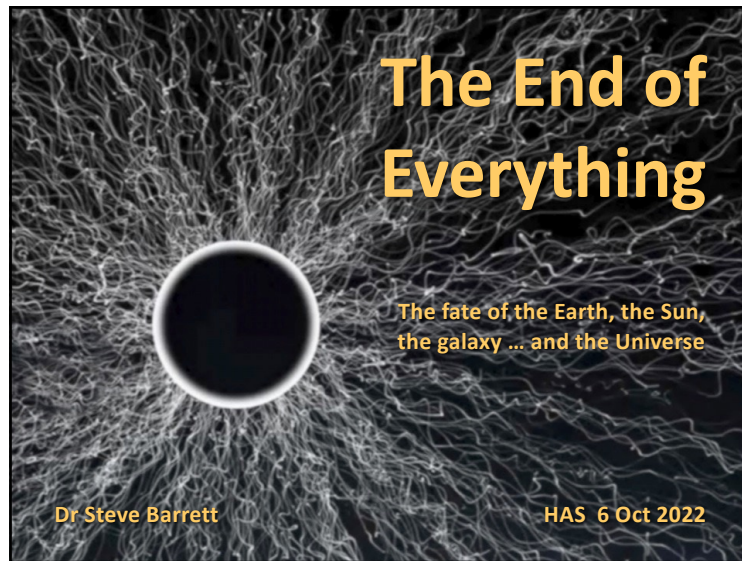


The End of Everything



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



2

The Story So Far

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 ($m_p < m_n$), and as protons outnumber neutrons in the ratio 7:1, the universe is now 75% protons and 25% neutrons. (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 ^{12}C . After 3 minutes, the relative abundance of H and He is determined.

Cosmic Web

The 'lumps' in the cosmic web have grown into the structures we see in the CMB. ... and over billions of years collapsed 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 ideas.

3

Future Timeline

0	1	2	3	4	5	6	7	8	9	10	11	12
			10^3			10^6			10^9			
			1000 (thousand) years			1000000 (million) years			1000000000 (billion) years			

Each small box in the timeline above means 10 times further into the future than the previous

Acknowledgements to Fred Adams and Gregory Laughlin who published calculations of the timescales on which many astrophysical phenomena are predicted to occur
Rev. Mod. Phys. **69** (1997) 337

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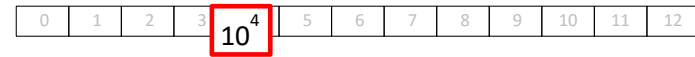
The End of Everything

Earth Rotation Slows

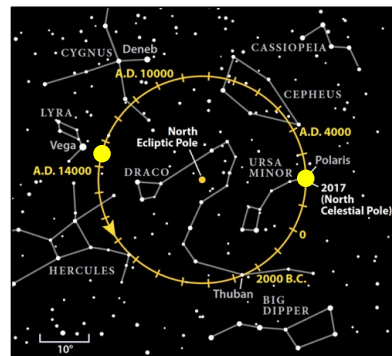


Leap seconds would need to be added to the clocks every few weeks.

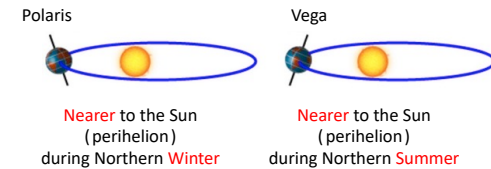
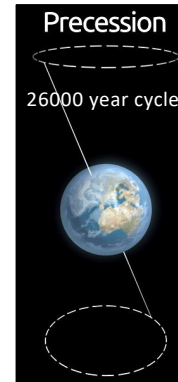
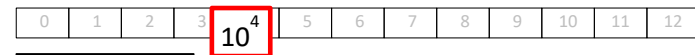
Antares Supernova



Vega Becomes the Pole Star

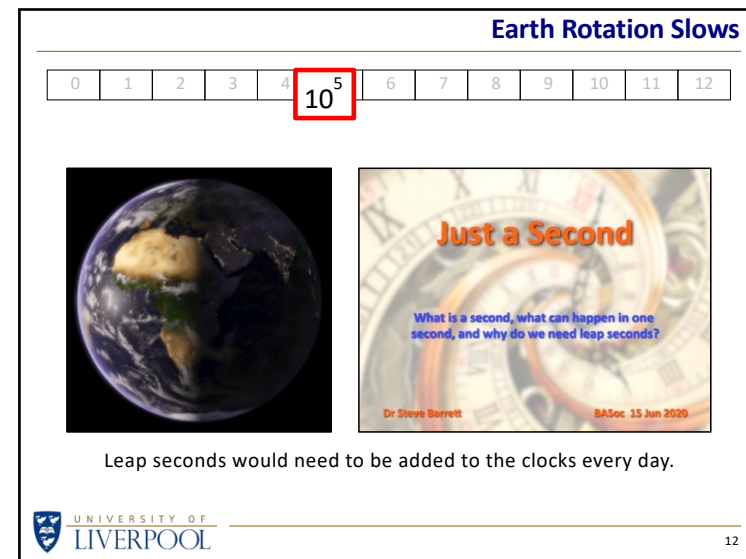
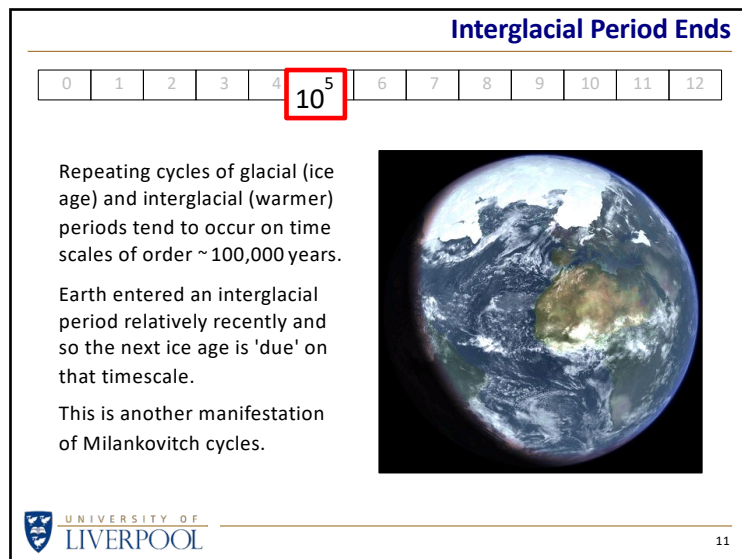
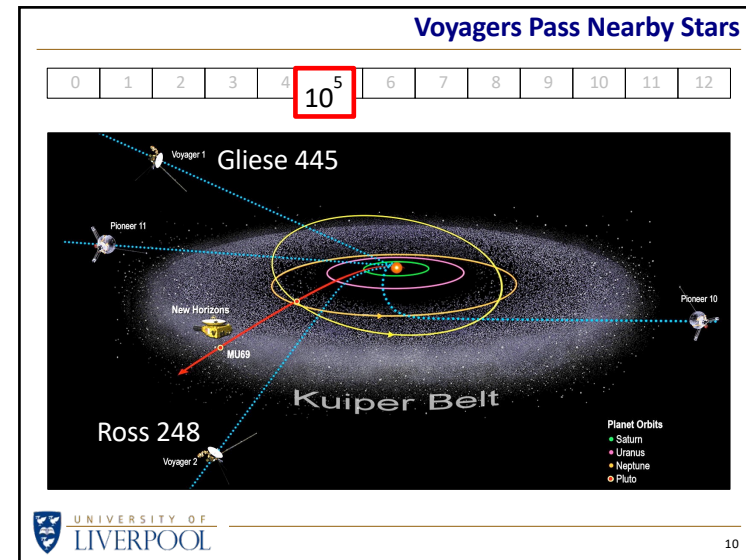
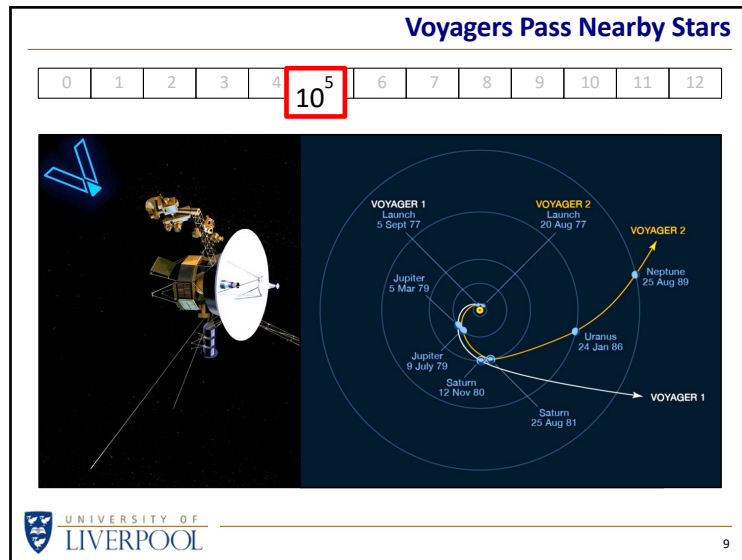


Vega Becomes the Pole Star



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.

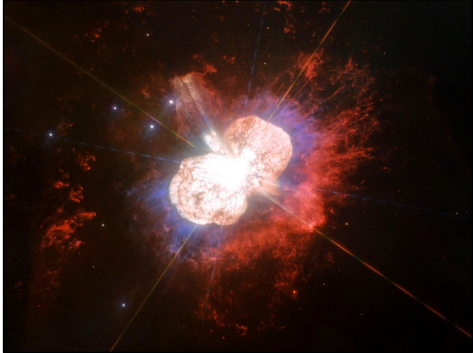
The End of Everything



The End of Everything

Eta Carinae Supernova

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




APOD 20 Feb 2019

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Betelgeuse Supernova

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



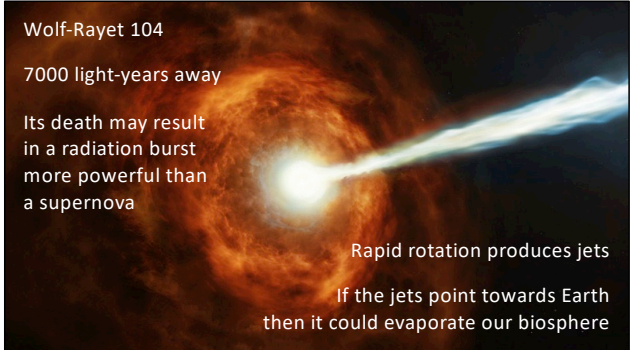
Petr Horálek Photography — Ondřejov Observatory, Prague

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Gamma-Ray Burst

0	1	2	3	4	10^5	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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Gliese 710 Passes By

0	1	2	3	4	5	10^6	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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The End of Everything

Gliese 710 Passes By

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

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



Meteor Crater

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



Apollo Footprints

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

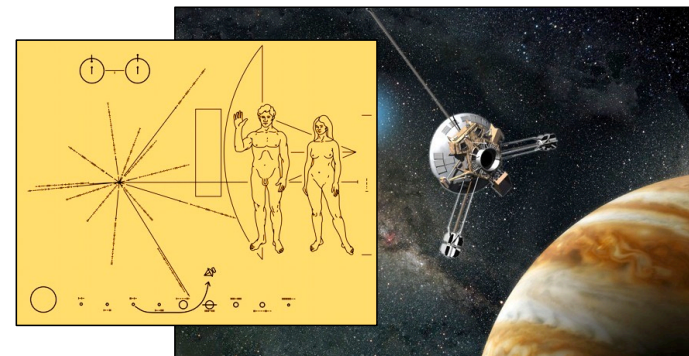
The Moon is
constantly
bombarded
with micro-
meteorites.

Eventually, all
evidence of
the Apollo
landings will
be erased.



Pioneer 10 Plaque


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




The End of Everything

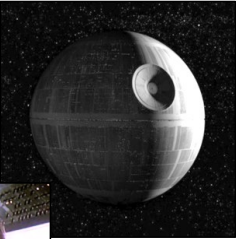
Saturn's Rings

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



Did the moon Mimas
make Saturn's rings?






21

Saturn's Rings

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

John Dubinski, Canadian Institute for Theoretical Astrophysics



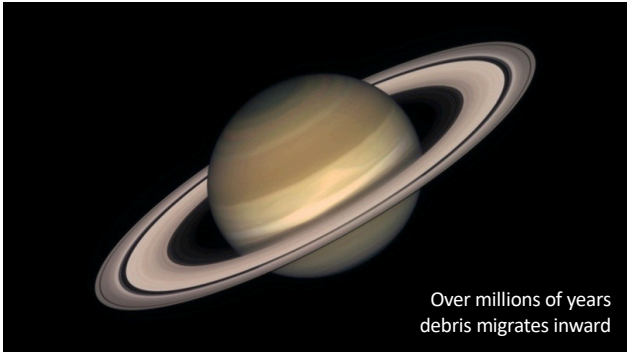
If a moon is smashed by a collision
with a comet, what would
happen to the debris?

22

Saturn's Rings

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

John Dubinski, Canadian Institute for Theoretical Astrophysics



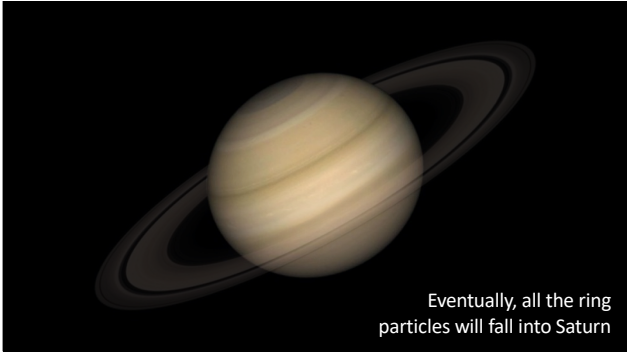
Over millions of years
debris migrates inward

23

Saturn's Rings

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

John Dubinski, Canadian Institute for Theoretical Astrophysics



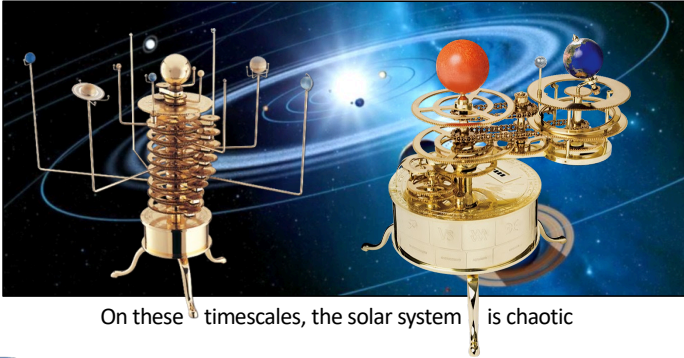
Eventually, all the ring
particles will fall into Saturn

24

The End of Everything

Solar System Unpredictable

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



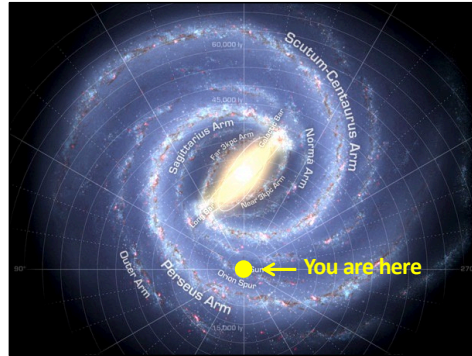
On these timescales, the solar system is chaotic

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Sun Moves Into Spiral Arm

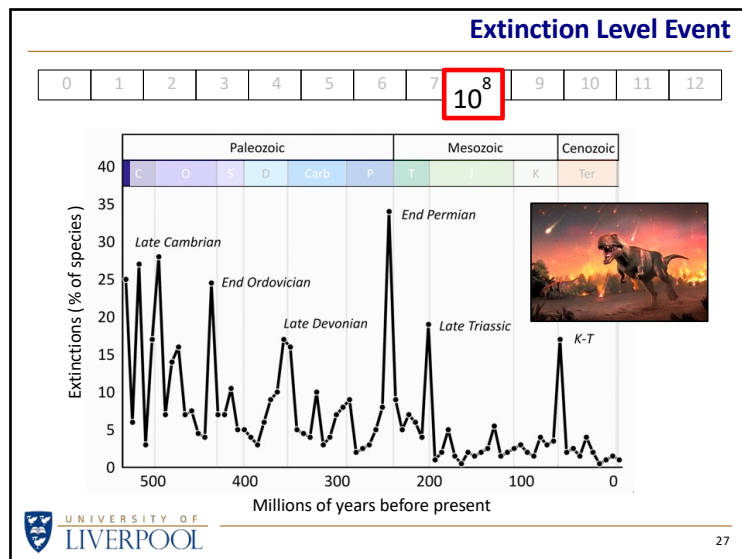
0	1	2	3	4	5	6	7	10 ⁸	9	10	11	12
---	---	---	---	---	---	---	---	-----------------	---	----	----	----



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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Extinction Level Event

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



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

Species will be exterminated.

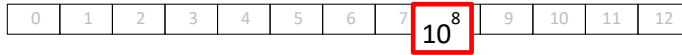
Will that include us?

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The End of Everything

Nearby Supernova

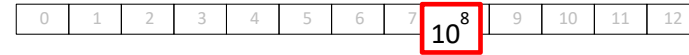


A supernova within 100 ly would be a danger to Earth

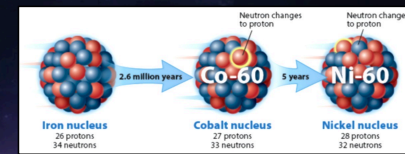


If less than 20 ly distant it might end all life on Earth

Nearby Supernova



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.

Distance to Moon Increases



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 ...

No More Total Solar Eclipses



Dr Steve Barrett



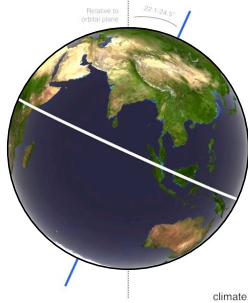
APOD 10 Feb 2020

The End of Everything

Earth Axis Tilt Unstable



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.

Voyager Gold Disc



Greenhouse Effect



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

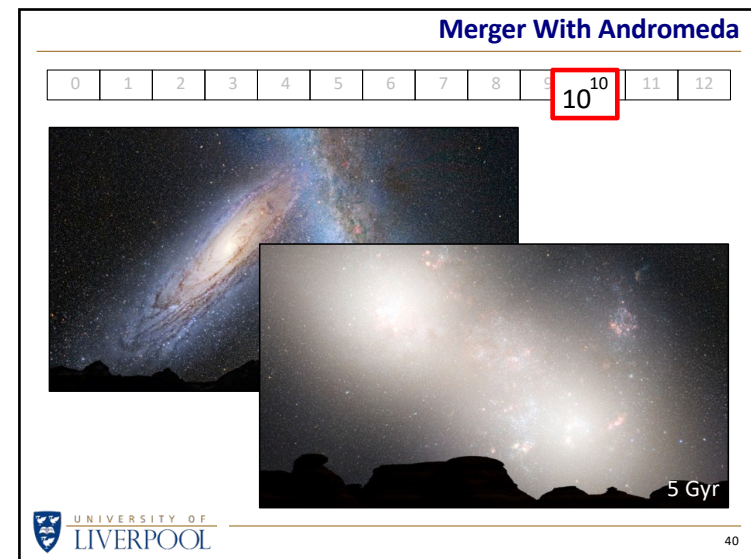
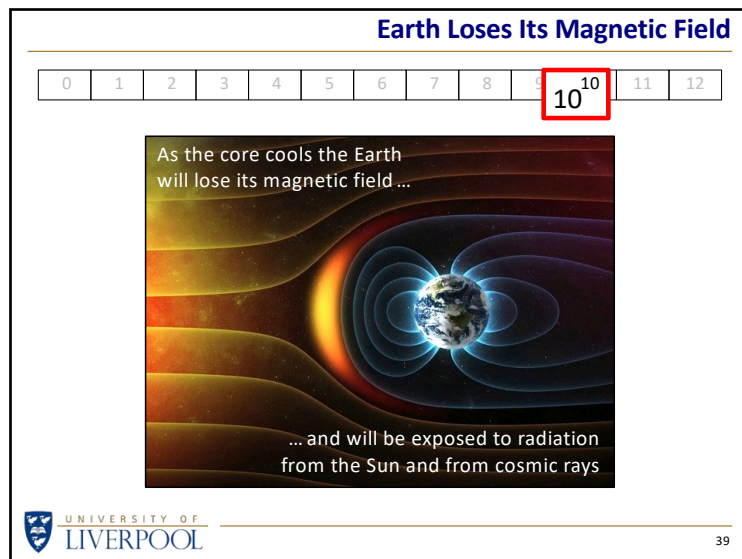
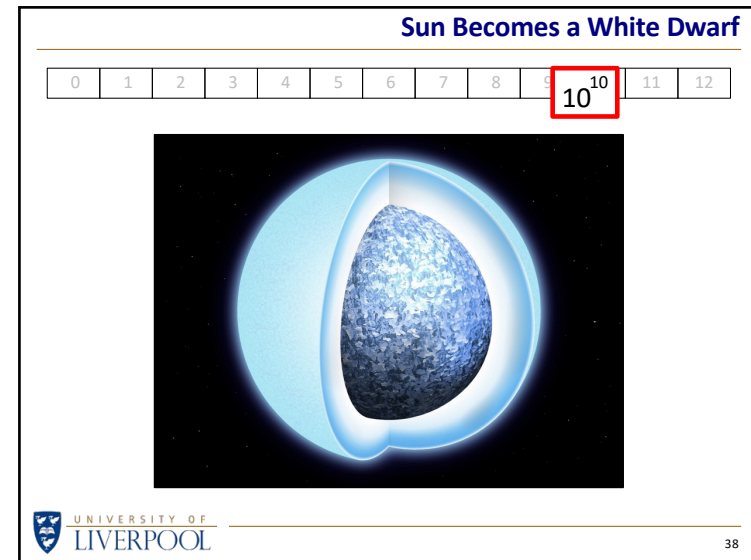
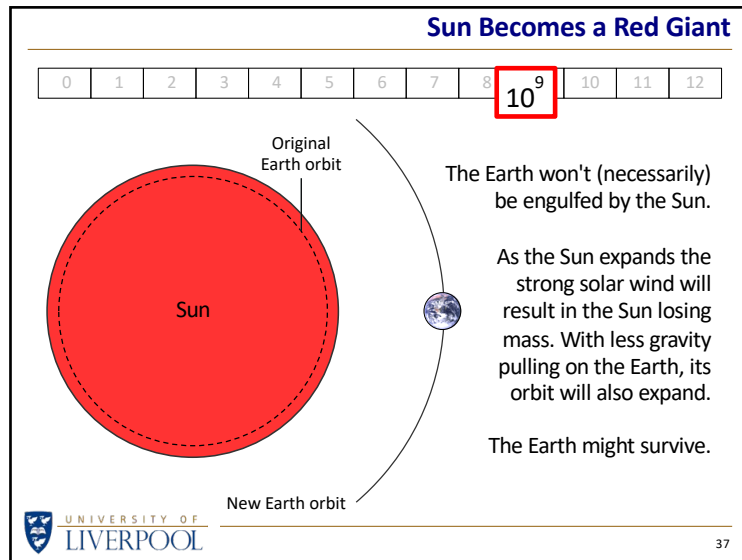
The greenhouse effect drives the surface of the Earth to a balmy 80°C .



Sun Becomes a Red Giant

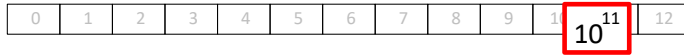


The End of Everything



The End of Everything

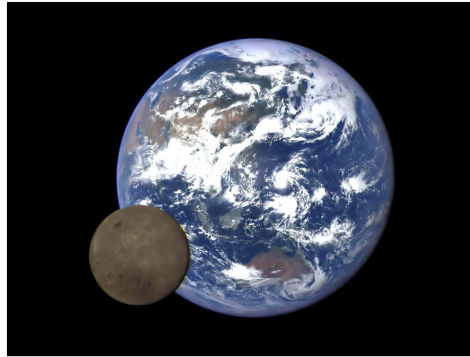
Earth Rotation Slows



1 day = 1 month

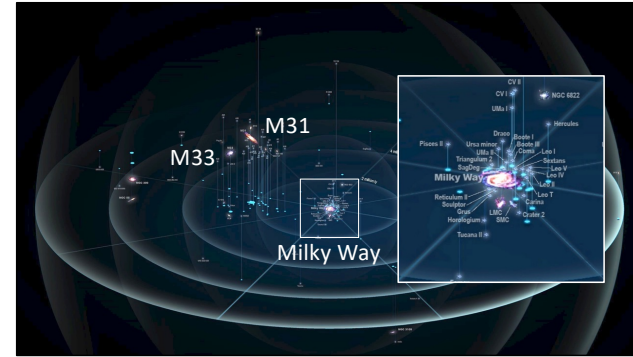
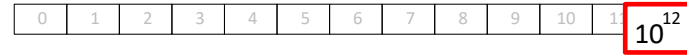
The Earth is now tidally locked to the Moon.

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

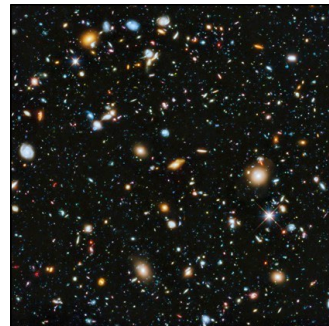
All Galaxies in Local Group Merge



Galaxies Move Beyond Our Horizon



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



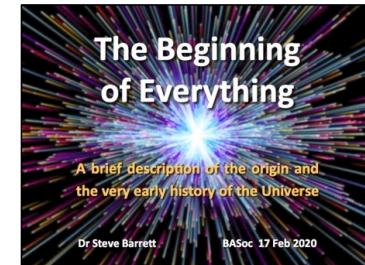
Hubble Ultra Deep Field

Universe Runs Out of Hydrogen



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.



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 $\sim 273\text{ K} = 0^\circ\text{ C}$.

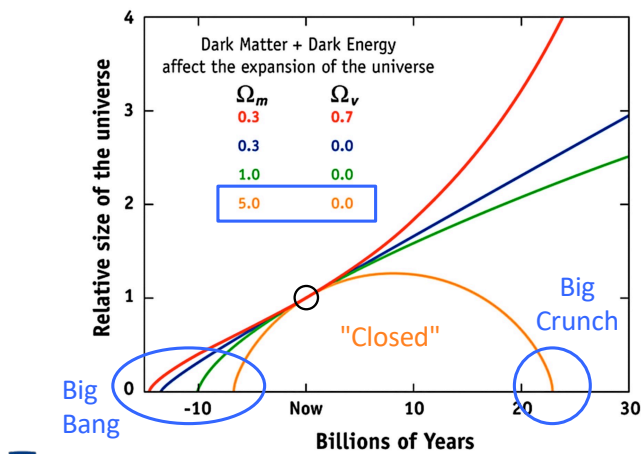
Frozen stars!

Cosmological Models

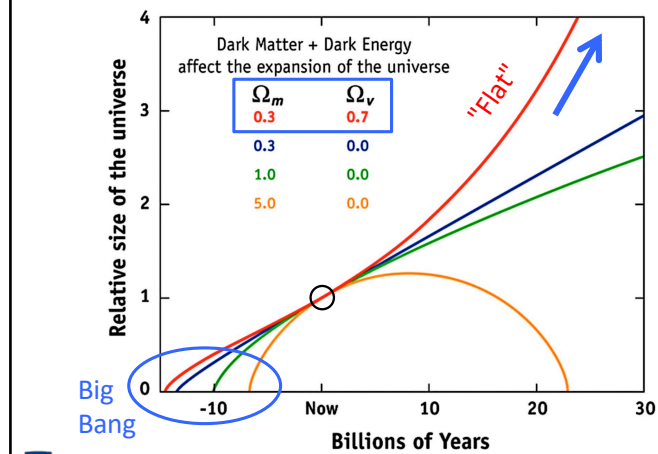
0 1 2 3 4 5 6 7 8 9 10 11 **10¹²**

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

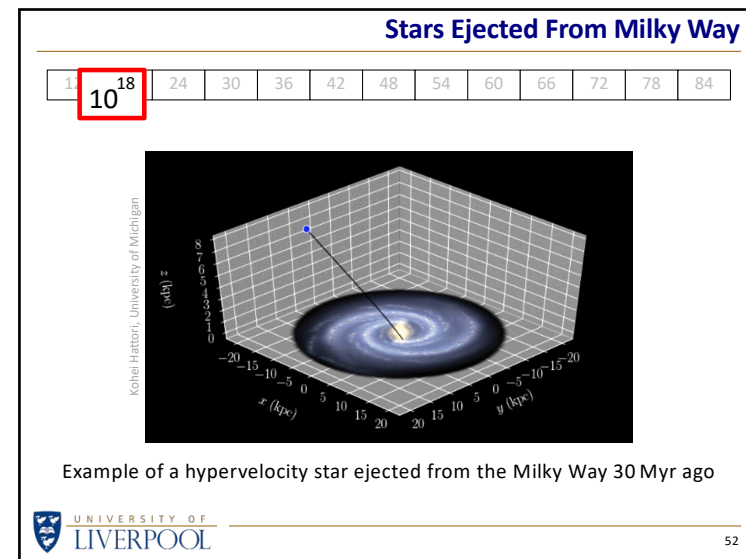
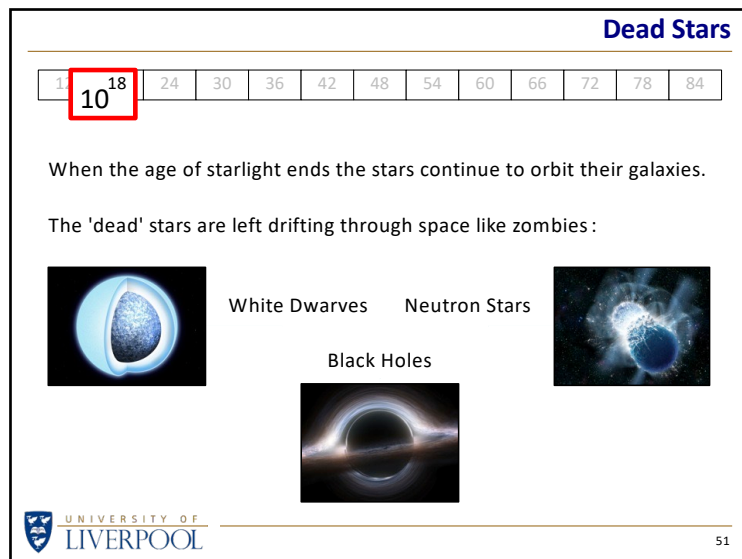
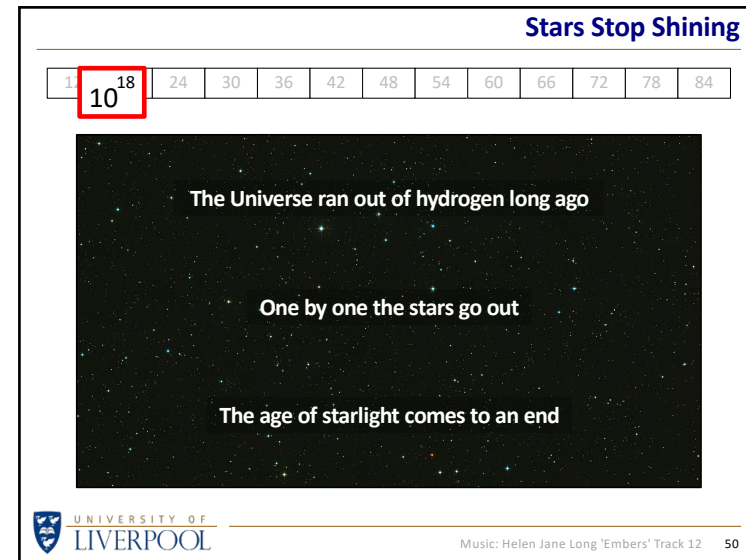
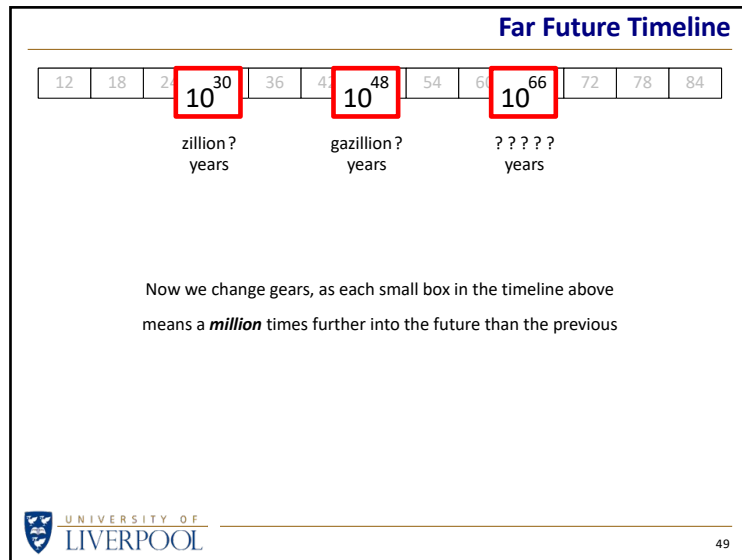
Cosmological Models



Cosmological Models



The End of Everything



The End of Everything

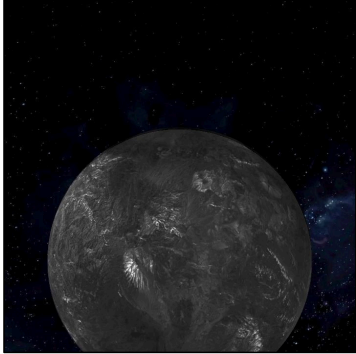
White Dwarf Stars Go Dark

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

10²⁴

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

Eventually they become black dwarves.



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SMBH Feed On Everything

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

10³⁰



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

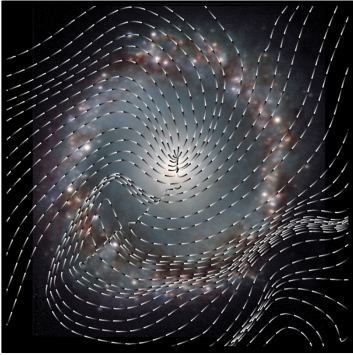
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SMBH Feed On Everything

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

10³⁰



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

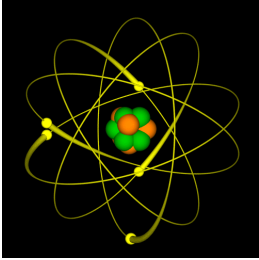
12	18	24	30	36	42	48	54	60	66	72	78	84
----	----	----	----	----	----	----	----	----	----	----	----	----

10³⁶

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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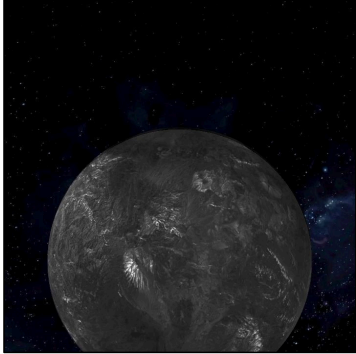
The End of Everything

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.

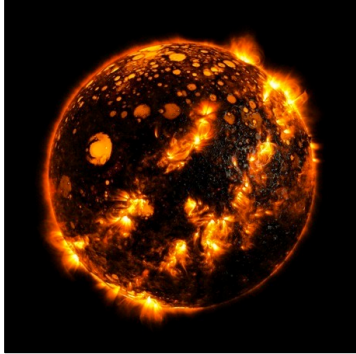


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Iron Stars

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 ... ?

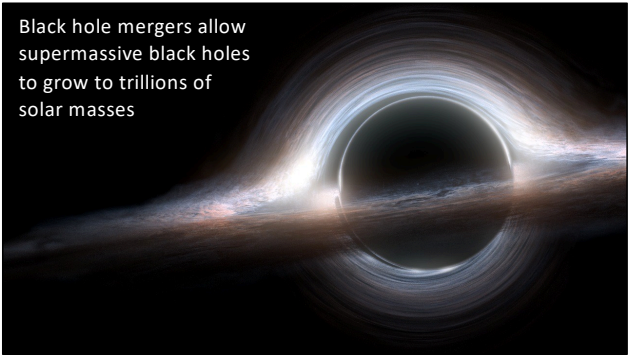
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SMBH Grow

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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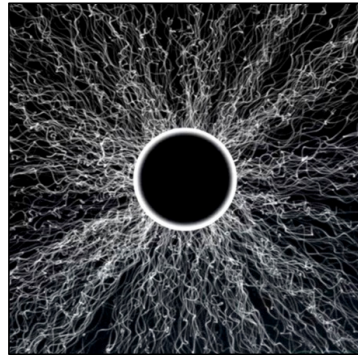
BH Evaporate

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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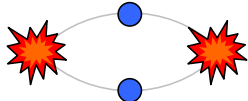
60

The End of Everything

BH Evaporate

12	18	24	30	36	42	48	54	60	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.



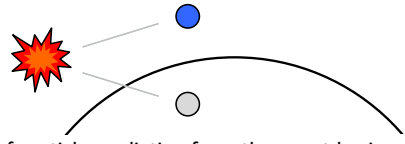
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BH Evaporate

12	18	24	30	36	42	48	54	60	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?



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	66	72	78	84
----	----	----	----	----	----	----	----	----	-----------	----	----	----

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



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SMBH Evaporate

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



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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
----	----	----	----	----	----	----	----	----	----	----	----	----

$$10^{100} = \text{Googol} \quad \left[\begin{array}{c} \text{No, not ...} \\ \text{Google} \end{array} \right]$$

After a googol years the last BH has evaporated.

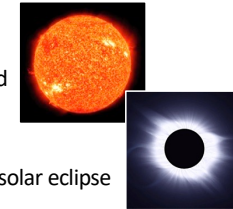
After this, **NOTHING** happens, and so time becomes ... meaningless.

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



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**



The End of Everything

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

Dr Steve Barrett

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