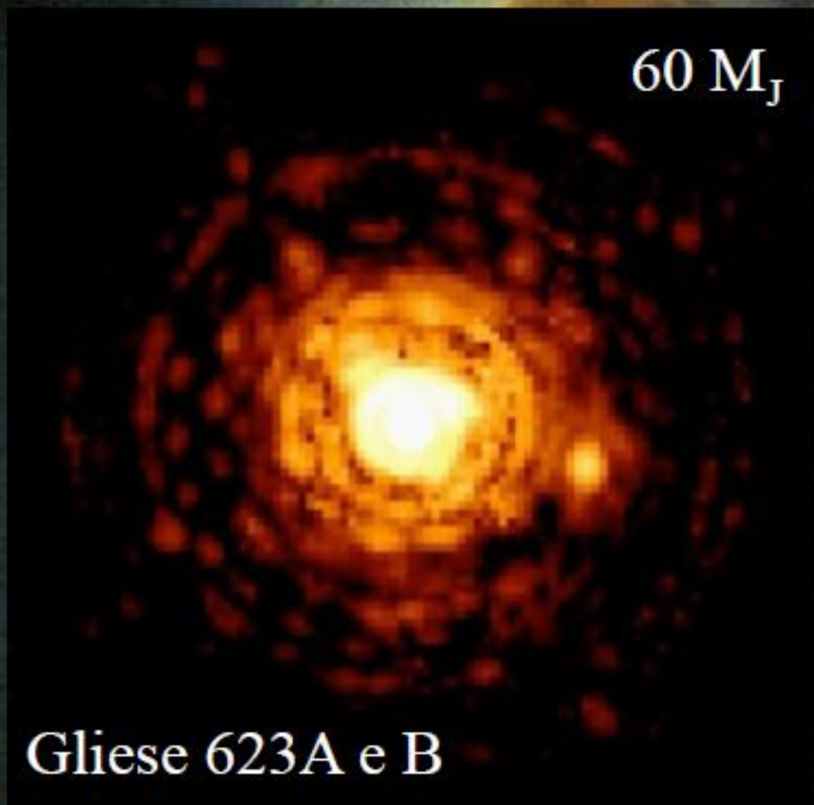
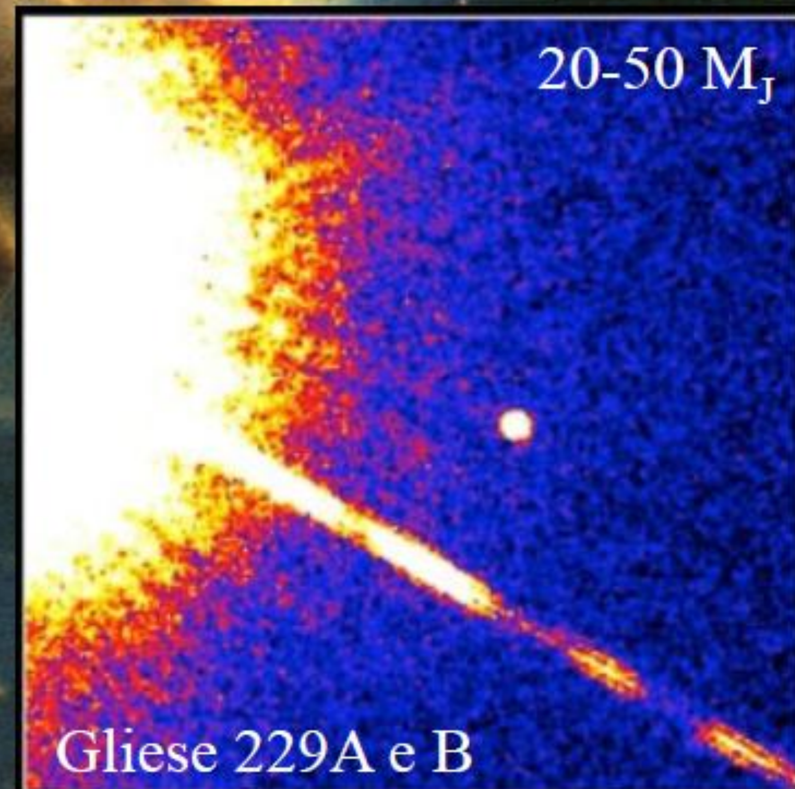
Characterization of Extrasolar Planets

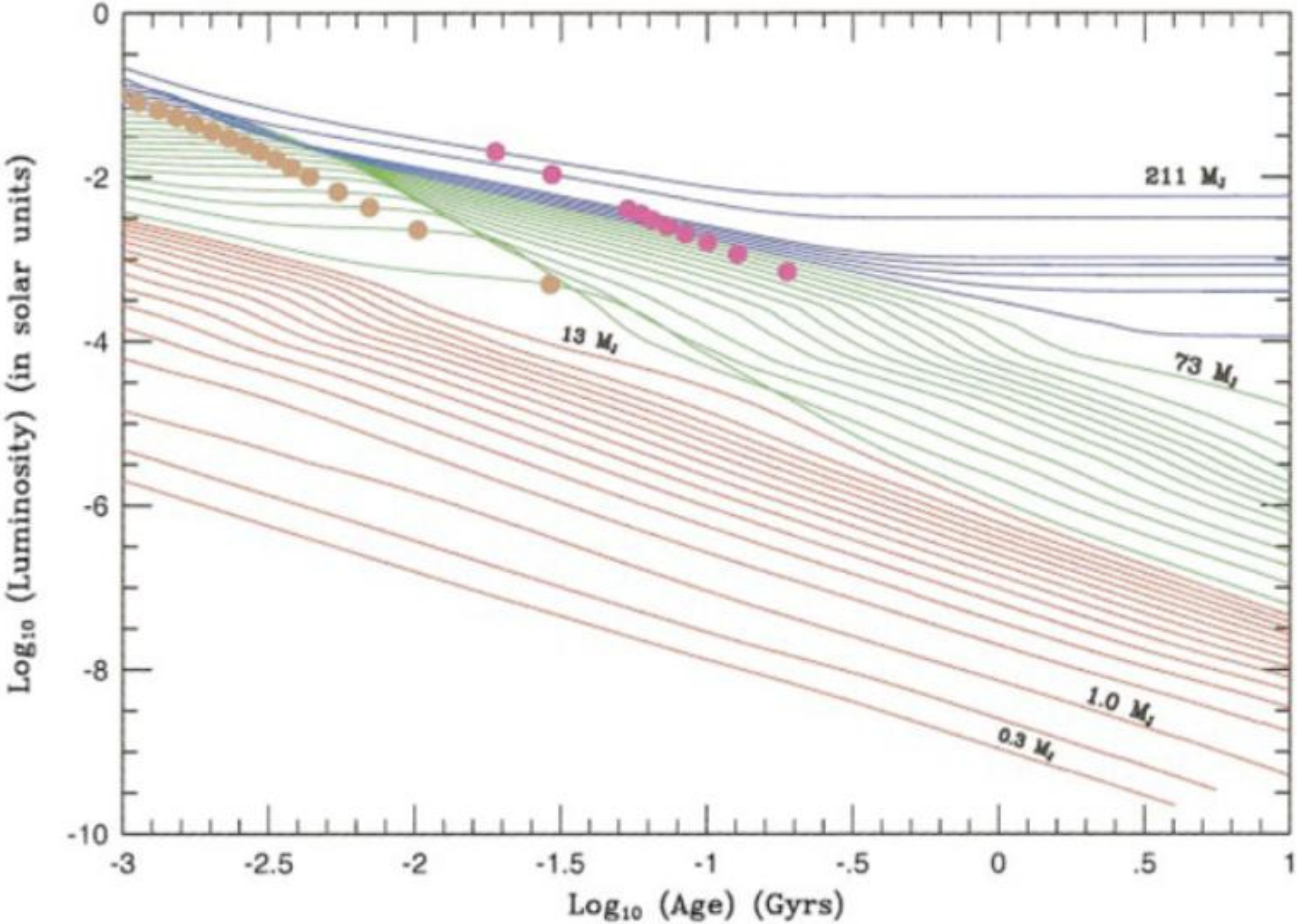
R.U. Claudi

Un pianeta già formato è molto piccolo rispetto ad una stella. Giove ha un diametro di 140 mila km e la sua luce riflessa sarebbe difficilissima da rivelare attorno ad un'altra stella.





Evoluzione della della luminosita'



Burrows 2009

CONTRASTO STELLA-PIANETA

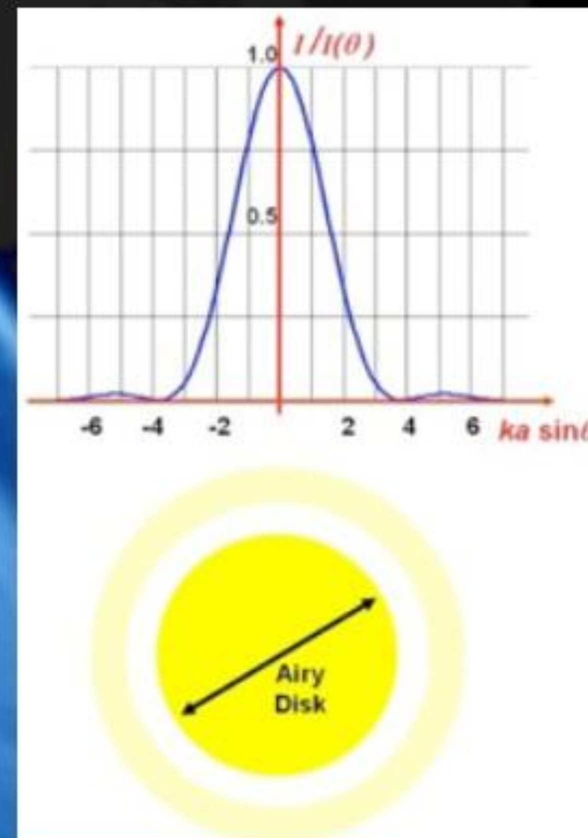
$$Contrast = F_{planet}/F_{star}$$

WARM PLANETS: Contrast is independent of separation

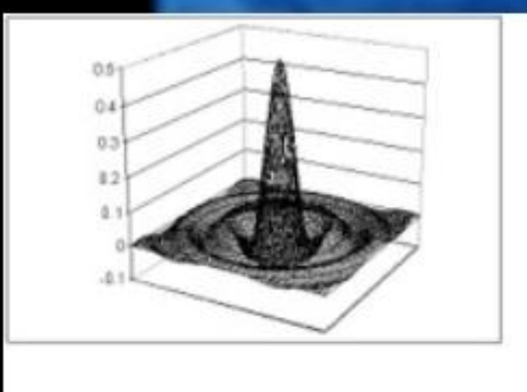
COLD PLANETS: Contrast is dependent on separation (closer the planet brighter it'll be) and on the orbital phase. It is independent of the parent star luminosity, age and planetary mass.

Diffraction Image: Airy Disk

$$I(\theta) = I(0)\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]^2$$

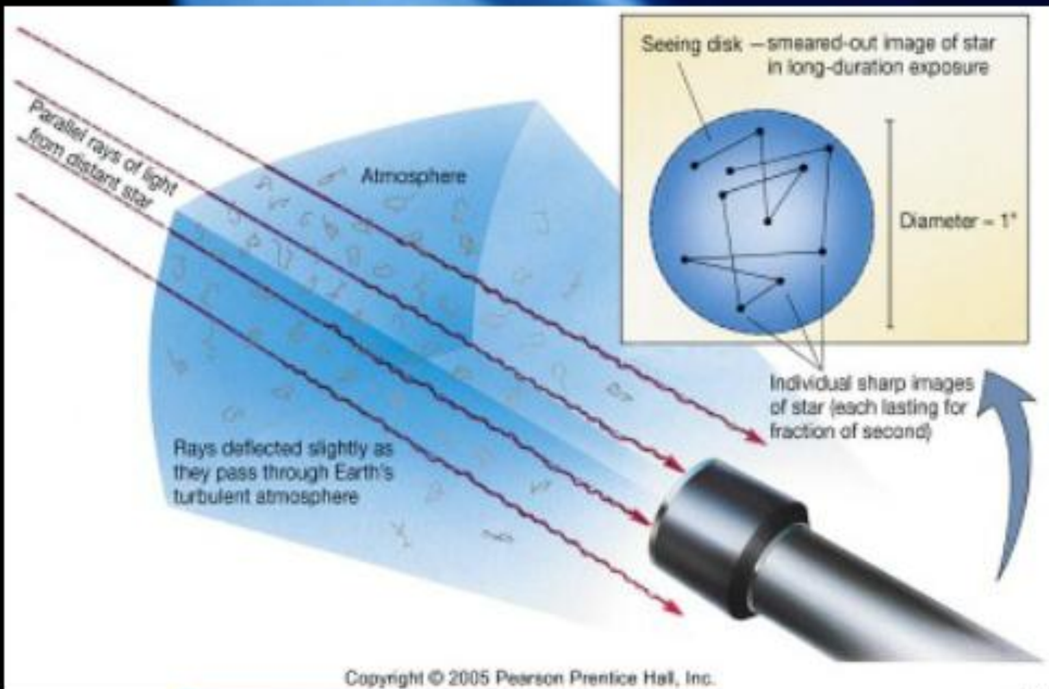


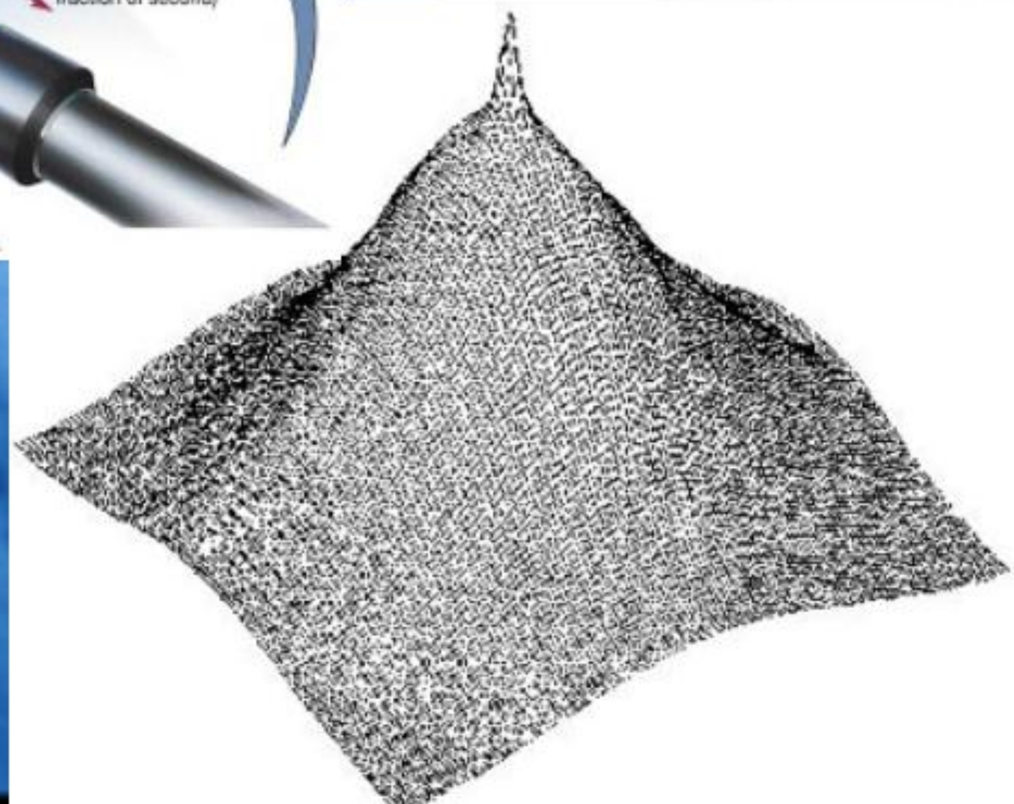
$$D\sin\theta = 1.22\lambda$$



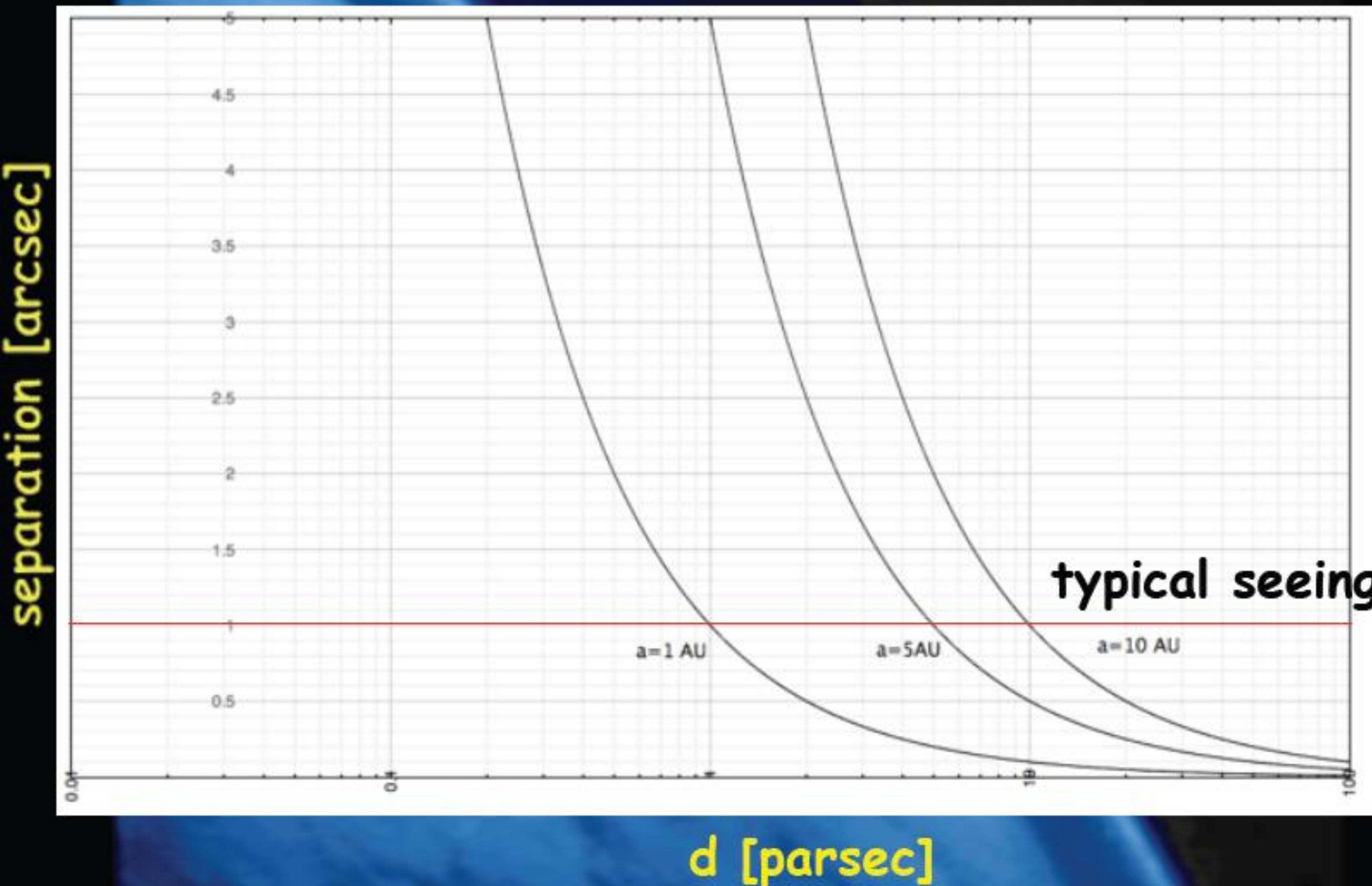
$$\theta \simeq 1.22\frac{\lambda}{D}$$

The Reality: Seeing Disk





distance versus separation



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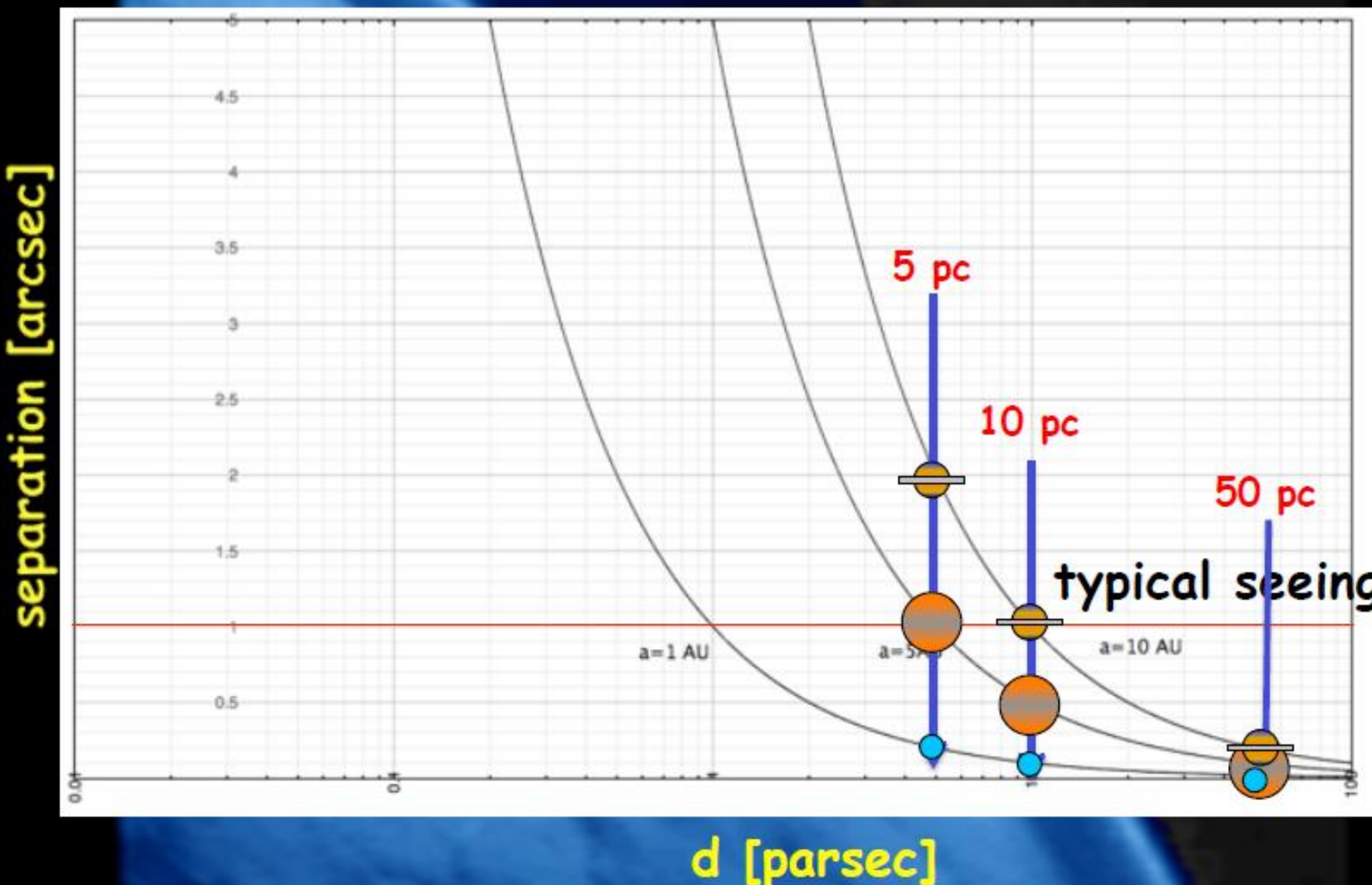
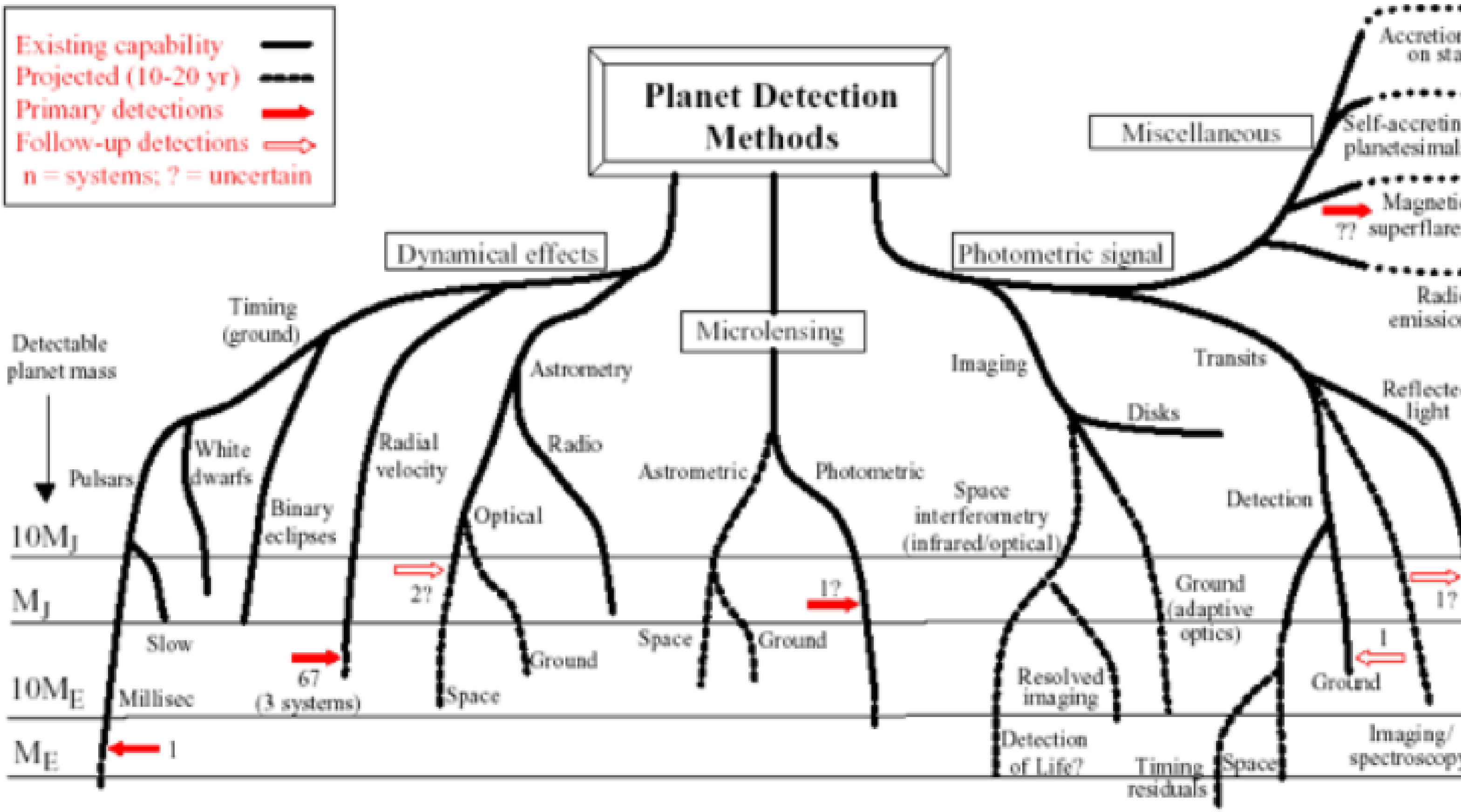




M. Perryman, 2001 (from: http://www.obspm.fr/encycl/searches.html)

Censimento dei Pianeti
(http://exoplanet.eu/)

I pianeti extrasolari noti a Marzo 2014 sono 1771:

Velocità Radiali 413 Sistemi (Marzo 2014)
550 pianeti
96 Sistemi multipli

Transiti 613 Sistemi (Marzo 2014)
1130 Pianeti
350 Sistemi multipli

μ-lenti 28 pianeti (Marzo 2014)

Imm. Diretta 47 pianeti (Marzo 2014)

Timing 14 pianeti (Marzo 2014)

Indirect Methods

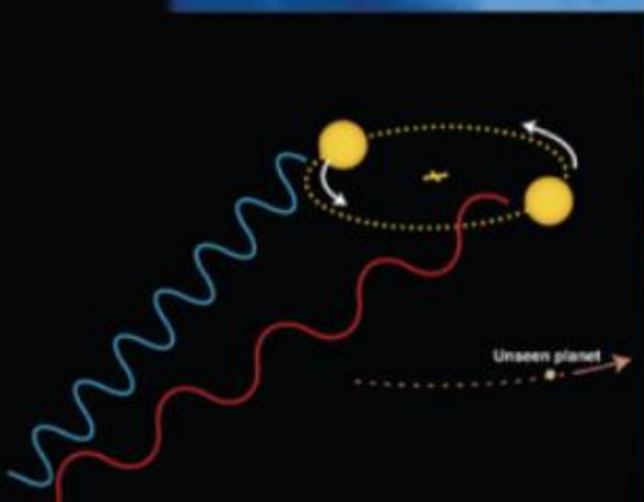
- Radial Velocities
- Astrometry
- Transits
- Gravitational Microlens
- Timing

Metodo delle velocità Radiali

Tecnica:

La velocità radiale di una stella in orbita attorno al baricentro del sistema stella-pianeta varia nel tempo con una semiampiezza K data da:

$$k_1 = \frac{28.4\,\mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}} \right)^{-2/3} \left(\frac{P}{1\,\mathrm{yr}} \right)^{-1/3}$$



Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

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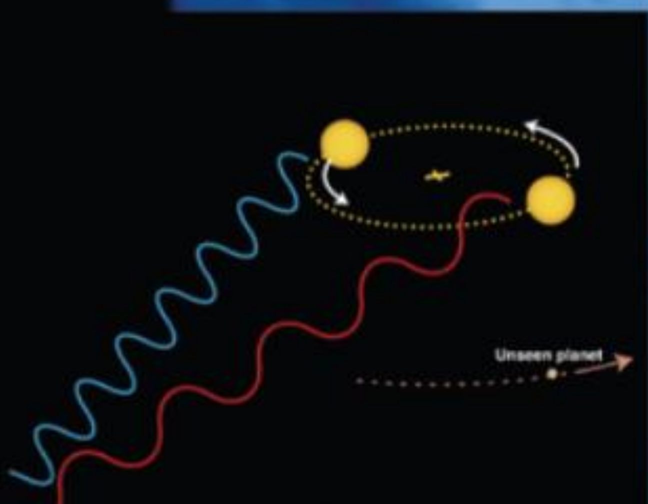

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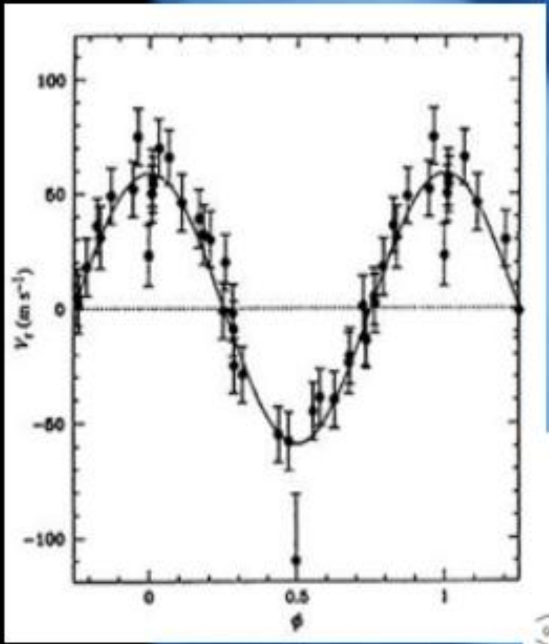
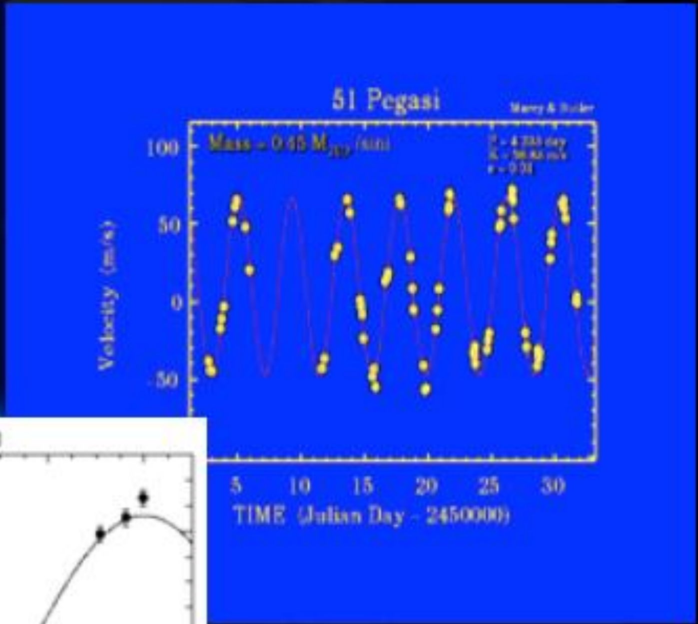
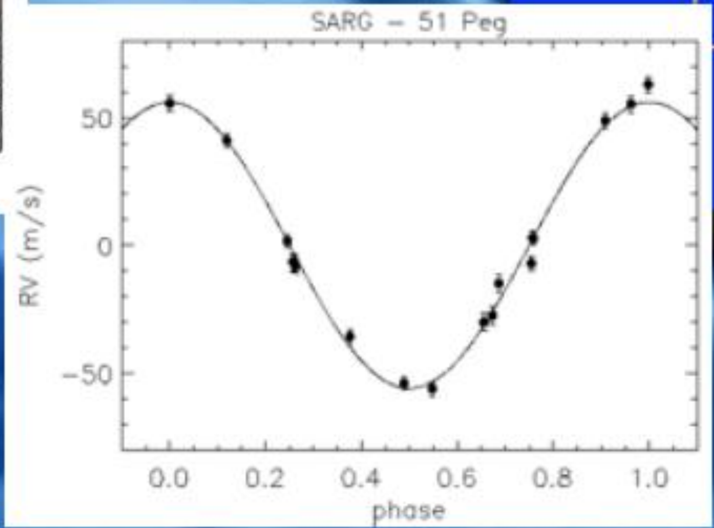
Curva di velocità per una stella con pianeta







La curva di velocità radiale di 51 Peg da Mayor e Queloz (1995, a destra) e da Marcy e Butler (a sinistra), e quella dal SARG

Misure di Velocità Radiali ad alta precisione

Le velocità vengono misurate confrontando la posizione delle righe spettrali della stella rispetto a quella misurata in laboratorio

Problema:

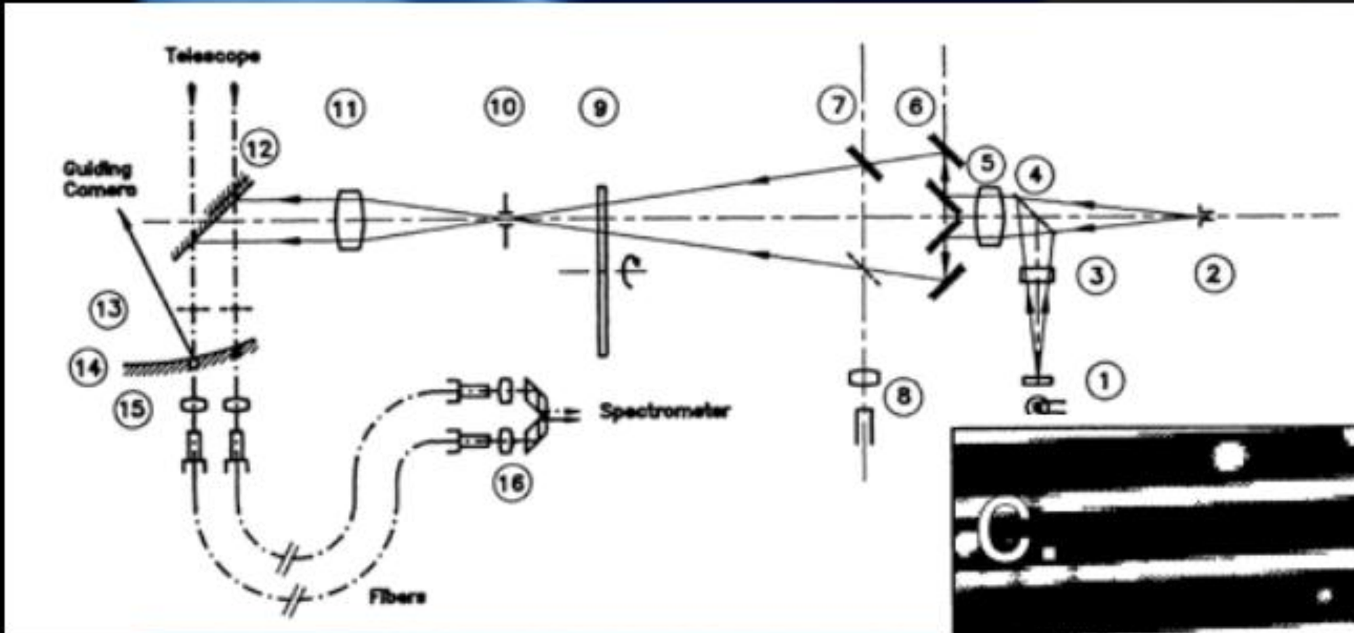
Piccoli spostamenti dell'immagine della stella sulla fenditura di ingresso dello spettrografo possono causare errori importanti nelle misure

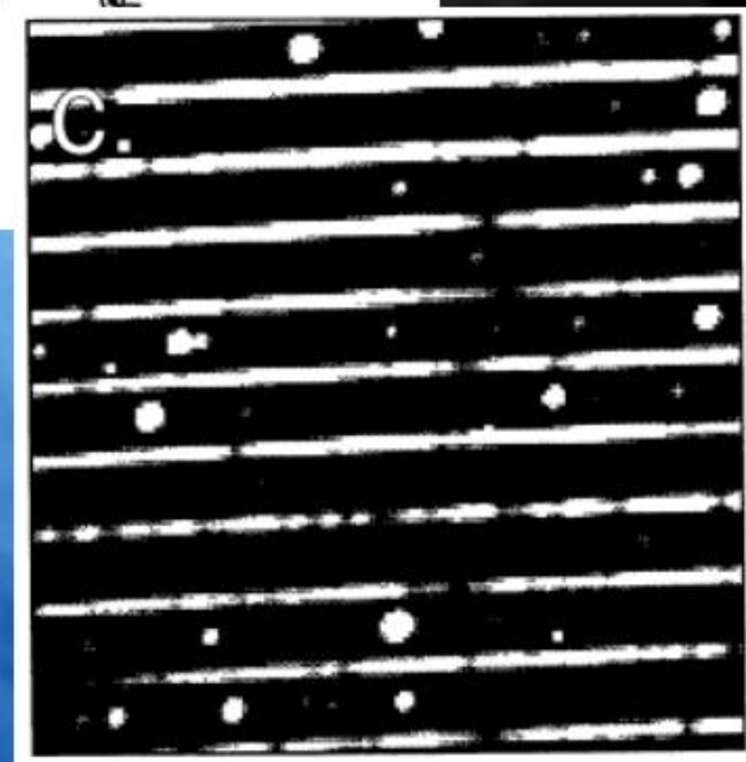
Soluzioni:

a)Tecnica del Thorio Simultaneo

b) Tecnica dela cella assorbente

Thorio Simultaneo



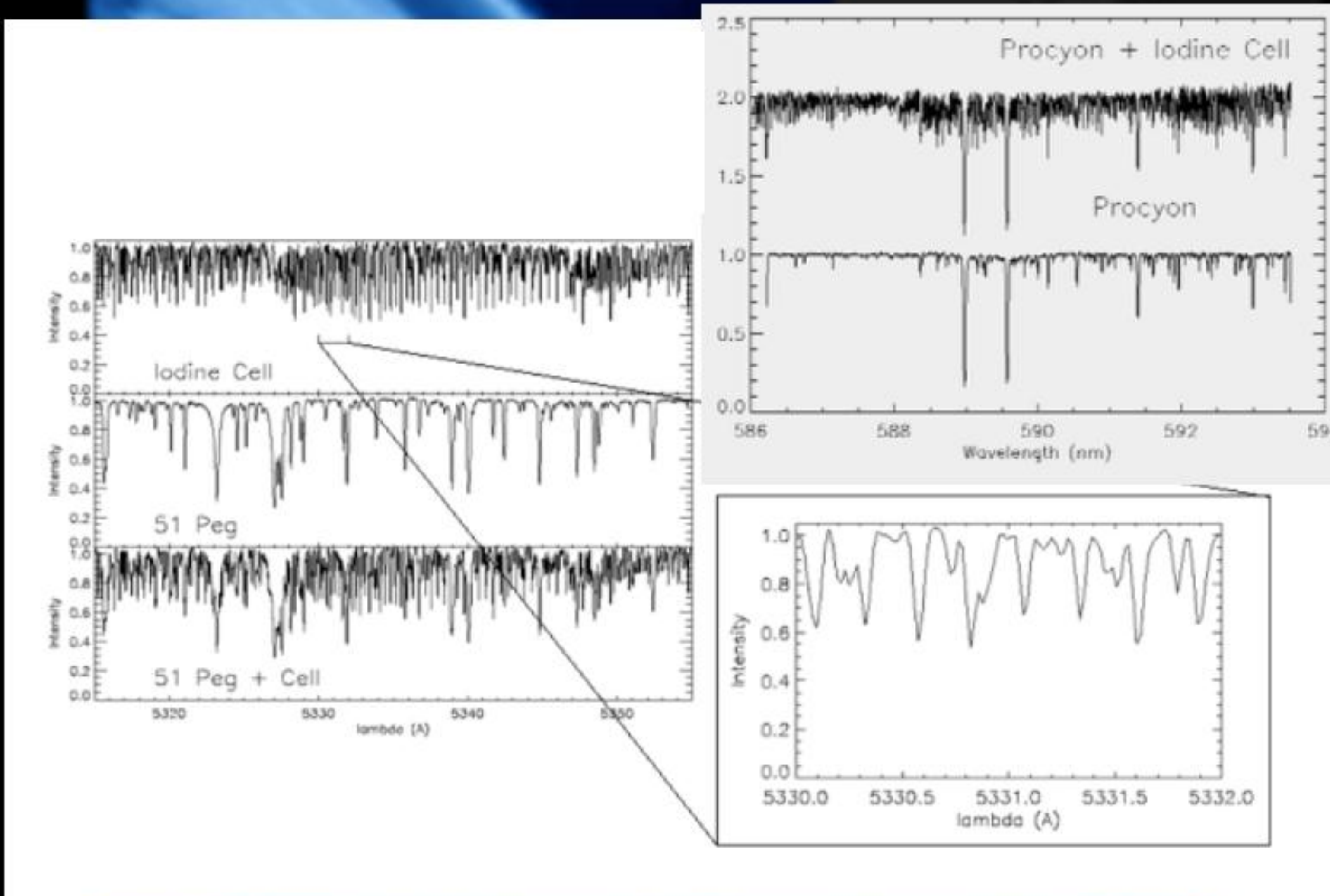


Baranne et al., 1996

Misure di velocità radiale con la cella assorbente

La cella allo iodio del SARG

SARG Spectra with I_2 Absorbing cell



Photon noise limit to radial velocity determinations

$$\delta V_{RMS} = c / (Q \sqrt{Ne-})$$

where:

δV_{RMS} = error in radial velocity variations

Q = spectrum quality factor $= RQ_0$(spectral type), R being resolution

N_{e-} = total number of photons detected in the useful spectral range

$$N_{e-} = F_* \, S_{tel} \, \varepsilon_{tot} \, t_{exp} / 2.512^V$$

where:

F_*=photons/cm^{2}s for a V=0 star

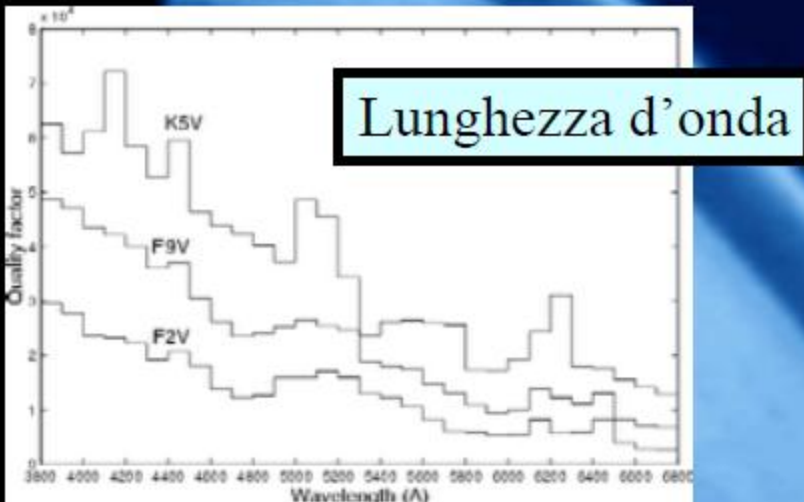
S_{tel}= telescope area (cm^2)

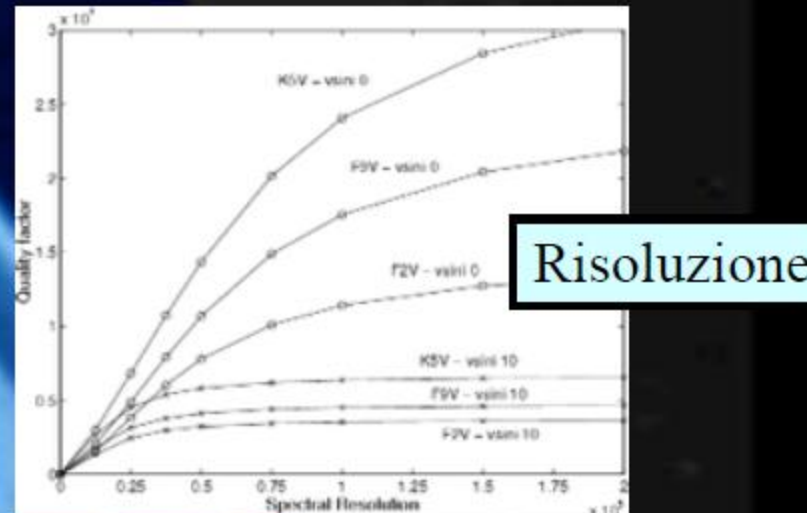
ε_{tot} = total efficiency

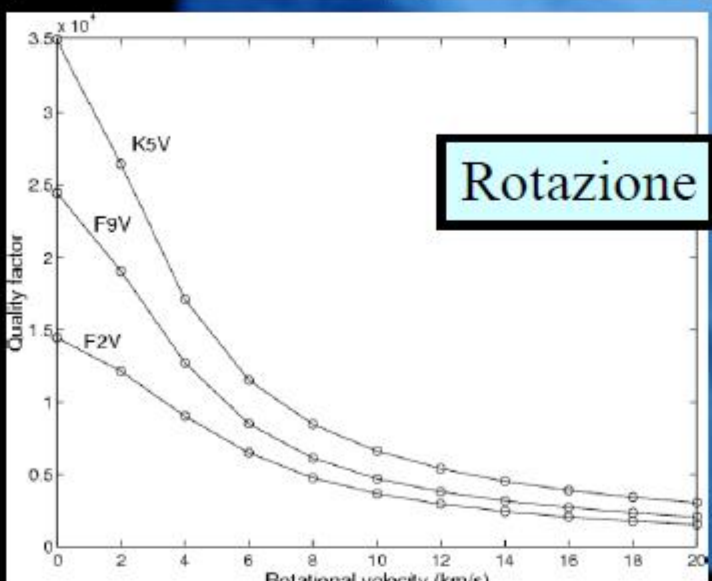
t_{exp} = exposure time (s)

from Bouchy et al. 2001, A&A, 374, 733

Dipendenze del fattore di qualita'



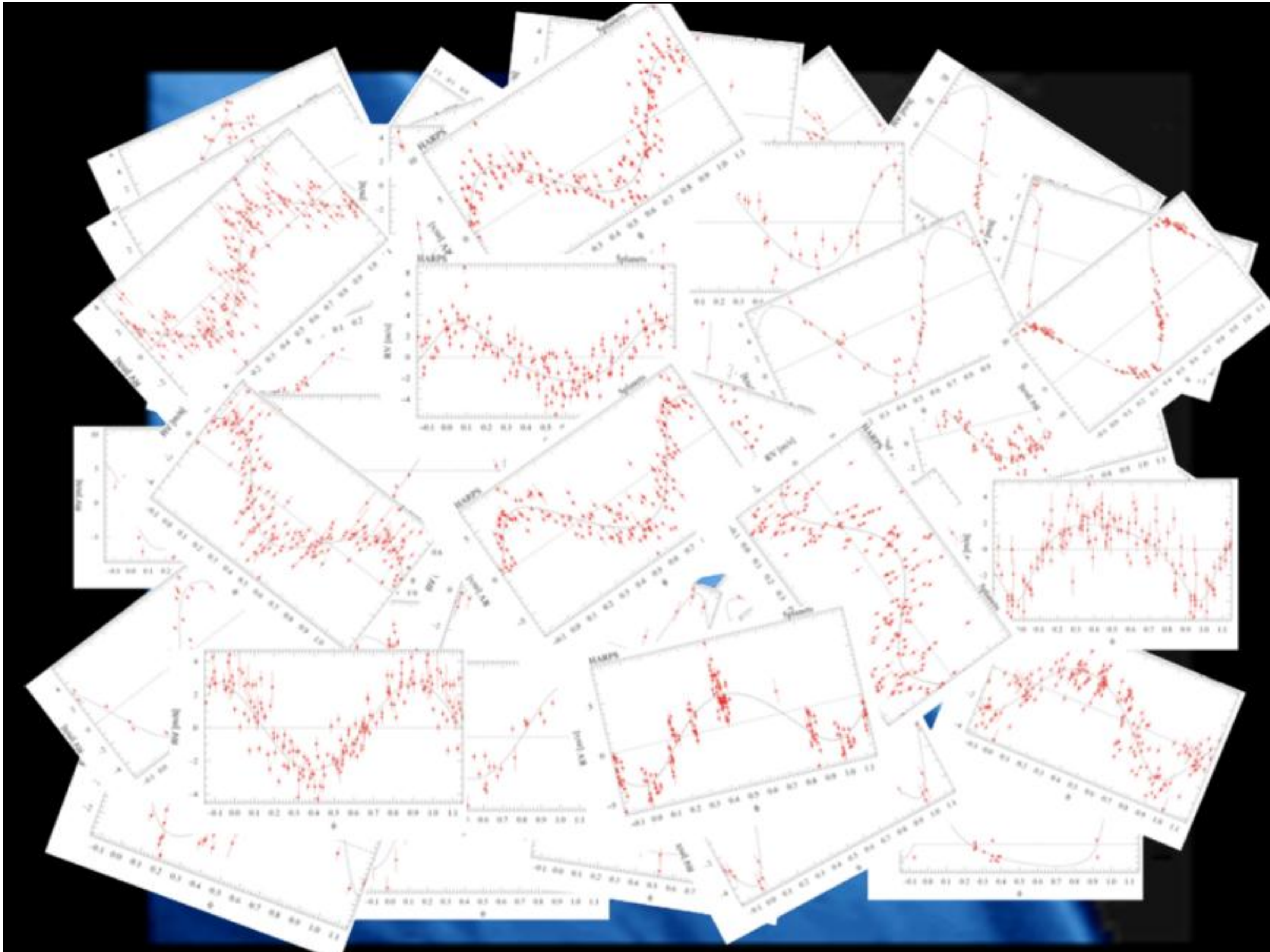


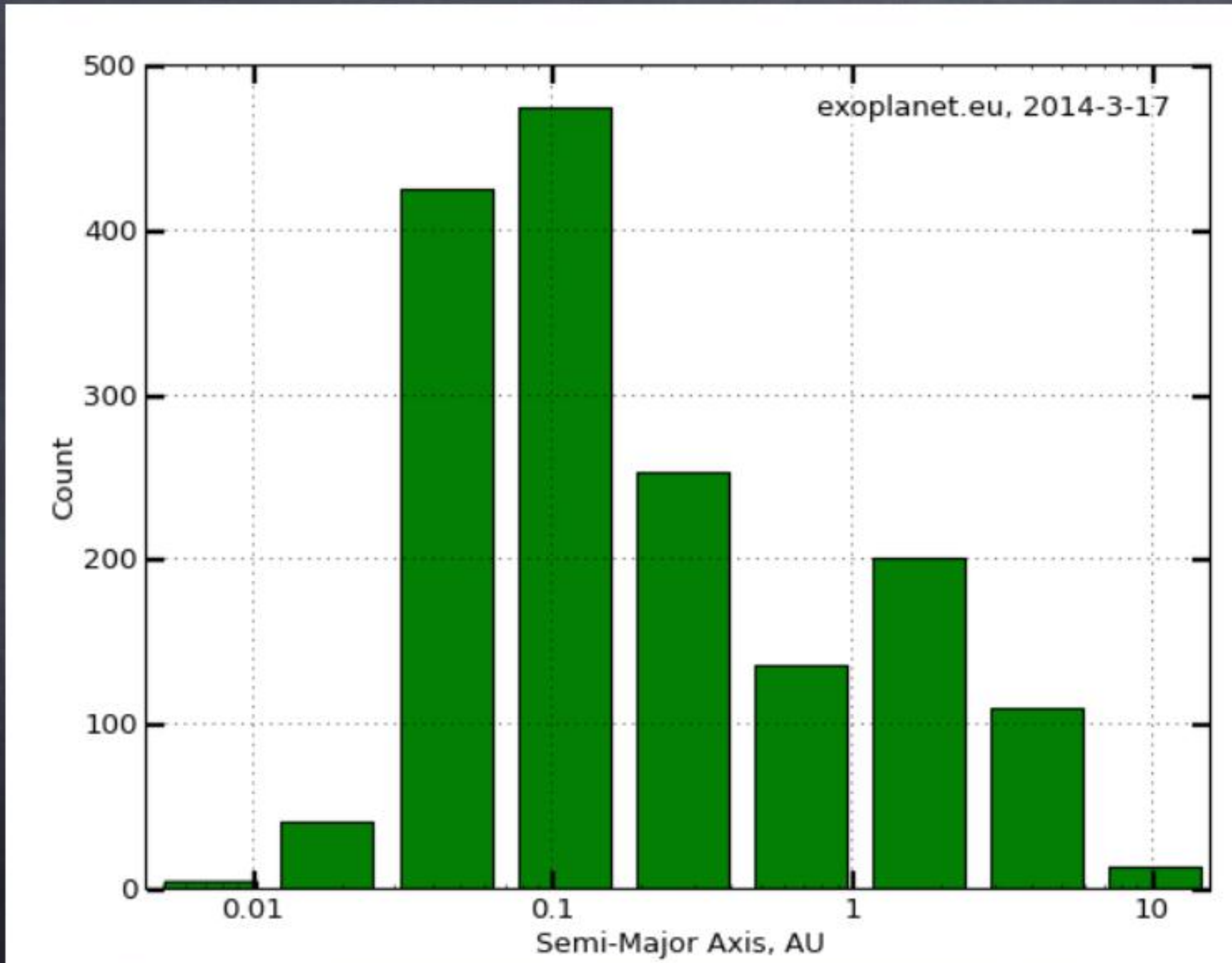


from Bouchy et al. 2001, A&A, 374, 733

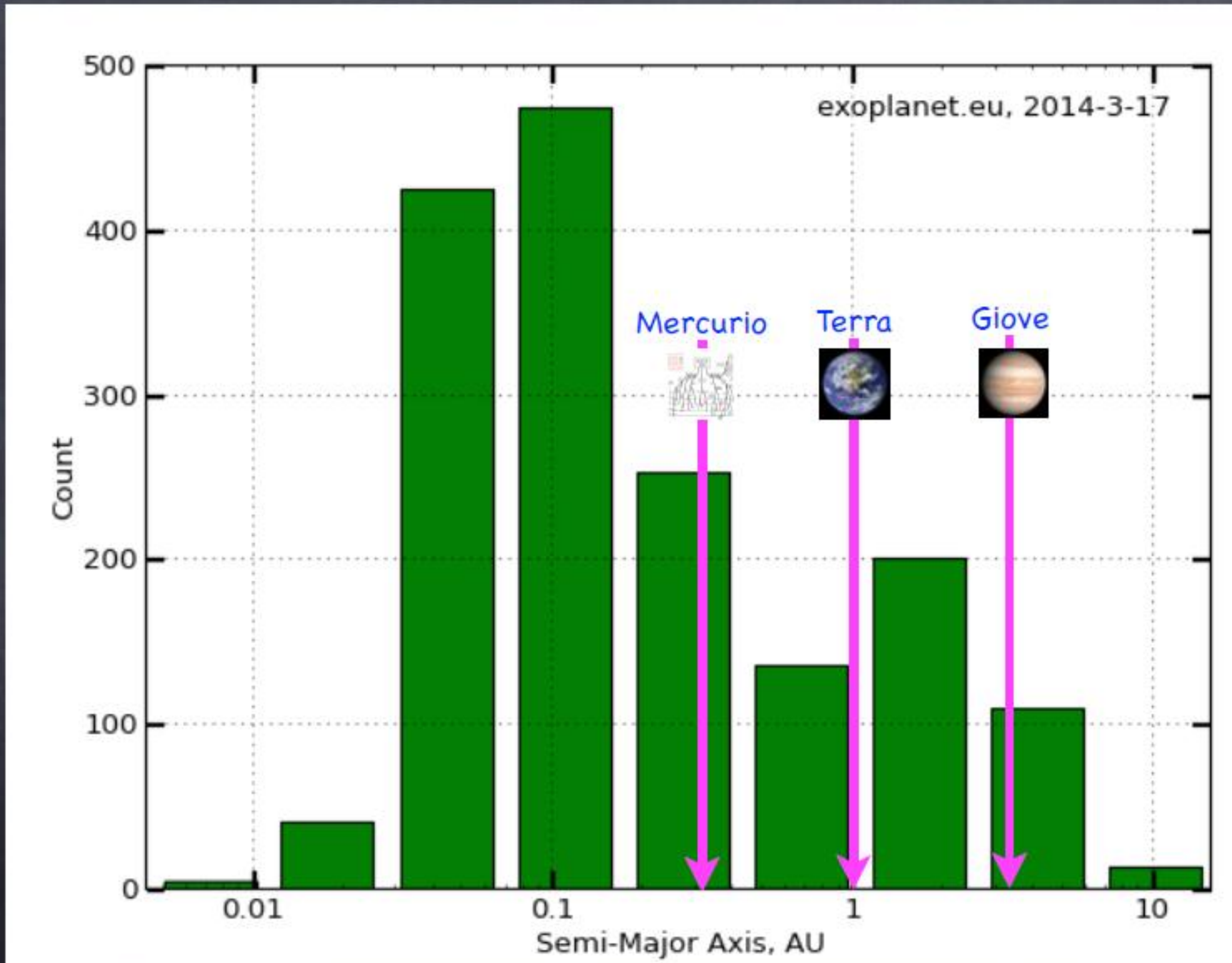
Difficoltà intrinseche delle survey di ricerca di pianeti con il metodo delle velocita' radiali

- Molteplicità
- Radial velocity jitter dovuto ad attività e convezione
- Pulsazioni Stellari

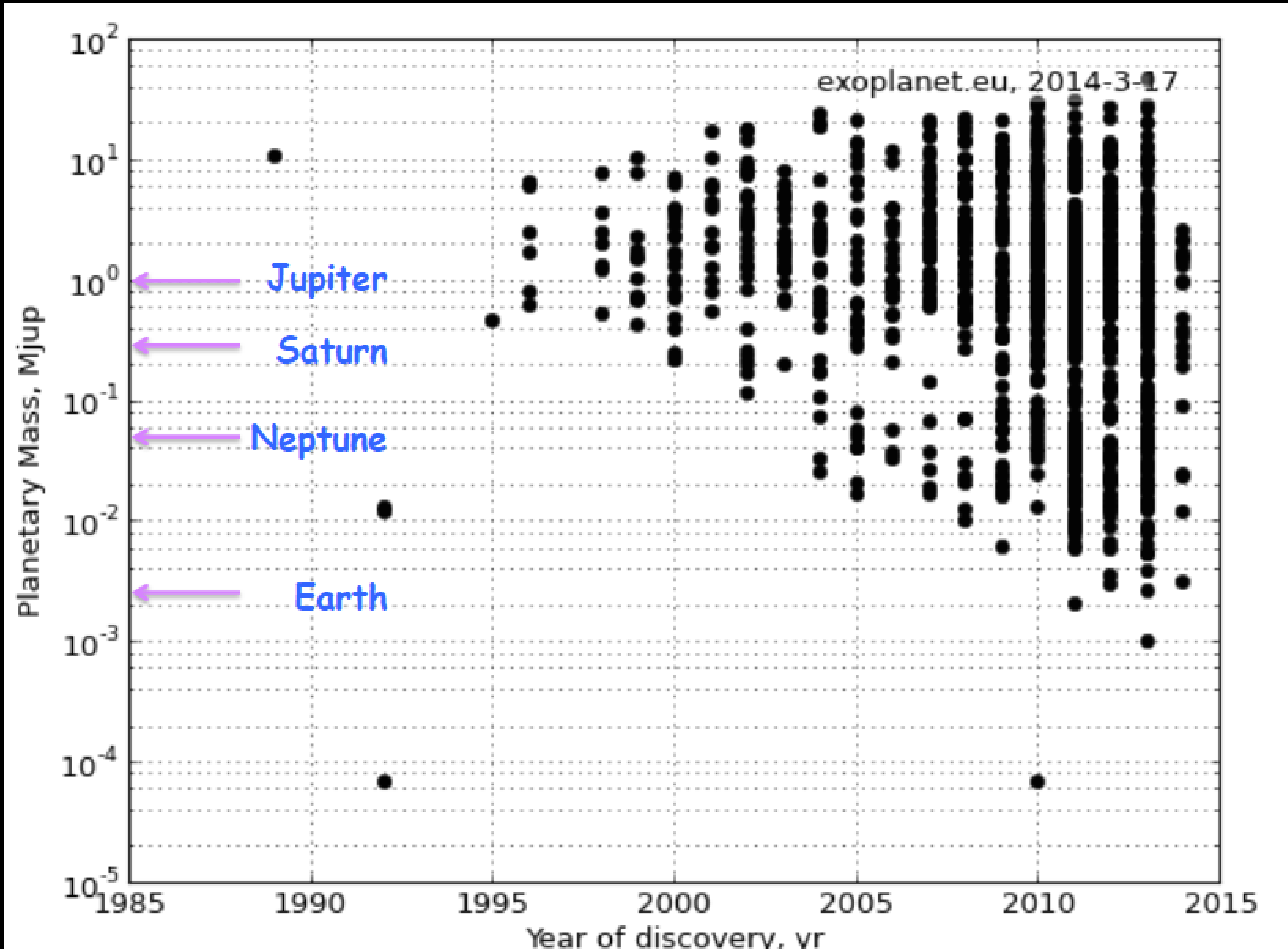




exoplanet.eu, 2014-3-17
500
400
300
200
100
0
Count
0.01
0.1
1
10
Semi-Major Axis, AU



exoplanet.eu, 2014-3-17
Mercurio
Terra
Giove
Count
500
400
300
200
100
0
0.01
0.1
1
10
Semi-Major Axis, AU



exoplanet.eu, 2014-3-17
Planetary Mass, Mjup
Year of discovery, yr
Jupiter
Saturn
Neptune
Earth
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1985
1990
1995
2000
2005
2010
2015

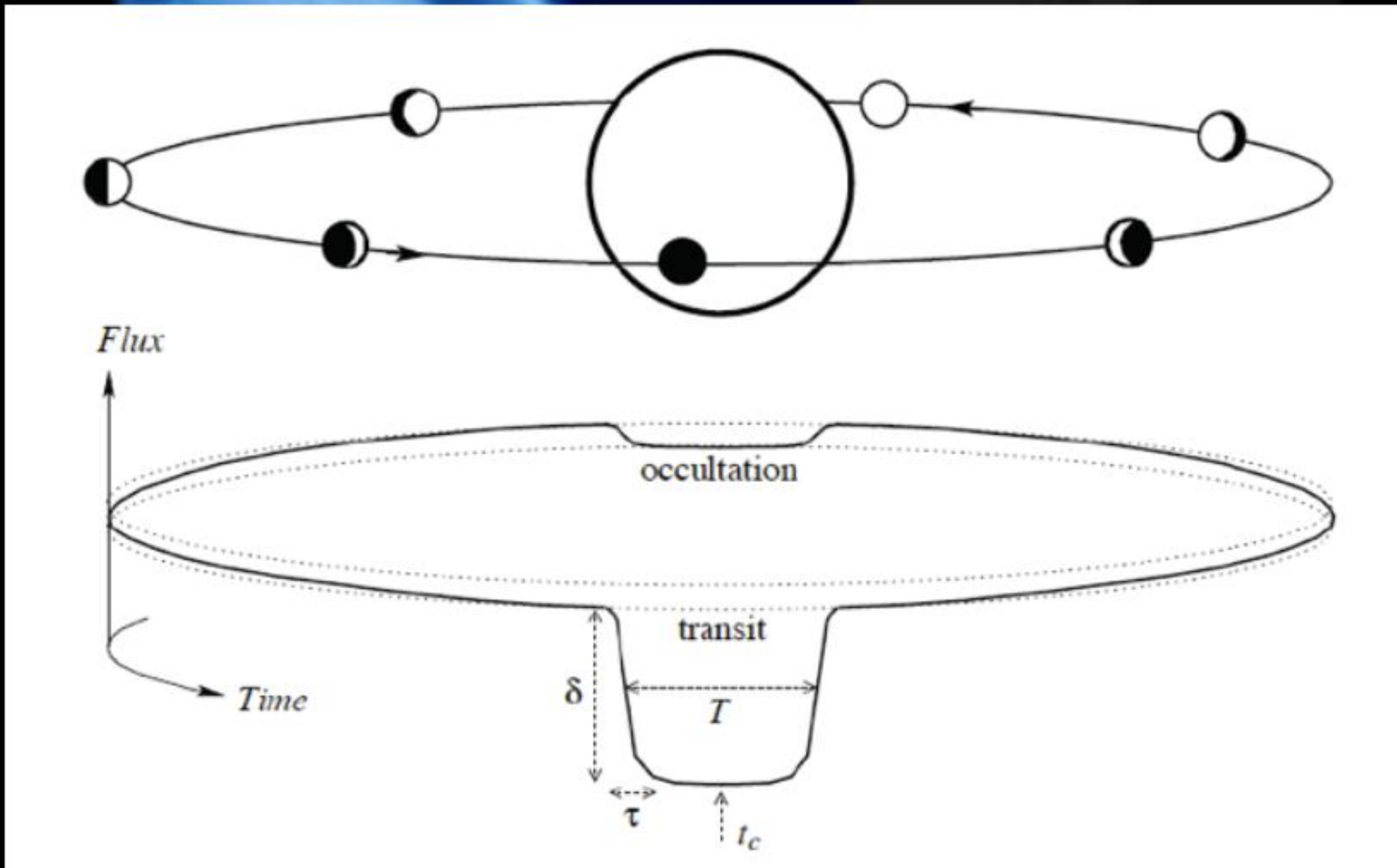
Terra!

0.1 M Sole

3 M Terra 2 M Terra 1 M Terra

d=38.7 pc

TRANSITI



Cosa se ne ricava?

$$\text{Radius ratio} \quad R_p/R_s \approx \sqrt{\delta},$$

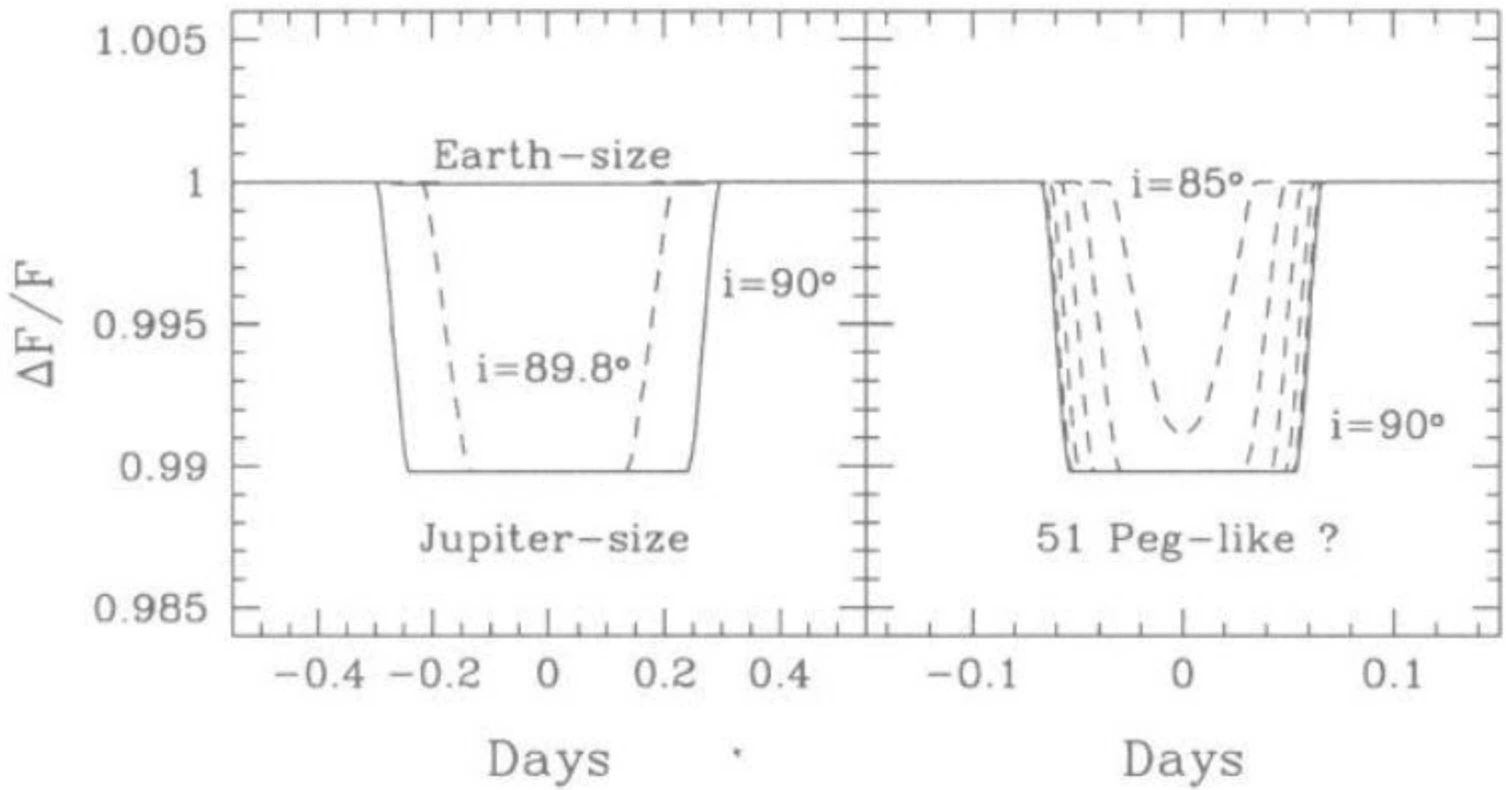
$$\text{Impact parameter} \quad b \approx 1 - \sqrt{\delta}\frac{T}{\tau},$$

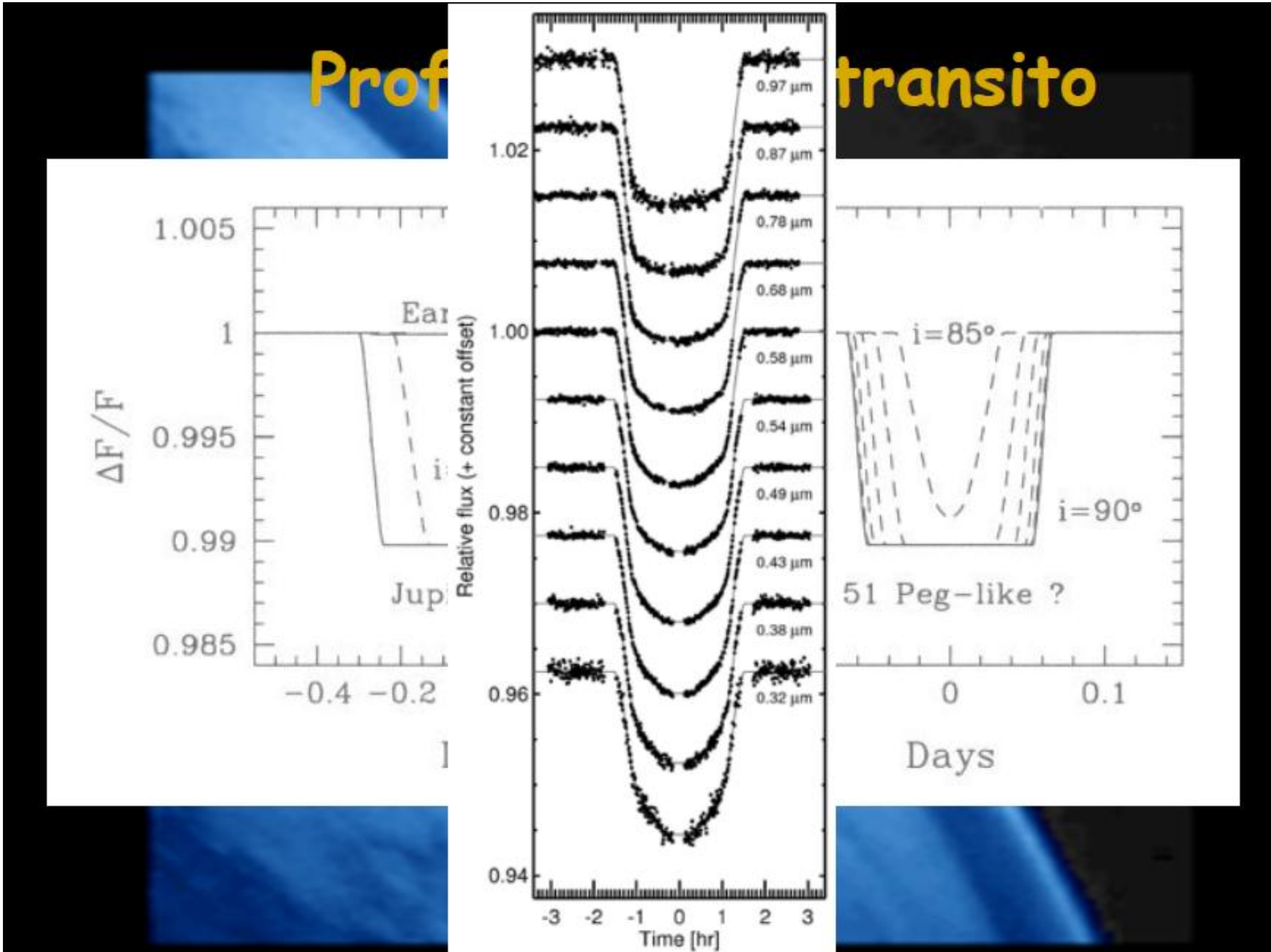
$$\text{Scaled stellar radius} \quad R_s/a \approx \frac{\pi\sqrt{T\tau}}{\delta^{1/4}P}\left(\frac{1+e\sin\omega}{\sqrt{1-e^2}}\right)$$

$$\text{Stellar mean density} \quad \rho_s \approx \frac{3P}{\pi^2 G}\left(\frac{\sqrt{\delta}}{T\tau}\right)^{3/2}\left[\frac{1-e^2}{(1+e\sin\omega)^2}\right]^{3/2}$$

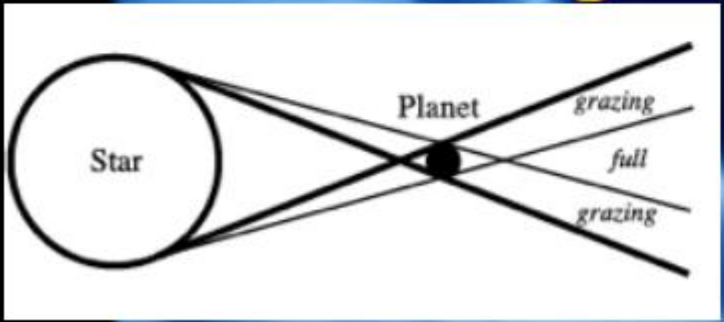
$$\text{Planetary surface gravity} \quad g_p \approx \frac{2\pi K_s}{P}\frac{\sqrt{1-e^2}}{\delta(R_s/a)^2\sin i},$$

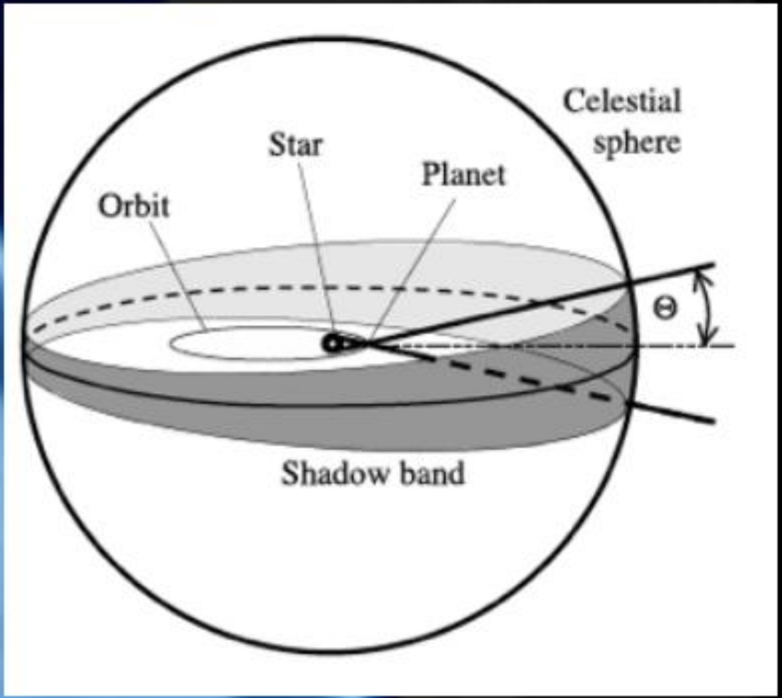
Profondità del transito




Prof
transito
1.005
1
0.995
0.99
0.985
ΔF/F
Ear
Jup
-0.4
-0.2
i=85°
i=90°
51 Peg-like ?
0
0.1
Days
Relative flux (+ constant offset)
1.02
1.00
0.98
0.96
0.94
0.97 μm
0.87 μm
0.78 μm
0.68 μm
0.58 μm
0.54 μm
0.49 μm
0.43 μm
0.38 μm
0.32 μm
-3
-2
-1
0
1
2
3
Time [hr]

Probabilita' geometrica di transito



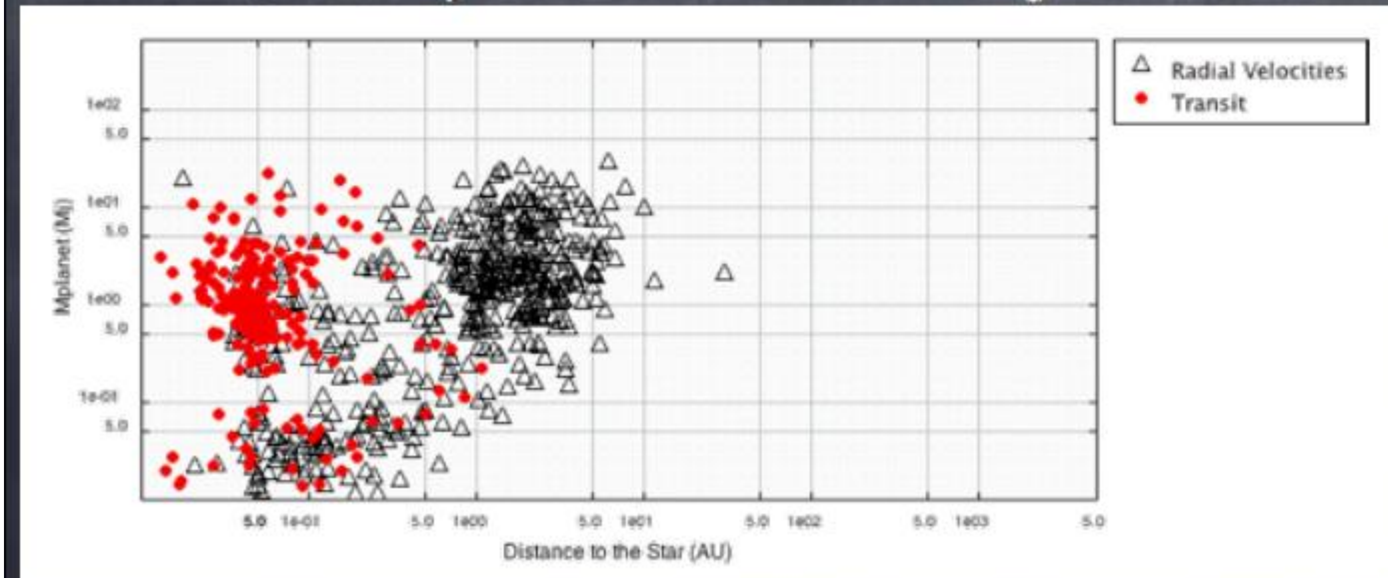


$a \cos i \leq R_* + R_p$

Inclinazione orientata a caso e cos i varia in modo casuale da 0 a 1

$$P\left(\cos i \leq \frac{R_* + R_P}{a}\right) = \frac{\int_0^{\frac{R_* + R_p}{a}} d(\cos i)}{\int_0^1 d(\cos i)} = \frac{R_* + R_P}{a} \approx \frac{R_*}{a}$$

Transit (In)direct technique: $1^{ary}/2^{ary}$ eclipse. (Targets: quiet stars; activity; crowded fields)



. Orbital and Physical properties:

- > R_*/R_p, M_p, P, a, i, T_o
- > Planetary Interiors
- > Multiple: Architecture and Stability

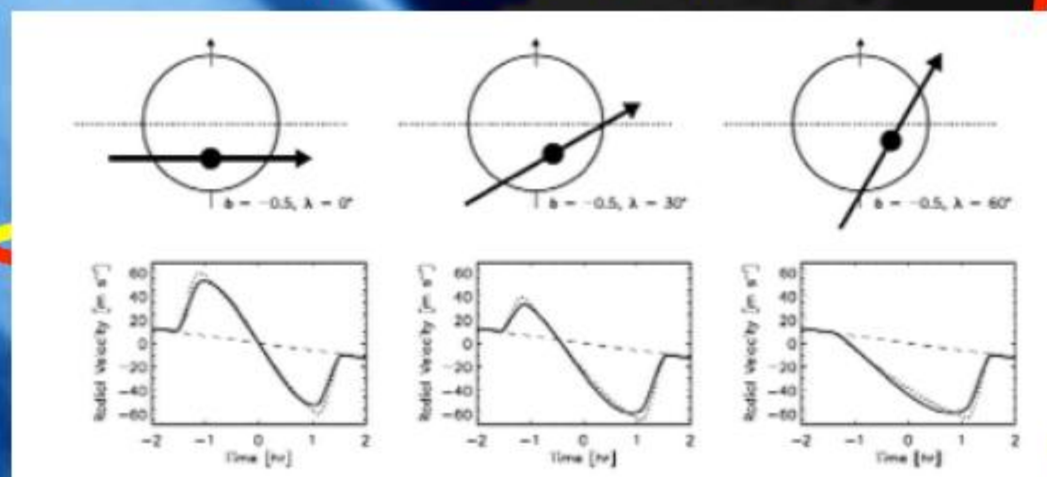
> Circumbinary planets
Leger et al. 09; Doyle et al. 11; Balatha et al. 12

Cacciatori di Transiti in giro per il mondo

"Zero" Order Characterization

Radial Velocities:

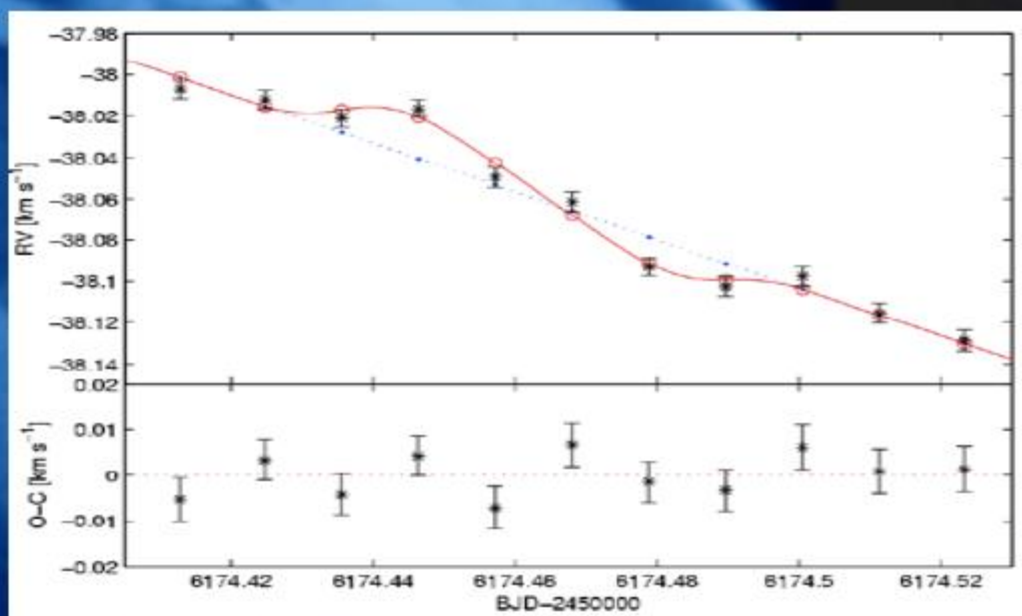
l and Physical properties: $M_p.\sin(i)$, P, e, a, ω, T_0



Transits:

al and Physical properties: R_*/R_p, M_p, P, a, i, T

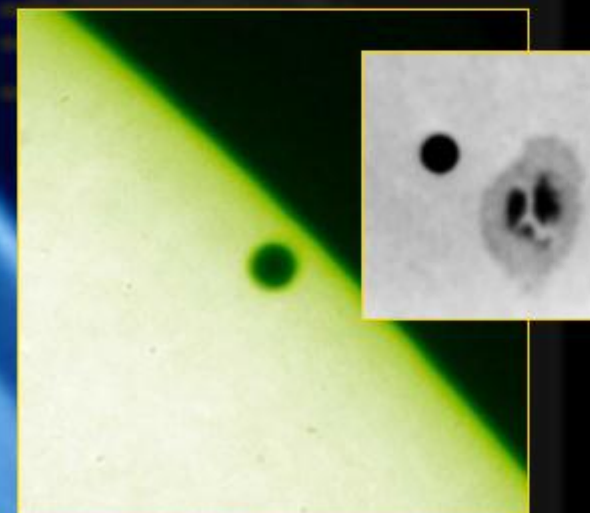
Effetto Rossiter McLaughlin



Problemi relativi alle Survey di transiti

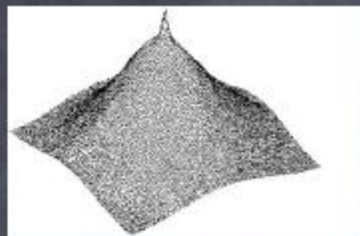
<u>Statistica</u> (solamente ~1/1000 delle stelle di tipo solare puo' mostrare transiti: grandi aree di cielo o magnitudini deboli)

<u>Accuratezza Fotometrica</u> (errore <0.01 mag per pianeti giganti, <0.0001 mag per pianeti terrestri; il secondo valore raggiungibile solo dallo spazio a causa della scintillazione)

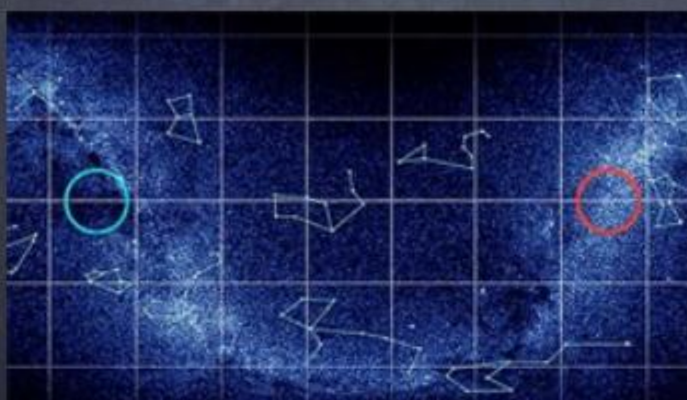


<u>Copertura temporale</u>

<u>Falsi allarmi</u> (<1/10 dei candidati sono confermati come pianeti in transito: sono richiesti follow-up con la tecnica delle high precision radial velocities)



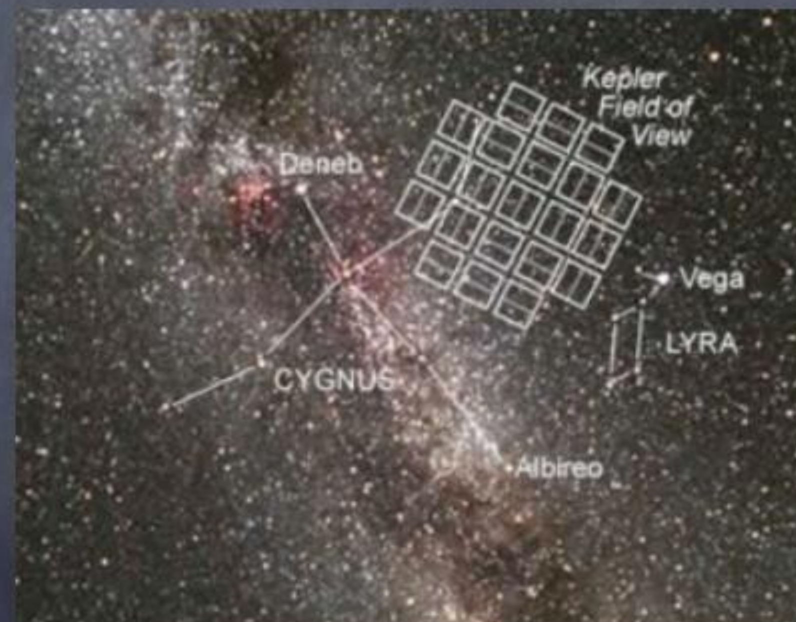
Field of view



- Will monitor 60,000 stars for 150 days
- Can detect Super-Earths

Kepler

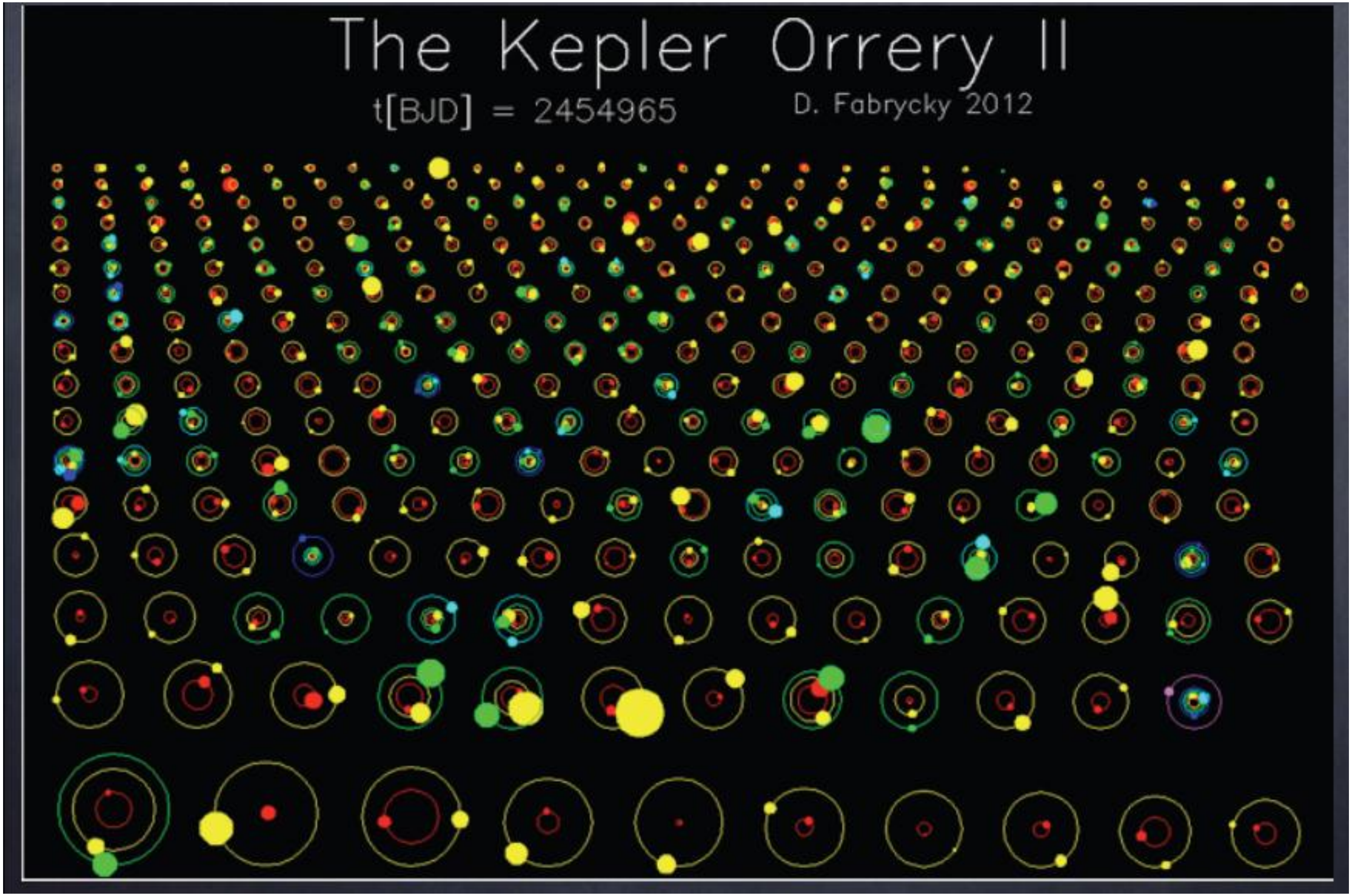
Field of view

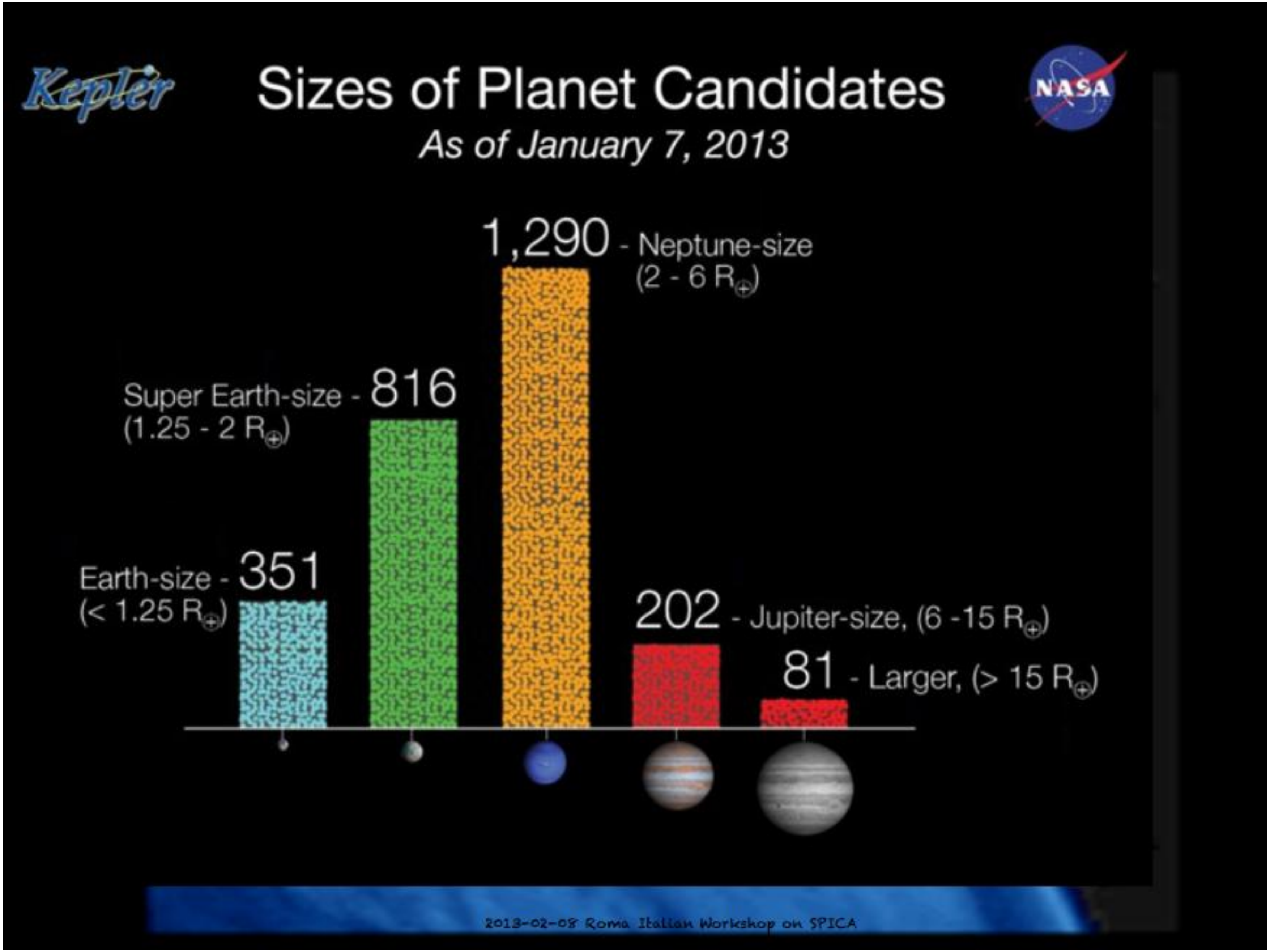


- Will monitor 150,000 stars for 3.5 years
- Will determine rate-of-occurrence of *true* Earth analogs

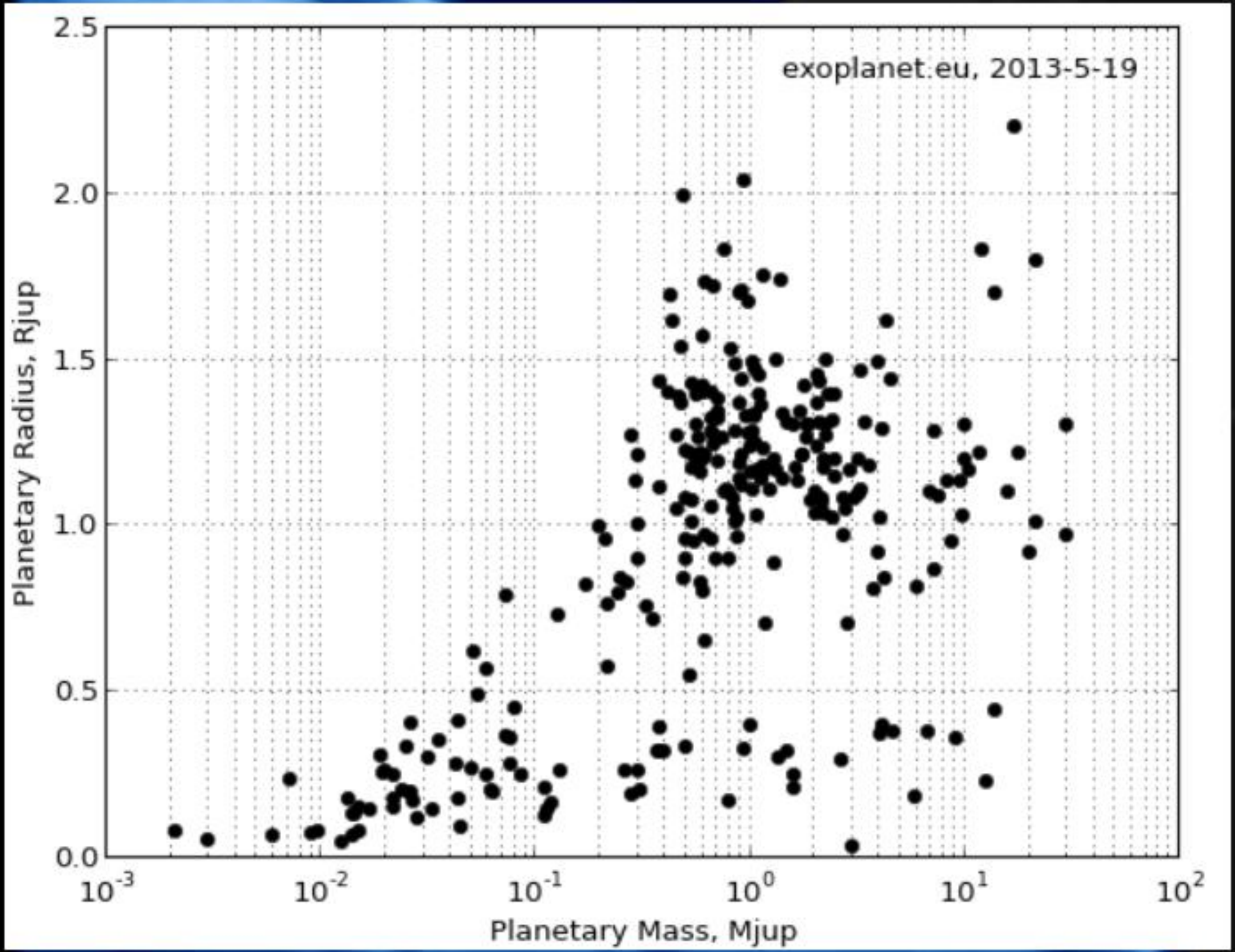
Per vedere l'animazione:

http://kepler.nasa.gov/multimedia/animations/?ImageID=219

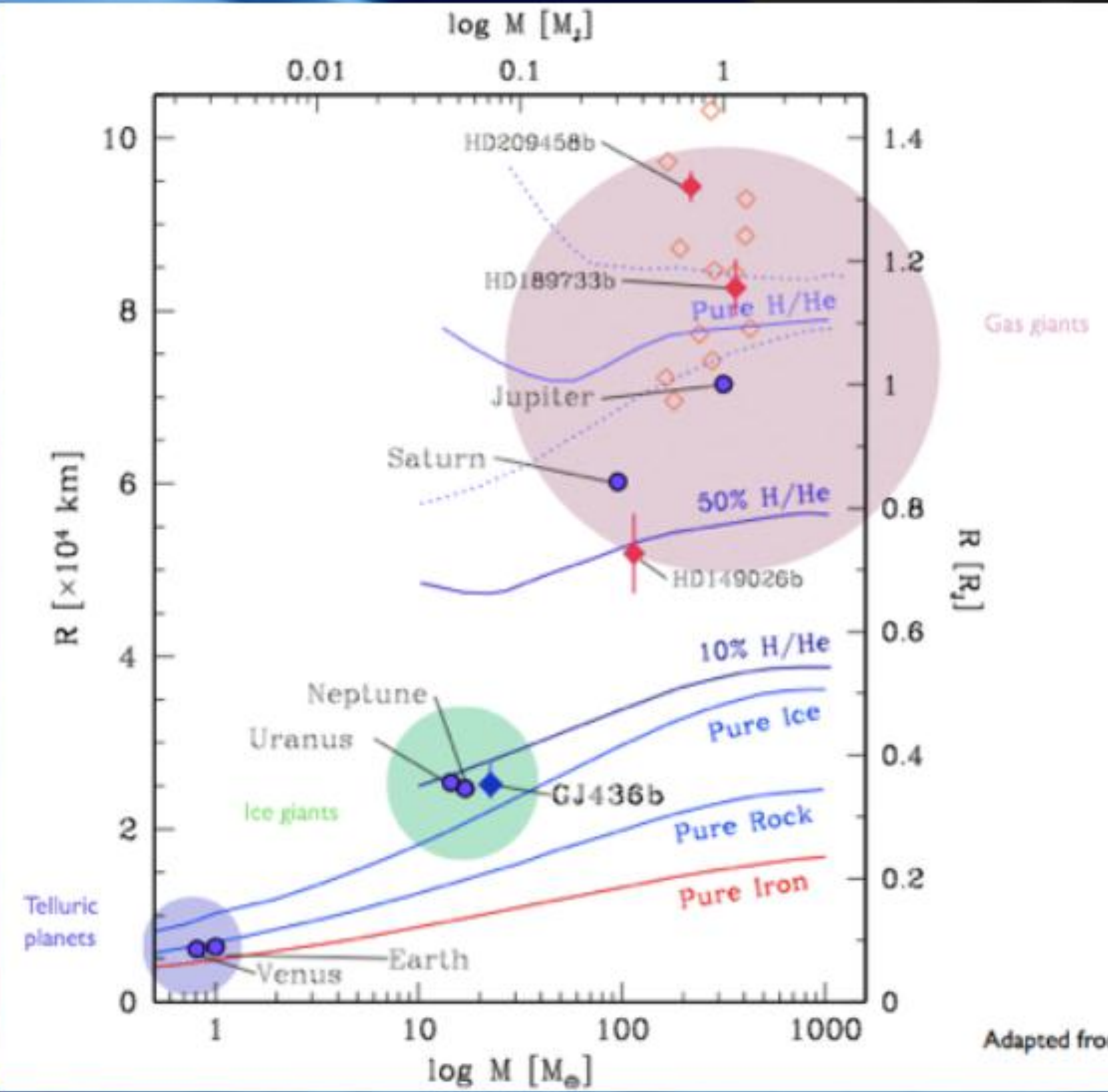



Kepler
Sizes of Planet Candidates
As of January 7, 2013
NASA
1,290 - Neptune-size
(2 - 6 R⊕)
Super Earth-size - 816
(1.25 - 2 R⊕)
Earth-size - 351
(< 1.25 R⊕)
202 - Jupiter-size, (6 -15 R⊕)
81 - Larger, (> 15 R⊕)
2013-02-08 Roma Italian Workshop on SPICA

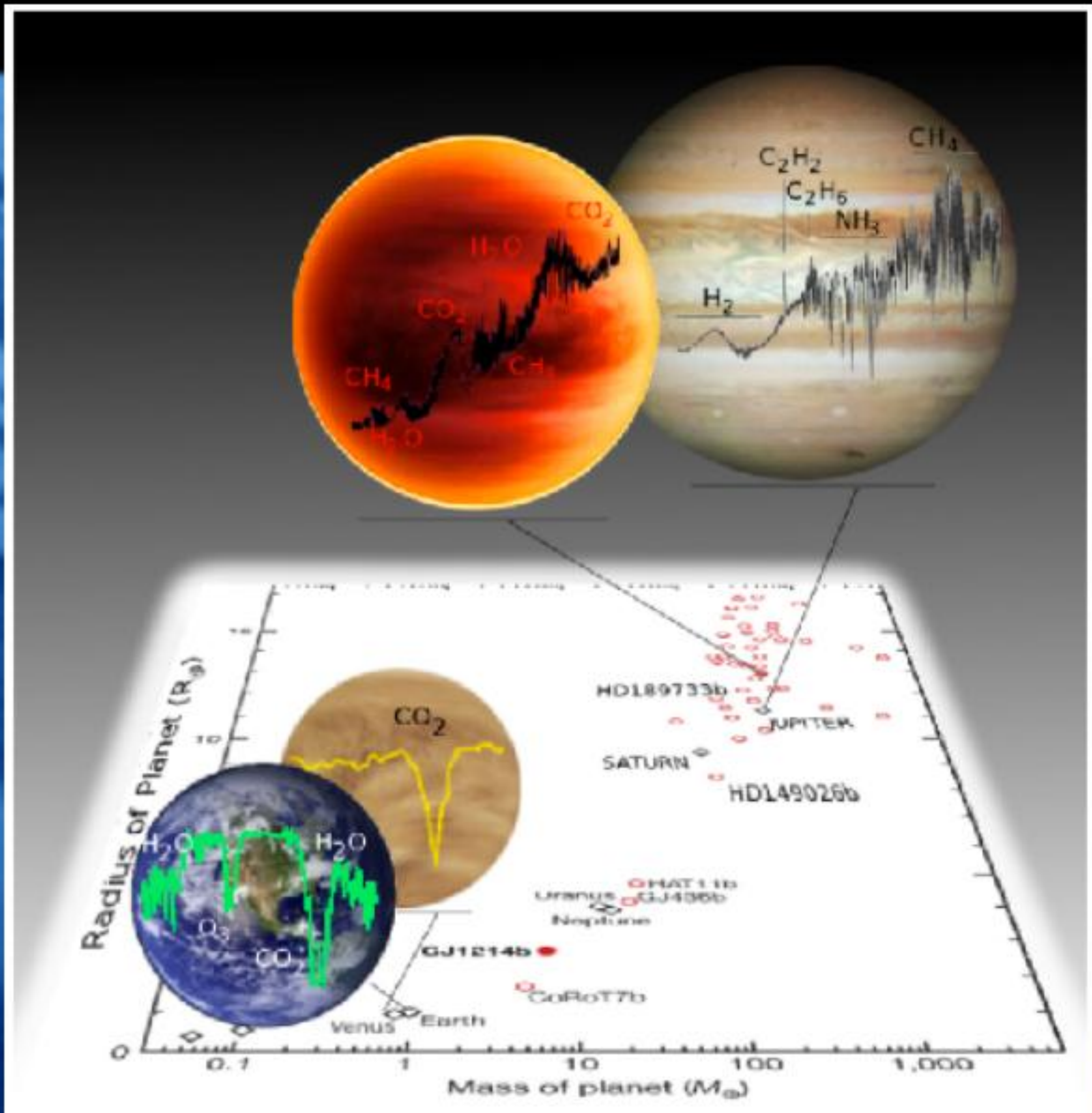
Risultati dai transiti



Relazione Massa Raggio



Adapted from Fortney et al. 2007

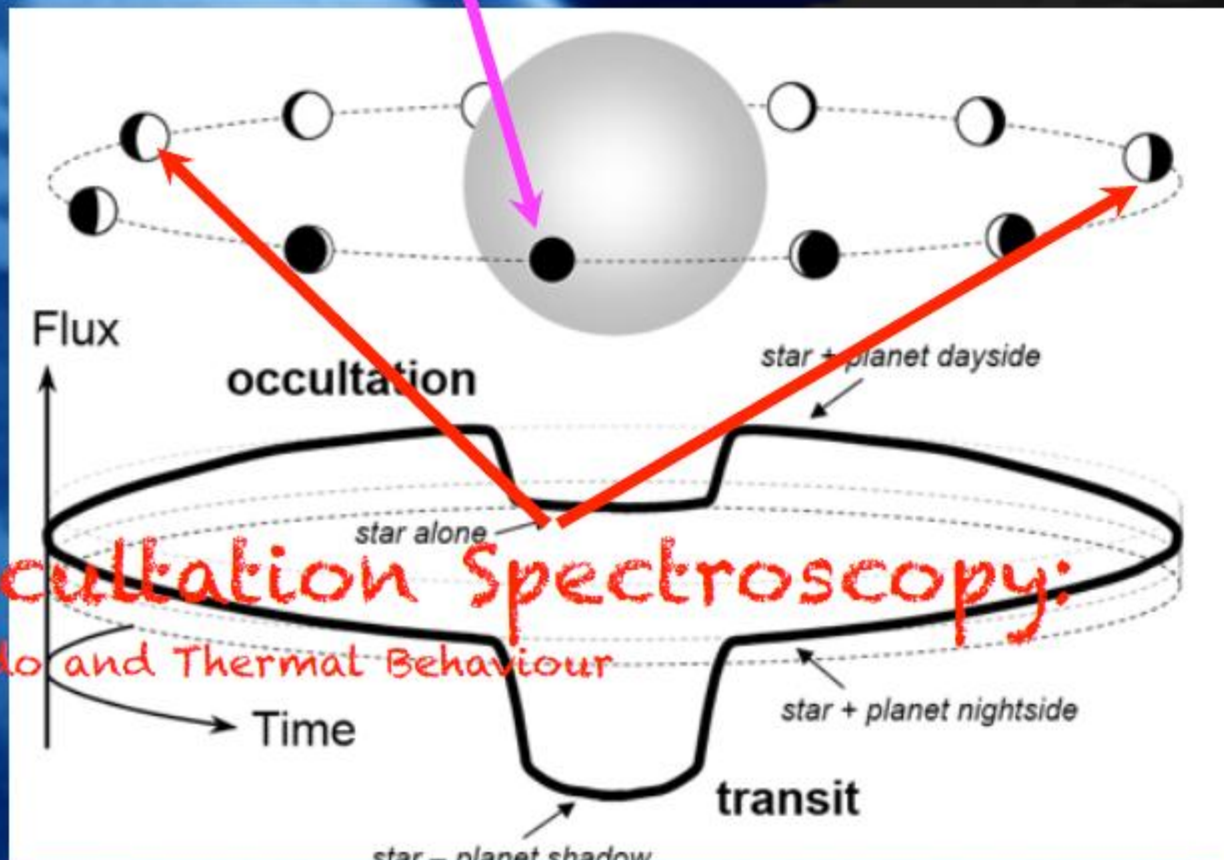


Ref: Tinetti et al., 2012;

Spectroscopy ...

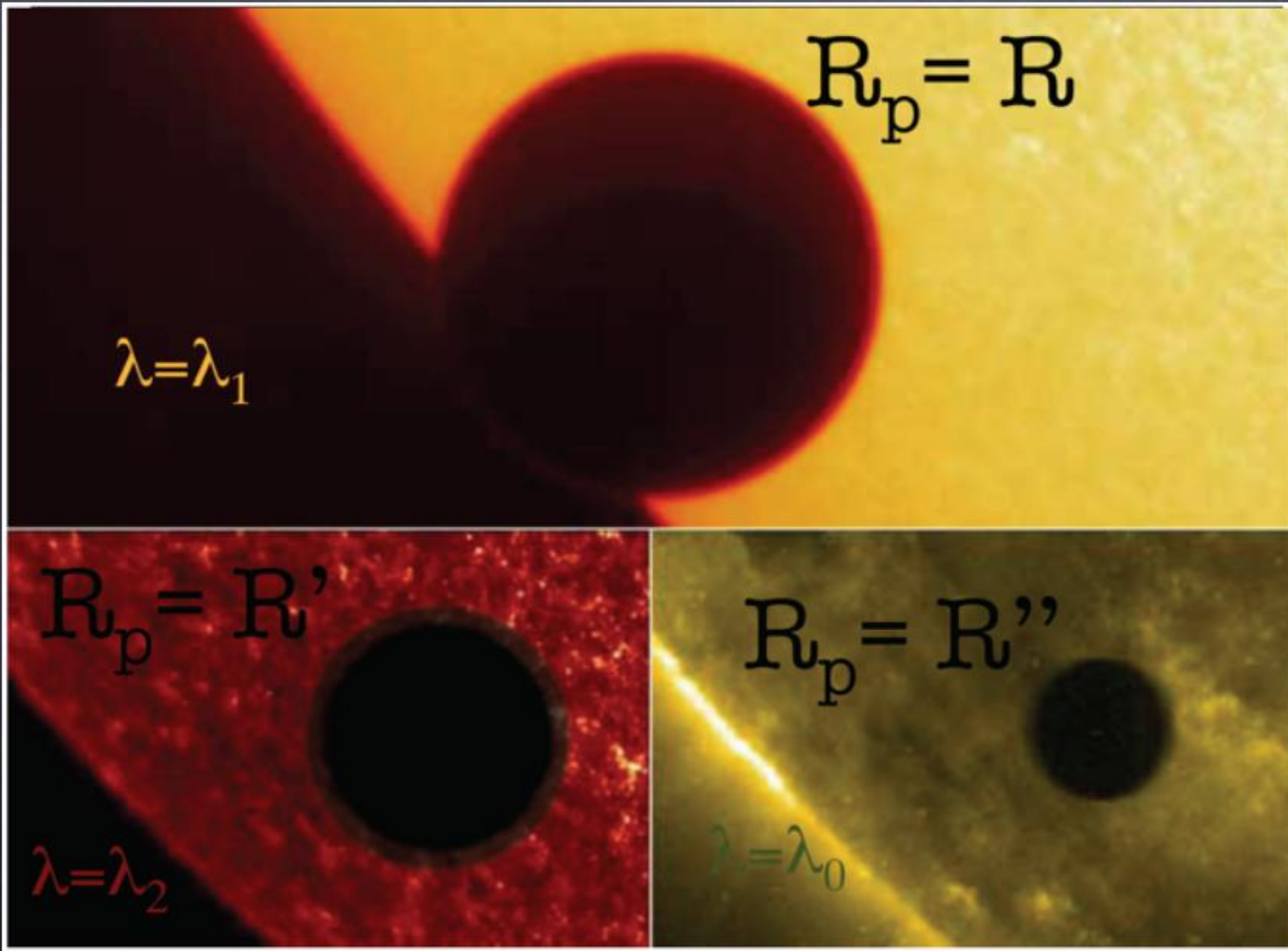
Transmission Spectroscopy:

Atmospheric composition



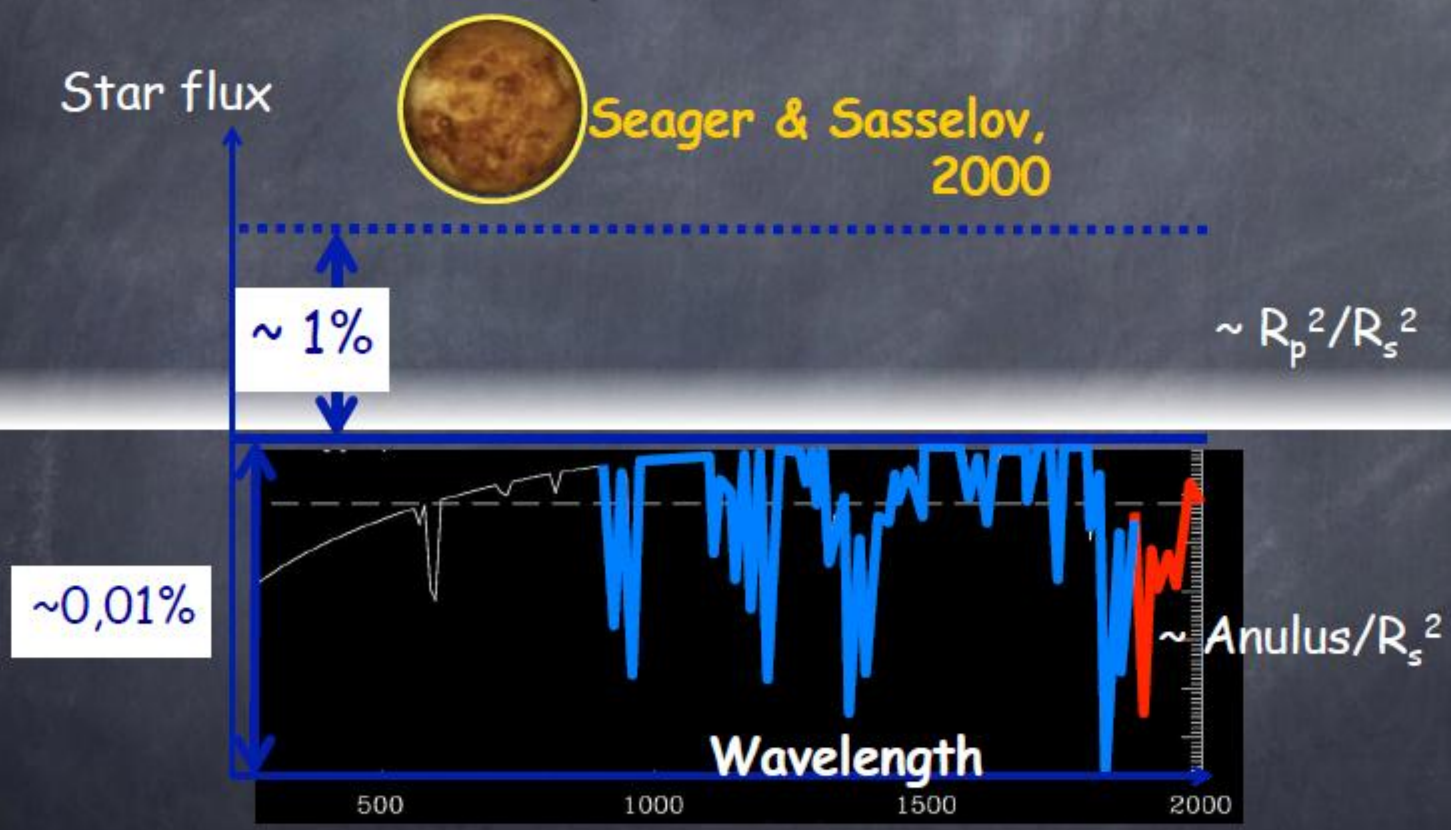
Occultation Spectroscopy:

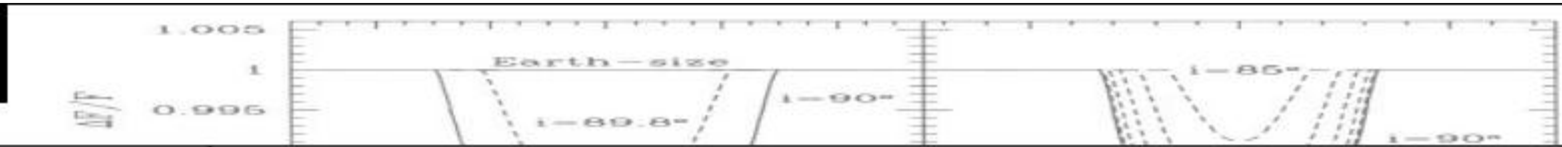
Albedo and Thermal Behaviour



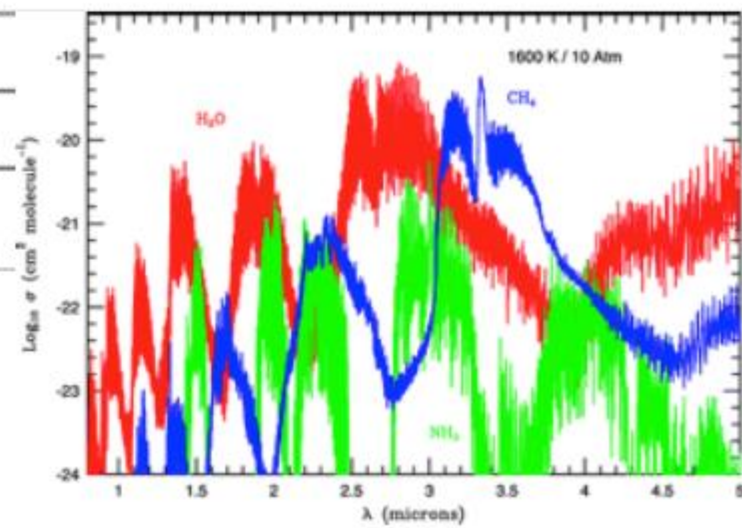
$R_p = R$
$\lambda=\lambda_1$
$R_p = R'$
$\lambda=\lambda_2$
$R_p = R''$
$\lambda=\lambda_0$

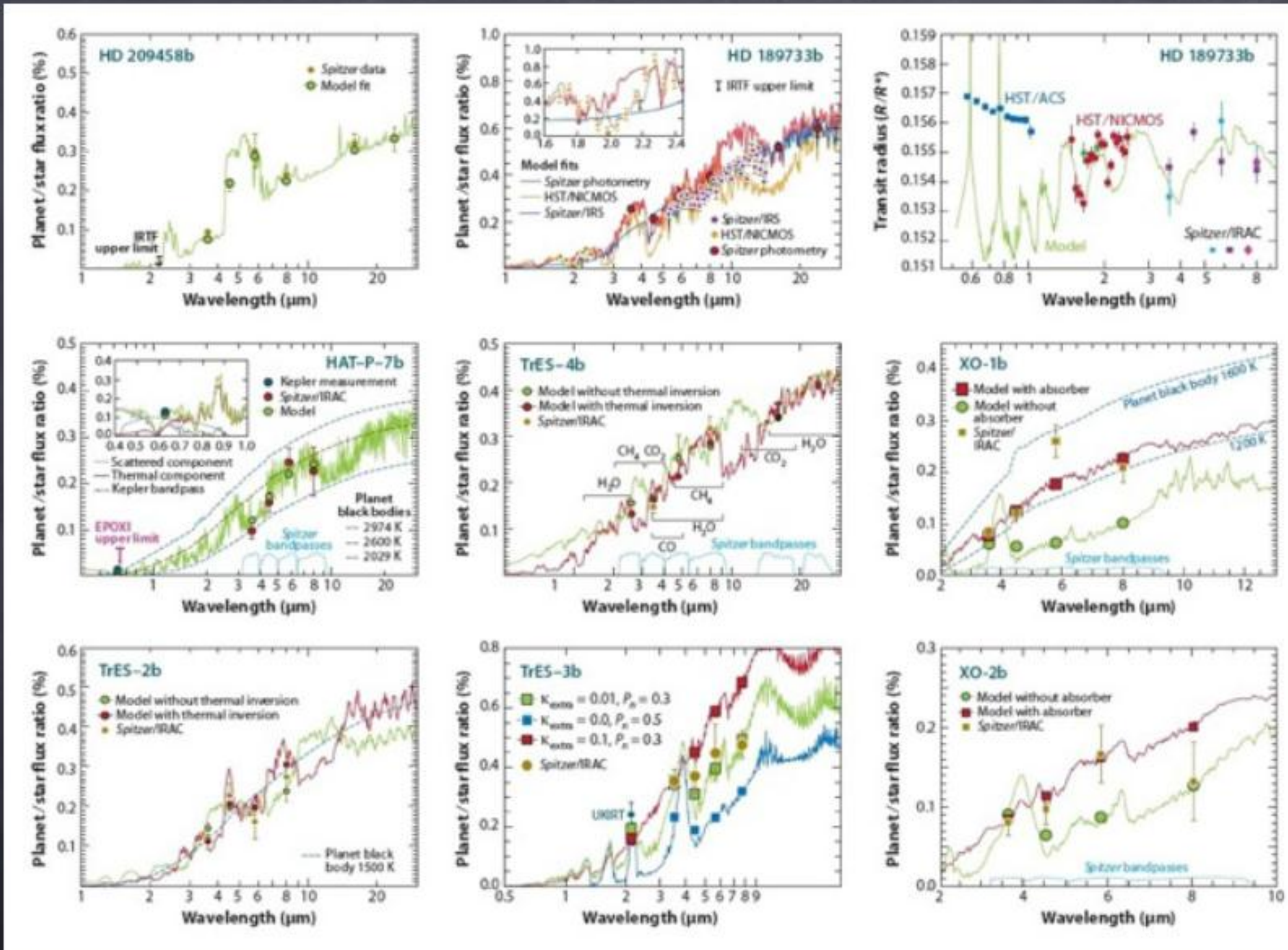
Trasparencies...and spectra





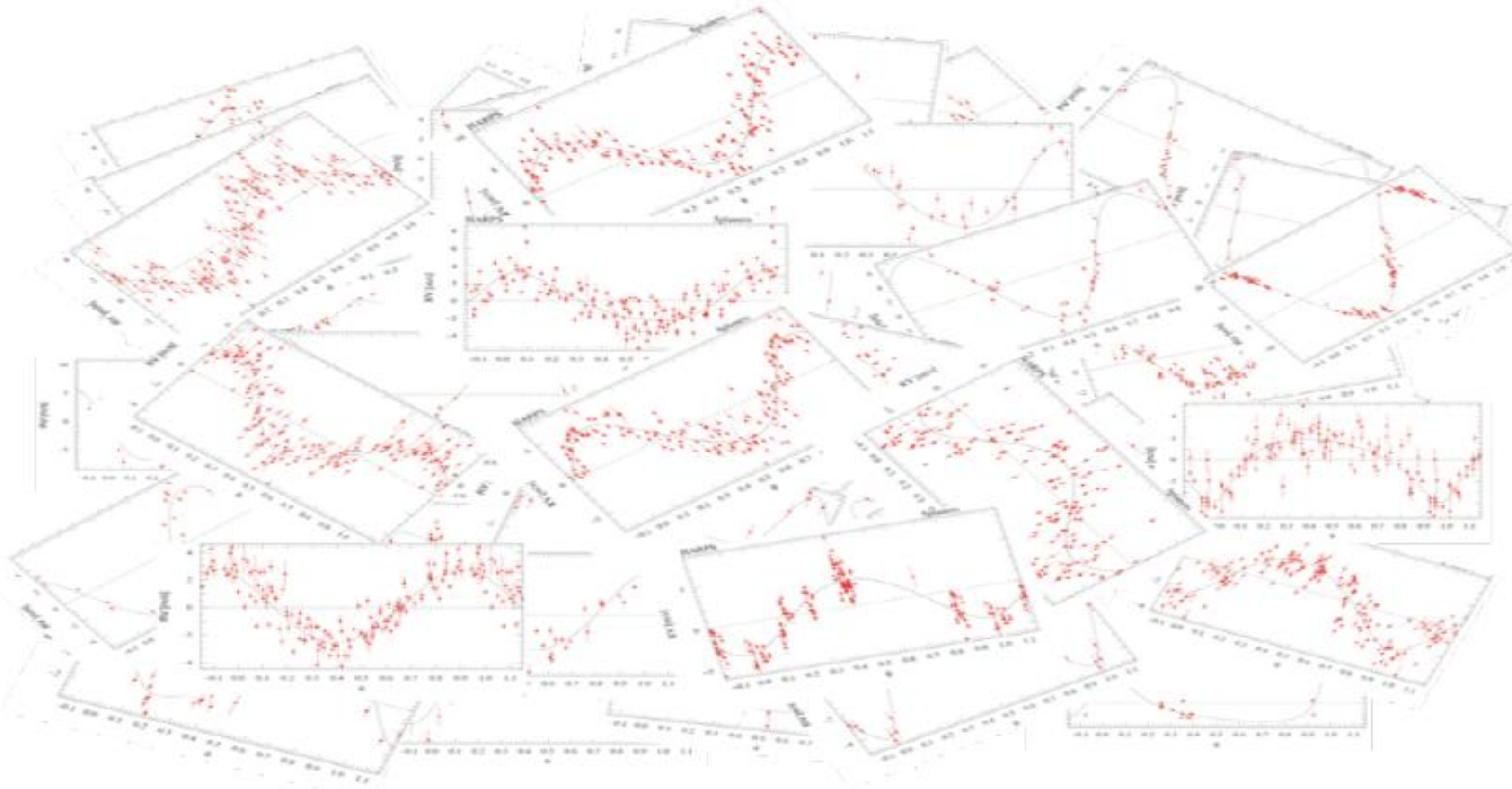
Molecule	Absorption bands (μm)
H_2O	0.51, 0.57, 0.61, 0.65, 0.72, 0.82, 0.94, 1.13, 1.41, 1.88, 2.6
CH_4	0.48, 0.54, 0.57. 0.6, 0.67, 0.7, 0.79, 0.84, 0.86, 0.73, 0.89, 1.69, 2.3
CO_2	1.21, 1.57, 1.6. 2.03
NH_3	0.55, 0.65, 0.93, 1.5, 2, 2.3
O_3	0.45-0.75 (the Chappuis band)
O_2	0.58, 0.69, 0.76, 1.27
CO	1.2, 1.7, 2.4
H_2S	1.56, 1.9





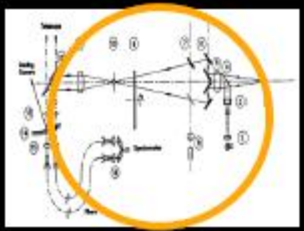
Ref: Seager & Deaming, 2010;

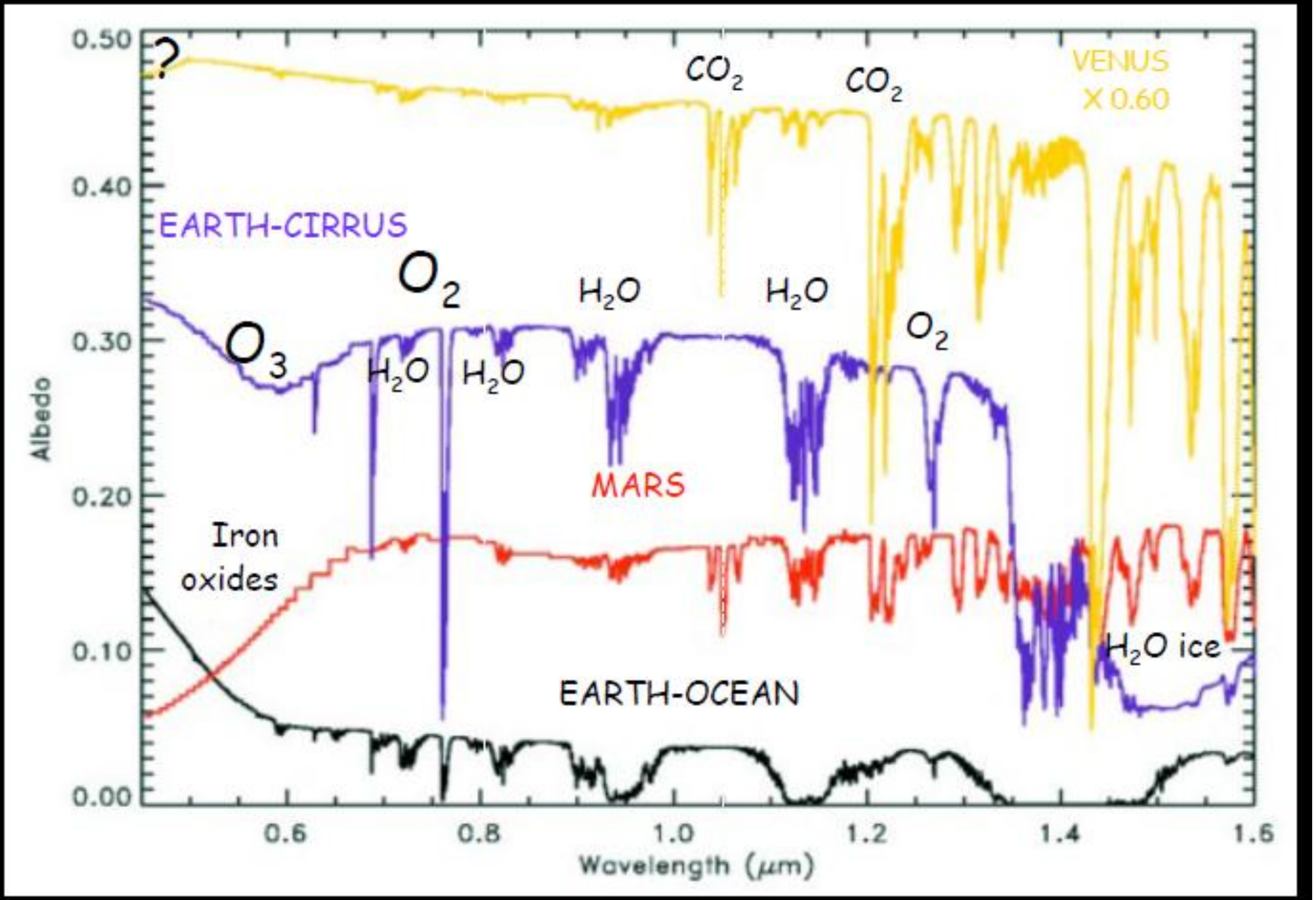
Giant Planets + Titan in the VIS



Karkoschka, Icarus, 1998

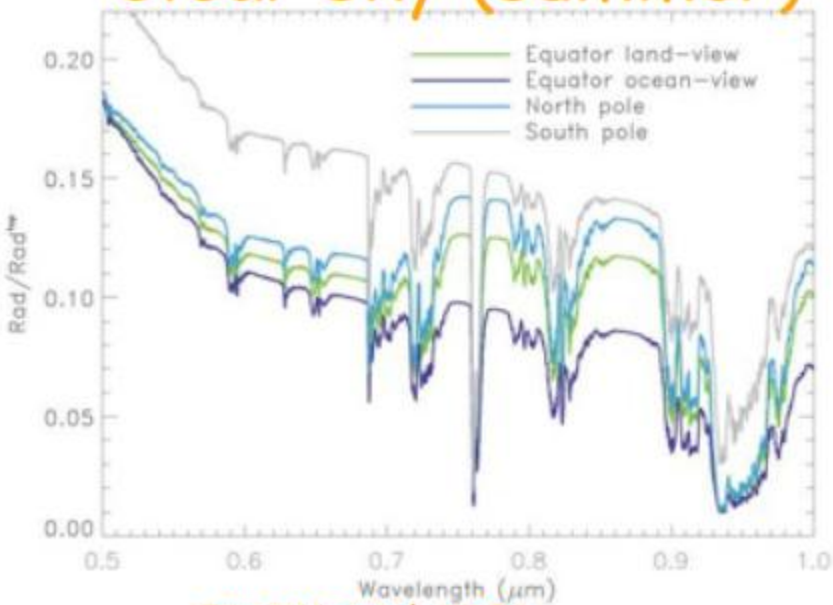
VIS-Near-IR signatures for terrestrial planets in our Solar System





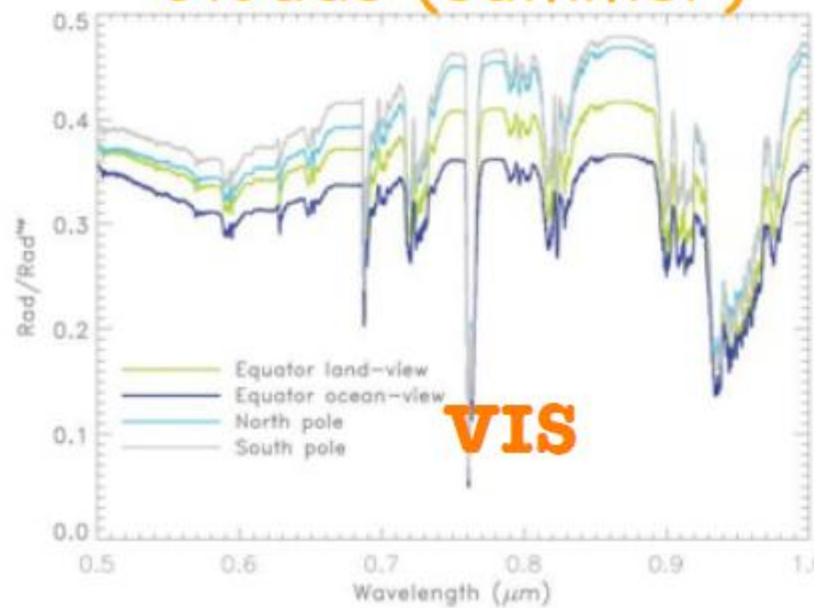
Sensitivity to Viewing geometry

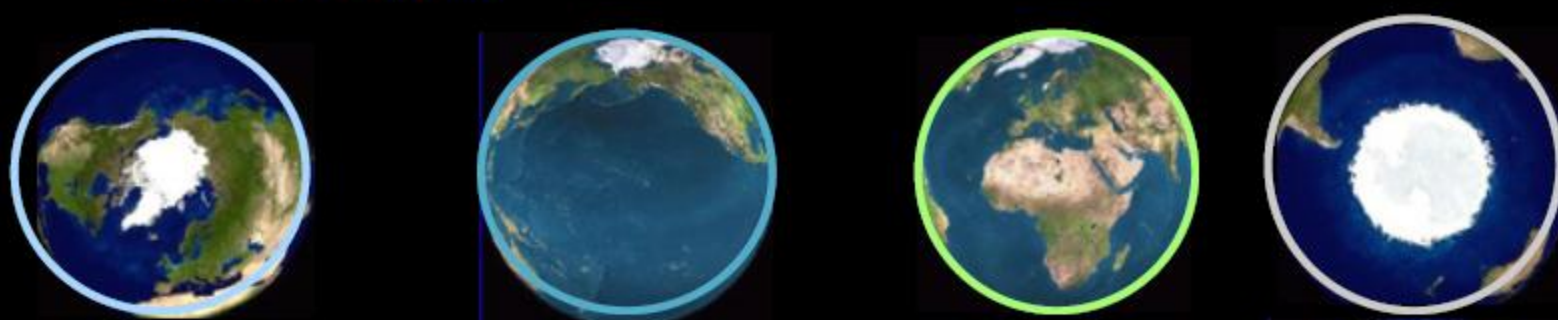
Clear sky (summer)



Tinetti et al.,2006

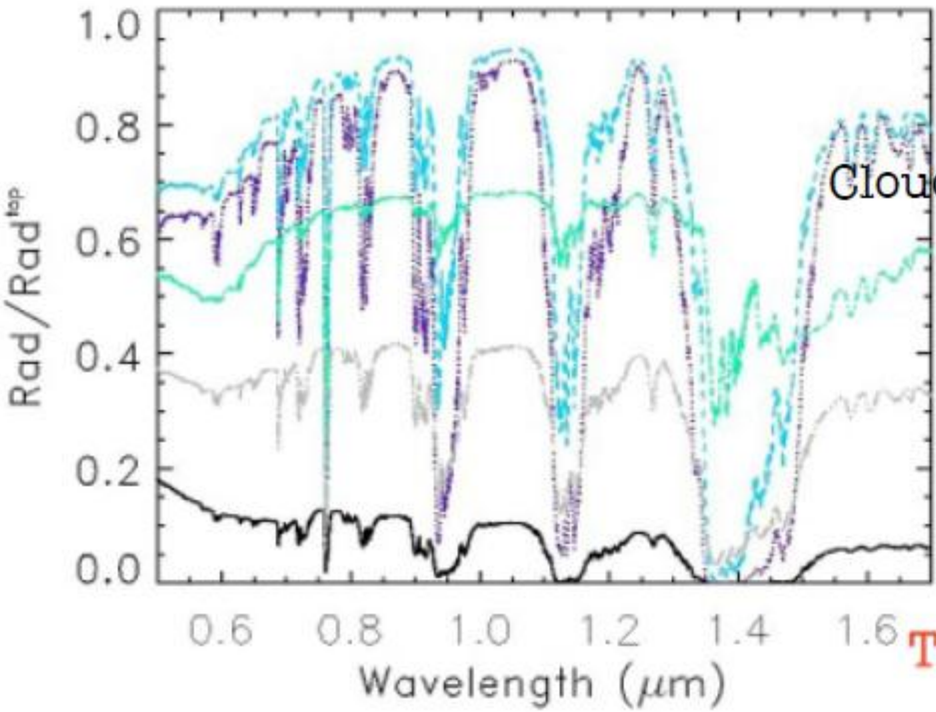
Clouds (summer)





Sensitivity to Phases

Earth disk-averaged spectra, 3D model

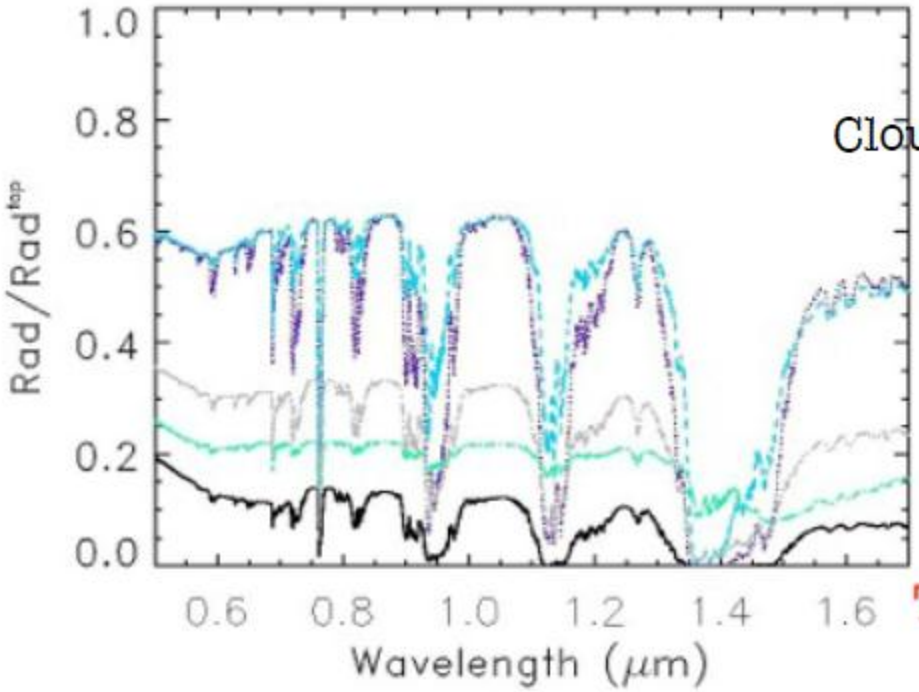


Cloud-less disk-averaged spectrum
Realistic clouds
100% Strato-cumulus clouds
100% Alto-stratus clouds
100% Cirrus clouds

Tinetti et al., *Astrobiology,, 2006*

Sensitivity to Phases

Earth disk-averaged spectra, 3D model



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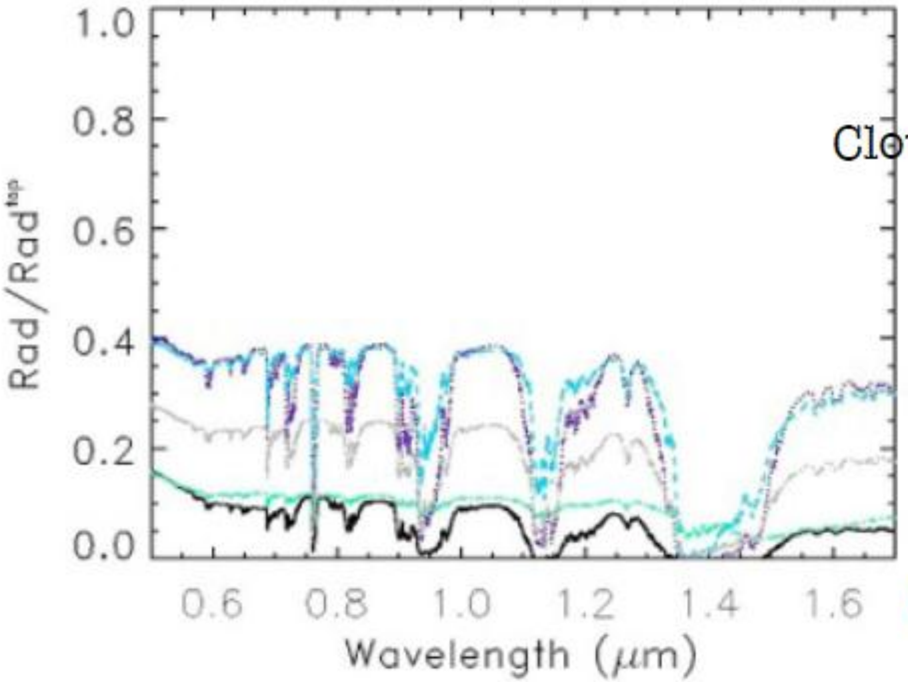

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Sensitivity to Phases

Earth disk-averaged spectra,
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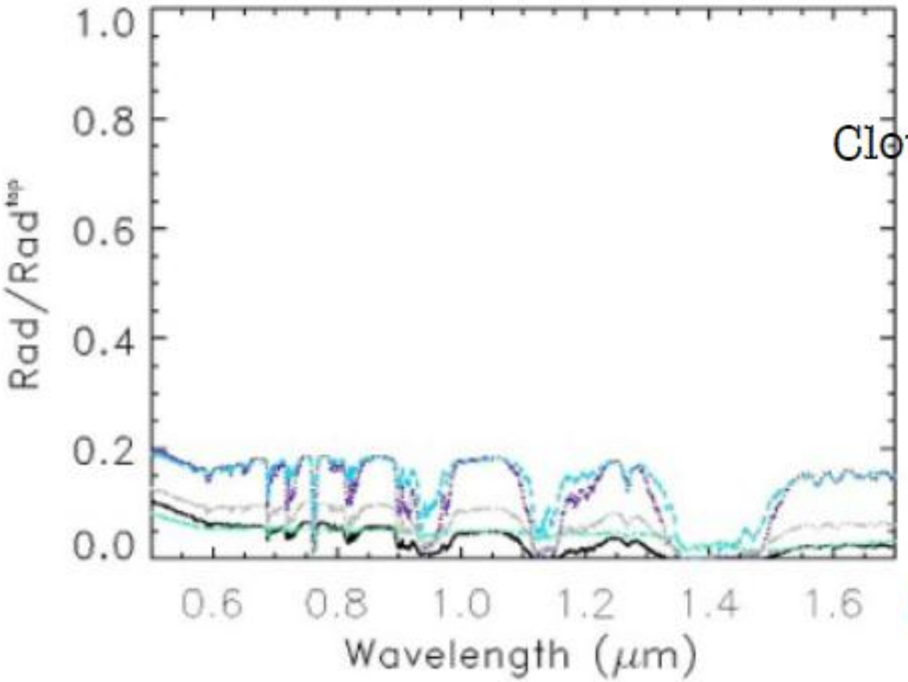
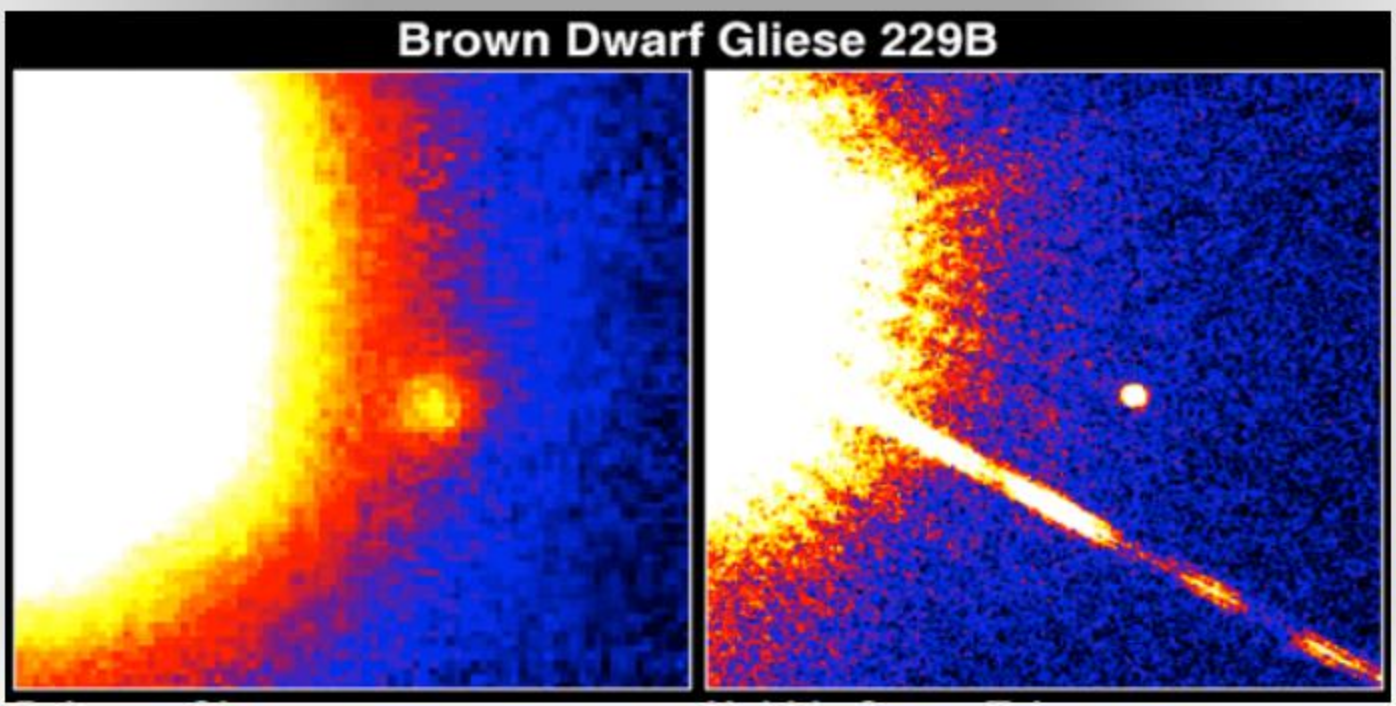


Cloud-less disk-averaged spectrum
Realistic clouds
100% Strato-cumulus clouds
100% Alto-stratus clouds
100% Cirrus clouds

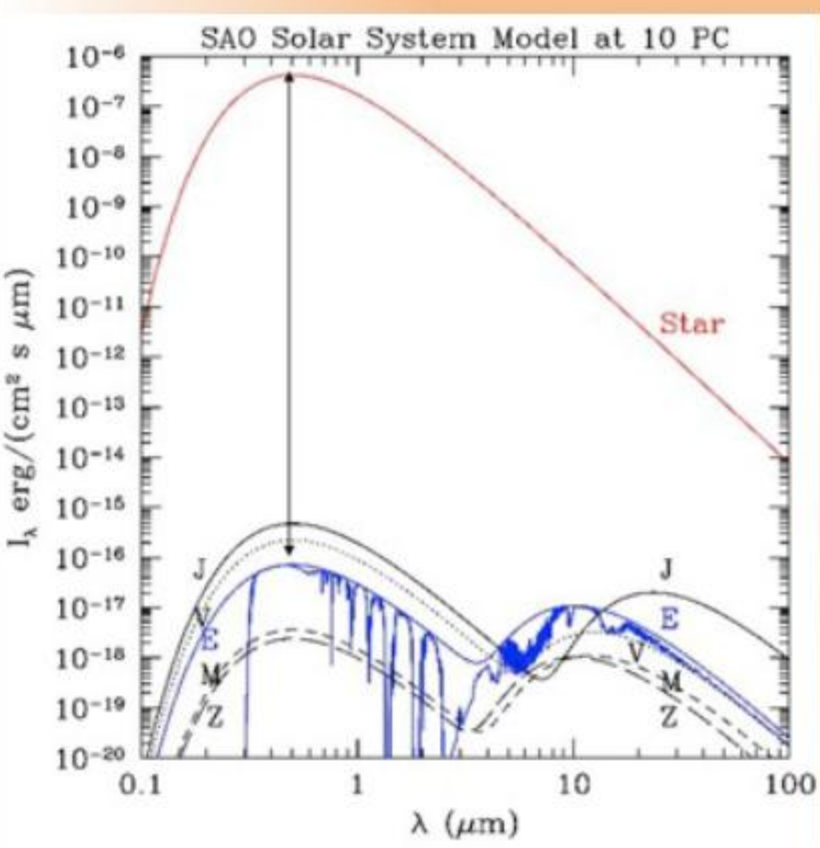
Tinetti et al., *Astrobiology,, 2006*

Difficoltà Osservative

- enorme differenza di luminosità tra la stella e il pianeta (10^8 volte nel caso Sole-Giove)
- piccola separazione angolare (0.5 arcsec per il sistema Sole-Giove visto da 10 pc di distanza)



La sfida dell'imaging diretto



Pianeta	a(AU)	ΔV(mag)	ρ_5(arcsec)	ρ_{10}(arcsec)	ρ_{50}(arcsec)	ρ_{100}(arcsec)
Mercurio	0.39	24.6	0.078	0.039	0.0078	0.0039
Venere	0.72	21.6	0.144	0.072	0.0144	0.0072
Terra	1.00	23.0	0.200	0.100	0.0200	0.0100
Marte	1.52	26.4	0.304	0.152	0.0304	0.0152
Giove	5.20	21.3	1.040	0.520	0.1040	0.0520
Saturno	9.54	22.9	1.908	0.954	0.1908	0.0954
Urano	19.18	26.2	3.836	1.918	0.3836	0.1918
Nettuno	30.06	27.4	6.012	3.006	0.6012	0.3006
Plutone	39.44	33.7	7.888	3.944	0.7888	0.3944

Contrasto di luminosità

Jupiter/Sun = 10^{-8} = 20 mag

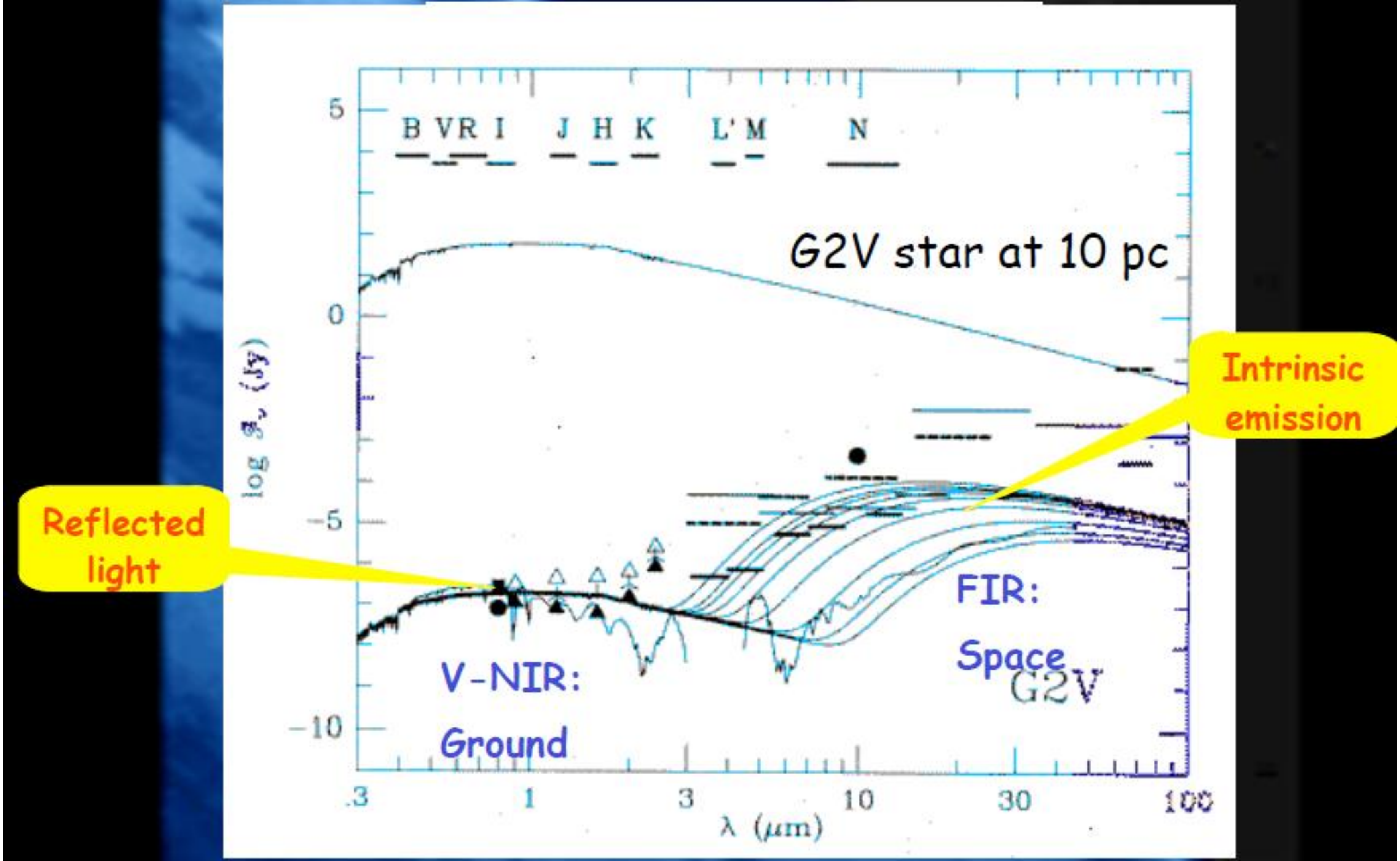
Earth/Sun = 10^{-10} = 25 mag

Separazione angolare:

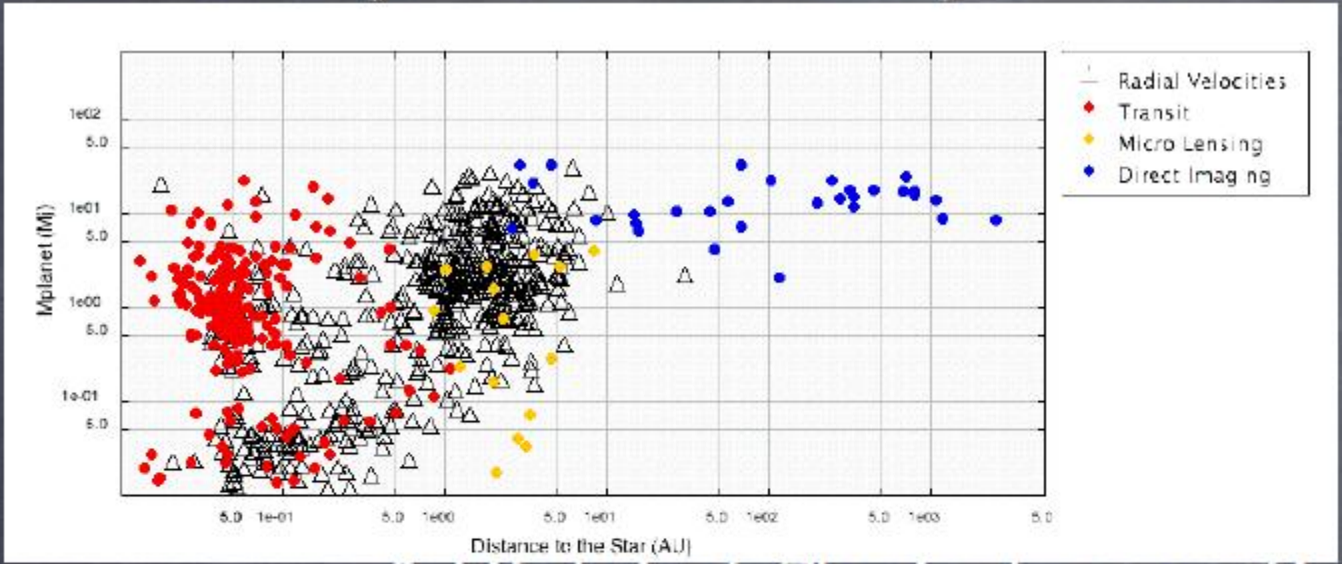
Jupiter = 0.5 arcsec @ 10 pc

Jupiter = 0.1 arcsec @ 50 pc

Selezione del range di lunghezza d'onda



Direct Imaging: Direct technique: Planet's photons (Targets: young and nearby stars)

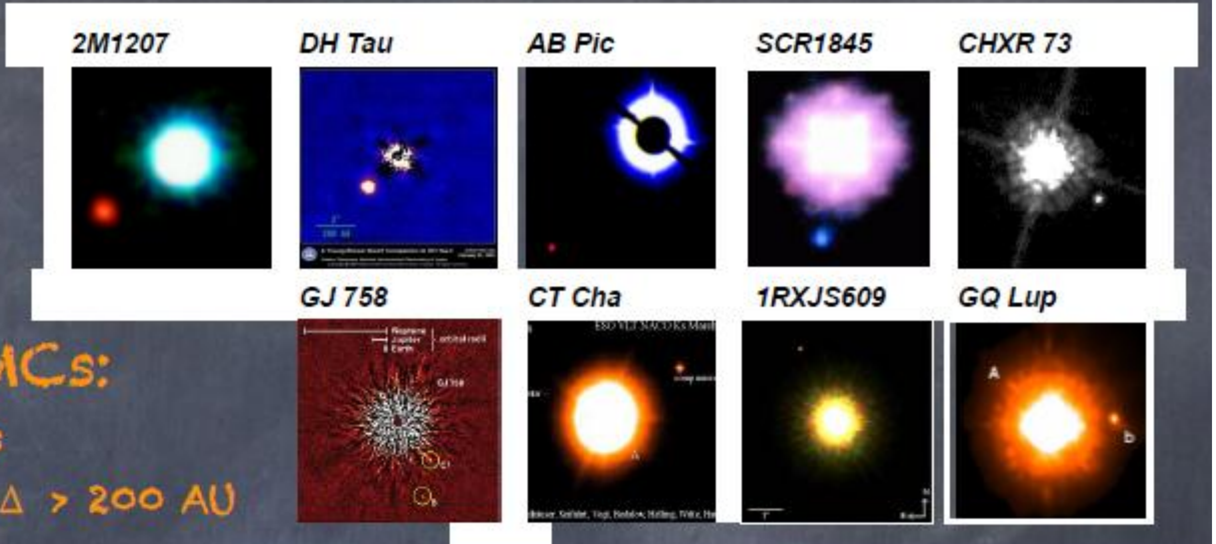


. Orbital And Physical properties:

> L, a , e, i, ω, T0
> Giant planets at wide orbits (>10 AU)
> Multiple: Architecture and Stability
> Planet - disk connection

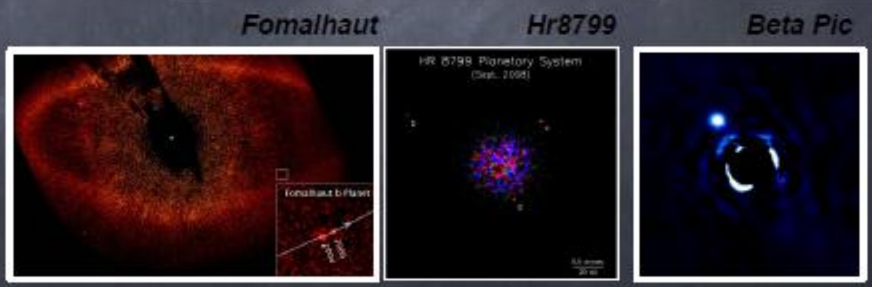
Chauvin et al. 05, 10; Lafrenière et al.
Soummer et al. 11; Vigan et al. 12

Family's Portrait



Wide orbit PMCs:

- low mass KM stars
- q = 0.02 - 0.2 or Δ > 200 AU

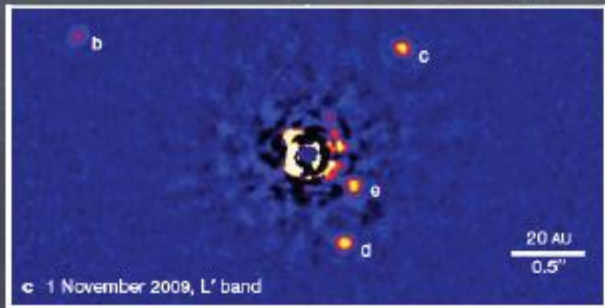


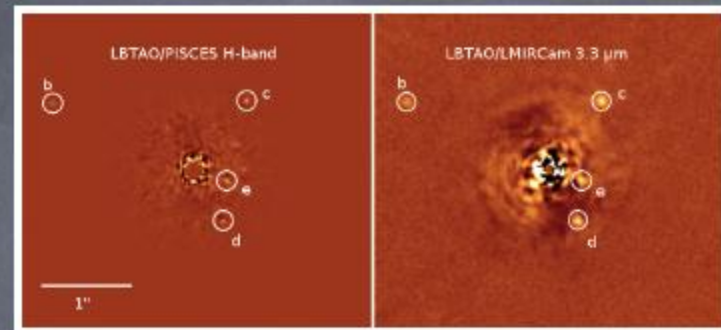
Closer PMCs:

- A4V-A5V massive primaries
- q < 0.005 ; Δ = 8 - 120 AU
- CS Disk signatures

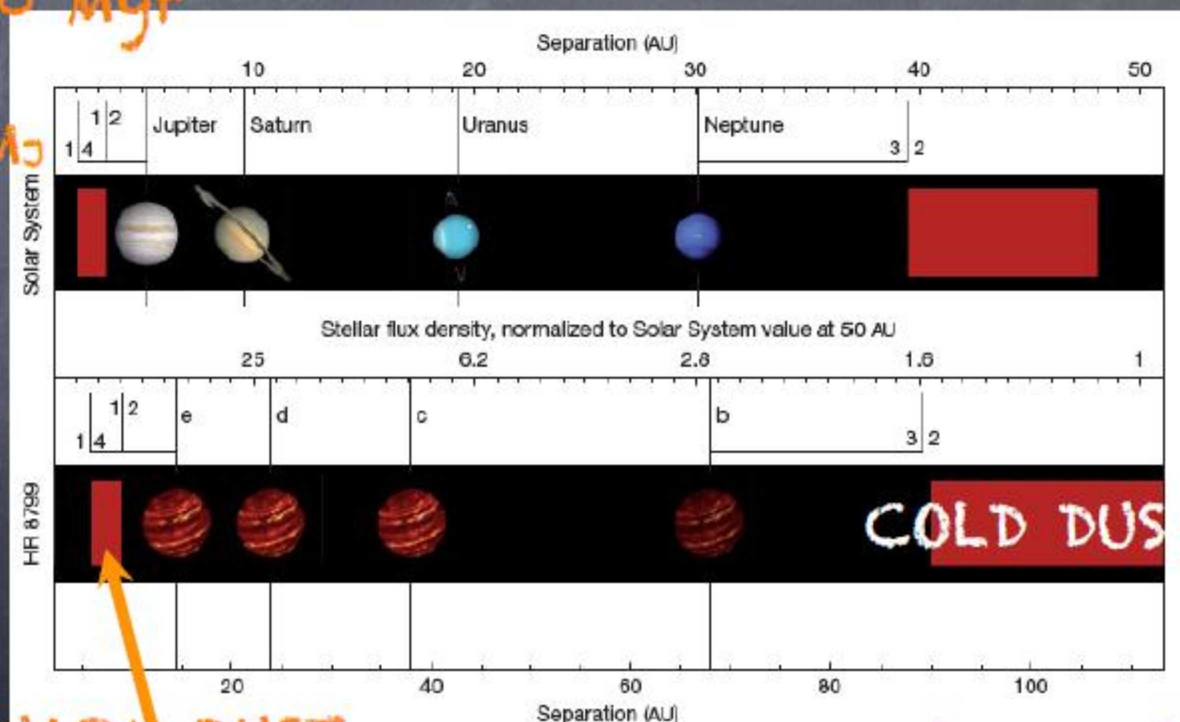
Ref: Chauvin et al. 04; Itoh et al. 05; Chauvin et al. 05; Biller et al. 05; Luhman et al. 06; Thalmann et al. 09; Lafrenière et al. 08; Neuhauser et al. 05; Schmidt et al. 09; Lagrange et al. 10; Kalas et al. 08; Marois et al. 08,10...

HR 8799 b, c, d, e





Age 30-60 Myr
A5V
5≤Mp≤10 MJ

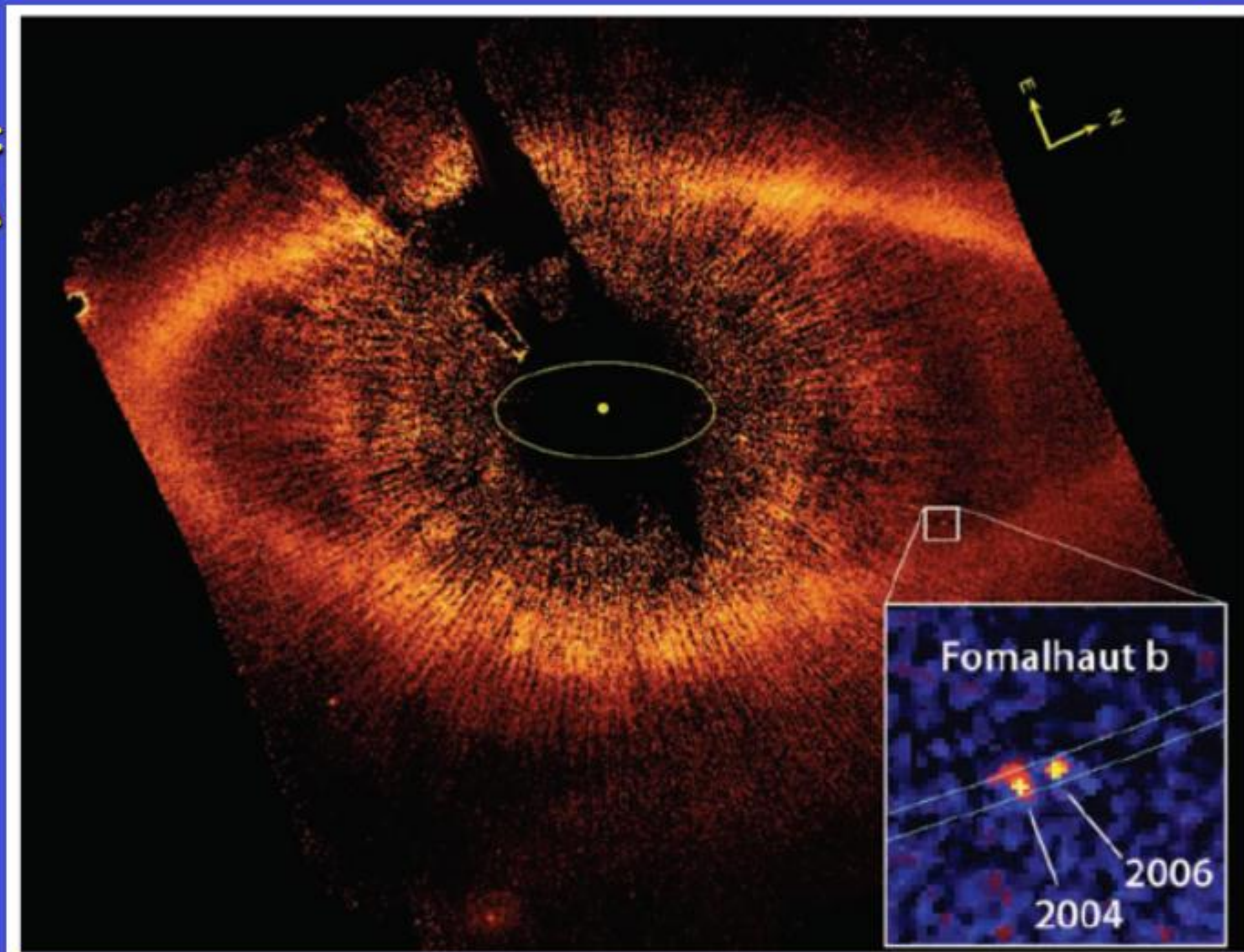


WARM DUST

Marois et al., 2010; Skemer et al., 2012

HST Coronographic image

d=7.7 pc
a=119 UA



Kalas et al. 2008