Exoplanets searches : Prospects and Future

Change of paradigm during the 20th century
25 years of discoveries
and after

Michel Mayor
University of Geneva

How many planetary systems in the Milky Way ?

Formation of planets by accretion of planetesimals

Discovery of protoplanetary disks

Orbital migration

Progress in Doppler spectroscopy

Diversity of planetary systems

Discovery of the important subpopulation of «super-Earths»

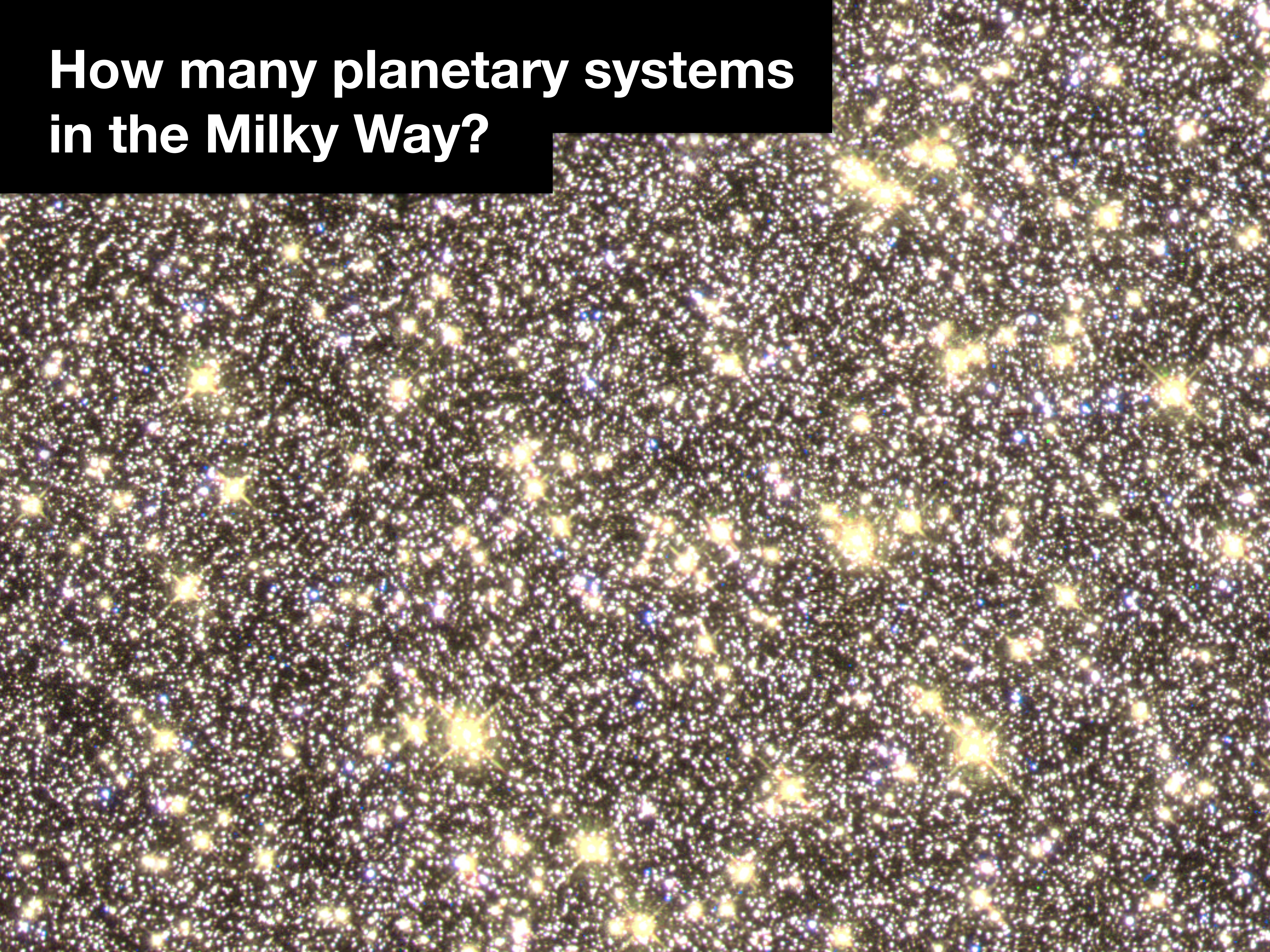
Estimation of the frequency of planetary systems (function of orbital period, planetary mass, eccentricity, metallicity of the host star , etc)

Spectroscopy + planetary transits

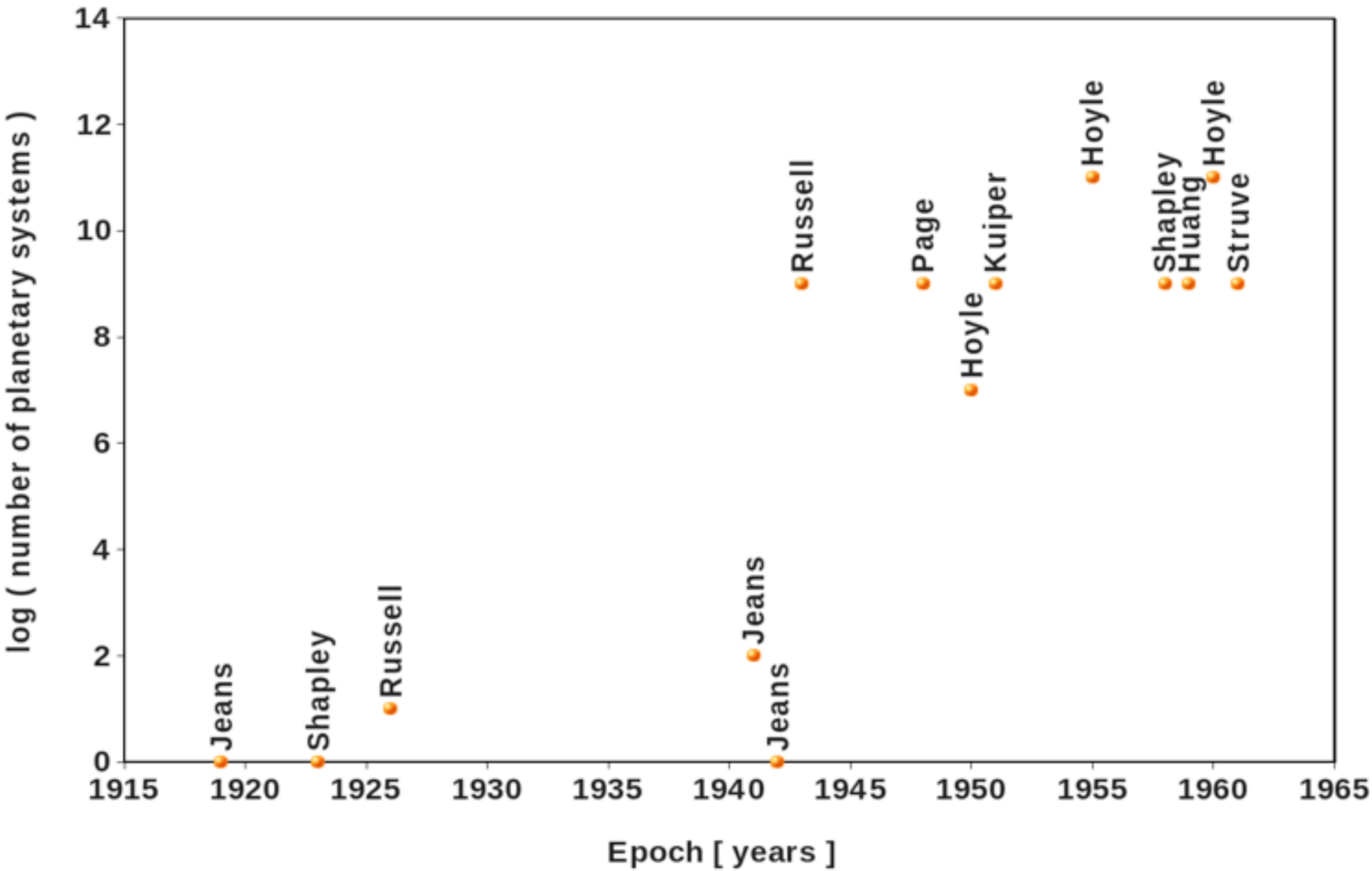
First steps toward the atmospheric composition of exoplanets

Upper mass for rocky planets

How many planetary systems in the Milky Way?



Estimated number of planetary systems in the Milky way



Observatory (1952) 72,199

PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

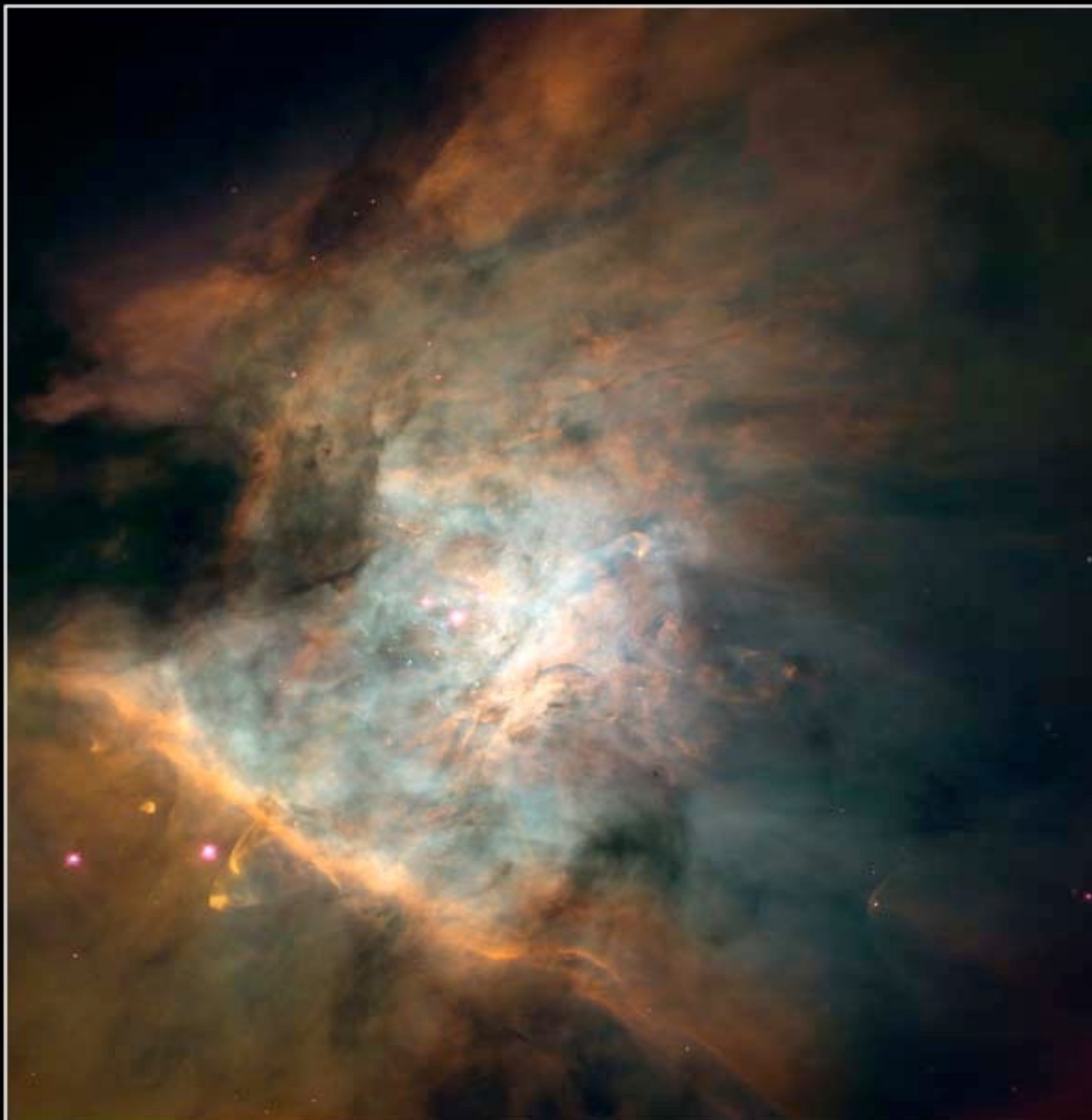
With the completion of the great radial-velocity programmes of the major observatories, the impression seems to have gained ground that the measurement of Doppler displacements in stellar spectra is less important at the present time than it was prior to the completion of R. E. Wilson's new radial-velocity catalogue.

I believe that this impression is incorrect, and I should like to support my contention by presenting a proposal for the solution of a characteristic astrophysical problem.

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun. K. A. Strand's[1] discovery of a planet-like companion in the system of 61 Cygni, which was recently confirmed by A. N. Deitch[2] at Poulkovo, and similar results announced for other stars by P. Van de Kamp[3] and D. Reuyl and E. Holmberg[4] have stimulated interest in this problem. I have suggested elsewhere that the absence of rapid axial rotation in all normal solar-type stars (the only rapidly-rotating G and K stars are either W Ursae Majoris binaries or T Tauri nebular variables,[5] or they possess peculiar spectra[6]) suggests that these stars have somehow converted their angular momentum of axial rotation into angular momentum of orbital motions of planets. Hence, there may be many objects of planet-like character in the galaxy.

But how should we proceed to detect them? The method of direct photography used by Strand is, of course, excellent for nearby binary systems, but it is quite limited in scope. There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.

Protoplanetary discs



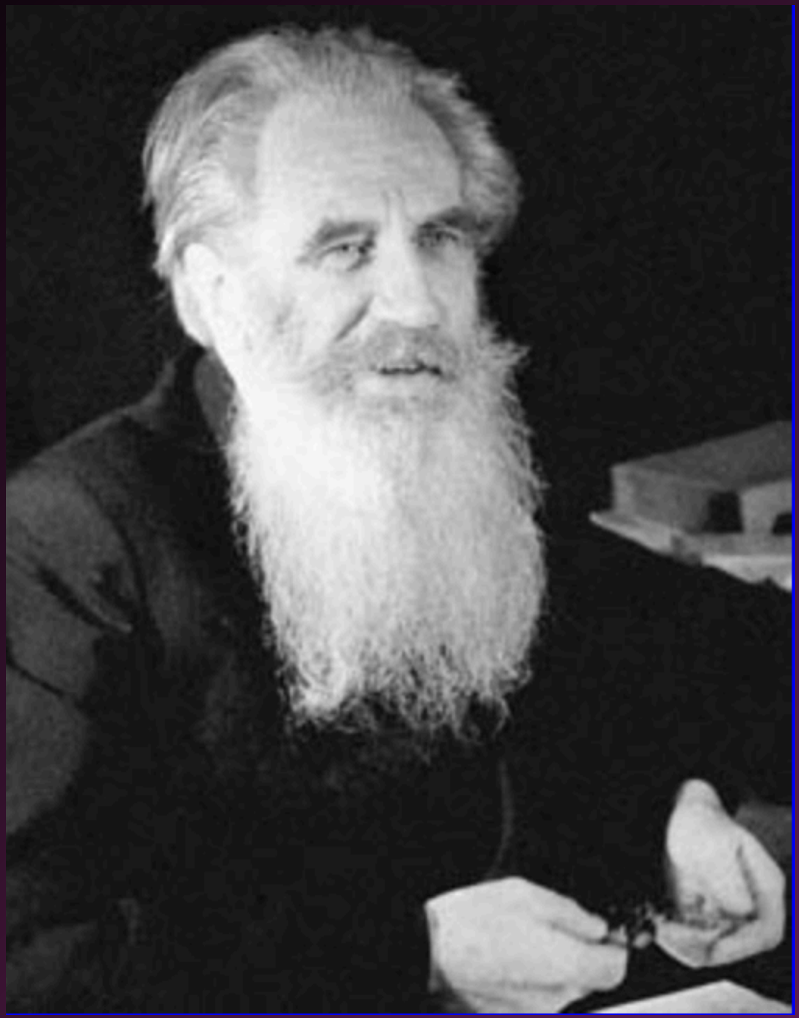
Orion Nebula Mosaic HST • WFPC2

PRC95-45a • ST ScI OPO • November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

Protoplanetary Disks
Orion Nebula HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Otto Yulyevitch Shmidt and Viktor Safronov



1891- 1956

1917- 1999

Propose the scenario to explain the formation of planetary systems by agglomeration of planetesimals from dust grains to planets.

Safronov,V.S. 1969 Evolution of the protoplanetary cloud and the formation of the Earth and planets

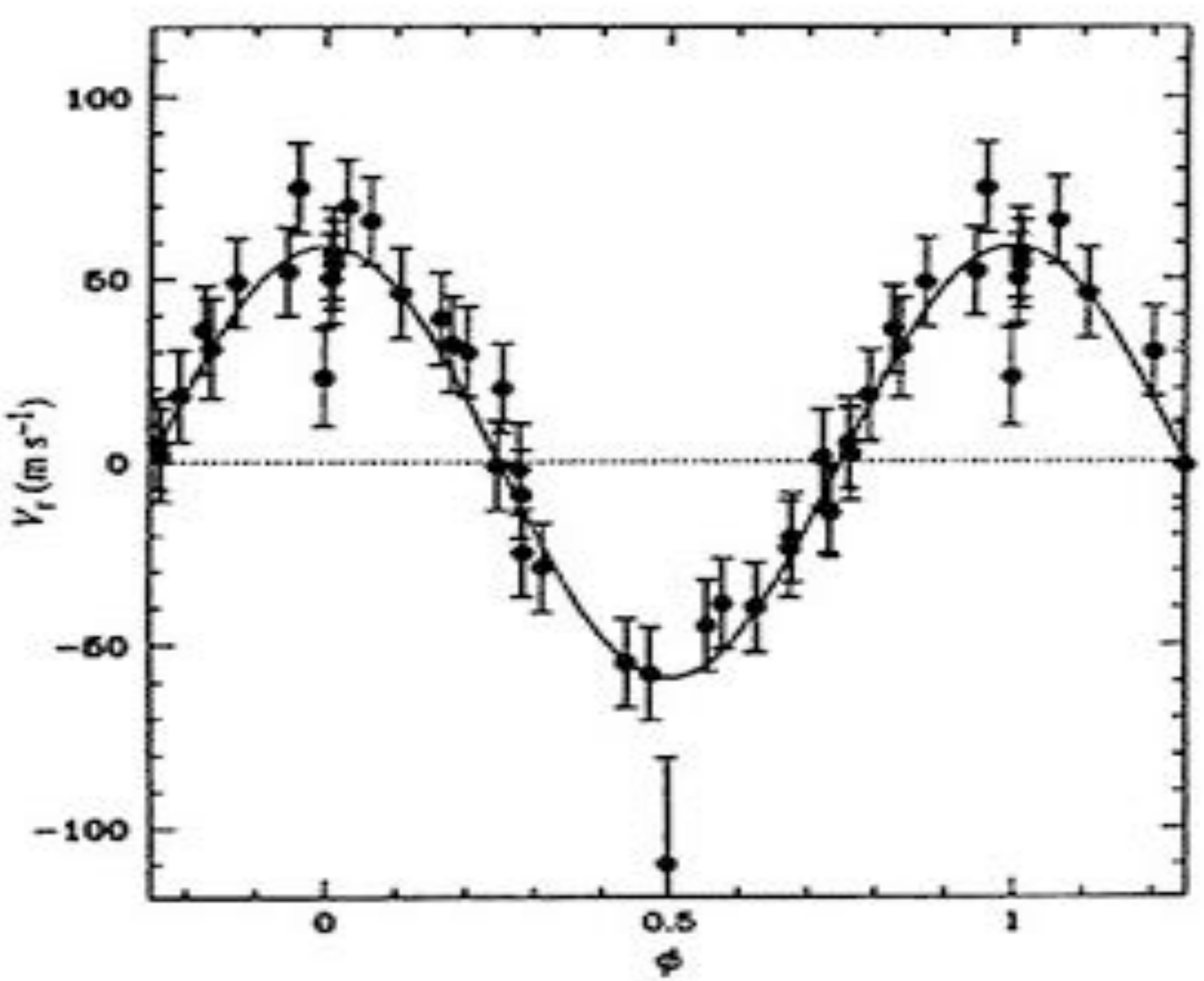
The first exoplanet hosted by a solar-type star: **51 Pegasi b** (Oct. 1995)

$M_{pl} = 0.5\ M_{Jup}$

P = **4.2 days**

a = 0.04 UA

Mayor, Queloz Nature 23 nov.1995



THE ASTROPHYSICAL JOURNAL, **241**:425–441, 1980 October 1

DISK-SATELLITE INTERACTIONS

PETER GOLDREICH
California Institute of Technology

AND

SCOTT TREMAINE
Institute for Advanced Study, Princeton, New Jersey
Received 1980 January 7; accepted 1980 April 9

ABSTRACT

We calculate the rate at which angular momentum and energy are transferred between a disk and a satellite which orbit the same central mass. A satellite which moves on a circular orbit exerts a torque on the disk only in the immediate vicinity of its Lindblad resonances. The direction of angular momentum transport is outward, from disk material inside the satellite's orbit to the satellite and from the satellite to disk material outside its orbit. A satellite with an eccentric orbit exerts a torque on the disk at corotation resonances as well as at Lindblad resonances. The angular momentum and energy transfer at Lindblad resonances tends to increase the satellite's orbit eccentricity whereas the transfer at corotation resonances tends to decrease it. In a Keplerian disk, to lowest order in eccentricity and in the absence of nonlinear effects, the corotation resonances dominate by a slight margin and the eccentricity damps. However, if the strongest corotation resonances saturate due to particle trapping, then the eccentricity grows.

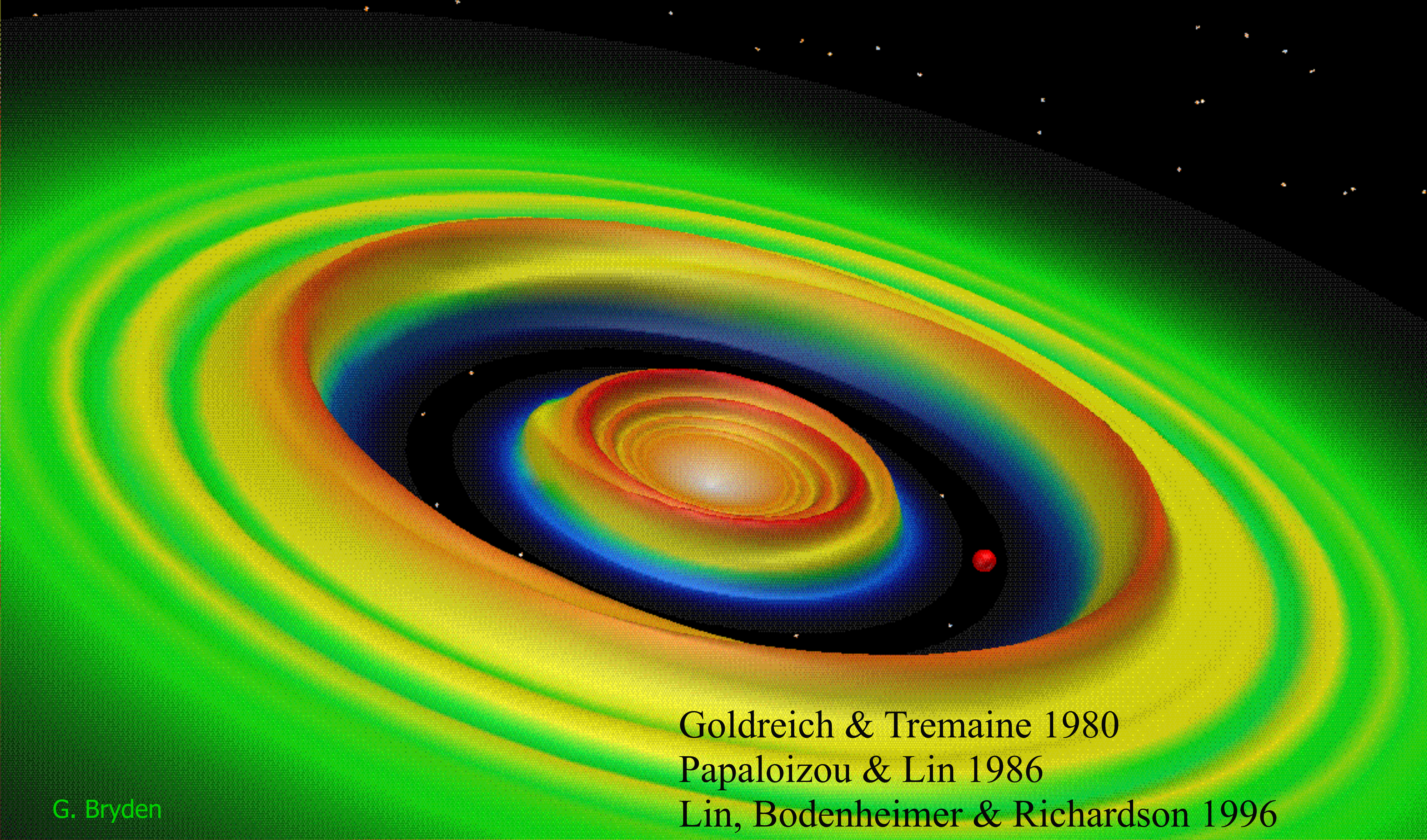
We present an illustrative application of our results to the interaction between Jupiter and the protoplanetary disk. The angular momentum transfer is shown to be so rapid that substantial changes in both the structure of the disk and the orbit of Jupiter must have taken place on a time scale of a few thousand years.

Subject headings: hydrodynamics — planets: Jupiter — planets: satellites — solar system: general

Formation of close-in planets : disk - planet interaction

Formation outside the “ice line” -> migration -> center

How to stop the migration ?



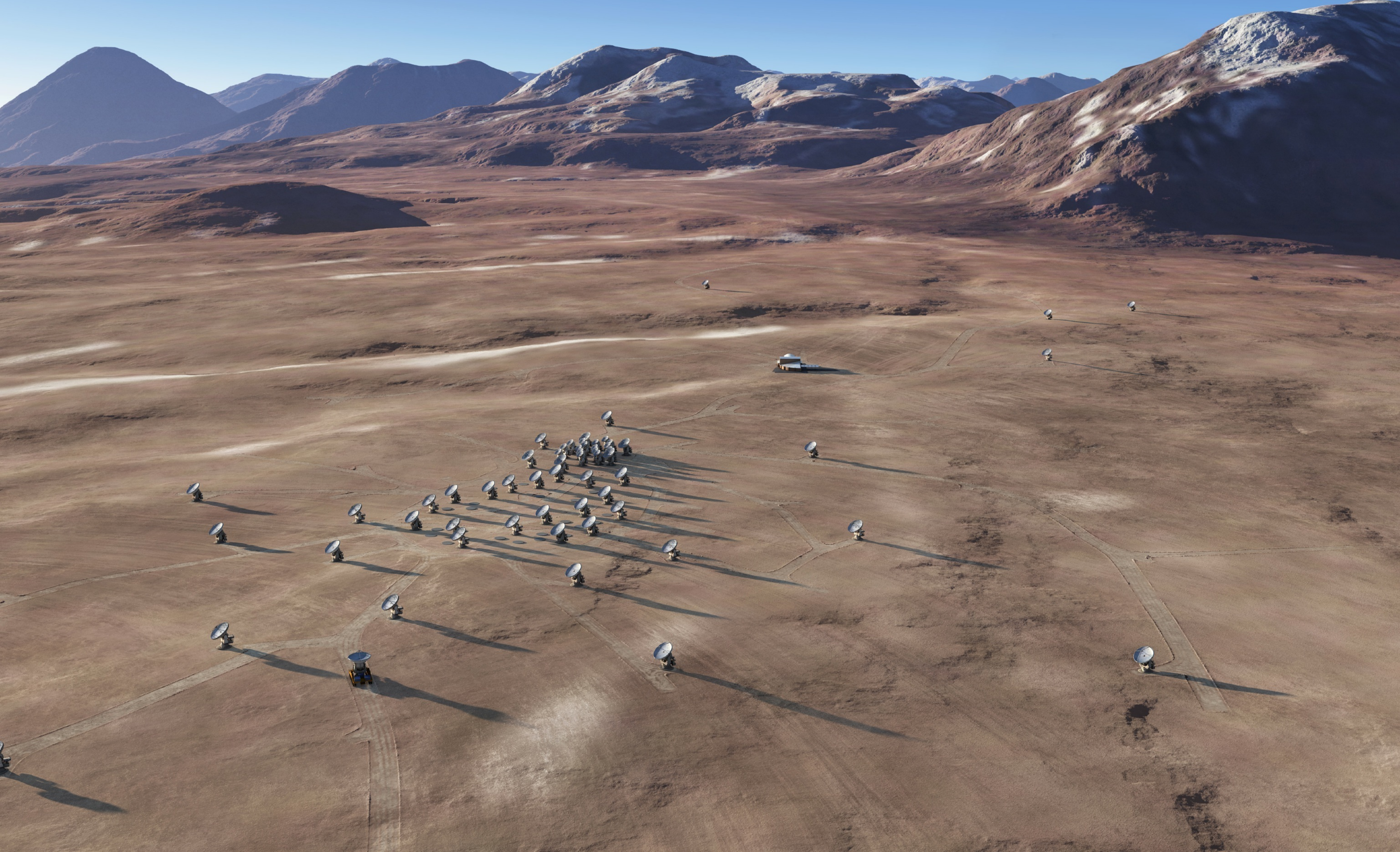
Goldreich & Tremaine 1980

Papaloizou & Lin 1986

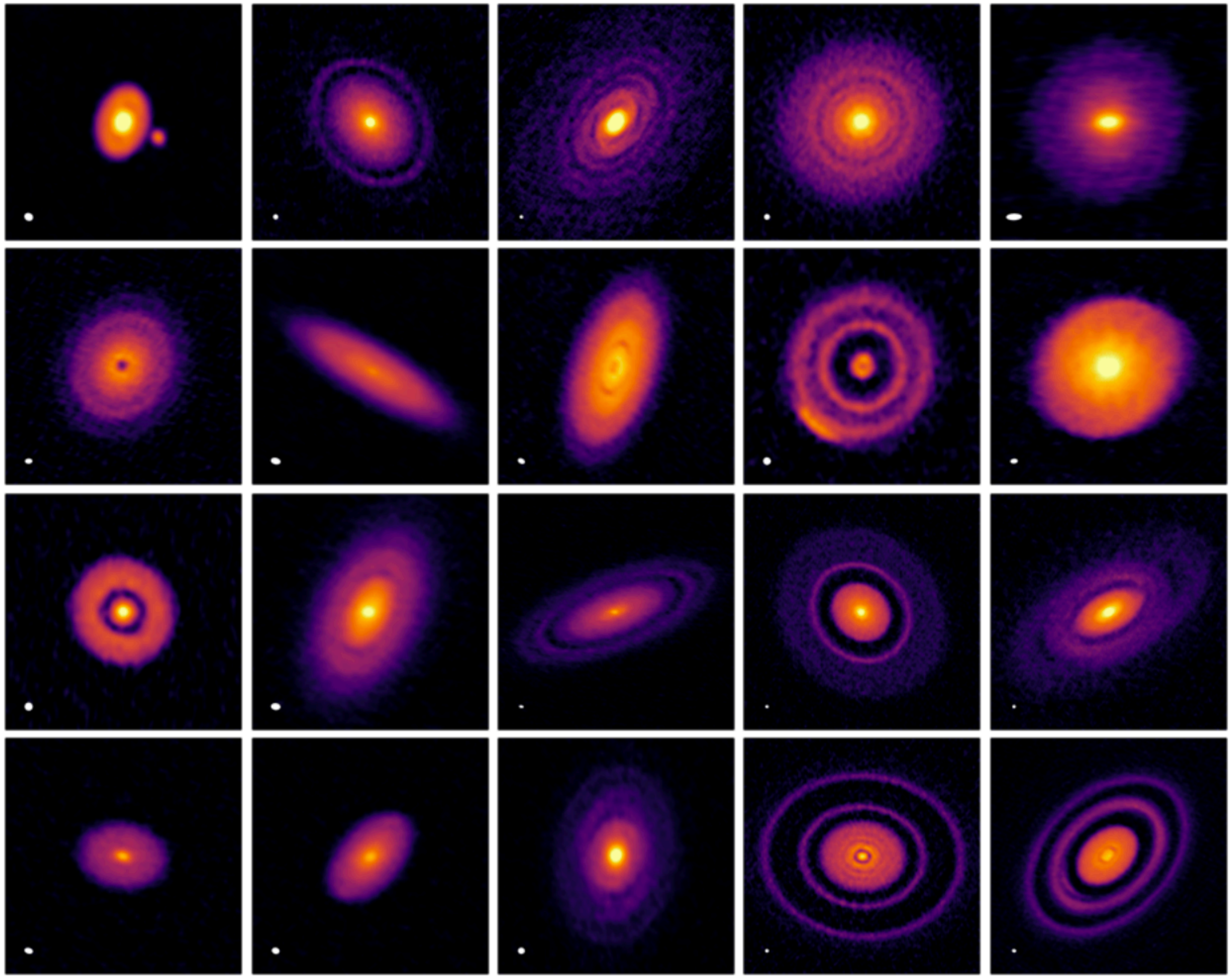
Lin, Bodenheimer & Richardson 1996

ALMA: A NIR interferometer at an altitude of 5000 meter to observe cold gas in the universe (ESO,US,Japan)

Formation of galaxies, stars, planets , interstellar matter, etc



Disk Substructures at High Angular Resolution Project (DSHARP)



This is the official Data Release webpage for the ALMA Cycle 4 Large Program *Disk Substructures at High Angular Resolution Project (DSHARP)*. DSHARP is a deep, high resolution (35 mas, or 5 au) survey of the 240 GHz (1.25 mm) continuum and ^{12}CO J=2-1 line emission from 20 nearby, bright, and large protoplanetary disks, designed to assess the prevalence, forms, locations, sizes, and amplitudes of small-scale substructures in the distributions of the disk material and how they might be related to the planet formation process.

Andrews et al.2018, ApJL submitted. *DSHARP I. Motivation,sample,calibration and overview .*

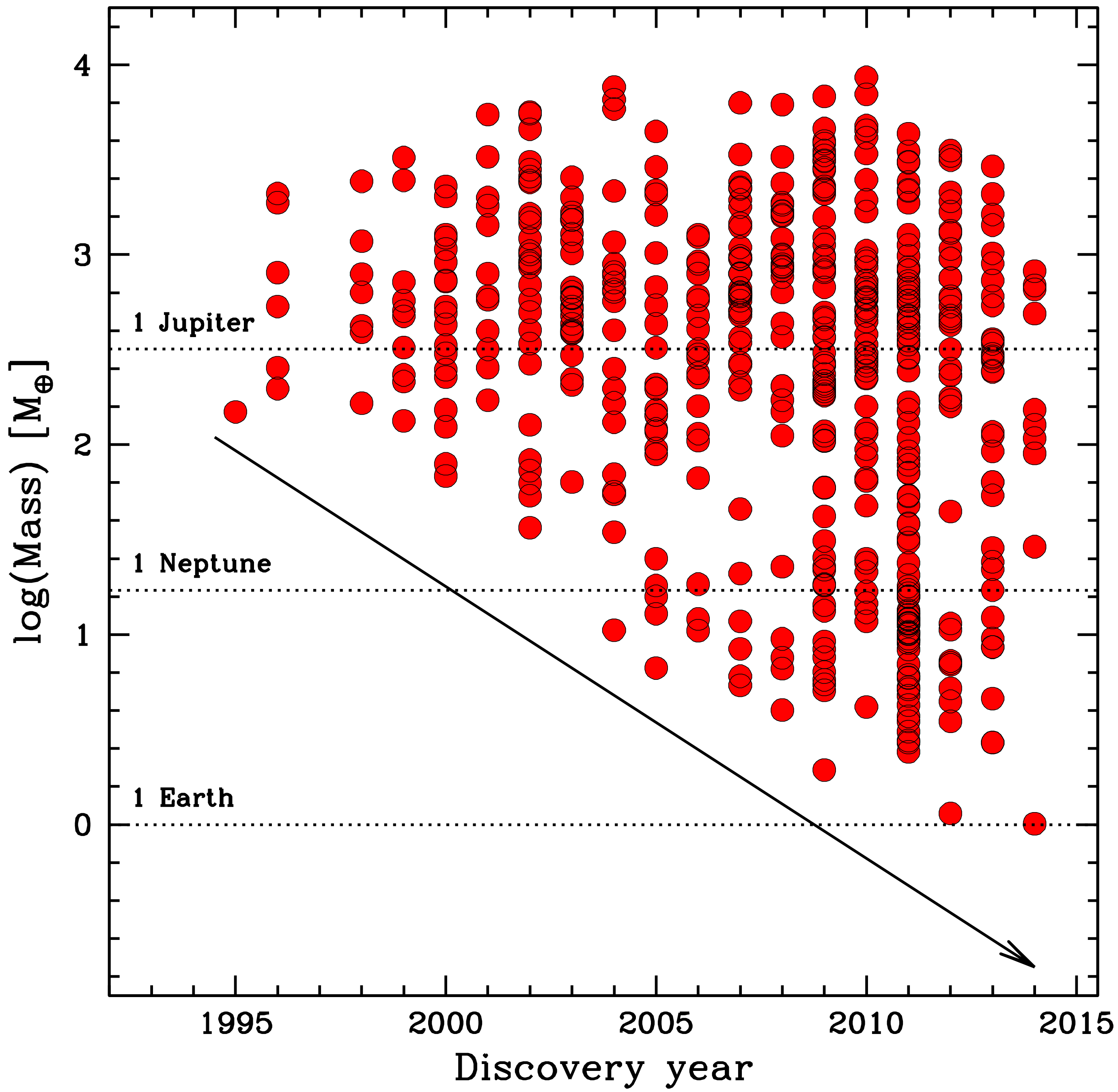
Increasing the precision

Radial velocity via cross-correlation spectroscopy:
A path to the detection of Earth-type planets

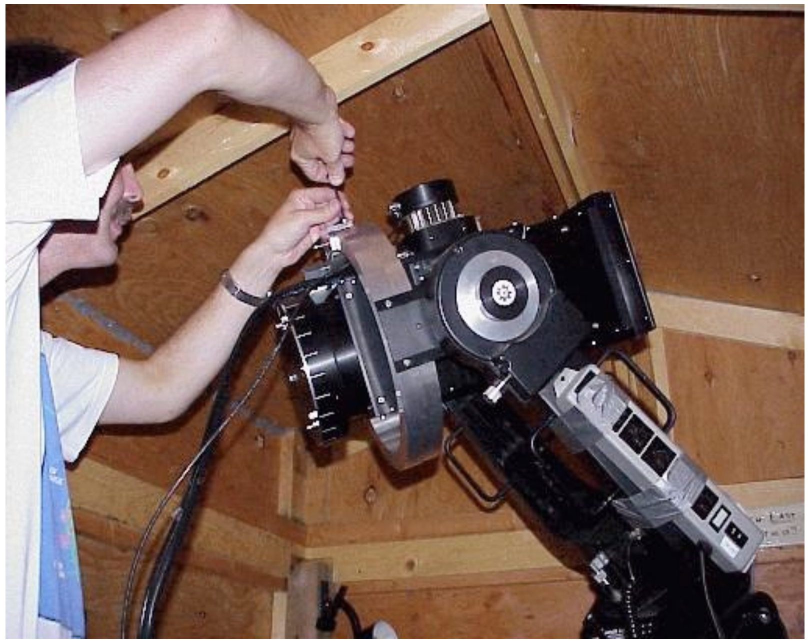
SPECTRO	year	precision	Telescope	
CORAVEL	1977	300 m/s	1 m	OHP
ELODIE	1994	13 m/s	1.9 m	OHP
CORALIE	1998	6 m/s	1 m	ESO Chile
HARPS	2003	1 m/s	3.6 m	ESO Chile
HARPS-N	2013	1 m/s	3.5 m	IAC La Palma
ESPRESSO	2018	0.1 m/s	8.2 m (x4)	ESO Chile

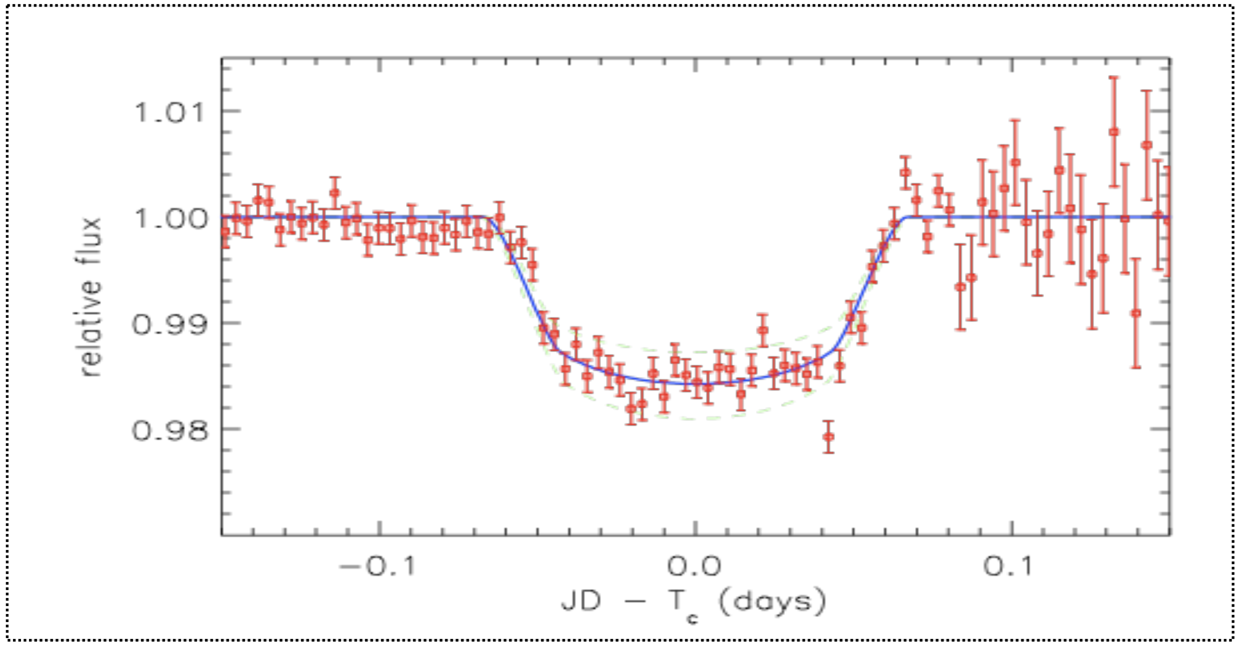
An increase of the sensibility by a factor 3000 during the last 40 years

Since 1995 : a huge number of discoveries and improvement of astronomical instrumentation

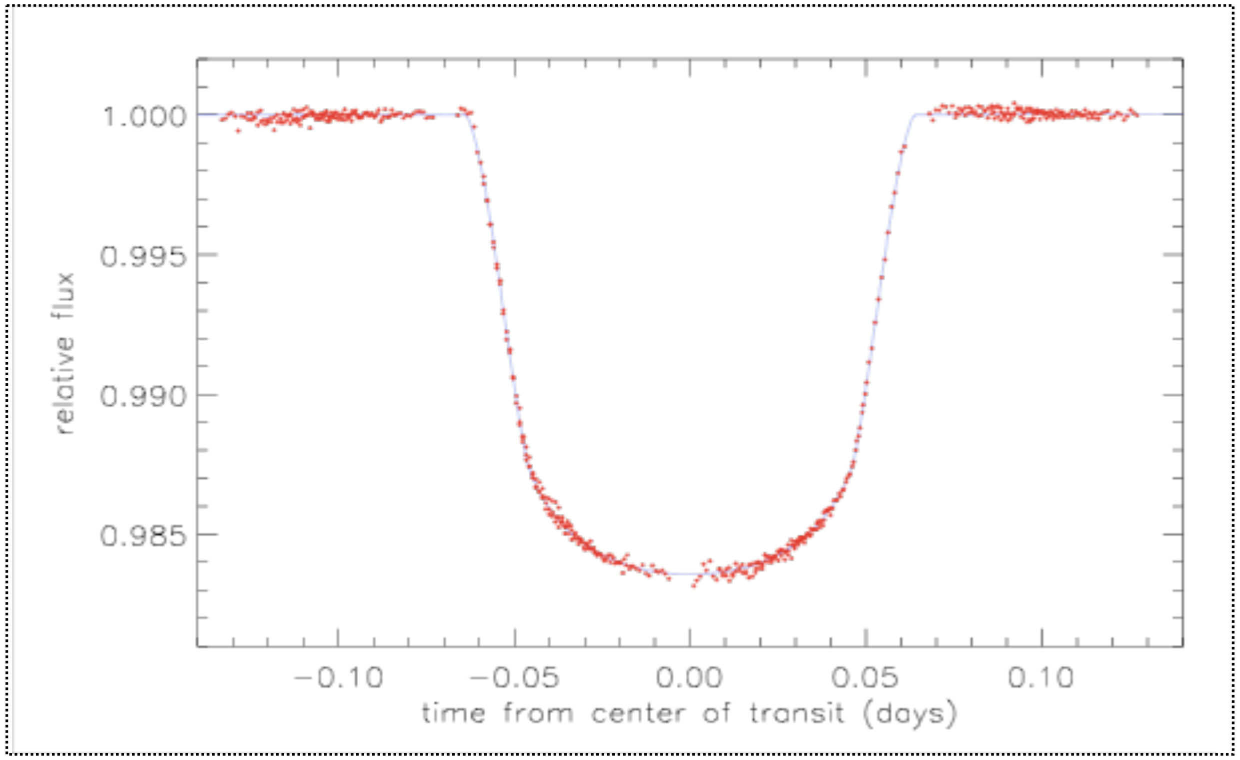


9 and 16th Sept 1999: A first planetary transit





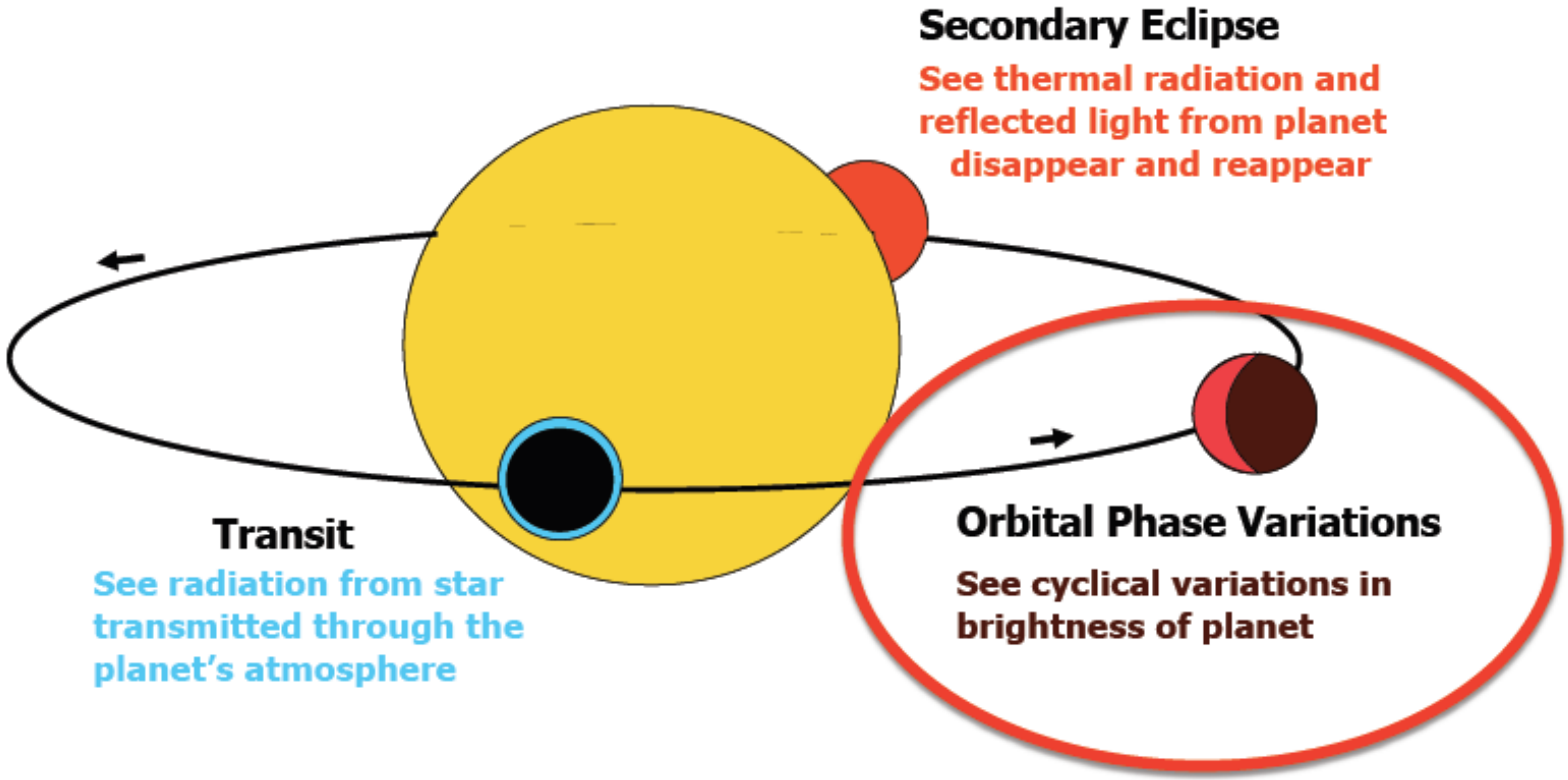
Charbonneau, Brown,Latham, Mayor 2000, ApJ,529



Brown, Charbonneau, Gilliland, Noyes, Burrows 2001,ApJ,552,699

HOT JUPITERS are gaseous giant planets : density = 0.3 g/ cm**3

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



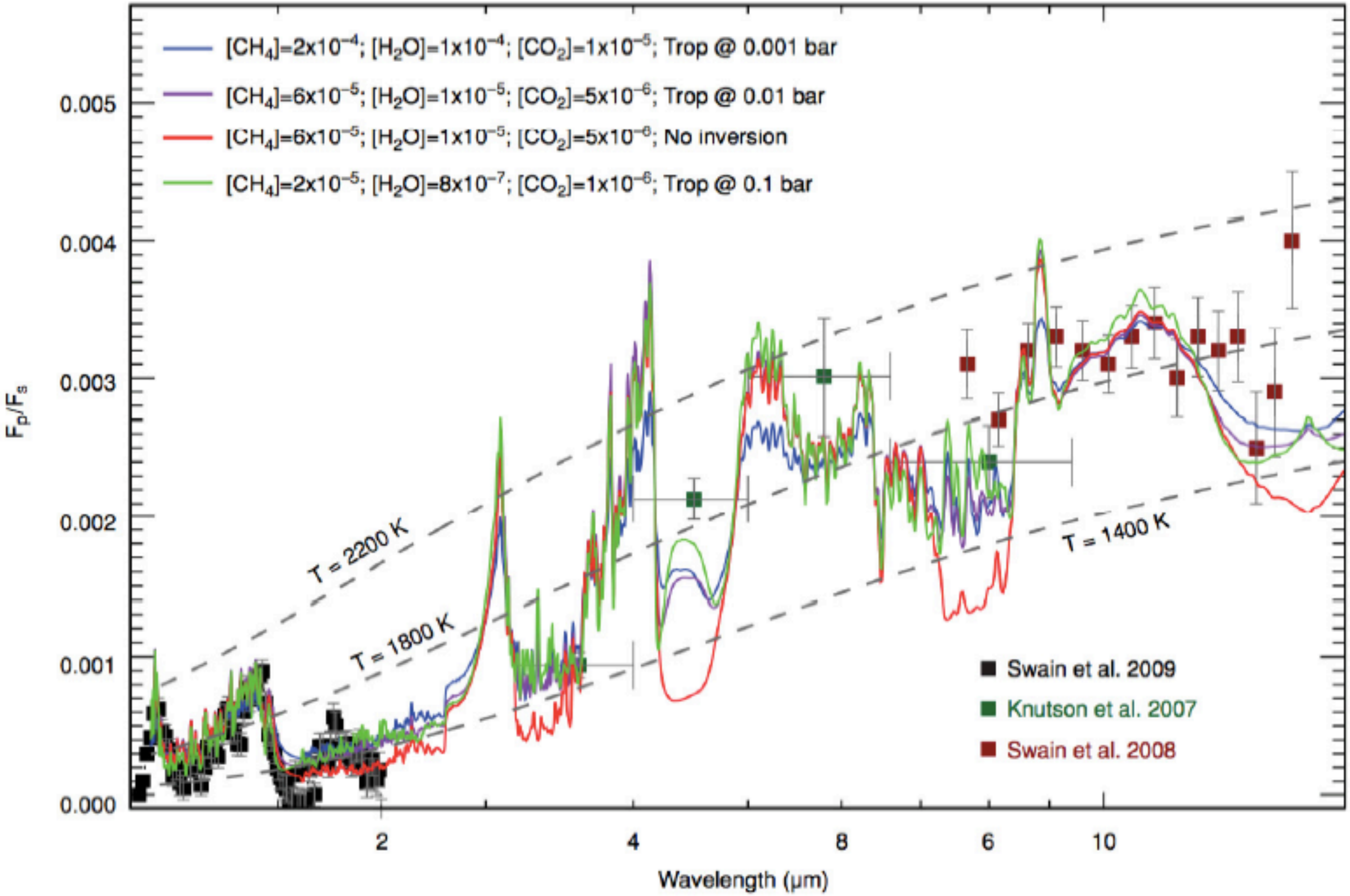
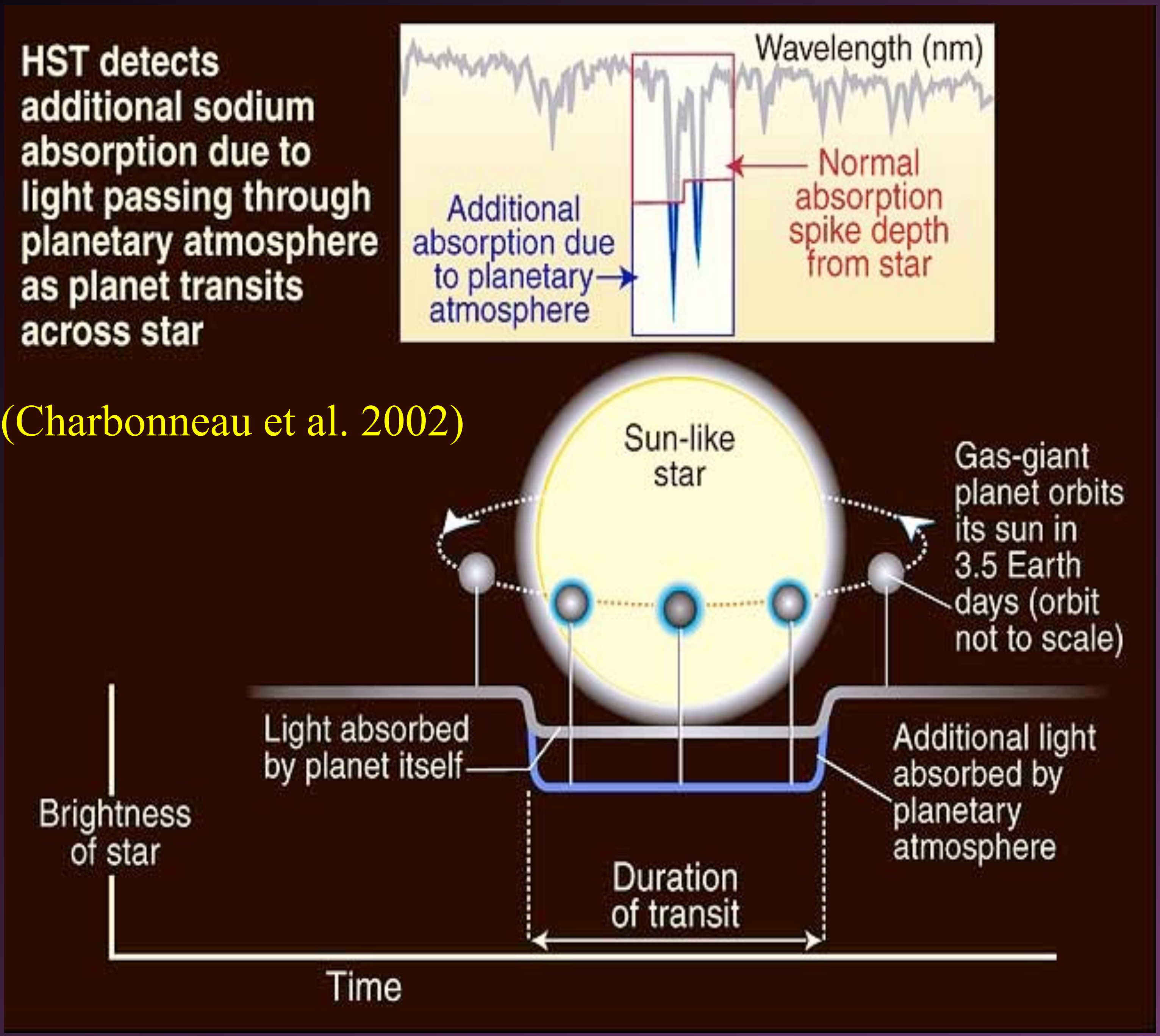


Figure 1: Synthetic emission spectra of the hot Jupiter HD209458b together with various observational data points (Swain et al. 2009). The data are from various sources, and there are gaps in the spectral coverage. Despite over a decade of study, the sparse data shown here represent the highest-quality exoplanet spectrum obtained to date.

Transmission spectroscopy
Identification of atoms and molecules



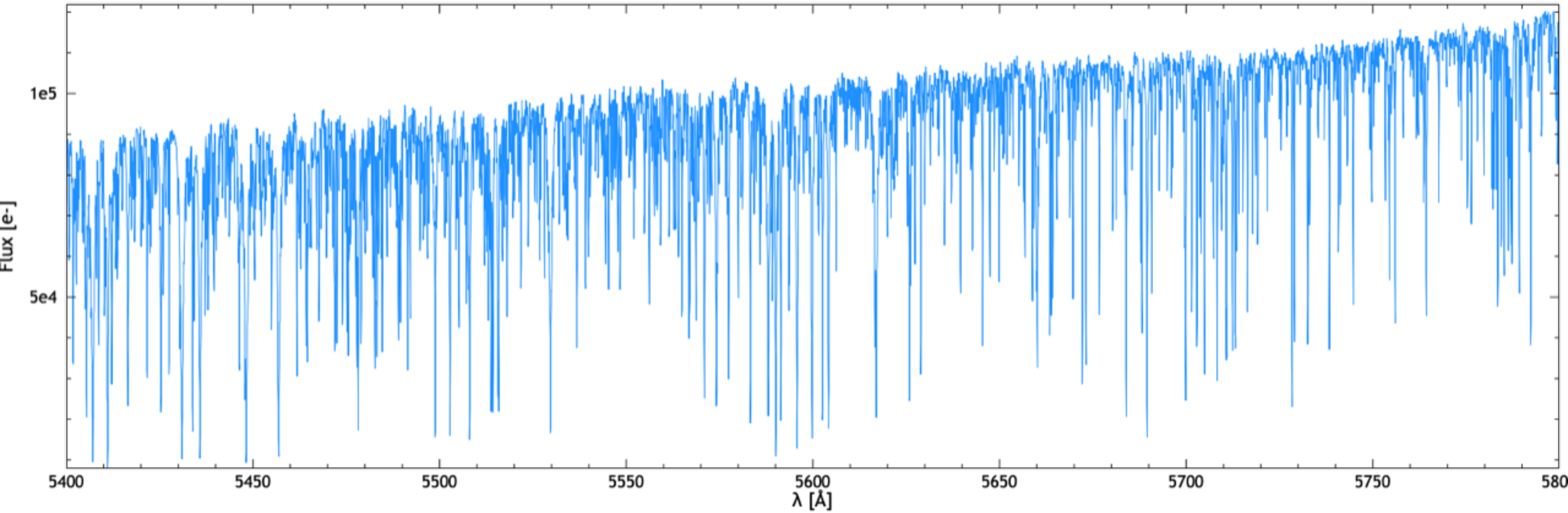
(Charbonneau et al. 2002)

- Na (Charbonneau et al. 2002)
- H_2, H_2O (Grillmaire et al. 2008, Swain et al. 2008, 2009)
- CO, CO2 (Swain et al. 2009ab, Madhusudhan & Seager 2009)
- CH_4 (Swain et al. 2008)
- Fe,Fe+,Ti+ (Hoejmakers et al,2018)

Rem: mainly for the 2 brightest stars with transit, HD209458 and HD189733

HARPS-N (la Silla observatory) 2003

Mayor, Pepe, Queloz et al. 2003, Msngr. 114,20



1e5
5e4
Flux [e-]
5400
5450
5500
5550
5600
5650
5700
5750
580
λ [Å]

HD10180 : A planetary system with more than 7 planets

P_1 = 1.18 day
e_1 = 0
m_1 sini = 1.5 $M_{\oplus}$

P_2 = 5.76 days
e_2 = 0.07
m_2 sini = 13.2 $M_{\oplus}$

P_3 = 16.4 days
e_3 = 0.16
m_3 sini = 11.8 $M_{\oplus}$

P_4 = 49.7 days
e_4 = 0.06
m_4 sini = 24.8 $M_{\oplus}$

P_5 = 122.7 days
e_5 = 0.13
m_5 sini = 23.4 $M_{\oplus}$

P_6 = 595 days
e_6 = 0.0
m_6 sini = 22 $M_{\oplus}$

P_7 = 2150 days
e_7 = 0.15
m_7 sini = 67 $M_{\oplus}$

Lovis et al. 2011, A&A 528,112

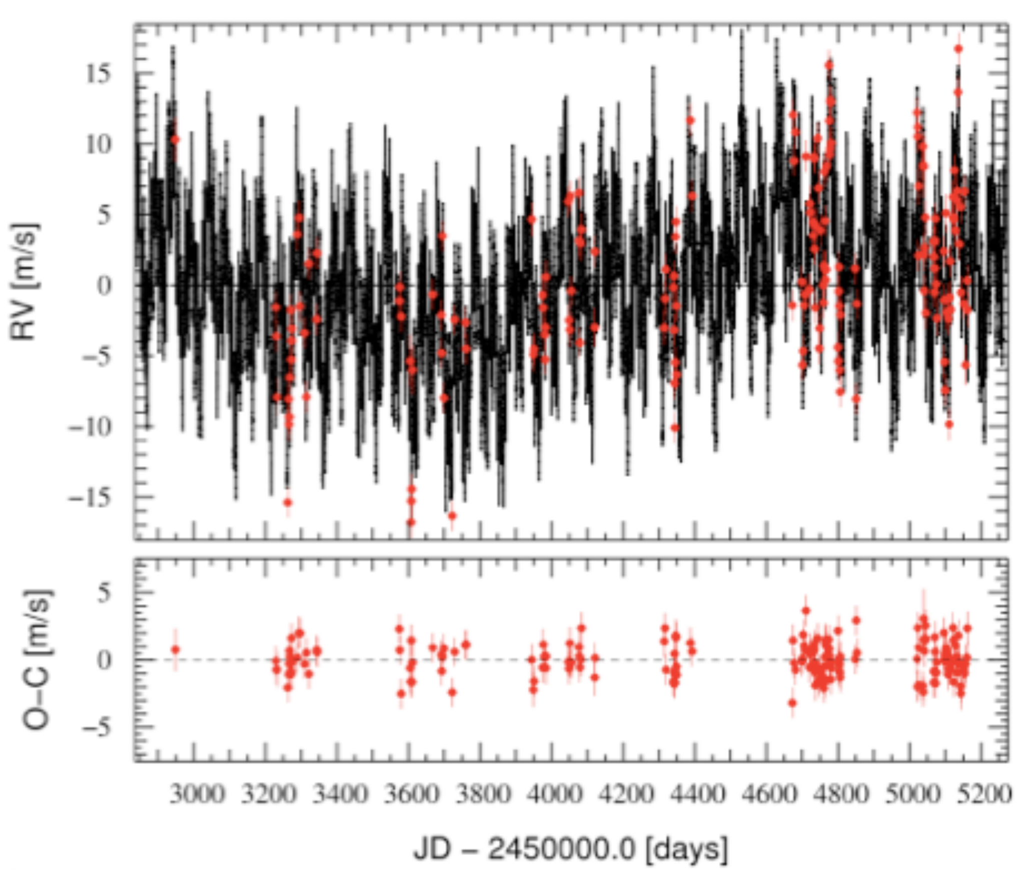
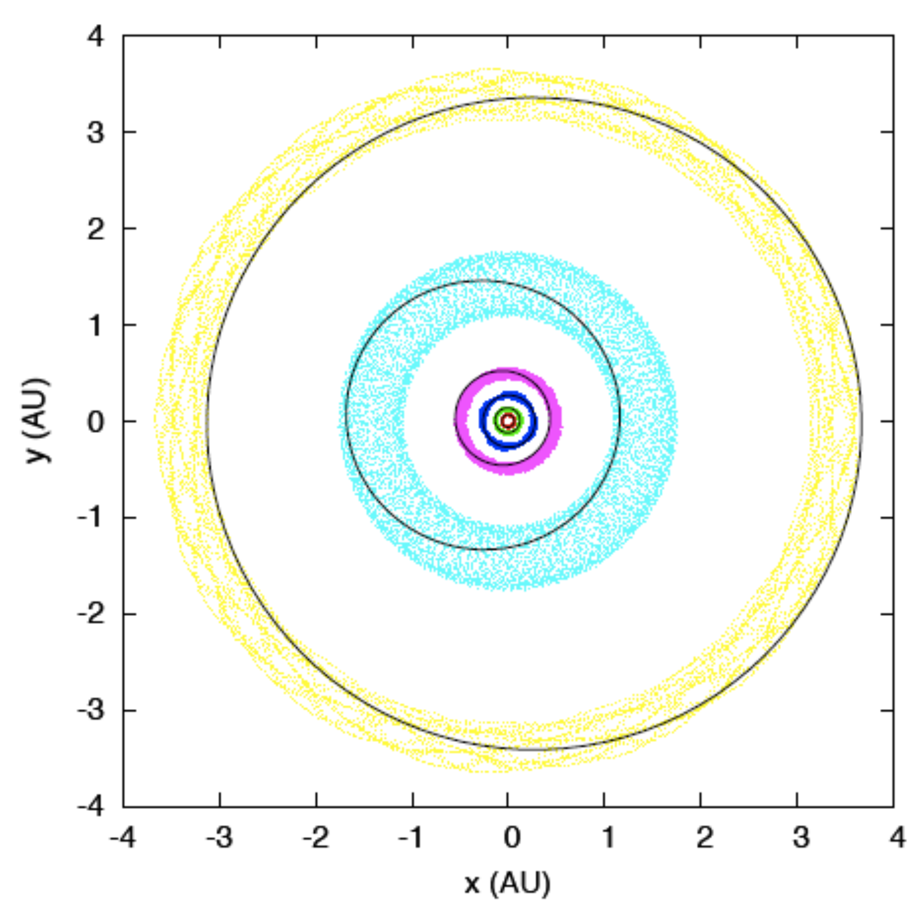
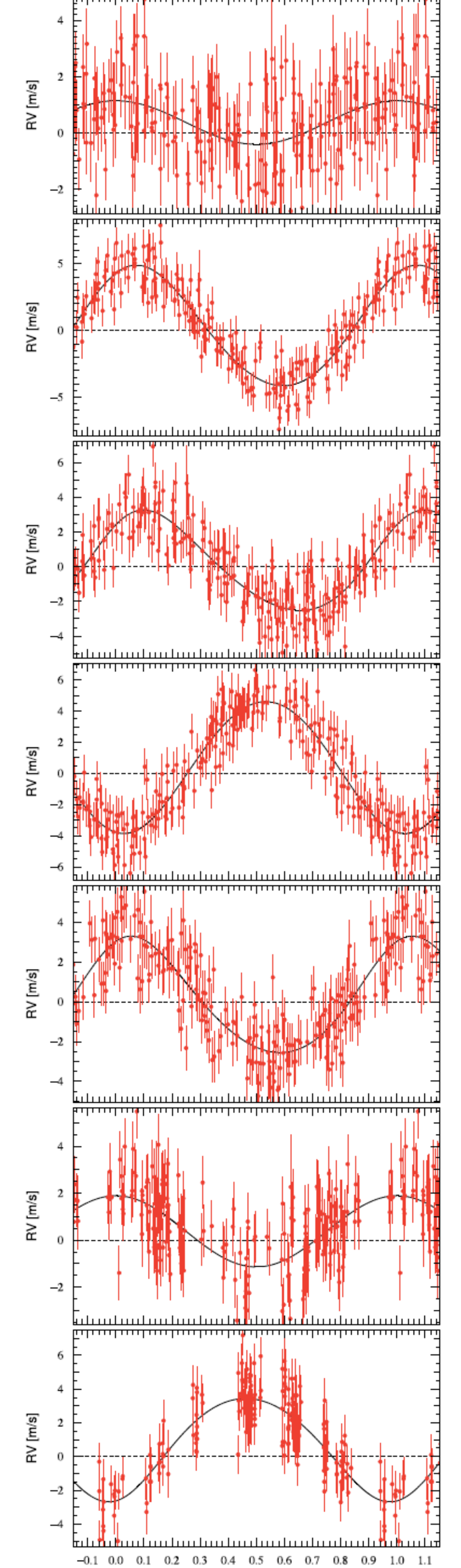


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo





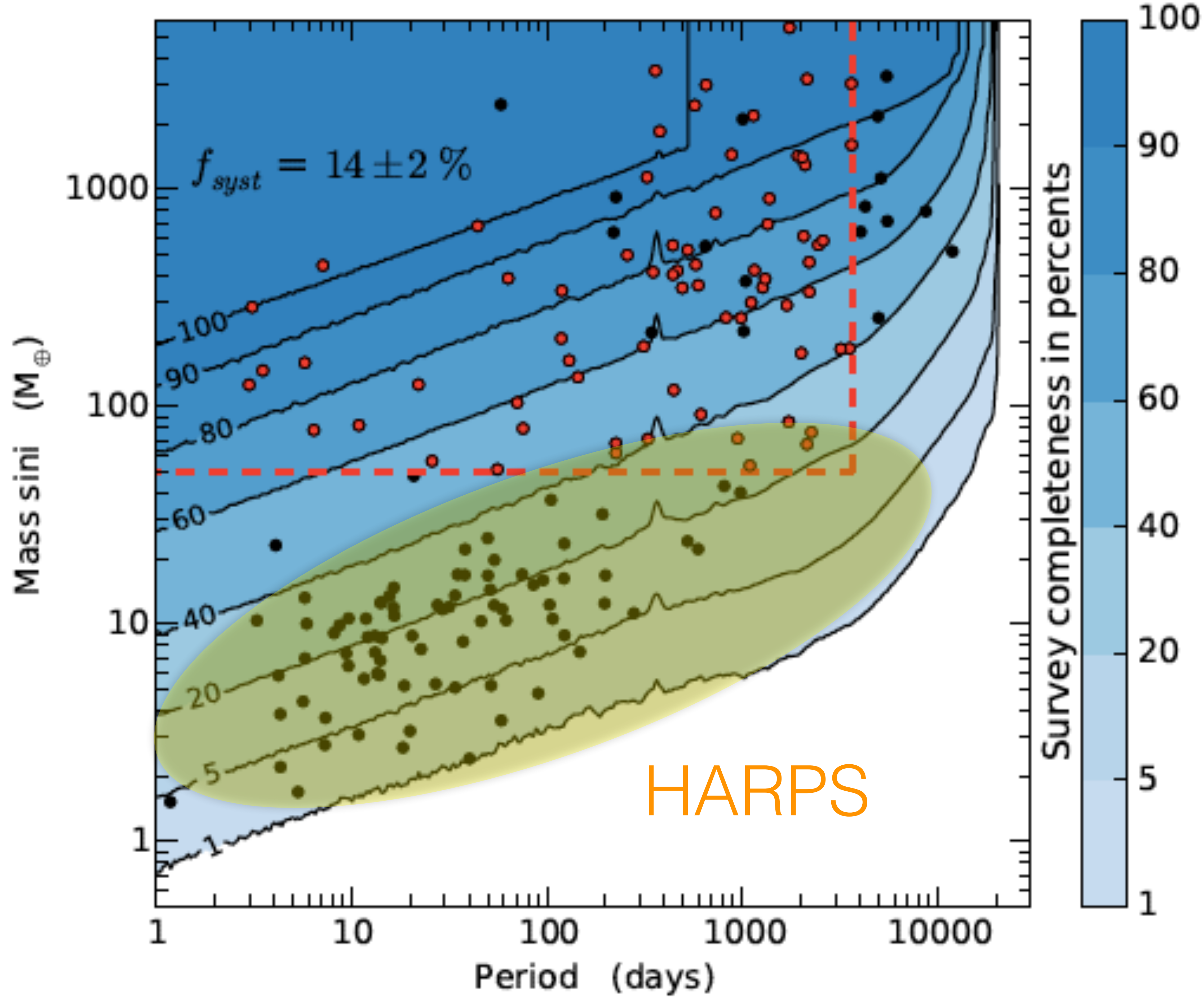


Fig. 5. Plot of the 169 planets of the considered HARPS+CORALIE sample in the $m_2 \sin i - \log P$ plane. The superimposed curves indicate the completeness of the survey. These detection probabilities are valid for the whole sample of 822 stars. After correcting for the detection bias, the fraction of stars with at least one planet more massive than 50 $M_\oplus$ and with a period smaller than 10 years is estimated to be 14 ± 2 %. The red points represent the planets which

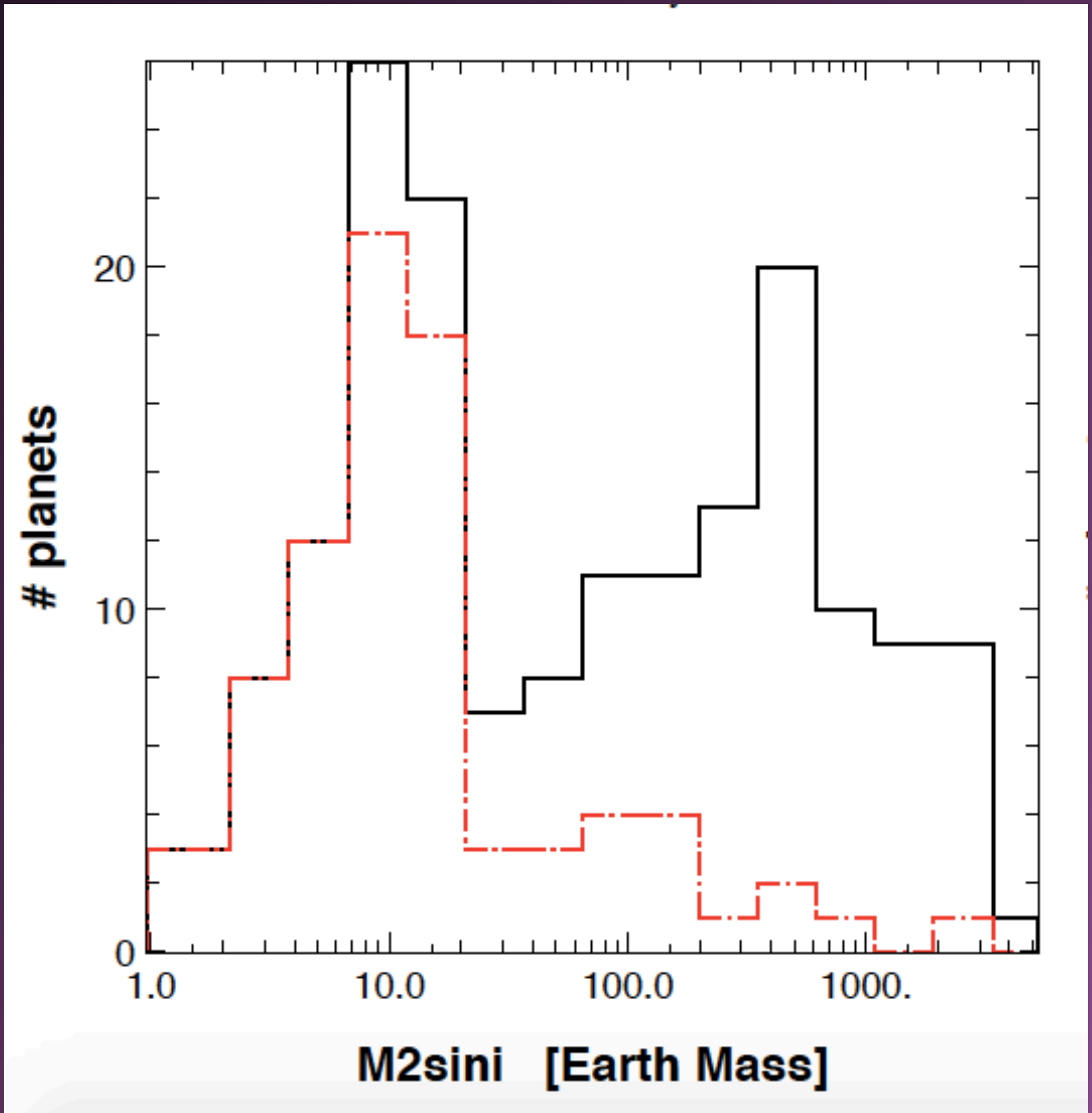
The HARPS survey at la Silla
continuing since 2003

*** % of planetary systems
as function of mass, period, metallicity
of the host star, …

Updated from
Mayor et al. 2011

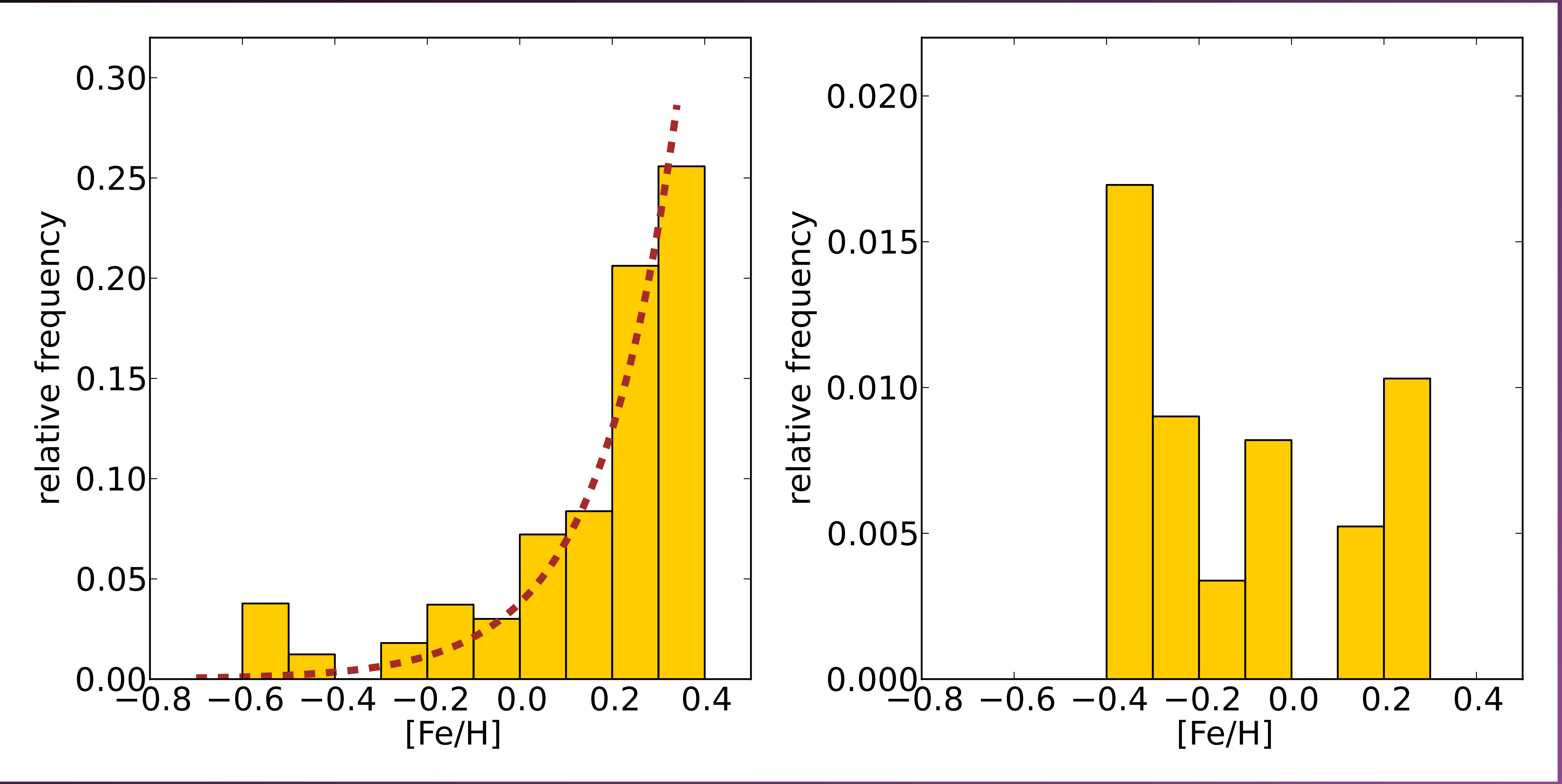
In red : Period < 100 days ……. Huge excess of planets in the domain of Super-Earths and Neptune-mass planets.

In black : Combined sample CORALIE ,volume and precision limited with HARPS sample higher precision ….. the « giant planet population is over represented »



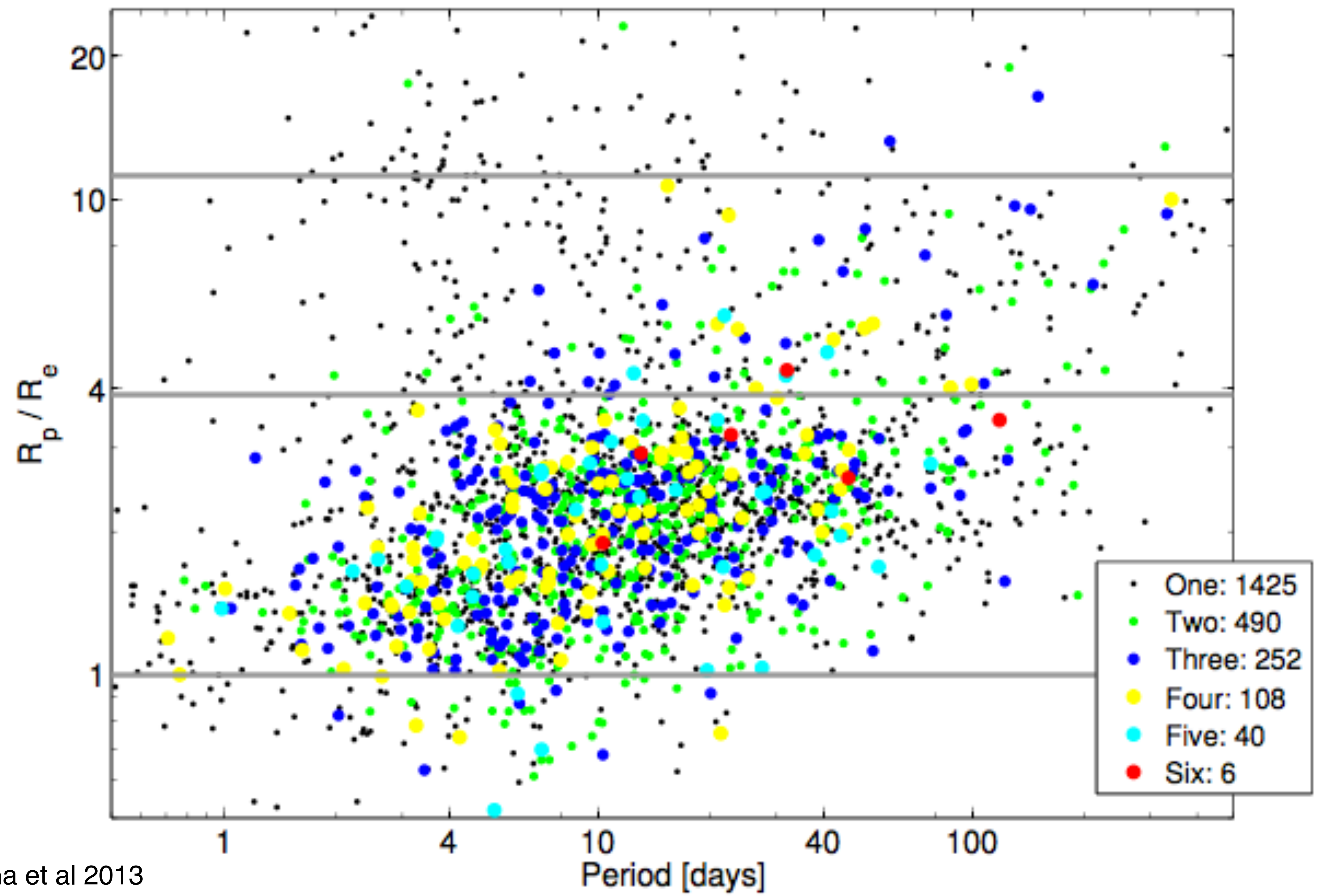
LEFT: Host star metallicity having Jupiter mass companions

RIGHT: Host star metallicity having planetary companions less massive than 30 Earth-mass.



HARPS Survey at La Silla

KEPLER discoveries

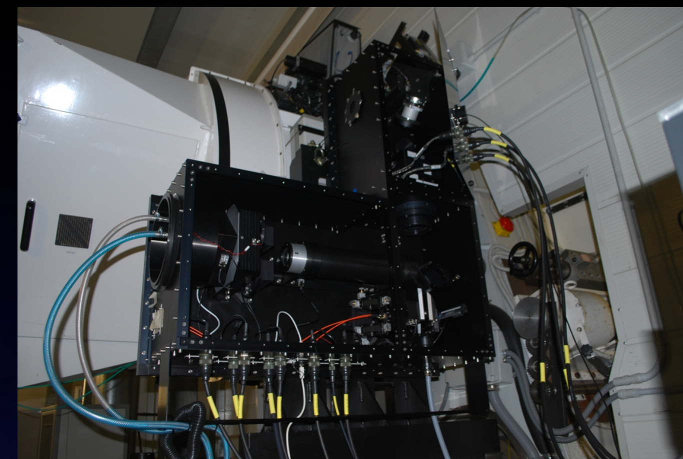


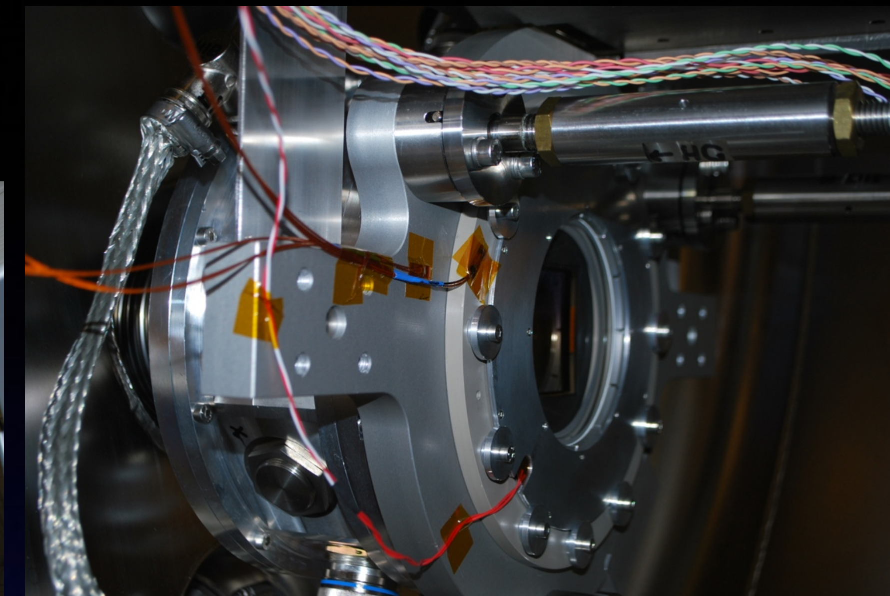
Batalha et al 2013

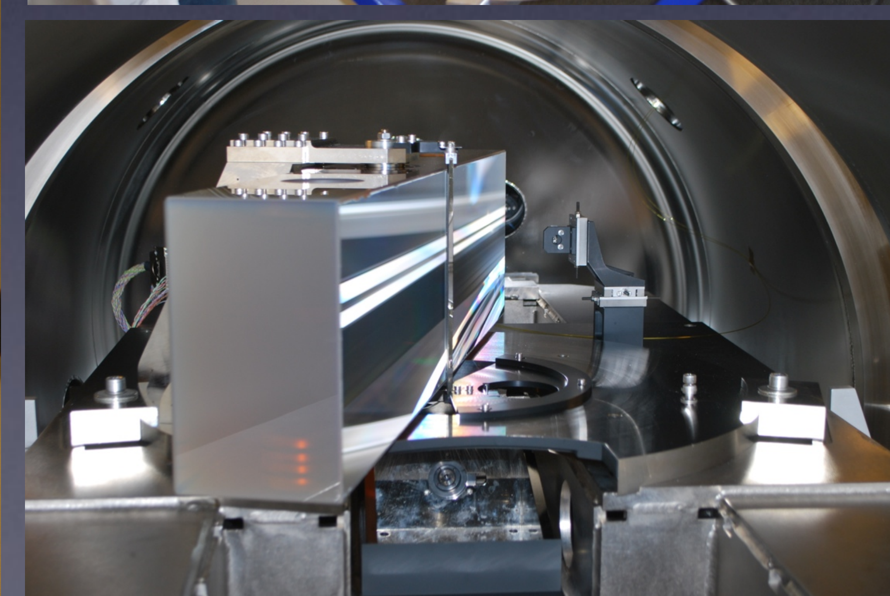
Planets with masses
from 1 to 10 Earth-mass
are the most frequent ones

(at least with our current
level of detection !)

HARPS-N @ Galileo telescope at La Palma Observatory







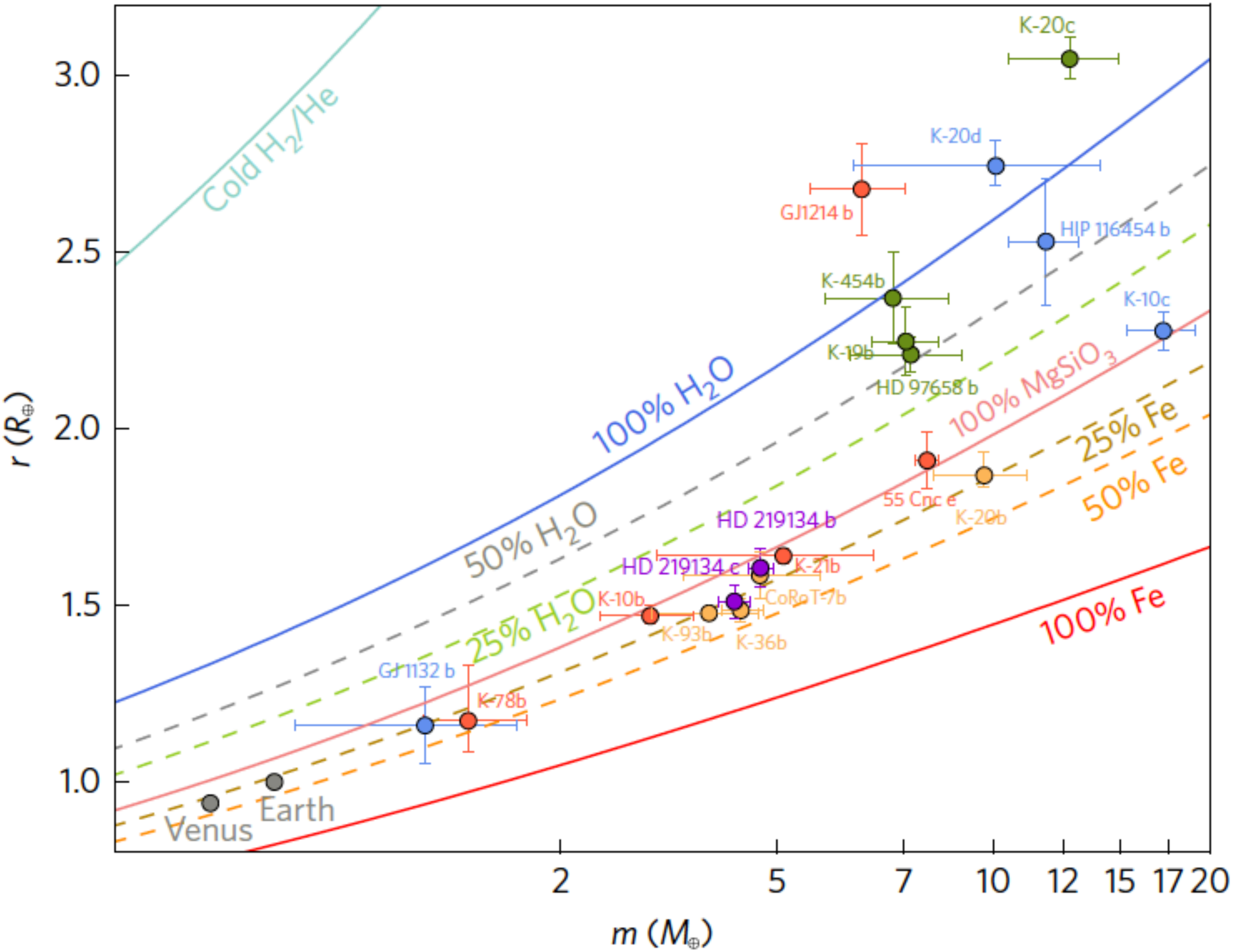
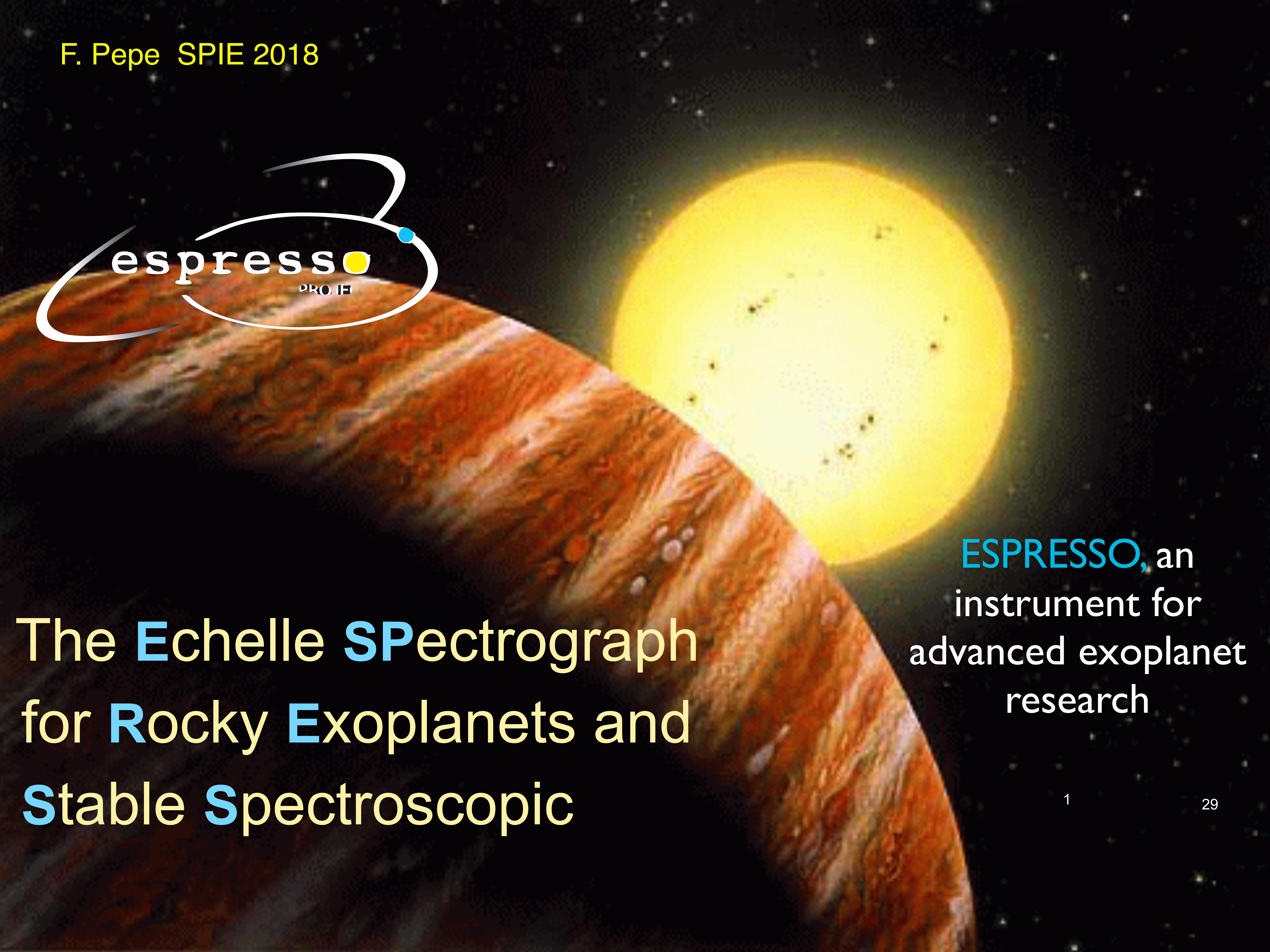


Figure 2 | Mass–radius relationship for small planets with precisions on the masses better than 20%. The solid lines are theoretical mass–radius curves from previous work[20].

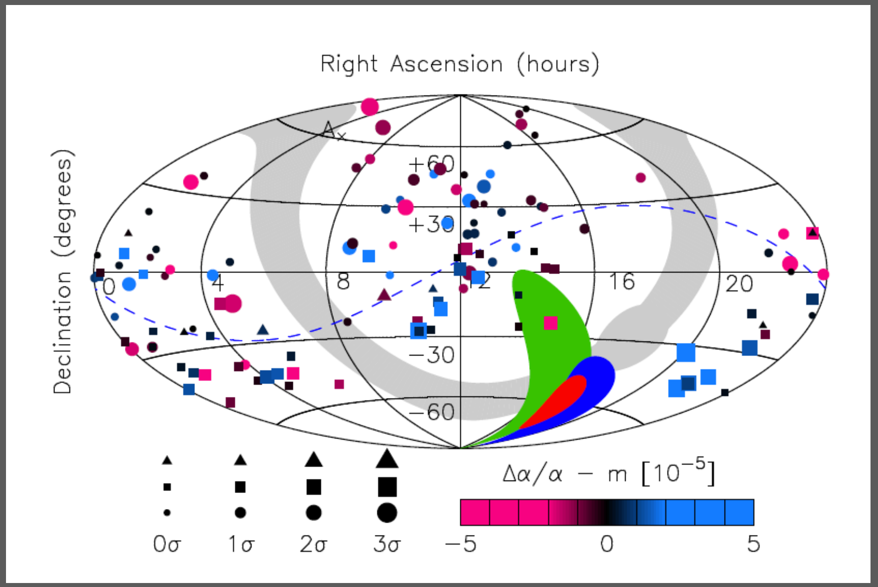

F. Pepe SPIE 2018
espresso
The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic
ESPRESSO, an instrument for advanced exoplanet research
1
29

A spectrograph on a 16 m telescope,

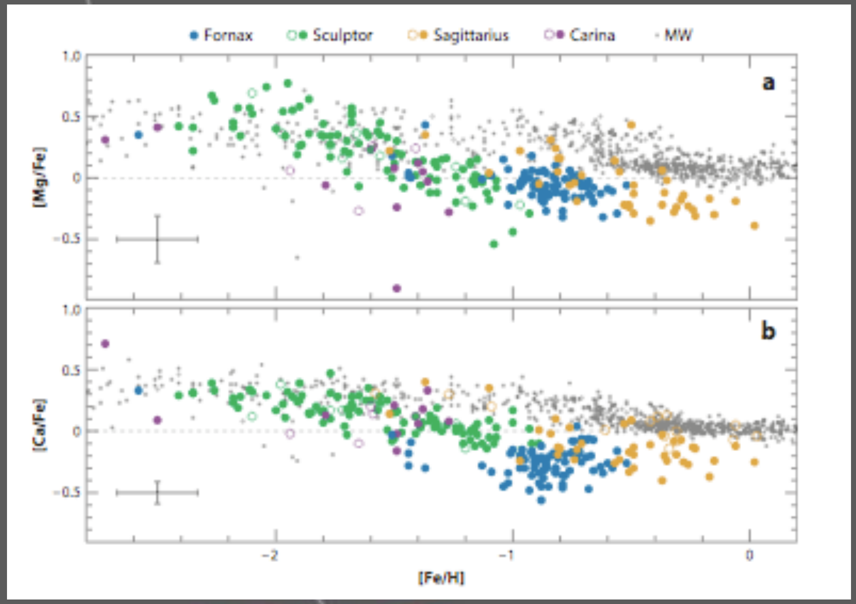
CfP: Science drivers

Rocky planets of
Earth-size (~10 cm/s)

Webb et al 2011

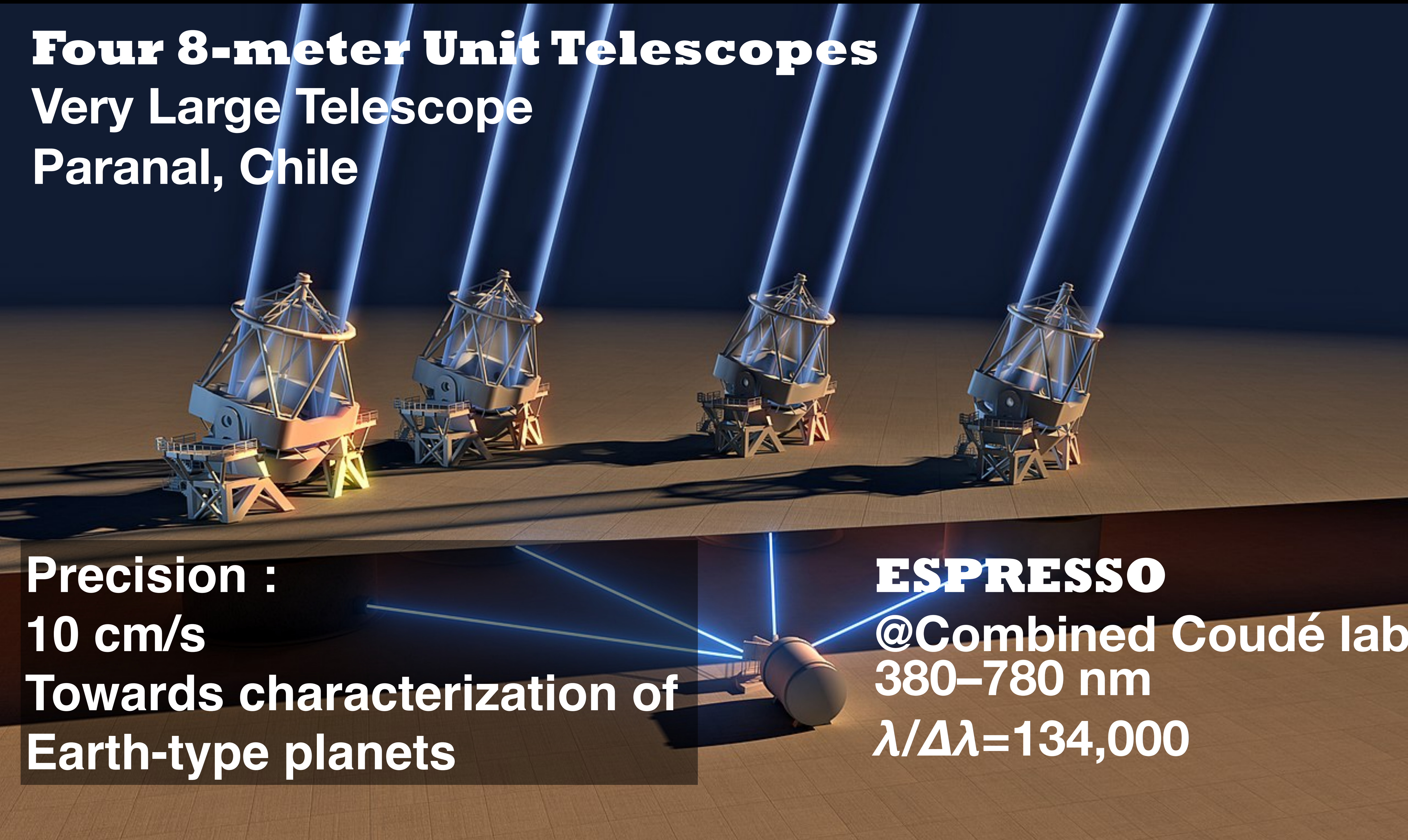


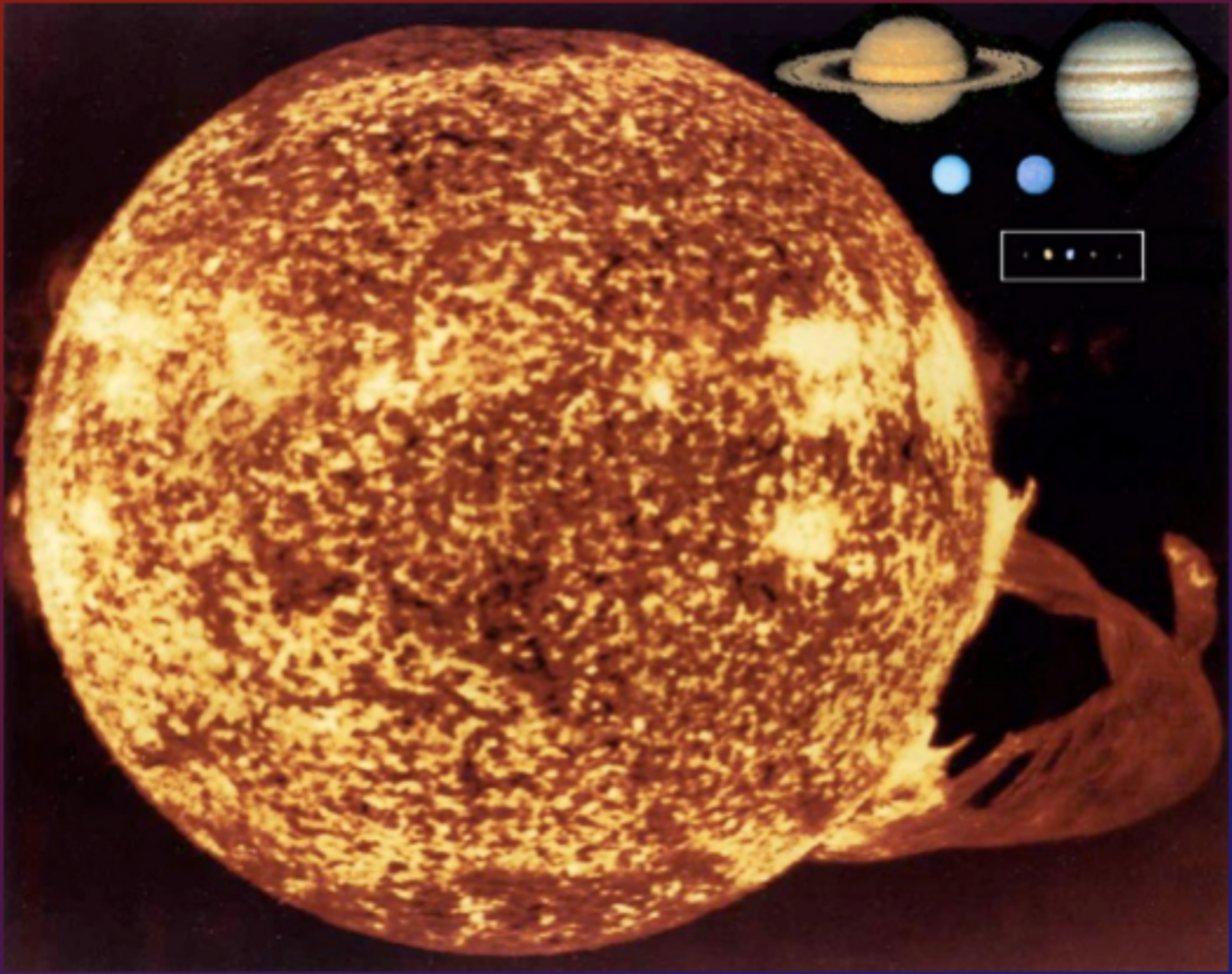
Variability of
fundamental constants



Tolstoy et al 2009

Abundances in local group
galaxies


Four 8-meter Unit Telescopes
Very Large Telescope
Paranal, Chile
Precision :
10 cm/s
Towards characterization of
Earth-type planets
ESPRESSO
@Combined Coudé lab
380–780 nm
λ/Δλ=134,000

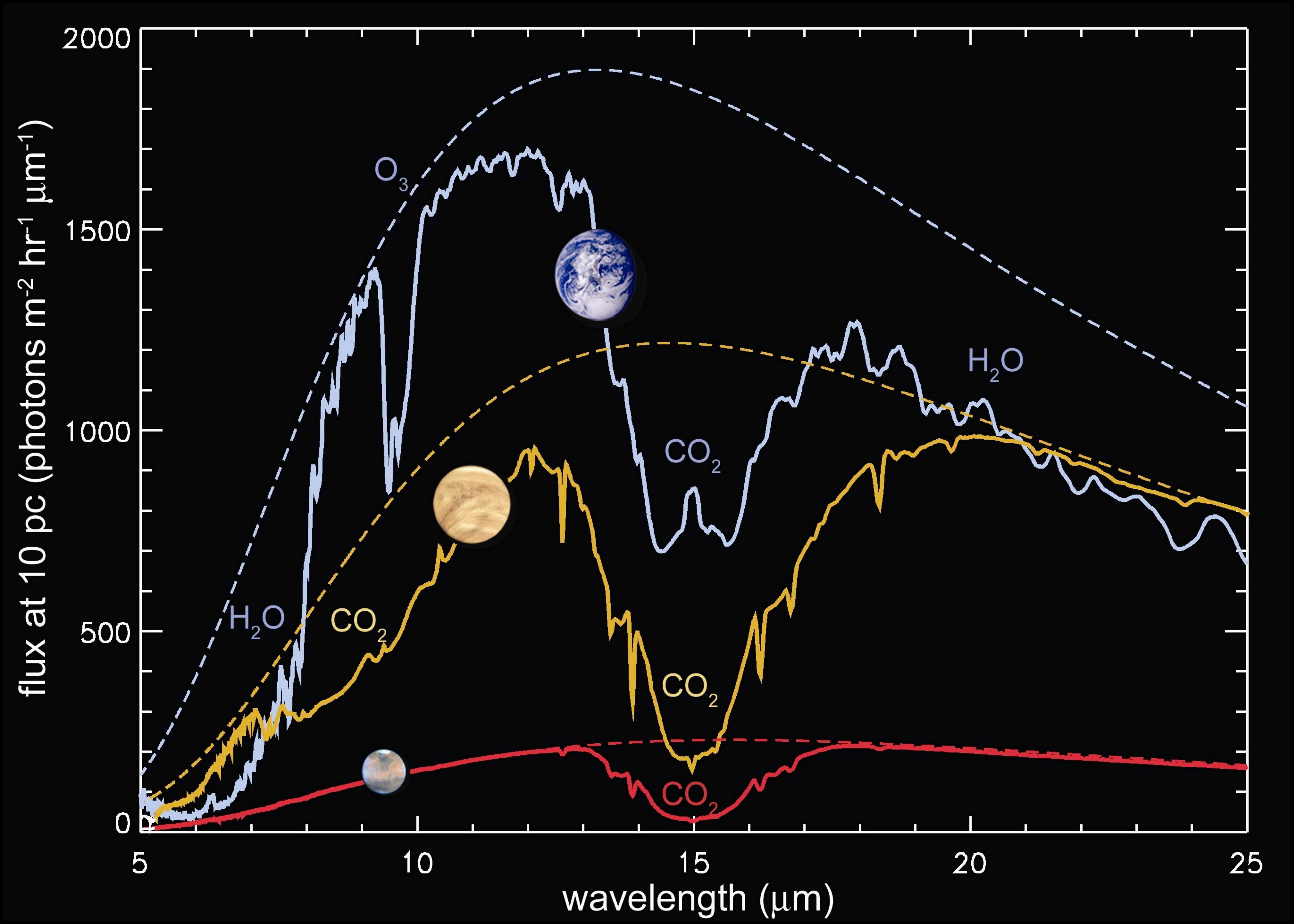



ESPRESSO
SPECULOS
NGTS
SPHERE


HARPS + NIRPS
MASCARA
EXTRA
CORALIE
TRAPPIST

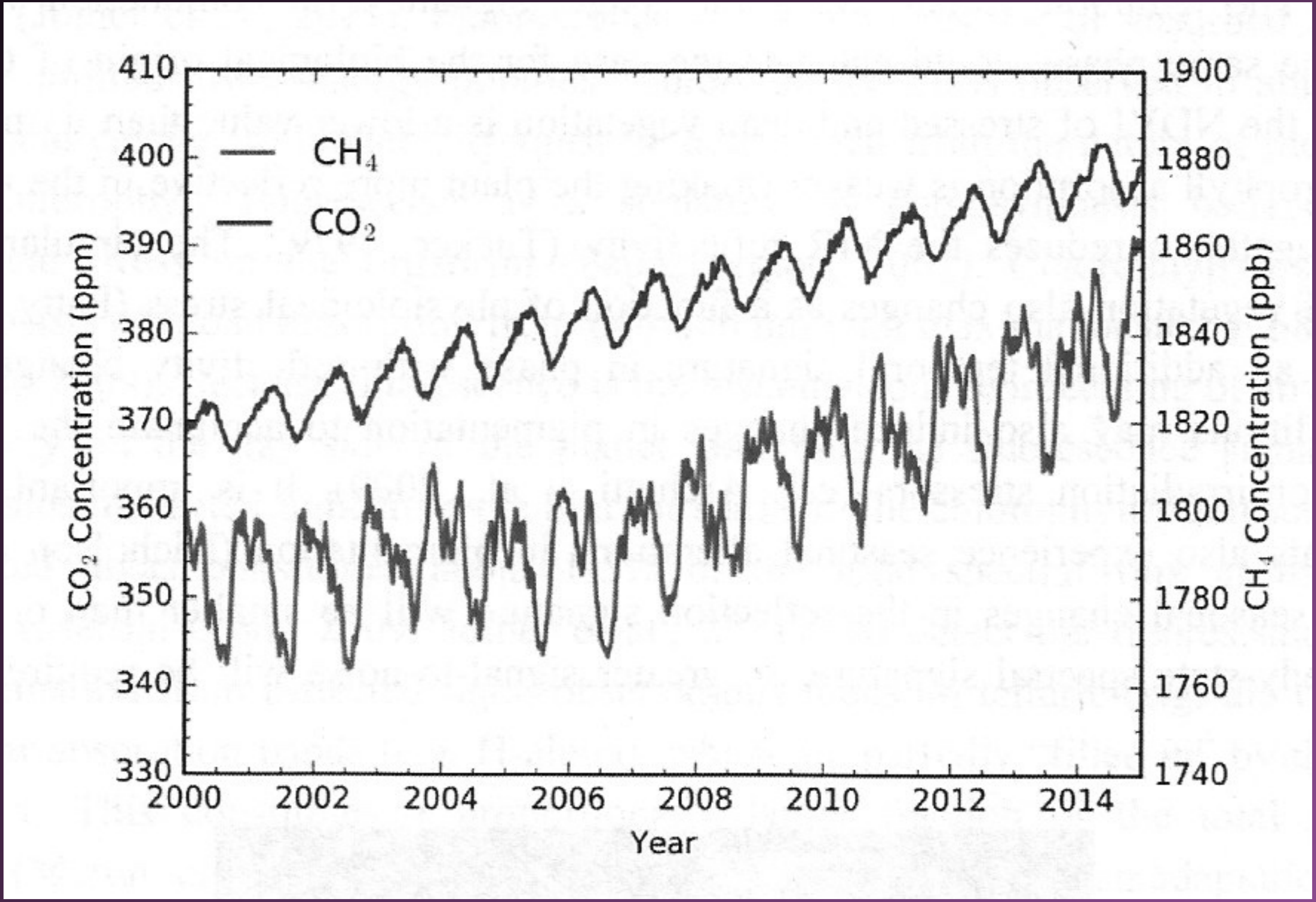
Life : A cosmic imperative ?

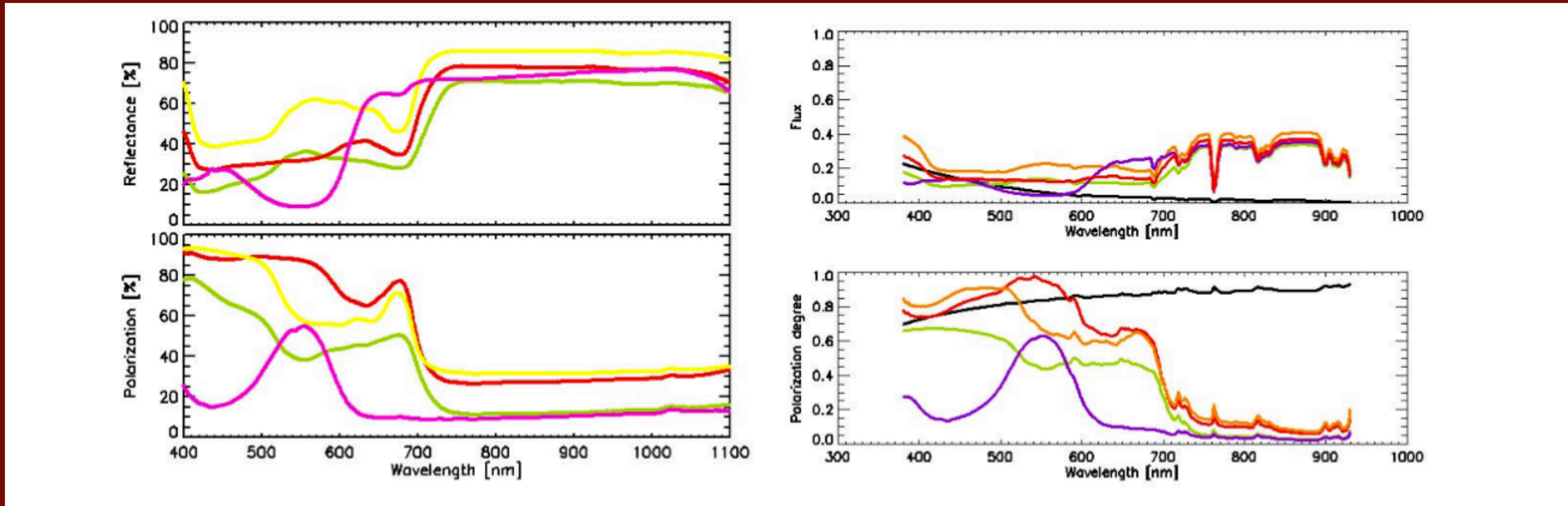
Christian de Duve


2000
1500
1000
500
0
flux at 10 pc (photons m-2 hr-1 μm-1)
5
10
15
20
25
wavelength (μm)
O3
H2O
CO2
H2O
CO2
CO2
CO2

Selsis 2007

Atmospheric Seasonality as an Exoplanet Biosignature
(see for example S.L.Olson et al. 2018, ApJ Lett May 18)





Reflectance and polarization of biopigments (left fig.)

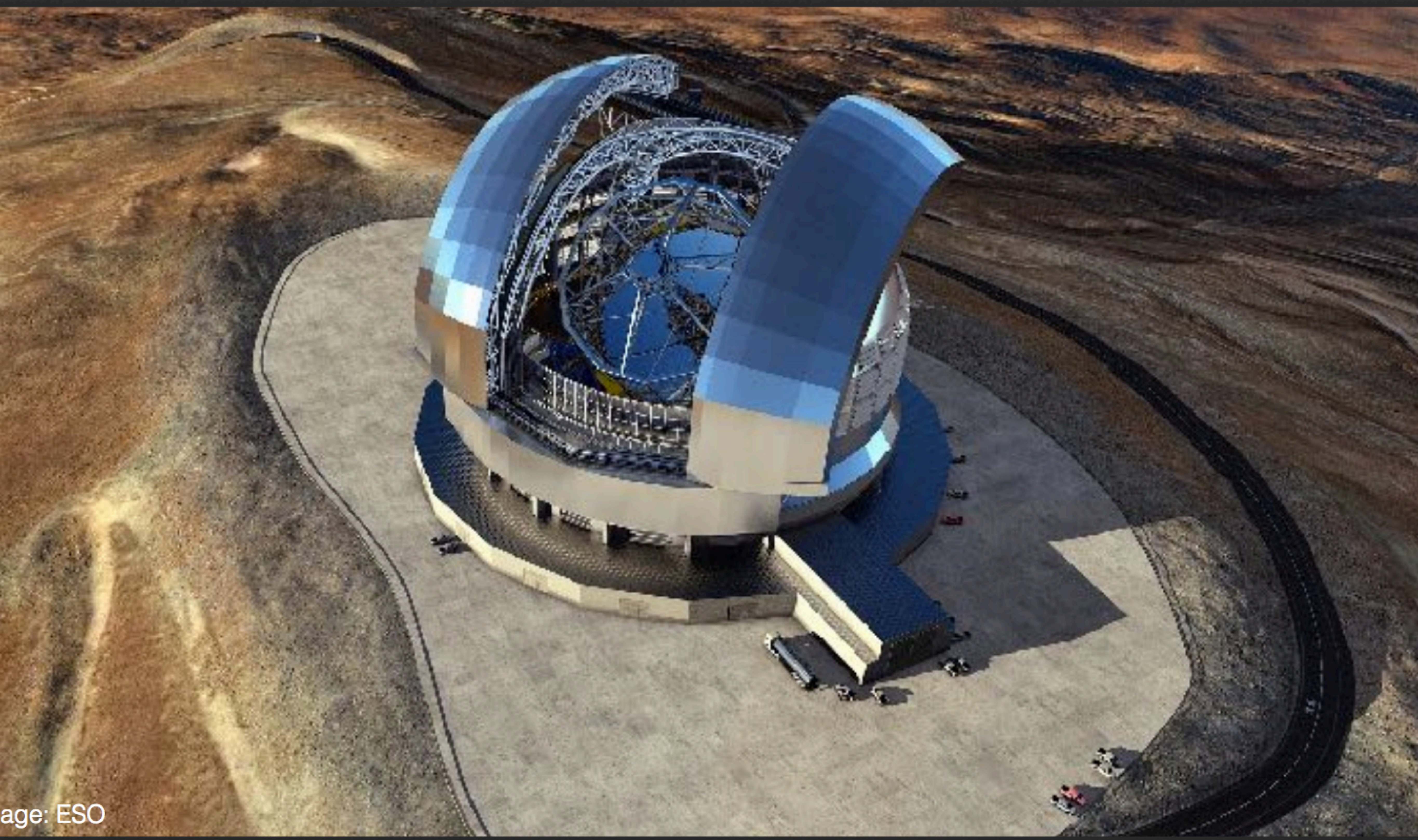
(for example : chlorophyll (green curve), carotenoids(yellow)

A planet with 80% vegetation + 20 oceans (right fig.)

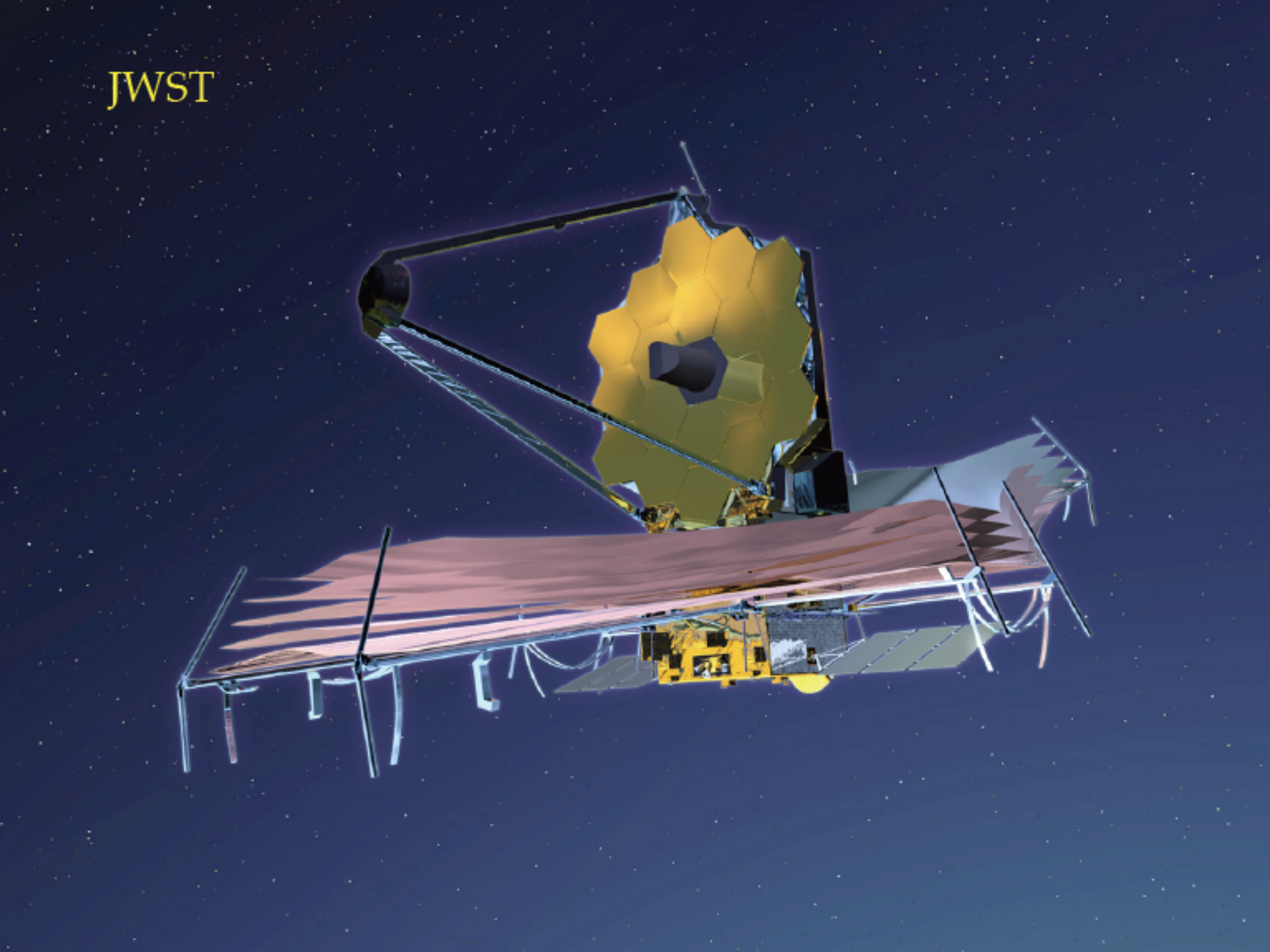
(with 100% of oceans : black curve)

(Berdyugina et al. 2016)

E-ELT Un télescope ESO, diamètre 39 m
Cerro Armazones Chili , 2024



JWST



Thank you