EXTRASOLAR PLANETS AT PADOVA OBSERVATORY

S. Desidera

INAF-Osservatorio Astronomico di Padova

OUTLINE

- An introduction on extrasolar planets
- Extrasolar Planets at Padova Observatory
    - Planets in binary systems
    - SPHERE
    - EPICS
    - PLATO

DETECTION TECHNIQUES

- Radial Velocities
- Transits
- Astrometry
- Direct imaging
- Timing
- Microlensing
- Indirect signatures (e.g. structures on disks)

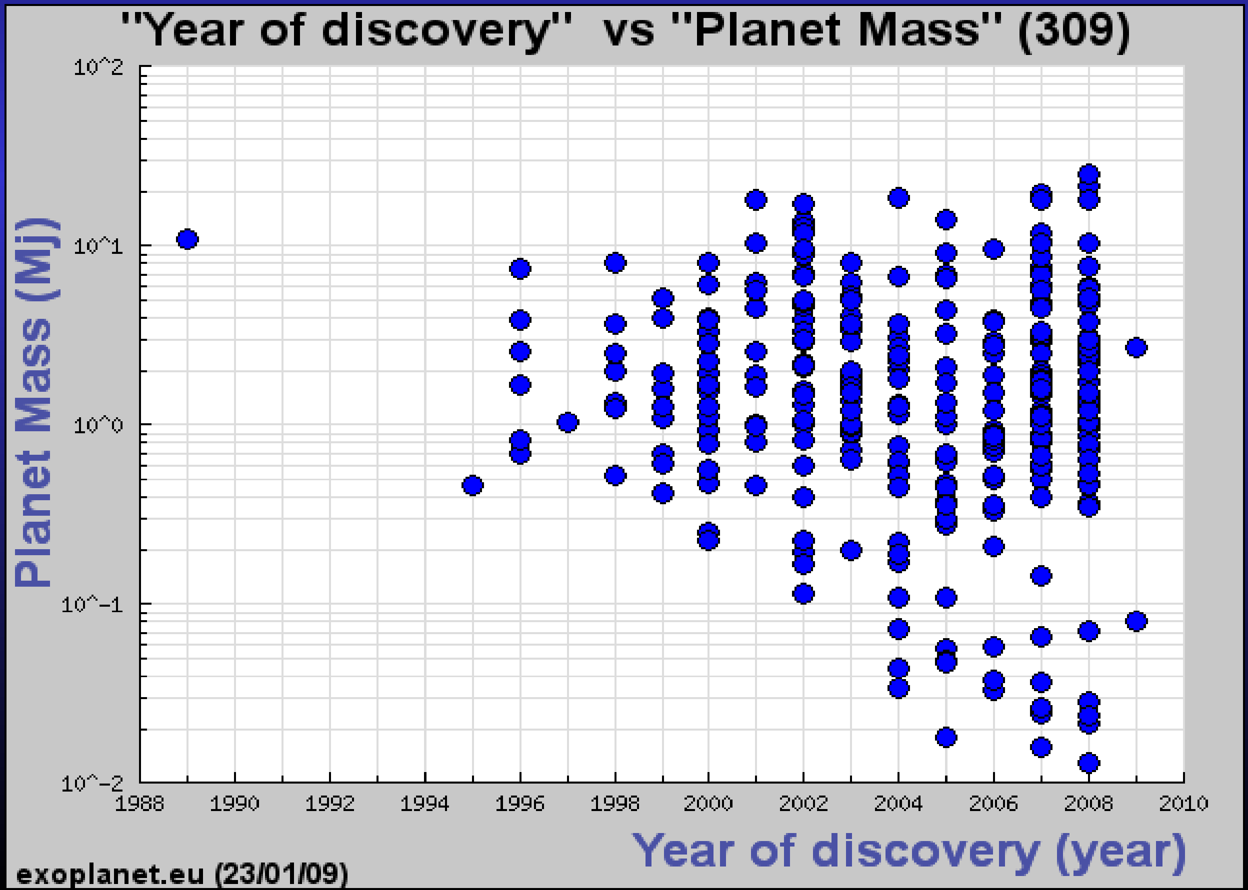
A short history: many surprises

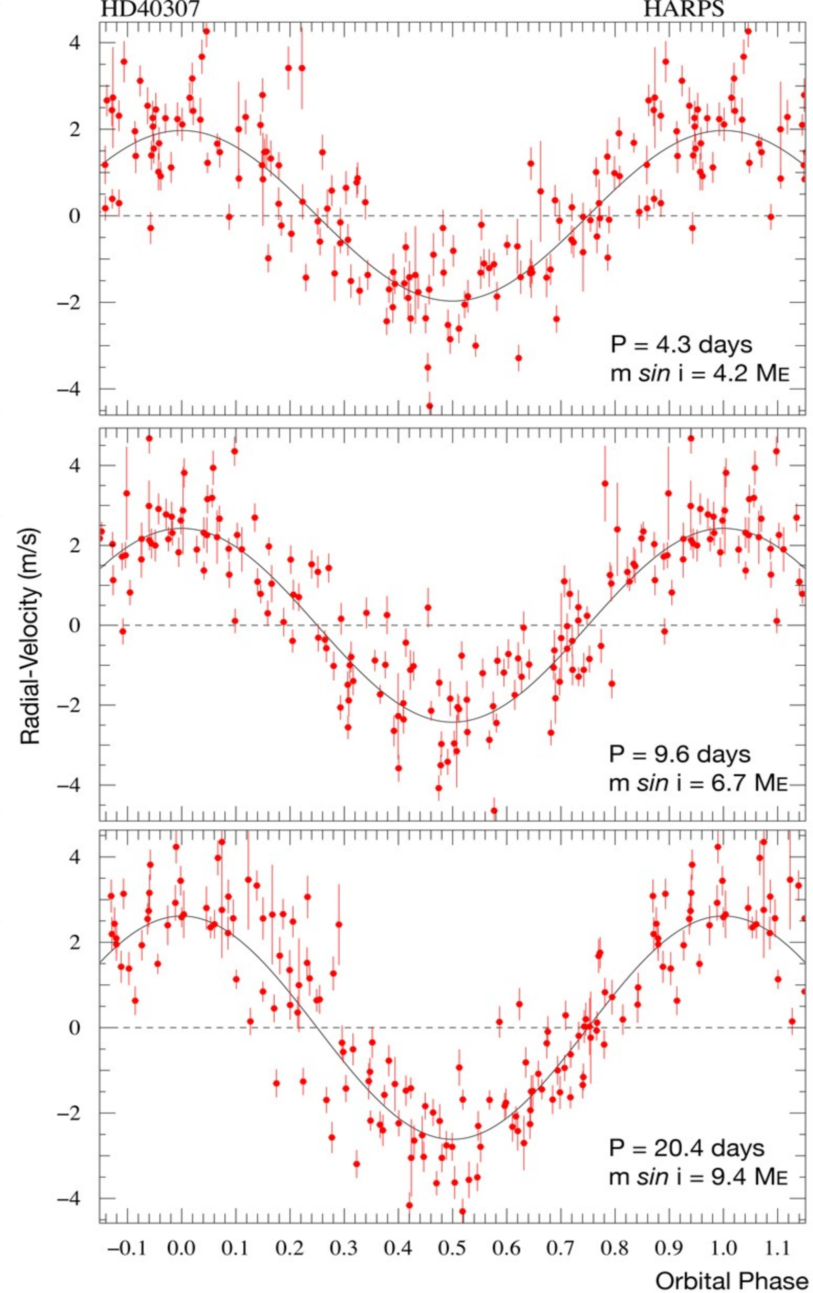
1992: first extrasolar planets around a pulsar (timing)

1995: first planets around a solar-type star (51 Peg)

1999: first transiting planet

2008: first planet detected by direct imaging





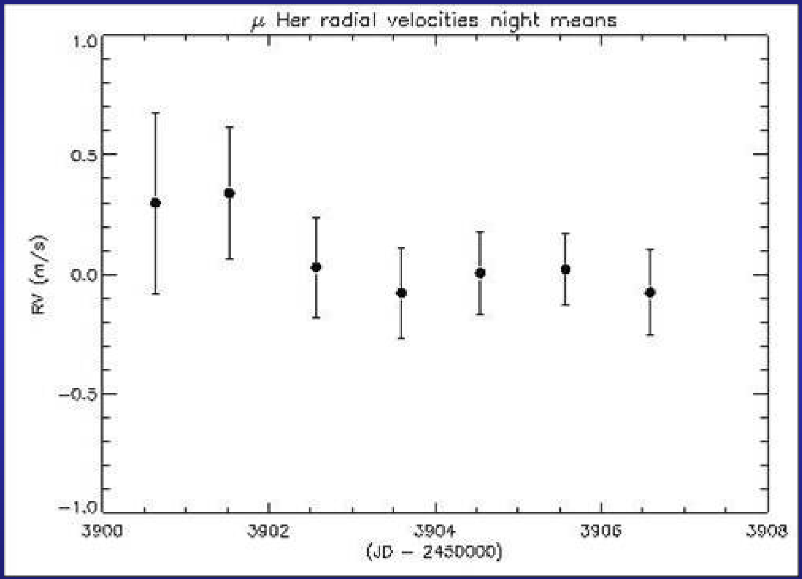
Measurements of HD 40307 (HARPS/3.6-m)

ESO Press Photo 19b/08 (16 June 2008)

Toward the detection of earth-like planets

New ultra-stable instruments (HARPS)

Better handling of stellar noise, diagnostics for stellar activity

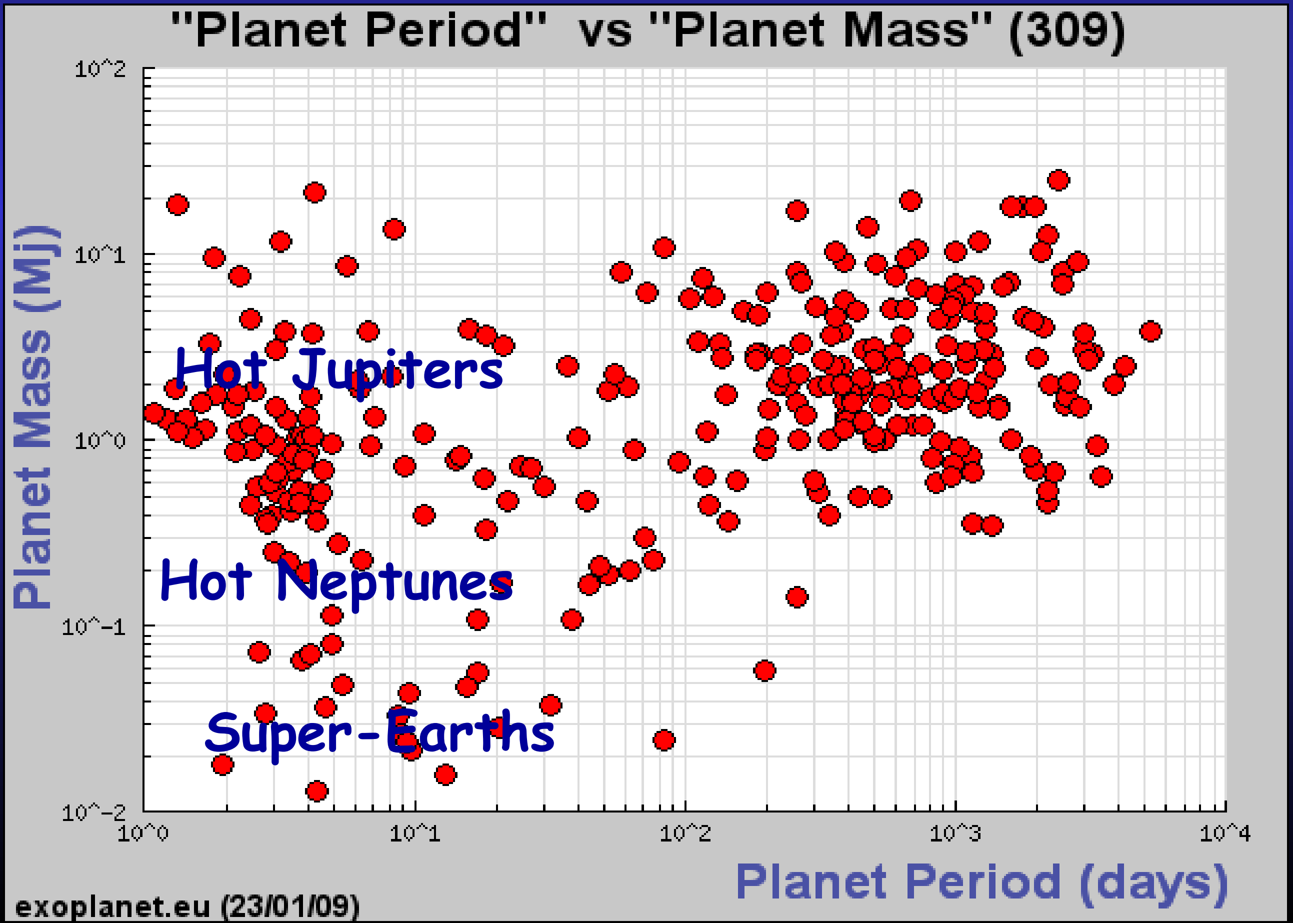


SARG use for asteroseismology campaigns reveals extreme RV performances: nightly averages over a week have dispersions of about 20 cm/s, sensitivity to 2 M_{Earth} planets in short periods

PLANETS PROPERTIES

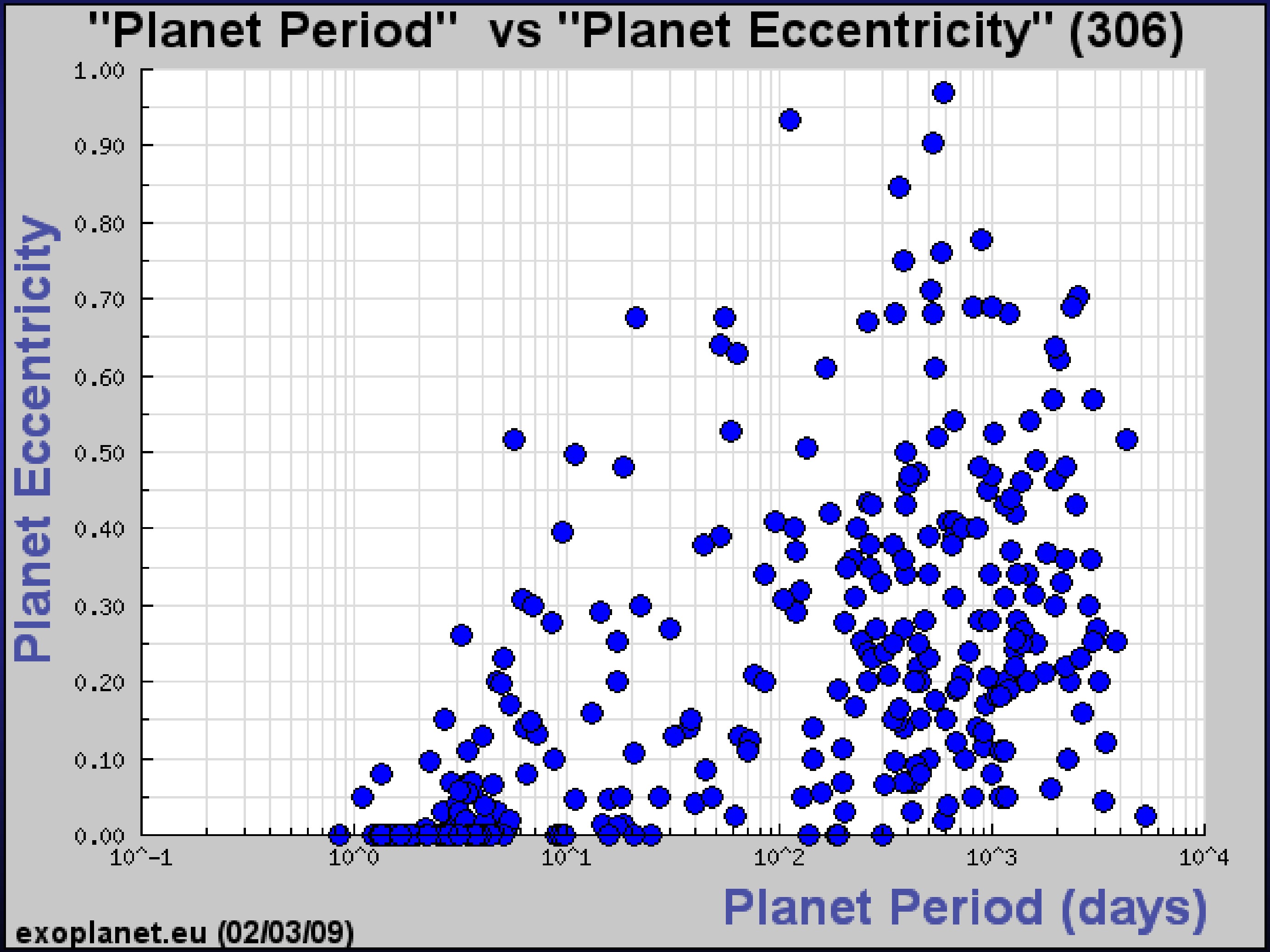
Giant planets in close orbits: orbital migration (migration within protoplanetary disk or planet-planet scattering

Radial velocity barely sensitive to large separation (>5 AU)



PLANETS ECCENTRICITY

Large eccentricities are typical for planets with period longer than 10 days. Eccentricities up to 0.9 observed



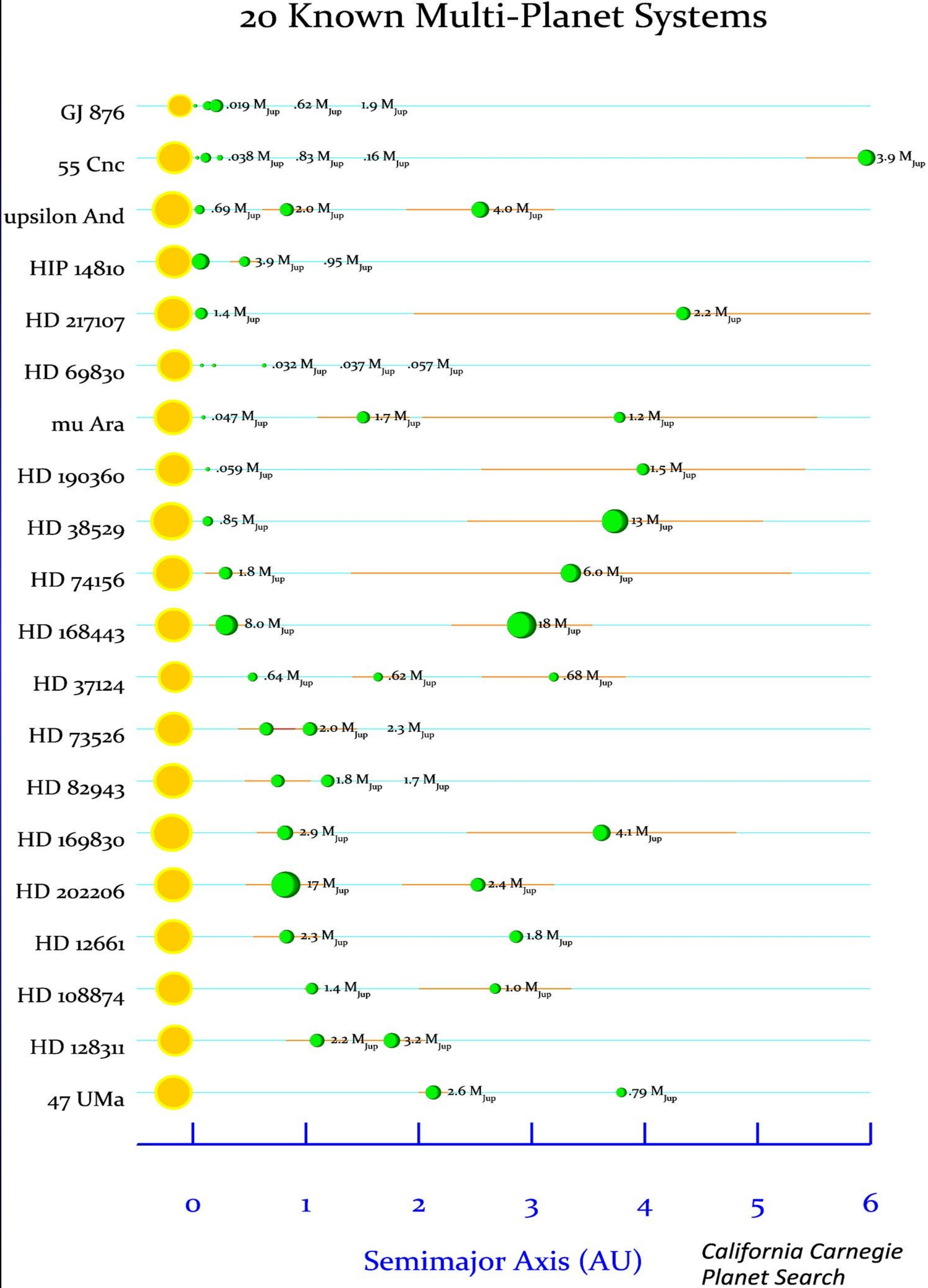
MULTI-PLANET SYSTEMS

>20% of stars with planets have multi-planet systems

Higher multiplicity for neptunes and super-earths (maybe 80%)

Large variety of system configurations (orbital resonances, interacting systems, well separated systems)

55 Cnc: 5 planets



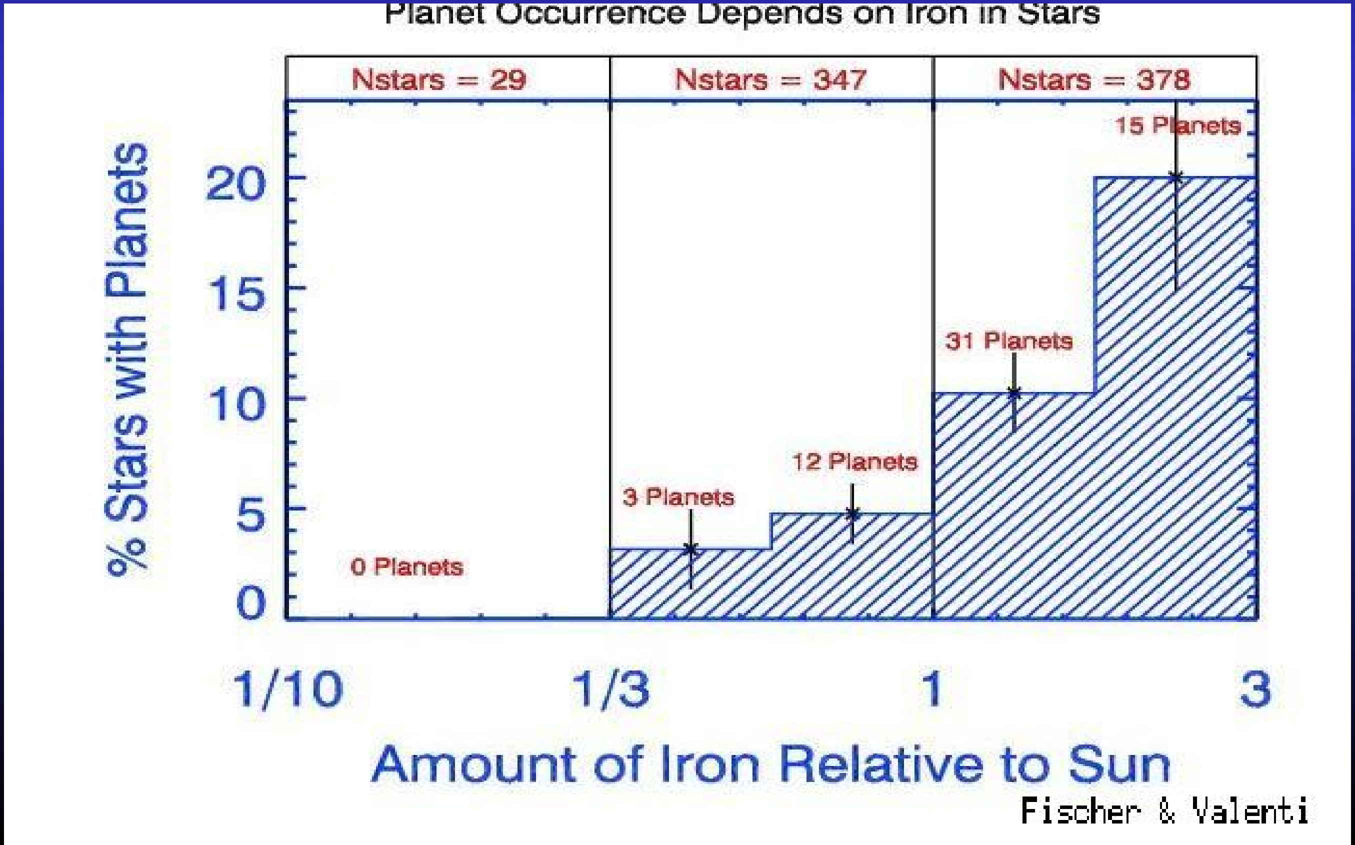
PLANET FREQUENCY

About 10% of solar-type stars host planets more massive than half of a Jupiter mass with period<2000 days

Hot Jupiters: about 0.7%

Strong dependence on metallicity

Super-Earth and Hot Neptunes: rather numerous, 30% ??

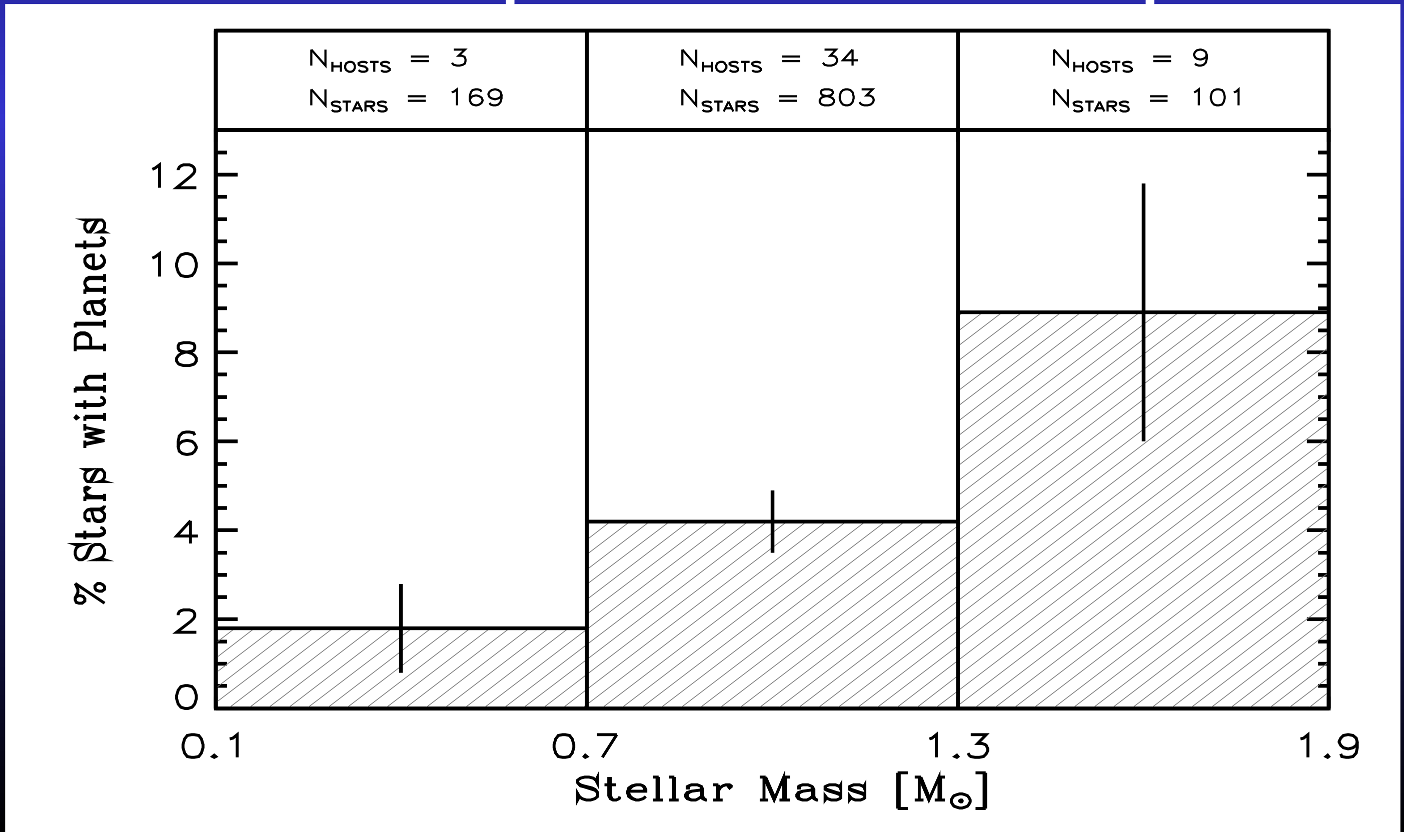


PLANET FREQUENCY

M dwarfs: lower frequency of giant planets (by a factor of 3-10), abundance of low-mass planets

Evolved intermediate mass stars: massive planets are more numerous, no dependence on metallicity, no short period planets (tidal interaction on RGB or different migration history?)

Evidence for mass-dependent outcome of planet formation

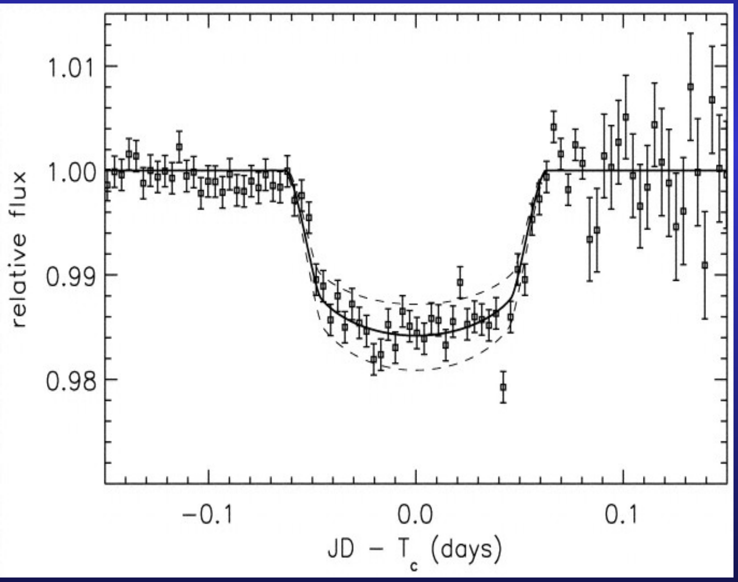


Johnson et al. 2088

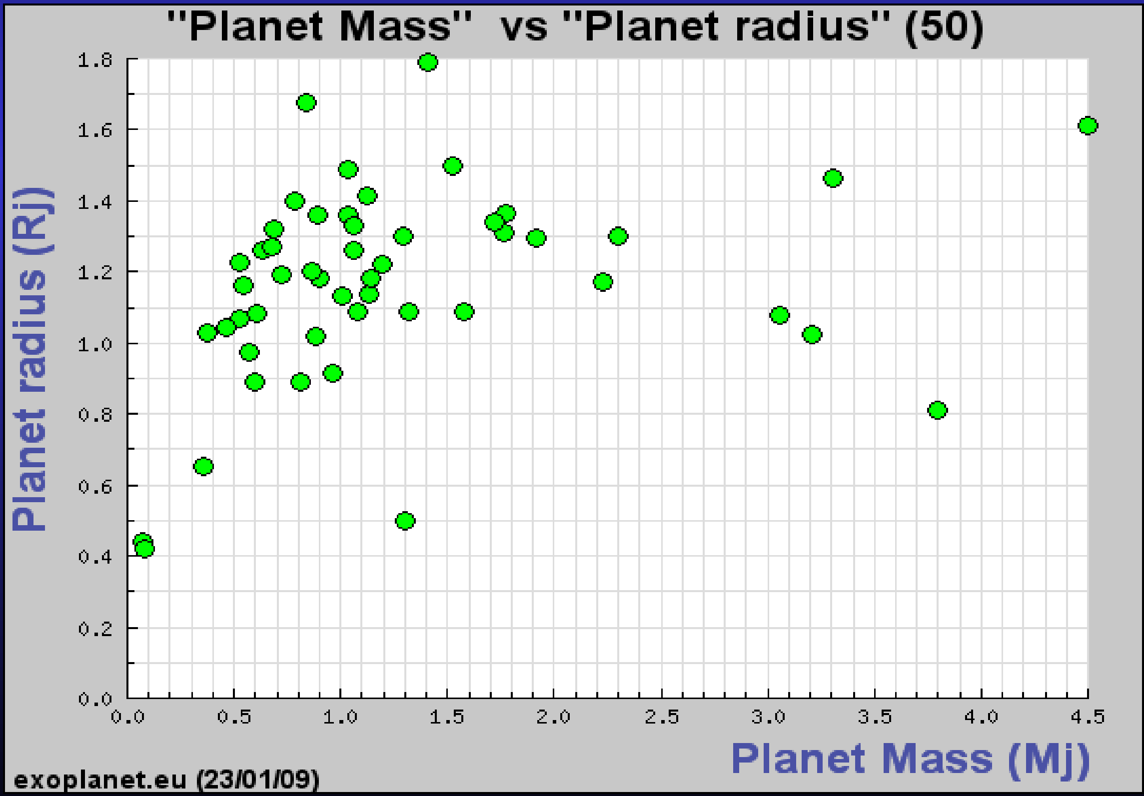
TRANSITING PLANETS

Radius and inclination from transit, projected mass from radial velocity: derivation of mean density of the planet

Significant dispersion in mass-radius relation: core mass, irradiation, extra energy by tides or other causes



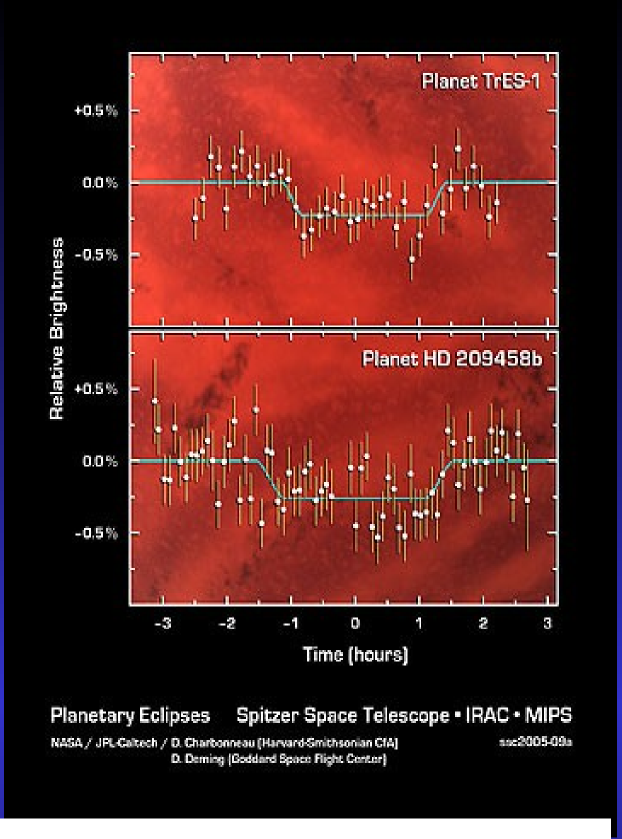
Charbonneau et al. 1999

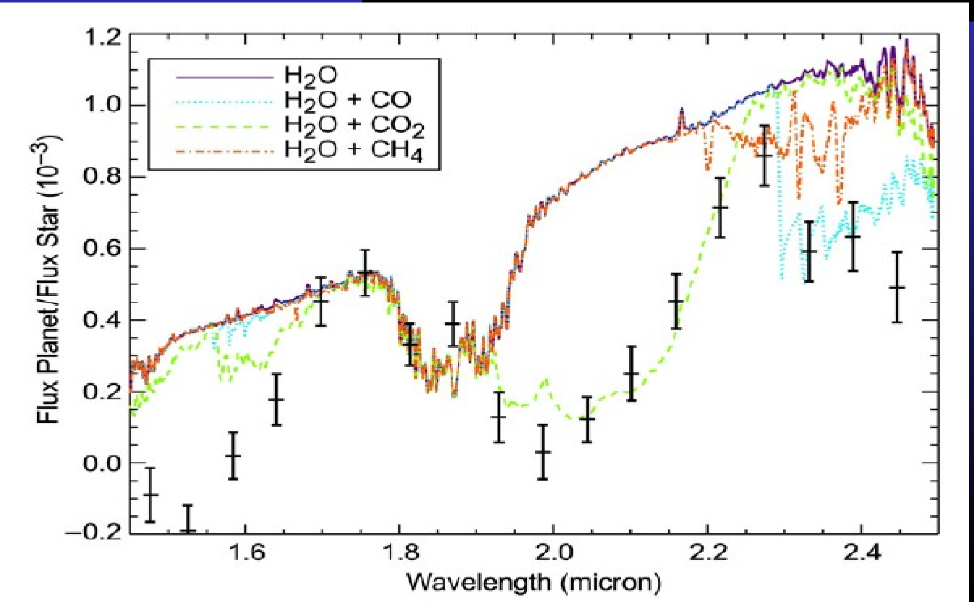


TRANSITING PLANETS

A number of follow-up investigations: start of physical characterization of extrasolar planets

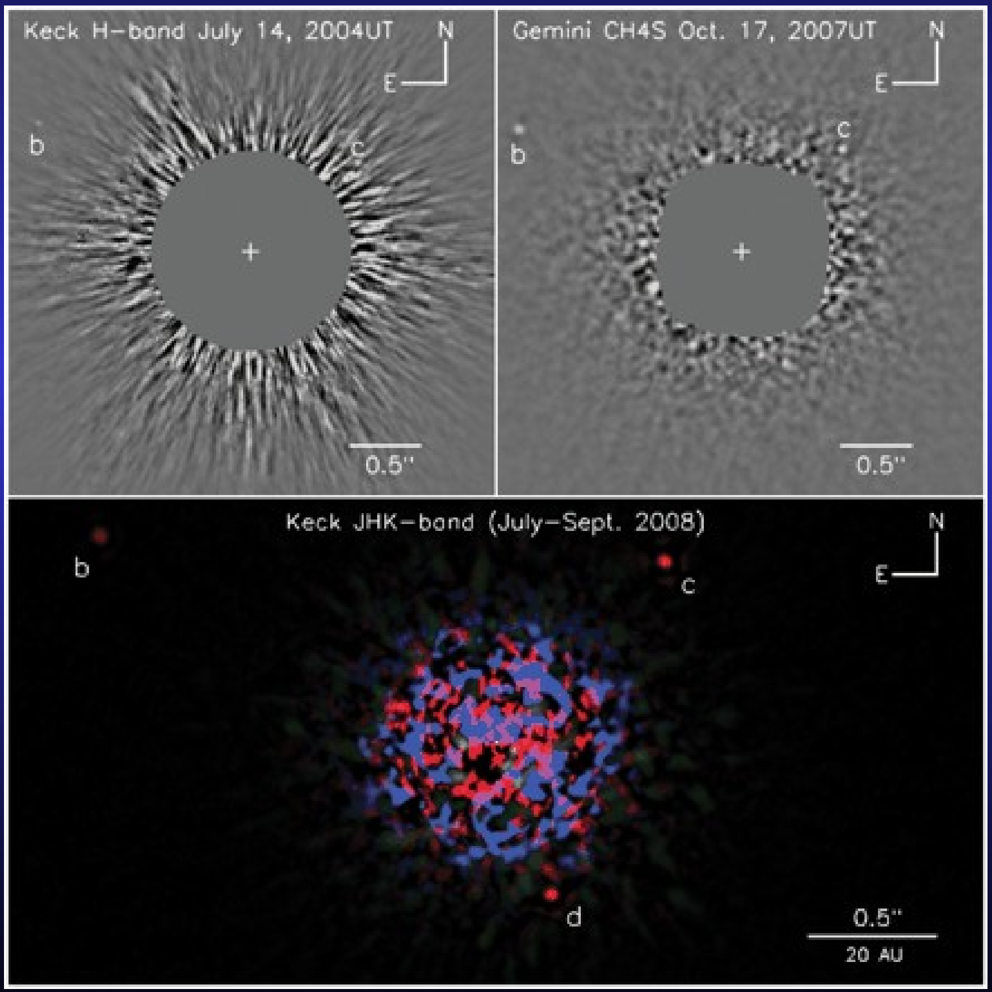
Secondary eclipses, atmosphere characterization, variations along the orbit, geometrical configuration of the system, planet evaporation





DIRECT IMAGING OF PLANETS

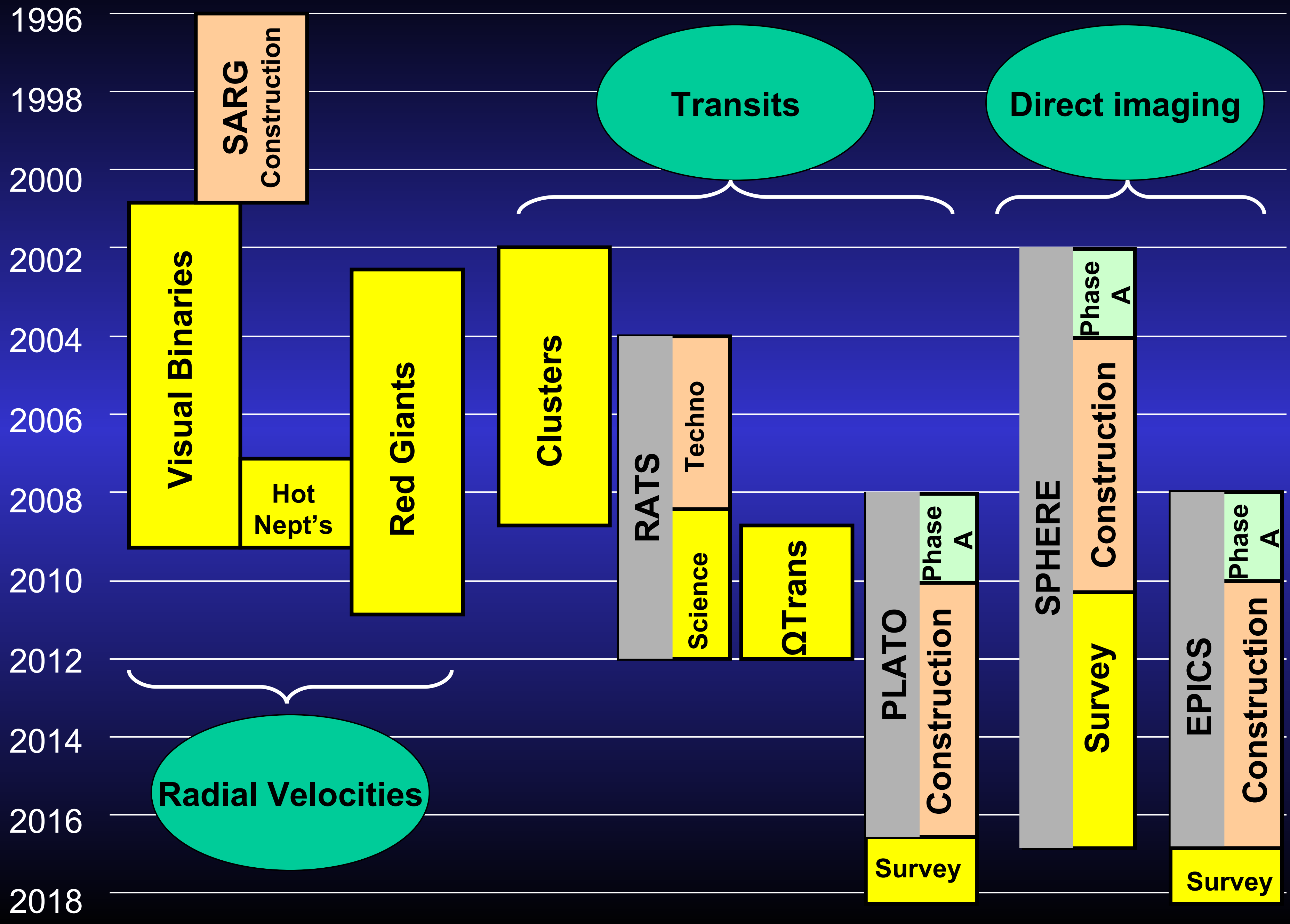
First planet detection in 2008 around 3 intermediate mass stars with debris disks (HR 8799, β Pic, Fomalhaut)



Marois et al. 2008

Previously detection of a few low mass-companions, even of planetary mass but probably formed more as binary stellar objects than as planets (e.g. a 5 MJ companion around a 25 MJ brown dwarf)

Projects on exoplanets at Padova Observatory



PLANETS IN BINARIES: SCIENTIFIC INTEREST

- Relevance for global statistics of planets (more than half of solar-type stars are in multiple systems)
- Study of environment effects on formation and evolution of planetary systems
- Study of accretion of metal-rich planetary material (the physical association between the components ensures a proper reference, not available for single field stars)

Several binaries included in "general" RV surveys

+

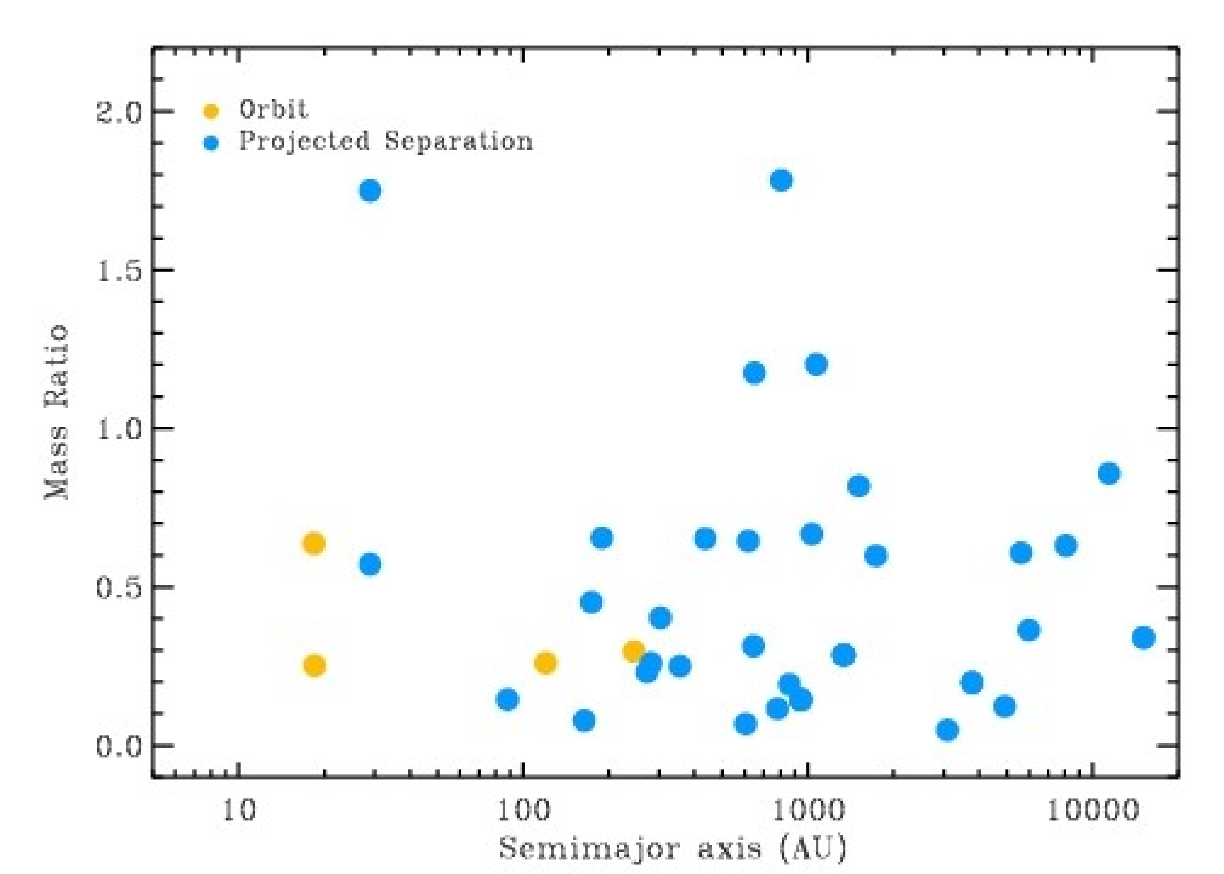
Dedicated RV search for planets in binaries

PLANETS IN BINARIES

20-25% of stars with planets are in multiple systems

Large variety of binary configurations (separation, mass ratio, triple systems, white dwarfs companions)

A few transiting planets in binary systems



PROPERTIES OF PLANETS IN BINARY SYSTEMS

Critical semimajor axis for dynamical stability (Holman & Wiegert 1999) adopted to divide close and wide binaries (it includes both binary orbit and mass ratio)

Desidera & Barbieri2007, based on planet catalog by Butler et al. 2006

- Planets in close binaries (a_{crit}<75 AU, corresponding to separation of about 300-400 AU): different mass distribution. Overabundance of short-period massive planets
- Long period planets (P>40 d): no significant difference in mass distrib. between planets in close, wide bin., single stars
- Period distribution: <u>marginal</u> lack of long period planets around components of close binaries
- Eccentricity distribution: <u>marginal</u> excess of high-eccentricity planets around components of wide binaries (more significant after recent discoveries, Tamuz et al. 2007 ?)
- No multi-planet system in close binaries (sign. 85%), similar frequency of multi-planet systems in wide bin and single stars

Discovery of many new planets and companions of planet hosts
Several new massive hot Jupiters (to be searched for

THE SARG PLANET SEARCH

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THE SARG PLANET SEARCH: LOOKING FOR PLANETS AROUND STARS IN WIDE BINARIES

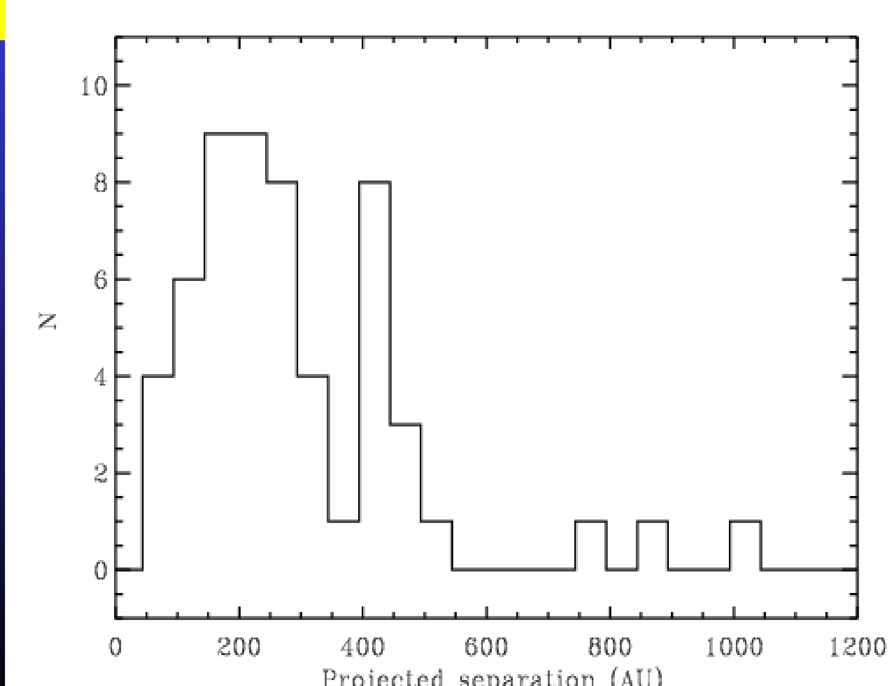
The sample:
50 pairs of moderately wide binaries (typical sep. 200 AU)
Similar components: main sequence late F-G-K stars with magnitude

difference $\Delta V<1$ (useful for the differential abundance analysis)
Separation > 2 arcsec V<10.0
All physical pairs (confirmed by our spectra)

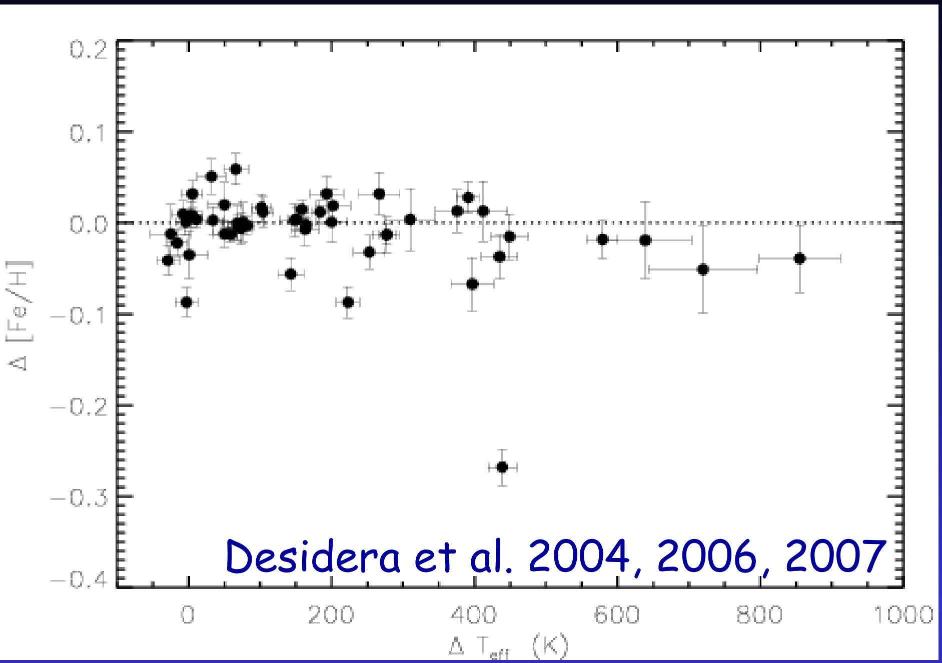
The survey: 7 years (2001-2008)
6-10 nights/semester

about 20 spectra/star on average
Both components under monitoring

resolution spectrograph of TNG).
Iodine cell RV derived using
AUSTRAL code by M. Endl
RV precision: 2-3 m/s for bright
stars, 3-10 m/s for the program
star (V=8-10)



HIGH PRECISION ABUNDANCE ANALYSIS

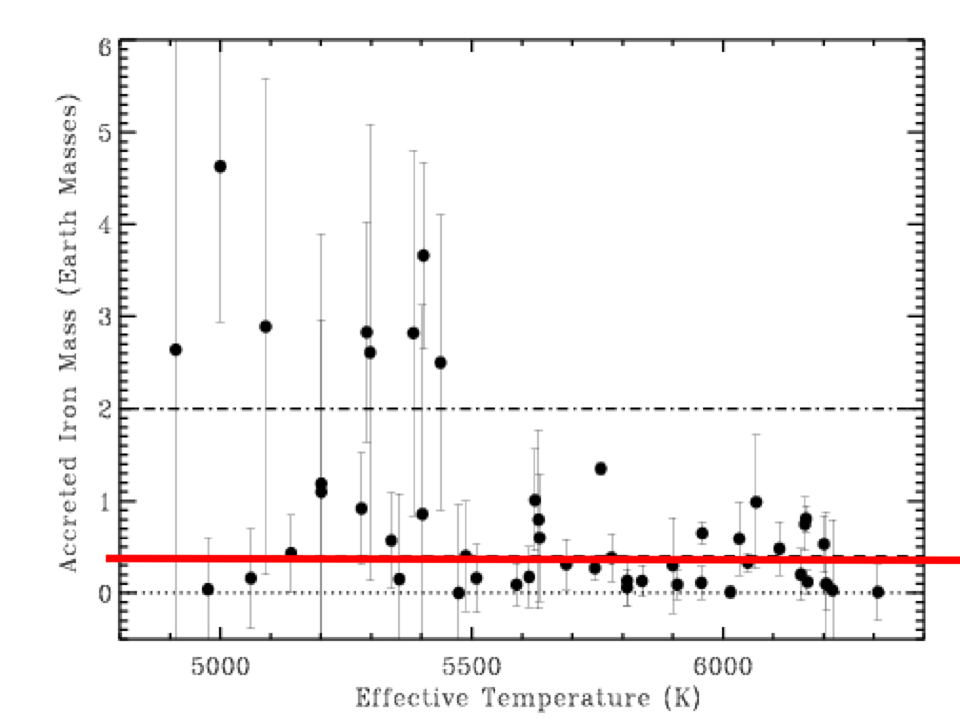


Line by line differential analysis

Errors on Δ[Fe/H] about 0.02 dex

Only one pair with large (>0.1 dex) abundance difference: HD113984, but the primary is a blue straggler (special case, not linked with the evolution of a planetary system ?)

For warm stars (thin convective zones) limits similar to the quantity of meteoritic material accreted by the Sun during its main sequence lifetime (0.4 Earth masses of iron, Murray et al. 2001)



No evidences for large abundance difference between the components with/without planets

CONTAMINATION OF THE SPECTRA

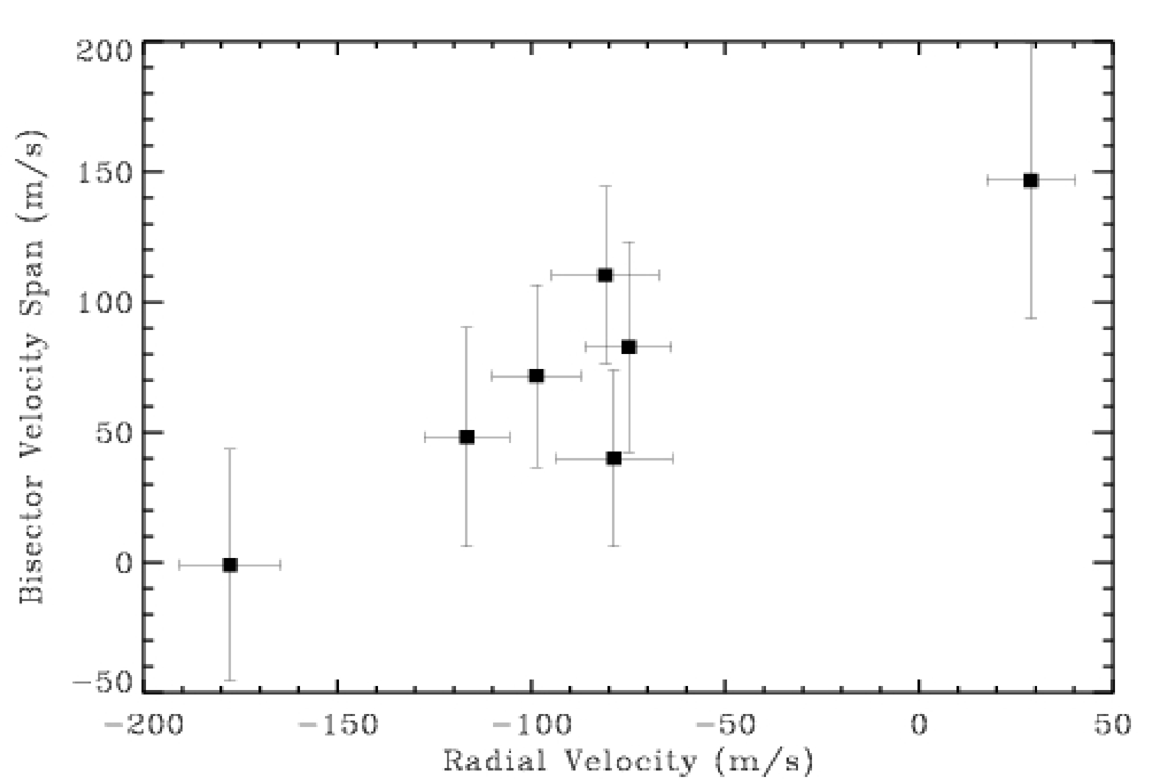
Possible additional source of error for radial velocity measurement <u>not included in internal errors</u> (all the chunks deviate by a similar amount)

How to handle:

1) Closest pairs observed only in good seeing conditions
2) Study of line profile (bisector)
3) Seeing measurement: correlation vs RV, model of expected contamination

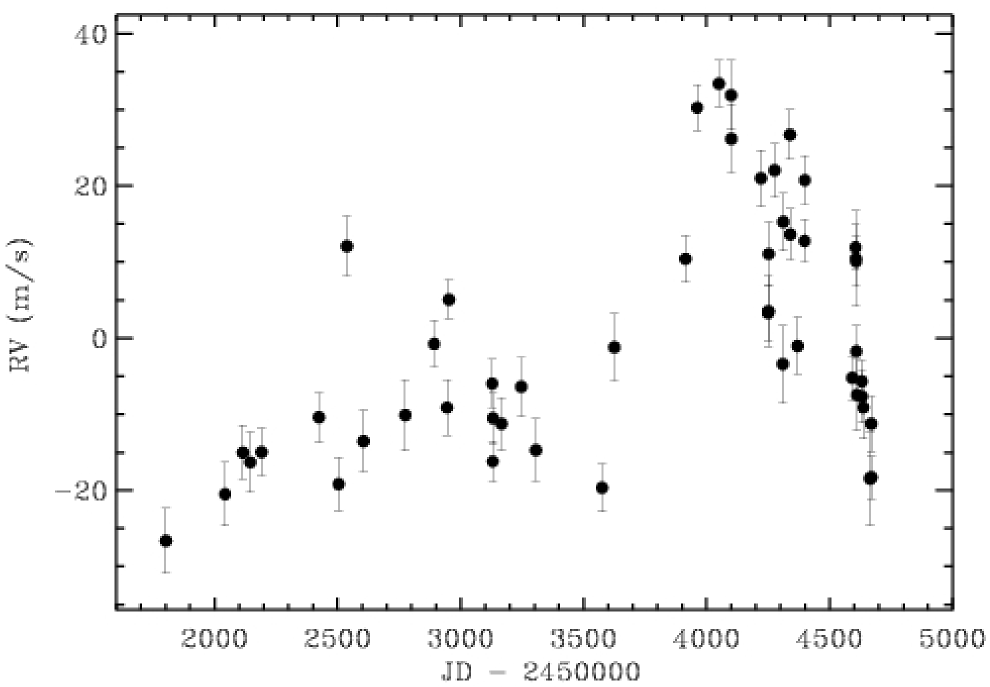
HD 8071 B
the closest pair in our sample (2.1") + contamination at variable velocity
(HD 8071 A is a SB)

Martinez Fiorenzano et al. 2005.

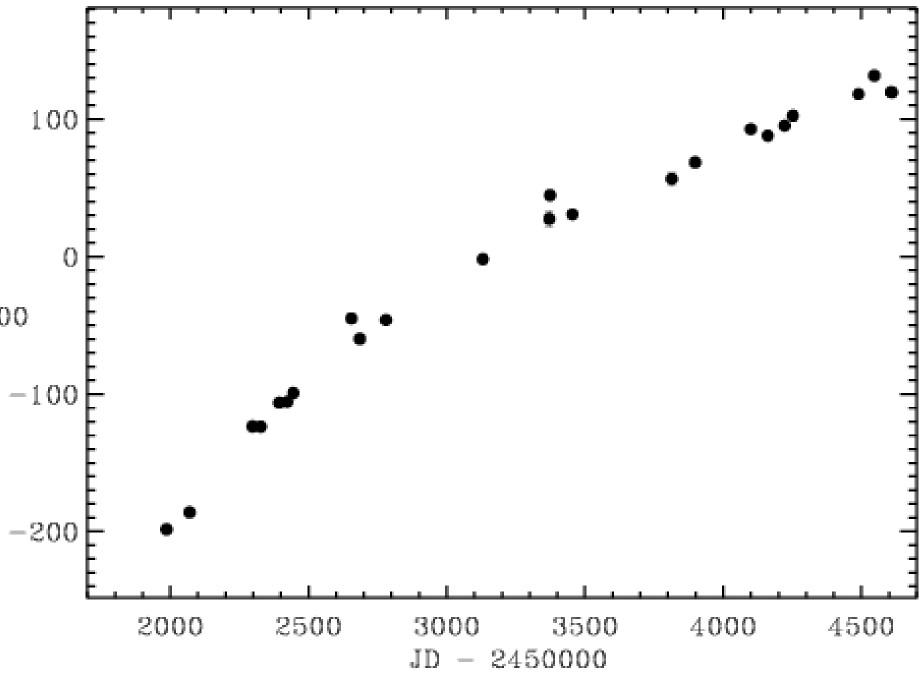


Planet Candidates

Search for periodicities using Lomb-Scargle periodogram + bootstrap to evaluate significance
No short-period planet candidates with FAP<3%
Some long period candidates



Multiplanet system, high eccentricity orbits ?



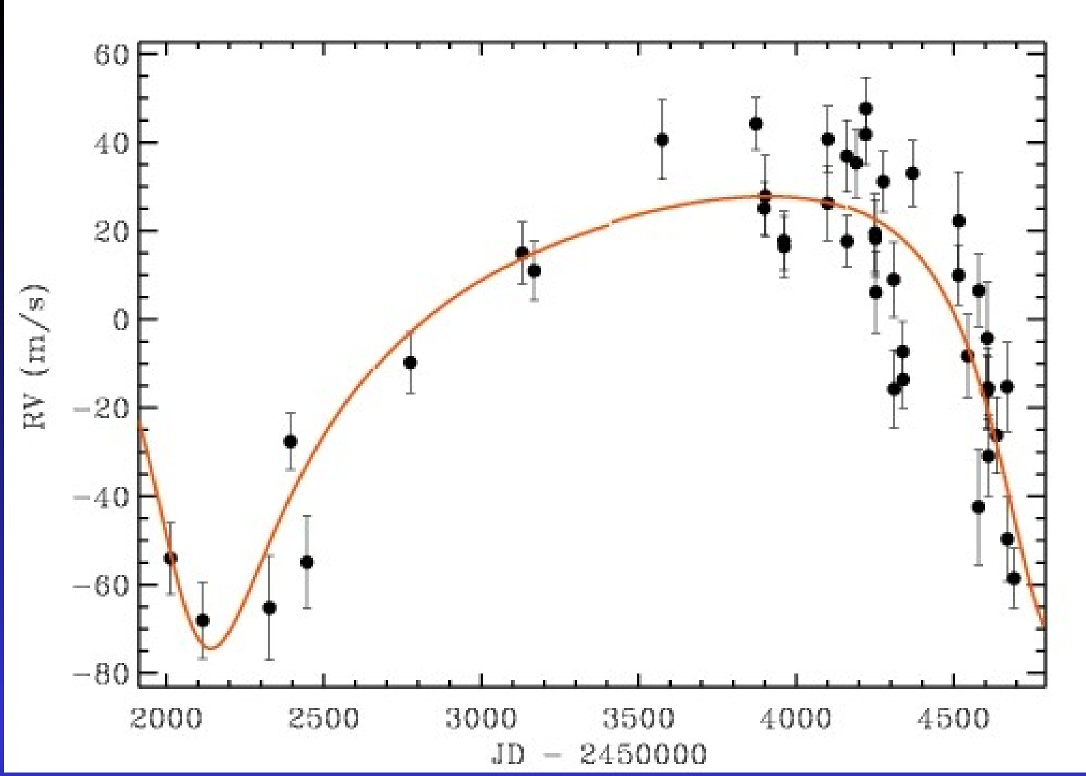
Planetary companion ?
Brown dwarf or low mass star more likely

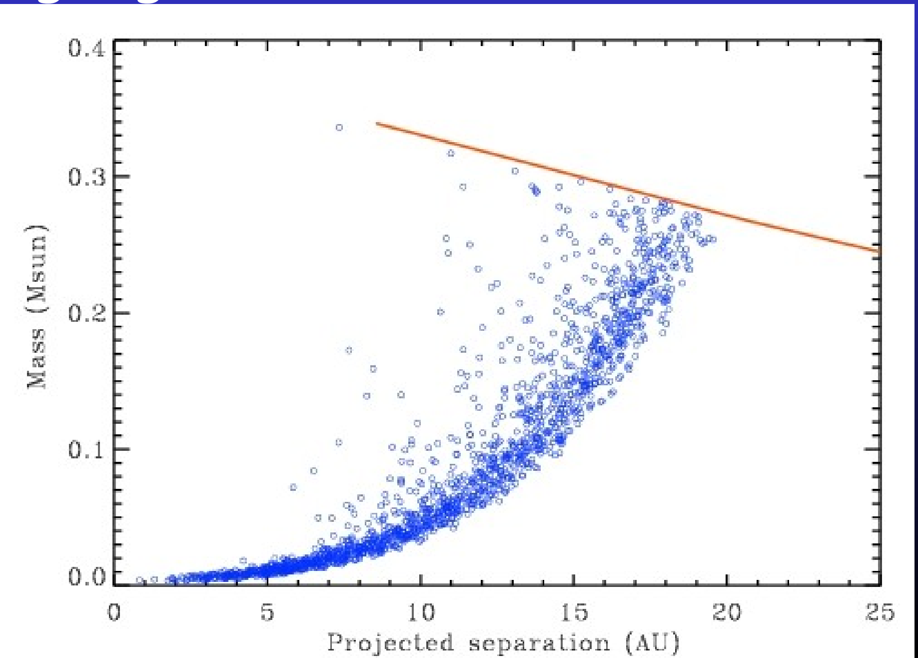
A long period planet candidate

Formal best-fit: P=7.4 y, msini=3.5 MJ, a=4AU

Longer period/larger mass possible: waiting for full orbital coverage

AO Astrometric monitoring on going

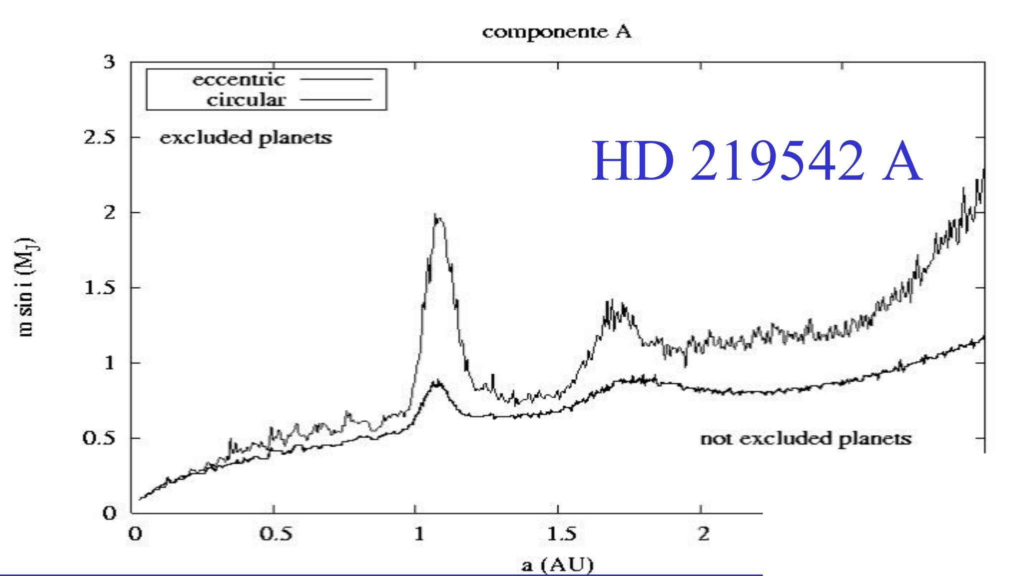




Additional clues on the mass of the companion from adaptive optics observations with AdOpt@TNG

MonteCarlo simulation: companions compatible with both RV signature and AO non detection

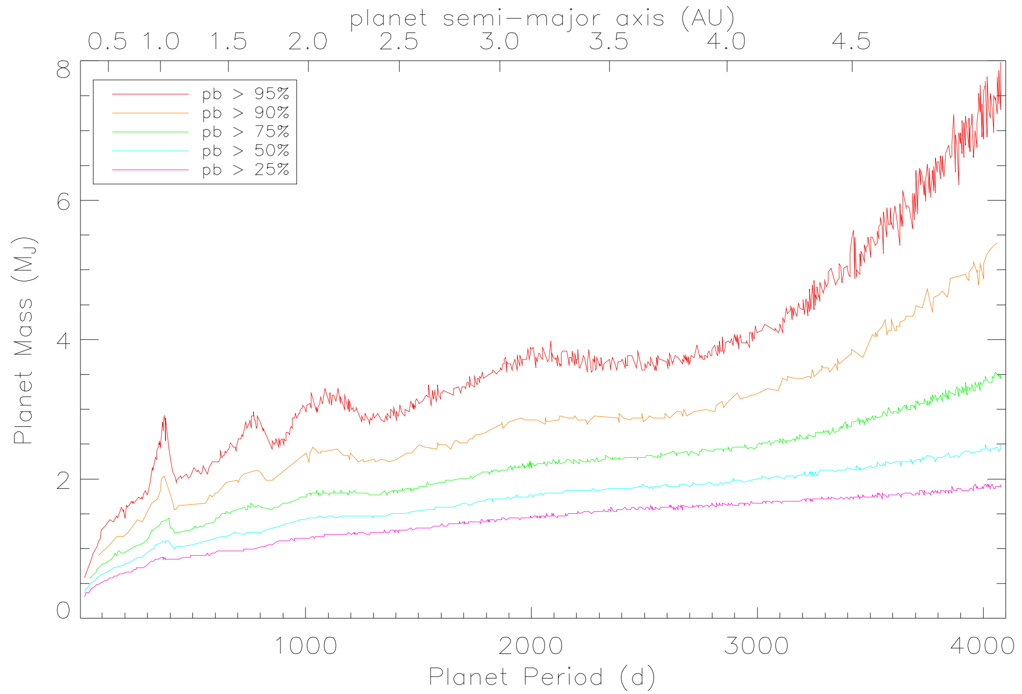
Analysis of negative results:
UPPER LIMITS ON PLANETARY COMPANIONS



- Star-by-star
- Including eccentric orbits

(while most of the similar works in the literature are based only on circular orbits)

General limits for the survey (25-50-75-90-95%, e<0.99)
Detailed statistical analysis in progress, indication for a lower frequency of planets in our sample



FREQUENCY OF PLANETS IN BINARY SYSTEMS

Null results of the SARG Planet search suggests a lower frequency of planets in the kind of binaries we are exploring

More general study of the frequency of planets in binaries performed using the **Uniform Detectability** sample by Fischer & Valenti (2005):

Advantages: completeness of planet detection (RV semiamplitude > 30 m/s, P < 4 yr), large sample size (850 stars)

Drawbacks: bias against binaries with separation < 2 arcsec, incompleteness of binary detections

Compilation of binaries in the UD sample from literature, similar frequencies of planets in single stars and binaries (Bonavita&Desidera2007)

UD sample: smaller planet frequency for a_{crit} < 20-30 AU (a=50-100 AU depending on mass ratio)

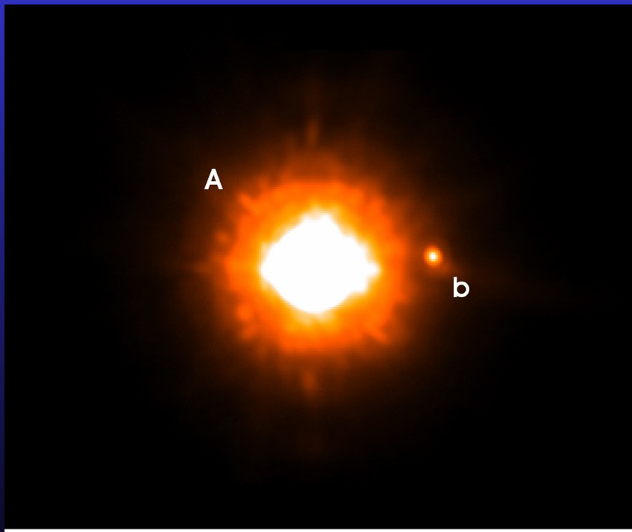
SARG results suggests that a further extension of the zone with a lower frequency (a_{crit} up to about 50 AU). This is probably due to incompleteness of binary detections at intermediate separation in the UD sample (AO needed) or to some effect of the mass ratio (most of the UD binaries have lower mass secondaries, SARG binaries are twins)

SPHERE

Planet Finder for VLT, with the goal of direct detection of extrasolar planets
Very challenging goal: need high contrast at sub-arcsec separation

A brief history:
2002: proposals to ESO
2003-2004: 2 feasibility studies: VLT-PF (LAOG) and CHEOPS (MPIA, including OAPD)
2005: merging of the projects (SPHERE)
Fall 2007: PDR
Fall 2008: FDR

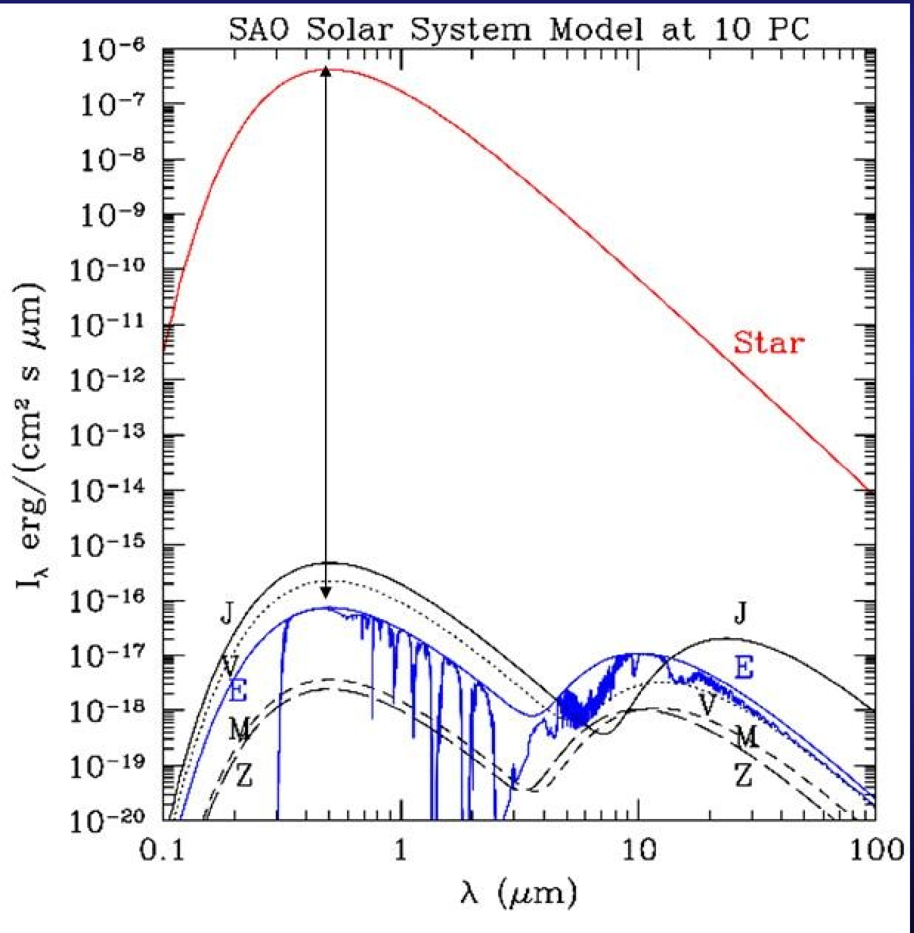
Schedule:
Commissioning: late 2010 / early 2011



The Sub-Stellar Companion to GQ Lupi
(NACO/VLT)
ESO PR Photo 10a/05 (7 April 2005)

SPHERE

The challenge of direct detection



Pianeta	a(AU)	ΔV(mag)	ρ_5(arcsec)	ρ_{10}(arcsec)	ρ_{50}(arcsec)	ρ_{100}(arcsec)
Mercurio	0.39	24.6	0.078	0.039	0.0078	0.0039
Venere	0.72	21.6	0.144	0.072	0.0144	0.0072
Terra	1.00	23.0	0.200	0.100	0.0200	0.0100
Marte	1.52	26.4	0.304	0.152	0.0304	0.0152
Giove	5.20	21.3	1.040	0.520	0.1040	0.0520
Saturno	9.54	22.9	1.908	0.954	0.1908	0.0954
Urano	19.18	26.2	3.836	1.918	0.3836	0.1918
Nettuno	30.06	27.4	6.012	3.006	0.6012	0.3006
Plutone	39.44	33.7	7.888	3.944	0.7888	0.3944

Luminosity Contrast

Jupiter/Sun = 10-8 = 20 mag

Earth/Sun = 10-10 = 25 mag

Angular Separation:

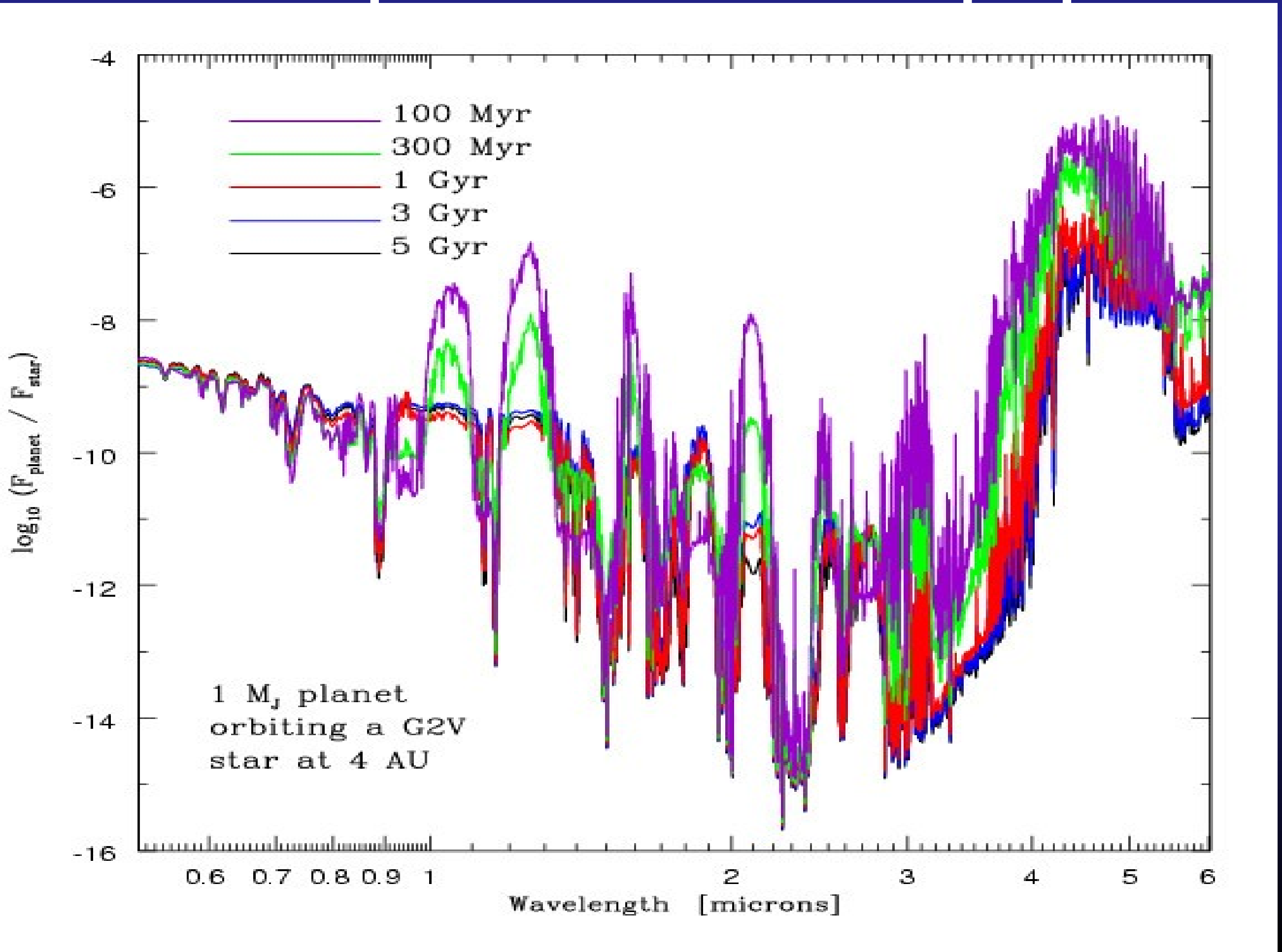
Jupiter = 0.5 arcsec @ 10 pc

Jupiter = 0.1 arcsec @ 50 pc

SPHERE

YOUNG PLANETS ARE MUCH BRIGHTER

Nearby, young stars best targets for direct detection of extrasolar planets: dedicated preparatory work on going



Burrows et al.

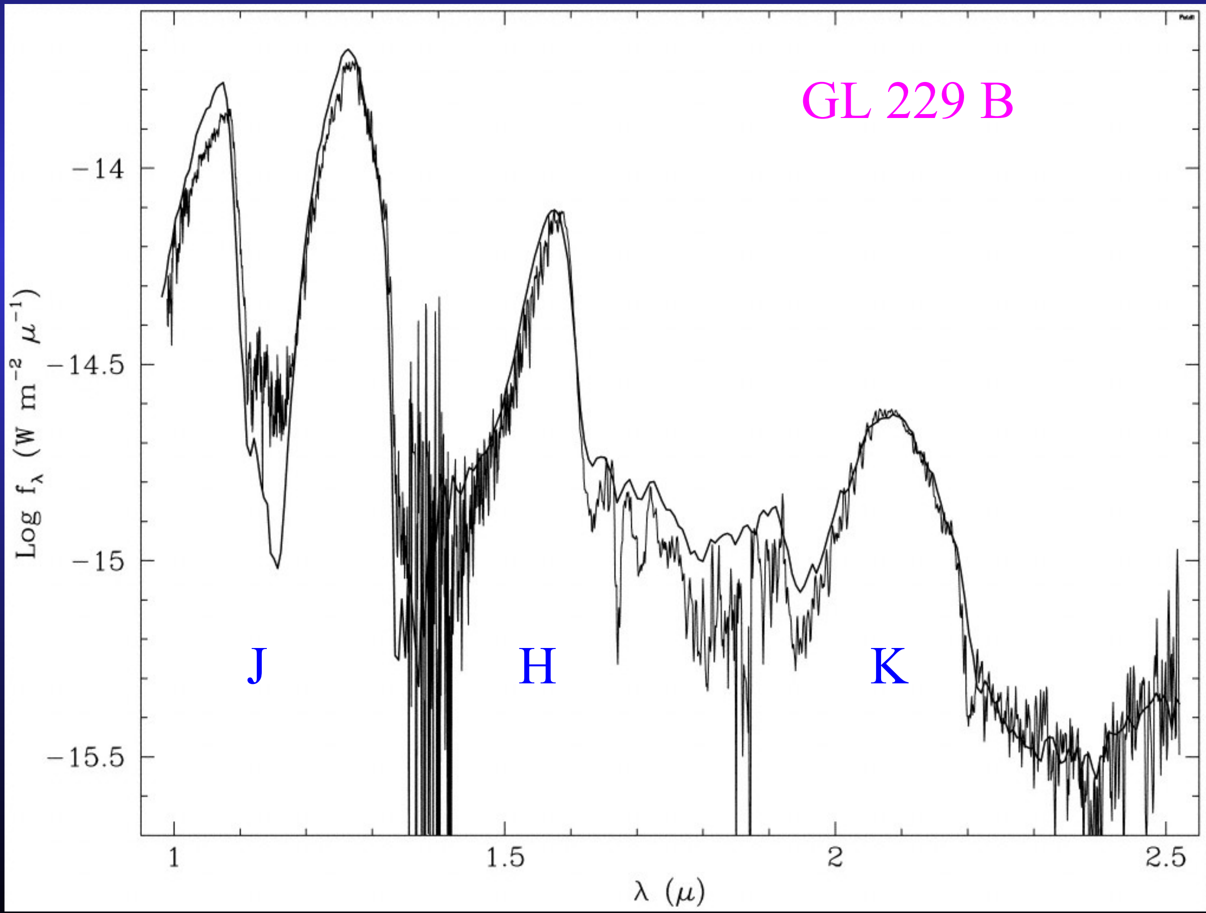
SPHERE

SPECTRAL ENERGY DISTRIBUTIONS

Intrinsic emission peaks at infrared wavelengths as the object cools but with very strong effects due to molecular bands and clouds.

Fluxes of substellar objects may be different by orders of magnitude with respect to black bodies of the same temperature

At Teff < 1300 K (spectral type T) methane absorptions dominate the near-infrared spectrum. Very useful features for planet detection



Oppenheimer et al. 1998

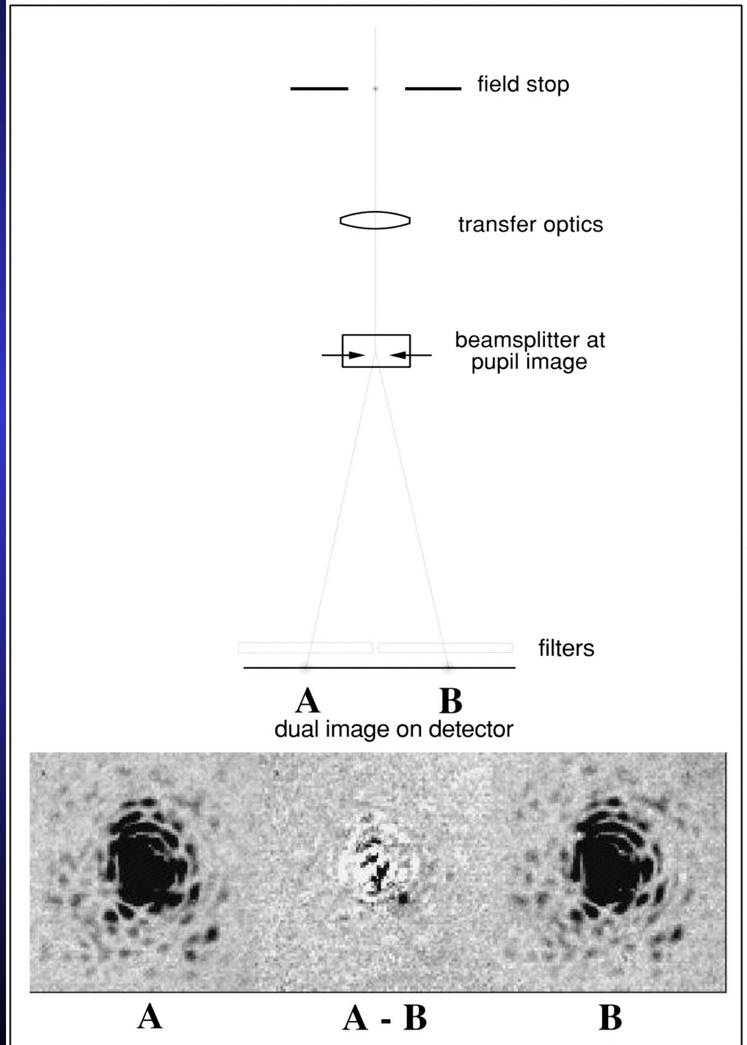
SPHERE

Simultaneous differential imaging

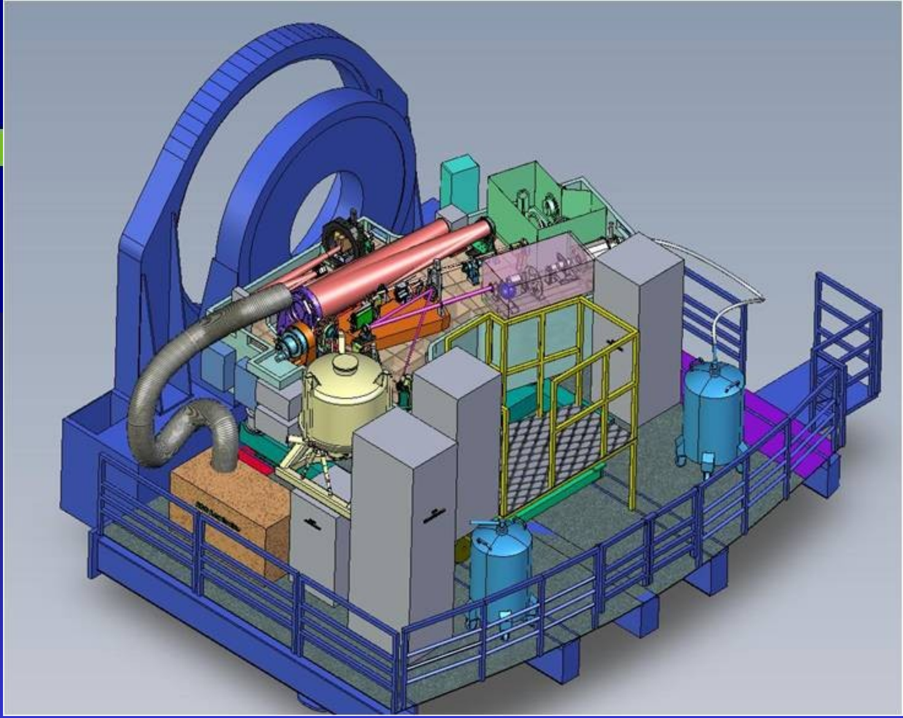
Concept: images taken simultaneously at two close wavelengths have similar speckle pattern, their difference allow to partially remove it.

If the companion has flux in only one the two bands, it can be detected in the differential image.
Methane absorptions in planet atmospheres: ideal spectral features for differential imaging

Integral field spectroscopy: generalization to several wavelengths, S-SDI (spectroscopic SDI)



Racine et al. 1999



SPHERE concept

The very challenging science goal of direct detection of planets requires a fully optimized instrument

▪ Extreme adaptive optics
▪ Coronagraphy
▪ Differential imaging to remove speckle noise: three instruments optimized for different types of planets (young, self-luminous planets, old planets shining in reflected light)
➢ IFS: spectral differential imaging Y-J-H bands (best contrast)
➢ IRDIS: differential imaging in H band over a wide field
➢ ZIMPOL: differential polarimetry in R-I bands for detection of reflected light
▪ Dedicated instrument modes for planet characterization

SPHERE

SPHERE Consortium

LAOG (PI), MPIA, LAM, ONERA, LESIA, INAF, ETH-Zurich, Geneva Obs., LUAN, ASTRON, UvA, ESO

INAF-OAPD role in SPHERE

- Responsible for the IFS channel
  (the most promising in terms of contrast and planet detection)
- Coordination of INAF contribution (Padova, Catania, Napoli, Milano)
- Responsible for instrument software (A. Baruffolo)
- Relevant role in the science group and in the preparation of the GTO survey (260 VLT nights)

SPHERE

SPHERE-IFS

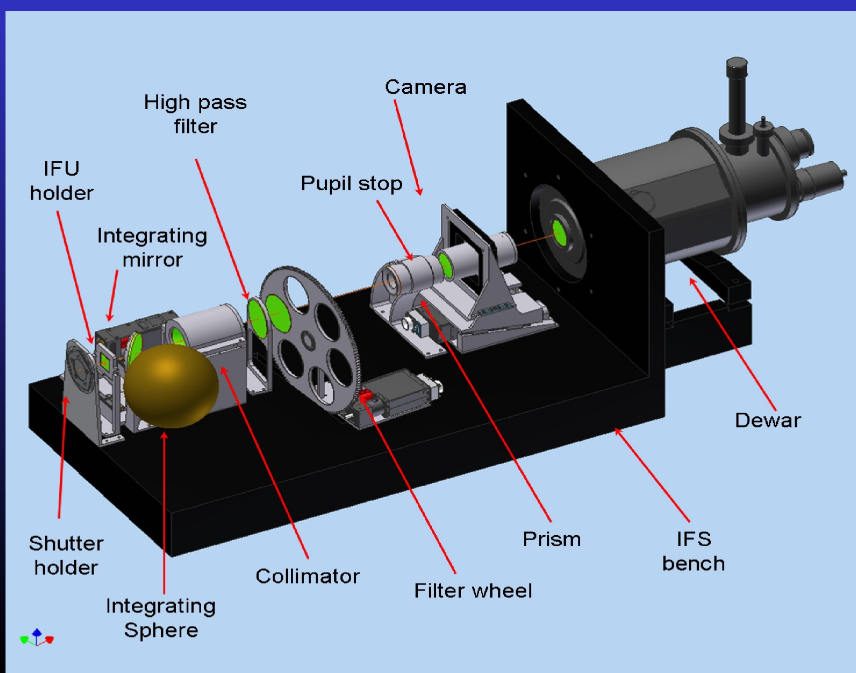
Co - I M. Turatto OAPD	PM & SE R. Claudi OAPD	Instr. Sci. R. Gratton OAPD
QA E. Giro OAPD		Instr. Control E. Cascone OANA

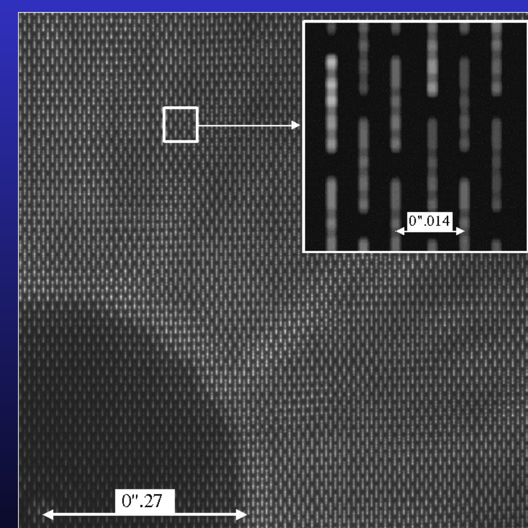
Optics J.Antichi OAPD	Detectors S. Scuderi OACT	Cryo P.Bruno OACT	Mechanics V. De Caprio IASF-MI	DR & Calib S. Desidera OAPD

SPHERE

SPHERE-IFS

- Low resolution spectroscopy (R=54 between 0.95 to 1.35 µm or R=33 between 0.95 to 1.70 µm) over a field of view 1.8x1.8 arcsec
- New concept of the microlens array (BIGRE) allows very low cross-talk level (Antichi et al. 2009)
- Availability of multiple wavelengths allows the achievement of better contrast with respect to standard differential imaging
- IFS spectra will also allow some physical charcacterization





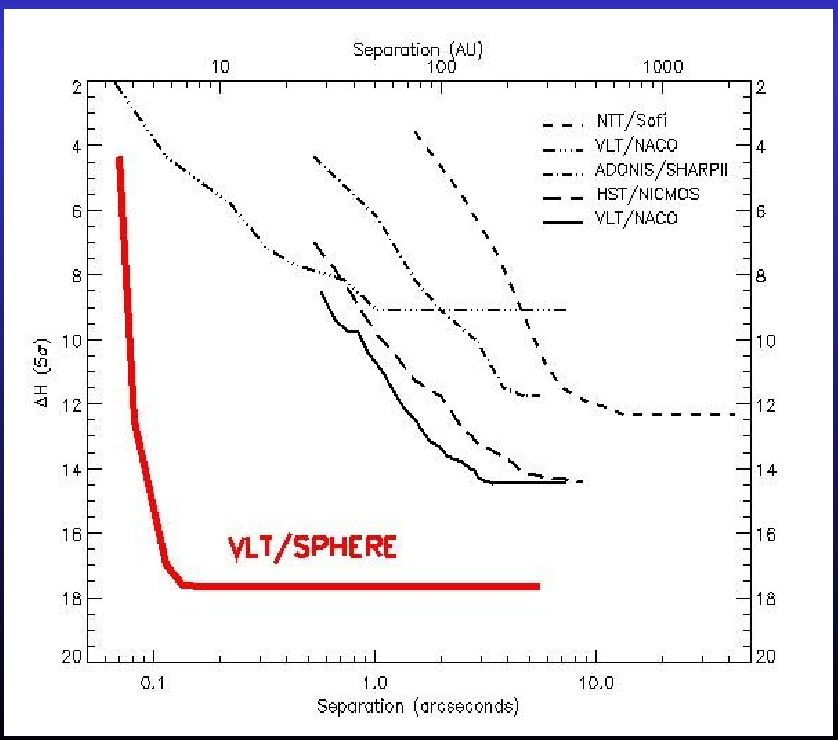
Simulated images

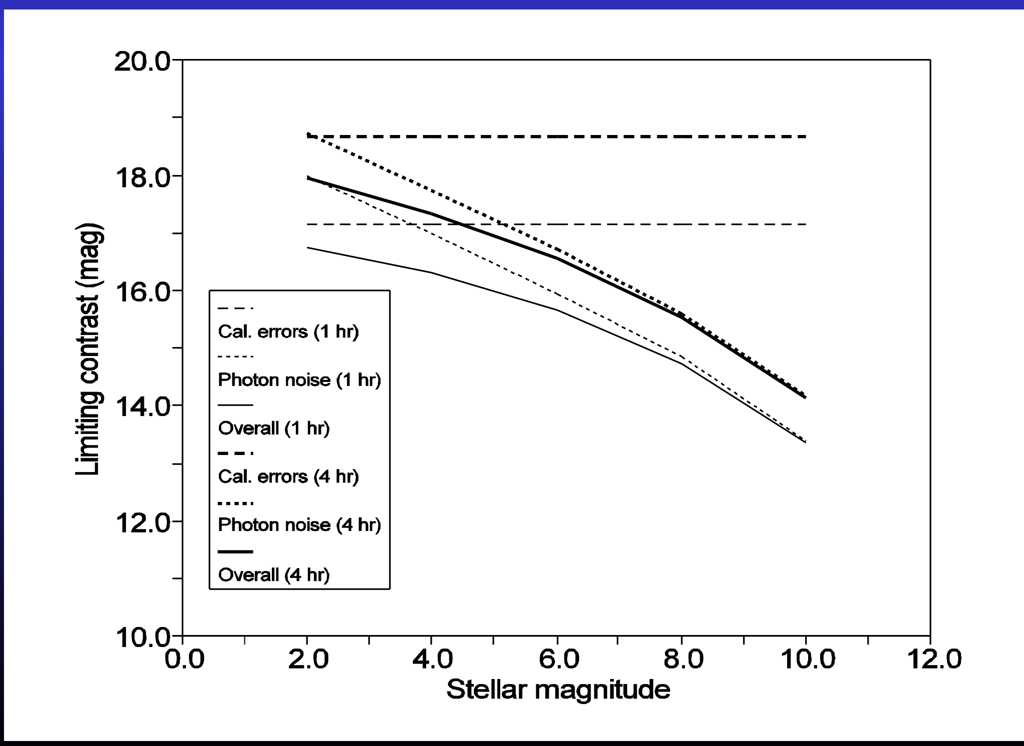
Berton et al. 2006, Mesa et al.2007

SPHERE

SPHERE performances

- Contrast of 16 mag at 0.5 arcsec from a J=5 star
- Improvement of 2 orders of magnitude with respect to current instrumentation
- *AO mag limit R=9*

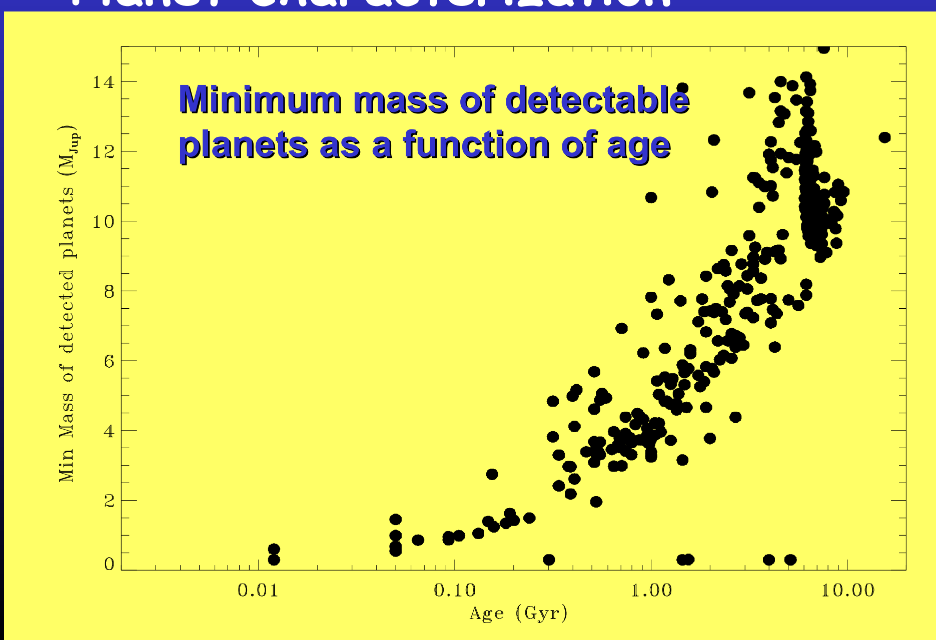


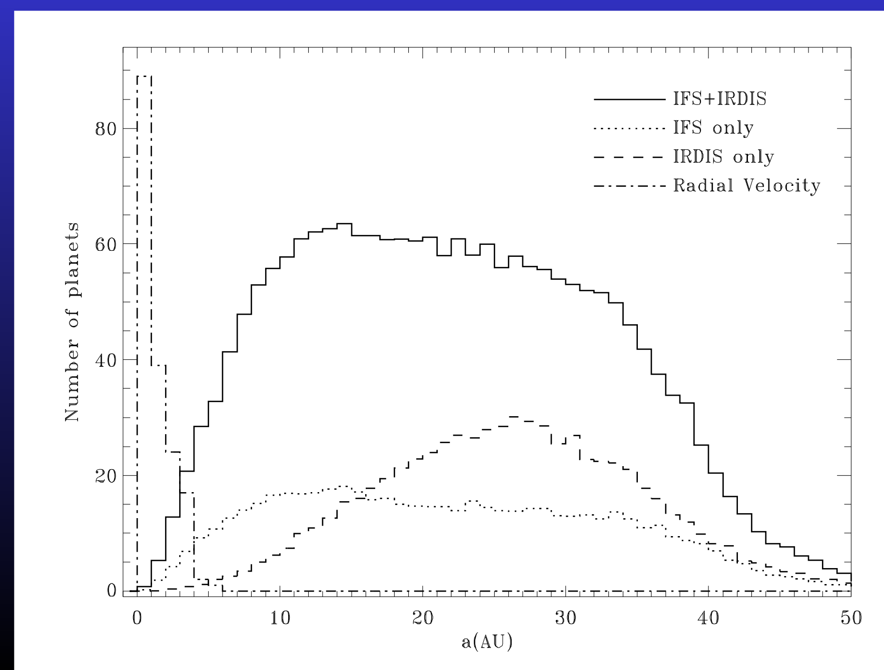


SPHERE

SPHERE science impact

- Direct detection of few tens of giant planets, mostly of rather young age
- Determination of the frequency of giant planets at wide separations
- Dependency on stellar properties (e.g. stellar mass)
- Detection of a few planets discovered by radial velocity
- Planet characterization



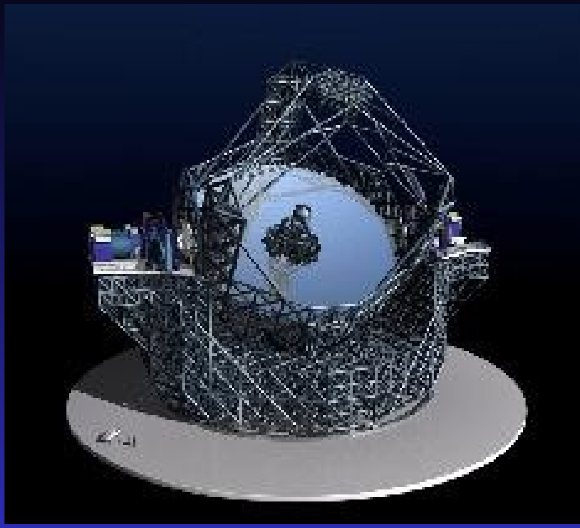


SPHERE

SPHERE GTO Survey

- 260 GTO nights to compensate manpower and funding by the SPHERE Consortium
- GTO organized at Consortium level (not divided in chunks between institutes/countries)
- Homogeneous NIR survey using simultaneously IFS in Y-J bands and IRDIS in H band (at least 200 nights)
- Sample of about 400 stars younger than 1 Gyr divided in bins of different mass and age + stars with RV signatures
- Main science goal: determination of the frequency of giant planets at separation larger than 5-10 AU
- Some overlap with RV should allow full reconstruction of the run of planet frequency with separation from the central star
- Exploration of different stellar masses

EPICS:
a planet finder for E-ELT



Consortium:
ESO (PI), LAOG, LAM, LESIA, LUAN,
Oxford Un., INAF-OAPD, ETH Zur.

2-year Phase A study funded by FP7 and ESO (2008-2009)

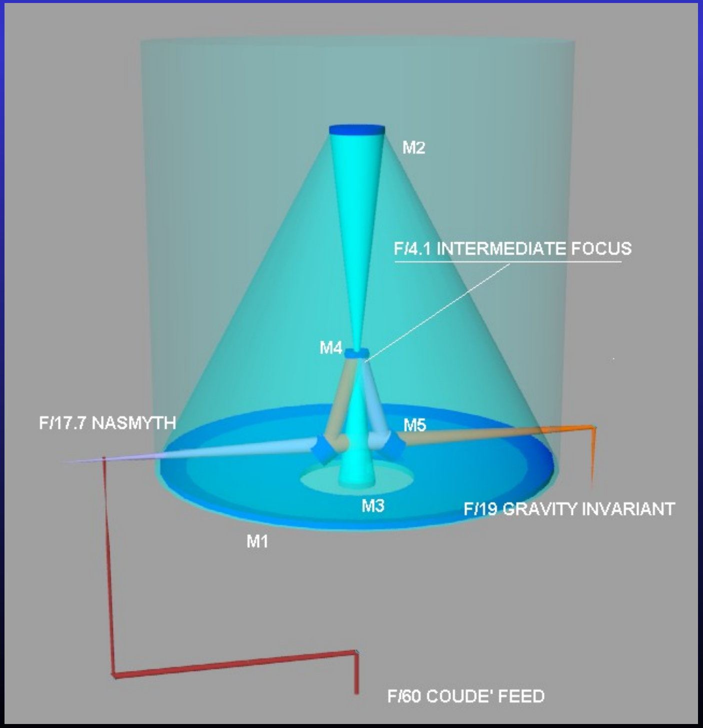
Role of INAF-OAPD:
- Science (R. Gratton chairman of SG, S. Desidera, M. Bonavita)
- Participation to the design of the Integral Field Spectrograph
  in collaboration with Oxford University (J. Antichi, R. Gratton,
  R. Claudi, D. Mesa)

Schedule: 2008-2009 Phase A
2017 on sky

EPICS science goals

- Detection of giant planets in star-forming regions
- Detection of mature giant planets (reflected light), including planets detected by radial velocity
- Physical characterization of giant planets
- Detection of Neptune and Earth-mass planets around nearby stars

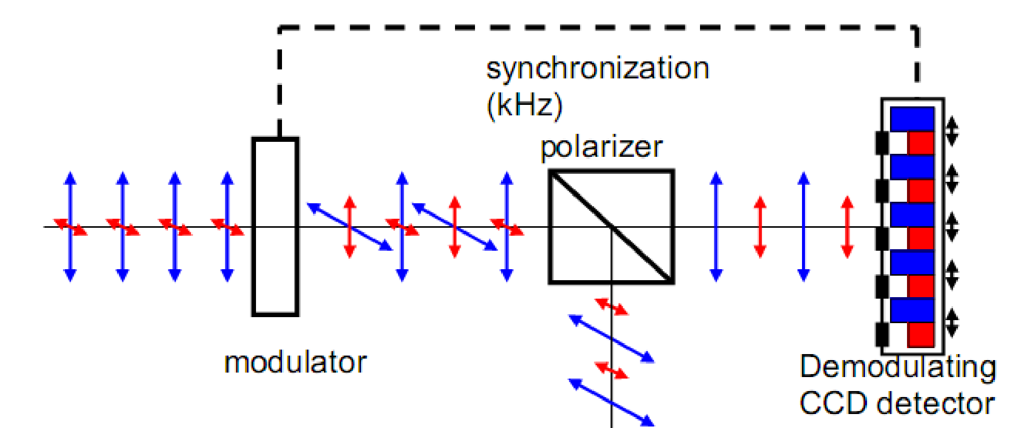
The direct detection of planets is the strongest science case to push for a 40 m-telescope.
EPICS Phase A will provide inputs for telescope design



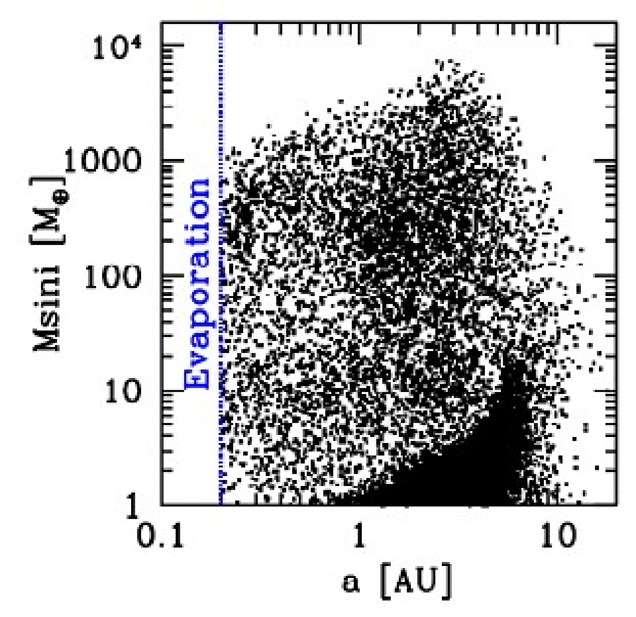
2 baseline instruments

1. Integral Field Spectrograph
- Y-H
- R ~50-100
- FoV ~2 arcsec
- Data cube
- Trade-off slicer vs lenslets (FP7 breadboards)

2. Differential polarimeter
- 600-900 nm
- FoV ~2 arcsec
- Achromatic
- Temporal modulation
- (Close to) zero differential aberrations

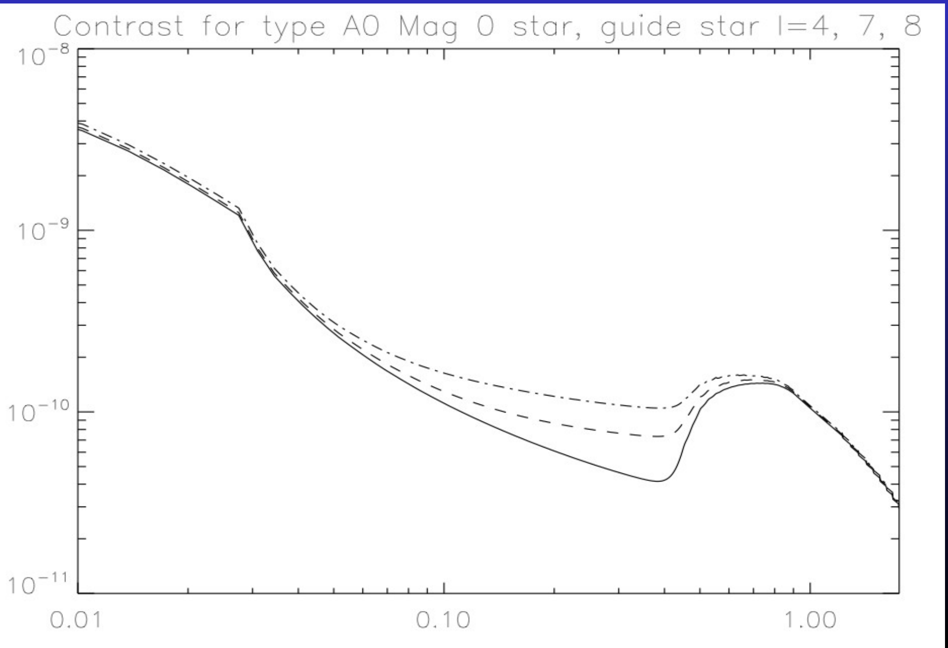


Predicted Science Output



Monte Carlo simulations

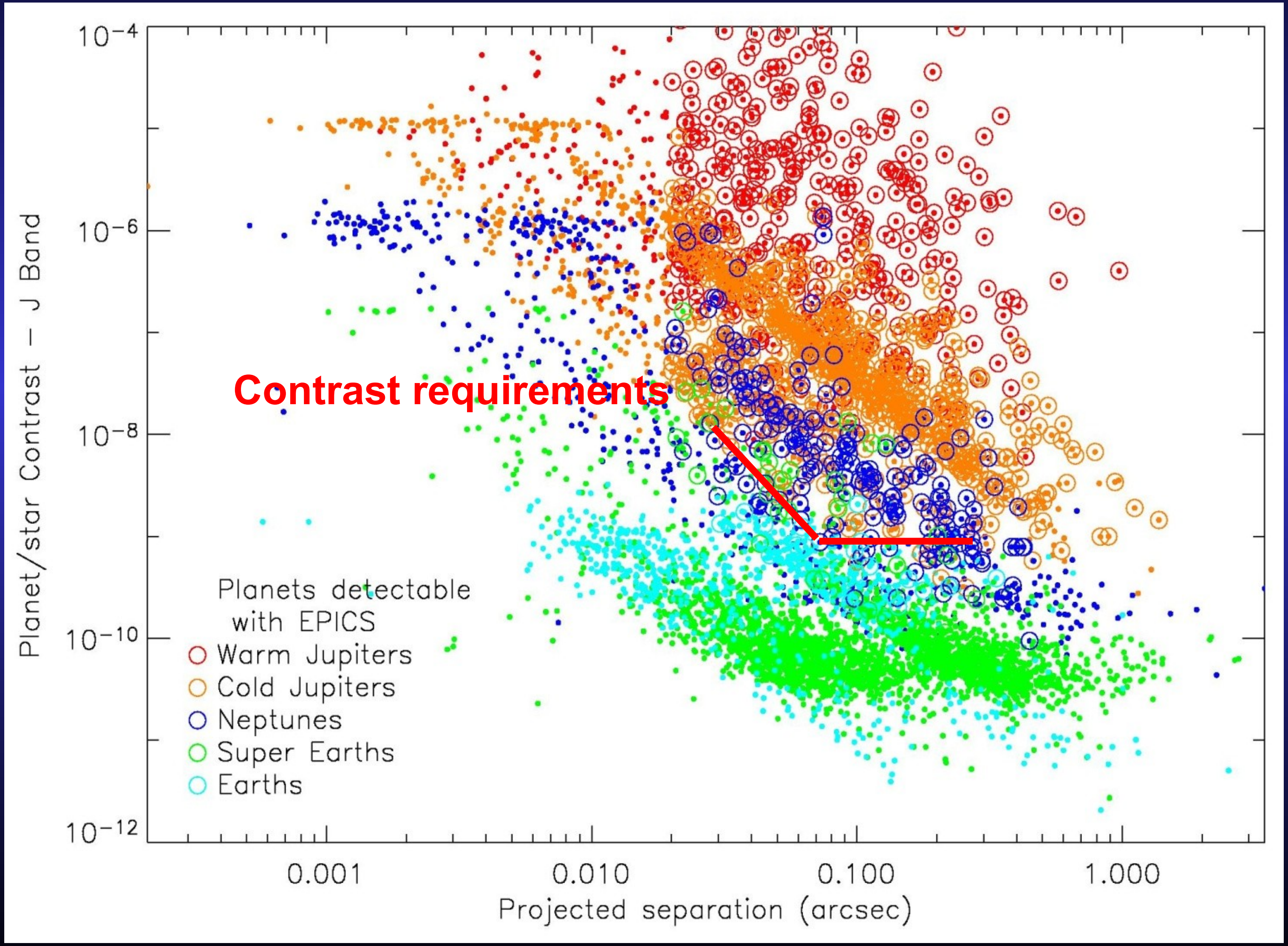
- planet population with orbit and mass distribution from e.g. Mordasini2007
- Model planet brightness (thermal, reflected, albedo, phase angle,…)
- Match statistics with RV results



Contrast model

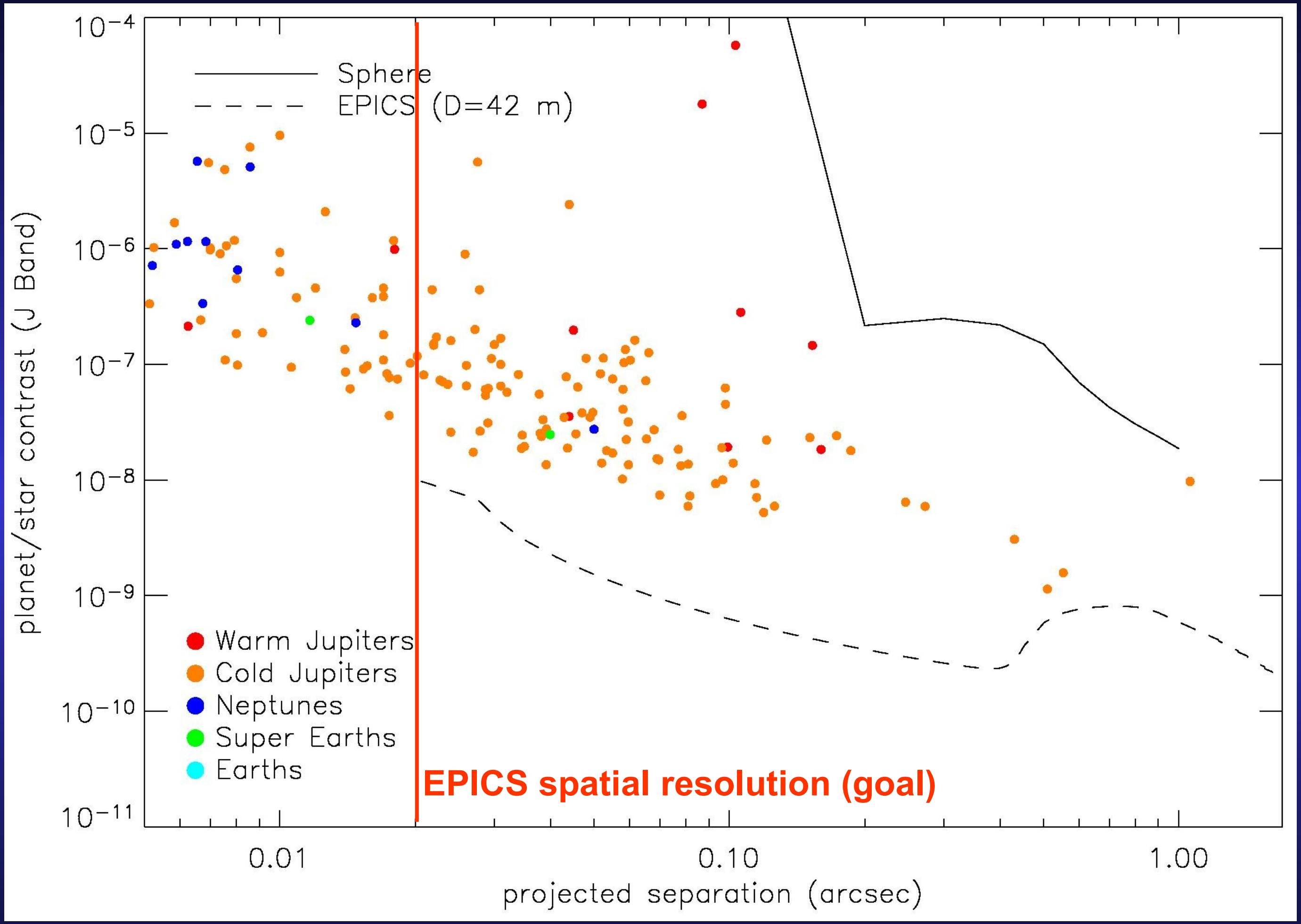
- Analytical AO model incl. realistic error budget
- Spectral deconvolution
- Perfect Coro + statics corr.
- Y-H, 10% throughput, 4h obs

Detection rates, nearby+young stars

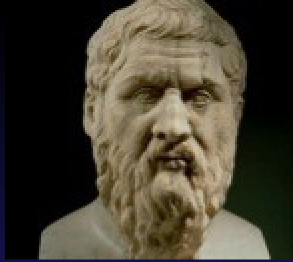


Mordasini et al. 2007

Known planets

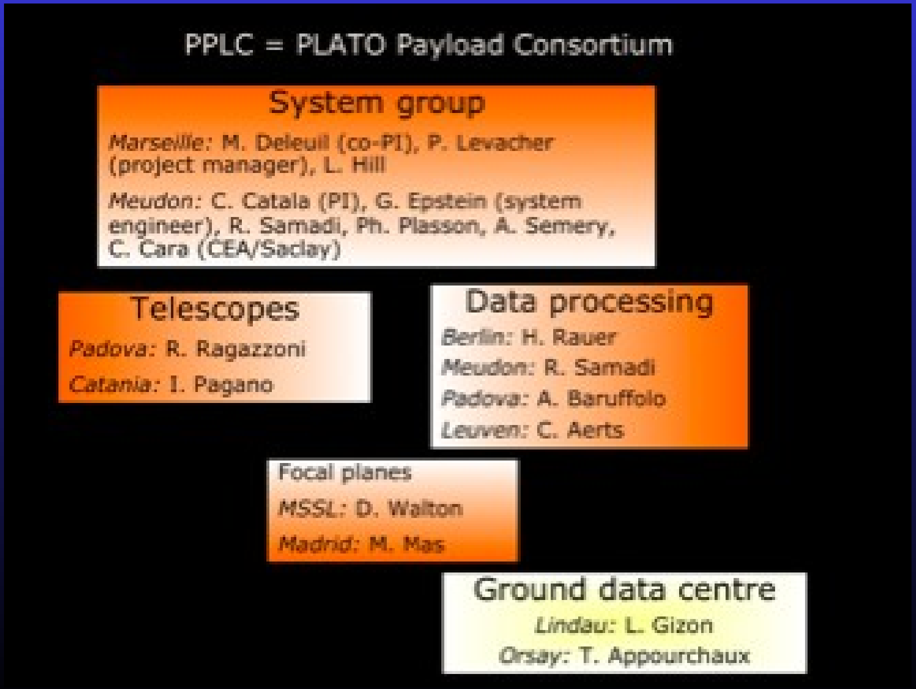


About 100 currently known targets are readily observable with EPICS, and many more are expected to be discovered by e.g. GAIA or SPHERE

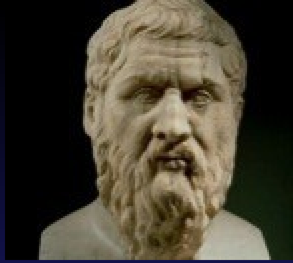


PLATO
(PLAnetary Transits and Oscillations of stars)

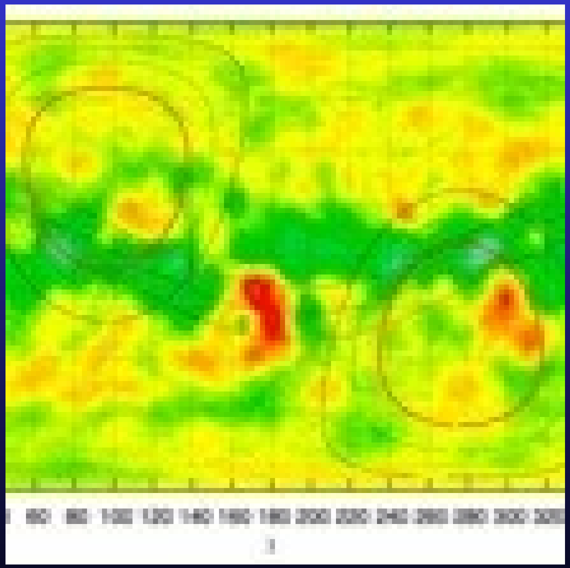
- ESA Cosmic Vision 2015-2015
- Selected by ESA for assesment study, launch 2017
- Partecipation of Austria, Belgium, Denmark, ESA, France, Germany, Italy, Spain, Switzerland, UK
- Payload Consortium + Science Consortium
- Italy: responsible for telescopes (R. Ragazzoni) + other contrib.

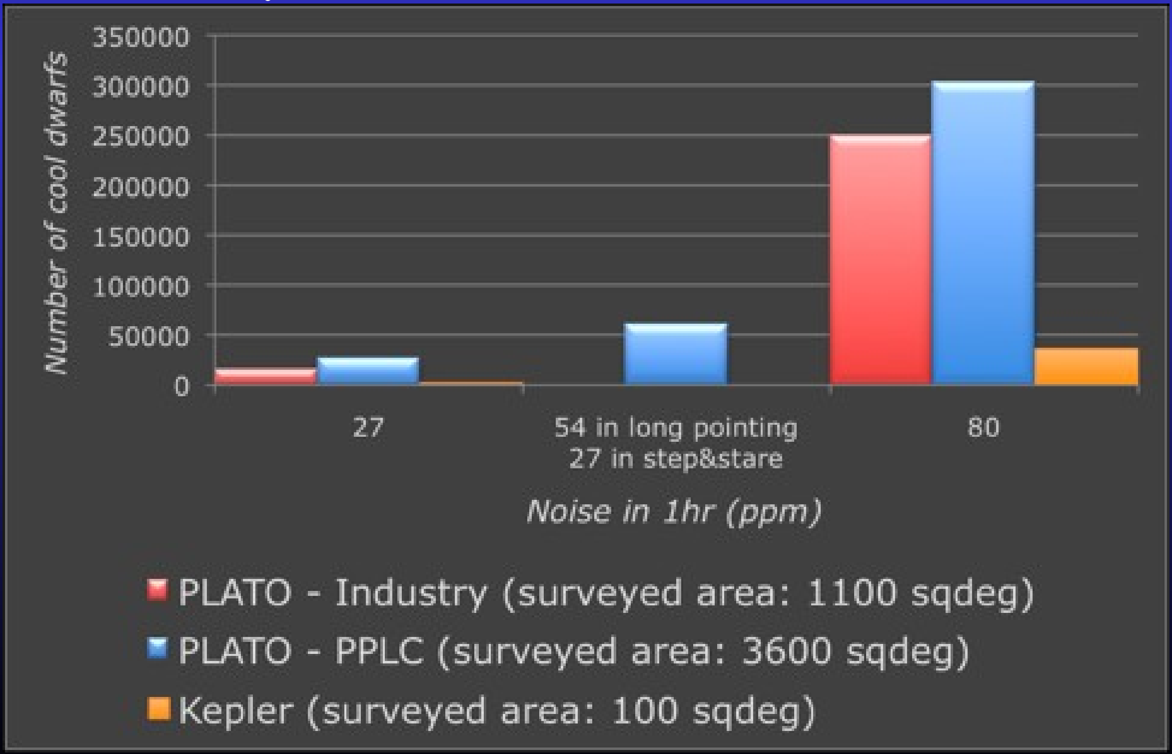


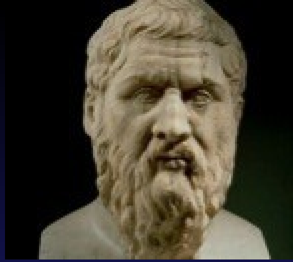
SCIENCE GOALS



- Detection of Earth-like planets
- Characterization of the host stars (through asteroseismology)
- Focusing on bright targets (easier RV follow-up and additional characterization observations)
- Requirement: > 20000 cool dwarfs V<11 with noise < 27ppm in 1 hr (planet search+asteroseismology characterization), >250000 cool dwarfs with noise <80 ppm in 1 hr (planet search)

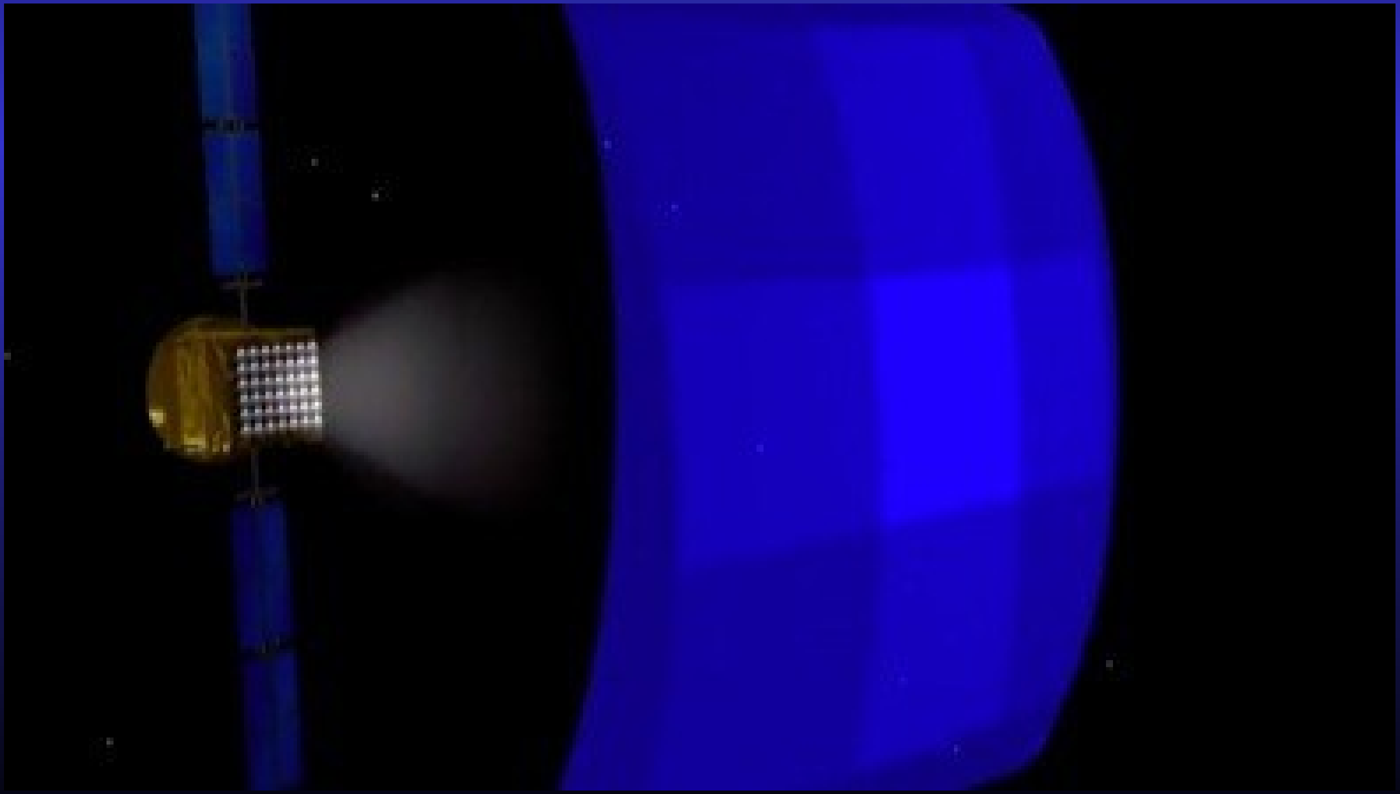




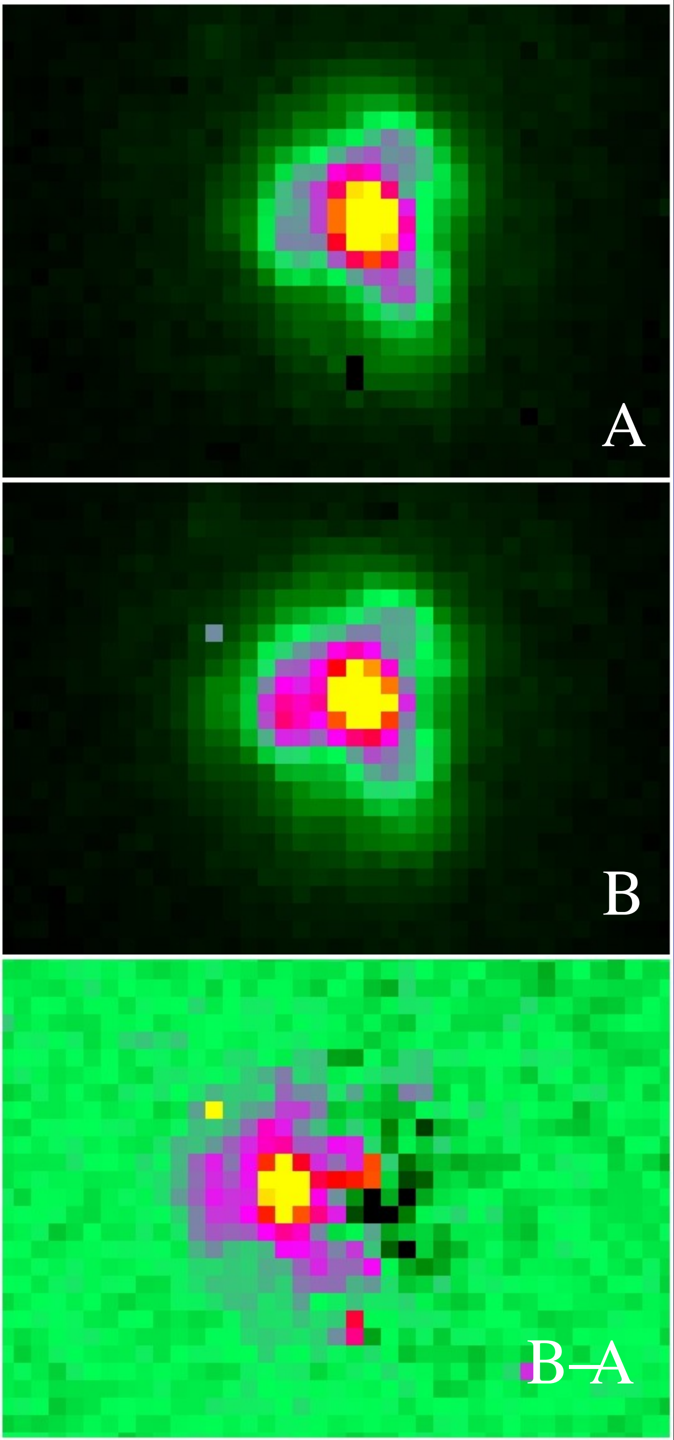


INSTRUMENT CONCEPT

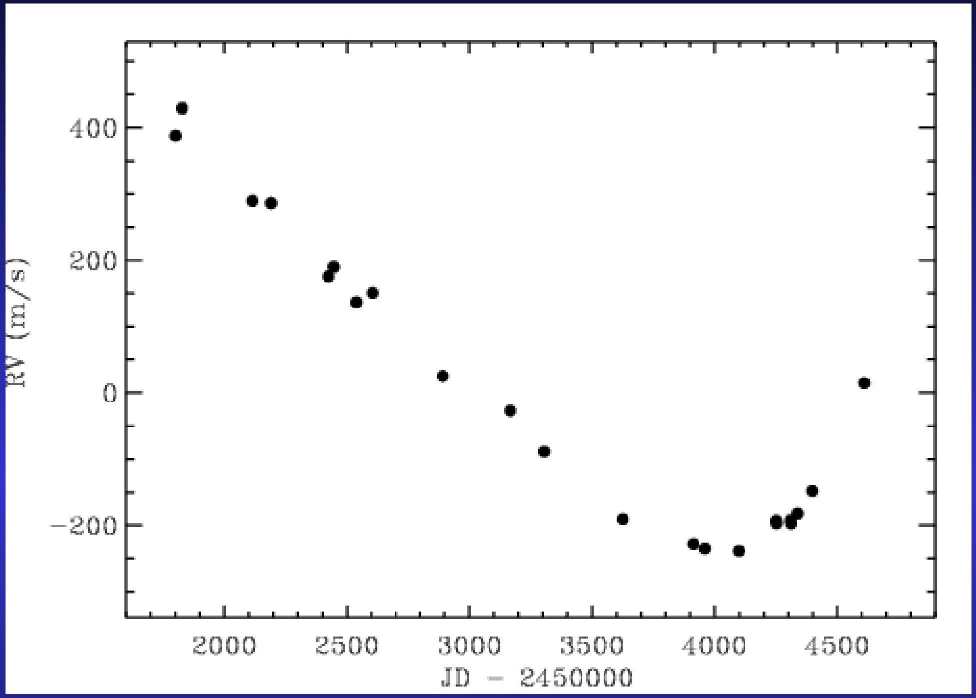
- 40 telescopes pointing partially overlapping fields
- Field coverage > 1000x2 sq. Deg. (Kepler: 100 sq. Deg., COROT:4)
- 2 fields observed for 3 years + step&stare phase



END



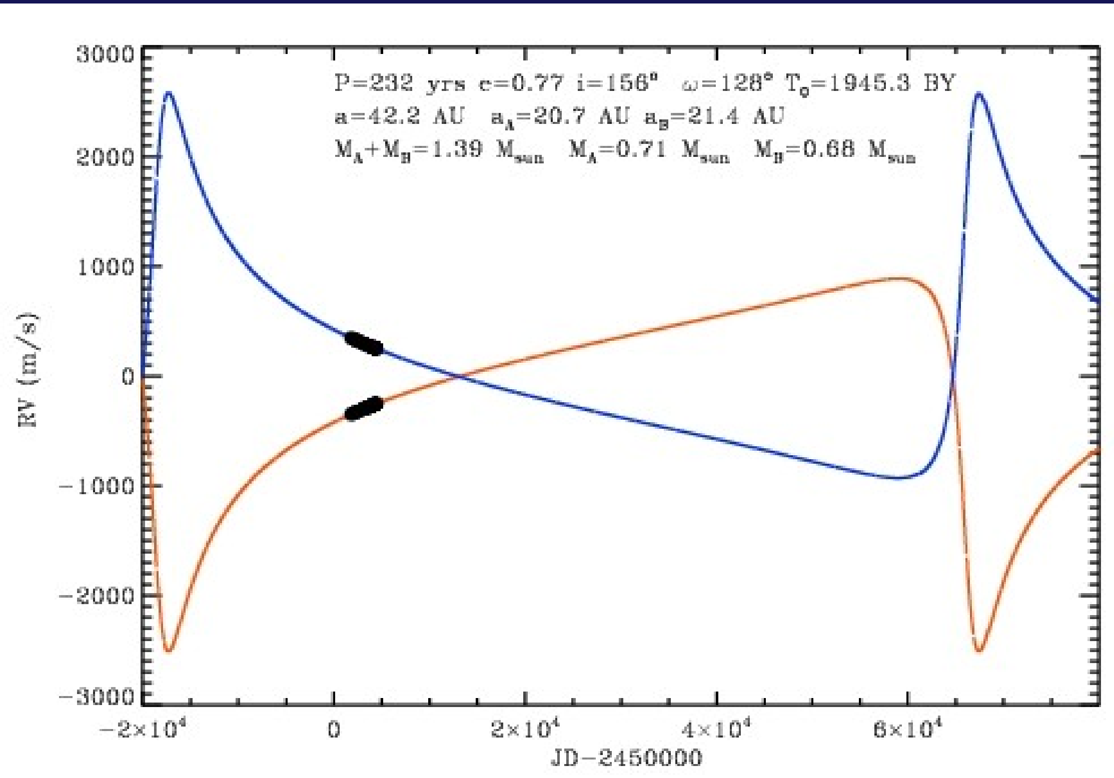
AdOpt@TNG observations of stars with long term RV trends



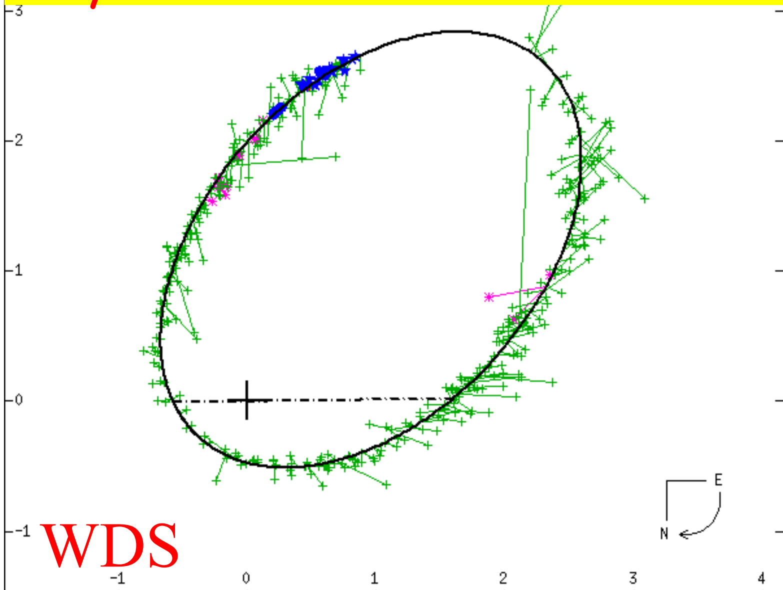
Minimum mass in BD regime, but stellar companion candidate identified in AdOpt@TNG images and seen also through study of line bisector.

BINARY ORBITS

Goal: constrain as much as possible the binary orbits for a better interpretation of the survey data



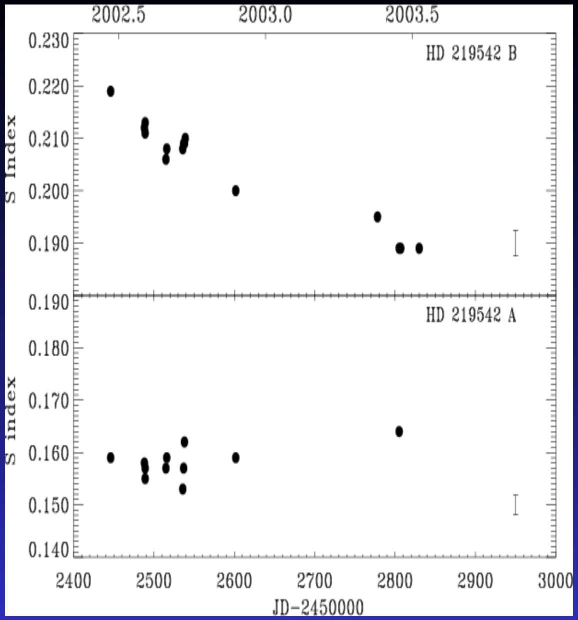
HD 186858: RV trends for both components that fits very well the visual orbit



Combination of RV trends + visual observations allows derivation or refinement of the orbit for other 4 pairs

For the remaining pairs we use the RV difference + available astrometric data (binary motion typically detected) between the components to constrain the binary orbit

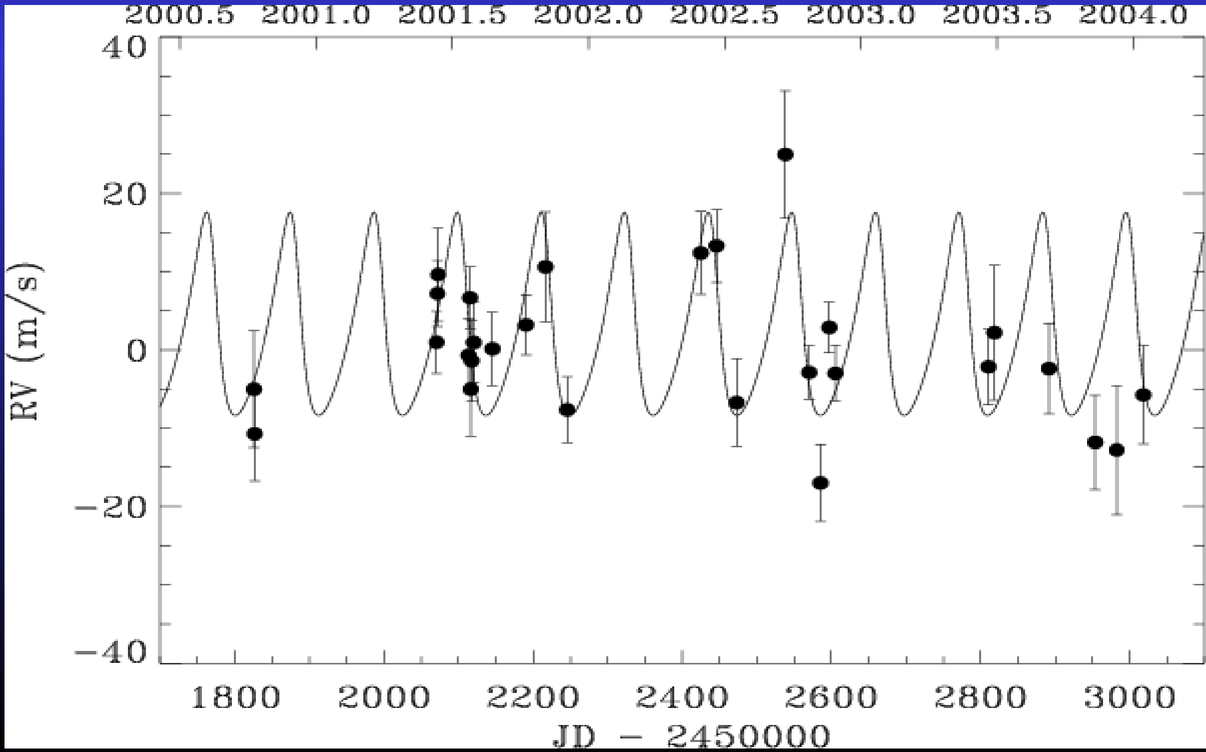
HD 219542 B: LOW AMPLITUDE RADIAL VELOCITY VARIATIONS



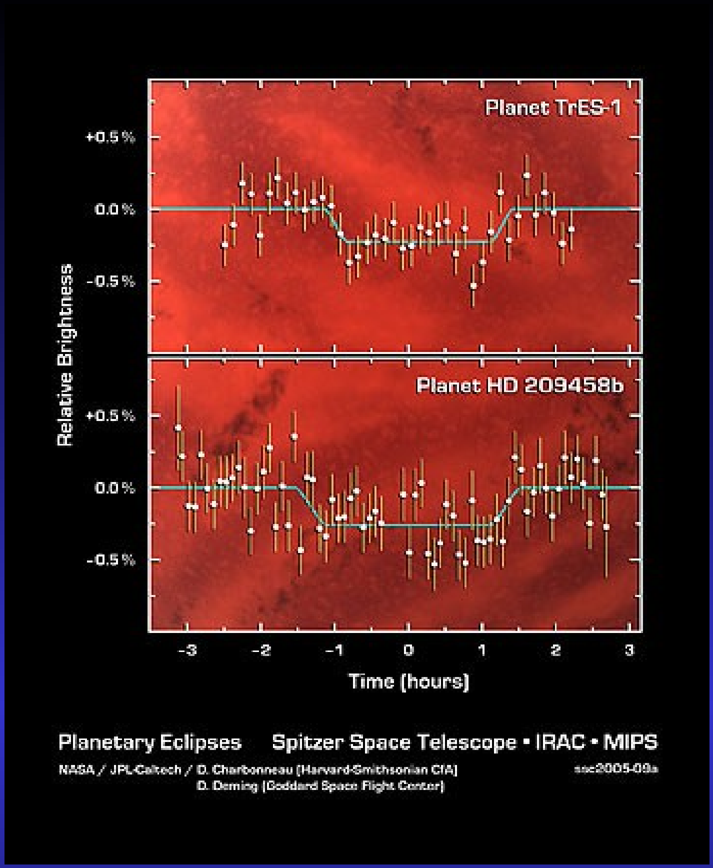
Activity data from Wright et al. 2003

After the 2002 season possible periodicity (P=111 days) significant at 97%.The significance decreased after the inclusion of 2003 season.

STELLAR ACTIVITY IS THE LIKELY SOURCE OF RV VARIATIONS



Desidera et al. 2003, 2004



Secondary eclipses observed with Spitzer: direct detection of the photons from the planet

HD 209458b: an evaporating planet

Detection of an extended exosphere, likely exceeding the Roche limit (about 3.5 R_J).
Occultation in the optical 1.5%, Lyα 15%
Deduced mass loss rate: > 10^{10} g/s

ABUNDANCES OF BINARIES WITH PLANETS

System		Δ [Fe/H]	Reference
16 Cyg	B	-0.025± 0.009 0.00 ± 0.01	Laws & Gonzalez 2001 Takeda 2005
HD 80606/7	A	-0.01 ± 0.11 +0.00 ± 0.08	Heiter & Luck 2003 Taylor 2005
HD 99491/2	B	-0.02 ± 0.03 +0.04 ± 0.13 +0.08 ± 0.06	Valenti & Fischer 2005 Heiter & Luck 2003 Taylor 2005
HD 20781/2	A	+0.12 ± 0.10	Nordstrom et al. 2004
ADS 16402 (HAT-P-1)	B	-0.01 ± 0.05	Bakos et al. 2007
XO-2	B	+0.02 ± 0.03	Burke et al. 2007

Optimized differential analysis available only for 16 Cyg but no evidences for large abundance difference between the components with/without planets

FREQUENCY OF PLANETS IN BINARY SYSTEMS

Null results of the SARG Planet search suggests a lower frequency of planets in the kind of binaries we are exploring

More general study of the frequency of planets in binaries performed using the **Uniform Detectability** sample by Fischer & Valenti (2005):

Advantages: completeness of planet detection ($K > 30$ m/s, $P < 4$ yr), large sample size (850 stars)

Drawbacks: bias against binaries with separation < 2 arcsec, incompleteness of binary detections

Compilation of binaries in the UD sample from literature

Frequency of planets		
Binary systems	15 / 207	$7.2 \pm 2.4\%$
Single stars	34 / 642	$5.2 \pm 1.1\%$

Small spurious increase of planet frequency in binaries because stars with planets are systematically searched for companions
(taking this bias into account very similar planet frequencies)

Bonavita & Desidera 2007

EXPLORING THE DEPENDENCE ON BINARY PARAMETERS

UD sample: smaller planet frequency for a_{crit} < 20-30 AU
(a=50-100 AU depending on mass ratio)

(a_{crit} <20 AU: 2/95 2.1± 1.7%)

Is t… 20 AU) ?:

This is probably due to incompleteness of binary detections at intermediate separation in the UD sample (AO needed, see A. Eggenberger et al. 2008) or to some special effect of the mass ratio (most of the UD binaries have lower mass secondaries)

Complete samples of stars with/without planets in binaries needed to derive the detailed run of planet frequency vs binary separation and mass ratio.

CONCLUSION on PLANETS in BINARIES

1) Planets do exist in a large variety of binary systems
2) The frequency of planets is similar to that of single stars for wide binaries but lower at small separation (a<100-200 AU, detailed run needs further works)
3) The properties of planets in close binaries are different to those of single stars: massive close-in planets are found mostly in close binaries; the properties of planets in wide binaries are similar to those of single stars
4) Implications for models of planet formation and evolution ?
5) The planet frequency of typical RV samples (usually biased against binaries) is not that of unbiased samples of solar-type stars. To be taken into account when comparing it to that of samples with no or different biases concerning binaries (e.g. statistics of planets from transit searches or other techniques).
6) Analysis of chemical abundances of binaries with and without planets indicates that accretion of significant amount of planetary material is not a common occurrence