Extrasolar Planets

- Why search for extrasolar planets?
- What is the best way to do it?
- What fraction of stars have planetary systems?
- What kinds of extrasolar planets are out there?

Radial Velocities

$$\left\{ \begin{array}{l} M \sin i \\ P \rightarrow a \\ \varepsilon \end{array} \right.$$

- Incompleteness:
  - Planets with $M<1M_J$
  - Planets with a>3UA (P>10yr)
  - Multiple planets
- Extrasolar planets encyclopaedia
  - Jean Schneider *(Obs. de Paris Meudon):*

    www.vo.obspm.fr/exoplanetes/encyclo/encycl.html
  - RV results till Dec 2005:

    163 planets discovered

    18 planetary systems
- http://exoplanets.org , http://obswww.unige.ch/planet

Transits

$\sin i \rightarrow M_p$
$P \rightarrow a$
R_p
ρ

- Incompleteness:
  - Planets with $R<R_N$
  - Only planets with a<<1UA (P<<1yr)
  - Many contaminants (WDs, BDs, M*s)
- OGLE transit survey
  - All sky searches & MW bulge and disk
    bulge.astro.princeton.edu/~ogle/ogle3/transits
  - Ephemerides: www.transitsearch.org
- Transit results till Dec 2005:
  >200 transit candidates
  9 confirmed planets

Topics lecture II

- ASTROMETRY
- MICROLENSING
  - Basic microlensing
  - Binary stars
  - Microlensing towards the galactic bulge
  - First microlensing planet detections
- TIMING
  - Pulsar timing
  - Eclipse timing: multiple planets, satellites
  - Resonances
- DIRECT DETECTIONS
  - Secondary eclipses in IR
  - Transmission spectra: UV, Optical, IR
  - Reflected light: UV, Optical
  - Extrasolar planets spectra
- HABITABLE PLANETS
  - Earthshine spectrum, biomarkers
  - The future

Extrasolar Planets

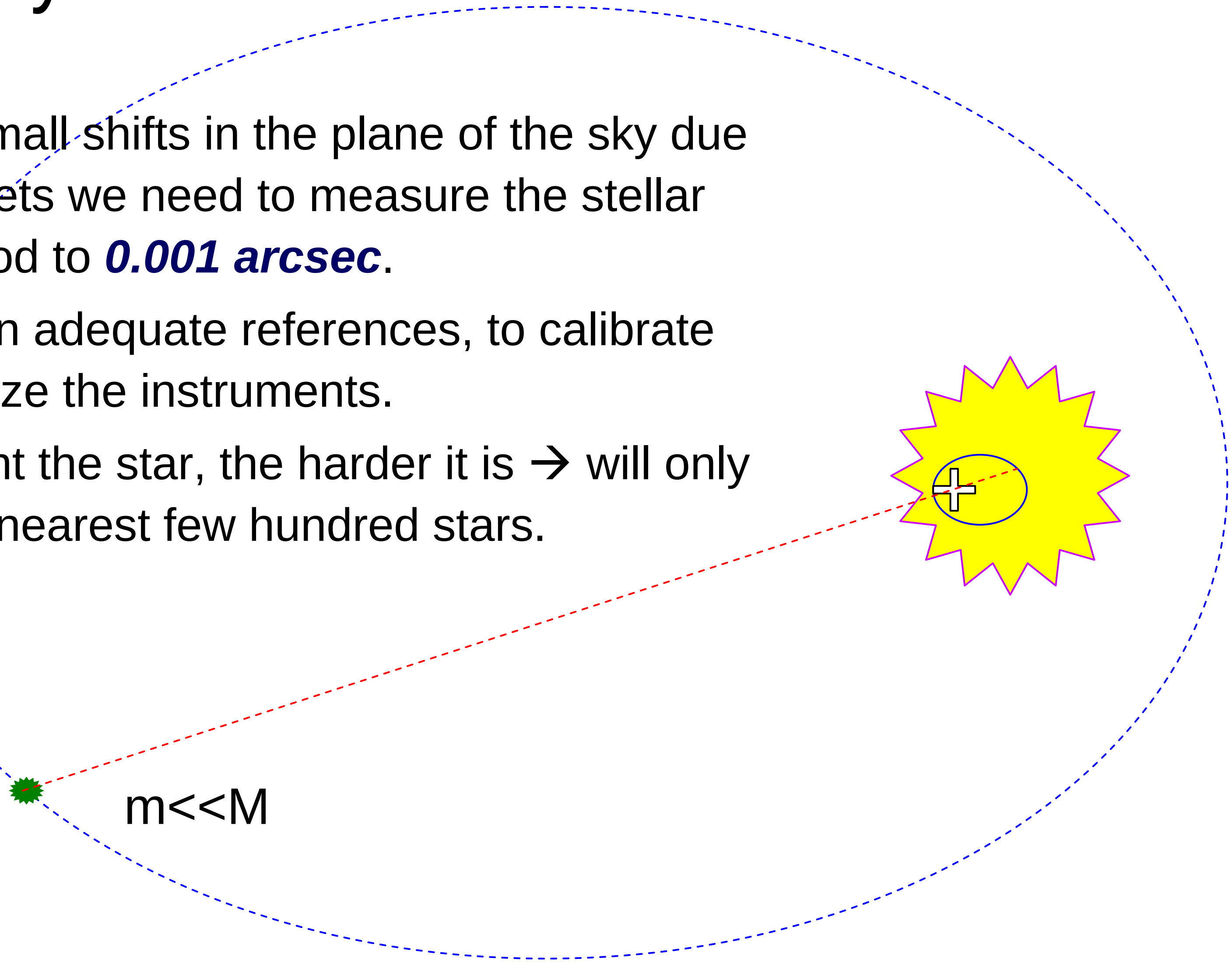
- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

Planetary orbits

To detect the small shifts in the plane of the sky due to giant planets we need to measure the stellar positions good to ***0.001 arcsec***.

Difficult to obtain adequate references, to calibrate and to stabilize the instruments.

The more distant the star, the harder it is → will only work for the nearest few hundred stars.

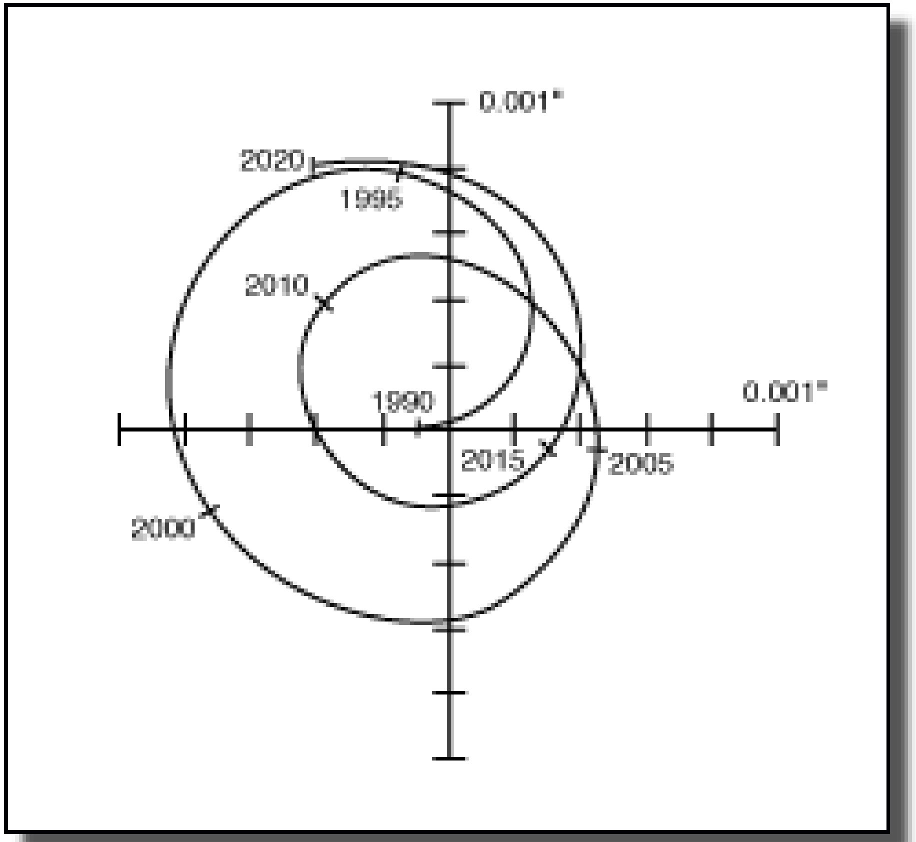


$\Delta\alpha = a/D \cos\delta$

$\Delta\delta = a/D$

Astrometry

- At least milli-arcsecond precision is needed for astrometric planet detections around nearby stars.
- This is at the limit of current ground based capabilities.
- The more massive the planet, the better.
- The larger the planetary orbit, the better.
- Long term observations are necessary (years).



Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

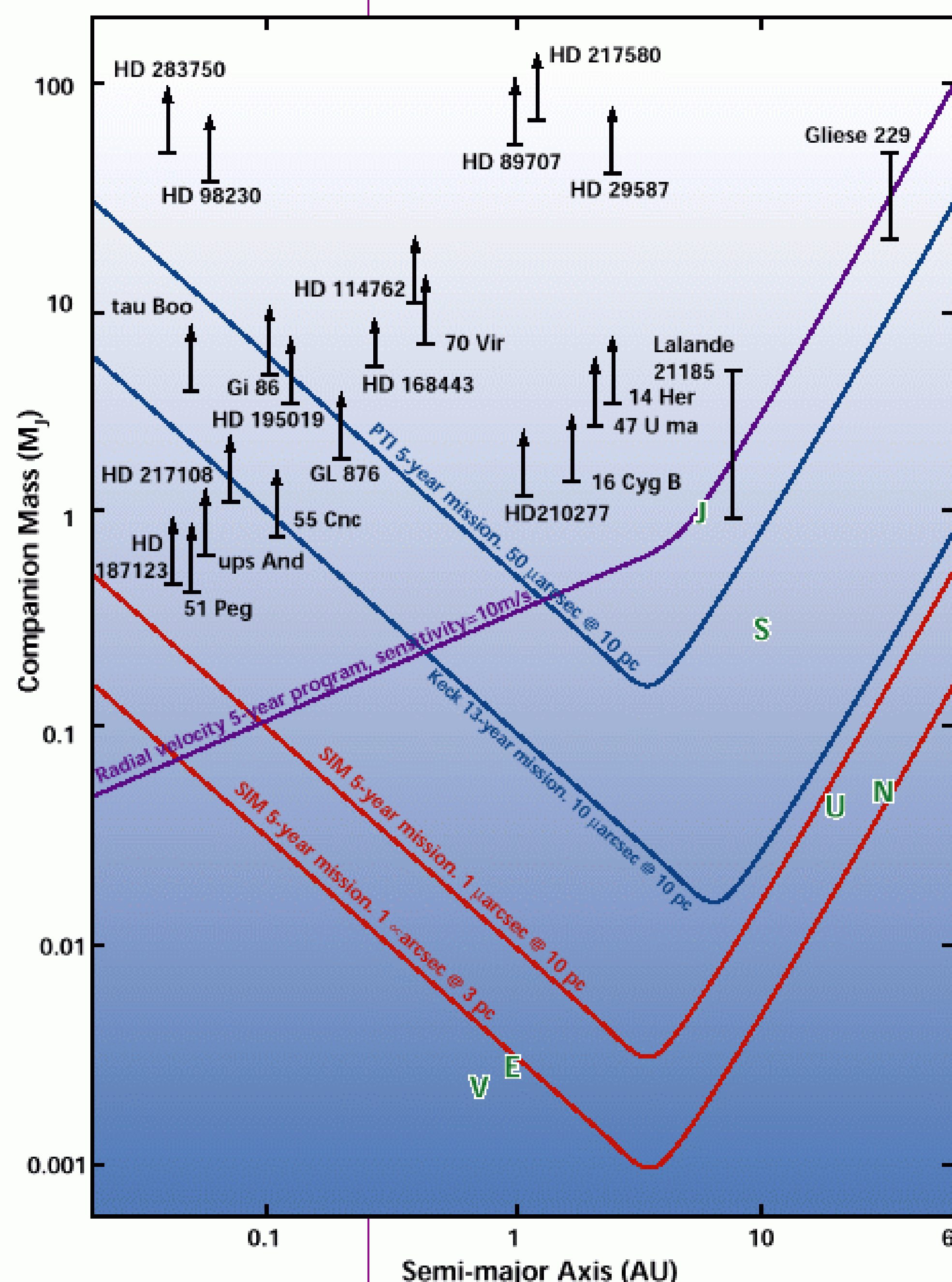
Cochran 1999

Search for extrasolar planets

No planets discovered so far, because of difficult milli-arcsec measurements from ground based facilities.
But this is a promising technique for the future from space. Micro-arcsec space measurements (SIM) will allow the detection of Earths around nearby stars

Reviews by Sozzetti 2005 and Marcy et al. 2005

TPF



Astrometry

$$\left\{ \begin{array}{l} M \\ P \rightarrow a \\ \varepsilon \end{array} \right.$$

- Incompleteness:
  - Planets with $M<1M_J$
  - Planets with a<3 AU (P<10 yr)
  - Distant stars
- Astrometry results till Dec 2005:

No planets discovered

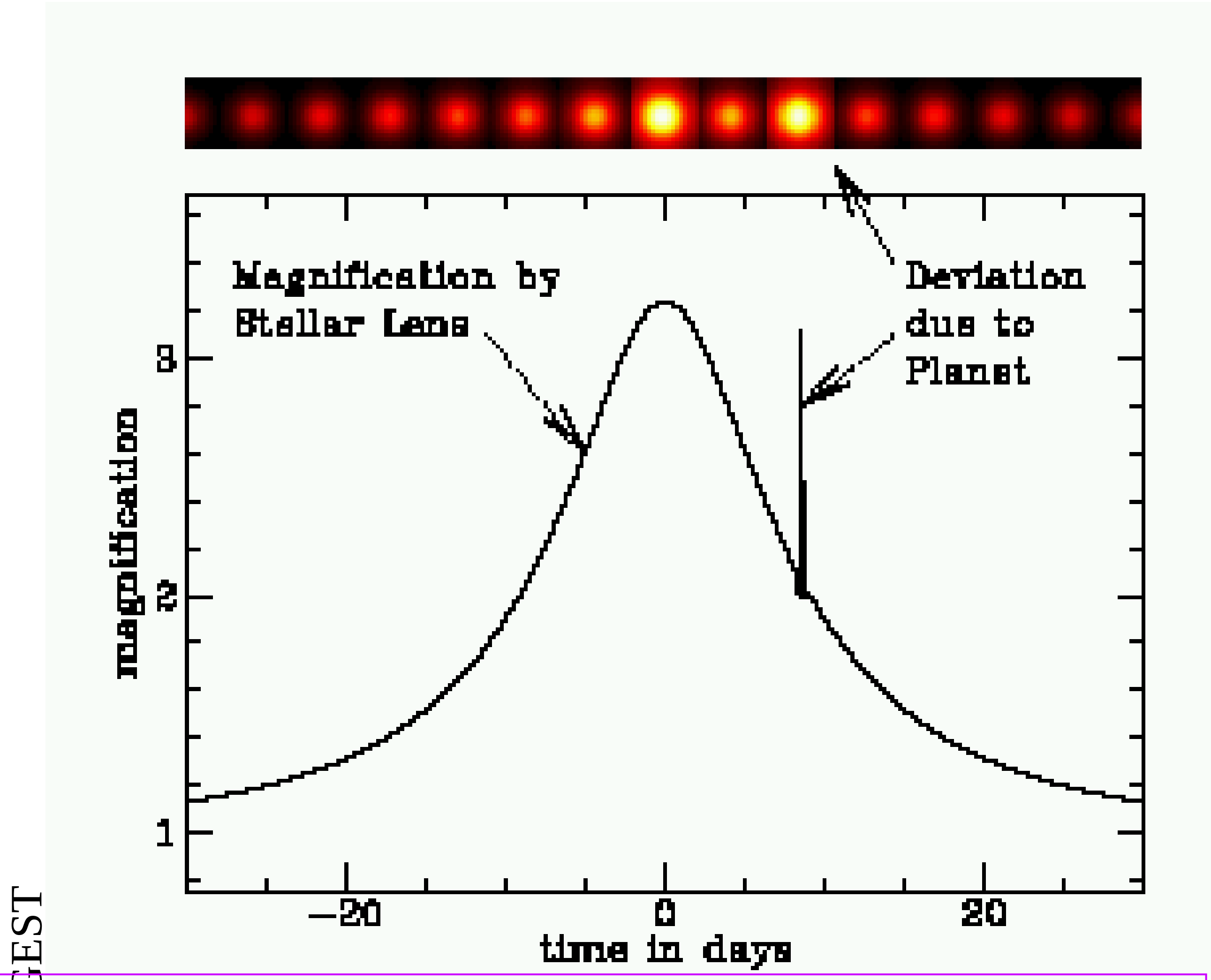
Upper masses for two RV planets in ρ Cnc with HST+FGS (McGrath et al. 2004, McArthur et al. 2004)

Extrasolar Planets

- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

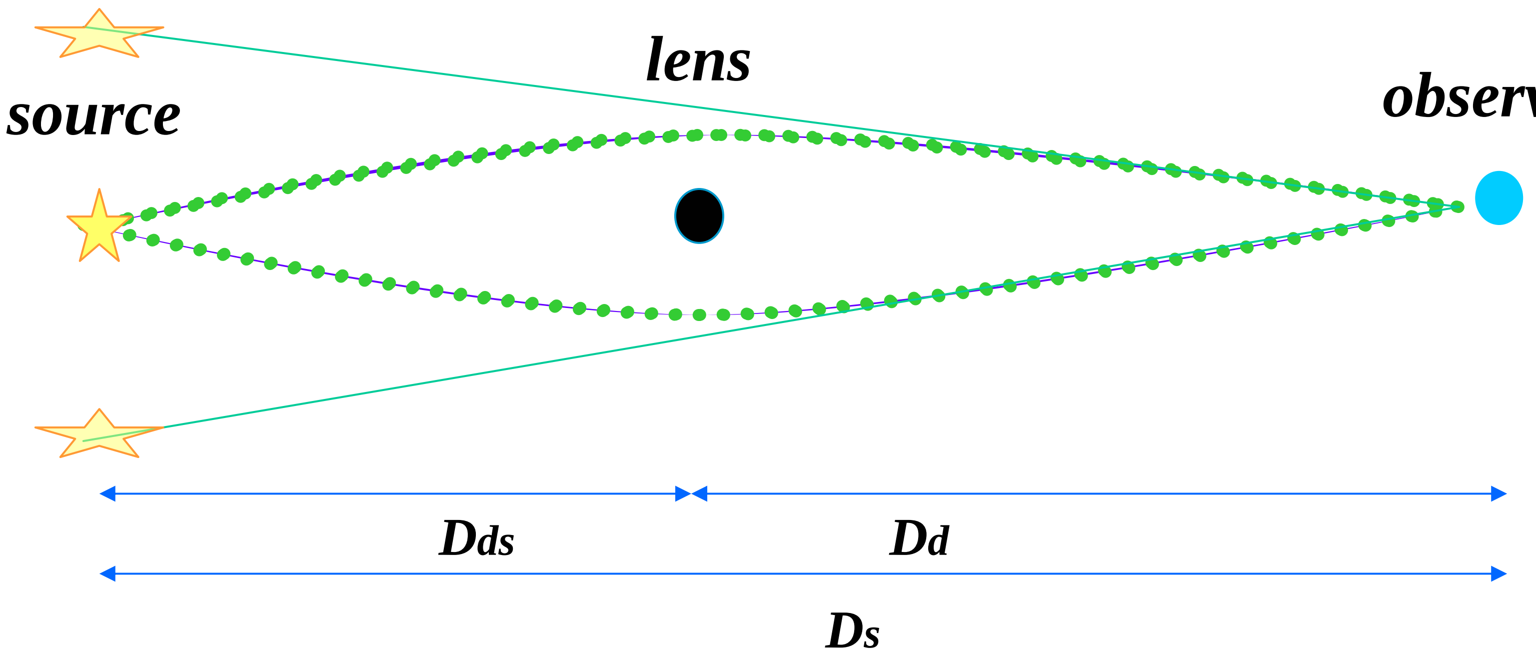
Binary microlensing events → planets

- Gravitational microlensing: searching the short perturbation due to a planet orbiting the lensing star. We can think a star+planet as a special case of a binary star.



Basic Microlensing

- A depends on u_{min}
- T depends on D, M, and Vt



Basic Microlensing

- **Light curve amplification** $$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$

  with $$u^2(t) = u_{min}^2 + [2(t - t_{max})/\hat{t}]^2$$

- **Einstein radius** $$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}}$$

- **Timescale** $$\hat{t} = 2R_E/v_{tg}$$

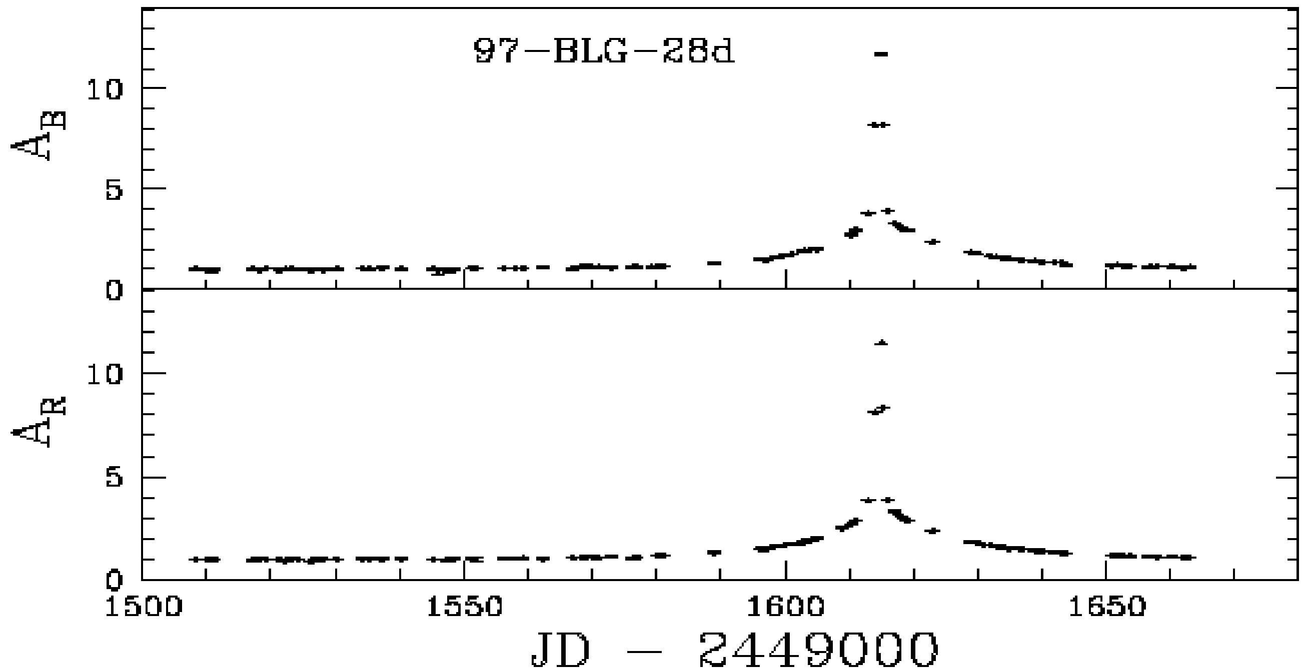
- **Impact parameter** $$u_{min} = \sqrt{-2 + \frac{2A_{max}}{\sqrt{A_{max}^2 - 1}}}$$

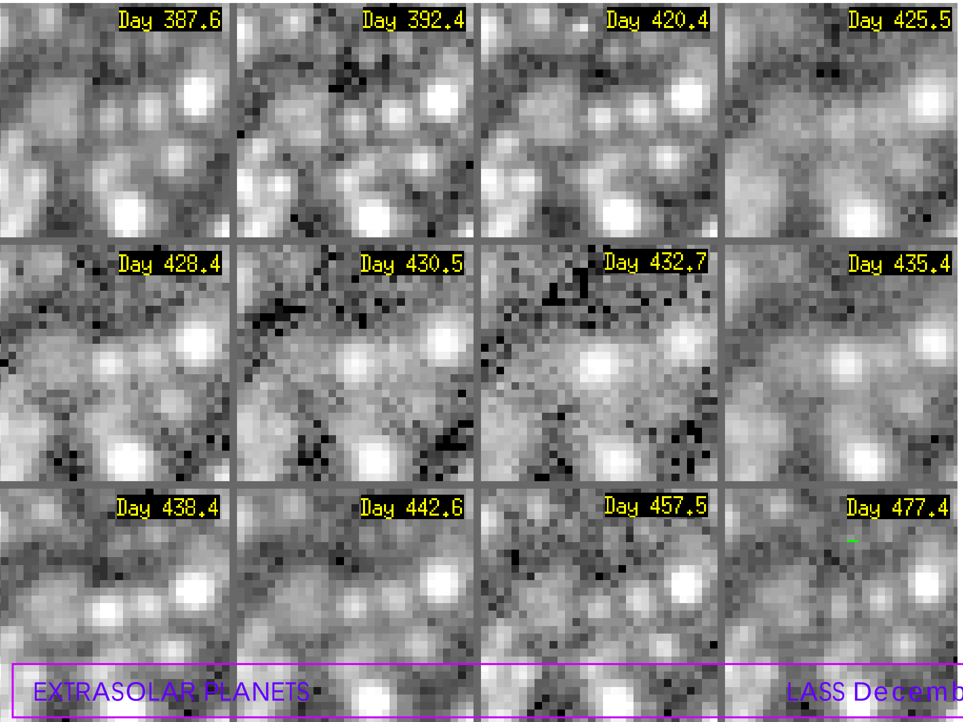
Basic Microlensing

- We would like to know
  1. the lens mass
  2. the lens/source distance
  3. the relative velocities
- The observables are:
  1. Timescale (Einstein radius crossing time)
  2. Amplitude of the light curve
- Degeneracy: only one relevant observable for three physical parameters
- The main problem is:

  Extremely rare: typically 1 event per million stars

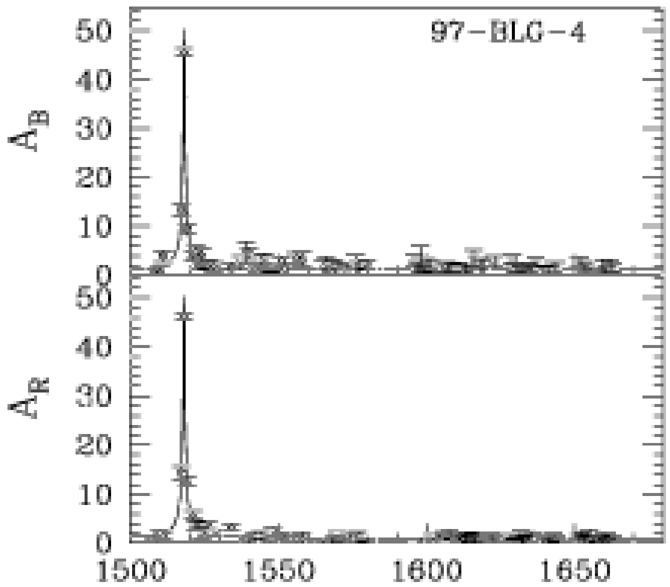
Photometric Effects

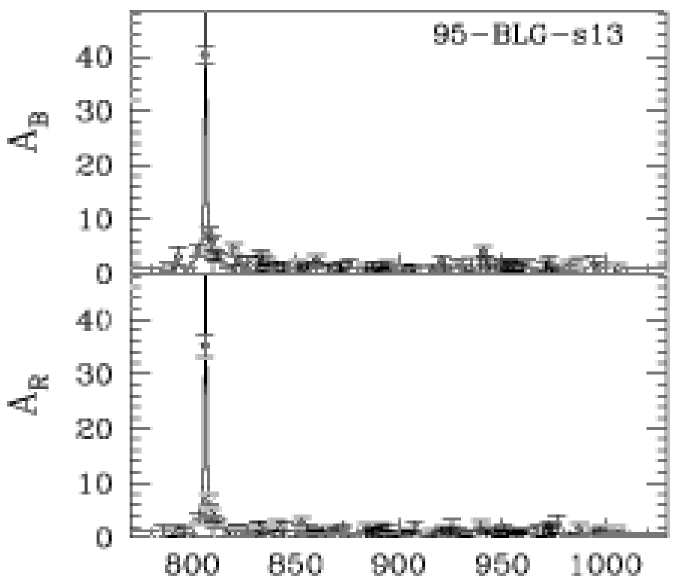




- Dramatic and easily recognized effect:
  - characteristic light curve
  - non repeatable
  - achromatic

Bulge Microlensing





Alcock et al. 1999

- **Towards the MW bulge**

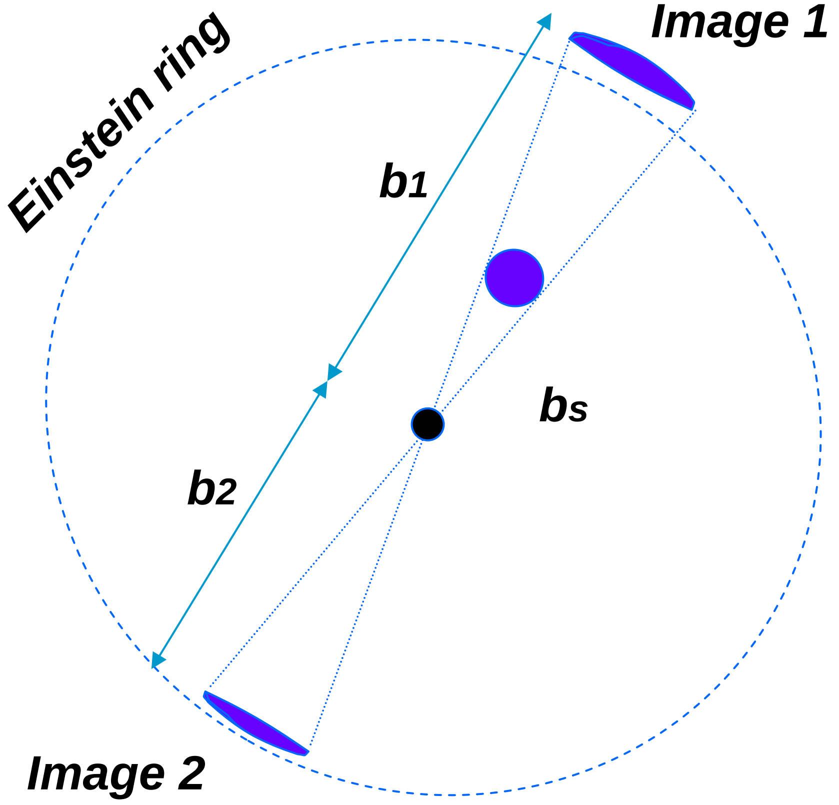
  $t = 40\ (M/M_o)^{1/2}$ days

OBJECT	*TIMESCALE*
Sun	*40 days*
Jupiter	*1 day*
Earth	*1 hour*

- **Einstein radius**

  $R_E = 3\ (M/M_o)^{1/2}$ AU

Basic Microlensing



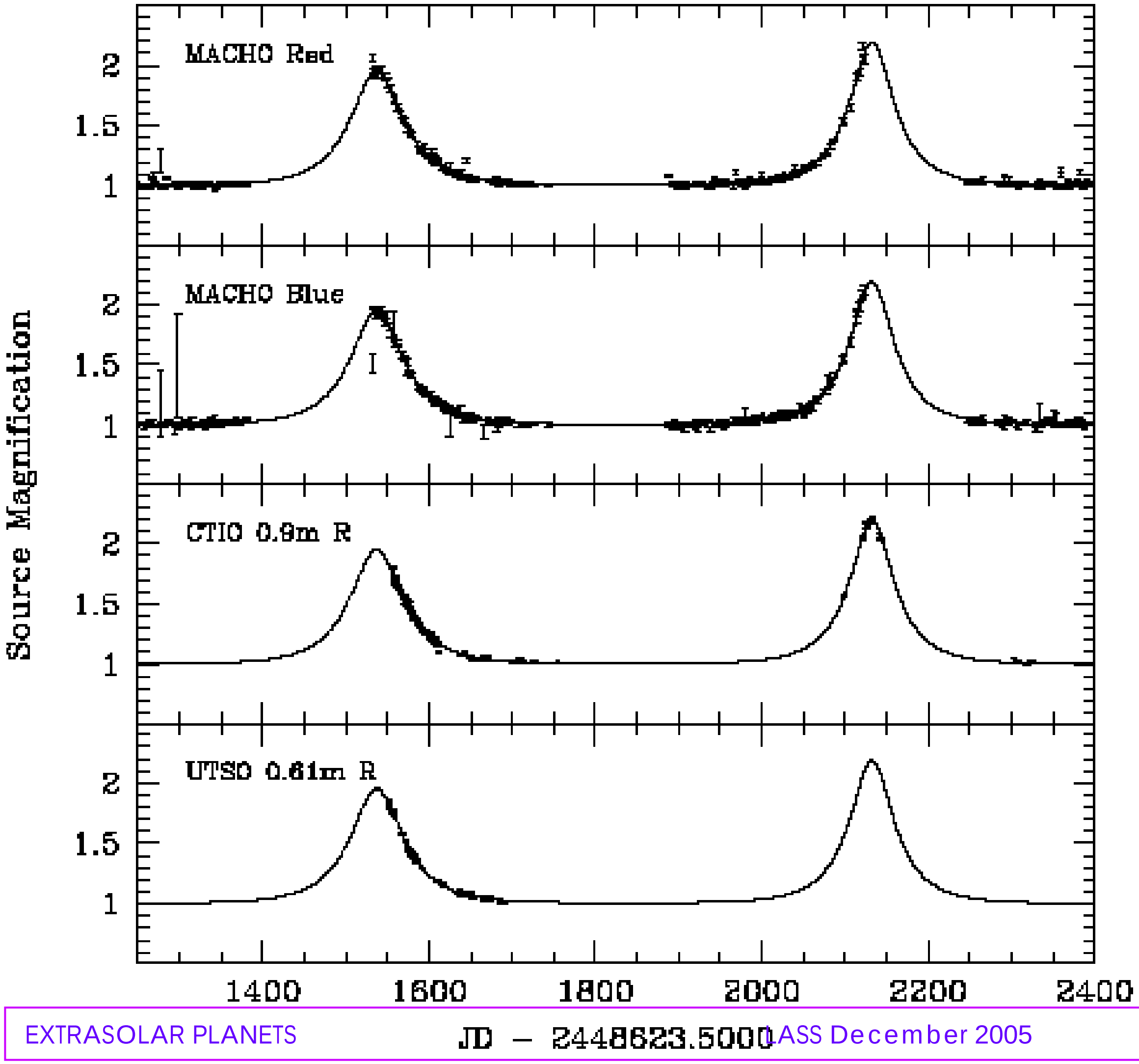
In the plane of the sky there are 2 stretched images of the source: one outside and one inside the Einstein ring.

Similar to gravitational lensing images of clusters of galaxies.

Binary Microlensing Events

- About ½ of all stars are in binaries, expect relatively high frequency of binary events
- Microlensing searches are not designed to look for binary events, but have detected more than 50 so far
- Binary events exhibit a wide variety of light curves
- They potentially provide with additional information ("proper motion" determinations) in order to break the degeneracy and estimate distances/masses
- However, extra parameters are needed to fit the light curves

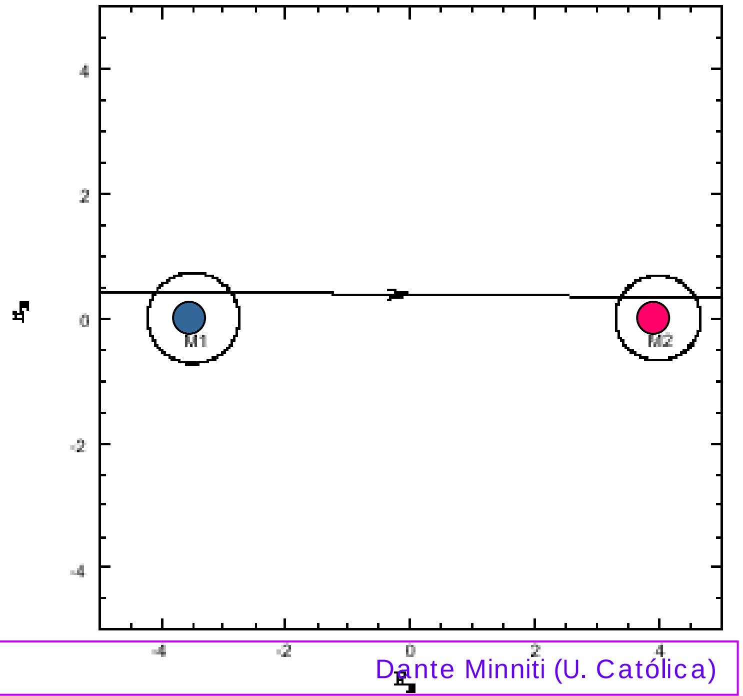
Binary events



96 BULGE 4:

Binary source with

a >> $R_{E1}+R_{E2}$



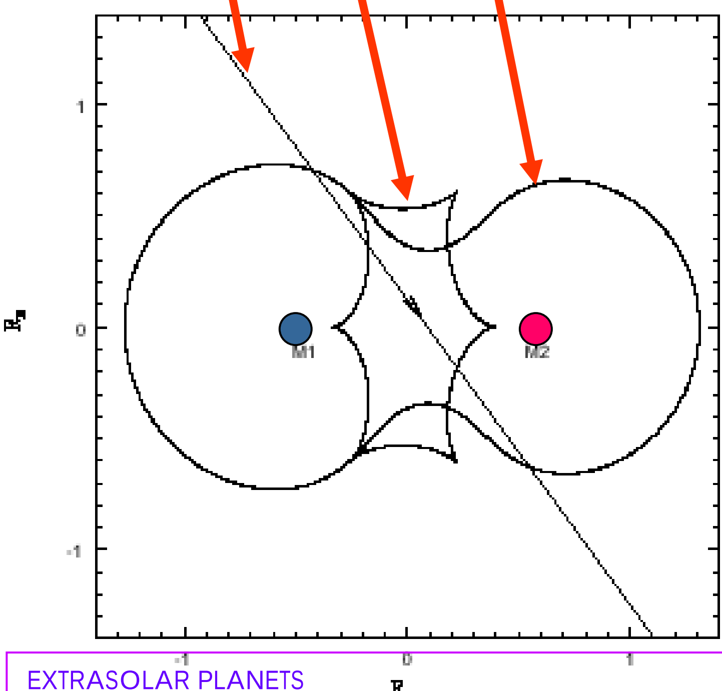
Binary events

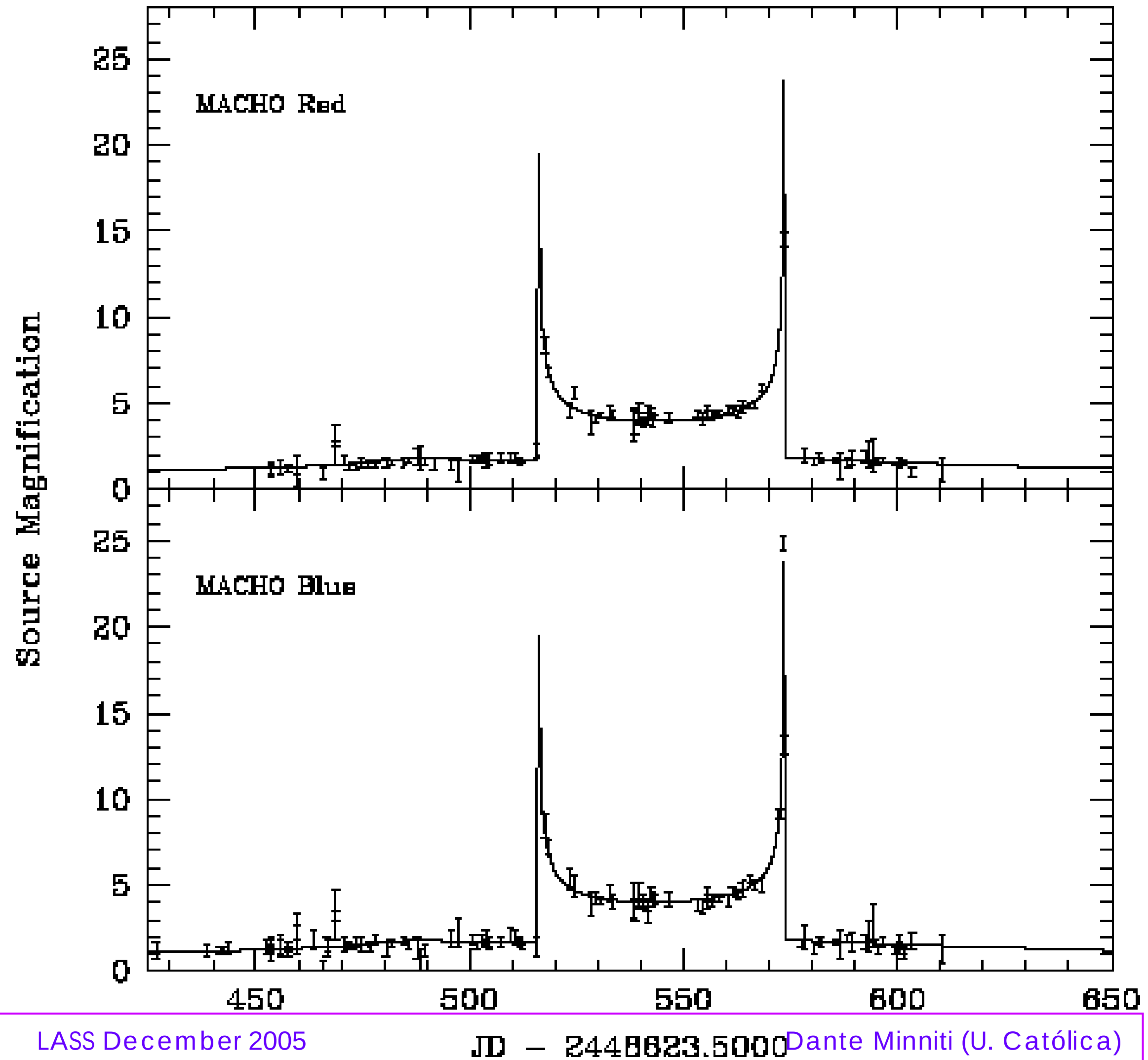
MACHO 119 A

source trajectory

caustic curve

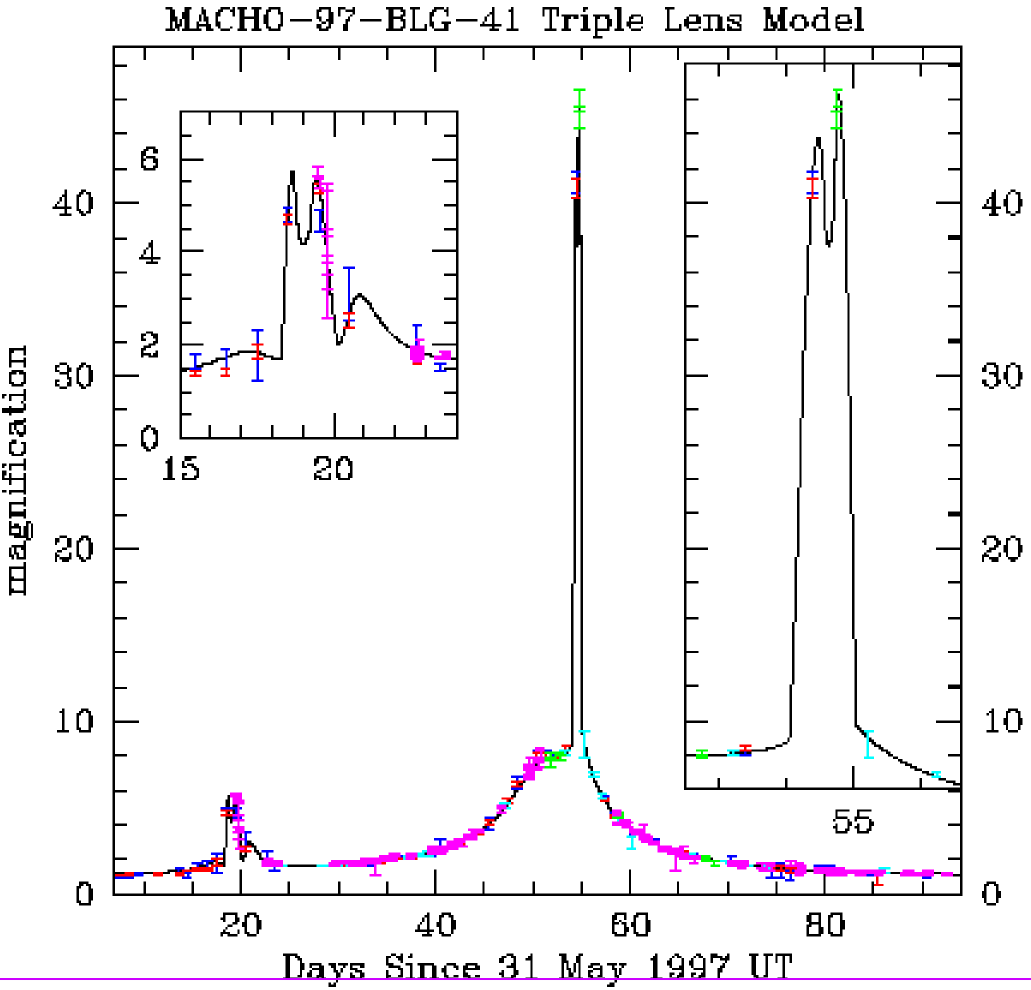
critical curve





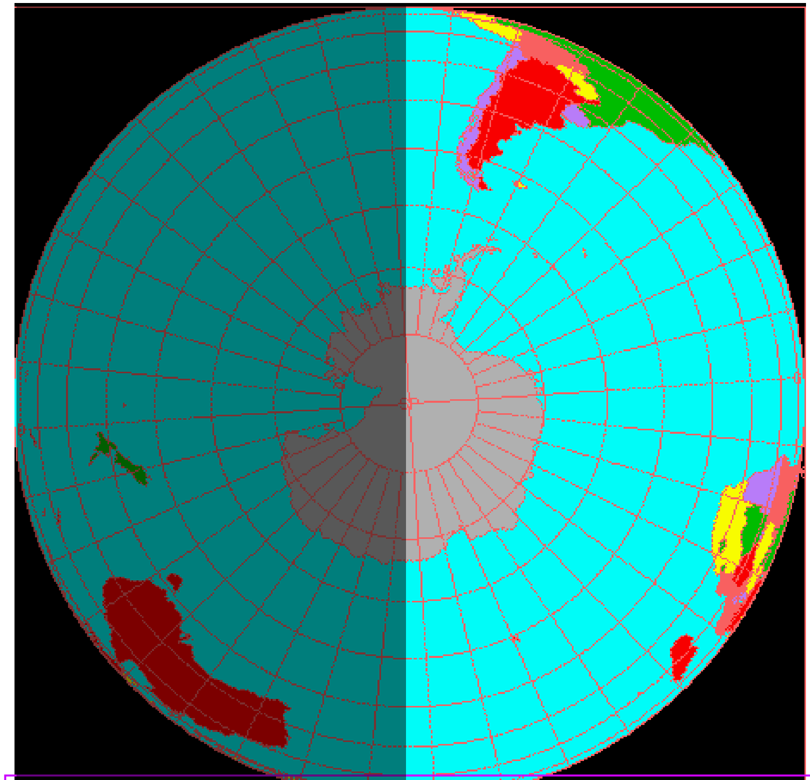
Binary events: Planets

- 97 BULGE 41
  (Bennett *et al* 1999)
- Two possible fits:
  - A triple lens with a planet
  - A rotating binary system



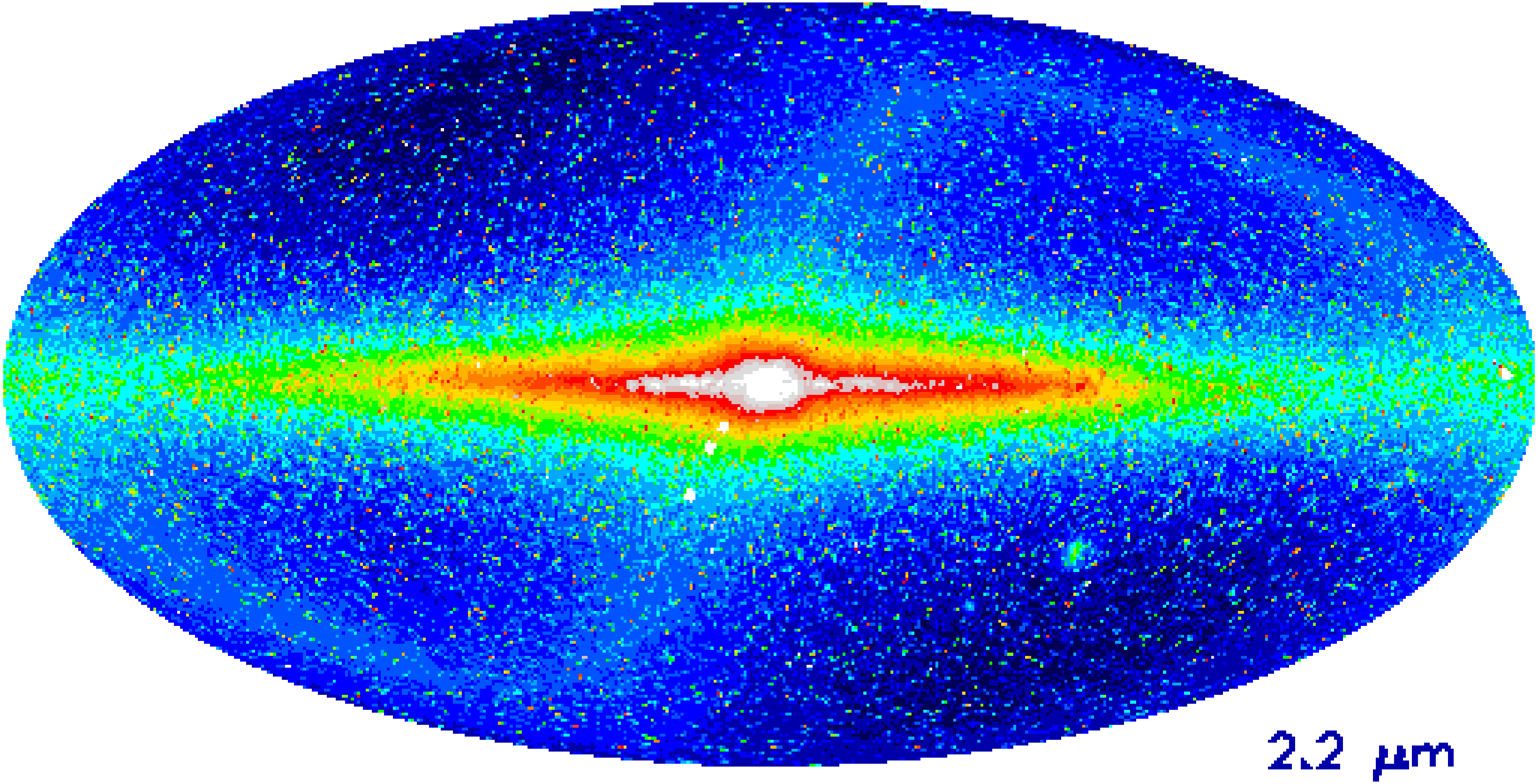
Microlensing Towards the Galactic Bulge

Gravitational microlensing is the best way to detect distant Earth-mass planets.



- The Galactic bulge requires observations from the Southern hemisphere.
- Round the world monitoring.
- Network of small telescopes (1-m class).
- Accurate and frequent photometry needed.

Microlensing Towards the Galactic Bulge

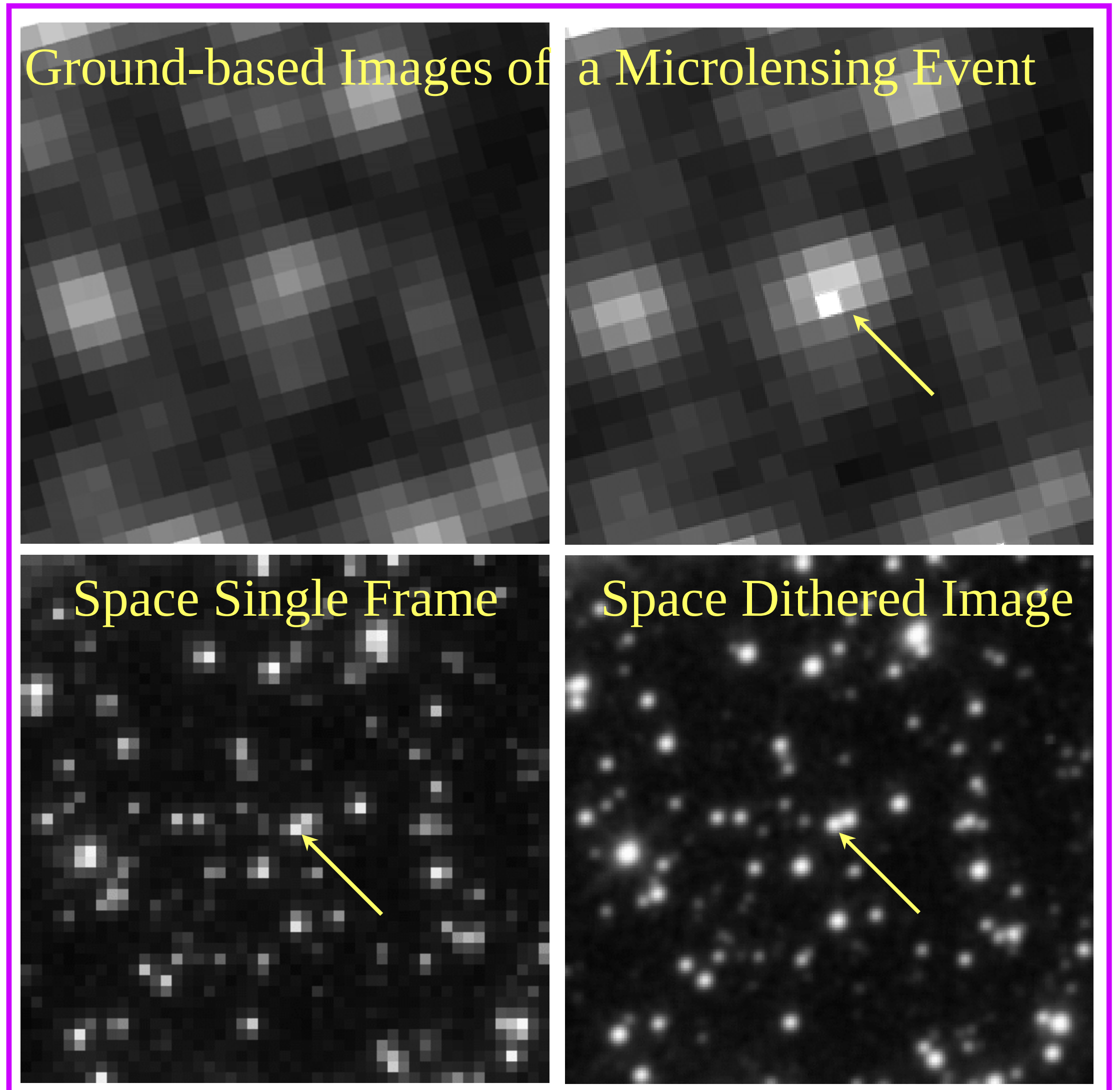


Main Sequence source stars needed for terrestrial planets.
High density of source and lens stars is required.
Microlensing rates are higher towards the Galactic bulge.

Microlensing Towards the Galactic Bulge

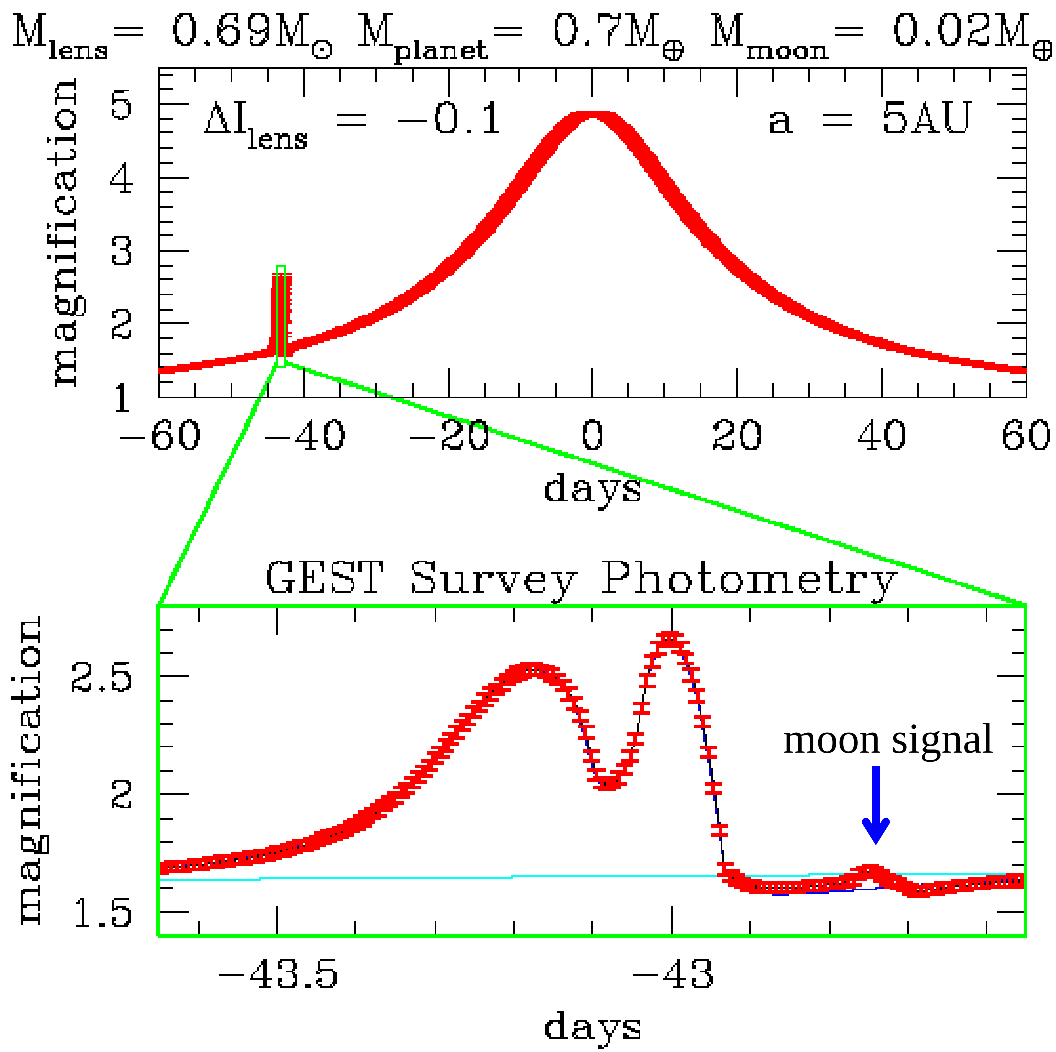
Microlensing From the Ground vs. Space

- Target main sequence stars are not resolved from the ground.
- Poor photometry for unresolved stars, except for the very high magnification events.
- Poor light curve coverage.
- Ground surveys can only find events with separation a ≈ R_E
- From space, continuous observations are possible (MPF).



Simulated Planetary Light Curves

- Planetary signals can be very strong
- There are a variety of light curve features to indicate the planetary mass ratio and separation
- High S/N detections are typical
- Exposures every 10-15 minutes, from space.



Bennett & Rhie 2000

Microlensing

$\left\{ \begin{array}{l} M_p \\ a \end{array} \right.$

- Incompleteness:
  - Large → few extrasolar planet detections so far.
  - Difficult to confirm.
  - Difficult to characterize the lens (the primary star).

- Results till Dec 2005:

  Three microlensing planets.

Extrasolar Planets

- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

Pulsar Timing

$\left\{ \begin{array}{l} M_p \\ P \\ i,\ e \end{array} \right.$

- Incompleteness:
  - Largely unknown → few detections so far.
- Results till Dec 2004:

  Two pulsars with planets.

Planet data							MORE DATA >>
PLANET	M[.sin*I*] (M_{JUP})	PERIOD (days)	SEM-MAJ AXIS (AU)	ECC.	INCL. (deg)	STATUS	UPDATE
PSR 1257+12 b	6.2926366797e-05	25.262	0.19	0	-	R	19/08/05
c	0.013529168861	66.5419	0.36	0.0186	53	R	19/08/05
d	0.012270641525	98.2114	0.46	0.0252	47	R	19/08/05
PSR B1620-26 b	2.5	100 y.	23	-	55	R	13/04/05

Pulsar planets

3 low mass planets in circular orbits were discovered in PSR 1257+12, (Wolszczan & Frail 1992,1994, Konacki & Wolszczan 2003)

Another planet with 2.6M_J in PSR B1260-26 of the globular cluster M4

>10 yrs later: the 4th planet of PSR 1257+12 with 1/5 Pluto's mass announced (Wolszczan & Konacki 2005)

Questions not answered:

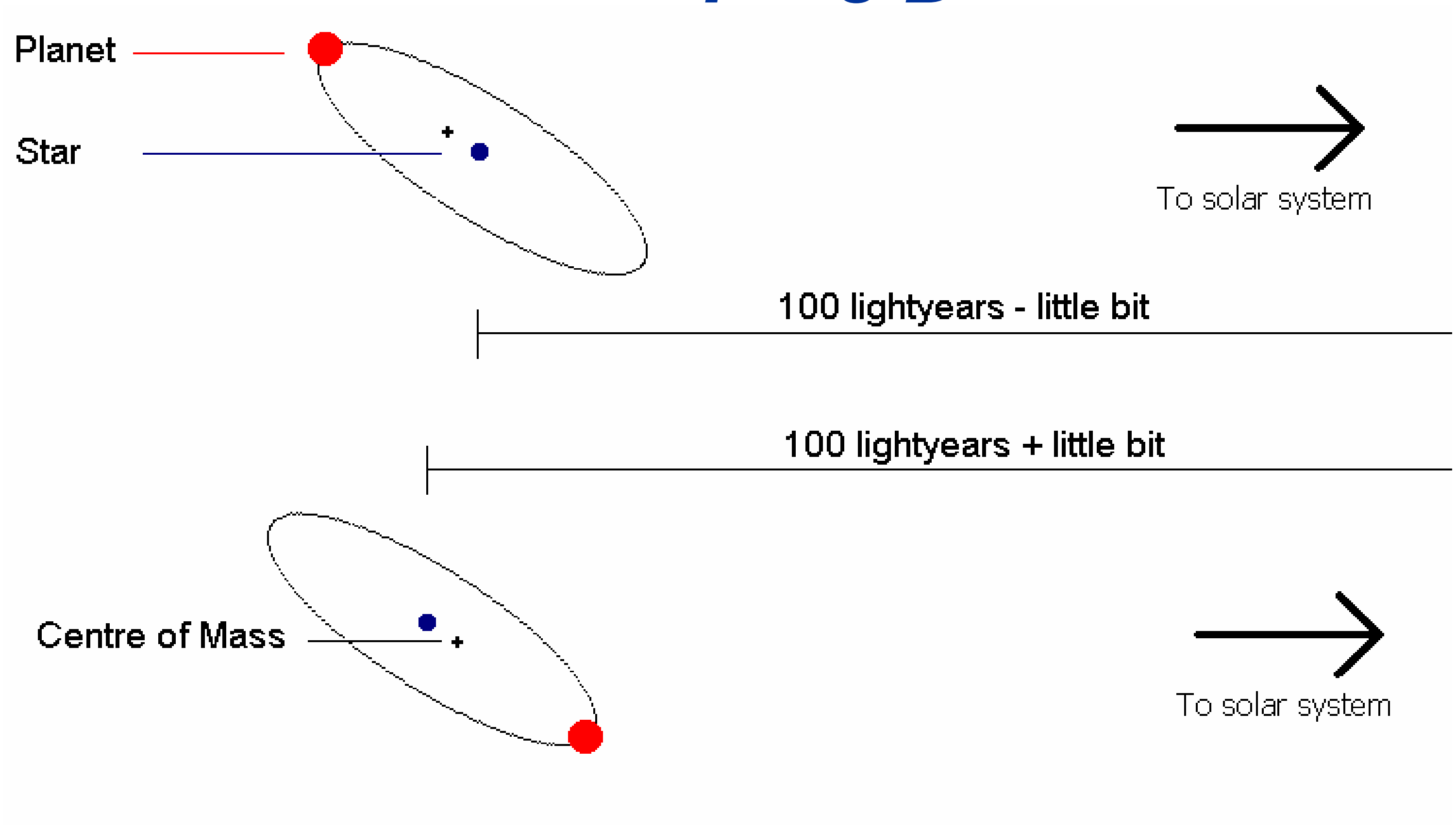
How do they form?

How did they survive?

How common are these systems?

Timing technique

$$T = c\,D$$



- Planets around pulsars
- Planets around WDs

Timing technique

T = c D

Velocity corrections $\Delta V=(V_S-V_{obs})$: log($T_{[sec]}$)

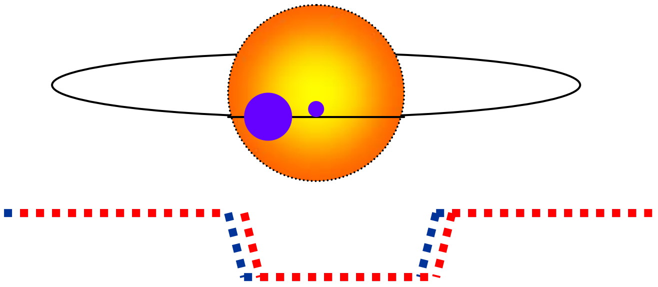
→ Earth's rotation	460m/s sinϕ, P=1d	-2
→ Earth-Moon Barycenter	13m/s, P=1m	-2
→ Earth's orbit	30km/s (+/-1km/s), P=1yr	3 (+/-1)
→ Sun-Jupiter barycenter	13m/s, P=12yr	0
→ -- Saturn barycenter	3m/s, P=29yr	0
→ -- Uranus barycenter	13m/s, P=84yr	-1
→ -- Neptune barycenter	13m/s, P=165yr	-1
→ ... Venus, precession, nutation, Mars, Ceres, Mercury, Pluto, etc.		<-2

RVCOR in IRAF, +/-5m/s, no planetary corrections,
BCVCOR SAO Telescope Data Center, +/-42cm/s

Timing technique

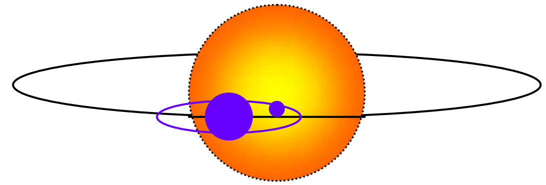
$$T = c\,D$$

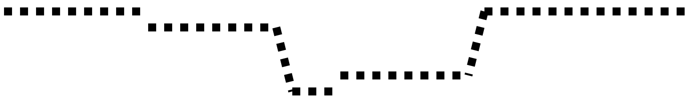
- Transit timing: search for satellites (Doyle & Deeg 2003)
- Even if satellite transits are not observed, tangential distance differences due to motion of the planet around barycenter P-S induce variations in mean transit times.



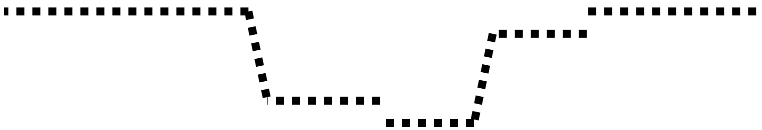
- Earth- Moon system: dt ~ 3 min
- Saturn-Titan system: dt ~ 30 sec

Transits of a single planet with moon(s)

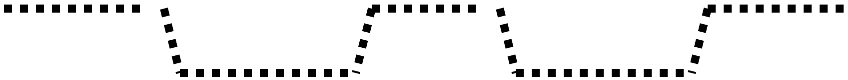


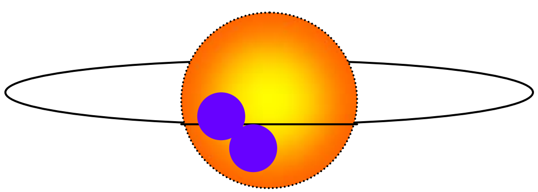


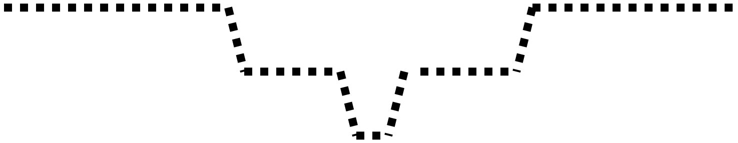
Many different possible shapes



or a binary planet





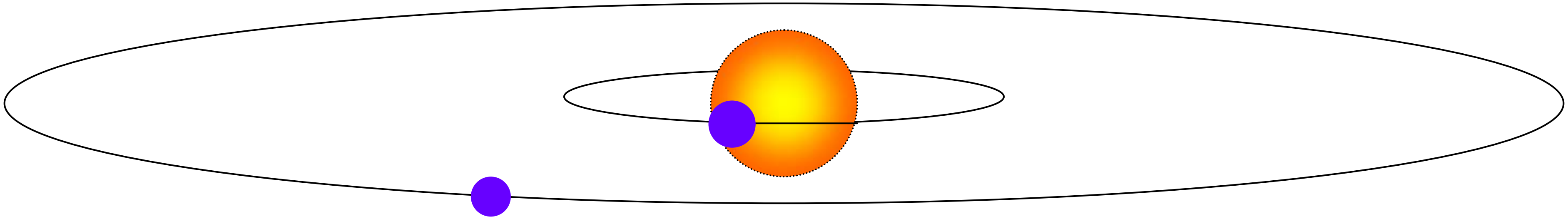


Sartoretti & Schneider 1999, Barnes & O'Brien 2002

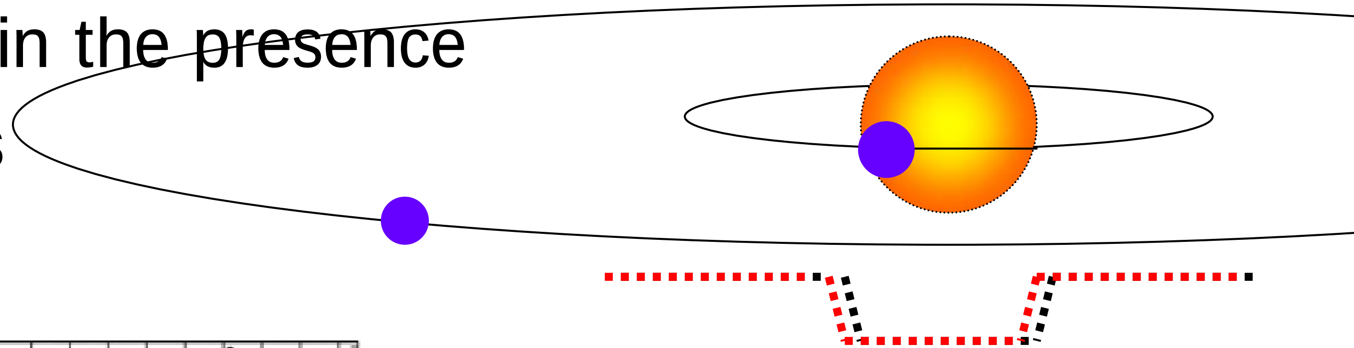
Timing technique

$$T = c\,D$$

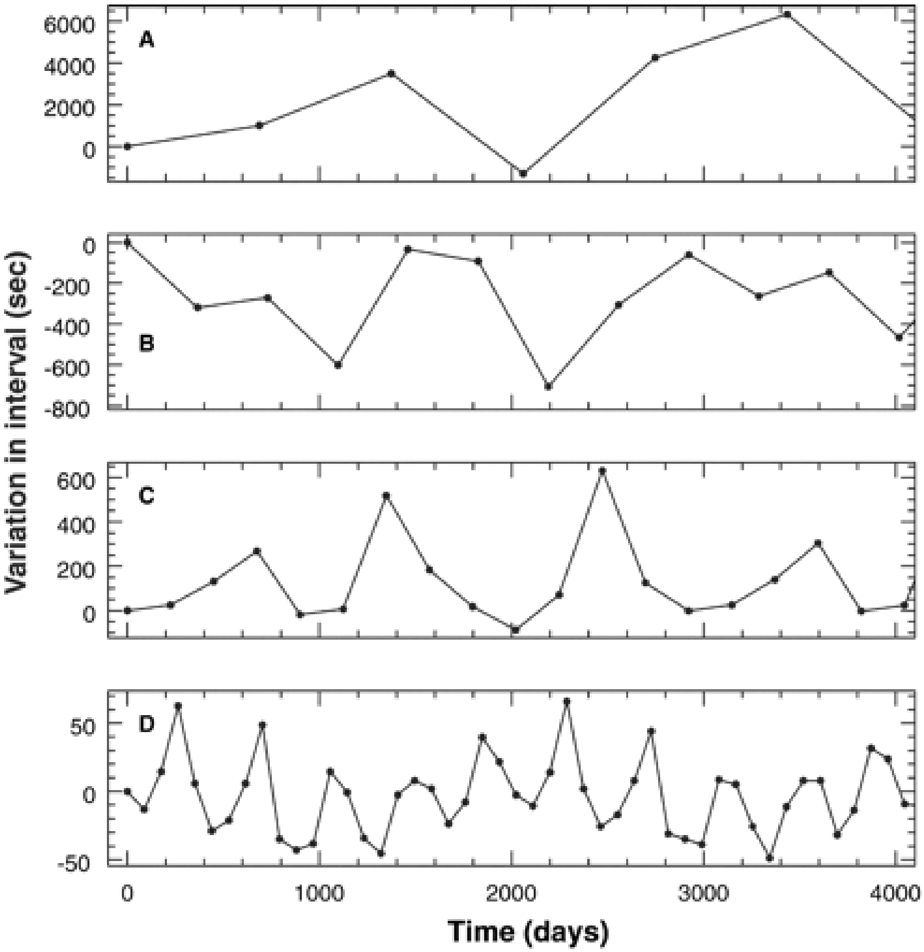
- Transit timing: method to search for additional planets (Miralda-Escudé 2002, Holman & Murray 2005, Agol et al. 2005)
- Even if additional planets are not observed, tangential distance differences due to motion of the star around the barycenter of the system induce variations in mean transit times of the inner planet.



Timing transits in the presence of other planets



Holman & Murray 2005

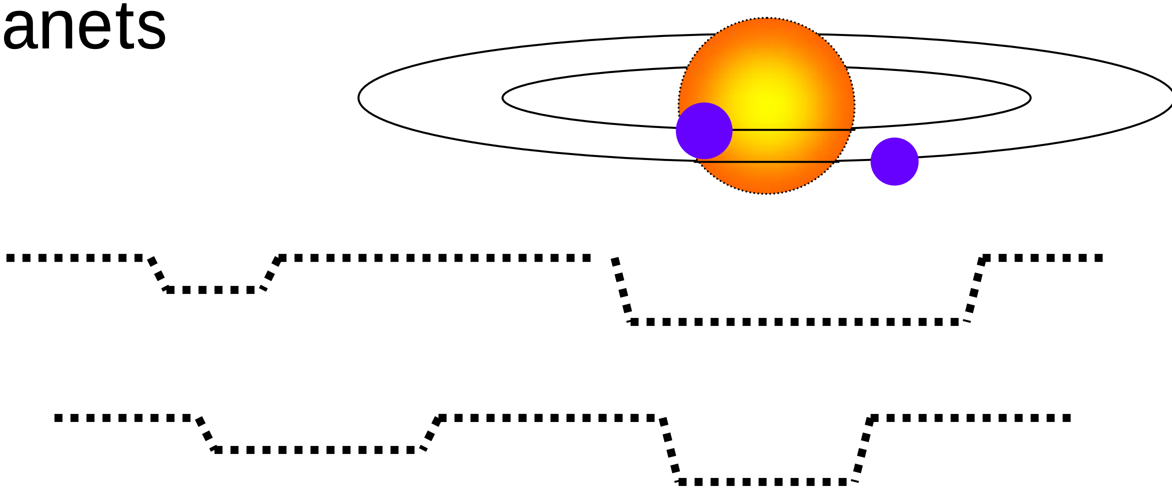


Example of the Solar System:

- →Mars transits: dt ~ 2 hr
- →Earth transits: dt ~ 10 min
- →Venus transits: dt ~ 10 min
- →Mercury transits: dt ~ 100 sec

Difficult to measure for planets at 1AU because total the transit time is 13 hr. May be detectable in hot planets.

Transits of multiple planets



Many different possible durations and depths

Small but non negligible probability of multiple transits.

Search for resonant systems.

Caveat: some may be discarded as binary systems.

Resonances

18 multiple planetary systems known (4 triple planet systems).

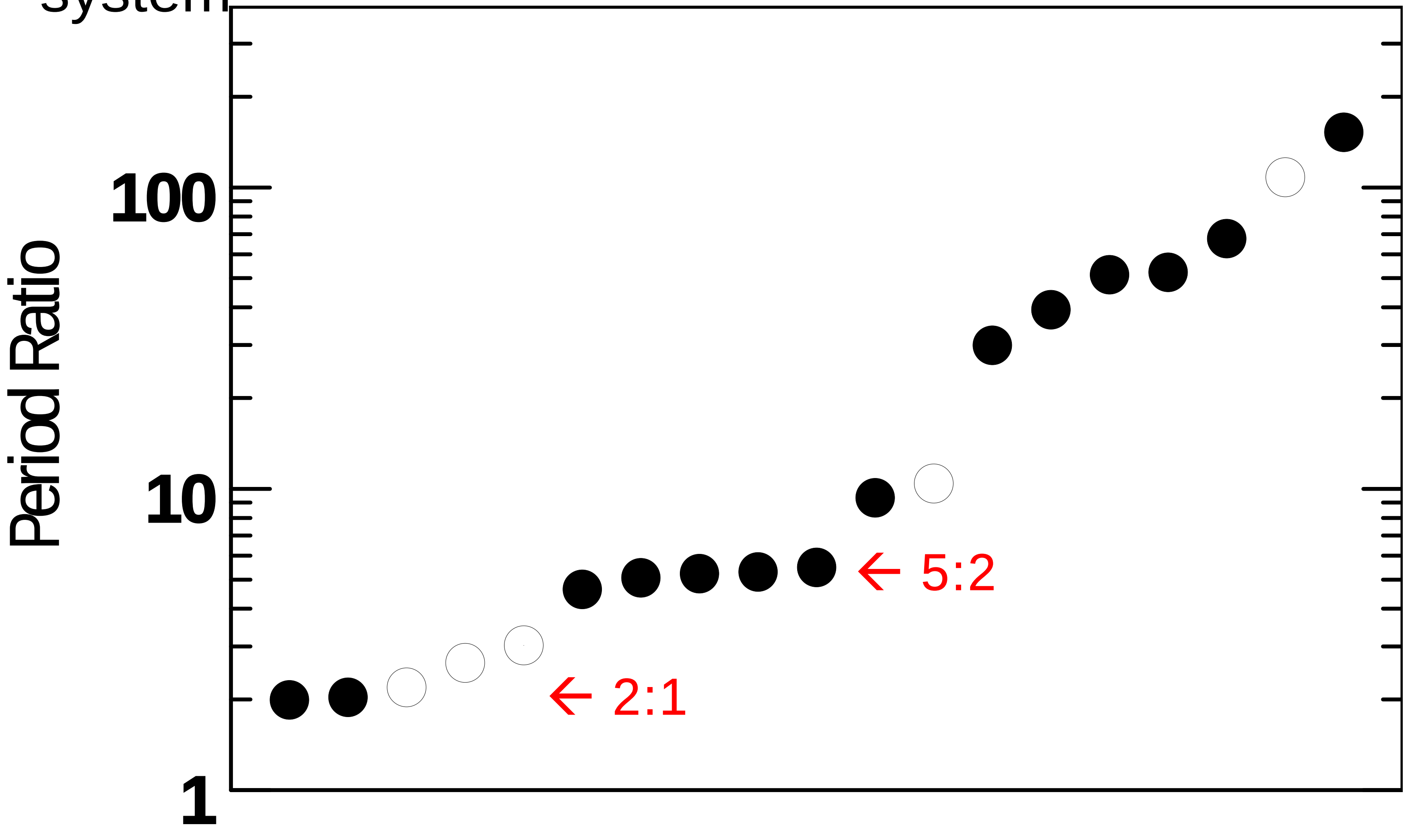
Resonances are very common in the Solar System:

- asteroids
- outer planets
- moons of Jovian planets

Laughlin, et al. 2001
Lee & Peale 2002
Mayor, et al. 2004
Vogt, et al. 2005

Three planets in *2:1* mean motion resonance

Period ratio of consecutive planets in a system



see Ferraz-Mello et al. (2005)

Extrasolar Planets

- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

Direct detections

- *Color*
- *A*
- T_p

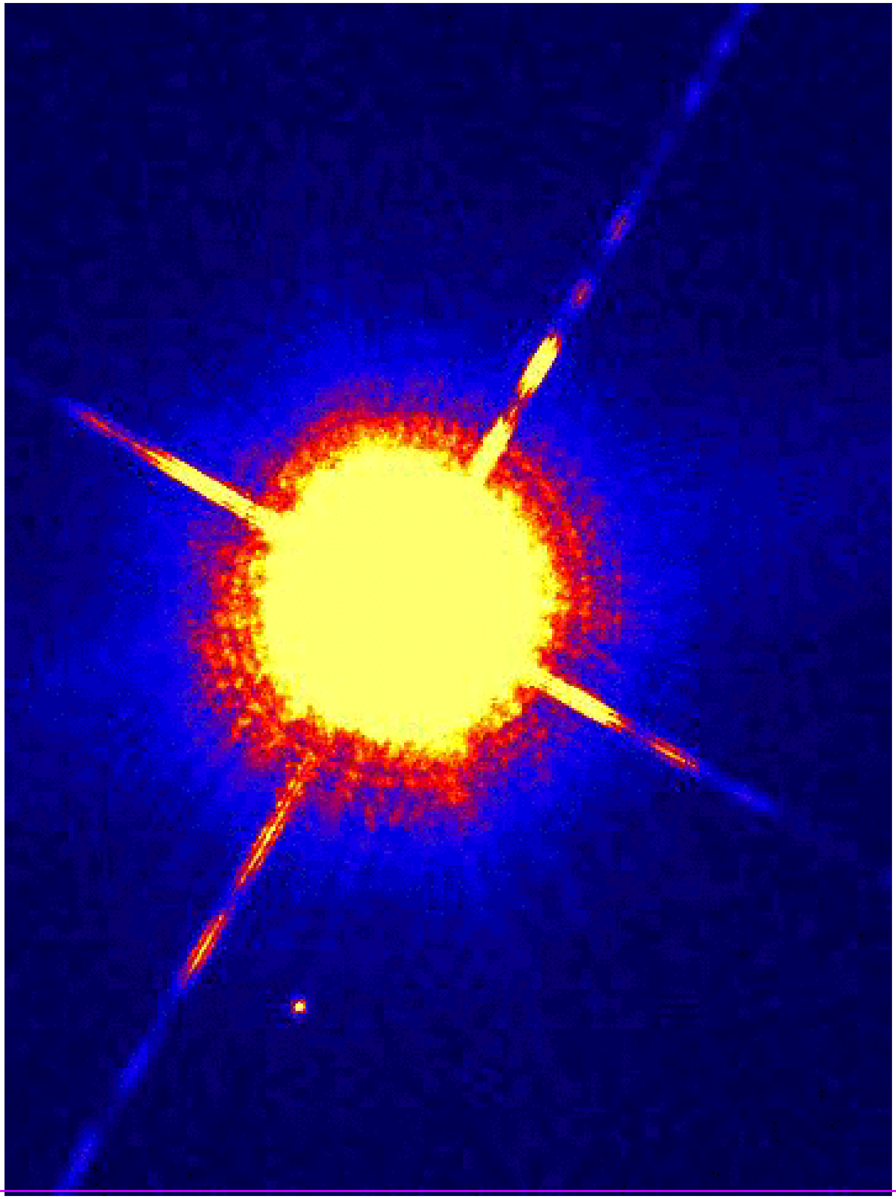
- Incompleteness:
  - Large → few direct extrasolar planet detection so far.

- Results till Dec 2005:

Planet data								MORE DATA >>
PLANET	M[.sin*I*] (M_{JUP})	PERIOD (days)	*-PLANET DIST. (PROJ.) (AU)	ECC.	INCL. (deg)	STATUS	UPDATE
2M1207 b	5	-	55	-	-	R	23/09/05
GQ Lup b	21.5	-	103	-	-	R	23/09/05
AB Pic b	13.5	-	275	-	-	R	23/09/05

Direct detections

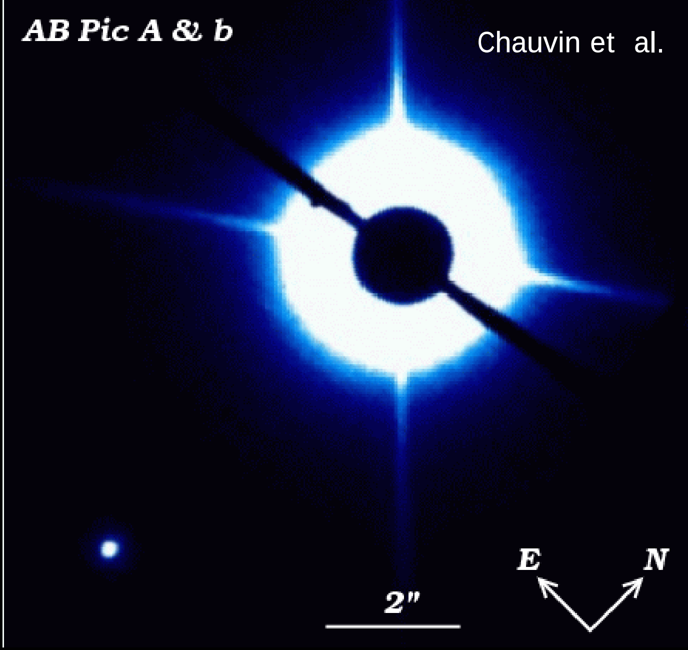
- Direct detections of extrasolar planets are very difficult, almost impossible.
- We can barely detect brown dwarf companions such as Gliese220b (Nakajima et al. 2005).
- Free floating young planets could be detected in the IR before they cool down (e.g. SOri70 Zapatero-Osorio et al. 2003).
- Always need proper motion confirmations.

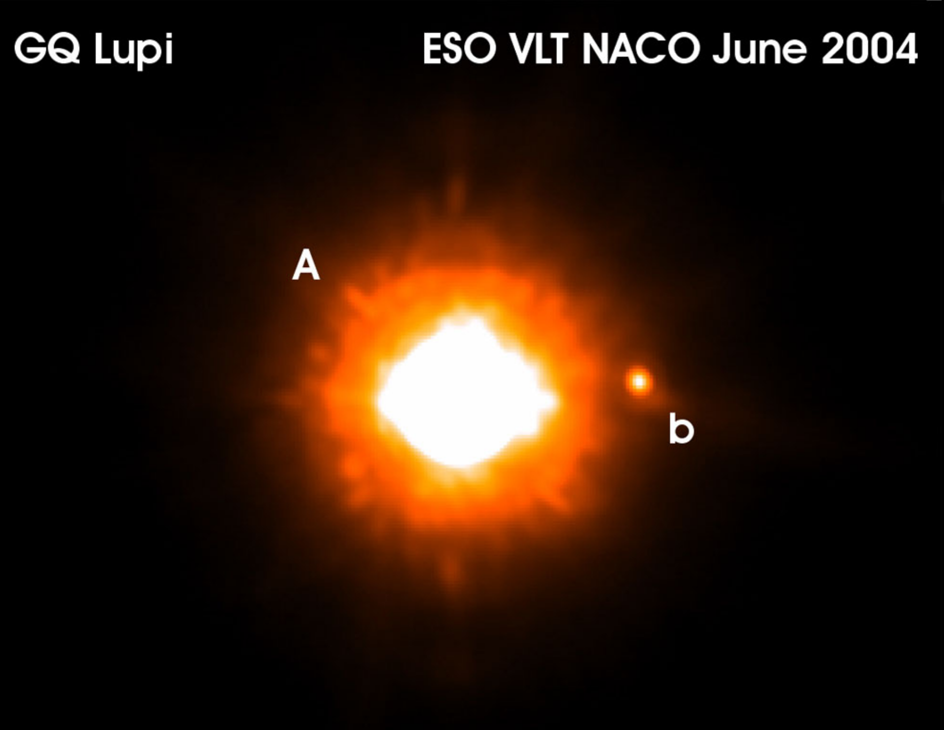


G229B

Direct detections

Many programs searching for faint companions to nearby stars.

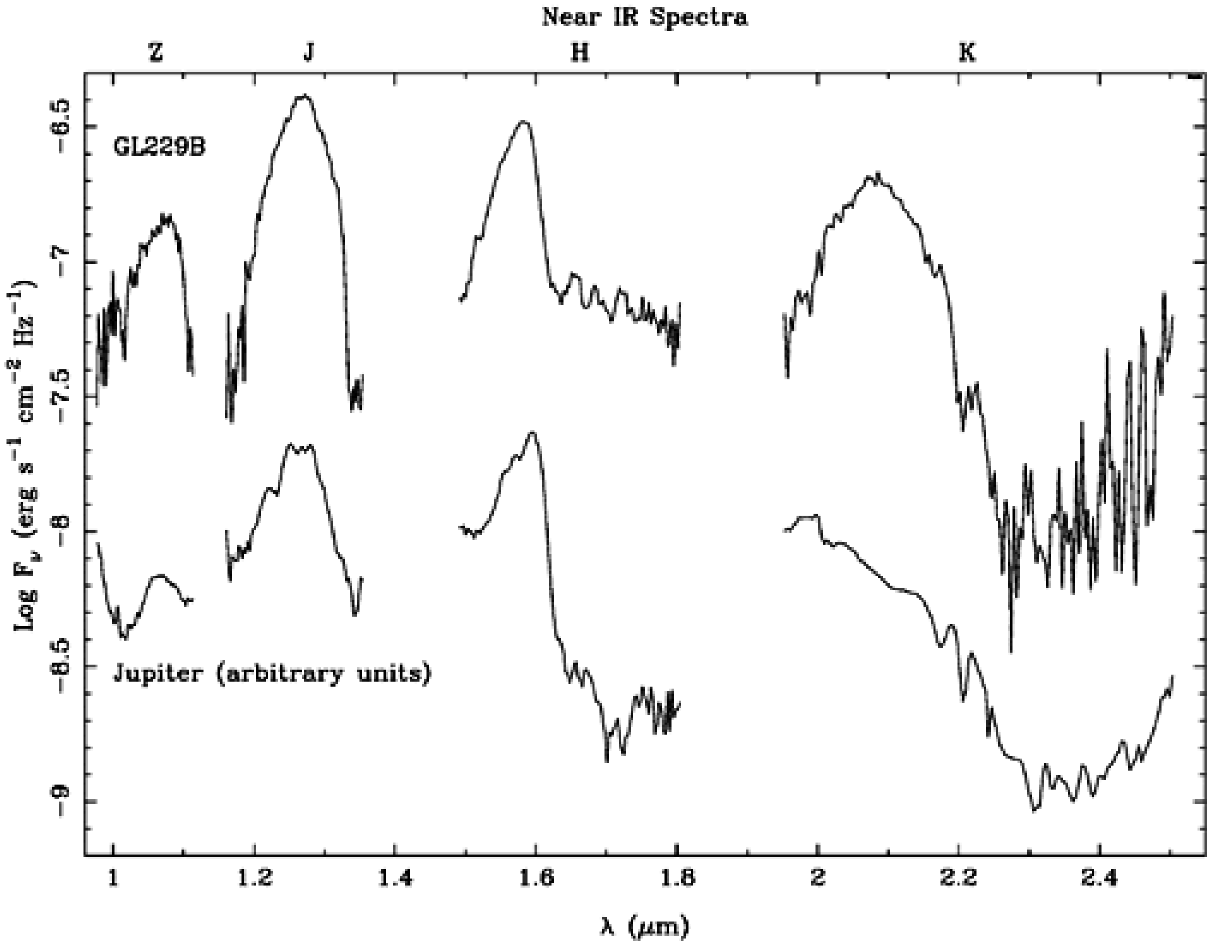




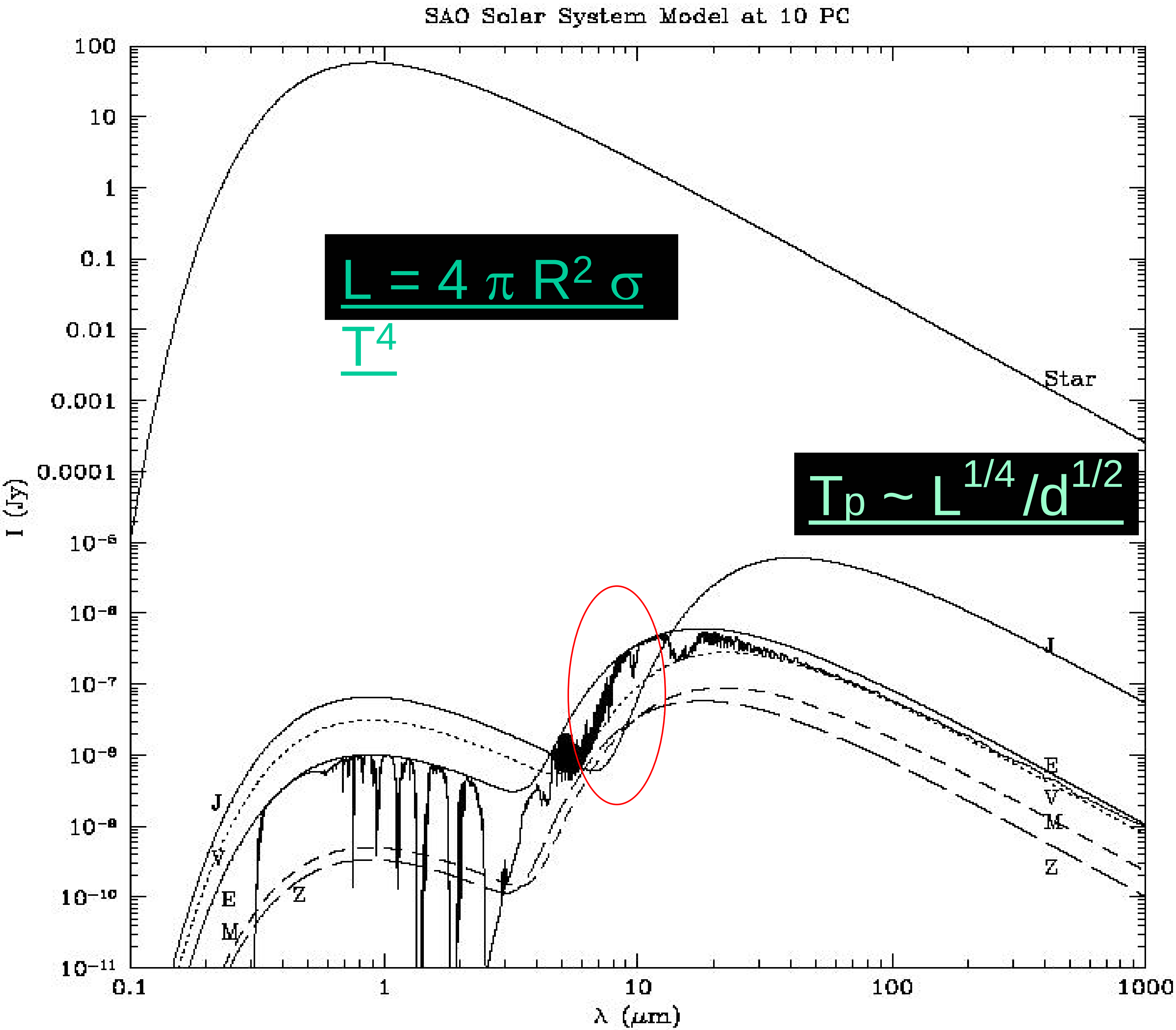
Neuhäuser, Guenther, Wuchterl, Mugrauer, Bedalov, Hauschildt

Chauvin, Lagrange, Dumas, Zuckerman, Moulliet, Song, Beauzit, Lowran

Direct detections



Near-IR spectrum of GL229B (top) and Jupiter (bottom).

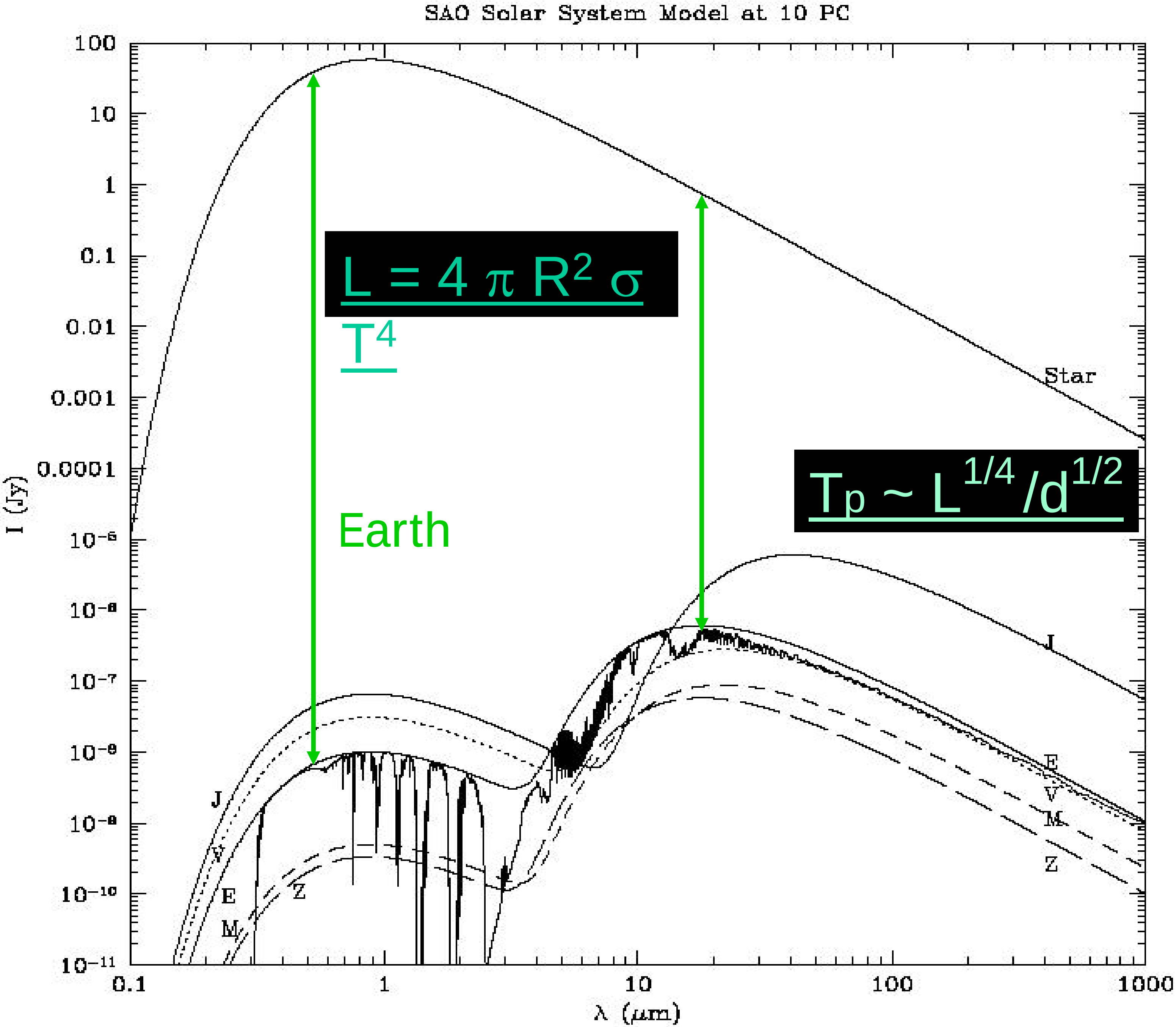


$L = 4 \pi R^2 \sigma T^4$

$T_p \sim L^{1/4} / d^{1/2}$

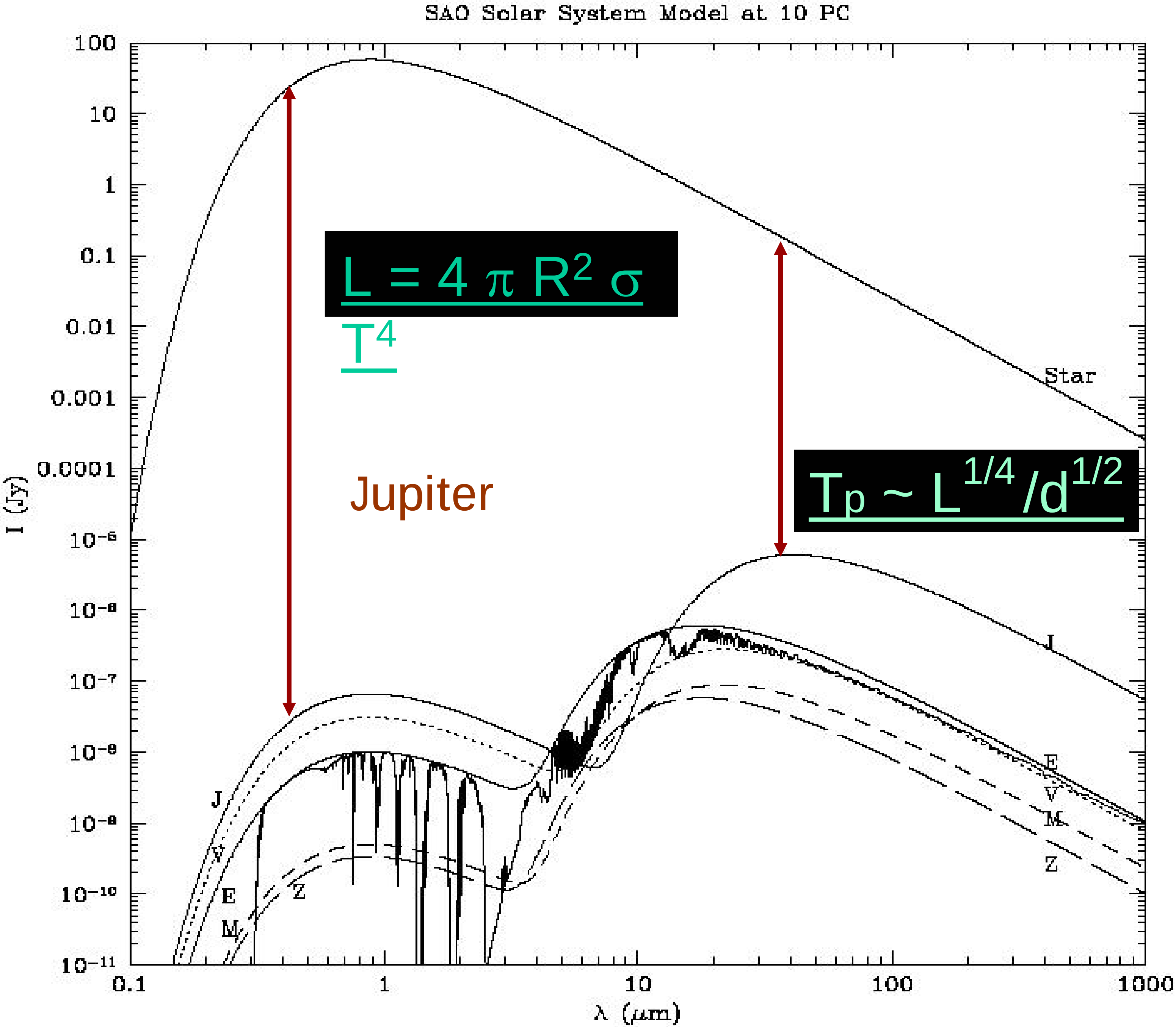
Direct planet detection

The Solar System at 10pc



Direct planet detection

The Solar System at 10pc

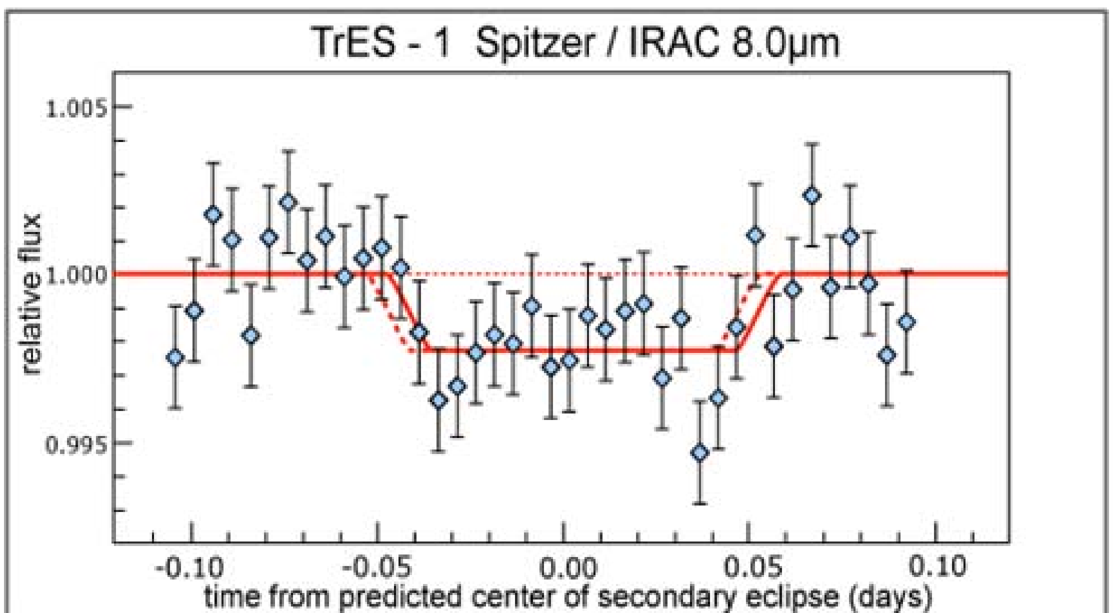


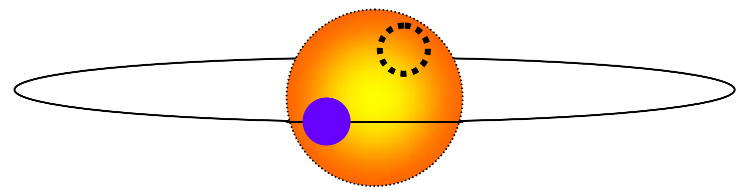
Direct planet detection

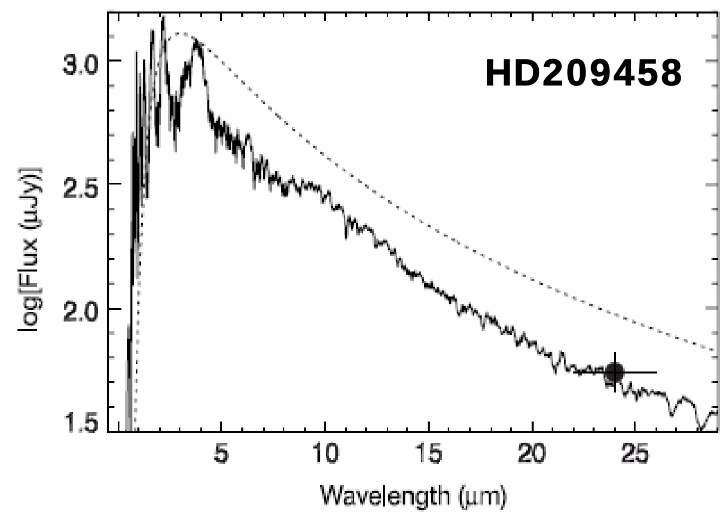
The Solar System at 10pc

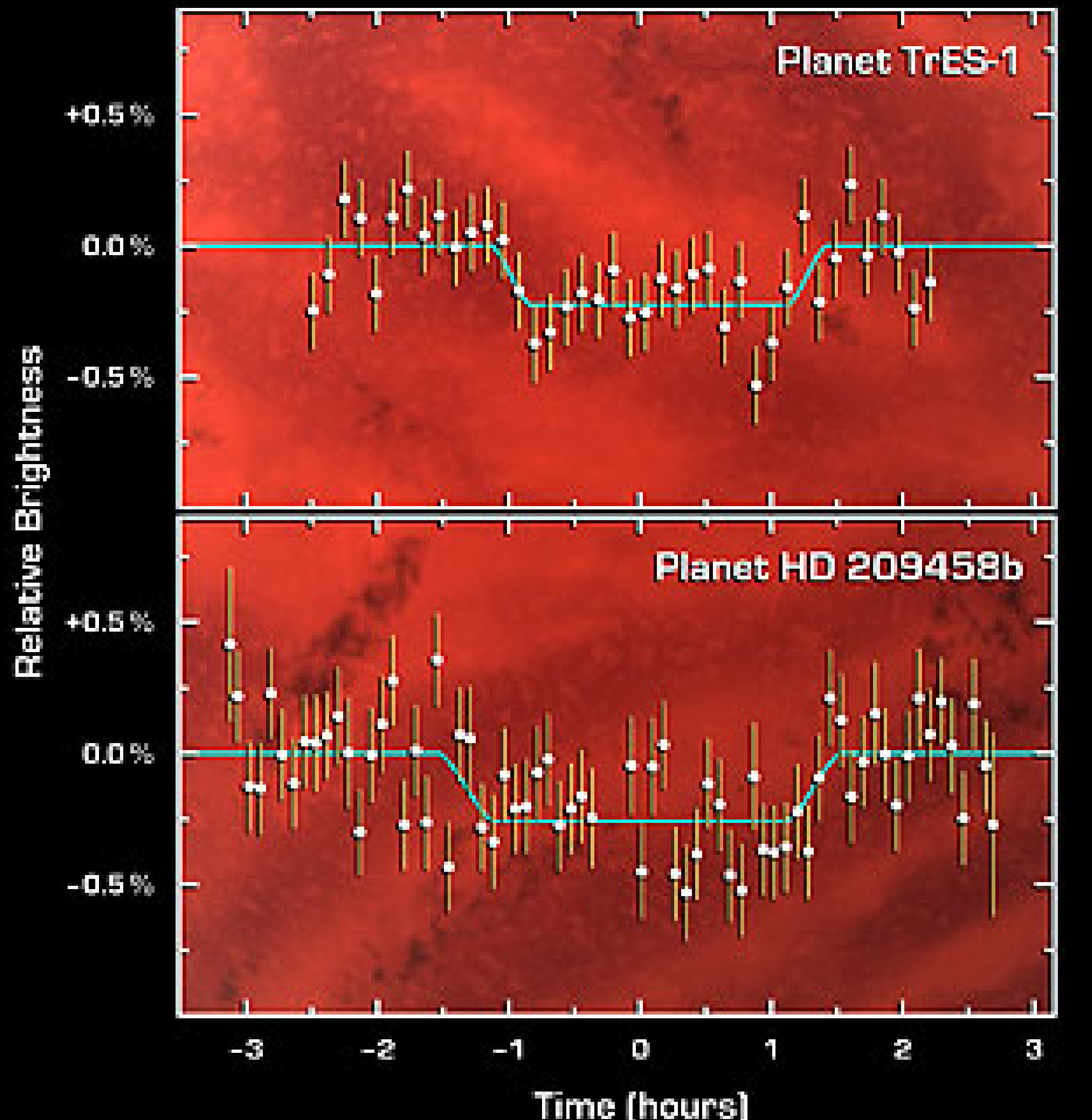
- Huge motivation to go to the IR.
- SPITZER detected secondary transits, i.e. the thermal emission of the planet passing behind the star.
- Constrain the planet temperature, size and albedo.
- HD209458 at 24μm: T=1130K (Deming et al. 2005).
- TrES1 at 8μm: T=1000K (Charbonneau et al. 2005).

$\Delta f = 0.00225 +/- 0.00036$









Planetary Eclipses Spitzer Space Telescope • IRAC • MIPS

NASA / JPL-Caltech / D. Charbonneau (Harvard-Smithsonian CfA) ssc2005-09a
D. Deming (Goddard Space Flight Center)

Reflected vs instrinsic light

Optical → reflected, attempts with VLT+UVES, HIRES+KECK, satellite MOST

Near-IR → reflected for old objects, intrinsic for young ones

Thermal-IR → intrinsic

Sub-mm → intrinsic ?

Radio → intrinsic, e.g. Jupiter's decametric radiation

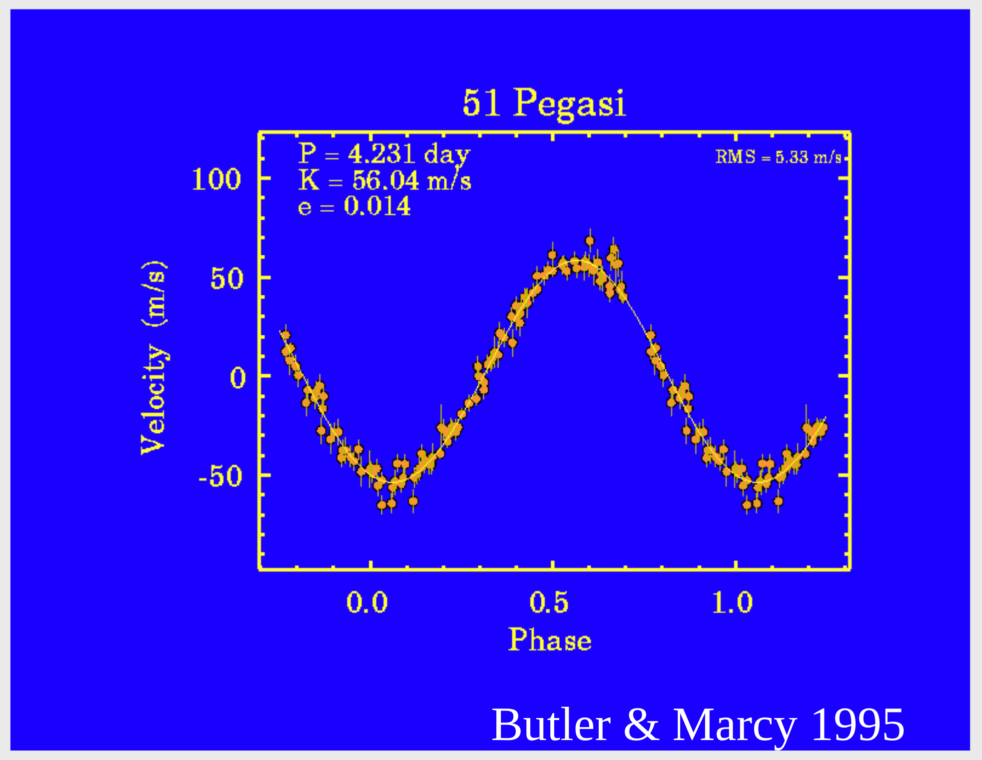
- $M_* V_* = M_p V_p$

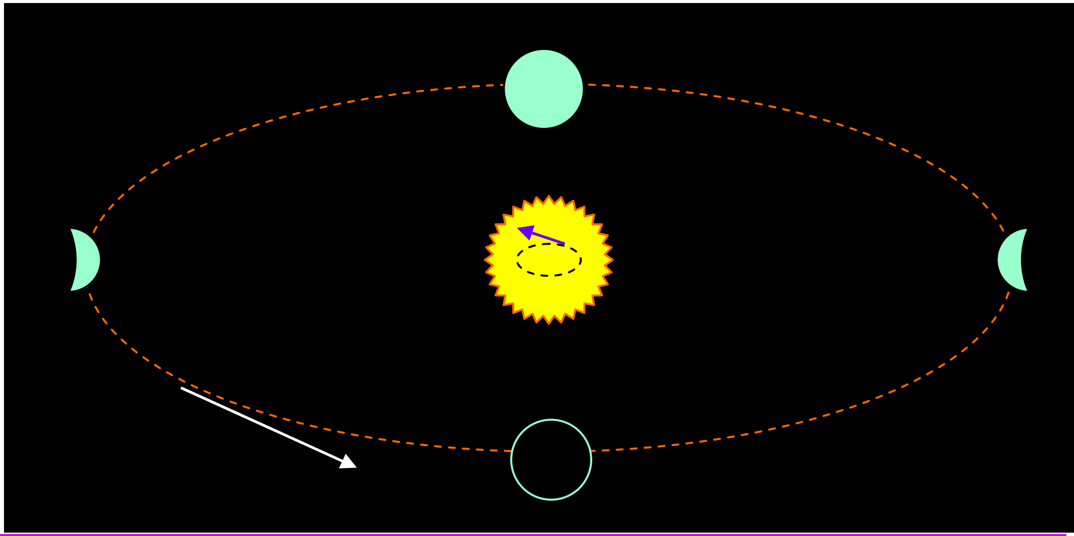
$V_* = 100 m/s \rightarrow V_p = 150 km/s$

$(\Delta\lambda > 10\ A)$

- The planetary spectrum:
  - Changes brightness
  - Changes velocity
- Maximum brightness is at conjunction, minimum at opposition, while RV=0
- Brightness is similar at quadratures, while the RV difference is maximum:

$(\Delta V = 2V_p \sin i)$





Exoplanet detection possibilities

The optical brightness of an extrasolar planet depends on:

1. The planet's radius R_p
2. The planet's albedo A
3. The semimajor orbital axis a
4. The star surface temperature T_{eff}

The signal to noise necessary to detect:

51Peg → S/N~10^4

exo-Jupiter → S/N~10^6

exo-Earth → S/N~10^8

hot exo-Earth with P<5d → S/N~10^6

Problems: CCDs saturate at ~10^5 counts. But they have the capability to accumulate ~10^{11} counts!

Exoplanet detection possibilities

$$F_{ref} = A/2(R_*/a)^2 F_*.$$

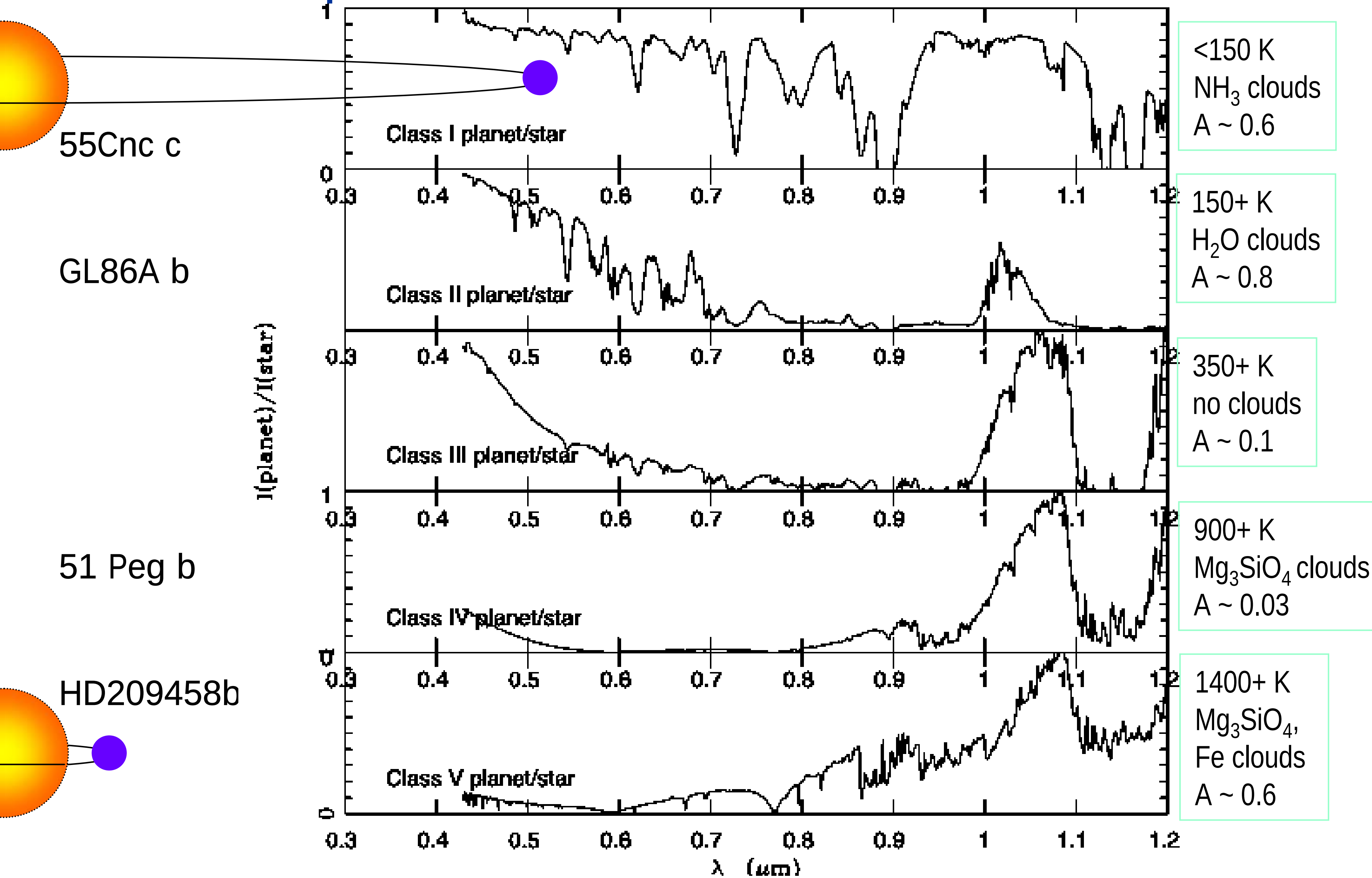
Table 1. Parameters of Target Stars

Star ID	ST	V	$M_p(M_J)$	$P(d)$	$a(AU)$	V_{amp} (kms^{-1})	F_{ref} ($\times 10^6$)
HD73256	G8/K0V	8.08	1.85/sini	2.55	0.037	141/sini	5.5
HD83443	K0V	8.23	0.41/sini	2.99	0.040	133/sini	4.2
HD46375	K1IV	7.94	0.25/sini	3.02	0.041	129/sini	3.2
HD179949	F8V	6.25	0.84/sini	3.09	0.046	147/sini	12.6
HD187123	G5V	7.90	0.52/sini	3.10	0.042	140/sini	5.8
τ Boo	F6V	4.50	3.87/sini	3.31	0.046	152/sini	17.4
HD75289	G0V	6.35	0.42/sini	3.51	0.046	147/sini	9.4
HD209458	G0V	7.65	0.69/sini	3.52	0.045	145/sini	9.8
HD76700	G6V	8.13	0.20/sini	3.97	0.049	129/sini	4.1
51Peg	G2IV	5.46	0.47/sini	4.23	0.052	131/sini	5.5
υAnd	F8V	4.09	0.69/sini	4.61	0.059	130/sini	7.7
HD49674	G5V	8.10	0.12/sini	4.95	0.057	121/sini	3.6

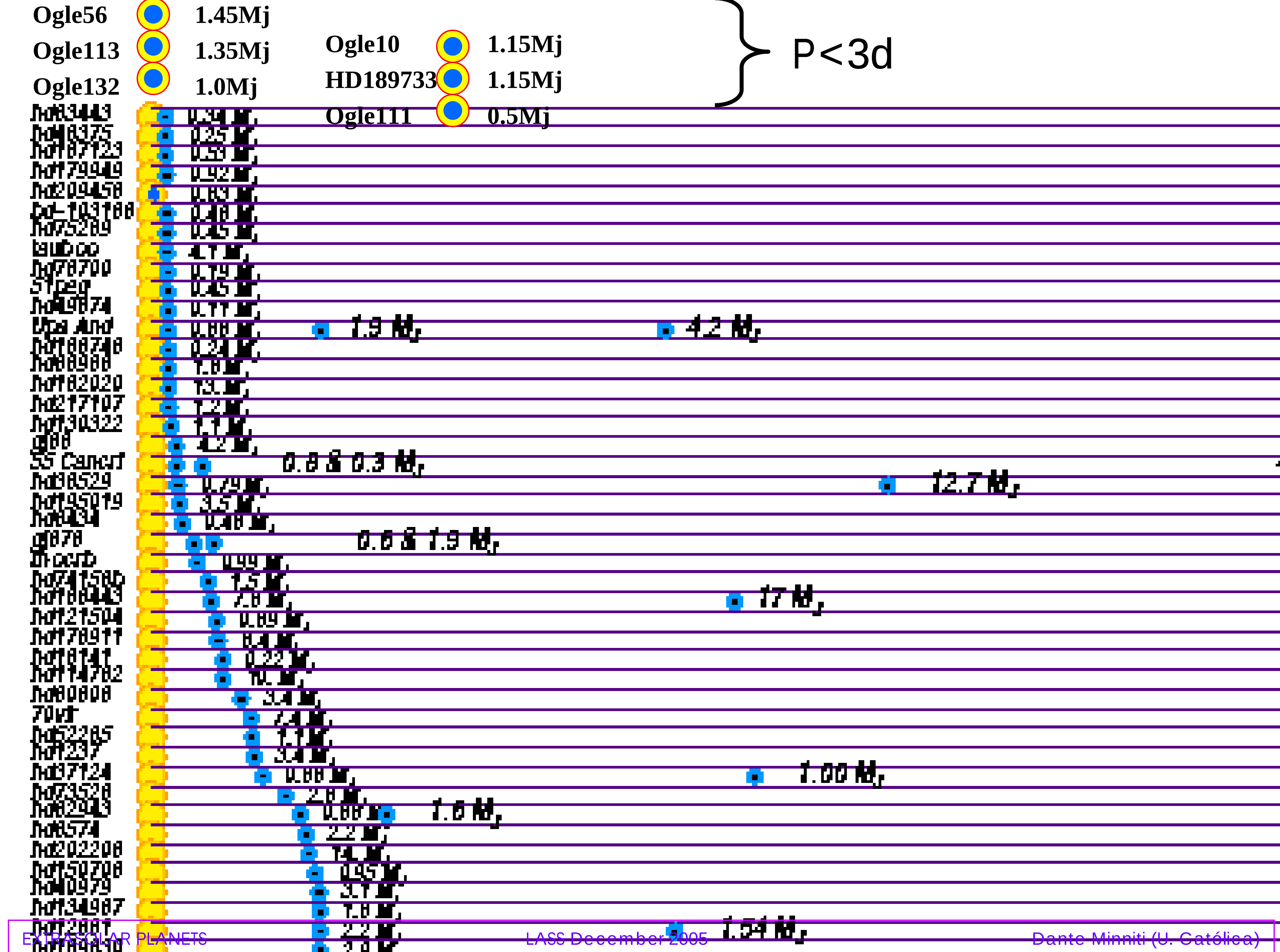
Add new ones: TrES-1, HD149099, HD189033

Giant Exoplanet Albedos Classes I-V

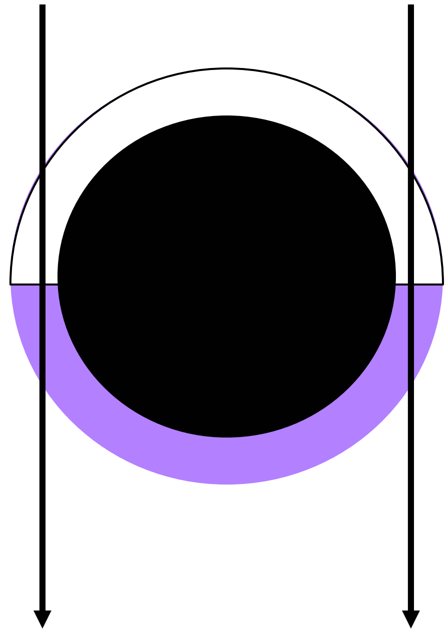
Burrows et al. 2001



A new class missing, the very hot Jupiters T=2000K (class VI).


Ogle56 1.45Mj
Ogle113 1.35Mj
Ogle132 1.0Mj
Ogle10 1.15Mj
HD189733 1.15Mj
Ogle111 0.5Mj
P<3d

Transmission spectroscopy



The transit time for a hot Jupiter typically is:

$$t_T \sim 2\text{-}3 \text{ hr}$$

But if there is a transiting planet at 1AU a longer integration is possible:

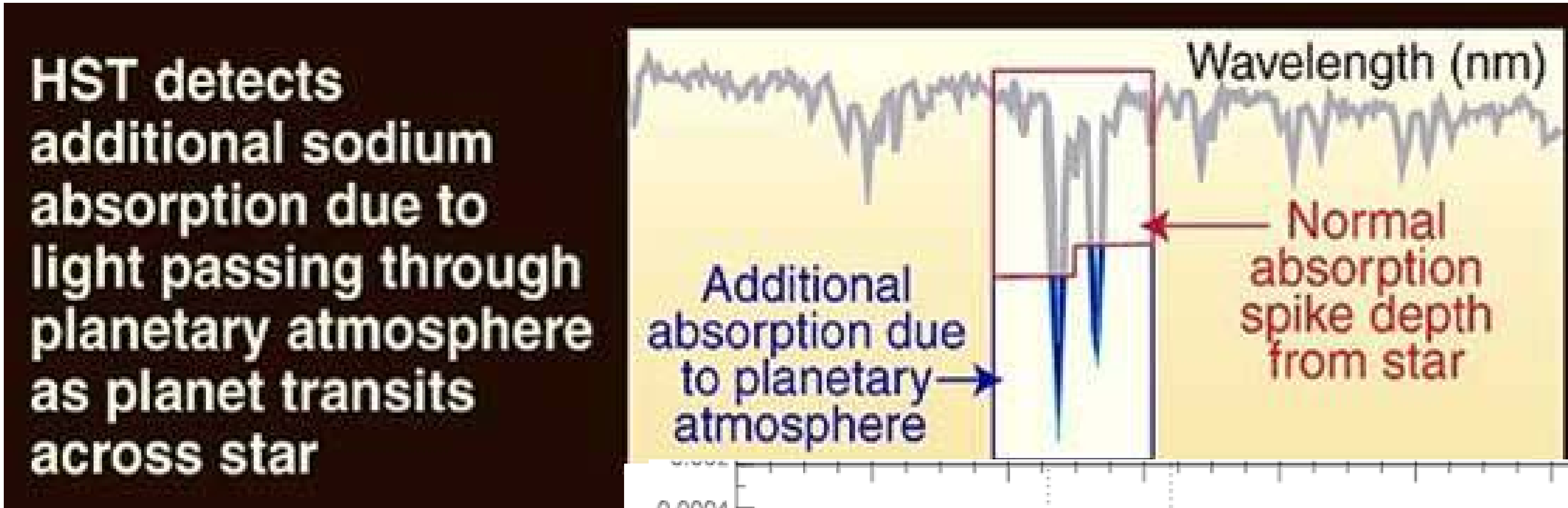
$$t_T \sim 13 \text{ hr}$$

Optical transmission spectroscopy:

Na 5890A doublet with STIS+HST, weak compared to models.

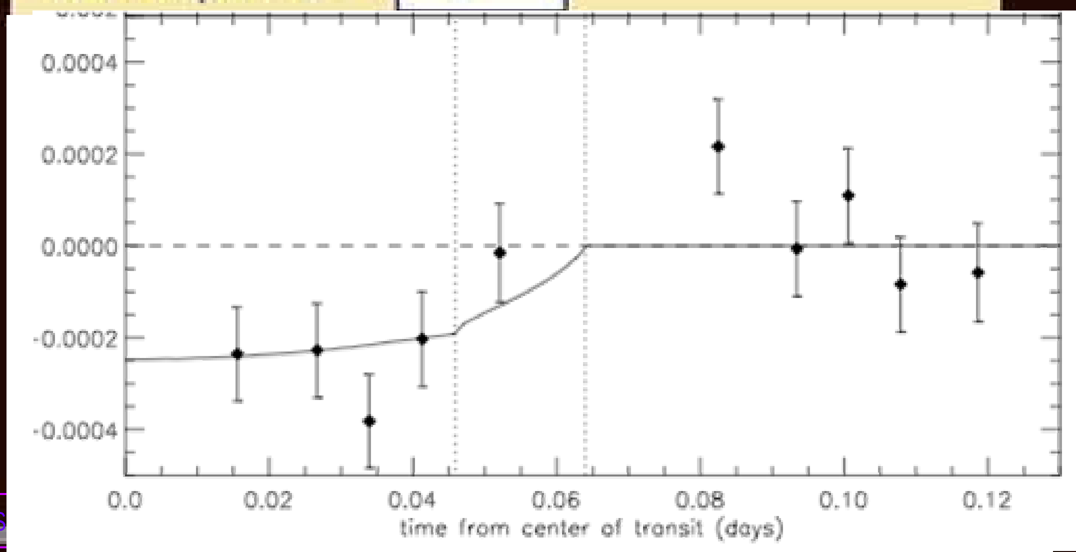
M=0.63 MJUP
R = 1.4 RJUP
ρ = 0.4 g/cm³
→ **Gas giant**

HD209458 transit



Brown & Charbonneau 2001.

SUBARU limits:
Narita et al. 2005



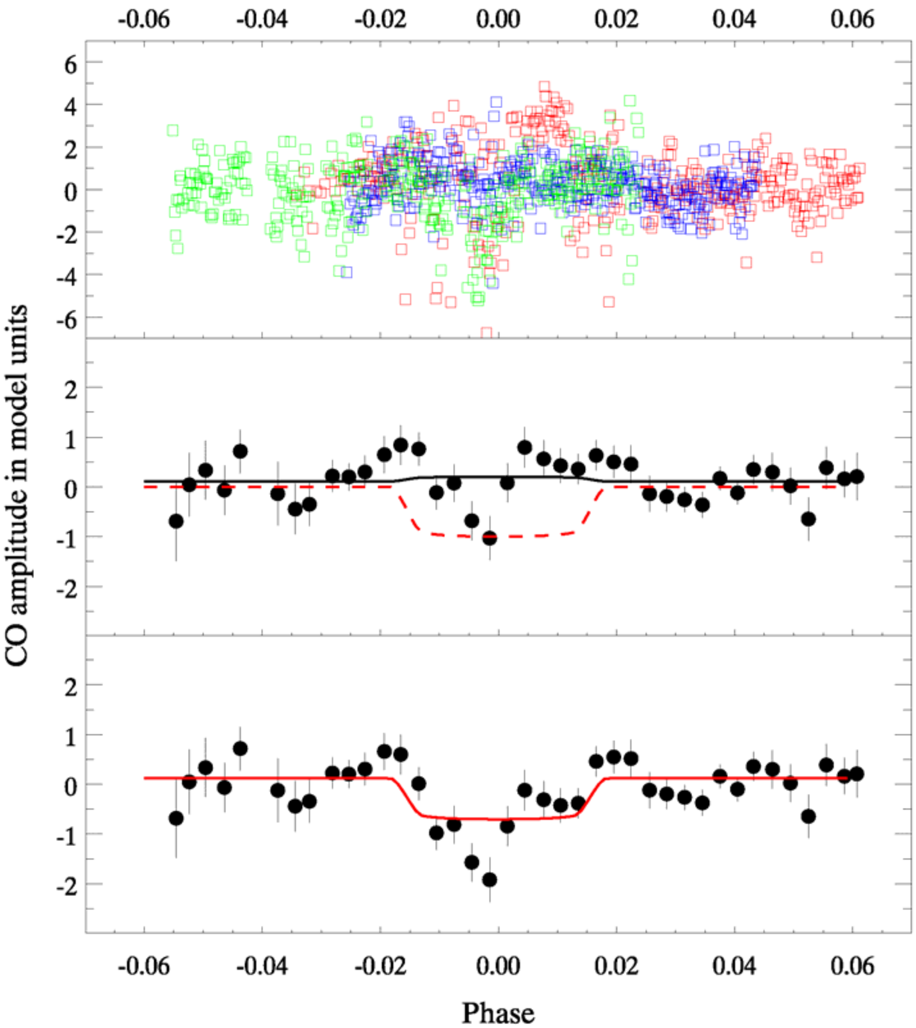
Transmission spectroscopy

IR transmission spectroscopy:

CO should be abundant in hot Jupiters, and has strong lines at 2μm.

Attempts to detect CO absorption during transit in HD209458 with KECK+ NIRSPEC (R=25000).

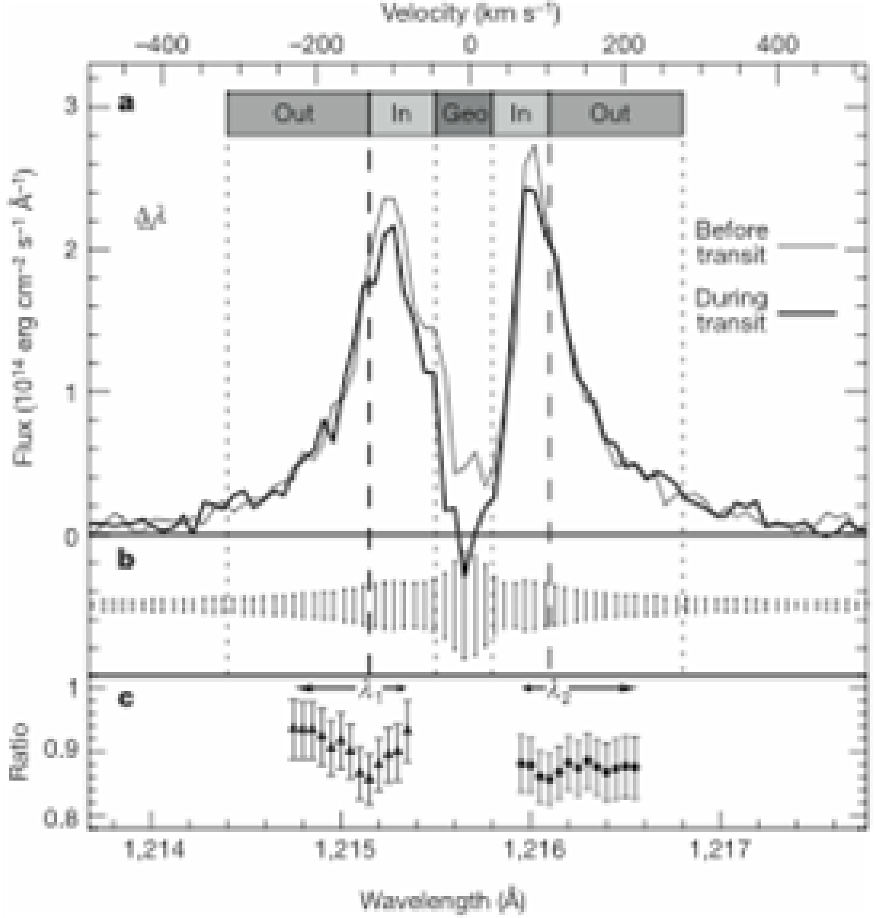
Obtained solid upper limits (Brown et al. 2002, Deming et al. 2005).

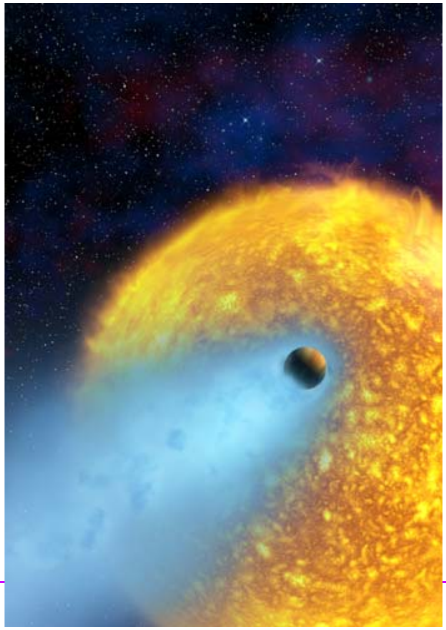


Transmission spectroscopy

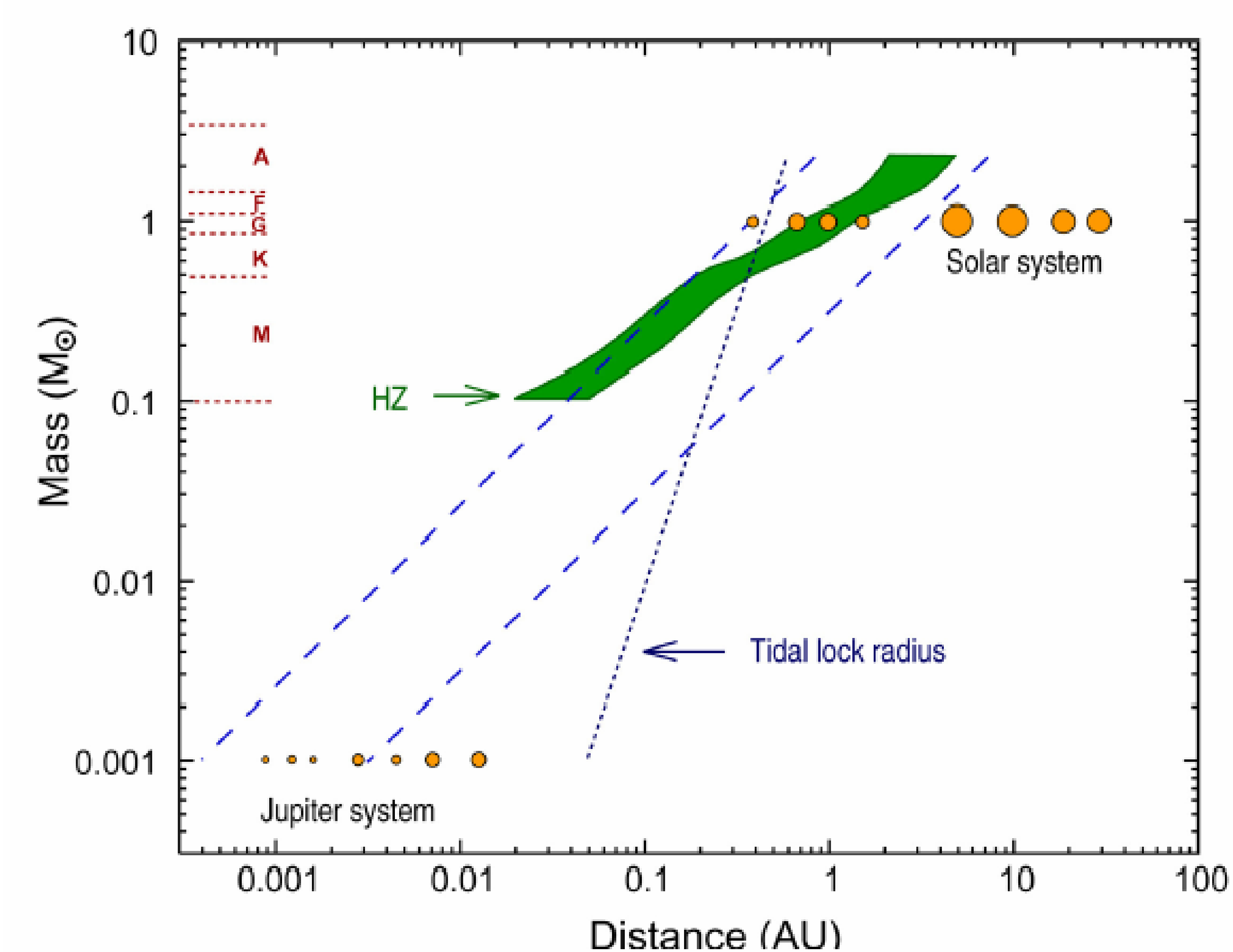
UV transmission spectroscopy:

detection of atomic H → Lyα in absorption (also C, O) in the HD209458 exosphere with HST: an evaporating planet (Vidal-Madjar et al. 2003, 2004).



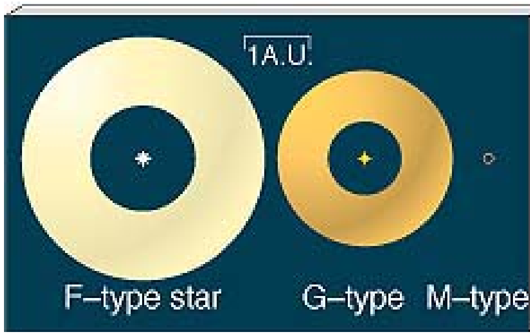


The habitable zone



Range of planetary orbits where water remains liquid

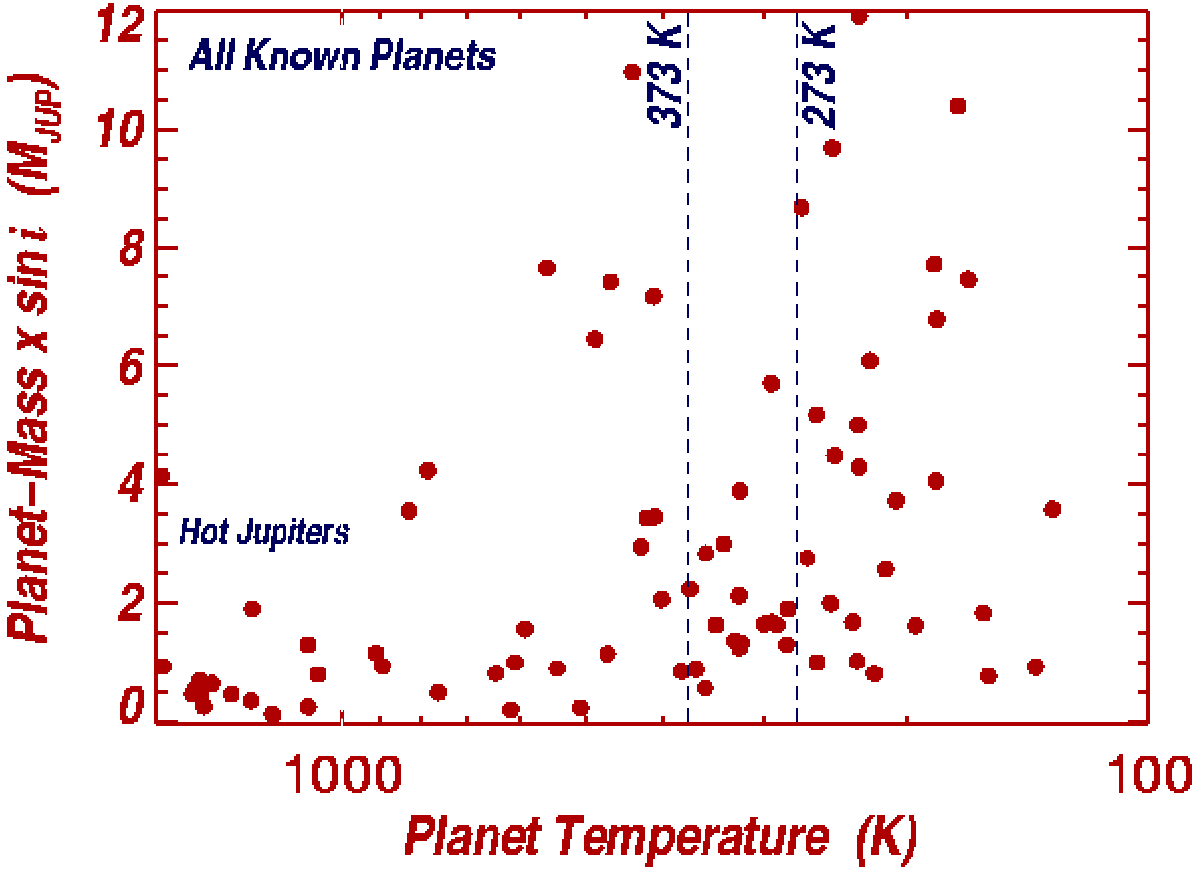
(Kasting et al. 1993)



If the planets are tidally locked, they rotate slowly, giving always the same face to the star. E.g. Prot = 10 hr for Jupiter, Prot = 4 d for HD209458. Note that this effect has to be considered in the irradiation models.

Exoplanet Temperatures

$$T \sim L^{1/4} / d^{1/2}$$

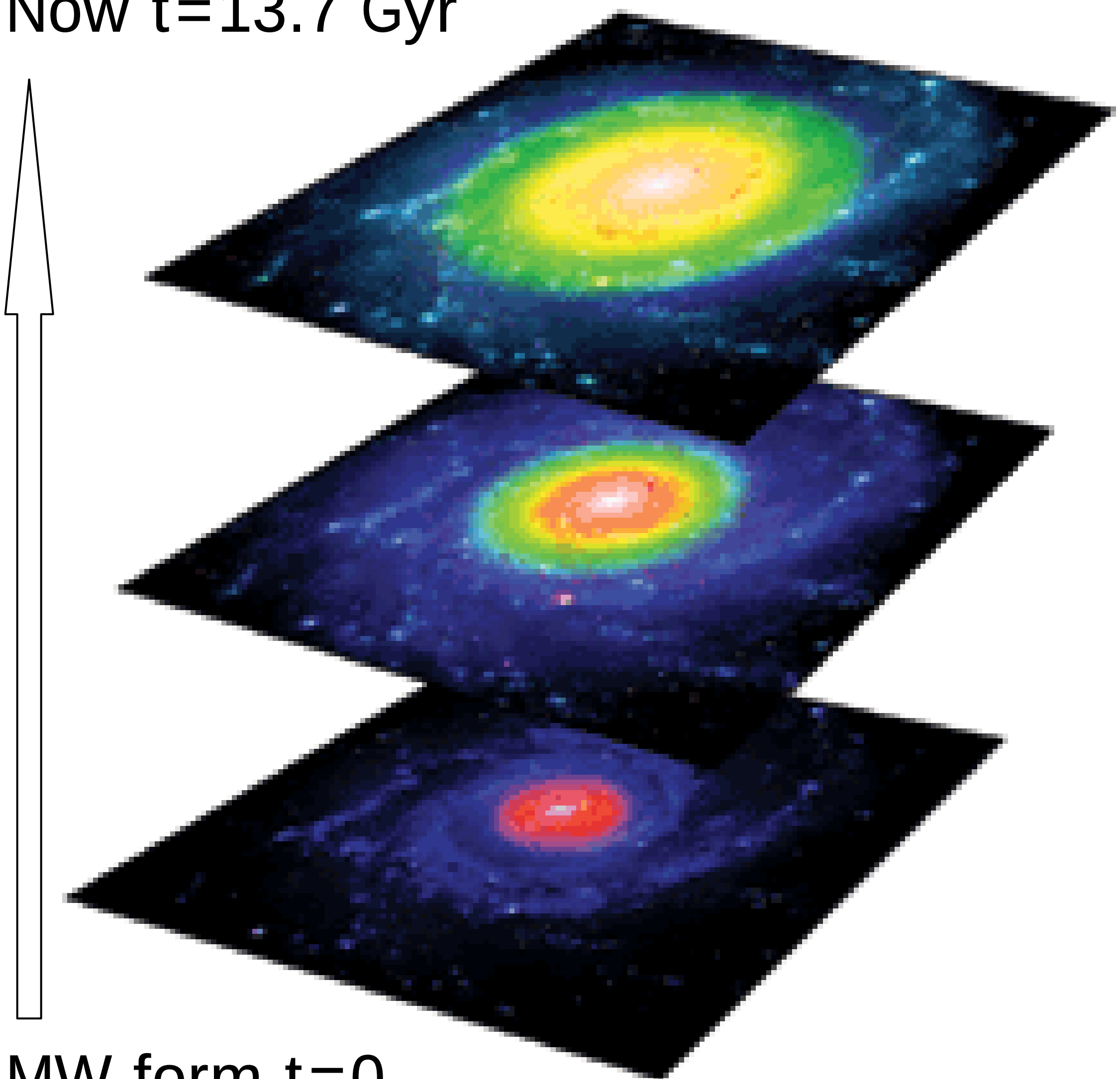


Butler & Marcy

e.g. ΔT between perihelium a(1+ε) and aphelium a(1-ε)

Exoplanets in the Milky Way

Now t=13.7 Gyr



MW form t=0

How is the distribution of planets throughout the Galaxy?

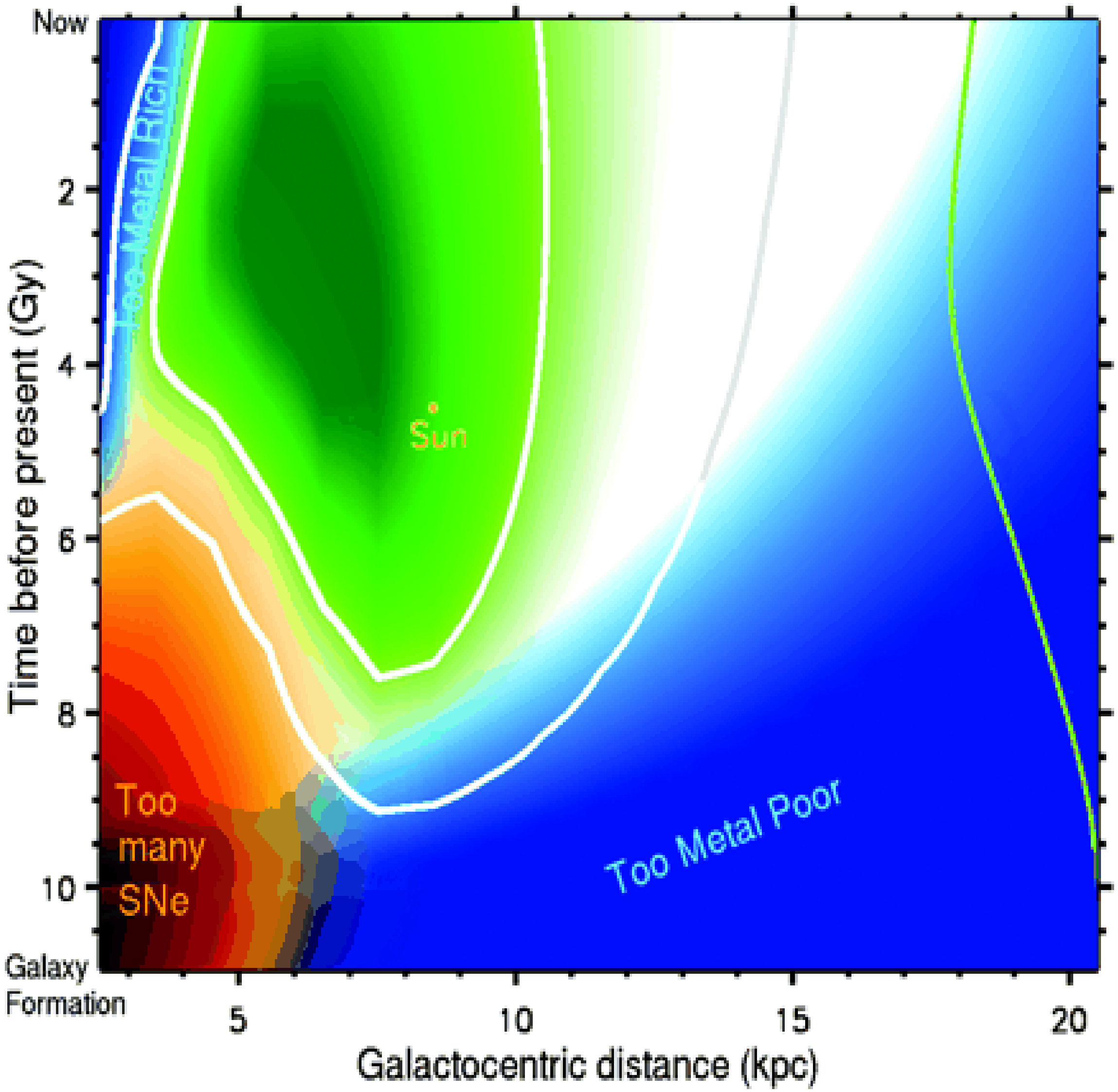
Where is the Galactic habitable zone?

We do not know, but metals are needed to form planets and life.

How does this Galactic habitable zone evolve with time?

Gonzalez 2000, Linewaever et al. 2004

Exoplanets in the Milky Way



Lineweaver et al. 2004

Main model assumptions:

No life if [Fe/H] < -1.0, ideal -0.5 < [Fe/H] < 0.3

T = 4 ± 1 Gyr needed for the development of complex life.

No life if SN rates are 20 times larger than the present local value.

~5000000000 stars available, ~70% of them should be older than the Sun.

Spectroscopic biomarkers

Can we detect some biomarkers using astronomer's tools?

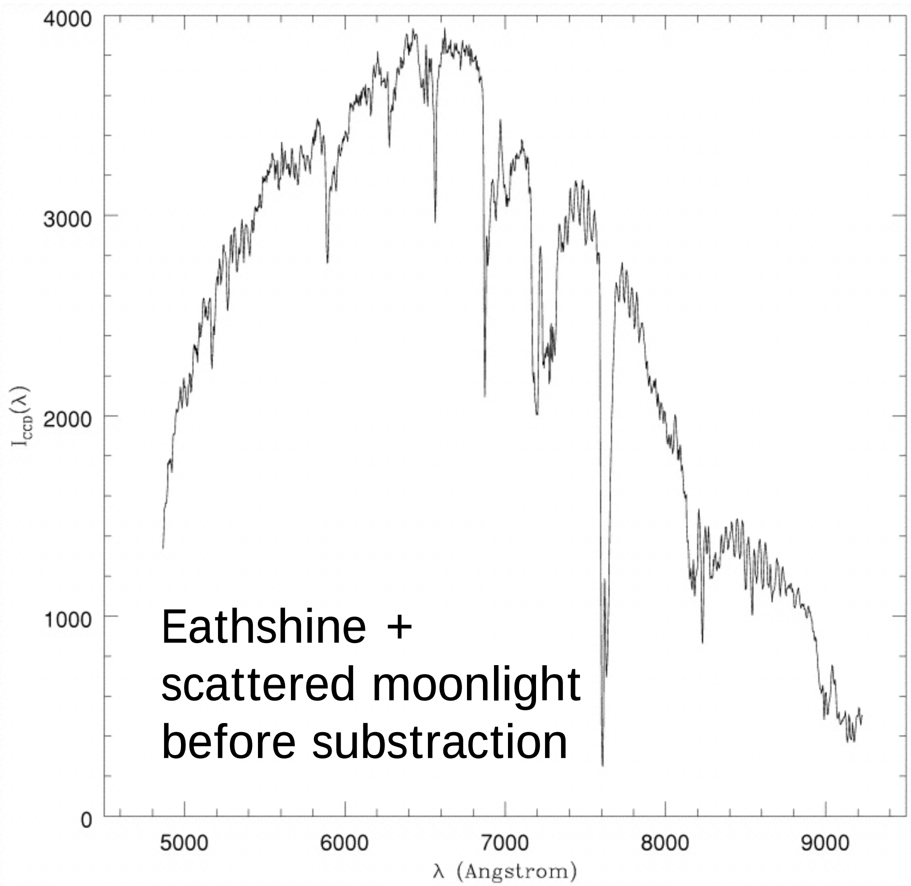
- UV → O_3 3200A
- Optical → O_2 7600A, O_3 5800A, H_2O,7200A, 8200A, 9400A, CH_4 7900A, 8900A, CO_2 10500A, chlorophyll edge 7200A
  → Earthshine spectrum (Woolf et al. 2002, Arnold et al. 2002): see the signature for the vegetation at 7200A
- IR → O_3 10μm, N_2O, O_2 , CH_4 , CO_2 , H_2O
  → Earthshine spectrum (Turnbull et al. 2005)

Des Marais et al. Astrobiology (2002)

Earthshine spectrum

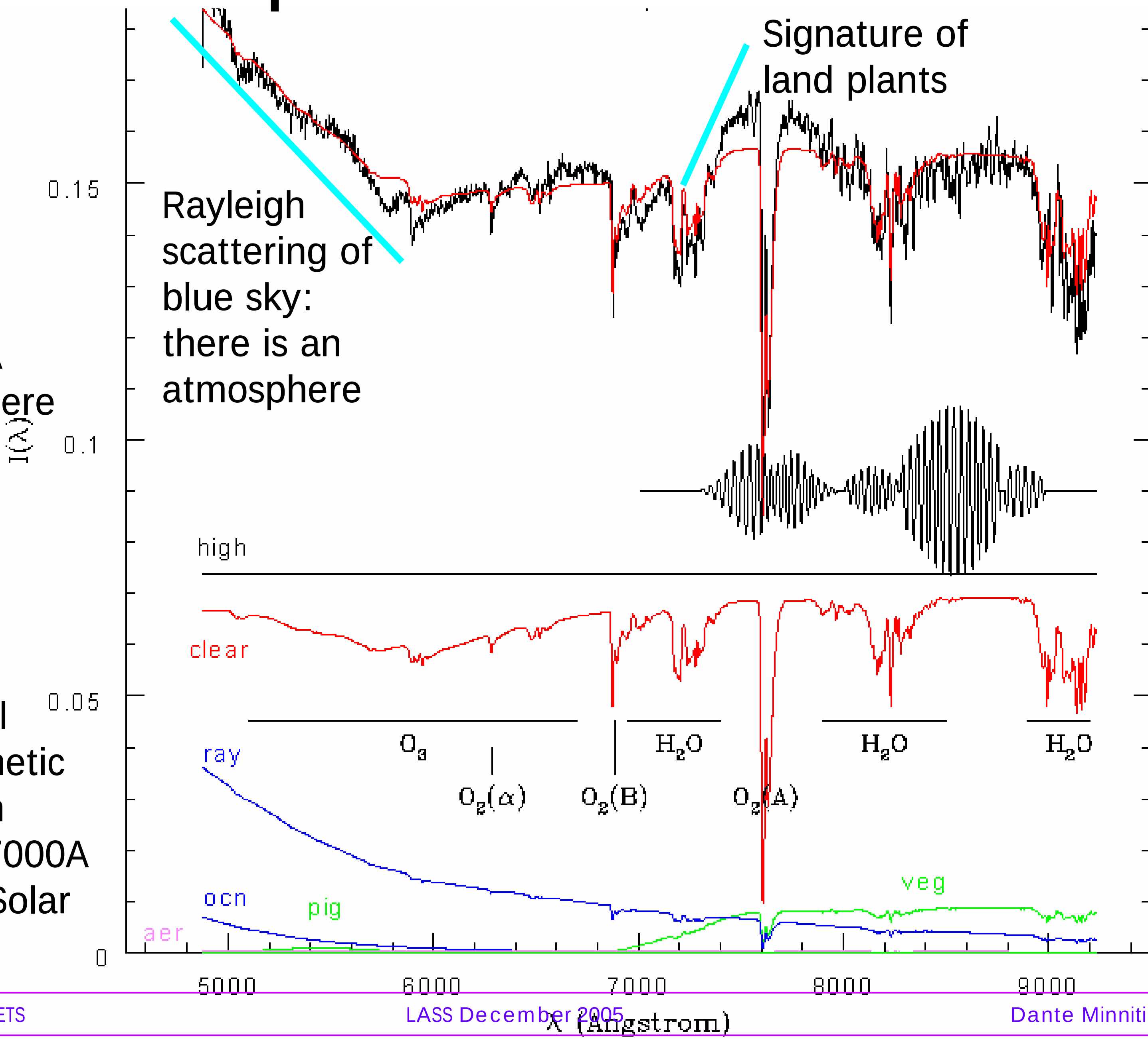
The Moon as seen from the Earth.

The Earth as seen from the Moon (only18% land).



Woolf et al. (2002), Arnold et al. (2002)

Earthshine spectrum



Signature of land plants

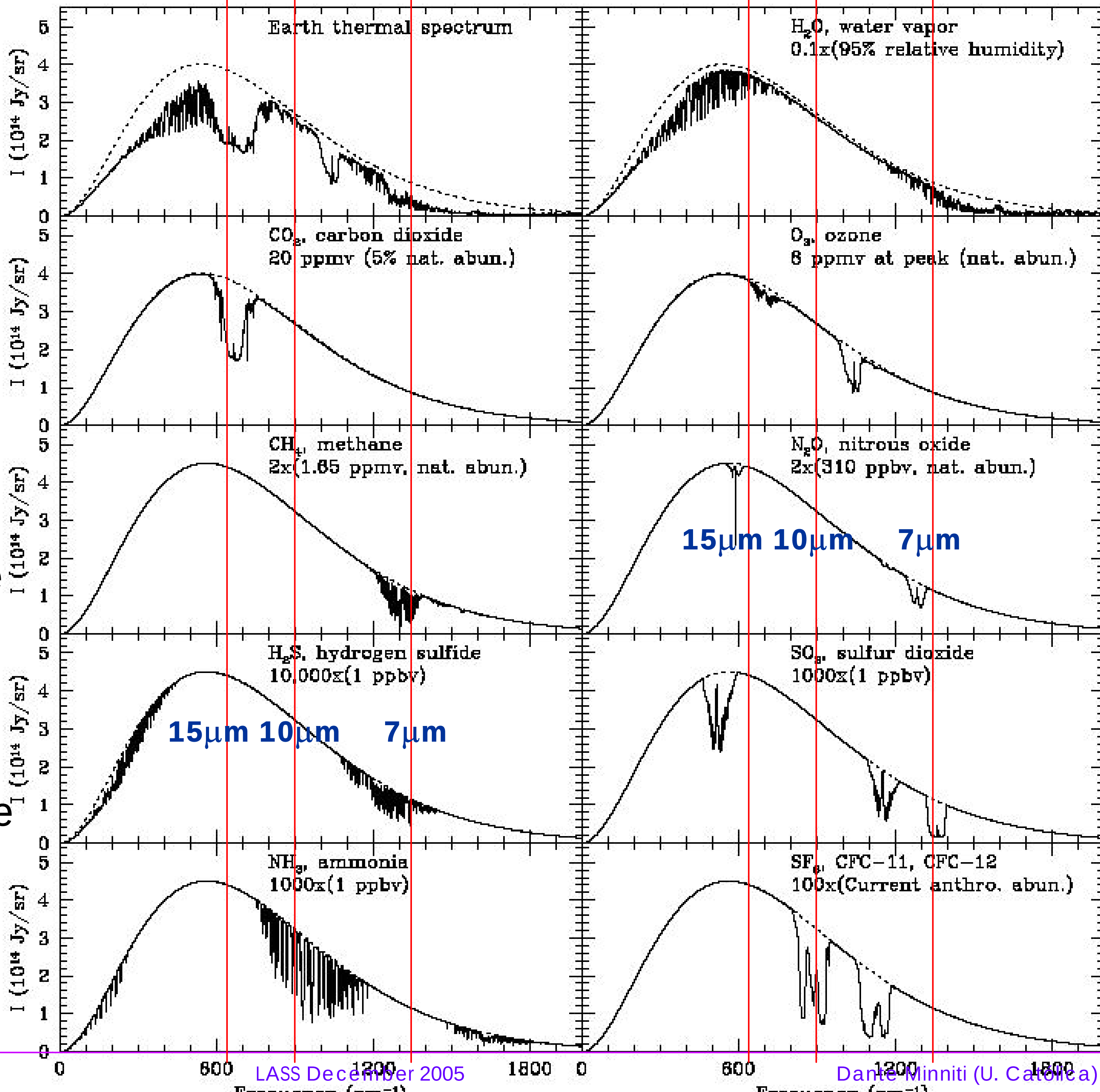
Rayleigh scattering of blue sky: there is an atmosphere

<3000 A atmosphere cut-off, ozone

NB: normal photosynthetic range from 4000A to 7000A (tuned to Solar BB peak)

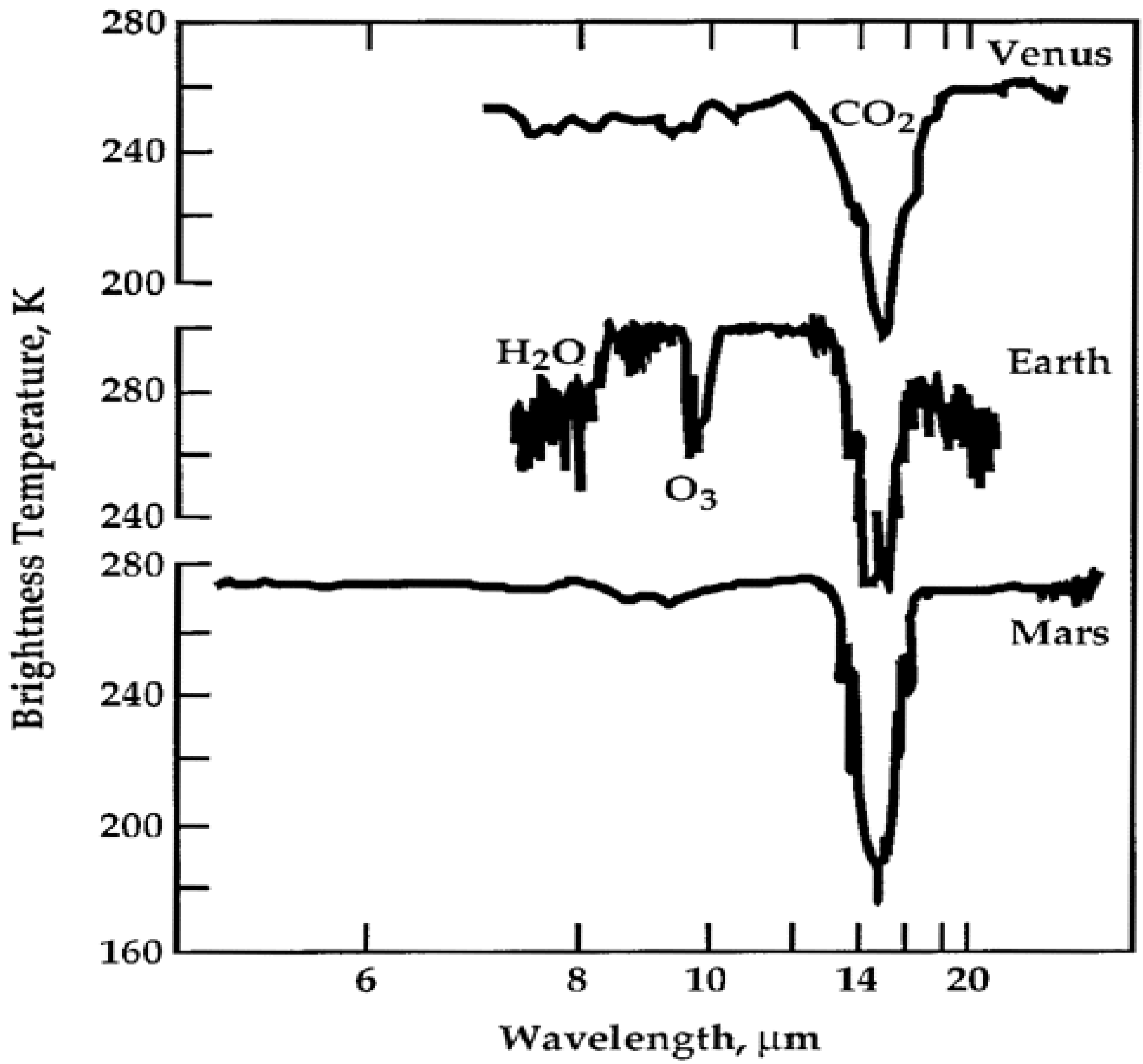
Earth's thermal spectrum

- different components
- O produced by living organisms
- CH_4, CO_2 maybe also
- H_2O suggests habitability
- CFCs suggest we are killing the planet



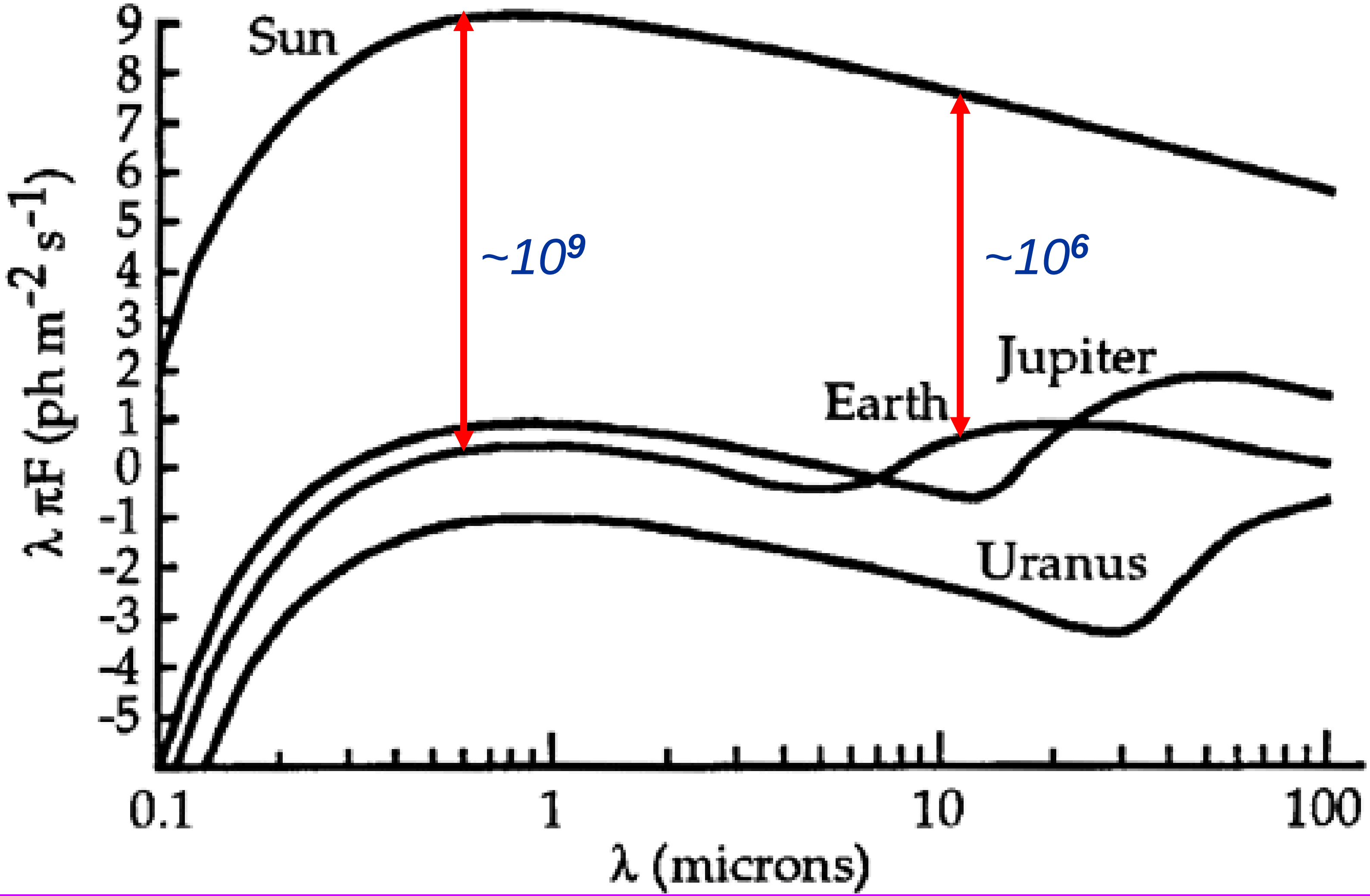
Searching for life

Infrared Spectra: The Ozone test



Searching for life

Contrast between the Earth and the Sun



Searching for life

No way to travel there, we must use telescopes.

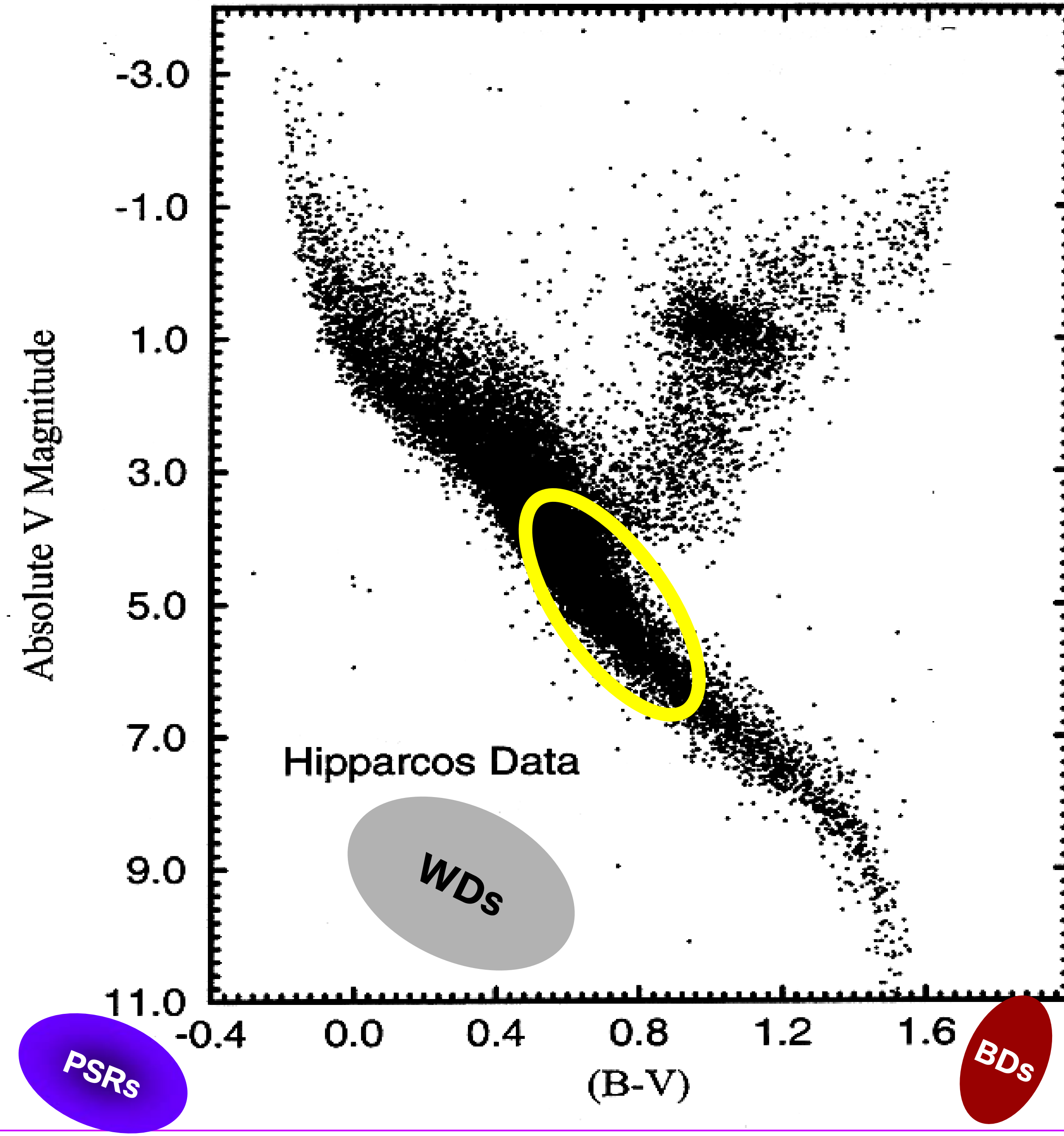
Searching for life as we know it:

- → The 1st step is to find a rocky planet in the stellar habitable zone (HZ), although it could also be a satellite of a gas giant.
- → The planet should be in the Galactic habitable zone, not in a globular cluster or close to the Galactic center.
- → The planet should not be tidally locked, ruling out most late-type stars.
- → The system should not be young, so that there are not too many catastrophic comet/asteroid impacts.
- → Find an atmosphere that shows out of equilibrium composition, containing known biomarkers. (But because our own atmosphere has changed, we have to catch the planet at the right time in evolution in order to see the biomarkers that we expect.)

Search for extrasolar planets

- The searches using radial velocities, timing, microlensing, and astrometry depend on the masses of the stars/planets.
- The transit searches depend on the sizes of the stars/planets.
- The direct detections depend on the brightness of the stars/planets (i.e. sizes, temperatures, albedos, semimajor orbital axis).

Remember: we only know a little bit about giant planets around Solar-type stars.



The future

Many possible follow-ups:

- Search for multiple planets
- Study planetary atmospheres
- Search for moons
- Search for rings

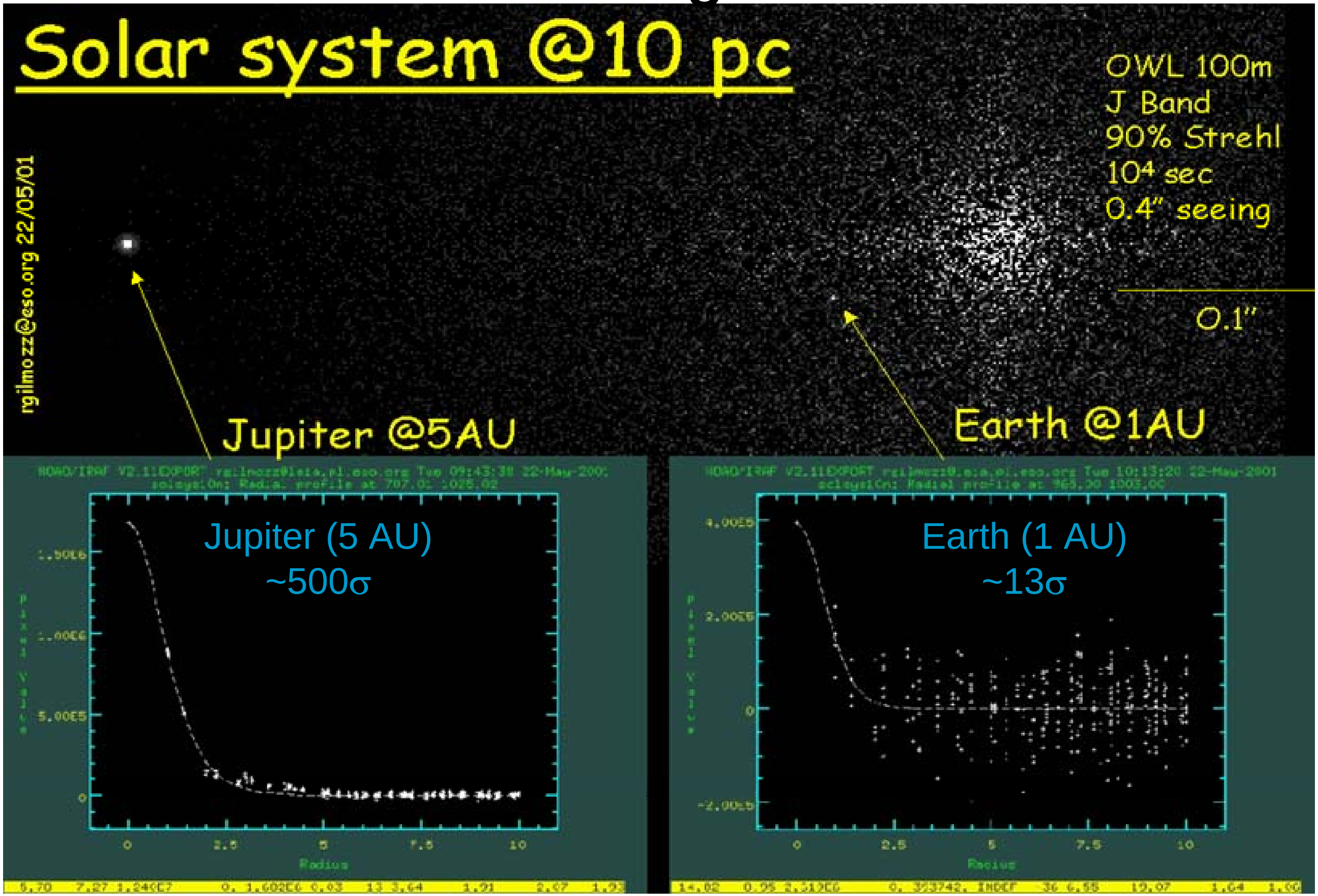
Lynette Cook

The future from the ground

- Role for small telescopes for search and follow-up.
- The extremely large telecopes (e.g. GMT, OWL).

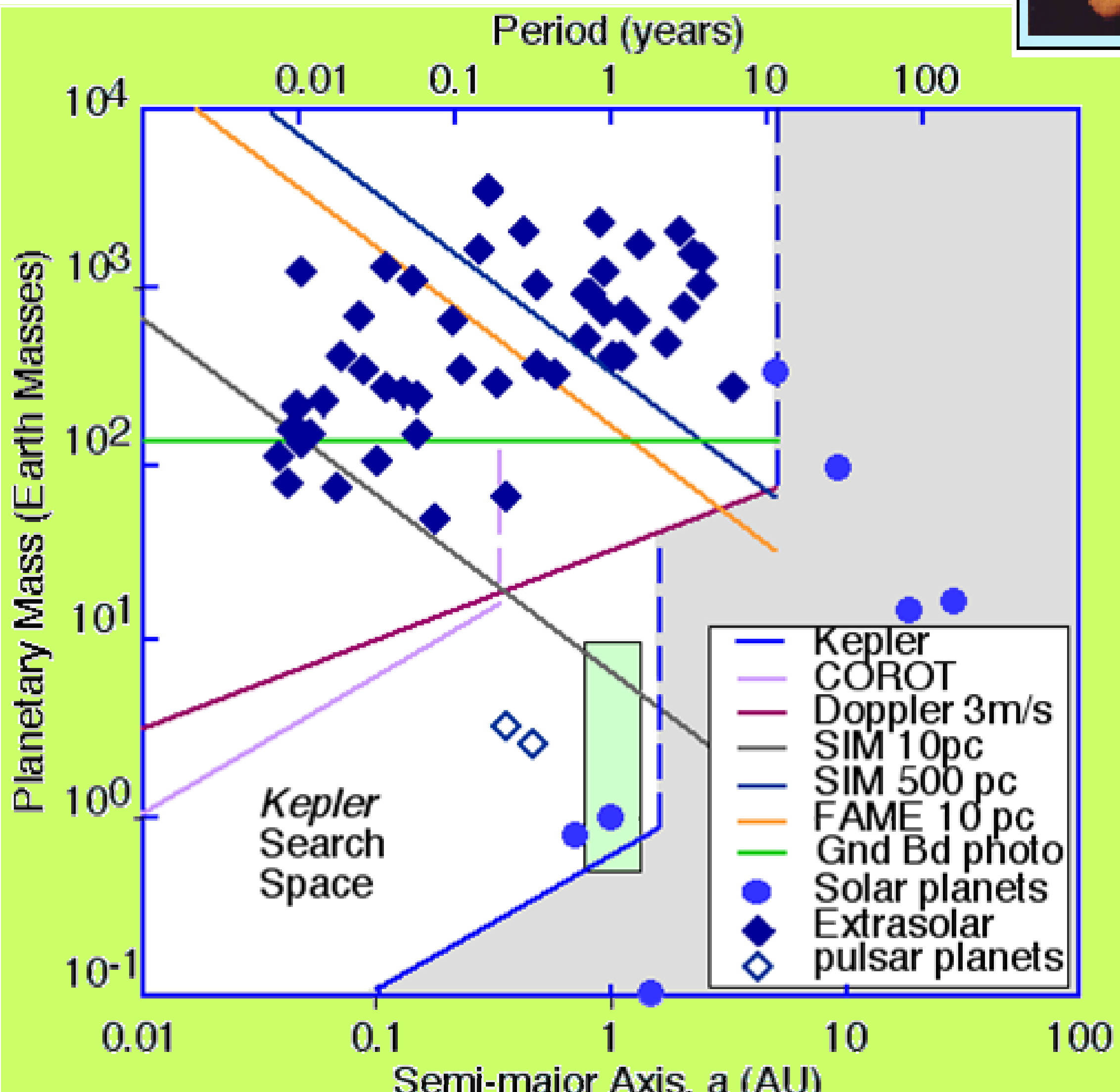
The 100m OWL telescope is being planned for the year ~2020. This kind of large telescopes is needed to detect and characterize Earths in nearby stars, using coronography or nulling interferometry.

The future from the ground



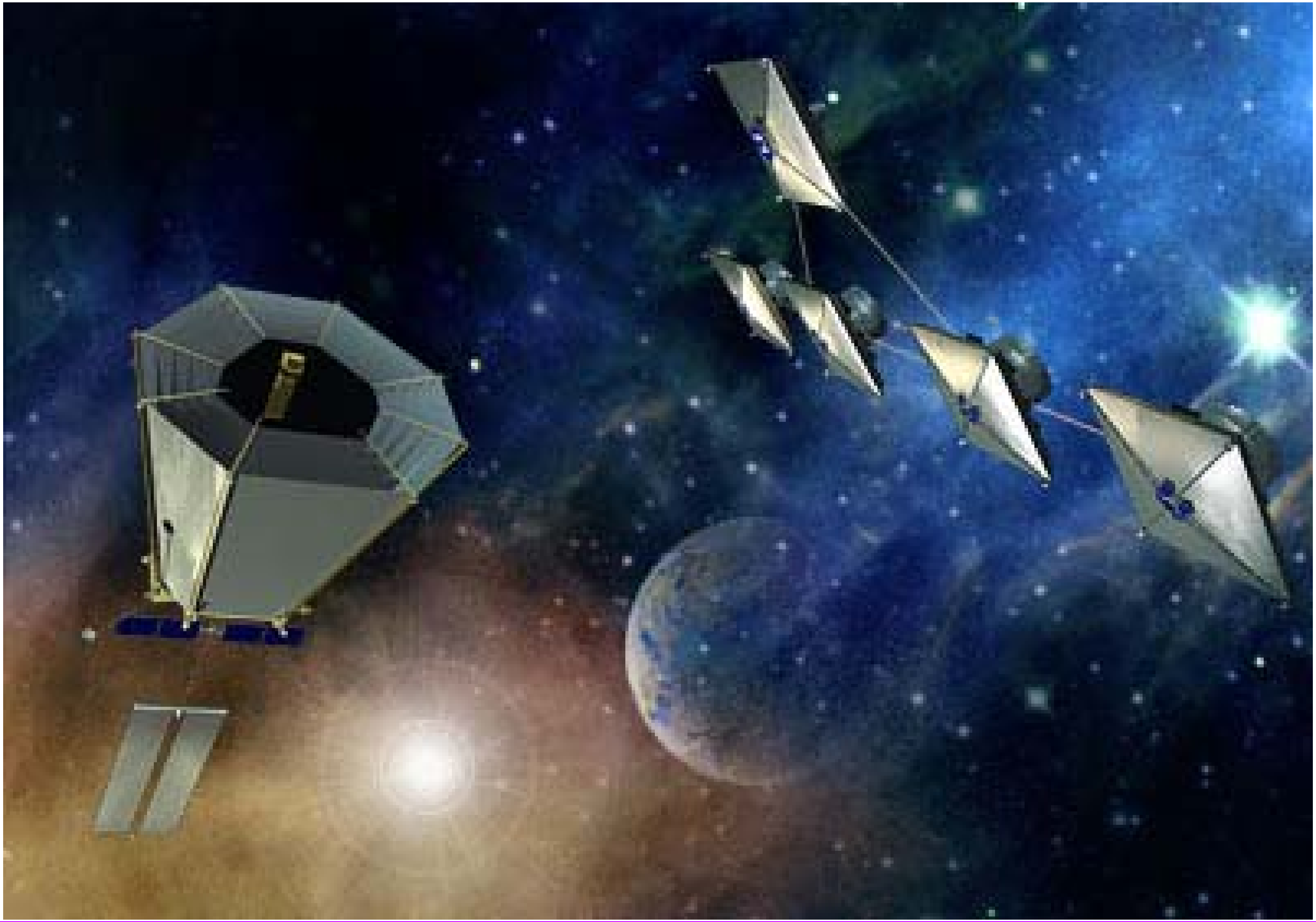
Simulation with 100m OWL: detection of Jupiter & Earth detections at 10pc

The future from space



- First results from CoRoT transits in just a couple of years:
  - Will detect many hot Jupiters
  - May detect hot Earths
- Kepler transits only a few years away:
  - Will detect many Earths in the habitable zone

TPF: The Terrestrial Planet Finder



Important things that I have not covered

Interferometry !

Coronography !

Planetary atmospheres !

Disks !

Extrasolar Planets

Carolina
Sebastian
Celeste
Jose Miguel
Claudia
Pablo
Pilar
Ignacio
Klara
Sergio
Nancy
Rodrigo

- Why search for extrasolar planets?
- What is the best way to do it?
- What fraction of stars have planetary systems?
- What kinds of extrasolar planets are out there?

Sources

Here is a list of basic papers (incomplete, but a good place to start from):

- Perryman M., 2000 Extra-solar planets. Rep. on Progress in Phys., 63, 1209
- Wolszczan, A. 1994, Confirmation of Earth mass planets orbiting the millisecond pulsar PSR B1257+12 Science, 264, 538
- Mayor, M., & Queloz, D. 1995, A Jupiter-mass companion to a Solar-type star, Nature, 378, 355
- Marcy, G., & Butler, R., 1998, Detection of extrasolar giant planets, ARA&A, 36, 57
- Charbonneau, D., et al. 2000, Detection of planetary transits across a Sun like star, ApJ, 529, L45
- Henry, G., et al. 2000, A transiting 51Peg-like planet, ApJ, 529, L41
- T. Brown, et al. 2001, Hubble Space Telescope Time-Series Photometry of the Transiting Planet of HD 209458 ApJ, 552, 699
- Udalski, et al. (The OGLE Collaboration), 2002 Acta Astron. 52, 1
- Konacki, M., et al. 2003, An extrasolarplanet that transits the disk of its parent star, Nature, 421, 507
- Sato, B., et al. (N2K) 2005, A Transiting Hot Saturn Around HD 149026 With a Large Dense Core, ApJ, 633, 465
- Lin, D., et al. 1996, Orbital migration of the planetary companion of 51Peg to its present location, Nature, 380, 606
- Santos et al. 2005, Extrasolar planets: constraints for planet formation models, Science, 310, 251
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- Burrows, A., et al. 2001, The theory of brown dwarfs and extrasolar giant planets, RvMP, 73, 719
- Guillot, T., 2005, The Interiors of Giant Planets: Models and Outstanding Questions, Annual Review of Earth and Planetary Sciences, vol 33, (2005)
- Ferraz Melo, S., 2003, Extrasolar planets in mean motion resonance, ApJ, 593, 1124
- Butler, et al. 1999, Evidence for multiple companions to uAnd, ApJ, 526, 91
- Sudarsky, D., et al. 2000, Albedo and reflection spectra of extrasolar giant planets, ApJ, 538, 885
- Sartoretti, P., & Schneider, J. 1999, On the detection of satellites of extrasolar planets with the method of transits , A&ASuppl, 134, 553
- Kasting, J. et al. 1993, Habitable zones around main sequence stars, Icarus, 101, 108
- Woolf, N., et al. 2002 The Spectrum of Earthshine: A Pale Blue Dot Observed from the Ground, ApJ, 574, 430

Sources

Here is a list of web pages to explore (or webear as we say here):

- Astronomía PUC: *http://www.astro.puc.cl*
- European Southern Observatory: *http://www.eso.org*
- Space Telescope: *http://www.stsci.edu*
- NASA: *http://www.gsfc.nasa.gov/NASA_homepage.html*
- Jet Propulsion Lab: *http://www.jpl.nasa.gov*
- Solar System: *http://nssdc.gsfc.nasa.gov/planetary*
- Astrobiology: *http://www.astrobiology.com*
- SETI: *http://www.seti-inst.edu*
- Picture of the Day: *http://antwrp.gsfc.nasa.gov/apod/archivepix.html*
- Extrasolar planets: *www.vo.obspm.fr/exoplanetes/encyclo/encycl.html*
- OGLE: *bulge.astro.princeton.edu/~ogle/ogle3/transits*
- Lick group: *http://exoplanets.org*
- Geneva group: *http://obswww.unige.ch/planet*
- Transit Ephemerides: *www.transitsearch.org*

Sources

Here is a list of general related books:

- D. Goldwin, *NASA Origins*, 1999 (NASA)
- L. Doyle, *Circumstellar Habitable Zones*, 1995 (Travis House: Menlo Park)
- W. H. Calvin, *How Brains Think,* 1996 (Science Masters Books: Seattle)
- S. J. Gould, *Eight Little Piggies*, 1993 (Jonathan Cape: London)
- S. J. Gould, *Wonderful Life*, 1989 (W.W. Norton &Co: New York)
- S. Hawkins, *The First Three Minutes*, 1993
- S. Mader, *Inquiry into Life*, 1991 (W.C. Brown: Dubuque)
- P. Raven & G. Johnson, *Biology*, 1992 (Mosby Year Book: St. Louis)
- C. Sagan, *Cosmos*, 1980 (Random House: New York)
- C. Sagan & A. Druyan, *The Daemon Haunted World*, 1997 (Ballantine Books: New York)
- M. Strickberger, *Evolution*, 1996 (Jones & Barlett, Boston)
- P. Ward & D. Brownlee, Rare Earth, 2000 (Springer-Verlag: Heidelberg)
- I. Asimov & P. Anderson, Green Planet, 1997

Nota: ***1 book = 100 Mb***

1 Human = 10^{17} Mb

1 Humanity = 10^{27} Mb

For the lectures, I have used figures/ideas/analysis from the papers/talks/web pages of:

Sources

- Paul Butler
- Geoff Marcy
- Debra Fischer
- Greg Laughlin
- Chris Tinney
- Buneii Sato
- Maciej Konacki
- David Carbonneau
- Sylvio Ferraz Melo
- Nuno Santos
- Frederic Pont
- Didier Queloz
- Michel Mayor
- Dave Bennett
- Jean Schneider,
- Andrezj Udalski
- Hans Deeg
- Alex Wolszczan
- Mike Deming
- Nick Woolf
- Charles Alcock
- Space missions: Eddington, Corot, Kepler, SIM, TPF, Darwin
- Archives: ESO, HST, NASA, astro-ph
- Journals: ApJ, AJ, A&A, MNRAS, Nature, Science