The cosmic foundations for the origin of life

Docente modulo II: R. Orosei, INAF-IRA
https://www.unibo.it/sitoweb/roberto.orosei

Why this lecture

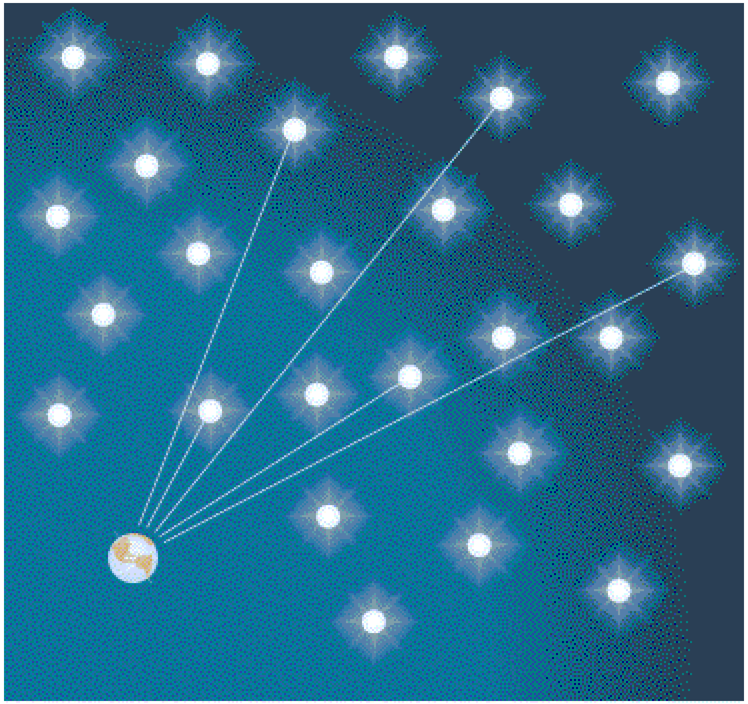
- Physical and chemical evolution of the cosmos sets the stage for the birth of life
- Is the cosmos tuned to allow life?

Goals for today

- Develop basic concepts to understand subsequent discussion
- Review current knowledge of the evolution of cosmos
- Discuss implications for the development of life

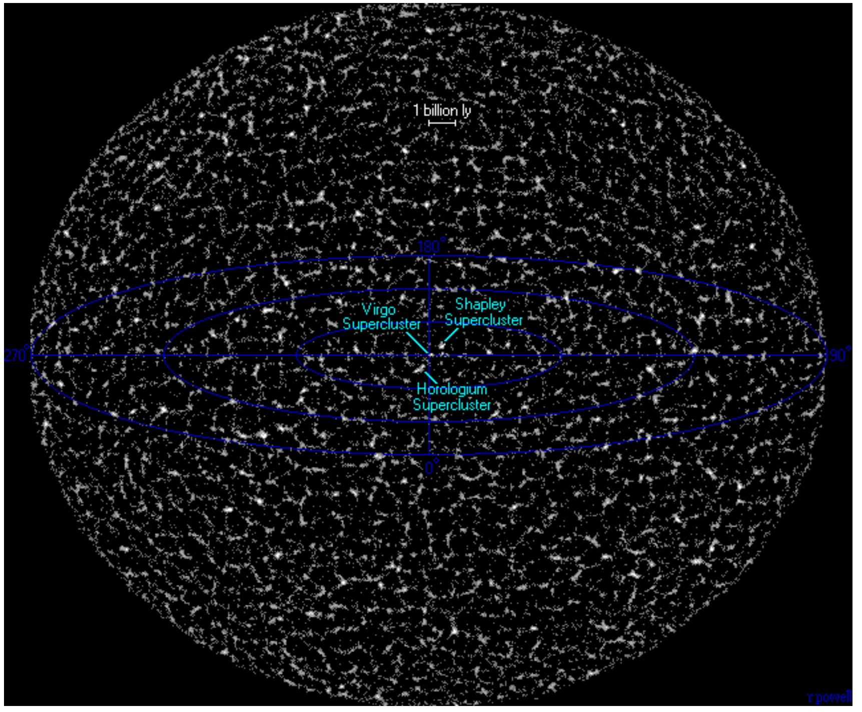
Olbers' paradox: "the sky is dark at night"

- Apparent brightness of stars drops as the square of distance
- In an uniform and infinite universe, the surface area of a spherical shell increases as the square of distance
- Thus, brightness per unit area of the sky remains constant
- The entire sky should have the surface brightness of a typical star



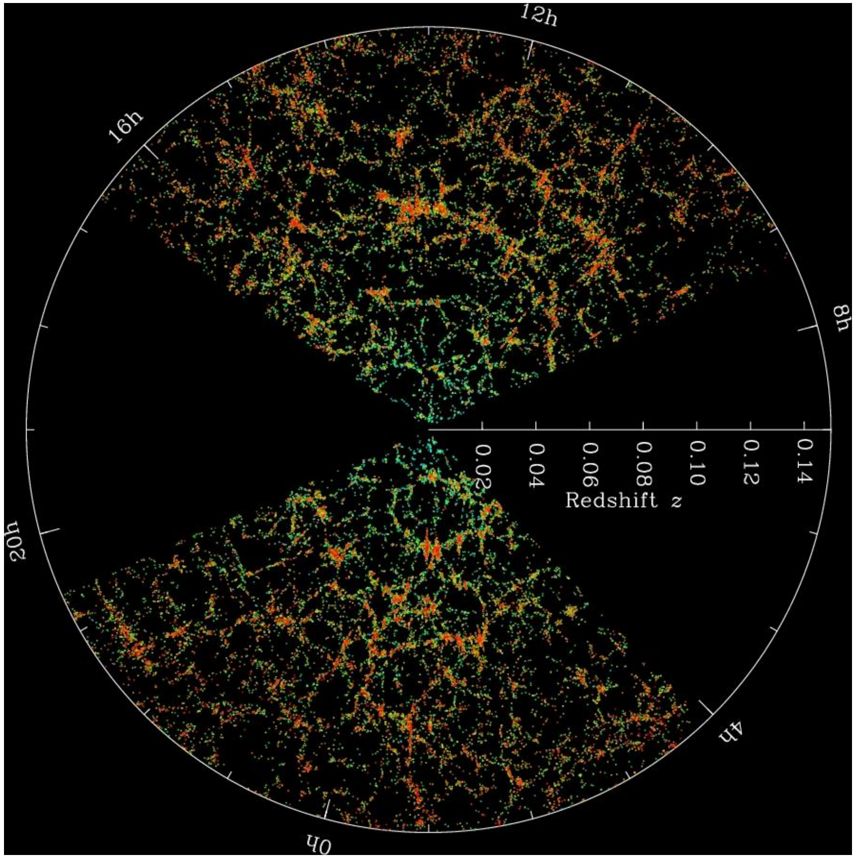
Can we solve the paradox?

- Any intervening medium capable of sufficiently attenuating starlight ("absorbing fluid", dust) would heat up and result in strong IR emission from the sky
- The solution is the finiteness of cosmos, both in space and in time
- The sky is dark because there are no stars beyond a certain distance in space and time (light has a finite velocity)



Determining the distribution of stars in the cosmos

- By the early 20th century, it was recognized that stars cluster in galaxies similar to the Milky Way
- In the second half of the 20th century, clusters and superclusters of galaxies were identified
- Spectroscopy of galaxies in the mid-20th century revealed that spectral lines of galaxies were red-shifted w.r.t. the milky way
- Fainter (more distant) galaxies were more red-shifted that brighter ones
- This is a fundamental property of the cosmos



Basic concepts: Doppler shift

- The number of wave crests reaching an observer every second is equal to the velocity of propagation divided by the wavelength:

$$\nu = \frac{c}{\lambda}$$

- If the source of radiation moves towards the observer, then the velocity of the source sums with the velocity of the wave, and

$$\nu' = \frac{c + V}{\lambda}$$

- Thus, the increase in frequency perceived by the observer is given by

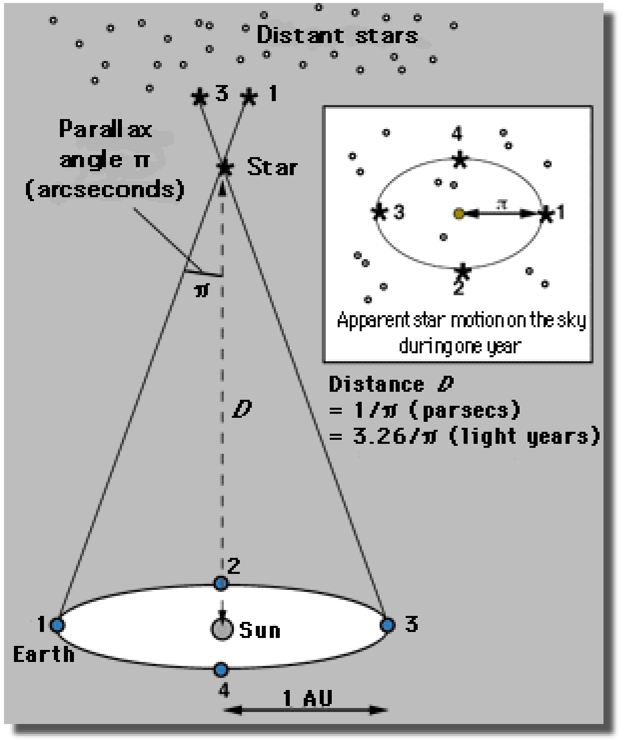
$$\Delta\nu = \frac{V}{c}\nu$$

- This can be generalized for an angle θ between the source velocity vector in the frame of the observer and the vector pointing from the source to the observer

$$\Delta\nu = \frac{V\cos\theta}{c}\nu$$

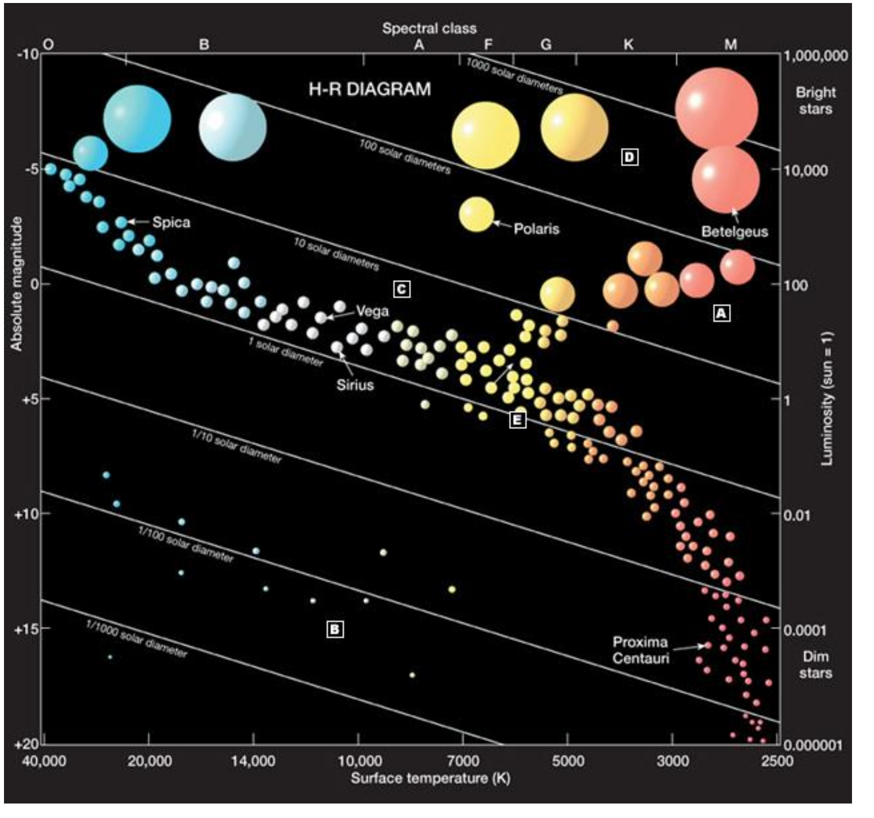
Basic concepts: Determining the distance of stars and galaxies

- The distance of individual stars is determined through parallax measurements
- D = 1 AU / theta
- Parallaxes measured through telescopes on Earth are limited to 0.01 arcseconds
- ESA's Hipparcos reaches 0.001 arcseconds (about 3000 light-years)
- The Milky Way is about 120'000 light-years across



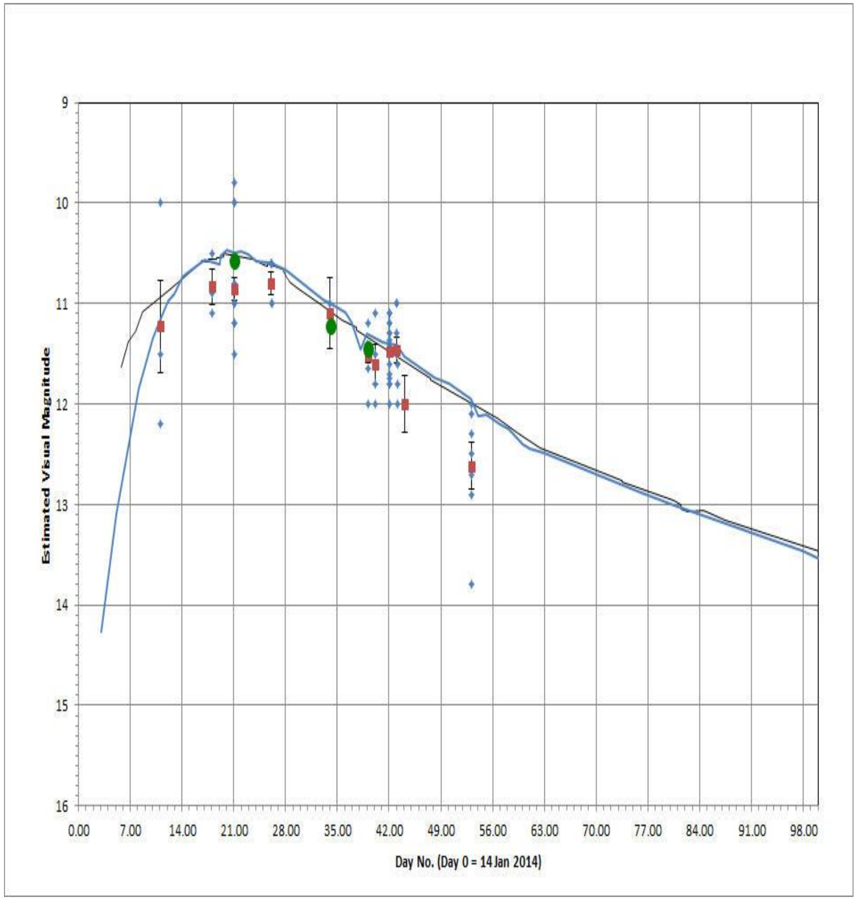
Basic concepts: Determining the distance of stars and galaxies (2)

- If the luminosity of a star can be determined, its distance can be computed from its apparent brightness
- Stars can be classified according to luminosity and colour (temperature)
- A plot of these properties is called Hertzsprung-Russel diagram
- Most stars sit along a specific line in the H-R diagram (main sequence stars)
- Plotting apparent brightness vs. colour for a group of close stars (globular cluster) allows the determination of brightness to luminosity ratio, and thus of the distance
- This method works as long as colour and brightness of individual stars can be measured



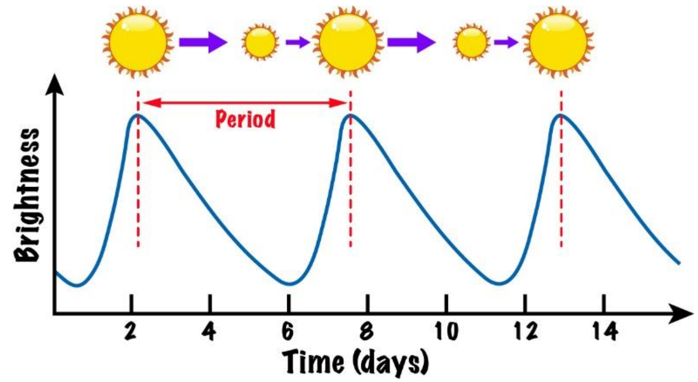
Basic concepts: Determining the distance of stars and galaxies (2)

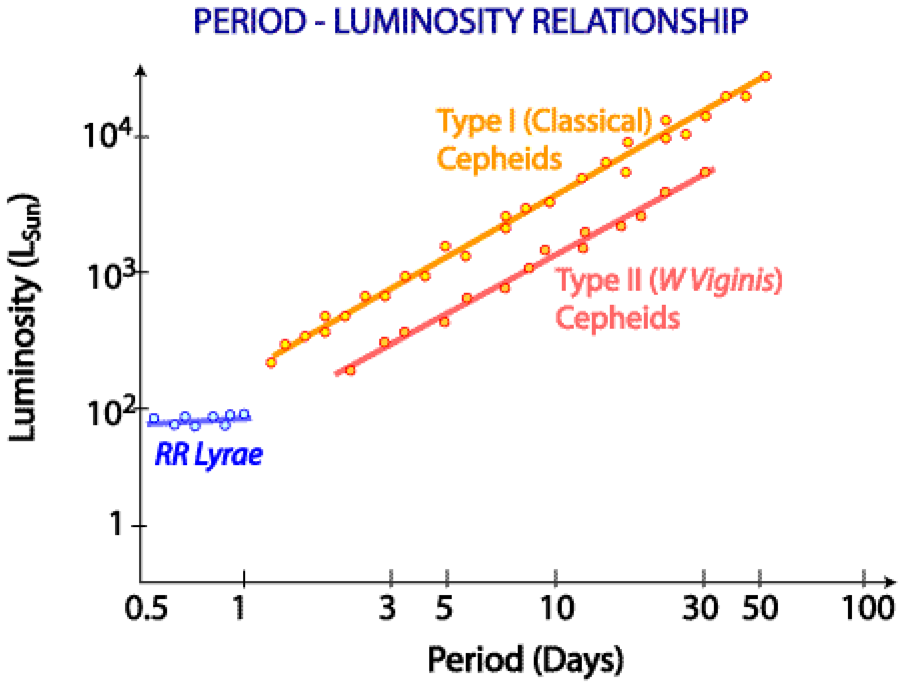
- There are classes of stars that are known to possess a specific luminosity: these are called stellar standard candles
- In Cepheid variables, the rate of brightness variation is inversely proportional to maximum luminosity
- Cepheid variables are too faint to be identified in other galaxies (tens of millions of light years distances)
- Stars much larger than the Sun end their lives in a catastrophic explosion called supernova
- Type Ia supernovae (originating from the infall of mass onto a white dwarf from a close companion star) have a constant maximum brightness
- They can be identified from their light cure, that is a plot of apparent brightness vs time
- Supernovae are rare event, but in galaxies containing hundreds of billions of stars, they are frequent enough to allow their use as standard candles
- Type Ia supernovae can be identified up to 100 million light-years away



Cepheid variables

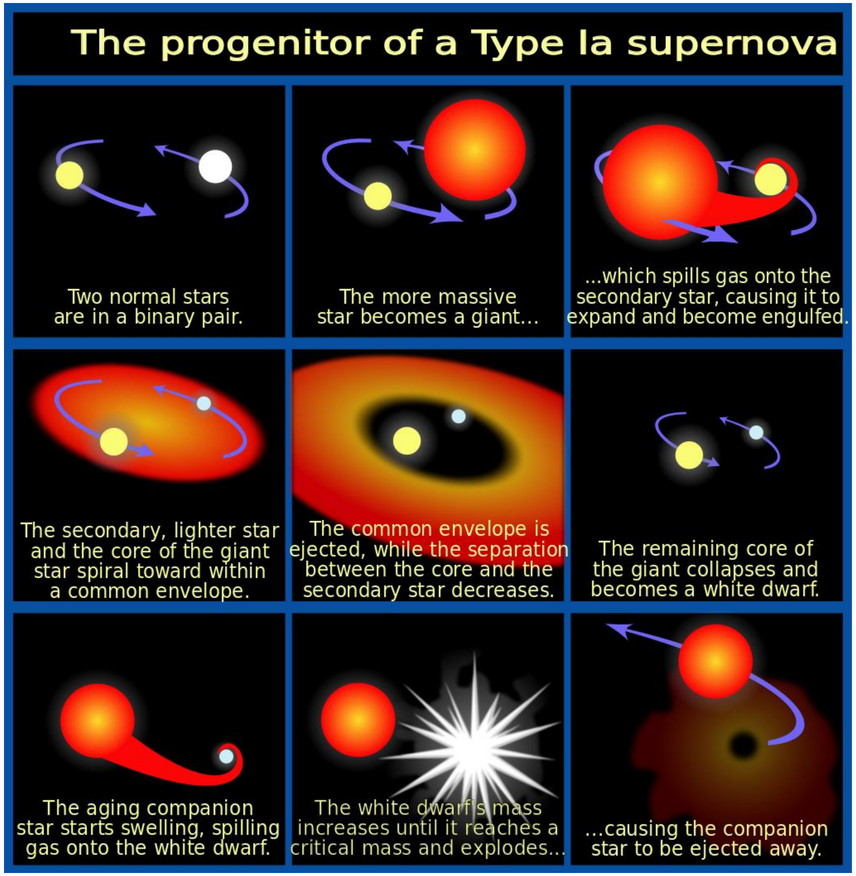
- A Cepheid variable is a type of star that pulsates radially, varying in both diameter and temperature and producing changes in brightness with a well-defined stable period and amplitude.
- A strong direct relationship between a Cepheid variable's luminosity and pulsation period established Cepheids as important indicators of cosmic benchmarks for scaling galactic and extragalactic distances.
- This discovery allows one to know the true luminosity of a Cepheid by simply observing its pulsation period.
- This in turn allows one to determine the distance to the star, by comparing its known luminosity to its observed brightness.





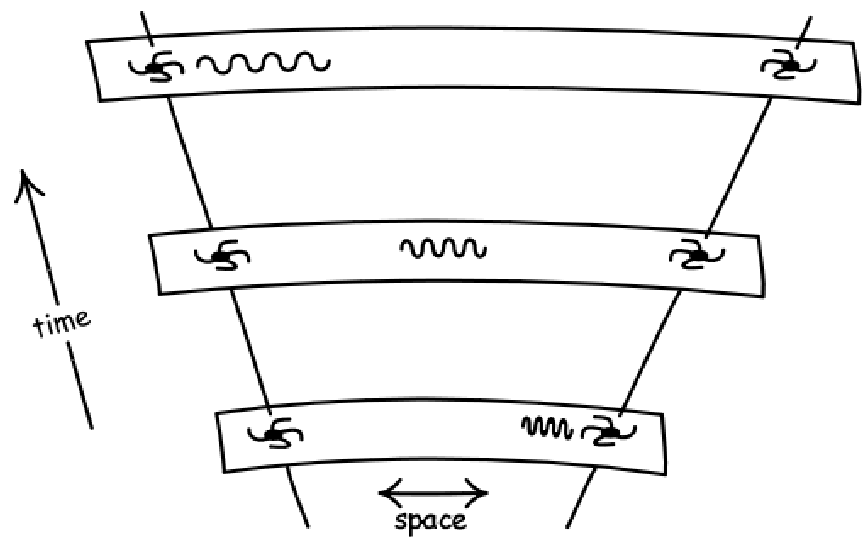
Type Ia supernova

- A type Ia supernova is a type of supernova that occurs in binary systems (two stars orbiting one another) in which one of the stars is a white dwarf. The other star can be anything from a giant star to an even smaller white dwarf.
- Physically, carbon–oxygen white dwarfs with a low rate of rotation are limited to below 1.44 solar masses. Beyond this, they reignite and in some cases trigger a supernova explosion.
- If a white dwarf gradually accretes mass from a binary companion, the general hypothesis is that its core will reach the ignition temperature for carbon fusion as it approaches the limit.
- However, if the white dwarf merges with another white dwarf (a very rare event), it will momentarily exceed the limit and begin to collapse, again raising its temperature past the nuclear fusion ignition point.
- Within a few seconds of initiation of nuclear fusion, a substantial fraction of the matter in the white dwarf undergoes a runaway reaction, releasing enough energy ($1–2\times10^{44}$ J) to unbind the star in a supernova explosion.

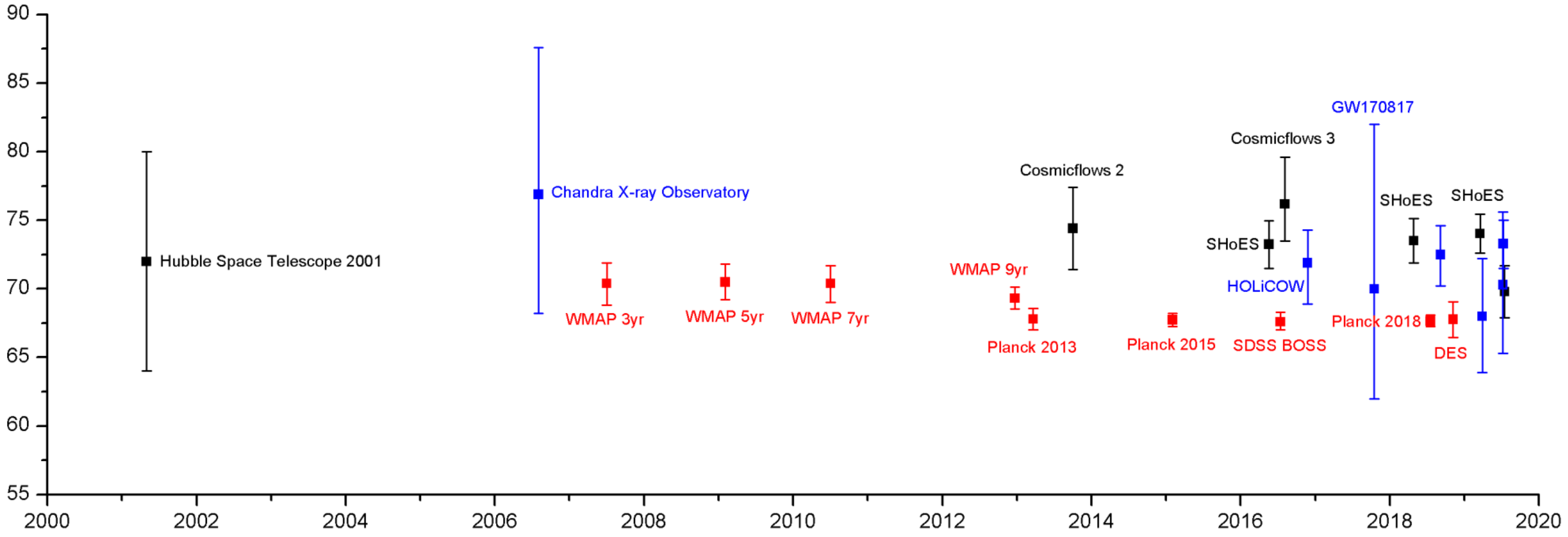


Basic concepts: Determining the distance of stars and galaxies (3)

- Once we move away from the neighbourhood of the Milky way, galaxies recede with a red-shift that is proportional to their distance
- This is interpreted as an expansion of space-time itself
- Hubble constant: 60-72 km/s/megaparsec
- Velocity of the most distant galaxies is a significant fraction of the speed of light.
- This corresponds to an age of about 13.7 billion years



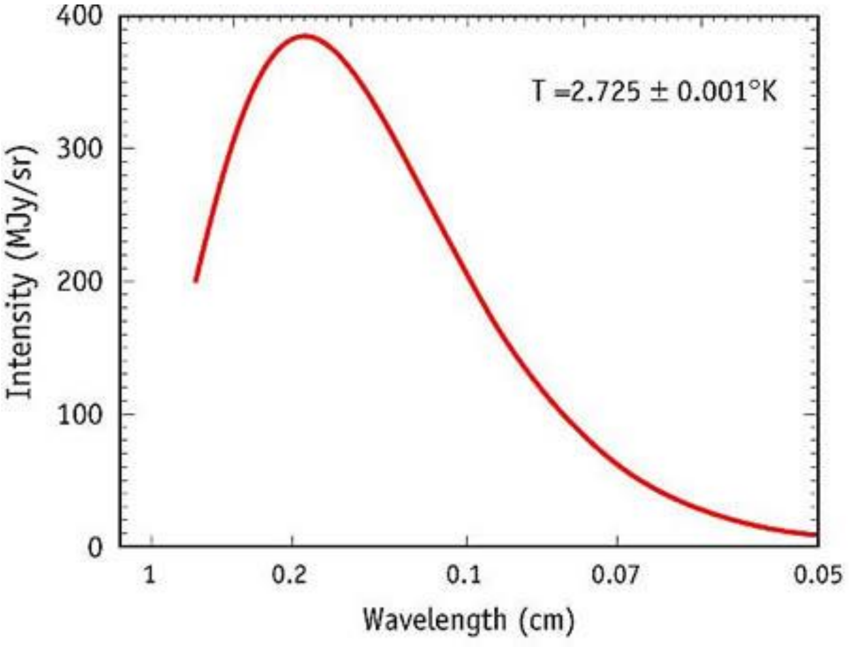
The Hubble «constant»



Estimated values of the Hubble constant, 2001-2019. Estimates in black represent calibrated distance ladder measurements, red represents early universe CMB/BAO measurements with ΛCDM parameters while blue are independent measurements.

The early universe

- If galaxies are receding, then the universe must have been much more compact in the distant past
- What was the state of the universe at the time?
- Cosmic background radiation discovered in the 1960's
- Its spectrum is a perfect blackbody emission curve at 3 K
- It permeates all space isotropically, no discernible source
- It originates at the moment in which the universe expanded enough to become transparent to radiation
- The decoupling between radiation and matter is estimated to have happened 13.7 billion years ago, ±200 million years

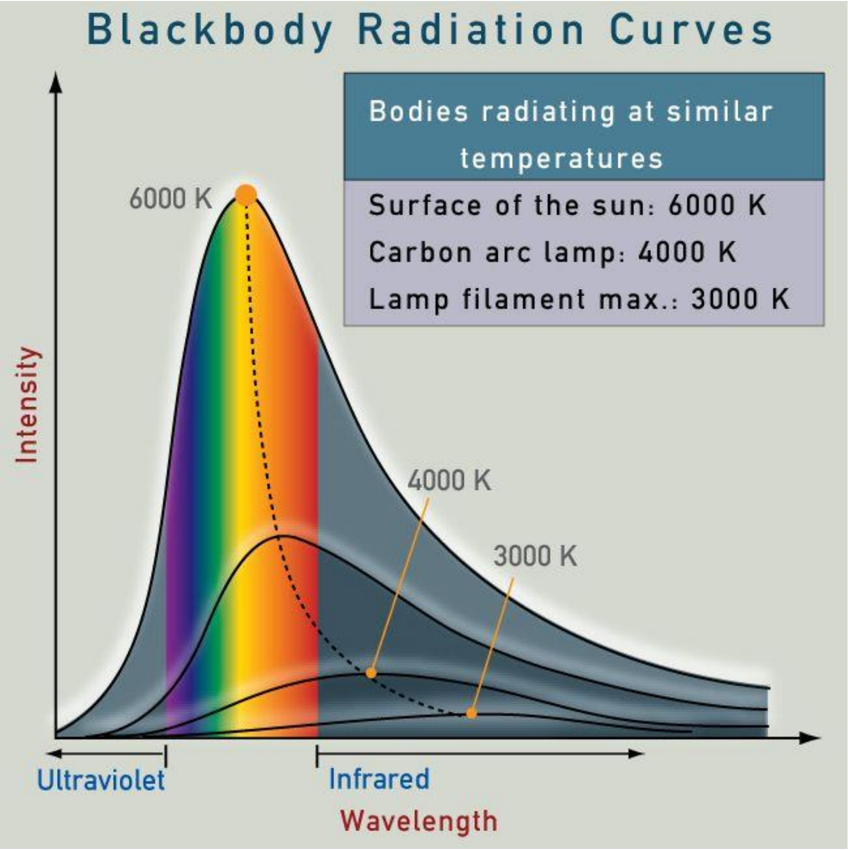


Basic concepts: the black body

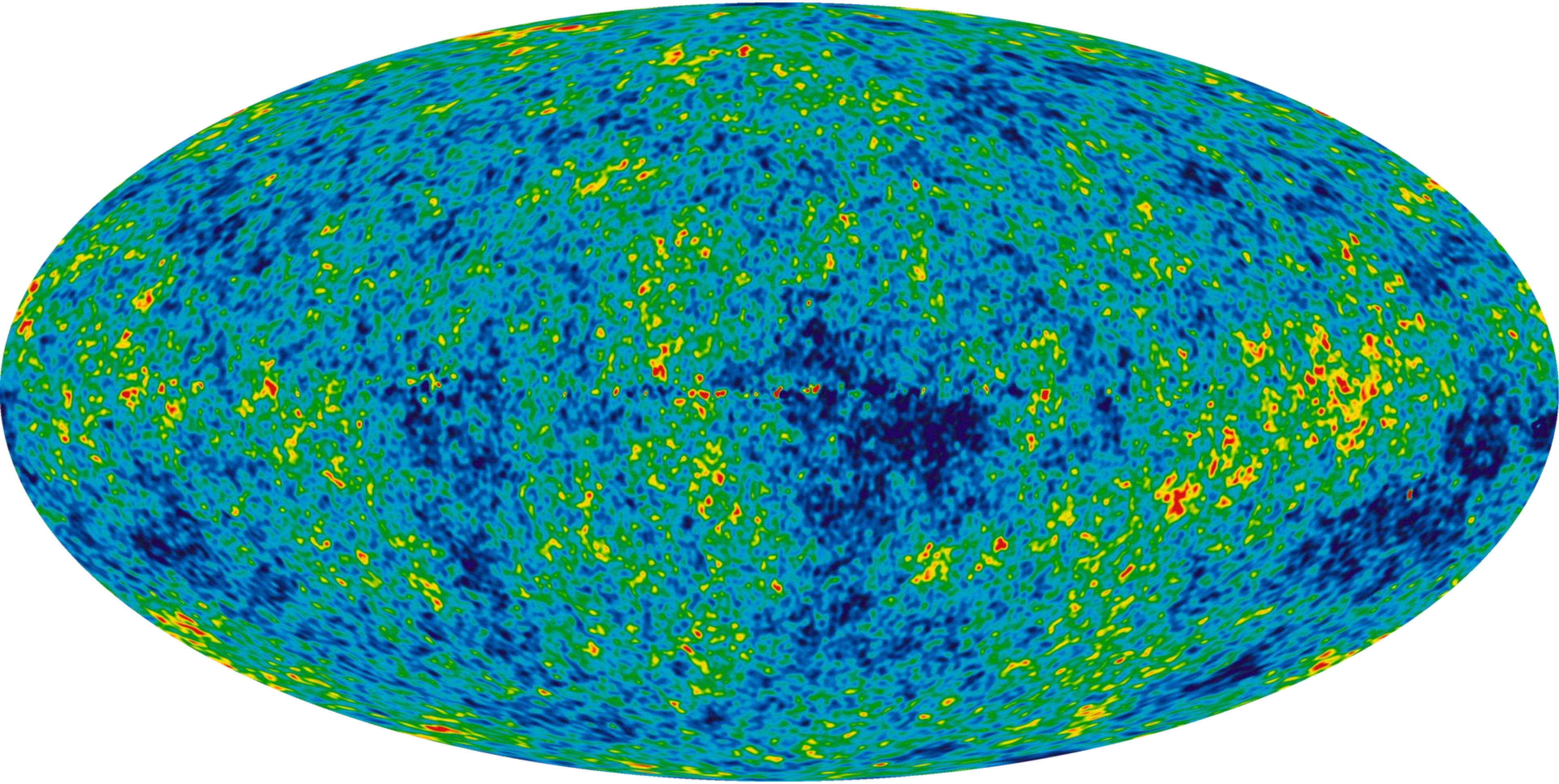
- A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence.

- A black body in thermal equilibrium (that is, at a constant temperature) emits electromagnetic radiation called black-body radiation. The radiation is emitted according to Planck's law, meaning that it has a spectrum that is determined by the temperature alone (see figure at right), not by the body's shape or composition.

- A black body in thermal equilibrium has two notable properties:
  - It is an ideal emitter: at every frequency, it emits as much energy as – or more energy than – any other body at the same temperature.
  - It is a diffuse emitter: the energy is radiated isotropically, independent of direction.

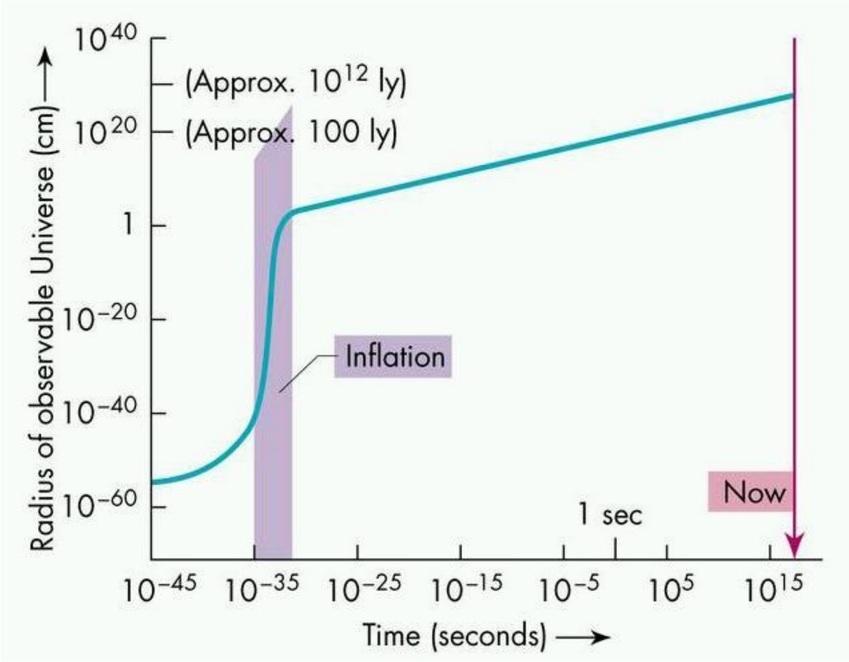


Background cosmic radiation



Before the Big Bang: inflation

- Cosmological inflation is a theory of exponential expansion of space in the early universe.
- Following the inflationary period, the universe continued to expand, but the expansion was no longer accelerating.
- The single mathematic assumption behind inflation theory is the existence of a scalar field that does not dilute with expansion.
- Quantum fluctuations in the microscopic inflationary region, magnified to cosmic size, become the seeds for the growth of structure in the Universe.
- Inflation explains why the universe appears to be the same in all directions (isotropic), why the cosmic microwave background radiation is distributed evenly, and why the universe is flat.
- The detailed particle physics mechanism responsible for inflation is unknown. The basic inflationary paradigm is accepted by most physicists, as a number of inflation model predictions have been confirmed by observation.



The evolution of the universe in a nutshell

- Our understanding of the early moments of the cosmos is based mostly on theoretical expectations of the behaviour of particle systems at various temperatures

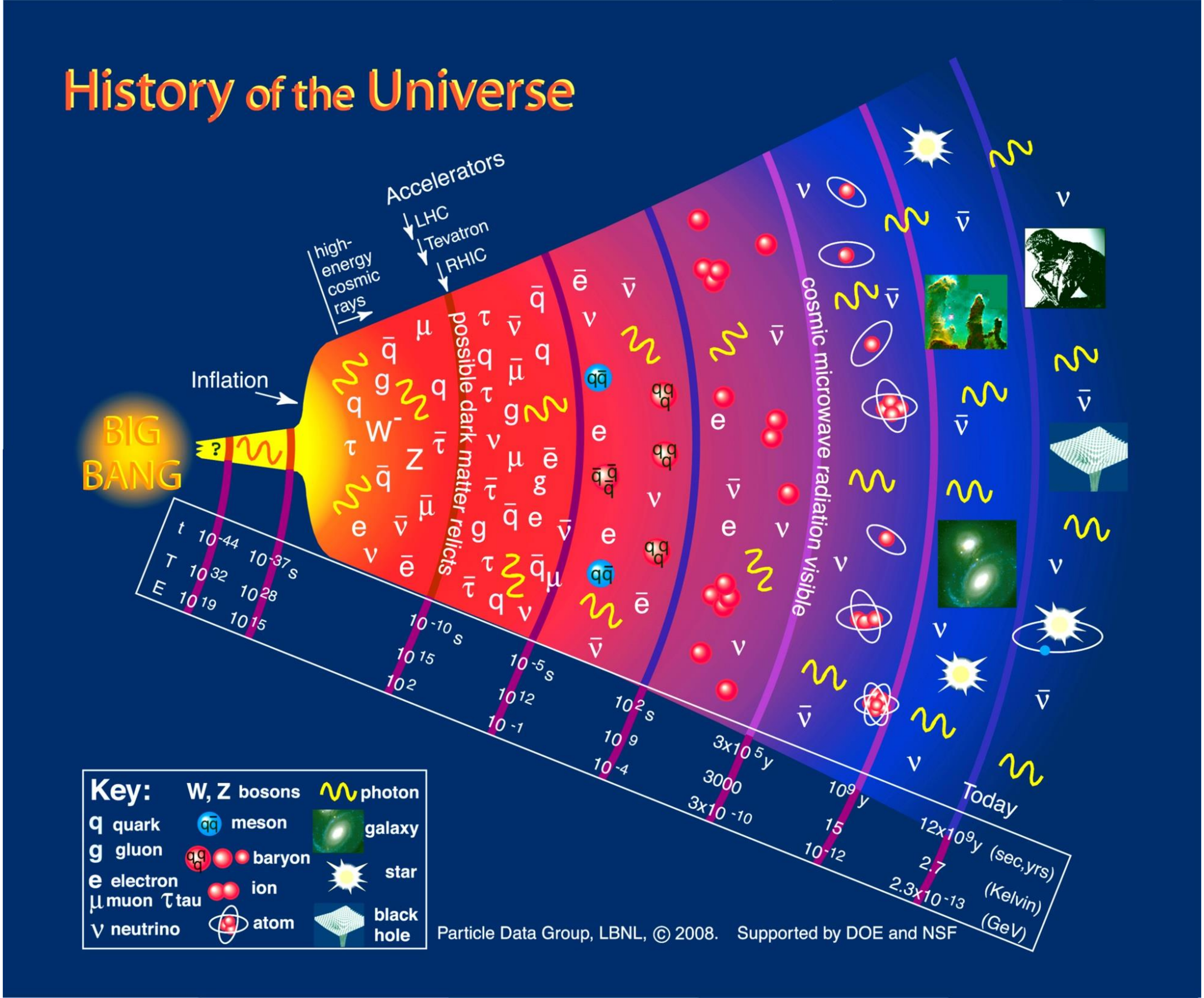
Time (s)	Name of epoch	Major events
"Detonation" to 10^{-43}	Planck	All forces were unified
From 10^{-43} to 10^{-35}	Grand unification	Three forces unified
At roughly 10^{-37}	Inflation	Exponential expansion of cosmos
From 10^{-35} to 10^{-6}	Quark	cosmos made of fundamental "quarks"
At roughly 10^{-11}	Electroweak	Weak and electromagnetic forces decouple
From 10^{-6} to 10^{-4}	Hadronic	Matter excess over antimatter frozen in
At roughly 1	Neutrino decoupling	Background neutrinos go free
From 10^{-4} to 10	Leptonic	Ratio of protons to neutrons frozen in
At roughly 100	Nucleosynthetic	Light atomic nuclei are formed
From 10 to 10^{11}	Radiation	Scale factor goes as $r^{1/2}$
At roughly 10^{13}	Recombination	Cosmos becomes transparent
From 10^{11} to today	Matter	Formation of galaxies, stars, planets, life

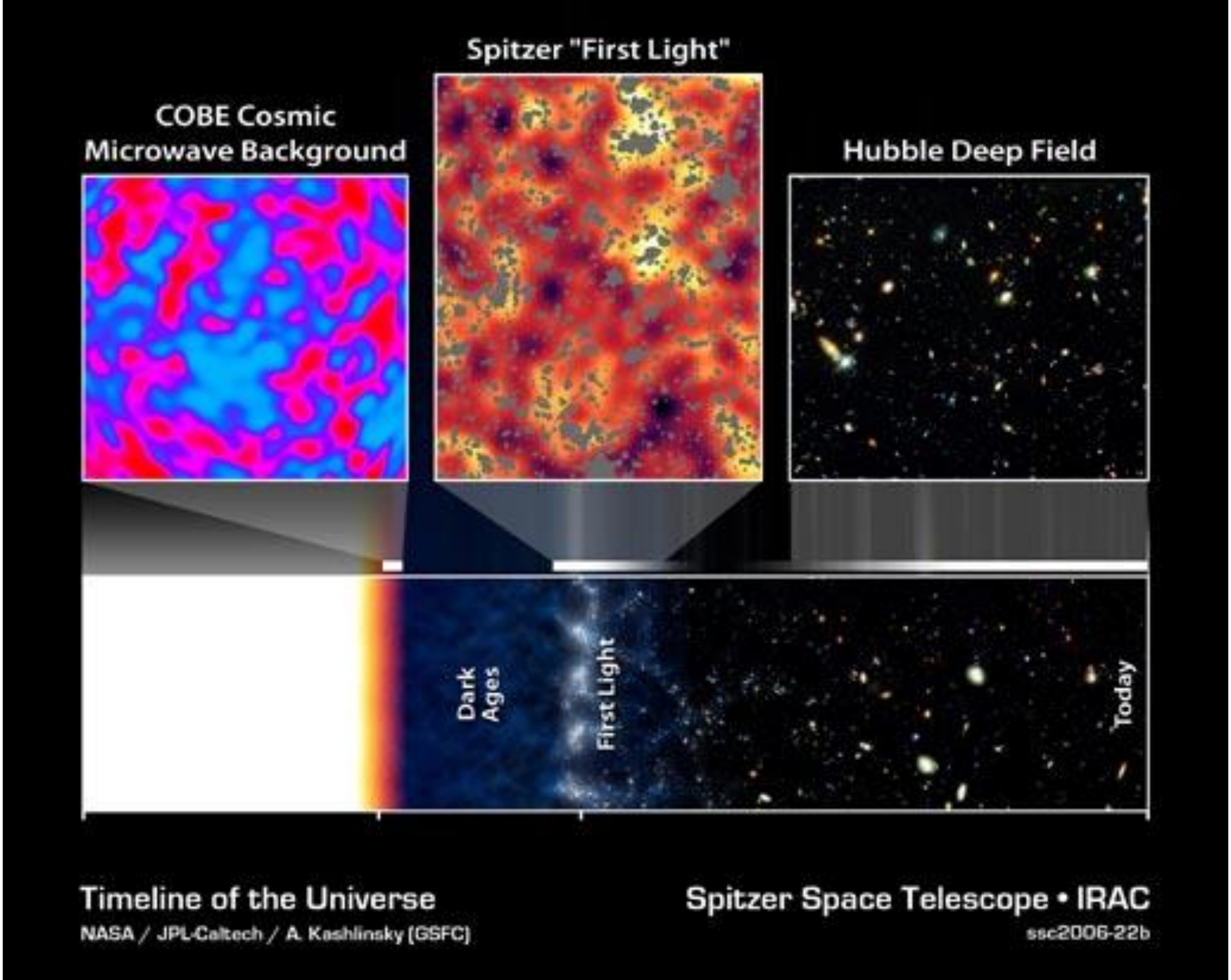
The epochs of the early universe (1)

- At 10^{-43} s gravity begins to dominate the interaction of matter and space, the universe is 3×10^{-35} m across
- Until 10^{-35} s, temperatures are 10^{26} K and above, and electromagnetism, and weak and strong nuclear forces behave identically: this grand unifications allows an asymmetry between matter and antimatter
- At 10^{-37} s the rate of expansion of the universe briefly increased (inflation)
- From 10^{-35} s to 10^{-6} s temperature falls to 10^{11} K, electromagnetism and the weak nuclear forces are still coupled, preventing the formation of stable charged particles
- At 10^{-6} s quarks combine to form hadrons and antihadrons, which annihilate when colliding: birth of the cosmic background radiation, only one particle out of 10^9 survives

The epochs of the early universe (2)

- At 1 s, the universe start cooling through the emission of neutrinos
- 10 s after the Big Bang, electrons become stable, neutrons and protons cannot convert one to the other any longer
- At 100 s, temperature is 10^9 K, and collision between hadrons could lead to the formation of (fully ionized) heavier nuclei, abundance of helium is about 25% that of hydrogen, Li/H is about 10^{-10}, deuterium is about 20 ppm w.r.t. hydrogen
- As the universe expands, nucleosynthesis becomes rare
- At 10^{13} s the universe is several 10^{18} km across, radiation decoupling occurs, temperature is 3000 K, electrons bind to nuclei to form atoms

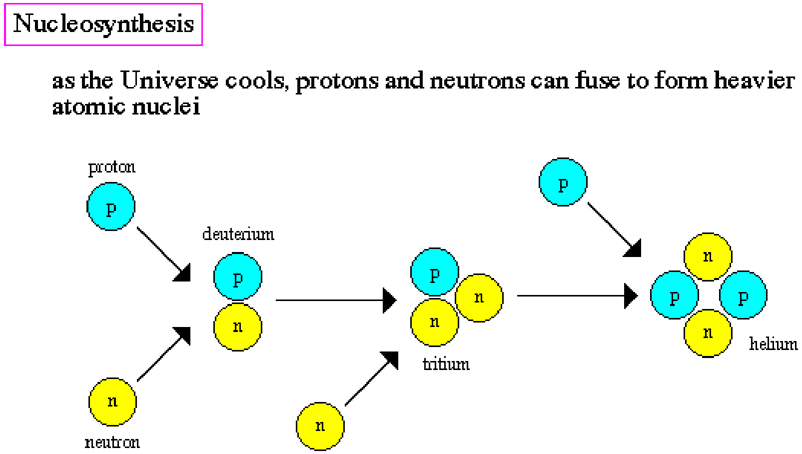

History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF



Spitzer "First Light"
COBE Cosmic
Microwave Background
Hubble Deep Field
Dark Ages
First Light
Today
Timeline of the Universe
NASA / JPL-Caltech / A. Kashlinsky (GSFC)
Spitzer Space Telescope • IRAC
ssc2006-22b

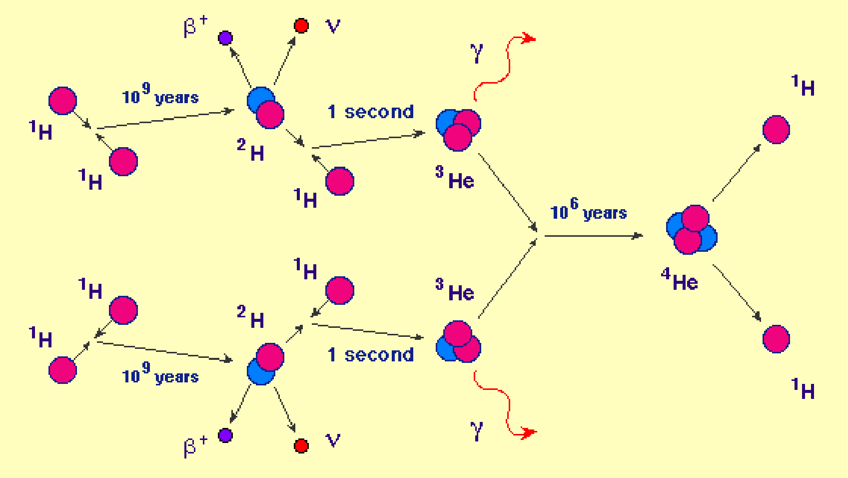
Origin of chemical elements

- The first nuclei were formed a few minutes after the Big Bang, through the process called Big Bang nucleosynthesis.
- After about 20 minutes, the universe had cooled to a point at which these processes ended, so only the fastest and simplest reactions occurred, leaving our universe containing about 75% hydrogen, 24% helium by mass.
- The rest is traces of other elements such as lithium and the hydrogen isotope deuterium.
- The universe still has approximately the same composition.



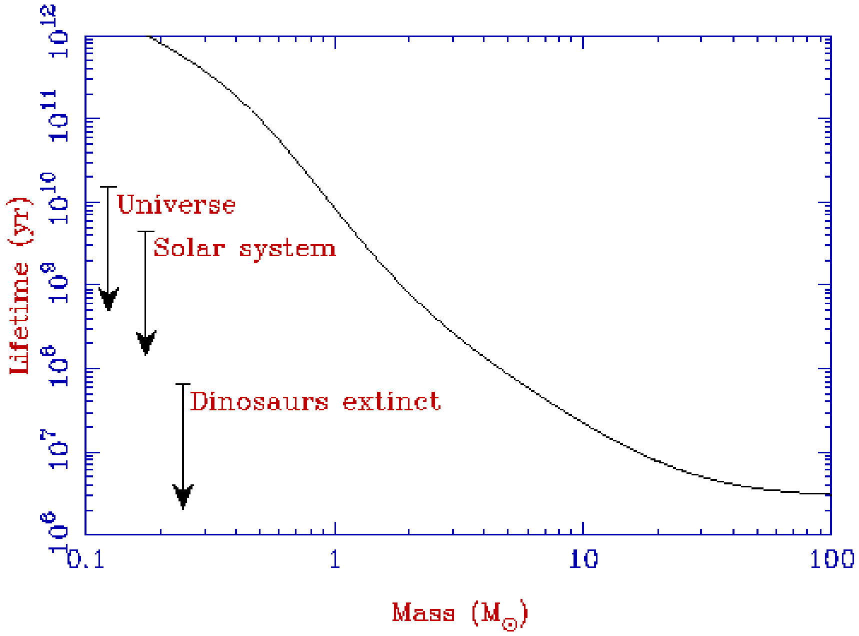
Where do heavier nuclei come from?

- The nuclei of light elements can be merged to produce heavier elements
- This process is exothermic, and thus energetically favoured, up to iron
- In the matter-dominated universe, electrostatic repulsion prevent contacts between nuclei
- Only in the core of stars pressures and temperatures are sufficient for nuclear fusion
- Nuclear fusion is what makes stars shine
- Two types of reaction sequences within stars: proton-proton chain (p-p), and carbon, nitrogen and oxygen cycle (CNO)



Nuclear fusion and stars

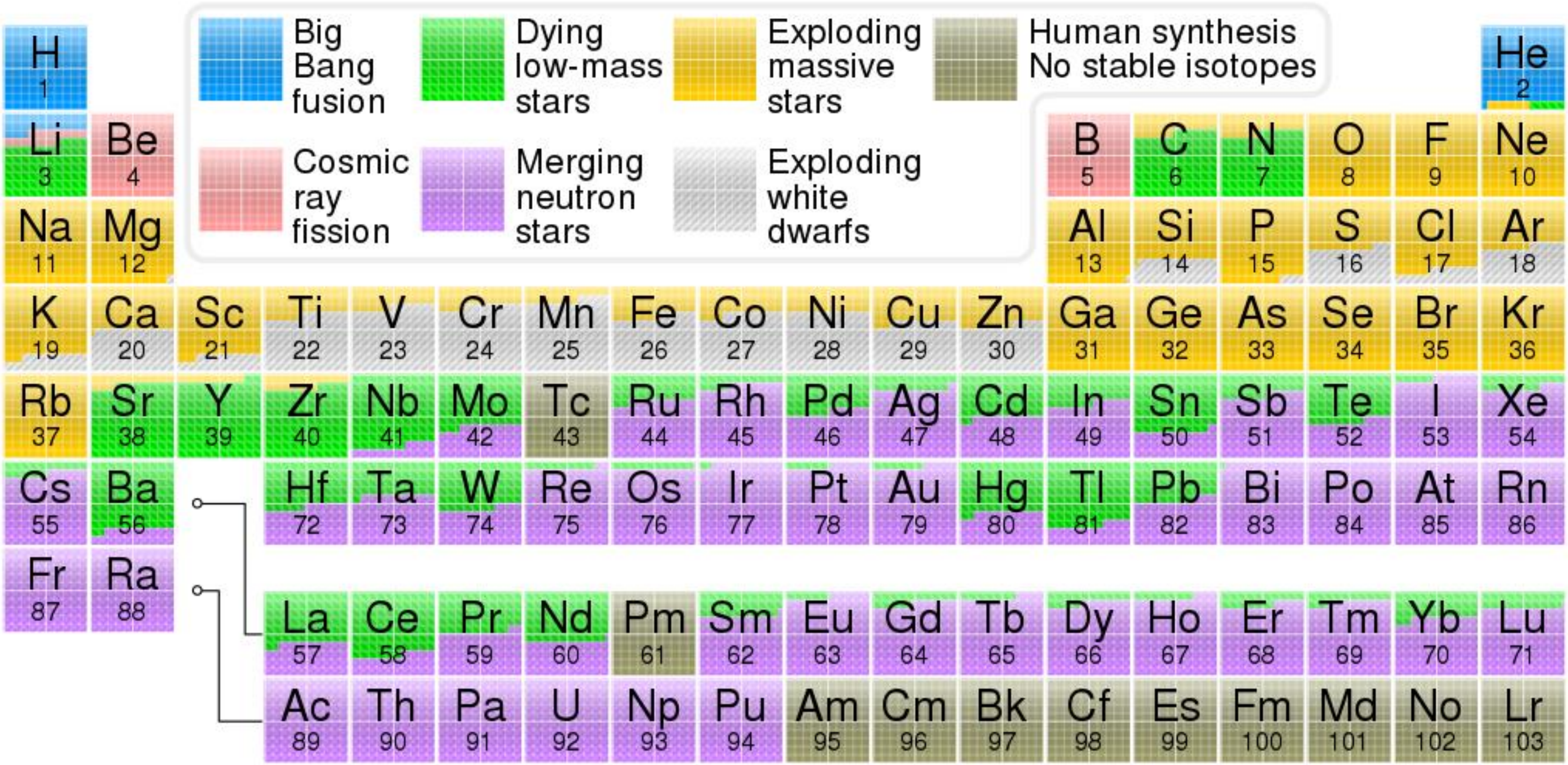
- The rate of nuclear fusions in star increases with temperature and pressure, and thus with the mass of the star
- The Sun could sustain its rate of nuclear fusions (main sequence) for 12 billion years, of which 4.5 have already passed
- Smaller ("dwarf") stars could last for hundreds billion years
- Larger ("giant") stars last only hundred millions years or less
- The time available for life to evolve depends on the star around which a planet is revolving



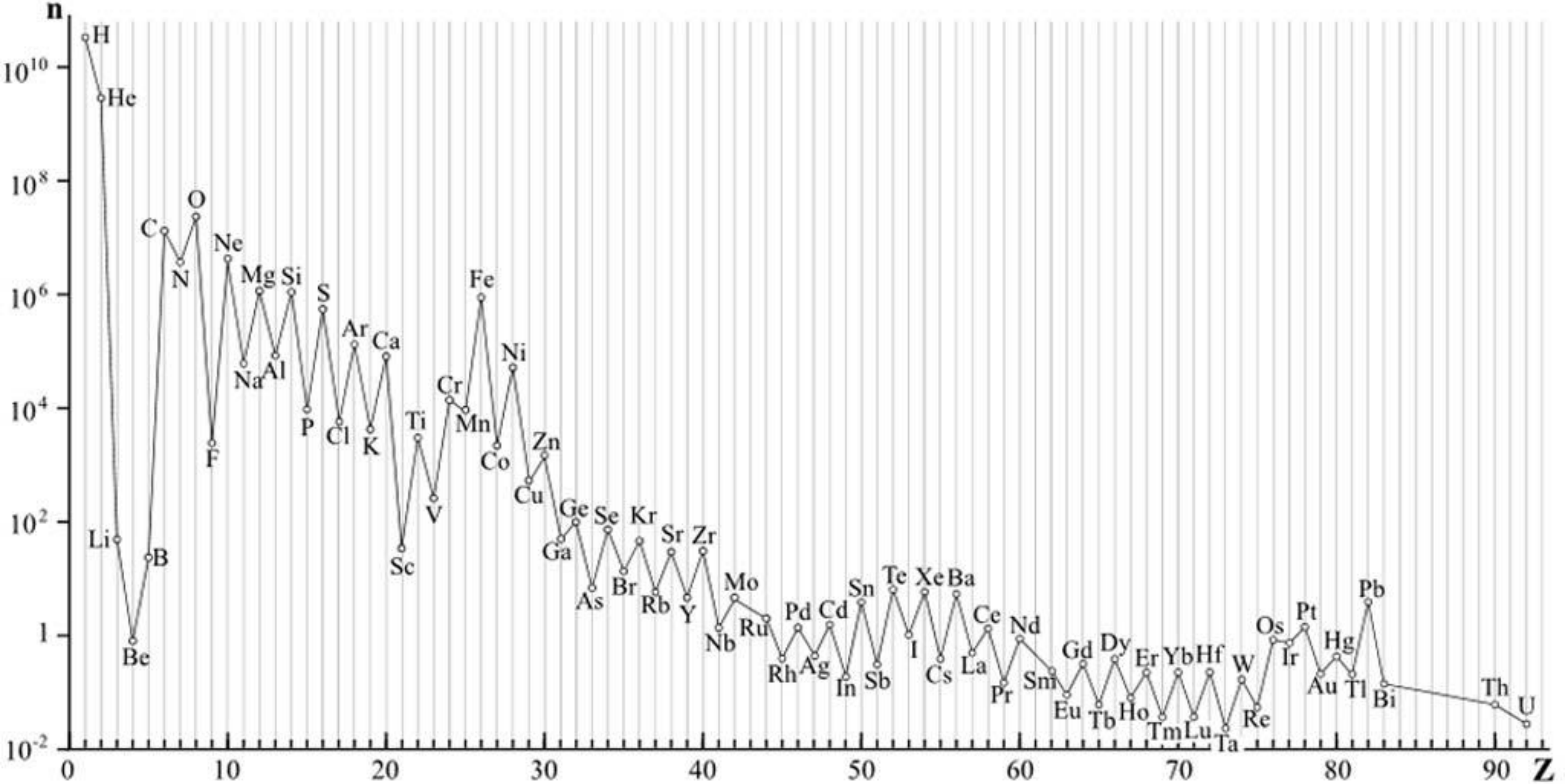
The synthesis of nuclei heavier than He

- Stars like the Sun do not have enough mass to merge He nuclei until they remain in the main sequence, i.e. until their main "fuel" is H
- Once H is depleted in the nucleus, the rate of reactions decreases, and the nucleus contracts under its gravity
- At a certain point, temperature reaches the point at which He nuclei can form elements up to oxygen, after which it collapses and becomes a white dwarf
- Larger stars can produce elements up to iron, after which nuclear reactions become endothermic, and the star collapses and then explodes
- Elements heavier than iron are formed during the collapse of a massive star through neutron addition (s-process and r-process)
- A supernova disseminates heavy elements through the universe, leaving a neutron star or a black hole as a remnant
- Stars of subsequent generations contain a progressively larger fraction of heavier elements

Origin of chemical elements



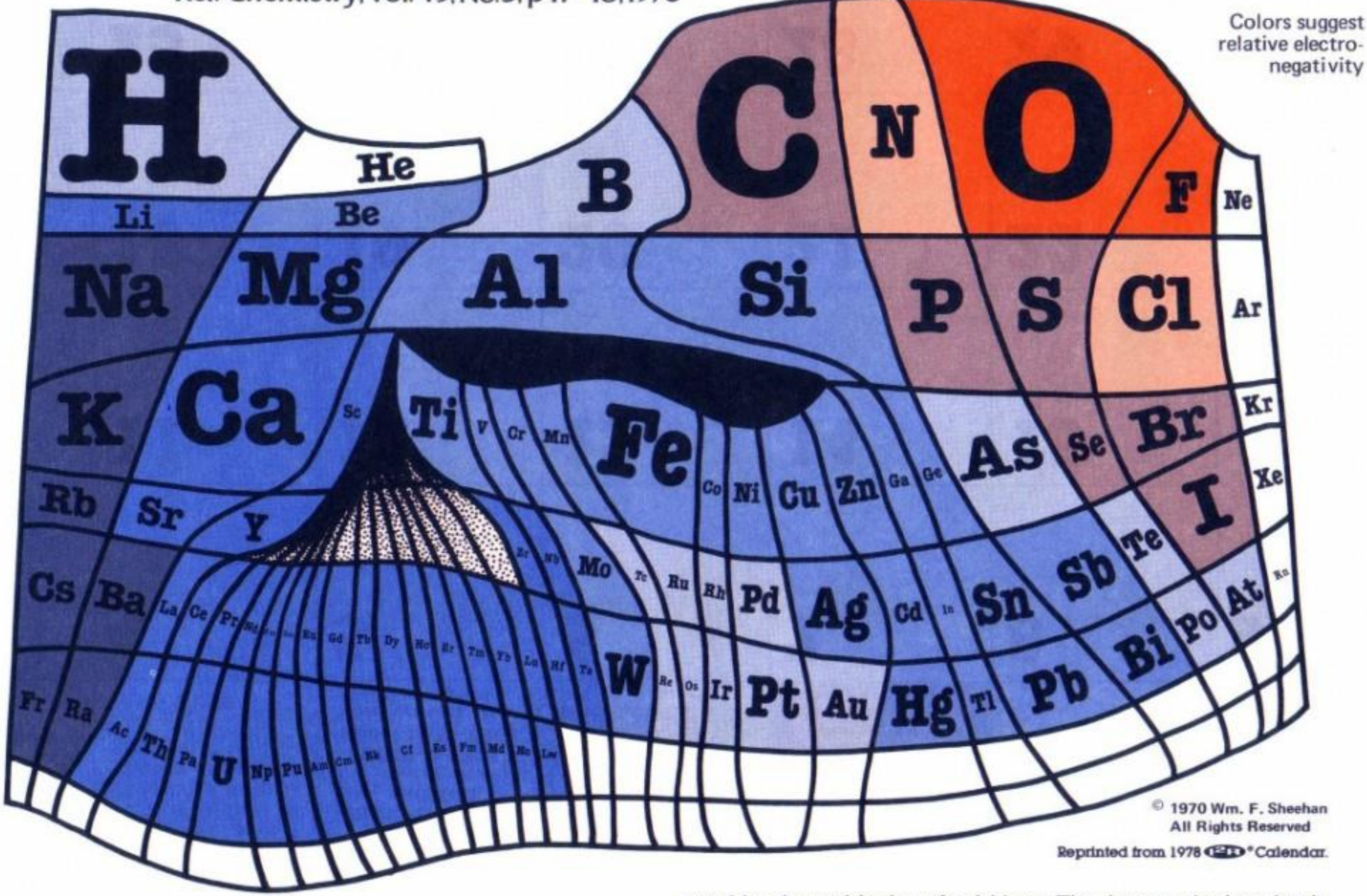
Cosmic abundance of elements



The Elements According to Relative Abundance

A Periodic Chart by Prof. Wm. F. Sheehan, University of Santa Clara, CA 95053

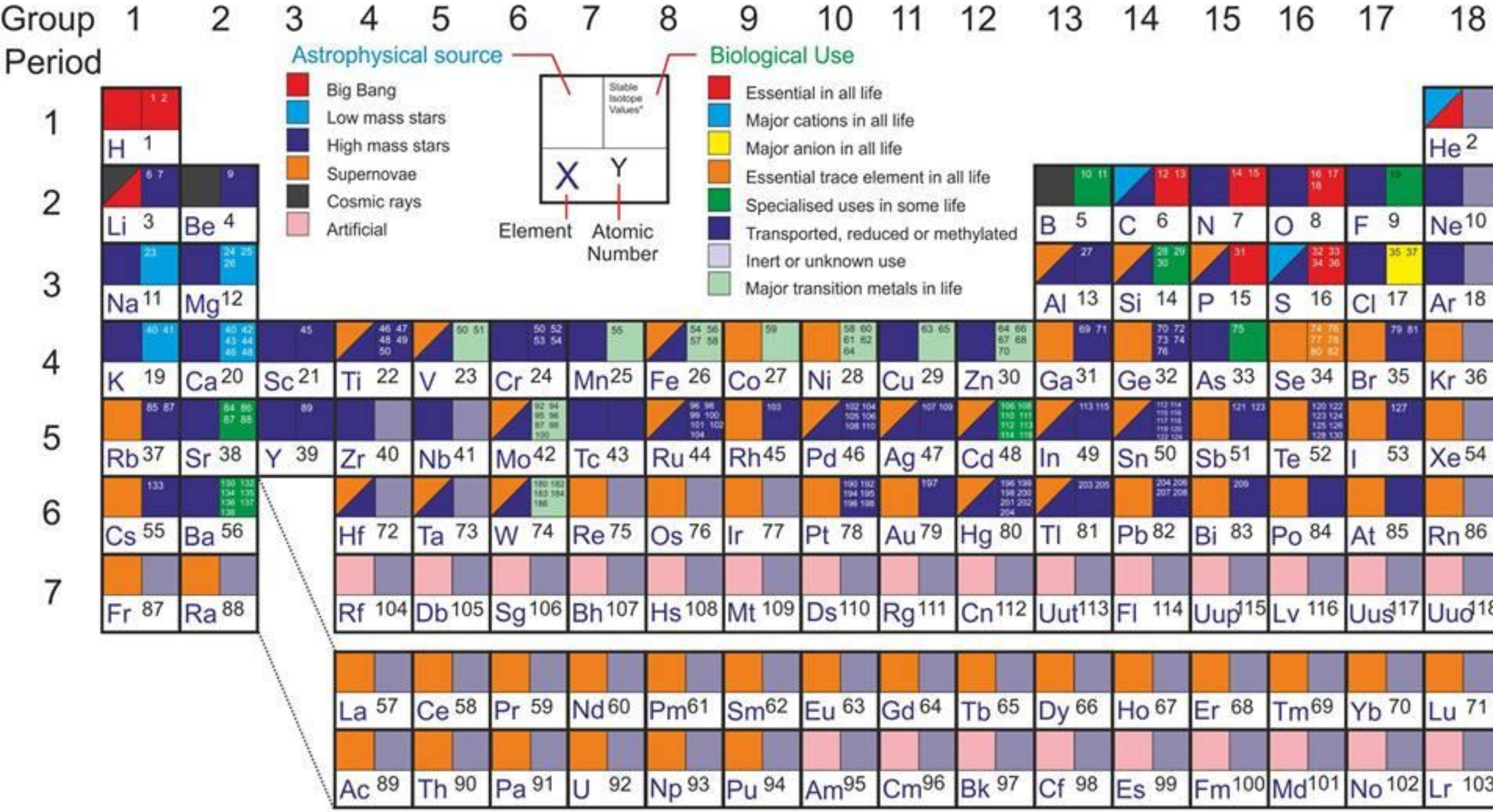
Ref. Chemistry, Vol. 49, No. 3, p 17–18, 1976



Roughly, the size of an element's own niche ("I almost wrote square") is proportioned to its abundance on Earth's surface, and in addition, certain chemical similarities (e.g., Be and Al, or B and Si) are suggested by the positioning of neighbors. The chart emphasizes that in real life a chemist will probably meet O, Si, Al, . . . and that he better do something about it. Periodic tables based upon elemental abundance would, of course, vary from planet to planet. . . W.F.S.

NOTE: TO ACCOMMODATE ALL ELEMENTS SOME DISTORTIONS WERE NECESSARY, FOR EXAMPLE SOME ELEMENTS DO NOT OCCUR NATURALLY.

The Astrobiological Periodic Table

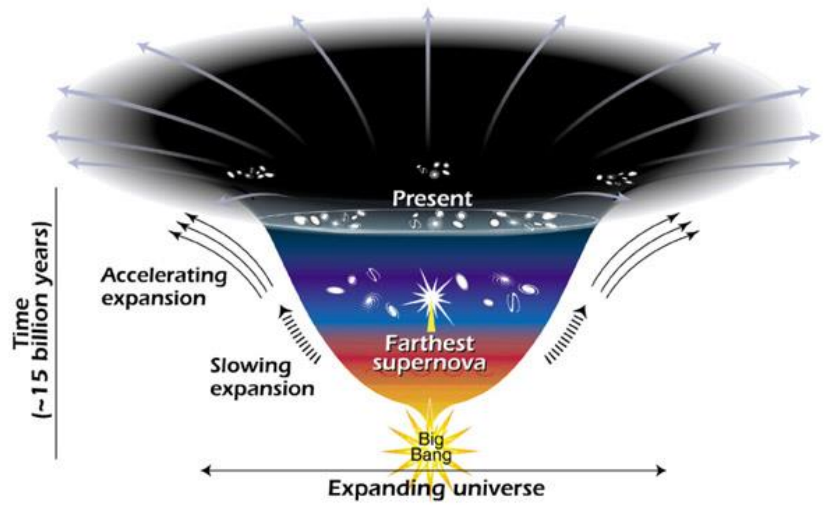


Biological data from Wackett, L.P., Dodge, A.G., Ellis, L.B.M. (2004) *Applied and Environmental Microbiology* **70**, 647-655.

* *Stable isotope values of biologically non-inert, non-radioactive elements*

A more complex story

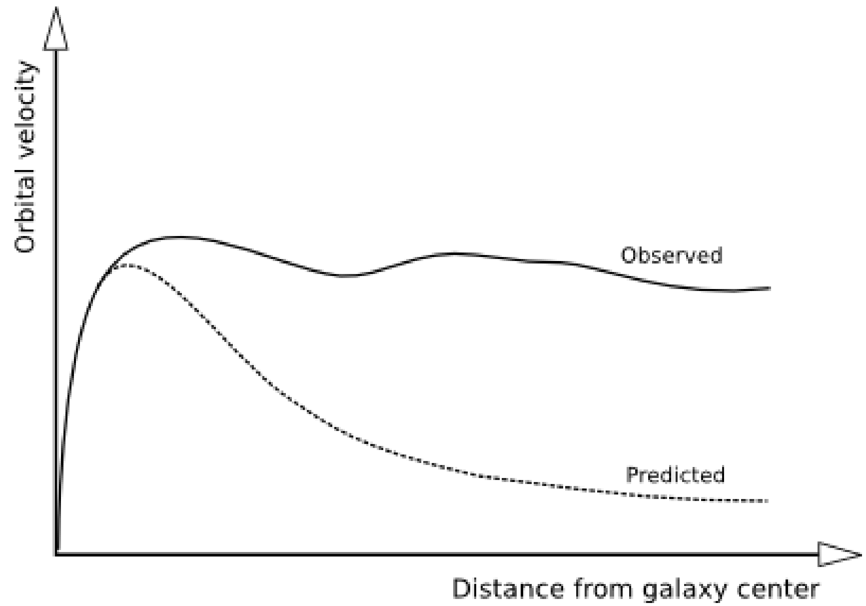
- About 90% of the cosmos seems to be made of matter that does not emit, scatter or absorb light
- The universe is nearly flat, rather than curved to some significant extent
- The expansion of the universe is accelerating at the largest scales, rather than slowing because of mutual gravitational attraction



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

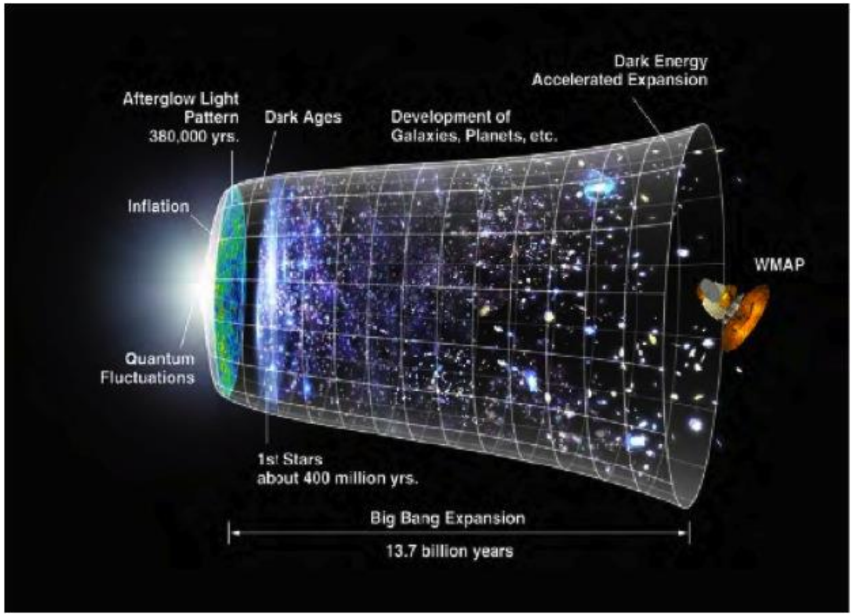
Dark matter

- Anomalies in the rotation curves of galaxies hint at the presence of massive halos around them
- "Brown dwarfs" were hypothesized as the cause, but they were not found
- Invoking other failed stars as the missing mass would require a rate of star formation inconsistent with observations
- If dark matter was gas, then it would alter the properties of cosmic background radiation
- Dark matter is thought to consist of exotic subatomic particles possessing mass but interacting very weakly with radiation



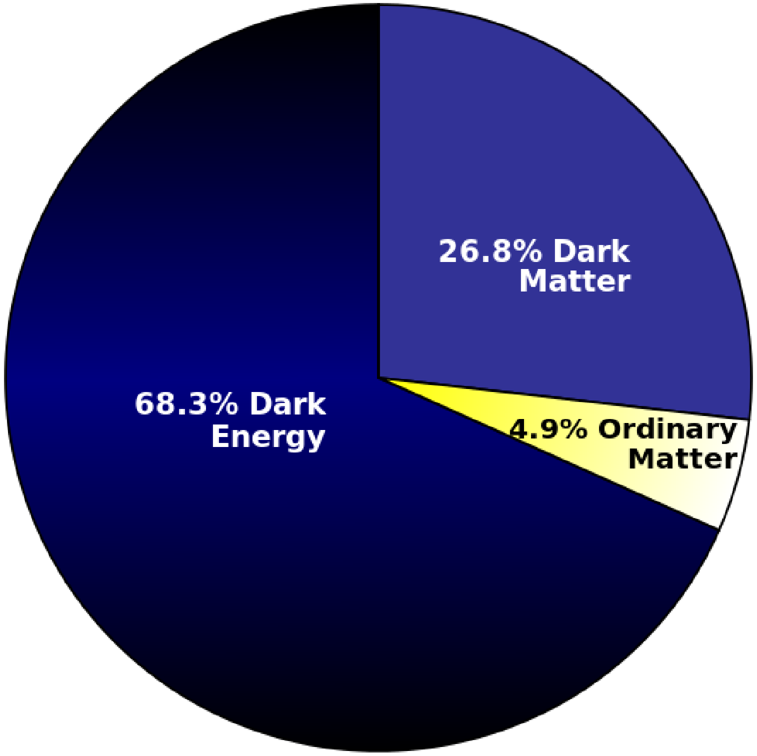
The nature of the universe

- Is there enough matter in the universe to allow its expansion to slow, stop and reverse, or will it expand forever? Is the universe open or close?
- Observations reveal that the universe is neither, there's just enough matter to make it "flat"
- Such property requires a sudden change in the rate of expansion of the universe in its early history (inflation), with an increase of scale by a factor between 10^{40} and 10^{100} in a very short time



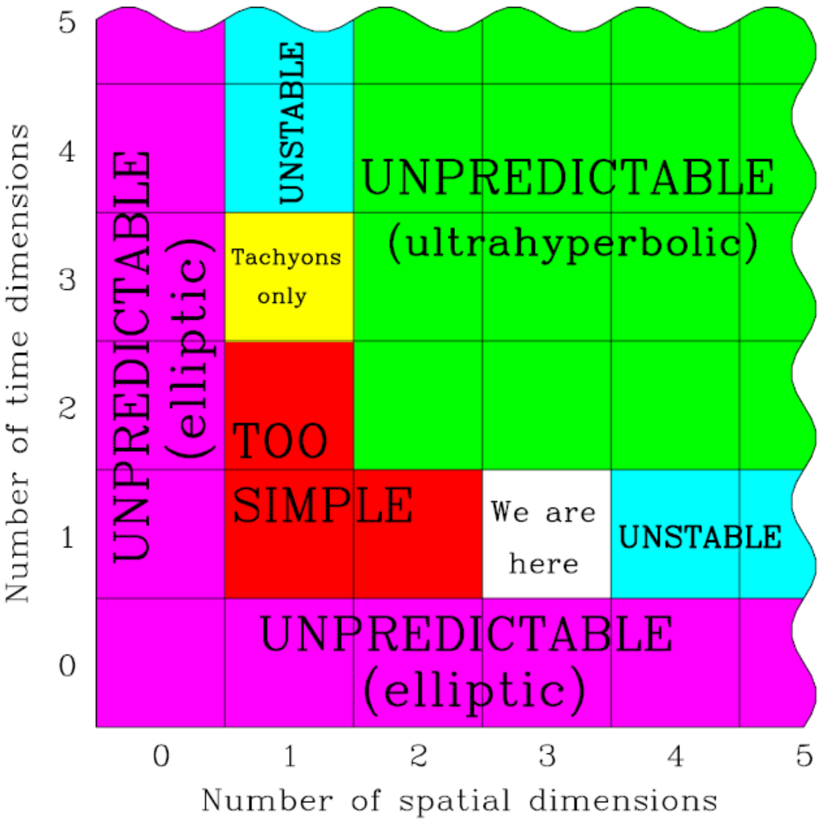
Dark energy

- Theories describing inflation require that our universe has more than four dimensions, some of which did non "inflate"
- Inflation suggests that the universe was born with a small repulsive tendency in its space-time dimensions
- In the theory of general relativity, this is represented by a "cosmological constant" forcing a repulsive component of gravity at the largest scales
- This repulsive force is called "dark energy"
- To contrast the gravitational attraction of normal and dark matter, dark energy should constitute about 70% of the cosmos
- What is dark energy? It is supposed to be a scalar field (like Higg's boson).



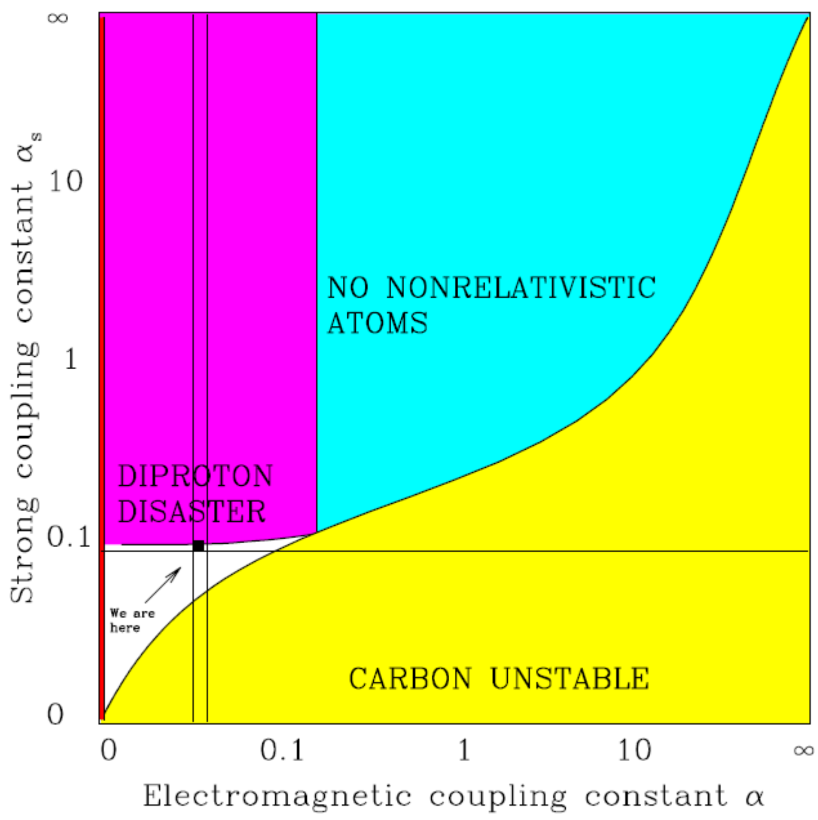
Does the universe need to be "special" to accommodate life? The anthropic principle

- If four spatial dimension had inflated, no stable orbit in a gravitational field could exist
- Similarly, electronic orbits around four-dimensional atoms would be unstable
- Two-dimensional universes do not allow sufficient complexity in chemistry or structural topologies for life to occur
- Without inflation, material particles could not exist
- Some inflation scenarios would cause an universe to rapidly collapse on itself
- If inflation had lasted too long, the density of matter would be too low for the formation of elements



Other unexplained facts

- The relative strength of the electromagnetic force relative to the fundamental quantum "coarseness" of the cosmos is measured by the fine structure constant:
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$
- It gives a measure of how well bounds atom are
- A change in the constant by a factor of 10 would not allow the existence of carbon atoms
- Life could develop only after a sufficient quantity of heavier elements has been produced within stars
- Too young or too old galaxies could not form stars with rocky planets
- Even the fact that the Earth has a moving crust recycling volatiles such as CO_2 and H_2O is partly enabled by a particular mix of heat-producing radiogenic elements

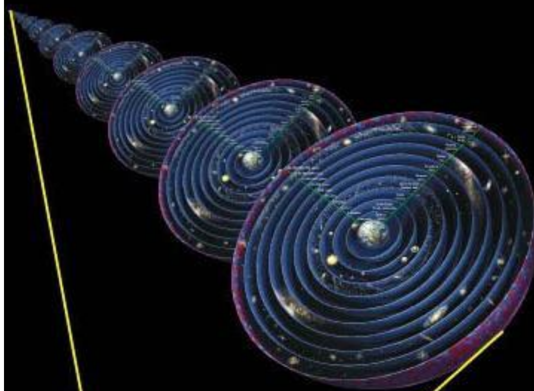


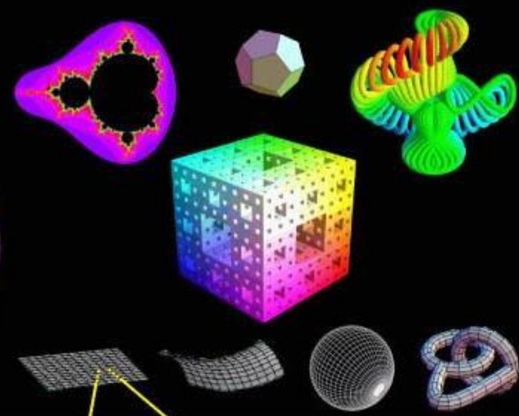
Level 1: Regions beyond our cosmic horizon

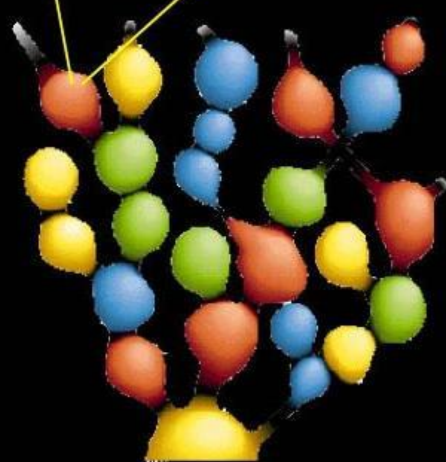
Features: Same laws of physics, different initial conditions
Assumptions: Infinite space, ergodic matter distribution
Evidence:
- Microwave background meaurements point to flat, infinite space, large-scale smoothness
- Simplest model

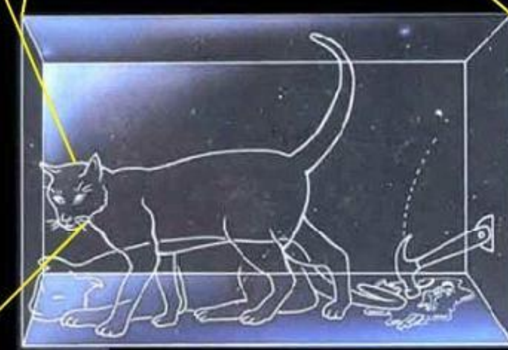
Level 4: Other mathematical structures

Features: Different fundamental equations of physics
Assumption: Mathematical existence = physical existence
Evidence:
- Unreasonable effectiveness of math in physics
- Answers Wheeler/Hawking question: "why these equations, not others"









Level 2: Other post-inflation bubbles

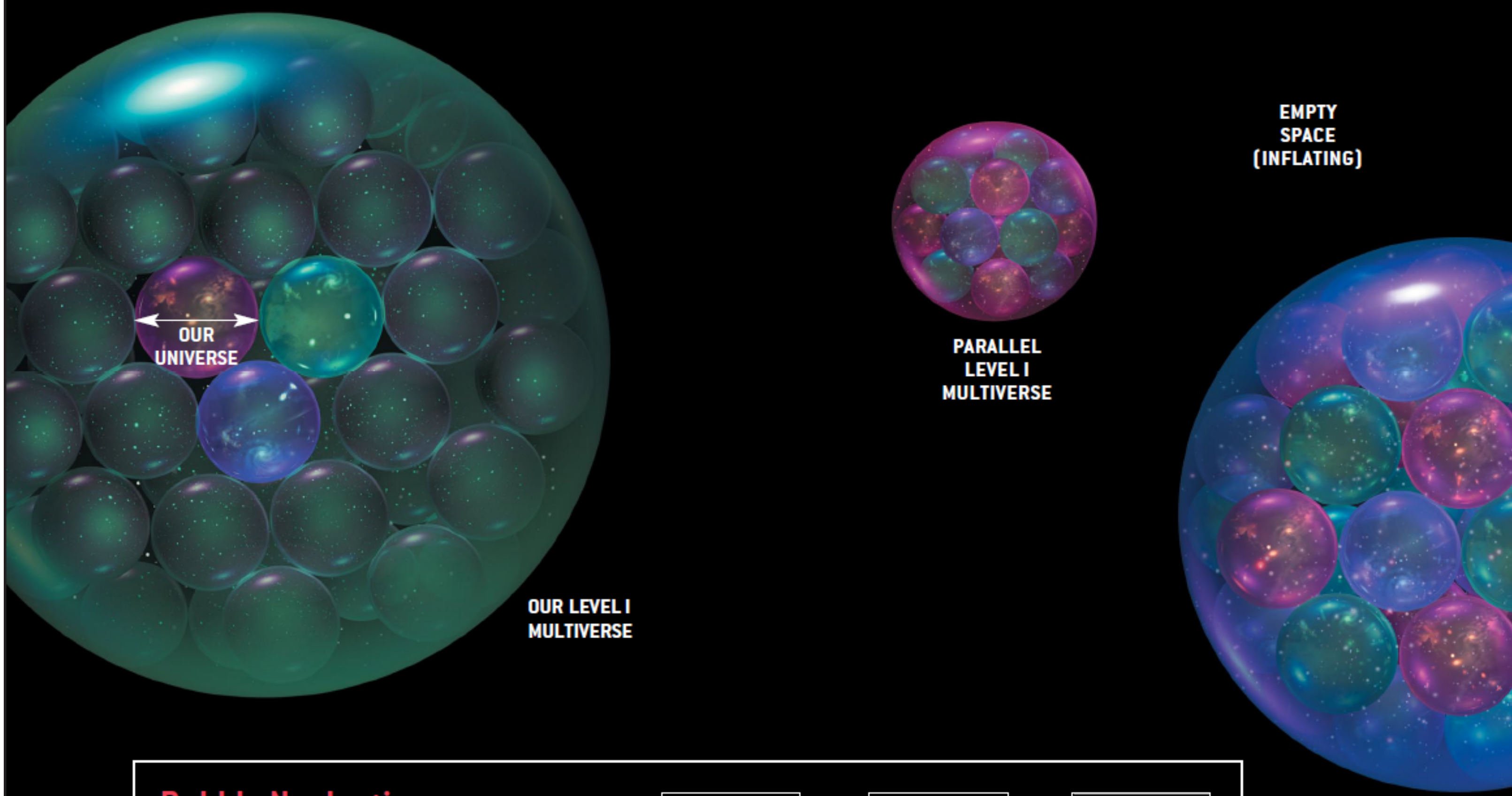
Features: Same fundamental equations of physics, but perhaps different constants, particles and dimensionality
Assumption: Chaotic inflation occurred
Evidence:
- Inflation theory explains flat space, scale-invariant fluctuations, solves horizon problem and monopole problems and can naturally explain such bubbles
- Explains fine-tuned parameters

Level 3: The Many Worlds of Quantum Physics

Features: Same as level 2
Assumption: Physics unitary
Evidence:
- Experimental support for unitary physics
- AdS/CFT correspondence suggests that even quantum gravity is unitary
- Decoherence experimentally verified
- Mathematically simplest model

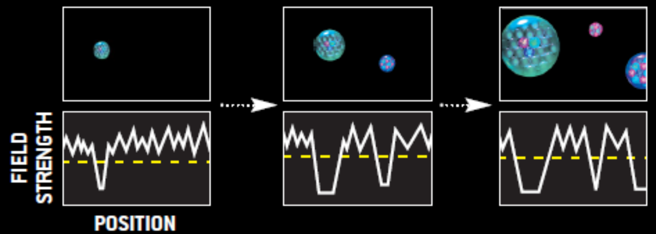
LEVEL II MULTIVERSE

A SOMEWHAT MORE ELABORATE type of parallel universe emerges from the theory of cosmological inflation. The idea is that our Level I multiverse—namely, our universe and contiguous regions of space—is a bubble embedded in an even vaster but mostly empty volume. Other bubbles exist out there, disconnected from ours. They nucleate like raindrops in a cloud. During nucleation, variations in quantum fields endow each bubble with properties that distinguish it from other bubbles.



Bubble Nucleation

A QUANTUM FIELD known as the inflaton causes space to expand rapidly. In the bulk of space, random fluctuations prevent the field from decaying away. But in certain regions, the field loses its strength and the expansion slows down. Those regions become bubbles.



References

- This presentation is entirely based on Chapter 5 of the book “Astrobiology – A Multidisciplinary Approach”, by Jonathan I. Lunine, Addison Wesley, 2005

Further reading

- Tegmark, Max. The multiverse hierarchy, in *Universe or Multiverse?* (Bernard Carr Ed.), Cambridge University Press, 2009. Freely available at http://arxiv.org/abs/0905.1283
- https://www.youtube.com/watch?v=W1YkGw9aA5Y
- https://www.youtube.com/watch?v=DMcsyuLYFaY
- https://www.youtube.com/watch?v=zORUUqJd81M