Introduction to cosmology

N. Regnault, LPNHE

Nicolas Regnault

(IN2P3 – LPNHE)

Jim Rich

(CEA Saclay)

Danièle Steer

(Université D. Diderot / IN2P3 - APC)

Outline

- The smooth expanding Universe [5x3h NR]
  - General Introduction – FRLW metric – Redshift and distances – Friedmann equations – classical universe models – (neo)classical cosmological tests.
- CMB Basics - Structure formation in the Universe [4x3h JR]
  - CMB – structure formation : spherical collapse - linear theory - sound waves
- Thermal history of the Universe [2x3h NR]
  - Equilibrium distributions - Boltzmann equation - decoupling – relic densities - primordial nucleosynthesis - recombination - reionization
- Inflation - modified gravity [2x3h DS]
  - Motivation for inflation - inflationary phase vs. late time acceleration - realisations of inflation - attractor solutions - primordial scalar and tensor power spectra - different models of modified gravity (massive gravity, galileons...)

Textbooks

- S. Serjeant, *Observational Cosmology*, Cambridge University Press, 2010.
- S. Dodelson, *Modern Cosmology*, Academic Press, 2003.
- J. A. Peacock, *Cosmological Physics,* Cambridge University Press, 1998.
- J. Rich, *Fundamentals of cosmology,* Springer, 2010.
- B. Ryden, *Introduction to cosmology,* Addison-Wesley, 2002,
- M. P. Hobson, G. P. Efstathiou, and A. N. Lasenby, General Relativity, Cambridge University Press (look at the chapters on FLRW metric and cosmology)

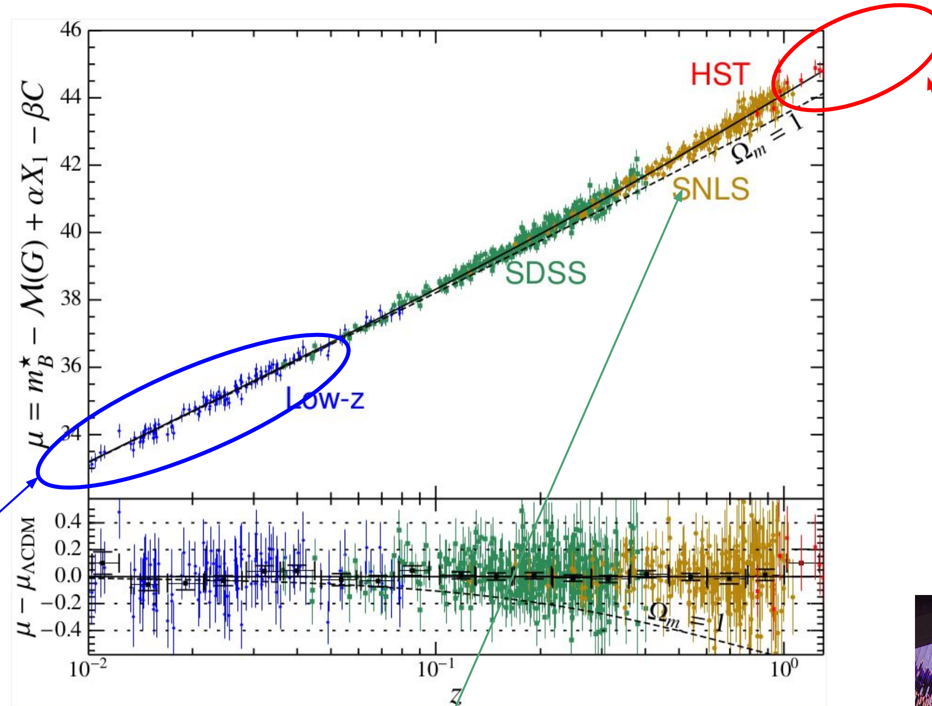
Nicolas Regnault

nicolas.regnault@lpnhe.in2p3.fr

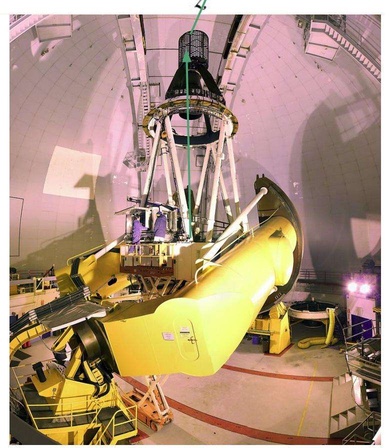
- LPNHE (Jussieu campus)
  - Barre 12-22 1st floor
- LPNHE cosmology group
  - SN Ia cosmology (LSST, Subaru…)
  - Baryon acoustic oscillations (BOSS, eBOSS, DESI)
  - Weak lensing (LSST)
  - Instrumentation (sensor studies…)

Research

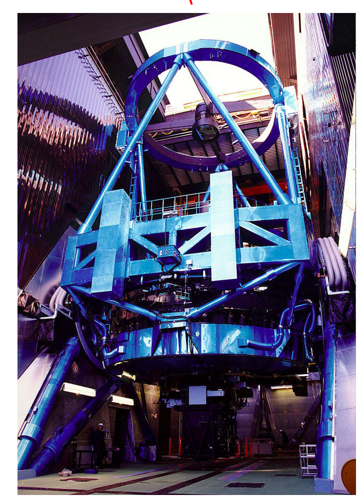
Hubble diagram of supernovae
(Expansion history of the Universe)



ZTF @ Palomar



MegaCam @ CFHT

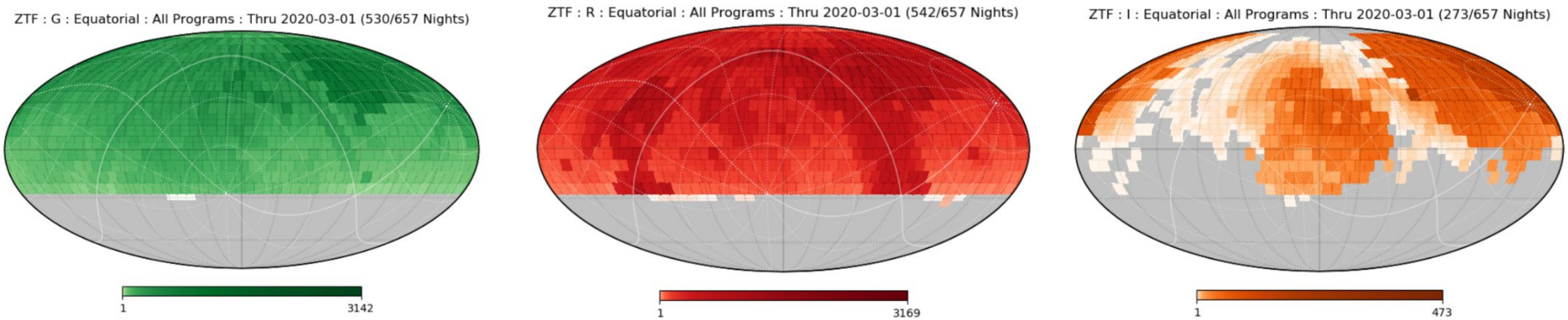


Subaru

ZTF | Fast *(30s exp.)* & Large *(full visible sky)*

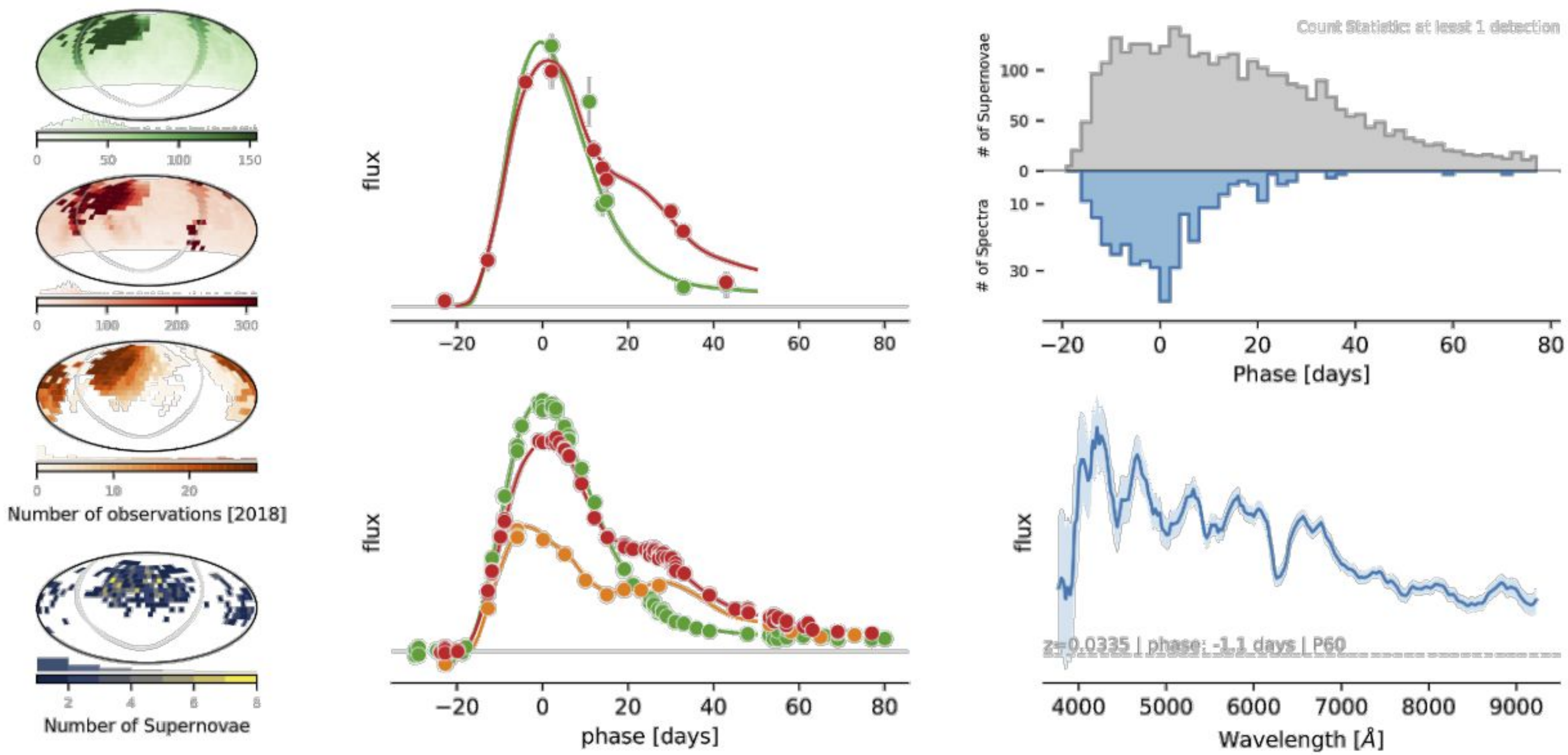
We have about 10^5 events/night ; 10% of LSST

Survey of the full northern sky



- 3 bands
  - g,r & I
- “MSIP” survey
  - LSST-like survey of northern sky in g & r (2-3 day cadence)
- Partnership survey
  - High cadence observations of 10% of the sky (5-6 visits/night)
  - I-band observations of 50% of the sky (~5 day cadence)
- + other partnership programmes (solar system, ToO monitoring of GW events …)

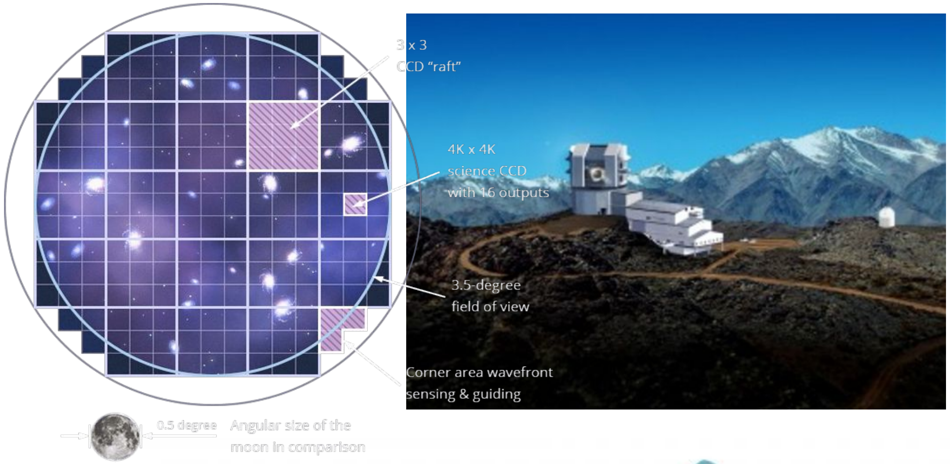
ZTF DR1 (2019)

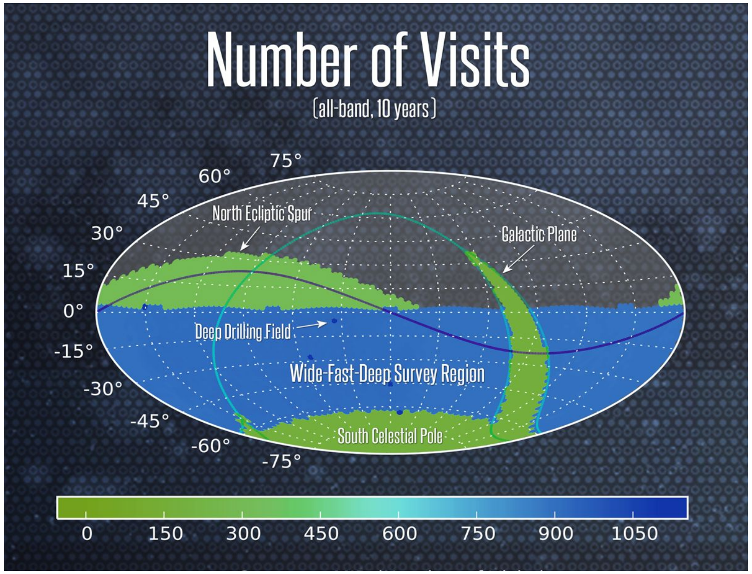


Number of observations [2018]
Number of Supernovae
flux
flux
phase [days]
Count Statistic: at least 1 detection
# of Supernovae
# of Spectra
Phase [days]
flux
z=0.0335 | phase: -1.1 days | P60
Wavelength [Å]

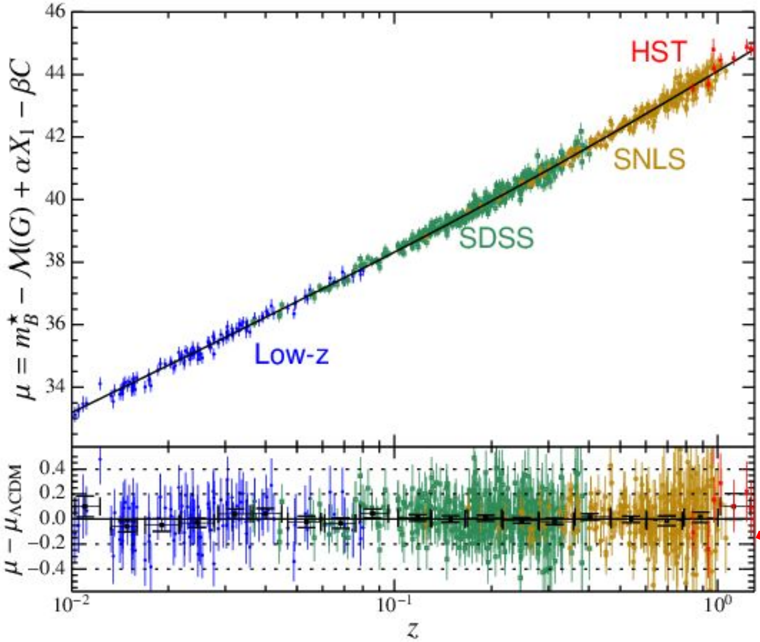
Research

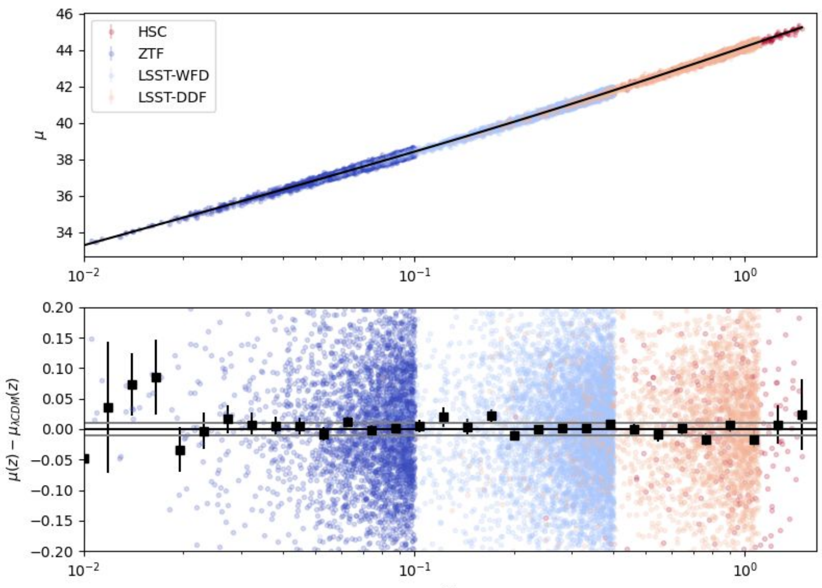
- LSST
- 8.4-m, 9.6 deg^2
- Chile





The LSST Era (2024 - …)





- 2014 : O(1000) SNe (JLA++)
- 2022 : O(5000) SNe
- 2025 : O(10000) SNe

Outline

- What is cosmology ?
- Cosmology through the ages
- The first revolution (1925) : the Universe is Big !
- The second revolution (1927 - 1931) : the Universe is expanding !
- The hot big-bang model
- Observables
- The third revolution (1999-2003) : accelerated expansion & ΛDCM
- Our strange Universe

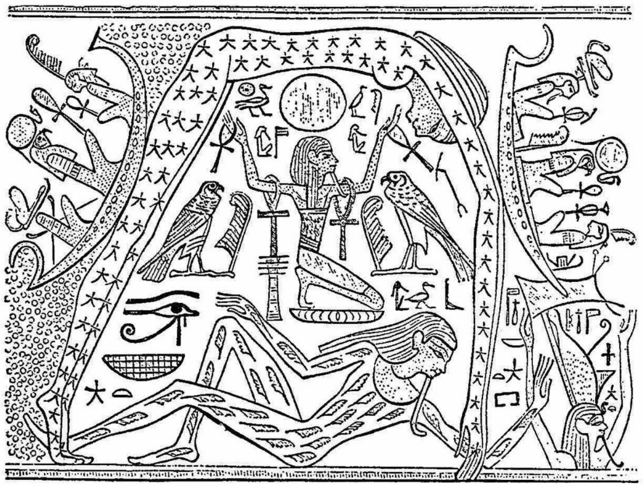
Cosmology ?

- Study of the Universe as a whole
  - Geometry / topology
  - History / age
  - Content (matter, photons, neutrinos, exotic stuff…)
  - Expansion history
  - Thermal history
  - Matter clustering, structure formation
- Messengers photons / gravitons
  - X, UV, visible light, IR, millimetric, radio
- ~~Experimental~~ Observational science
  - We have only one Universe
  - Cannot vary the initial conditions and replay ...

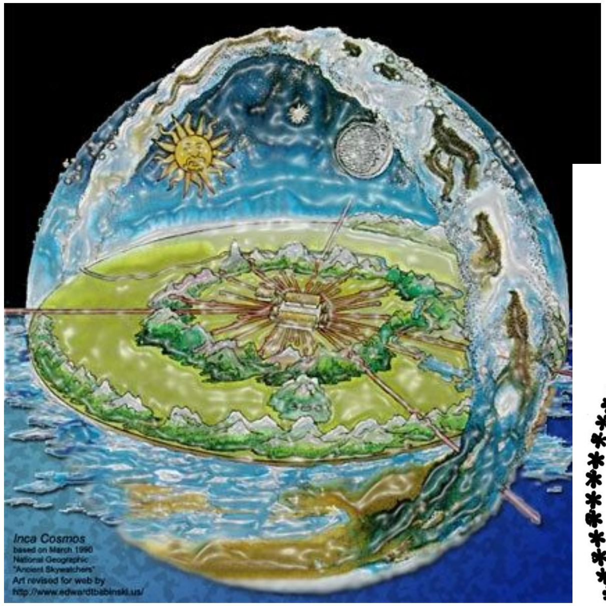
APOD 200520

APOD 200520

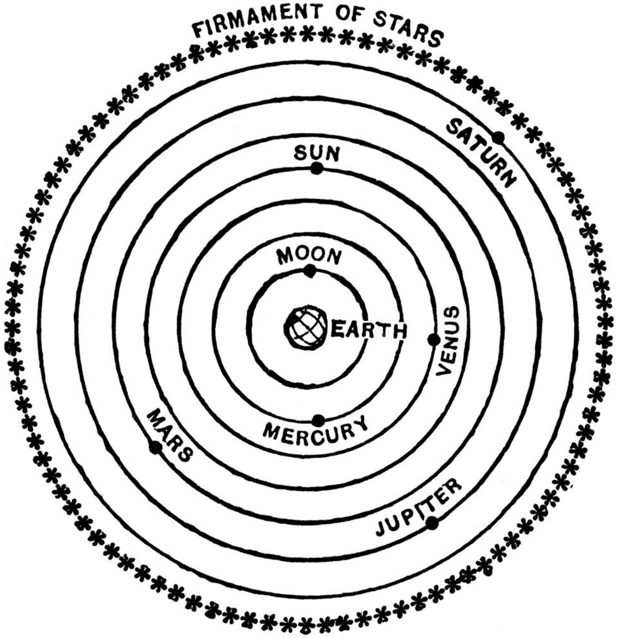
Past cosmogonies



Egypt

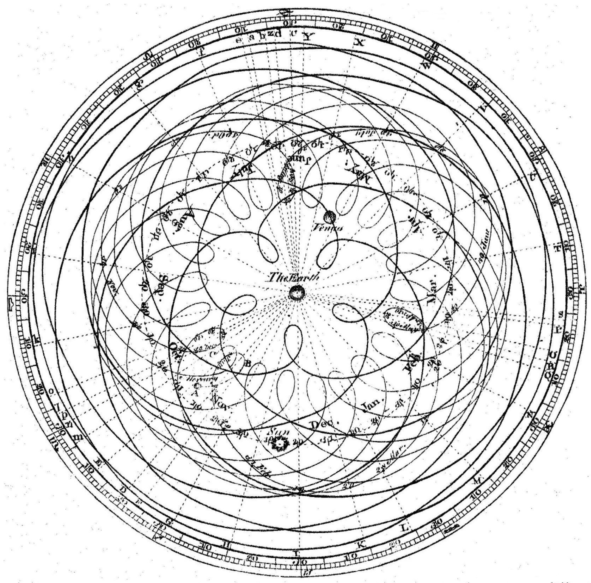


Thales of Miletus
~ 624 - 547 BC

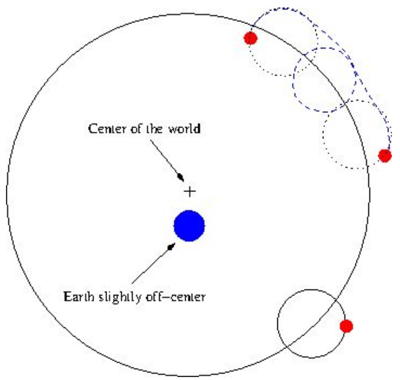


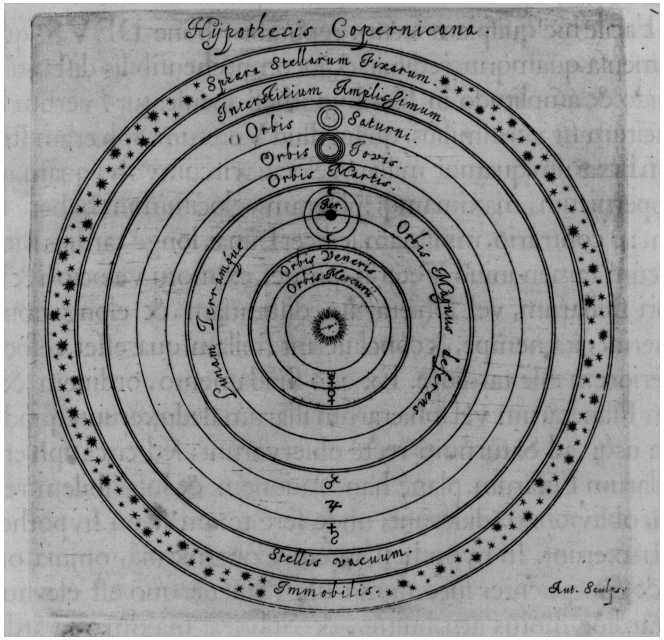
Eudoxus ~ 409 - 356BC
Hipparchus of Rhodes ~ 190-120 BC

Motion of planets -> “minor tweaks”



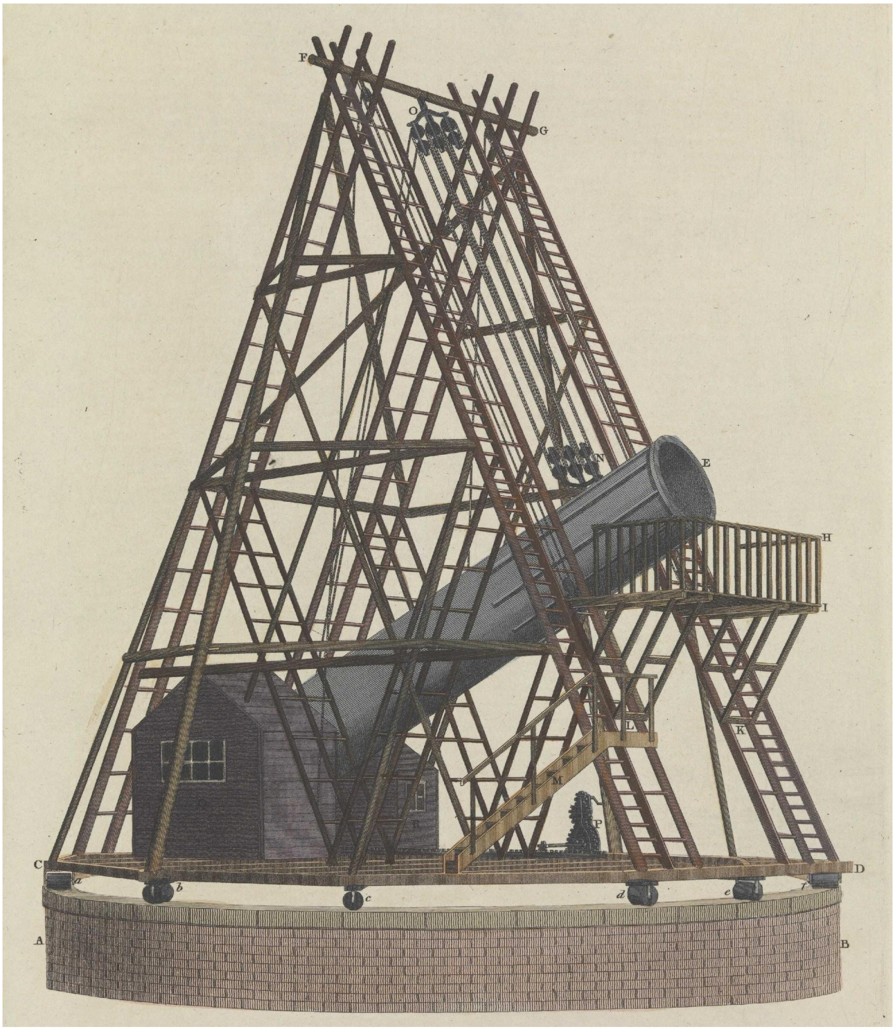
Hipparchus of Rhodes
Ptolemy (85-165)



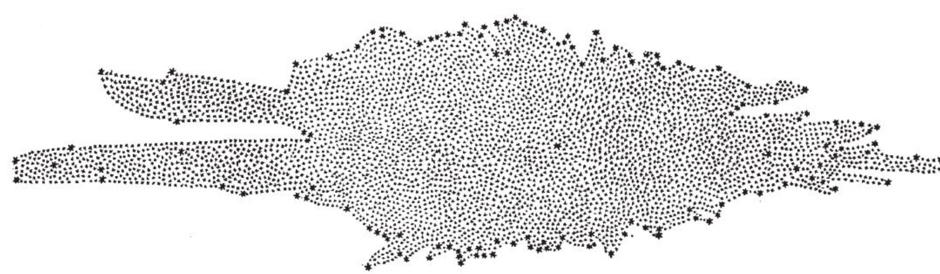


Copernican revolution
Kepler (elliptical orbits of planets)

First deep sky surveys

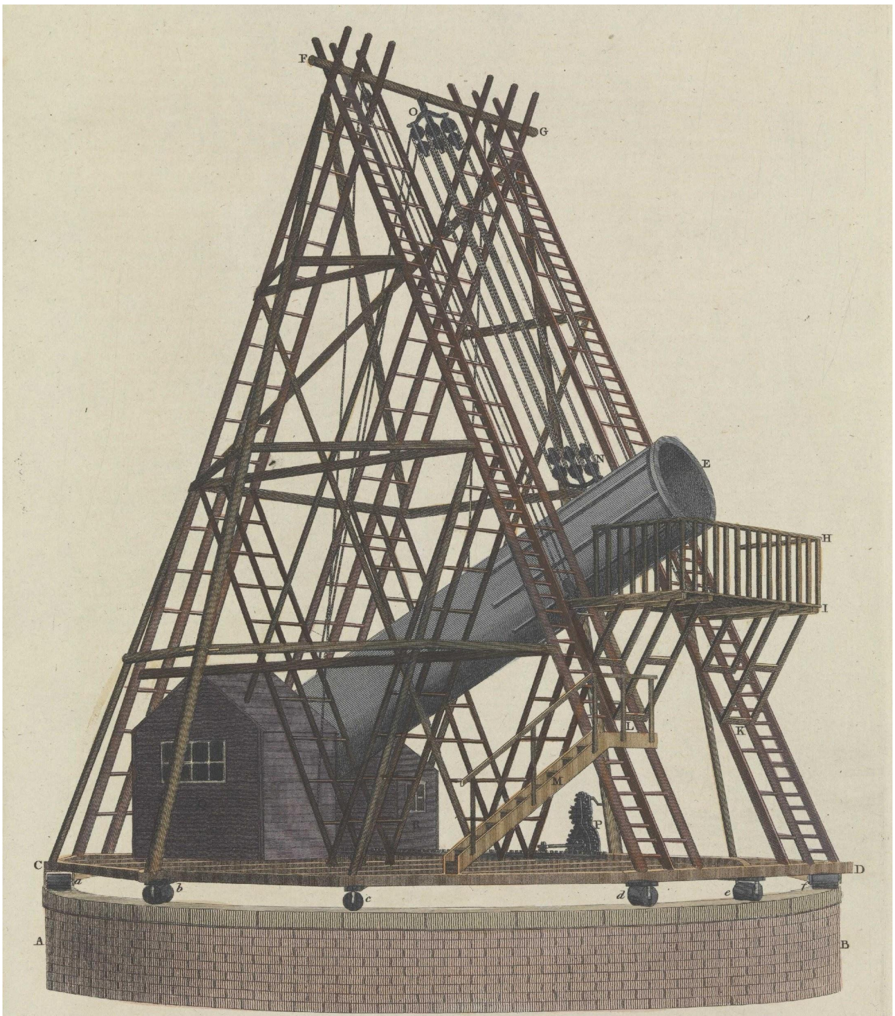


- Herschell (1738 - 1822)
- Discovers more than 2400 “nebulae”
- Star counts reveal anisotropies in star distributions

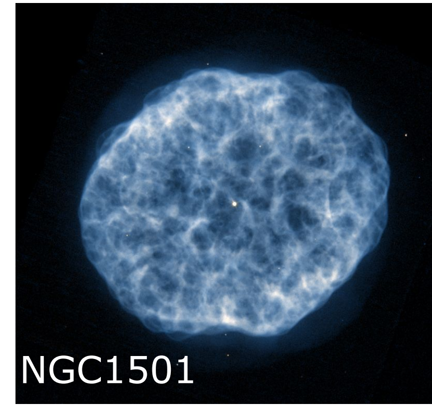


(see 1112.3635)

First deep sky surveys



Planetary nebulae →



← Globular clusters

Galaxies →

The first revolution: the Universe is huge !

APOD 150817

The scale of the Universe

Harlow Shapley

THE SCALE OF THE UNIVERSE

By Harlow Shapley
Mount Wilson Observatory, Carnegie Institution of Washington
and
Heber D. Curtis
Director, Allegheny Observatory

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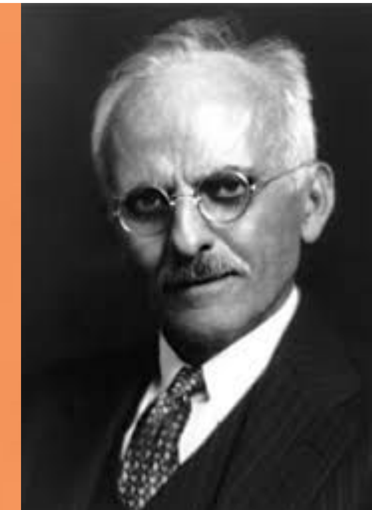
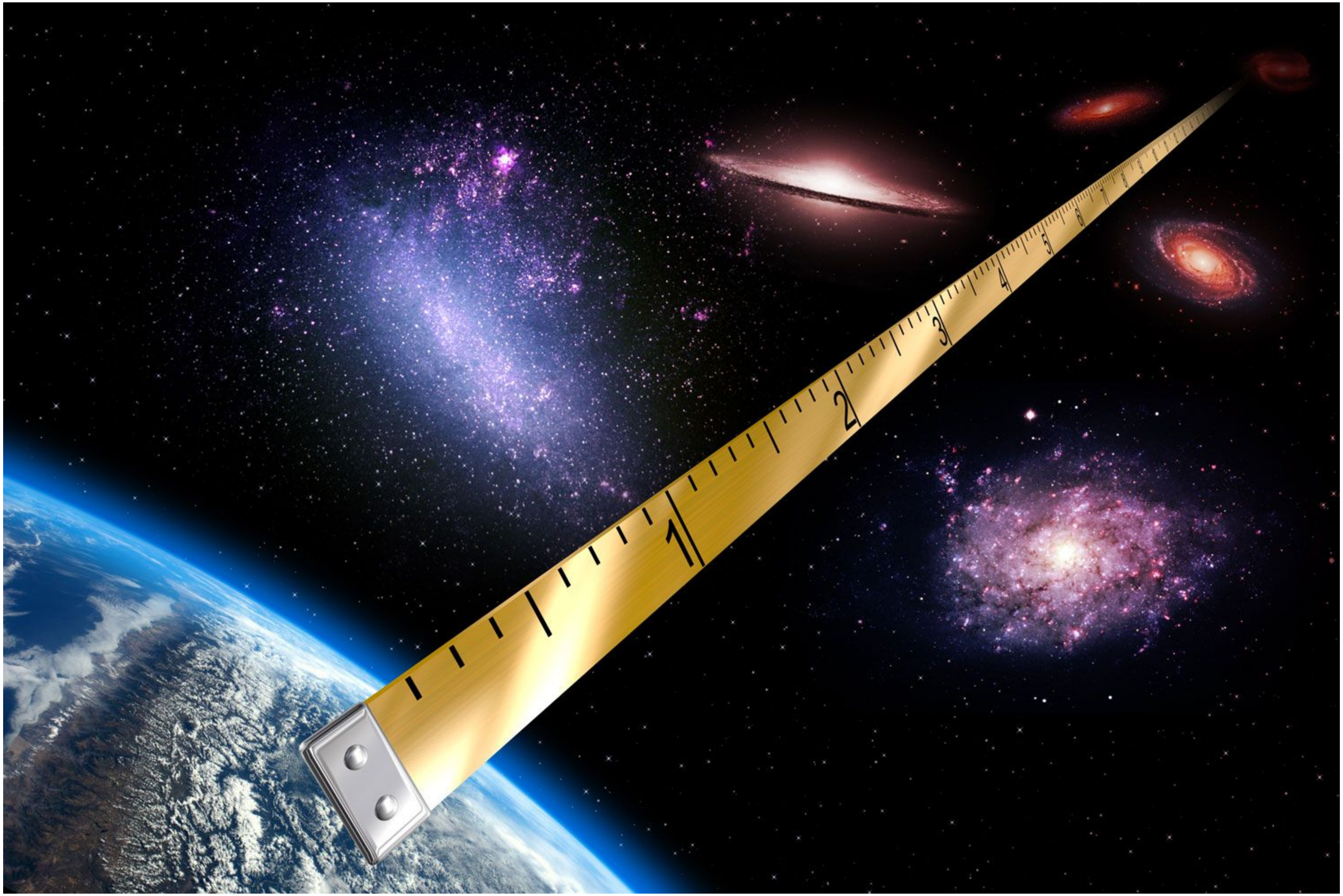


Heber D. Curtis

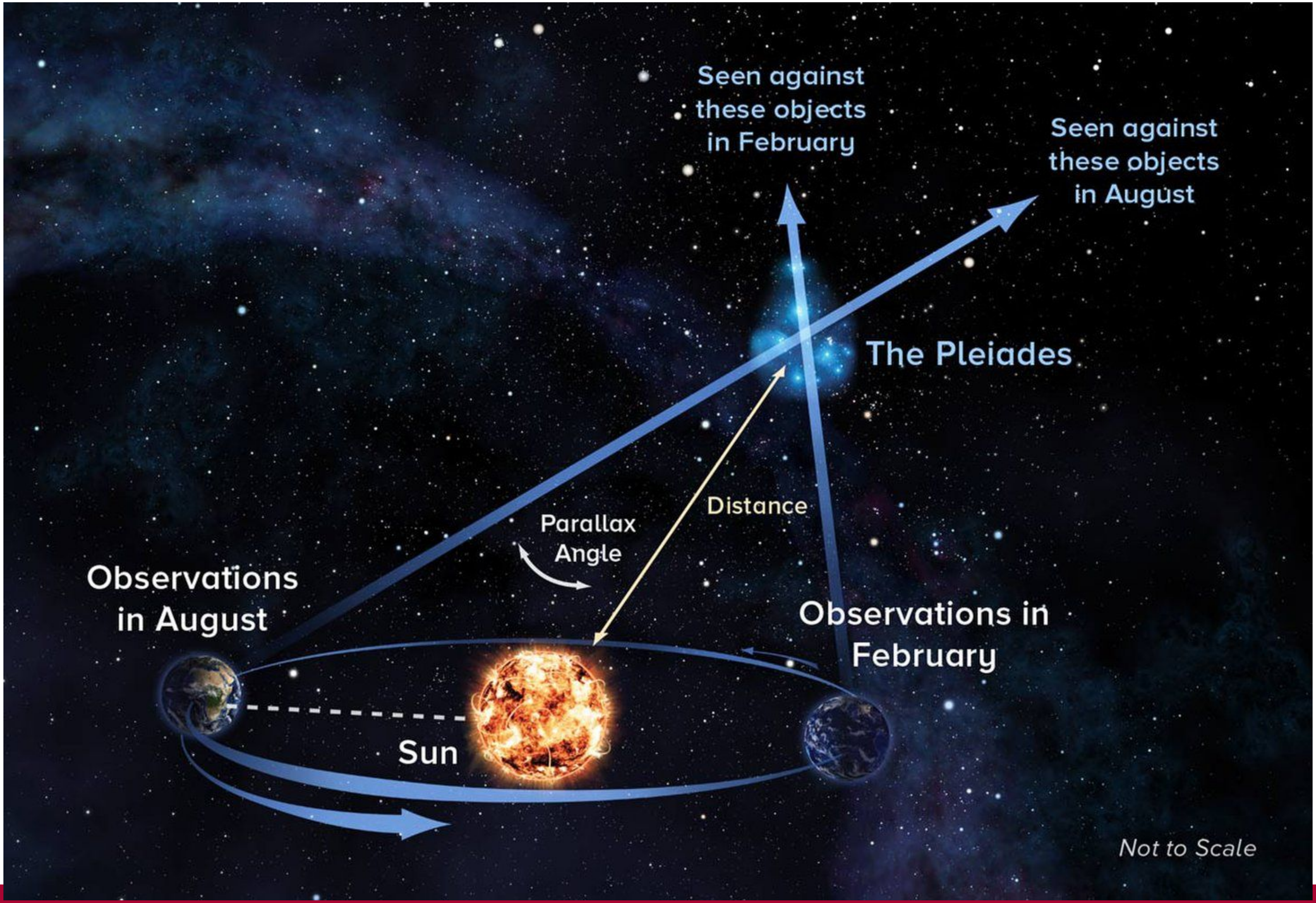
I hold, therefore, to the belief that the galaxy is probably not more than 30,000 light-years in diameter; that the spirals are not intra-galactic objects but island universes, like our own galaxy, and that the spirals, as external galaxies, indicate to us a greater universe into which we may penetrate to distances of ten million to a hundred million light-years.

(

Measuring distances in the Universe

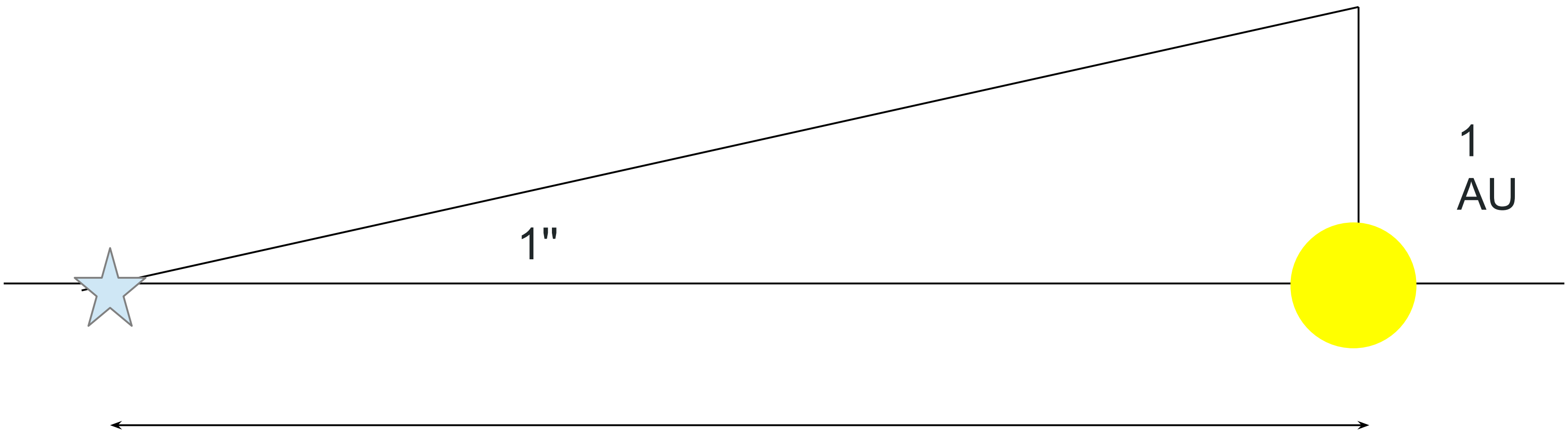


Parallax



Seen against
these objects
in February
Seen against
these objects
in August
The Pleiades
Distance
Parallax
Angle
Observations
in August
Observations in
February
Sun
Not to Scale

Parallaxes



1 AU = *average distance earth-sun* = 149 597 870.7 km
~ 1.5 10^{11} m

1 pc = ?

Standard candles

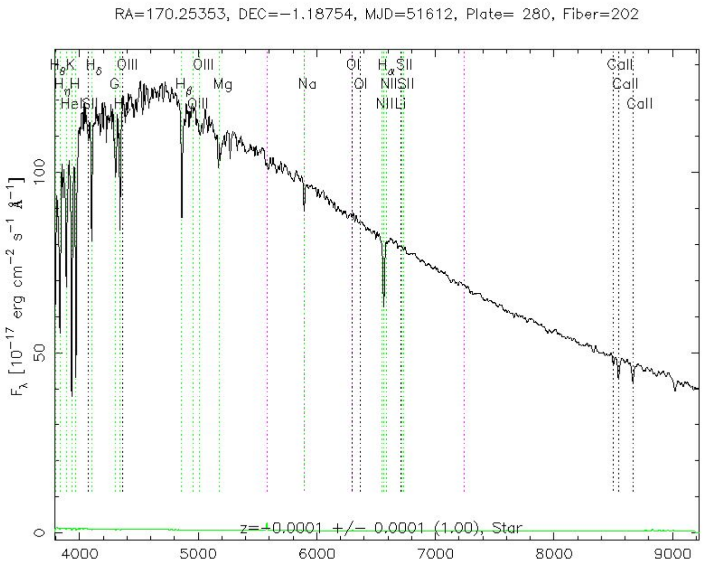
- Objects with a known luminosity

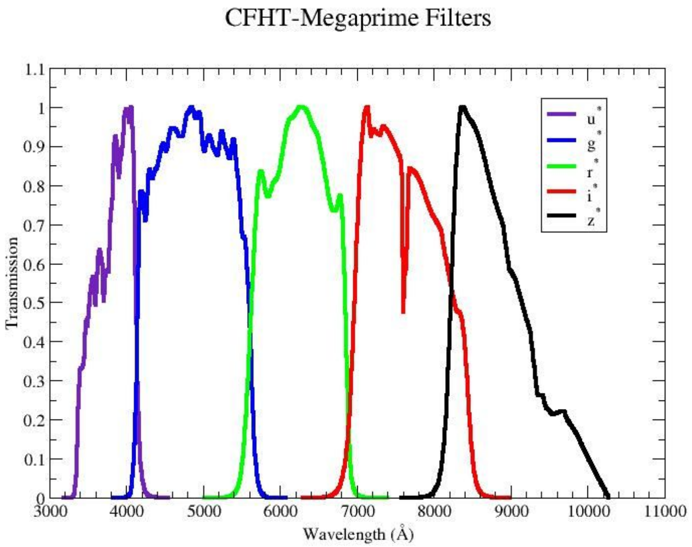
$$f = \frac{\mathcal{L}}{4\pi d_L^2}$$

Measured flux

distance

Stars / stellar photometry





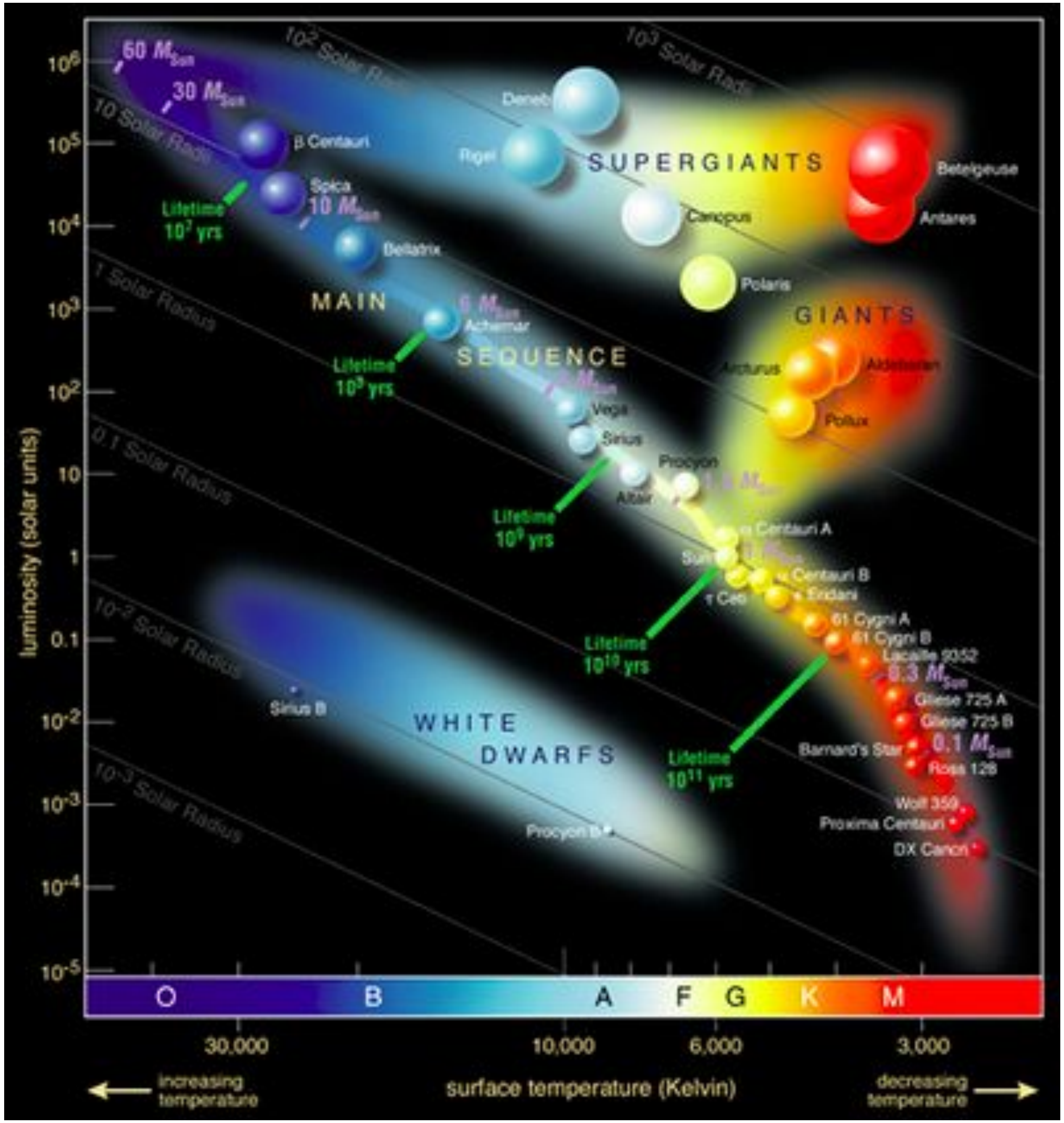
- Stellar spectrum
  - Black body
  - Emission / absorption lines
  - Spectral classification
  - OBAFGKM
- Apparent magnitude

$$m - m_{\mathrm{ref}} = -2.5 \times \log_{10}\left(\frac{f}{f_{\mathrm{ref}}}\right)$$

- Absolute magnitude
  - Magnitude of the object @ 10pc
- Distance modulus

$$\mu = m - M = 5\log_{10}\left(\frac{d}{10\mathrm{pc}}\right) = 5\log_{10} d - 5$$

Absolute luminosity



Color

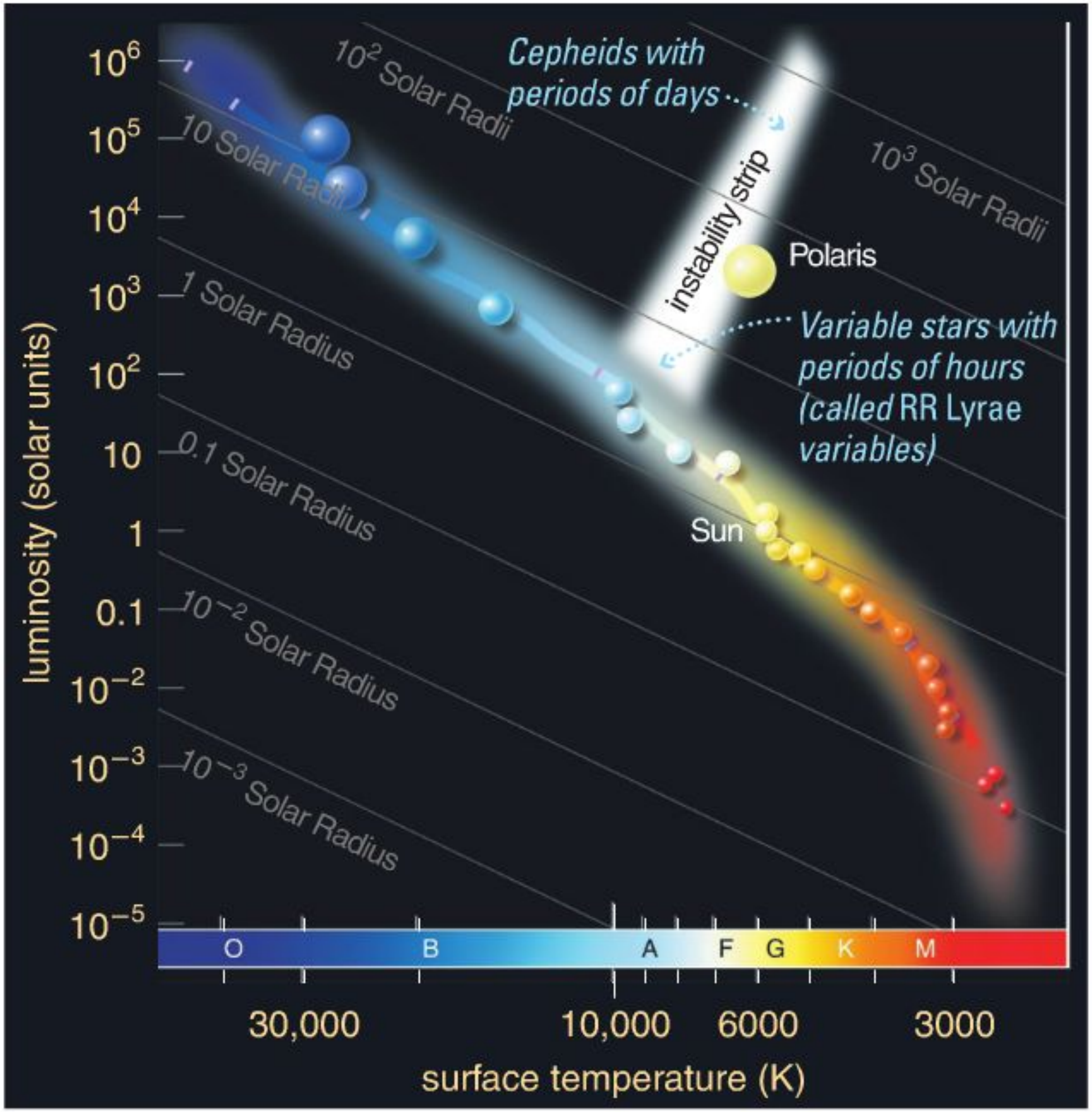
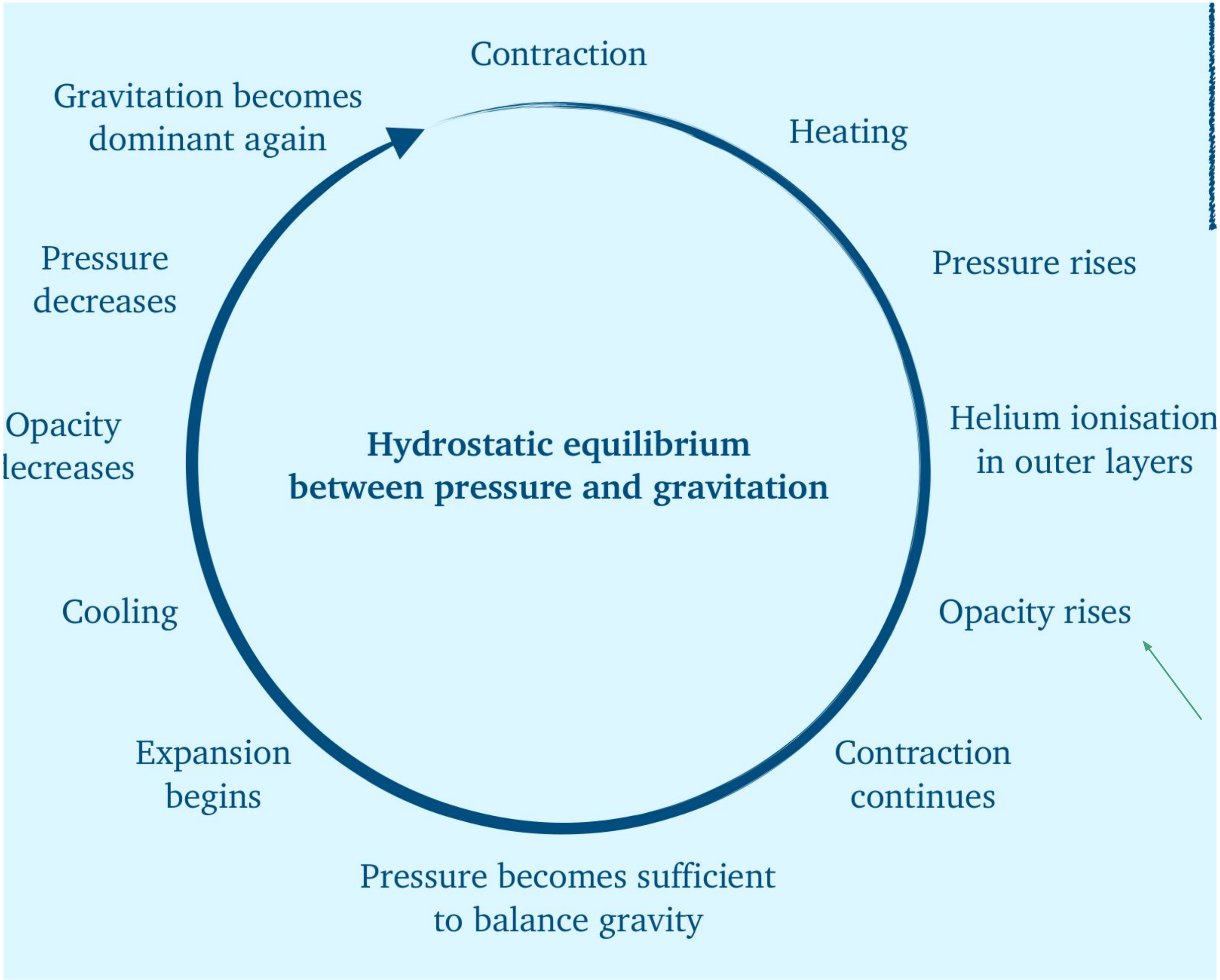


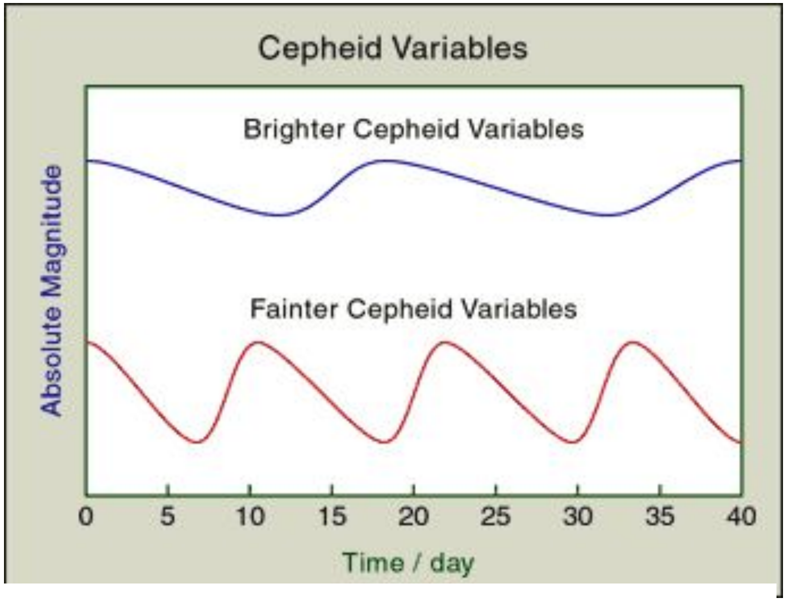
FIGURE 15.15 An H-R diagram with the instability strip highlighted. Notice that Polaris, the North Star, is a Cepheid variable star.

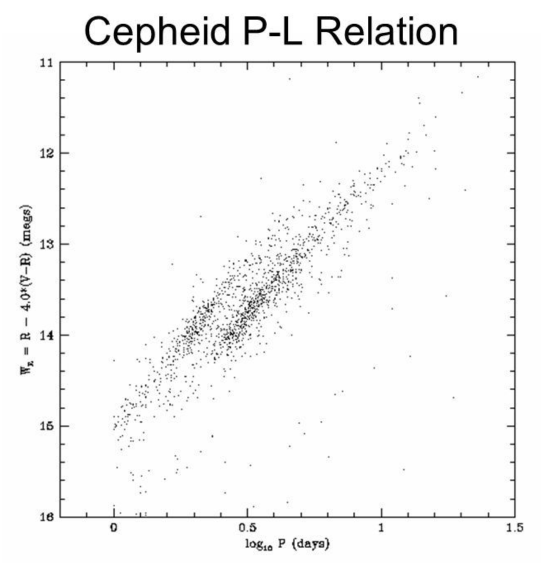
Why pulsating ? κ-mechanism



Key thing here. In "normal" stars, opacity decreases with temperature / pressure.

Pulsating variables





- Cepheids
  - Very bright
  - Pulsating, P=1-50 days
  - Rare
  - Distances up to 30 Mpc
- RR-Lyrae
  - Pulsating variables
  - P~ 0.1 - 1 days
  - Galaxy / local group

Henrietta Leawitt

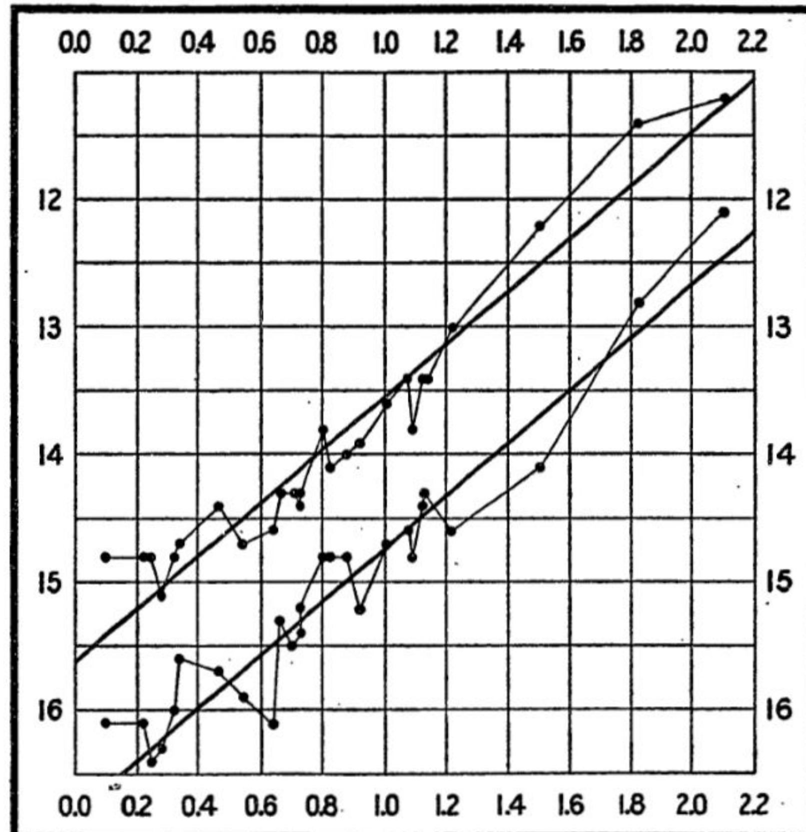


FIG. 2.

Leawitt's PL relation

Measuring distances with Cepheids

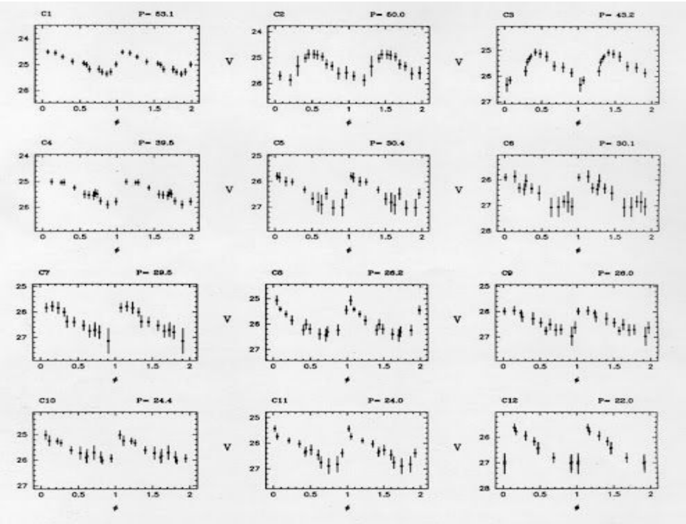
$$m - M = 5\log_{10} d_{pc} - 5$$

Measure the apparent magnitude from the light curve

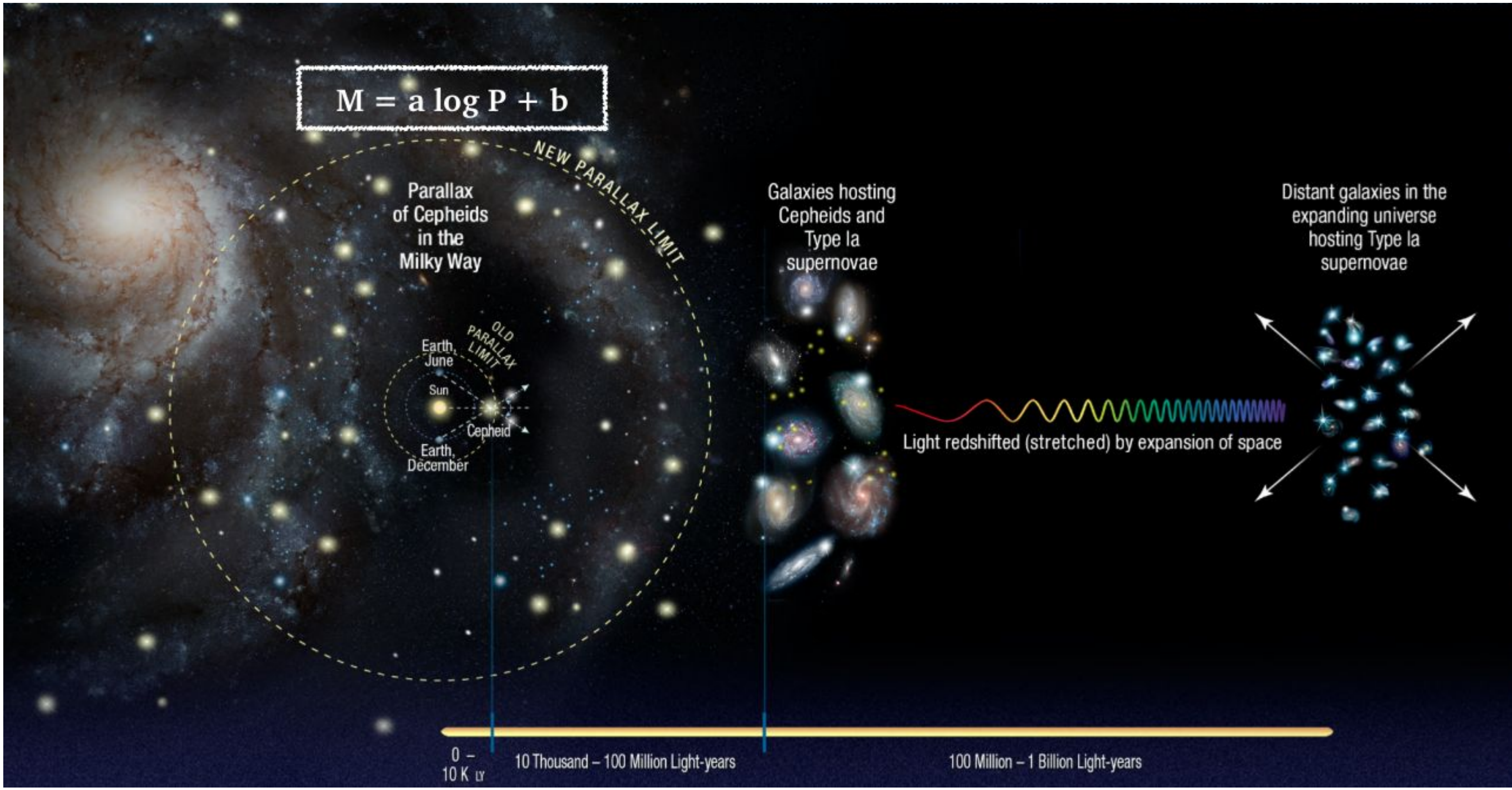
Infer absolute magnitude from measurement of cepheid period, and PL relation

$$M = a \log P + b$$

Q: how do we calibrate the PL relation ?



Measuring distances with Cepheids



Distance to M31

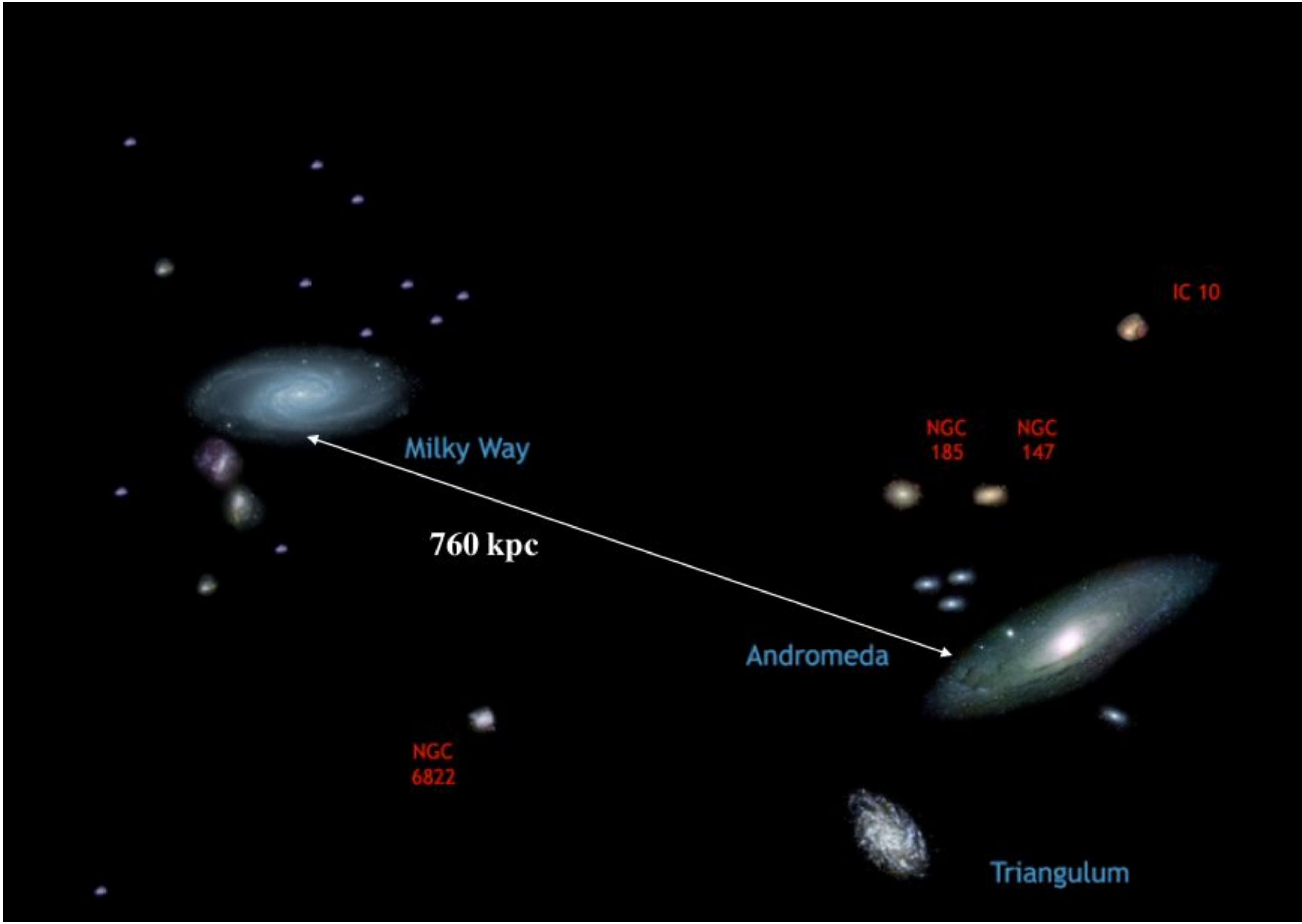
CEPHEIDS IN SPIRAL NEBULAE.

BY EDWIN P. HUBBLE.

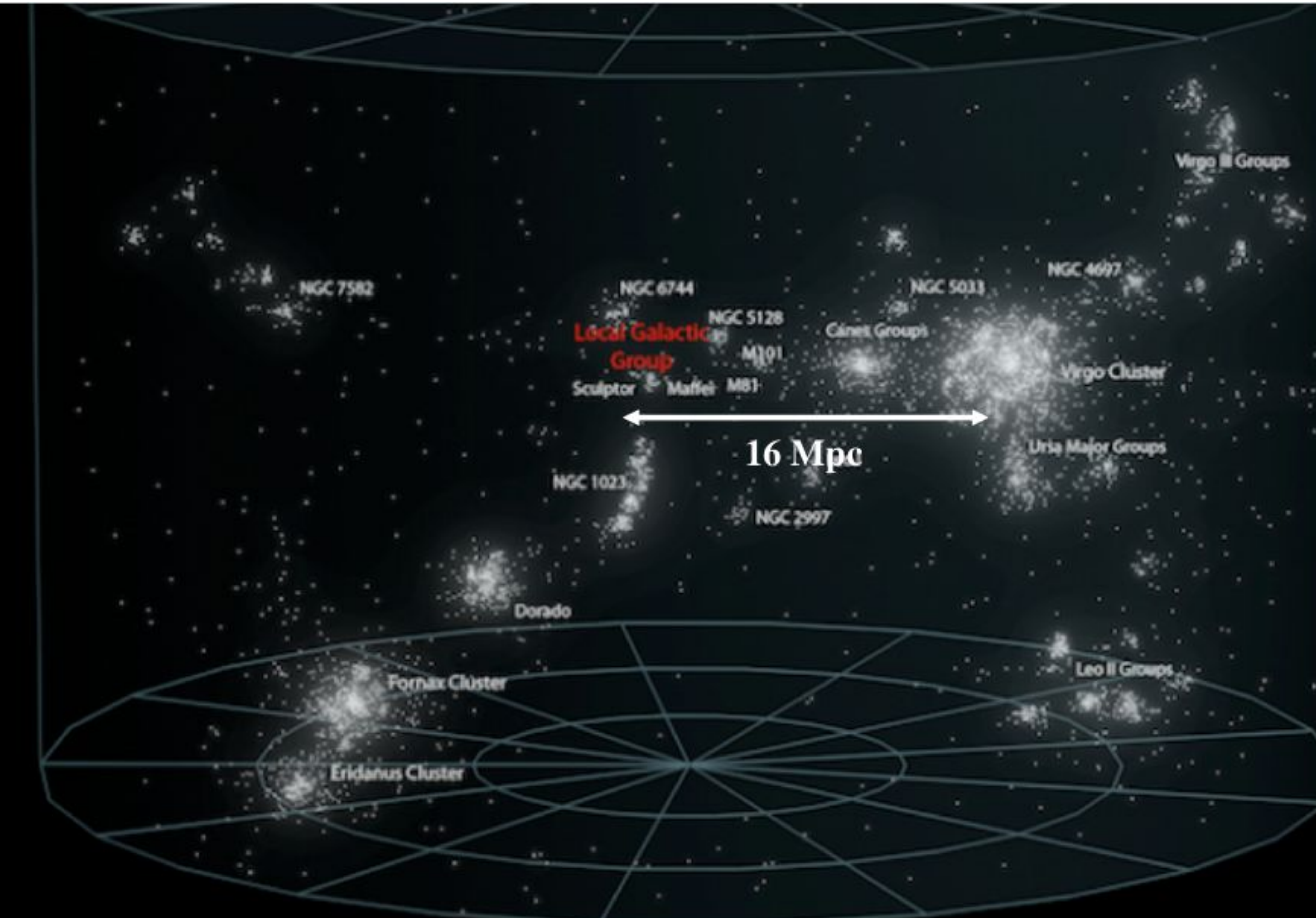
Messier 31 and 33, the only spirals that can be seen with the naked eye, have recently been made the subject of detailed investigations with the 100-inch and 60-inch reflectors of the Mount Wilson Observatory.

—21.8 and —21.9 for M 31 and M 33, respectively. These must be corrected by half the average ranges of the Cepheids in the two spirals, and the final values are then on the order of —22.3 for both nebulae. The corresponding distance is about 285,000 parsecs. The greatest uncertainty is probably in the zero point of Shapley's curve.

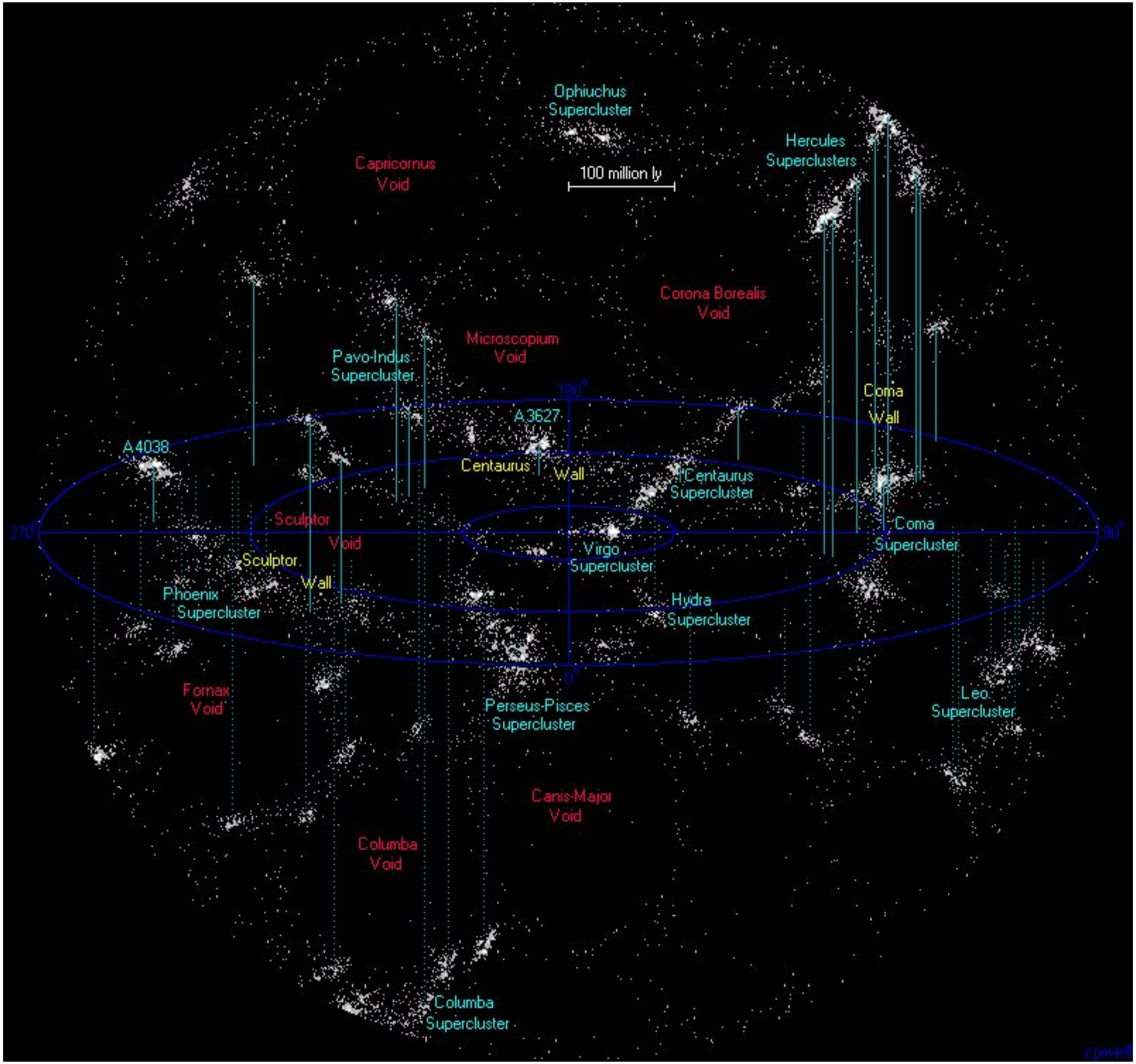
This estimate was wrong, by a factor ~ 2.5
But shows that M31 is well outside Milky Way



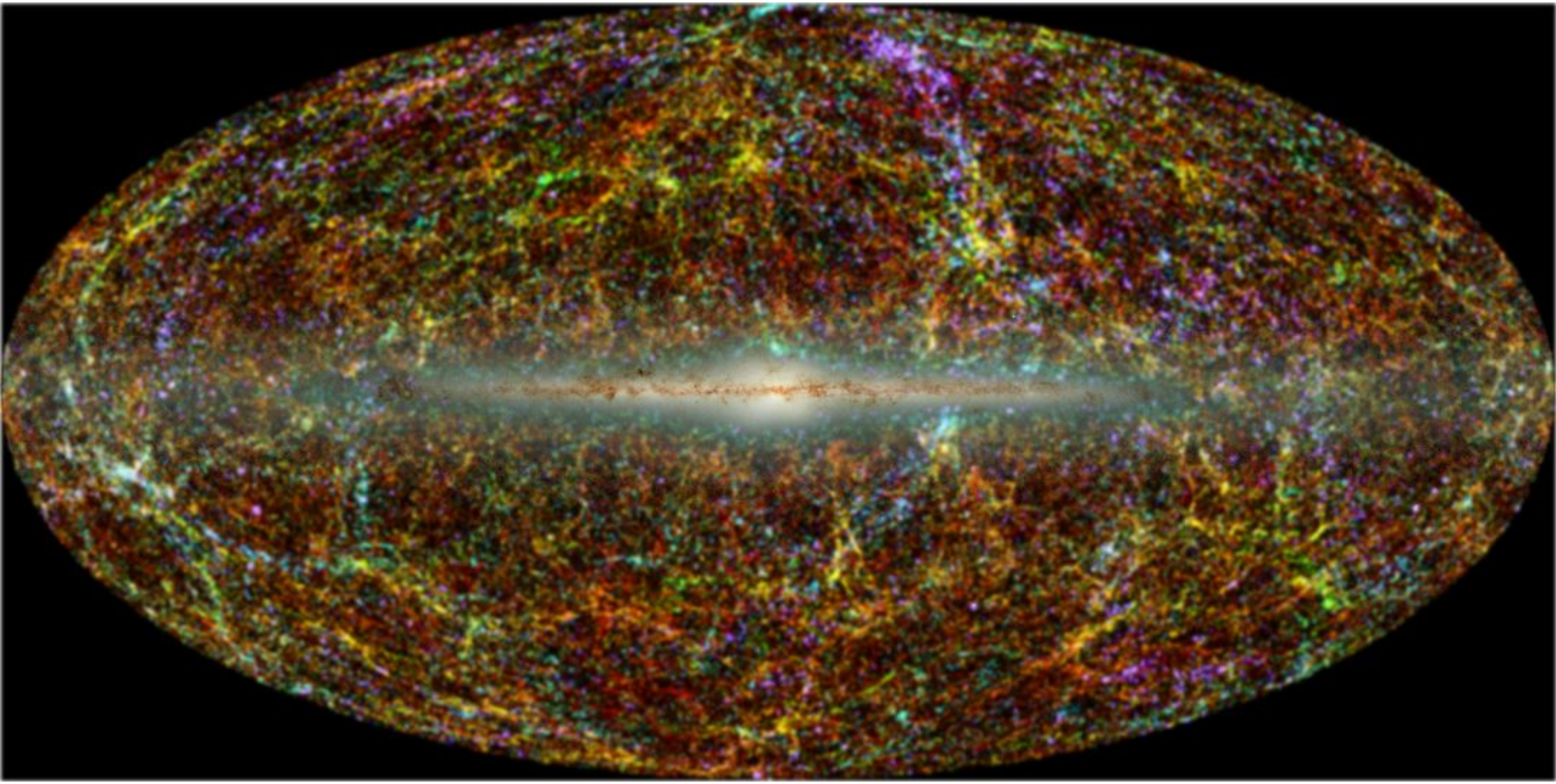
IC 10
Milky Way
NGC 185
NGC 147
760 kpc
Andromeda
NGC 6822
Triangulum



Virgo III Groups
NGC 7582
NGC 6744
NGC 5033
NGC 4697
NGC 5128
Local Galactic Group
Canes Groups
M101
Virgo Cluster
Sculptor
Maffei
M81
16 Mpc
Ursa Major Groups
NGC 1023
NGC 2997
Dorado
Fornax Cluster
Leo II Groups
Eridanus Cluster



Ophiuchus
Supercluster
Hercules
Superclusters
Capricornus
Void
100 million ly
Corona Borealis
Void
Microscopium
Void
Pavo-Indus
Supercluster
180°
Coma
Wall
A3627
A4038
Centaurus
Wall
Centaurus
Supercluster
Sculptor
Void
270°
Coma
Supercluster
90°
Virgo
Supercluster
Sculptor
Wall
Phoenix
Supercluster
Hydra
Supercluster
0°
Fornax
Void
Perseus-Pisces
Supercluster
Leo
Supercluster
Canis-Major
Void
Columba
Void
Columba
Supercluster



2MASS redshift survey

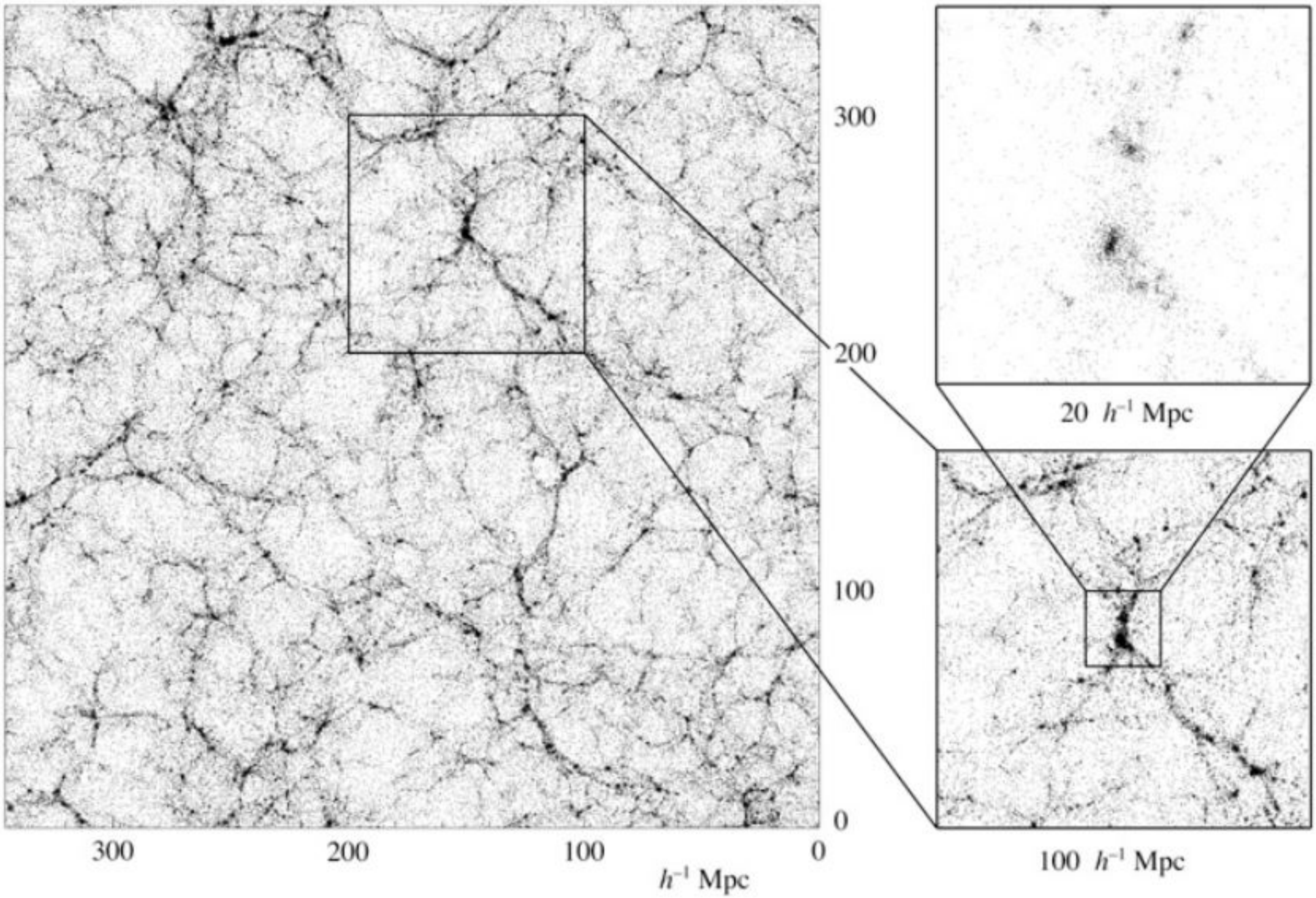


Fig 8.16 (D. Weinberg) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The second revolution: the Universe is expanding !

Expansion

- Slipher (1915) notes that most "nebulae" are red-shifted (=> receding from us)

SPECTROGRAPHIC OBSERVATIONS OF NEBULAE.

By V. M. Slipher.

During the last two years the spectrographic work at Flagstaff has been devoted largely to nebulae. While the observations were chiefly concerned with the spiral nebulae they also include planetary and extended nebulae and globular star clusters.

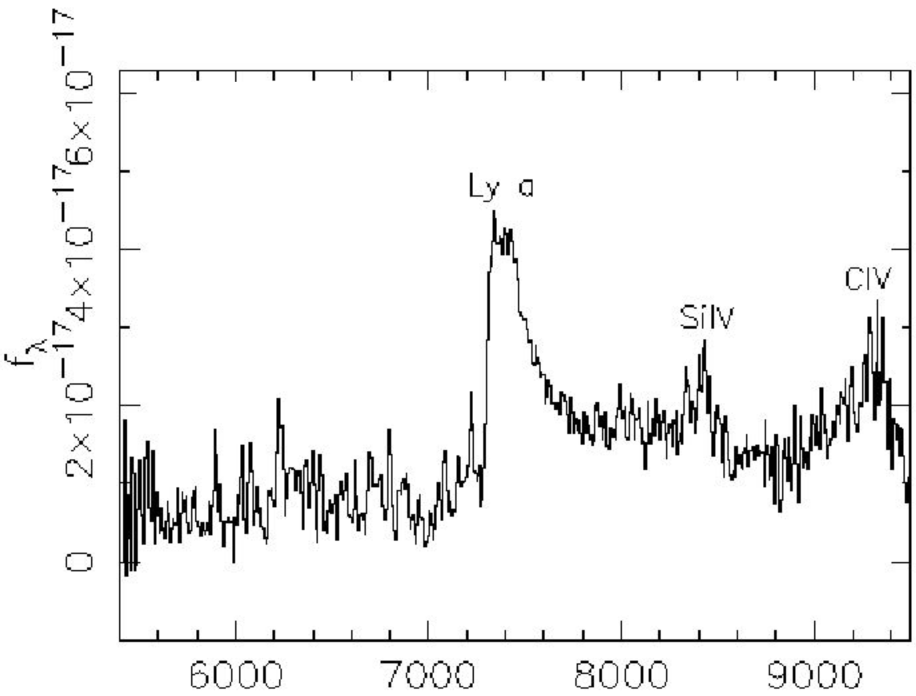
From the 1915 paper

N.G.C.	Velocity	
221	— 300 km	These nebulae are on the south side of the Milky Way.
224 †	— 300	
598	—	
1023	+ 200 roughly	
1068	+ 1100	
7331	+ 300 roughly	
3031	+ small	These are on the north side of the Milky Way
3115	+ 400 roughly	
3627	+ 500	
4565	+ 1000	
4594	+ 1100	
4736	+ 200 roughly	
4826	+ small	
5194	± small	
5866	+ 600	

- By 1924 :
  - 41 measured
  - 36 receding

Redshift

$$1 + {\color{red}z} = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} \approx \sqrt{\frac{1+\beta}{1-\beta}} \approx 1 + \beta$$



- Ly-α : λ = 1216 Å
- Ly-α : λ_{obs} = 7400 Å
- z = ?

The Universe is expanding (!)

— 49 —

UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

Note de M. l'Abbé G. LEMAÎTRE

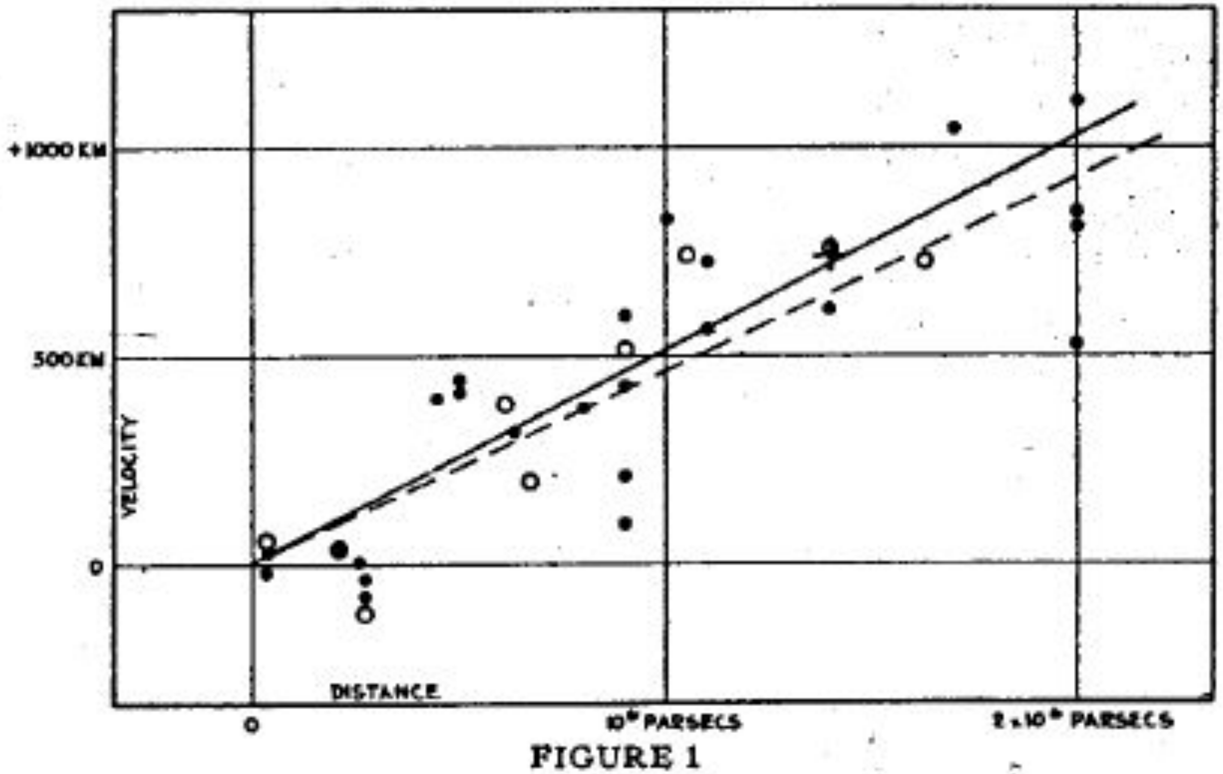
1. GÉNÉRALITÉS.

La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où toutes les positions de l'espace sont équivalentes, il n'y a pas de centre de gravité. Le rayon R de l'espace est constant, l'espace est elliptique de courbure positive uniforme $1/R^2$, les droites issues d'un même point repassent à leur point de départ après un parcours égal à πR, le volume total de l'espace est fini et égal à $\pi^2 R^3$, les droites sont des lignes fermées parcourant tout l'espace sans rencontrer de frontière [1].

Uses Slipher's measurements
Find v = H x d with H ~ 575 km/s/Mpc

Lemaitre, 1927
Annales de la société scientifique de Bruxelles

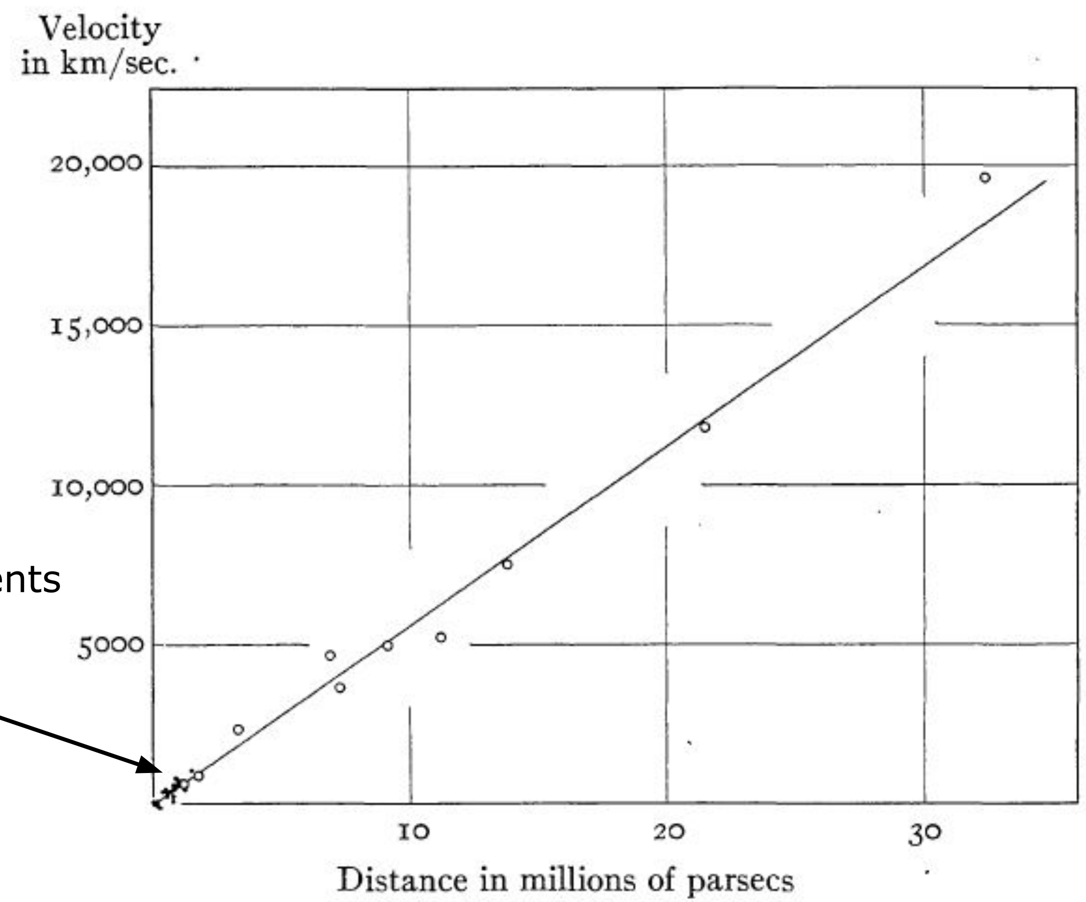
The Universe is expanding (!)



Hubble Law : $$v = H \times d$$

"Hubble constant" [km/s/Mpc]

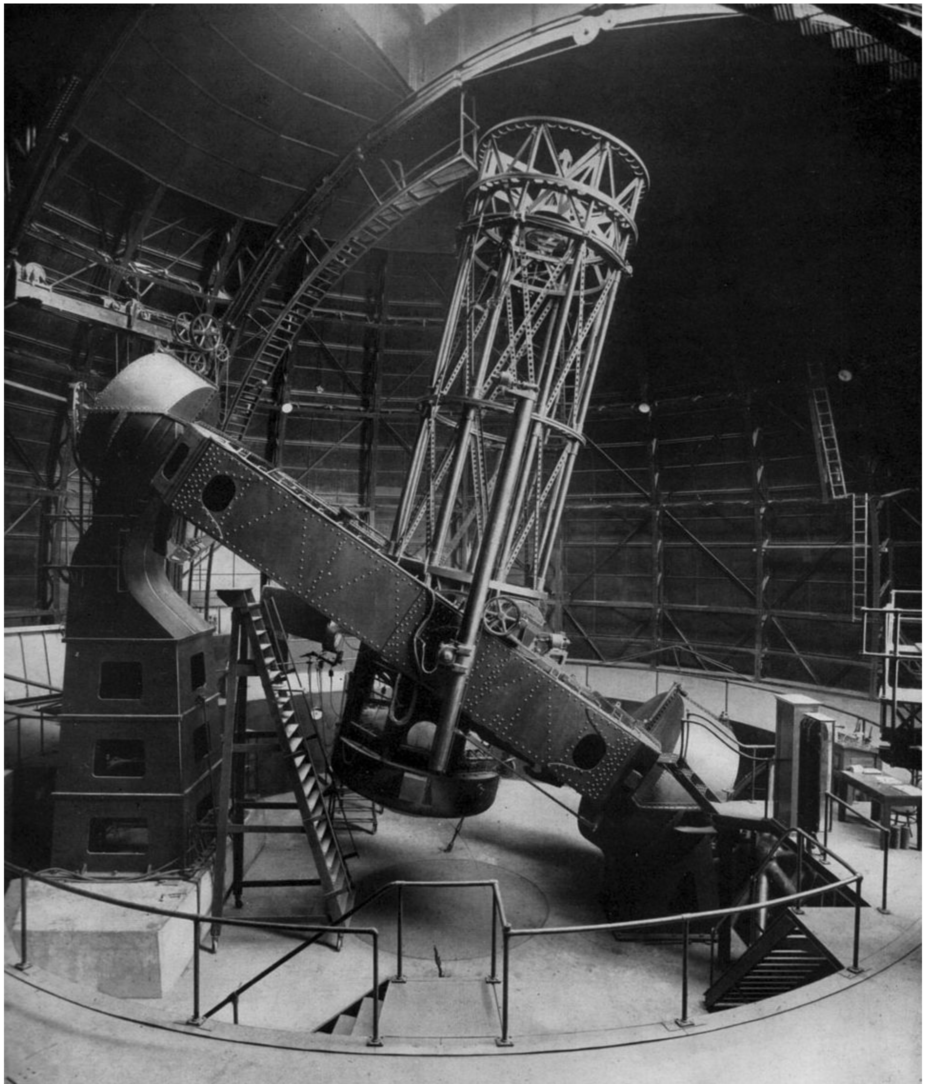
Hubble & Humason (1931)



Original measurements
(Hubble 1929)

Mount Wilson 100 inch Hooker

New instruments that changed the world ...

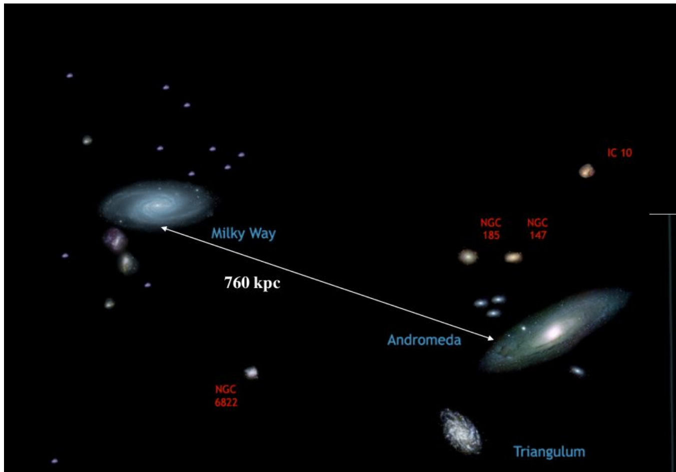


Edwin Hubble at the
100-inch Hooker telescope

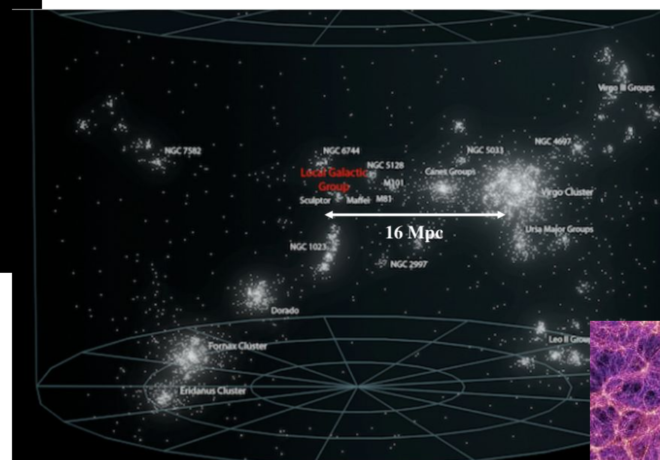
Expansion

- The Universe is dynamic
  - In the past, the Universe was
    - Denser
    - Hotter
    - -> “initial singularity”
- *Isotropic* expansion in a *homogeneous* Universe
  - All observers see the same expansion

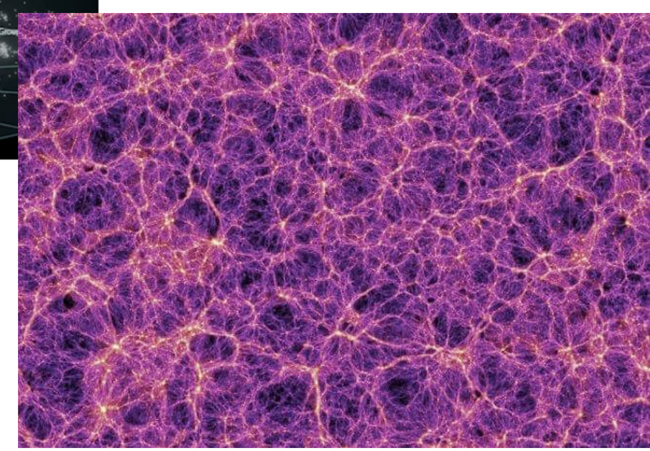
Isotropy



1 Mpc : not isotropic



20 Mpc : not isotropic



100 Mpc : not isotropic

Homogeneity

- Universe obviously not homogeneous on the small scales, but seems very homogeneous on the large scales (galaxy counts)
    - ~ a few meters around us: ~ 100 kg / m^3
        - -> 10^{28} orders of magnitude above Universe density
    - ~ a few AUs around us: 10^{-5} kg / m^3
        - -> 10^{21} orders of magnitude above Universe density
    - ~ a few Mpc around us: 3 10^{-26} kg / m^3
        - -> 1 order of magnitude above Universe density
    - Very homogeneous above 100 Mpc

Beware that ...

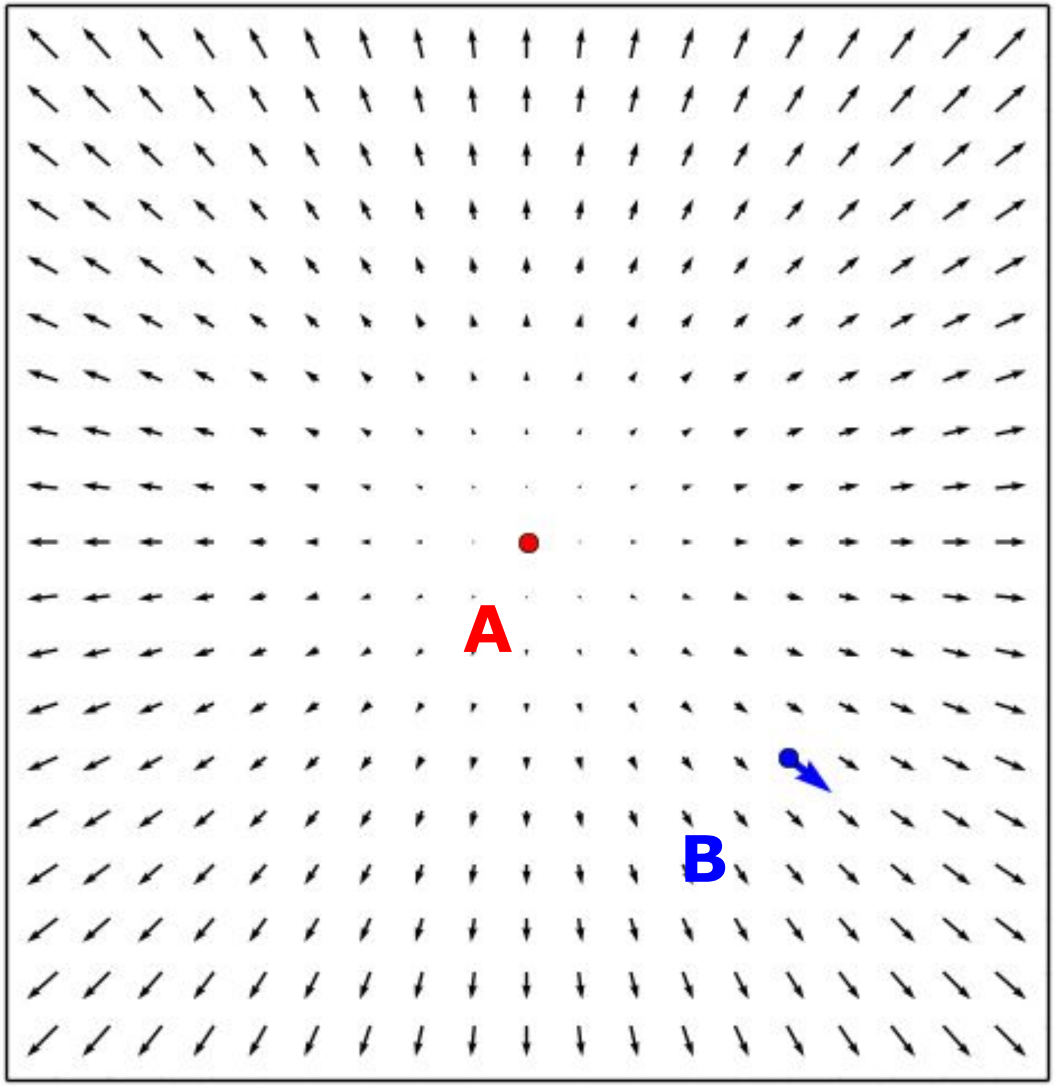
- Homogeneity does not imply isotropy !
- Isotropy does not imply homogeneity !

- Copernican Principle:

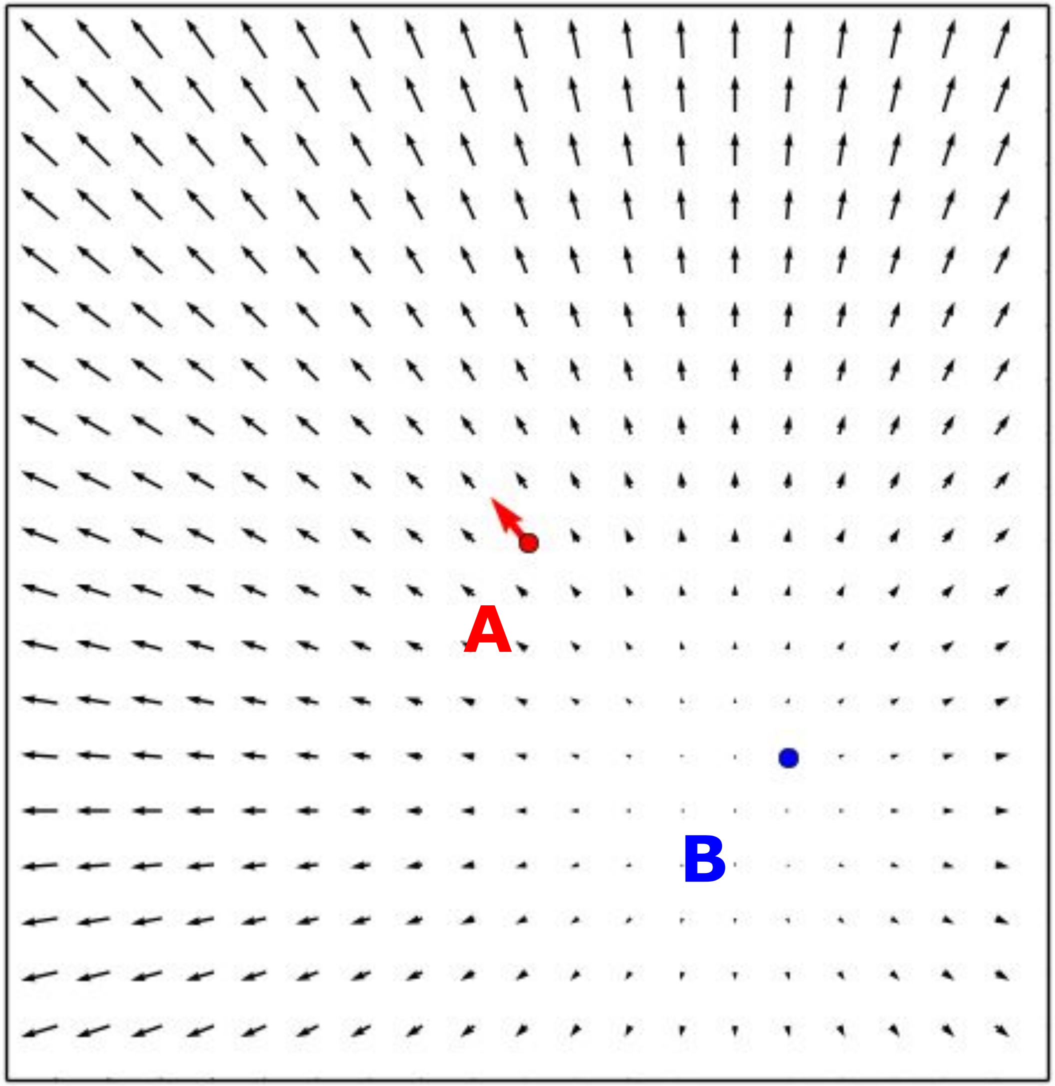
no privileged position in the Universe

Copernican Principle + Isotropy => homogeneity

Copernican Principle + isotropy -> strong constraints on the expansion law.

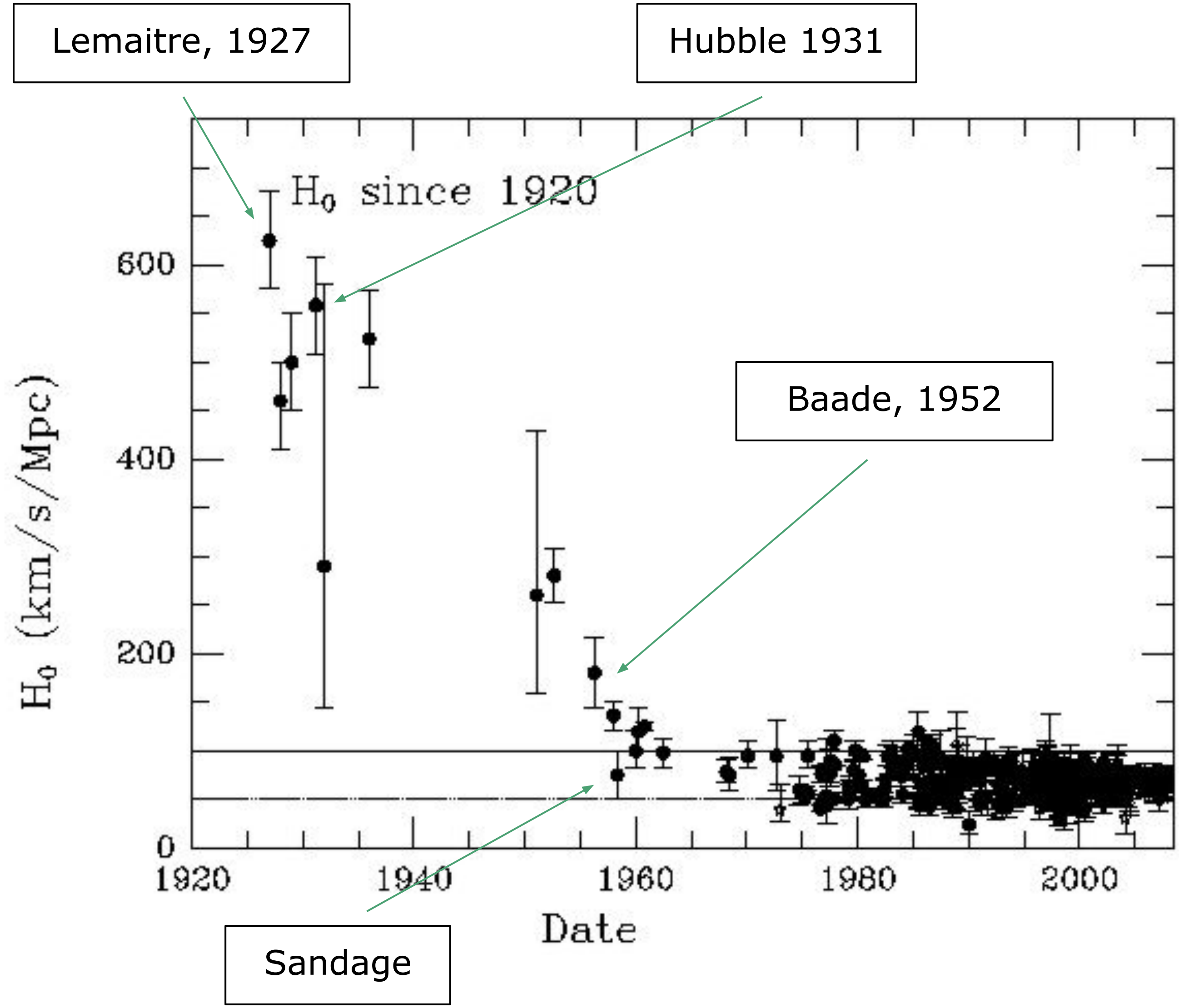


What galaxy A sees



What galaxy B sees

Measuring H_0

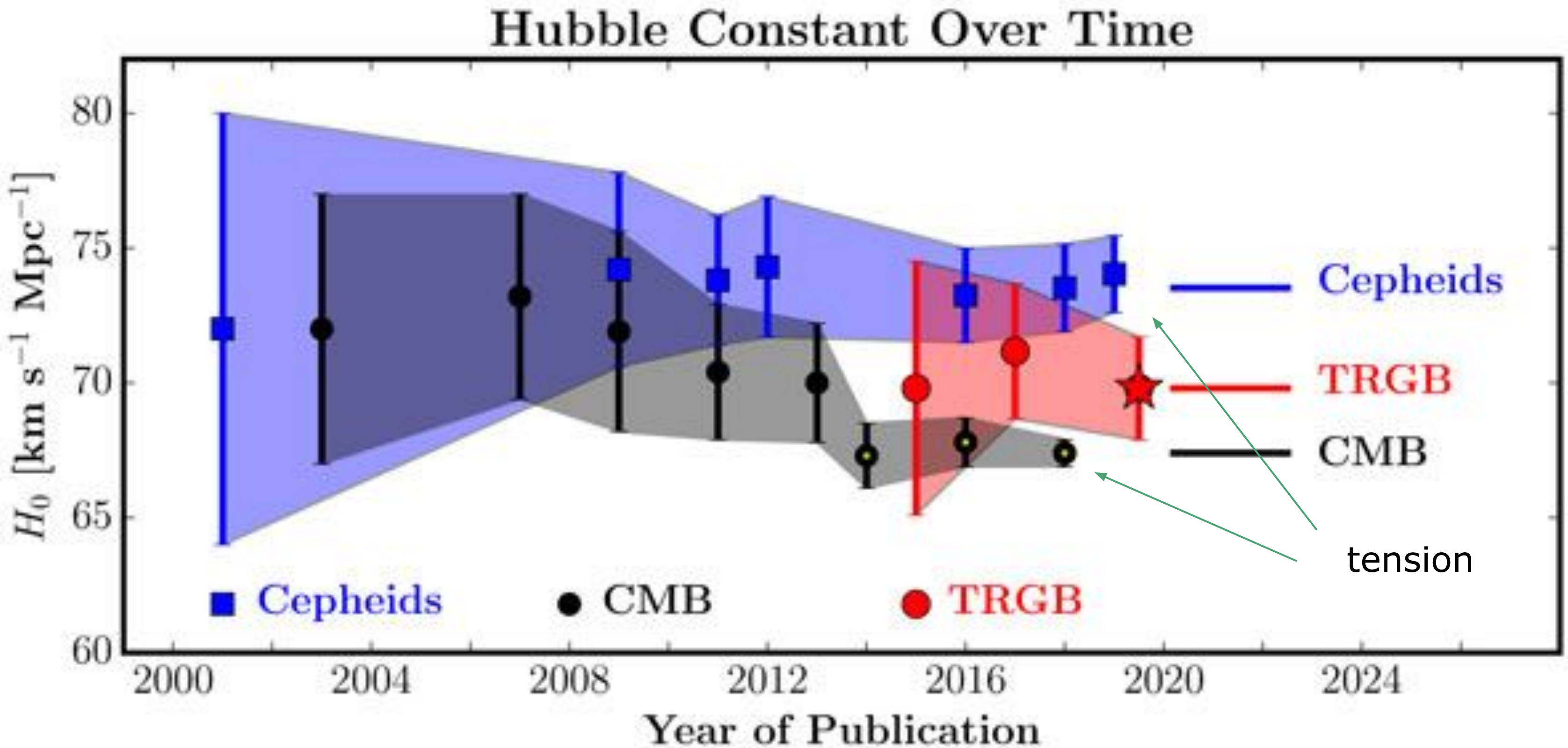


Today:

H0 ~ 70 km/s/Mpc

Measuring cosmological distances is *very* hard !

… today …



But this is another story which will be told later in this class.

Value of the Hubble constant

$$v \approx cz = H_0 \times d$$

$$H_0 = 100\ h\ \mathrm{km/s/Mpc} \qquad H_0 = 70\ h_{70}\ \mathrm{km/s/Mpc}$$

Allows to carry uncertainties on H0 in the computations

Hubble Key Project : $H_0 = 72 \pm 8$

Riess et al, 2016 : $H_0 = 73.24 \pm 1.74$

Local Universe

WMAP : $H_0 = 70.5 \pm 1.3$

Planck : $H_0 = 67.8 \pm 0.9$

Early Universe (CMB)

Hubble time

- H_0 has the dimension of $[T^{-1}]$

$$t_H = \frac{1}{H_0} = 13.97\ 10^9\ h_{70}^{-1}\ \ \mathrm{yr}$$

Hubble time

Time elapsed since so-called “singularity”

Not exactly though, just the scale, extrapolating today’s measurement of H

(Remember: 1Mpc = 3.086 10^{22} m)

Hubble length

- Hubble length

$$d_H = \frac{c}{H_0} = 4300\ h_{70}^{-1}\ \mathrm{Mpc}$$

- Typical size of observed Universe
- If z << 1, easy to get distances from redshift

$$d \approx z \times d_H$$

Critical density

- With H_0 [T^{-1}] and G [$M^{-1}L^3T^{-2}$], one can form a density

$$\rho_c = \frac{3H^2}{8\pi G}$$

- Called "critical density" (see later why "critical")

$$\rho_c = 0.91\ h_{70}^2\ 10^{-26}\ \mathrm{kg\ m^{-3}}$$

$$\rho_c = 1.34\ h_{70}^2\ 10^{11} \mathrm{M_\odot Mpc^{-3}}$$

$$\rho_c = 0.51\ h_{70}^2\ 10^{10} \mathrm{eV\ m^{-3}}$$

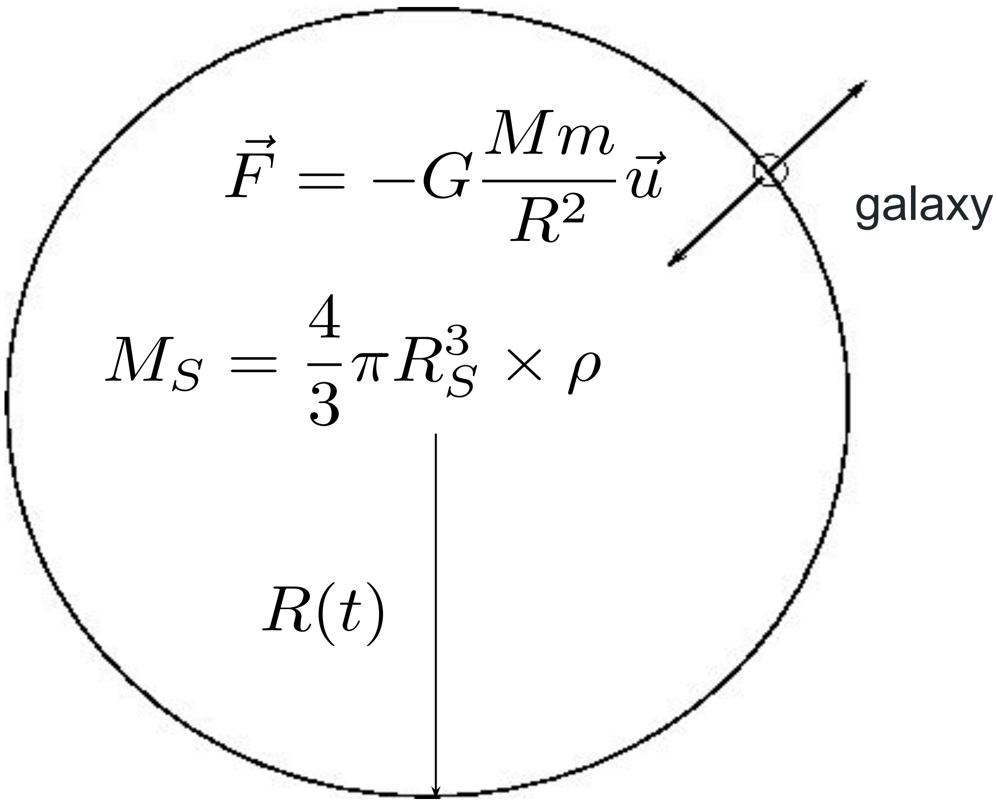
- Densities often expressed in units of $\rho_{c,0}$ (today)

$$\Omega_x = \frac{\rho_x}{\rho_c}$$

Summary

- 1915 : general relativity
- 1915 - 1920's Slipher and others notice that most distant “nebulae” are redshifted
- 1922 : Alexander Friedmann finds evolving solutions to Einstein equations
- 1927 : Lemaitre's paper
- 1929 : Hubble & Humason find proportionality between distances and recession velocity

A newtonian approach to expansion



$$\vec{F} = -G\frac{Mm}{R^2}\vec{u}$$

$$M_S = \frac{4}{3}\pi R_S^3 \times \rho$$

$$m\frac{d^2R}{dt^2} = -G\frac{mM_S}{R^2}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G\rho}{3}$$

- Uniform density ρ ; ~ loose application of Gauss theorem

A newtonian approach to expansion

$$\frac{\ddot{R}}{R} = -\frac{4\pi G\rho}{3}$$

$$\rho \propto R^3$$

Expansion should be decelerated

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} + H_0^2(1-\Omega_M)\left(\frac{R}{R_0}\right)^{-2}$$

$$\left(\frac{\dot{R}}{R}\right)^2 = H_0^2\left(\Omega_M\hat{R}^{-3} + (1-\Omega_M)\hat{R}^{-2}\right)$$

$$\left(\frac{\dot{R}}{R}\right)^2 = H_0^2\left(\Omega_M \hat{R}^{-3} + (1-\Omega_M)\hat{R}^{-2}\right)$$

$\Omega_M > 1$ ⟶ Expansion stops at $R = R_0 \dfrac{\Omega_M}{\Omega_M - 1}$

Then, contraction, because d2R/dt2 < 0

$\Omega_M = 1$ ⟶ $R(t) = R_0 \left(\dfrac{t}{(2/3)H_0^{-1}}\right)^{2/3}$

"critical"

Eternal (decelerated) expansion – smaller Hubble time

$\Omega_M > 1$ ⟶ Eternal (decelerated) expansion

Hubble time

Special case: empty Universe: $R(t) = R_0 \dfrac{t}{H_0^{-1}}$

Outline

- What is cosmology ?
- Cosmology through the ages
- The first revolution (1925) : the Universe is Big !
- The second revolution (1927 - 1931) : the Universe is expanding !
- The hot big-bang model
- Observables
- The third revolution (1999-2003) : accelerated expansion & ΛDCM
- Our strange Universe

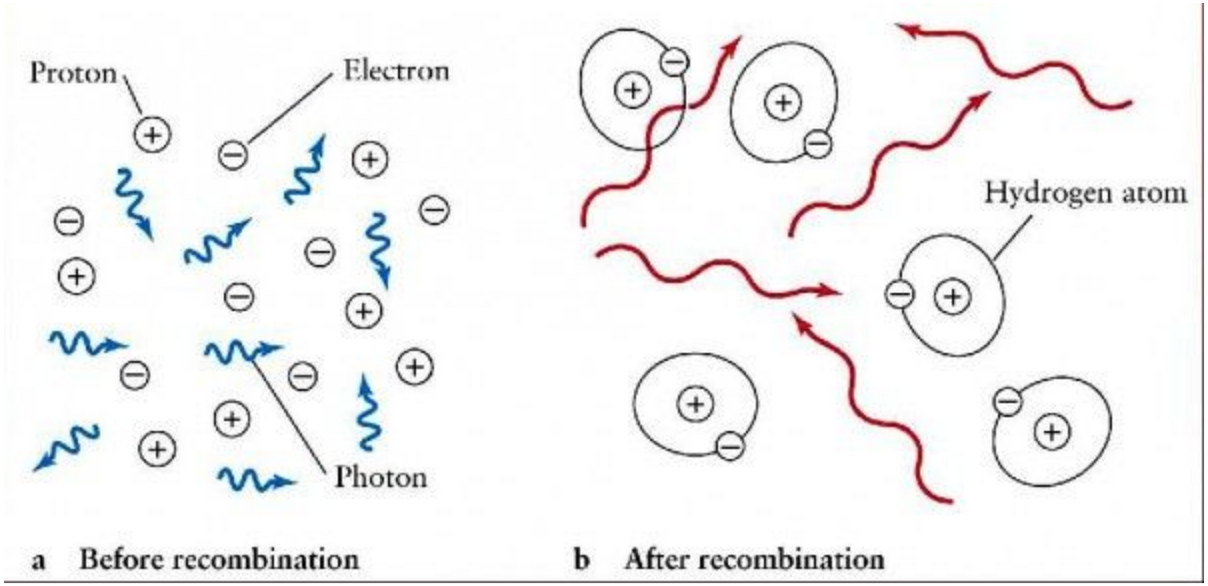
The Hot Big-Band model

Modeling the Universe

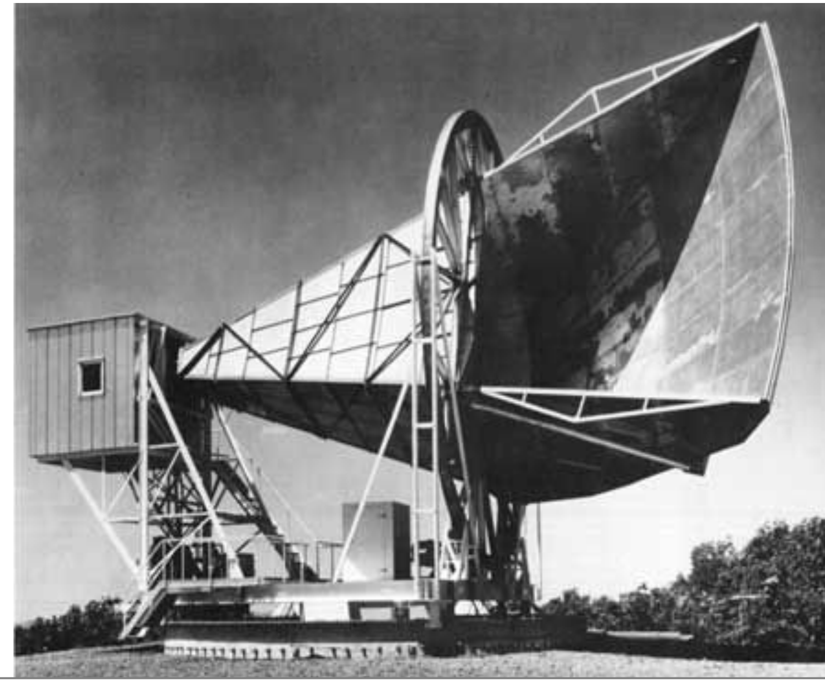
- Foundations
  - The Universe is big
  - The Universe is expanding from some kind of “initial singularity” that occurred ~ $1t_H$ = 14 Gyr ago
  - Beyond ~ 100 Mpc, the Universe is
    - Isotropic
    - Homogeneous
  - Copernican principle: no privileged position in the Universe

Cosmological microwave background

- Predicted by Gamow (1948)
  - ~ 300000 yrs after BB
  - Universe was an opaque plasma
  - Expansion -> Universe getting colder -> recombination e/γ -> decoupling matter and photons
- We should be able to see this relic !



- Discovered by Penzias & Wilson
- In 1963
- Nobel Prize in 1978



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

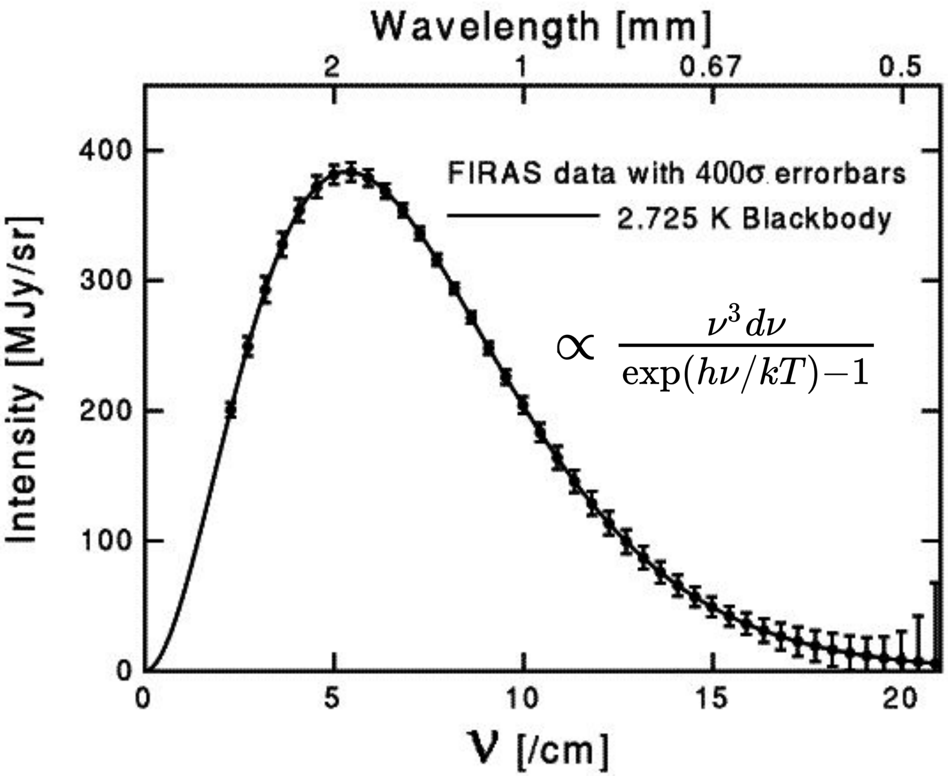
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

- The Dicke et al paper
- With the correct cosmological interpretation of the P&W result

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

CMB spectrum



Best blackbody spectrum ever measured

$$T = 2.726 \pm 0.0012$$

(Fixen et al, 2009)

$$\varepsilon_\gamma = aT^4$$

(a = 7.566 10^{-16} J/m^3/K^4)

$$e_\gamma \approx 2.7kT$$

$$n_\gamma \approx \quad ?$$

$$\Omega_\gamma \approx \quad ?$$

BTW, how many photons from stars ?

Not very well known. Diverges at small galaxy luminosities (which do not contribute much to the total luminosity.

- Number of galaxies per volume

$$n_{gal} \sim 0.015 \ h_{70}^3 \ \mathrm{Mpc}^3$$

- Average luminosity of a galaxy

$$L_{gal} \sim 10^{10} L_{\odot}$$

- Time ~ 10 Gyr, e_γ ~ 2 eV

??? photons / cm^3

1 Mpc = 3.0856 10^{24} cm

1 $L_{\odot}$ = 3.84 10^{26} W

How much visible matter ?

- Typical mass-to-luminosity ratio for galaxies

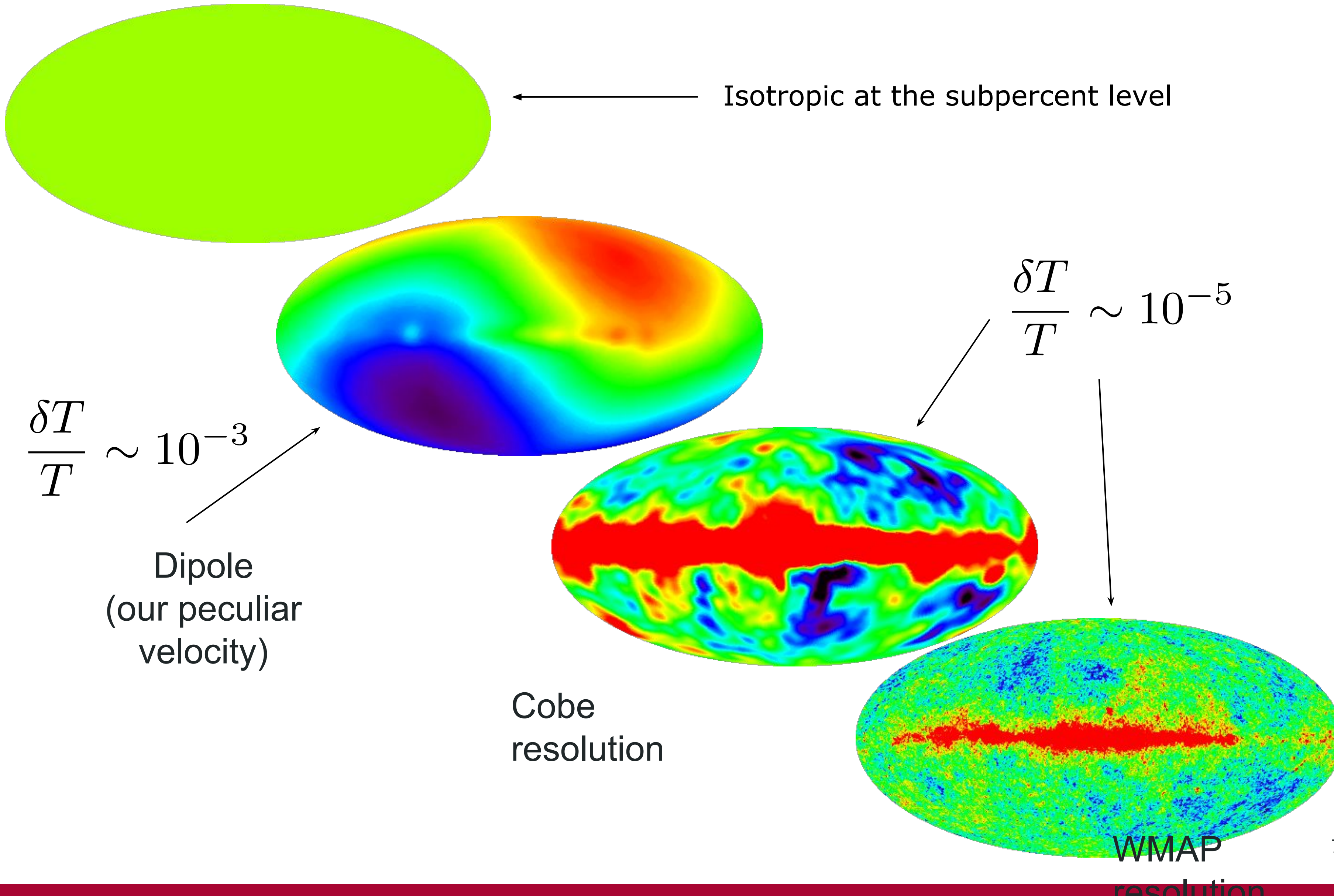
$$\left\langle \frac{M}{L} \right\rangle \sim 2.5 \frac{M_\odot}{L_\odot}$$

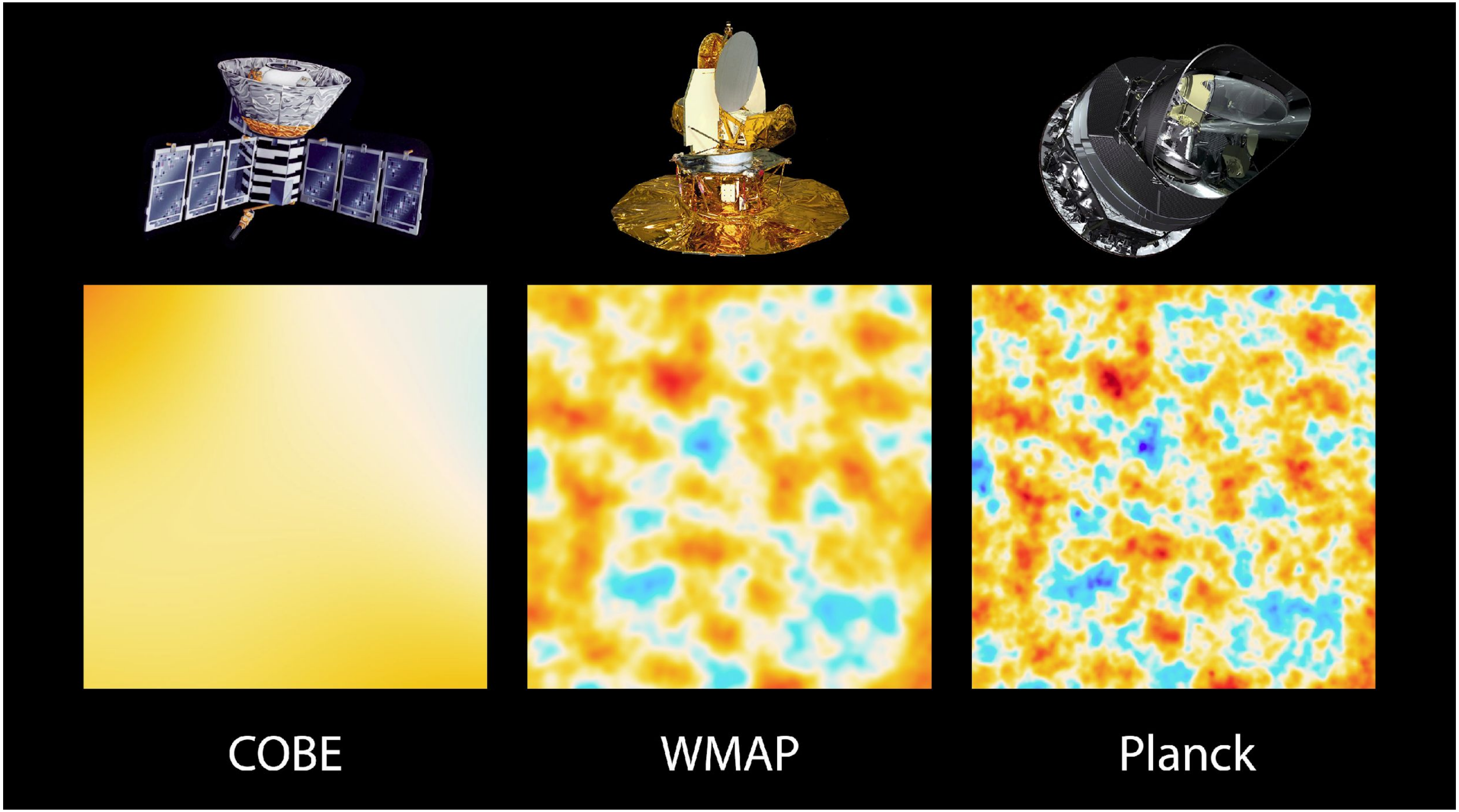
- Density of visible matter in units of the critical density ?

$n_{gal} \sim 0.015\ \mathrm{Mpc}^{-3}$

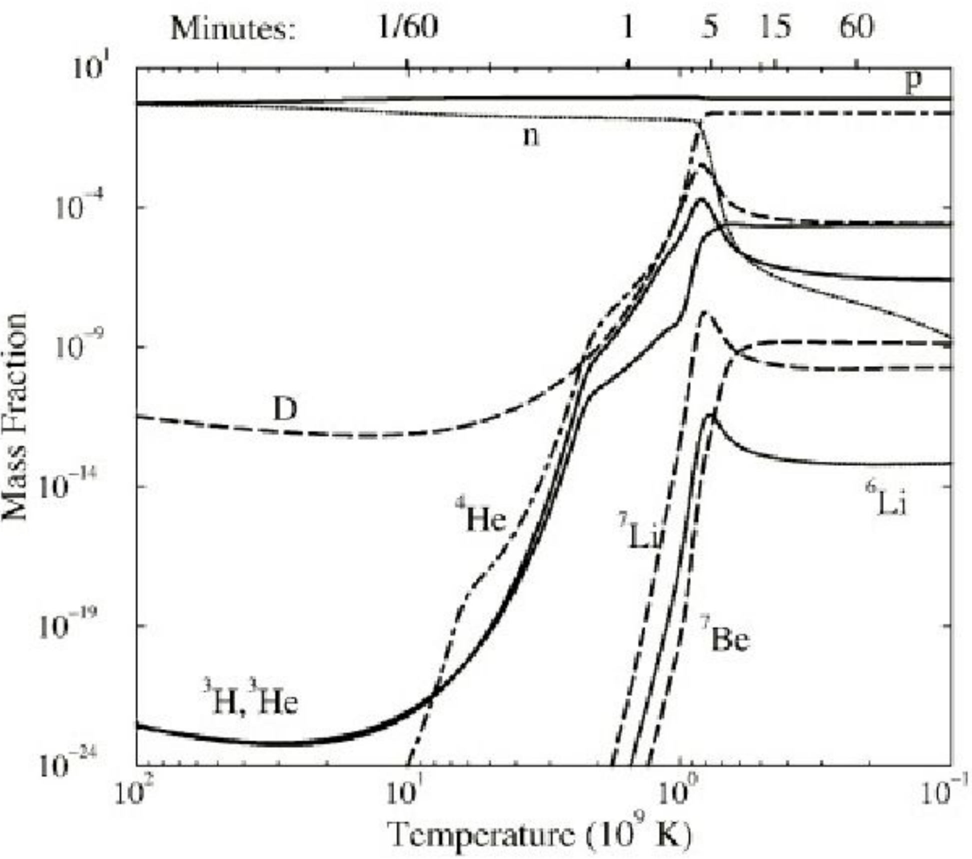
$\rho_{crit} = 1.34\ 10^{11}\ M_\odot/\mathrm{Mpc}^3$

CMB anisotropies

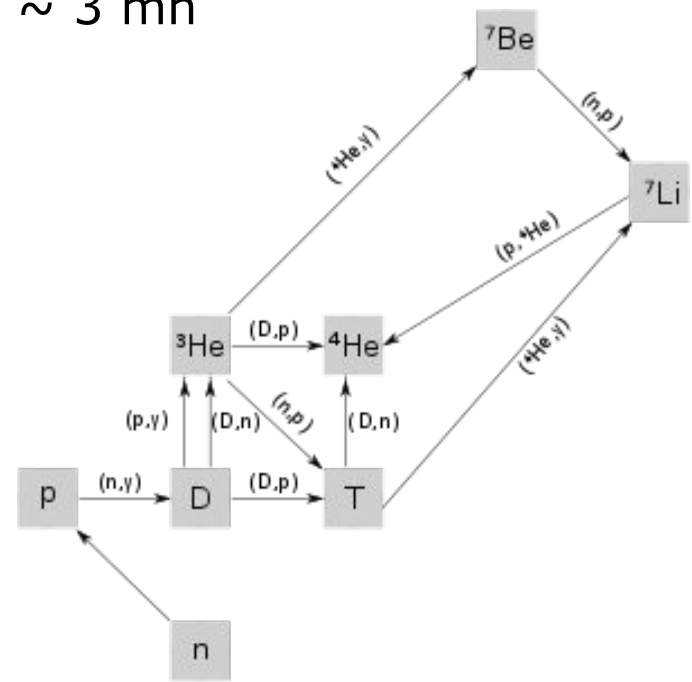



COBE
WMAP
Planck

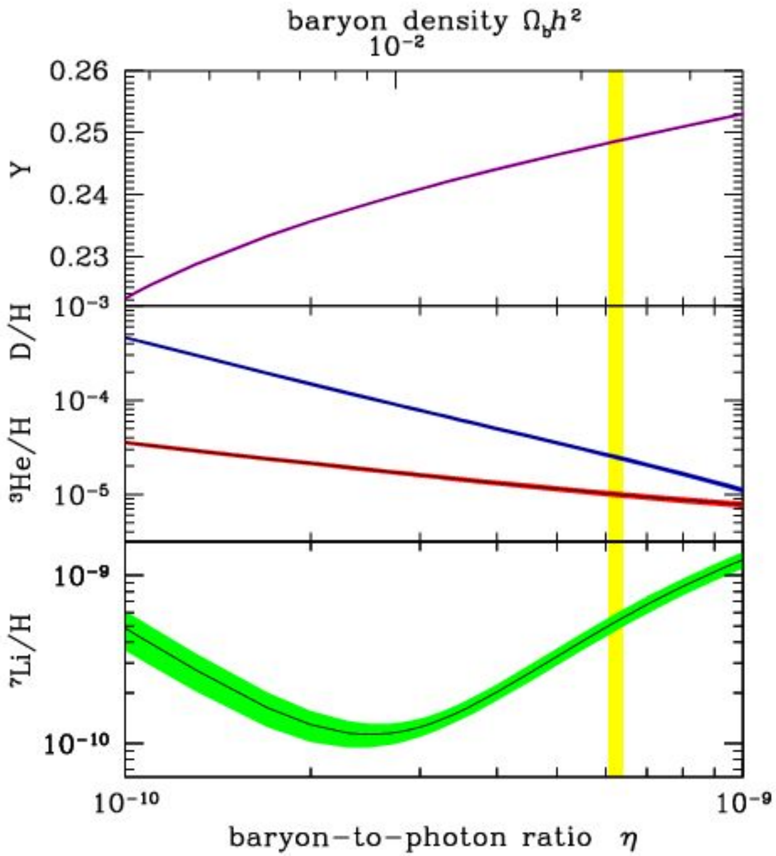
Big-Bang nucleosynthesis



- T ~ MeV -> ~ 60 keV
- Synthesis of light elements
  - D, He3, He4, Li6, Li7
- Stops when density gets too low
- ~ 3 mn



Big-Bang nucleosynthesis

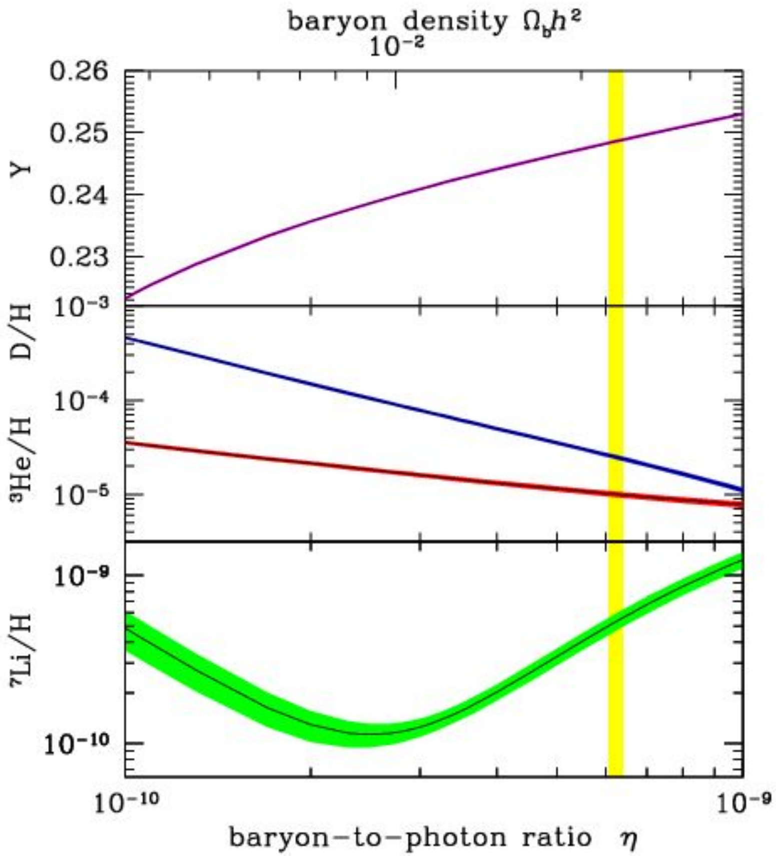


- Fundamental parameter

$$\eta = \frac{N_b}{N_\gamma}$$

- + expansion history
- Constraining abundances
  - Tests of model
  - Constraints on $\Omega_b h^{-2}$
  - Since n_γ is known

Big-Bang nucleosynthesis



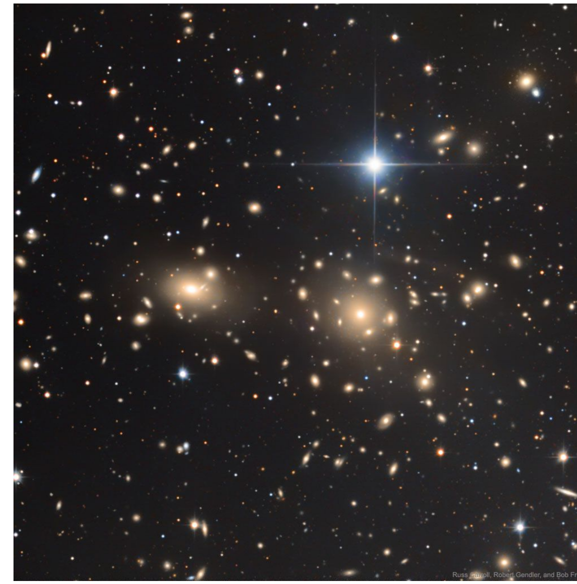
- Measurements from quasar absorption systems
- Absorption lines from primordial clouds on the line of sight

$$\eta \sim 6.10^{-10}$$

$$\Omega_b h^{-2} \approx \ ?$$

Conclusion ?

M/L ratio of clusters



ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower

Zwicky, ApJ, 1937

Virial theorem

- Statistical theorem of classical mechanics
  - For a system of particles in stable equilibrium bound by gravitation (e.g. a cluster of galaxies), we have

$$2\langle T \rangle = -V_g$$

Kinetic energy of particles (random motions)

Gravitational potential energy due to mutual attraction of particles

Can be measured

Give access to total mass

For a galaxy cluster

$$V_g = -\frac{16\pi^2}{15} G \langle\rho\rangle^2 R^5 = -\frac{3}{5}\frac{GM^2}{R}$$

$$\langle T \rangle = \frac{1}{2}\sum_i M_i \left\langle v_i^2 \right\rangle \approx \frac{1}{2} M \left\langle \left\langle v^2 \right\rangle \right\rangle$$

$$M = \frac{5R\left\langle \left\langle v^2 \right\rangle \right\rangle}{3G}$$

In the case of the Coma cluster...

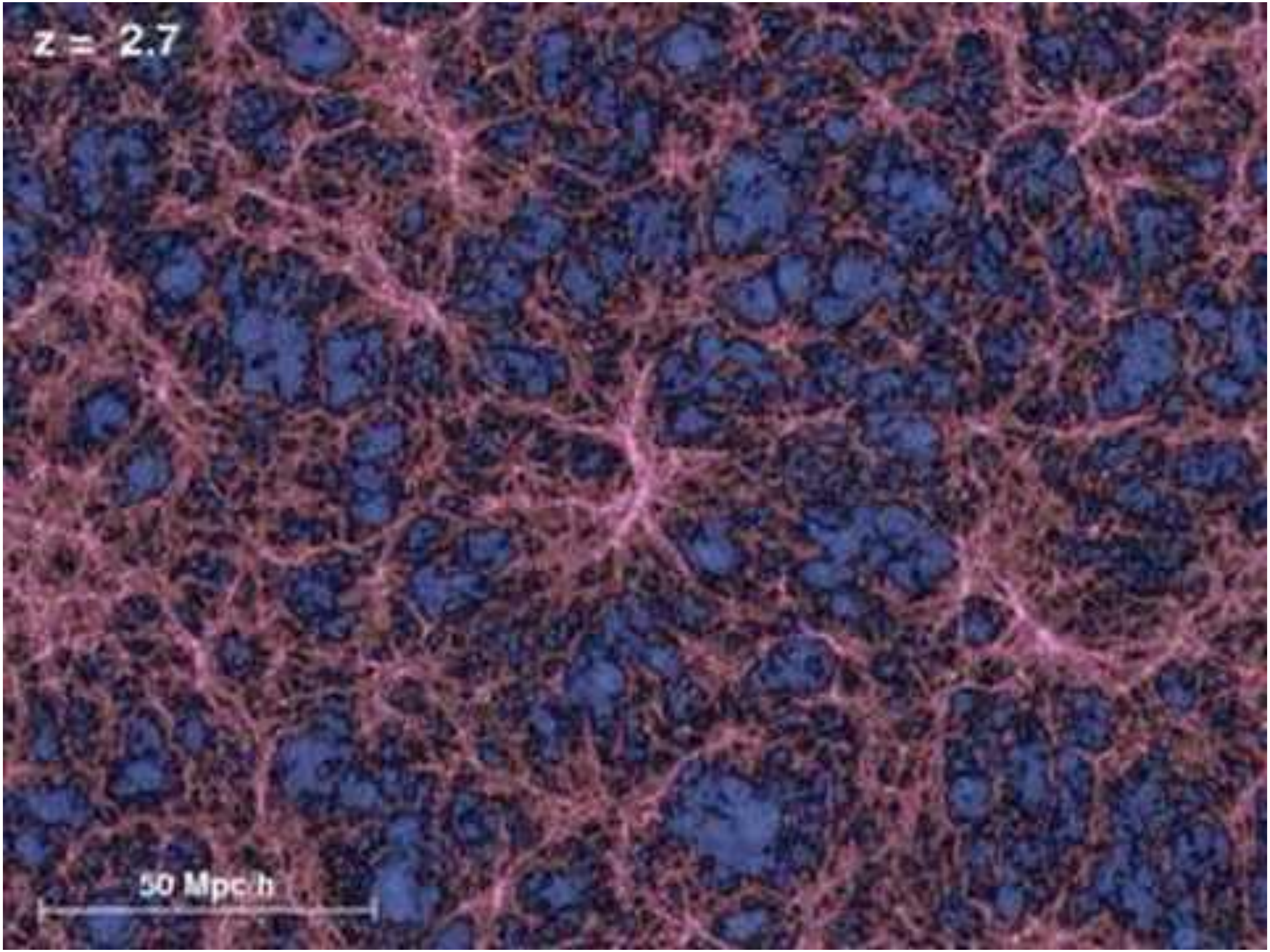
- R ~ 613 kpc
- v ~ 435 km/s
- Msun = 1.99E30 kg
- ~ 1000 galaxies, L_gal ~ 8.5E7 Lsun

$$\frac{M}{L} = ?$$

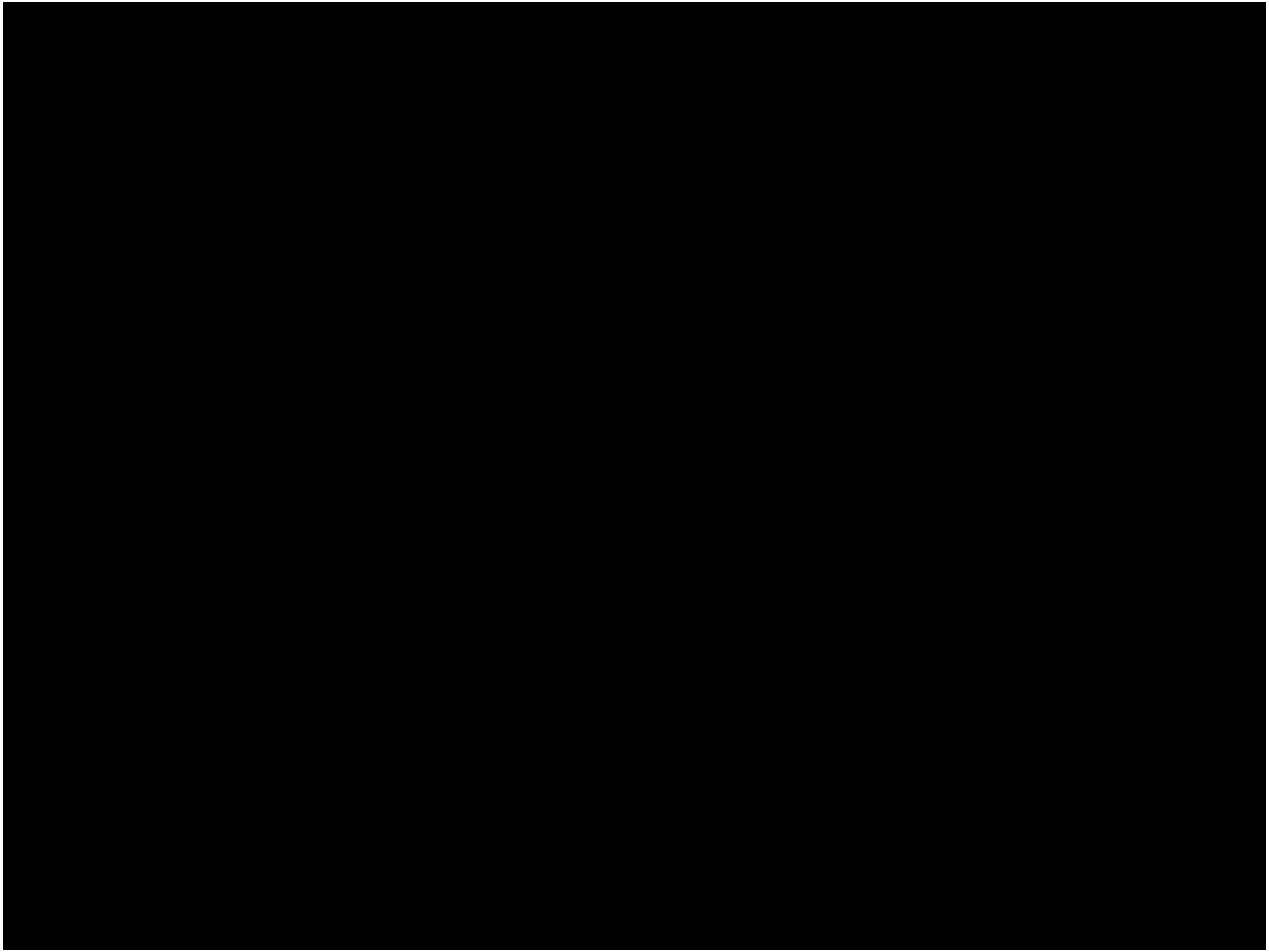
Summary

- So, we live in a Universe
  - Bathed in a CMB diffuse background (most abundant particles, weight nothing)
  - With very little visible matter
  - With very little baryons
  - And strong hints from large amounts of non-baryonic dark matter
- What happens next ?
  - Structure formation !
  - Filaments, haloes, first galaxies, first stars, first supernovae, re-ionization, second and third generation stars, planets, life ! (baryon physics)

Description of the Universe at smaller scales


z = 2.7
50 Mpc/h


time since Big Bang
9.5 Gyr
1 cMpc



https://www.oca.eu/en/research-fields/1706-cosmological-simulations

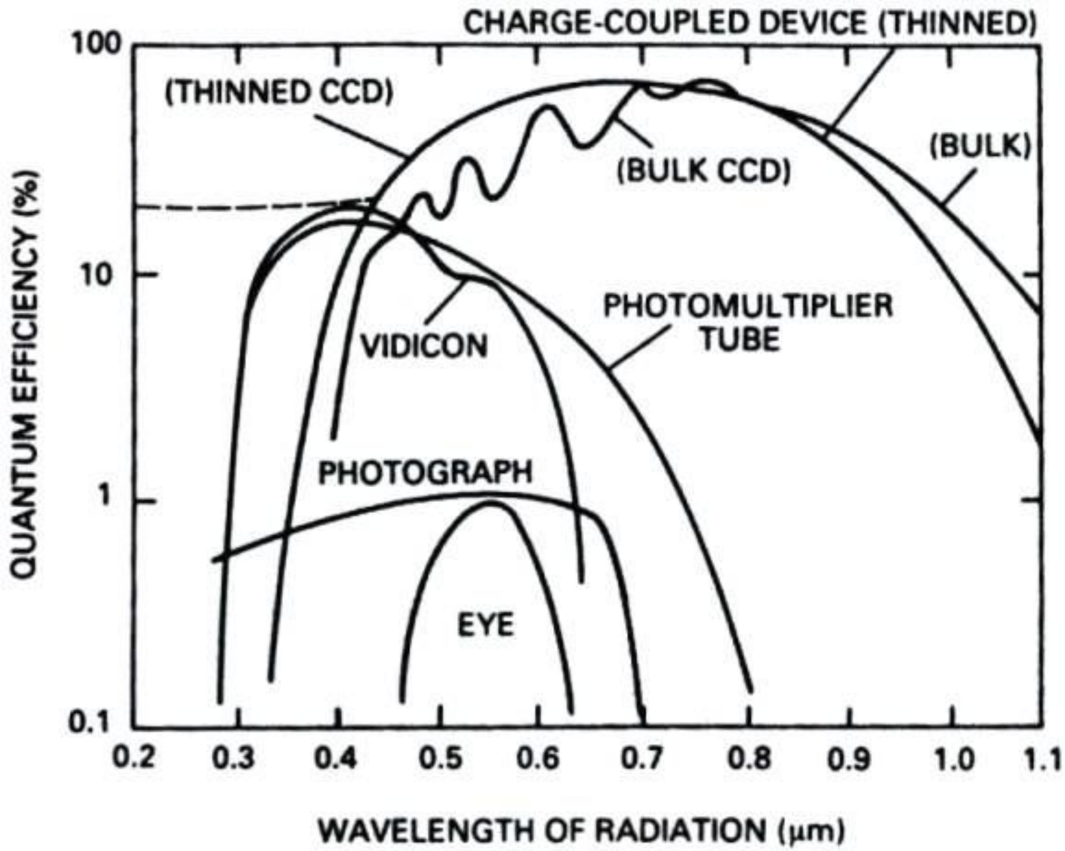
Nothing more about the smooth Universe ?

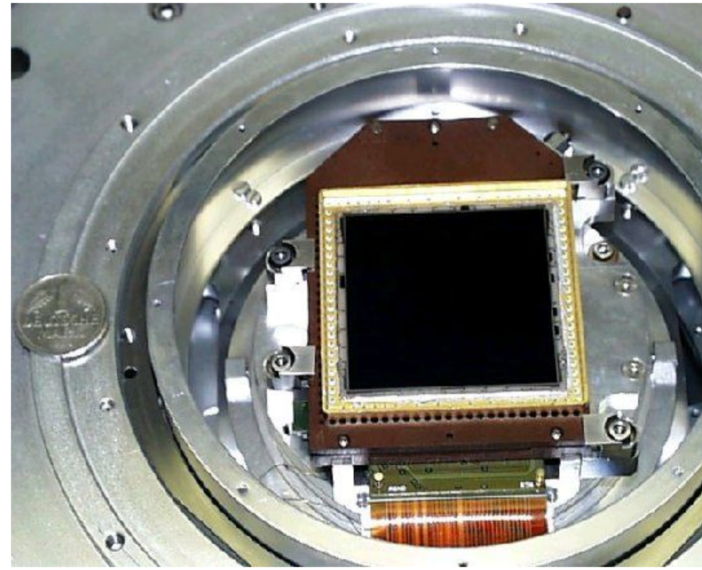
In fact, yes, there is.

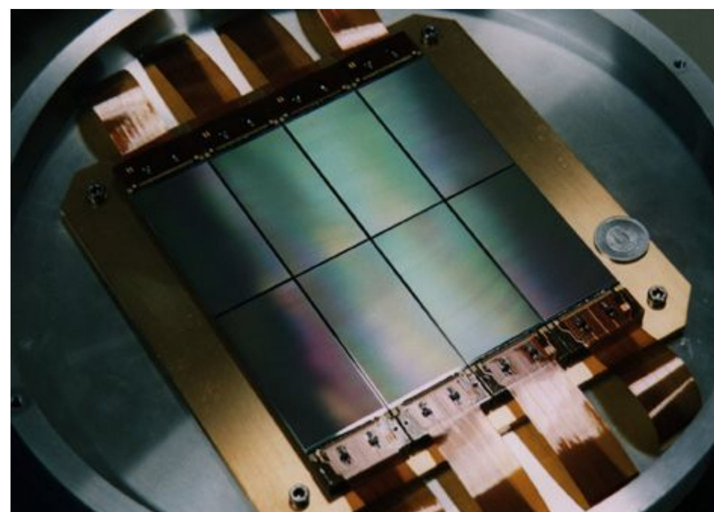
One last tiny detail ...

- For 50 years, astronomers have tried (unsuccessfully) to get the first measurements of expansion history
- The reason why this was so difficult:
    - Lack of reliable standard candles (galaxies are not really standard)
    - Lack of data
- then...

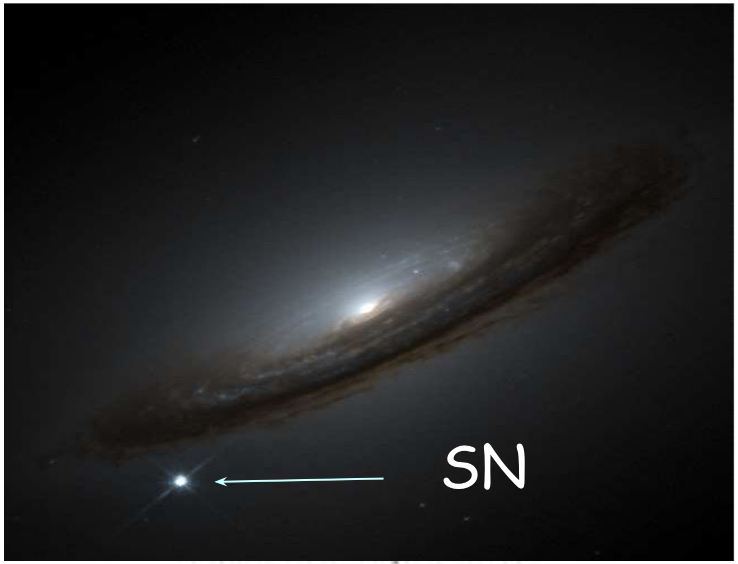
Technological breakthrough : CCD’s

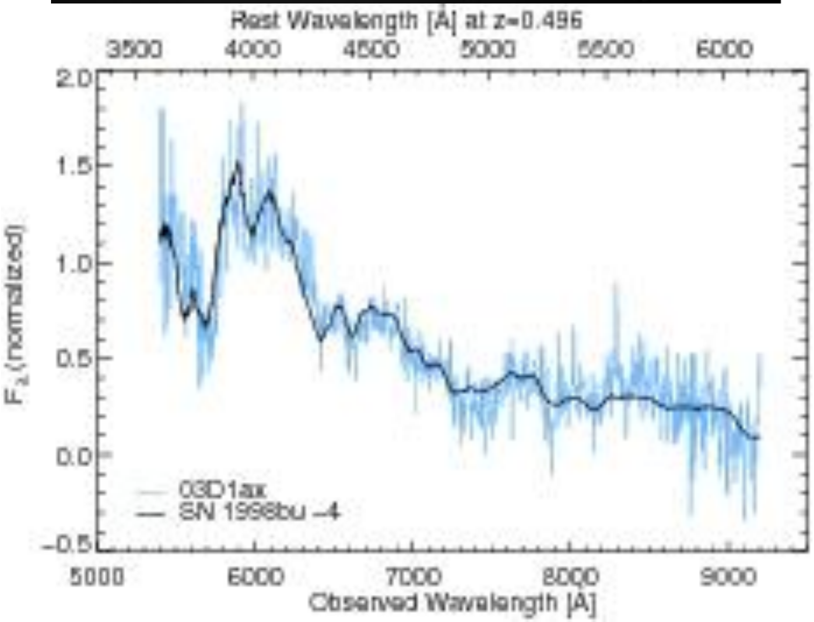






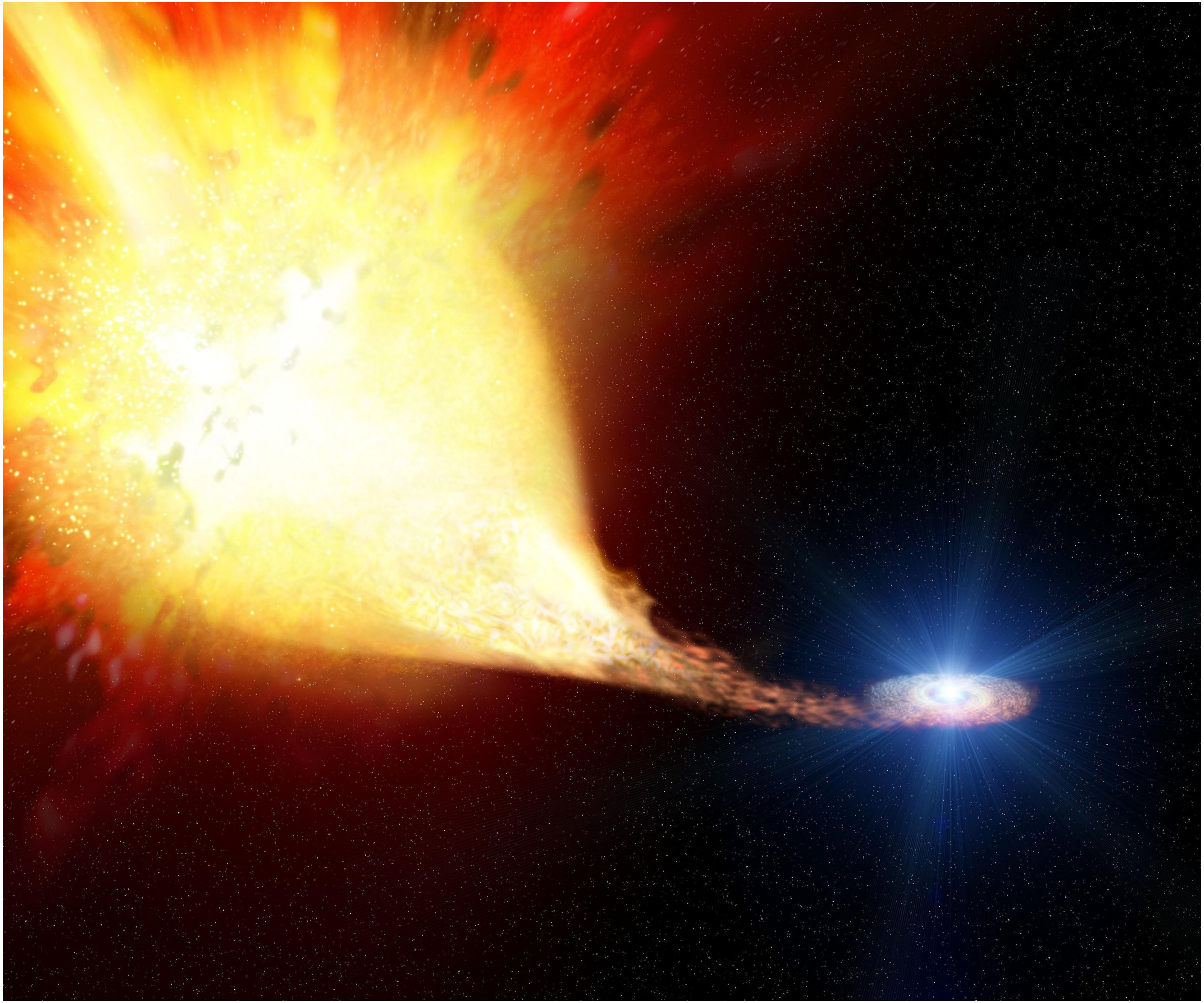
Type Ia supernovae

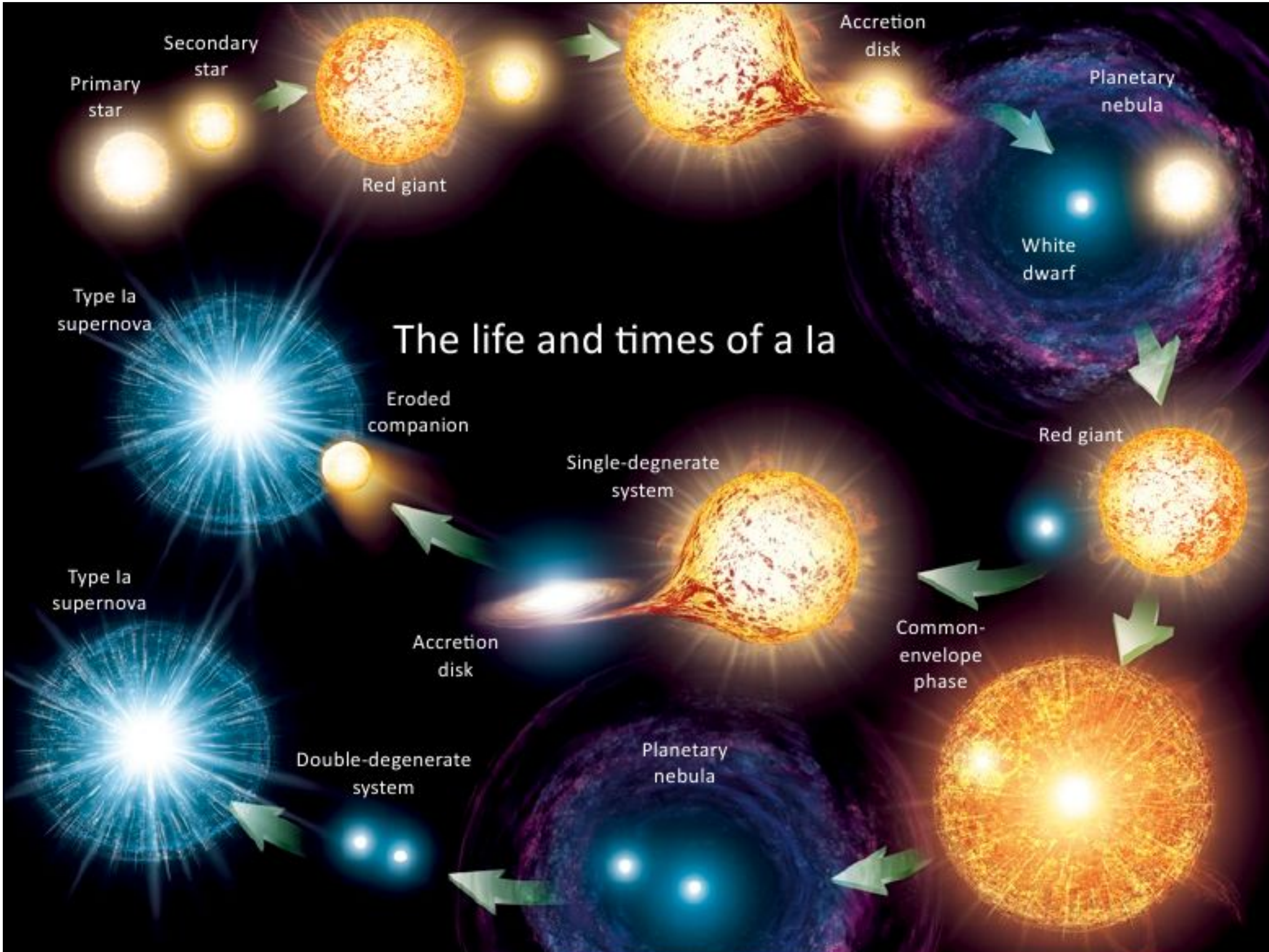




- Thermonuclear explosions of WD's
  - Rare events
  - Very bright ($10^{10}\ L_\odot$)
  - Transients (1 month)
  - $\sigma(L_{max}) \sim 40\%$
- Standardizable
  - $\sigma(L_{max}) \sim 12\%$
- Spectroscopy
  - Identification (broad features)
  - Chemical composition & velocities
  - Redshift (better from host gal)

Hillebrandt & Niemayer, 2000
Maoz et al,2014




The life and times of a Ia
Primary star
Secondary star
Red giant
Accretion disk
Planetary nebula
White dwarf
Red giant
Type Ia supernova
Eroded companion
Single-degnerate system
Accretion disk
Common-envelope phase
Type Ia supernova
Double-degenerate system
Planetary nebula

Beyond the Hubble law

- Program

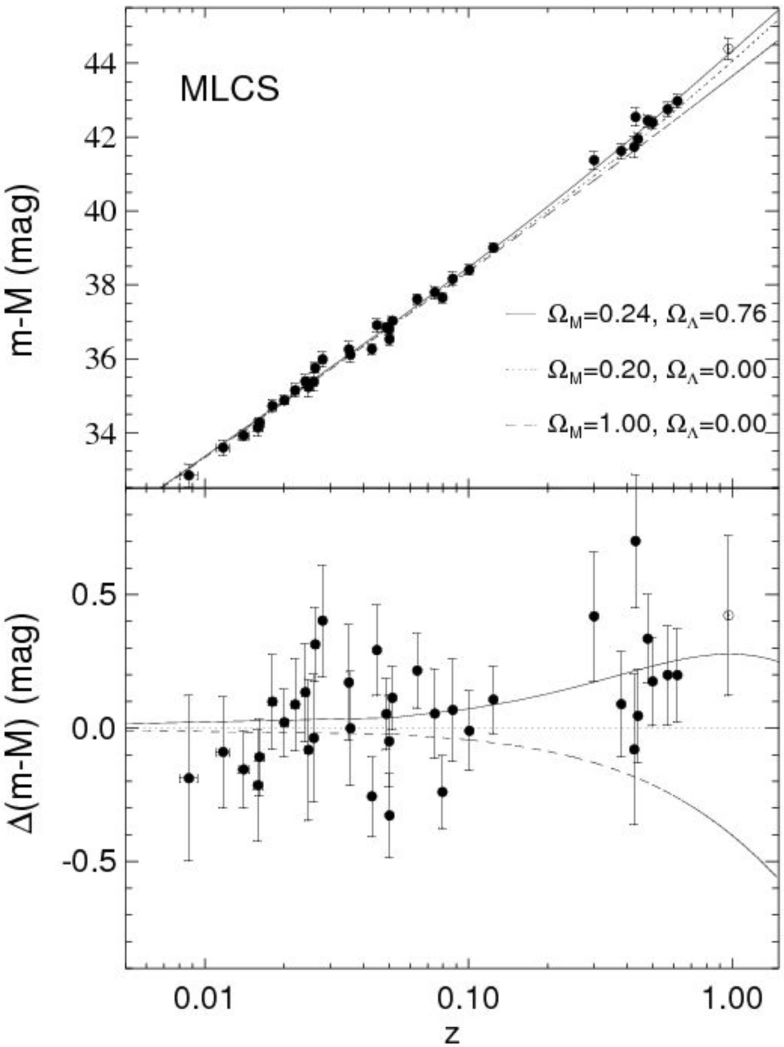
$$H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \ldots$$

$$q_0 \approx \frac{\Omega_m}{2}$$

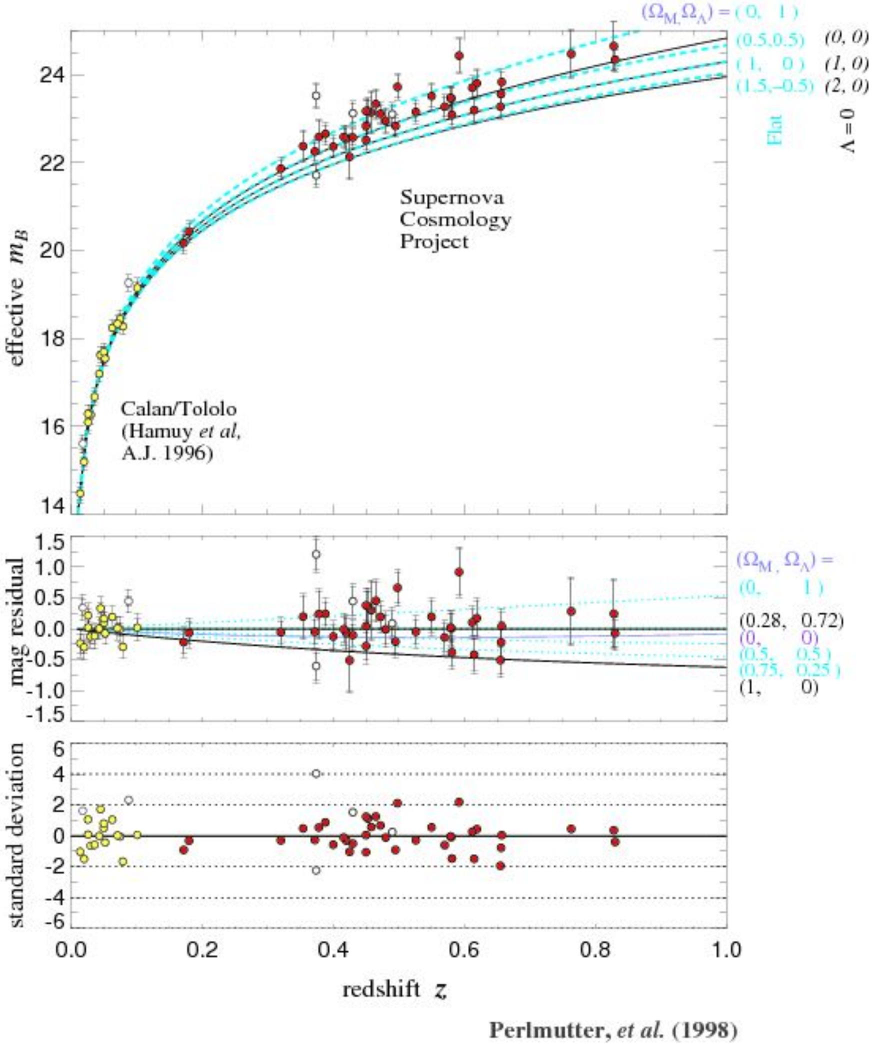
"Deceleration parameter"

- If we measure q_0, we have access to Ω_m !
  - SNe Ia are ideal candidates to map the Hubble flow
  - But they are rare and faint !

First measurements @ z ~ 0.5

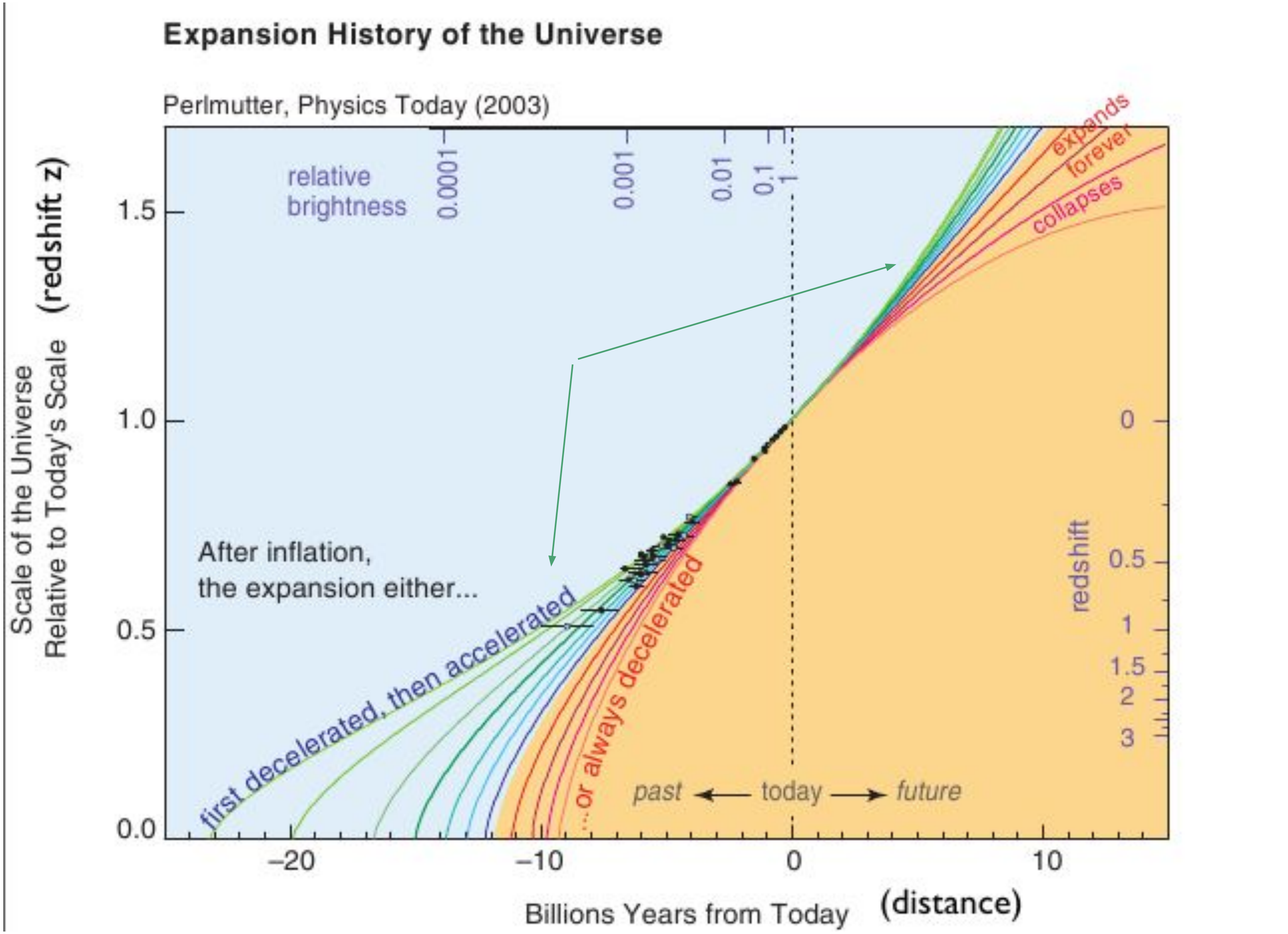


East coast

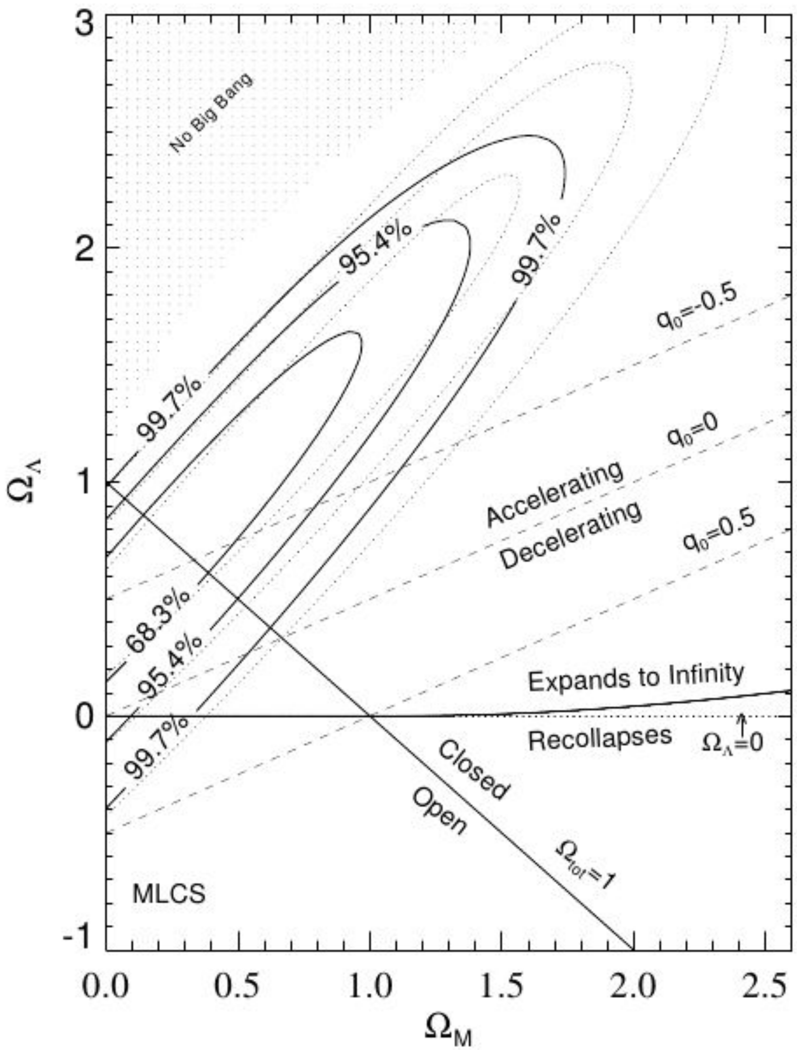


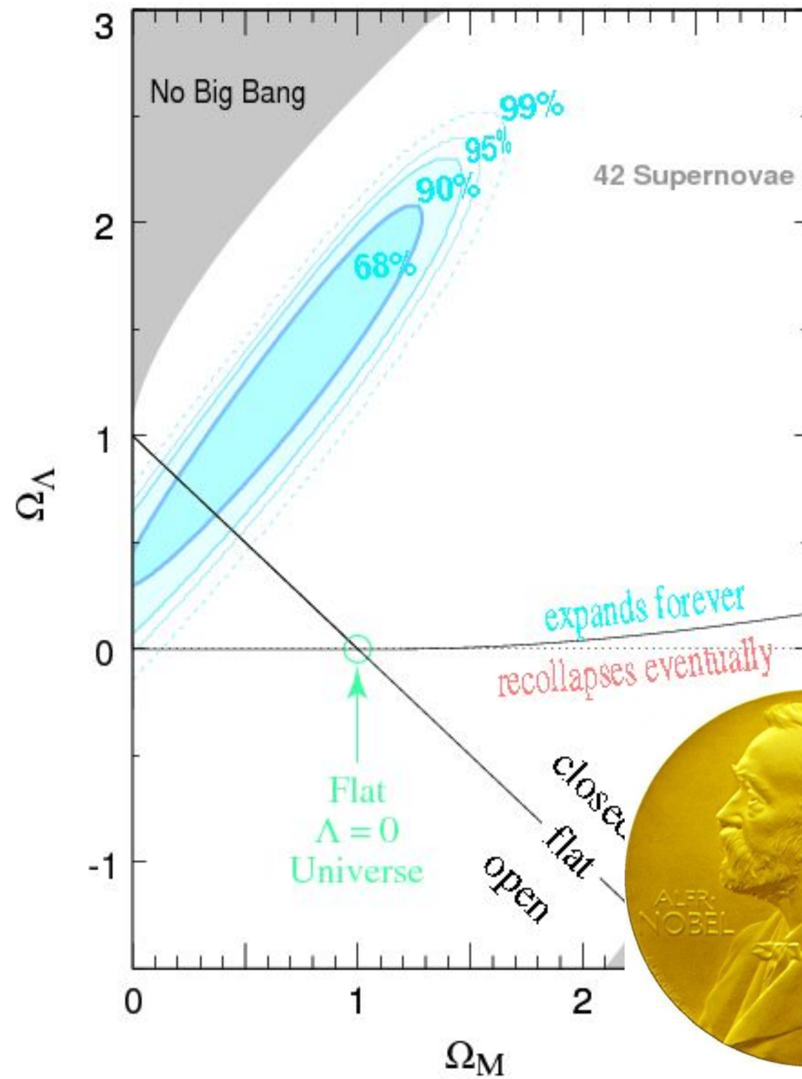
West coast

Expansion history

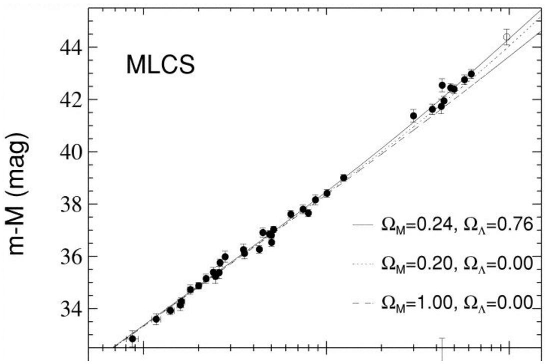


Evidence from “repulsive stuff at large scales”

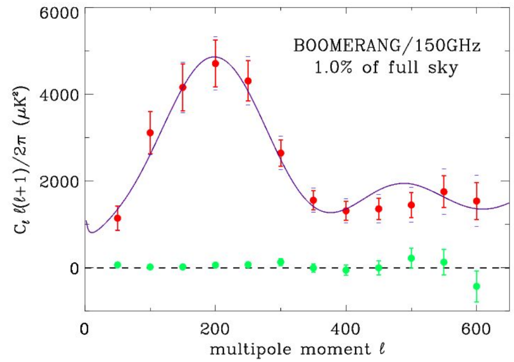




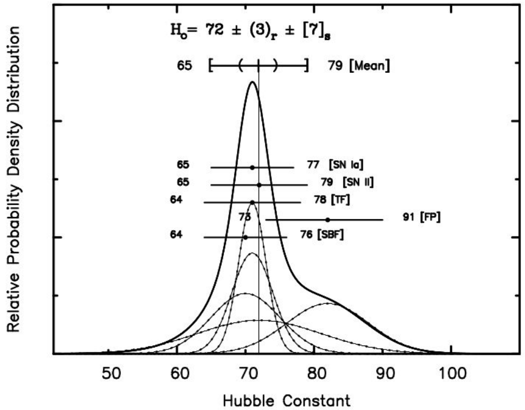
At the turn of the century...



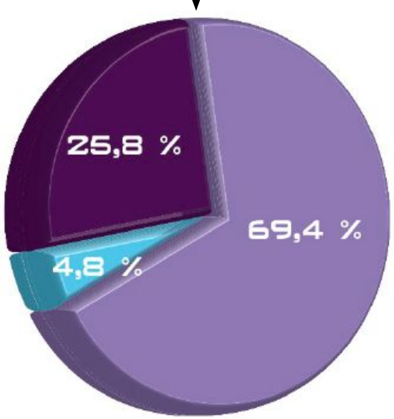
First convincing evidence for acceleration (e.g. Riess et al 1998, Perlmutter et al, 1999)



First precise measurements of CMB accoustic peak (e.g. de Bernardis et al, 2000)



First precise measurement of H0 (Freedman et al, 2000)



An accelerated Euclidian Universe, dominated by Dark Energy (Λ) and by Cold Dark Matter

Nature of Dark Energy ?

- Cosmological constant ? Fluid of unknown nature ?
  - Measure its equation of state ! $w = \frac{p}{\rho}$
  - With potentially

$\Lambda \Rightarrow w = -1$

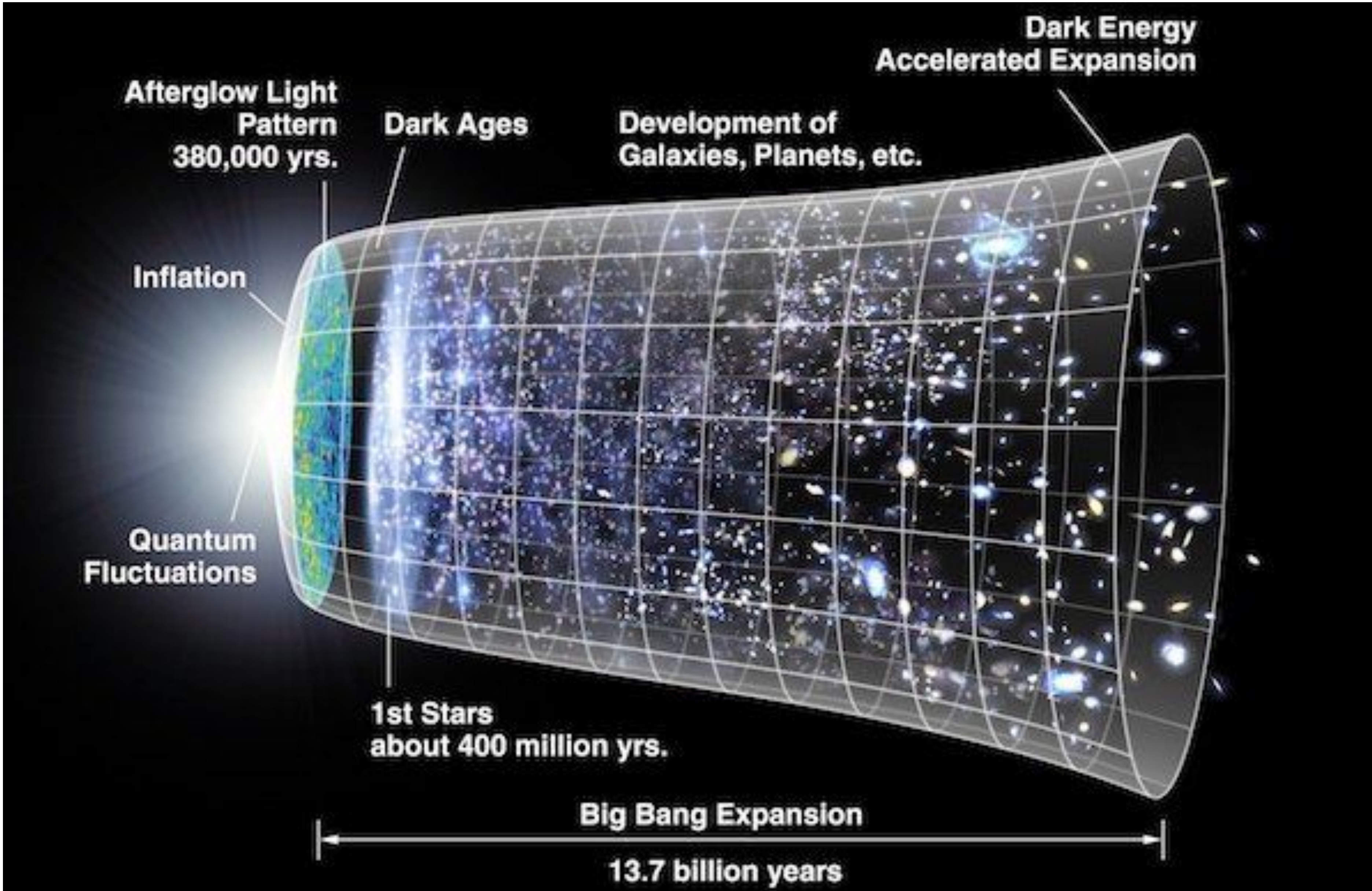
$$w(a) = w_p + w_a(a_p - a)$$

- Something wrong with GR at cosmological scales ?
  - Then expect a different phenomenology
  - E.g. growth of structure should be different
  - -> precision test of GR at cosmological scales

$$f \propto \Omega_m^{\gamma}$$

Growth rate

GR predicts $\gamma \sim 0.55$


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years