The Frequency of Elephants in the Galaxy

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The human brain is the product of over 3 billion years of evolution…

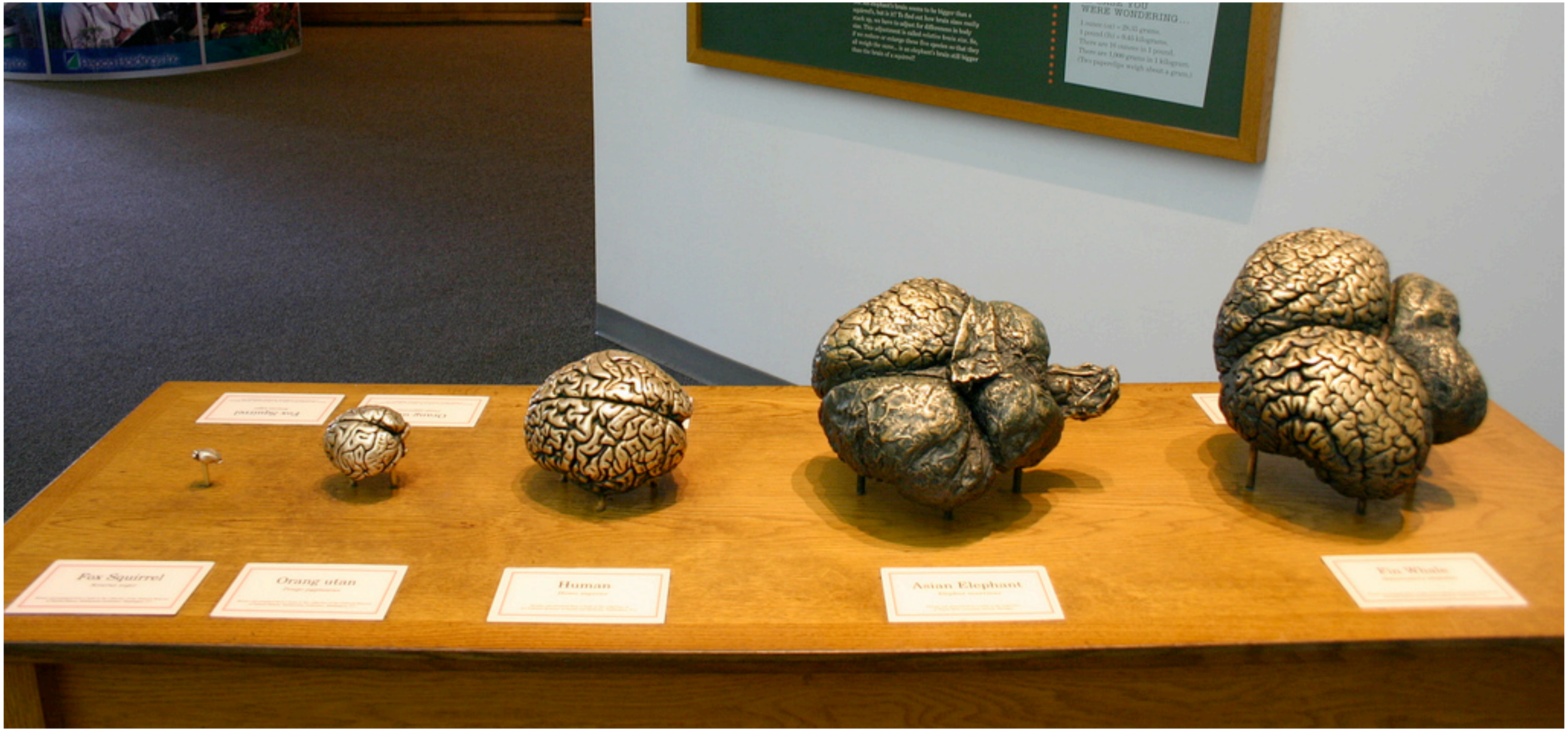
•100 billion neurons in our brain communicate via electro-chemical signals across a parallel network of axon & dendrite wiring that is over 100,000 kilometres long

•Neurons are connected to up to 10,000 others, forming complex multi-voltage, multi-timed logic gates. Calculating rate is ~10^16 operations per second.

•The network speed is slow ~100 milliseconds, but vast and operates in parallel.

•100 trillion synapses form the network junctions and memory – capable of storing at least 100 terabytes of information

•Requires only 30 watts of power



The brain of an elephant is capable of 100 peta-flops. Elephants are smart, so what are the conditions necessary to evolve an elephant and advanced life?

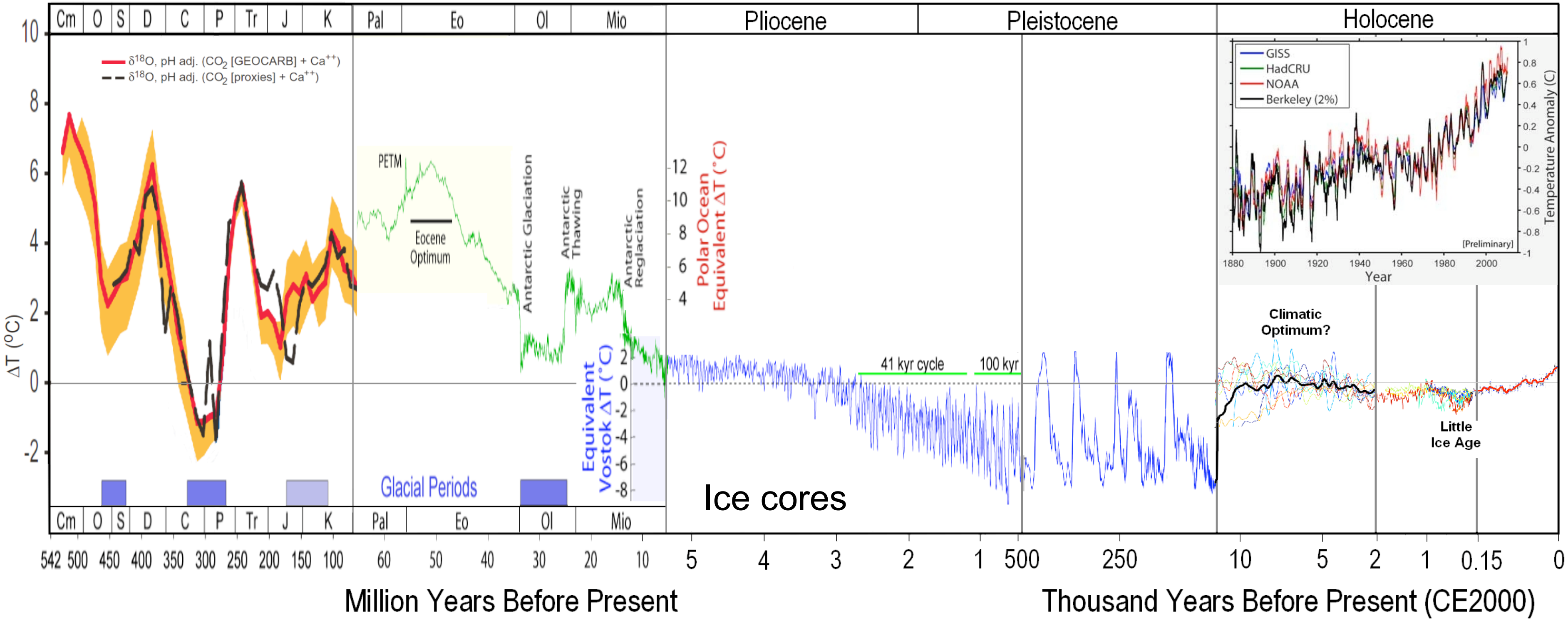
From the emergence of bacteria and the evolution to plants on land, mobility and brains took well over two billion years.

The brain requires about 20% of our energy to function.

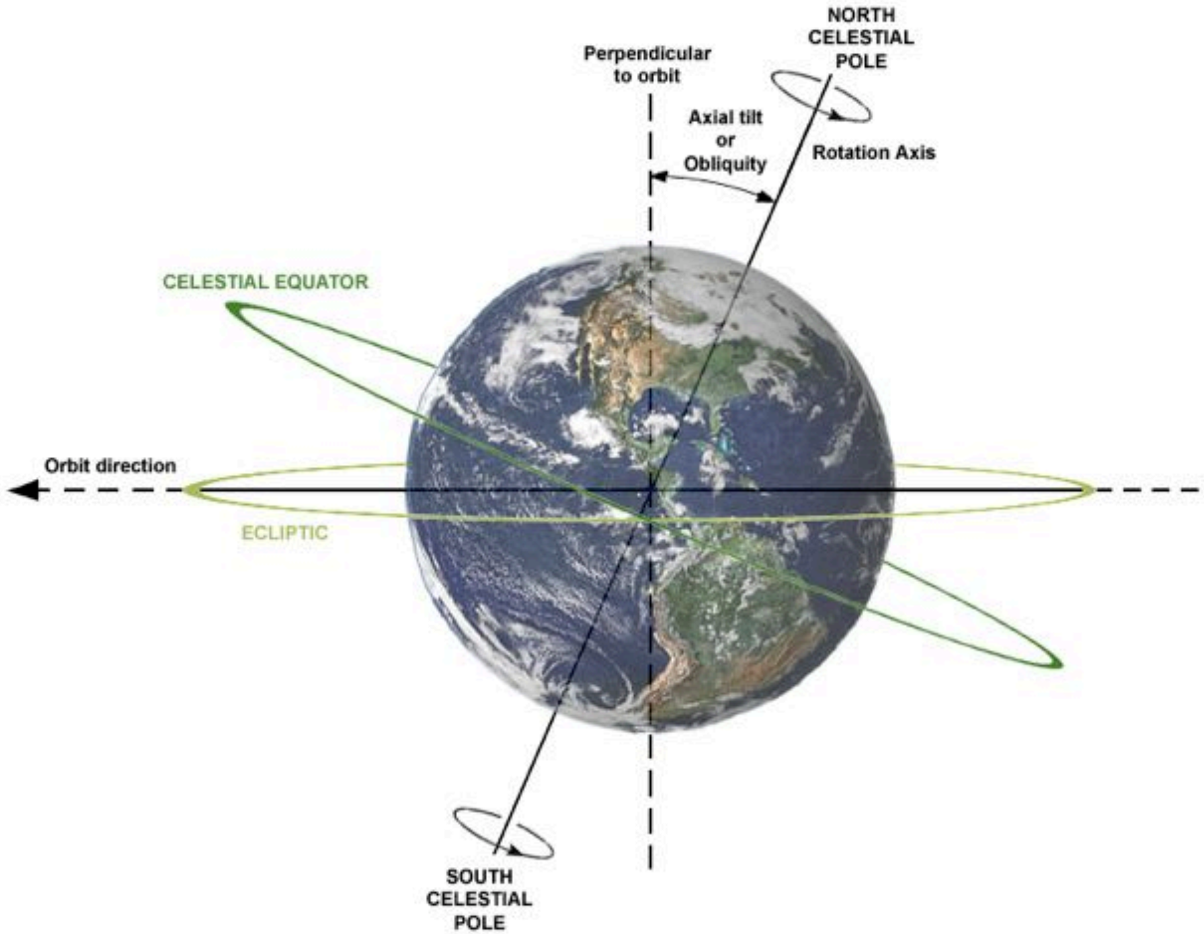
Why is intelligent life rare in our Galaxy???

A stable climate is good for life, especially on land

Temperature of Planet Earth



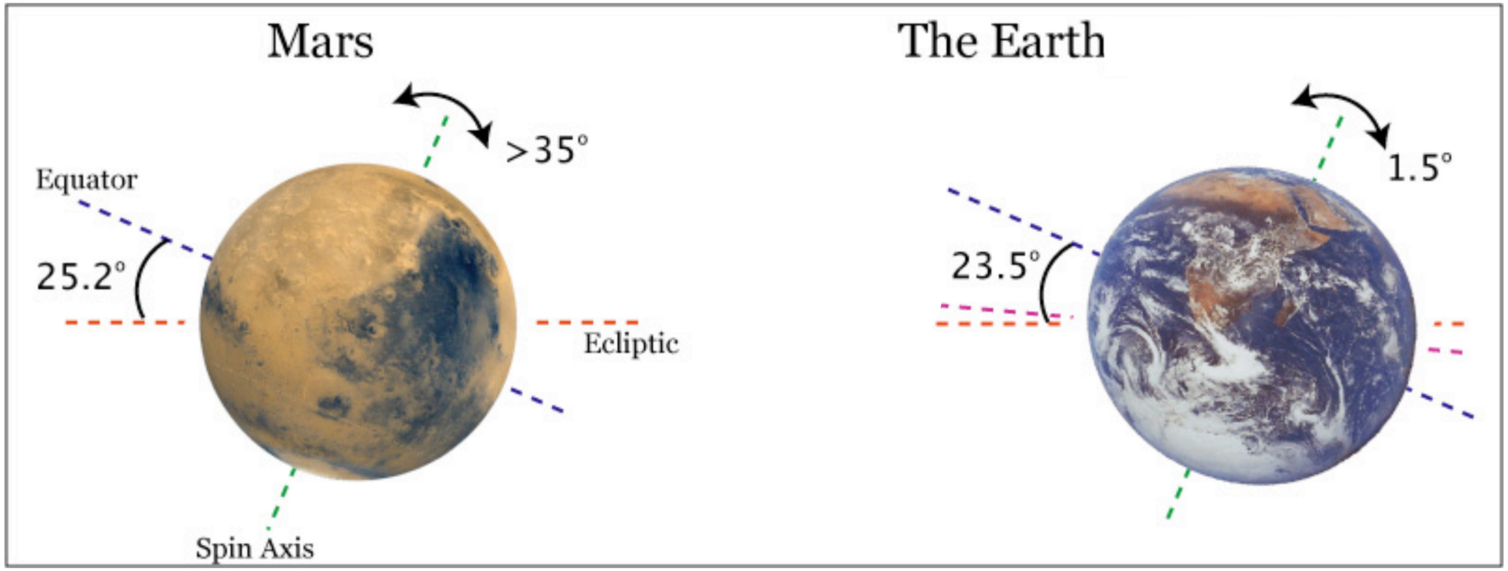
The temperature on Earth varies by at most a few degrees over hundreds of millions of years.

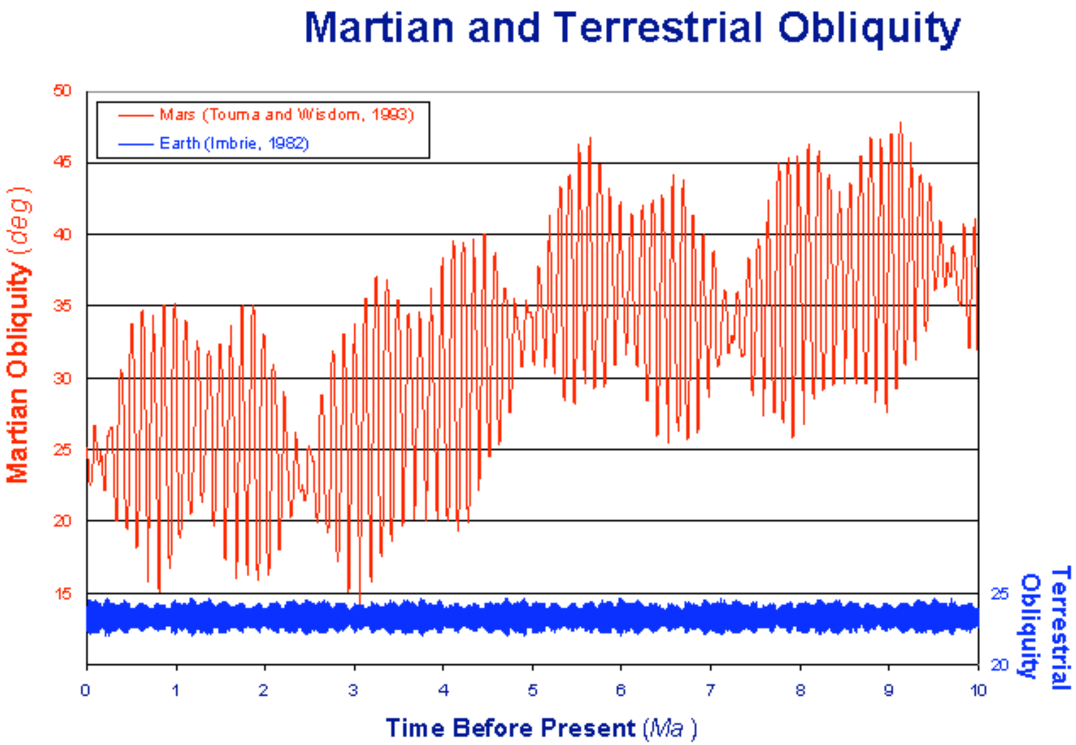


The Earth is an oblate spinning sphere, ~1% wider at the equator.

Resonant ‘spin-orbit’ perturbations from the other planets cause the spin axis (obliquity) to vary.

(The spin axis precesses on a 26,000yr timescale – Milankovitch theory of ice ages….)


Mars
The Earth
>35°
1.5°
Equator
25.2°
23.5°
Ecliptic
Spin Axis


Martian and Terrestrial Obliquity
Mars (Touma and Wisdom, 1993)
Earth (Imbrie, 1982)
Martian Obliquity (deg)
Terrestrial Obliquity
Time Before Present (Ma)
50
45
40
35
30
25
20
15
25
20
0
1
2
3
4
5
6
7
8
9
10

Stabilization of the Earth's obliquity by the Moon

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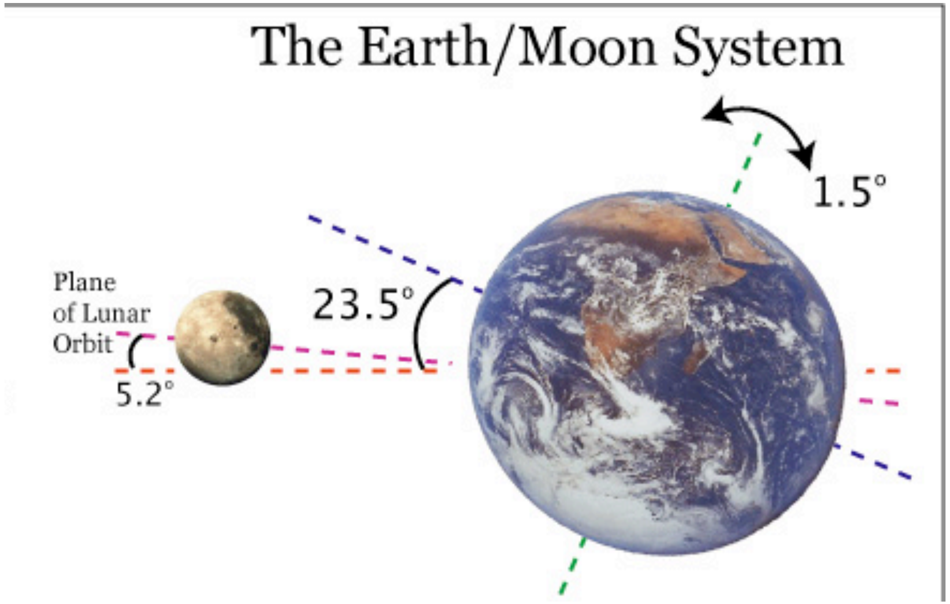
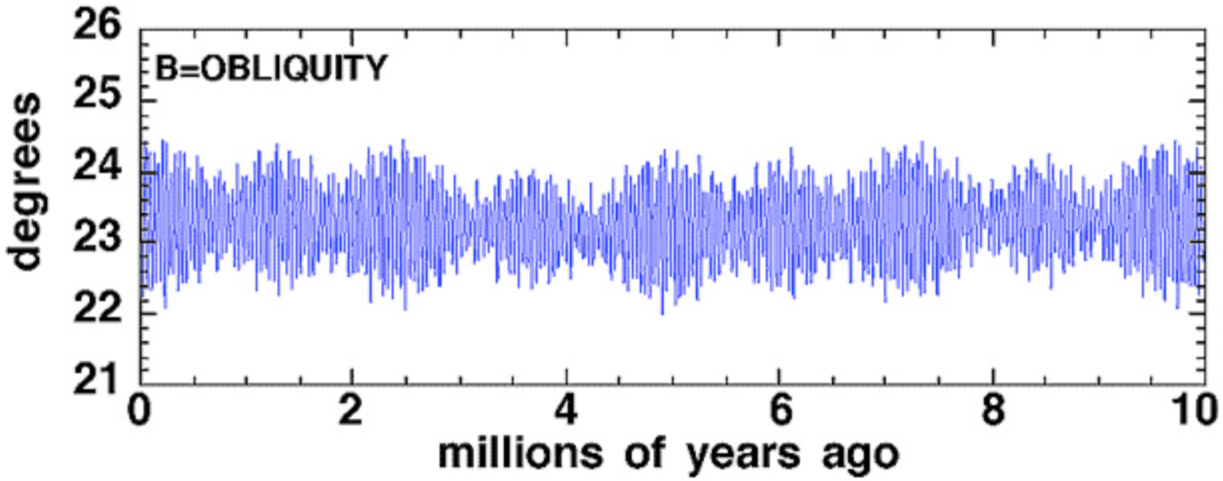
ACCORDING to Milankovitch theory[1,2], the ice ages are related to variations of insolation in northern latitudes resulting from changes in the Earth's orbital and orientation parameters (precession, eccentricity and obliquity). Here we investigate the stability of the Earth's orientation for all possible values of the initial obliquity, by integrating the equations of precession of the Earth. We find a large chaotic zone which extends from 60° to 90° in obliquity. In its present state, the Earth avoids this chaotic zone and its obliquity is essentially stable, exhibiting only small variations of ±1.3° around the mean value of 23.3°. But if the Moon were not present, the torque exerted on the Earth would be smaller, and the chaotic zone would then extend from nearly 0° up to about 85°. Thus, had the planet not acquired the Moon, large variations in obliquity resulting from its chaotic behaviour might have driven dramatic changes in climate. In this sense one might consider the Moon to act as a potential climate regulator for the Earth.





The obliquity of the Earth has not changed by more than a few degrees over the past 4.5 Gyrs.

This is thanks to the gravitational torque from our massive Moon.

In the absence of our Moon, the Earth would spin chaotically and its obliquity would change by 80 degrees in less than a million years.

The spin-axis variations are caused by perturbations from the other planets.

Earth-Moon to scale: Image taken from Mars express satellite

The Moon formed from a giant impact between a Mars sized planet called ‘Theia’ and the proto-Earth about 50-100 million years after the Sun formed. (Isotopes of Moon + upper Earth mantle identical)

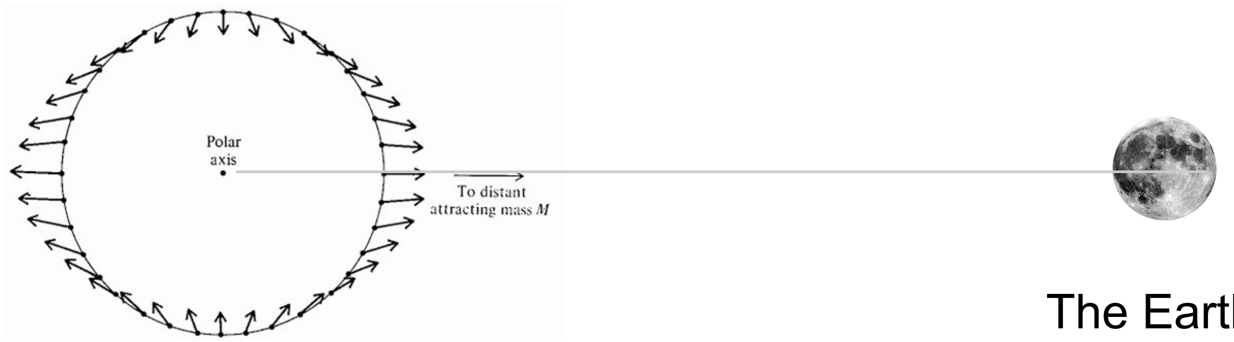
The Moon formed just beyond the Hill radius, about ten times closer than its current position.

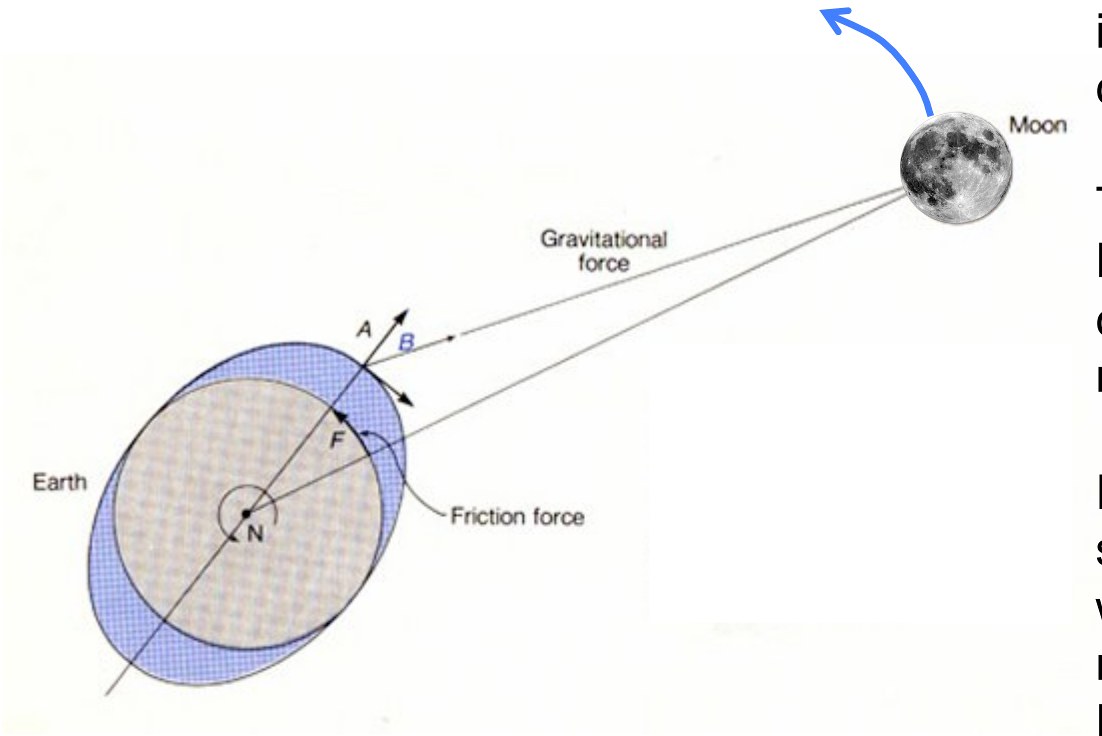
At this time the Earth was spinning about 5 times faster and the strength of the tides was 1000 times larger!

We know there were ocean’s and sedimentary rock over 4 billion years ago.

The Moon caused >100m high tidal waves that crossed the Earth’s surface several times per day, possibly promoting the cyclic replication of early biomolecules in tide pools and profoundly affecting the early evolution of life.

At least for the first billion years, nothing was crawling out of the ocean…!





The Earth and Moon have lost spin angular momentum thanks to the tidal bulges and energy dissipation. (This is shown in the growth rings of fossil coral for example.)

The Moon is now tidally locked to the Earth and has drifted away into its current position. (4cm/year lunar ranging).

In a few billion years, the Earth-Moon system will be fully tidally locked when our day becomes about two months long and one side of the Earth always faces the Moon.

From planetesimals to terrestrial planets: N-body simulations including the effects of nebular gas and giant planets

Ryuji Morishima[1,2], Joachim Stadel[3], Ben Moore[3]

Icarus 2010

How common are Earth-Moon planetary systems?

S.Elser[a,*], B.Moore[a], J.Stadel[a], R.Morishima[b]

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Icarus 2011

How common are Earth like planets? How likely is our Moon?

•First stage – runaway growth and interaction with the gaseous nebula surrounding the sun. Follow as many bodies as possible, track collisions and growth/disruption/friction.

•Include gas giant planets on different orbits (circular/eccentric etc)

•Second stage – long term evolution of a few bodies. Small N, many dynamical times, high precision.

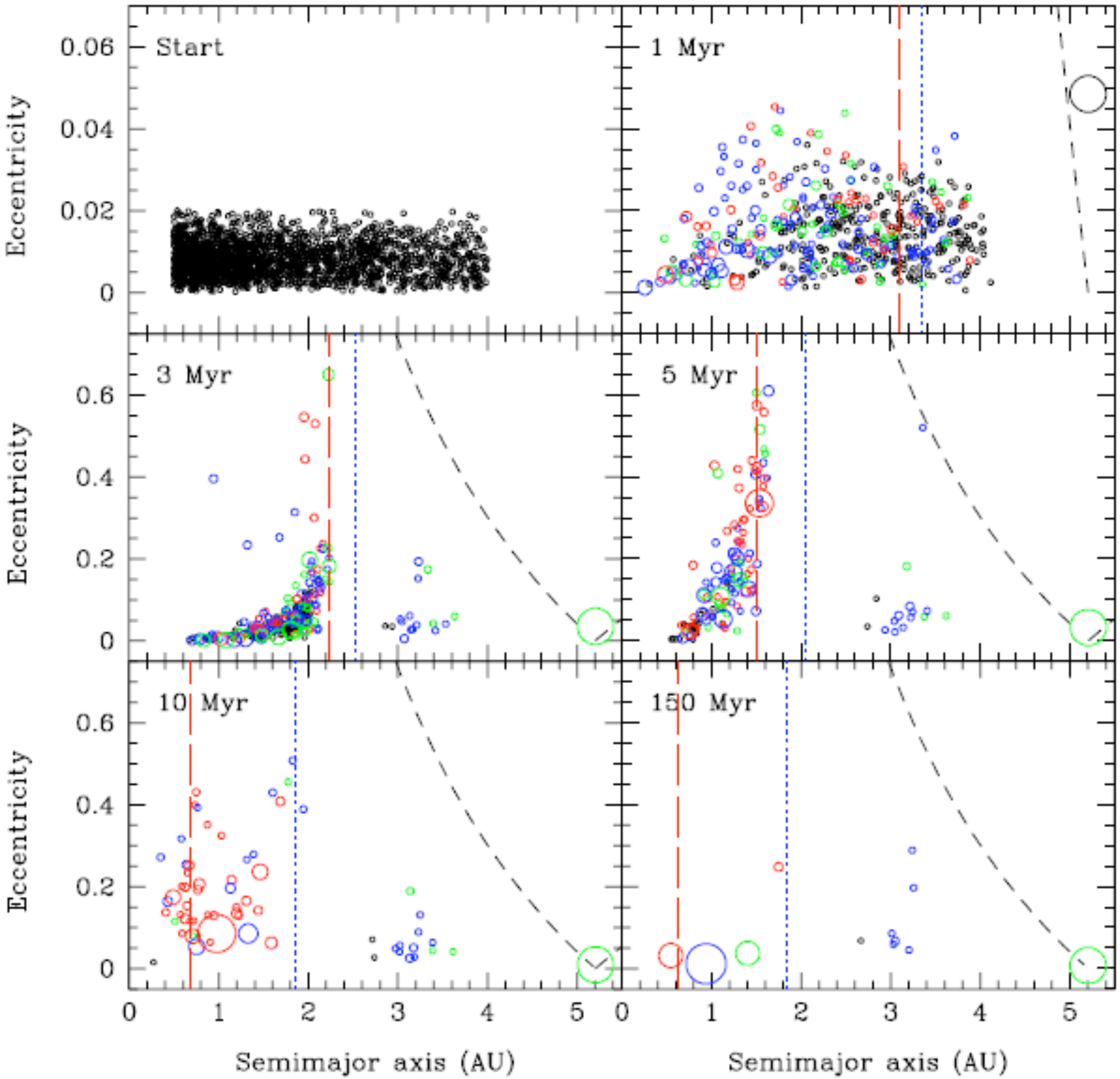
•100 simulations, explore different initial configurations (biggest unknown….we know far more about the initial conditions that lead to structure formation in the universe than we do for planetary systems).

•Mixed variable symplectic integrator ‘SyMBA’ splits the Hamiltonian into the Keplerian motion around the star and perturbations from other planets.

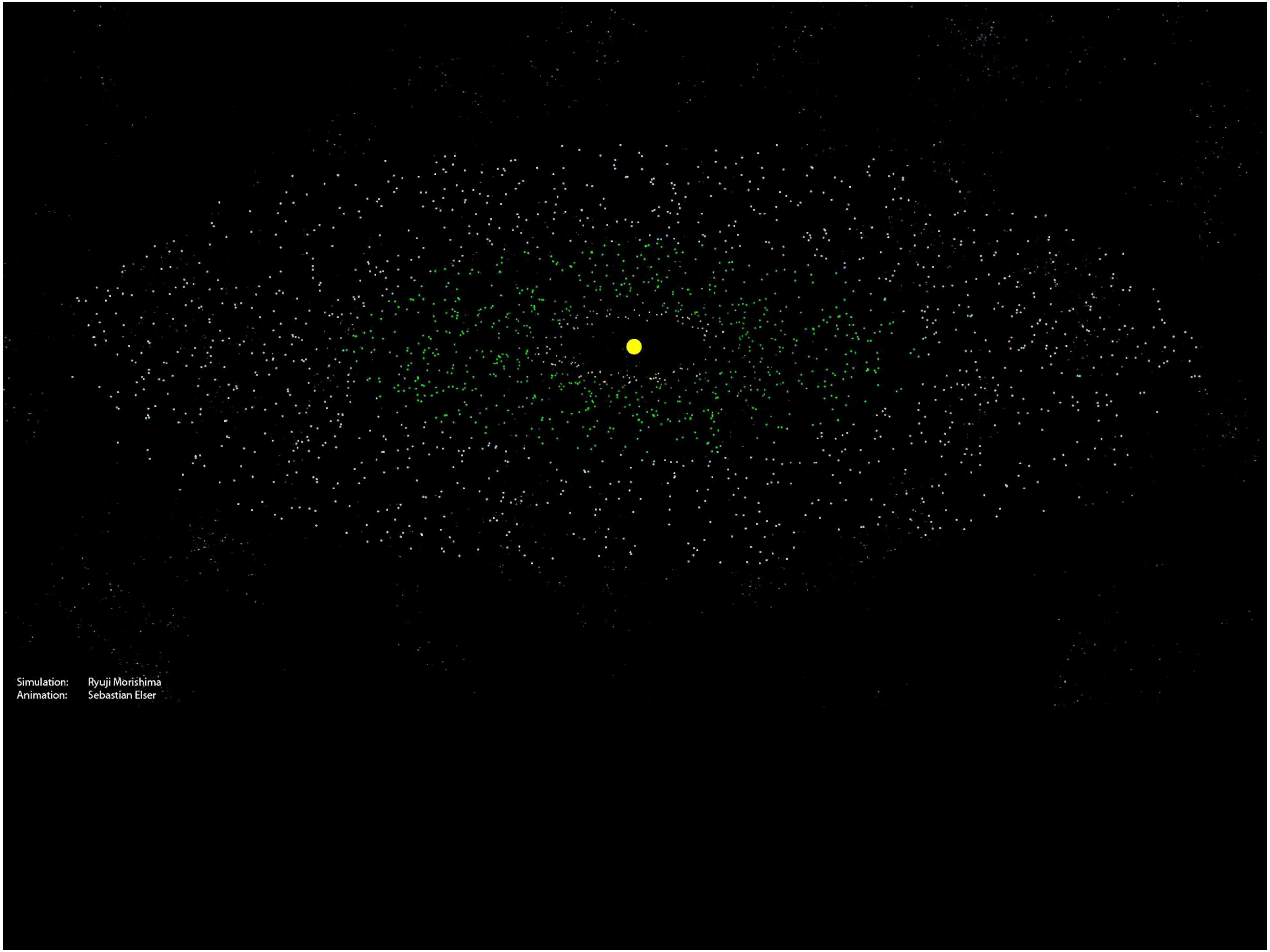
•Timestep 6 days, sufficient for collision detection

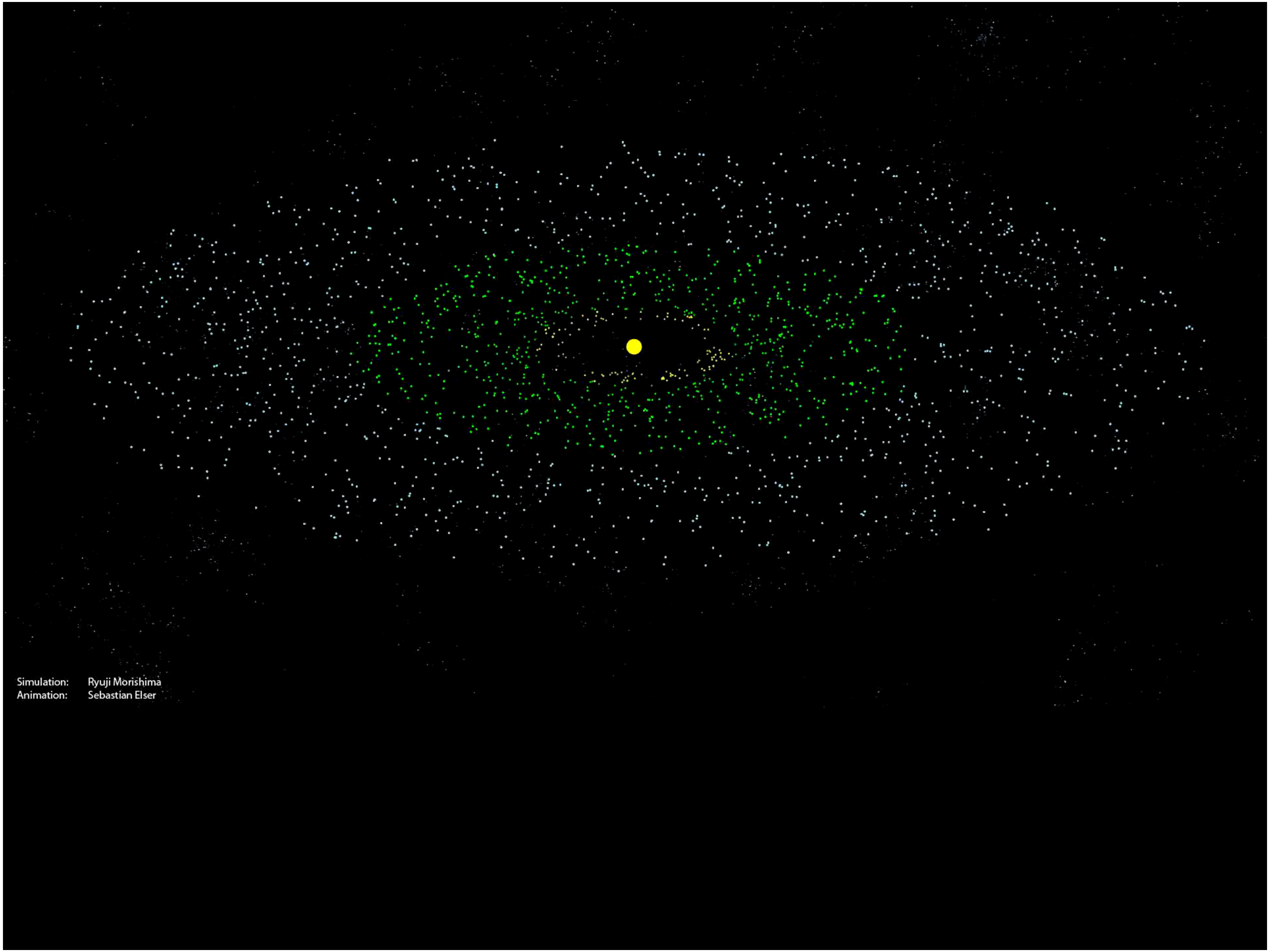
•Parallel simulations, each takes 3 months

•Have to integrate >10^12 orbits accurately



Start
1 Myr
3 Myr
5 Myr
10 Myr
150 Myr
Eccentricity
Semimajor axis (AU)
0
0.02
0.04
0.06
0.2
0.4
0.6
1
2
3
4
5


Simulation: Ryuji Morishima
Animation: Sebastian Elser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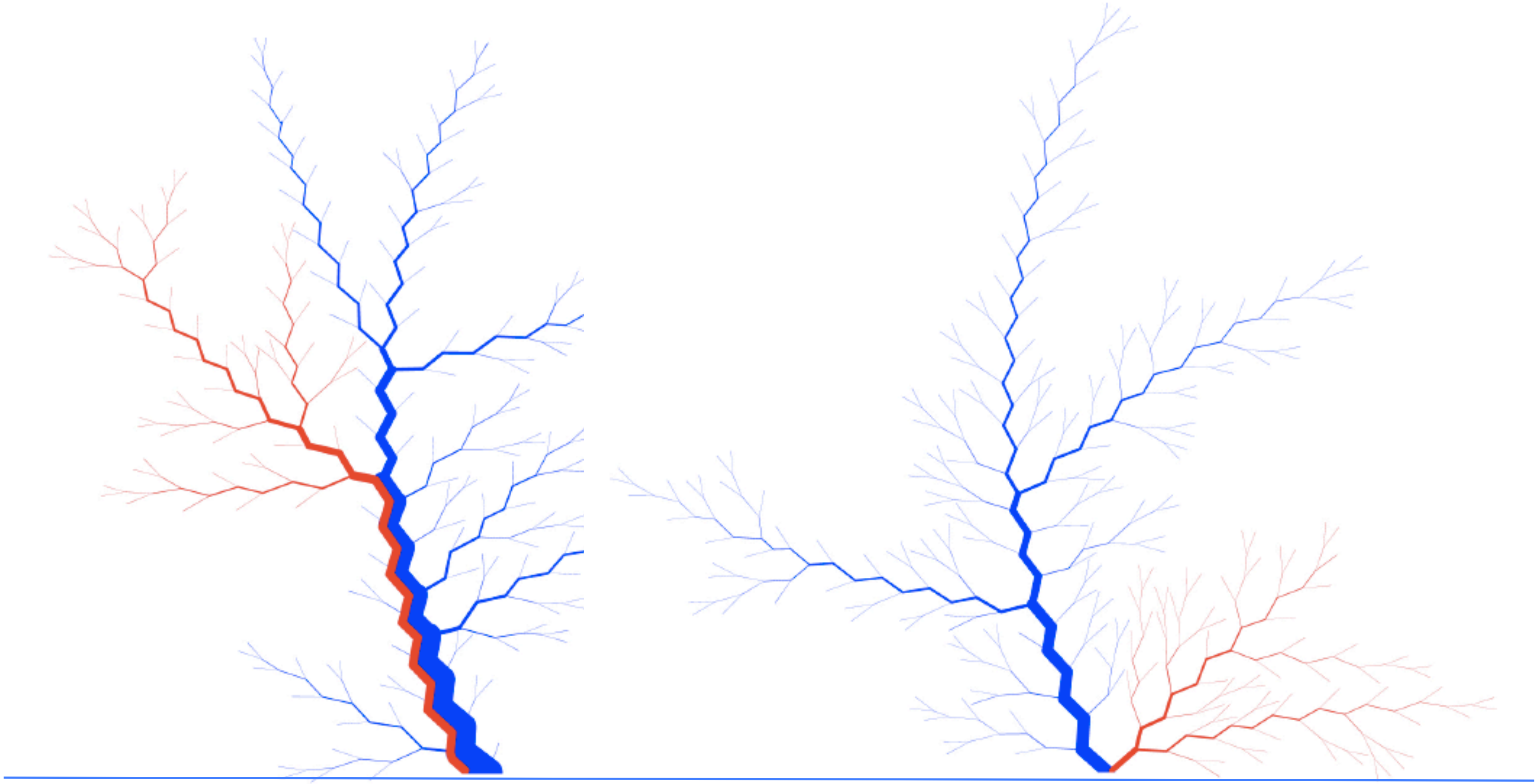
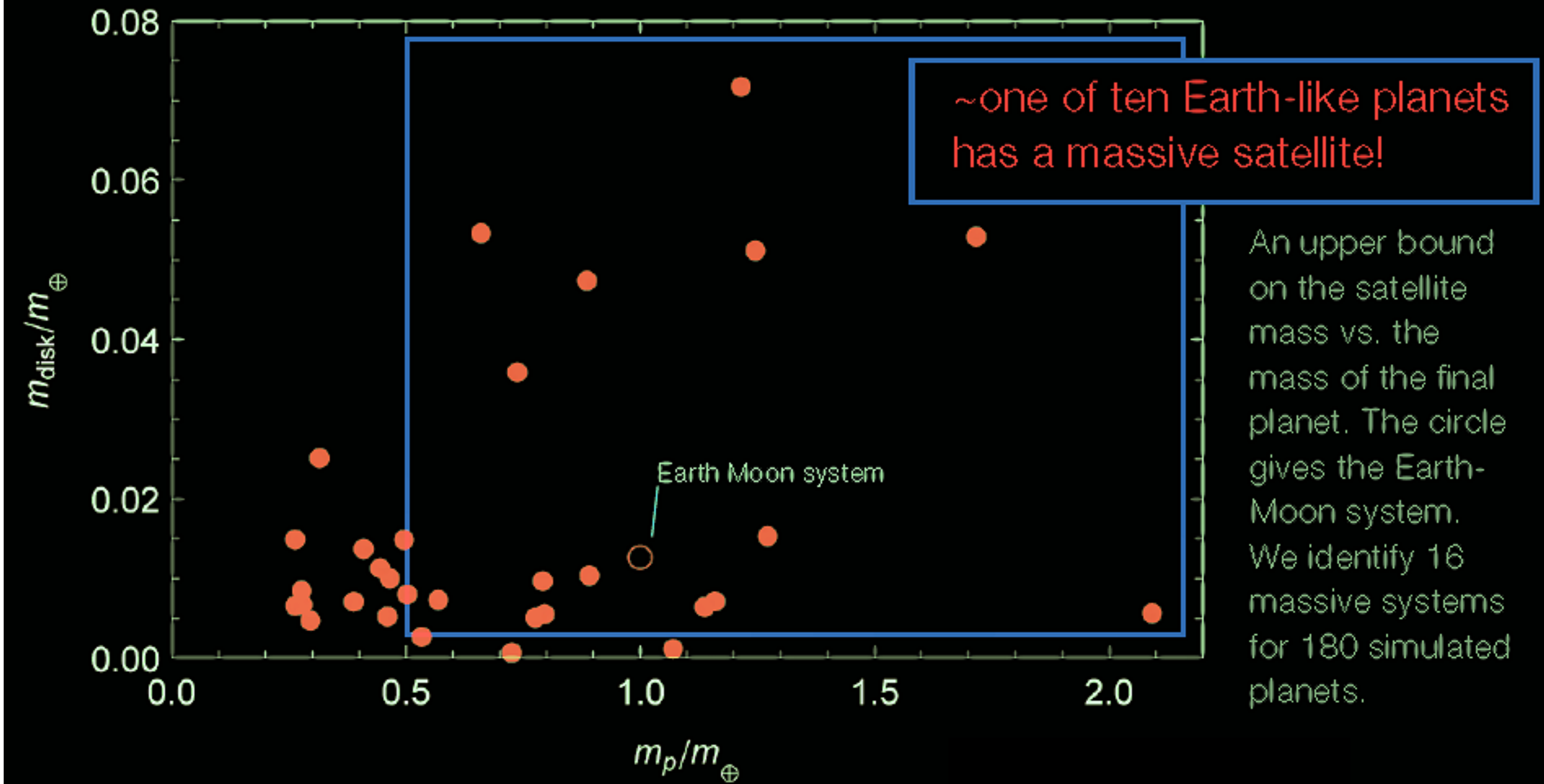


Merger trees that show the hierarchical build up of the final Earth mass planets. The impactor that would lead to the formation of a stabilising Moon is shown in red. Each kink is a collision and the length is proportional to the time between collisions whilst the thickness is proportional to the mass of the emerging planet.



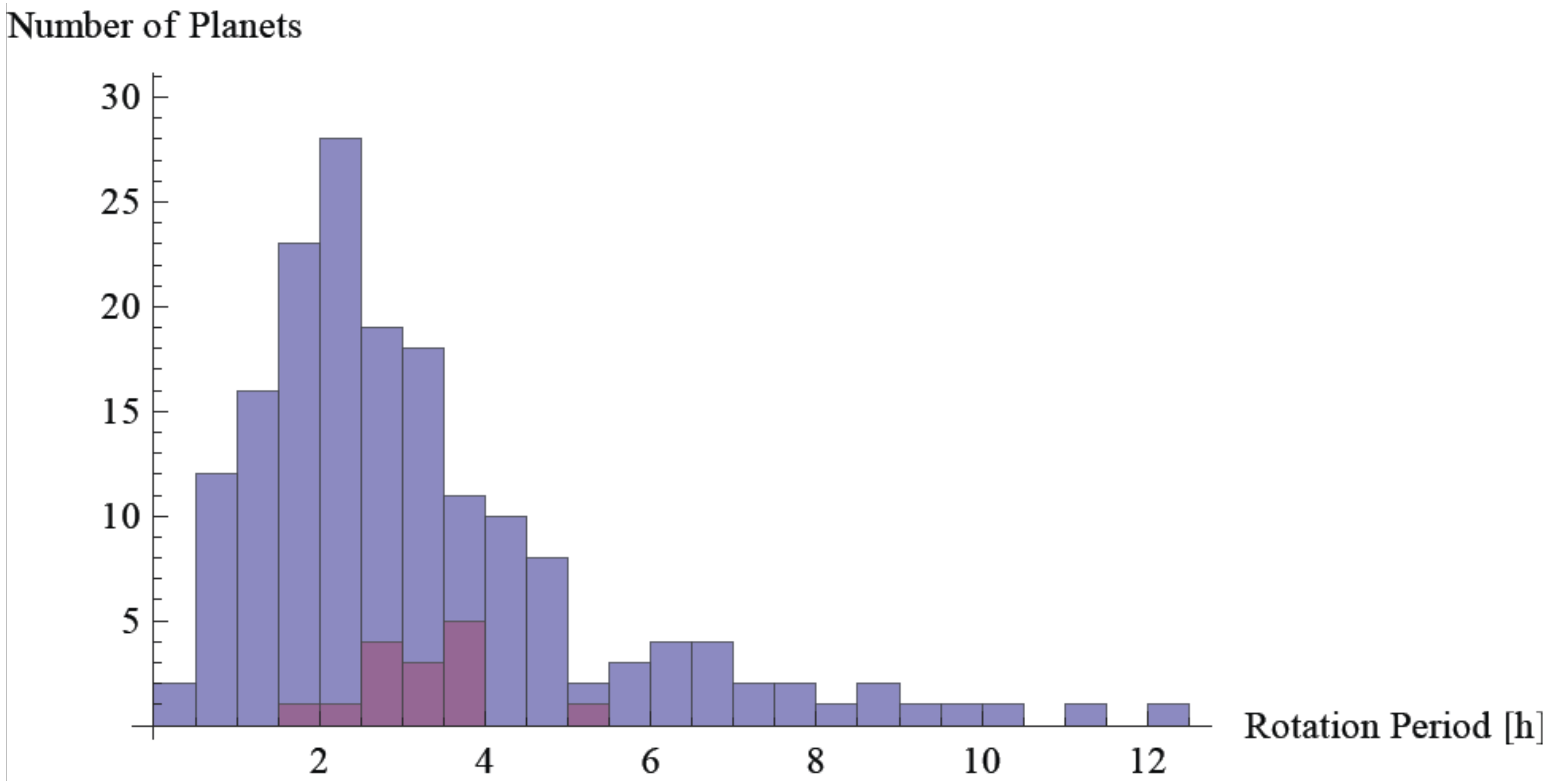
SPH simulations of Canup et al allow us to determine the mass of the resulting Moon and its distance from the parent planet.

We can then calculate how long the resulting Moon would stabilise the planet.

Some Moon's are 'lost' because of later giant impacts.

Some Moon's are retrograde and crash onto the surface of the planet.

Some Moon's are too small.


Number of Planets
30
25
20
15
10
5
2
4
6
8
10
12
Rotation Period [h]

	Gyrs	Timeline
	13.7	Origin of space/time/matter
	13.6	First dark matter haloes
	13.5	First stars
	12.0	First galaxies
	8.00	Half of the stars in the MW have formed
Tidal waves several times per day	4.50	Sun and gas giants in the solar system
	4.40	Theia collides with the Earth to form Moon
	4.30	Earth's surface solidifies/water/atmosphere
	3.70	Bacteria/single celled structures
3 billion years to develop mobility.	2.30	Eukaryotes/multicellular creatures
	0.60	Cambrian explosion/mobility/brains
	0.47	Land plants
	0.35	Amphibians explore land
	0.25	Dinosaurs
	0.06	No dinosaurs
	0.05	Hominids diverge from apes; elephants
	0.01	Fire

•Earth like planets occur frequently around single stars

•Usually at least one rocky planet in the habitable zone around each star.

•One in ten rocky planets has a massive Moon, spinning the correct way that can stabilise its obliquity for several billion years.

•Prospects for advanced life on land, e.g. elephants, on other planets are good….at least one billion planets with long term stable climates in our Galaxy

•Ocean's less effected by obliquity changes, but its difficult to control fire underwater…

•You would not be here if it were not for our Moon; life on the surface of the Earth would be unlikely

•There are about 10 billion solar systems with the conditions that can lead to elephants and intelligent civilisations.