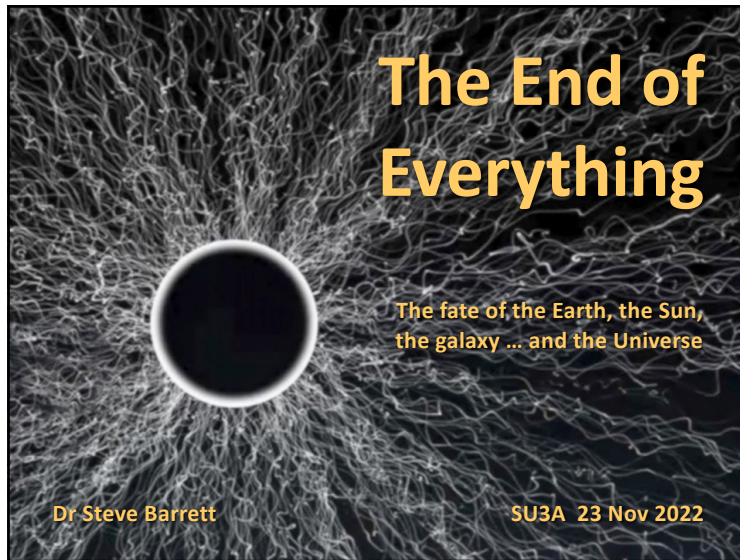


The End of Everything



Contents

Prologue

The Future
... of the Earth, Sun and Solar System

The Far Future
... of Stars and Galaxies

The Far, Far, Far Future
... and the Ultimate Fate of the Universe

Epilogue

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2

The Story So Far

The First Few Seconds

At the unimaginably early time of 10^{-35} seconds after its creation, the Universe has expanded to the size of a golf ball.

Just like a golf ball, the Universe is not perfectly smooth, but has "irregularities" in it.

Eventually, when the Universe is much, much bigger, these irregularities give rise to variations in the density of matter spread across the Universe. These will result in the formation of large-scale structures such as clusters of galaxies.

The First Few Seconds

The Universe has cooled to $T = 1$ billion K. It is now too cold for protons and neutrons to readily snap back and forth. Protons are a little lighter than neutrons ($\sim 1.2\%$), and so protons outnumber neutrons in the ratio 7:1:25.

A Nature always favours the lower energy! (or the lower mass)

The First Few Minutes

Neutrons are unstable and some decay into protons. The ratio of protons:neutrons is now $\approx 14:2$.

The Universe has cooled to $T \approx 100$ million K. Nuclei can now form. 12 nuclei of ^4He + 1 nucleus of ^2H .

After 3 minutes, the relative abundance of H and He is determined.

Cosmic Web

The "irregularities" in the cosmic golf ball give rise to the variations in the CMB.

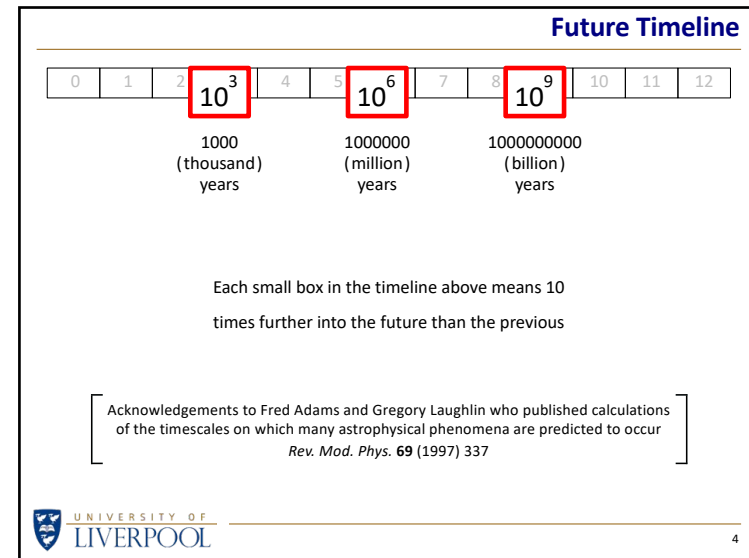
...and over billions of years collapse into a cosmic web of filaments and voids.

The Next 13.8 Billion Years

Now that we have hydrogen atoms we can understand. There are still some details of cosmic evolution to be worked out, but you get the basic idea.

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3




The End of Everything

Earth Rotation Slows

0	1	2	10^3	4	5	6	7	8	9	10	11	12
---	---	---	--------	---	---	---	---	---	---	----	----	----






Leap seconds would need to be added to the clocks every few weeks.


5

Antares Supernova

0	1	2	3	10^4	5	6	7	8	9	10	11	12
---	---	---	---	--------	---	---	---	---	---	----	----	----



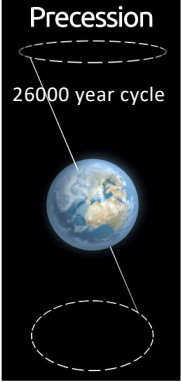

6

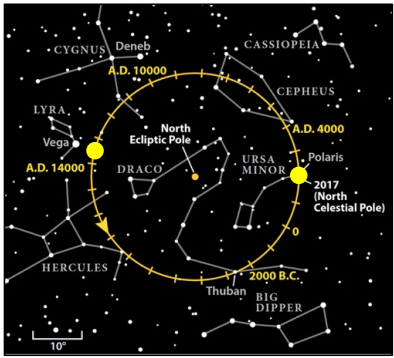
Vega Becomes the Pole Star


0	1	2	3	10^4	5	6	7	8	9	10	11	12
---	---	---	---	--------	---	---	---	---	---	----	----	----

Precession

26000 year cycle





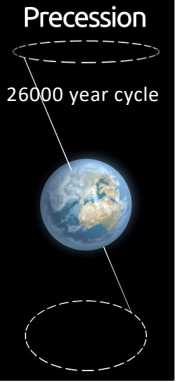

7

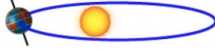
Vega Becomes the Pole Star

0	1	2	3	10^4	5	6	7	8	9	10	11	12
---	---	---	---	--------	---	---	---	---	---	----	----	----

Precession

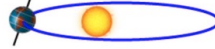
26000 year cycle





Polaris


Nearer to the Sun (perihelion) during Northern **Winter**



Vega

Nearer to the Sun (perihelion) during Northern **Summer**

Variations in the Earth's climate due to changes in the Earth's spin axis or its orbit around the Sun are called Milankovitch cycles.


8

The End of Everything

Voyagers Pass Nearby Stars

0	1	2	3	4	10 ⁵	6	7	8	9	10	11	12
---	---	---	---	---	-----------------	---	---	---	---	----	----	----

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9

Voyagers Pass Nearby Stars

0	1	2	3	4	10 ⁵	6	7	8	9	10	11	12
---	---	---	---	---	-----------------	---	---	---	---	----	----	----

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10

Interglacial Period Ends

0	1	2	3	4	10 ⁵	6	7	8	9	10	11	12
---	---	---	---	---	-----------------	---	---	---	---	----	----	----

Repeating cycles of glacial (ice age) and interglacial (warmer) periods tend to occur on time scales of order ~100,000 years.

Earth entered an interglacial period relatively recently and so the next ice age is 'due' on that timescale.

This is another manifestation of Milankovitch cycles.

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11

Earth Rotation Slows

0	1	2	3	4	10 ⁵	6	7	8	9	10	11	12
---	---	---	---	---	-----------------	---	---	---	---	----	----	----

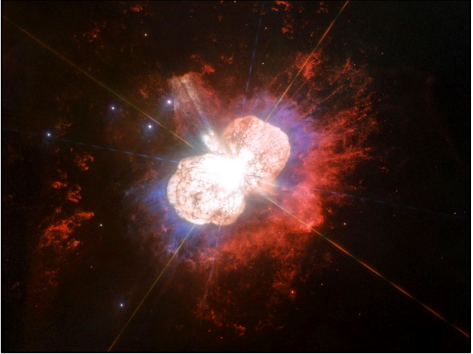
Leap seconds would need to be added to the clocks every day.

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12

The End of Everything

Eta Carinae Supernova

0 1 2 3 4 **10⁵** 6 7 8 9 10 11 12




APOD 20 Feb 2019

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13

Betelgeuse Supernova

0 1 2 3 4 **10⁵** 6 7 8 9 10 11 12



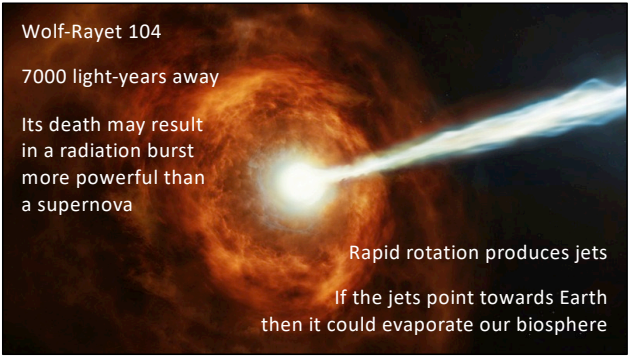
Peir Horálek Photography — Ondřejov Observatory, Prague

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14

Gamma-Ray Burst

0 1 2 3 4 **10⁵** 6 7 8 9 10 11 12



Wolf-Rayet 104
7000 light-years away
Its death may result in a radiation burst more powerful than a supernova


Rapid rotation produces jets
If the jets point towards Earth then it could evaporate our biosphere

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15

Gliese 710 Passes By

0 1 2 3 4 5 **10⁶** 7 8 9 10 11 12



Oort cloud

Gliese 710

The disruption to the Oort cloud will result in naked-eye comets every month ... for a million years

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16

The End of Everything

Gliese 710 Passes By

0 1 2 3 4 5 **10⁶** 7 8 9 10 11 12

For a while, our solar system will have two suns, just like ...




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17

Meteor Crater

0 1 2 3 4 5 **10⁶** 7 8 9 10 11 12




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18

Apollo Footprints

0 1 2 3 4 5 **10⁶** 7 8 9 10 11 12

The Moon is constantly bombarded with micro-meteorites. Eventually, all evidence of the Apollo landings will be erased.

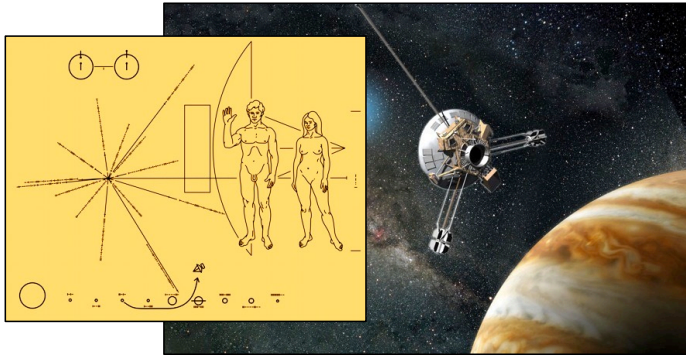


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19

Pioneer 10 Plaque

0 1 2 3 4 5 6 **10⁷** 8 9 10 11 12




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20

The End of Everything

Saturn's Rings

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12




Did the moon Mimas make Saturn's rings?

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21

Saturn's Rings

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



If a moon is smashed by a collision with a comet, what would happen to the debris?

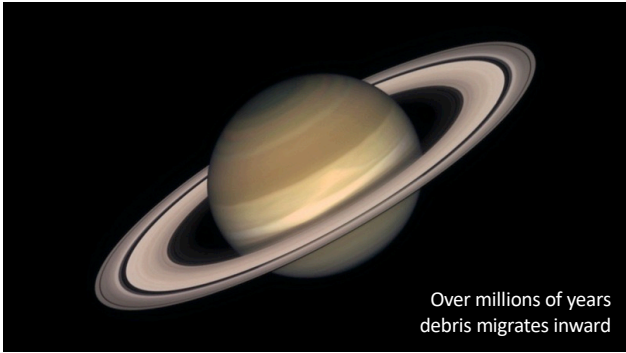
John Dubinski, Canadian Institute for Theoretical Astrophysics

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22

Saturn's Rings

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



Over millions of years debris migrates inward

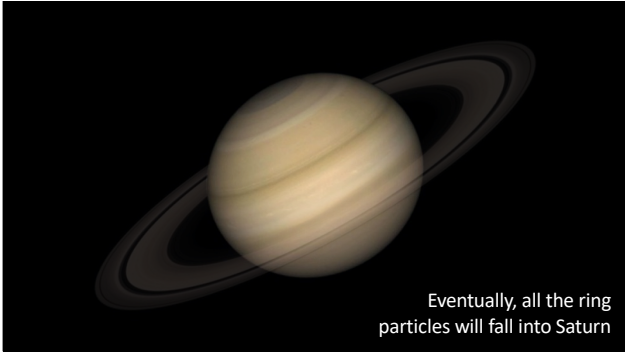
John Dubinski, Canadian Institute for Theoretical Astrophysics

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23

Saturn's Rings

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



Eventually, all the ring particles will fall into Saturn

John Dubinski, Canadian Institute for Theoretical Astrophysics

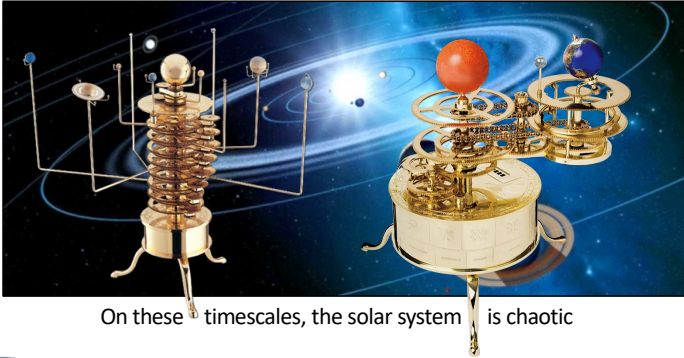
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24

The End of Everything

Solar System Unpredictable

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12




On these timescales, the solar system is chaotic

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25

Sun Moves Into Spiral Arm

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



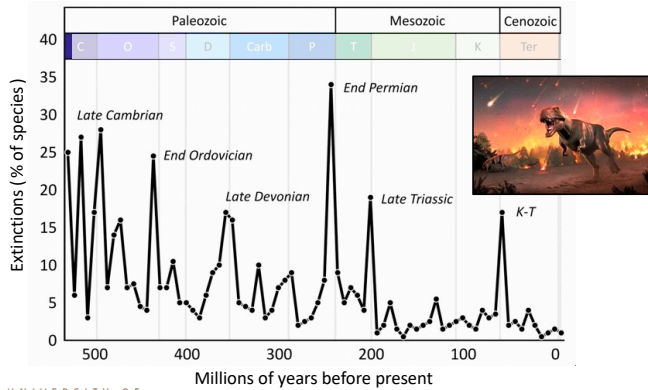
As the Milky Way rotates, the Sun will move from a low-density region in between two spiral arms into a higher-density region of a spiral arm, where it will have many more stellar neighbours.

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26

Extinction Level Event

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12




Period	Approximate Extinction Level (%)
Late Cambrian	~25
End Ordovician	~25
Late Devonian	~15
End Permian	~35
Late Triassic	~18
K-T	~18

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27

Extinction Level Event

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



This will be bad news for Italy ... and probably the rest of Earth.

Species will be exterminated.

Will that include us?

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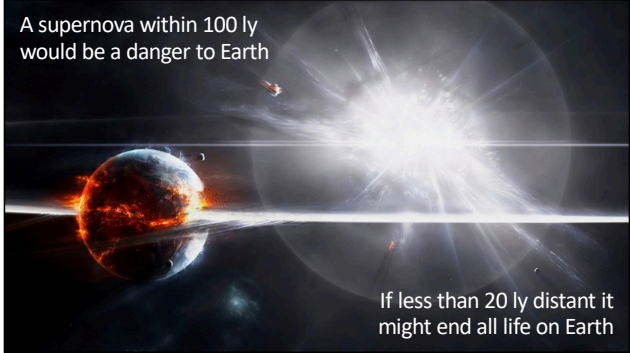
28

The End of Everything


Nearby Supernova

0	1	2	3	4	5	6	7	10^8	9	10	11	12
---	---	---	---	---	---	---	---	--------	---	----	----	----

A supernova within 100 ly would be a danger to Earth



If less than 20 ly distant it might end all life on Earth



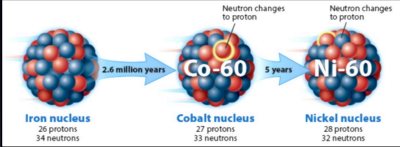
29


Nearby Supernova

0	1	2	3	4	5	6	7	10^8	9	10	11	12
---	---	---	---	---	---	---	---	--------	---	----	----	----

Supernovae within 100 ly have left deposits of the isotope ^{60}Fe in Earth sediments.

After a few million years ^{60}Fe decays into nickel and so any ^{60}Fe found on Earth must have 'arrived' relatively recently.






30

Distance to Moon Increases


0	1	2	3	4	5	6	7	10^8	9	10	11	12
---	---	---	---	---	---	---	---	--------	---	----	----	----



Through tidal friction, the Moon continues to rob the Earth of some of its angular momentum (spin) and increase the size of the Moon's orbit.

The length of a day is now 25 hours.


The distance from the Earth to the Moon will soon be so large that ...



31


No More Total Solar Eclipses

0	1	2	3	4	5	6	7	8	10^9	10	11	12
---	---	---	---	---	---	---	---	---	--------	----	----	----




Eclipse of the Sun

Dr Steve Barrett



APOD 10 Feb 2020



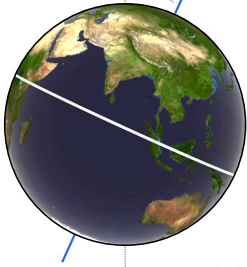
32

The End of Everything

Earth Axis Tilt Unstable

0 1 2 3 4 5 6 7 8 **10⁹** 10 11 12

Changes in Obliquity (Tilt)
41,000-year cycles



The Moon has a stabilising influence on the tilt of the Earth's axis (aka *obliquity*).

Historically, the tilt has varied by $\pm 1^\circ$ either side of $\sim 23.5^\circ$


However, if the Moon is 25% further away the Earth's axial tilt could change erratically, resulting in wild variations in the Earth's climate.

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33

Voyager Gold Disc

0 1 2 3 4 5 6 7 8 **10⁹** 10 11 12




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34

Greenhouse Effect

0 1 2 3 4 5 6 7 8 **10⁹** 10 11 12

The Sun's luminosity slowly increases as it evolves and moves towards its Red Giant phase.



The greenhouse effect drives the surface of the Earth to a balmy 80°C .

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35

Sun Becomes a Red Giant

0 1 2 3 4 5 6 7 8 **10⁹** 10 11 12



This could be a problem for us

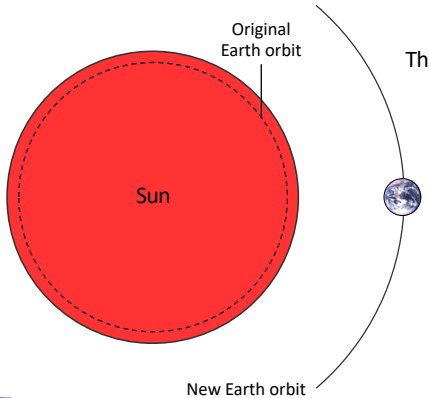
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36

The End of Everything

Sun Becomes a Red Giant

0 1 2 3 4 5 6 7 8 **10⁹** 10 11 12



The Earth won't (necessarily) be engulfed by the Sun.

As the Sun expands the strong solar wind will result in the Sun losing mass. With less gravity pulling on the Earth, its orbit will also expand.

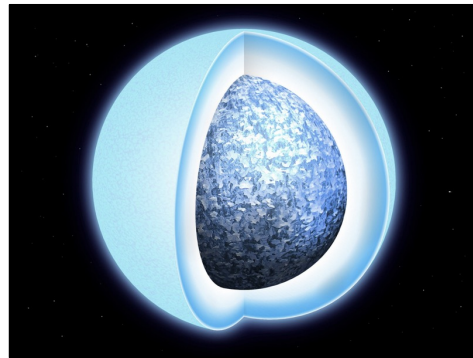
The Earth might survive.

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37

Sun Becomes a White Dwarf

0 1 2 3 4 5 6 7 8 9 **10¹⁰** 11 12

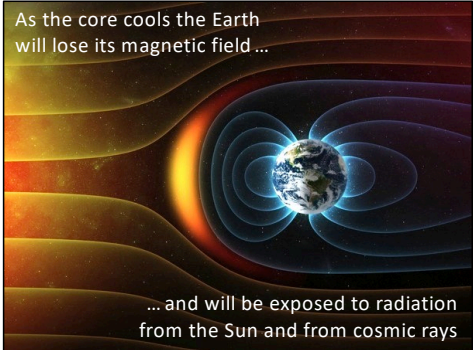


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38

Earth Loses Its Magnetic Field

0 1 2 3 4 5 6 7 8 9 **10¹⁰** 11 12



As the core cools the Earth will lose its magnetic field ...


... and will be exposed to radiation from the Sun and from cosmic rays

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39

Merger With Andromeda

0 1 2 3 4 5 6 7 8 9 **10¹⁰** 11 12



5 Gyr

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40

The End of Everything

Earth Rotation Slows

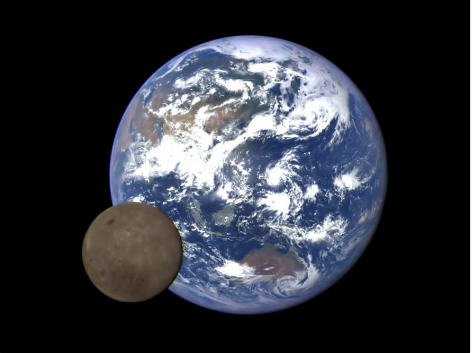
0123456789101112

10^{11}


1 day = 1 month

The Earth is now tidally locked to the Moon.

One side of the Earth now always faces the Moon (mirroring what the Moon has been doing for billions of years).



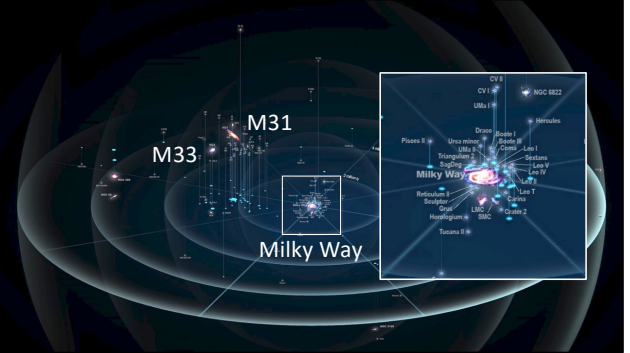
Deep Space Climate Observatory



41

All Galaxies in Local Group Merge

0123456789101112

10^{12}

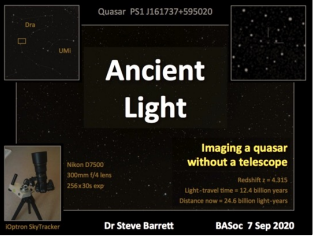



42

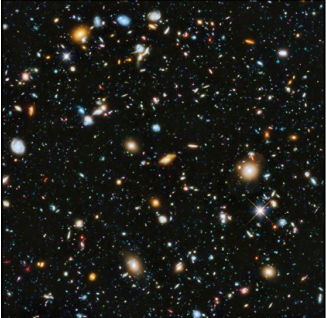
Galaxies Move Beyond Our Horizon

0123456789101112


10^{12}



Even if receding from us at twice the speed of light, galaxies can be imaged



Hubble Ultra Deep Field


43

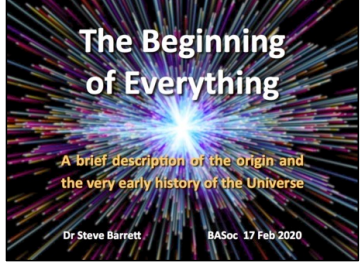
Universe Runs Out of Hydrogen


0123456789101112

10^{12}

It took **3 minutes** to make all the hydrogen in the Universe.

After a **trillion years** it is nearly all gone and so there will be no new star formation.





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The End of Everything

Aside – Frozen Stars

0 1 2 3 4 5 6 7 8 9 10 11 **10¹²**



With the hydrogen nearly all gone, stars might form from gas having a greater proportion of the heavier elements.

Some may have nuclear fusion reactions in their cores even though the surface temperatures are as low as $\sim 273\text{ K} = 0^\circ\text{ C}$.

Frozen stars!

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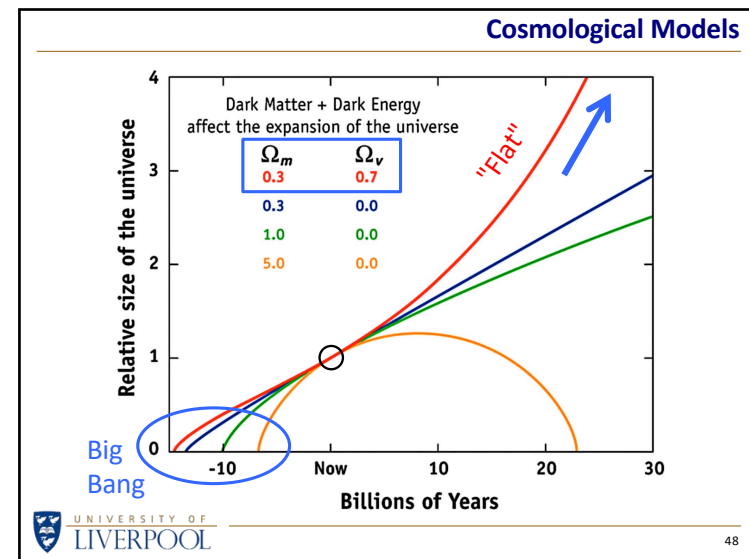
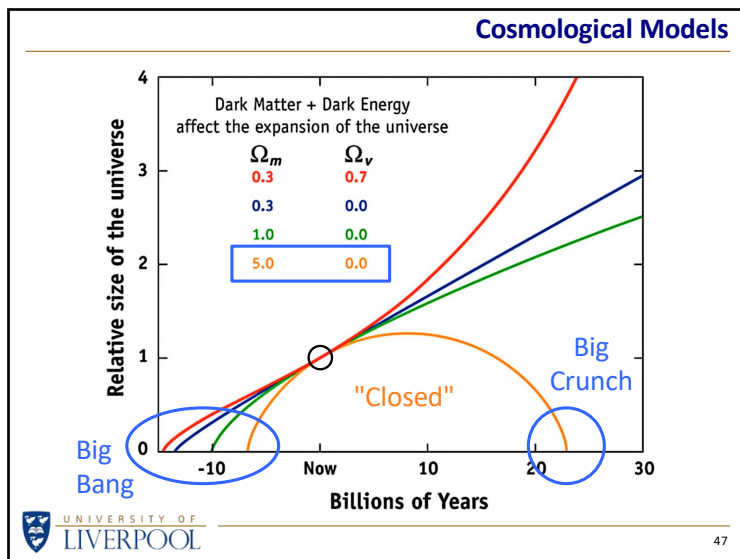
Cosmological Models

0 1 2 3 4 5 6 7 8 9 10 11 **10¹²**

Before going any further into the future we need to consider what the expansion of the Universe will look like

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The End of Everything

Far Future Timeline

12	18	24	10³⁰	36	42	10⁴⁸	54	60	10⁶⁶	72	78	84
			zillion? years			gazillion? years			????? years			

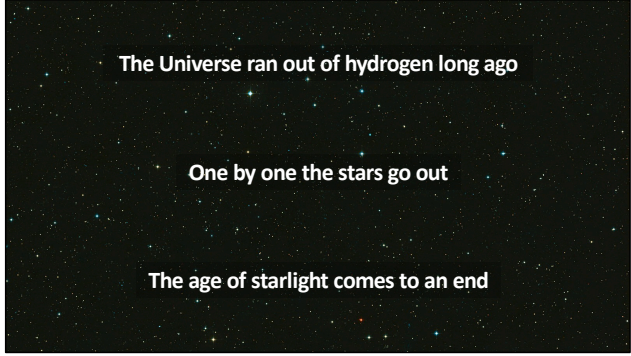
Now we change gears, as each small box in the timeline above means a *million* times further into the future than the previous

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Stars Stop Shining

12	18	24	30	36	42	48	54	60	66	72	78	84
	10¹⁸											



The Universe ran out of hydrogen long ago

One by one the stars go out

The age of starlight comes to an end

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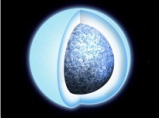
Music: Helen Jane Long 'Embers' Track 12 50

Dead Stars


12	18	24	30	36	42	48	54	60	66	72	78	84
	10¹⁸											

When the age of starlight ends the stars continue to orbit their galaxies.


The 'dead' stars are left drifting through space like zombies:



White Dwarves



Neutron Stars



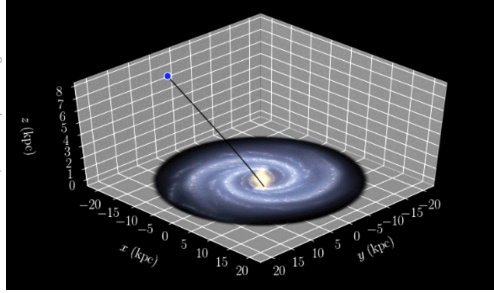
Black Holes

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51

Stars Ejected From Milky Way

12	18	24	30	36	42	48	54	60	66	72	78	84
	10¹⁸											



Example of a hypervelocity star ejected from the Milky Way 30 Myr ago

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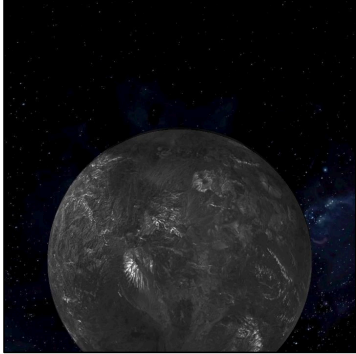
The End of Everything

White Dwarf Stars Go Dark

12 18 24 **10²⁴** 30 36 42 48 54 60 66 72 78 84

With no nuclear reactions to keep them hot, white dwarf stars cool down.

Eventually they become black dwarves.

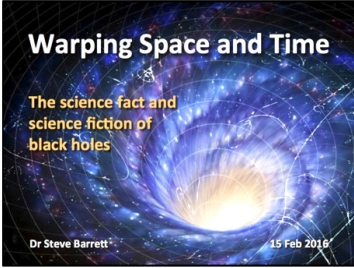


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53

SMBH Feed On Everything

12 18 24 **10³⁰** 36 42 48 54 60 66 72 78 84



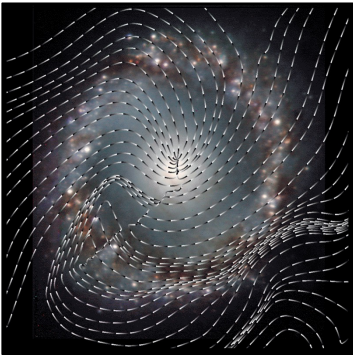
Any stars not ejected from the galaxy will be eaten by the central SMBH.

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54

SMBH Feed On Everything

12 18 24 **10³⁰** 36 42 48 54 60 66 72 78 84



The magnetic fields in NGC 1097 have been mapped out by SOFIA.



Matter follows these magnetic field lines into the SMBH at the centre of the galaxy.

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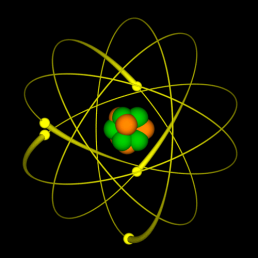
Protons Decay

12 18 24 30 **10³⁶** 42 48 54 60 66 72 78 84

Protons are charged particles that are a part of every atomic nucleus.

If protons decay, then all atoms will fall apart.

The timescale over which this is expected to happen is not known.



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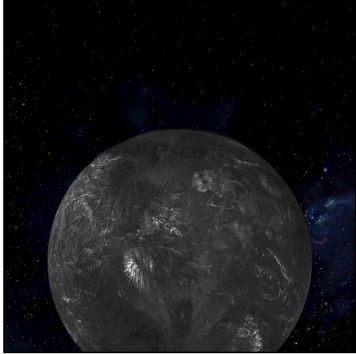
The End of Everything

Black Dwarf Stars Evaporate

12	18	24	30	36	10^{42}	48	54	60	66	72	78	84
----	----	----	----	----	-----------------------------	----	----	----	----	----	----	----

Assuming that protons don't decay, atoms may survive for a while longer ...

... but even black dwarf stars will evaporate (a quantum effect) leaving no atoms in the Universe.

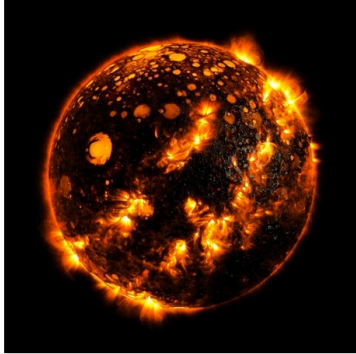


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Iron Stars

12	18	24	30	36	10^{42}	48	54	60	66	72	78	84
----	----	----	----	----	-----------------------------	----	----	----	----	----	----	----



It has been hypothesised that all the elements in dead stars will fuse to make iron stars.

Nuclear fusion at low temperatures is a very improbable event, but given enough time ... ?

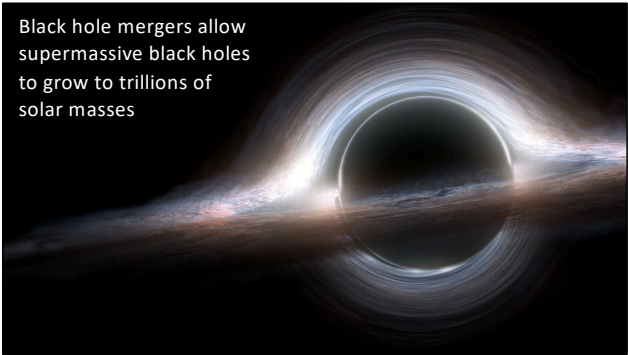
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58

SMBH Grow

12	18	24	30	36	42	48	10^{54}	60	66	72	78	84
----	----	----	----	----	----	----	-----------------------------	----	----	----	----	----

Black hole mergers allow supermassive black holes to grow to trillions of solar masses



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59

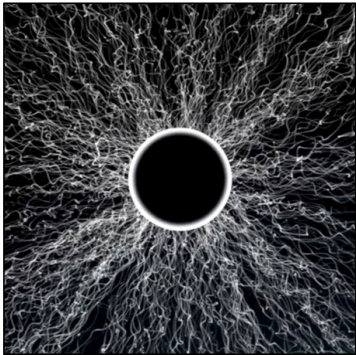
BH Evaporate

12	18	24	30	36	42	48	54	60	10^{66}	72	78	84
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Black holes are not eternal. They evaporate ...

... providing that you wait for a *really* long time.

Why do they evaporate?



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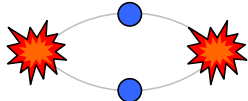
60

The End of Everything

BH Evaporate

12 18 24 30 36 42 48 54 60 **10⁶⁶** 72 78 84

Quantum Mechanics allows particles and antiparticles to be created from borrowed energy, as long as they annihilate and pay back the borrowed energy on very short time scales.



The diagram shows two blue spheres representing particles and two red starburst shapes representing antiparticles. Two curved lines connect the blue spheres to the red starbursts, illustrating the process of pair production and subsequent annihilation.

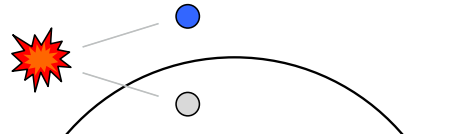
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BH Evaporate

12 18 24 30 36 42 48 54 60 **10⁶⁶** 72 78 84

How is this particle-antiparticle creation relevant to the lifetime of BH? What might happen if they are created *just* outside the event horizon?



The diagram shows a black hole represented by a curved line. A blue sphere (particle) is shown being created just outside the event horizon, and a red starburst (antiparticle) is shown falling into the black hole. This illustrates the process of Hawking radiation.

There is a net flux of particles radiating from the event horizons of BH called **Hawking radiation**. This radiation increases with decreasing mass, so smaller BH evaporate faster than larger ones.


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BH Evaporate

12 18 24 30 36 42 48 54 60 **10⁶⁶** 72 78 84

As a BH evaporates the radiation levels increase until it finally disappears in a flash of radiation.



The image shows a bright, glowing point of light surrounded by a dense field of radiating lines, representing the final stages of a black hole's evaporation.

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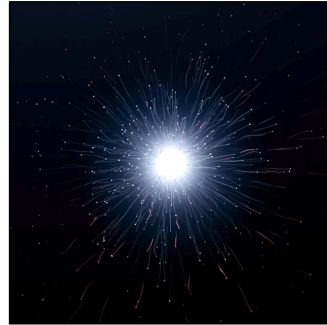
63

SMBH Evaporate

12 18 24 30 36 42 48 54 60 66 72 78 **10⁸⁴**

Even the supermassive BH lurking at the centres of most galaxies will evaporate eventually...

... though it will take trillions of times longer than for stellar-mass BH.



The image shows a bright, glowing point of light surrounded by a dense field of radiating lines, representing the final stages of a supermassive black hole's evaporation.

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The End of Everything


The End of Time?

12	18	24	30	36	42	48	54	60	66	72	78	84
----	----	----	----	----	----	----	----	----	----	----	----	----

$10^{100} = \text{Googol}$ [No, not ...
Google]


After a googol years the last BH has evaporated.


After this, **NOTHING** happens, and so time becomes ... meaningless.


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Epilogue

We live in a Golden Age ...

The **Sun** is middle-aged and well-behaved 

The **Moon** is at the right distance to
stabilise the Earth's axis and seasons
... and give us the spectacle of a total solar eclipse 


We are able to **explore** and **discover** and **understand** the Universe
by visiting our closest neighbours
... or seeing galaxies billions
of light-years distant 


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Epilogue

The Past
Humankind could not have arisen in the very early Universe, as generations of stars were needed to make the heavier elements that were essential for life to evolve.

The Future
Trillions of years from now the Universe will be empty and boring.

Hence, the best time to exist is ... **NOW** 

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The End of Everything

www.liverpool.ac.uk/~sdb/Talks

Dr Steve Barrett SU3A 23 Nov 2022

