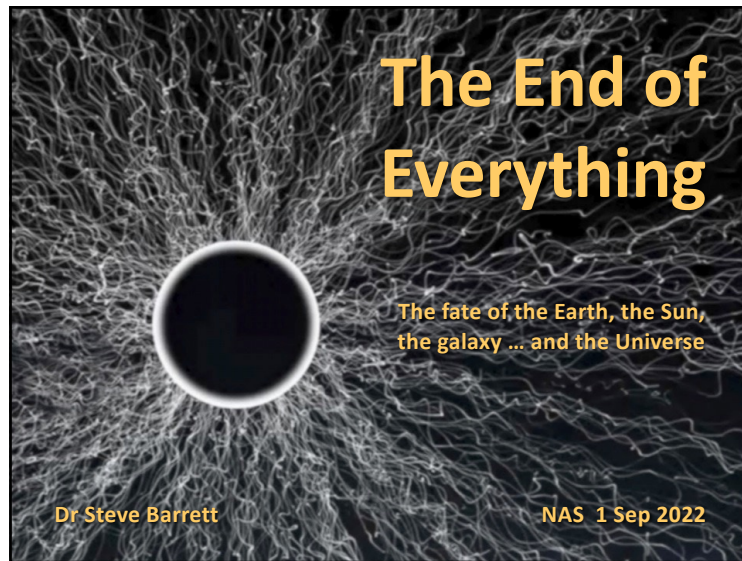


# The End of Everything



## 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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## 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 so protons outnumber neutrons in the ratio 7:1.

**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  $^4\text{He}$  = 1 nucleus of  $^{12}\text{C}$ .

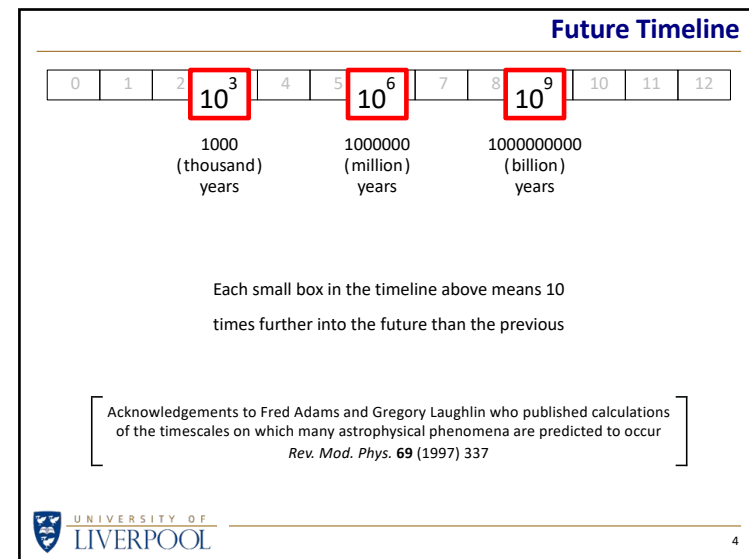
After 3 minutes, the relative abundance of H and He is determined.

**Cosmic Web**

The 'clumps' in the cosmic web are the sites of galaxy formation. The 'voids' are the sites of galaxy destruction.

**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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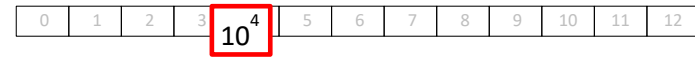
# The End of Everything

## Earth Rotation Slows

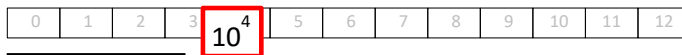


Leap seconds would need to be added to the clocks every few weeks.

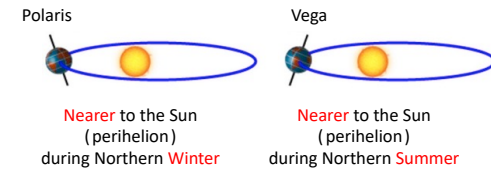
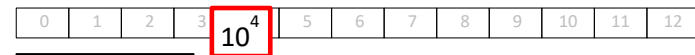
## Antares Supernova



## Vega Becomes the Pole Star

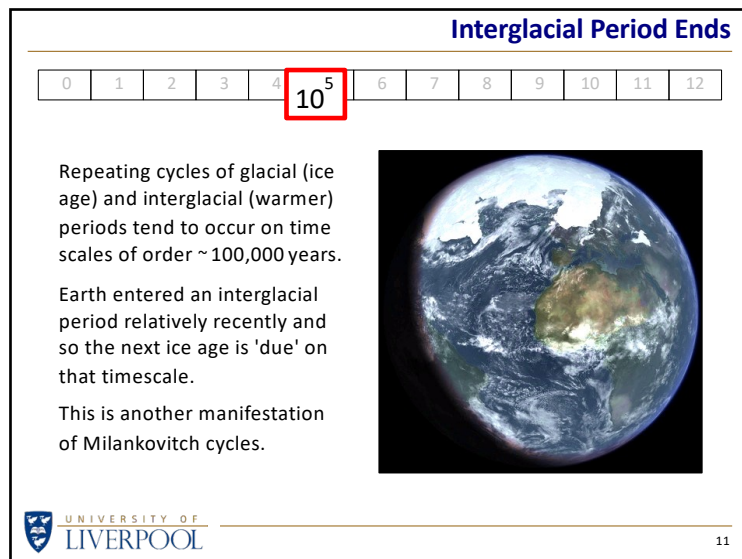
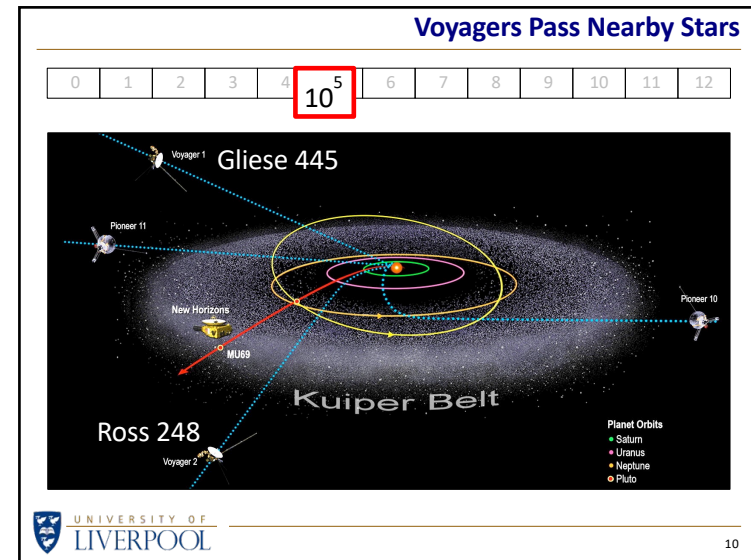
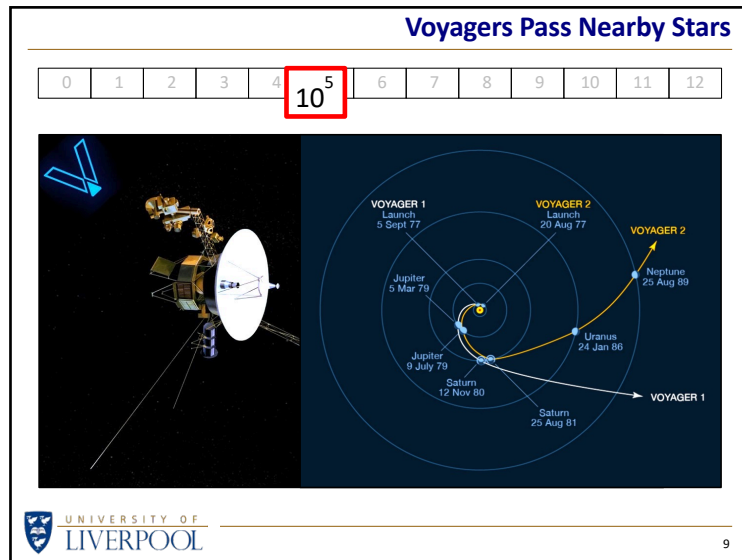


## Vega Becomes the Pole Star



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.

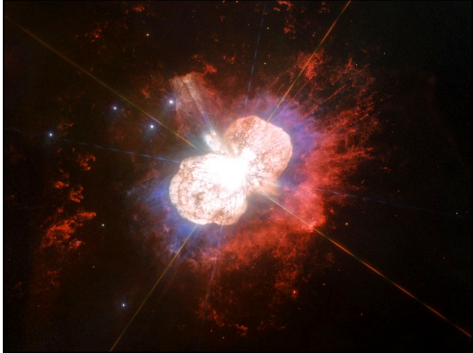
# The End of Everything



# The End of Everything

### Eta Carinae Supernova

0	1	2	3	4	<b><math>10^5</math></b>	6	7	8	9	10	11	12
---	---	---	---	---	--------------------------	---	---	---	---	----	----	----




APOD 20 Feb 2019

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### Betelgeuse Supernova

0	1	2	3	4	<b><math>10^5</math></b>	6	7	8	9	10	11	12
---	---	---	---	---	--------------------------	---	---	---	---	----	----	----



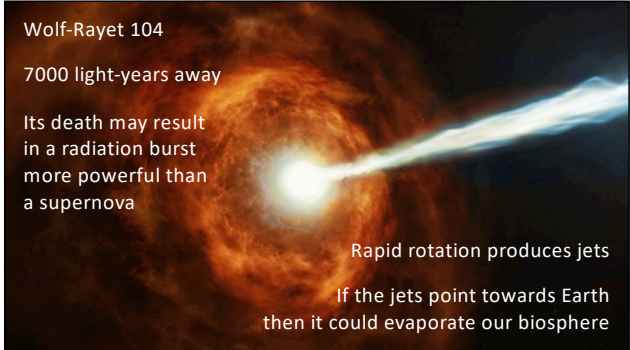
Petr Horálek Photography — Ondřejov Observatory, Prague

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### Gamma-Ray Burst

0	1	2	3	4	<b><math>10^5</math></b>	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	<b><math>10^6</math></b>	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

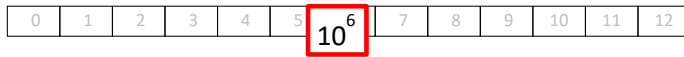
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# The End of Everything

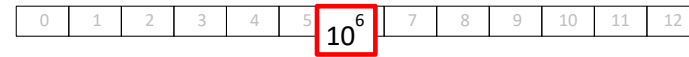
## Gliese 710 Passes By



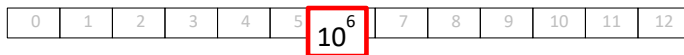
For a while, our solar system  
will have two suns, just like ...



## Meteor Crater



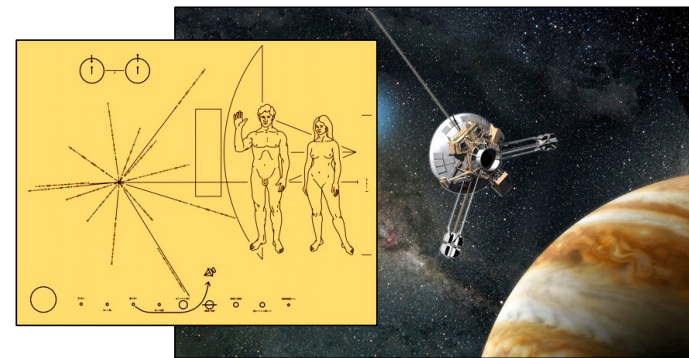
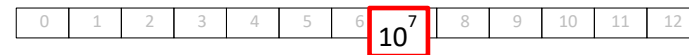
## Apollo Footprints



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




## Pioneer 10 Plaque




# The End of Everything

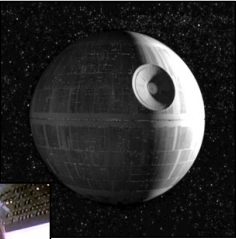
Saturn's Rings

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



Did the moon Mimas  
make Saturn's rings?






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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?

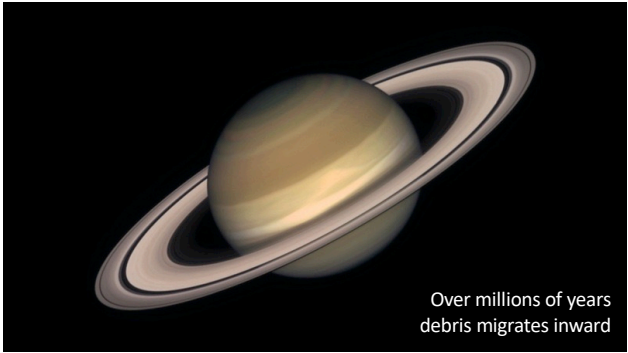
22

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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

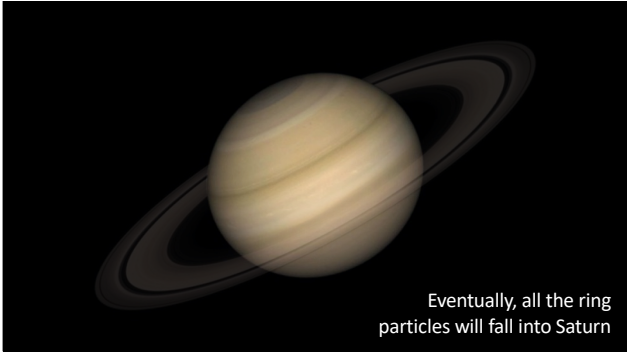
23

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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

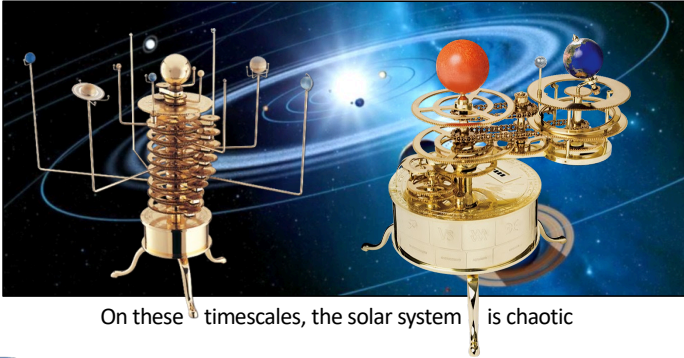
24

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# The End of Everything

## Solar System Unpredictable

0 1 2 3 4 5 6 7 **10<sup>8</sup>** 9 10 11 12



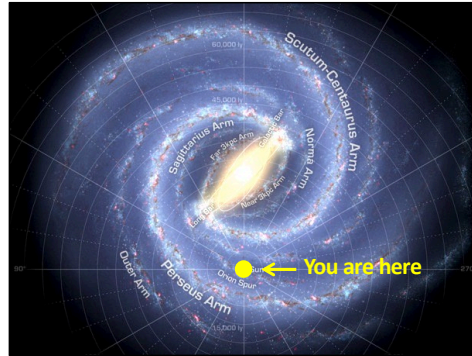
On these timescales, the solar system is chaotic

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## Sun Moves Into Spiral Arm

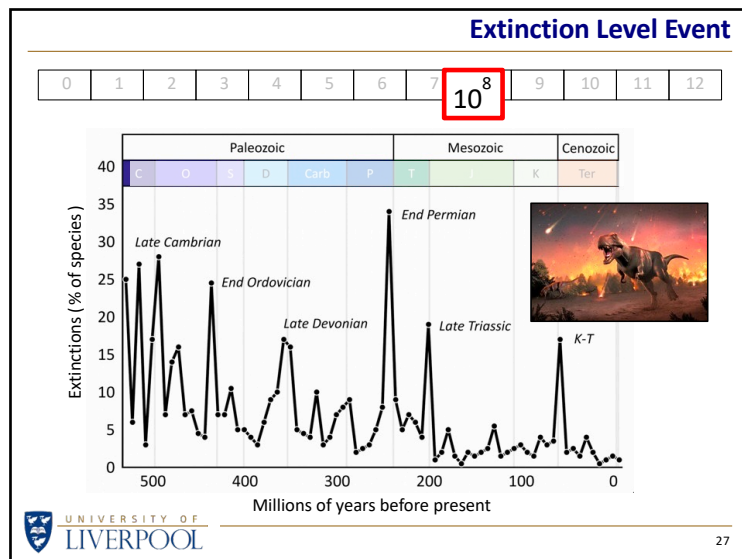
0 1 2 3 4 5 6 7 **10<sup>8</sup>** 9 10 11 12



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<sup>8</sup>** 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

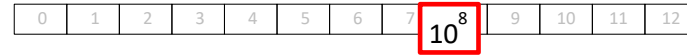


A supernova within 100 ly would be a danger to Earth

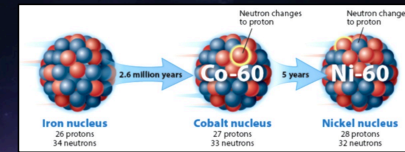


If less than 20 ly distant it might end all life on Earth

## Nearby Supernova



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



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

## Distance to Moon Increases

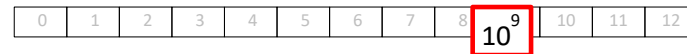


Through tidal friction, the Moon continues to rob the Earth of some of its angular momentum (spin) and increase the size of the Moon's orbit.

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

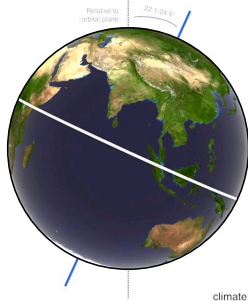


# The End of Everything

## 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

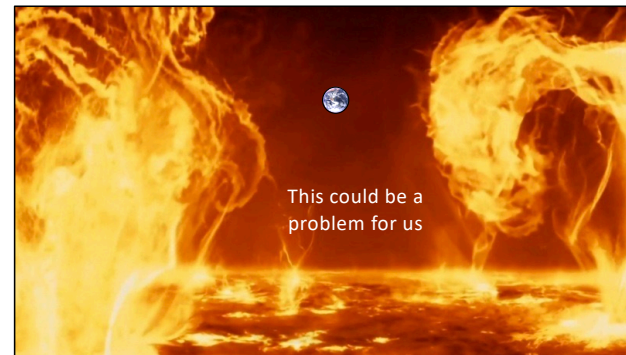


The Sun's luminosity slowly increases as it evolves and moves towards its Red Giant phase.

The greenhouse effect drives the surface of the Earth to a balmy  $80^\circ\text{C}$ .

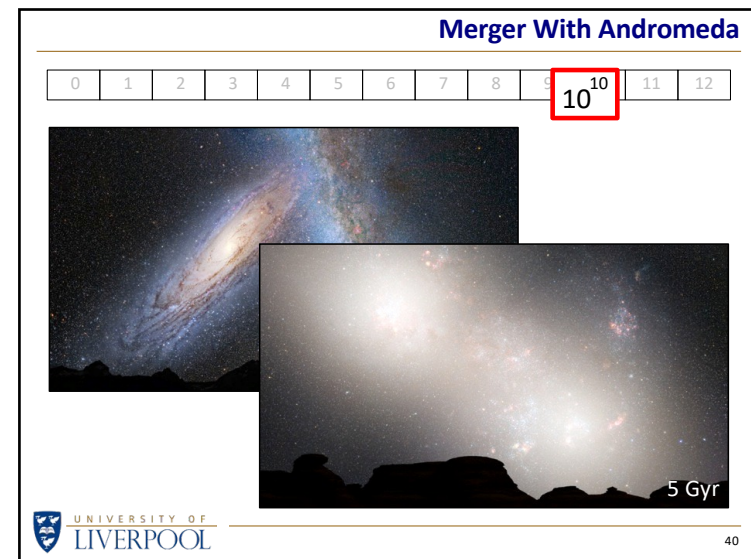
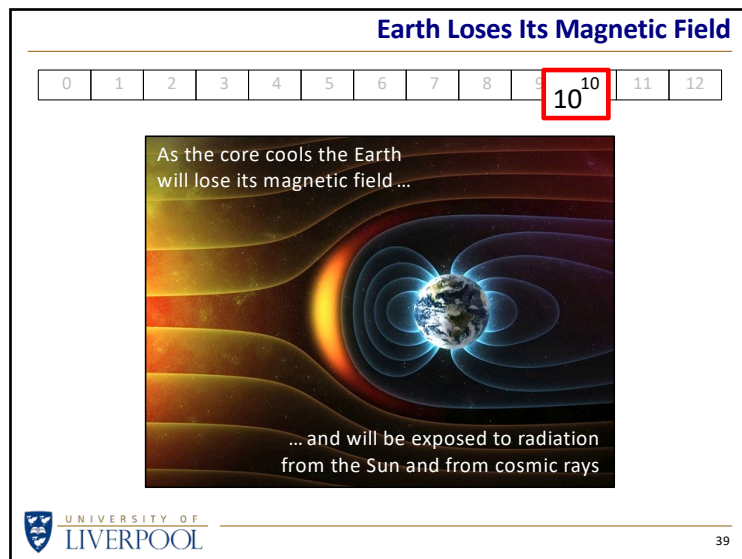
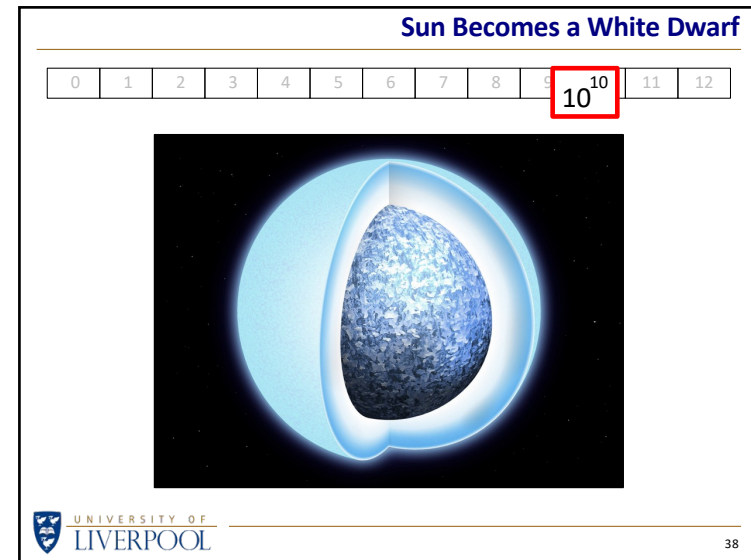
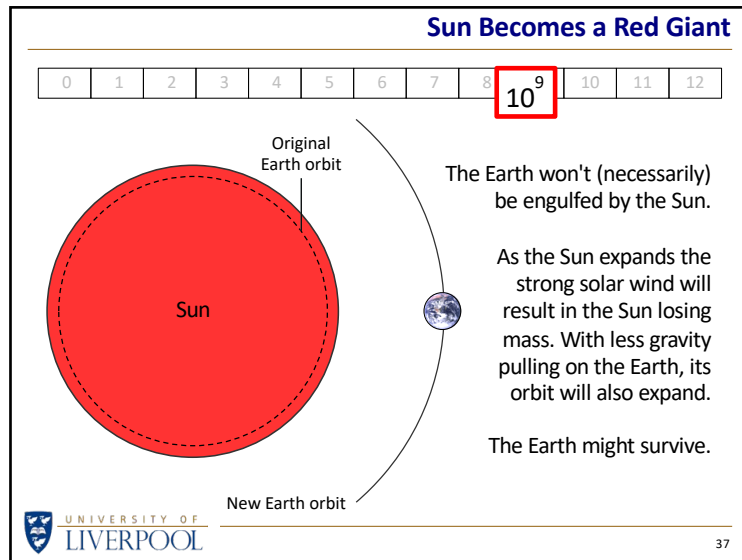


## Sun Becomes a Red Giant



This could be a problem for us

# The End of Everything



# The End of Everything

## Earth Rotation Slows



1 day = 1 month

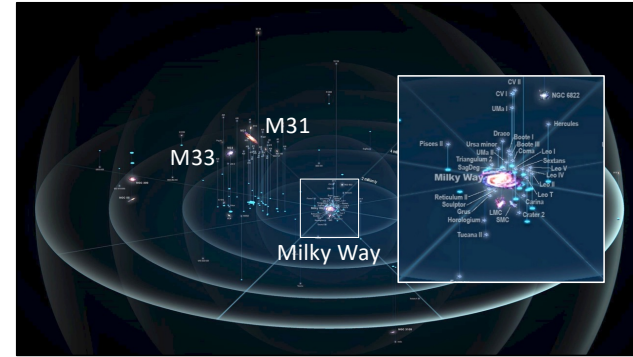
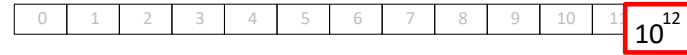
The Earth is now tidally locked to the Moon.

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

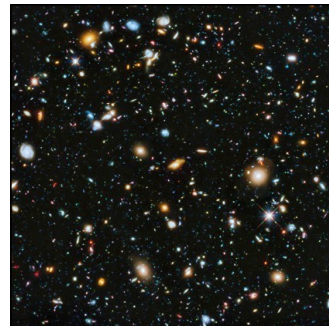
## All Galaxies in Local Group Merge



## Galaxies Move Beyond Our Horizon



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



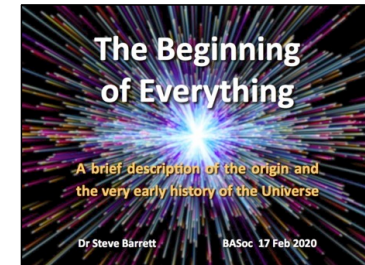
Hubble Ultra Deep Field

## 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 **10<sup>12</sup>**



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

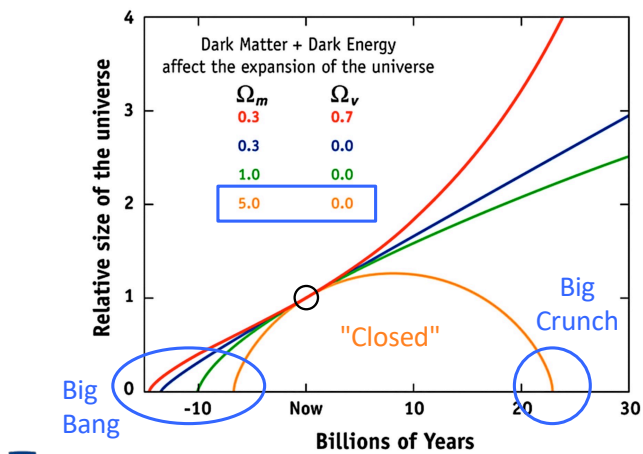
Frozen stars!

## Cosmological Models

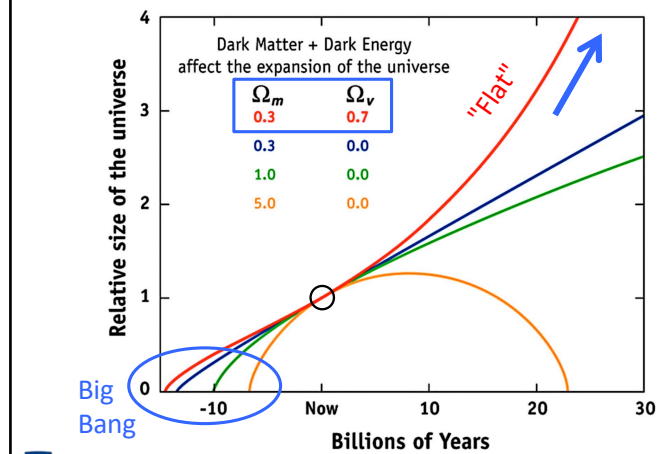
0 1 2 3 4 5 6 7 8 9 10 11 **10<sup>12</sup>**

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

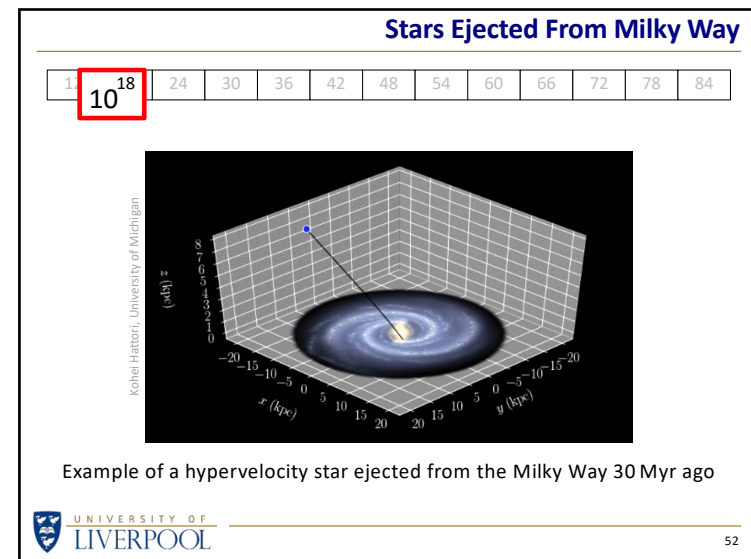
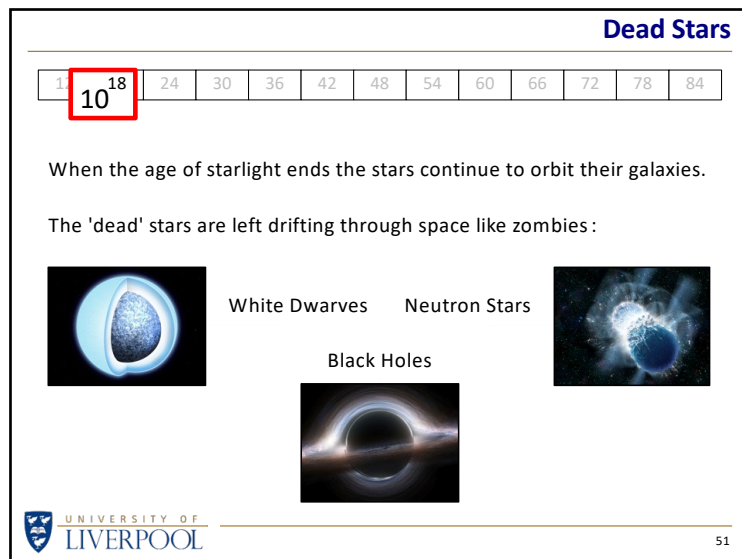
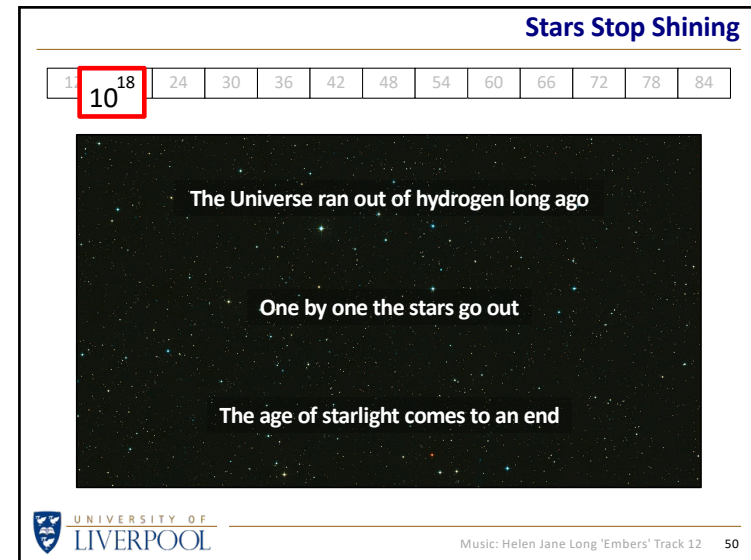
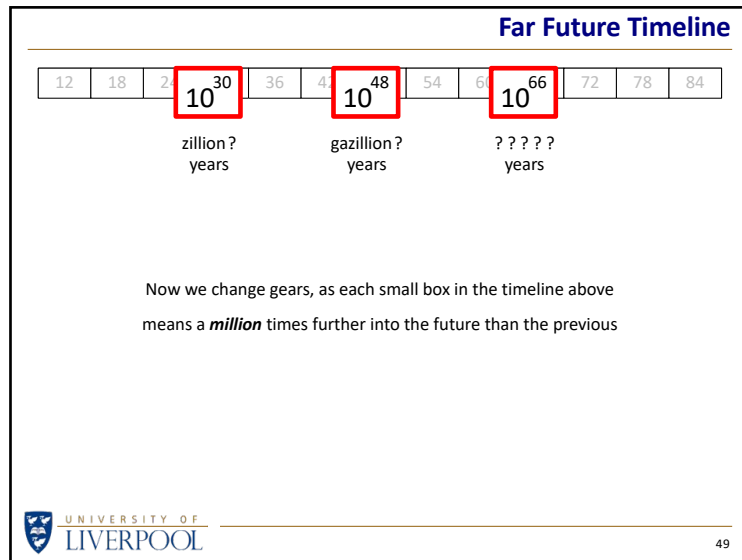
## Cosmological Models



## Cosmological Models



# The End of Everything



# The End of Everything

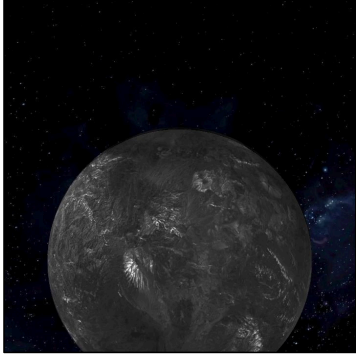
## White Dwarf Stars Go Dark

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

10<sup>24</sup>

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

10<sup>30</sup>



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

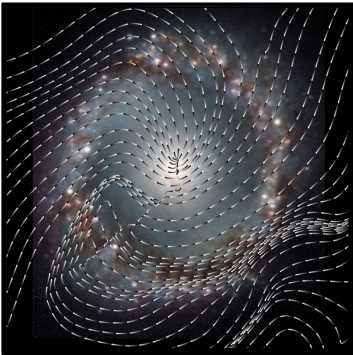
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## SMBH Feed On Everything

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

10<sup>30</sup>



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

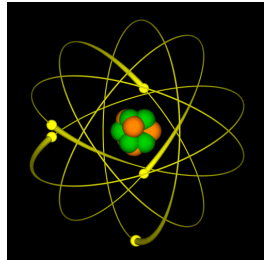
12	18	24	30	36	42	48	54	60	66	72	78	84
----	----	----	----	----	----	----	----	----	----	----	----	----

10<sup>36</sup>

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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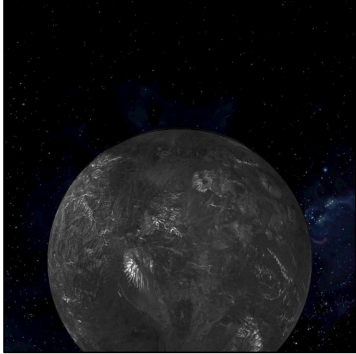
# The End of Everything

## Black Dwarf Stars Evaporate

12	18	24	30	36	<b>10<sup>42</sup></b>	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.

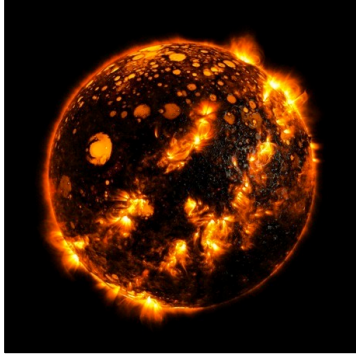


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## Iron Stars

12	18	24	30	36	<b>10<sup>42</sup></b>	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 ... ?

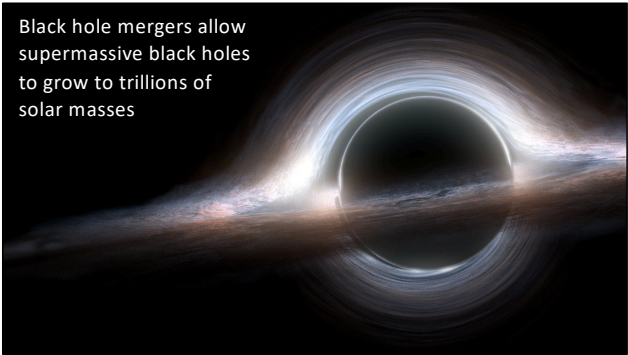
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## SMBH Grow

12	18	24	30	36	42	48	<b>10<sup>54</sup></b>	60	66	72	78	84
----	----	----	----	----	----	----	------------------------	----	----	----	----	----

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



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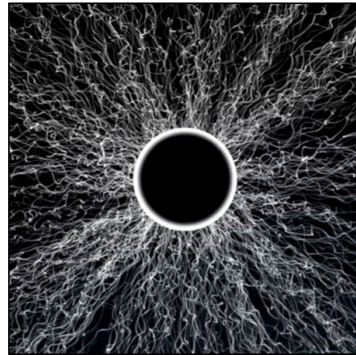
## BH Evaporate

12	18	24	30	36	42	48	54	60	<b>10<sup>66</sup></b>	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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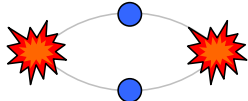
60

# 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.



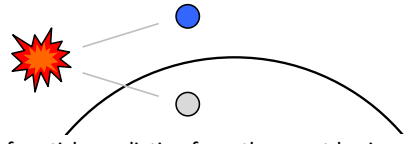
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**BH Evaporate**

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?



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	$10^{66}$	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	$10^{84}$
----	----	----	----	----	----	----	----	----	----	----	----	-----------

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.



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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.

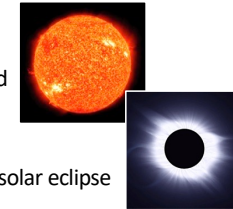
After this, **NOTHING** happens, and so time becomes ... meaningless.

## 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](http://www.liverpool.ac.uk/~sdb/Talks)

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