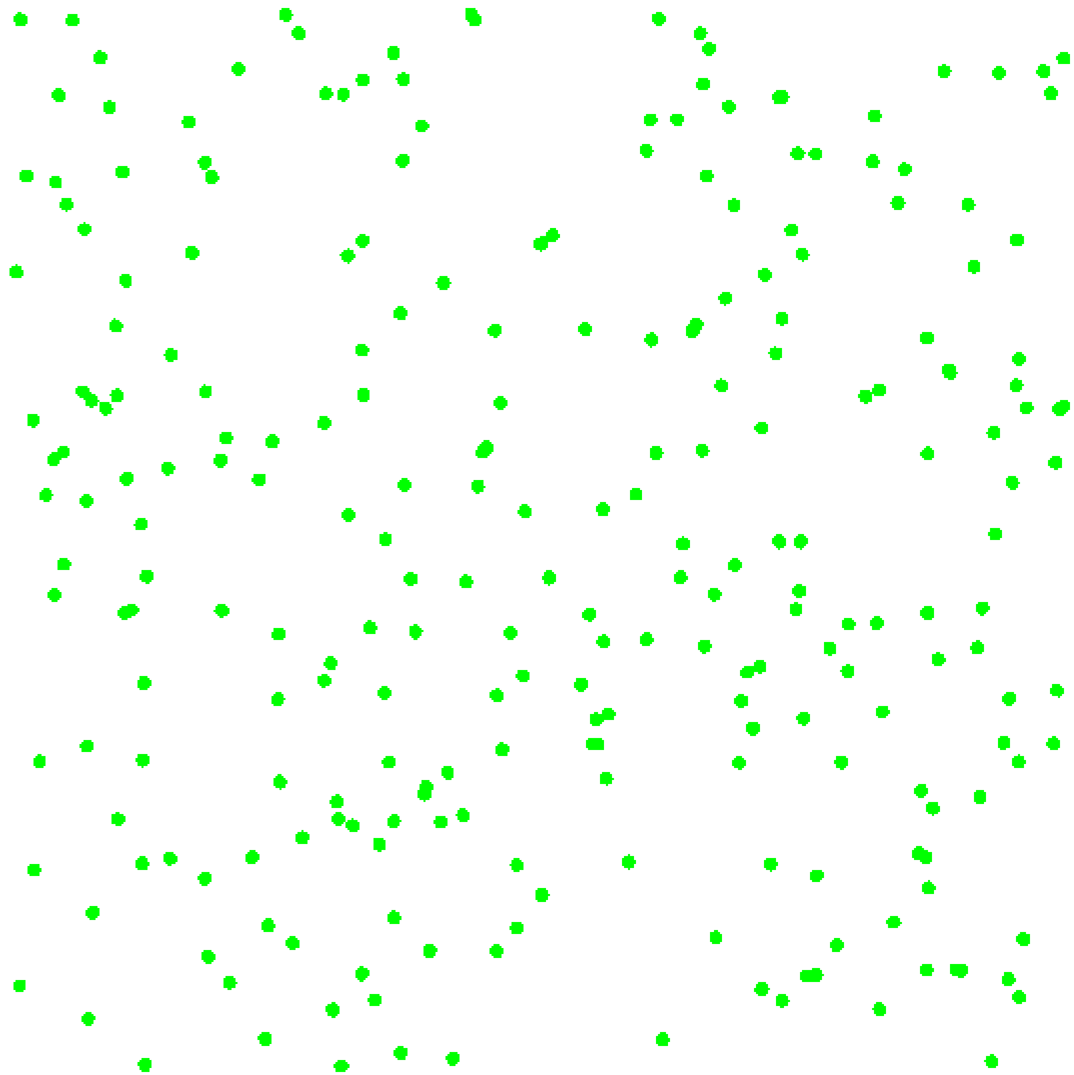
Space expands:

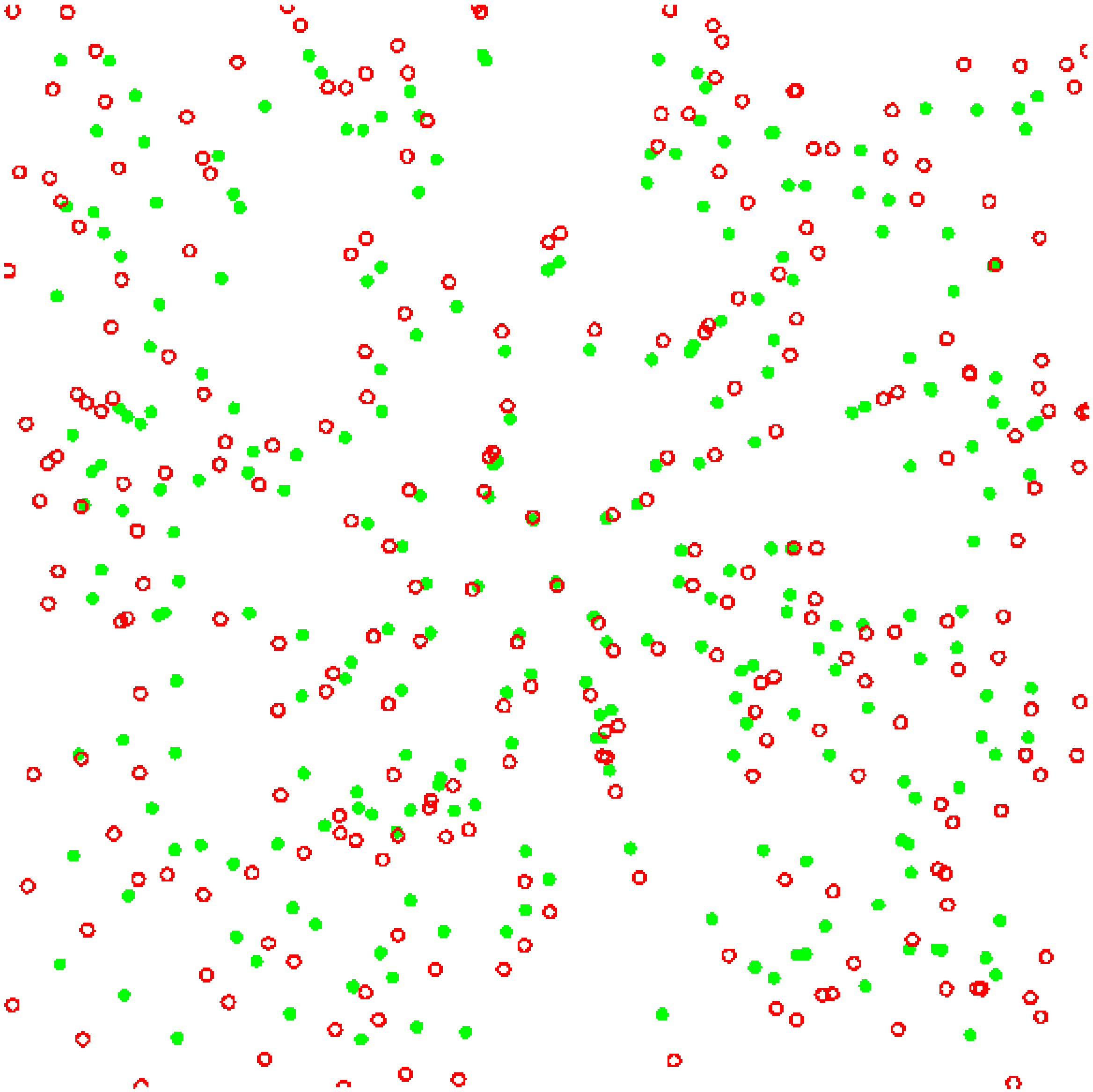
displacement - distance

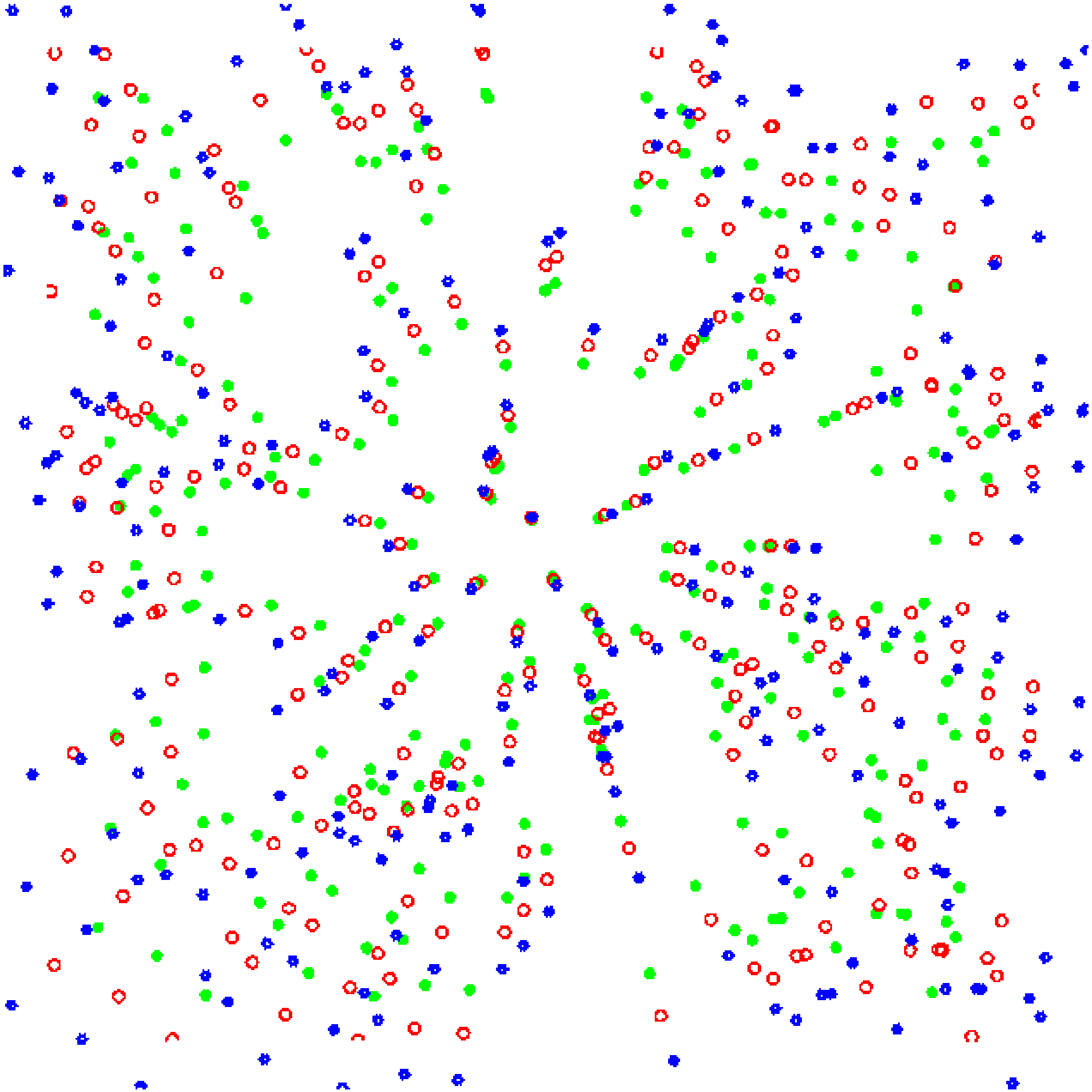
$$v = H\, r$$

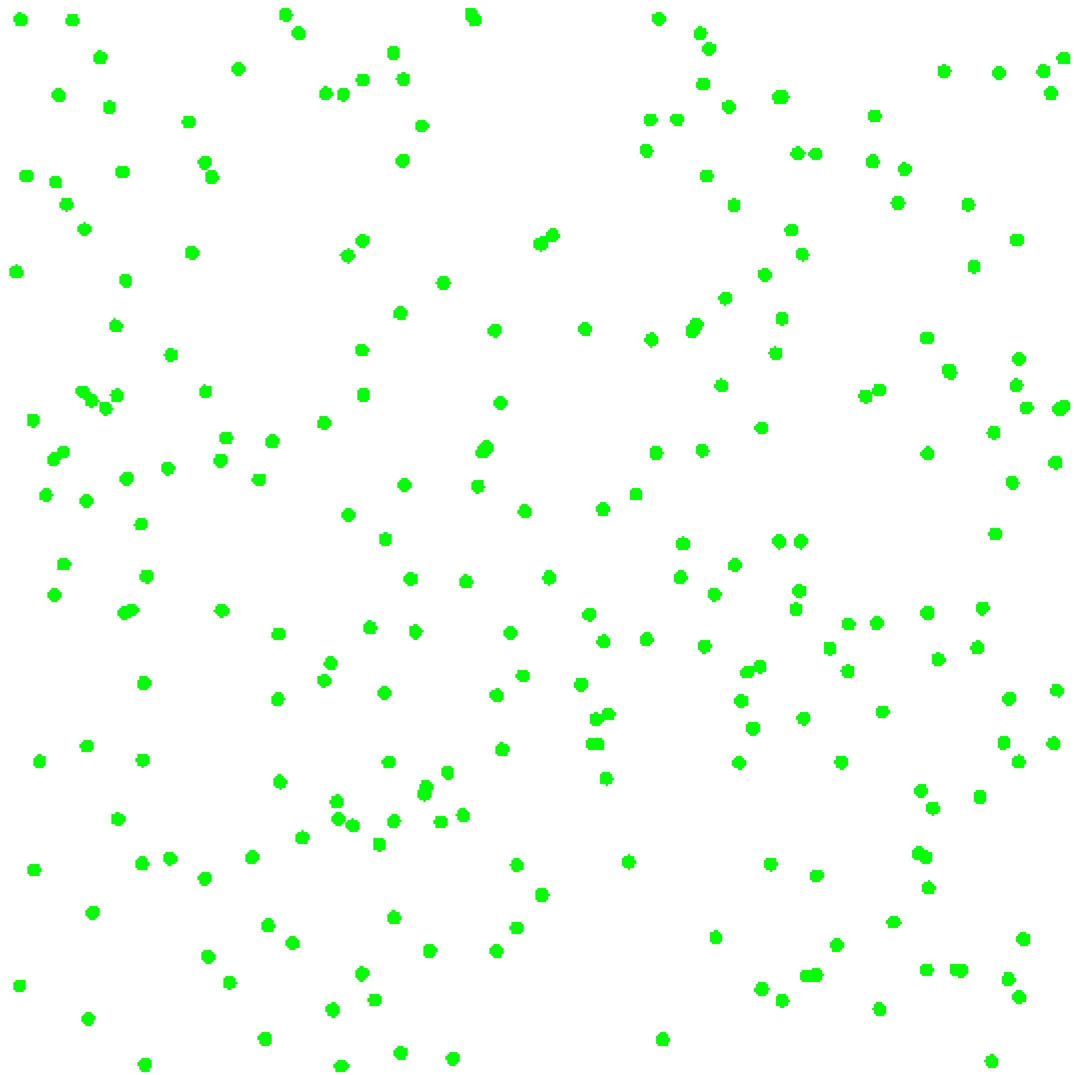
Hubble law: velocity - distance

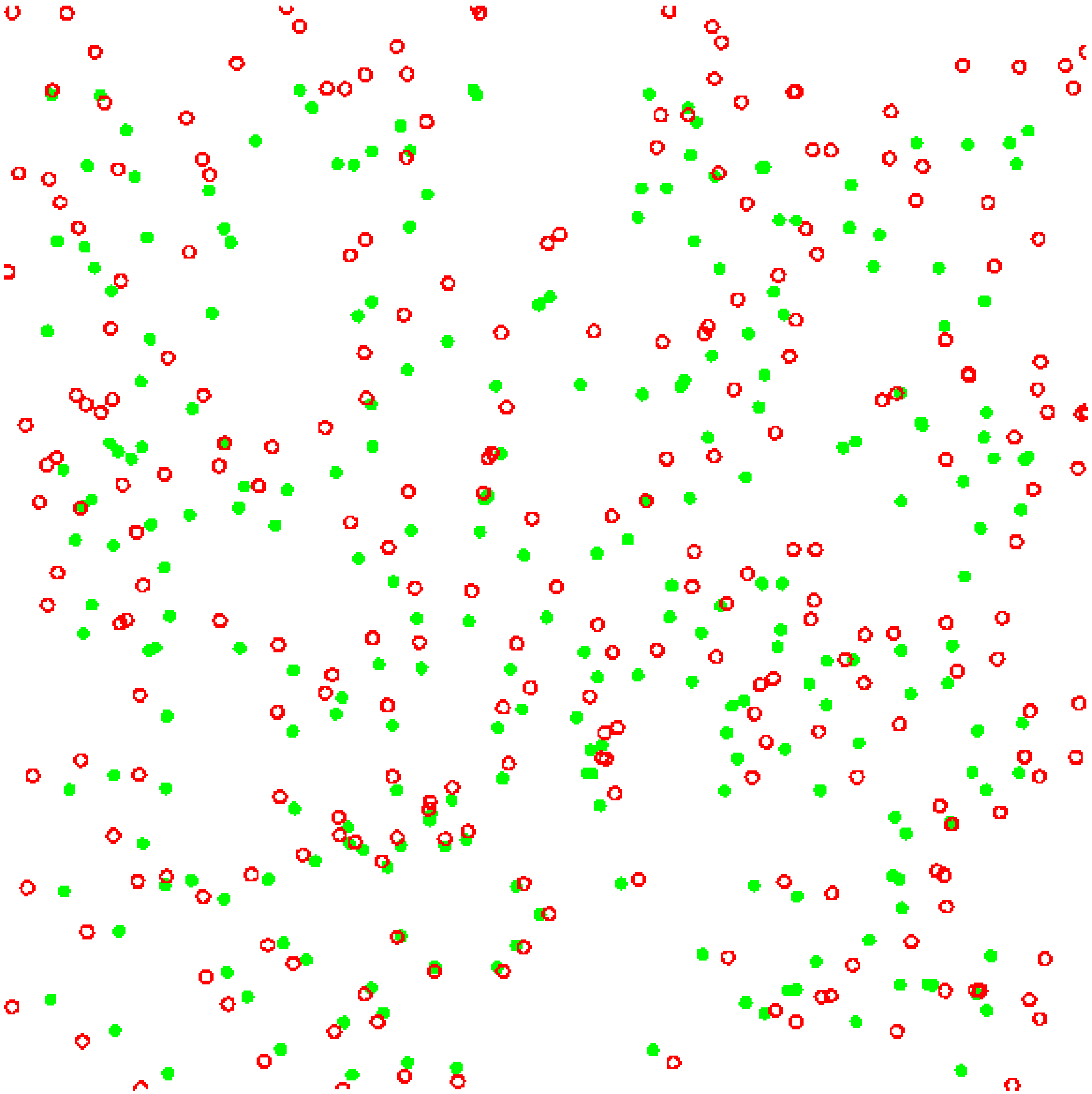


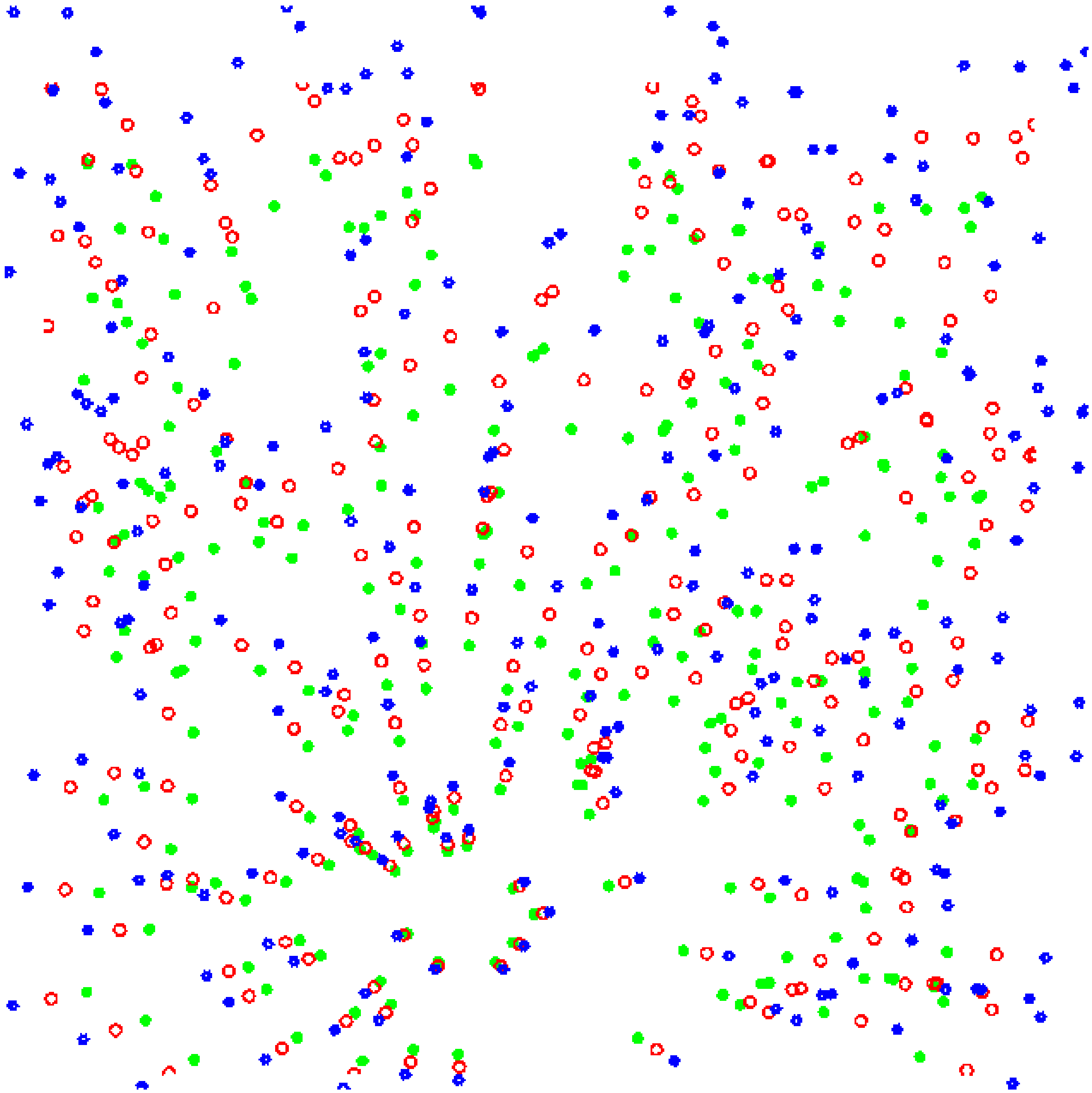












Hubble Parameter

- **For a long time, the correct value of the Hubble constant H_0 was a major unsettled issue:**

$H_0 = 50$ km s^{-1} Mpc^{-1} ⟷ $H_0 = 100$ 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

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

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

$$\Downarrow$$

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

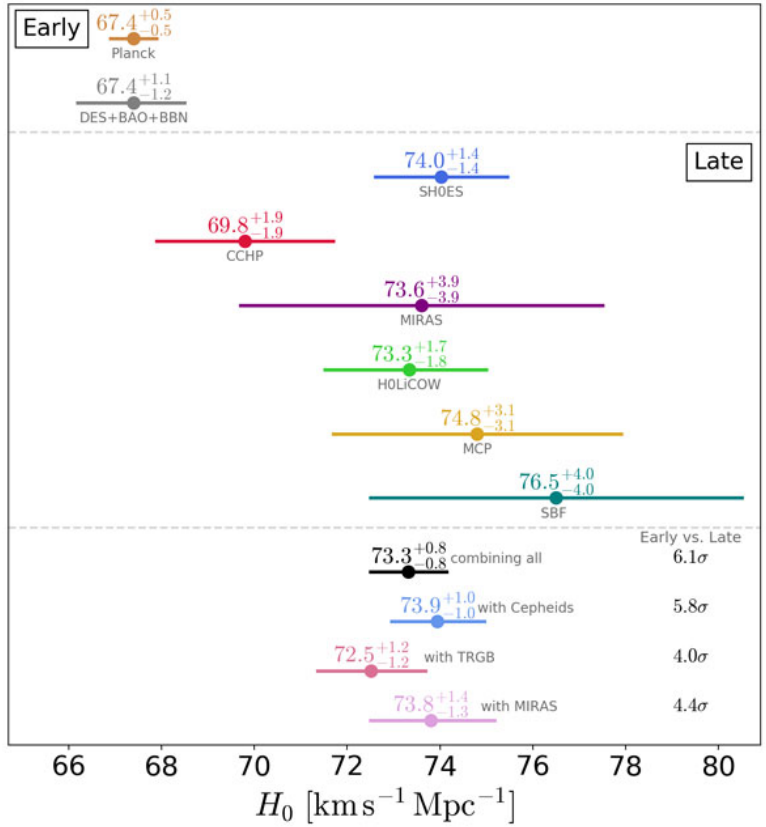
Hubble Constant: Tension

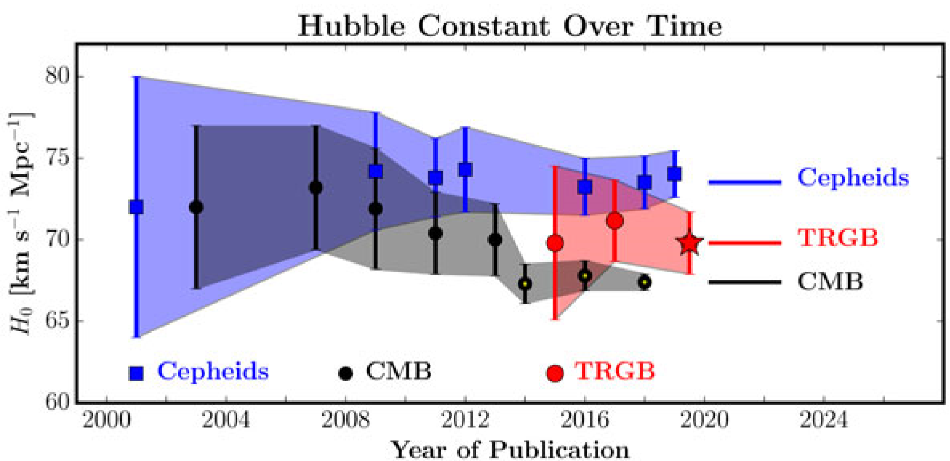
- As more accurate measurements of H_o become available,
  gradual rising tension

- CMB determination much lower than
  "local values"

- Latest value:
  strong grav. lensing

  Ho = 82.4 +/- 8.3 km/s/Mpc





Cosmic

Redshift

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

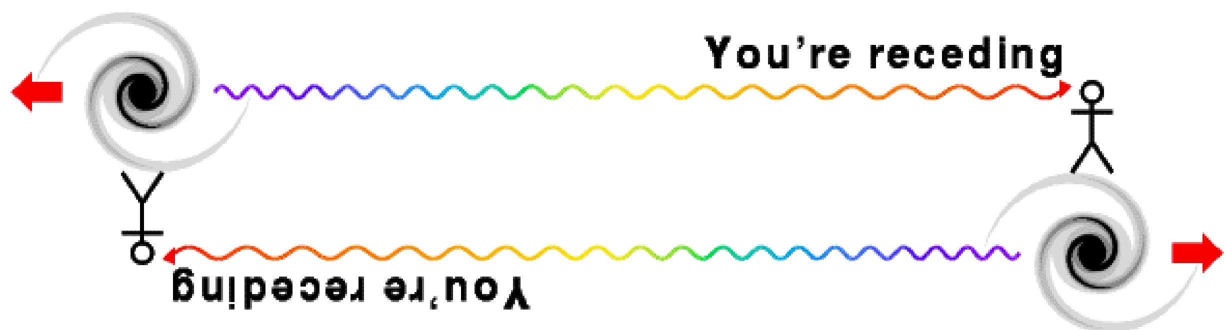
- Cosmic Redshift z:
  directly related to the expansion factor a(t) at which light gets emitted

- 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

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

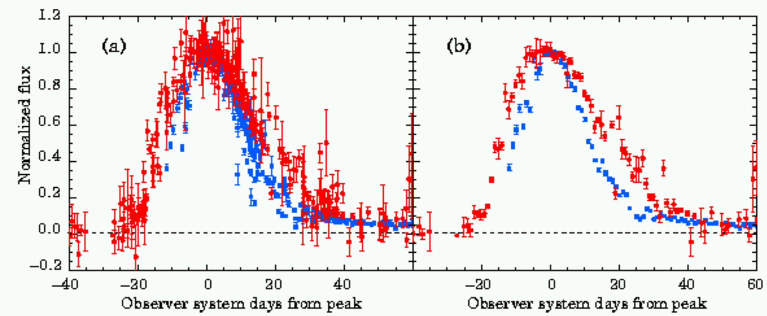
$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Cosmic Time Dilation

Cosmic Time Dilation

$$\Delta t_{obs} = \frac{\Delta t_e}{a(t_e)}$$

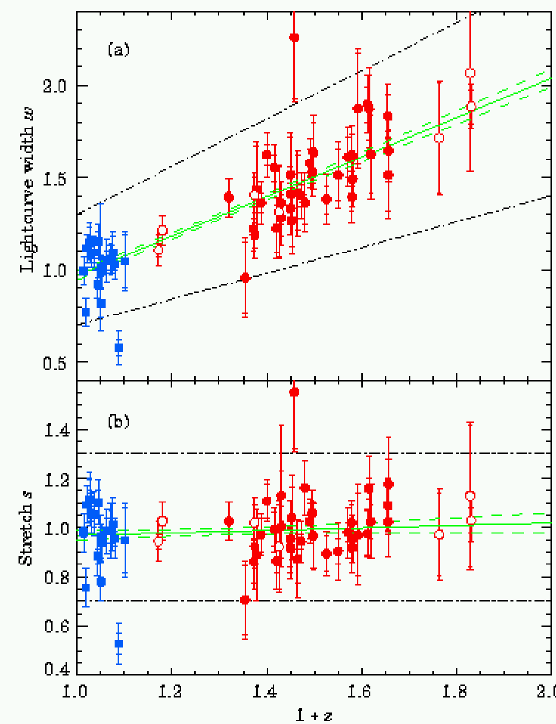


Evidence Cosmic Time Dilation:

light curves supernovae (exploding stars):

characteristic time interval over which the supernova rises and then dims:

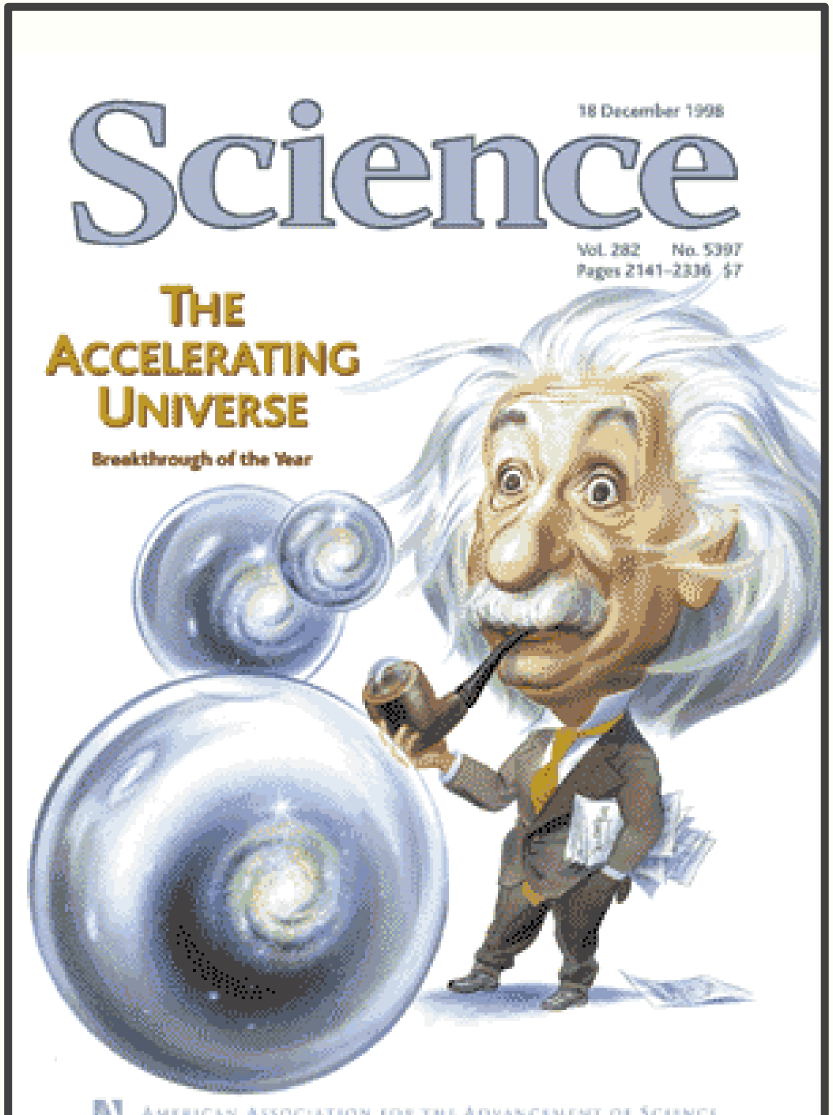
systematic shift with redshift (depth)



Expansion

Accelerates !

Science Magazine 1998



Science
Breakthrough of the Year
1998

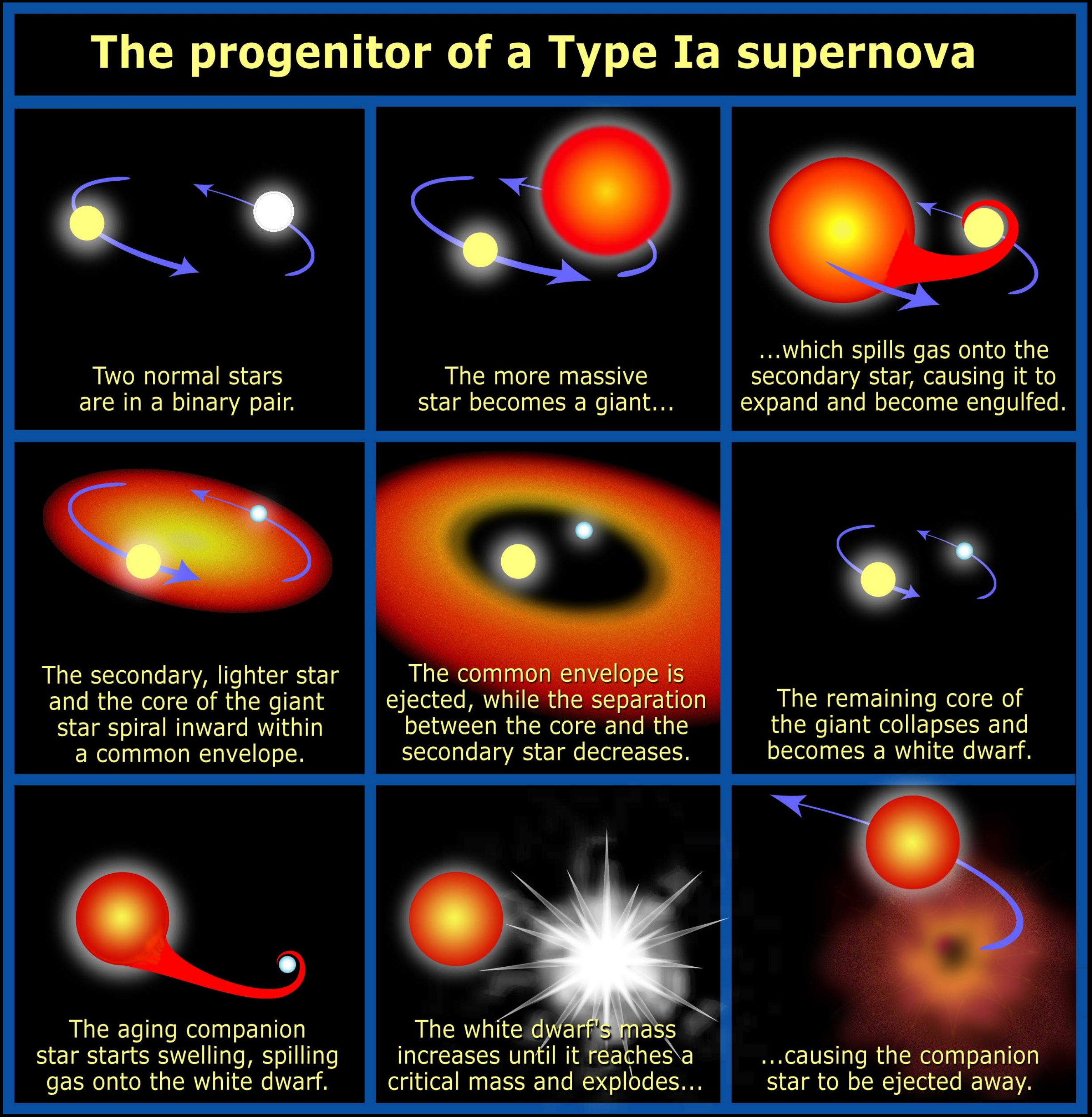

Λ
Einstein’s Biggest Blunder

Type Ia Supernovae

Supernova Explosion & Host Galaxy

M51 supernovae

Type Ia Supernova Explosion



The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral inward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.

Type Ia Supernova

- Amongst the most energetic explosions in our Universe:

  $E \sim 10^{54}$ 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

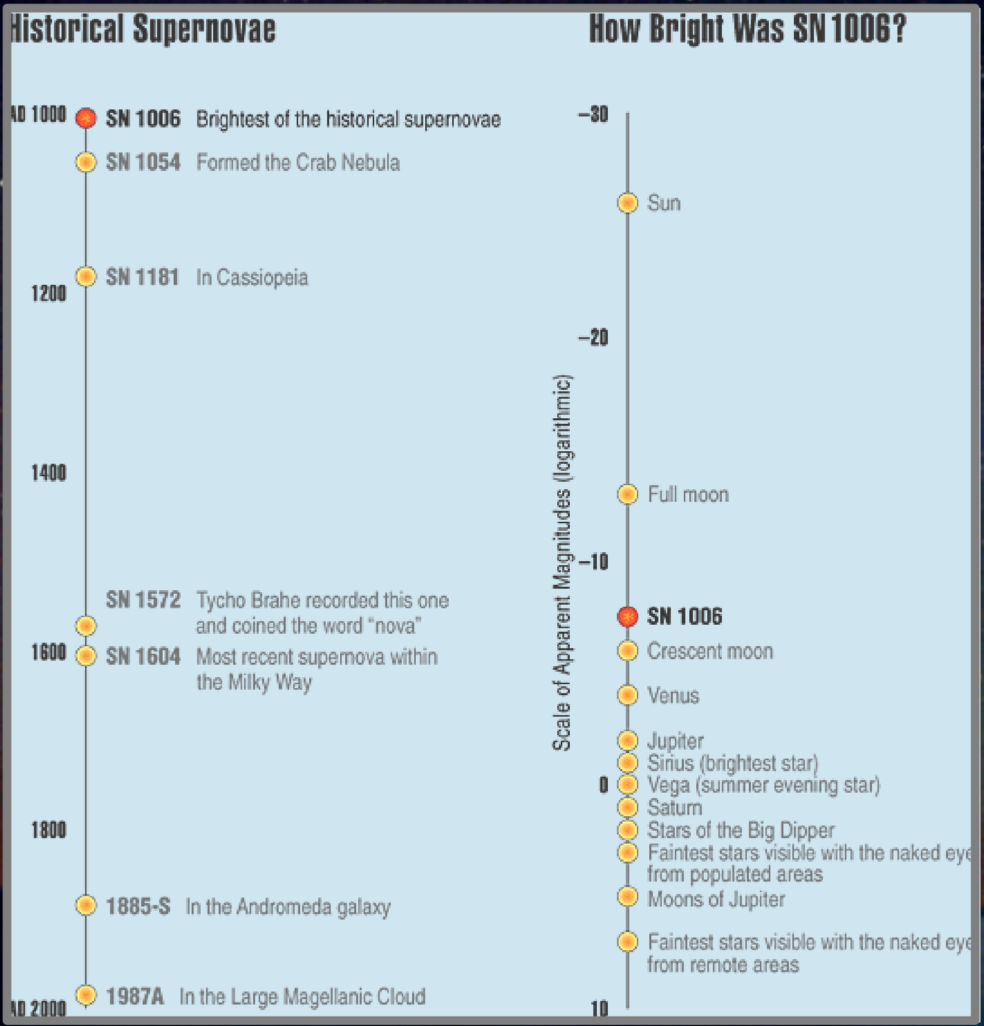
- Because exploding stars have nearly uniform progenitor (~1.38 $M_{\odot}$ white dwarf), their luminosity is almost the same: $M \sim -19.3$

  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

Supernova SN1006:

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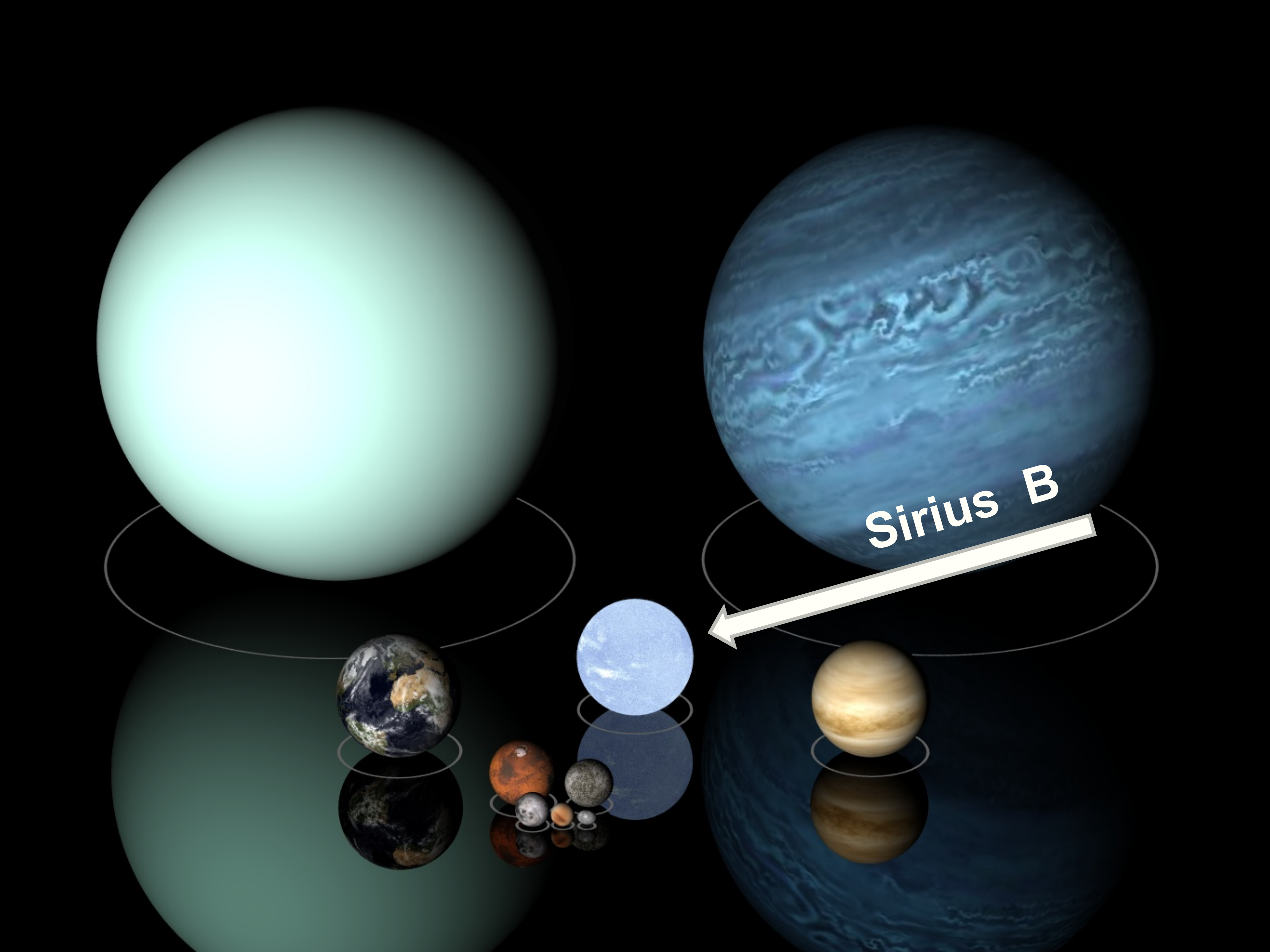
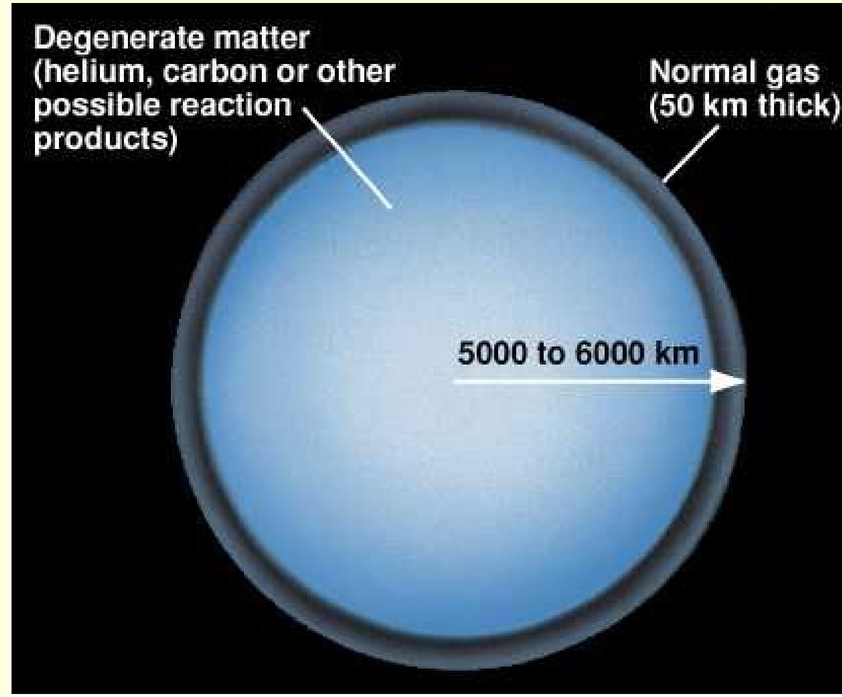
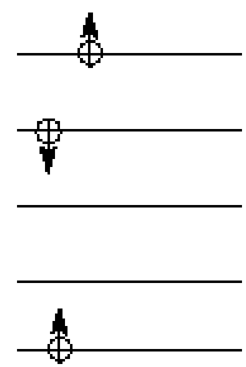
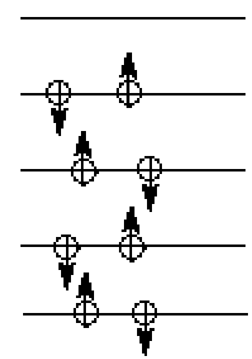
White Dwarfs


Sirius B





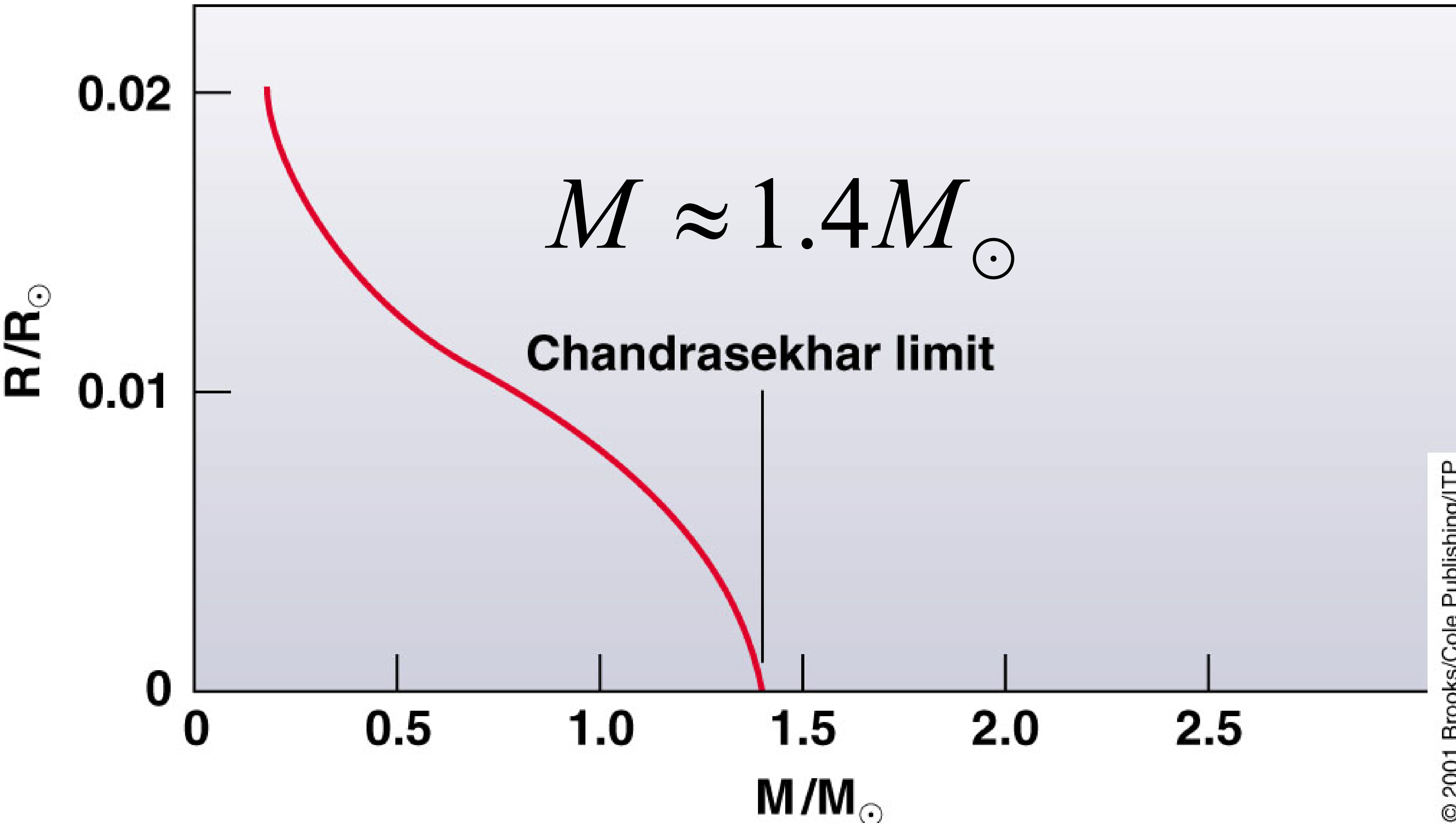
Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

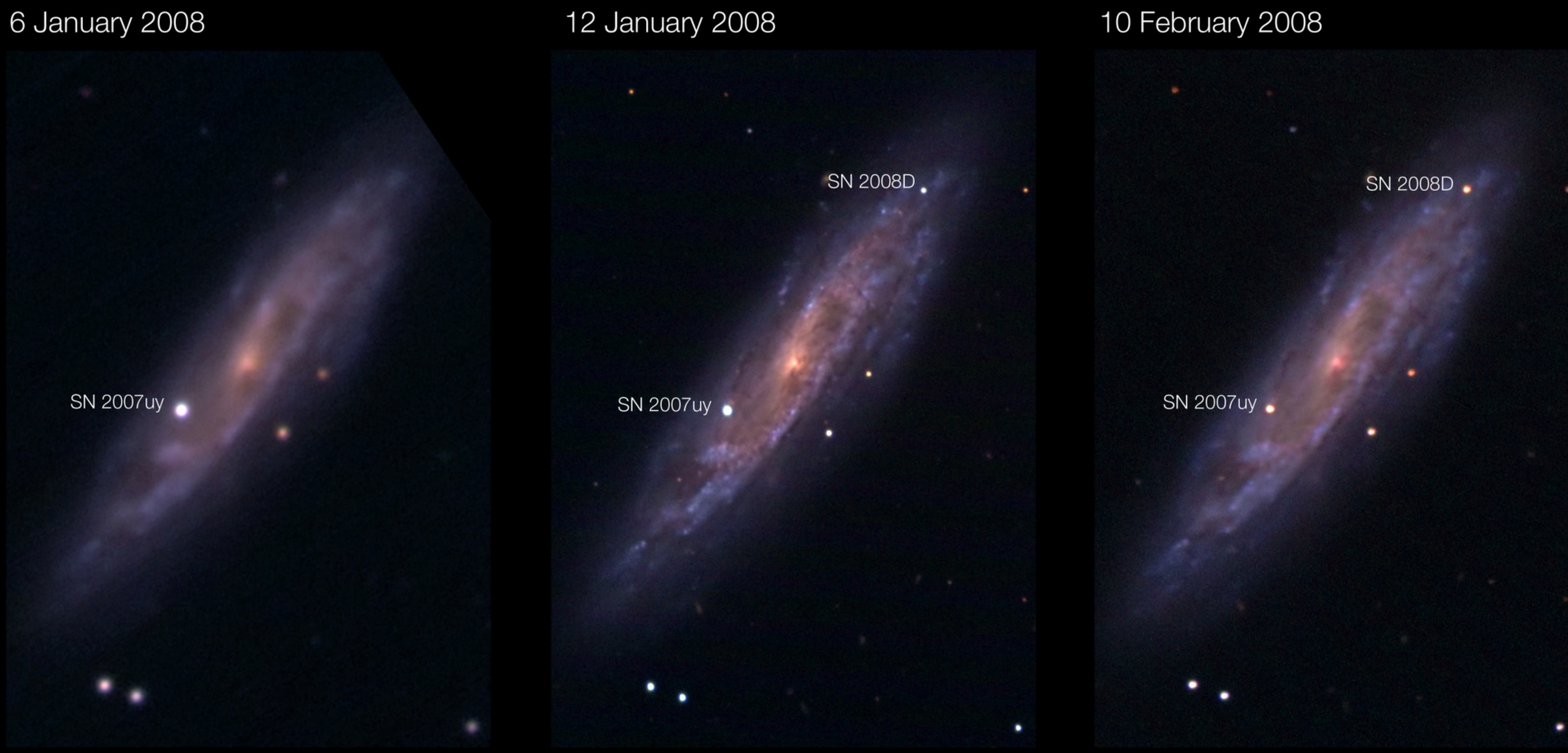
Chandrasekhar Mass Limit

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



Supernova Lightcurves

SN 2007uy

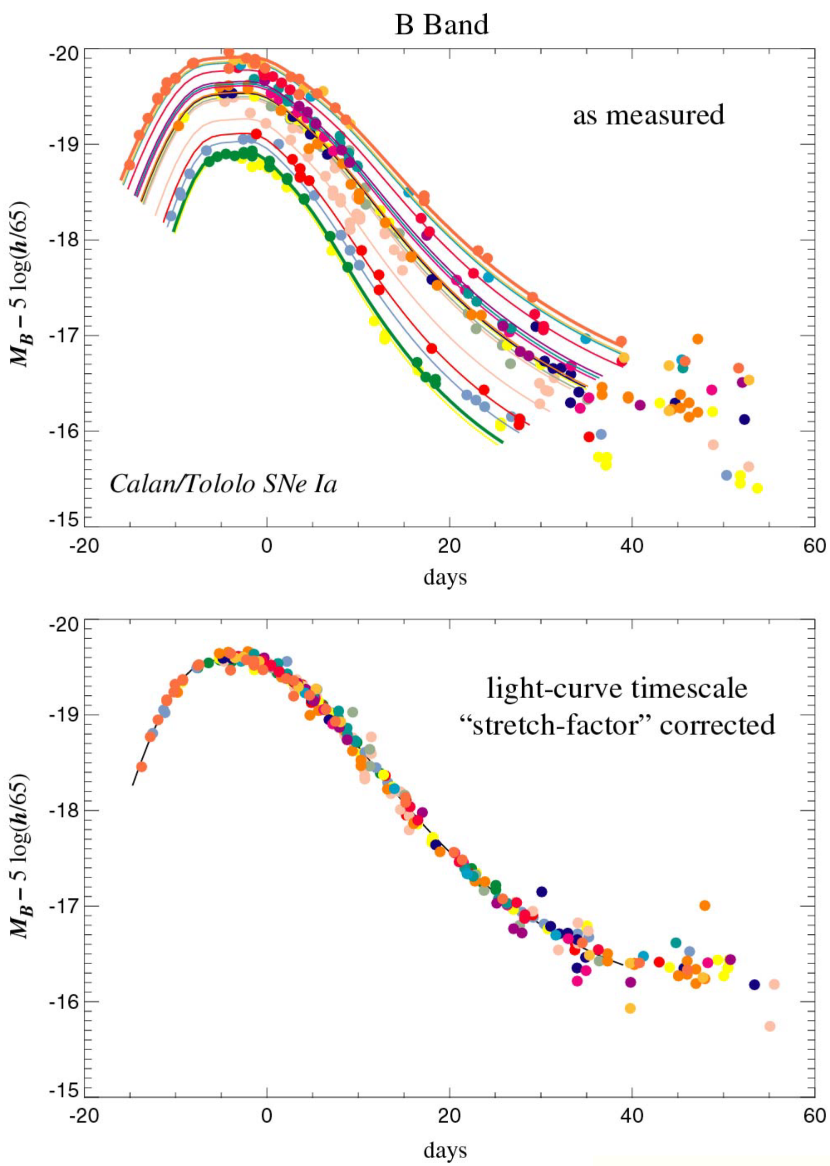


Supernova SN 2007uy in NGC2770

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

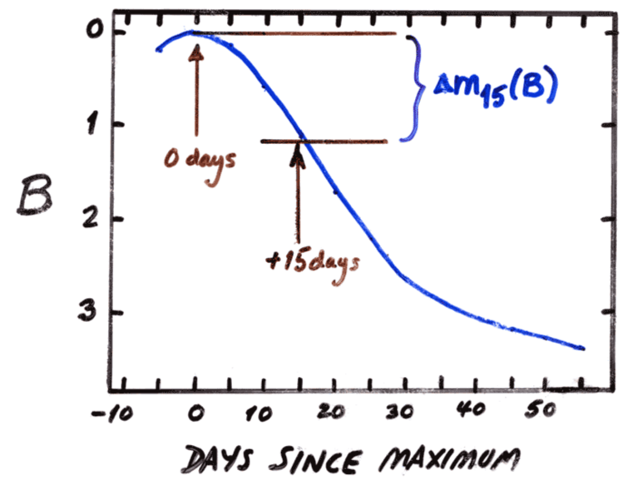
Supernova Lightcurve & Spectrum

the Phillips Relation



Relationship between

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



Mark Phillips (1993):

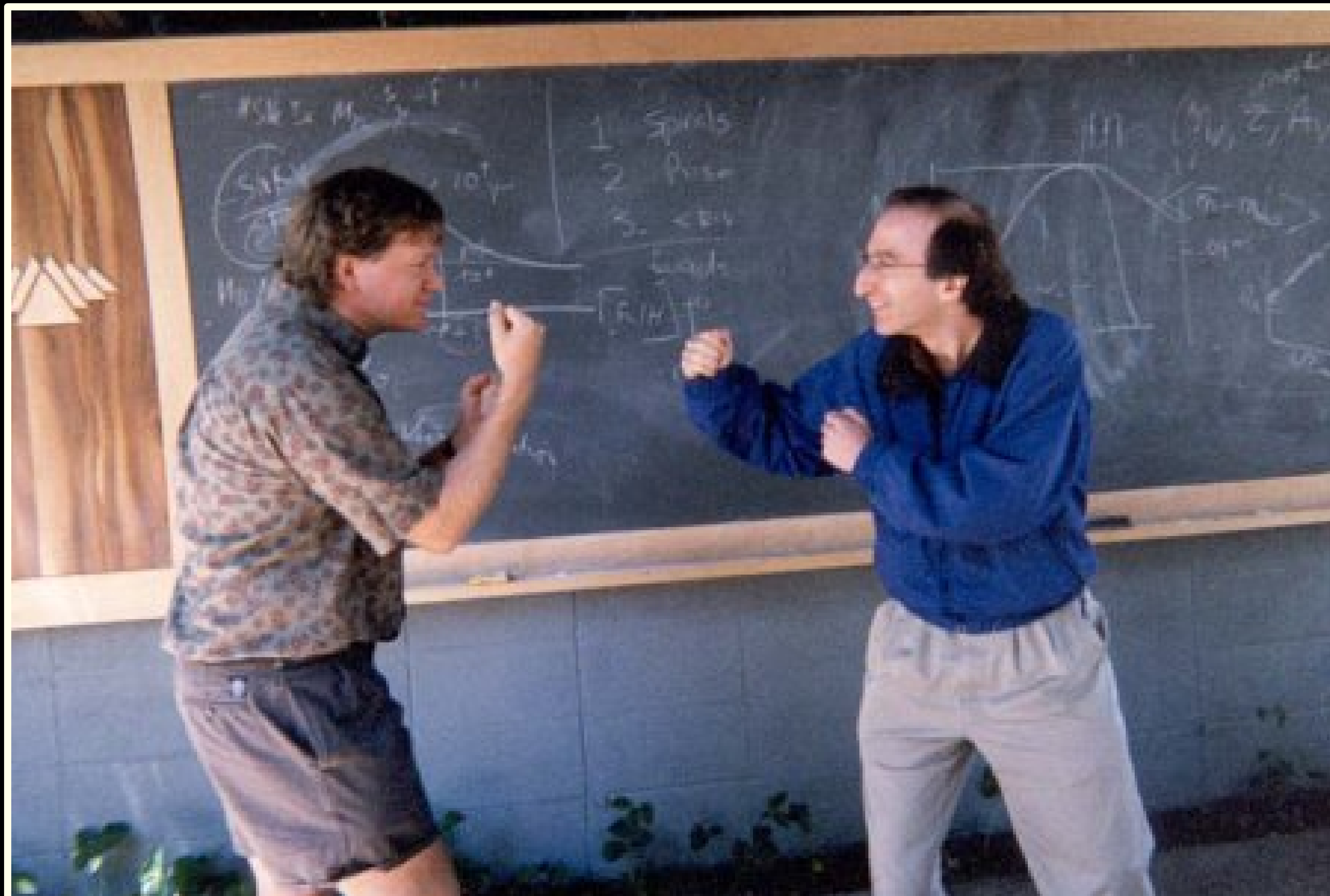
- **on the basis of Calan/Tololo Supernova Survey**

- **the faster a supernova fades after peak,**
- **the fainter its intrinsic peak luminosity**

- **reduces scatter in Hubble diagram to □<0.2 mag**
- **heuristic relationship, as yet not theoretically "understood"**

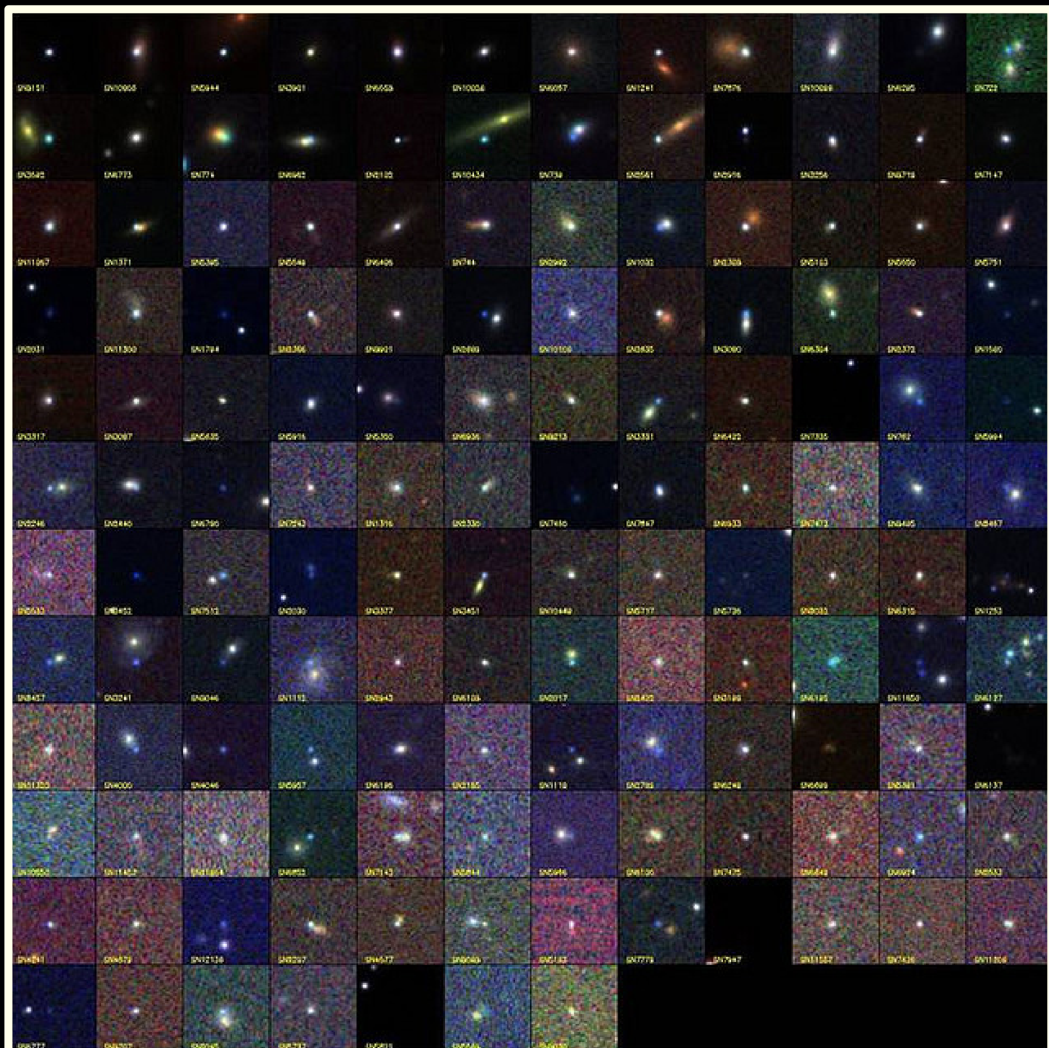
Cosmic Acceleration

Supernova Cosmology Project



High-z Supernova Search Team

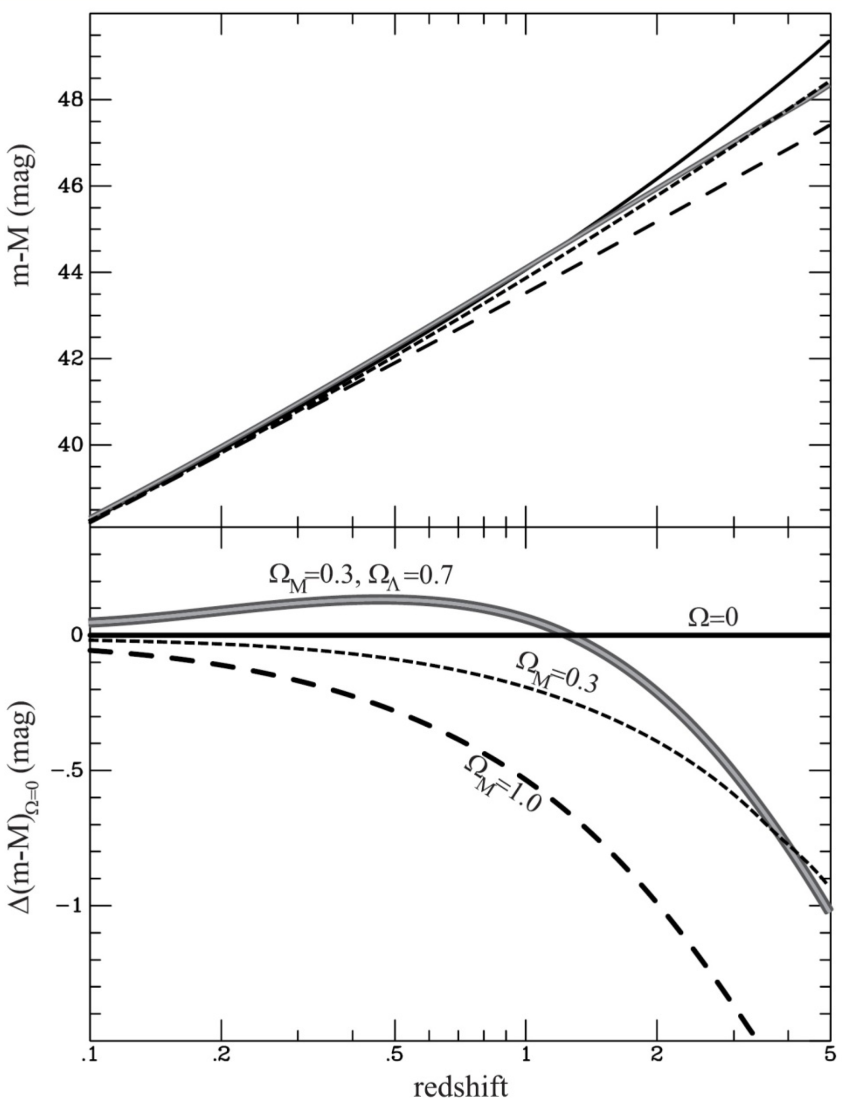
Supernova Cosmology Project



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

High-z Supernova Search Team

Cosmic Acceleration



Hubble Diagram high-z SNIa

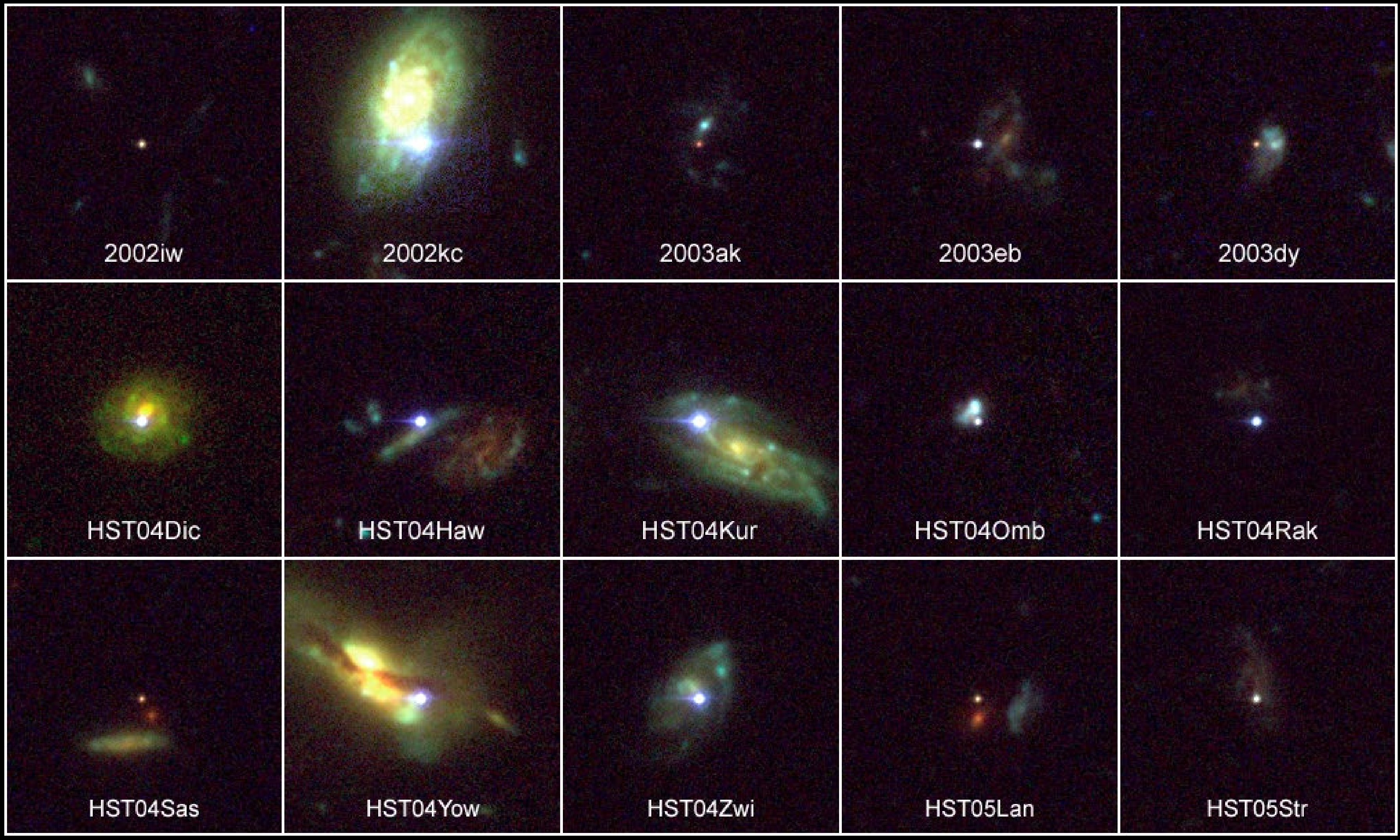
- distance vs. redshift z
  m-M vs. redshift z

- determine:
  - absolute brightness of supernova Ia
  - from dimming rate (Phillips relation)

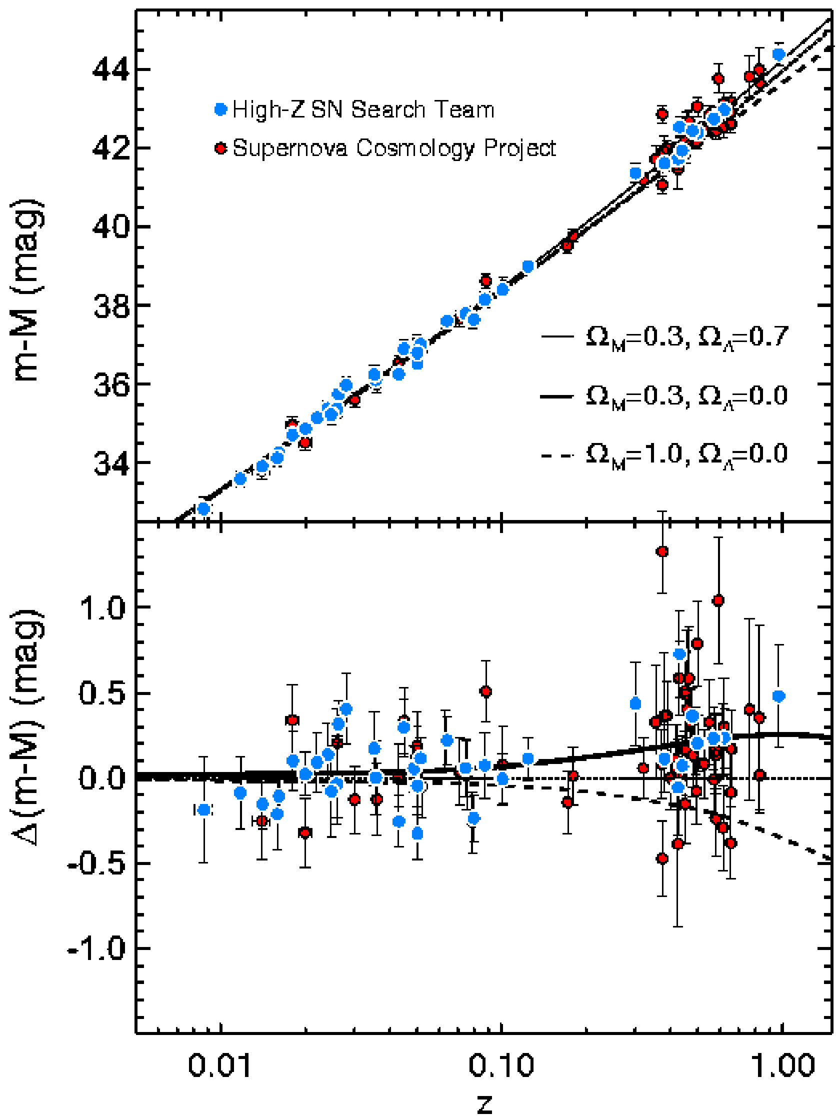
- measure:
  - apparent brightness of explosion

- translates into:
  - luminosity distance of supernova
  - dependent on acceleration parm. q

High-z SNIa: sample



Cosmic Acceleration



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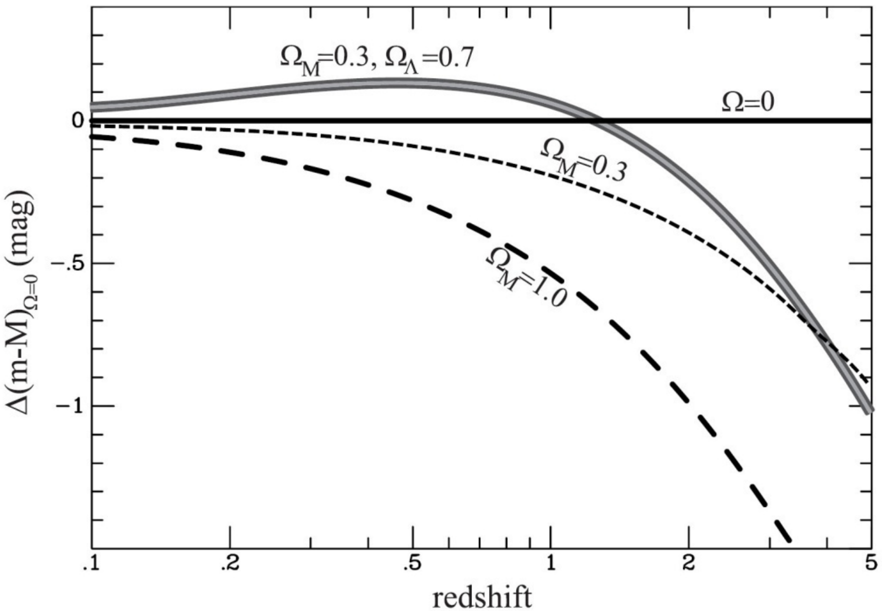
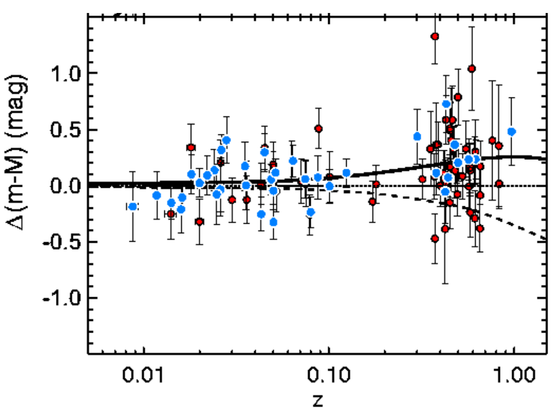
Cosmic Acceleration





Relative Hubble Diagram

Δ(m-M) vs. Redshift z

with Hubble diagram for empty Universe

Ω_m=0.0, Ω_Λ=0.0

as reference.

Acceleration of the Universe:

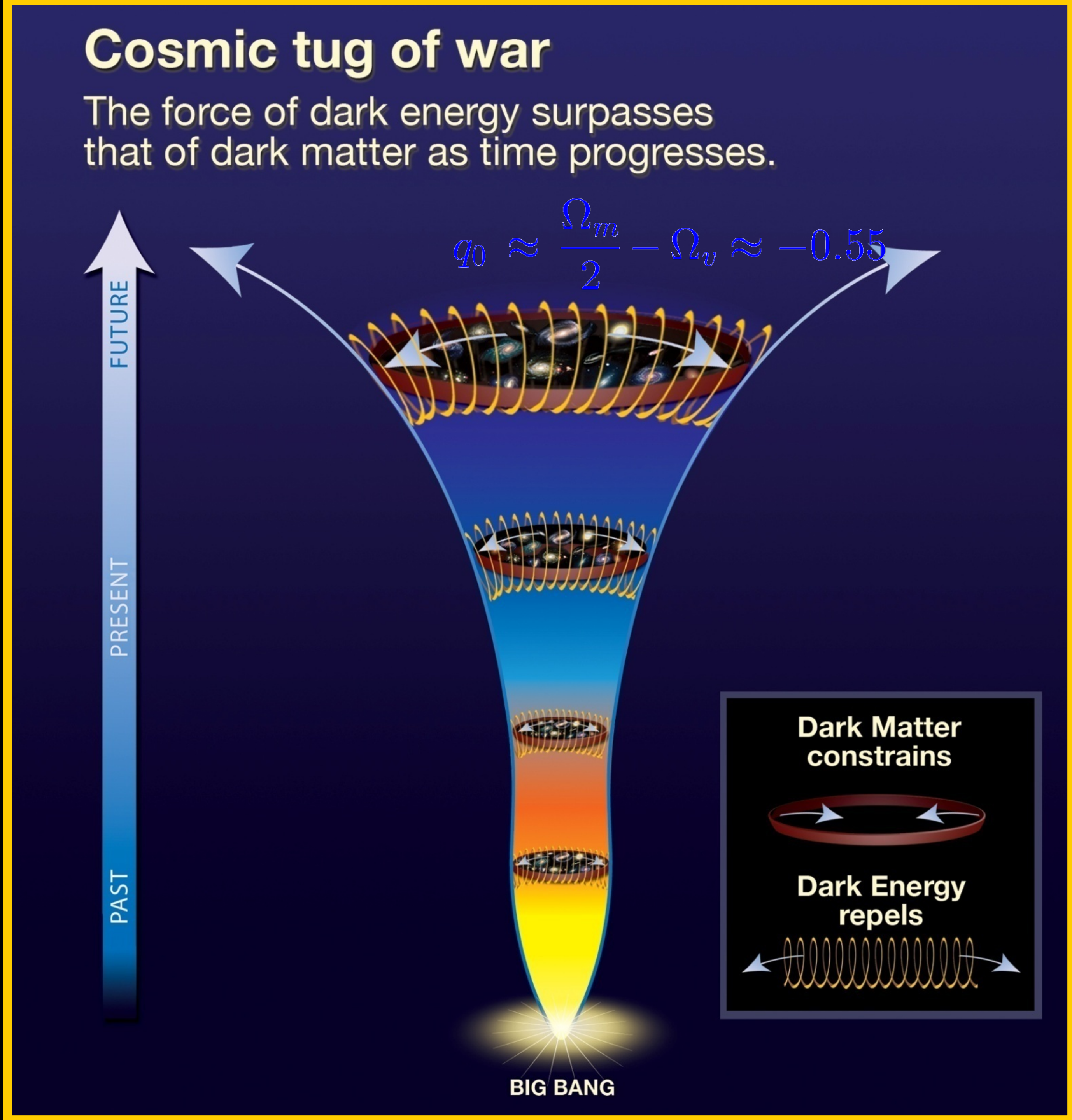
$$q_0 \approx \frac{\Omega_m}{2} - \Omega_v \approx -0.55$$

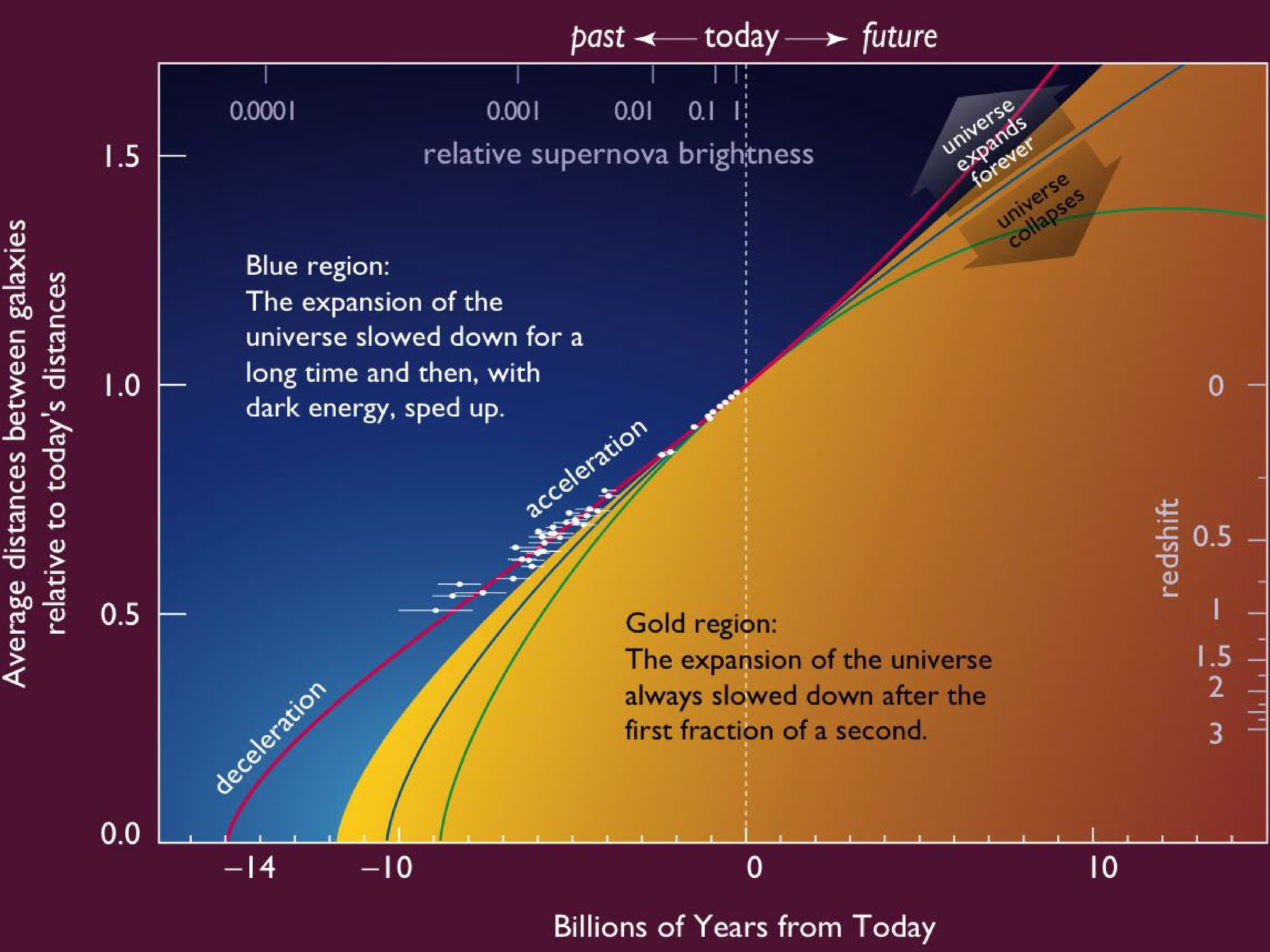
Present:

ACCELERATION

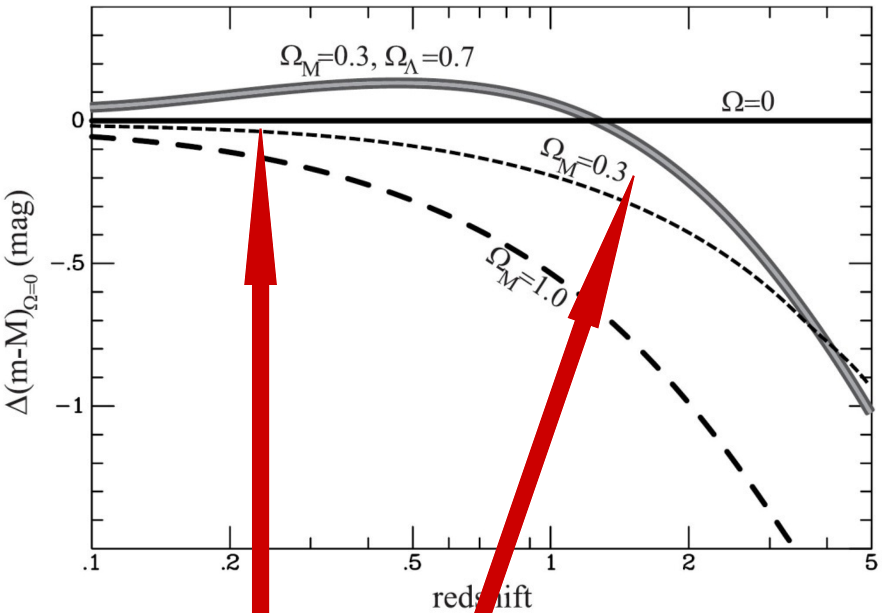
Past:

DECELERATION




past ← today → future
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
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.
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

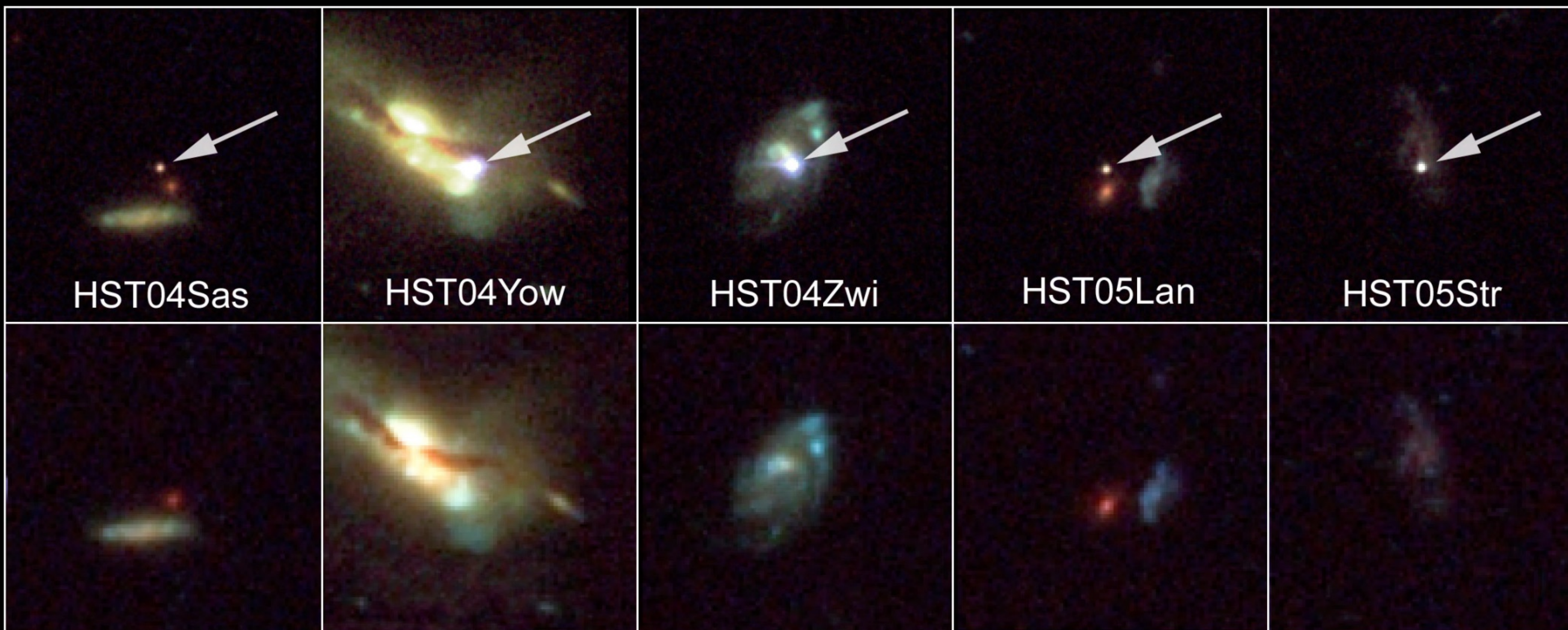
- **Universe dominated by matter:**

  Decelerating Expansion

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

  z > 0.73

Beyond Acceleration: SNe Ia at z > 0.7

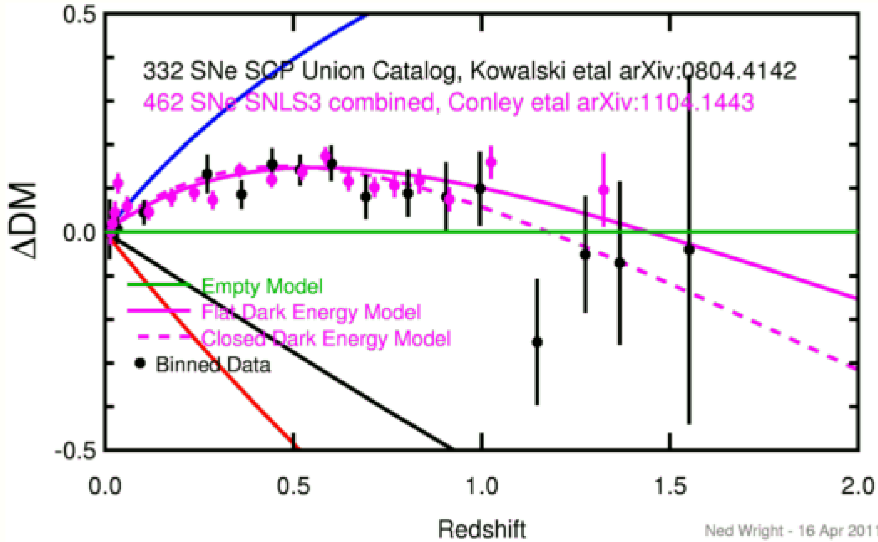


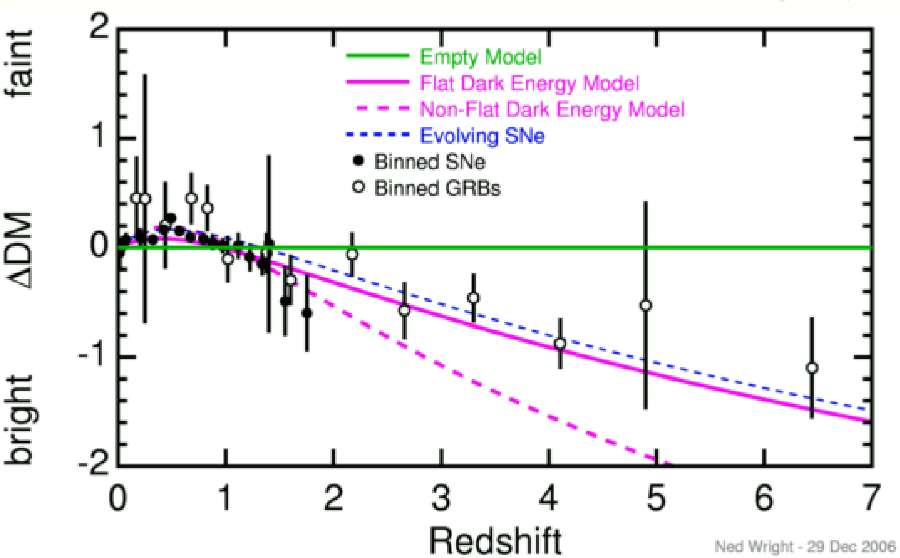
Five high-z SNIa, images HST-ACS camera

SNIa and host galaxies lower panel: before

top panel: after explosion)

Cosmic Deceleration





Before current Dark Energy epoch

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Nobel Prize Laureates