The Universe Around Us Expands.

We see the most distant parts of space receding from us at nearly the speed of light in all directions. Extrapolating back to the earliest times we conclude that the Universe must have initially been very dense. It must also have been very hot since it can only have cooled on expansion.

But how compact and how hot could the Cosmos have been in the beginning? To think about these questions we need to ask

What is the highest density we can conceive?

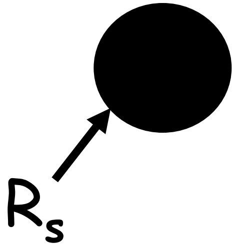
WHAT IS THE EARLIEST CONCEIVABLE TIME?

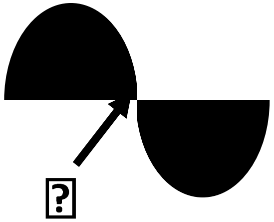
The Highest Conceivable Density

The radius of a black hole of mass m is the Schwarzschild radius $R_s = 2mG/c^2$

The Compton Wavelength of this mass is

$$\lambda/2\pi = \hbar/mc$$





Setting these two lengths equalfor the smallest mass, we have the Planck mass

$$m_P = (hc/G)^{1/2} = 2.2 \times 10^{-5} g$$

The time to traverse R_s at the speed of light is the shortest conceivable time:

$$\text{Planck time,} \quad t_p = \left(\frac{\hbar G}{c^5}\right)^{1/2} = 5.38 \times 10^{-44}\,\text{s.}$$

The mean density of matter within a volume ℓ_p^3 is

$$\rho_p \sim m_p/\ell_p^3 = \frac{c^5}{hG^2} \sim 5 \times 10^{93} \text{g cm}^{-3}$$

The corresponding temperature is $T_P \sim 10^{32}$ K

The Causality Problem

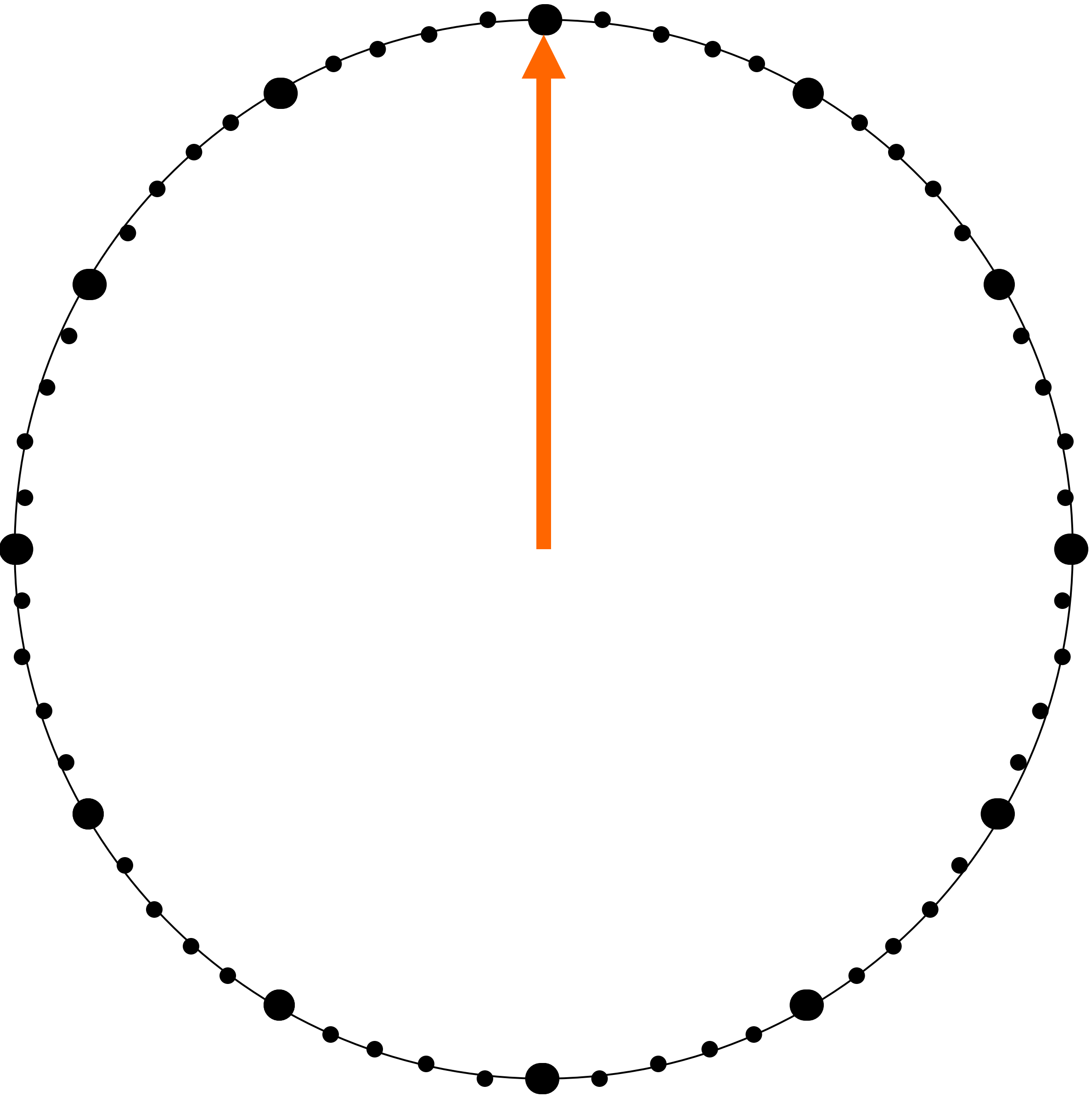
Out to the horizon where the Universe expands with the speed of light the mass of the Cosmos seen today is ~10^{55} g.

At the density prevailing at the Planck time, this would have filled a volume of at least 10^{-39} cm^3 or 10^{-13} cm on a side. At the speed of light this would take 3×10^{-24} sec to traverse. That is long compared to the Planck time, and raises the question:

How could these separate parts have been causally connected?

This question has led to an Inflationary Model of the Universe

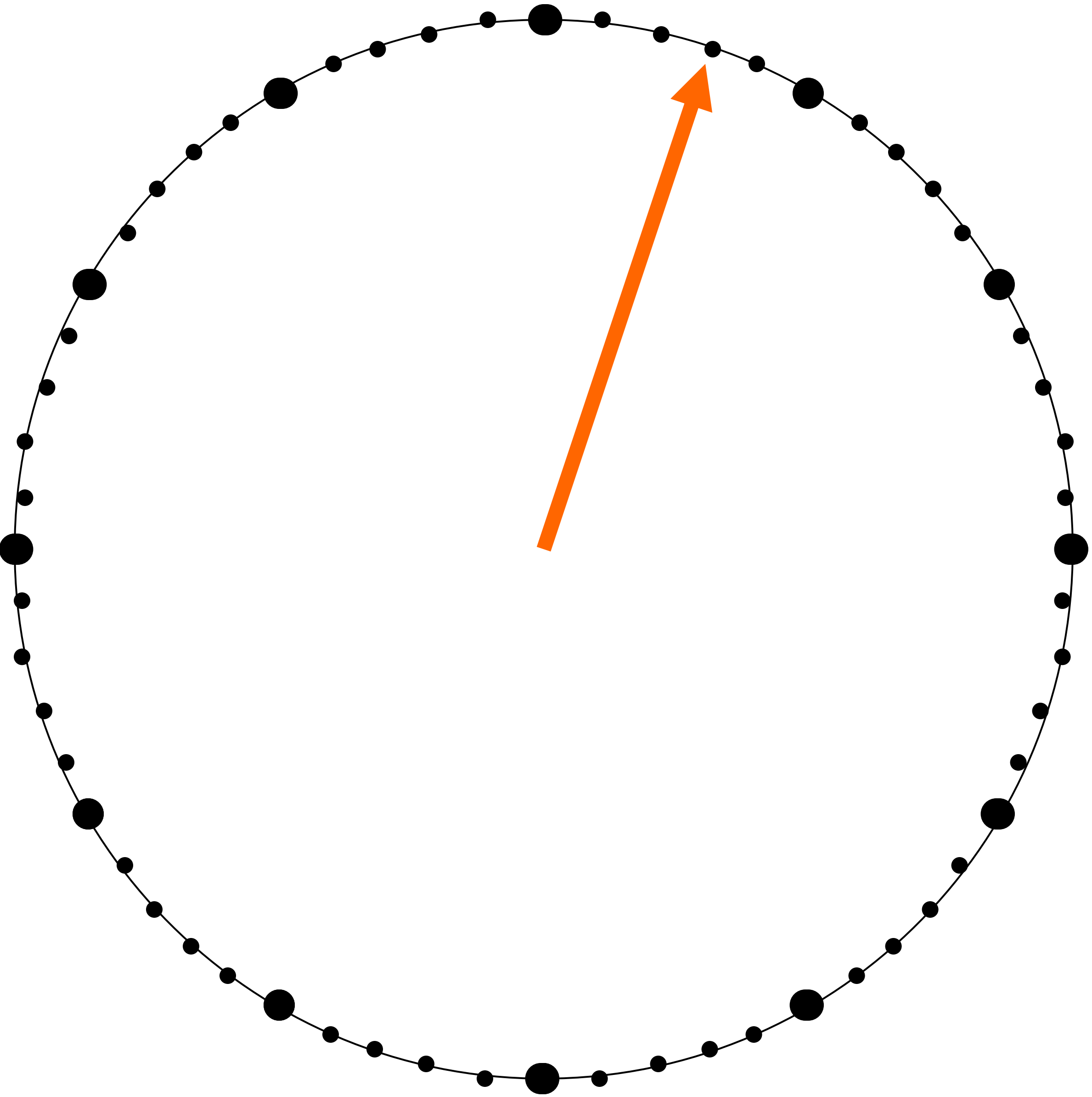
$t \sim 10^{-43}$ s



We may think of the Universe as a peculiar Clock. It has by now ticked 60 times, but each successive tick has taken 10 times longer than the previous one.

At times earlier than the Planck time $t_p = (\hbar G/c^5)^{1/2}$ $\sim 5 \times 10^{-44}$ s. the current laws of physics would not have applied. So, we can say nothing about such an epoch.

10^{-43} - 10^{-35} s



Inflationary Theory postulates that the Universe began to gradually expand at 10^{-43}s, driven by the high density of matter. This continued for ~10^{-35} s. By that age regions ~10^{-25} cm in diameter could have interacted at the speed of light and come to equilibrium. Over such distances each part of the Cosmos could have become aware of its neighboring regions.

The Initial Expansion at t ~ 10^{-43} to 10^{-35} s

The Einstein equations tell us that the square of the expansion rate of the scale *a* of the Universe is driven by its density ⍰

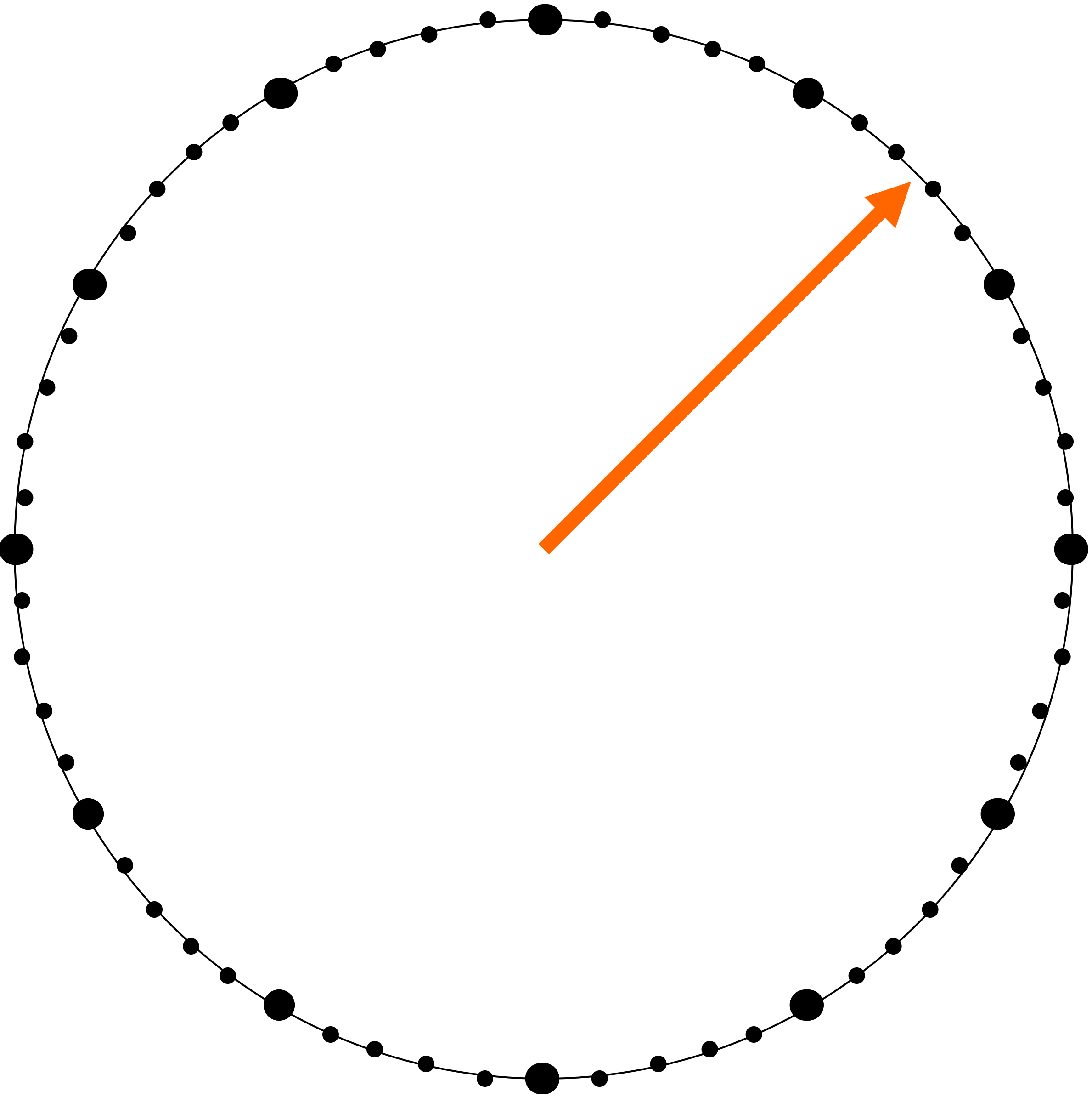
$$\frac{8\pi G\rho}{3} = \frac{\dot{a}^2}{a^2}$$

making

$$a \propto t^{1/2} \propto T^{-1} \propto \rho^{-1/4}$$

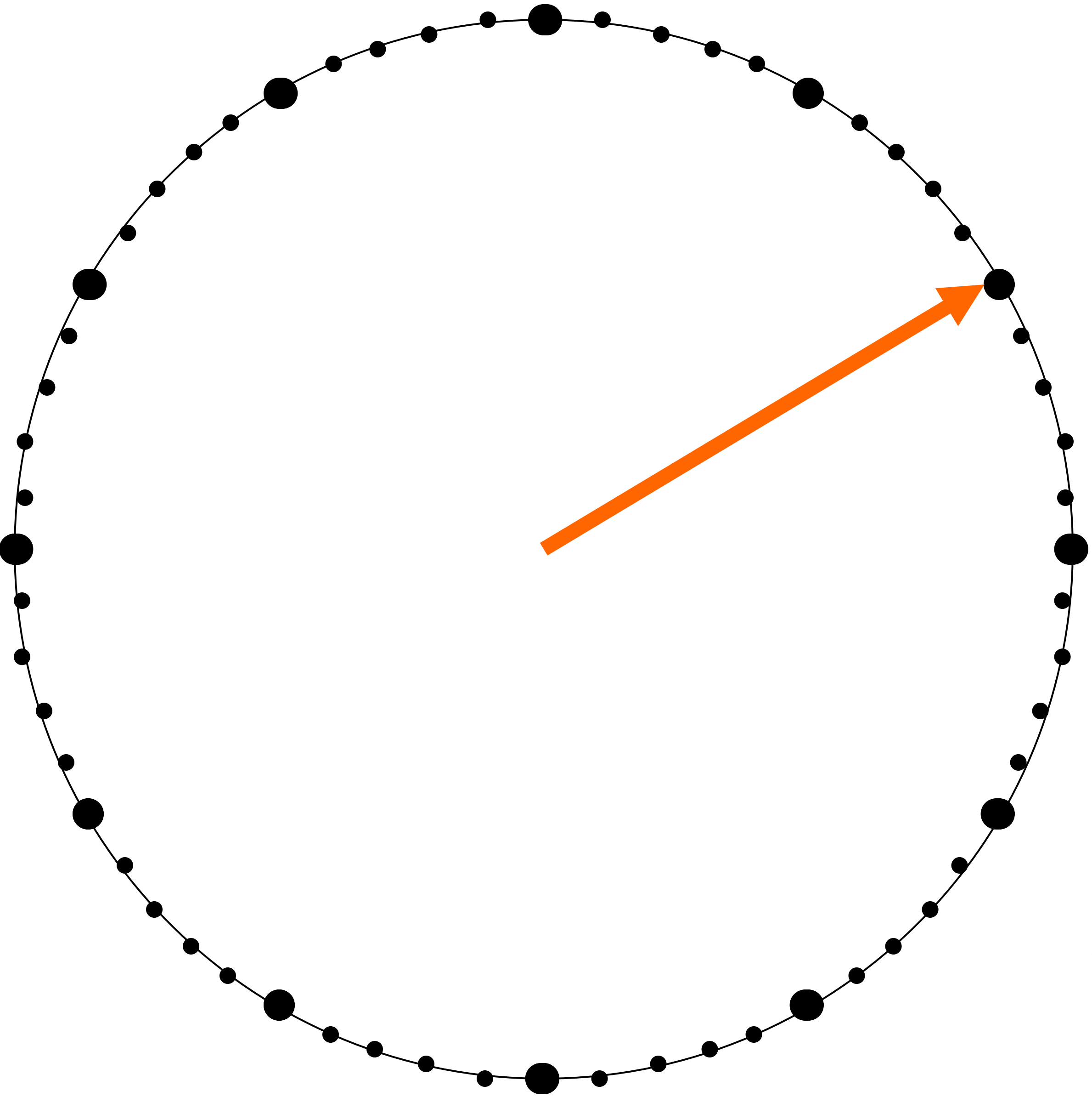
As time increased from 10^{-43} to 10^{-35} s, the age of the Universe, t, increased by a factor of 10^8, so that the temperature, T, dropped from its initial 10^{32} K to 10^{28} K and the density diminshed by 10^{16} to $\sim 5 \times 10^{77}$ g cm^{-3}, while the Universe expanded by a factor of 10^4. Over this interval of 10^{-35} seconds, regions as large as $\sim 10^{-25}$ cm across would have established physical contact and pressure equilibrium.

$t \sim 10^{-35}$ s



The expansion that set in at $t \sim 10^{-43}$ s cooled the Cosmos from $\sim 10^{32}$ to 10^{28} K, and left particle energies at $\sim 10^{15}$ GeV, the Grand Unified Theory level where the forces of Nature were all equal. At this epoch, the "Higgs" vacuum energy density became the dominant density, setting the stage for a rapid exponential expansion followed by a phase transition to a new vacuum state.

$t \sim 10^{-33}$ s



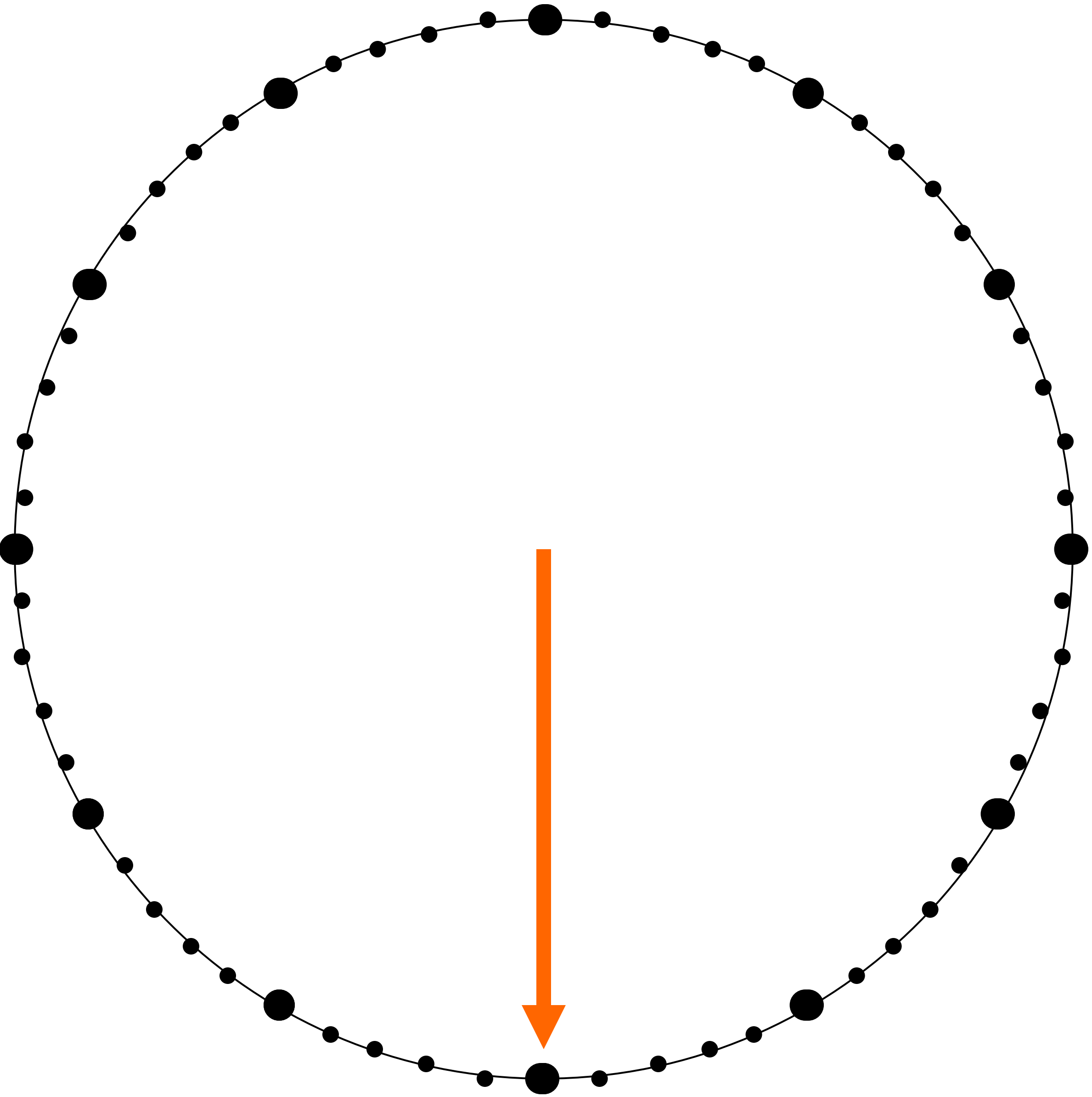
While this phase transition could have occurred at $\sim 10^{-35}$ s the Cosmos instead continued to expand, driven by the constant energy density of the Higgs vacuum. This expansion supercooled the Universe until $\sim 10^{-33}$ s, when a phase transition violently set in. The Higgs vacuum was replaced by the present-day vacuum, and the excess energy of the Higgs vacuum reheated the Cosmos.

The Post-Inflation Era

At the end of the inflationary period, the energy released by the Higgs field reheated the Universe to almost the same temperature it had at the onset of inflation, though somewhat less ~ 10^{14} GeV or 10^{27}K, since the vacuum energy was not all released at once, and because a large number of particles and their antiparticles were now created, and shared the released energy.

The portion of the Universe that today lies within our horizon started out at 10^{-25} cm at t ~ 10^{-35} s, and expanded to 10 cm by the time inflation had ended.

10^{-33} - 10^{-8} s



The Desert: Many generations of particles could have come and gone as the Universe expanded and cooled. At high temperatures massive particles and their antiparticles could have existed in nearly equal numbers. But as temperatures fell, annihilation could no longer be compensated by regeneration. Massive particle species successively became extinct.

Extinction of Species

As the Universe continued to expand and cool, the most massive quarks and their antiquarks will have successively annihilated and become extinct.

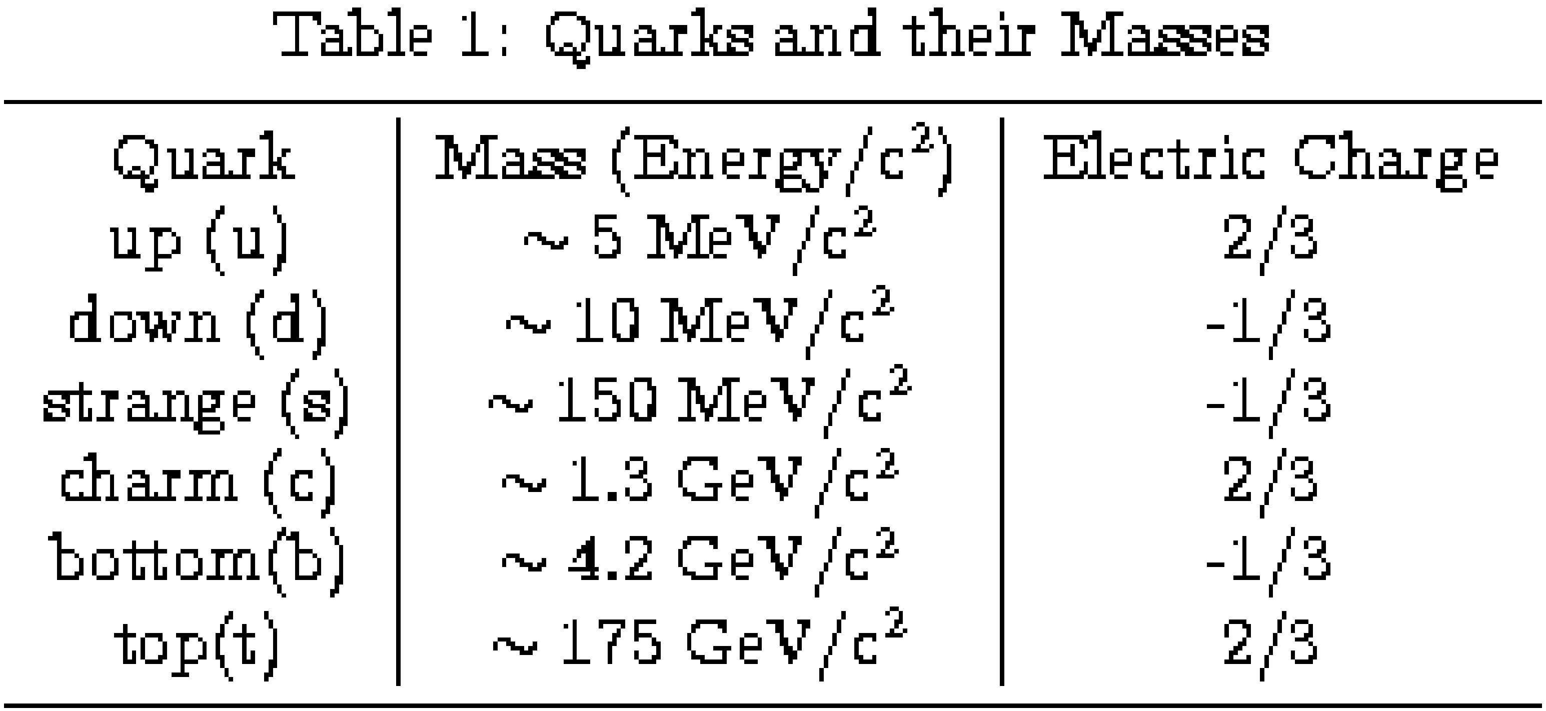
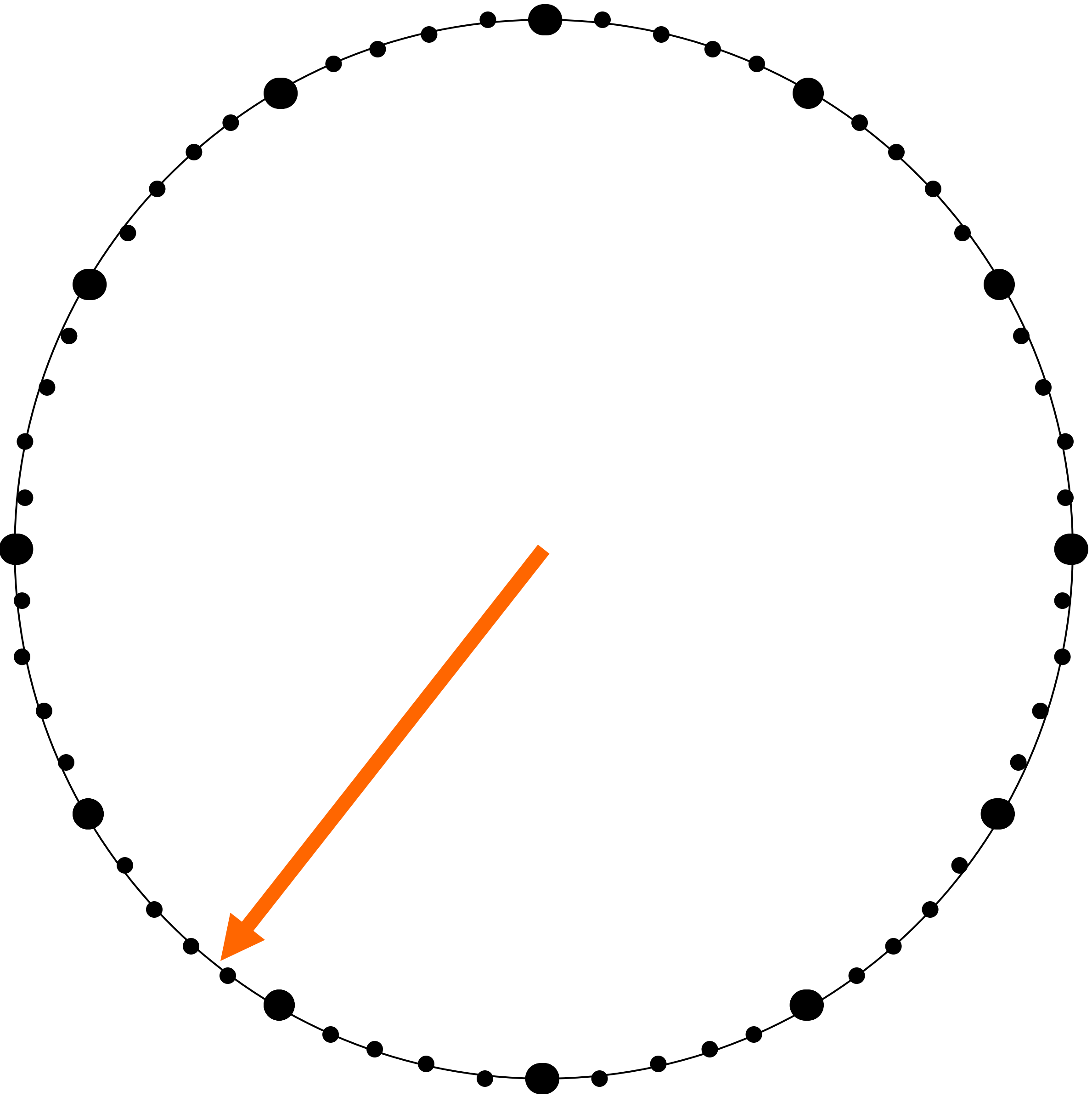


Table 1: Quarks and their Masses

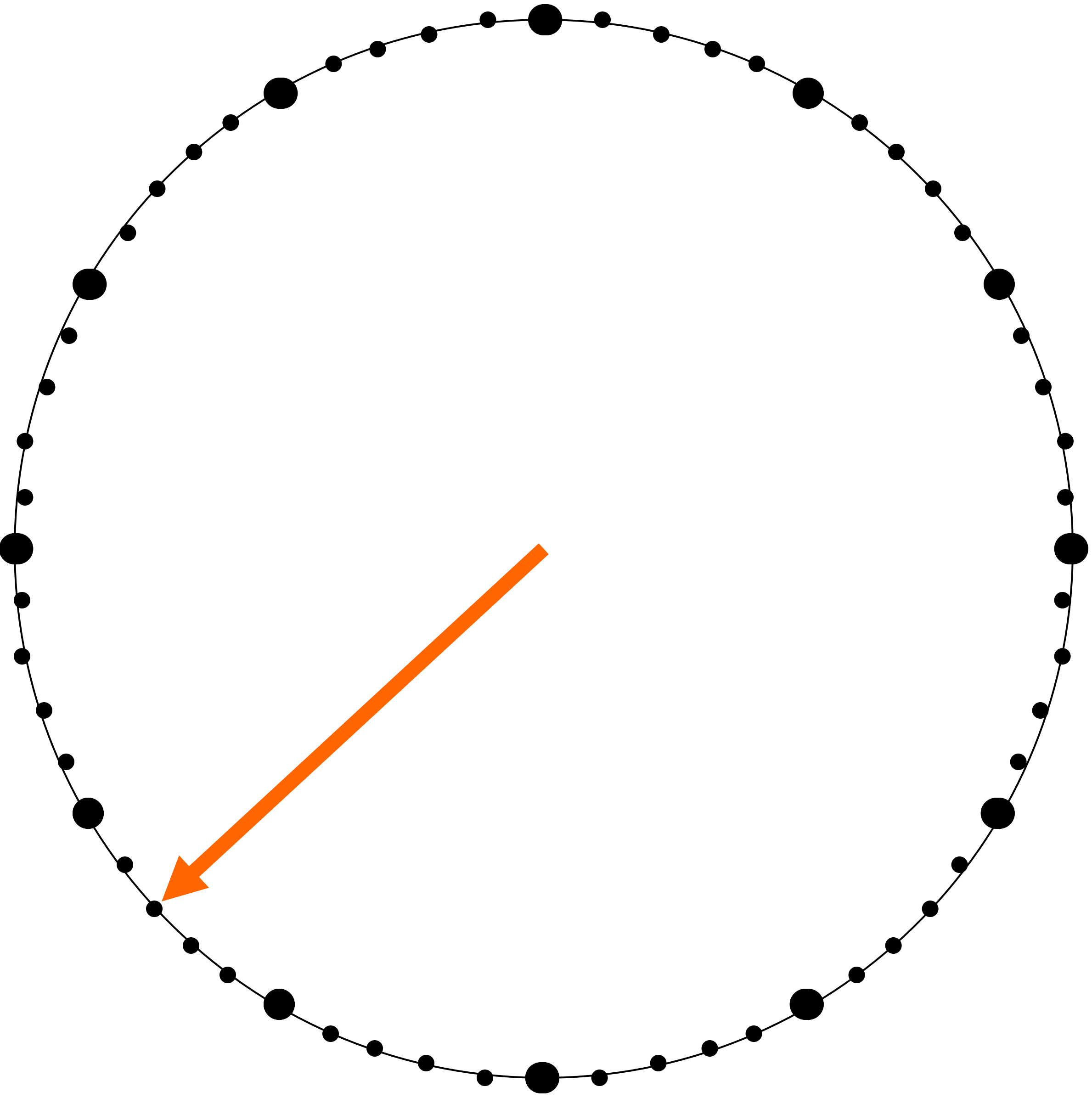
Quark	Mass (Energy/c^2)	Electric Charge
up (u)	$\sim$ 5 MeV/c^2	2/3
down (d)	$\sim$ 10 MeV/c^2	-1/3
strange (s)	$\sim$ 150 MeV/c^2	-1/3
charm (c)	$\sim$ 1.3 GeV/c^2	2/3
bottom(b)	$\sim$ 4.2 GeV/c^2	-1/3
top(t)	$\sim$ 175 GeV/c^2	2/3

10^{-7} to 10^{-5} s



By the time the expansion had continued for ~ 10^{-6} s the temperature had dropped to ~ 10^{13} K, where conditions today simulated at particle accelerators set in. In addition to photons, leptons and antileptons an up+down quark-gluon plasma would have existed at the time. Quarks, gluons and antiquarks are the constituents of mesons and baryons i.e. pions, protons and neutrons

$t \sim 10^{-5}$ s



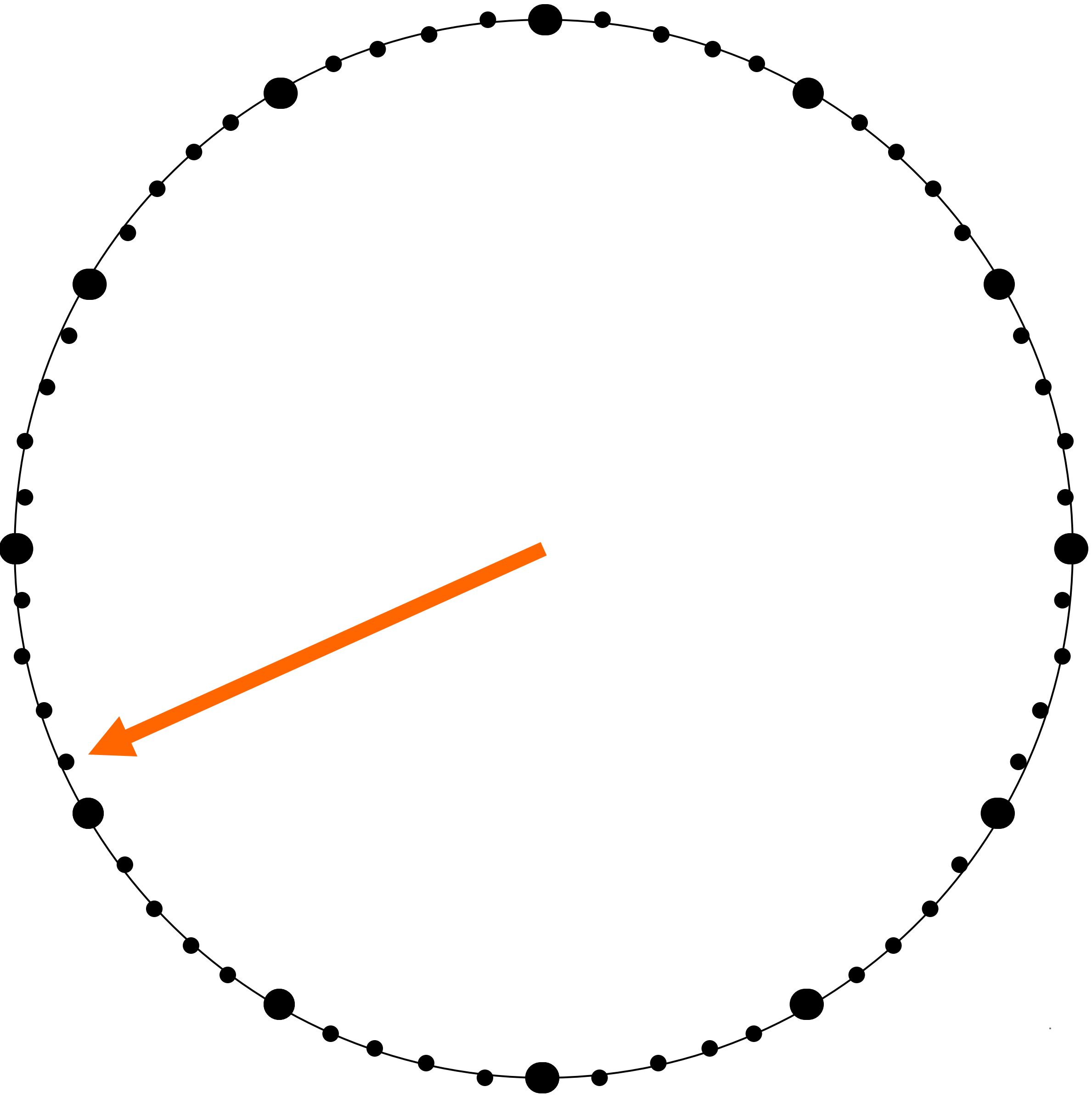
By 10 μs, the temperature had dropped to 10^{12} K. The quark-gluon plasma now broke up, as the mean density of the Universe dropped below the density of nuclear matter. Up and down quarks and gluons assembled themselves to form protons and neutrons. Antimesons and mesons also formed but soon annihilated as the temperature fell further.

The Particle-Antiparticle Asymmetry:

Why did protons and neutrons emerge as the quark-gluon plasma cooled? Why was there not an equal number of protons and antiprotons, neutrons and antineutrons?

The answer to this is still unknown. A number of symmetry violating decay modes of neutral kaons and B particles are known. But the scale of these effects does not seem adequate to explain why we live in a universe of matter. Had the Cosmos been totally symmetric all particles would by now have annihilated and the Universe would be filled solely with photons, neutrinos and antineutrinos. This very nearly happened. There are about 10^9 photons, neutrinos and antineutrinos for every proton and electron in the Universe. Had there been no remaining protons, neutrons, and electrons, we would not be here today to talk about life in the Universe.

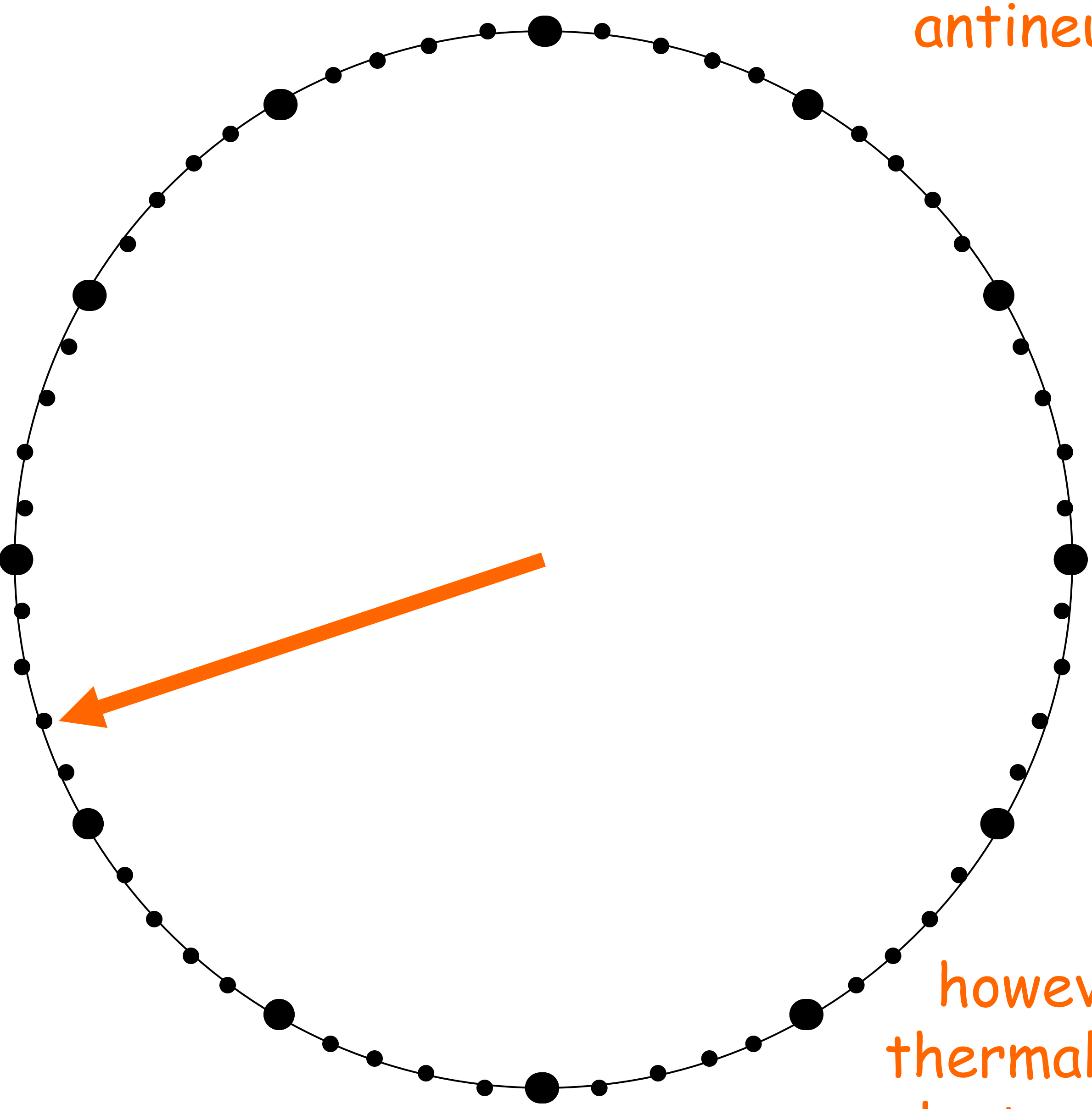
$t \sim 10^{-2}$ s



The temperature has by now dropped below 10^{11} K, and the neutrons and protons have number densities reflecting thermal equilibrium through a Boltzmann factor determined by their mass difference Δm:

$$\frac{n(N)}{n(P)} = \exp\left(-\frac{c^2\Delta m}{kT}\right) .$$

$t \sim 10^{-1}\ s$



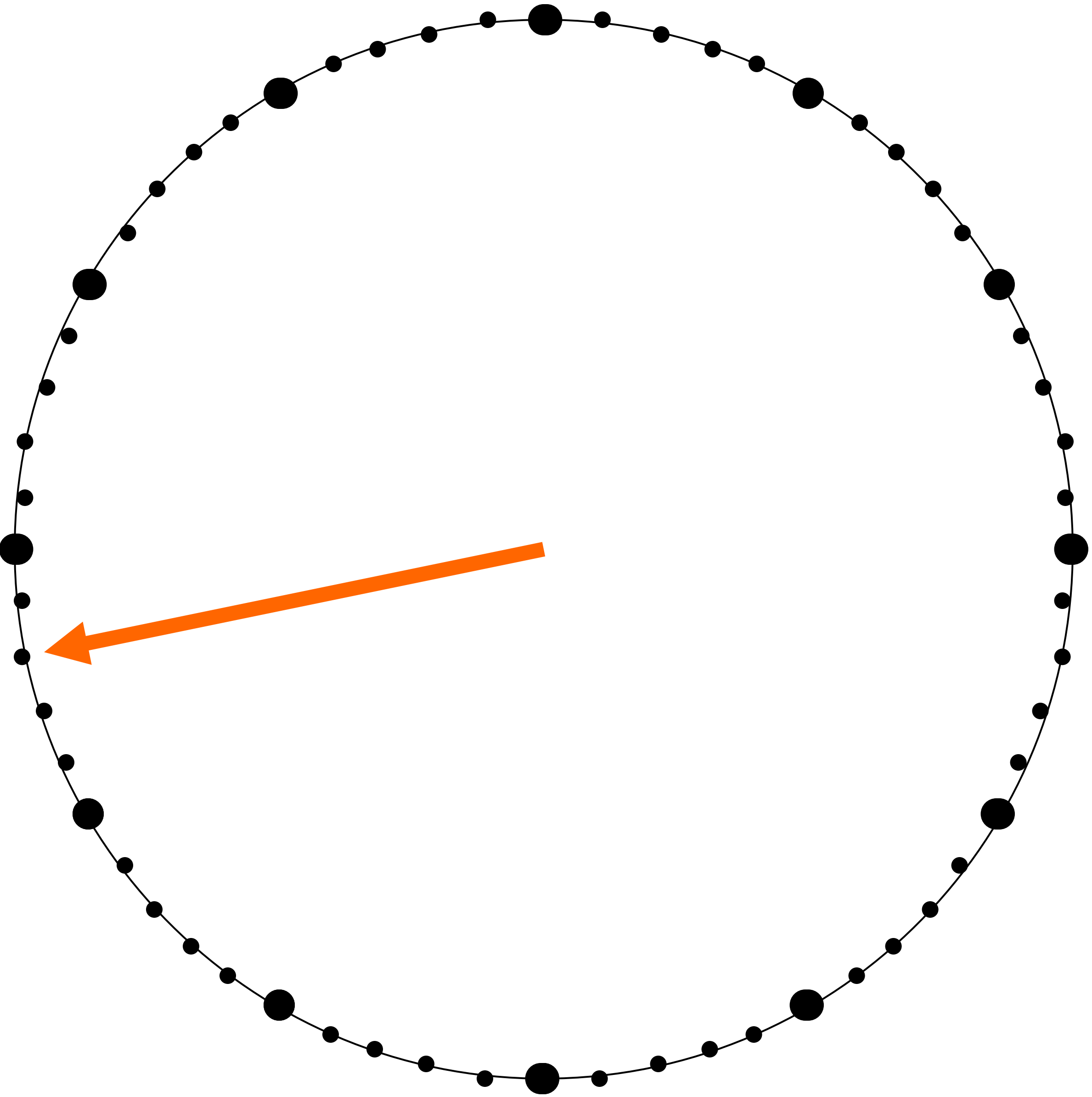
The cross-sections for the interactions of neutrinos and antineutrinos

$e^{+} + e^{-} \Leftrightarrow$ ⍰ + $\bar{⍰}$

now are not large enough to keep up with the cosmic expansion. Neutrinos and anti-neutrinos decouple from all the other contents of the Cosmos and cool with the ongoing expansion. The reaction

$e^{+} + e^{-} \Leftrightarrow$ ⍰ + ⍰

however keeps photons in thermal equilibrium with electrons and positrons t ~ 1 s



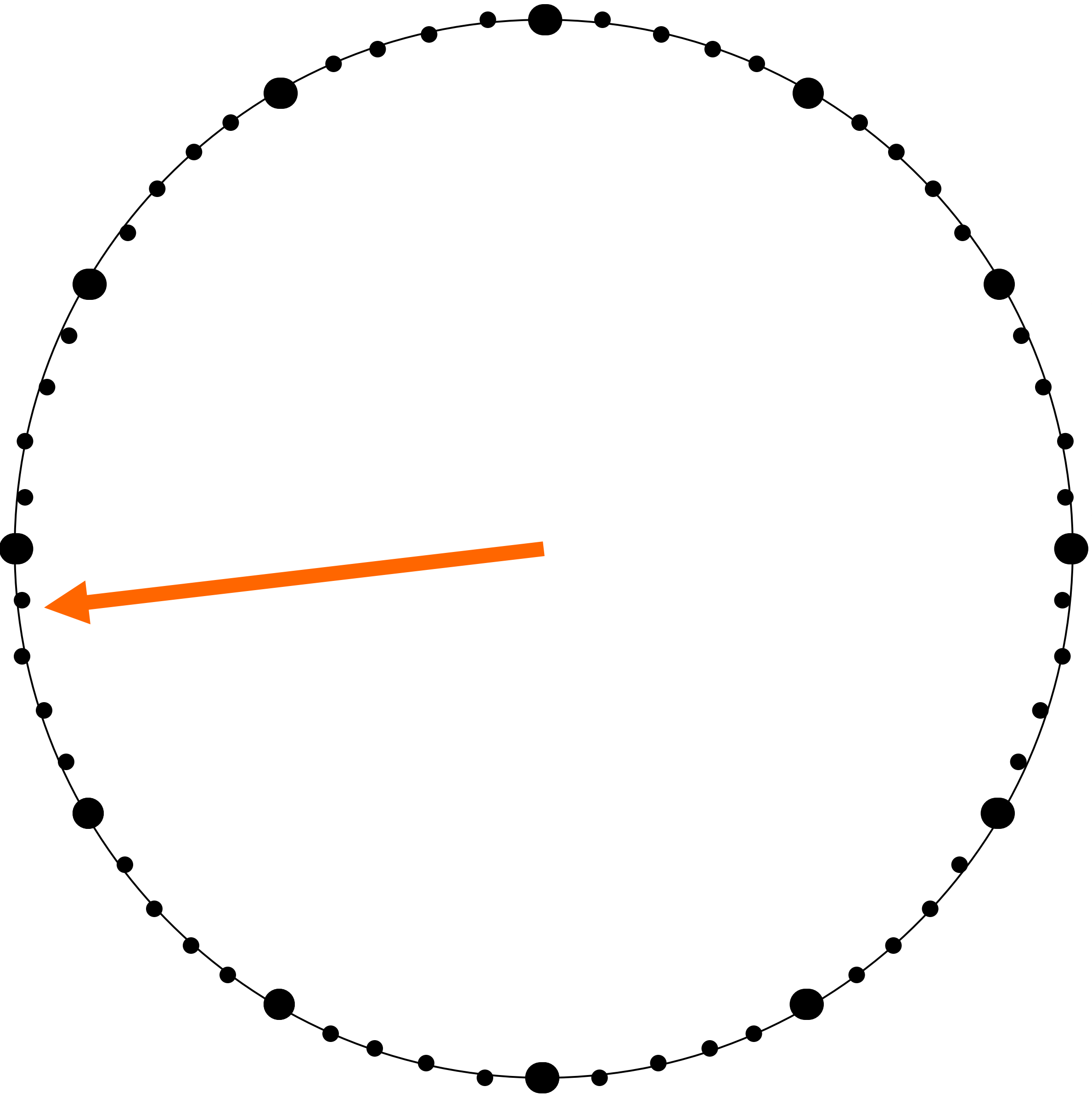
The temperature is now 10^{10} K and particle energies are ~ 1 MeV. Electrons and positrons no longer have enough energy to keep neutrons and protons in equilibrium through the reactions

$$e^+ + N \Leftrightarrow P + \bar{⍰}$$

$$⍰ + N \Leftrightarrow P + e^-$$

The neutron to proton ratio freezes out at 1/6, but then neutrons begin to decay into protons with a half-life of ~ 10 minutes.

t ~ 10 s

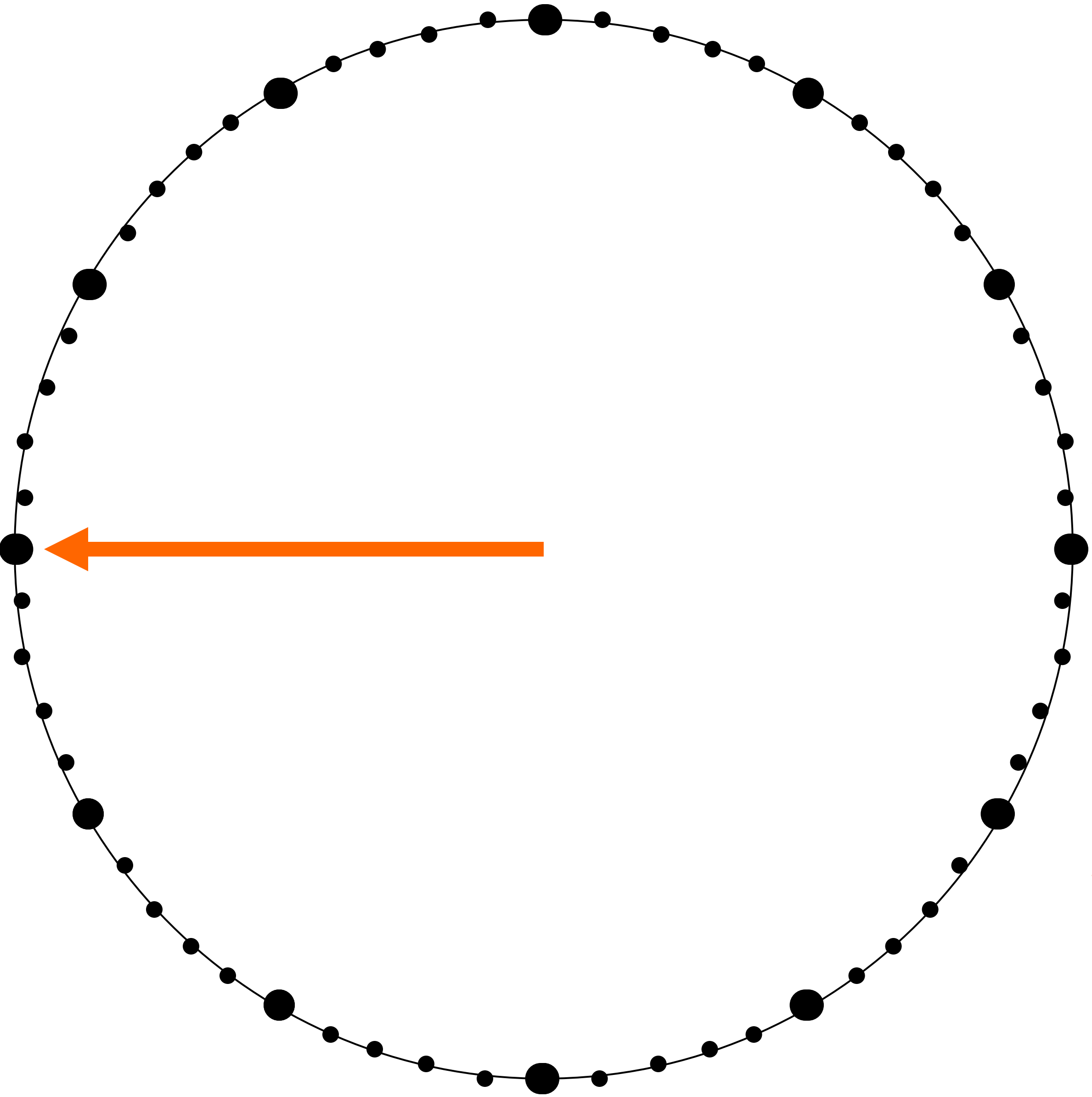


The temperature now is ~ 3×10^9 K. The energy drops below the 0.5MeV rest mass of electrons and positrons, which now annihilate through

$$e^- + e^+ \rightarrow 2\gamma ,$$

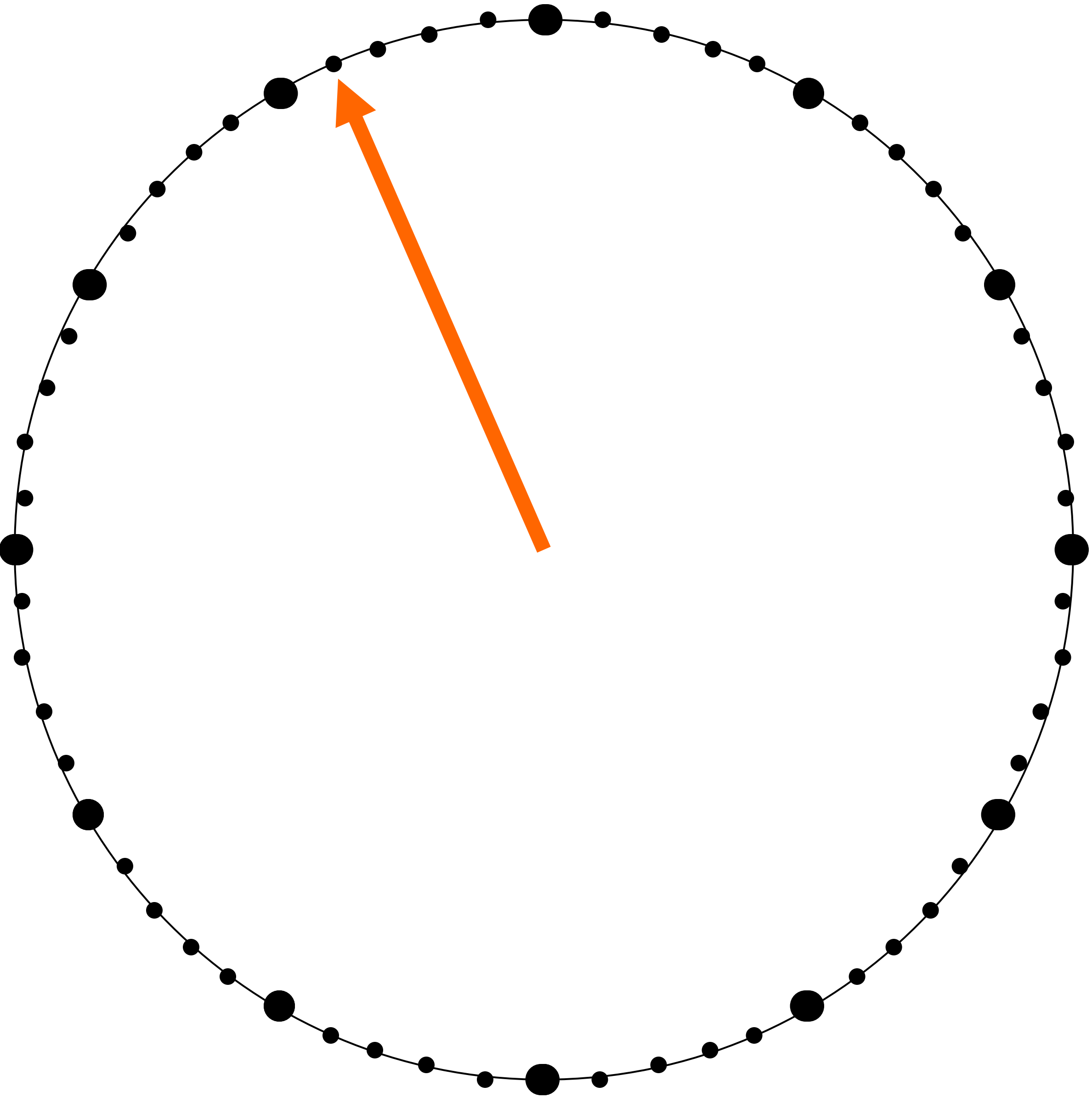
heating the radiation and remaining particles. This raises the temperature of the photon bath above that of the decoupled neutrinos. However, the neutrinos remain unobserved, so we cannot yet test this.

t ~ 100 s



The temperature has dropped to 10^9 K permitting the protons and neutrons to begin to stick to each other to form deuterium, D, helium, He, and trace quantities of lithium, Li, and beryllium, Be. The Universe emerges from this epoch with abundances by mass of: H(0.76), ^{4}He(0.24), (D+^{3}He)(~10^{-4}) and ^{7}Li(~10^{-9}). Stable elements above 7 atomic mass units do not form at this epoch.

t ~ 10^{13} s



Between 10^2 and 10^{13} s the Universe continues to expand with no other notable activity. At 10^{13} s the temperature is ~4000 K. Electrons and protons combine to produce hydrogen atoms. The energy of the photons drops too low to excite atomic states of either H or He. Matter and radiation decouple, and then continue to cool as the Cosmos expands. The particles cool faster than photons.

The Evolution of Cosmic Structure

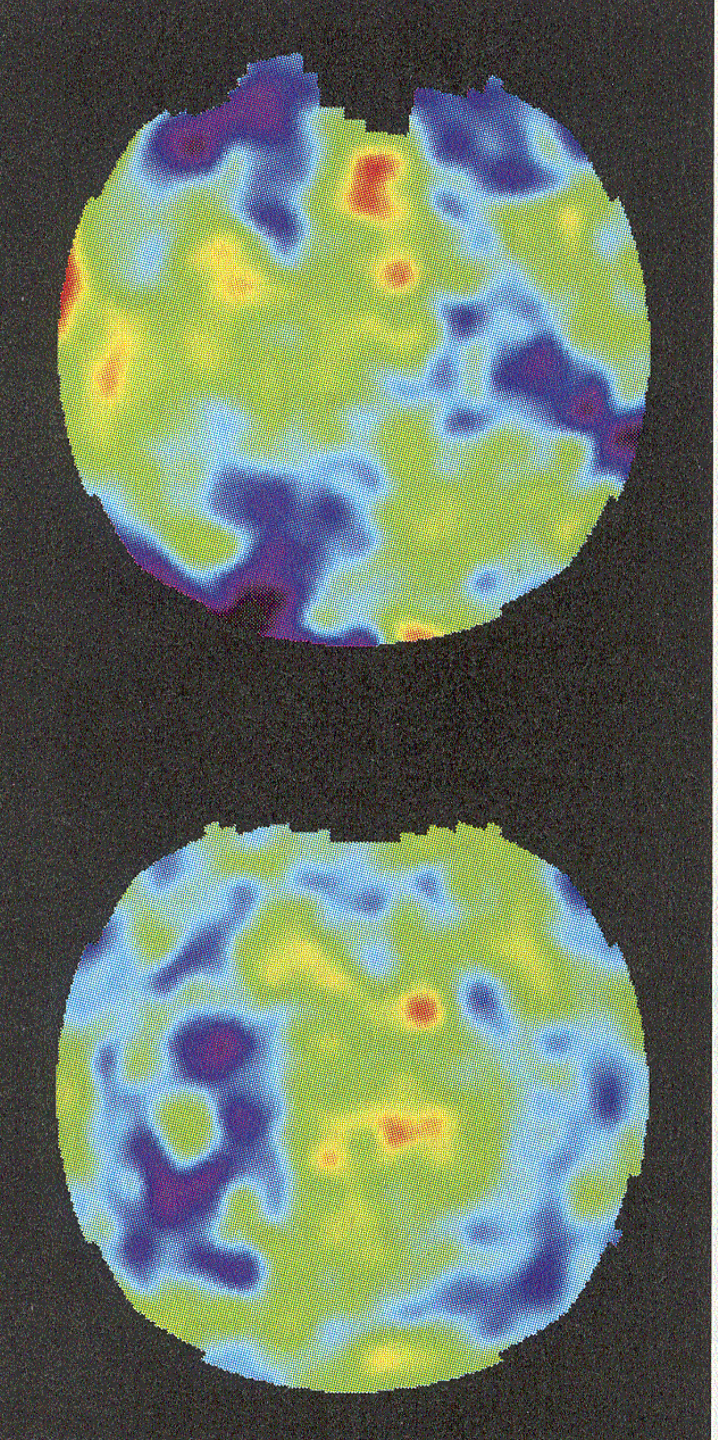
At 10^{13} seconds, or 300,000 yr, the redshift is $z \sim 1500$. The Universe consists of a radiation bath with fluctuations of the order of a few parts in 10^5 and a comparably clumped gas consisting of hydrogen and helium atoms with minute admixtures of deuterium and lithium.

Detecting the Fluctuations from the Inflation Era

No assembly of particles or photons can ever be completely smooth. Small fluctuations due to finite temperature always prevail. At the high temperatures of the inflationary era, fluctuations -- density clumps -- would have been quite substantial.

Because of the extremely rapid expansion of the Universe during inflation, the earliest density fluctuations became spread across many cosmic horizons and frozen in place. A fluctuation could not disappear when spread across a horizon. Later, as the expansion of the Universe slows down, and these regions no longer are moving apart as quickly, gravitational forces begin to produce local density concentrations that progressively grow. When we observe the microwave background radiation today, representing the patchiness of the Universe at $z \sim 1500$, we see what are believed to be the imprint of these earliest fluctuations.

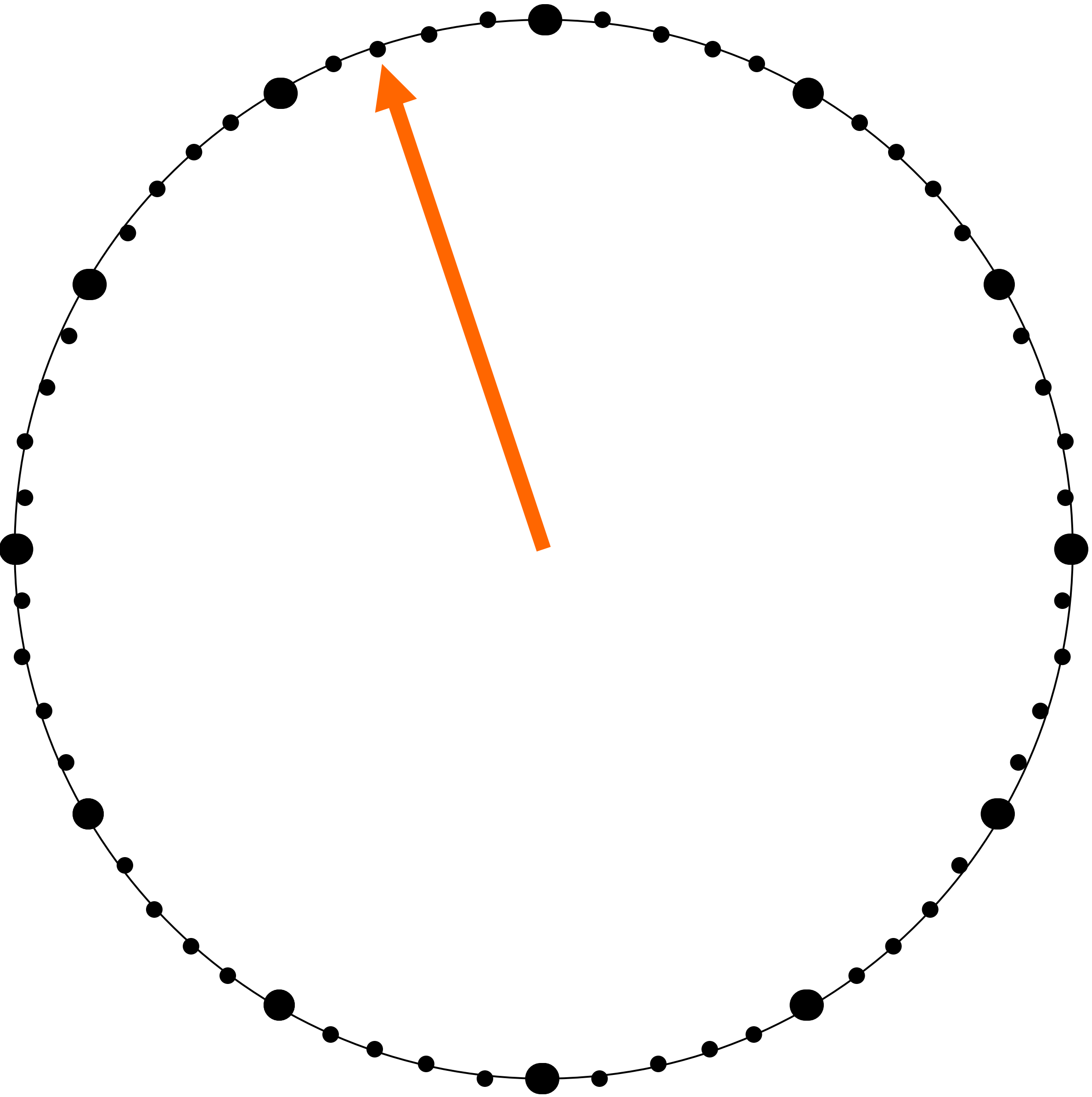
Fluctuations in the Cosmic Microwave Background Radiation



This sky map of cosmic background radiation temperature covers most of the northern and southern Galactic hemispheres, as viewed from the local cosmic standard of rest. The warmest and coldest spots have respective temperatures about 100 microkelvin above and below the mean value of 2.725 K. The correlated structures stretching across the sky are real. According to inflationary cosmology, they originated as elementary particles.

From C. J. Hogan, Science 295, 2223, 2002

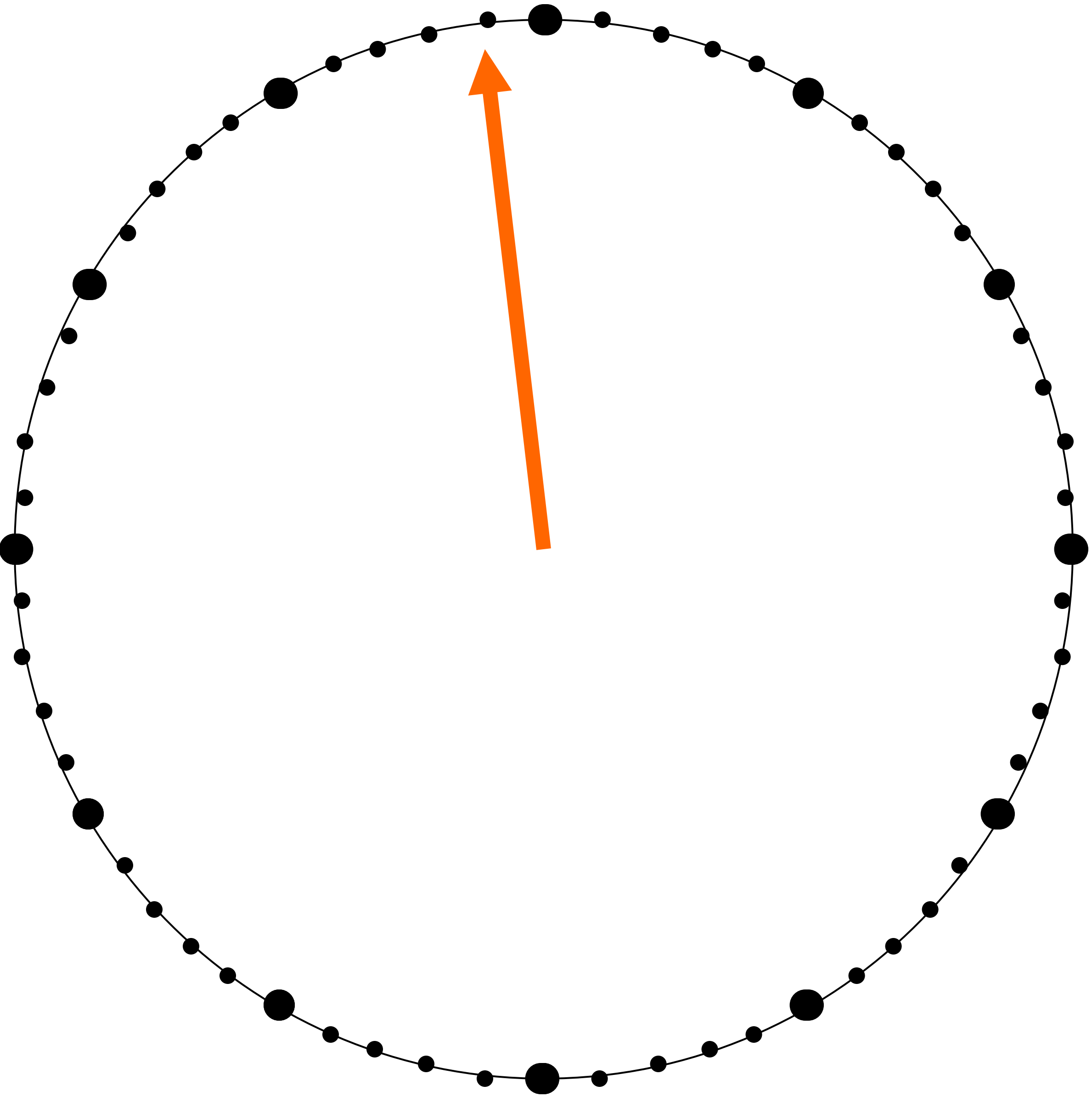
$t \sim 10^{14}$ s



The mass-density of particles in the Universe now exceeds that of radiation. The rate of expansion of the Cosmos becomes “matter-dominated” while it was earlier “radiation-dominated”.

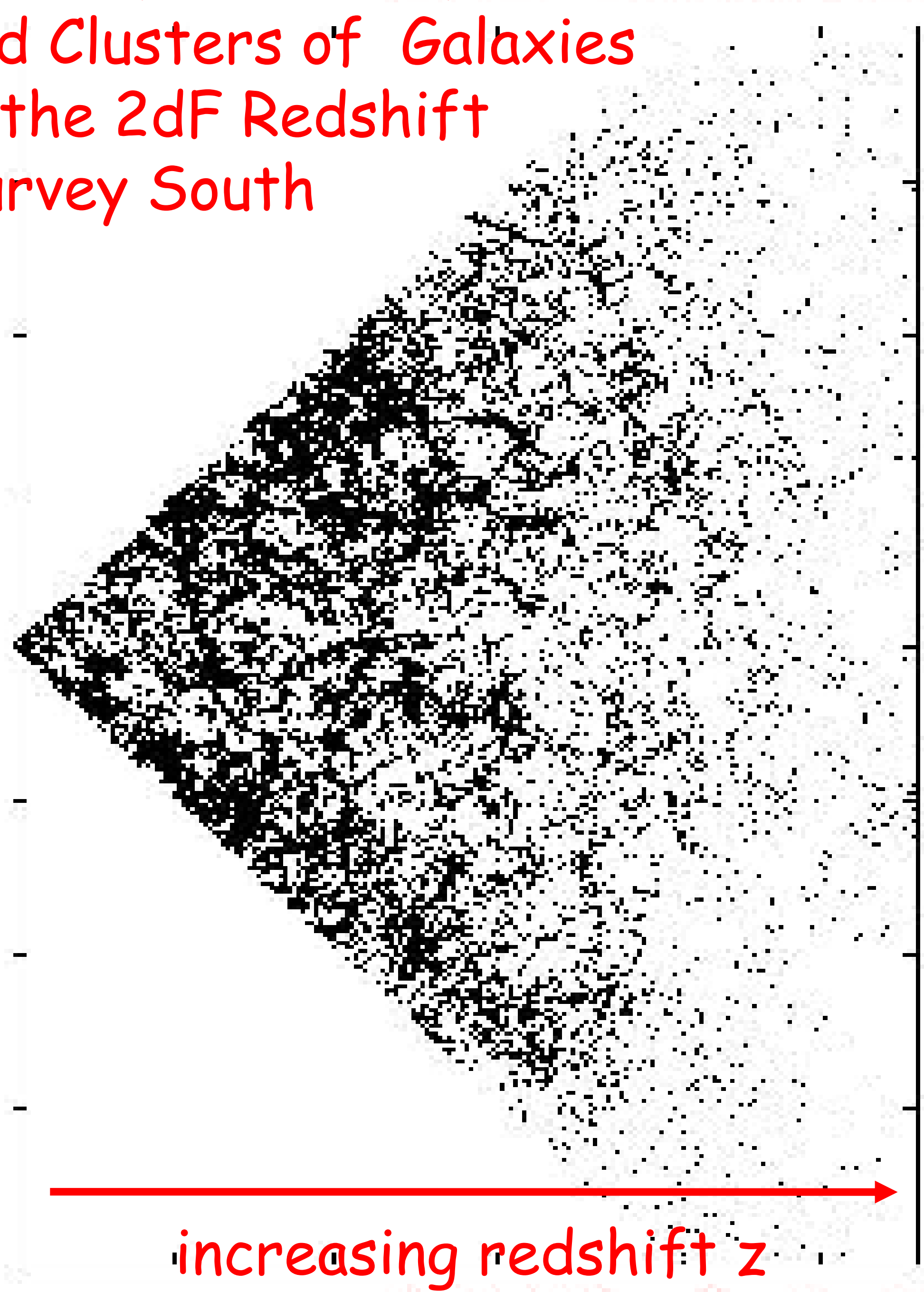
Where there are density fluctuations, contraction into denser regions continues, but no stars have yet formed. We are in the “Dark Ages” before the stars began to shine.

$t \sim 10^{16}$ s



At 300 Myr and z ~15, the first generation of condensations forms and lights up the Universe. The entire history of star- and galaxy-formation, the formation of the heavy chemical elements, and the formation of planetary systems and life, is now squeezed into the last tick of the clock, an almost insignificant epoch in the complex evolution of the Cosmos.

Sheets, Filaments, Voids and Clusters of Galaxies in the 2dF Redshift Survey South



When a self-gravitating aggregate collapses, it does this most rapidly by collapsing first into a thin slab, rather than into a spherical blob; it takes less time to do this. So, early cosmic condensations collapsed into slabs, producing so-called walls of galaxies. These intersected producing filaments and clusters of galaxies. There also are voids surrounded by walls. Each point in this figure is a galaxy. The voids and walls they form are clear.

The Unimaginable Size of the Universe

Of importance in the Inflationary Model of the Universe is the recognition that the portion of the Universe we now see is only an unimaginably small fraction of a larger Universe which will forever remain unknown to us --- out of touch, beyond physical reach, beyond study by physical means.

Since physics normally confines itself to statements about systems that can be examined observationally or through experiment, the proposition that such remote realms of the Universe exist, though they could never be observed, breaks with traditional ideas about the range of permissible scientific inference!

Population III

The first stars that formed have to date never been observed but are believed to have been extremely massive compared to today's stellar populations. For stars with masses 140 to 260 $M_\odot$ a helium core quickly develops through hydrogen to helium conversion. At the high central temperatures a *pair instability* develops. The energy of colliding photons produces electron-positron pairs that have rest mass but exert little pressure. The star's core collapses, burning fuel primarily through α-particle addition to nuclei, first forming nuclei like ^{16}O and ^{28}Si, which eventually form massive nuclei up to ^{56}Ni. The inertial collapse overshoots and is followed by a nuclear-powered supernova explosion.

All the earliest galaxies and quasars seen to the greatest distances accessible today, where redshifts are of order z ~ 6, exhibit spectra of the elements produced in Population III explosions, C, O, Mg, Si produced in the (α,γ) and *equilibrium processes* that effectively add α-particles to nuclei.

The Hubble Deep Field – The deepest optical survey

WPC2 / STScI

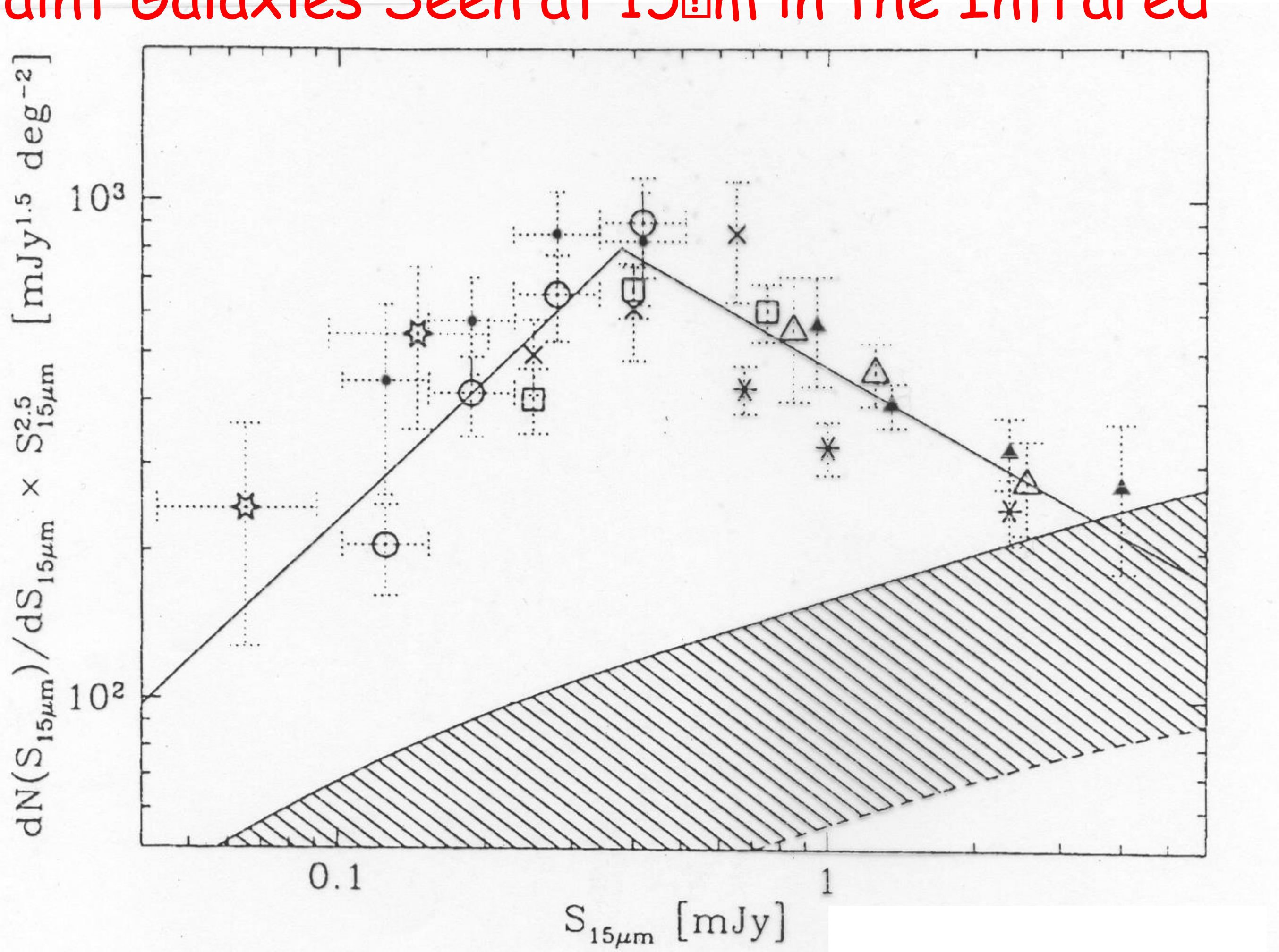
The Merging of Galaxies

Most noticeable in the Hubble Deep Field is the large number of small blue galaxies. These will eventually merge to form the larger galaxies we see locally today. In these mergers the gas in the colliding galaxies becomes shock compressed, giving rise to further generations of massive stars.

Though less massive than Population III stars these O and B stars also produce heavy chemical elements in their interiors, particularly the neutron-rich elements not produced earlier. On eruption, they eject some of these newly created elements in nova and supernova explosions.

We see these changes in elemental abundances in stars born at later epochs.

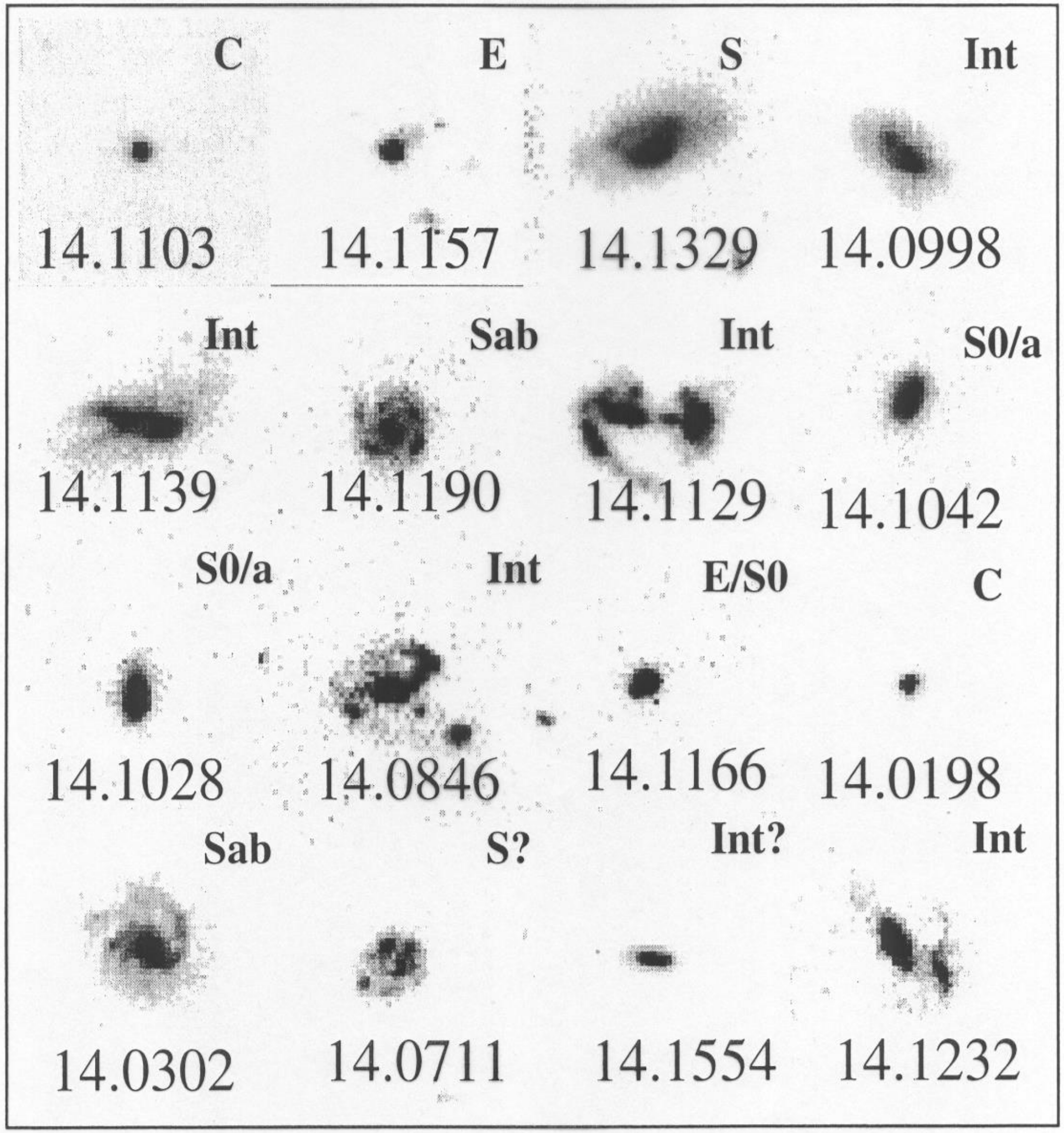
Faint Galaxies Seen at 15μm in the Infrared



The hatched band shows the number of galaxies at different flux levels expected if galaxies did not evolve. The peak in the data is due to massive star formation at redshift z ~ 1.

Elbaz et al, 2000

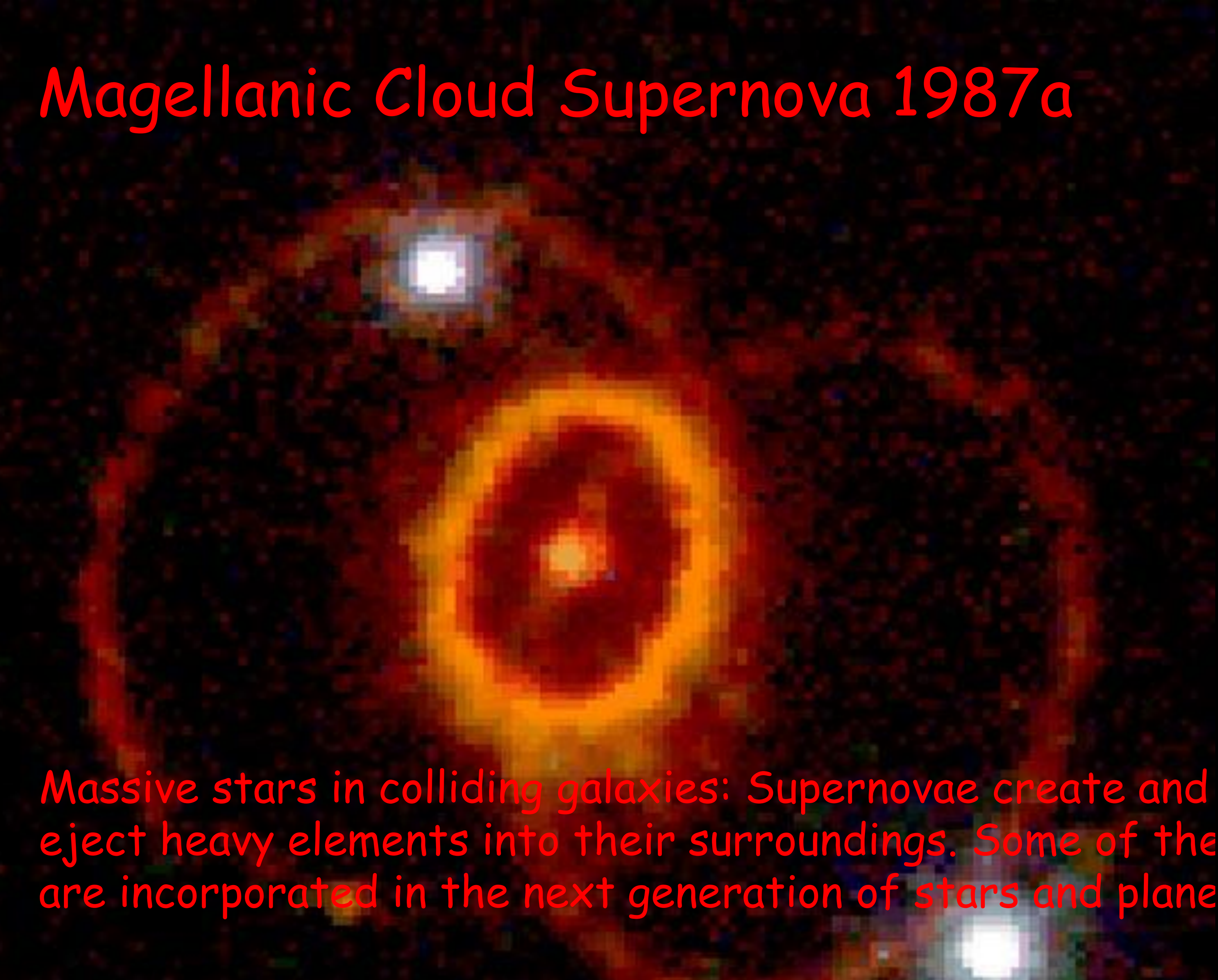
An Infrared Survey at 15μm Shows many Identified Sources to be Luminous Merging Galaxies at redshift z ~ 0.7 to 1.5



HST 5″ x 5″. F814W Filter Images

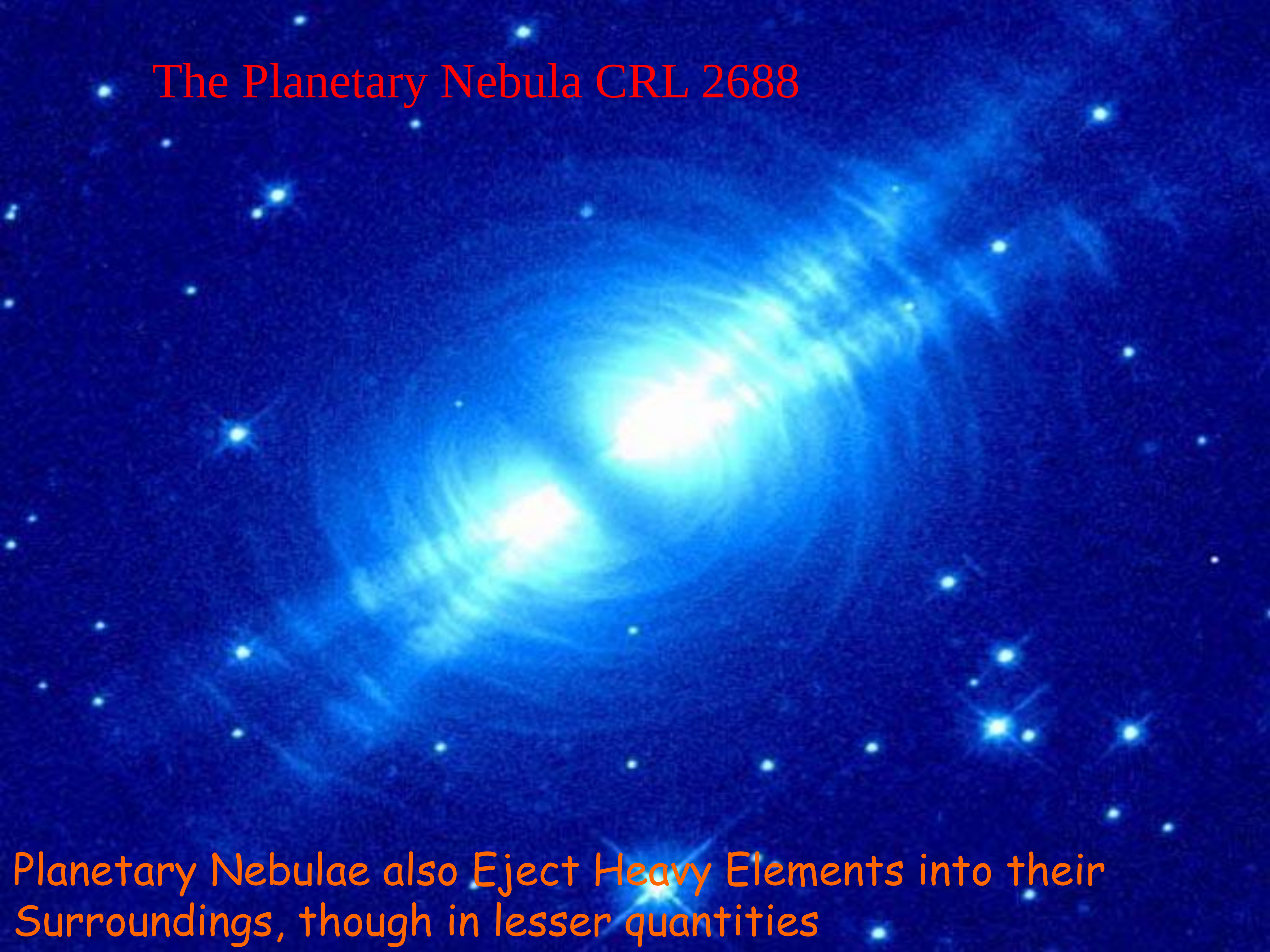
H. Flores, et al..ApJ 517, 148, 1999

Magellanic Cloud Supernova 1987a



Massive stars in colliding galaxies: Supernovae create and eject heavy elements into their surroundings. Some of the are incorporated in the next generation of stars and plane

The Planetary Nebula CRL 2688



Planetary Nebulae also Eject Heavy Elements into their Surroundings, though in lesser quantities

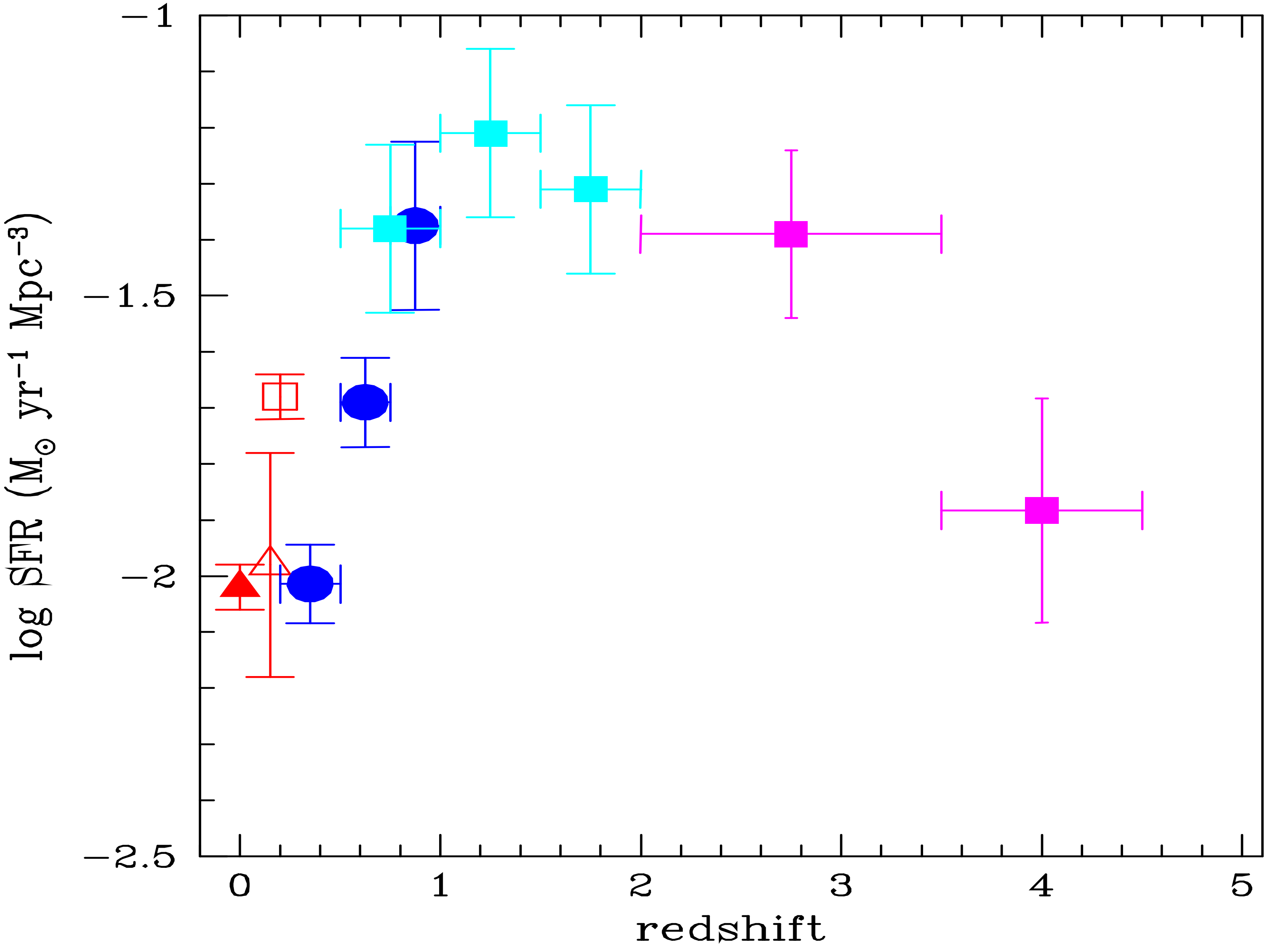
Chandra Image of the Galaxy Merger Arp 220

Galaxy mergers, though much less common now than at earlier epochs, can be seen in such galaxies as Arp 220.

The bright central region shown in yellow is due to a massive burst of star formation. The two red lobes may be tracing an outflow. The upper blue dot coincides with the nucleus of one of the merging galaxies. The other blue dot may possibly be due to high-energy emission from a supermassive black hole in the nucleus of the merger companion.

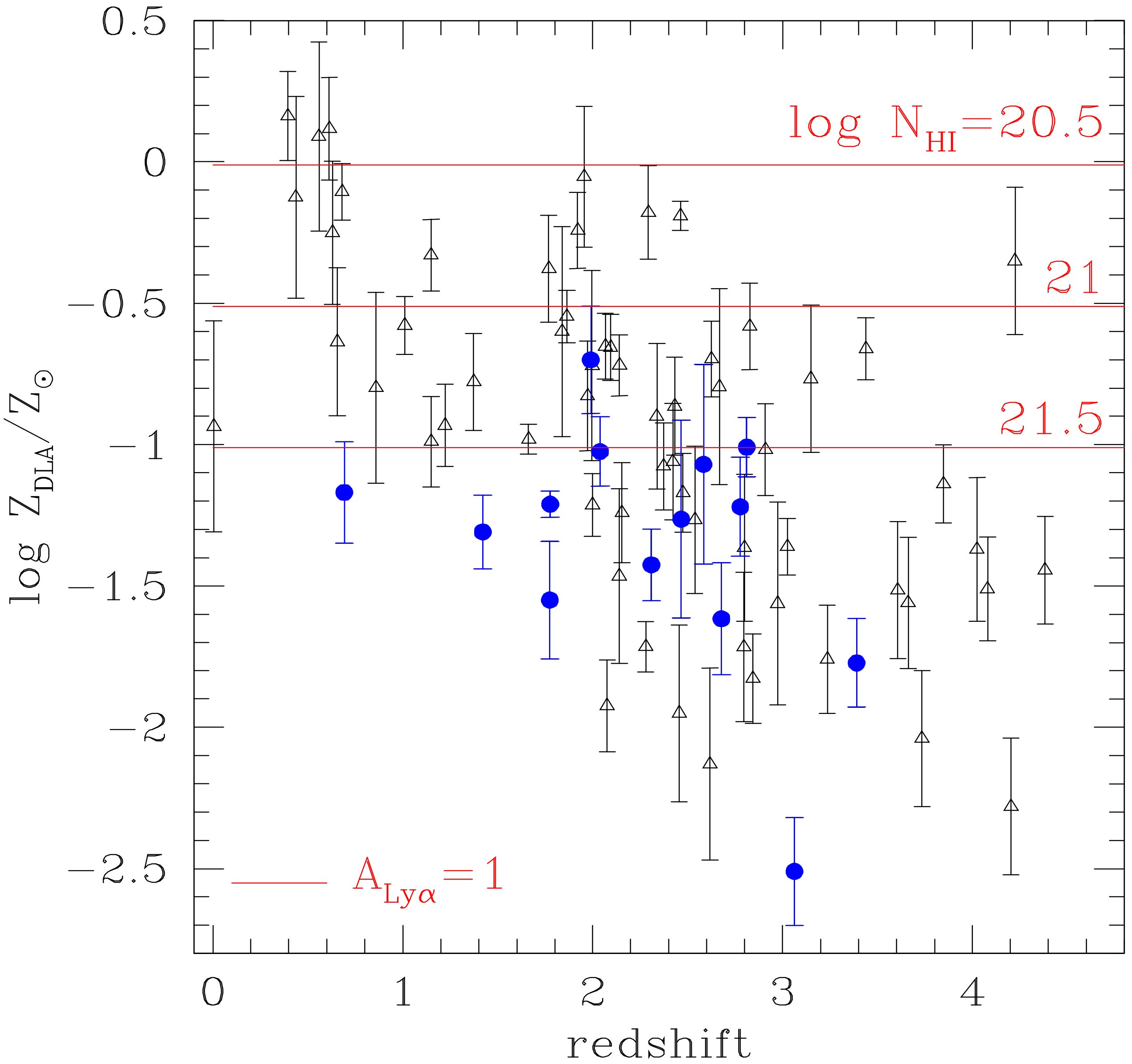
Star Formation Rates at Different Epochs

Salpeter IMF, no dust correction



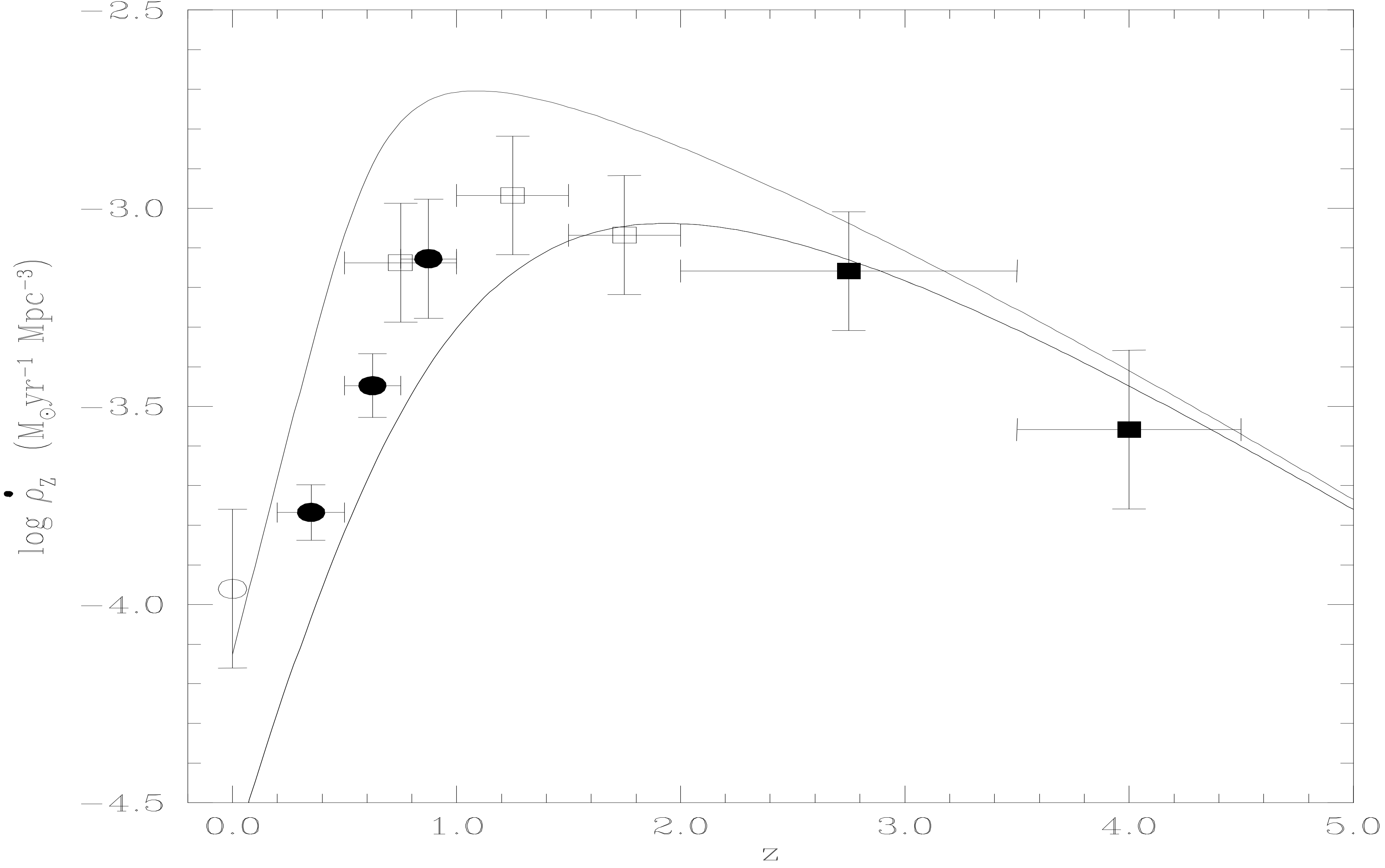
After Piero Madau

Chemical Abundances in Damped Lyman Absorbers



S. Savaglio, IAU 204, 2001

Rate of Heavy Element Production



Michael Fall, 2001

Molecules, Dust and Polyaromatic Hydrocarbons

With the formation of the heavy elements, and their ejection into interstellar space, a variety of molecules, dust grains, and polyaromatic hydrocarbons begin to form.

But what determines the abundances of the molecules? This is a complex issue, as Bill Klemperer explained. Cosmic rays play a role through their ability to ionize the gases they traverse. Ultraviolet radiation is important too, as is the abundance of helium.

A few molecules, especially CO and H_2O, can radiate away energy and cool interstellar clouds collapsing to form new generations of stars and planets.

Interstellar molecules may also be important in supplying prebiotic molecules.

NGC 6303

Leo Blitz spoke about the formation of stars in massive clouds. It is not yet clear how, or whether, the presence of young stars shock-induces the formation of further generations of stars, or even hinders their formation.

Orion Nebula Proplyds

Recently-formed stars, enveloped by disk-shaped remnants of the clouds of gas and dust from which they were formed, seen silhouetted against the bright background of the Orion Nebula.

Such disks have maximal lifetimes of the order of half a million years, and appear to give rise to planetary systems if they are not prematurely disrupted by external ionization or shocks.

IRAS 04302+2247

Dust particles in a proto-planetary disk can coagulate to form small planets that repeatedly collide, disrupt, and ultimately gather to form a system containing only one or a few planets.

Doppler motions of stars have revealed planets around nearly 100 nearby stars. A number of further searches are being initiated to look for Earth-like planets.

Michel Mayor told us about the Kepler and Eddington missions to search for occultations of stars by planets.

Interferometric searches with ESA's Darwin and NASA's Space Interferometer Mission also are being planned.

A Terrestrial Planet Finder Mission, TPF, will seek to locate and obtain spectra of terrestrial planets, quite possibly using an optical coronagraph.

Comet Linear July 7, 2000

Cometary and meteoritic matter falling on Earth may have provided the prebiotic material needed for life. The water in the oceans may have had a similar origin, since the high D/H ratio found on Earth and Mars far exceeds that of the Sun and giant planets, and is only matched by that of the comets.

Panspermia:

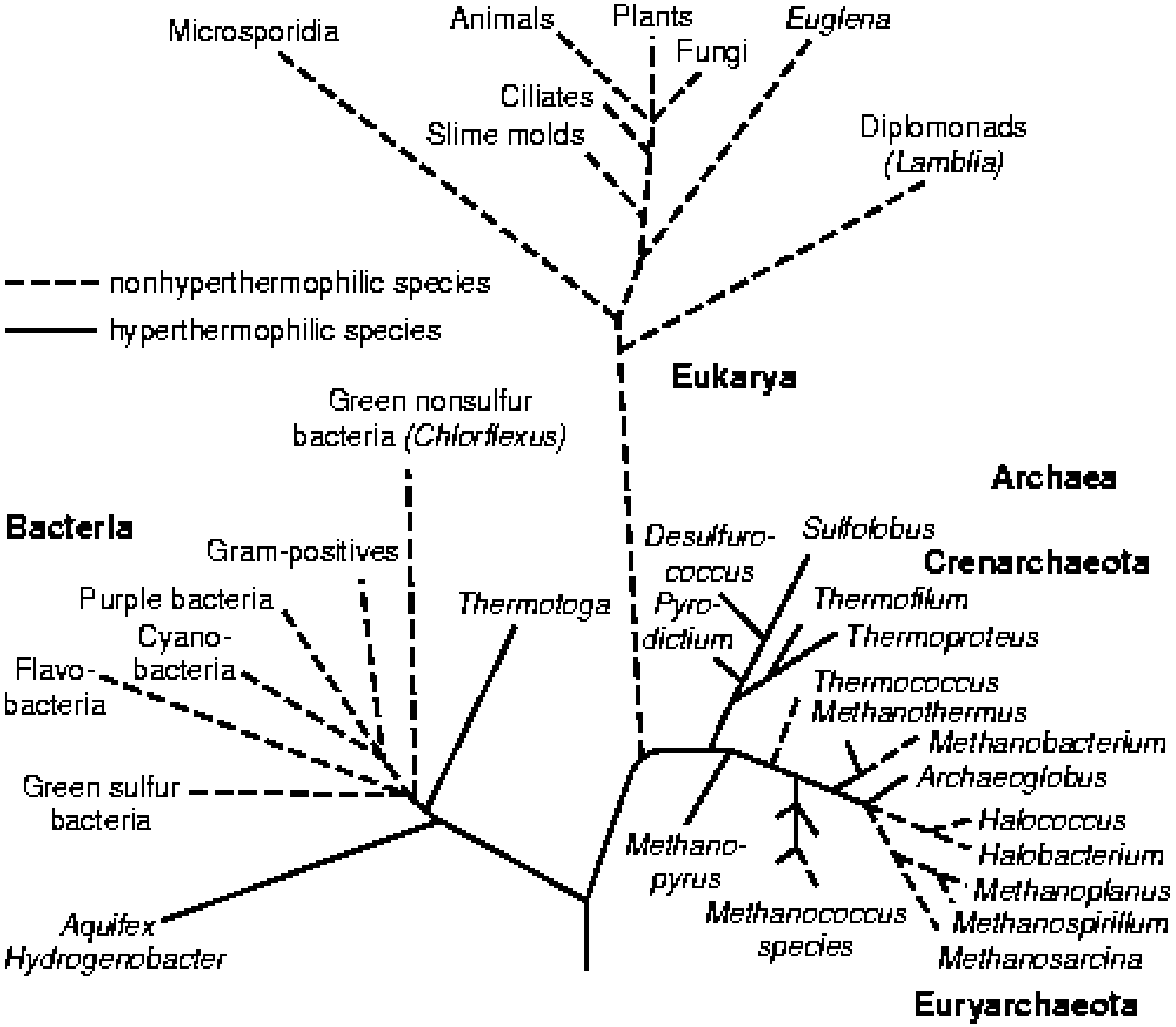
Sidney Leach spoke on the different theories of panspermia, including the weak theory principally discussed at this conference, which suggests that prebiotic material might have seeded life on Earth.

Manfred Eigen whose work has elucidated the age of the genetic code, felt that life cannot have originated either much before the conditions for its initiation were there, and not much later. This suggests that panspermia is not the source.

One might, however, counter that, if life were continually seeded, a second generation might not be able to establish a foothold, once life had already become established, just as L-amino acids could stay dominant once firmly established.

Harry Kroto suggested a search for microorganisms on the Moon as a useful test of the panspermia hypothesis.

There may be no pressing need for panspermia: Enzio Gallori pointed out that DNA nucleotides can be assembled on clays and that adhesion to clay surfaces can lead to preservation of DNA strands as well as their replication.



We also know that some of the most primitive organisms are hyper-thermophiles. Does this hint that the first organisms were bred in volcanic vents?

At the end of the lecture by Ivica Picek and Eric Blaugrund asked: "What can we have as a definition of life?" Gustav Arrhenius gave us an answer which, in many ways parallels the specifications that Daniel Koshland has recently listed.

Living matter requires:

- A Program: An organism needs to have a plan for existence.
- Improvisation: There must be room for long-term change in this plan through mutation or other evolutionary means.
- Adaptability: Responses to unanticipated stimuli on a shorter time scale than improvisation.
- Compartmentalization: A living organism must be contained within in a well-defined volume.
- Energy: Energy is needed for movement of all kinds.
- Regeneration: Worn out parts need replacement, and eventually the entire organism must be replaced.
- Seclusion: Different chemical (metabolic, neural) pathways required simultaneously must not interfere with each other

Koshland, Science 295, 2215, 2002

But such a definition may still be too abstract:
As illustrated by the talks of Peter Toennies and Thomas Ebbesen, we still know too little about mesoscopic physics to hope to understand all the basic processes relevant on microbial and submicrobial scales.

The real question is:

"How will we recognize life when we see it?"

Perhaps we will recognize and truly understand living matter only after Charles Cantor, Manfred Eigen, Enzo Gallori, Giacinto Scoles, and others construct it for us in the laboratory.

As Harry Kroto and Bill Klemperer reminded us:
You don't really understand how a watch works until you have taken it apart and put it back together again. Life, which is considerably more complicated, may require the same attention.

How would we know a habitable planet if we saw one?

If water is an essential element of life, a planetary temperature range between –20 and +120° Celsius may be required.

This determines the distance range for a habitable planet from its parent star. Too close, and the water boils. Too distant, and it freezes over.

Spectral features of water, methane, molecular oxygen (or ozone that might be a tracer for O_2), and carbon dioxide also might be indicators for life, though at earliest times, CO_2 dominated the Earth's atmosphere. One has to be careful to take planetary evolution into account.

The Search for Extraterrestrial Intelligence

SETI, has largely rested on a strategy for detecting radio signals from advanced civilizations. Leo Blitz showed us how the Allen array of telescopes operating at 500 MHz to 10 GHz will reach out to a distance of 1800 light years.

But how will we distinguish an intelligent message from an inanimate signal when we see it? We probably won't until we have artificially built a superior intelligence.

Again, it may be a matter of engineering rather than science. We may not be able to recognize superior intelligence until we have also taken it apart and put it back together again.

The question arose whether a technological civilization might not quickly destroy itself -- if not through careless use of nuclear weapons, then perhaps through unpremeditated changes in climate.

While Henrik Svensmark tried to reassure us regarding climate, we will not have a definite answer until we put historians to work to study a representative sample of extraterrestrial civilizations.

We'll just have to make sure we don't accidentally end their efforts prematurely.

What about space travel?

Joao Magueijo indirectly warned us that we could expect visiting civilizations – bringing, we hope, civilized visitors – once they engineer ways of changing the fine structure constant or construct a general relativistic worm-hole for frequent travel.

(Traveling at relativistic speeds through gas and dust would be extremely hazardous.)

These few examples suggest that a future Brijuni conference might gain valuable insights by including a number of far-sighted engineers.