Habitability --- from a stellar evolution perspective

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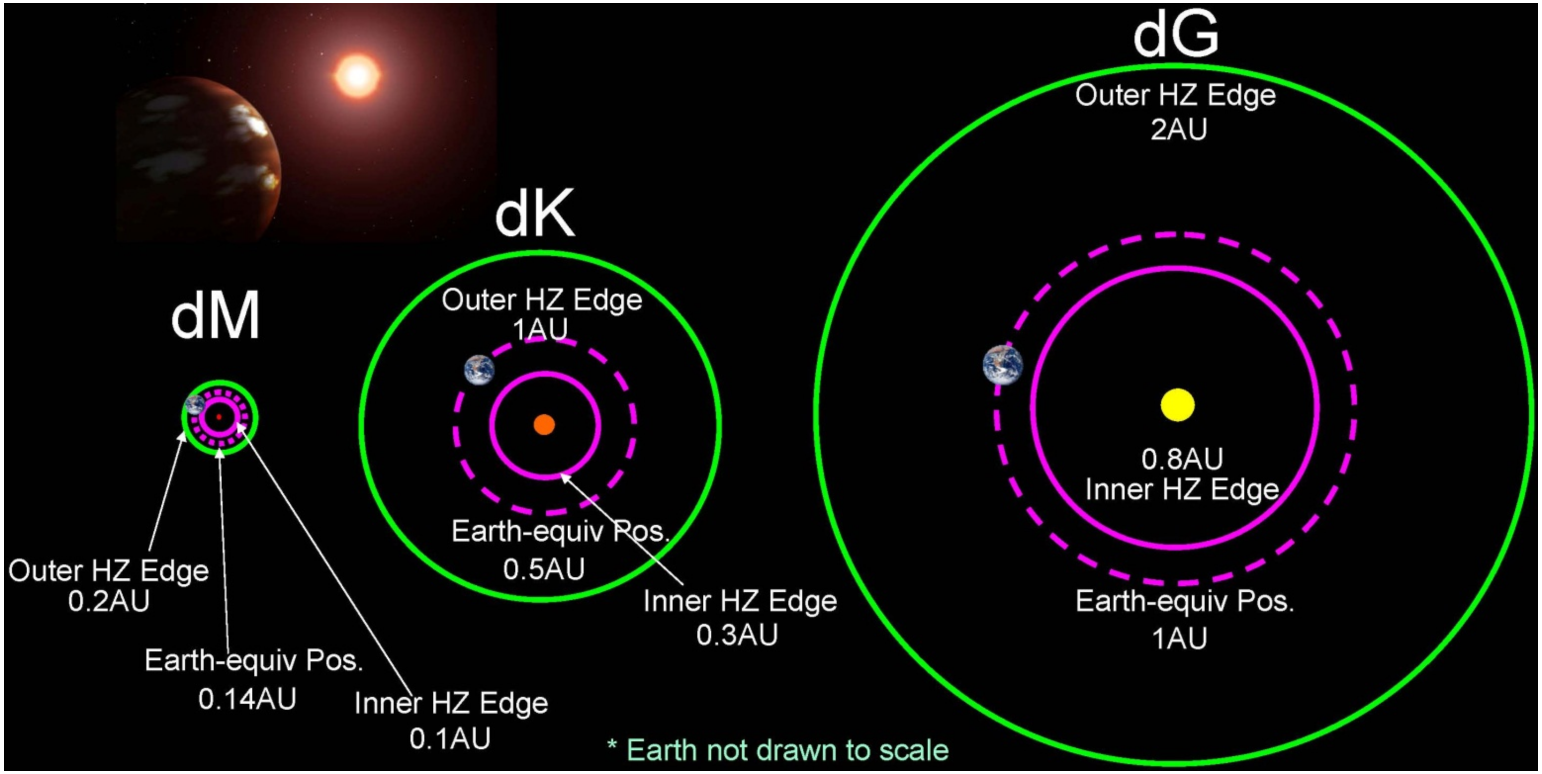
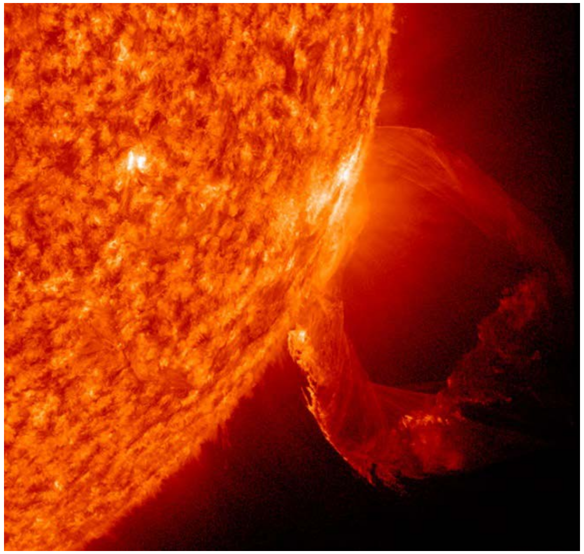
Heating and Chemistry of Planetary Atmospheres



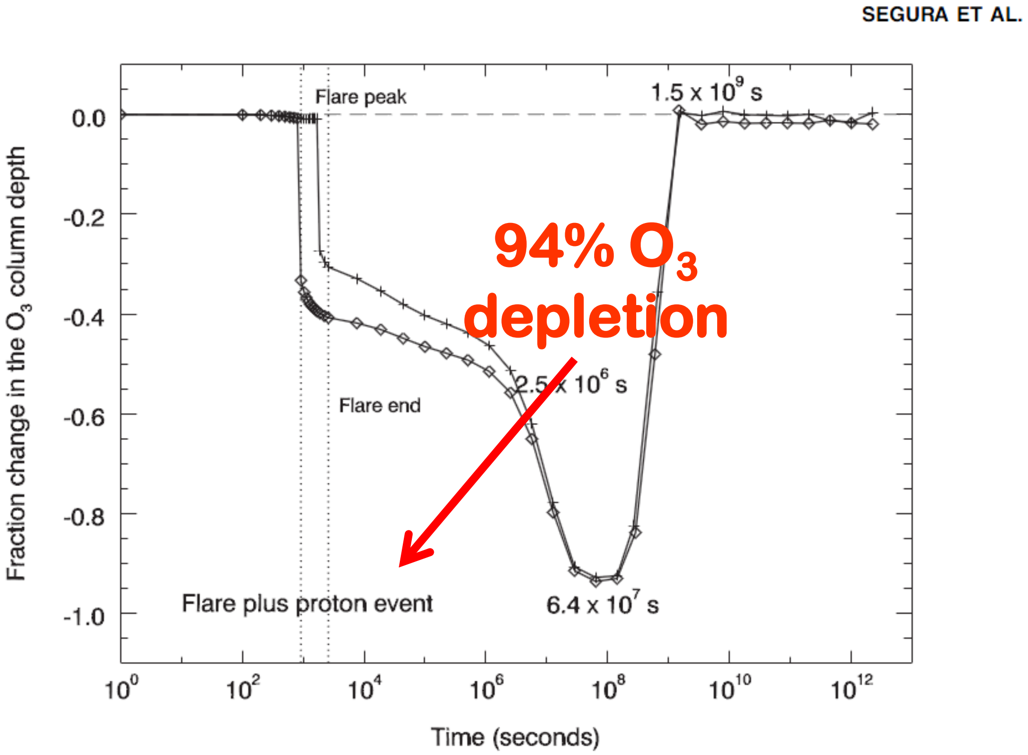
Classical Picture – Where surrounding a particular star would conditions be right for liquid water to exist on an Earth-like planet?

Heating and Chemistry of Planetary Atmospheres



Classical habitability determined by photospheric optical/near-IR flux

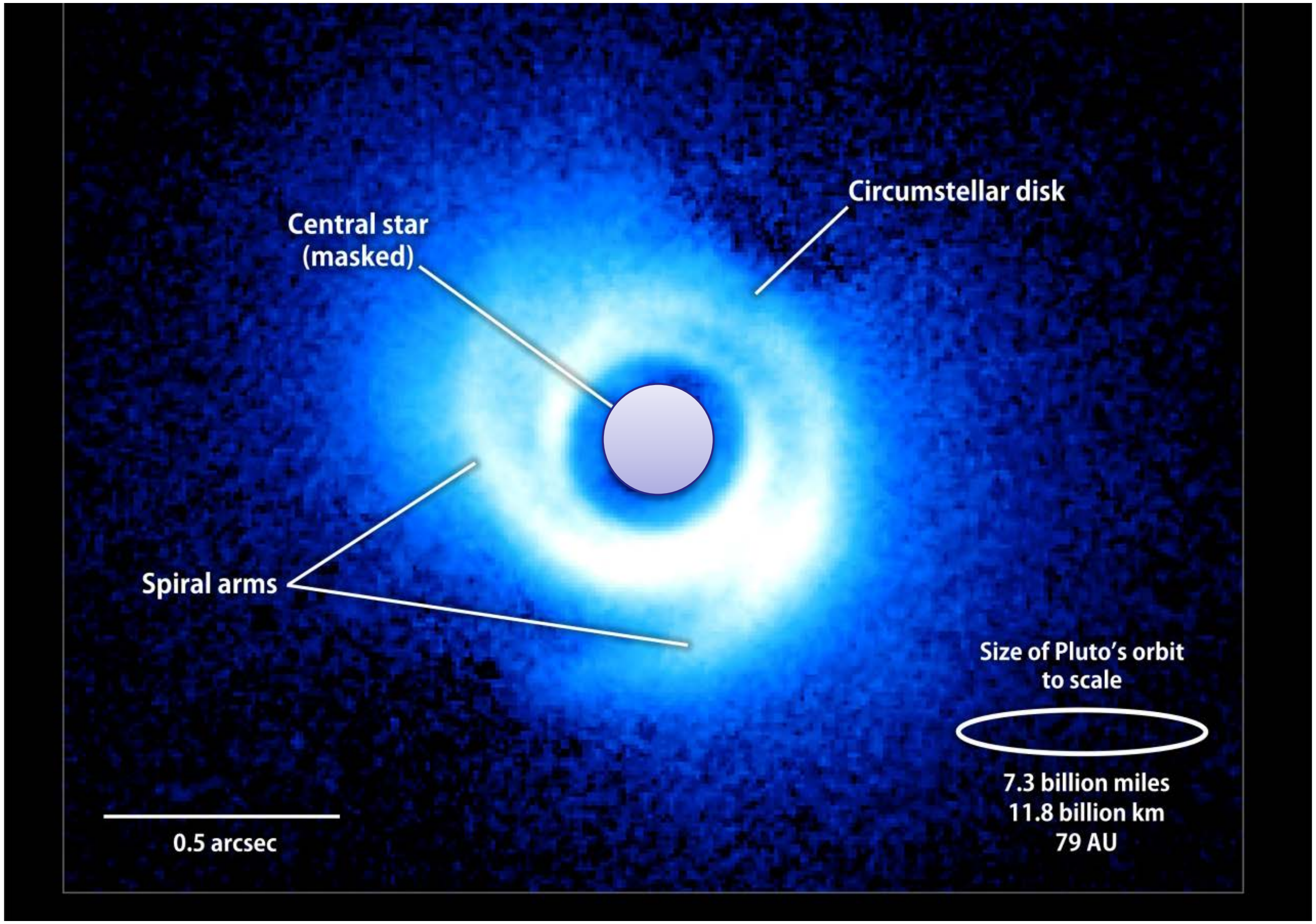
Stellar magnetic activity --- flares, UV/X-ray radiation, wind/CMEs --- imposes other habitability constraints



94% O_3 depletion

Segura+, AsBio, 2010

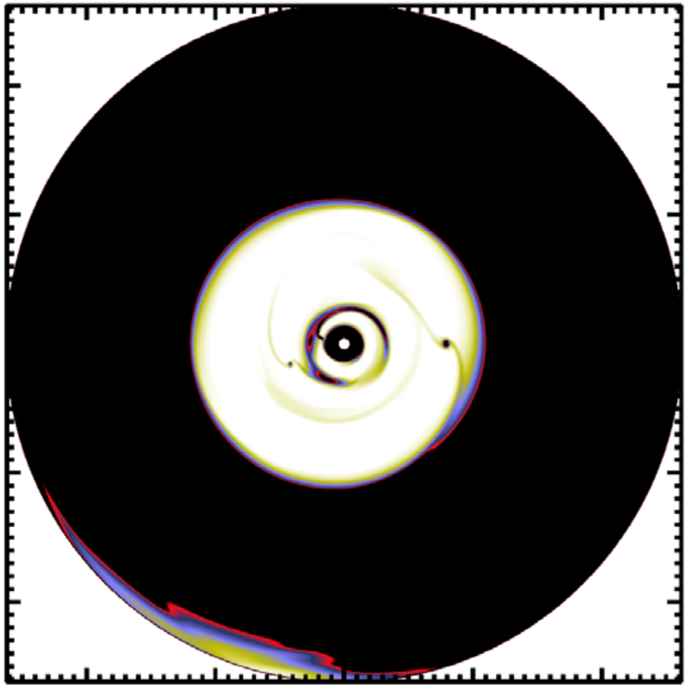
PMS Gas & Dust Disk Lifetimes and Structure: What is happening in the hole?



**Muto et al. 2012,
Subaru/HiCIAO**

Garufi et al. 2013 + Poster
VLT/NACO

Dust at *r* < 10 AU



13 μm optical depth

(Dodson-Robinson & Salyk 2011)

Dust disks are thought to clear between ~ 3 – 10 Myr

"Primordial" → "Transitional"? → "Debris"

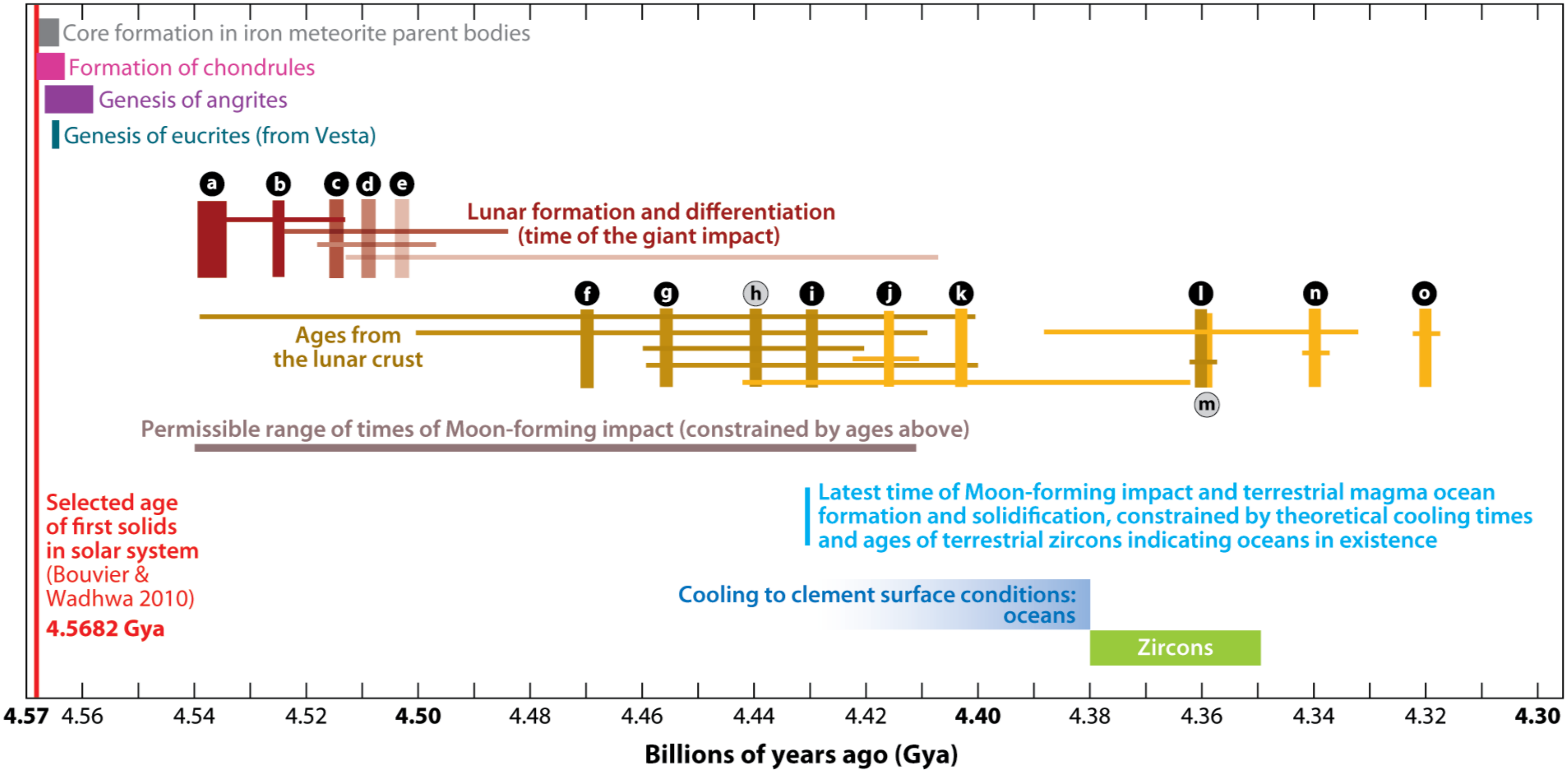
- (multi-)Planetary systems (w/Magnetorotational instability?)

Dodson-Robinson & Salyk 2011
Chiang & Murray-Clay 2007

- UV + X-ray photoevaporation

Alexander et al. 2006
Alexander & Armitage 2007
Gorti & Hollenbach 2009
Alexander et al. PPVI 2013

Timeline for Accretion and Early Evolution of Primitive Earth



Elkins-Tanton LT. 2012.
Annu. Rev. Earth Planet. Sci. 40:113–39

First 270 Myr of Earth’s evolution

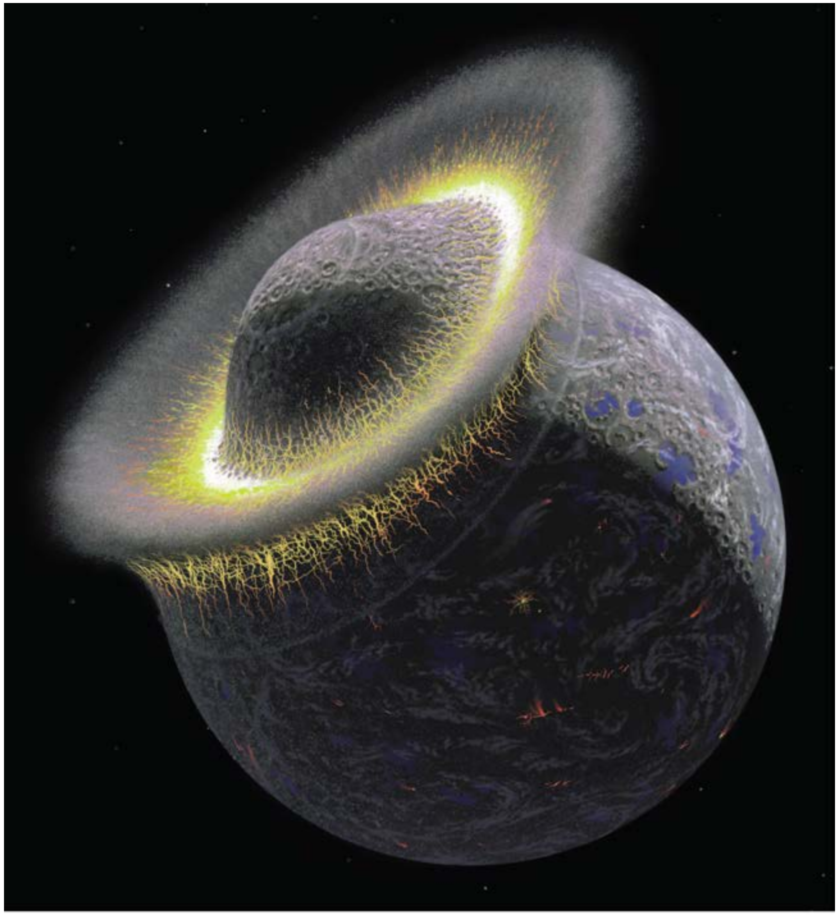
Impact Formation of Earth – Moon System

Very early in the Earth’s evolution
a catastrophic collision between the proto-Earth and a smaller protoplanet resulted in the current Earth–Moon double planet.

This probably occurred at an age of 30-70 Myr (and definitely no later than an age of 140 Myr).

This corresponds to the stellar Debris Disk era.

All water was delivered to Earth at this time by asteroids and planetesimals on highly-perturbed orbits.



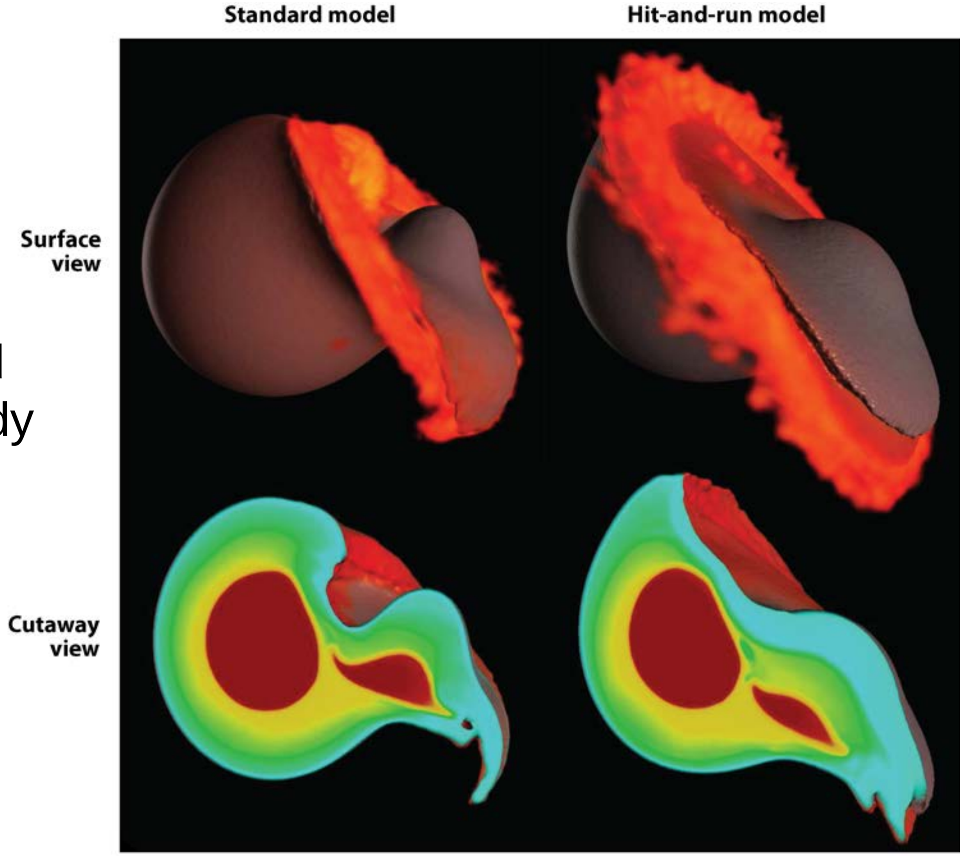
AR Asphaug E. 2014.
Annu. Rev. Earth Planet. Sci. 42:551–78

Impact Formation of Earth – Moon System

The collision redistributed the primitive core and mantle material and resulted in two very hot molten bodies.

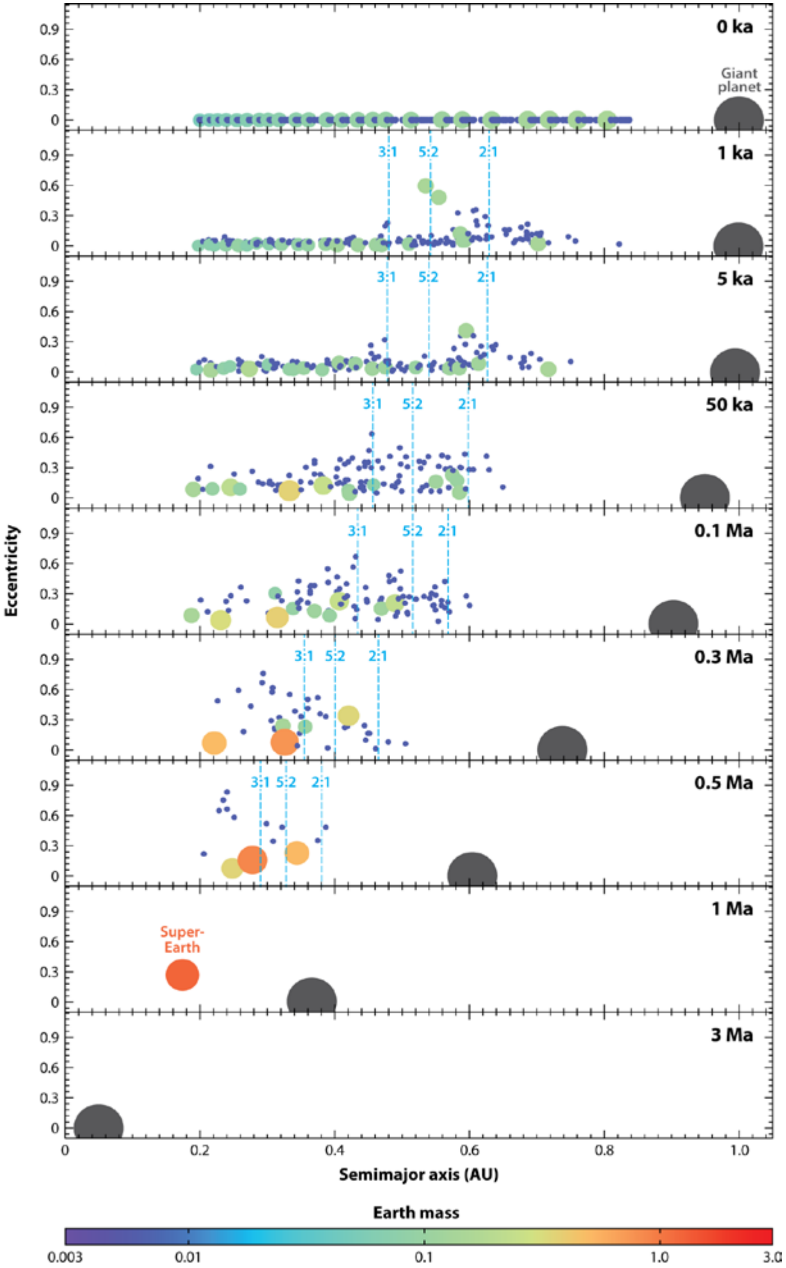
The collision could have resulted in most of the smaller object being accreted by the Earth (Left) or with the smaller body escaping (Right).

In either case significant melting and vaporization occur.



Asphaug E. 2014.
Annu. Rev. Earth Planet. Sci. 42:551–78

Annual Reviews

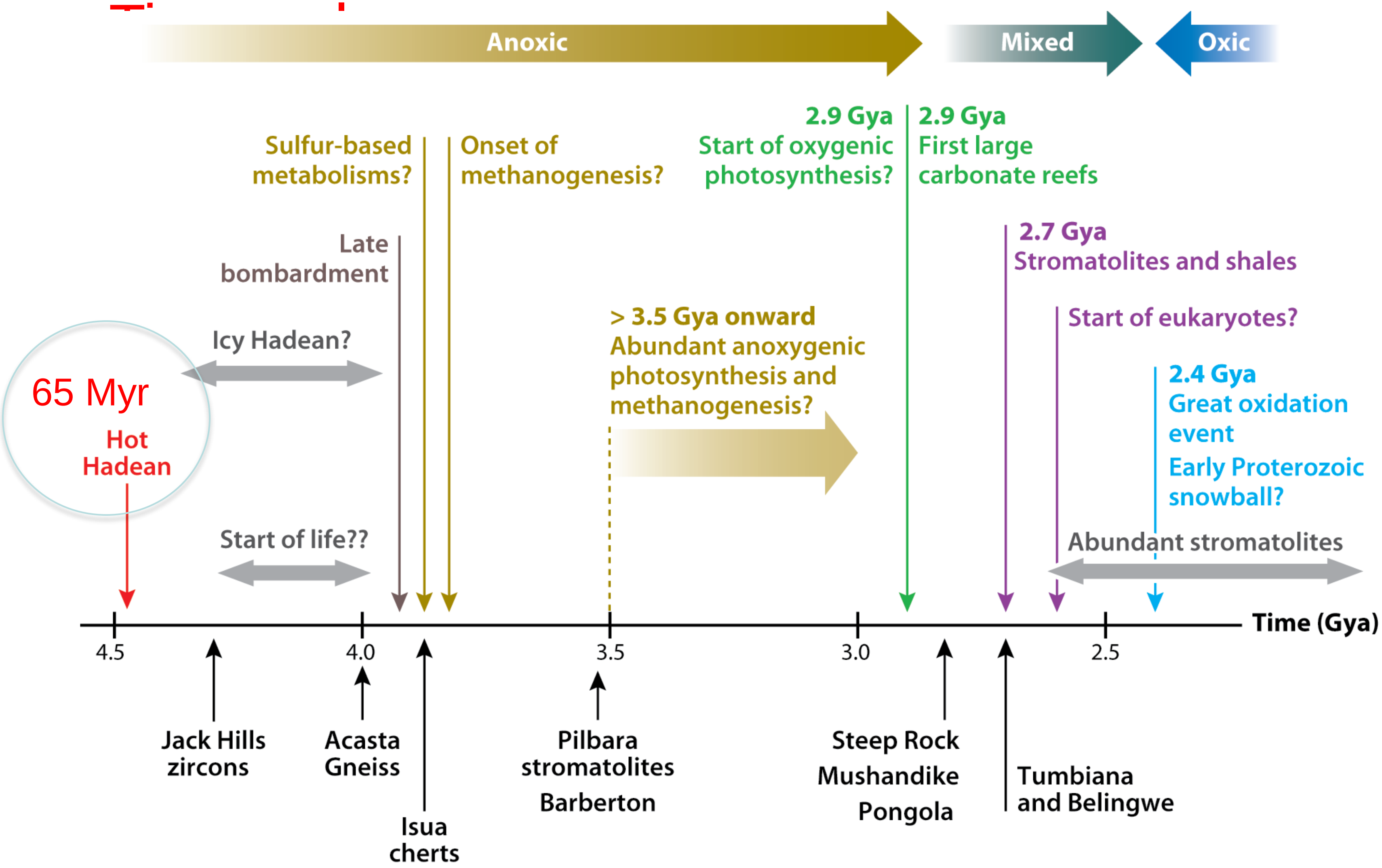


AR Haghighipour N. 2013.
Annu. Rev. Earth Planet. Sci. 41:469–95

Planetary Migration has serious consequences for smaller objects in young planetary systems.

Multiple collisions between protoplanets and planetesimals lead to the growth of a final planetary system --- these systems are often structured very differently from the Solar System.

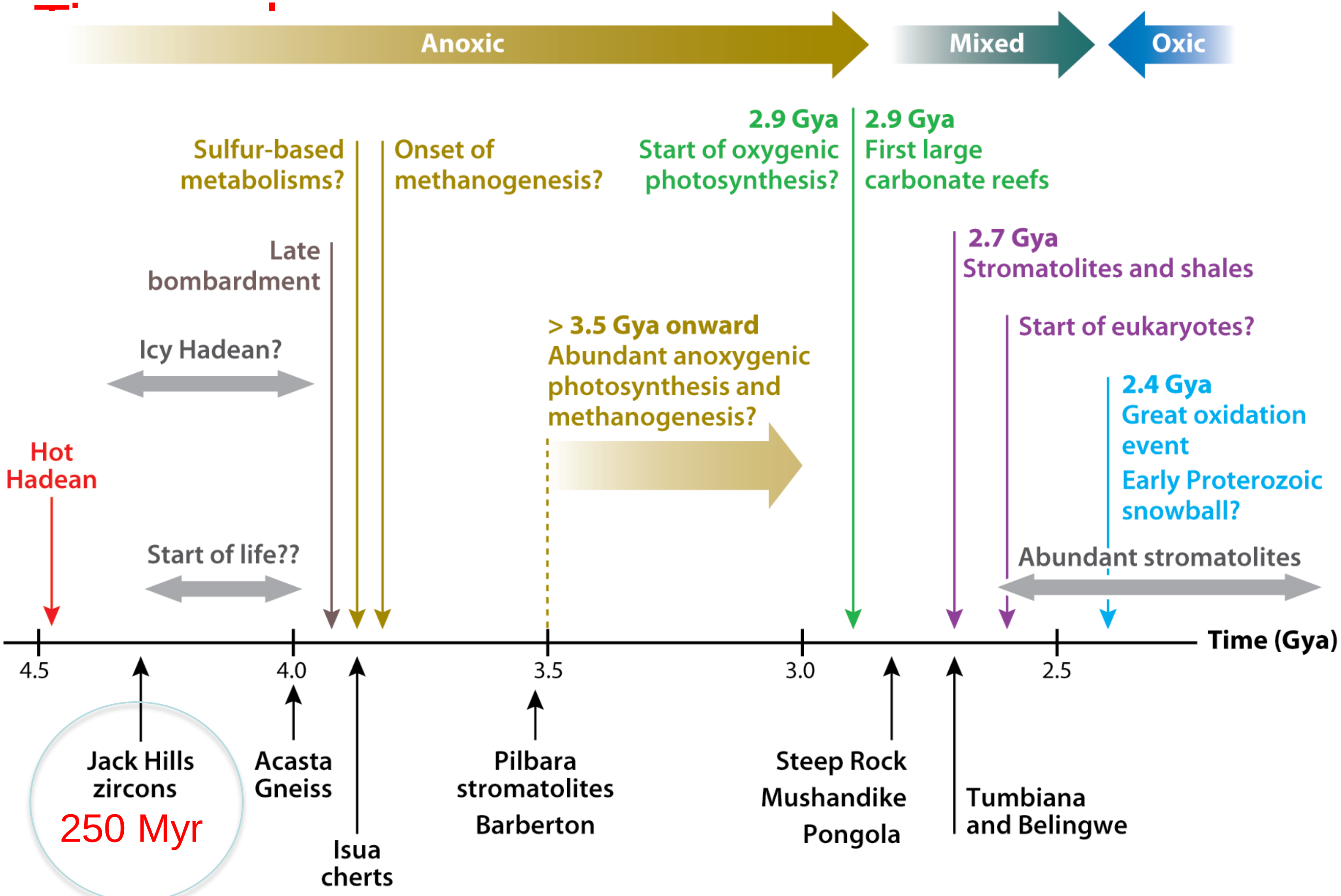
Earth Science and Solar Evolution



Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

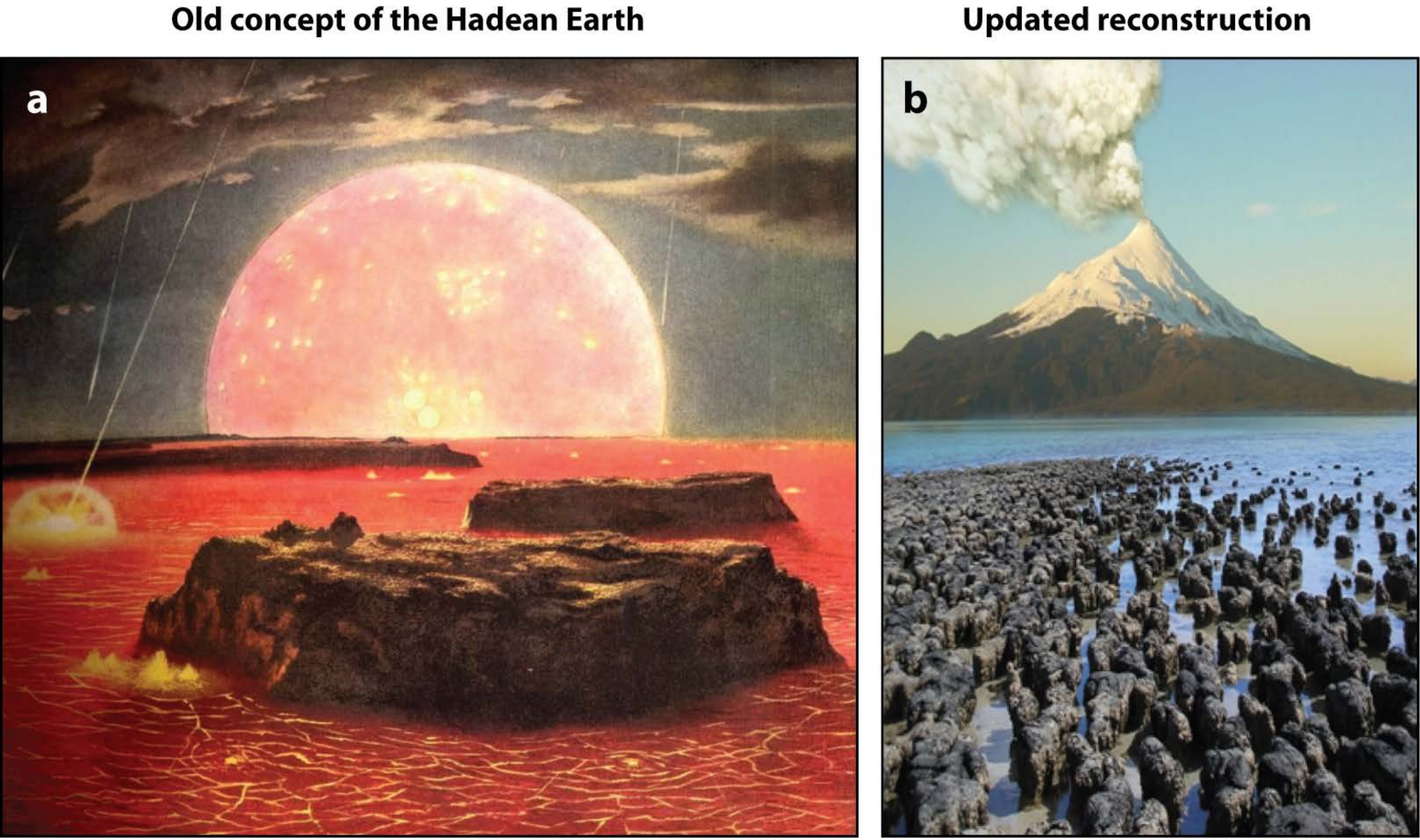
Offset – Earth-Moon split at ~50 Myr

Earth Science and Solar Evolution



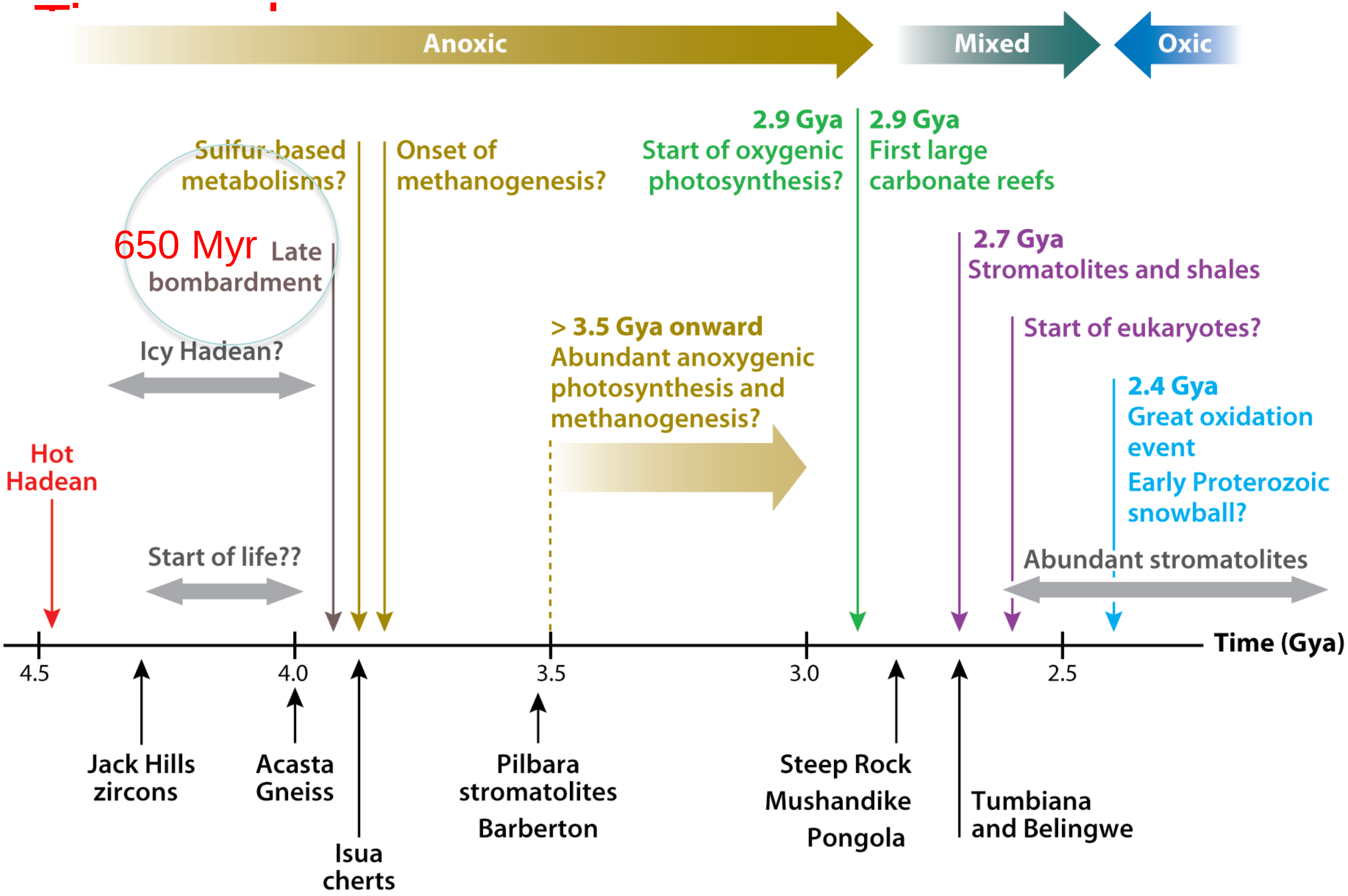
Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

Likely abundant water at 2 x age of Pleiades



Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

Earth Science and Solar Evolution



Anoxic

Mixed

Oxic

Sulfur-based metabolisms?

Onset of methanogenesis?

2.9 Gya
Start of oxygenic photosynthesis?

2.9 Gya
First large carbonate reefs

650 Myr

Late bombardment

2.7 Gya
Stromatolites and shales

Start of eukaryotes?

> 3.5 Gya onward
Abundant anoxygenic photosynthesis and methanogenesis?

Icy Hadean?

2.4 Gya
Great oxidation event
Early Proterozoic snowball?

Hot Hadean

Start of life??

Abundant stromatolites

4.5 4.0 3.5 3.0 2.5 Time (Gya)

Jack Hills zircons

Acasta Gneiss

Isua cherts

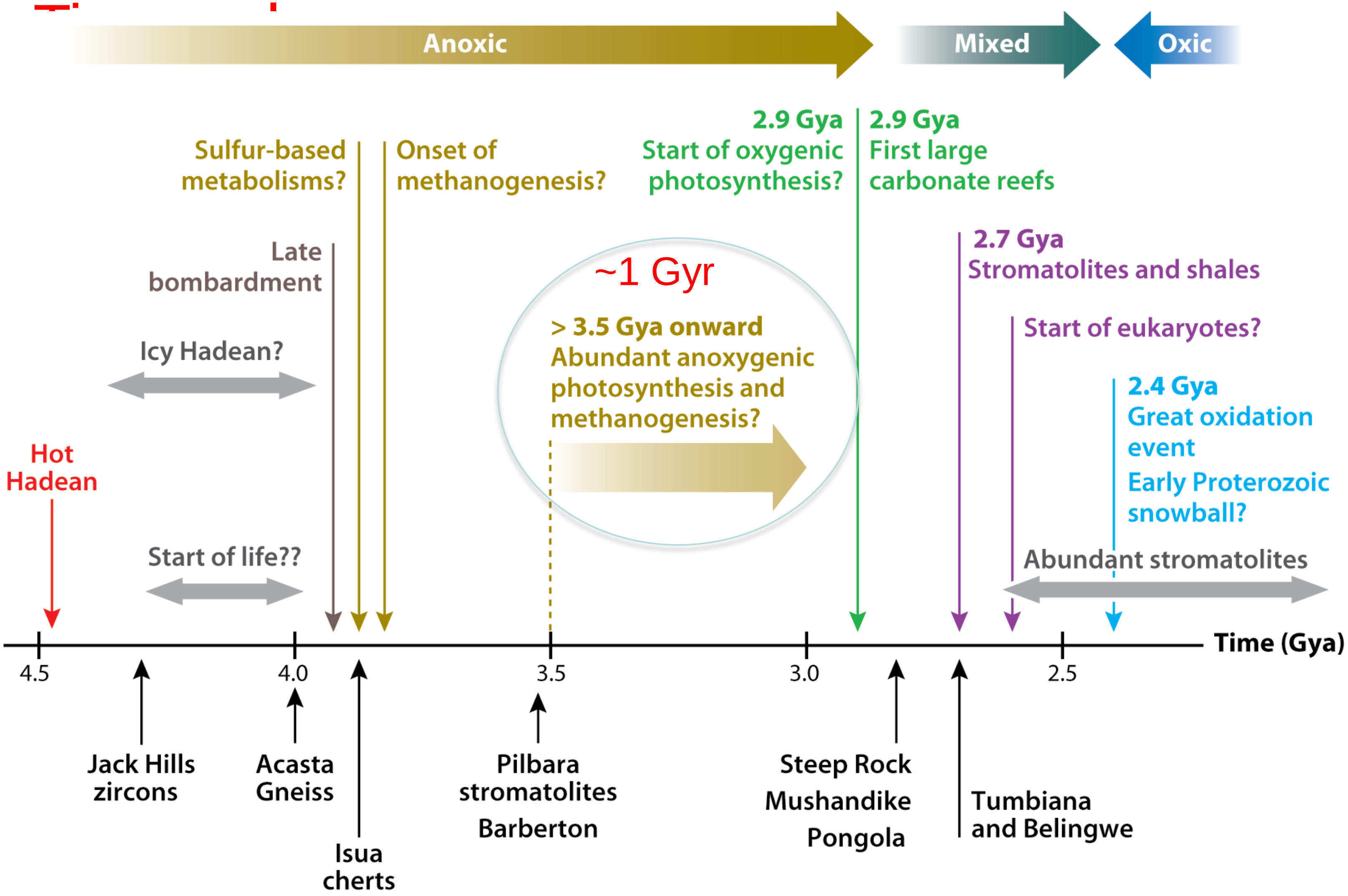
Pilbara stromatolites
Barberton

Steep Rock
Mushandike
Pongola

Tumbiana and Belingwe

Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

Earth Science and Solar Evolution



Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

Life --- anoxgenic photsynthesis by 1 Gyr

Astronomical Timescale

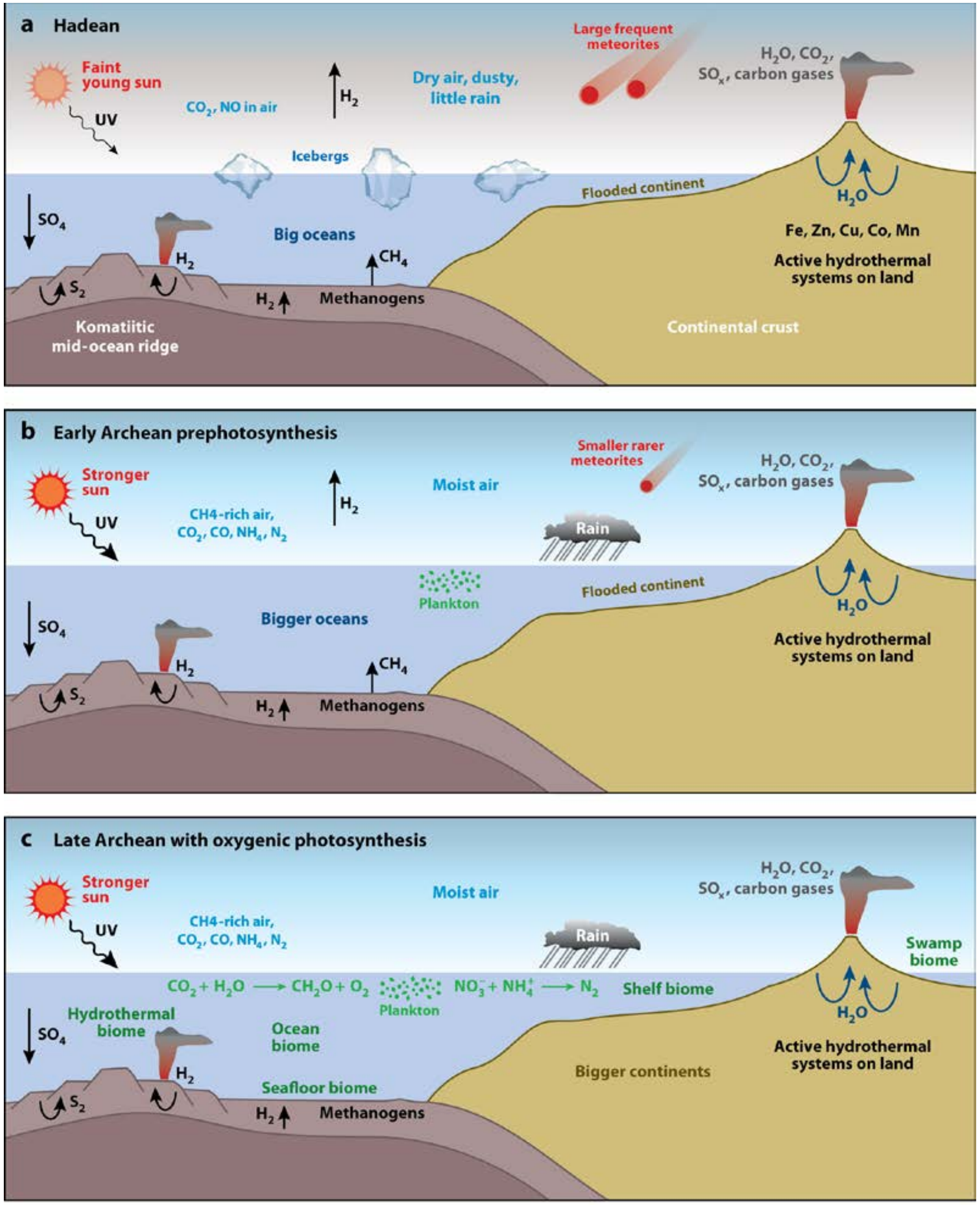
70 - 570 Myr

Optical probably fainter but UV/X-ray always strong

570 Myr – 1.5 Gyr

Life no later than 770 Gyr

1.5 – 2.0 Gyr



Arndt NT, Nisbet EG. 2012.
Annu. Rev. Earth Planet. Sci. 40:521–49

Rotational and Activity Evolution of Young Stars

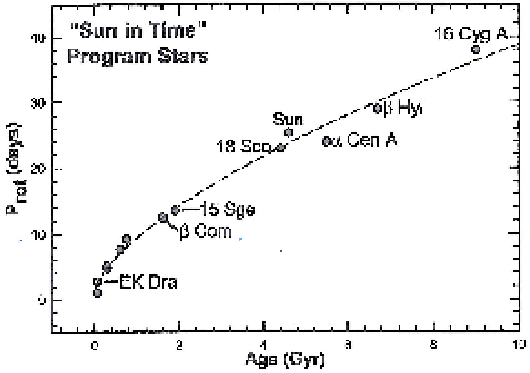


Figure 1: Plot showing the increase in P_{rot} for dG0–5 stars with increasing age. This spin-down with age arises from magnetic breaking from angular momentum loss via magnetized winds.

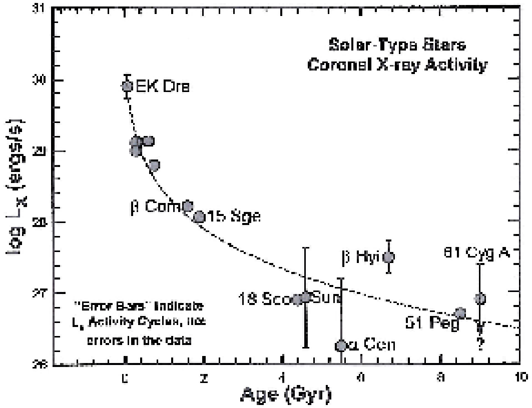


Figure 2. The variation of X-ray luminosity (L_X) for solar type dG0–5 stars are shown and plotted against age. The ranges in L_X for the Sun and other older solar-type stars arise mainly from activity cycles.

Guinan et al. "Sun in Time"

Stars do not have arbitrary rotation periods!

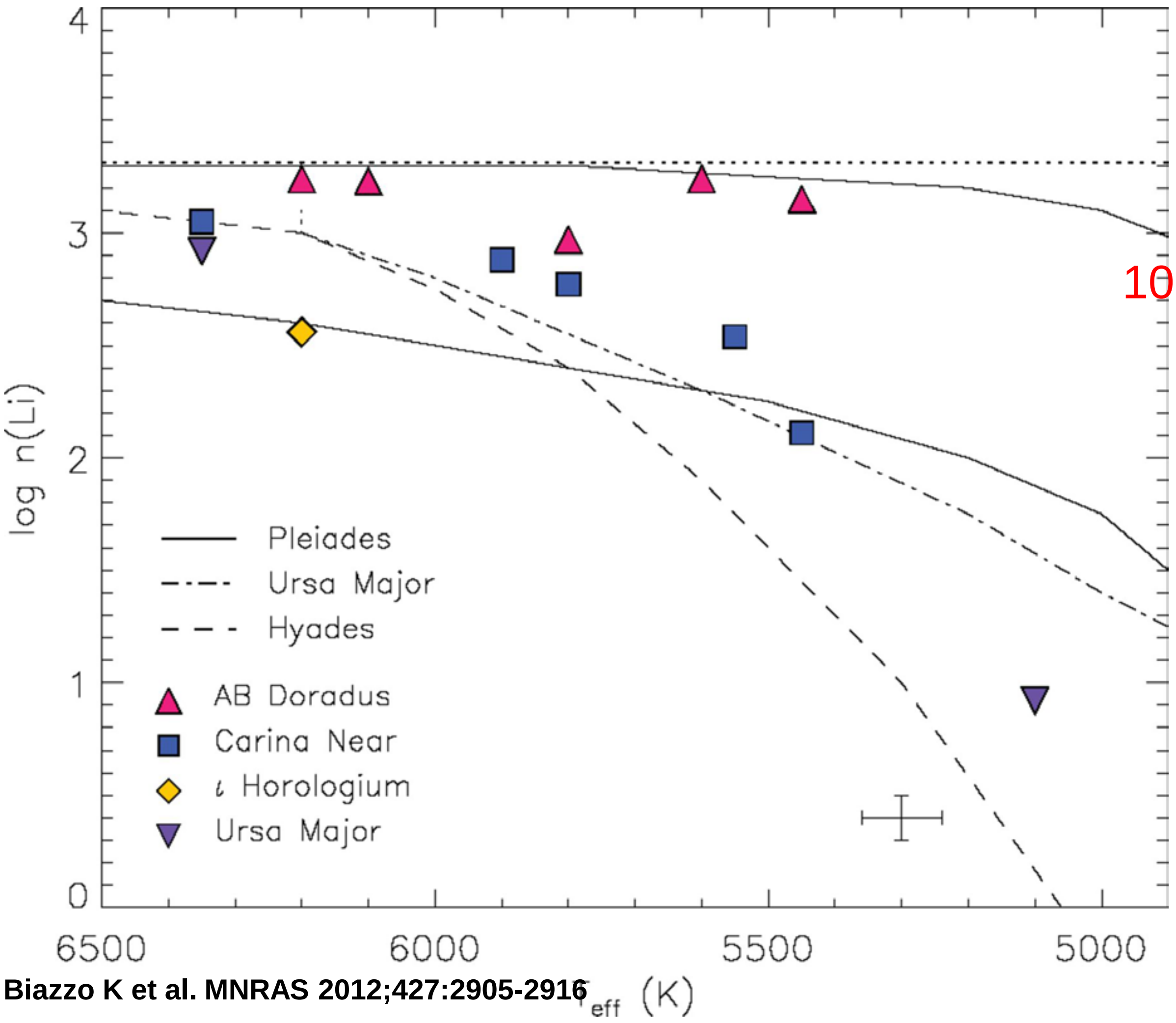
Old G dwarf stars, like the Sun, are slow rotators –with periods of 25-30 days.

If a star has a rotation period of a few days then it is either young (<1 Gyr often much less) or a close binary.

Stellar activity strongly correlated with rotation.

Young Clusters and Moving Groups Sample the Critical Age Range

Lithium abundance versus effective temperature.



100 Myr

300 Myr

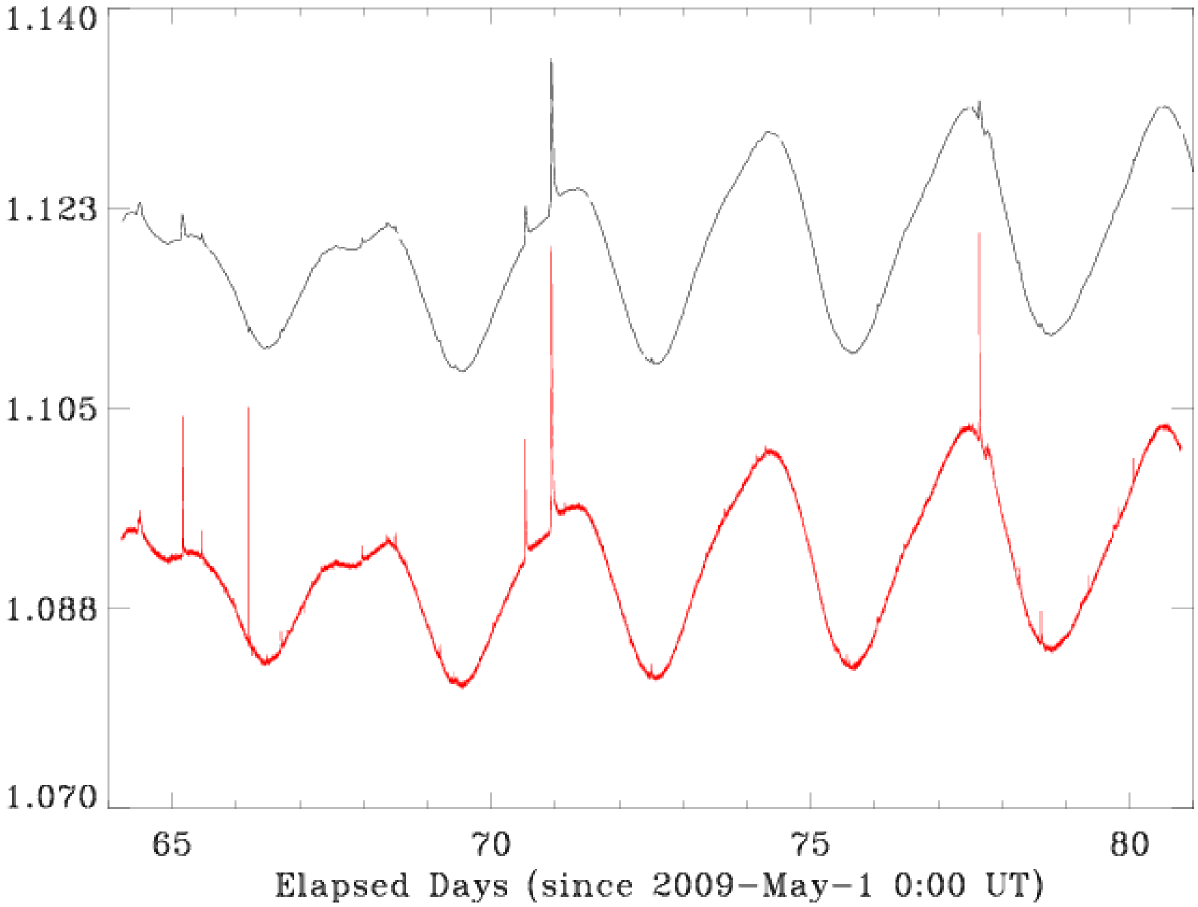
600 Myr

Biazzo K et al. MNRAS 2012;427:2905-2916

Flares on KIC 11560431 (G9 V, V=9.8)

LC
(30
min)

SC
(1 min)



For 15 “simple” flares

Mean rise = 4 min

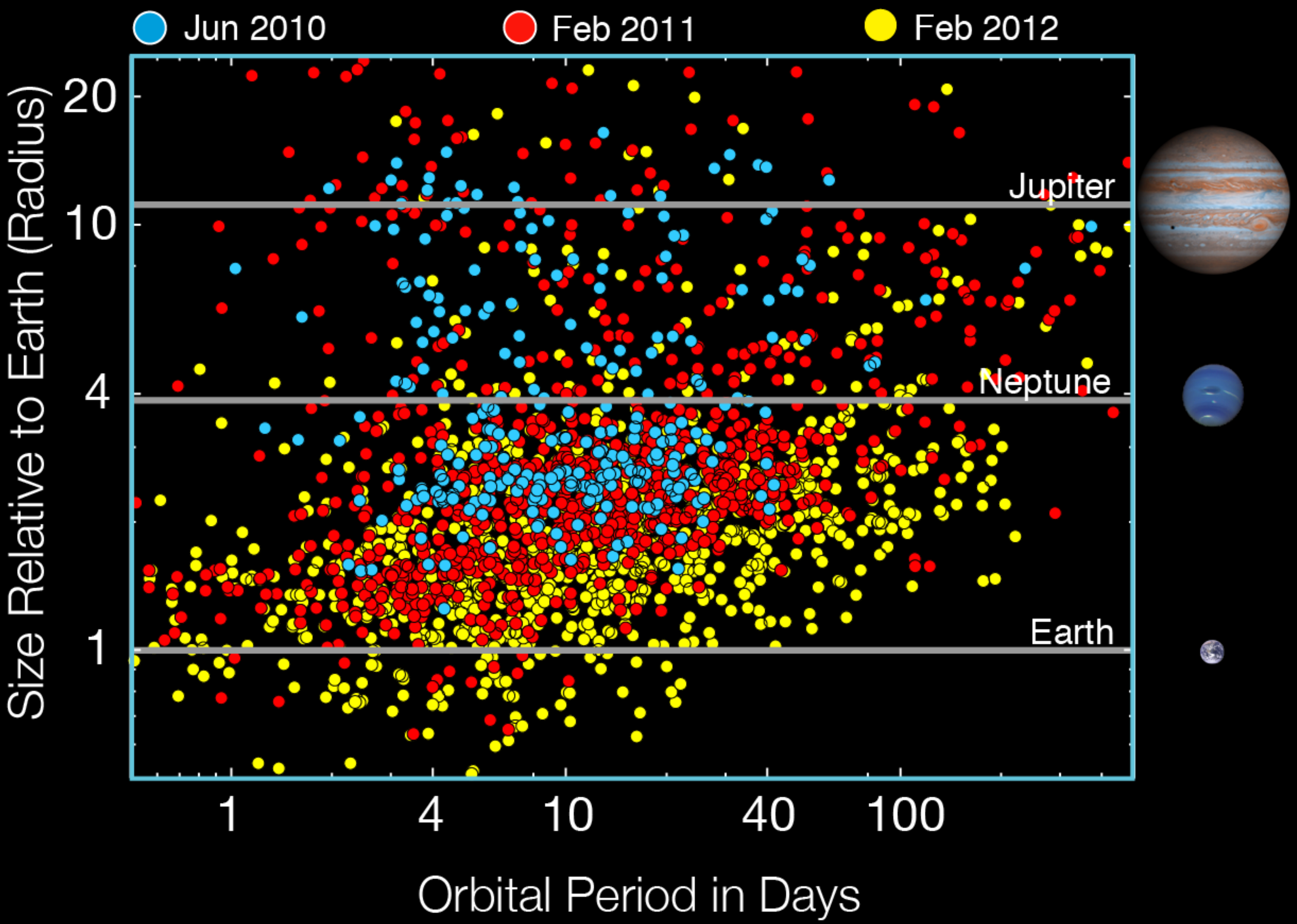
Mean decay= 25 min

Observed with HST and Chandra in 2012

Short-cadence (SC) data with 1 minute sampling reveal how well short duration flares propagate into long Cadence (LC) data.

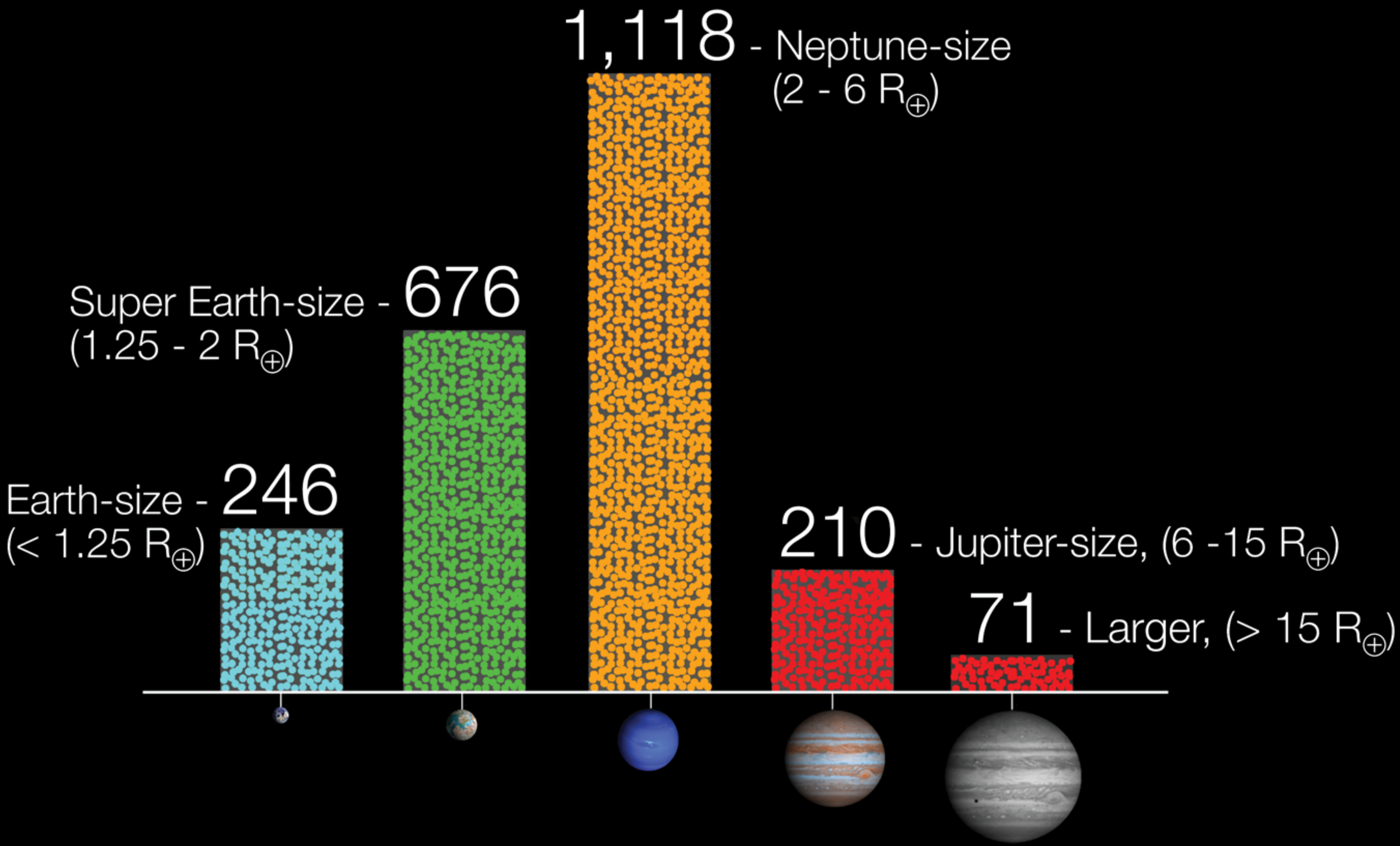
Planet Candidates

[redacted]



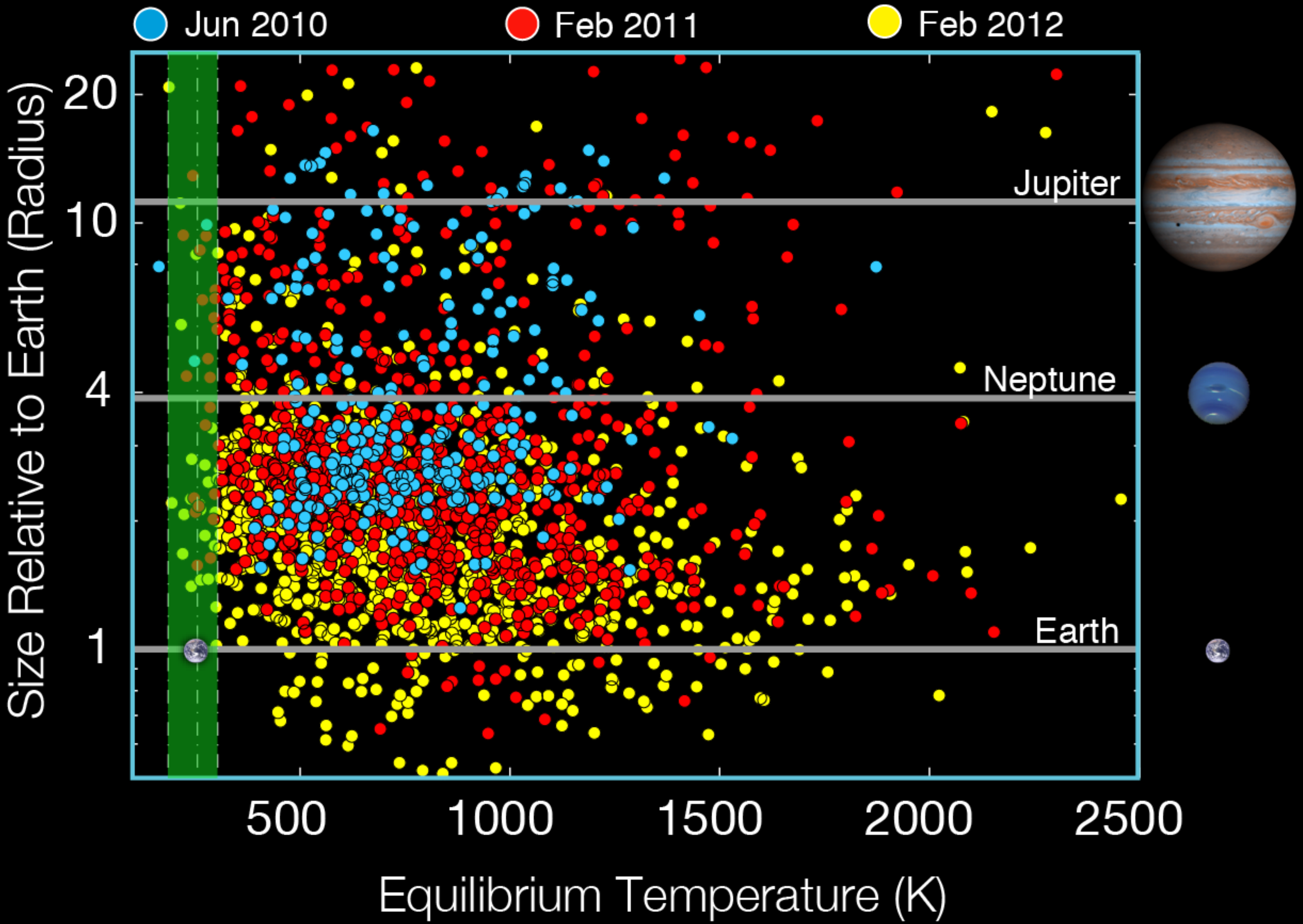
Sizes of Planet Candidates

[redacted]

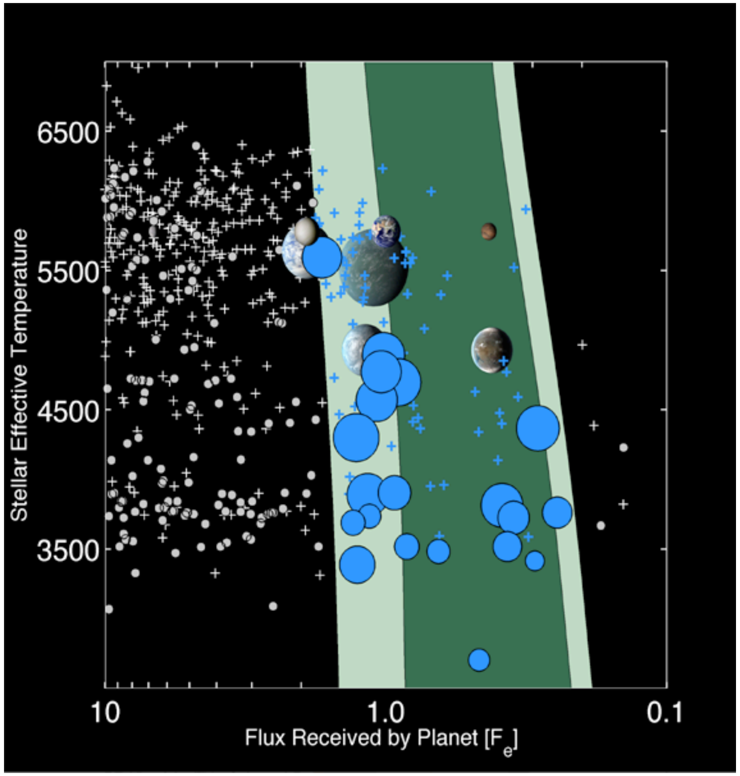


Candidates in the Habitable Zone

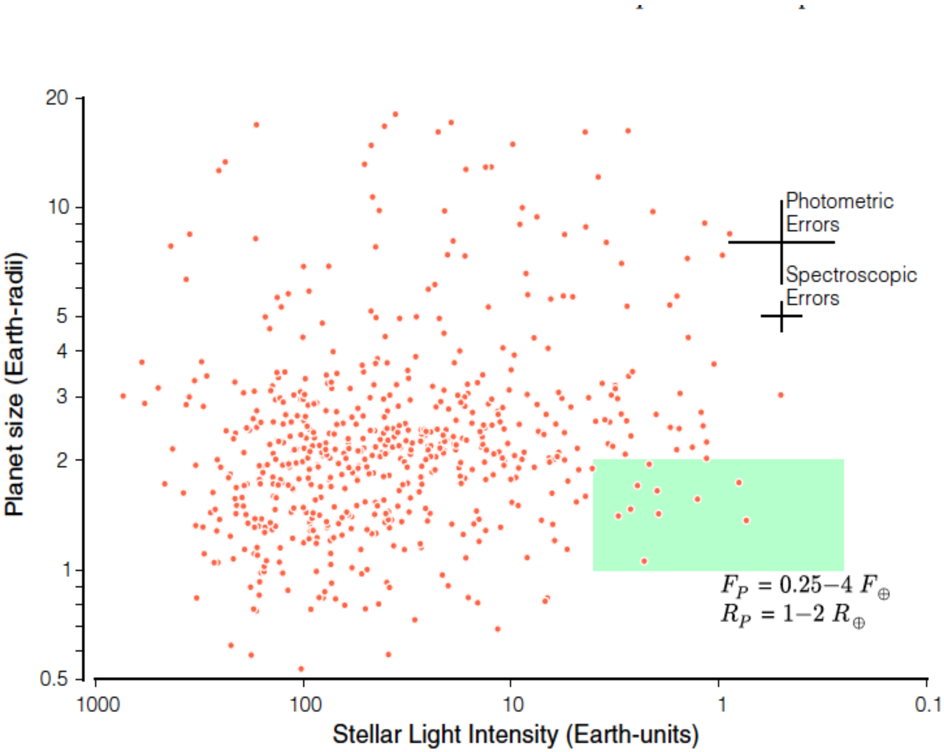
[redacted]



Planet Occurrence Rates: Habitable Zone



Approximately 50% of M dwarfs harbor a planet smaller than 1.4 R_e in the HZ (Dressing & Charbonneau 2013; Kopparapu 2013; Gaidos 2013)



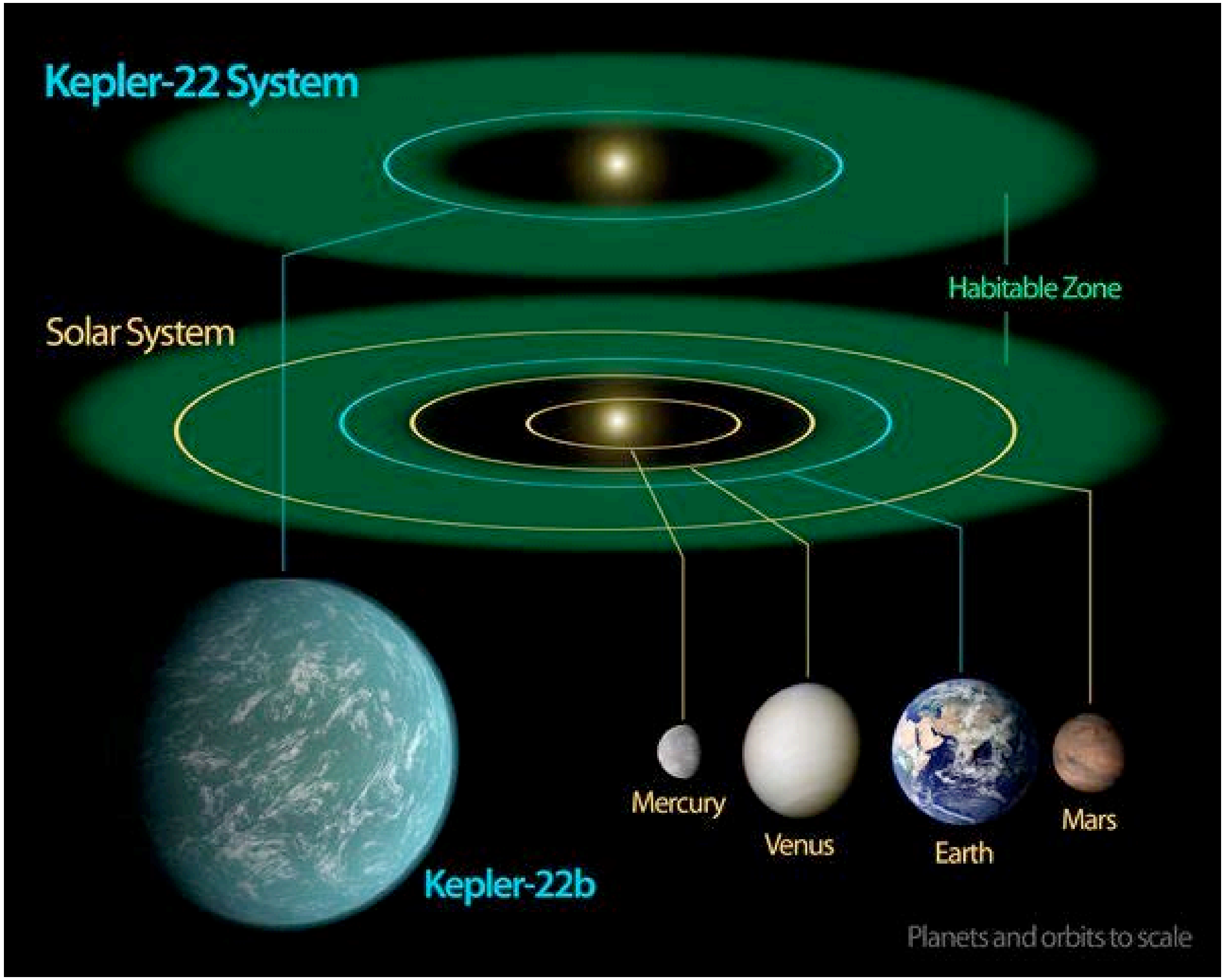
Approximately 7% of G & K dwarfs harbor a planet smaller than 1.4 R_e in the HZ (Petigura et al. 2013) based on results from independent pipeline, extrapolated to longer orbital periods.

Kepler Exoplanet Highlights

Examples of conventional, habitable planets now known.

Kepler 22b – First transiting HZ planet

2.4 R_e
289 day orbit

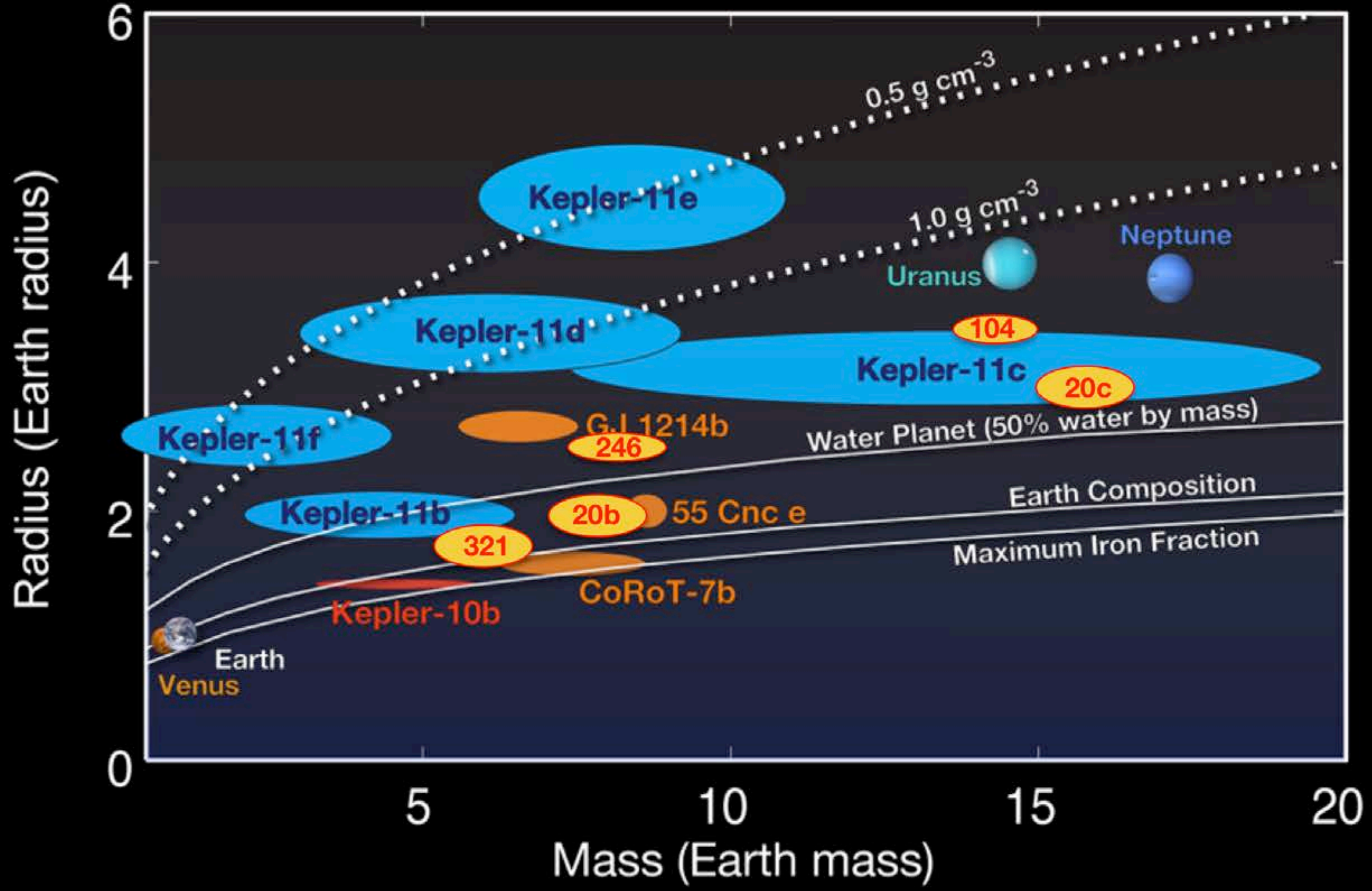


Kepler Exoplanet Highlights

Kepler 10b,c - 1.4, 2.2 Earth radii. 10b mass = 4.6 Earth masses

Kepler first rocky planet
Mean density of 8.8 grams/cc
Star: 5627K , 0.9 M-sun, 1.1 R-sun, Fe/H = -0.15 R~11

Distinguishing Rocky Planets



Kepler 16, 34, 35 -- Circumbinary Planets

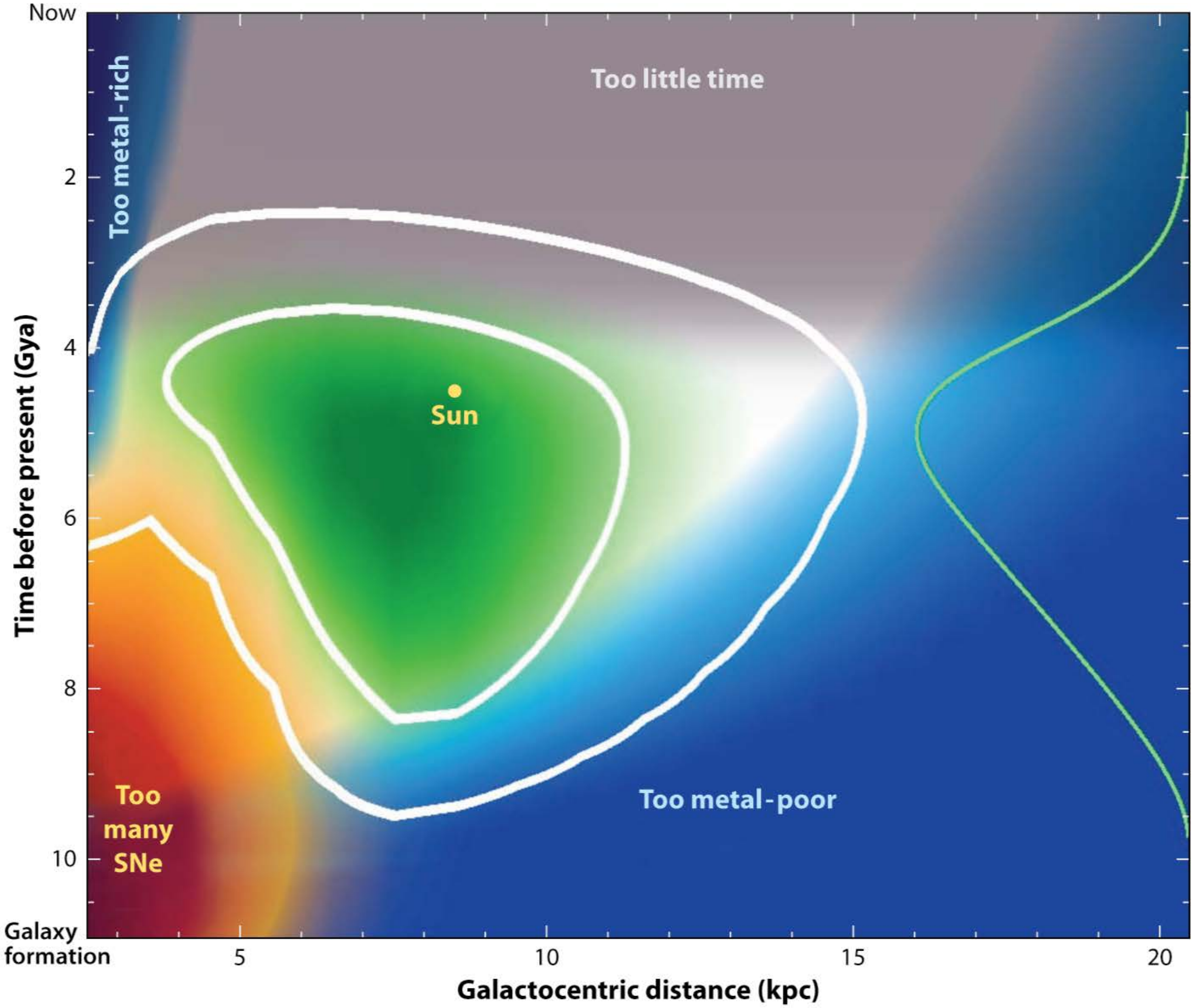
Saturn size planets orbiting around binary stars.

The two stars, orbiting each other every 41, 28, 21 days.

The planet orbits the pair every 229, 289, 131 days, similar to Venus in our Solar System

Very different scenario than Solar System

The Right Place at the Right Time ……..



Lineweaver CH, Chopra A. 2012.
Annu. Rev. Earth Planet. Sci. 40:597–623

Galactic HZ …
and development of life

Planets are common in the Solar neighborhood.

The solar galactocentric distance and age are near the sweet-spot for forming terrestrial planets.

Exoplanet Atmospheres: Exo-Earths

- Habitable planet candidates exist today (but almost all orbit old stars)

- The FUV+NUV radiation fields of their host stars control the photochemical structure of their atmospheres – including formation of biomarkers (e.g., O_2, O_3, CO_2, CH_4)

- But we know ***very*** little about chromospheric/coronal structure of average low-mass (M and late K) stars

GJ 667 Cc
(Anglada-Escudé et al. 2012)

Definitions:
EUV = 10 – 90 nm
LUV = 91 – 116 nm
FUV = 117 – 170 nm
NUV = 171 – 310 nm

MUSCLES

- Project MUSCLES: HST Treasury (125 orbit) survey of M and K dwarf exoplanet hosts at d < 20 pc

- What is the UV radiation environment in the habitable zones of KM dwarf exoplanetary systems?

- UV and X-ray variability on not-so ``inactive'' dwarfs?

GJ 667 Cc

(Anglada-Escudé et al. 2012)

http://cos.colorado.edu/~kevinf/muscles.html

Exoplanet Atmospheres: Exo-Earths

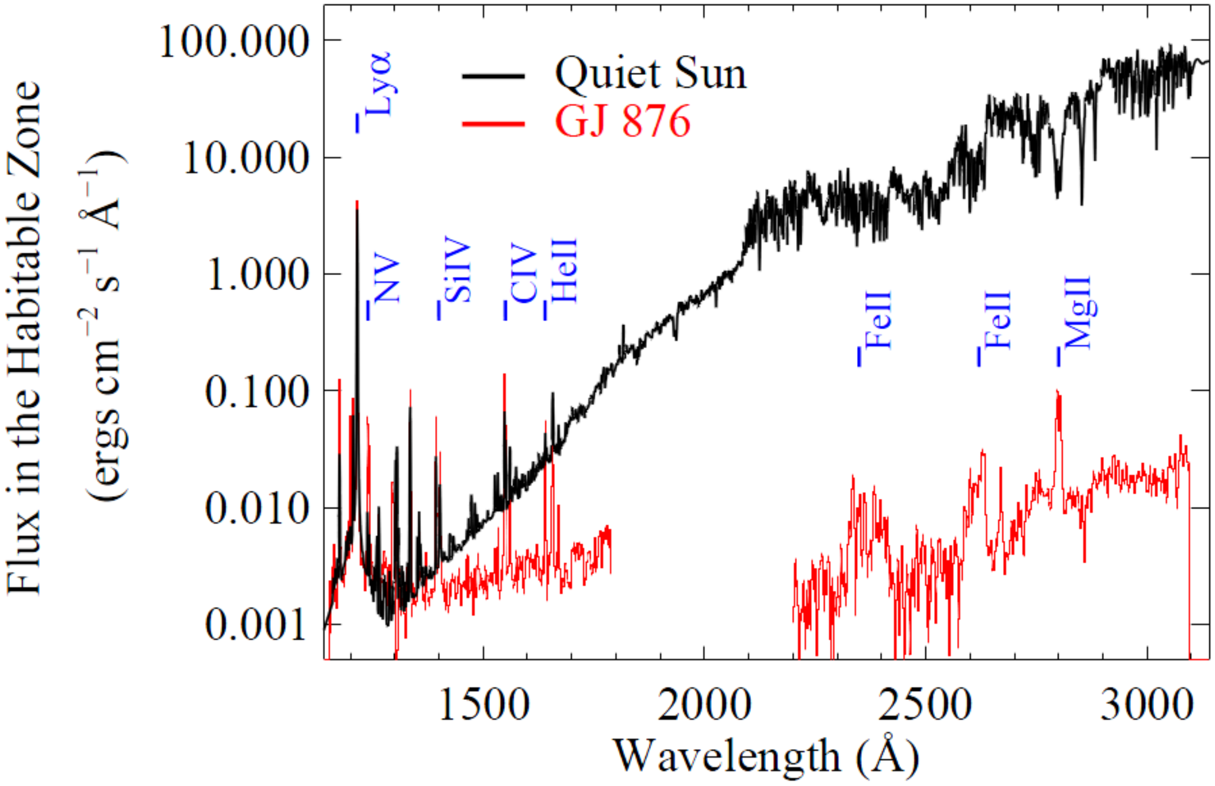
•Many models assume zero activity/UV flux, influencing the predicted atmospheric chemistry and therefore, habitability

<u>Specific Challenges:</u>

- FUV Sensitivity
- Proper treatment of Lyα is impossible with most existing M-dwarf data sets
- EUV radiation (10 – 91 nm) is important for atmospheric heating, mass-loss, and photochemistry, but is impossible to observe for *most* M dwarfs
- Time scale for flares and energy deposition into atmospheres

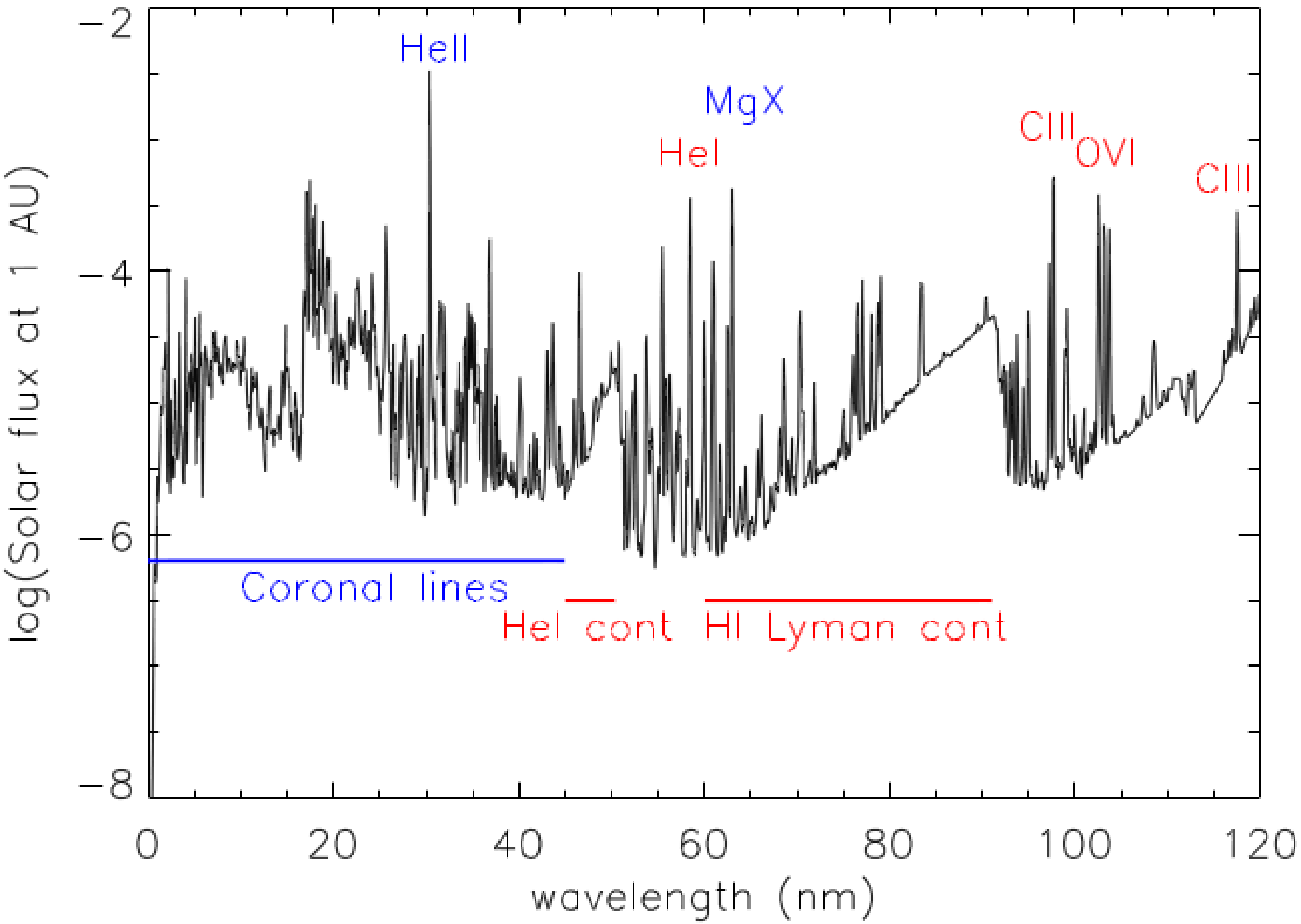
M dwarf FUV and NUV vs. Solar

- Project MUSCLES: GJ 876, UV Spectrum



France et al. (ApJL-2012c)

EUV Estimates: F(EUV) / F(Lyα)



Linsky et al. (ApJ-accepted)

SUMMARY

Planets form very efficiently during the earliest phases of stellar evolution but often result in planetary systems structured very differently than the Solar System.

Being different does not mean they are necessarily less habitable!

The Earth’s history shows how quickly habitable conditions can be produced and foster development of life.

Understanding the role of stellar magnetic activity and the many ways it can affect planetary surfaces and atmospheres during the first Gyr is extremely important.

THE END