Exoplanets : state-of-the-art and prospects for 2025+

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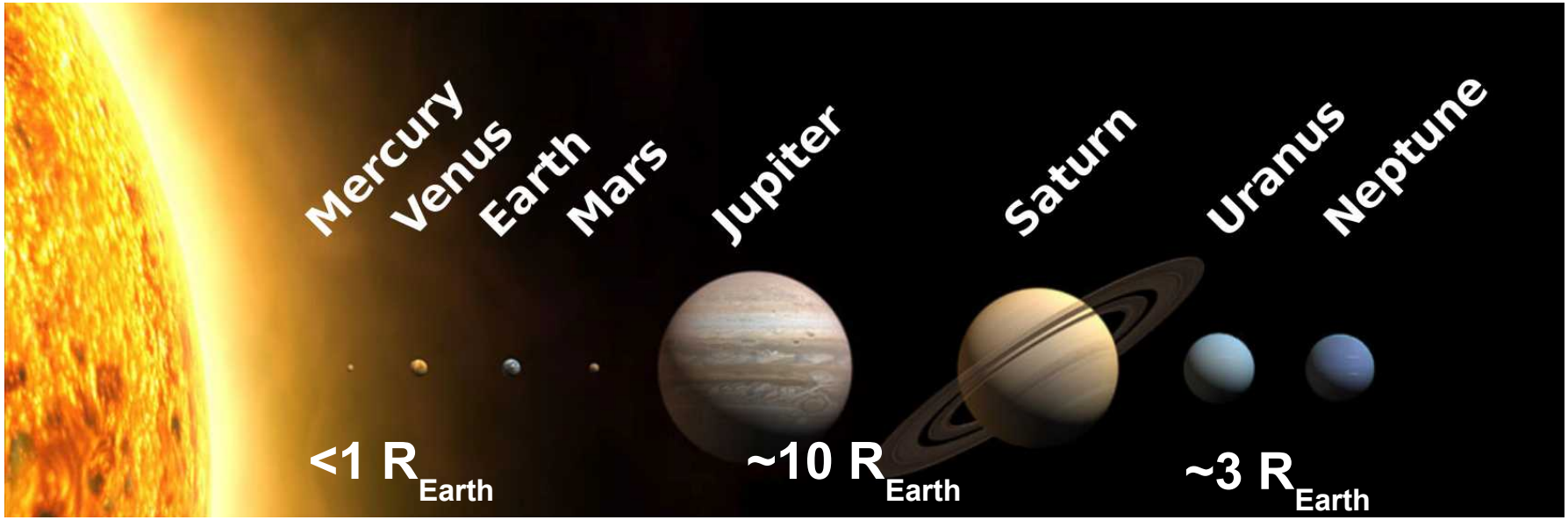
Planetary systems : pre-1995

Starved of gas, too irradiated, high orbital speeds and star tides

Gas giants form where enough cold gas is available for cores to grow

Ice giants where the gas density is too low to accrete massive envelopes



Rocky or telluric planets

Gas giants

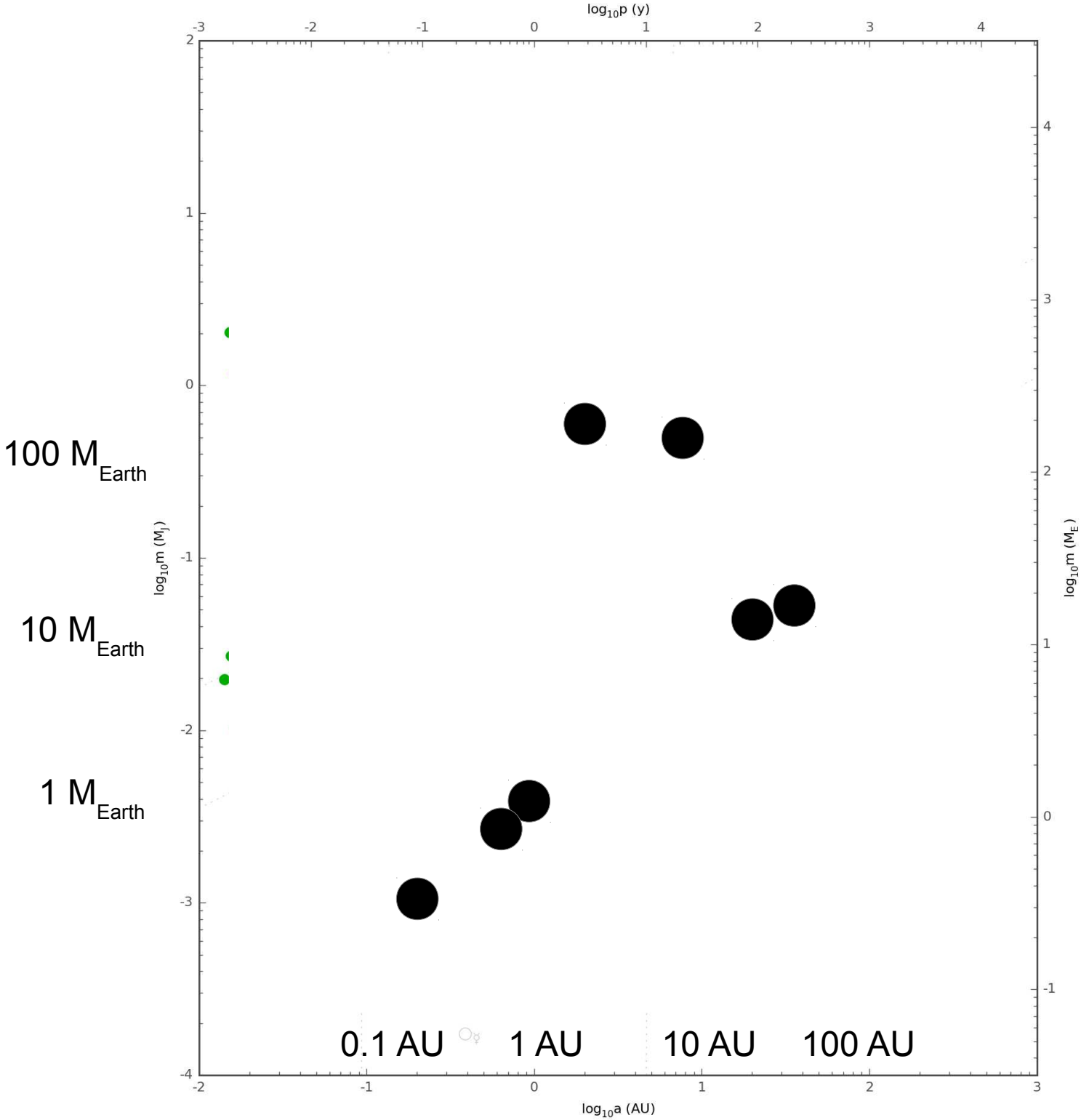
Ice-giants or Neptunes

All in quasi-circular orbits

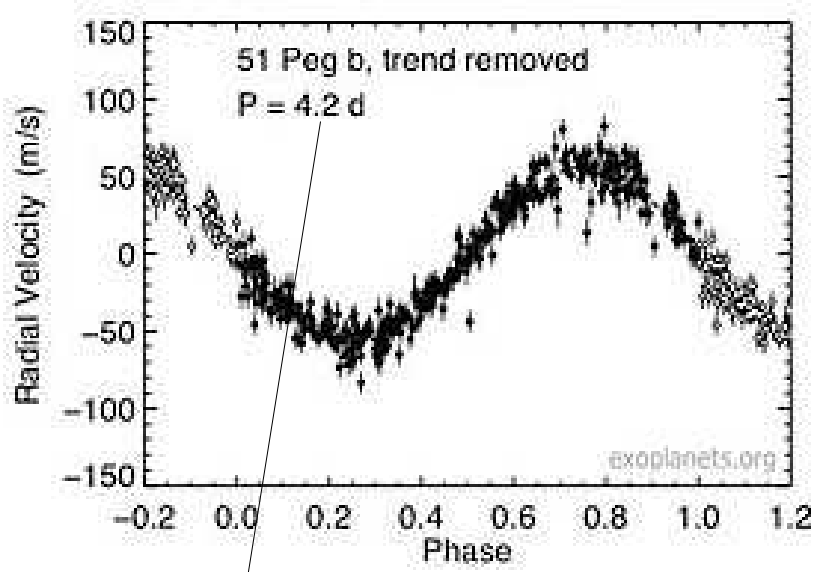
Nebular hypothesis
Swedenborg, Kant, Laplace 1750-1795

Protoplanetary disk
Reformulated by many. Late XX century Victor Safronov and George Wetherill (runnaway accretion)

Planet formation is a universal process so there should be many Solar Systems


log10p (y)
log10m (MJ)
log10m (ME)
log10a (AU)
100 MEarth
10 MEarth
1 MEarth
0.1 AU
1 AU
10 AU
100 AU

First exoplanets around MS stars

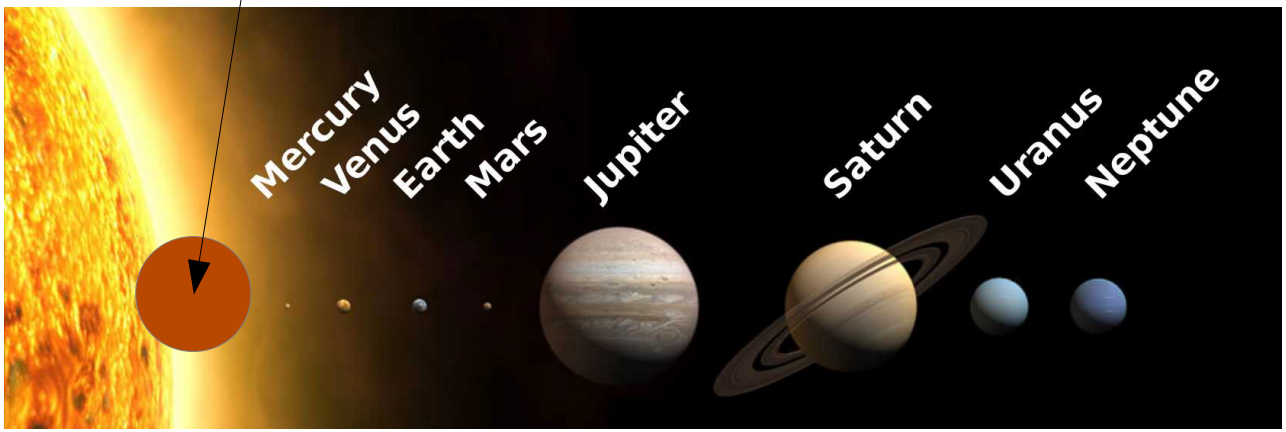


A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Nature 1995

November 1995



First exoplanets around MS stars

April 1996

A PLANETARY COMPANION TO 70 VIRGINIS[1]

GEOFFREY W. MARCY[2] AND R. PAUL BUTLER[2]
Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132; gmarcy@etoile.berkeley.edu

Received 1996 January 22; accepted 1996 April 2

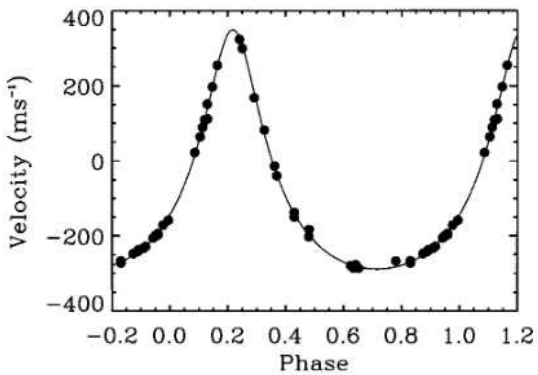
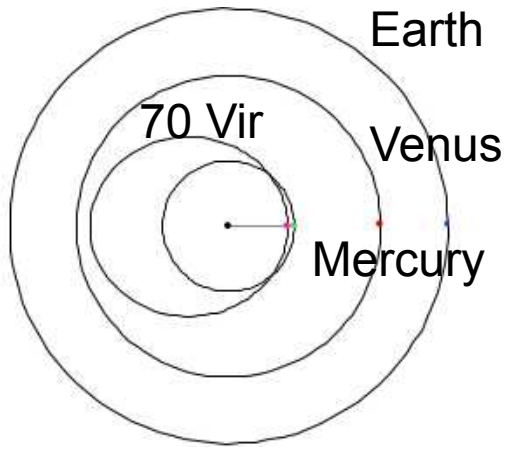
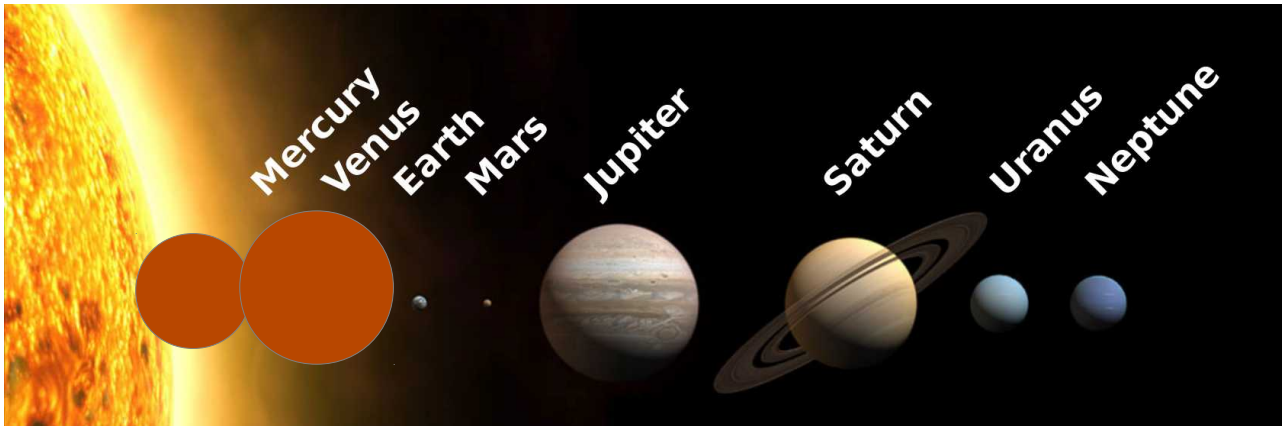


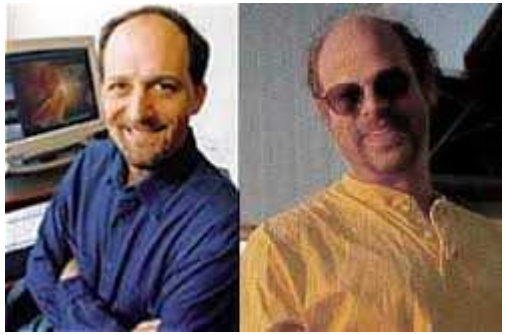
FIG. 3.—Velocities for 70 Vir phased with the orbital fit for $P = 116.67$ days. Error bars are smaller than the points. The derived minimum companion mass is $M_{comp} \sin i = 6.6\ M_J$.

P=110 days
M sin i = 6.6 Mjup
e = 0.4 (!!!)

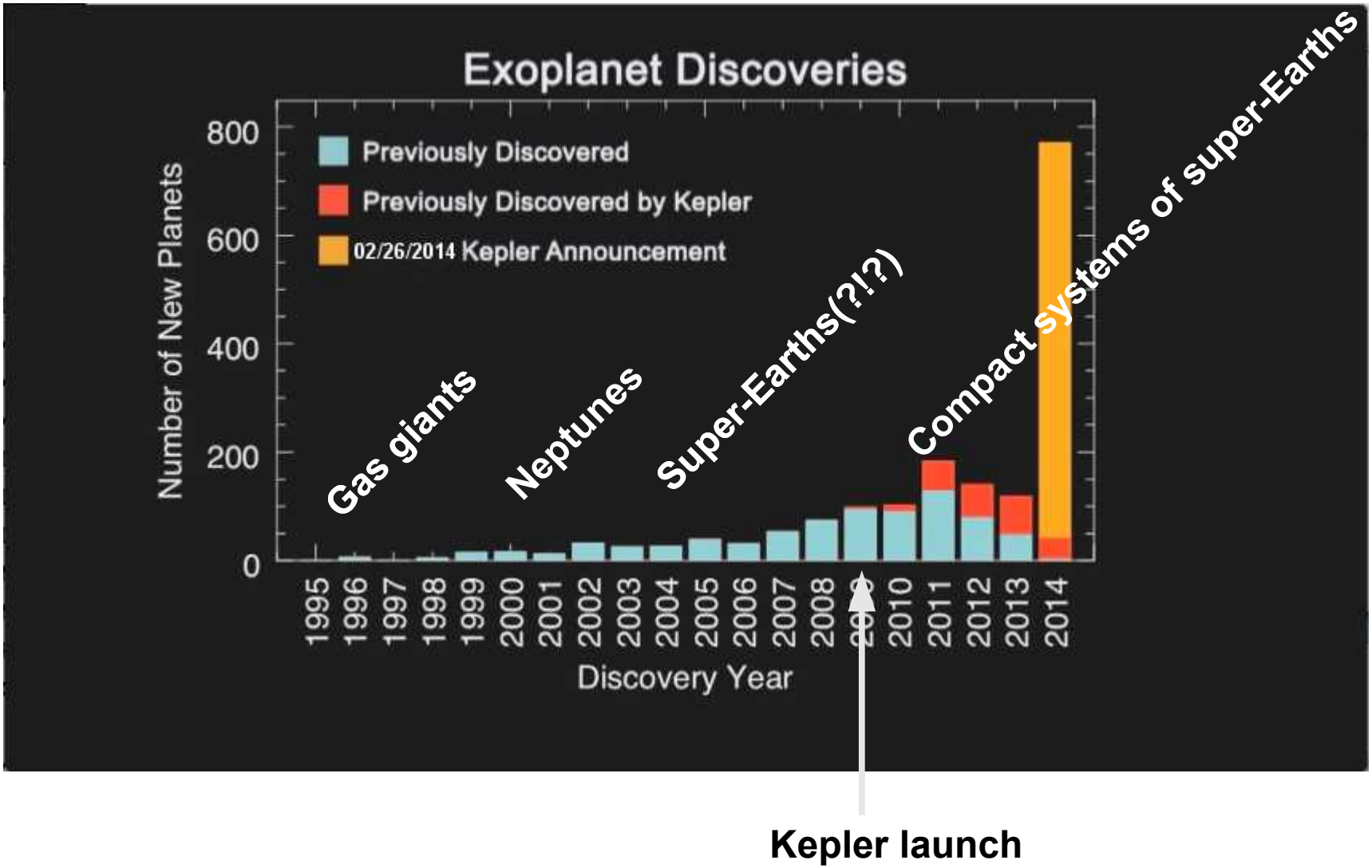




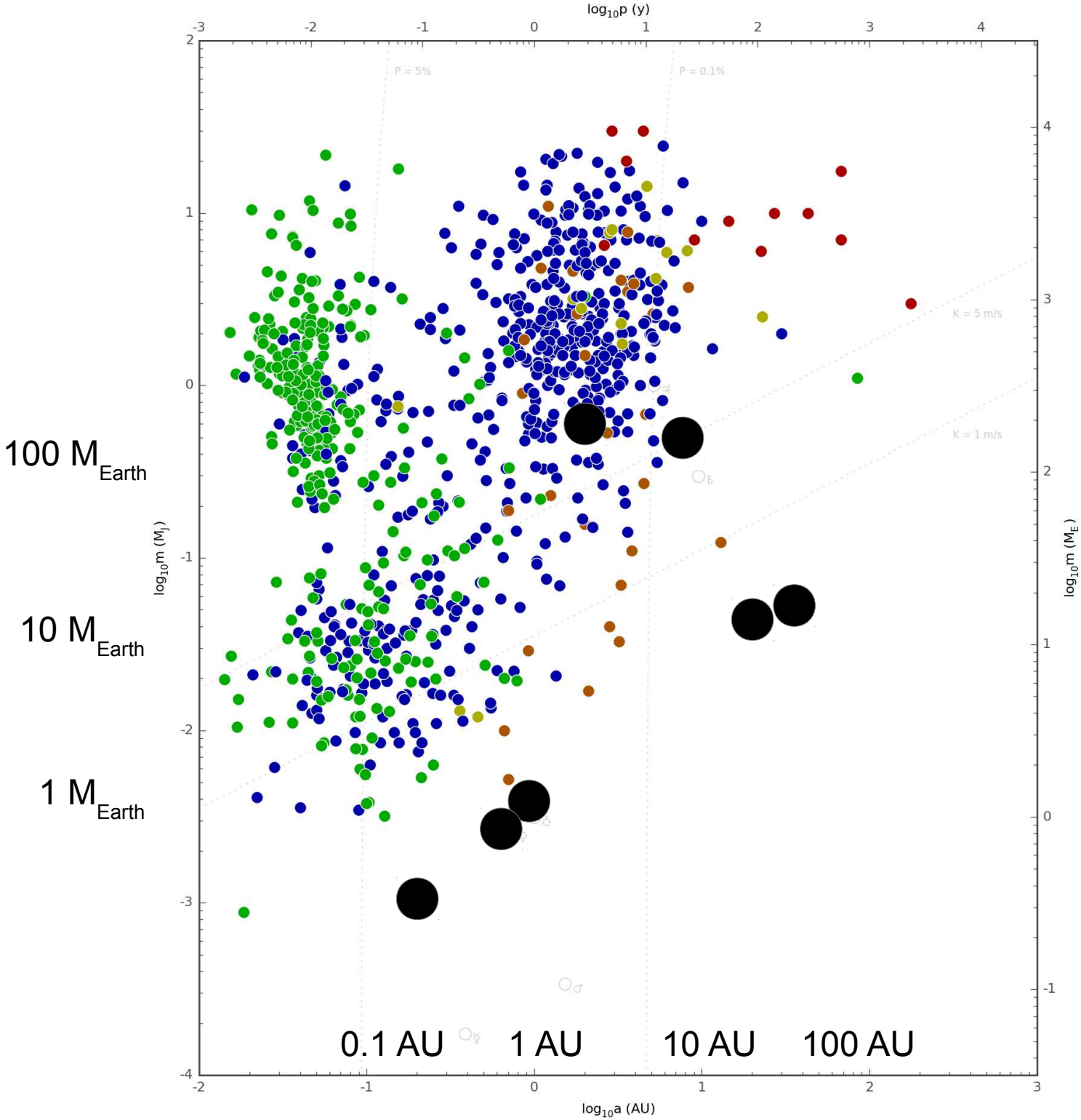
0.47 M_{Jup} 6.6 M_{Jup}



20 years of exoplanets around MS stars

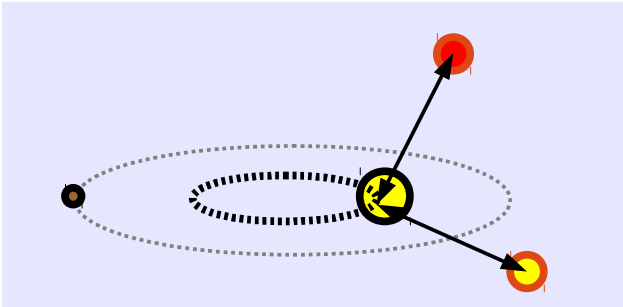


The exoplanet portrait

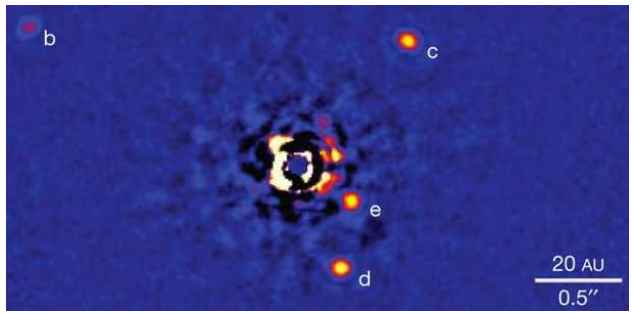


Detection techniques

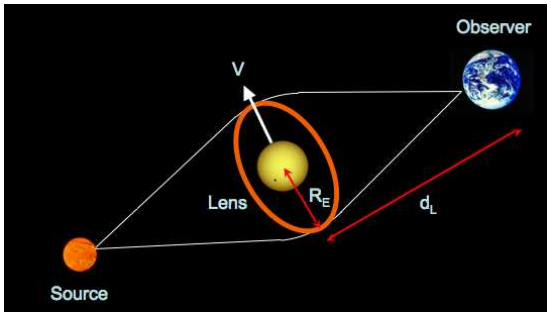
Astrometry



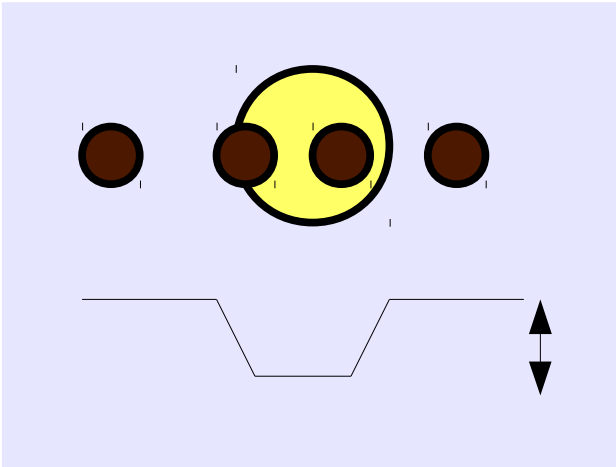
Direct imaging



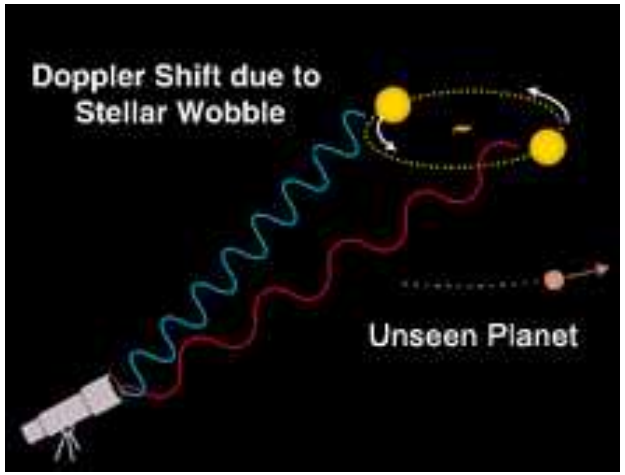
Microlensing



Photometric transits

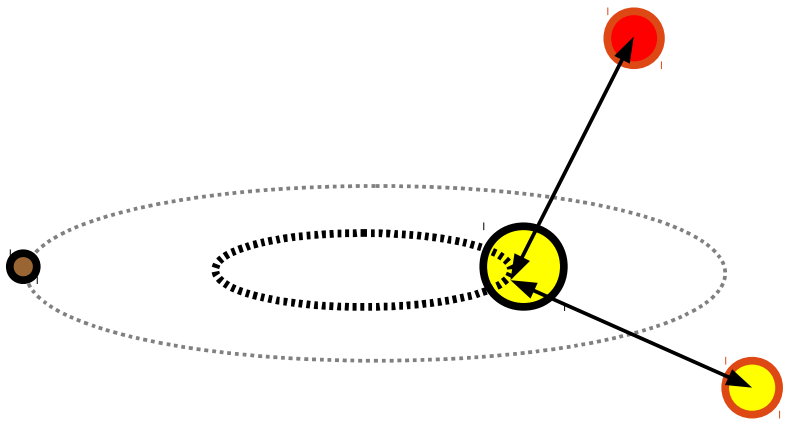


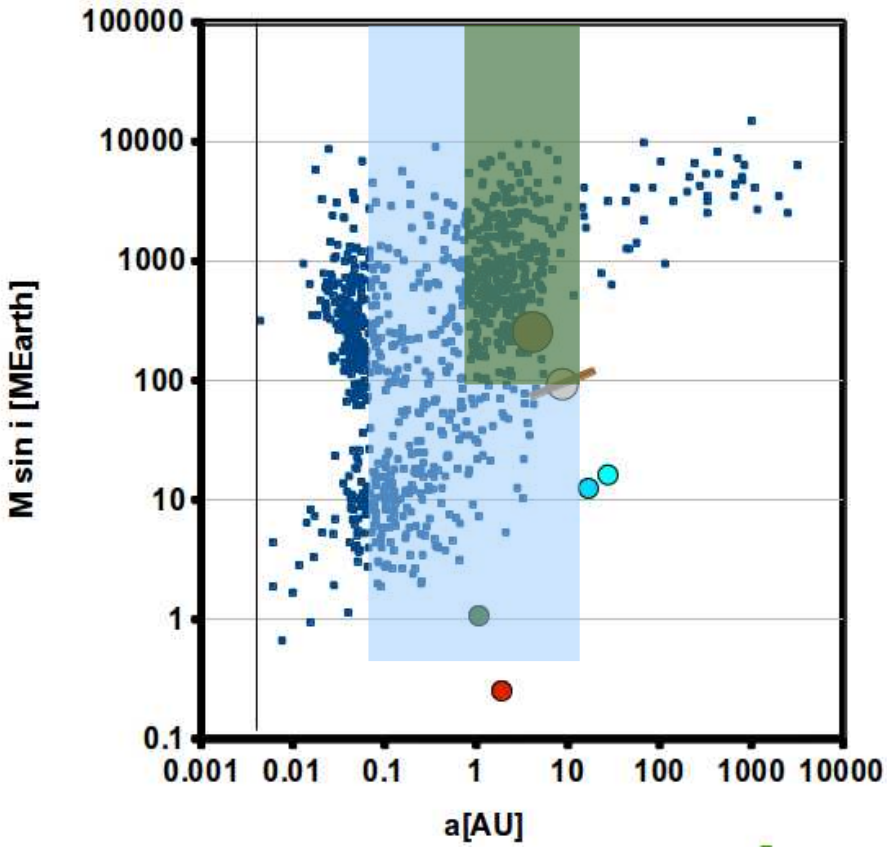
Doppler spectroscopy



Astrometry

- Sensitivity





α_{jup} = *1 mas* [m/m$_{Jup}$] [M$_{sun}$/M$_*$] [a/AU] [pc/D]

α_{Earth} = *3 μas* [m/m$_{Earth}$] [M$_{sun}$/M$_*$] [a/AU] [pc/D] **~10^{-11} rad**

1 deg

3474 km

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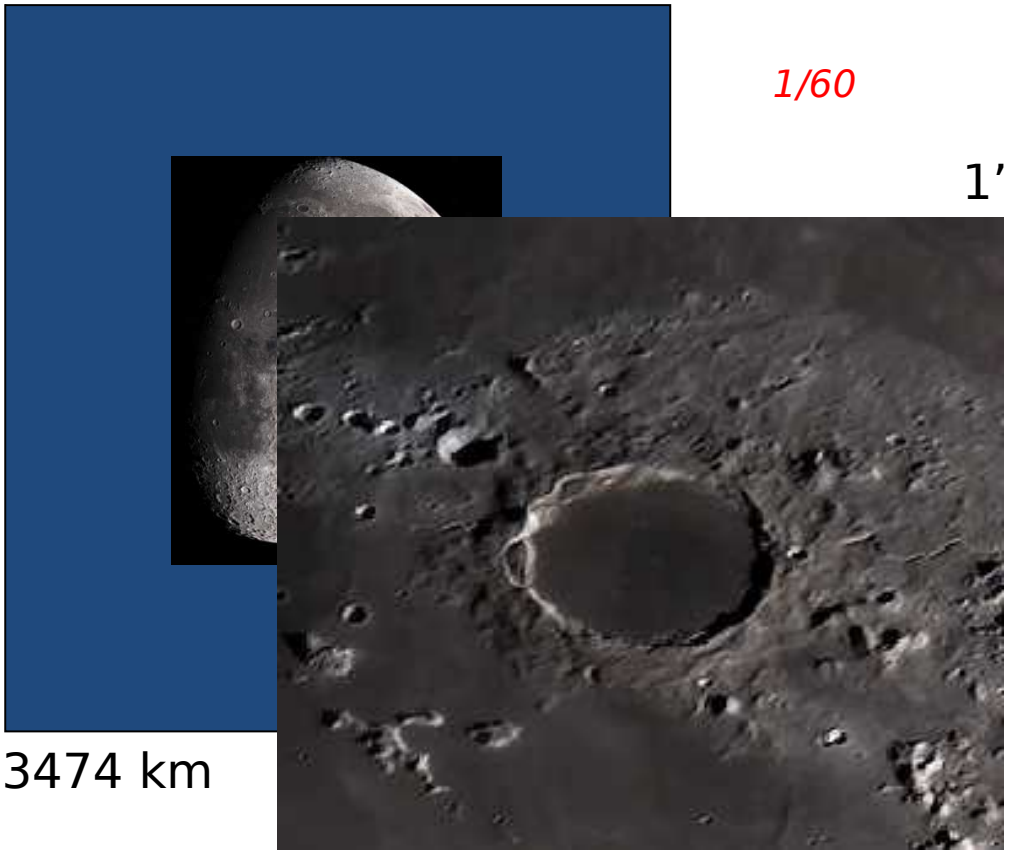
1 deg



1/60

1’

3474 km

120 km

α_{jup} = *1 mas* [m/m_{Jup}] [M_{sun}/M_*] [a/AU] [pc/D]

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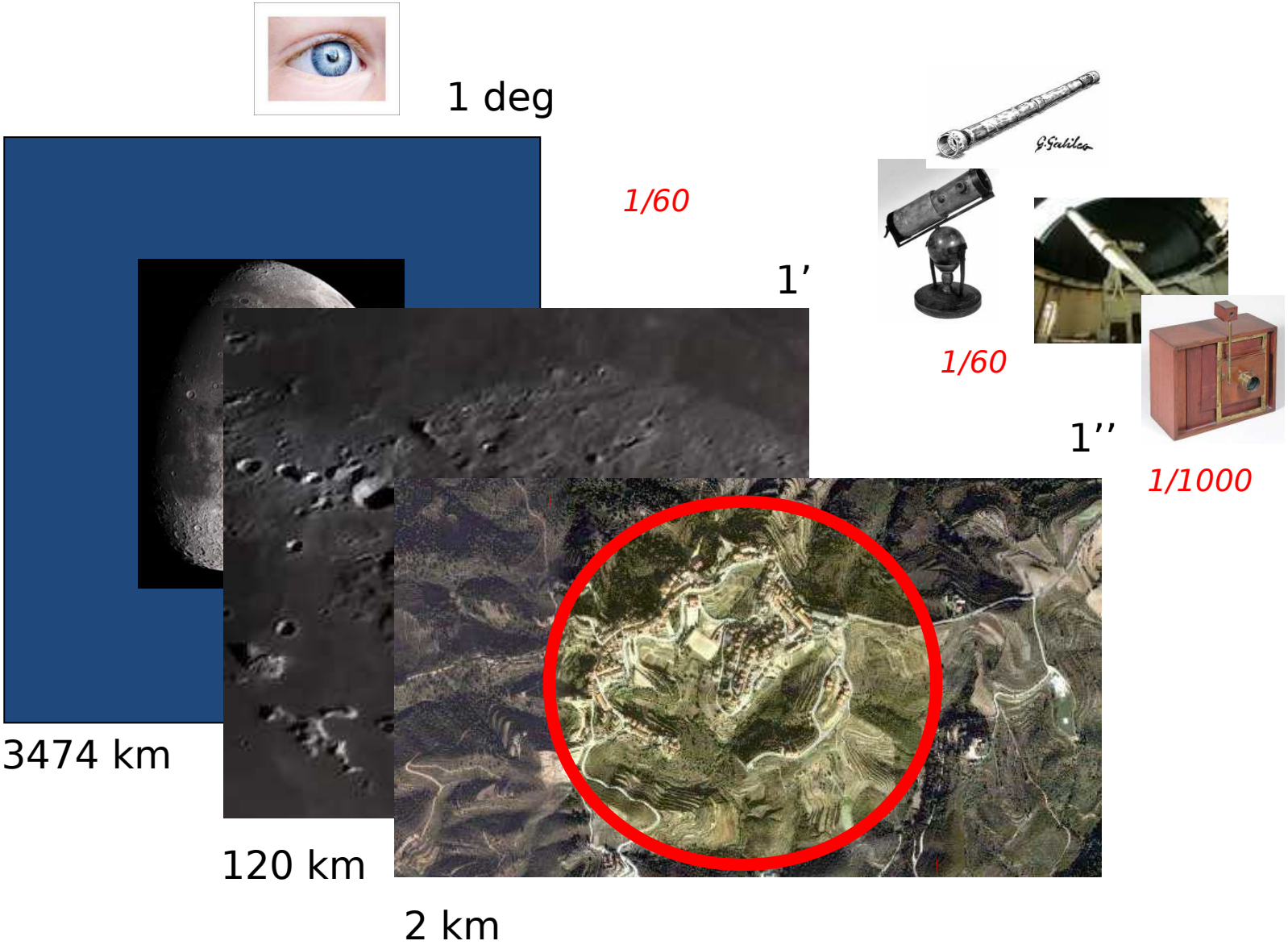

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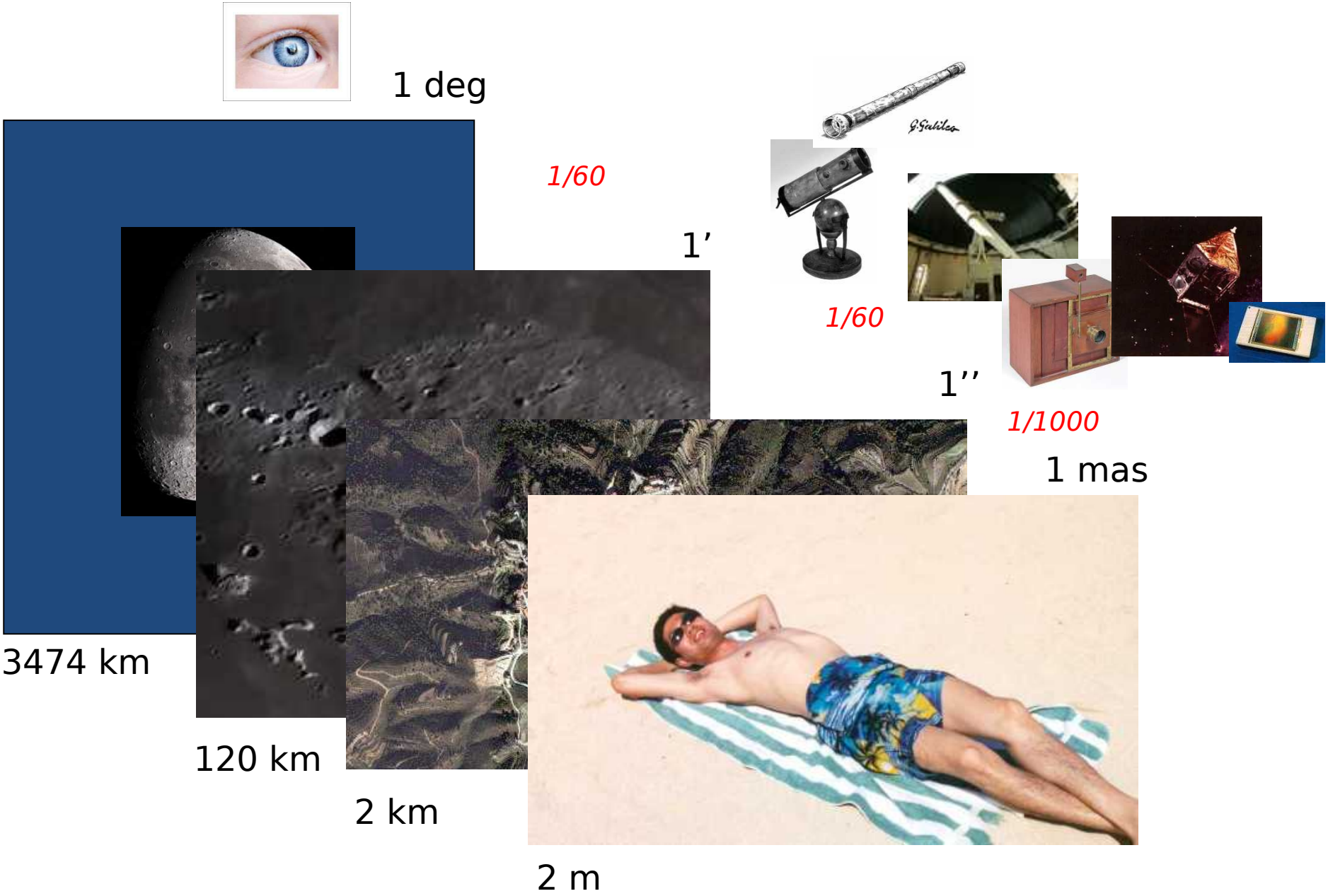

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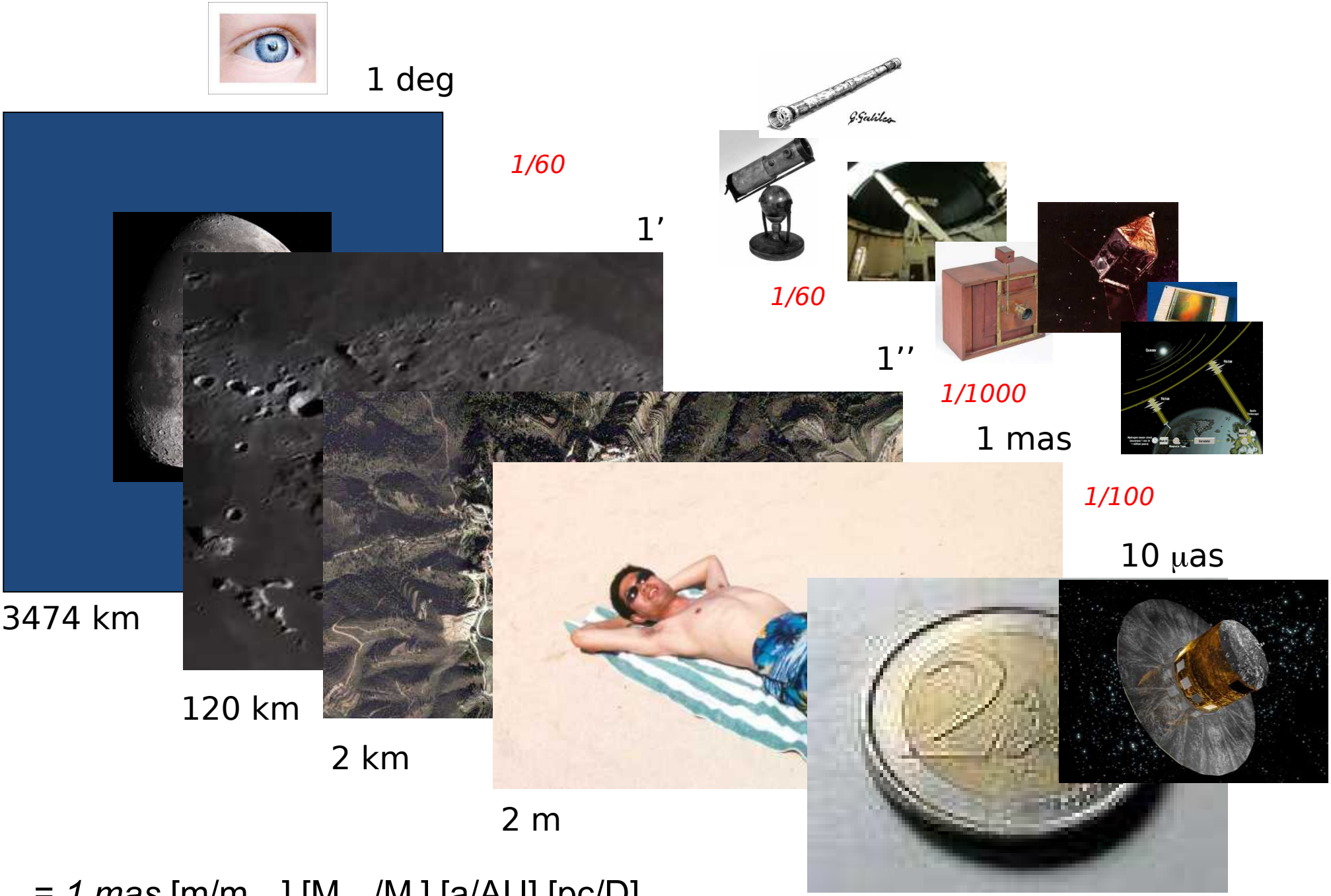

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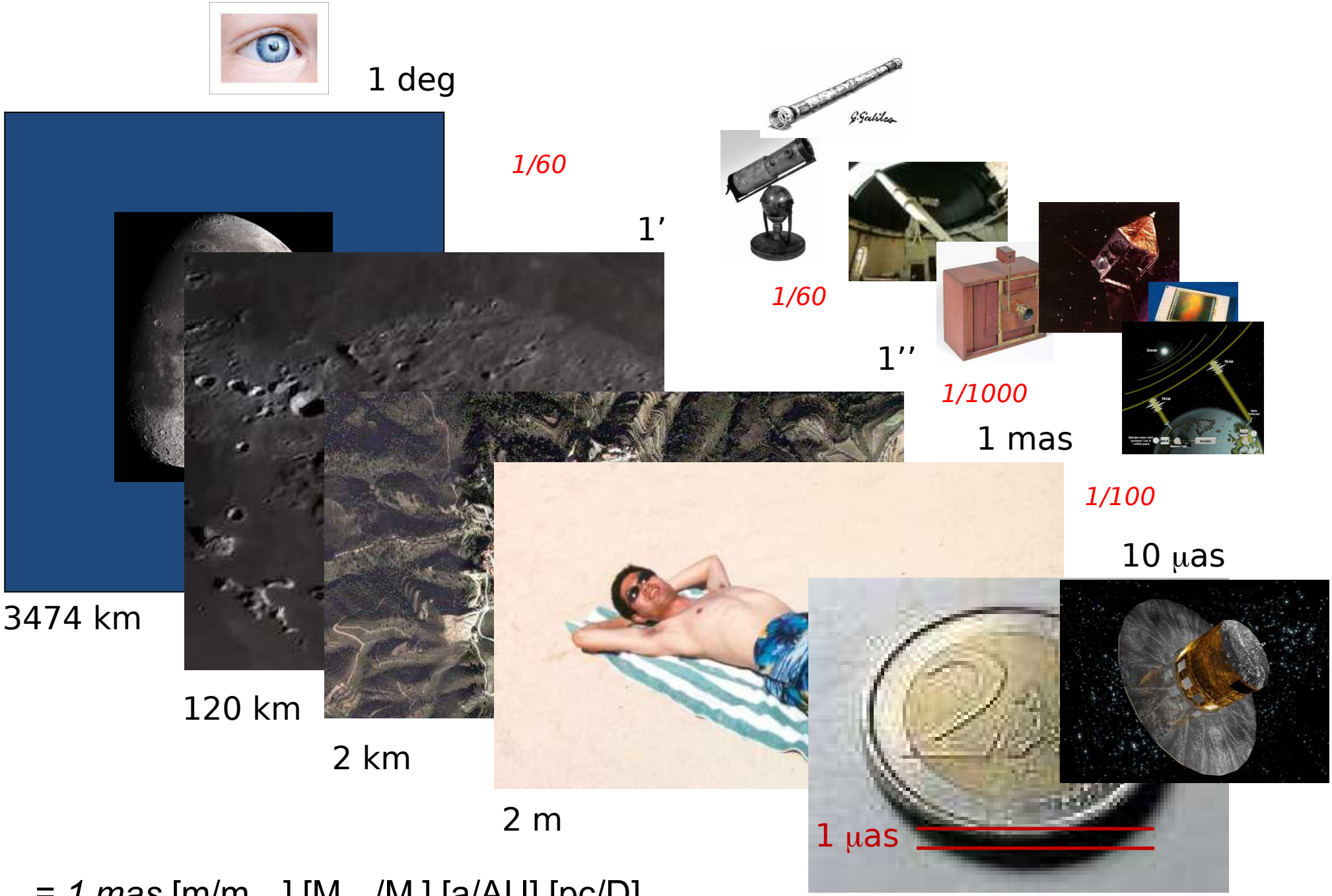

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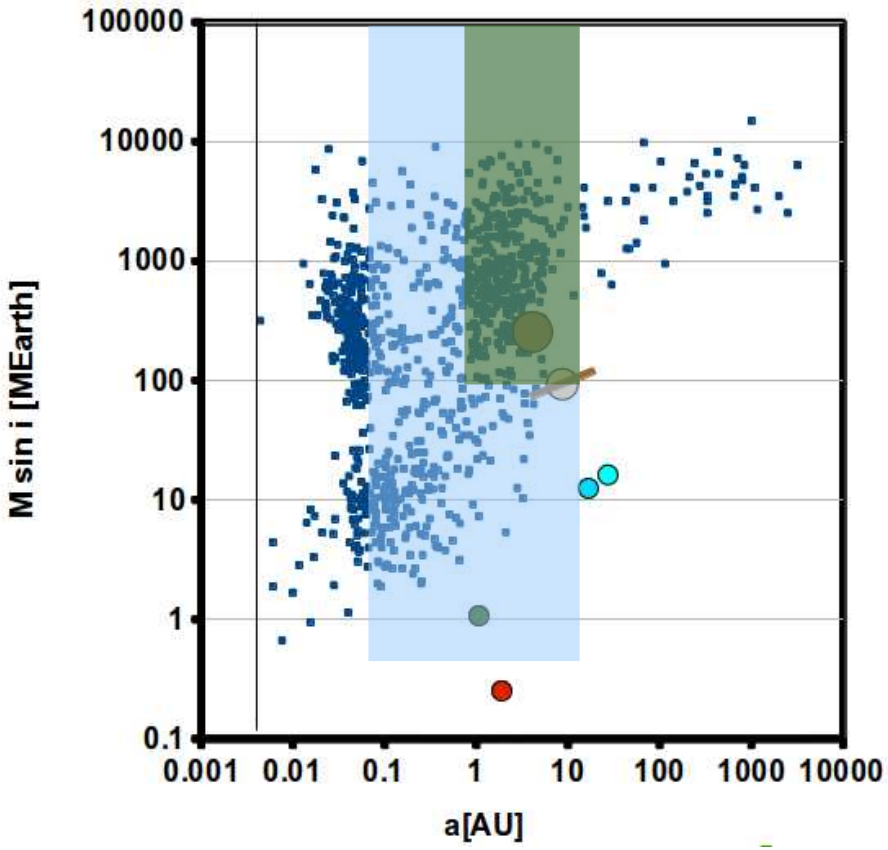
Astrometry : results

No detections so far...

(ON GOING) Ground based
Seaarch Jupiters around M-stars
3 ongoing surveys

(ON GOING) Gaia/ESA mission
Launch Dec 2013, results by 2020

Mid-to-long period Gas giants
Masses and mutual inclinations
(3000-10 000?)



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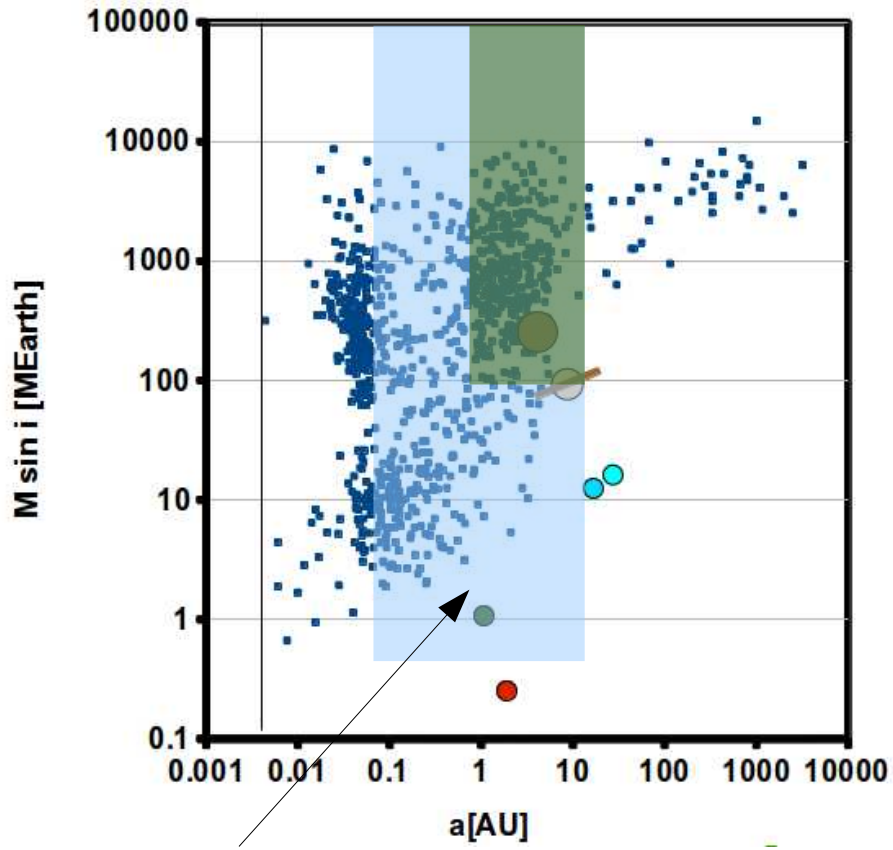
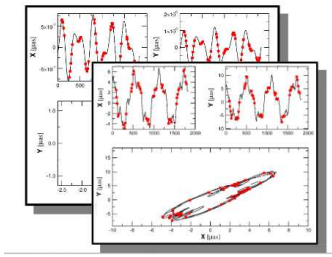


Theia : observing the universe in motion



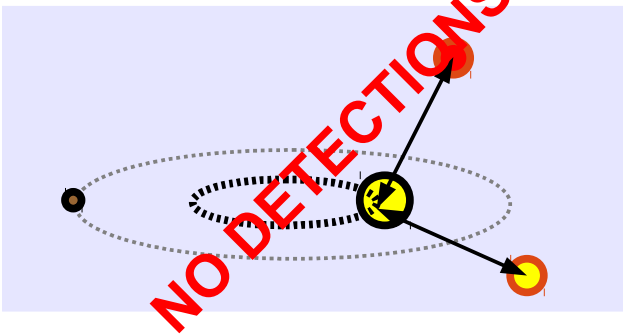
M4 mission proposal

search for another Earth ...
yourself!

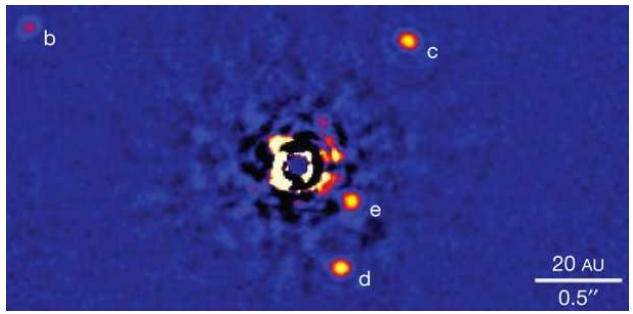
Astrometry : Gaia

Detection techniques

Astrometry



Direct imaging



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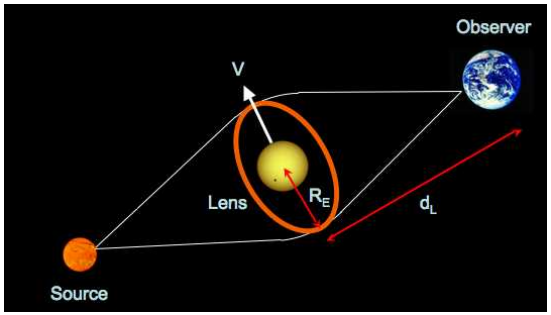

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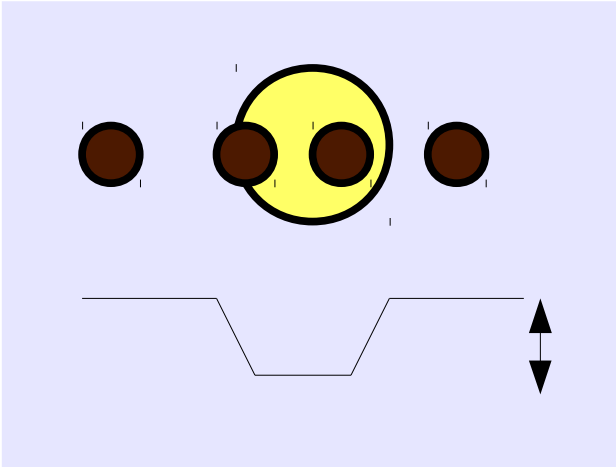
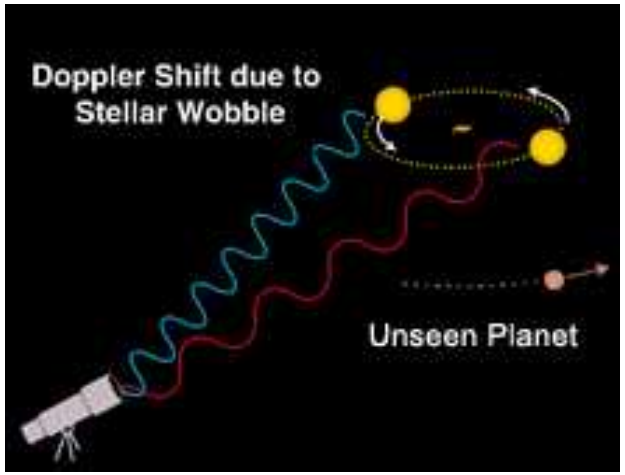
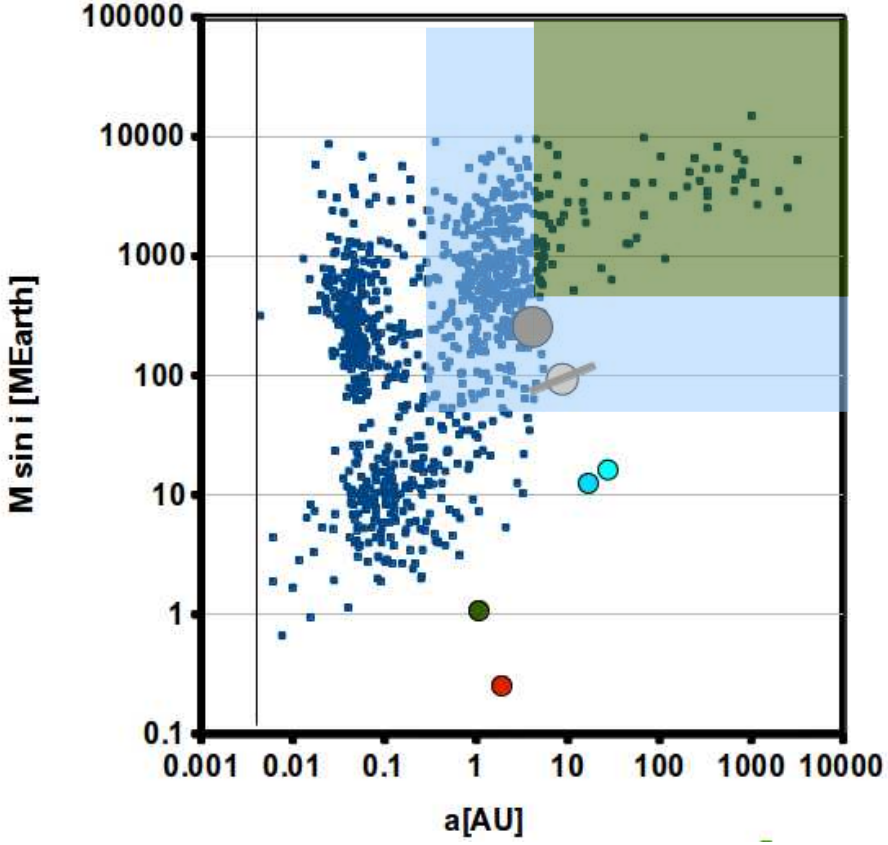


Doppler spectroscopy



Direct imaging : discovery space

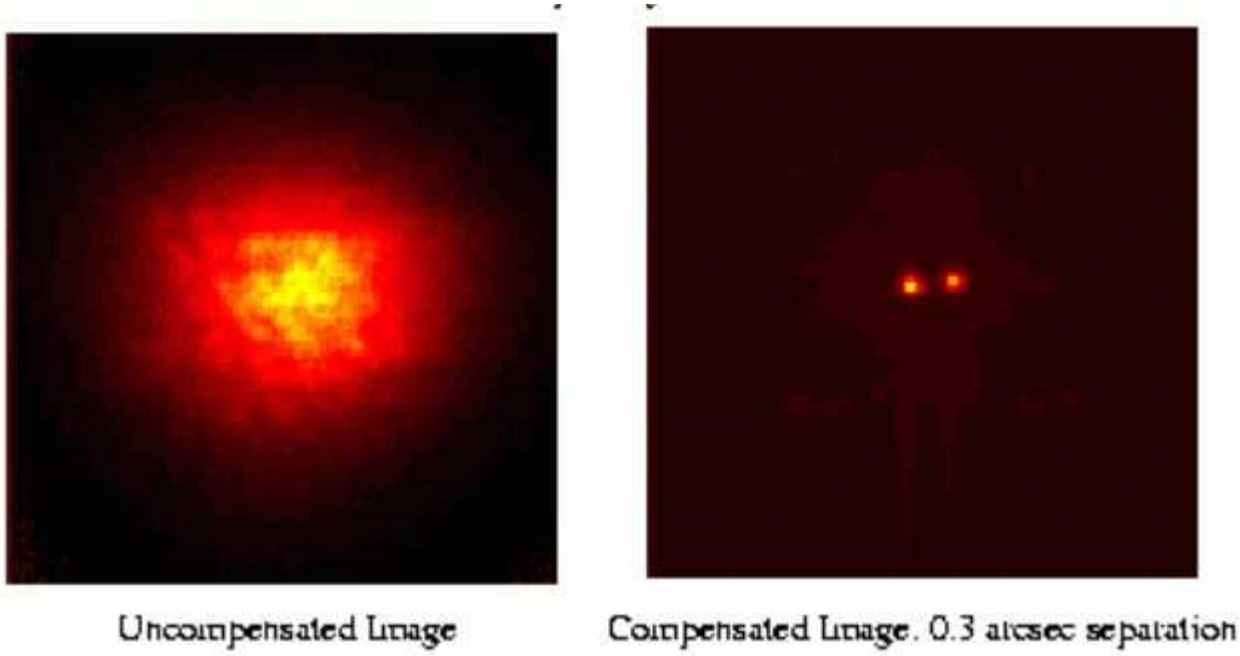
- Young/self luminous
- Long-period (super)Jupiters
- 'Non-cool A-stars' & some M-dwarfs (planets or BD?)
- Structures in disk (controversial : planet in the making?, turbulent disk, geometric artifact?)



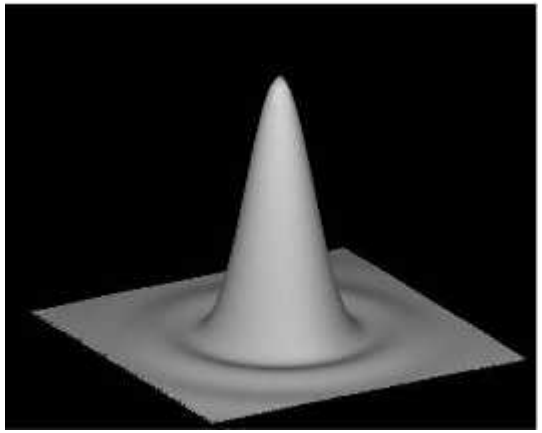
Direct imaging : discovery space

Reflected light : $\frac{1}{2}(r/a)^2 = 8\ 10^{-8}\ (R_{jup}/a_{AU})^2$

Re-emitted light : cooler blackbody → nIR enhanced (10^2-10^3?)



Monochromatic PSF of point source



Technically very challenging & expensive (notable failures in the past)

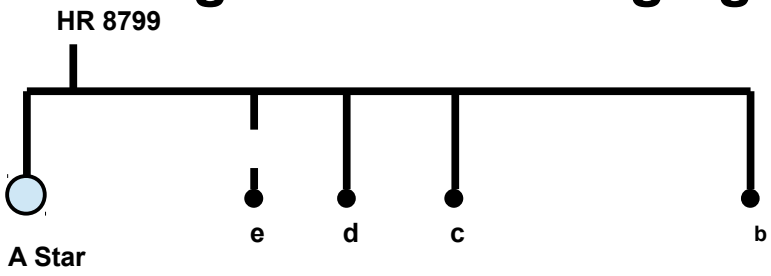
Direct imaging : results

- Classic imaging planets
  (AO, large apperture, nIR)

- Common proper motion pairs or free floating objects
  (nIR,mid-IR, survey)

- Disk structures
  (optical,nIR, sub-mm, AO)

High contrast imaging

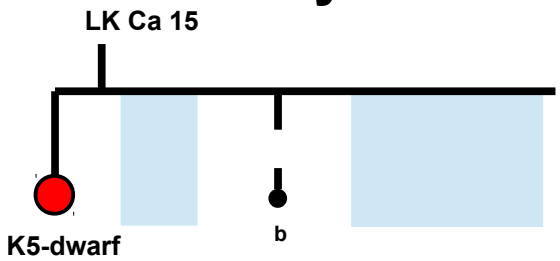


Marois et al. 2008, Science

Infrared surveys

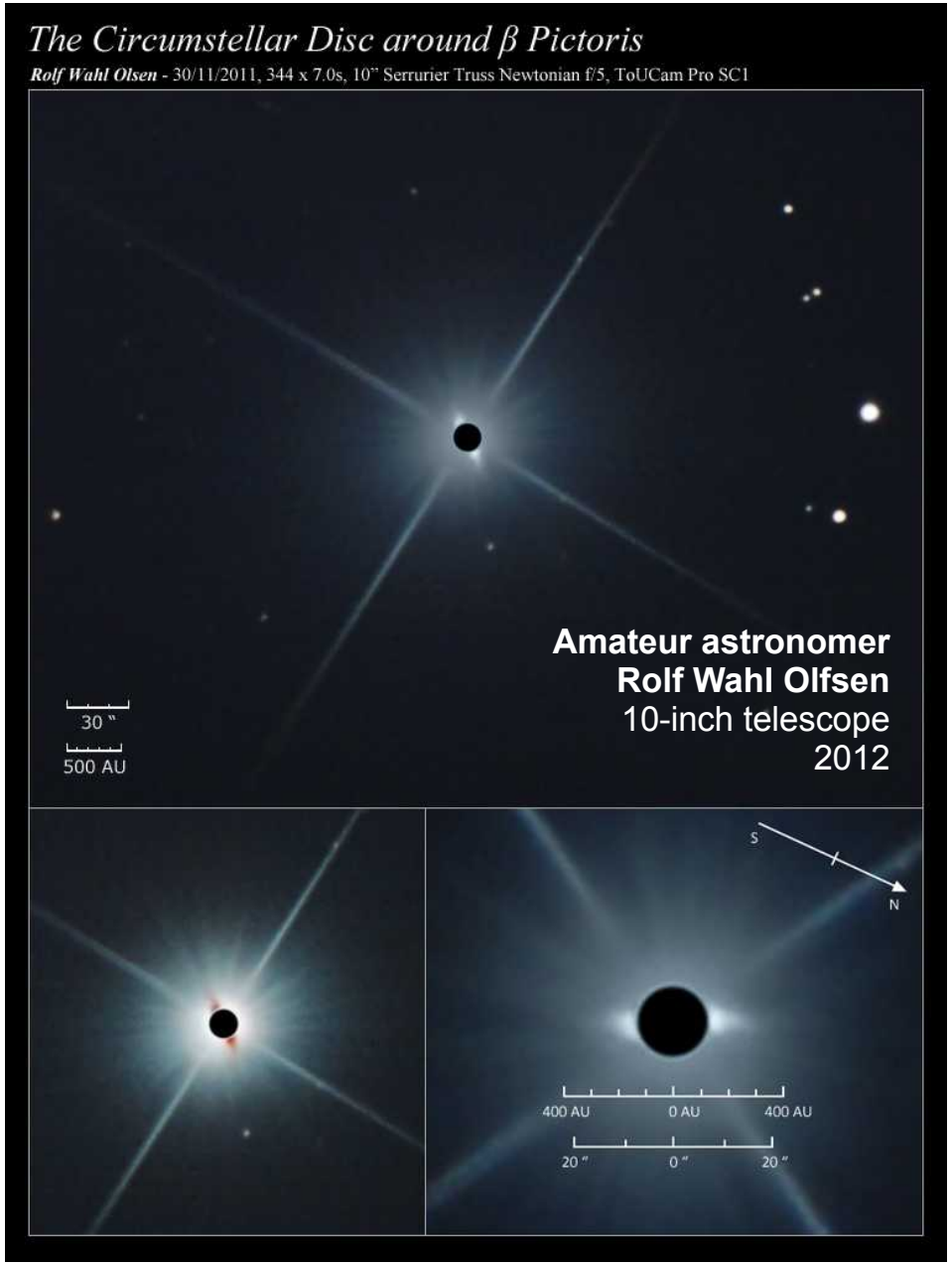
Naut et al. 2014, ApJ

High contrast+dynamics



Kraus & Ireland, 2012 ApJ

Direct imaging : present



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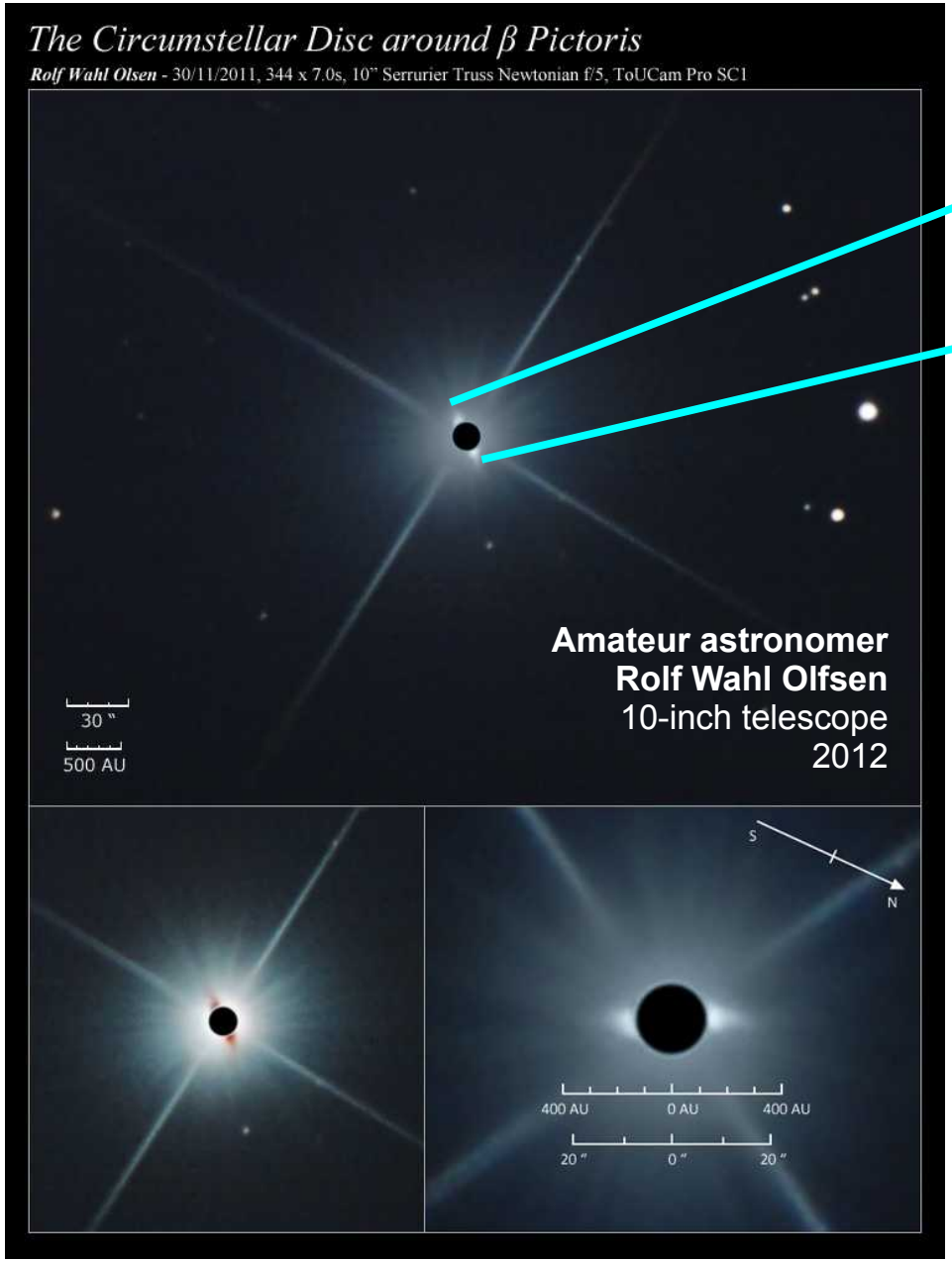
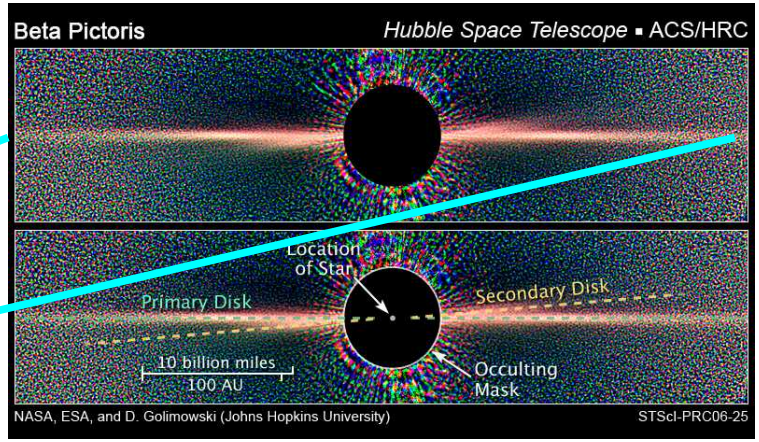
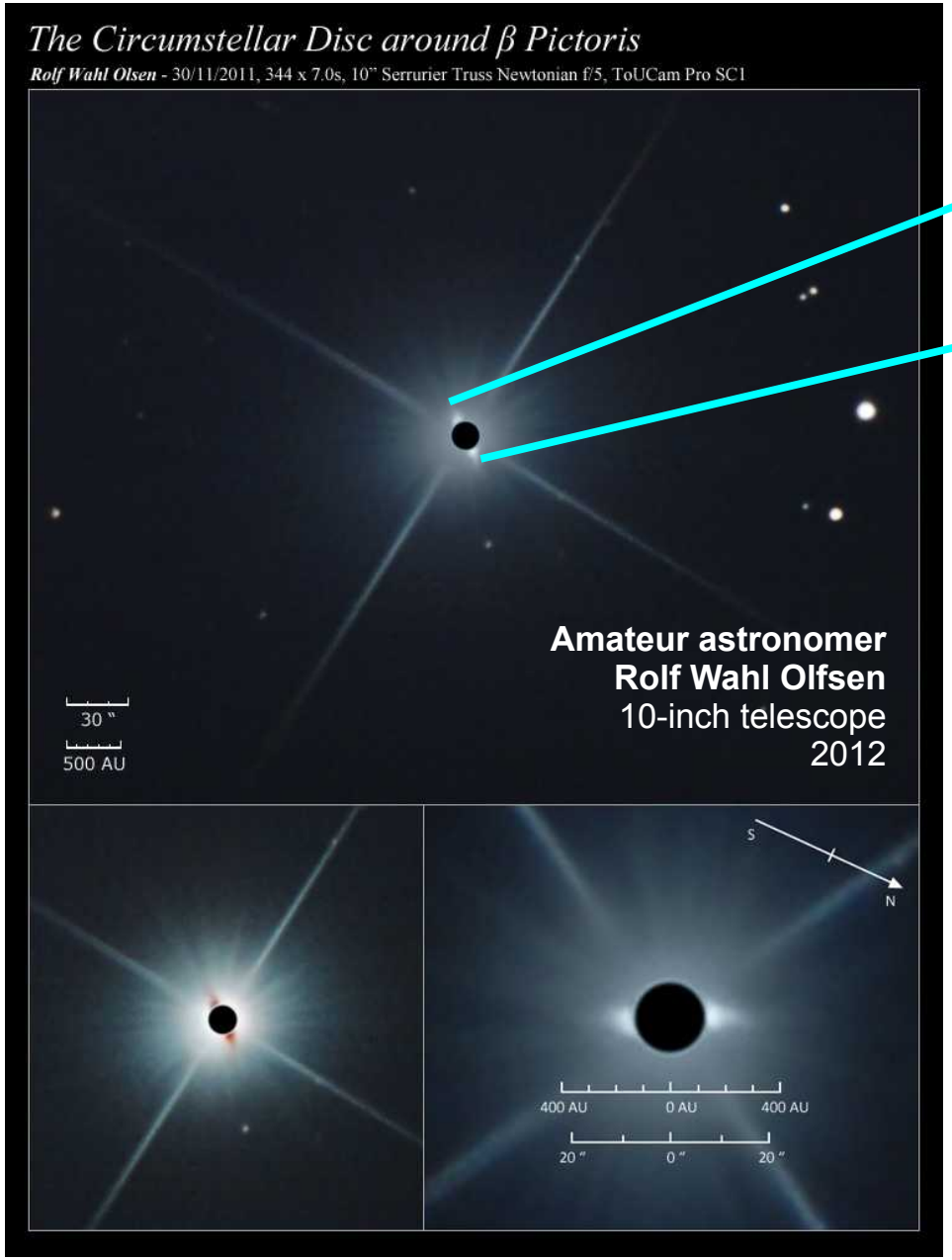
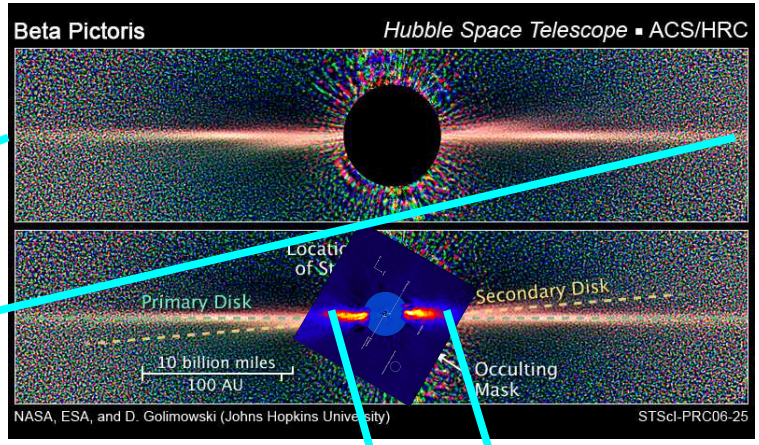




HST image of Beta Pic's disk
Golimowsky et al. 2006 AJ

Direct imaging : present





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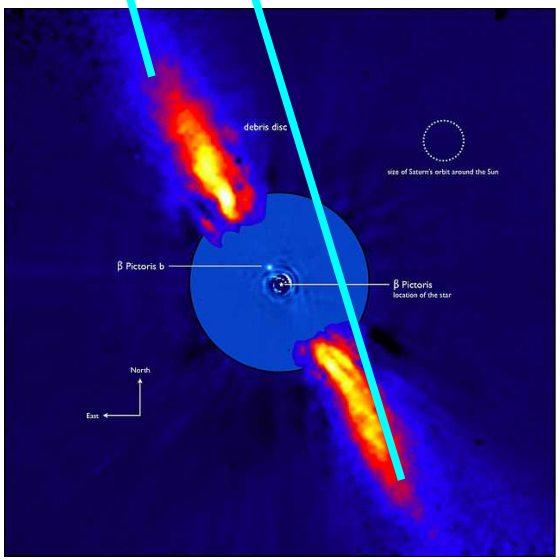
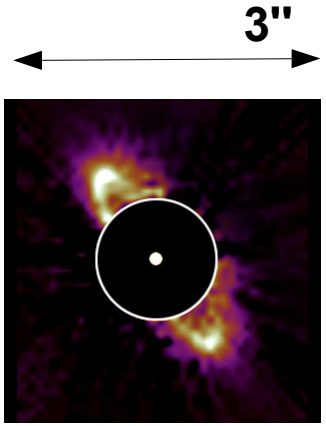


ESO/VLT : detection of
Beta Pic b in motion
Lagrange et al. 2010

Direct imaging

- **SPHERE/ESO and GPI/Gemini**

Schneider, G. et al **"NICMOS imaging of the HR 4796A Circumstellar Disk,"** 1999



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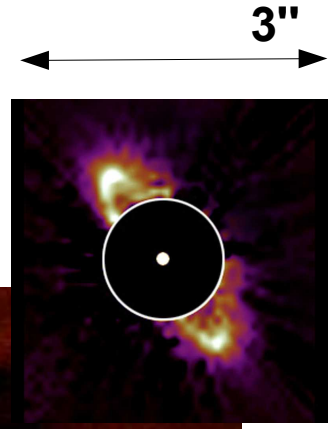
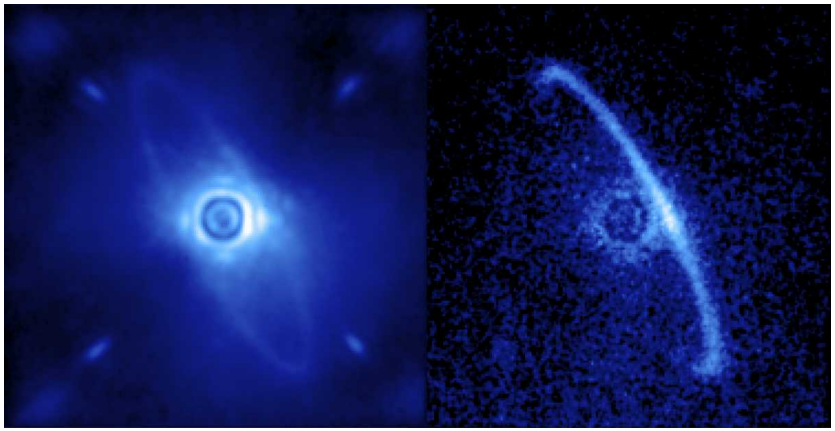
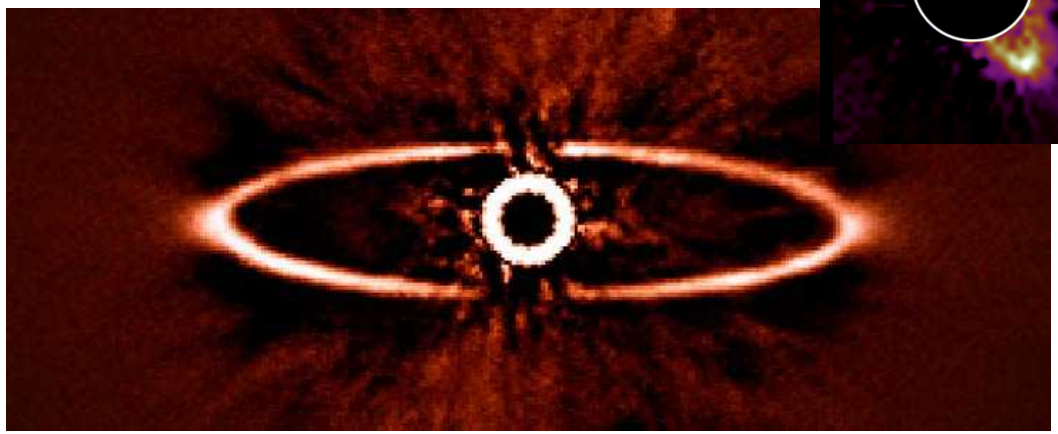
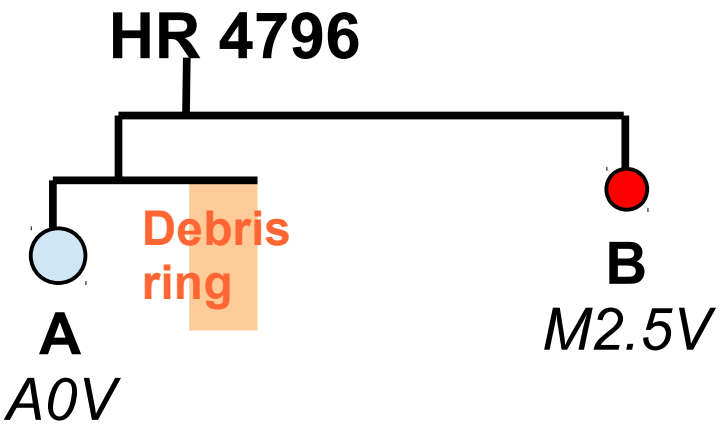




GPI, first light. Ring on HR4796A
Credit : Gemini, GPI team



SPHERE, first light. Ring on HR4796A
Credit : ESO, SPHERE team



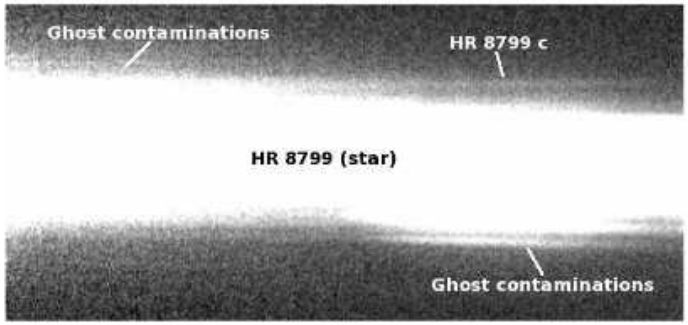
Plans for direct imaging mission depend on success of GPI & SPHERE.

Direct imaging : characterization

- First **low-resolution spectra** and colors

Large aperture
Adaptive Optics
low-resolution spec.

NACO/VLT

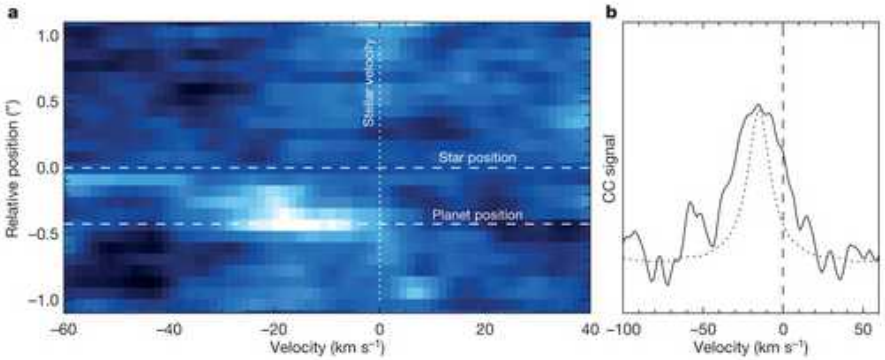


Janson et al. **"Spatially resolved spectroscopy of the exoplanet HR 8799 c"**, 2010 ApJ

- First detection in **high-res spectra**?

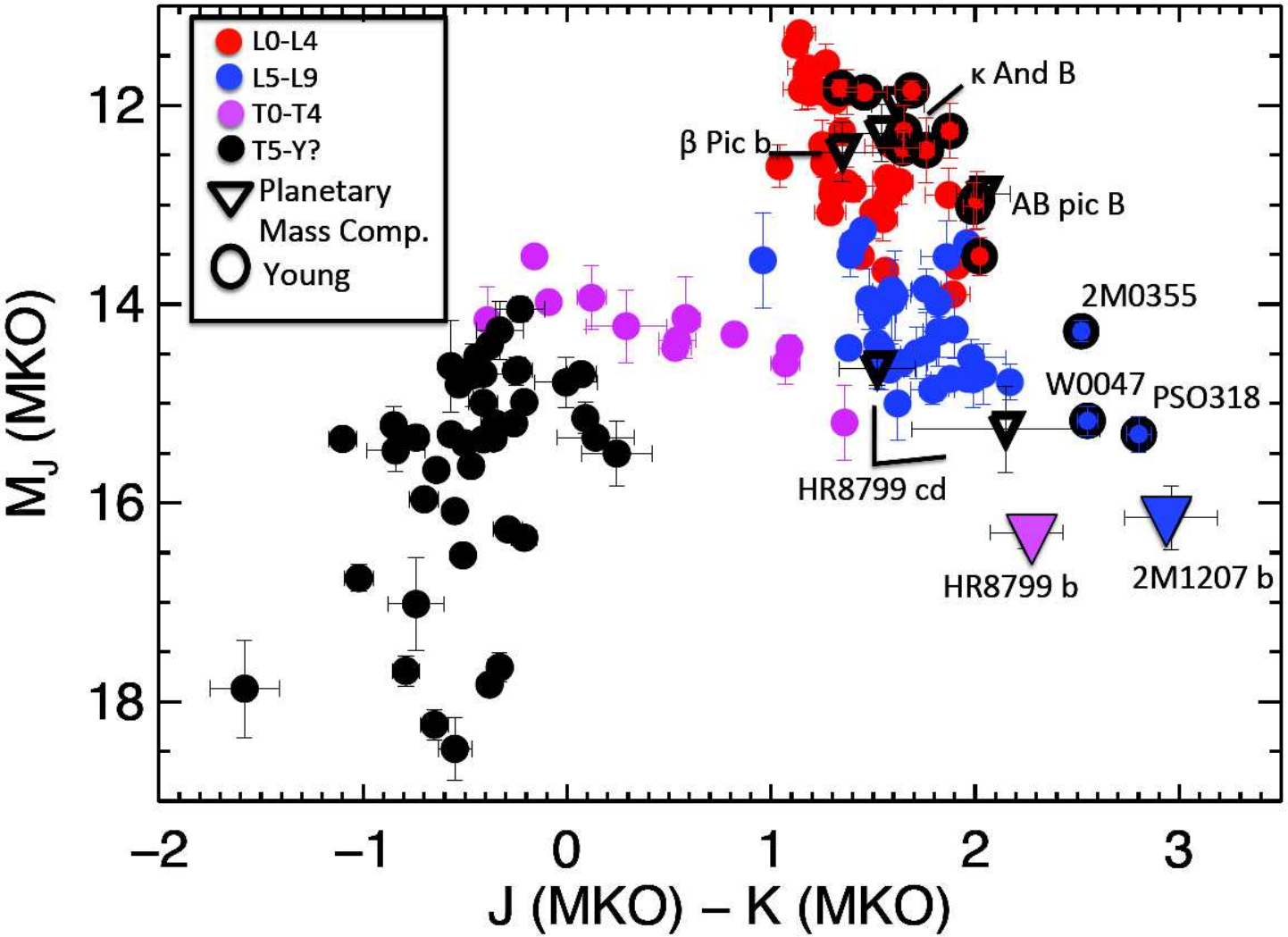
Large aperture
Adaptive Optics
High-resolution spec.

CRIRES/VLT



Snellen et al. **"Fast spin of the young extrasolar planet β Pictoris b"**, 2014, Nature

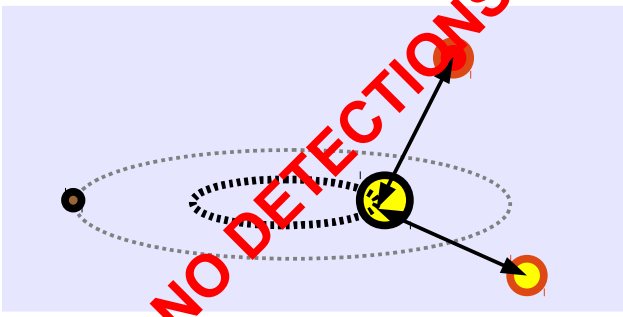
Direct imaging : Brown dwarf or planet?



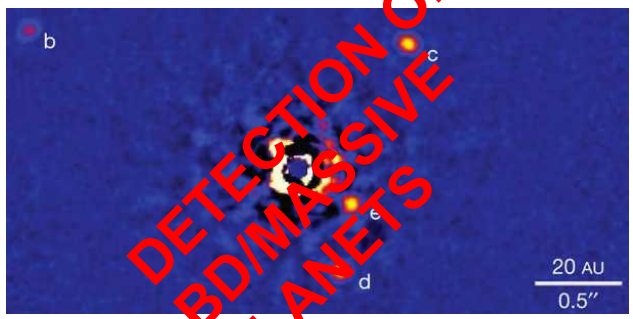
Parallaxes from Faherty+2012, Dupuy & Liu+2012, Liu+2013, Zapatero Osorio+2014, Gizis+submitted

Detection techniques

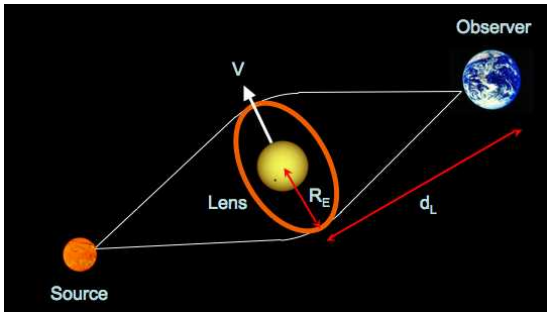
Astrometry



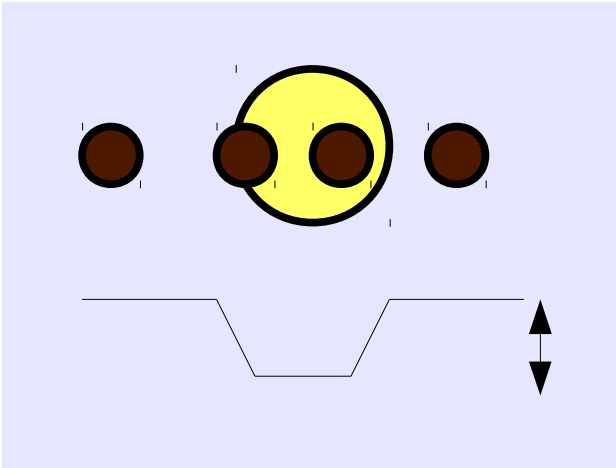
Direct imaging



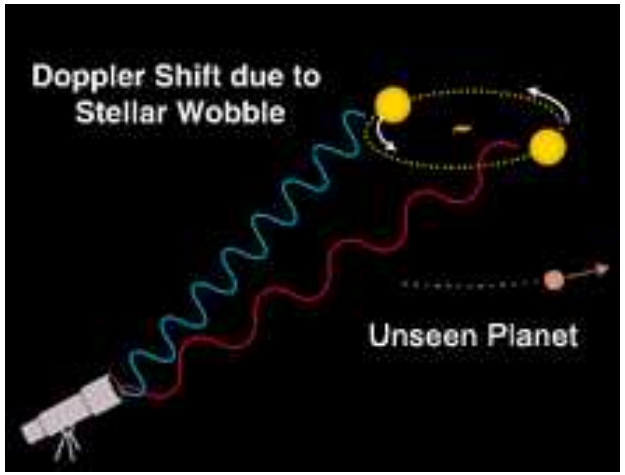
Microlensing



Photometric transits

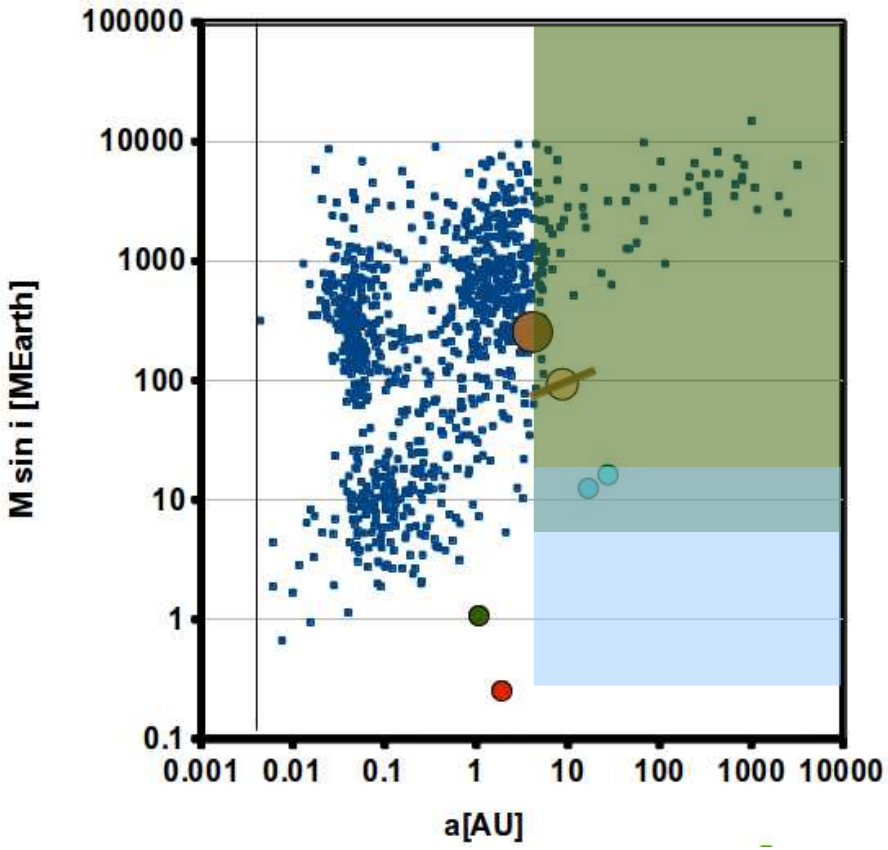


Doppler spectroscopy

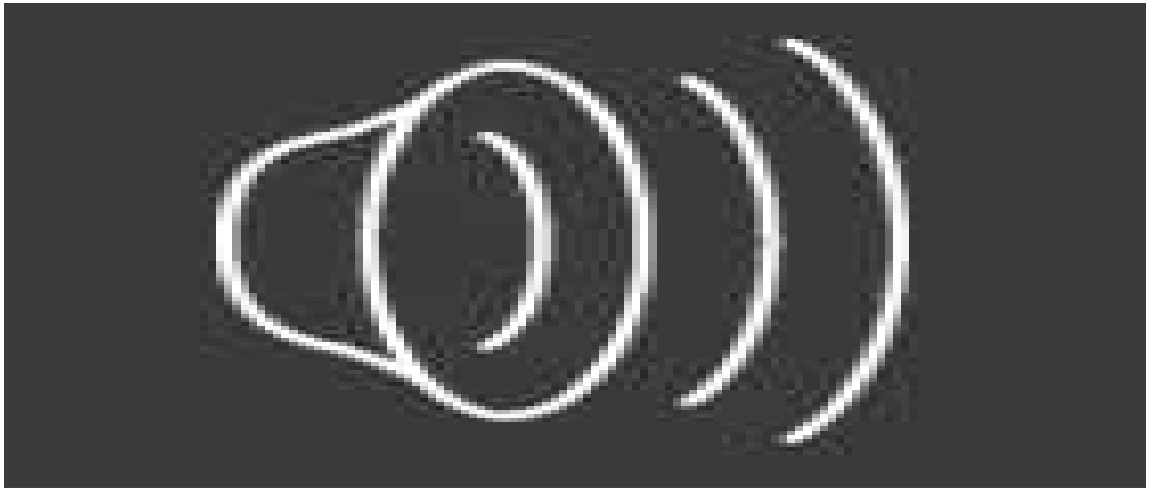


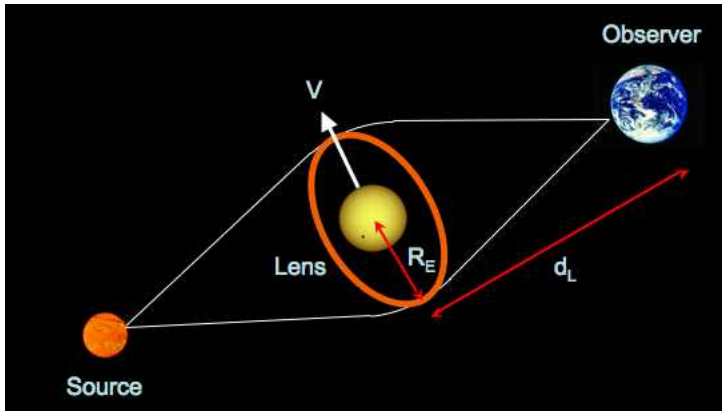
Microlensing

- Sensitivity
  - Random alignments → most stars are **red-dwarfs!**
  - Weakly sensitive to lens mass → low masses
  - Planets beyond 'snow-line'
  - No possible characterization



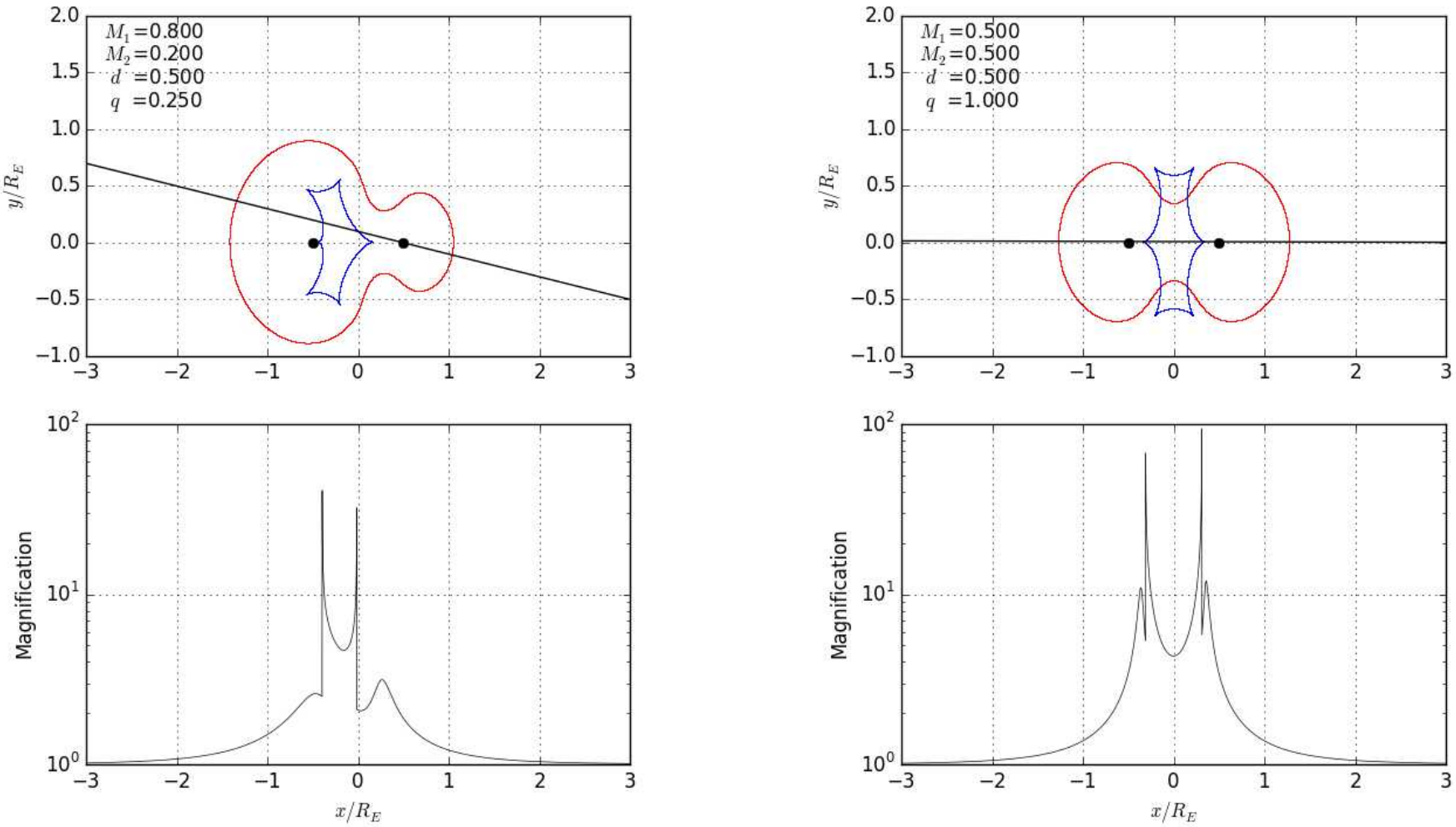
Microlensing





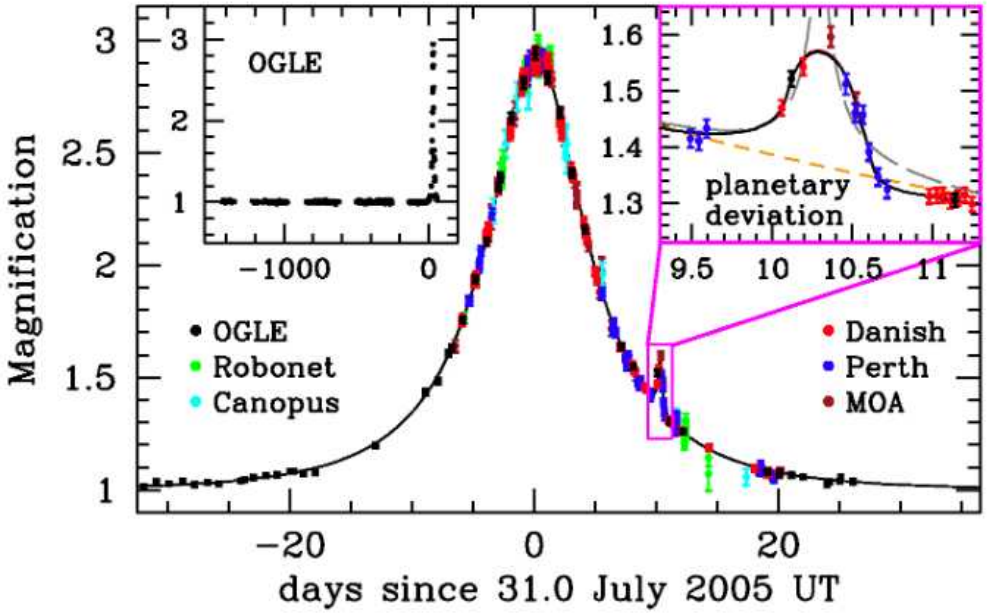
Provided by
Yiannis Tsapras – QMUL
(moving to Heidelberg)

Microlensing



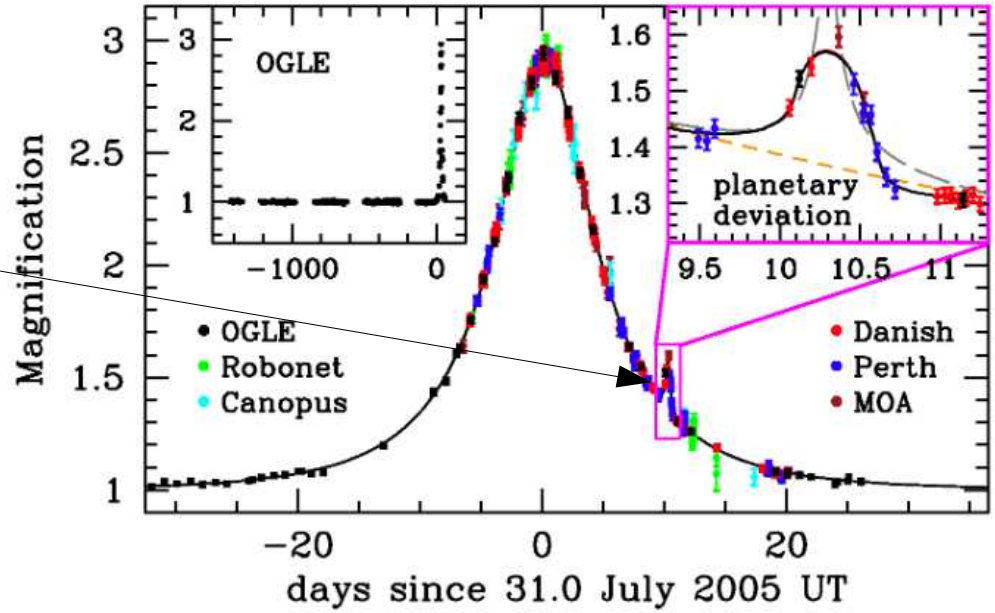
Provided by
Yiannis Tsapras – QMUL
(moving to Heidelberg)

Microlensing : results



Microlensing : results

- Detection reports on ½ dozen planets
- First indications of super-Earth's ubiquity (OGLE-2005-BLG-390Lb)



Beaulieu, J.-P. et al. (January 2006). "***Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing***". Nature 439

Microlensing : big picture

- **Bound planets :**
  >1x star between 0.5-10 AU

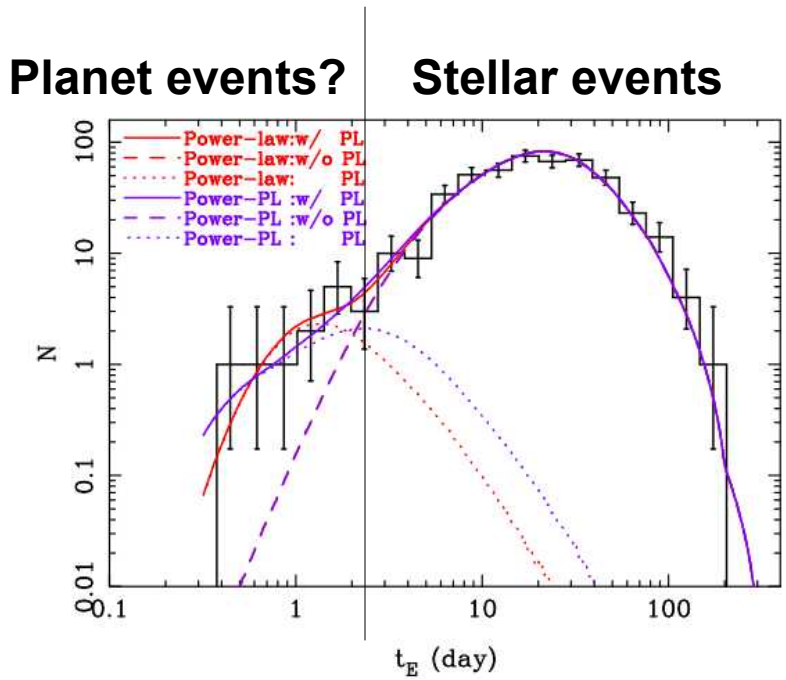
  Cassan et al. **"One or more bound planets per Milky Way star from microlensing observations"**, Nature 2012

17% Gas giants
52% Ice giants
60% super-Earths

- **Unbound planets :**
  ~2x star

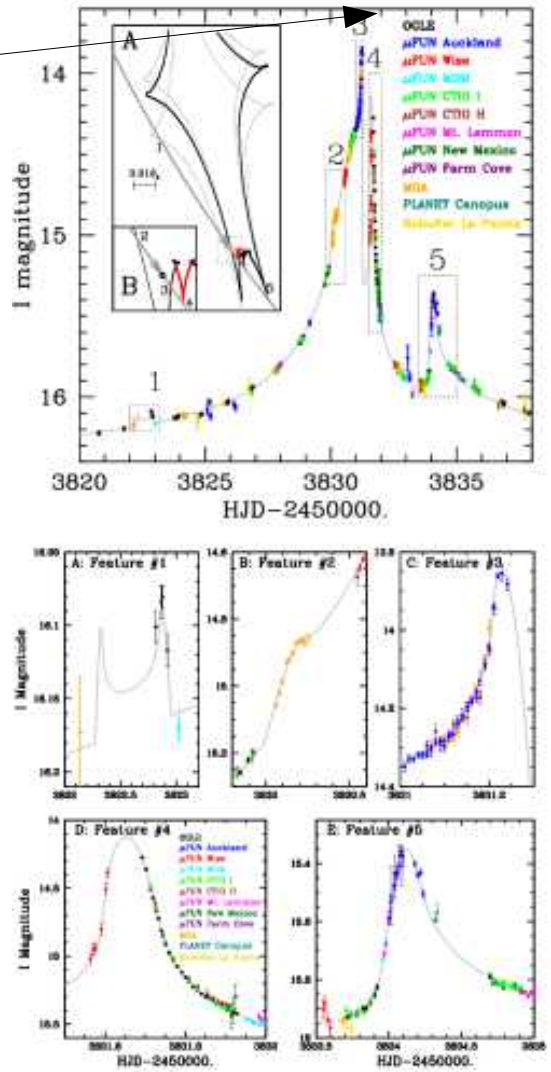
  Sumi et al. **"Unbound or distant planetary mass population detected by gravitational microlensing"**, Nature 2011

Controversial but very active area of research



Microlensing : present/future

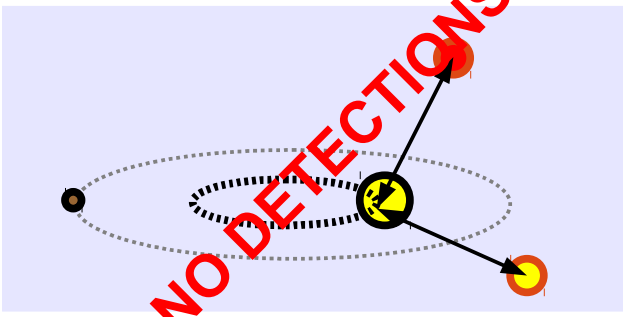
- New sites and follow-up networks : Larger telescopes, faster readout & processing,
- Continuous monitoring around the globe : LCOGT-like
- Space-based? → smaller planets, long baselines for plx effects (WFIRST?). **<u>Gaia</u>**
  <u>Galaxy model updates</u>
- Free-foating planets versus infrared surveys? (e.g. WISE : lack of low-mass brown dwarfs)



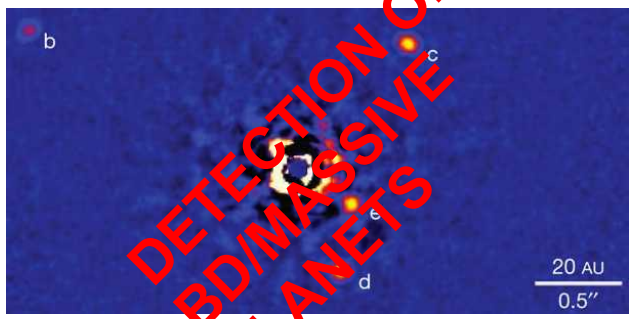
Two planet microlensing event

Detection techniques

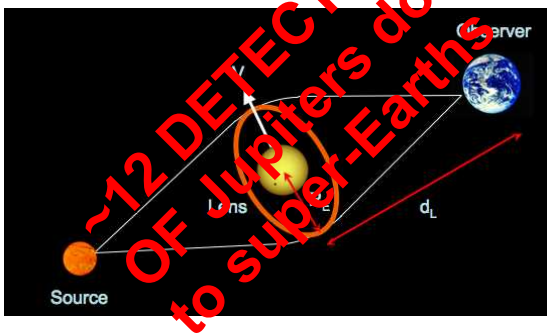
Astrometry



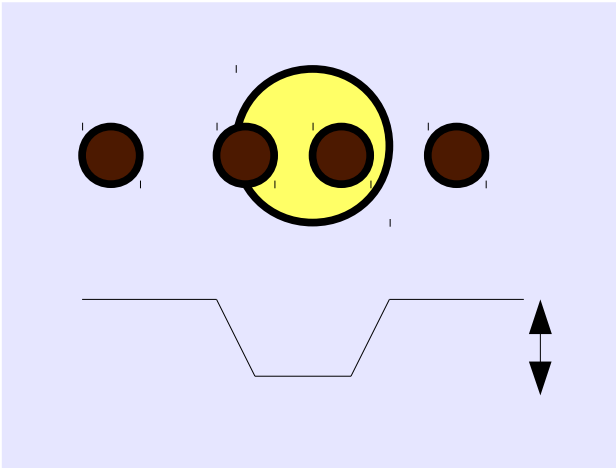
Direct imaging



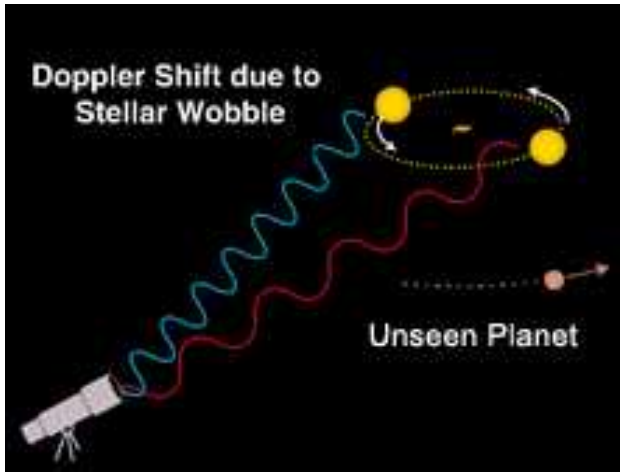
Microlensing



Photometric transits



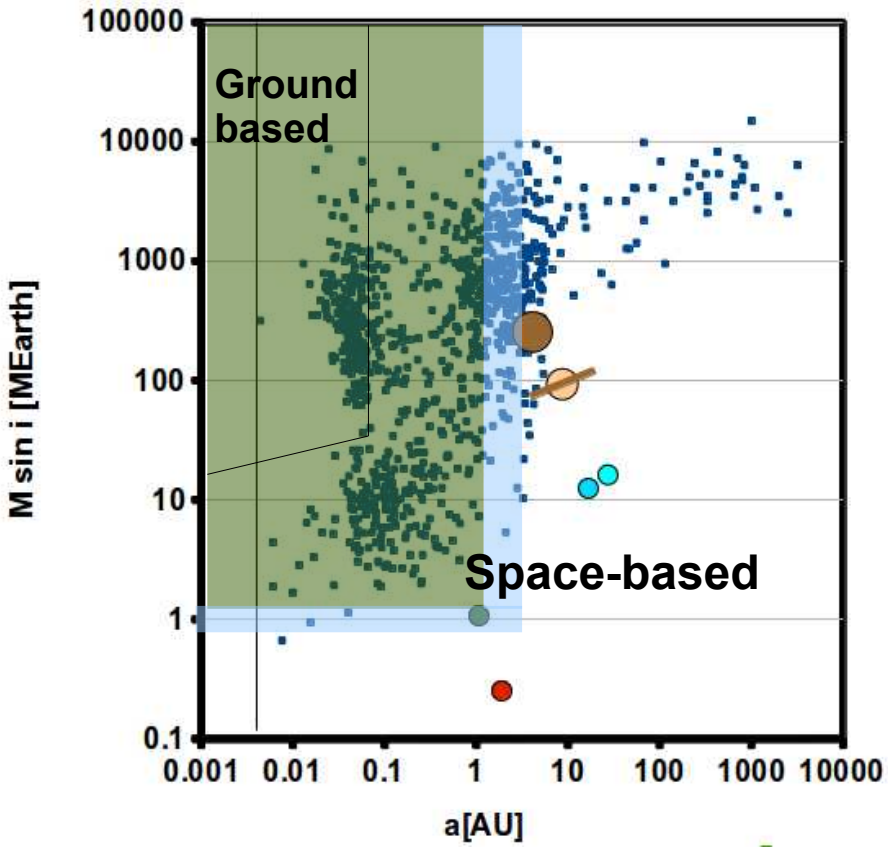
Doppler spectroscopy

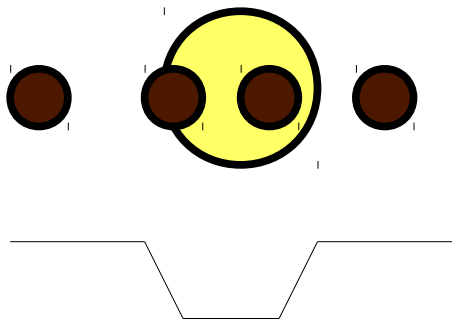


Transits

Sensitivity

- Depends on size ratio $(r_p/R_*)^2$
- Geometric probability : needs MANY of targets
- Allow further characterization

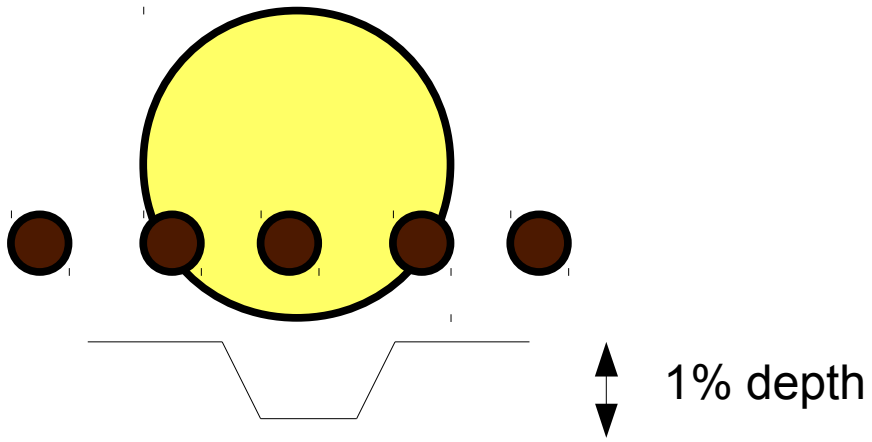




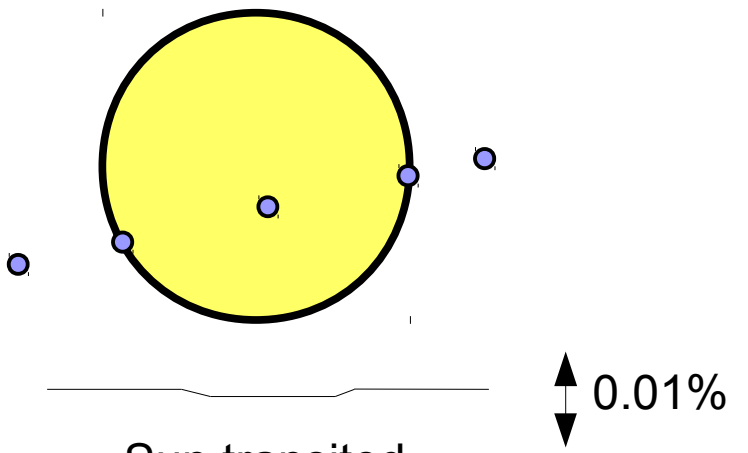
Sun transited by Jupiter

1% depth

Transits



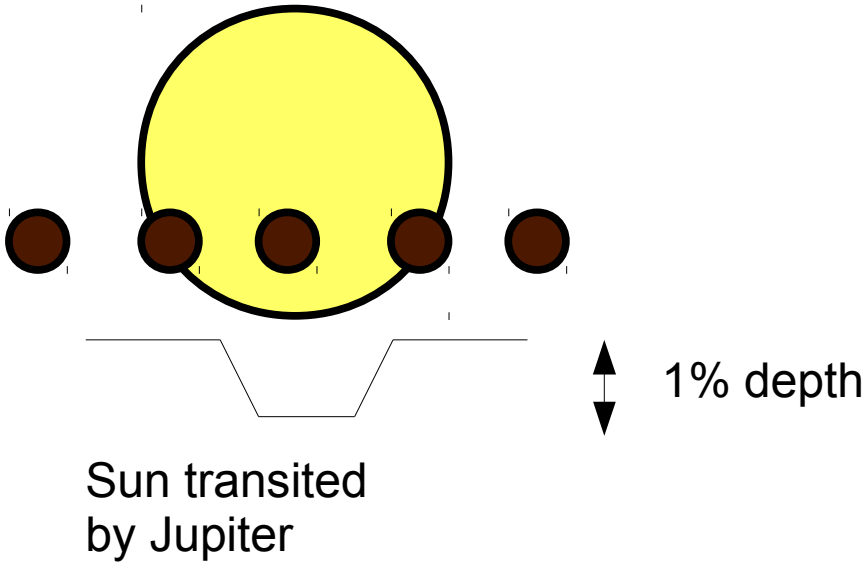
Sun transited
by Jupiter

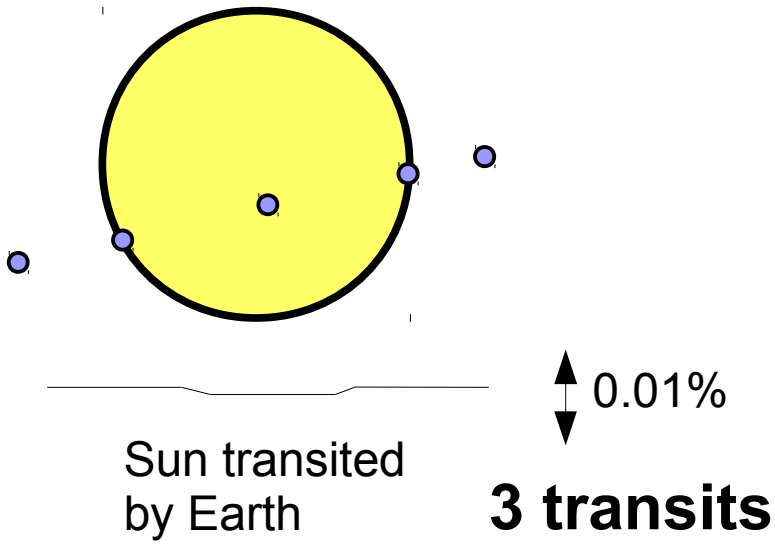


Sun transited
by Earth

x3 times

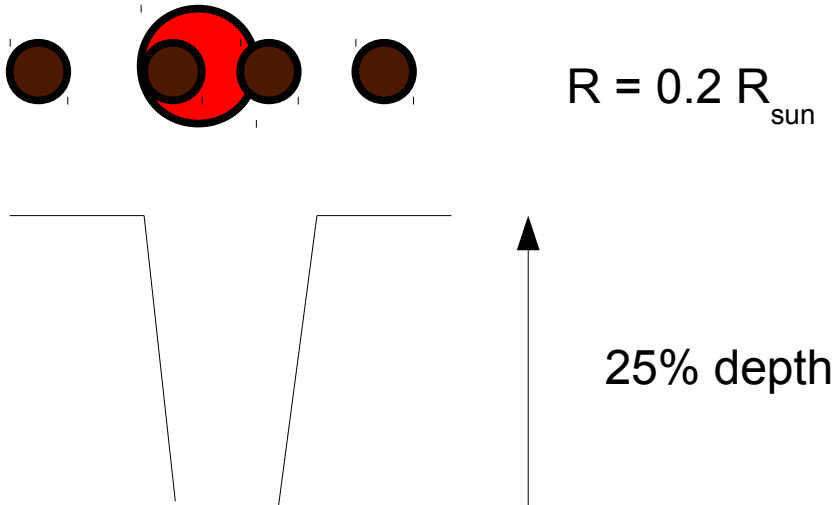
Transits

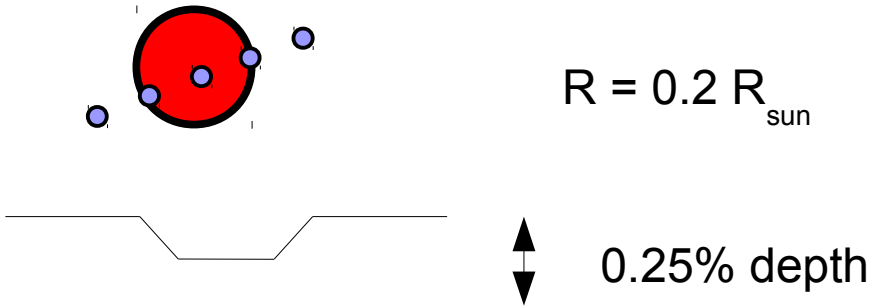




x25

x10





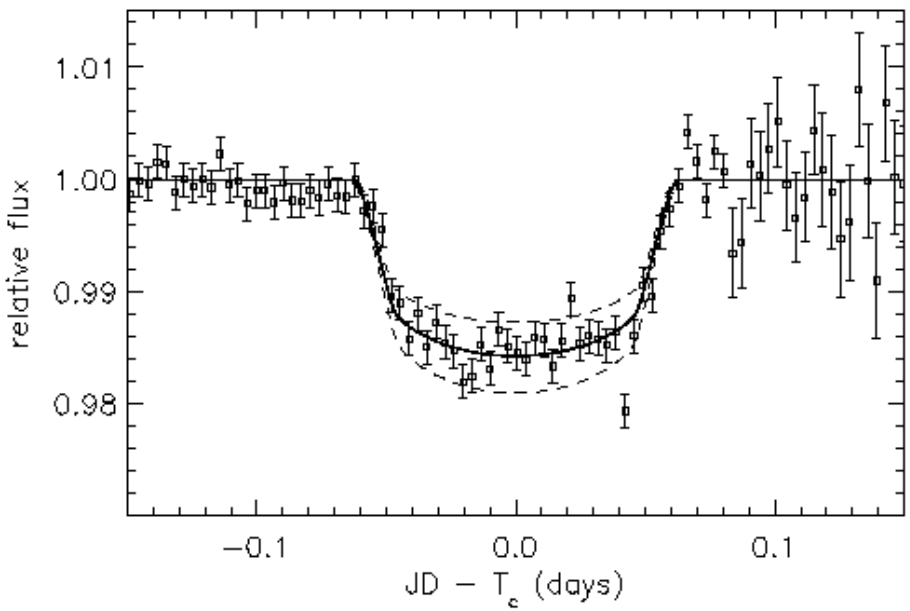
x30 transits

Transits : results

Ground-based detections

~200 Hot Jupiters around F,G,K dwarfs
1 x Iron ball → (Doppler + space-based)
3 x Mini-Neptunes, all around M-dwarfs

Ground based



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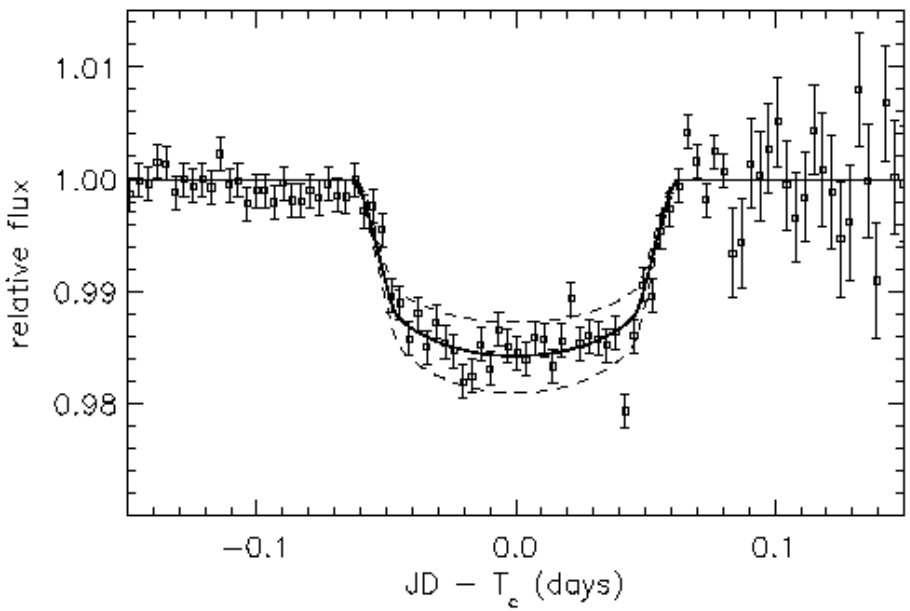
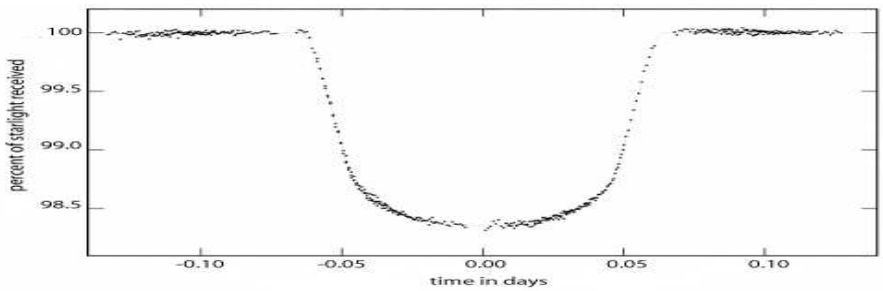
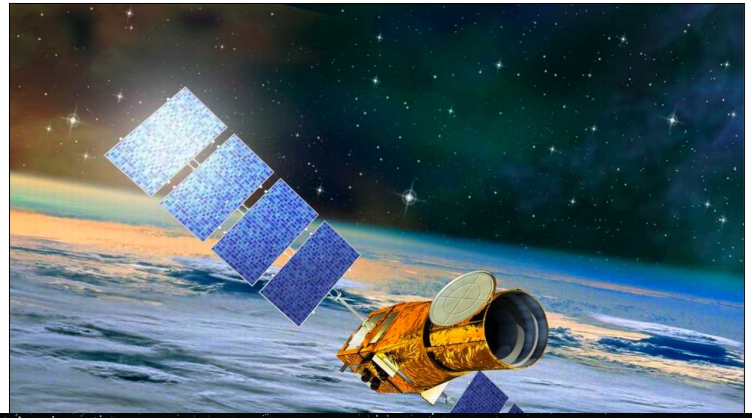


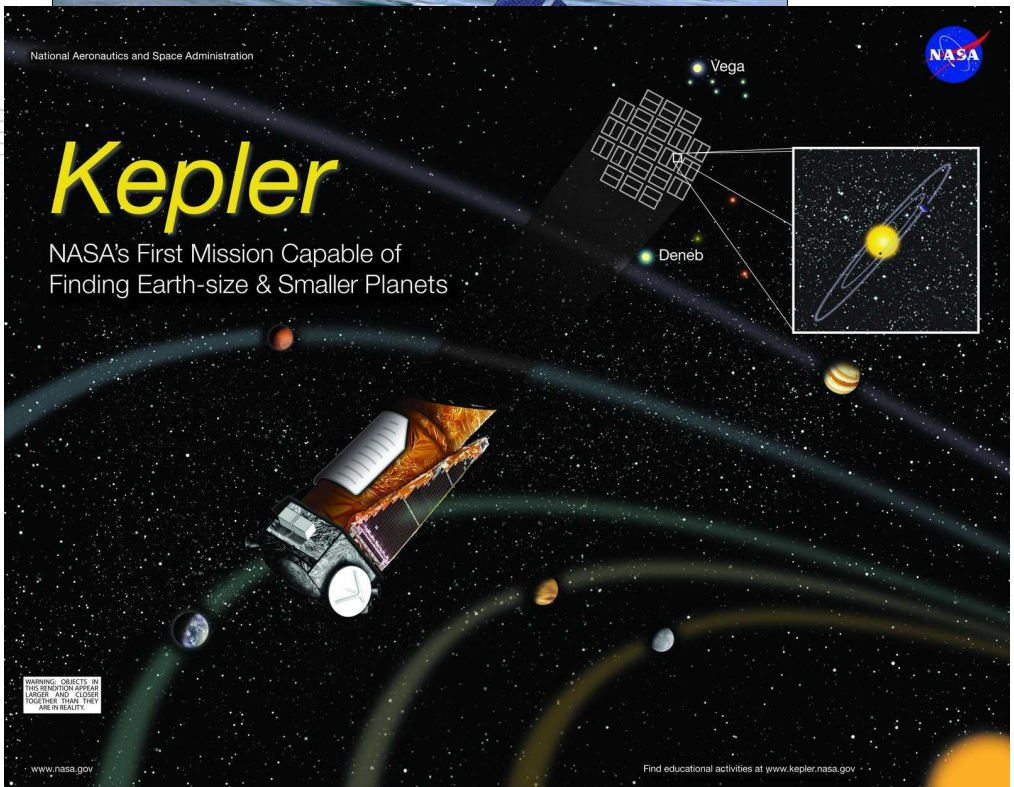
Space-based/HST



Space transits : Corot & Kepler

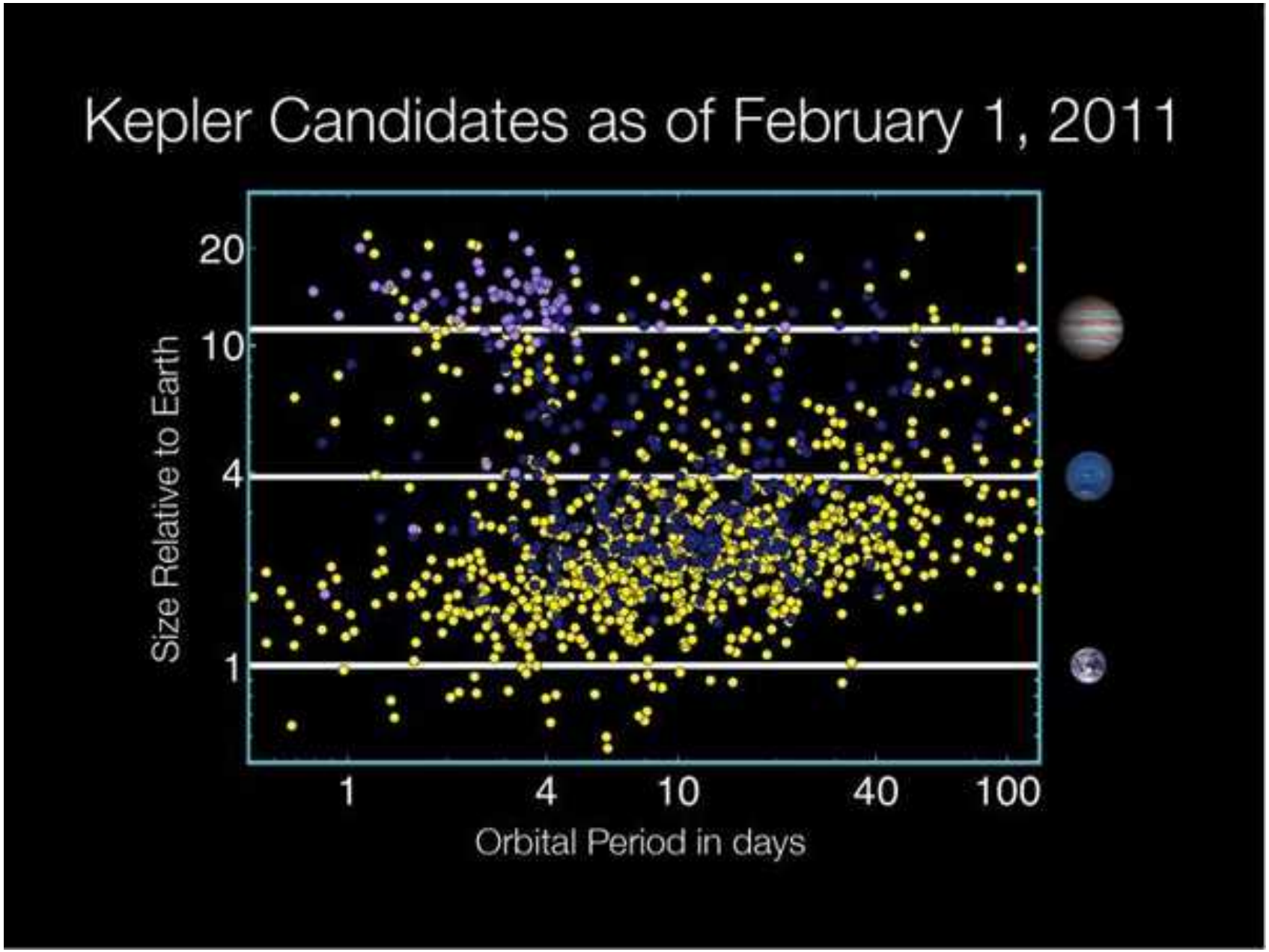
1.2m space
~150 000 stars





ONLY 4000
M-DWARFS

Space transits : Kepler



Space transits : Kepler

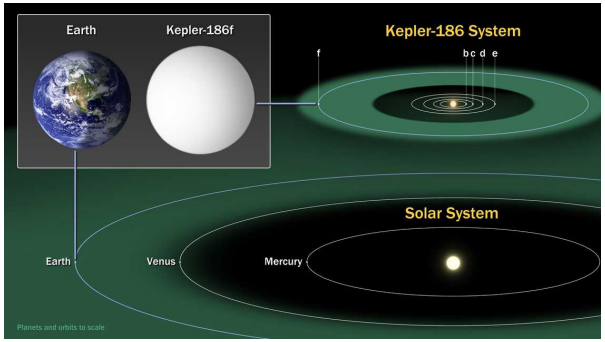
Sample of Kepler results

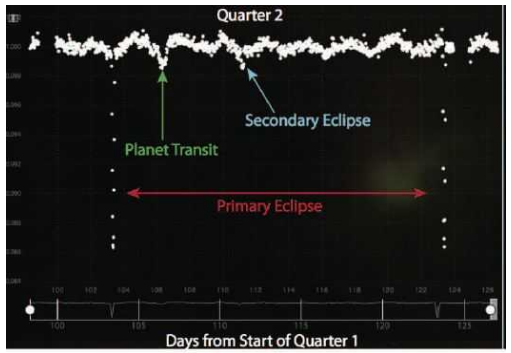
- **Multi-transiting Earth-sized planets**
  Muirhead et al. 2013, ApJ; KOI-961 (Kepler 42, ~ Barnard star)

- **Shorter period planet?**
  4.5 hours KOI.1843, also in 3 planet system, Ofir & Dreizler 2013, A&A;

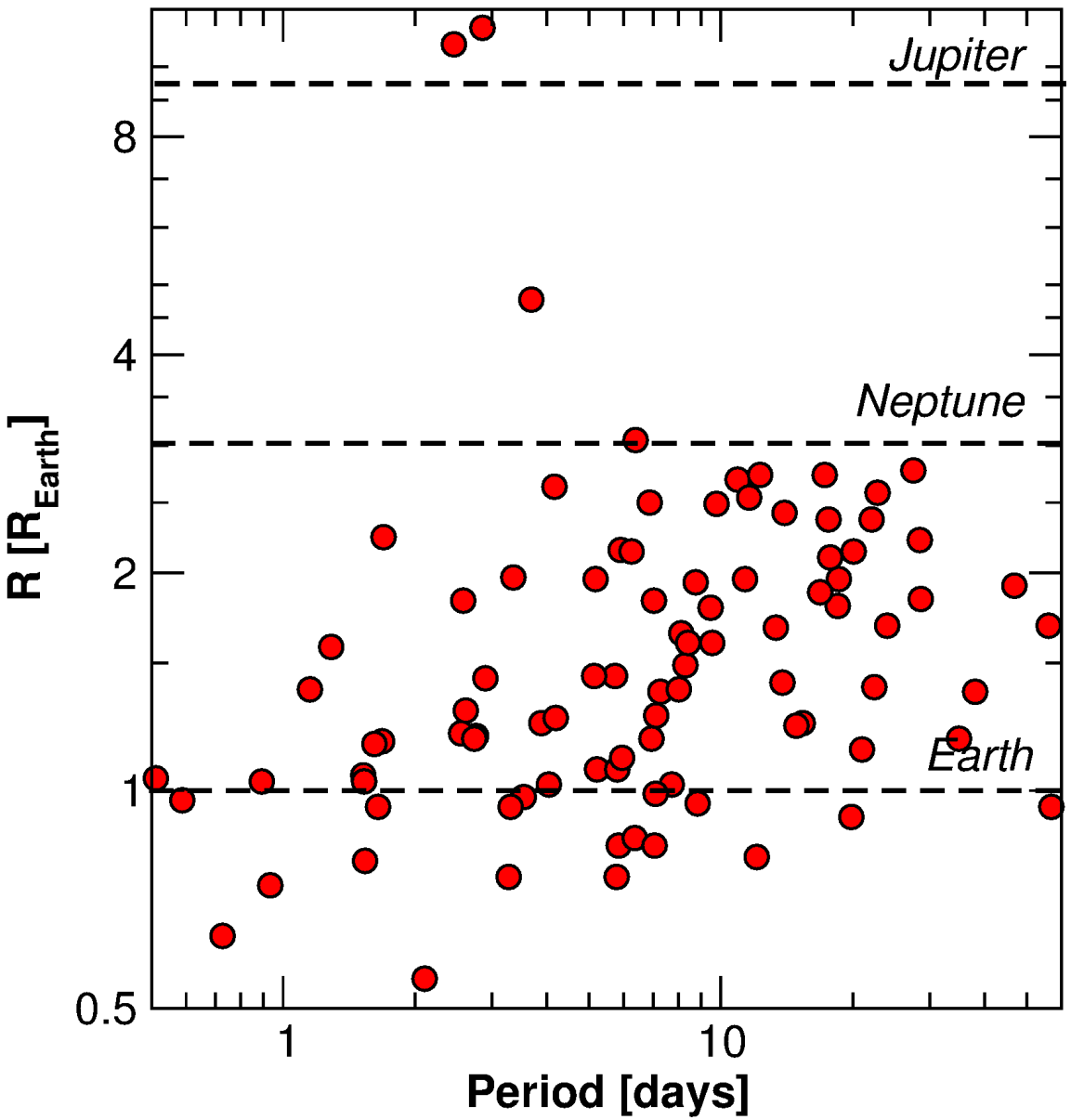
- **Earth-sized planet in HZ in multi-planet system**
  Quintana et al. 2014, Science, Kepler-186f

- **Circumbinary planets**
  Schwamb et al. 2014 ApJ (*by Planethunters*)





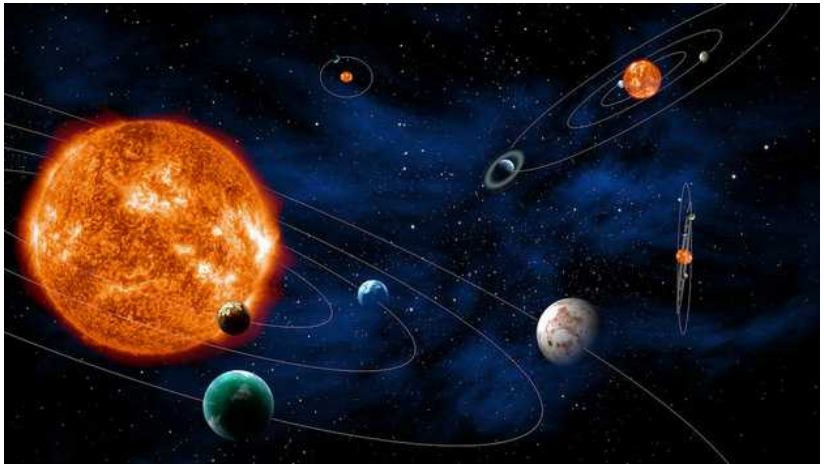
Transits on low mass stars

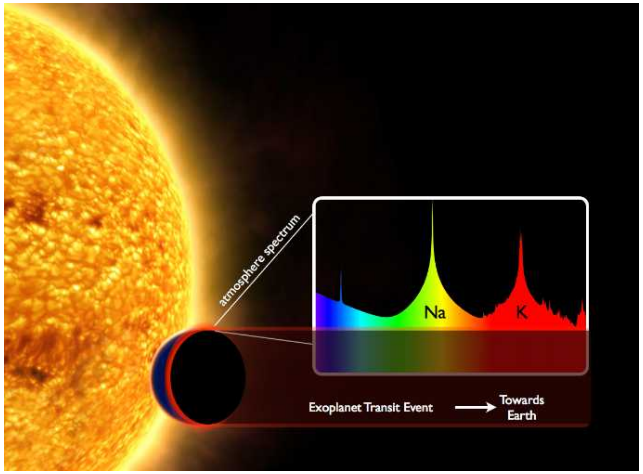


Transits searches : near future

- NGTS – ground wide field
- TESS & PLATO – space wide field
- Doppler educated searches:

  CHEOPS, LCOGT.net, nano-satellites...
- **Detection attempts of 'biomarker' molecules on transiting super-Earths → JWST and CRIRES+VLT**





TECHNICALLY POSSIBLE WITHIN NEXT 4 YEARS

Transits : bizarre stuff

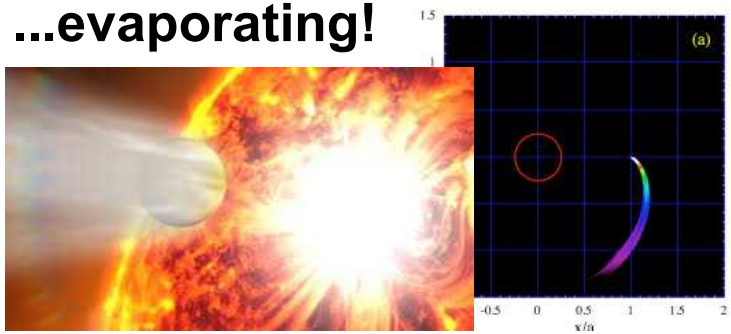
Hell worlds

Crematoria (The Chronicles of Riddick)
Credits : David TwohyVin Diesdel

Habitable mega worlds

Gozilla
Credits : G.Edwards

...evaporating!

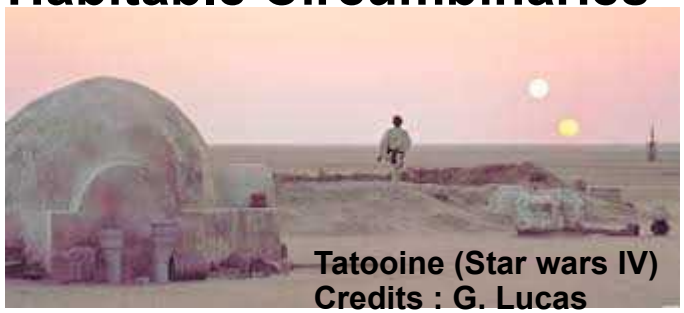


Habitable exomoons

Pandora (Avatar),Credits : J. Cameron

LV-223 (Prometheus)
Credits : Ridley Scott

Habitable Circumbinaries



Tatooine (Star wars IV)
Credits : G. Lucas

SETI?

Contact, C. Sagan/R. Zemickis

Transits : bizarre stuff

Hell worlds

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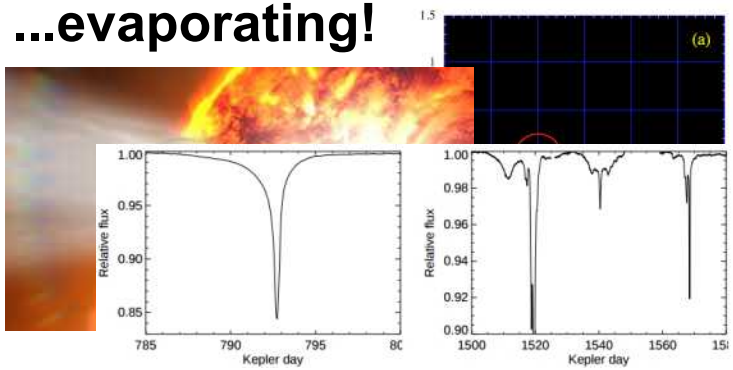

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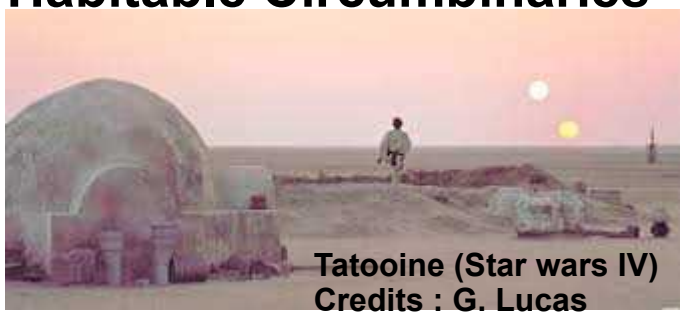

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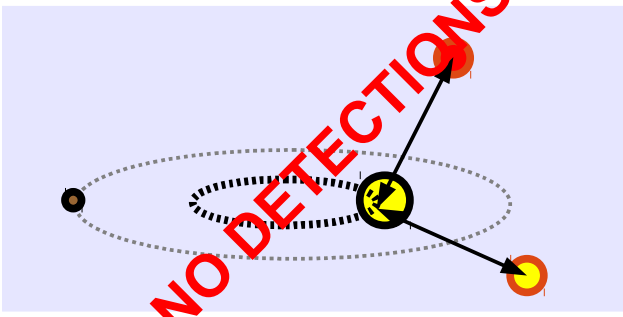
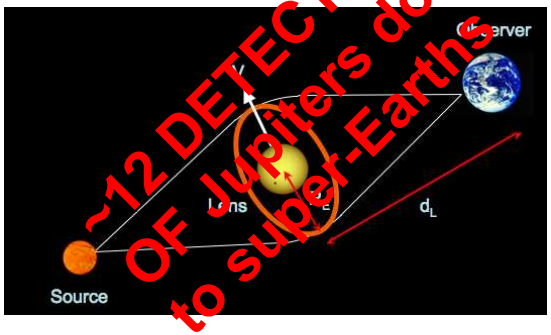
Detection techniques

Astrometry

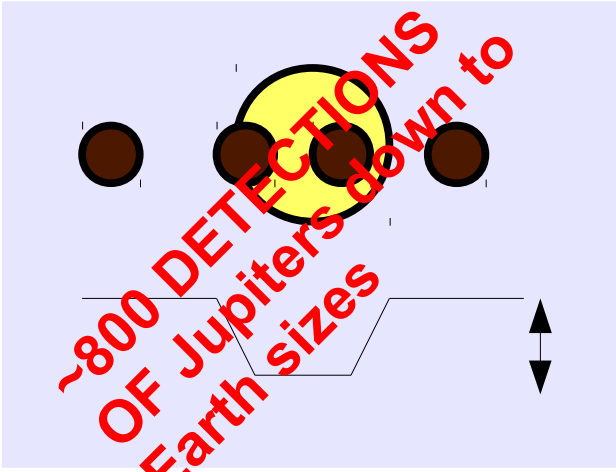


Direct imaging

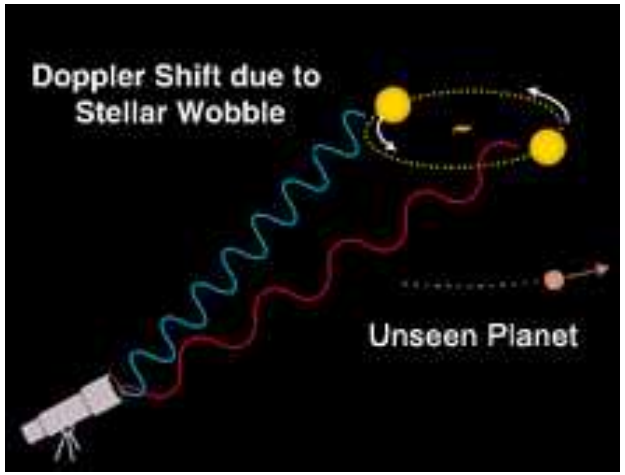
Microlensing



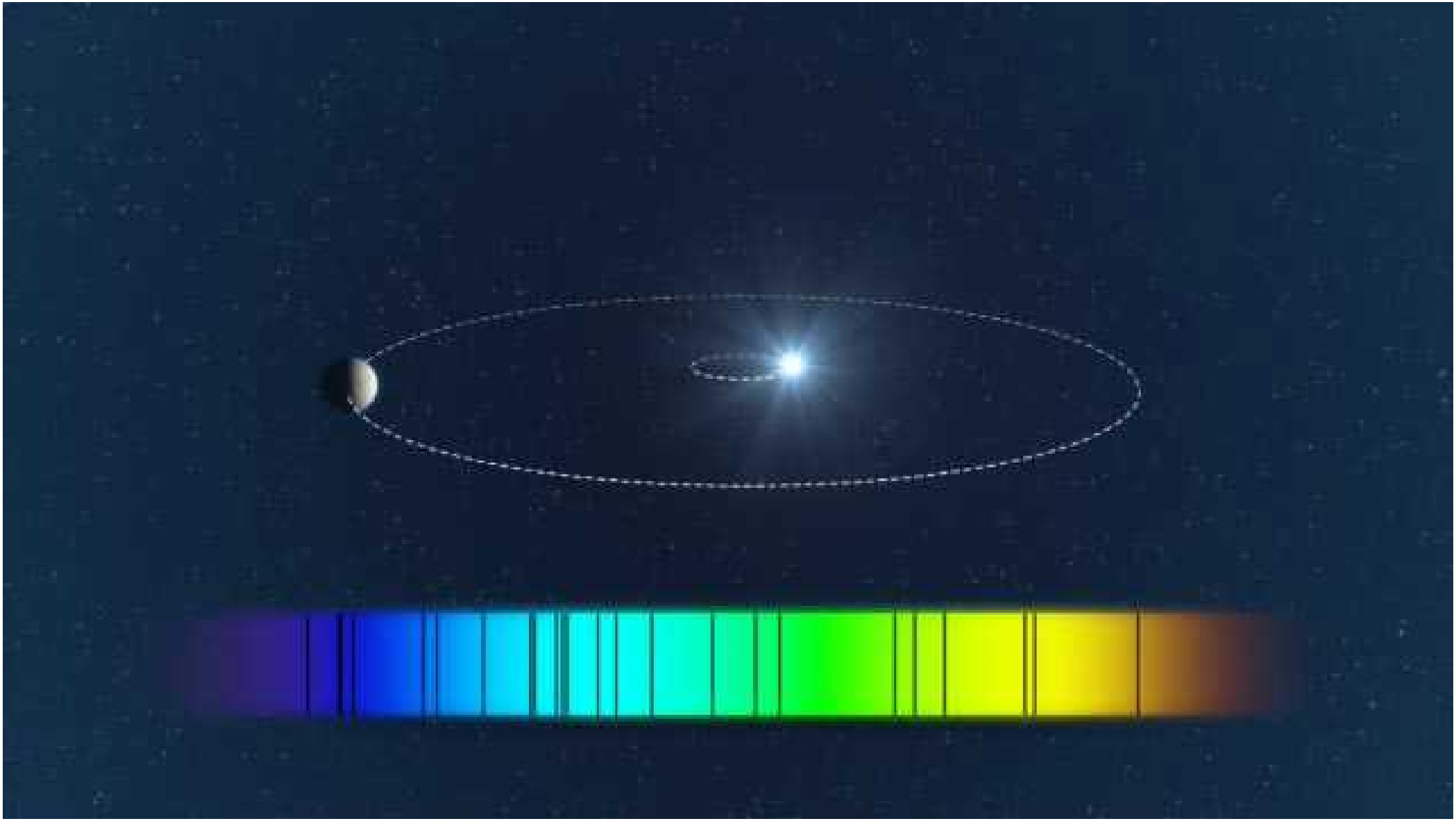
Photometric transits



Doppler spectroscopy



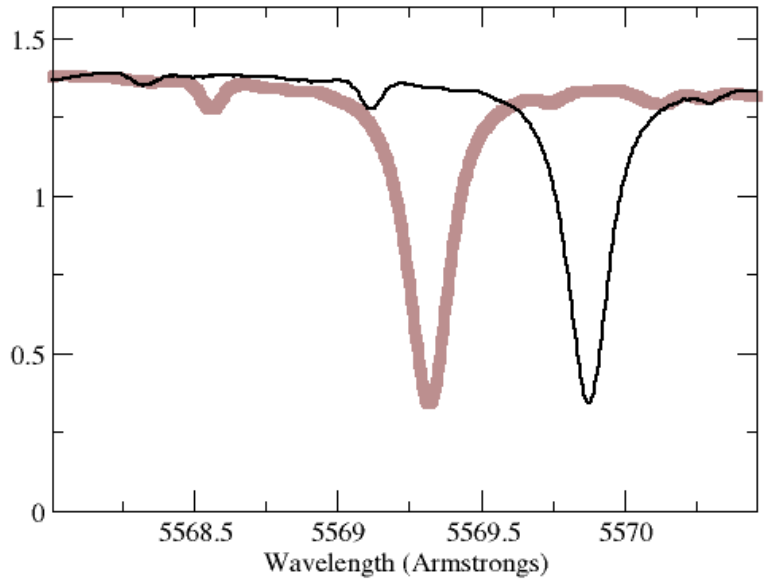
Doppler spectroscopy

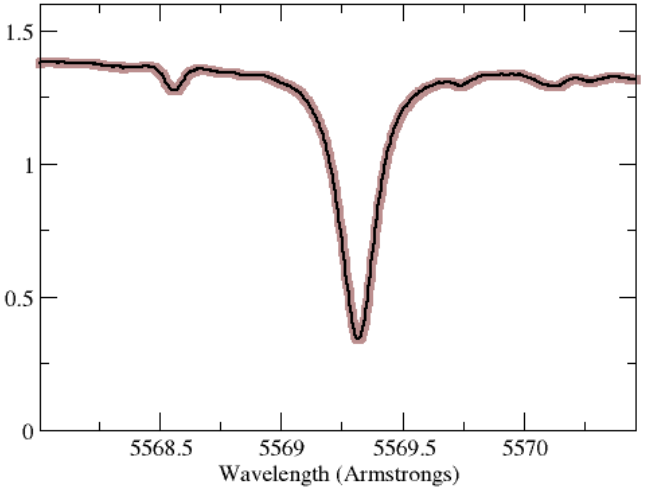


Credits : ESO

Doppler spectroscopy

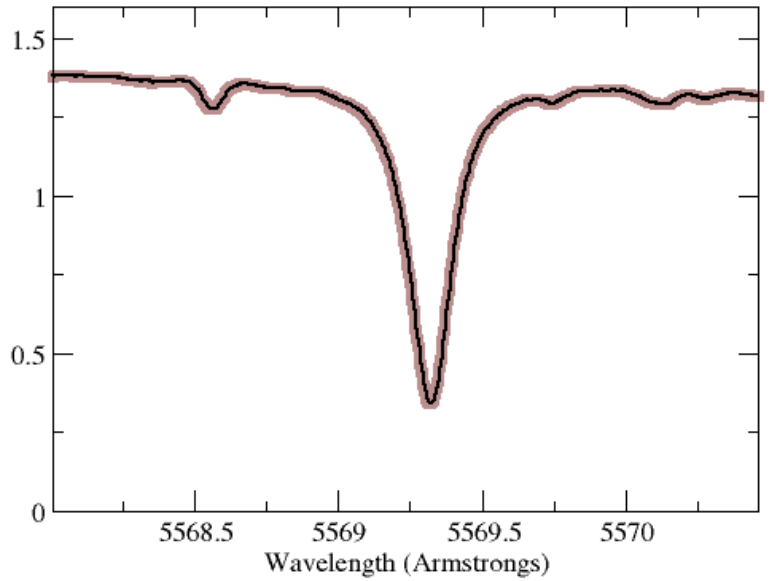
Spectroscopic binary K=30 km/s



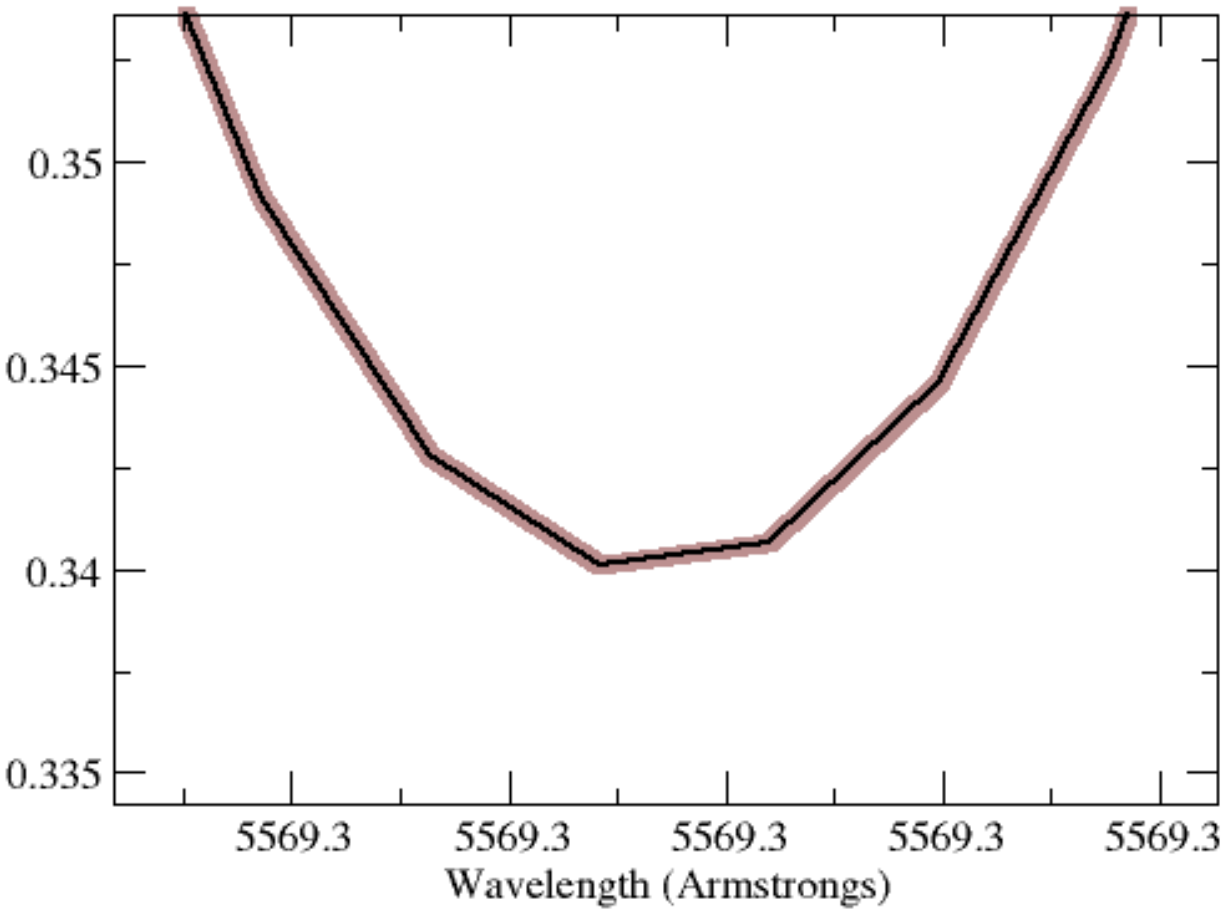


Width of a typical solar line is ~10 km/s

Hot jupiter K=0.3 km/s

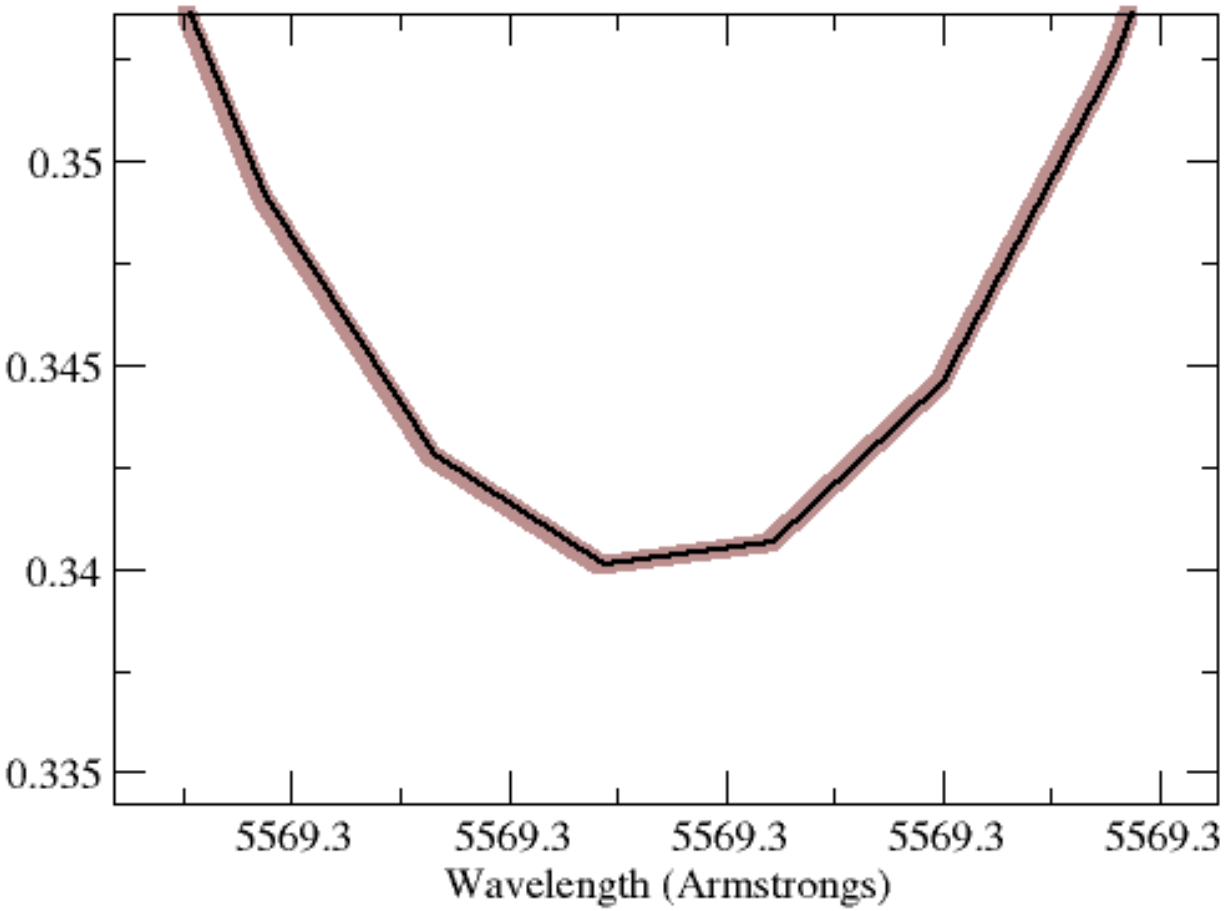


Doppler spectroscopy



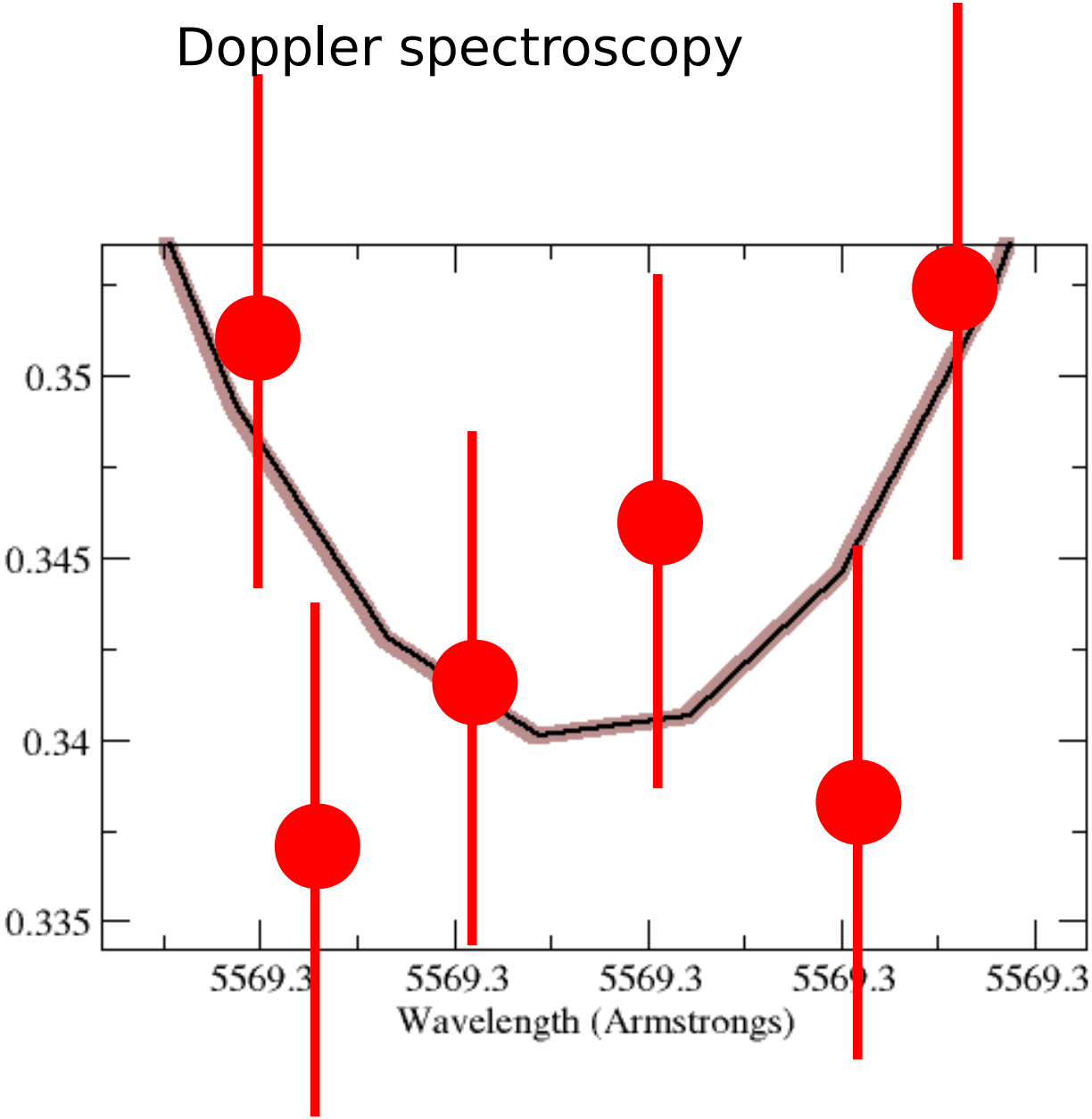
0 m/s

Doppler spectroscopy



+ 3 m/s

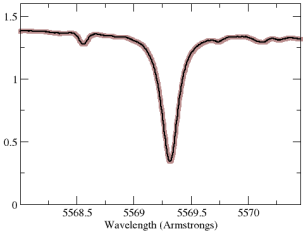
Doppler spectroscopy

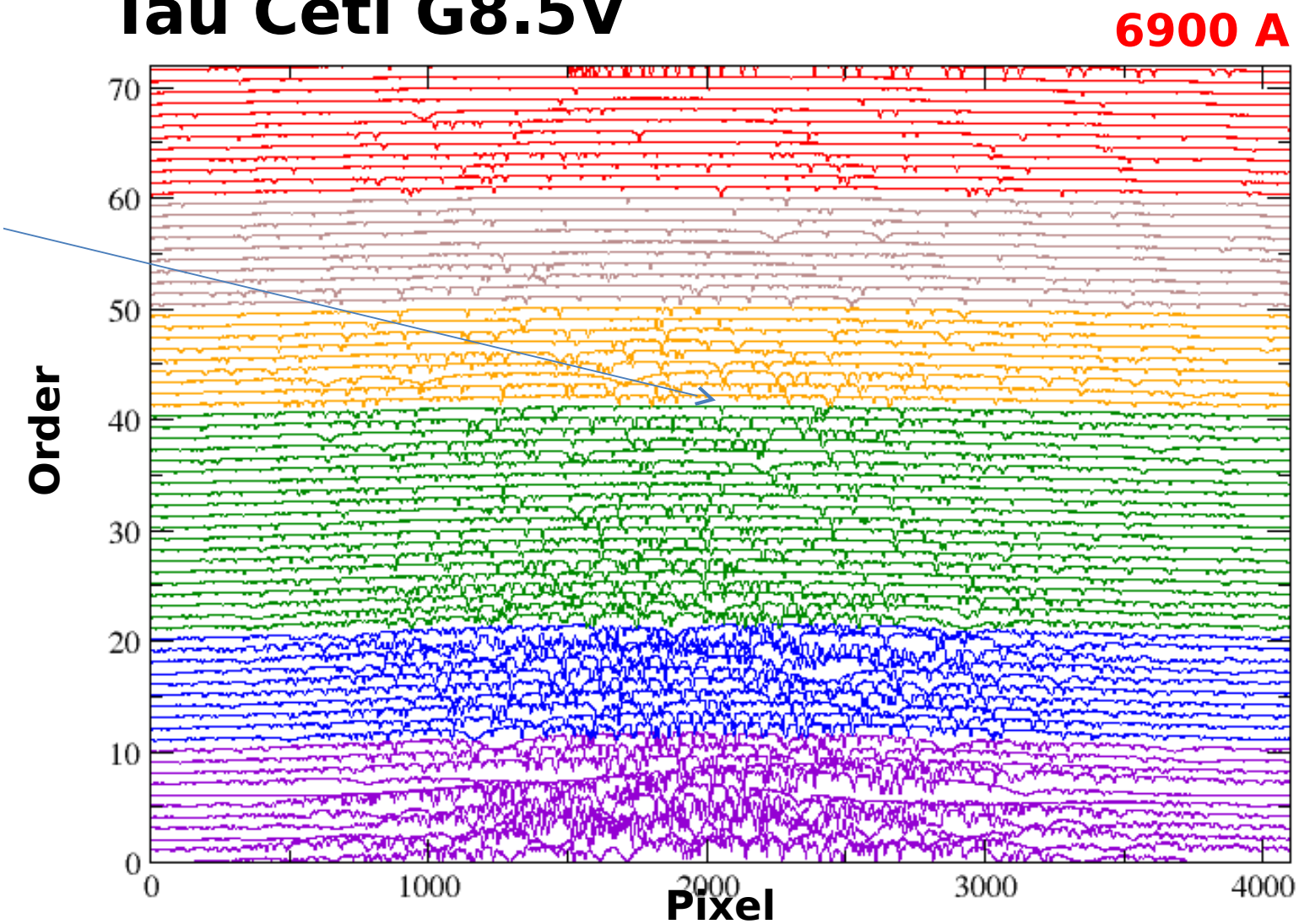


+ 3 m/s

Doppler spectroscopy

Tau Ceti G8.5V





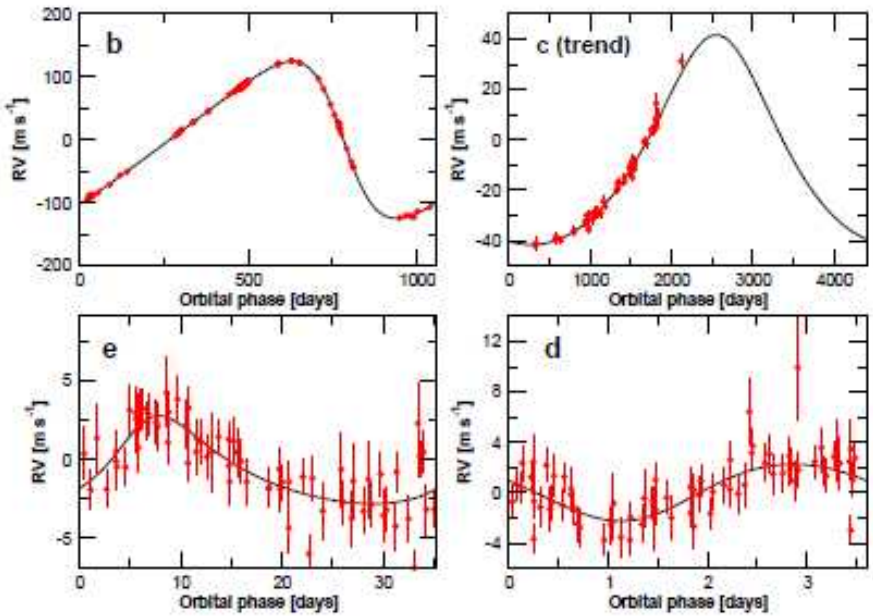
HARPS-ESO
Echelle
spectrum

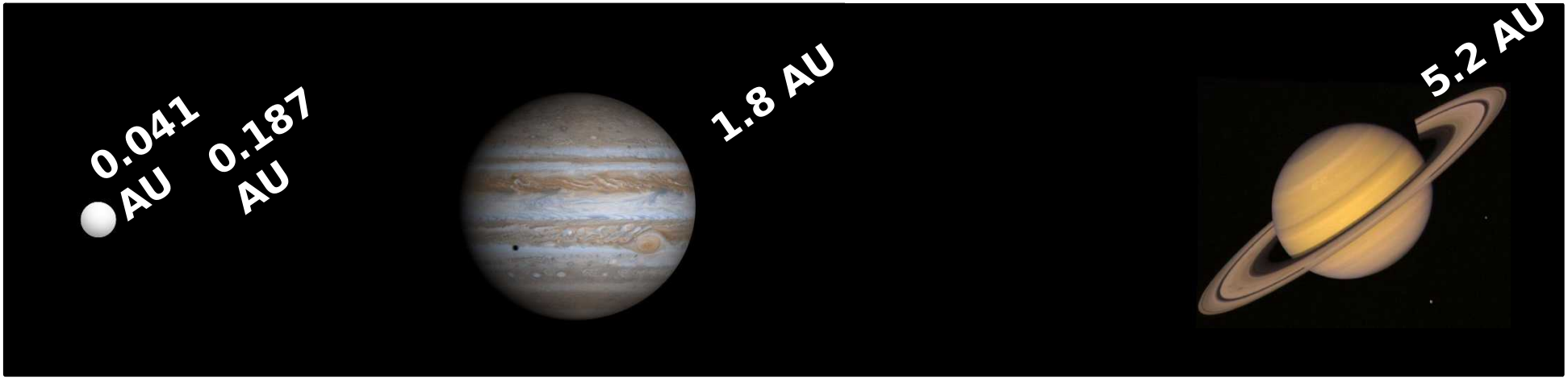
Doppler spectroscopy

GJ 676A, M0V

2 gas giants (1)
+1 hot Neptune(2)
+1 hot super-Earth(2)

(1)Forveille et al. 2009 A&A
(2)Anglada-Escude & Tuomi, 2012 A&A





Doppler spectroscopy : results

First planet candidates around sun-like stars

γ Cephei, Campbell Walker Yang 1988 (unsure at the tiem) confirmed in 2002

55 Cnc, Mayor & Queloz 1995 Nature

70 Vir, Marcy & Butler 1996 ApJ

1985-1999

5 m/s

First unambiguous planet confirmed by transit

HD209458b, Charbonneau et al. 1999, Henry et al. 1999 (almost simultaneously)

First multiplanet systems

GJ 876bc, Marcy et al. 1998 ApJ, Delfosse et al 1998 ApJ

First transiting Neptune

GJ 436, Butler et al. 2004 ApJ

1999-2005

3 m/s

First super-Earths

GJ 876d

Doppler spectroscopy : results

First evidence of multi-planets with super-Earths
HD 40307, Mayor et al. 2009 A&A, Tuomi et al 2013 A&A
GJ 581, Udry et al. 2007

2005-2010

1.5 m/s

First potentially habitable super-Earths
GJ 581d, Udry et al. 2007, Mayor et al. 2009 (fg disputed)
GJ 667Cc, Anglada-Escude et al. 2012 ApJL, Bonfils et al. 2013 A&A

First occurrence rate estimates of close-in super-Earths (>30 %)
Howard et al. 2010, Science
Mayor et al. 2011, arXiv

2010-2012

1 m/s
Stellar noise floor

First estimate of η-Earth on low mass stars
Bonfils et al. 2013 A&A
Vogt et al. 2011 ApJ

Doppler spectroscopy : results

Several potentially habitable super-Earths around the same star

GJ 667Cc(dfg), Anglada-Escude et al 2013 A&A
GJ 180bc, Jenkins et al. 2014 submitted MNRAS
GJ 887bc(d), Tuomi et al 2014 submitted MNRAS

Mass and radius of (hot) terrestrial planets

Kepler 78, transit + RV, Pepe et al. 2013 Nature
Howard et al. 2013 Nature
Kepler 10c, rocky planet with the mass of Neptune

First HZ super-Earths around a halo star : Kapteyn's star

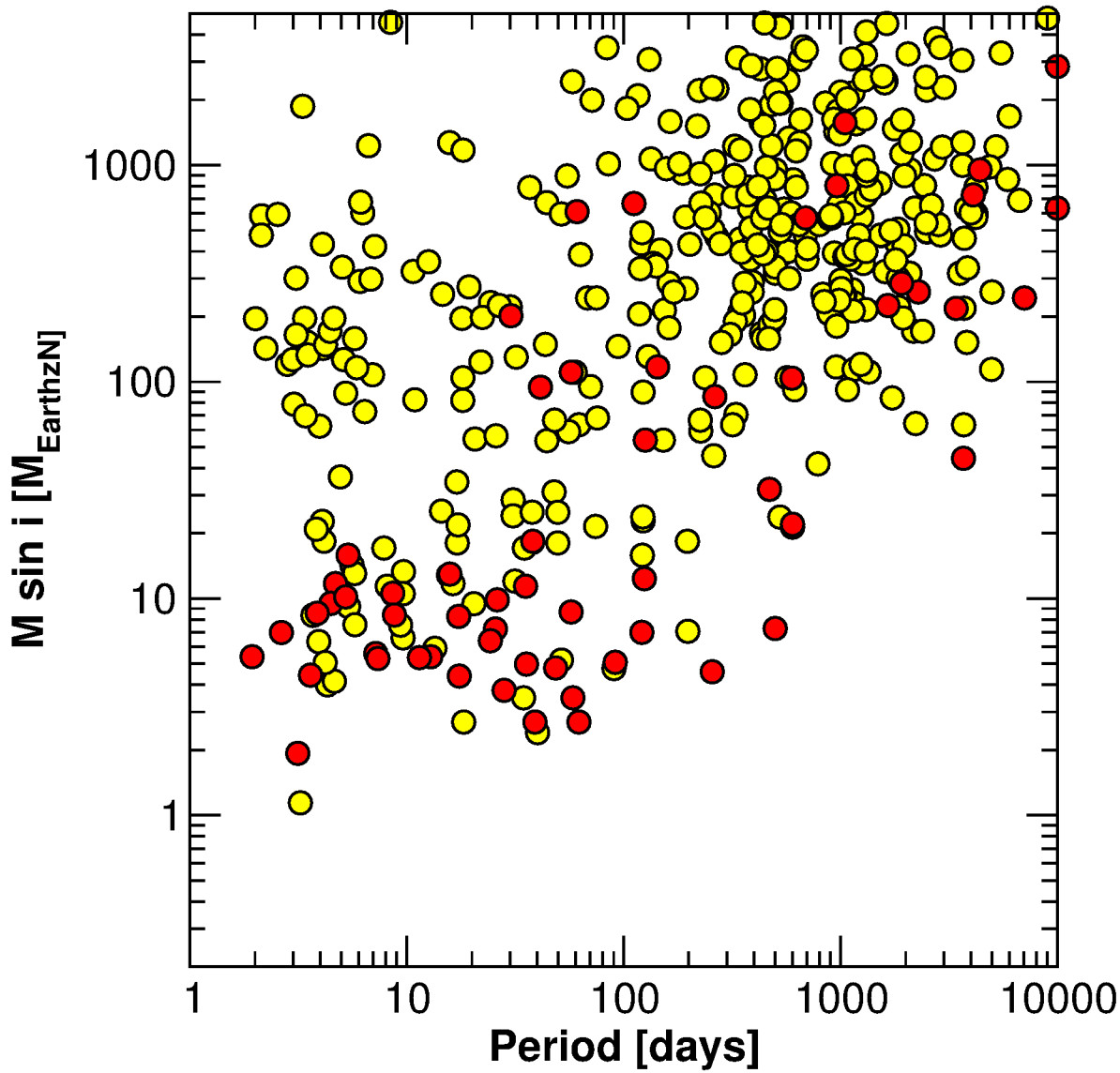
Anglada-Escude et al. 2014 MNRAS
And one is in its habitable zone!

2012-2014

<1 m/s
targeting M-dwarfs with improved cadences

More rocks coming soon!

Doppler spectroscopy



Last 15 years, G & K dwarfs received about 5x more telescope time than M-stars

Still most small planet candidates are on M-dwarfs!

Data from exoplanet.eu (Oct 23, 2014)

Doppler spectroscopy next 5 years
Taming the M-dwarfs

1.- Low mass star → larger Doppler signal

2.- Lower luminosity → close-in habitable zone → larger Doppler signal

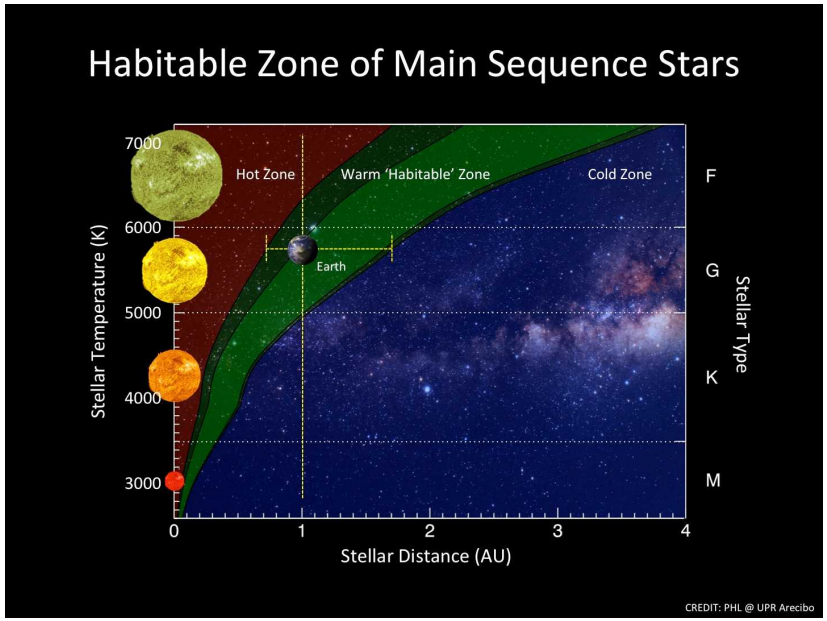
3.-Close in habitable zone → More cycles covered

4.-Cool atmosphere → Molecular bands → higher Doppler precision!!

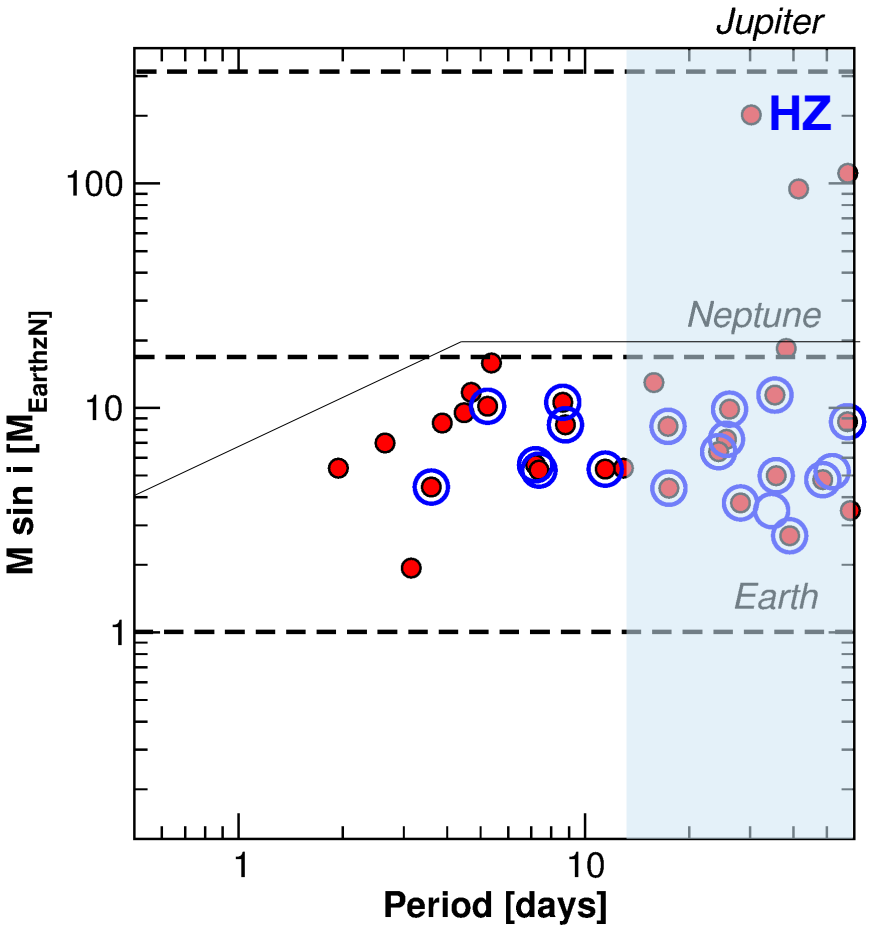
Exo-Earth formula

$$K = 10\, cm/s \frac{m_p / m_e}{M_¿ / M_{Sun}} \sqrt{1/a_{AU}}$$

0.1 m/s **3.1 m/s**

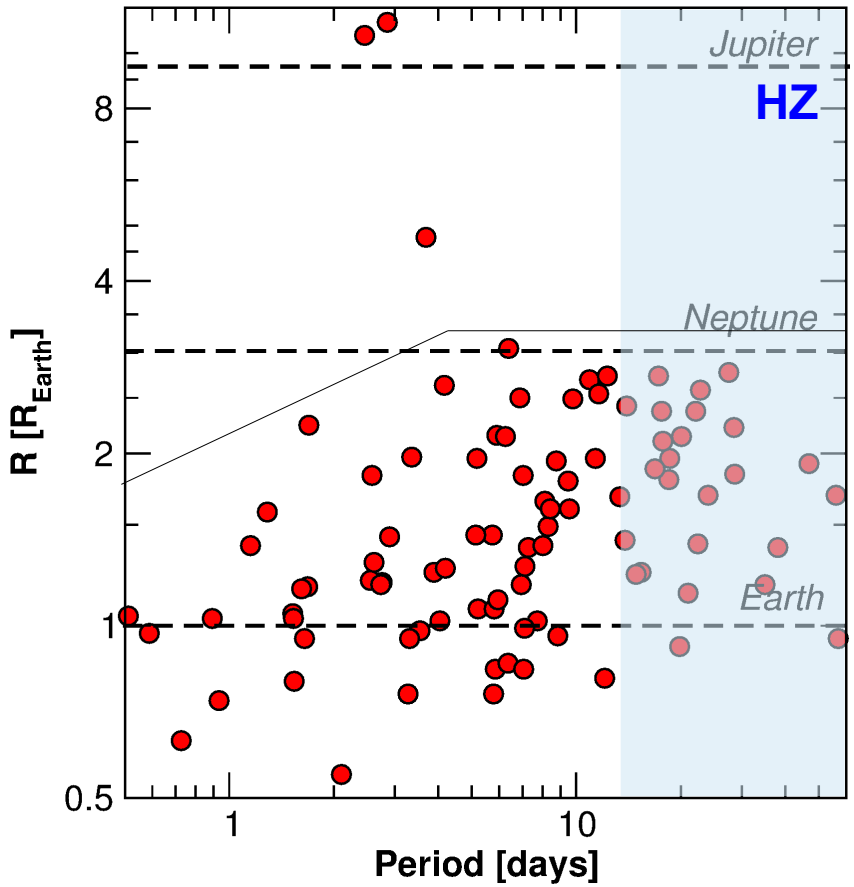


Doppler spectroscopy & Tranits
Taming the M-dwarfs



Tuomi et al. 2014 MNRAS, Anglada-Escude et al. 2014 MNRAS, Jenkins et al 2014 submitted...

KOIs (unconfirmed)



Dressing & Charbonneau, 2013, ApJ

New High-resolution spectrographs coming on-line!

Instrument	Telescope/Observatory	Start of Operations	Wavelength band (um)	Resolution	Precision (m/s)
HIRES	Keck I/Mauna Kea	1993	0.3–1.0	25,000–85,000	1-2
HARPS	**3.6m/ESO La Silla**	**2003**	**0.38-0.69**	**115,000**	**<0.8**
SOPHIE	1.93m/OHP	2006	0.38-0.69	39,000-75,000	1-2
PFS	Magellan II/Las Campanas	2010	0.39–0.67	38,000–190,000	1
CHIRON	1.5m/CTIO	2011	0.41-0.87	80,000	<1
HARPS-N	TNG/ORM	2012	0.38-0.69	115,000	<0.8
LEVY	APF/Lick	2013	0.37-0.97	114,00-150,000	<1
IRD	Subaru/Mauna Kea	2014	0.98-1.75	70,000	1
MINERVA	4x1-m/Mt. Hopkins	2015	0.39-0.86	53,000	1
CARMENES	Zeiss 3.5-m/Calar Alto	2015	0.55-1.7	82,000	1
SPIROU	CFHT/Mauna Kea	2017	0.98-2.35	70,000	1

Instrument	Telescope/Observatory	Start of Operations	Wavelength band (um)	Resolution	Precision (m/s)
ESPRESSO	**VLT/ESO Paranal**	**2017**	**0.38-0.78**	**60,000-200,000**	**0.1**
G-CLEF	GMT/Las Campanas	2019	0.35-0.95	120,000	0.1

x5
by 2020
(already in construction)

HARPS-INT, i-locater/LBT, HZ Planet Finder/HET, i-shell/NASA-IRTF, etc...

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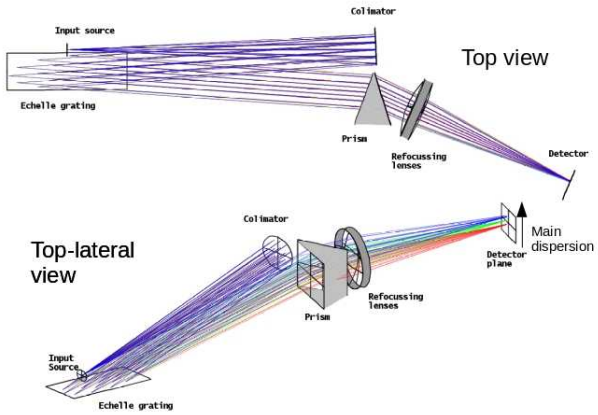
G-CLEF	GMT/Las Campanas	2019	0.35-0.95	120,000	0.1

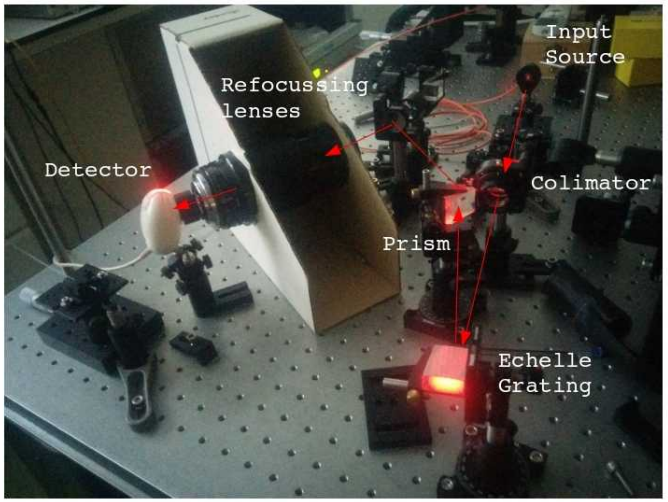
x5
by 2020
(already in construction)

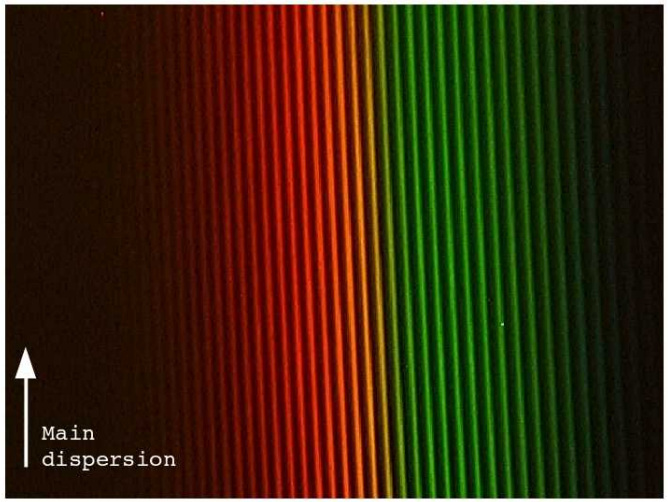
x25-50?
by 2025
(cheap stabilized spec)

HARPS-INT, i-locater/LBT, HZ Planet Finder/HET, i-shell/NASA-IRTF, etc...

New High-resolution spectrographs coming on-line!

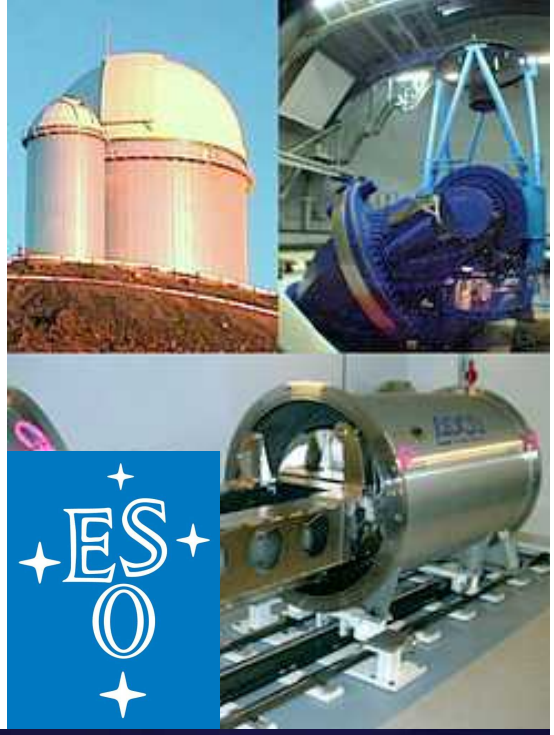






Not stabilized, but cheap

PALE RED DOT



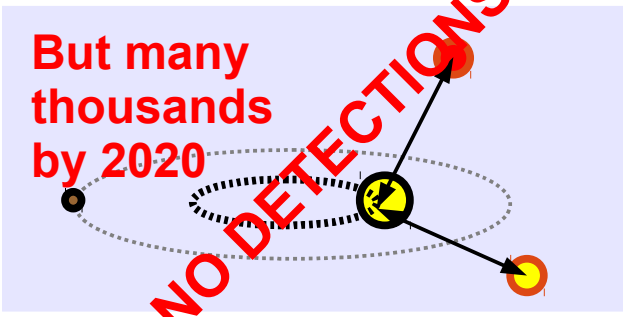
LCOGT

A search of Earth-like planets around Proxima Centauri

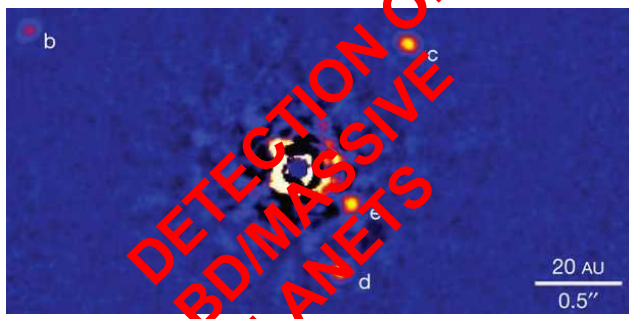
- 60 nights with HARPS
- Simultaneous UBVRI using 2 telescope networds

Detection techniques

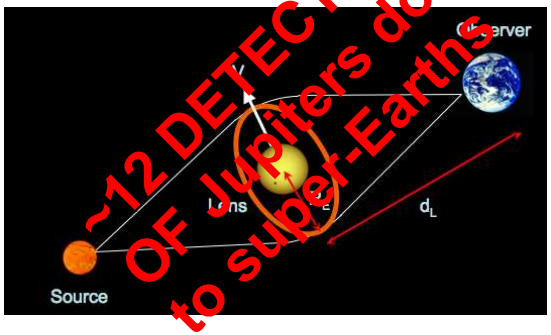
Astrometry



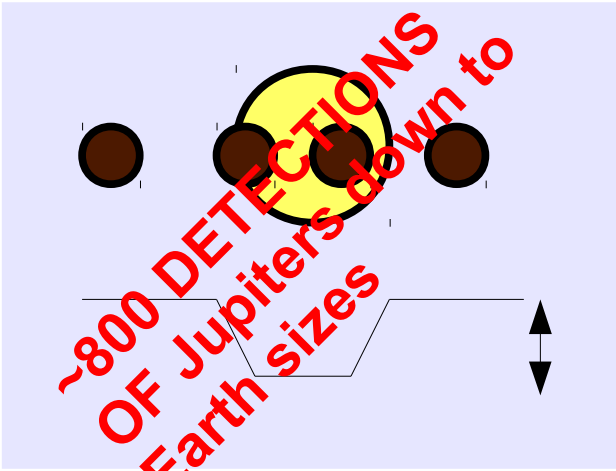
Direct imaging



Microlensing



Photometric transits



Doppler spectroscopy

Moving from detection to astrophysics

More exoplanets than exoplanets researchers

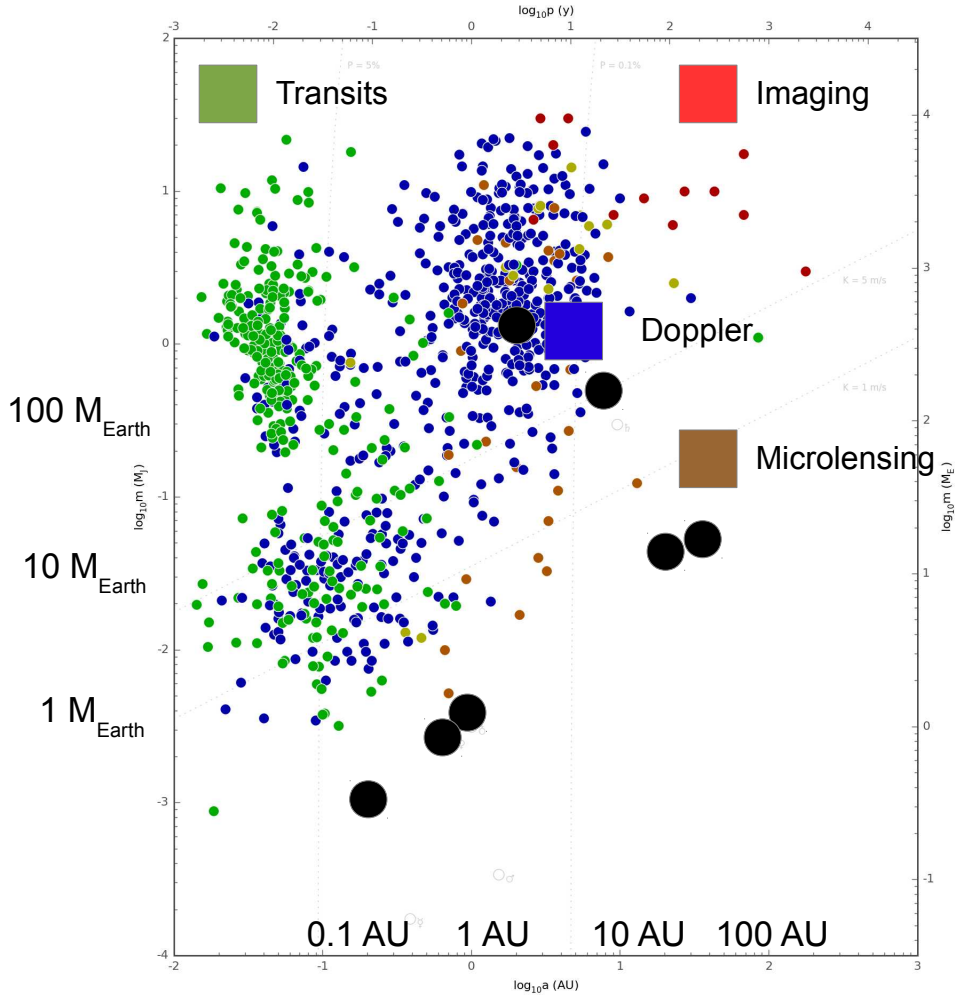
Five detection techniques

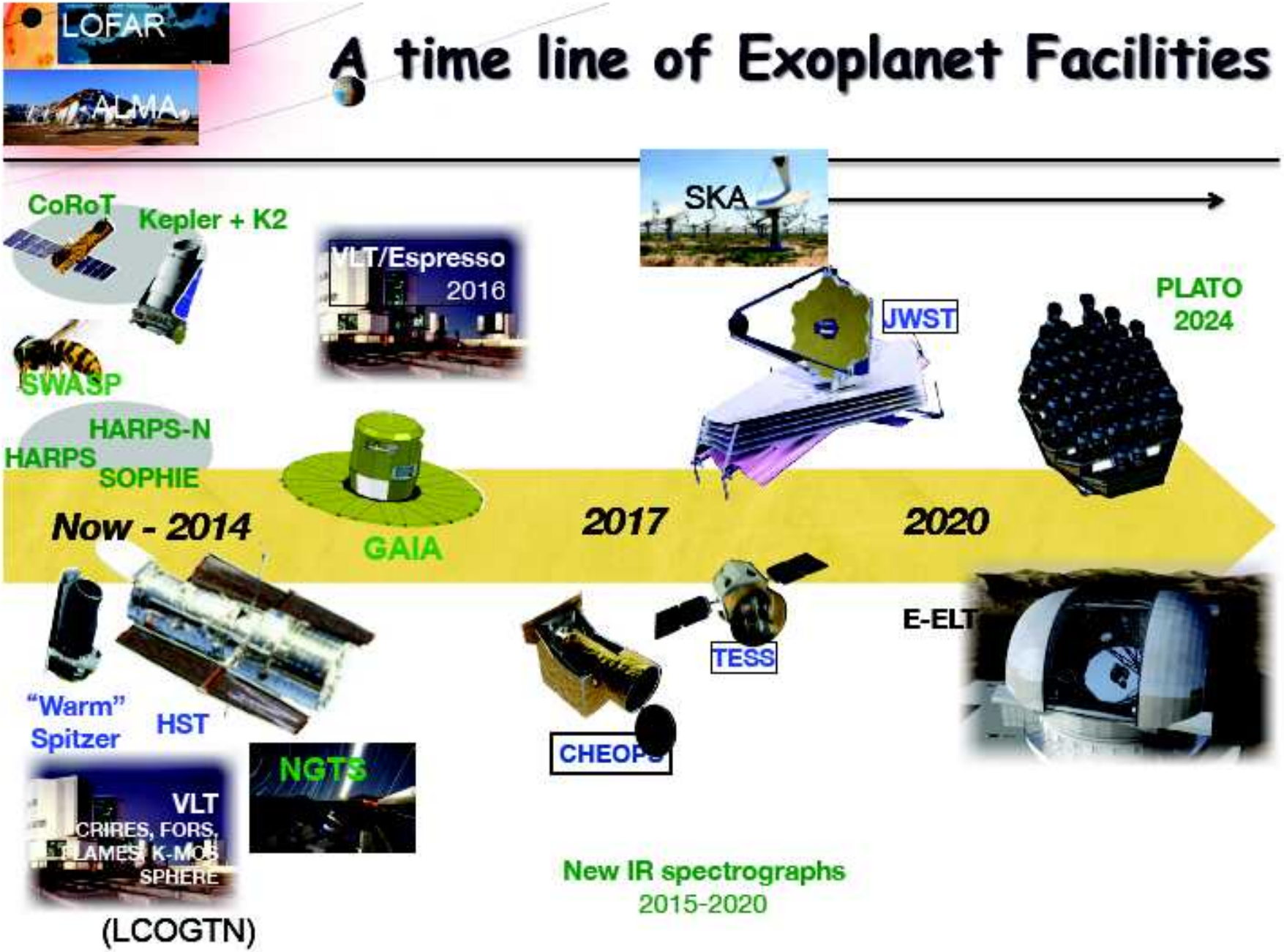
> Microlensing, Transit & Doppler

> Astrometry and direct imaging

Several competing planet formation models

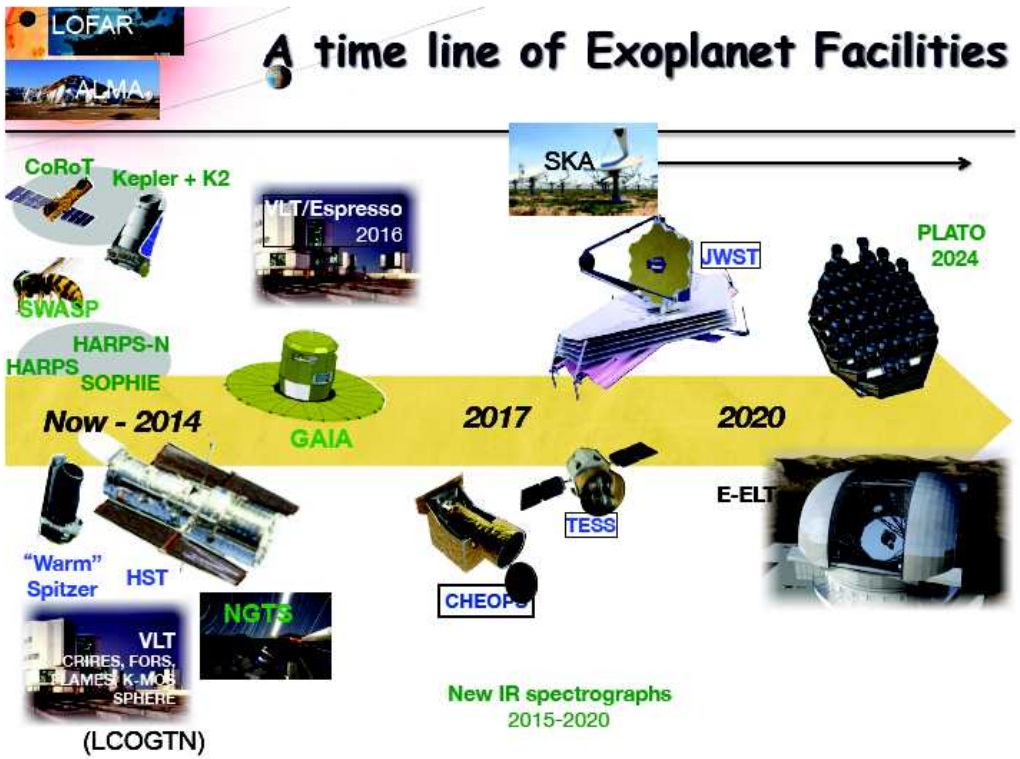
Tons of data and projects in next years





Borrowed from, UK-Exoplanet Science Review 2015

The astrometry exoplanet niche for a space mission at 2025+



Borrowed from, UK-Exoplanet Science Review 2015

Detection and mass of Earth-analogs around nearby stars for imaging

- L5 mission (2035?)
- E-ELT+AO+HIRES-IFU (2nd gen, 2030?)

Community feels we don't need a fully M-class mission

[already wary about Ariel getting the M4 slot]

Mid to Large scale architectures of planetary systems (within 5 AU)

- Gaia follow-up
- Astrometric follow-up of RV multiplanets
- Masses of direct imaging planets
- Mutual inclinations and masses