Nuovi mondi possibili: i pianeti extrasolari

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Difficoltà di “osservazione” dei pianeti extrasolari: distanza, …

1 Unità Astronomica (AU) = 1.496×10^8 km = 149.6 milioni di km
(dimensioni del Sistema Solare ≈ 30-40 AU)

1 anno luce = 63241 AU
(distanza stella più vicina ≈ 4.22 anni luce)
(diametro della Galassia ≈ 10^5 anni luce)
(distanza della galassia più vicina ≈ 2×10^6 anni luce)

1 parsec (pc) = 3.26 anni luce

Difficoltà dell'osservazione diretta

Come apparirebbe Venere se fosse osservata
alla distanza di una delle stelle più vicine al Sole?

	Sole	Stella a 1 pc	Stella a 10 pc
Distanza dalla Terra	1 AU	200,000 AU	2,000,000 AU
Angolo stella-pianeta	50°	5”	0.5”
Luminosità relativa	1	1×10^{-10}	1×10^{-12}
Magnitudine	-4	23	28

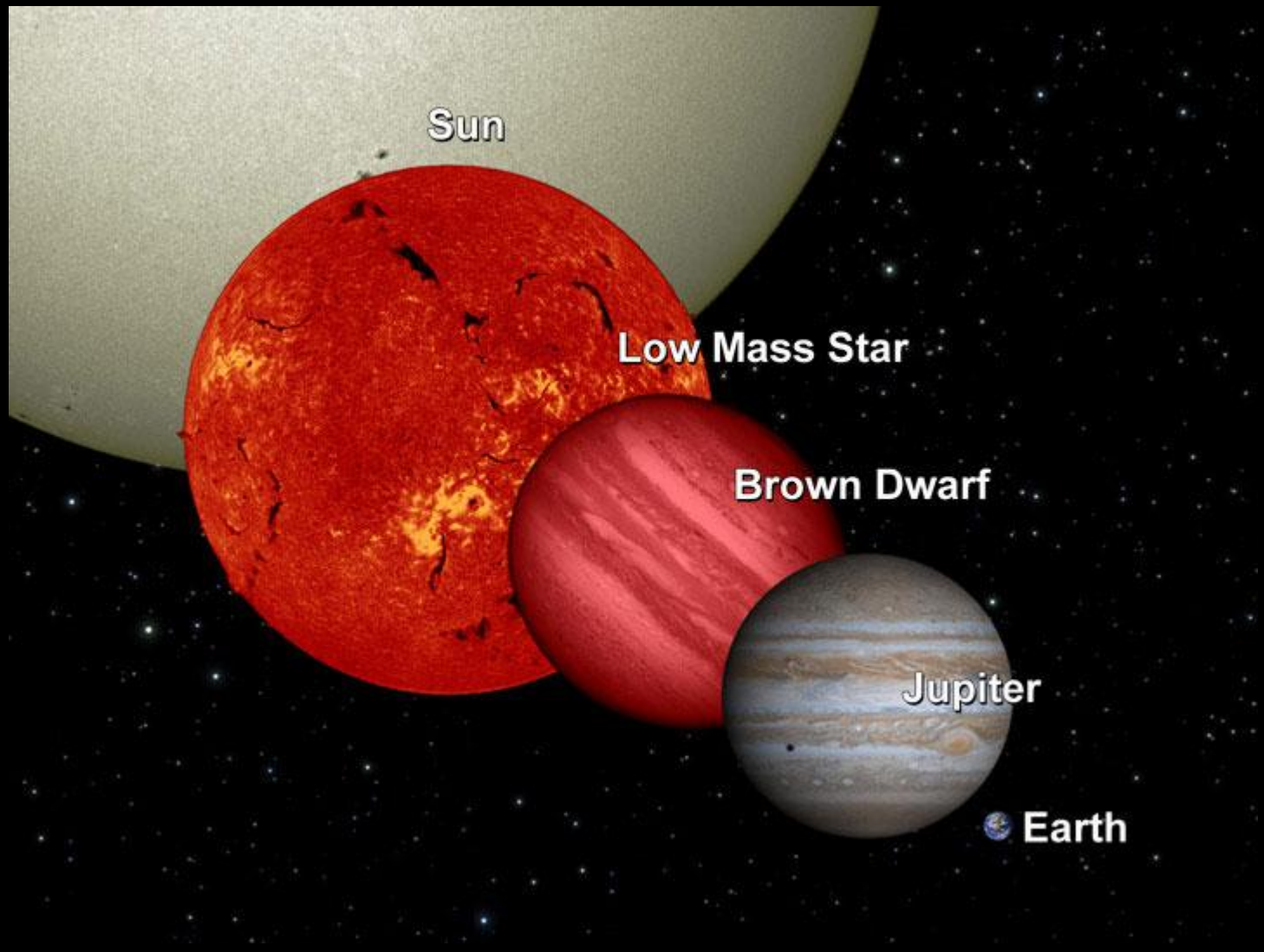
Difficoltà di “osservazione” dei pianeti extrasolari: …, luminosità, …

Difficoltà di "osservazione" dei pianeti extrasolari: …, massa.

massa terrestre (M_E) = 5.97×10^{24} kg
massa di Giove (M_J) = 318 M_E
massa del Sole (M_S) = 333000 M_E = 1047 M_J

pianeta:			M	< 13-15 M_J
nana bruna:	13-15 M_J	<	M	< 70-80 M_J
stella :	70-80 M_J	<	M	

Stella, nana rossa, nana bruna, pianeta



Tappe della scoperta

1984: anello di polveri attorno a β Pictoris

1988: prima scoperta di un pianeta extrasolare
(γ Cephei, conferma 2003)

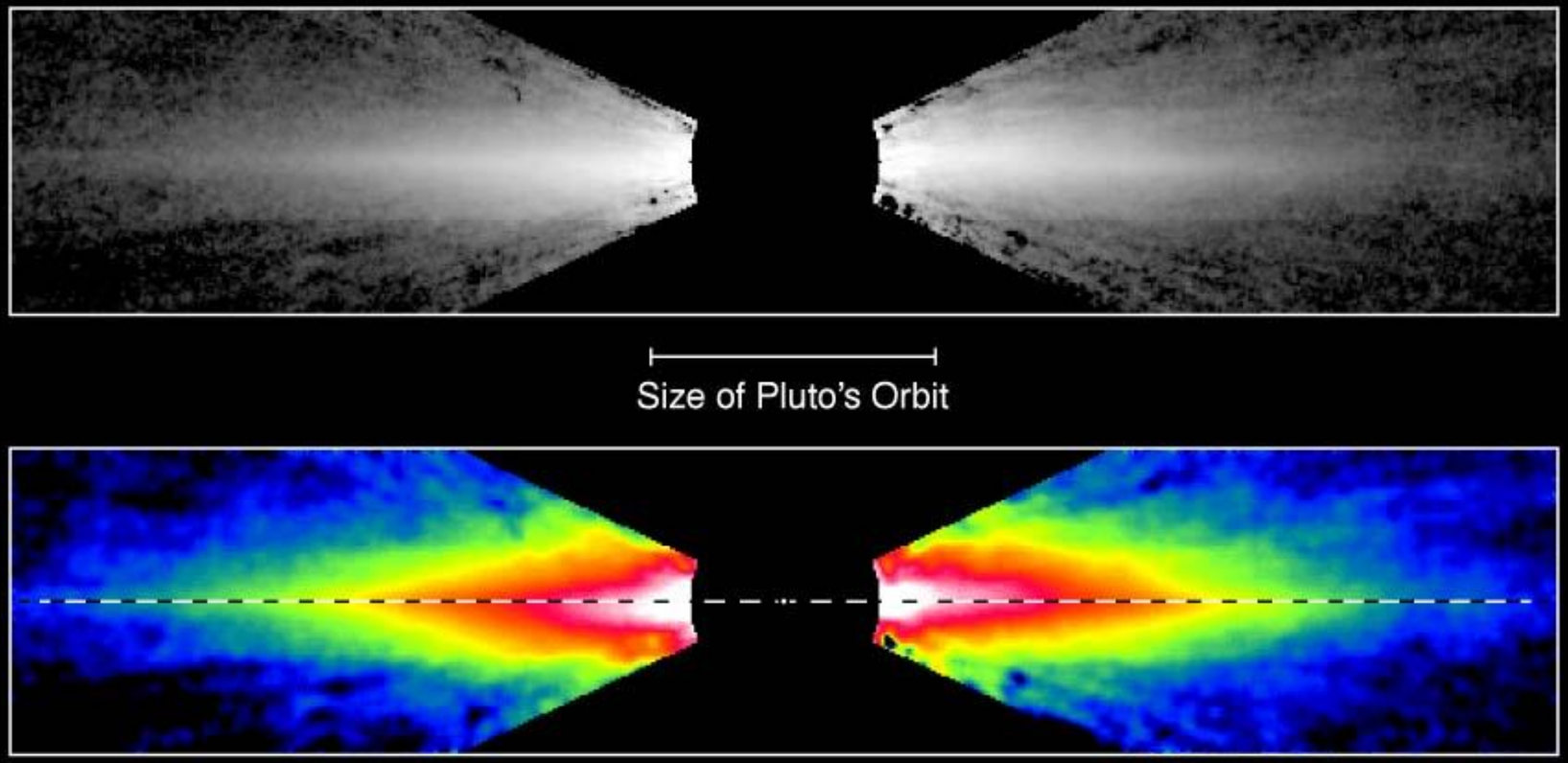
1992: primo pianeta attorno a una pulsar

1995: prima scoperta sicura (51 Pegasi)

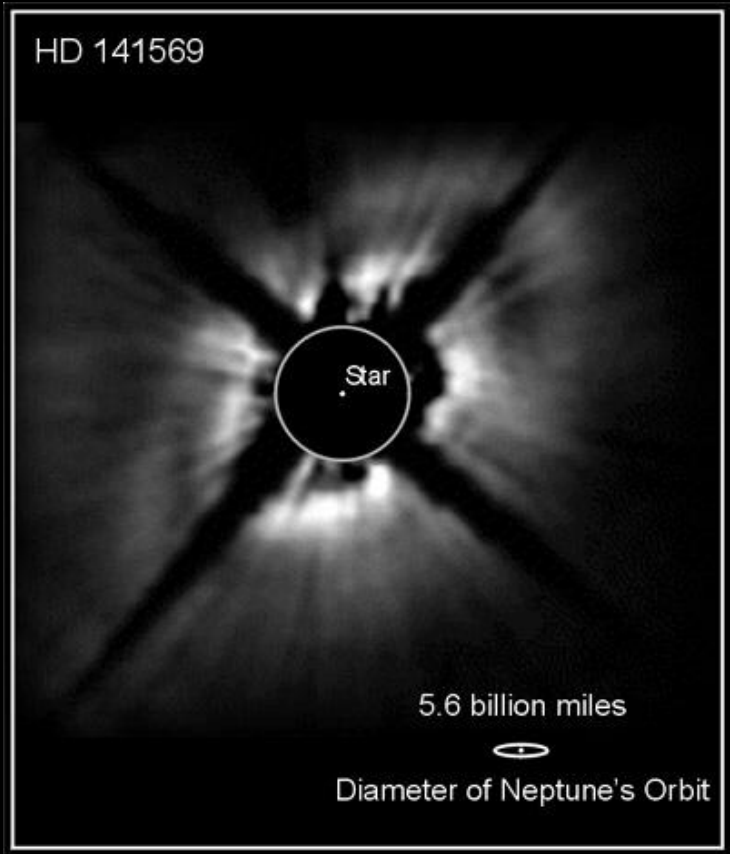
2004: prima osservazione ottica diretta

2018: 3906 pianeti, 2910 sistemi planetari

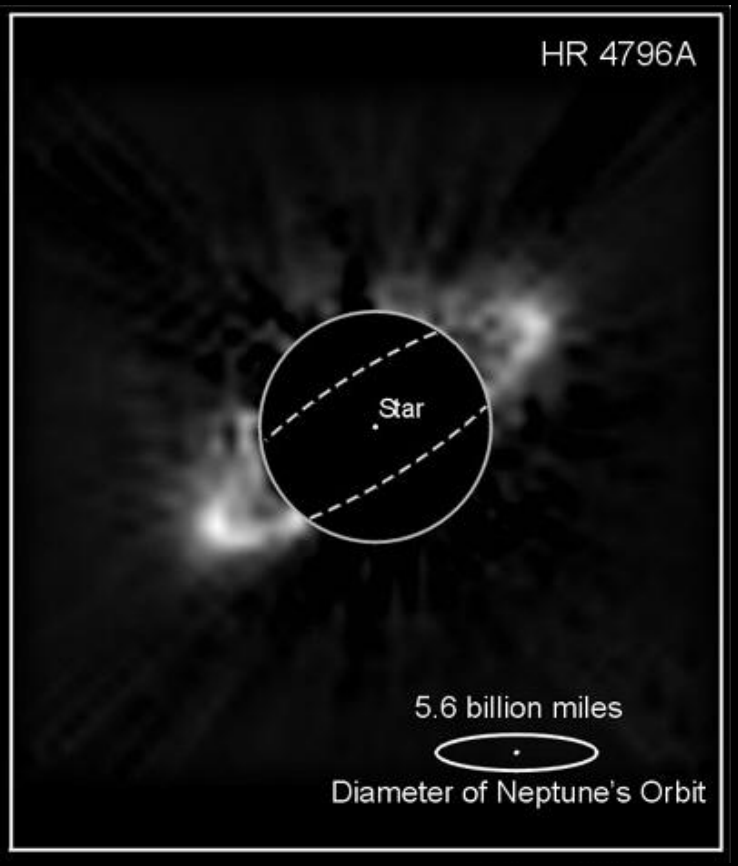
Anelli di polvere
attorno ad altre stelle



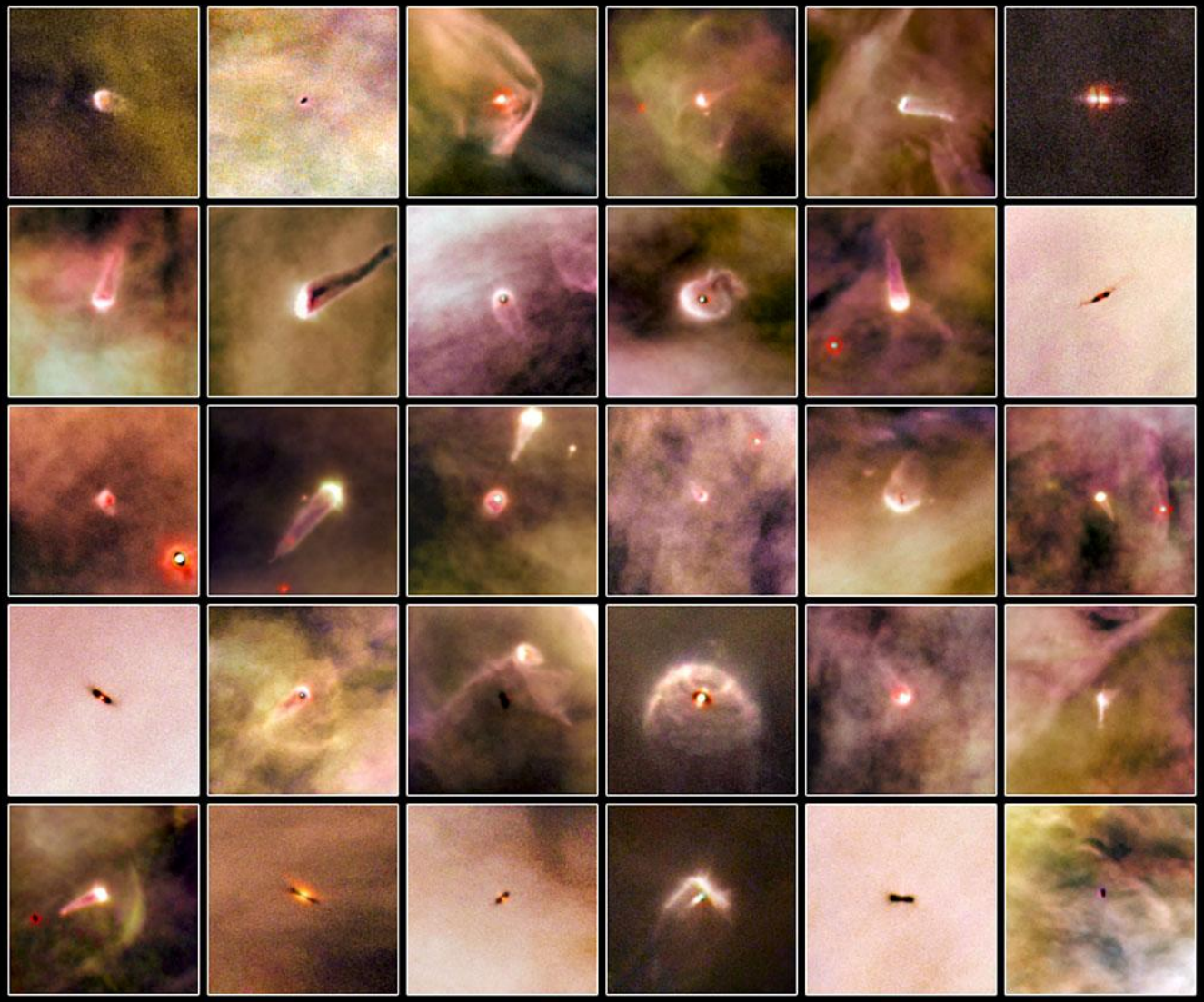
Anelli di polvere
attorno ad altre stelle



Anelli di polvere
attorno ad altre stelle



Dischi protoplanetari



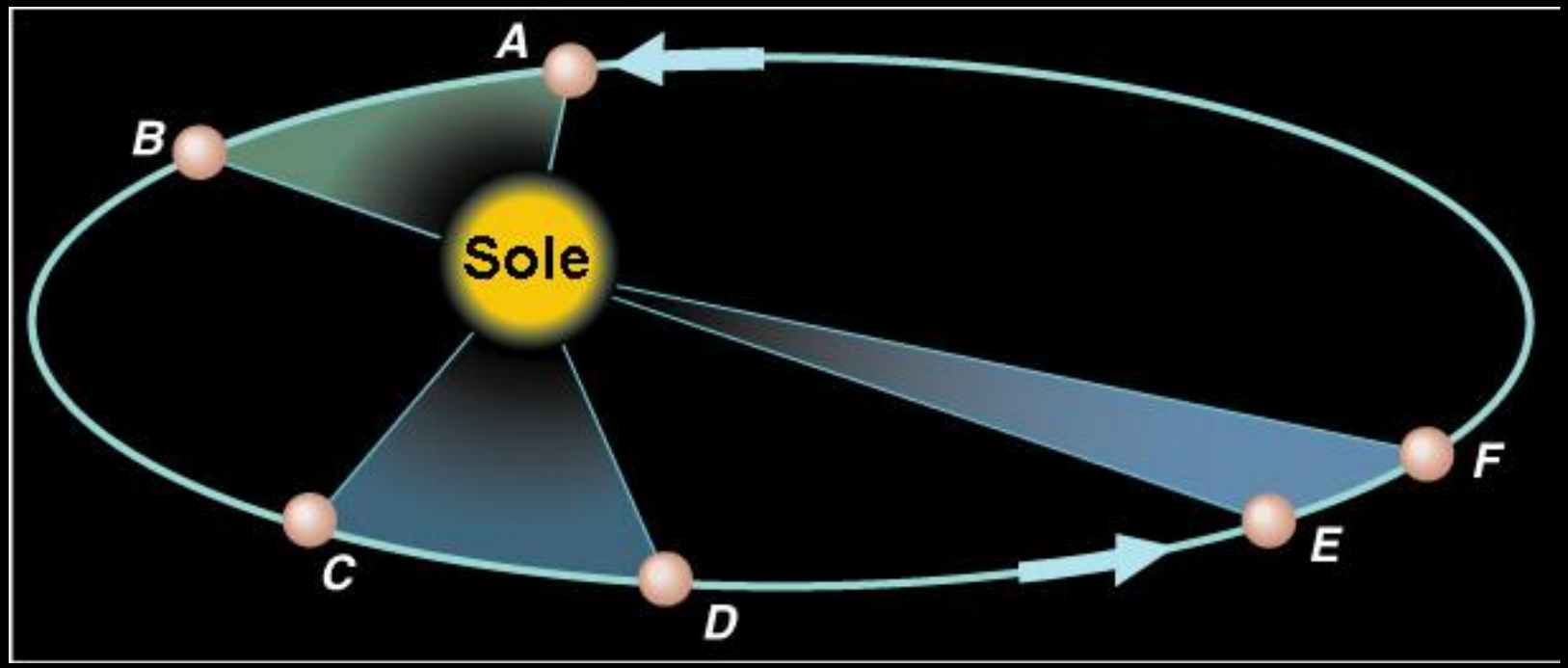
Metodi di detezione

- spettroscopia (velocità radiale)
- fotometria (occultazioni)
- ritardi nei segnali di *pulsar*
- astrometria di precisione
- *microlensing* gravitazionale
- immagini dirette:
  - ottiche adattive
  - interferometria (da terra e dallo spazio)
  - immagini nell'infrarosso termico

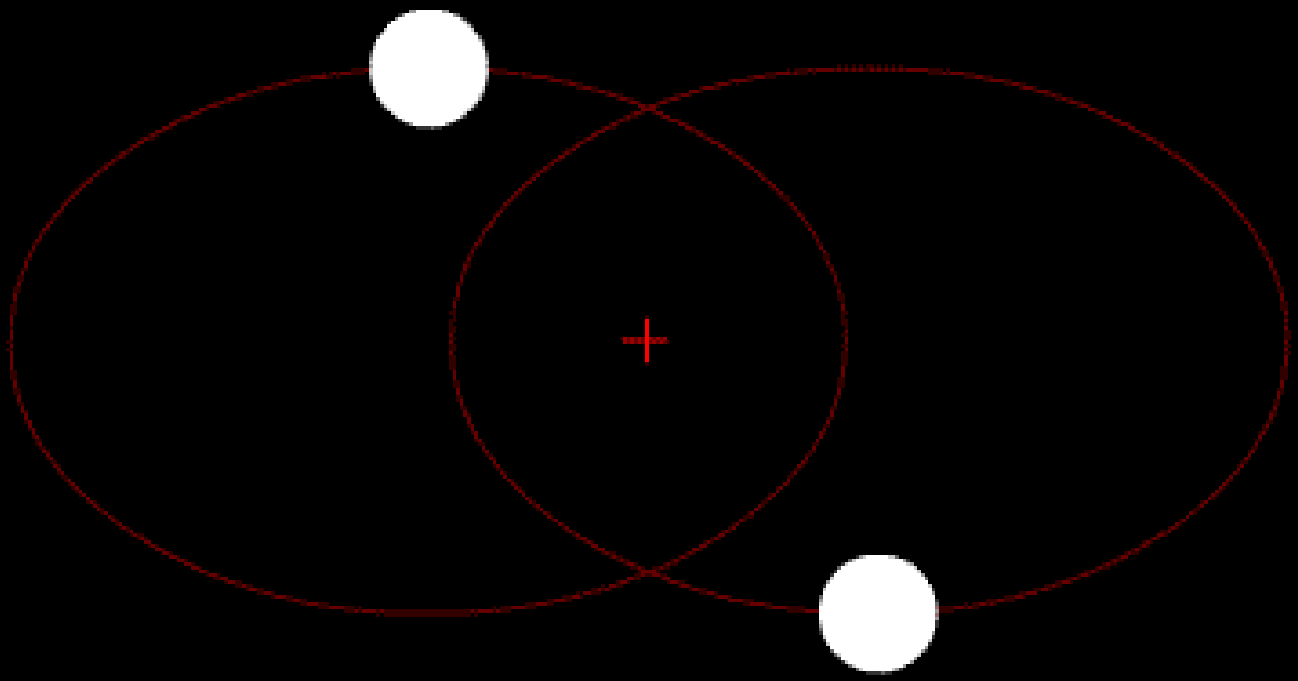
Metodi di detezione

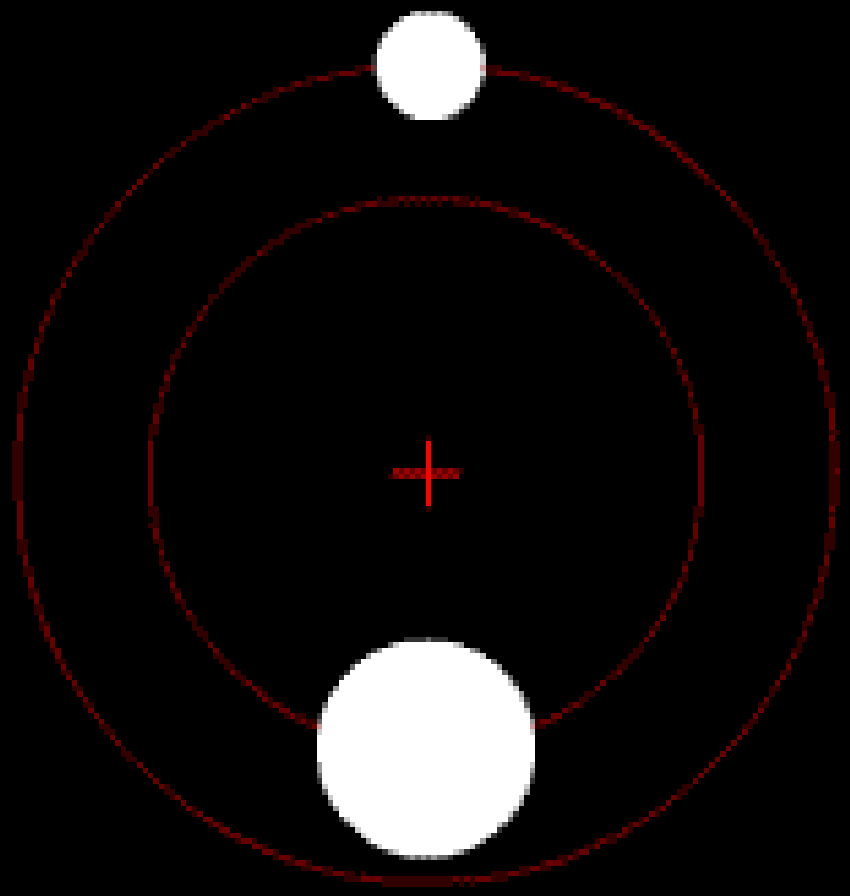
Misure di velocità radiale (effetto Doppler)

I pianeti si muovono attorno al Sole



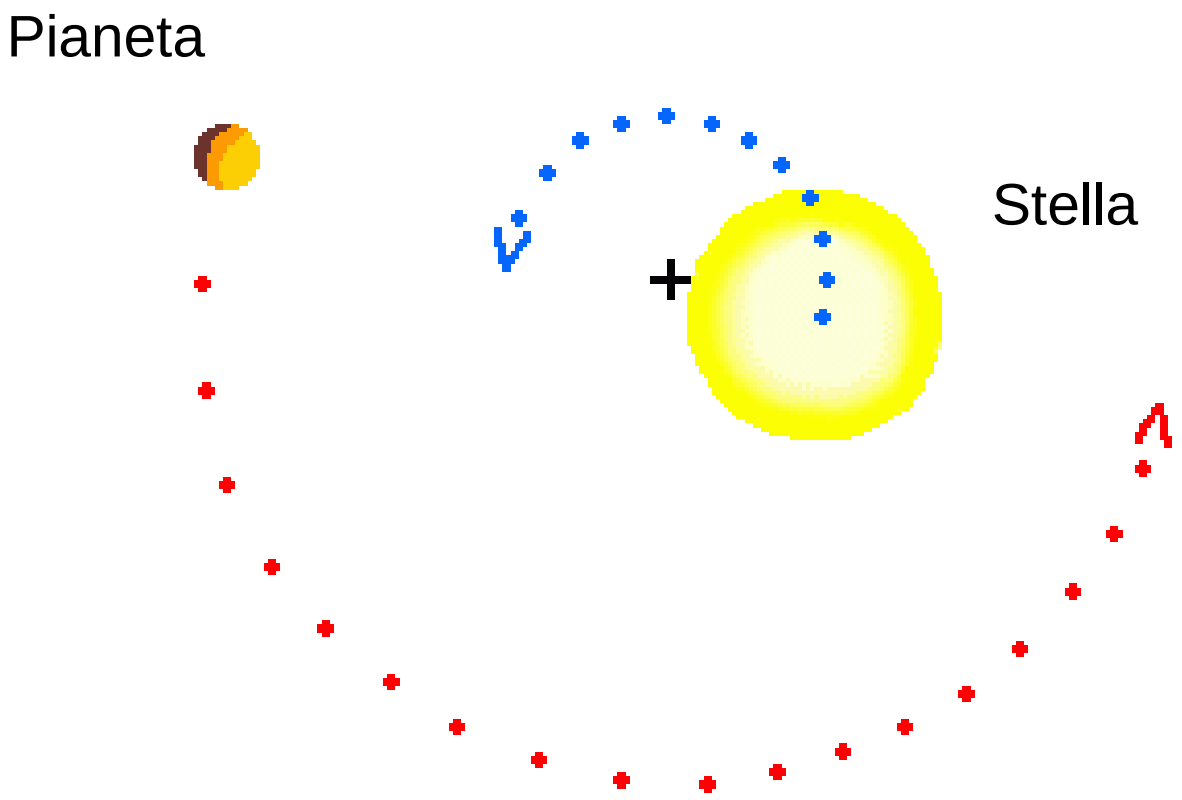
Ma è proprio vero che il Sole è immobile?

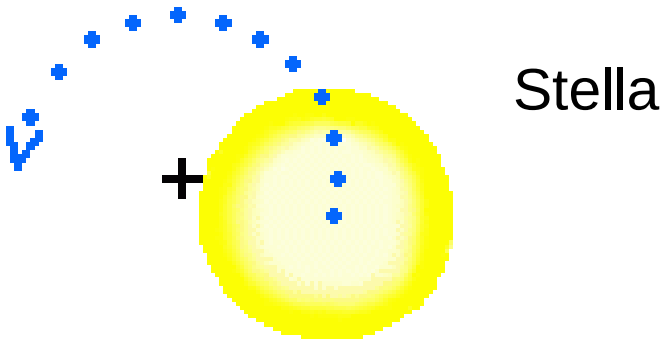




$$M_1 R_1 = M_2 R_2$$

$$\frac{R_1}{R_2} = \frac{M_2}{M_1}$$

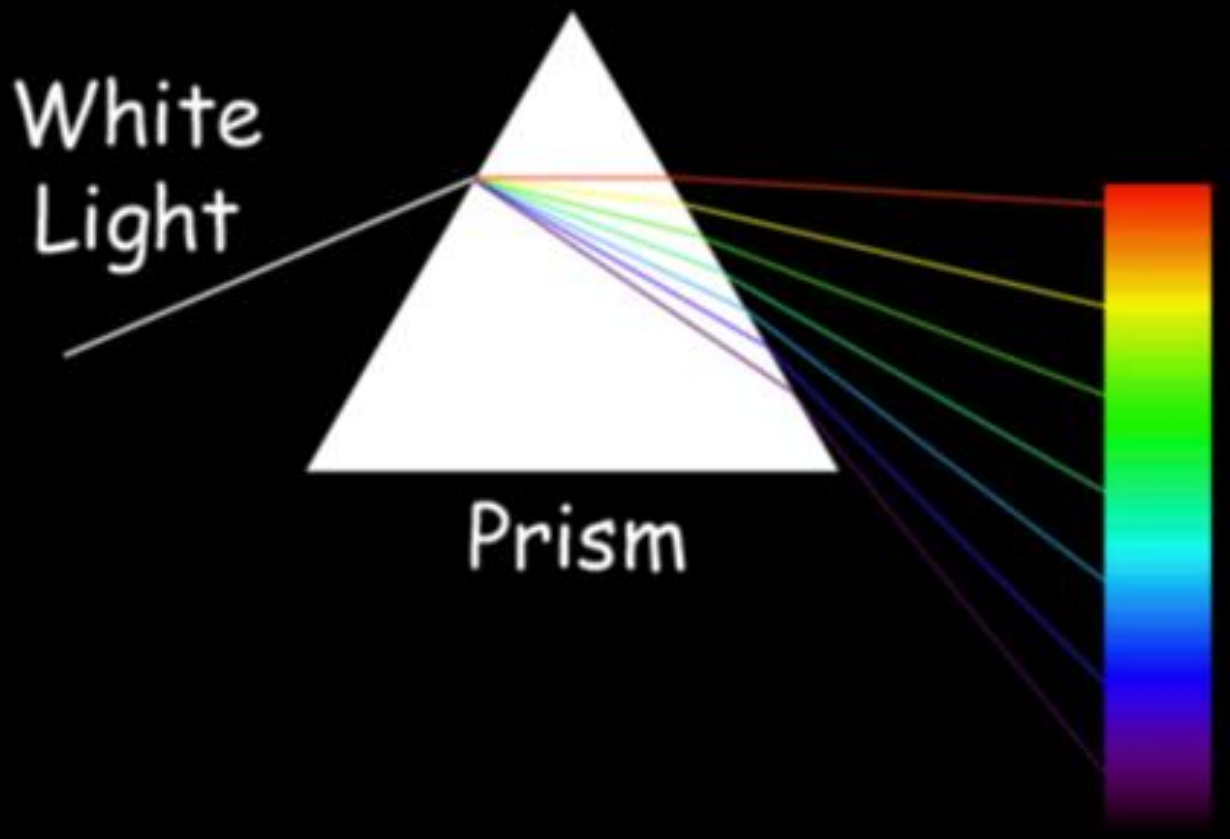

Pianeta
Stella


v
Stella

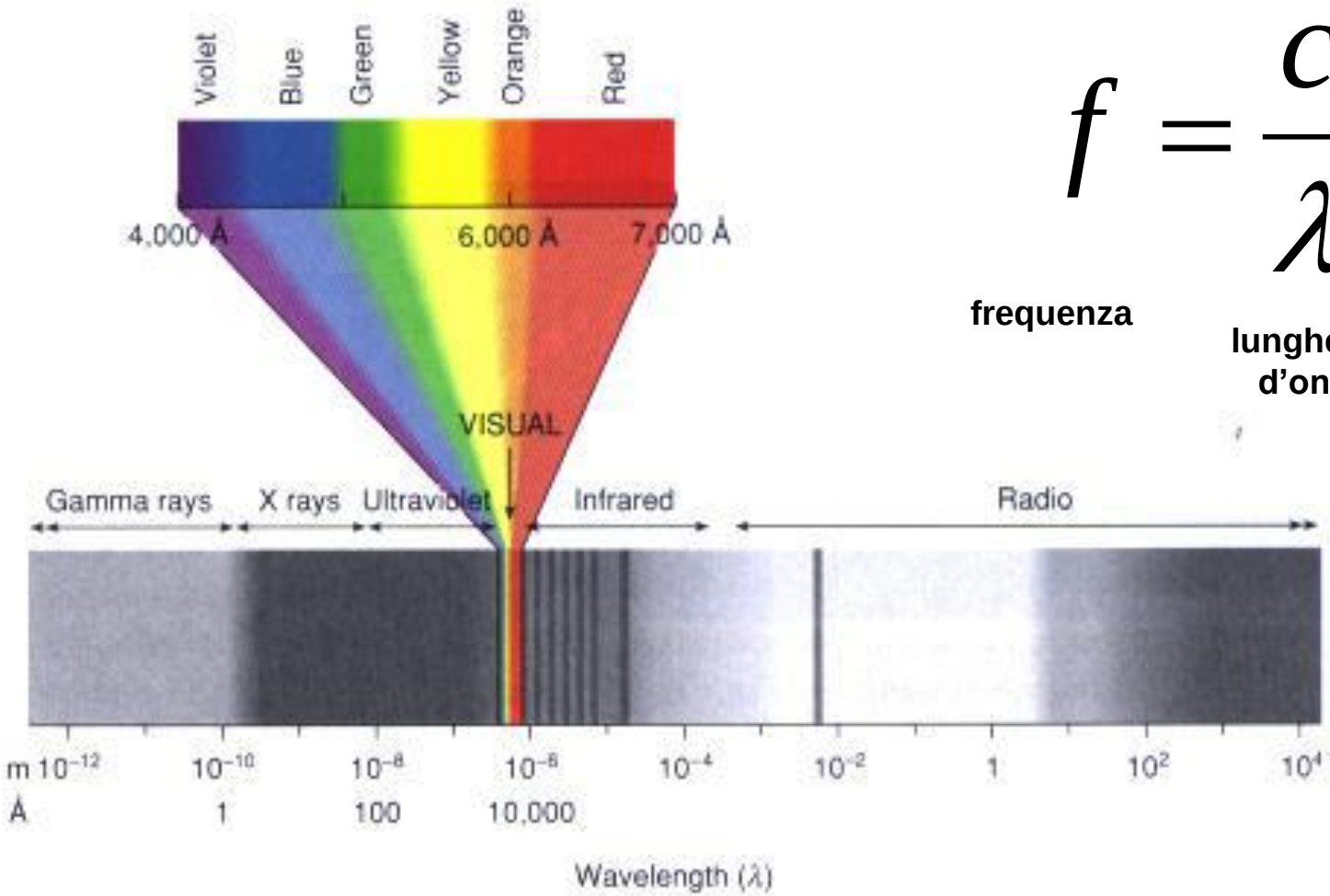
Ricerca di pianeti extrasolari con il metodo spettroscopico

Pianeta	Massa (M_S)	Velocità orbitale	Velocità del Sole
Giove	1×10^{-3}	13 km/s	13 m/s
Terra	3×10^{-6}	30 km/s	10 cm/s

Scomposizione spettrale della luce



La luce come forma di radiazione elettromagnetica



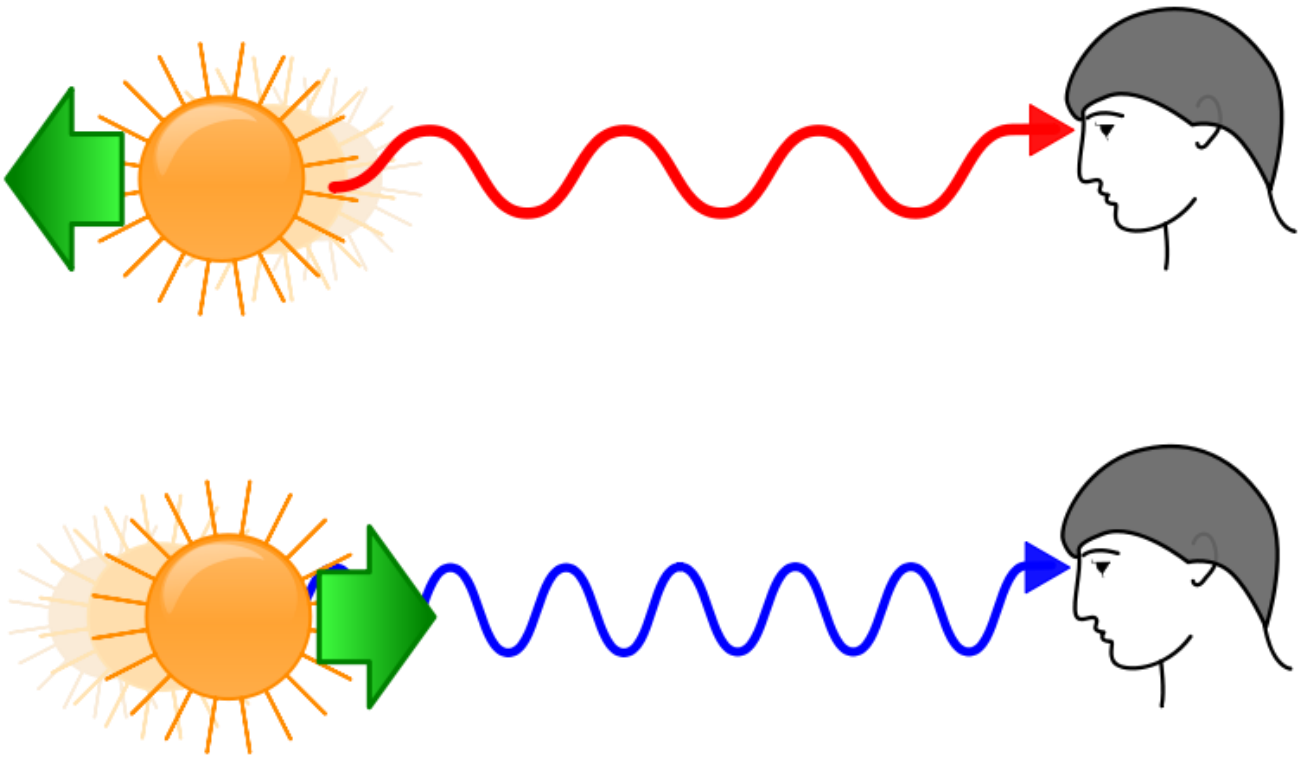
$$f = \frac{c}{\lambda}$$

frequenza

lunghezza d'onda

Effetto Doppler

$$\frac{\Delta f}{f} = \frac{\Delta v}{c}$$



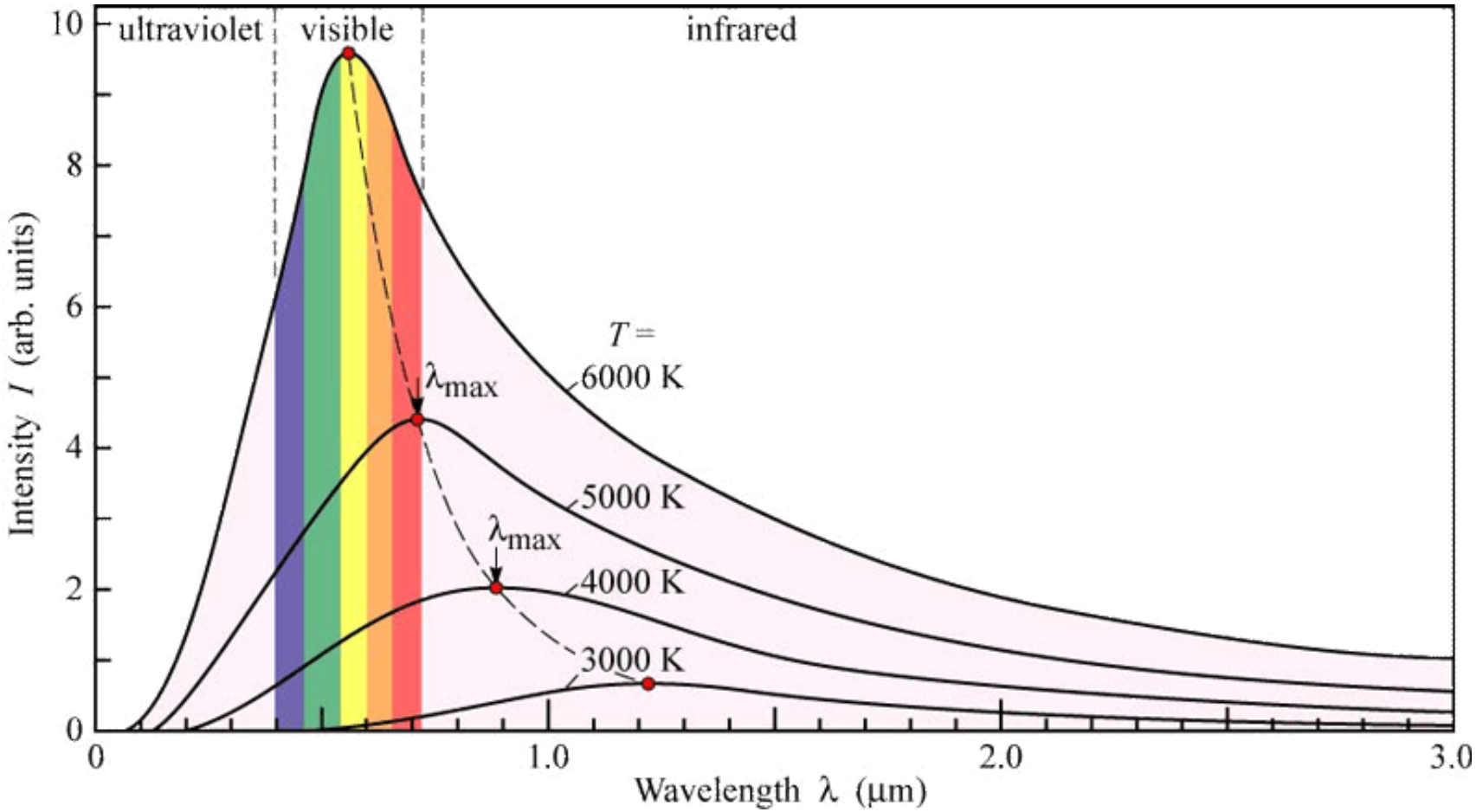
Generazione di onde elettromagnetiche

Moto accelerato di cariche elettriche → Radiazione elettromagnetica

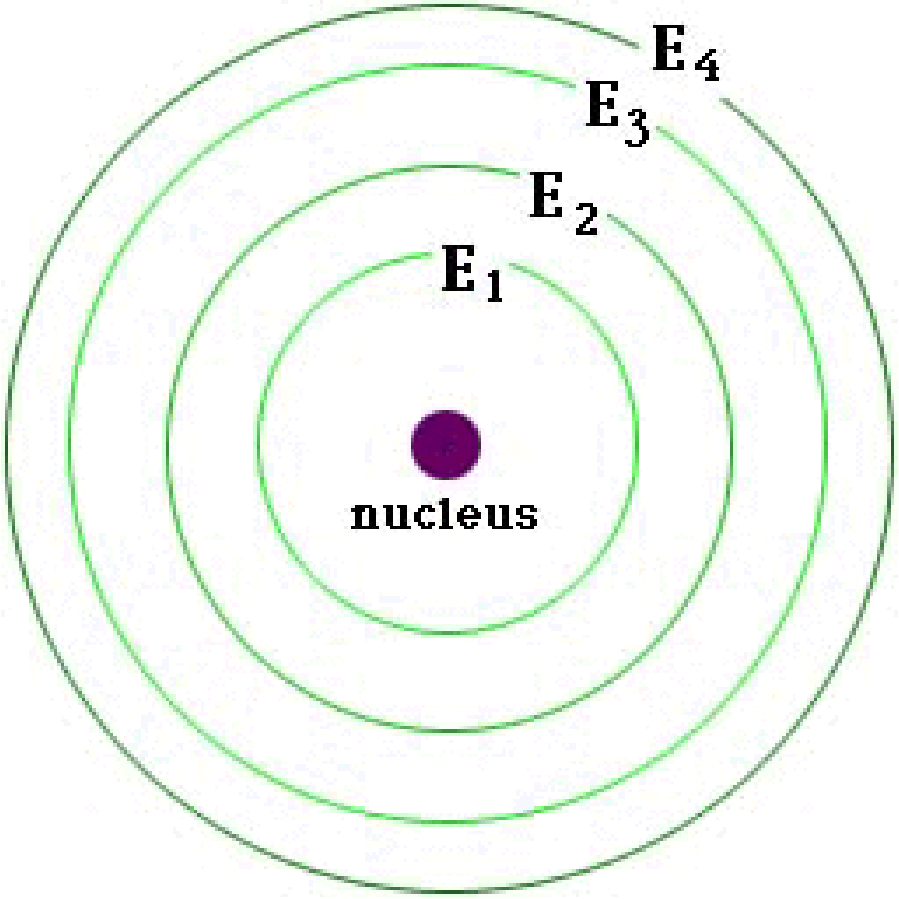
$$E = hf$$

costante di Planck

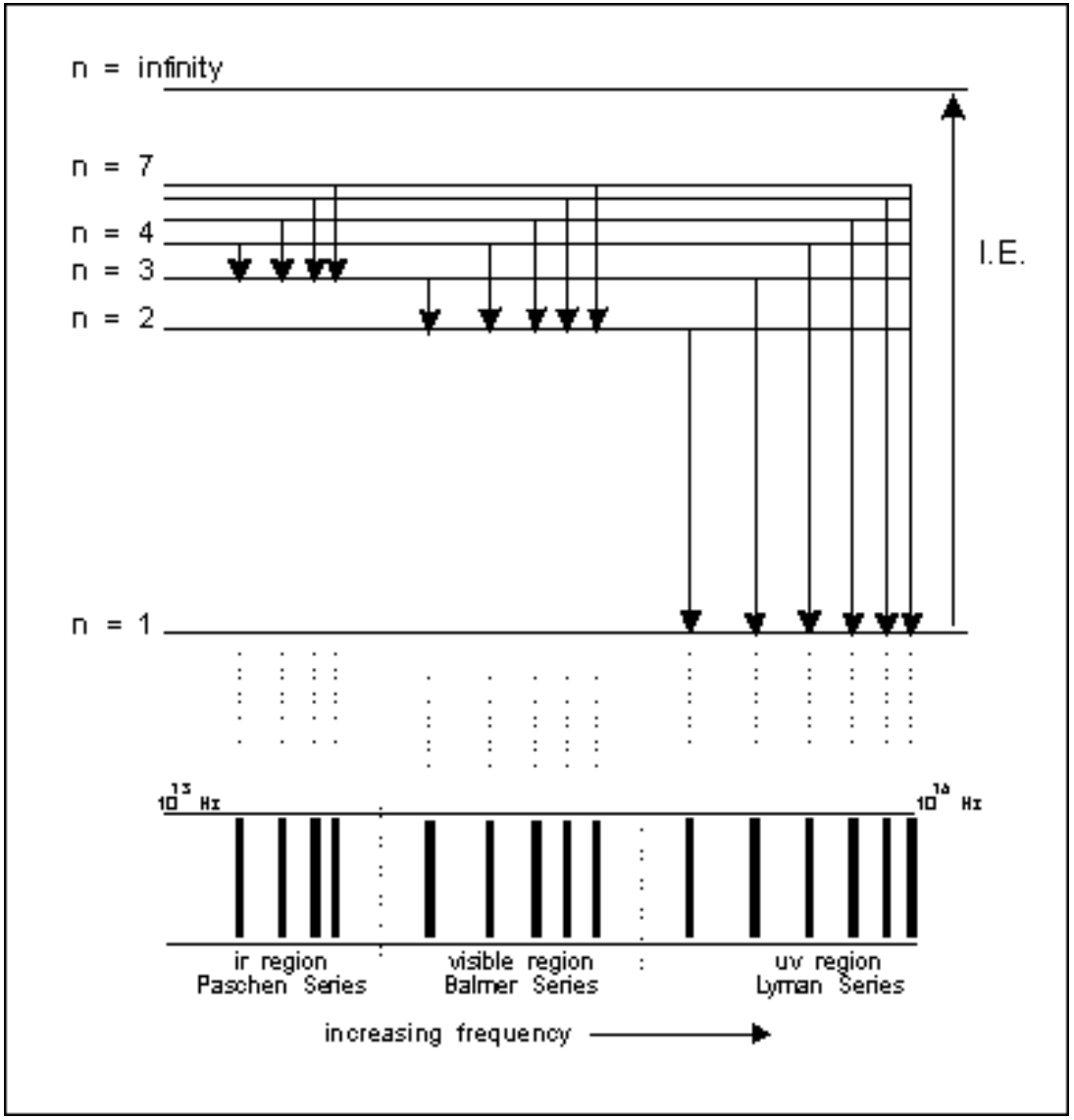
Radiazione termica (di corpo nero)



Radiazione generata da transizioni atomiche



Radiazione generata da transizioni atomiche



Righe spettrali di alcuni elementi chimici

Hydrogen

Magnesium

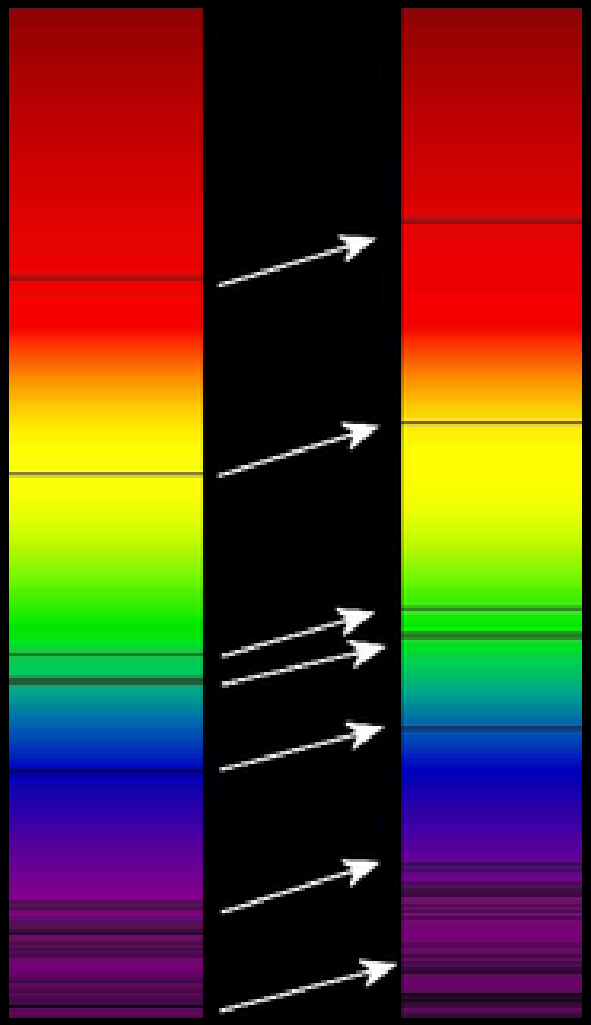
Iron

Calcium

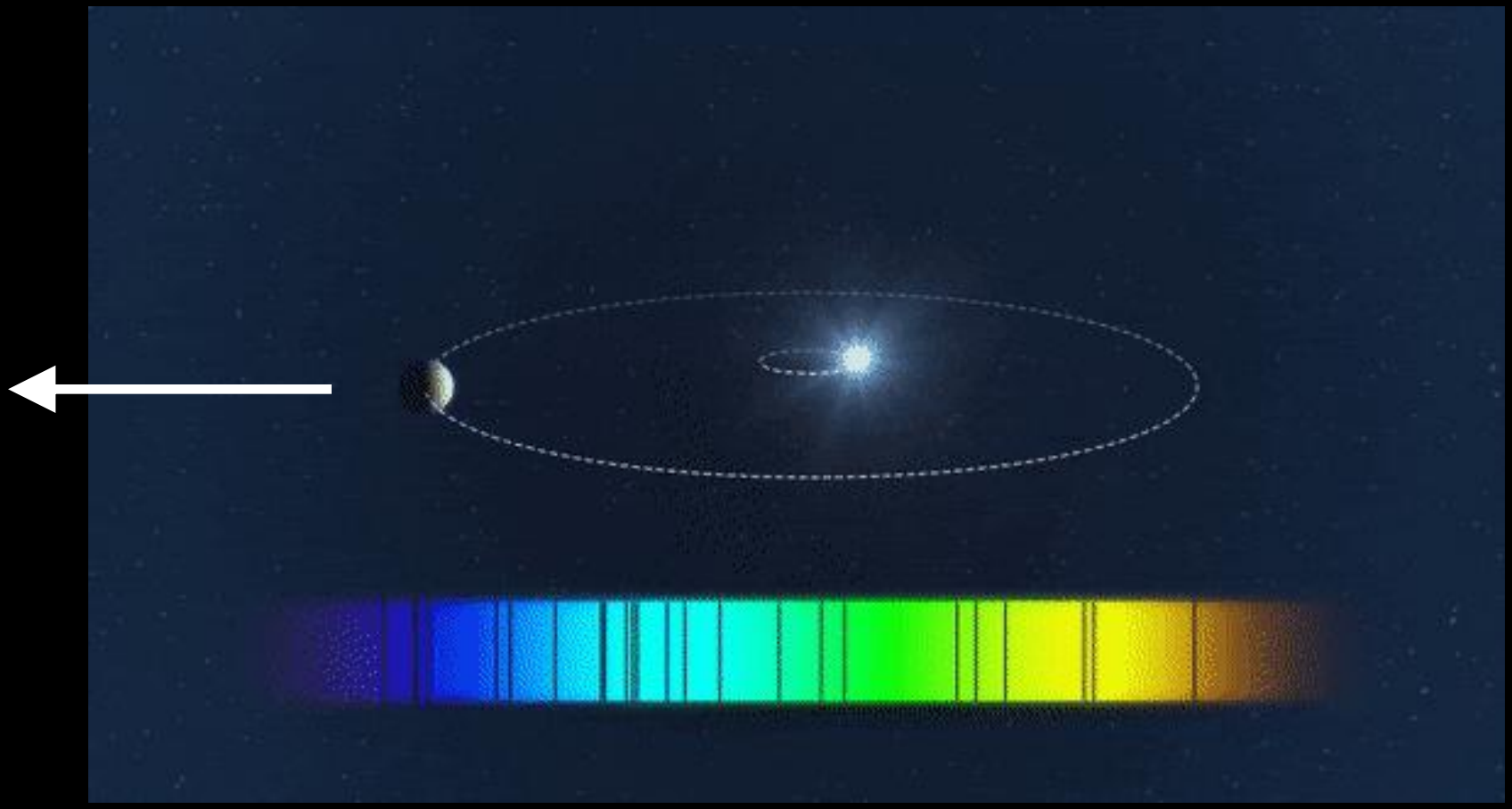
Spettro della luce solare

Effetto Doppler

(spostamento delle righe spettrali)



$$\frac{\Delta f}{f} = \frac{\Delta v}{c}$$



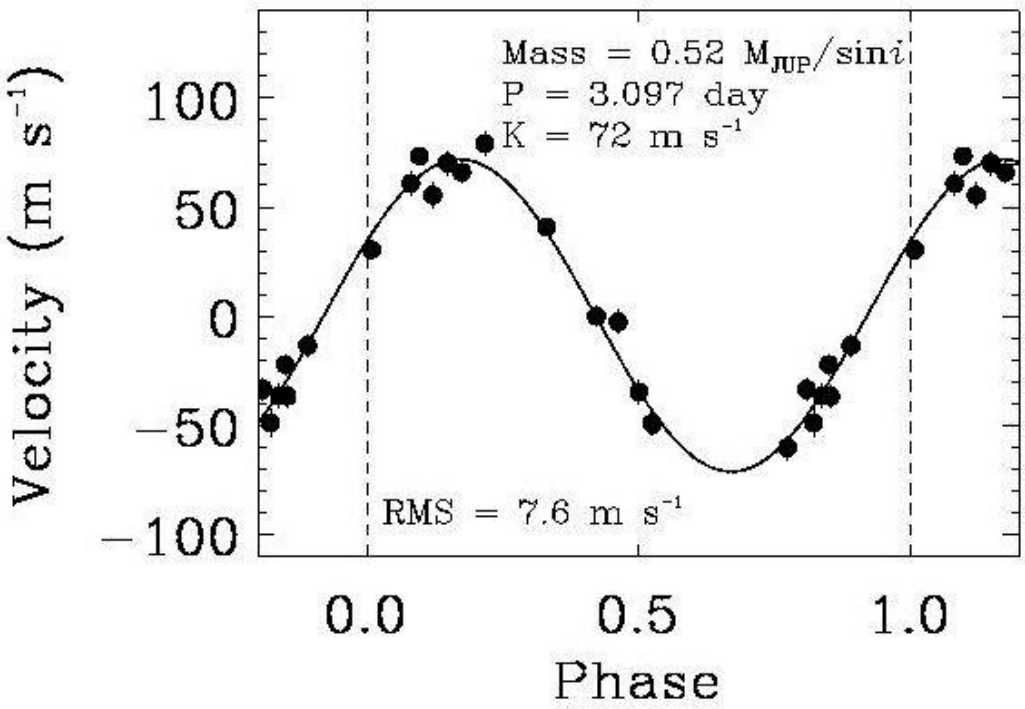
Che cosa si ricava dalla curva di velocità?

Periodo orbitale
Velocità orbitale

Massa della stella

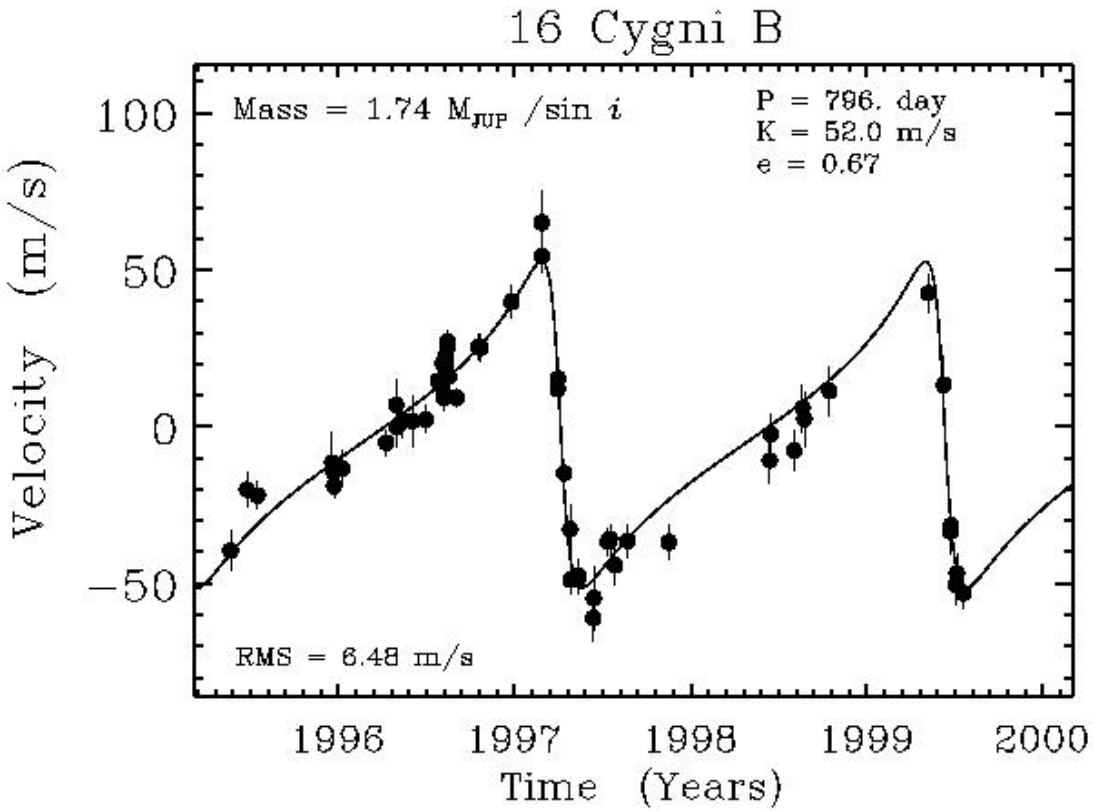
Semiasse maggiore
Massa del pianeta

Sistema HD187123



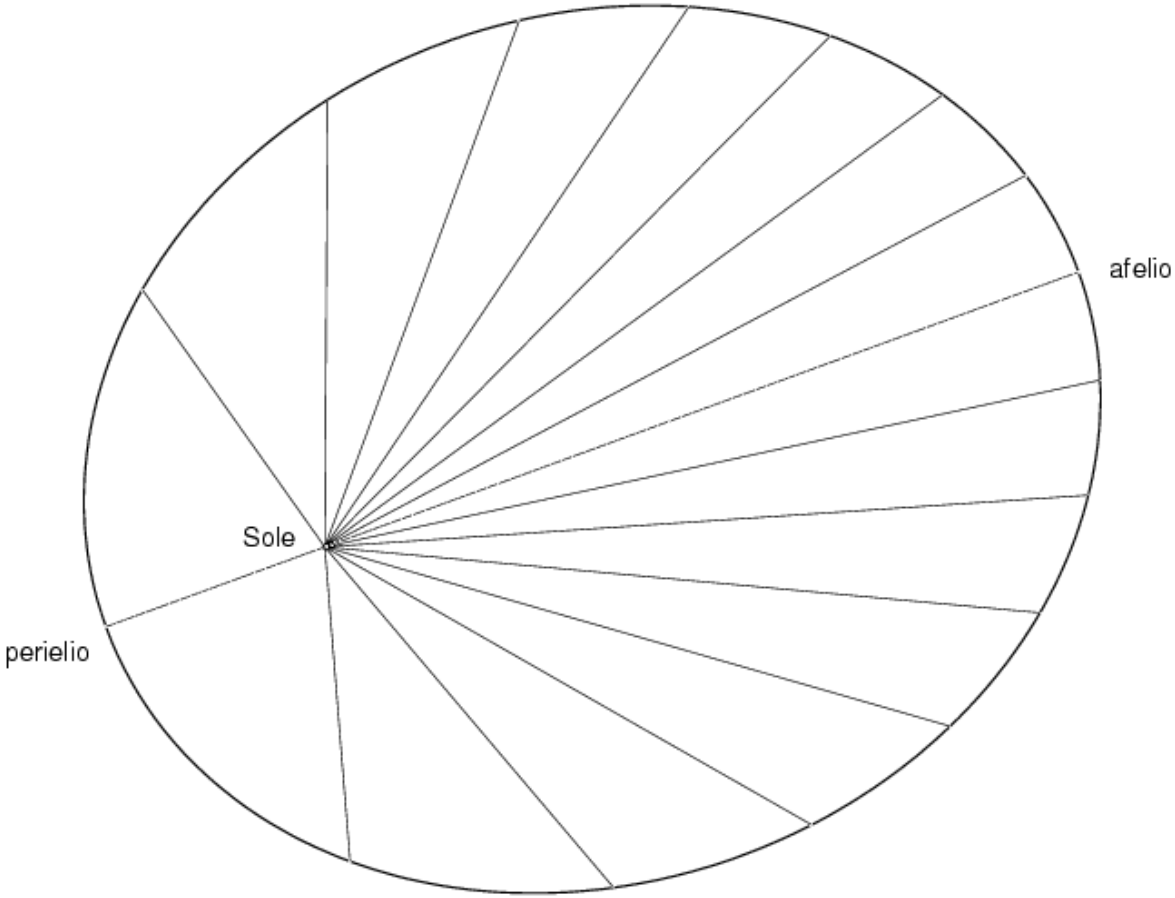
$M \sin I = 0.52\ M_{\text{Giove}}$ $a = 0.042$ AU periodo = 3.09 d $e = 0.03$

Sistema 16 *Cyg* B



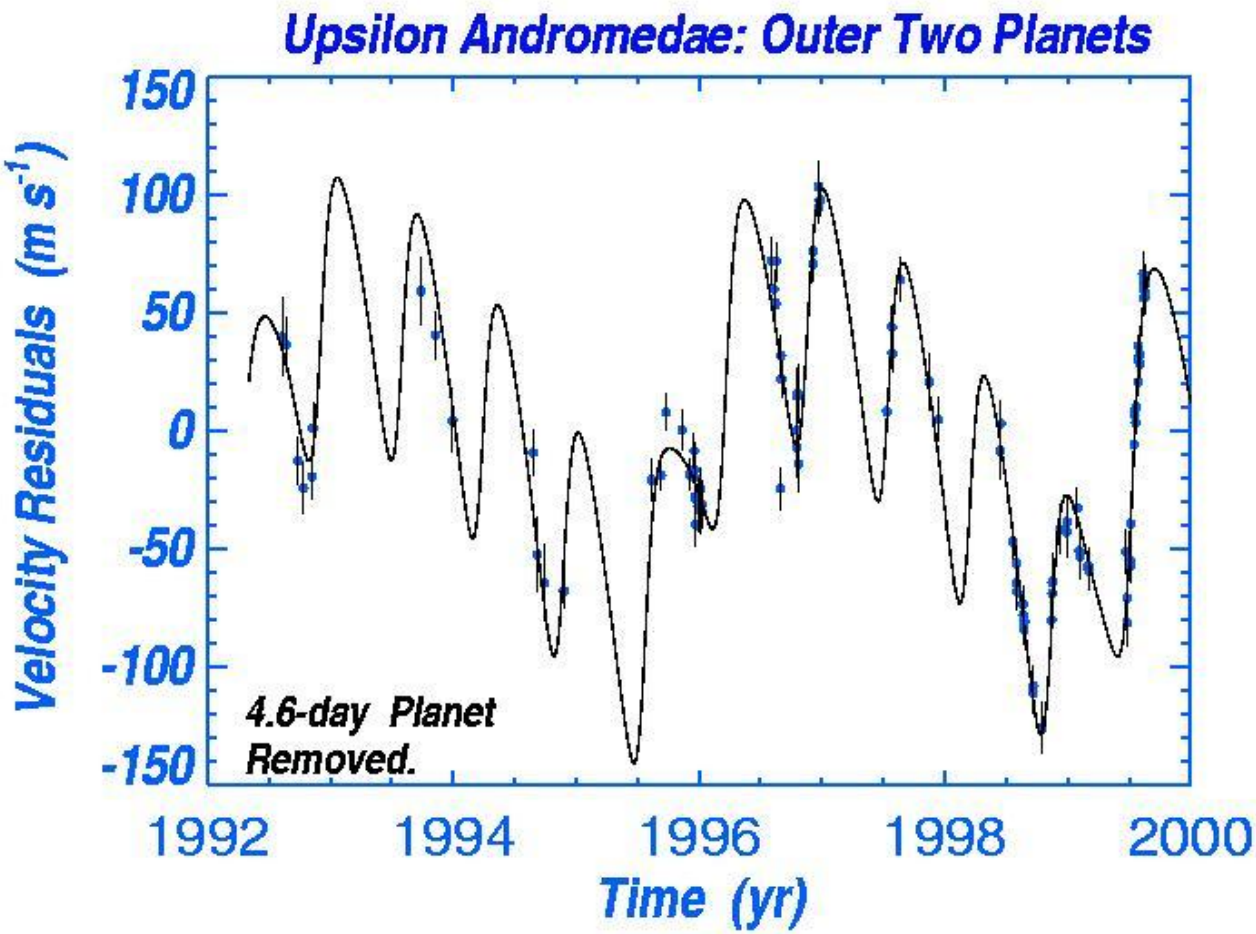
$M\ sinI = 1.5\ M_{\text{Giove}}$ $a = 1.72$ AU periodo = 804 d $e = 0.63$

Seconda legge di Keplero

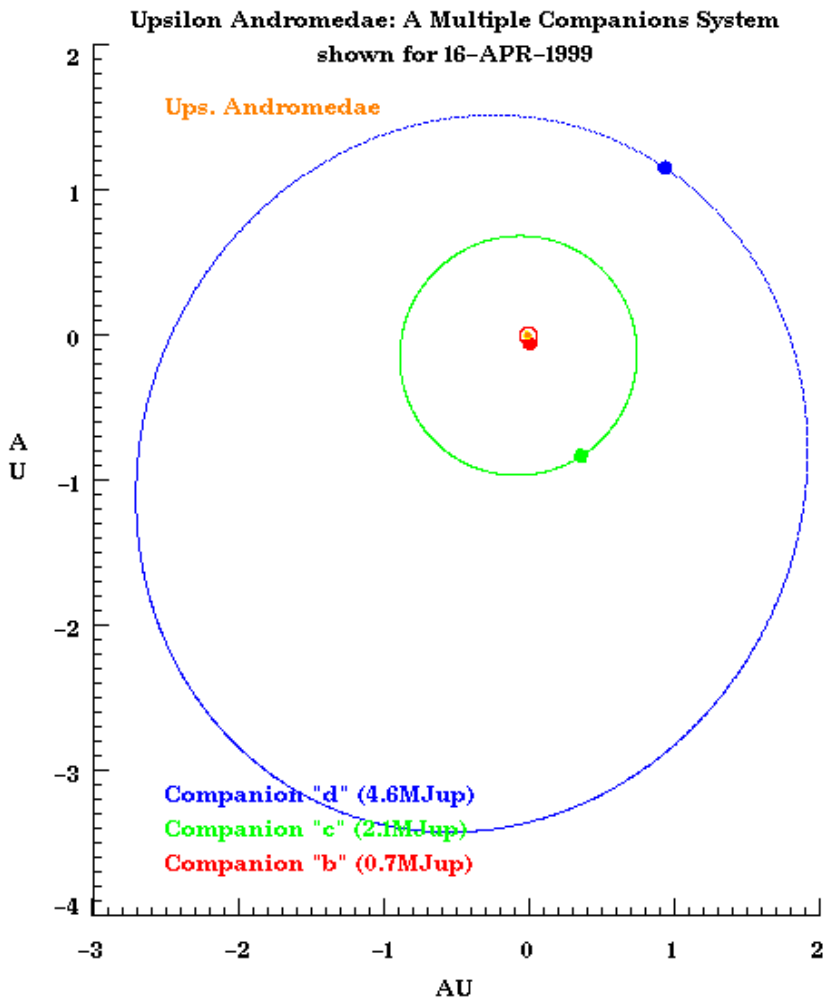


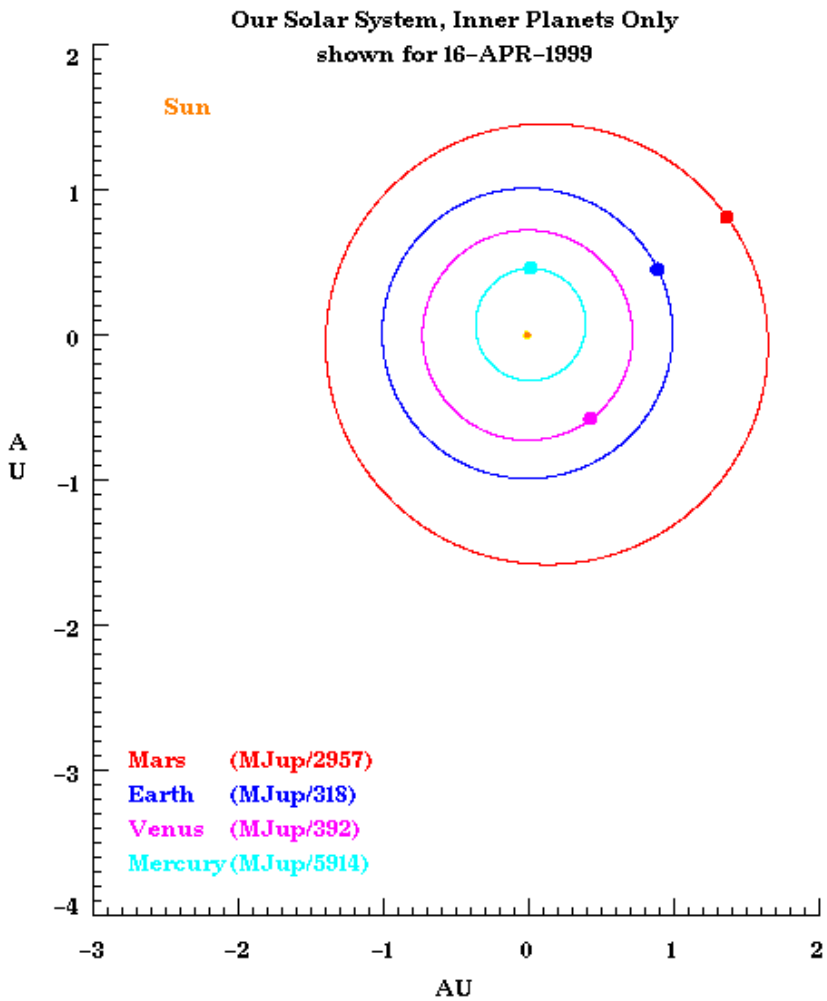
(velocità *areolare* costante → velocità *lineare* maggiore al periastro)

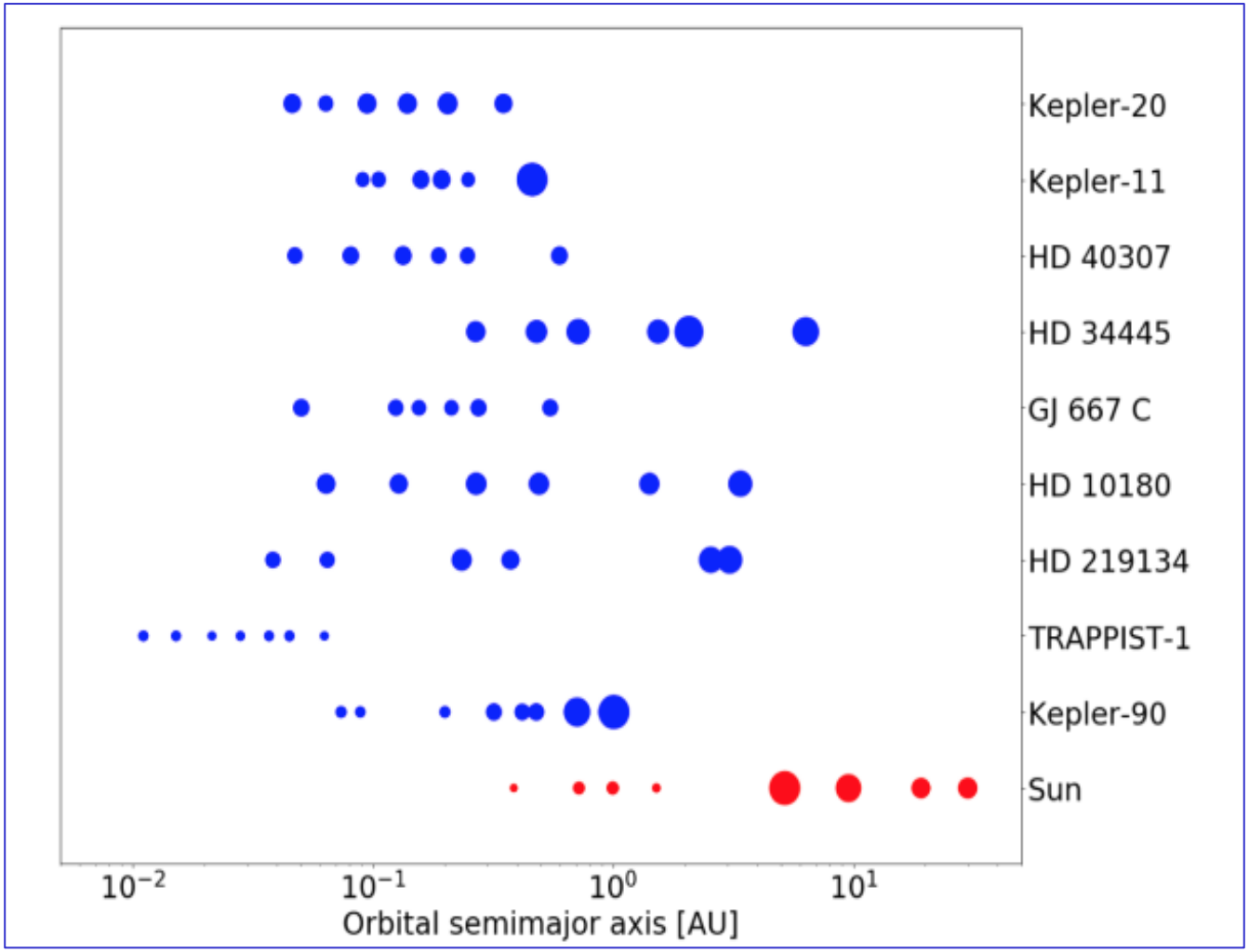
Sistema υ *Andromedae*



Sistema υ *Andromedae*






Kepler-20
Kepler-11
HD 40307
HD 34445
GJ 667 C
HD 10180
HD 219134
TRAPPIST-1
Kepler-90
Sun
10^{-2}
10^{-1}
10^{0}
10^{1}
Orbital semimajor axis [AU]

Cosa è possibile determinare con il metodo spettroscopico?

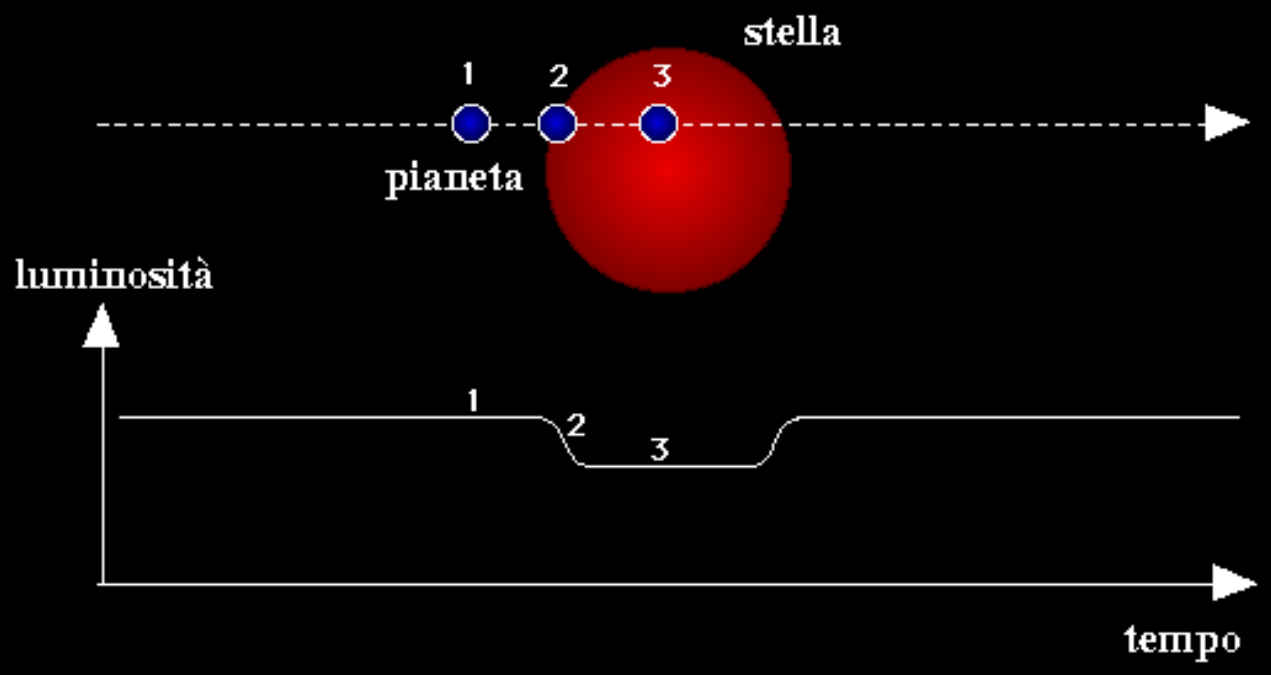
Grandezza	Determinabile?
Periodo orbitale	sì
Semiasse maggiore	sì
Diametro	no
Forma dell'orbita (eccentricità)	sì
Orientazione dell'orbita (inclinazione)	no
Massa	sì (*)

(*) valore *minimo* della massa (incertezza sull'inclinazione dell'orbita)

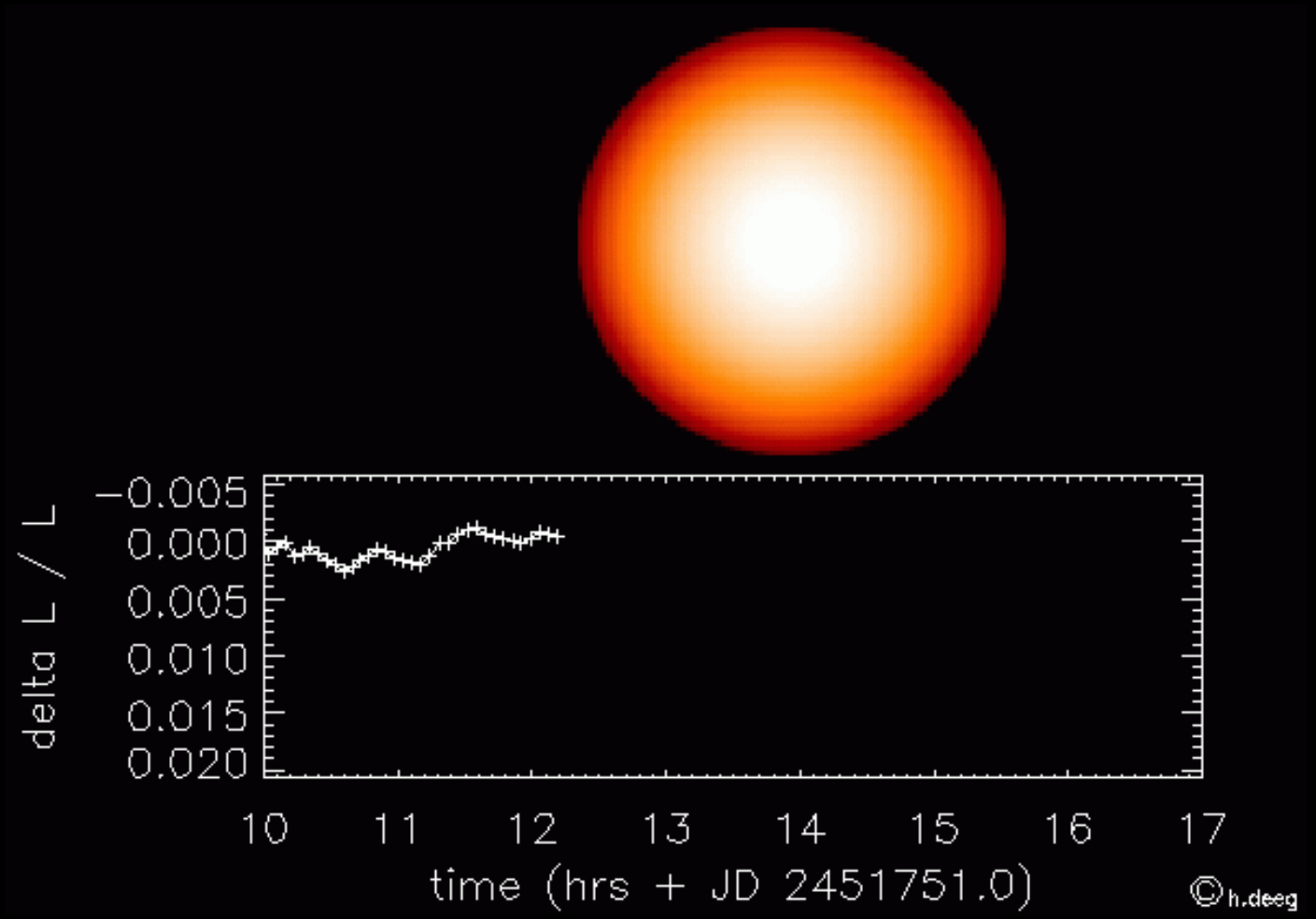
Metodi di detezione

Metodo fotometrico (occultazioni)

Fotometria (occultazioni)



Sistema HD209458



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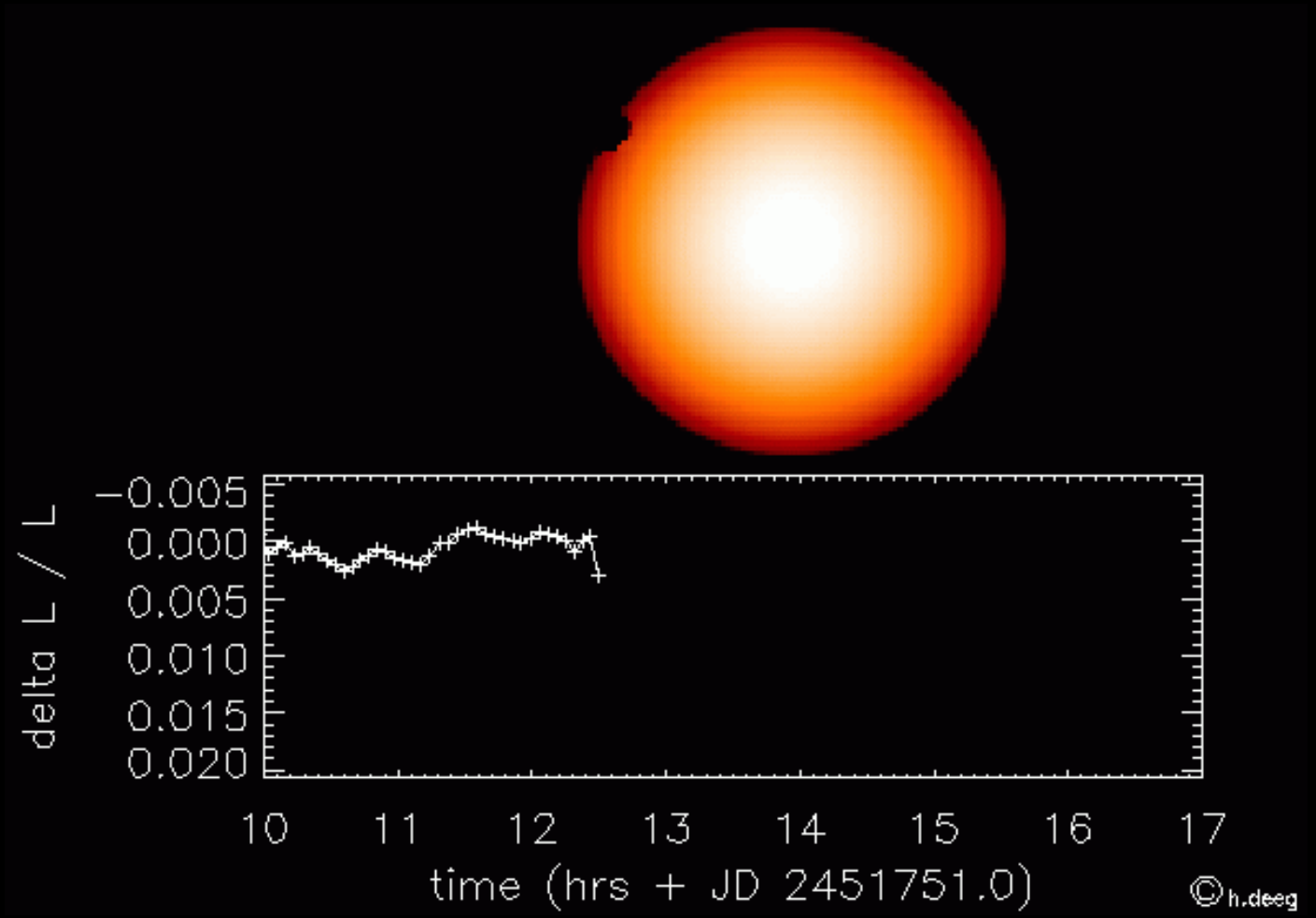

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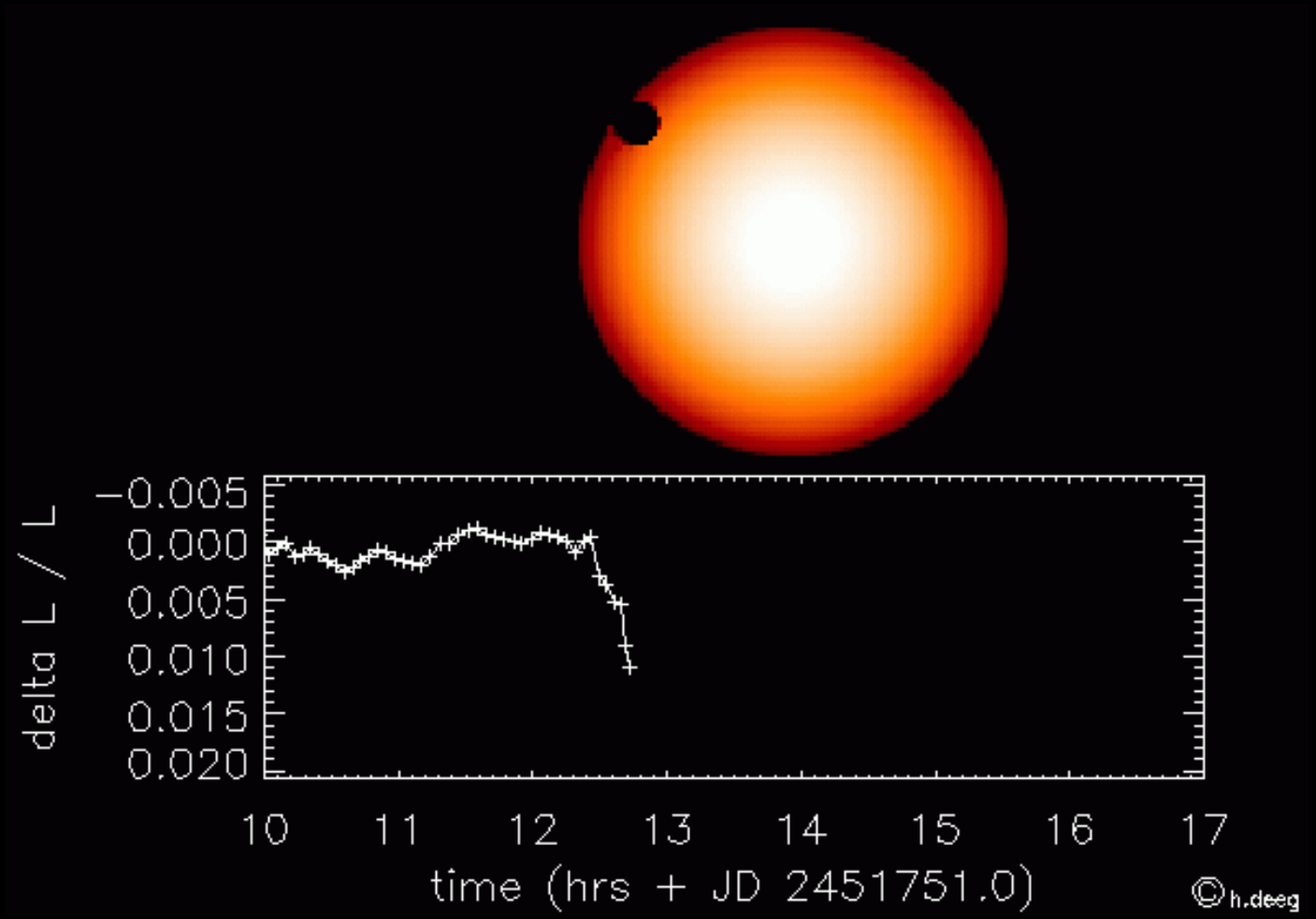
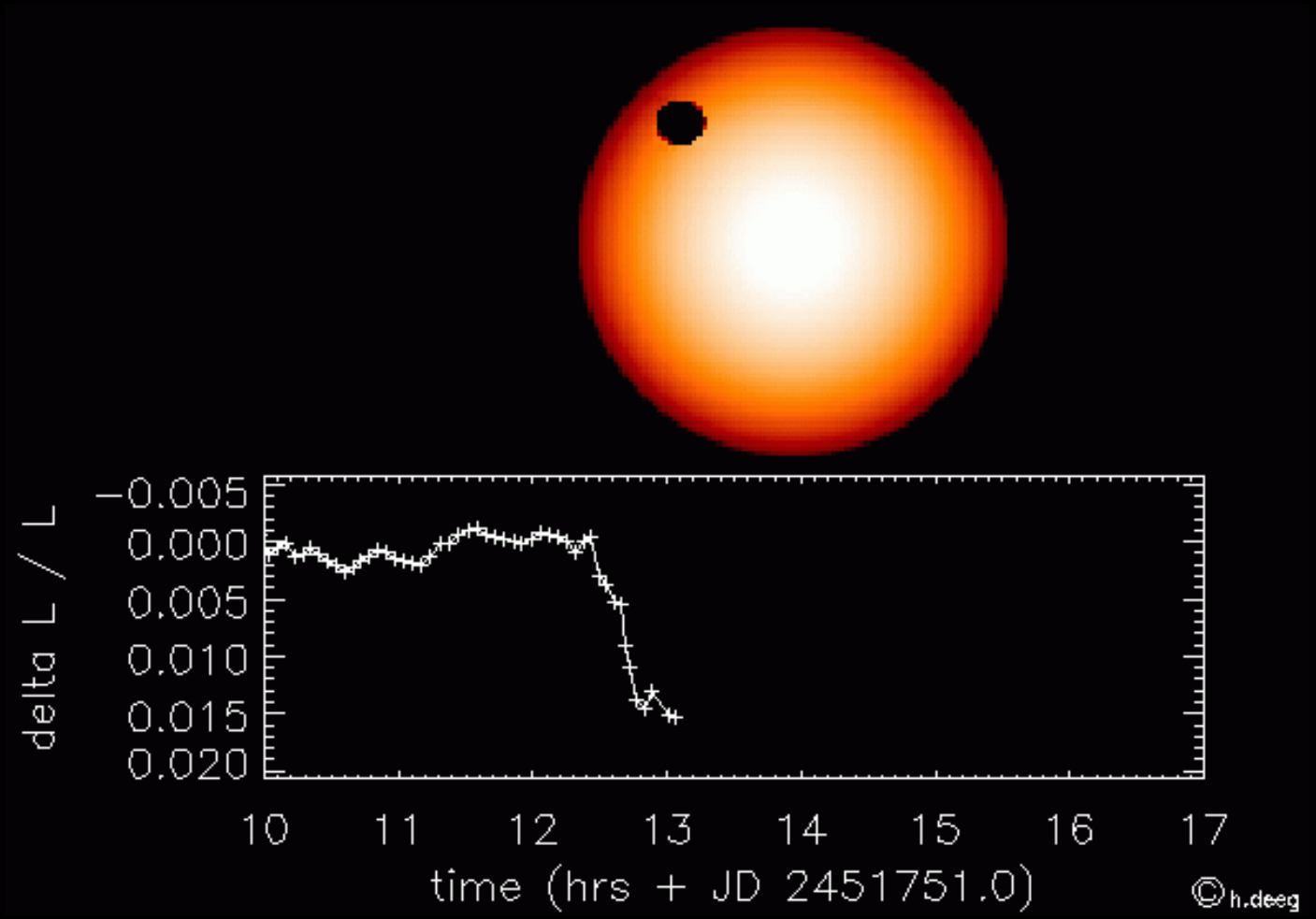


Sistema HD209458



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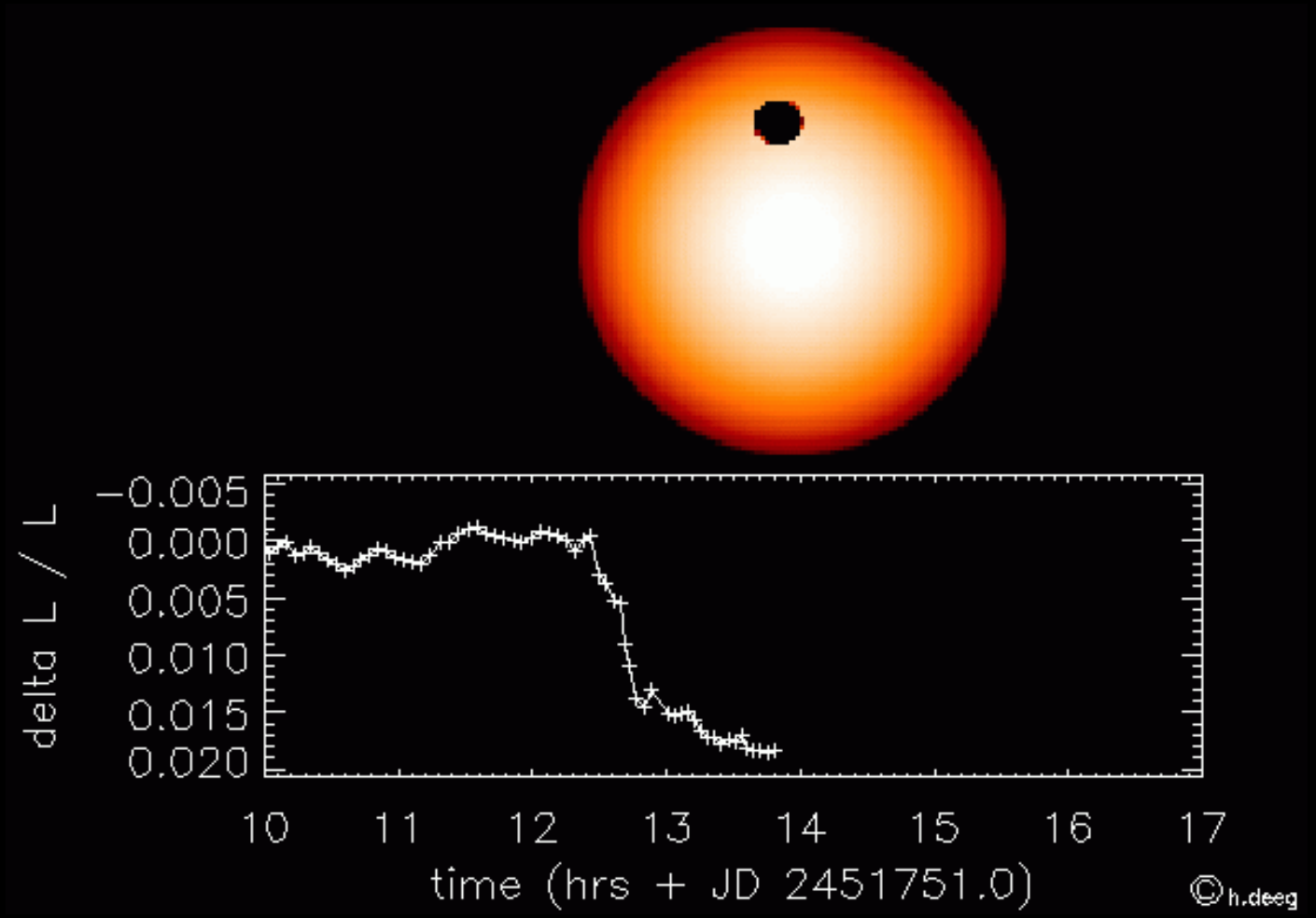

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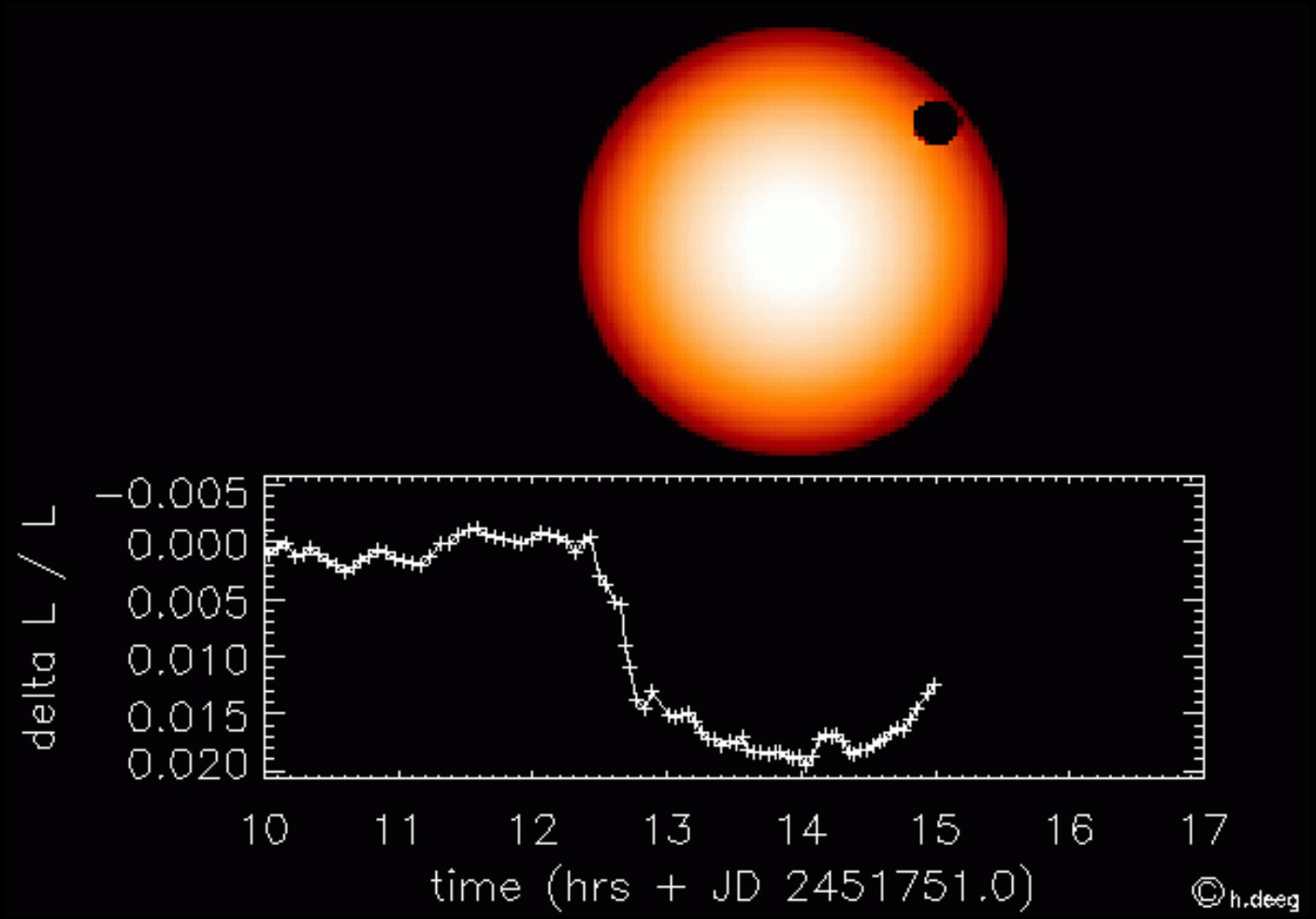

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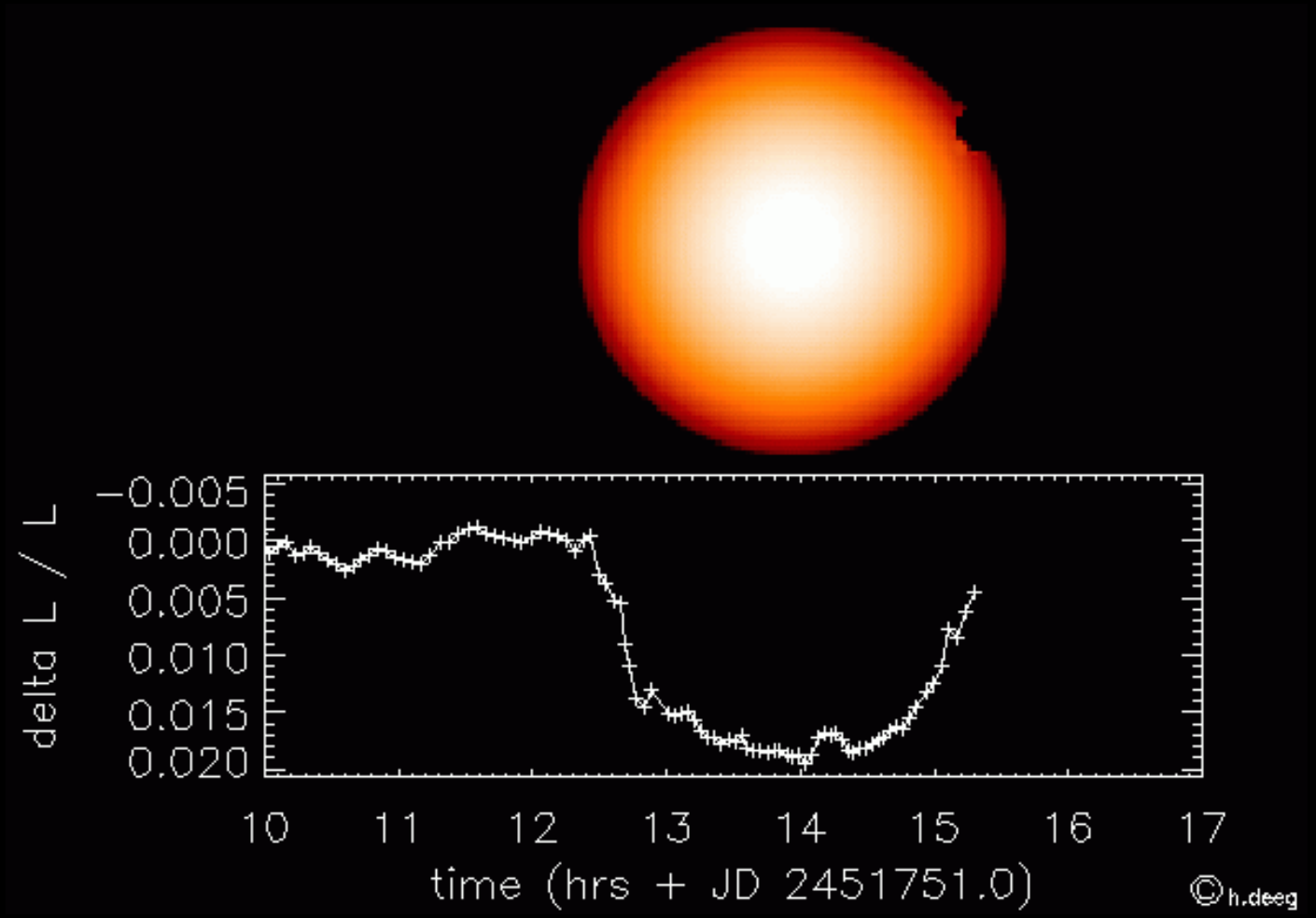

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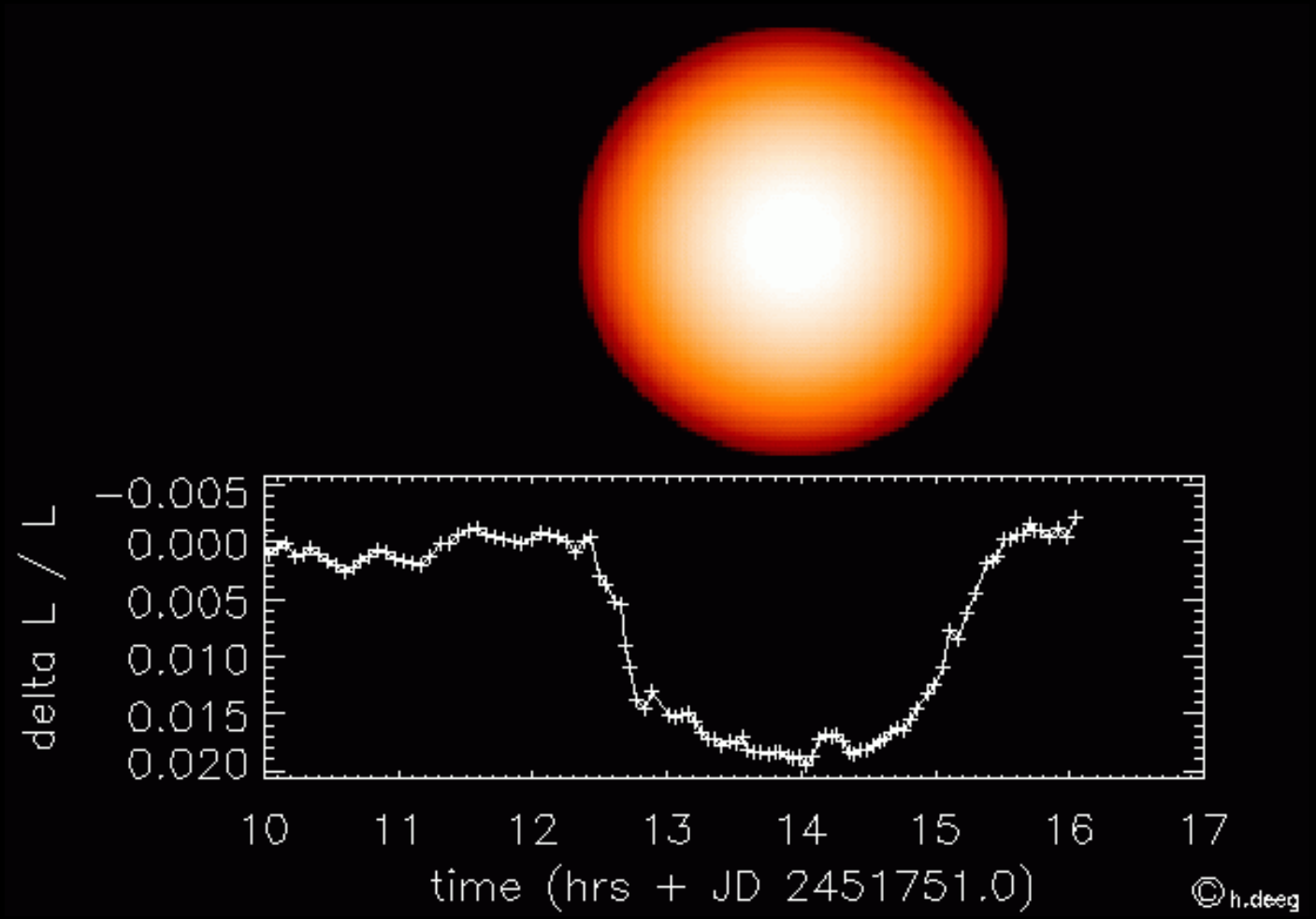


Che cosa si ricava dalla curva di luminosità?

Periodo orbitale
Durata dell'eclissi
Durata della fase di contatto

Massa della stella

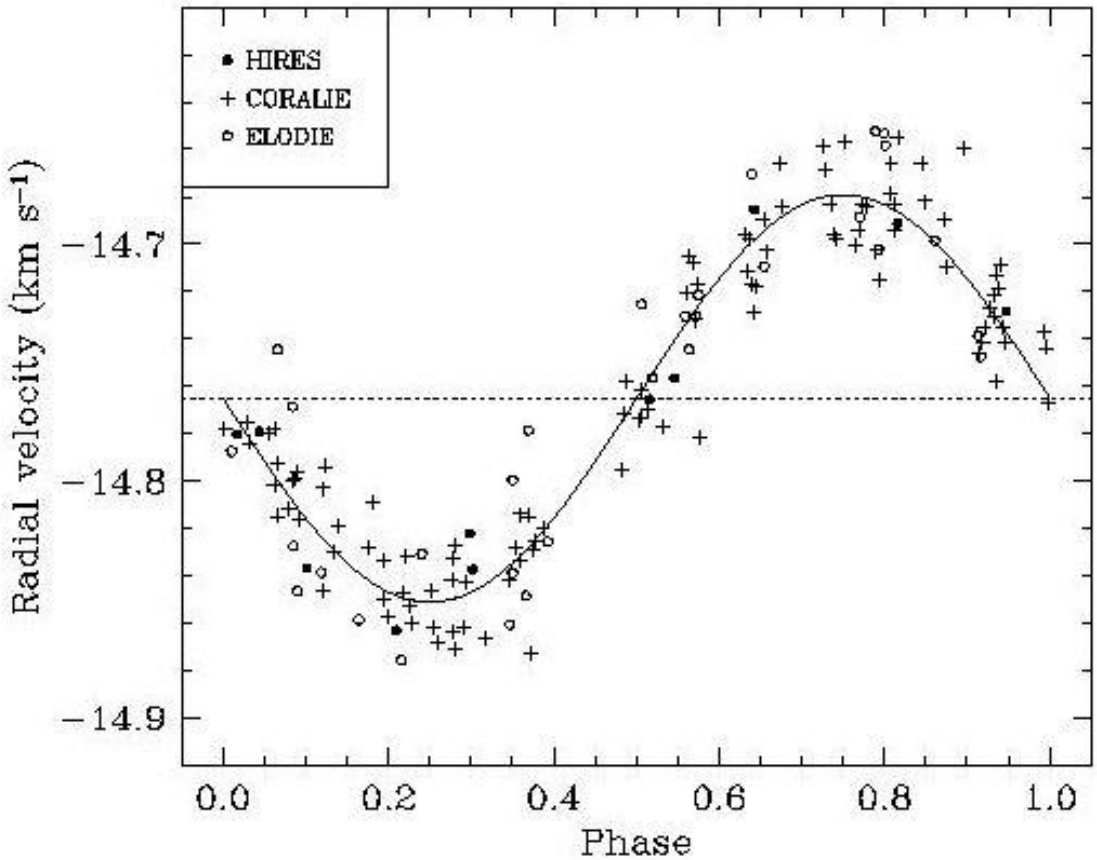
Semiasse maggiore
Diametro del pianeta

Cosa è possibile determinare con il metodo fotometrico?

Grandezza	Determinabile?	
	Spettroscopia	Fotometria
Periodo orbitale	sì	sì
Semiasse maggiore	sì	sì
Diametro	no	sì
Forma dell'orbita (eccentricità)	sì	no
Orientazione dell'orbita (inclinazione)	no	sì
Massa	sì (*)	no

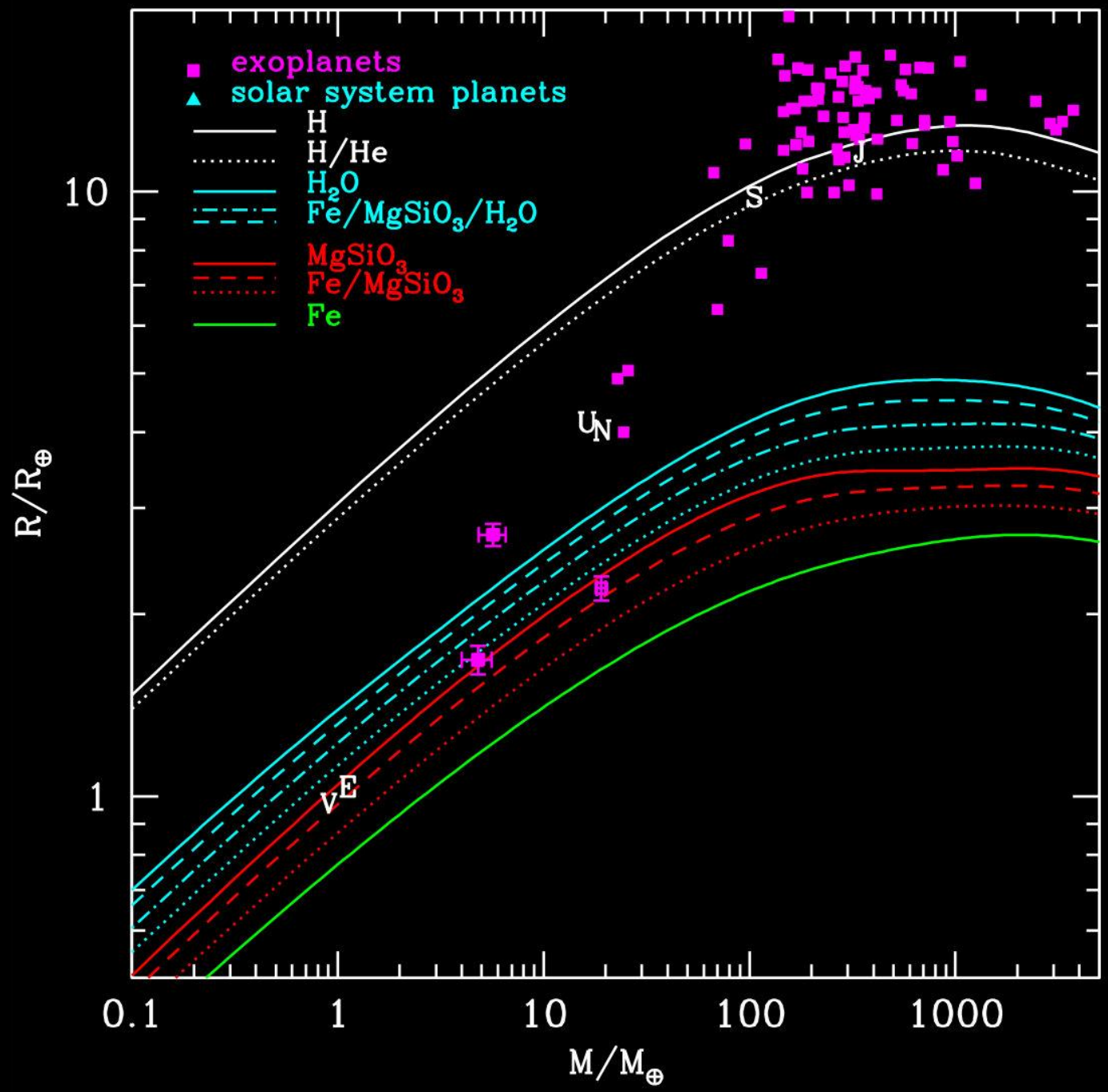
(*) valore *minimo* della massa, ma l'incertezza sull'inclinazione dell'orbita è rimossa se il pianeta occulta la stella

Sistema HD209458

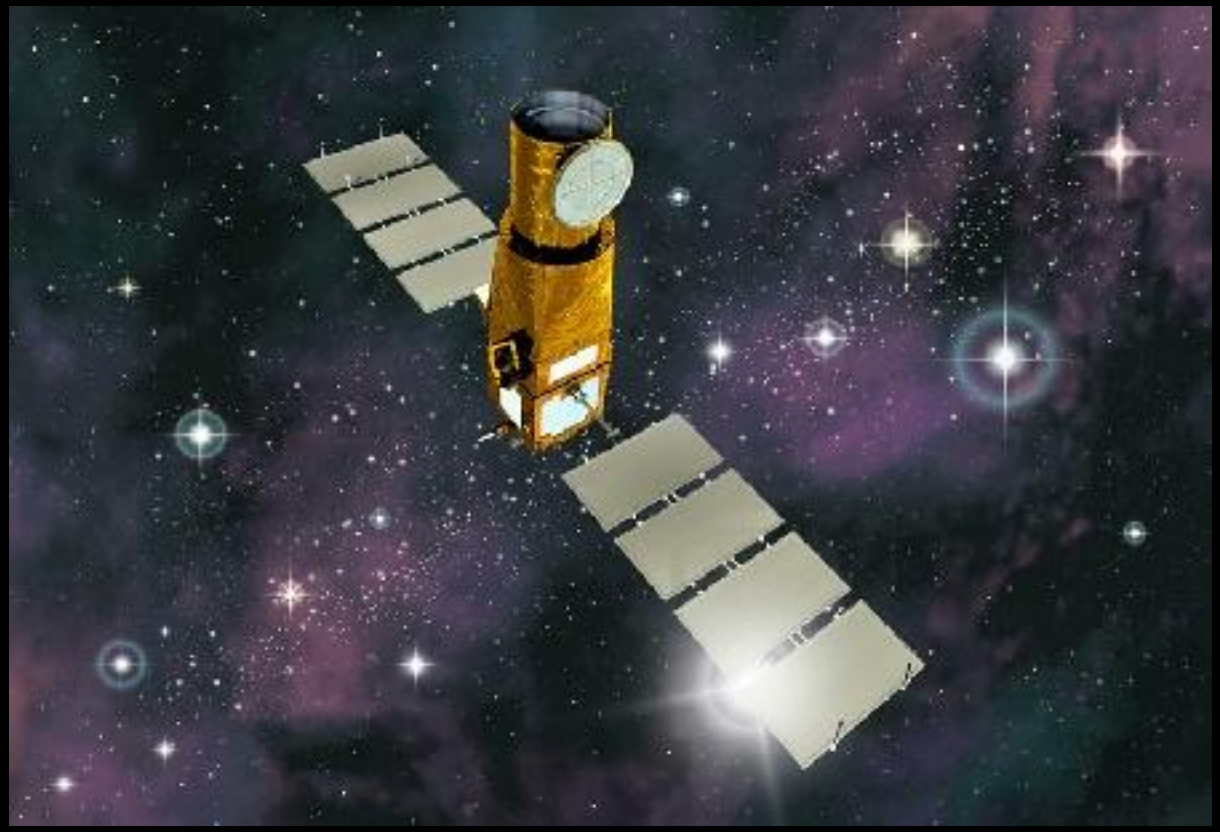


$M = 0.71\ M_{\text{Giove}}$ $a = 0.045$ AU periodo = 3.5 d $R = 1.38\ R_{\text{Giove}}$

densità = 1/3 dell'acqua

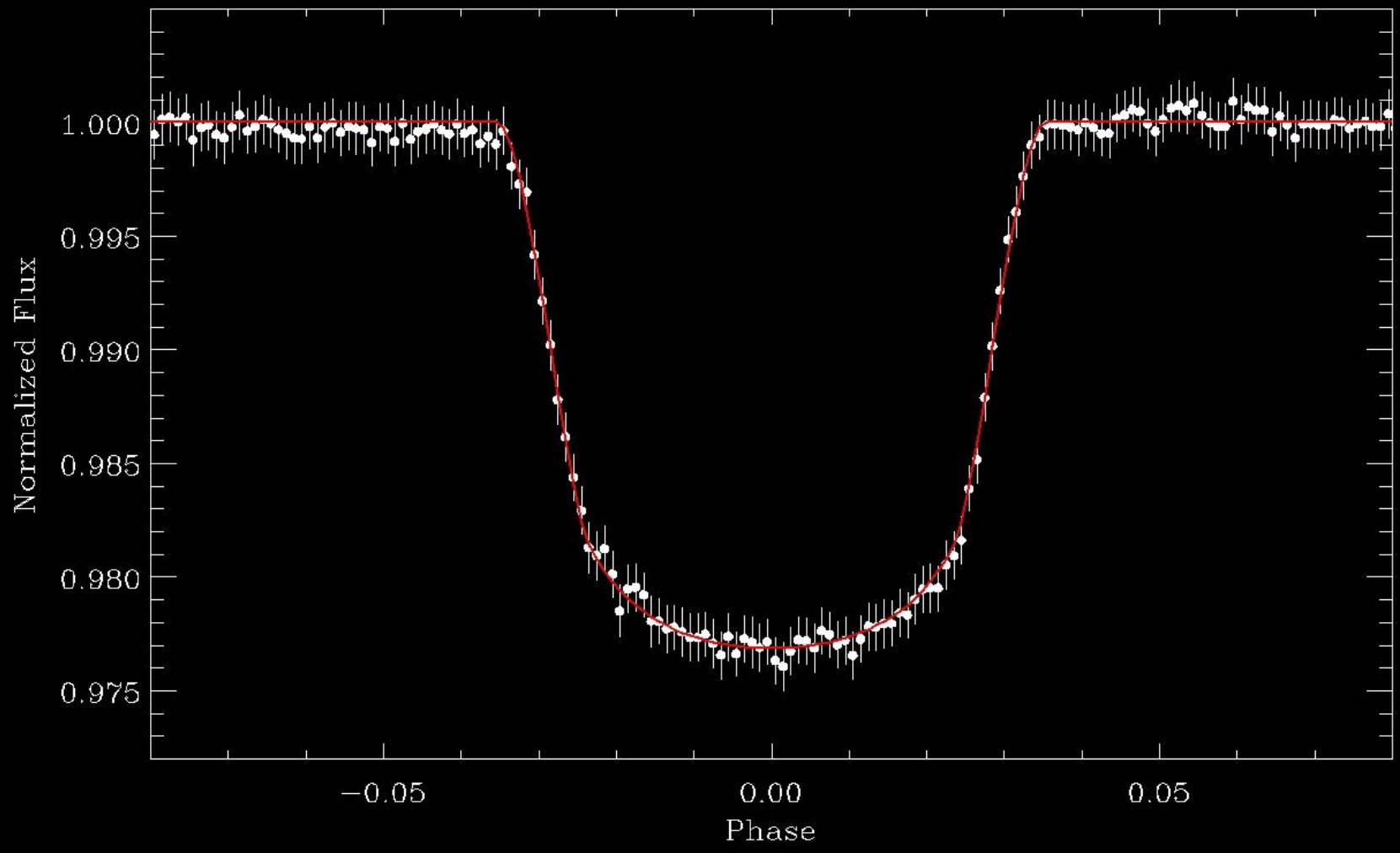

exoplanets
solar system planets
H
H/He
H_2O
$Fe/MgSiO_3/H_2O$
$MgSiO_3$
$Fe/MgSiO_3$
Fe
J
S
U
N
V
E
10
1
$R/R_\oplus$
0.1
1
10
100
1000
$M/M_\oplus$

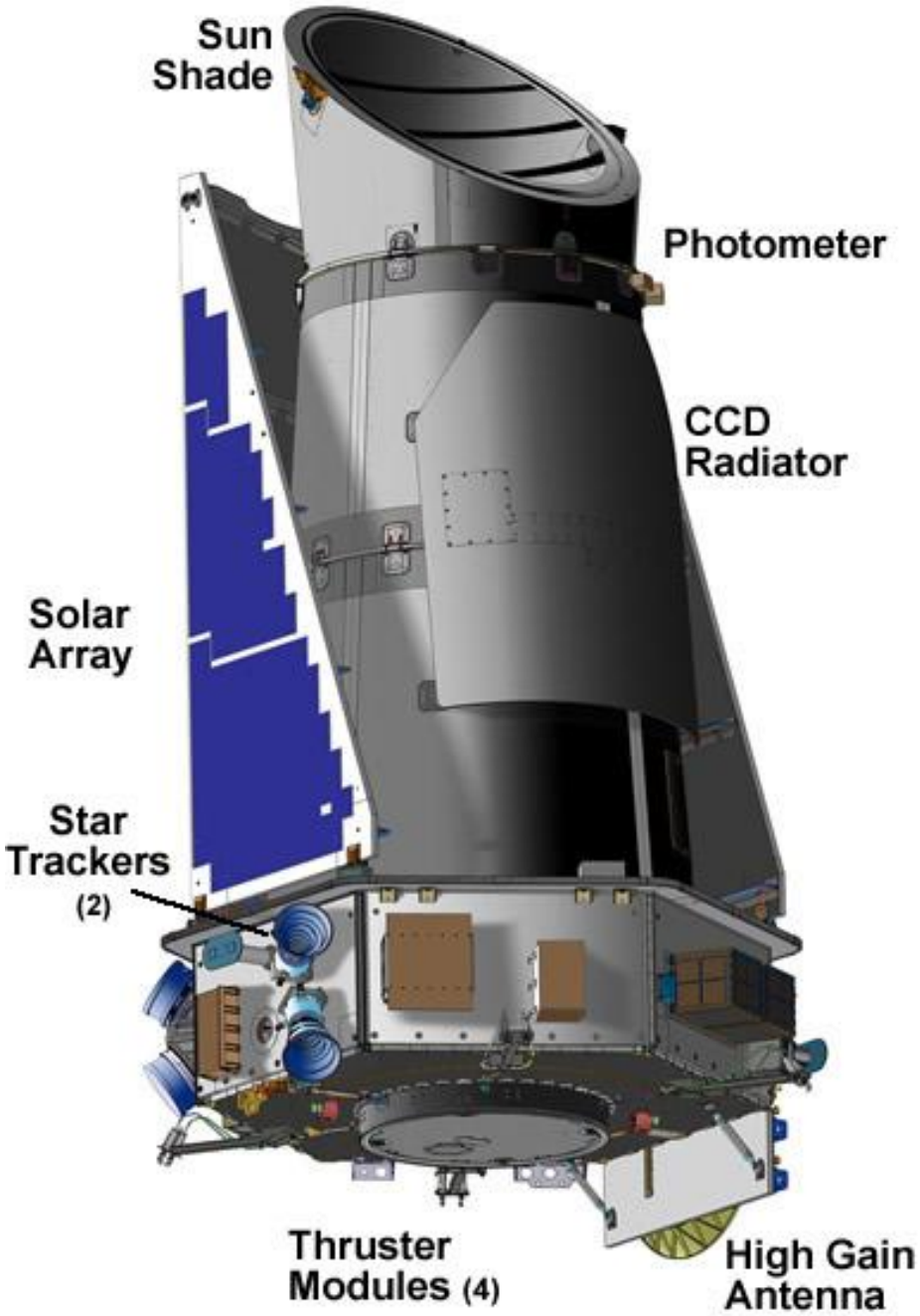
COROT (**CO**nvection **RO**tation and planetary **T**ransits)



(2007-2012)

COROT (**CO**nvection **RO**tation and planetary **T**ransits)

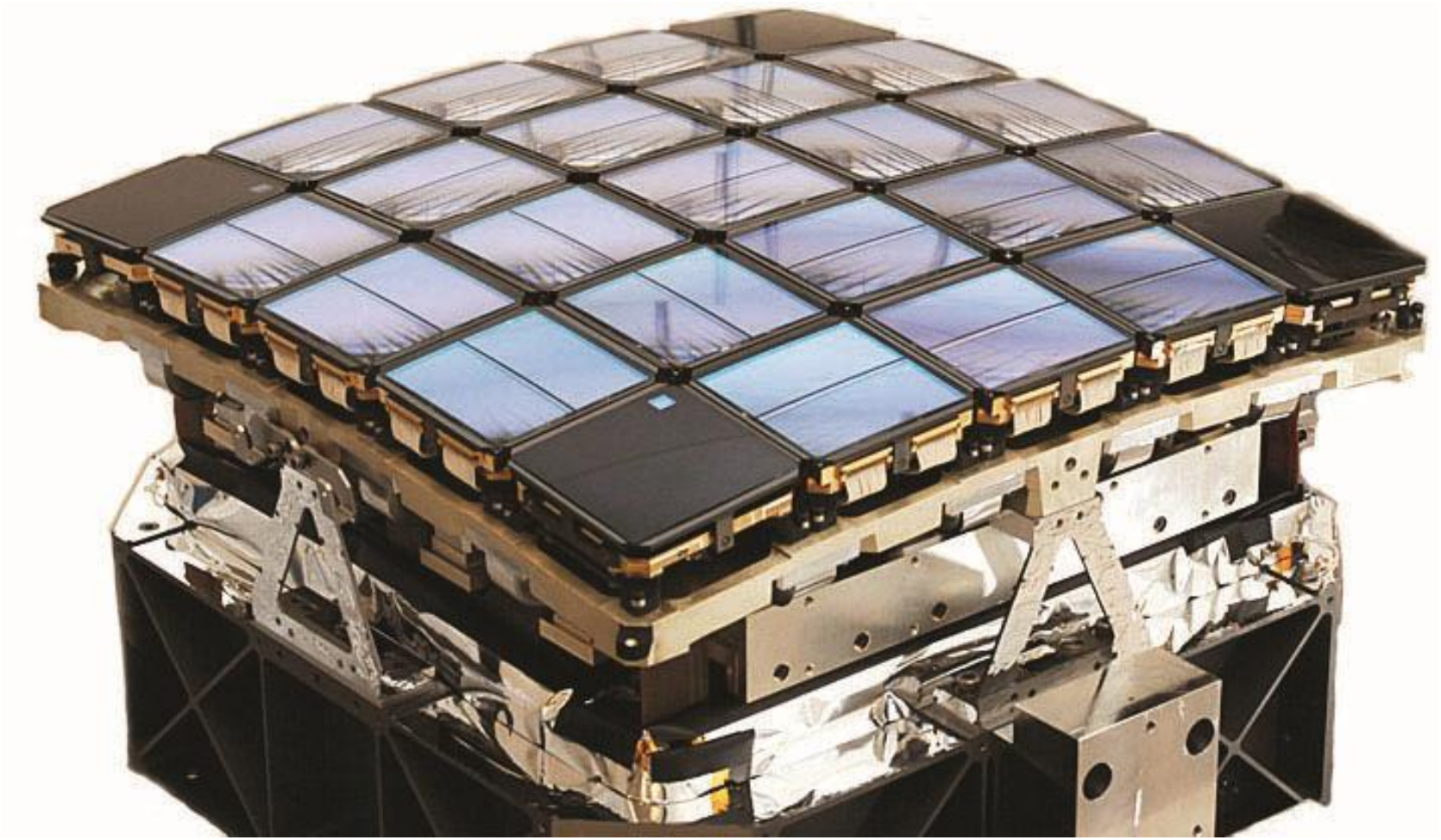




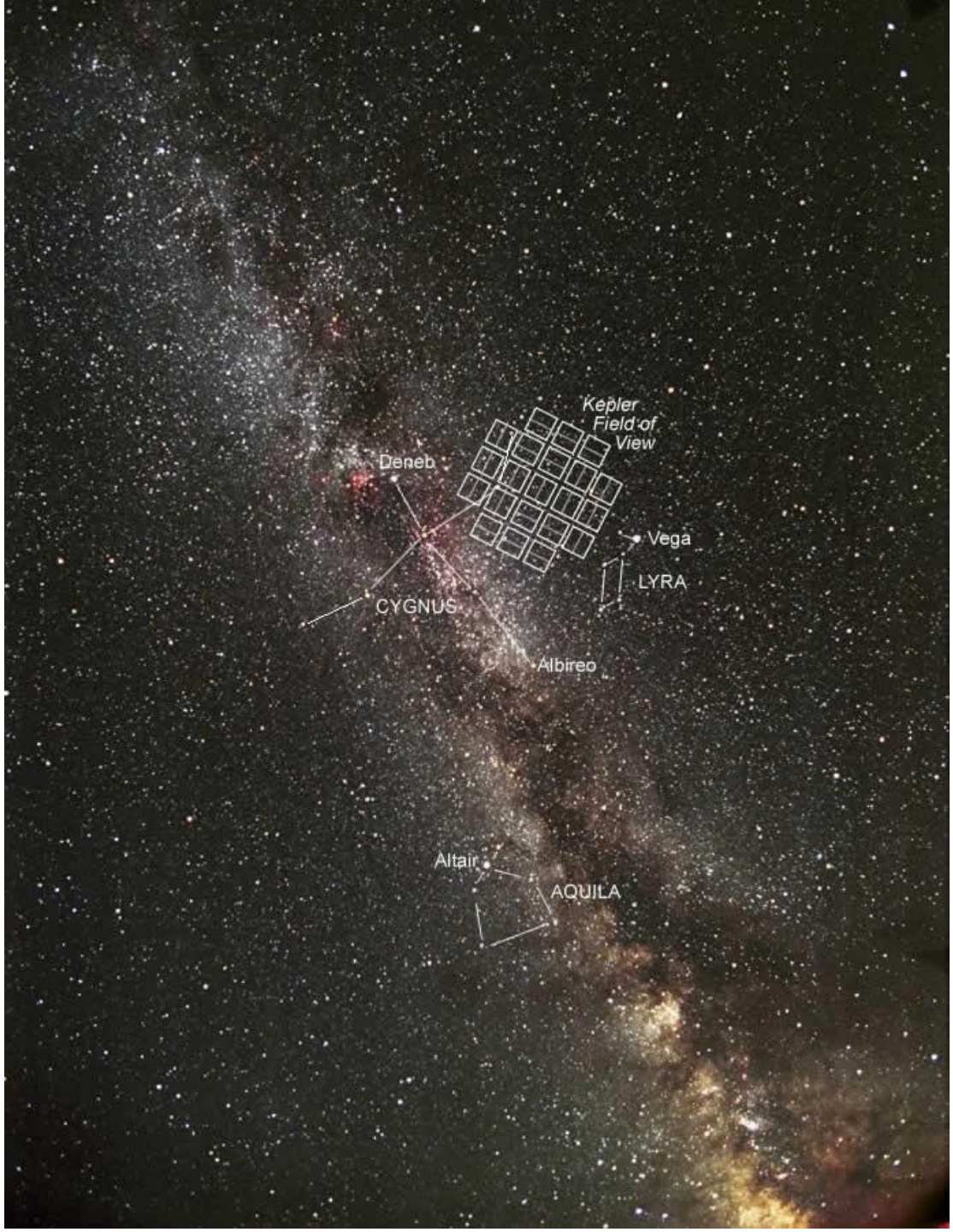
Kepler

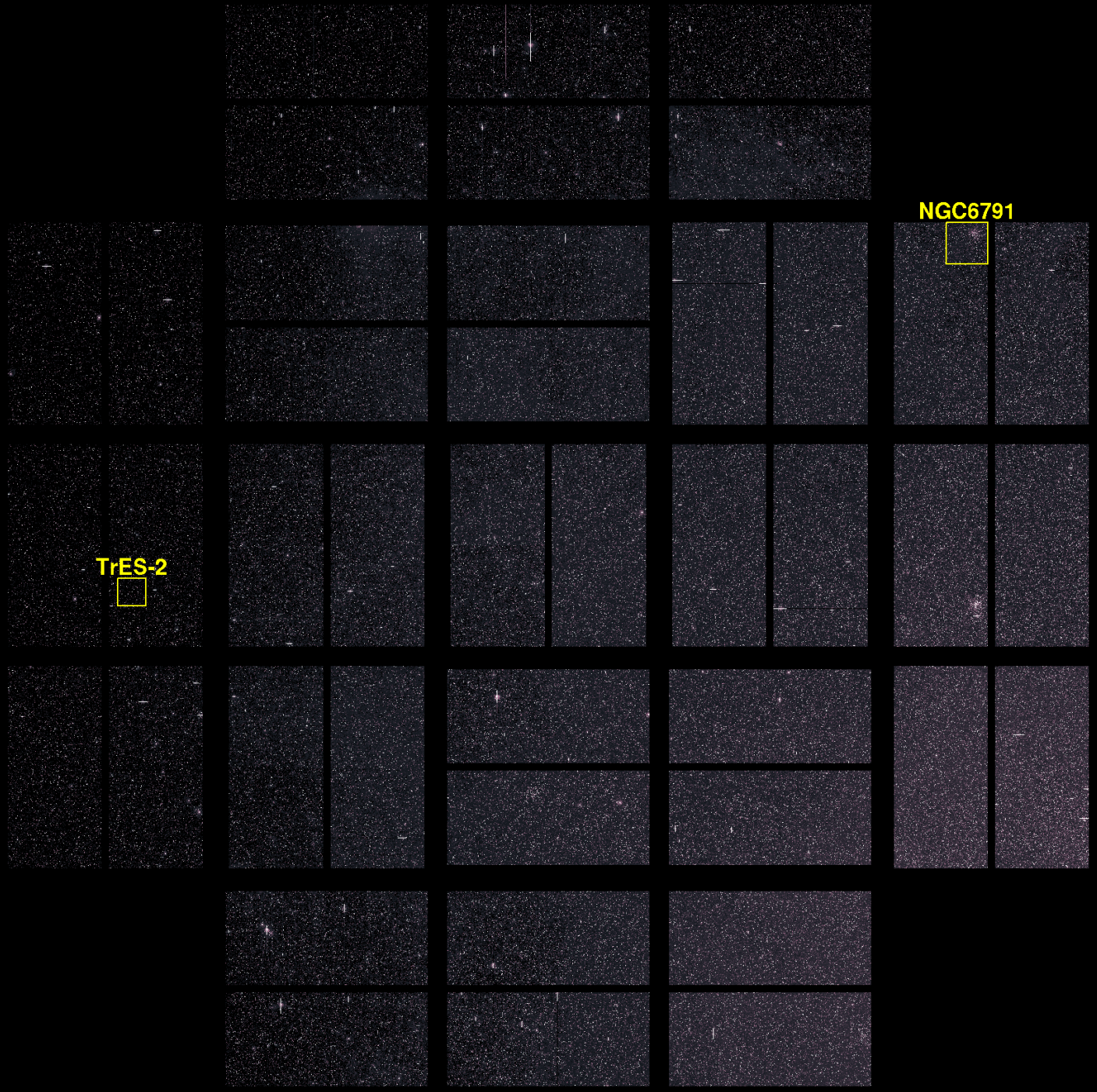
(2009-2013)

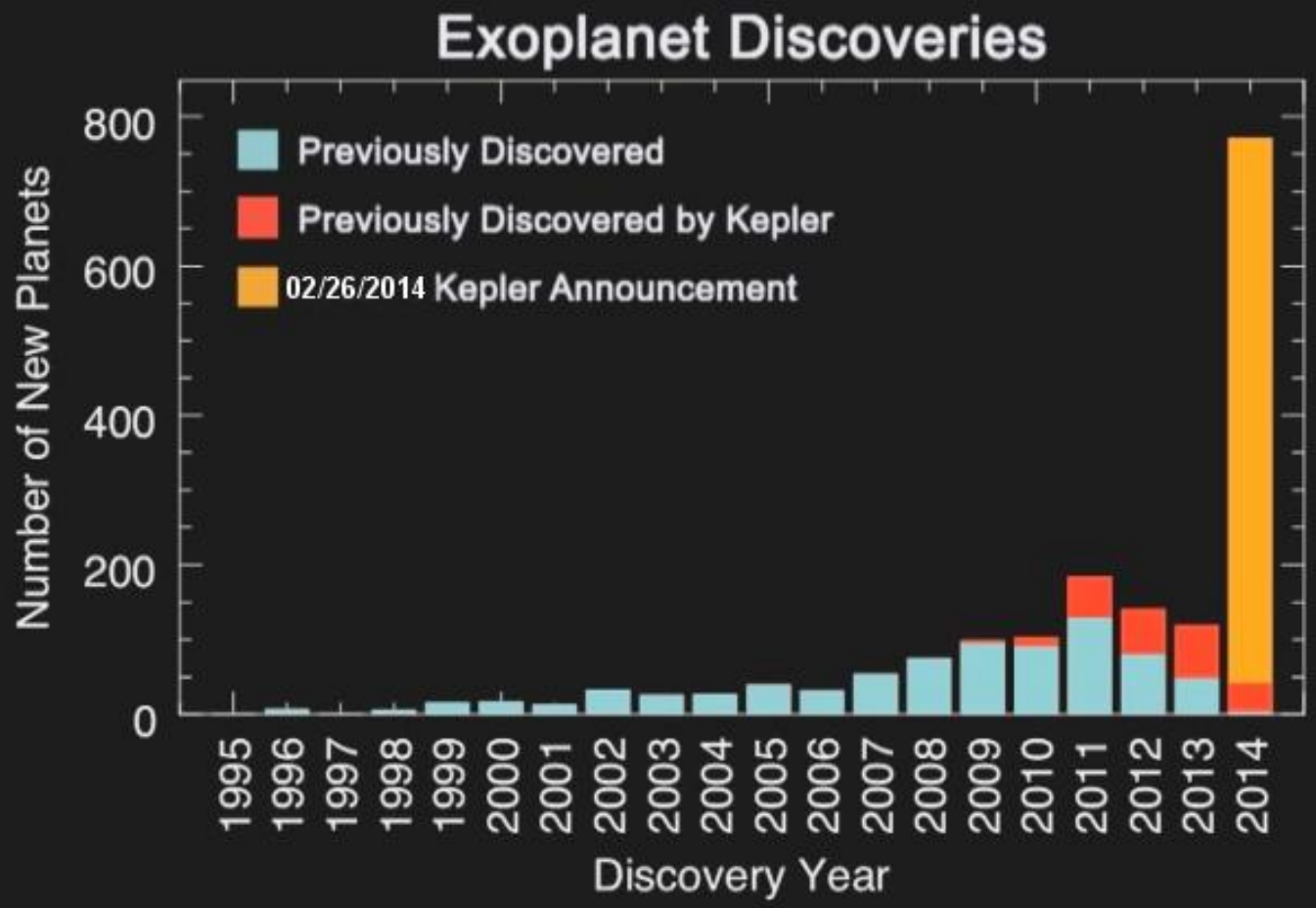
Diametro: 95 cm



Matrice di 42 CCD di 2200×1024 pixel ciascuno (95 Megapix)


Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

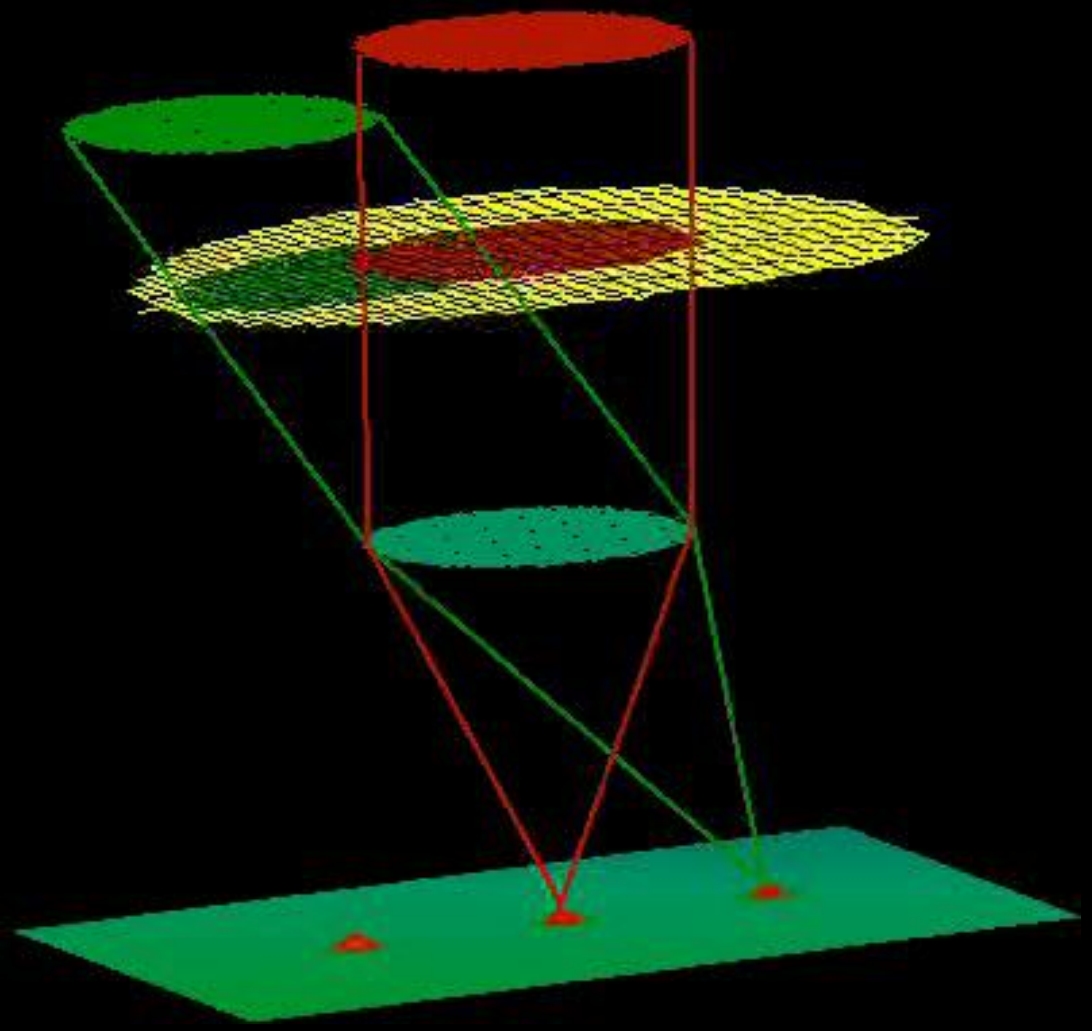

NGC6791
TrES-2


Exoplanet Discoveries
Previously Discovered
Previously Discovered by Kepler
02/26/2014 Kepler Announcement
Number of New Planets
0
200
400
600
800
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year

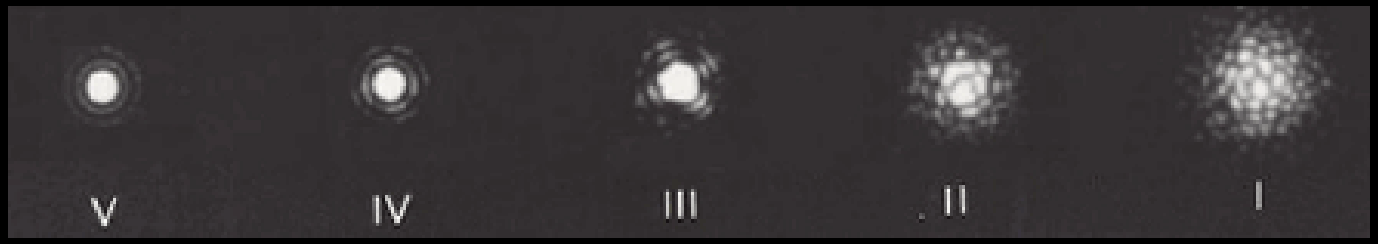
Metodi di detezione

Osservazione diretta (ottico o infrarosso)

Effetto della turbolenza atmosferica
sulla risoluzione dell’immagine



Effetti della turbolenza atmosferica (*seeing*)

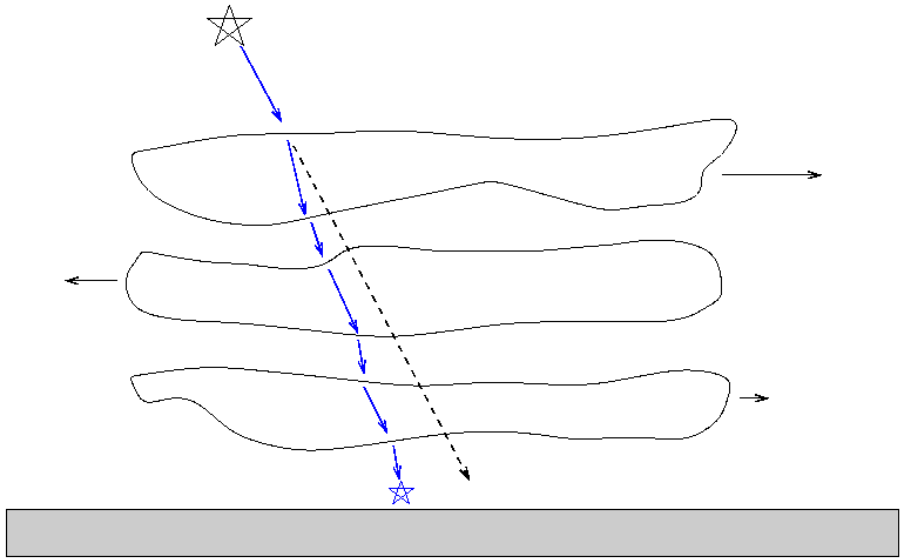


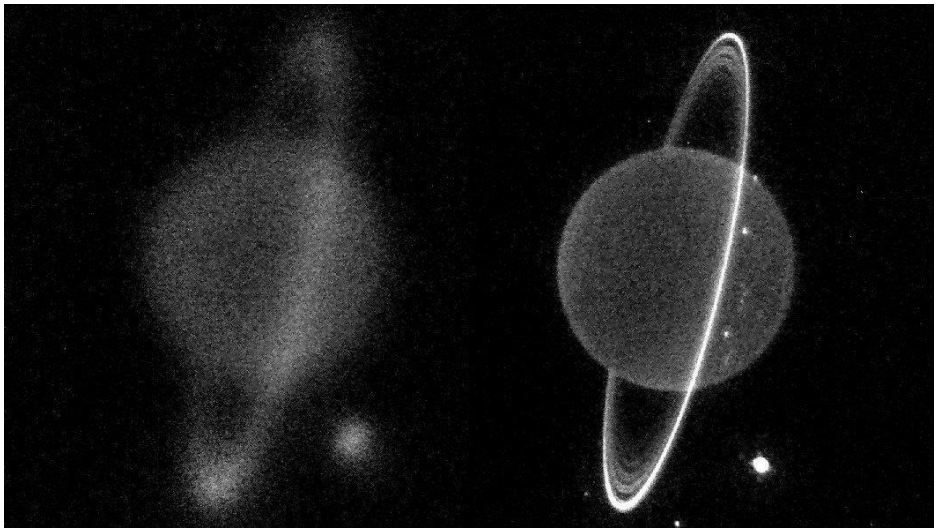
Miglioramento della risoluzione dell'immagine
per mezzo di *ottiche adattive*

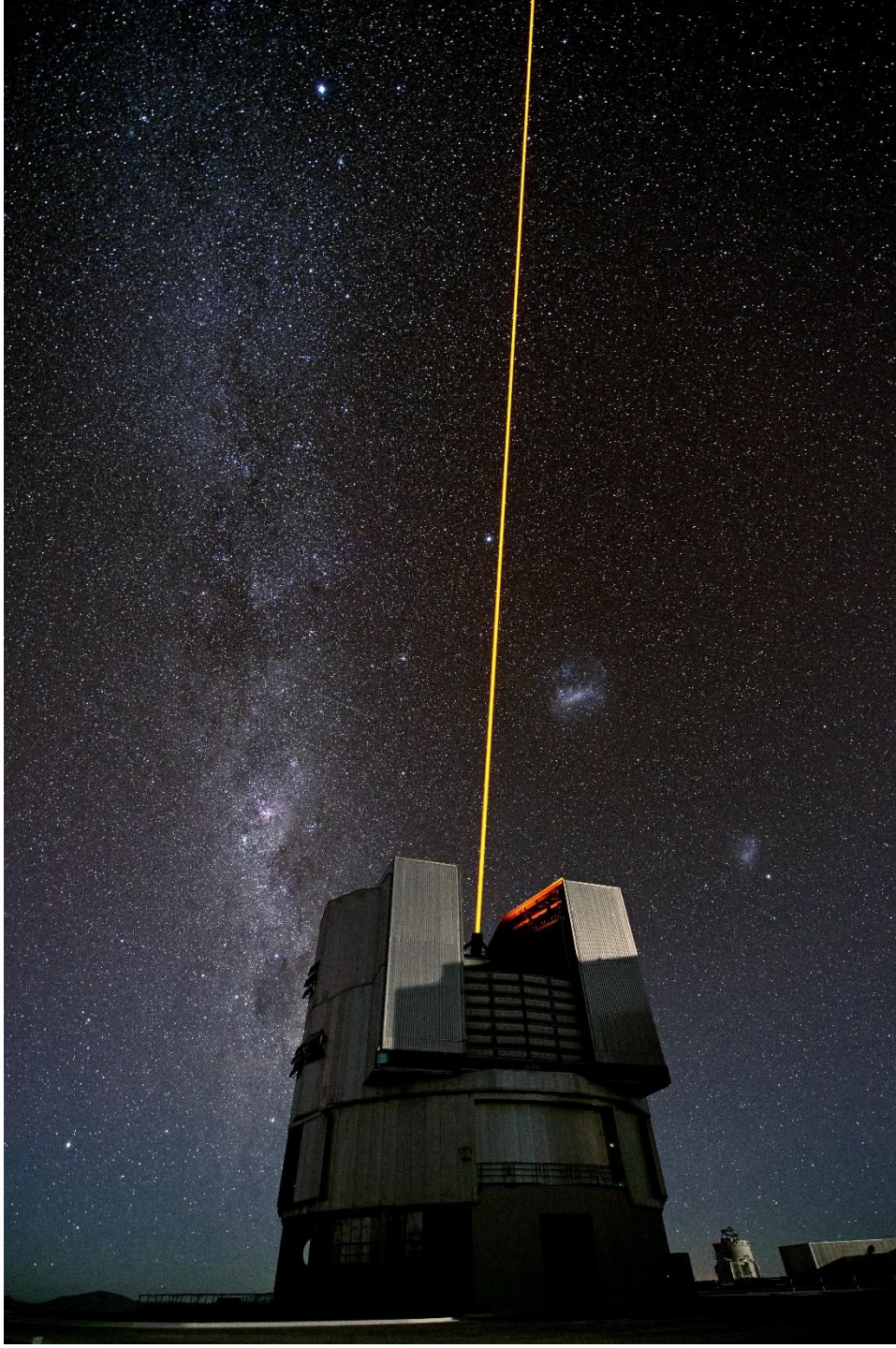
ESO VLT (Cerro Paranal, Cile)

Apertura: 4 × 8.2 m
Lunghezza focale: 14/120 m

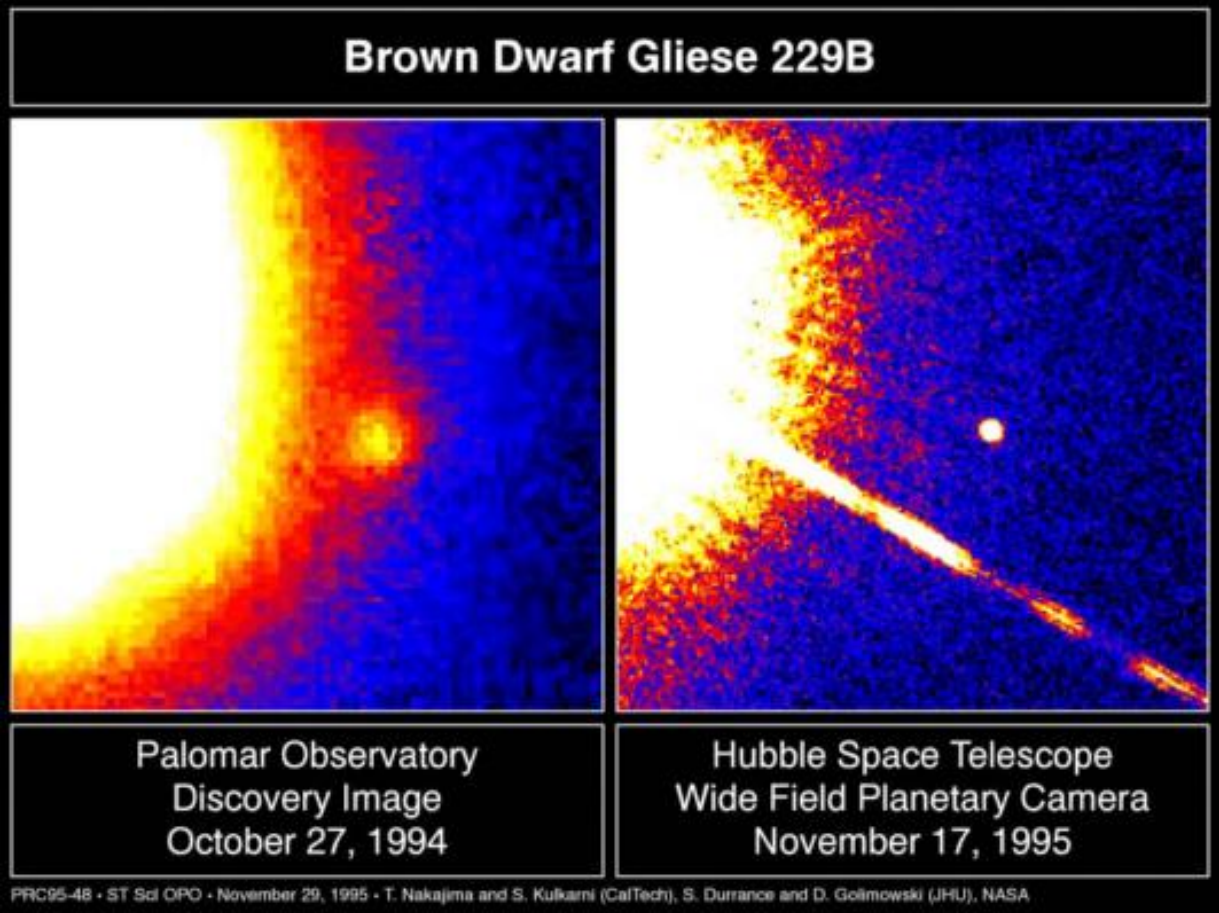
Turbolenza atmosferica e ottiche adattive





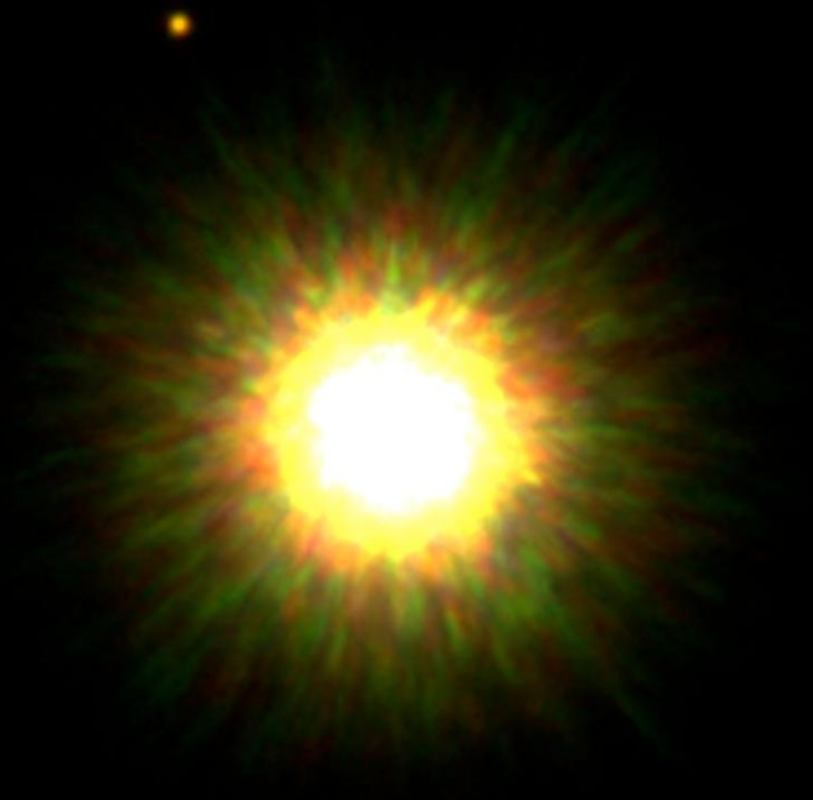


Ottiche adattive



(ottica adattiva) (telescopio spaziale)

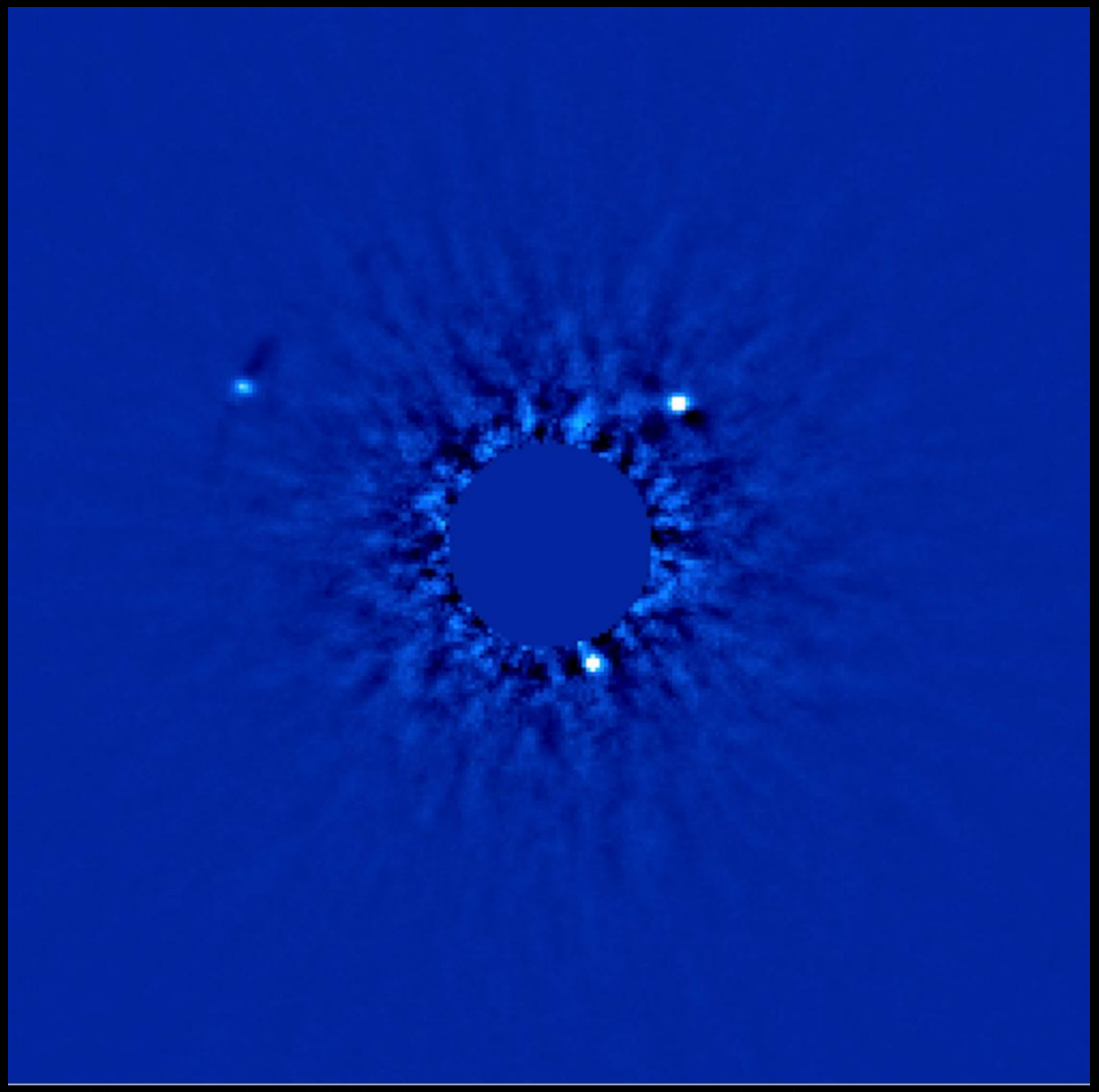
Pianeta 1RXS1609 b



Distanza: 500 anni luce
Massa: 14 M_{Giove}

Scoperta: settembre 2008
Raggio: 1.7 R_{Giove}

Conferma: luglio 2010
Raggio orbitale: 330 AU



Sistema planetario di HR 8799

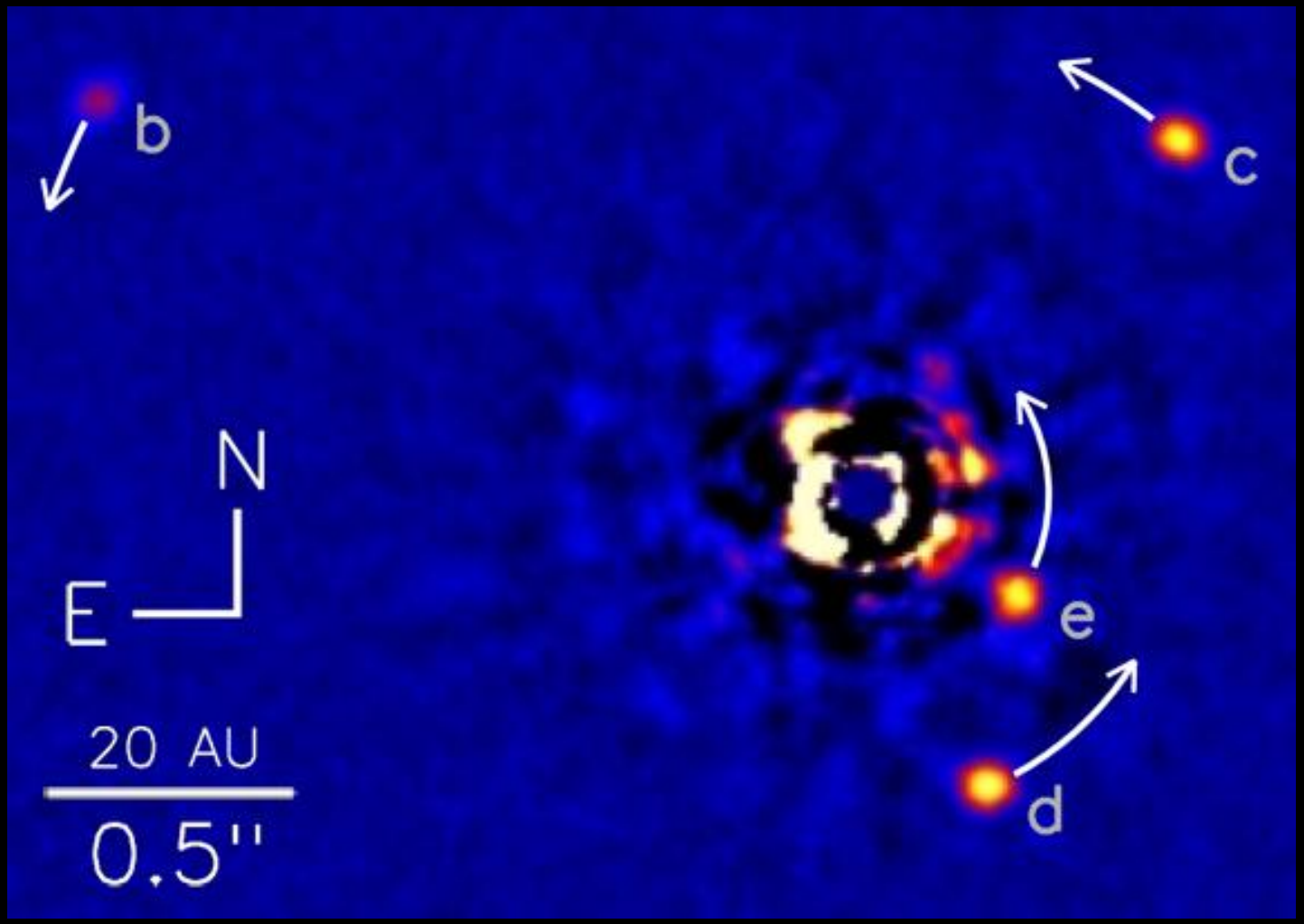
Distanza: 130 anni luce

Scoperta: novembre 2008 (telescopio Gemini, Hawaii)

Sistema planetario di HR 8799

Pianeta	Massa (M_J)	Raggio (R_J)	Distanza (AU)
b	7	1.1	68
c	10	1.3	43
d	10	1.2	27
e	9		15

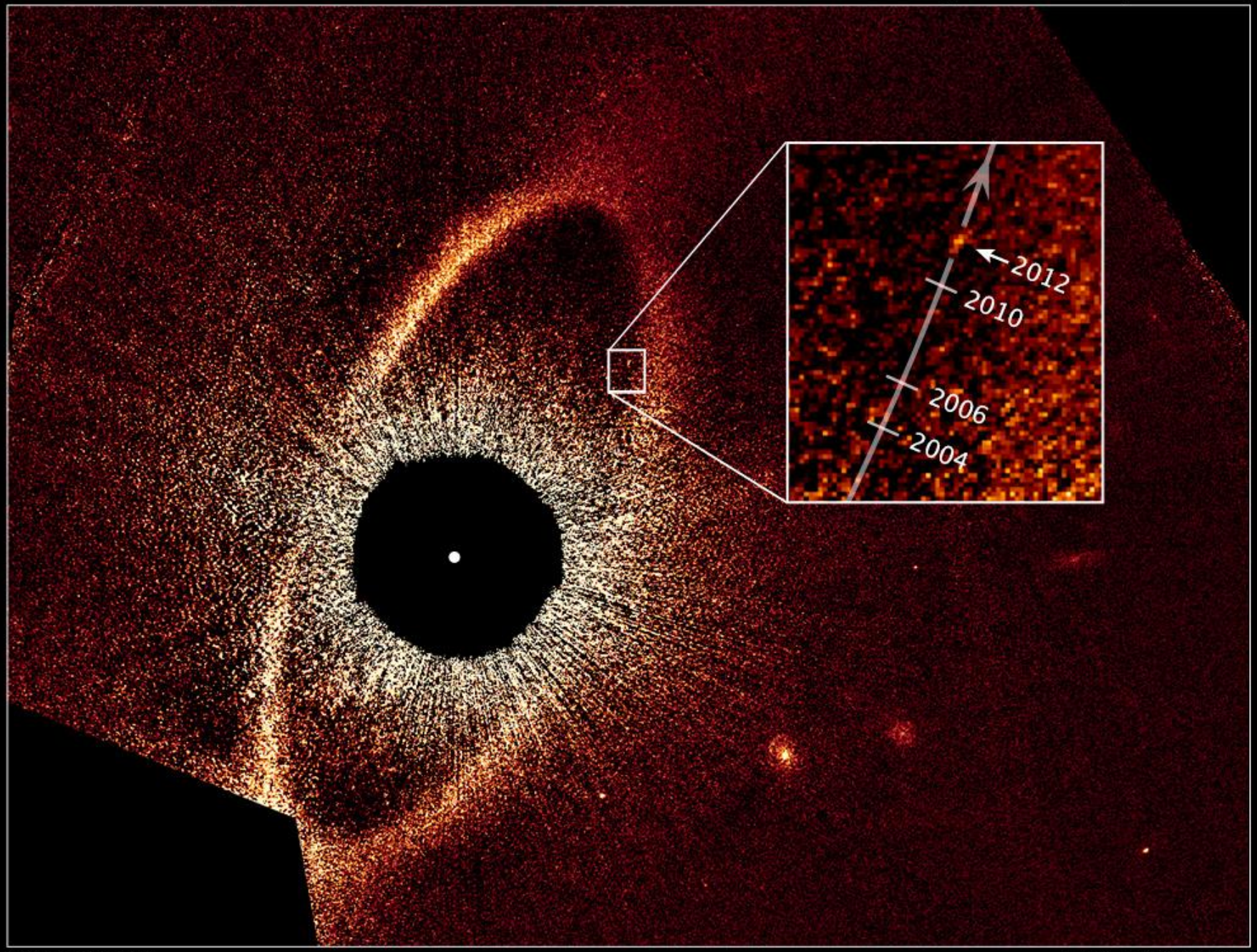
Sistema planetario di HR 8799 (quarto pianeta)



Distanza: 130 anni luce

Scoperta: dicembre 2010 (telescopio Keck II, Hawaii)

Fomalhaut System *Hubble Space Telescope • STIS*



NASA and ESA STScI-PRC13-01a

Statistica dei sistemi trovati finora (gennaio 2013)

676 sistemi planetari

859 pianeti

128 sistemi multipli

Statistica dei sistemi trovati finora (ottobre 2015)

~~676~~ 1250 sistemi planetari

~~859~~ 1970 pianeti

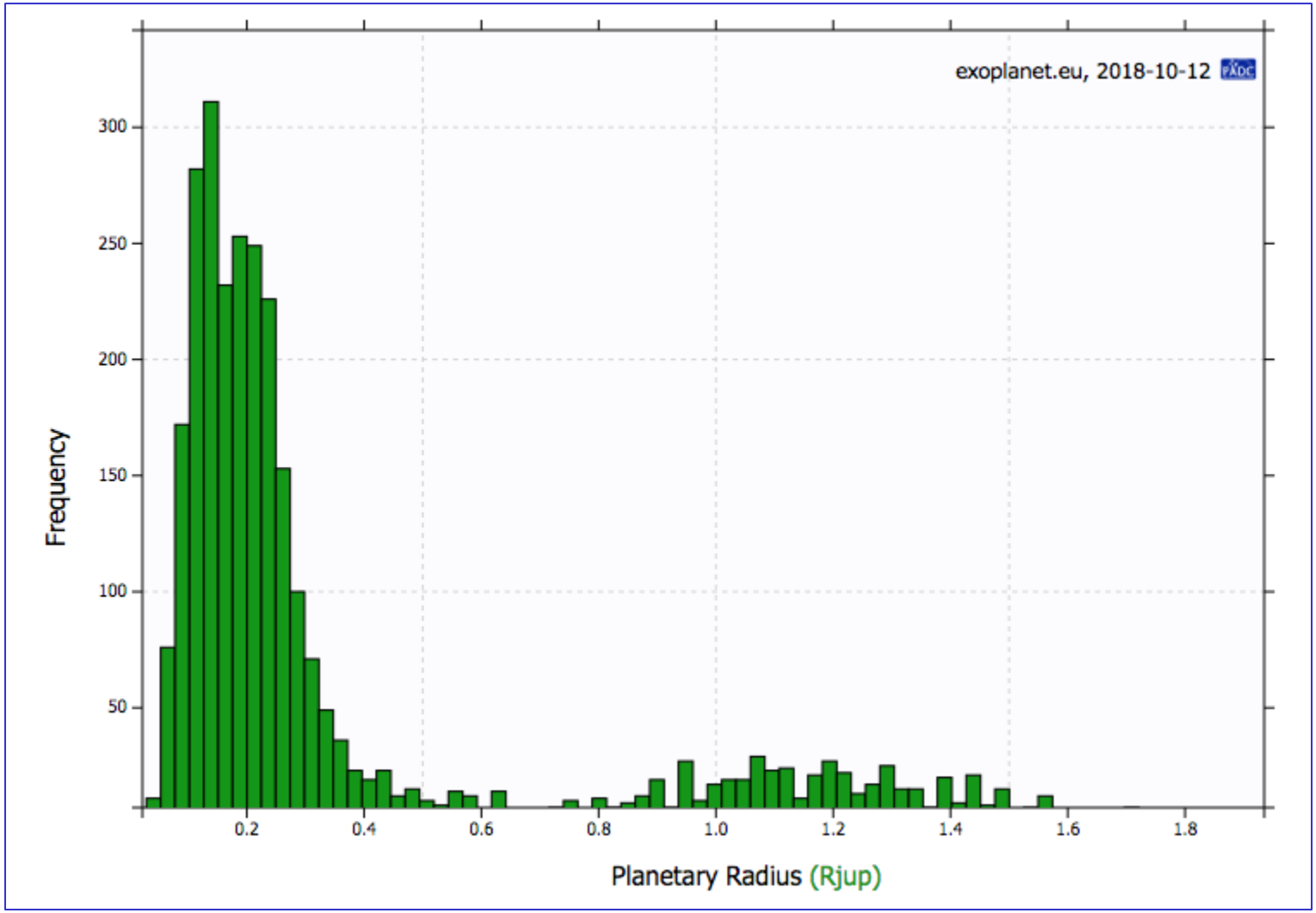
~~128~~ 490 sistemi multipli

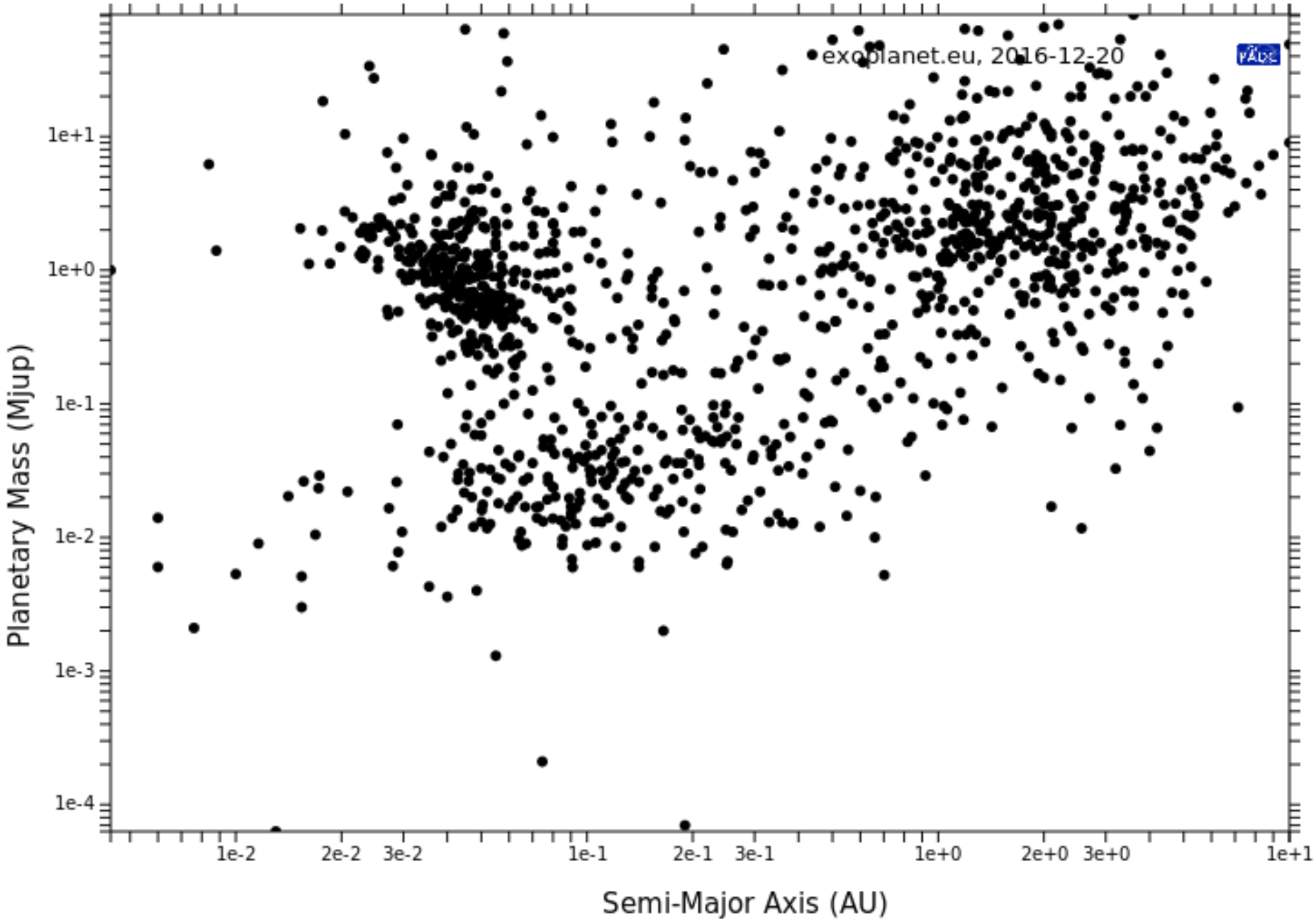
Statistica dei sistemi trovati finora (dicembre 2019)

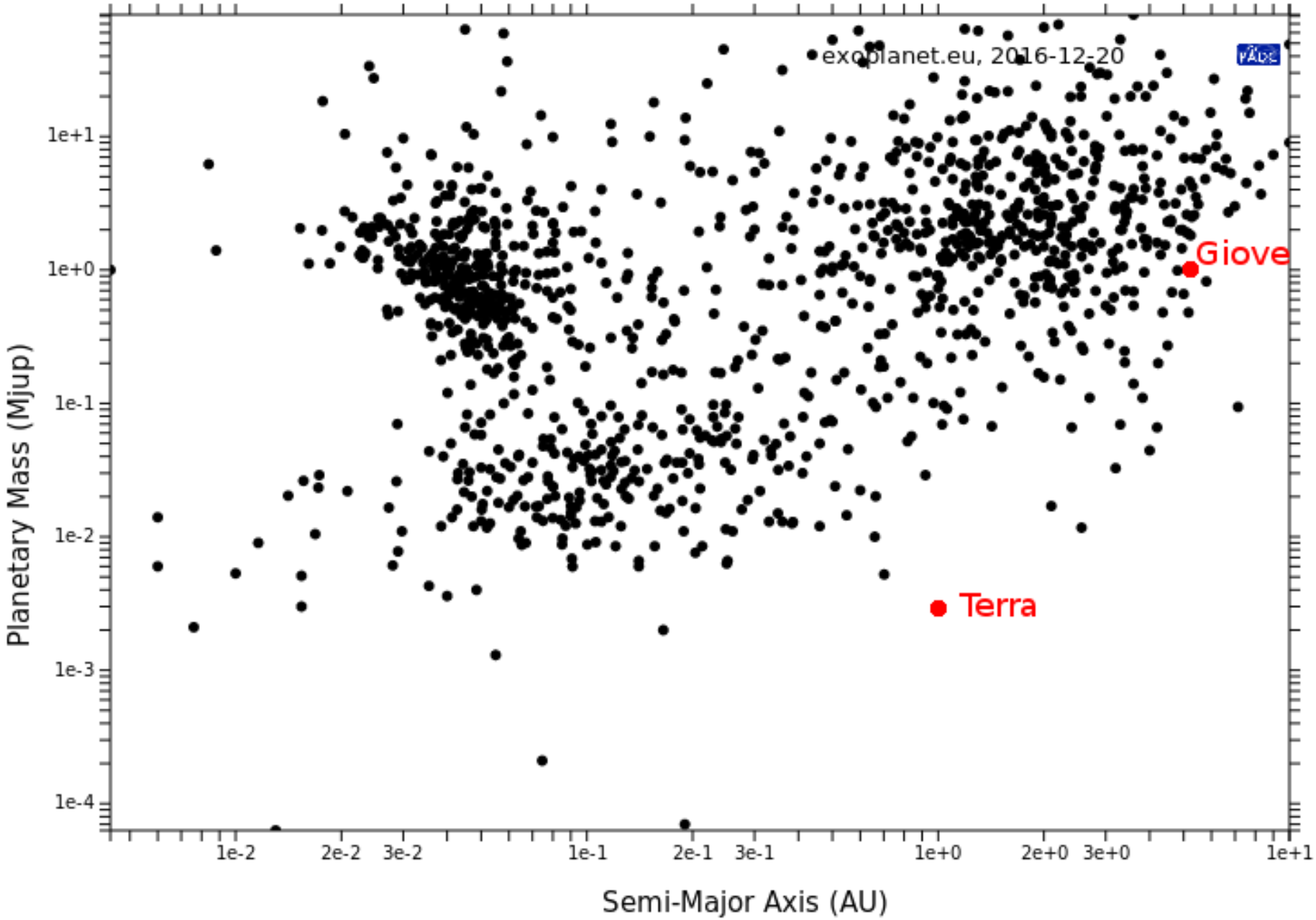
3073 sistemi planetari

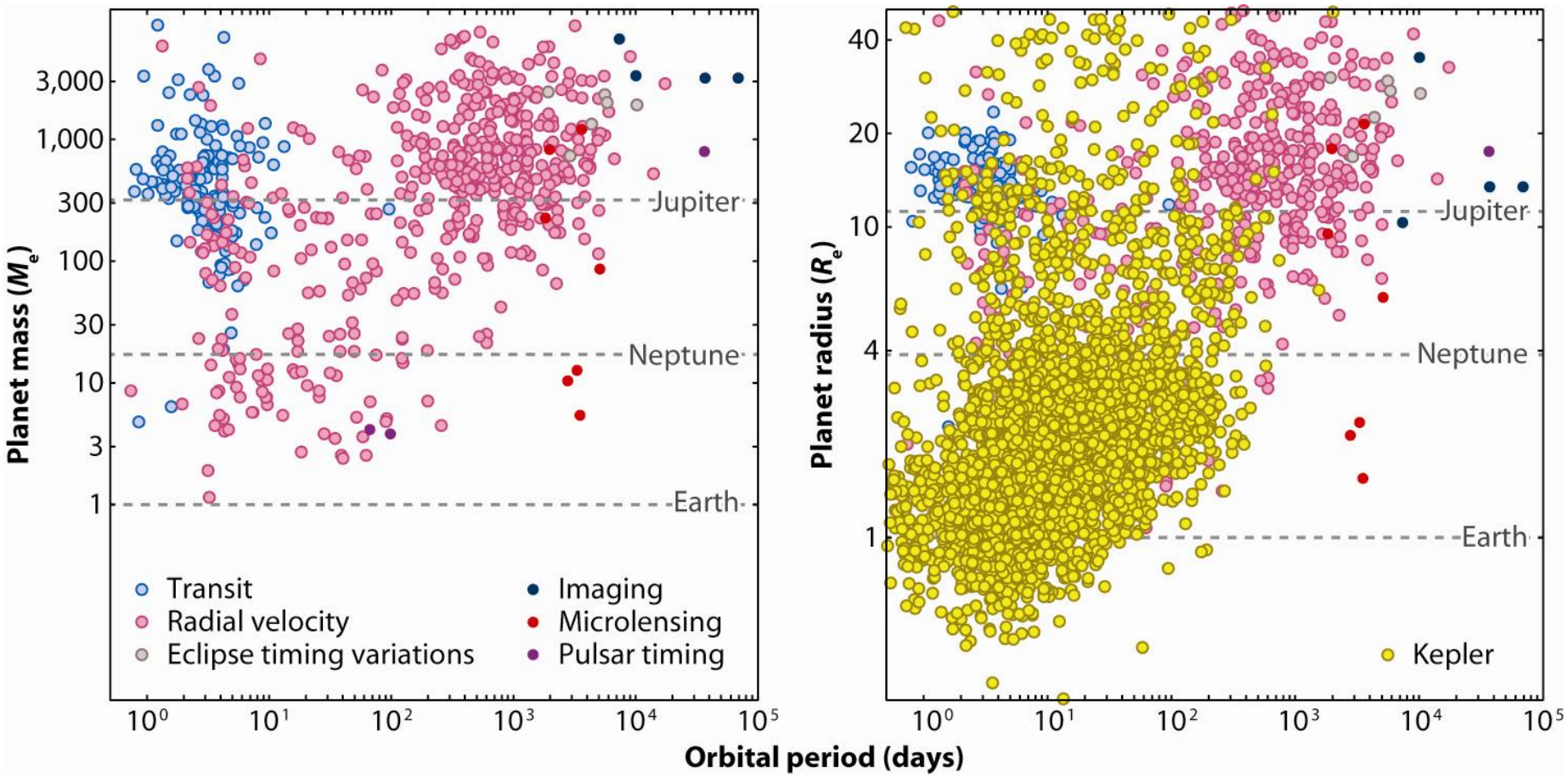
4133 pianeti

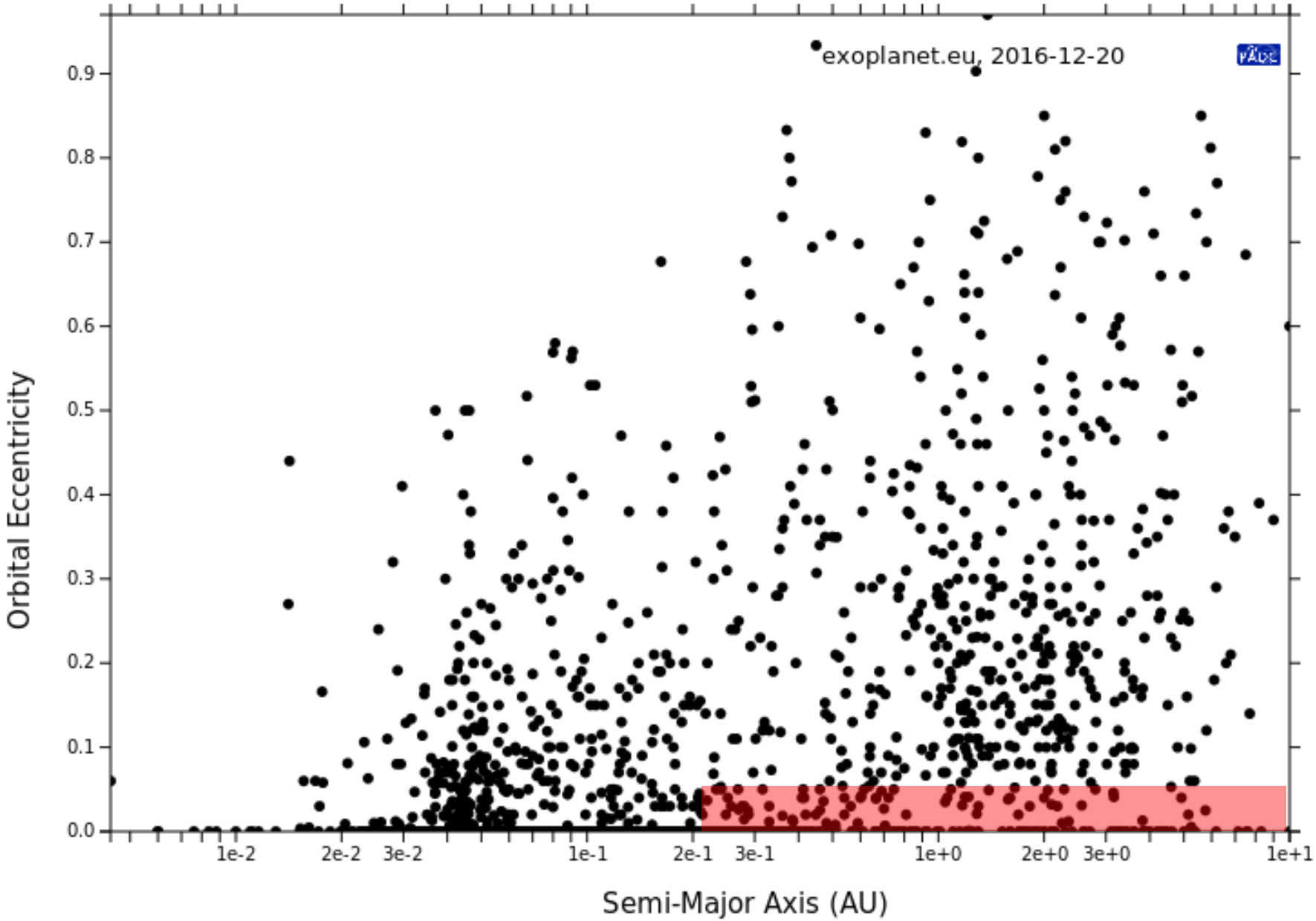
672 sistemi multipli


exoplanet.eu, 2018-10-12
Frequency
300
250
200
150
100
50
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Planetary Radius (Rjup)

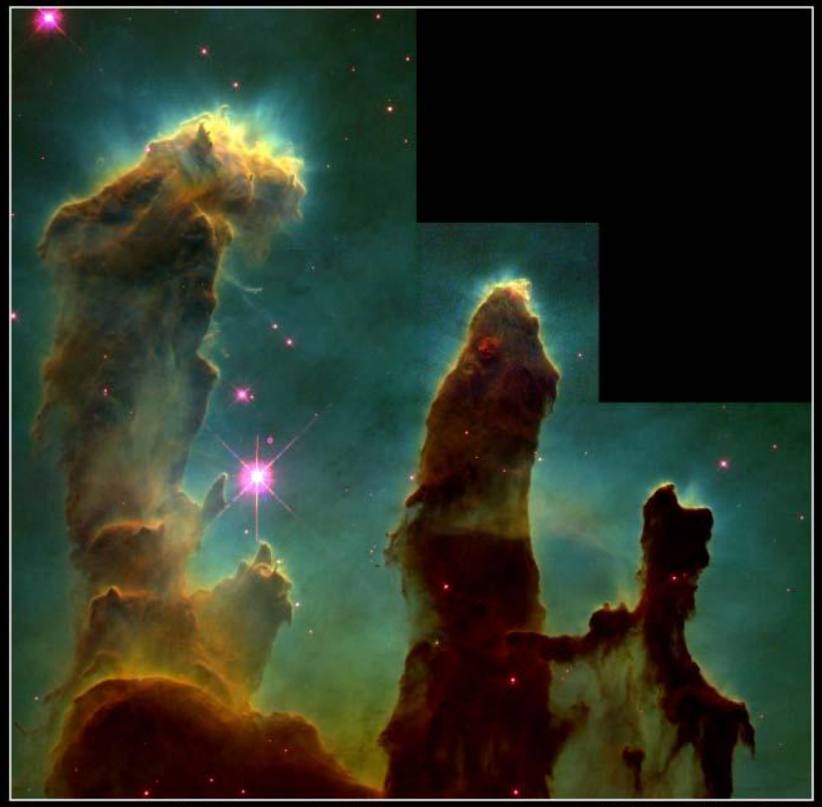

exoplanet.eu, 2016-12-20
Planetary Mass (Mjup)
Semi-Major Axis (AU)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-2
2e-2
3e-2
1e-1
2e-1
3e-1
1e+0
2e+0
3e+0
1e+1


exoplanet.eu, 2016-12-20
Giove
Terra
Planetary Mass (Mjup)
Semi-Major Axis (AU)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-2
2e-2
3e-2
1e-1
2e-1
3e-1
1e+0
2e+0
3e+0
1e+1


Planet mass (M_e)
3,000
1,000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial velocity
Eclipse timing variations
Imaging
Microlensing
Pulsar timing
Planet radius (R_e)
40
20
10
4
1
Jupiter
Neptune
Earth
Kepler
10^0
10^1
10^2
10^3
10^4
10^5
Orbital period (days)

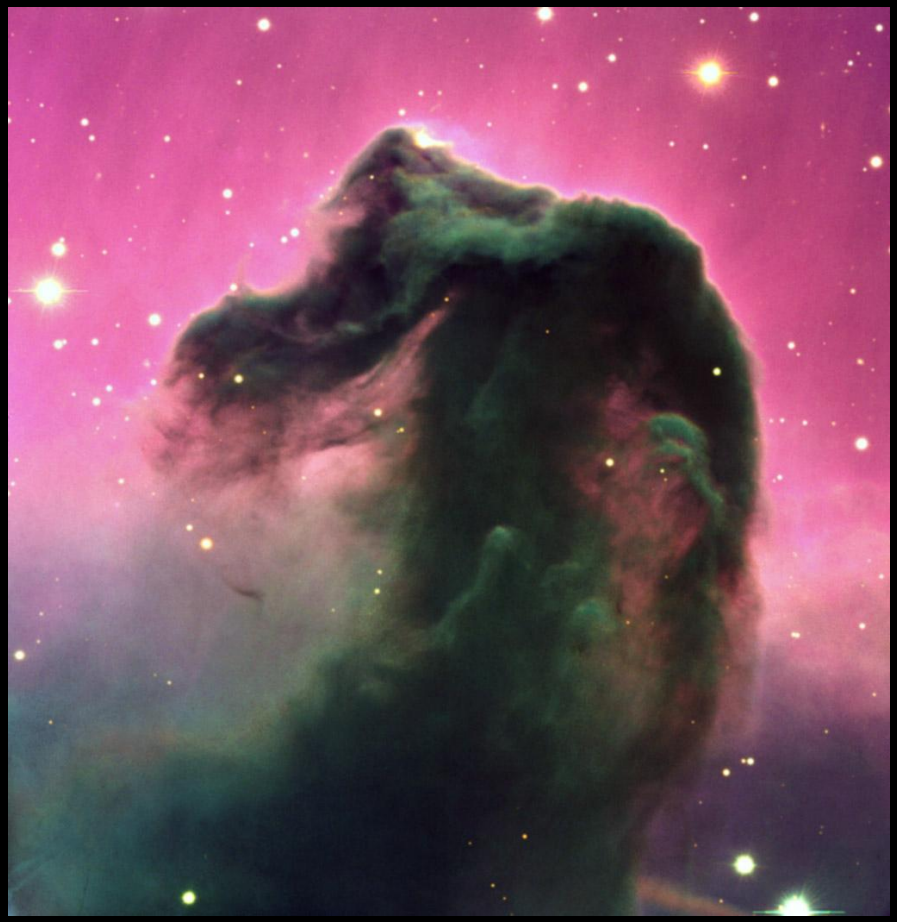

exoplanet.eu, 2016-12-20
Orbital Eccentricity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1e-2
2e-2
3e-2
1e-1
2e-1
3e-1
1e+0
2e+0
3e+0
1e+1
Semi-Major Axis (AU)

Nubi molecolari giganti

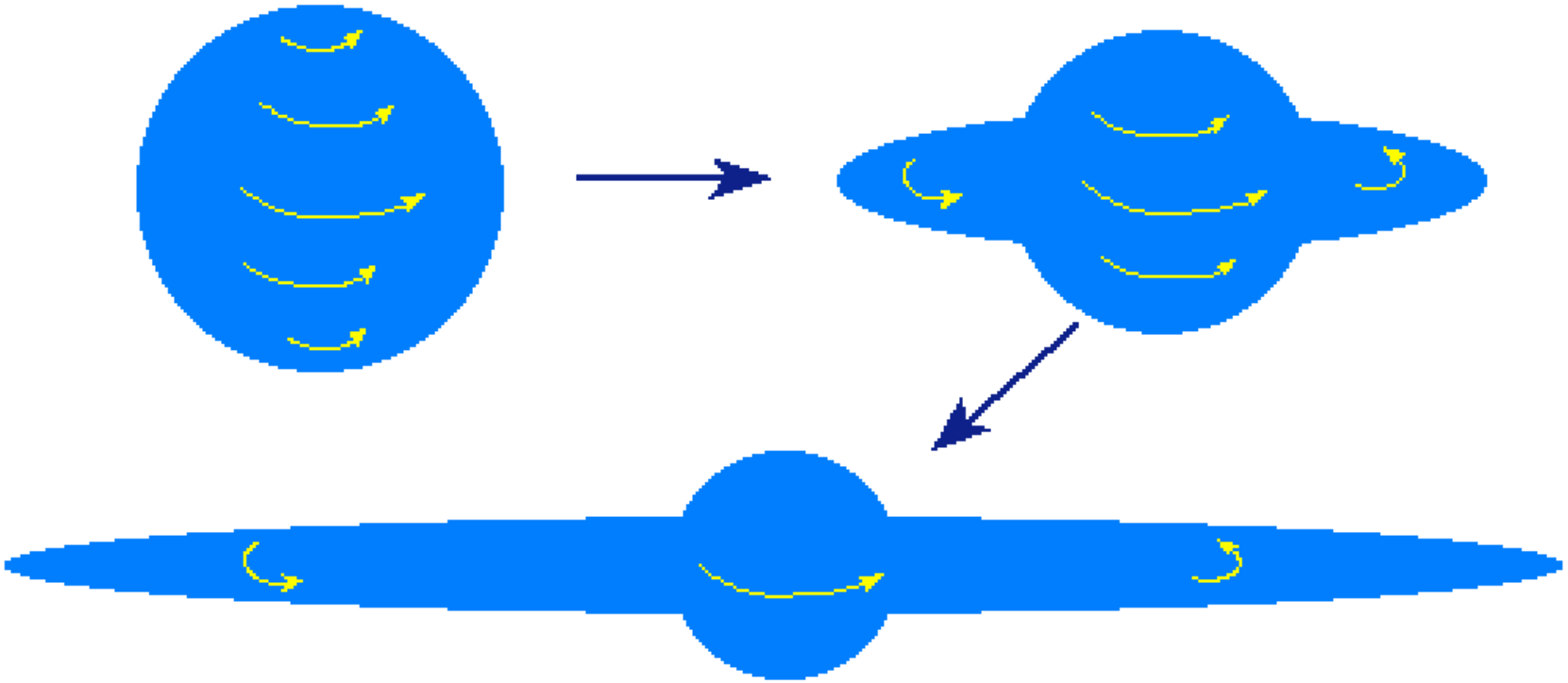


Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

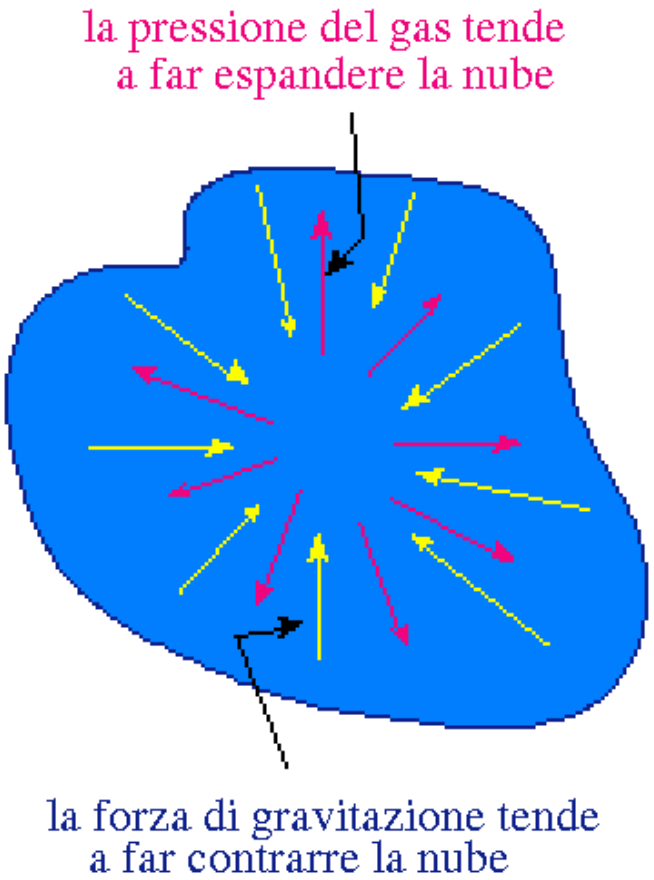


Formazione del Sistema Solare - 3

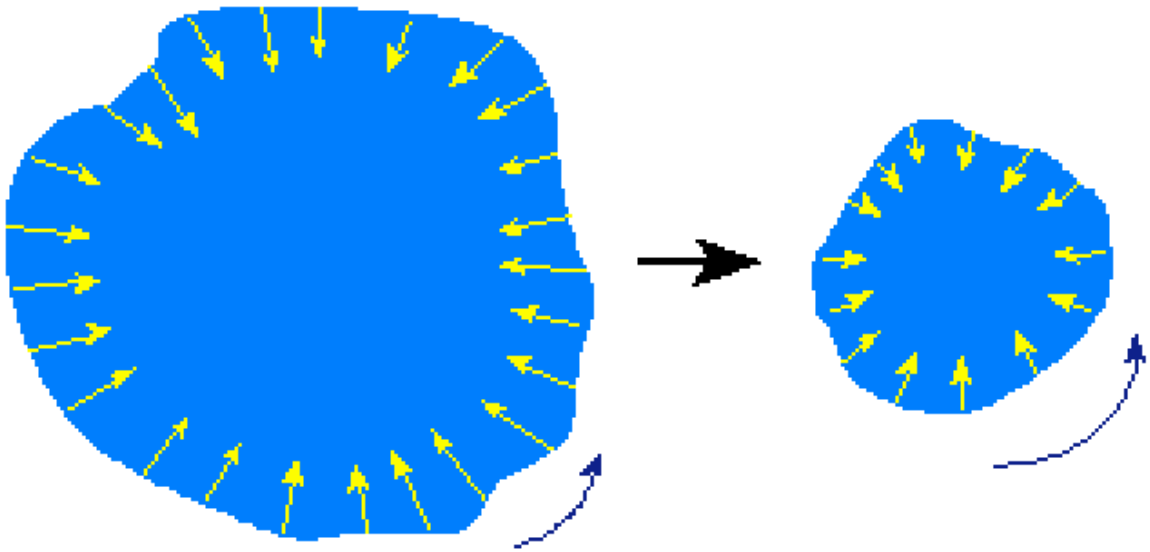


Formazione del disco (veduta laterale)

Formazione del Sistema Solare - 1

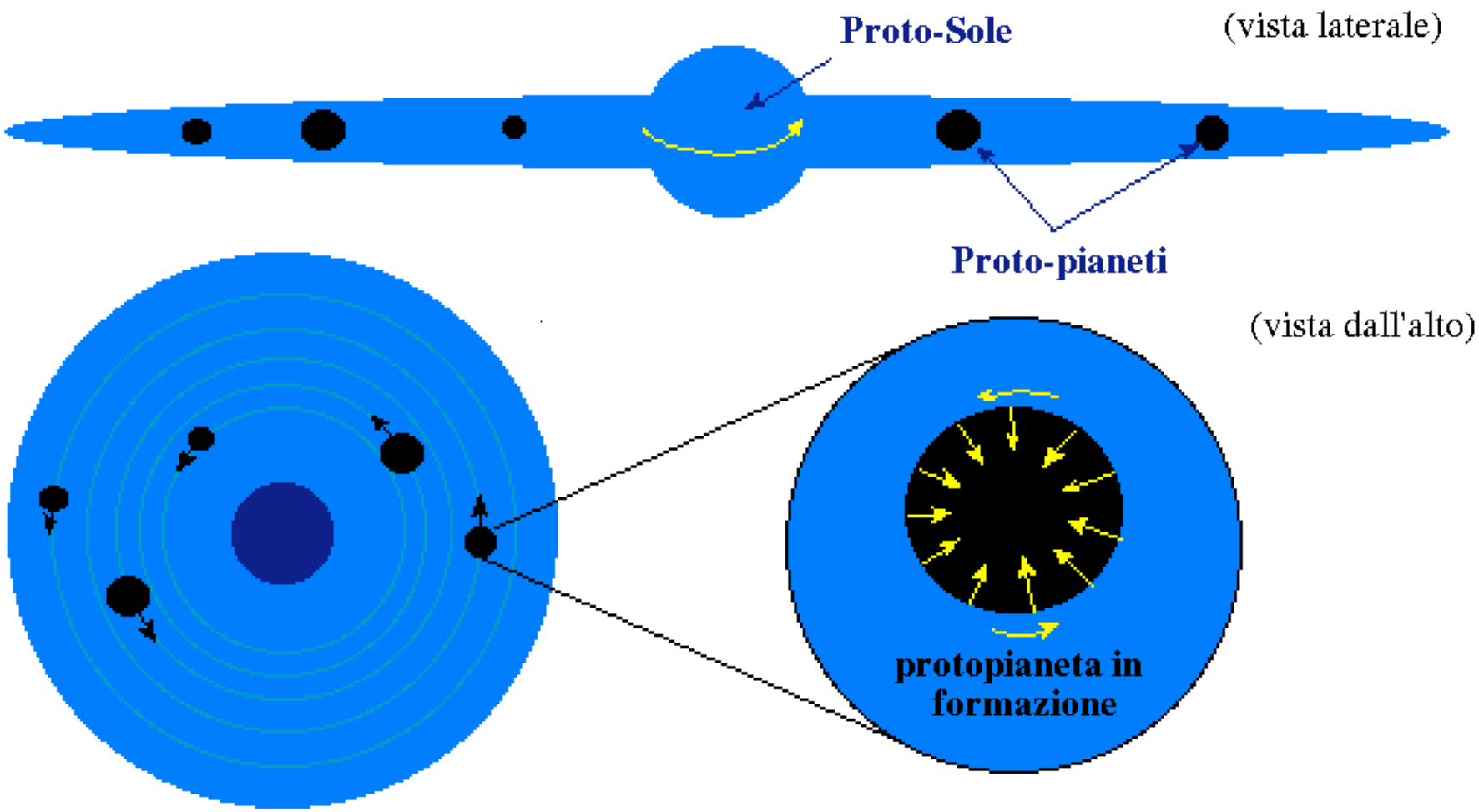


Formazione del Sistema Solare - 2

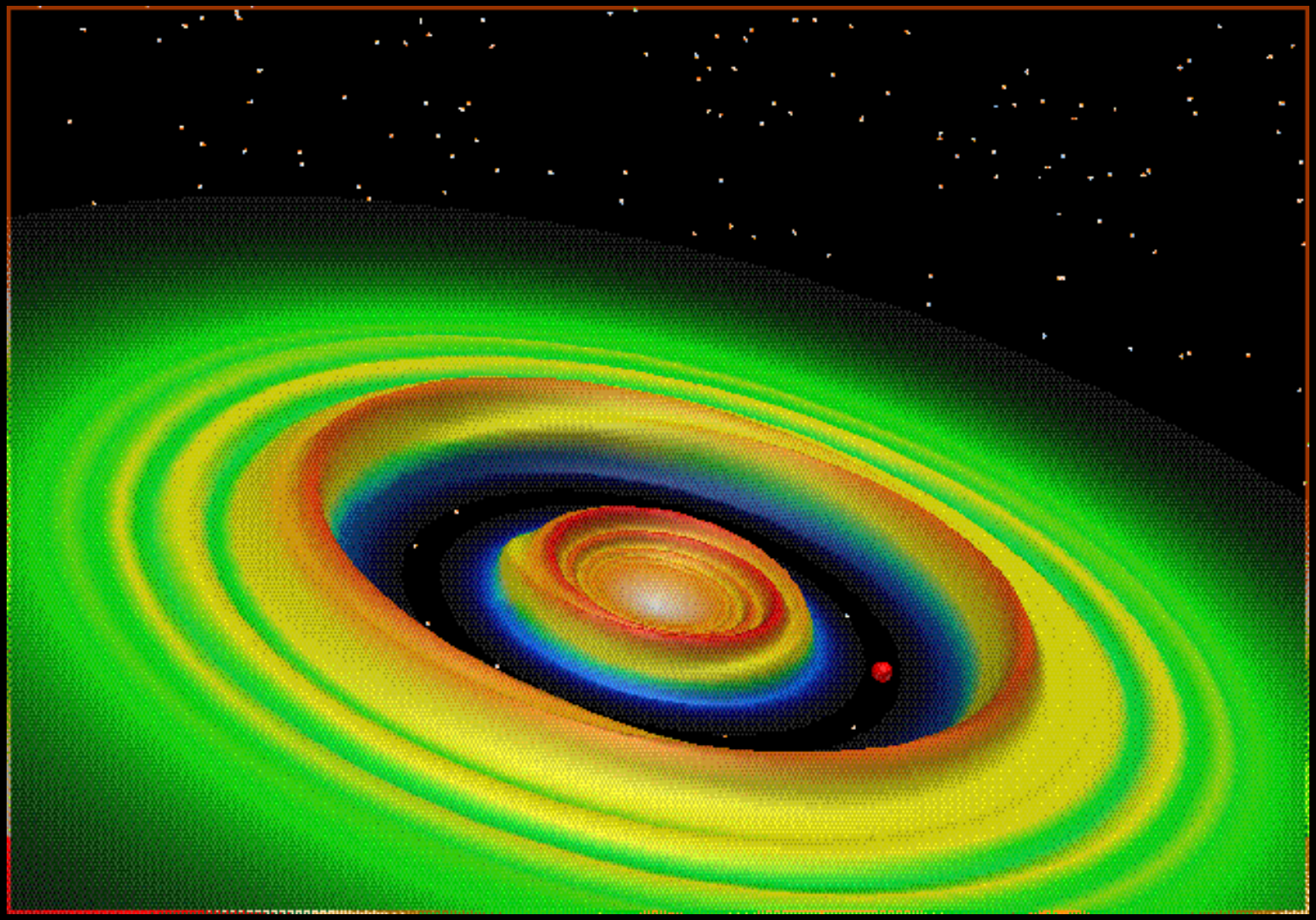


Collassando la nube accelera la sua velocità di rotazione per la conservazione del momento angolare

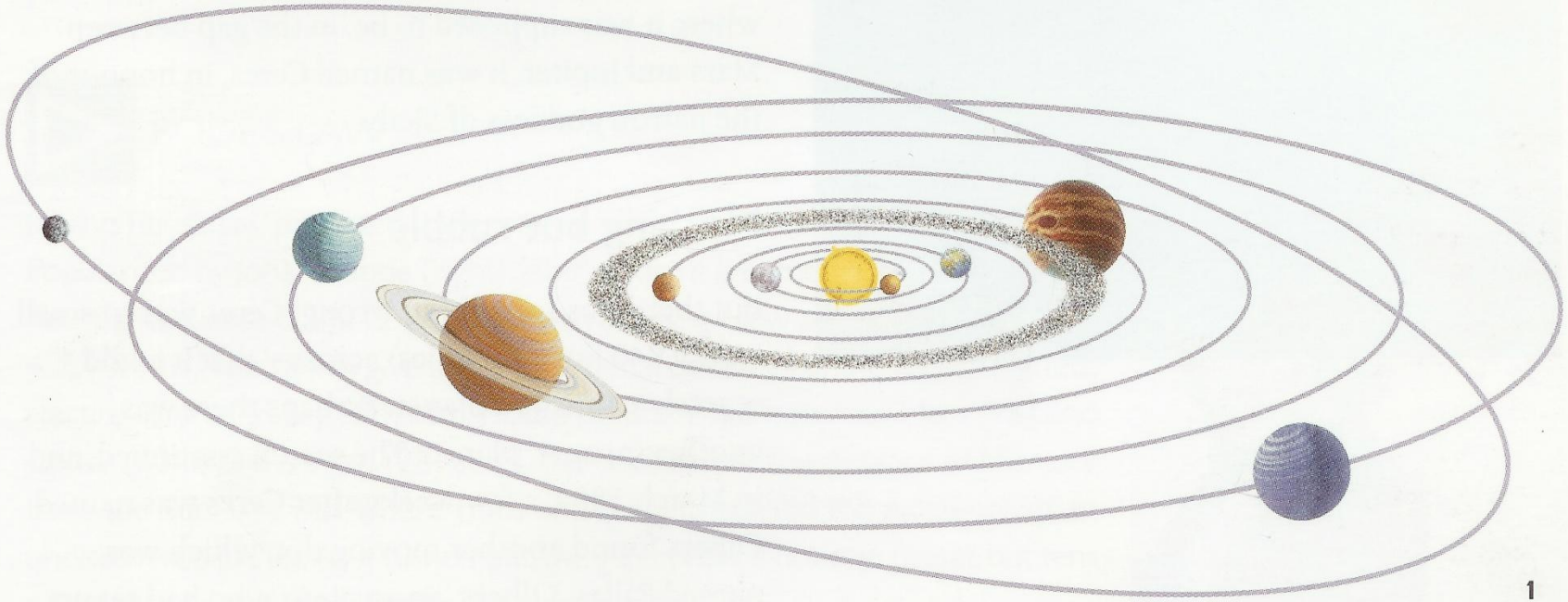
Formazione del Sistema Solare - 4



Formazione del Sistema Solare

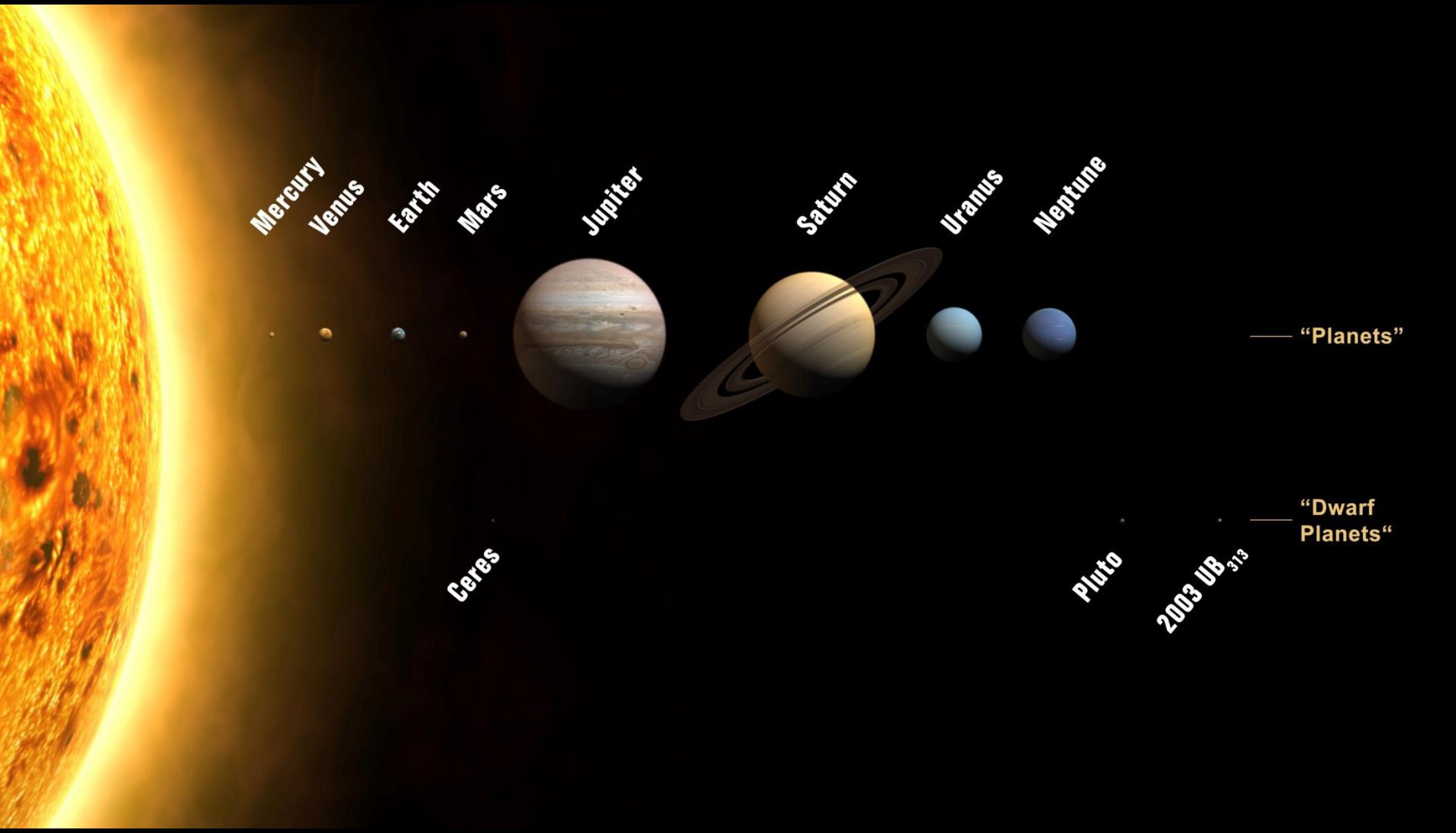


Struttura del Sistema Solare

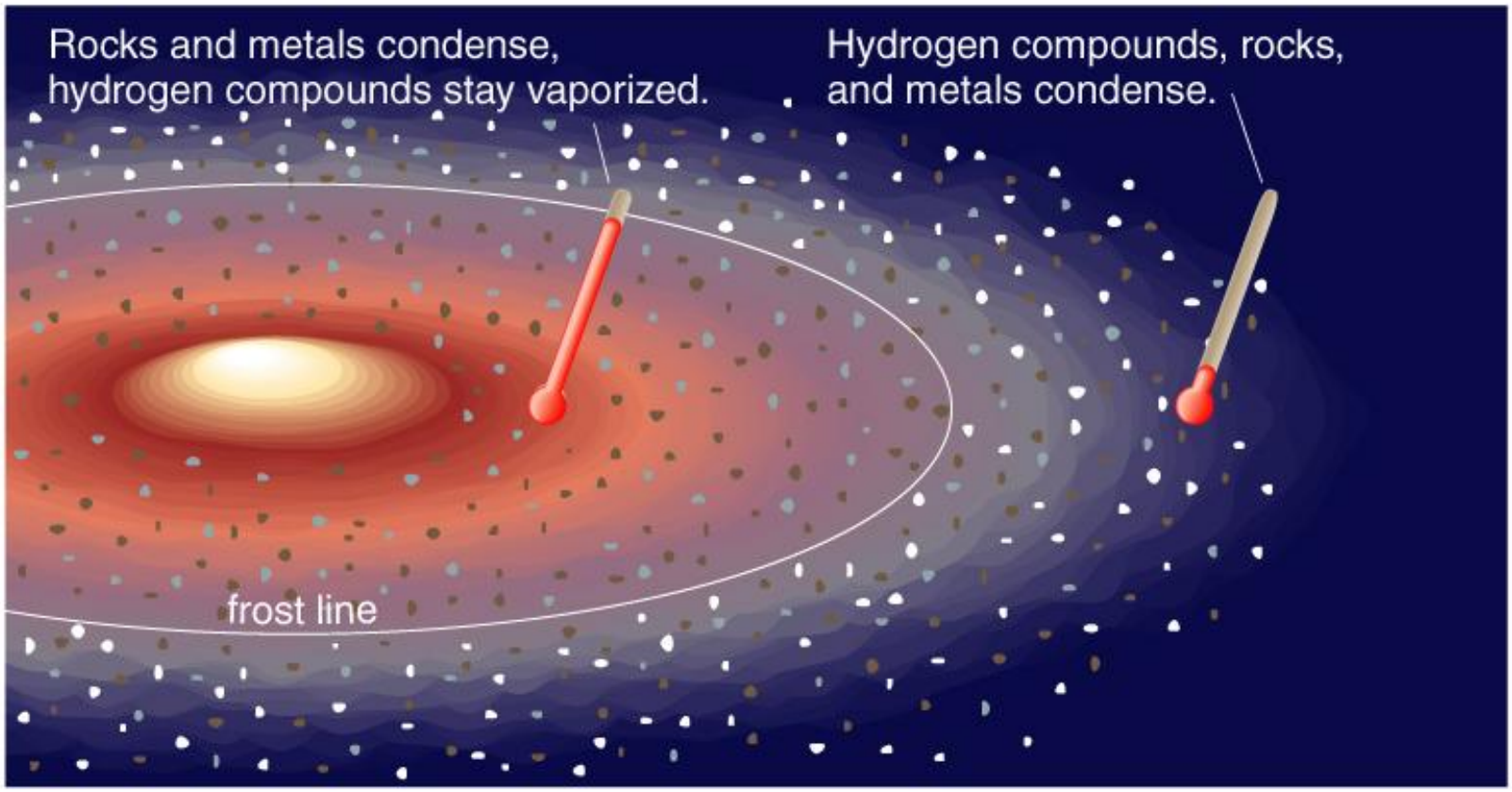


1

Struttura del Sistema Solare

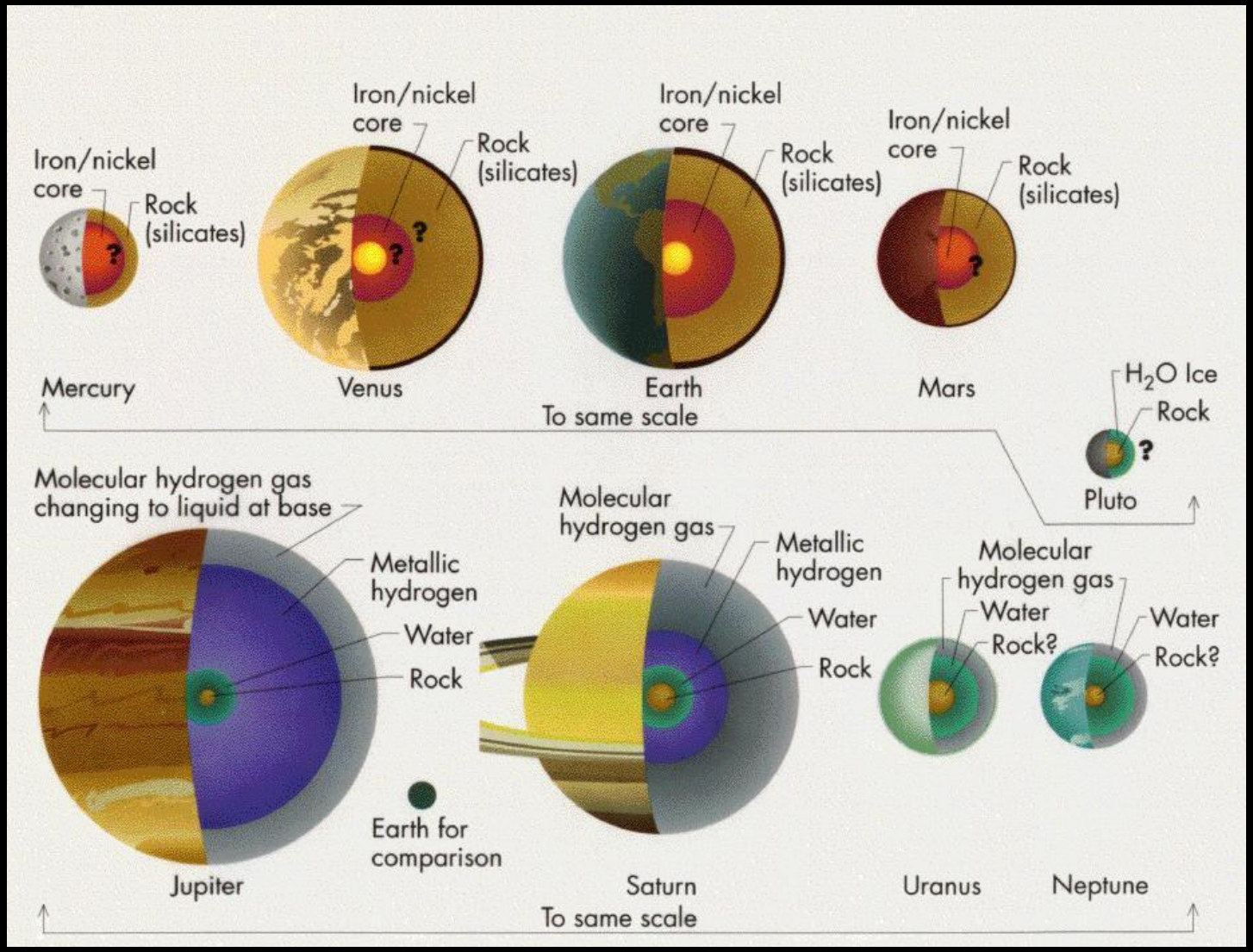


Gradiente di temperatura



© Addison-Wesley Longman

Differenze di composizione interna



pianeti "terrestri" (interni)

pianeti "giganti" (esterni)

~~Esistono pianeti abitati da forme di vita?~~
Esistono pianeti abitabili?
Cosa vuol dire “abitabile”?

Requisiti ragionevoli:

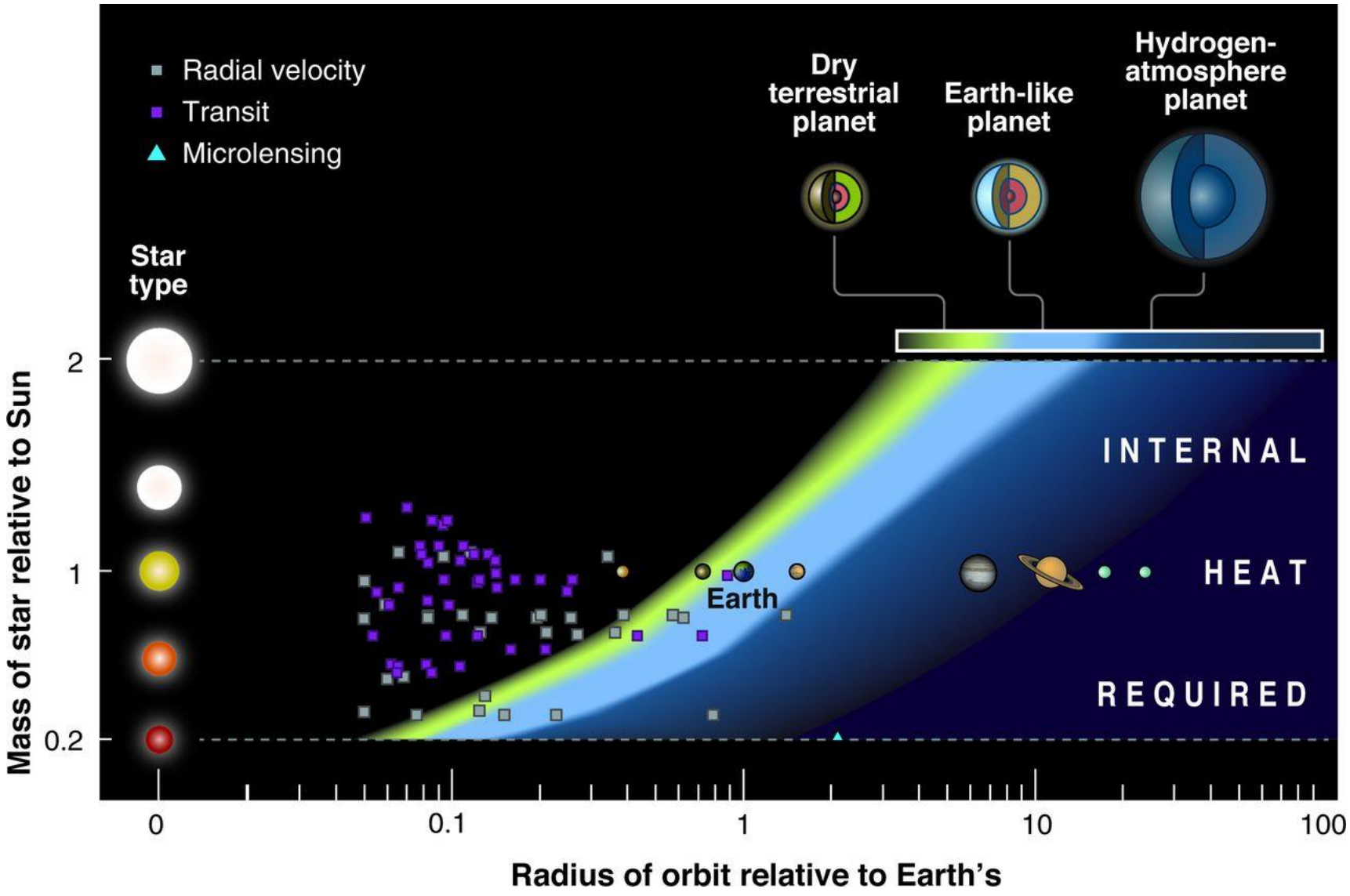
Atmosfera (massa, temperatura, composizione chimica)

Acqua liquida (temperatura)

Campo magnetico (massa, composizione chimica, età)

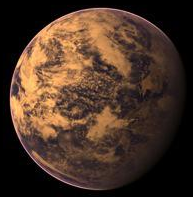
Composizione chimica

Zona di abitabilità



Potentially Habitable Exoplanets

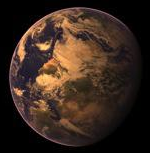
Earth



Gliese 667C c

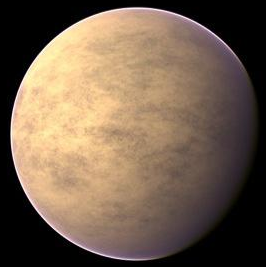
Kepler-62 e

Tau Ceti e*



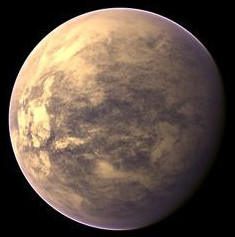
Gliese 581 g*

Gliese 667C f

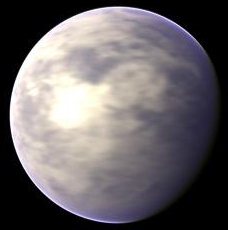


HD 40307 g

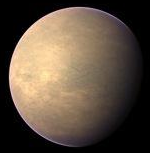
Gliese 163 c



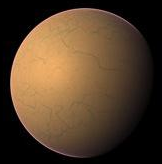
Kepler-61 b



Kepler-22 b



Kepler-62 f

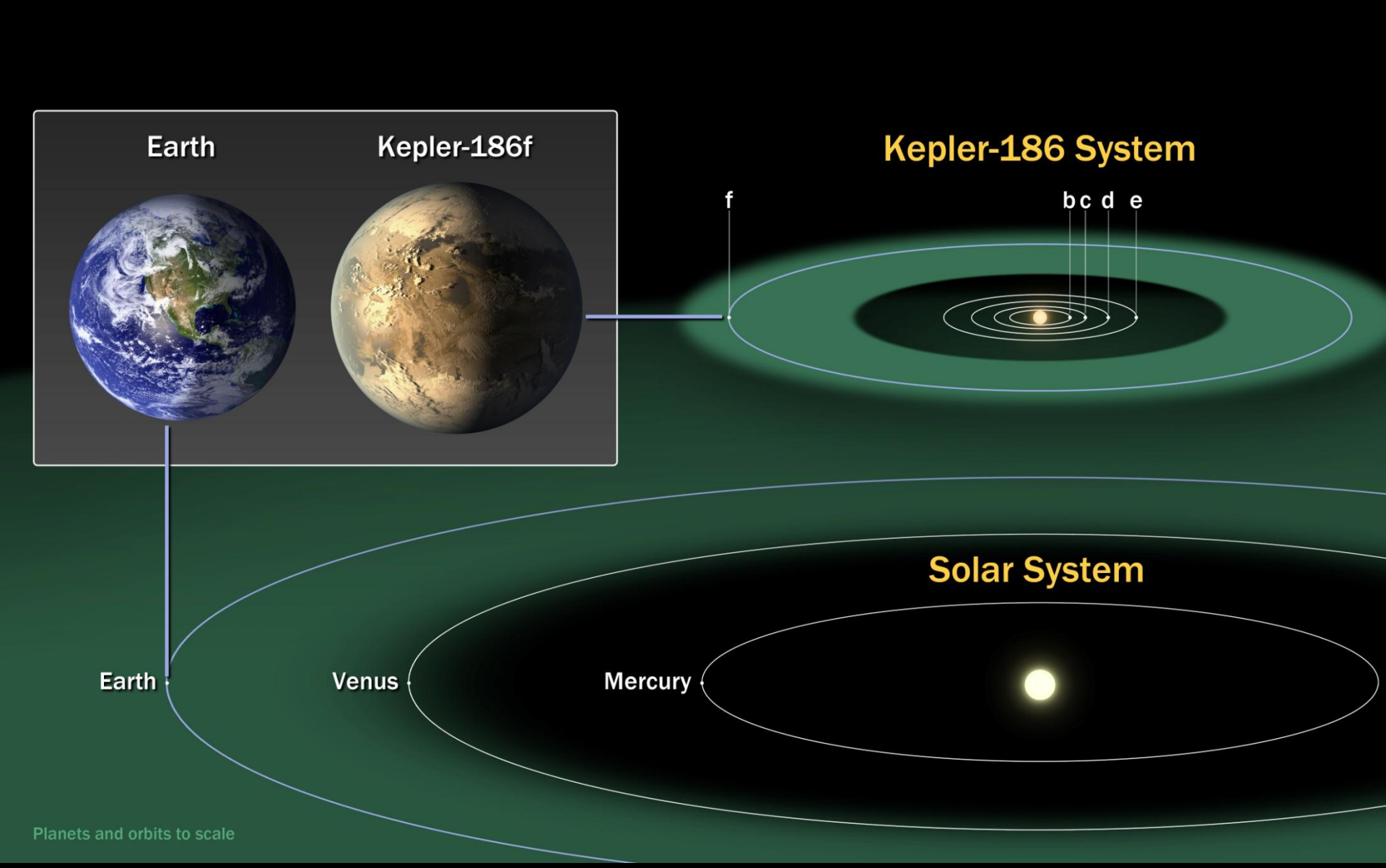


Gliese 667C e

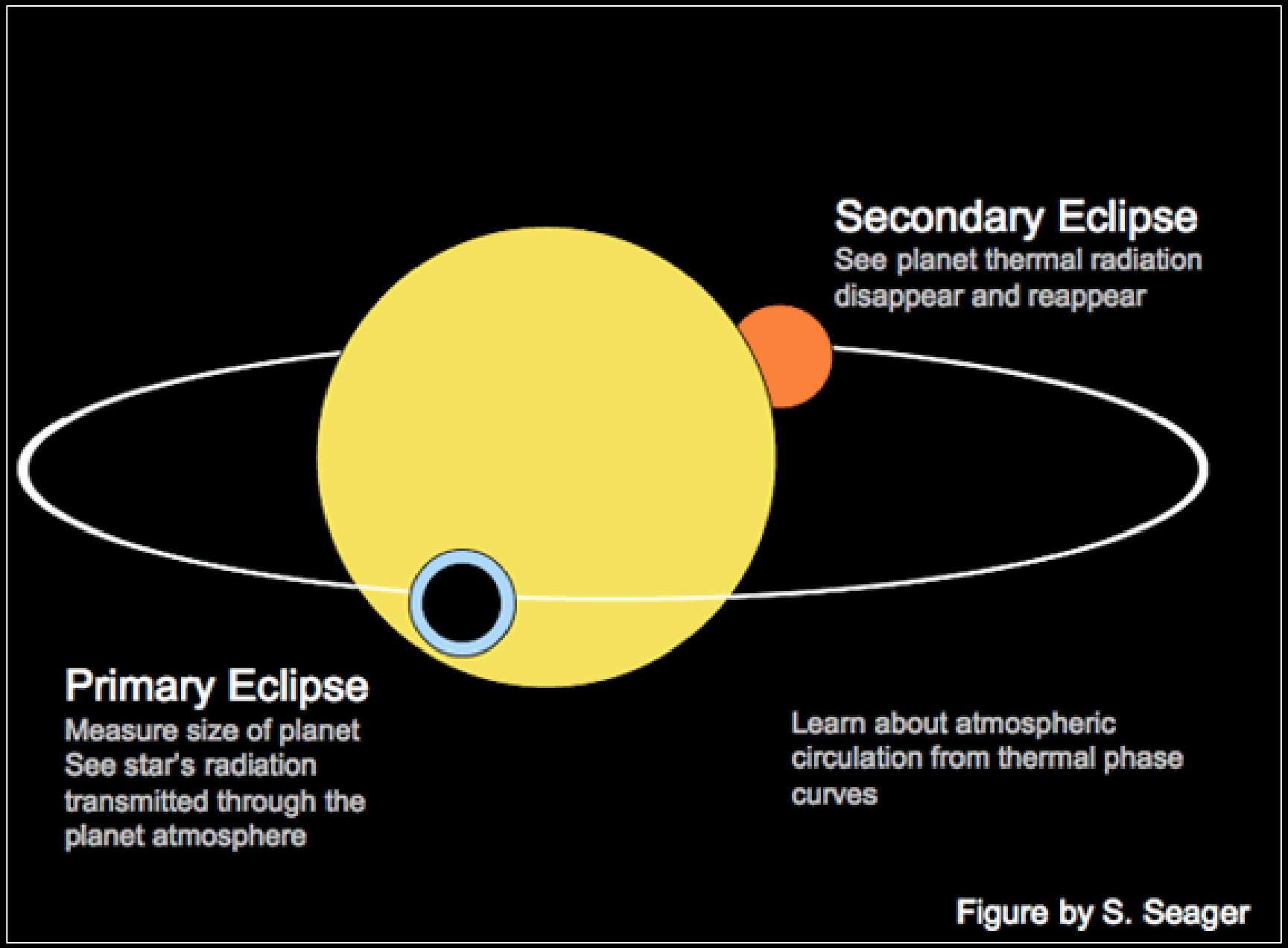
Gliese 581 d

*planet candidates

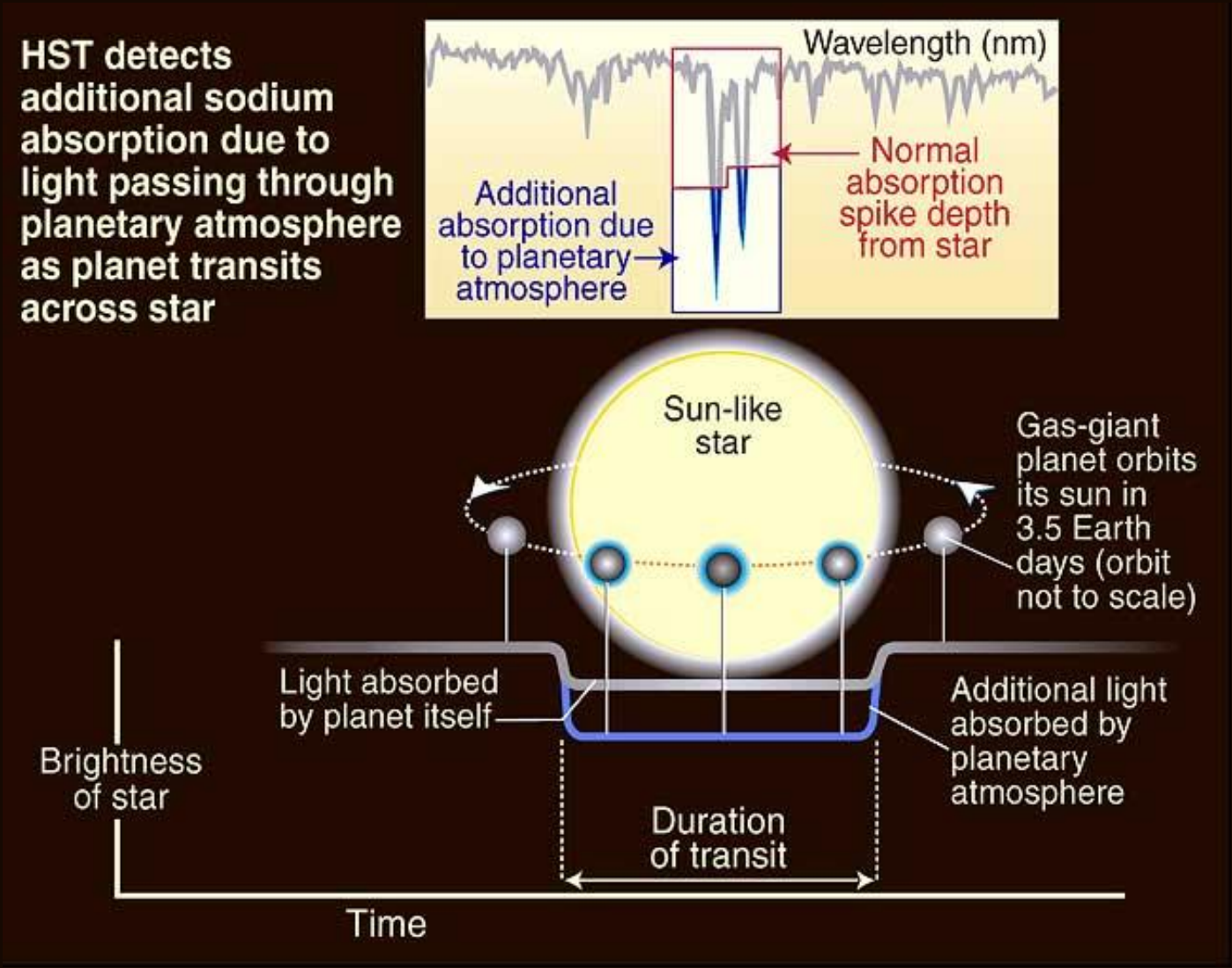
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) December 5, 2013

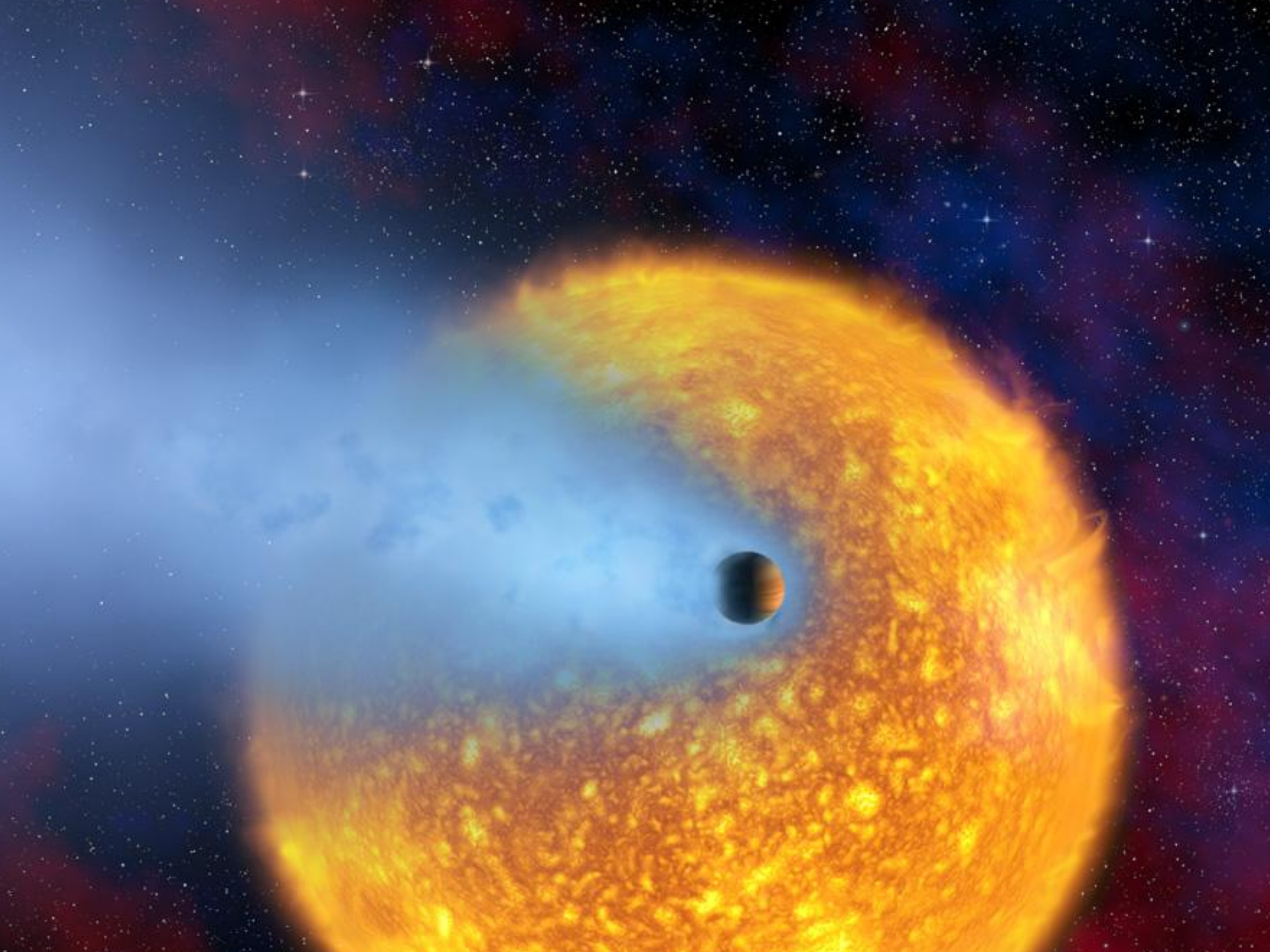


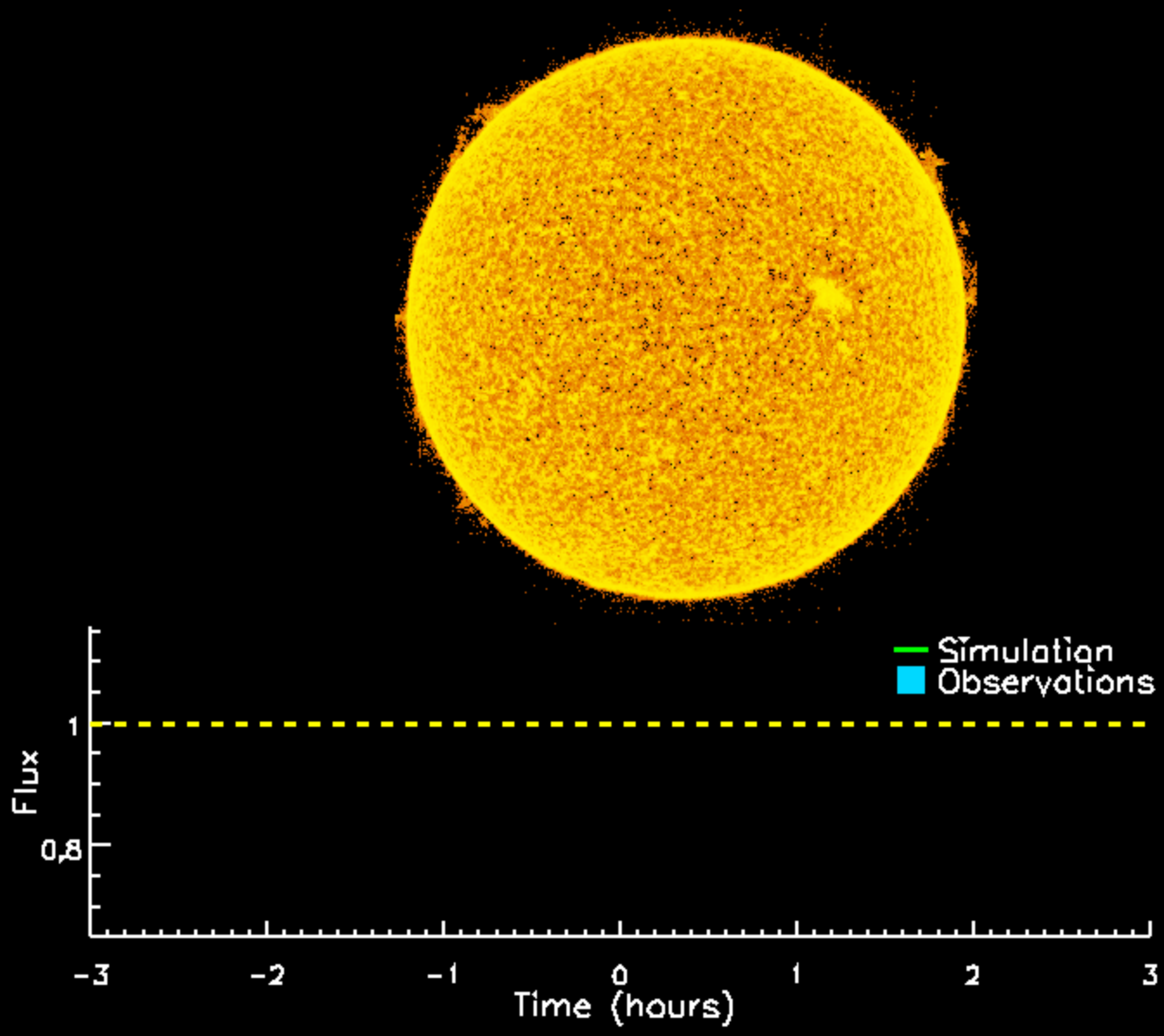
a = 0.356 AU; P = 130 d; R = 1.1 R_T


Secondary Eclipse
See planet thermal radiation disappear and reappear
Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere
Learn about atmospheric circulation from thermal phase curves
Figure by S. Seager

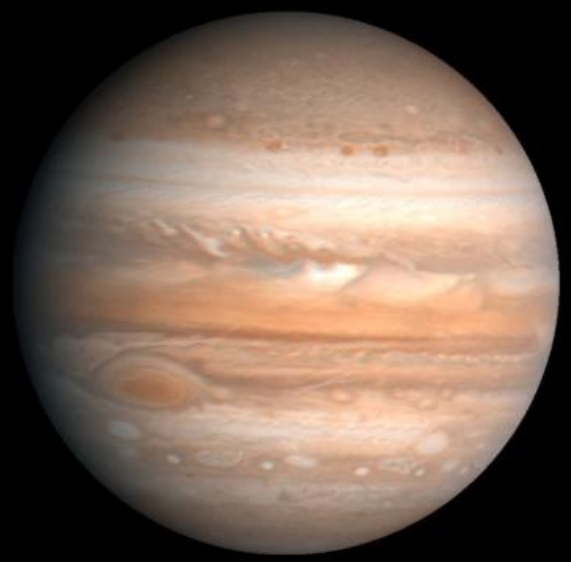
Sistema HD209458

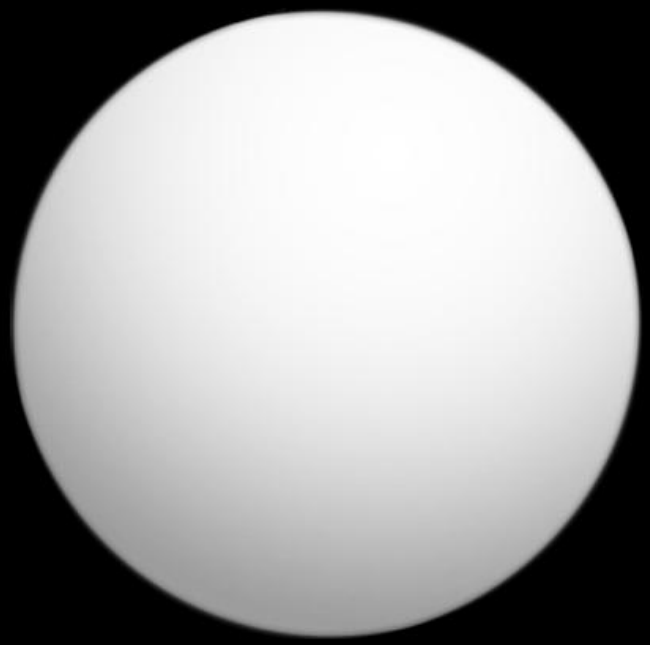





Simulation
Observations
Flux
1
0,8
-3
-2
-1
0
1
2
3
Time (hours)

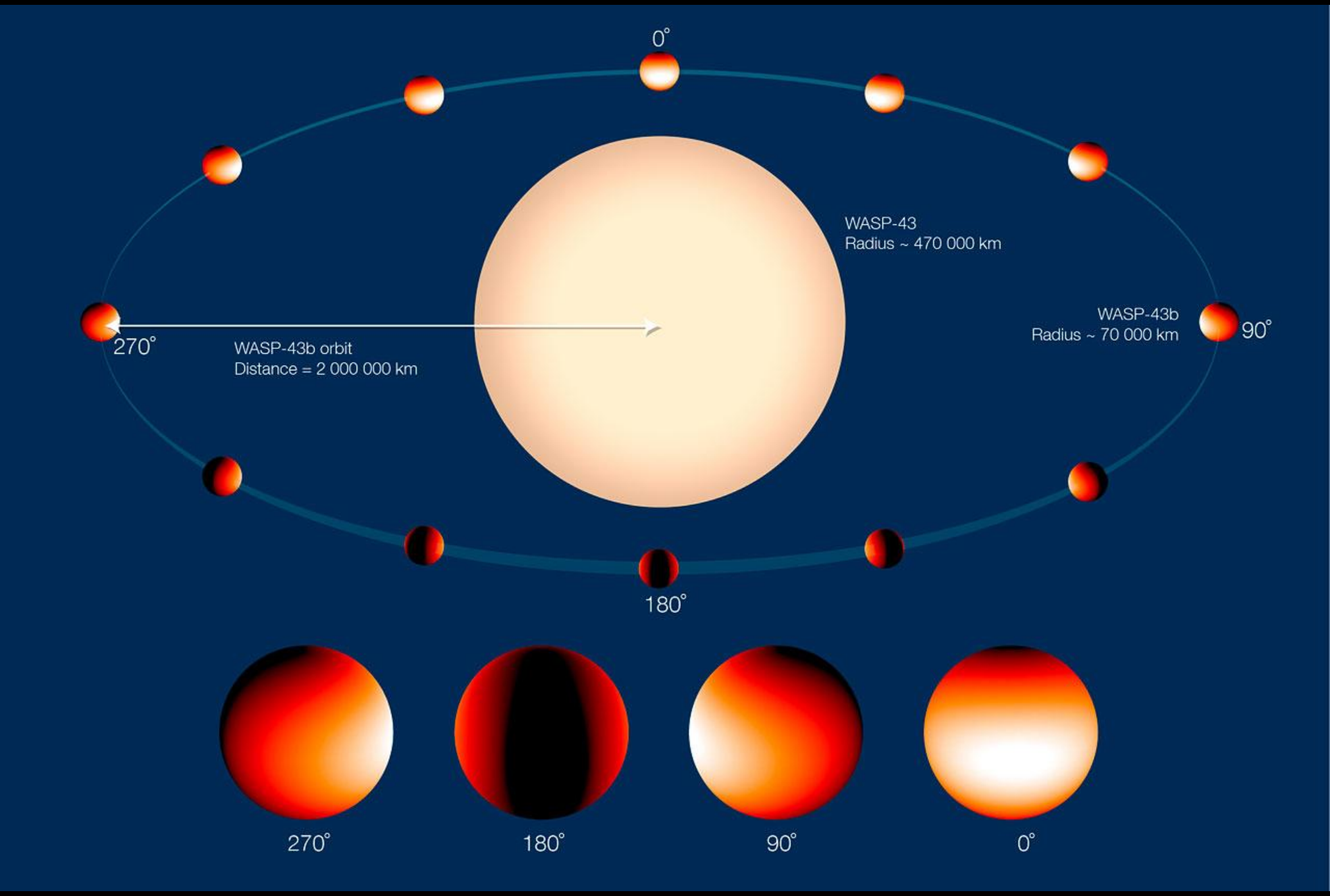
Sistema HD189733 (scoperta: 2005)



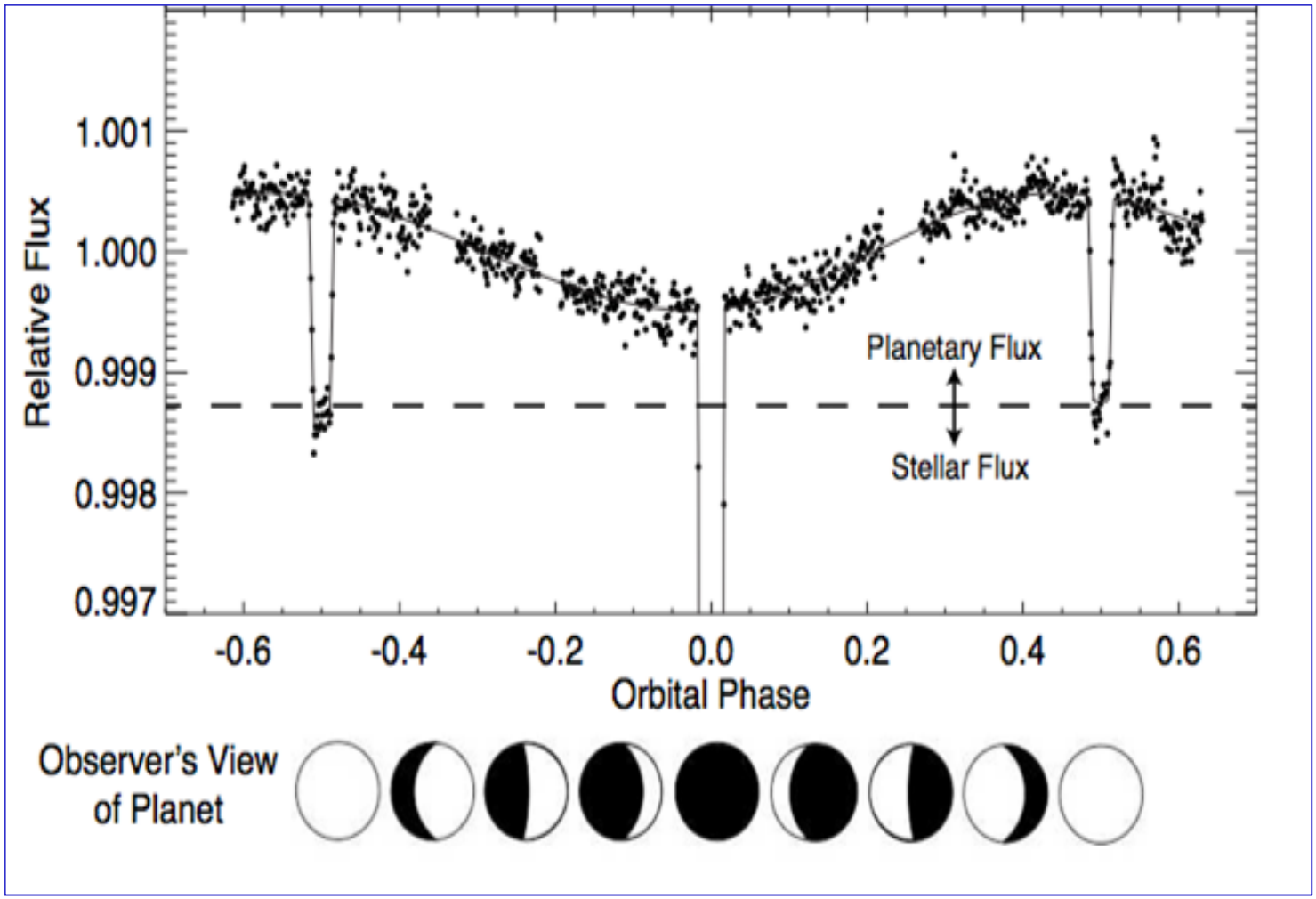


Massa = 1.13 M_J
Raggio = 1.14 R_J
a = 0.03 AU
P = 2.2 d

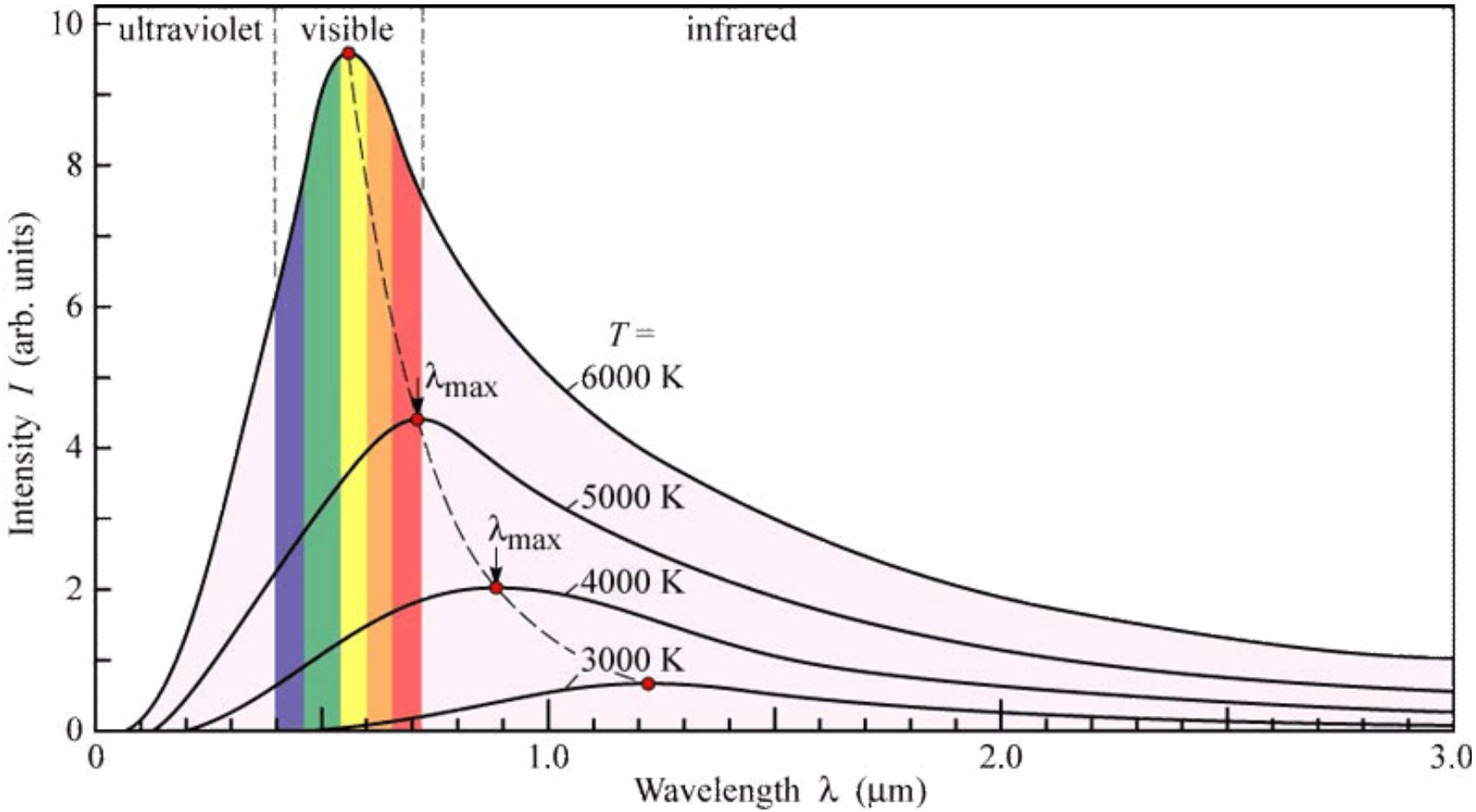
Composti rilevati: idrogeno, ossigeno, vapor d'acqua, metano, monossido di carbonio


0°
WASP-43
Radius ~ 470 000 km
WASP-43b
Radius ~ 70 000 km
90°
270°
WASP-43b orbit
Distance = 2 000 000 km
180°
270°
180°
90°
0°

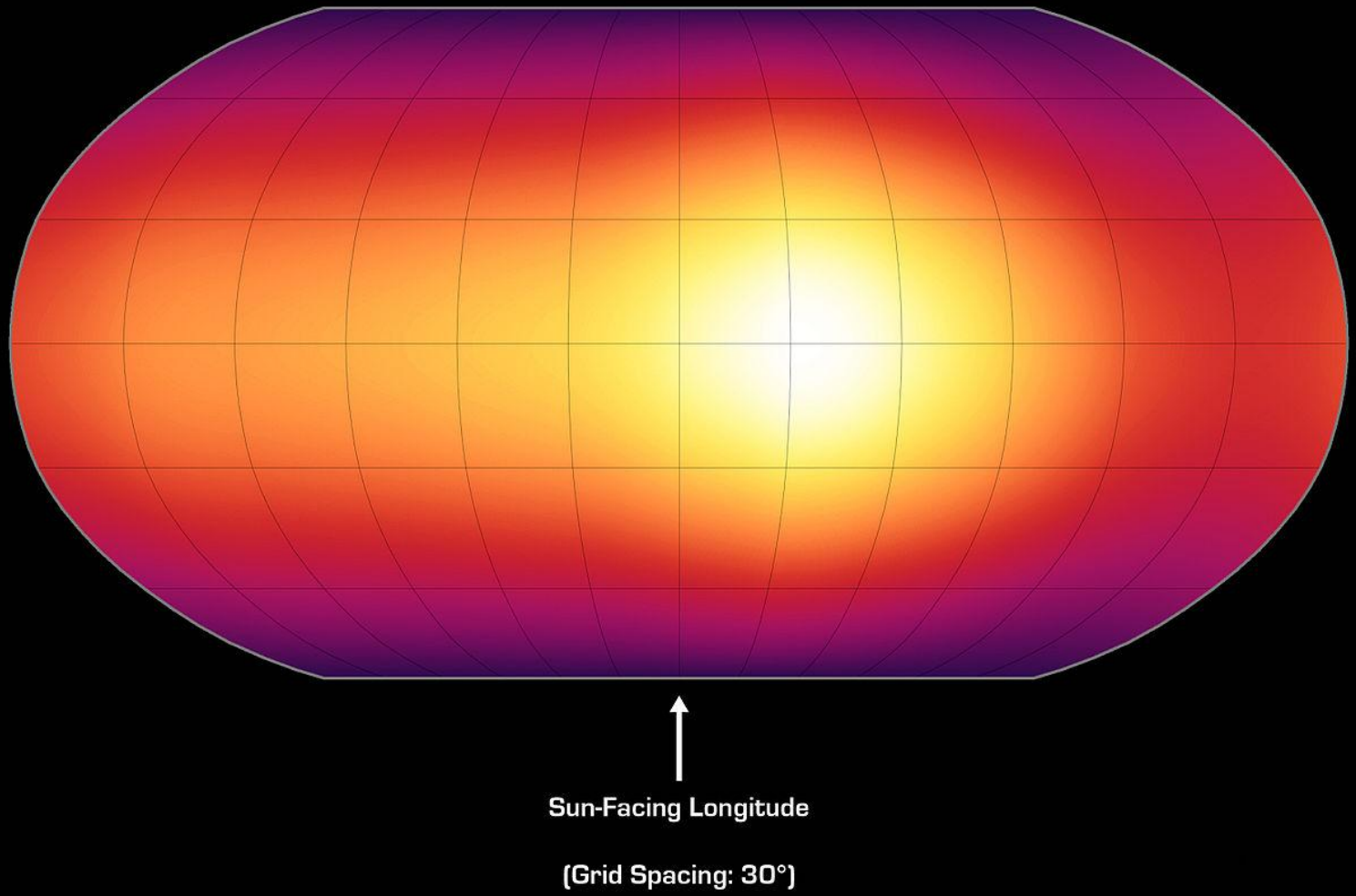
Fotometria infrarossa



Radiazione termica (di corpo nero)

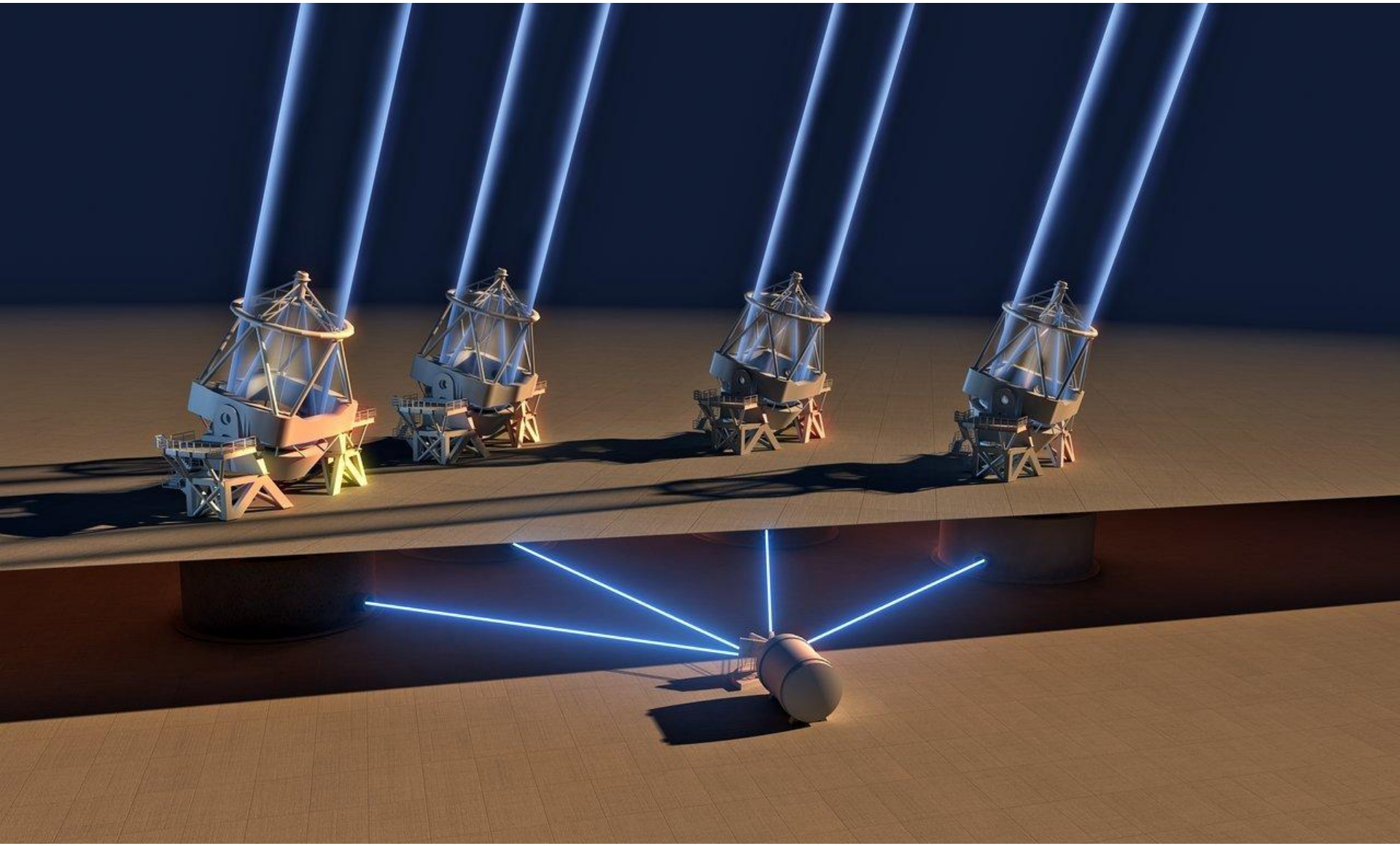


Sistema HD189733

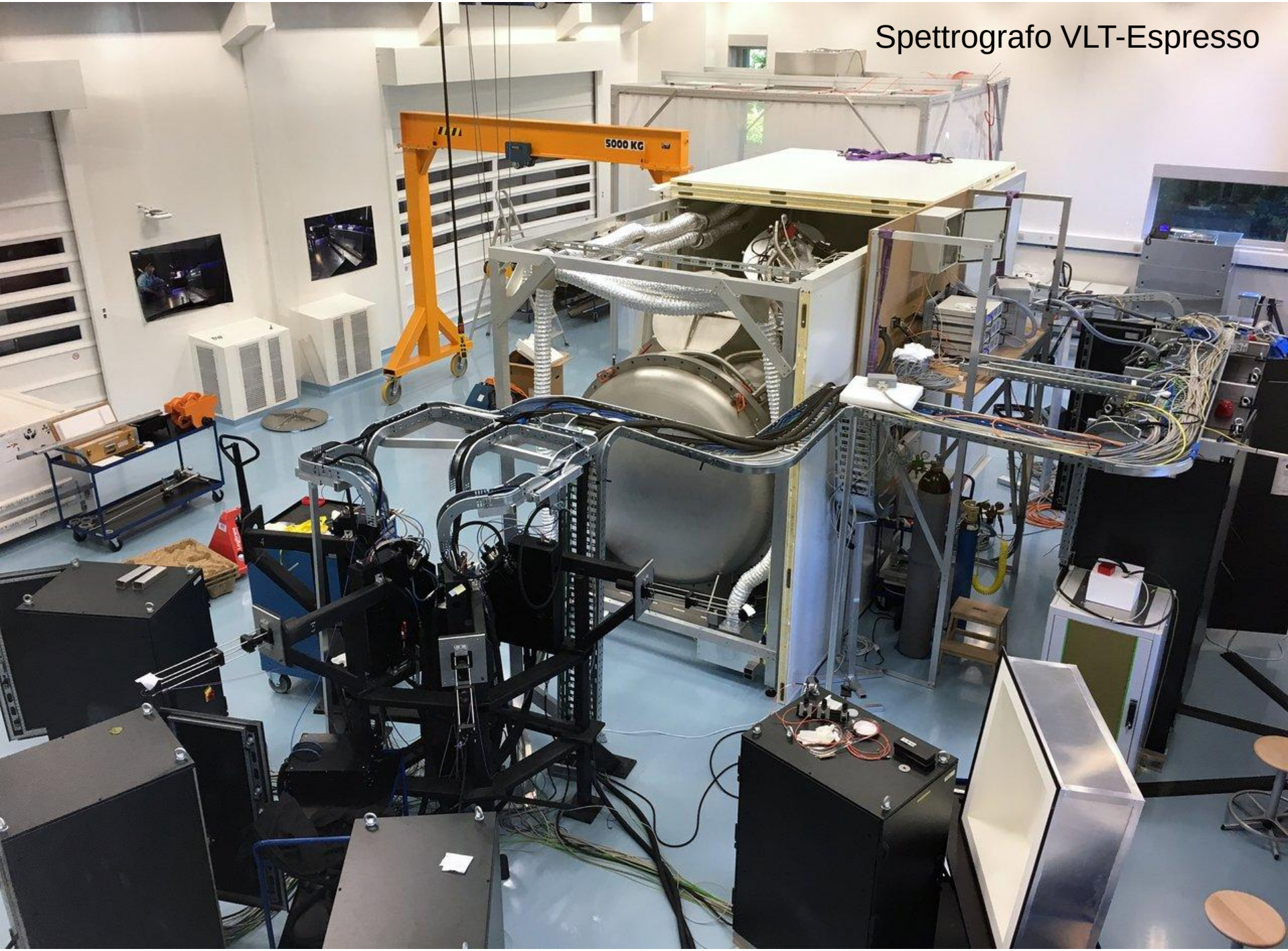


Global Temperature Map for Exoplanet HD 189733b Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / H. Knutson (Harvard-Smithsonian CfA) ssc2007-09a



ESO VLT (Cerro Paranal, Cile)

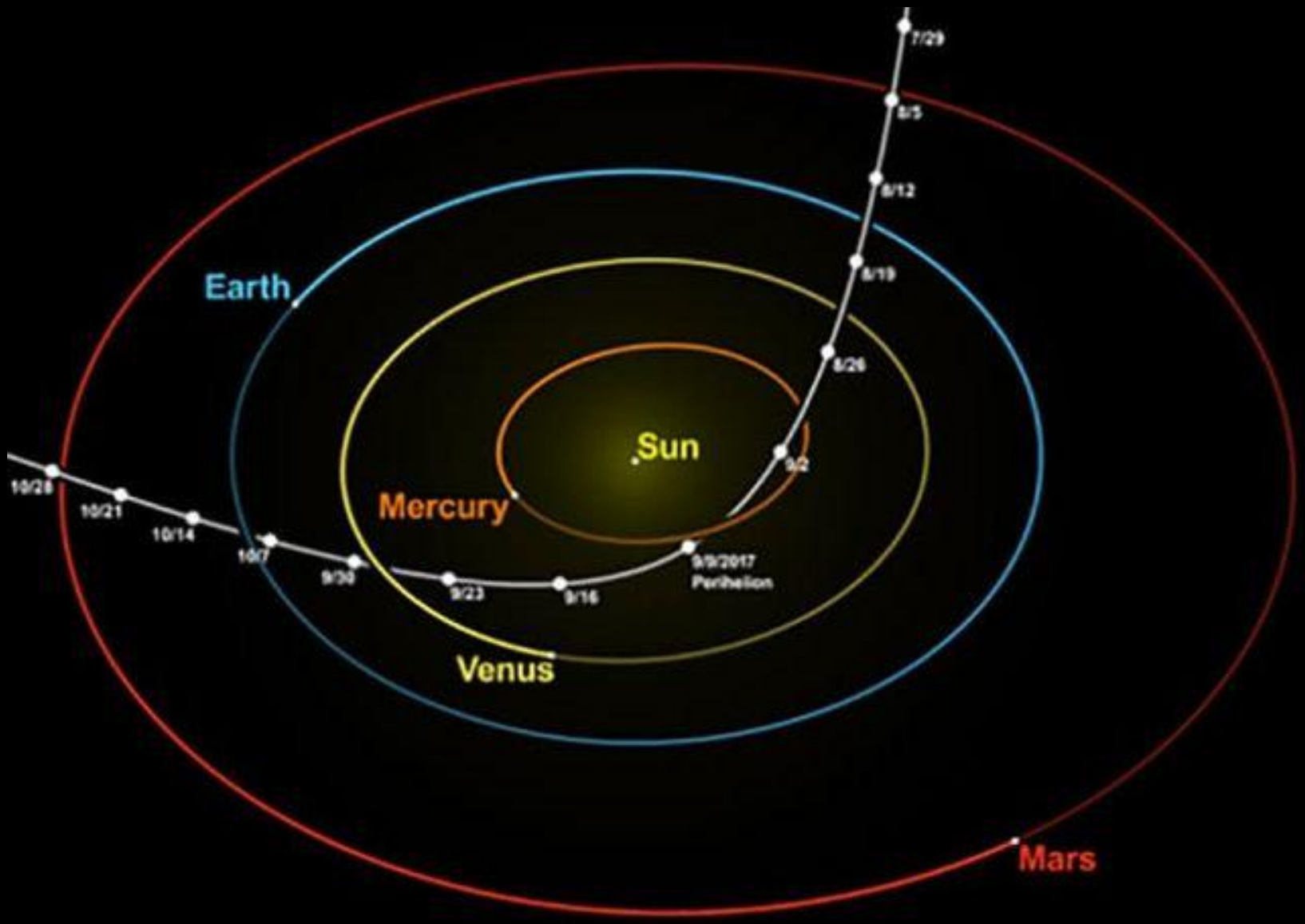


Spettrografo VLT-Espresso

Oggetti di origine interstellare

1I/'Oumuamua (2017)

2I/Borisov (2019)


7/29
8/5
8/12
8/19
8/26
9/2
9/9/2017
Perihelion
9/16
9/23
9/30
10/7
10/14
10/21
10/28
Earth
Sun
Mercury
Venus
Mars

Bibliografia

Giovanna Tinetti,
I pianeti extrasolari. Alla ricerca di nuovi mondi nella nostra galassia,
Il Mulino (2013)

Bibliografia

Iris Fry,
L'origine della vita sulla Terra,
Garzanti (2002, orig. 2000)

Bibliografia

Stephen Webb,
Se l'universo brulica di alieni... dove sono tutti quanti? 75 soluzioni al paradosso di Fermi sulla vita extraterrestre,
Sironi ed. (2018)

Siti web

- Wikipedia (inglese!)
- The Extrasolar Planet Encyclopedia (exoplanet.eu)

The Extrasolar Planets Encyclopaedia

Prima versione: Febbraio 1995
Jean Schneider, CNRS/LUTH - Osservatorio di Parigi
Last update: 17 gennaio 2013 (859 planets)
Please report any problems to vo.exoplanet@obspm.fr

Catalog

Filter, sort, export — arbitrary data manipulations with the Extrasolar Planets Encyclopaedia

Diagrams

Analyze the Extrasolar Planets Encyclopaedia data online. Simple plotting tool right in the browser

News

22 settembre 2011 KIC 10905746 b e KIC 6185331 b: i primi 2 Kepler candidati pianeti transitanti rivelati da PlanetHunters (Fischer et al.).

15 settembre 2011 Kepler-16 (AB)b : il primo pianeta transitante attorno a un binaria (Doyle et al.)

12 settembre 2011 41 nuovi pianeti HARPS tra cui 16 Super-Terre - Mayor et al.) et 23 nuovi pianeti WASP.
HD 97658 b è un pianeta transitante (Henry et al.).

31 agosto 2011 Un pianeta abitabile attorno a HD 85512? E cinque altre super-Terre (Pepe et al).
PSR 1719-14 b: un nuovo pianeta attorno a una pulsar (Bailes et al.).

02 febbraio 2011 6 pianeti attorno alla stella Kepler-11, tutti transitanti (Lissauer et al.)

Informazioni introduttive

Last update: 17 maggio 2012

Bibliografia

Last update: 17 maggio 2012

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Last update: 18 aprile 2012

Congressi

Last update: 17 maggio 2011

Lavoro teorico

Last update: 03 aprile 2012

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Last update: 16 aprile 2012