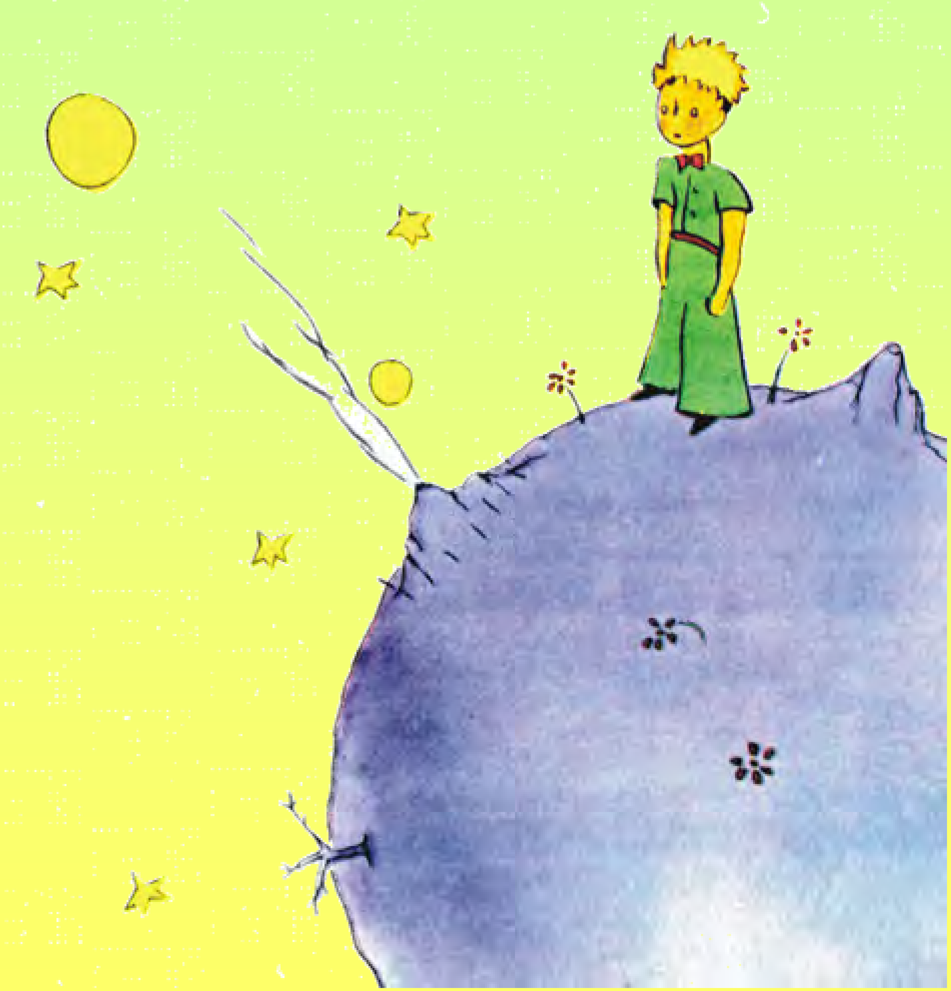
HABITABLE ZONES IN EXTRASOLAR PLANETARY SYSTEMS: THE SEARCH FOR A SECOND EARTH



Siegfried Franck

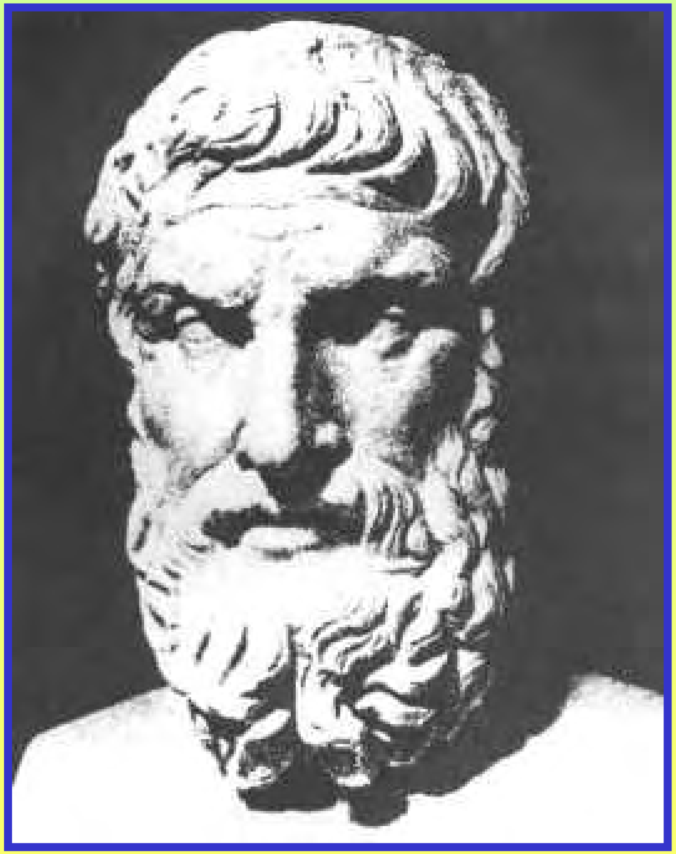
P I K

Potsdam Institute for Climate Impact Research

THE FIRST SUMMER SCHOOL IN ASTRONOMY AND GEOPHYSICS, BELGRADE, 6.8.-10.8.07

HAMANGIA

Already known?



„Es gibt unendlich viele Welten,
sowohl dieser Welt ähnliche,
wie auch von ihr verschiedene.
... Wir müssen annehmen dass es
in allen Welten lebende Geschöpfe
gibt, und Planeten, und andere Dinge
die wir in dieser Welt sehen.“

Epikur, griechischer Philosoph (um 300 v. Chr.)

The 16th century – the (first) Copernican revolution

Nicolaus Copernicus
De revolutionibus orbium caelestium
The Earth is *not* the centre of the Universe.

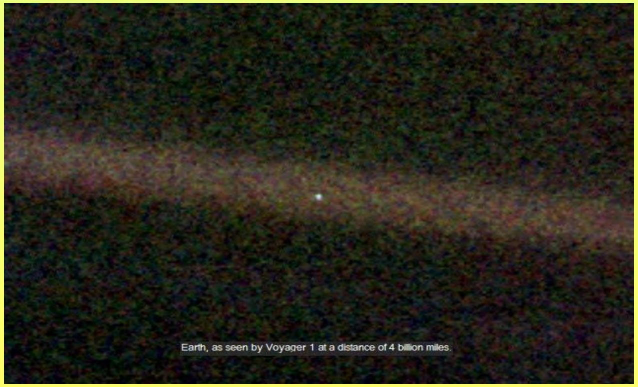
- Late 1500: Tycho Brahe – Precise measurements of stellar planetary positions
- Johannes Kepler (1609) – Planets on elliptical Orbits
- Giordano Bruno – Stars in the sky are Suns like our own
  This was too much! – He was burned at the stake in Rome (1600)

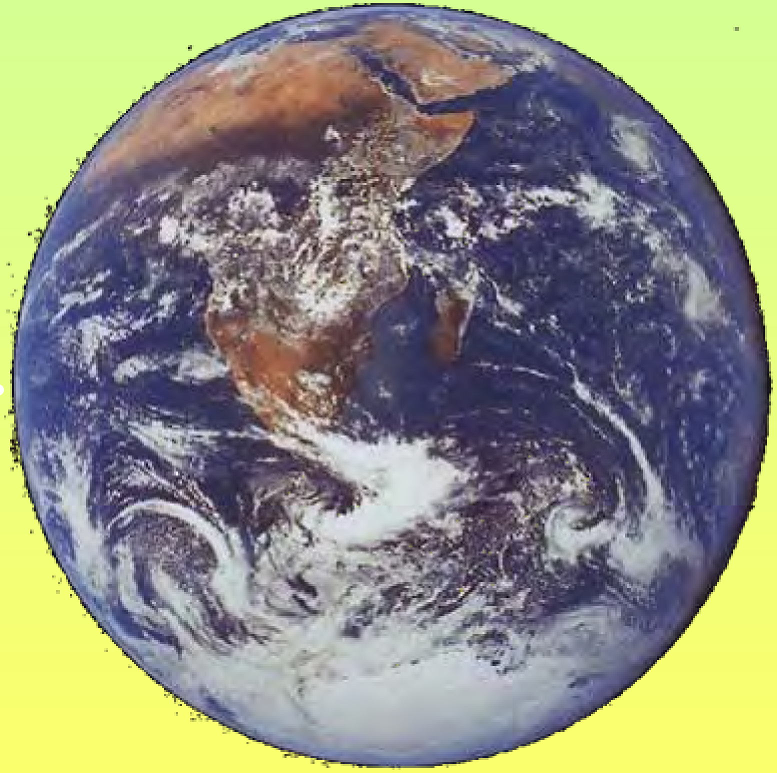
„Es gibt zahllose Sonnen und zahllose Erden, die alle ihre Sonnen umlaufen, genau in der Weise, wie die Planeten unseres Systems unsere Sonne umlaufen. Wir sehen nur die Sonnen, denn sie sind die größten Körper, und sie leuchten selbst. Aber ihre Planeten bleiben für uns unsichtbar, denn sie sind kleiner und erzeugen kein eigenes Licht. Die zahllosen Welten im Kosmos sind nicht schlechter und nicht weniger bewohnt als unsere Erde.“

Giordano Bruno, neuzeitlicher Denker (1548 - 1600)

Are we alone in the universe?

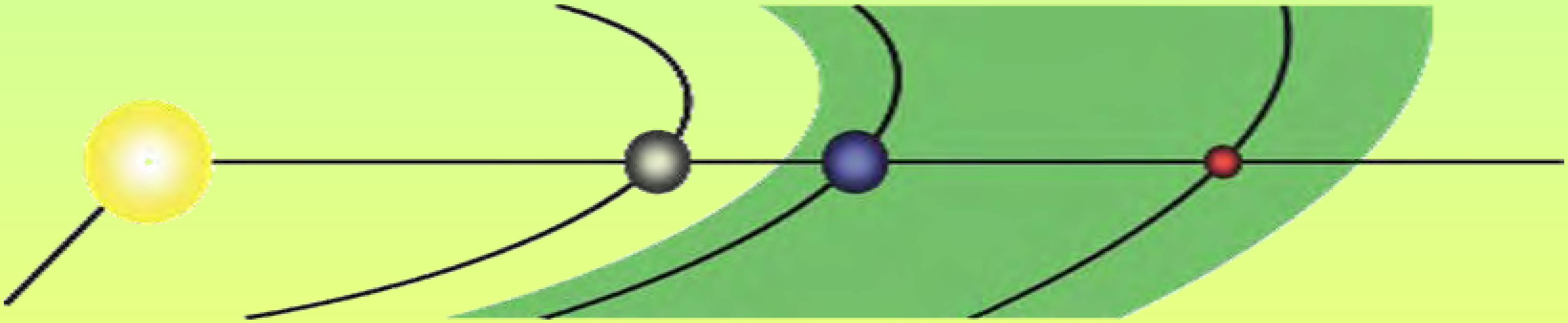
In order to answer this qestion we have to understand how the Earth system operates…





Earth seen from Voyager 1 at distance of 4 bill. miles

HABITABLE ZONES



The range of distances around a central star at which Earth-like planets maintain conditions sufficient for the existence of life at the surface.

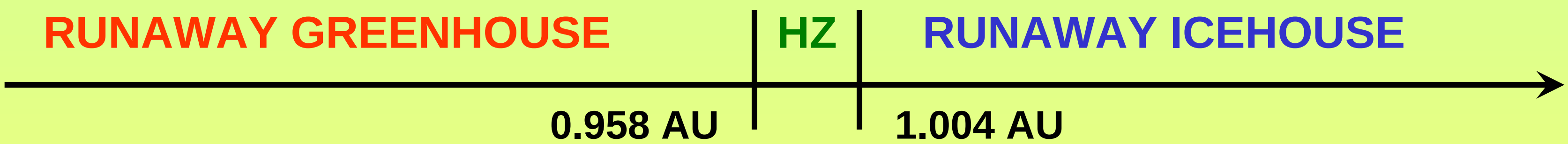
First publications:

Huang (1959, 1960), Dole (1964), Shklovski & Sagan (1966)

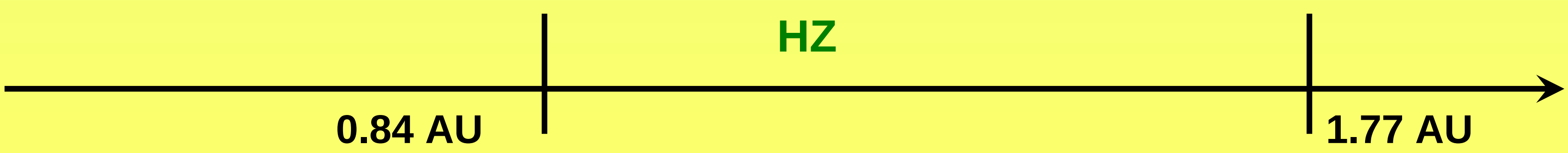
HABITABLE ZONES

First numerical model for the HZ:

Hart (1978,1979)

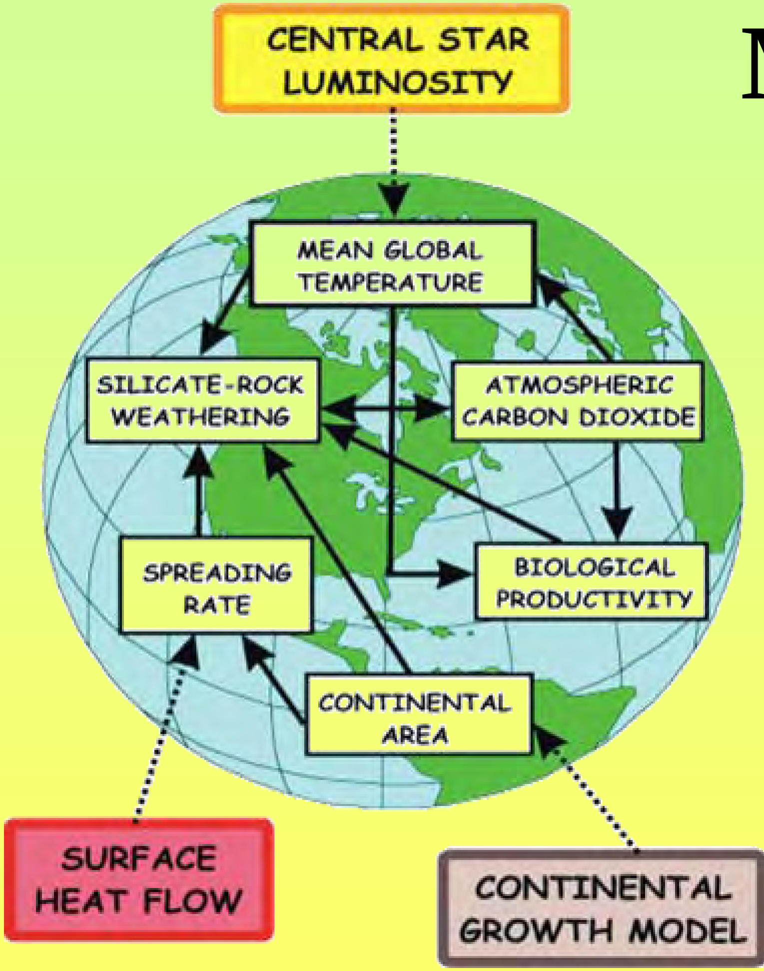


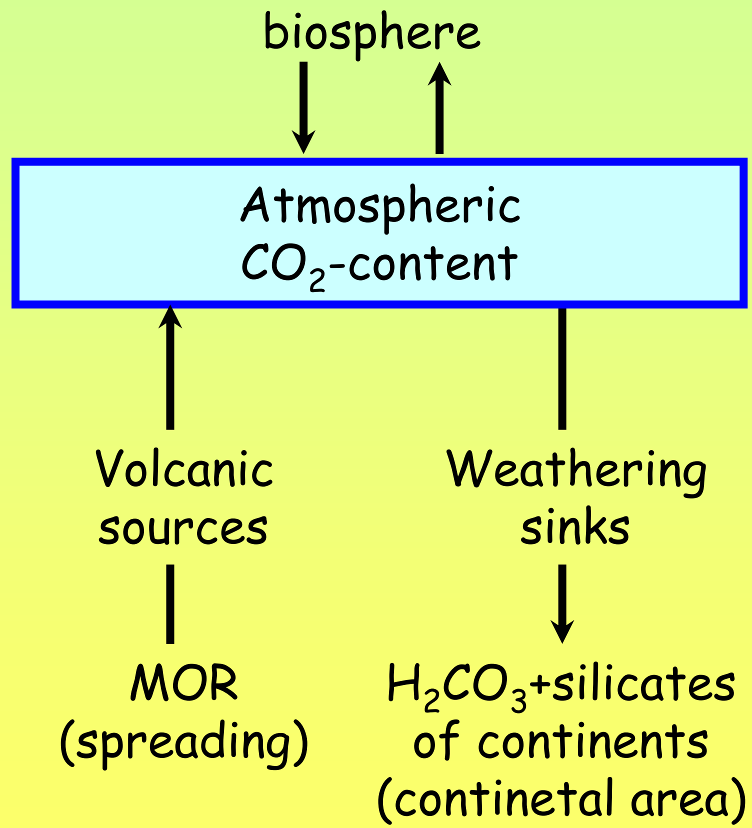
Kasting et al. (1988,1993): Implementation of a negative feedback mechanism between the atmospheric CO_2-content and the mean global surface temperature



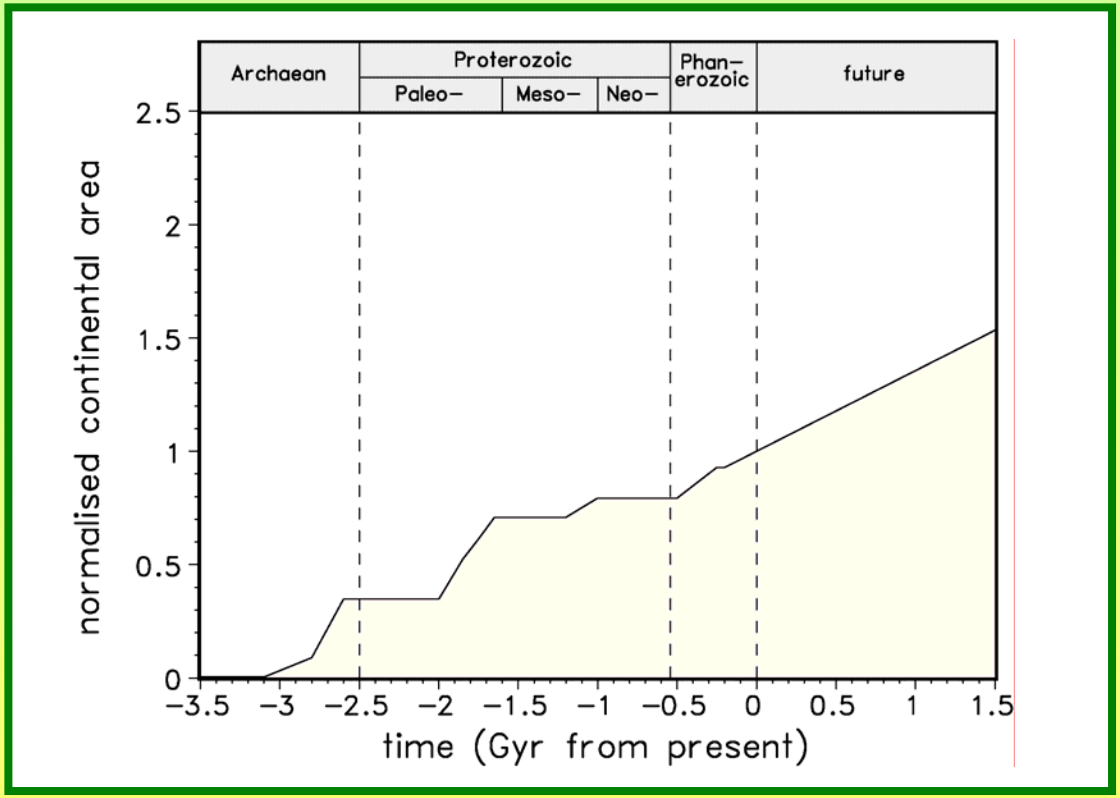
INTEGRATED SYSTEM APPROACH

SIMPLE EARTH SYSTEM MODEL



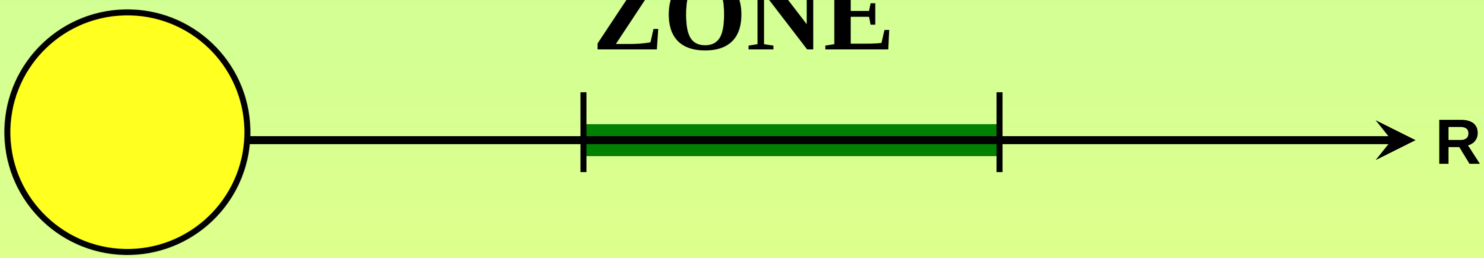


THE CONTINENTAL GROWTH MODEL



Cumulative continental growth model derived from the best studied region, North America and Europe, according to Condie (1990). Note that crustal growth had two major pulses in the Archaean and Proterozoic. The continental area $A_c(t)$ is normalised to the present value $A_{c,0}$. Future values are estimated by linear extrapolation.

DEFINITION OF HABITABLE ZONE



$$HZ := \{R \mid \Pi(P_{atm}(R,t), T_s(R,t)) > 0\}$$

$$\Pi = \Pi_{max}\left(1 - \left(\frac{T_s - 50°C}{50°C}\right)^2\right)\left(\frac{P_{atm} - P_{min}}{P_{1/2} + (P_{atm} - P_{min})}\right)$$

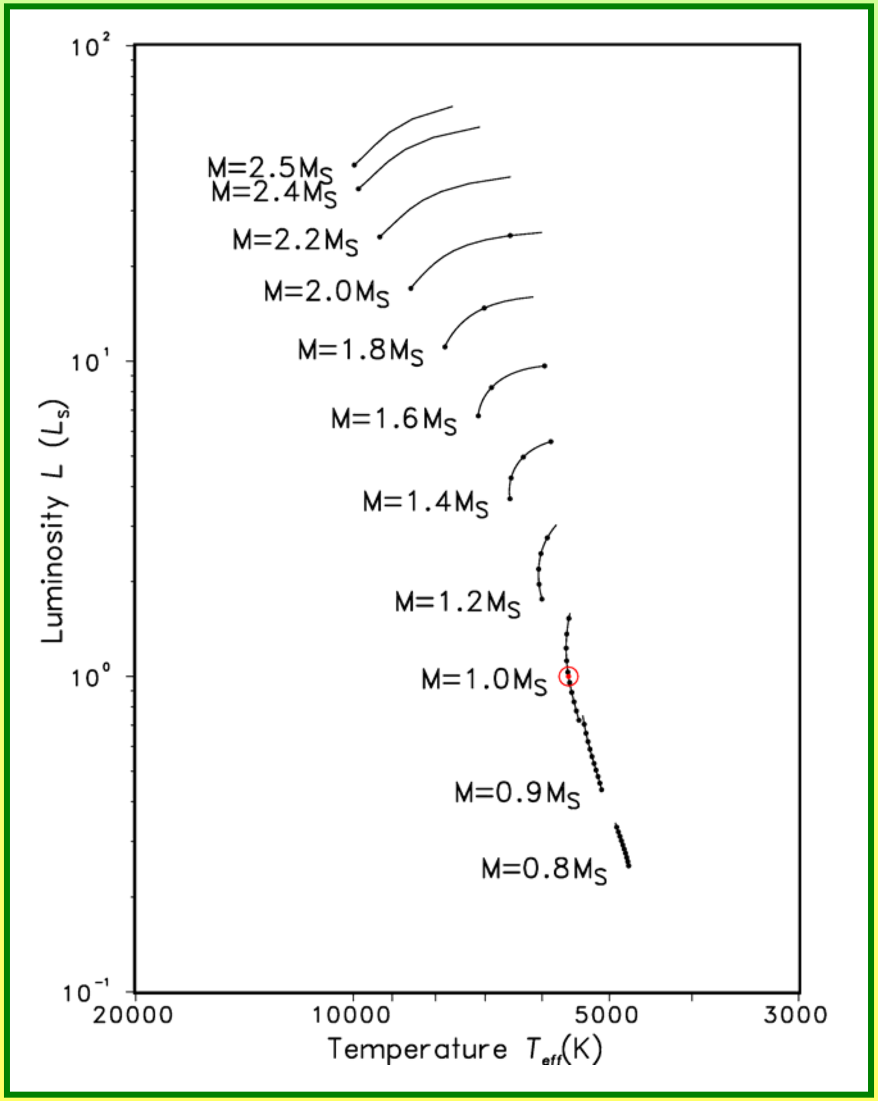
Temperature interval: [0°C, 100°C]

P_{min}: 10^{-5} bar

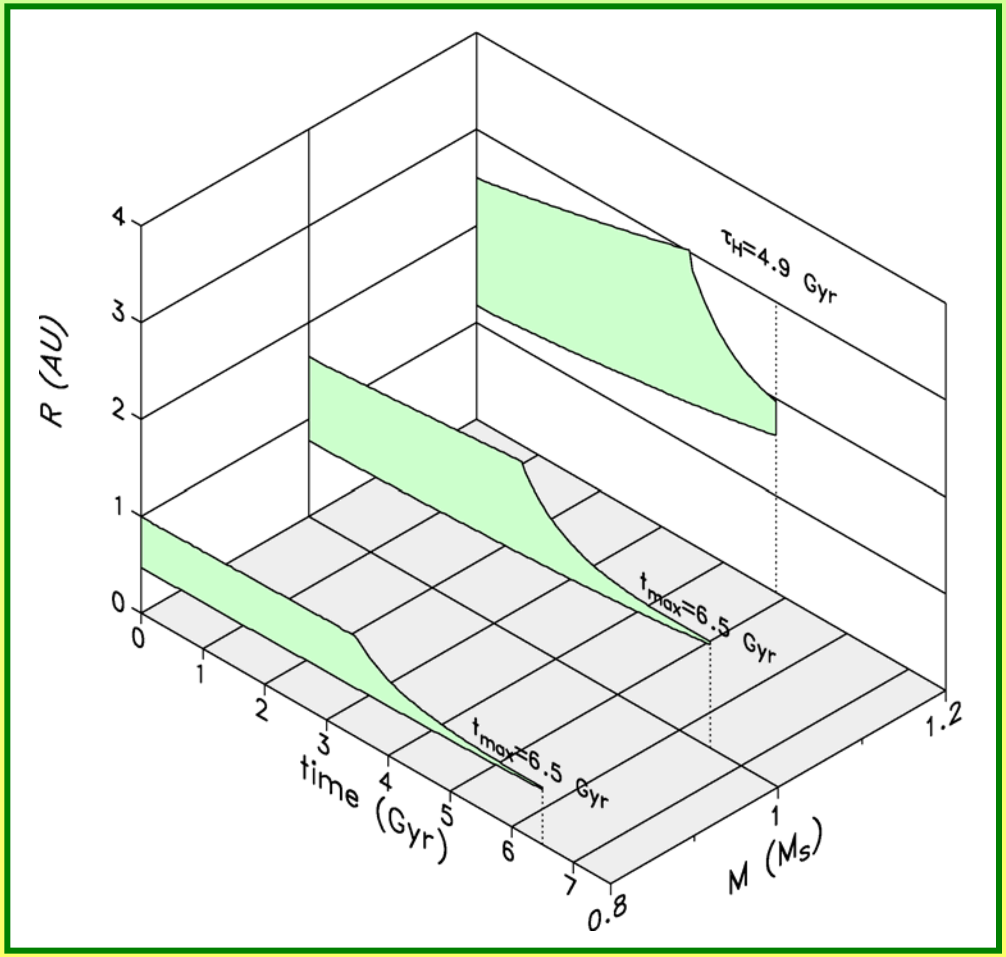
P_{max}: 10 bar

NATURWISSENSCHAFTEN

HERTZSPRUNG-RUSSELL-DIAGRAM

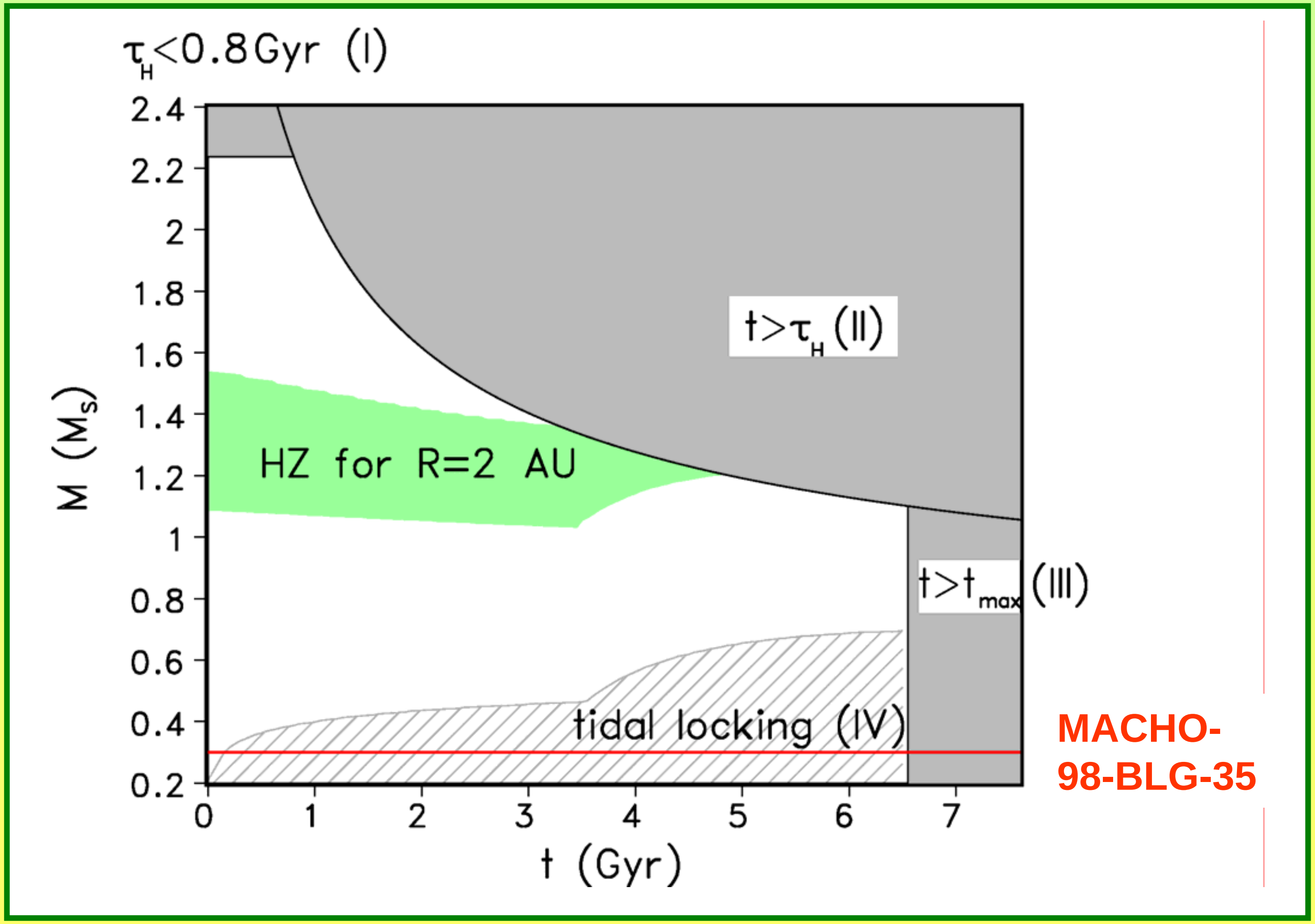


HZ FOR DIFFERENT CENTRAL STAR MASSES



Franck S., Block A., von Bloh W., Bounama C., Steffen M., Schönberner D., Schellnhuber H.-J. 2000: Determination of habitable zones in extrasolar planetary systems: where are Gaia's sisters? JGR-Planets 105(E1), 1651-1658.

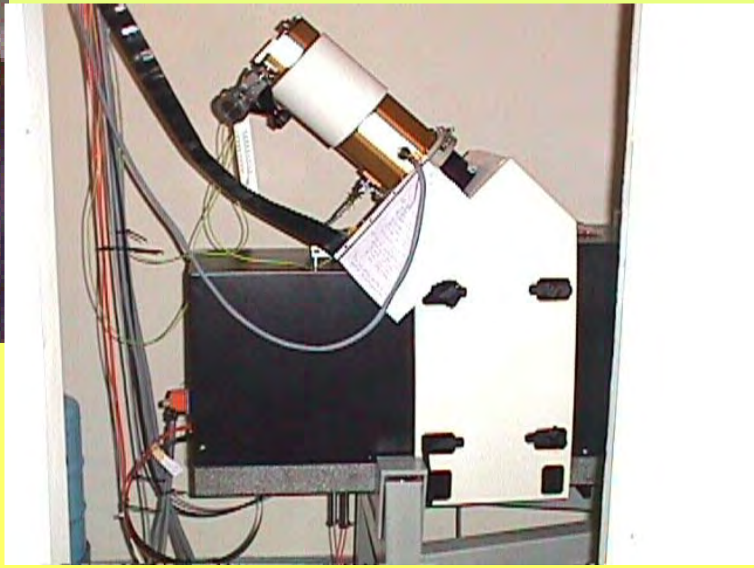
POTENTIAL OVERALL DOMAIN FOR HZ



Extrasolar planets: First detection

Michel Mayor
Didier Queloz
(Observatorium Genf)

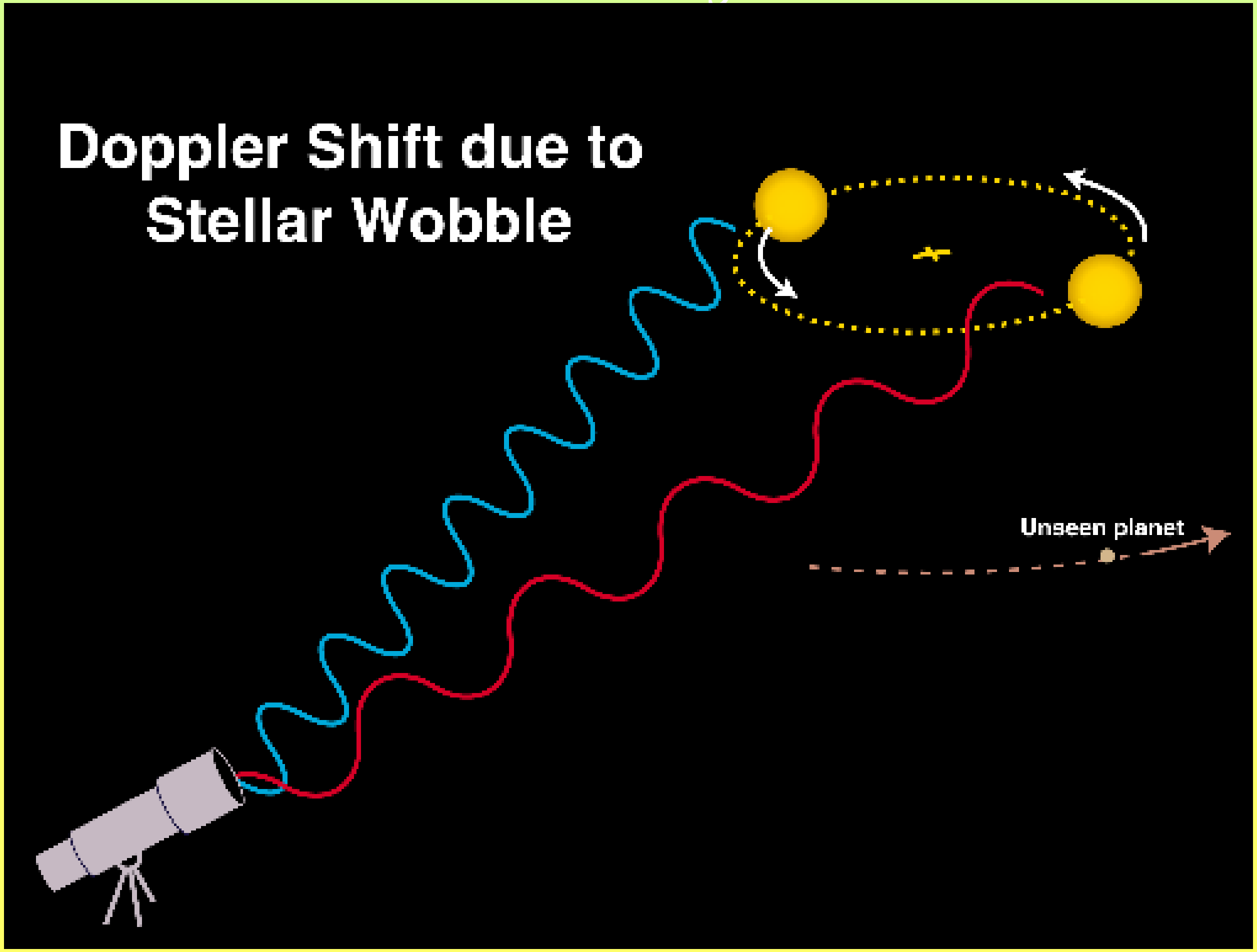
6.10.1995



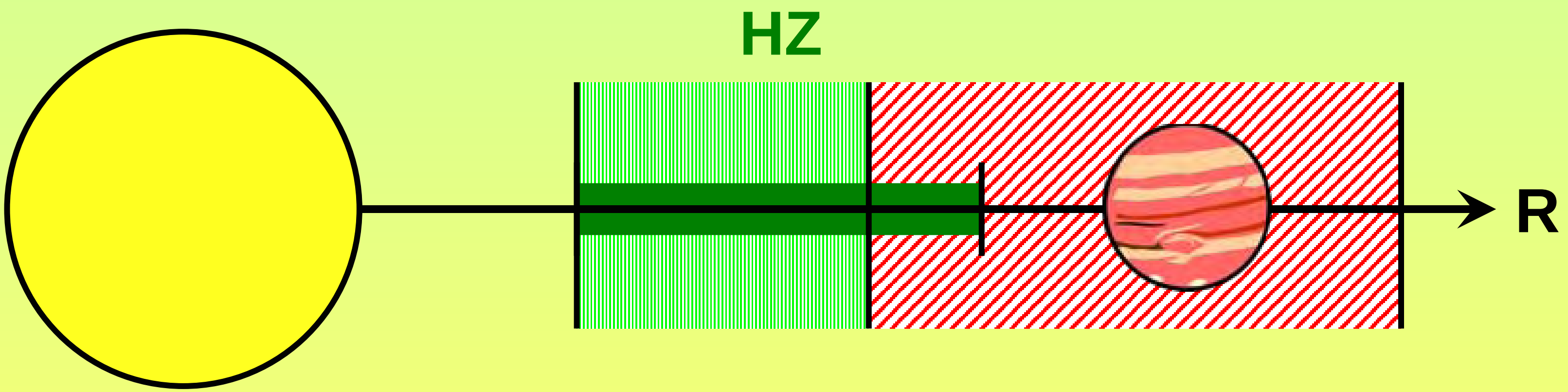
First detection of an extrasolar planet around a main-sequence star:
51 Pegasi

Detection method

Radial velocity method



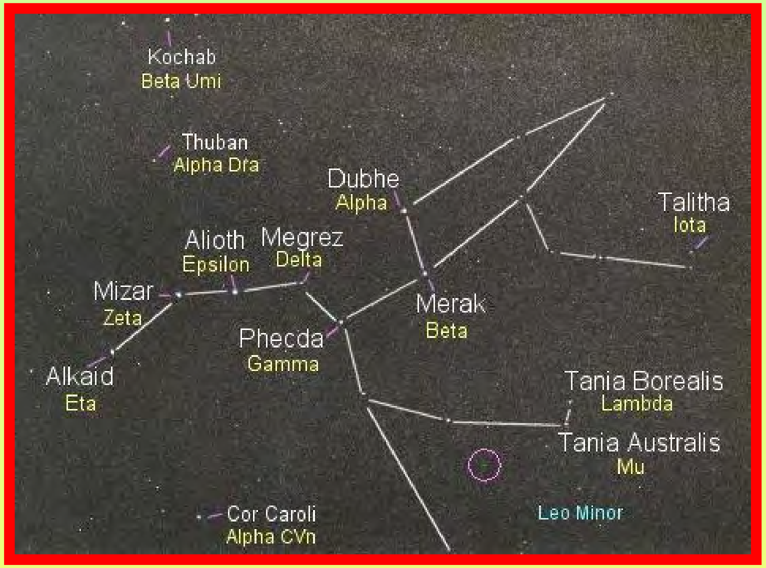
DEFINITION OF HZ & DYNAMICAL HZ

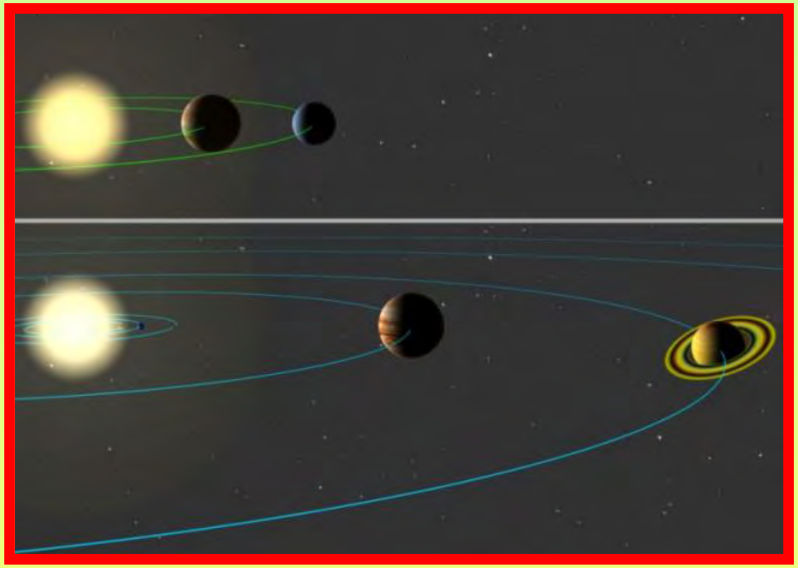


Dynamical HZ

Unstable orbits due to a giant planet

THE EXOPLANETARY SYSTEM 47 UMa





The star 47 Ursae Majoris

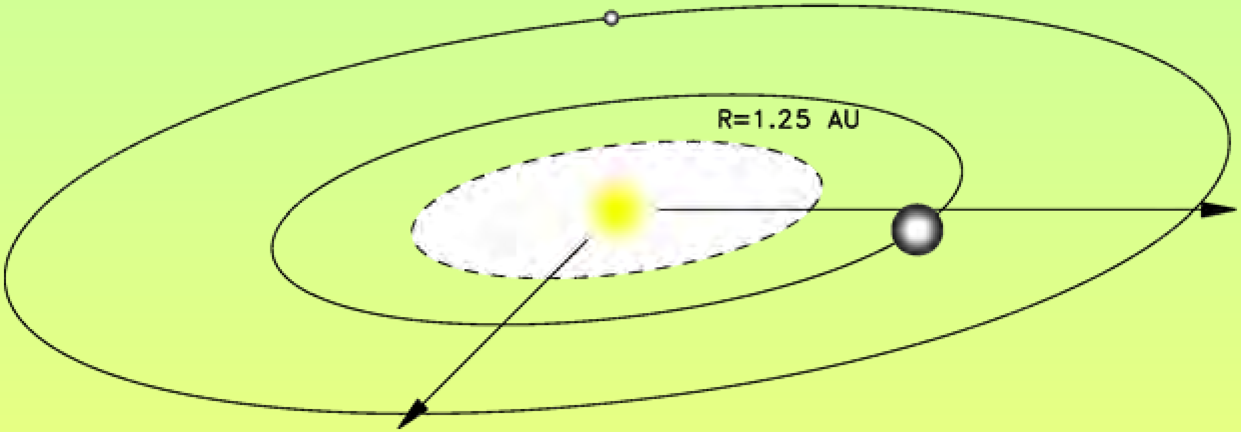
Spectral class: G0V
Typ: Yellow dwarf (main sequence)
Distance: 45 lightyears
Luminosity: 1.54 L_{solar} (± 0.13)
Mass: 1.03 Solar masses
Age: 6.32 Gyr (+1.2, –1.0)

Discovered giant planets

47 UMa b: 1996
2.54 Jupiter masses
2.09 AU

47 UMa c: 2002
0.76 Jupiter masses
3.73 AU

DYNAMICAL HABITABILITY



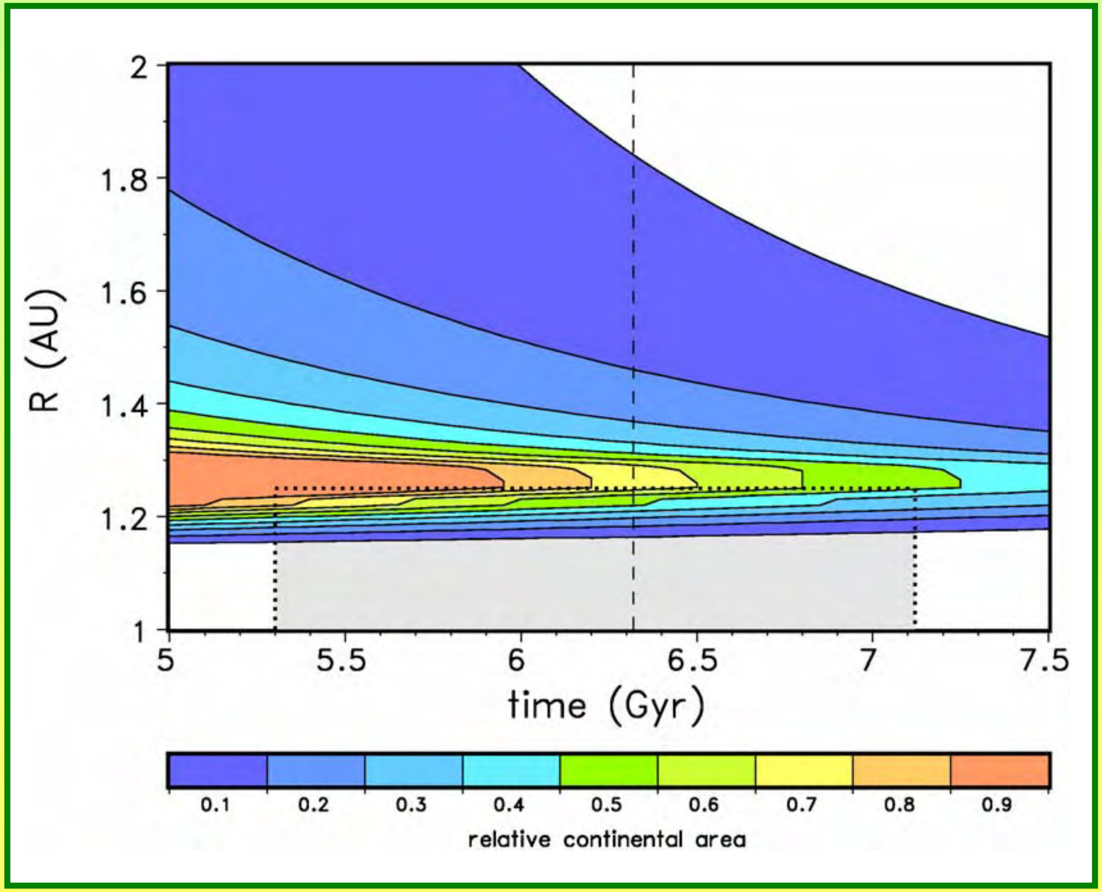
Jones et al. (2001, 2002, 2003)
MVS (Mixed Variable Symplectic Integration Method)
R_{out} ~ 1.32 AU

Gozdziewski (2002)
MEGNO (Mean Exponential Growth Factor of Nearby Orbits)
R_{out} ~ 1.30 AU

Noble et al. (2002)
R_{out} ~ 1.25 AU

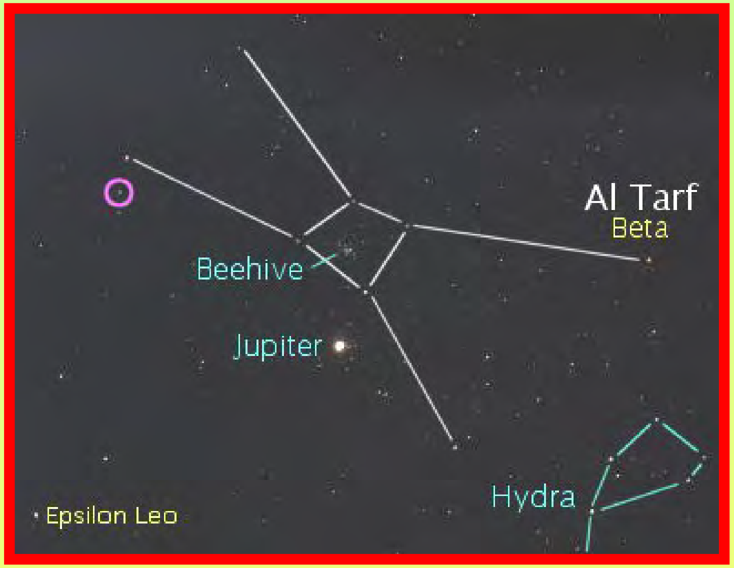
Asghari et al. (2004)
Lie-Series-Integration
R_{out} ~ 1.30 AU

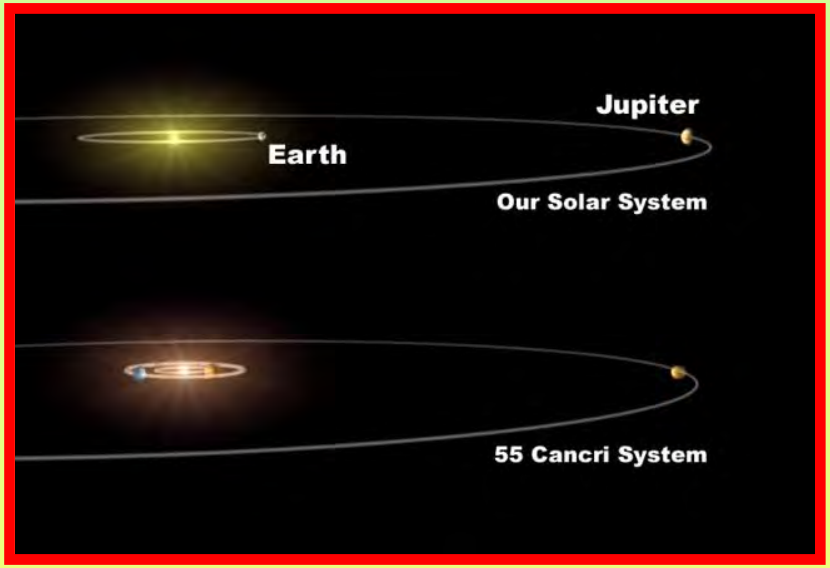
DYNAMICAL HABITABILITY OF 47 UMa



- Principle possibility of Earth-like habitable planets on stable orbits
- „Water worlds“ are favoured
- Planet Earth (=„water world“) would be dynamically habitable at about 1.2 AU

THE EXOPLANETARY SYSTEM 55 Cnc





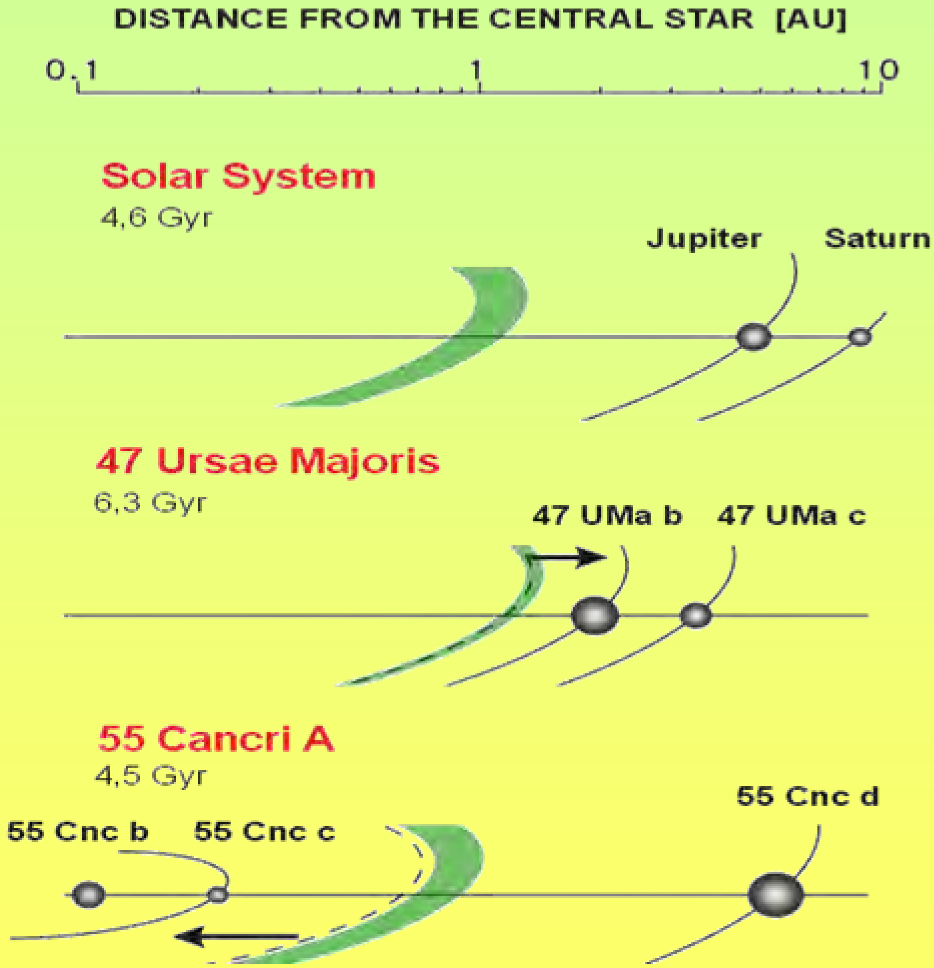
The star 55 Cancri

Spectral class: G8V
Typ: Yellow dwarf (main sequence)
Distance: 41 lightyears
Luminosity: 0.61 L_{solar}
Mass: 0.95 Solar masses
Age: 4.5 Gyr (+1.0, –1.0)

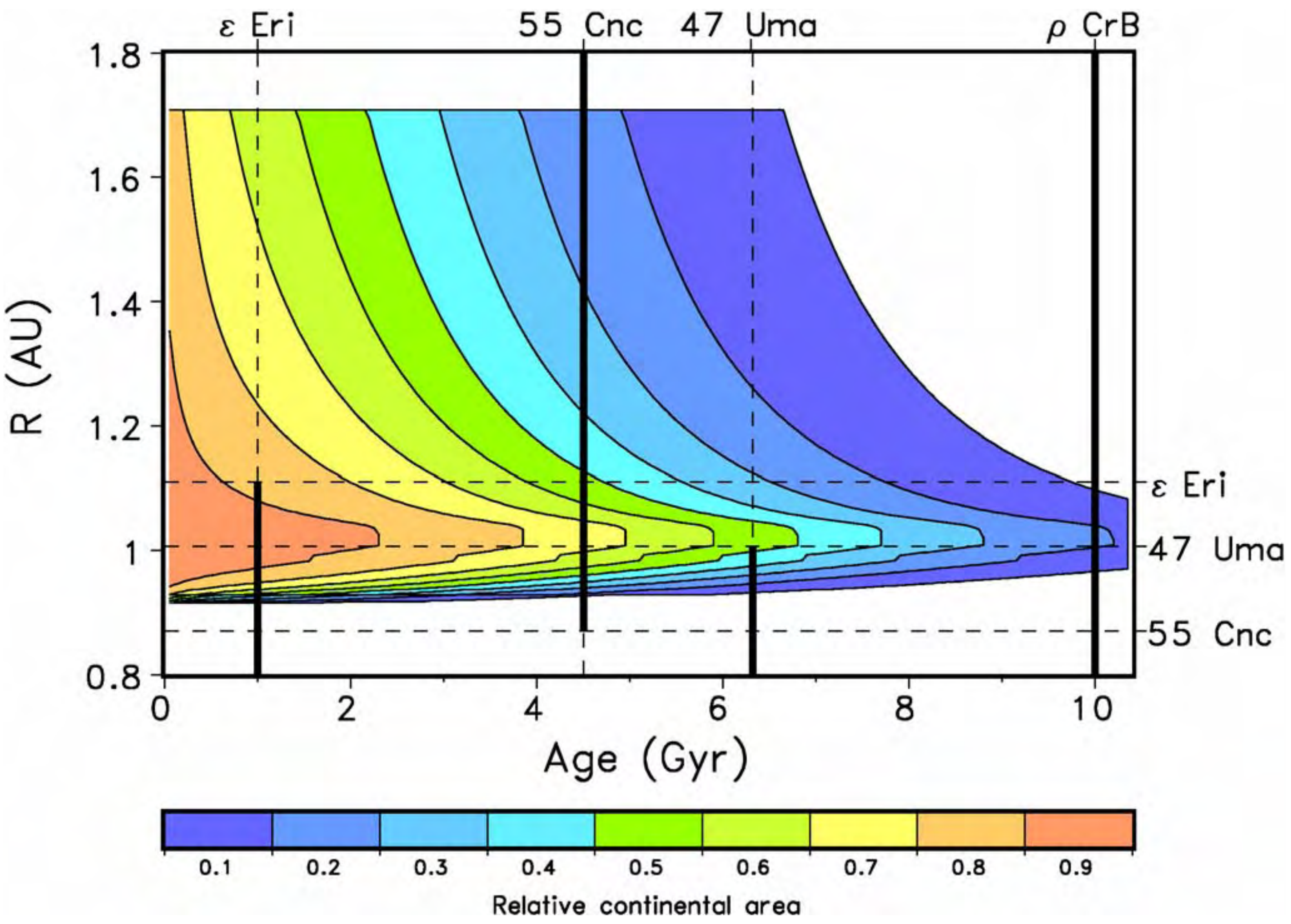
Discovered giant planets

55 Cnc b: 0.115 AU
0.84 Jupiter masses
55 Cnc c: 0.241 AU
0.21 Jupiter masses
55 Cnc d: 5.9 AU
4.05 Jupiter masses

HABITABLE ZONES BY COMPARISON I



HABITABLE ZONES BY COMPARISON II



CATALOG OF 86 PLANETARY SYSTEMS

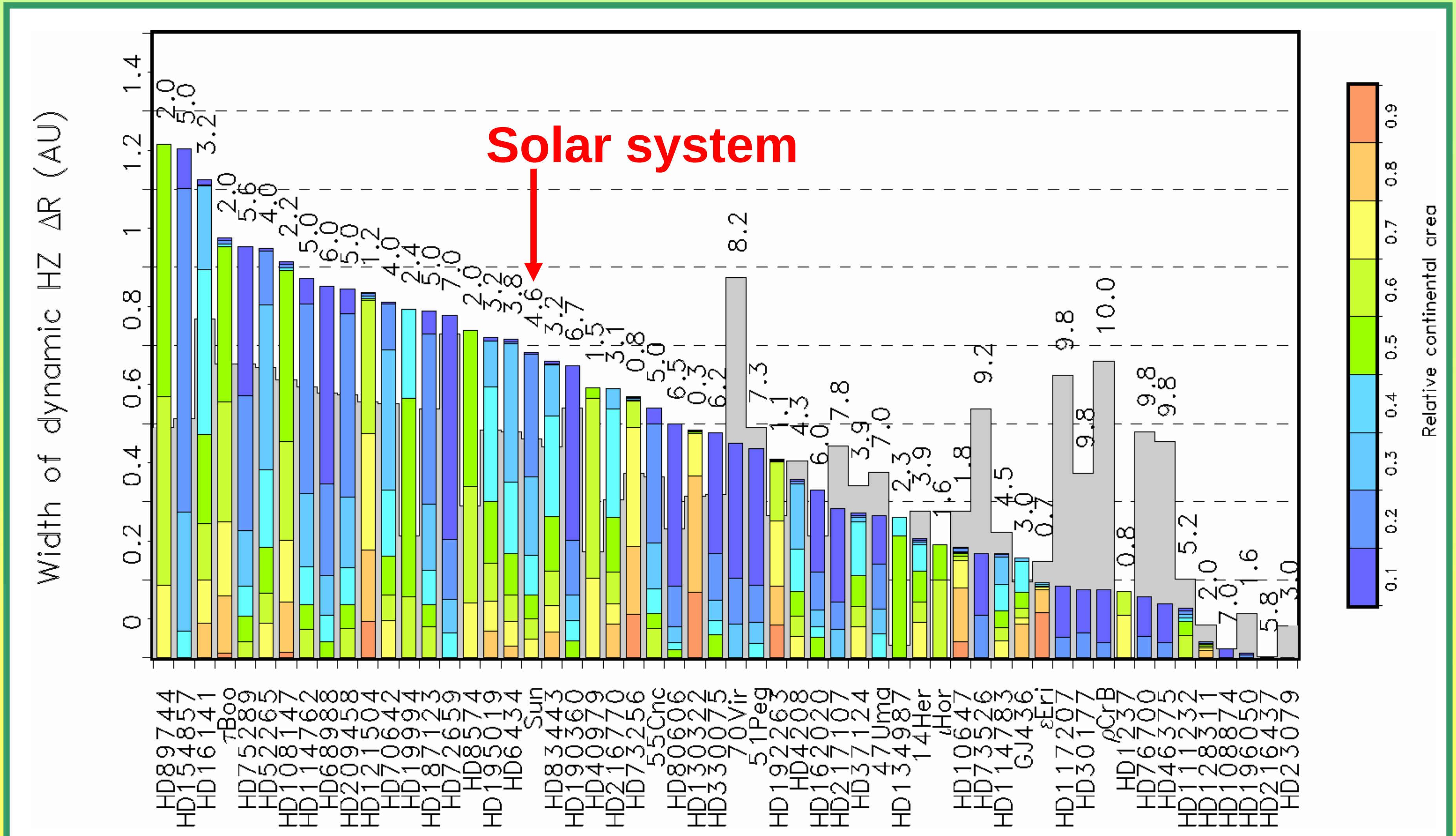
- The catalogs of Espresate (2005) and Jones et al. (2005) contain necessary information for 86 extrasolar planetary systems.

TABLE 2

HOSTS STAR DATA

Star No.	Identifier	Spectral Type	Mass $M_\odot$	Luminosity $L_\odot$	T_{eff} K	[Fe/H]	P_{rot} days	R_* $R_\odot$	Age Gyr	Number of planets
1	OGLETR56	G - -	1.04	-	-	-	-	1.12	-	1
2	OGLETR113	K - -	0.77	-	-	0.14	-	0.765	-	1
3	OGLETR132	F - -	1.35	-	-	0.43	-	1.43	1.4	1
4	HD73256[5]	K 0 V	1.05	0.69	5570	0.29	13.9	1.03	0.83	1
5	GJ436	M 2.5V	0.41	0.025	-	0.25	-	0.43	-	1
6	HD75732[5]	G 8 V	0.95	0.61	5250	0.16	38.5	0.96	5.0	4
7	HD63454[5]	K 4 V	0.8	0.26	4841	0.11	-	0.84	-	1
8	HD83443[5]	K 0 V	0.9	0.88	5454	0.35	35.3	0.92	3.2	1
9	HD46375[1]	K 1 V	1.0	1.0	5770	0.34	-	1.0	-	1
10	TrES-1[6]	K 0 V	0.87	0.5	5250	0.001	-	0.85	-	1
11	HD179949[2]	F 8 V	1.24	1.99	6155	0.02	9.	1.24	-	1
12	HD187123	G 3 V	1.06	1.35	5830	0.16	25.4	1.18	-	1
13	OGLE-TR-10	G - -	1.22	-	-	0.12	-	-	-	1
14	HD120136[2]	F 8 V	1.3	2.31	6498	0.28	3.3	1.2	2.0	1
15	HD330075	K 1 -	0.7	0.47	5017	0.08	48	-	6.2	1
16	HD88133[1]	G 5 IV	1.2	3.06	5494	0.34	48	1.93	-	1
17	HD2638	G 5 -	0.93	0.47	5192	0.16	37	-	-	1
18	BD103166[6]	K 0 V	1.1	0.62	5400	0.50	-	0.9	-	1
19	HD75289[5]	G 0 V	1.15	1.99	6000	0.29	15.95	1.08	5.6	1
20	HD209458[5]	G 0 V	1.03	1.61	6025	0.04	14.4	1.02	5.	1
21	HD76700[4]	G 8 V	1	1	5423	0.14	-	1	-	1
22	OGLETR111[1]	G - -	0.82	0.43	5070	0.12	-	0.85	-	1
23	HD217014[1]	G 5 V	1.06	1.2	5946	0.20	28.	0.03	-	1
24	HD9826	F 8 V	1.3	3.4	6210	0.1	10.2	1.4	-	3
25	HD49674[1]	G 5 V	1	1.0	5770	0.25	27.2	1	-	1
26	HD68988[1]	G 2 V	1.2	1.79	6338	0.24	26.7	1.1	6.	1
27	HD168746	G 5 -	0.88	1.1	5610	-0.06	-	-	-	1
28	HD217107[4]	G 7 V	0.98	0.94	5700	0.32	39	0.98	7.76	1
29	HD162020[5]	K 2 V	0.75	0.25	4830	0.01	-	0.79	-	1
30	HD160691[5]	G 5 V	1.1	1.77	5813	0.32	31	1.05	2.	3
31	HD130322[5]	K 0 V	0.79	0.5	5330	-0.02	8.7	0.83	0.35	1
32	HD108147[5]	G 0 V	1.27	1.93	6265	0.20	8.7	1.15	2.17	1
33	HD38529[4]	G 4IV	1.39	5.96	5370	0.35	34.5	2.82	-	2
34	HD13445[5]	K 0 V	0.8	0.4	5350	-0.24	31	0.84	-	1
35	HD99492[6]	K 2 V	0.88	0.33	4954	0.36	-	0.79	-	1
36	HD27894[5]	K 2 V	0.75	0.36	4875	0.3	-	0.79	-	1
37	HD195019[4]	G 3 V	1.02	1.06	5600	0.0	24.3	1.01	3.16	1
38	HD6434[5]	G 3 V	0.79	1.12	5835	-0.52	18.6	0.83	3.8	1
39	HD192263[5]	K 2 V	0.75	0.34	4840	-0.14	9.5	0.79	-	1
40	Gl876[5]	M 4 V	0.3	0.014	3200	0.0	-	0.38	-	2*
41	HD102117[5]	G 6 V	1.03	1.57	5672	0.3	34	1.02	-	1

HABITABLE ZONES BY COMPARISON V



CONCLUSIONS

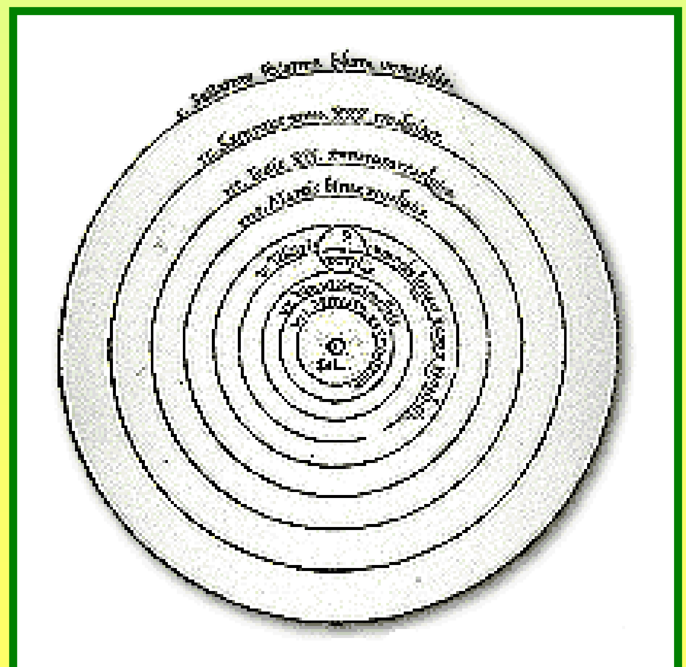
Habitability does not depend only on characteristics of the central star, does depend explicitly on age of the virtual Earth-like planet.

The solar system is a relative ordinary system, 18 systems have better requisites.

→„Principle of mediocrity“

THE MEDIOCRITY PRINCIPLE

The solar system and life on Earth are about average and life will develop by the same rules wherever the proper conditions and the needed time are given.



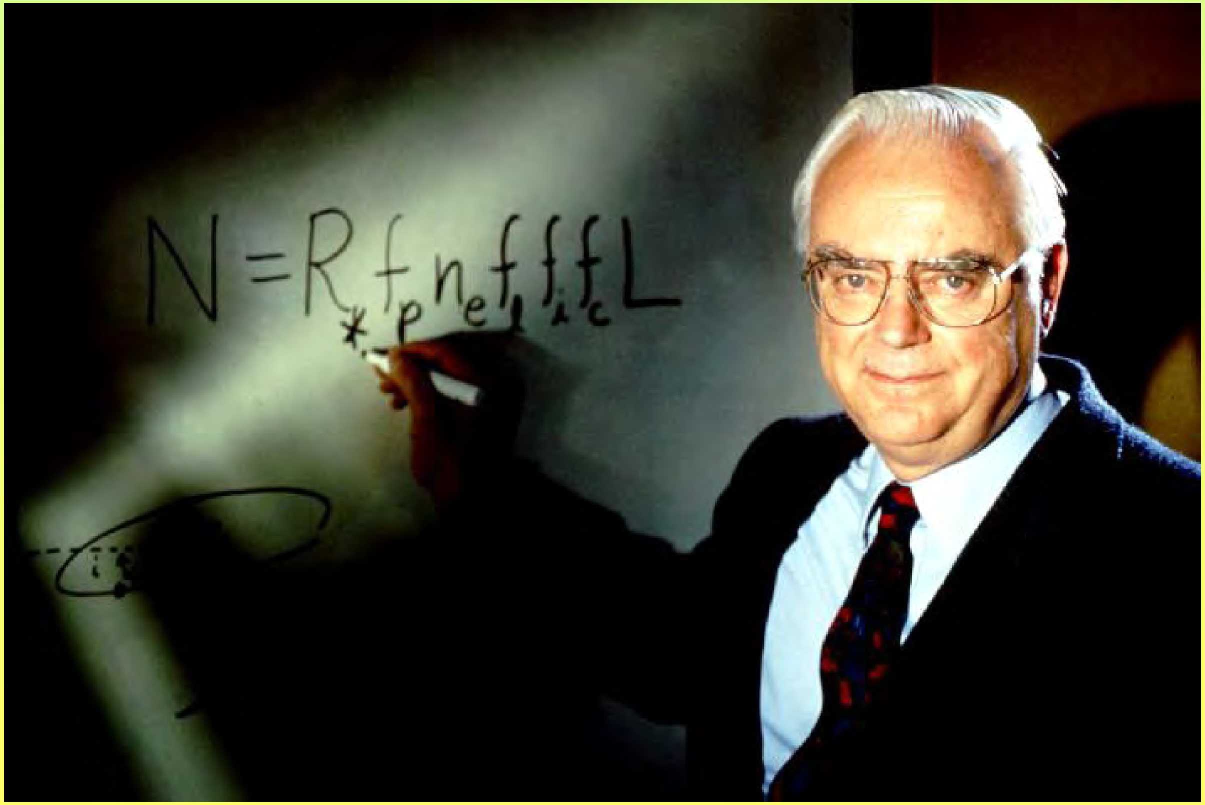
CALCULATING THE NUMBER OF HABITABLE PLANETS IN THE MILKY WAY

(1) DRAKE formula

(2) convolution integral

CALCULATING THE NUMBER OF HABITABLE PLANETS IN THE MILKY WAY

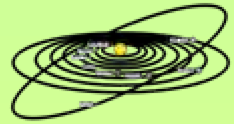
Drake Formula



$N_{civ} =$

total number of stars in the Milky Way

×

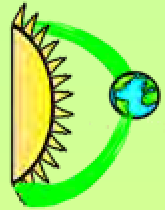


fraction of stars that have planets

×

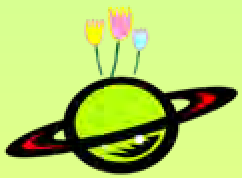
fraction of planets that are Earth-like

×



fraction of Earth-like planets in the HZ

×



fraction of habitable planets that develop life

×

fraction of habitable planets that develop intelligent life

×

fraction of intelligent life that develops radio technology

×

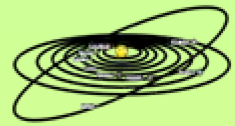
normalized mean life time of an intelligent civilisation

Franck et al. (2001): *Naturwissenschaften* 88, 416-426

$N_{civ} =$

total number of stars in the Milky Way

×

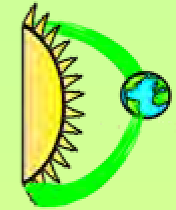


fraction of stars that have planets

×

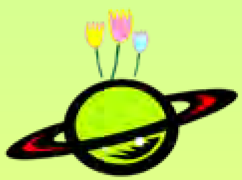
fraction of planets that are Earth-like

×



fraction of Earth-like planets in the HZ

×

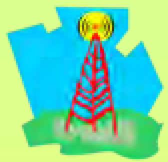


fraction of habitable planets that develop life

×

fraction of habitable planets that develop intelligent life

×



fraction of intelligent life that develops radio technology

×

normalized mean life time of an intelligent civilisation

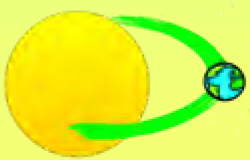
$N_{hab} =$

total number of stars in the Milky Way

×

fraction of stars with Earth-like planets

×



fraction of Earth-like planets in the HZ

$$N_{MW} \times f_P \times n_{CHZ}$$

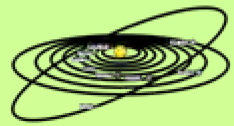
$$4 \cdot 10^{11} \qquad 0.01 \qquad 0.012$$

Franck et al. (2001): *Naturwissenschaften* 88, 416-426

$N_{civ} =$


total number of stars in the Milky Way

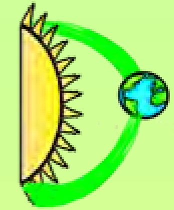
×


fraction of stars that have planets

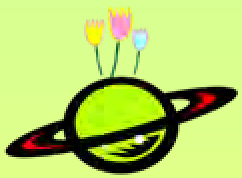
×


fraction of planets that are Earth-like

×


fraction of Earth-like planets in the HZ

×


fraction of habitable planets that develop life

×


fraction of habitable planets that develop intelligent life

×


fraction of intelligent life that develops radio technology

×


normalized mean life time of an intelligent civilisation

$N_{hab} =$


total number of stars in the Milky Way

×


fraction of stars with Earth-like planets

×


fraction of Earth-like planets in the HZ

$$N_{MW} \times f_P \times n_{CHZ} = 4.8 \cdot 10^7$$

$$4 \cdot 10^{11} \qquad 0.01 \qquad 0.012$$

Franck et al. (2001): *Naturwissenschaften* 88, 416-426

CONVOLUTION INTEGRAL

$$P(t)=\int_0^t PFR(t')\times p_{hab}(t-t')\,dt'$$

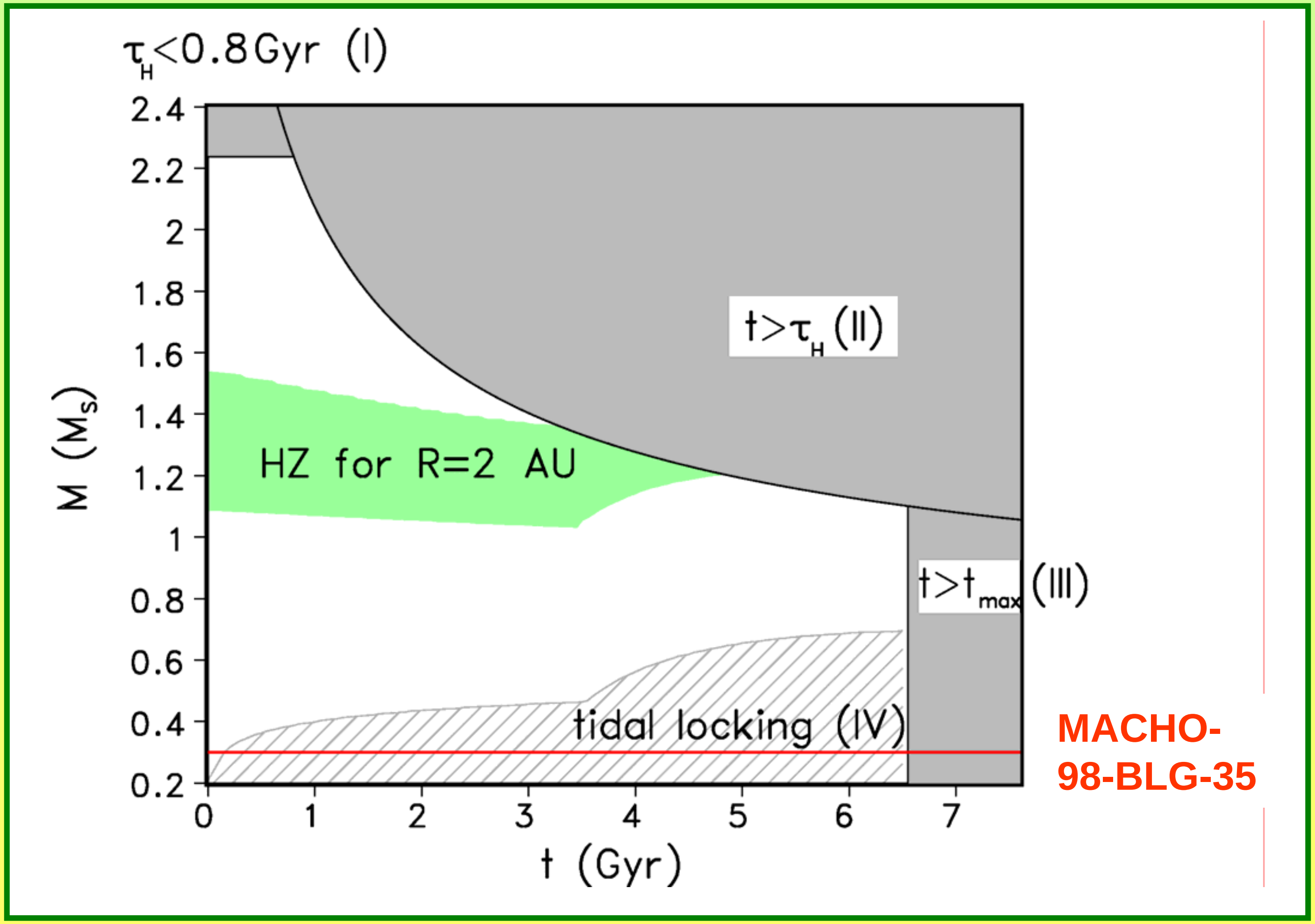
$$p_{HZ}(M,\Delta t)=\frac{1}{C_1}\int_{R_{inner}(M,\Delta t)}^{R_{outer}(M,\Delta t)} R^{-1}dR$$

Whitmire and Reynolds (1996)

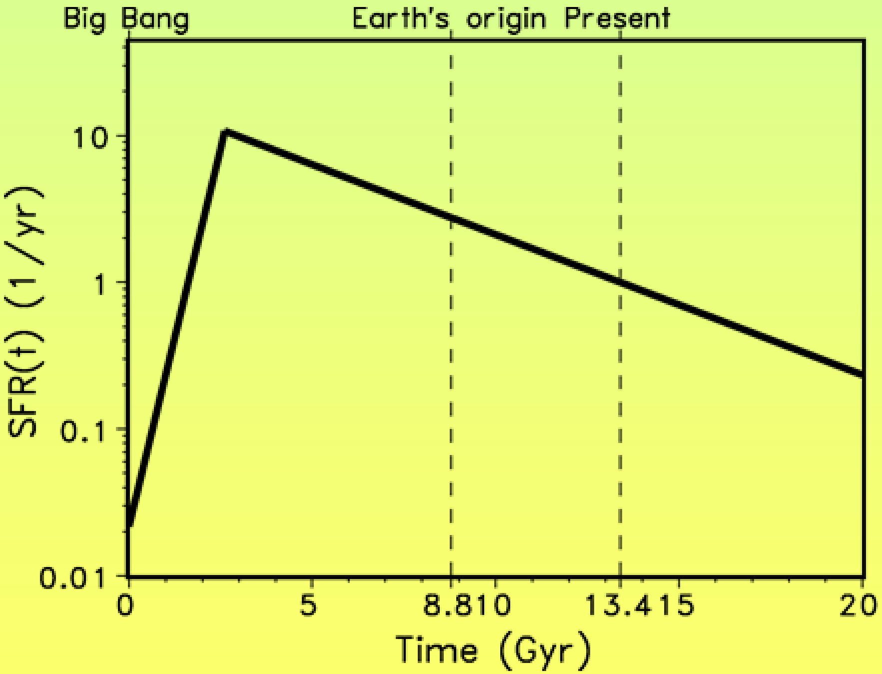
$$p_{hab}(\Delta t)=\frac{1}{C_2}N_P\int_{0.8M_s}^{1.2M_s} M^{-2.5}\left(1-\left(1-p_{HZ}\left(M,\Delta t\right)\right)^{N_P}\right)dM$$

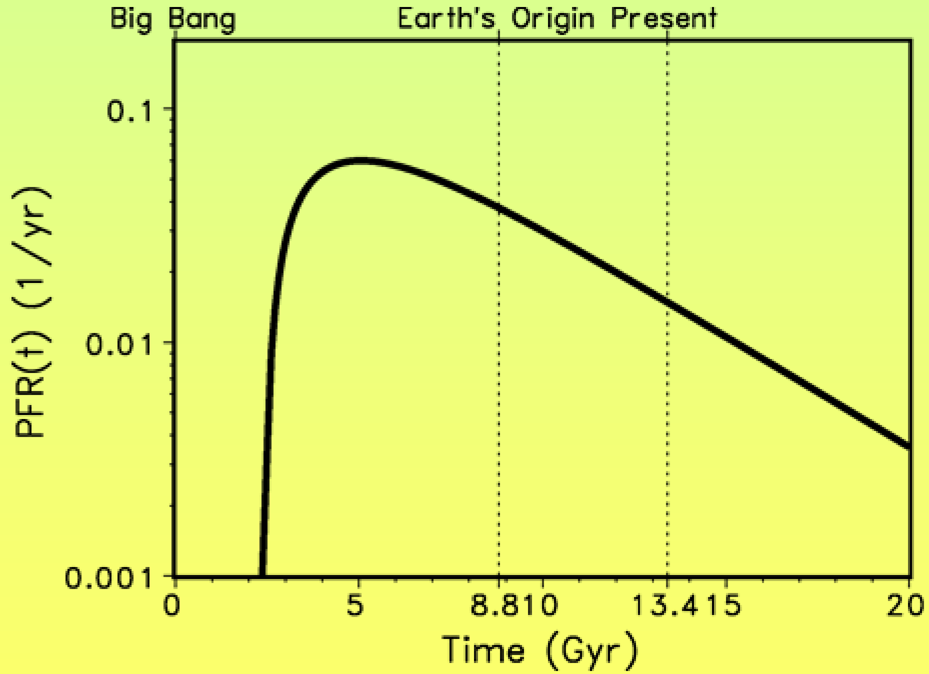
$$p_{hab}(\Delta t)=\frac{1}{C_2}N_P\int_{0.8M_s}^{1.2M_s} M^{-2.5}p_{HZ}\left(M,\Delta t\right)dM$$

POTENTIAL OVERALL DOMAIN FOR HZ



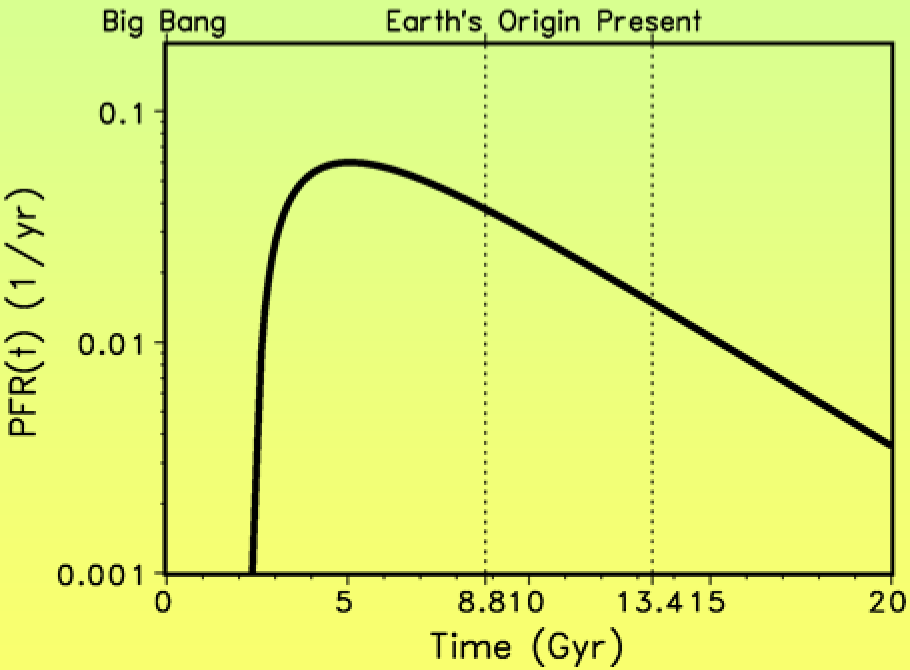
$$N_{\mathrm{hab}}(t) = \int_0^t PFR(t') \times p_{\mathrm{hab}}(t - t')\, dt'$$

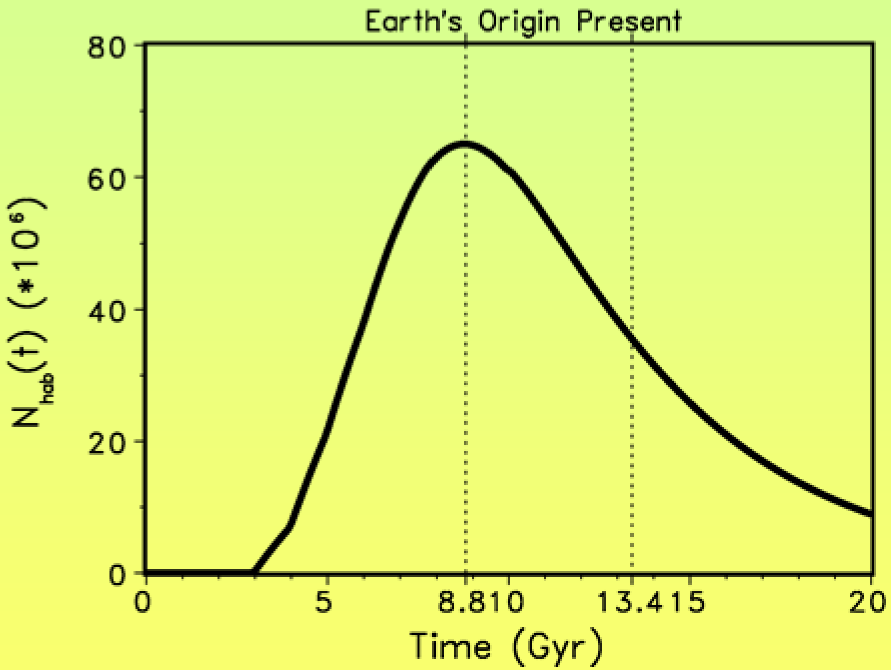




Lineweaver (2001): *Icarus* 151, 367-313

$$N_{\mathrm{hab}}(t) = \int_0^t PFR(t') \times p_{\mathrm{hab}}(t - t')\, dt'$$

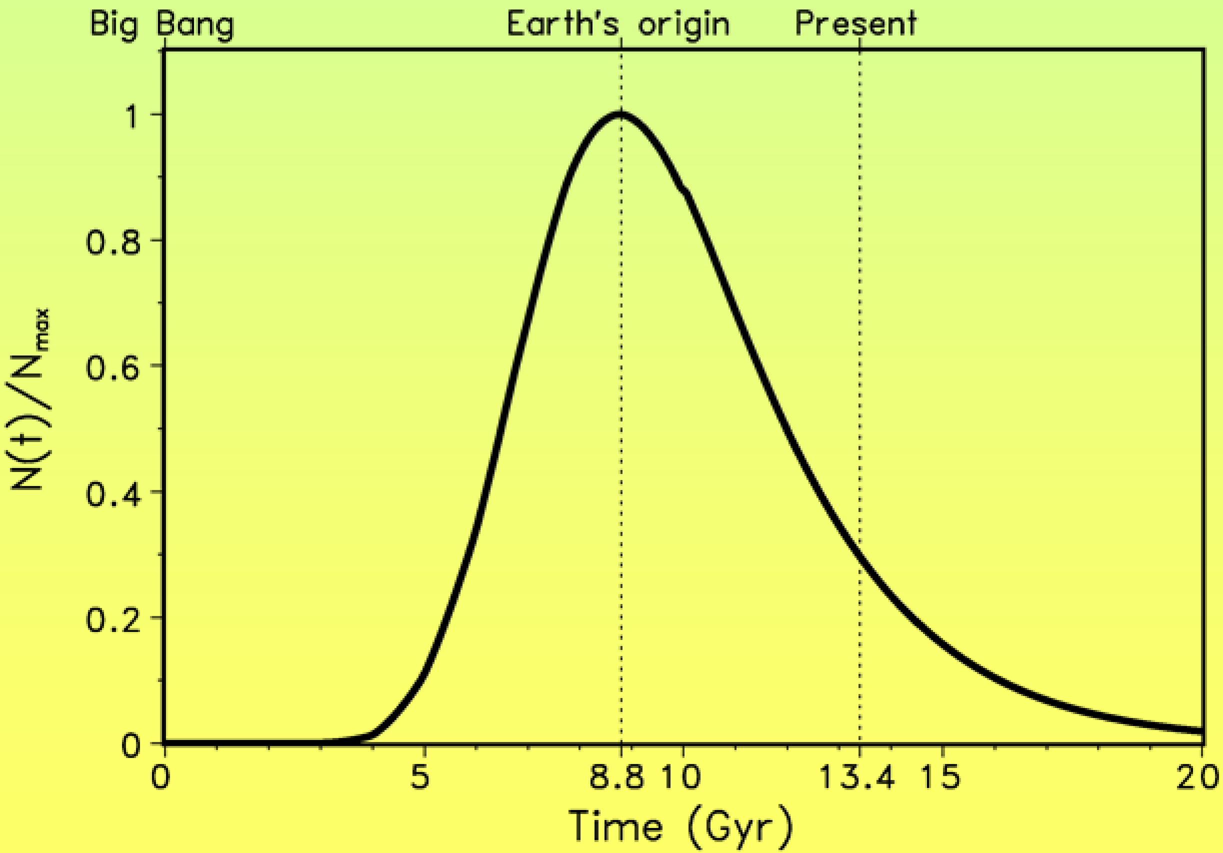




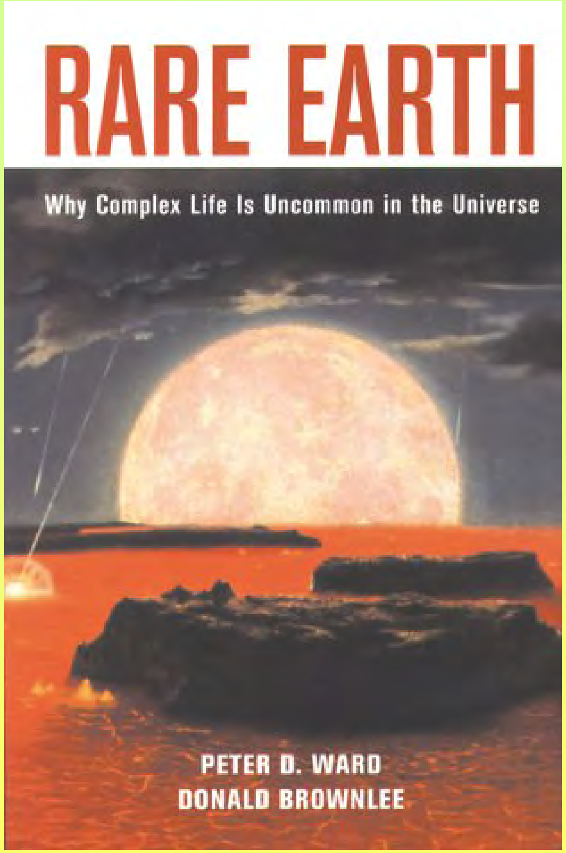
Von Bloh et al. (2003): *Origins Life Evol. Biosph.* 33, 219-231

NUMBER OF PANSPERMIA EVENTS

$$N(t) \propto N_{\mathrm{hab}}(t') \cdot N_{\mathrm{hab}}(t'')$$



PROSPECTS



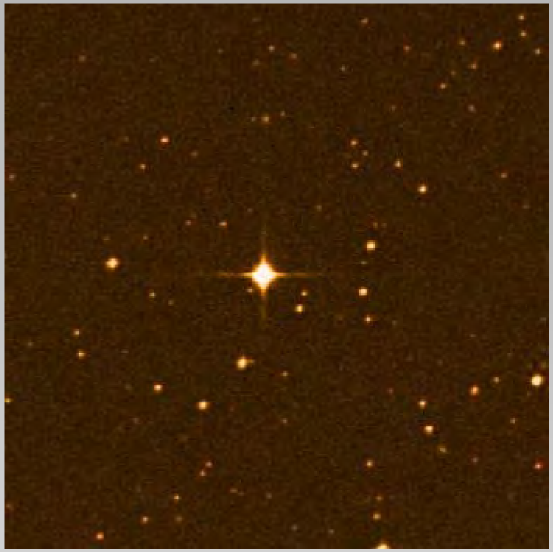
$$P(t) = \int_0^t PFR(t') \times p_{\text{hab}}(t - t')\, dt'$$

Von Bloh et al. (2003)

First detection of a „super-Earth“

- 24. April 2007: Udry et al. announced detection of an Earth-like planet around Gliese 581
- Planetary mass of 5 Earth masses: „Super-Earth“
- Surface temperature between 0°C und 40°C
- But: Calculation of surface temperature without considering greenhouse effect of an atmosphere!
- A second planet with 8 Earth mass was additionally detected

Planetary system around Gliese 581



The star Gliese 581

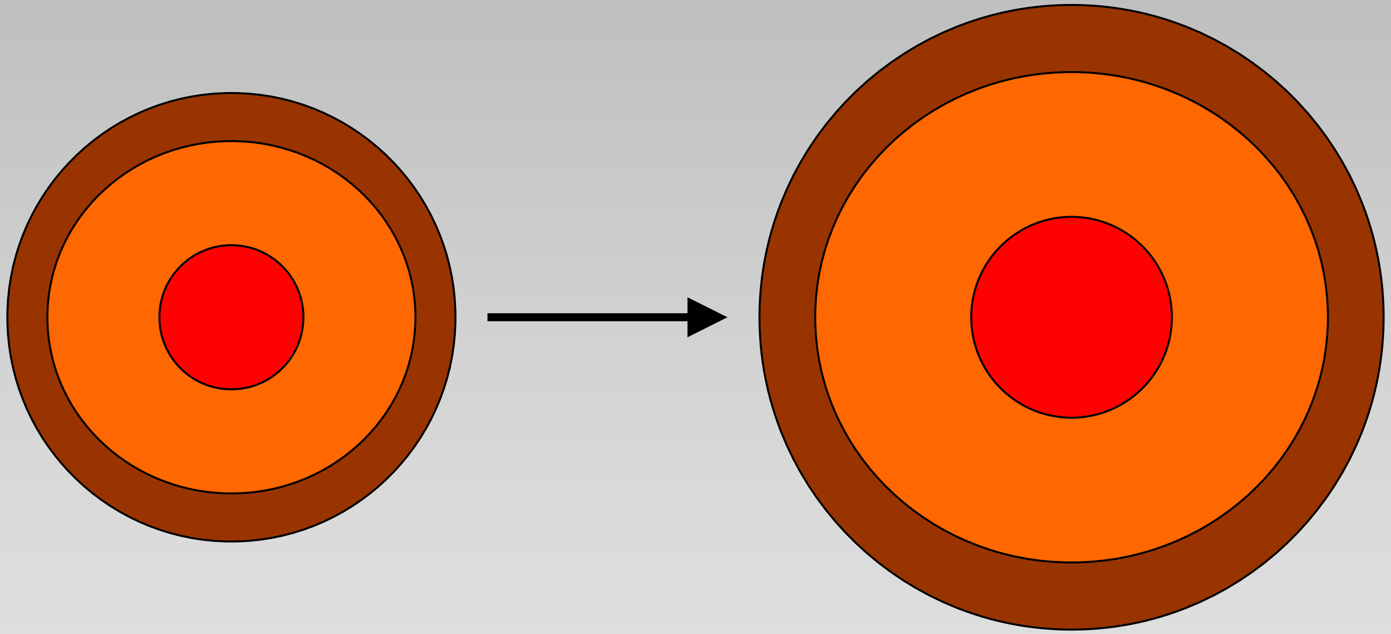
Spectral class: M3V
Type: Red dwarf
Distance: 20.5 lyr
Luminosity: 0.013 L_{solar} (±0.002)
Mass: 0.31 Solar masses
Age: >2 Gyr

Detected planets

Gl 581 b: 17.8 Earth masses
0.041 AU
Gl 581 c: 5.06 Earth masses
0.073 AU
Gl 581 d: 8.3 Earth masses
0.25 AU

Thermal evolution of super-Earths

$$\frac{4}{3}\pi\rho c(R_m^3 - R_c^3)\frac{\mathrm{d}T_m}{\mathrm{d}t} = -4\pi R_m^2 q_m + \frac{4}{3}\pi Q(R_m^3 - R_c^3)$$

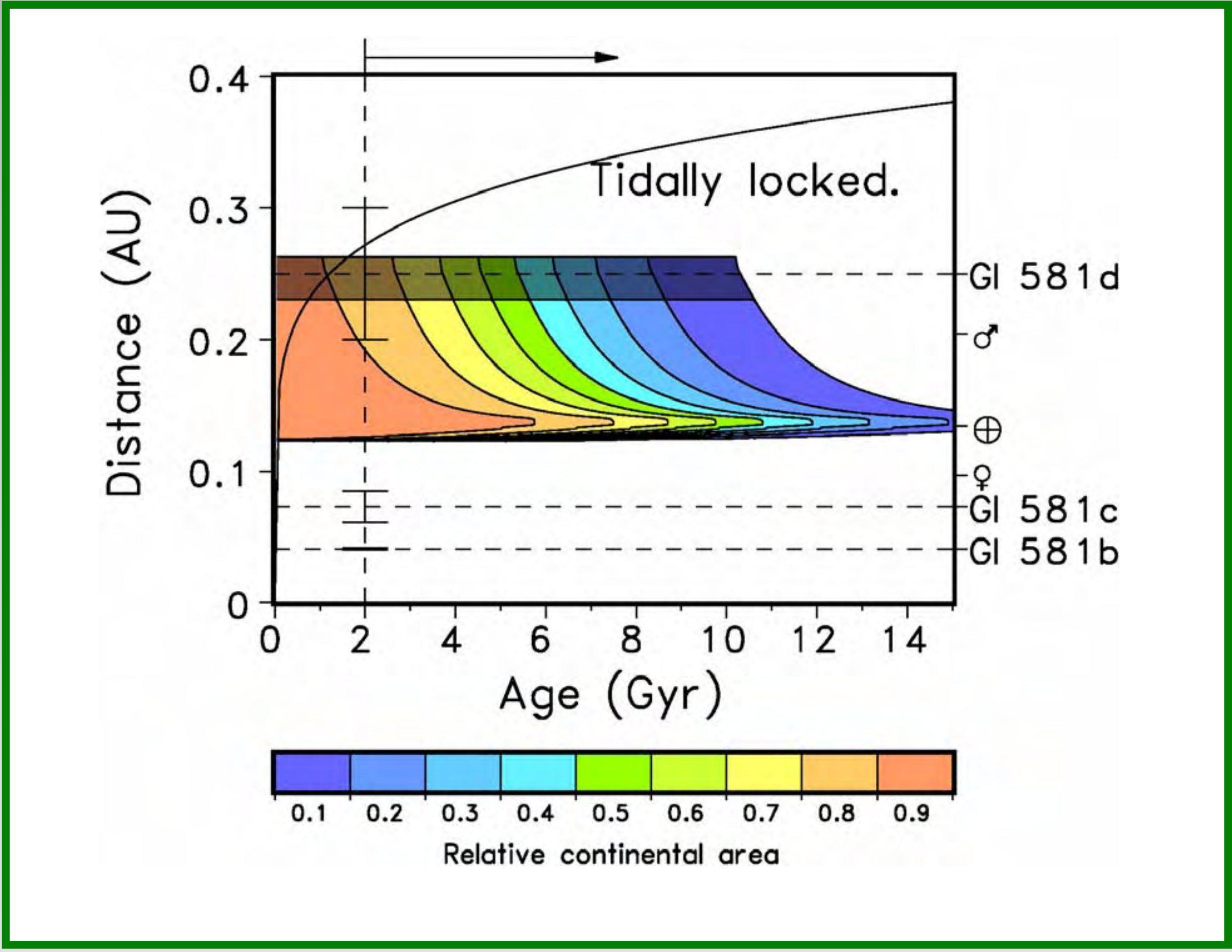


Scaling of planetary radius according to Valencia et al. 2006:

$$R \propto M^{0.27}$$

Habitable Zone for Super-Earths in Gl 581

Relative continental area= 0.1...0.9 kept constant:



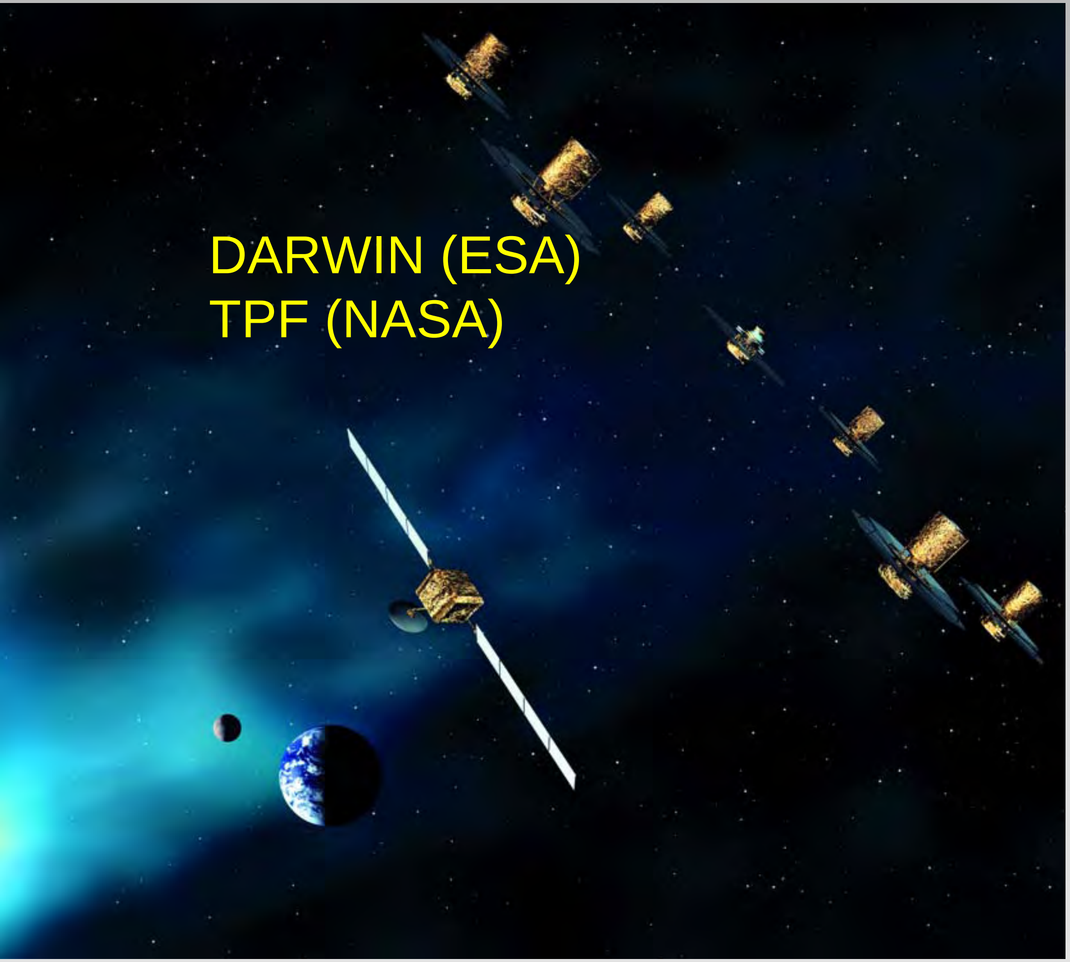
Results for Gliese 581

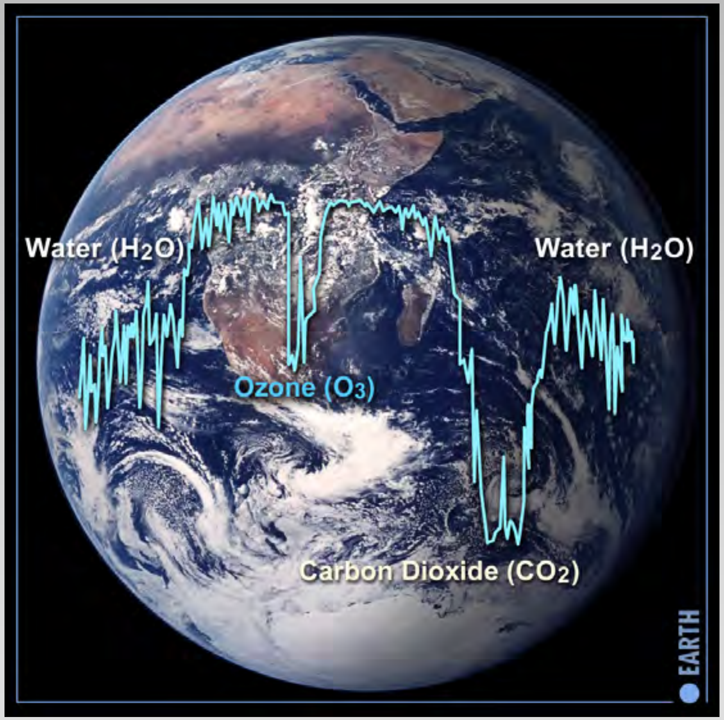
- Gliese 581c is not habitable. Planet receives more insolation than planet Venus in the solar system
- Outer planet Gliese 581d might be within the habitable zone, primitive life is possible
- Higher life forms are unlikely due to the rather harsh environmental conditions

⇒The search for a second Earth is still ongoing…

The future: Space missions

Direct detection of Earth-like planets within the habitable zone





Life detection via biomarker

npg nature publishing group

nature

Water worlds make a splash as the best hope for alien life

QUIRIN SCHIERMEIER

[MUNICH] Kevin Costner's 1995 film Waterworld might have flopped at the box office, but researchers think that real water worlds — Earth-sized planets predominantly covered by oceans — are more likely than land-covered planets to host life.

Simple assumptions about the likely distribution of planets in the Milky Way suggest that many water worlds exist in our Galaxy, but elude existing methods of detection. "There could be as many as one billion stellar systems with potentially habitable zones," says Siegfried Franck, a geophysicist at the Potsdam Institute for Climate Impact Research in Germany.

To try to pin down the locations of planets that might host life, Franck and Manfred Cuntz, an astrophyicist at the University of Texas in Arlington, used a mathematical model to locate the 'habitable zone' of 47 UMa, a Sun-like star some 45 light years away. The pair devised equations coupling stellar age and luminosity, distance from the star, and planetary climate, to determine the chance of habitable planets existing near 47 UMa. They also calculated geodynamic constraints on the biospheres of planets that could have formed there. (S. Franck *et al. Int. J. Astrobiol.* 2, 35–39; 2003).

Earth-like planets in stable orbits in habitable zones are the most likely places to harbour life. "Earth would have a slight chance of being habitable in the 47 UMa system," says Franck, "but a water world almost entirely covered by oceans would have a better chance." The 47 UMa system intrigues experts because the star has roughly the same mass, age and spectrum as the Sun. Moreover, it hosts two giant gas planets, analogous to Jupiter and Saturn. It is thought that such large planets help to shelter Earth from bombardment by comets and asteroids.

"Studies like this help to publicize the notion of habitable zones," says Jim Kasting, an atmospheric scientist at Pennsylvania State University. But he warns that 'models of early planetary evolution are not particularly well constrained' and may not provide a reliable pointer to where inhabitable planets can be found.

NASA plans to launch two space-based telescopes, perhaps by 2013, dedicated to the pursuit of Earth-like planets, and to the analysis of their atmospheric composition. "Then the whole thing will get really exciting," says Kasting.

Bild

UNABHÄNGIG · ÜBERPARTEILICH

BERLIN-BRANDENBURG

Mittwoch, 20. August 2003, 0,45 € 193/34

Er sagt, die Aliens wohnen im Großen Bären

Von NICOLA BAUER

Da oben, irgendwo im Sternbild des Großen Bären, könnten sie wohnen – die Aliens. Davon ist zumindest Physiker Dr. Werner von Bloh (39) vom Institut für Klimafolgenforschung in Potsdam überzeugt.

Überall im Weltall sucht er seit drei Jahren Gebiete, die (theoretisch) bewohnbar wären. Und hatte jetzt Erfolg: Im Großen Bären gibt es eine Zone, in der es sogar wir Menschen aushalten könnten! „Würde man die Erde dahin versetzten, gäbe es für uns keine Probleme", sagt er.

Wer seinen Schulunterricht vergessen hat: Das Weltall ist äußerst lebensfeindlich – luftleerer Raum, minus 273 Grad, tödliche kosmische Strahlung.

Die Erde ist wie eine Oase. Selten, vielleicht sogar einzigartig. Doch in dem kleinen Gebiet des Großen Bären hat Professor von Bloh eine zweite Oase entdeckt. Mit einer Sonne, Kohlenmonoxid... Warum ist das wichtig? Wissenschaftler sind sicher: Aliens müssen ähnlich funktionieren wie wir. Aufgebaut u.a. aus Kohlenstoff, mit Wasser als Lösungsmittel (und das taut im All nur, wenn es warm ist).

Leben da jetzt wirklich Außerirdische? Der Forscher: „Die Wissenschaft weiß noch nicht, ob in dieser Umlaufbahn wirklich ein bewohnbarer Planet unterwegs ist." Hinfliegen und nachsehen geht leider nicht: Das Gebiet ist 425 Billionen Kilometer (= 45 Lichtjahre) entfernt. **Da hilft nur: Zum Großen Bären hoch kucken – und von den Aliens träumen...**

► Physiker Dr. Werner von Bloh vermutet die Außerirdischen im „Großen Bären"
Foto: MICHAELIS

Seite 8 ★ BILD ★ Berlin, 20. August 2003