Astrophysics and Nuclear Astrophysics (LPHY2263)

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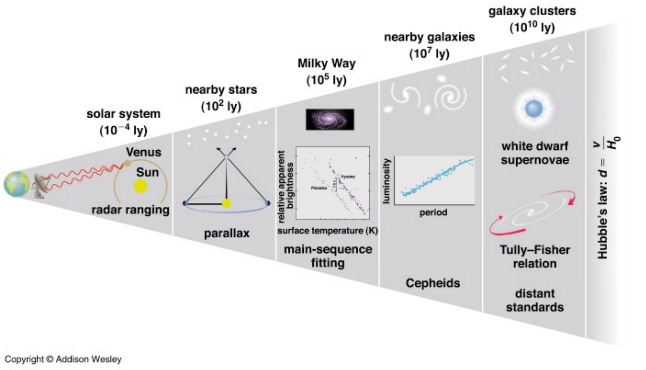
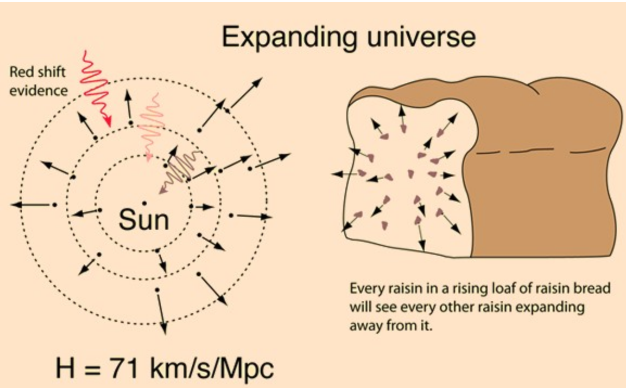
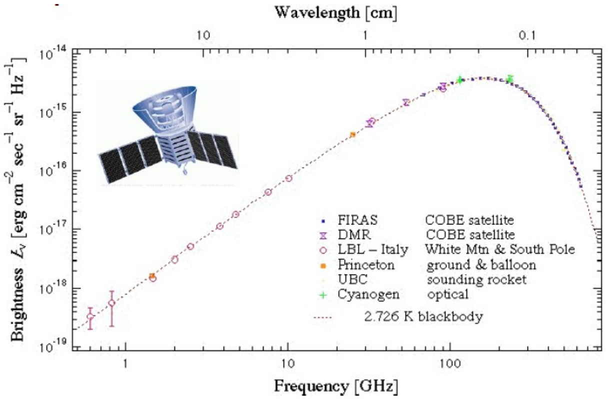
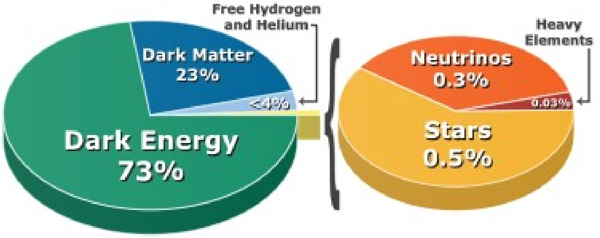
Chapter #9

- Introduction to Cosmology
  - Galactic red shifts and distances
  - Hubble Law
  - Expanding Universe
  - Big Bang
  - Quark-Gluon Plasma
  - Inflation
  - Accelerating Universe









Red shift / blue shift

Definition of *red shift / blue shift*:

$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e} = \frac{\lambda_0}{\lambda_e} - 1$$

It has three components:

$$z_{\text{total}} = z_{\text{grav}} + z_{\text{physical}} + z_{\text{H}}$$

The first term (z_{grav}) is due to the effect from gravity:

$$\frac{\Delta\nu}{\nu} = \frac{-GM}{c^2}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

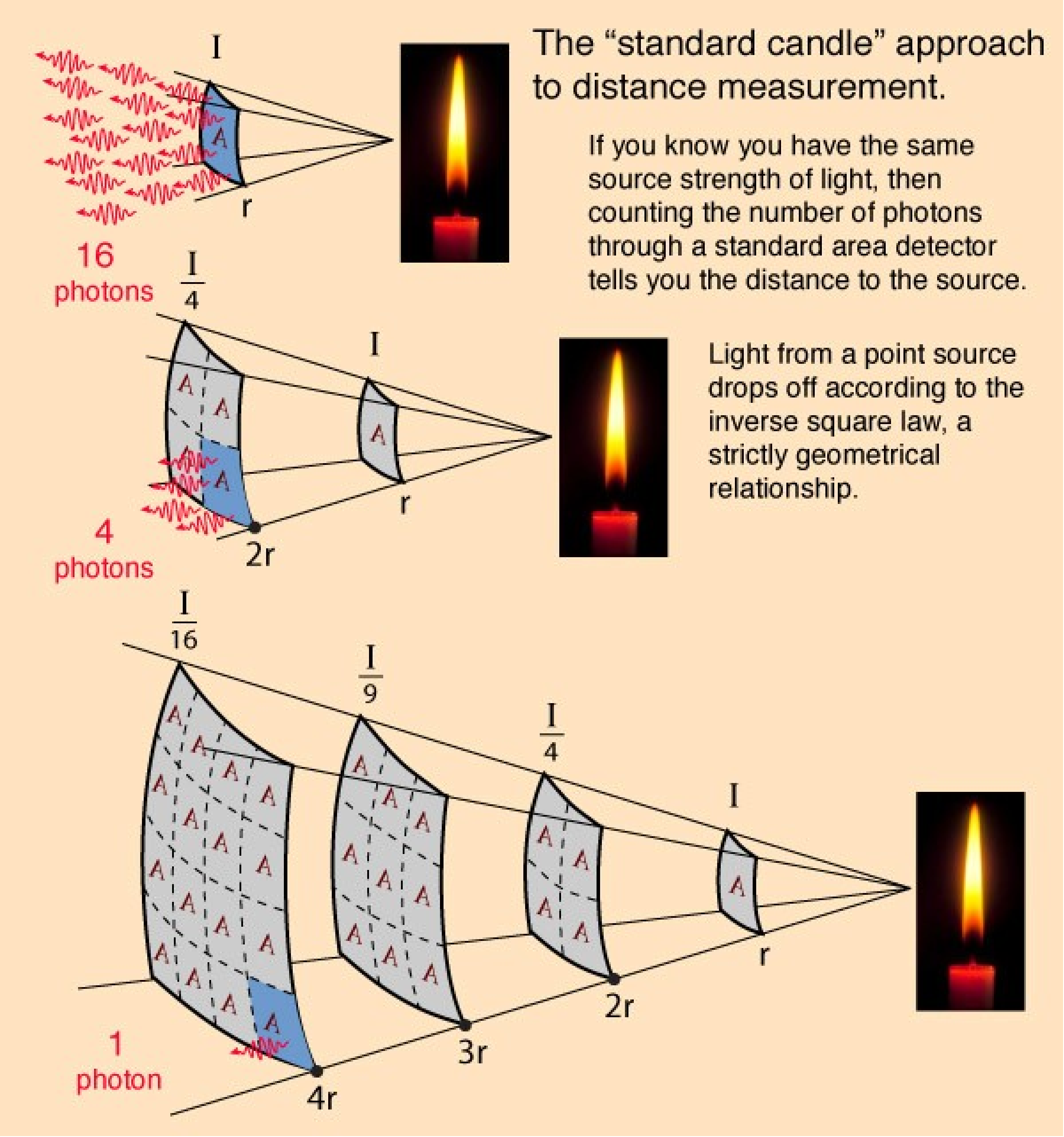
The second term (z_{phys}) is due to motion within galaxy / cluster / supercluster; the third term (z_H) is cosmological and we will try to understand it today

First surprising discovery

- Between 1914 and 1922, Vesto Slipher used this technique to measure the speed of 25 galaxies
- He found that 21 out of 25 had a redshift, i.e., they go away from us
- Some of them with speeds of > 1000 km/s
- Local or global phenomenon? Not known, because distance was not measurable yet
- Hubble was able in 1929 to measure their distances, and notice a speed-distance relationship
- Next slides are about how we measure galactic distances over very large scales

Measurements of distances

- Parallax method cannot work for galaxies
  - *(Do you remember why?)*
- Methods that work are based on "standard candles", i.e., objects of known luminosity, for example:
  - Cepheids
  - Most luminous supergiants
  - Supernovae
  - Tully-Fisher relation



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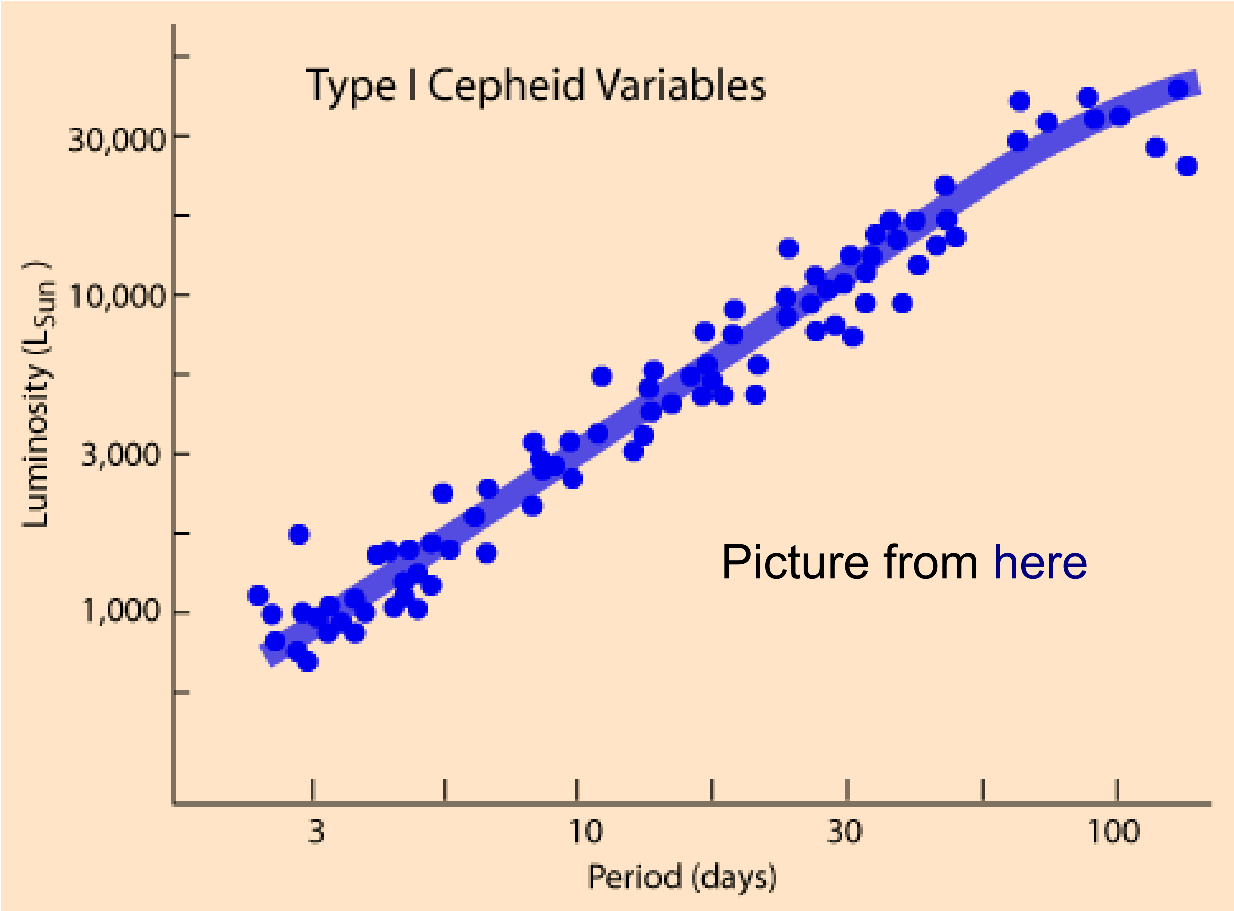
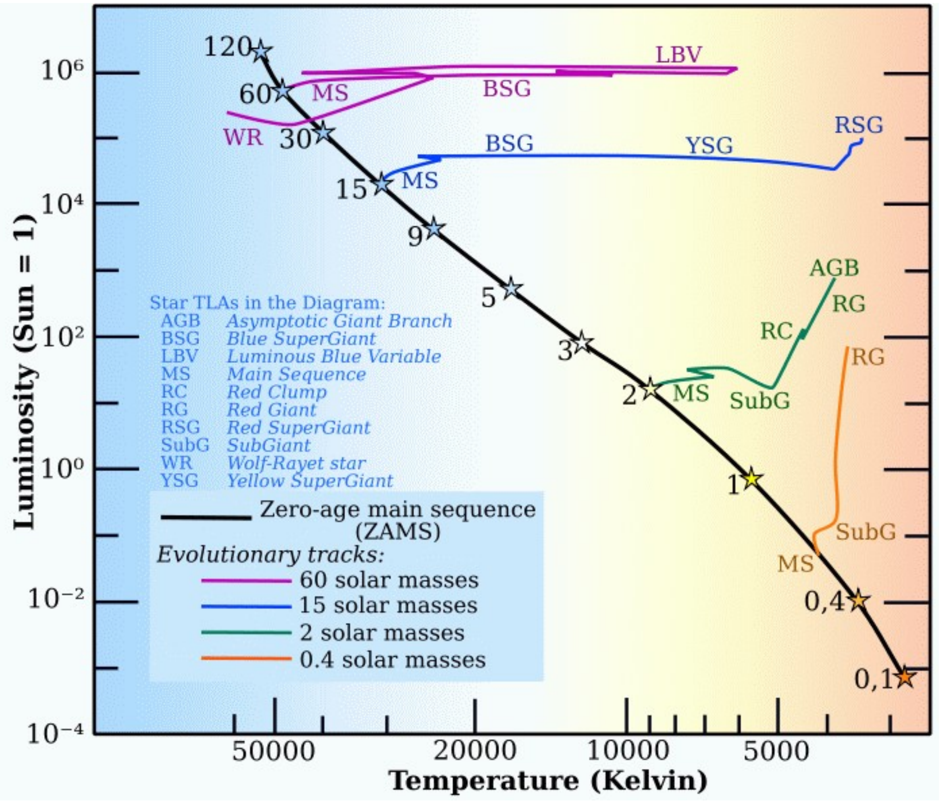
Cepheids



Cepheid variables can measured out to ~20 Mly (million light years)

Most luminous supergiant

- The brightest supergiants in a given galaxy will have about the same absolute magnitudes
  - -8 for red supergiants and -9 for blue supergiants
  - Visible from about 50 Mly and 80 Mly respectively
  - Method works because there is a well-defined maximum in path in the H-R diagram of a star that goes out of the Main Sequence

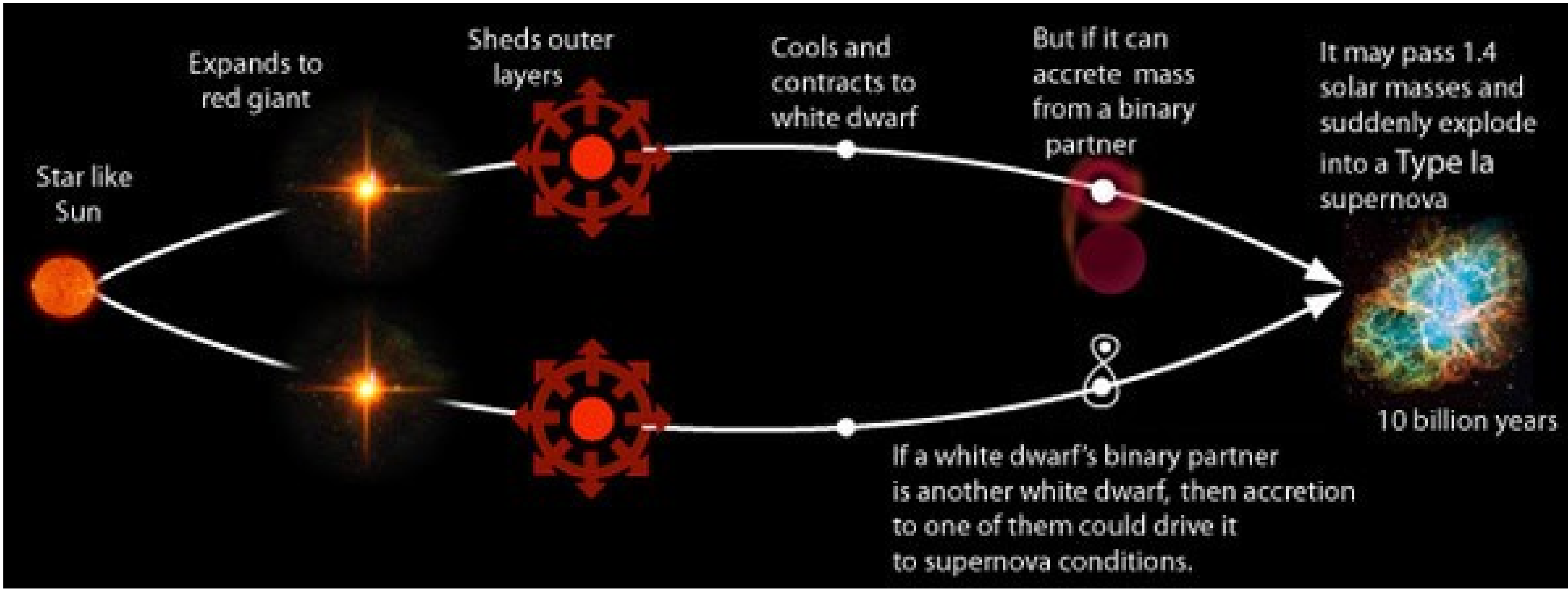


Remember chapters 4 and 5 of these lessons

Supernovae

- Beyond 300 Mly, good standard candles are the supernovae, which can reach a peak magnitude of -19
- In principle, such a magnitude should be visible to 8 billion light years
- Supernovae of types Ib, Ic and II are not good candles, because they have too much variety in L
- Type-Ia supernovae instead are very uniform, for the reason explained in the next slide

Type-Ia supernovae



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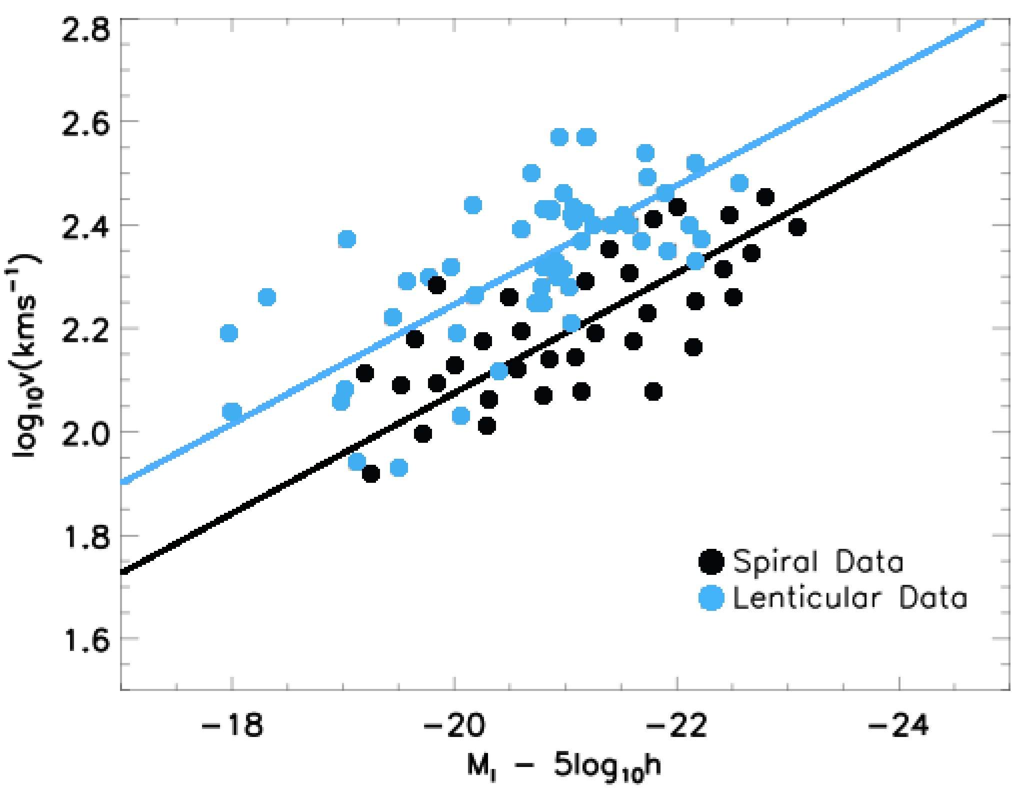
Accretion is gradual, and explosion happens as soon as the mass passes the Chandrasekhar threshold of 1.44 M_{sun}.

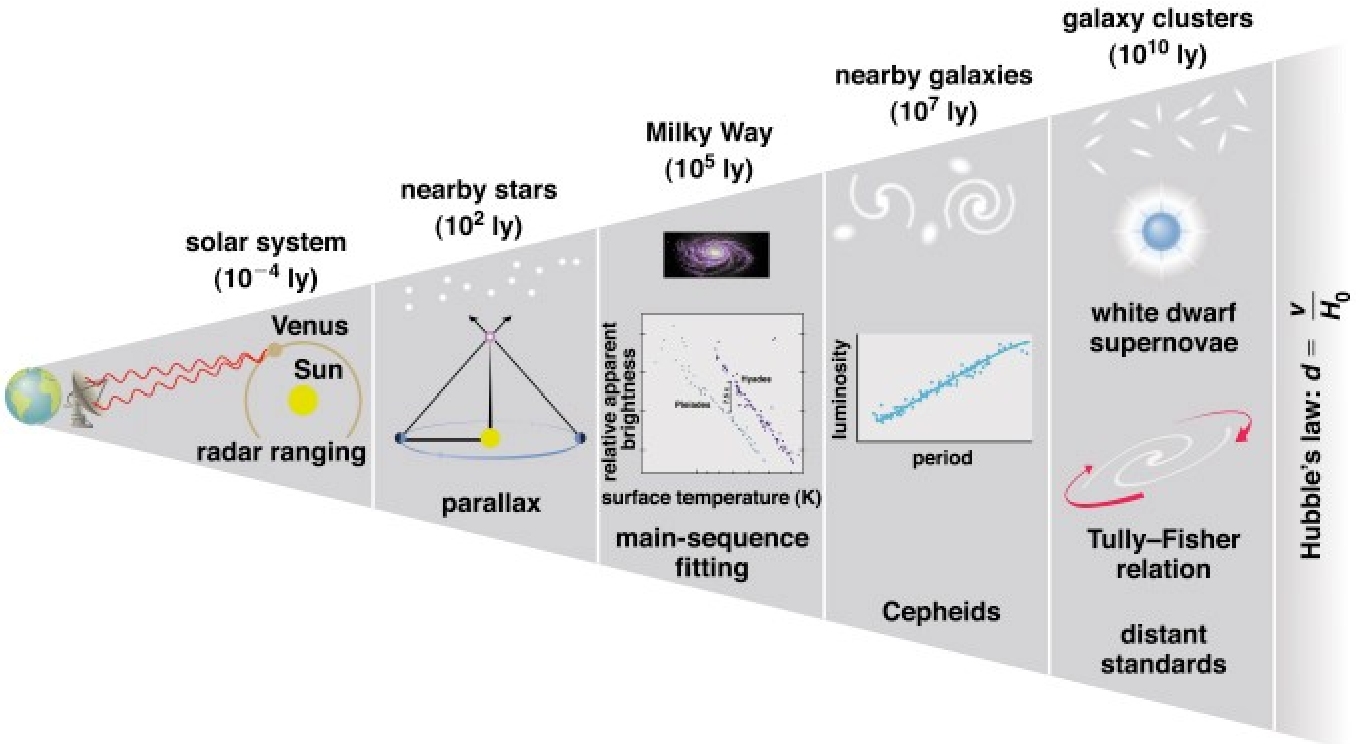
Important point: it always starts at the same mass. Therefore, the energy output is almost the same

Tully-Fisher relation



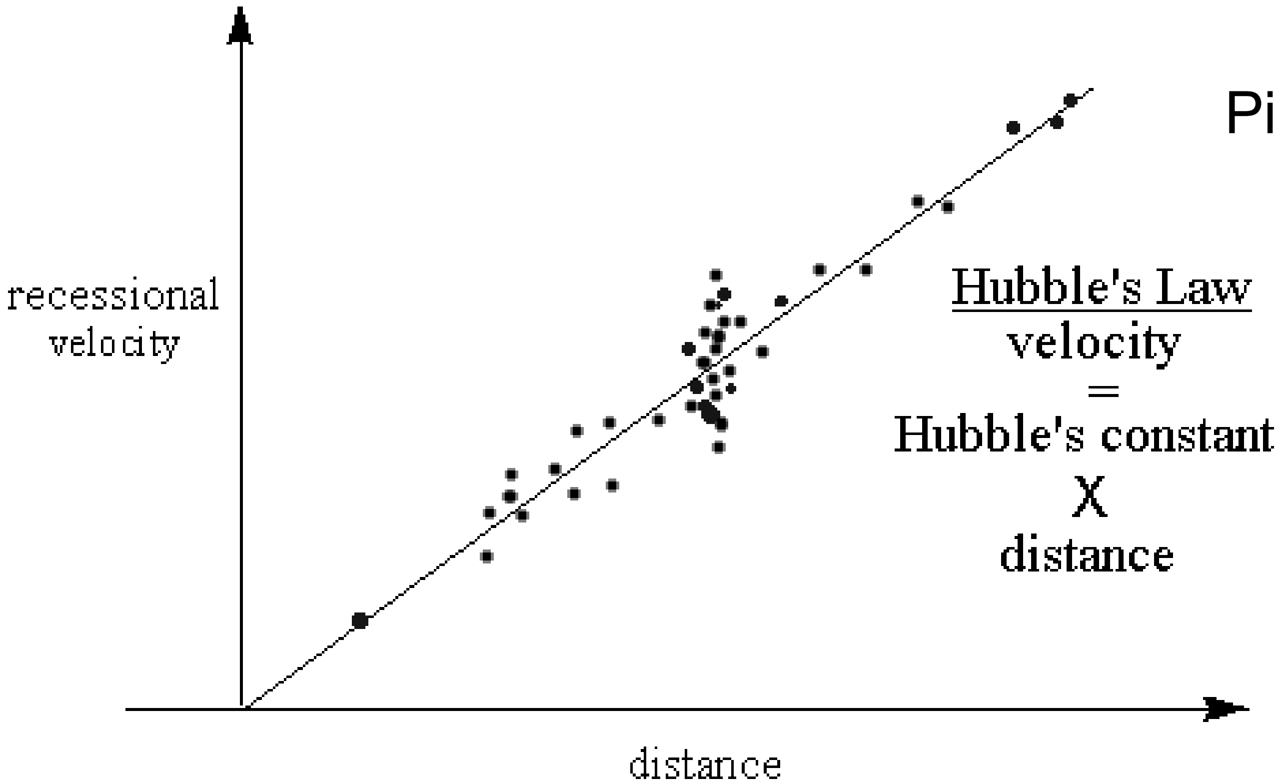
Empirical relation between a galaxy's intrinsic luminosity and the width of its emission lines, which is related to its rotation speed

The "distance ladder"



Each step is validated and calibrated by the previous one and helps to calibrate the next one

Hubble's law



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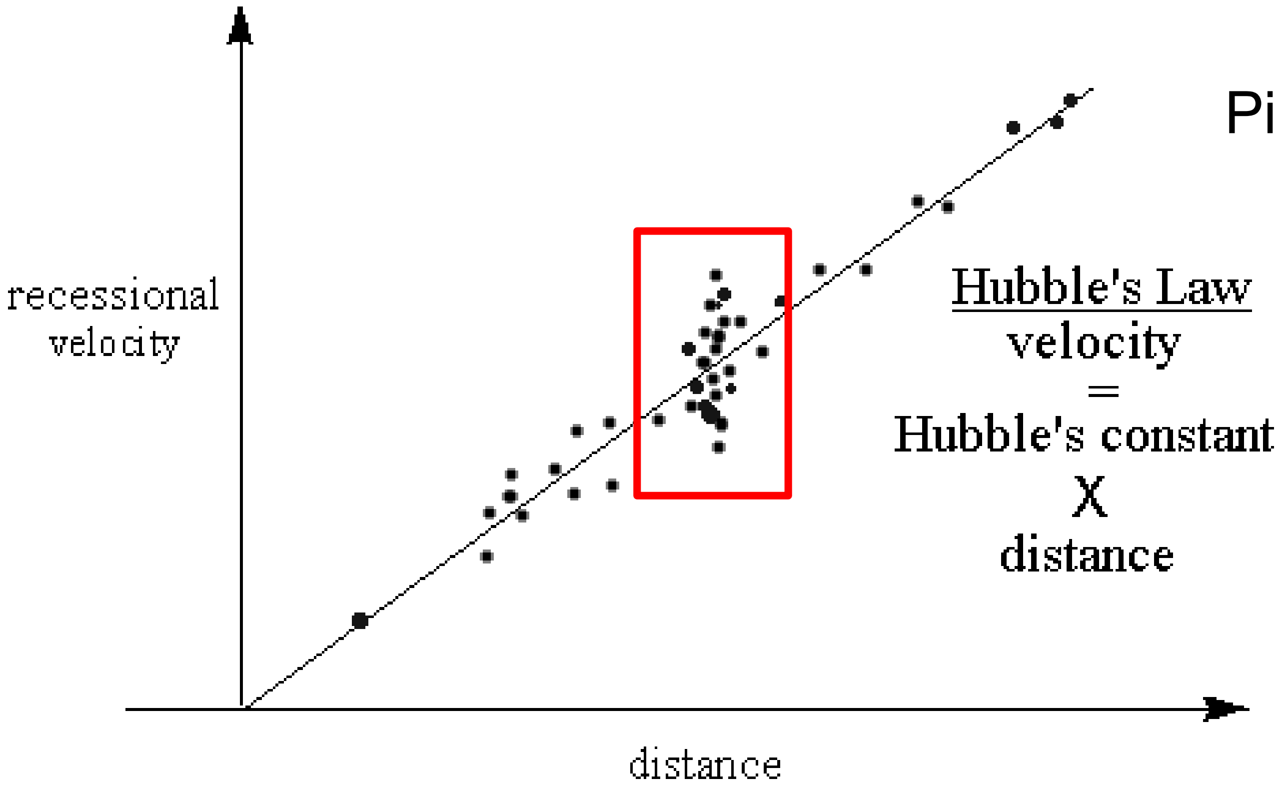
- Deviations from the straight line are attributed to the fact that all galaxies have additional motion in addition to pure expansion
- This is called the "cosmic velocity dispersion" or "cosmic scatter"

Hubble's law



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- Here in the diagram there are a bunch of galaxies at around the same distance but spread out a lot in velocity
- Attributed to galaxies from the Virgo cluster: extra velocity from cluster orbital motion, that can be very large

Type-Ia supernovae give very precise measurements:

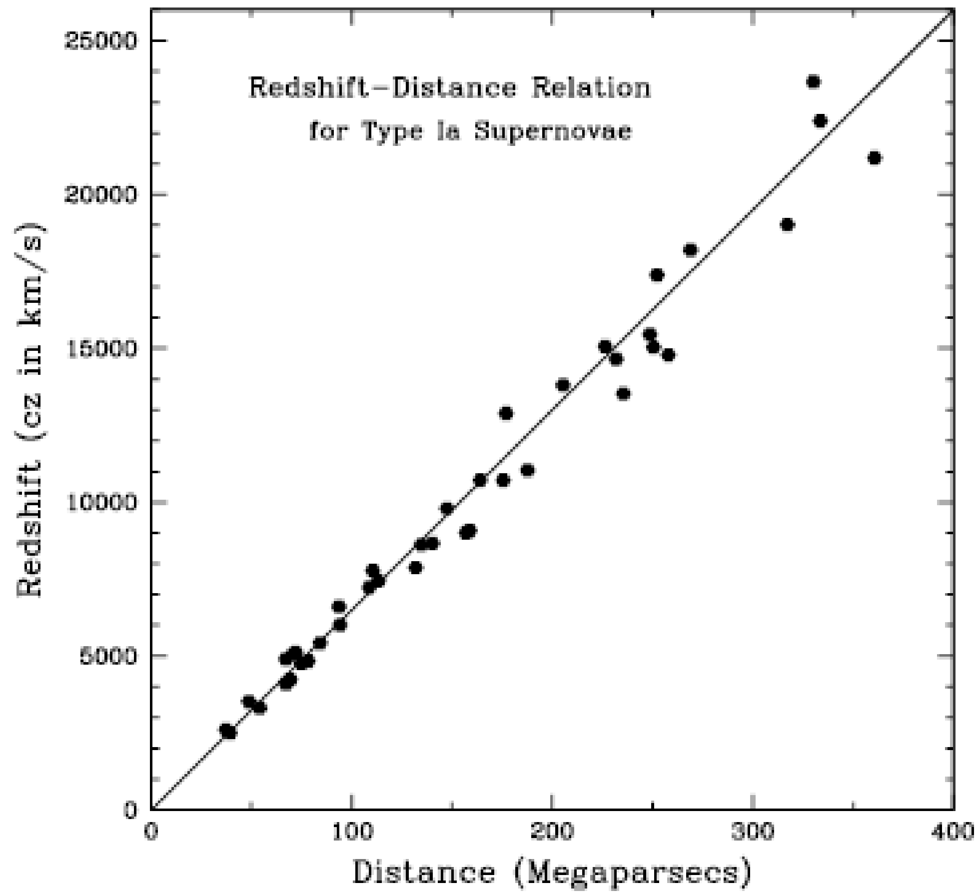
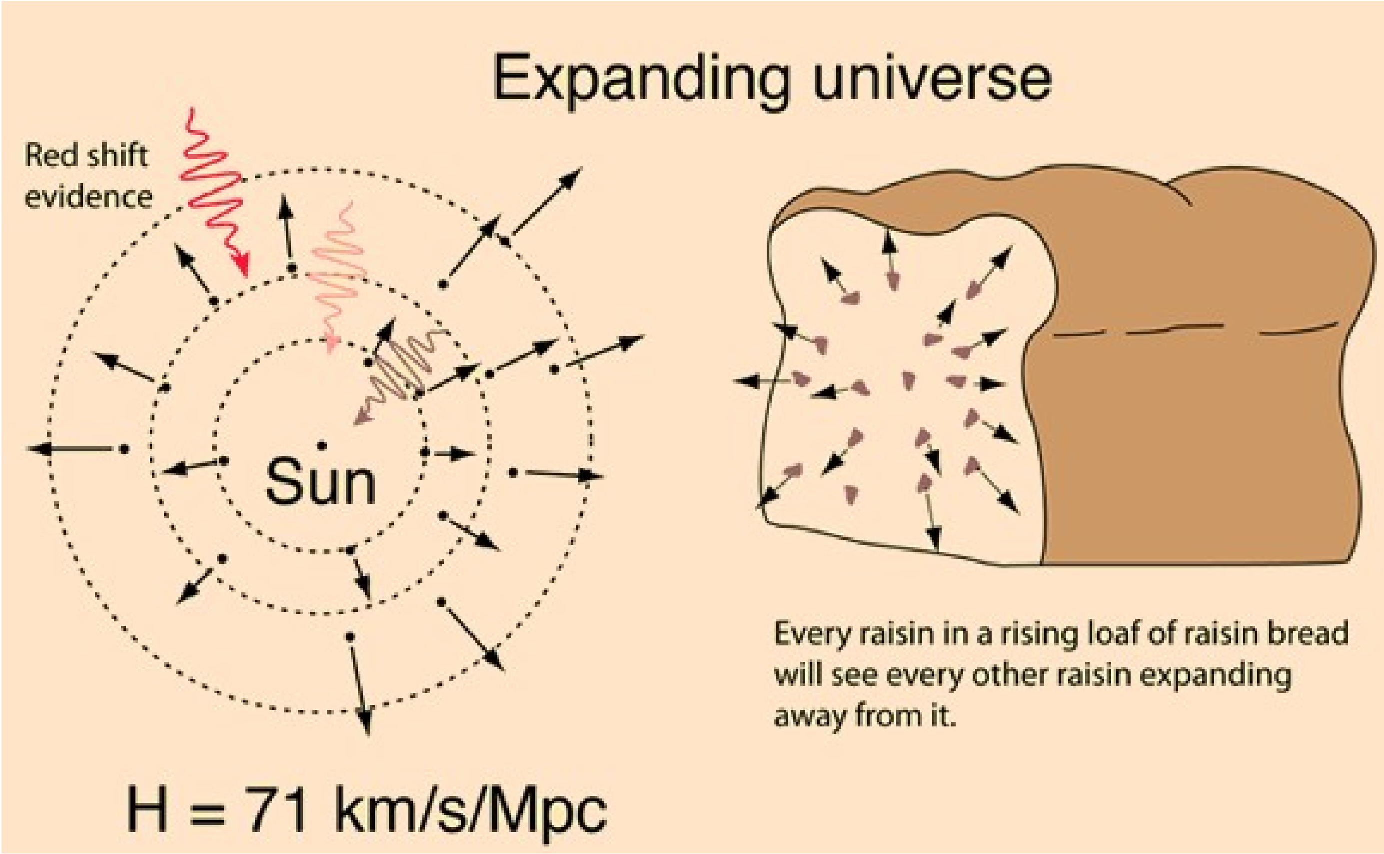


Figure 1. The redshift–distance relation for type Ia supernovae from the Calan-Tololo supernova survey (from data courtesy of S Jha, Harvard-Smithsonian). Redshift is given as *cz* and the distance is in megaparsecs (1 Mpc is approximately 3.26 million light years). The line through the data represents a Hubble constant of 65 km s^{-1} Mpc^{-1}, close to the value astronomers measure today.

Cepheids also help a lot at small distances; combination of both methods gives ±5-10% precision on H

Expanding Universe



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Questions

- This is an expansion of space itself; does it mean that galaxies become larger too?
  - (...and solar systems, and planets, and ourselves...)
- At sufficiently large distances, the velocity calculated from the redshift is larger than c; does it mean that relativity is wrong?
- If you assume that the v=Hd relationship was always true, how old is the Universe?

Big Bang

- Simply by extrapolating to the past, we are forced to think that at some point (at time 1/H) the current Visible Universe was very small, and therefore very dense
- George Lemaître (UCL) was the first to propose that all Universe started in a "singularity"
  - Einstein and others studied the consequences in General Relativity, based on two principles: universality of the physics laws, and the "cosmological principle", which states that the Universe is <u>homogeneous and isotropic at large scales</u>
- Not obvious that the singularity must be taken literally: it may be that a coherent theory of quantum gravity, when we will know it, will get rid of singularities
  - (e.g., it is plausible that the limit is a volume of size ~h^3)

Alternative: the Steady State theory

- Not everybody was happy with a model that violates the intuitive idea that the Universe is invariant in time
- Fred Hoyle proposed an alternative, based on the principle that the Universe looks the same at any point in time ("perfect cosmological principle") → no start!
- To concile it with expansion, it meant that matter is continuously and uniformly created from vacuum
- The model started to loose popularity when we started to know phenomena (like quasars) that happened in the distant past but not anymore
- Then, the model was definitely dead when the following "smoking guns" of Big Bang were found

"Smoking guns" of the Big Bang

- The most striking prediction of the Big Bang concept is that, at the beginning, the Universe was very dense and hot
- The next slides present:
  - An indirect proof: primordial nucleosynthesis (it was hot enough to allow nuclear fusion)
  - A direct proof: Black Body radiation of the Universe

Primordial Nucleosynthesis

- There are indications that only part of the Helium in the Universe was produced by stellar nucleosynthesis:
  - Population I stars (e.g., the Sun): 70% H, 28% He, ~2% metals
  - Population II stars (i.e., poor in metals): 75% H, 25% He, < 0.01% metals *(remember: "metal" means heavier than He, in astro jargon)*
- Where does the He in Pop.II stars come from?
  - If it comes from previous generation stars, where are the metals?
- When the Universe had less than 2 minutes: too hot for nuclei
- Around ~2 minutes, T~O(10^9 K) and started to be cold enough to allow ^{2}H formation without immediate fission; all n were used
- Between 2 and 4 minutes, most ^{2}H fused into ^{4}He
- After 4 minutes, too cold for nuclear fusion ($\Rightarrow$ no metals)

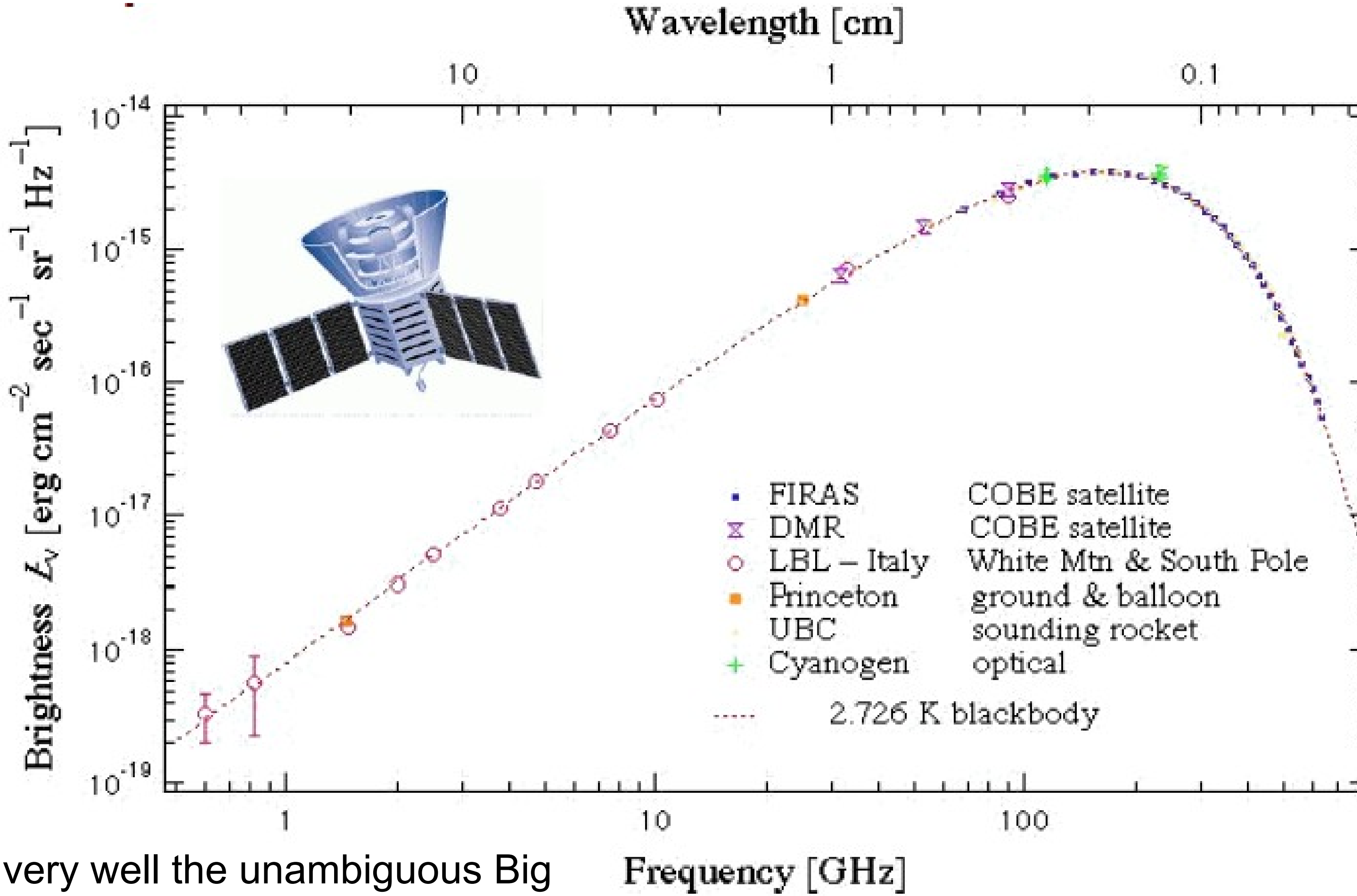
Cosmic Microwave Background (1)

- After nucleosynthesis, for 300k years nothing dramatic happens; in that period, Universe cooled down to 3000 K
- Before reaching that temperature, Universe was too hot to allow atoms to form
- Universe was a plasma of free electrons and nuclei (p, α)
  - Free electrons easily scatter photons
  - $\Rightarrow$ Universe was completely opaque to light
  - $\Rightarrow$ Perfect Black Body
- When T=3000 K, Universe suddenly became transparent
  - The oldest photons that we can observe come from that precise point in time, and were produced with a Black Body spectrum for T=3000 K; and then redshifted...

Cosmic Microwave Background (2)

- In 1965, Penzias and Wilson (telecommunication engineers at Bell Labs) mapped the microwave sky
- There was a faint isotropic noise
- They made very deep studies to understand the source of that noise
  - It was not electronic noise from the amplifiers
  - And not the pigeons that were "dirtying" the antennas
  - ...etc.
- In the end, they discovered that it was of cosmic origin
- It corresponds to a Black Body of 2.7 K

COBE satellite result, 1989

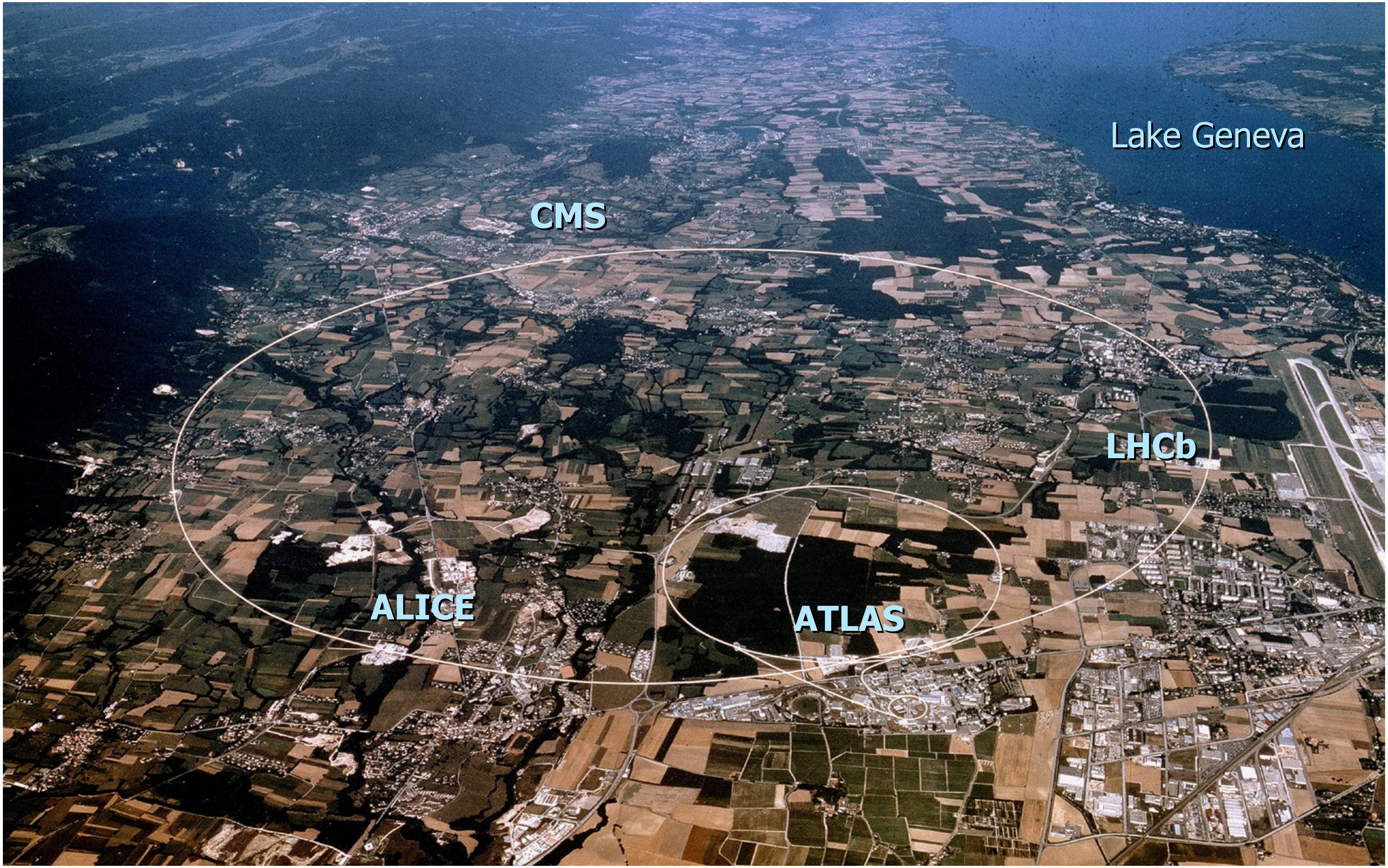


It fits very well the unambiguous Big Bang prediction of a perfect Black Body with a <u>single</u> temperature

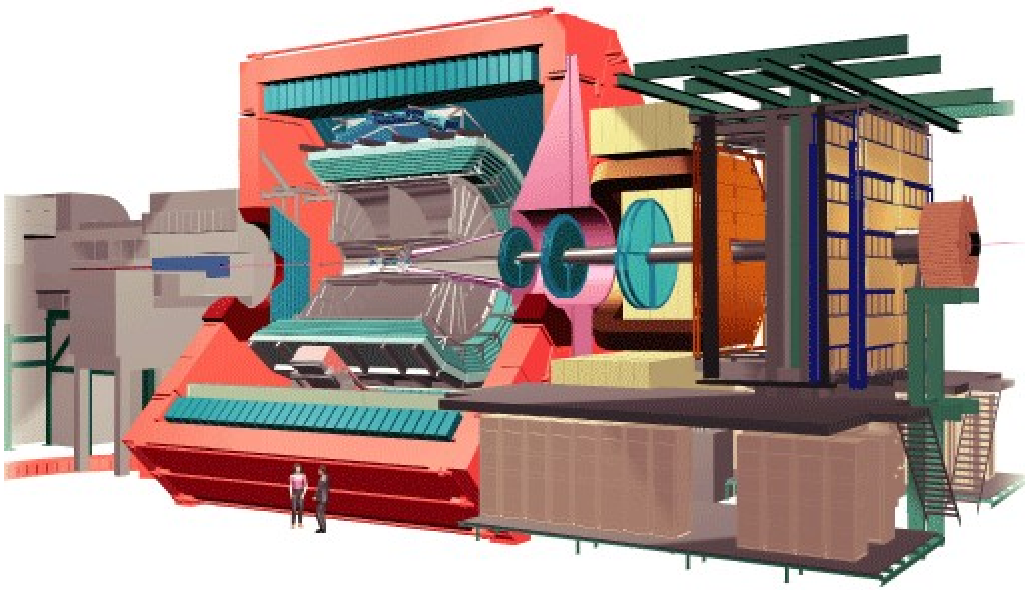
Quark-Gluon Plasma (QGP)

- There must have been a period in the history of the Universe (order of milliseconds) when temperature was so high that even protons and neutrons could not form
  - i.e., Universe was filled with a plasma of quarks and gluons
- The properties of QGP (e.g., T of phase transition; liquid or gas; etc.) affected the evolution of the Universe
- The problem is that we have no idea of the temperature of this phase transition
  - Astronomical observations can't tell us much, because this was much before the "first light"
  - Quantum Chromo-Dynamics (QCD) is not in the perturbative regime in these density conditions → calculations are very imprecise, and based on semi-empirical models

Large Hadron Collider (LHC)

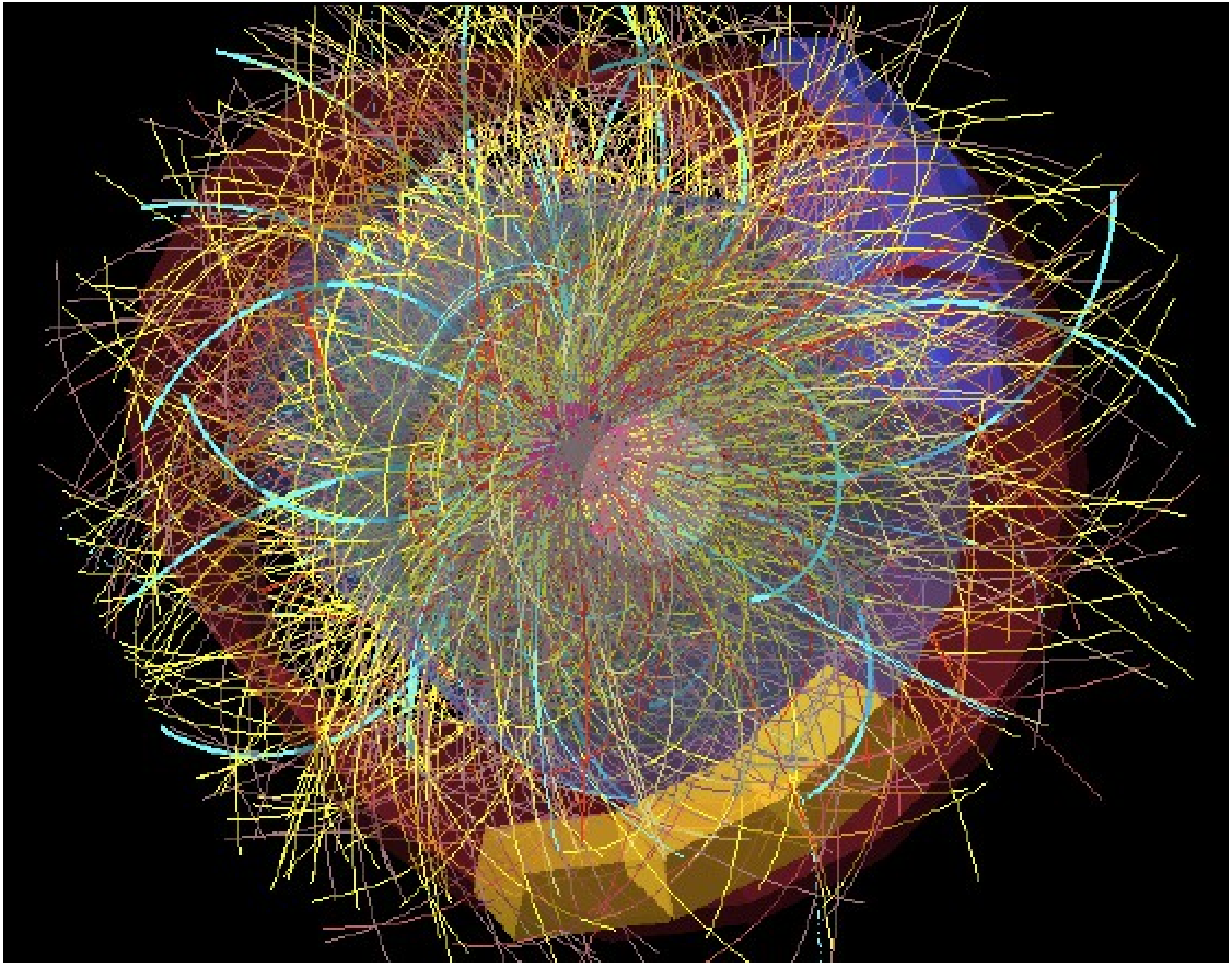


ALICE experiment
(A Large Ion Collider Experiment)



- One month per year, LHC accelerates heavy-ions (so far only Pb) instead of the usual protons
- The goal is to create, for a short time, a quark-gluon plasma and therefore study the properties of matter in a very young Universe
- The ALICE detector is optimized for those studies (although ATLAS and CMS are somewhat complementary also on that)

Pb-Pb collision in ALICE

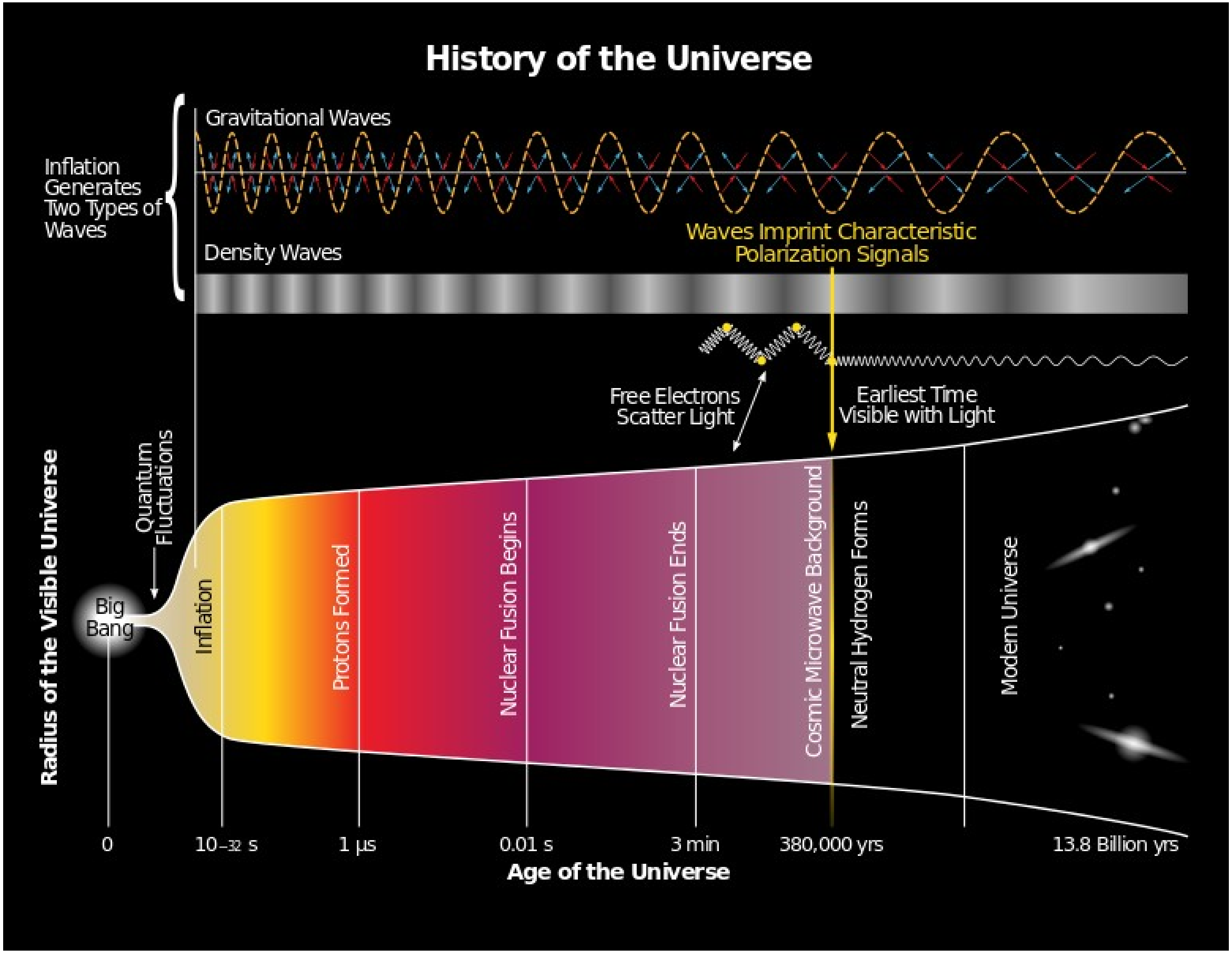


Three main historical problems of the Big Bang theory

- Horizon problem
  - Although space may expand faster than c, Relativity imposes that no information can travel faster than c
  - If so, how comes that the Black Body temperature is homogenous on so large scales? "Thermalization" requires exchange of energy
- Flatness problem
  - The geometry of the Universe seems very flat; but any departure from flatness should have been amplified
  - There is probably a global curvature, but several orders of magnitude less than predicted by General Relativity
- Magnetic monopoles
  - Grand Unification Theories predict magnetic monopoles; Universe must have enough temperature to create them

Inflation (1)

- An unknown scalar field permeates the Universe (like the Brout-Englert-Higgs field, but with a larger mass)
- At a certain temperature it underwent a phase transition, which released a lot of energy (analogy: think about ice↔water transitions)
  - This phase transition happened very early in the history of the Universe because the mass of the field's quanta is very large and therefore T is very large
- This sudden release of energy caused, for a short period, an exponential expansion of the Universe

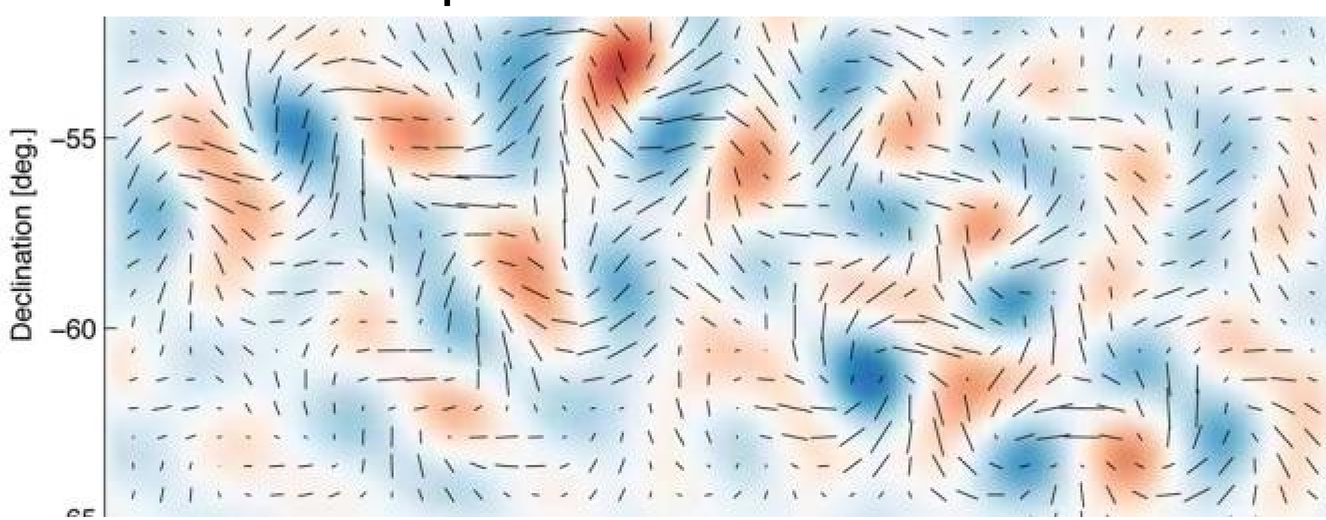

History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10-32 s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

Inflation (2)

- Horizon problem
  - Black Body temperature is homogenous on large scales just because those corresponded to a very small volume, such that it thermalized quickly
- Flatness problem
  - Departures from flatness were indeed amplified, but then space was so much inflated that global curvature became small again
- Magnetic monopoles
  - Grand Unification Theories created them in large quantities, indeed, but this huge expansion has diluted their density so much that they became extremely rare
  - (However, some experiments are still looking for them...)

Gravity waves from Inflation

- One of the prediction of Inflation is that a lot of energy was released in the form of gravity waves
- In General Relativity, gravity is a tensorial field (gravitons have spin=2)
- Waves of vectorial fields (spin=1) cause movements up and down, waves of tensorial fields cause torsions
- Recent excitation when the BICEP2 collaboration seemed to have measured this torsion of space:

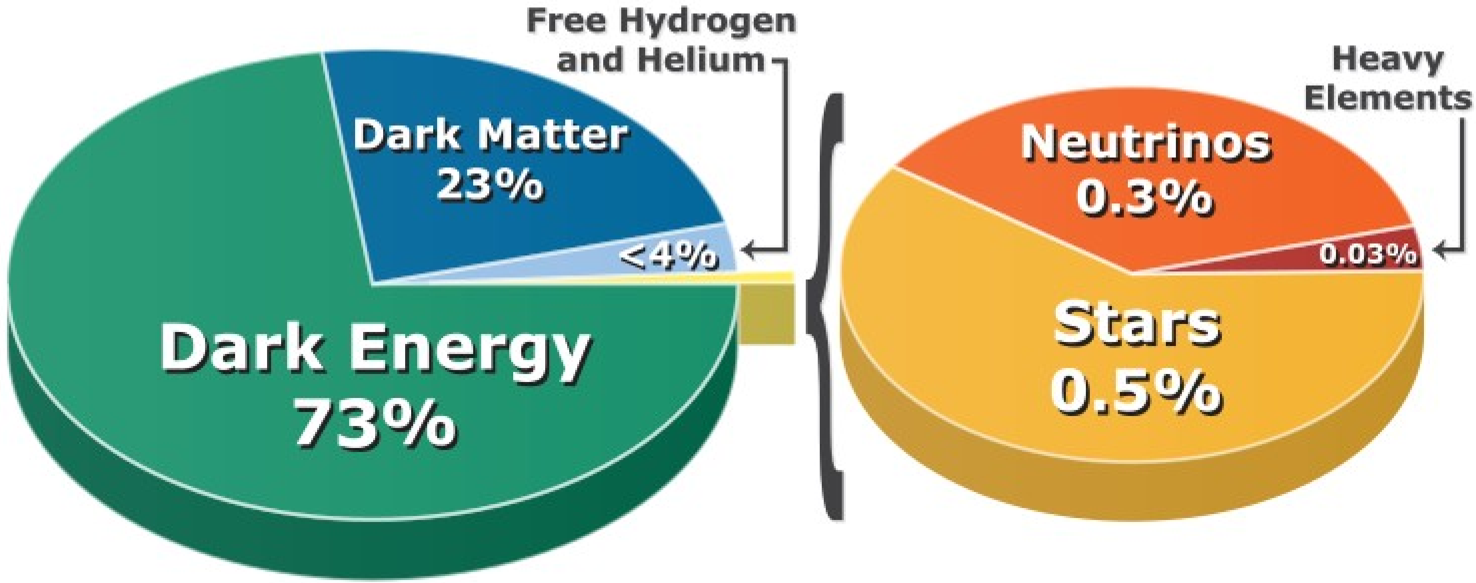


- Status: **not confirmed** (foreground subtraction was wrong)

Accelerating expansion

- The Hubble constant is constant only in space, not in time
- The redshift data on the most distant supernovae have shown that the expansion of space is currently accelerating (H is increasing), since around half of its life
- This can be accommodated in the equations by adding a term of pure energy of the space (not linked to any source) that has negative pressure; called "Dark Energy"
  - Analogy: space is like a spring that releases its potential energy into its expansion
- We don't know what it is, yet
- Very recent research line; attend C.Ringeval's course and the specialistic cosmology seminars to know more!

Energy composition of the Universe



Picture from wikipedia