Universität Zürich[UZH]
Physik-Institut

PAUL SCHERRER INSTITUT

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Cosmic Frontier: Particles and radiation in the universe

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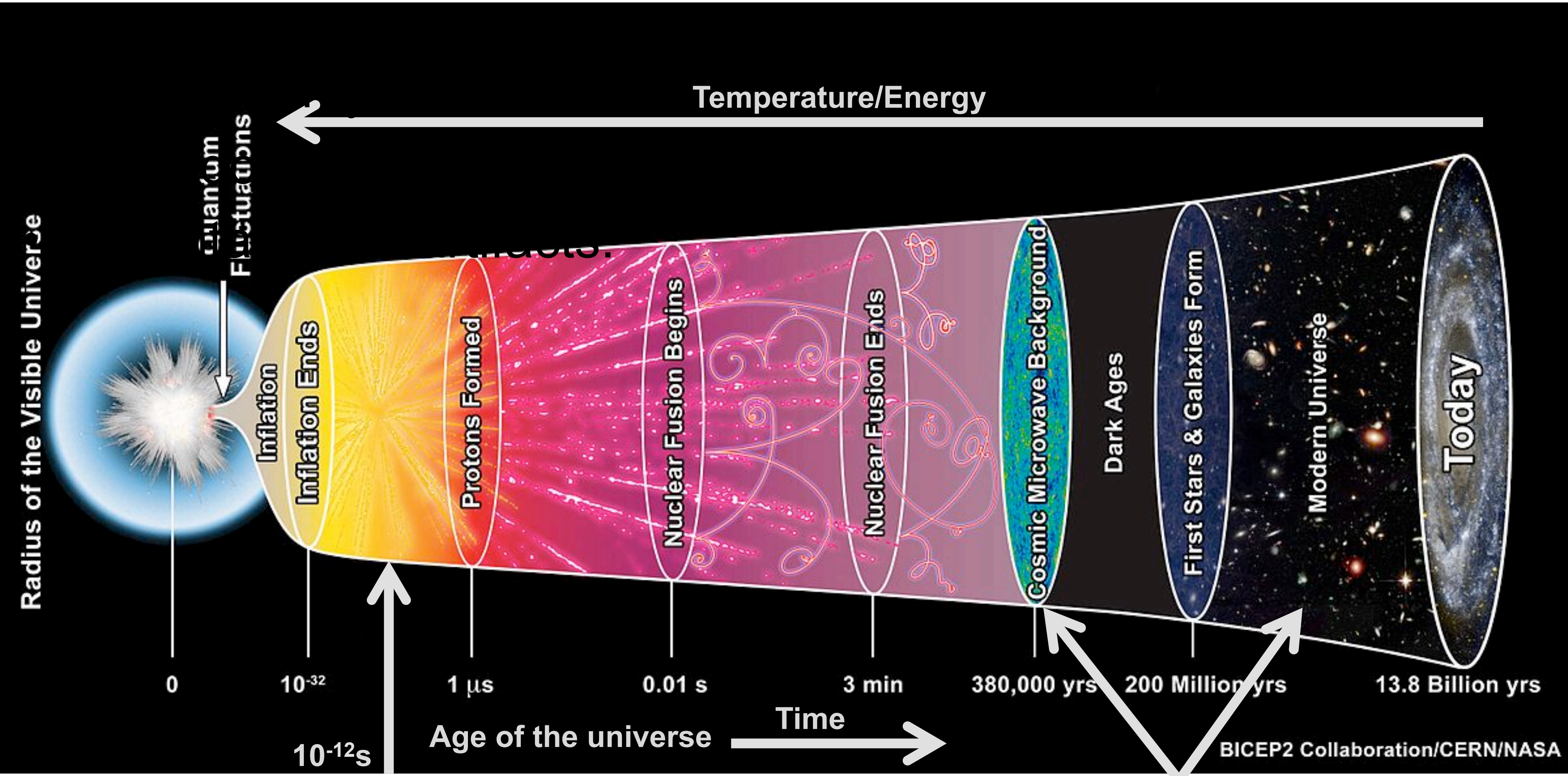
What do we know about the universe?

- The universe is old. About 13.8 billion years.
  - earth: 4.5 billion years (from radioactive elements)
  - sun: 5 billion years
  - oldest stars: about 14 billion years
- The universe is big. The most distance objects are about 30 billion light-years away. (distance of earth to sun is 8 light minutes.) This is for the observable universe. The size of the entire universe is unknown.
- The universe contains huge number of clusters of galaxies, which are made from matter, but mostly dark matter
- The universe is expanding
- The expansion is accelerating

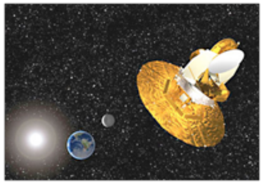
How do we know?

- From ground-based and space-based experiments



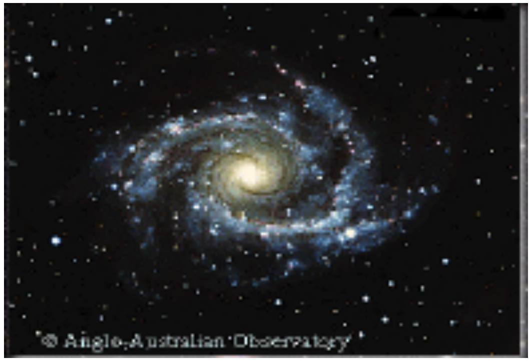
LHC

Satellites

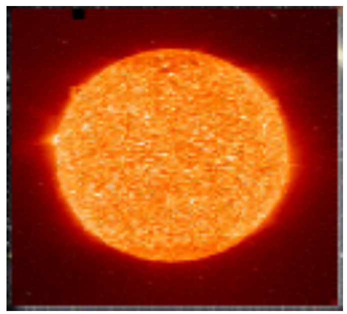


Telescopes

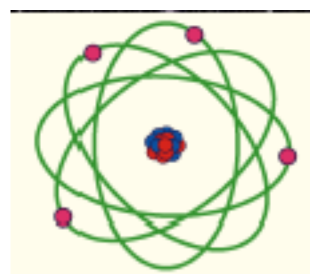
Content of the universe



~10^{11} galaxies



~10^{21} stars



~10^{78} atoms

~10^{88} photons

Galaxies visible with the naked eye in the Southern hemisphere

Galaxies: ~60,000 light-years across, contain ~10 billion stars, Rotation period ~ 200 Million years (typically)

Image taken with the Dark Energy Camera

Galaxies clump together into Galaxy Clusters

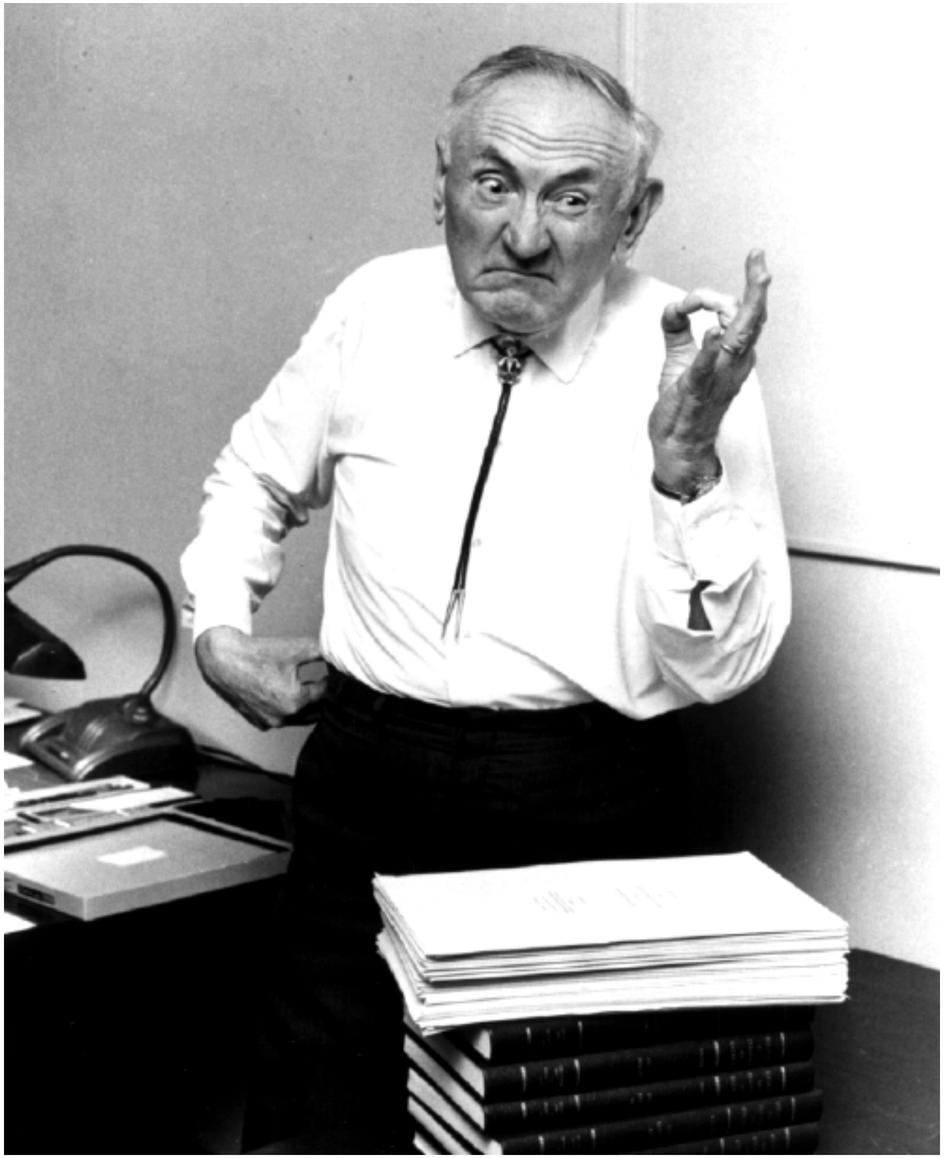
Image taken with the Dark Energy Camera

Clusters of Galaxies: Size ~ few Million light years
Mass ~ 1 quadrillion (1000 x 1 trillion) M_{sun}
Contain ~10s to 1000s of galaxies
Evolution time scale: ~few billion years

Coma Cluster of Galaxies

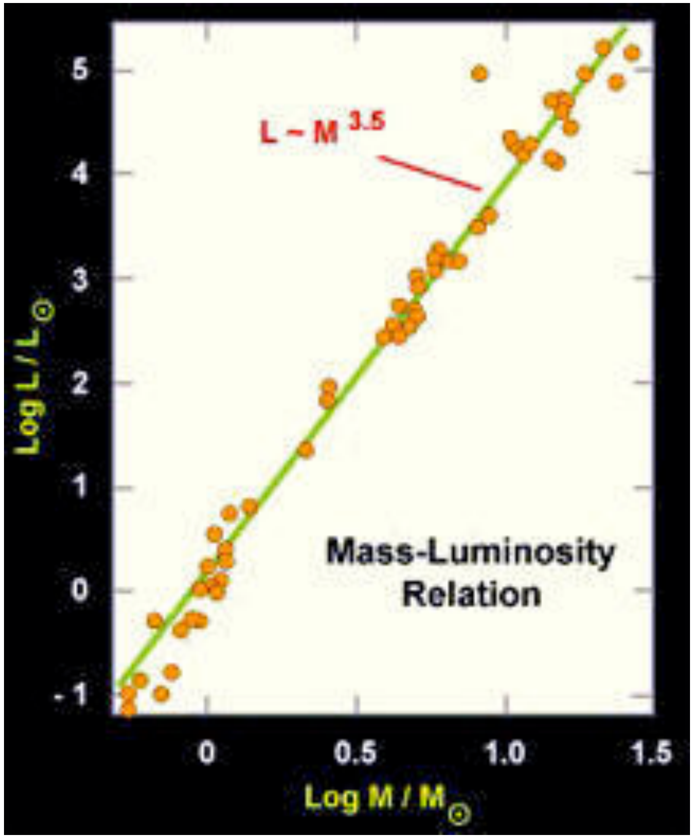
Coma Cluster: First evidence of dark matter

- Fritz Zwicki (1898-1974)
- Studied the motions of galaxies within the Coma cluster
- Found that galaxies are moving to fast (about 1000km/h) to remain confined by Coma's gravitational field
- So why is the Coma cluster still there?
- 1933: introduced the concept of "Dunkle Materie"
- Widely accepted only many years later



Mass luminosity relation

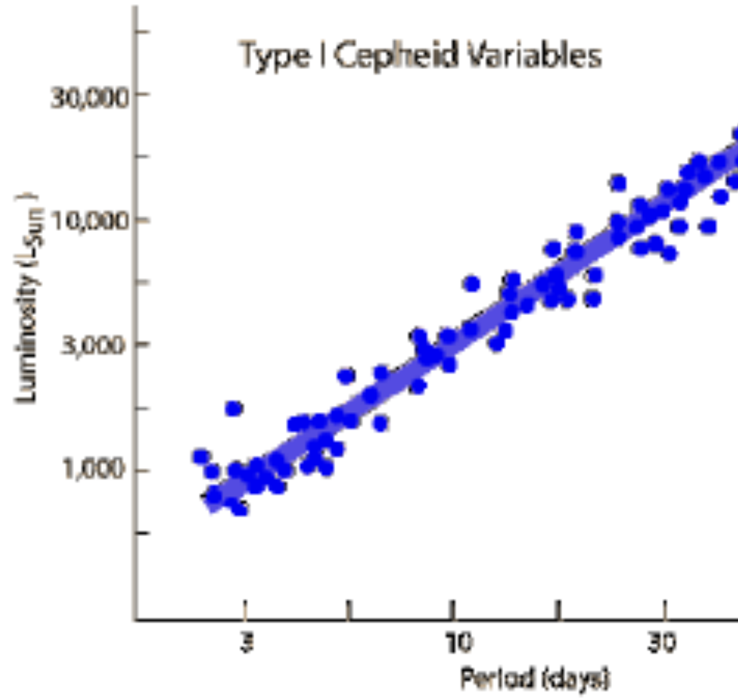
- Observe flux of star or a group of stars (cluster, galaxy)
- Flux[W/m^2] = $L/(4\pi d_L^{\,2})$ with d_L: luminosity distance
- Flux measured integrated over all wavelengths (bolometric), typically blue-violet band (B band)
- Relation between mass and luminosity using M/L of sun as a reference $$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^a$$

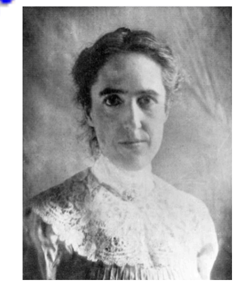


- Object with known emission/absorption lines: can measure z, F to get luminosity
- Objects with known luminosity (standard candles): can measure flux to get d_L

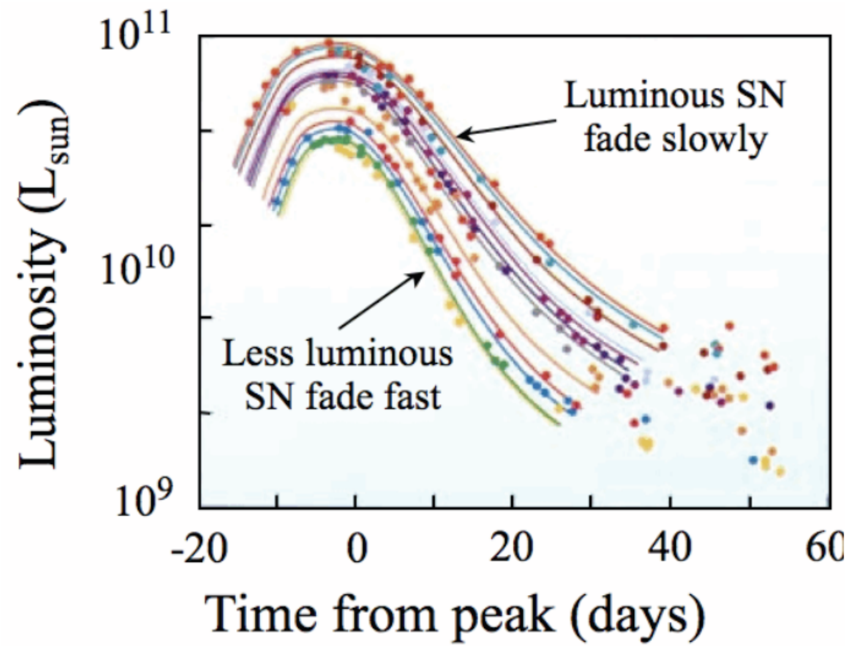
Standard candles

- Cepheid variable stars
  - to ~15Mpc
  - period-luminosity relation (longest period stars have highest mean flux)
  - distances measured to nearby Cepheids (parallax)
  - distance can be extrapolated to further Cepheids by measuring the period
- Type Ia supernovae
  - to ~200 Mpc
  - 10^5 times brighter than Cepheids
  - Peak luminosity is tightly coupled to shape of the light curve





Henrietta Swan Leavitt (1868-1921)



Zwicki's measurements of the Coma cluster

- Used two different methods to estimate the mass

- From mass-luminosity ratio

$L_{Coma,B} = 8 \times 10^{12}\, L_{sun,B}$
$\langle M/L_B \rangle \sim 4 M_{Sun}/L_{sun,B}$
$M_{coma,\star} = 3 \times 10^{13}\, M_{sun}$

- Inferred the total mass from how fast galaxies are moving:
  Equating kinetic and potential energy for steady-state system

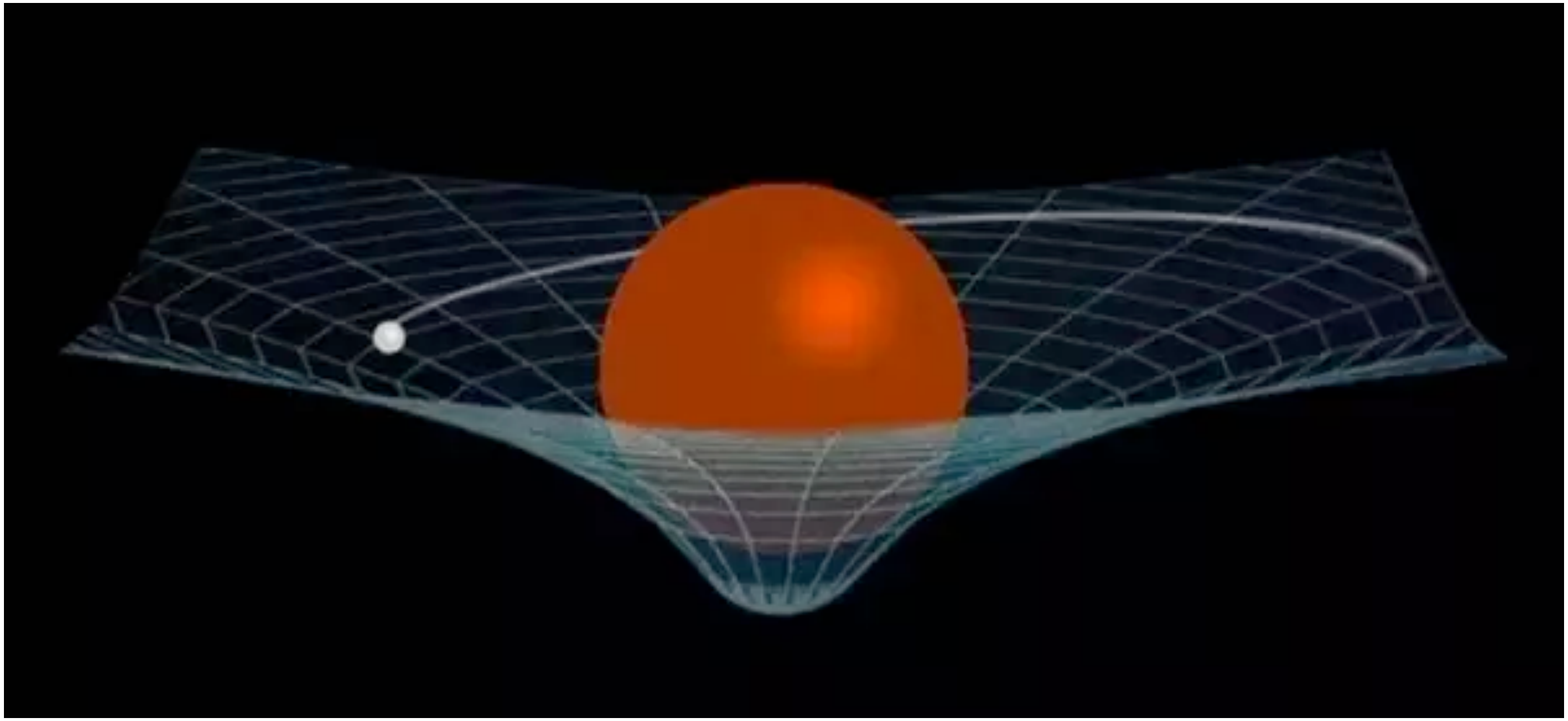
  $M = \langle v^2 \rangle R/(\alpha G)$

  α depends on the way the mass is distributed in the cluster
  v is the mean velocity dispersion
  R radius of the system
  G gravitational constant

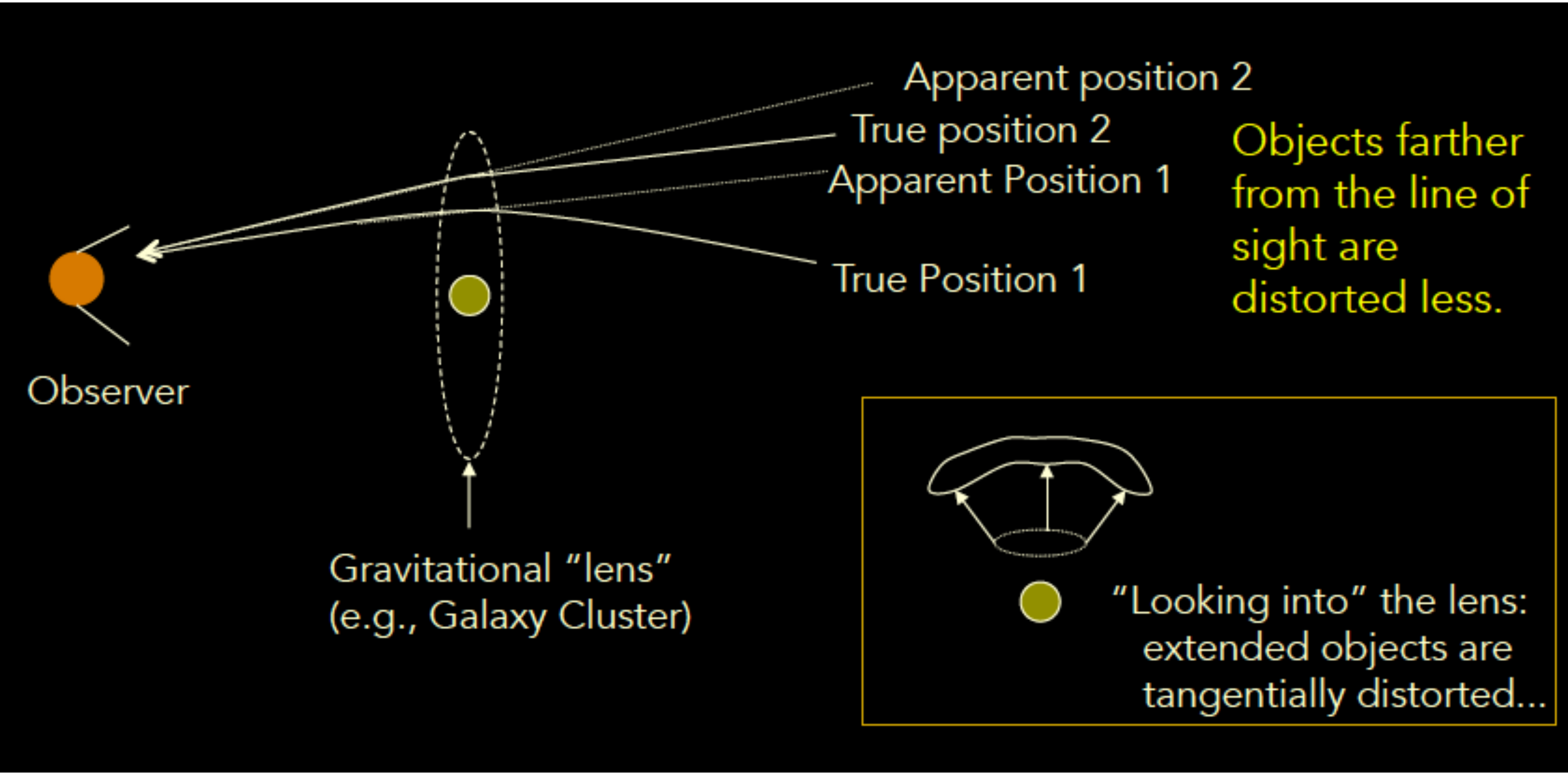
$R_{Coma} \sim 3$ Mpc $\quad M_{coma} = 2 \times 10^{15}\, M_{sun}$

Curved spacetime

- Einstein's theory of general relativity says that energy and matter curve spacetime
- A massive star attracts nearby objects by distorting spacetime
- Everything, including light, moves in this curved spactime
- Dark matter will also have an effect on spacetime curvature



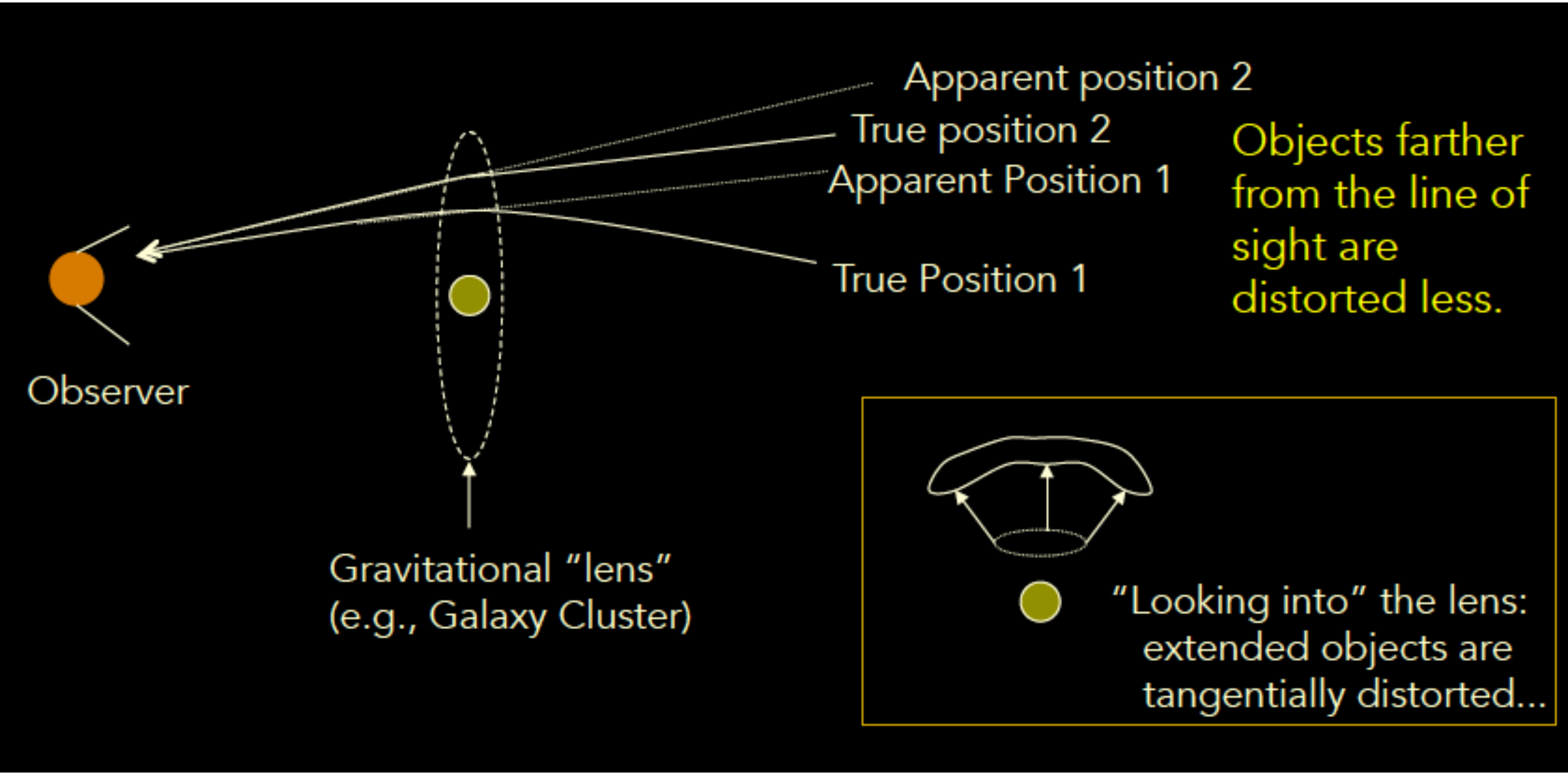
Gravitational lensing



“Seeing” Dark Matter in a Cluster

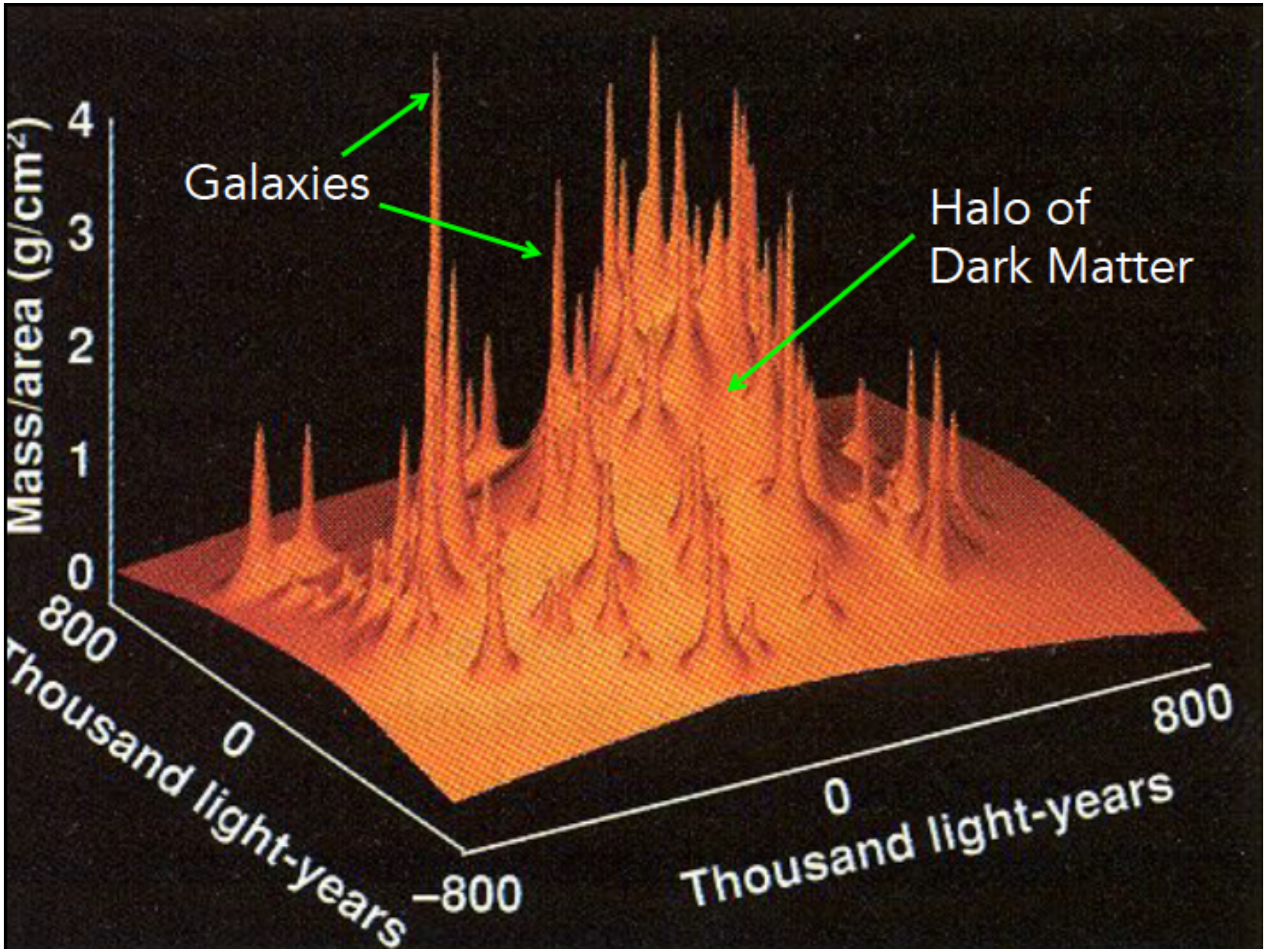
Abell 2218 HST

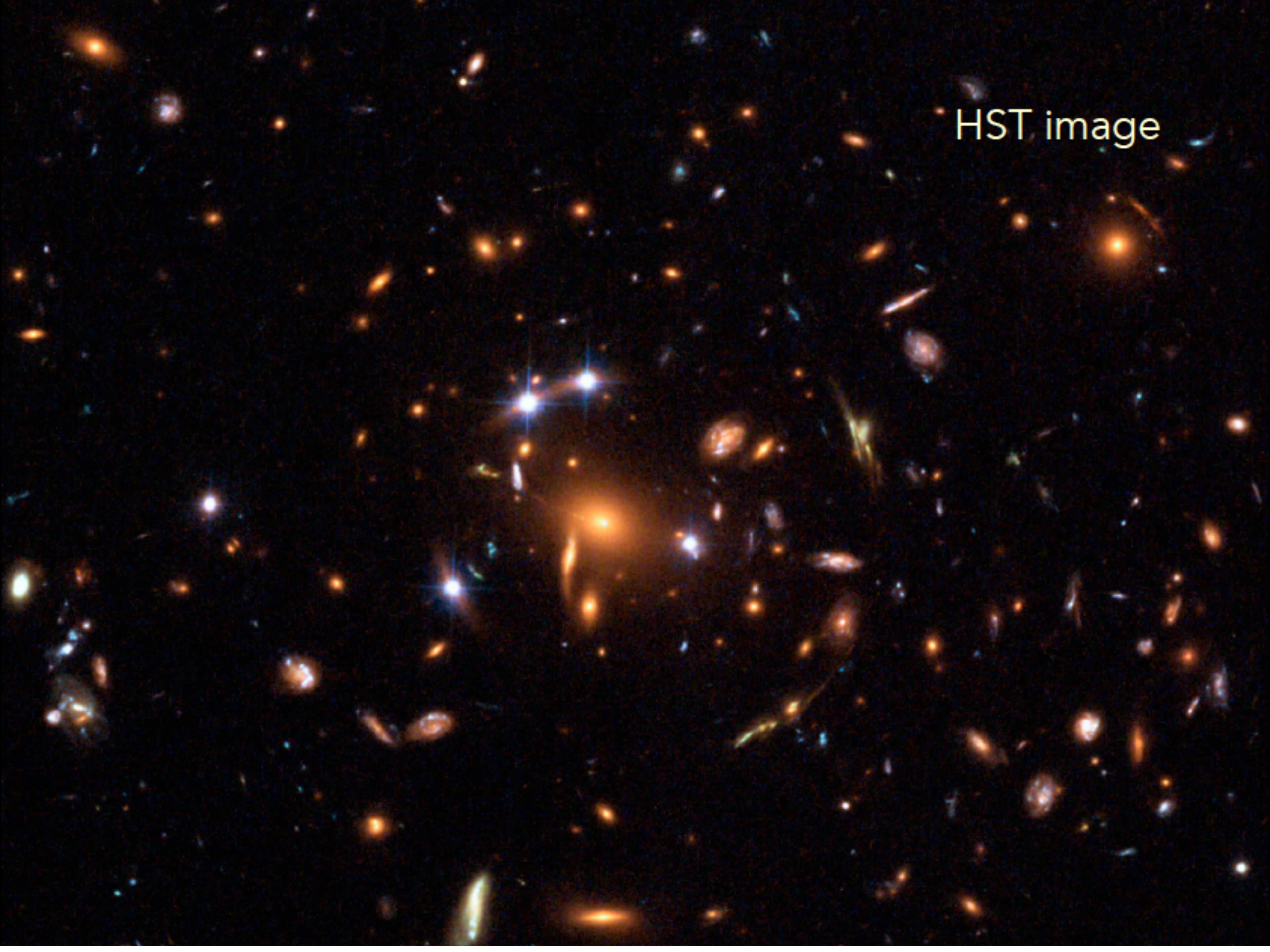
Gravitational lensing

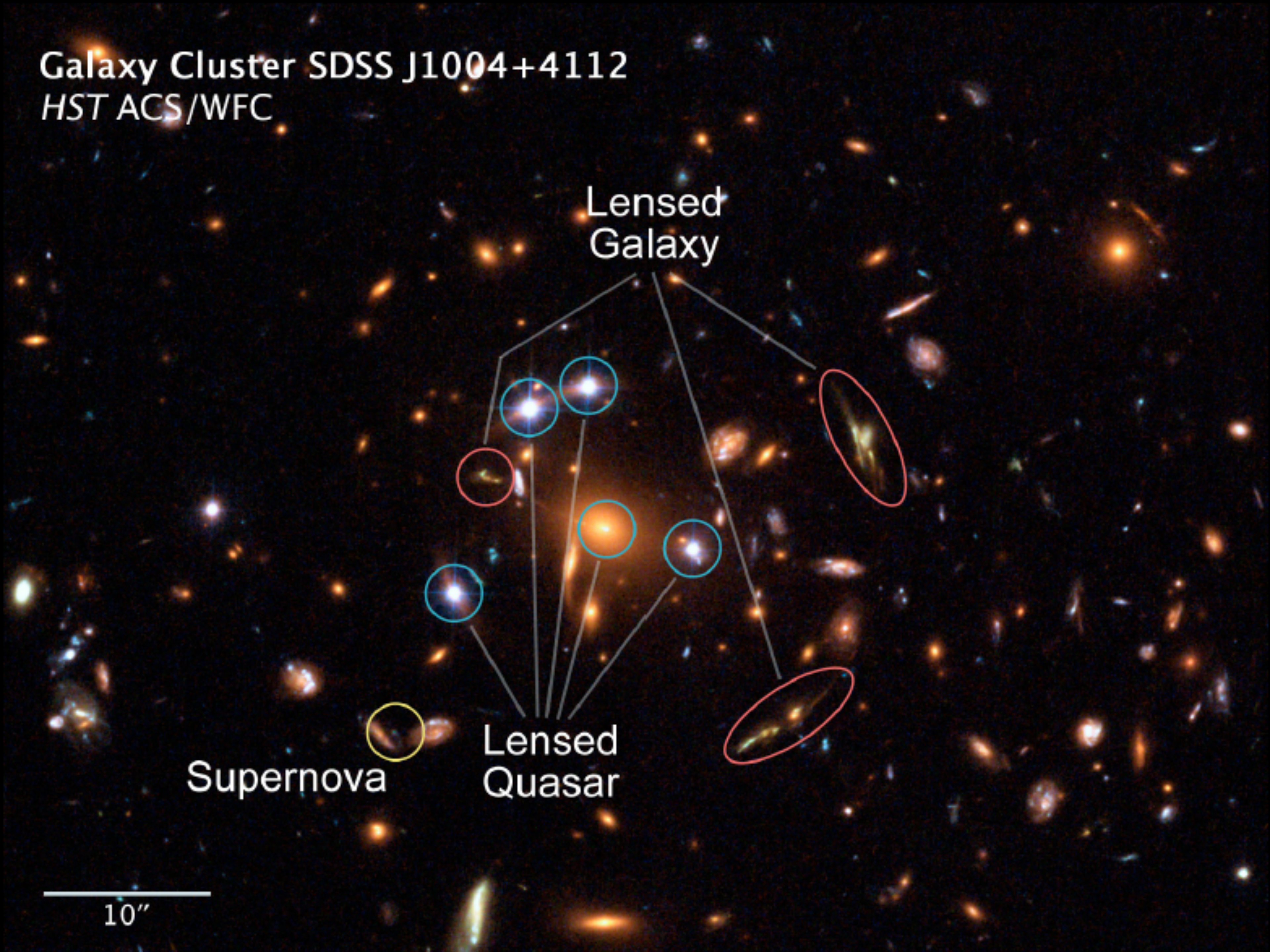


Mass distribution in a cluster of galaxies inferred from gravitational lensing

- Clusters mainly consist of dark matter!




HST image


Galaxy Cluster SDSS J1004+4112
HST ACS/WFC
Lensed
Galaxy
Lensed
Quasar
Supernova
10″

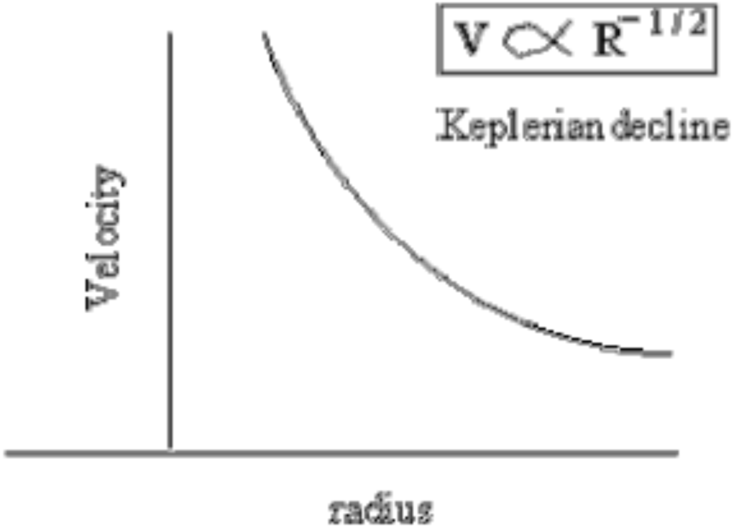
Galactic rotation curves

The rotation curve of a galaxy is the rotational velocity about the center [km/s] plotted as a function of radius [km/s or arc seconds]. The curve, if from true circular velocity, is a tracer of the force (~$1/r^2$) and therefore the mass distribution in a galaxy.

Measurement of radial velocity, distance to each star

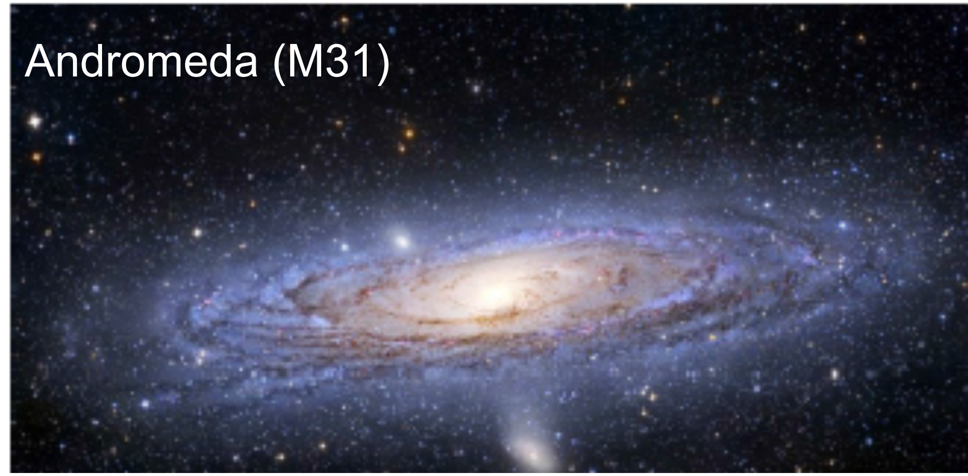
Keplerian rotation: $$\frac{mv_r^2}{r} = G\frac{M_r m}{r^2}$$

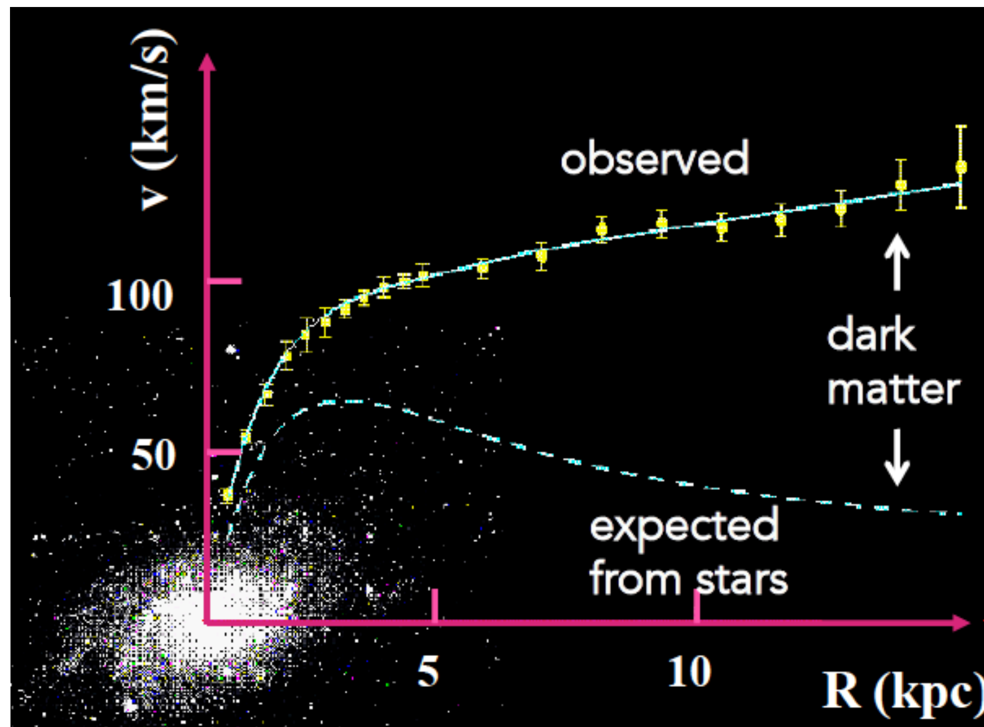
$$\boxed{V \propto R^{-1/2}}$$



Galactic rotation curves

Vera Rubin (1928-2016)



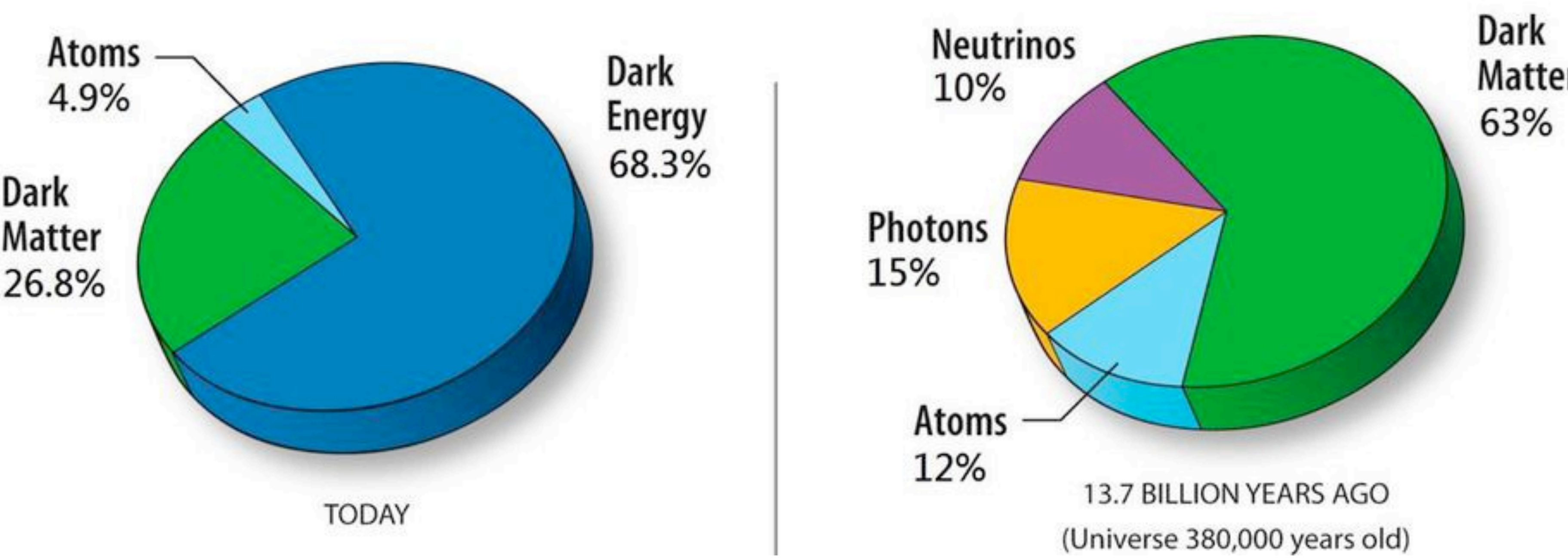


Expected: $v_r \propto \frac{1}{\sqrt{r}}$

Observed: velocity at large radii nearly constant (enclosed mass must increase with radius).

Quantifying dark matter

- Amount of dark matter and evolution predicted from measurements of large scale structure, gravitational lensing, big bang nucleosynthesis and cosmic microwave background
- About 84% of matter in our universe is dark matter



- What is dark matter made of? Topic of upcoming lectures

The expanding universe

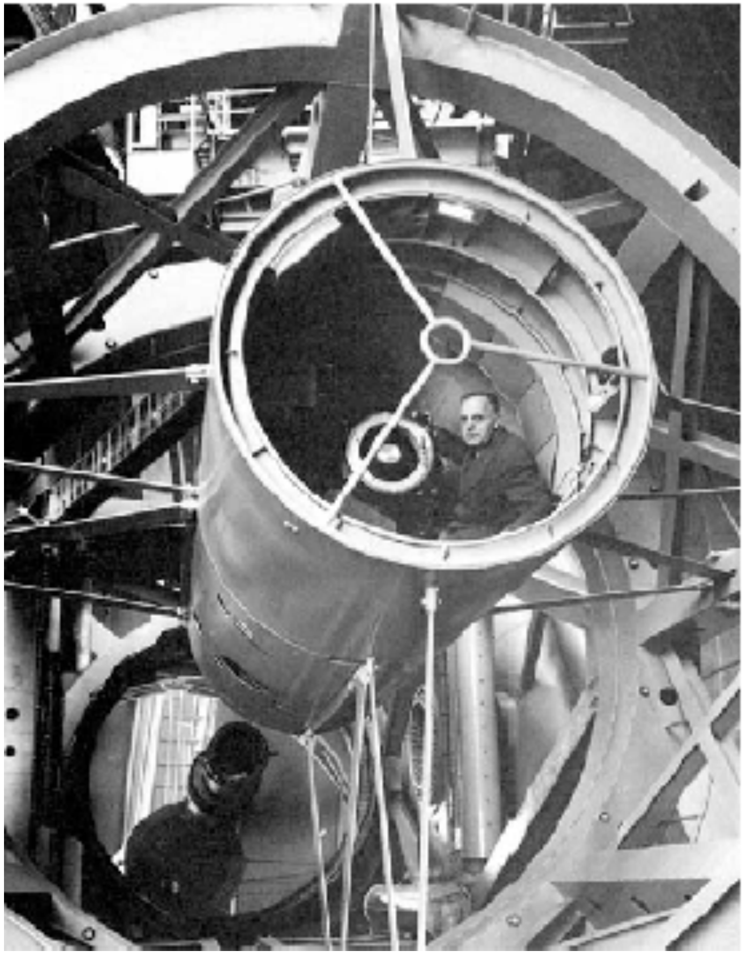
- 1929: Edwin Hubble observes spectral lines from distant galaxies
- Lines shifted towards red end of the spectrum (Doppler effect). Amount of shift depends on the brightness, hence on the distance.
  - measured velocity of galaxy recession

$$\lambda' = \lambda\sqrt{\frac{1+\beta}{1-\beta}} = \lambda(1+z)$$

where $\beta = \frac{v}{c}$, $z = \Delta\lambda/\lambda$ – redshift

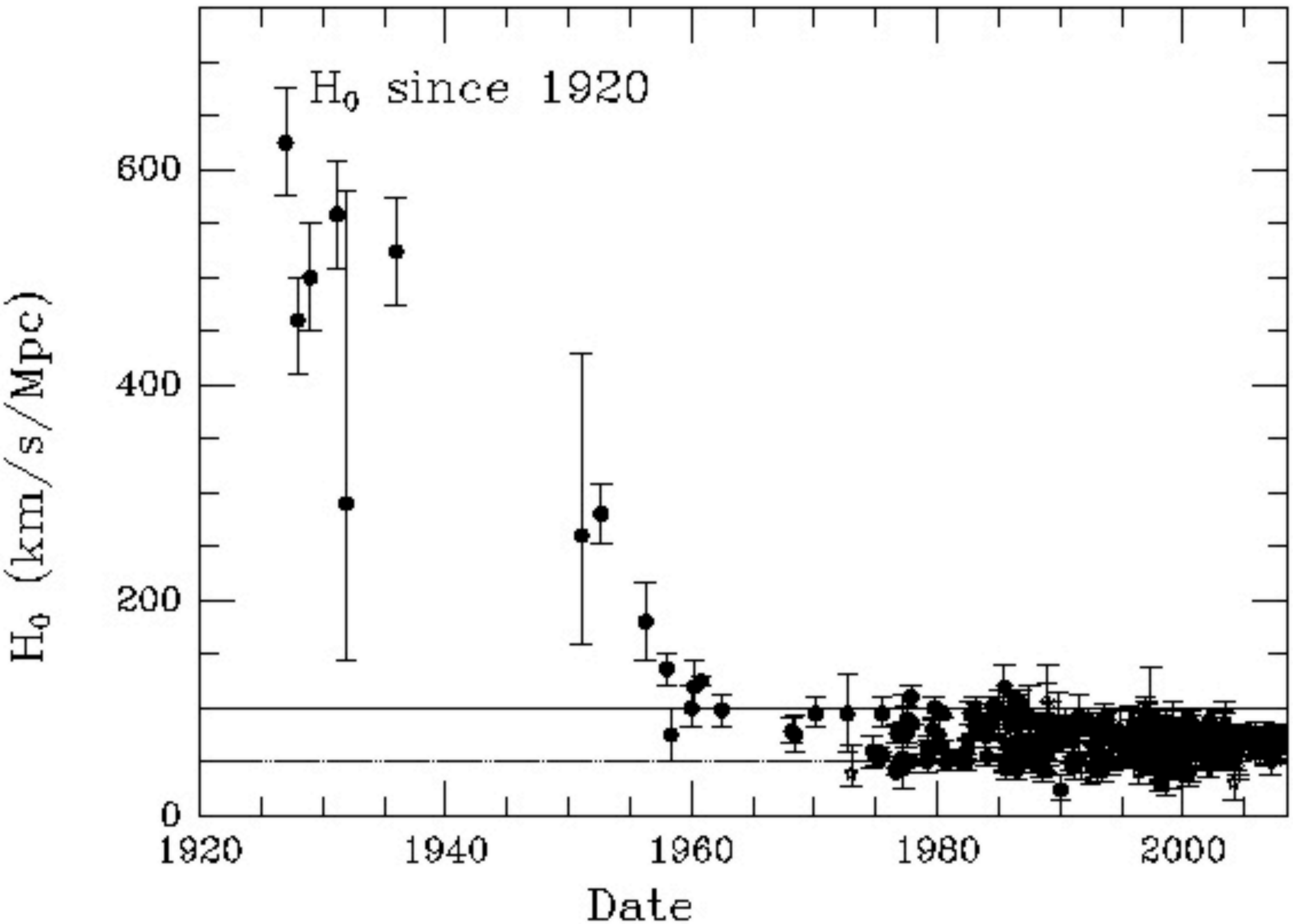
- Discovered relation between velocity and distance

$v = H_0 D$ → Expansion predicted by Einstein's GR is real



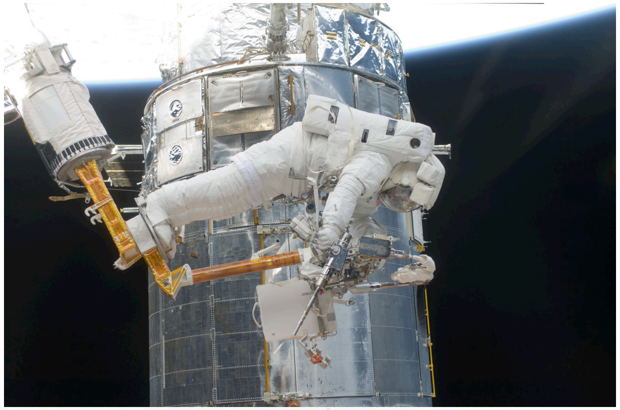
Edwin Hubble (1889-1953)

Evolution of the Hubble constant



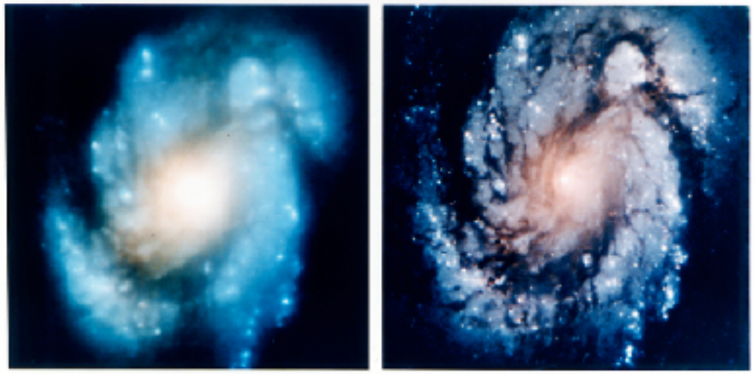
The Hubble space telescope (HST)

- Launch into orbit in the early 1990
- Features a 2.4m diameter mirror
- Problem in the mirror production
  - mirror too flat at the perimeter by 2.2µm (tolerance 10nm)
  - introducing spherical aberration (light from point sources spread out over radius > 1arcsec, instead of specified < 0.1 arcsec)



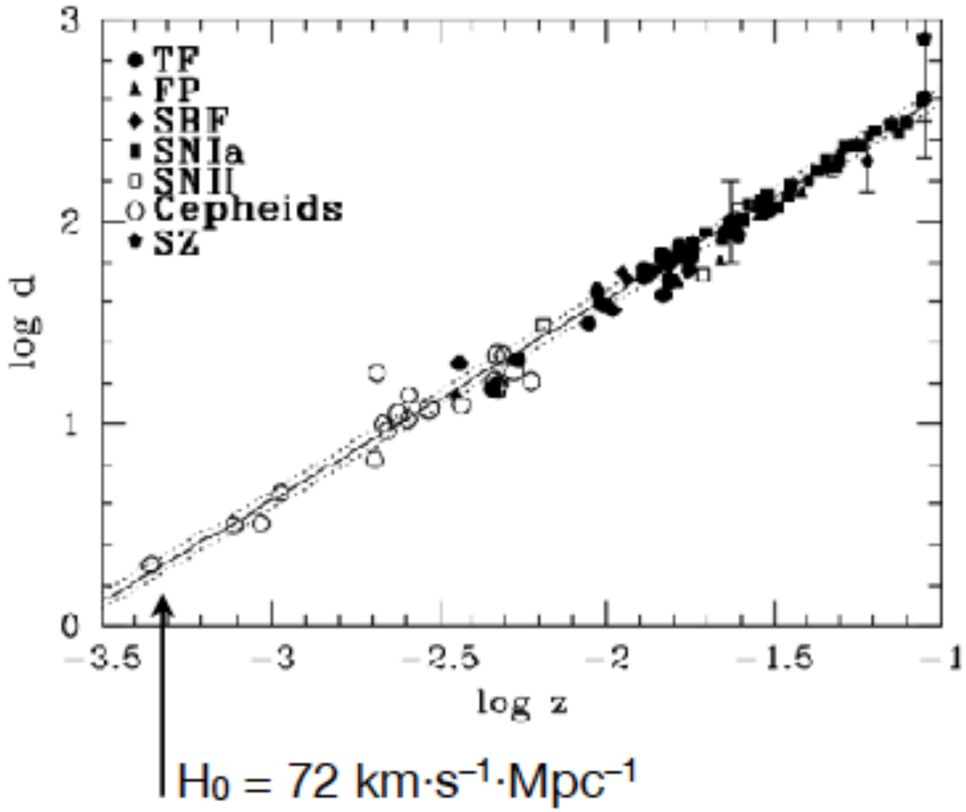
- Designed new optical components with the same error, but in opposite sense
- Installed by spaceshuttle astronauts

Spiral galaxy before and after corrective optics



The Hubble space telescope (HST)

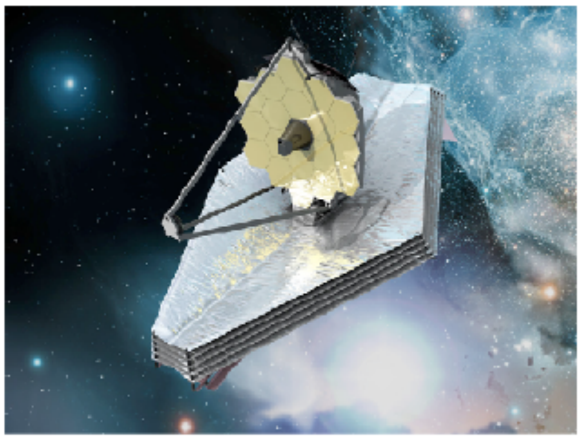
- Direct measurement of Hubble constant
  - W.L. Freedman et al., ApJ 553, 47 (2001)

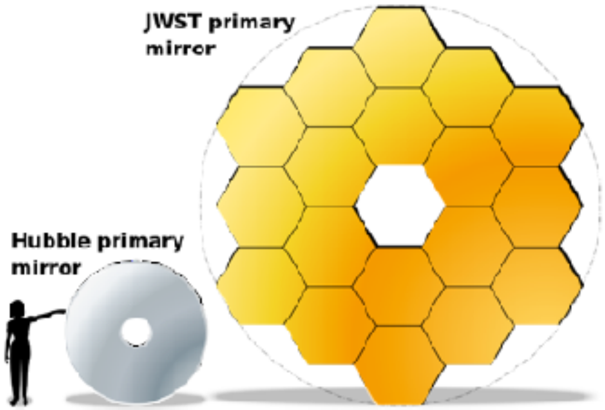


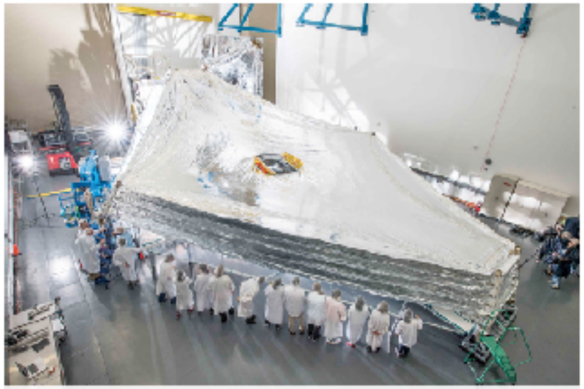
- Consistent with constant "Hubble flow" at low z
- At high z, H_0 is not constant with time, was smaller in the distant past (more later)

Next generation space telescope

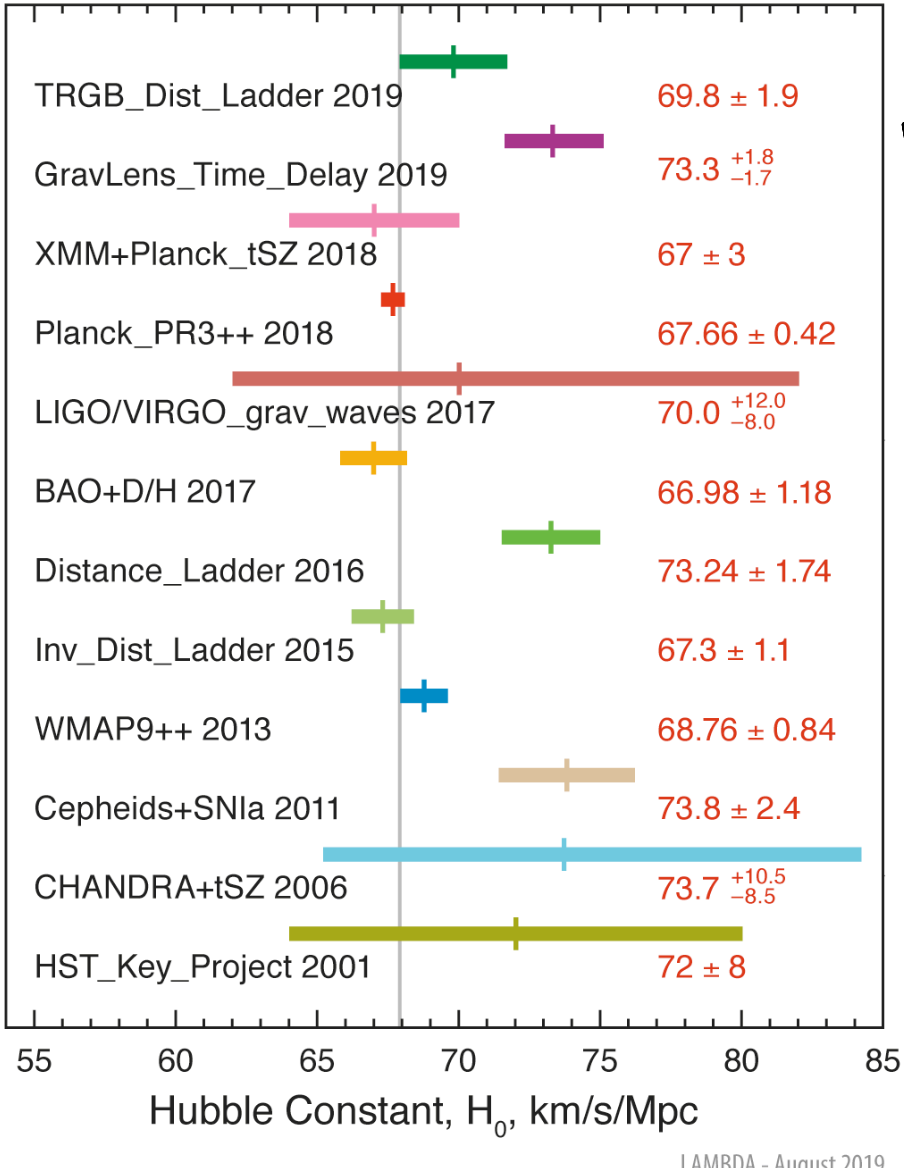
- HST still operational
  - Final service mission completed in 2009
- Successor: James Webb Space Telescope
  - to be launched in 2021
  - Primary mirror is 6.5m diameter gold-plated beryllium reflector





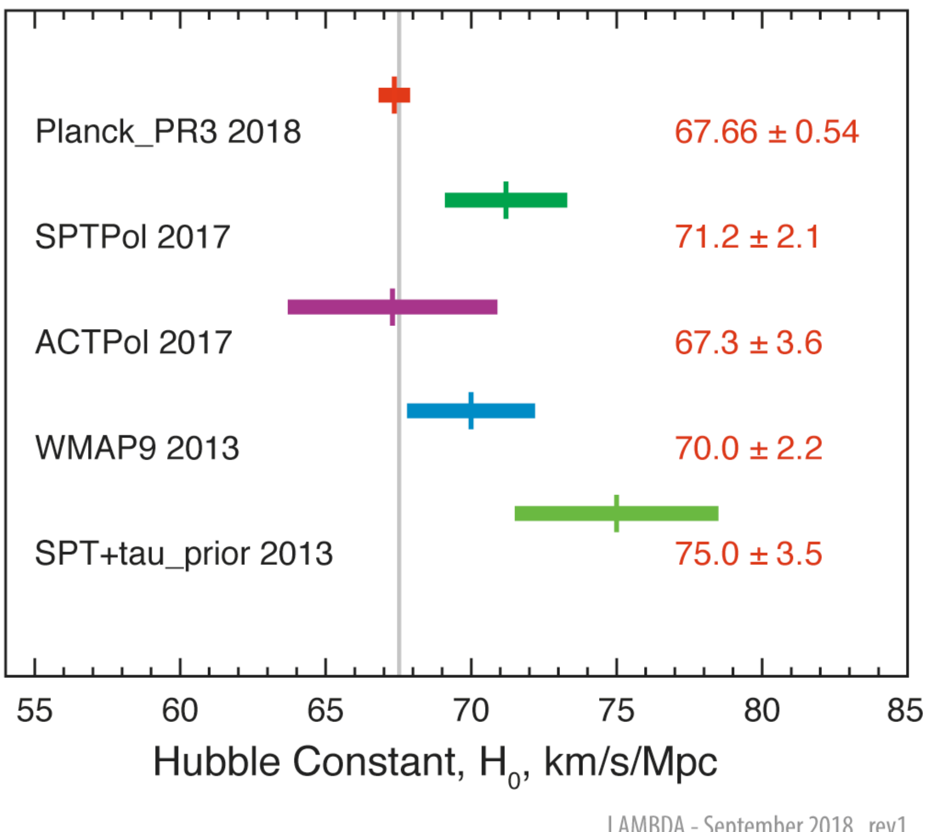


The value of the Hubble constant



Measurements of distances and velocity based on observation of far away objects (supernovae, Cepheid variables, GW sources)

Measurements using CMB power spectrum



Cosmic dynamics

- Cosmological principal: On a sufficiently large scale the universe is homogeneous and isotropic
  - no direction or location is preferred over any other
  - universe appears the same to every observer, independent of where they are
- On those scales gravitation is the only relevant force

→ System described by General Relativity

→ Spacetime curvature defined by matter density

Friedmann equation

- Dynamics following from Einstein's field equation described by Friedmann equation
  - assuming isotropic and homogeneous distribution of matter and radiation behaving like a perfect frictionless fluid

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_{tot} - \frac{k}{R^2} + \frac{1}{3}\Lambda$$

where R(t) is the so-called scale parameter related to the distance of an object via

D(t) = r R(t) with r: co-moving coordinate (coordinate extending with expansion)

The normalization is chosen such that $R(t_0) = 1$ (t_0: today)

ρ_{tot} total density of matter, radiation and vacuum energy

k curvature

Λ cosmological constant

Friedmann equation

- Friedman equation gives evolution of the universe depending on energy densities. The model is characterized by these quantities

1) Expansion rate (Hubble constant)

$$H(t)^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_{tot} - \frac{k}{R^2} + \frac{1}{3}\Lambda$$

2) Curvature parameter k (=+1,0,-1 for closed, flat, open)
3) The average density of the universe ρ_0 and the density parameter Ω_0

$$\Omega_0 = \frac{\rho_0}{\rho_c} = \frac{8\pi G}{3H_0^2}\rho_0$$

4) The cosmological constant Λ and the density parameter Ω_c

$$\Omega_\Lambda = \frac{\Lambda}{\Lambda_c} = \frac{\Lambda}{3H_0^2}$$

Friedmann equation

$$\Omega_R + \Omega_M + \Omega_\Lambda + \Omega_k = 1$$

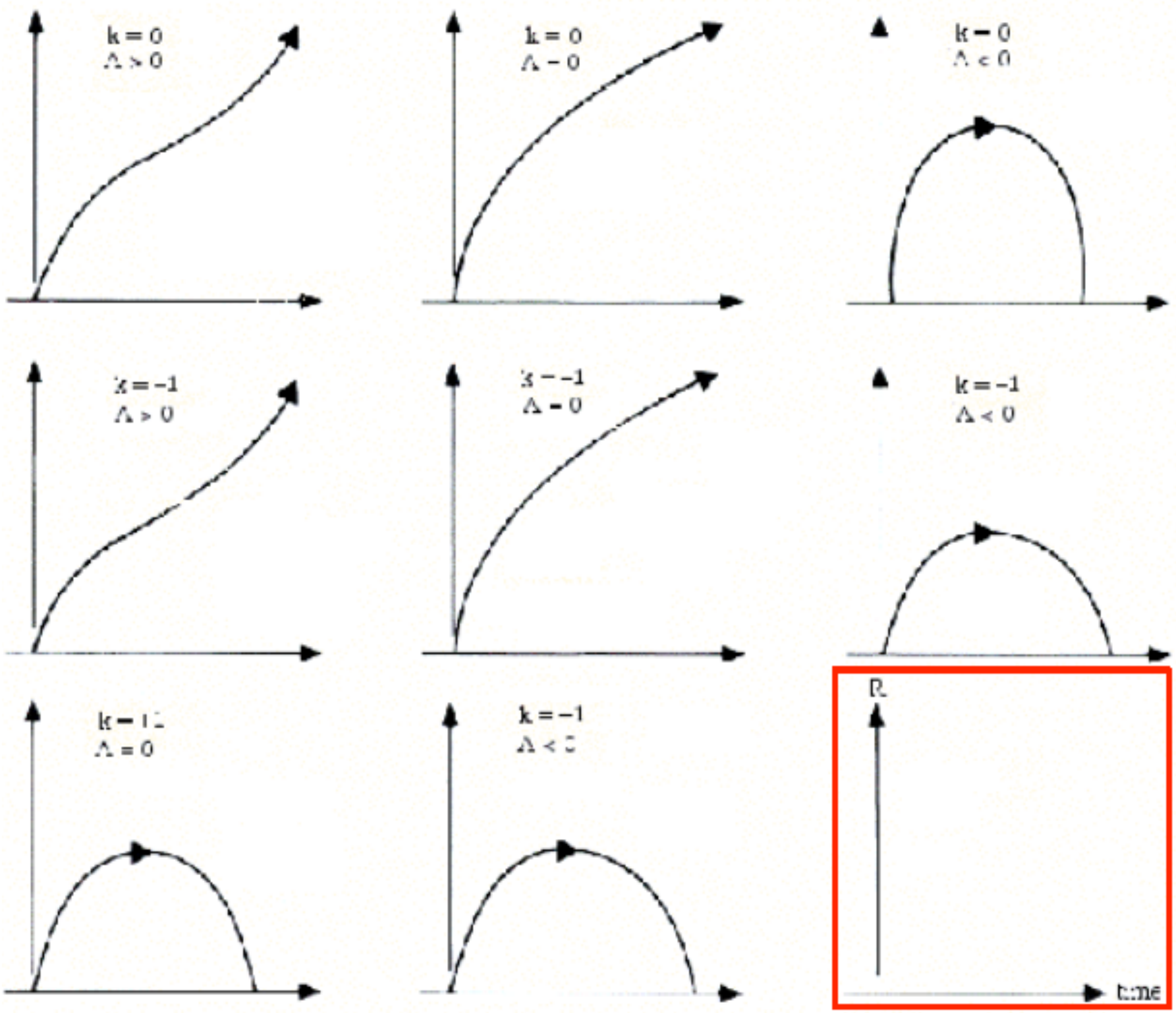
Ω_R – radiation density
Ω_M – non-relativistic matter density (baryonic + dark)
Ω_Λ – cosmological constant (vacuum density)
Ω_k – spatial curvature density

- At the present time:

- Ω_R is negligible compared to $\Omega_M = 0.308 \pm 0.012$
- Luminous baryonic matter is $\Omega_{lum} = 0.01$
- Spatial curvature very close to zero: $|\Omega_k| < 0.005$
- Major contribution from $\Omega_\Lambda \rightarrow$ related to dark energy

Friedmann equation

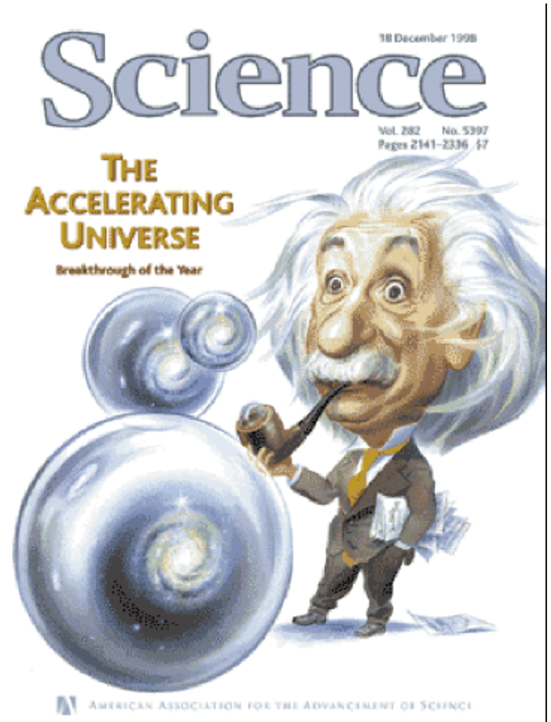
- Evolution of the size of the universe depending on curvature and cosmological constant



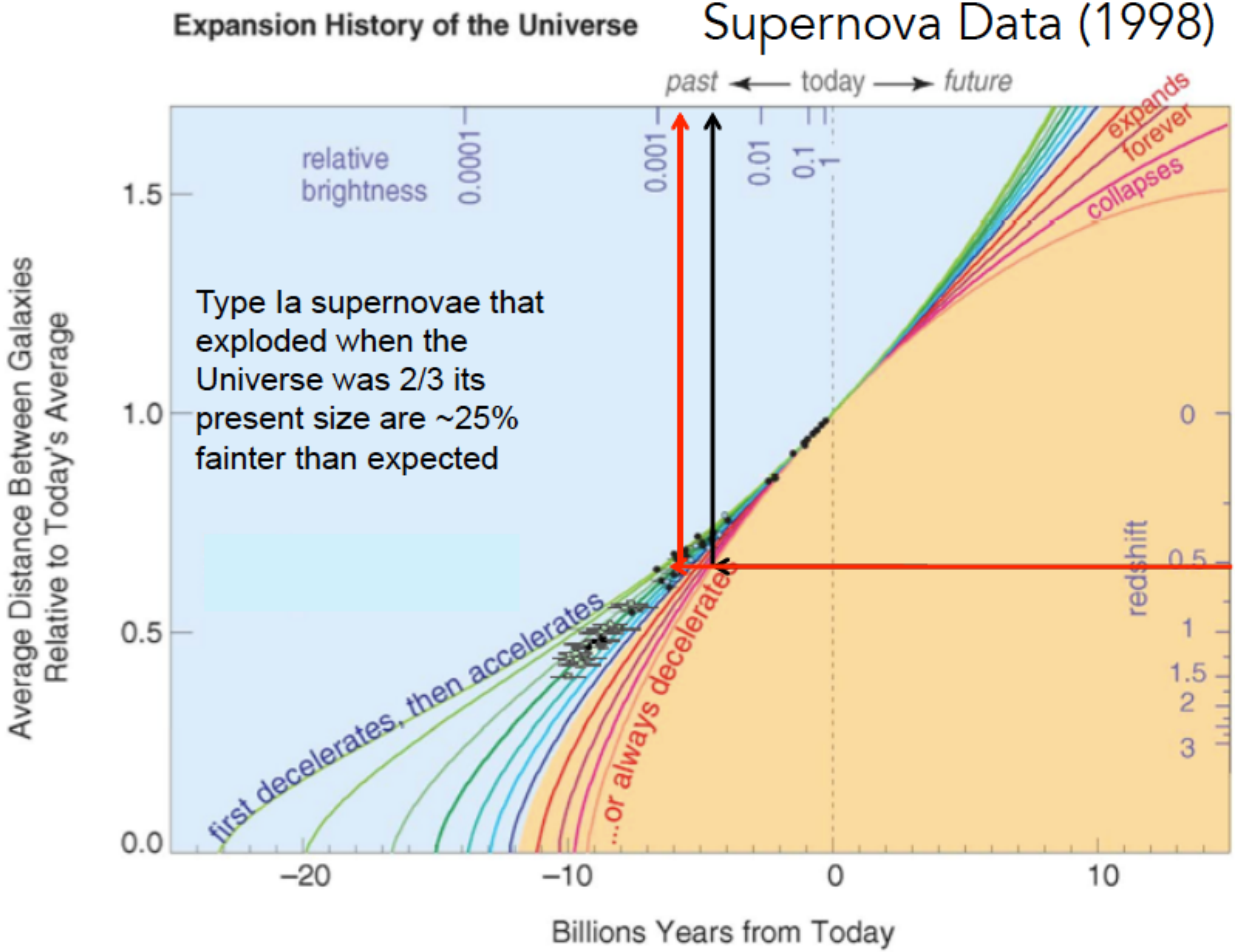
Does the expansion of the universe change over time?

- From gravity: everything in the universe attracts everything else. Expect that the expansion should slow down over time.

- Instead discovered in 1998 that the expansion of the universe is speeding up
- Nobel prize in 2011 for Perlmutter, Schmidt and Riess (Supernova Cosmology Project and High-z Supernova Search Team)



Supernova Data (1998)



Evolution of the universe

Basic effect: Competition between equilibrium (thermal, kinetic, chemical) and expansion

- State of equilibrium described by Γ: rate of reactions
- Expansion described by H: Hubble constant

- As long as $\Gamma/H > 1$: interactions between particles strive towards equilibrium
- As the temperature decreases → Γ decreases
- At some point $\Gamma/H < 1$ → Deviation from equilibrium: "freezing" of reactions

→ Today's abundances are very close to the primordial abundances at the time of freezing

Expansion of the universe

- The vacuum is not empty → quantum fluctuations produce the universe

$t=10^{-43}$ s: PLANCK TIME

Quantum limit on general relativity:

We do not know anything before this time

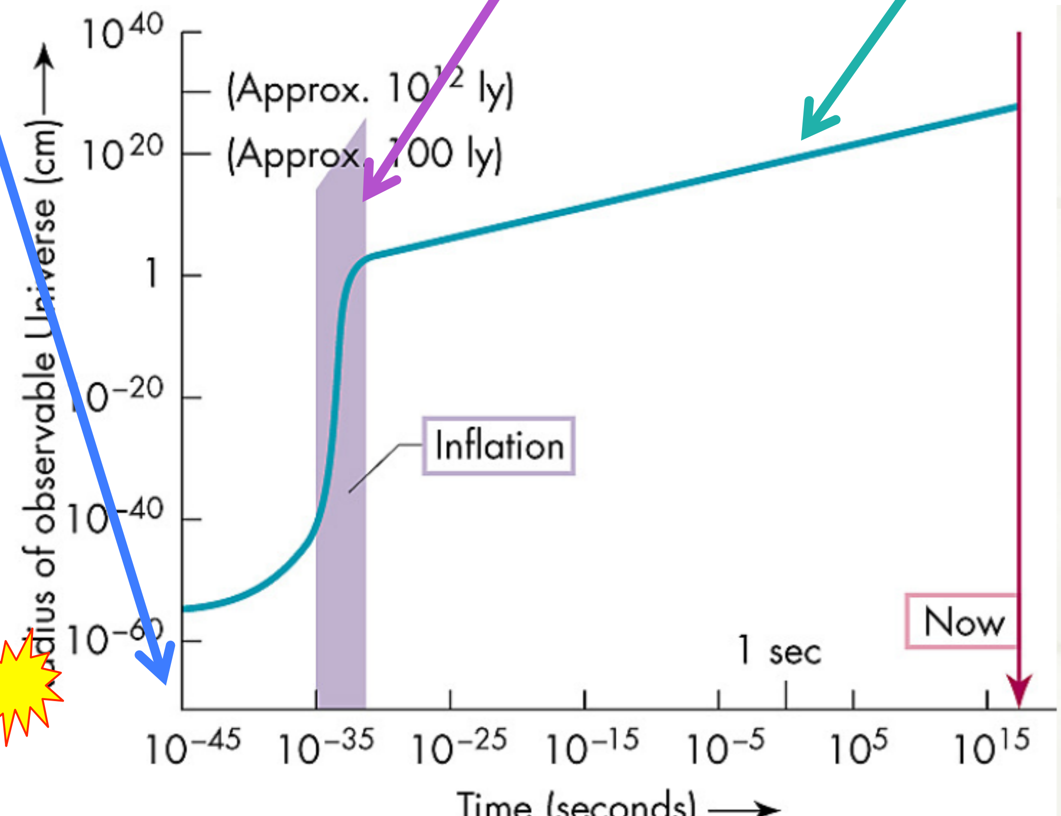
$t=10^{-37}$ s: INFLATION

Period of rapid exponential expansion

$t > 10^{-35}$ s:

Structure formation

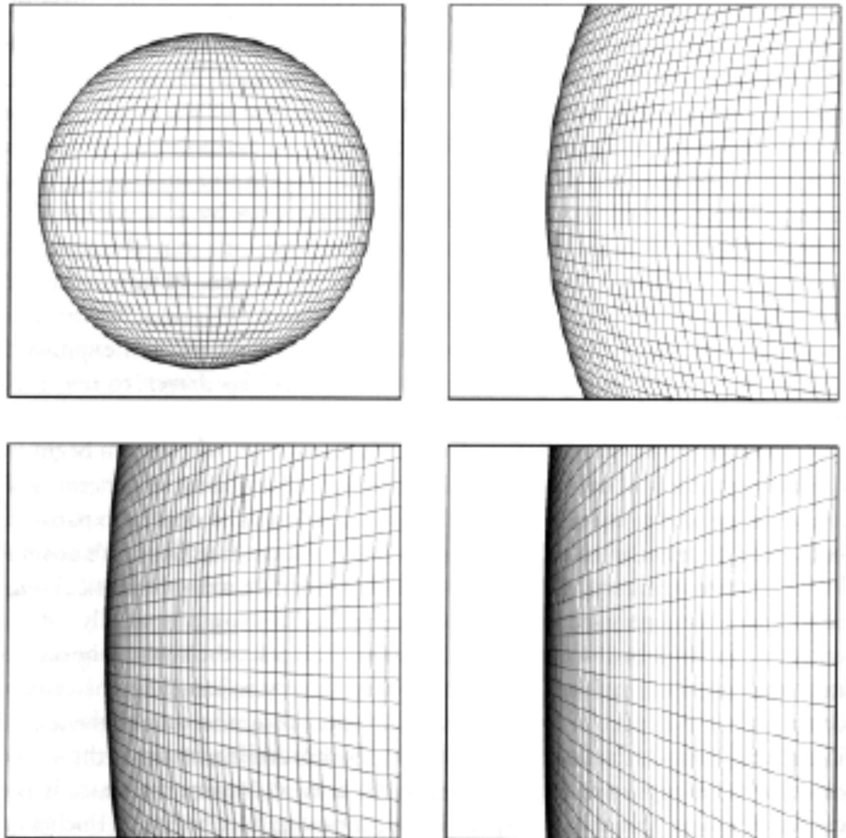
Expansion continues at lower rate



t=0
The BIG BANG

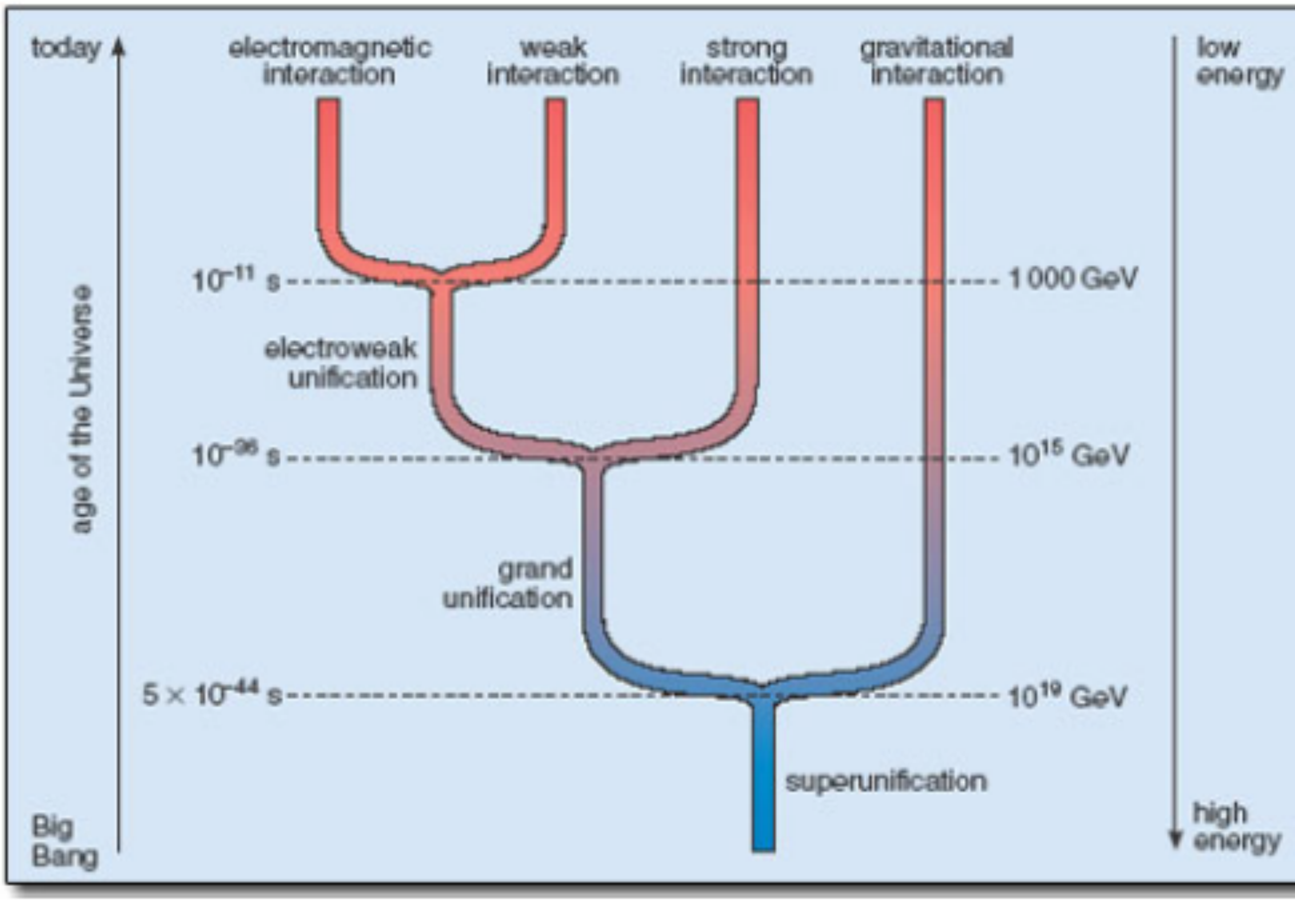
Inflation

- During inflation the universe expanded from a size of about 10^{-40} cm to a size of about 1cm
- The universe ended up much bigger than the observable universe at that time
  - d= tc = $(10^{-35}s)(3x10^{8}m/s) \sim 3x10^{-27}$ m
- What was curved, now is flat
  - Space-time now is flat
  - two parallel photons remain parallel
- What was small, now is big
  - quantum fluctuations became large energy/density fluctuations
  - Act as seeds for large scale structure formation: matter would condense in these fluctuations producing the clusters of galaxies and voids that we observe today



Unification of forces

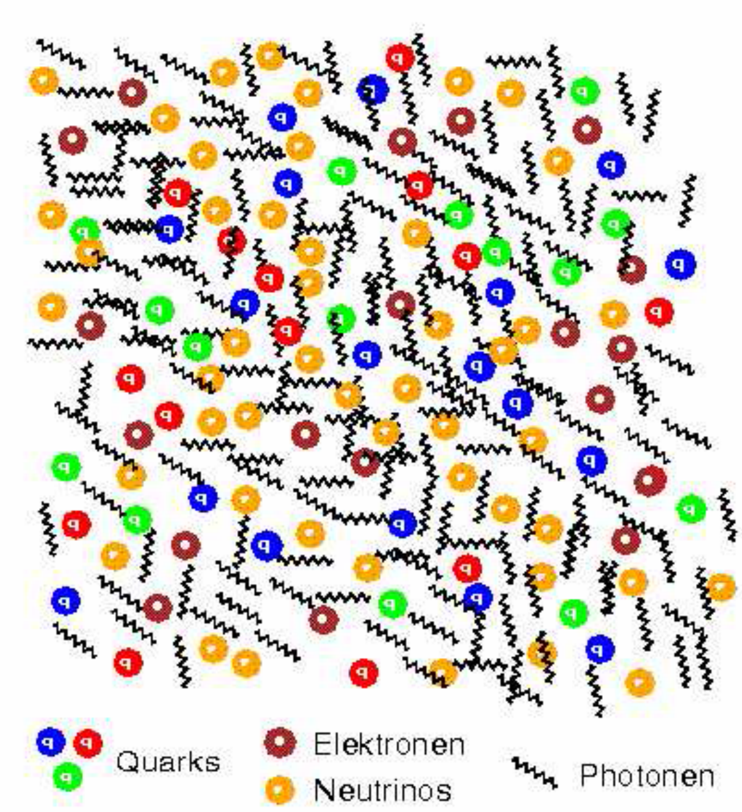
- Early in the history of the universe it was not possible to distinguish between the forces
- But we still don't have any prove of the unification of electroweak and strong force, much less of the unification with gravity...



Primordial soup

- $t=10^{-35}$ s: Inflation ends
  - Inflation field is unstable, it "decays" ending inflation
  - Energy driving inflation is dumped into matter and radiation in the early universe, forming a hot, dense "primordial soup" ("Ursuppe")

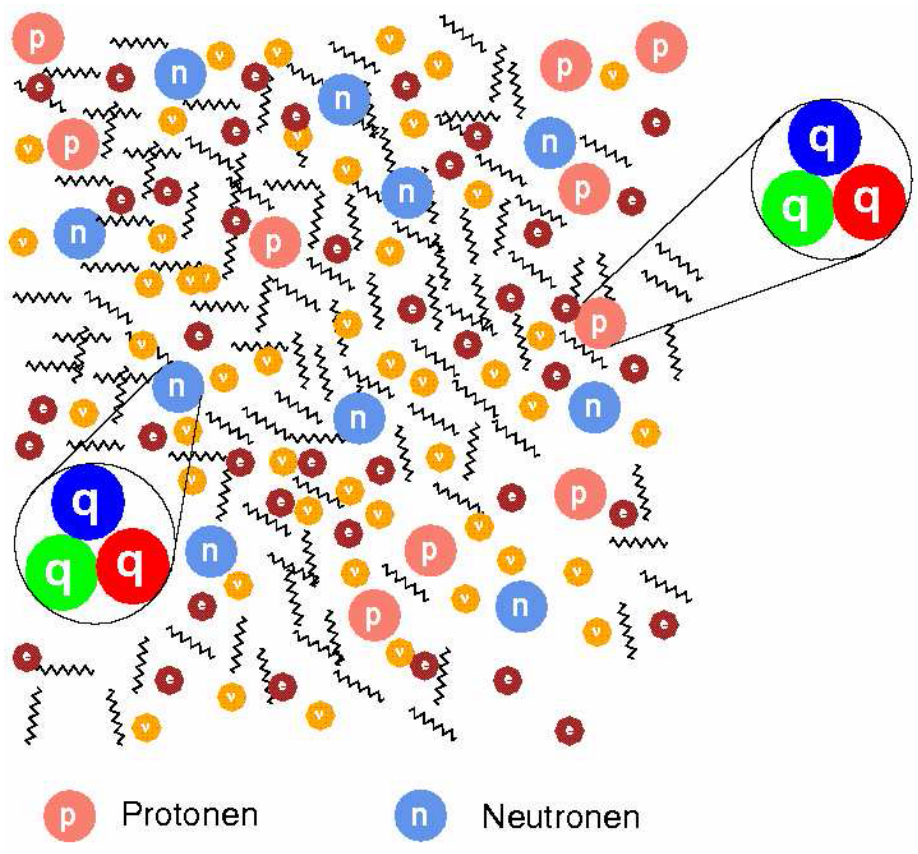
- $t=10^{-35}$ s to 10^{-5} s or $T=10^{28}$ K to 10^{15} K (Temperatures fall with $1/\sqrt{t}$)
  Quark-gluon-plasma
  - Composed of elementary particles (quarks, gluons, W, Z, photons, neutrinos)
  - Matter and radiation components are in thermal equilibrium and undergo continuous interactions
  - Universe keeps expanding, but at lower rate ~80km/s/Mpc



Baryogenesis

- $t=10^{-5}$ s, $T= 10^{13}$ K thermal energy about 1 GeV
- This corresponds roughly to the rest mass of the proton and neutron. As the temperature keeps falling, nucleons can no longer be generated/destroyed from radiation field

→ Nucleons form (baryogenesis)



- As long as $T>10^{10}$ K:
- Protons and neutrons are in thermal equilibrium with a relative abundance of

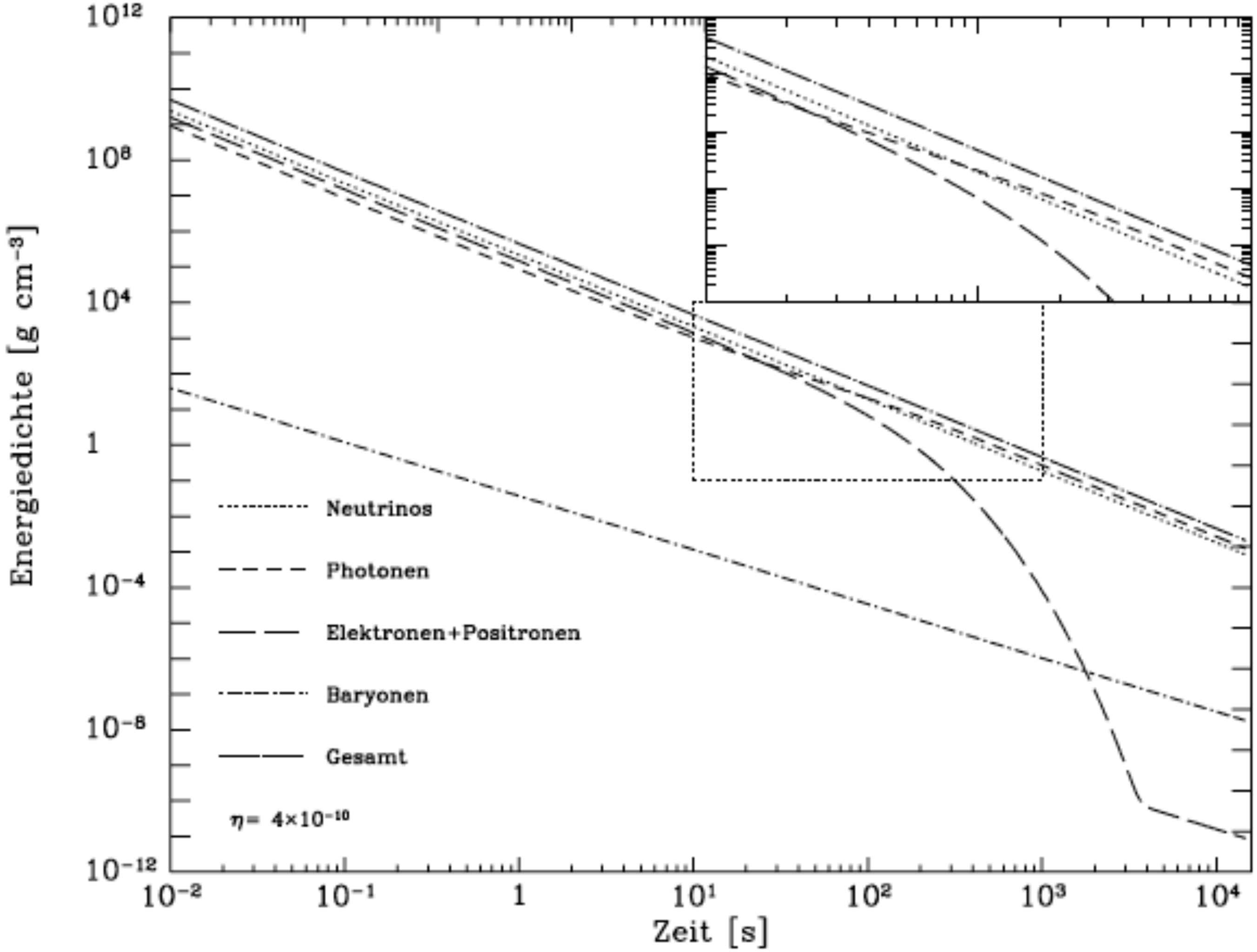
$$\frac{N_n}{N_p} = \exp\left[-c^2(m_n - m_p)/kT\right]$$

~1

Freeze-out of weak interaction

- t=1s, T=10^{10} K
- Weak interaction freezes
- No more transformations among leptons
- Neutrinos decouple
- Electron-positron annihilation
- Neutrons and protons leave thermal equilibrium at an abundance of about 1:6

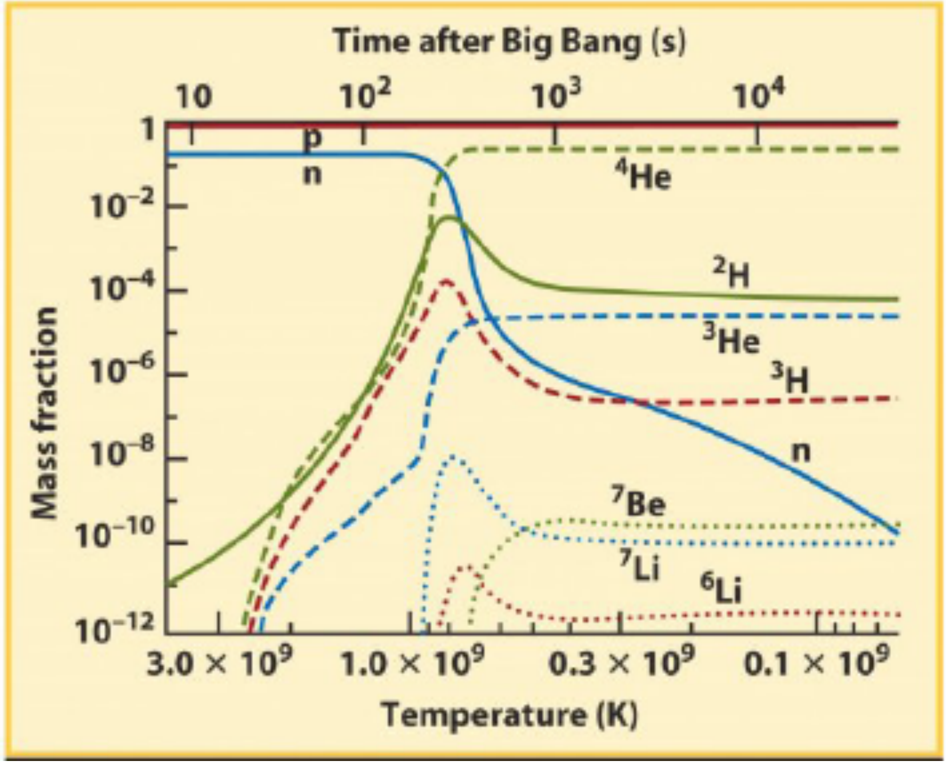
Energy densities



- Note:
- Annihilation of e^+e^- leads to increase in photon energy density
- Different slope of baryons compared to relativistic particles → predicting matter dominance at later times

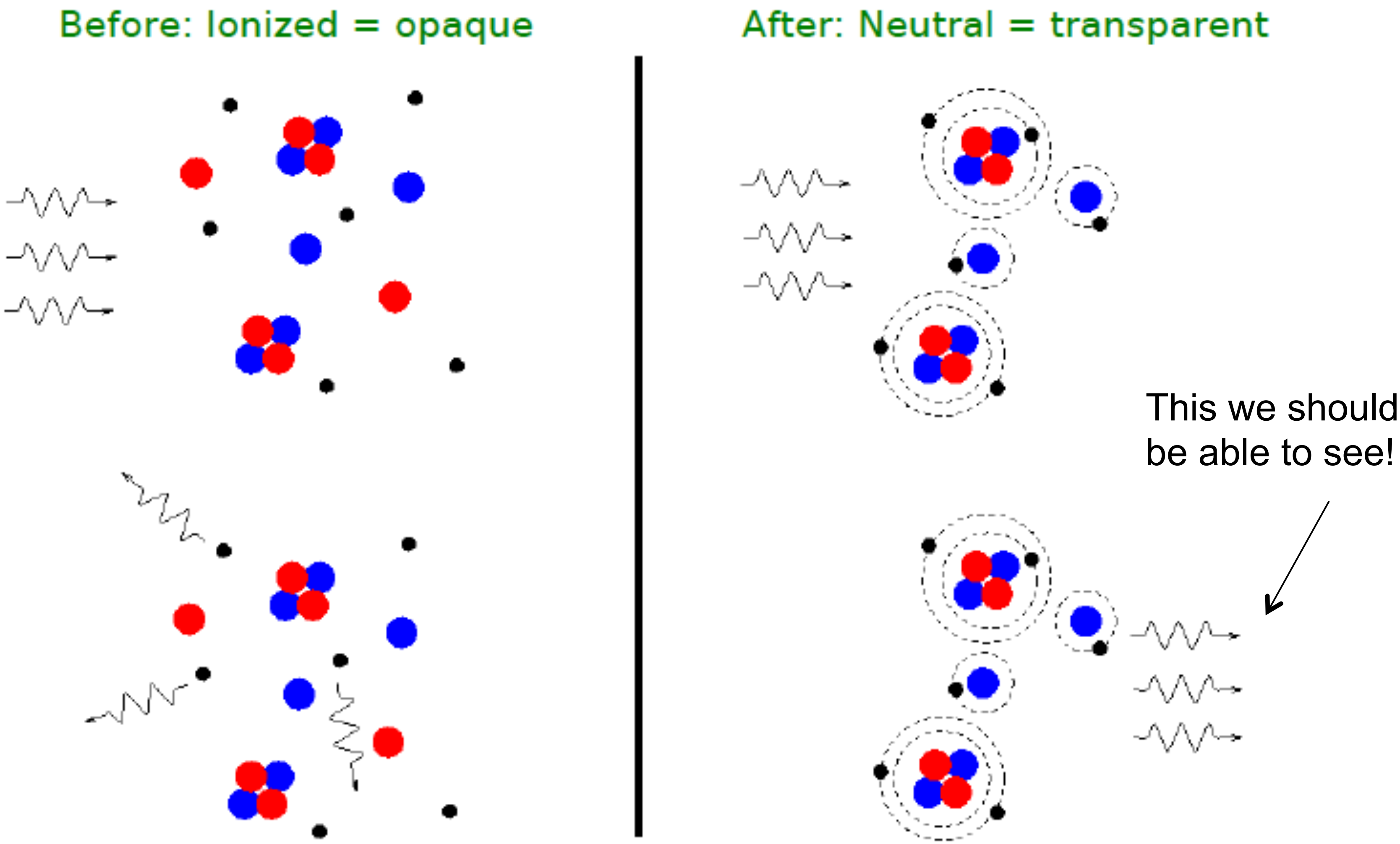
Nucleosynthesis

- t=3min, E = 0.1MeV:
- Cool enough for light nuclei to form: Deuterium, He, Li, Be
- No heavier elements than Be could form
- The abundance of H and He is set by the temperature and density of normal matter between 3 and 30min after the Big Bang:
  - H~75%, He~25%
- Photons are too energetic to allow neutral atoms to form
- Electrons are not bound into atoms → everything is ionized
- Light cannot travel through ionized gas → the universe is opaque and its blackbody radiation is trapped



Transparent universe

- t=400'000 years, T=3000K
- Neutral atoms can form → universe becomes transparent

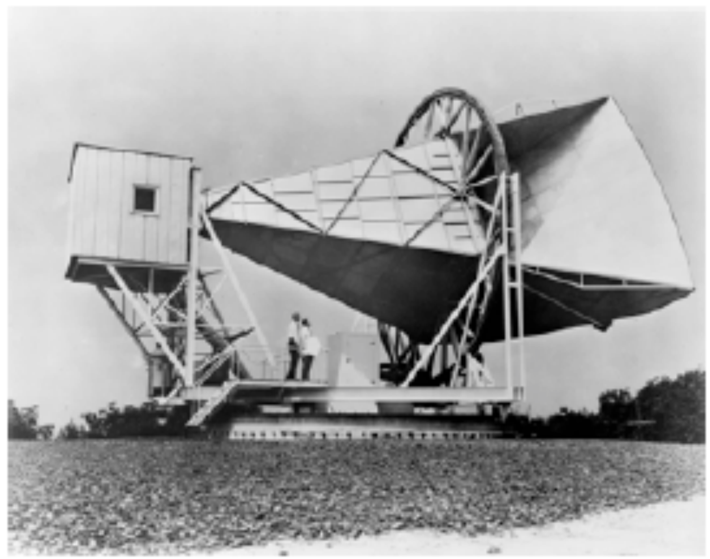


Cosmic Microwave background (CMB)

- Expect CMB with temperature of ~2.7K (due to cooling and redshift) → discovered in 1964

Nobel Prize 1978

· Arno Penzias, Robert Wilson
"for their discovery of cosmic microwave background"

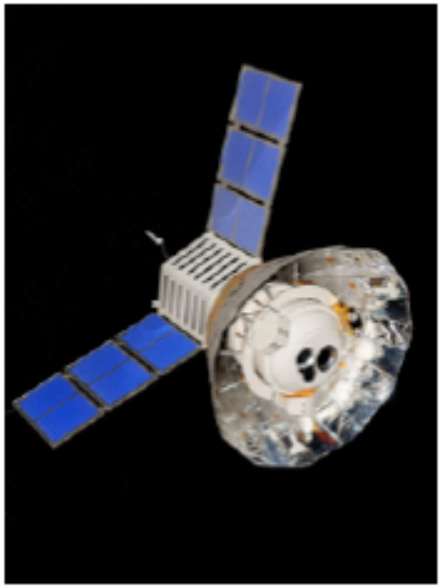


the Holmdel Horn Antenna

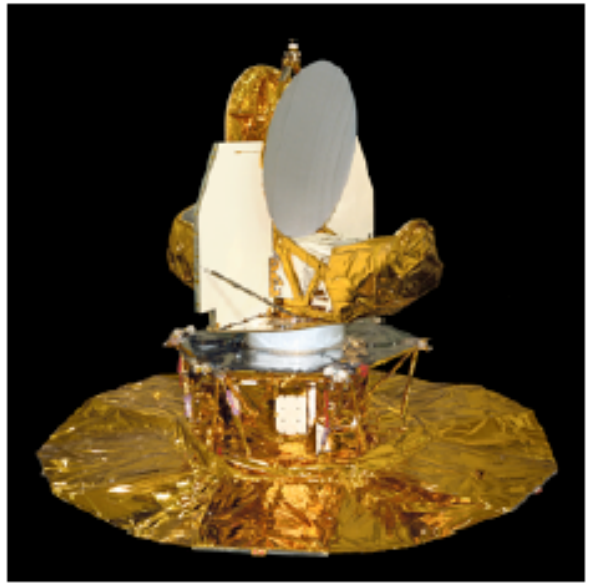
· The mysterious noise of unknown origin was first thought to be interference caused by pigeon droppings on the antenna equipment

Cosmic Microwave background (CMB)

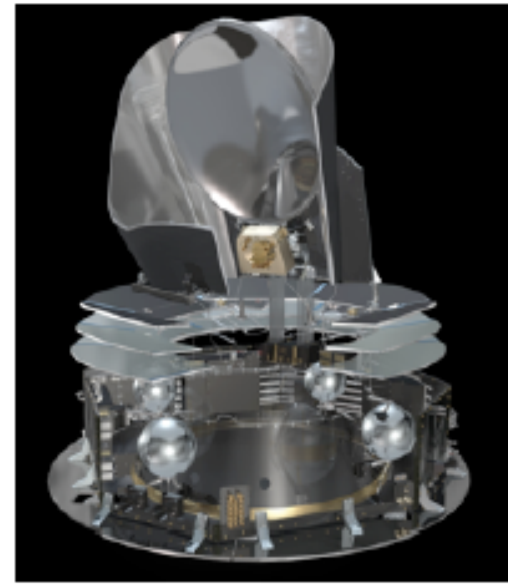
- CMB precision measurements with satellites



Cosmic Background Explorer
Launched in 1989
Mission length 4 years



Wilkinson Microwave Anisotropy Probe
Launched in 2001
On heliocentric orbit since 2010



Launched in May 2009

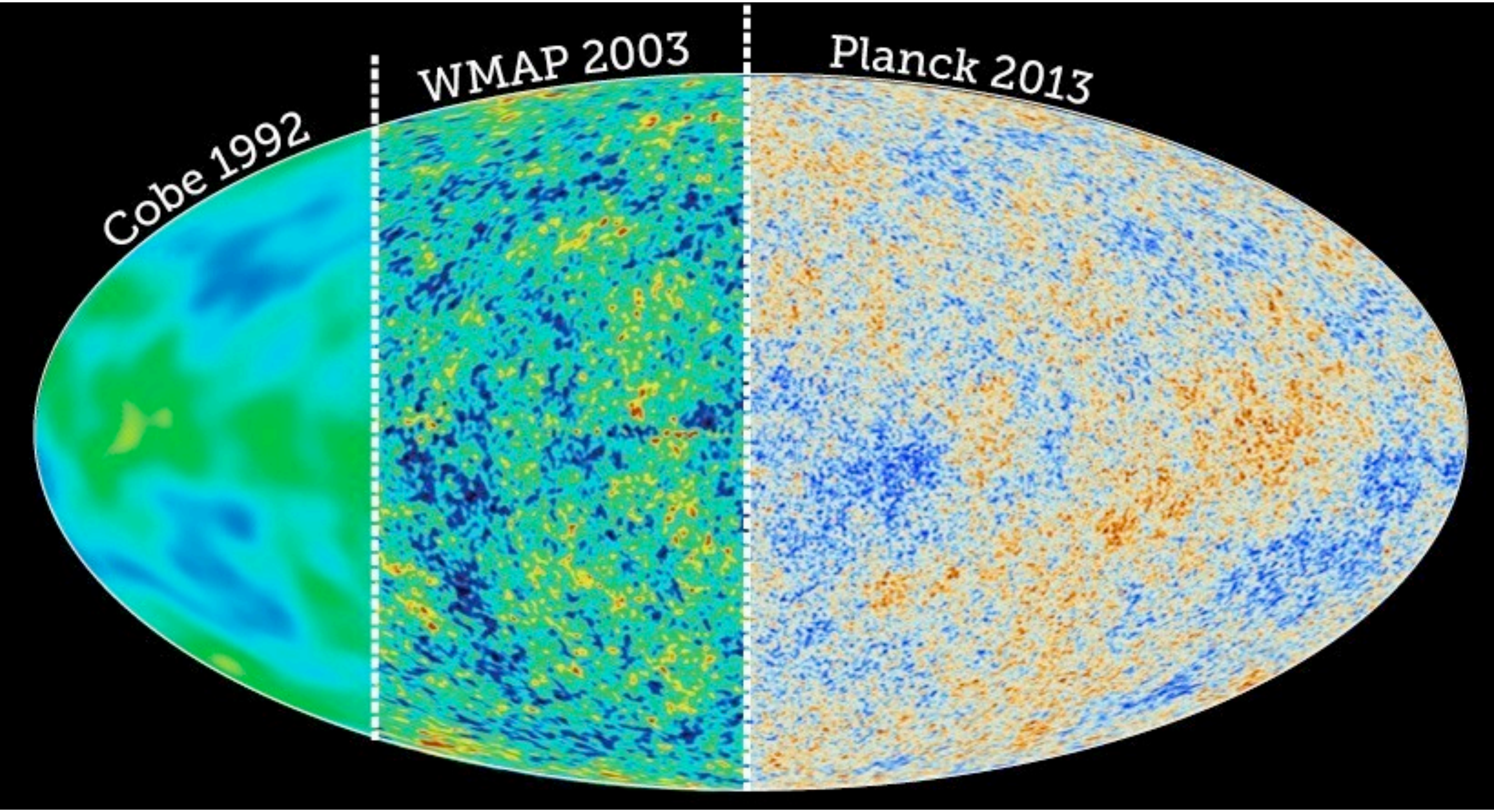
Deactivated and put into a heliocentric orbit in Oct. 2013

Nobel Prize 2006

· John Mather, George Smoot

“for their discovery of the blackbody form and anisotropy of the cosmic microwave radiation”

Cosmic Microwave background (CMB)

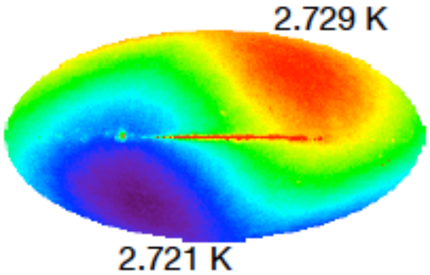


note that fluctuations measured by COBE are about 30μK!

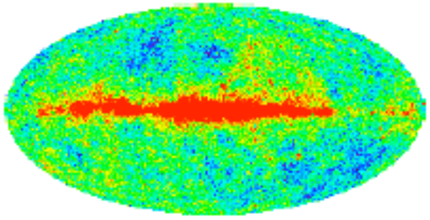
Cosmic Microwave background (CMB)

- The CMB radiation is isotropic
- Temperature variations directly related to density variation at the time of last scattering

black body spectrum

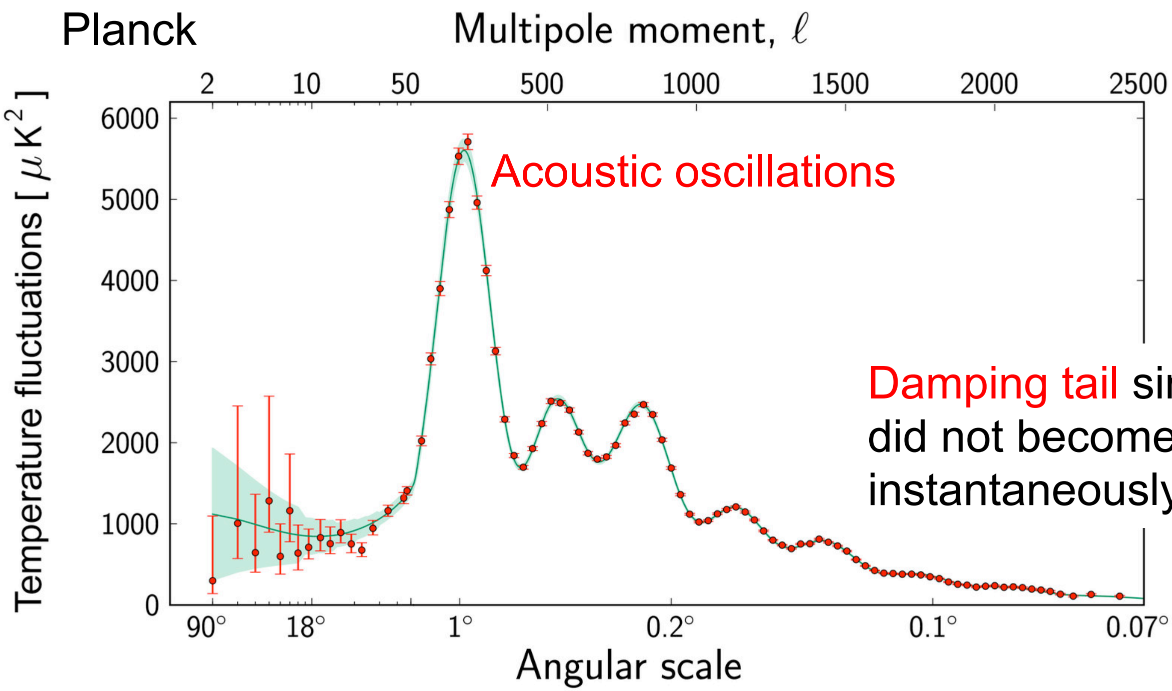


$\Delta T/T \sim 10^{-3}$
motion of the sun relative to the rest frame of the CMB → dipole anisotropy



$\Delta T/T \sim 10^{-5}$
dipole anisotropy subtracted → primordial density fluctuations

Temperature power spectrum of CMB



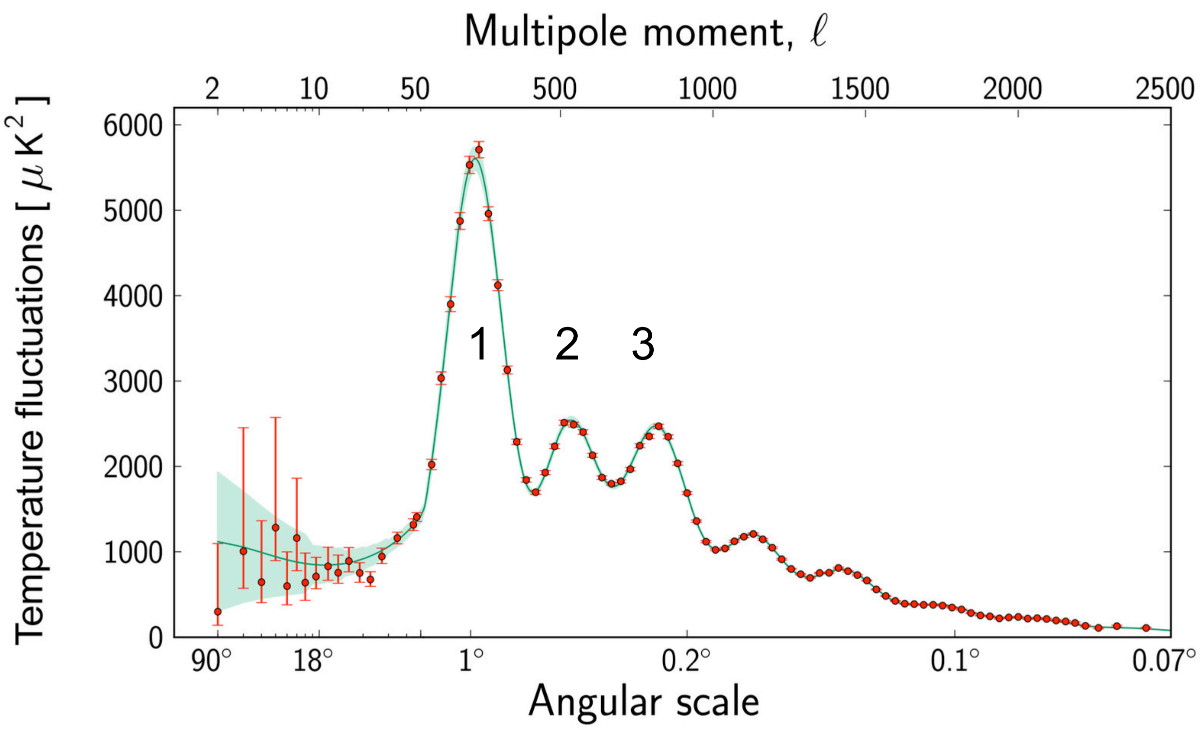
Damping tail since universe did not become transparent instantaneously

- Spherical harmonic transforms

- Matter density after inflation is not completely homogeneous. Regions with more dark matter gravitationally attract baryonic matter. Density of baryons increases. Photon pressure increases and counter acts the increase in baryon density → baryonic acoustic oscillations

  → Position of peaks gives information about matter distribution

Temperature power spectrum of CMB



- Angular scale of first peak determines curvature of universe
  - shift to the right open universe, shift to the left closed universe
- Relative height of odd and even peaks related to relative density of baryonic and dark matter
  - higher baryon density would enhance peak 1 and 3

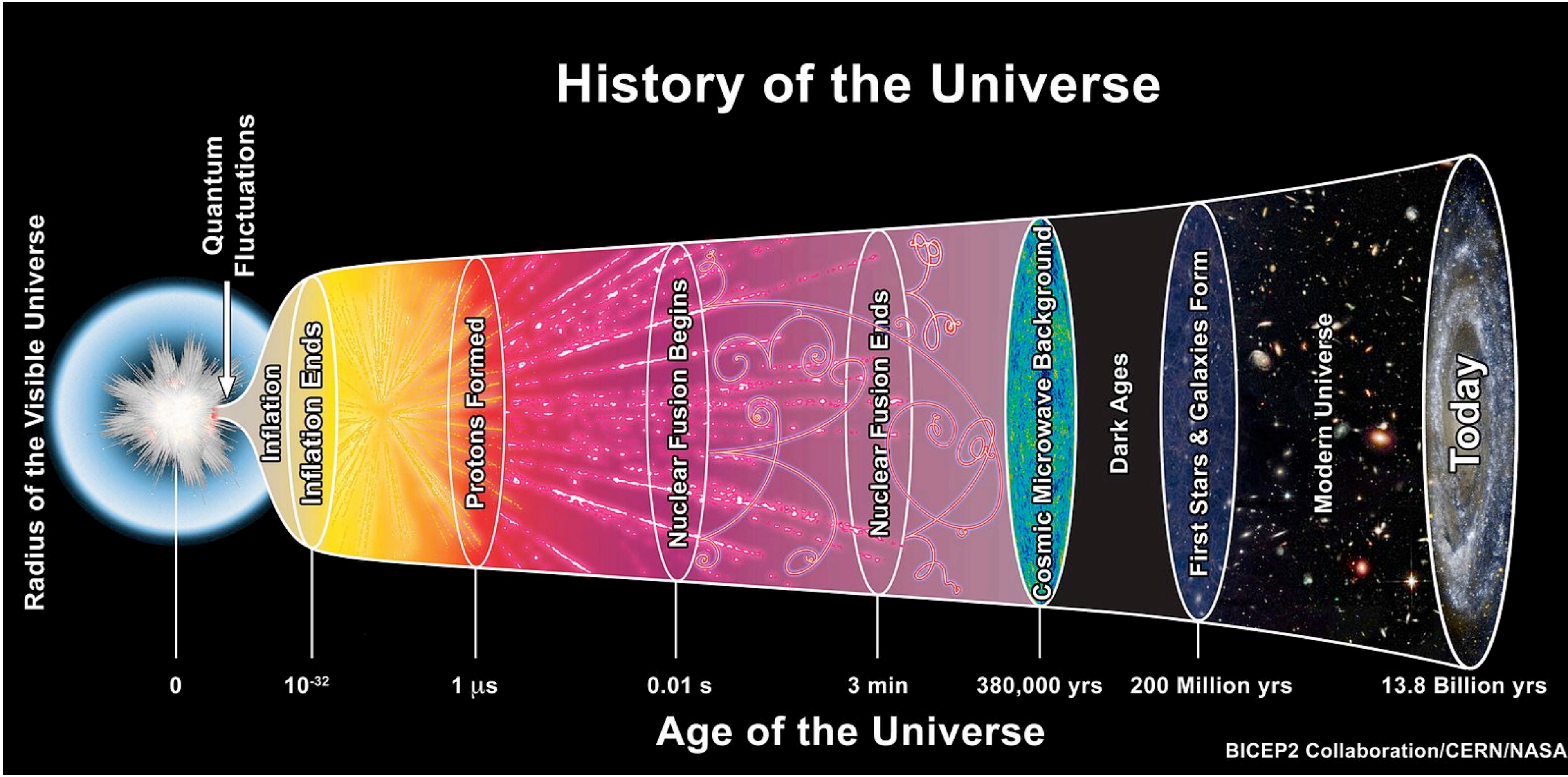
Closer to Truth with Alan Guth
"How did our universe begin?"
https://www.youtube.com/watch?v=YQCGmBFXc5E

References

- Lecture includes material prepared by L. Baudis, J. Frieman, M. Galloway, A. Garcia-Bellido, A. Kish, F. Pauss, D. Perkins

Backup

Large structures in the universe



- t = 200 million years: first stars
- t = 1 billion years: first galaxies
- t = 9 billion years: our solar system
- t=13.8 billion years: today

Scaling with red shift z

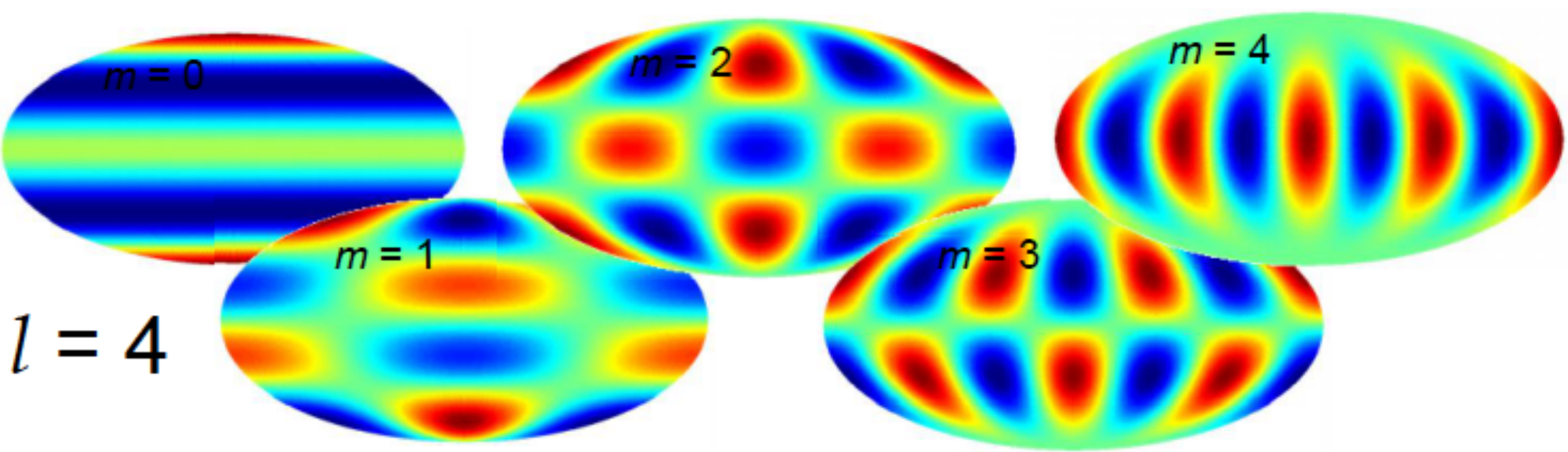
- The wave length of light grows with the scale parameter according to $R(t_0)/R(t_e) = \lambda_0 \backslash \lambda_e = 1 + z$
  - λ_0: wavelength today
  - λ_e: wavelength at the time of emission
- Light that arrives today on earth has wavelength larger by a factor 1+z
  - For today: $z = 0$, for $t=0$: $z \rightarrow \infty$
- Other physical quantities' scaling with red shift:
- Linear dimensions $\sim 1/(1+z)$ → smaller earlier
- Photon energy $h\nu = hc/\lambda \sim 1+z$ → more earlier
- Energy density E/V: $\rho(t) = (1+z)^n \rho(t_0)$ → denser earlier
  - with n=3 for dust (p=0, no interaction)
  - n=4 for relativistic matter (neutrinos, photons, $p=\rho c^2/3$)
- Temperature $T \sim 1+z$ → hotter earlier

Spherical harmonics

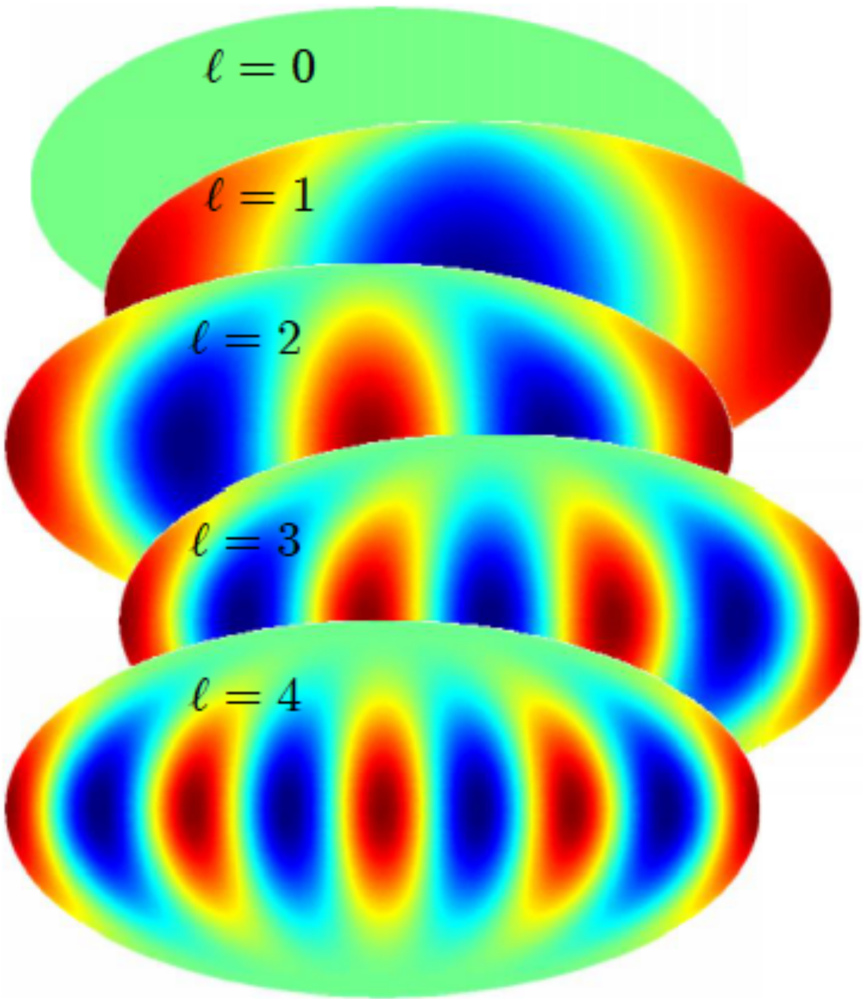
- The spherical harmonics are wave functions on the sphere
  - Completely analogous to the complex exponential in flat space

$$e^{ikx} \leftrightarrow Y_{\ell m}(\theta, \phi)$$

- Instead of wave number k, these are described by l and m
  - l determines "the wave length" of the mode
    - l is the number of waves along a meridian
  - m determines the "shape" of the mode
    - m is the number of modes along equator



Relationship between l and scale

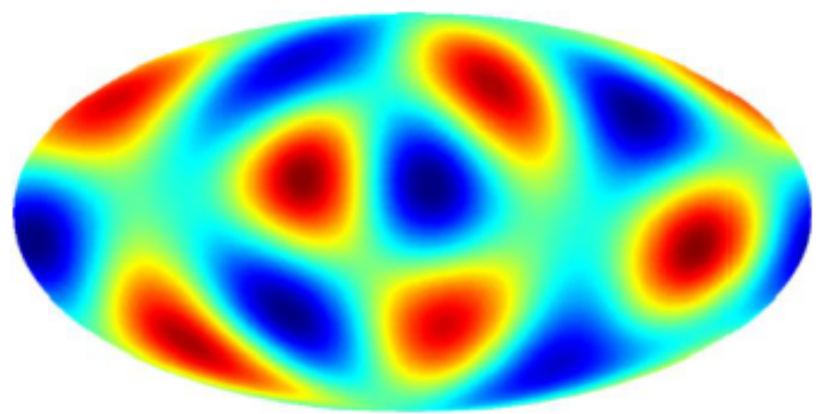


- If l increases by one, the number of waves between 0 og 2π increases by one
- The wave length is therefore

$$\lambda = \frac{2\pi}{\ell}$$

- This only holds along equator
- For a general mode (summed over m) we say more generally that the typical ”size ”of a spot is

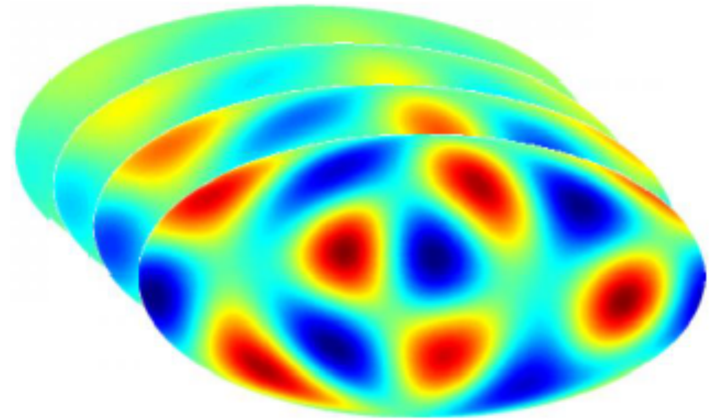
$$\lambda \sim \frac{180°}{\ell}$$

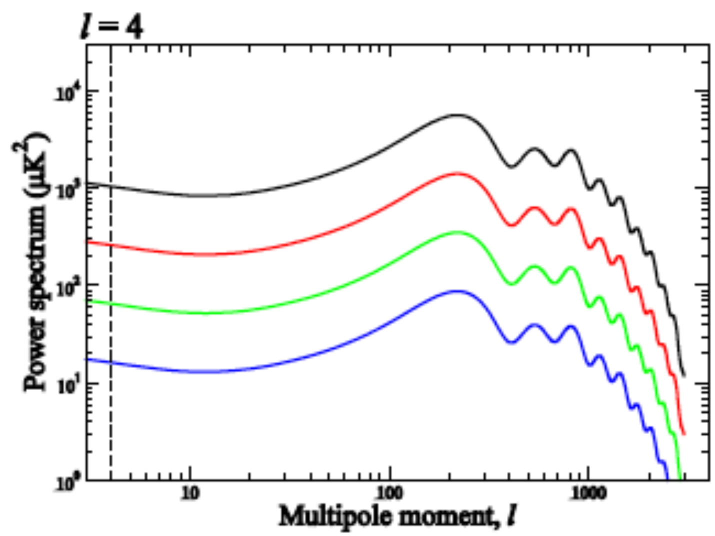


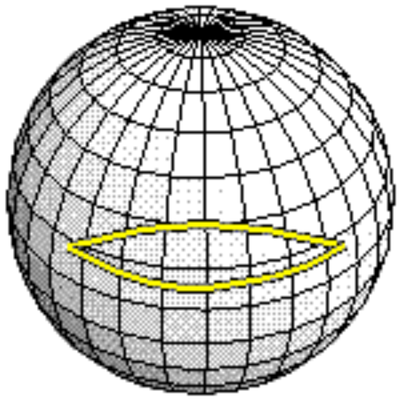
The angular power spectrum

- The angular power spectrum measures *amplitude* as a function of *wavelength*
- Defined as an average over over *m* for every *l*:

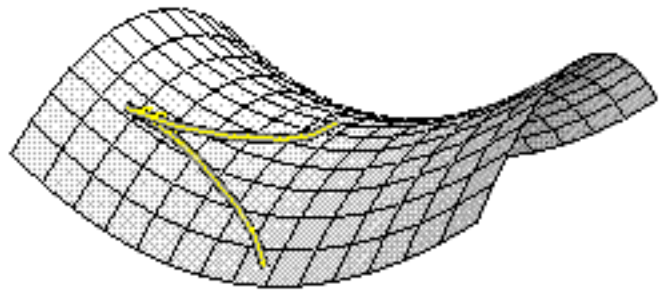
$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$



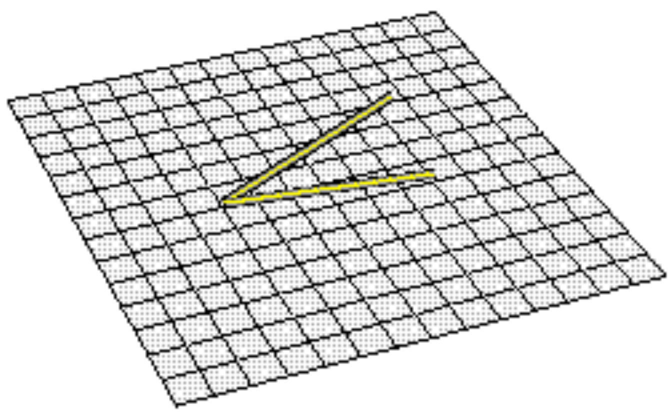




A *closed* universe curves “back on itself”. Lines that were diverging apart come back together. Density > critical density.



An *open* universe curves “away from itself”. Diverging lines curve at increasing angles away from each other. Density < critical density.



A *flat* universe has no curvature. Diverging lines remain at a constant angle with respect to each other. Density = critical density.