# OBSERVATION OF EXOPLANETS WITH LLAMA AND ALMA

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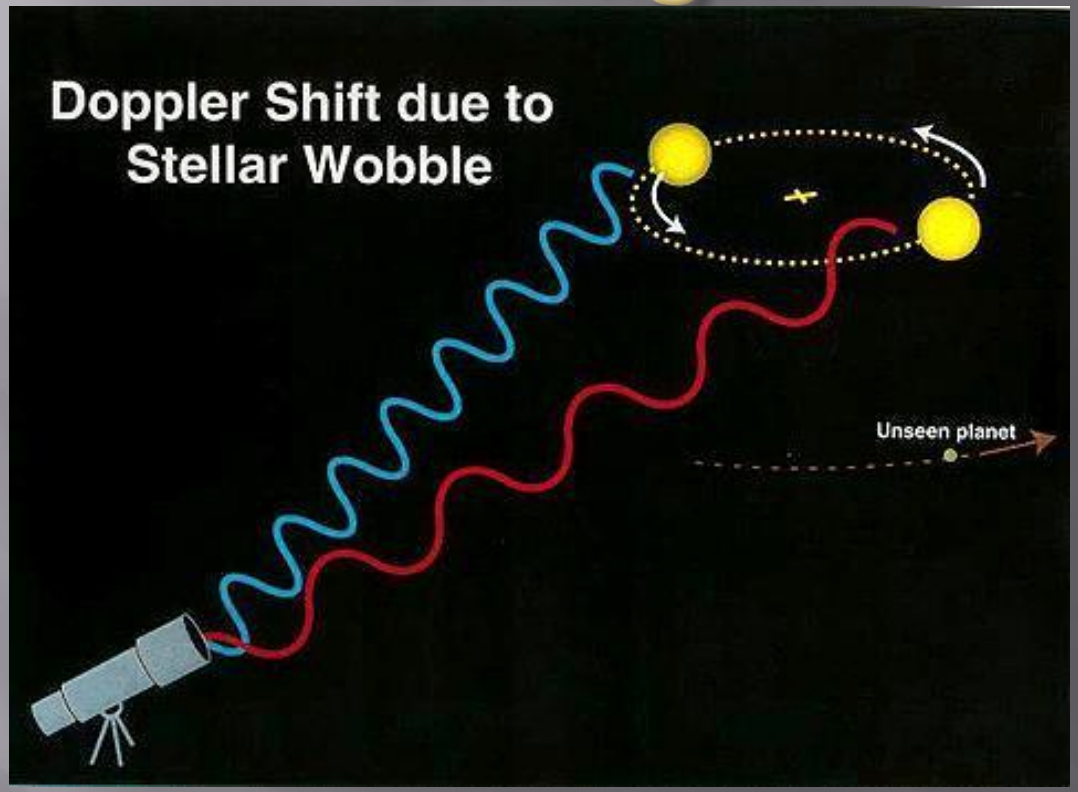
# Extrasolar Planets

- The Extrasolar Planets Encyclopaedia (http://exoplanet.eu/catalog.php)
- 7-Aug-2011: 573 planets
- Dynamical effects on the host star:
  - Radial velocity (522)
  - Arrival time of periodic signal (13)
  - Astrometry (1)
- Gravitational microlensing (13)
- Photometric effects:
  - Transits (144)
  - Direct detection (24)

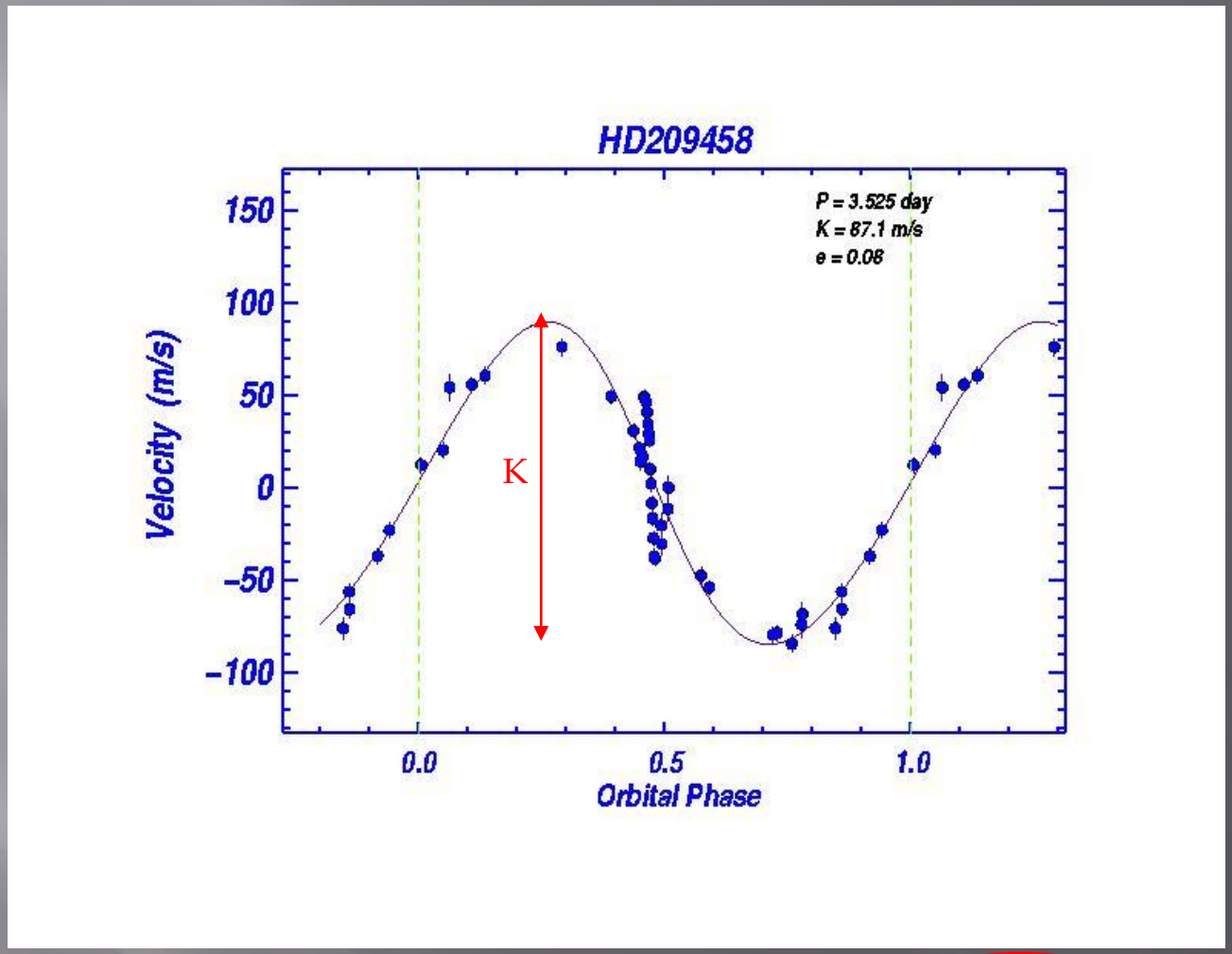
# Radial Velocity

# Starlight




$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}$$

- Obs. Doppler effect on the starlight;
- High spectroscopy precison needed (m/s)
- Majority of planets (375)

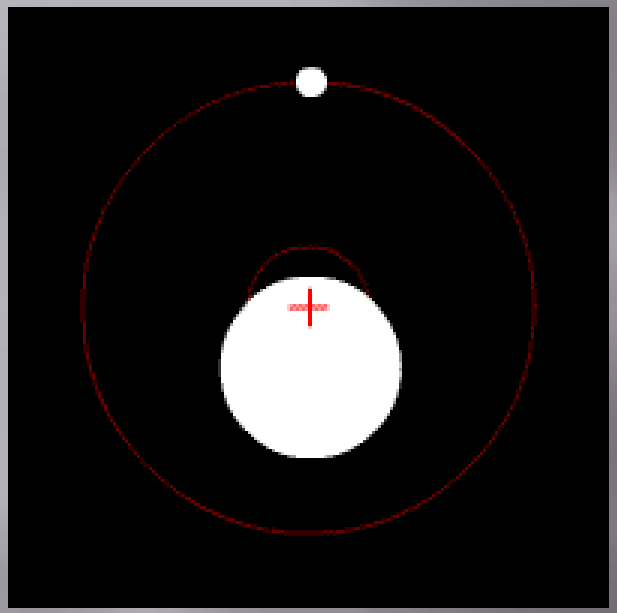


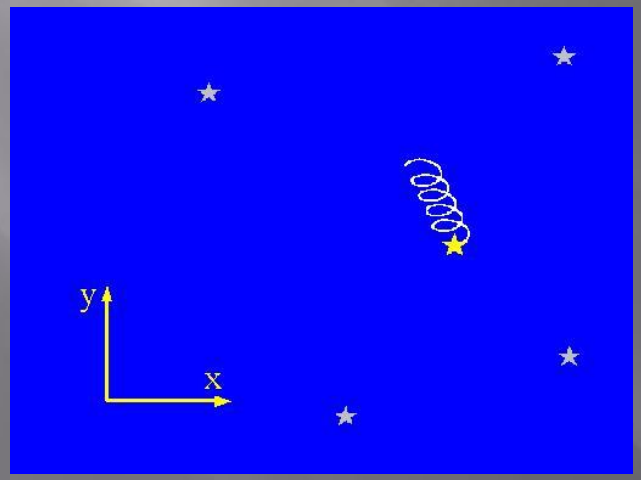

Lower limit on the planet mass

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \operatorname{sen} i}{(M_* + M_p)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

# Astrometry

# Astrometry



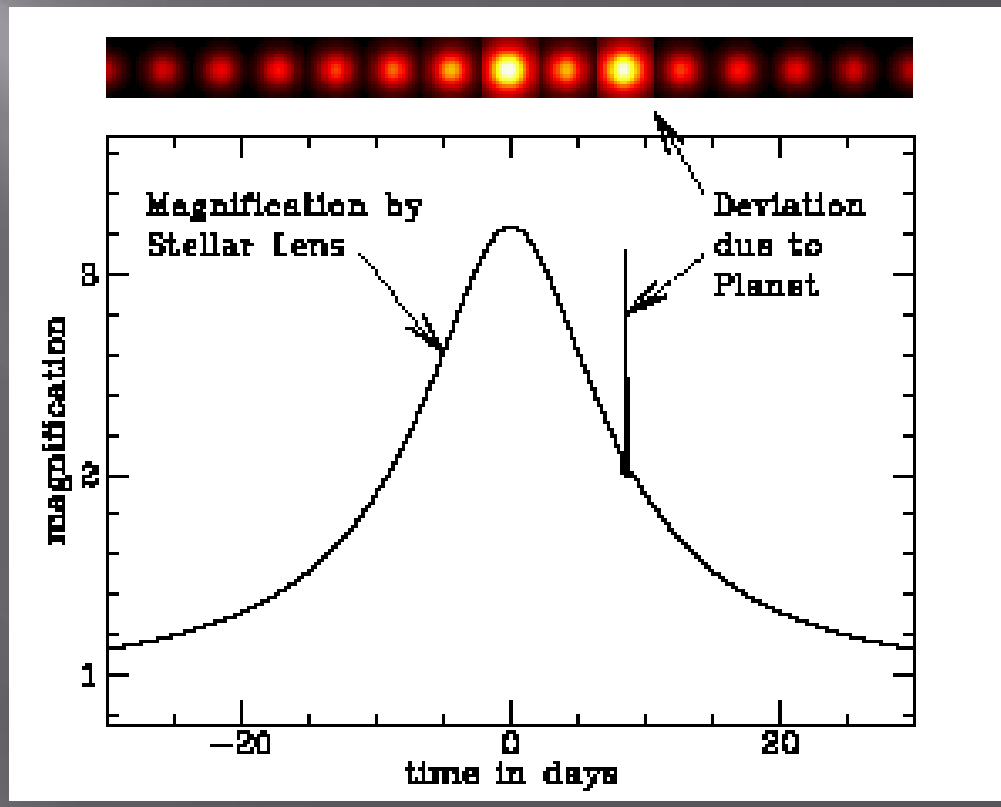



- Valid for the cases where the planetary orbit is in the plane of the sky and for nearby stars.
- Star and planet orbit around the common center-of-mass of the system (the higher the planet mass, the larger the stellar displacement).
- High precision measurements of the stellar position are needed.

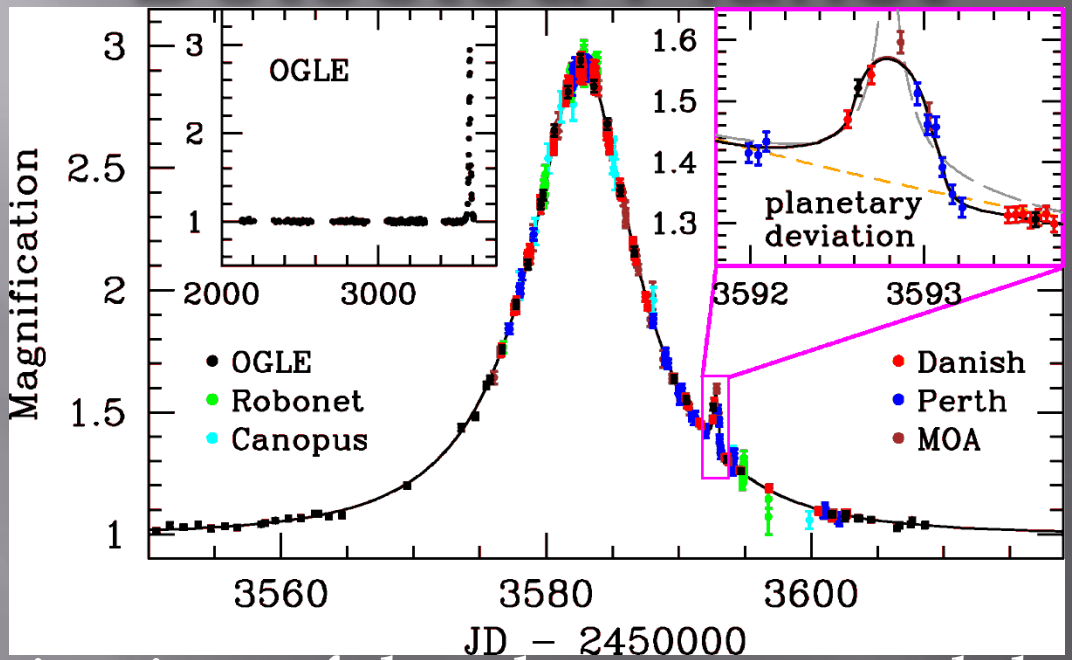
# Gravitational Microlensing

# Gravitational microlensing

- Massive objects located in the disk or buldge of our Galaxy can act as gravitational lenses.
- The light of a star in the buldge or the Galaxy is amplified.
- A planet in orbit (1 to 5 AU) around a distant (up to 1 kpc) star can be detected as a secondary amplification peak.
- Precision to detect even a 0.1 $M_{Earth}$ Planet.

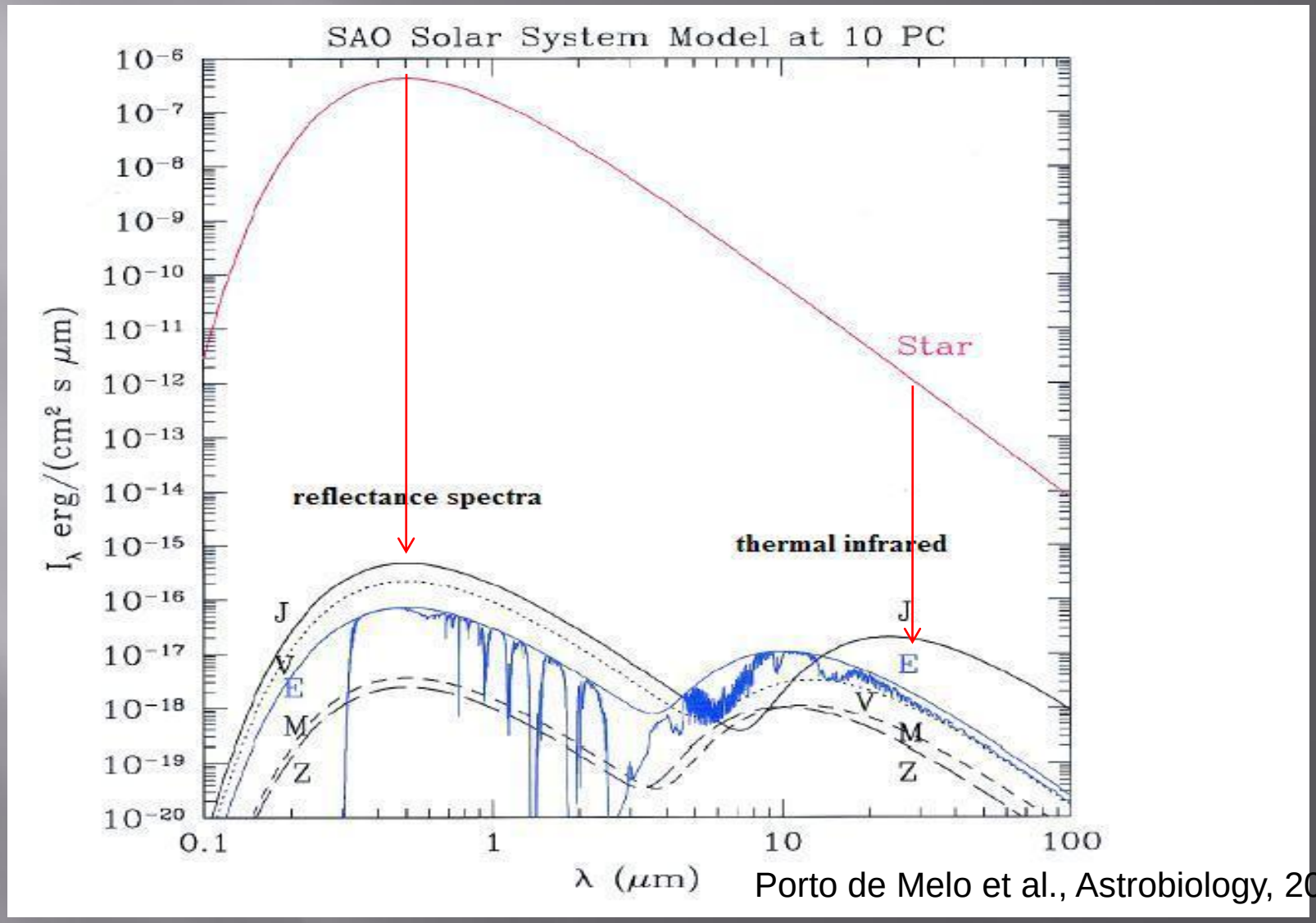


# Detected Planet




- Determination of the planet mass and the orbital radius.
- Jan 2006: OGLE-2005-BLG-390Lb
- Orbital radius=2.9 AU and Mass=5.5 $M_{Earth}$
- 13 planets detected
- Irreproductible

# Direct Detection



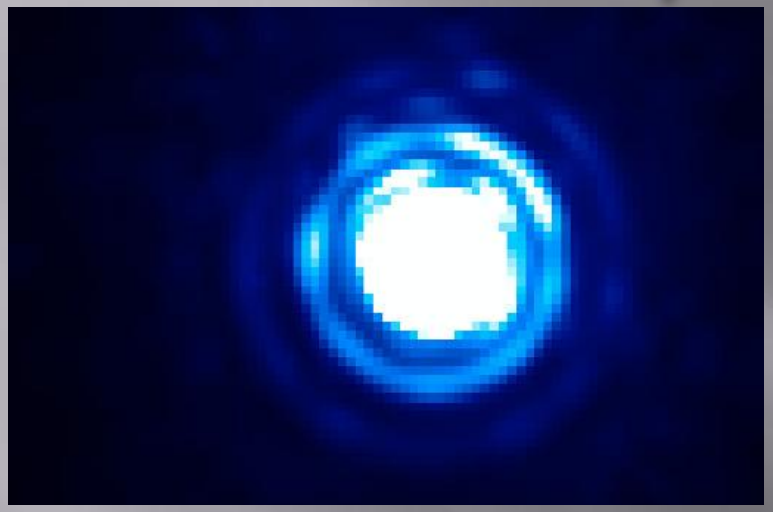

Porto de Melo et al., Astrobiology, 2006

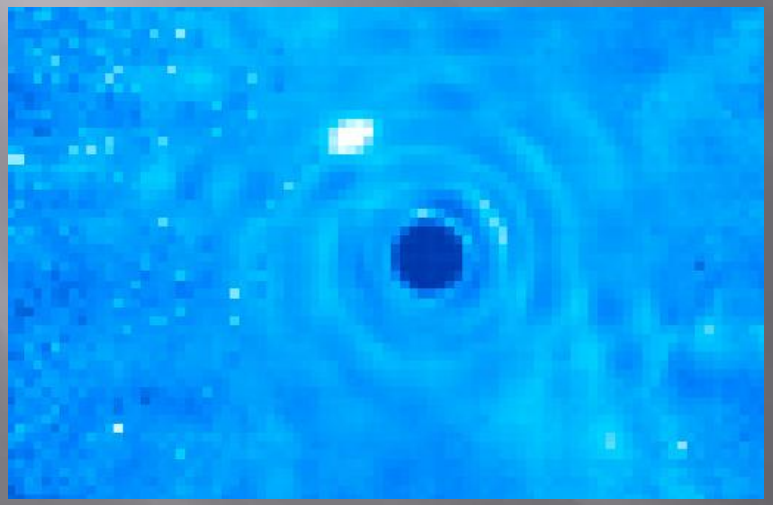
- At mm and submm wavelenths the ratio between the stellar and planet fluxes is about 1000

# Direct Detection

- Light from the planet about  a billion times smaller than that of the star (solar-like star)
- Obs. fainter stars:
  - young stars
  - brown dwarfs
  - obs. at infrared wavelengths infravermelho (brithness ratio of about a million)
  - obs. at  millimeter and submm wavelengths (ratio of about 1000)

# β Pictoris

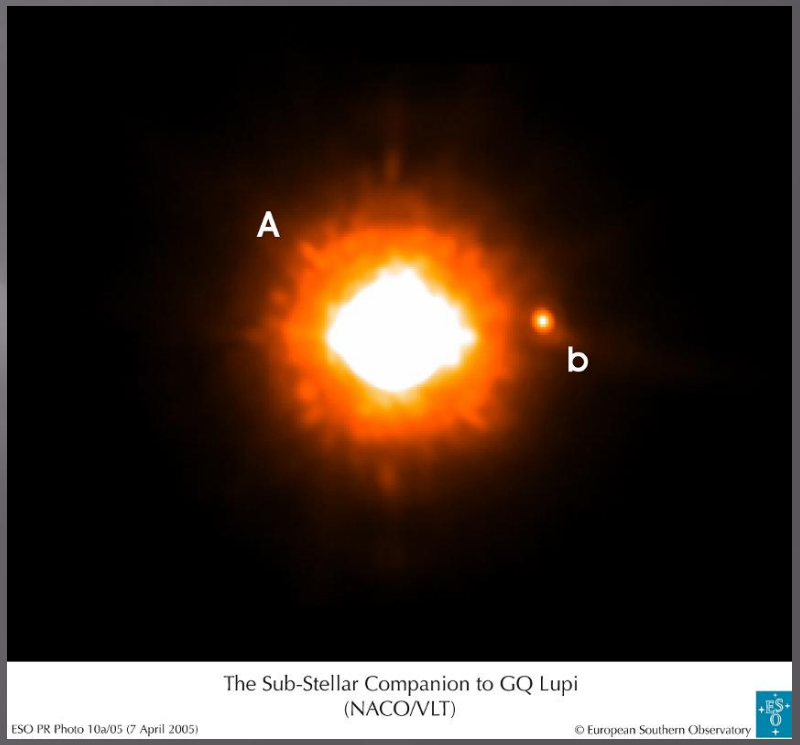




- Disk of dust around the star β Pic
- Subtraction and division of VLT/NaCo images revealed the planet.
- Mass = 8 $M_{Jup}$
- Semi-axis = 8 AU
- Lagrange et al. A&A (2009)

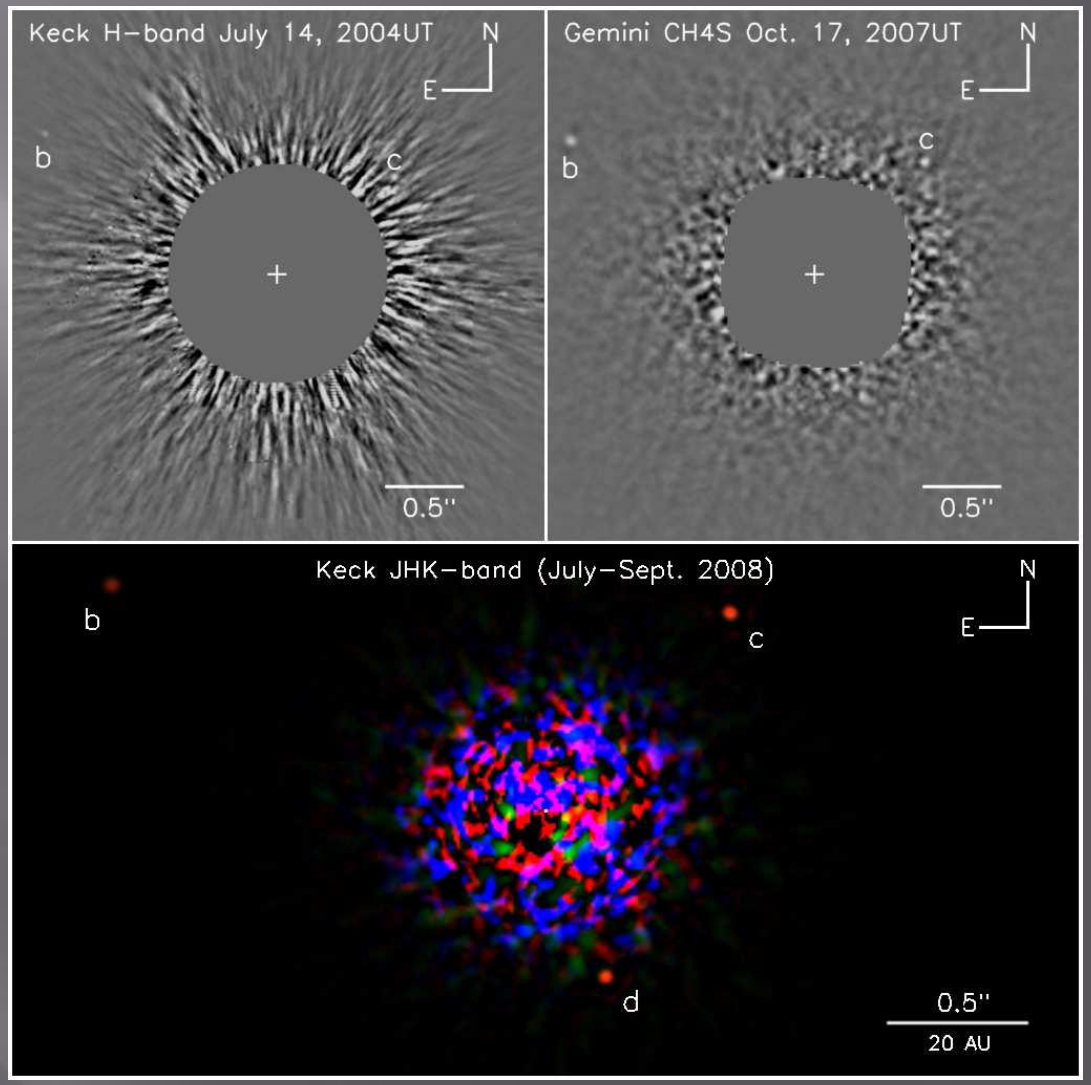
# GQ Lup – young star

- GQ Lup is a T Tauri star;
- Detection of the companion that is 250 times fainter at a distance of 100 AU (Neuhäuser et al. 2005);
- Mass of a few $M_{Jup}$ ;
- Very Large Telescope;
- 31-Mar-2005

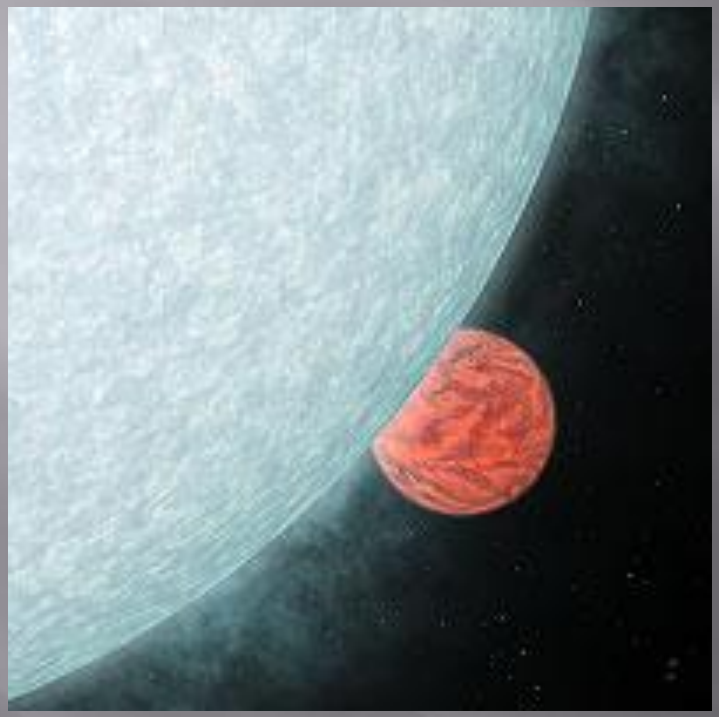


# HR 8799

- Multiple system with 3 planets:
- Masses: 7, 10, and 10 $M_{Jup}$
- Semi-axes: 68, 38, and 24 AU
- Periods: 466, 189, and 100 years
- Obs: Keck
- Marois et al. (Science 2008)



# Planet Thermal Emission

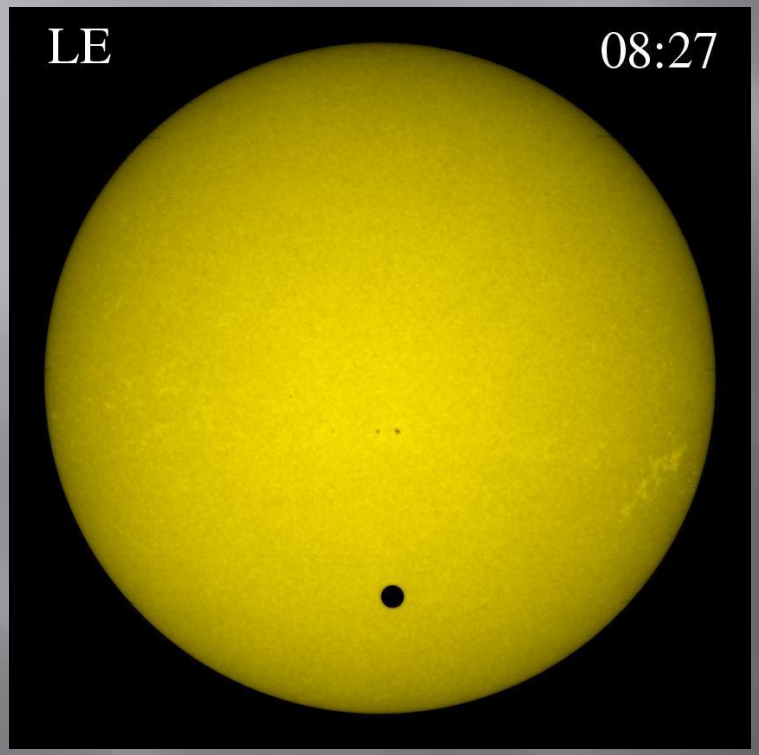


- Direct detection of the planet thermal emission at infrared wavelengths:
  - HD 209458 b (Deming et al, *Nature*)
  - TrES-1 (Charbonneau et al, *ApJ Let.*)
- Spitzer Space Telescope
- 22-Mar-2005

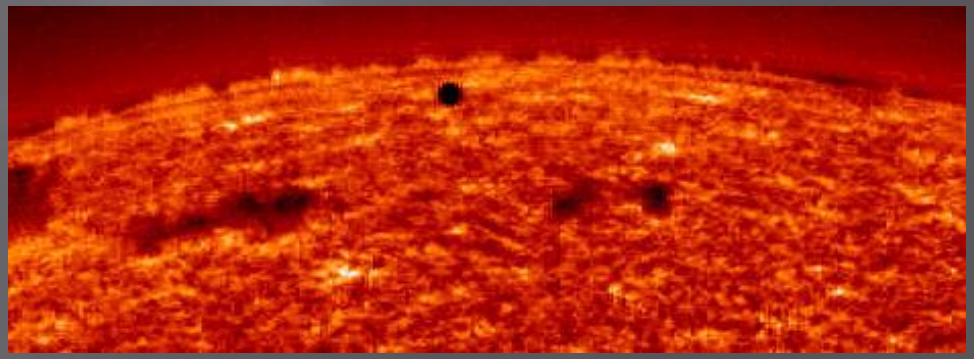
# Transits
# (or eclipses)

# Transit of Mercury and Venus

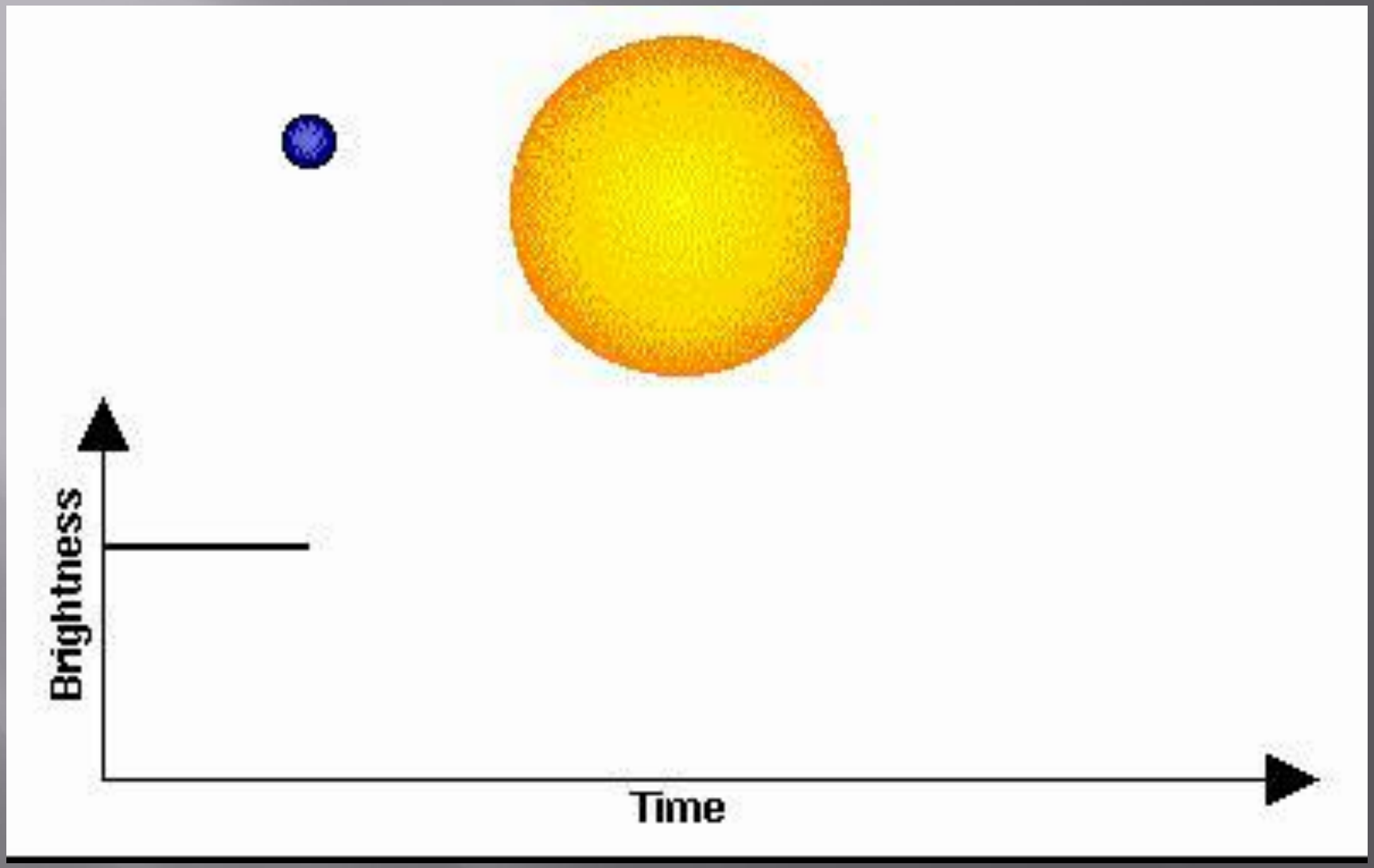
- Venus transit on 08-Jun-2006.



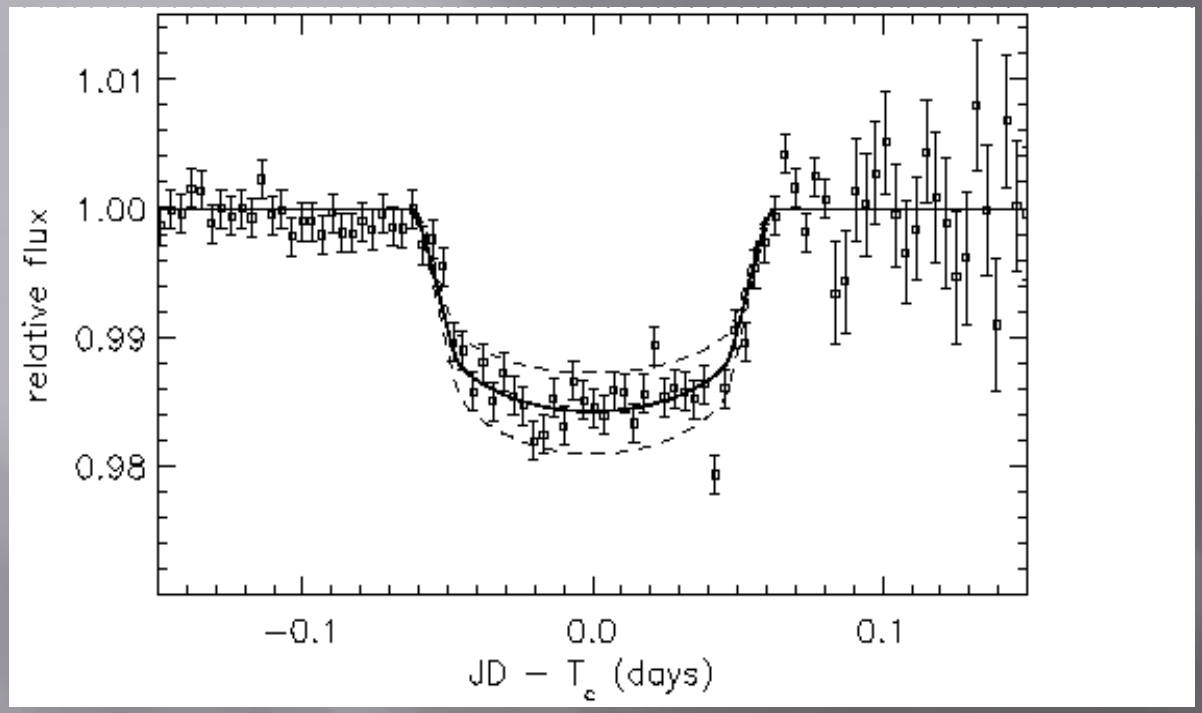




- Mercury transit on 15-Nov-1999 and 07-May-2003 lasting for one hour.


Brightness
Time

# HD 209458




- Mass: 0.685 $M_{Jup}$
- Period: 3.5 days
- Orbit: 0.045 AU
- Transit duration: 2.5 h
- Brightness decrease: 1.8%
- 408 articles

In 2000, first planet detected from its transit, that was a posteriori confirmed to be a bonafide planet by radial velocity measurements.

# Transiting planets

- Orbits nearly perpendicular to the sky plane ($i=90^o$).
- For a solar-like star, the brightness decrease due to a planetary transit amounts to:
  - 1 % for Jupiter size planet
  - 0.01% for Earth size planet
- Ground based telescopes are able to detect Jupiter size planets, for teluric planets, satellite observations are necessary (CoRoT and Kepler)
- Kepler detected 1235 candidates (Borucky et al. 2011)

# Physical properties

**Radial velocity:**

- Mass
- Orbital period
- Excentricity
- Orbit semi major axis(from Kepler's 3rd law)

**Transit:**

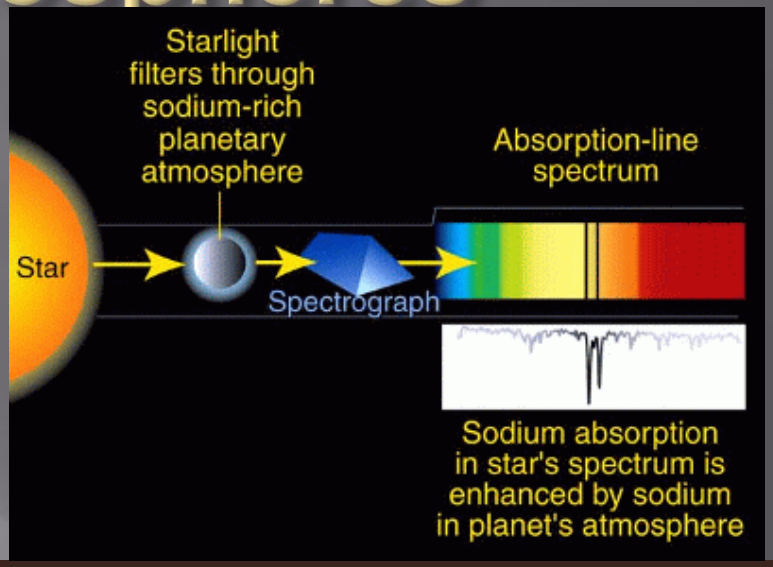
- Radius
- Orbital period
- Orbital inclination angle

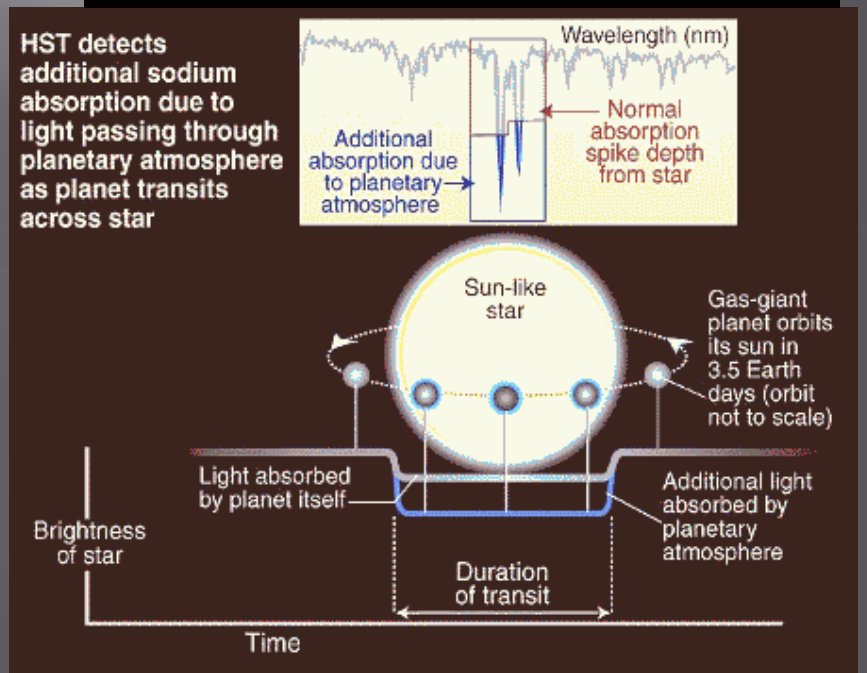
**Mass + radius:**

- Obtain the planet density: allows to for the determination of the planet composition (gaseous, aqueous, or rocky)

# Planetary atmospheres

- Studied from obs. of the primary and secondary eclipeses.
- Molecules detected in HD 209458b: H, $H_2O$, Na, TiO (Titanic oxide), VO (Vanadium oxide)
- 1/3 of the expected Na => condensed in clouds



# Radio telescopes
# LLHAMA and ALMA

# LLAMA

- Not possible to detect giant planets with a single dish – dilution in the beam
- Can be used in VLBI mode with the full ALMA array and improve the spatial resolution of the observations.

# ALMA

- ALMA is capable of observing :
- Young giant planets embebed forming in protoplanetary disks (gaps);
- Giant planets orbiting nearby stars;
  - Direct imaging/detection (Butler et al.)
  - High precision astromety (Butler et al.)
  - Transits

# Sensitivity

- Flux density (blackbody):

$$F_\lambda \approx \frac{2kT}{\lambda^2}\frac{\pi R^2}{d^2}$$

- ALMA sensitivity (1 min)

| Freq (GHz) | $S_{cont}$ (mJy) | $SNR_{cont}$ | $S_{line}$ (mJy) | $SNR_{line}$ |
|---|---|---|---|---|
| 110 | 0.047 | 2.57 | 7.0 | 0.017 |
| 140 | 0.55 | 0.36 | 7.1 | 0.027 |
| 230 | 0.10 | 5.29 | 10.2 | 0.052 |
| 345 | 0.195 | 6.10 | 16.3 | 0.073 |
| 409 | 0.296 | 5.65 | 22.6 | 0.074 |
| 675 | 1.042 | 4.37 | 62.1 | 0.073 |

$$SNR \propto \frac{\upsilon^2}{\Delta S}$$

- Best to observe at 345 GHz (continuum)

# Planet signal

- Consider 3 cases:
  - Jupiter (T = 200 K, R = 1 Rjup)
  - Hot-Jupiter (T = 1000 K, R = 1.5 Rjup)
  - Proto-Jupiter (T = 2500 K, R = 30 Rjup)
- Flux densities at 345 GHz in μJy:

| Distance (pc) | Jupiter | Hot-Jupiter | Proto-Jupiter |
|---|---|---|---|
| 1 | 12 | 130 | 59000 |
| 5.7 | 0.36 | 4.1 | 1820 |
| 10 | 0.12 | 1.3 | 590 |
| 120 | 0.0008 | 0.009 | 4.1 |

- Detection possible at 345 GHz with SNR=5 with a few hours to days of integration time.

# Orbital distance

- For detection, the separation between the planet and its central star needs to be larger than the  spatial resolution of ALMA.
- Obs. at 345 GHz with max baselines of 4 km is about 45 mas, whereas for 15 km the resolution is 12 mas.
- For a planet at 5 AU and 120 pc, the separation is 40 mas.
- Integration time not too long such the planet does not move significantly in its orbit.

# Astrometry

- Angular size of the stellar orbit due to the presence of the planet:

$$\theta_r = \frac{m\, a_{AU}}{M_*\, d_{pc}}$$

- Astrometric resolution of ALMA (distance necessary to discriminate the stellar wobble):

$$\Phi = \frac{\theta_{HPBW}}{2\, SNR_*} = \frac{\lambda}{2 B_{\max}\, SNR_*}$$

- For a SNR=10, ALMA is able to detect the astrometric wobble for stars as far as 10 pc.
- For a solar like star, an integration of 10 min will suffice.

# Transit

- Solar-like star fluxes at 1, 10, and 100 pc at 345 GHz (in mJy):
- Jupiter size planet: 1% decrease (SNR=5)
- Sensitivity = stellar flux/0.01/5
- Integration time at 345 GHz in continuum with full array (Observing Tool)

| Distance (pc) | Star Flux (mJy) | Sensitivity (mJy) | Integration Time |
|---|---|---|---|
| 1 | 34.4 | 0.069 | 6 min |
| 5 | 1.38 | 0.0027 | 2.8 d |
| 10 | 0.34 | 0.00069 | 43 d |
| 100 | 0.0034 | $6.9 \times 10^{-6}$ | 1180 yr |

# LLAMA

- Not possible to detect giant planets with a single dish – dilution in the beam
- As a very long baseline interferometry (200 km baselines), even higher spatial resolution may be achieved = 1.2 mas @ 300 GHz
- Can improve the detection capability of exoplanets:
  - By astrometry
  - Forming planets in proto-planetary disks.

# Thank you