

La cerca de vida més enllà del sistema solar

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Investigador Ramón y Cajal

Institut de Ciències de l'Espai/CSIC

Institut d'Estudis Espacials de Catalunya (IEEC)

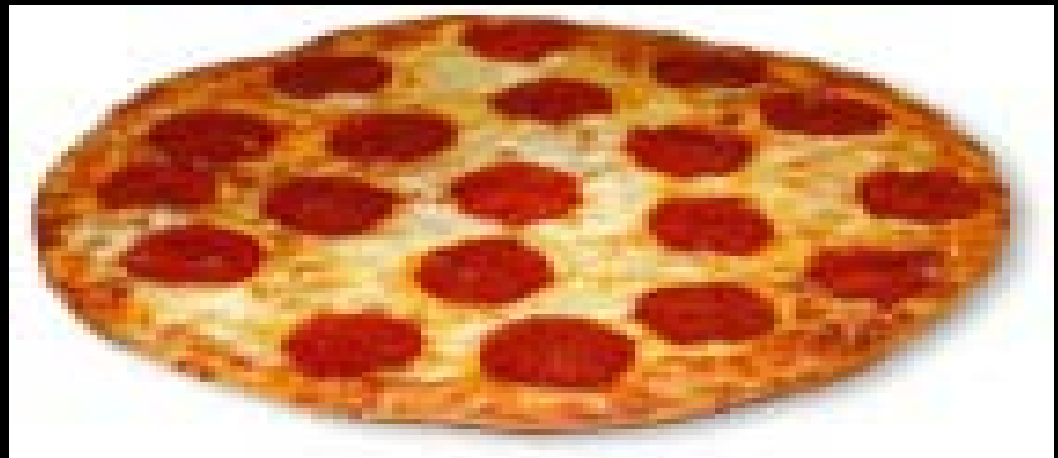
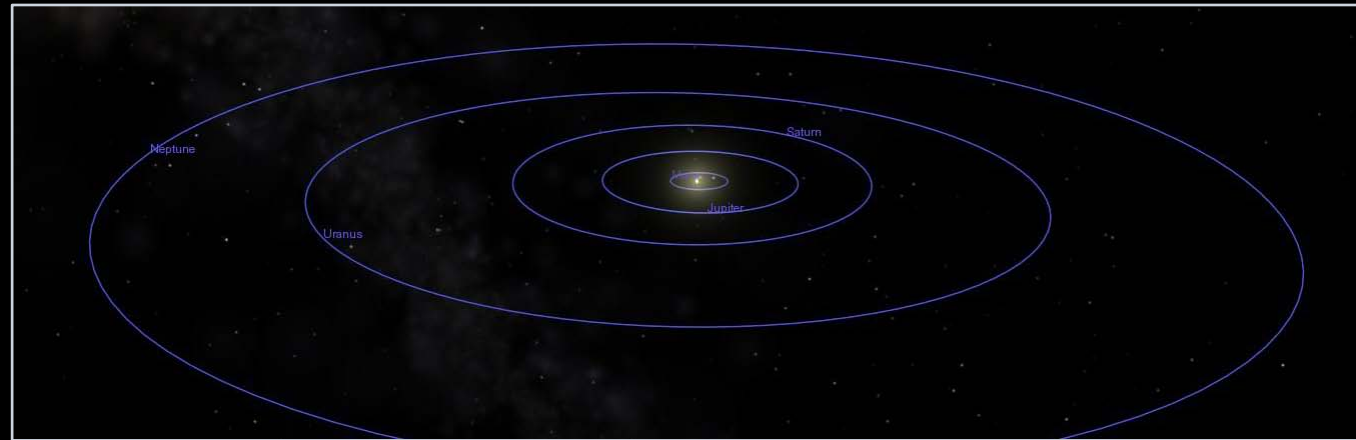




L'entorn Solar i nanes vermelles

Sistema Solar

Exterior



Estels propers



Alpha
Centauri



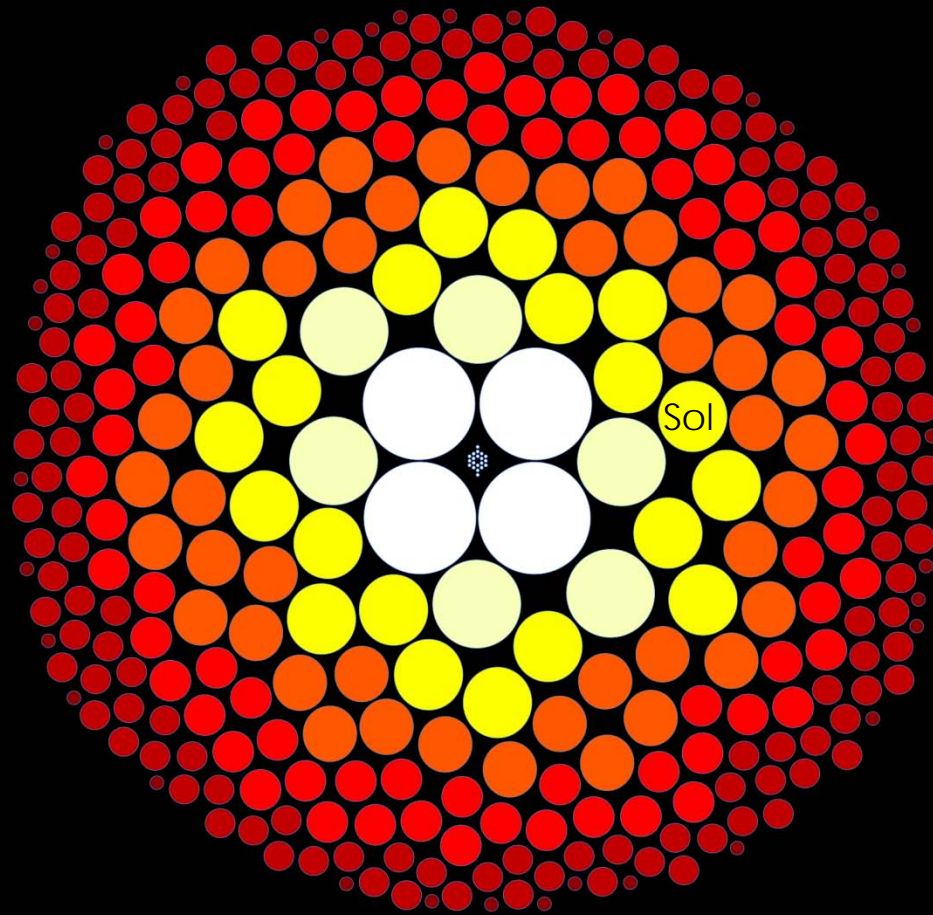
Estels propers

Alpha
Centauri



Estels propers

10 pc sample

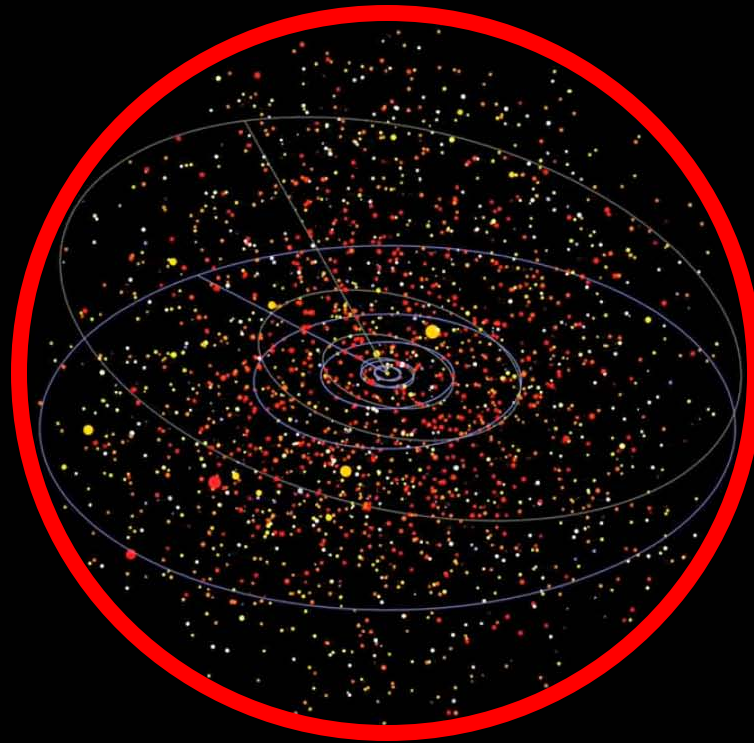


Credits : Todd Henry, RECONS group

www.recons.org

Missatge 1

La majoria d'estels son nanes
vermelles



Distance: 25.00 pc
Star Systems: 2167
Objects: 3069

The Solar neighborhood

L'entorn Solar







Detecció d'exoplanetes

És complicat...

Tau Ceti

Spectral type : G8V

Distance : 11.9 light-years

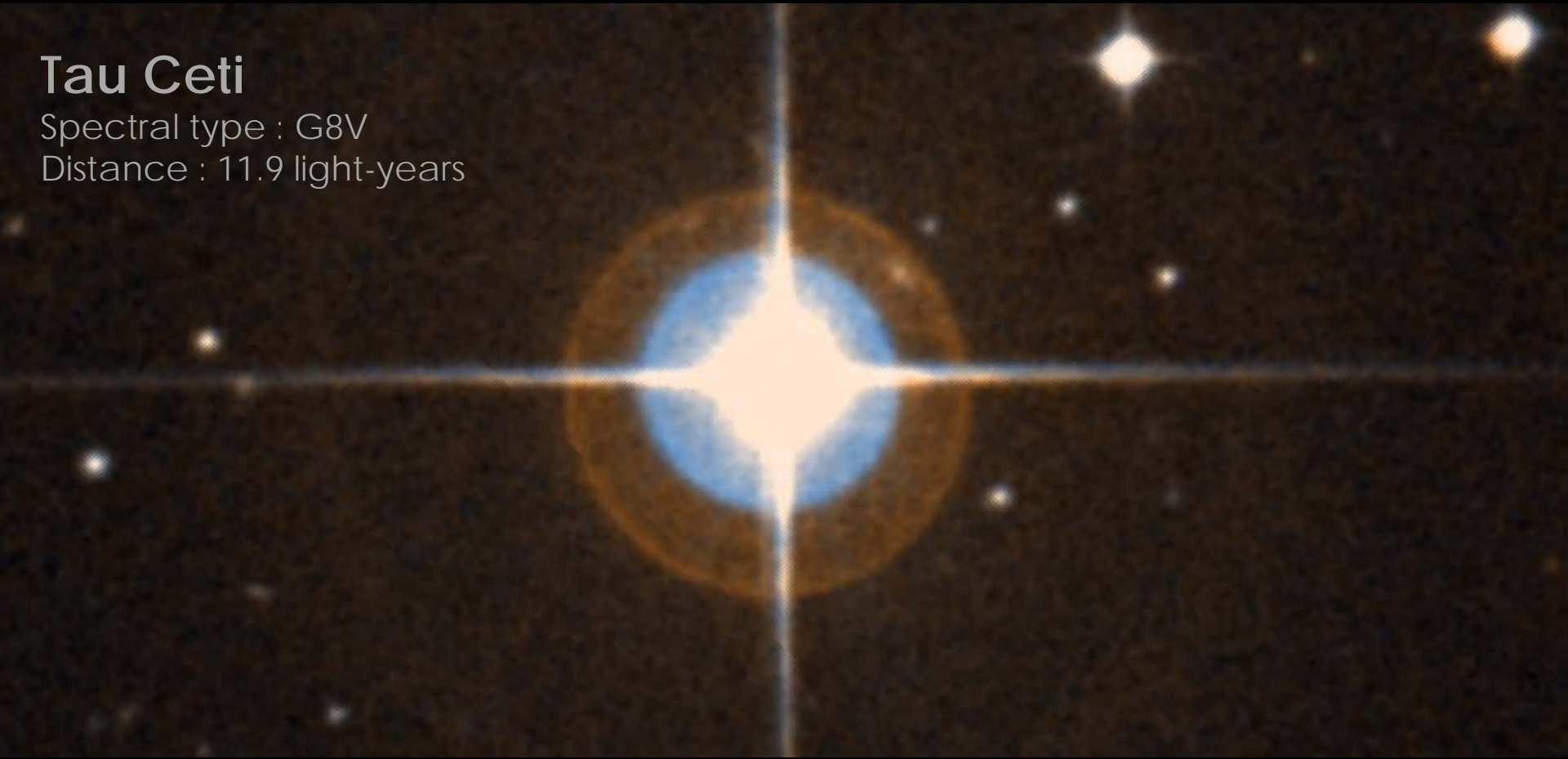


És complicat...

Tau Ceti

Spectral type : G8V

Distance : 11.9 light-years

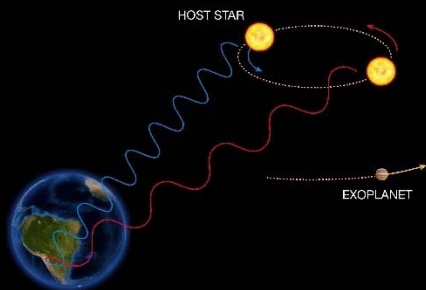




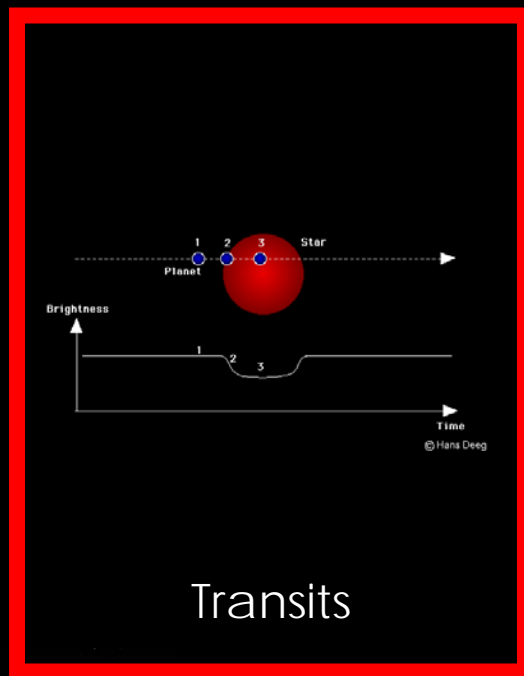


1 / 10 000 000 000

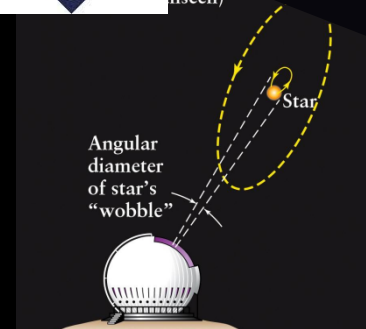
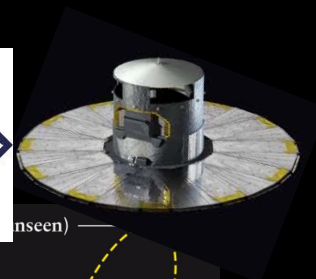
Com trovem planetes?



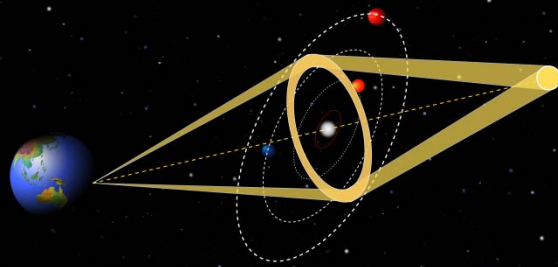
Radial velocity



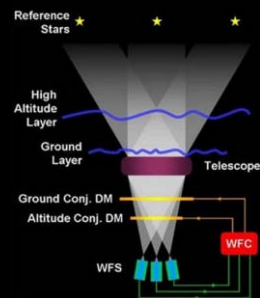
Transits



Astrometry

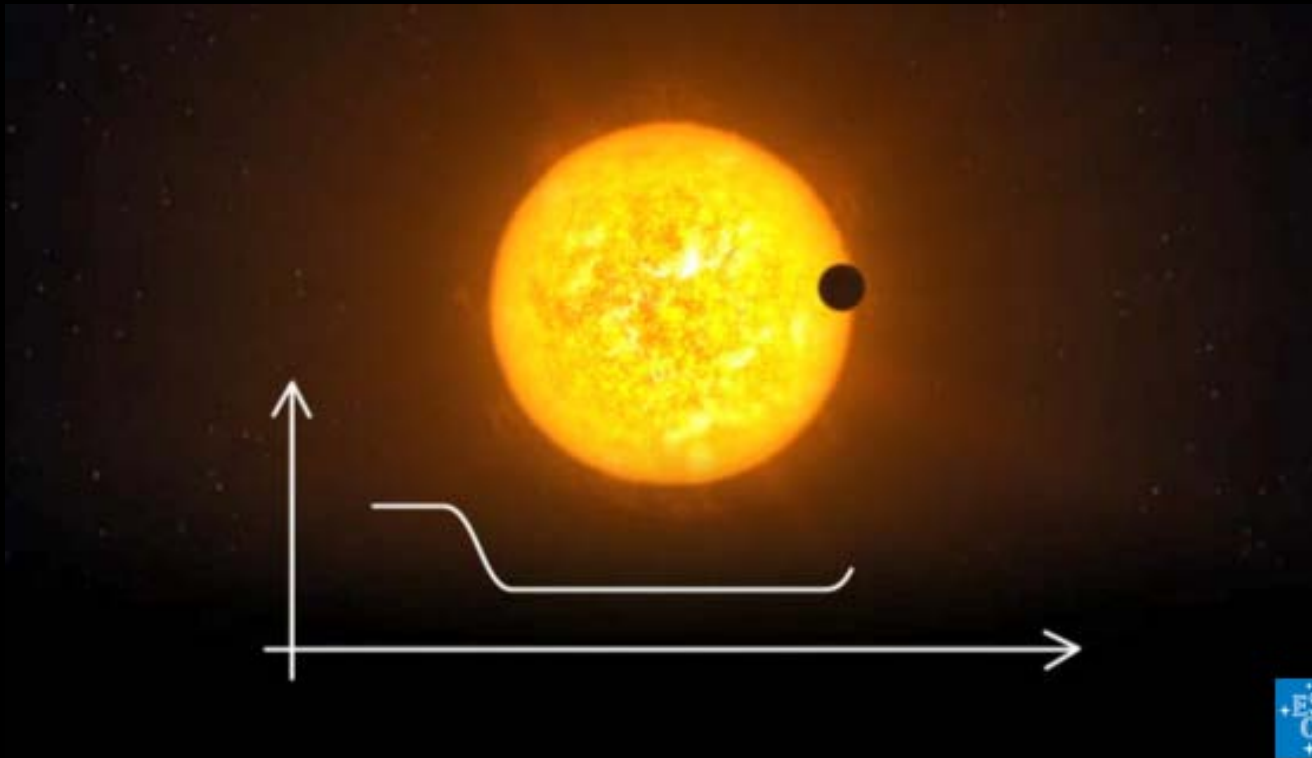


Microlensing

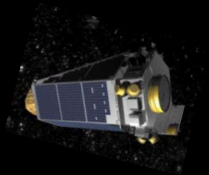
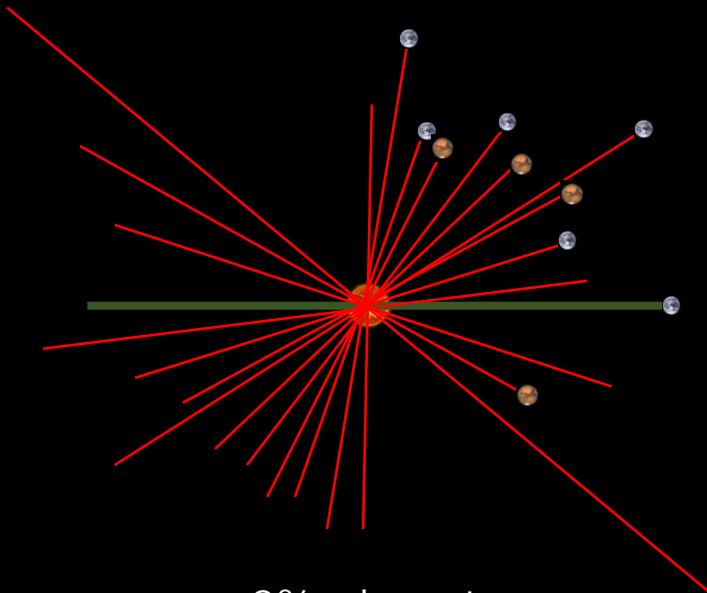
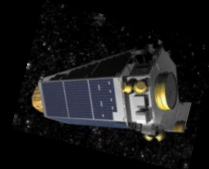
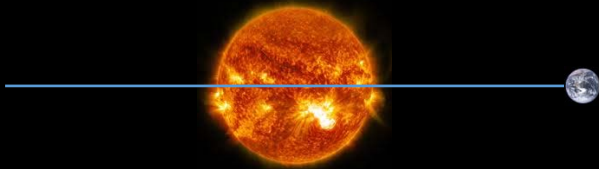
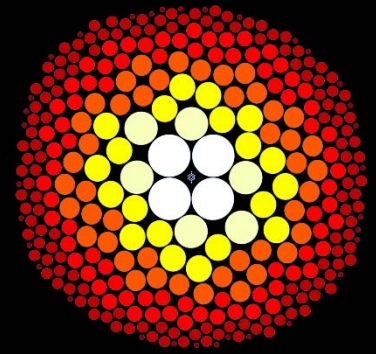


Direct imaging

Fotometria de trànsits



Fotometria de trànsits



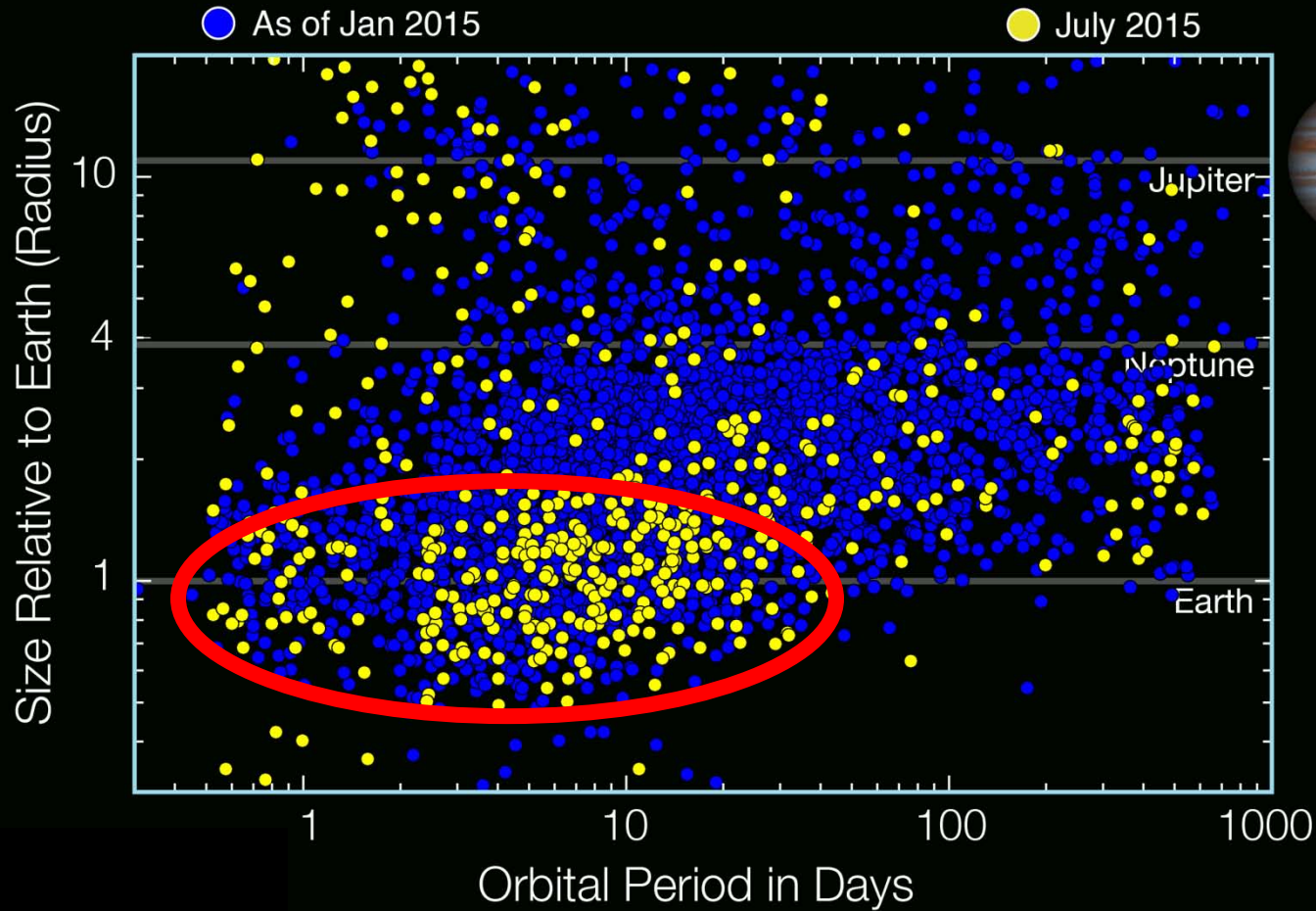
110 000 stars

~2% planets
transit

~2200 planets

**but ~4000
candidates!!**

Fotometria de trànsits



Resultats de Kepler/NASA

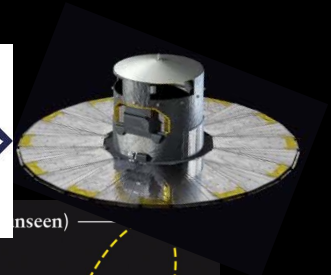
Missatge 1

La majoria d'estels son nanes
vermelles

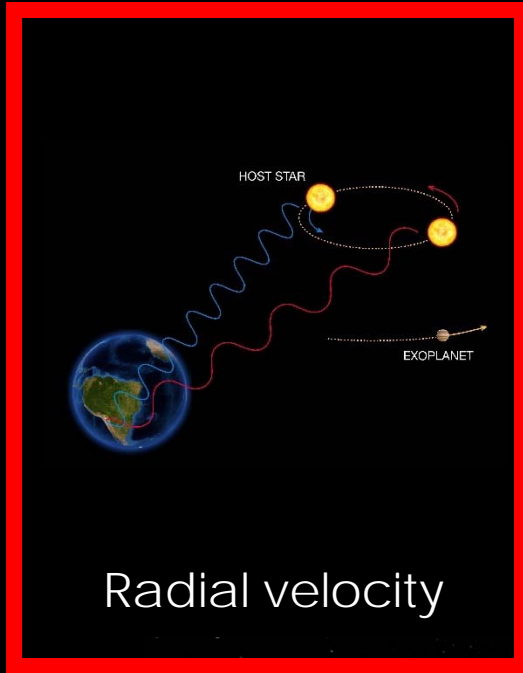
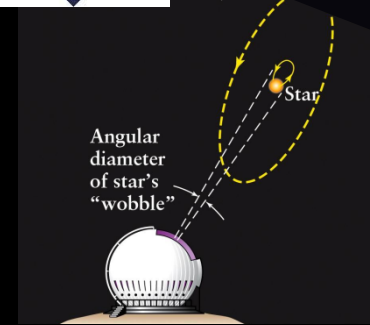
Missatge 2

La majoria d'estels tenen
planetes petits en periodes
orbitals curts

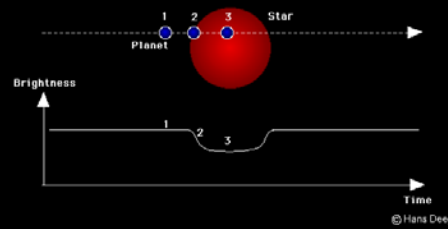
Com trovem exoplanets?



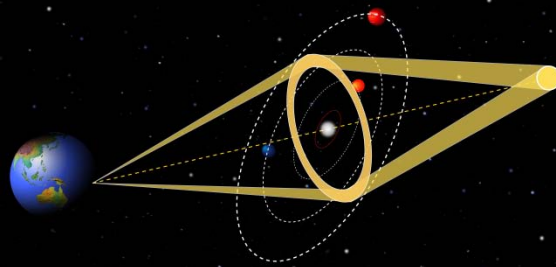
(unseen)



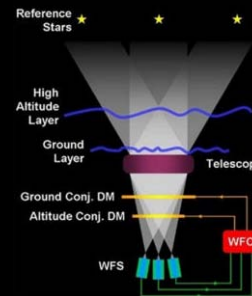
Radial velocity



Transits

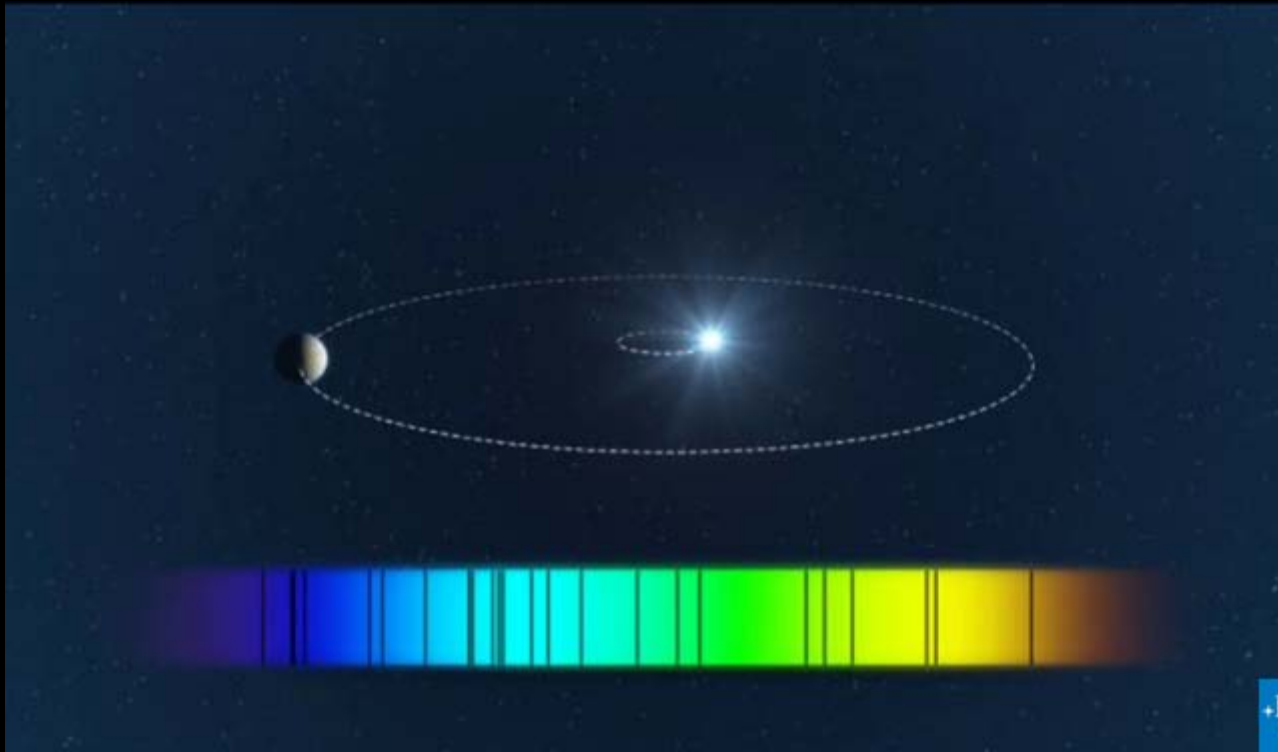


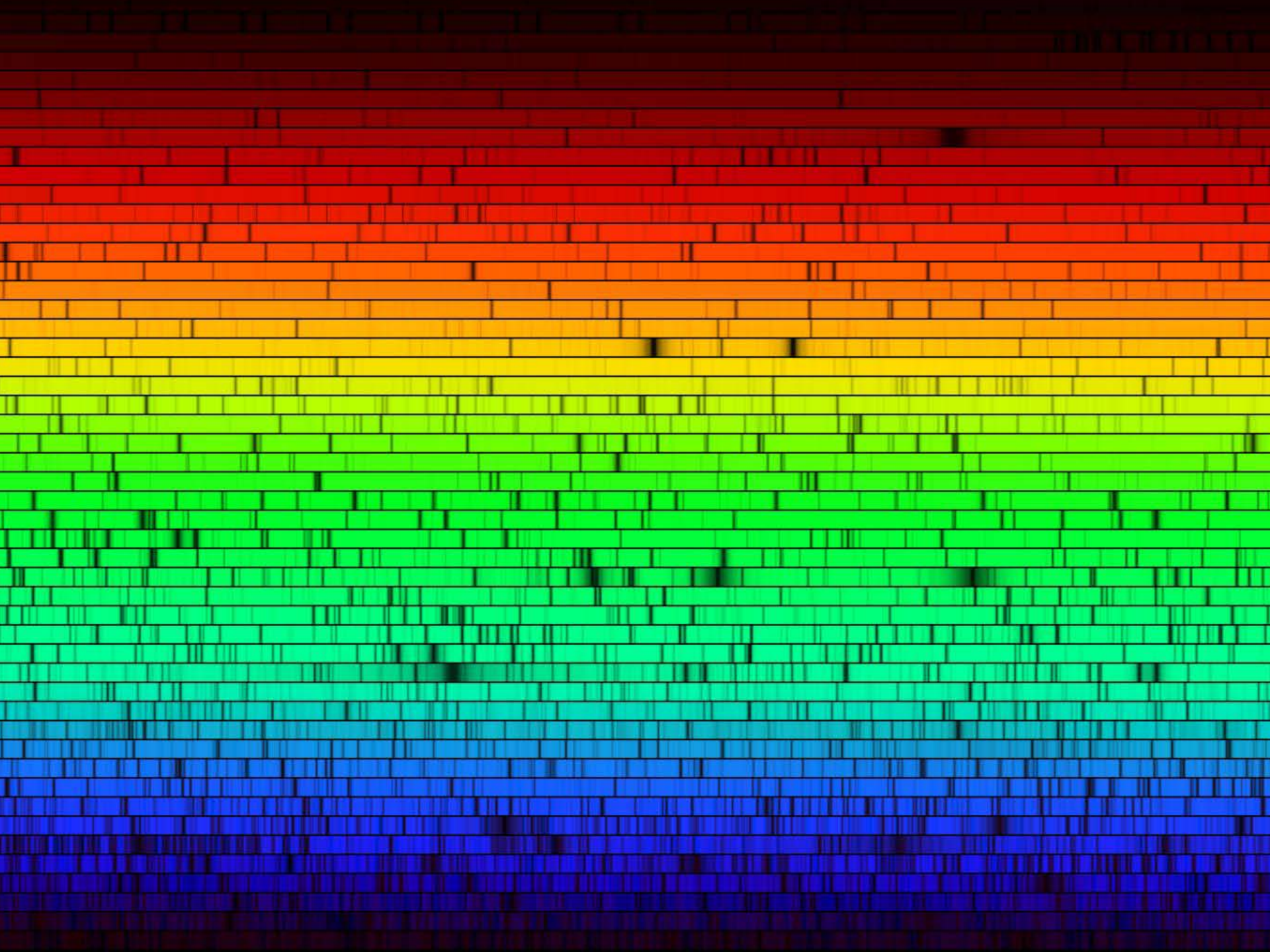
Microlensing



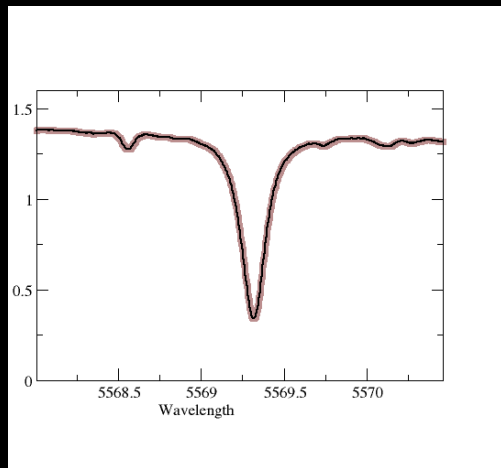
Direct imaging

El mètode de les velocitats radials



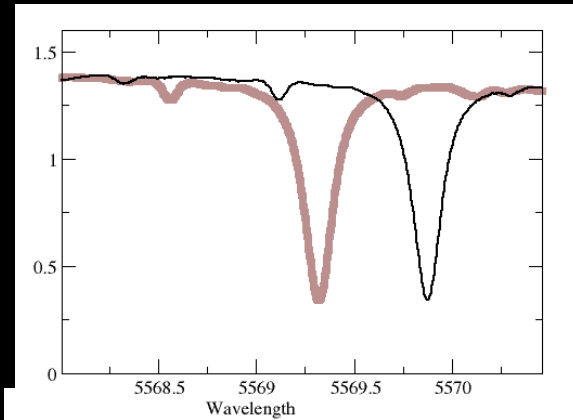


El mètode de les velocitats radials

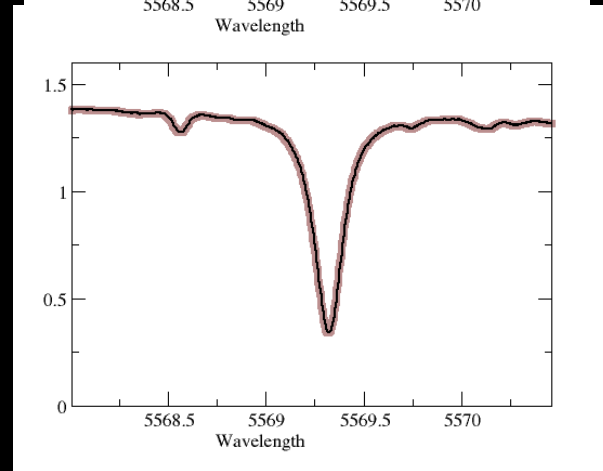


**Solar line is 15
km/s**

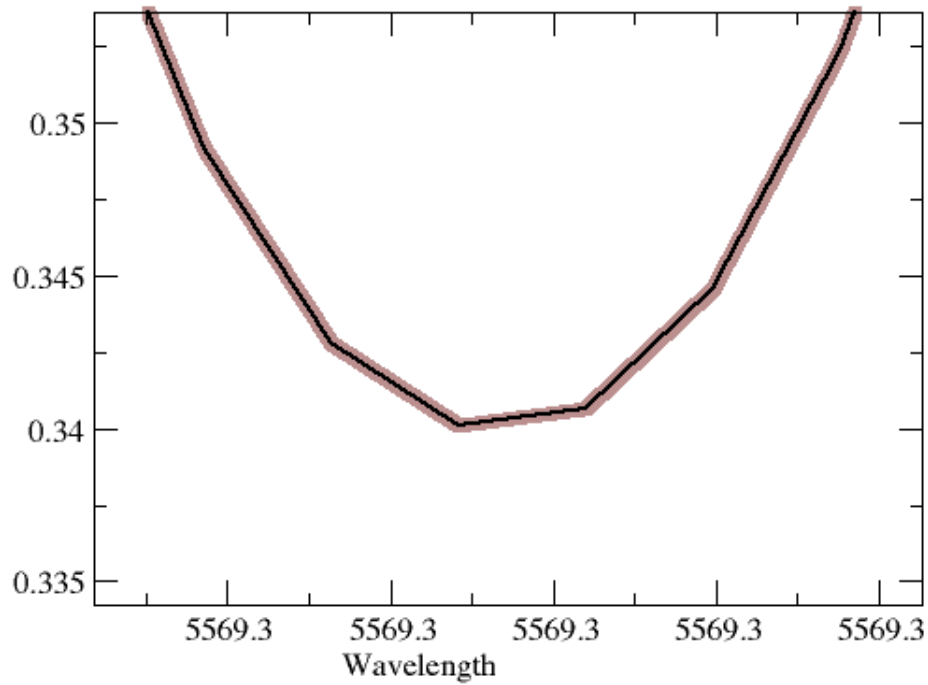
**Spectroscopic
binary
K=30 km/s**



**Hot jupiter
K=300 m/s**

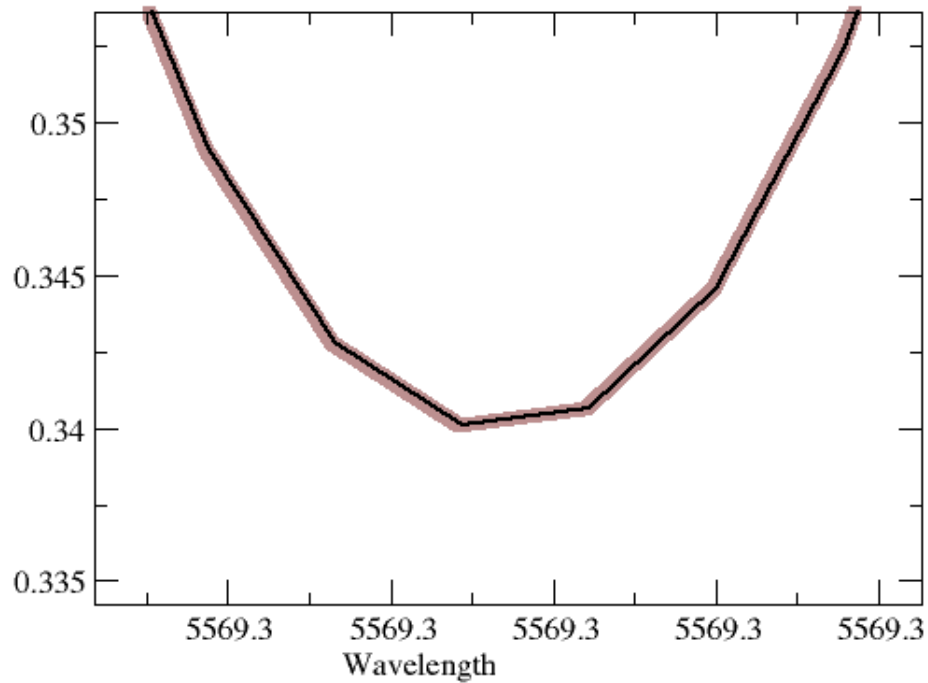


El mètode de les velocitats radials



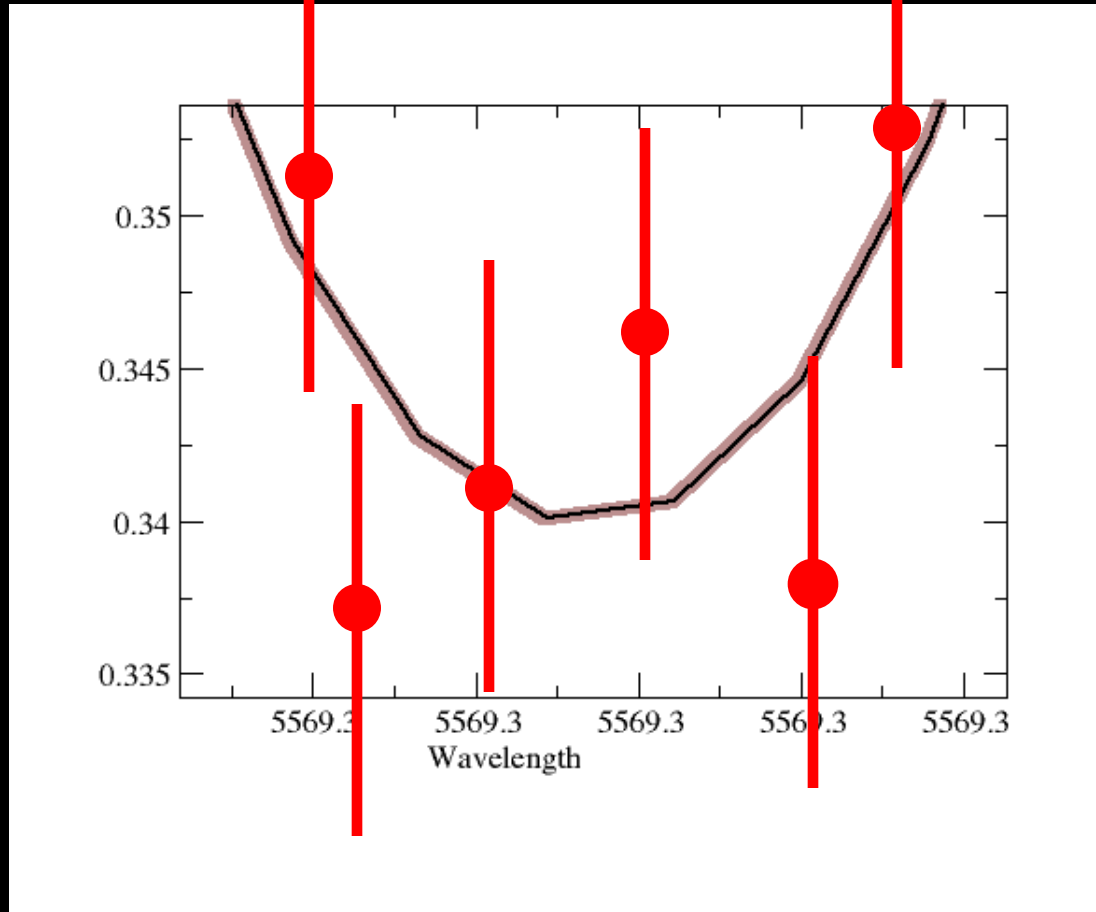
0 m/s

El mètode de les velocitats radials



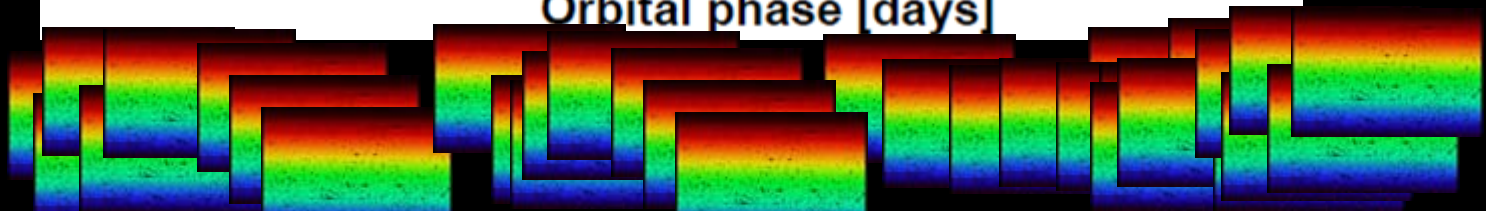
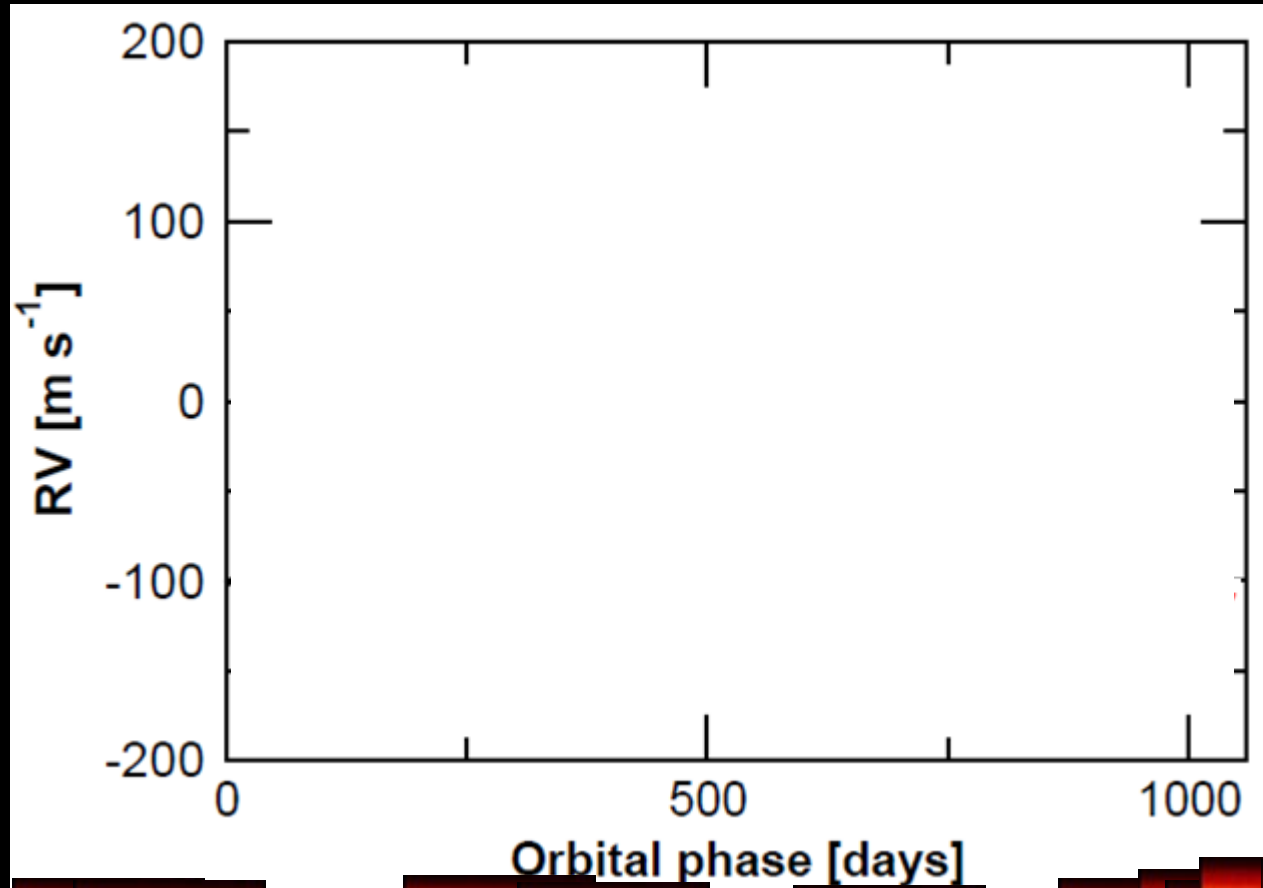
+ 3 m/s

El mètode de les velocitats radials

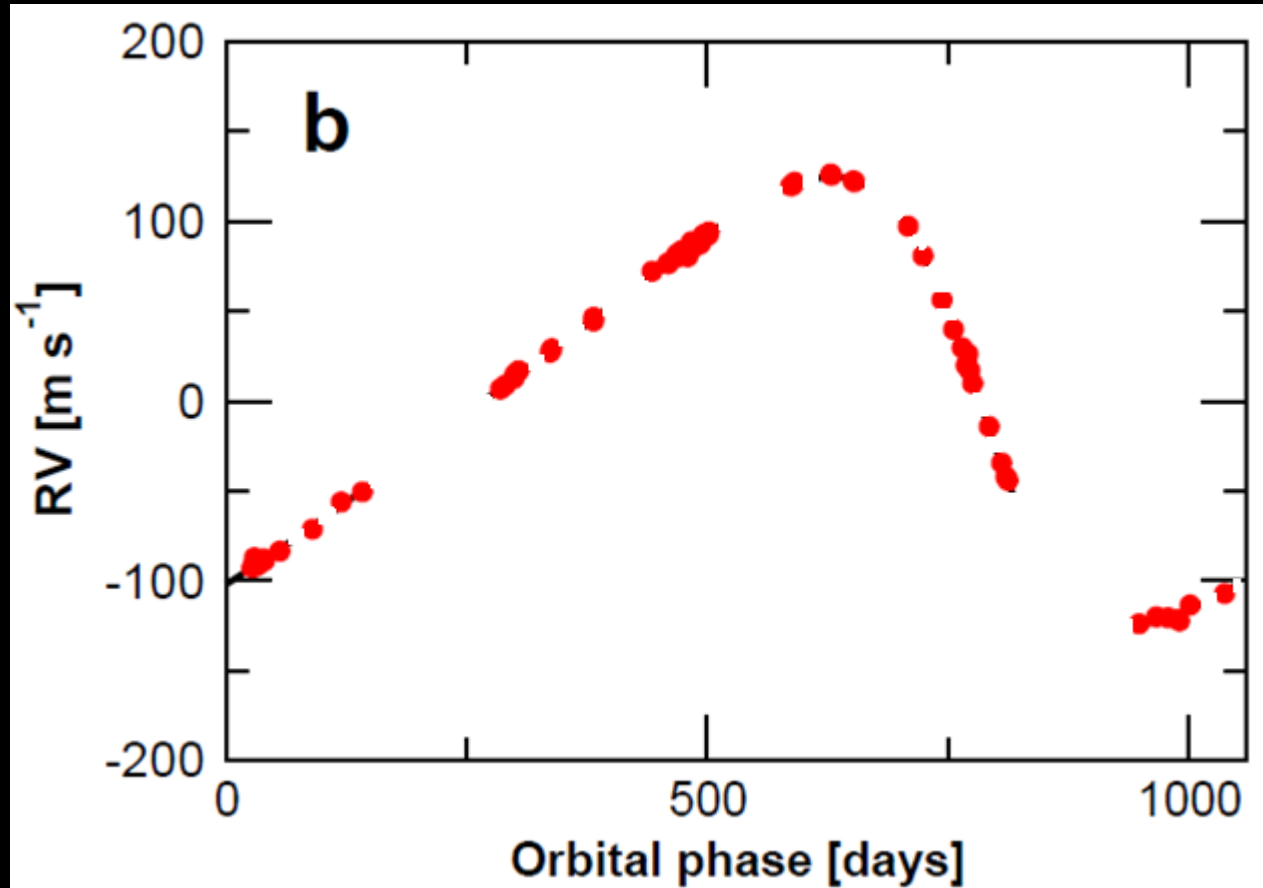


+ 3 m/s

El mètode de les velocitats radials



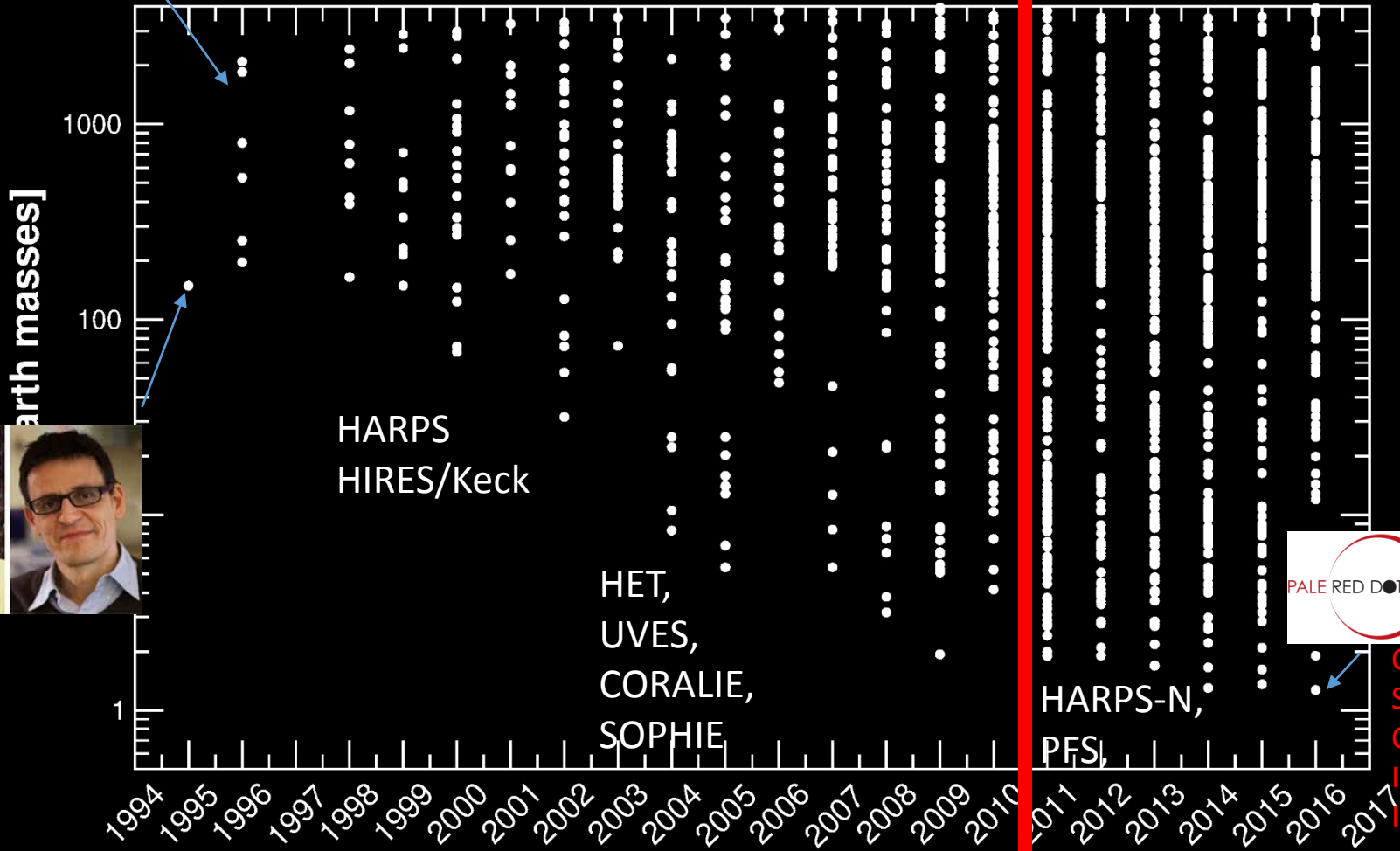
El mètode de les velocitats radials





El mètode de les velocitats radials

~1-2 m/s

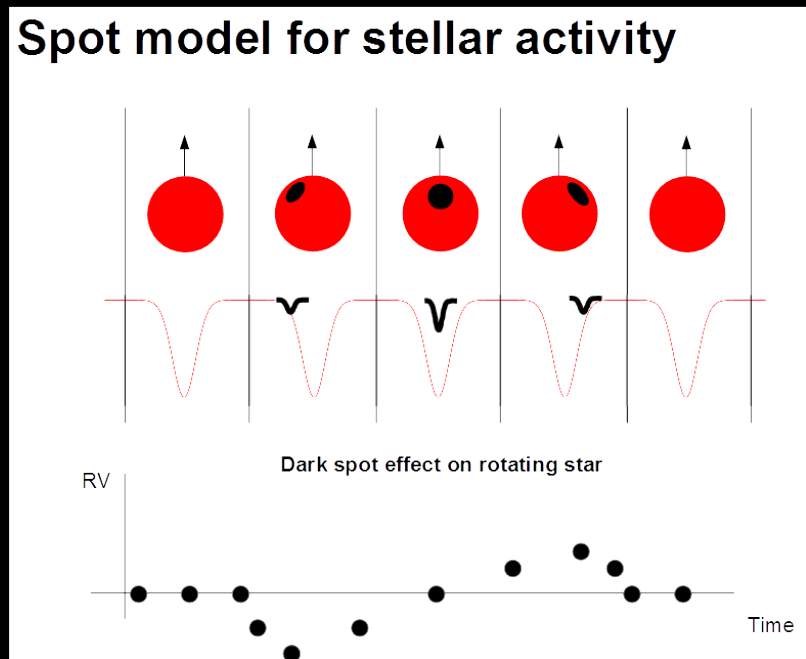


CARMENES
SPIROU,
CRIRES+,
IRS, HET,
IRTF/i-shell

ESPRESSO



Activitat estelar com a límit

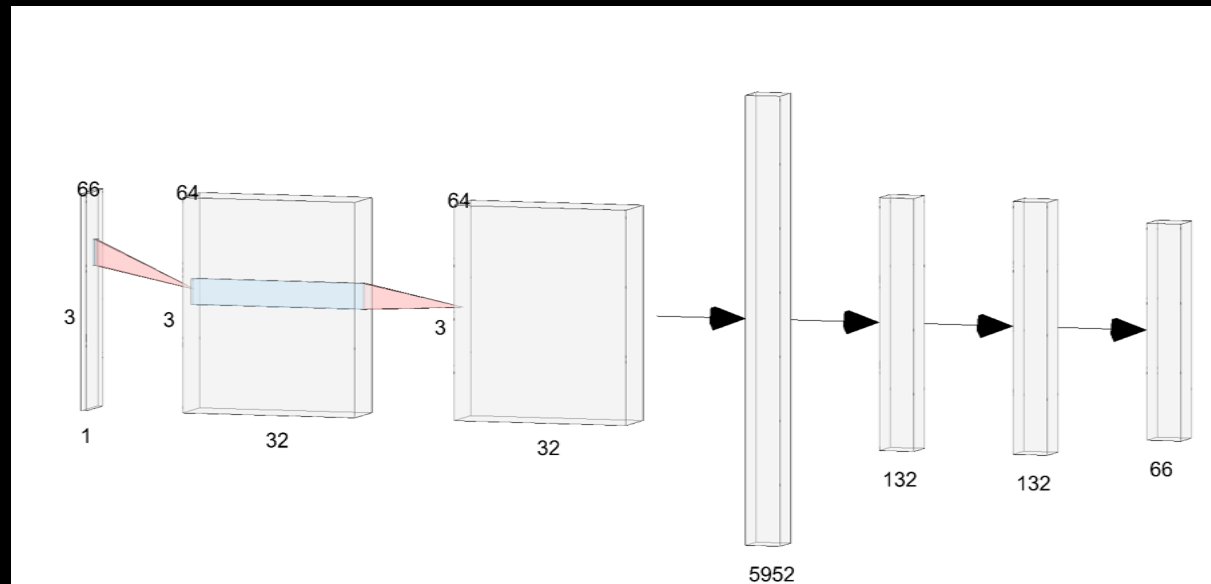


Soroll astrofísic
2-3 m/s

Terra al voltant del sol
0.20 m/s

Activitat estelar com a límit

Mètodes d'intel·ligència artificial
Xarxes Neuronals profundes + Simulacions
STARSIM 3 (IEEC)



4 m/s

Generem 1 milió
d'observacions reals
simulades

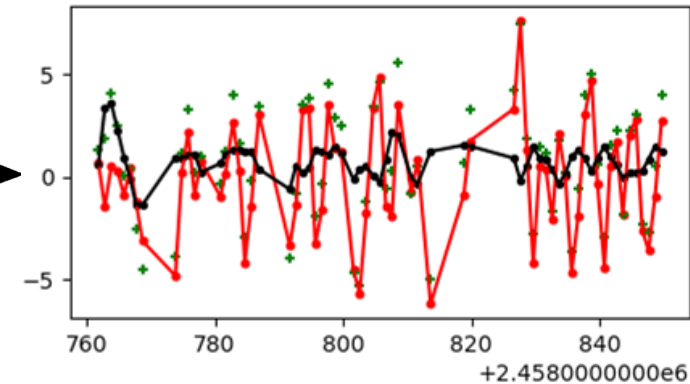
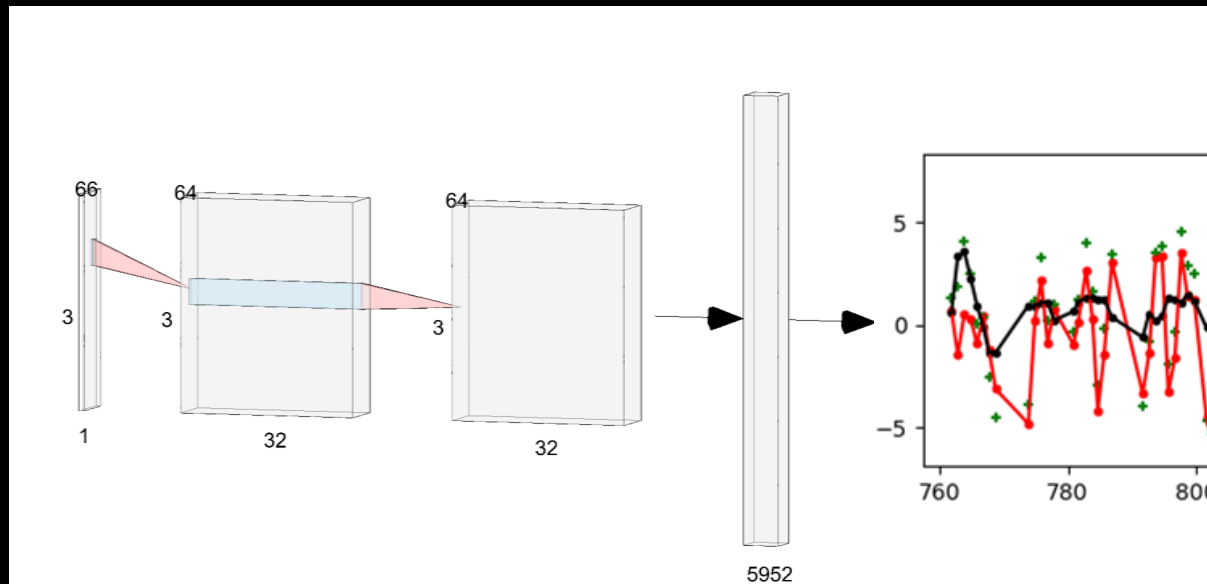
Terra al voltant del sol
20 cm/s

Activitat estelar com a límit

Mètodes d'intel·ligència artificial
Xarxes Neuronals profundes + Simulacions
STARSIM 3 (IEEC)

1.1 m/s

1 banda
Fotometrica



Generem 1 milió
d'observacions reals
simulades

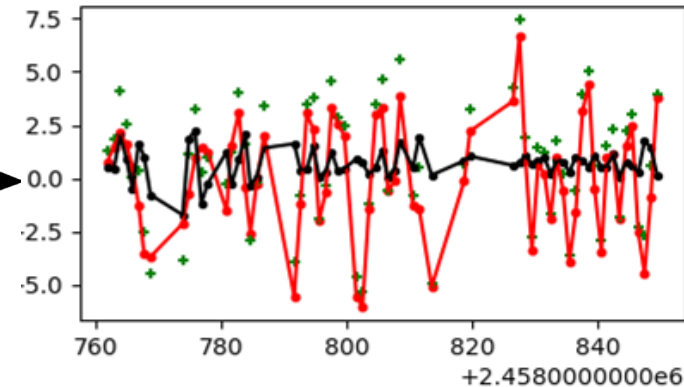
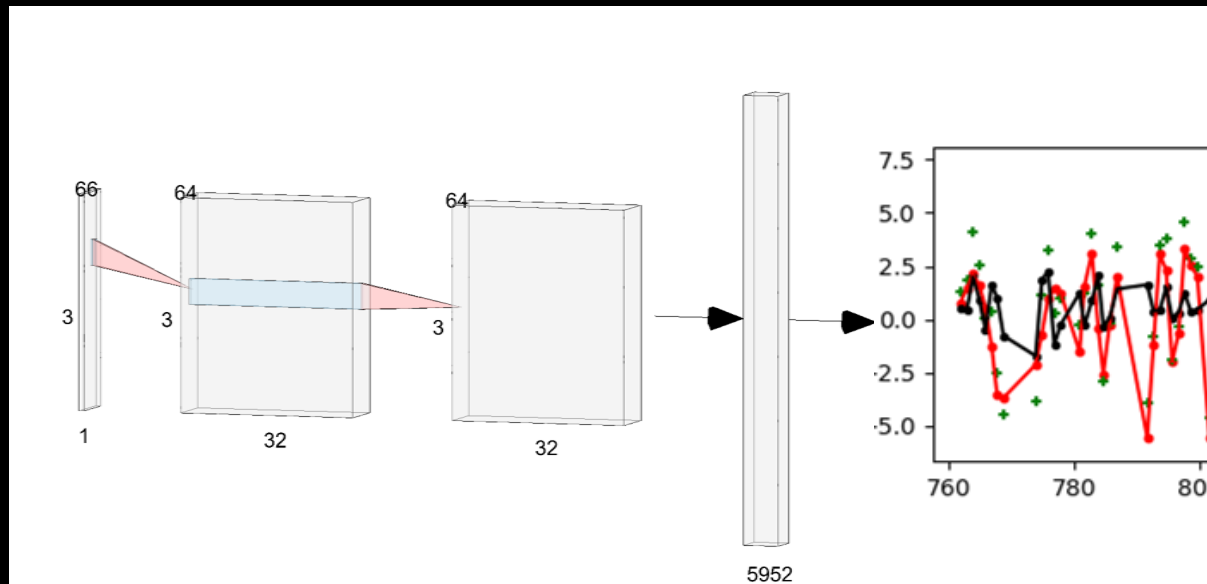
Terra al voltant del sol
20 cm/s

Activitat estel·lar com a límit

Mètodes d'intel·ligència artificial
Xarxes Neuronals profundes + Simulacions
STARSIM 3 (IEEC)

0.8 m/s

1 Bandes
fotometrica +
1 index
spectroscopic



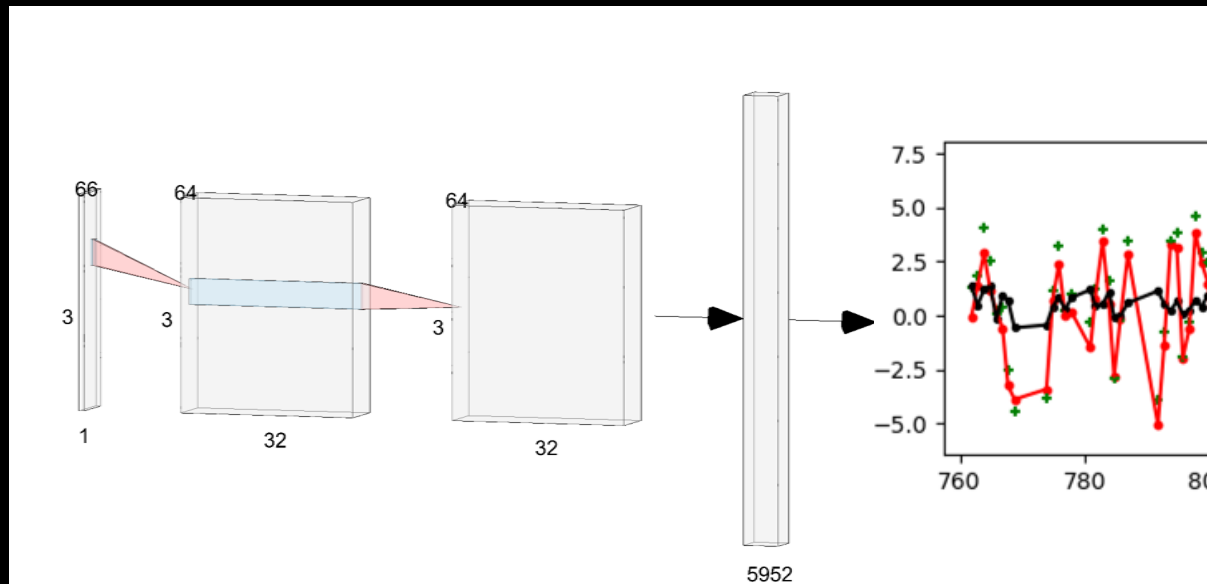
Generem 1 milió
d'observacions reals
simulades

Terra al voltant del sol
20 cm/s

Activitat estel·lar com a límit

Mètodes d'intel·ligència artificial
Xarxes Neuronals profundes + Simulacions
STARSIM 3 (IEEC)

0.5 m/s



2 Bandes
fotometriques +
2 índex
spectroscopica

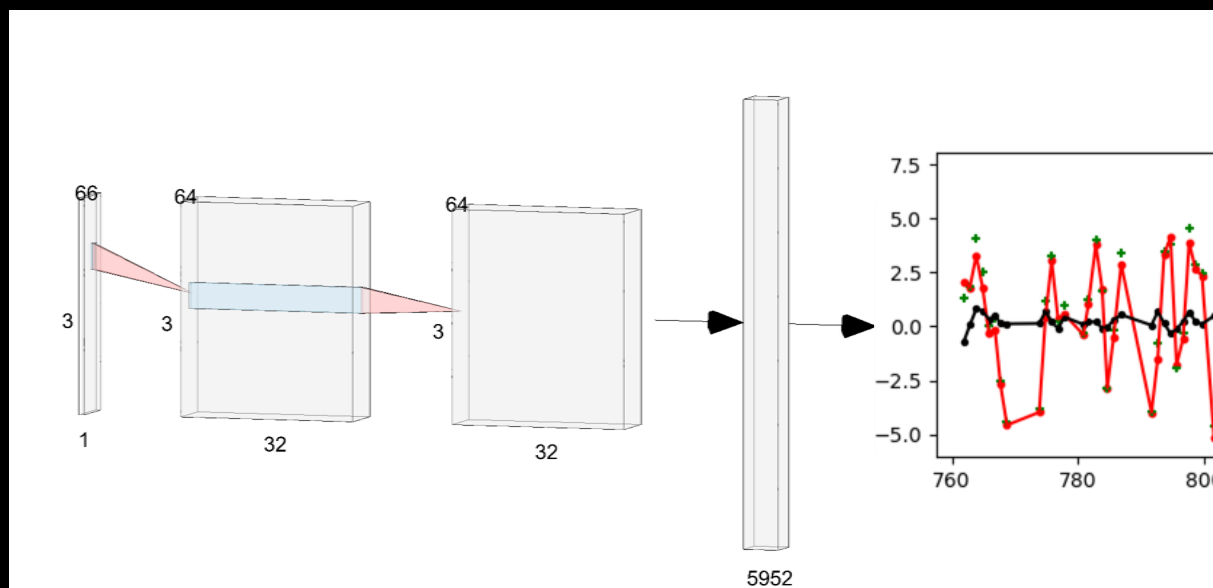
Generem 1 milió
d'observacions reals
simulades

Terra al voltant del sol
20 cm/s

Activitat estel·lar com a límit

Mètodes d'intel·ligència artificial
Xarxes Neuronals profundes + Simulacions
STARSIM 3 (IEEC)

3 Bandes
fotometriques +
3 index
spectroscopics



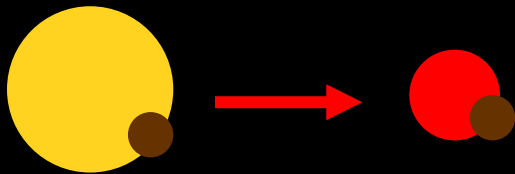
0.15 m/s

Generem 1 milió
d'observacions reals
simulades

Terra al voltant del sol
20 cm/s

... sembla que **aviat hauriem batut el límit astrofísic** també

Planetes al voltant de nanes vermelles



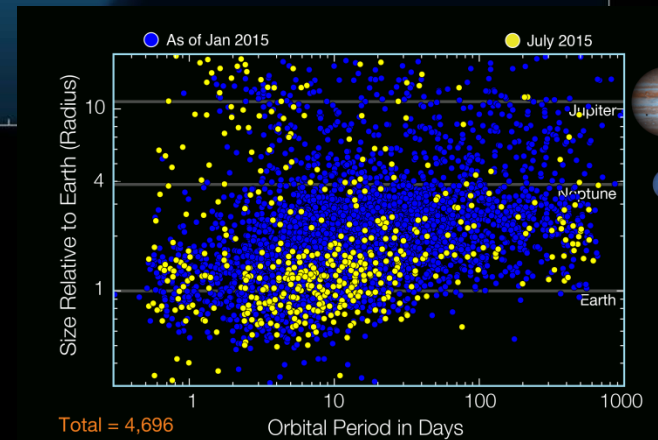
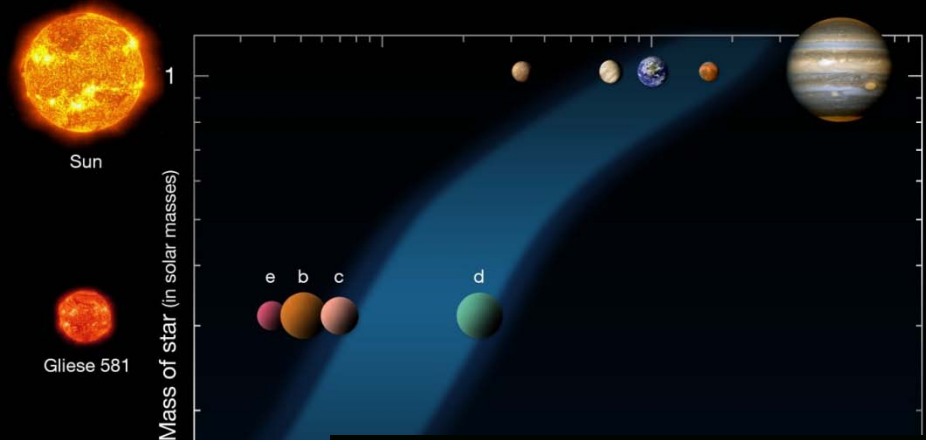
G2V

M5.5V

Transit x30-100
Doppler > x15

Nperiods >x30

> X50-200 easier



Missatge 1

La majoria d'estels son nanes
vermelles

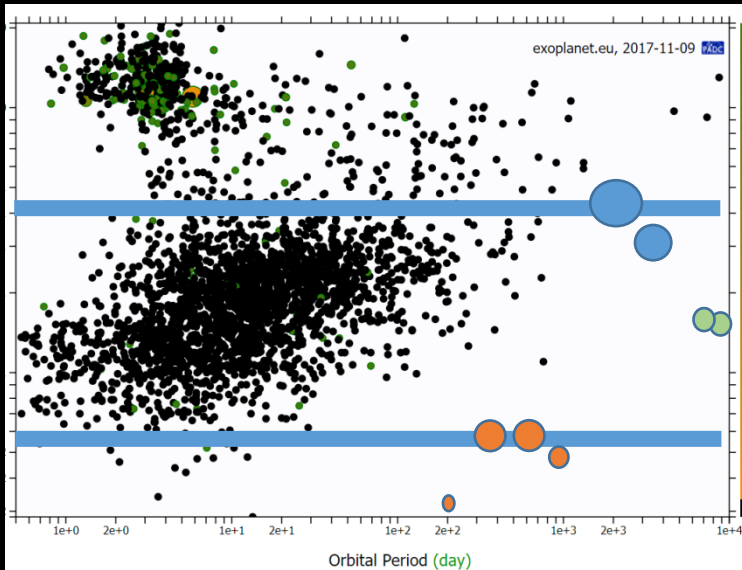
Missatge 2

La majoria d'estels tenen
planetes petits en periodes
orbitals curts

Missatge 3

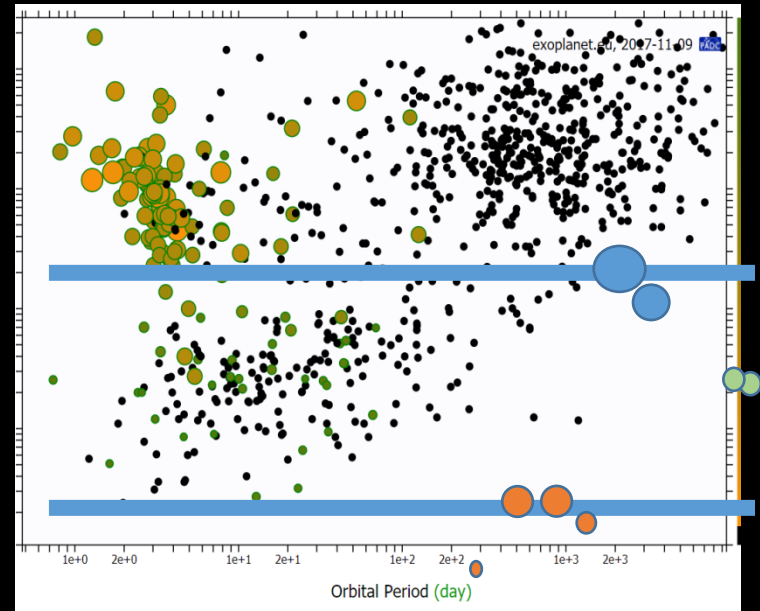
Els Planetes orbitant nanes
vermelles son (molt més) fàcils
de detectar

El zoo dels exoplanetes



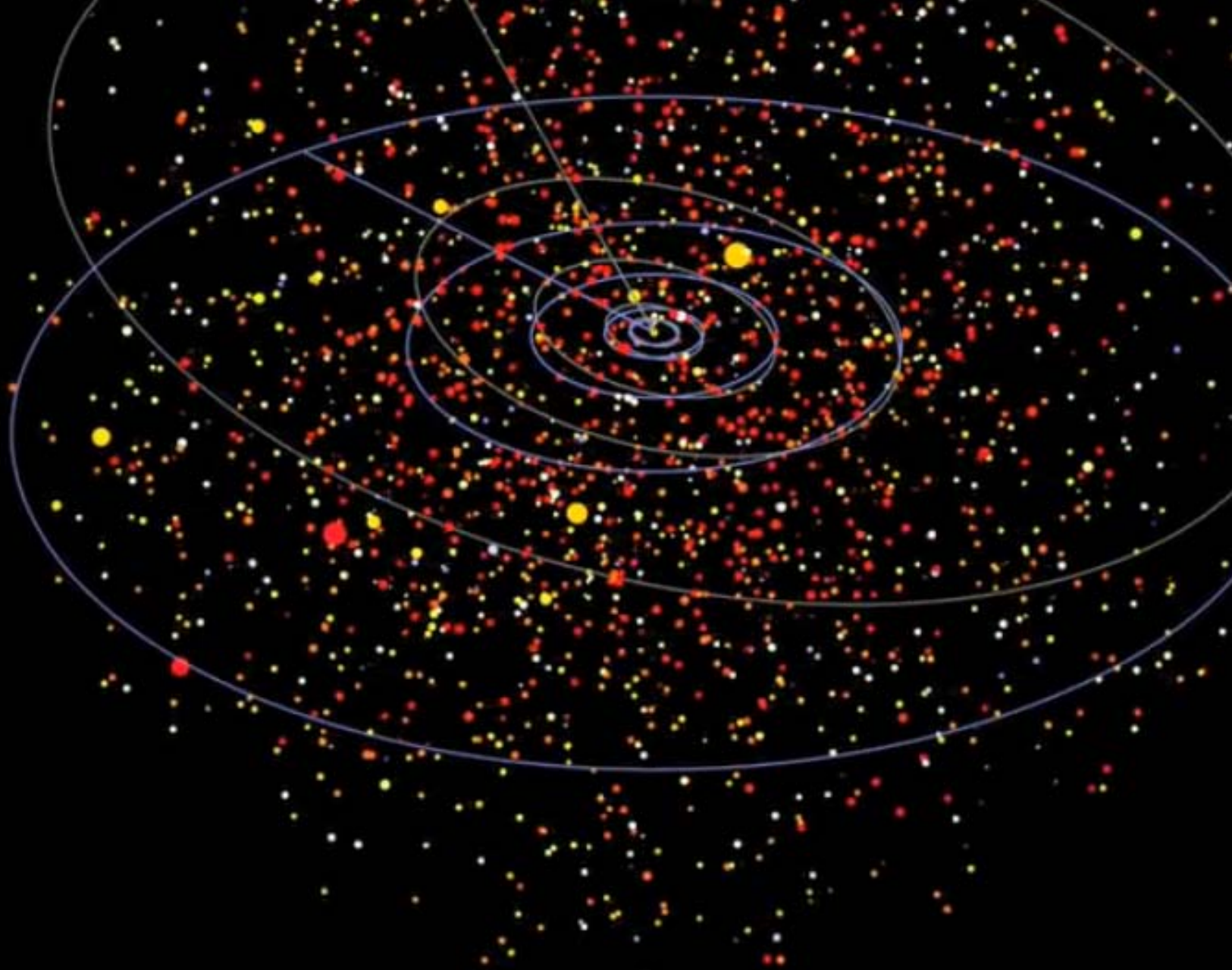
Mètode del trànsit

Radi



Velocitat radial

Massa



Caçant Proxima b

Planetes orbitant Proxima Centauri

2000-2008 : UVES planet search	232
2002-2012 : HARPS team	70
2013-2014 : HARPS – new data	194
Pre 2016	496
2016 : HARPS – Pale Red Dot	<u>54</u>

Pale Red Dot



Doppler Spectroscopy (HARPS) Guillem Anglada-Escude, Mathias Zechmeister

Doppler Spectroscopy (UVES) R. Paul Butler, Martin Kuerster, Michael Endl

Data analysis Mikko Tuomi, James Jenkins, Hugh R. A. Jones

Spectroscopic Analyses John Barnes, Zaira M. Berdinas, John P. Strachan

Photometry Cristina Rodríguez-Lopez, Eloy Rodríguez, Nicolas Morales, Jose Ortiz, Ignacio de la Cueva, María J. Lopez Gonzalez(ASH2), Yiannis Tsappras (lcoqt.net), Aviv Ofir, Marcin Kiraga

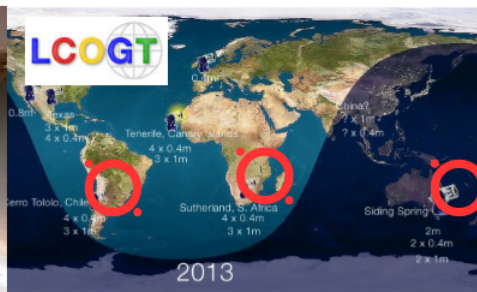
Stellar physics and activity Ansgar Reiners, Pedro Amado, Sandra V. Jeffers, Julien Morin

Planet formation and Dynamics Richard P. Nelson, Gavin Coleman, Sijme-Jan Paardekooper, Stefan Dreizler, Benjamin Giesers

Observers Christopher Marvin, Luis F. Sarmiento



HARPS, La Silla/ESO, Doppler RV



LCOGT.net, Photometry



ASH2-SpaceObs, Photometry

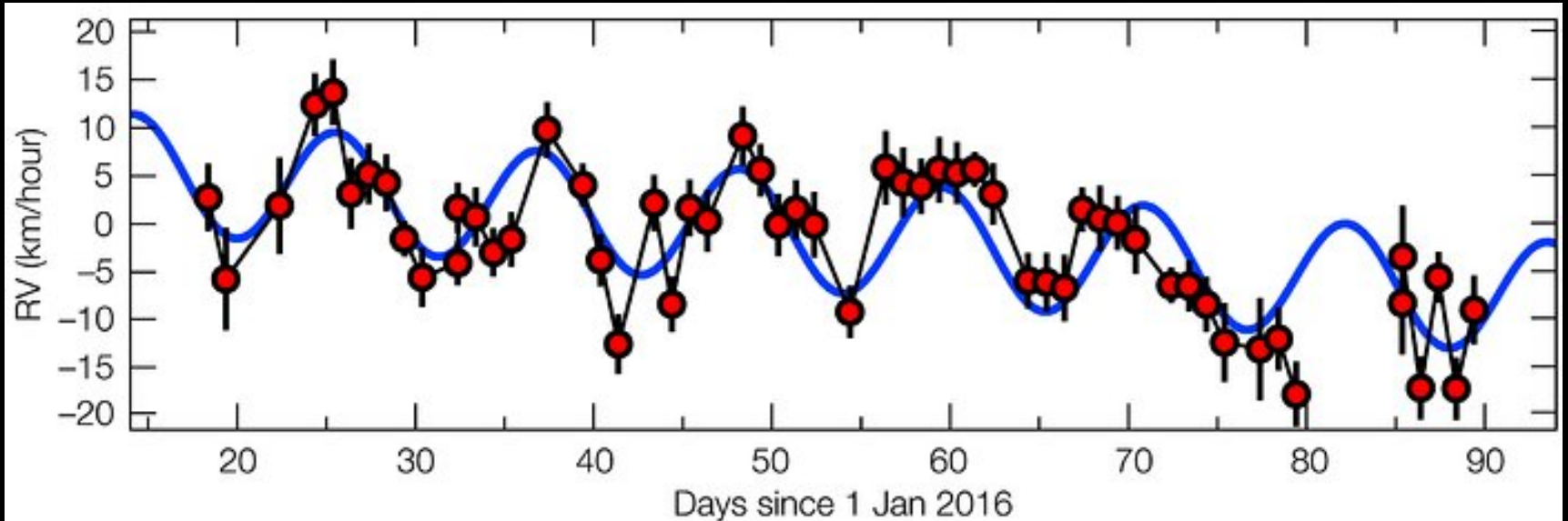
Outreach website
www.palreddot.org

Twitter
[@Pale_red_dot](https://twitter.com/Pale_red_dot)
[#palreddot](https://twitter.com/palreddot)

Facebook page
[Pale Red Dot](https://www.facebook.com/PaleRedDot)

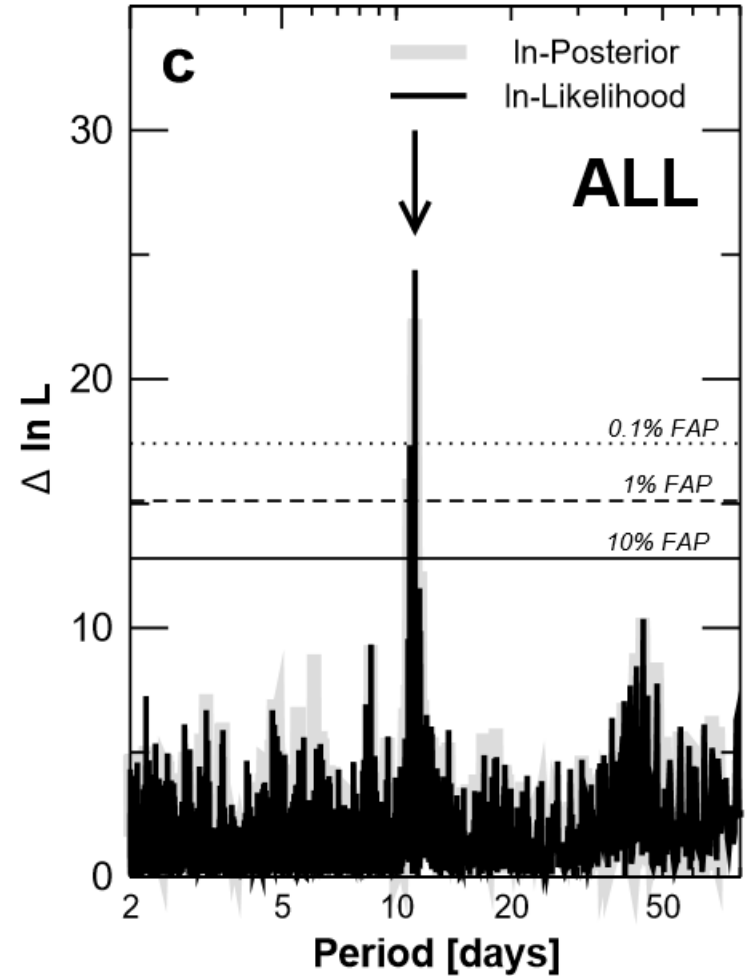
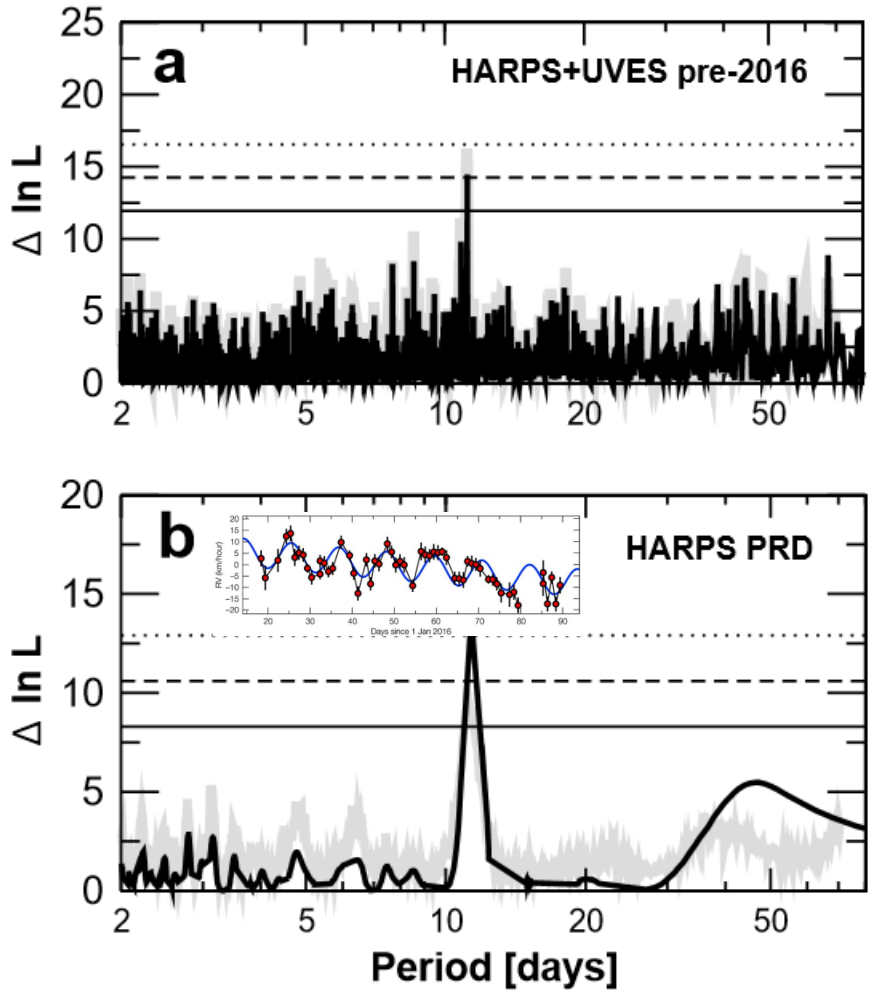


Pale Red Dot



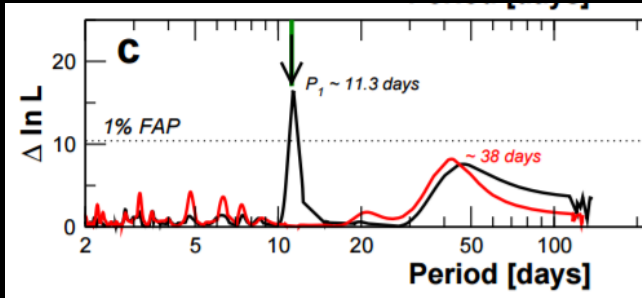
Mesures de
velocitat radial

Pale Red Dot

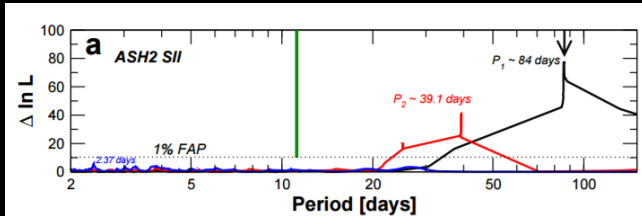




RV

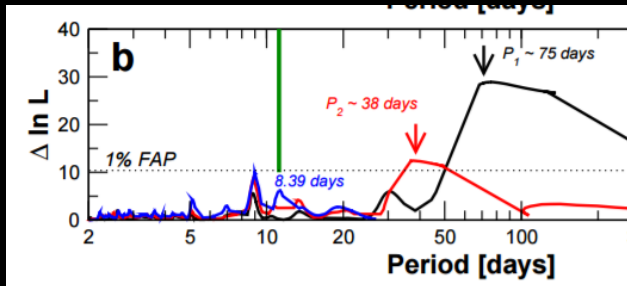


Photometry

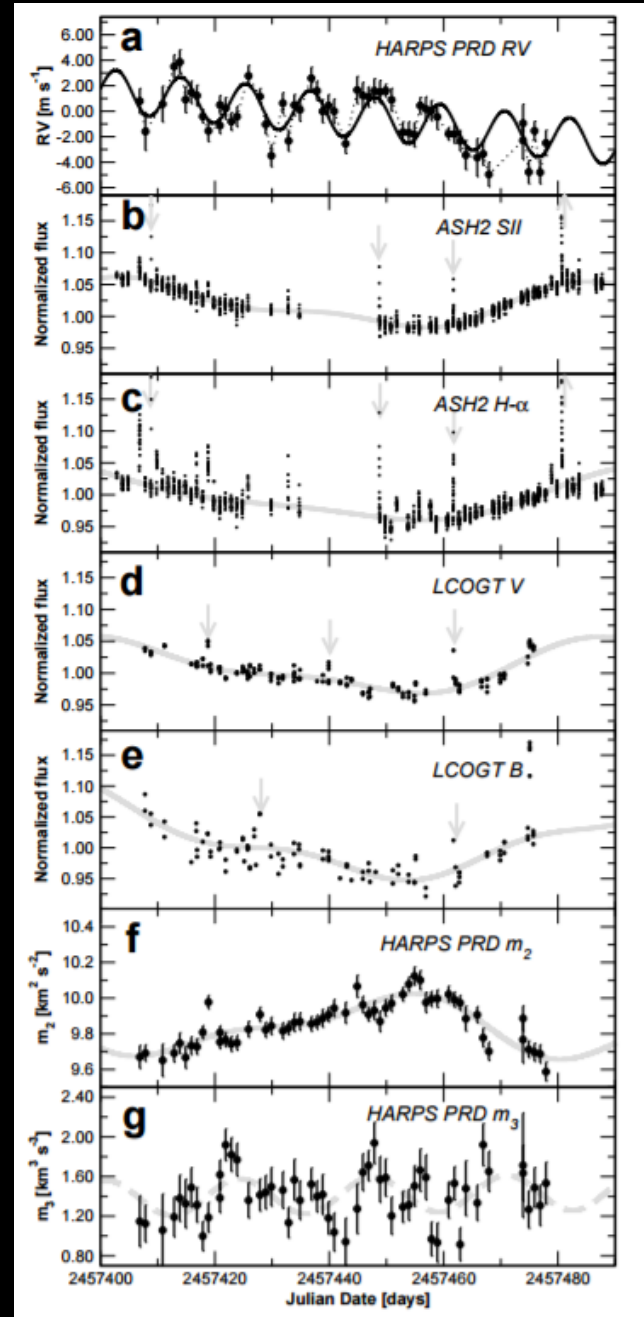


Rotació
~80 dies

Width of the spectral lines



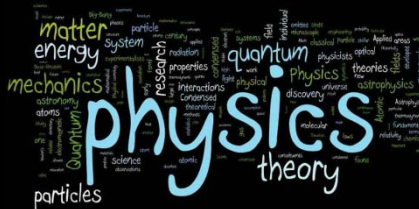
Rotació i
taques
~80 dies



Pale Red Dot

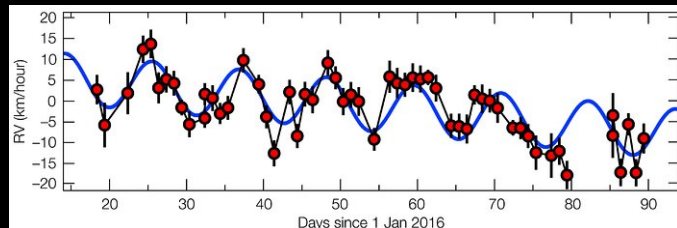
Senyal

Amplitud : 1.4 m/s
Periode orbital : 11.2 dies



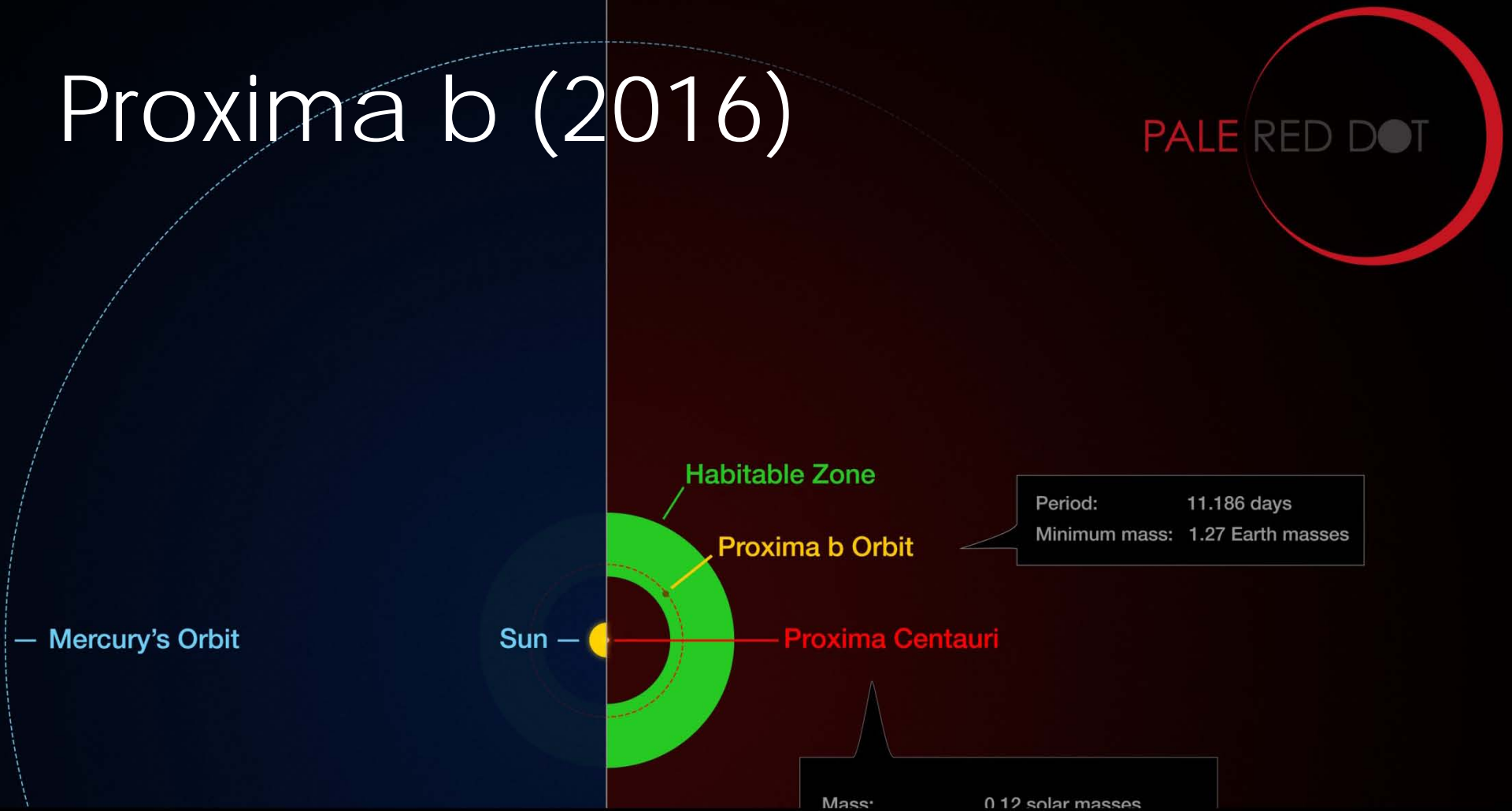
Proxima b

Massa min. : 1.3 Mearth
Dist. orbital : 5% d'AU
Irradiància : 65% de la terrestre
Temperatura : ~235 K (-40 C)



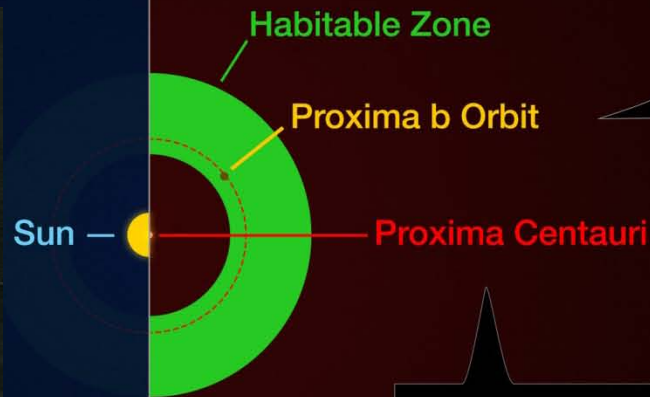
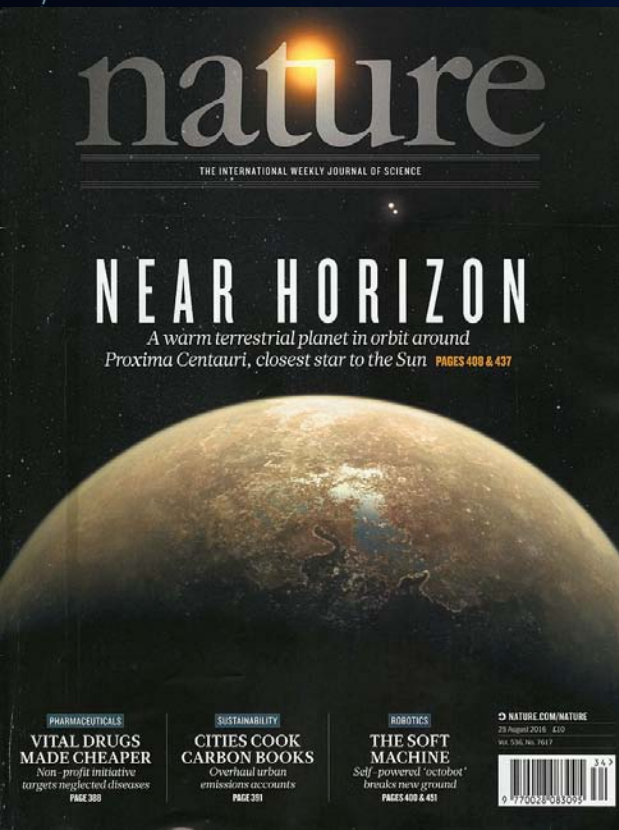
Proxima b (2016)

PALE RED DOT



Proxima b (2016)

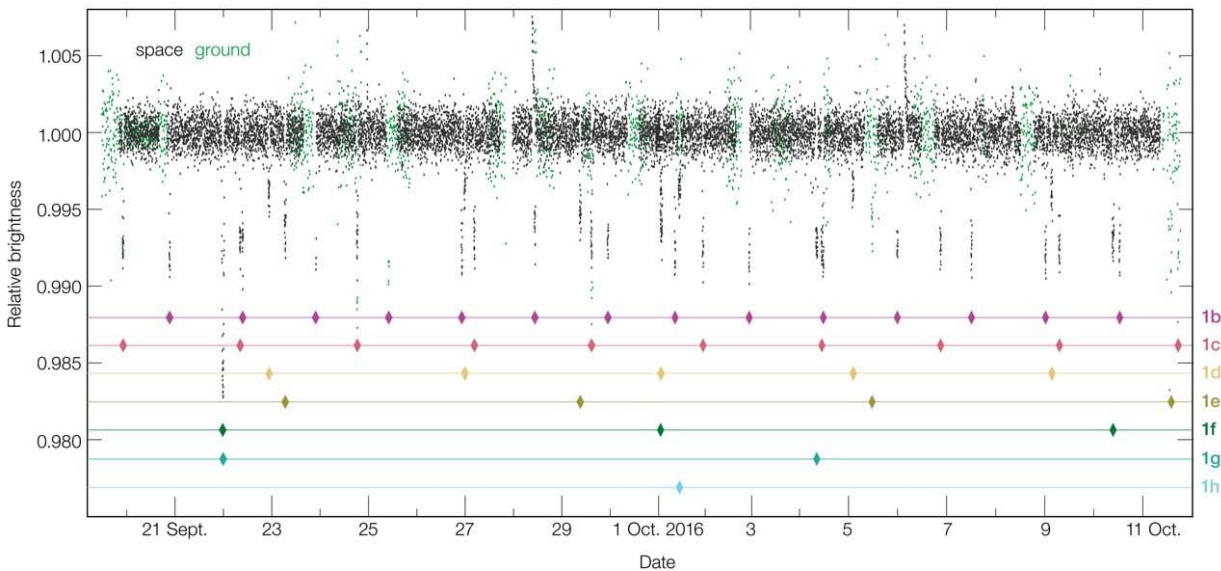
PALE RED DOT



Period: 11.186 days
Minimum mass: 1.27 Earth masses

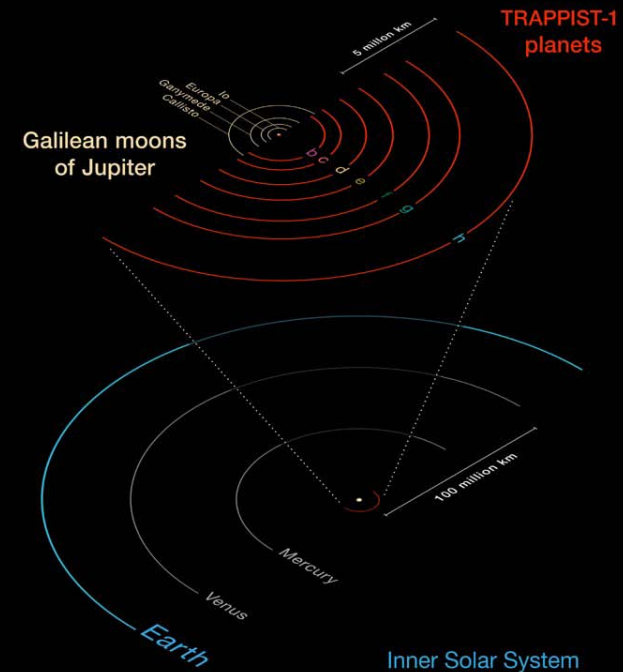
Mass: 0.12 solar masses

TRAPPIST-1 (2017)



Orbit Comparison

between TRAPPIST-1 planets, Galilean moons of Jupiter and inner Solar System



PALE RED DOT



Sun

Habitable Zone

Proxima b Orbit

Proxima Centauri

Period: 11.186 days
Minimum mass: 1.27 Earth masses

Mass: 0.12 solar masses

Mercury's Orbit

Estels propers

#1 Proxima (3x planets), Alpha Cen A+B

#2 Barnard's star (planet)

#3 Luhmann 16A+B

#4 Wolf 359 (?)

#5 Ross 248 (?)

#6 Sirius

#7 BL Ceti + UV Ceti

#8 Ross 154 (?)

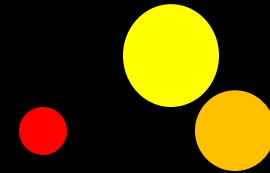
#9 Epsilon Eridani (gegant gasos)

#10 Lacaille 9235 – 3 planetes

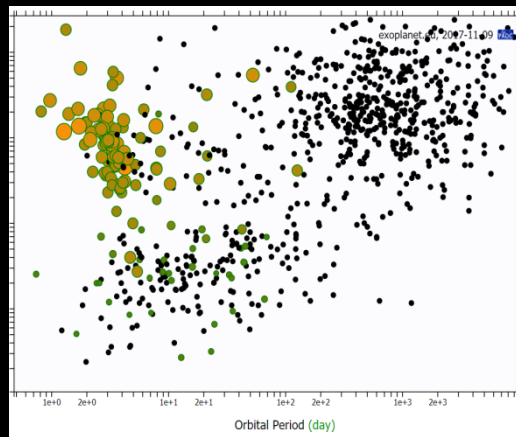
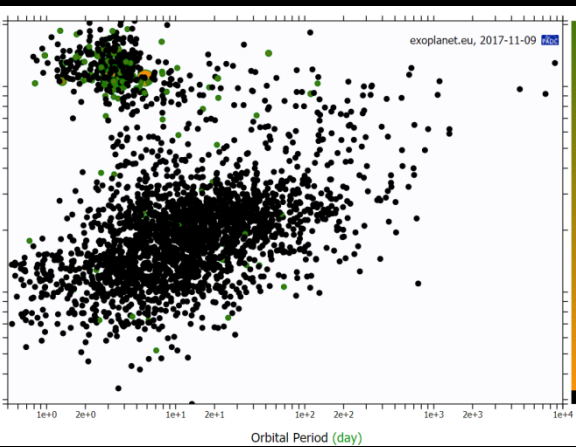
#11 Ross 128 (planet)

...

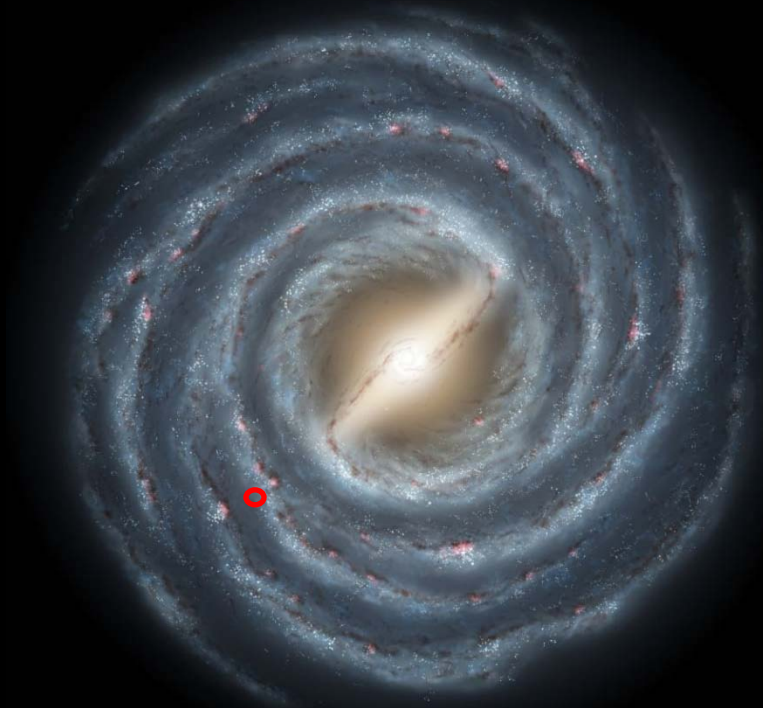
*Més del 50% de les estrelles
tenen planetes terrestres
temperats*



200 000 000 000

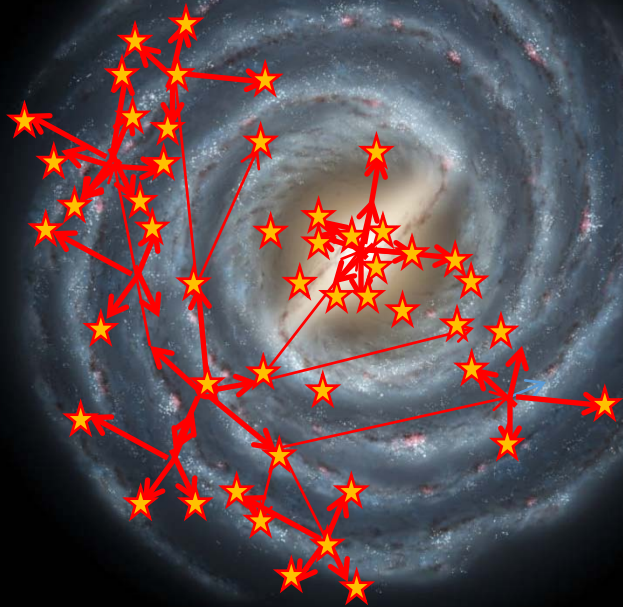


Paradoxa de Fermi



100 anys

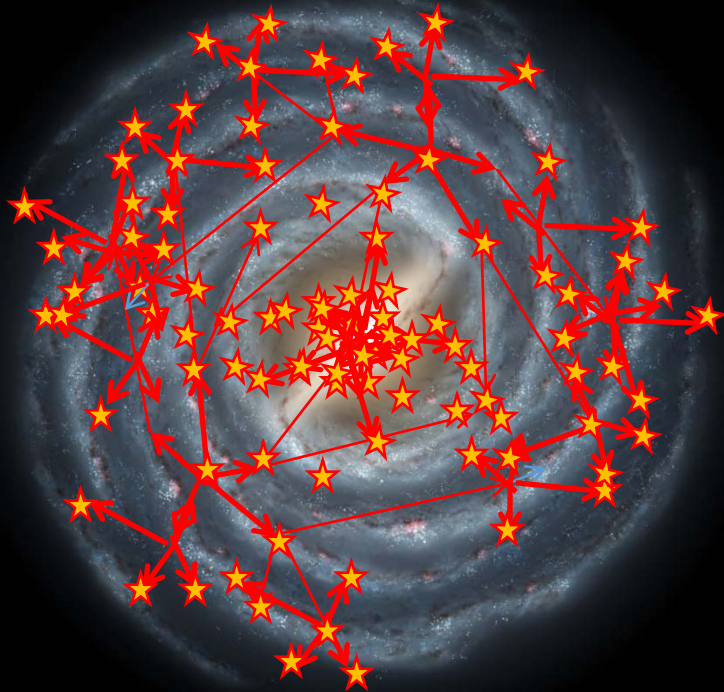
Paradoxa de Fermi



10 000 anys

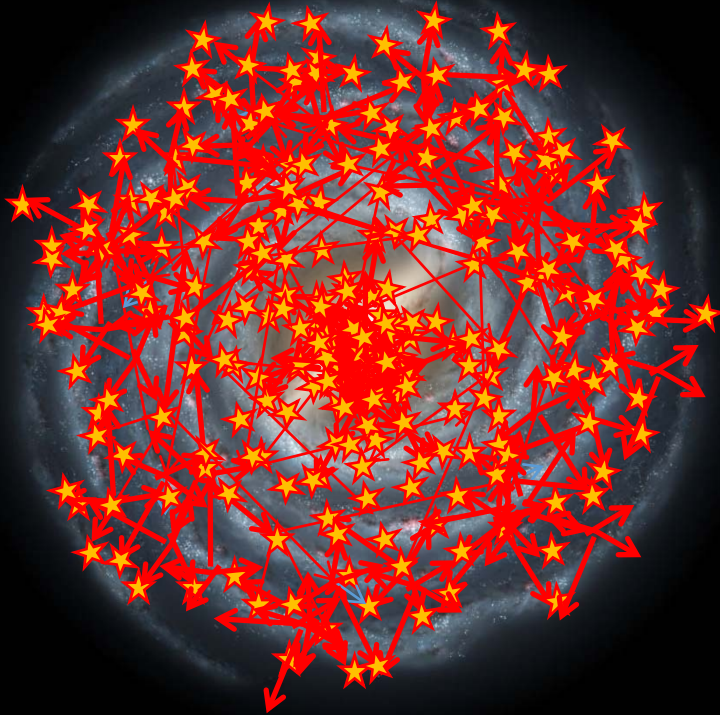
Paradoxa de Fermi

1 000 000 anys

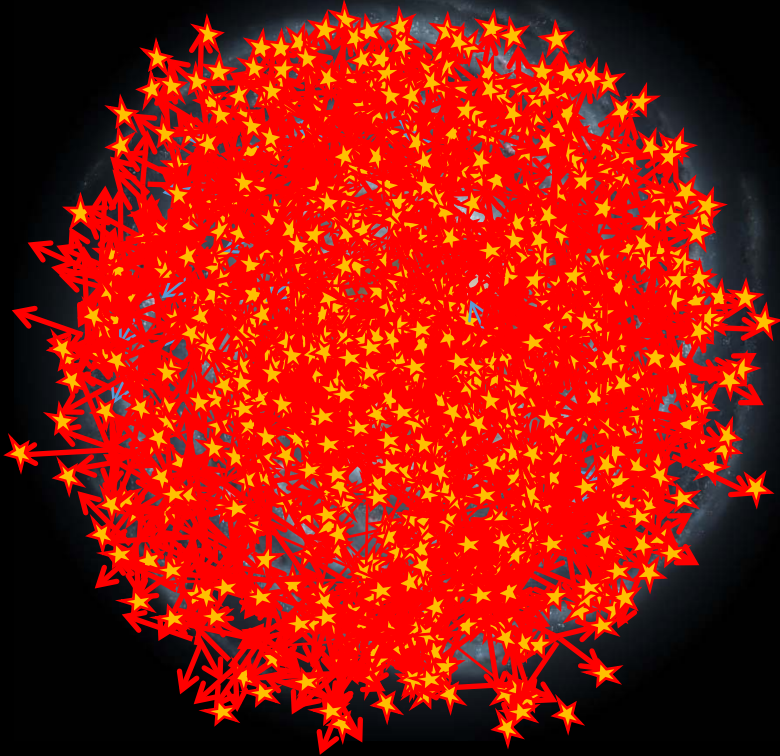


Paradoxa de Fermi

10 000 000 anys



Paradoxa de Fermi



100 000 000 anys

100 milions d'anys \ll 13 500 milions d'anys



Equació de Drake

$$N/\text{any} = R \times f_p \times f_h \times f_v \times f_i$$



Equació de Drake

$$N_{\text{any}} = R \times f_p \times f_h \times f_v \times f_i$$

$10^*/\text{any}$ ~ 1 ~ 0.5 ~ 0.5 ~ 0.5

Equació de Drake

$$N/\text{any} = R \times f_p \times f_h \times f_v \times f_i$$

$10^*/\text{any}$ ~ 1 ~ 0.5 ~ 0.5 ~ 0.5

~ 1.25 civilitzacions
per any!





Equació de Drake

$$N/\text{any} = R \times f_p \times f_h \times f_v \times f_i$$

$10^*/\text{any}$ ~ 1 ~ 0.5 ~ 0.5 ~ 0.5

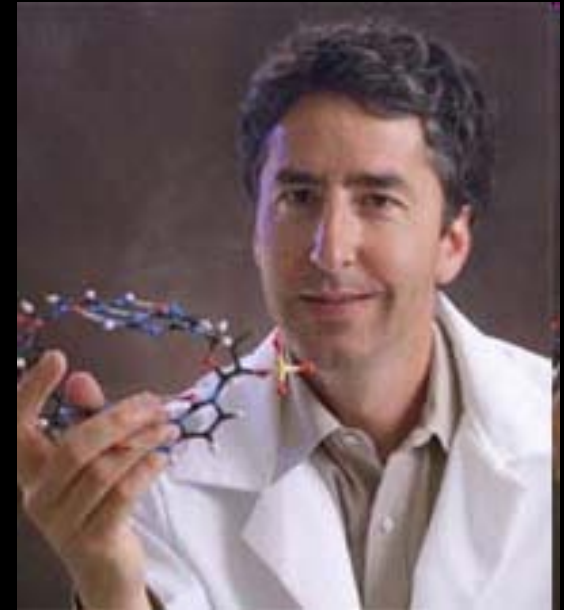


Cercant vida

(o evidència de...)

Què és la vida?

Definició 1: “ La vida és un Sistema químic capaç de replicar-se i experimentar evolució Darwiniana



Jerry Joyce, Salk Institute

Val per un laboratori, la Terra o fins i tot planetes del sistema Solar, però no és molt útil per a cercar-la en estels remots on la informació és molt més limitada.

Quins processos són essencials?

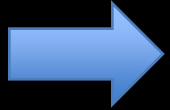
Cockell et al. (2016)

Font d'energia per permetre
les reaccions metabòliques

Solvent líquid per mediar
aquestes reaccions

Nutrients per contruir biomassa
i produir enzims per catalitzar
reaccions metabòliques

Que creiem que sabriem identificar

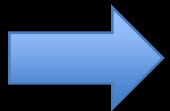


Aigua en estat líquid

L'aigua líquida és el solvent ideal per moltes reaccions

És molt abundant – H i O són dos dels elements més abundants a l'univers

Te ún rol essencial per a la química de proteïnes i enzims



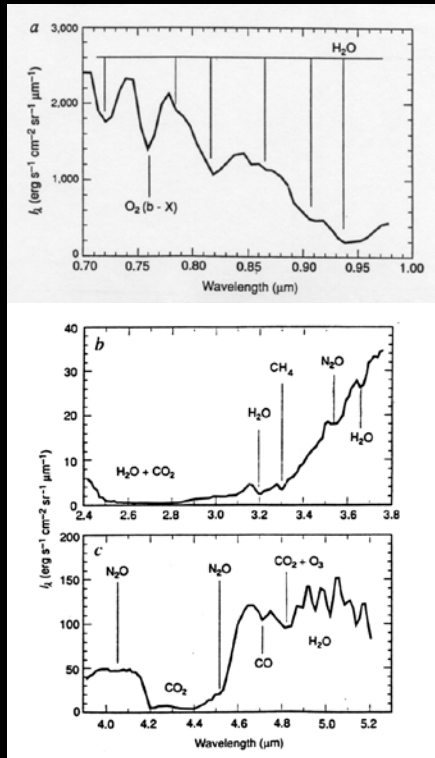
Química basada en el Carboni

Molt abundant també cosmic abundance

Forma molècules molt complexes amb H i O a baixes temperatures

Alternatives? Potser, però ni tant sols demostrades en laboratori i per tant ni tant sols sabem que estem buscant

Biosignatures



(Combinacions de) Gasos detectables remotament en l'atmosfera d'un exoplaneta que indiquen la presència d'una química fora de l'equilibri, probablement basada en aigua i carboni

NATURE · VOL 365 · 21 OCTOBER 1993

A search for life on Earth from the Galileo spacecraft

Carl Sagan^{*}, W. Reid Thompson^{*}, Robert Carlson[†], Donald Gurnett[‡]
& Charles Hord[§]

^{*} Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA

[†] Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA

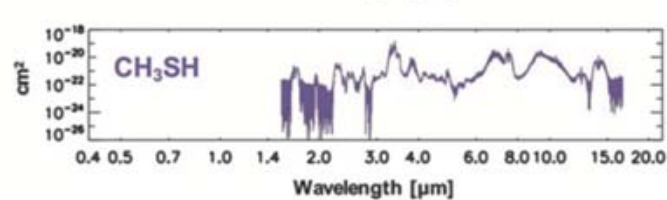
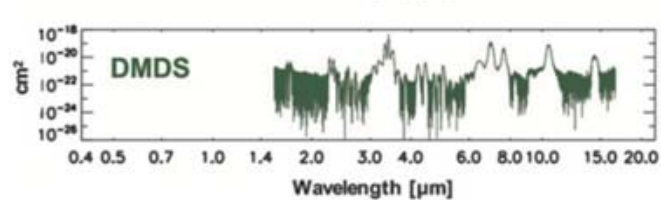
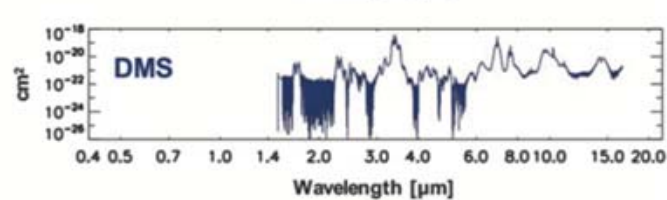
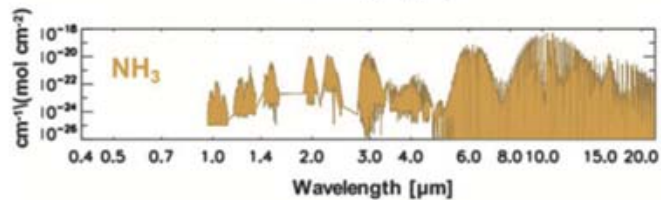
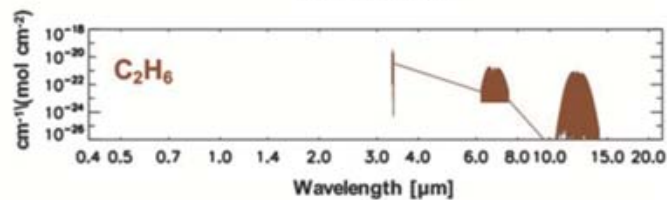
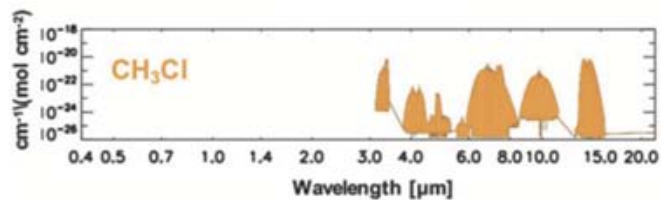
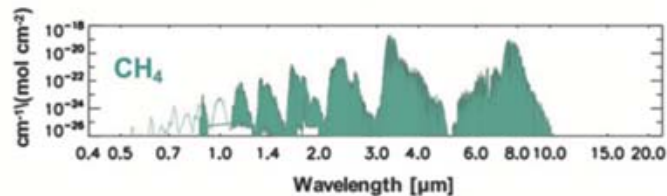
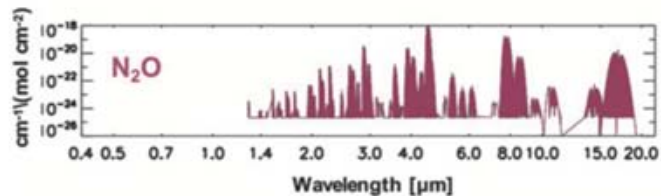
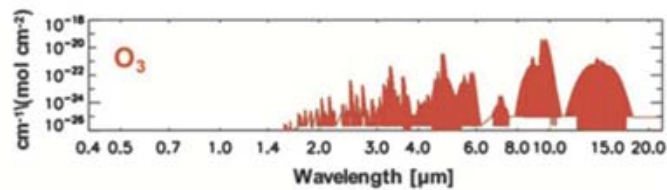
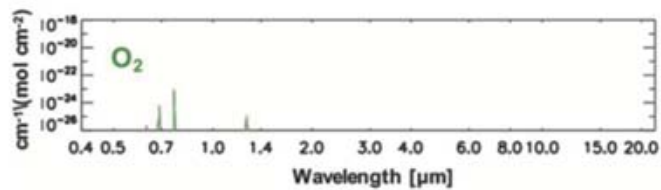
[‡] Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA

[§] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

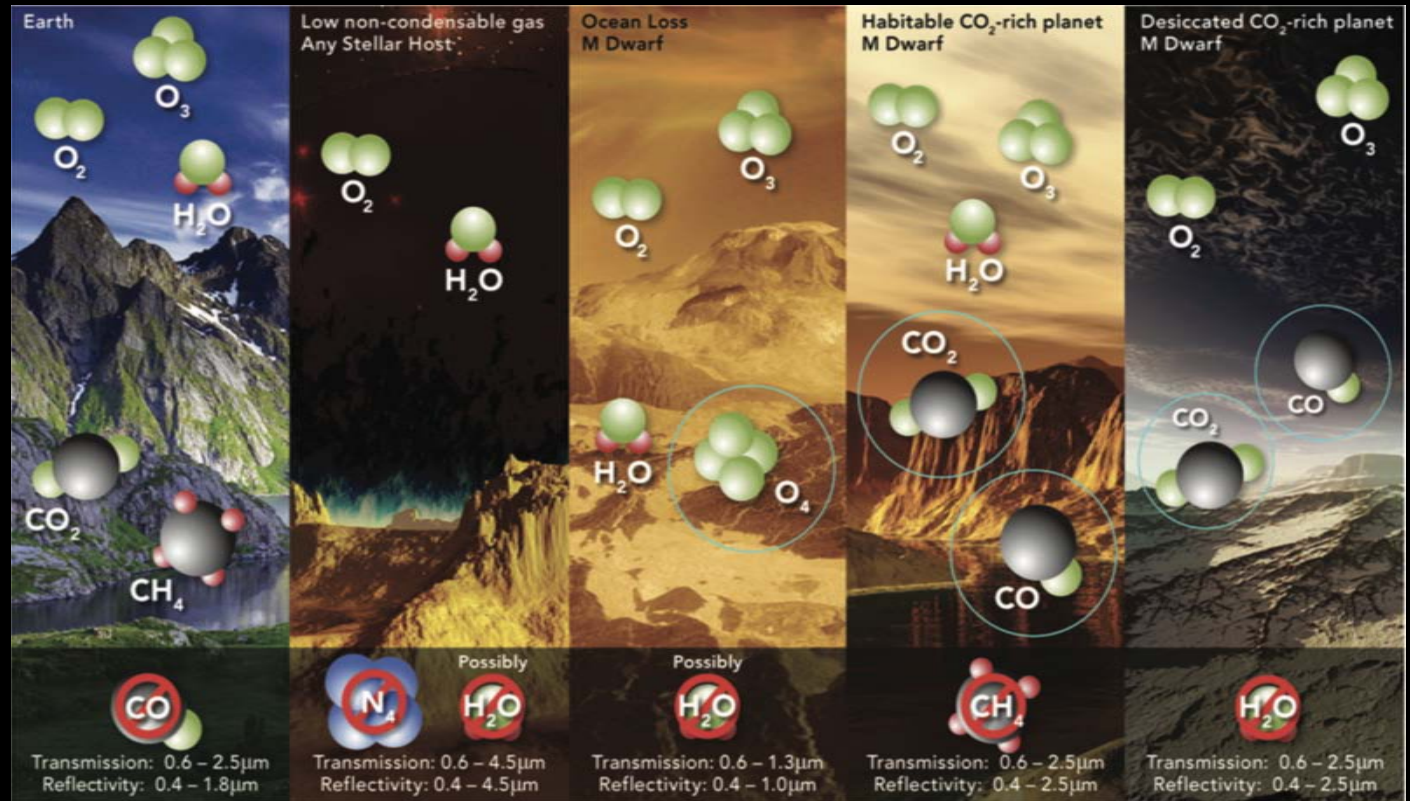


Biosignatures

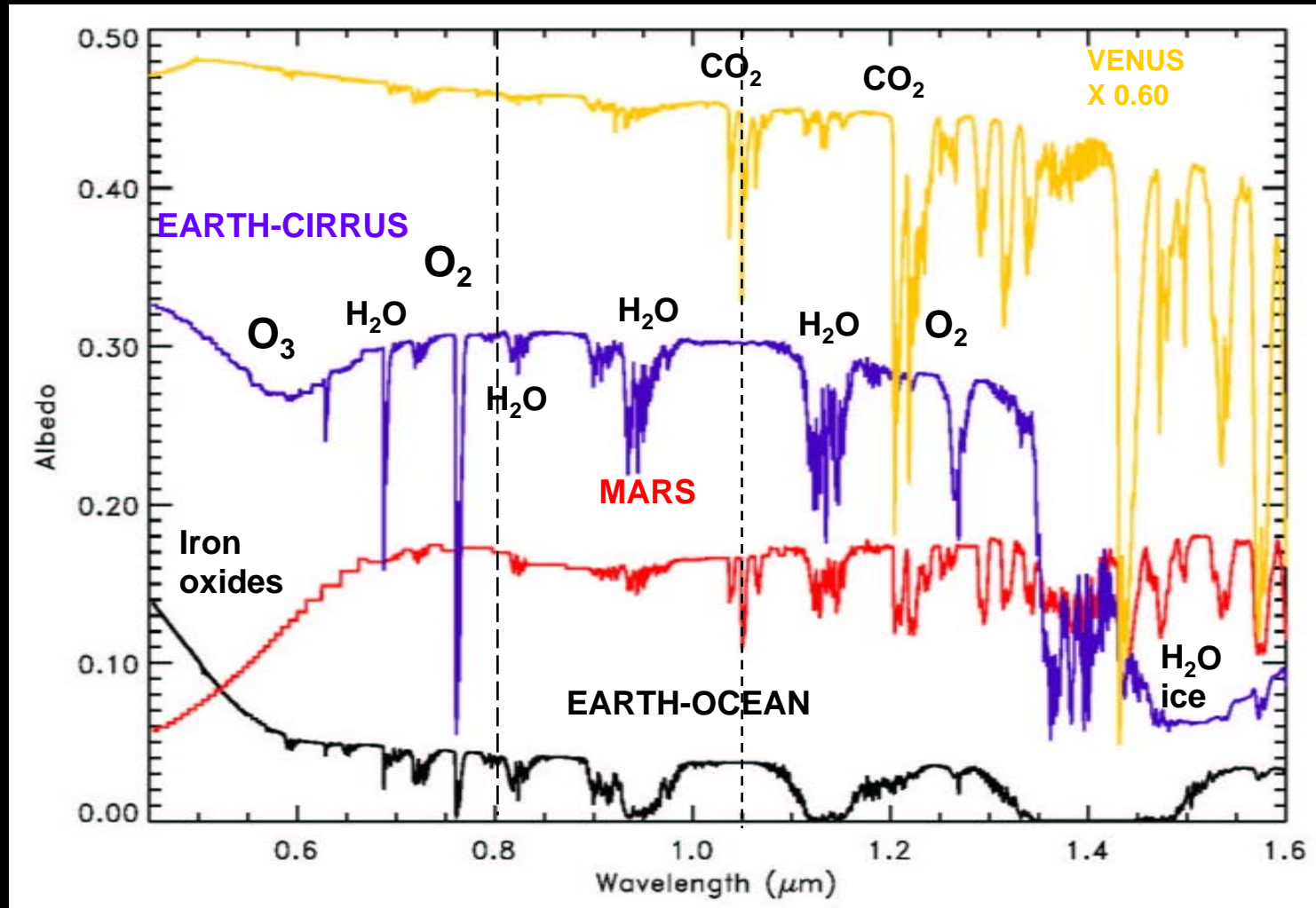


Biosignatures

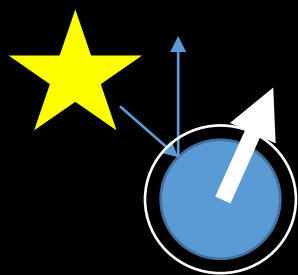
Però compte amb els falsos positius!...



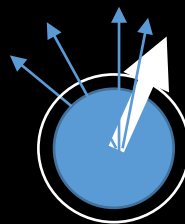
Biosignatures



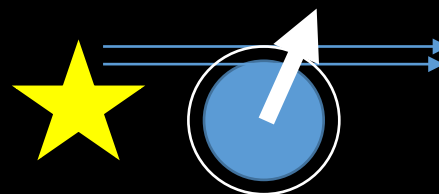
Caracterització



Reflexió



Emissió

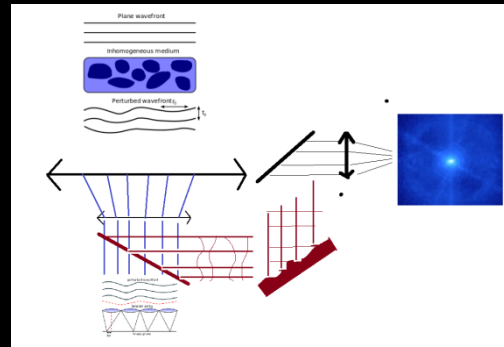
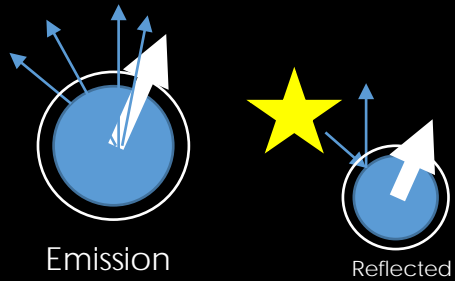
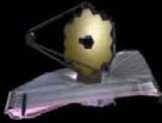


Transmissió

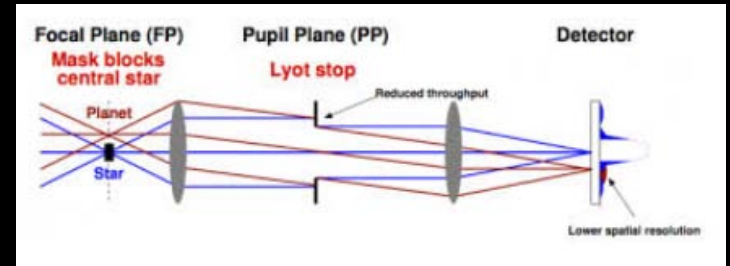
Caracterització



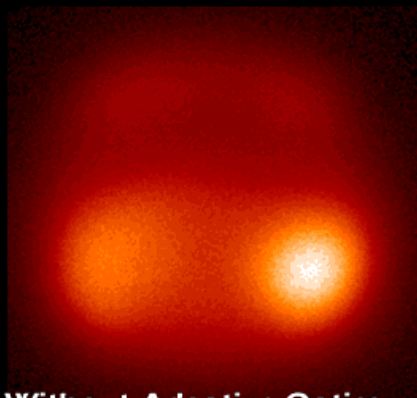
Imatge directa



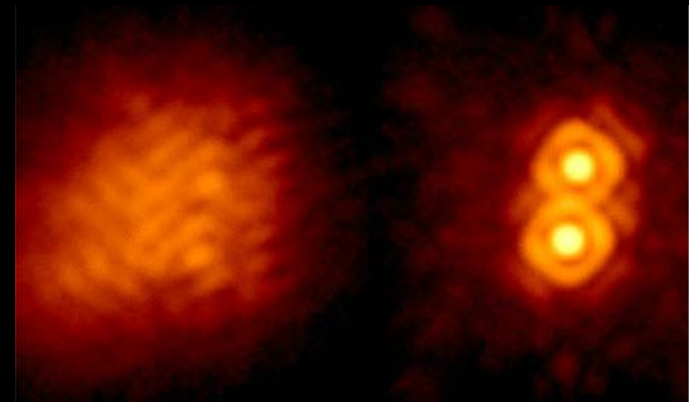
Adaptive Optics



Coronagraph



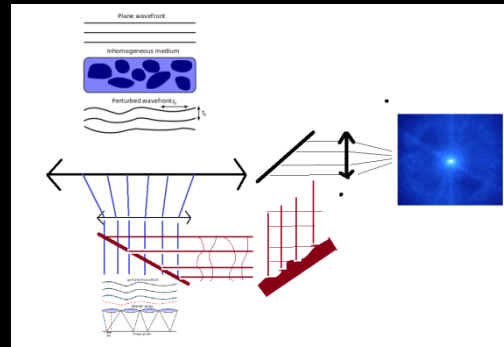
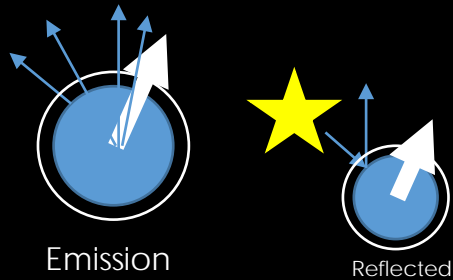
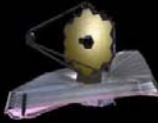
Without Adaptive Optics



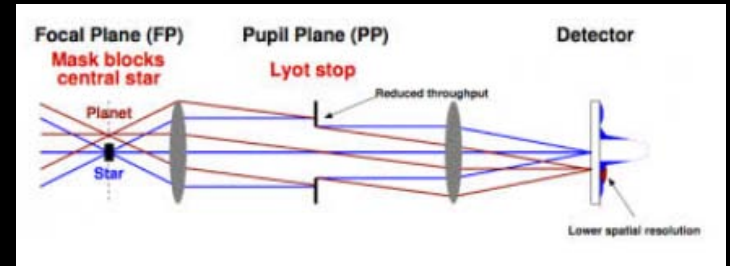
Caracterització



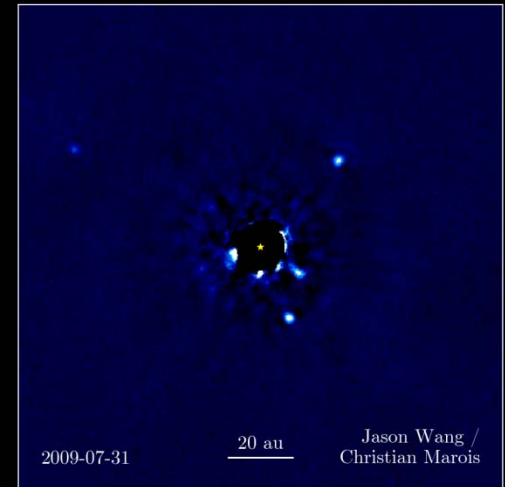
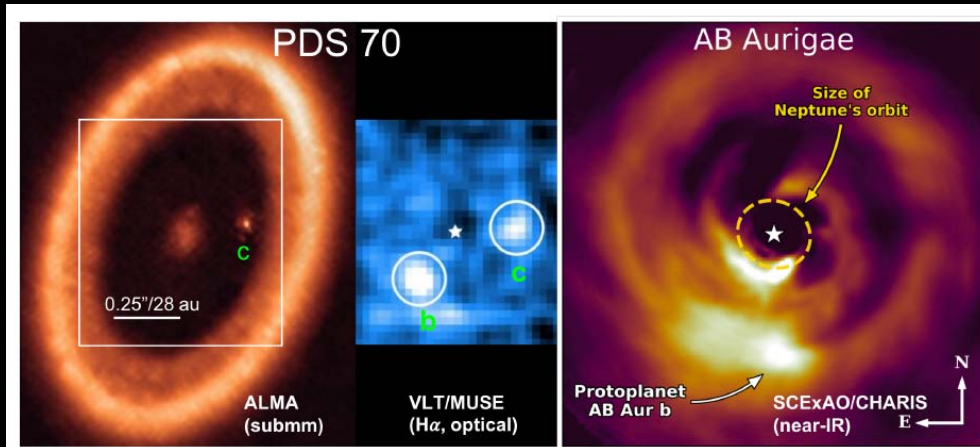
Imatge directa



Adaptive Optics

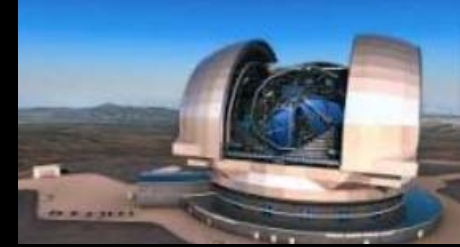


Coronagraph

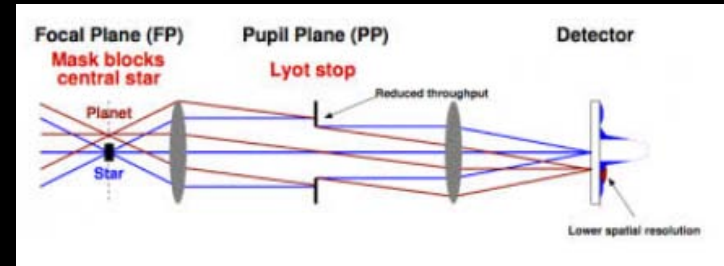
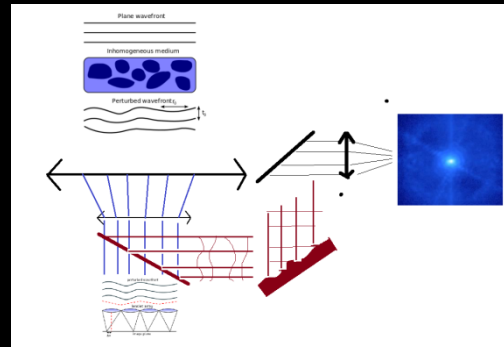
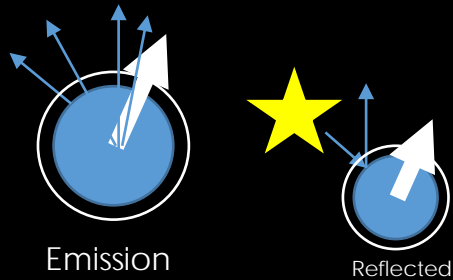
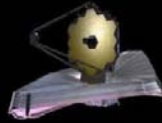


HR 8799 (~30 pc, young A type)
Marois et al. 2008, Science (3p)

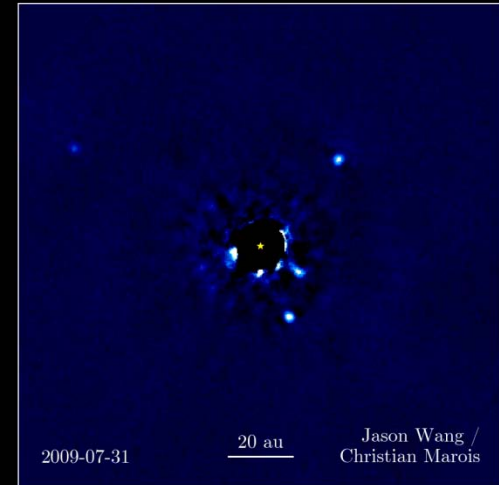
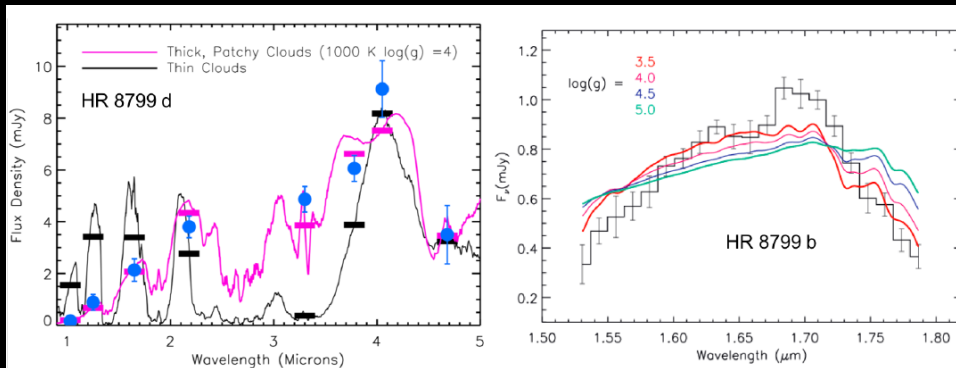
Caracterització



Imatge directa



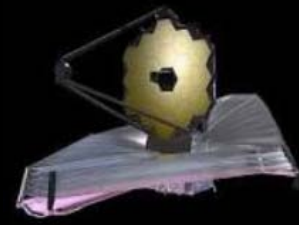
Coronagraph



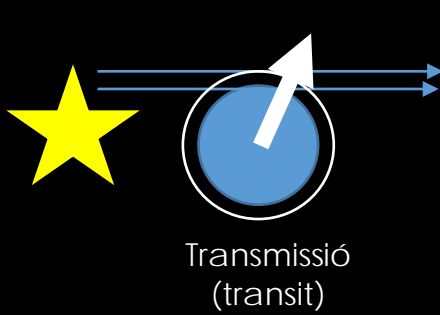
Ara mateix només funciona per planetes gegants joves que si que emeten llum pròpia

HR 8799 (~30 pc, young A type)
Marois et al. 2008, Science (3p)

Caracterització



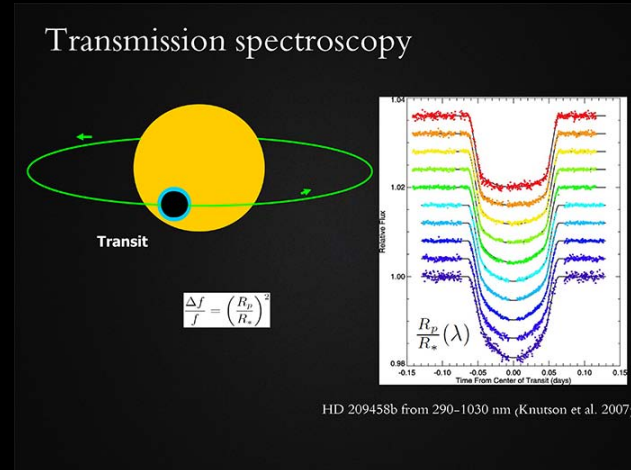
Espectroscopia de trànsits



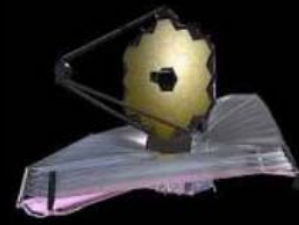
Transmissió
(transit)



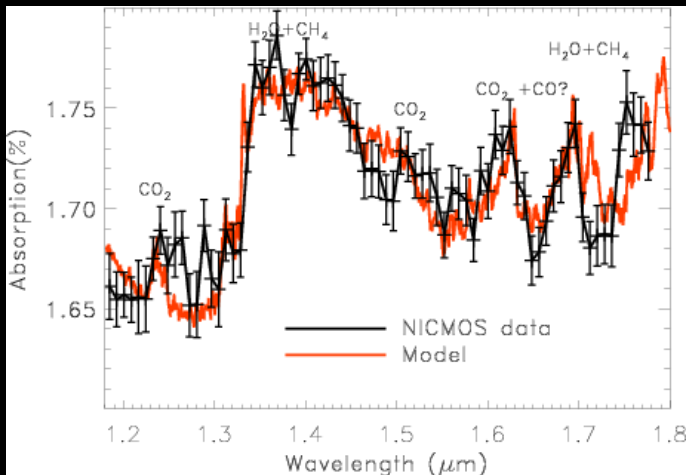
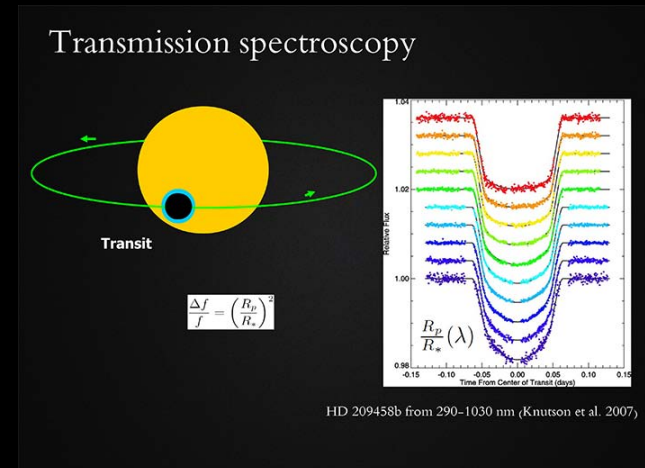
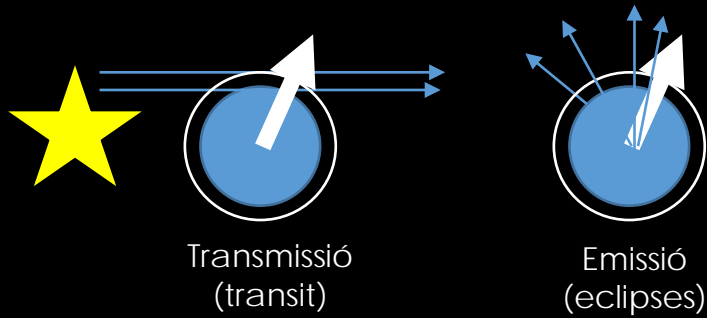
Emissió
(eclipses)



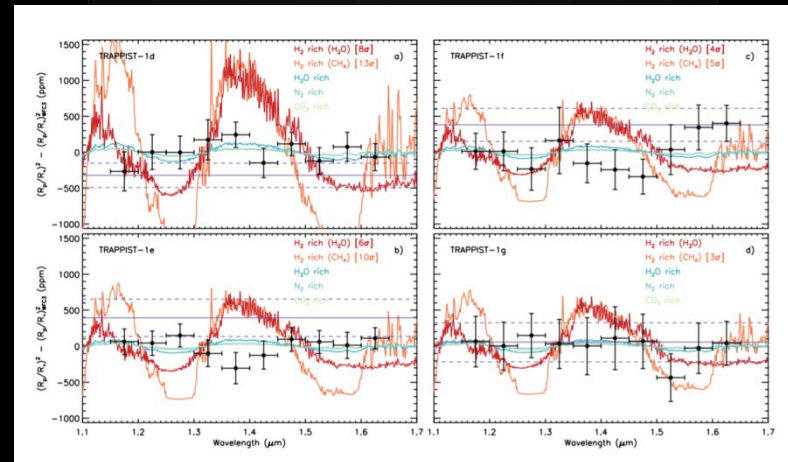
Caracterització



Espectroscopia de trànsits



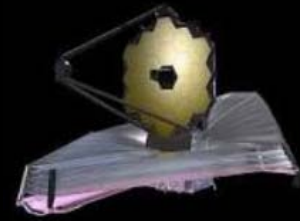
Tinetti et al. 2010 ApJ
XO-1



De Wit et al. 2018, Nature
TRAPPIST-1

Caracterització

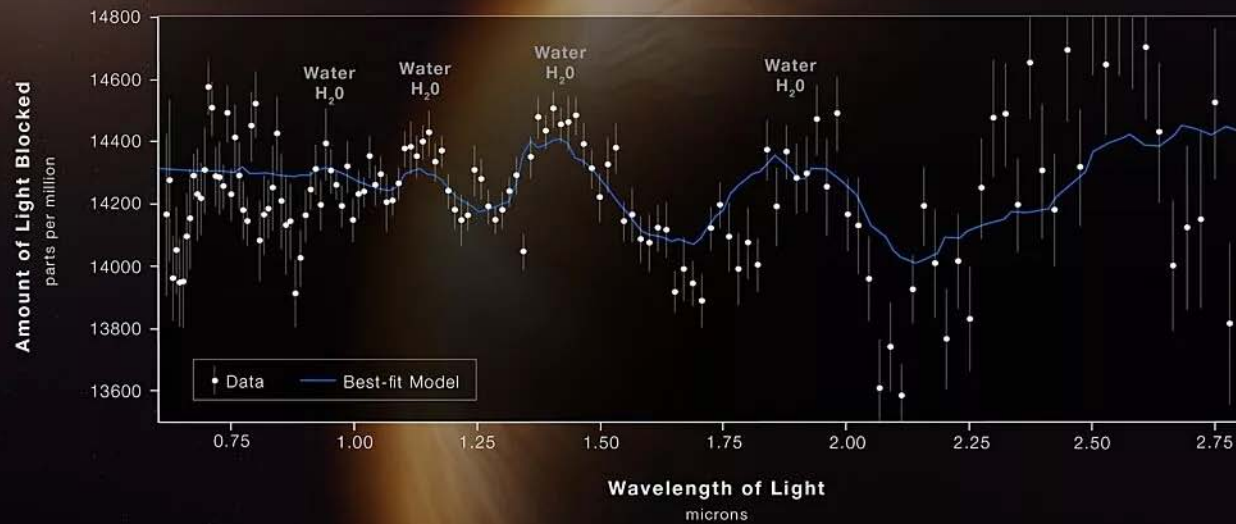
Espectroscopia de trànsits



HOT GAS GIANT EXOPLANET WASP-96 b

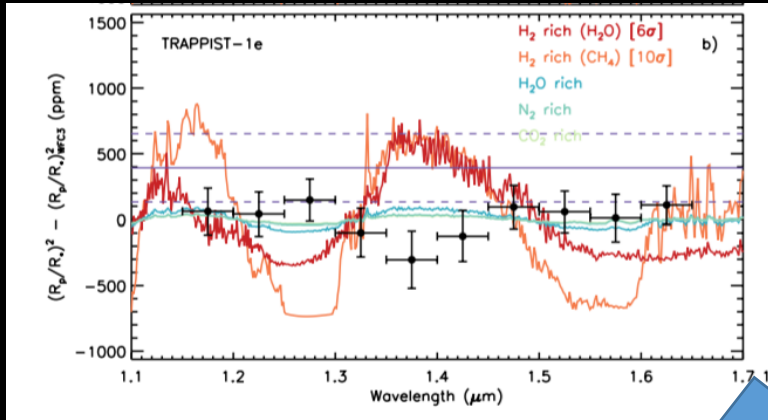
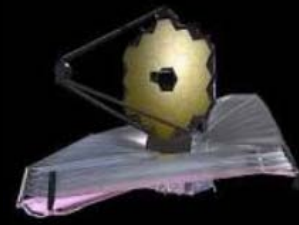
ATMOSPHERE COMPOSITION

NIRISS | Single-Object Slitless Spectroscopy

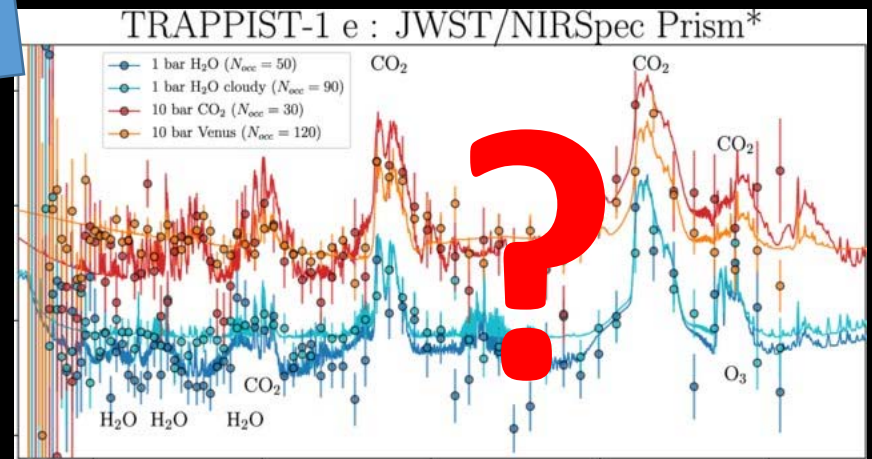
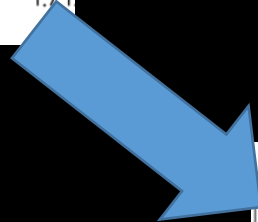


Caracterització

Espectroscopia de trànsits

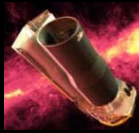


Hubble Space Telescope (2019)

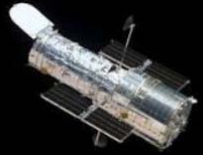


JWST propers mesos...

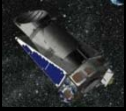
HST
2.5m class
NASA/ESA



SPITZER
1m, infrared, NASA



Kepler
NASA, 1m



Space Gaia
1m, astrometry,
ESA



NOW

2020

2030

Ground-based



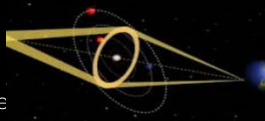
Doppler spec.
2m class telescopes
HARPS (ESO)
CARMENES
HARPS-N
APF, PFS



Transit searches
10cm-1.5m telescopes
NGTS, Mearth,
SPECULOOS, QATAR



Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini



Microlensing
0.5m class telescope
OGLE, LCOGT

HST
2.5m class
NASA/ESA



SPITZER
1m, infrared, NASA



CHEOPS
(30cm, ESA)

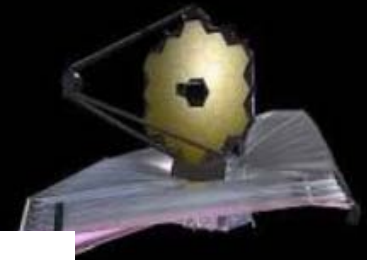


JWST
6.5m, NASA/ESA

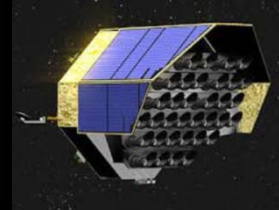
Project BLUE?
1m class telescope

Kepler
NASA, 1m

TESS
10x20 cm, NASA)



PLATO
ESA, 50x10 cm



ARIEL
ESA, 1m, spectra



Space Gaia
1m, astrometry,
ESA



Ground-based



Doppler spec.
2m class telescopes
HARPS (ESO)
CARMENES
HARPS-N
APF, PFS



Transit searches
10cm-1.5m telescopes
NGTS, Mearth,
SPECULOOS, QATAR



Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini



Direct imaging
ELF concept, Mutil 8m
class telescope

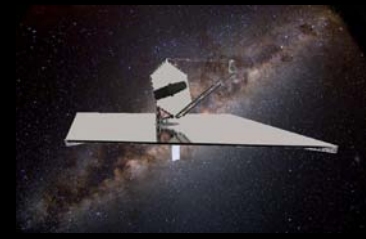
Microlensing
0.5m class telescope
OGLE, LCOGT



HST
2.5m class
NASA/ESA



SPITZER
1m, infrared, NASA



CHEOPS
(30cm, ESA)



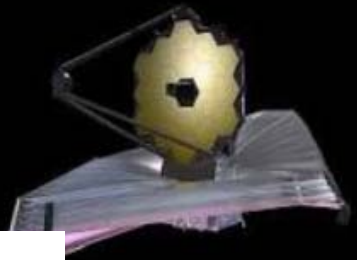
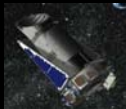
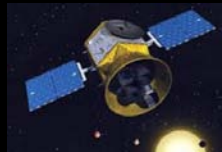
JWST
6.5m, NASA/ESA

Project BLUE?
1m class telescope

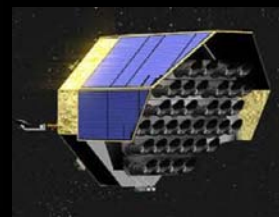
LUVOIR/HabEx?
16m, NASA

Kepler
NASA, 1m

TESS
10x20 cm, NASA)



PLATO
ESA, 50x10 cm



ARIEL
ESA, 1m, spectra



Space Gaia
1m, astrometry, ESA



LIFE
Interferometer, ESA



Ground-based



Doppler spec.
2m class telescopes
HARPS (ESO)
CARMENES
HARPS-N
APF, PFS



Transit searches
10cm-1.5m telescopes
NGTS, Mearth,
SPECULOOS, QATAR



Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini



Direct imaging
ELF concept, Mutli 8m
class telescope



E-ELT
European
Southern
Observatory



TMT
USA, China, India



GMT
USA

**Direct imaging
and spectroscopy**
Mutli 8m class telescope

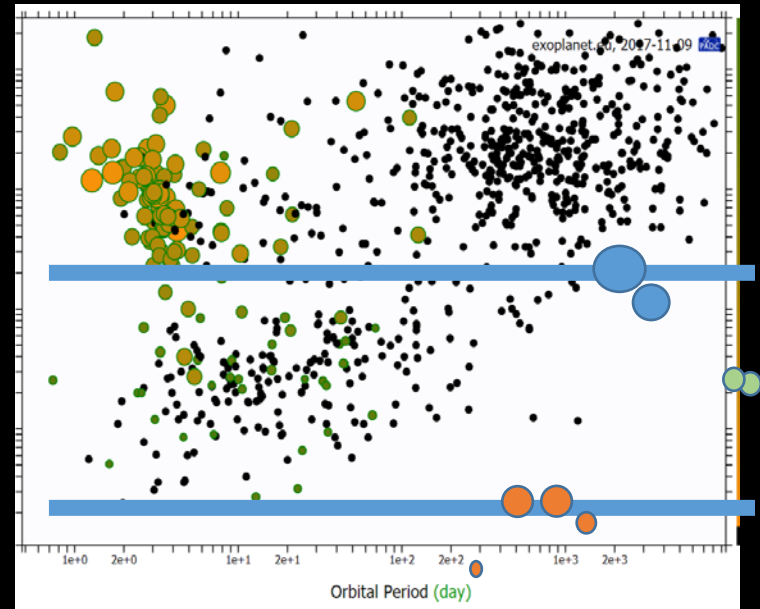
Microlensing
0.5m class telescope
OGLE, LCOGT



Conclusions

Ja estem detectant planetes terrestres en nanes vermelles

Encara ens falta gairebé una dècada per detectar-los en estells com el Sol



Velocitat radial

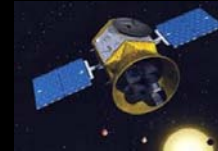
Massa

Conclusions

Més del 50-60% d'estels tenen planetes terrestres en òrbites temperades



TESS
10x20 cm, NASA)

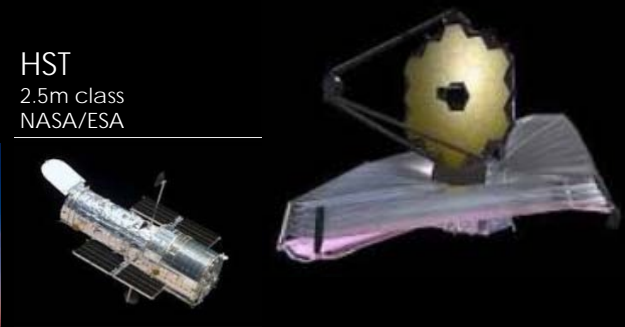


La caracterització d'algunes atmosferes planetàries ja pot fer-se amb instruments existents



Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini

HST
2.5m class
NASA/ESA

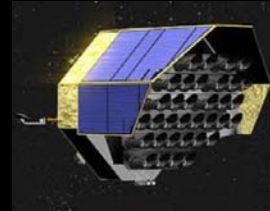


Conclusions

Per **detectar Anàlegs terrestres** farem servir instruments que estan gairbé apunt

Amb millors simulacions i tècniques d'aprenentatge de màquina (IA), podrem **eliminar el soroll estelar**

PLATO
ESA, 50x10 cm



Spectroscopia Doppler

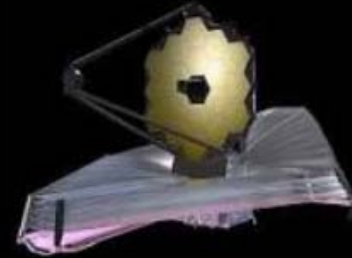
2m class telescopes
HARPS (ESO)
CARMENES
HARPS-N
APF, PFS

Conclusions

Les **primeres pistes** sobre biomarcadors vindran de **planetes terrestres en nanes vermelles** (està passant)

Per tenir **informació completa de biomarcadors**, caldran missions d'imatge directe d'alt contrast, que estant encara en estudi (una o dues dècades)

Caldrà detectar diversos planetes **i veure si hi ha una població anòmala** amb característiques similars a la Terra

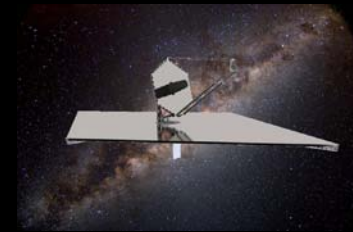


JWST
6.5m, NASA/ESA

European
Southern
Observatory



**Direct imaging
and spectroscopy**
Multi 8m class telescope



LUVOIR/NASA



LIFE

2030-2040?

Conclusions

Recerca puntera **feta a Catalunya**, en col.laboració internacional

...però tremendament limitada per falta de personal



CARMENES survey
Calar Alto, Andalusia
Hispano-Alemanya



Telescopi Joan Oró
Observatori del Montsec

