Habitable Exoplanets

Margarita Safonova

M. P. Birla Institute of Fundamental Research

Indian Institute of Astrophysics

Bangalore

There are countless suns and countless earths all rotating round their suns in exactly the same way as the seven planets of our system.... The countless worlds in the universe are no worse and no less inhabited than our earth.

— Giordano Bruno (circa 1584)

- Margarita Safonova. Habitable exoplanets: Overview.

- C. Sivaram. Astrochemistry and search for biosignatures on exoplanets. 11 May, 2018

- Snehanshu Saha. Exploring habitability of exoplanets via modeling and machine learning. June 15, 2018

Exoplanets – extra solar planets

But we cannot exclude Solar System objects.

Firstly, some can be habitable, or even *inhabited*. Mars may still have subterranean kind of life, Europa&Enceladus have subsurface oceans kept warm by the tidal stresses. Titan has essentially Earth-like surface, albeit with lakes and rivers of liquid methane, and thick organic hazy atmosphere.

Secondly, they can be used as calibrators. E.g., based on the composition, the simplified planet taxonomy using the SS:

- Rocky (>50% silicate rock), but Mercury ~64% iron core.
- Icy (>50% ice by mass), but both N&U have significant rock and gas.
- Gaseous (>50% H/He).

- Thousands of detected exoplanets now called as super-earths, hot earths, mini-neptunes, hot neptunes, sub-neptunes, saturns, jupiters, hot jupiters, jovians, gas giants, ice giants, rocky, terrestrial, terran, subterran, superterran, etc…

Exoplanets

Is there a limit on the size/mass of a planet?

The *lower* mass limit *may* be assumed as of Mimas (3.7_x10^{19} kg) – approx. min mass required for an icy body to attain a nearly spherical hydrostatic equilibrium shape. To quote the IAU second law of planets, ``*sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape*''. In 1986, *Sivaram* derived the radius for an asteroid as 300 km with mass (assuming typical density as 2 g/cm^3) as 6.4_x10^{19} kg. *Lineweaver & Norman* (*2010, The Potato Radius: a Lower Minimum Size for Dwarf Planets*) redefined the limits to: 300 km radius for rocky objects, and 200 km for icy owing to their weaker yield strength – easier to conform to a spheroidal shape with less self-gravity. But Mimas, Enceladus... are not now in HE, though could have been in the past (e.g. *Schubert et al. 2006*). Vesta was in HE, but collision may have undone its sphericity.

The smallest known exoplanet PSR B1257+12A orbits a pulsar (0.02 EU ~1/2 of Mercury). The smallest exoplanet orbiting a MS star: Kepler-37b Is slightly larger than the Moon (0.01 EU, 0.354 EU).

The debate over what is and isn't a planet continues

Exoplanets

Is there a limit on the size/mass of a planet?

The *upper* mass limit may be easier – there is a natural lower limit to what constitutes a star: ~0.08 SU.

But then there are brown dwarfs: IAU has defined brown dwarfs as objects that exceed the deuterium burning limit (~13 JU for solar metallicity) irrespective of formation mechanism.

The distinction between brown dwarfs and *actual* stars is subtle: both low-mass stars and brown dwarfs burn primordial deuterium at first, but a star will eventually settle down to stable H-burning; in the case of a 0.08 SU star this will take ~1 Gyr (*Massey & Meyer, 2001*).

Below a mass of 0.015 SU (~13 JU) not even deuterium burning can occur, and these objects are perhaps best called planets. But it has been suggested that giant planets formed by core-accretion in a proplyd can exceed the deuterium burning, and indeed most exoplanets and brown dwarfs discovered to date include bodies ranging from ~1 to ~60 JU. Gas giant exoplanets generally have masses of ~0.3 to ~60 JU (*Hatzes & Rauer 2015*).

A physically motivated mass scale

A difficulty with characterizing exoplanets as Earths, Neptunes, or Jupiters is that these names indicate not only a general mass range, but are also associated with composition and structural characteristics. However, a 10-20 EU planet might be predominantly planetary ices by mass and have a Neptune-like ice giant composition and structure, or it could be predominantly rock composition, so it could be a super-Earth.

In 2016, *Chen & Kipping* proposed a physically motivated scheme based on empirical data.

In their steps, using the Solar System data (*NASA Planetary Fact Sheet*), latest version of TEPCat (*Southworth, 2011*) for exoplanets with measured both M and R, and the data for low-mass stars, brown dwarfs and gas giants from *Chen & Kipping* (*2016*) available at

http://iopscience.iop.org/0004-637X/834/1/17/suppdata/apjaa4b8ct1_mrt.txt, we made the updated M-R plot with ~clear distinctions of planetary taxonomy.
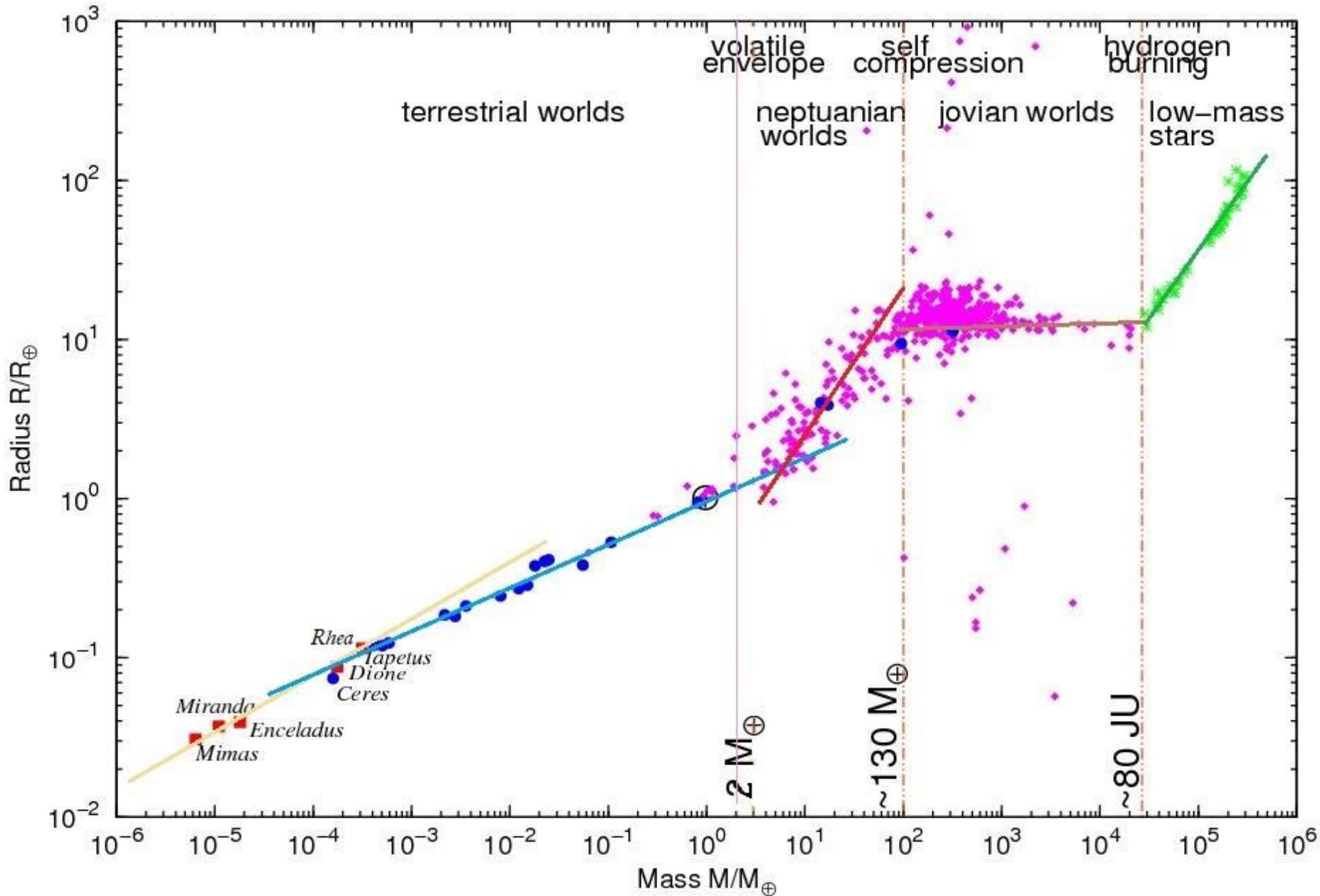
With the developed theoretical models, it is already possible to exclude planets from the potential habitability list based on mass/radius values.
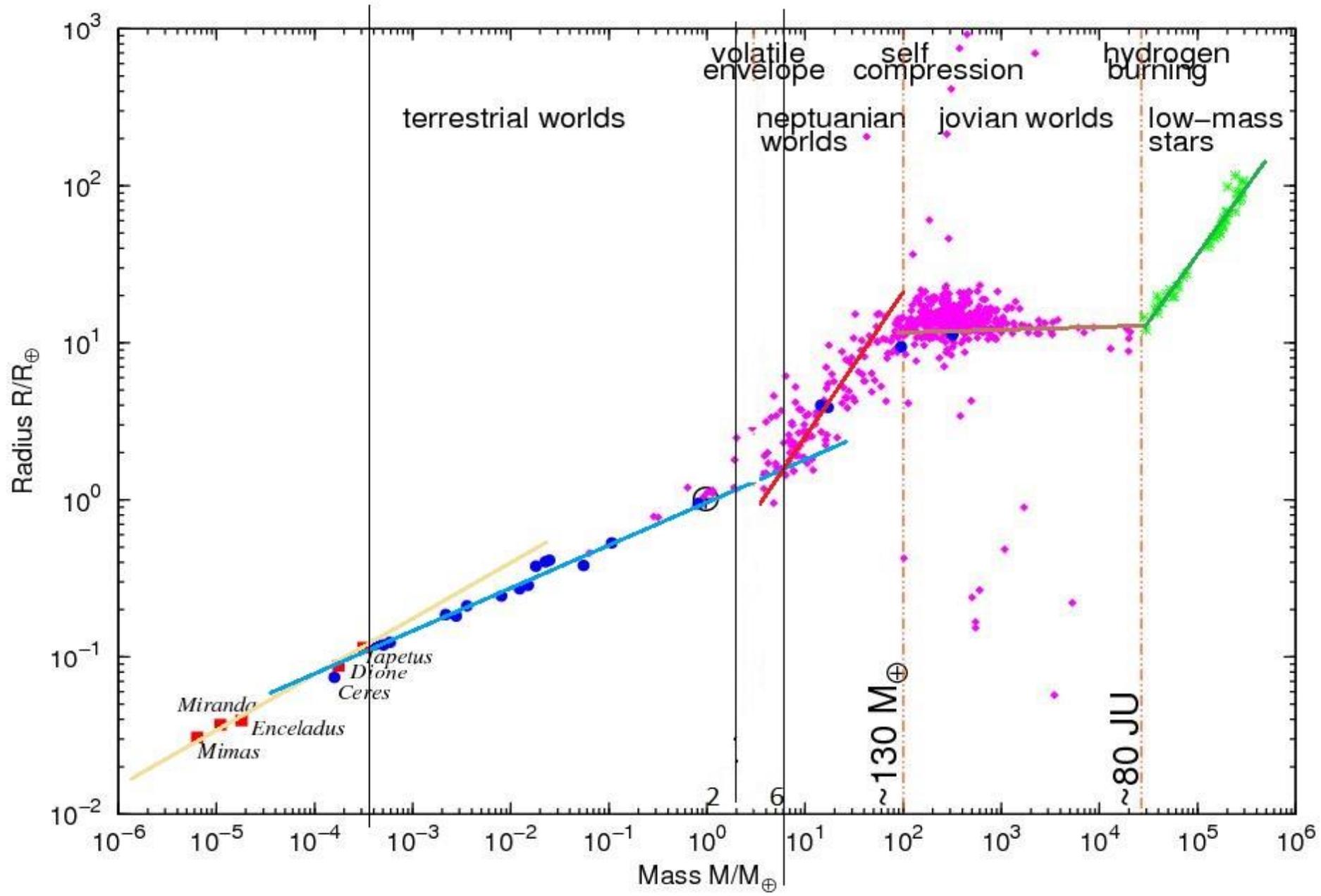
As of 8 March 2018, there are 3,743 confirmed planets in 2,796 systems, with 625 systems having more than one planet.

|		With Kepler candidates	Only confirmed planets
earths (EU):	0.05 - 6	2888	1414
neptunes:	6 - 60	2332	1533
jupiters:	60 - 1600	1011	726
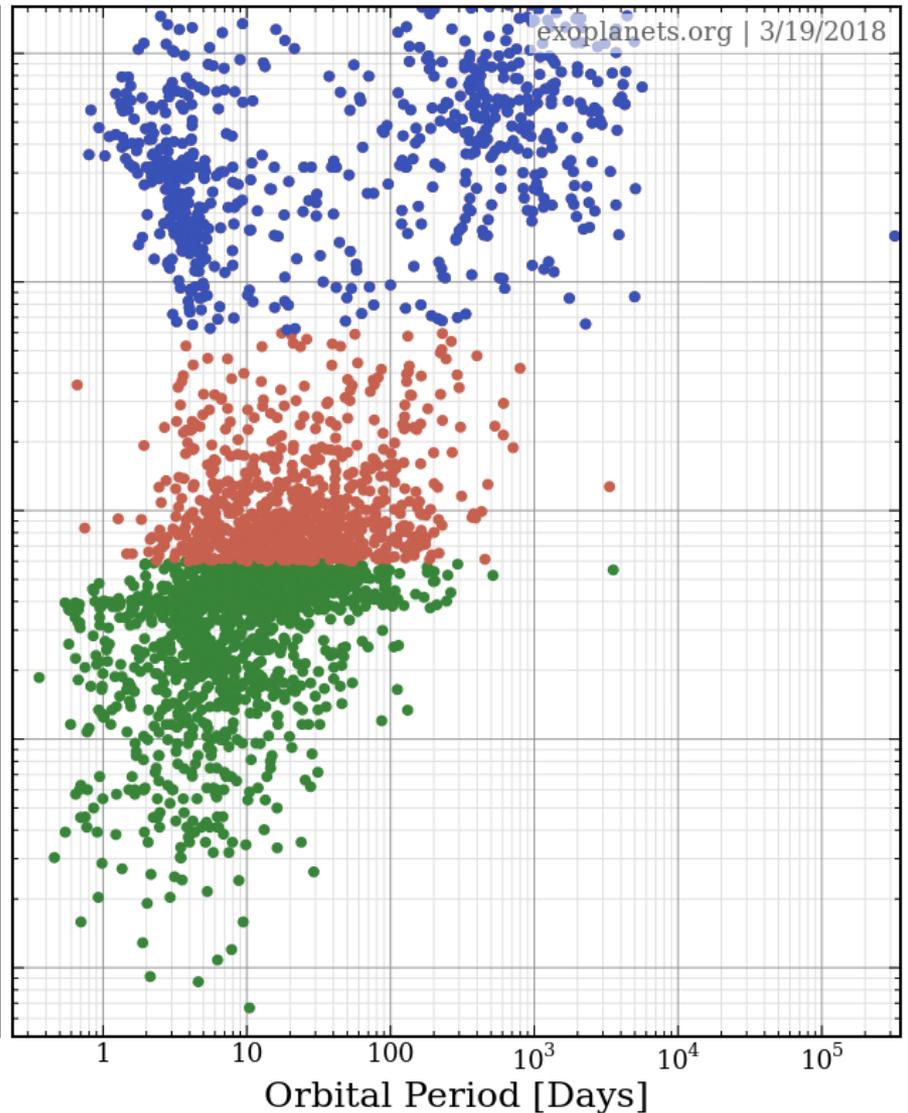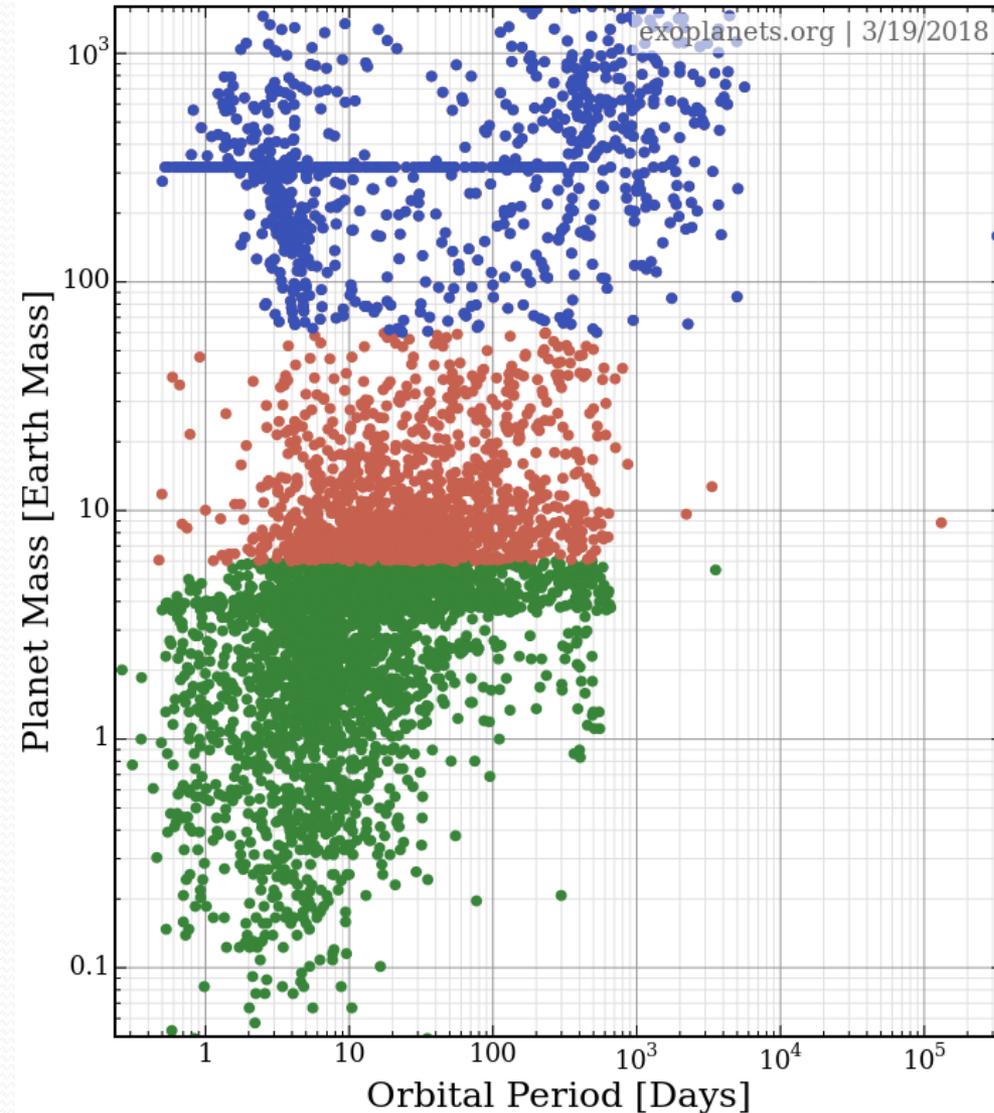
How many what planets are there?

With Kepler candidates
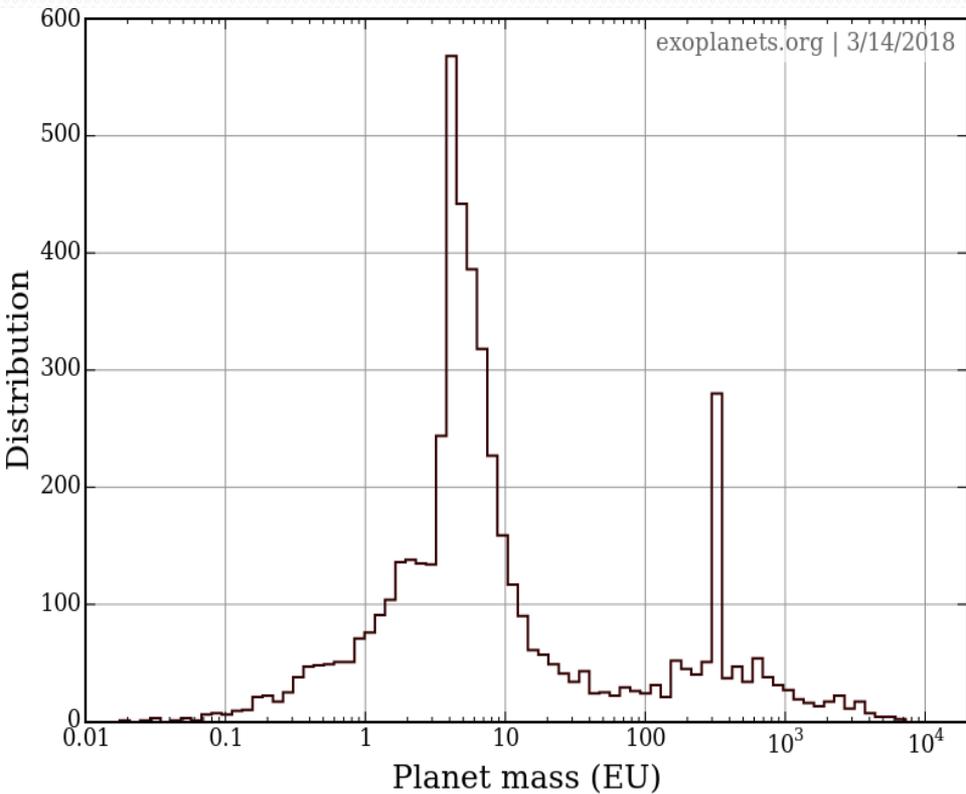
Only confirmed planets
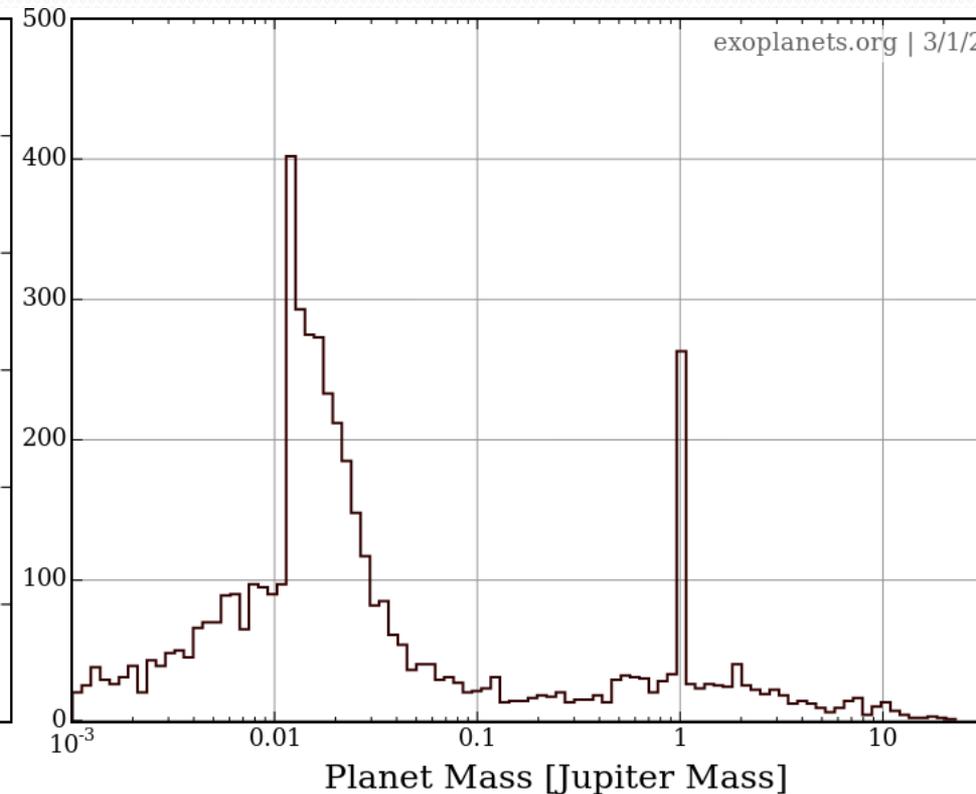
"*Planets orbiting stars in our Galaxy is the rule, rather than the exception*," writes the team of researchers led by Arnaud **Cassan.** "*Planets are common, and low-mass planets are as common as dirt in some sense*," Scott **Gaudi**.

Estimates are: more planets than stars in our Milky Way (>200-400 billion bound planets), while unbound, or free-floating, planets may even exceed their numbers (*Strigari et al. 2012*).

Frequency of host stars

exoplanets.org | 3/26/2018

Virtually all exoplanets known are around ~1 solar mass stars. Roughly in the Milky Way MS stars are: 75% *M*-stars, 15% *K*, 7% G, 2% *F*, 1% *A*, 0.1% *B*, and 0.01 *O* stars.
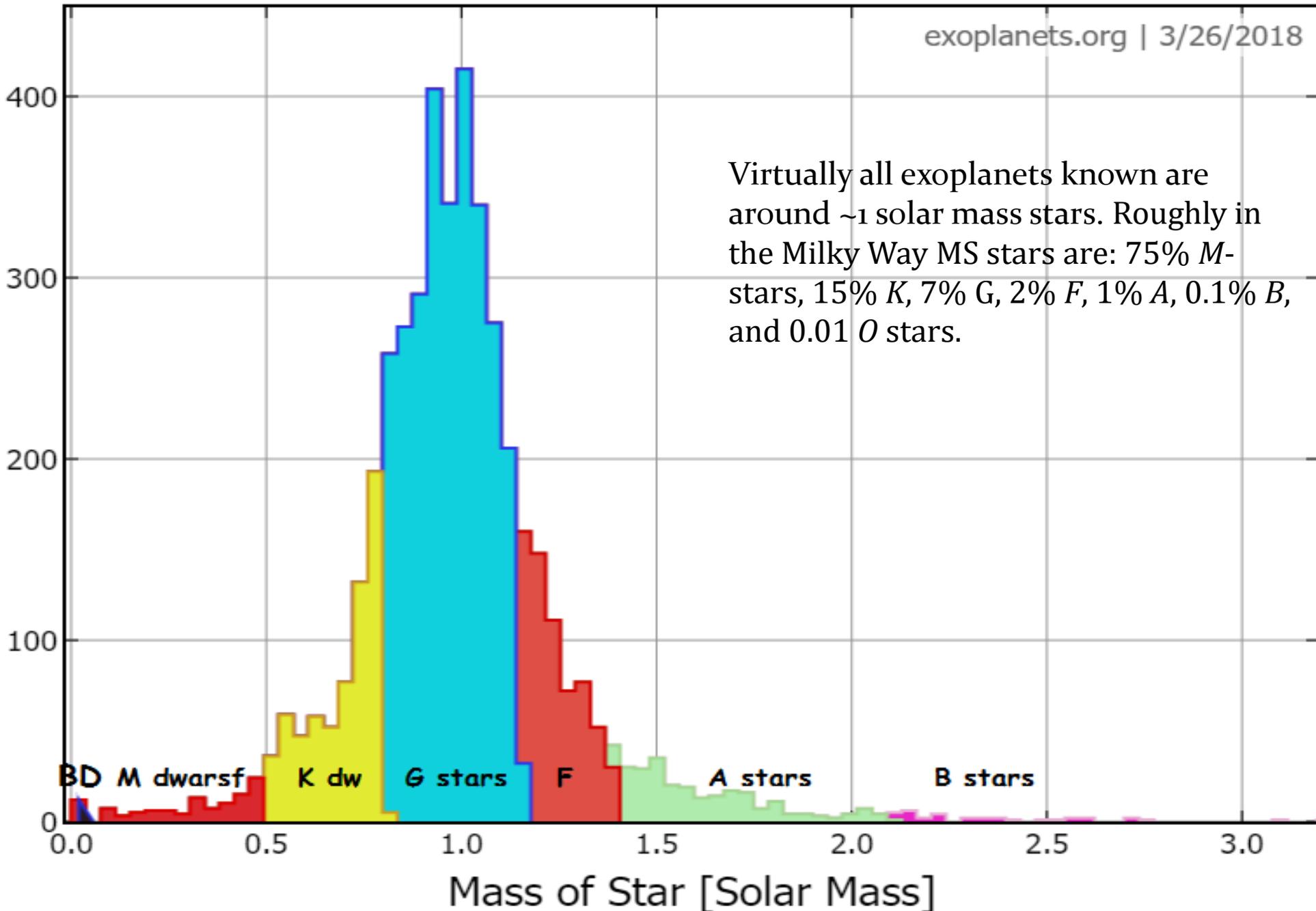
March 2018: we live in a universe of planets

Kepler **mission:**
- Candidate exoplanets: 2,245
- Confirmed exoplanets: 2,342
- Confirmed exoplanets less than 2 Earth-size in the habitable zone: 30

*"It helps buoy our confidence that planets are everywhere."*

\- Sara Seager, MIT

Earth-size planets are common in the *Kepler* field. If the stars in the *Kepler* field are representative of stars in the solar neighbourhood, then Earth-size planets are common around nearby Sun-like stars (*Petigura, Howard&Marcy '13*).

So, totalling on average – between 800 billion and 3.2 trillion planets, with some estimates placing that number as high a 8 trillion!

Kepler has observed about 150,000 stars. Found that about 24% of M stars may harbour Earth-size planets ~10 billion Earth-like worlds.

Free-floating planets estimates come from *Sumi et al. 2011*: 10 planetary mass events → inference is twice more planets than stars!

Kepler search beam

Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com
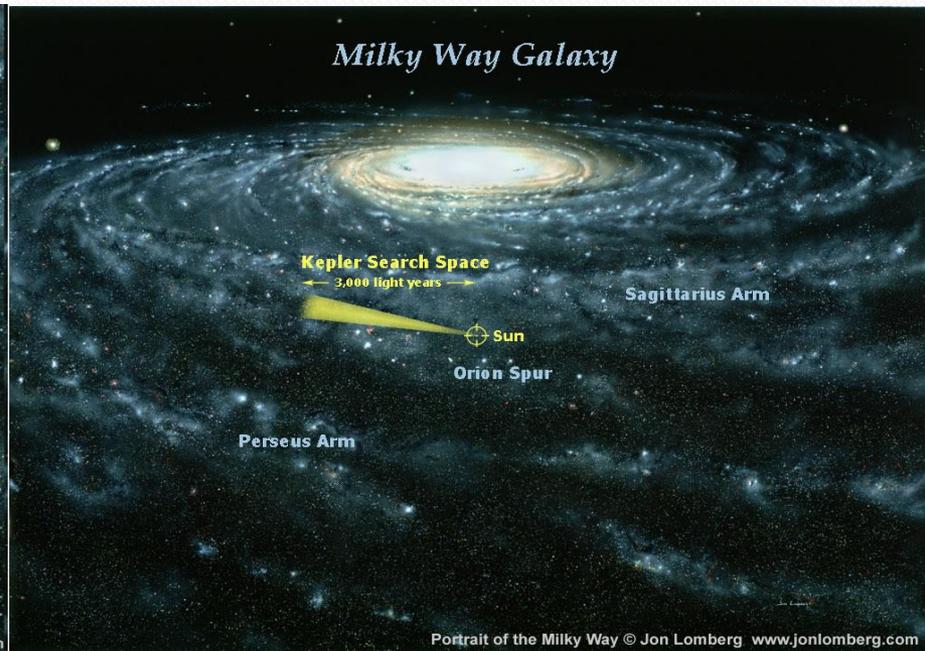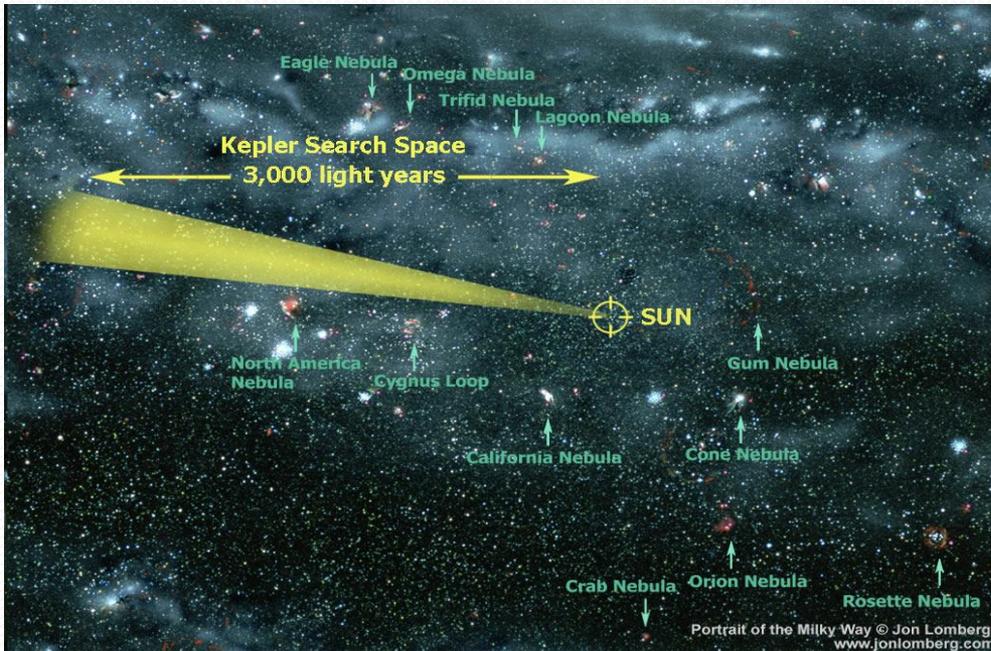
Detection
four basic methods

- **Transit photometry**: planet passing in front of its host star reduces slightly the star's luminosity, which then returns to its former level when the transit is complete.

- **Doppler spectroscopy**: shift in spectral lines of the host star as a result of its radial motion due to the gravitational influence of any orbiting planetary companion(s).

- **Microlensing**: transient change in the brightness of background star (the source) due to the unresolved images resulting in an observable magnification. Presence of a planet results in a third image of the source star as a temporary spike of brightness, lasting hours to days, superimposed upon the regular pattern of the microlensing event.

- **Direct imaging**: young planets are bright in IR making possible to image them. Sometimes possible to see planet in reflected light.

Doppler spectroscopy—mass

$$\frac{v_{rad}}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

The beginning: planet orbiting γ Cephei A (*Campbell et al. '98*). Finally confirmed in 2003 (*Hatzes et al. '03*). The radial velocity technique is based on perturbations of the star's velocity induced by the orbiting bodies: when the star moves towards us, its spectrum is blueshifted, when it moves away from us, it is redshifted—Doppler effect. It is more sensitive to large planets: e.g., Sun moves by about 13 m/s due to Jupiter, but only about 10 cm/s due to Earth, around the common CM. For purely circular orbit, the radial velocity curve is sinusoidal.

✓ used only for relatively nearby stars, out ~160 light-years from Earth, to find lower-mass planets. Jovian mass can be detectable around stars up to a few thousand light years away.
✓ only one star at a time can be observed
✓ unsuitable for finding planets around variable stars, as changes in the stellar emission spectrum swamps the small effect caused by a planet. Same for fast rotating stars—lines become too broadened
✓ only measure movement along the line-of-sight—low limit on mass. But if planets spectral lines can be distinguished, then Vr planet determined, which gives i

HD114762b
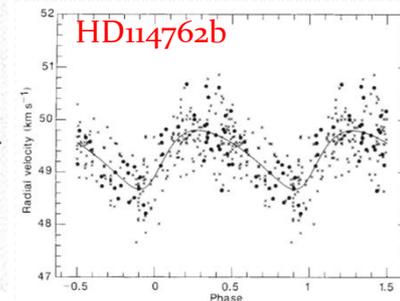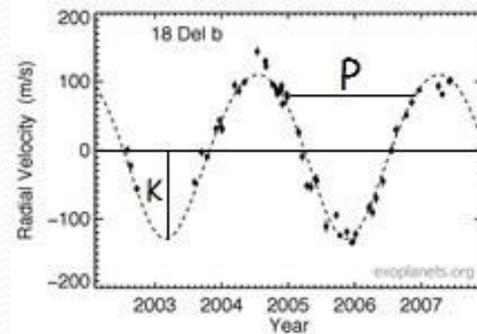
Latham et al., Nature 339, 38, 1989

exoplanets change position and velocity of the host star
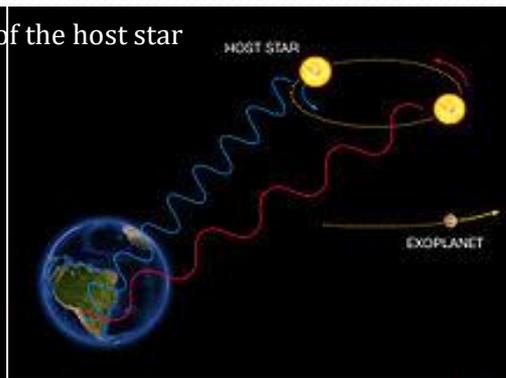
The Radial Velocity Method

$$K \equiv \frac{2\pi}{P} \frac{a \sin i}{(1-e^2)^{1/2}}$$

$$M_p \sin i = \left(\frac{P}{2\pi G}\right)^{1/3} K_* M_*^{2/3} \left(1-e^2\right)^{1/2}$$

Transit photometry—radius

The dip in a star's luminosity during transit is directly proportionate to the size of the planet. Since the star's size is known with a high degree of accuracy, the planet's size can be deduced from the degree to which it dims during transit.

Jupiter blocks about 1% of the Sun's disk, while the Earth blocks 0.01%.

$$\text{Depth} = \left(\frac{R_p}{R_\star}\right)^2$$

✓ the planets' orbits must be seen edge-on from Earth
✓ must see at least three transits to confirm that the dimming of a star was caused by a transiting planet
✓ variable stars are not useful in this search
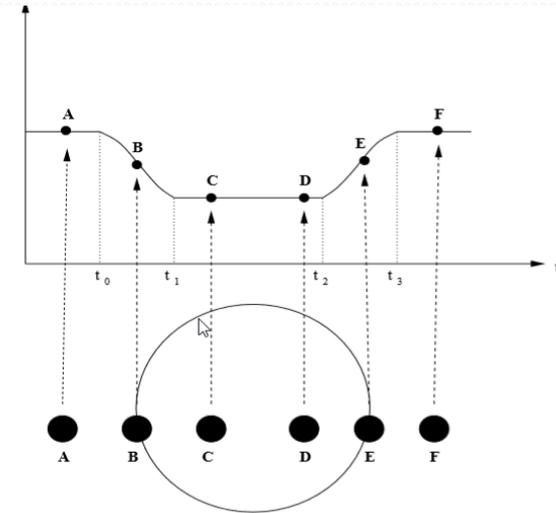
Transit Light Curves

credit: NASA
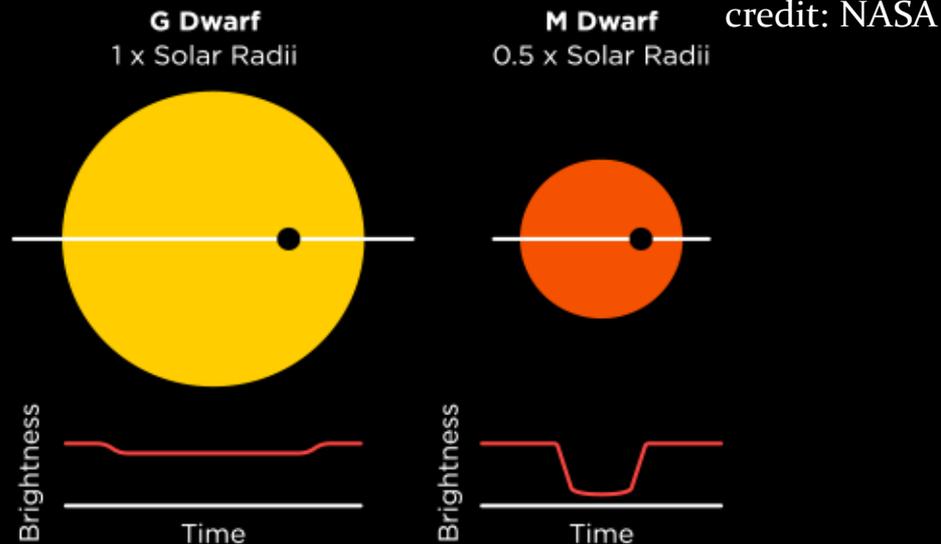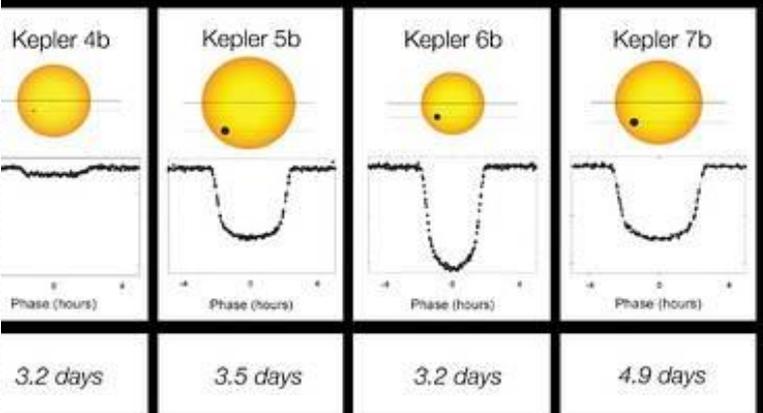
Transit spectroscopy — when the planet transits the star, light from the star passes through the upper atmosphere of the planet.

The newest frontier is probing exoplanet atmospheres, looking at what changes as a planet slips on and off the face of its star (as seen from Earth).

Starlight

Planet | Cloudy atmosphere | Slim atmosphere | Clear atmosphere
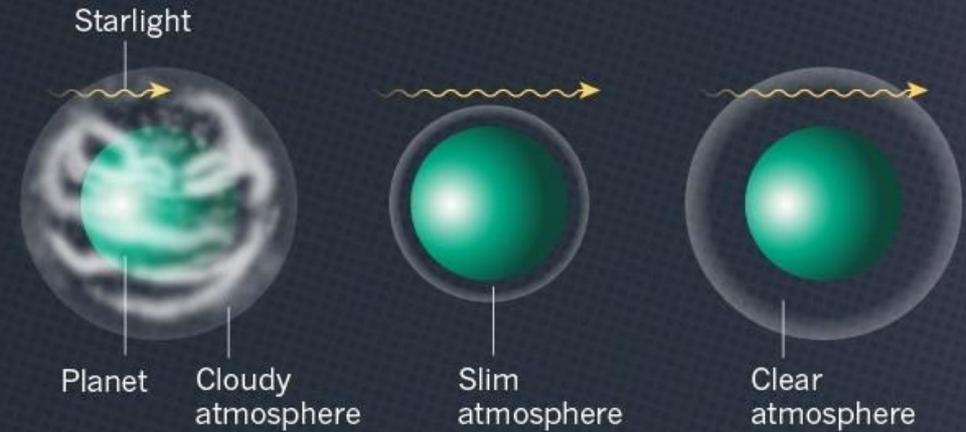
Chemical analyses of how the starlight is absorbed reveals compounds such as water in the cloudy skies of distant exoplanets.

— Model spectra with more haze
— Model spectra with less haze

Presence of water

Transit depth (fractional change in brightness)

0.4 0.6 0.8 1.0 1.2 1.4 1.6
Wavelength (µm)
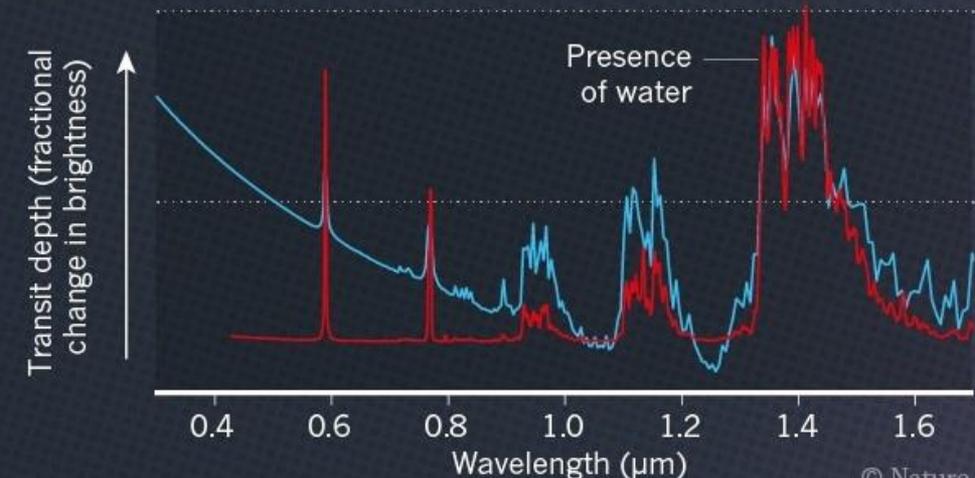
© Nature

Planet's temperature can be measured — if the star's intensity during the secondary eclipse is subtracted from its intensity before or after, then only the signal caused by the planet remains.
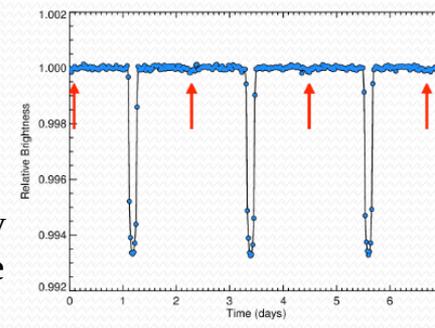
Transit timing variations—acceleration due to gravitational pull of other planets causes the orbital period of each planet to change.

Transit Signature of a Multiple-Planet System

Planets can be distinguished by:
• Different periods
• Different depths
• Different durations

Transit durations are greatly exaggerated

Time (days)
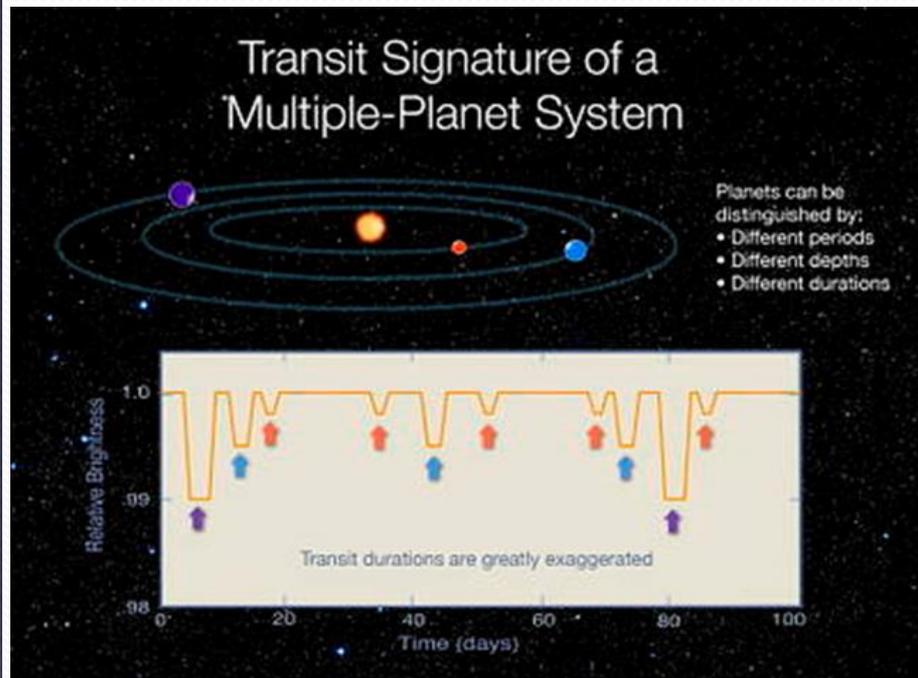
Not so easy as it looks

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2 \qquad t = \frac{P_p}{\pi}\left(\frac{R_* \cos\delta + R_p}{a_p}\right) = \frac{PR_*}{\pi a_p}\sqrt{\left(1+\frac{R_p}{R_*}\right)^2 - \left(\frac{a_p}{R_*}\cos i\right)^2}$$

r_p is the star-planet distance at the time of transit, corresponding to a phase angle ϕ.

$$t = 2\sqrt{\frac{1-\left(r_p\cos i\right)^2}{\left(R_*+R_p\right)^2}}\left(R_*+R_p\right)\frac{\sqrt{1-e^2}}{1+e\cos\phi}\left(\frac{P}{2\pi GM_*}\right)^{1/3} \qquad P^2 = \frac{4\pi^2}{GM_*}$$

P is the orbital period of the planet
e is the planet's orbital eccentricity
i is the inclination of the planet's orbit
a_p is the planet's semi-major axis
F is the star's flux or brightness
t_F/t_T gives the shape of the transit curve
δ is the latitude of the transit
p is the probability of observe transits for Randomly oriented systems

$$i_{min} = \cos^{-1}\left(\frac{R_*}{a_p}\right) \qquad \cos i = \frac{R_*\sin\delta}{a_p} \qquad \left(\frac{t_F}{t_T}\right)^2 = \frac{\left(1-\frac{R_p}{R_*}\right)^2 - \left(\frac{a_p}{R_*}\cos i\right)^2}{\left(1+\frac{R_p}{R_*}\right)^2 - \left(\frac{a_p}{R_*}\cos i\right)^2}$$

$$p = \frac{R_*}{a_p} = \cos i_{min}$$

The timing offset of the planet produced by the presence of a moon orbiting the planet/moon barycenter is given by, $\Delta t \approx \frac{a_m M_m P_p}{\pi a_p M_p}$ where a_m and M_m are the semi-major and mass of the exomoon.
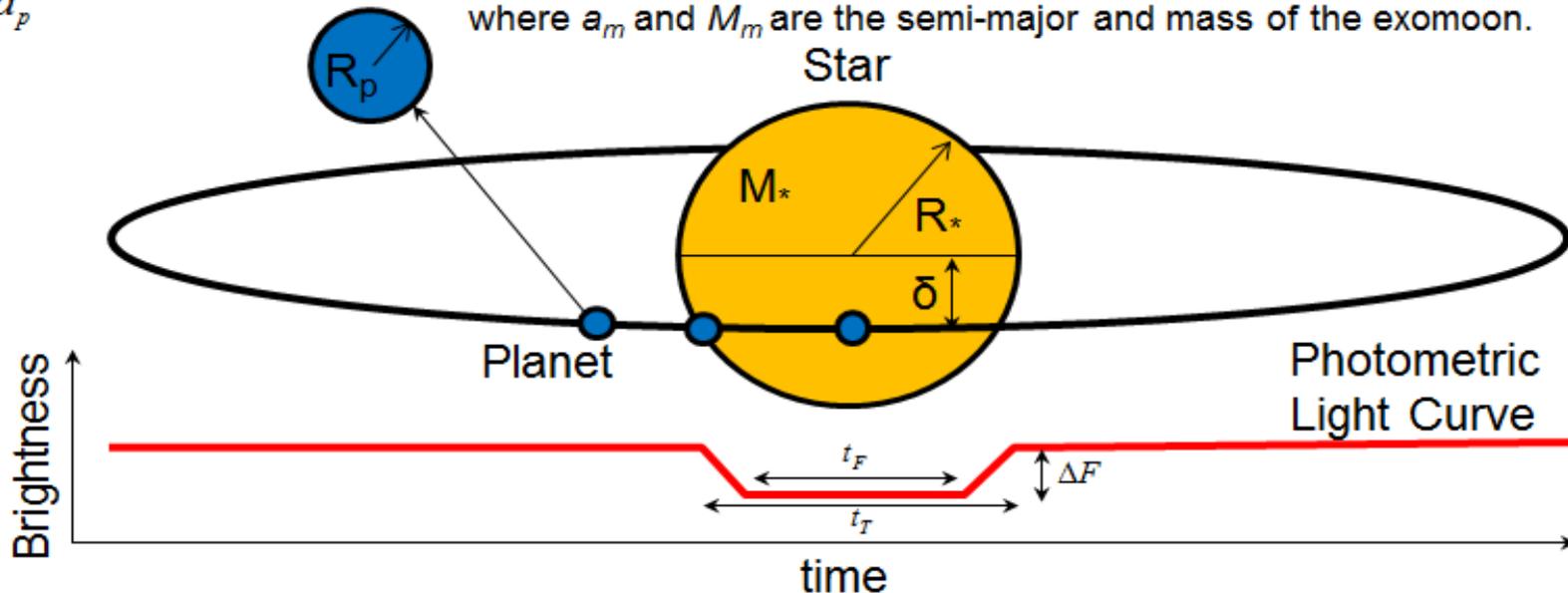
Microlensing

Proposed in 1986 to discover dark matter in halo (*Paczyński, 1986*)

In 1992 – to discover extrasolar planets (*Gould & Loeb, 1992*)

2003 – first extrasolar planet OGLE 2003-BLG-235 (MOA 2003-BLG-53) discovered at ~5.8 Kpc.

Need large number of background stars

One time event

Only mass can be determined

Probability low as exact alignment needed

Most sensitive to wide orbits (1-10 au)

Can detect low-mass planets (in principle, down to Mars mass)

Easier to detect planets around low-mass stars

best to detect planets around very distant stars (Kpc away)

the only way to detect far away free-floating planets
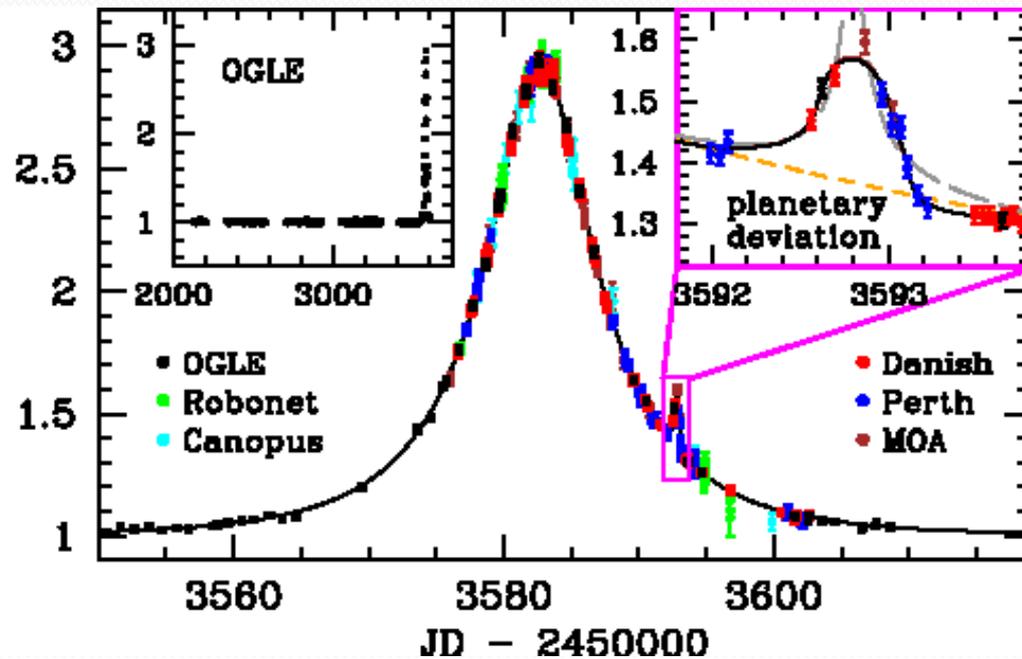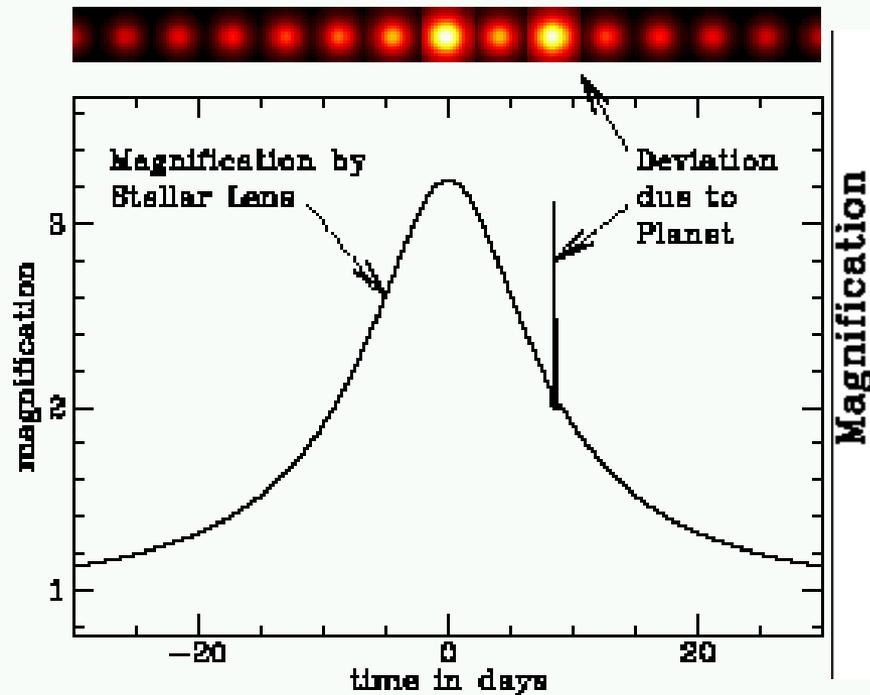
Direct Imaging

The first ever direct detection of the visible light spectrum reflected from an exoplanet was 51 Pegasi b ~0.5 JM planet - hot Jupiter, 4-day P (*Mayor & Queloz 1995).* Planets are extremely faint light sources compared to stars.

Easier when:

1. star system is relatively near us
2. when the planet is especially large (much larger than J)
3. on wide orbit
4. hot so that it emits intense infrared radiation

Works better with planets with face-on orbits rather than edge-on orbits

Can detect free-floating nearby planets

For Earth/Sun at 10 pc @λ~10 μm

$$\frac{F_\nu^{\text{pl}}}{F_*} = \frac{T_E}{T_\odot}\left(\frac{R_E}{R_\odot}\right)^2 \sim 4 \times 10^{-6}$$

Estimated temperatures inside its clouds made of hot dust and molten iron exceed 800 °C, @ ~80 ly

Free-floating planet
PSO J318.5-22

Pan-

Fomalhaut System — Hubble Space Telescope + STIS

2012
2010
2006
2004

NASA and ESA
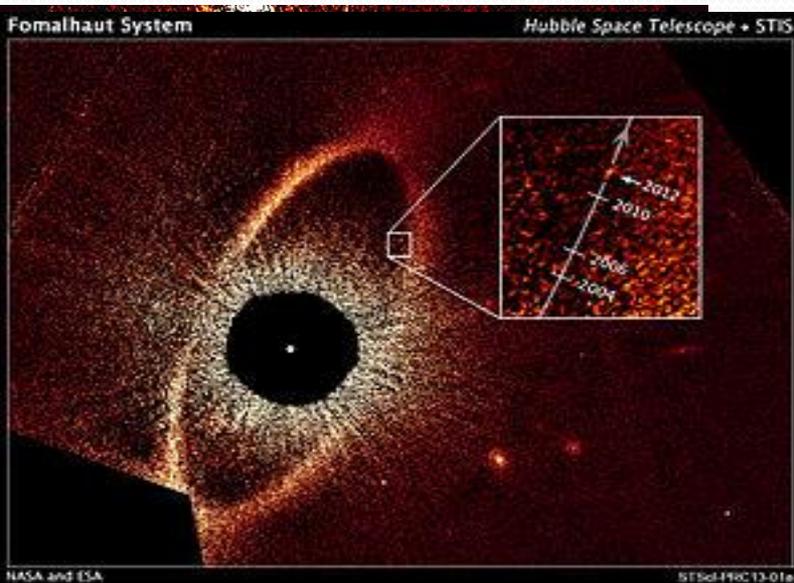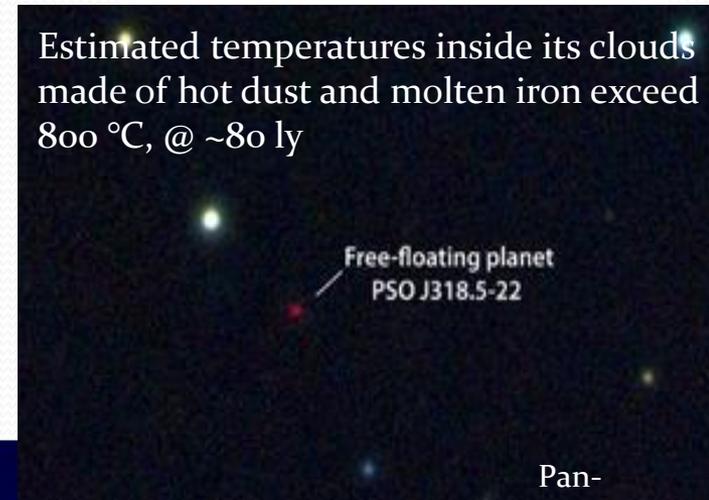
HR 8799, Keck observatory, NIR

2009-07-31   20 au   Jason Wang / Christian Marois
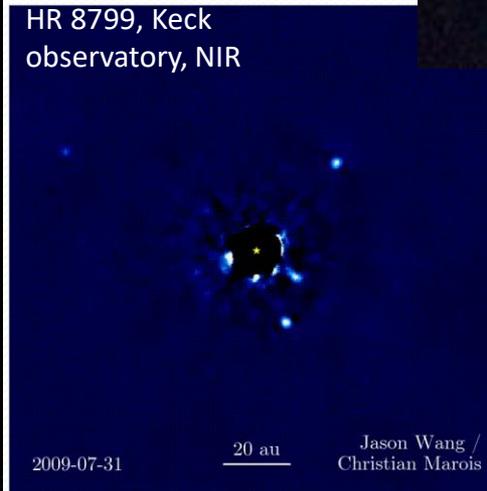
Additional methods

- **Pulsar Timing**
  - 1992: PSR 1257+12 c and d: pulses were sometimes arriving a little earlier than expected and at other times a little later. These variations were attributed to the displacement of the pulsar by the gravitational pull of 2 small objects (a third was added a few years later).
  - 1999: PSR B1620–26 M4 globular cluster planet (*Thorsett et al.*) – the only planet yet in all globular clusters.

- **Polarimetry**: light is reflected off the atmosphere of a planet becomes polarized while stellar light is not

- **Astrometry:** precisely measuring a star's position in the sky, and observing how that position changes over time. To detect an Earth-like planet orbiting a sun-like star at 1 au and observed at 5 pc of distance, we need resolution 0.6 μas, not yet possible. Future planned missions can achieve 1 μas.

- **Auroral radio emissions**: auroral radio emissions from giant planets (right now, it is possible to detect Jupiter at about 0.2 parsec.)

Formation pathways

- **Core accretion scenario**: planets form through the agglomeration of submicron dust into grains, pebbles, rocks and then km-size planetesimals which form the planetary cores, until they are sufficiently massive to accrete a gaseous envelope. Once the core reaches a critical mass, a phase of rapid gas accretion occurs. The model has a metallicity condition ([Fe/H] > −1.17 in case of G-type stars), and the mass of planets formed is less than 6 JU. Some problems:

- Time to form--giant planets might require longer than 10^6 years to form; disk evaporates

- Infamous "mm/cm/meter size barrier" problem: when dust aggregates reach sizes beyond roughly 1 cm, they partially decouple dynamically from the gas and can reach high velocities leading to bouncing, electrostatic repulsion, inward drift... rather than sticking. Already at mm sizes the dust aggregates stick insufficiently well for coagulation to continue, as seen in the lab&modelling experiments (*Guilera&Sándor 2016*).

Before collision

Sticking (S)   Bouncing (B)   Mass Transfer (MT)   Fragmentation (F)

Erosion (E)

collision velocity

Windmark et al. 2012
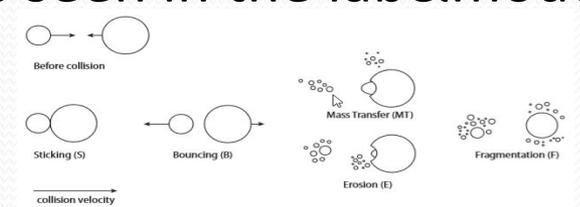
Gravitational instability

In a massive circumstellar disk, the self-gravity triggers the fragmentation and collapse of gas into a gas giant planet directly. Such clumps can contract to form giant gaseous protoplanets in several hundred years. Gas giants are quickly formed before the gas in the disk depletes. No metallicity condition, but requires the disk to be 15 times more massive. The trigger of the instability might come from material of the protostellar cloud infalling onto the disk, or through the interaction of a passing star with a circumbinary disc (pulsar planet in M4 *Beer et al. '04*). Requires a marginally unstable disk (Q_{min} <1.4-1.5), in which radiative cooling is efficient during the initial growth of the overdensities.

$$Q = \frac{\Sigma_{crit}}{\Sigma_g} \approx \frac{c_s \Omega_k}{\pi G \Sigma_g} < 1$$

Toomre parameter for disk instability onset

sound speed $c=(P/\rho)^{1/2}$, angular velocity Ω, gas surface density Σ.
A measure of the competition between stabilizing pressure, stabilizing rotation, and destabilizing self-gravity (e.g. *Binney&Tremaine '08*)

Dependence on metallicity?

Because iron is easiest to measure with spectral data in the visible spectrum, the abundance ratio is defined as the logarithm of the ratio of a star's iron abundance compared to that of the Sun. A star with a [Fe/H]=0.0 has the same iron abundance as the Sun.

$$[\text{Fe/H}] = \log(\text{Fe/H}) - \log(\text{Fe/H})_{\odot}$$

``hypothesis that almost all of the planets detected so far were formed by core accretion" is supported by observational facts"
— 2007
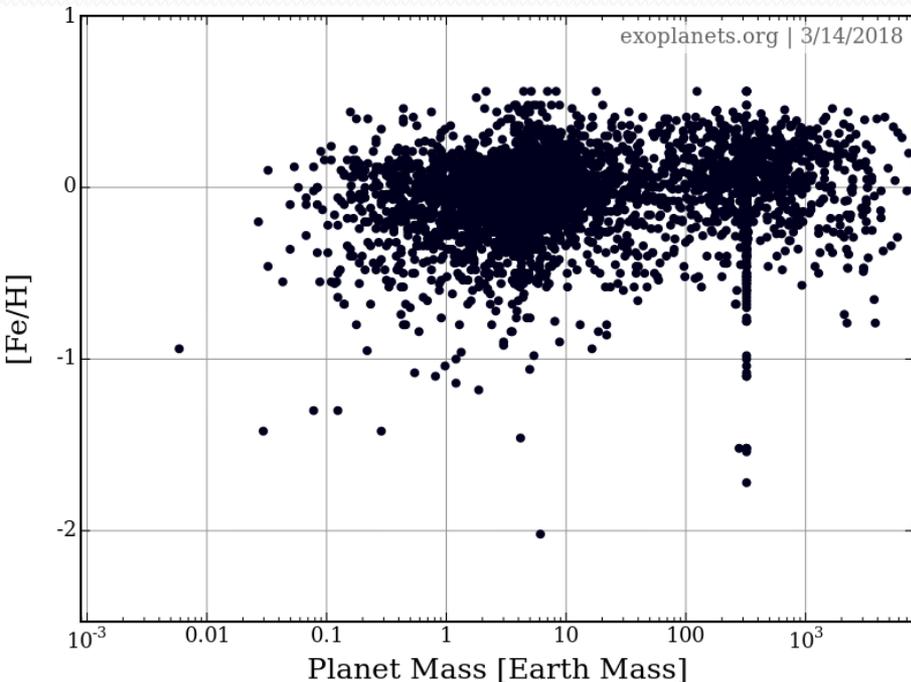
Blue filled: low FE: <-0.1; median mass: 4.57 EU
Green: medium FE: -0.1<= FE <0.3; median mass: 4.75
Red: high FE: >= 0.3; median mass: 34.52 EU

Low: 1292
Medium: 2146
High: 226
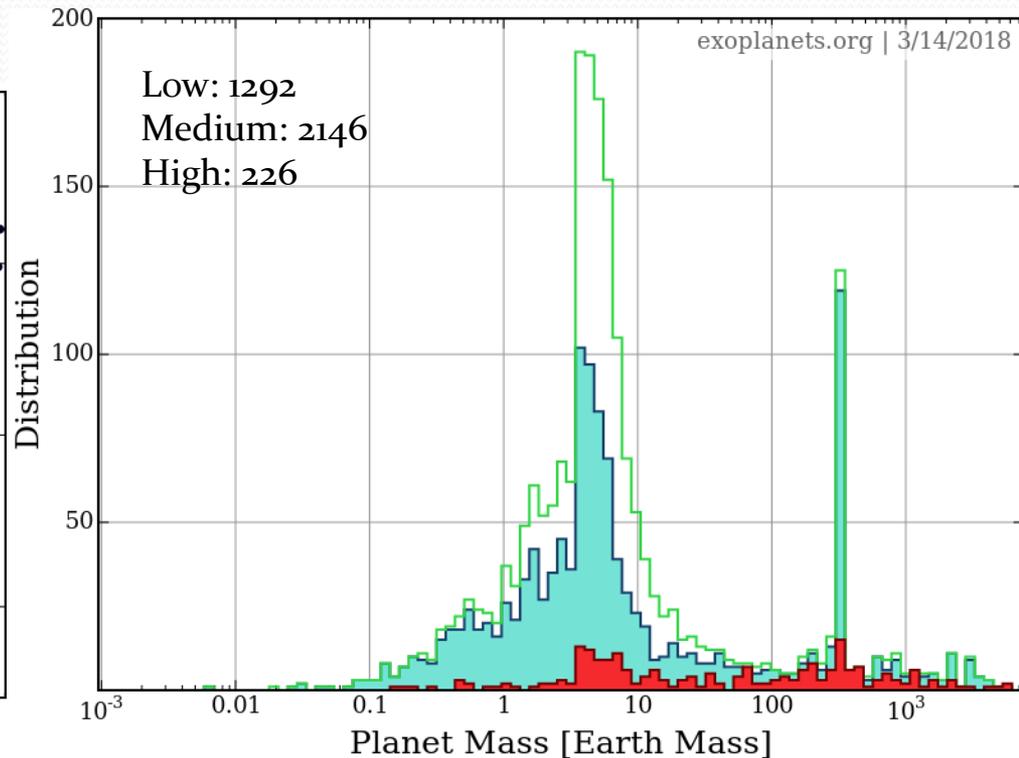
Core accretion scenario puzzles

Jupiter is believed to form in 10 mln yrs. But in 2013 a planet was found @TW Hyd that defies this scenario - it's too far away from the star, about Pluto's distance, and it's a small planet, ~20 Earths.

TW Hya Disk
HST NICMOS/NIC2
F171M+F180M+F222M

Disk

Location of Star

Coronagraphic Spot

Gap

15 billion miles

160 AU   3"

N

E
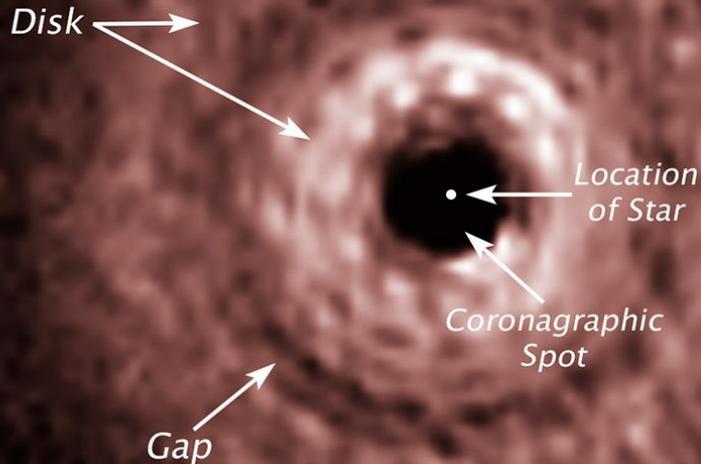
At that distance, it should take 200x longer to form (slow moving, less matter and the star is only 55% of Sun), but the star is only 8 mln yrs old. In addition to all these problems, the dust grains seen by ALMA orbiting near the gap are still smaller than sand grains.

Comparison of TW Hydrae System and Solar System

TW Hydrae Disk

Kuiper Belt

Asteroid Belt

Sun

Jupiter

Neptune
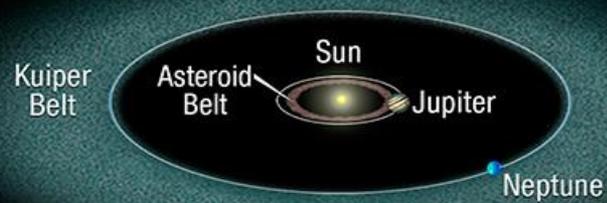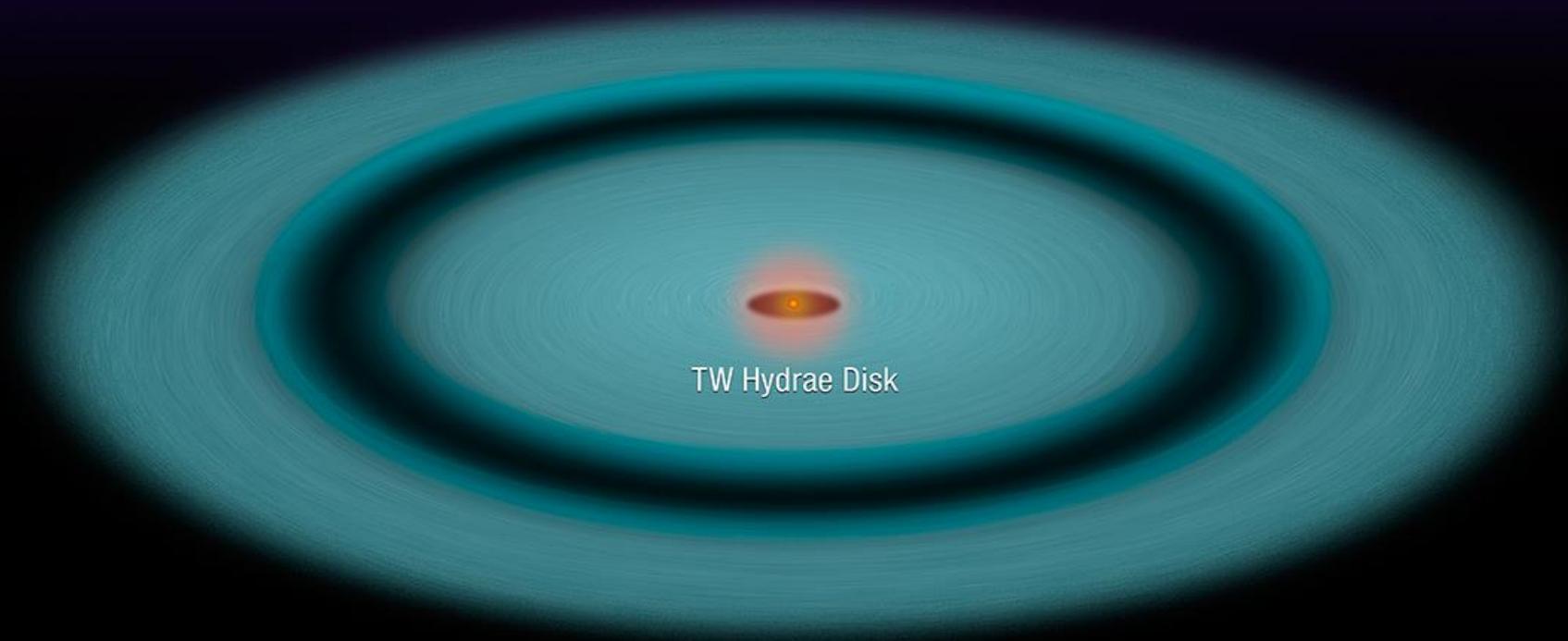
4.5 billion miles

Time is on planet's mind

- May be it shall take only thousands of years, after all as gravitational instability theory suggests, or even hundreds — **Mayer, L., T. Quinn, et al. *Formation of giant planets by fragmentation of protoplanetary disks*. Science 298, 1756 (2002).**

- How about 3 years? Take TYC 8241 2652–10 mln-yr-old star with warm dust disk. Since 1983 observed by IRAS, on Jan '10 the NASA's WISE telescope finds NO disk; on May 1st 2012 Gemini observatory—still no disk!

  Melis, C. et al., *Rapid disappearance of a warm, dusty circumstellar disk*, Nature 487, 74 (2012).
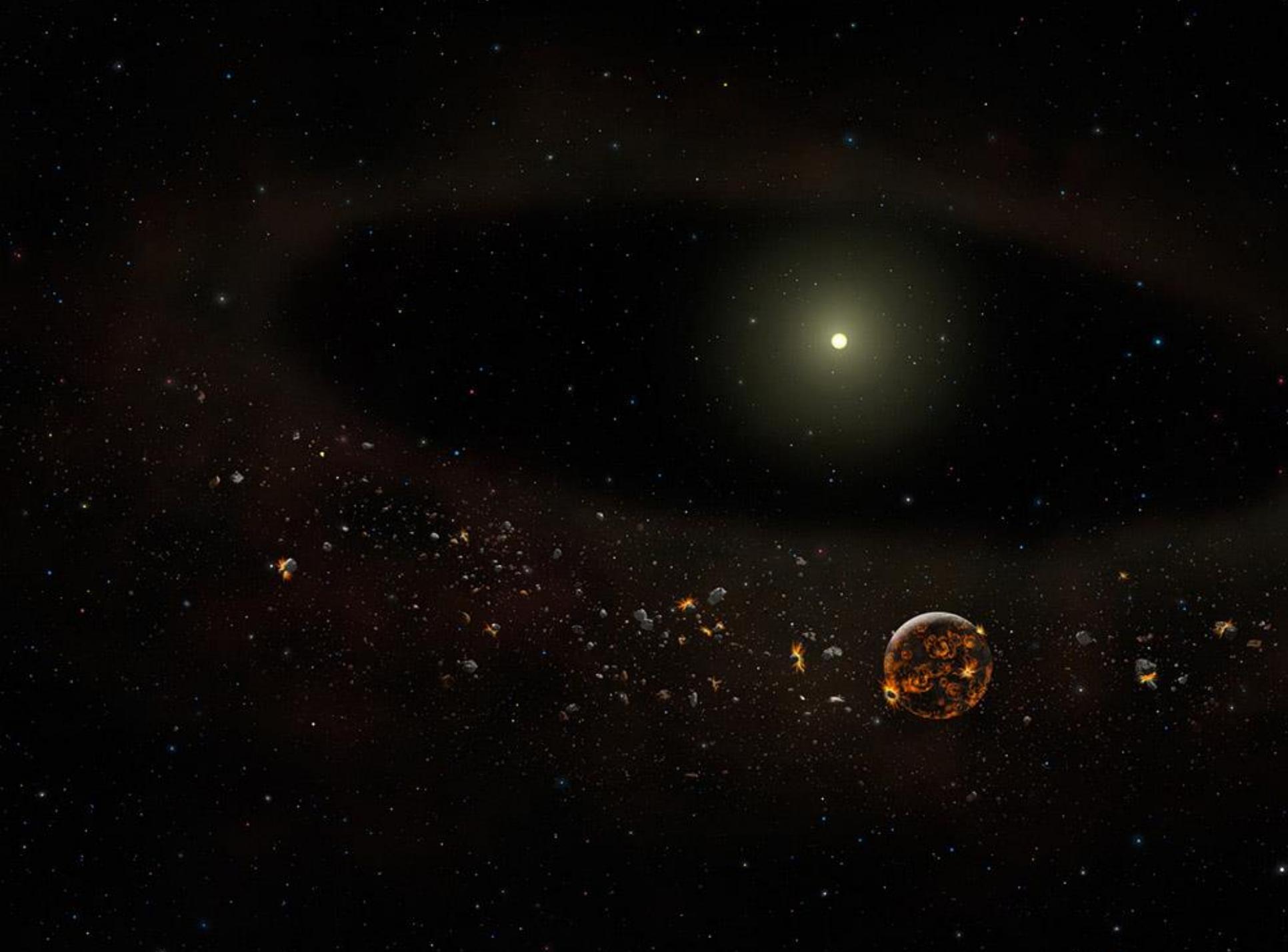
Other possible pathways

- Collapse from *cometary blobs:* observed in large numbers in nearby supernova remnants, planetary nebulae and star formation regions. They'd slow down in the ISM by sweeping in the ambient matter in their way and grow in mass. They cool by radiation and if their mass exceeds the Jeans mass, they contract gravitationally into giant jupiters.

- In *low-metallicity* environment, two scenarios are possible to form planets (*Schchekinov, Safonova & Murthy, 2013*):
  - *Centrifugal assembling of accreting dust in external regions*. After decoupling from the gas dust particles in metal-deficient disks accumulate mostly in outer regions of the disk forming the ring, where dust particles start assembling due to self-gravity. Enhanced metallicity in the ring.
  - *Radiation-driven assembling of dust*. Radiation from the central protostar can stimulate formation of clumps through the mock-gravity instability caused by radiation pressure on dust grains. The characteristic masses of such clumps are close to the Jovian mass.

HST zoom on Helix nebula. Each *cometary blob* is about twice the size of our solar system with ~1--3 Earth mass of H and other gases that were expelled from the nebula's central star thousands of years ago. In Helix Nebula there are >40,000 CBs. *Dado et al. 2011*

Dust particles concentrate in a ring
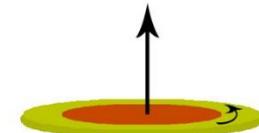
Habitability

- Planets in our Galaxy alone running into billions. We do have life thriving on one of these billions of planets, why not on others?

- Humanity for a long time believed in numerous life forms on numerous other worlds. But only recently all pieces of evidence came together:

  - Nature makes planets with ease

  - Small rocky planets are overabundant

  - Space chemistry is extremely rich in organics. Early chemical steps believed to be important for the origin of life do not require an already-formed planet - they are there in deep space before even planets form. If these compounds encounter a hospitable environment like our Earth, they can jump-start life.

  - Life on Earth exists in a very broad range of conditions: from -200^0 to 150^0 C; some species can even withstand vacuum and pressure of 6,000 atm (tardigrades); pH extremes of <3 and >9; concentrated salt levels; toxic metal levels; high ionizing radiation; no water…

  - Life-essential elements *CHNOPS* are all made by the 1st stars

  - Planets can be made in very early Universe

The prerequisites and ingredients for life seem to be abundantly available in the Universe.

The Cologne Database for Molecular Spectroscopy, CDMS

Molecules in the Interstellar Medium or Circumstellar Shells (as of 03/2018)

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	C_3 *	c-C_3H	C_5 *	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	C_{60} *
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{70} *
AlCl	C_2O	C_3N	C_4Si	C_2H_4 *	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	C_{60}^+ *
C_2 **	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$?	c-C_6H_5CN 2018
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O 2016			
CH^+	HCN	C_2H_2 *	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH 2017			
CN	HCO	NH_3	CH_4 *	CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	$HNCO$	HCOOH	NH_2CHO	CH_3NCO	H_2NCH_2CN	CH_3CH_2SH (?)				
SiC	H_2O	HNCS	H_2CNH	C_5N	HC_5O 2017	CH_3CHNH	CH_3NHCHO ? 2017				
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H *		CH_3SiH_3 2017	HC_7O 2017				
KCl	HNC	H_2CO	H_2CNN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							

Habitability—what we are looking for?

The search for habitable exoplanets has essentially two goals, both of which (if fulfilled) will have profound implications to our civilization.

➢ One is to seek life elsewhere outside the Earth.

➢ Another one is to seek a twin Earth, preferably nearby. This goal, in principle, is to have a planet habitable for our kind of life, but uninhabited, so that we can shift there in the far away future, if needed ☺

But what is a *habitable* exoplanet in our current understanding: a planet able to beget and sustain life? inhabited by any kind of life? suitable for us to live on? suitable for some kind of life yet unknown?

❖ Intelligent life, once evolved, is no longer in need of a very precisely defined biosphere – we humans can already create our own biospheric habitats on planets that are lifeless in our definition: Mars, Venus, or the Moon. Even space is habitable for us – ISS is the example!

Defining Habitability

Habitable or potentially-habitable – is it the same?

In *Safonova, Shchekinov&Murthy 2016*, we proposed slightly different definitions:

- *Potentially-habitable planet* – a rocky, terrestrial-size planet in a habitable zone of a star.

- *Habitable planet* – a rocky, terrestrial-size planet in a HZ with detected surface water and some of the biogenic gases in atmosphere.

- *Inhabited planet* – the best case scenario: a rocky, terrestrial-size planet in a HZ with simultaneous detection of species such as water, ozone, oxygen, nitrous oxide or methane in the atmosphere.

the measure of a planet potential to develop and/or sustain life.

Habitability extreme views

➢ Life is very rare in the Universe (*Spiegel &Turner, 2011*), through a Bayesian analysis of the probability of abiogenesis.

➢ The whole Universe is habitable (starting with *Dicke 1961*)

<p style="color:red; text-align:center">*Not too cold, not too hot,*</p>

<p style="color:red; text-align:center">*Not too young, not too old…*</p>

<p style="color:red; text-align:center">*Just right for life* → anthropic principles (>30)</p>

➢ Habitability of the Universe only increasing; will keep increasing until the final stars die out over the next hundreds of billions of years (*Dayal, Ward&Cockell, '16*)

➢ Life originated before 20 Myr after the BB: primordial planets formed in clumps at the plasma-to-gas transition; planets merged to form stars; the supernovae from stellar over-accretion of planets produced elements (C, N, O, P, etc.) and abundant liquid-water domains (*Gibson et al. 2010*). Requires HGD – alternative hydro-gravitational dynamics cosmology.

➢ Life could have originated 10-17 Myr before the BB at redshift of z~100. Requires standard ΛCDM cosmology and normal formation of planets after the 1st stars enriched the medium (*Loeb 2014*). Problems with 1 Myr for life & formation ways.

Last two theories based on of CMB temperature of ~300K @ z~100 – warm floor allowing early rocky planets to have liquid water on their surface.

"Anything is habitable if you are clever enough," –Freeman Dyson

Quantifying Habitability

- Can we quantify it? Isn't it a high time to start characterizing planets, sorting them into classes/types just like stars, to better understand their formation paths, their properties and, ultimately, their ability to beget/sustain life.

- Which planets are better suited for life and which ones are definitely not worth spending expensive telescope time on? We need a sort of quick assessment score, a metric, using which we can make a list of promising planets and dedicate our efforts to them.

Estimated Number of `Habitable' Worlds
40B - 49B

INTERSTELLAR NEIGHBORHOOD
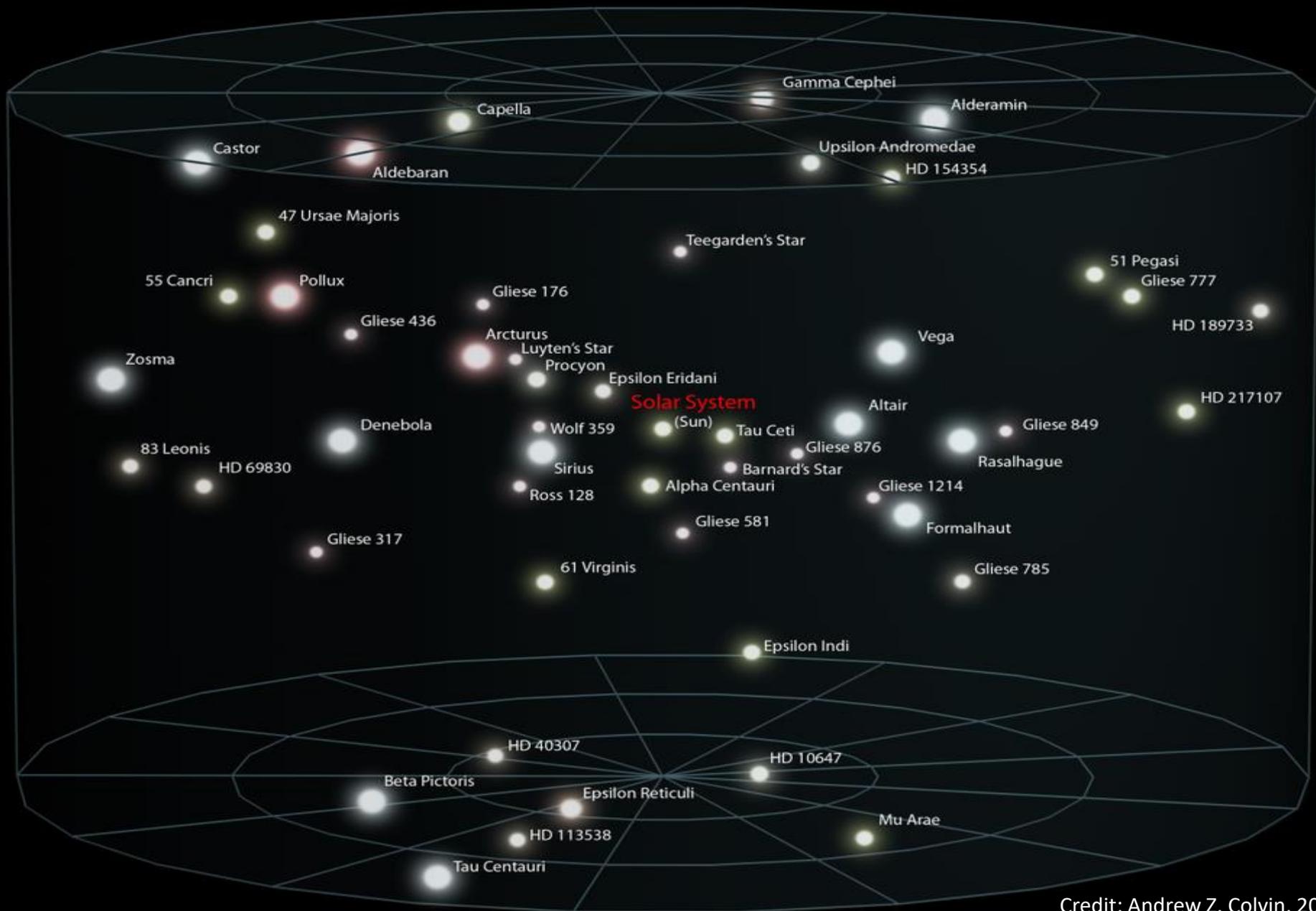
INTERSTELLAR NEIGHBORHOOD

Red are the stars with detected planets; pink are unconfirmed planets
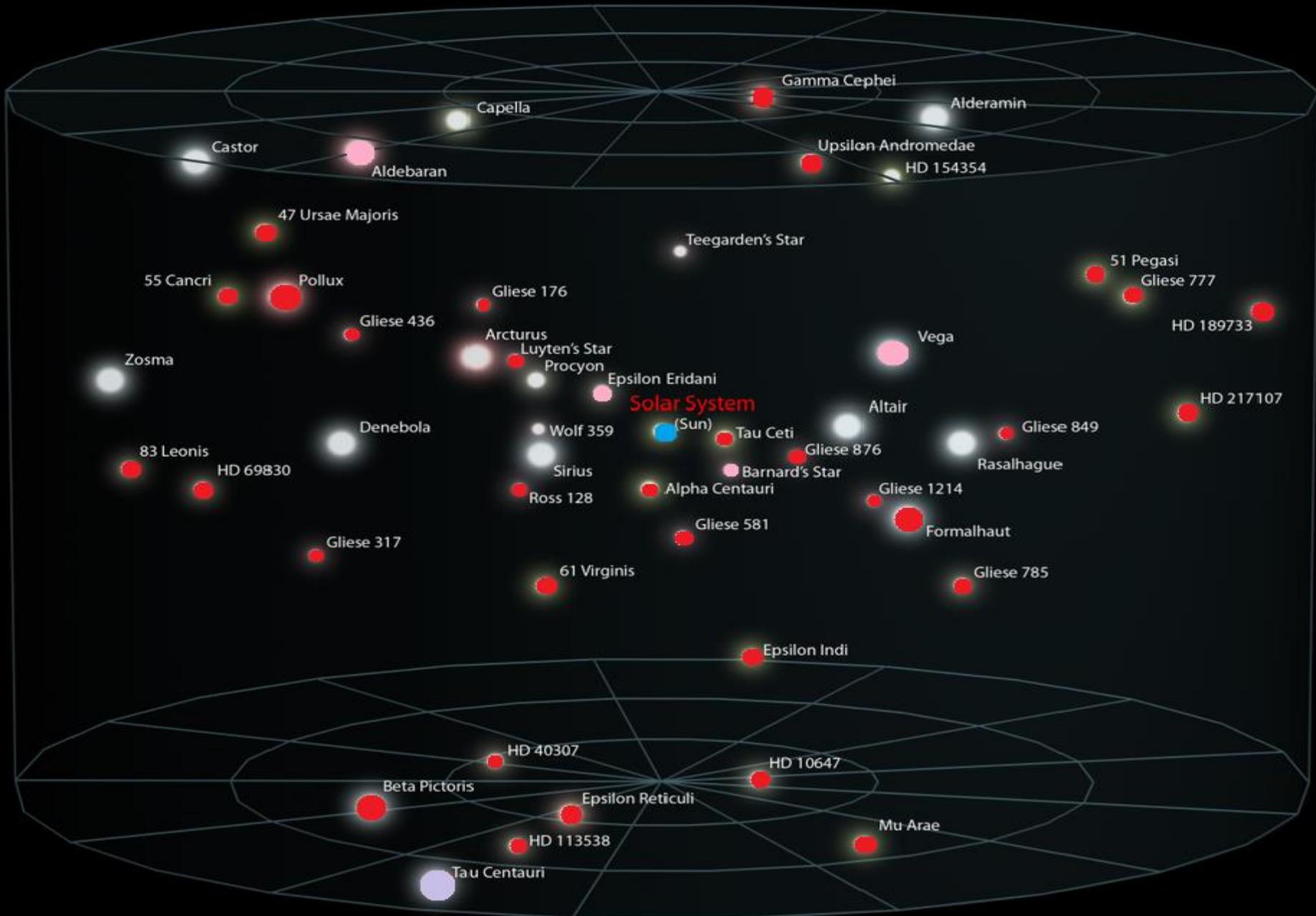
INTERSTELLAR NEIGHBORHOOD

Green are the stars potentially habitable planets
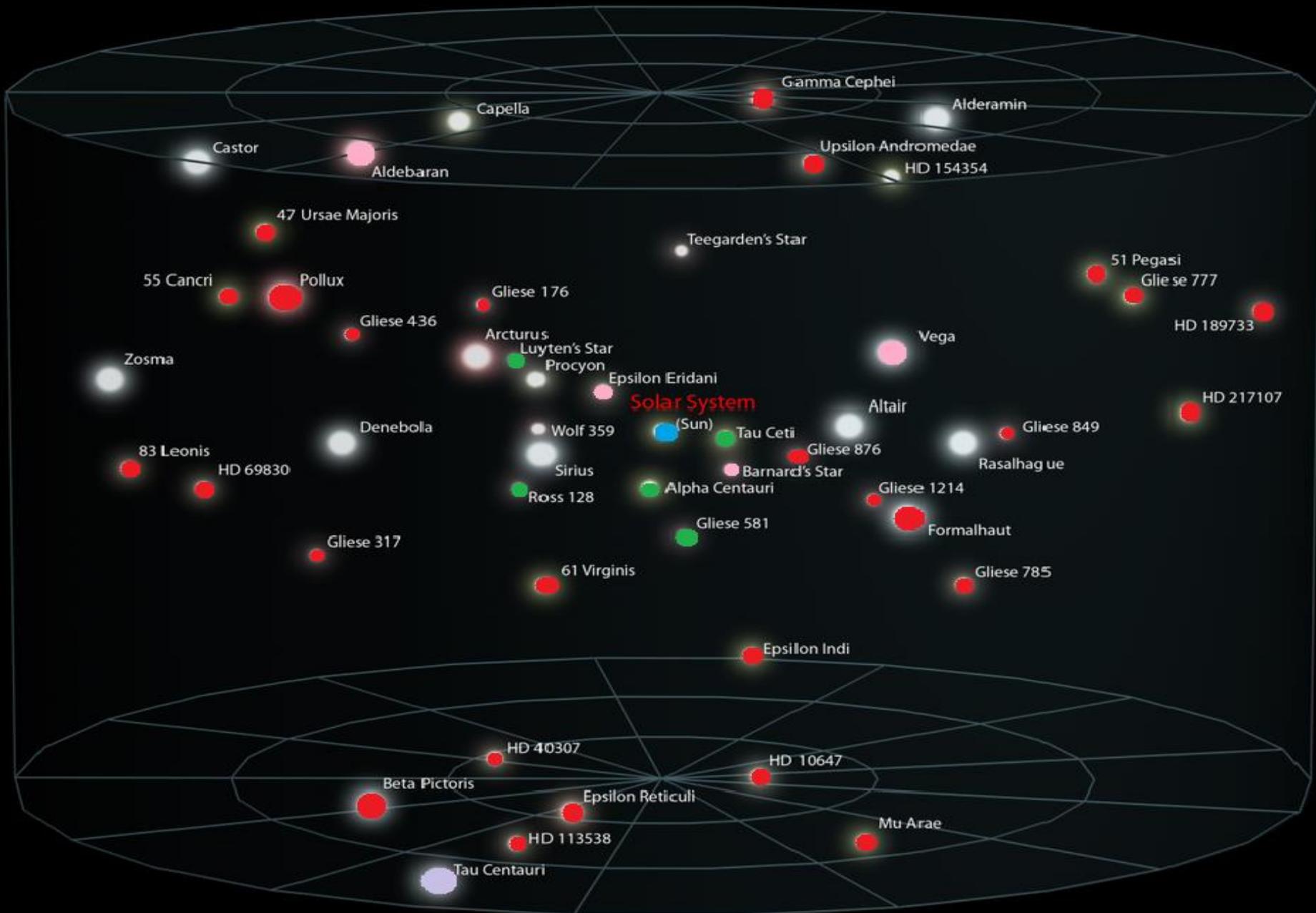
Exoplanetary ranking

- Habitable Zone (HZ): range of orbital distances from the host star that allows the preservation of the water in liquid state on the surface of a planet (*Kasting et al. 1993*).

$$r_{inner} = \sqrt{L_\star / S_{inner}} \qquad r_{outer} = \sqrt{L_\star / S_{outer}},$$

$$S_{inner} = 4.190 \times 10^{-8} T_{eff}^2 - 2.139 \times 10^{-4} T_{eff} + 1.268$$

$$S_{outer} = 6.190 \times 10^{-9} T_{eff}^2 - 1.319 \times 10^{-5} T_{eff} + 0.2341.$$

using the boundary conditions of runaway greenhouse and maximum greenhouse effects at the inner and outer edges of the HZ (*Kane&Gelino '12*)

A binary criterion: assumes once a planet is in the HZ, it is potentially habitable.

HABITABLE ZONE

Too Hot   Just Right   Too Cold

Surface Liquid Water
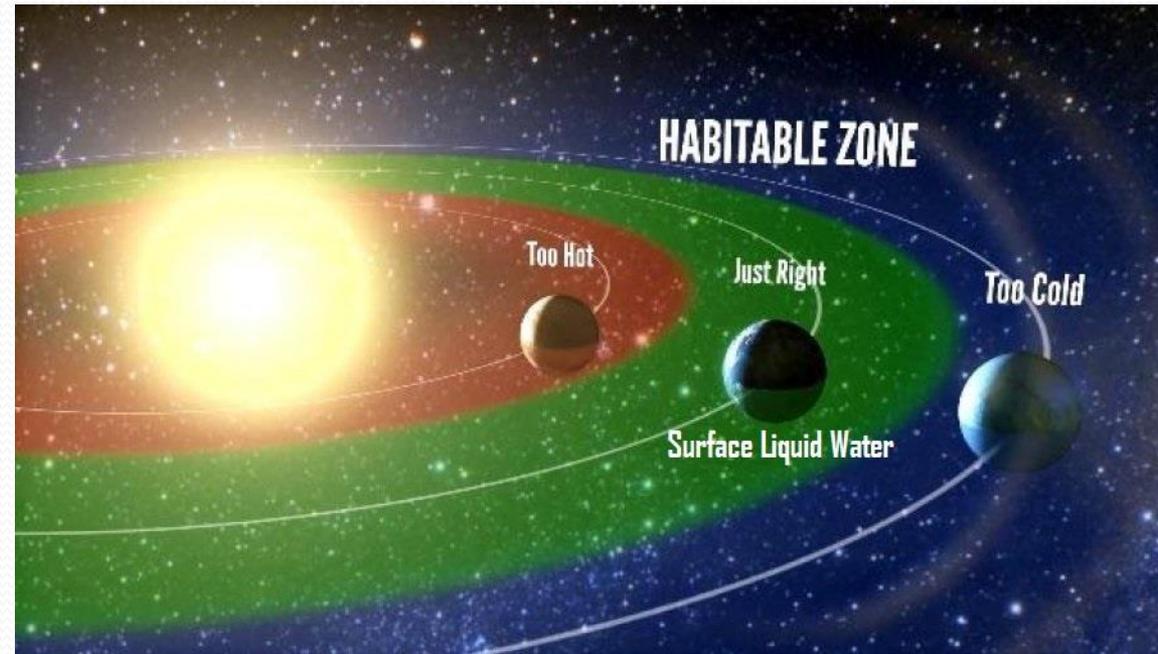
Moon is inside the HZ, and is a rocky planetary body, but definitely not potentially habitable for our kind of life. Earth is on the very edge of the HZ (making it marginally habitable) and will get out of it in the next 1-3 billion years. Mars is technically inside the HZ, and Venus once was. Titan, on the other hand, is totally outside the HZ but may host a life, albeit dissimilar to ours. *Free-floating planets --?*
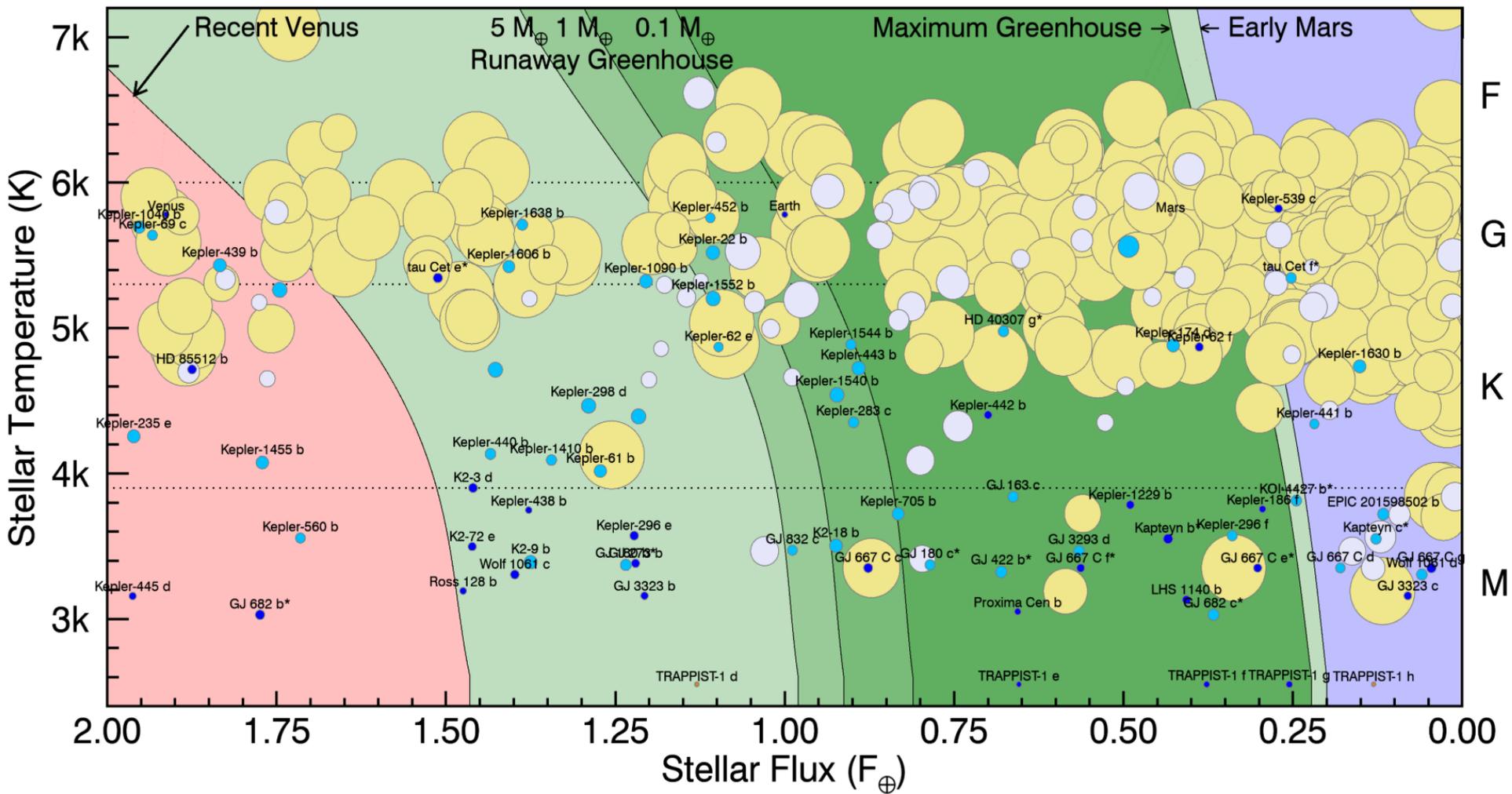
Based on these calculations, PHL @UPR Arecibo created a plot. Darker green shade is the conservative habitable zone and the lighter green shade is the optimistic habitable zone. Only those planets <10 Earth masses or <2.5 Earth radii are labelled.

Earth Similarity Index

An ensemble of planetary physical parameters (R, D, T_s and V_e) with Earth as reference frame for habitability (*Schulze-Makuch et al. 2011*). Based on the well-known statistical Bray-Curtis scale of quantifying the difference between samples, frequently used by ecologists to quantify differences between samples based on count data. [0-1] range with 0.2 gradation for very low, low, …, very high similarity.

$$\text{ESI}_x = \left[1 - \left| \frac{x - x_0}{x + x_0} \right| \right]^{w_x} \qquad w_a = \frac{\ln V}{\ln[1 - |\frac{x_0 - x_a}{x_0 + x_a}|]}$$

weight exponents are found ~*ad hoc* using the threshold value 0.8 for each parameter. E.g. Earth-like range: radius 0.5-1.9 EU, mass 0.1-10 EU, density 0.7-1.5 EU, surface temperature 273-323 K, and escape velocity 0.4-1.4 EU.

Parameters chosen arbitrary&depend on each other: only 1 observables (R).

Problem to extend to include more parameters.

Advantage: can be extended to other reference value, e.g. to small planets suitable for extremophiles — `extremophile' habitable?

Like Mars: MSI (*Jagadeesh et al. 2017*)
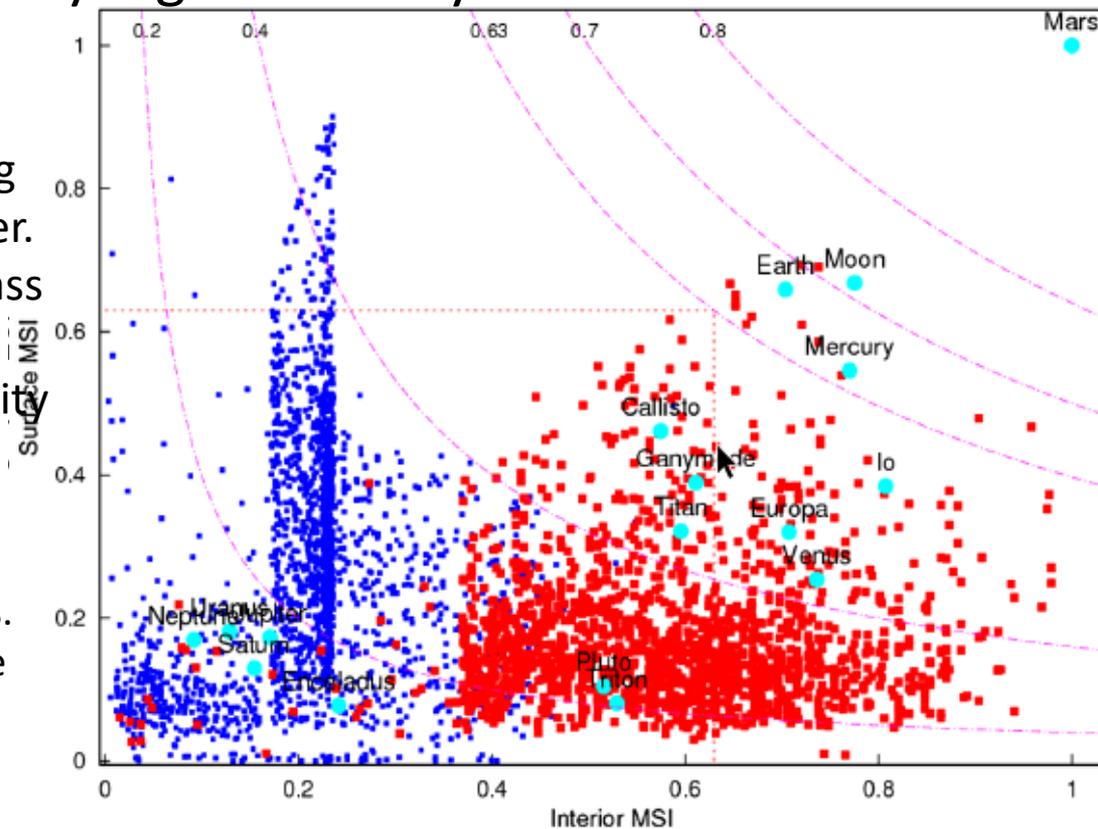
Habitability index for transiting exoplanets (HITE)

- Based on the certain limit of planetary insolation at the surface (*Barnes et al. 2015*). Predicts that planets that receive between 60-90% of same amount of insolation as Earth are likely to be habitable. It however assumes only circular orbits and the location inside HZ, which again refers back to mostly Earth similarity. It was assumed earlier that low eccentricities favour multiple systems, in turn favouring habitability.

- Our Solar System has a unique feature of very low ellipticities., but most know exoplanets have high eccentricities.

- high ellipticity orbits can have low effect on planetary climate provided they are in a certain spin-orbit resonances. For *e = 0.4*, if *p = 0.1* (*p* = orbital period/spin period), the HZ is the widest and the climate is most stable (*Wang et al. 2017*)

Histogram of exoplanets' eccentricities
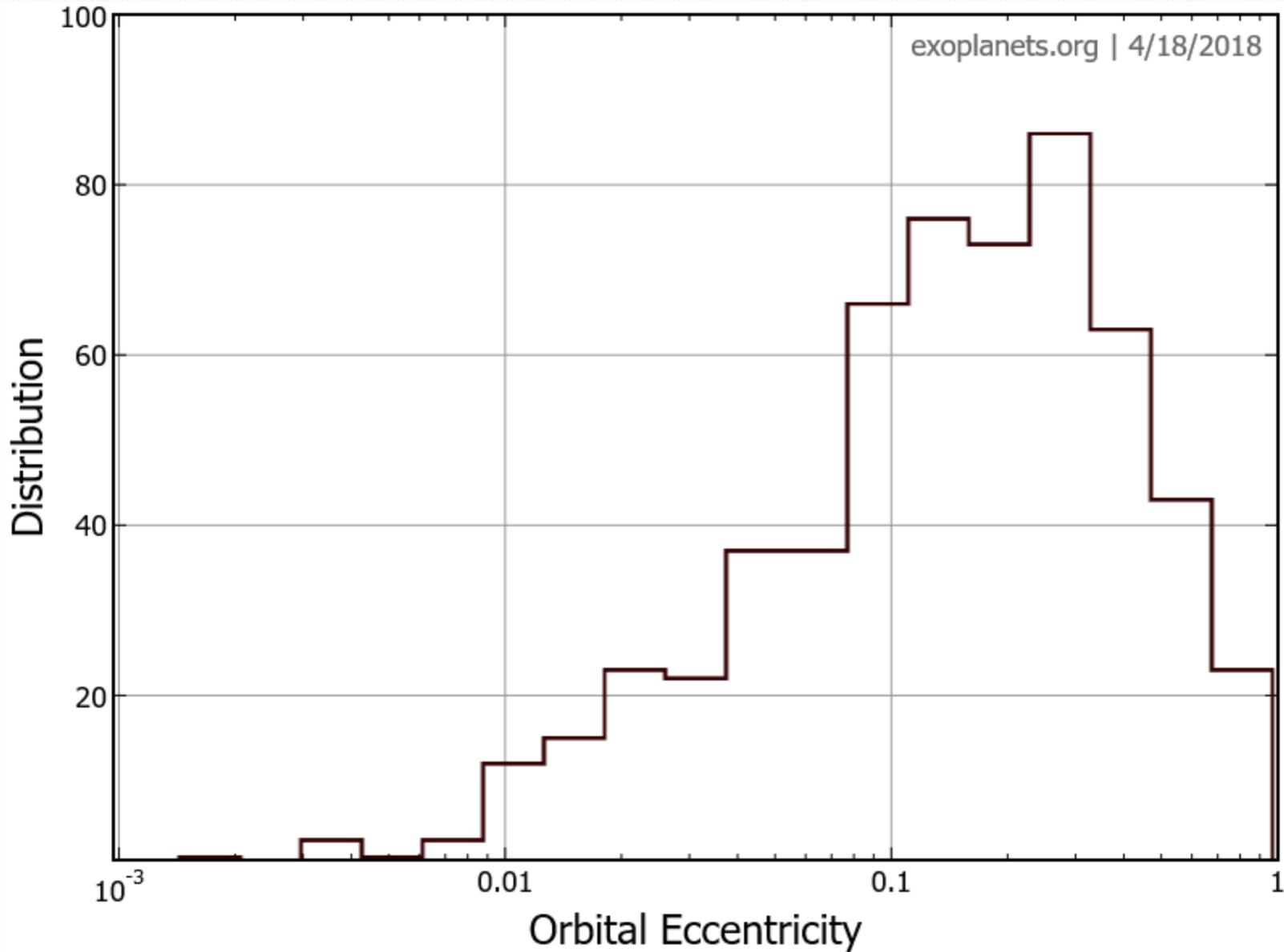
Planetary Habitability Index PHI

Defined as geometric mean of values related to known biological requirements:

substrate *S*, available energy *E*, solvent *L*, chemistry *C* (*Schulze-Makuch et al. '11*).

$$PHI = (S \cdot E \cdot C \cdot L)^{1/4}$$

Range [0-1]: 1 – potentially habitable; 0 – absence of habitability potential

Biological Complexity Index BCI

Evolution of PHI – accessing probability of complex life to appear on exoplanets, using same basic structure of the PHI with addition of age (A) and geophysical complexity (G) (*Irwin et al. 2014*). For lack of information on chemical composition and the existence of liquid water on exoplanets, C&L were removed:

Basic criticism: `They all have no physical meaning' (*Rodríguez-Mozos & Moya 2017*), introducing in turn their own.

$$BCI = (S \cdot E \cdot T \cdot G \cdot A)^{1/5}$$

But if we to perceive habitability as a probabilistic measure, and not a binary concept as in *hab* or *not hab*, or a measure with varying degrees of certainty? The approach requires classification methods that are part of machine learning techniques and convex optimization. We have introduced a new metric: CDHS, where PHI is a special case— *please see a lecture (3rd in this series) by Prof. Saha.*

Superhabitability

Earth may not be the ideal place for life, other places could be more habitable (*Heller & Armstrong, 2014*). Though this concept got rid of a HZ limits, admitting the tidal heating as a possible heat source, it still assumes the necessity of liquid water on the surface as a prerequisite for life, preferably as a shallow ocean with no large continuous land masses.

- Recent simulations showed that too much water is not good: >50 Earth oceans of water will weight down the mantle processes; without molten rock near the surface, there'd no volcanoes; heat-trapping gases like CO_2 won't reach atmosphere; could lead to *runaway snowball* effect (*Unterborn et al. 2018).*

- Even five times Earth's oceans without any exposed land would prevent carbon and phosphorus to enrich the water. There would be no ocean organisms (e.g. plankton) to build up oxygen in the planet's atmosphere.

- Exoplanets without land would have life with much slower biogeochemical cycles and oxygen in the atmosphere would be indistinguishable from the one produced abiogenically (*Desch et al. 2018*).

- On our planet, oceans are called aqueous deserts – most of the sea is almost lifeless – 98% of biomass is on land. Even the sea life tends to concentrate on land/ocean border – nutrients (*Morris 1999*).

All this puts sort of a sign on water planets: The question now shifts to the definition of habitability as our ability to detect it - if we cannot get to the planets which may have life not on the surface, they are as good as uninhabited.

Visible habitability

- Even though atmospheric oxygen appeared about 2.5 Ga, the Earth itself became visibly habitable only about 750-600 Ma, when the biosphere became active and complex enough to modify the environment sufficiently to be noticed from space (e.g. *Mendez et al. 2013*).

- Concepts such as the habitable zone around stars or/and ESI can guide our initial search. All we know is the Earth-based habitability, our search for habitable exoplanets (an Earth-like life clearly favoured by the Earth-like conditions) has to be by necessity anthropocentric, and any such indexing has to be centred around finding Earth-like planets, at least initially.

And this search has already been quite successful!

So, do we have any habitable planets?

- According to the Planetary Habitability Laboratory @UPR Arecibo, there are 53 potentially habitable planets:

Subterran (Mars-size)	Terran (Earth-size)	Superterran (Super-Earth/Mini-Neptunes)	Total
1	22	30	53

So, do we have any habitable planets?

- Actually quite a number, and some not very far away ☺

Earth T_{eq} =254.3 K

Planet	Distance (ly)	Mass (EU)	Age (Gyr)	Host	HZ	T(K)
Proxima Centauri *b*	4.244	1.27	4.85	Mdwarf	Y	229
Kapteyn's *b*	12.8	4.8	~11	Red subdwarf	Y	205
GJ 667C *c*	22	≥3.7	2-10	Mdwarf	Y	247
Luyten's *b*	12	2.89	Me: -0.16	Mdwarf	Yopt	267
Ross 128 *b*	11	≥1.5	9.45	Mdwarf	Yopt	280
Tau Ceti *e*	11.88	3.93	5.8	G8V	Yopt	282
Wolf 1061 *c*	13.82	>3.4	Me: -0.09	Mdwarf	Yopt	276

TRAPPIST-1 system with 7 terrestrial planets. M8 dwarf, 7.6 Gyr, 39 ly (12.1 pc)

c	1.156	almost entirely rocky, may have surface eruptions of silicate magma
d	0.297	appears to have a liquid water ocean comprising about 5% of its mass
e	0.772	terrestrial rock and iron composition

d and e are the most likely to be habitable　　　　(*Grimm et al. 2018*)

M dwarfs

Very close by ->
excellent for follow-up.
Small and faint->
HZ is close to the star ->
relatively large transiting
& RV signals (1m/s for
Proxima b->
good for studies.

Living with a Red Dwarf program NSF/RUI AST-109903
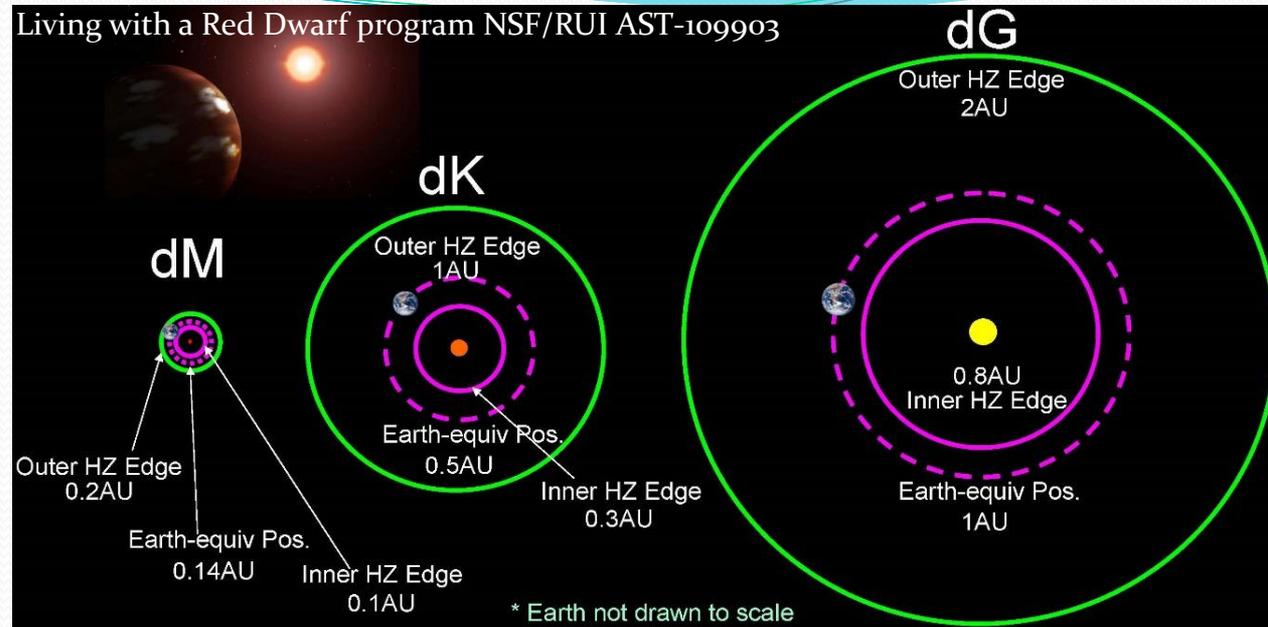
- Can maintain a steady power output for tens of billions of years (high mass dM) to trillions of years (low mass dM).

- Flaring problem can be mitigated by the stronger magnetic field combined with stronger gravity on super-Earths, would allow it to hold onto its atmosphere against stripping by stellar flares.

- For super-Earth with M ~5 ME, R~2 RE, Teq = 300K, orbiting the star with T = 3000 K and R~0.1 SR – an M dwarf – at 10 pc and @λ~10 μm, the flux ratio is much improved (*Safonova et al. 2016*)

$$\frac{F_{\nu}^{pl}}{F_*} = 3.4 \times 10^{-3}$$

THE NEXT FRONTIER

Astronomers now have to figure out what to do with this bonanza of planet discoveries. The research goals for the next two decades include gathering data on what the planets actually look like, from the clouds in their atmospheres to the conditions on their surfaces.

What's next?

GEMINI PLANET IMAGER

This mission is teasing out the heat of planets from that of their host stars, allowing direct measurements of characteristics such as mass, temperature and atmospheric composition.

NEXT-GENERATION TRANSIT SURVEY

An ongoing project to search for exoplanets in Southern Hemisphere skies.

TRANSITING EXOPLANET SURVEY SATELLITE

The spacecraft, set to launch in 2017, will search for rocky worlds around nearby bright stars. Astronomers can then follow up the finds using ground-based telescopes.

Transiting Exoplanet
Survey Satellite

JAMES WEBB SPACE TELESCOPE

Targeted for a 2018 launch, the telescope will measure planetary atmospheres in infrared wavelengths to probe their chemical compositions.

James Webb
Space Telescope

PLATO

The space observatory, set to begin operating in 2024, will search for Earth-like worlds in the habitable zones of up to 1 million stars.
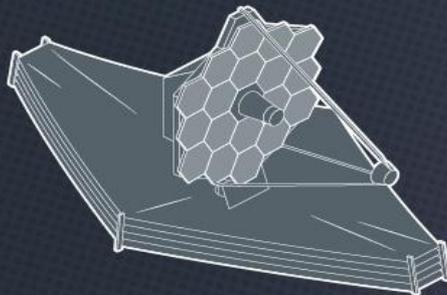
© Nature

Great News!

Transiting Exoplanet Survey Satellite (TESS) launched on 18 April into highly elliptical orbit with 373,000 km apogee. TESS will survey the entire sky over the course of two years, but mostly will study 200,000 of the stars around the Sun. It will create a catalogue of, hopefully, thousands new exoplanet candidates using the transit photometry method.

Prerequisites for habitability… absolute

- Substrate: rocky composition planet/moon, or least with a rocky/metal core – can't yet imagine a life on Neptune ☺
- Source of energy
  - Host star as a source of energy/
  - Host giant planet inducing tidal stresses
  - Internal radioactivity for free-floating planets
- Medium supplying nutrients
  - Water on the surface (only 5.2% of total Earth supply)
  - Subsurface water, or locked in rocks/aquifers
  - Other liquid (liquid hydrocarbons)
  - Atmosphere
- Protective medium against cosmic/stellar radiation/impacts
  - Magnetic field
  - Layer of ice

What to look for?

Detecting a biosignature is the second step to determining the habitability potential of an exoplanet. A biosignature, or biomarker, is any substance, group of substances, or phenomenon that provides evidence of life.

Look for atmosphere, and gas species such as water, ozone, O_2, CO_2 …

Surface water reflections

Day/night variations of concentrations of gases, illumination

Even pollution

Please see next lecture (2nd in this series) of Prof. Sivaram on Biosignatures and Astrochemistry

Extremophiles

Life *as we know it* has evolved strategies that allow it to survive beyond normal parameters of usual existence.

- To survive, *known* organisms can assume forms that enable them to withstand freezing, desiccation, starvation, high levels of radiation exposure, other physical & chemical challenges. They can survive exposure to such conditions for years, or even centuries.

- But these *extremophiles* are still terrestrial – recorded and counted on one planet with exactly terrestrial conditions: 1 EM, 1 ER, at right distance from the star, with liquid water on the surface and *right* atmosphere. We don't know if these extreme forms, once placed on the Moon, for example, start active life and develop a habitat for themselves. They may survive, albeit in the same dormant form. But that is *not* habitability!

We should think outside the box to really find life as we do not know it!

Acknowledgments

- Extrasolar Planets Encyclopaedia http://www.exoplanet.eu

- Exoplanets Data Explorer http://exoplanets.org

- Exoplanet Exploration Program
  https://exoplanets.nasa.gov/exep/

- NASA Exoplanet Archive
  http://exoplanetarchive.ipac.caltech.edu

- NASA Planetary Fact Sheet
  https://nssdc.gsfc.nasa.gov/planetary/factsheet/

- Planetary Habitability Laboratory, U. Puerto Rico, Arecibo
  http://phl.upr.edu/

Bibliography

- Sivaram, C. 1986. *The angular momentum of the asteroids.* Earth, Moon, and Planets, 34:231
- Lineweaver, C. H., & Norman, M. 2010. *The Potato Radius: a Lower Minimum Size for Dwarf Planet.* arXiv:1004.1091
- Gerald Schubert et al. 2006. *Enceladus: Present internal structure and differentiation by early and long-term radiogenic heating.* Icarus, 188:345
- Massey, P. & Meyer, M. 2001. *Stellar Masses, in* Encyclopedia of Astronomy and Astrophysics, 1882
- Hatzes, A.~P., & Rauer, H. 2015. *A Definition for Giant Planets Based on the Mass-Density Relationship.* APJL, 810, L25
- Chen, J., & Kipping, D. 2016. *Probabilistic Forecasting of the Masses and Radii of Other Worlds.* ApJ, 834:17
- John Southworth. 2011. *TEPCat: catalogue of the physical properties of transiting planetary systems.* MNRAS. 417.2166S
- Strigari, L. E., et al. 2012. *Nomads of the Galaxy.* MNRAS, 423:1856
- Cassan, A., Kuhas, D., Beaulieu, J. P., etal. 2012. *One or more bound planets per Milky Way star from microlensing observations.* Nature, 481:167
- E. A. Petigura, A. W. Howard, G. W. Marcy. 2013. *Prevalence of Earth-size planets orbiting Sun-like stars.* PNAS, 110:19175
- Hatzes, A. P., et al. 2003. *A Planetary Companion to Gamma Cephei A.* ApJ, 599: 1383
- Mayer, L., T. Quinn, et al. 2002. *Formation of giant planets by fragmentation of protoplanetary disks.* Science, 298:1756.
- Melis, C. et al. 2012. *Rapid disappearance of a warm, dusty circumstellar disk.* Nature, 487:74
- A. Wolszczan & D. A. Frail. 1992. *A planetary system around the millisecond pulsar PSR1257+12.* Nature, 355:145

Bibliography

- M. E. Beer, A. R. King, J. E. Pringle. 2004. *The planet in M4: implications for planet formation in globular clusters.* MNRAS, 355:1244

- O. M. Guilera & Zs. Sándor. 2017. *Giant planet formation at the pressure maxima of protoplanetary disks.* A&A, 604:A10

- Binney, J. & Tremaine, S. 1987. *Galactic dynamics.* Princeton, NJ, Princeton University Press

- Windmark e t al. 2012. *Planetesimal formation by sweep-up: how the bouncing barrier can be beneficial to growth.* A&A, 540:A7

- S. Dado, A. Dar & E. N. Ribak. 2011. *Misaligned And Alien Planets From Explosive Death Of Stars.* arXiv:1102.2622v2

- Shchekinov, Y. A., Safonova, M. & Murthy, J. 2013. *Planets in the early Universe.* ApSS, 346:31

- S. S. Limaye, et al. 2018. *Venus' Spectral Signatures and the Potential for Life in the Clouds.* Astrobiology, doi:10.1089/ast.2017.1783

- C. P. Endres et al. 2016. *The Cologne Database for Molecular Spectroscopy, CDMS, in the Virtual Atomic and Molecular Data Centre, VAMDC.* J. Mol. Spectrosc. 327:95

- C. H. Gibson, R.E. Schild & N.C. Wickramasinghe. 2010. *The origin of life from primordial planets.* Int. J. Astrobiology, doi:10.1017/S1473550410000352

- A. Loeb. 2014. *The habitable epoch of the early Universe.* Int. J. Astrobiology, *13: 337*

- Latham, D.W. et al. 1989. *The unseen companion of HD114762 - A probable brown dwarf.* Nature, 339:38

- Dicke, R. H. 1961. *Dirac's Cosmology and Mach's Principle.* Nature, 192, 440

- M. Safonova, Yu. Shchekinov & J. Murthy. 2016. *Age Aspects of Habitability.* Int. J. Astrobiology, 15:93

- Kasting, J. F., Whitmire, D. P. & Reynolds, R. T. 1993. *Habitable zones around main sequence stars.* Icarus, 101:108.

- S. R. Kane & D. M. Gelino. 2012. *The Habitable Zone Gallery.* PASP, 124:914.

- C. T. Unterborn, et al. 2018. *Inward migration of the TRAPPIST-1 planets as inferred from their water-rich composition.* Nature Astronomy, **2**:297

- Méndez, A., González, Z., Jimenez, S. A. Pérez, W., Bracero, K. 2013. *The Visible Paleo-Earth Project: A look from space to the evolution of a habitable planet.* [PHL @UPR Arecibo]

Bibliography

- Grimm, S. L., Demory, B., Gillon, M. et al. 2018. *The nature of the TRAPPIST-1 exoplanets.* Astronomy & Astrophysics. doi:10.1051/0004-6361/201732233

- Jagadeesh, M., Gudennavar, S., Doshi, U. & Safonova, Margarita. 2017. *Indexing of exoplanets in search for potential habitability: application to Mars-like worlds.* Astrophysics and Space Science. 362. 10.1007/s10509-017-3131-y.

- L. N. Irwin, A. Méndez, A. G. Fairén & D. Schulze-Makuch. 2014. *Assessing the Possibility of Biological Complexity on Other Worlds, with an Estimate of the Occurrence of Complex Life in the Milky Way Galaxy.* Challenges, 5:159

- J. M. Rodríguez-Mozos & A. Moya. 2017. *Statistical-likelihood Exo-Planetary Habitability Index (SEPHI). MNRAS, 471:4628*

References to Techniques

- Christophe Lovis & Debra A. Fischer. *Radial Velocity*

http://exoplanets.astro.yale.edu/workshop/EPRV/Bibliography_files/Radial_Velocity.pdf

- Kelsey I. Clubb. *A detailed derivation of The Radial Velocity Equation*

http://relativitycalculator.com/pdfs/RV_Derivation.pdf

- Michael Richmond. *Field Guide to Extrasolar Planets Course*

http://spiff.rit.edu/classes/resceu/resceu.html

Anthropic principle(s)

- **weak anthropic principle:** if our Universe weren't hospitable to life, then we wouldn't be here to wonder about it. As such, there's no sense in asking why.

- **strong anthropic principle:** since we live in a universe capable of supporting life, then only life-supporting universes are possible.

- Some 30 others…

- **participatory anthropic principle**: no universe can be real until it is observed.

- **final anthropic principle**: intelligence is a necessary property of the Universe; once created it can never be destroyed.

Alien life already here?

- Nuclear energy life.

Bacterium *Desulforudis audaxviator* thrives 3 km under the ground in groundwater at temperatures up to 60^0C. No sunlight, oxygen or organic compounds. Derives its energy from the radioactive decay of uranium in the rocks. The uranium breaks down the water molecules to produce free radicals. The free radicals `attack' the surrounding rocks, especially pyrite, producing sulfate. The bacteria use the sulfate to synthesise ATP. The ecosystem survives directly on the basis of nuclear energy.

Thiago Altair et al. 2018. Microbial habitability of Europa sustained by radioactive sources. Scientific Reports 8, Article number: 260. doi:10.1038/s41598-017-18470-z

Multicellular life that doesn't need O_2

Three new multicellular marine species that appear to have never lived in aerobic conditions, and never metabolized oxygen were discovered in sediment basin 3 km under the Mediterranean seafloor — the first observation of multicellular organisms, or metazoans, that spend their entire lifecycle under permanently anoxic conditions. Belong to the animal phylum *Loricifera* (less than 1 mm length), typically live in sediment.
The three new organisms belong to different genera (*Spinoloricus*, *Rugiloricus*, and *Pliciloricus*).

Live in deep hypersaline anoxic basin rich in methane and hydrogen sulphide. New species do not have mitochondria; they have organelles that resemble hydrogenosomes.

Roberto Danovaro, et al. The first metazoa living in permanently anoxic conditions. BMC Biology 2010, 8:30 doi:10.1186/1741-7007-8-30

- Bacteria living on pure electricity

- 1987. The microbes, called *Geobacter metallireducens*, were getting their electrons from organic compounds, and passing them onto iron oxides. In other words they were eating waste – including ethanol – and effectively "breathing" iron instead of oxygen. They do this through special hair-like wires that protrude from the cell's surface. These tiny wires act in much in the same way that copper wire does when it conducts electricity. They have been dubbed "microbial nanowires". *D. R. Lovley et al. 1987. Anaerobic production of magnetite by a dissimilatory iron-reducing microorganism. Nature, 330:252*

- Many more electron-loving bacteria have now been found. In fact all you have to do is stick an electrode in the ground and pass electrons down it, and soon the electrode will be coated with feeding bacteria. *Rowe A.R. et al. 2015. Marine sediments microbes capable of electrode oxidation as a surrogate for lithotrophic insoluble substrate metabolism. Front. Microbiol.*

  doi.org/10.3389/fmicb.2014.00784

   In fact, there's more ....

Shadow Biosphere

 Paul Davies introduced the idea of the alternative life on contemporary Earth. Alternative life could have emerged before the advent of life as we know it only to be outcompeted by familiar life, or it can/could have co-existed with familiar life. Despite diversity, all known life is biochemically similar (same 20 amino acids and 4 bases; but there are >100 amino acids and ~dozen bases in nature). Though, according to recent research, the current estimate for the number of species on Earth is ~8.75 million. Among these species, only ~14% on land and ~9% in the ocean have been catalogued (*Mora et al. 2011*). Of all varieties of microbes less than 1% is identified (*Davies et al.'09*).

This life can be based on different biochemistry and we do not see it because we do not know what to look for. Plausible example:

Desert varnish: an orange-yellow to black coating found on exposed rock surfaces in arid environments. There are even signs of it on Mars (e.g. *Lanza et al. 2014*).

- *Davies, P. C. W., Benner, Steven A., Cleland, Carol E., et al. 2009, Signatures of a shadow biosphere, Astrobiology, 9, 241- 249.*
- *Mora C, Tittensor D.P., Adl S., Simpson A.G.B, Worm B. 2011, How Many Species Are There On Earth and in the Ocean? PLoS Biol 9(8): e1001127. https://doi.org/10.1371/journal.pbio.1001127*
- *N. L. Lanza et al., 2014. Manganese Trends with Depth on Rock Surface in Gale Crater, Mars. 45th Lunar and Planetary Science Conference, Texas.*