# on the habitability of the universe

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Campinas
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# summary

- habitable zones
- habitable epochs
- why are we now?
- resilience of life to astrophysics events
- varying constants & anthropics
- conclusions and prospects

# habitable planets

**what is habitability?**

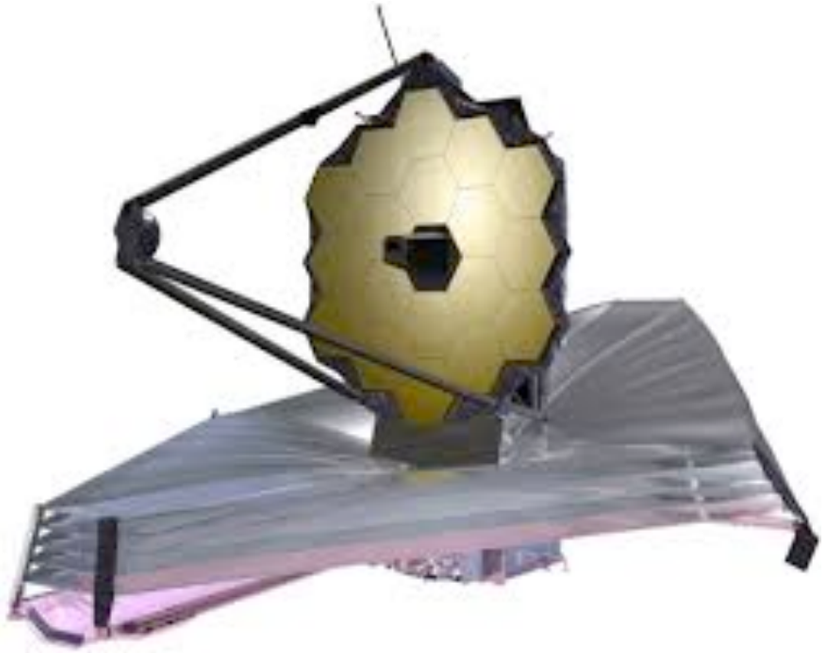
- only life we know is carbon-based
- water is a requirement
- atmosphere (?)

**where to look for life?**

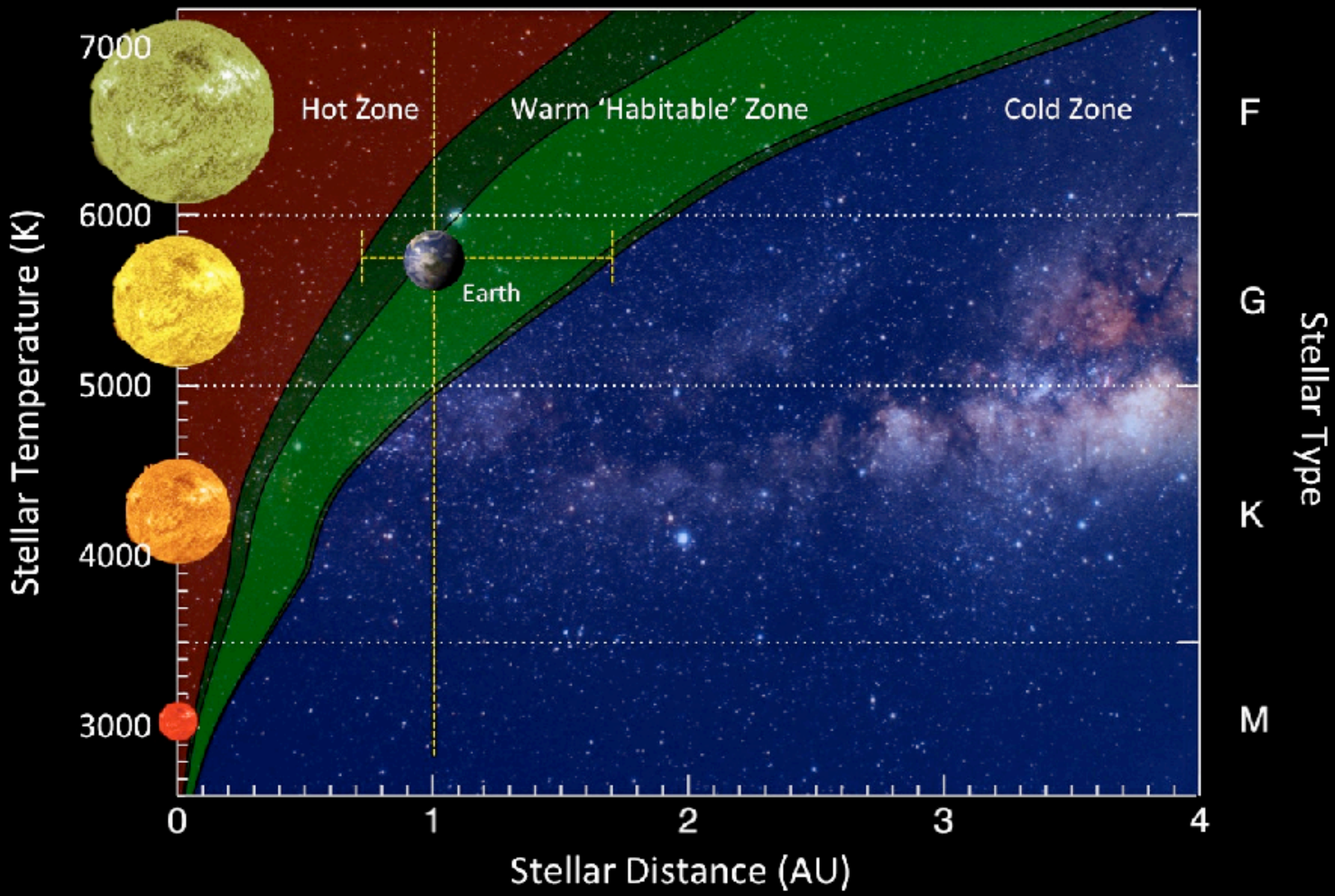
- planets
- moons
- asteroids (?)

**discovering exoplanets**

- Kepler mission
- *(upcoming - 2018)* James Webb Space Telescope
- *(2025?)* Darwin mission

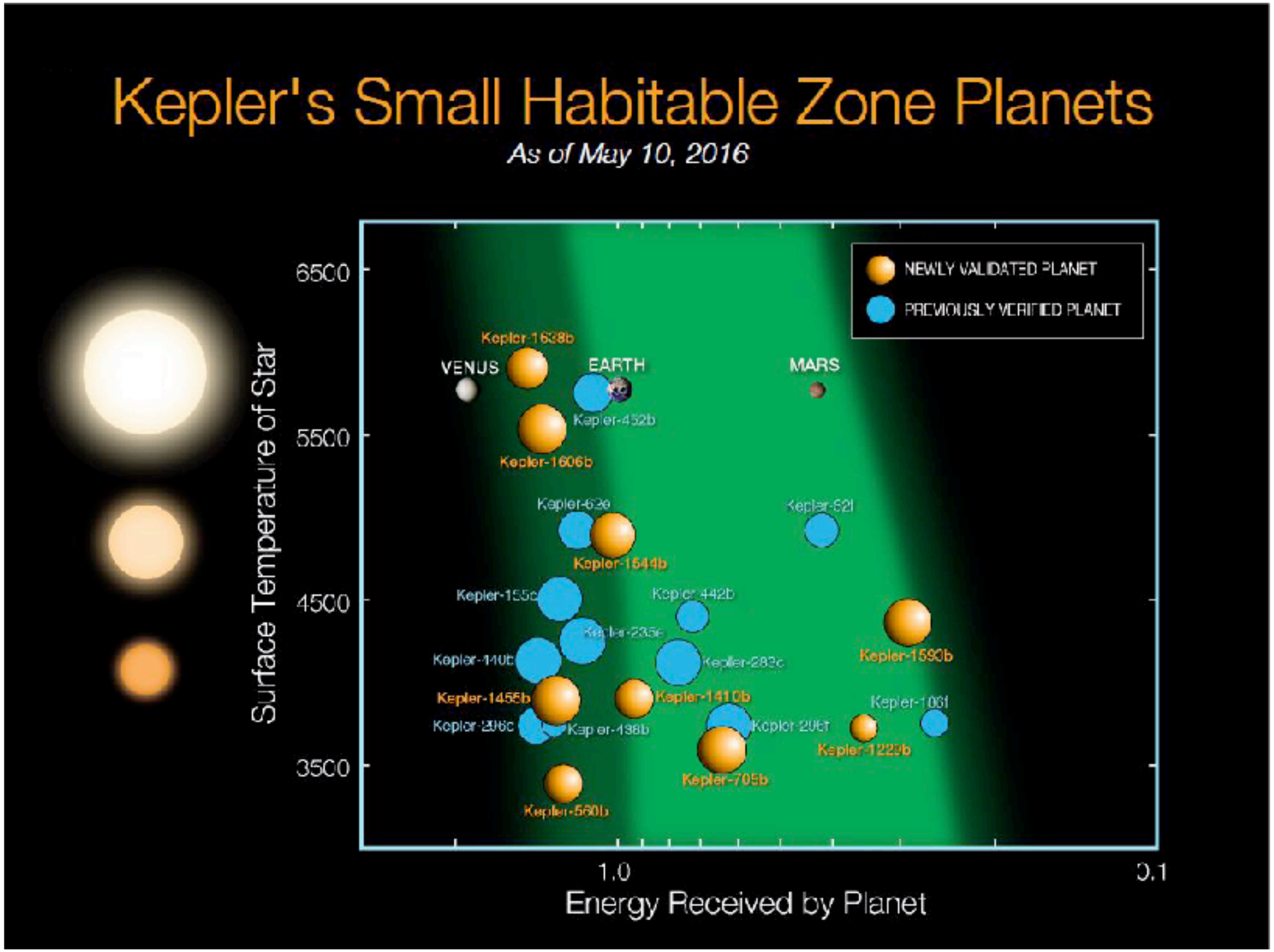


# habitable zones



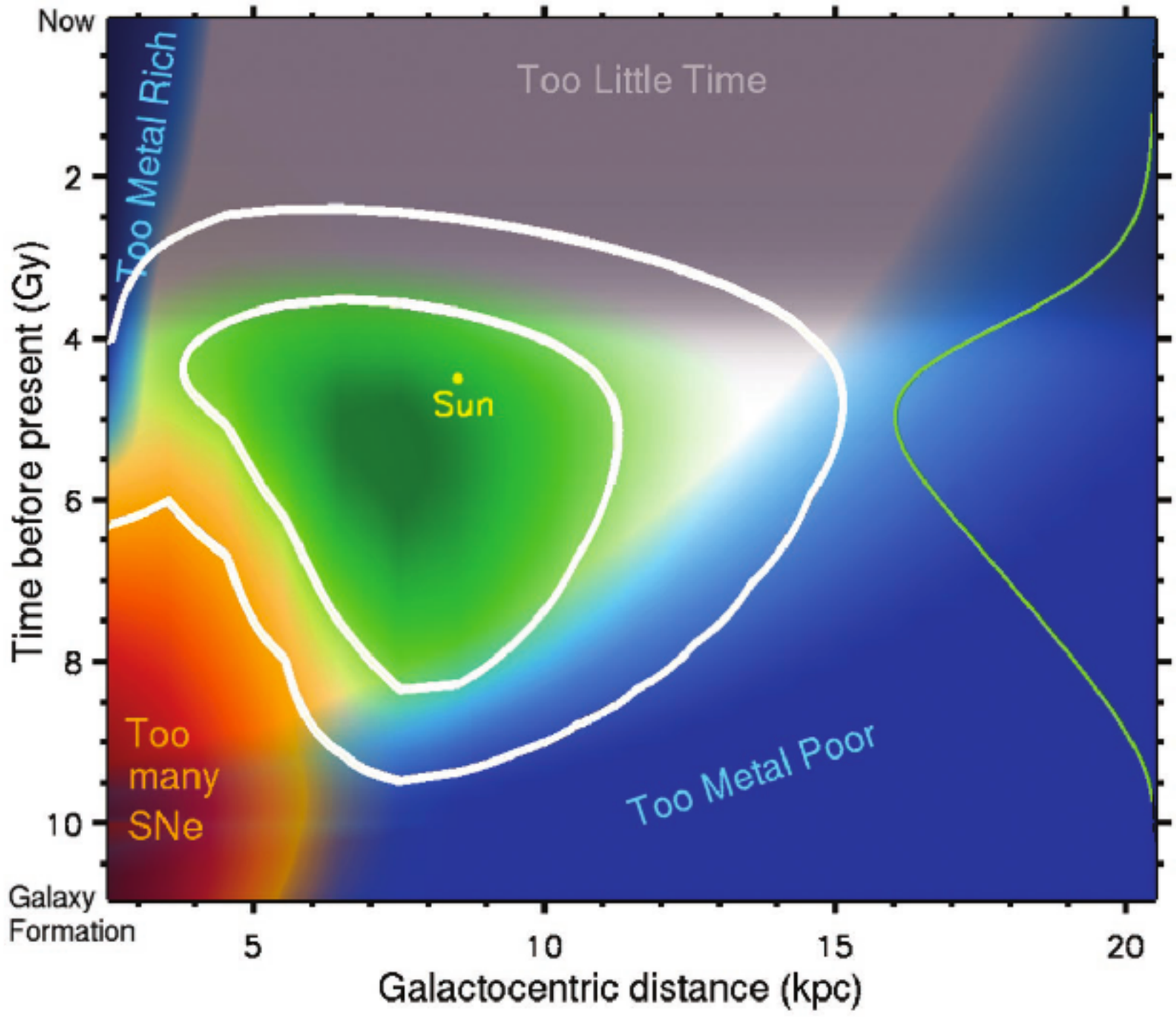

CREDIT: PHL @ UPR Arecibo

# Kepler's observations of planets in the HZ




*Credits: NASA Ames / N. Batalha and W. Stenzel*

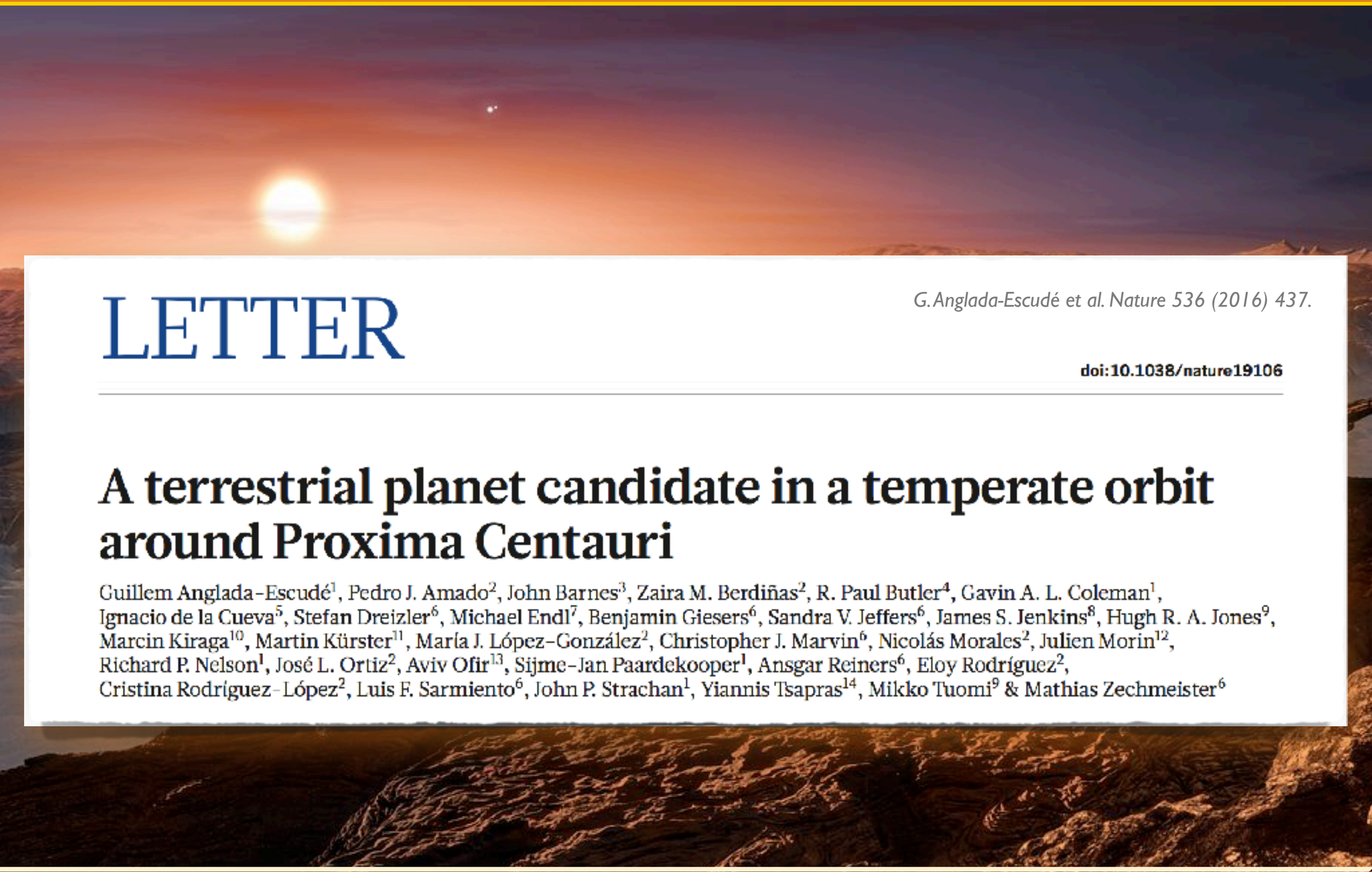
# galactic habitable zones




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 harboring 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*

# Proxima Centauri b



LETTER

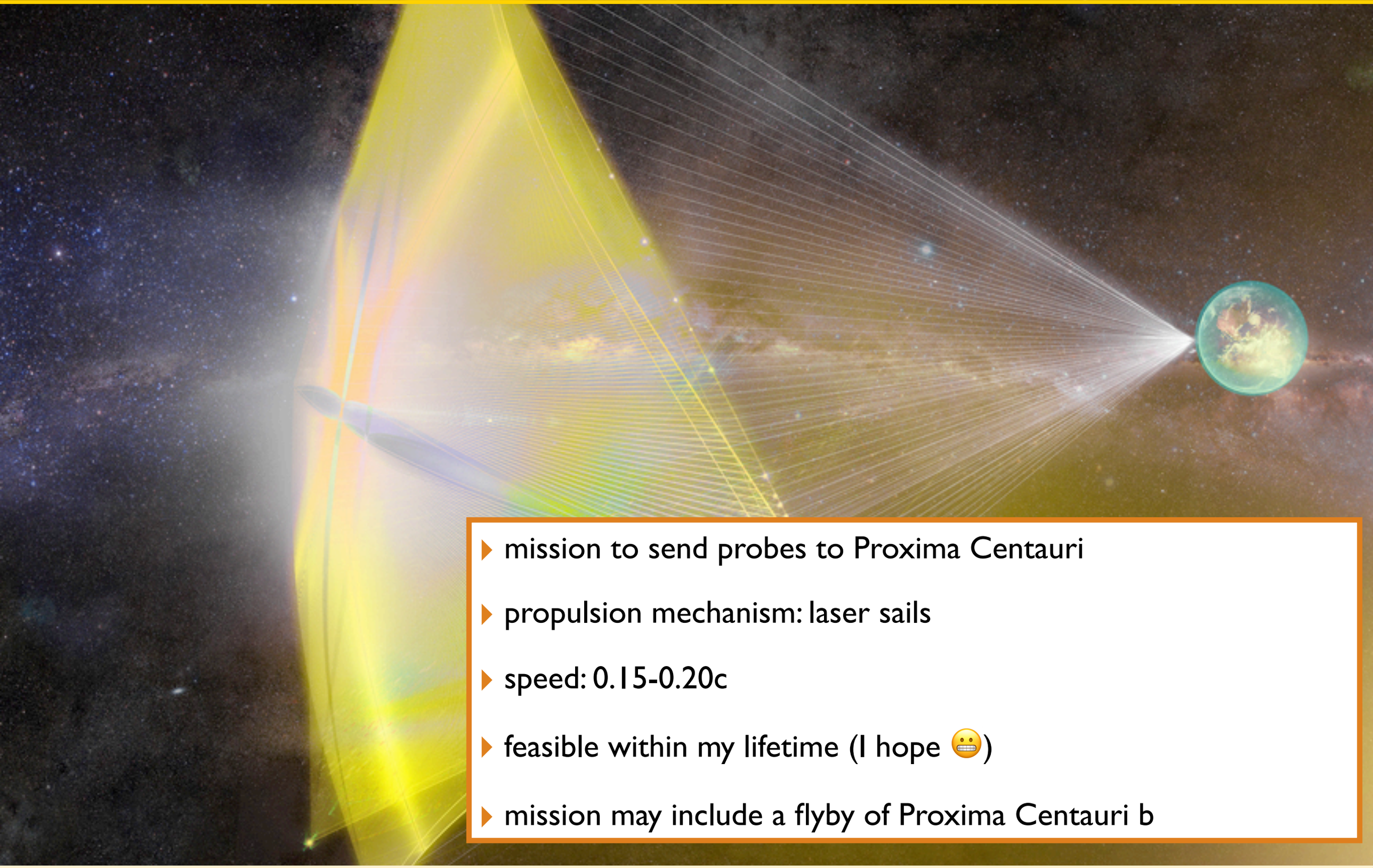
G. Anglada-Escudé et al. Nature 536 (2016) 437.

doi:10.1038/nature19106

## A terrestrial planet candidate in a temperate orbit around Proxima Centauri

Guillem Anglada-Escudé[1], Pedro J. Amado[2], John Barnes[3], Zaira M. Berdiñas[2], R. Paul Butler[4], Gavin A. L. Coleman[1], Ignacio de la Cueva[5], Stefan Dreizler[6], Michael Endl[7], Benjamin Giesers[6], Sandra V. Jeffers[6], James S. Jenkins[8], Hugh R. A. Jones[9], Marcin Kiraga[10], Martin Kürster[11], María J. López-González[2], Christopher J. Marvin[6], Nicolás Morales[2], Julien Morin[12], Richard P. Nelson[1], José L. Ortiz[2], Aviv Ofir[13], Sijme-Jan Paardekooper[1], Ansgar Reiners[6], Eloy Rodríguez[2], Cristina Rodríguez-López[2], Luis F. Sarmiento[6], John P. Strachan[1], Yiannis Tsapras[14], Mikko Tuomi[9] & Mathias Zechmeister[6]

# Breakthrough Initiative: StarShot



- mission to send probes to Proxima Centauri
- propulsion mechanism: laser sails
- speed: 0.15-0.20c
- feasible within my lifetime (I hope 😬)
- mission may include a flyby of Proxima Centauri b

# how resilient is life to astrophysical events?

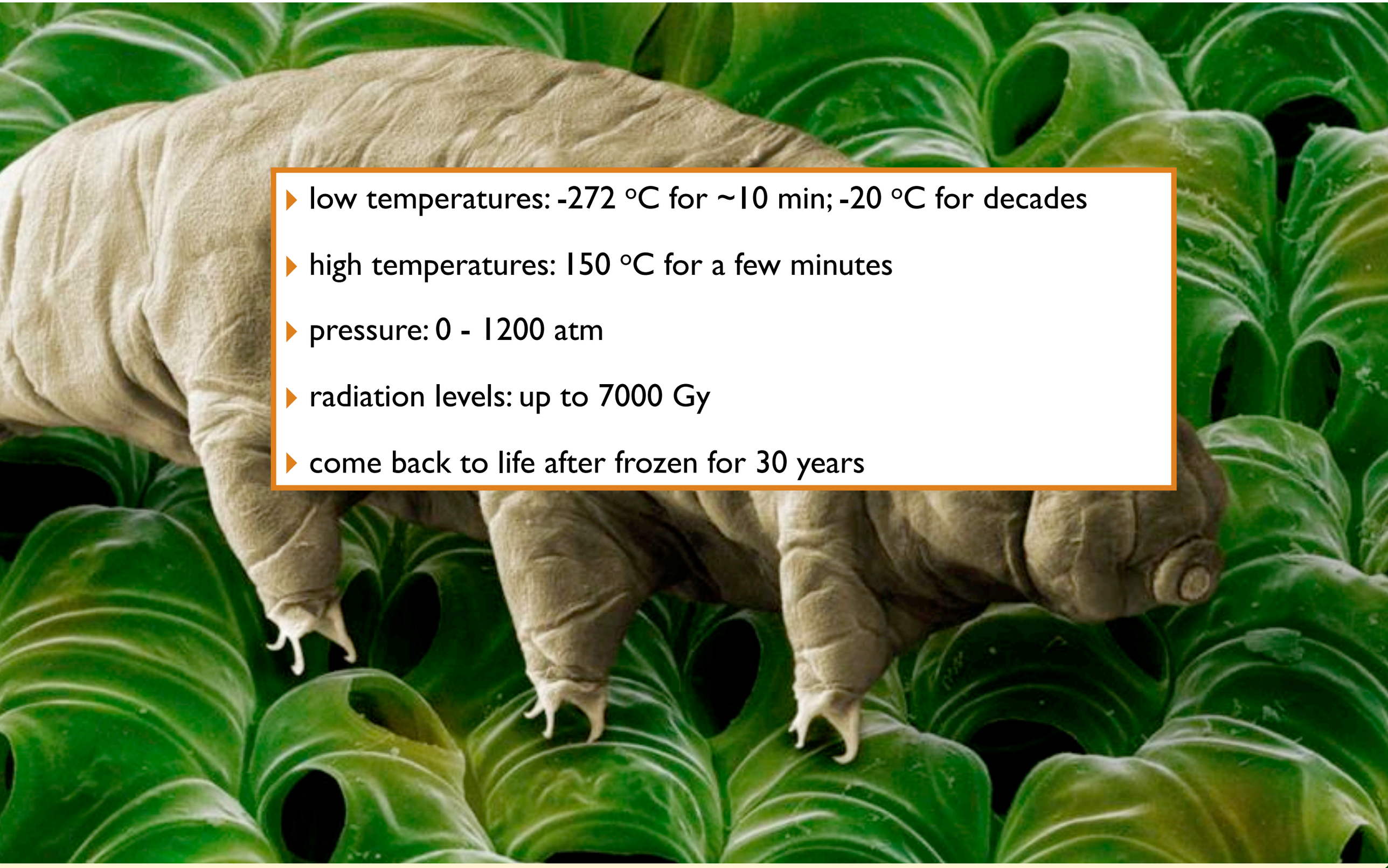
**what can sterilise <u>all</u> life on a planet?**

- asteroid impacts
- supernovae
- gamma-ray bursts
- death of host star

**life-threatening effects**

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

# most resistant form of life: tardigrades



- low temperatures: -272 °C for ~10 min; -20 °C for decades
- high temperatures: 150 °C for a few minutes
- pressure: 0 - 1200 atm
- radiation levels: up to 7000 Gy
- come back to life after frozen for 30 years

# high-energy threats: SNe and GRBs

**goal**: boil all the water of the ocean beyond recovery

*D. Sloan, RAB, A. Loeb. Submitted. 2016*

**SN sterilisation radius**

$$d_{SN} = \left(\frac{3}{32\pi M_p^{1/2}\rho}\right)^{\frac{1}{3}} \left(\frac{E_s}{\alpha \mathcal{C} T}\right)^{\frac{1}{2}}$$

sterilisation radius = 0.04 pc

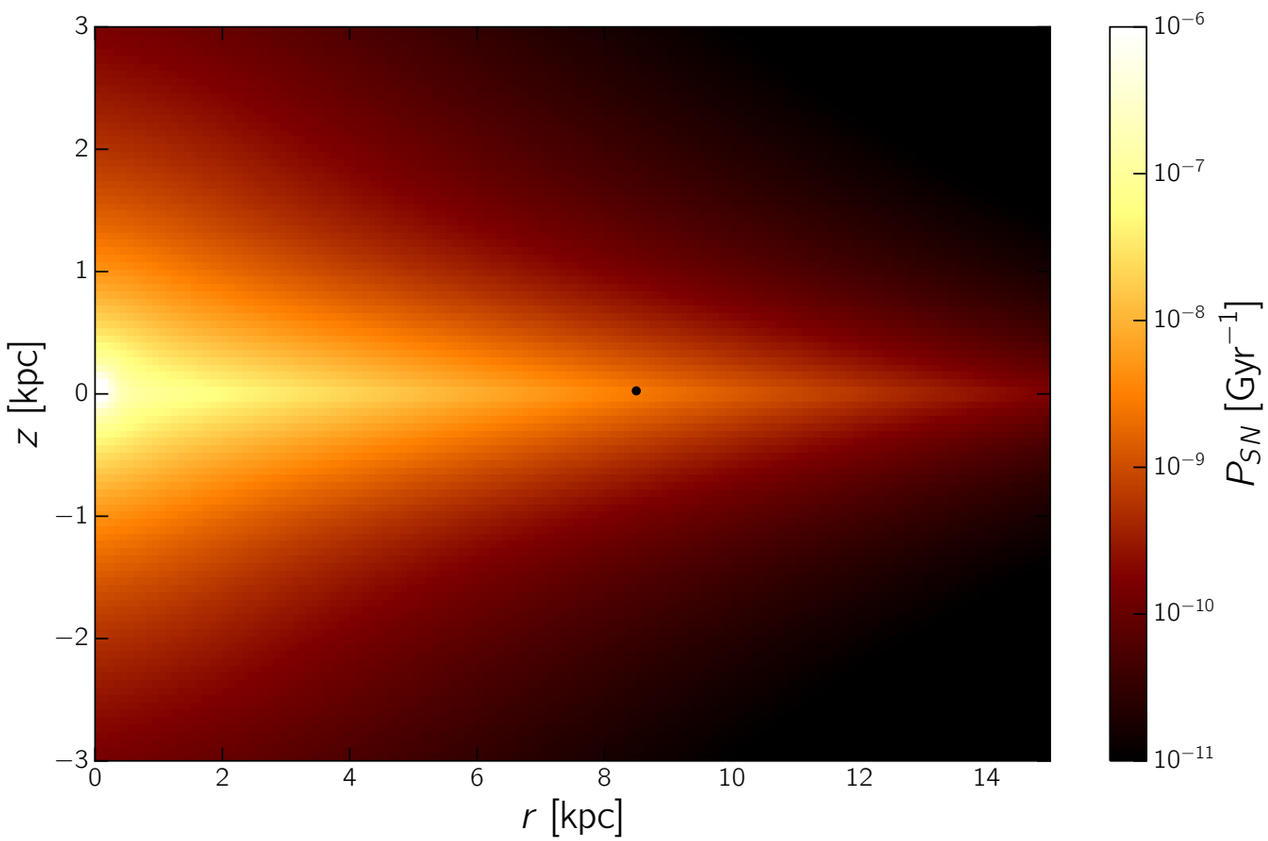
**GRB sterilisation radius**

$$E_s \leftrightarrow E_{GRB}\frac{\pi r^2}{\Omega d_{GRB}^2}$$

sterilisation radius = 13.6 pc

rate of occurrence of SNe within sterilisation radius

$$P_{SN}(r,z) = \chi \int_{M_{min}}^{M_{max}} dm\, \underbrace{\xi(m)}_{\text{initial mass function}} \underbrace{n_\star(r,z)}_{\text{stellar density profile}} \underbrace{\tau^{-1}(m)}_{\text{stellar lifetime}},$$



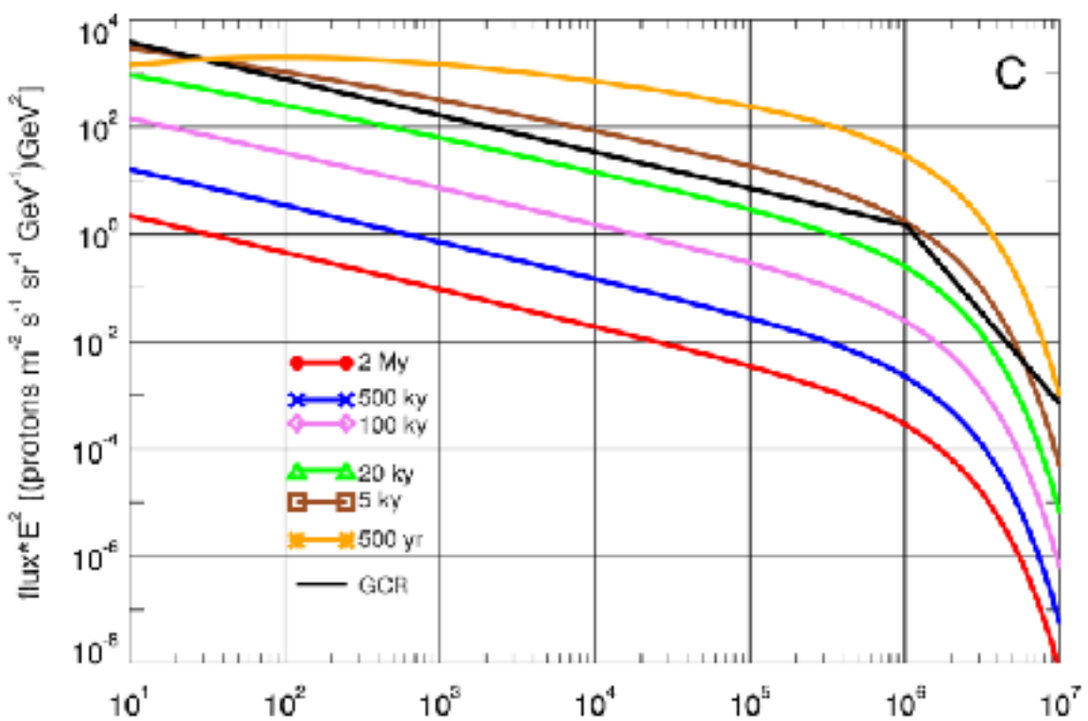
# SNe in our galaxy

*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*

- 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



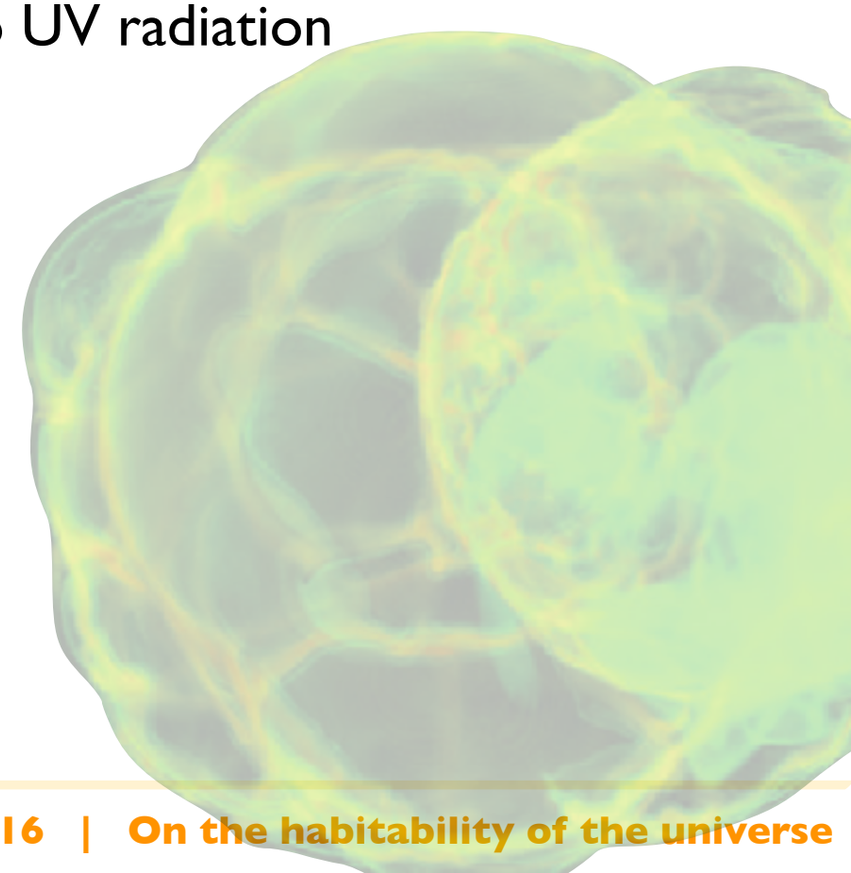

- ozone layer depletion:

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

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

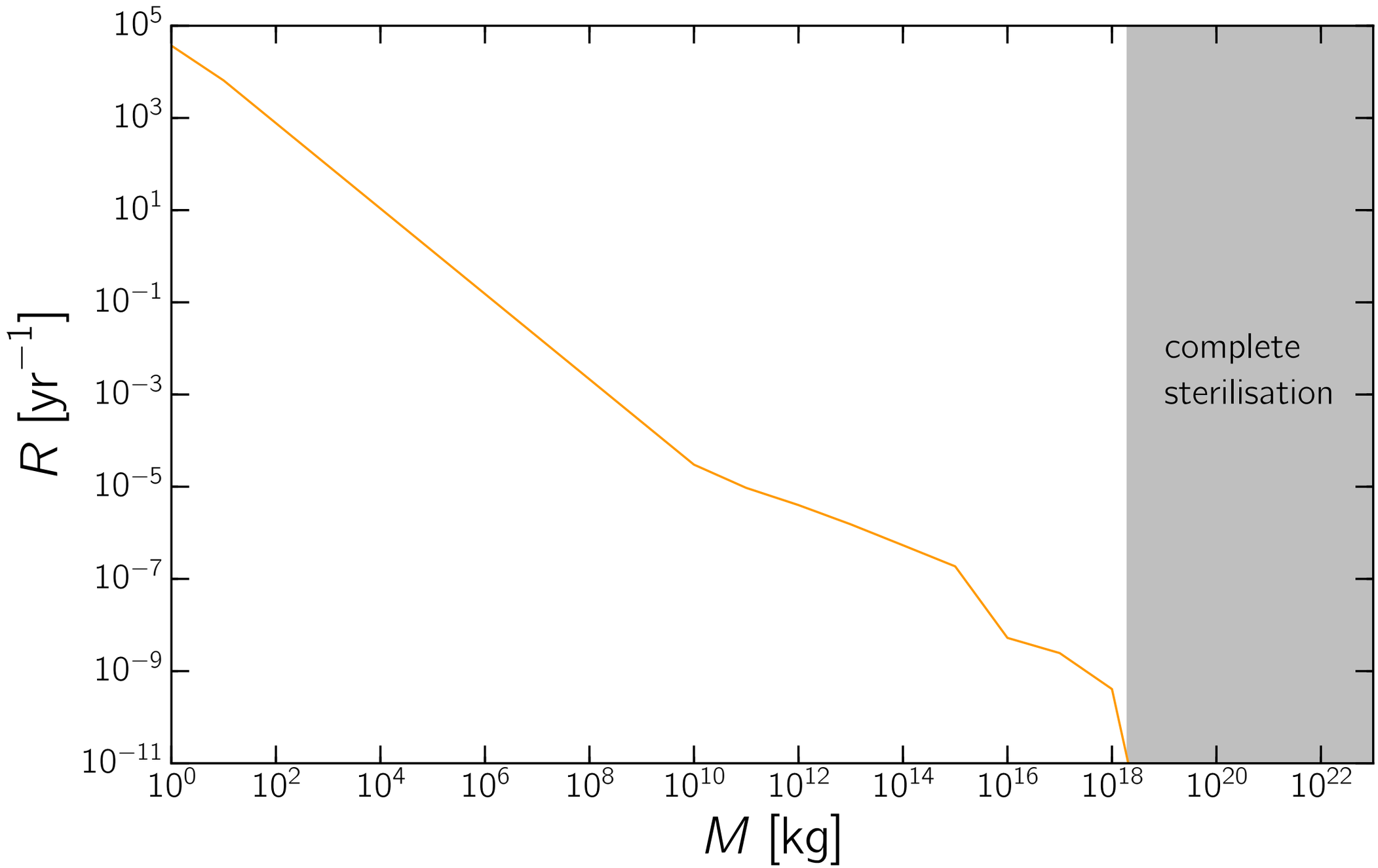
$$O_3 + O \rightarrow O_2 + O_2$$

- exposure to UV radiation



# impact threats: asteroids, comets, NEOs

*D. Sloan, RAB, A. Loeb. Submitted. 2016*



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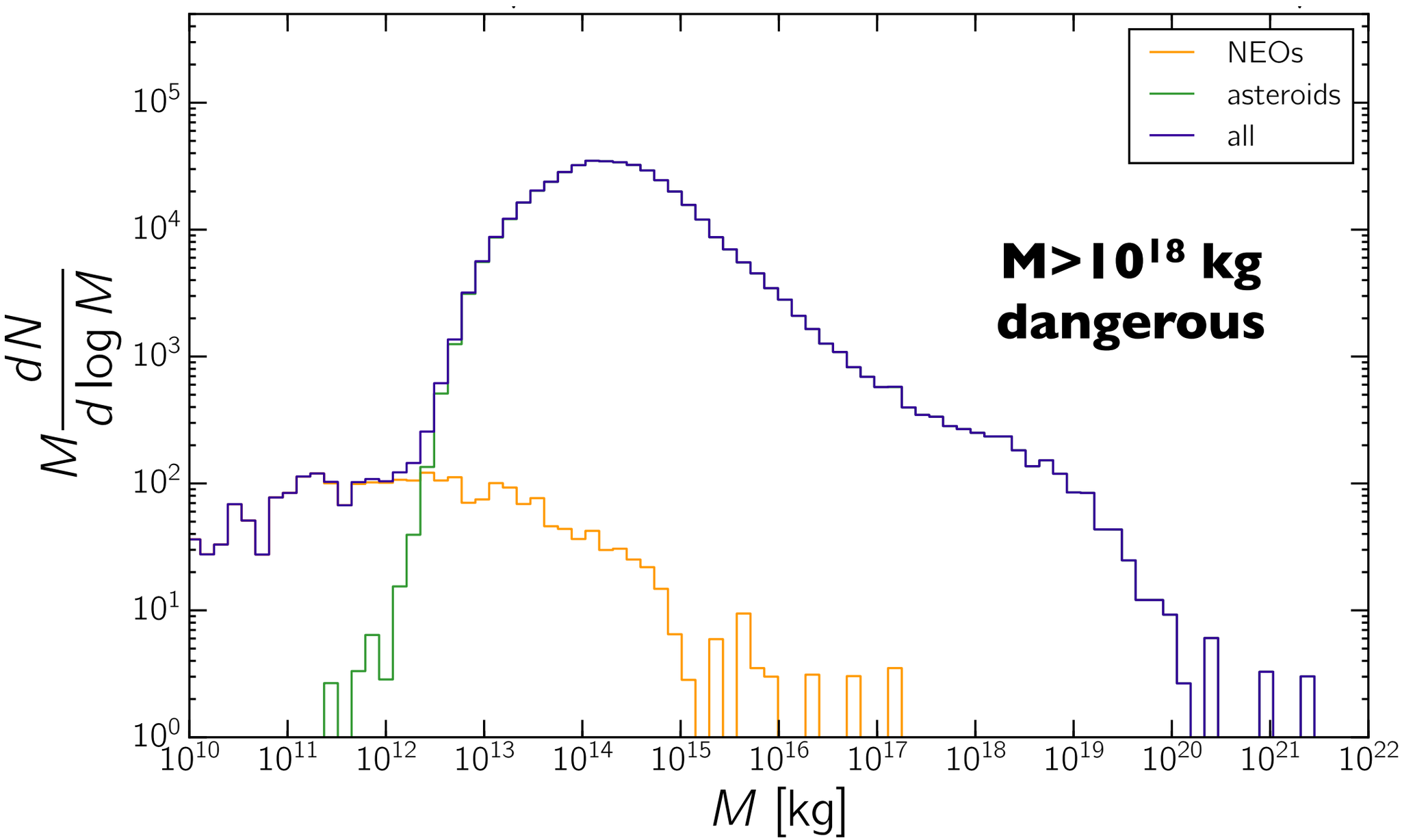
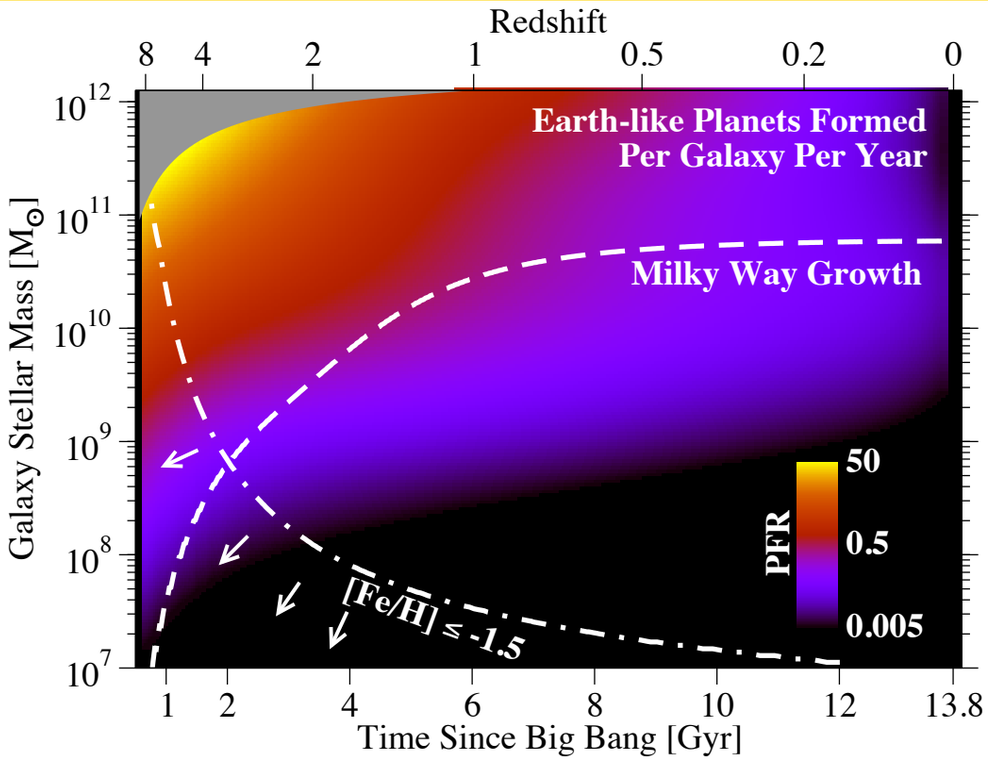
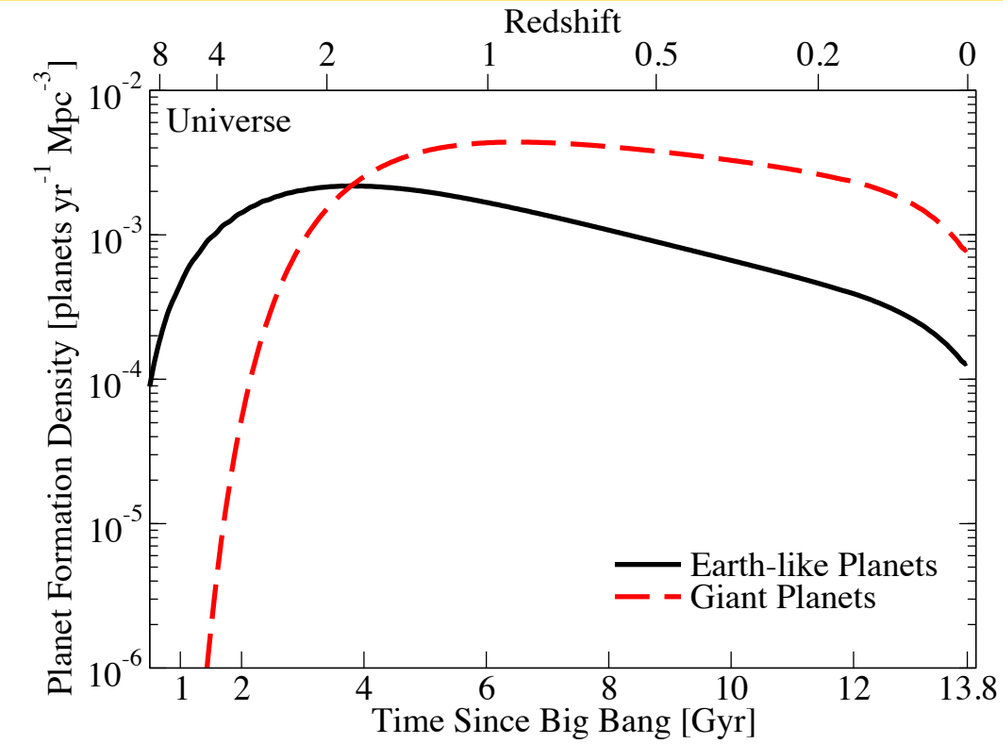
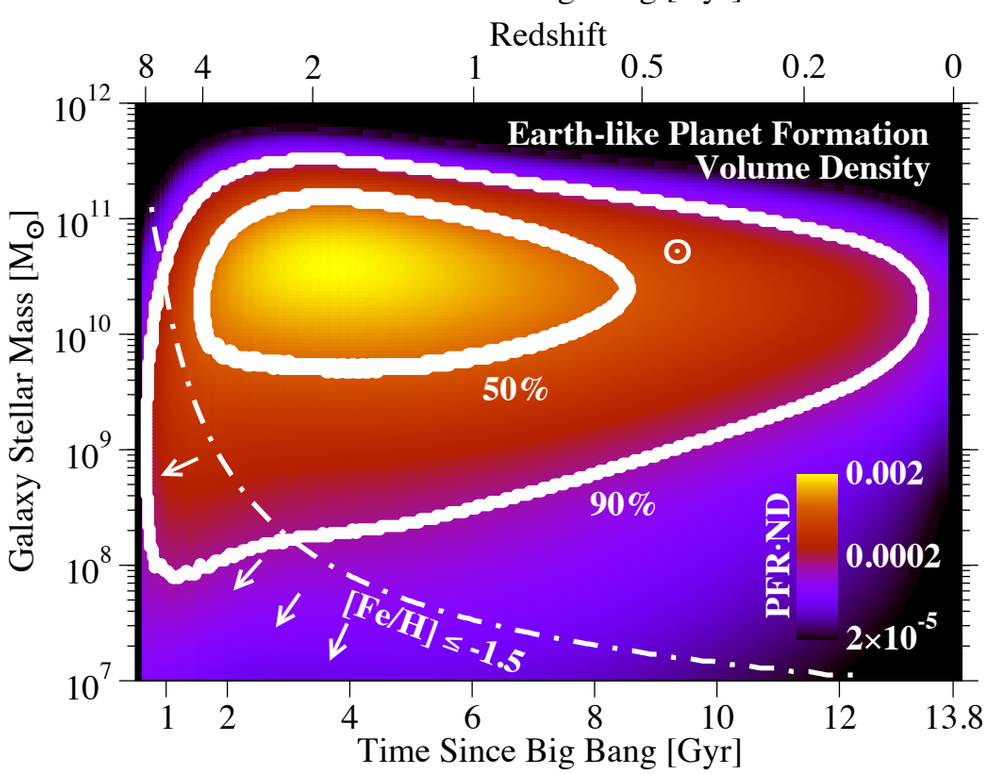


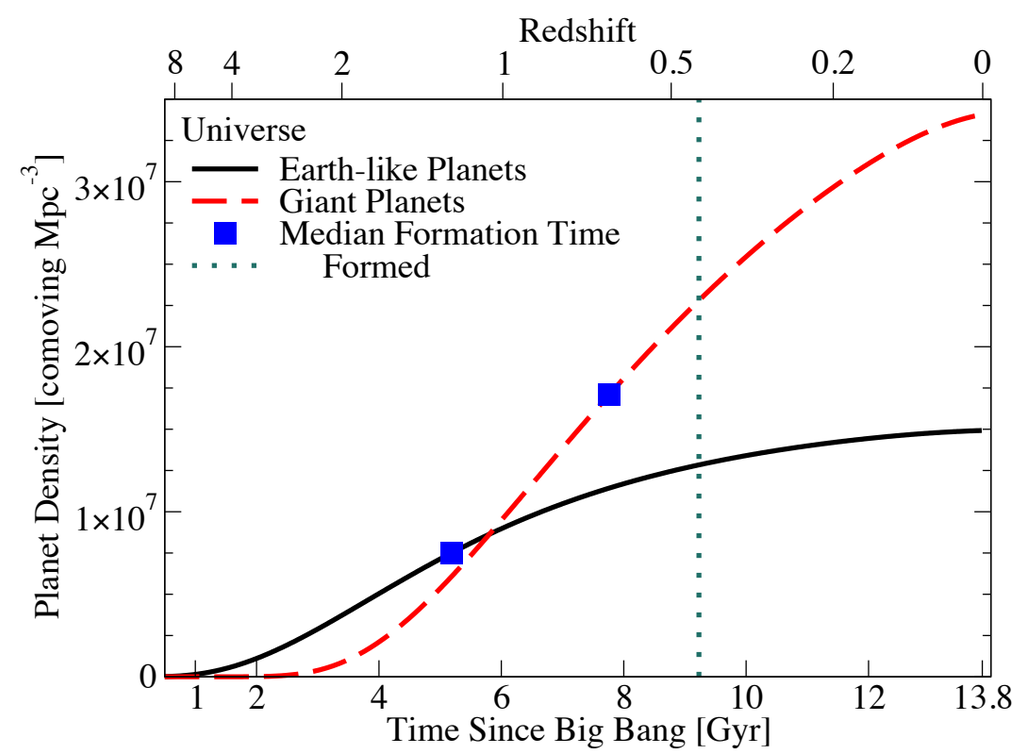
# other threats: atmospheric stripping

# history of formation of Earth-like planets



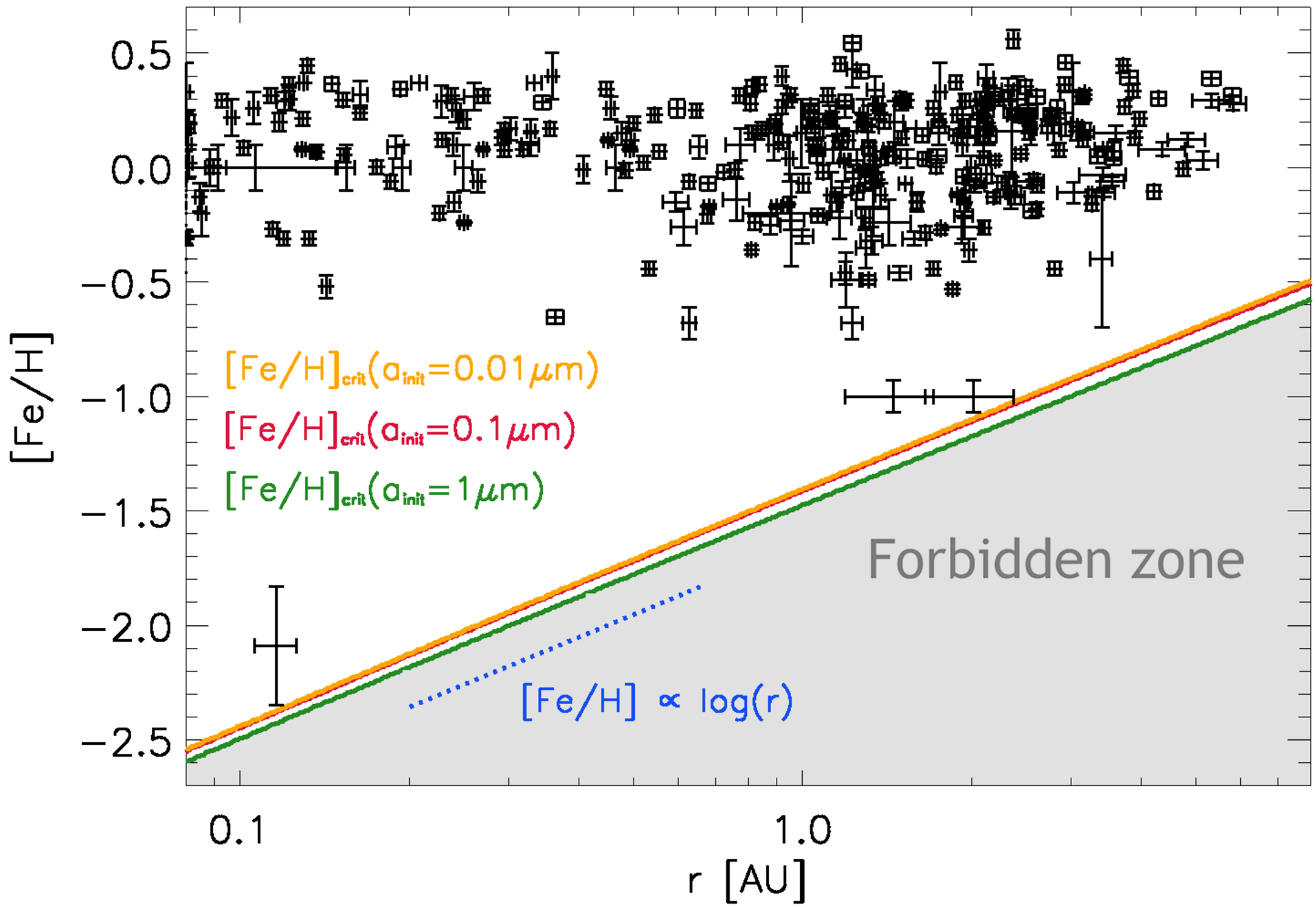




*P. Behroozi, M. Peeples. MNRAS 454 (2015) 1811. arXiv:1508.01202*

# history of formation of Earth-like planets

## constraints on metallicity




*J. Johnson, H. Li. Astrophys. J. 751 (2012) 1. arXiv:1203.4817*

# when is life first possible?

*A. Loeb. Int. J. Astrobio. 13 (2014) 337. arXiv:1312.0613*

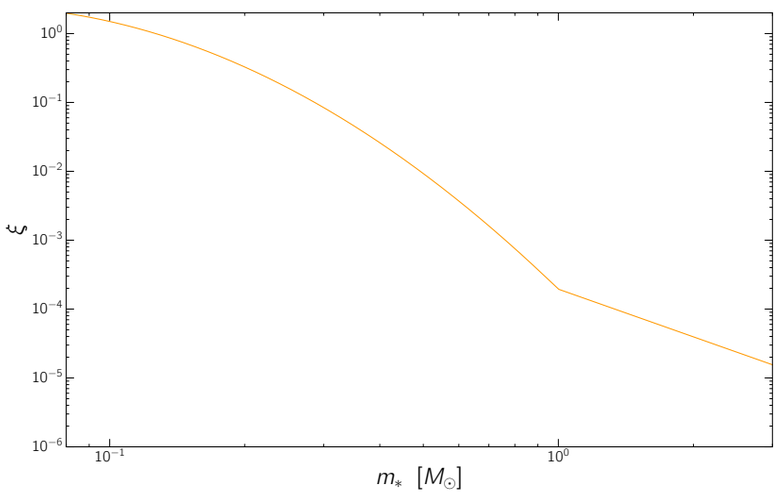
- $T_{CMB}(z=100) = 273$ K; $T_{CMB}(z=137) = 373$ K → conditions for habitability
- first generation of haloes, formed ~7 Myr after the Big Bang
- formation of metals possible due to short lifespan of massive stars
- tail of the density fluctuation distribution: $8.5\sigma$

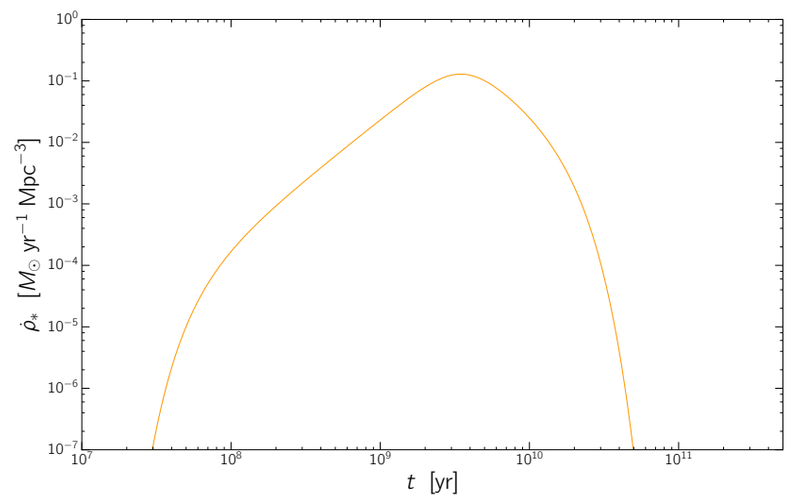
# when is life likely?

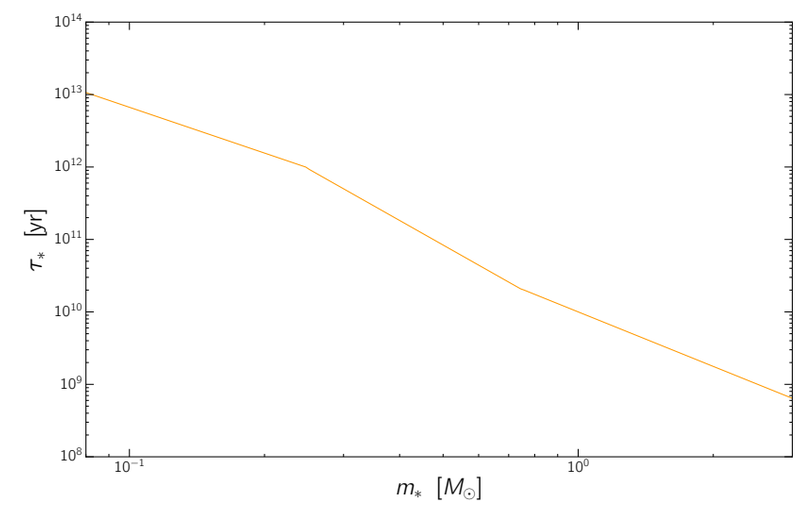
A. Loeb, RAB, D. Sloan. JCAP 08 (2016) 040. arXiv:1606.08448

master equation

$$\frac{dP}{dt}(t) = \frac{1}{N}\int_0^t dt' \int_{m_{min}}^{m_{max}} dm' \underbrace{\xi(m')}_{\text{initial mass function}} \underbrace{\dot{\rho}_\star(t', m')}_{\text{star formation rate}} \underbrace{\eta_{\rm Earth}(m')}_{\text{probability of finding Earth-like planets in the HZ}} \underbrace{p(\text{life}|\text{HZ})}_{\text{probability of finding life in a habitable planet}} \underbrace{g(t-t', m')}_{\text{window function: birth/death of stars}}$$




nEarth = 0.19; Kepler observations + no mass dependence

p(life|HZ): constant

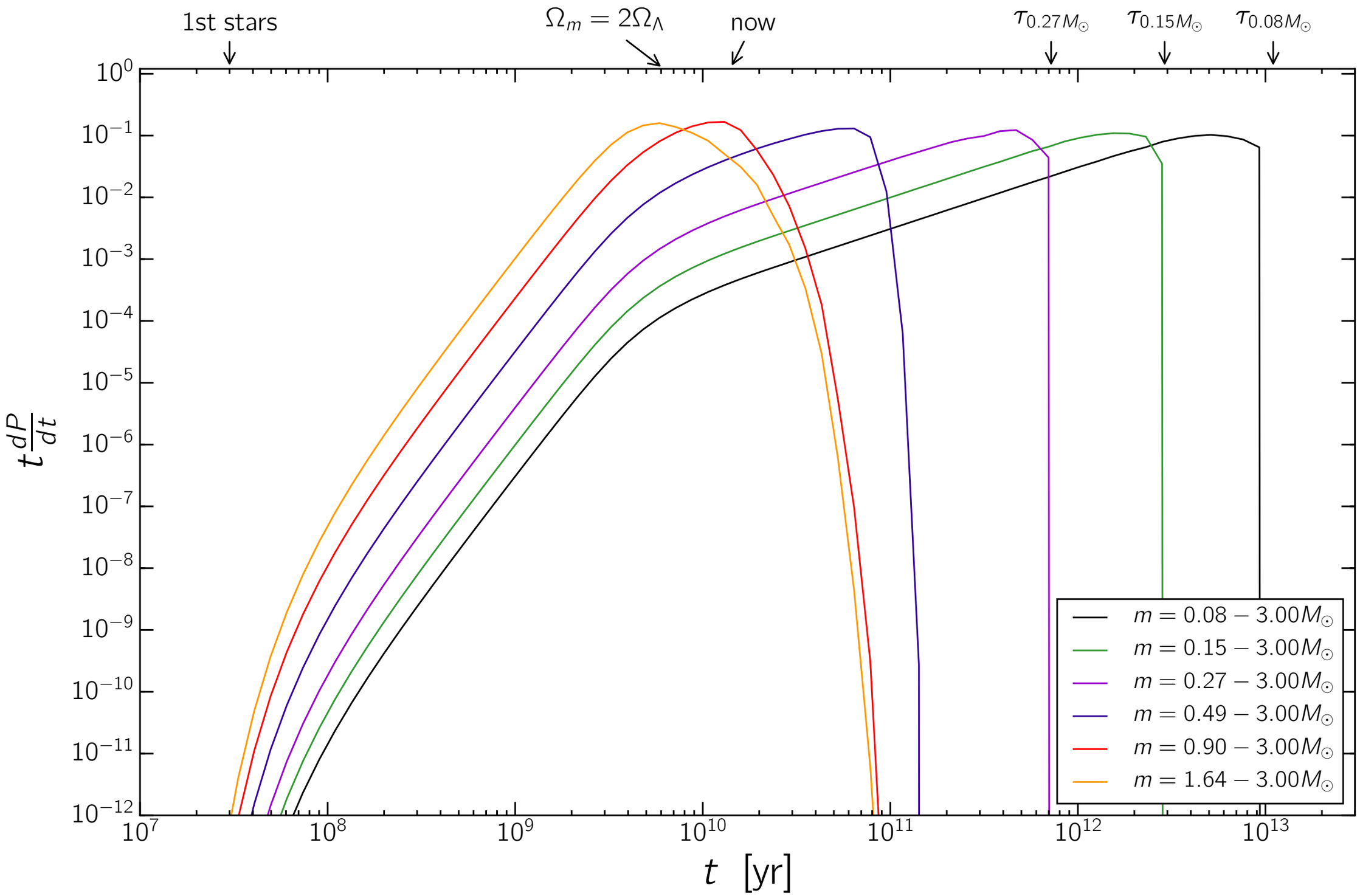
g(t-t', m'): 1 whilst star lives; 0 otherwise

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

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

# when is life likely?

*A. Loeb, RAB, D. Sloan. JCAP 08 (2016) 040. arXiv:1606.08448*



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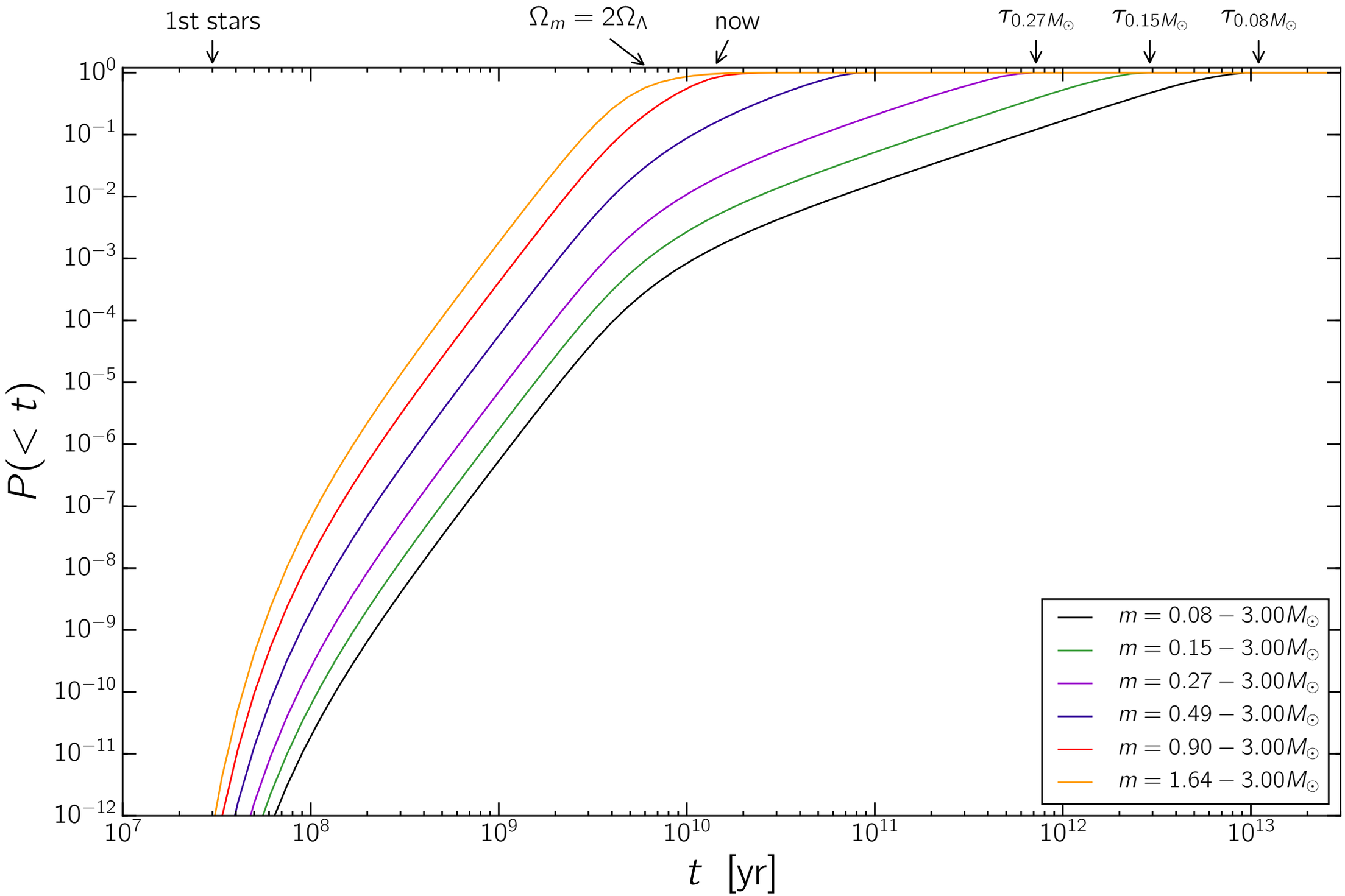


# the cosmological constant "problem"

**Einstein's field equation**

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

**energy-momentum tensor**

$$T_{\mu\nu} = (\rho + p) U_\mu U_\nu + p g_{\mu\nu}$$

**Friedmann equations**

$$H^2 = \left(\frac{\ddot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2(t)}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

- expected vacuum energy density from QFT: $\rho_{\Lambda,th} \sim M_{Pl}^4 \sim (10^{25}\ \mathrm{eV})^4 \sim 10^{109}\ \mathrm{J\ m^{-3}}$
- observed cosmological constant: $\rho_{\Lambda,obs} \sim 10^{-11}\ \mathrm{J\ m^{-3}}$
- 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?

# “why now?” - the coincidence problem

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

**tentative explanations**

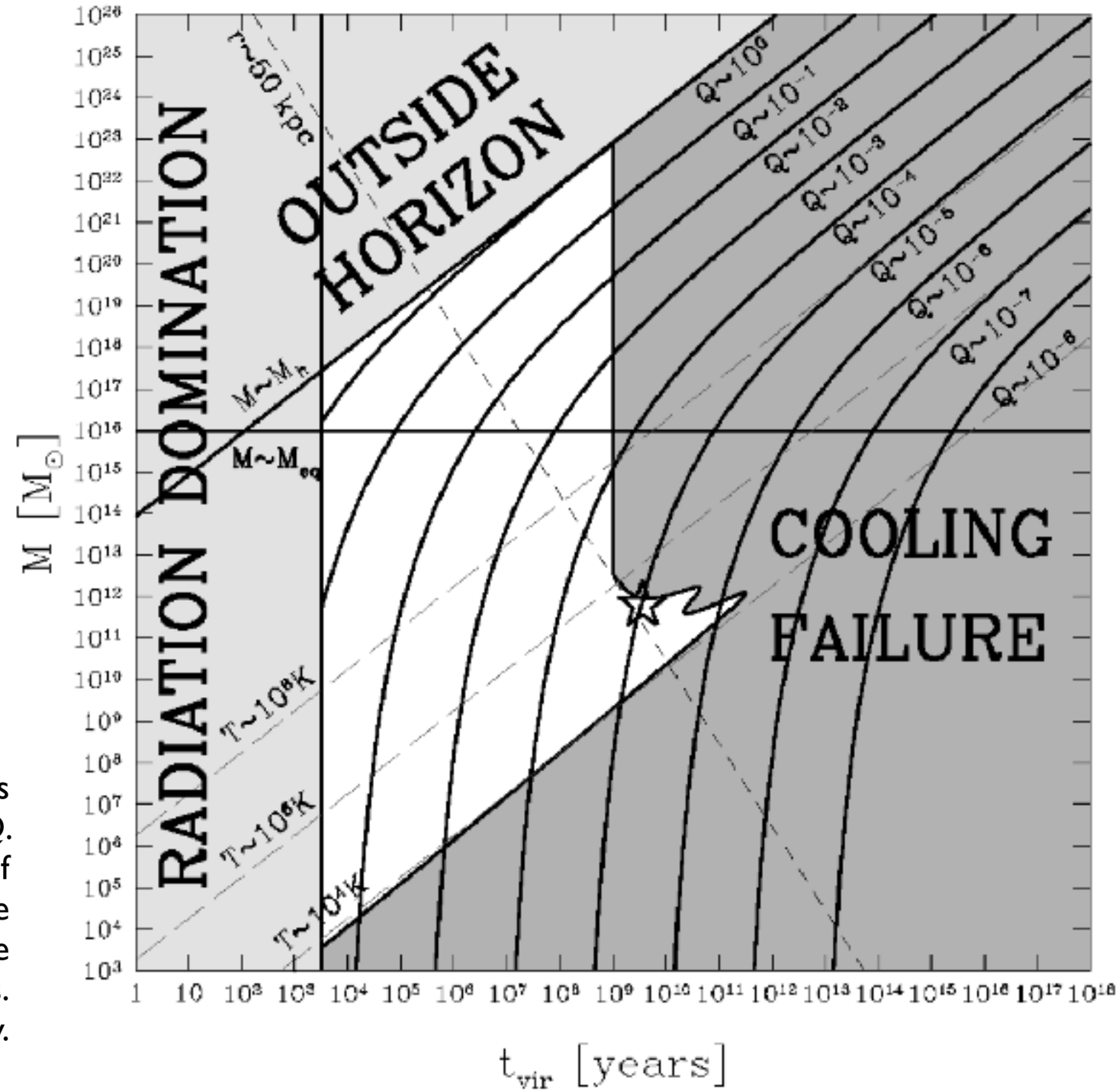
- anthropics → there can only be observers if this is true
- coincidence → we could live at (almost) any other time
- dynamical dark energy models (e.g. quintessence, k-essence, …)

**motivation**

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

# anthropic bounds on Q

- 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

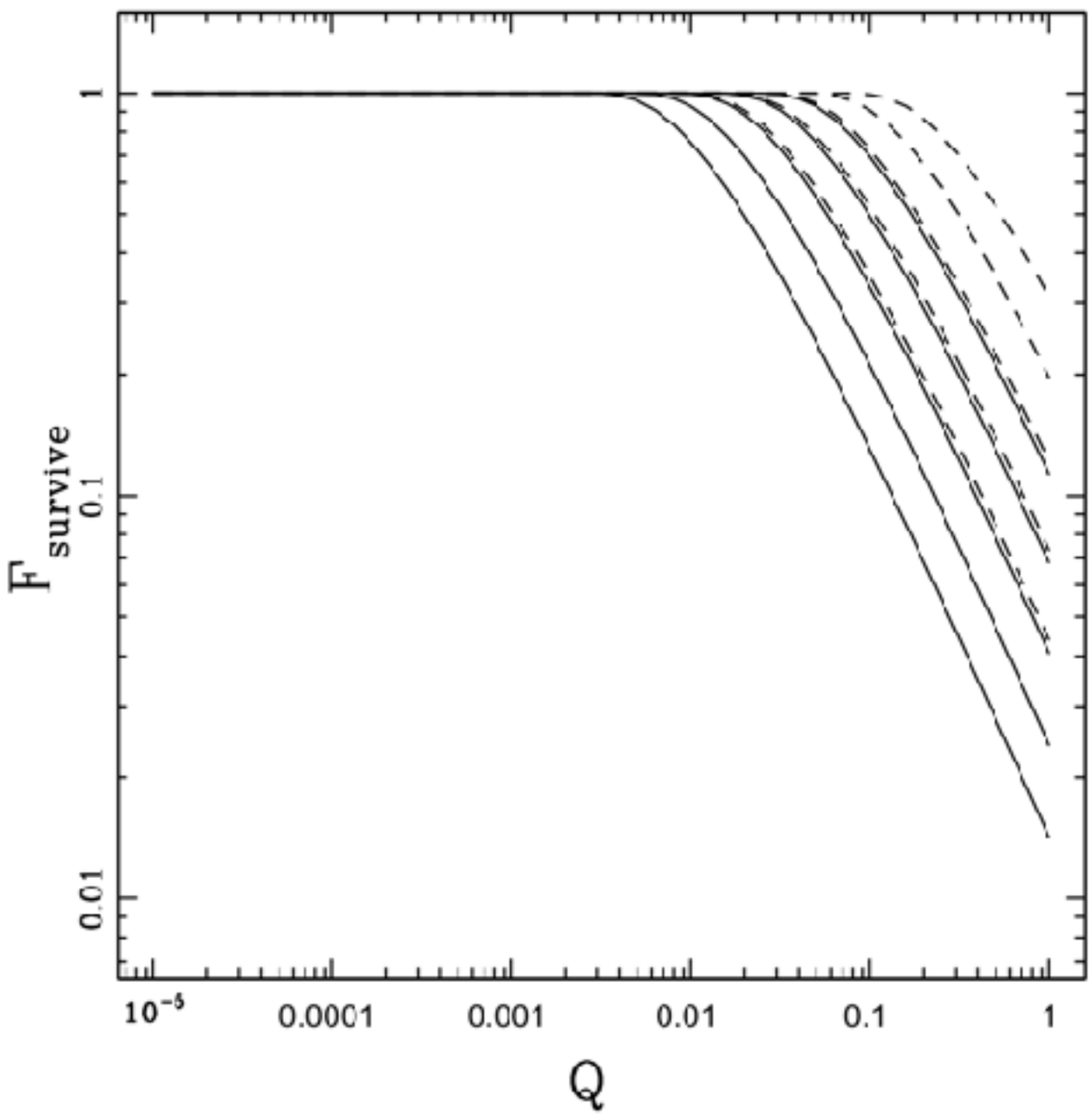



Rising curves show the largest virialised mass scale as a function of time for different values of Q. Structures with $M<M_{eq}$ virialise $Q^{-3/2}$ after the end of the radiation-dominated epoch. For later times, the virialised mass scale converges to $Q^{3/2}$ times the horizon mass.
The star corresponds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

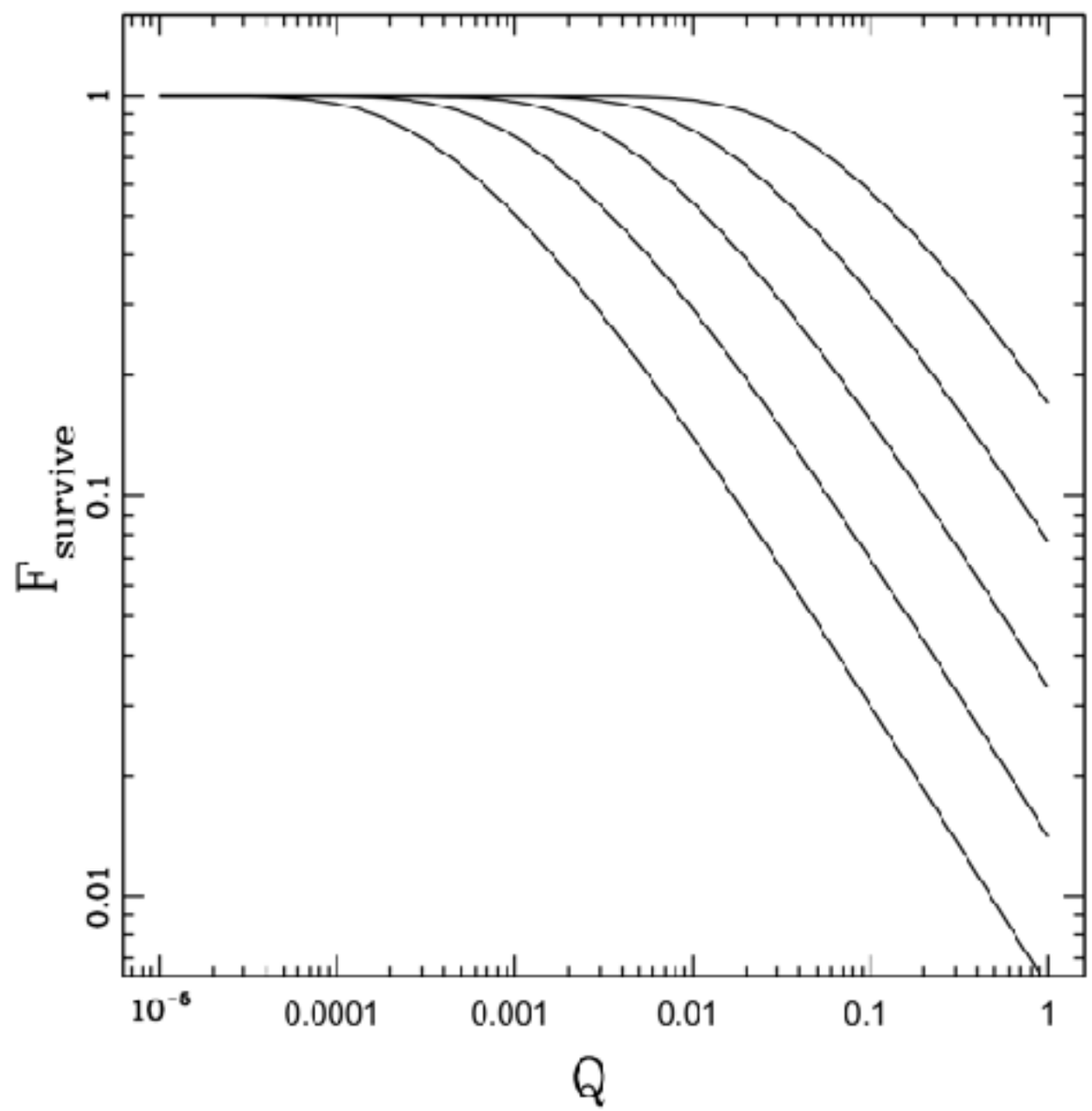
*M. Tegmark, M. Rees. Astrophys. J. 499 (1998) 526.*

# anthropic bounds on Q

**temperature**




**collisions**



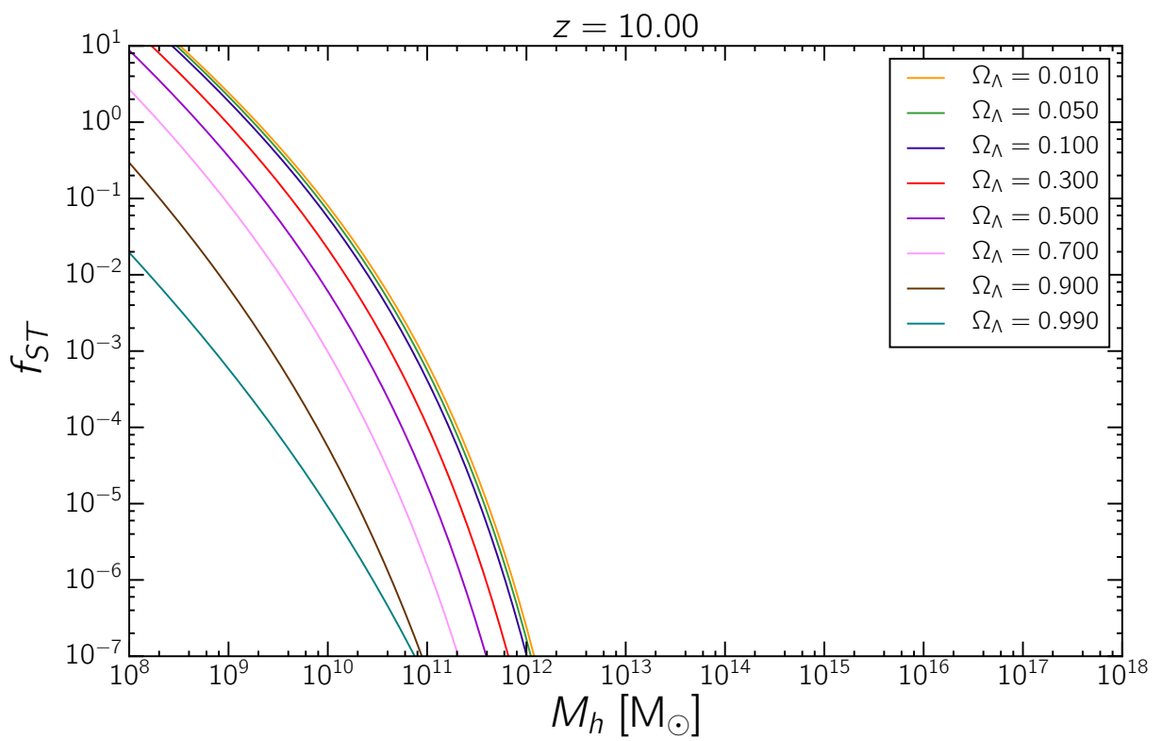

$F_{survive}$: fraction of planetary systems that survive

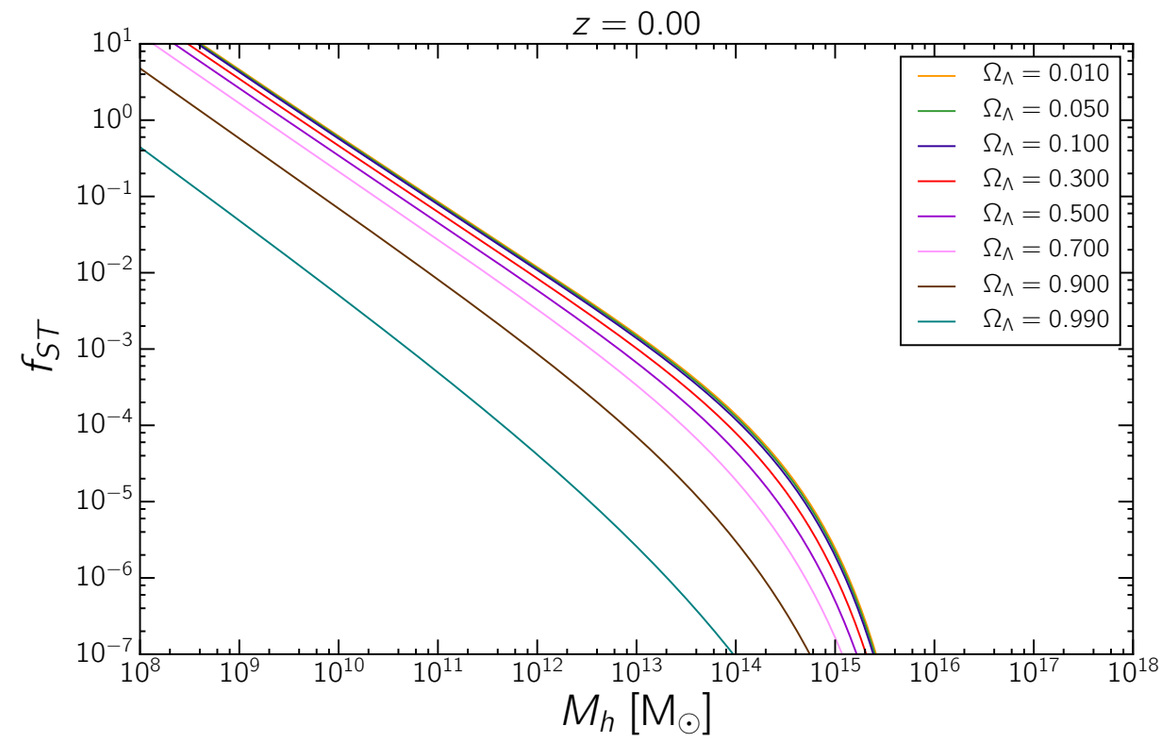
*F. Adams et al. J Cosmol. Astropart. Phys 09 (2015) 30. arXiv:1505.06158*

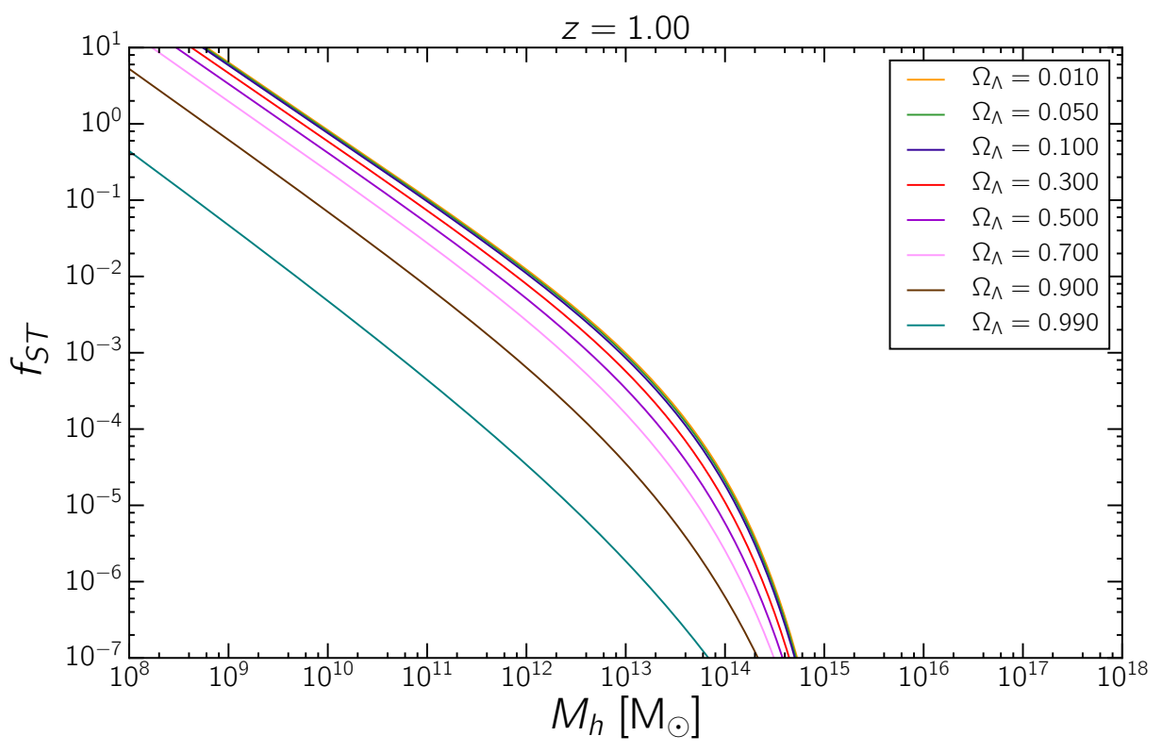
# when is life likely for arbitrary Λ?

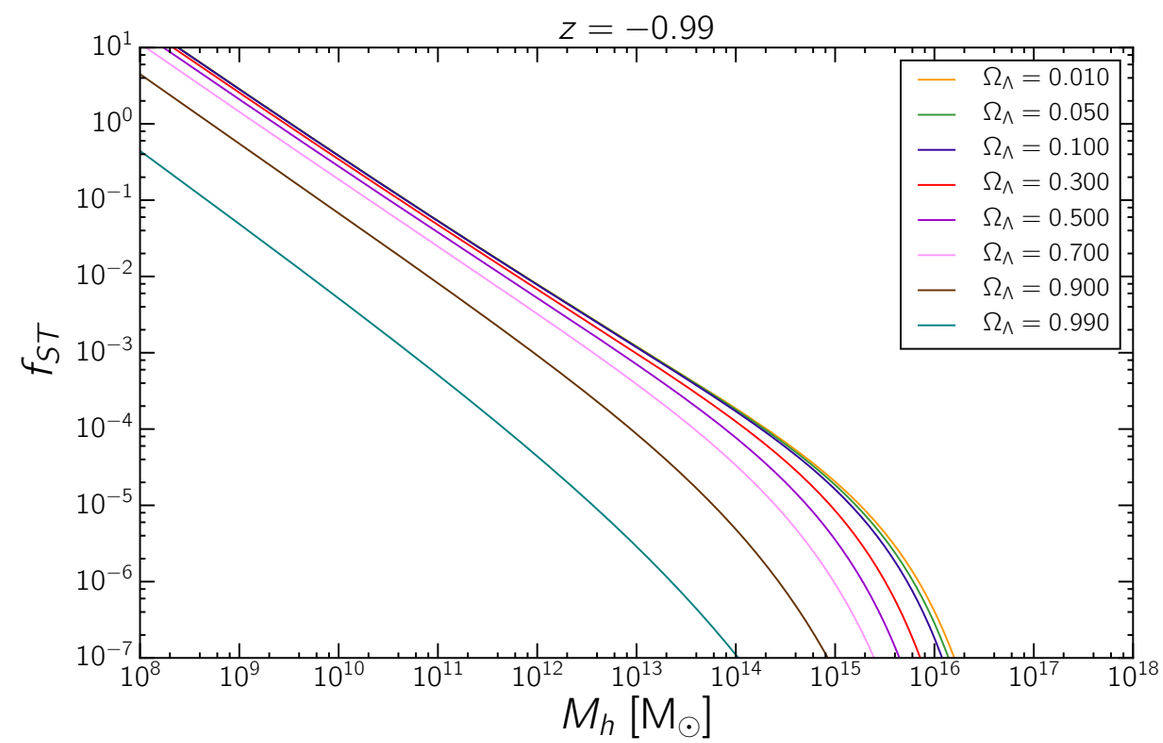
## halo mass functions

*RAB, D. Traykova, D. Sloan, A. Loeb. In preparation.*



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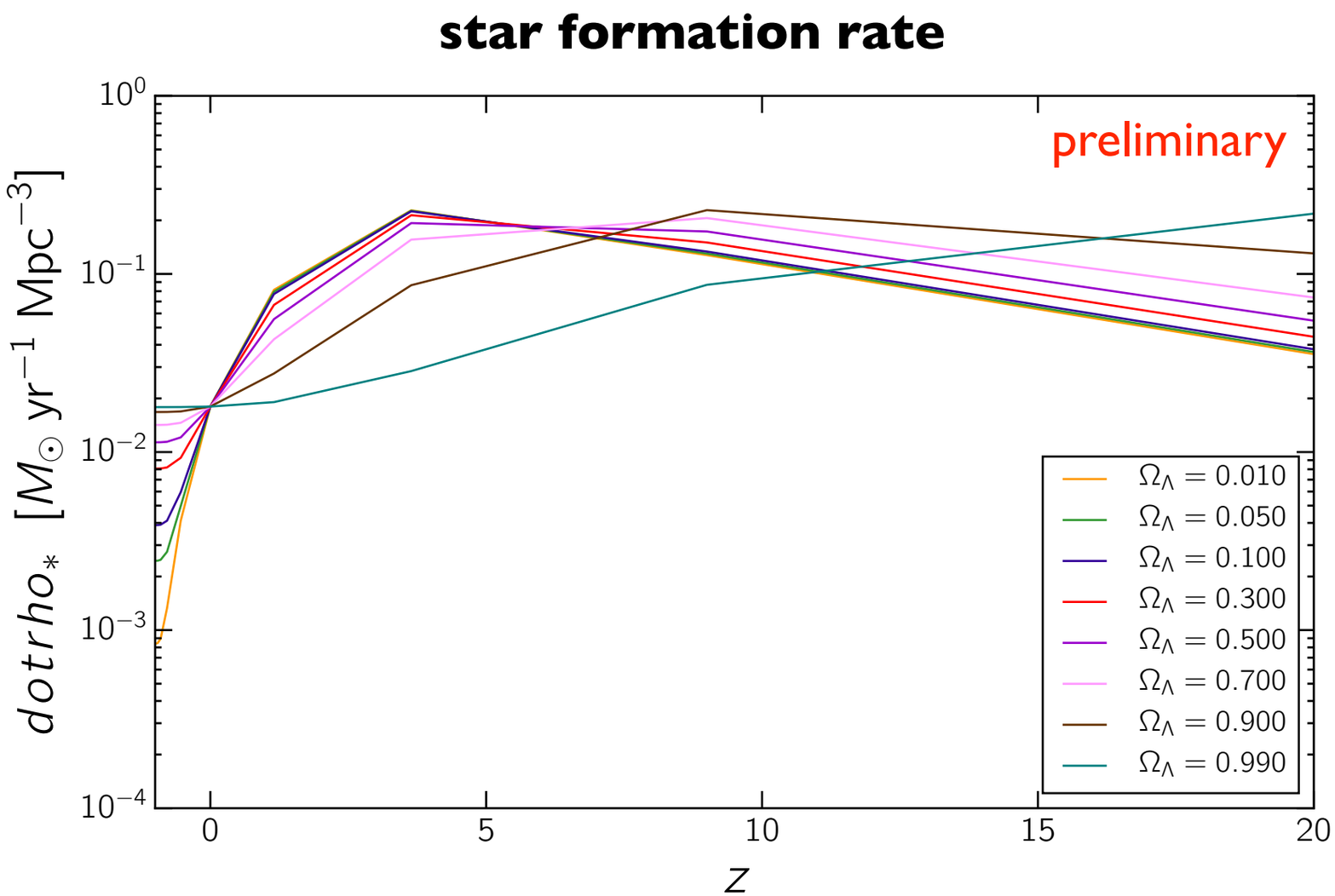
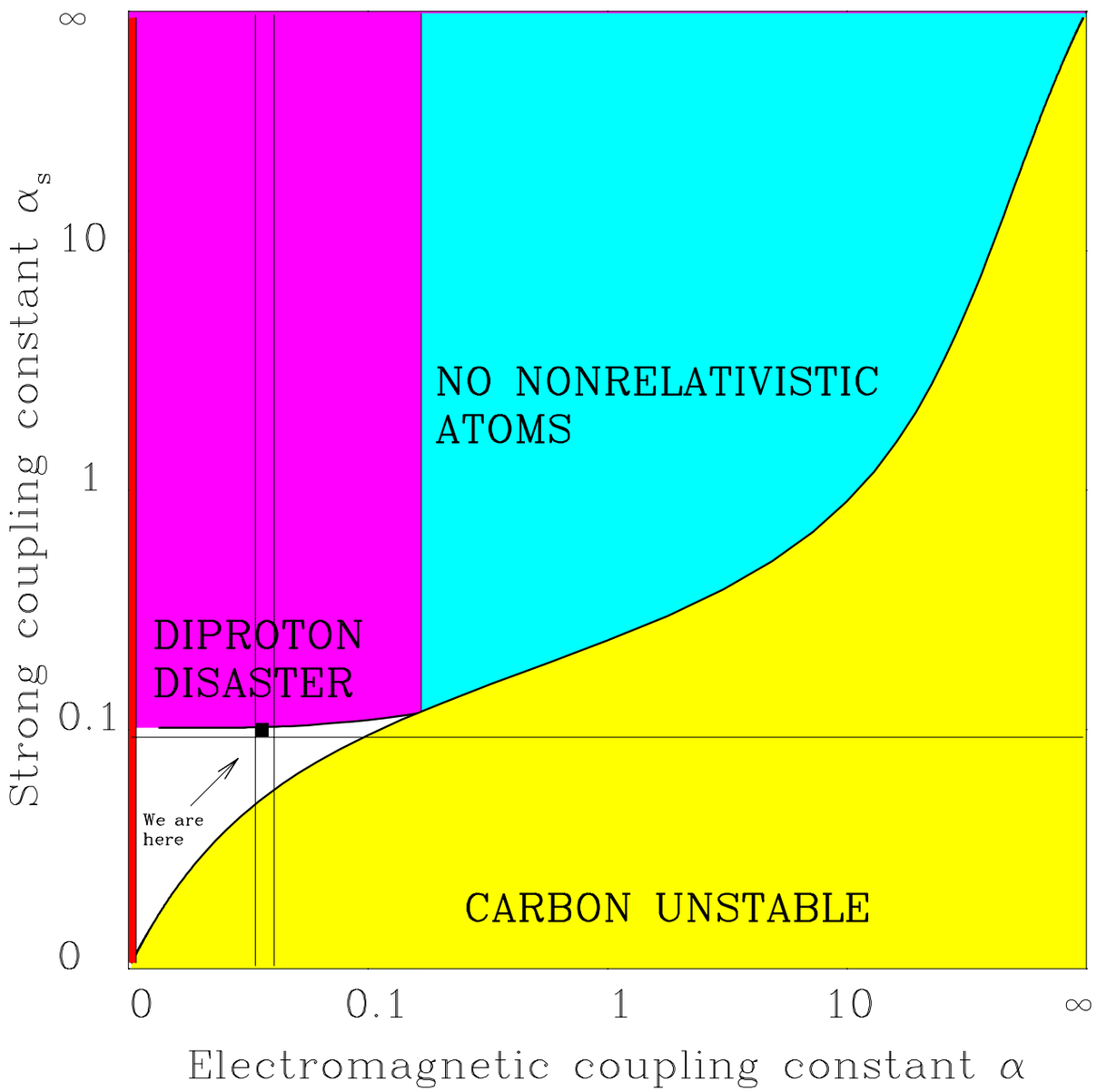
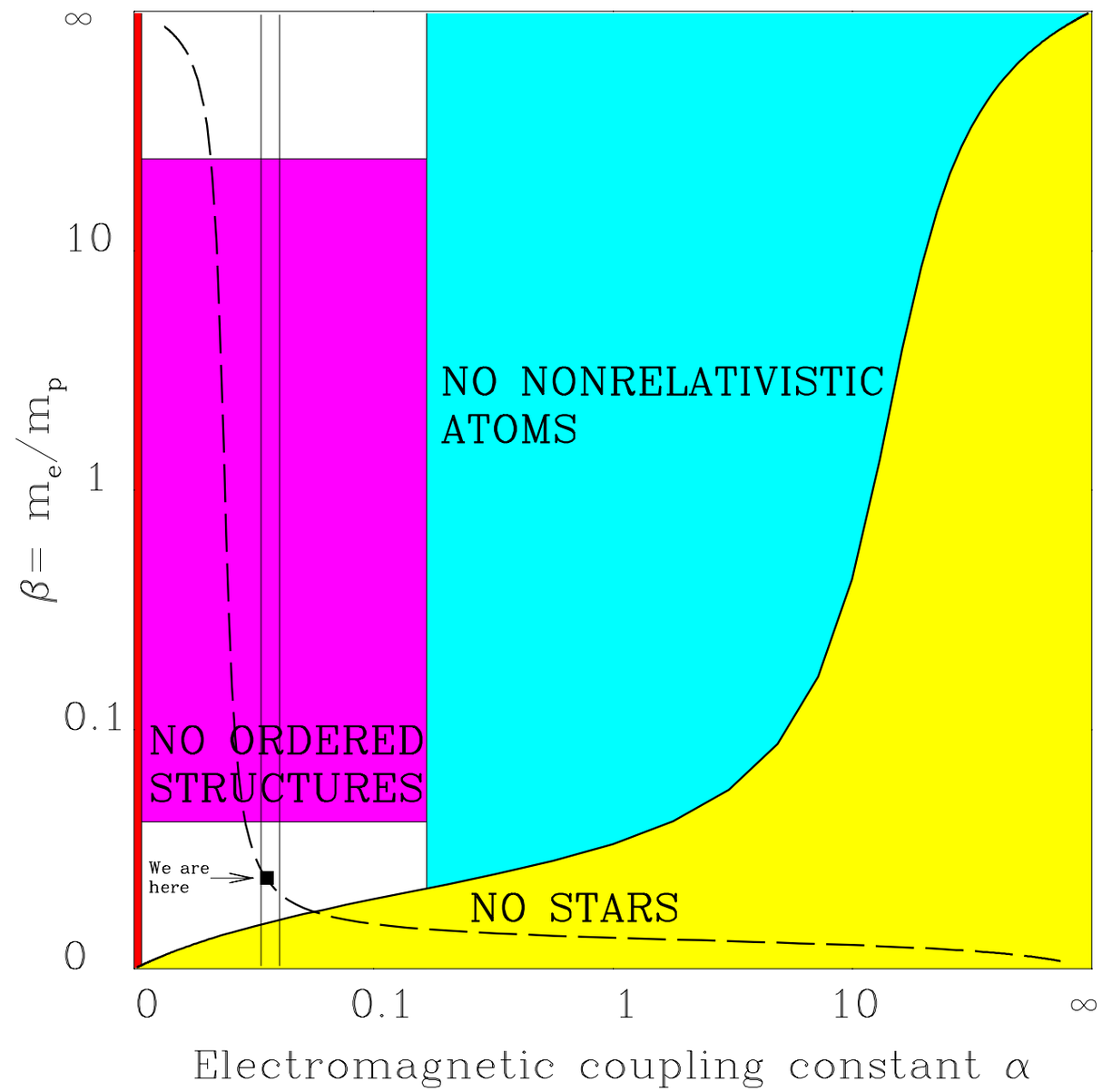



- effect of dark energy: shift formation of structures along time axis (total number of stars formed changes though)
- existence of structures require $\Omega_\Lambda < 0.85$

# varying constants and habitability

*M. Tegmark. Annals Phys. 270 (1998) 1. arXiv:gr-qc/9704009*

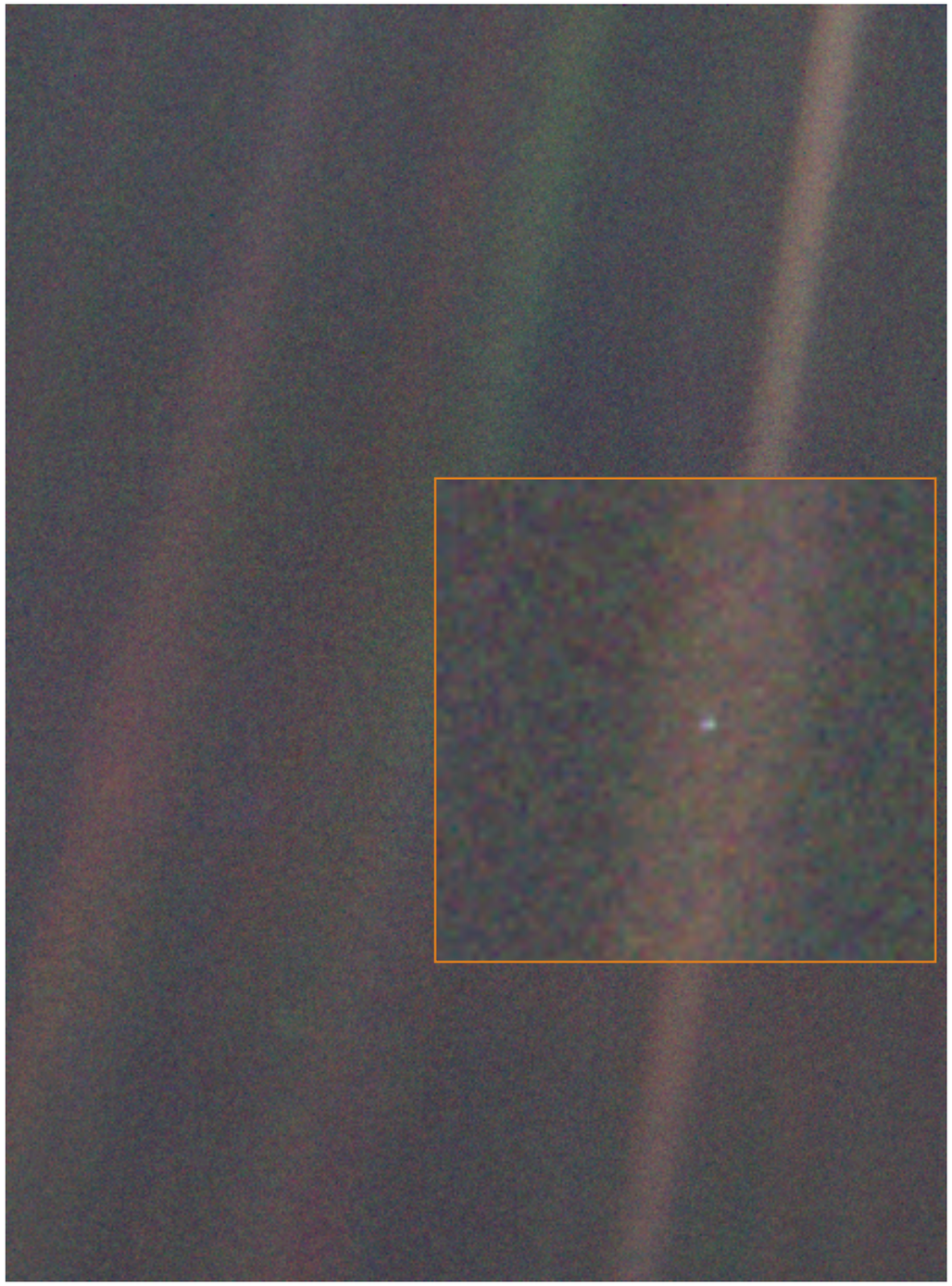


# conclusions and perspectives

- 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
- there is a habitable epoch in the early universe (z~100-137)
- many potentially habitable planets found by Kepler
- JWST will allow us to look for biomarkers in planetary atmospheres
- life seems to be fairly resilient to cataclysmic events
- biggest threat to (all) life: asteroid impacts!
- is the observed cosmological constant "bio-friendly"? → apparently NOT, although there seems to be an anthropic upper bound
- the coincidence "problem" and the "principle of mediocrity"

# direct image of a habitable planet



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

**pale blue dot...**


Phys FiT
International conference on
John Templeton Foundation
The Physics of Fine-Tuning
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Topics Include:
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Khalil Chamcham
Michael Hicks
Nick Kylafis
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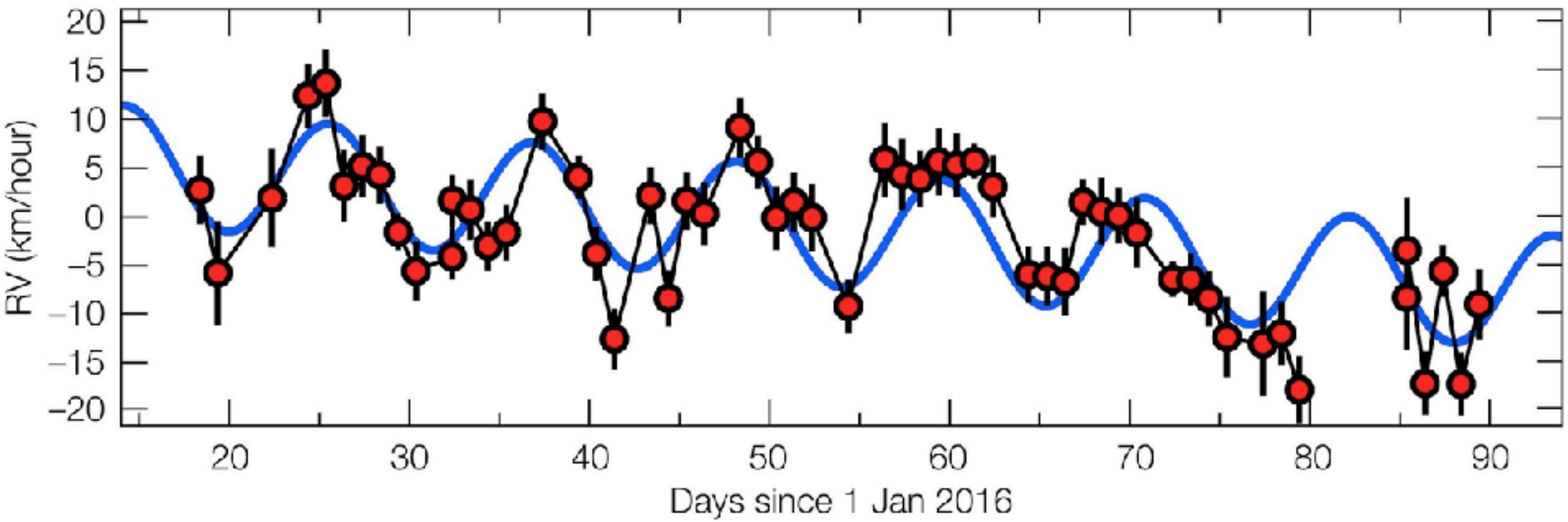
Leanne O'Donnell

# thank you 😊

# Proxima Centauri b




Velocity of Proxima Centauri towards and away from the Earth over 3 months. Red: data. Blue: fit to data.

# formation of DM haloes for arbitrary Λ

*RAB, D. Traykova, D. Sloan, A. Loeb. In preparation.*

**Sheth-Tormen halo mass function**

$$\frac{dN}{dM_h} = \frac{\rho_0}{M_h}\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}M_h} A\sqrt{\frac{2a}{\pi}}\left[1+\left(\frac{\sigma^2}{2\delta_c}\right)^p\right]\frac{\delta_c}{\sigma}\exp\left(-\frac{a\delta_c^2}{2\sigma^2}\right)$$

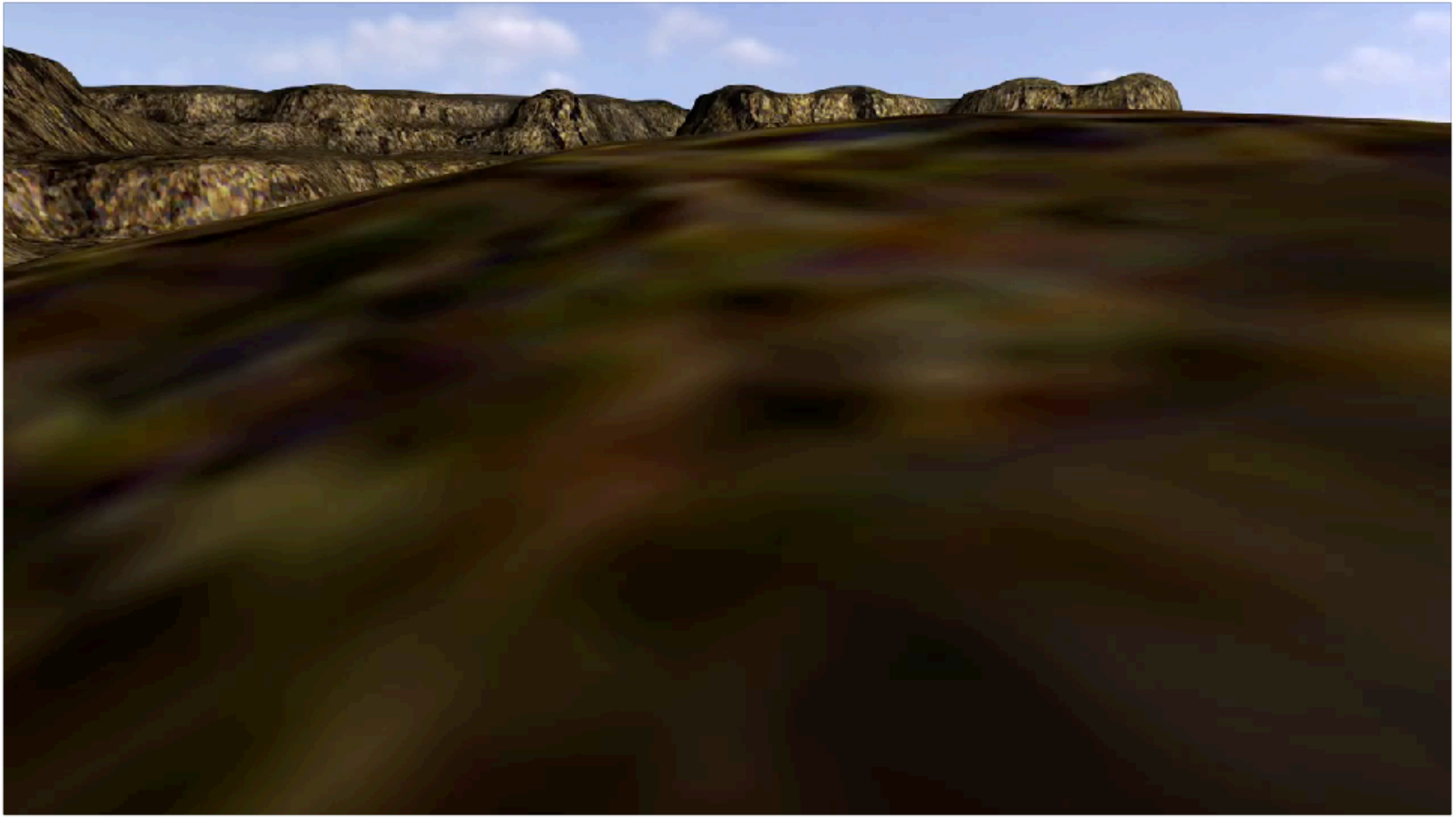
**dispersion of halo masses**

$$\sigma^2(M_h, z) = \frac{D(z)}{2\pi^2}\int_0^\infty \mathrm{d}k P(k) k^2 \left[\frac{3j_1(kR)}{kR}\right]^2$$

**evolution of growth factor**

$$D(z) = D_0 H(z)\int_z^\infty dz' \frac{1+z'}{H^3(z')}$$

# Breakthrough Initiative: StarShot



# Breakthrough Initiative: StarShot

# the (meta?)physics of the multiverse

*G. Ellis & J. Silk. Nature 516 (2014) 321.*

## Defend the integrity of physics

Attempts to exempt speculative theories of the Universe from experimental verification undermine science, argue **George Ellis** and **Joe Silk**.

In the meantime, journal editors and publishers could assign speculative work to other research categories — such as mathematical rather than physical cosmology — according to its potential testability. And the domination of some physics departments and institutes by such activities could be rethought[1,2].

The imprimatur of science should be awarded only to a theory that is testable. Only then can we defend science from attack. ■