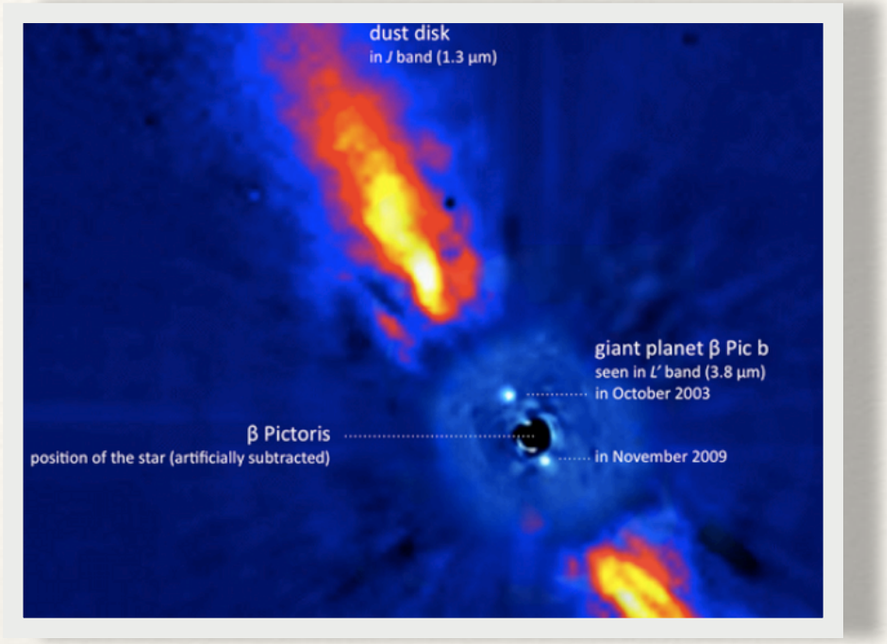
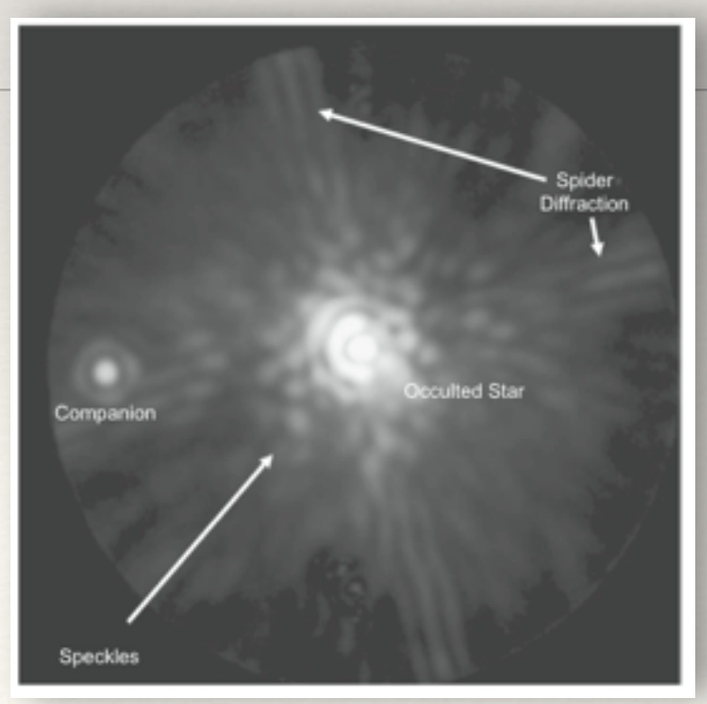


R. Claudi - INAF - Astronomical Observatory of Padova

DIRECT IMAGING OF EXTRASOLAR PLANETS

I: INTRODUCTION AND ASTROPHYSICAL MOTIVATION



1st ADVANCED SCHOOL OF EXOPLANETARY SCIENCE
METHODS OF DETECTING EXOPLANETS
MAY 25-29, 2015 - VIETRI SUL MARE (SA)

Introduction

Astrophysical Motivation

Observation Issues

Adaptive Optics

Coronagraphy

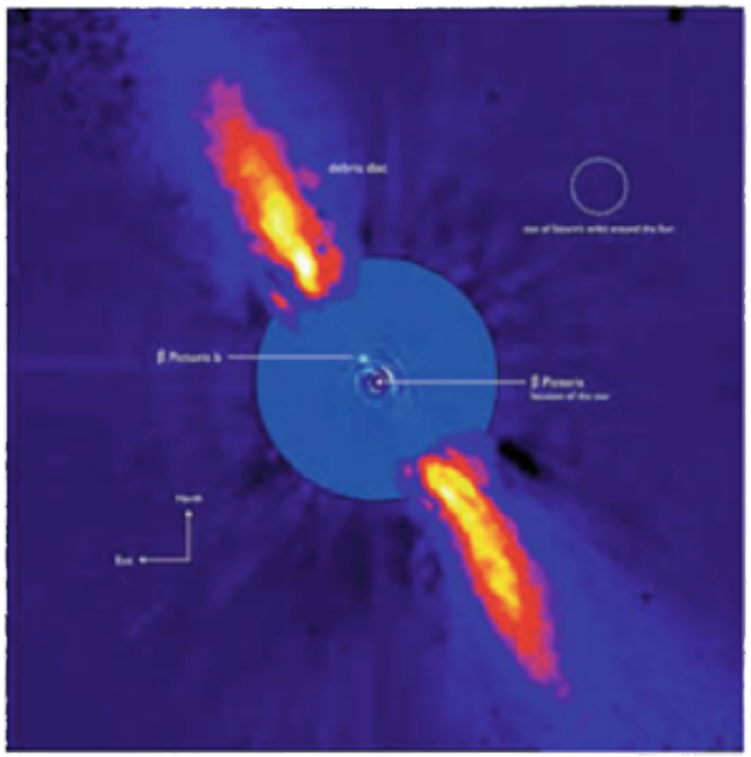
Speckle Suppression

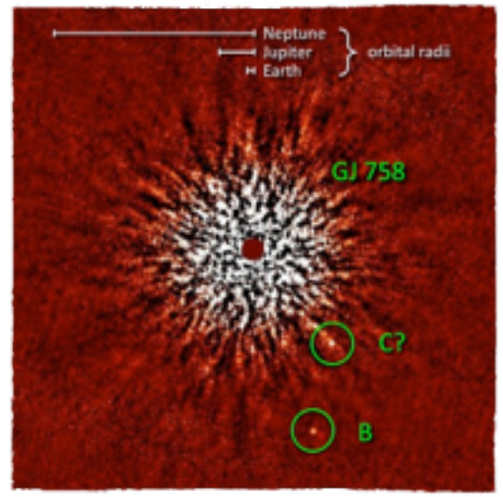
Instrumentation

Updated Results and Perspectives

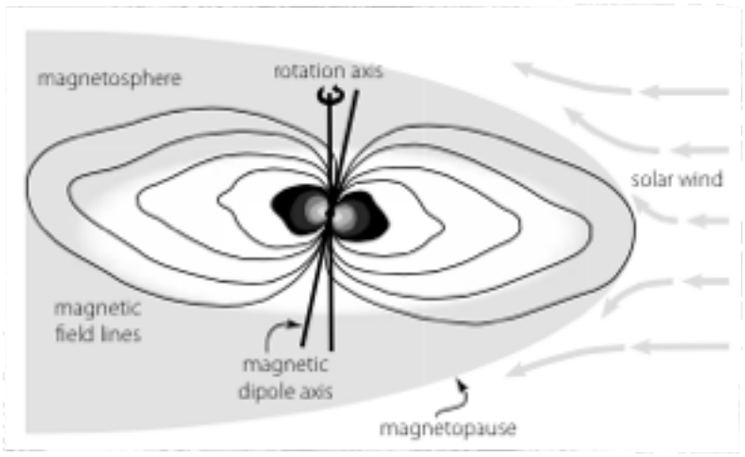
Introduction

DIRECT IMAGING:





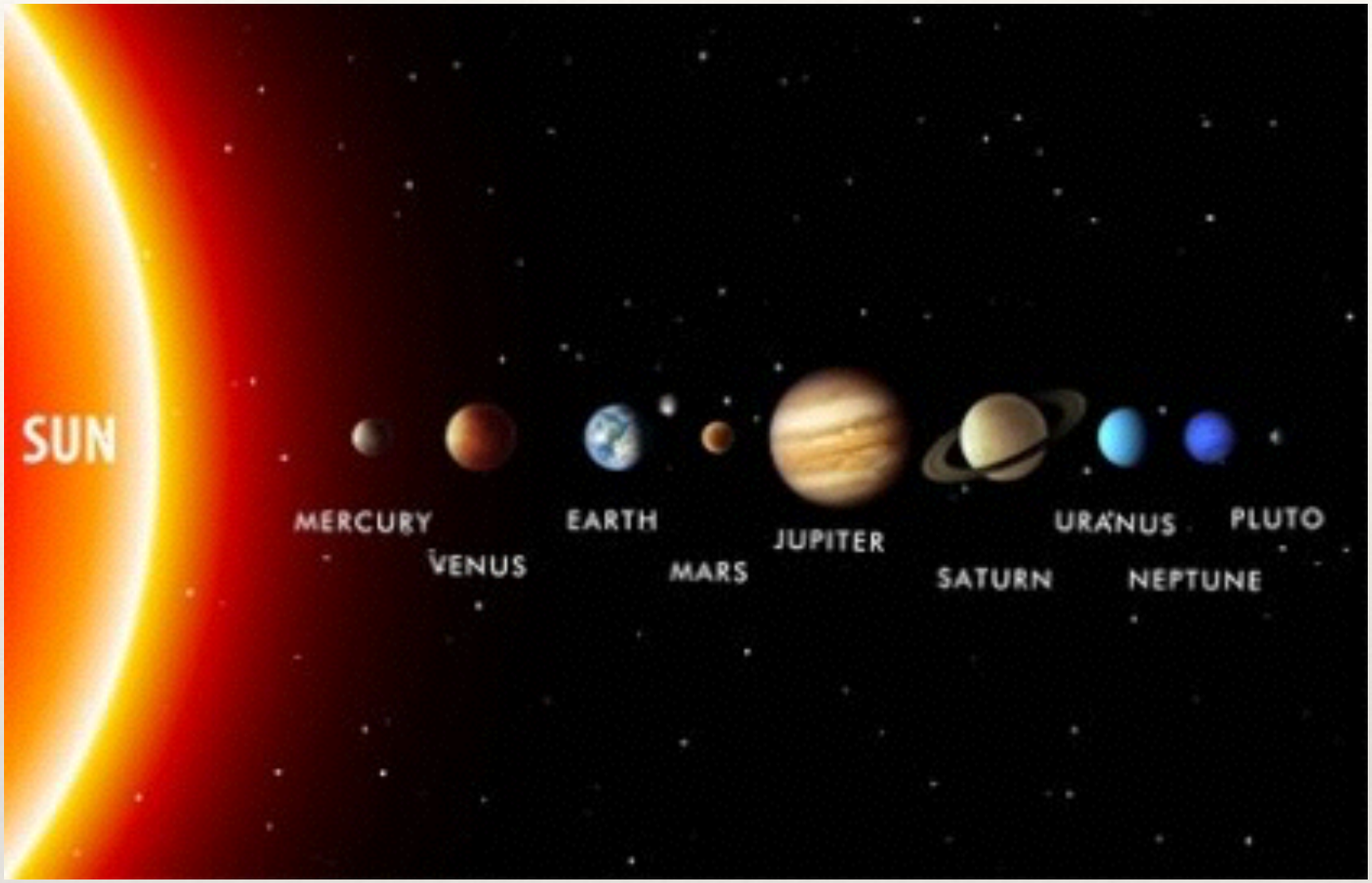
- **DETECTION OF IMAGE OF EXOPLANETS AND PROTOPLANETARY DISKS:**
  - **Reflected Light (Visible)**
  - **Thermal Emission (Infrared)**
- **EMISSION FROM MAGNETOSPHERIC INTERACTION WITH STELLAR WIND (Radio)**



We don't take into account …

- **COMBINED LIGHT (STAR+PLANET):**
  - **Star light curve Modulation due to orbital motion of the low mass companion**
- **Emission Spectroscopy**
- **Transmission Spectroscopy**

Need of High Angular Resolution



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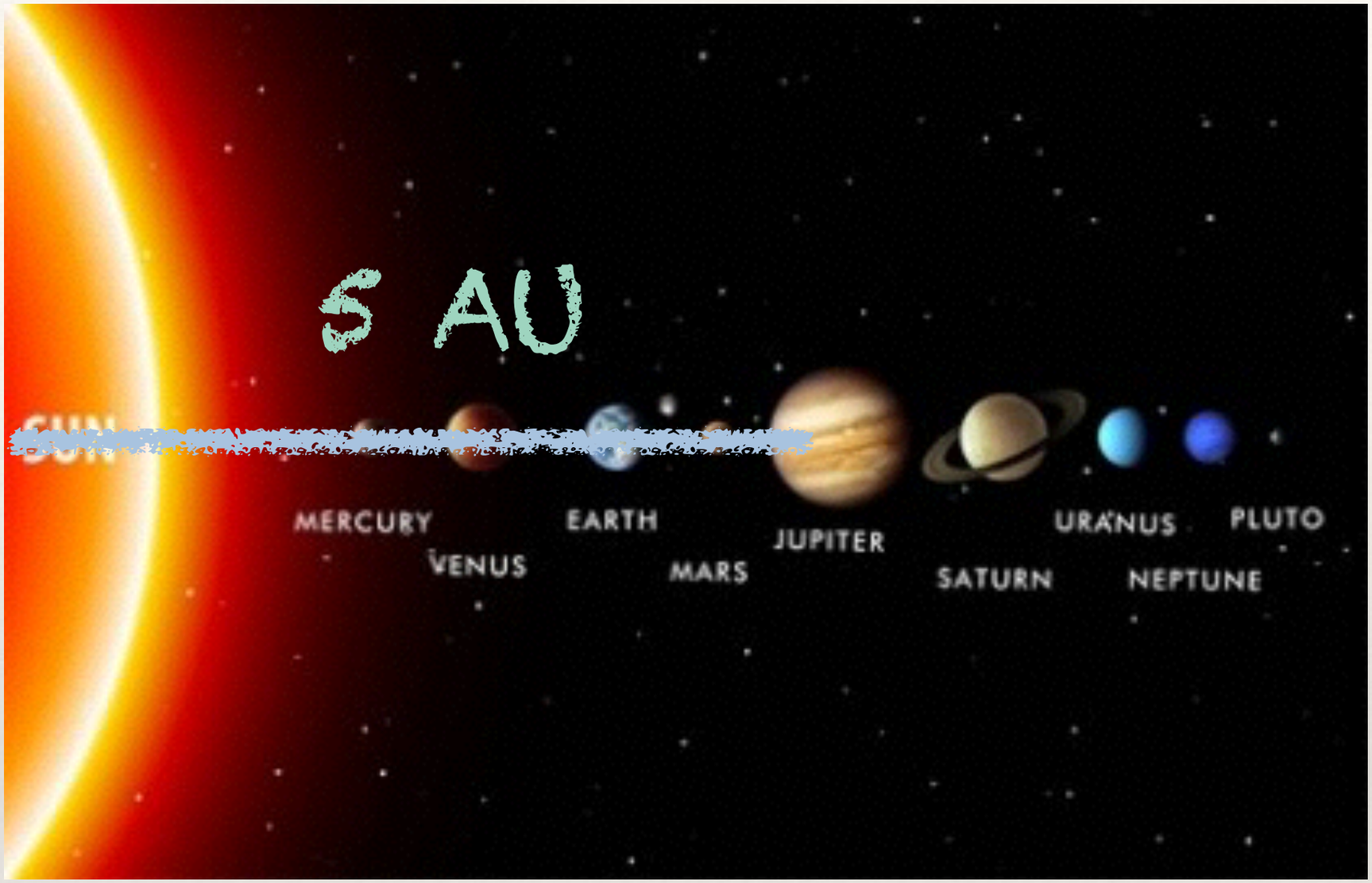

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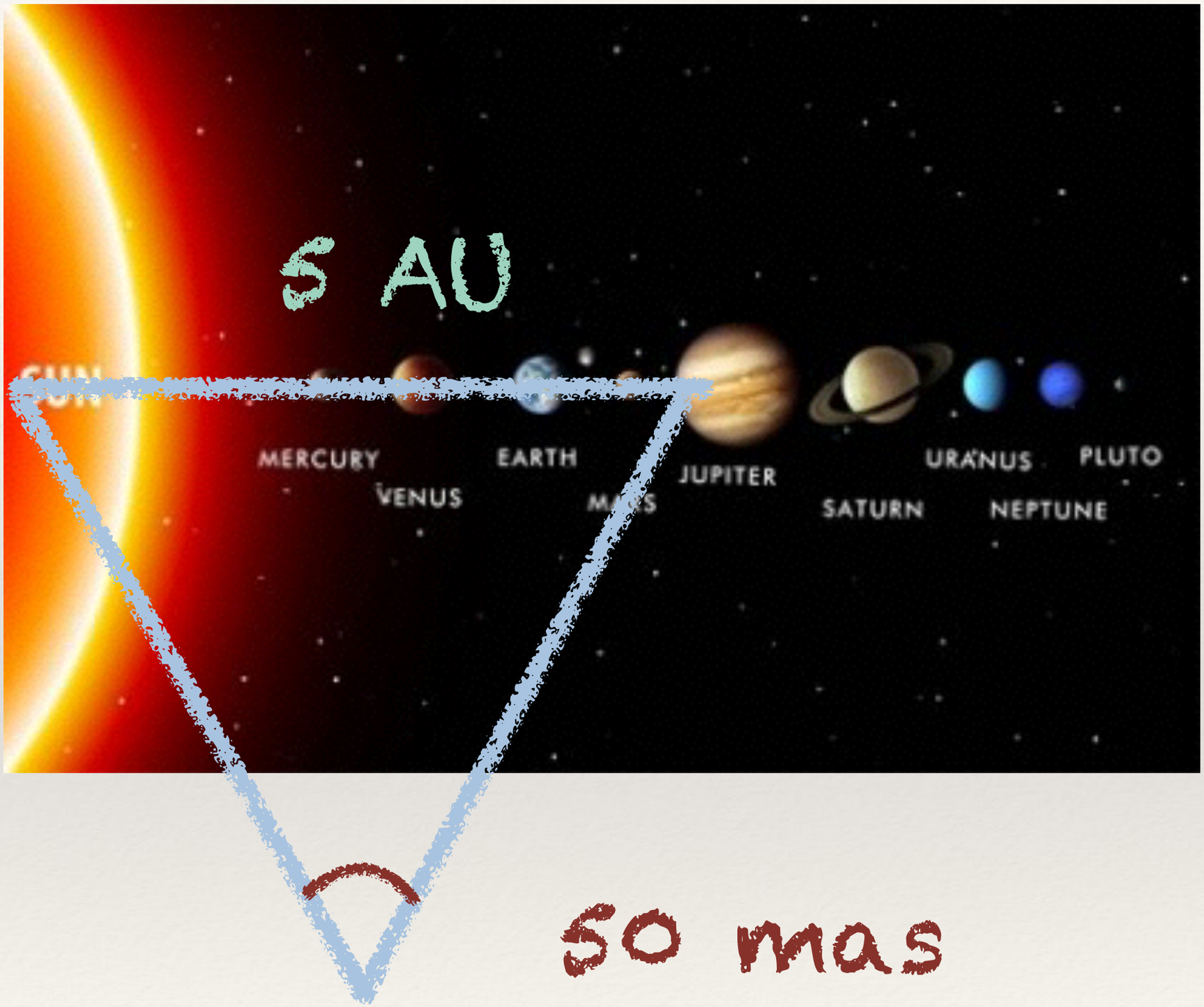

Two Techniques: Single Pupil Systems …

Large telescopes working close to diffraction limit

$$\vartheta \sim \frac{\lambda}{D}$$

Instrument	Telescope	Wavelength (μm)	Ang. Resol. (mas)	Coronagraph
ACS	HST	0.2-1.1	20-100	Lyot
STIS	HST	0.2-0.8	20-60	Lyot
NAOS-CONICA	VLT	1.1-3.5	30-90	Lyot/FQPM
VISIR	VLT	8.5-20	200-500	-
SINFONI-SPIFFI	VLT	1.1-2.45	28-62	-
SPHERE	VLT	0.95-2.32	24-62	Lyot/APLC/FQPM
PUEO	CFHT	0.7-2.5	4-140	Lyot
CIAO	SUBARU	1.1-2.5	30-70	Lyot
OSIRIS	Keck I	1.0-2.4	20-100	-
AO-NIRC2	Keck II	0.9-5.0	20-100	Lyot
ALTAIR-NIRI	Gemini N.	1.1-2.5	30-70	Lyot
GPI	Gemini S.	0.9-2.4	24-62	Lyot/APLC
PALM-3000 PHARO	Hale 200”	1.1-2.5	60-140	Lyot/FQPM
PALM-3000 Project1640	Hale 200”	1.06-1.76	43-71	APLC
AO-IRCAL	Shane 120”	1.1-2.5	100-150	-

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… and Multiple Pupil System

Interferometric observations coherently combining the light from individual telescopes

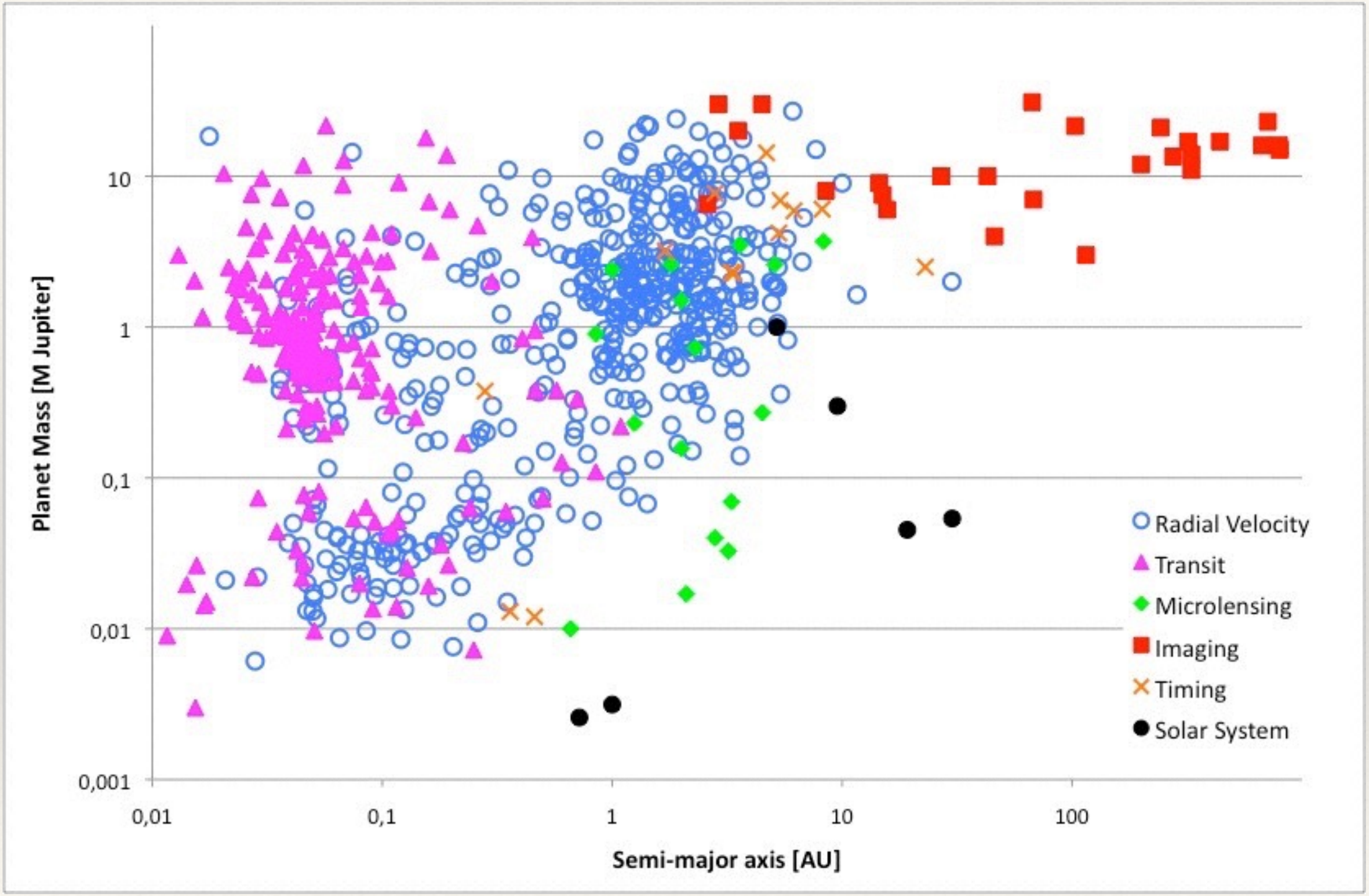
… and Multiple Pupil System

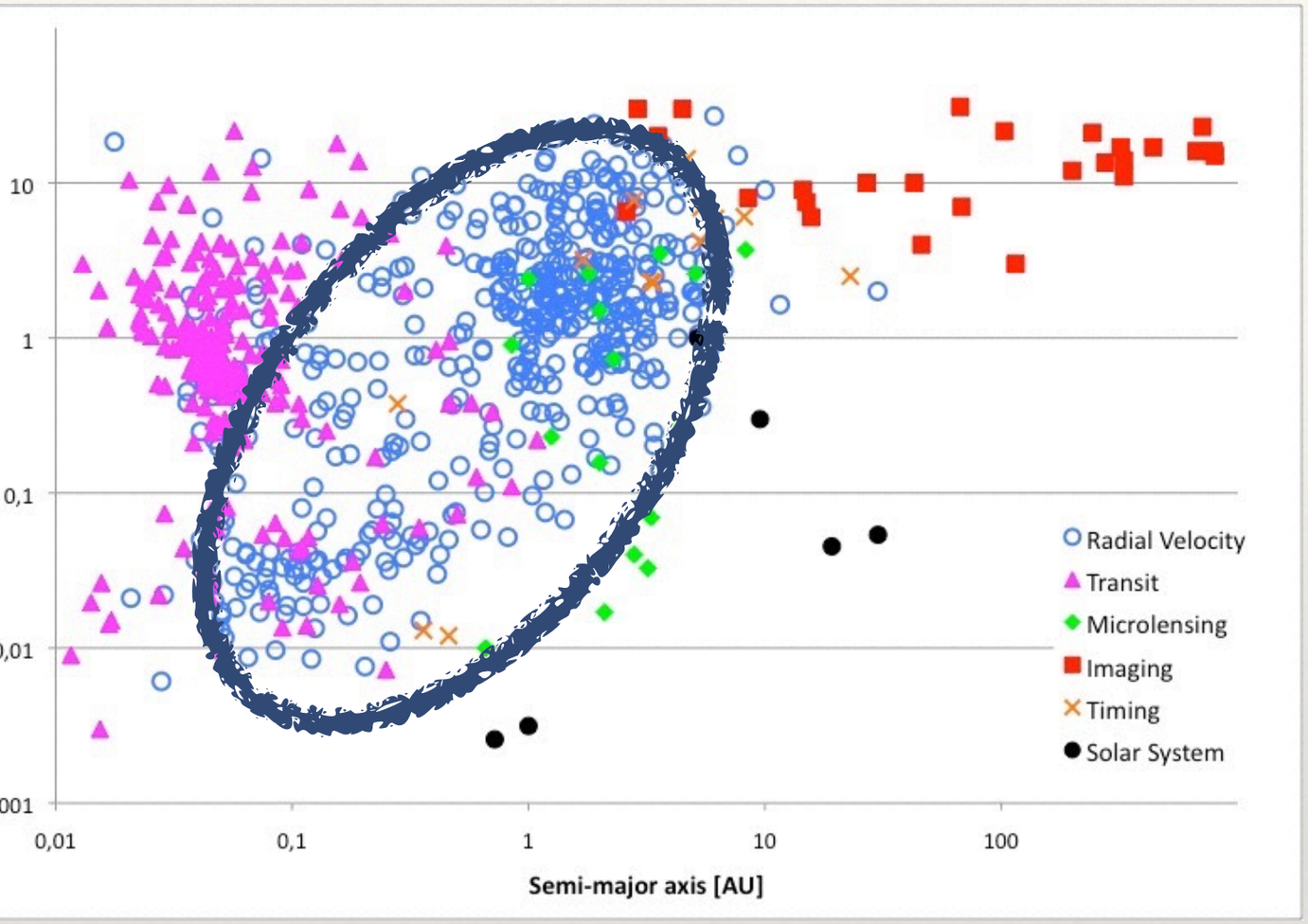
Interferometric observations coherently combining the light from individual telescopes

$$\vartheta = \frac{\lambda}{2B}$$

Multiple Pupil Systems

Instrument	Interf.	Baseline (m)	Bands	Ang. Res. (mas)	Spec. Res.	Aperture
AMBER	VLTI	16-200	J,H,K	0.6-14	35-15,000	3
MIDI	VLTI	16-200	N	4-80	20-220	2
PIONIER	VLTI	16-200	H,K	1.5-45	15	4
V2	Keck - I	85	H,K,L	2-5	25-1800	2
Nuller	Keck-I	85	N	10-16	40	2
Mask	Keck	1-10	J to L	13-400	None	2
Classic	CHARA	34-330	H,K	0.5-7	None	2
FLUOR	CHARA	34-330	K	0.7-7	None	2
MIRC	CHARA	34-330	J,H	0.4-5	40-400	4
BLINC	MMT	4	N	250	None	2
LMIRCAM	LBTI	14-23	L,M	27-72	None	2
NOMIC	LBTI	14-23	N	72-200	None	2


Planet Mass [M Jupiter]
10
1
0,1
0,01
0,001
0,01
0,1
1
10
100
Semi-major axis [AU]
Radial Velocity
Transit
Microlensing
Imaging
Timing
Solar System

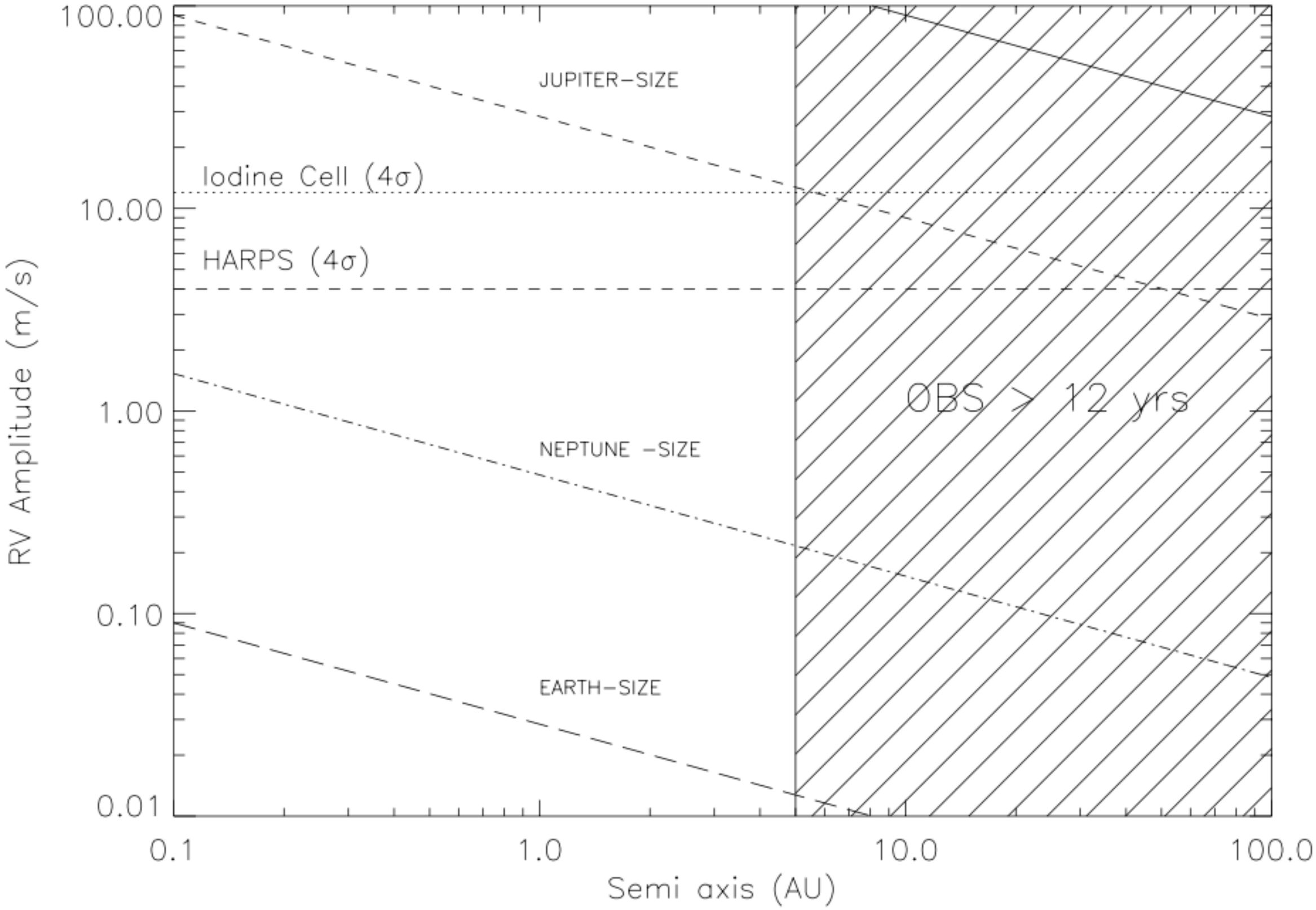


☑ Radial Velocity

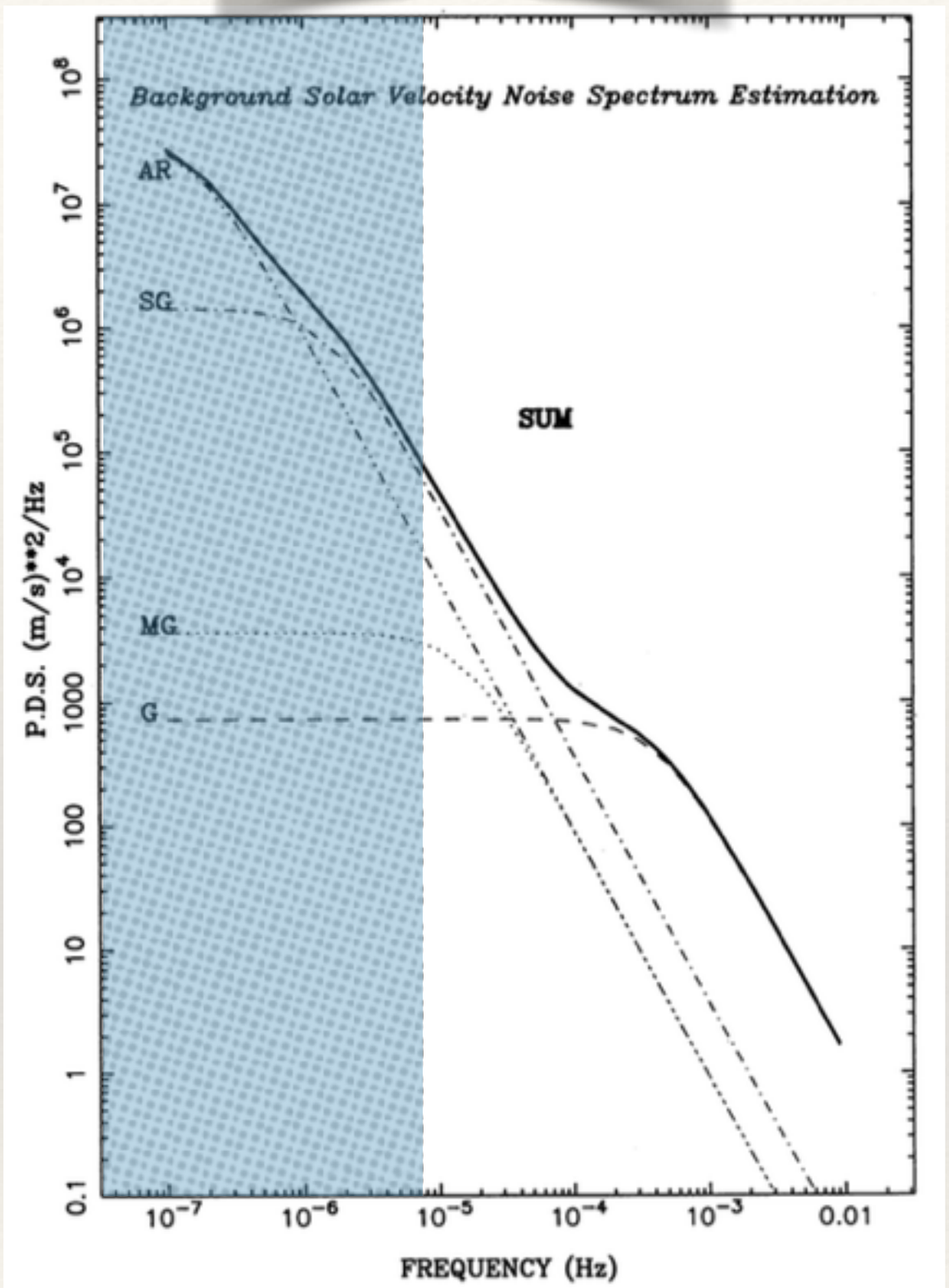
. Indirect technique: Doppler shift
(Targets: quiet stars; *activity*)

. Orbital & Physical properties:
> $M_p.sin(i)$, P, e, a, ω & T_0
> Spin-Orbit Alignment
> Architecture & Stability
> exo-Earths & Habitable Zone
Dumusque et al. 12; Triaud et al. 11

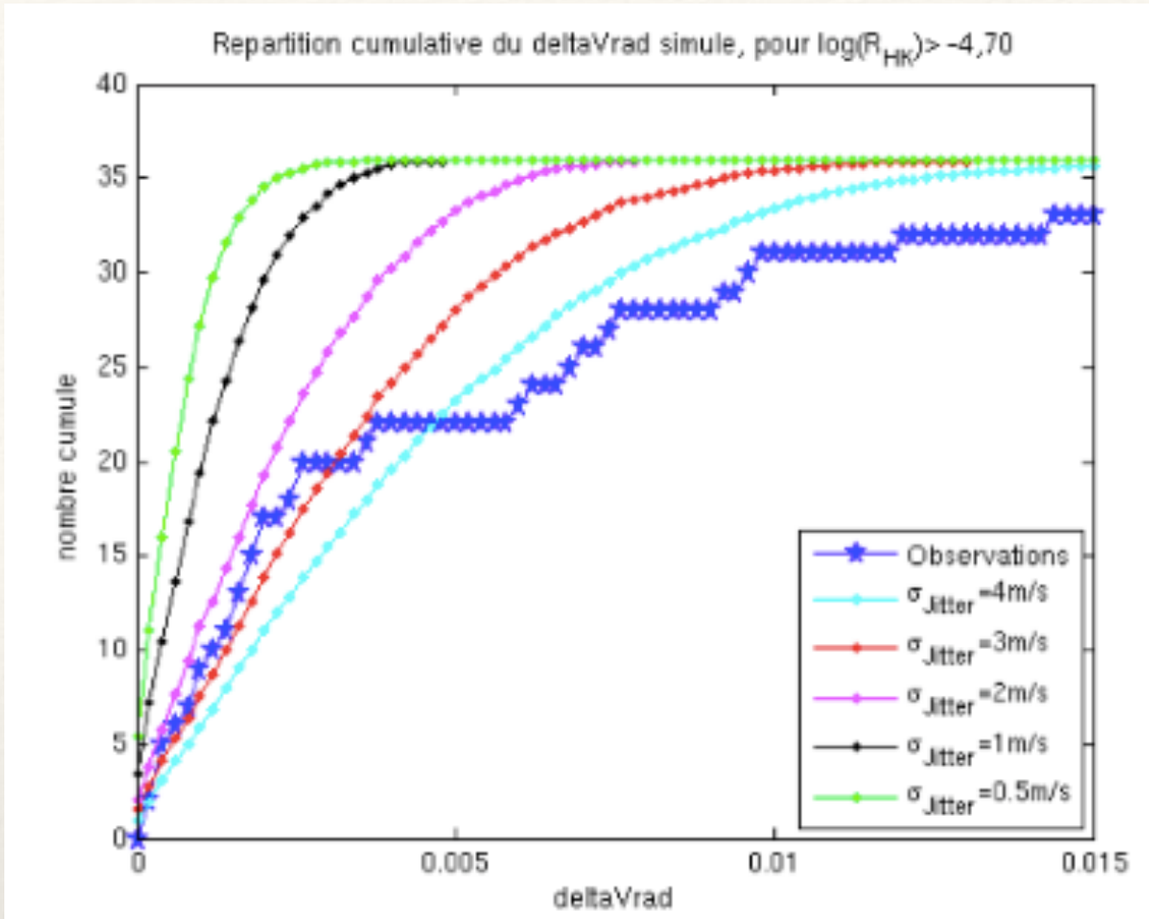
. Statistics: more than 600 exoplanets
> Occurrence down to Super-Earths
> Planetary host: Fe/H & binarity
De Sousa et al. 11; Udry & Santos 07

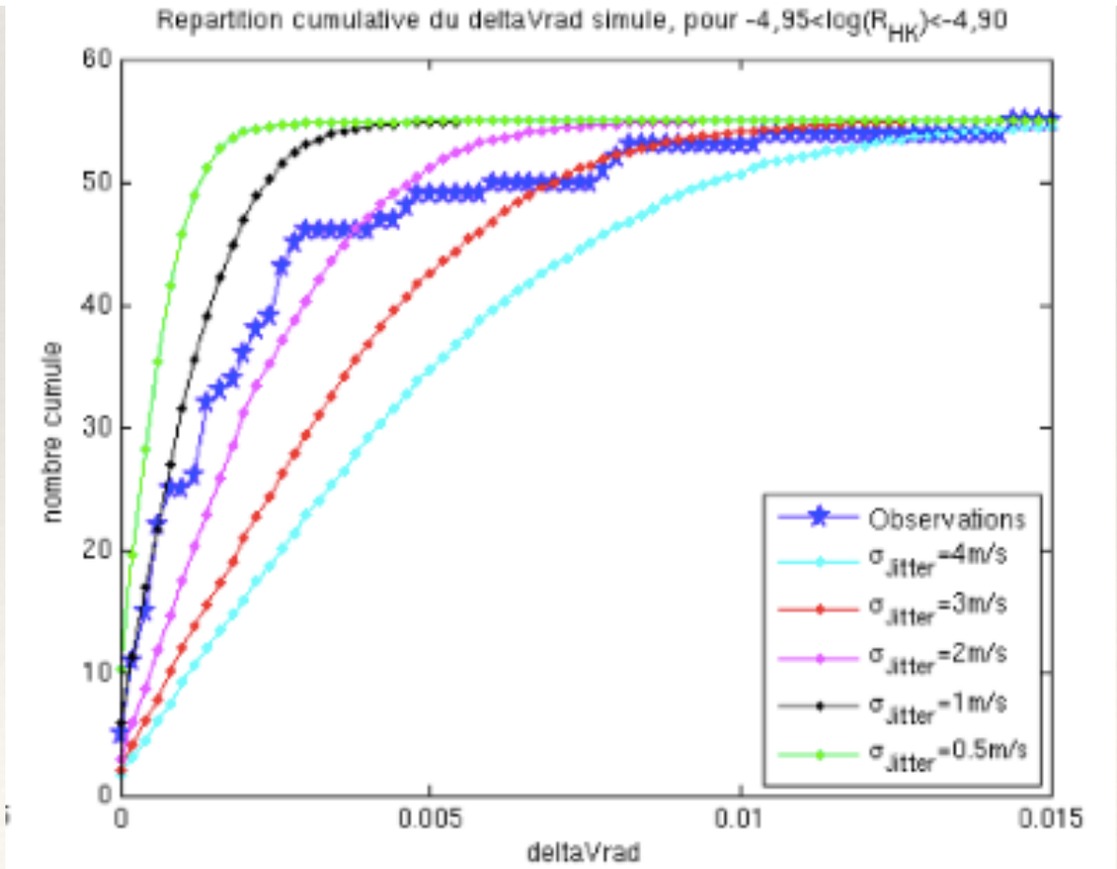

100.00
10.00
1.00
0.10
0.01
RV Amplitude (m/s)
JUPITER−SIZE
Iodine Cell (4σ)
HARPS (4σ)
NEPTUNE −SIZE
EARTH−SIZE
OBS > 12 yrs
0.1
1.0
10.0
100.0
Semi axis (AU)

Palle et al. 1995

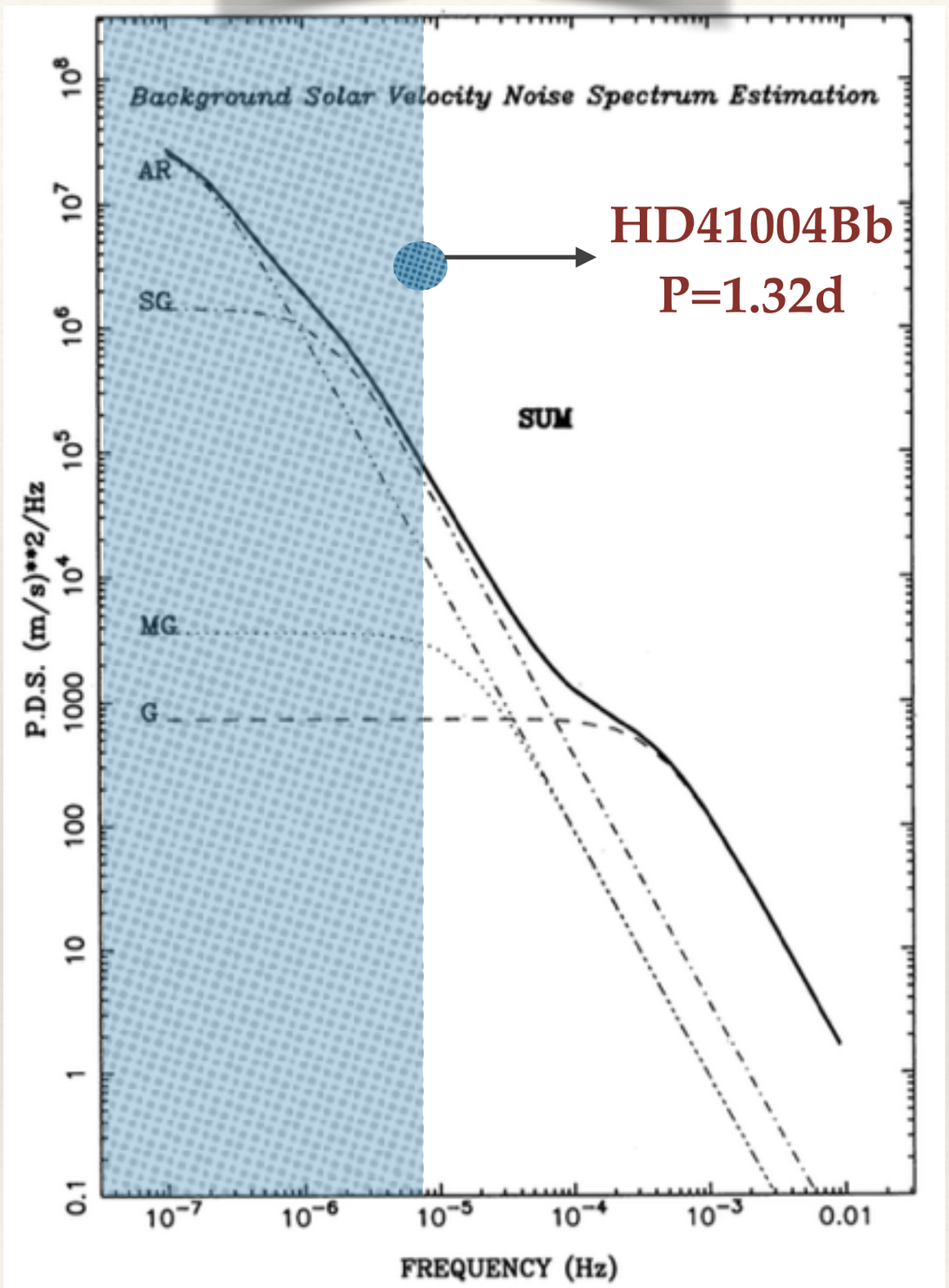


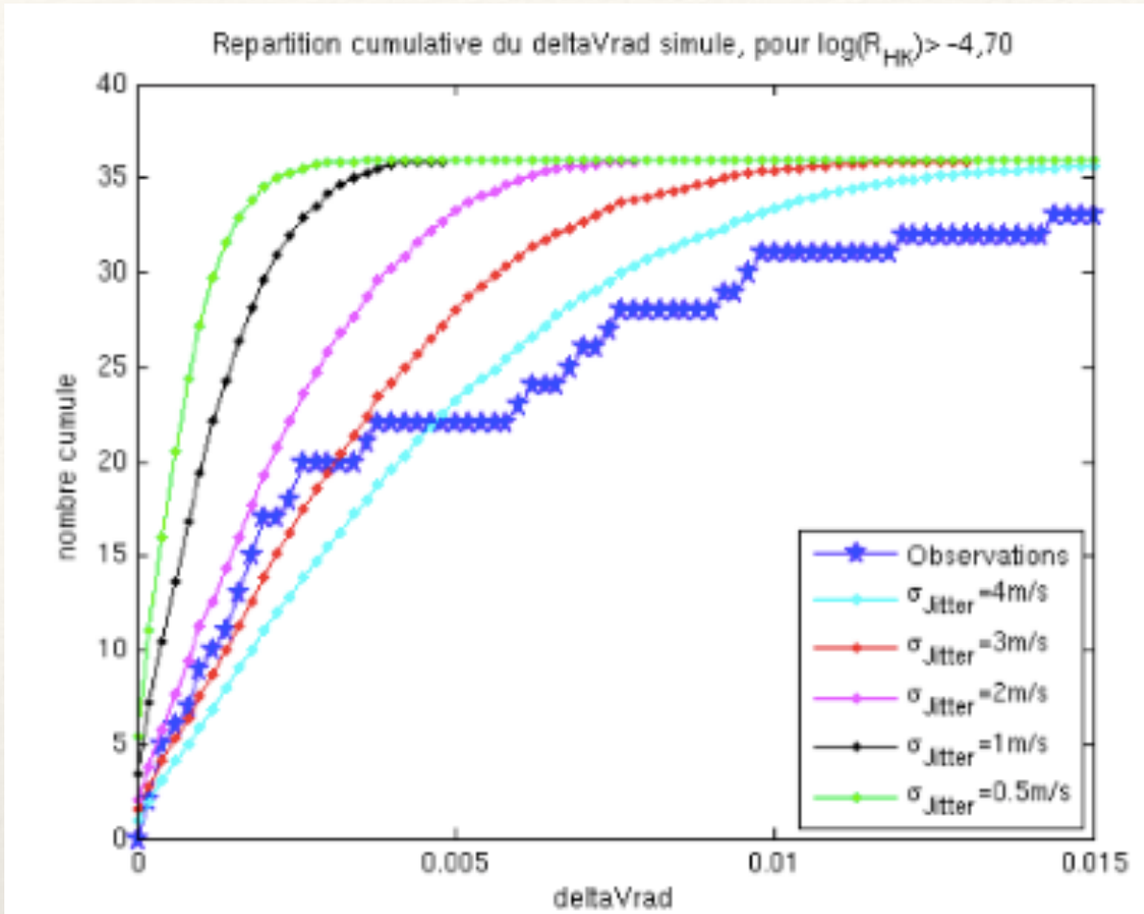
Pepe & Lovis 2008





Palle et al. 1995





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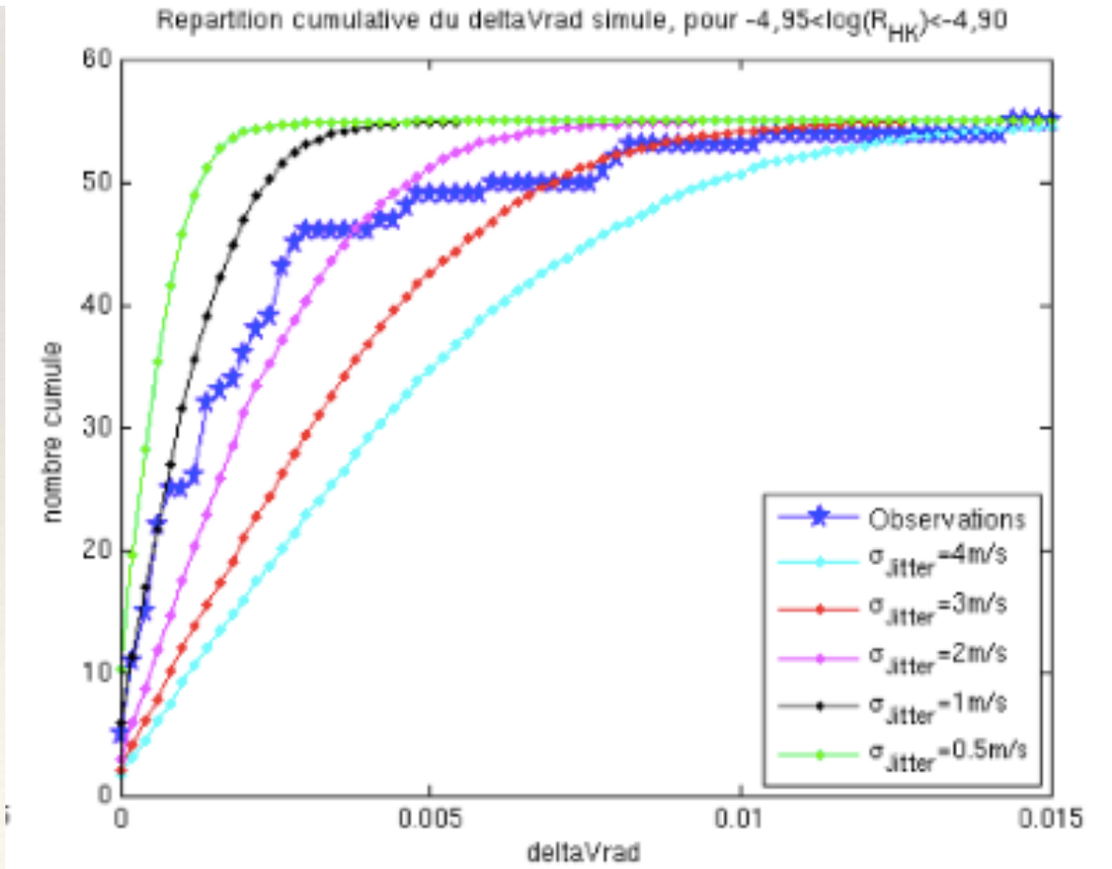

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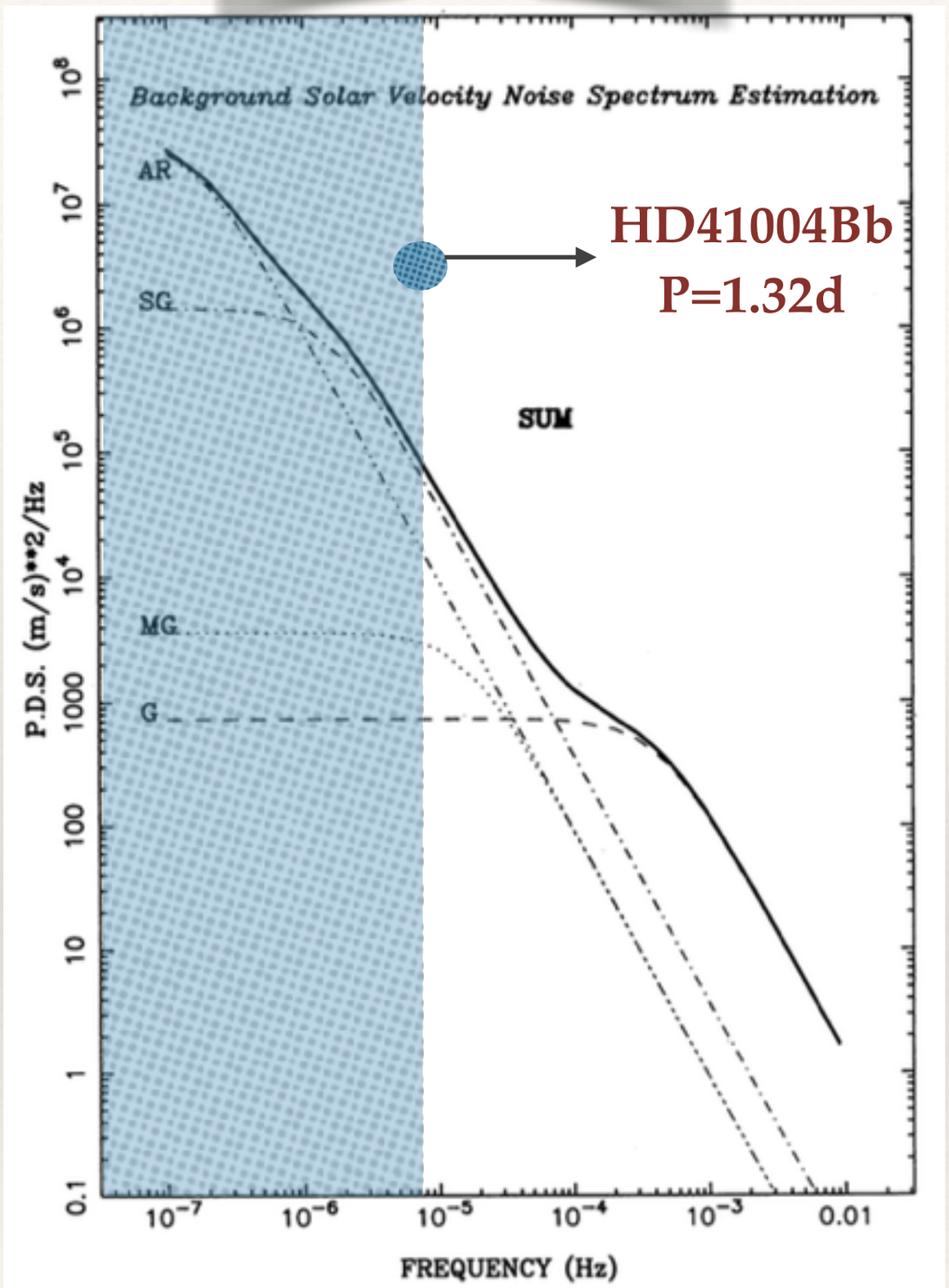

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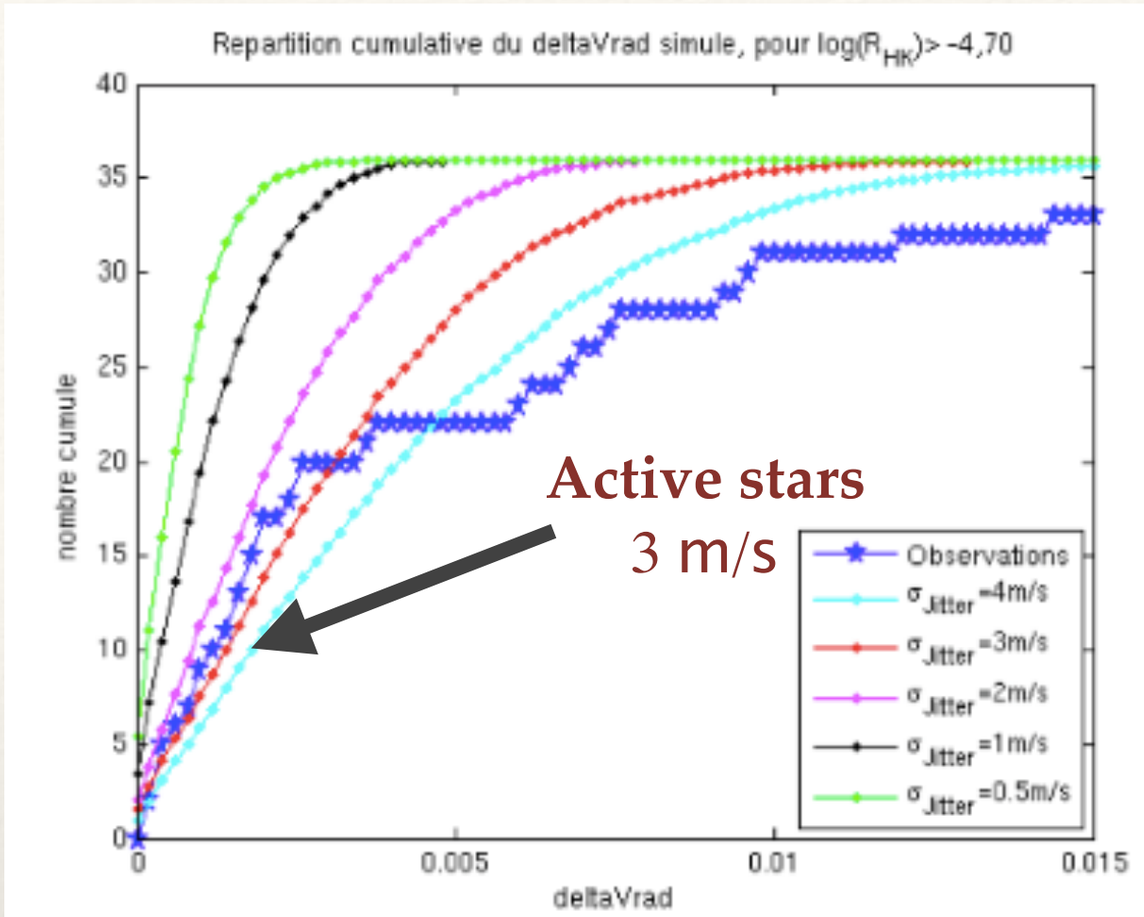
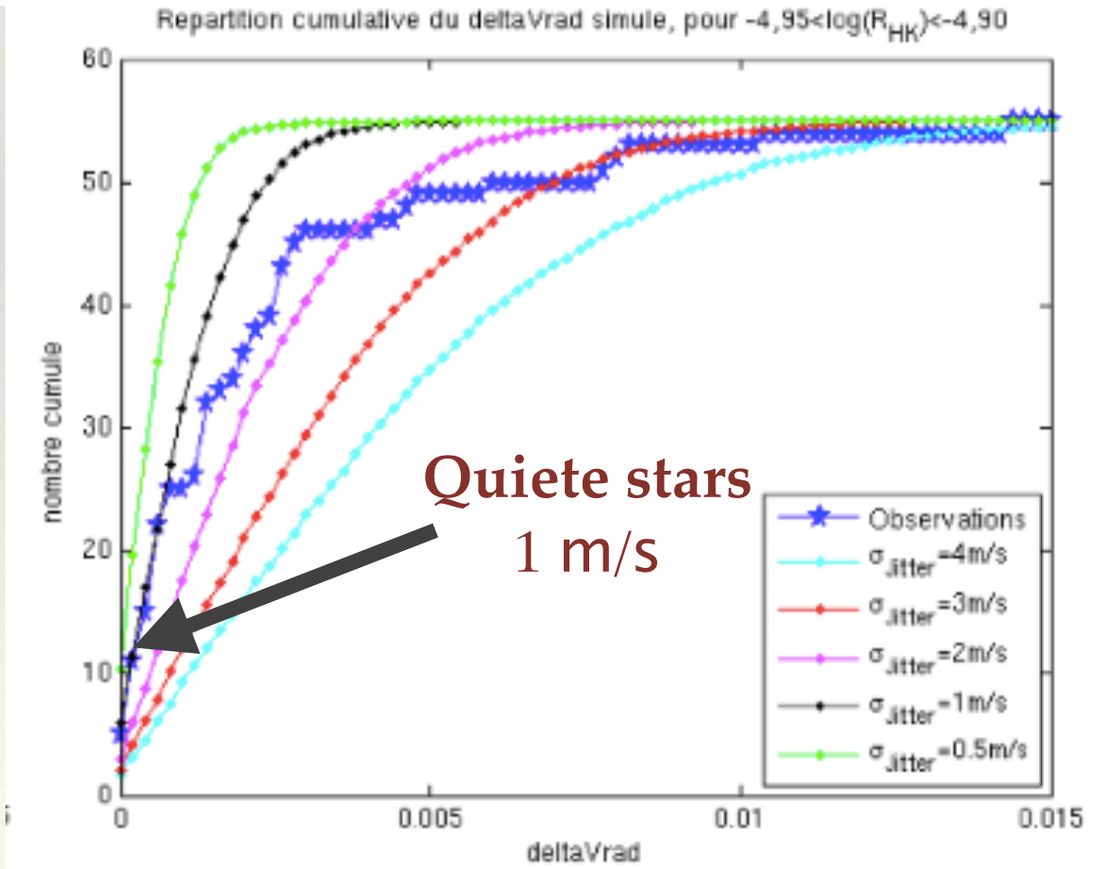
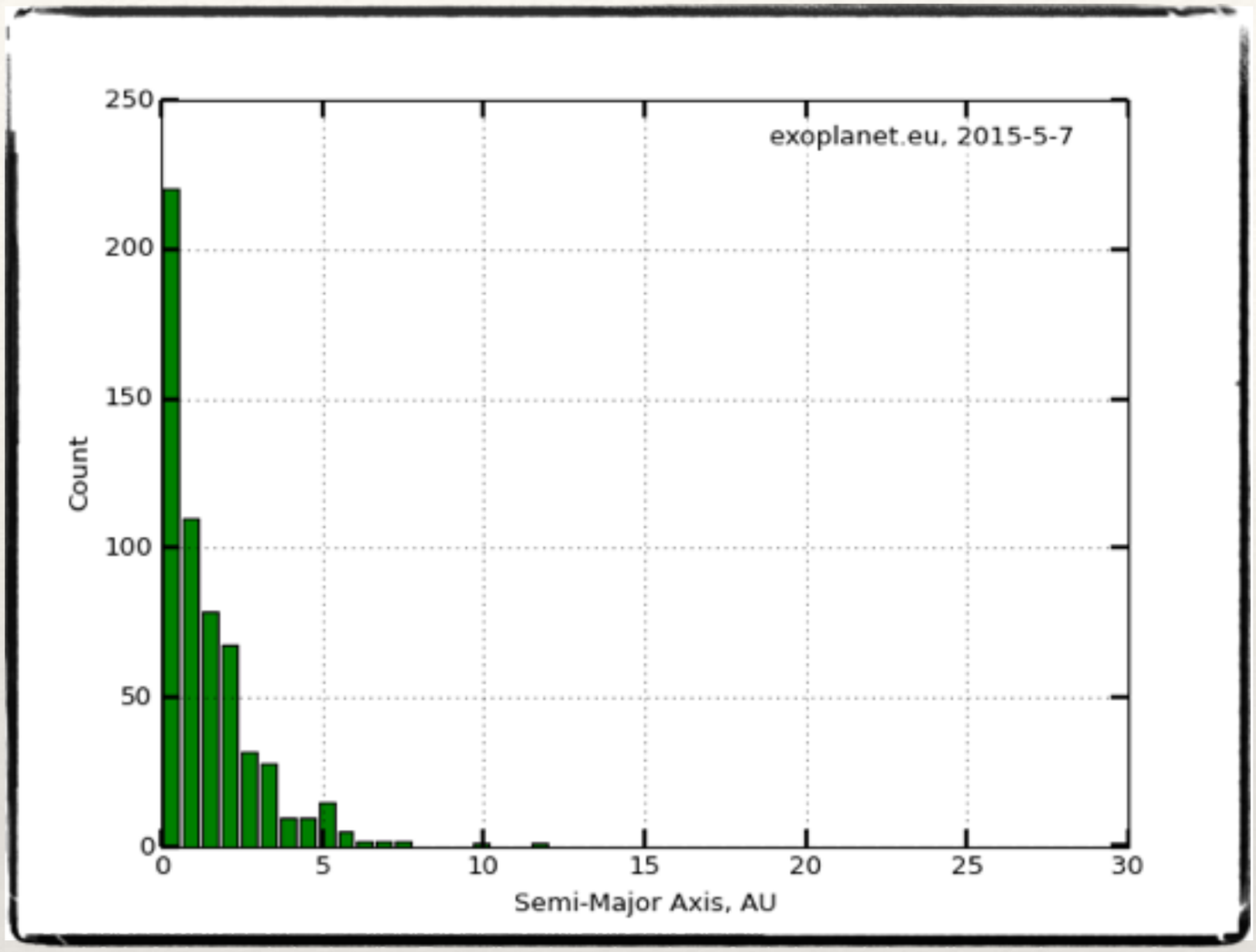


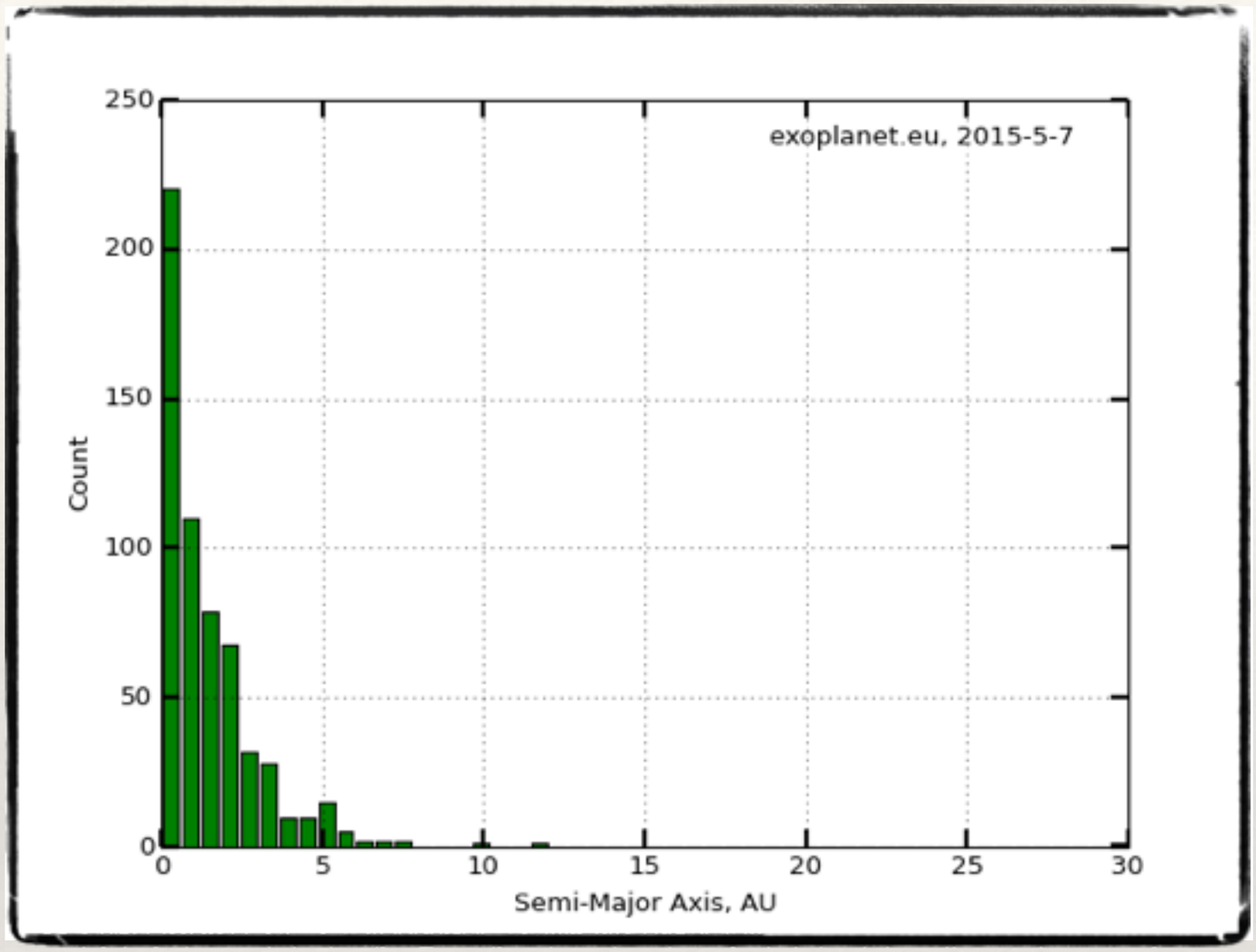


Radial Velocity Biases



$$K \propto \frac{M_p \sin i}{M_*^{1/2} a^{1/2}}$$

Radial Velocity Biases



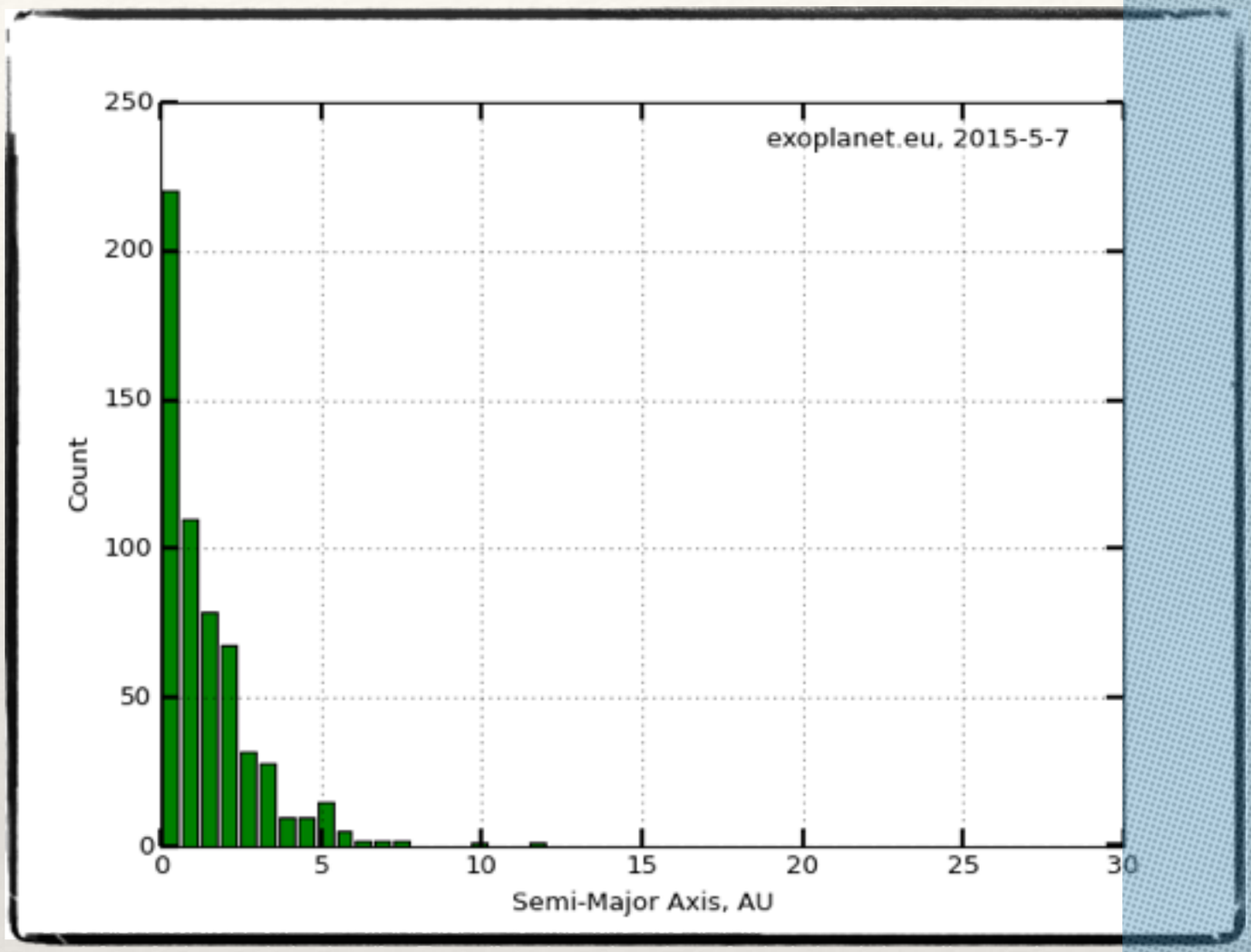
◉Larger Planets

$$K \propto \frac{M_p \sin i}{M_*^{1/2} a^{1/2}}$$

◉Smaller Stars

◉Closer Planets

Radial Velocity Biases



◉QUIETE STARS

◉Larger Planets

$$K \propto \frac{M_p \sin i}{M_*^{1/2} a^{1/2}}$$

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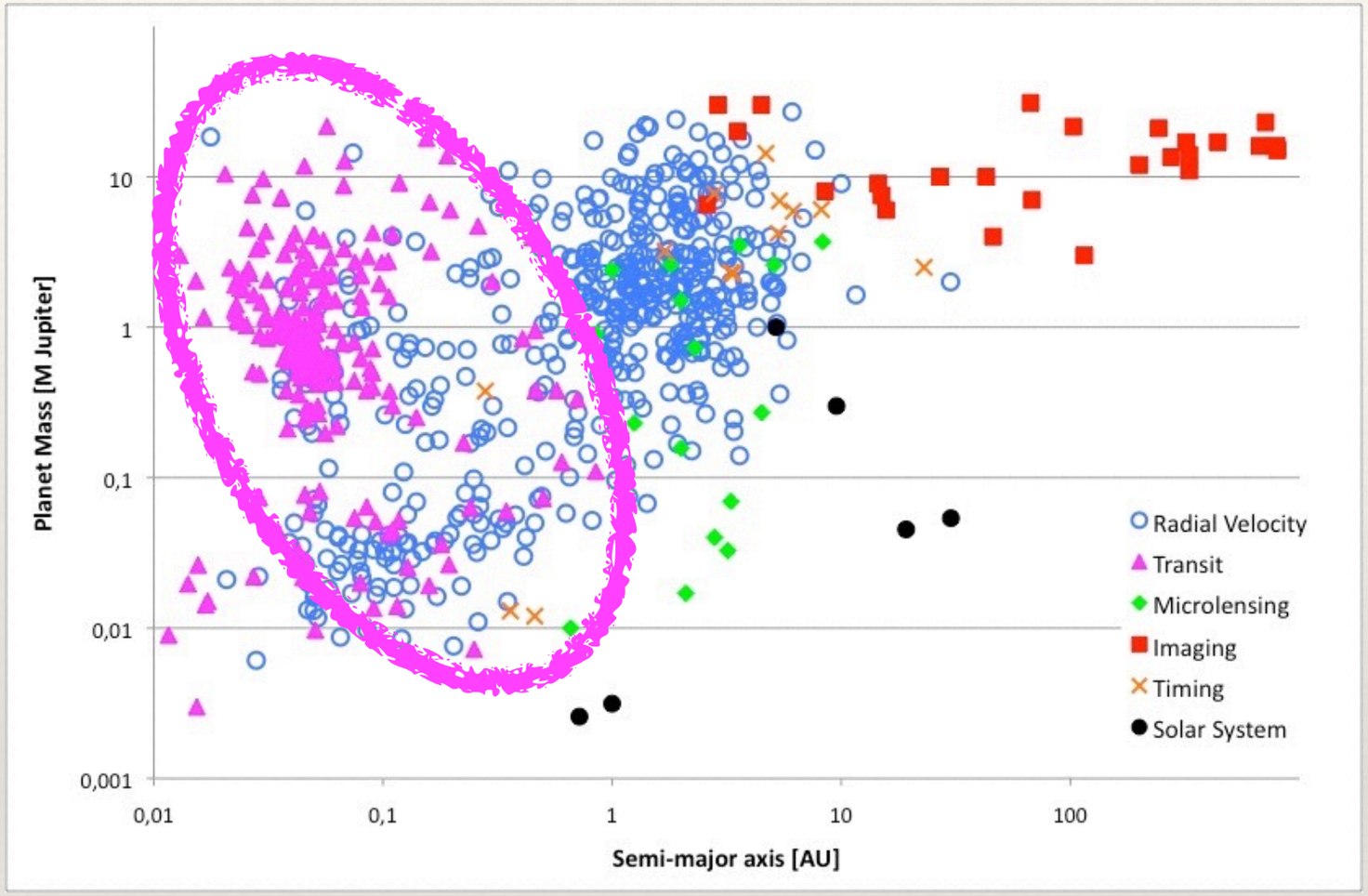


Transit

. (In)direct technique: $1^{ary}/2^{ary}$ eclipse.

(Targets: quiet stars; *activity;* crowded fields)

. Orbital & Physical properties:

> R_*/R_p, M_p, P, a, i, T_0

> Planetary Interiors

> Multiple: Architecture & Stability

> Circumbinary planets

Leger et al. 09; Doyle et al. 11; Balatha et al. 12

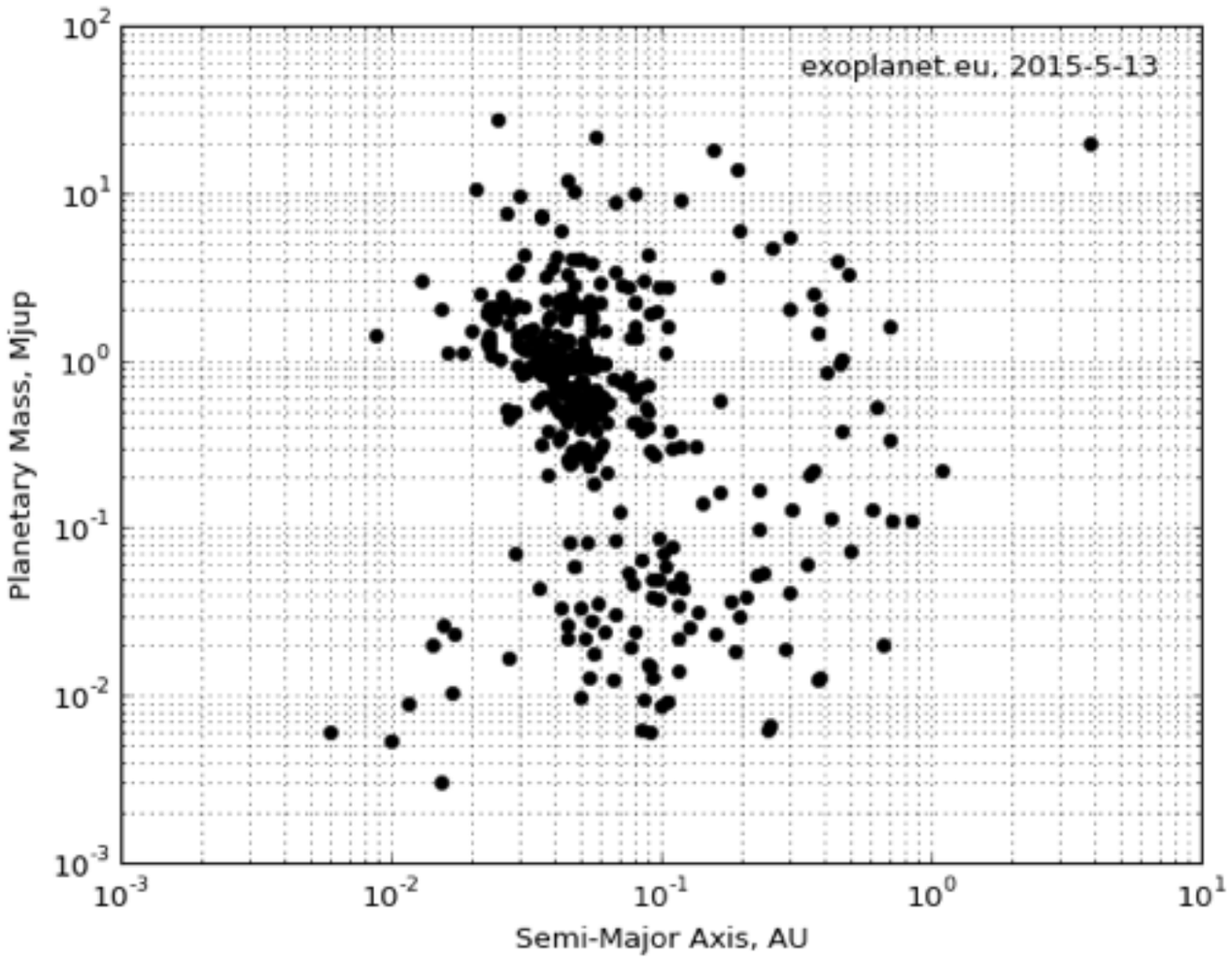
. Transmission/emission spectroscopy

> Composition (H20, CO, NaI, KI... Haze)

> Vertical T-P structure, atmospheric circulation & evaporation

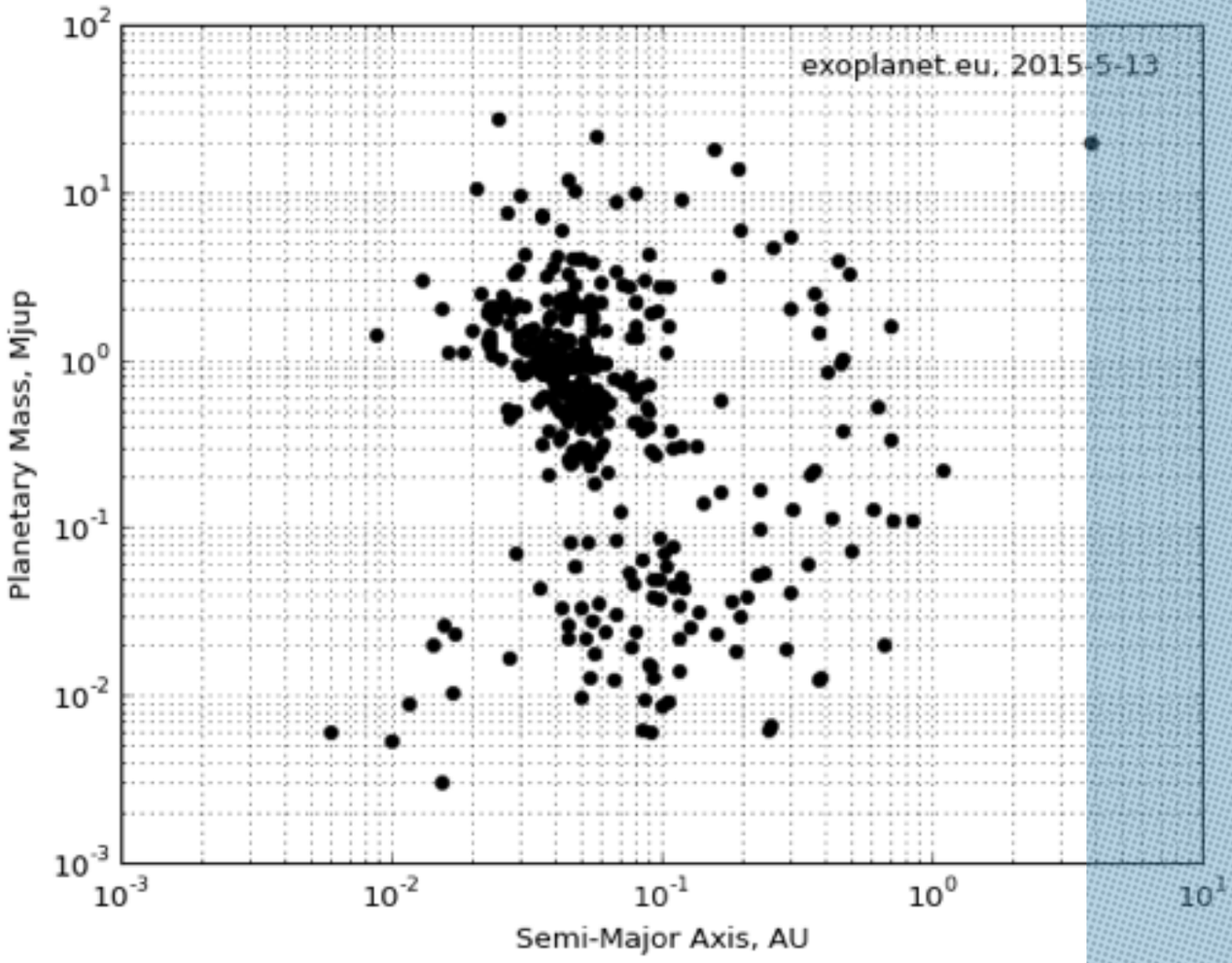
Swain et al. 08; Knutson et al. 09; Desert et al. 12

Transit Biases



$$\frac{dN_p}{dadM_p} \propto \frac{R_P^3}{R_*^{5/4}} \frac{L^{3/2}}{a^{7/4}}$$

Transit Biases



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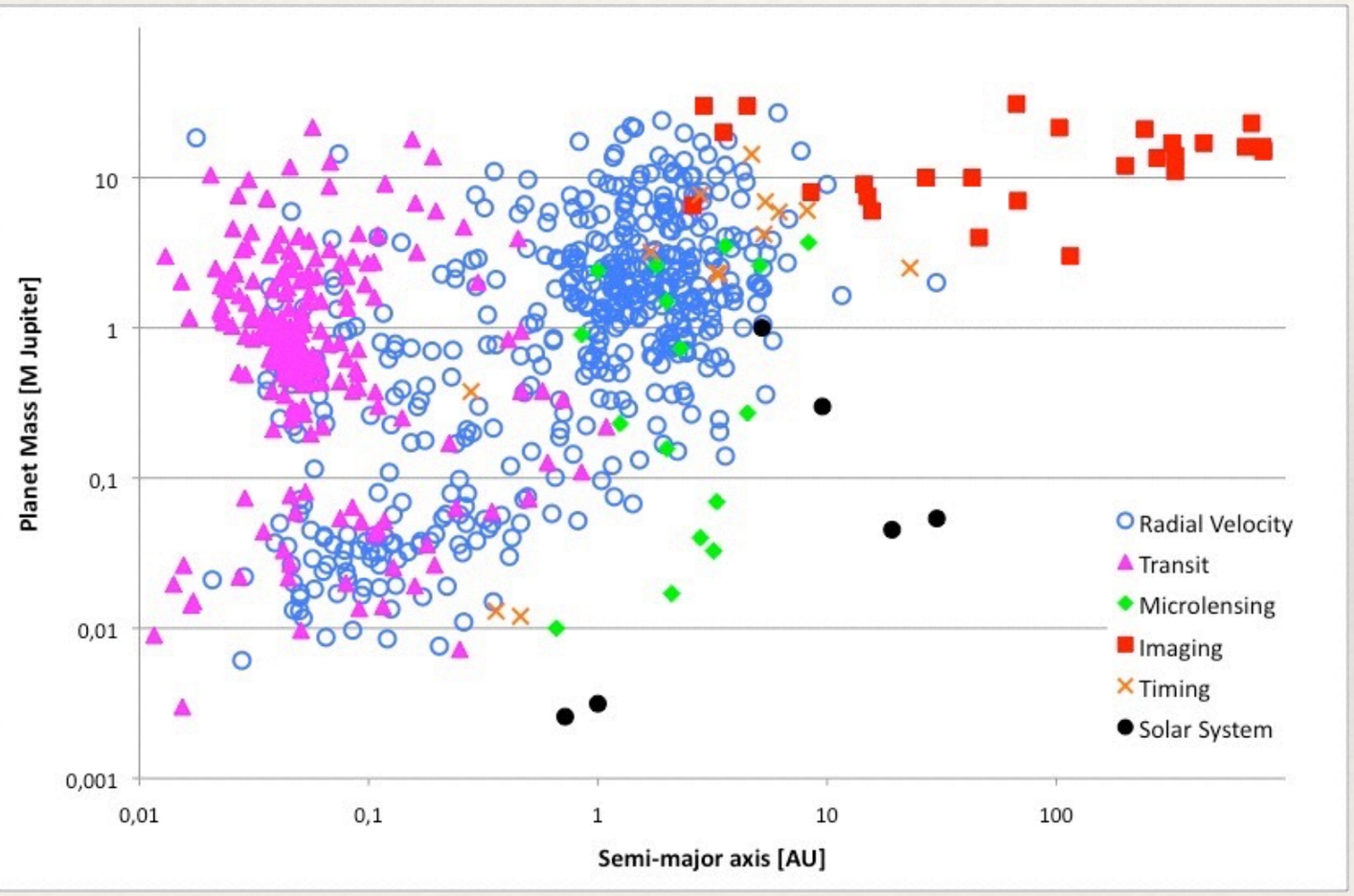


☑ Direct Imaging

. Direct technique: Planet's photons

(Targets: young & nearby stars)

. Orbital & Physical properties:

> L, a , e, i, ω, T0

> Giant planets at wide orbits (>10 AU)

> Multiple: Architecture & Stability

> Planet – disk connection

Chauvin et al. 05, 10; Lafrenière et al. 07

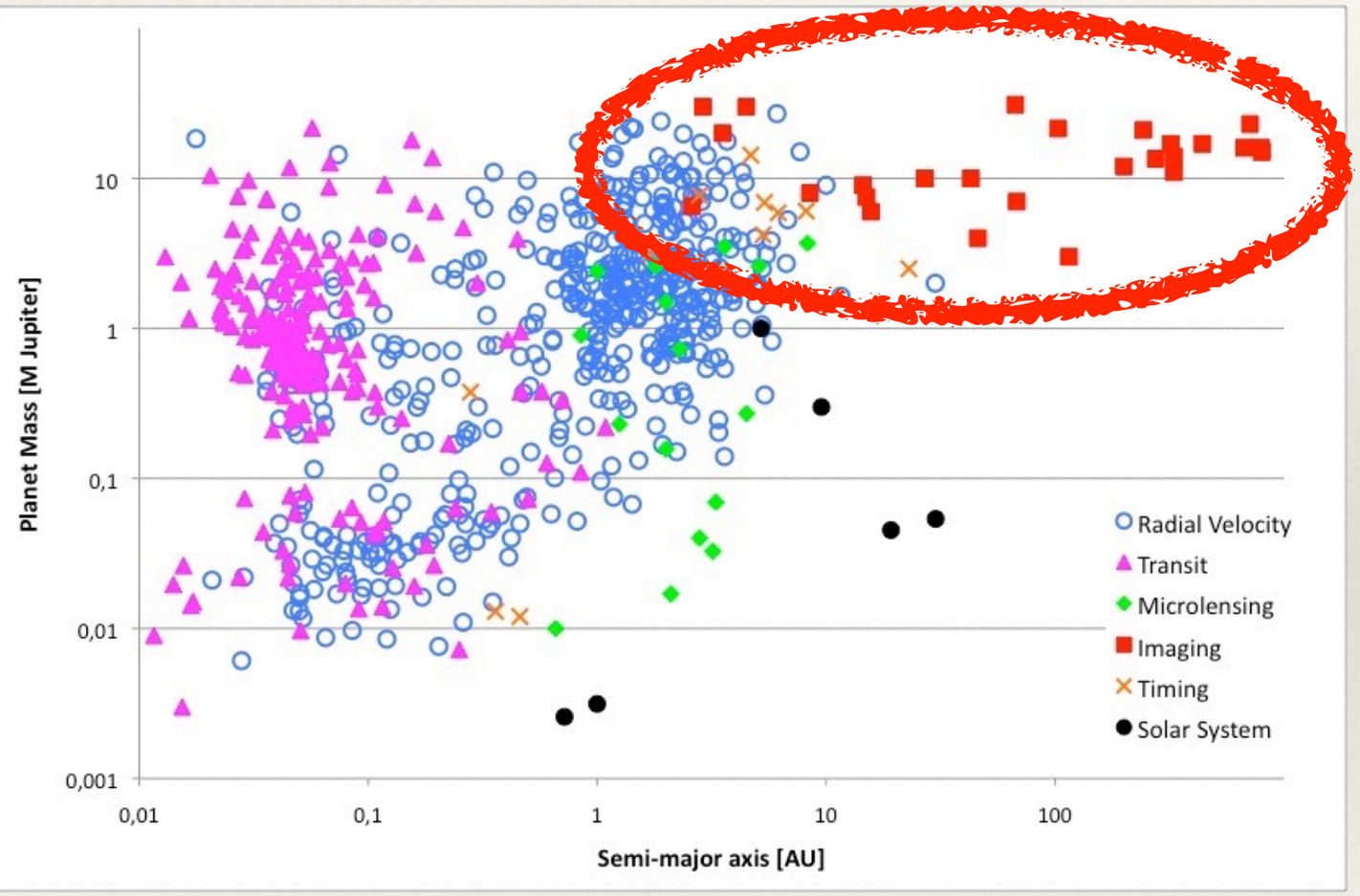
Soummer et al. 11; Vigan et al. 12

. High-contrast spectroscopy

> Non-strongly irradiated EGPs

> Low-gravity, composition, non-LTE chemistry, cloud coverage...

Janson et al. 10; Bonnefoy et al. 09, 12



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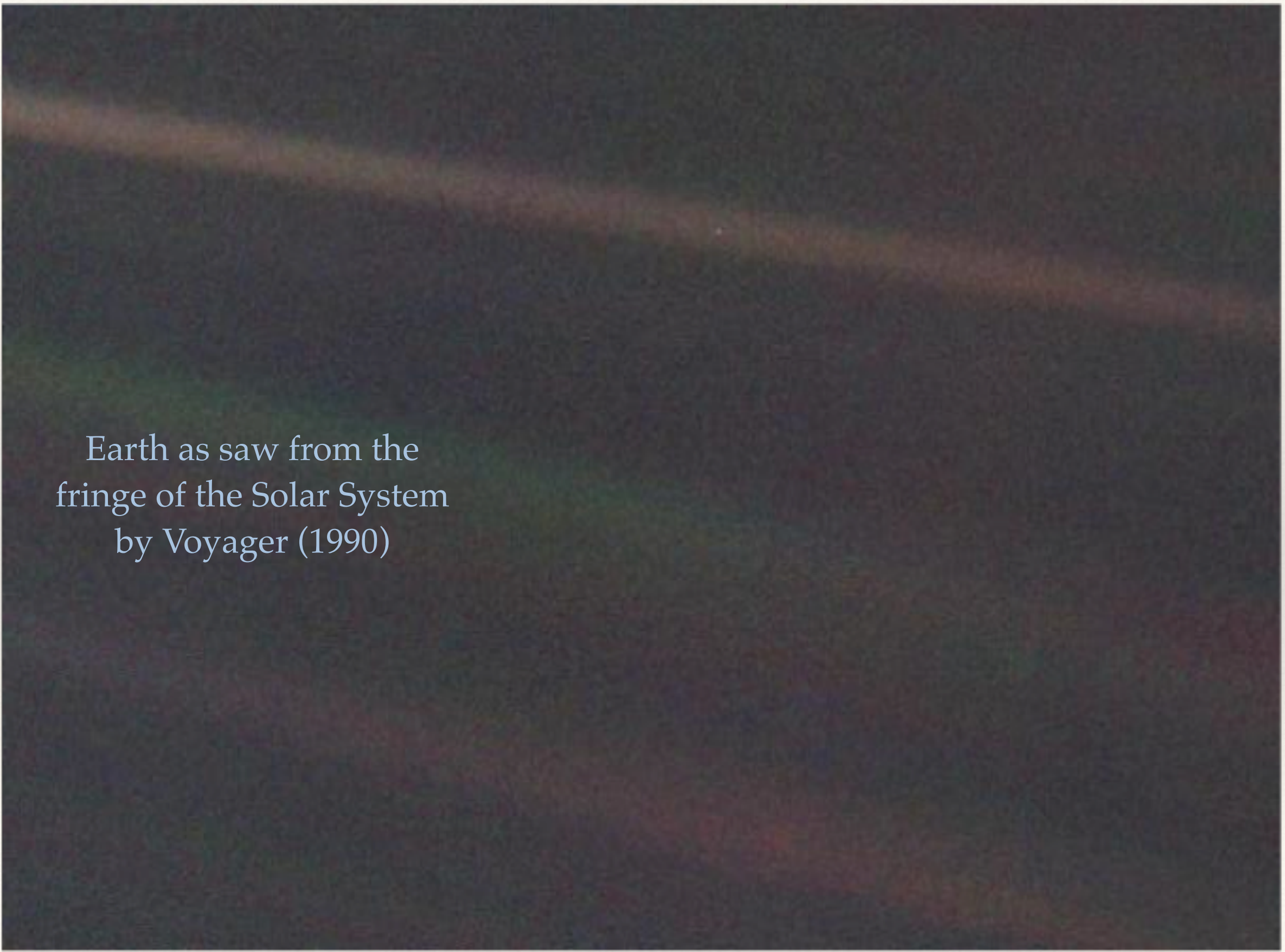
Schematic of methods goals

	Hot Planets (P~days)	<snow line (P~a few days)	>snow Line (P~several days)
Discovery: detection and statistics	Radial Velocities and Transits	Radial velocities space Astronomy (GAIA) Microlenses ELT Imaging	8m imaging
Dynamical Characterization & Structure	Radial Velocities and Transits	Radial velocities space Astronomy (GAIA) ELT Imaging	Coupling 8 m Imaging and GAIA?
Atmospheric Characterization & search for biosignatures	Transits Duration Transmission spectroscopy Secondary transit	ELT imaging	8m imaging (and) JWST ELT MIR

However, situation may differ for specific target groups (M-stars)!

Where is Earth?



Earth as saw from the
fringe of the Solar System
by Voyager (1990)

Where is Earth?

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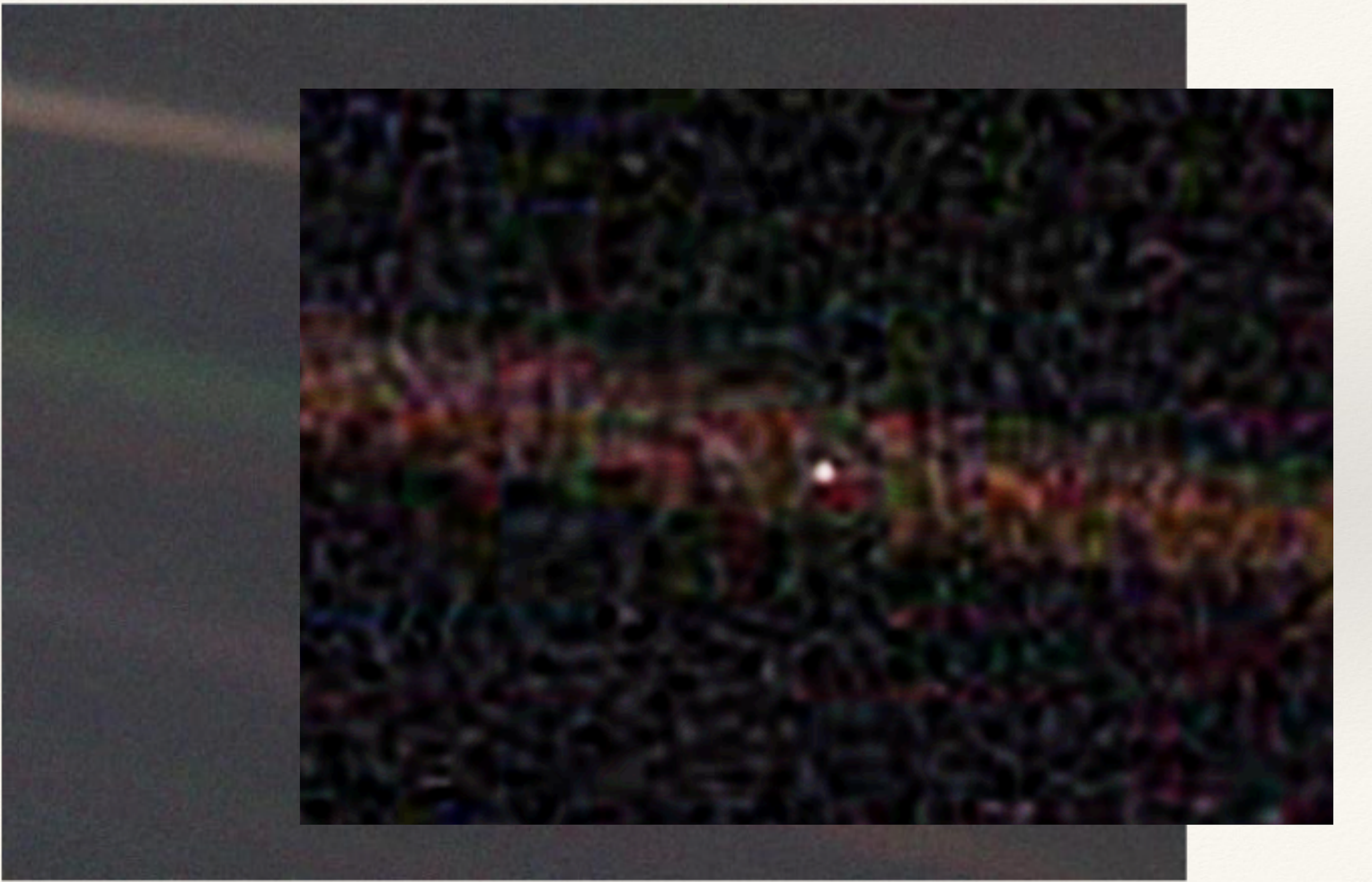
Where is Earth?



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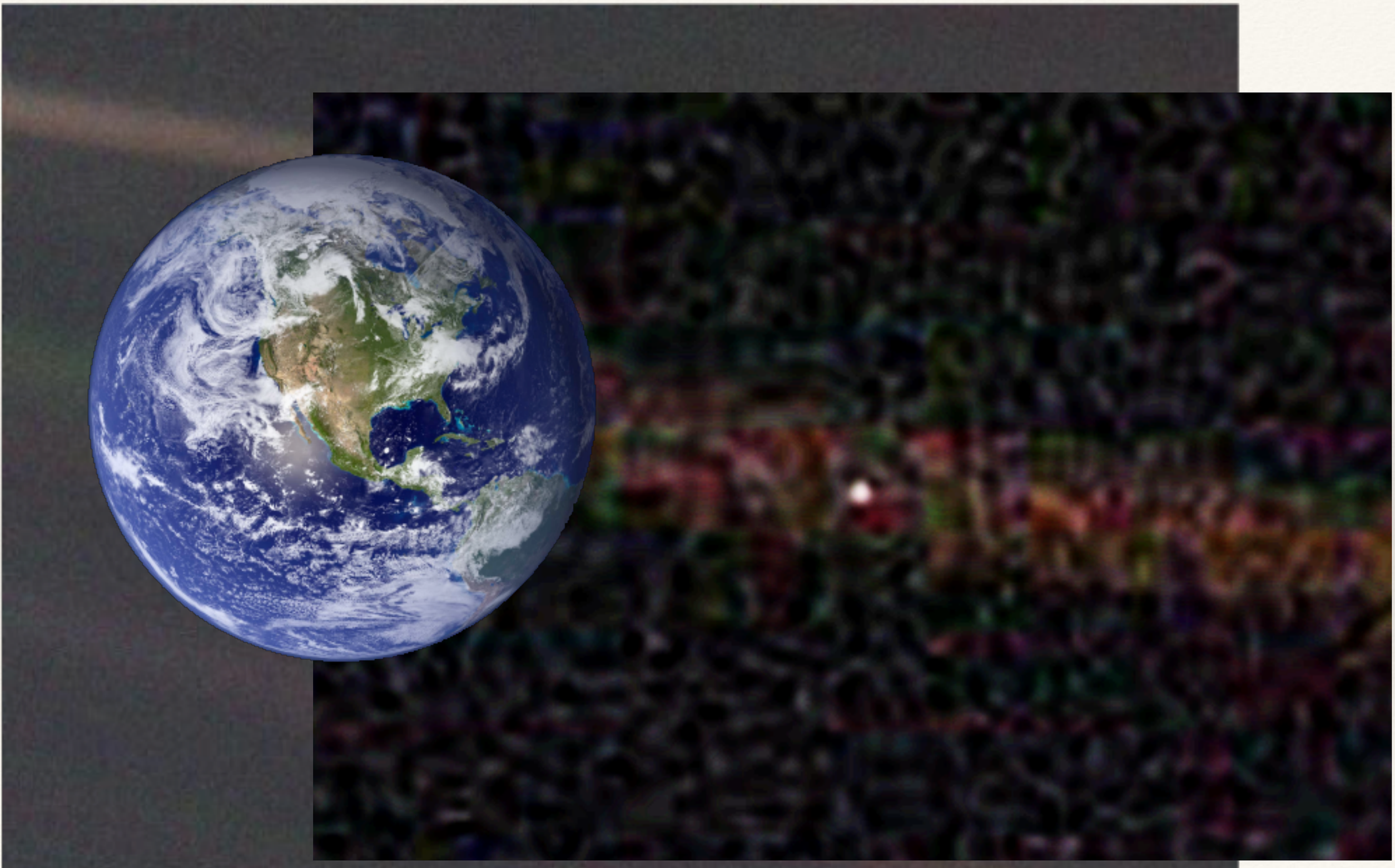
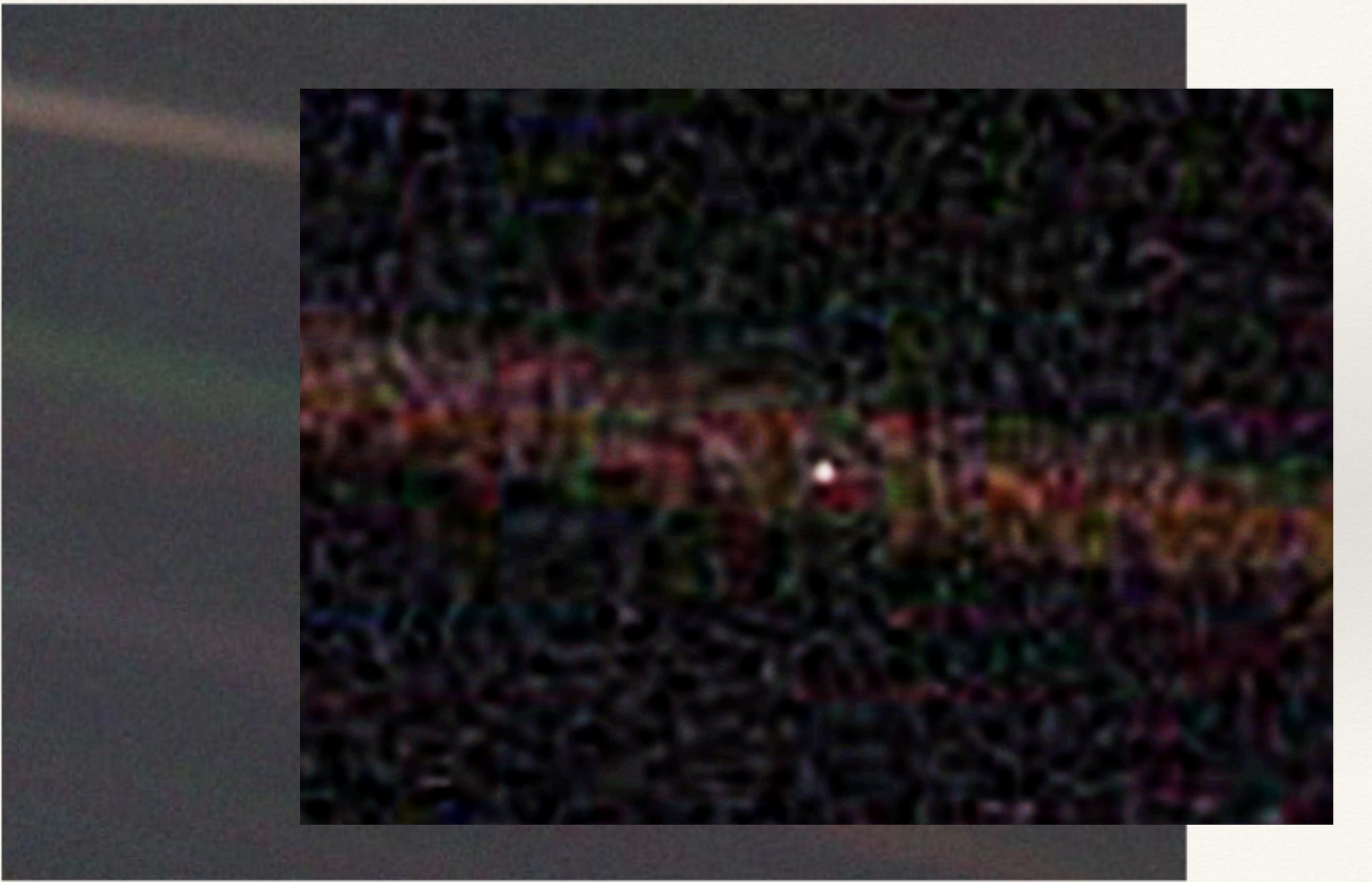


Where is Earth?



Astrophysical Motivation

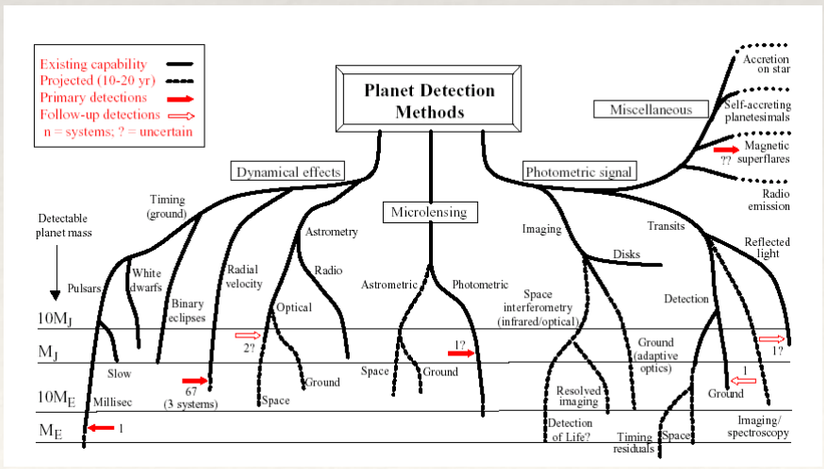
Astrophysical Interests

- architecture of Planetary Systems
- planets formation: core accretion/ disk instability
- planetary atmosphere composition
- presence and characteristics of clouds
- structure of planetary atmospheres (vertical distribution)
- composition and structure of planetary surfaces (if present and visible)
- temporal variation of atmospheric composition and structure
- Planetary rotation velocity
- discovery of “weird” planets in planetary systems
- Exo-zodiacal powder properties
- morphology of circumstellar disks

...Towards Characterization....

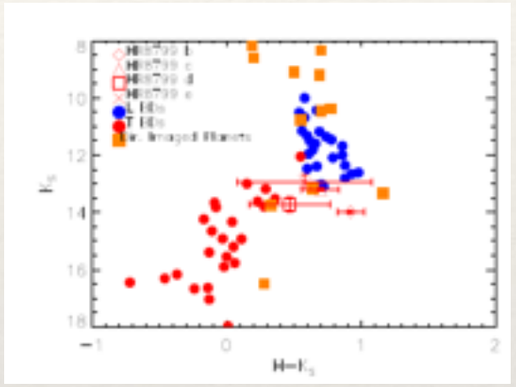
...Towards Characterization....

Discovery ...

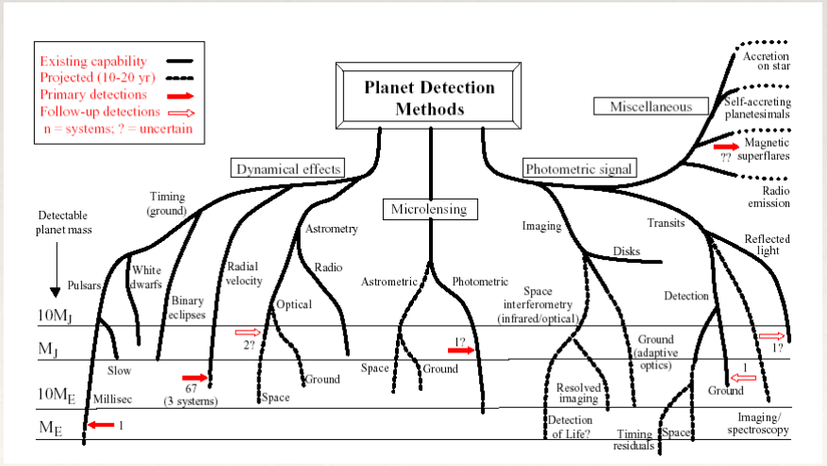


...Towards Characterization....

Color ...

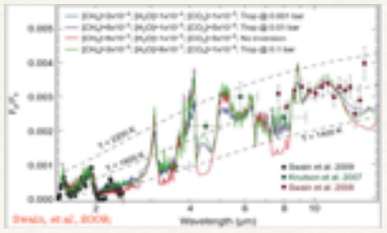


Discovery ...

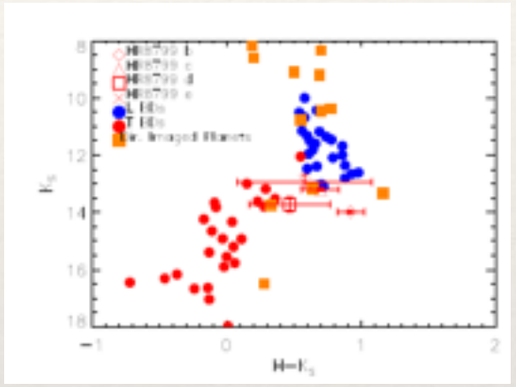


...Towards Characterization....

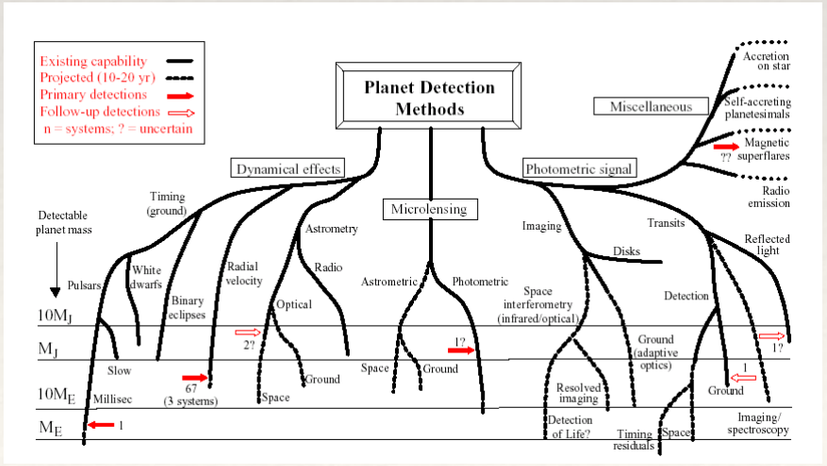
Spectroscopy ...



Color ...



Discovery ...



The Observables

- Sensibility to all the componets of a Planetary system
- Positions in the Image

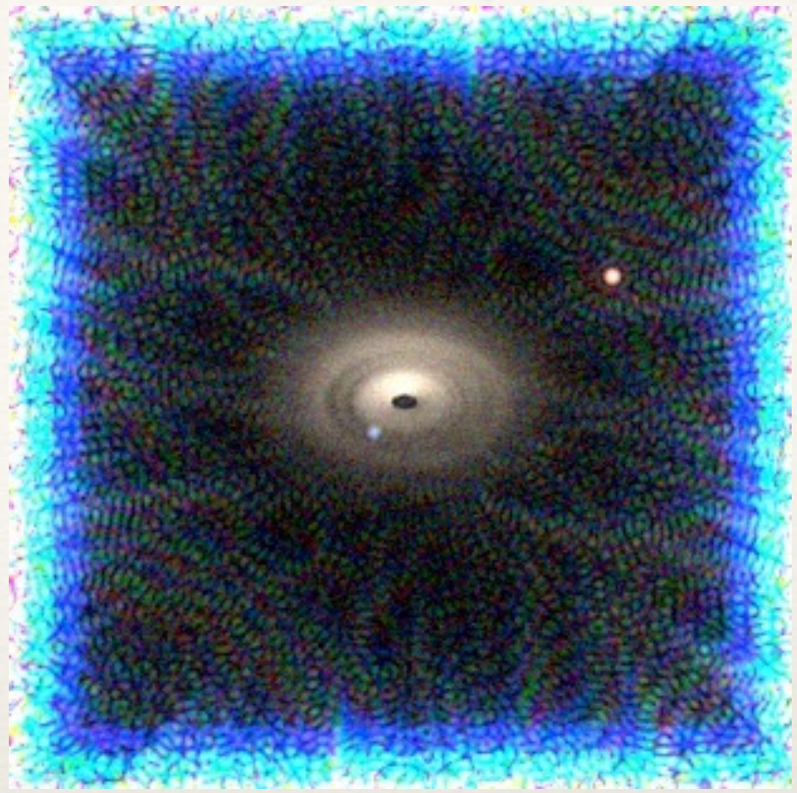
  Orbital parameters, Architecture of the planetary systems, planet position distribution; disk orientation
- Flux (intensity and polarization)

  Spectrum/ polarization: characterization of the planet and disk

  Temporal variations (yearly, seasons, eccentricity)

  Habitability, bio signature

The Observables



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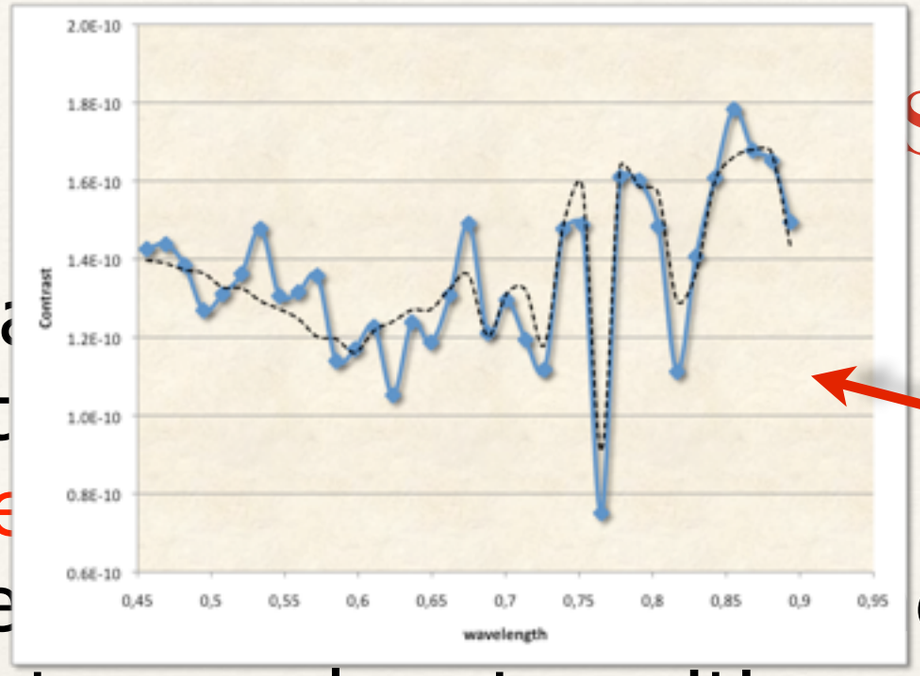
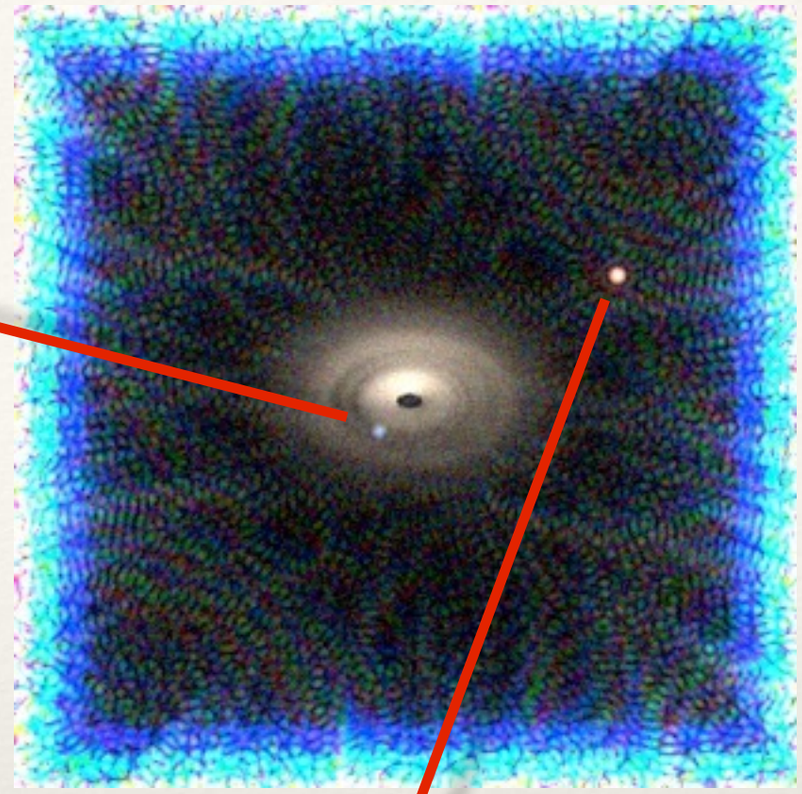
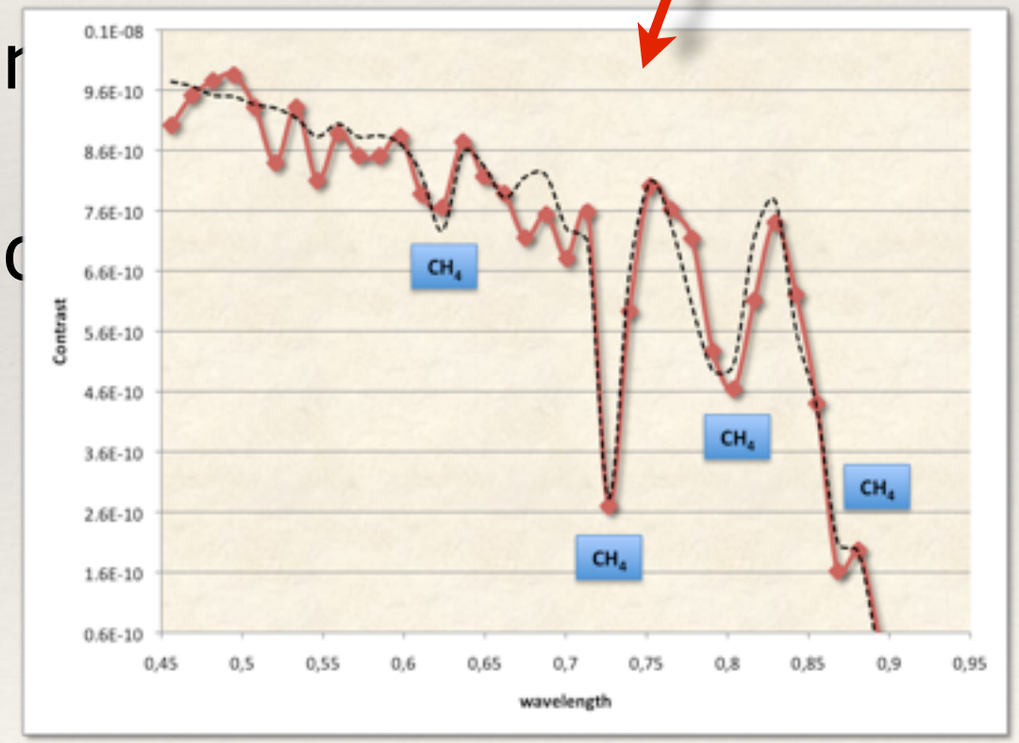
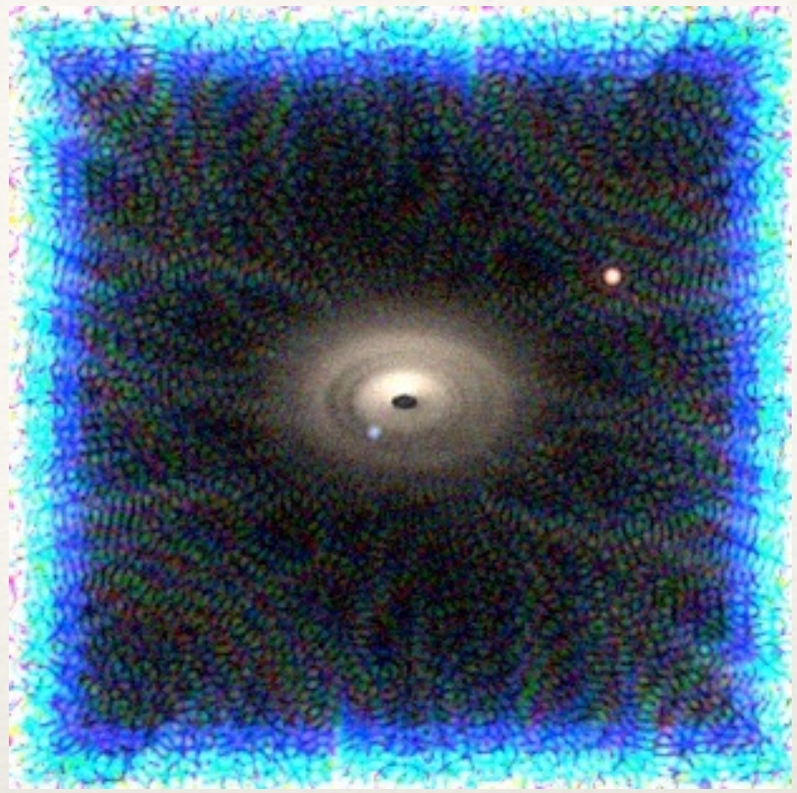






The Observables



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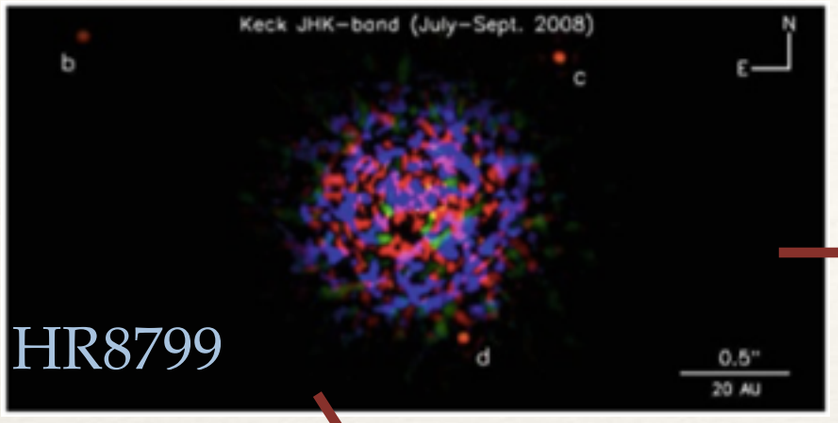
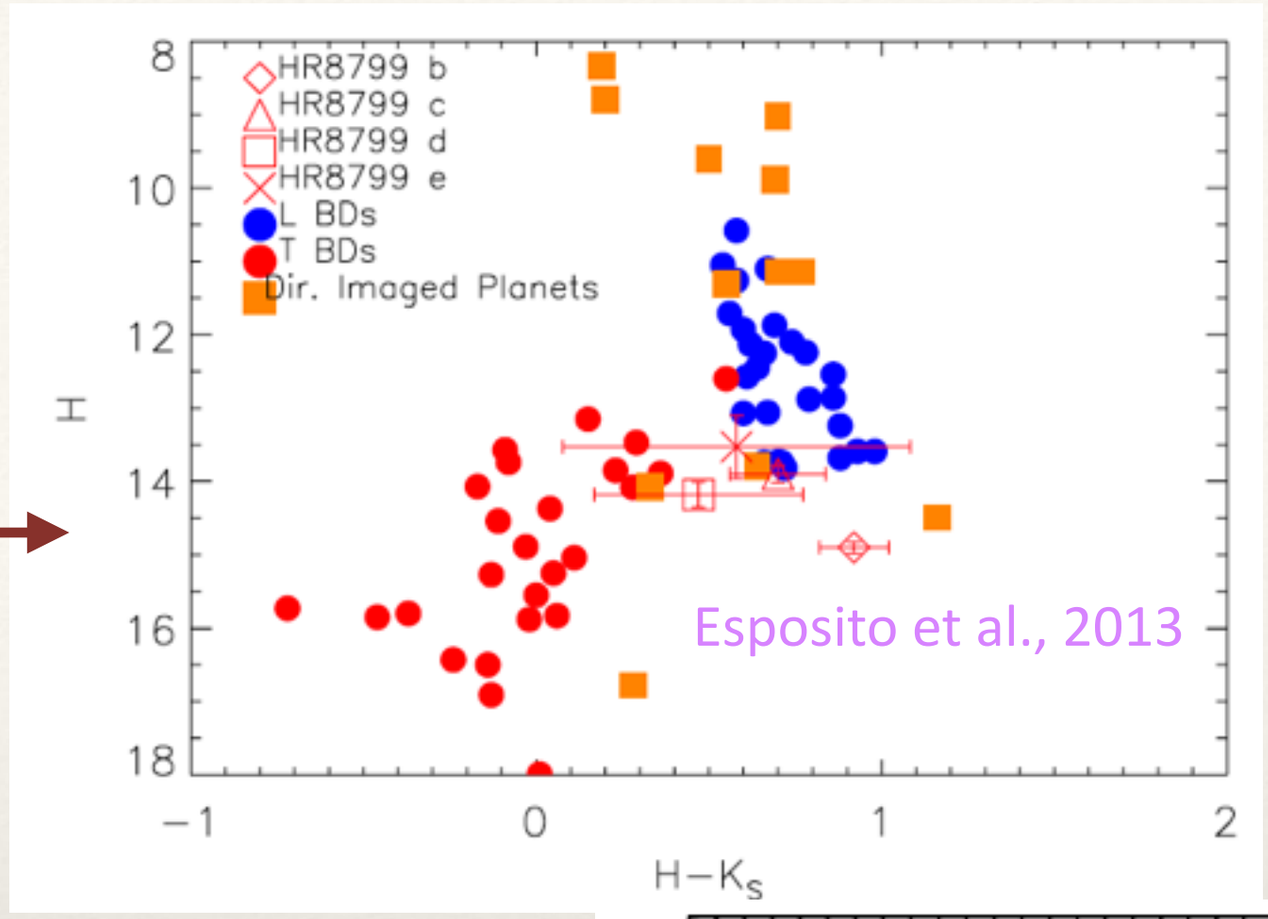
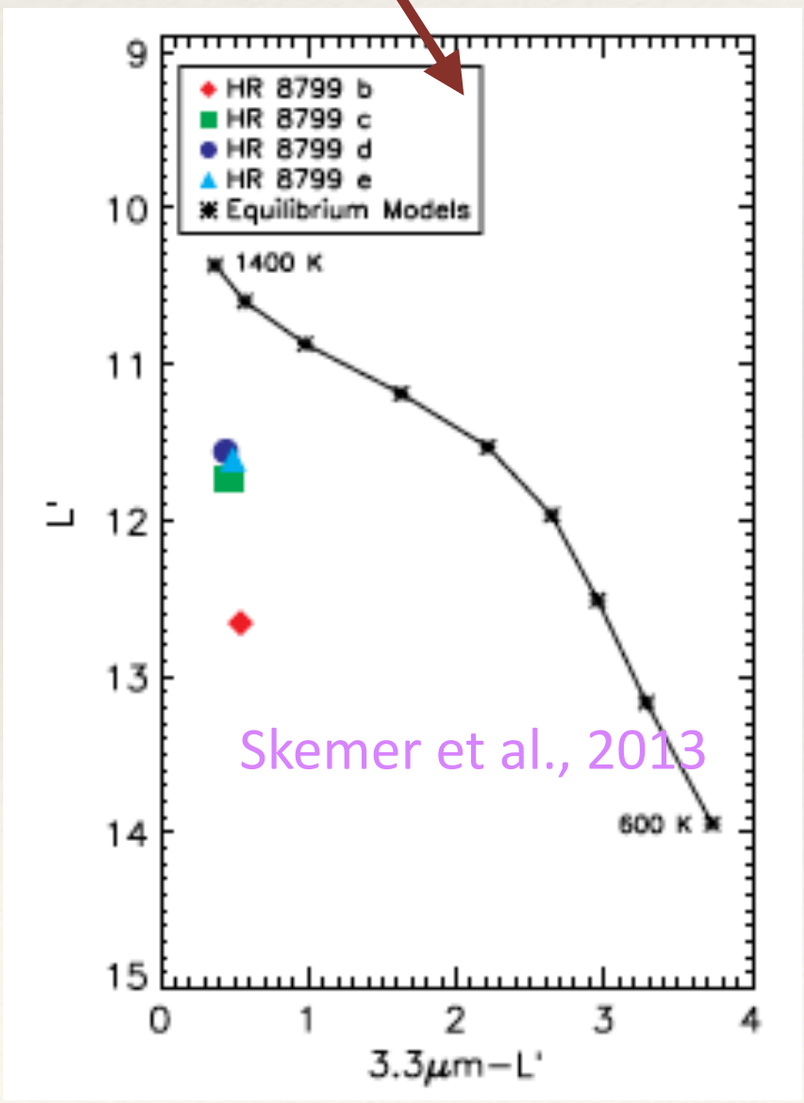
Direct Imaging is useful in order to characterize the exolanetary atmospheres. All wavelength bands are interesting from visible to the infrared.

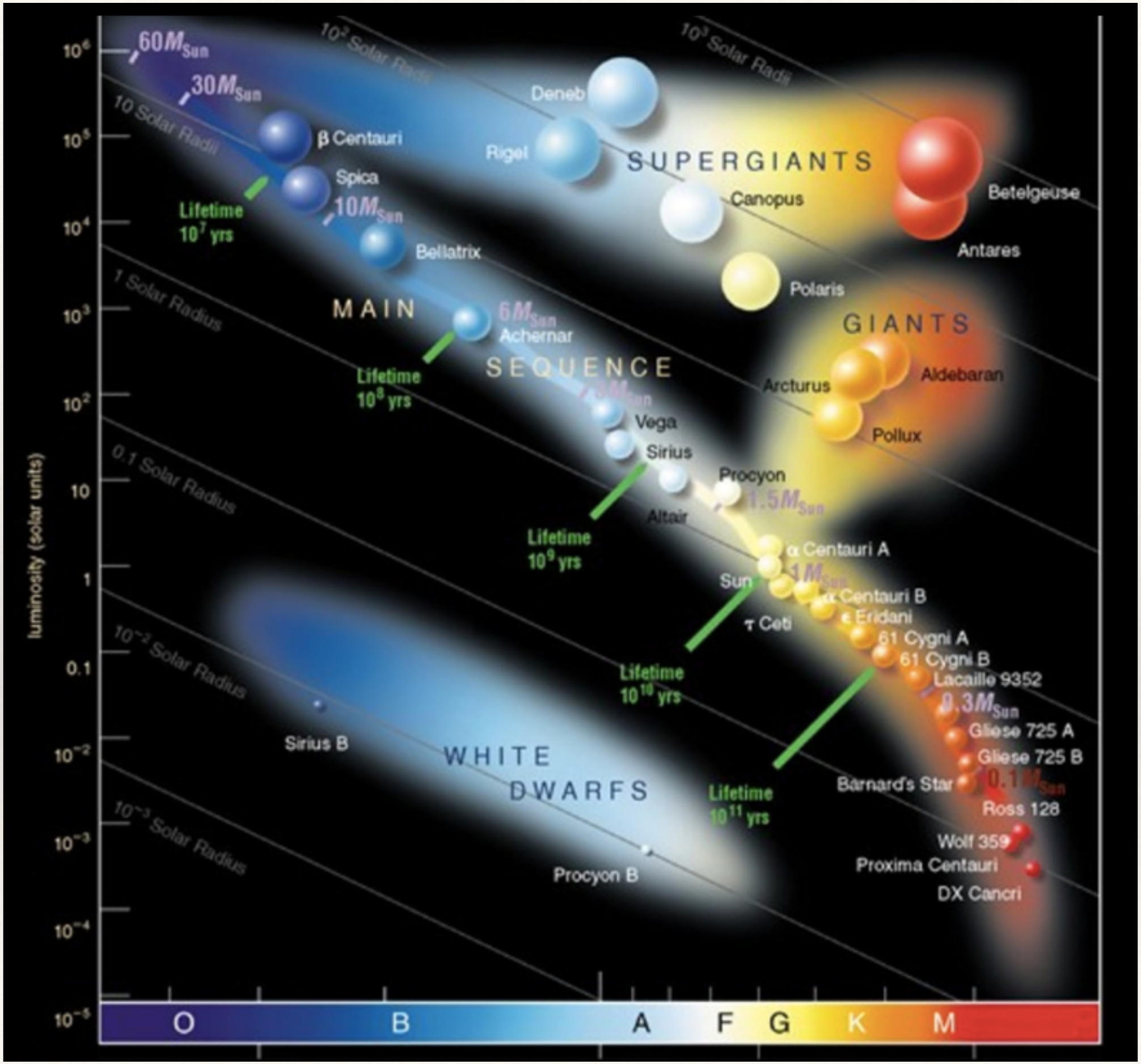
COLORS

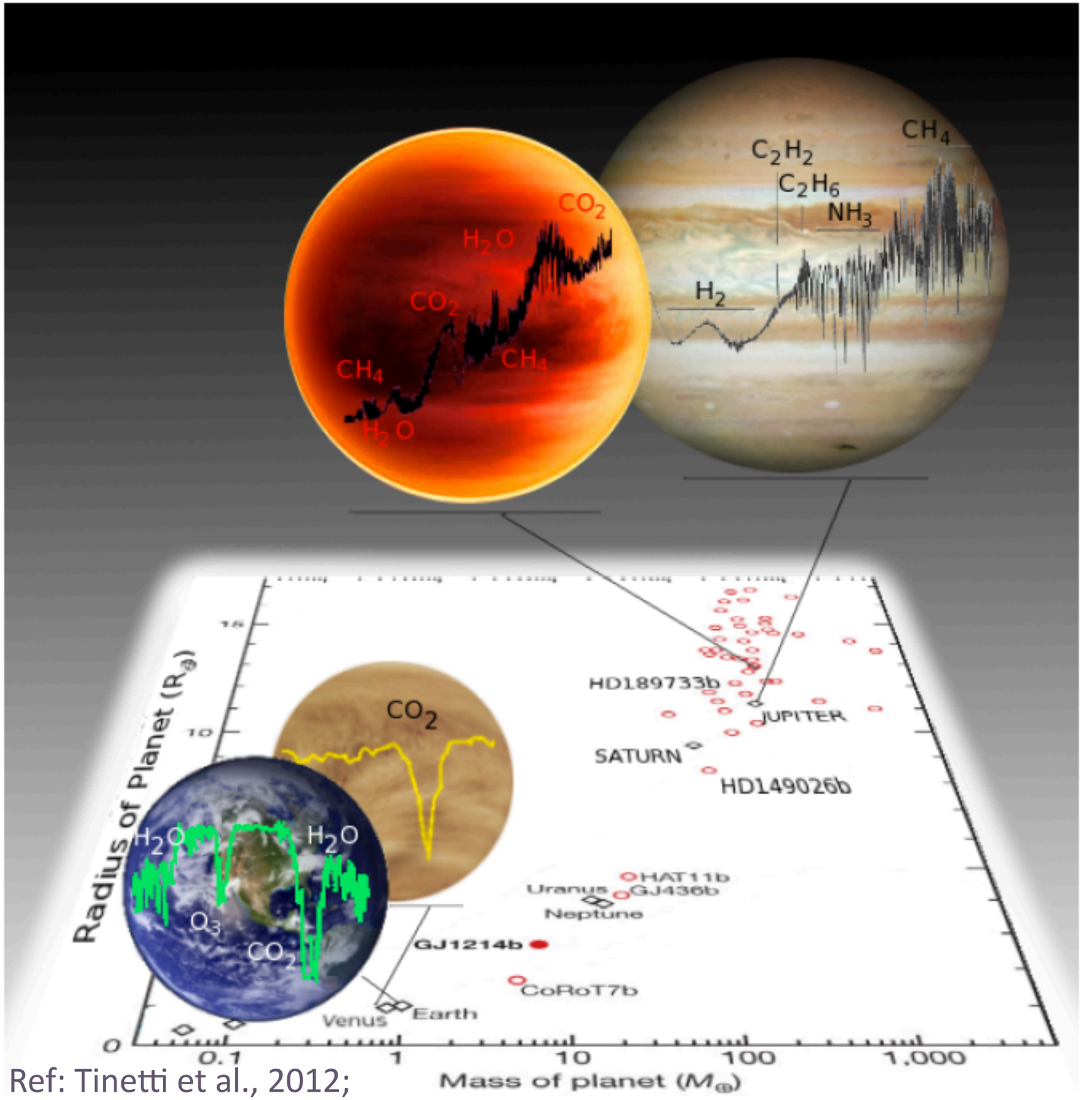

Keck JHK-band (July-Sept. 2008)
N
E
b
c
d
HR8799
0.5"
20 AU


HR8799 b
HR8799 c
HR8799 d
HR8799 e
L BDs
T BDs
Dir. Imaged Planets
H
H−Ks
Esposito et al., 2013


HR 8799 b
HR 8799 c
HR 8799 d
HR 8799 e
Equilibrium Models
1400 K
600 K
L'
3.3μm−L'
Skemer et al., 2013

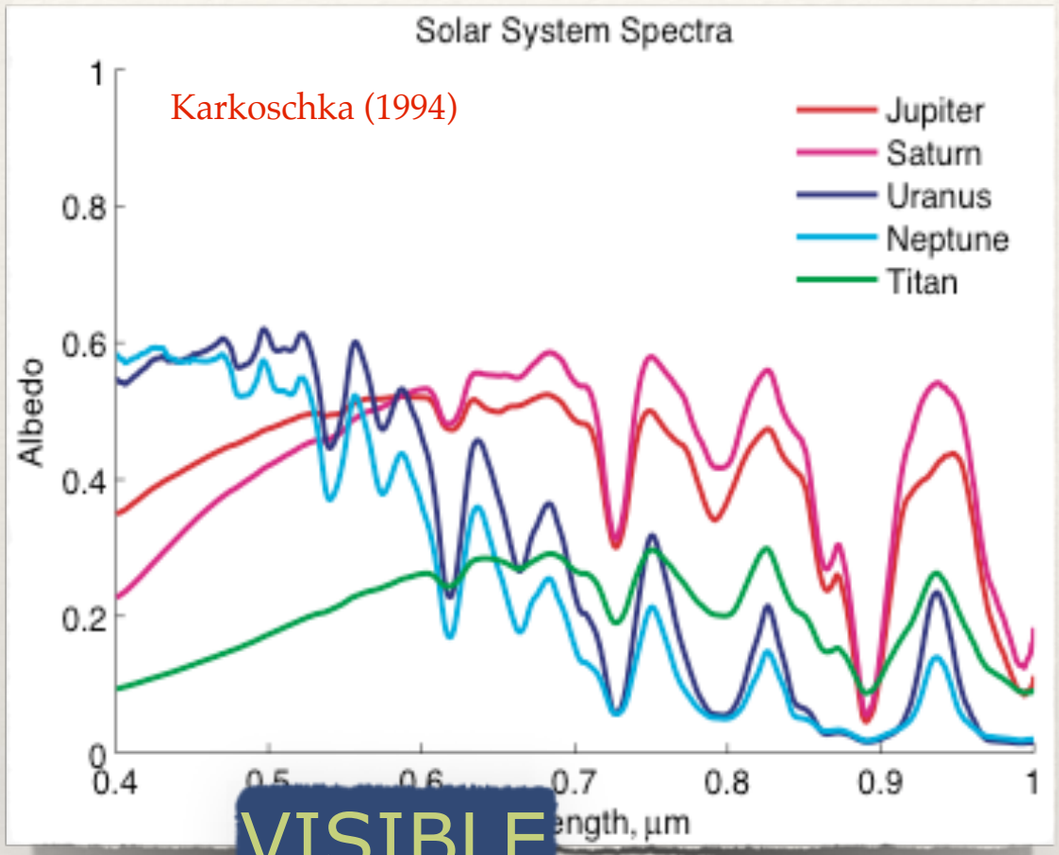
Albedo Colors of Planets
Mercury
Moon
Mars
Earth
Venus
Saturn
Titan
Jupiter
Neptune
Uranus
m(green) − m(red)
m(blue) − m(green)


Luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$60M_{Sun}$
$30M_{Sun}$
$10M_{Sun}$
$6M_{Sun}$
$1.5M_{Sun}$
$1M_{Sun}$
$0.3M_{Sun}$
$0.1M_{Sun}$
10 Solar Radii
10^2 Solar Radii
10^3 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
MAIN SEQUENCE
SUPERGIANTS
GIANTS
WHITE DWARFS
Deneb
Rigel
Canopus
Betelgeuse
Antares
Polaris
β Centauri
Spica
Bellatrix
Achernar
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
O
B
A
F
G
K
M

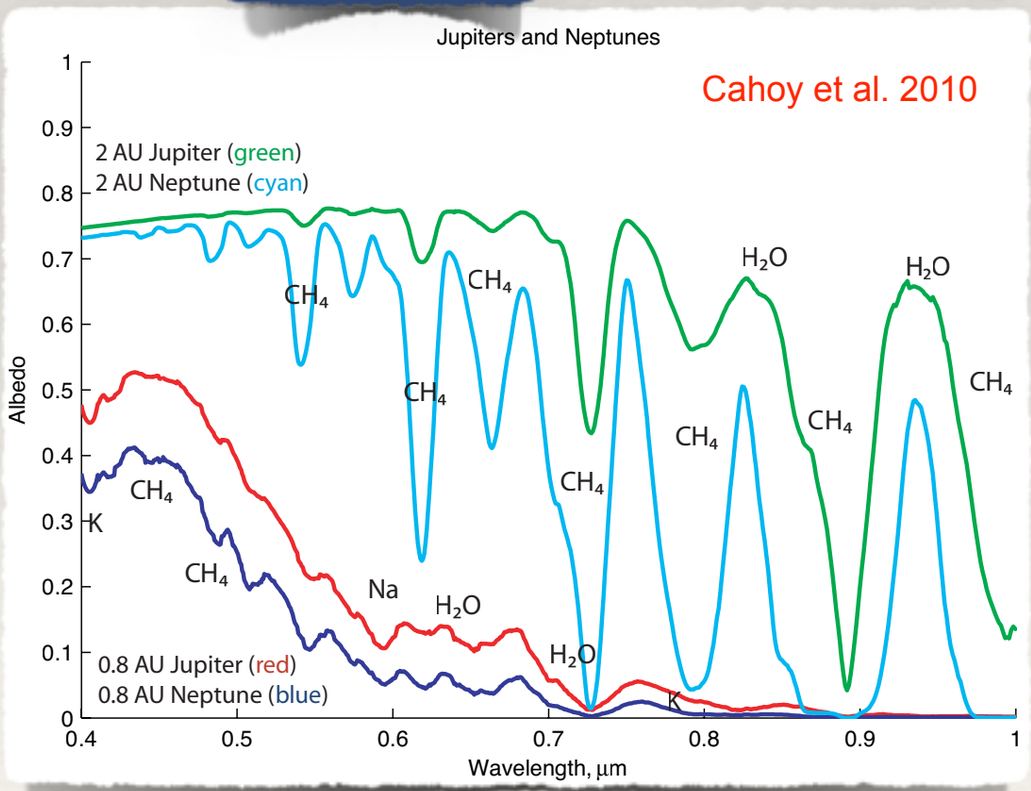


Ref: Tinetti et al., 2012;

SPECTRAL SIGNATURES



VISIBLE

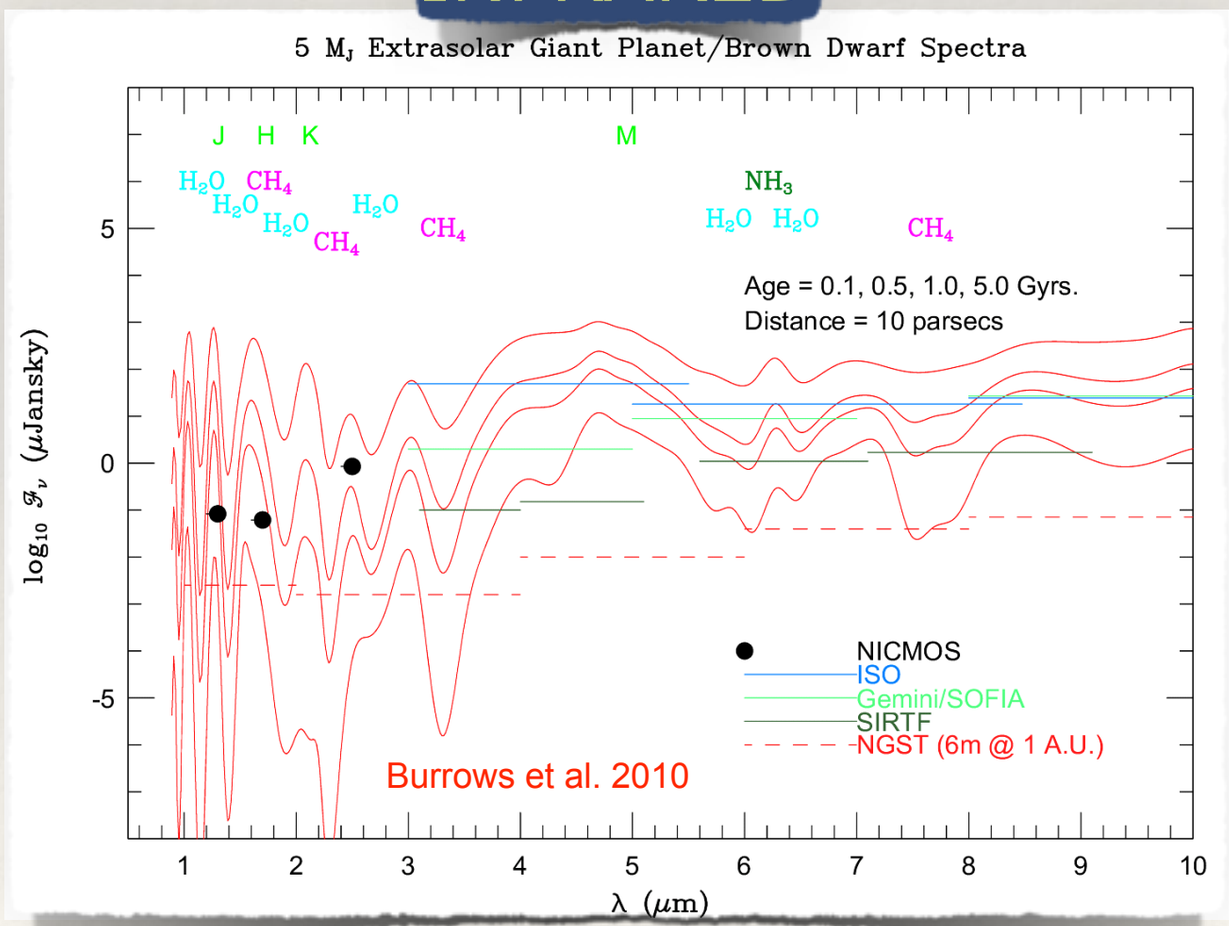


GIANT PLANET SPECTRA

Contains information about:

- ☑ Chemical species
- ☑ Pressure and temperature
- ☑ Clouds and grounds

INFRARED



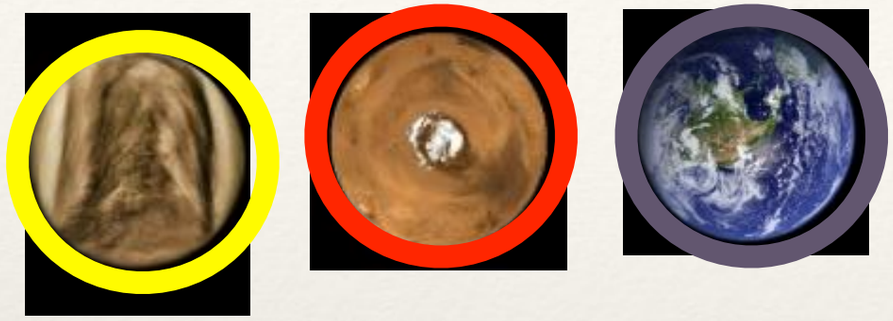
Species	λ_0 (μm)*	$\Delta\lambda$ (μm)†	Depth‡
O_3	0.32	0.02	0.69
O_3	0.58	0.13	0.20
O_2	0.69	0.01	0.12
H_2O	0.72	0.02	0.37
CH_4	0.73	0.01	0.002
O_2	0.76	0.01	0.47
CH_4	0.79	0.03	0.001
H_2O	0.82	0.02	0.32
CH_4	0.89	0.03	0.002
H_2O	0.94	0.06	0.71
CH_4	1.00	0.05	0.011
CO_2	1.05	0.02	0.0006
H_2O	1.13	0.07	0.80
CO_2	1.21	0.03	0.01
O_2	1.27	0.02	0.15
H_2O	1.41	0.14	0.95
CO_2	1.59	0.14	0.03
CH_4	1.69	0.16	0.012
H_2O	1.88	0.18	0.97
CO_2	2.03	0.12	0.31
CH_4	2.32	0.29	0.009
H_2O	7.00	0.70	0.83
CH_4	7.65	0.59	0.09
N_2O	7.75	0.14	0.10
N_2O	8.52	0.37	0.02
CO_2	9.31	0.49	0.05
O_3	9.65	0.58	0.41
CO_2	10.42	0.65	0.04
CO_2	14.96	3.71	0.52
H_2O	20.49	7.64	0.21

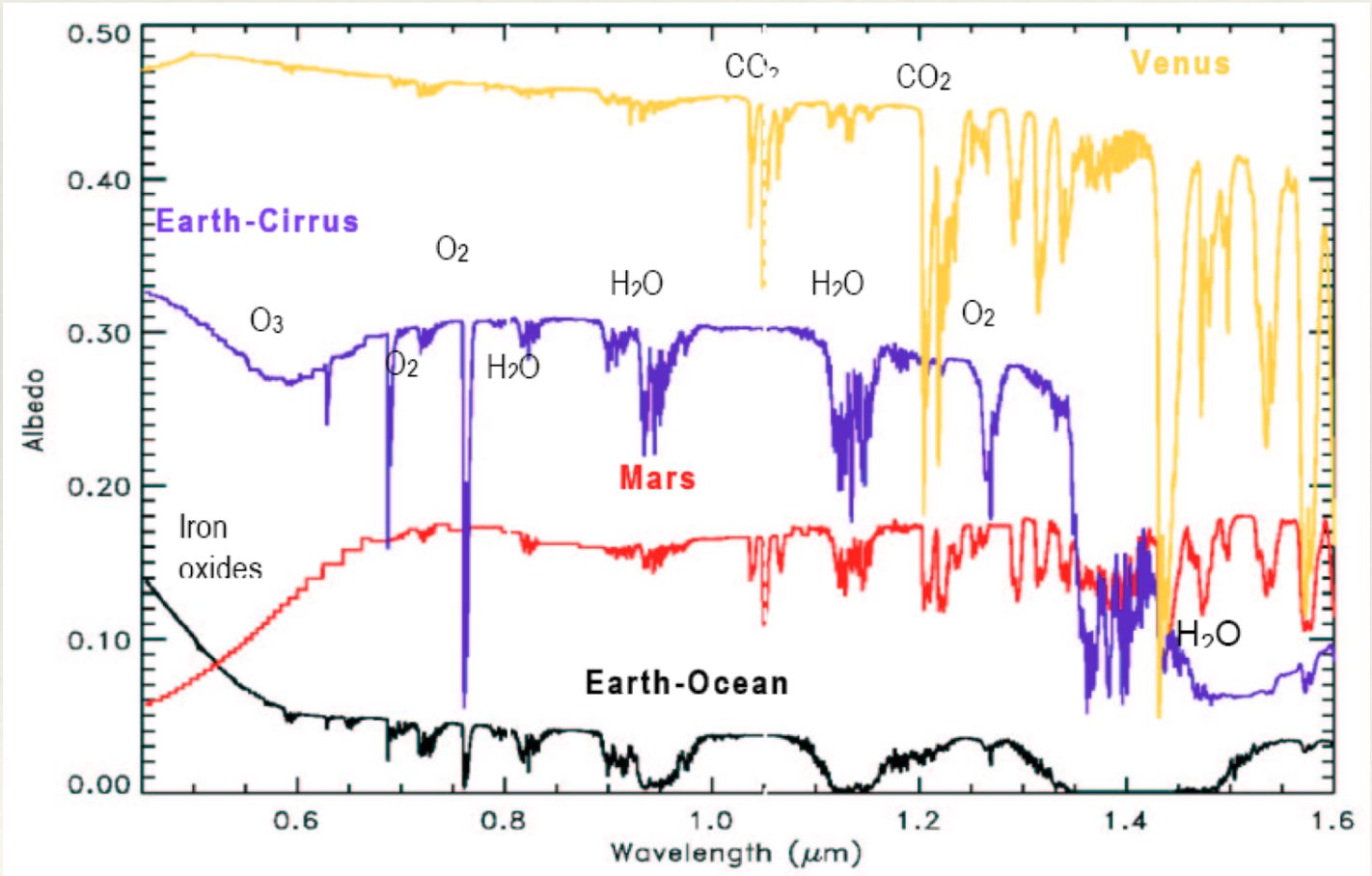
From Traub & Oppenheimer,2010 and Des Marais et al., 2002

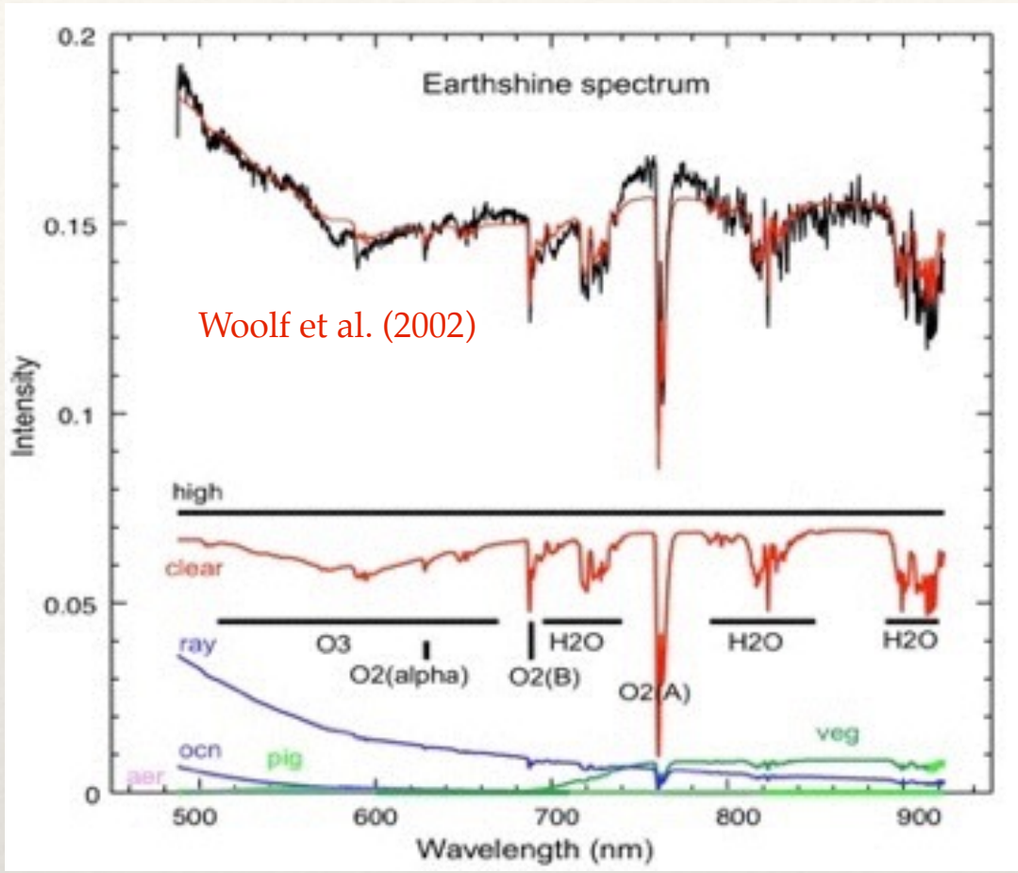
SPECTRAL SIGNATURES

TELLURIC PLANET SPECTRA

Visible



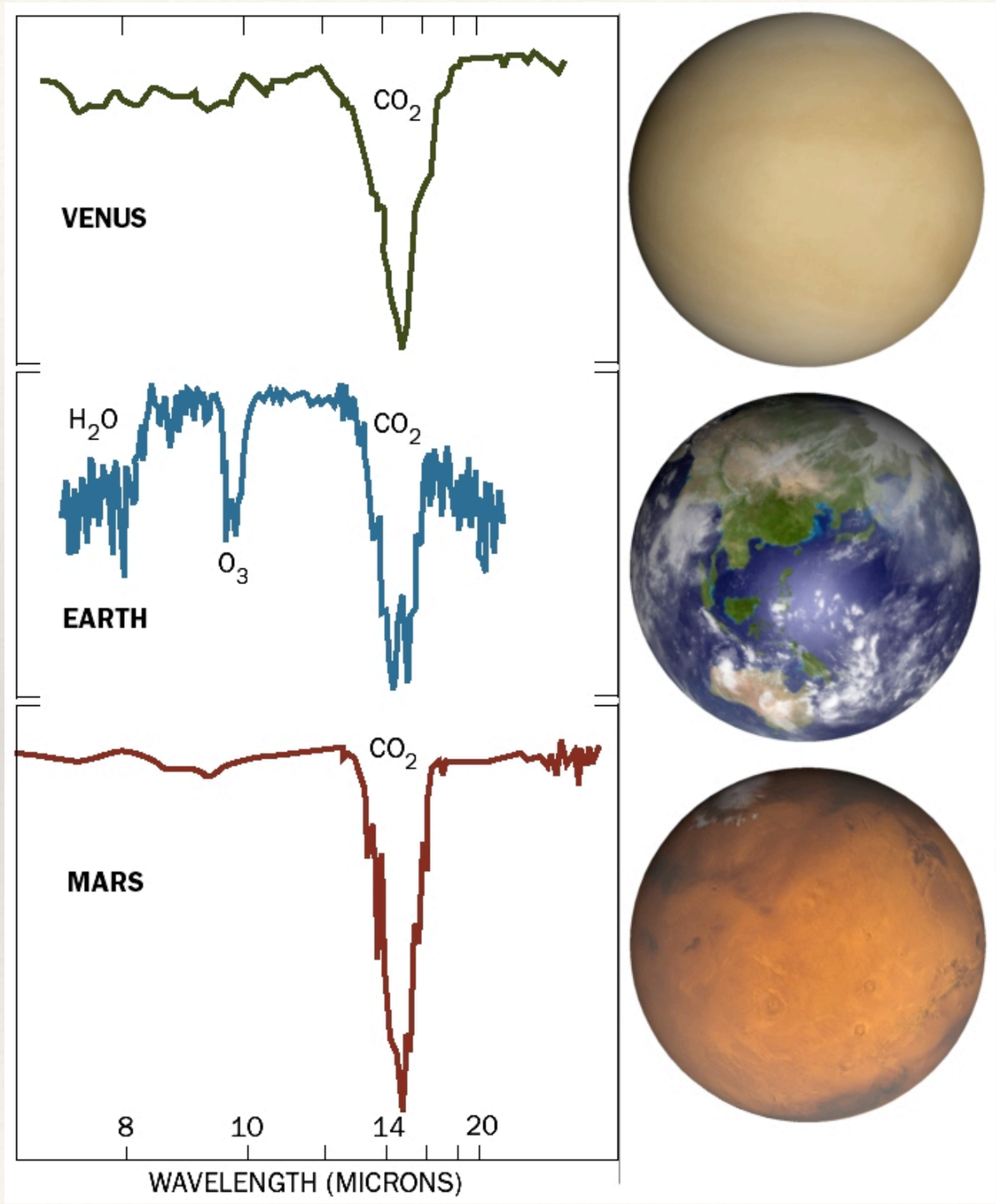


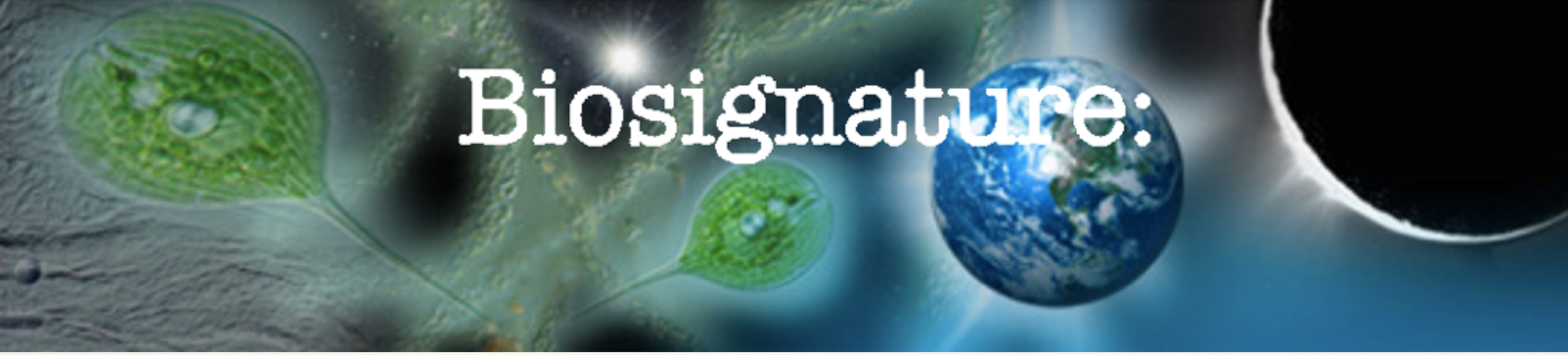


SPECTRAL SIGNATURES

TELLURIC PLANET SPECTRA

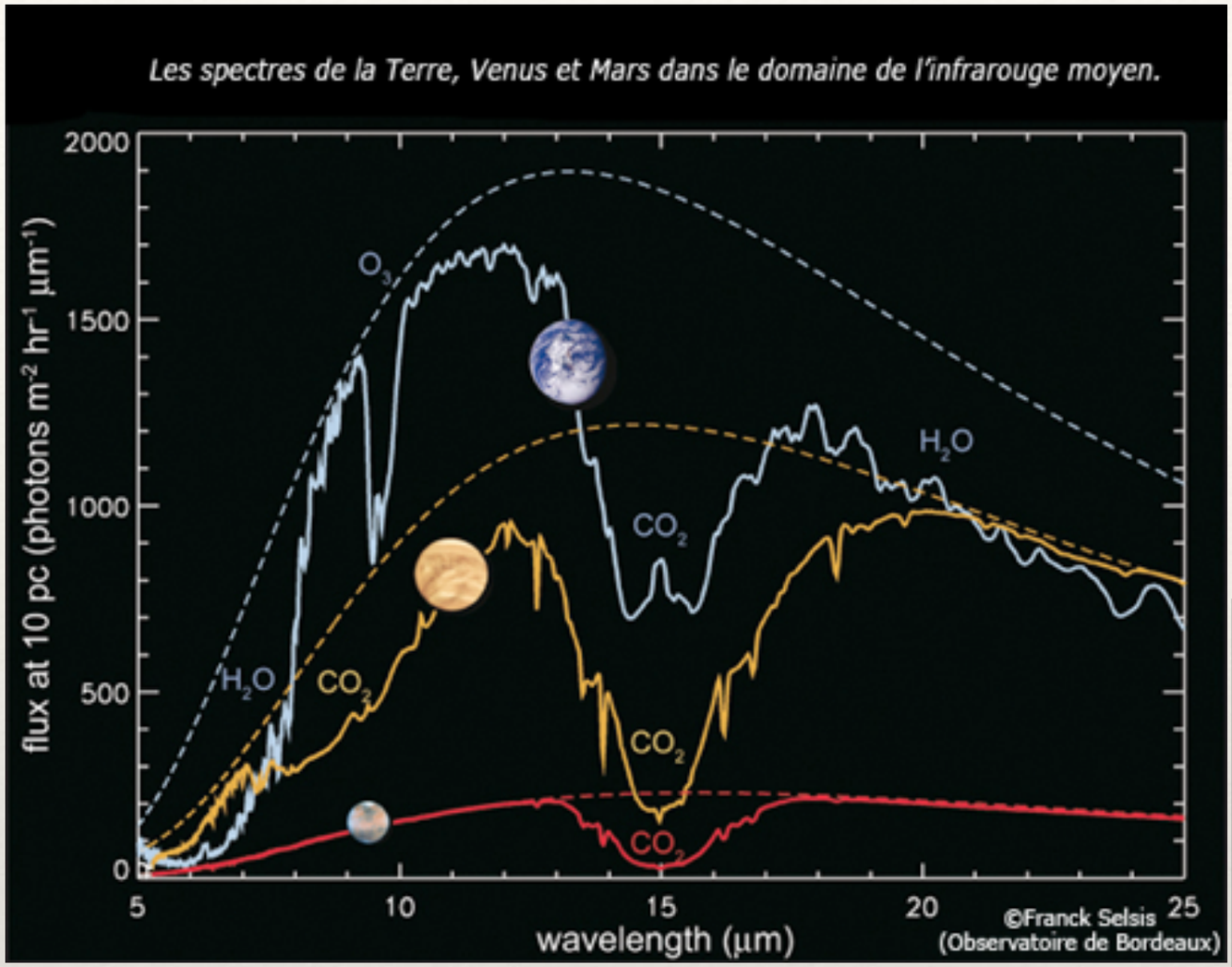
INFRARED





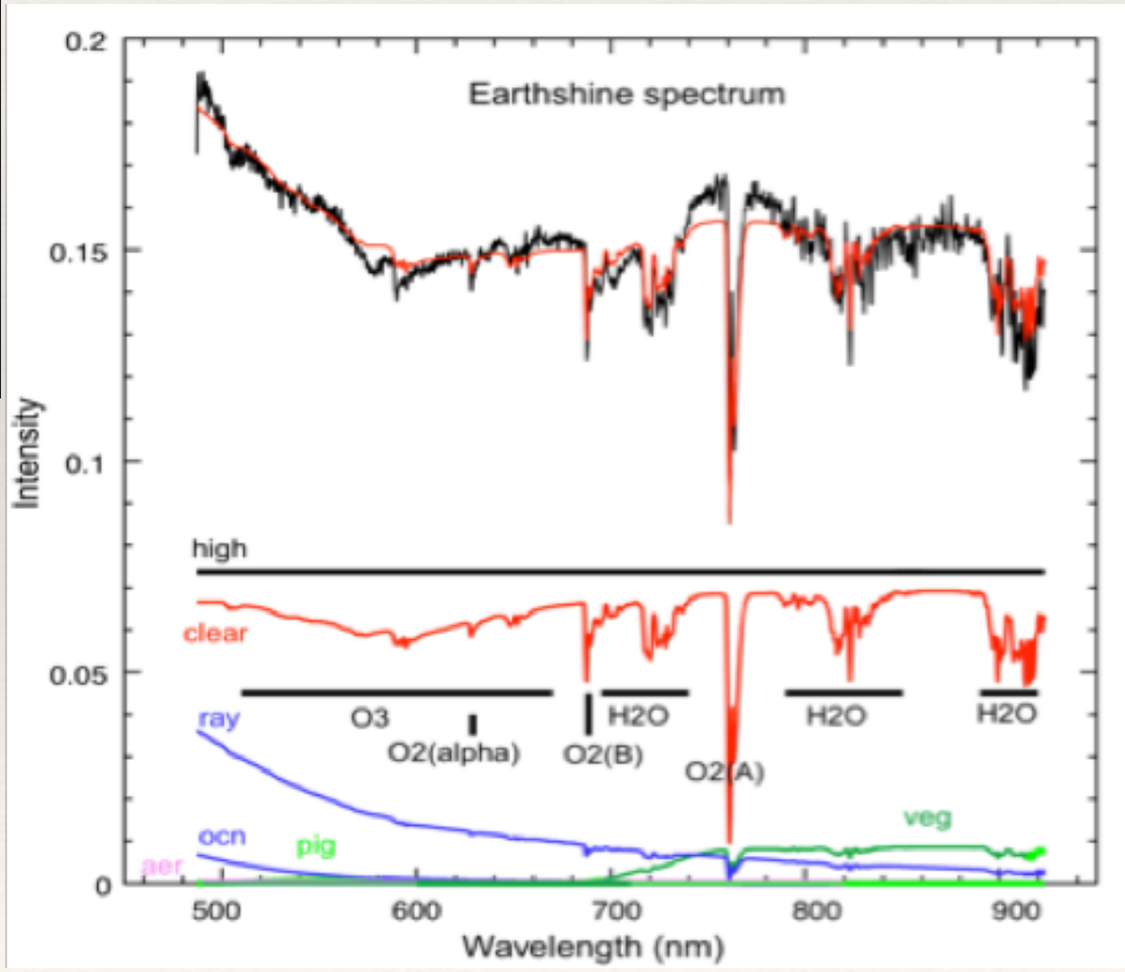
- the presence of chemically based life on a planet would change the composition of its atmosphere away from the biological steady state
- the change would be recognisable even at astronomical distances
- a global sign of life manifest in the planetary characteristics and detected in the spectrum of light reflected or emitted by a planet's atmosphere or surface

BIOSIGNATURES



Research for Biosignatures based on Earth life:

- Carbon Chemistry
- Water as solvent



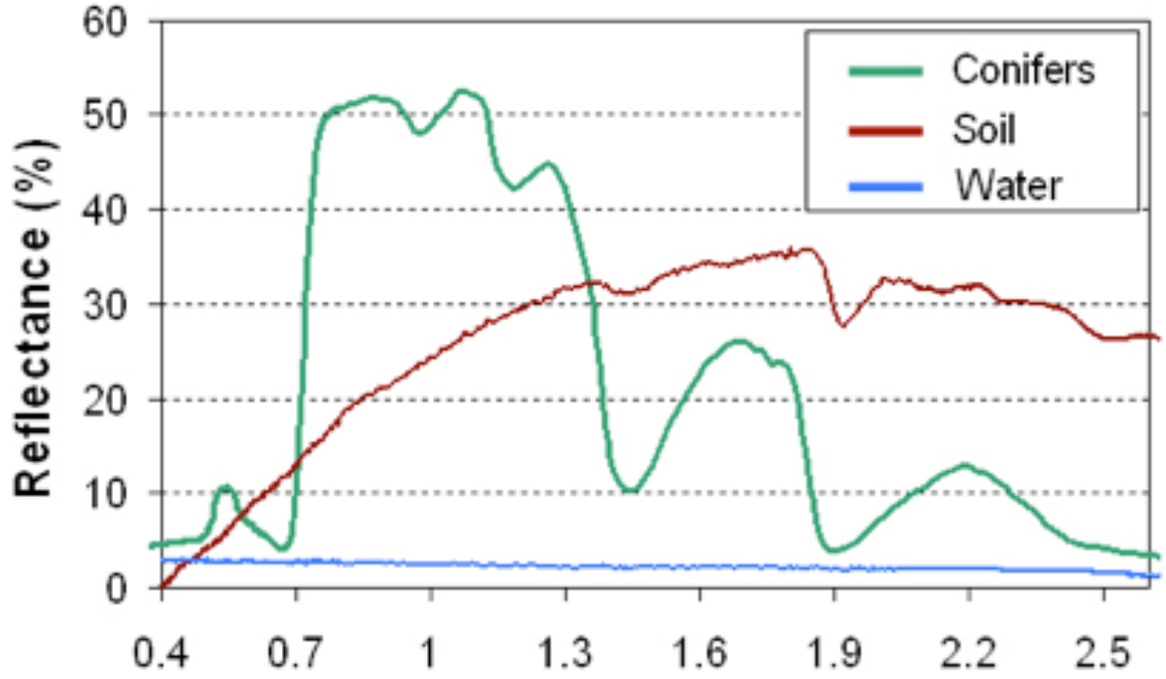
Only one biomarker -> Ambiguity

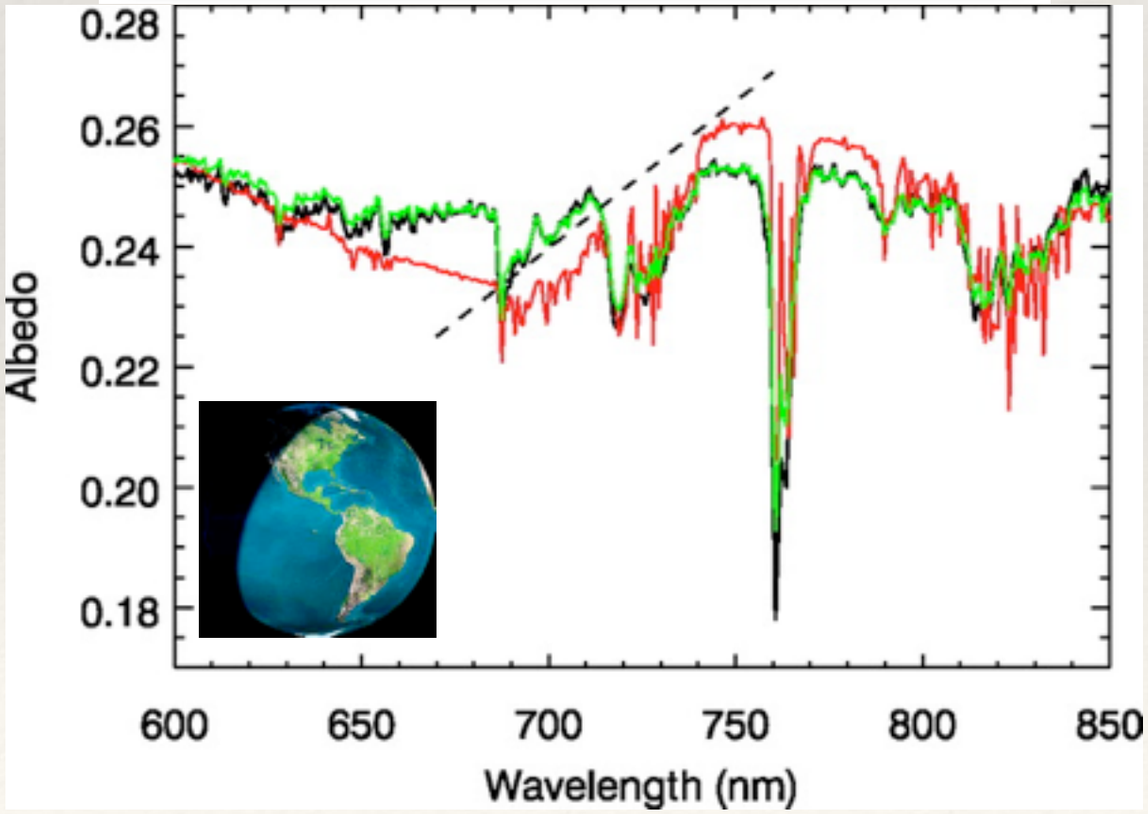
Good life markers

$O_2 + H_2O + CO_2$

$CH_4/NH_3 + O_2/O_3$

VEGETATION



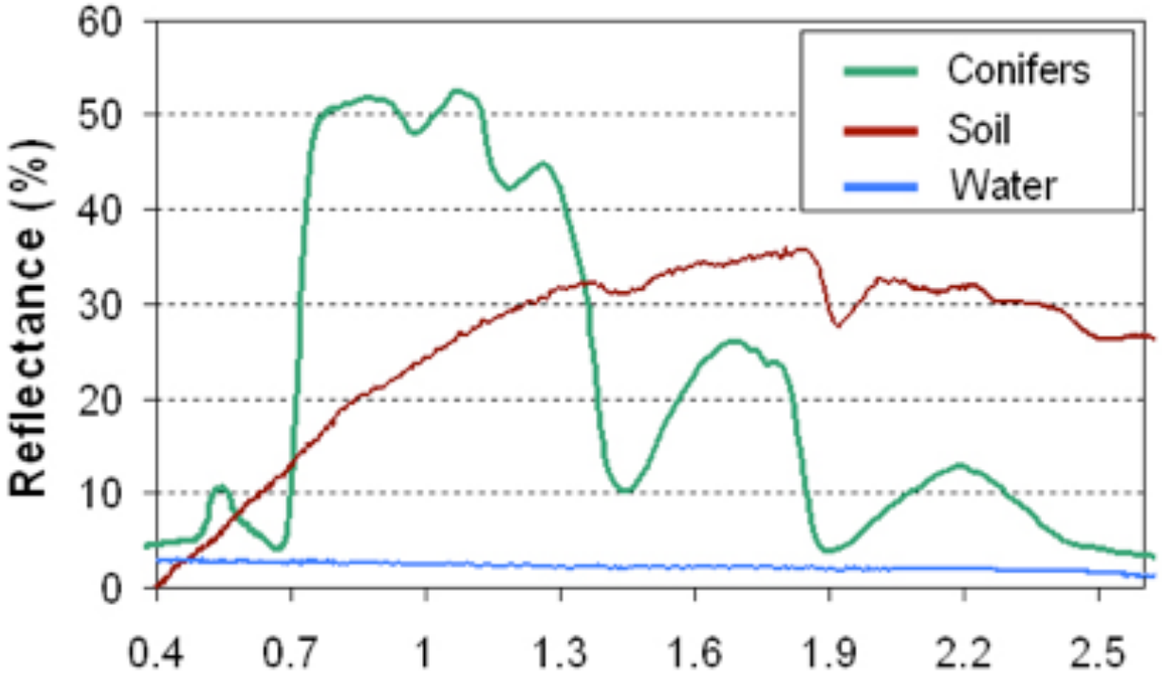


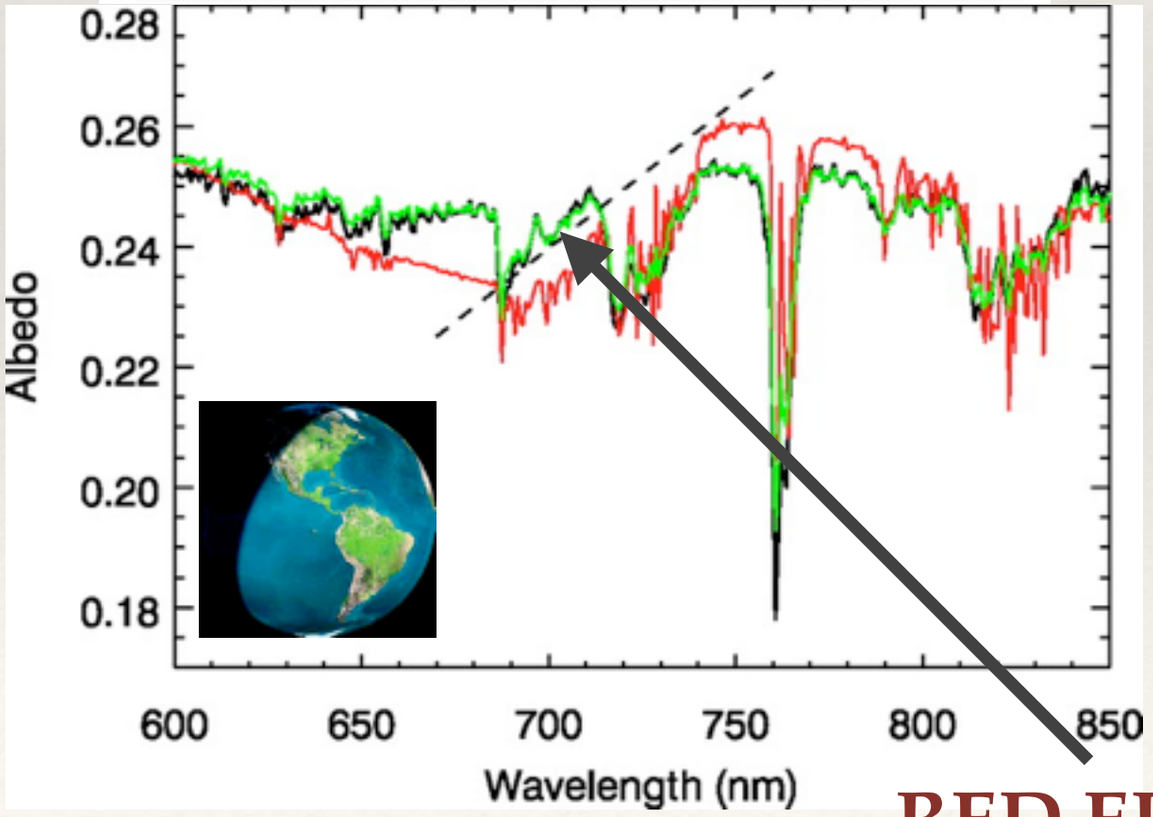
Chlorophyll reflection enhances at 700 nm

For Earth is difficult to observe

it depends by the quantity and the observable emisphere

VEGETATION





Chlorophyll reflection enhances at 700 nm

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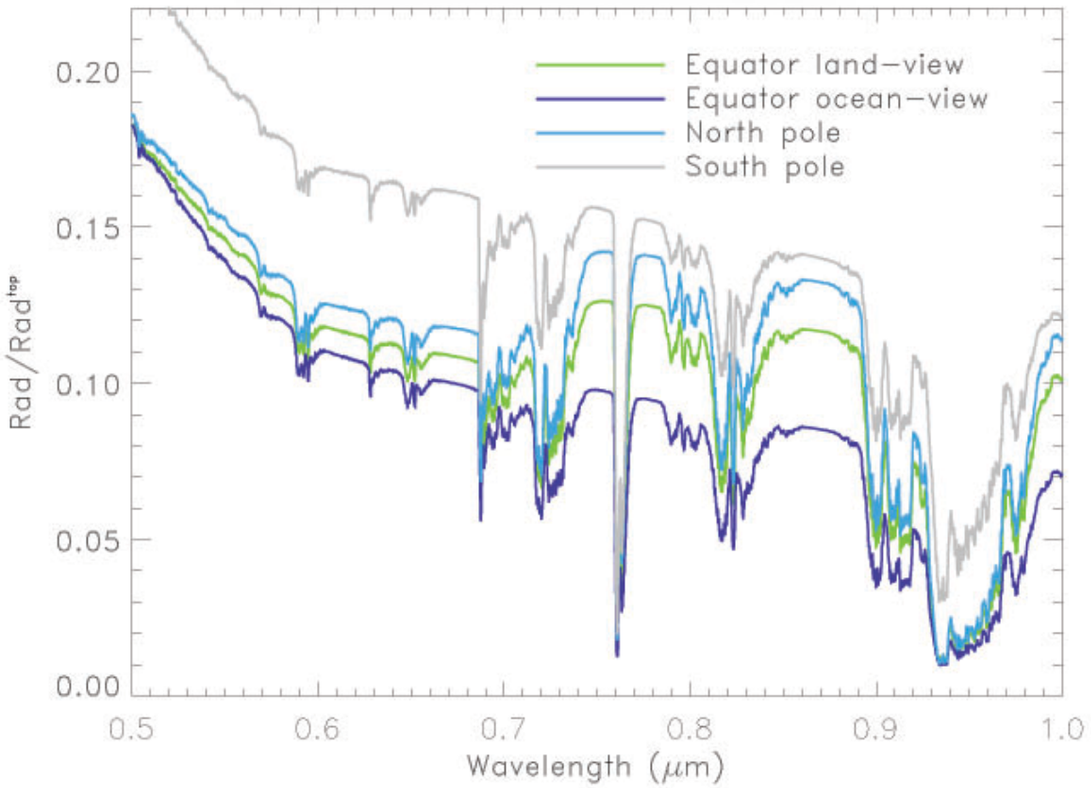
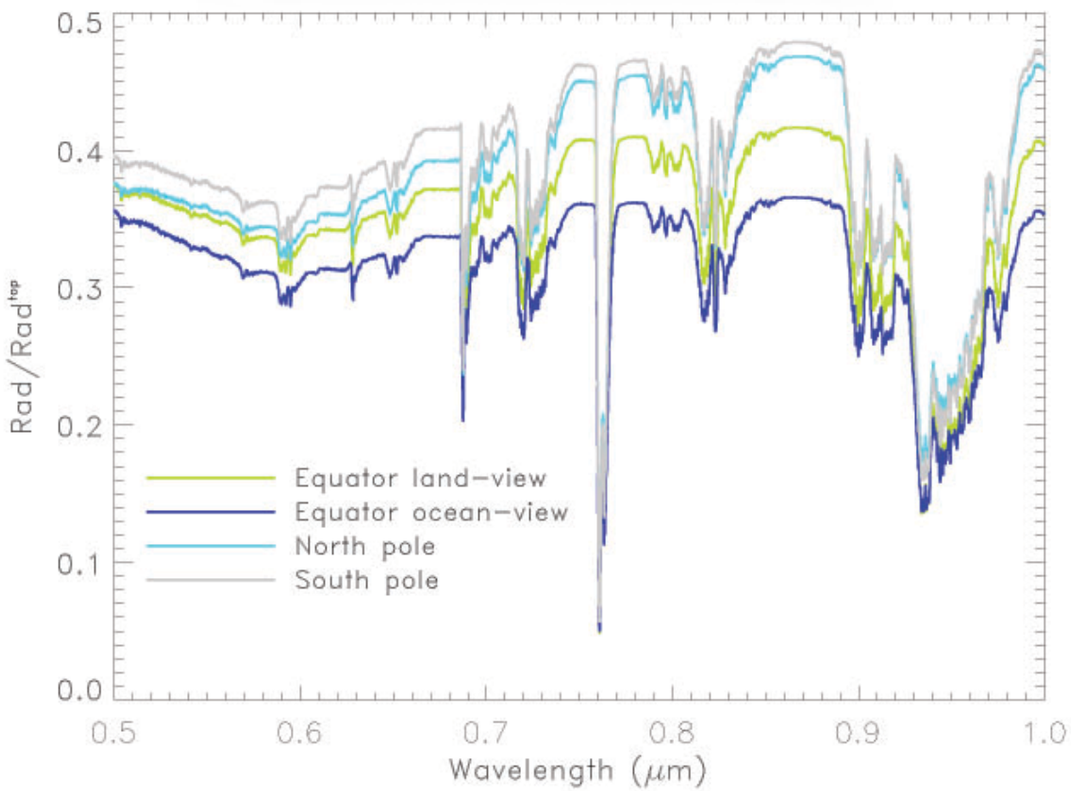
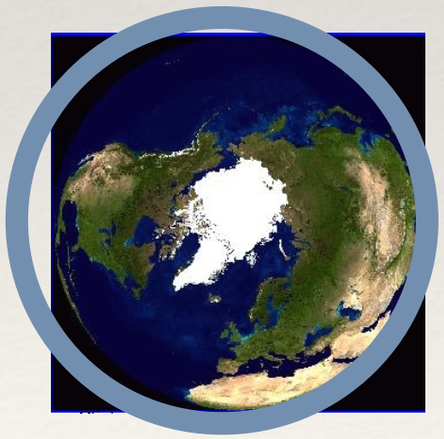
RED EDGE

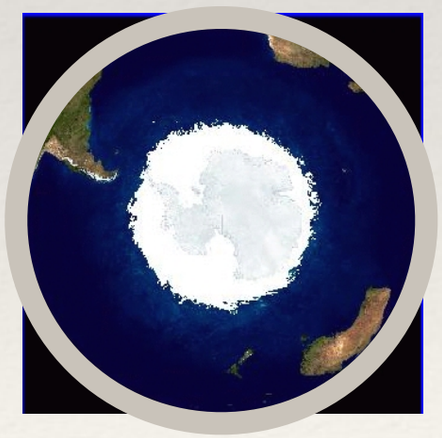
Clear - Summer



Cloudy - Summer







Summary of Astrophysical Interests

- ☑ Architecture of Planetary Systems
- ☑ Astrometry of the planets
- ☑ Dynamical Characterization
- ☑ Interaction plant - Disk
- ☑ Atmospheric Characterization
- ☑ Biosignatures