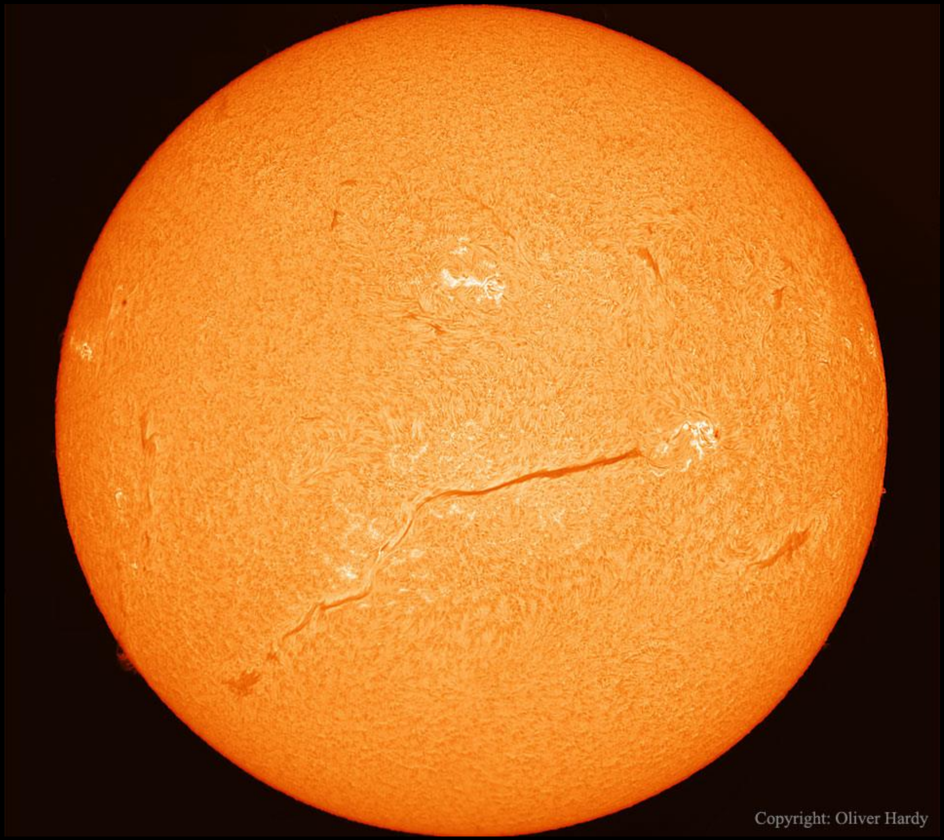
FK5024, Particle & Nuclear Physics, Astrophysics & Cosmology

Lars Bergström (Teaching assistant: Francesco Torsello)

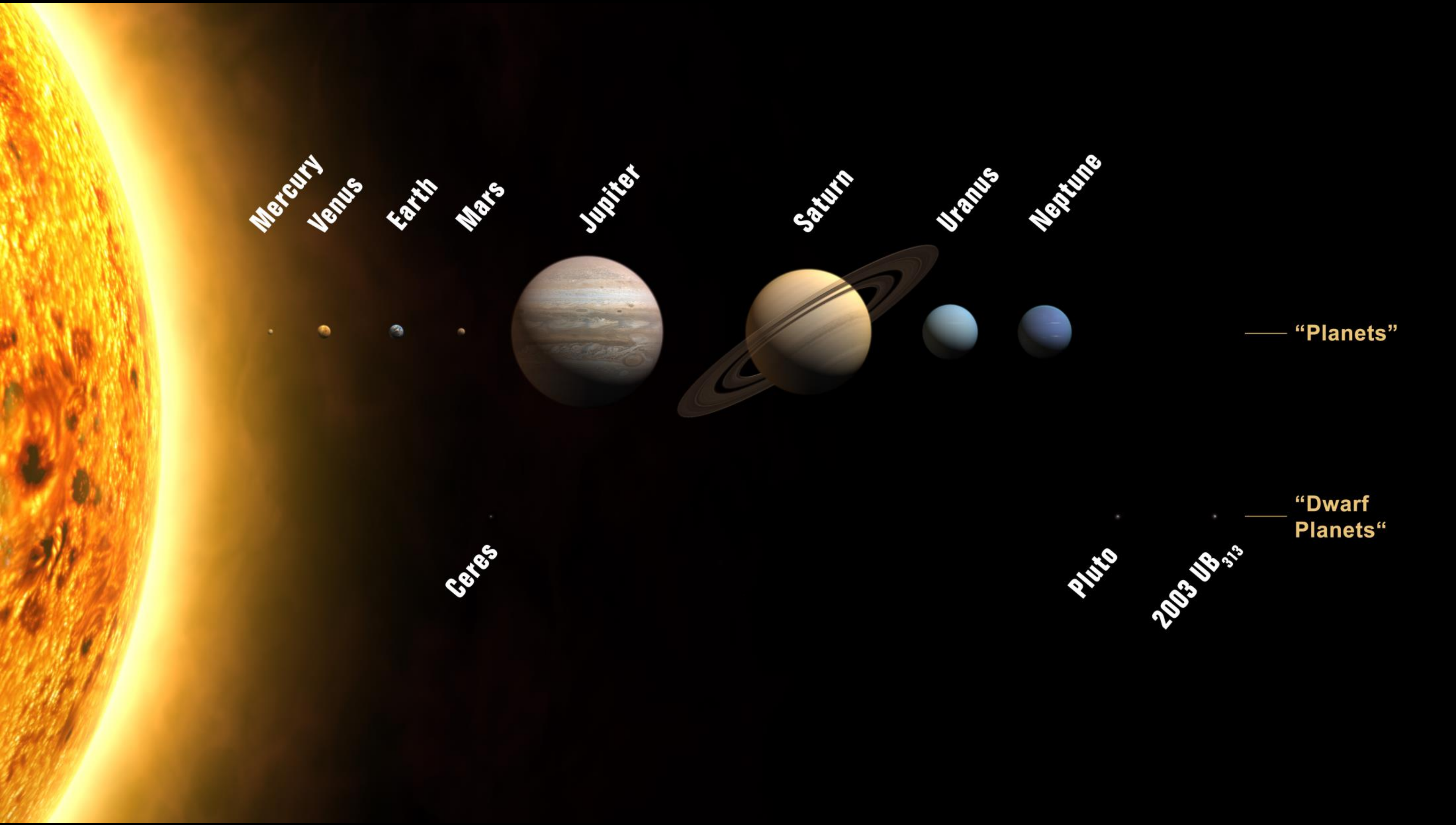
Lecture 12: Basics of modern astrophysics and cosmology

The nearest star – our Sun

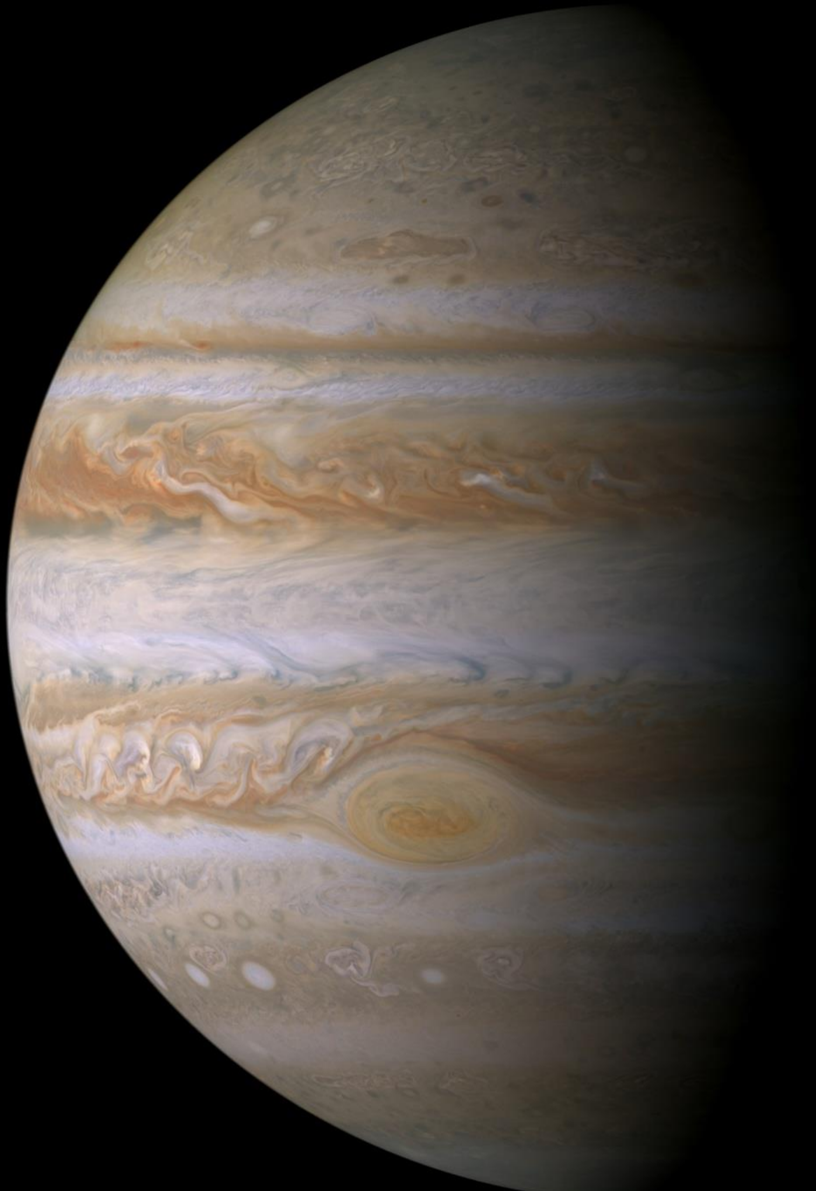


The Sun's energy is generated by nuclear fusion

Mass $= 1.989 \times 10^{30}$ kg (330 000 times that of the Earth)
Distance $= 1.496 \times 10^{11}$ m
Temperature $=$ 5800 K (15 million K at the center!)
Emitted power $= 3.9 \times 10^{26}$ W
Energy flux at Earth $= 1400$ W/m^2

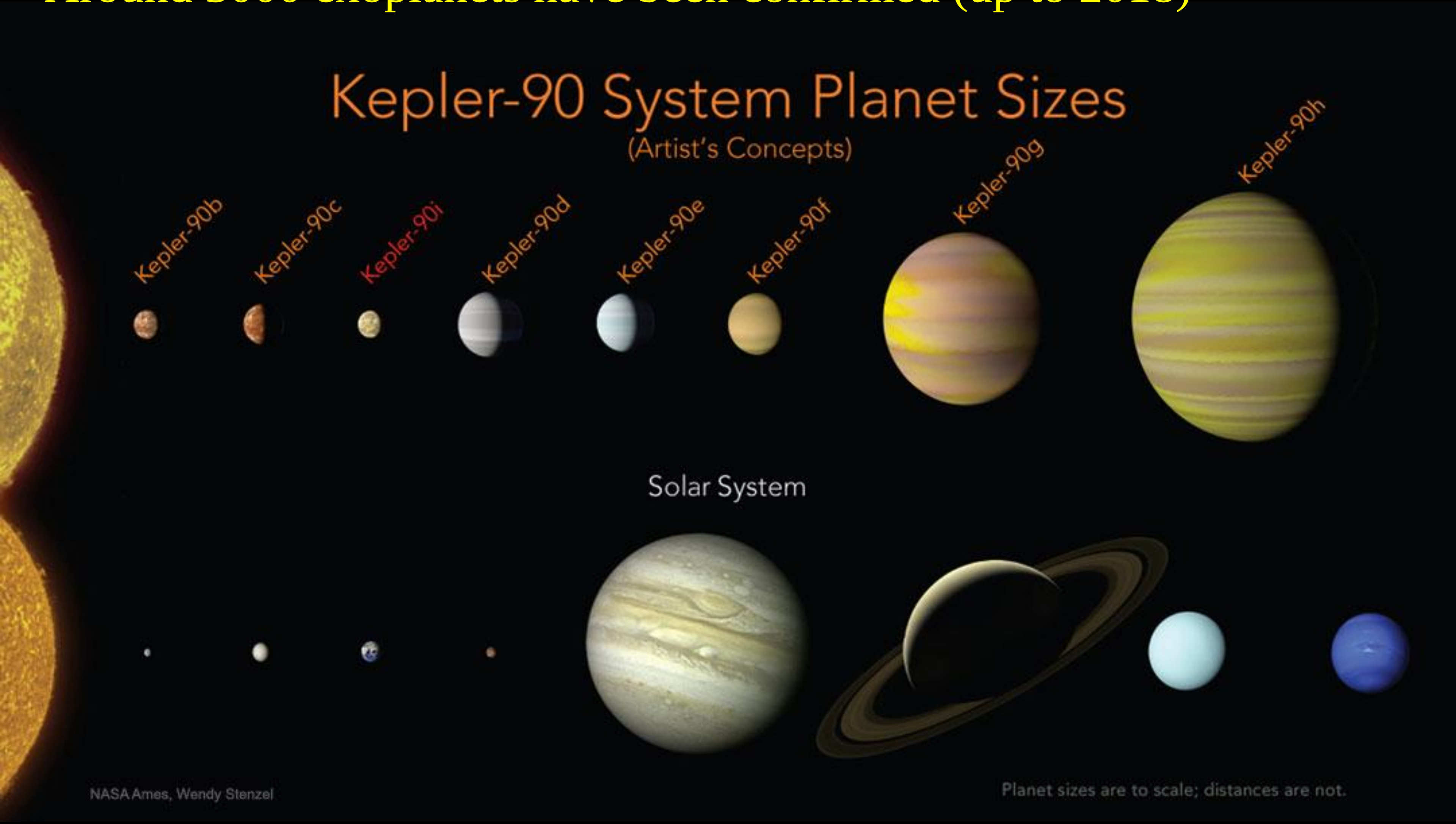


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
“Planets”
Ceres
Pluto
2003 UB313
“Dwarf Planets“



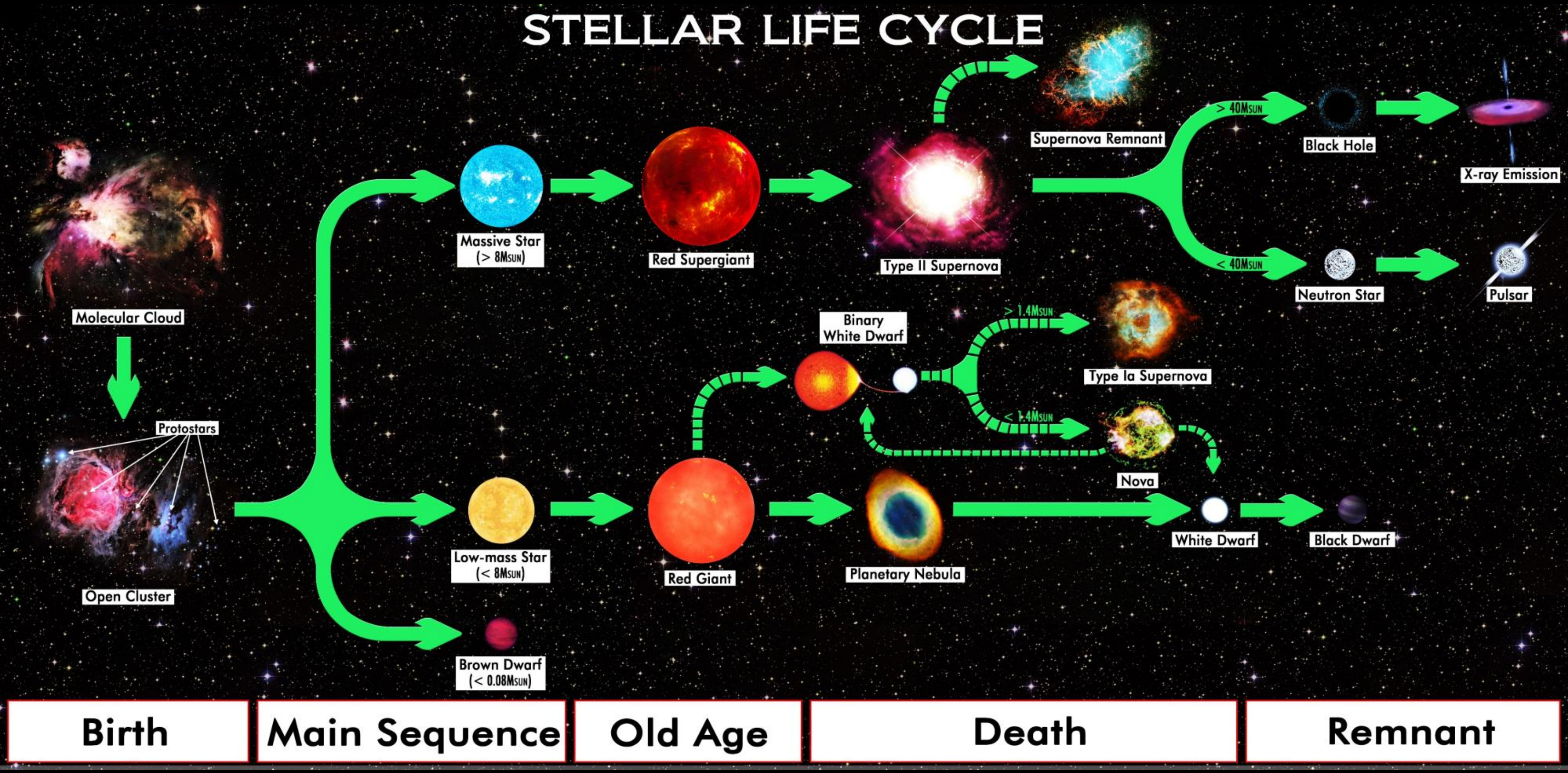
Extrasolar planets (exoplanets)

Around 3000 exoplanets have been confirmed (up to 2018)

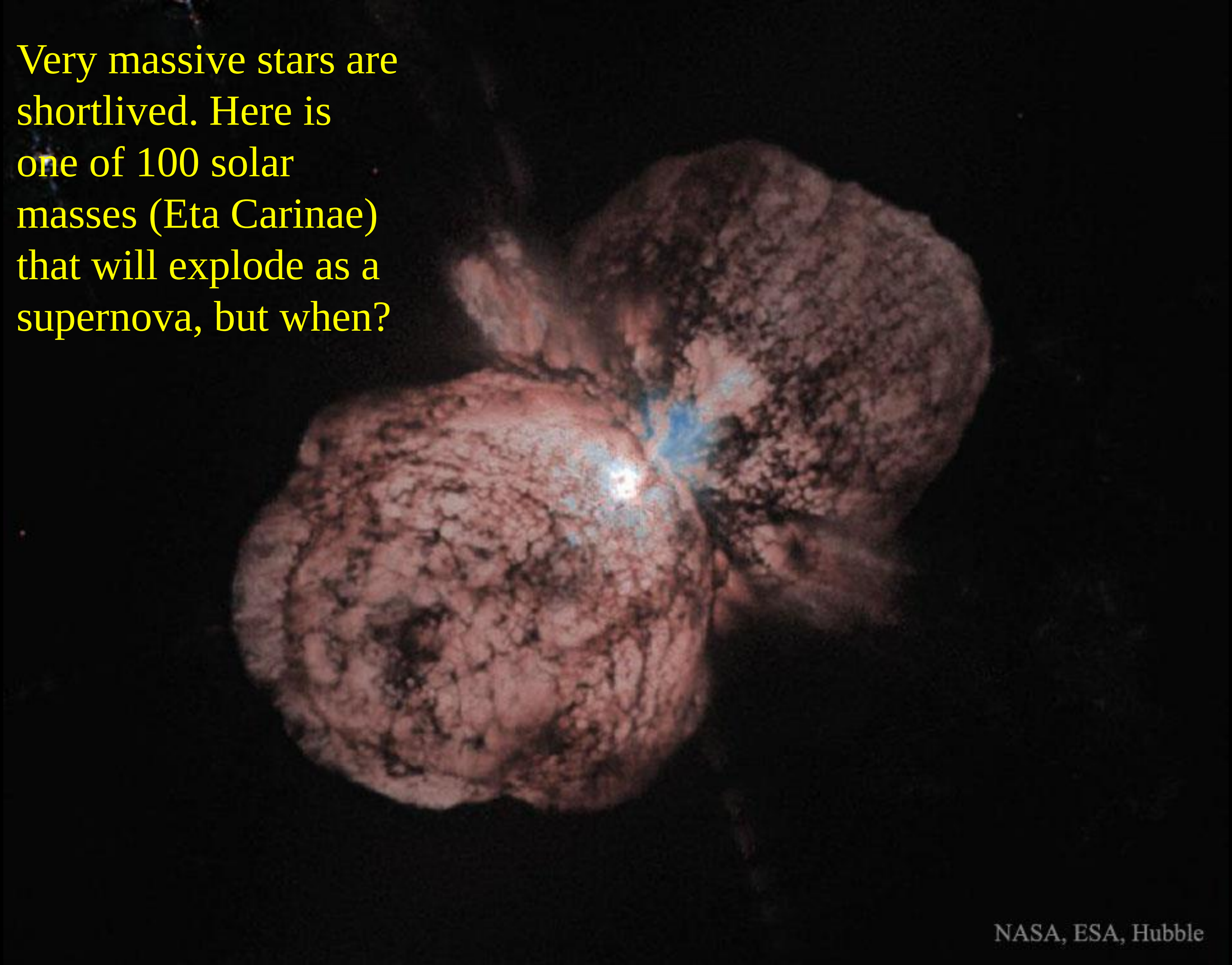


But is there life on other planets?

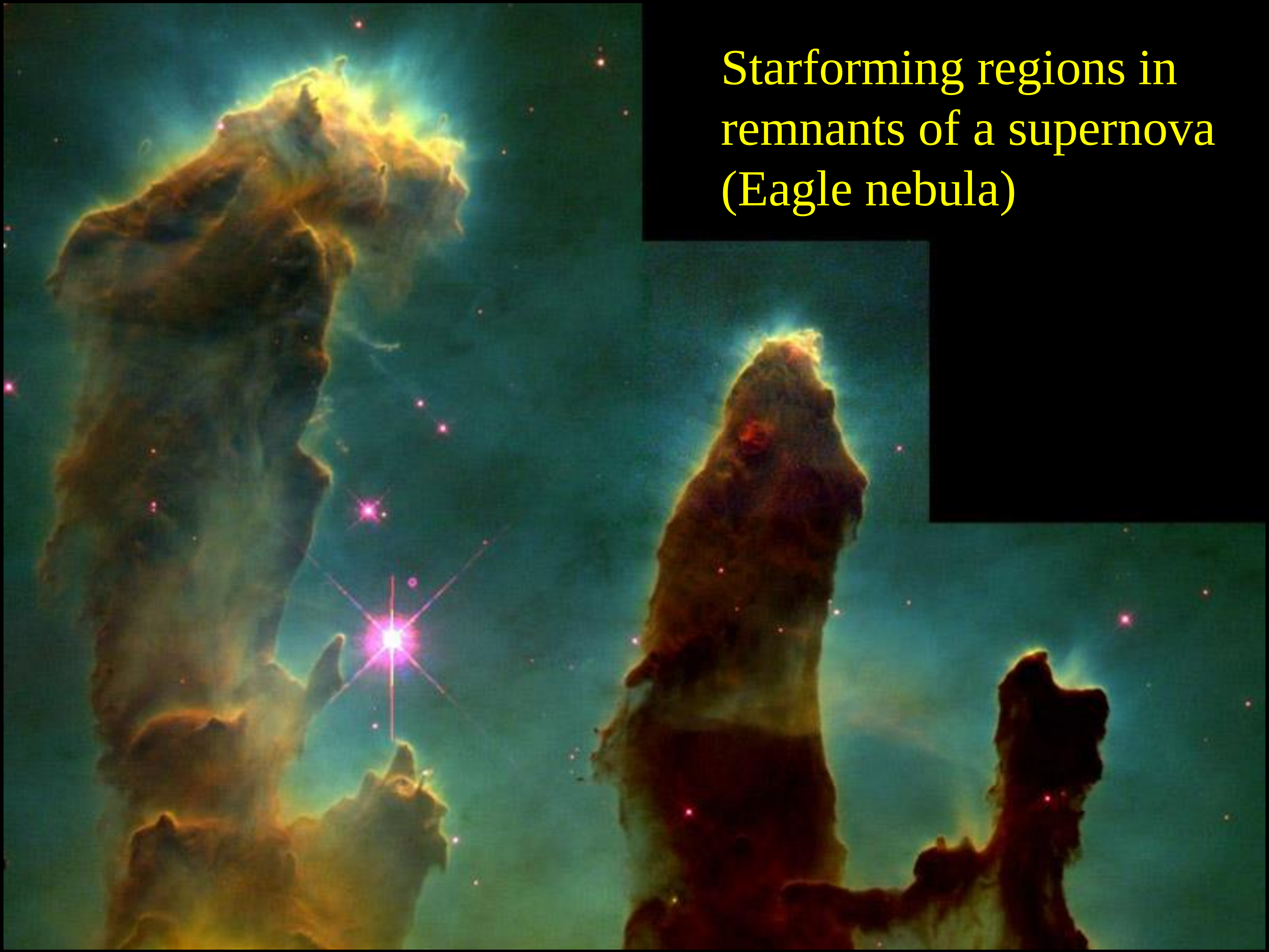
We don't know


STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star (> 8MSUN)
Low-mass Star (< 8MSUN)
Brown Dwarf (< 0.08MSUN)
Red Supergiant
Red Giant
Type II Supernova
Supernova Remnant
> 40MSUN
< 40MSUN
Black Hole
X-ray Emission
Neutron Star
Pulsar
Binary White Dwarf
> 1.4MSUN
< 1.4MSUN
Type Ia Supernova
Nova
Planetary Nebula
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

Very massive stars are shortlived. Here is one of 100 solar masses (Eta Carinae) that will explode as a supernova, but when?

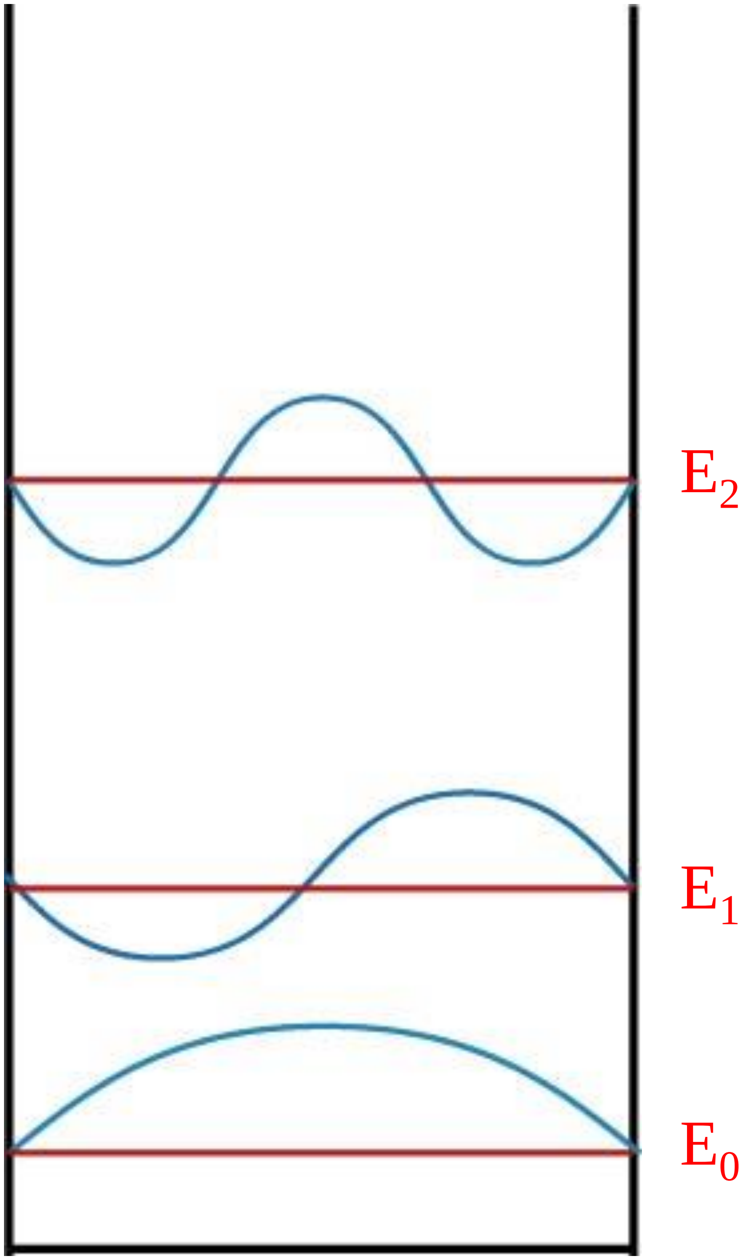


”The Jellyfish Nebula”, remnant of a supernova 500 years ago



Starforming regions in remnants of a supernova (Eagle nebula)

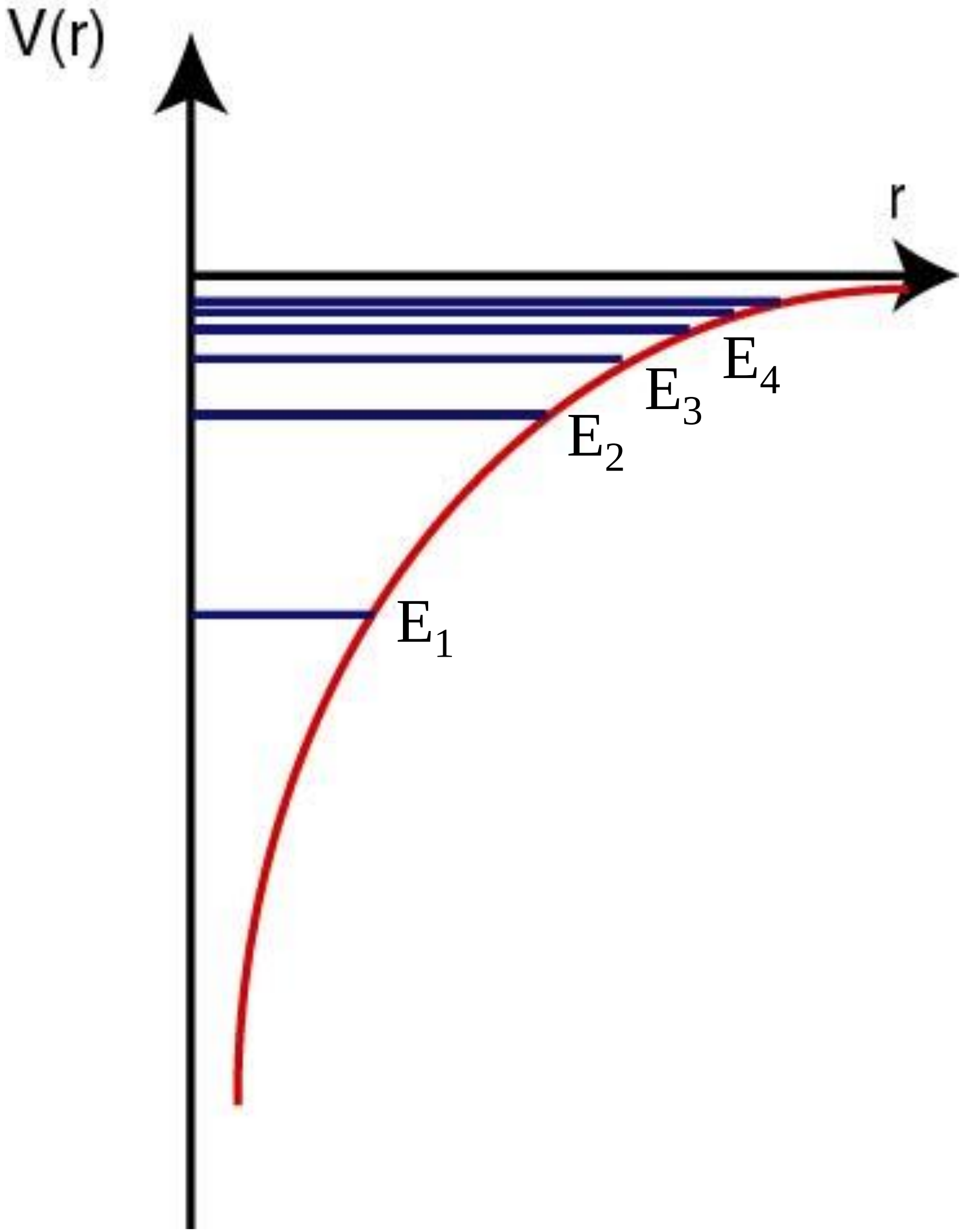
Now some important facts of quantum mechanics…



Remember this? Solutions of the Schrödinger equation for a particle in box:

Explains among other things:

- The quantization of energy
- The stability of atoms
- The incompressibility of matter
- Line spectrum (”discrete”)

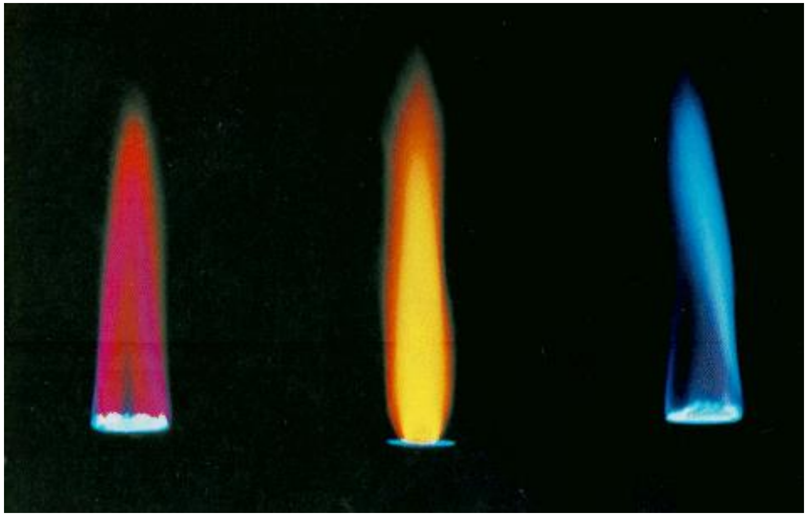


Hydrogen atom,
Coulomb potential

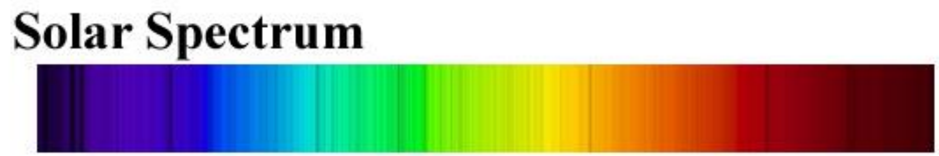
$$V(r) = -\frac{Q_1 Q_2}{r}$$

gives

$$E_n = \frac{-13.6\ eV}{n^2}$$

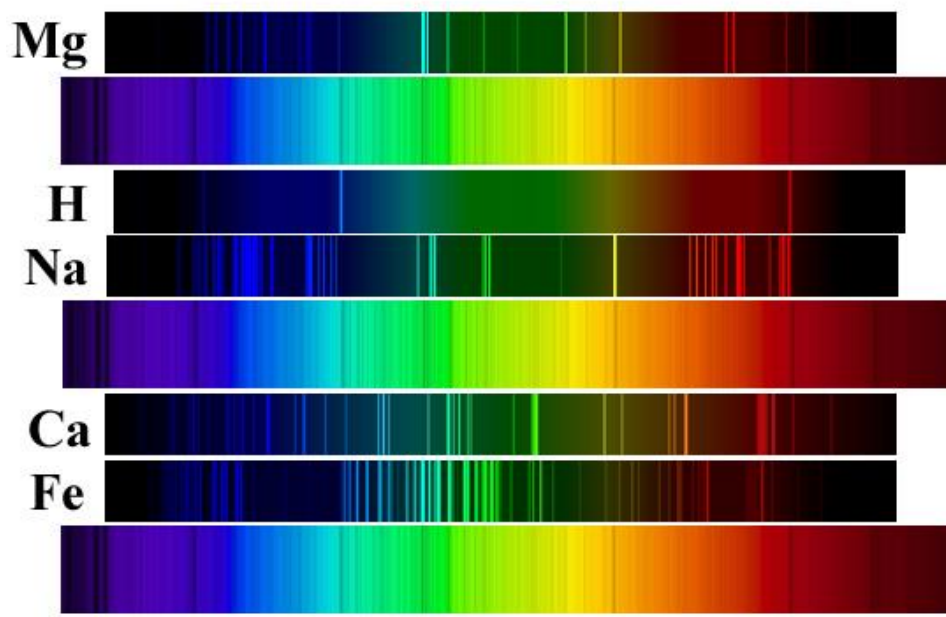


Gas flames get different coulour if different salts are added to the gas. (This is also the trick behind the different colours of fireworks!)



Different atoms (chemical elements) give different line spectra. This has many uses, besides in astronomy also for monitoring pollutions in the atmosphere, for instance.

Star spectra (like the Sun) contain absorption lines from elements in their atmosphere.

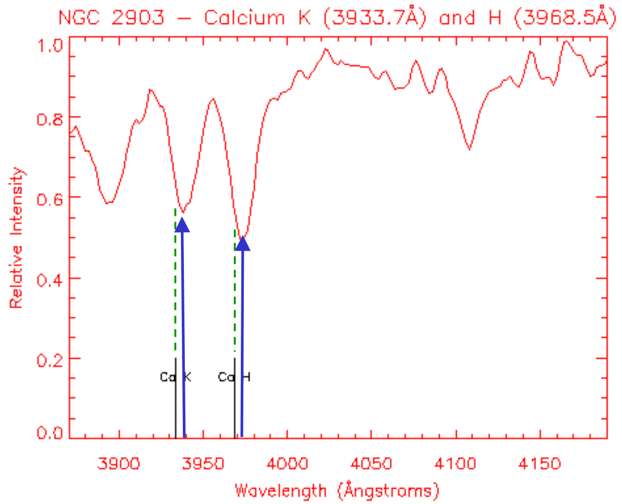


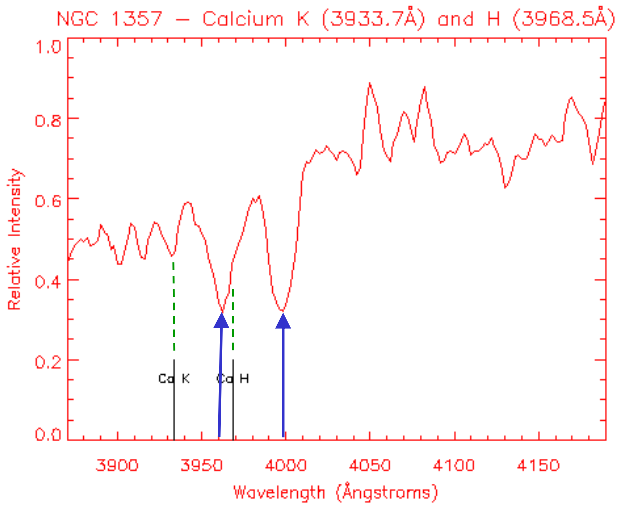
The Hubble
Space Telescope

Andromeda galaxy

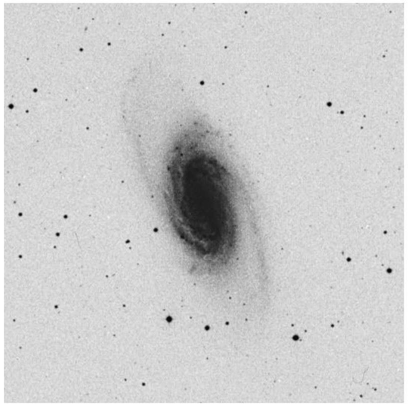
Distant galaxy with
exploding supernova

The amazing discovery of Hubble, Lundmark, Lemaître in the 1920's: The spectral lines of distant galaxies are red-shifted, the shift increasing in proportion to the distance.

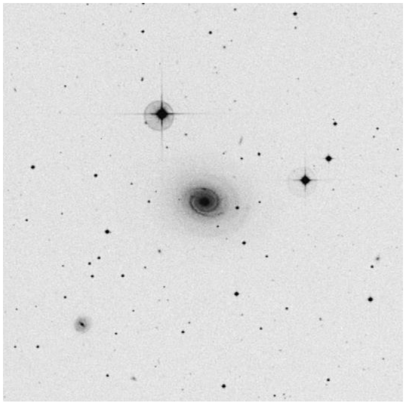




Dashed lines: Position measured in the lab. Arrows: Measured in light from galaxies



Nearby galaxy



Distant galaxy

Blue light: short wavelength

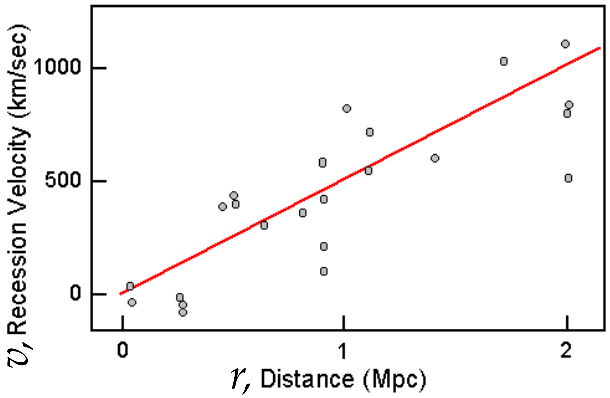
Red light: long wavelength

The explanation uses Einstein's general theory of relativity, which makes time and space dynamical, governed by energy (mass) and momentum in the universe. If space is expanding, then lightwaves are ”stretched” when they travel through the expanding universe. The red-shift becomes equal to the ratio between the ”size” of the universe at the time of observation, to that at the time of emission.

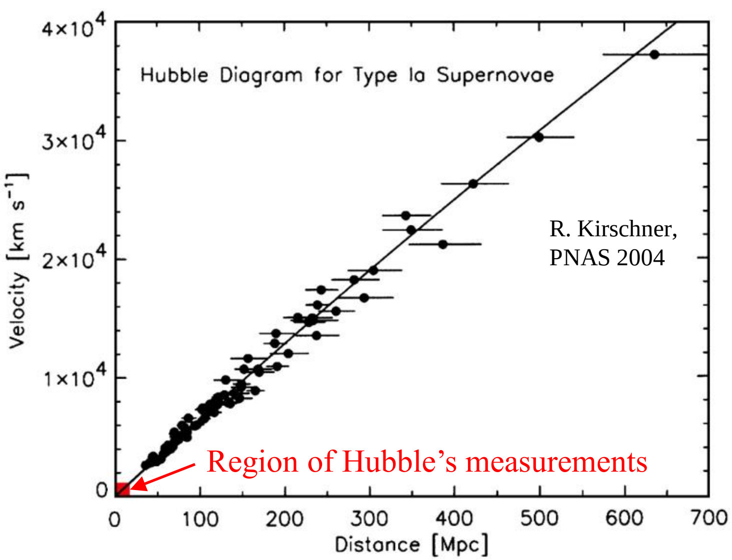
For low velocities, $v << c$, the redshift can be seen as a Doppler shift, with wavelengths being stretched by the Doppler factor $D \approx 1 + \frac{v}{c}$

However, this does not work for larger velocities (more later).

Hubble's Data (1929)



Modern version, with supernovae



$v = H_0 \cdot r$ Hubble's law

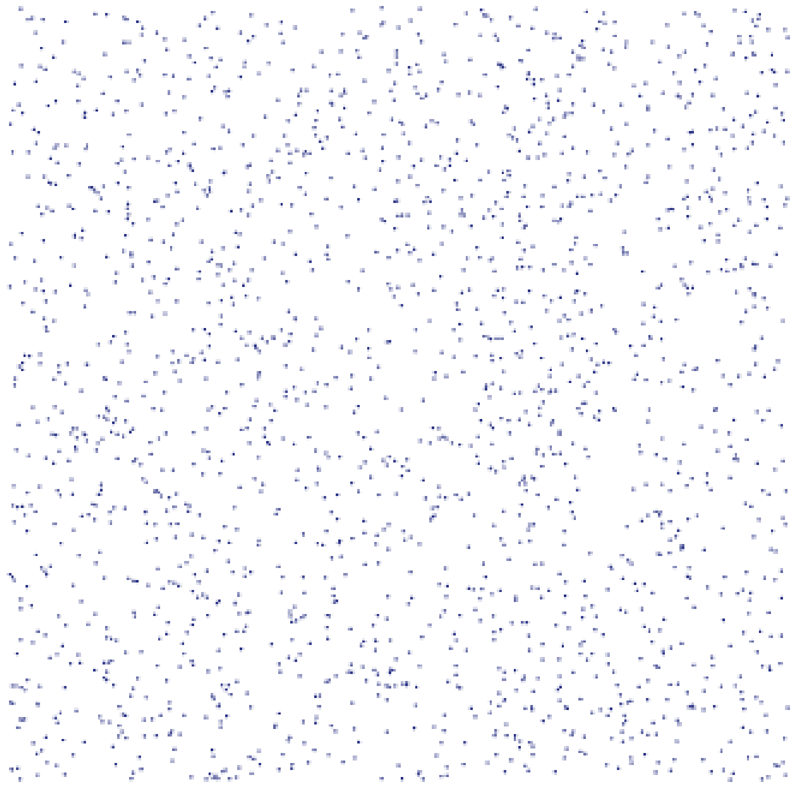
H_0 is the **Hubble constant** (or Hubble-Lemaître constant), the modern value is

$H_0 = 70 \pm 3$ km/s per Mpc

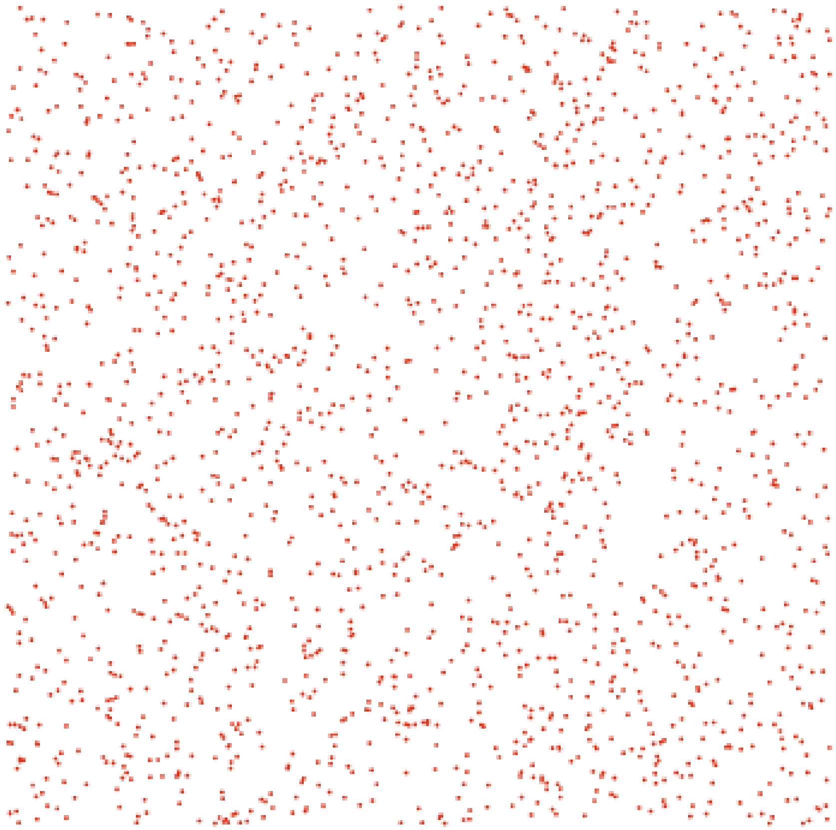
The modern interpretation (based on Einstein):

The whole universe is expanding!

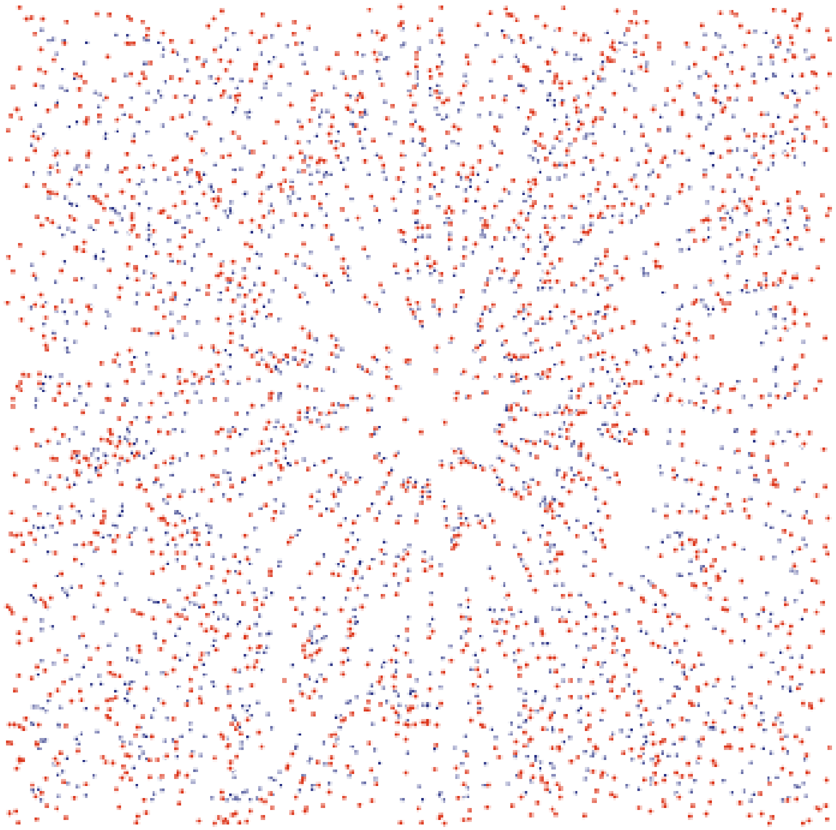
A ”toy universe” with randomly placed ”galaxies”:



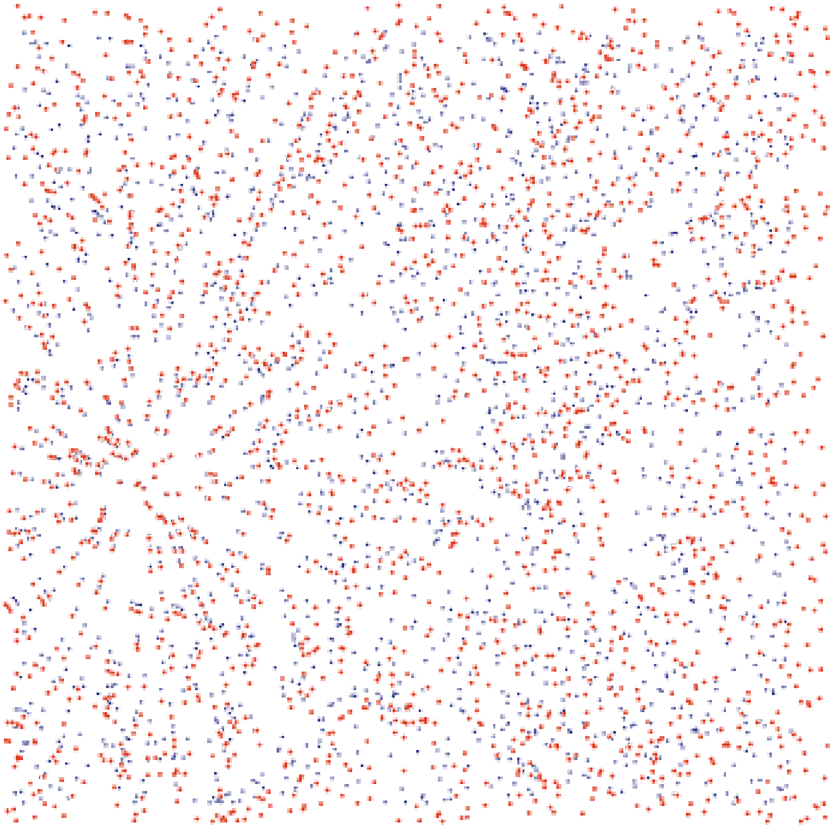
A ”toy universe” with randomly placed ”galaxies” with all distances from the centre increased by 5 %:



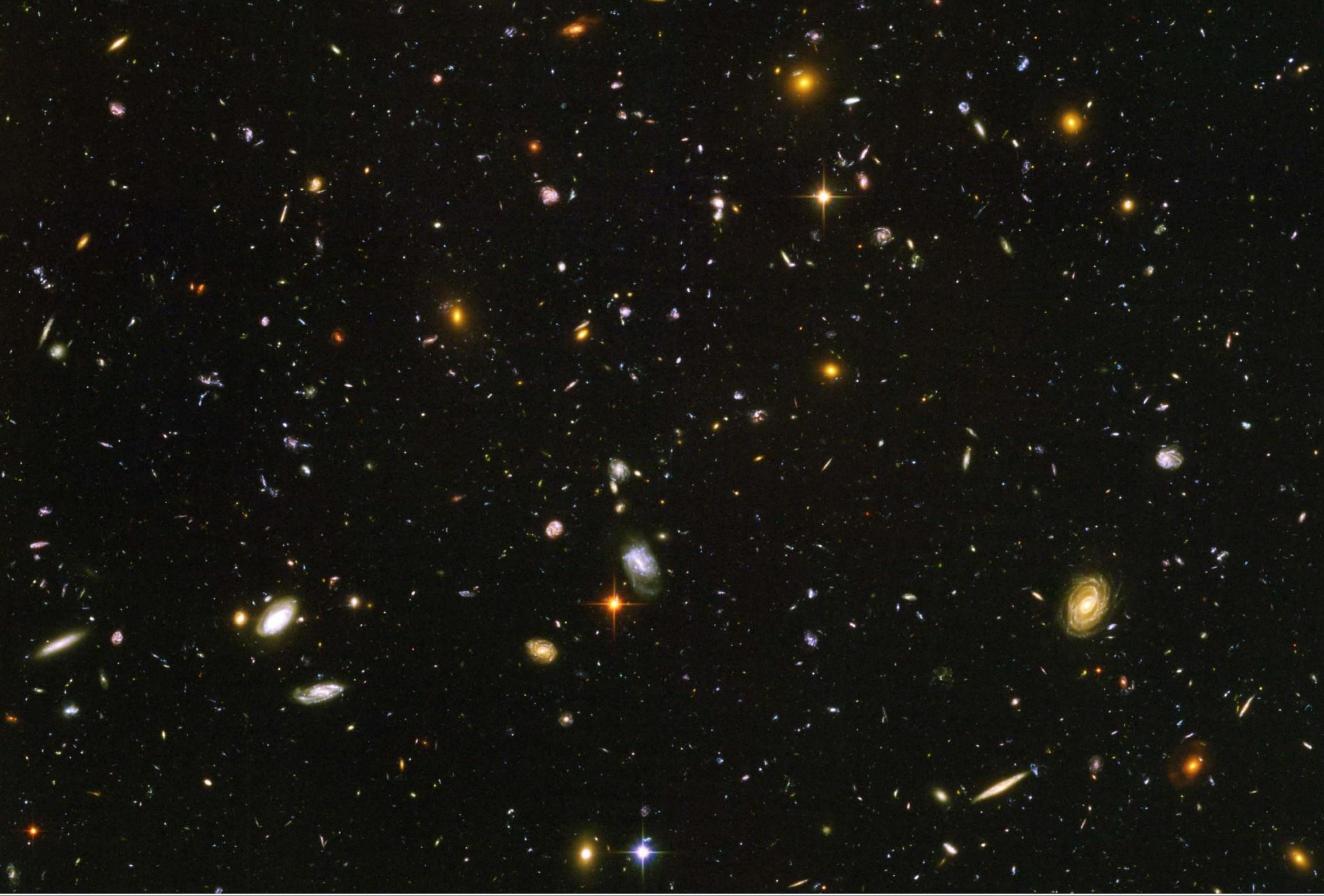
Imagine that we live at the centre



We notice a ”Hubble flow”, with recession speed proportional to distance



But we could have chosen another point – from there also a Hubble flow is seen. Thus all observers will notice a Hubble flow in an expanding universe! This was once a hypothesis (”the cosmological principle”) which has now been vindicated through studies of the Cosmic Microwave Background Radiation (CMB or CMBR)



Hubble Ultra Deep Field

Measurement of the temperature spectrum of the cosmic microwave background radiation (COBE satellite – Nobel Prize 2006)

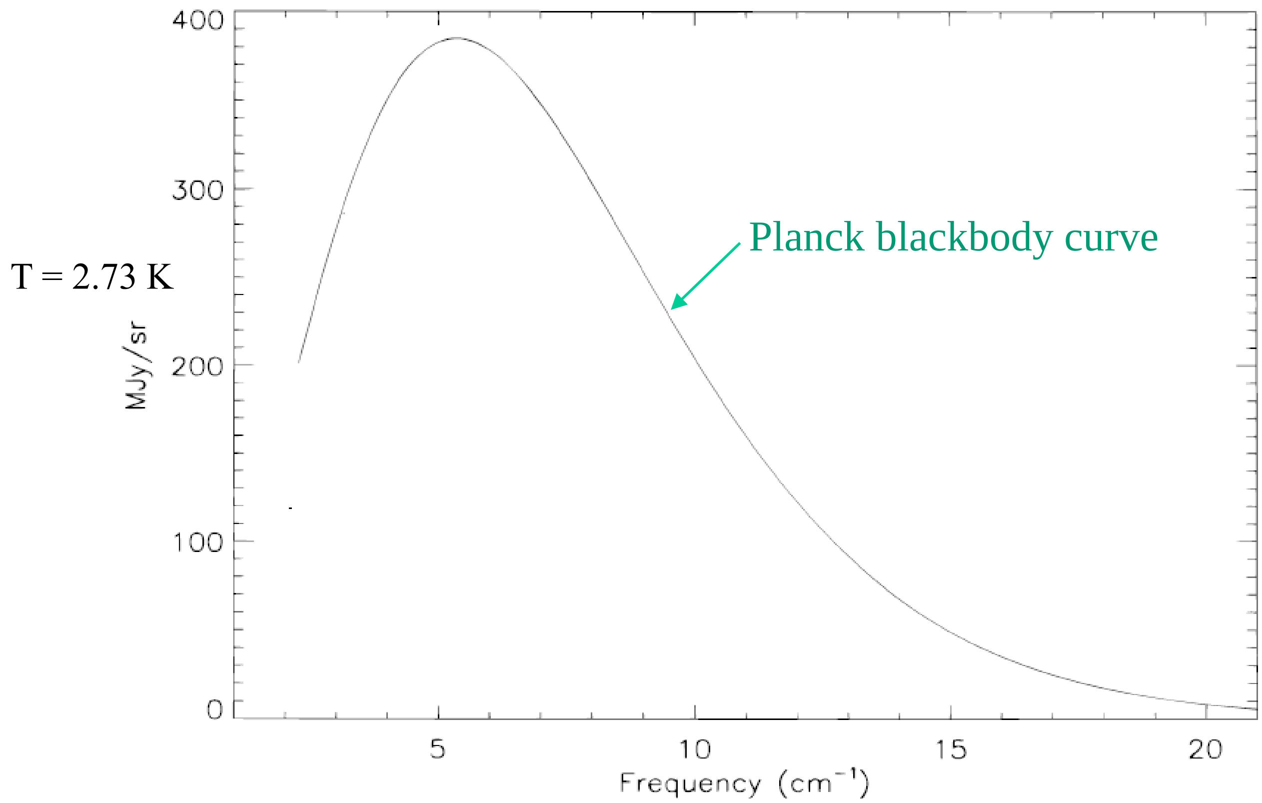


FIG. 4.—Uniform spectrum and fit to Planck blackbody (T). Uncertainties are a small fraction of the line thickness.

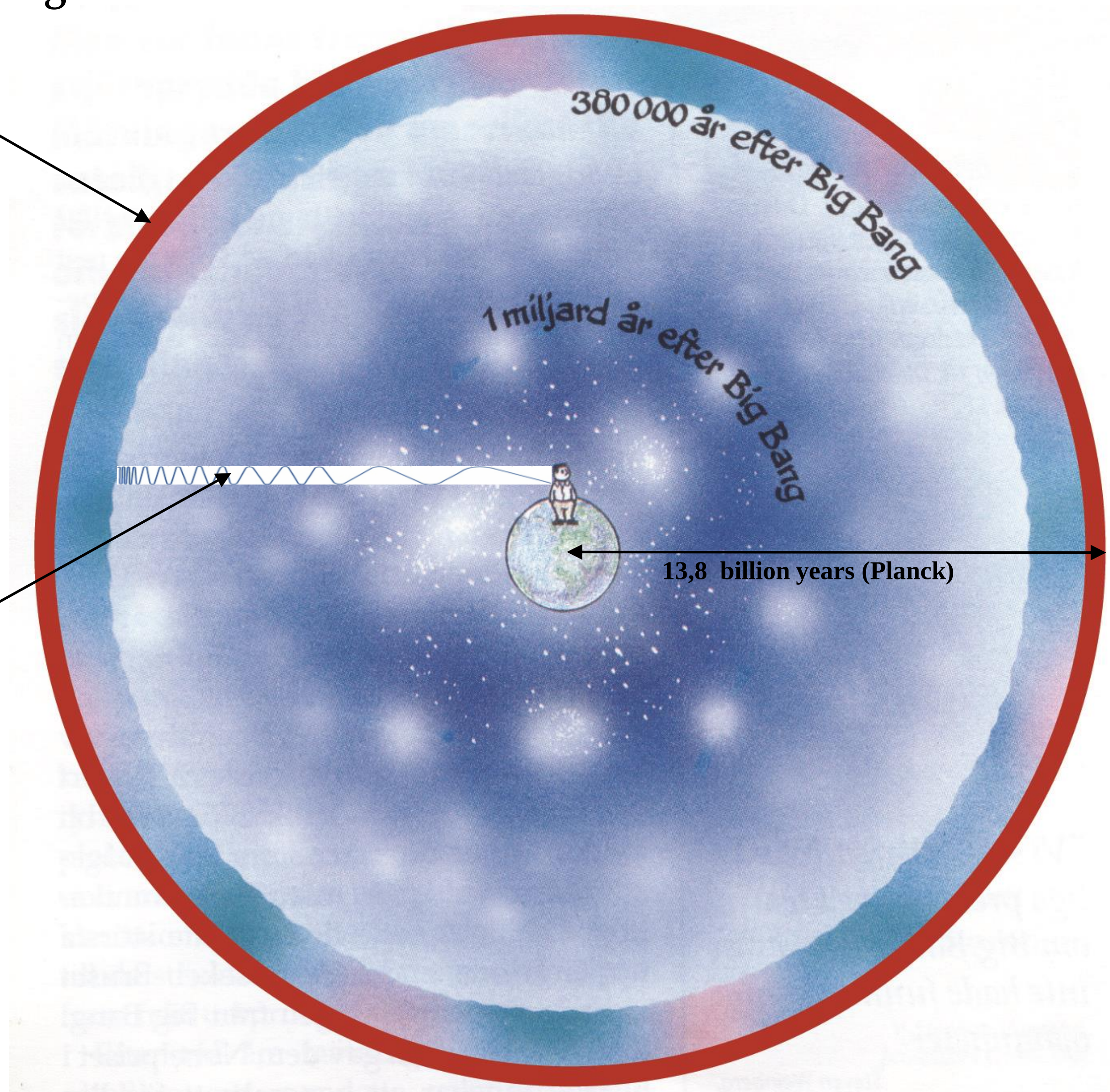
The Planck curve is a direct proof that the early universe was very compressed and hot (so that processes were near thermal eqiuilibrium). The redshift can be computed to be around 1100, so when the photons were emitted, the temperature was hot, 3000 K, and the universe was a hot, dense plasma.

Observations in an expanding Universe:

Time = 0, **Big Bang**.

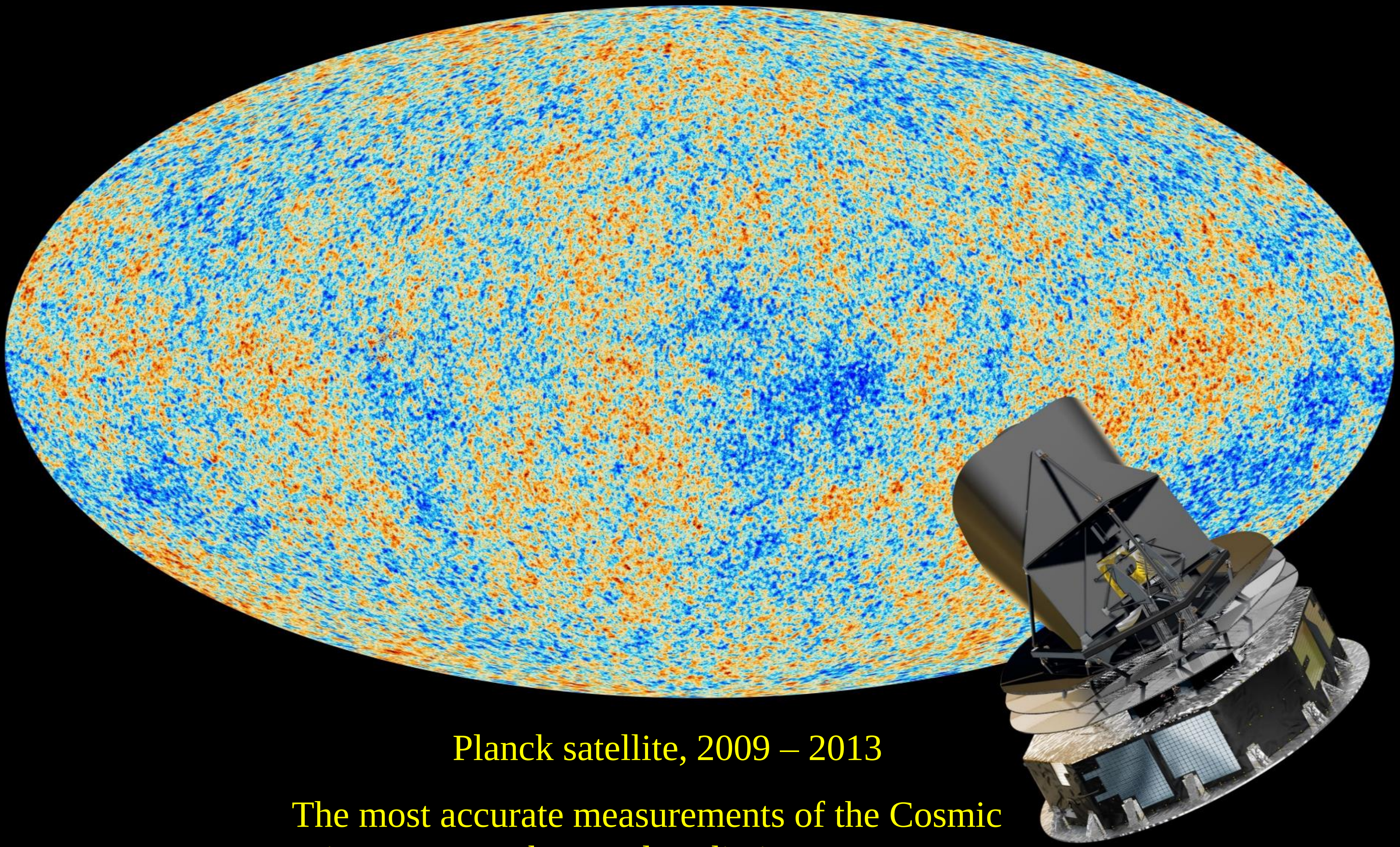
This moment cannot yet be treated scientifically (need quantum gravity).

Universe may be bigger, but we cannot see further (our cosmic horizon)



Ill: Hans Nilsson/Lars Bergström

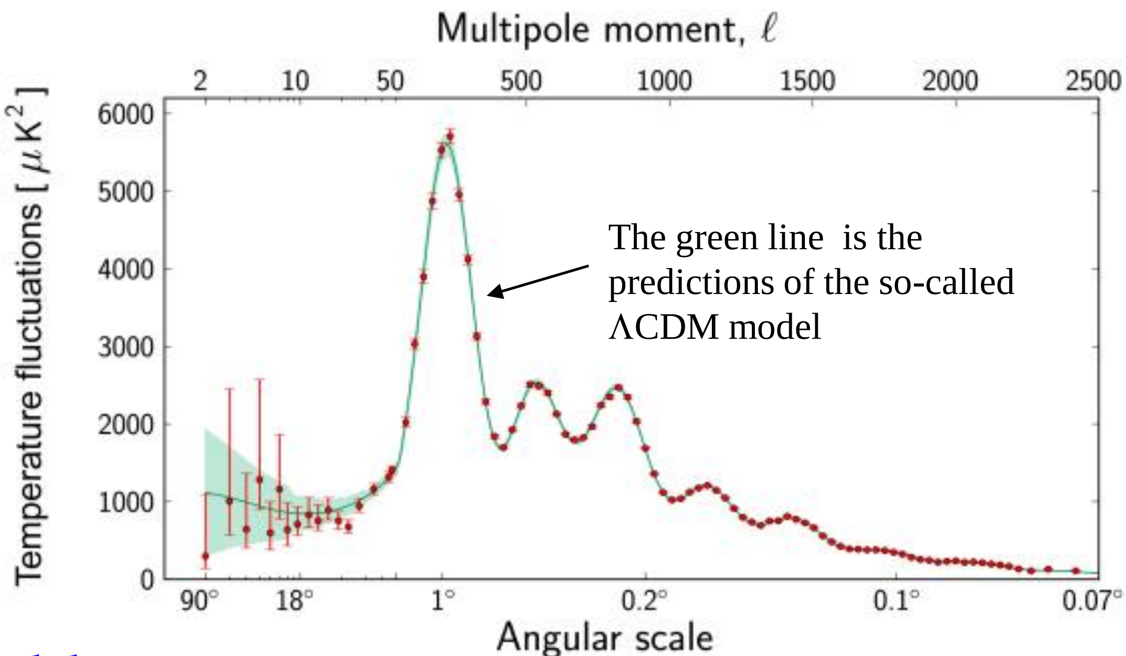
Lightwaves are being stretched as they travel to us – the radiation which was 3000 K at emissions become microwaves – a Planck distribution of only 2.7 K



Planck satellite, 2009 – 2013

The most accurate measurements of the Cosmic Microwave Background Radiation

The Planck satellite measurements of angular temperature fluctuations:



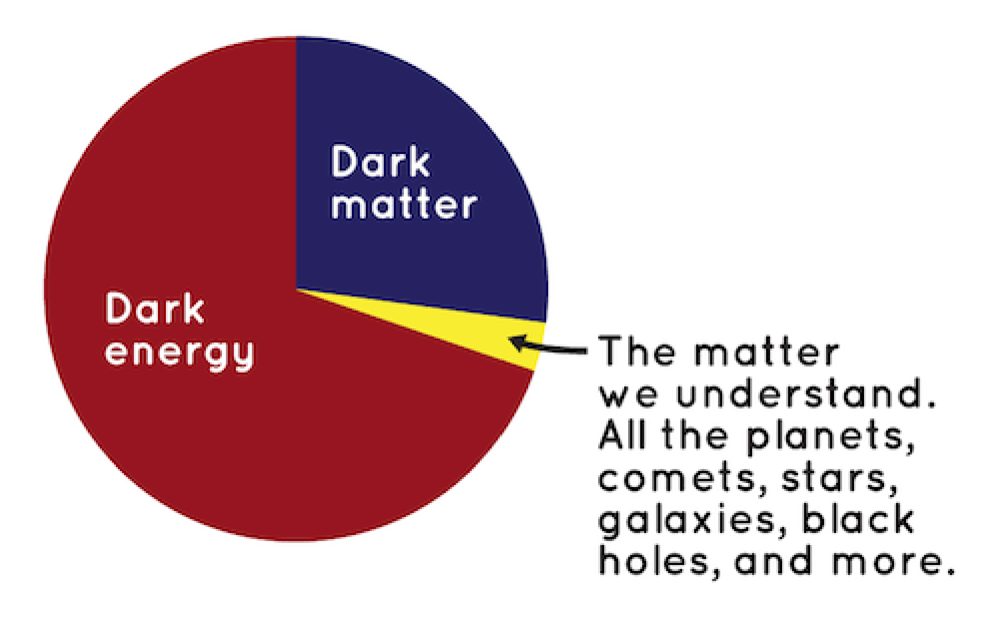
Best fit model:

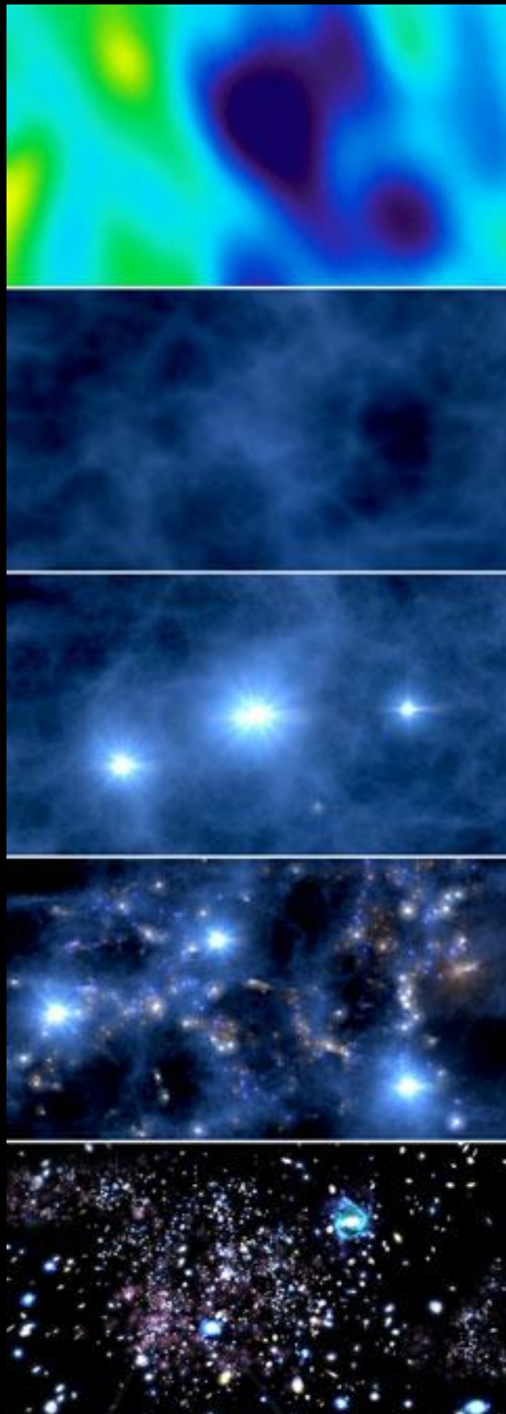
Λ, the cosmological constant (or ”dark energy”) – 70 % of the energy density of the universe

CDM: Cold Dark Matter (”slow-moving particle dark matter”) – 25 %

Ordinary matter: Atoms & molecules - only 5 % of the energy density!

Age of universe: 13.8 billion years. In the first fraction of a second, there was probably an exponential ”inflation” of the universe.


Dark matter
Dark energy
The matter we understand. All the planets, comets, stars, galaxies, black holes, and more.



380 000 years after the Big Bang: red-shift = 1100

”The dark ages”, red-shift larger than 20

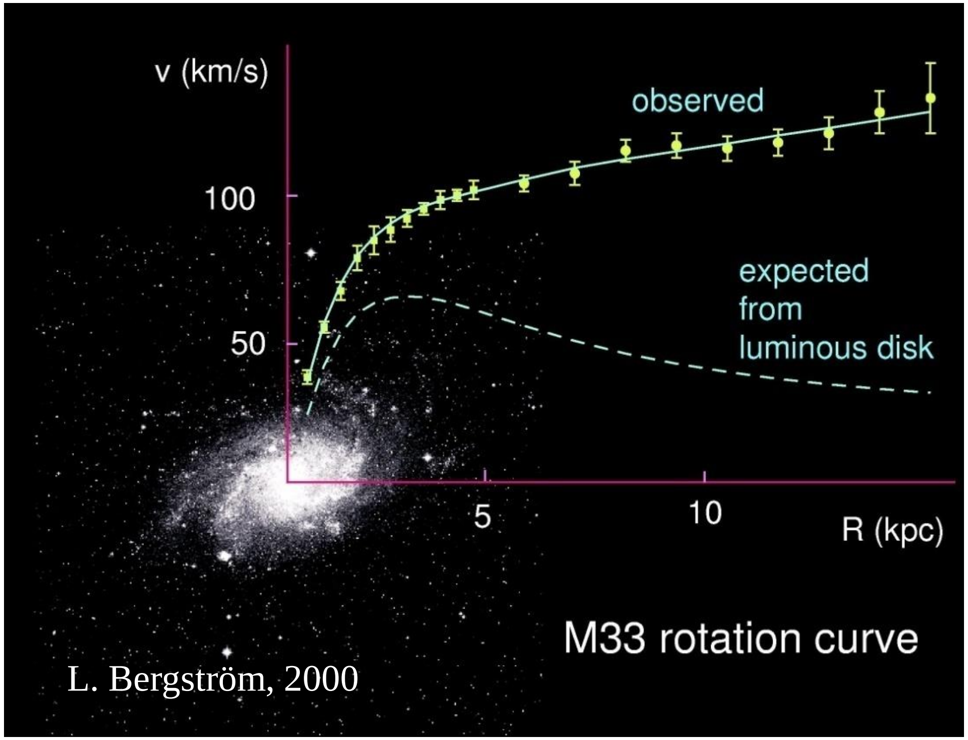
The first stars and galaxies, red-shift = 5-15, many supernovas

Big galaxies and galaxy clusters, red-shift = 1-3, active star formation

Today’s universe, red-shift = 0. Star formation has decreased.

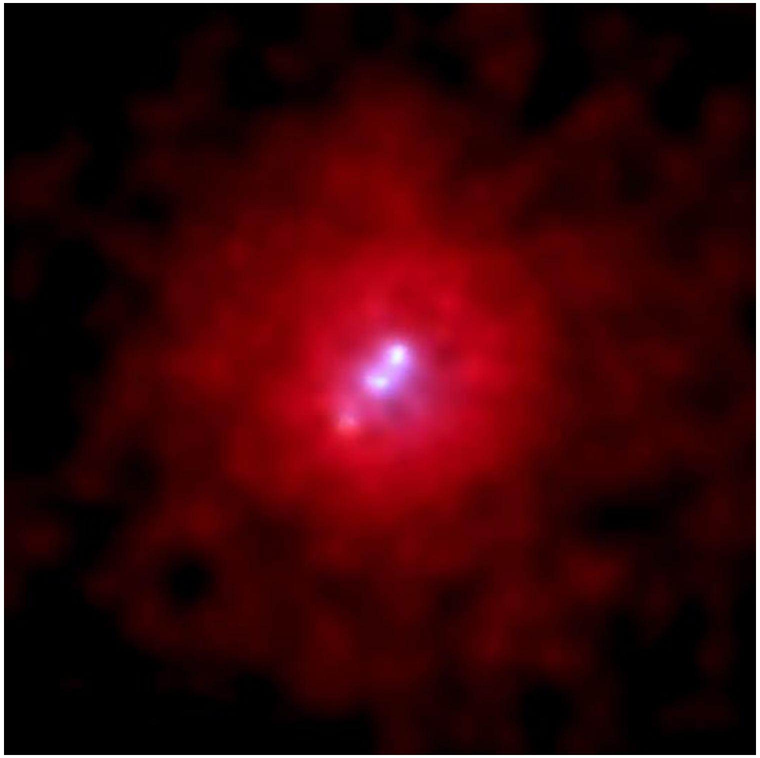
The mystery of the dark matter of the universe

Rotation curve of galaxies



Pioneers: Vera Rubin (1928-2016) and Ken Ford (1931-) noticed several flat galaxy rotation curves in the 1970's

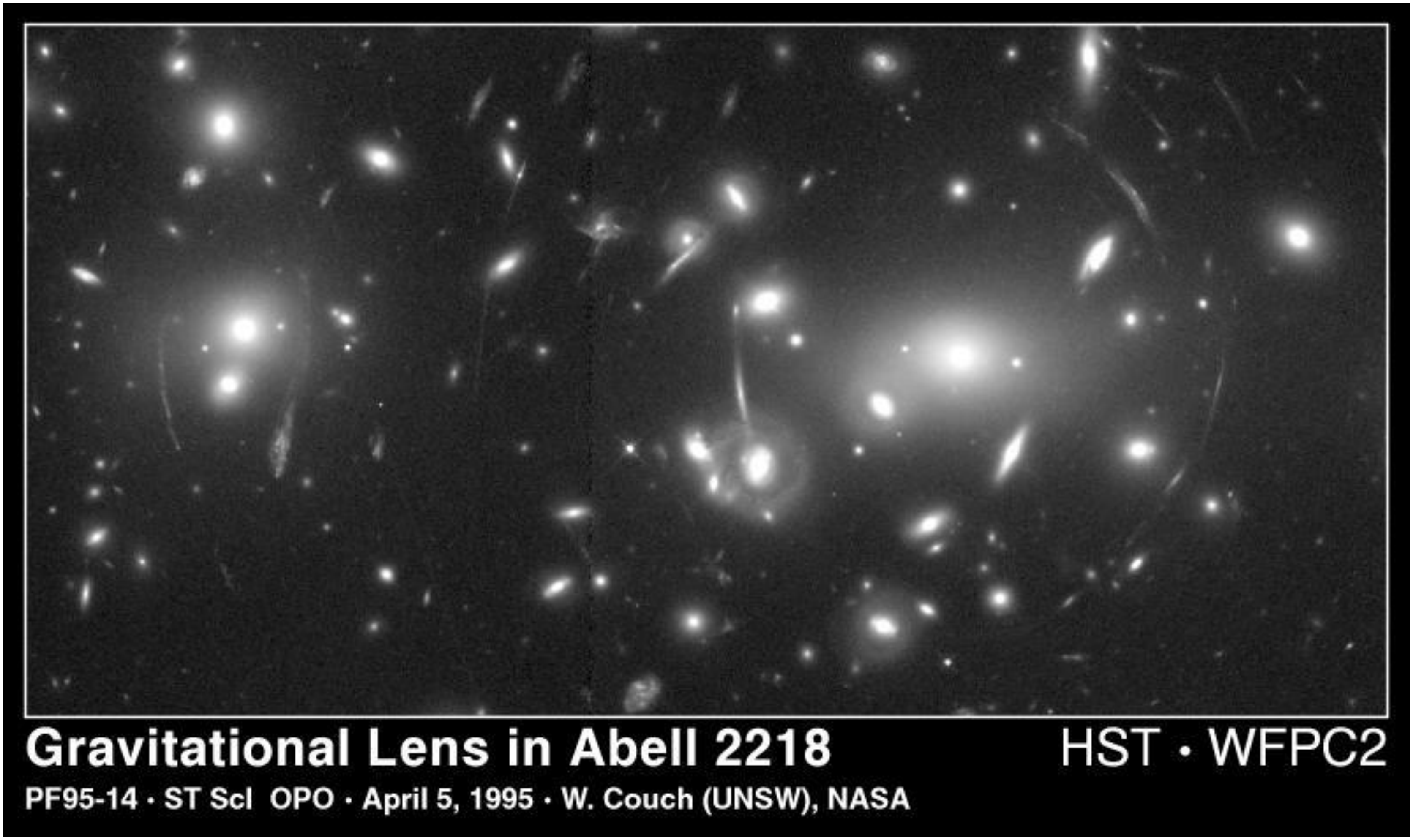
X-ray emitting galaxy clusters

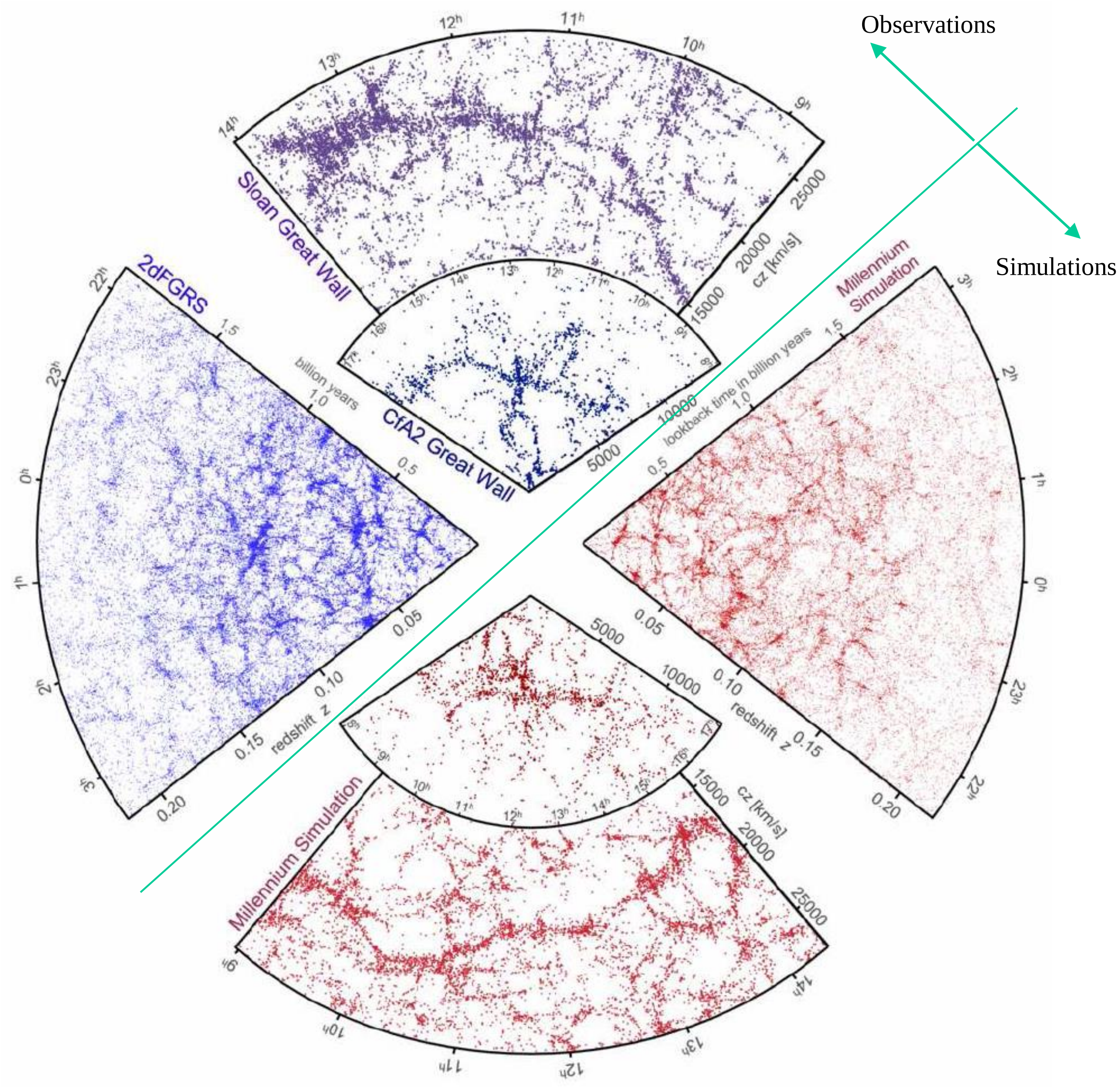


Galaxy cluster 3C295 (Chandra)

The hot gas has such fast-moving atoms and molecules, that someting massive has to keep the cluster of galaxies together (dark matter). The first observation of dark matter in galaxy clusters came already in 1933 by Fritz Zwicky.

Galaxy cluster bends the light of galaxies further away to give arcs and rings (gravitational lensing). Estimates give that 80 % of the matter in the cluster is dark (invisible) – dark matter!

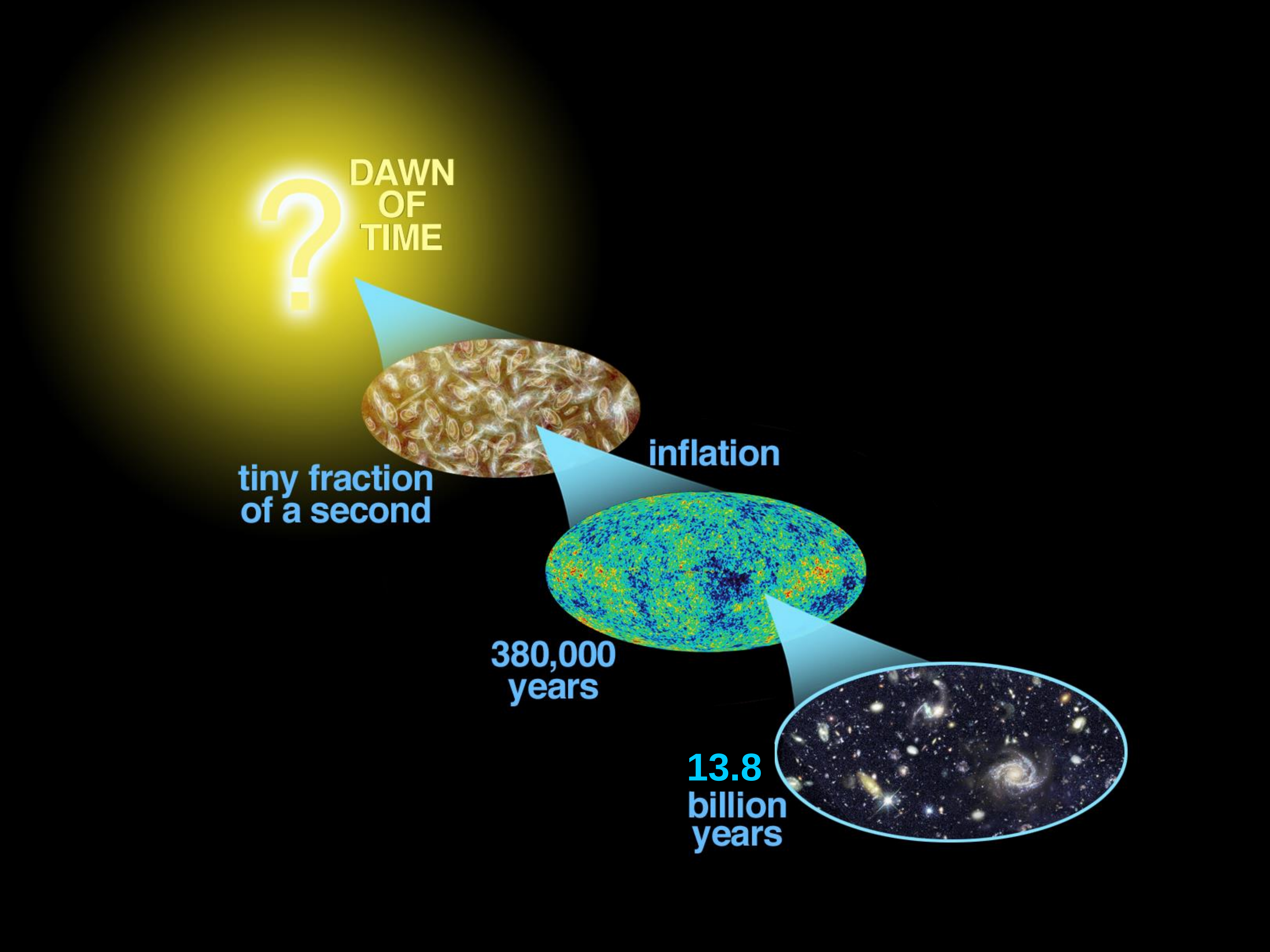




Supercomputer simulations of galaxy formation agree very well with observations – but only with

Dark Matter!

Springel, Frenk & White, 2006



DAWN OF TIME
tiny fraction of a second
inflation
380,000 years
13.8 billion years