habitability: a cosmological perspective

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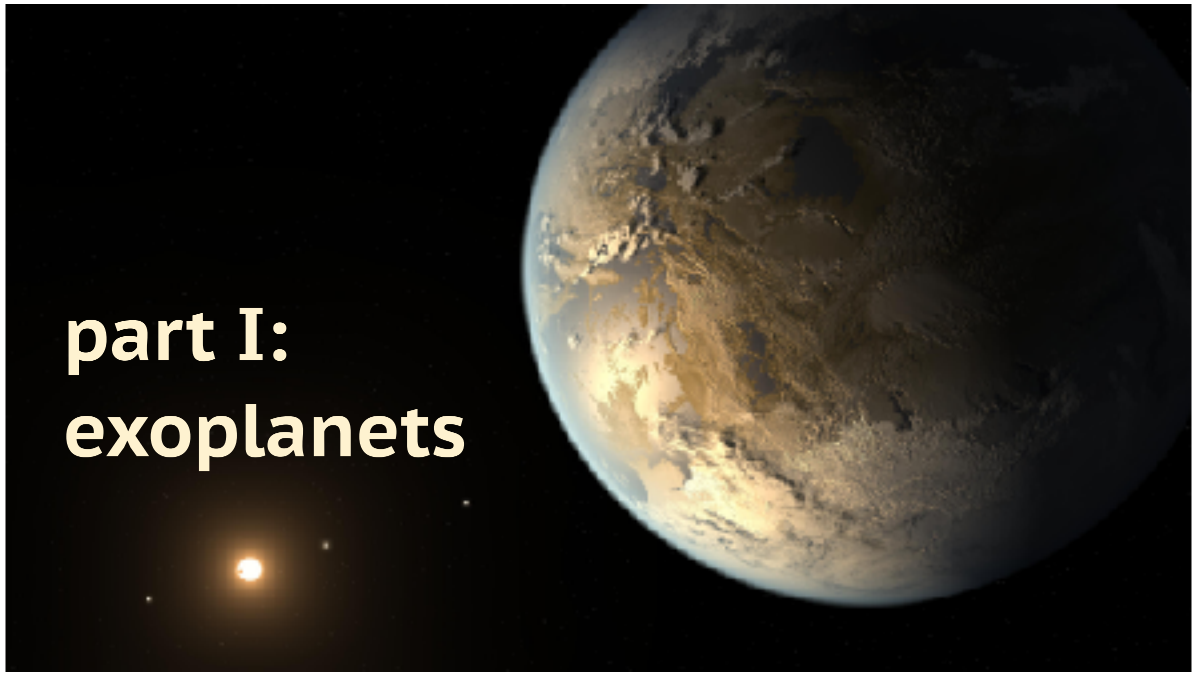
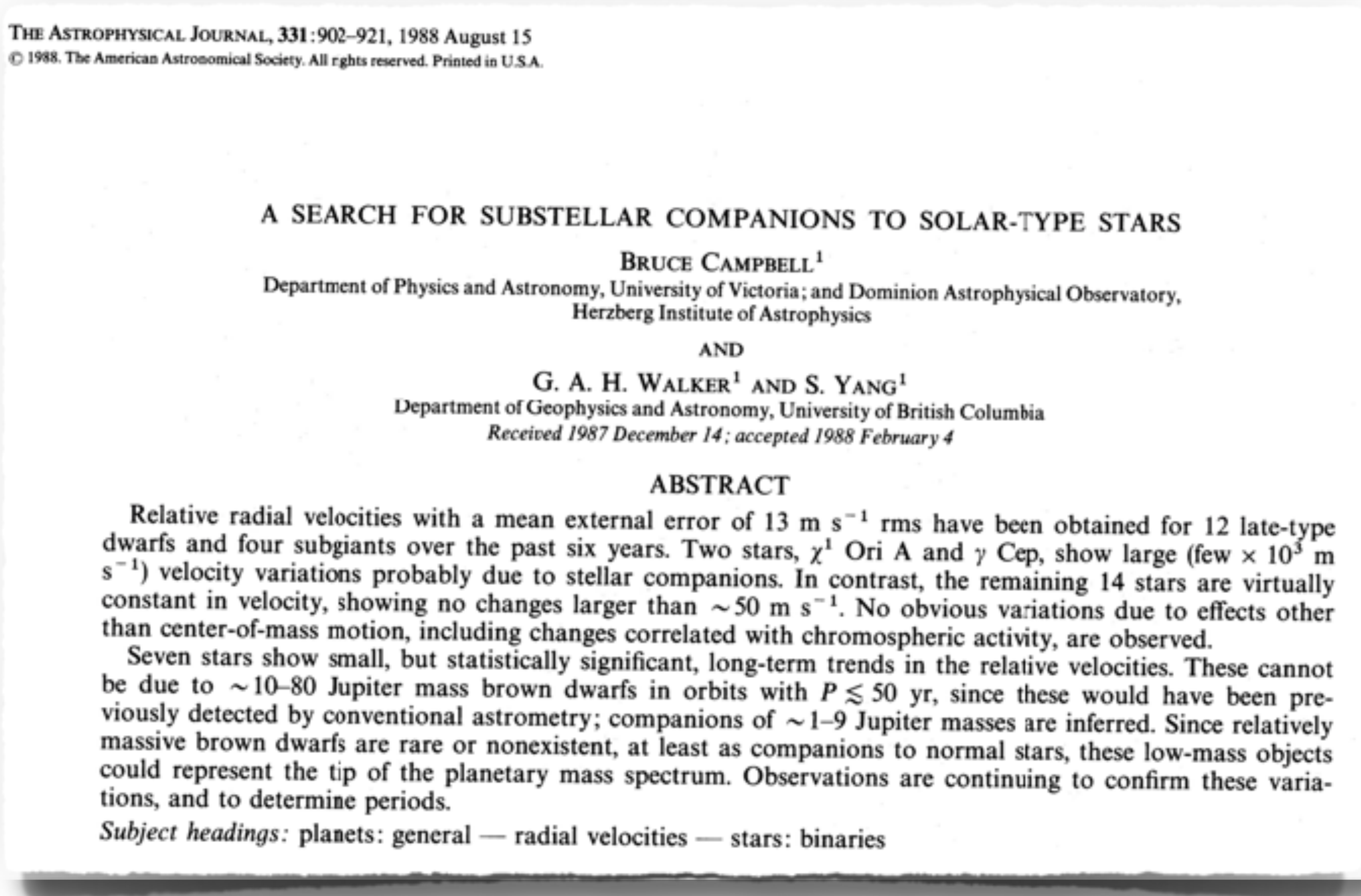
structure of this talk



part I: exoplanets

the first exoplanet


THE ASTROPHYSICAL JOURNAL, 331:902–921, 1988 August 15
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A SEARCH FOR SUBSTELLAR COMPANIONS TO SOLAR-TYPE STARS

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ABSTRACT

Relative radial velocities with a mean external error of 13 m s^{-1} rms have been obtained for 12 late-type dwarfs and four subgiants over the past six years. Two stars, χ^1 Ori A and γ Cep, show large (few $\times 10^3$ m s^{-1}) velocity variations probably due to stellar companions. In contrast, the remaining 14 stars are virtually constant in velocity, showing no changes larger than ~50 m s^{-1}. No obvious variations due to effects other than center-of-mass motion, including changes correlated with chromospheric activity, are observed.

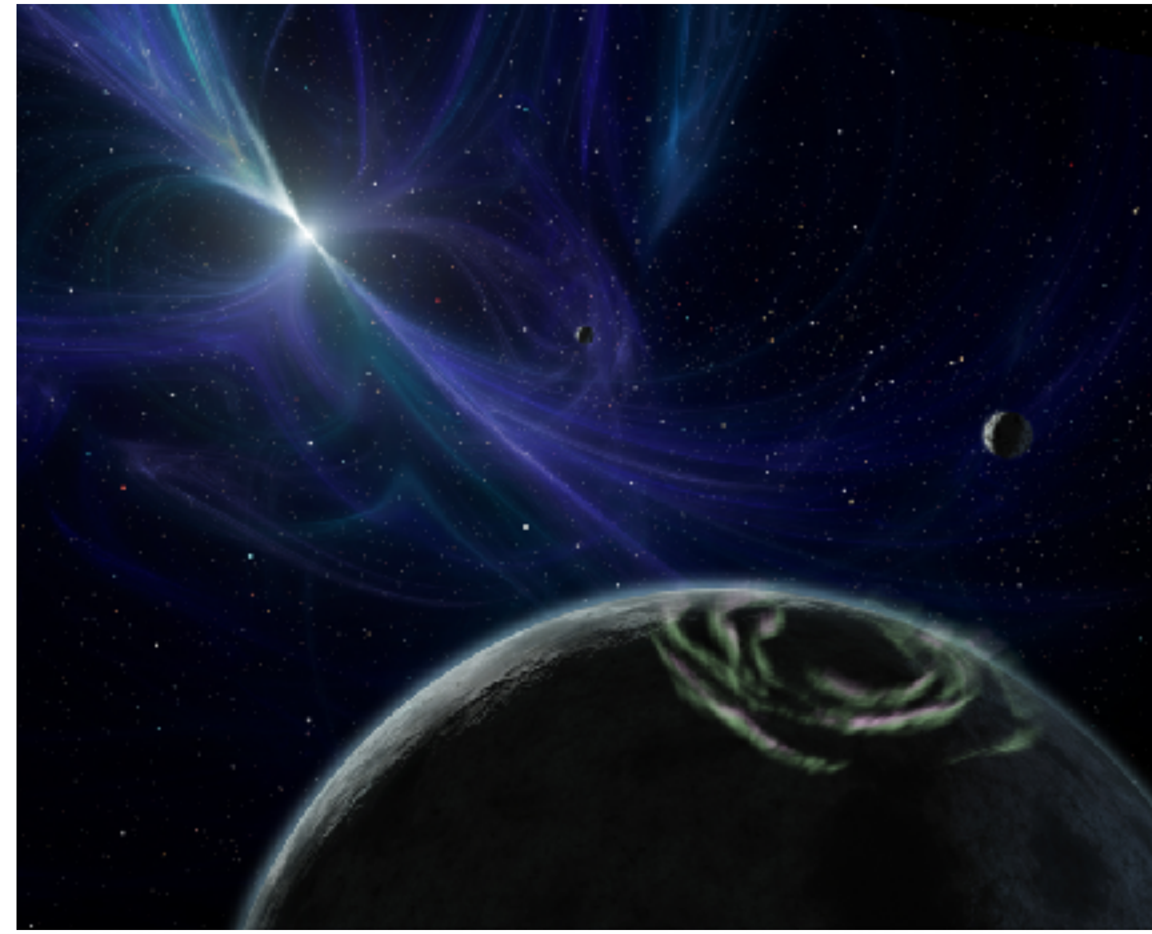
Seven stars show small, but statistically significant, long-term trends in the relative velocities. These cannot be due to ~10–80 Jupiter mass brown dwarfs in orbits with $P \lesssim 50$ yr, since these would have been previously detected by conventional astrometry; companions of ~1–9 Jupiter masses are inferred. Since relatively massive brown dwarfs are rare or nonexistent, at least as companions to normal stars, these low-mass objects could represent the tip of the planetary mass spectrum. Observations are continuing to confirm these variations, and to determine periods.

Subject headings: planets: general — radial velocities — stars: binaries

- discovered in 1988
- the authors did not claim their observation was an exoplanet
- unambiguous confirmation came only in 2003

the second exoplanet

- discovered by Aleksander Wolszczan and Dale Frail (Jan/1992)
- two rocky planets orbiting PSR1257+12 in the constellation of Virgo
- host star is a pulsar → **planets not very hospitable**



letters to nature

Nature **355**, 145 - 147 (09 January 1992); doi:10.1038/355145a0

A planetary system around the millisecond pulsar PSR1257 + 12

A. WOLSZCZAN* & D. A. FRAIL†

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†National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA

MILLISECOND radio pulsars, which are old (~10^9yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257 +12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_{\oplus}$ and 3.4 $M_{\oplus}$ where $M_{\oplus}$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829–10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

the third exoplanet

- planet PSR B1620-26b (a.k.a. Methuselah)
- 2.5 the mass of Jupiter
- constellation of Scorpius
- host stars: PSR B1620-26A (pulsar) and WD 1620-26 (white dwarf)
- first planet found to orbit a binary system

the first exoplanets orbiting a sun-like star

- 1995: first exoplanet orbiting a **sun-like** star is discovered
- host star: 51 Pegasi
- 2019: Nobel Prize in Physics

ARTICLES

A Jupiter-mass companion to a solar-type star

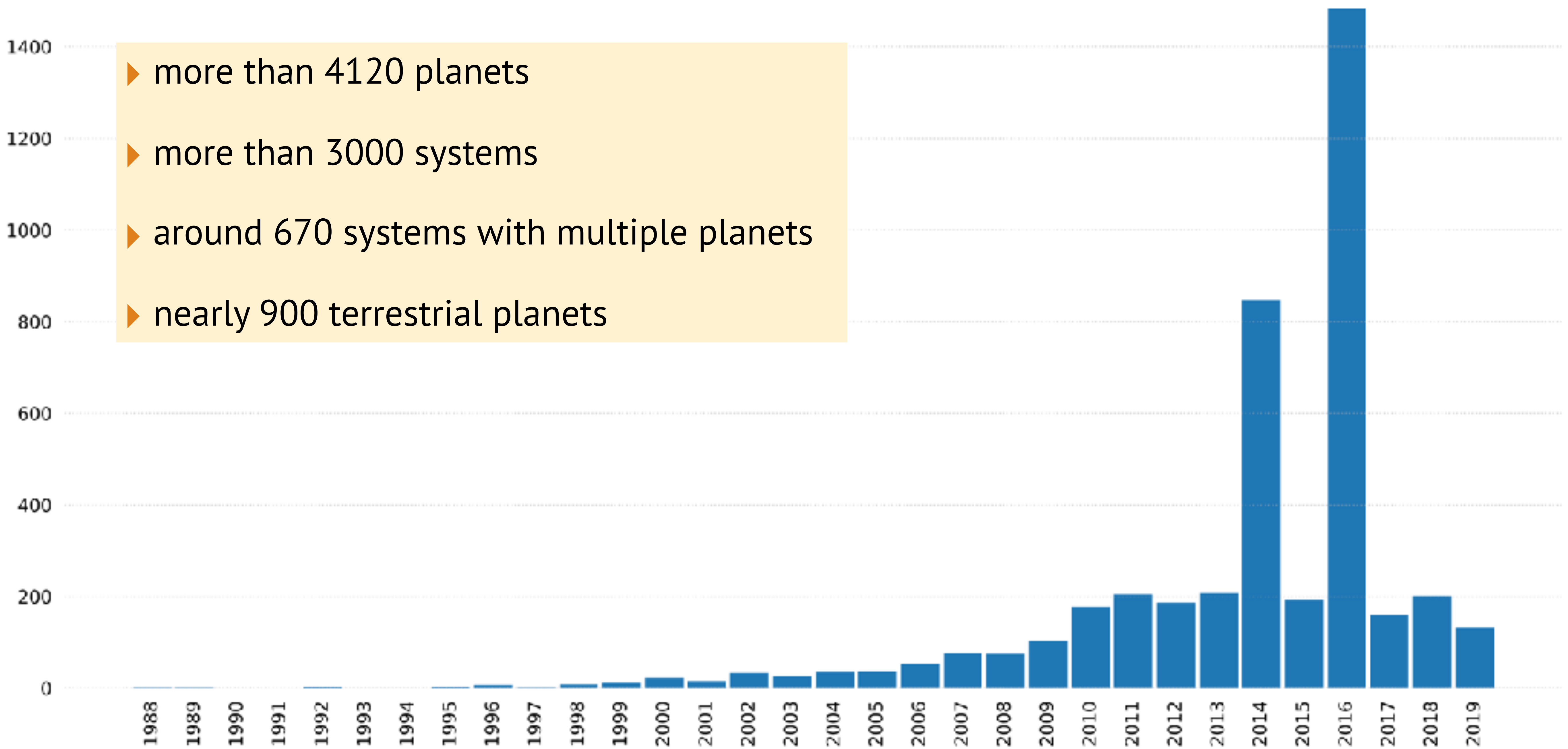
Michel Mayor & Didier Queloz

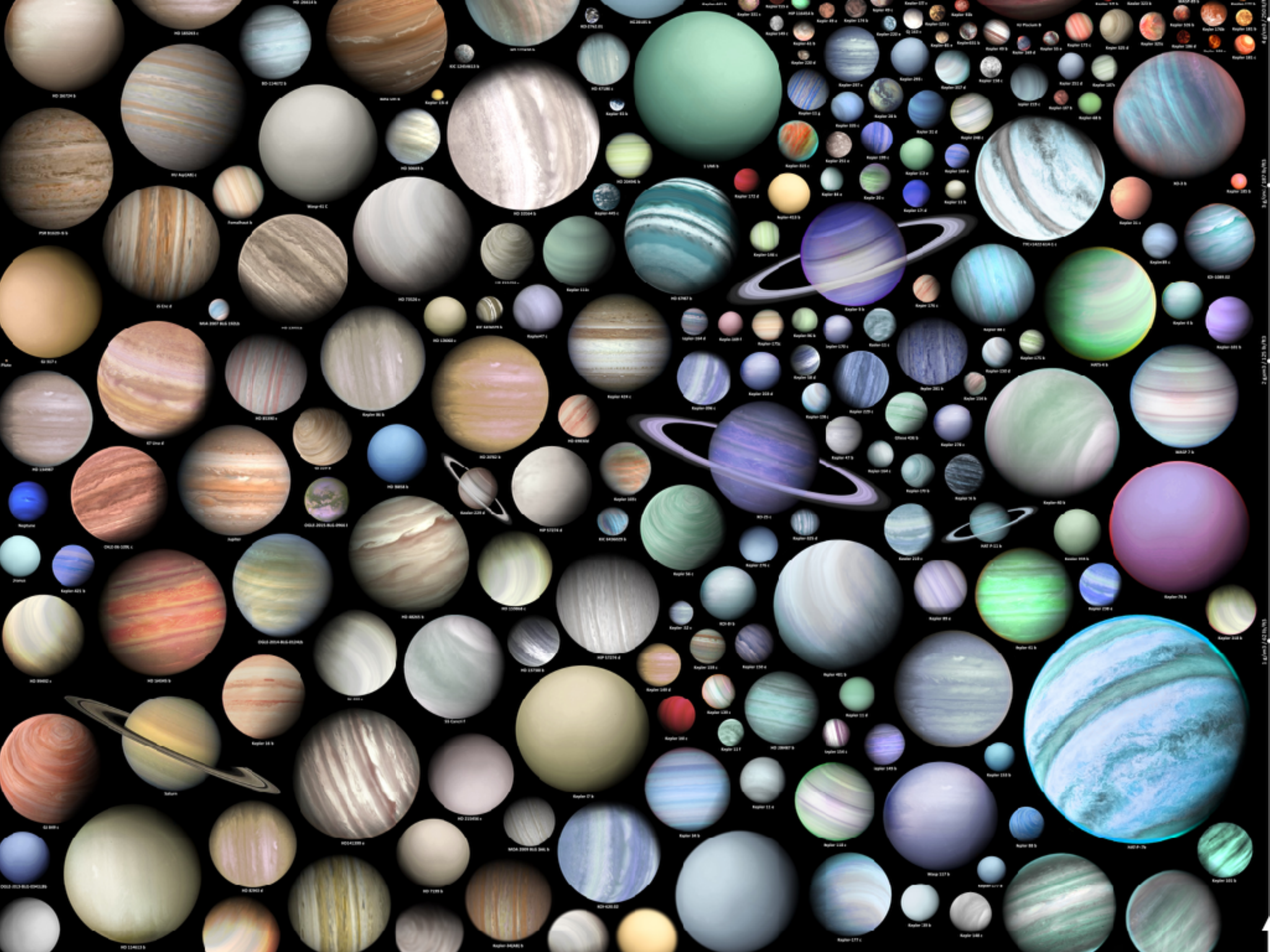
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

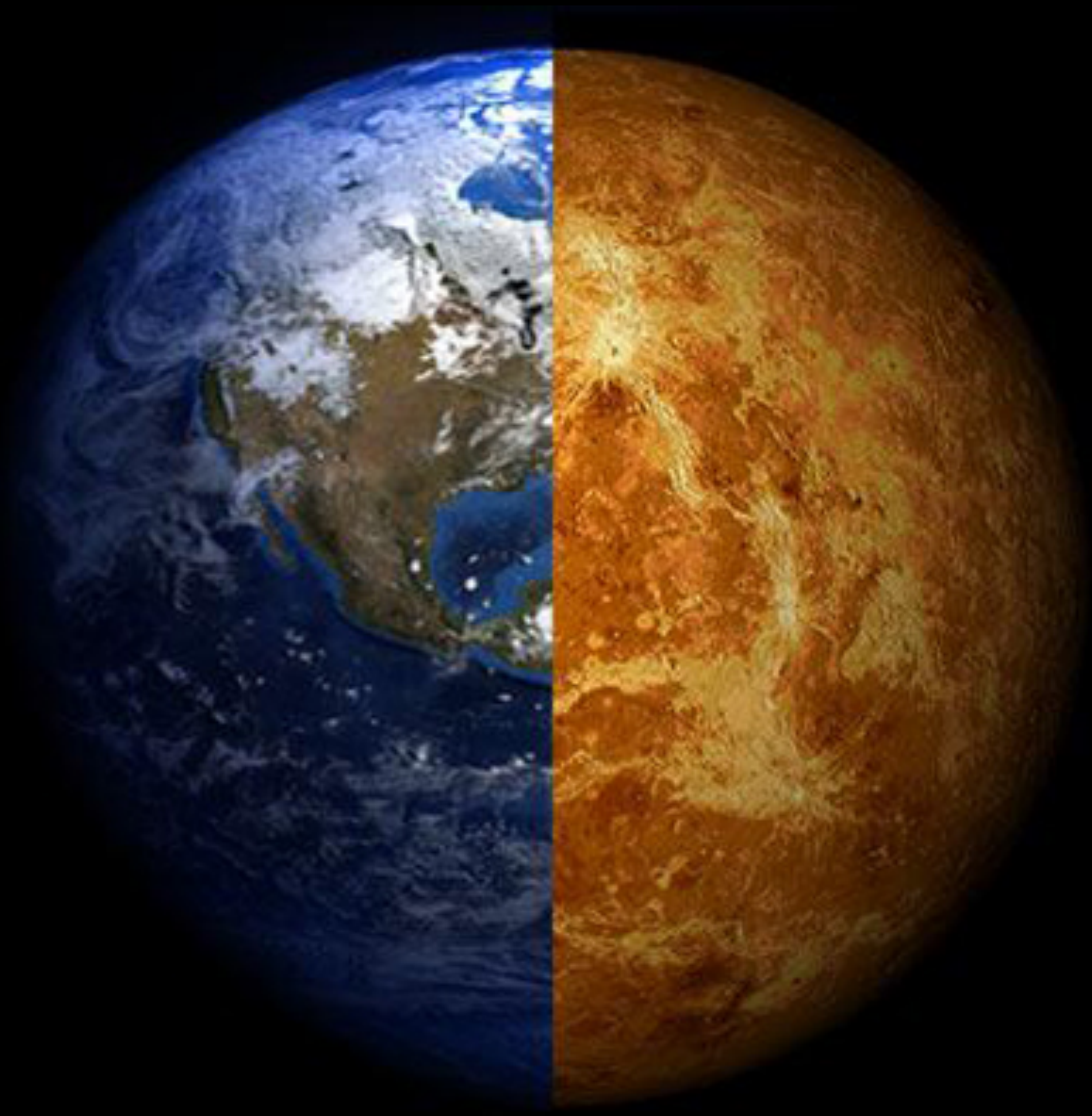
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

the exoplanetary zoo

- more than 4120 planets
- more than 3000 systems
- around 670 systems with multiple planets
- nearly 900 terrestrial planets





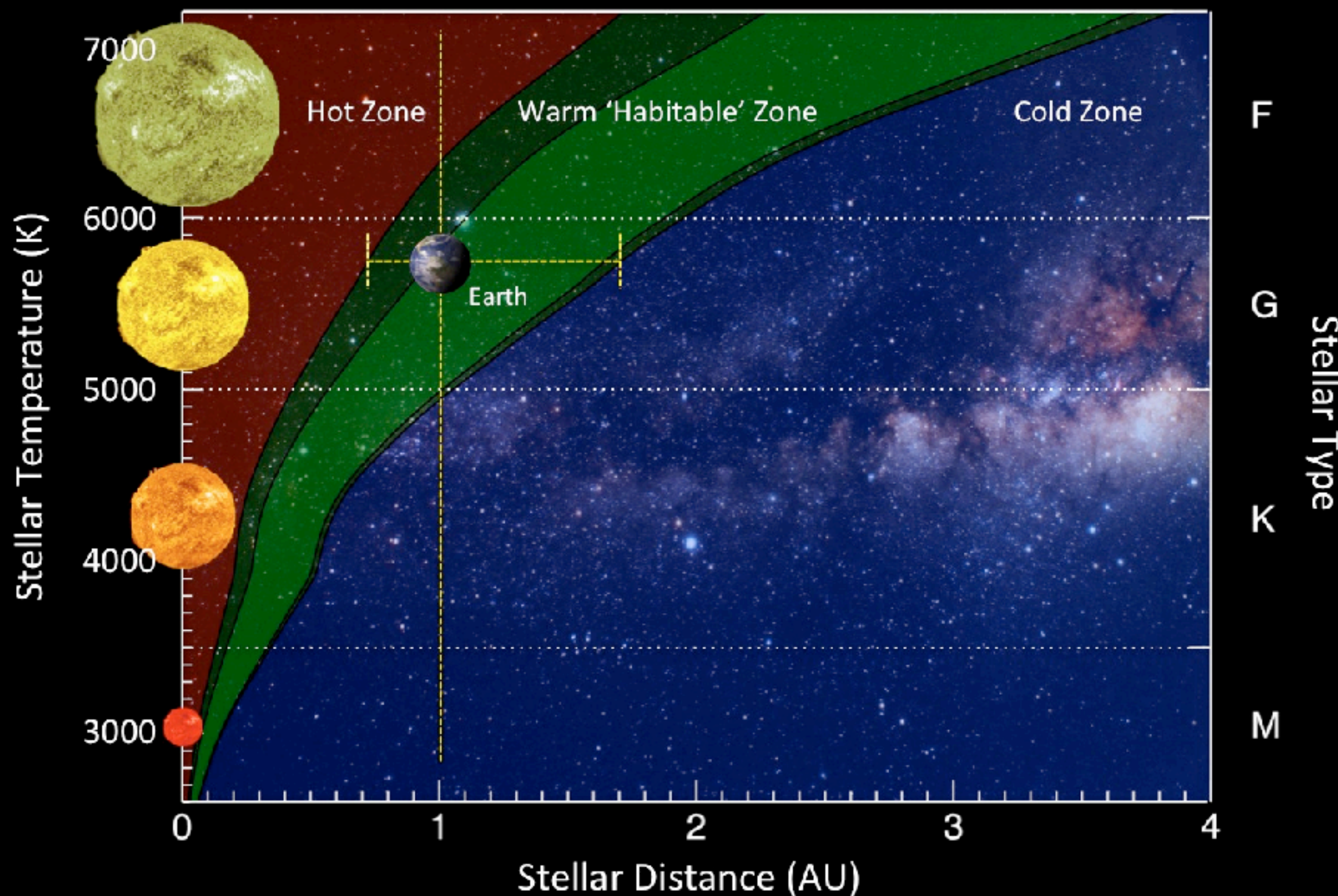


part II: habitability

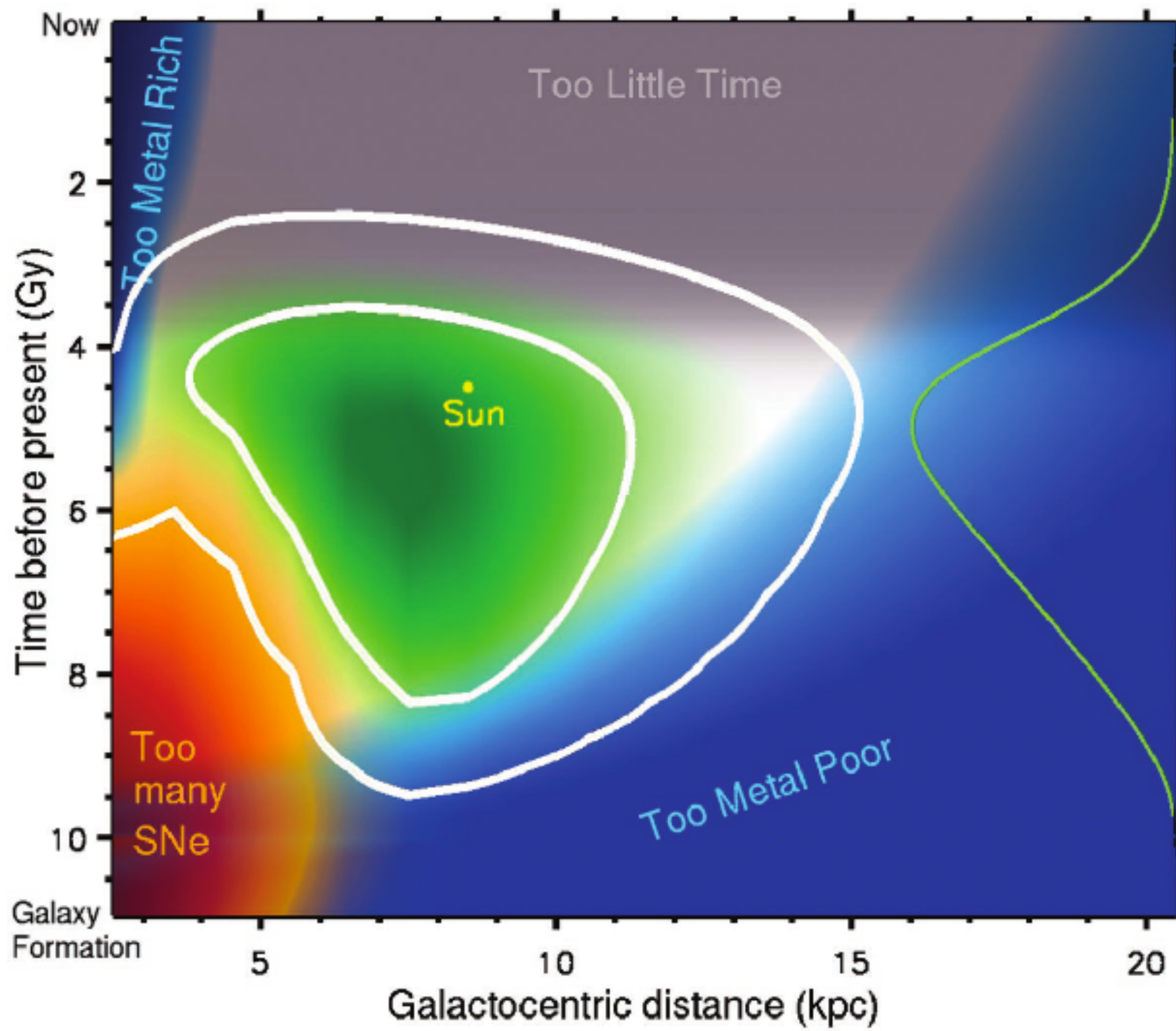
- **life**: "the condition that distinguishes animals and plants from inorganic matter, including the capacity for growth, reproduction, functional activity, and continual change preceding death"
- life as we know is **carbon-based**
- **complex molecules** are more easily found in planets than elsewhere
- **water** is a necessary condition for life (as we know it)
- **habitable**: a place that provides adequate conditions to be lived in → **PLANETS**
- planets are in galaxies, which are part of *a* universe → **habitability in galactic and cosmological scales**

habitable planets

- **atmosphere**: useful to stabilise climate
  holds liquid water (due to pressure)
  provides shielding against high-energy radiation
- **mass**: needs to be large enough to heat up the planet's core
- **lifetime of host star**: should be large enough so that life can evolve (> a few Gyr)
- **magnetic field**: protects from cosmic rays
- **surface temperature**: needed for liquid water (together with pressure)
- **position in the galaxy**: nearby supernovae may hinder emergence of life
  metallicity should be enough to form planets
- **epoch in history**: temperature and metallicity constraints
- …


7000
6000
5000
4000
3000
Stellar Temperature (K)
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Earth
F
G
K
M
Stellar Type
0
1
2
3
4
Stellar Distance (AU)

The GHZ in the disk of the Milky Way based on the star formation rate, metallicity (blue), sufficient time for evolution (gray), and freedom from life-extinguishing supernova explosions (red). The white contours encompass 68% (inner) and 95% (outer) of the origins of stars with the highest potential to be harbouring complex life today. The green line on the right is the age distribution of complex life and is obtained by integrating $P_{GHZ}(r, t)$ over r.



C. Linneweaver. Science 303 (2004) 59. arXiv:astro-ph/0401024

how resilient is life to astrophysical events?

? once life emerges on a planet, for how long will it survive?

what can sterilise all life on a planet?

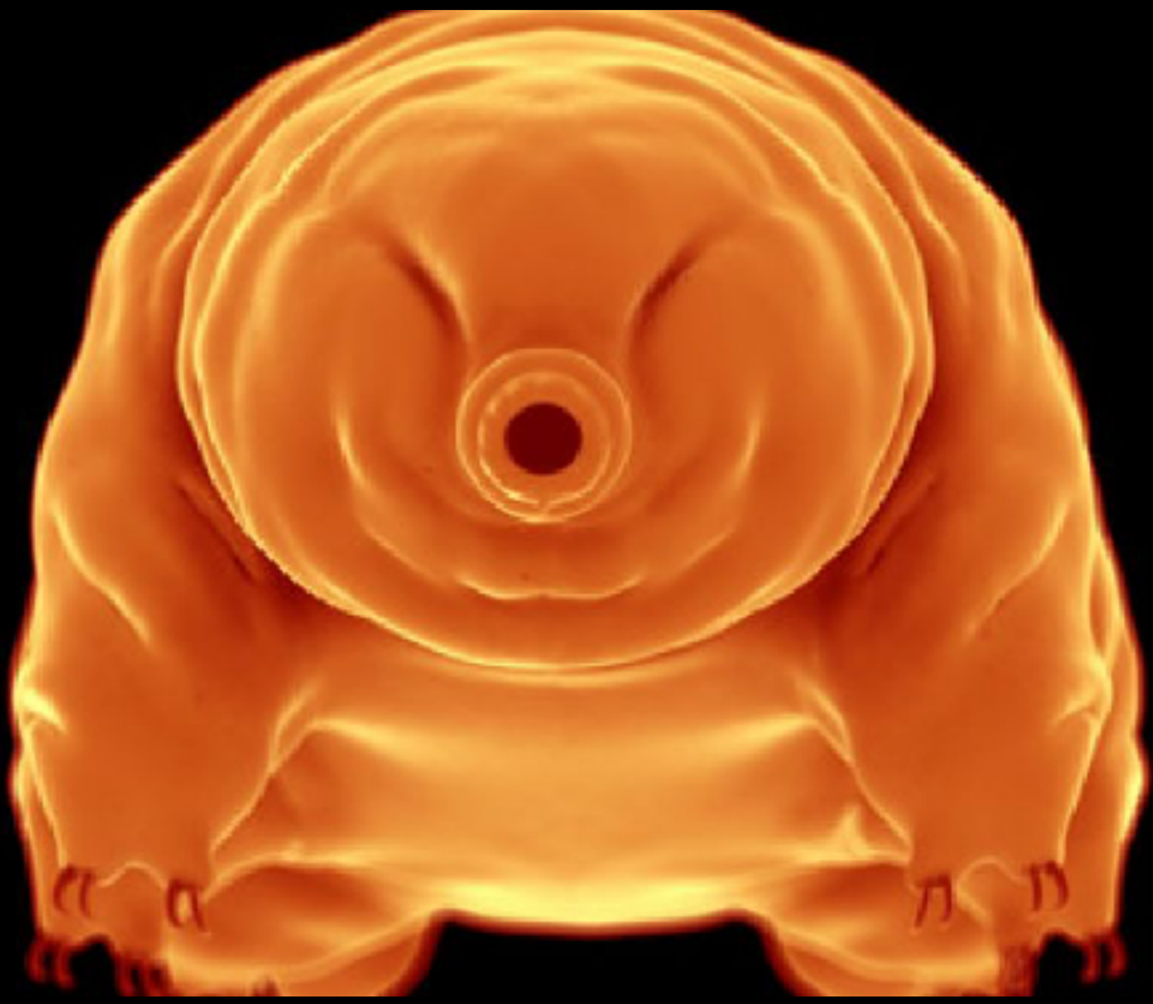
- asteroid impacts
- supernovae
- gamma-ray bursts
- death of host star
- disruption by wandering objects
- stellar winds (?)

life-threatening effects

- stripping of atmosphere
- fragmentation
- radiation levels
- pressure
- temperature **dominates**

hardy creatures: the tardigrades

Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253



- low temperatures: -272 ^{o}C for ~10 min; -20 ^{o}C for decades
- high temperatures: 150 ^{o}C for a few minutes
- pressure: 0 - 1200 atm
- radiation levels: up to 7000 Gy
- can reduced their metabolism almost completely → cryptobiosis
- good candidates for the last survivors on Earth

we can use tardigrades as a benchmark species

the resilience of life to astrophysical events

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SCIENTIFIC REPORTS

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The Resilience of Life to Astrophysical Events

David Sloan[1], Rafael Alves Batista[1] & Abraham Loeb[2]

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Much attention has been given in the literature to the effects of astrophysical events on human and land-based life. However, little has been discussed on the resilience of life itself. Here we instead explore the statistics of events that completely sterilise an Earth-like planet with planet radii in the range 0.5–1.5$R_{\oplus}$ and temperatures of ~300 K, eradicating all forms of life. We consider the relative likelihood of complete global sterilisation events from three astrophysical sources – supernovae, gamma-ray bursts, large asteroid impacts, and passing-by stars. To assess such probabilities we consider what cataclysmic event could lead to the annihilation of not just human life, but also extremophiles, through the boiling of all water in Earth's oceans. Surprisingly we find that although human life is somewhat fragile to nearby events, the resilience of Ecdysozoa such as *Milnesium tardigradum* renders global sterilisation an unlikely event.

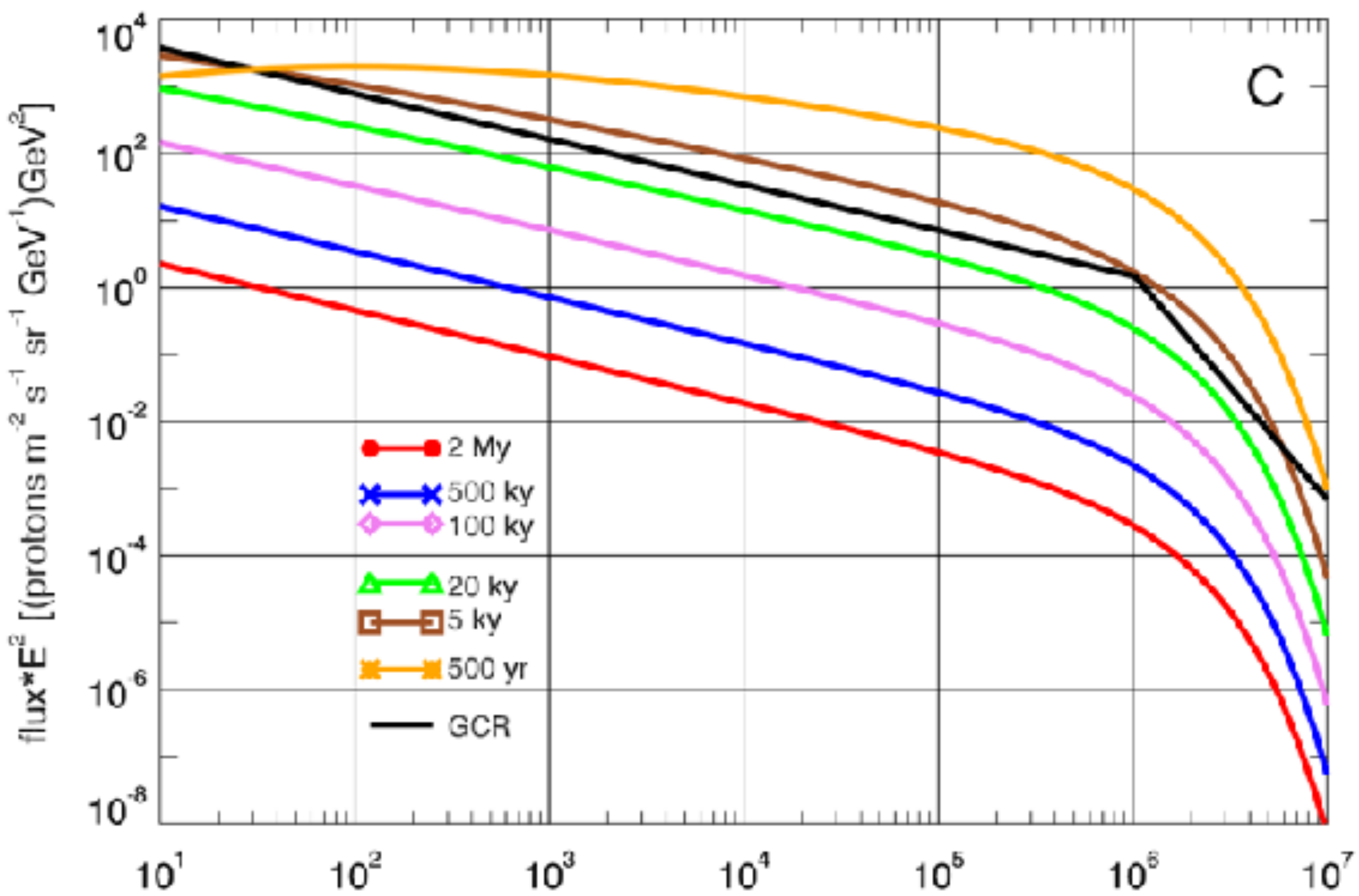
- numerous SNe explosions up to ~300 pc could have contributed to life extinctions during the Pleistocene
- this is corroborated by observing the cosmic-ray spectrum
- ozone layer depletion:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

$$O_3 + O \rightarrow O_2 + O_2$$

- exposure to UV radiation



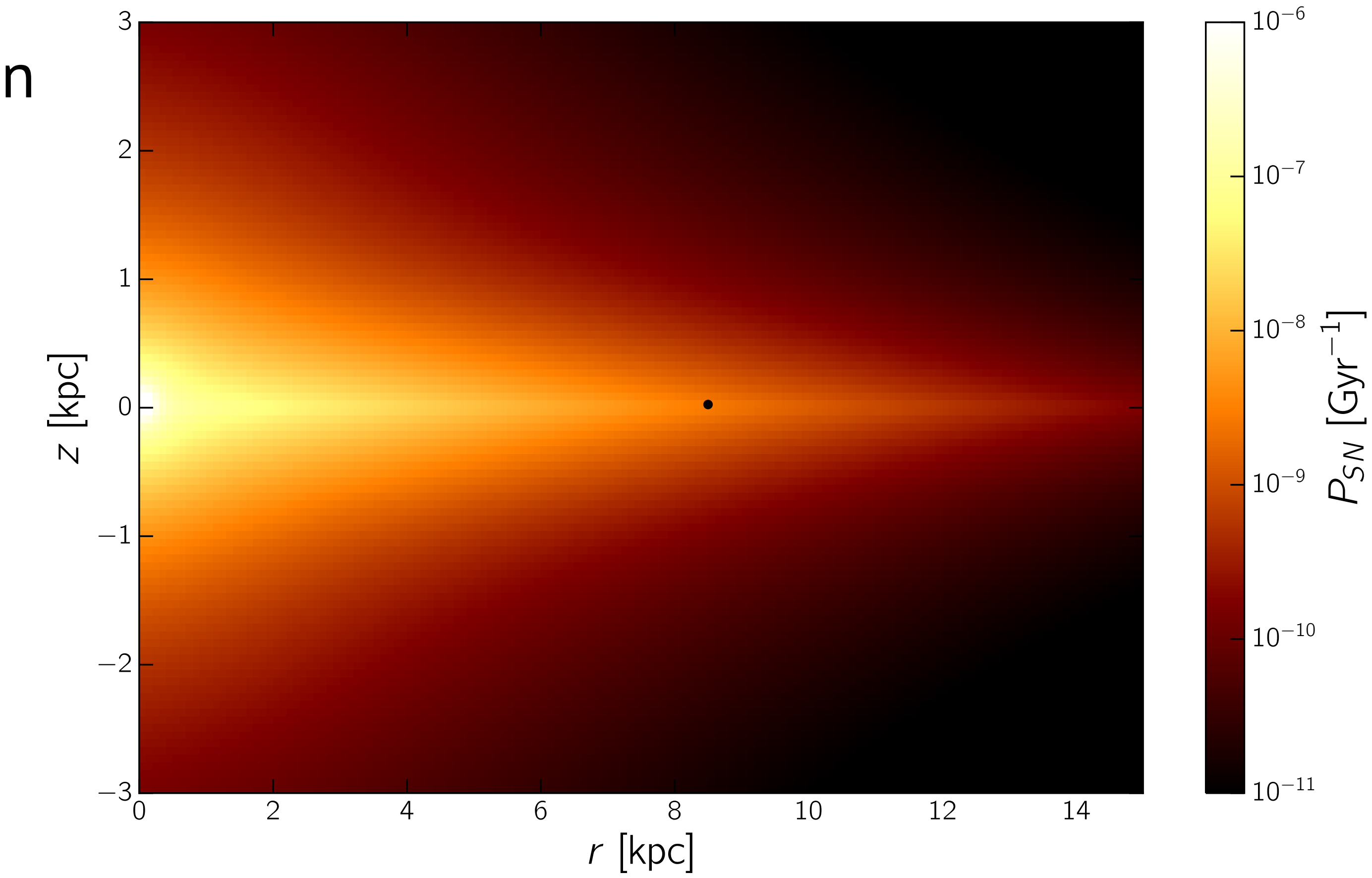
A. Mellot. Nature 532 (2016) 40.
A. Mellot et al. Int. J. Astrobio. 14 (2015) 373. arXiv:1406.4151
B. Thomas et al. Astrophys. J. Lett. 826 (2016) L3. arXiv:1605.04926

Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253

rate of occurrence of SNe within sterilisation radius

$$P_{SN}(r,z) = \chi \int_{M_{min}}^{M_{max}} dm\, \underline{\xi(m)}\, \underline{n_\star(r,z)}\, \underline{\tau^{-1}(m)},$$

initial mass function — stellar density profile — stellar lifetime

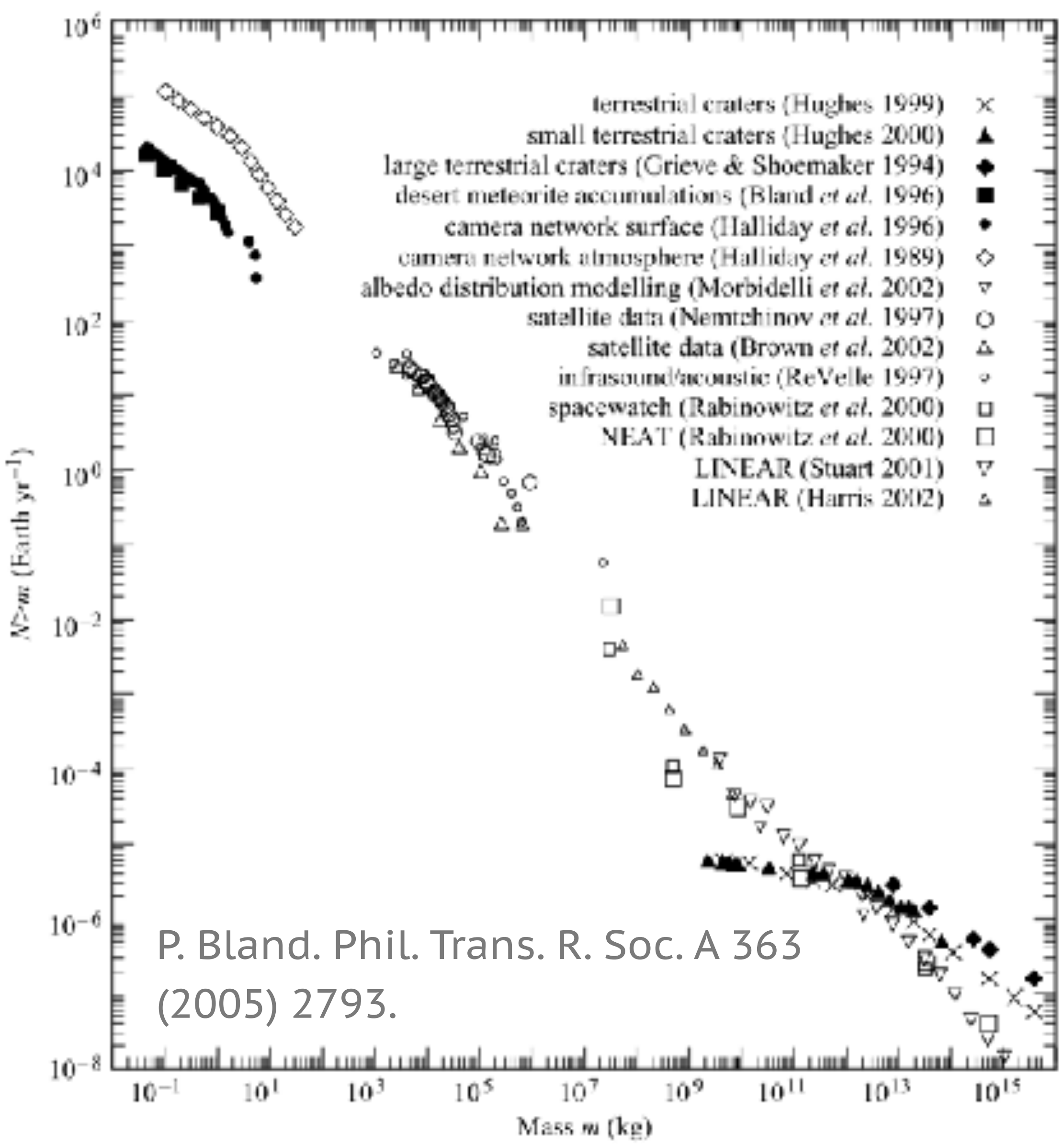


rate of occurrence of GRBs: 0.04-0.15 Gpc^{-3} yr^{-1}

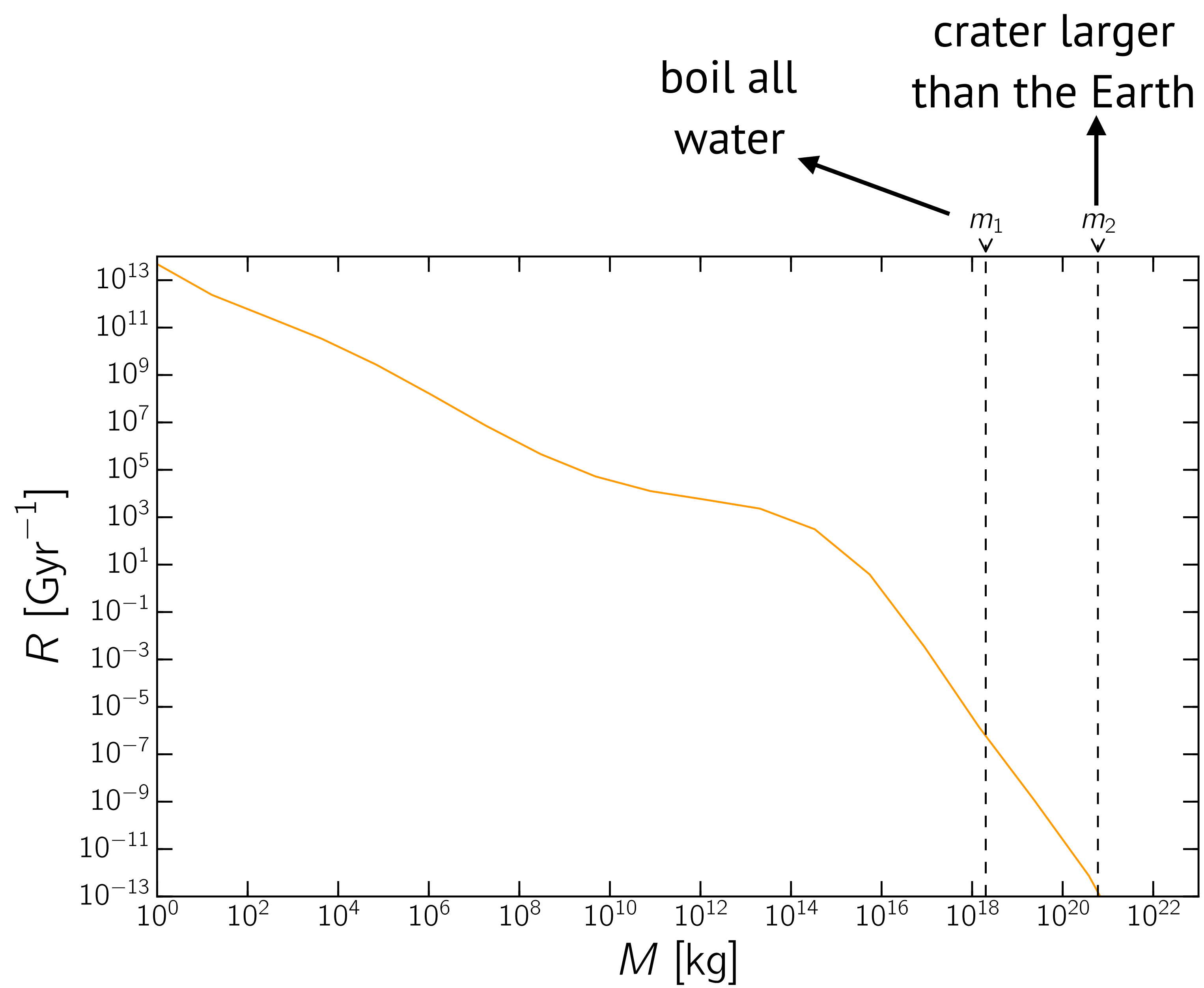
- sterilisation radius for SNe: 0.03 pc
- sterilisation radius for GRBs: 13.8 pc
- closest star that can become a SN: IK Pegasi (~40 pc)

impact threats: asteroids, comets, NEOs

Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253

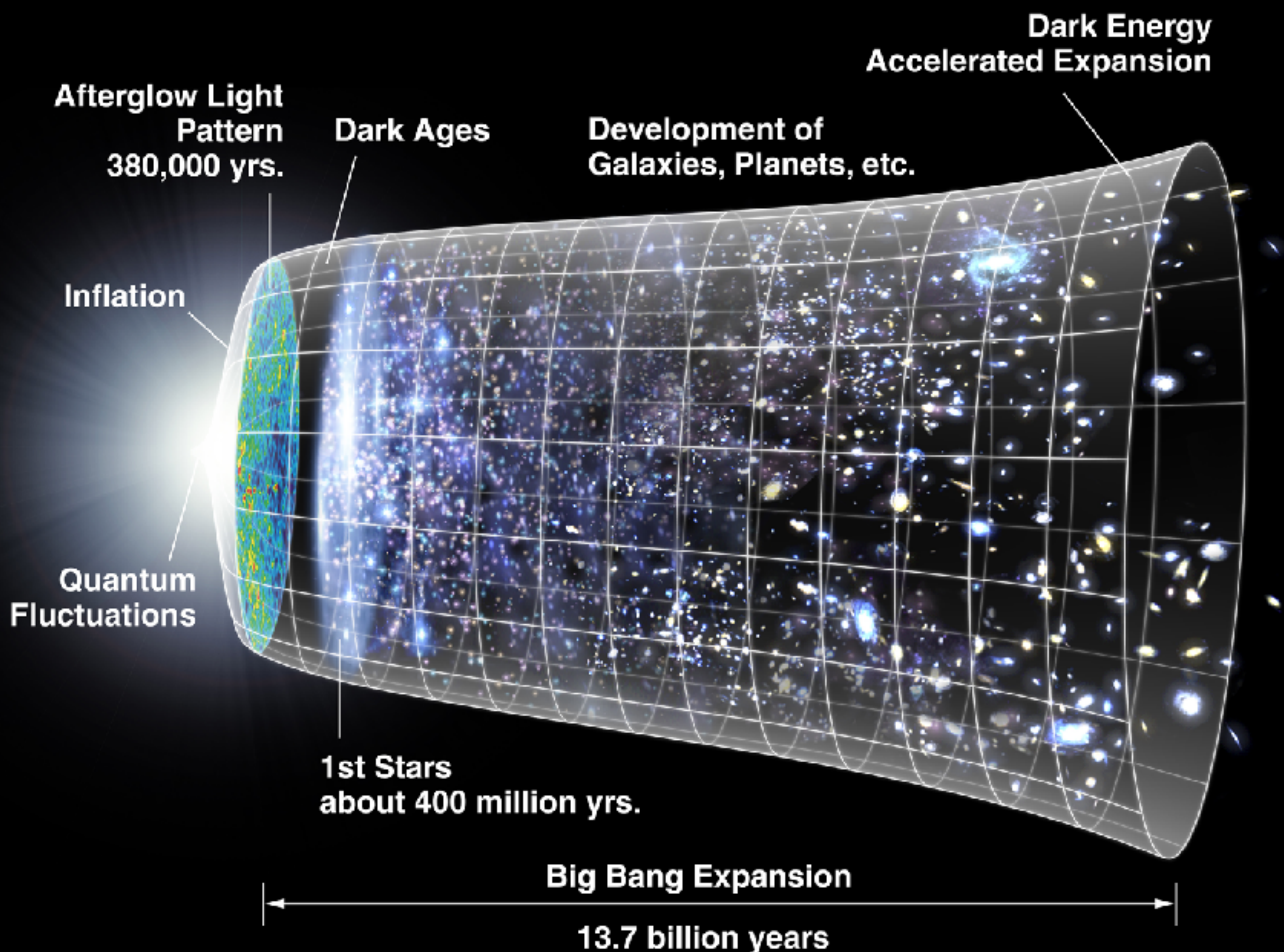


P. Bland. Phil. Trans. R. Soc. A 363 (2005) 2793.



- number of impacts as a function of the object's mass
- we use a catalogue containing all (known) objects in the Solar System

when is life likely?

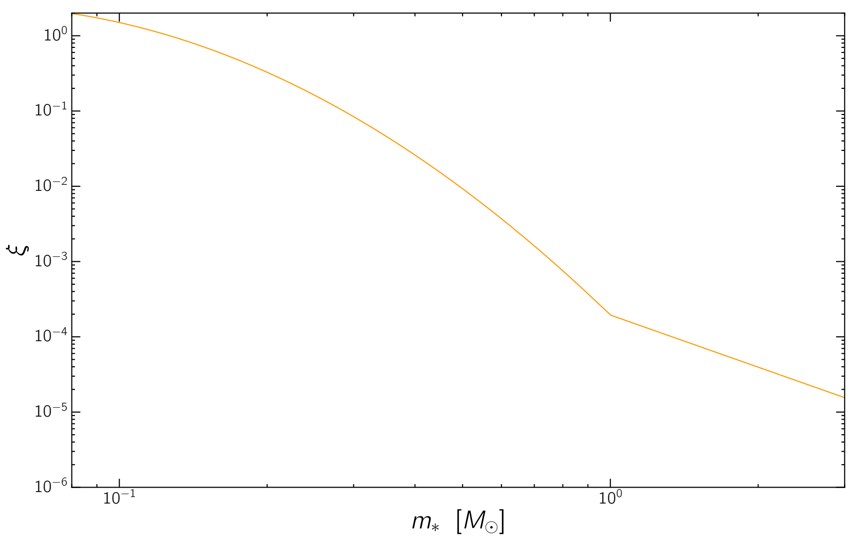


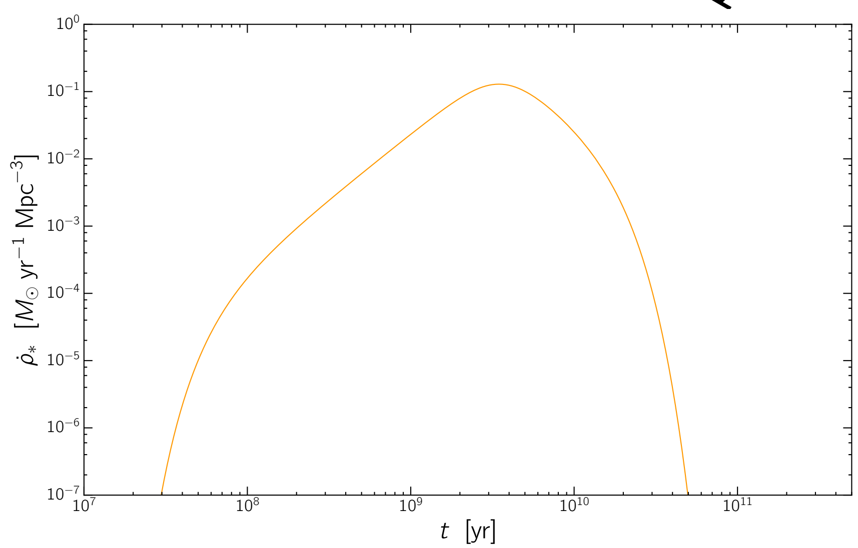
Loeb, Alves Batista, Sloan. JCAP 08 (2016) 040. arXiv:1606.08448

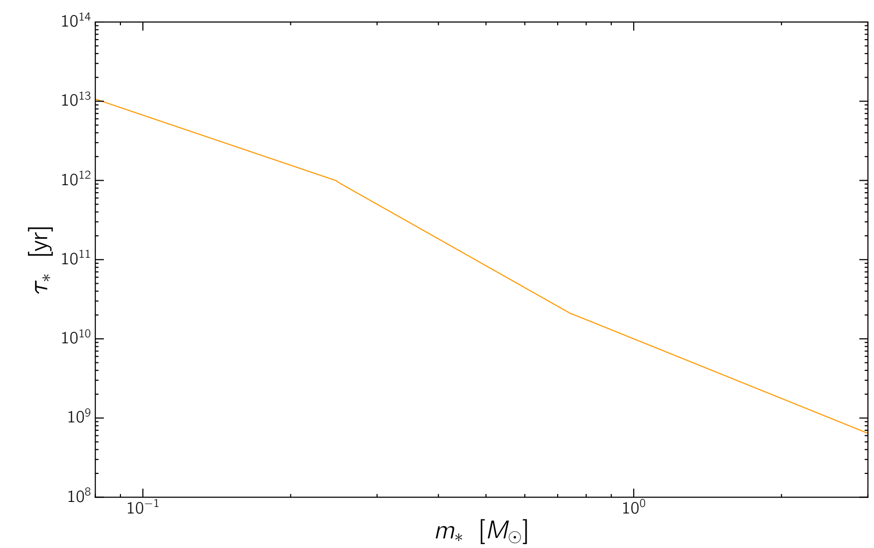
master equation

$$\frac{dP}{dt}(t) = \frac{1}{N}\int_0^t dt' \int_{m_{min}}^{m_{max}} dm' \xi(m') \dot{\rho}_\star(t', m') \eta_{\mathrm{Earth}}(m') p(\mathrm{life}|\mathrm{HZ}) g(t-t', m')$$

- $\xi(m')$: initial mass function
- $\dot{\rho}_\star(t', m')$: star formation rate
- $\eta_{\mathrm{Earth}}(m')$: probability of finding Earth-like planets in the HZ
- $p(\mathrm{life}|\mathrm{HZ})$: probability of finding life in a habitable planet
- $g(t-t', m')$: window function: birth/death of stars







nEarth = 0.19; Kepler observations + no mass dependence

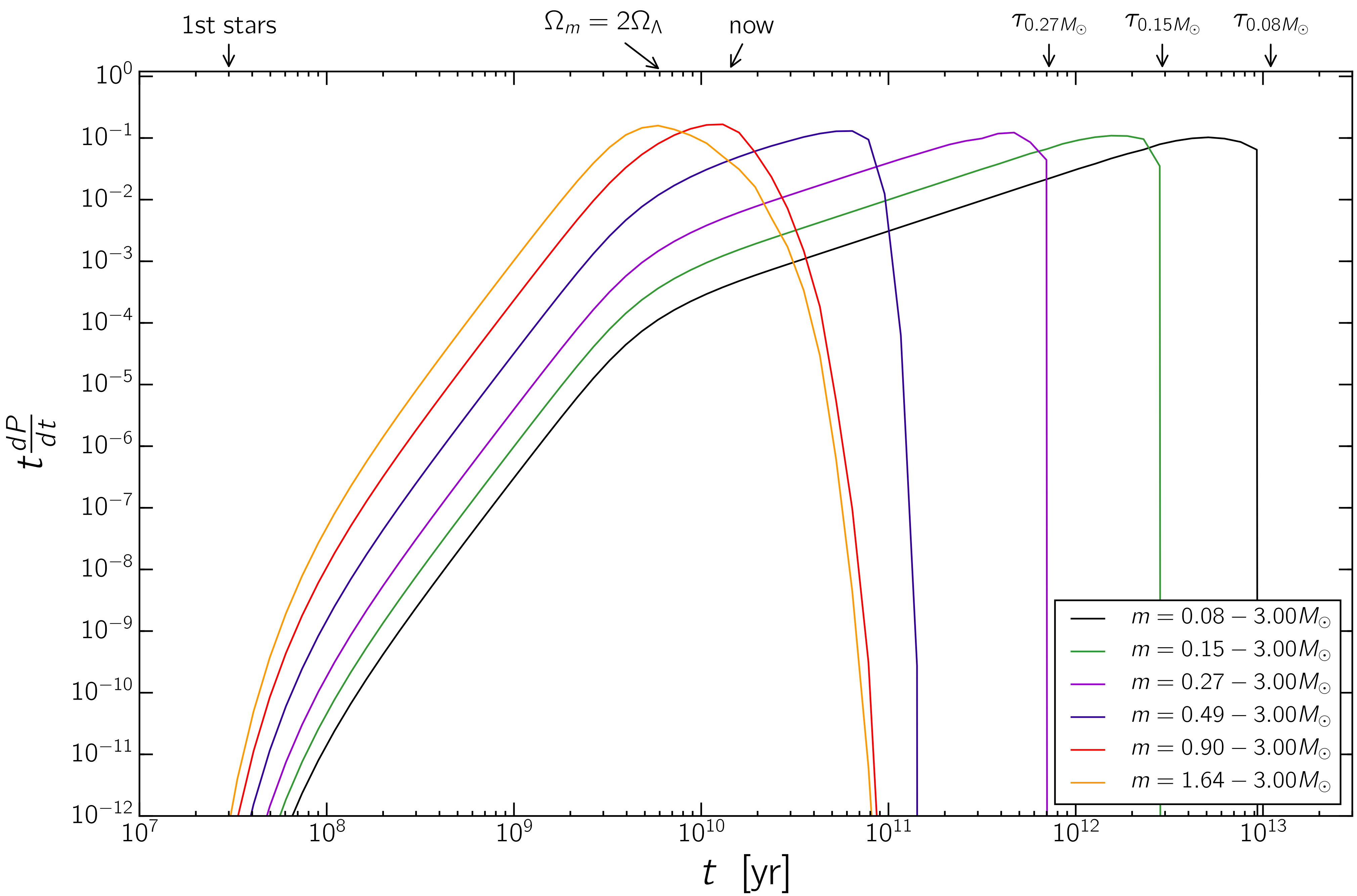
p(life|HZ): constant

m_{min} = 0.08M_{sun}; brown dwarf mass threshold

m_{max} = 3M_{sun}; life time allows emergence of life

when is life likely?

Loeb, Alves Batista, Sloan. JCAP 08 (2016) 040. arXiv:1606.08448

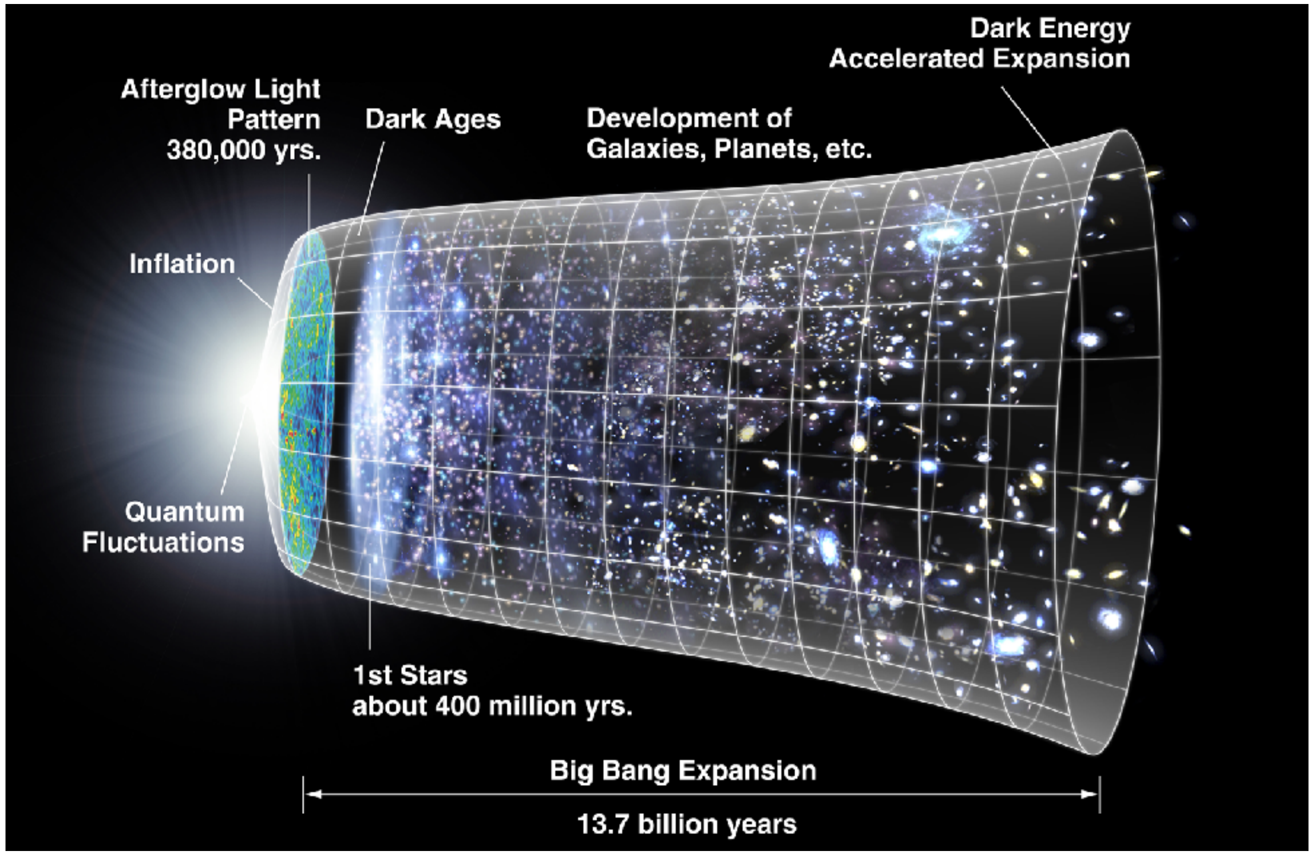


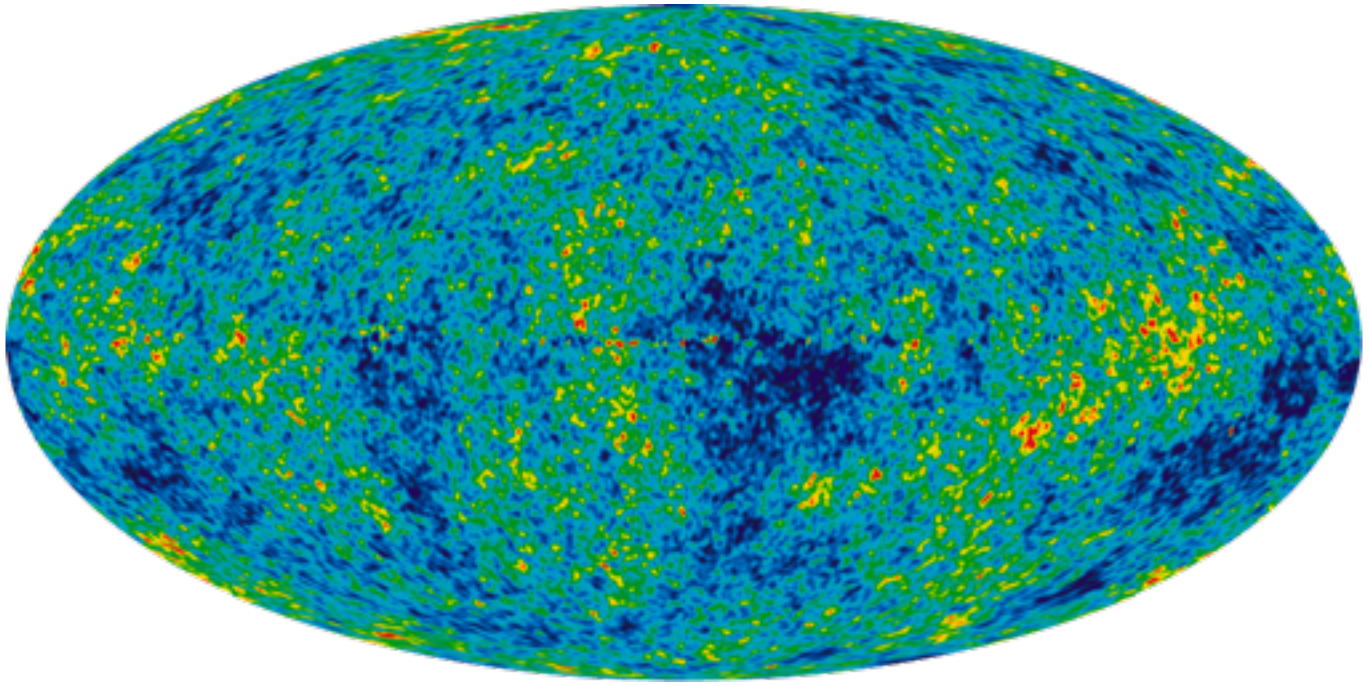
we may be premature - unless low-mass stars are inhabitable

part III: foundational issues

detour: on initial condition & outcomes

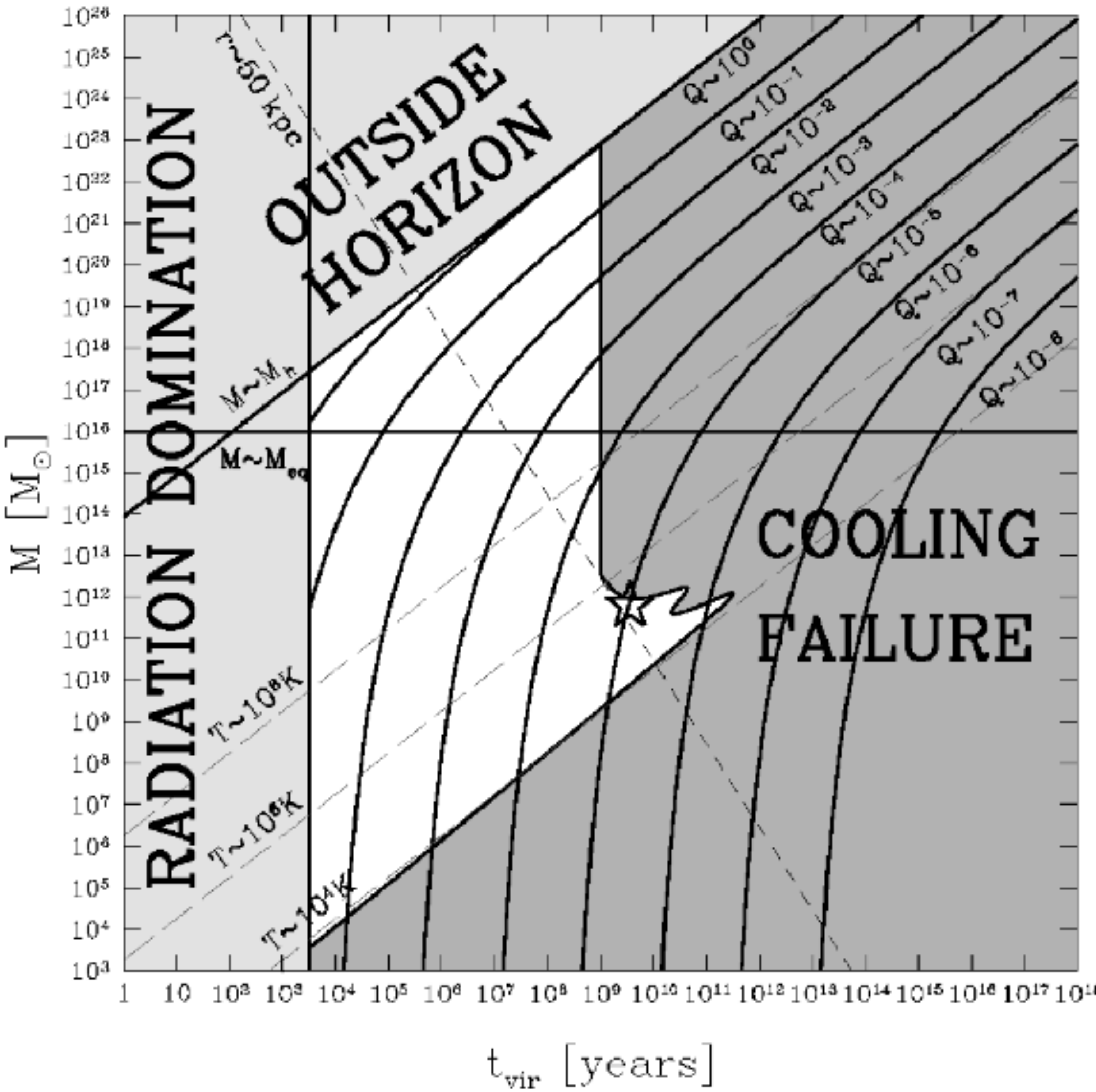
- inflation solves the horizon and flatness problems
- it fits very well the standard cosmological model
- our physical theories describe these processes using distributions → of all possible outcomes, why *this one* that lead to a habitable universe?





the amplitude of density fluctuations

- Q: amplitude of density fluctuations
- if $Q<10^{-6}$ → virial temperatures low → no formation of stars
- if $Q>10^{-4}$ → disturbance of exoplanetary systems due to high density of objects

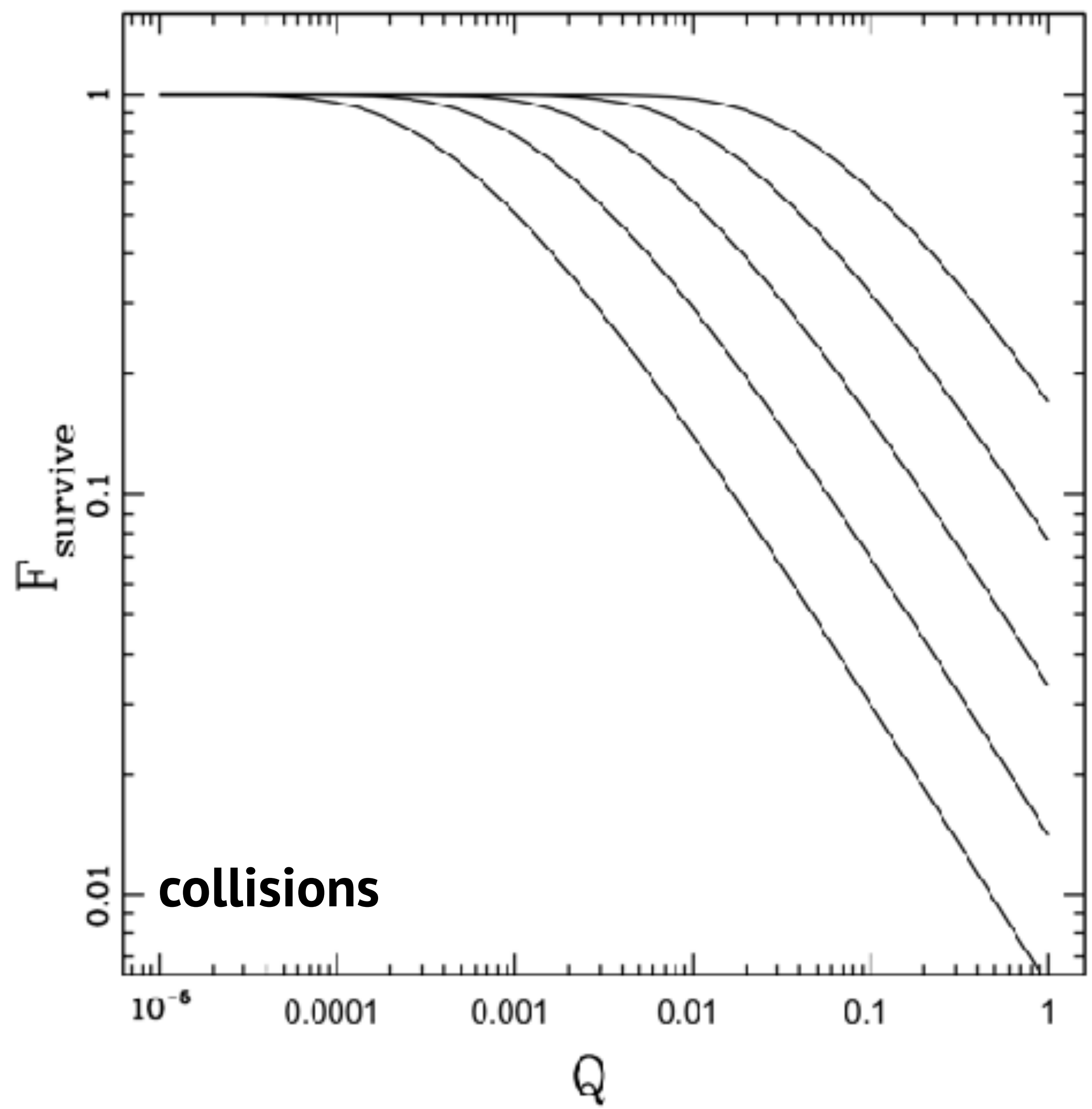


Rising curves show the largest virialised mass scale as a function of time for different values of Q. Structures with $M<M_{eq}$ virialise $Q^{-3/2}$ after the end of the radiation-dominated epoch. For later times, the virialised mass scale converges to $Q^{3/2}$ times the horizon mass. The star corresponds to the Milky Way.

M. Tegmark, M. Rees. Astrophys. J. 499 (1998) 526.

the amplitude of density fluctuations & habitability

F. Adams et al. J Cosmol. Astropart. Phys 09 (2015) 30. arXiv:1505.06158



$F_{survive}$: fraction of planetary systems that survive

"why now?" - the coincidence "problem"

? why do we live at a time when $\Omega_m \sim \Omega_\Lambda$?

tentative explanations

- anthropics → there can only be observers if this is true
- coincidence → we could live at (almost) any other time
- dynamical dark energy models (e.g. quintessence, k-essence, ...)

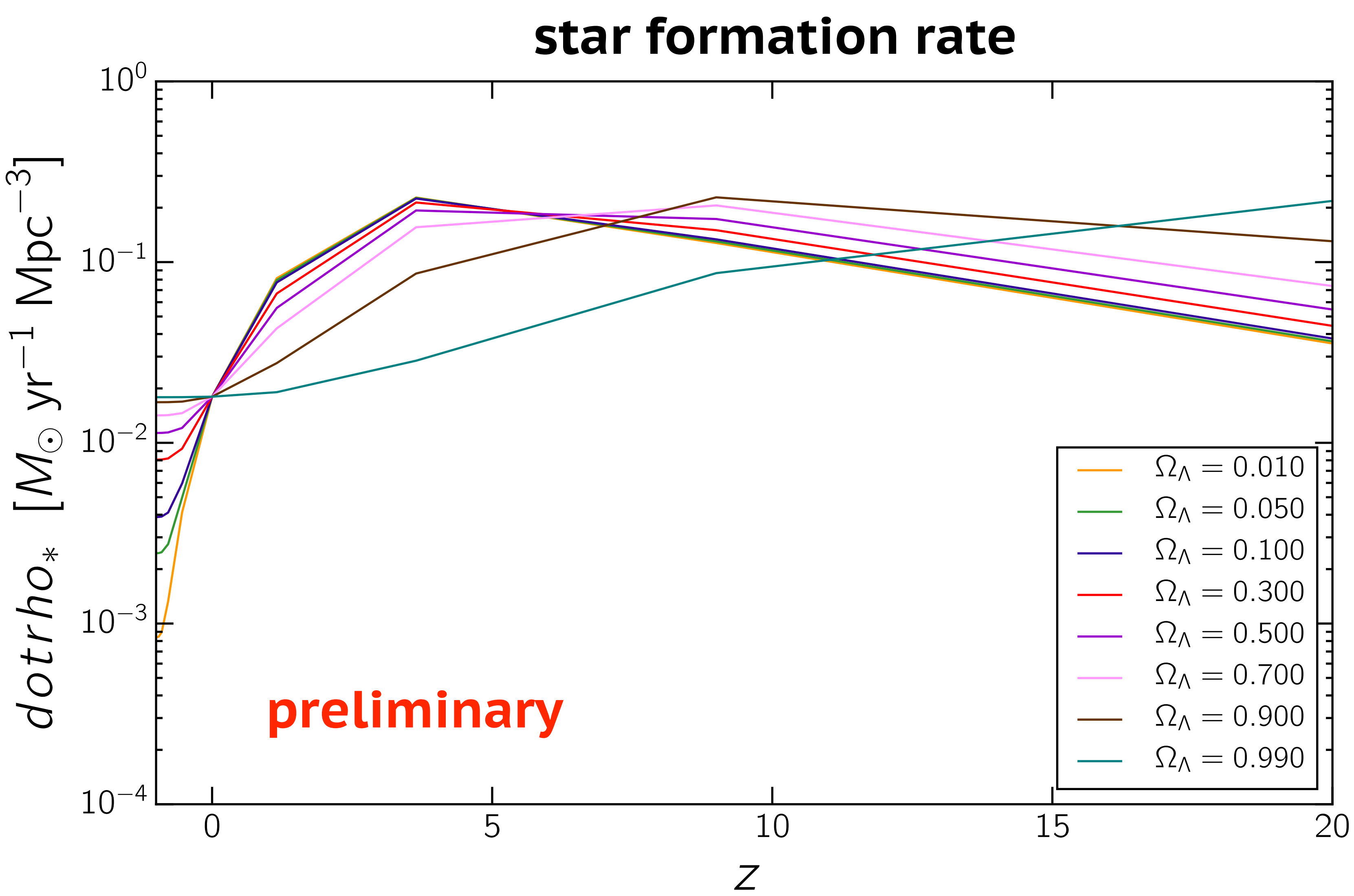
motivation

- inflationary models (e.g. eternal inflation) postulates an ensemble of universes with different Λ → we happen to live in one realisation thereof
- string landscape provides an alternative solution
- our universe is one realisation of a randomly distributed variable (Λ)
- problem: too metaphysical → not scientific because it is not falsifiable (popperian perspective)

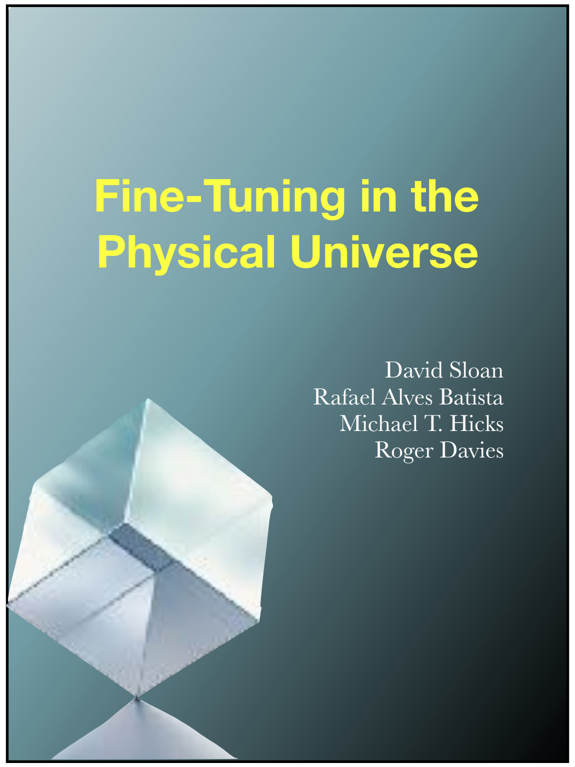
the cosmological constant "problem"

- expected vacuum energy density from QFT: $\rho_{\Lambda,th} \sim M_{Pl}^4 \sim (10^{25}\ eV)^4 \sim 10^{109}\ J\ m^{-3}$
- observed dark energy: $\rho_{\Lambda,obs} \sim 10^{-11}\ J\ m^{-3}$
- discrepancy: $\rho_{\Lambda,th} / \rho_{\Lambda,obs} \sim 10^{120}$
- *"the worst theoretical prediction in the history of physics"*
- anthropic upper bound on $\Lambda \rightarrow \Omega_\Lambda \sim 10\text{-}100\ \Omega_{m,0}$ (Weinberg 1987)
- 120 orders of magnitude discrepancy seem unnatural
- parameters be of O(1) → matter of aesthetics or intrinsic feature of the theory?
- three-part "problem":
  1. why is it not large?
  2. why is it not zero?
  3. why is it comparable to the density of matter *now*?

Alves Batista, Loeb, Sloan. In preparation.



- effect of dark energy: shift formation of structures along time axis (total number of stars formed changes though)
- existence of structures require $\Omega_\Lambda < 0.85$



in press,
Cambridge
University Press

- Ch. 1: Fine-tuning, complexity, and life in the multiverse
- Ch. 2: Hierarchy of fine-structure constants
- Ch. 3: Naturalness, fine-tuning, and observer selection in cosmology
- Ch. 4: Cosmic Inflation: trick or treat?
- Ch. 5: Is the universal matter-antimatter asymmetry fine-tuned?
- Ch. 6: Structure formation
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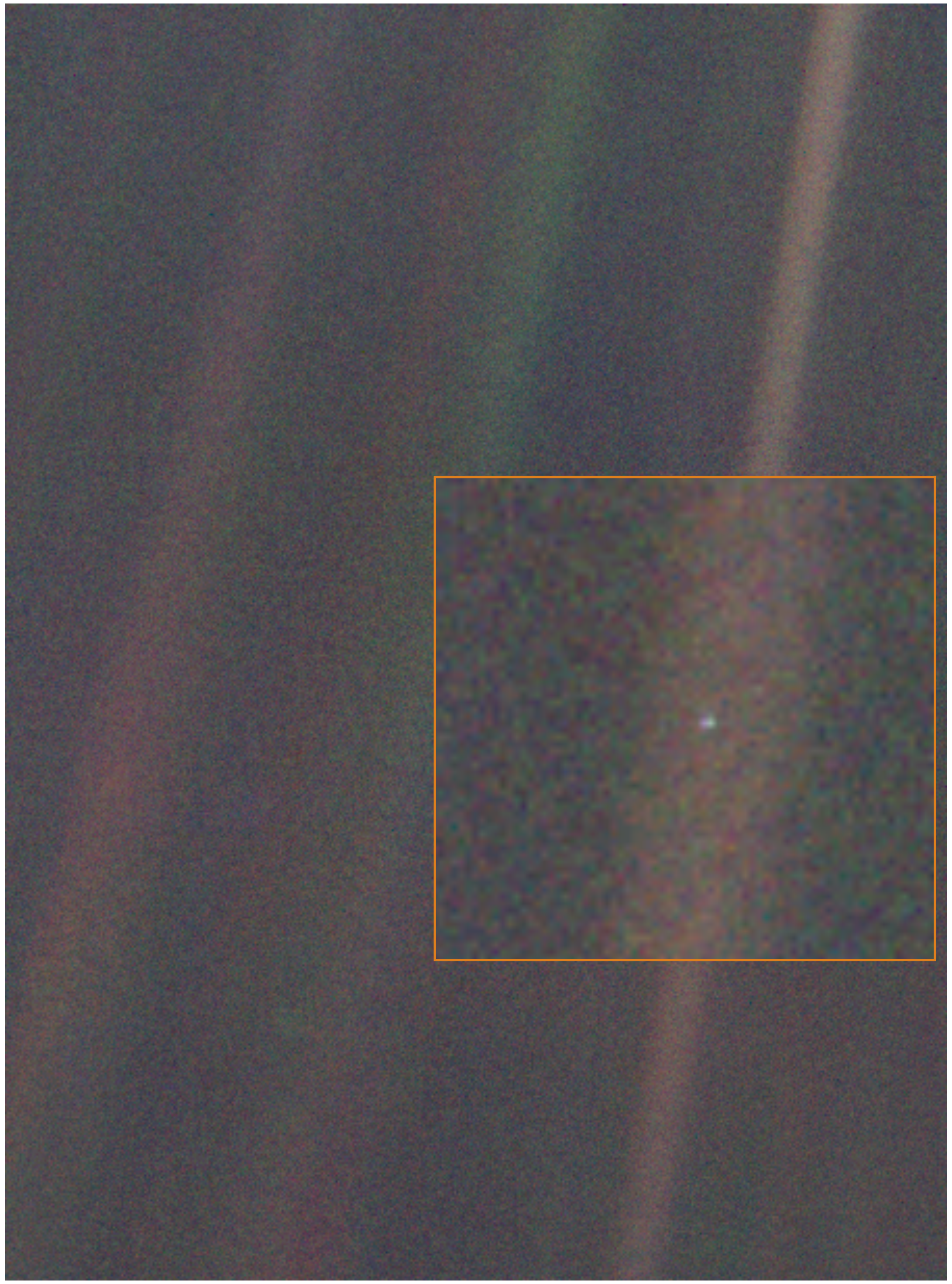
- Ch. 11: How special is the Solar System?
- Ch. 12: On the temporal habitability of our Universe
- Ch. 13: Climbing up the theories of Nature: fine-tuning and biological molecules

conclusions and perspectives

- many potentially **habitable** planets found by Kepler
- life is surprisingly resilient to astrophysical events (asteroids, SNe, GRBs, ...)
- the universe should brim with life (mostly around low-mass stars) in the far future (~10 trillion years from now) --- unless low-mass stars are inhospitable
- the amplitude of density fluctuations seem to be such that allow for inhabited planets
- is the observed cosmological constant "bio-friendly"?
- fine-tuning is important because it may be hinting at something more fundamental in Nature, which may be linked to our very existence

direct image of a planet with life



Earth as seen by Voyager.
Picture taken in 1990.
Distance: 4 billion km

pale blue dot...