Terrestrial Planets

Week 2

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FD Adams 131C

The matter of the Universe

We know the Earth is old… 4.567 billion years old! We know that it is made up of minerals and rocks and water and atmosphere but we may reasonably ask, ***"Where did all the elements and isotopes that make up this stuff of the Earth come from?".***

- In 1957, Burbidge, Burbidge, Fowler and Hoyle (**B^2FH**) described a sequence of development for the origin of all normal elements and materials: **Nucleosynthesis**.
- In an infinitesimal moment of time after some initiating process, an incredibly hot (perhaps more than 10^{27}K) extremely compressed ball of pure energy exploded forth our universe... ***Big Bang***...
- As this explosion expands, it cools by adiabatic expansion.

Energy condenses matter

- As the energy cools, the basic building blocks of ordinary (***baryonic***) matter begin to condense from the energy: $\boldsymbol{E \equiv mc^2}$.
- Within 1 second of the Big Bang we have all the necessary ***quarks*** and ***leptons*** to form the mass of all the baryonic matter we know. Within about 3 seconds (T = 10^{10}K), triplets of quarks have combined to form all the original ***protons*** and ***neutrons*** of the Universe.
- The expanding ***plasma*** now comprises a neutrally charged mix of protons, neutrons, ***electrons*** and ***muons***. It is still far too hot for electrons to attach to protons to form atoms. It will take another 380000 years for the first neutral atoms to form.
- It seems that almost no anti-matter was created… the symmetry of matter-antimatter was somehow broken in the moments following the ***Big Bang***!

The matter reassembles

During the next 500 or so seconds, **hydrogen fusion!**

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \beta^{+}$$
$$^{1}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$$
$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} + \gamma$$
$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$
$$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li} + \beta^{+} + \gamma$$
$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + \gamma$$

The net result of these reactions:

$$8\ {}^{1}\mathrm{H} \rightarrow 2\ {}^{4}\mathrm{He} + 3\ \gamma + 4\ \beta^{+}\ ,$$

At this time, the composition of the Universe is 95% hydrogen (**^{1}H** and **^{2}H**) and 5% (**^{4}He**) with some **^{3}He** and traces of **^{7}Li** and **^{7}Be** by nuclear (atom) count.

The matter disperses

- After about 500 seconds of these fusion reactions, the density and temperature of the involved particles is too low to sustain the reaction. What has been created now disperses into the ever expanding volume of the Universe.
- In another 380000 years, the expanding plasma will cool sufficiently (T ~ 3500K) allowing free electrons to attach to these nuclei forming neutral ***atoms*** of H, He, Li and Be. The previous 380000 years are hidden by the ***CMB***.
- The **Universe becomes transparent** to the passage of light and electromagnetic radiation.

The “Baby Picture”

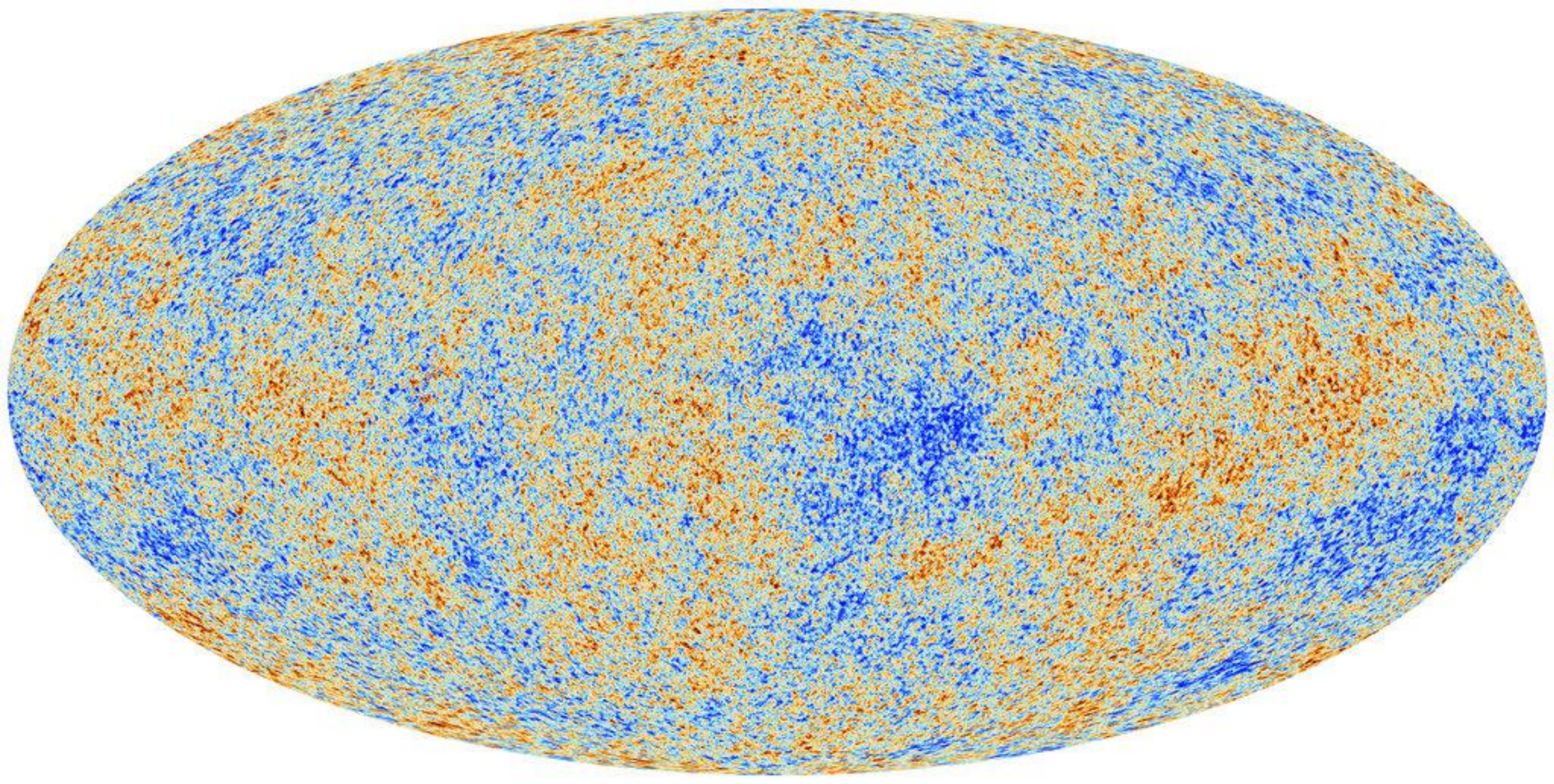
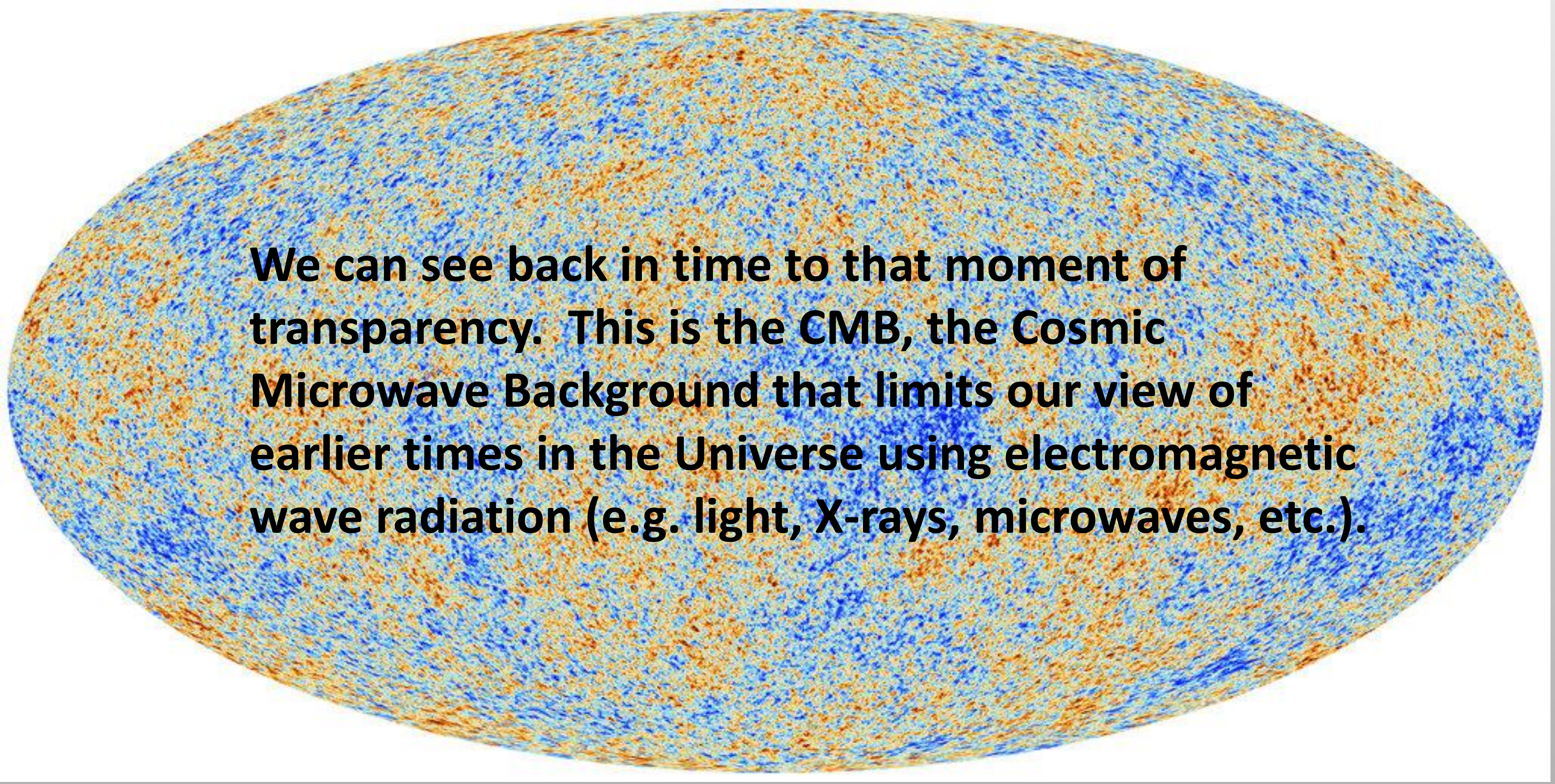


Image from the ESA (European Space Agency) Planck Mission. For a story: http://www.nytimes.com/2013/03/22/science/space/planck-satellite-shows-image-of-infant-universe.html

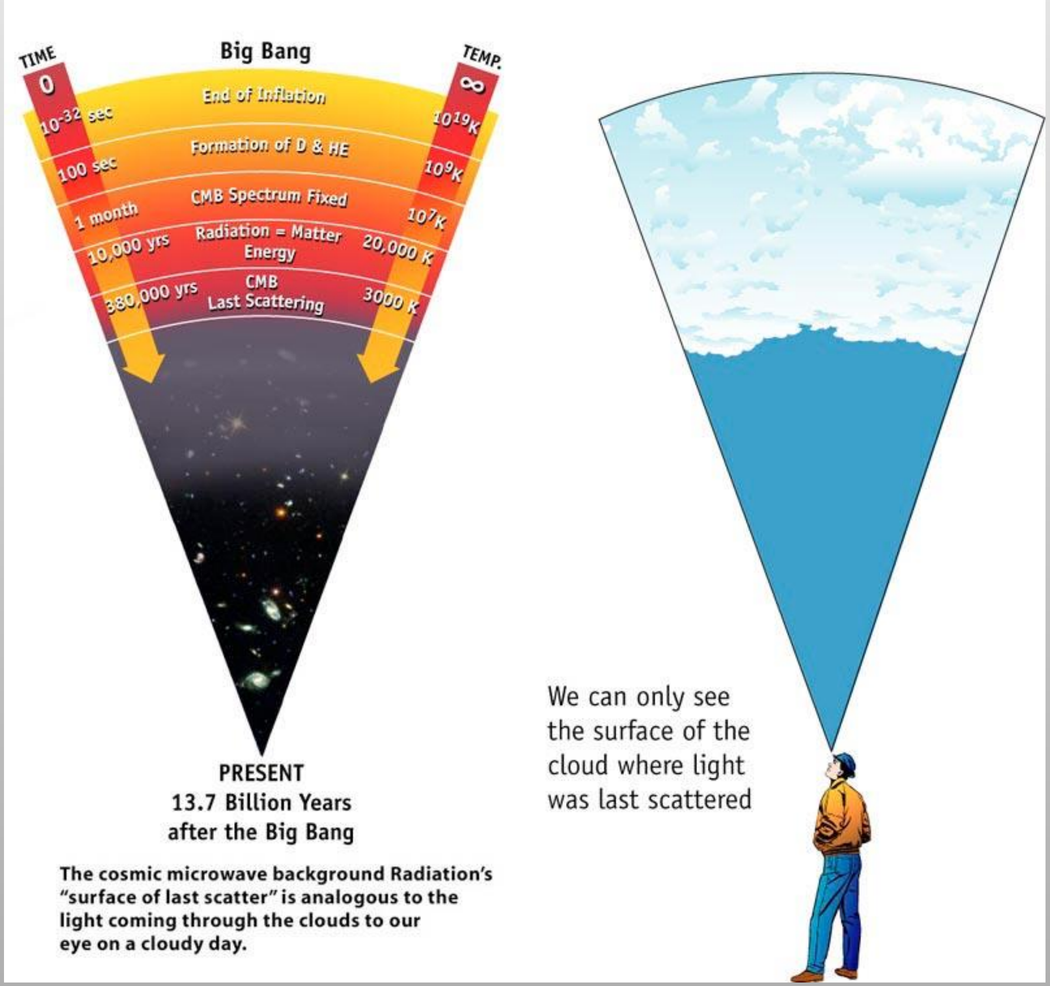
The “Baby Picture”



We can see back in time to that moment of transparency. This is the CMB, the Cosmic Microwave Background that limits our view of earlier times in the Universe using electromagnetic wave radiation (e.g. light, X-rays, microwaves, etc.).

Image from the ESA (European Space Agency) Planck Mission. For a story:
http://www.nytimes.com/2013/03/22/science/space/planck-satellite-shows-image-of-infant-universe.html

The “CMB” veil



The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

Image by NASA/WMAP: https://map.gsfc.nasa.gov/media/990053/990053sb.jpg

The Universe quietly expands

- Nothing much happens for the next 100 – 200 million years. There are no stars, there is only an expanding mass of gases composed of the primitive elements.
- After about 100 million years, though, gravity has had time to start pulling volumes of the mass of gases together.
- As the gases assemble and compress under gravitational force, they heat up (adiabatically) and in these concentrated, dense contracting volumes, temperatures reach levels ($T > 10^{10}K$) that allow hydrogen fusion to re-ignite locally in the first gigantic "***stars***".
- It is in these stars that the ***nucleosynthetic reactions*** that give us our rich chemistry now begins.

Stellar nucleosynthesis

All elements beyond ^{7}**Be** in the periodic table have been formed by nucleosynthetic reactions within stars.

- Elements up to ^{56}**Fe** are largely produced in fusion reactions.
- Elements beyond ^{56}**Fe** are almost entirely produced in supernoval explosions of large stars.

Our ***Sun*** is a late-forming star (about 4.6 billion years ago and almost 9 billion years after the Big Bang), formed of materials that have gone through many cycles of stellar nucleosynthesis. Our Sun’s composition is somewhat richer in He than the original Big Bang plasma: ~ 93% **H**, ~ 7% **He** by atom count with all other elements contributing less than 1%.

Stellar nucleosynthesis

Life cycle of a Sun-like star

Our Sun, sometimes called ***Sol***, is a very ordinary star in terms of mass and size. It radiates **3.84×10^{26} J · s^{-1}** or 384 000 000 000 000 000 000 000 000 **W**, as bright as 4 sextillion 100W light bulbs.

Stellar nucleosynthesis

Life cycle of a Sun-like star

4.6 billion years ago, a gravity assembled mass of ***H (93%)*** and ***He (7%)*** ignited fusion reactions.
While there is a mixing of all the trace elemental nuclei that form the periodic table of elements throughout the Sun, density differentiation formed a predominantly ***He core*** and ***H mantle***.

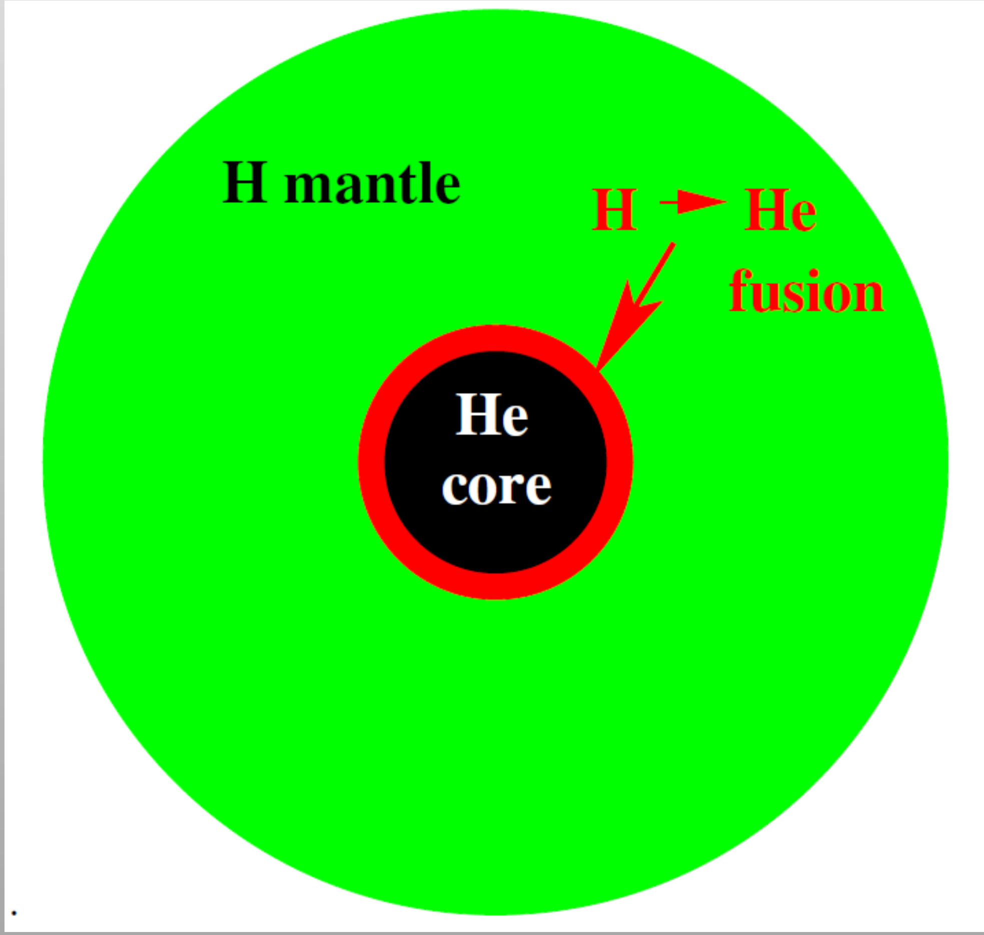
Stellar nucleosynthesis

Life cycle of a Sun-like star

This **fusion "fire"** has been burning continuously for the past 4.6 billion years but as the **He core** (the cinder of the fusion) grows, the **fusion shell** grows in volume and the Sun radiates ever more heat. It is 40% more radiant now that it was 4.6 billion years ago.

Stellar nucleosynthesis

Life cycle of a Sun-like star



Stellar nucleosynthesis

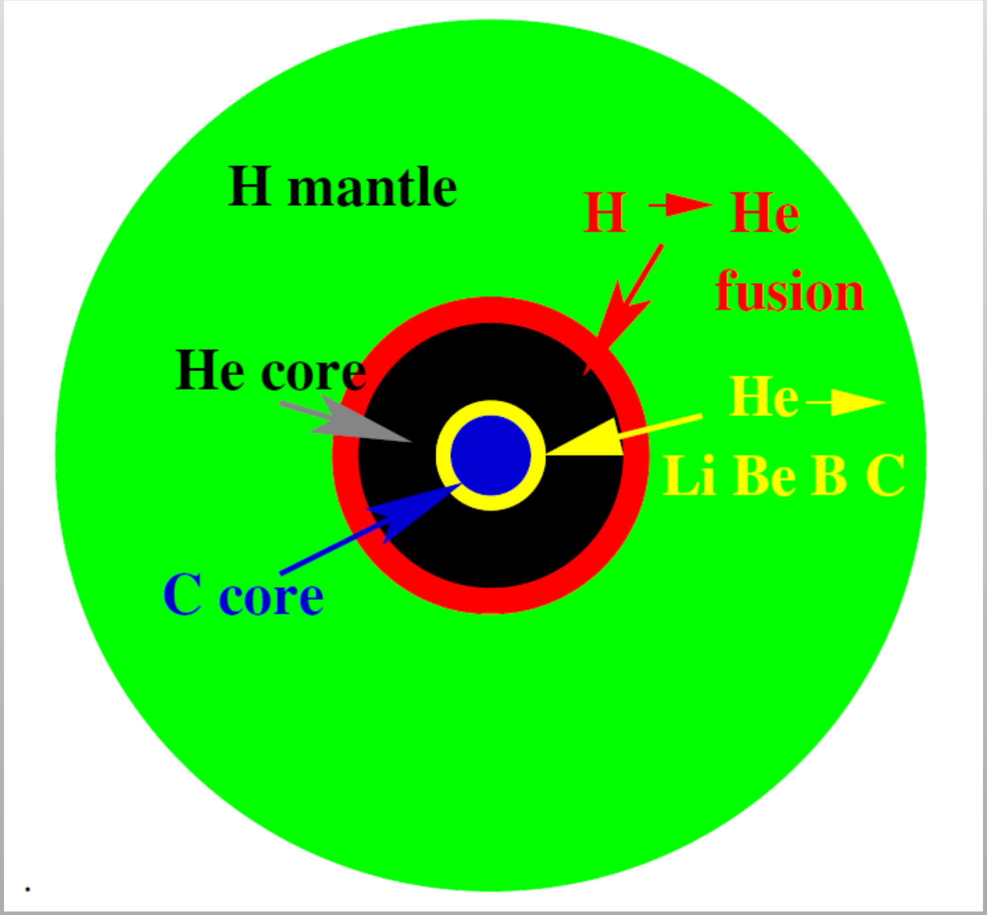
Life cycle of a Sun-like star

Helium (denser than *hydrogen*) sinks into a core. There, it can be ignited into the helium burning stage if the star is large enough that its overlying mass compresses this core to temperatures exceeding about 10^{10}K.

^{4}**He** fusion synthesizes more lithium, **Li**, and beryllium, **Be**, as well as **B**, terminating with the synthesis of carbon, ^{12}**C**. In this stage, the star expands into a **"*red-giant*"** star.

Stellar nucleosynthesis

Life cycle of a Sun-like star



Stellar nucleosynthesis

Life cycle of a Sun-like star

If the star is large enough (Our Sun is, barely large enough!), it will even bring this ^{12}**C** to burn through the "***CNO process***" fusing substantial quantities of ^{13}**C**, ^{13}**N**, ^{14}**N**, ^{15}**N** and ^{15}**O**

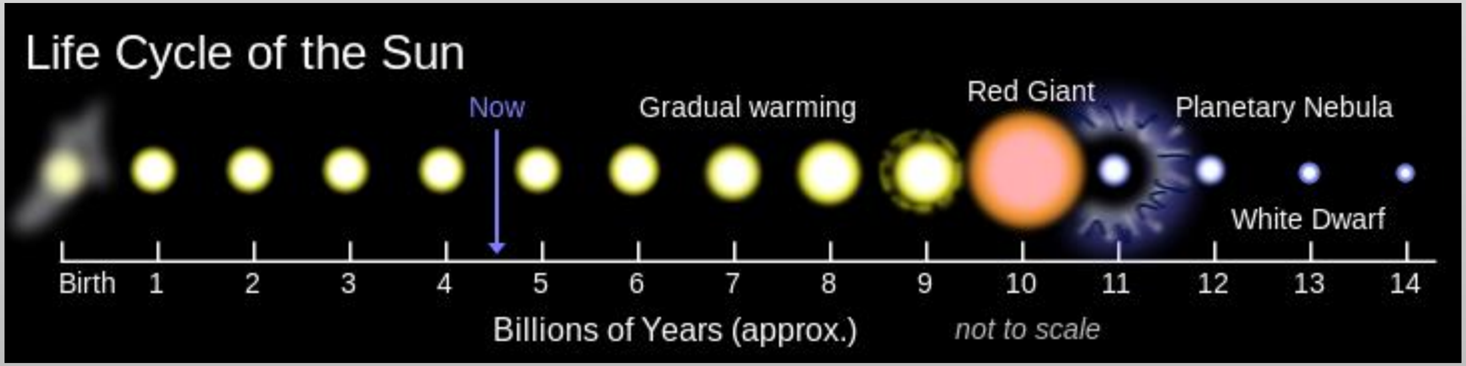
Stellar nucleosynthesis

Life cycle of a Sun-like star

This is not the endpoint for our Sun but stars only slightly less massive that our Sun do not evolve beyond this point. For them, the fusion fires eventually burn out and the star collapses under gravity to form a "***white dwarf***" star.

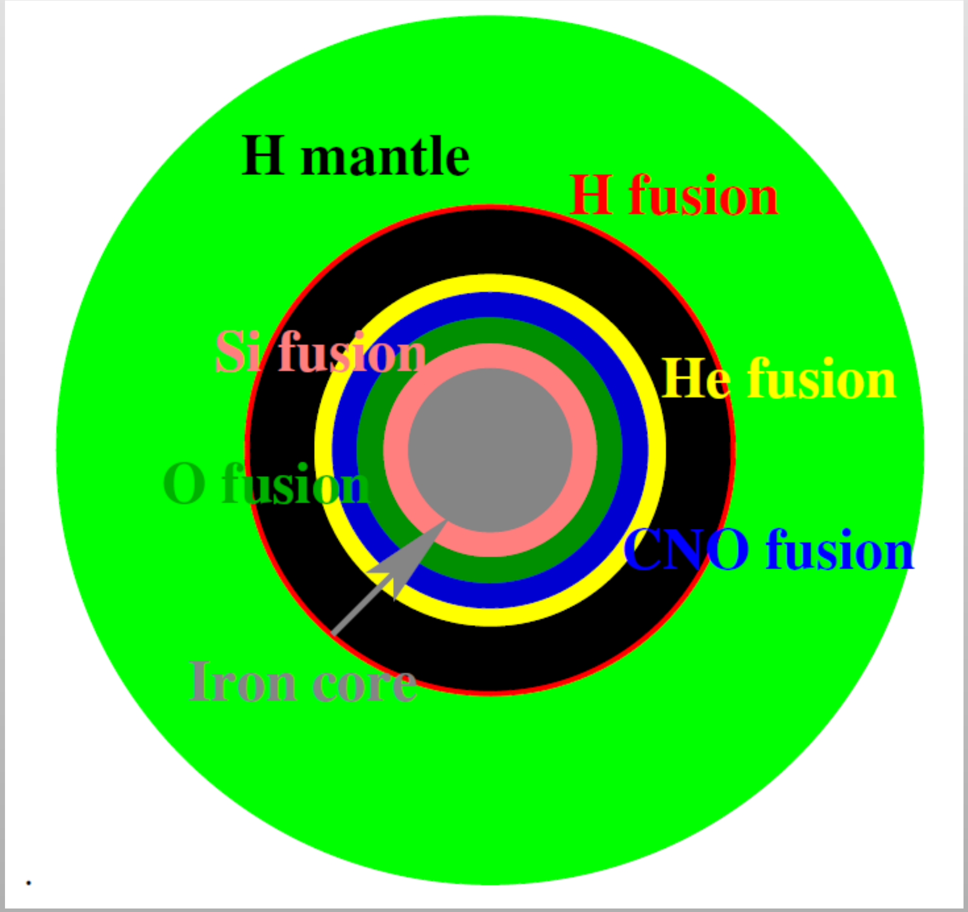
Stellar nucleosynthesis

Life cycle of a Sun-like star



By Oliverbeatson (Own work) [Public domain], via Wikimedia Commons

The heavy elements



The heavy elements

Fusion processes in large stars, up to 3 or 4 times the mass of the Sun, can fuse all elements and isotopes up to and including those of iron ^{56}**Fe**... but, then, nothing!

Nothing?

The heavy elements

Life cycle of a star 10x the mass of our Sun.

- Hydrogen fusion (from **H**, produce **He** and traces of **Li** and **Be**): ≈ 10,000,000 years.
- Helium burning (produce Li, Be, B and C): ≈ 1,000,000 years.
- Carbon burning (produce **N** and **O**): ≈ 300 years.
- Oxygen burning (produce **F, Ne, Na, Mg, Al** and **Si**): ≈ 8 months.
- Silicon burning (produce **P, S, Cl, Ar, K, Ca, Sc, Ti, V , Cr, Mn** and isotopes of **Fe** of atomic mass 56 or less): ≈ 2 days...
- ***Then nothing?***

The heavy elements

Supernoval explosion

Supernovae

So far, we have described the life-cycle of a very large star that eventually explodes as a **core-collapse** or **massive-star supernova**.   These are designated ***Type II***

Early in the Universe, the largest of the stars (100 – 300 $M_{\odot}$) that formed in the first few hundred million years explode as what we call **hypernovae**. These are even more exotic explosions that result from what is called Quantum pair-production.

Some of these super-sized stars left "neutron star" cinders following explosion. Coalescing pairs of such neutron stars explode with incredible energy as **kilonovae**. One such explosion has just recently been observed with gravitational waves, gamma rays and visible light.

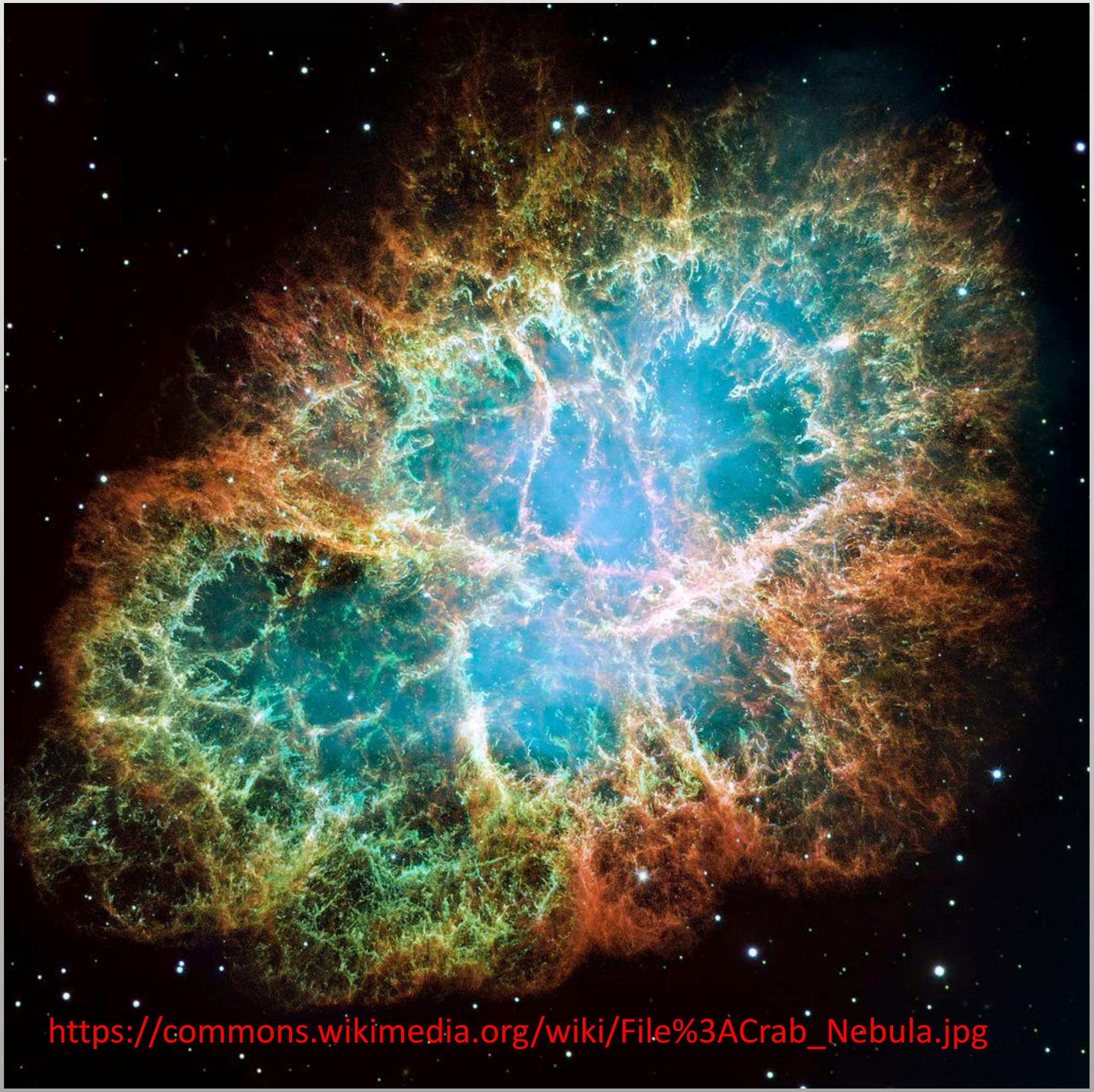
Type II Supernovae

The **Crab Nebula (SN 1054)** is the remnant of such a supernoval explosion that was seen on Earth in 1054 AD. It is 6000 light years from Earth. At the center of this bright nebula is a rapidly spinning neutron star, or pulsar that emits pulses of radiation 30 times a second.

The remnant core of a massive star that explodes as **Type II** usually forms as an extremely compressed neutron star.

https://commons.wikimedia.org/wiki/File%3ACrab_Nebula.jpg

SN 1054



Type Ia Supernovae

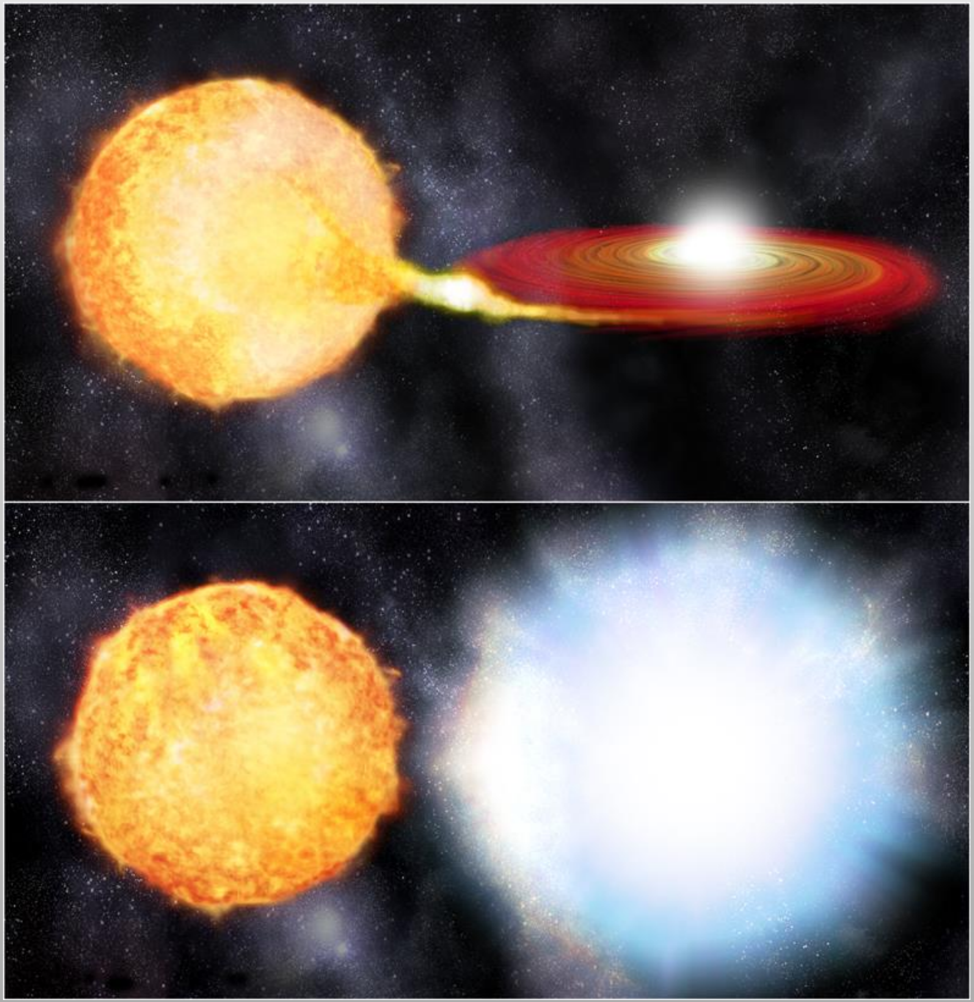
There are other events that produce supernoval explosions. Even an ordinary star like our Sun might become involved in one such explosion.

After our Sun's nuclear fires are burnt out and there is not enough energy being produced within the aged Sun to hold it up against gravitational collapse, it becomes a white dwarf.

Type Ia Supernovae

If a star comes close enough to our now white-dwarf Sun, its intense gravity field can tidally rip materials off the passing star. If the mass of material is sufficient to bring the Sun's mass to about 1.4x its present mass, it reaches the Chandrasekar limit and explodes. It explodes because the new overlying mass is sufficient to compress and heat the inner layers of our aged Sun to bring explosive thermo-nuclear fusion.

Type Ia Supernovae



SN 1006

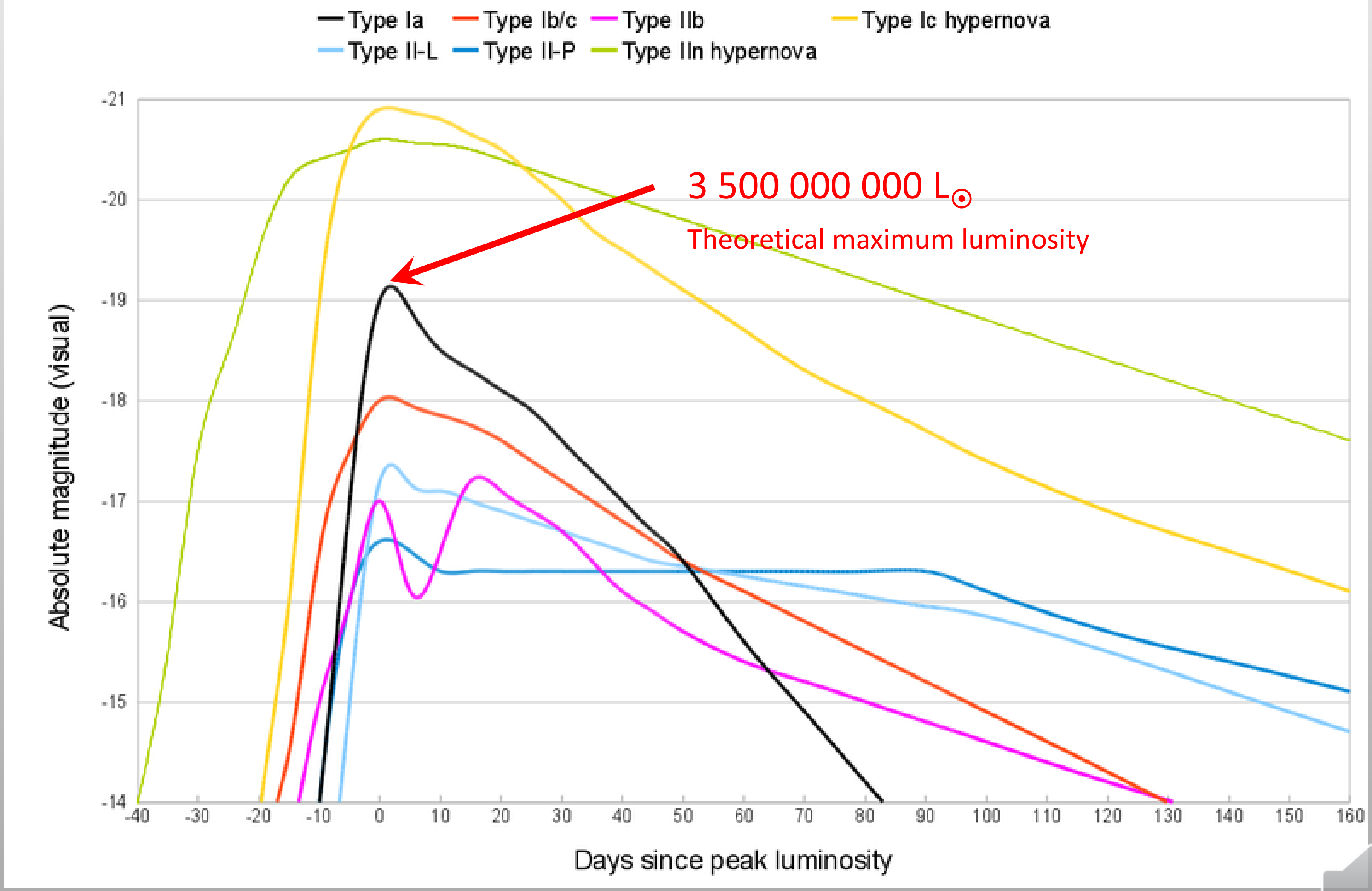
In 1006 CE, the brightest supernoval explosion in recorded history occurred. The peak brightness of the explosion was more than 7x the maximum brightness of Venus in our night sky. It was a **Type Ia** explosion.

Type Ia explosion remnants tend to be nearly circular and symmetric.

SN 1006

SN 1006 Supernova Remnant
Image Credit: NASA, ESA, Zolt Levay (STScI

Light curves of Supernovae



https://en.wikipedia.org/wiki/Pair-instability_supernova

Beyond ^{56}Fe

Almost all the elements beyond isotope 56 of iron are produced by the prodigious neutron/proton flux in supernoval, hypernoval or kilonoval explosions forcing them into lighter nuclei: ***r-process***.

Why are other naturally occurring isotopes of **Fe** relatively plentiful? Substantial quantities of ^{57}**Co** and ^{58}**Co** are produced in supernoval explosions; these are radioactive isotopes that decay via β-capture to ^{57}**Fe** and ^{58}**Fe**.

It is now thought that the very heavy elements like **Au** and **Pt** are largely produced by kilonova.

As well, in any star, small-to-trace quantities of all elements are continuously produced by the non-fusion endothermic ***s-process***.

Beyond ^{56}Fe

Group / Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																		2 He 4.0026
2	3 Li 6.94	4 Be 9.0122												5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305												13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078		21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.63	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.798
5	37 Rb 85.468	38 Sr 87.62		39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.96	43 Tc [97.91]	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	*	71 Lu 174.97	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po [208.98]	85 At [209.99]	86 Rn [222.02]
7	87 Fr [223.02]	88 Ra [226.03]	**	103 Lr [262.11]	104 Rf [265.12]	105 Db [268.13]	106 Sg [271.13]	107 Bh [270]	108 Hs [277.15]	109 Mt [276.15]	110 Ds [281.16]	111 Rg [280.16]	112 Cn [285.17]	113 Nh [284.18]	114 Fl [289.19]	115 Mc [288.19]	116 Lv [293]	117 Ts [294]	118 Og [294]

*Lanthanoids	*	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [144.91]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05
**Actinoids	**	89 Ac [227.03]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237.05]	94 Pu [244.06]	95 Am [243.06]	96 Cm [247.07]	97 Bk [247.07]	98 Cf [251.08]	99 Es [252.08]	100 Fm [257.10]	101 Md [258.10]	102 No [259.10]

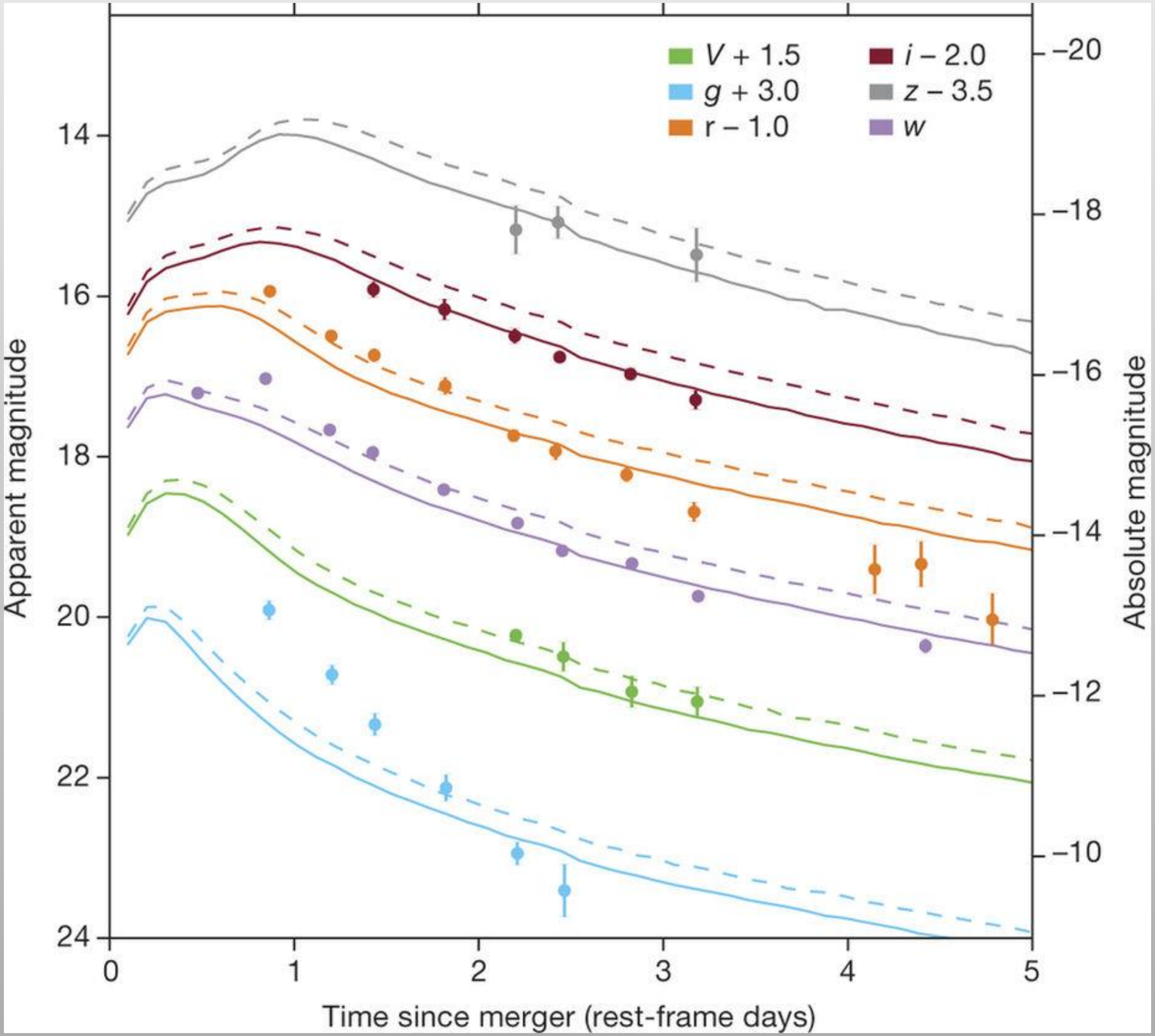
From webelements.com

Light curve of Kilonova AT 2017gfo

Kilonova AT 2017gfo was discovered as a gravitational wave radiator 17 August 2017 at 12:41:04 UTC. Now, with 3 gravitational wave detectors operational, it was localized in the sky near **NGC 4993**. Immediately, several optical, X-ray and infrared telescopes were trained on the location. This was the first combined GW-EM observation of a Gwave source.
The decay in several bands of electromagnetic radiation obtained this first empirical light curve from a kilonova.

https://www.nature.com/articles/nature24291?WT.feed_name=subjects_physics

Light curve of Kilonova AT 2017gfo



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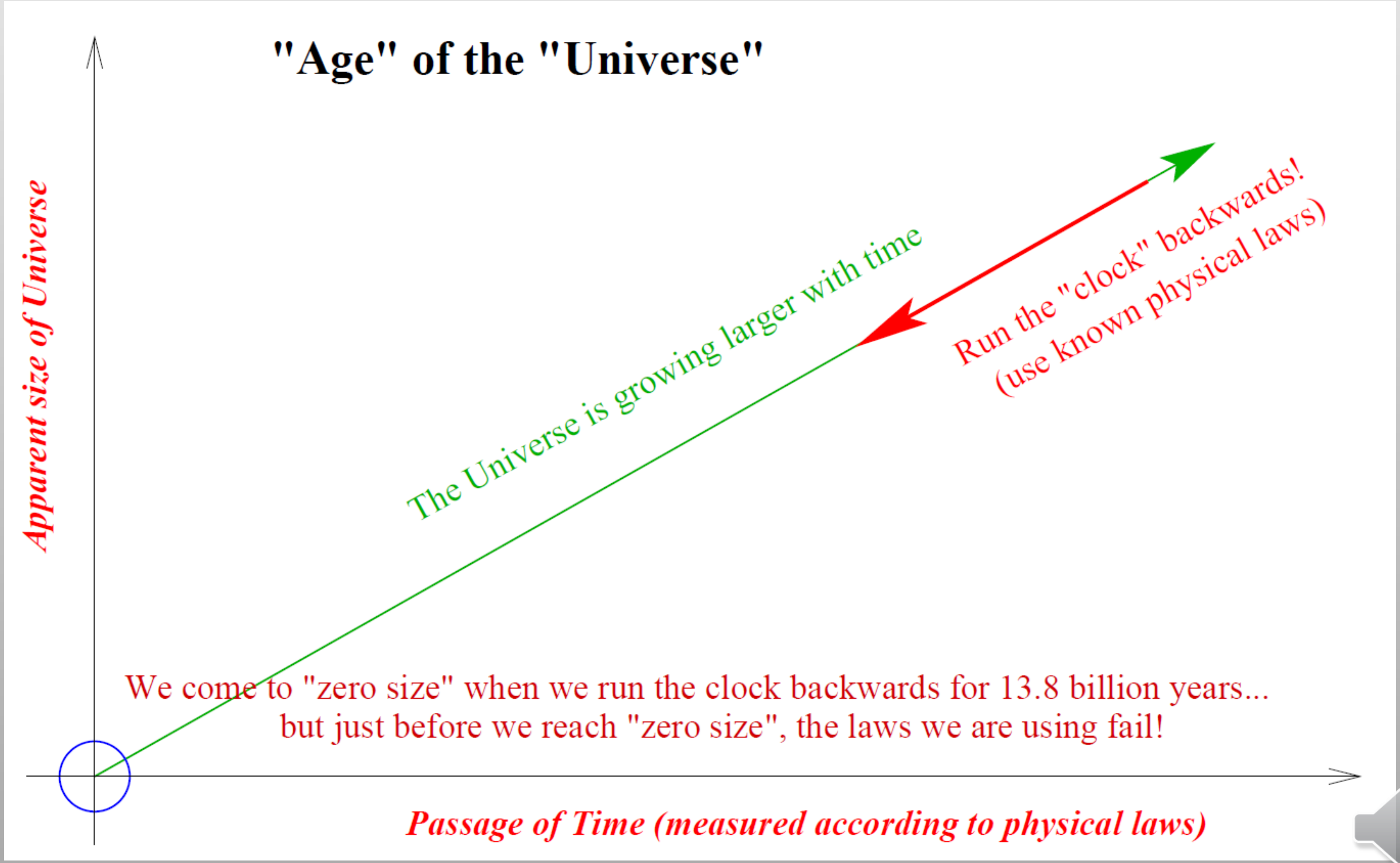
Unravelling the story of the *"Big Bang"*



Unravelling the story of the "*Big Bang*"

Using our ***contemporary physics,*** which comprises two great theories: ***Quantum Mechanics*** and ***Gravitation*** (General Relativity), we recognize the Universal space and the passage of time.

We determine that there are some ***Universal constants*** and expect that they hold everywhere and "*everywhen*" (or, at least since 10^{-33} seconds following the Big Bang) in the Universe.

Unravelling the story of the "*Big Bang*"

Some Universal constants of physics

c 299 792 458 m / s   (speed of light in vacuo)

G 6.67408 × 10^{-11} m^3 kg^{-1} s^{-2} (Cavendish constant of gravitation)

h 6.62607004 × 10^{-34} m^2 kg / s (Planck's constant – the quantum of action)

Unravelling the story of the "*Big Bang*"

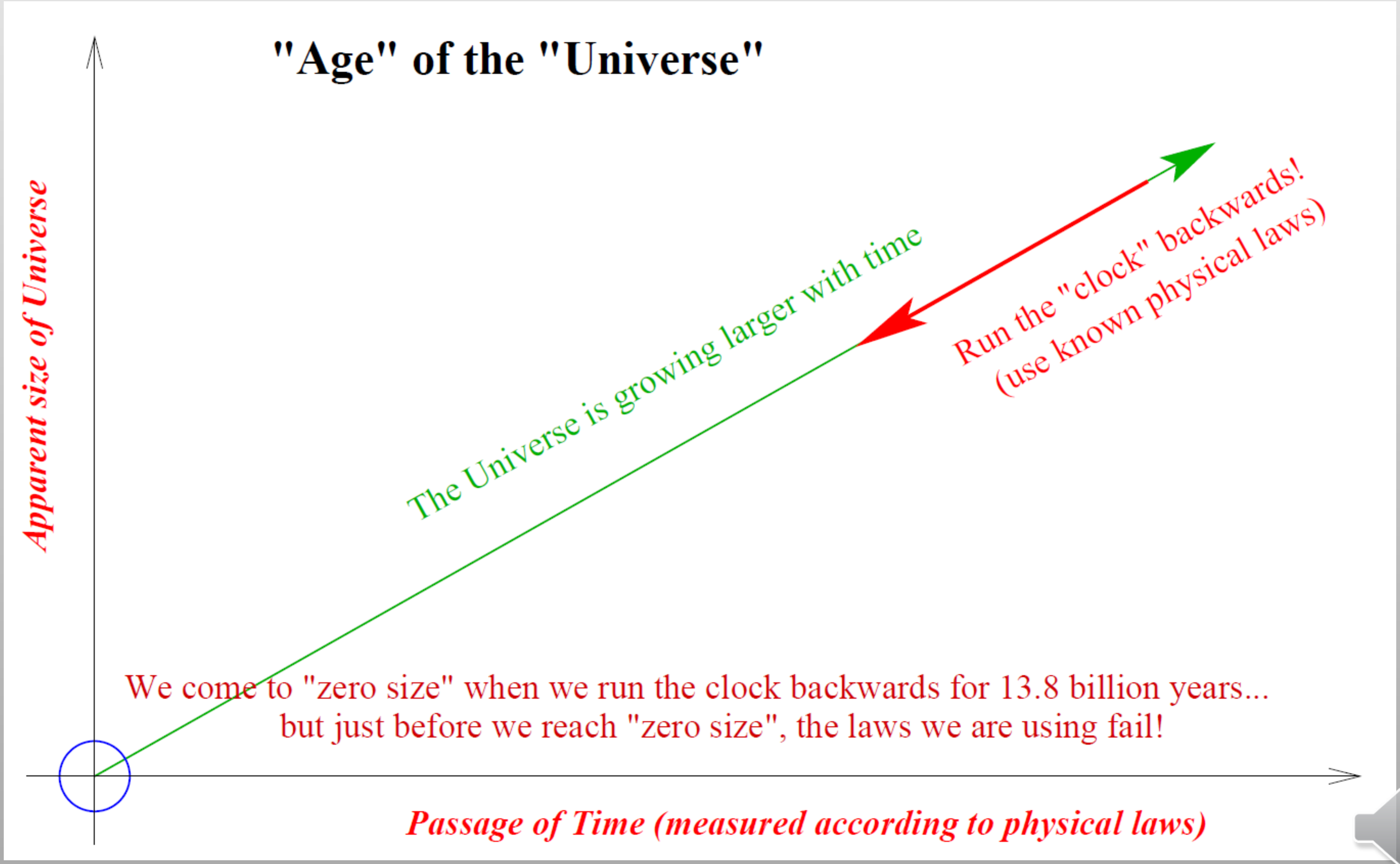
Universal constants can be re-arranged to define what might be "***indivisible***" units of time and length (and mass?):

Planck time: $\sqrt{hG/2\pi c^5}$ = 5.391×10^{-44} s

Planck length: $\sqrt{hG/2\pi c^3}$ = 1.616×10^{-33} cm

Planck mass: $\sqrt{hc/2\pi G}$ = 2.176×10^{-8} kg

Unravelling the story of the *"Big Bang"*



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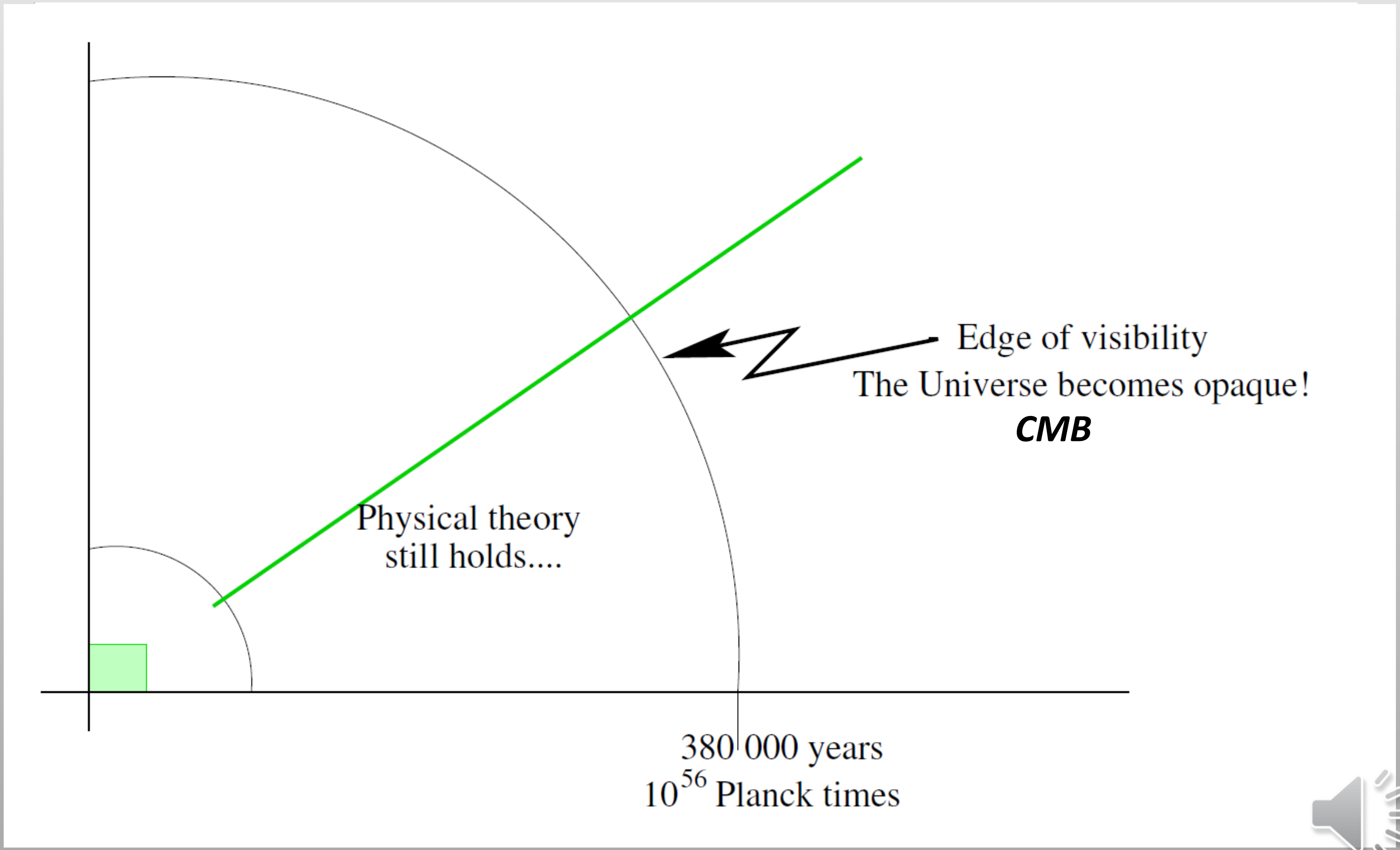
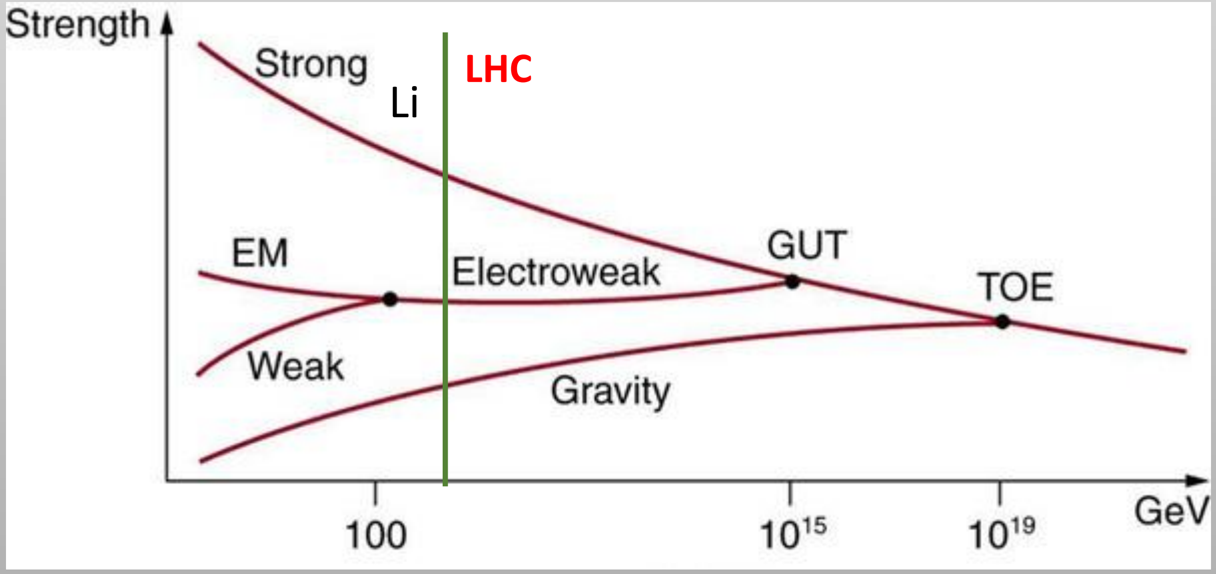


Backing up to the beginning

Using our known physics, we reverse the direction of time to back up toward the beginning of expansion but our physics breaks down at very high energy densities that must have existed shortly following the Big Bang.



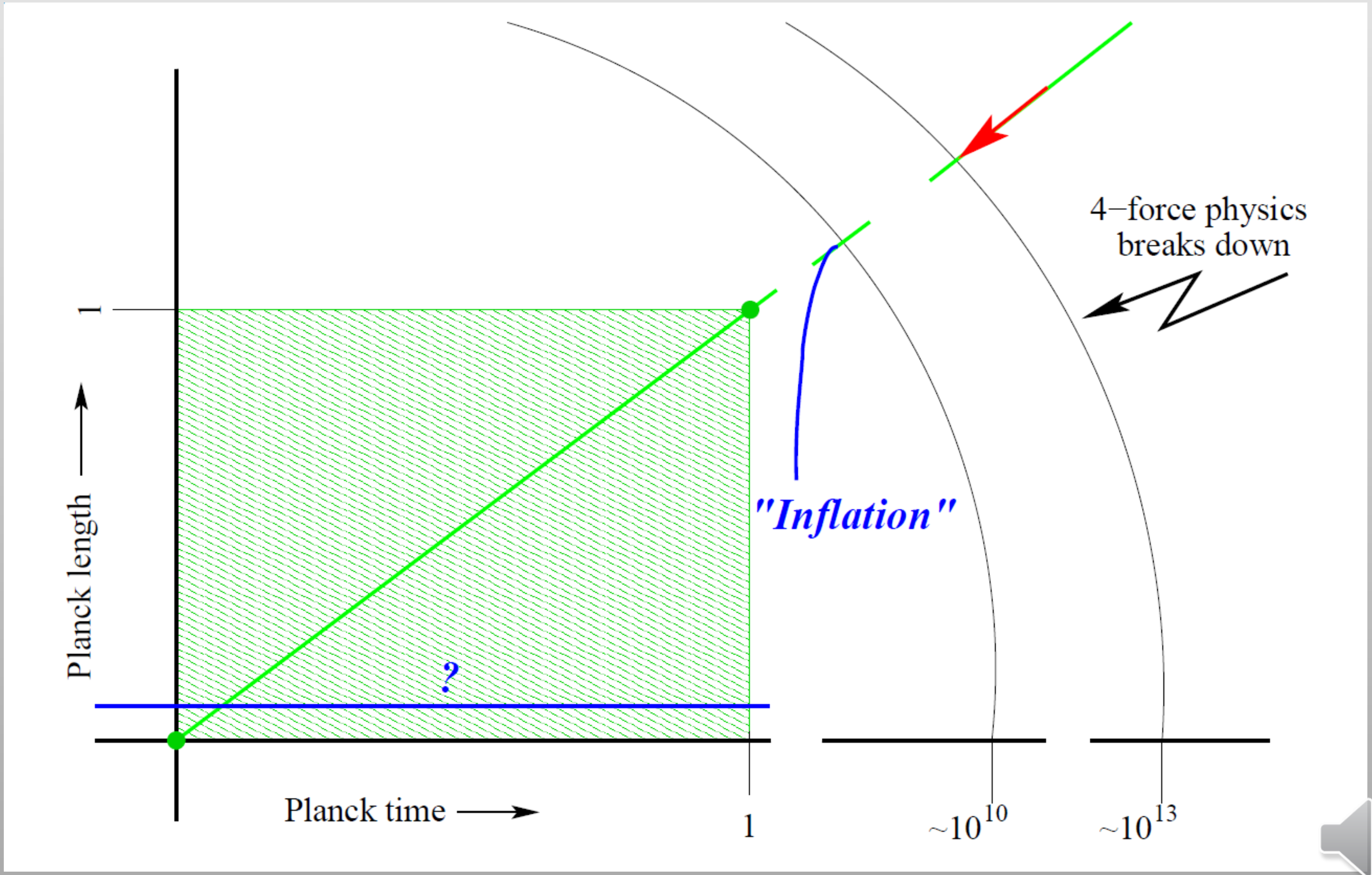
Energy →

← **Time**

e

[GUTs and TOEs](#)

Unravelling the story of the *"Big Bang"*



What of before?
Metaphysics, Philosophy, Theology

Our current understanding of ***Big Bang cosmology*** based on our knowledge of ***physics*** determines that **time** and **space** come into existence at a moment following the Big Bang.

Measuring by what we take to be the passage of time as we do and can, ***there was no precedent time.***

Time begins with the Big Bang. ***Space emerges*** in the Big Bang.

Should we want to discuss "before", we must abandon science and retreat into ***metaphysics***, ***philosophy and theology***.