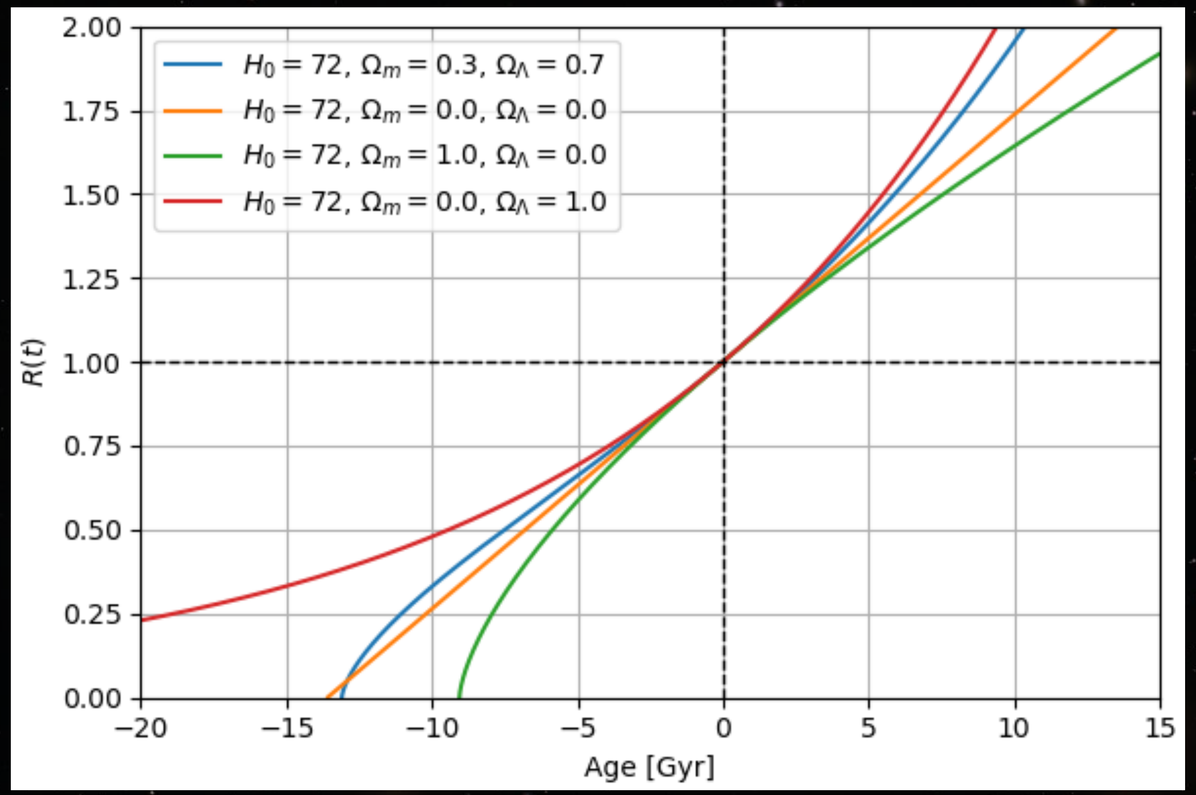
The Future of the Universe

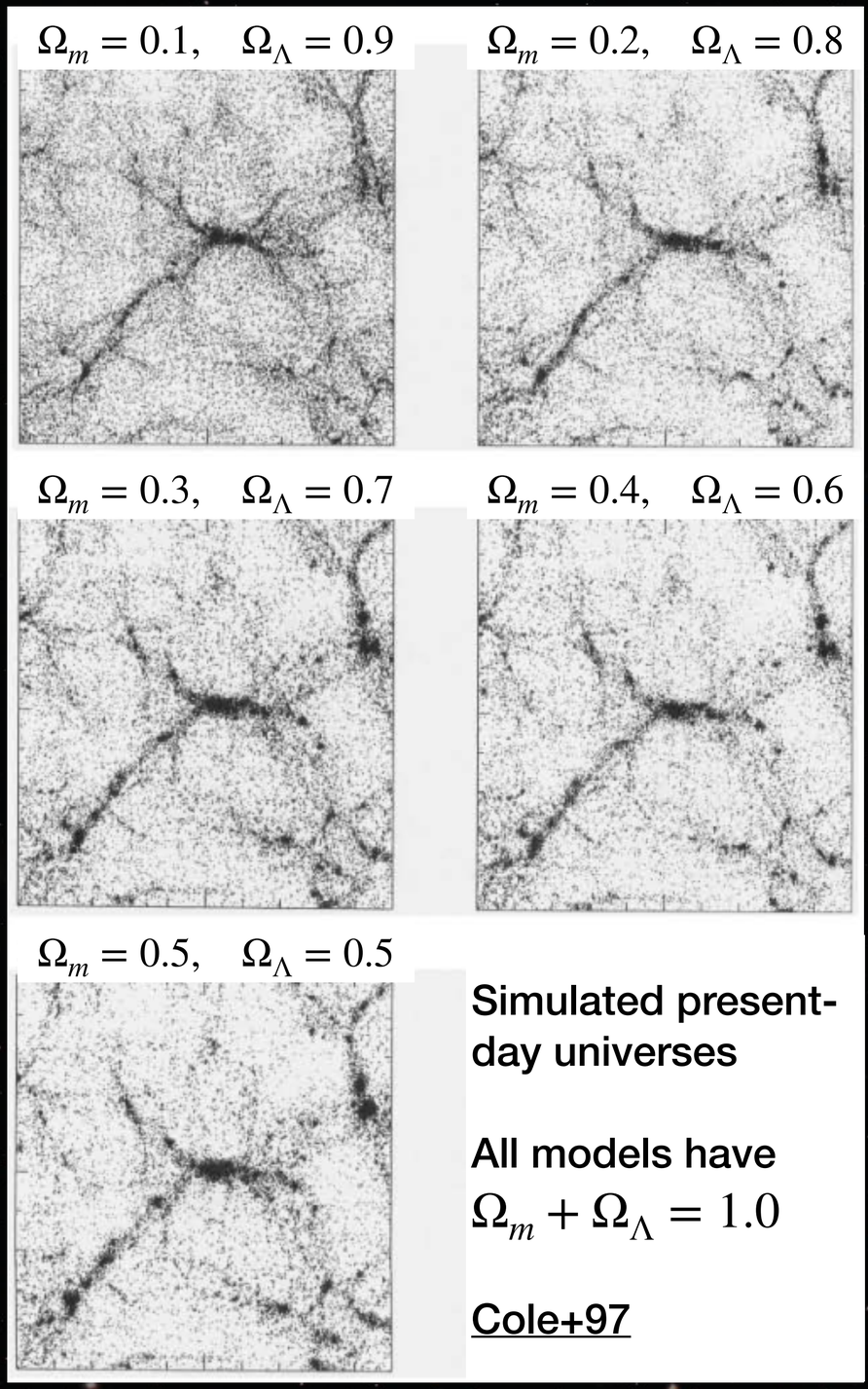
aka Everything, Everywhere All At Once

Structure Formation… stops?

Remember that under various cosmological models, we expect structure formation to slow down and stop

But at late times, in a Λ-dominated universe, the scale factor increases exponentially, so matter is separating faster than gravity can assemble it!





Simulated present-day universes

All models have $\Omega_m + \Omega_\Lambda = 1.0$

Cole+97

We can’t see anything else?

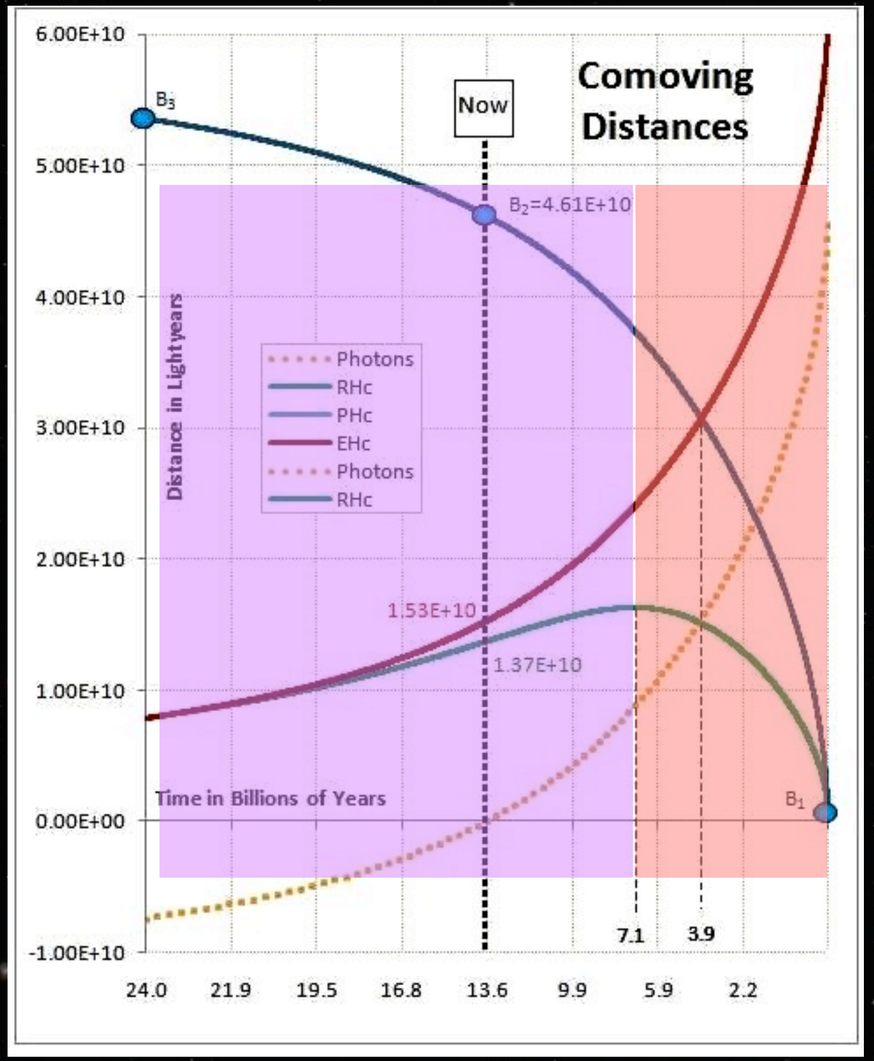
The most distant object we can see is limited by the speed of light and the age of the universe: a photon that takes longer than the age of the universe to reach us will *never* be visible

At z=0, the proper distance to the horizon is about 14.6 Gpc (blue line)

In the matter-dominated era, the horizon distance increases faster than the scale factor, so more and more of the universe comes into view

In the Λ-dominated era, the horizon distance increases exponentially, but so does the scale factor! Everything that will *ever* be visible is contained in a present proper distance of ~19 Gpc

As time goes by, regions closer to us will be accelerated out of our horizon!

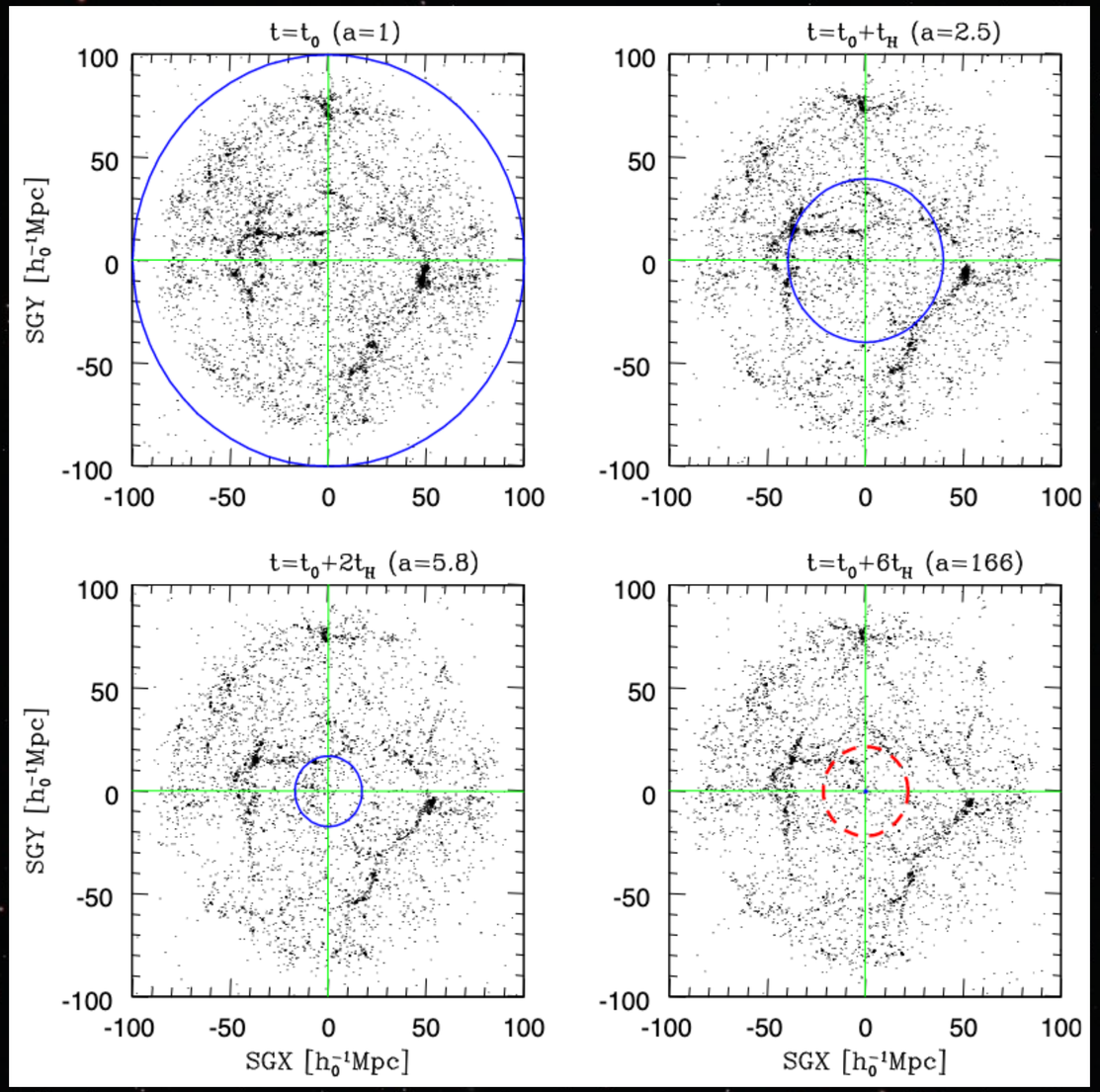


We will see less and less?

As structure formation slows down, Λ dominates, and the horizon shrinks, we will see less and less of the universe!

Notes:

- Coordinate system is comoving, so structure doesn't appear to expand. Instead, the blue circle shows a physical radius of ~140 Mpc
- "a" is what we have called R
- Red circle at late times shows the horizon distance of ~5 Gpc
- Structure is done forming by 2 Hubble times (a=5.8)
- Structure is expanding out of our horizon



Nagamine & Loeb (2003)

The Future of Cosmology

Let’s imagine you’re a cosmologist when the universe is 100 Gyr old. What will you be studying?

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The Microwave Background?

At 100 Gyr, $R(t) \sim 200$, so $T_{\rm CMB} \sim 0.015$ K. The CMB will be:

- Redshifted to 1 meter wavelengths (radio!)
- Dimmer by a factor of $\sim 10^{12}$

At even later times (500 Gyr), the CMB is redshifted to frequencies where it will be scattered by the ISM, making it invisible!

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By 100 Gyr, even the Virgo Cluster will have moved out of our horizon. No large scale structure will be visible!

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The Expansion History of the Universe?

Nope. The density of local galaxies is very small, and not really conducive to measuring the Hubble expansion. Plus, many of the galaxies will have fallen into the Local Group and not be participating in the expansion

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Light elements will have been processed by generations of star formation. No ability to measure primordial abundances at high redshift. No CMB to compare to or even motivate the comparison!

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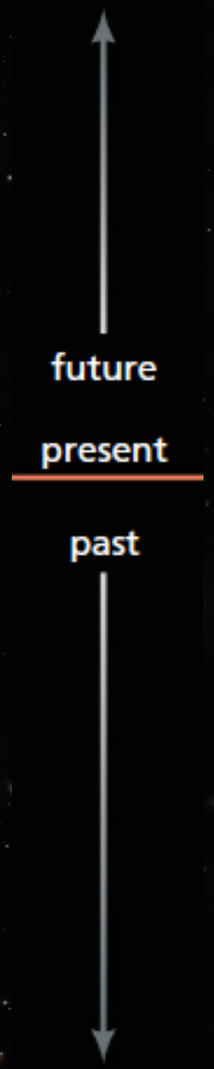
Basically, no cosmology!

The End of the Universe

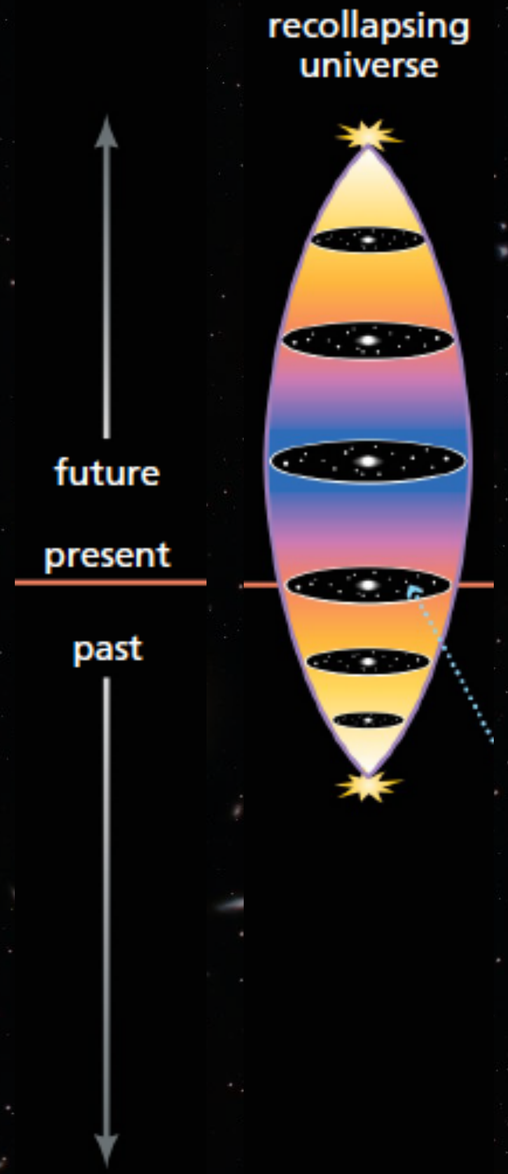


The End of the Universe

“The Big Crunch”

If $\Omega > 1$, then the Universe is closed and the Big Crunch will happen:

At some point in the future, the Universe will stop expanding and begin contracting. All matter and spacetime will collapse into a singularity!



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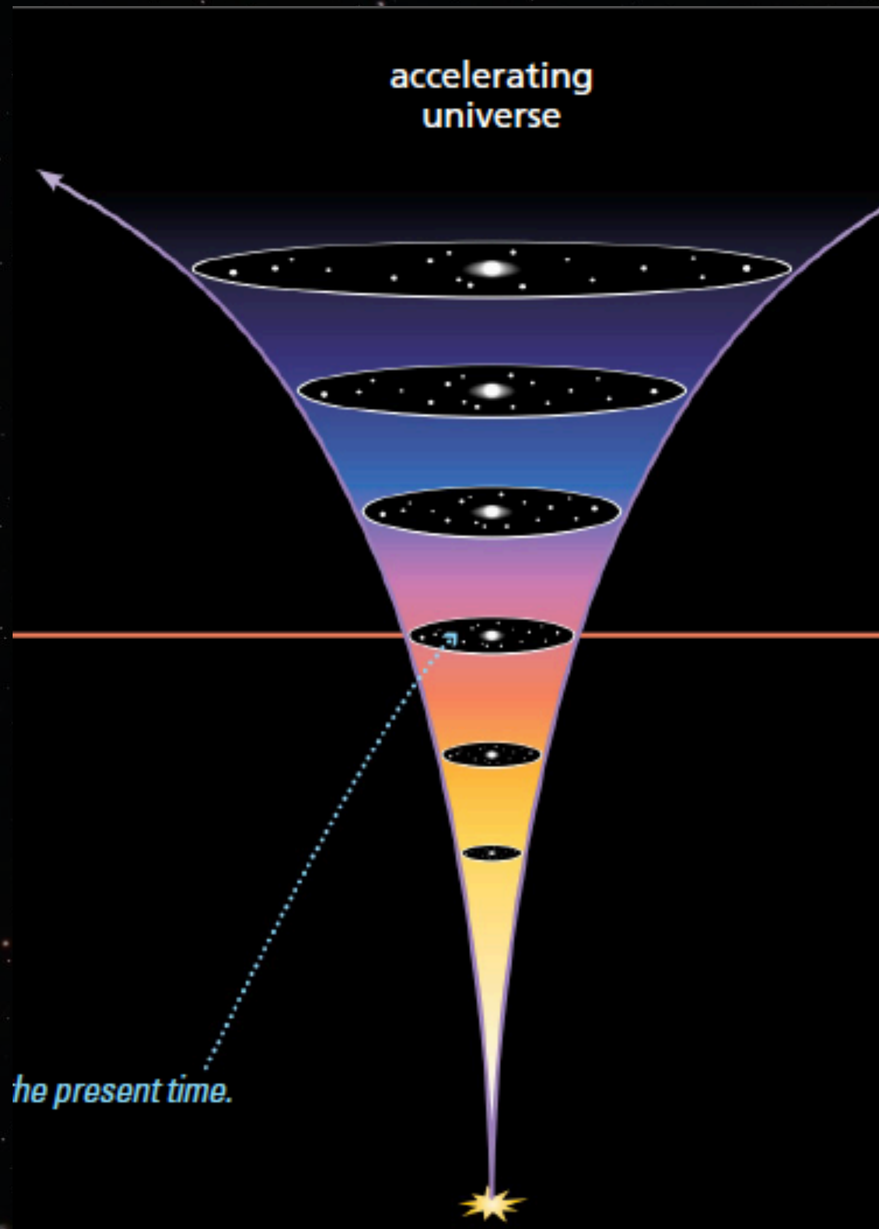

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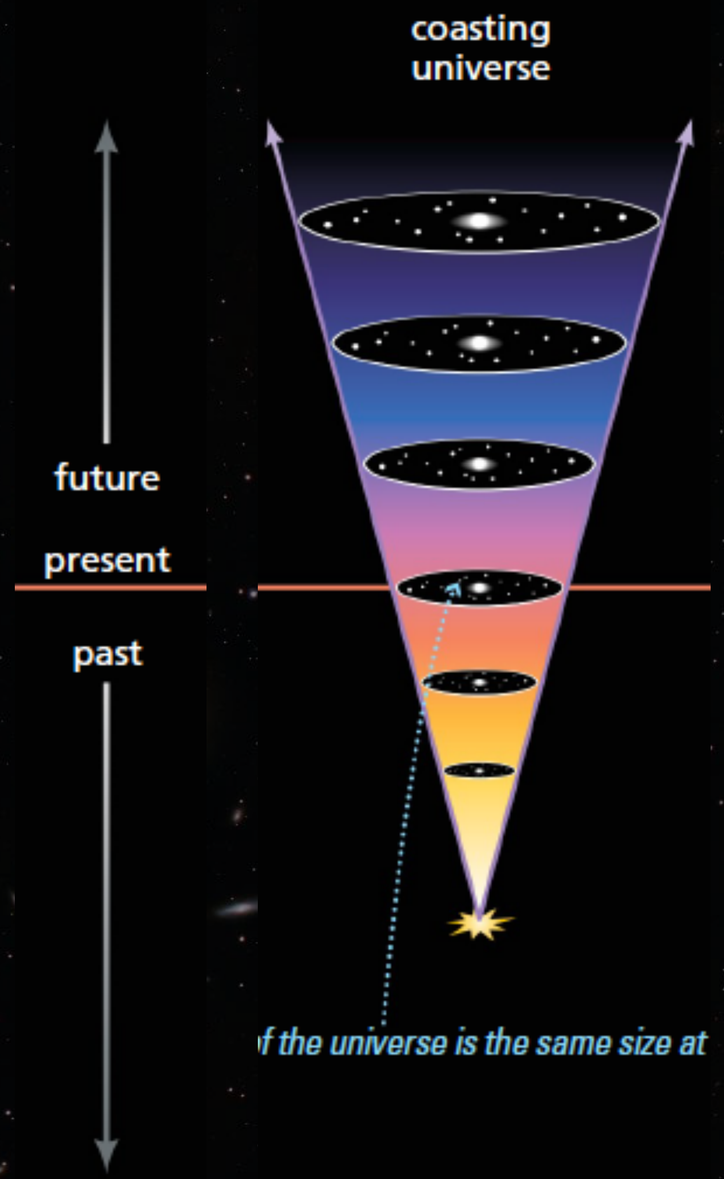
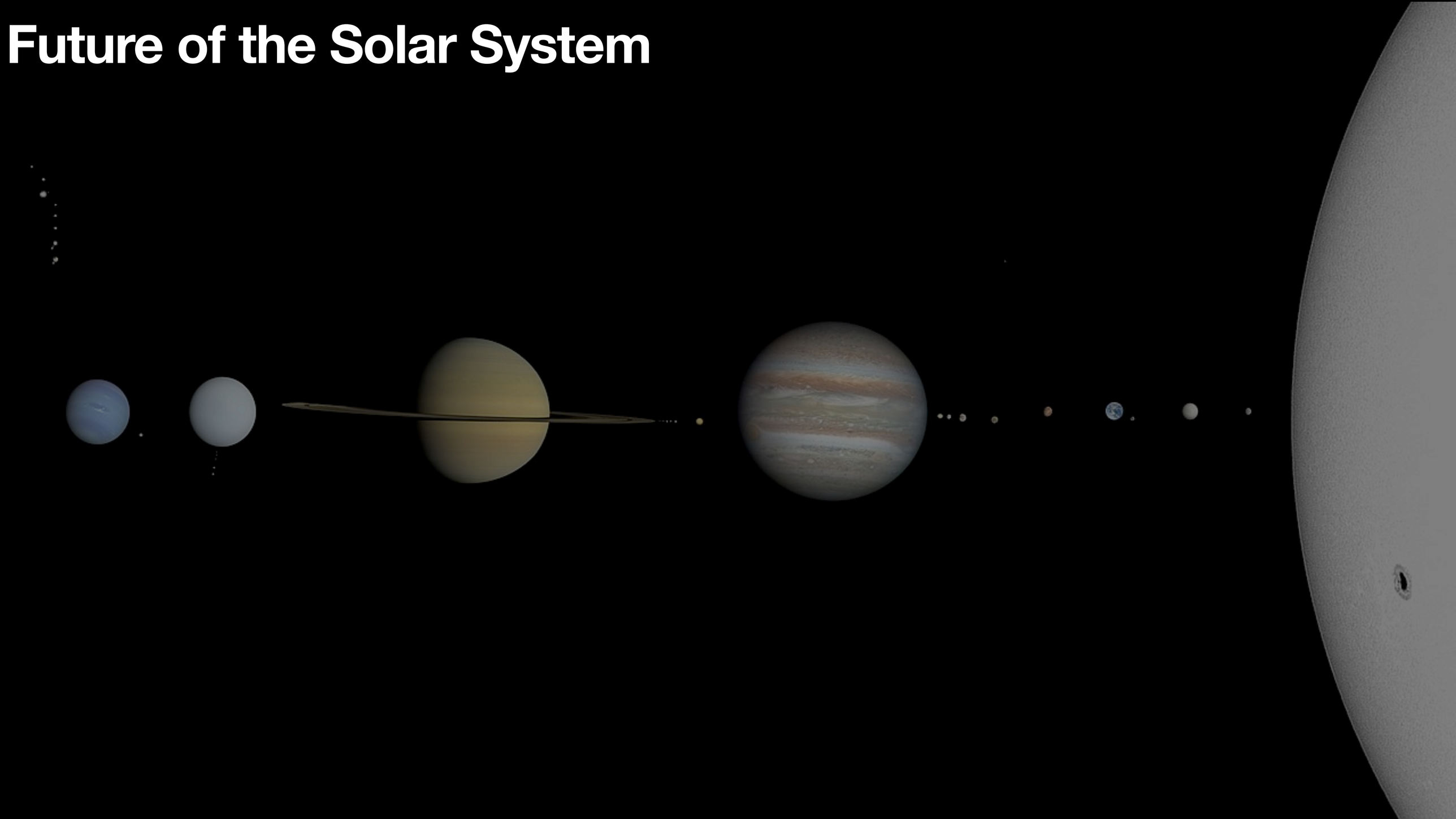
“The Big Freeze”

If $\Omega = 1$, then the Universe is flat and the Big Freeze will happen:

Also known as “heat death”, stars will form normally for trillions of years, but eventually the gas will be exhausted. As stars die out, the Universe will grow darker and darker, nothing happening for the rest of time.

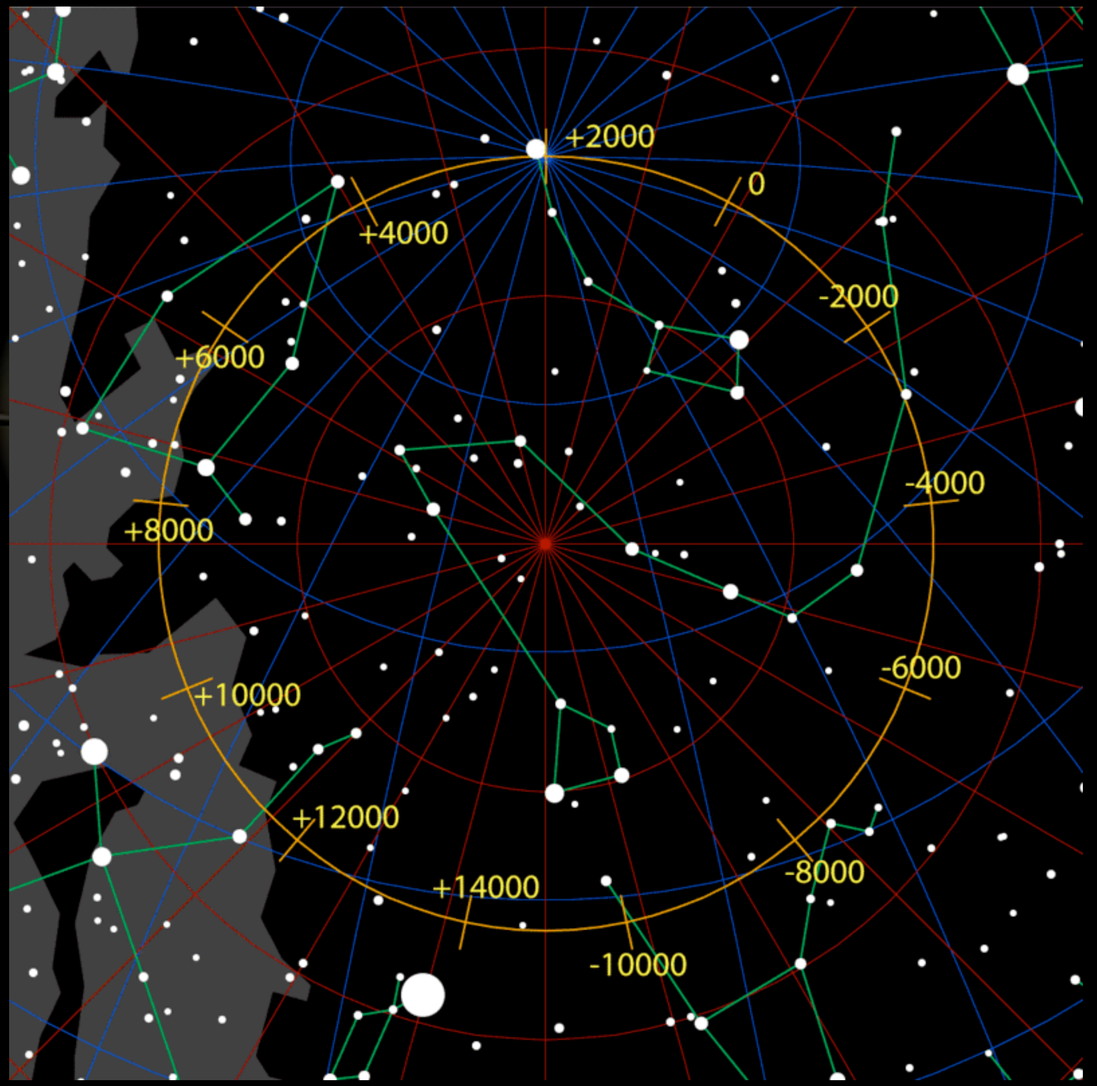


Future of the Solar System



Future of the Solar System

1.1 kyr Gamma Cephei replaces Polaris as the north pole star



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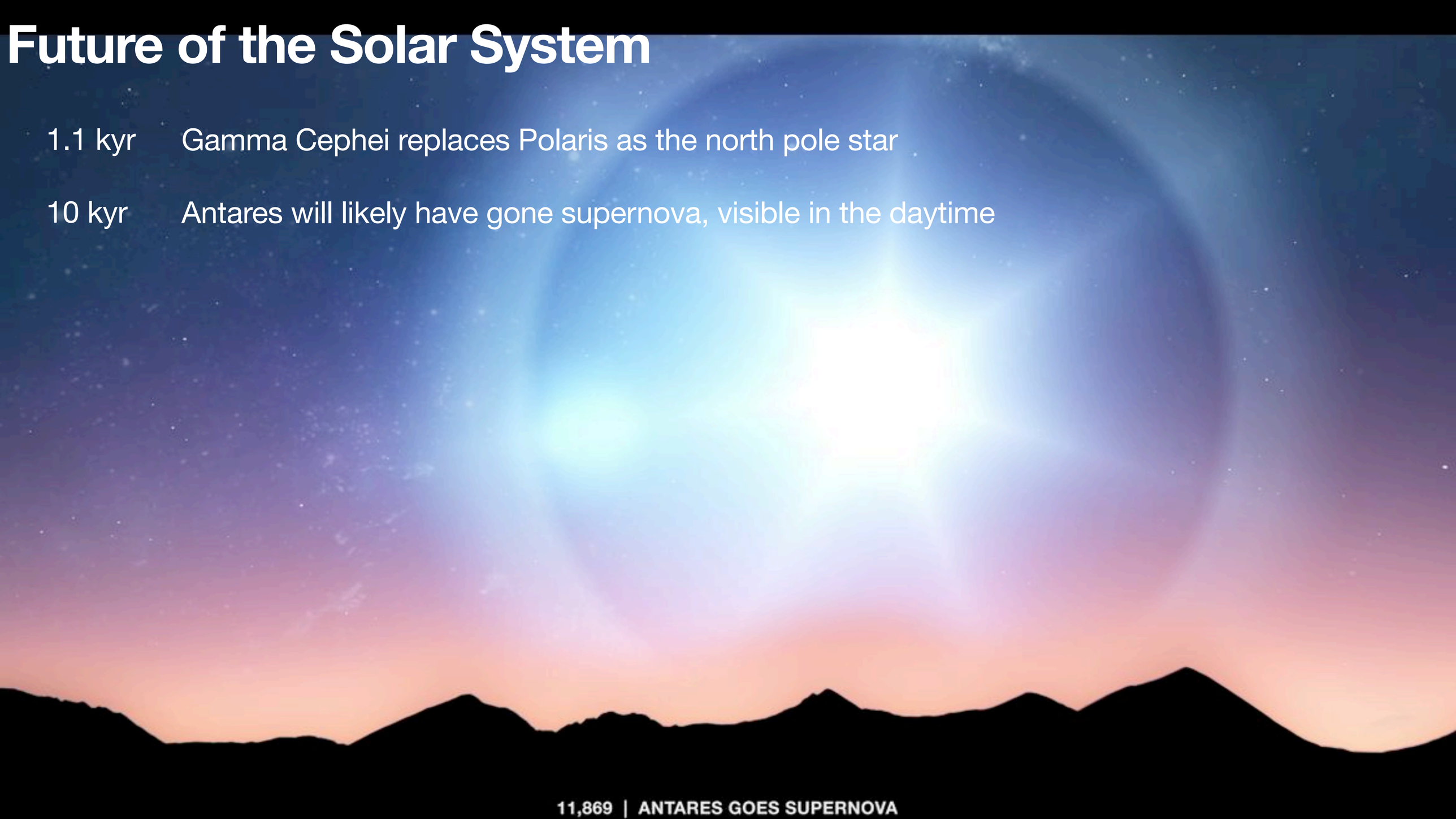

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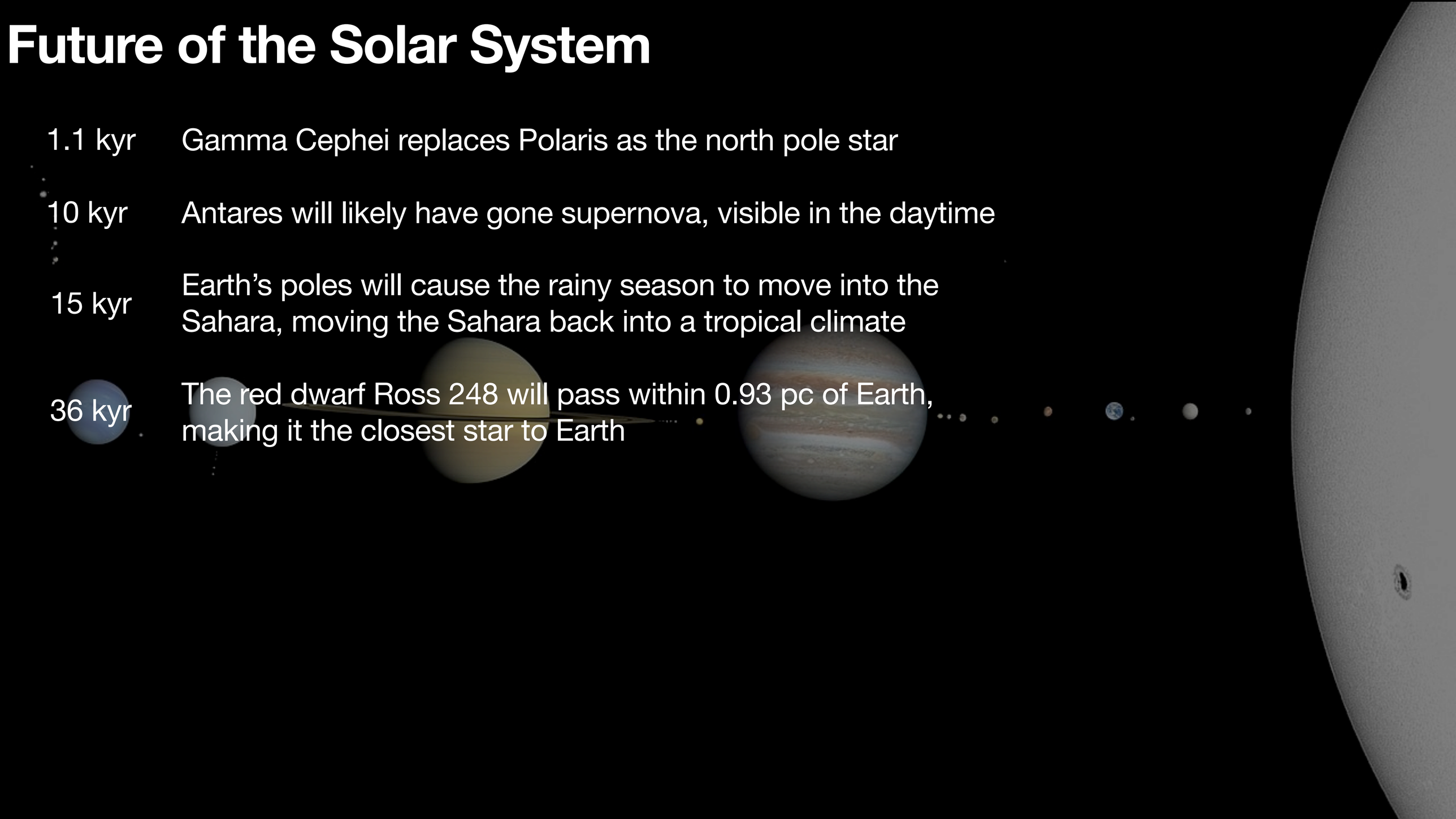

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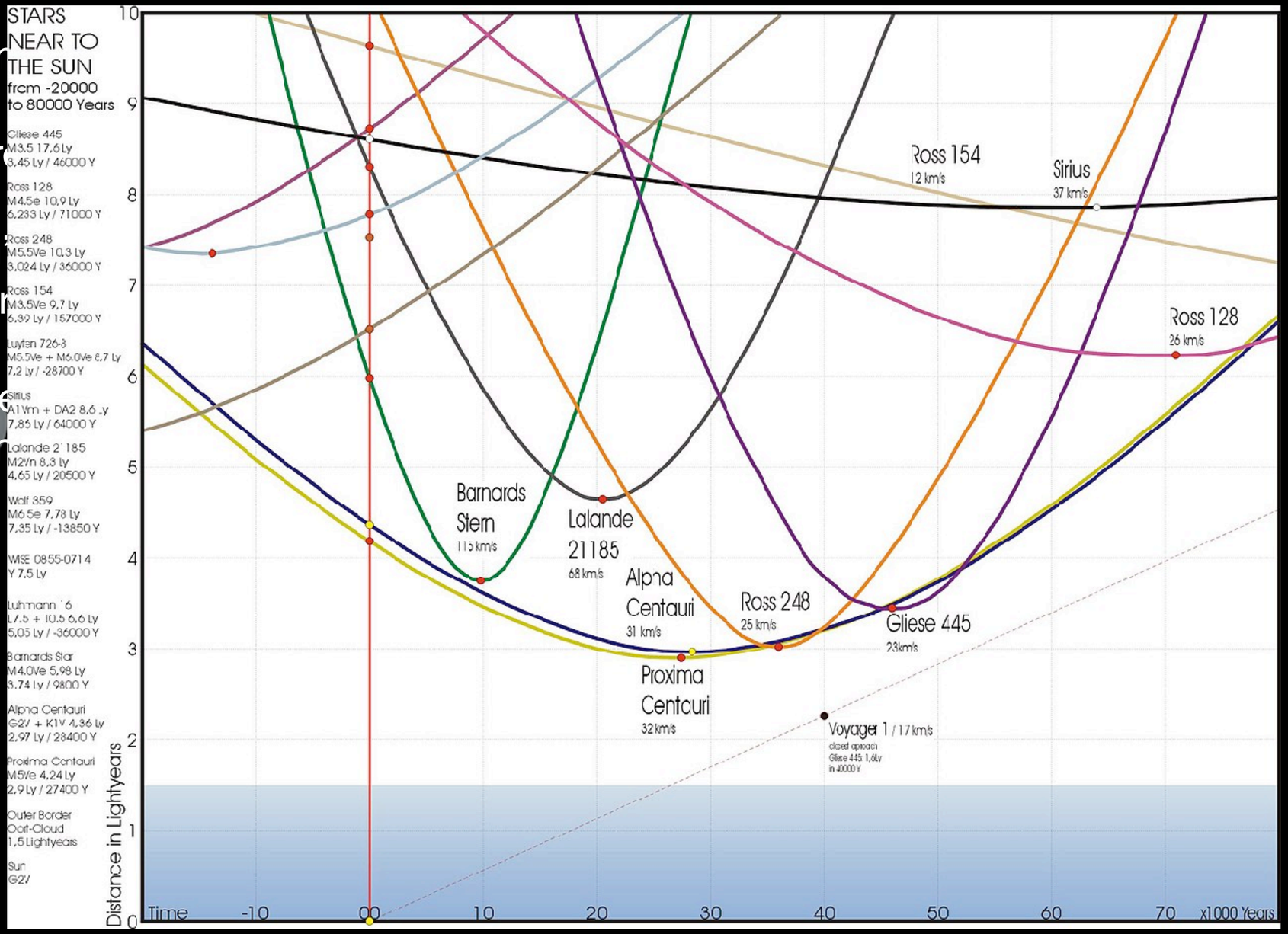

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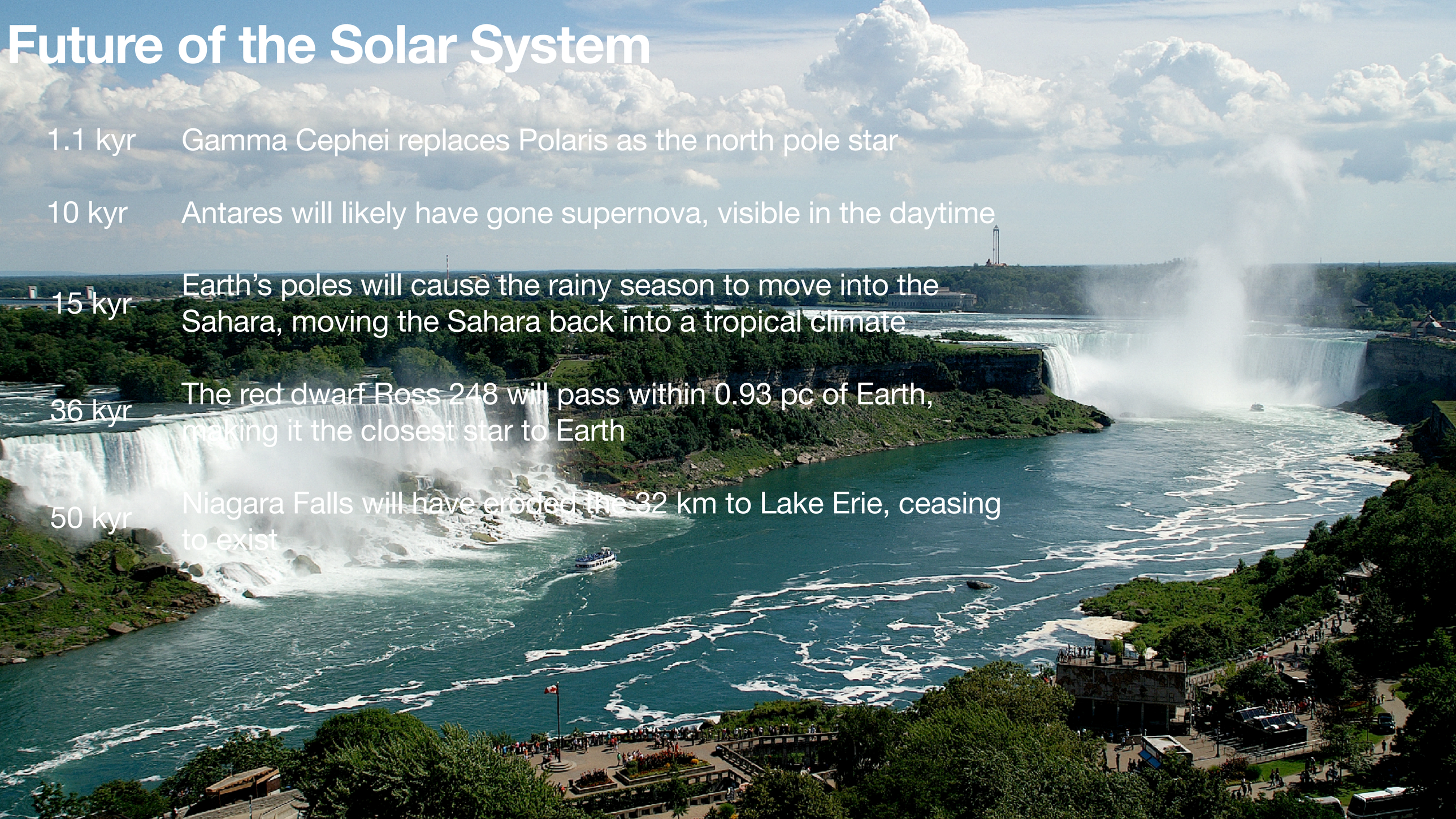

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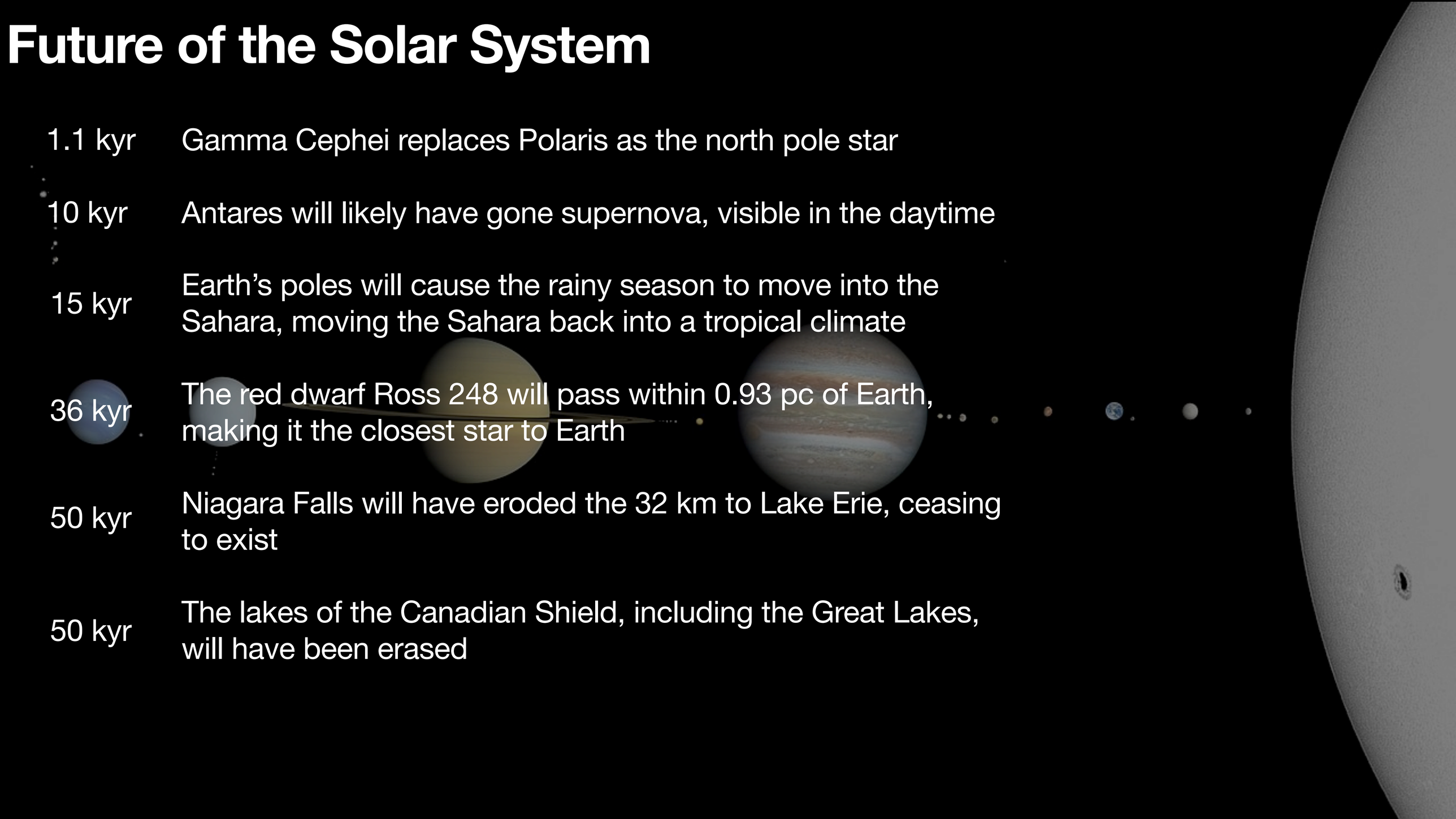

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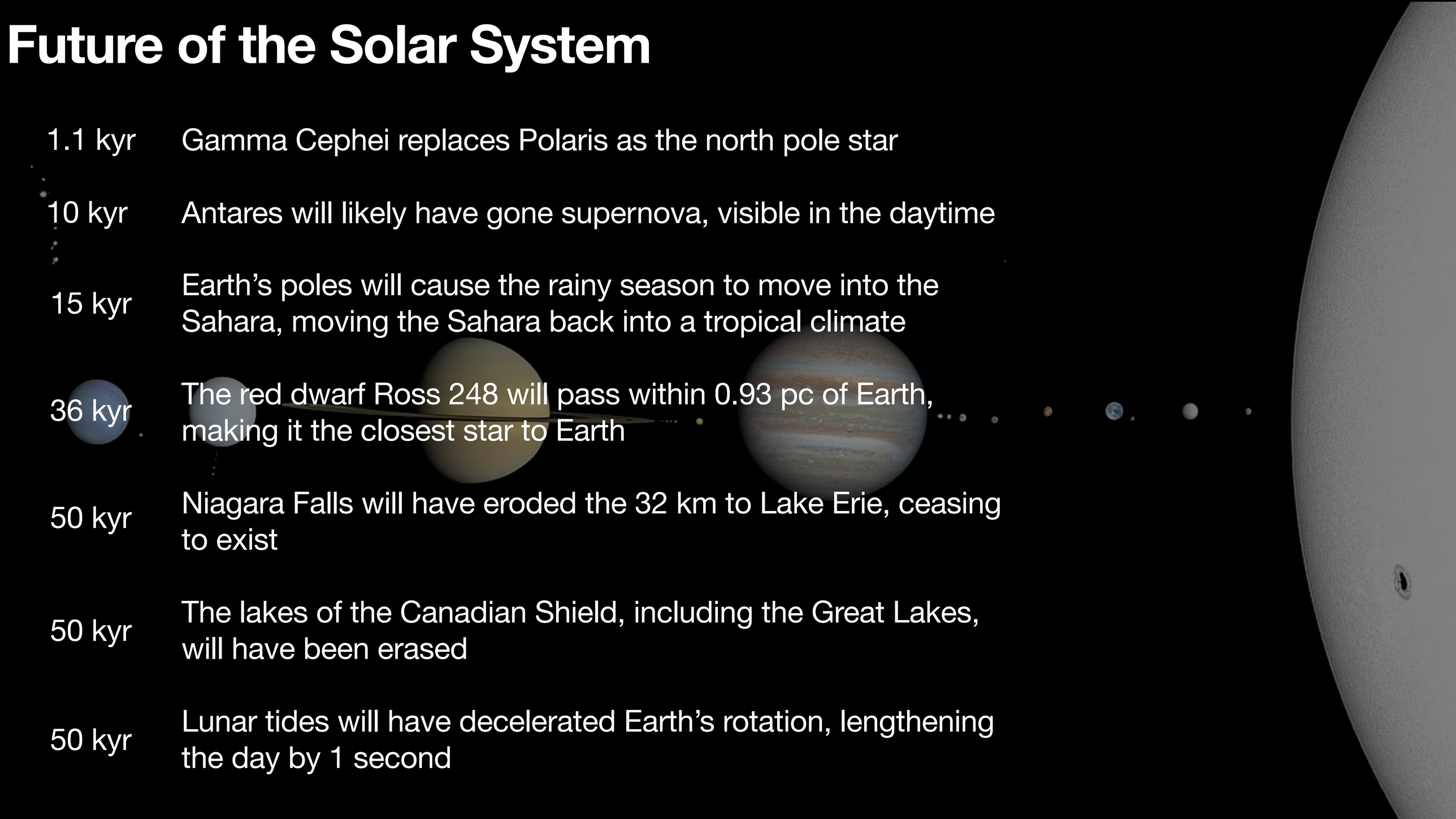

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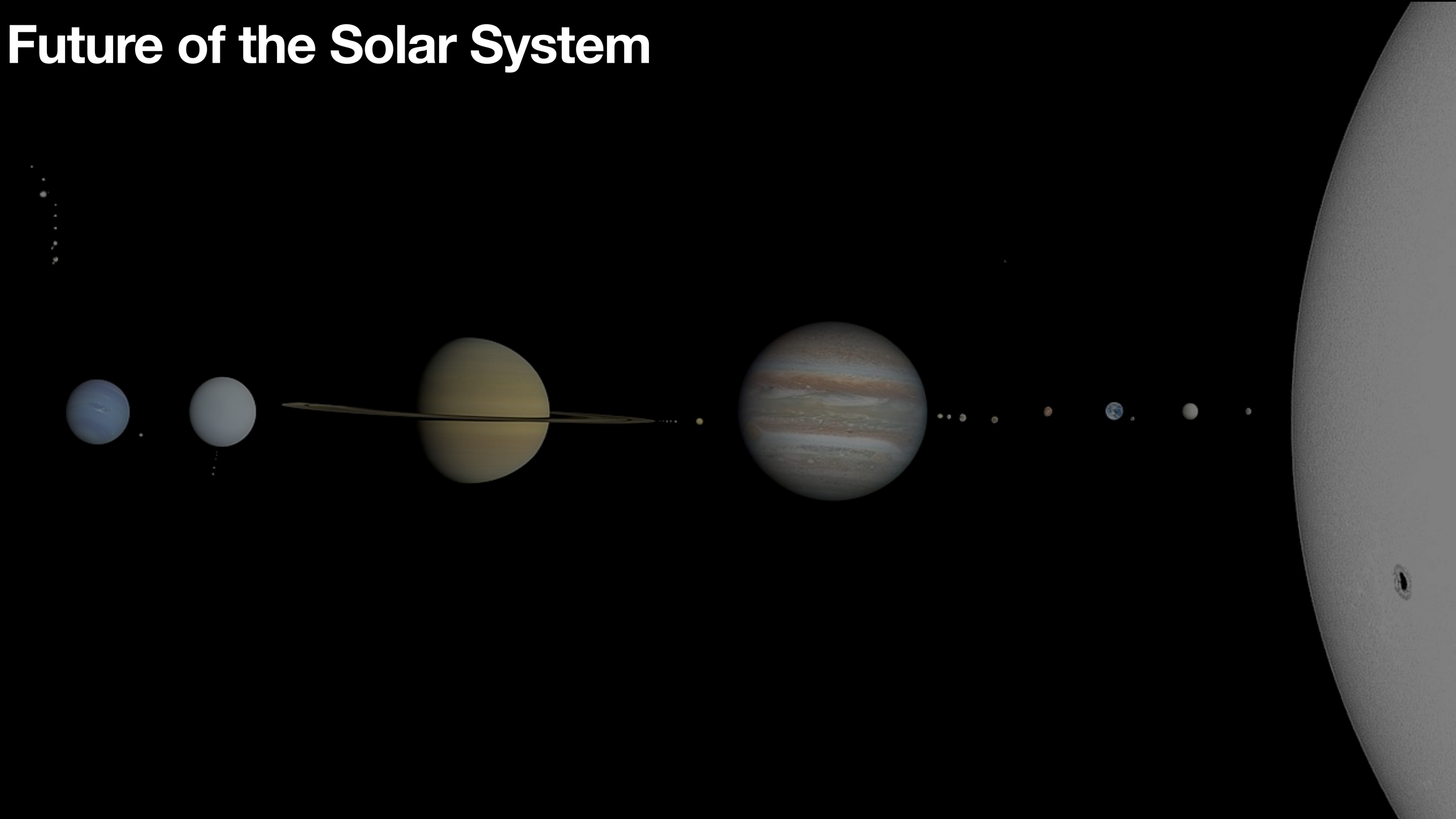
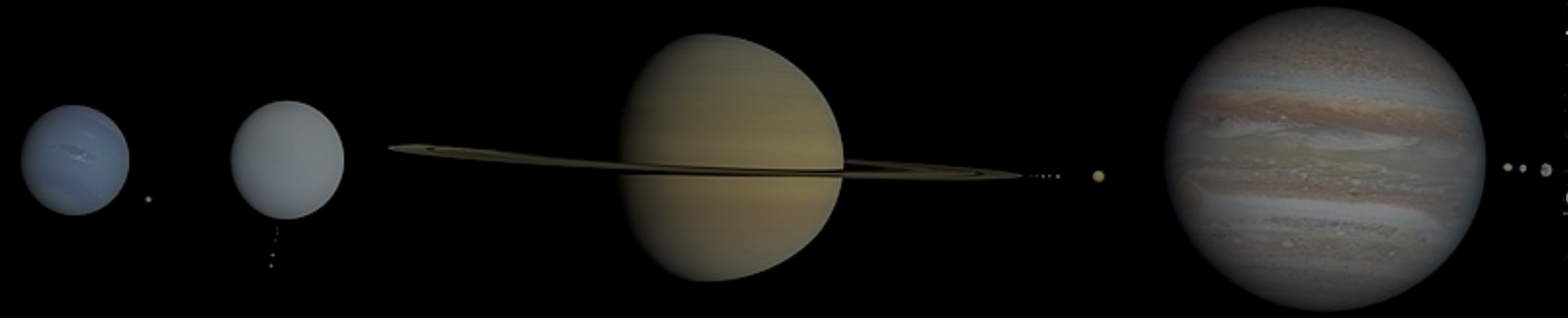
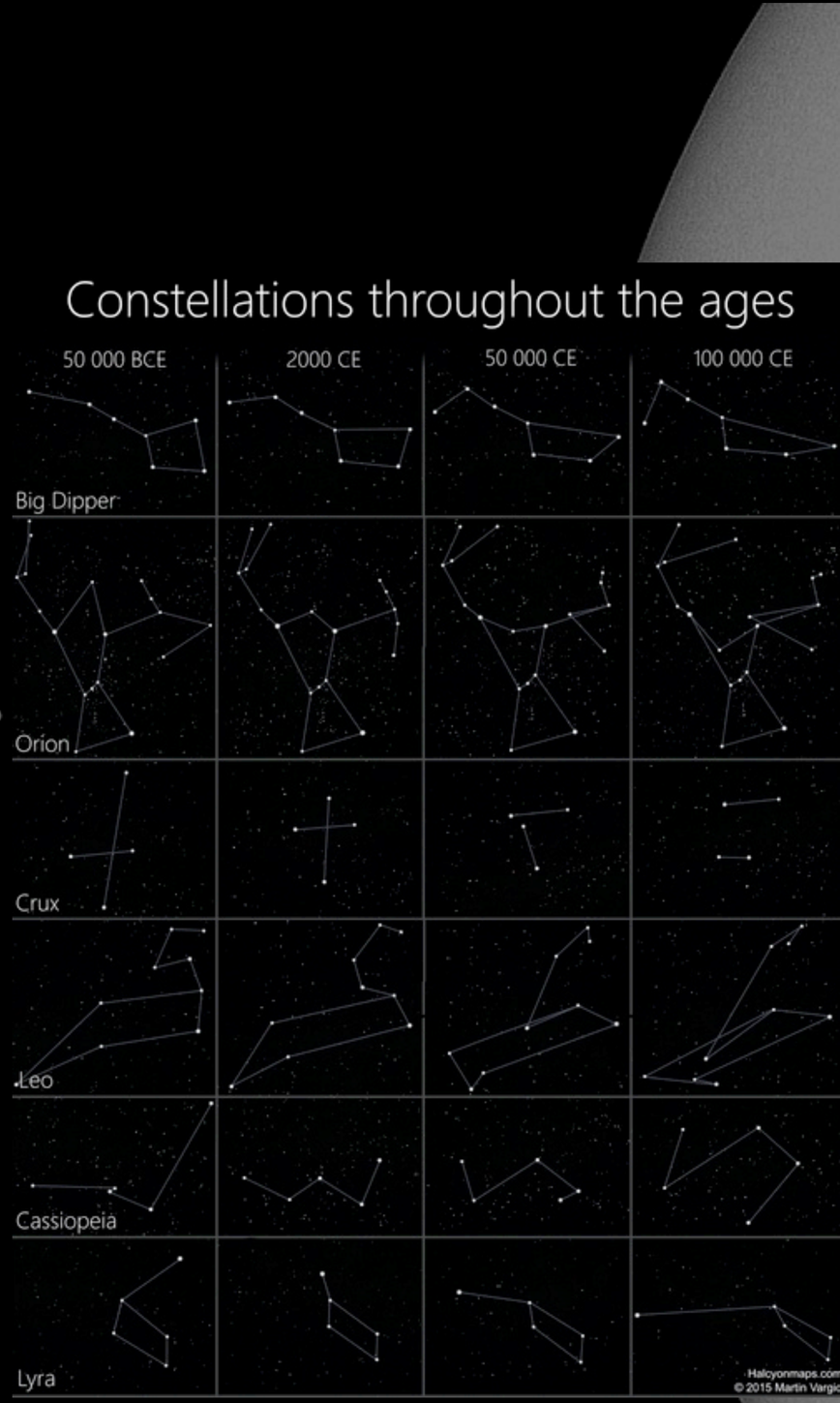


Future of the Solar System

100 kyr

Proper motion of stars causes most of the constellations to become unrecognizable





Future of the Solar System

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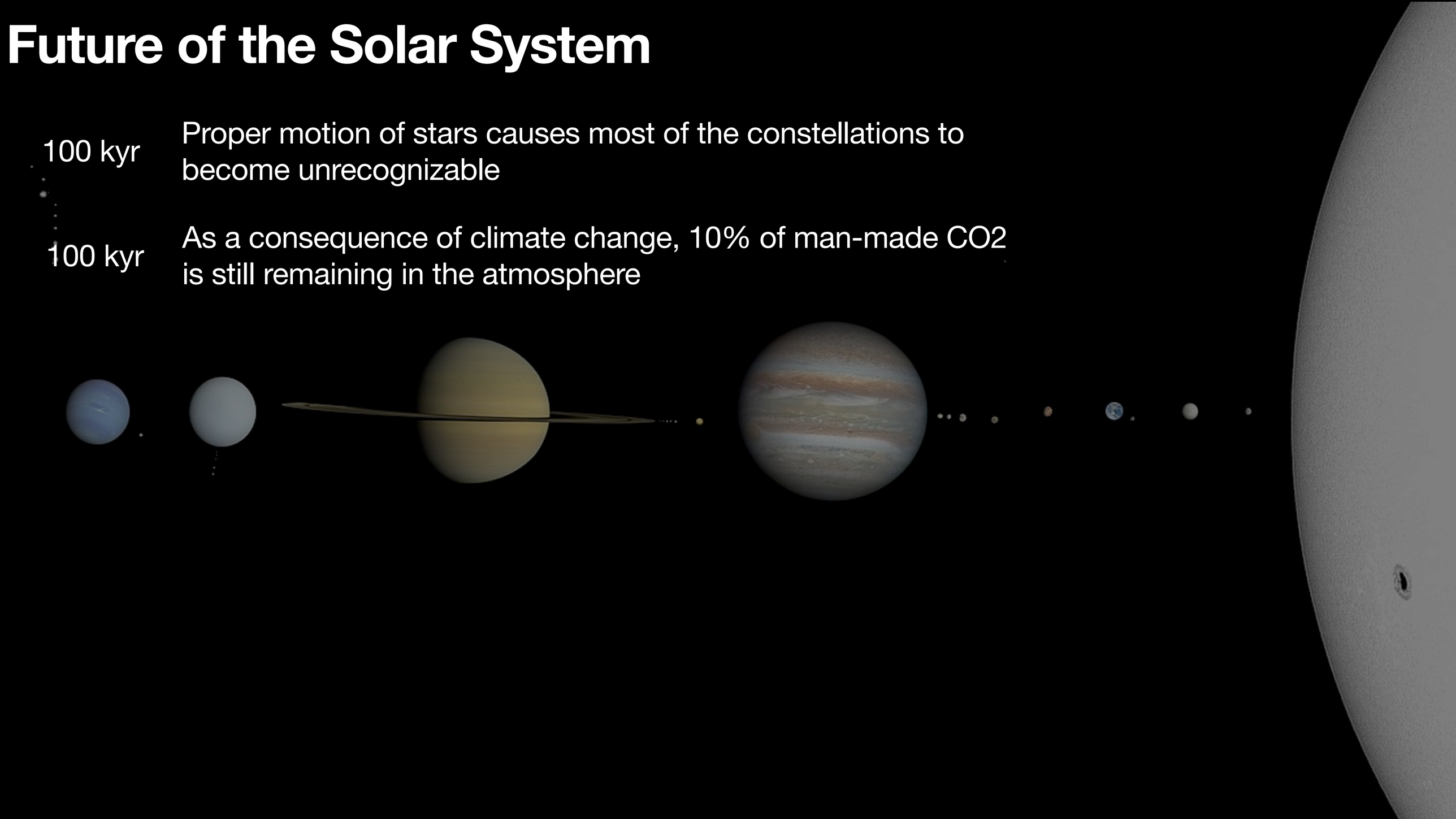
As a consequence of climate change, 10% of man-made CO2 is still remaining in the atmosphere



Future of the Solar System

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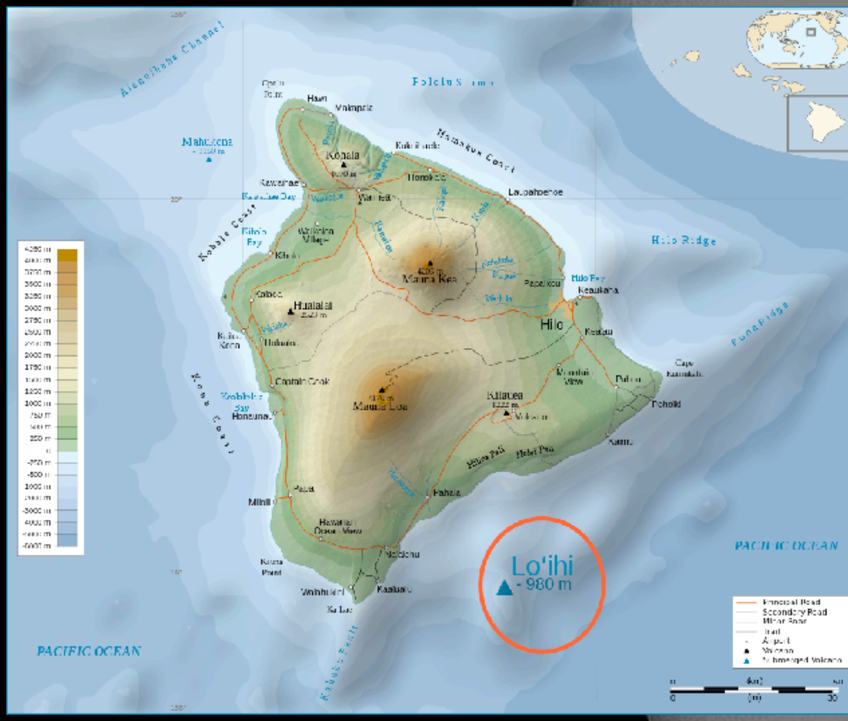
250 kyr — A new island has been added to the Hawaiian island chain, named Kama’ehuakanaloa



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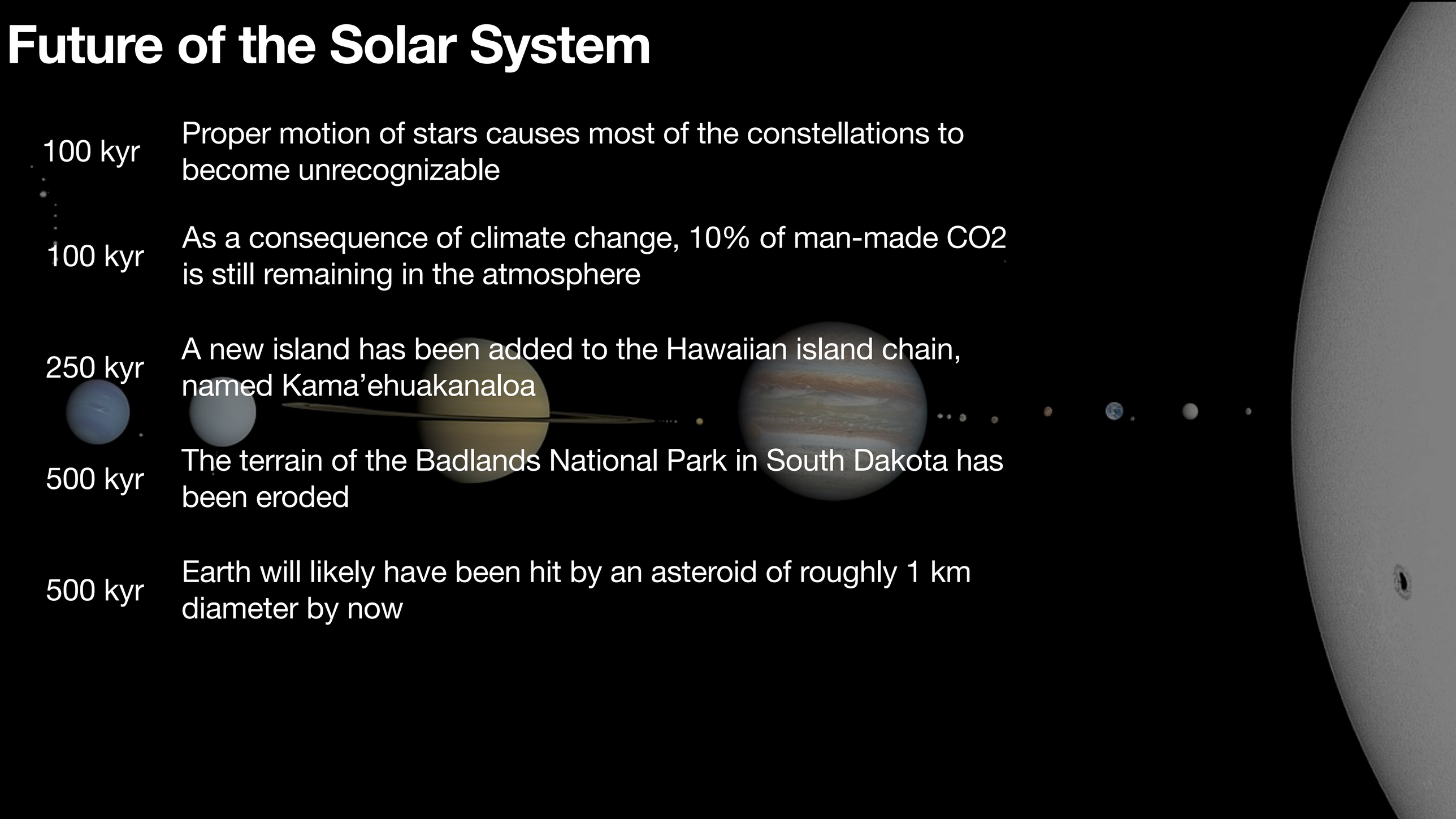
500 kyr — Earth will likely have been hit by an asteroid of roughly 1 km diameter by now



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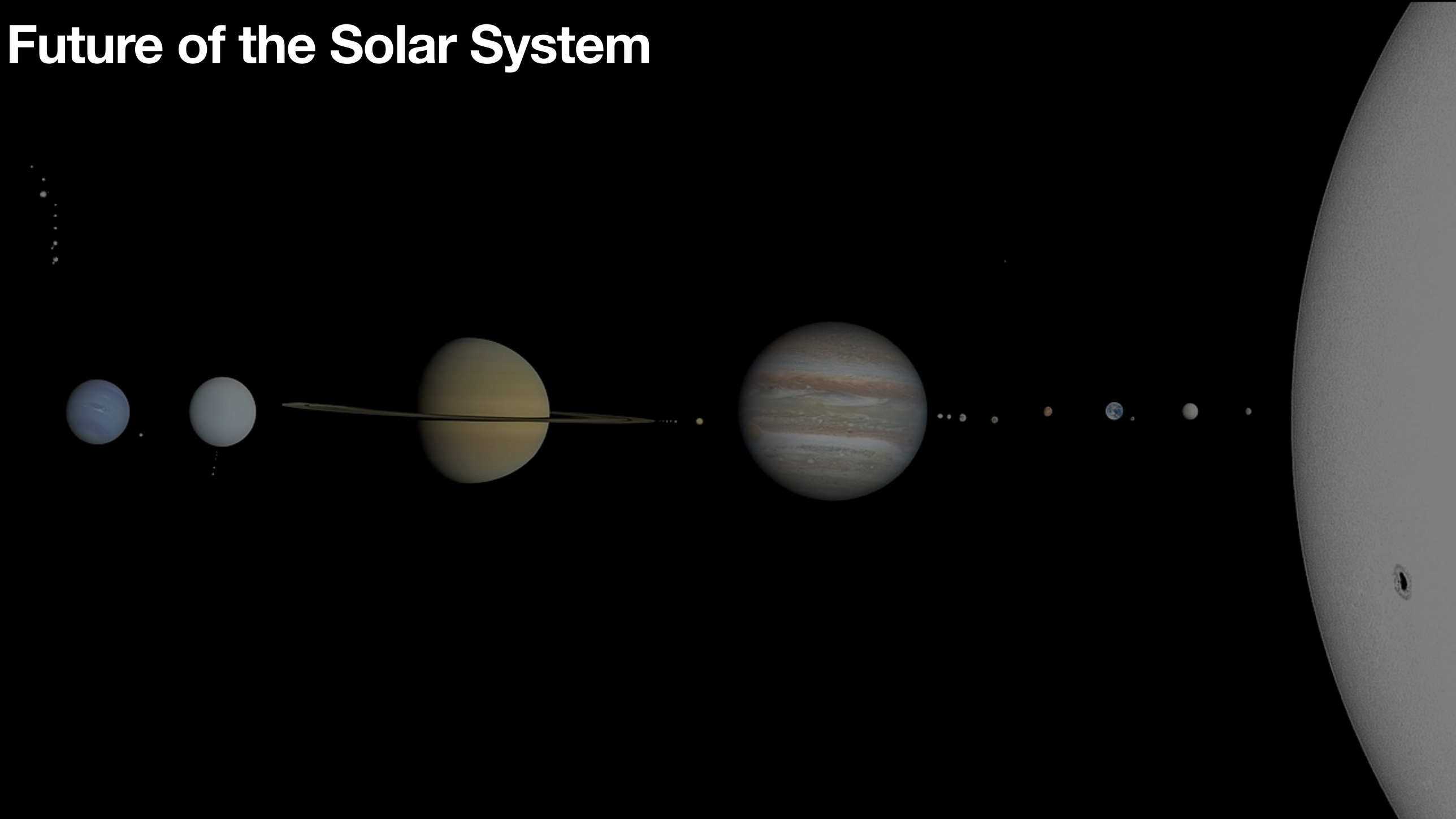
500 kyr	Earth will likely have been hit by an asteroid of roughly 1 km diameter by now
1 Myr	Meteor Crater in Arizona will have worn away

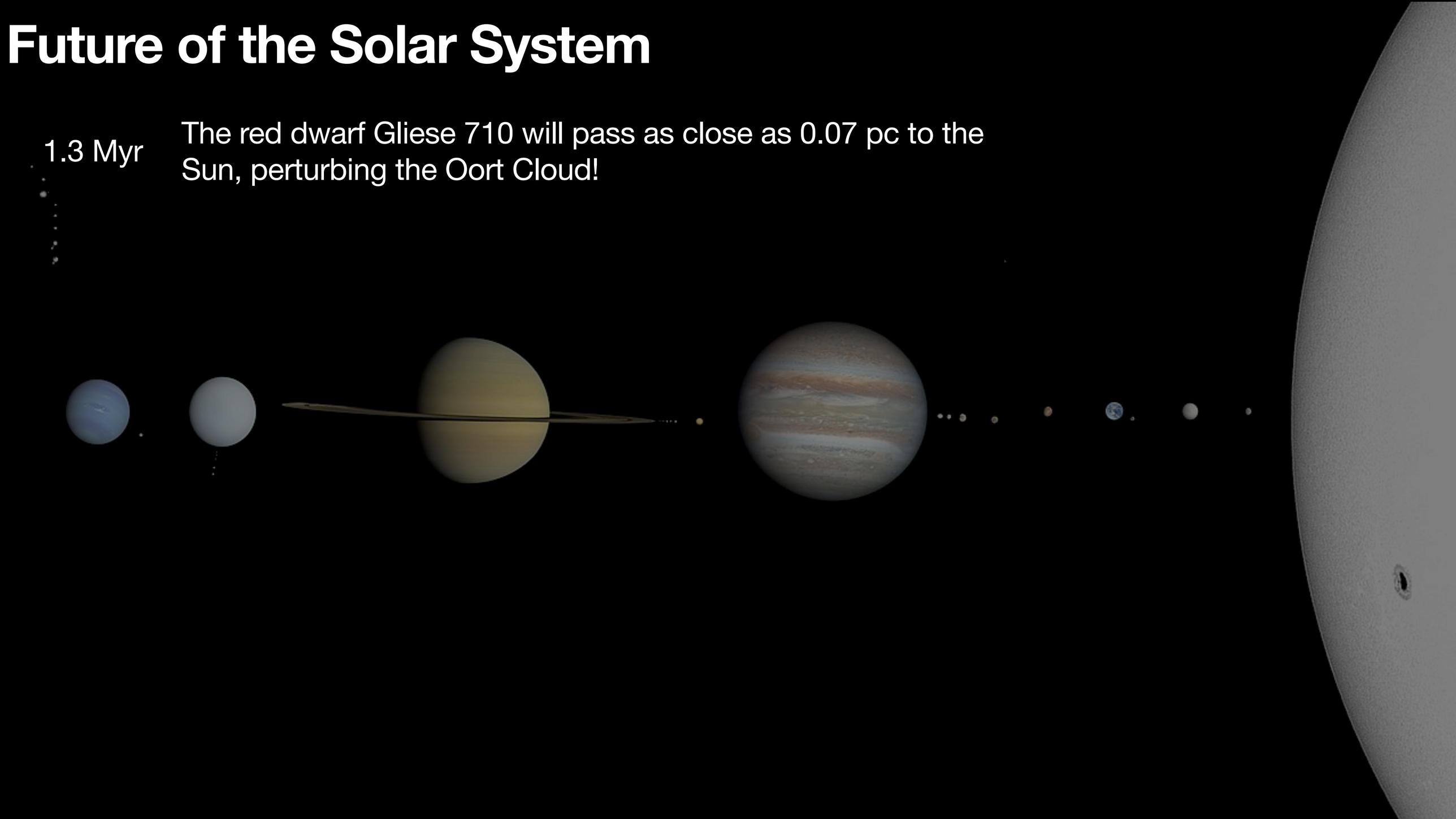
Future of the Solar System



Future of the Solar System

1.3 Myr

The red dwarf Gliese 710 will pass as close as 0.07 pc to the Sun, perturbing the Oort Cloud!



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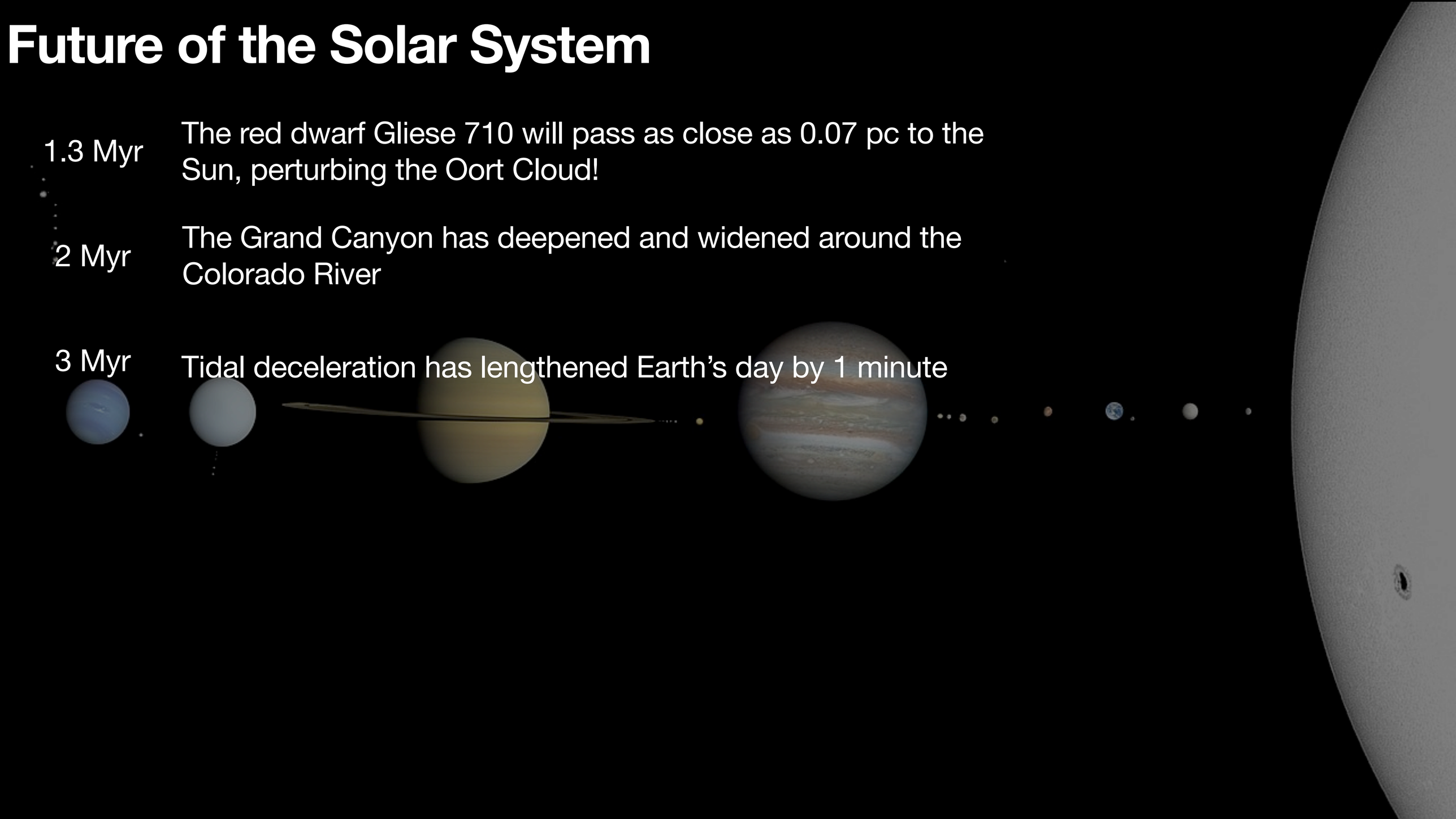

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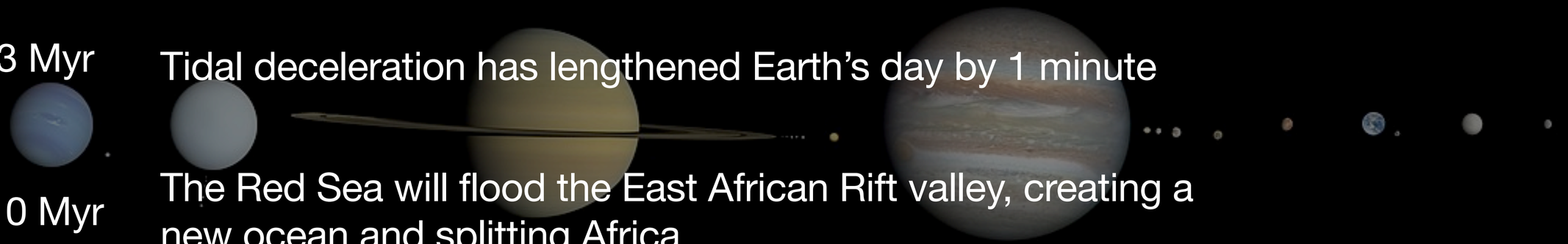
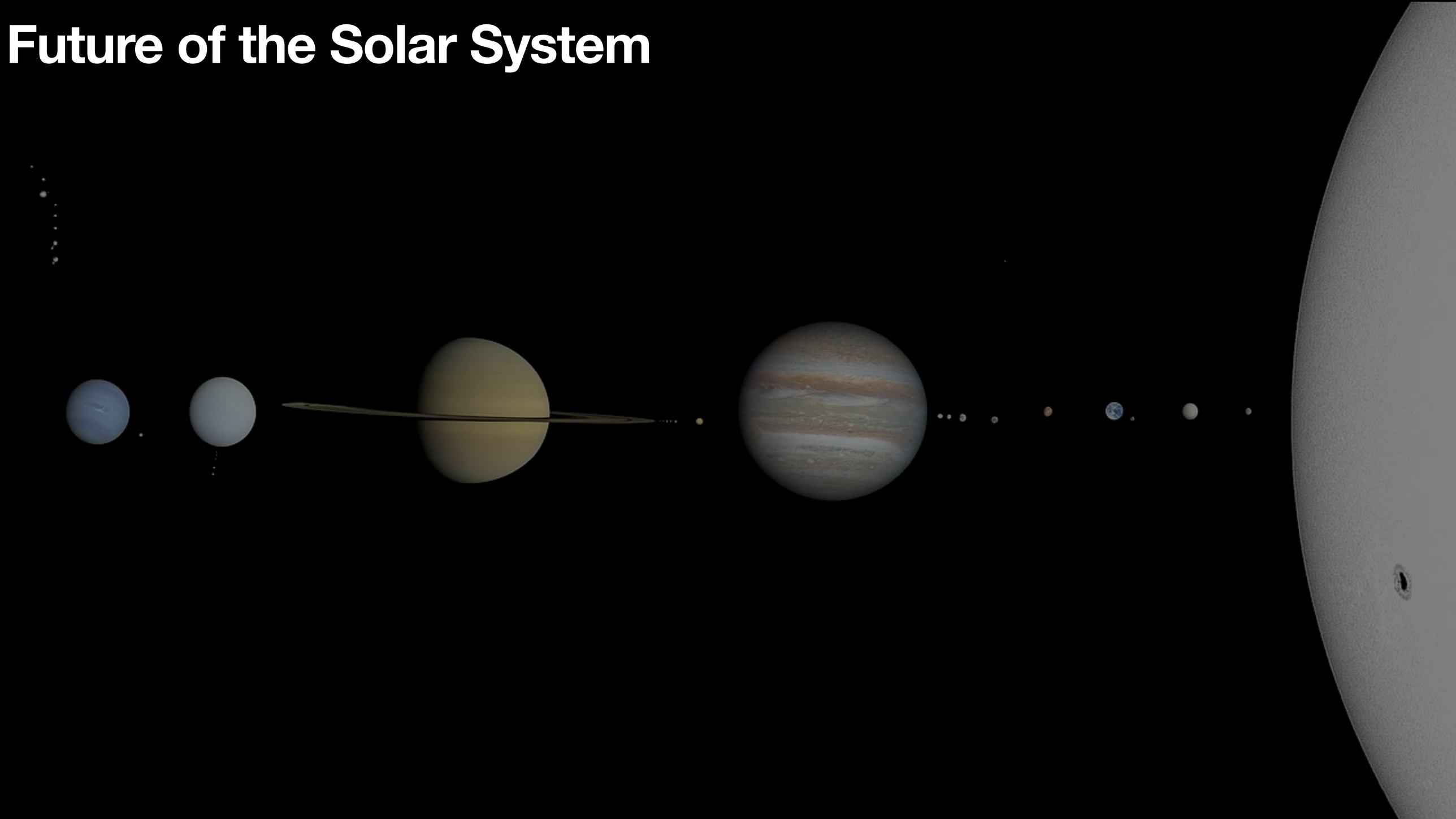


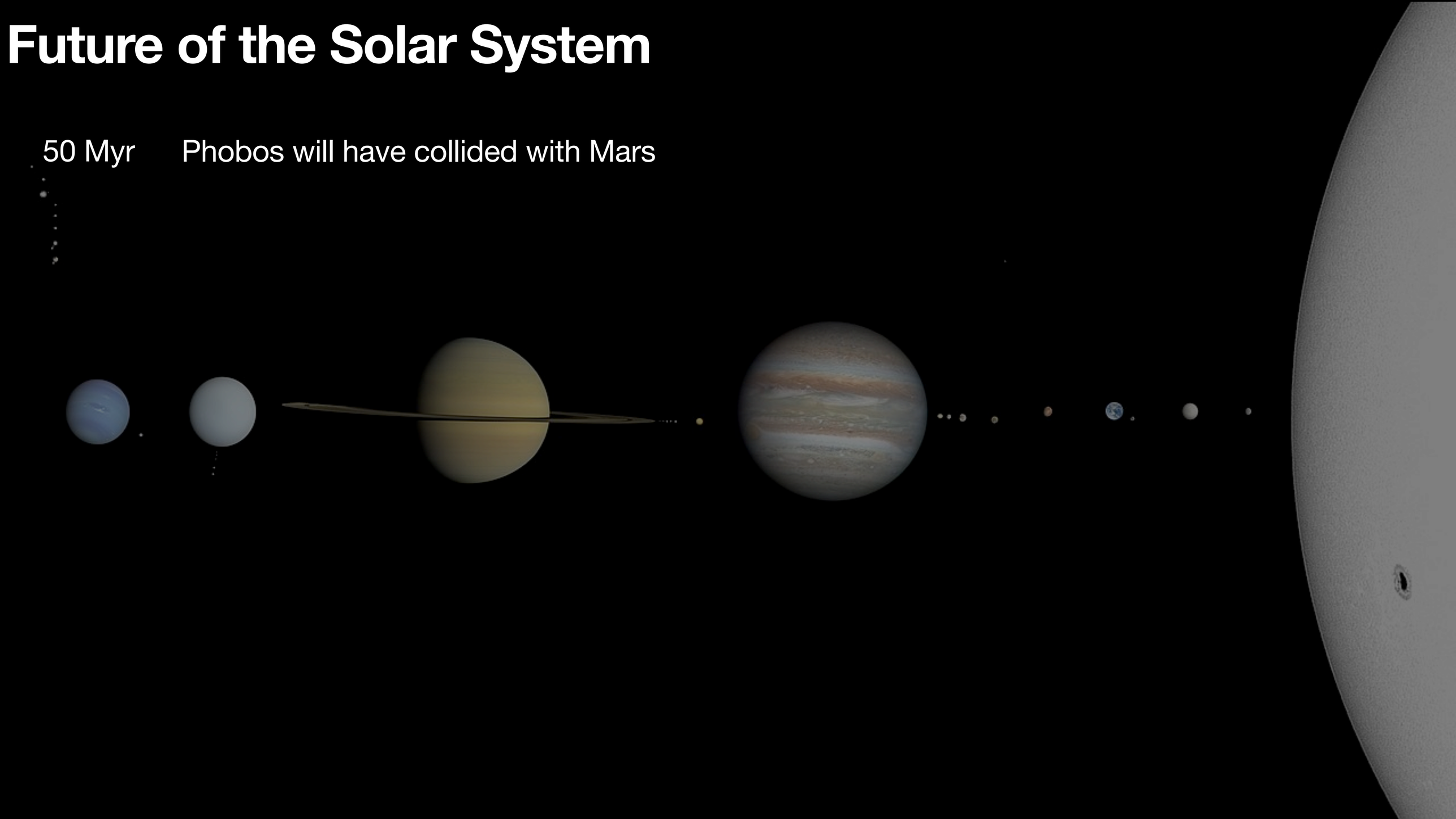
10 Myr — The Red Sea will flood the East African Rift valley, creating a new ocean and splitting Africa

Future of the Solar System



Future of the Solar System

50 Myr Phobos will have collided with Mars



Future of the Solar System

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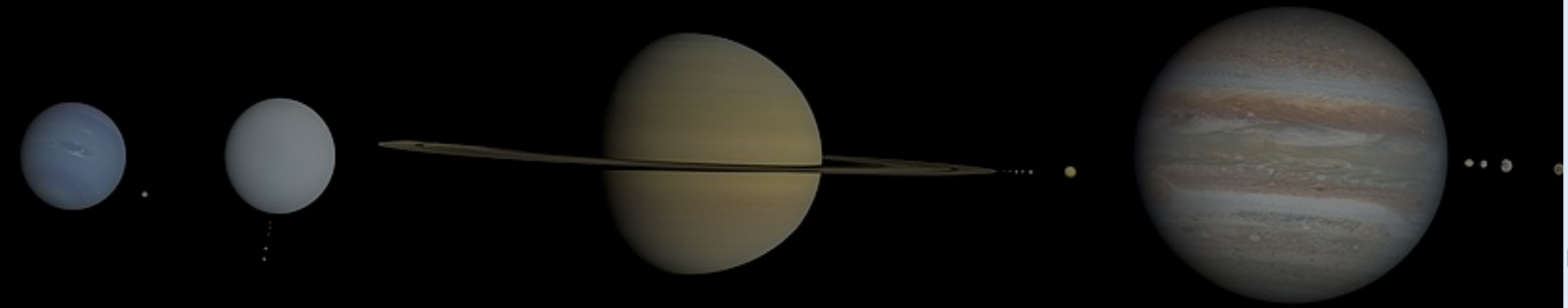
50 Myr — The Gulf of California will flood the Central Valley, creating a new sea along the west coast



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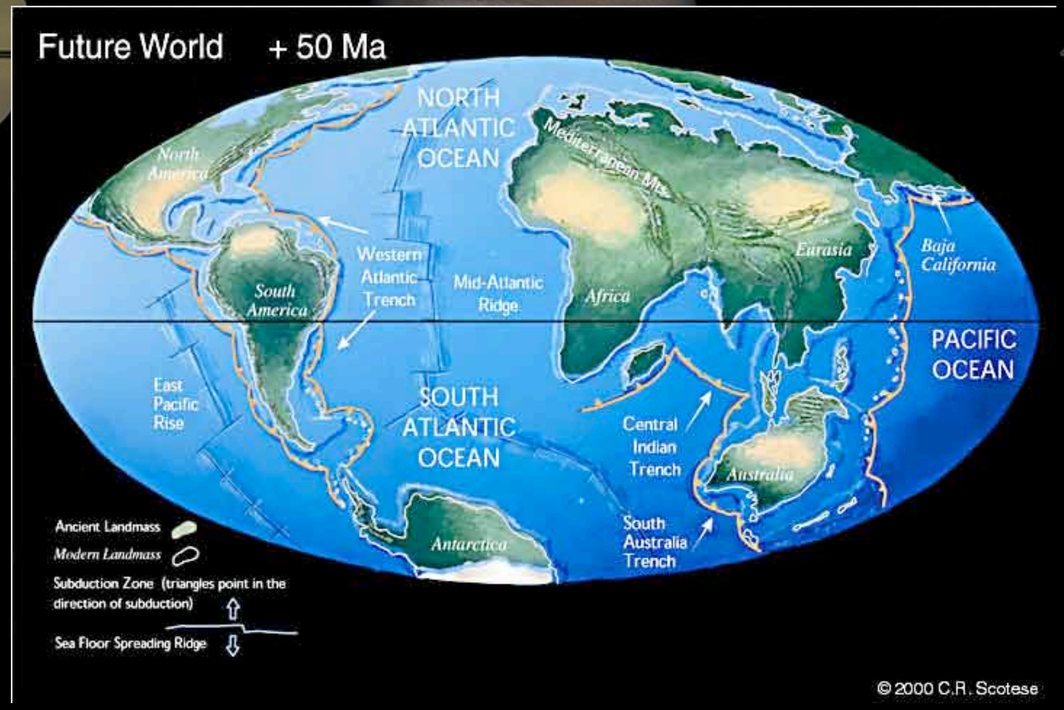

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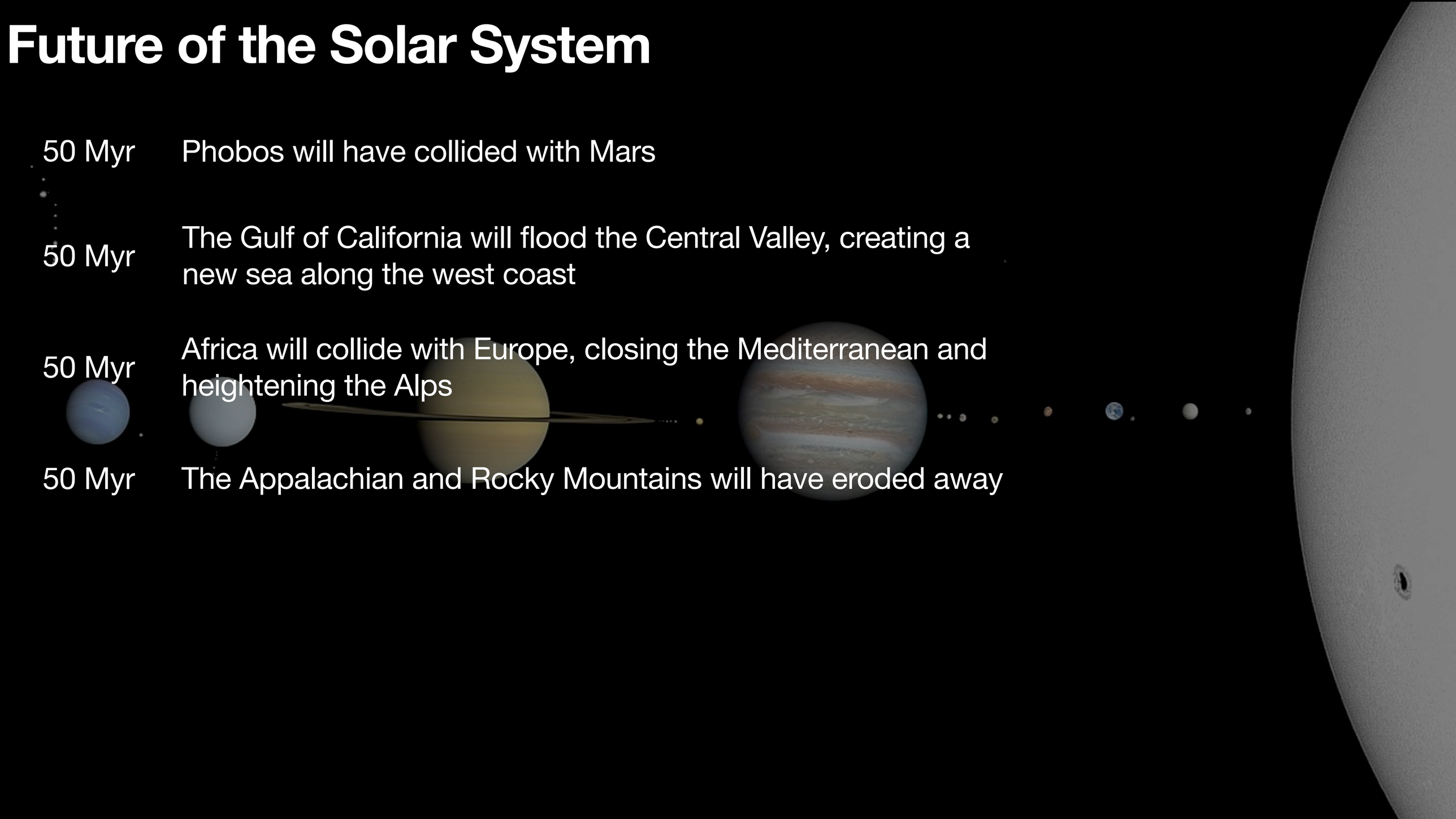

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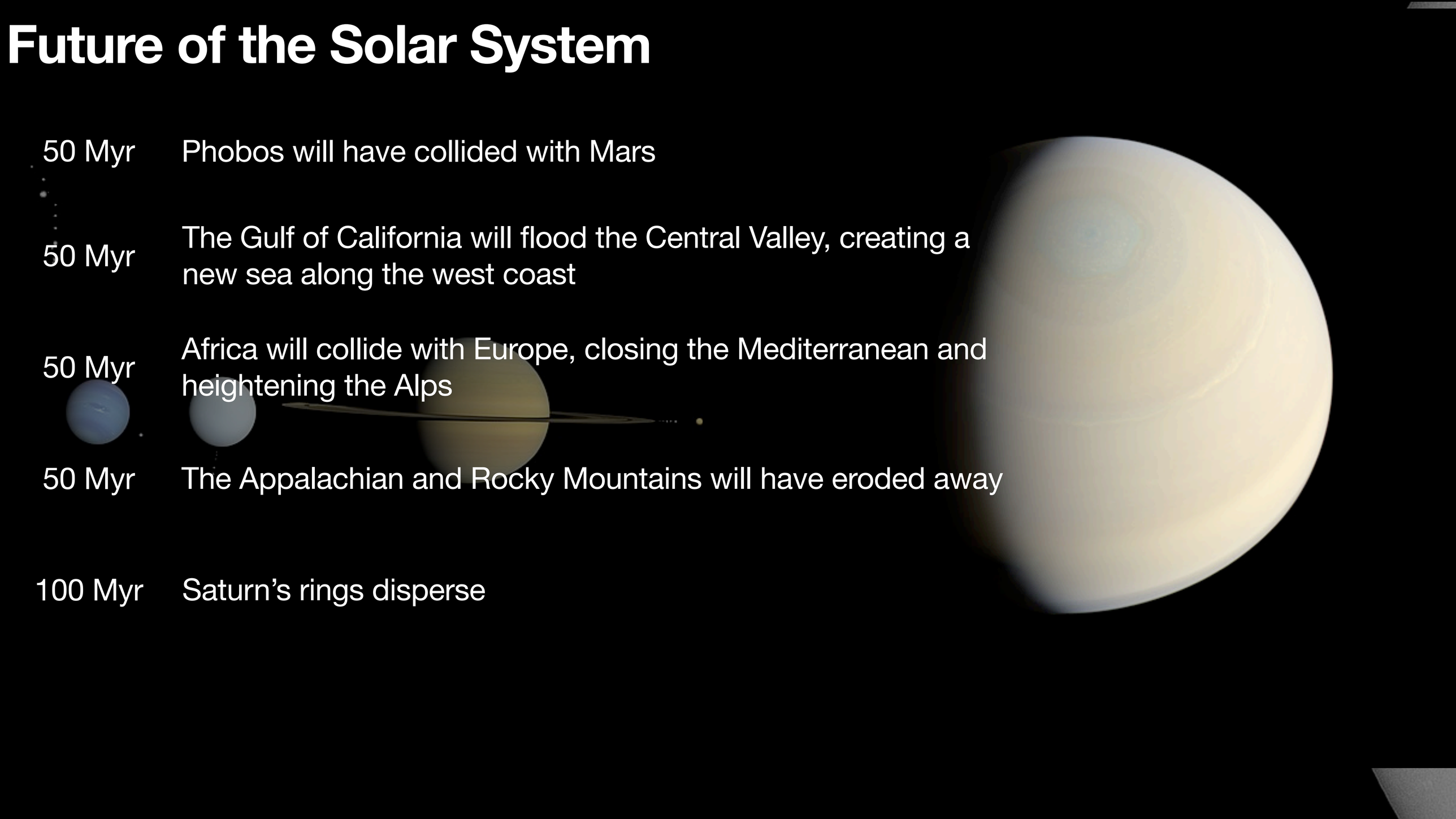
100 Myr	Saturn’s rings disperse



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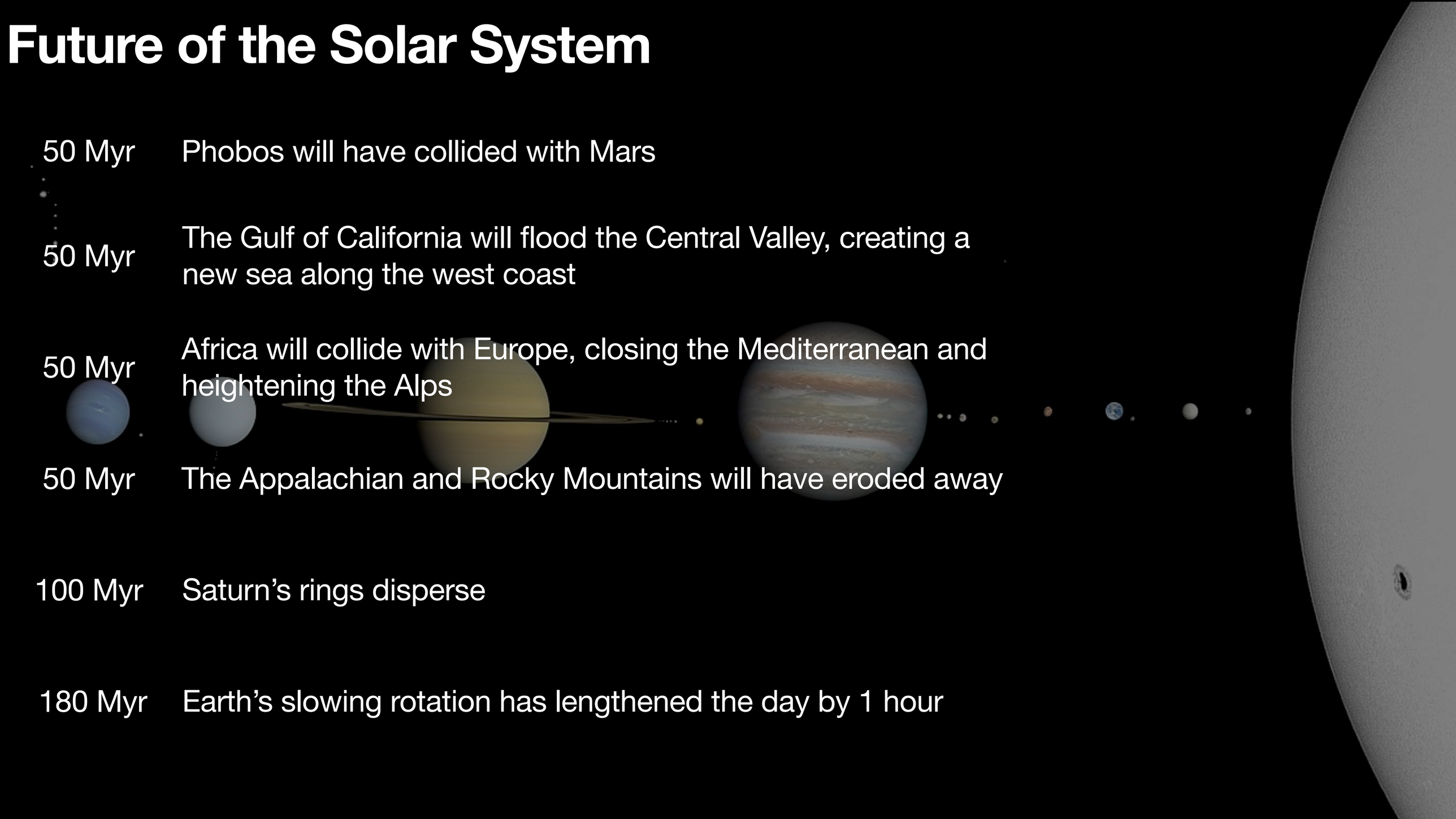
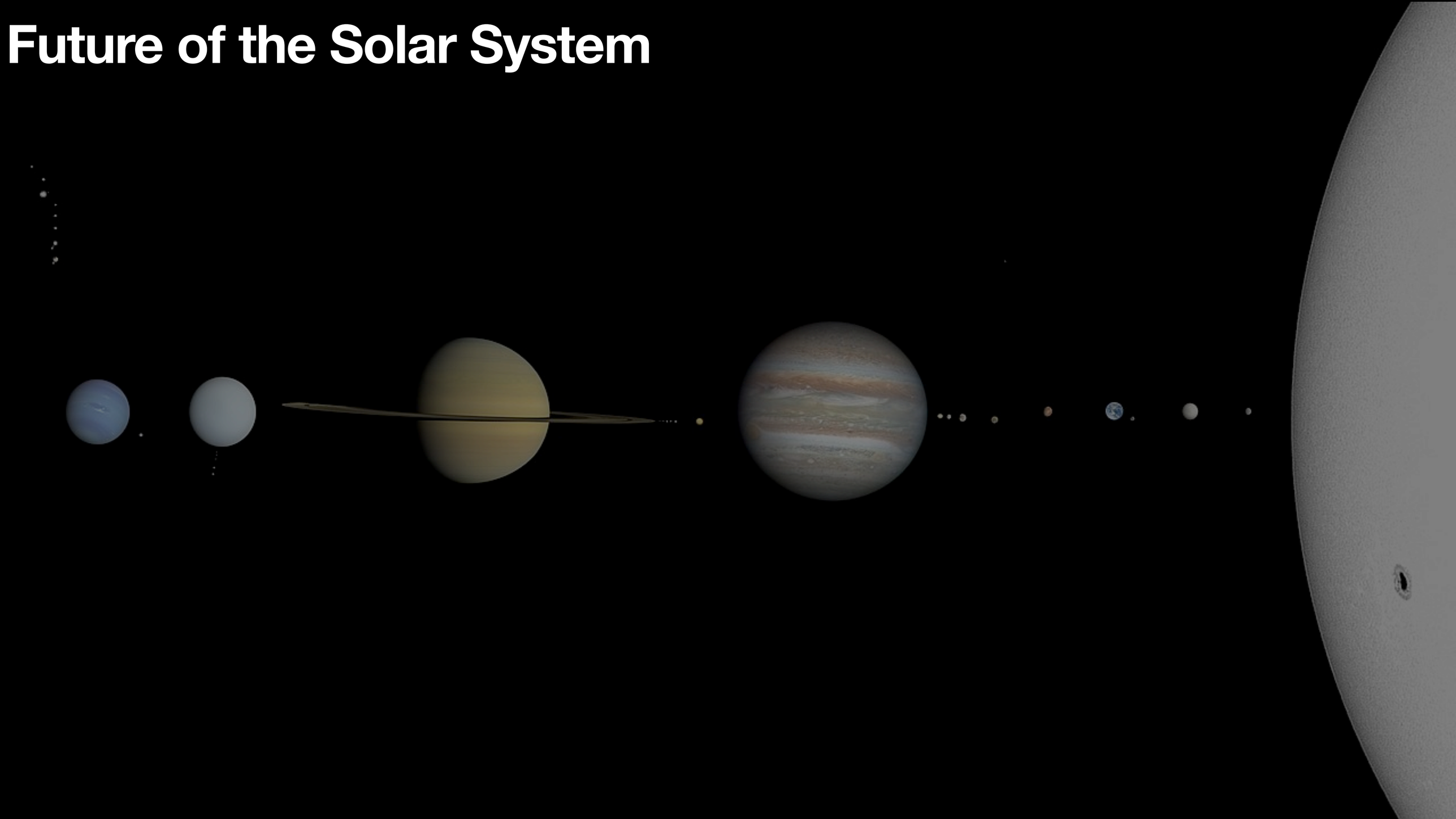
100 Myr	Saturn’s rings disperse
180 Myr	Earth’s slowing rotation has lengthened the day by 1 hour



Future of the Solar System



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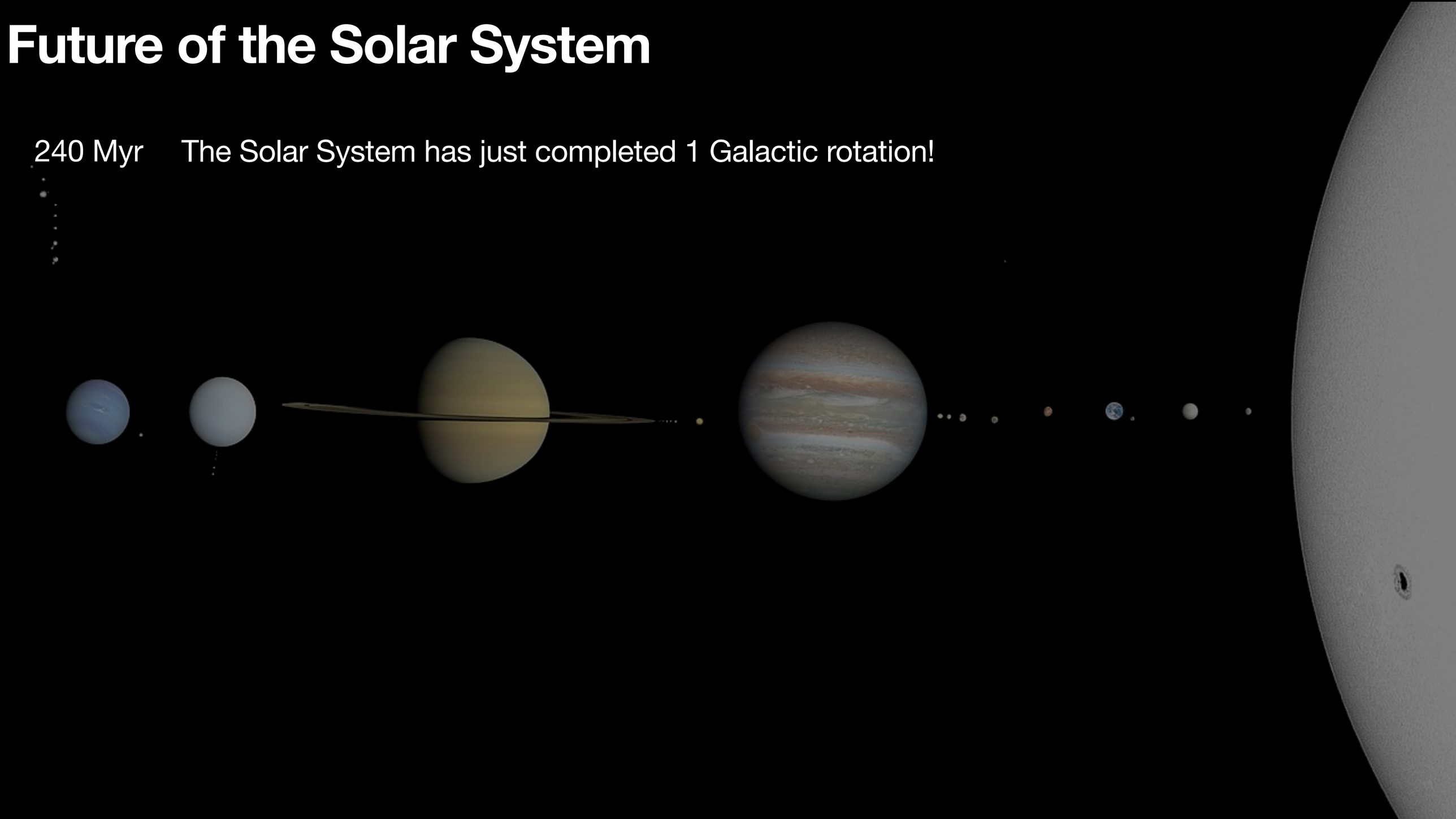
240 Myr The Solar System has just completed 1 Galactic rotation!



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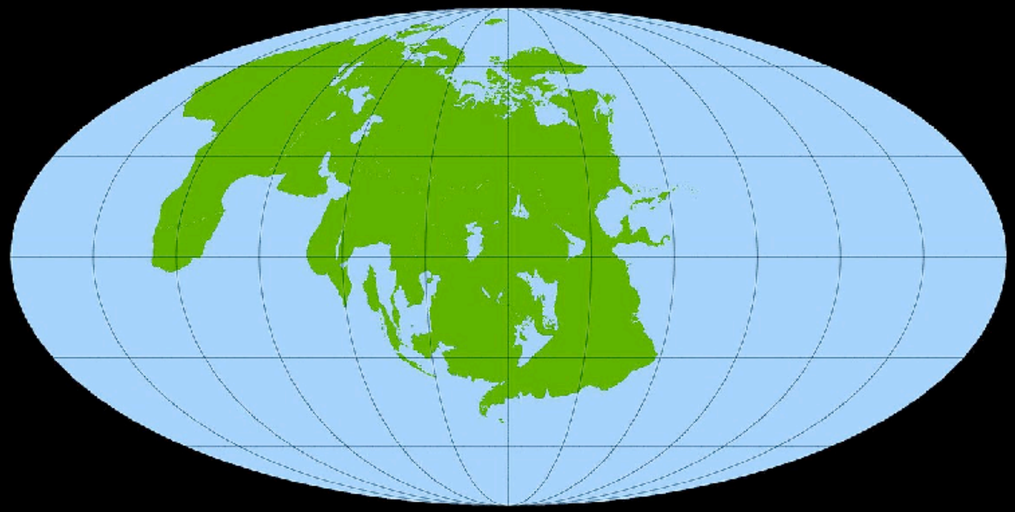

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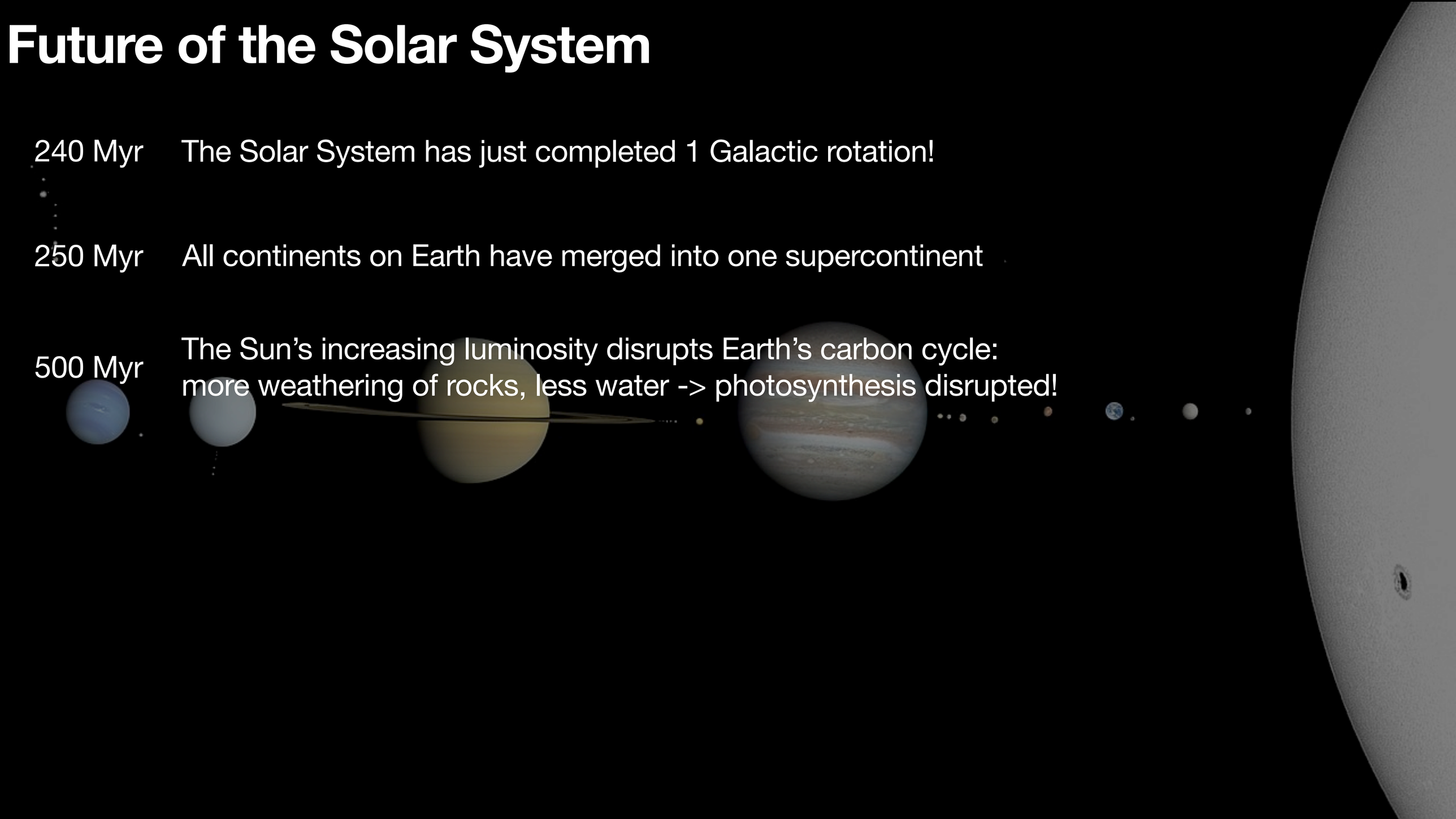

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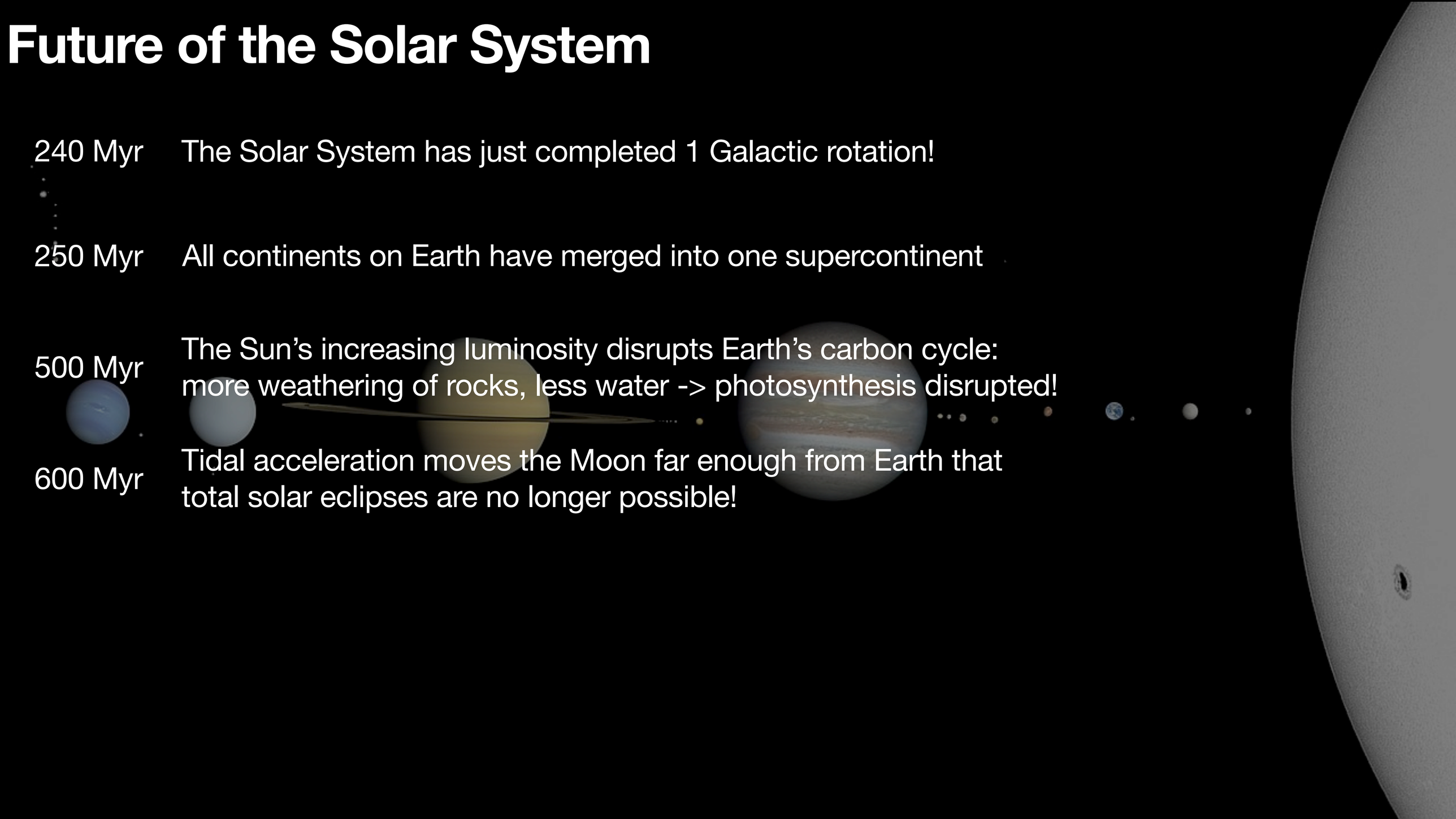

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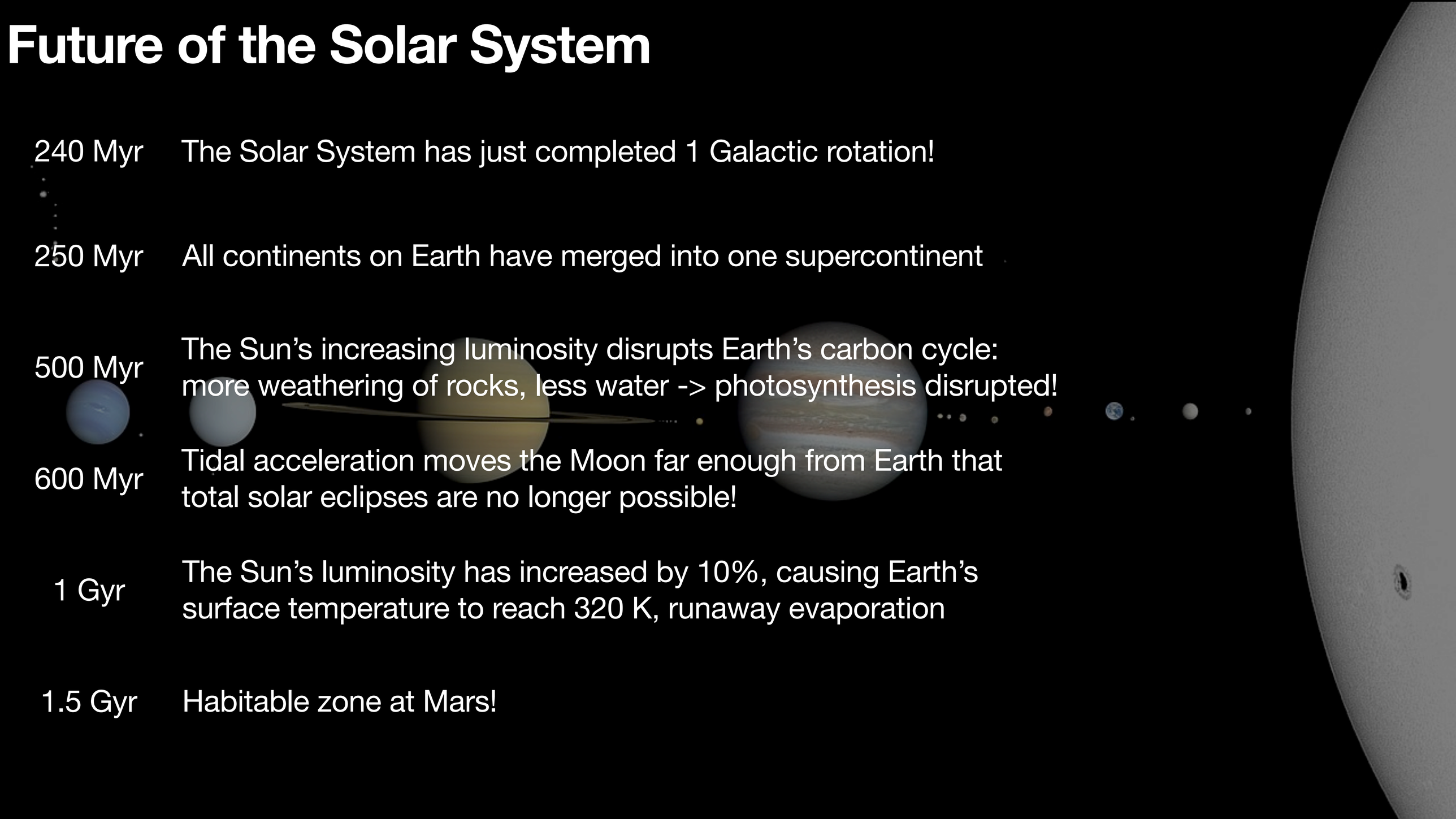

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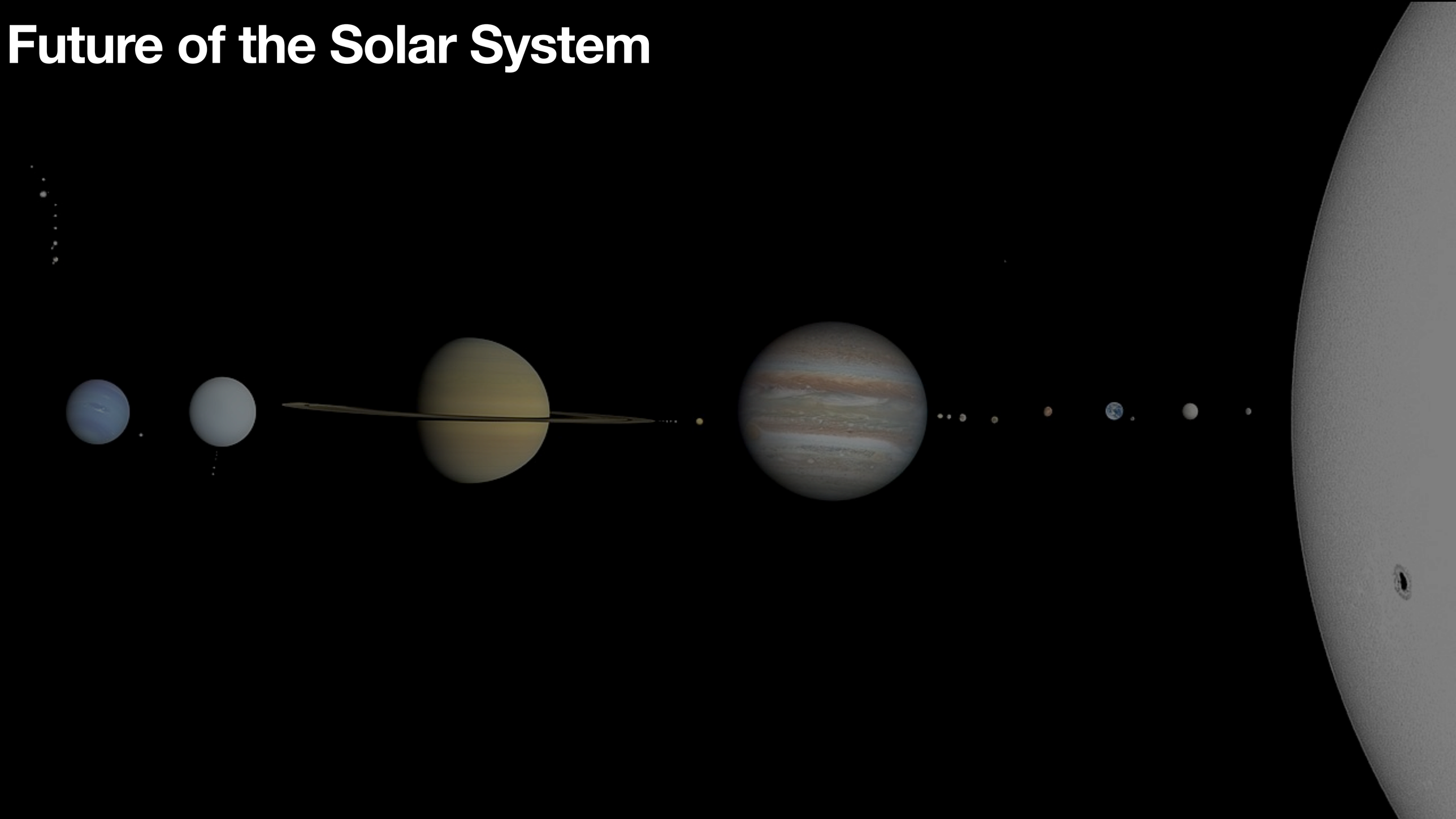
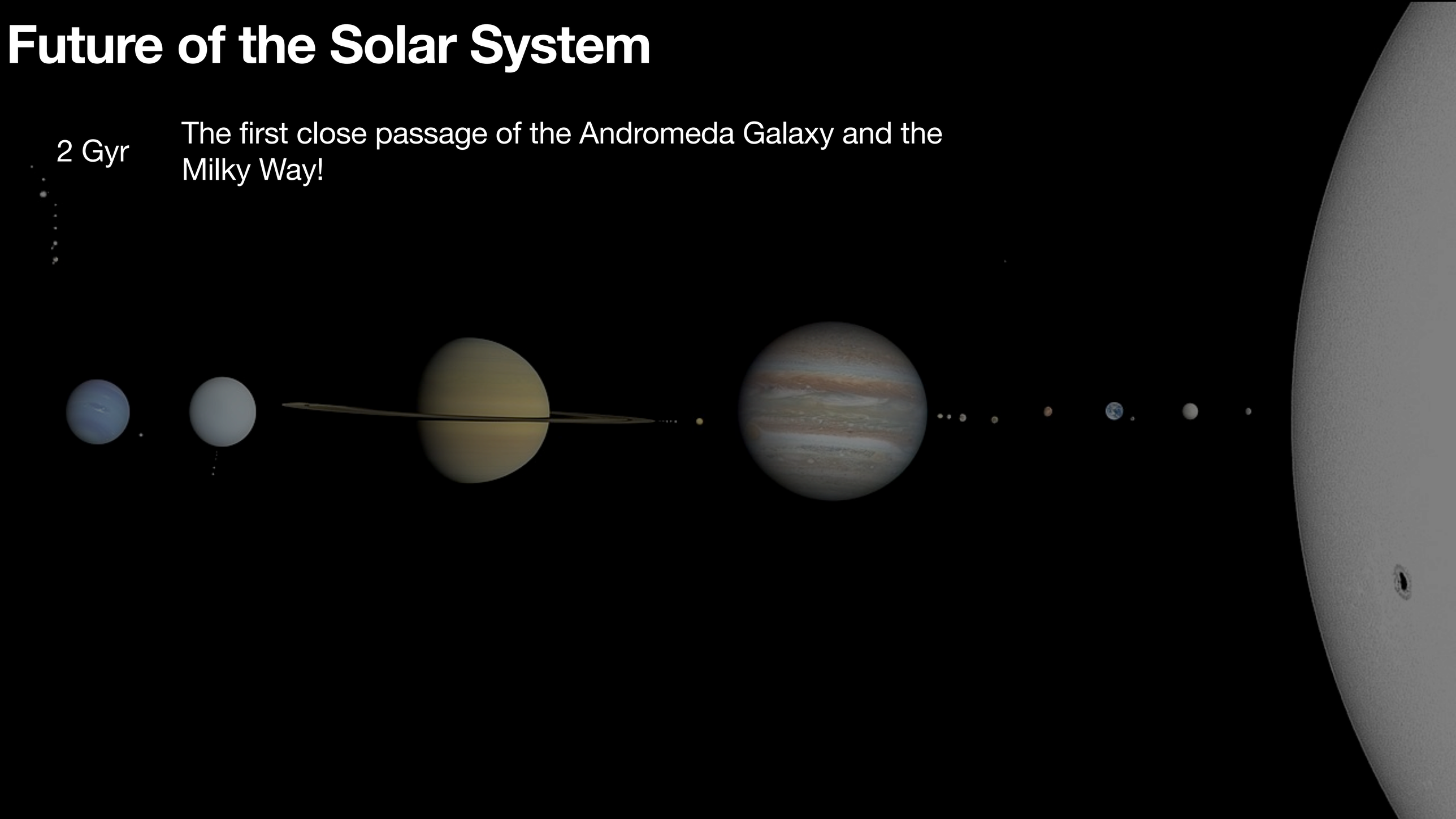


Future of the Solar System

2 Gyr

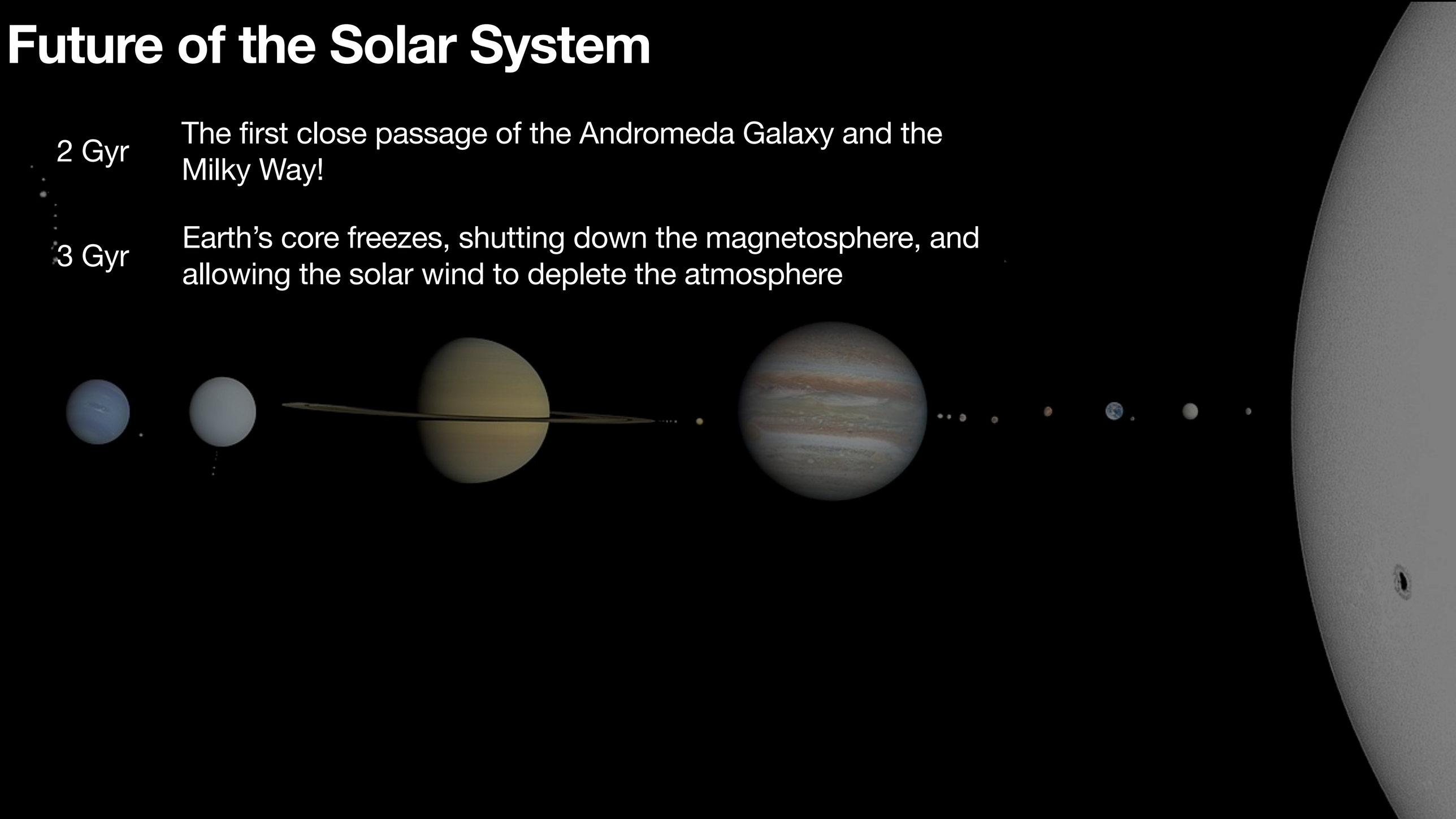
The first close passage of the Andromeda Galaxy and the Milky Way!



Future of the Solar System

2 Gyr — The first close passage of the Andromeda Galaxy and the Milky Way!

3 Gyr — Earth’s core freezes, shutting down the magnetosphere, and allowing the solar wind to deplete the atmosphere



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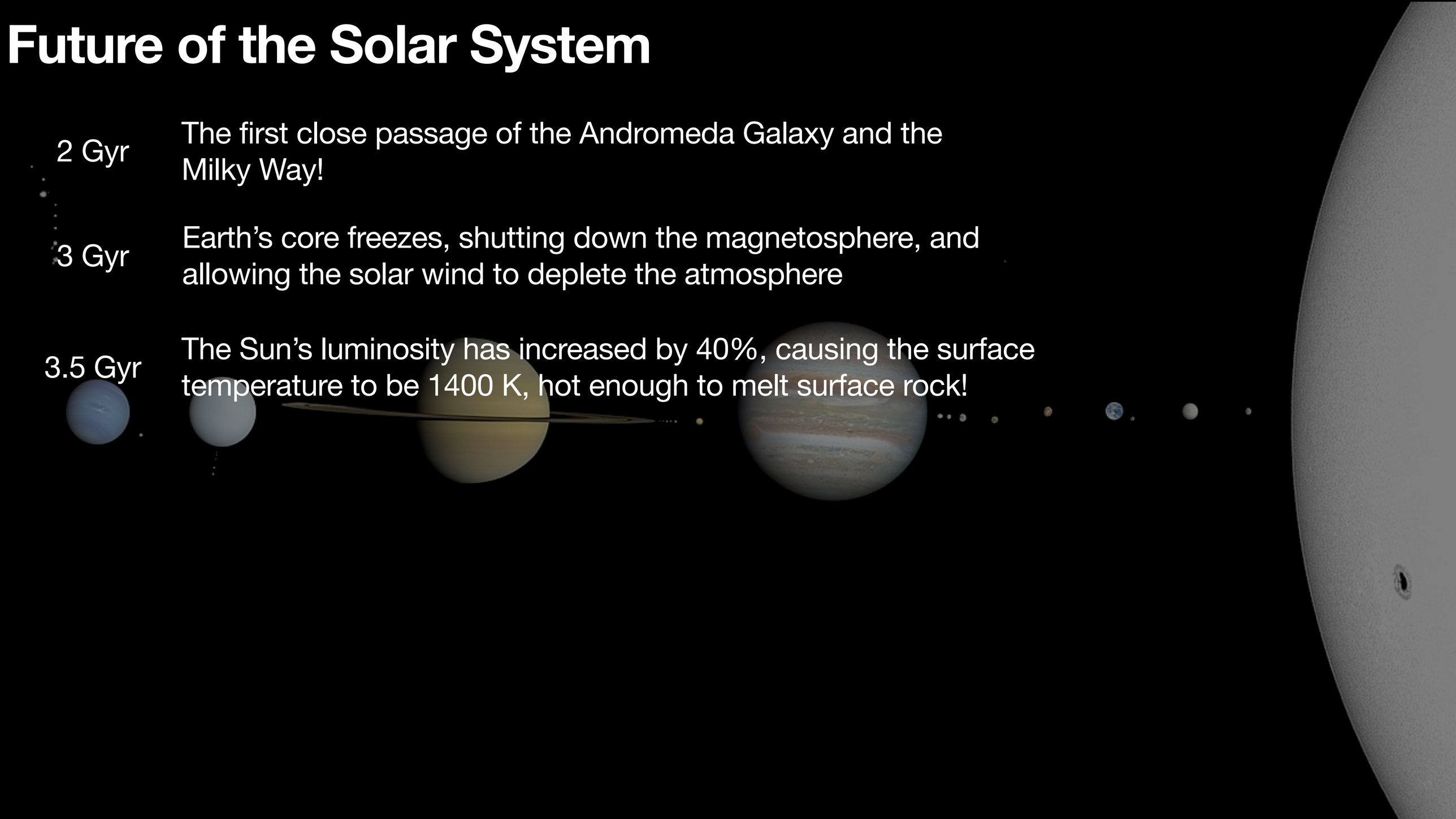

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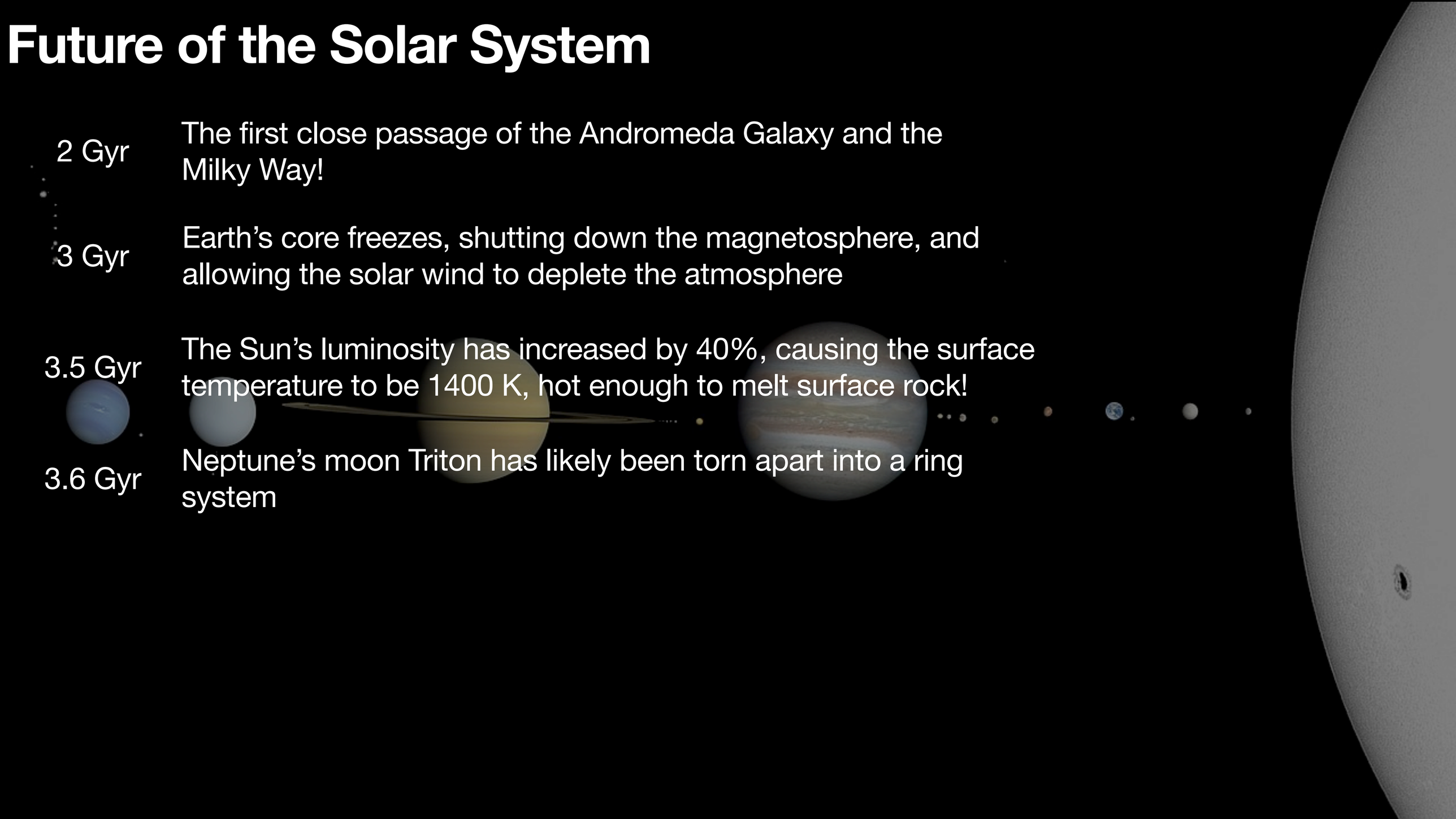

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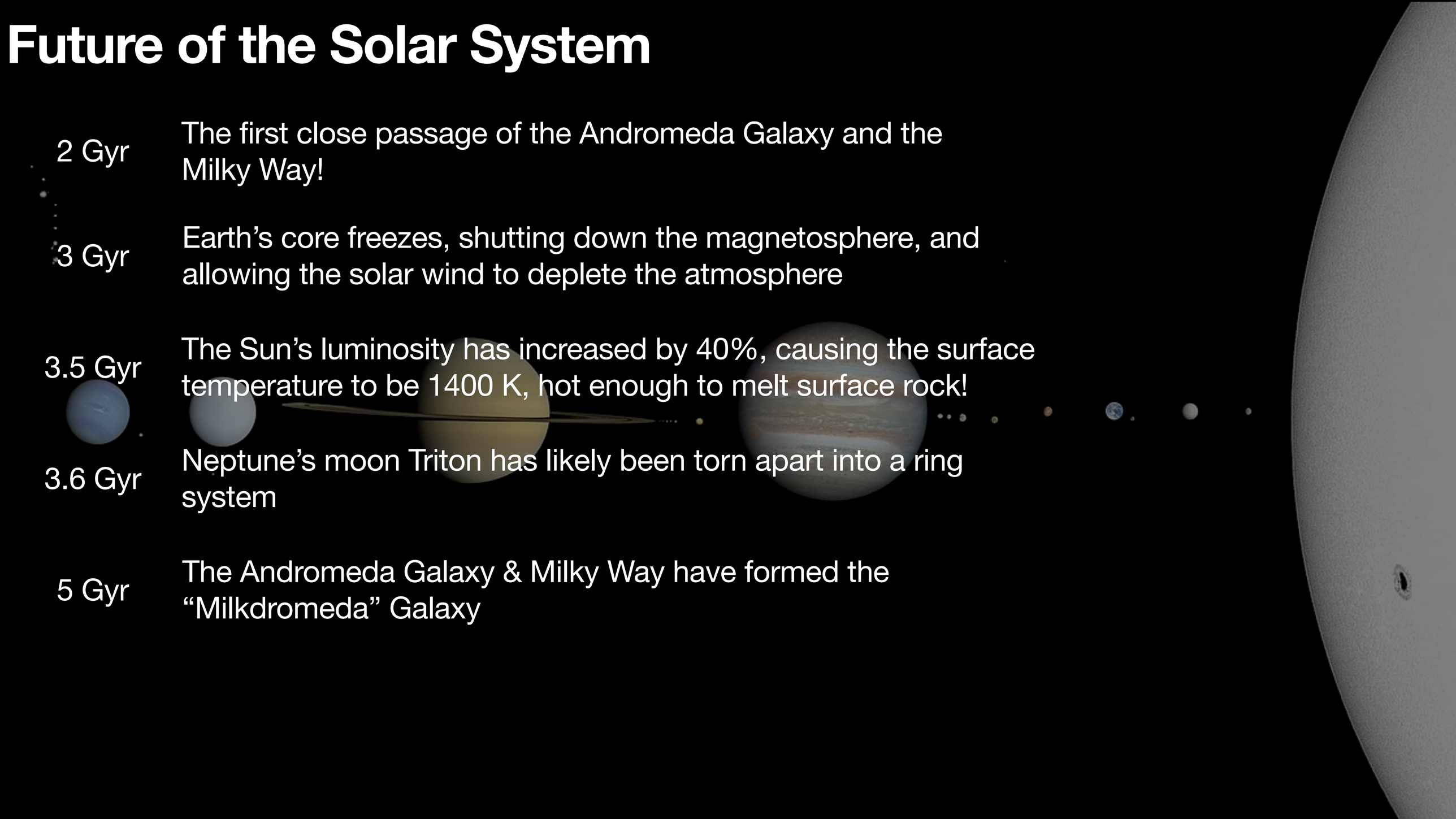

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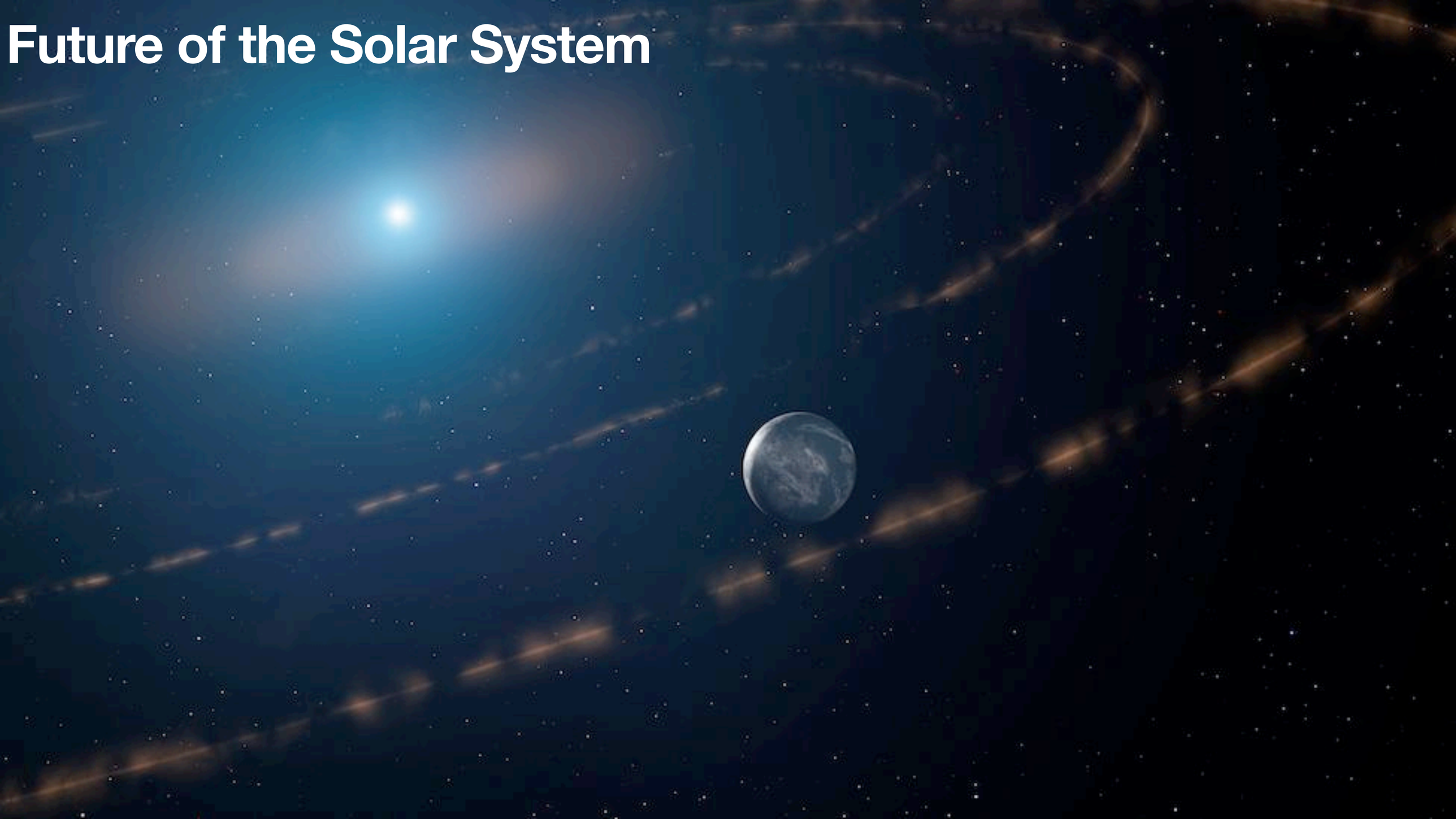
5.4 Gyr	Sun leaves the main sequence and becomes a red giant

Future of the Solar System



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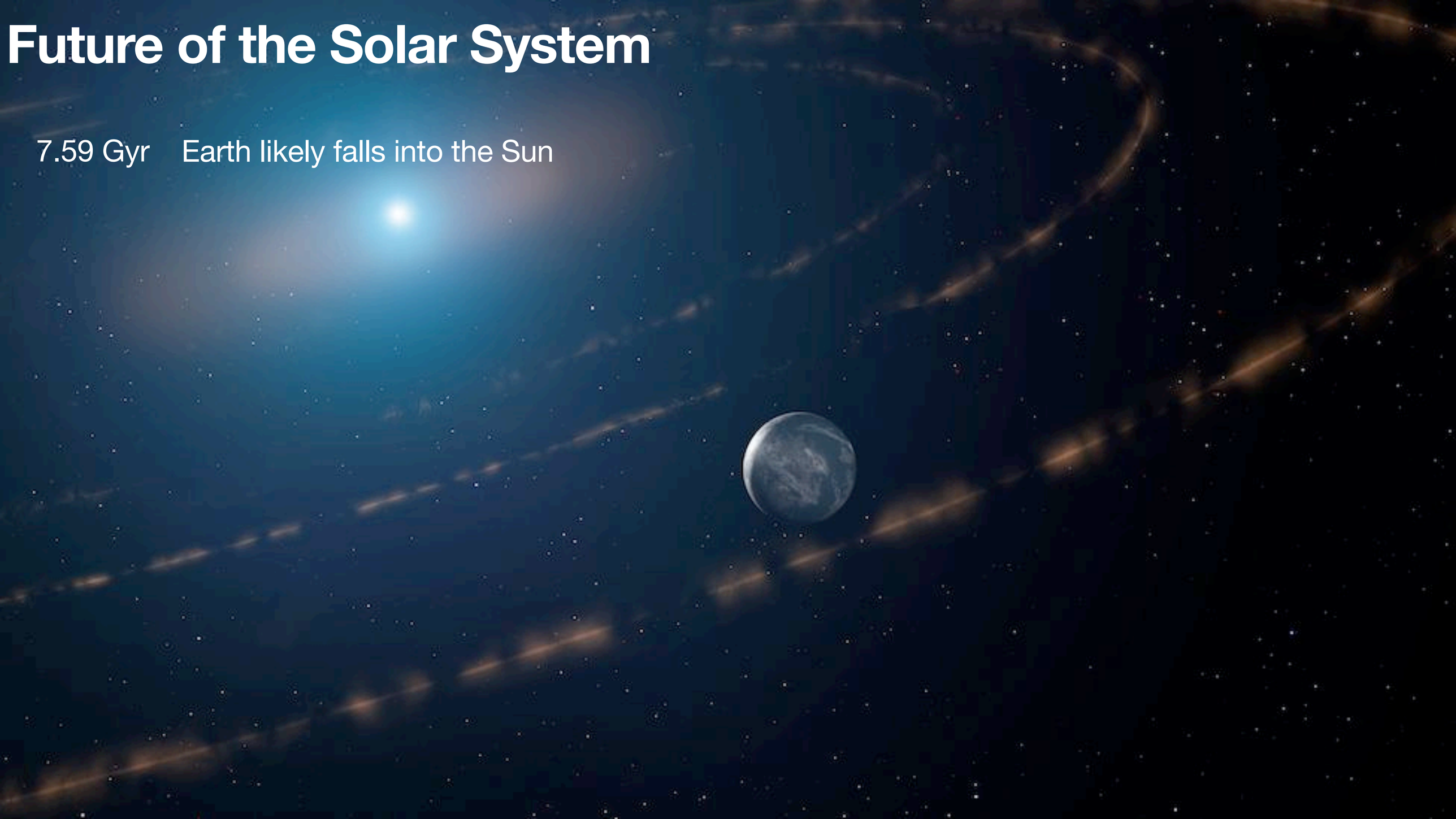
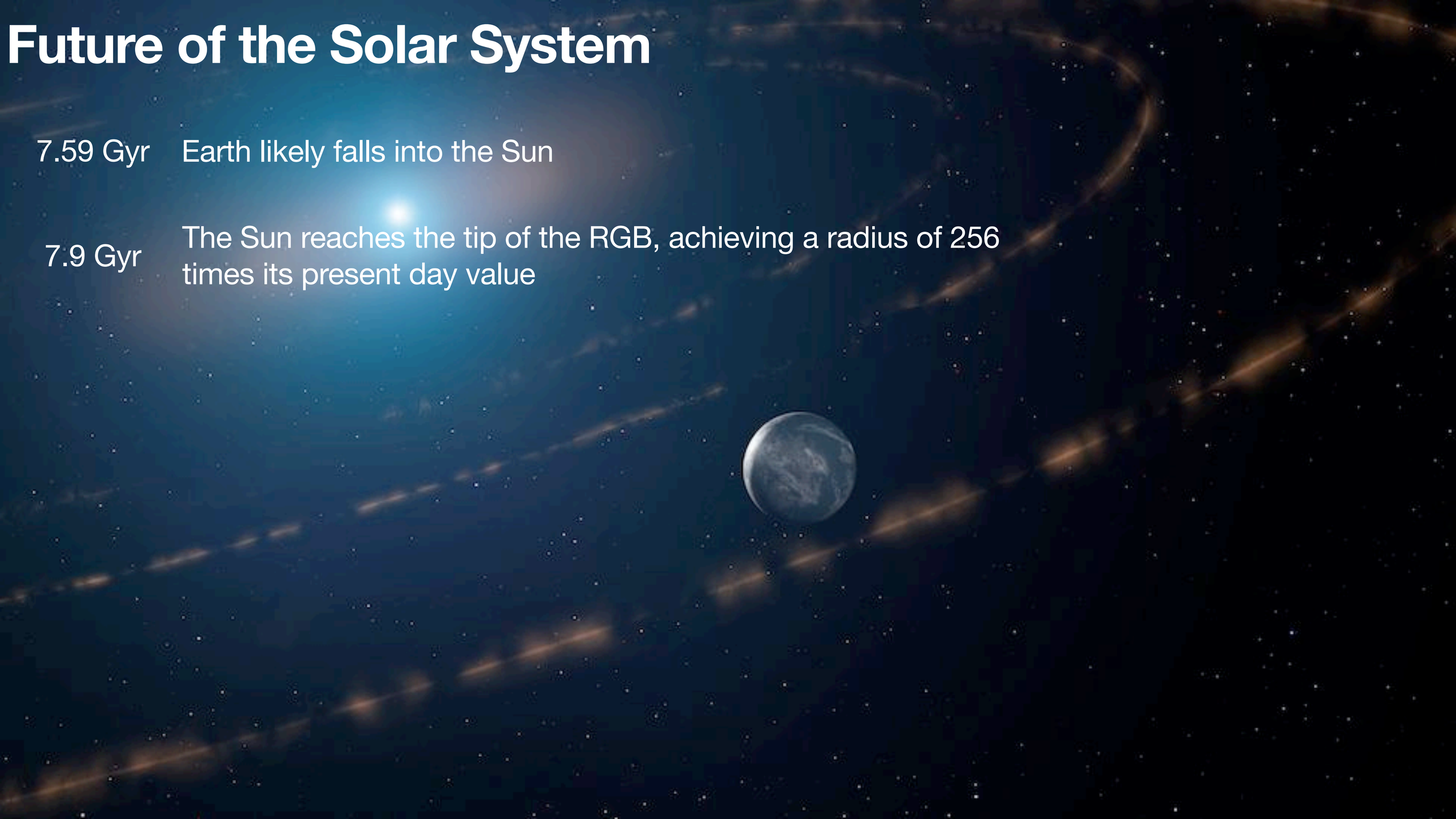


Future of the Solar System

7.59 Gyr	Earth likely falls into the Sun
7.9 Gyr	The Sun reaches the tip of the RGB, achieving a radius of 256 times its present day value



Future of the Solar System

7.59 Gyr	Earth likely falls into the Sun
7.9 Gyr	The Sun reaches the tip of the RGB, achieving a radius of 256 times its present day value
8 Gyr	The Sun becomes a carbon-oxygen white dwarf with about half its current mass

Future of the Universe

Future of the Universe

22.3 Gyr Estimated end of the Universe if the Big Rip happens

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TABLE I: The history and future of the Universe with $w = -3/2$ phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^{5}$ yr	Atoms Formed
~ 1 Gyr	First Galaxies Formed
~ 15 Gyr	*Today*
$t_{rip} - 1$ Gyr	Erase Galaxy Clusters
$t_{rip} - 60$ Myr	Destroy Milky Way
$t_{rip} - 3$ months	Unbind Solar System
$t_{rip} - 30$ minutes	Earth Explodes
$t_{rip} - 10^{-19}$ s	Dissociate Atoms
$t_{rip} = 35$ Gyrs	Big Rip

Caldwell+03

Future of the Universe

22.3 Gyr	Estimated end of the Universe if the Big Rip happens
100 Gyr	All of the ~50 galaxies in the Local Group have merged into a single large galaxy

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1 Tyr	Low estimate for the end of star formation as galaxies run out of gas needed to form stars

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100 Tyr	High estimate for the end of star formation; transition from the Stelliferous Era to the Degenerate Era

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Future of the Universe

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$10^{10^{10^{56}}}$	Quantum tunneling could generate new inflationary events, resulting in new Big Bangs giving birth to new universes