Observational cosmology: Basic overview

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UCL

Outline

- Lecture X: Slides
- Lecture Y: Blackboard
  - Participation
  - Appologies if I got too fast or too slow -> feedback

- Further reading:
  - Liddle: An introduction to basic cosmology (syllabus)
  - Peacock: Cosmological Physics (harder, off syllabus)
  - Dodelson: Modern Cosmology (harder , off syllabus)

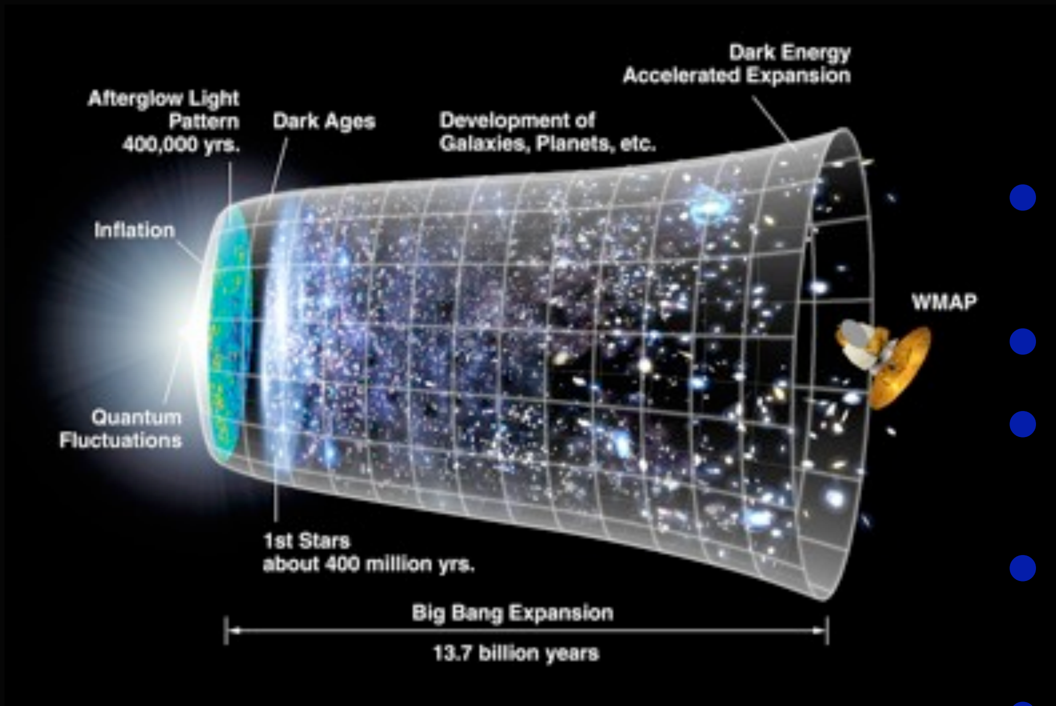
What is cosmology?

- Study of the origin and evolution of the Universe
- Census of it's contents
- Different from other sciences as there is no experiment, only observations, no ensemble of Universes… to discuss -> is it a science?

"The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds." G. Lemaitre 1931.

- A combination of Particle physics, mathematics and astrophysics.

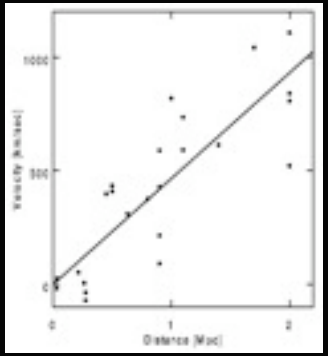
Our current standard model.



- Universe started with the Big Bang
- Inflation
- adiabatic, near Gaussian fluctuations
- Homogeneous with tiny fluctuations
- Einstein gravity
- Baryons, photons, neutrinos (we know them)
- CDM + Cosmological Constant (not a clue!!!)

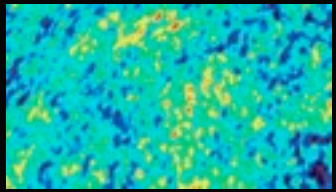
A quick view of the cosmological century:

- 1910 Are “spiral nebulae” galactic or extragalactic?
- 1912 Slipher measures large Doppler shifts for them



Hubble 1929

- 1918 Shapley gets distances from Cepheids
- 1924-9 Hubble suggests v=H0 r
- 1952 Baade discovers Milky way is a typical galaxy
- 1964 Penzias & Wilson discover CMB

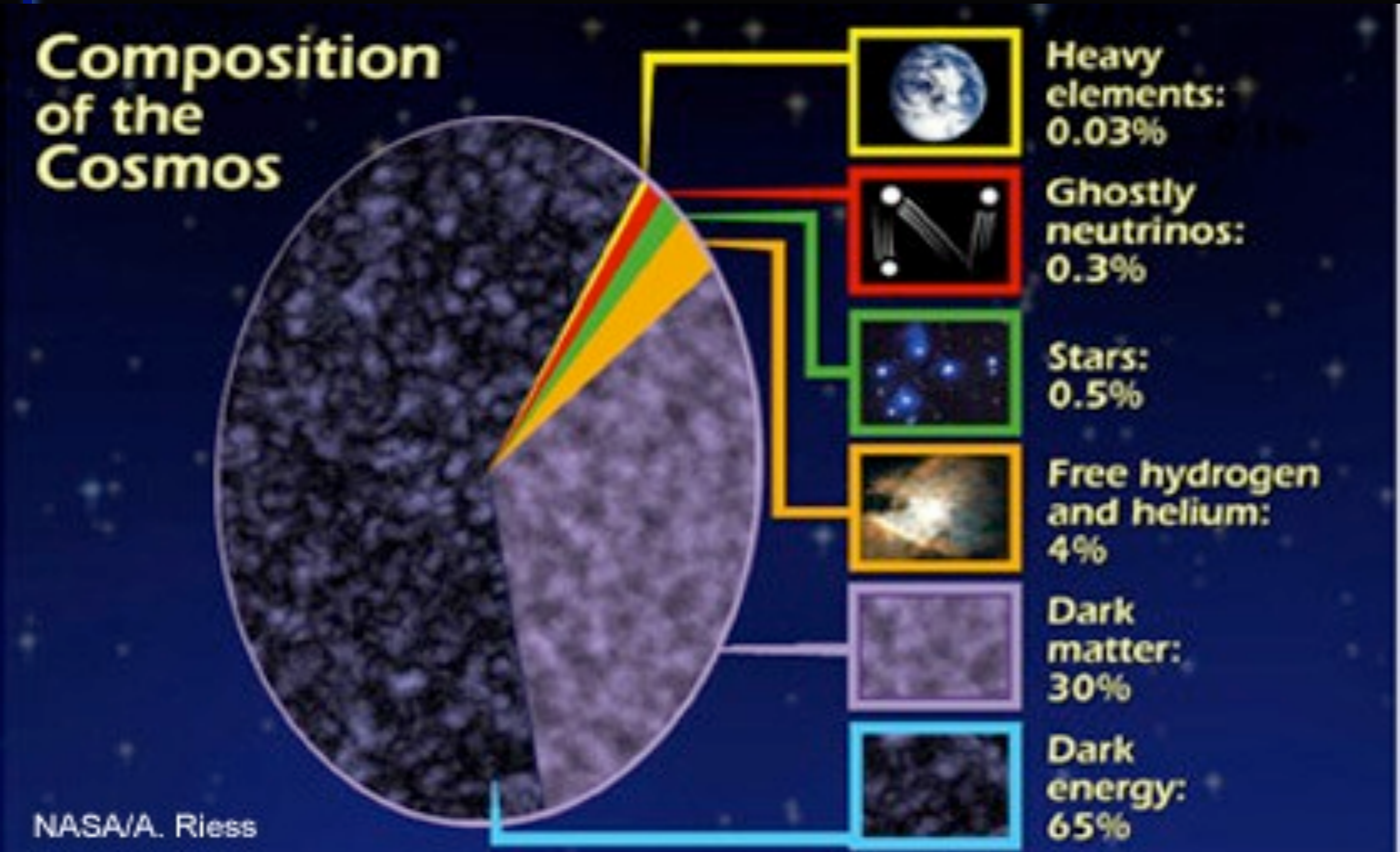


WMAP team

- 1992 COBE discovers fluctuations in CMB WMAP team
- 1997 Supernovae suggest existence of dark energy

Outline:

- Components of the Universe
- Cosmic history
- The distance scale for the modern cosmologist
- Olber's paradox and the cosmological principle



http://www.space.com/scienceastronomy/astronomy/cosmic_darknrg_020115-1.html

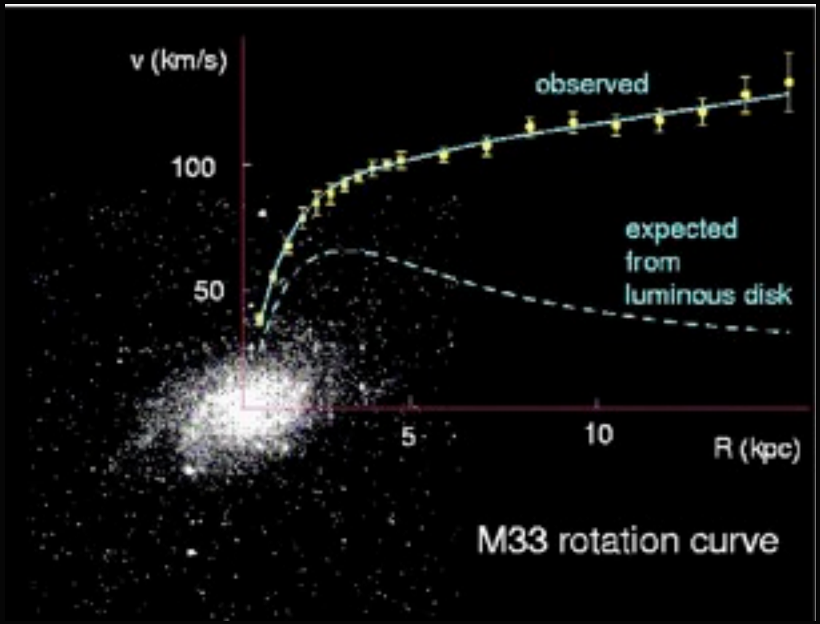
Baryons

- Technically baryons are made up of 3 quarks
  - Protons, neutrons
  - Other combinations of 3 quarks unstable

Photons

- Mostly Cosmic Microwave Background
  - T=2.7K implies 400 photons /cm^3
  - ~ 10^9 photons per baryon (we will prove these facts…)
- Also Cosmic Infrared Background… but less important cosmologically

Evidence for dark matter



- Flat rotation curve of spirals
- Cluster masses cf light
- CMB fluctuations are too small to explain local structure
  - if no non-baryonic dark matter
- Matter power spectrum gives Ω_m ~0.25
  - Nucleosynthesis gives $\Omega_b \sim 0.04$
  - So must be non-baryonic dark matter to compensate.

Non-baryonic dark matter

- Temperature / mass
  - Hot (small mass)
    - fast moving
    - escapes gravitational potential wells
  - Warm
  - Cold (large mass)
    - slow moving
    - aids structure formation
- Lifetime: must be >~ age of Universe
- Self interaction cross section: must not be too large
- Cross section for interaction with baryons: Small
- Cross section for interaction with photons: Zero!

Dark Matter Candidates

- Hot
  - Neutrinos
- Warm
  - Sterile neutrinos
  - Gravitino
- Cold (some examples only)
  - Lightest supersymmetric particle

Neutrinos

- 3 flavours known, electron, muon, tau
- Interact only very weakly with baryons: hard to detect

- Thermal neutrino background expected from Big Bang
  - (like photon background i.e. CMB)
  - can predict neutrino density today
  - ~ same number density as photons

- Neutrino oscillation experiments
  - Neutrinos have summed mass >=0.06 eV
  - 0.06eV would be negligible in cosmology

- Particle physics experiments
  - mass of electron neutrino <~ 2eV
  - 2eV would give 40% of dark matter!

Dark Energy

- The universe seems to be accelerating in its expansion
- Dark matter only causes deceleration
- There must be something else
- Often called dark energy
  - A cosmological constant Λ is a special case of dark energy
- Properties:
  - Energy density
  - Pressure ("equation of state")
  - Sound speed

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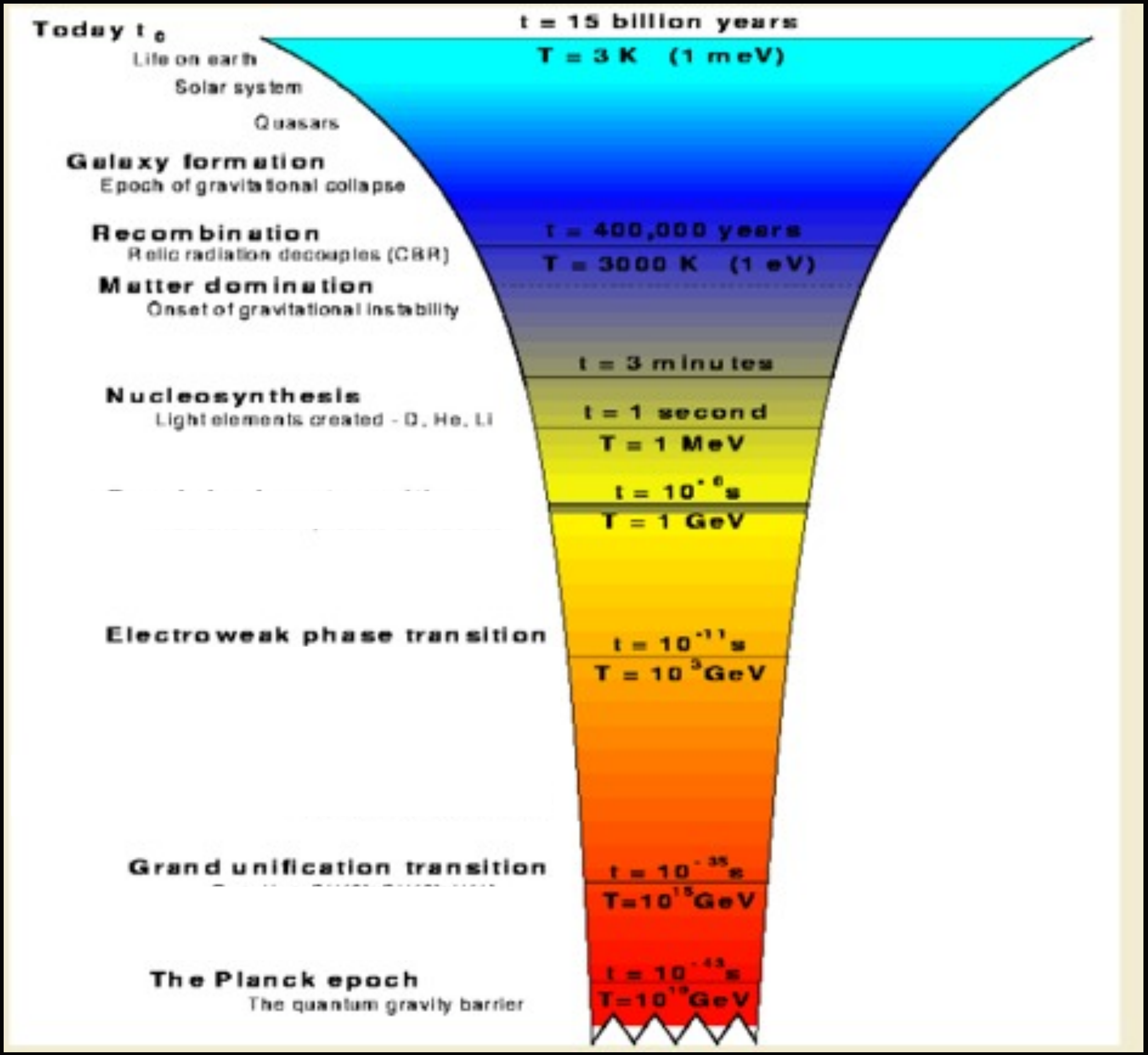
Cosmic history



Simplified from
http://www.damtp.cam.ac.uk/user/gr/public/images/bb_history.gif

The Planck Time

- "Planck scale": energy formed from G, h, c

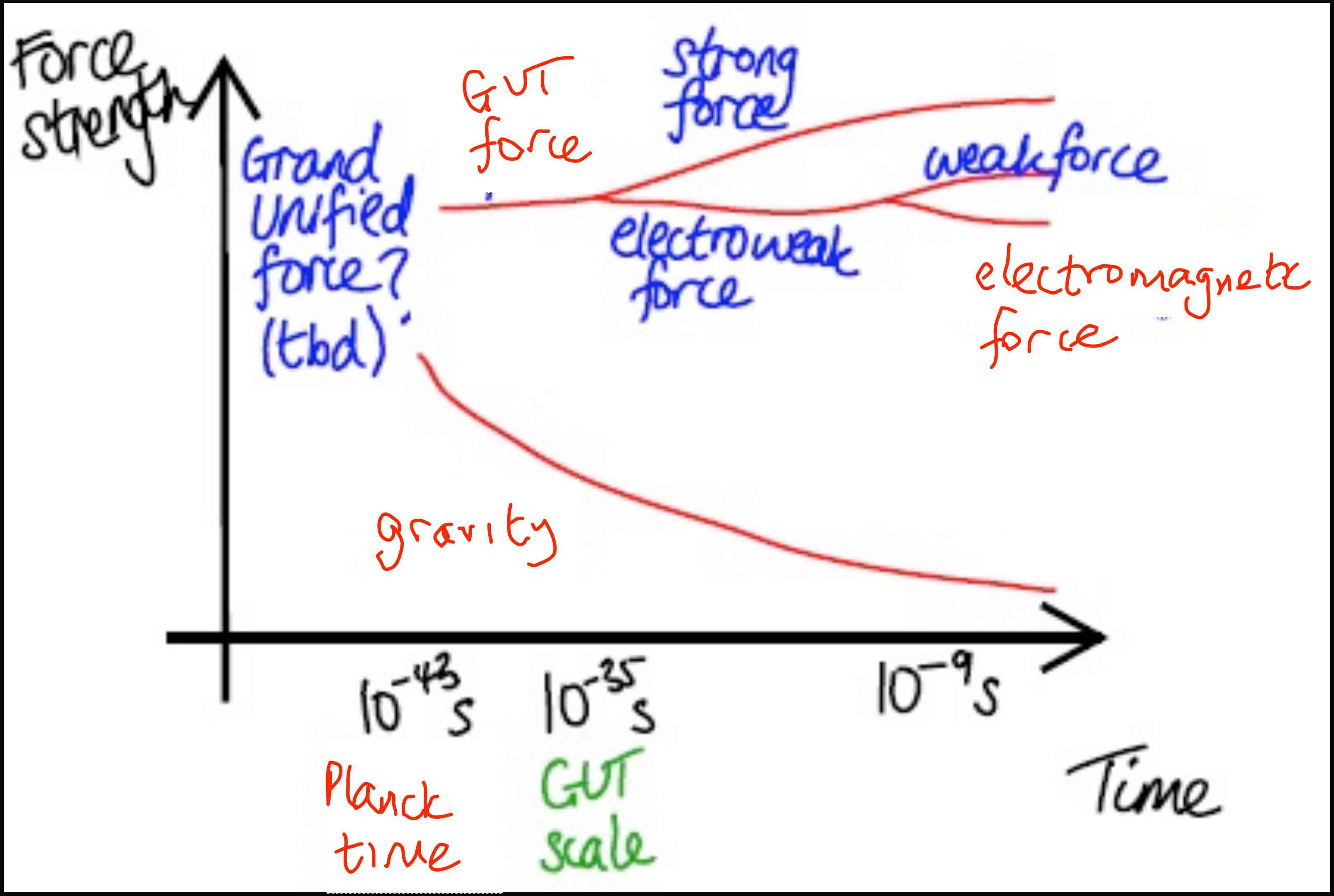
$$E_{pl} = \sqrt{\frac{\hbar c^5}{G}} \simeq 10^{19}\mathrm{GeV}$$

- Universe was this energy density at "Planck time

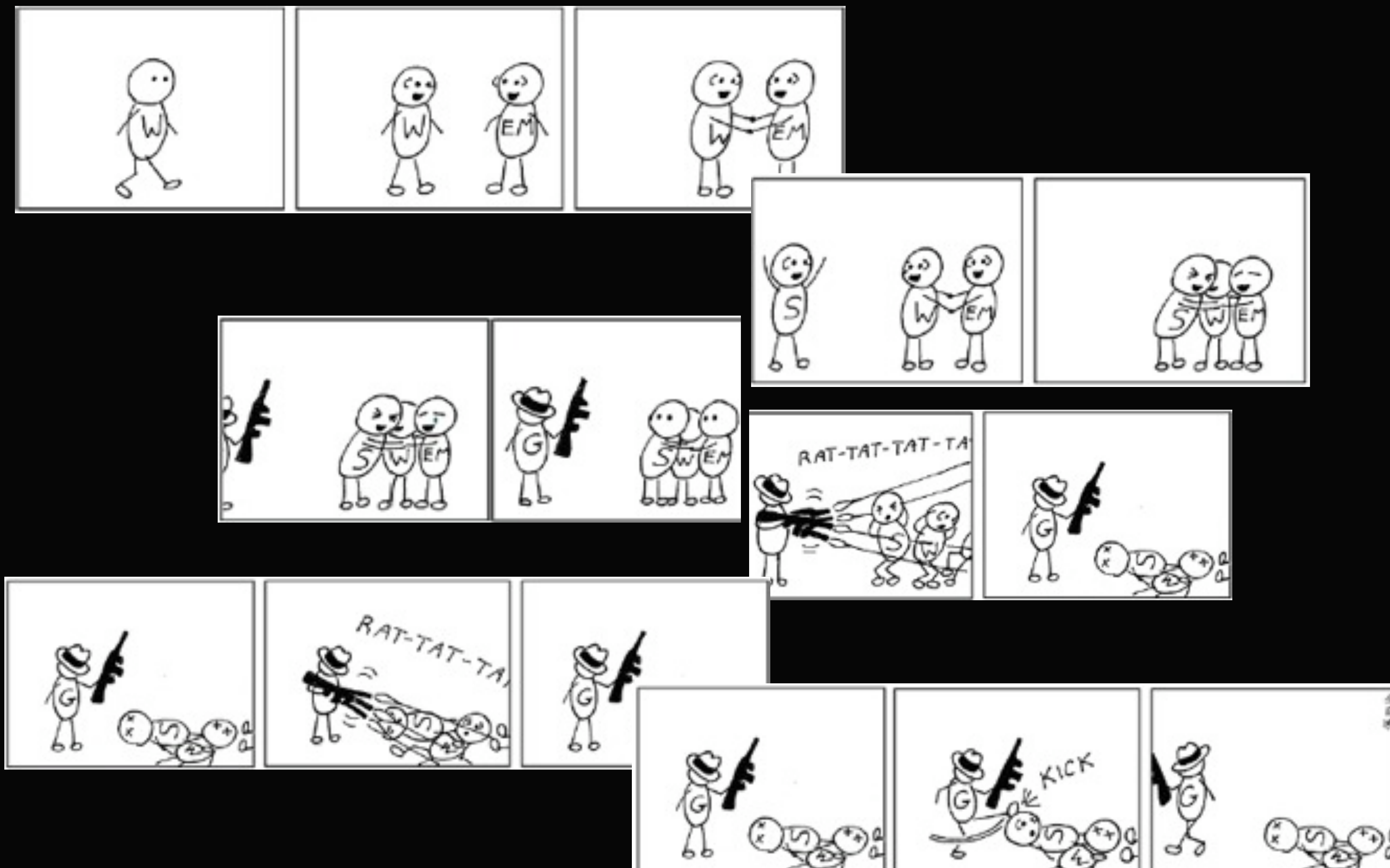
$$t_{pl} = \sqrt{\frac{\hbar G}{c^5}} \simeq 10^{-43}s$$

- Density of Universe so great that need quantum theory of gravity (not yet established)
- $T_{Pl} \sim 10^{32}$ K
- $z_{Pl} \sim 10^{32}$

Decoupling of forces



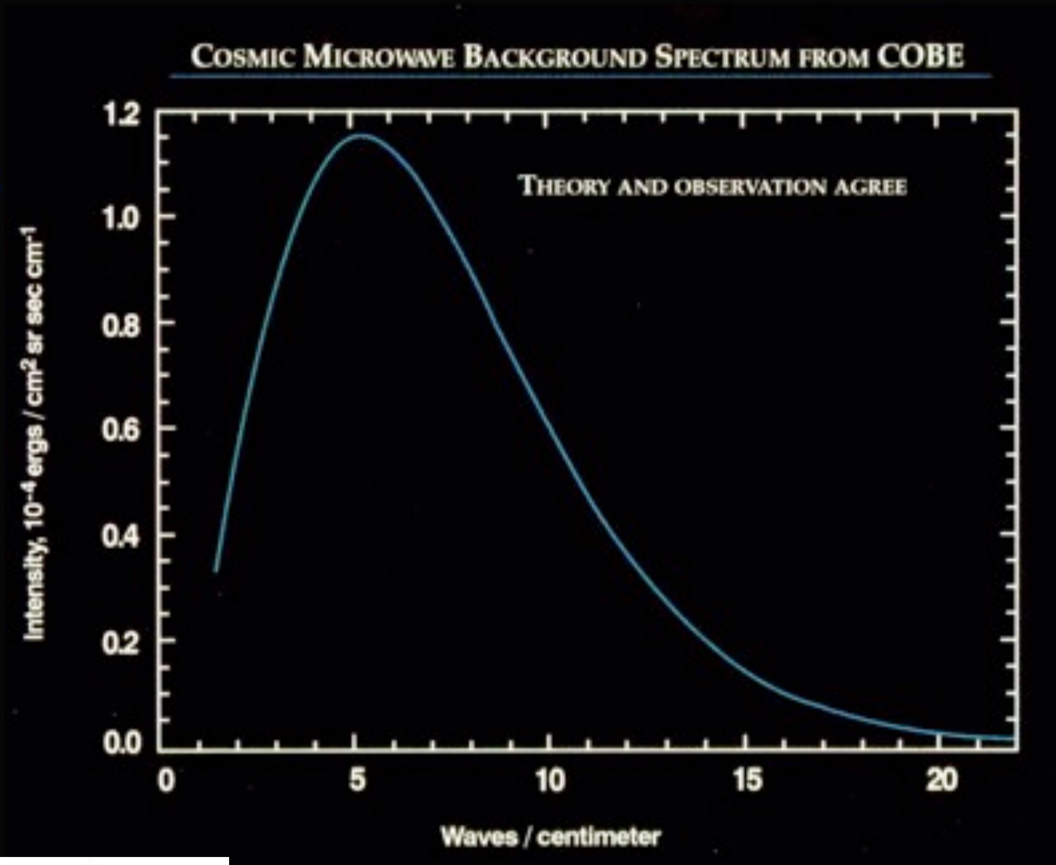
Decoupling of forces



Inflation: first a piece of evidence:

- Universe thermalised at microwave frequencies (this happens much later but requires thermal equilibrium and regions to be causally connected)

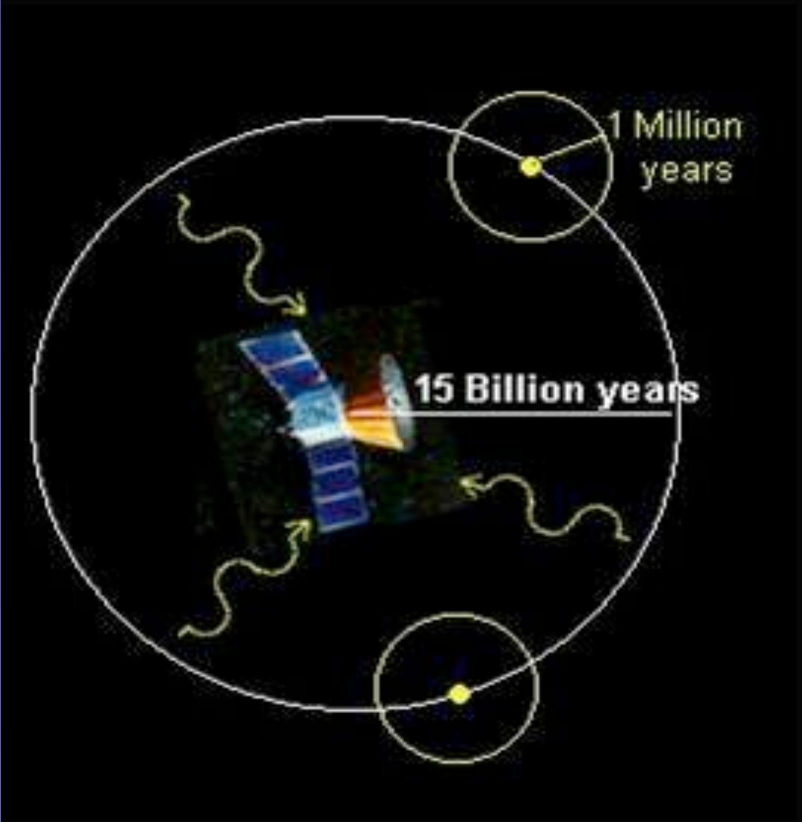
COBE

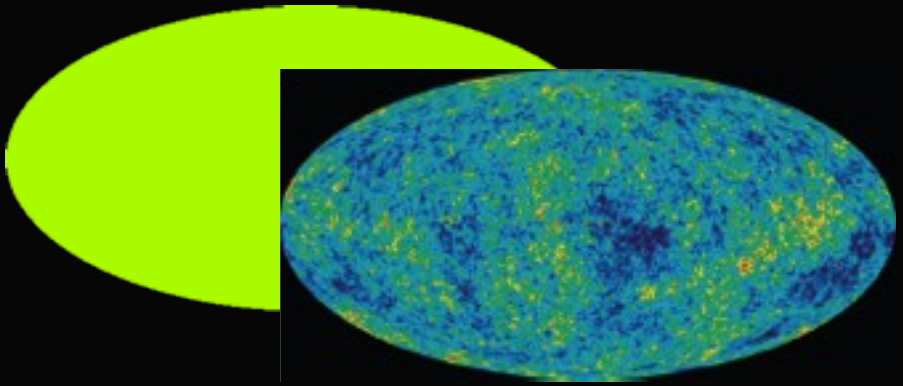


$$B(\nu,T)\mathrm{d}\nu = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{e^{\frac{h\nu}{kT}}-1}d\nu$$

$t = 10^{-35}$ s

Inflation:
Why do we need inflation?





- Temperature is uniform to 10-5, but opposite sides of sky (at z=1000) should not have been in causal contact.
- A phase of rapid expansion of the Universe
- Explains isotropy and curvature of universe
- Thought to occur around the GUT scale

$t<10^{-9}$ s

Baryogenesis

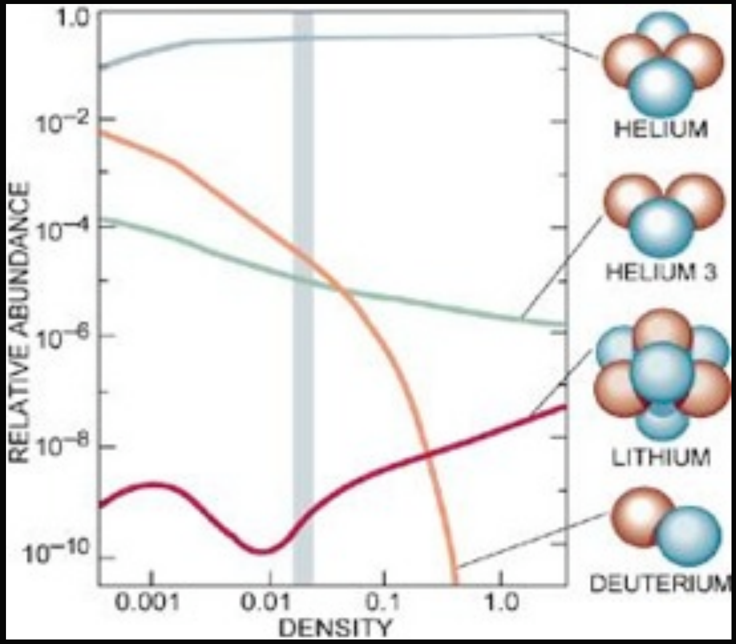
- Particle / antiparticle imbalance must have occurred
  - we don't observe significant antimatter
- Thought to occur before electroweak splits into weak and electromagnetic

$t \sim 10^{-6}$ s

- quarks and antiquarks annihilate
- leaves some quarks left with no counterparts
- neutrons and protons are formed

Nucleosynthesis

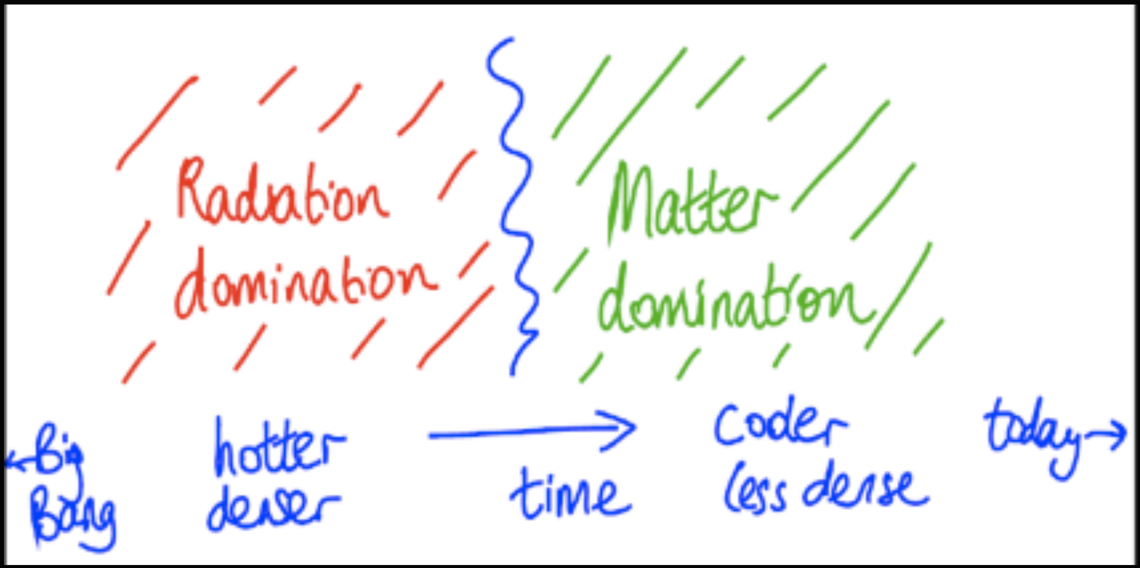
- Formation of He, Li etc from protons and neutrons
- When Universe was ~2 minutes old
- k_B T ~ 0.1 MeV
- T ~ 10^9 K



http://departments.weber.edu/physics/carroll/Wonder/big_bang_nucleosynthesis.htm

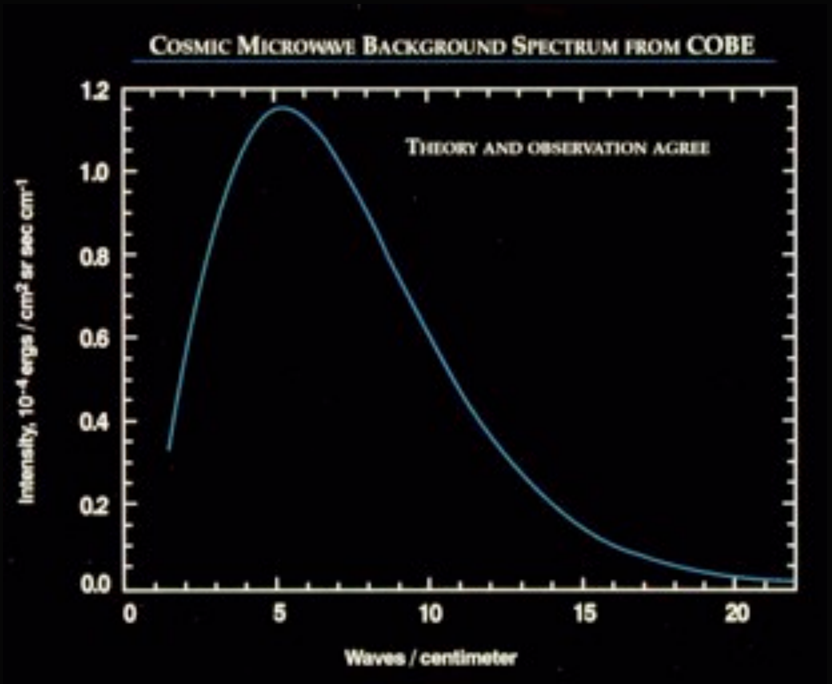
Matter-radiation equality

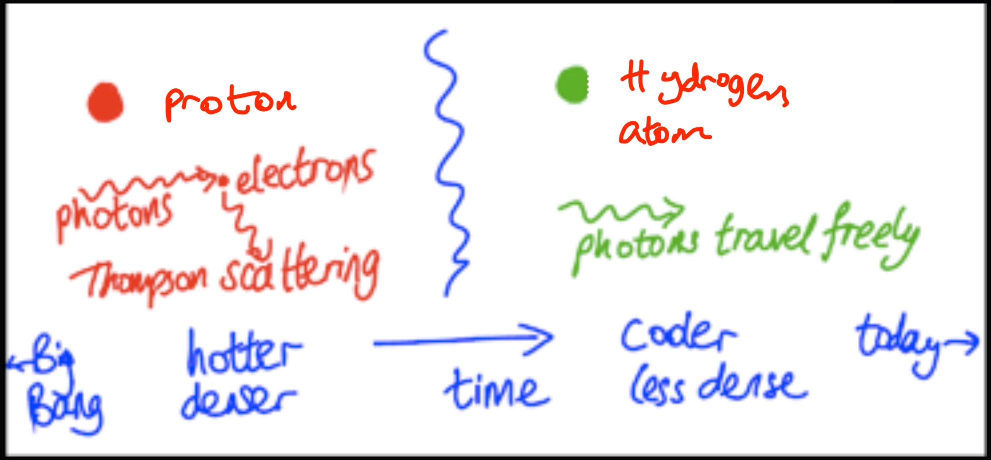
- Matter density $\propto a^{-3}$
- Radiation density $\propto a^{-4}$
- As we go back in time radiation becomes more important.

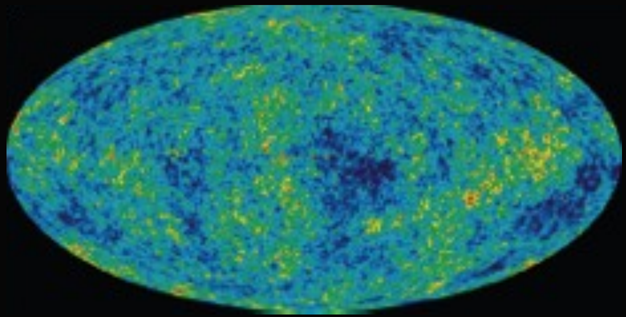


Recombination

- Universe cools so photons can no longer dissociate protons and electrons
- This gives rise to the CMB we can observe today

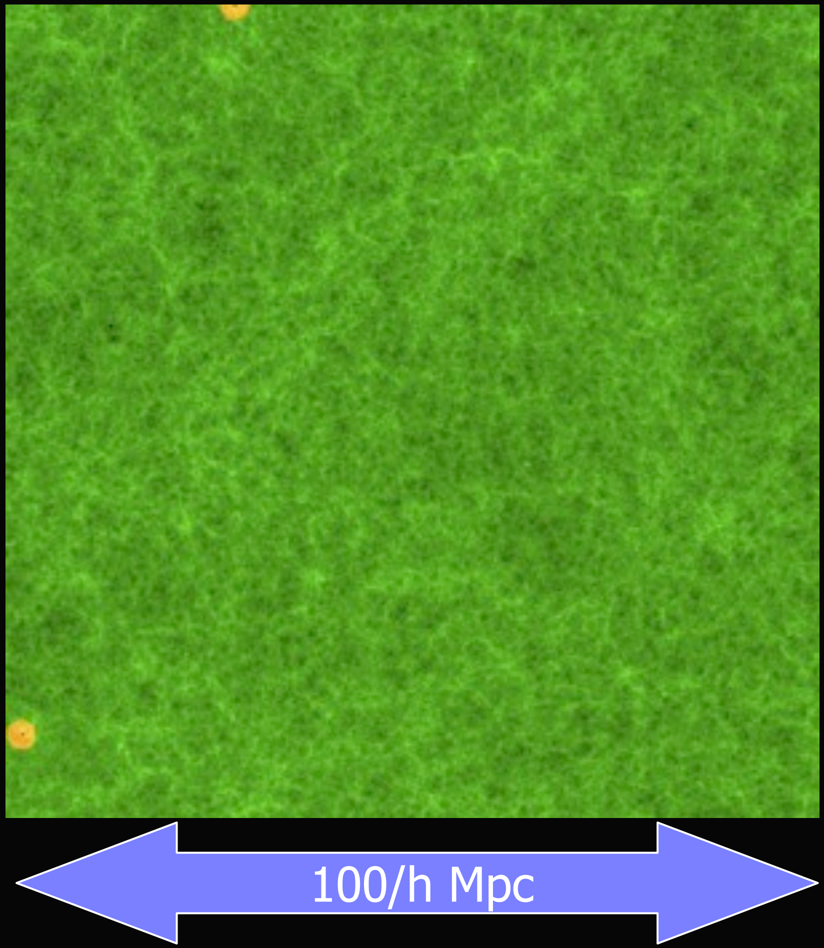






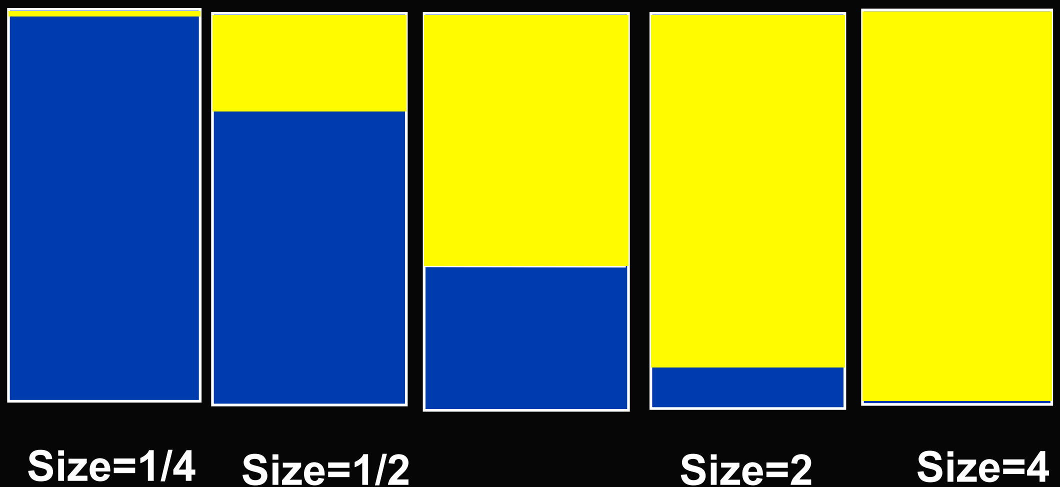
Dark Ages and Reionisation

- Universe starts forming stars and AGN, and those photons ionise the atoms free in the universe.
- Movie of (slice of) density field and HII regions (Iliev et al. 2006)
- Green: neutral
- Orange: ionized
- Black dots: sources



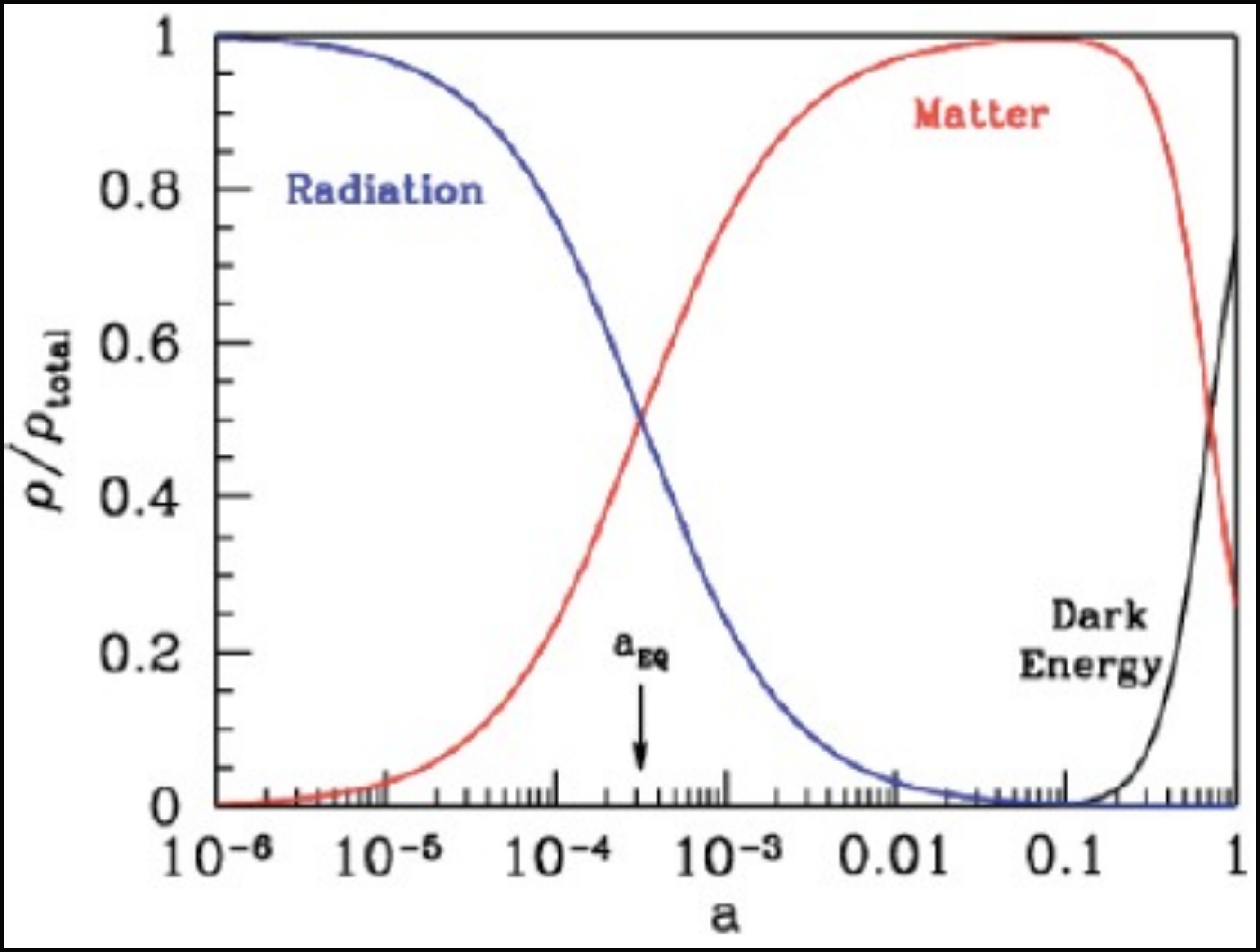
Matter-dark energy equality

- Matter density $\propto a^{-3}$ (decreasing!)
- Dark energy density ~ constant
- Eventually dark energy dominates
- Causes rapid expansion of the Universe
- Cosmic coincidence: dark energy only recently



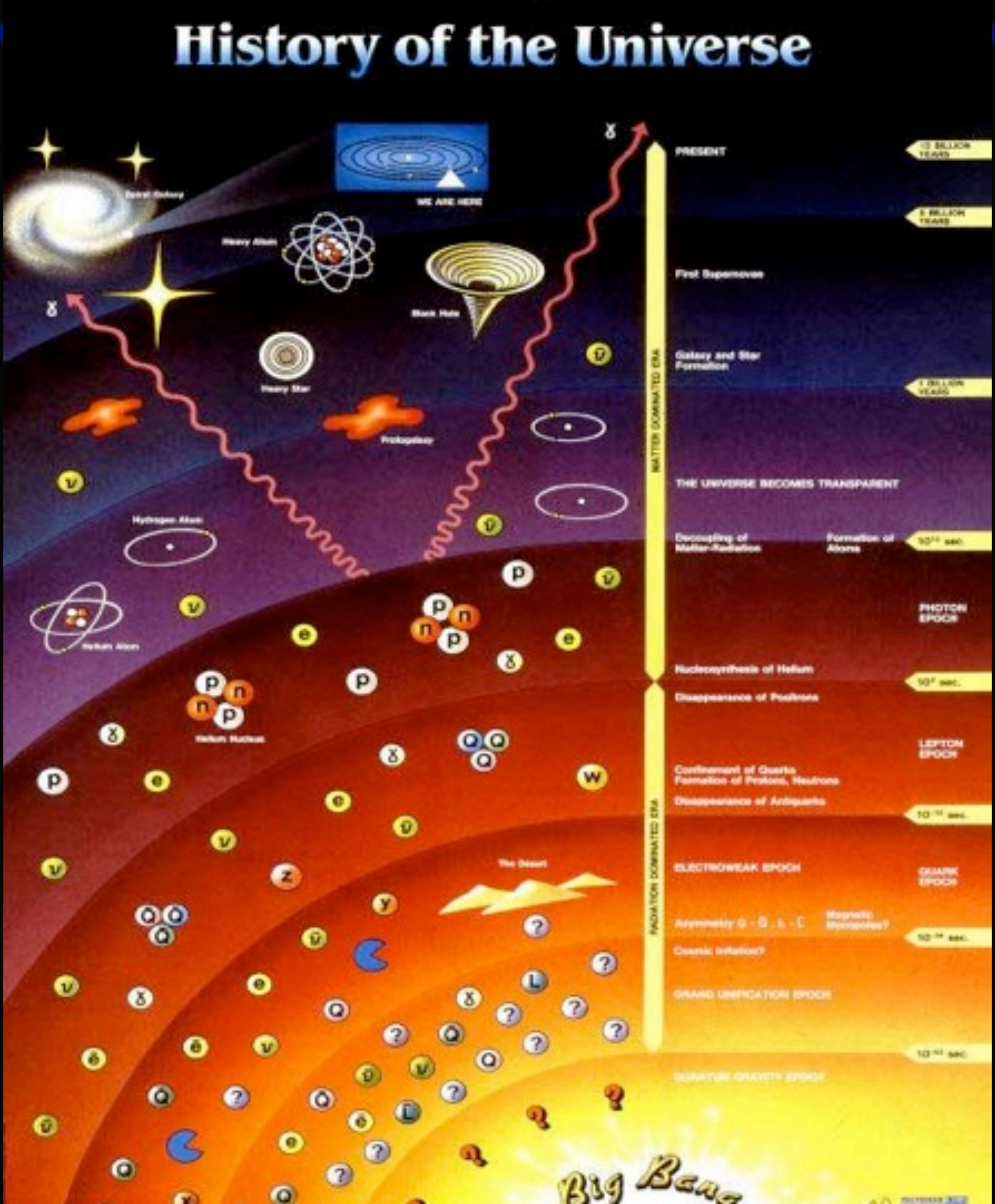
From http://supernova.lbl.gov/~evlinder/linderdoegeneral.ppt

Components of the universe:



Summary of key cosmic history events

- $t \sim 10^{-32}$ mins Inflation
  - $T \sim 10^{32}$ K
- $t \sim 2$ mins Nucleosynthesis
  - $T \sim 10^{10}$ K
- $t \sim 10000$ yr Matter-radiation equality
  - $T \sim 10000$ K
- $t \sim 400{,}000$ yr Recombination
  - $T \sim 3000$ K
- ~ few billion years Dark ages and reionisation
  - $T \sim 300$ K



Credit: CERN. http://www.exploratorium.edu/origins/cern/ideas/bang.html

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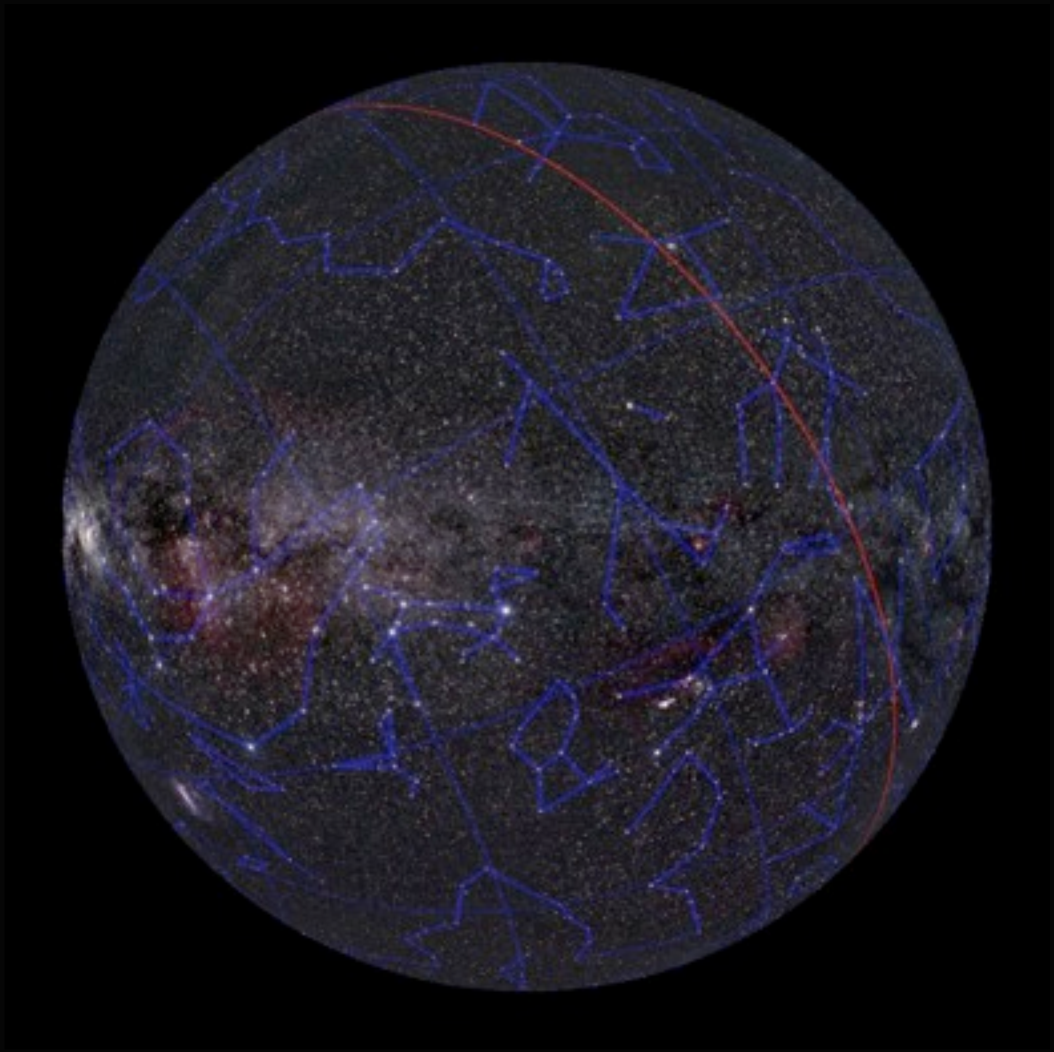
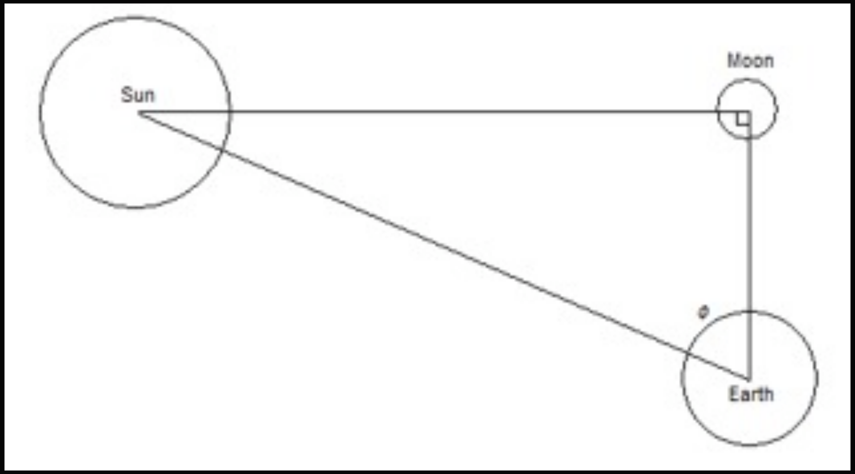
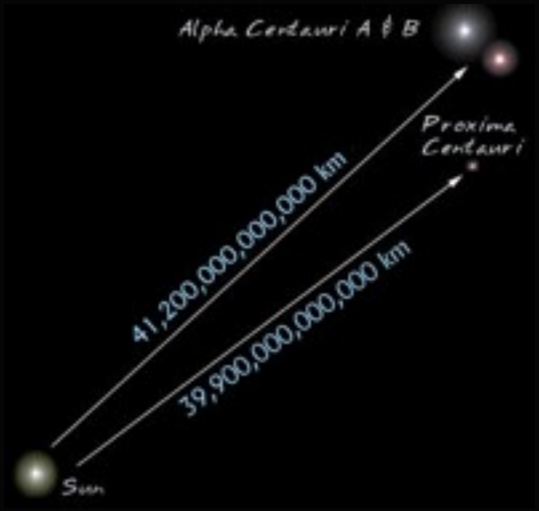
The Sky is 2D

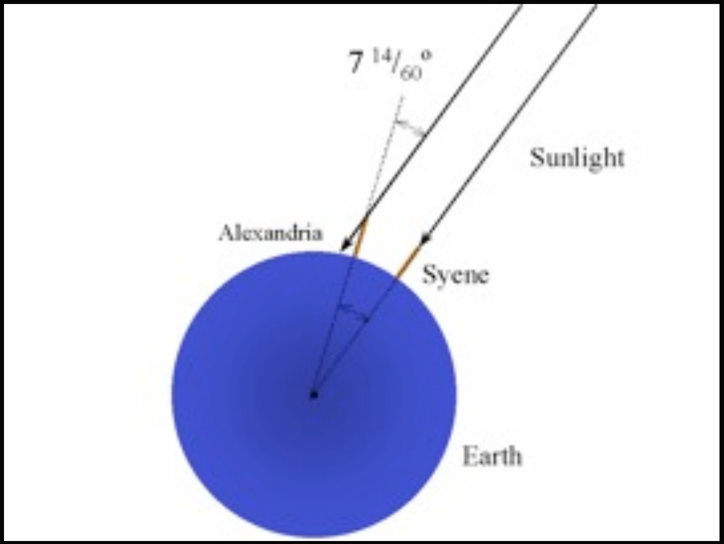
- How de we find distances to objects is very important on how we understand the universe around us.



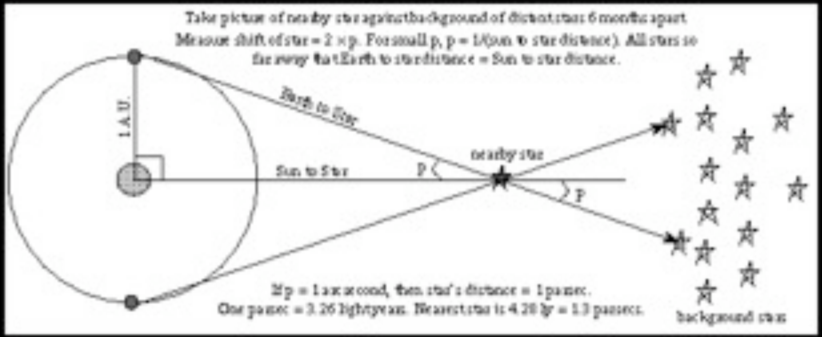
The Greeks and geometry…



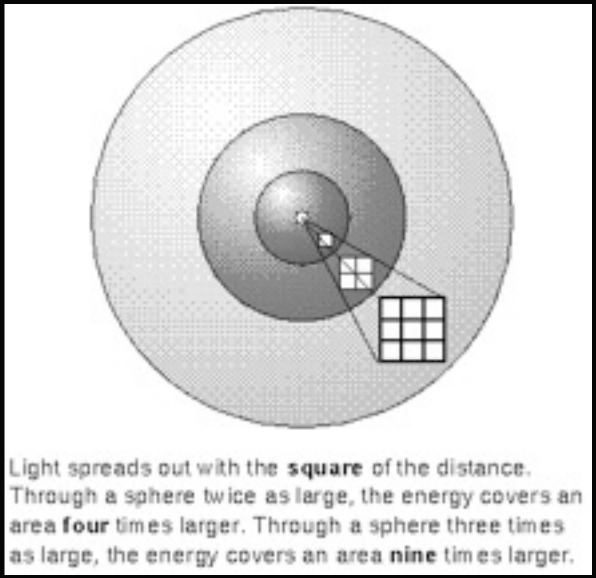


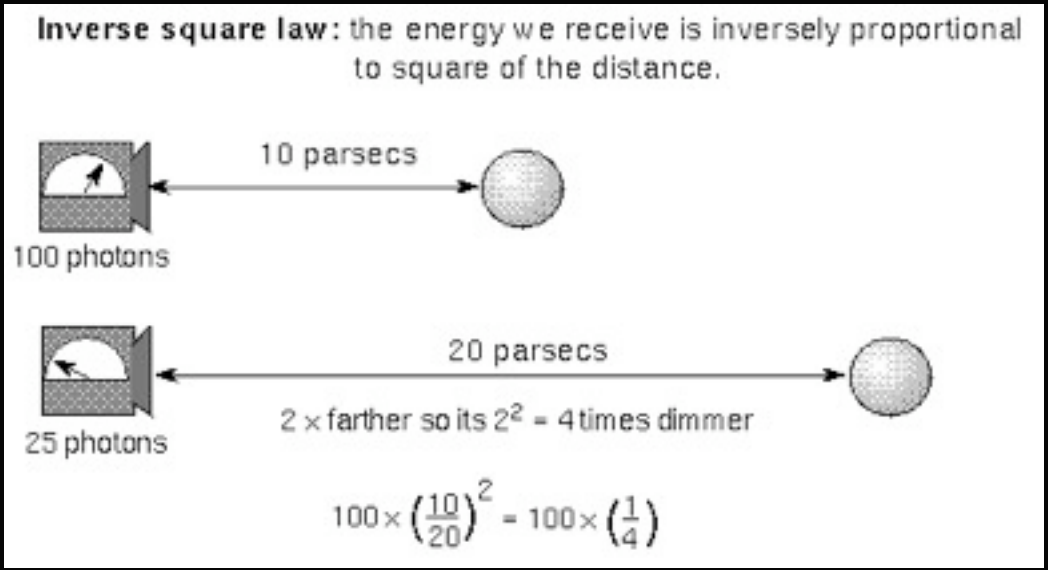


- 200 BC: Eratosthenes calculated Earth's diameter to ~ few %. With Geometry.Earth measured by spacecraft = 40,070 km
- [Aristarchus of Samos] measured the sizes and distances of the Sun and Moon…
- Later: Galileo & the Telescope: parallax…



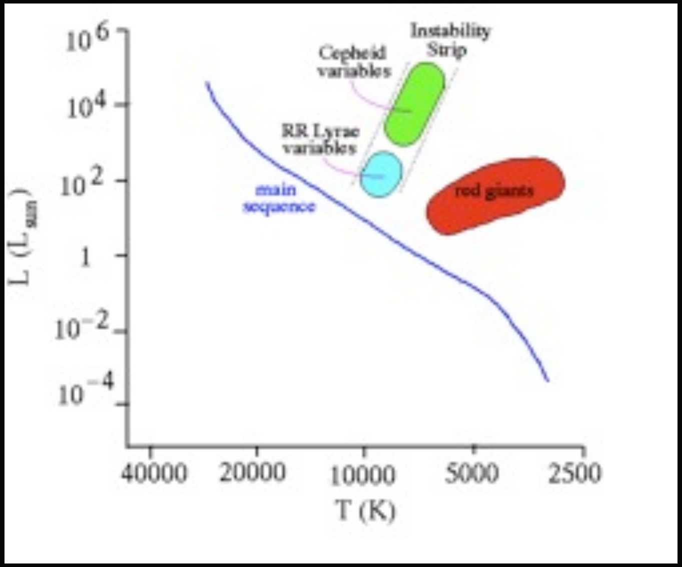
Distances: Inverse Square Law

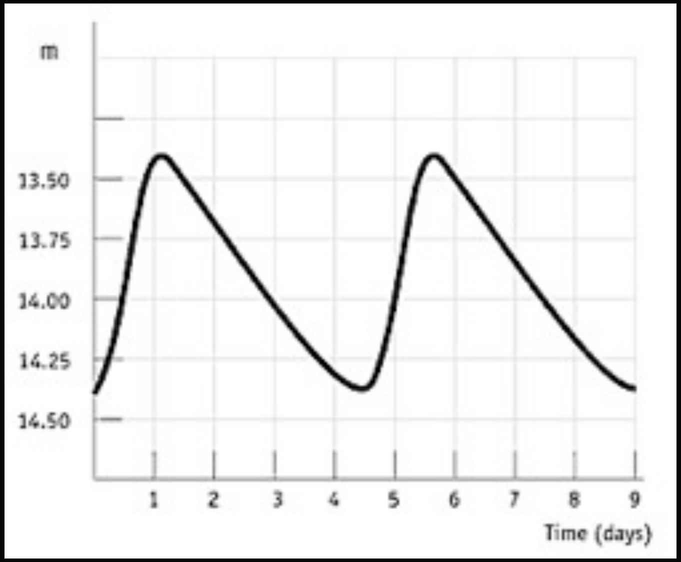




- A star 's flux (apparent brightness) decreases with the square of the distance between us & it.
- Stars become fainter with increasing distance because their energy is spread out over a larger & larger surface.
- If we know how much energy a star gives off & we measure how much energy we detect here on Earth, we can derive the star's distance.

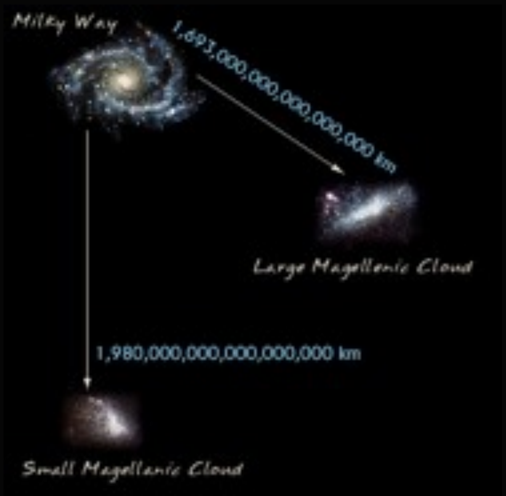
Cepheid Variables





Cepheid lightcurve. Variations caused by changes in star's radius – grows & shrinks

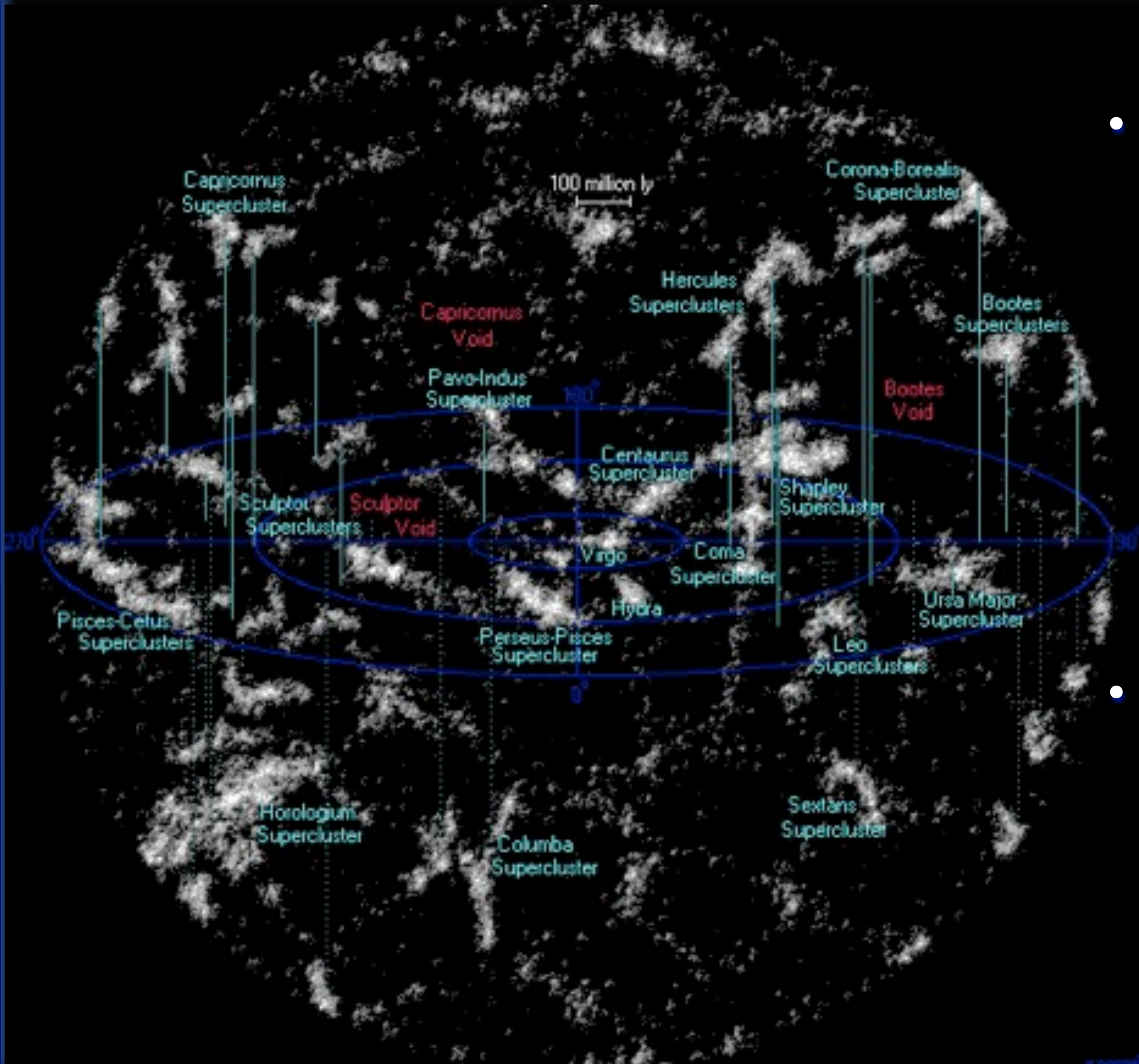
- In 1912, Henrietta Leavitt (Harvard) : Period in Cepheids is related to the average apparent magnitude of the star.
- Brighter stars -> longer periods!



Other distance indicators that may be used up to 100 Mpc:

- Tully-Fisher relation
- Fundamental plane
- Novae
- Globular cluster luminosity functions
- Surface brightness distance indicators

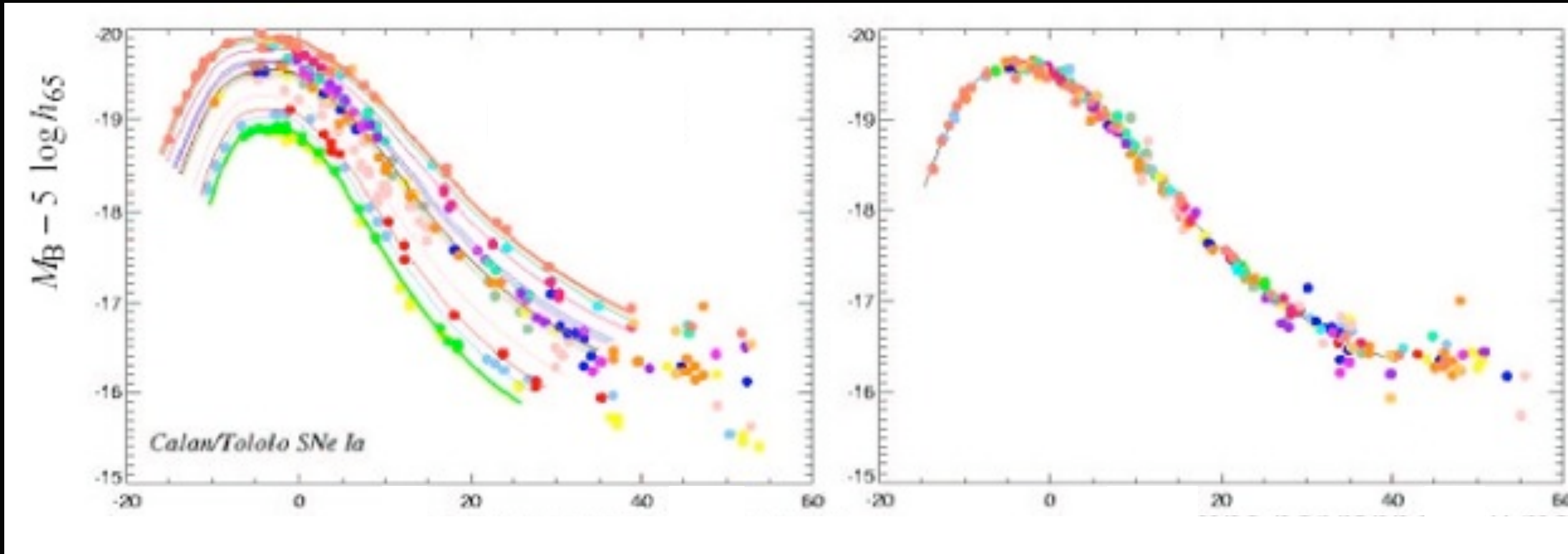
Superclusters around Virgo



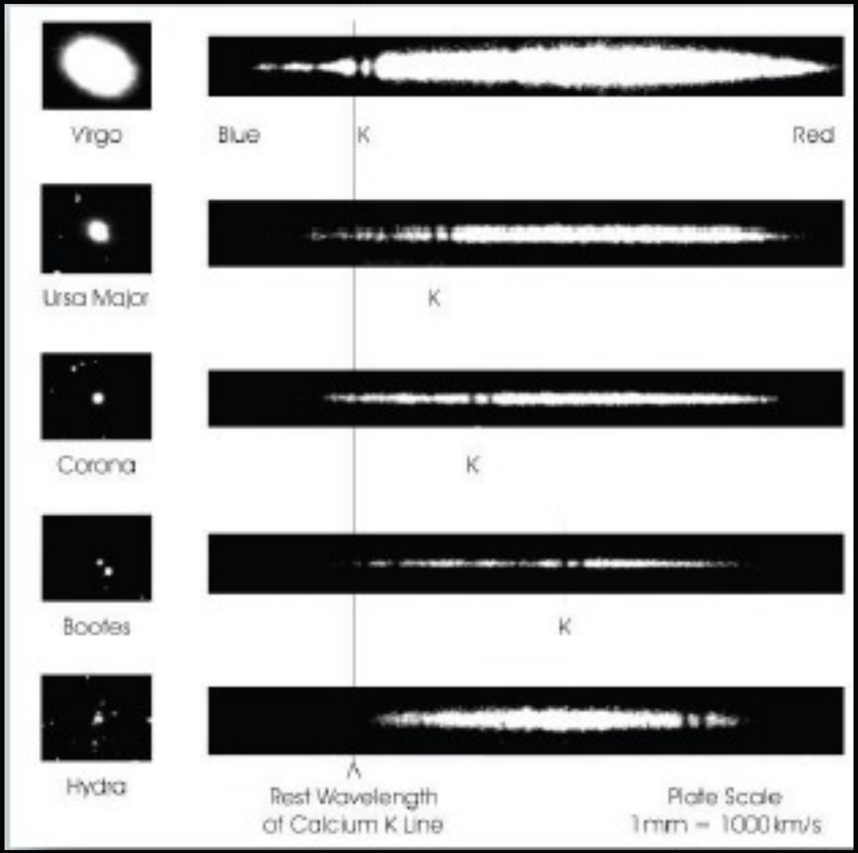
- **Galaxies & galaxy clusters collect into vast clusters and sheets & walls of galaxies interspersed with large voids.**
- **This map shows about 7% of the diameter of the entire visible Universe!**
- **Virgo:20Mpc**

Another standard candle: SN Ia Lightcurve

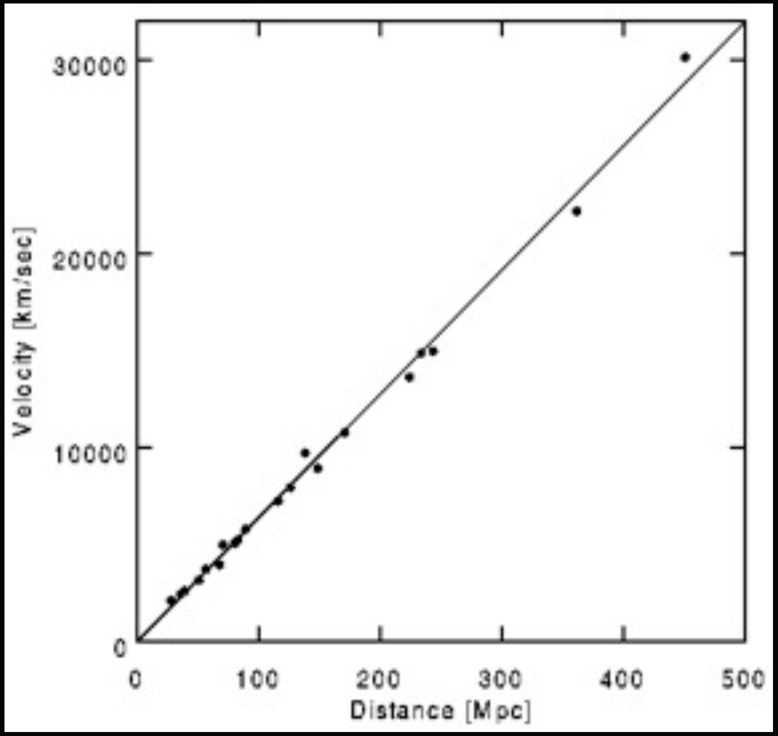
- A binary star: a white drawf and a red giant.
- One overflows into the other.
- The WD receives mass until the pressure is so great it ignites. Because of degeneracy pressure being a function of the mass this happens theoretically at the same mass: Chandrasekar mass.



The Universe is expanding:



- Hubble got is wrong the first time > an order of magnitude off…
- Hubble constant tells us how the universe is expanding today.



The metric:

- Spatial coordinates: r, θ, φ
- Comoving: proper 'distance' is $R(t)r$
- Metric of transverse element (define r by this)

$$dl_{\perp}^2 = R^2(t)[r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2]$$

- Radial part is not necessarily dr². By isotropy it may be written

$$dl_{\parallel}^2 = R^2(t)[f(r)dr^2]$$

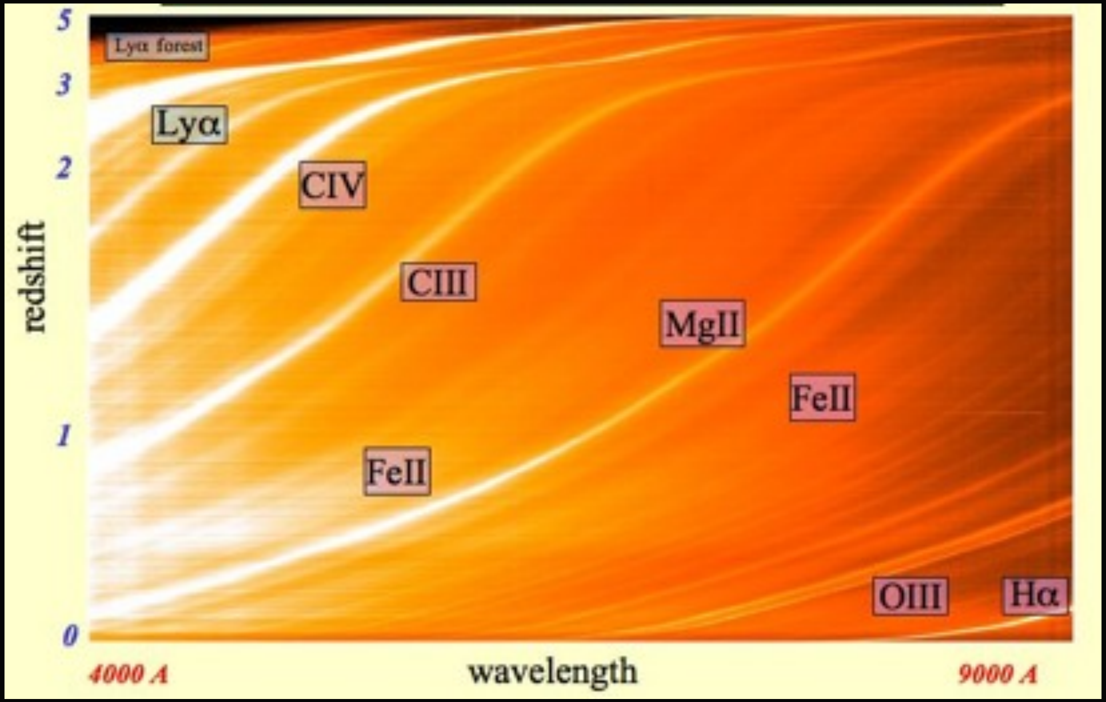
- Choosing t to be time measured by comoving observers, metric may be written

$$ds^2 = c^2dt^2 - R^2(t)[f(r)dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\varphi^2]$$

$$a(t) = \frac{R(t)}{R_0}$$

Redshift

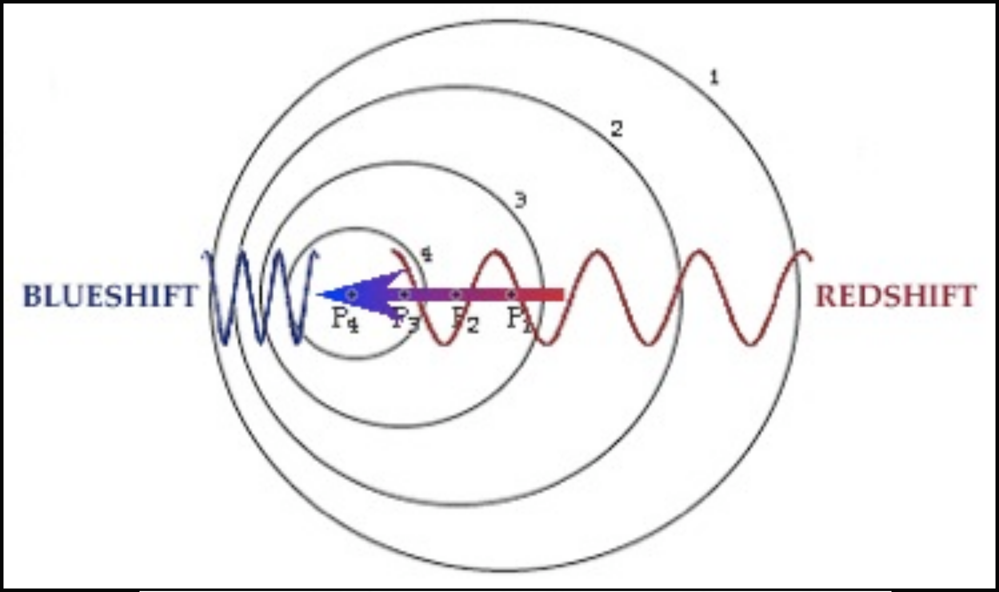
$$1 + z = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_{obs}}{a_{em}}$$

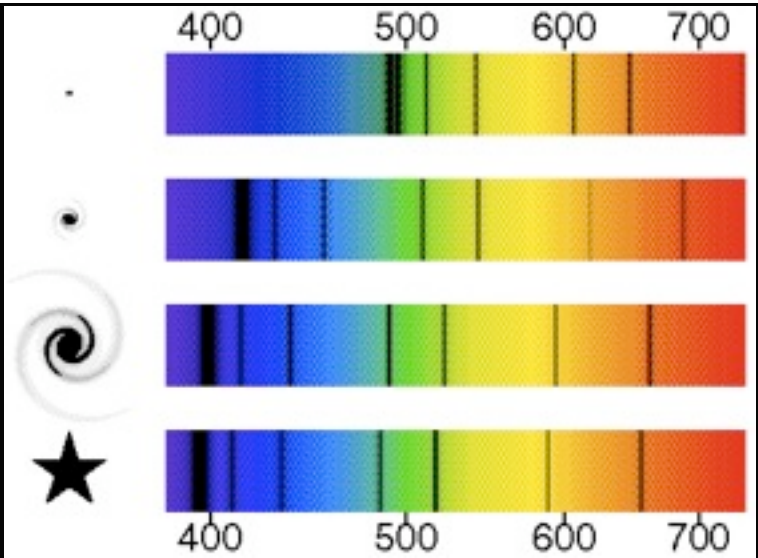


- For photons, we will prove later that redshift is indeed a stretching of the photon, i.e. a change in wavelength.
- Below all the quasars from the SDSS survey stacked in increasing redshift. We can see emission lines changing.
- a is the scale factor.

Measuring the Redshift

- Measure light coming from galaxy
- Light 'stretched' if object moving away --> longer wavelength
- Light 'squashed' if moving towards --> shorter wavelength





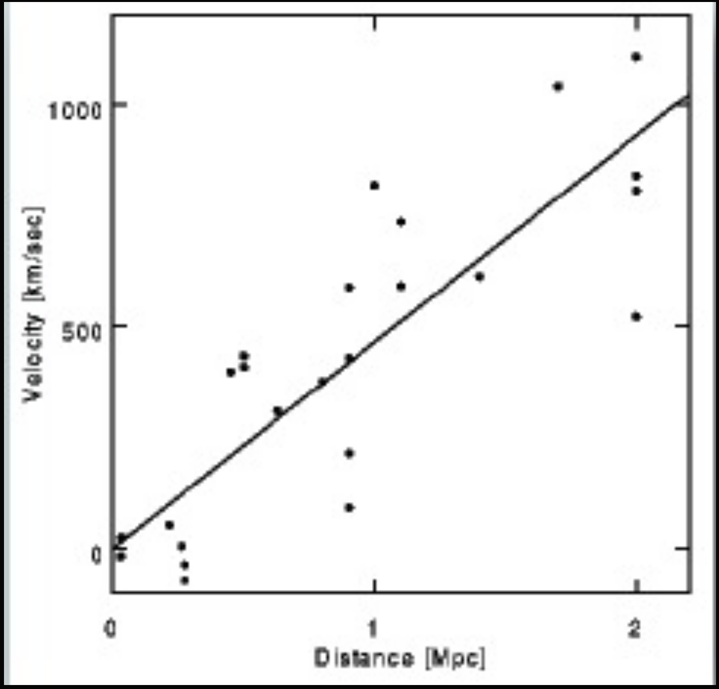
Similar to the 'Doppler effect'

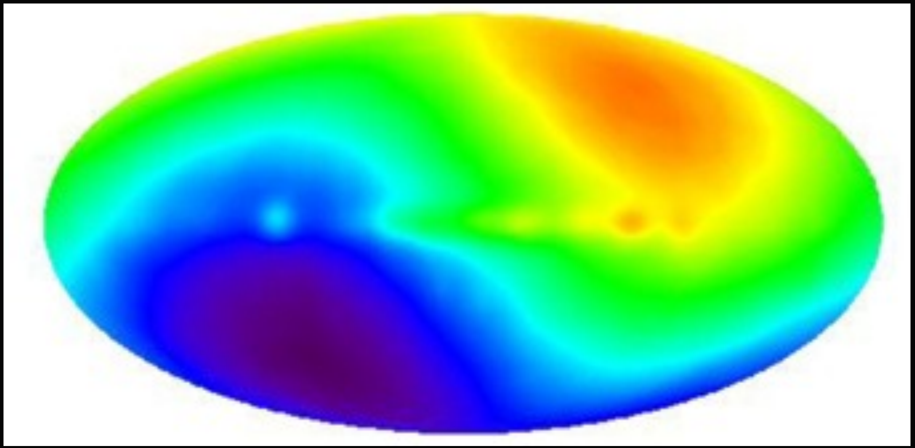
Peculiar velocities

- We can see our motion compared to the CMB as a dipole.
- Peculiar velocities that are the effect of gravity: interfered with Hubble's measurements
- Each galaxy has a peculiar velocity

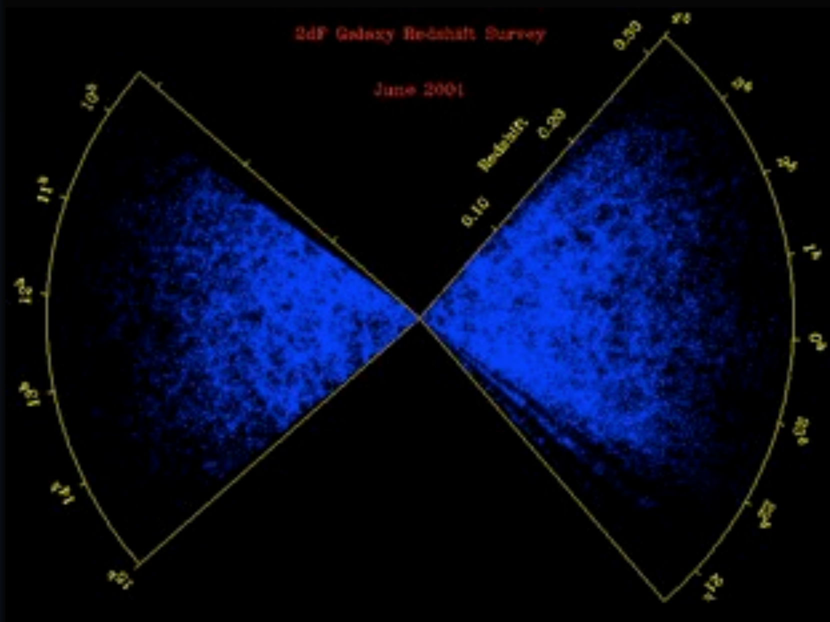
$$v = H_0 r + v_{pec}$$

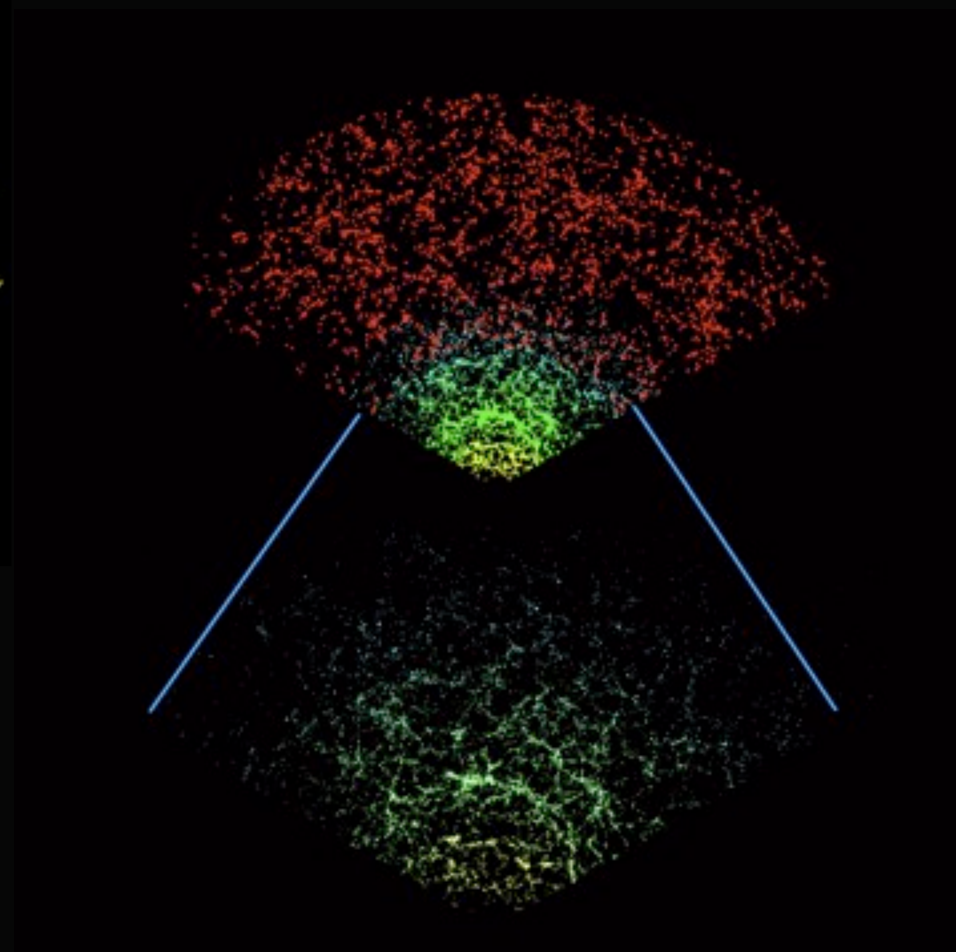
$$T_{obs} = \frac{T_0}{\gamma[1 - (v/c)cos(\theta)]}$$





2dF and SDSS:





Our universe is expanding in an accelerated way.

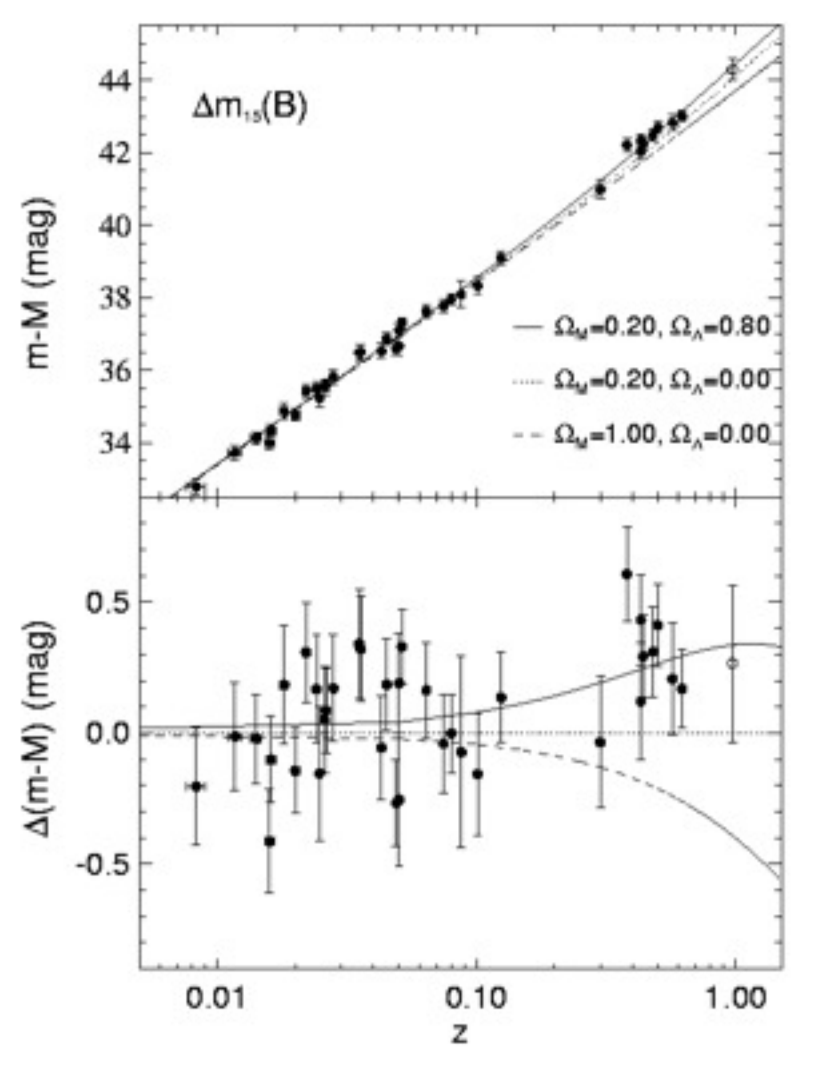
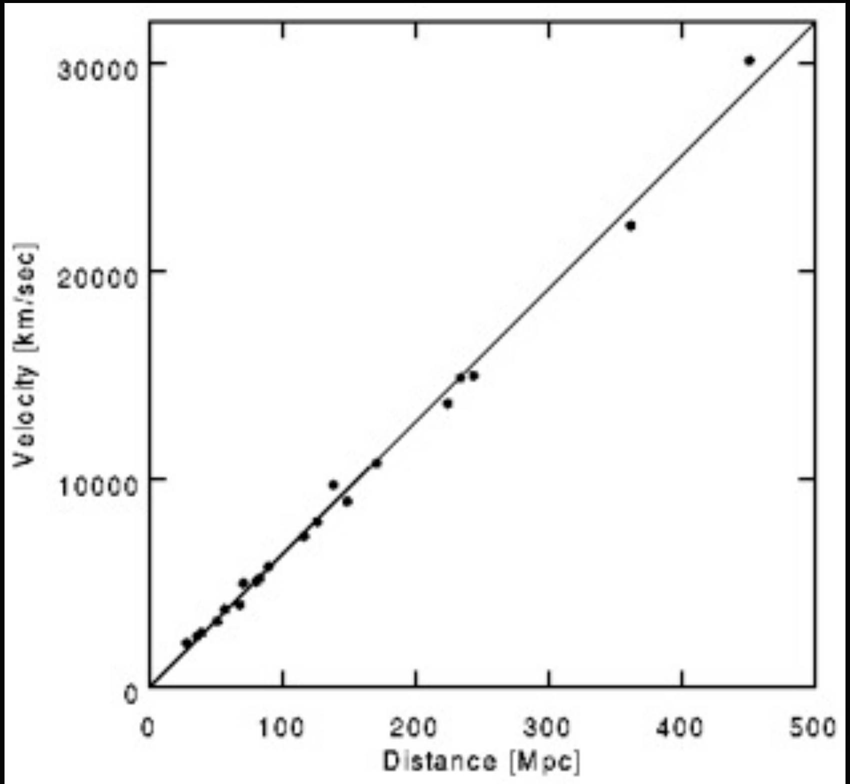


Figure aside shows the relative brightness compared to simple Hubble law. At high redshift supernovae are fainter. We will show that this implies a dark energy component.



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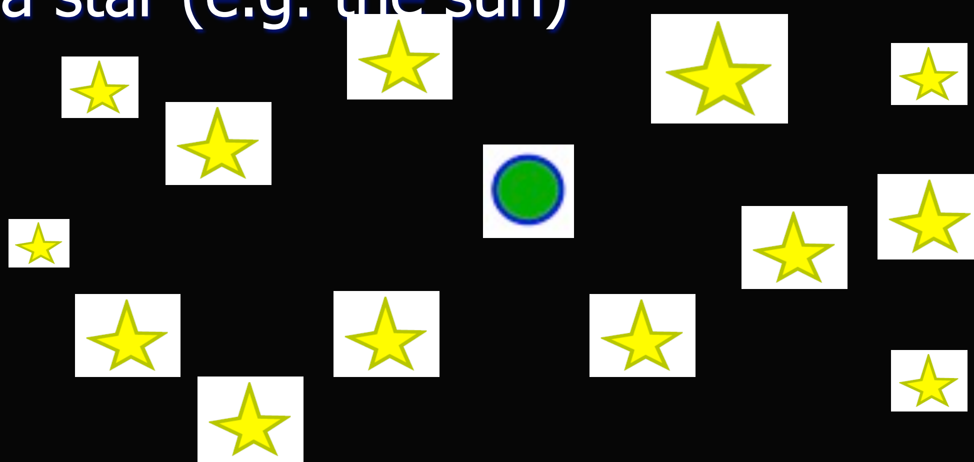
- Components of the Universe
- Cosmic history
- The distance scale for the modern cosmologist
- Olber's paradox and the cosmological principle

Olber's Paradox (1826): Why is the sky dark at night?

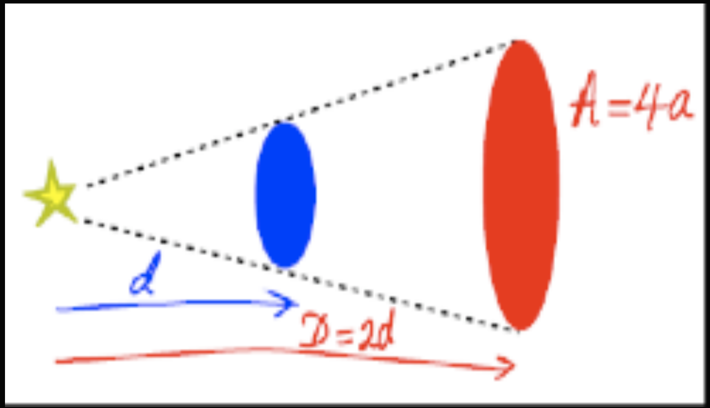
- Assume:
  - The universe is infinite
  - The universe is filled uniformly with stars
  - The universe is eternal and unchanging
- Can show that every line of sight should end on a star

  $\Rightarrow$ The night sky should be as bright as the surface of a star (e.g. the sun)



Deriving Olbers' Paradox

- Total flux we receive from a star goes as $1/d^2$



- Angular area of a star goes as $1/d^2$
- Surface brightness (light per unit area on sky)
  = total flux / angular area
  = contant
- If every line of sight ends on a star, the sky should be as bright as the average star.

Deriving Olbers' Paradox: a more mathematical approach!

- We start with the radiative transfer equation:

$$\frac{dI_\nu}{d\tau_\nu} = \frac{j_\nu}{\alpha_\nu} - I_\nu \qquad \tau_\nu = \int \alpha_\nu ds$$

where I is the specific intensity, tau the optical depth over path s, j the emissivity and alpha the absorption coefficient.

- Here $\alpha_\nu = n\pi^2 R$ $\quad j_\nu = n\pi^2 RB(\nu, T)$

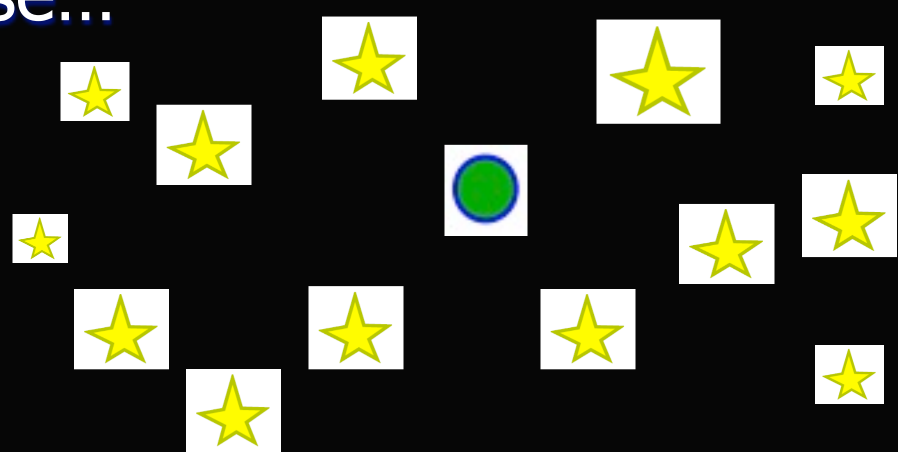
where n is the number density of stars and R the radius the the star. Here alpha is one over the mean free path.

$$I_\nu = \exp(-\tau_\nu)I_\nu(0) + (1 - \exp(-\tau_\nu))B(\nu, T)$$

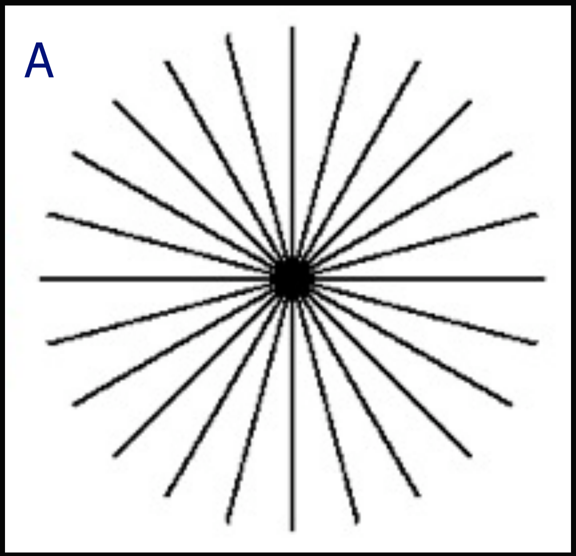
- Hence we have
- So as s goes to infinity I goes to the brightness of the

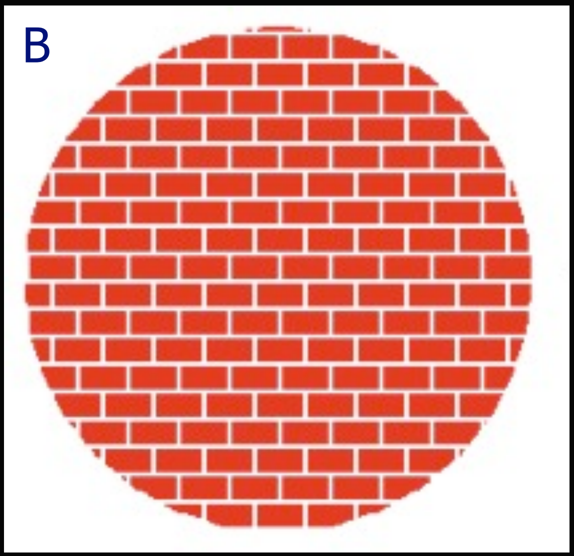
What do you think the solution to Olber’s paradox is?

A. Light is absorbed by dust
B. The Universe is expanding
C. The Universe is finite in extent
D. The Universe has a finite age
E. Paradox!!!! What paradox!!!! This is not a paradox!!! Because…

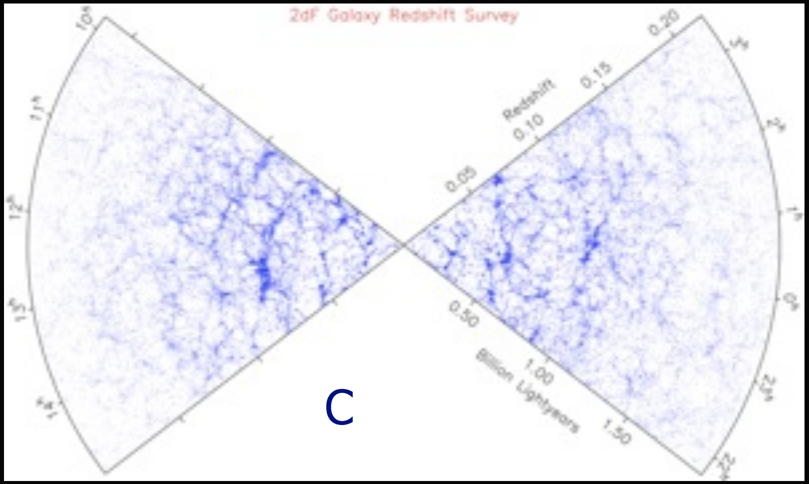


Homogeneity and Isotropy





Picture from http://www.astro.ucla.edu/~wright/CMB-MN-03/A275.ps

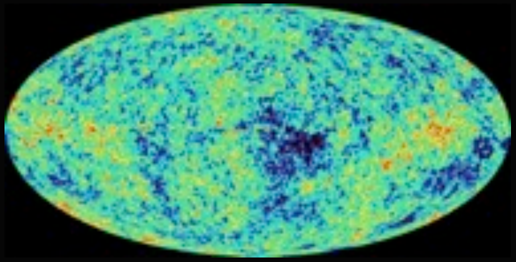


- We believe that we live in a homogeneous and isotropic Universe.
- Figure A: isotropic and not homogeneous
- Figure B: not isotropic and homogeneous
- Figure C: isotropic? and/or homogeneous?

The Cosmological Principle

- The Universe looks the same wherever you are
  - We do not live in a special place in the Universe
  - The universe is isotropic and homogeneous
- Believed true as we look on larger and larger scales
- Supported by observations e.g.
  - galaxy surveys
  - Cosmic Microwave Background

WMAP results



Color scale zoomed by 10^5

After these sections, you should be able to:

- Give a brief history of cosmology and it’s contents.
- Summary of the history of the Universe
- Derive and explain Olbers’ paradox
- Summary of the contributions to our motion through the Universe.
- State the cosmological principle

END for now!!!