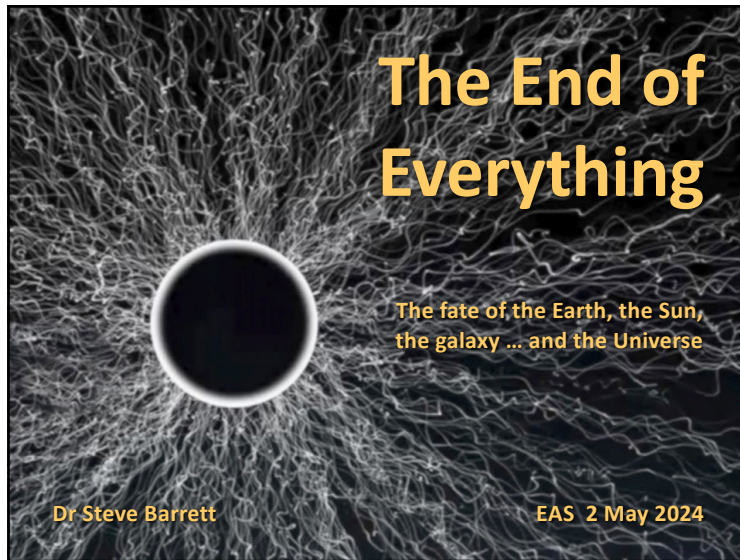


The End of Everything



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**

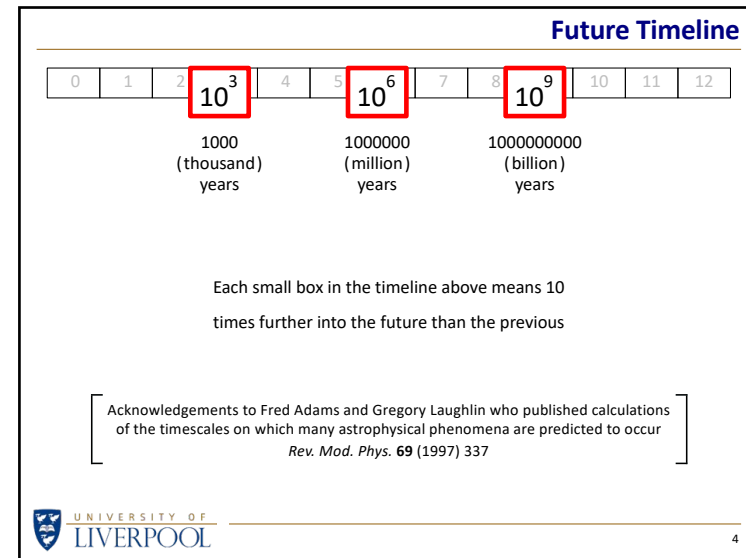
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2

The Story So Far

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3



The End of Everything

Earth Rotation Slows

0 1 2 **10³** 4 5 6 7 8 9 10 11 12




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

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5

Antares Supernova

0 1 2 3 **10⁴** 5 6 7 8 9 10 11 12

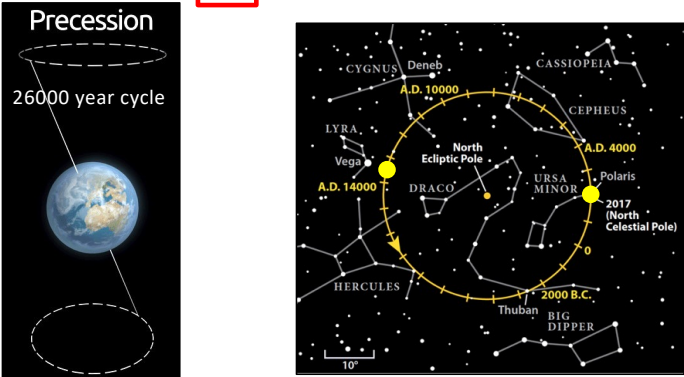


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6

Vega Becomes the Pole Star

0 1 2 3 **10⁴** 5 6 7 8 9 10 11 12

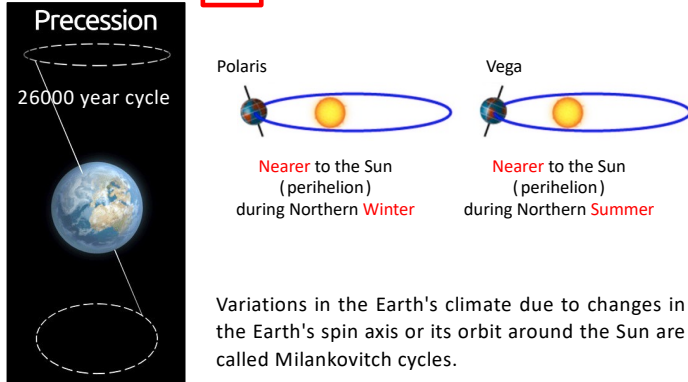


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7

Vega Becomes the Pole Star

0 1 2 3 **10⁴** 5 6 7 8 9 10 11 12



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.

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8

The End of Everything

Voyagers Pass Nearby Stars

0 1 2 3 4 **10⁵** 6 7 8 9 10 11 12

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9

Voyagers Pass Nearby Stars

0 1 2 3 4 **10⁵** 6 7 8 9 10 11 12

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10

Interglacial Period Ends

0 1 2 3 4 **10⁵** 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 $\sim 100,000$ 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 **10⁵** 6 7 8 9 10 11 12

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

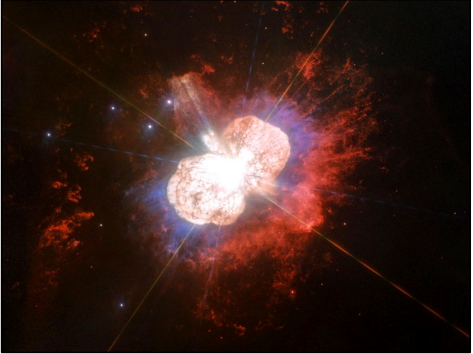
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12

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



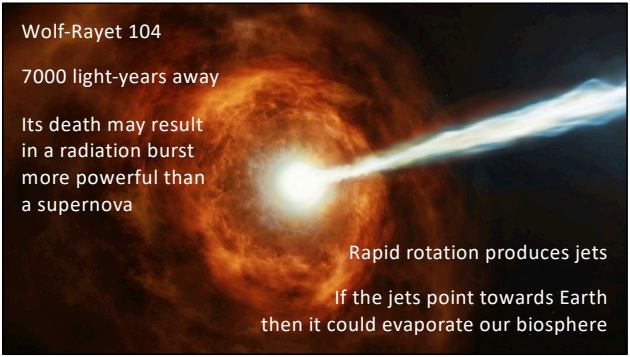
Petr Horálek Photography — Ondřejov Observatory, Prague

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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.

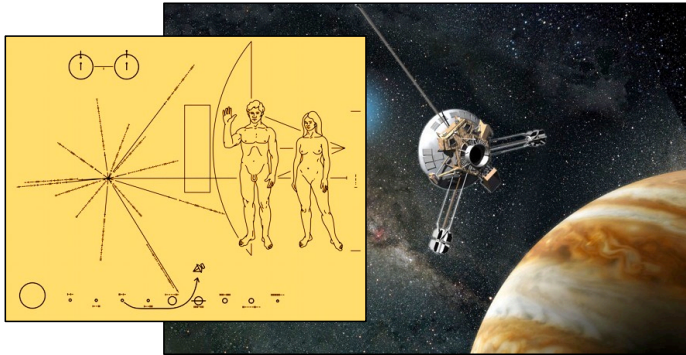


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19

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?

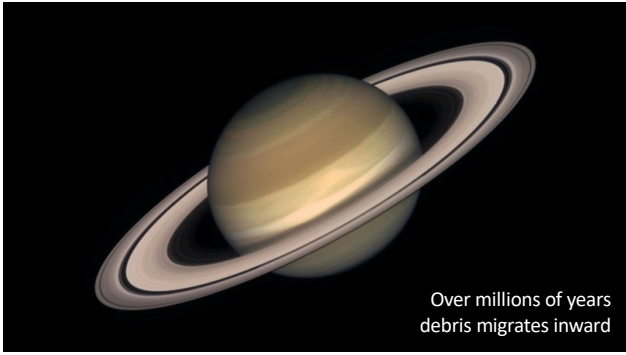
John Dubinski, Canadian Institute for Theoretical Astrophysics

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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

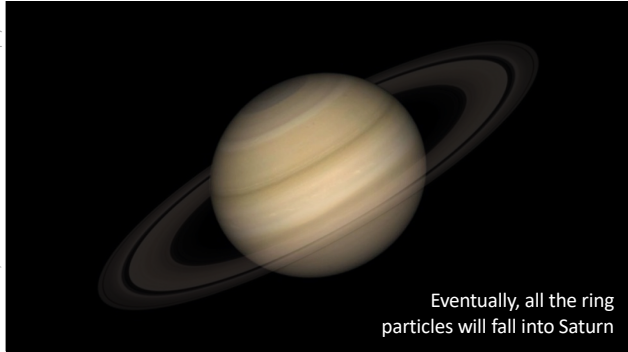
John Dubinski, Canadian Institute for Theoretical Astrophysics

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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

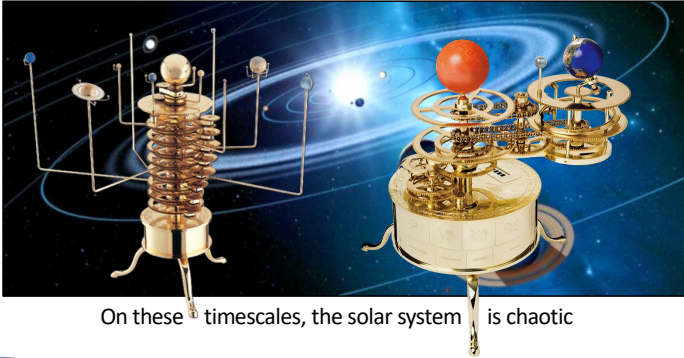
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The End of Everything

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



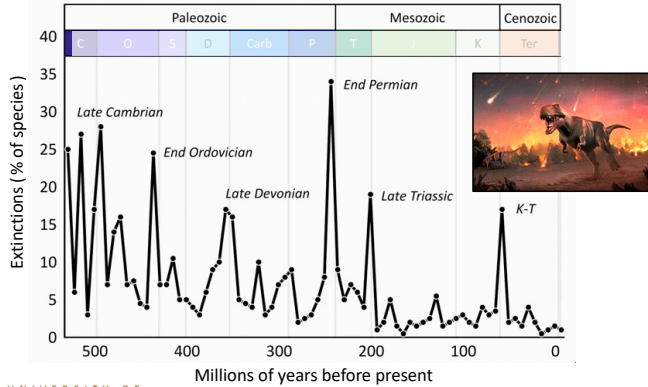
As the Milky Way rotates, the Sun will move from a low-density region in between two spiral arms into a higher-density region of a spiral arm, where it will have many more stellar neighbours.

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26

Extinction Level Event

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12



Extinctions (% of species)


Millions of years before present

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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?

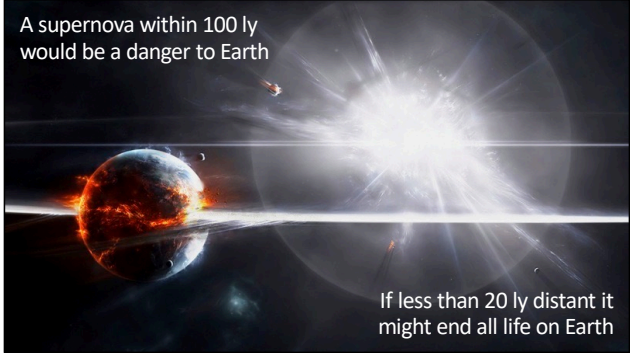
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28

The End of Everything

Nearby Supernova

0 1 2 3 4 5 6 7 **10⁸** 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

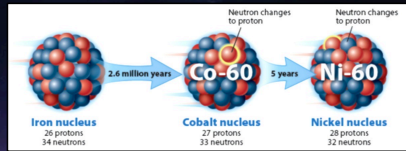
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29

Nearby Supernova

0 1 2 3 4 5 6 7 **10⁸** 9 10 11 12

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




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

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30

Distance to Moon Increases

0 1 2 3 4 5 6 7 **10⁸** 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 ...

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31

No More Total Solar Eclipses

0 1 2 3 4 5 6 7 8 **10⁹** 9 10 11 12

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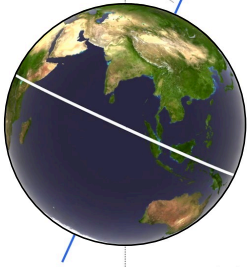
32

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.


climate.nasa.gov

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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

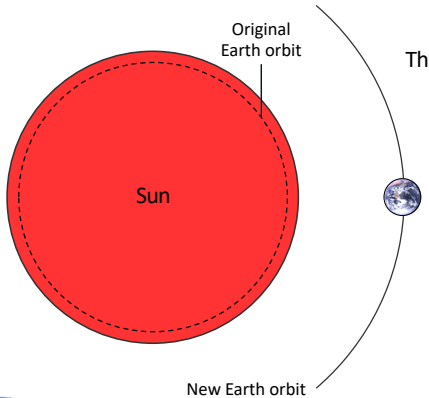
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36

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.

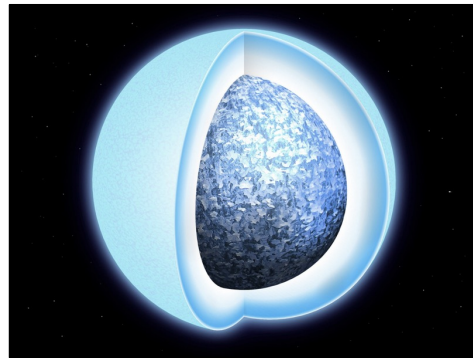
The Earth might survive.

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37

Sun Becomes a White Dwarf

0 1 2 3 4 5 6 7 8 9 **10¹⁰** 11 12

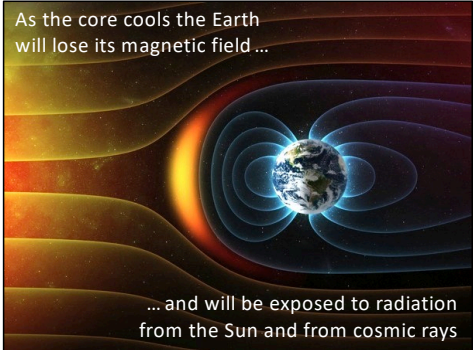


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38

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

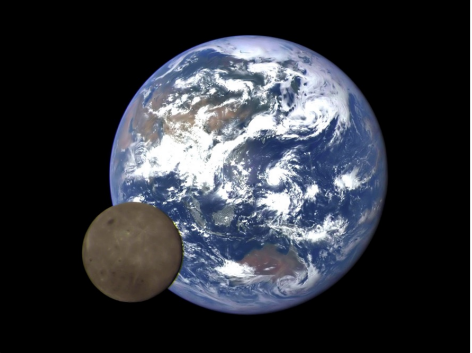
Earth Rotation Slows

0123456789 10^{11} 12


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).

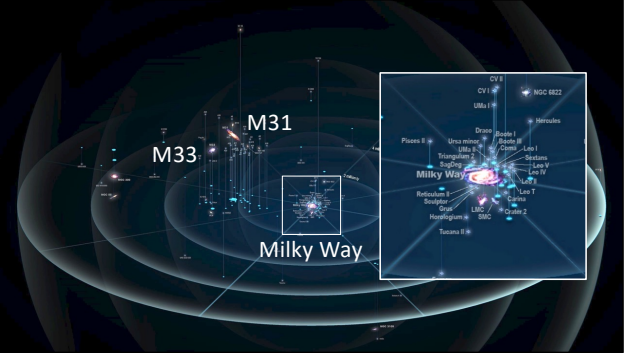



Deep Space Climate Observatory


41

All Galaxies in Local Group Merge

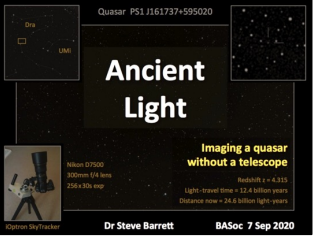
012345678910 10^{12}



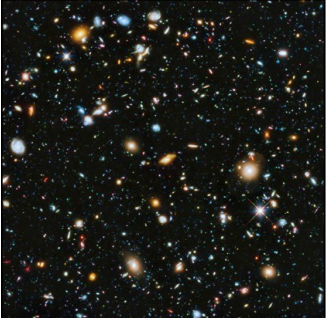

42

Galaxies Move Beyond Our Horizon


012345678910 10^{12}



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



Hubble Ultra Deep Field

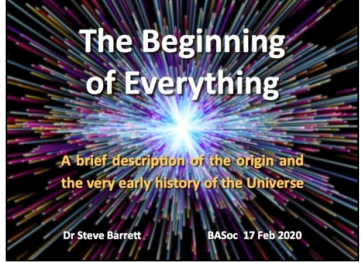

43


Universe Runs Out of Hydrogen

012345678910 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.





44

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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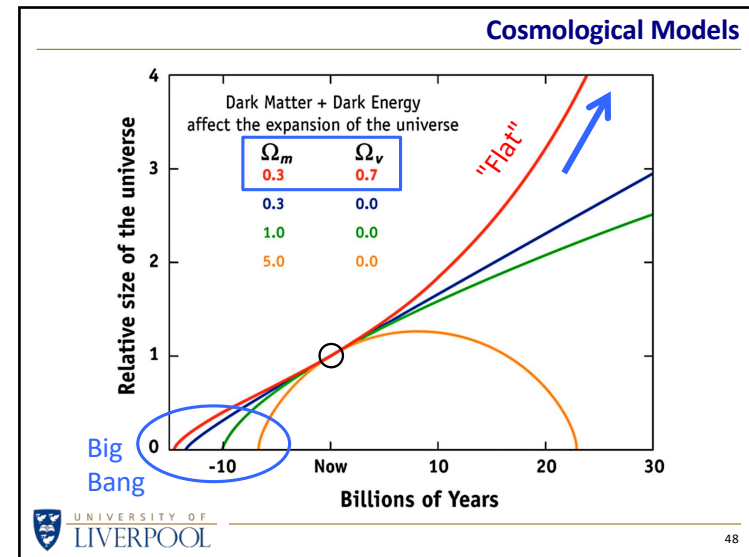
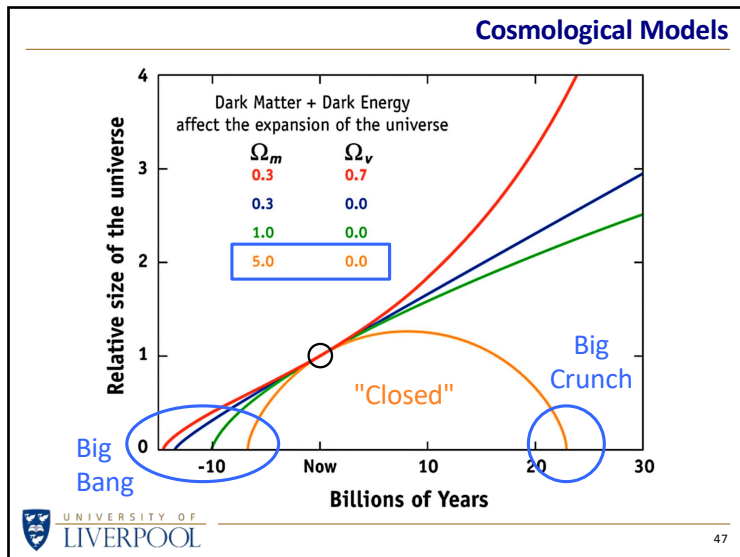
Cosmological Models

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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46




The End of Everything

Far Future Timeline

12	18	24	10^{30}	36	42	10^{48}	54	60	10^{66}	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


49


Stars Stop Shining

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

The Universe ran out of hydrogen long ago

One by one the stars go out

The age of starlight comes to an end

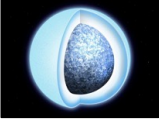

Music: Helen Jane Long 'Embers' Track 12 50

Dead Stars


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

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

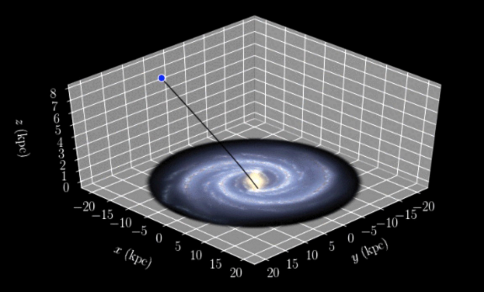


Black Holes


51


Stars Ejected From Milky Way

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



Kohei Hattori, University of Michigan

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


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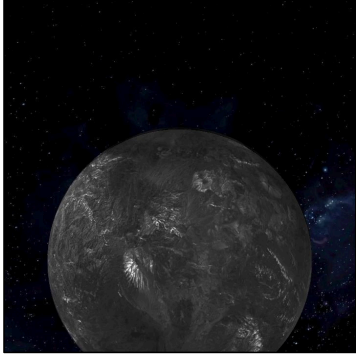
The End of Everything

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



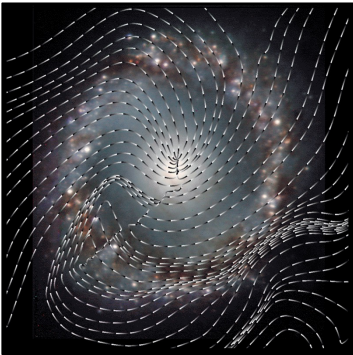
Any stars not ejected from the galaxy will be eaten by the central SMBH.

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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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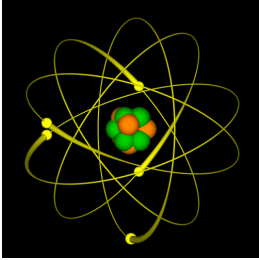
Protons Decay

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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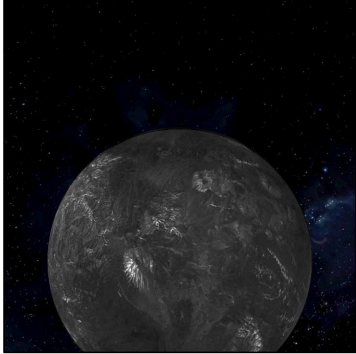
The End of Everything

Black Dwarf Stars Evaporate

12	18	24	30	36	10⁴²	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.

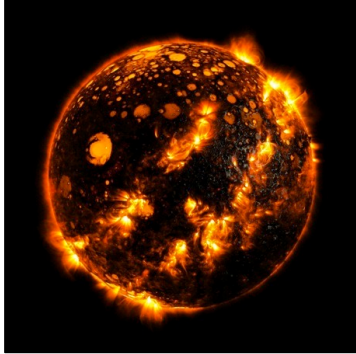


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57

Iron Stars

12	18	24	30	36	10⁴²	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 ... ?

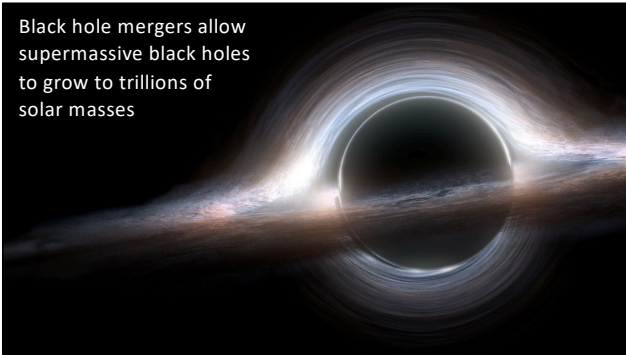
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58

SMBH Grow

12	18	24	30	36	42	48	10⁵⁴	60	66	72	78	84
----	----	----	----	----	----	----	------------------------	----	----	----	----	----

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



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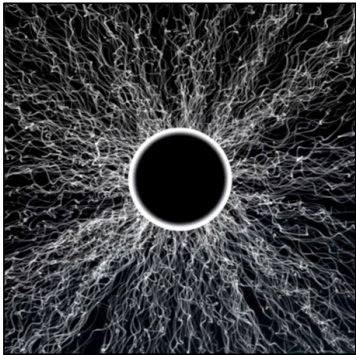
BH Evaporate

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

Black holes are not eternal. They evaporate ...

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

Why do they evaporate?



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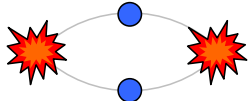
60

The End of Everything

BH Evaporate

12	18	24	30	36	42	48	54	60	10^{66}	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 creation and annihilation.

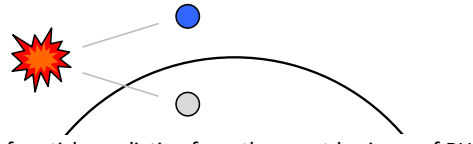
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61

BH Evaporate

12	18	24	30	36	42	48	54	60	10^{66}	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) and a grey sphere (antiparticle) are shown just outside the event horizon. A red starburst (radiation) is shown being emitted from the horizon.

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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62

BH Evaporate

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

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 central 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 EAS 2 May 2024