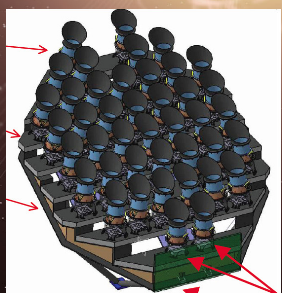
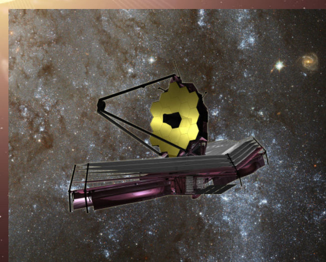
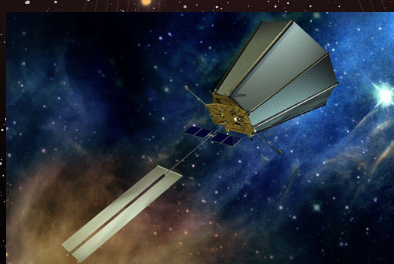
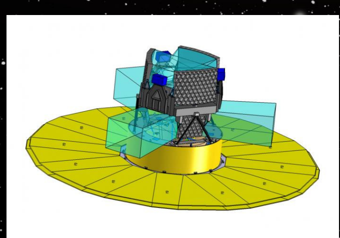
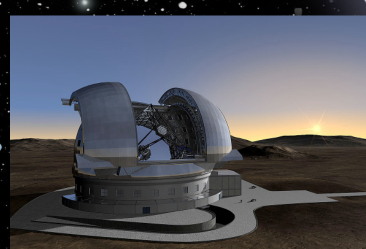
Multiple Planet Systems Characterization: Successes, Challenges, and the Future

Alessandro Sozzetti

(INAF - Osservatorio Astronomico di Torino)

Gaia DPAC Data Processing & Analysis Consortium

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Osservatorio Astronomico di TOrino

Sit-in di protesta dei precari INAF
INAF-Roma (Monte Mario), 24 Marzo 2011

I ricercatori precari contro un investimento miope nelle risorse umane RNPI

IO supporto pienamente!!

Today, 16 years ago:

THE END

THANKS FOR YOUR ATTENTION!

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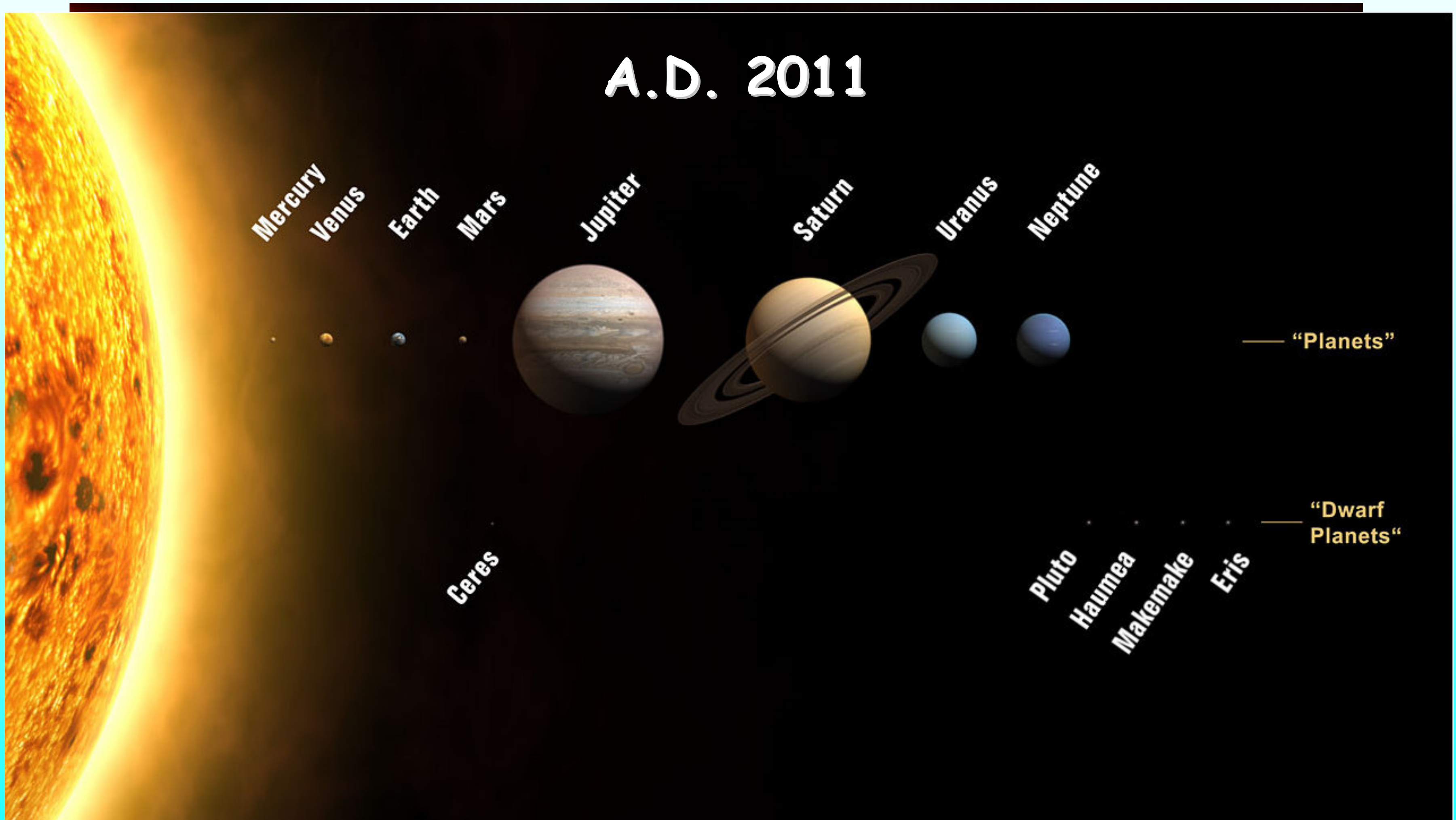
First, we must agree!



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2003: IAU members try to Agree…

- A planet is any object in orbit around the Sun with a diameter greater than 2000 km.
- A planet is any object in orbit around the Sun whose shape is stable due to its own gravity.
- A planet is any object in orbit around the Sun that is dominant in its neighborhood.
- A planet is a planet if enough people say it is

…but they end up having to call a General Assembly (2006)

The IAU therefore resolves that planets and other bodies in our Solar System, except satellites, be defined into three distinct categories in the following way:

(1) A "planet" is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

(2) A "dwarf planet" is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite.

(3) All other objects except satellites orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".

Exoplanets are not planets!!

2003: IAU Working Group on Exoplanets:

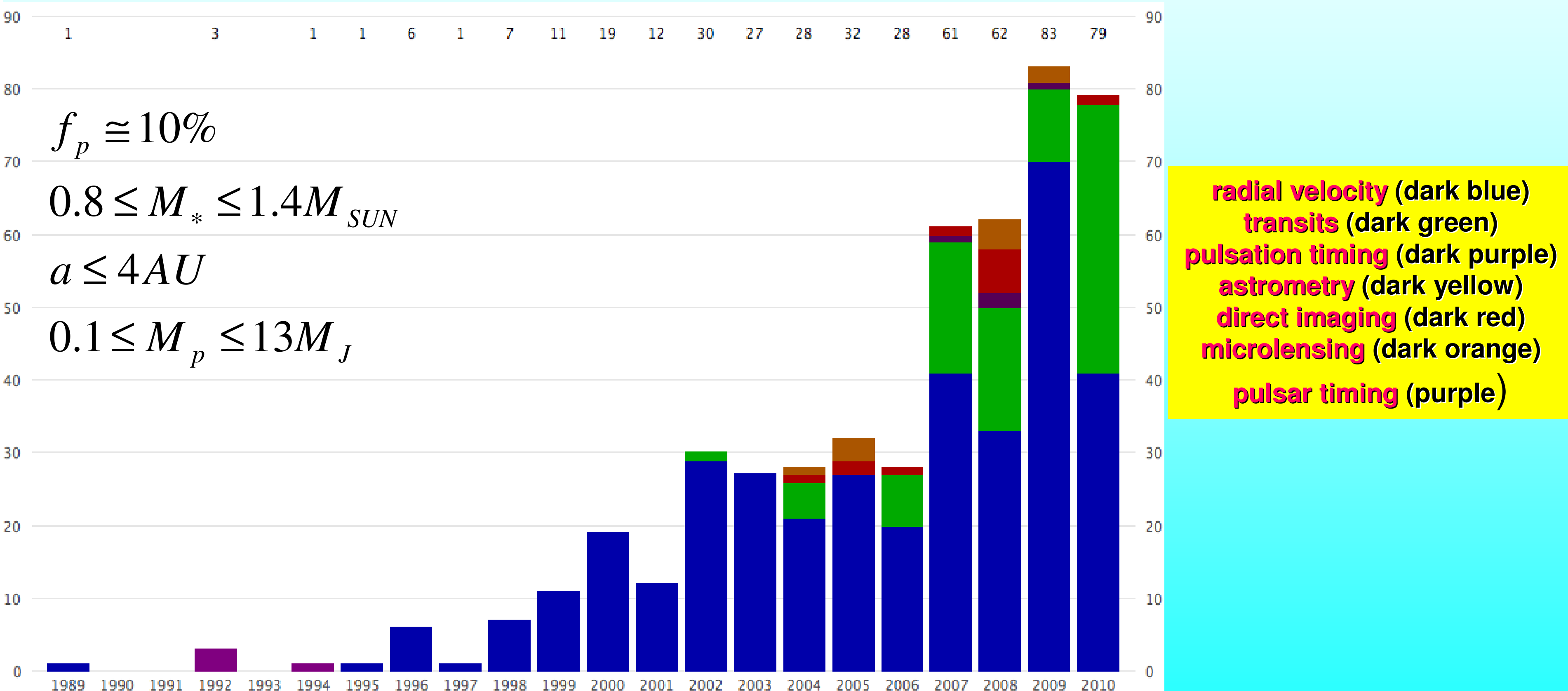
- ✓ Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.

- ✓ Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.

- ✓ Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).

Since 2006, no updates (yet) from IAU Commission 53

Exoplanets: 538 and counting…

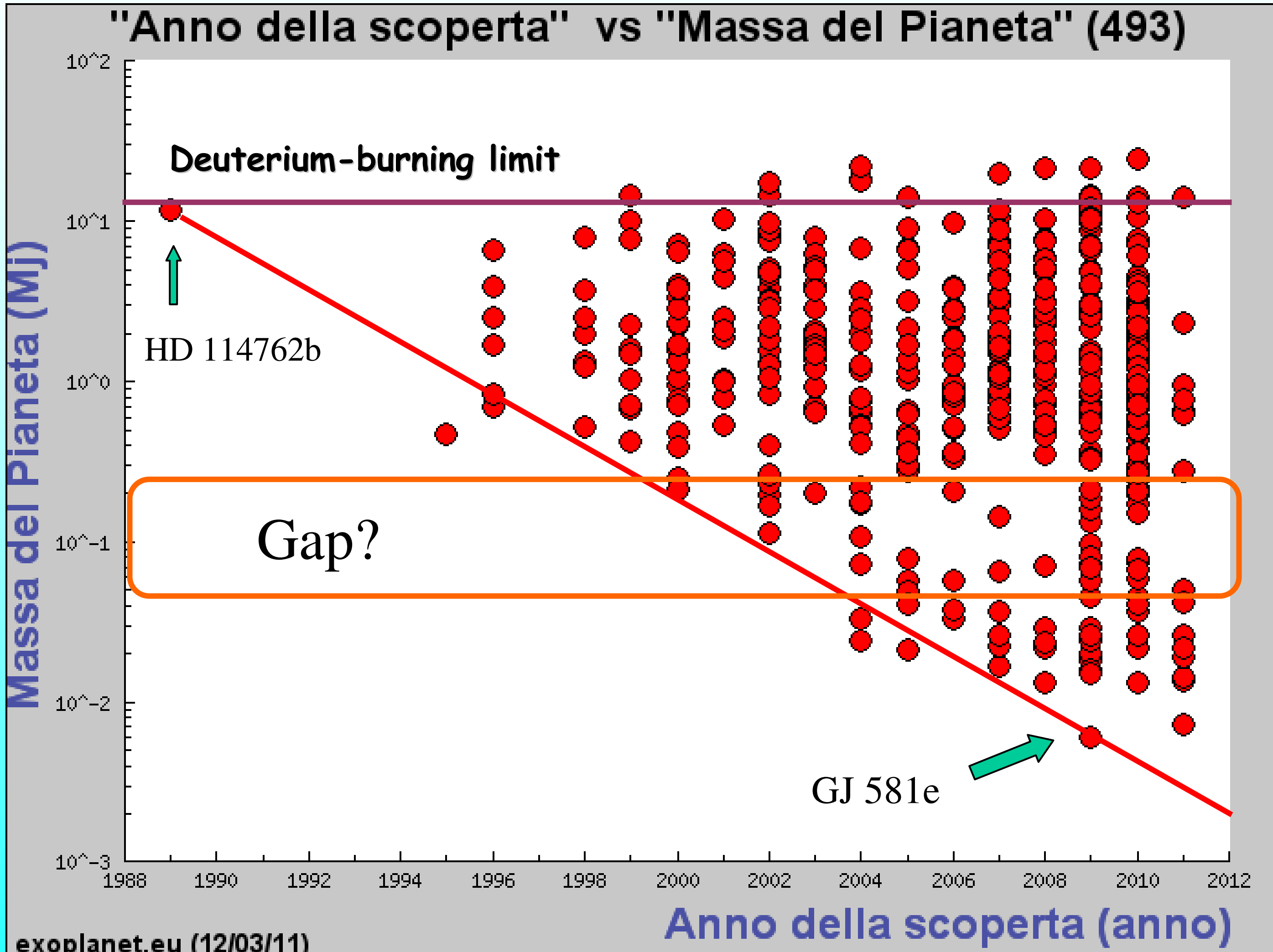


$$f_p \cong 10\%$$

$$0.8 \leq M_* \leq 1.4 M_{SUN}$$

$$a \leq 4AU$$

$$0.1 \leq M_p \leq 13 M_J$$

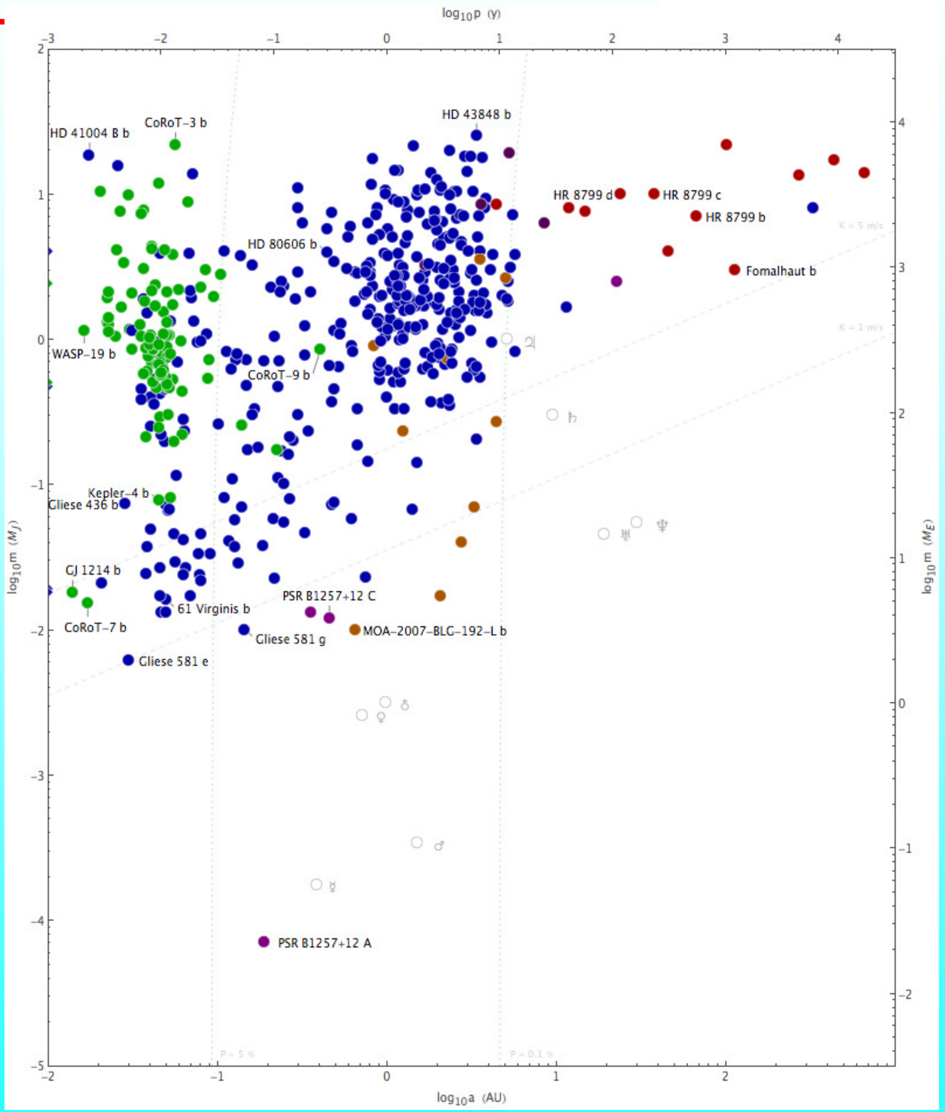

"Anno della scoperta" vs "Massa del Pianeta" (493)
Deuterium-burning limit
HD 114762b
Gap?
GJ 581e
Massa del Pianeta (Mj)
Anno della scoperta (anno)
10^2
10^1
10^0
10^-1
10^-2
10^-3
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
exoplanet.eu (12/03/11)

- **Indirect detection (Visible):**
  - Doppler spectroscopy (95%)
  - Transit photometry (20%)
  - Gravitational microlensing (3%)
  - Pulsar/pulsation timing (1.5%)
  - Astrometry (0/493)

- **Direct detection (Visible)**
  - imaging (0.5%, still debatable)

- **Indirect characterization (Visible/IR):**
  - Transit timing
  - Transmission spectroscopy
  - Rossiter-McLaughlin effect

- **Direct characterization (Visible/IR):**
  - Reflected light
  - Infrared emission



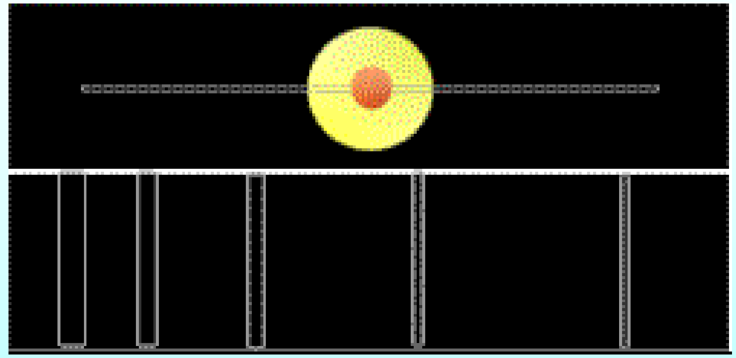
Exoplanets Properties

- Orbital elements, mass distributions, multiplicity
- Correlations between planetary parameters and between planet characteristics and frequencies and the properties of the stellar hosts
- Internal structure, atmospheric composition and circulation

→ **The era of comparative exoplanetology!**

Doppler Spectroscopy

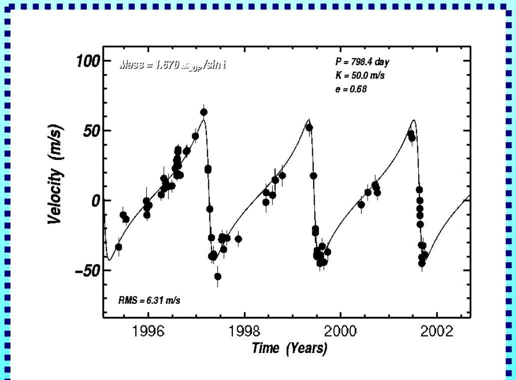
Observed quantity: radial component of stellar velocity in the star's motion around the center of mass of the star-planet system

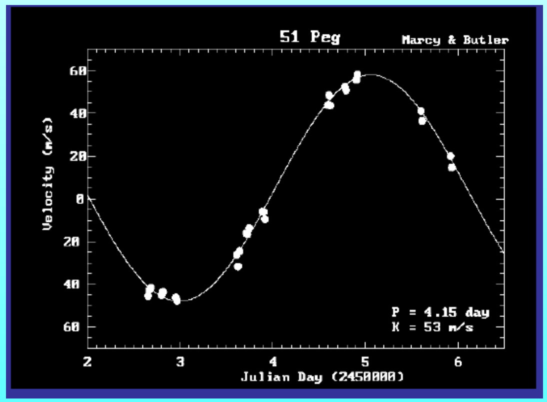


$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{(M_p + M_*)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

A planetary mass (times sin *i*) is found given a guess for the primary's:

$$f(m_2) = \frac{m_2^{\,3} \sin^3 i}{M^2} = \frac{(1-e^2)^{3/2} K^3 P}{2\pi G}$$





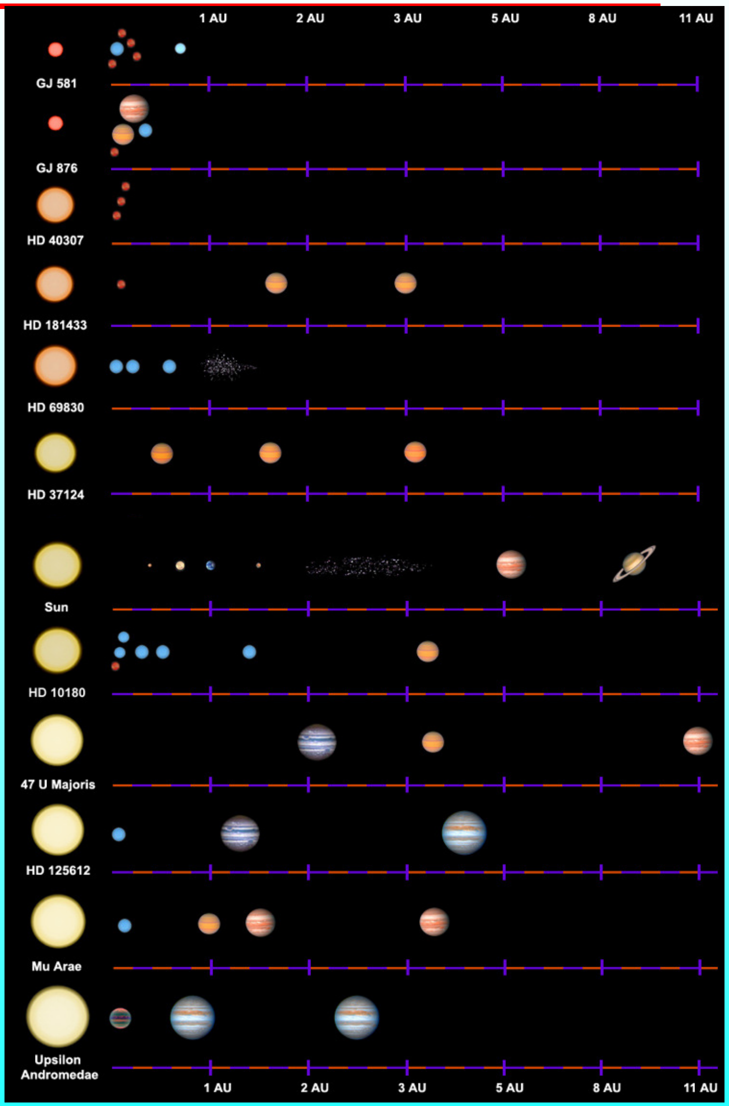
For binaries: σ_{RV} ~ 1 km/s

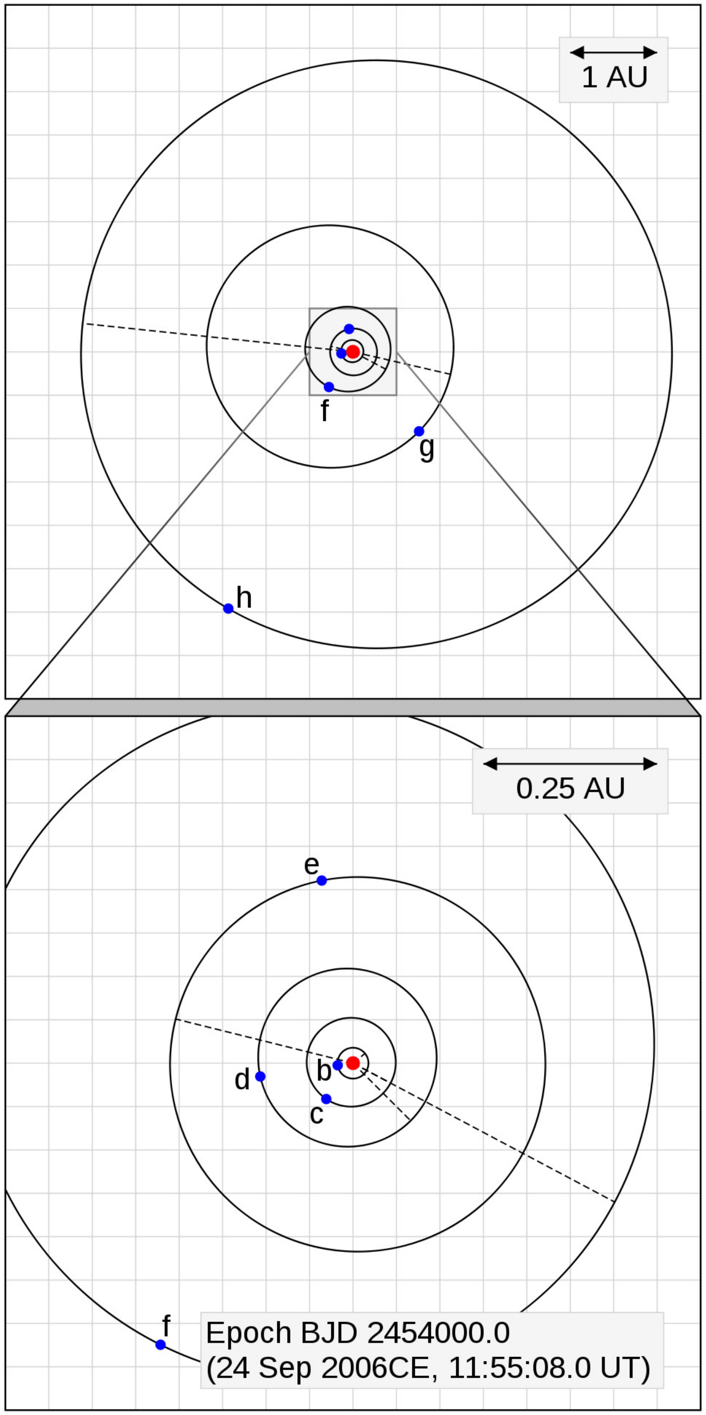
For planets: σ_{RV} ~ 1-5 m/s

Multiple Planet Systems

• Take all (F-G-K-M) stars within 200 pc with Doppler-detected planets
• Second planet detection rate:~20%
• Including trends: >35%
• This includes 10 stars with three planets, 4 with four, 1 with five, 1 with six, 1 with seven, and 1 with eight

4 planets: μ Ara, GJ 581(?), GJ 876, HR8799
5 planets: 55 Cnc
6 planets: Kepler-11
7 planets: HD 10180
8 planets: the Sun!





7 low-mass planets for HD 10180!

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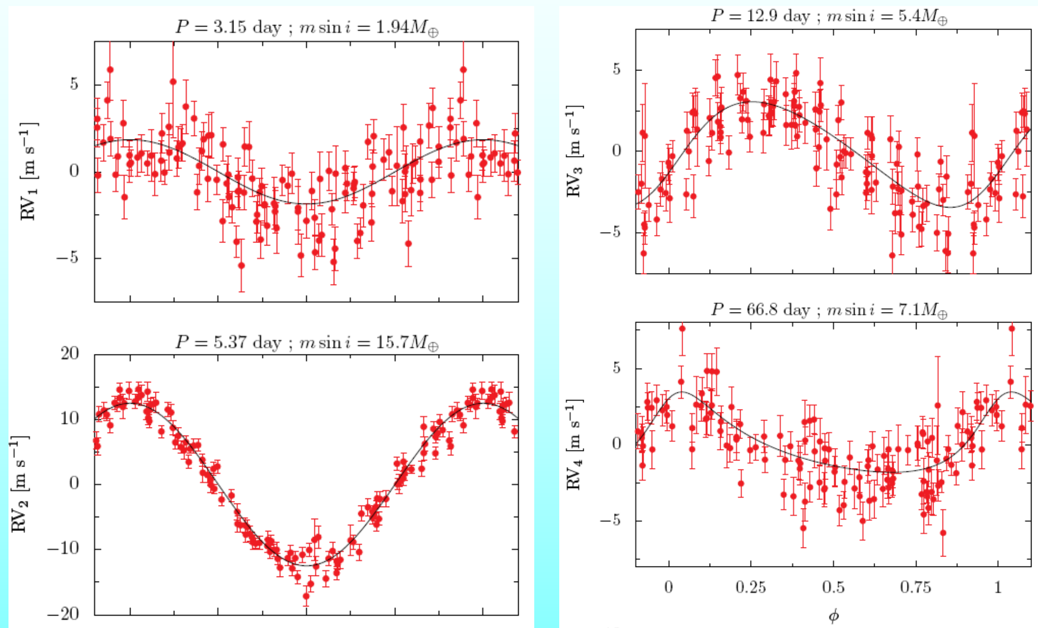
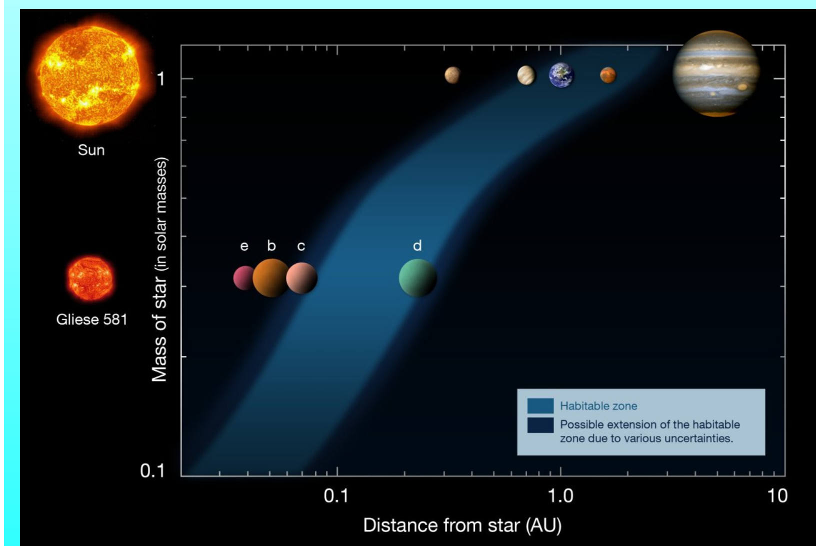
Mayor et al. 2008



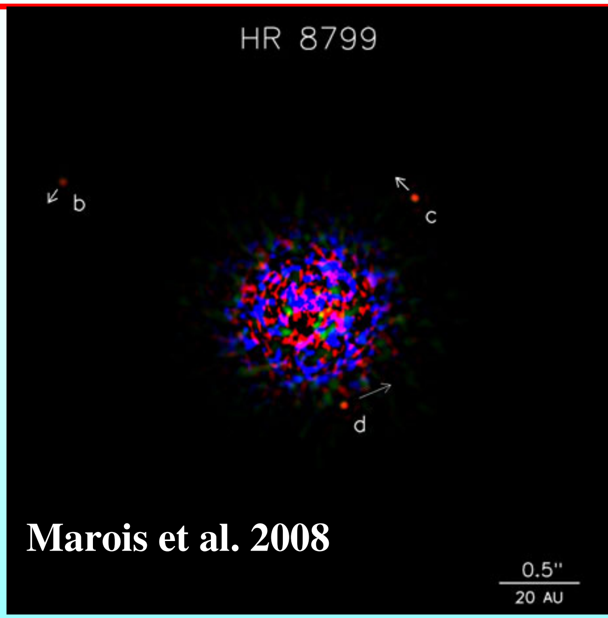
GJ 581:

A habitable Super-Earth(?) and a hot Earth!

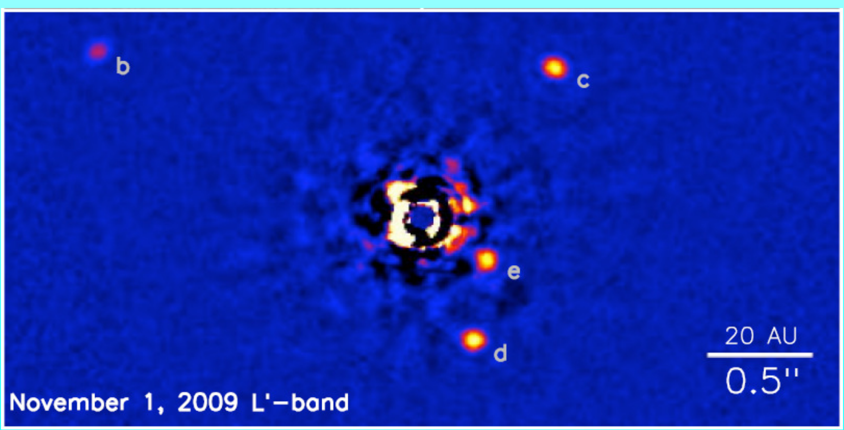


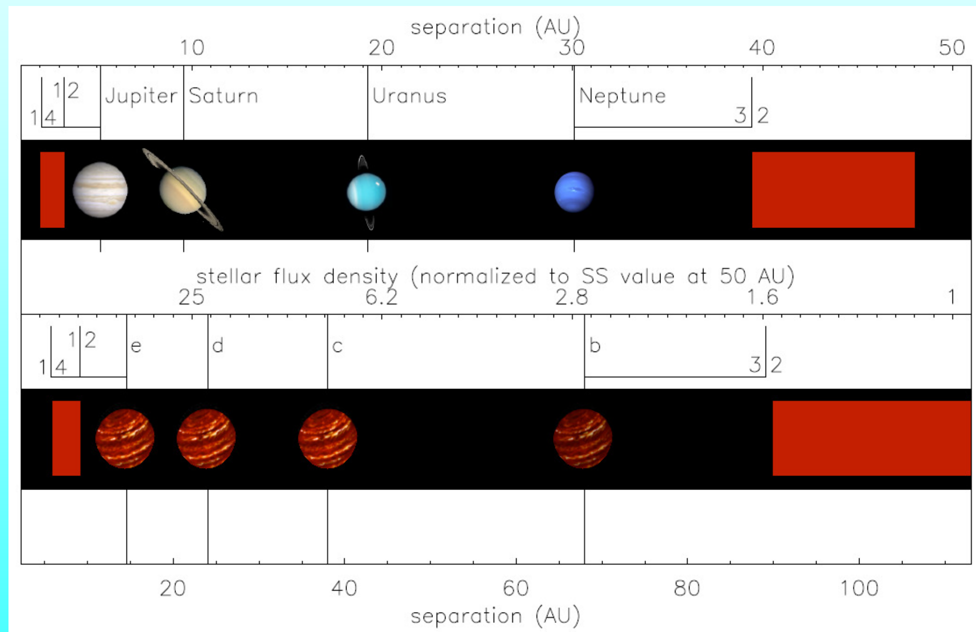
Great laboratory to test low-mass planetary systems formation

An imaged tri(quadru)plet: Evidence for planet formation in the 20-70 AU range



Marois et al. 2008





Marois et al. 2010

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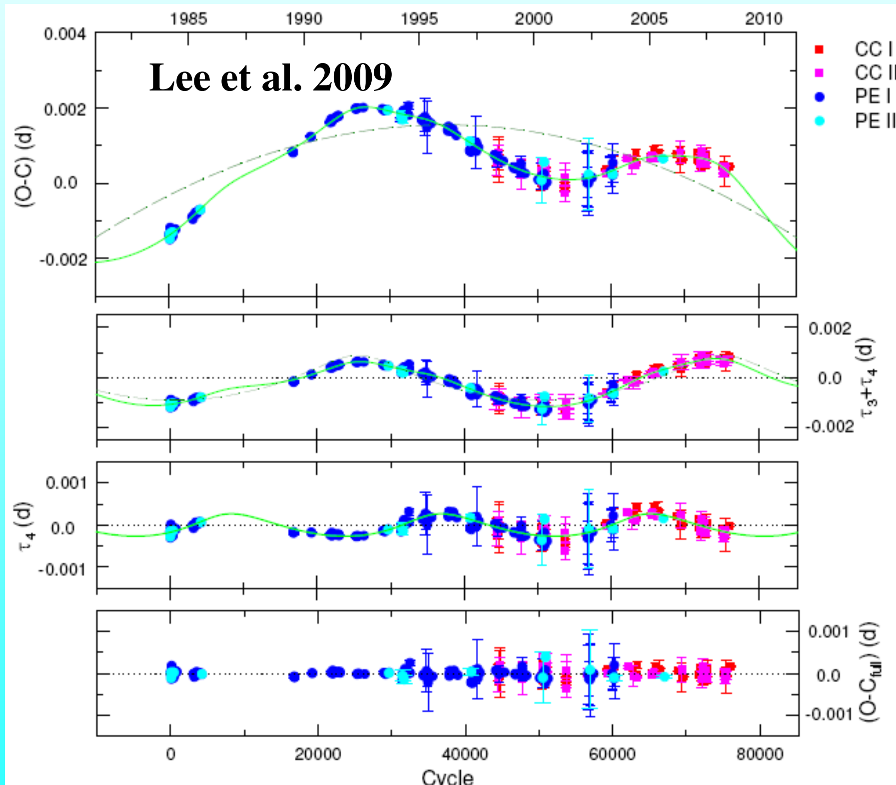
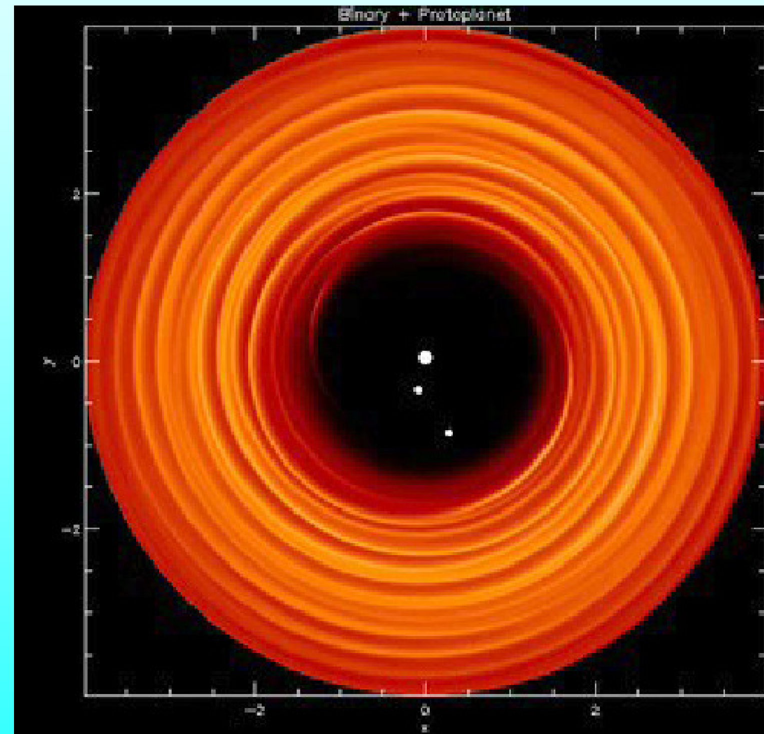
The SdB+M eclipsing binary HW Vir: A Circumbinary Planetary System!





Nelson 2003

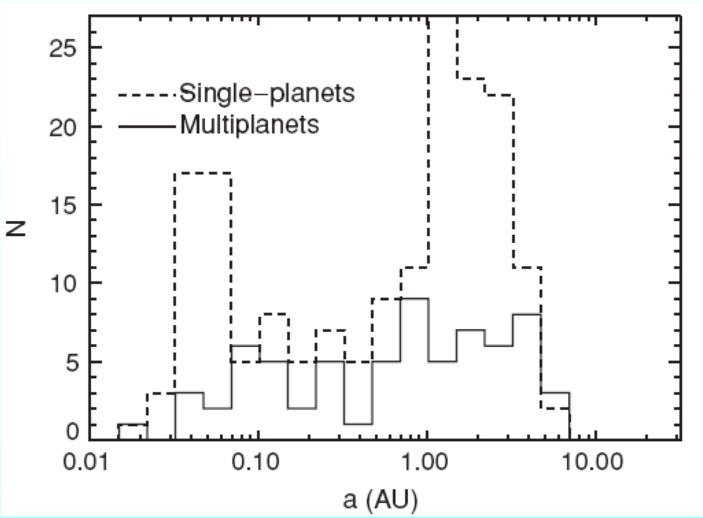
Apparent Period Commensurabilities in Well-characterized Multiplanet Systems

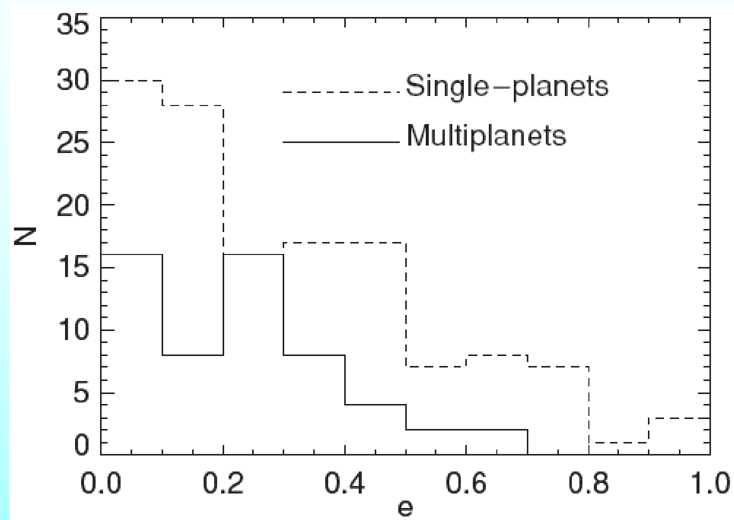
System	Components	Period Ratio	References
GJ 876	*e, c, b*	4:2:1	Marcy et al. (2001); Rivera et al. (2010)
HD 82943	*b, c*	2:1	Mayor et al. (2004); Ji et al. (2003); Lee et al. (2006)
HD 37124	*c, d*	2:1	Vogt et al. (2005); this work
HD 128311	*c, b*	2:1	Sándor et al. (2007); Vogt et al. (2005); others
HD 73526	*c, b*	2:1	Tinney et al. (2006); Sándor et al. (2007)
μ Ara	*b, e*	2:1	Pepe et al. (2007); Goździewski et al. (2007)
KOI 152[a]	2,3	2:1	Steffen et al. (2010)
KOI 877[a]	2,1	2:1	Steffen et al. (2010)
24 Sex	*c, b*	2:1	Johnson et al. (2011)
Kepler-9	*c, b*	2:1	Holman et al. (2010)
PSR B1257+12	*B, C*	3:2	Wolszczan & Frail (1992); Malhotra et al. (1992); Konacki et al. (1999)
HD 45364	*c, b*	3:2	Rein et al. (2010); Correia et al. (2009)
HD 200964	*c, b*	4:3	Johnson et al. (2011)
55 Cnc	*c, b*	3:1	Fischer et al. (2008); Zhou et al. (2008)
HD 10180	*d, e*	3:1	Lovis et al. (2010)
HD 60532	*c, b*	3:1	Desort et al. (2008, 2009); Laskar & Correia (2009)
HD 108874	*c, b*	4:1	Vogt et al. (2005); Goździewski et al. (2006)
Solar	♄, ♃	5:2	
HD 10180	*e, f*	5:2	Lovis et al. (2010)
KOI 896[a]	1,2	5:2	Steffen et al. (2010)
HD 202206	*c, b*	5:1	Correia et al. (2005); Goździewski et al. (2006)

Notes. [a] This is a candidate exoplanet system based on *Kepler* photometry, but the planets are at present considered unconfirmed. For example, KOI 877 could, in principle, be a blend of two stars, each hosting one transiting planet in a coincidental apparent PC.

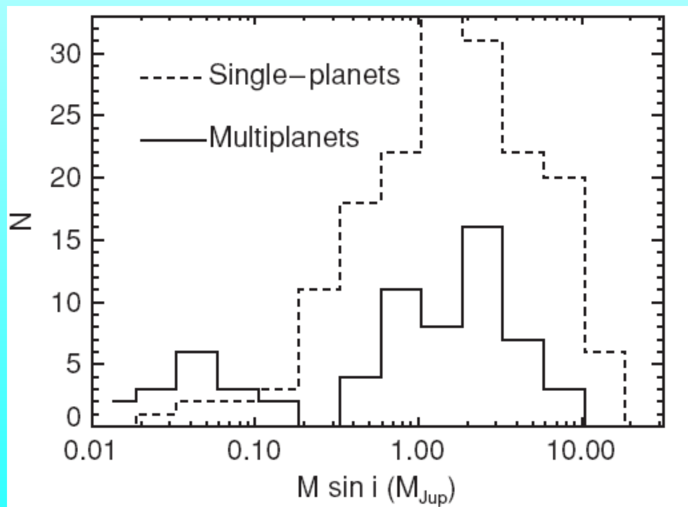
Emerging Properties of Planetary Systems

- Great dynamical diversity (hierarchical systems, secularly interacting systems, systems in mean motion resonances)
- Planetary systems appear to have different orbital elements distribution functions with respect to those of single-planet systems
- In addition, distributions for low-mass systems may also differ from those of systems containing gas giants
- There are hints that f_p may also be a different function of M_* and [Fe/H] in single- and multiple-planet systems



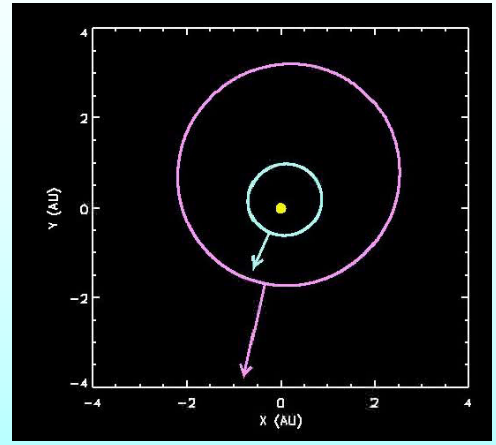


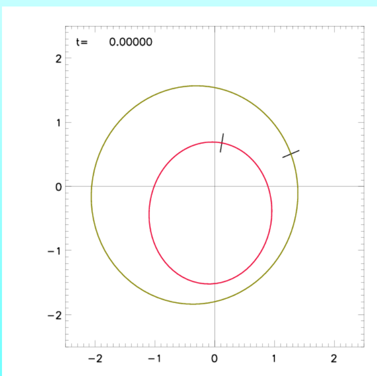
Wright et al. 2009

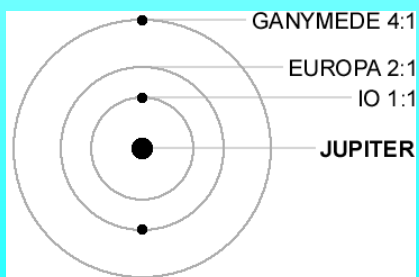


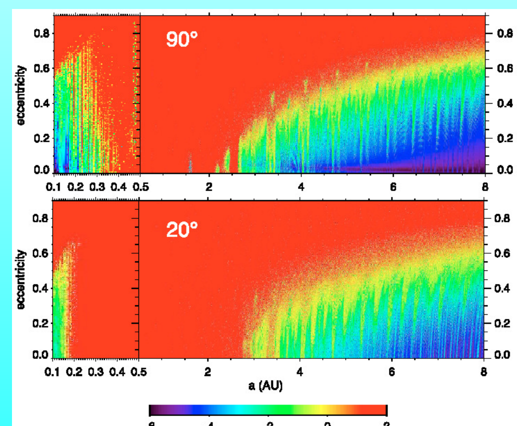
Dynamics: Long-term Evolution

- *Hierarchical systems*
- *Secularly interacting systems*
- *Systems in mean motion resonances*
- *Regions of stable habitable orbits*

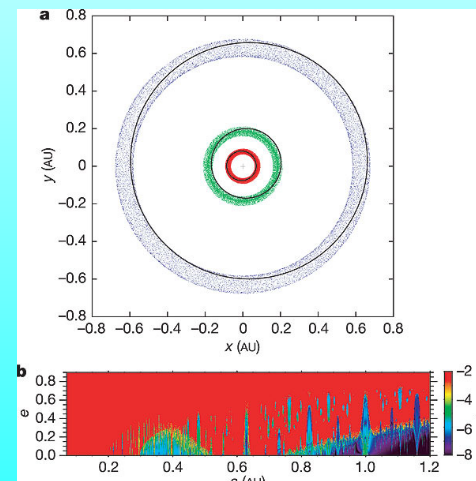








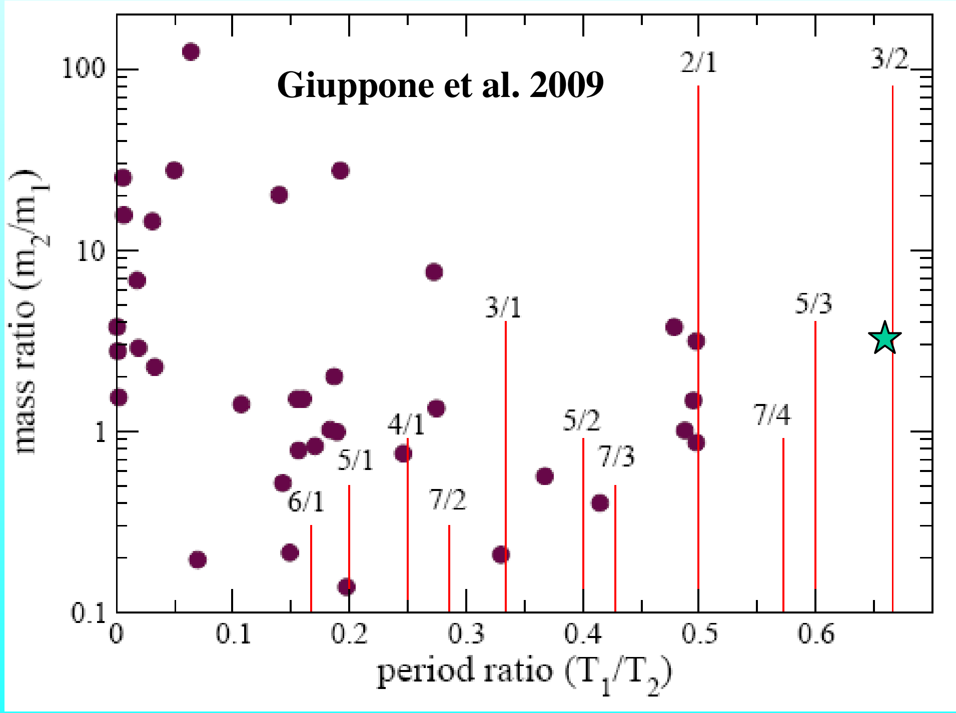
Laskar & Correia 2009

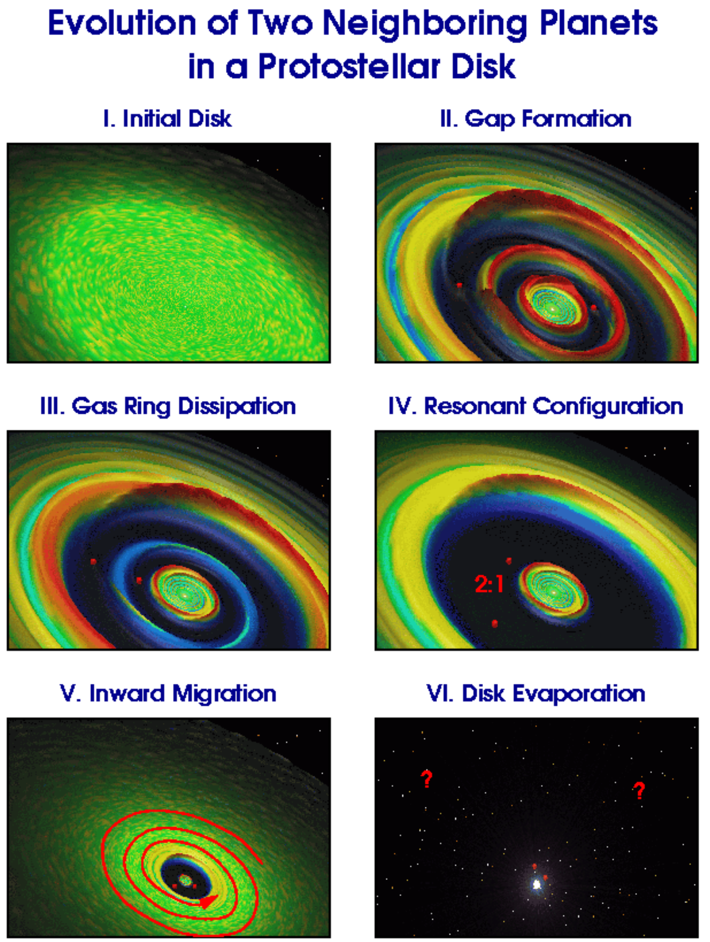


Lovis et al. 2007

Dynamics: Resonances

Possible fossil evidence of orbital migration processes?



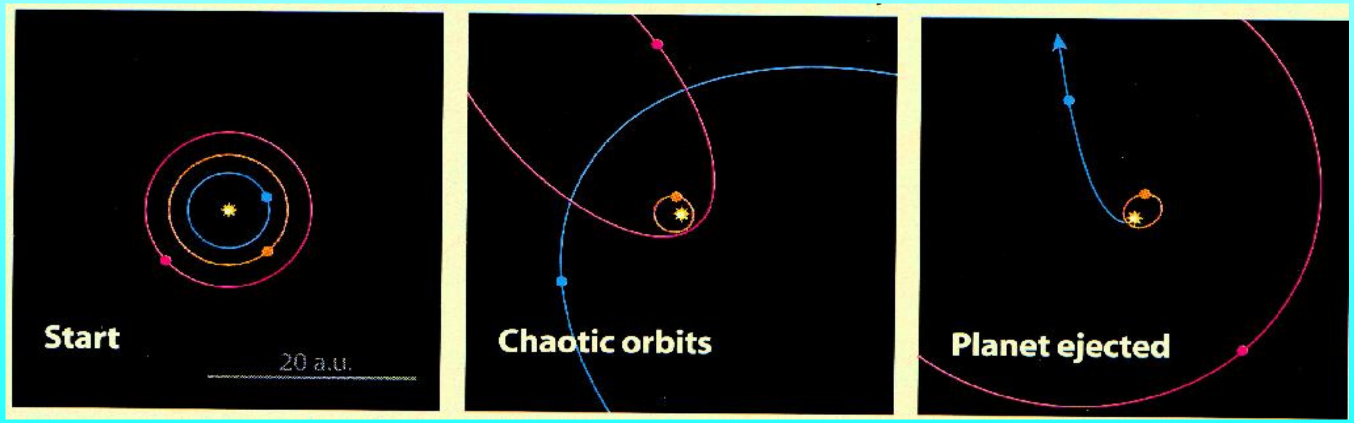


Bryden/Lin 2001
http://www.ucolick.org/~bryden/2planet

Dynamics: Origin of Eccentricities ?

- ✓**Planet – gaseous disk interactions**
- ✓**Planet – planetesimal disk interactions**
- ✓**Planet-Planet secular/resonant interactions**
- ✓**Planet-planet close encounters/scattering**
- ✓**Secular interactions with a distant companion star**
- ✓**Propagation of eccentricity disturbances**

Ford & Rasio 2008

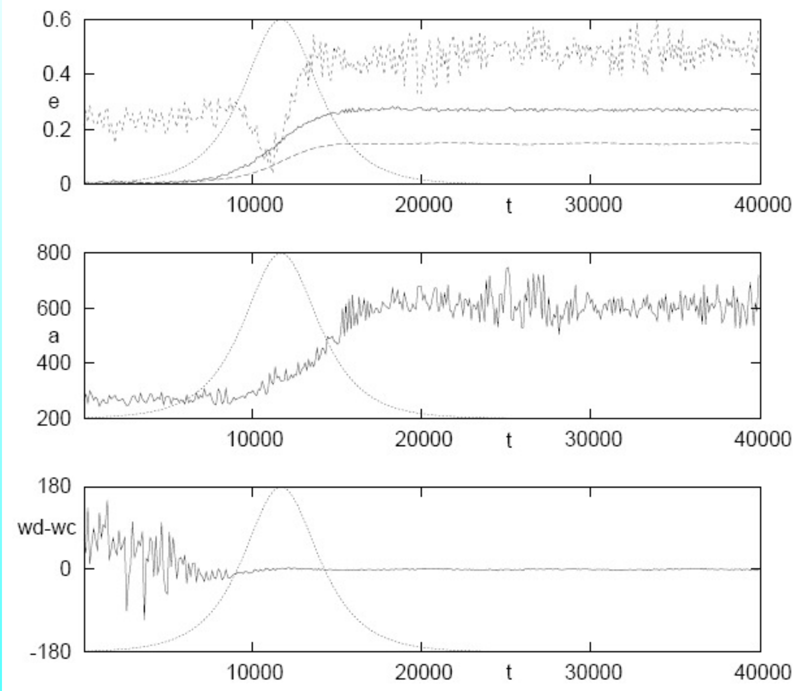


'Eccentric' Systems: Problems

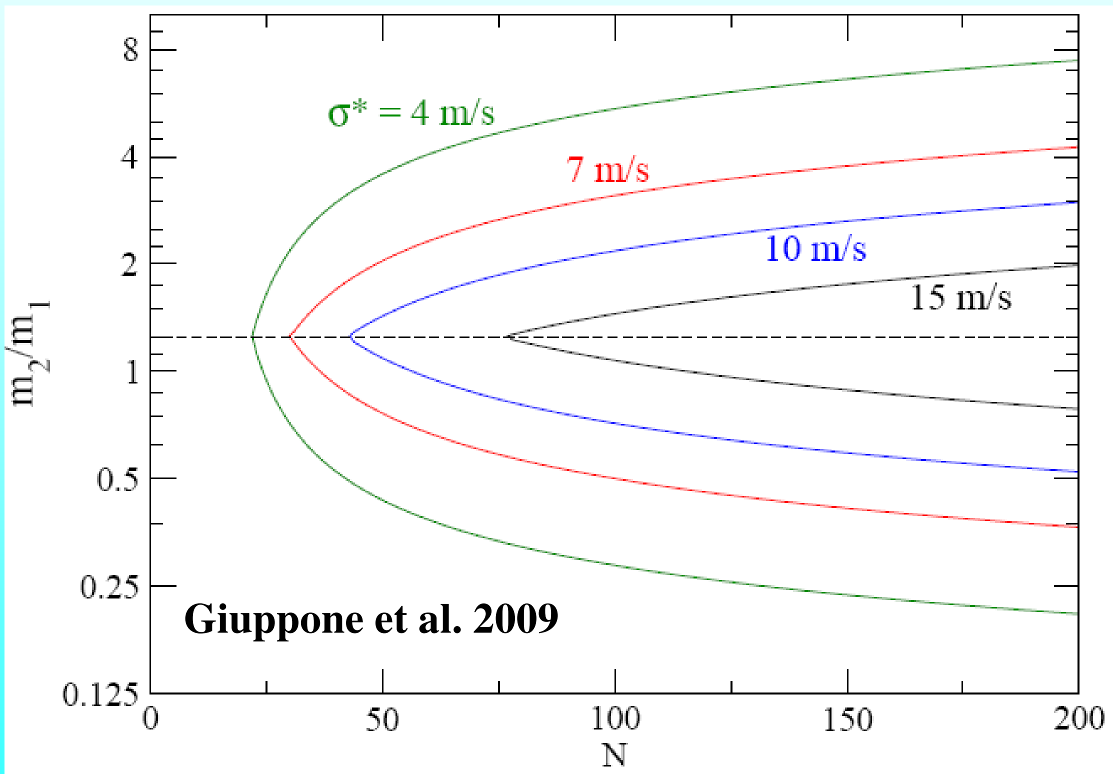
1) Eccentricity excitation mechanisms are often ad hoc

2) Non-coplanar orbits are a likely outcome

3) All conclusions on the long-term orbital stability and evolution are very sensitive to the actual orbital alignment as determined from observations



Problem: Doppler Characterization of MMRs



Resonant systems with large mass ratios need many RV observations in order to be correctly identified

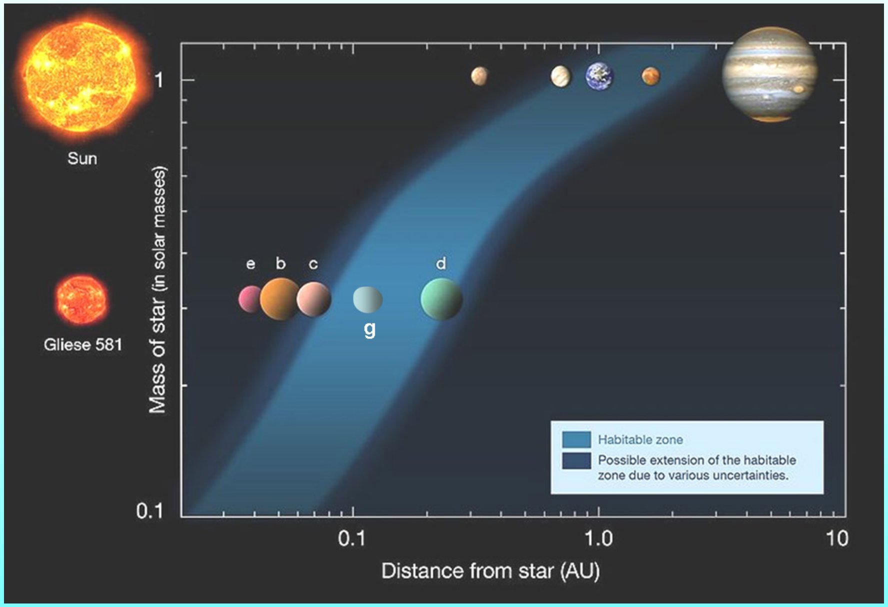
Problem: Agreement on System Architecture

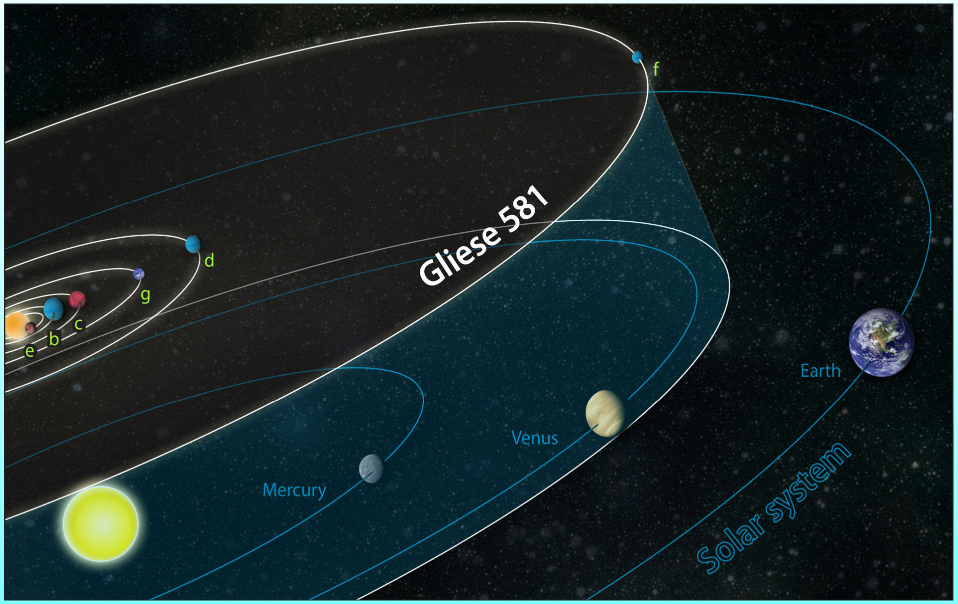
To characterize complex RV-detected systems/signals, use:

a) state-of-the-art instrumentation (best precision)
b) improved understanding of associated physics (impostors)
c) refined methods of data analysis (orbital fits)

As for the latter, different approaches disagree on the systems architectures (e.g., GJ 176, HD73526), and sometimes on the number of detected planets (e.g., HD 11506, HD 11964)!

GJ 581g, a 3.1 M_E H-Z Planet?





241 RVs, 4.3 yr timespan: 'new' 6-planet best-fit model

180 RVs, 6.5 yr timespan: 'old' 4-planet best-fit model

Who's right??

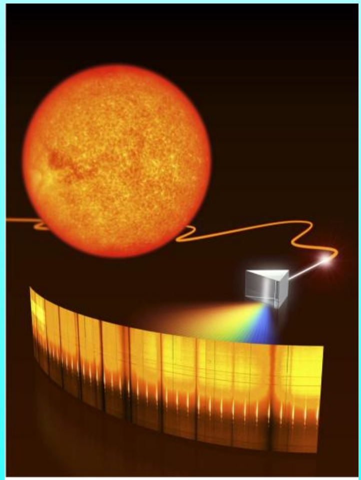
Some Open Questions

- **How many dynamical families?**
- **What are their true masses?**
- **Are their orbits coplanar?**
- **What is the origin of their eccentricities?**
- **What are their distribution functions and frequencies?**

RV and Transits: The Near Future

- Transit timing measurements (CoRoT, Kepler) allow to detect additional planets in a system (not necessarily transiting), and e.g. determine their densities (if they also transit).

- RV surveys will unveil a wider variety of systems at increasingly longer periods and increasingly lower masses



A Laser Comb for Astronomy
(Artist's Impression)
ESO Press Photo 26a/08 (4 September 2008)

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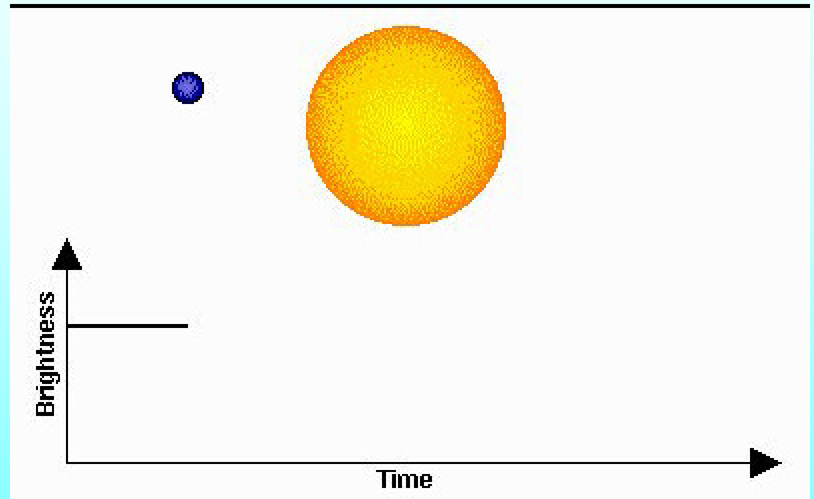
Transit Photometry

* Observable: decrease of stellar brightness, when planet moves across the stellar disk

* Condition of observability: planetary orbit must be (almost) perpendicular to the plane of the sky

•The method allows to determine parameters that are not accessible with Doppler spectroscopy, e.g. ratio of radii,orbital inclination, limb darkening of the star



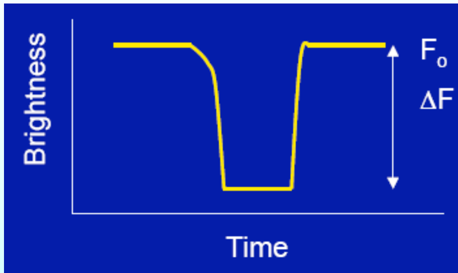
Probability of Eclipses:

$$P_{\rm tr} = 0.0045 \left(\frac{1\mathrm{AU}}{a}\right)\left(\frac{R_\star + R_{pl}}{R_\odot}\right)\left[\frac{1+e\cos(\frac{\pi}{2}-\varpi)}{1-e^2}\right]$$

It is easier to detect an eclipse by a planet on a tight orbit

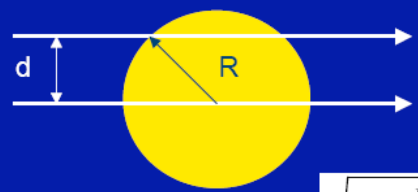
Must combine with RV in order to derive mass and radius of the planet

Pr... y of astro... alarms



$$\frac{\Delta F}{F_0} = \left(\frac{r_{pl}}{R_*}\right)^2$$

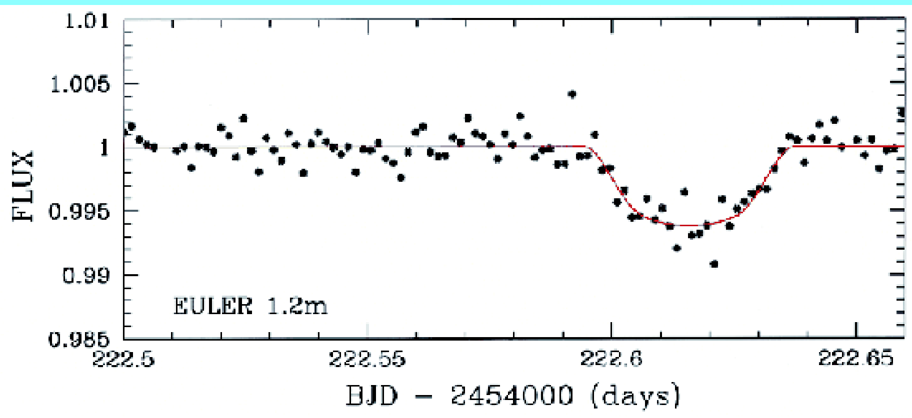
- Jupiter - 0.1
- Neptune - 0.001
- Earth - 0.0001
- Neptune, star of type M - 0.01



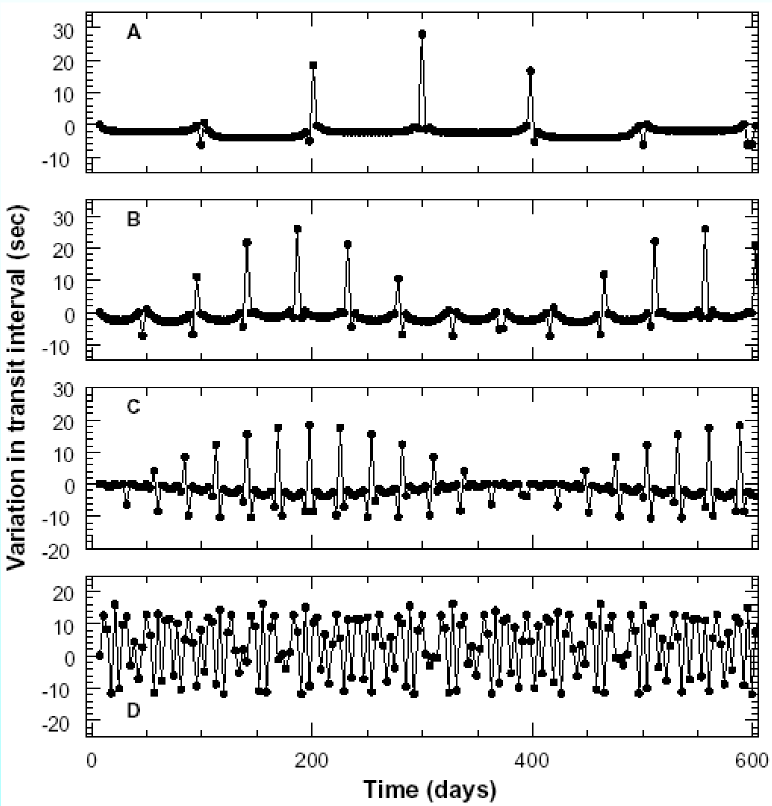
$$\tau(hrs) = 13\left(\frac{R_*}{R_{sun}}\right)\left(\frac{P}{1yr}\right)^{1/3}\left(\frac{M_*}{M_{sun}}\right)^{-1/3}$$

τ = 3 hours for P=3 days

Reduction of τ by $\sqrt{1-\frac{d^2}{R_*^2}}$ for a non-central transit

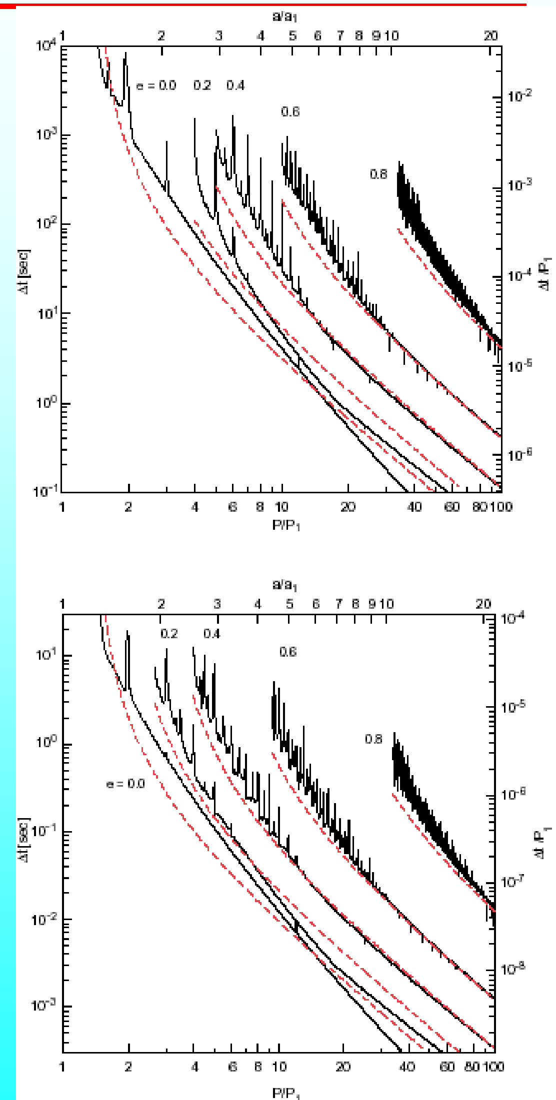


Transit Timing Variations

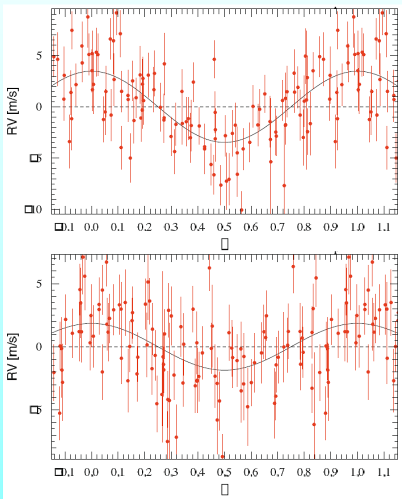


Holman & Murray 2005

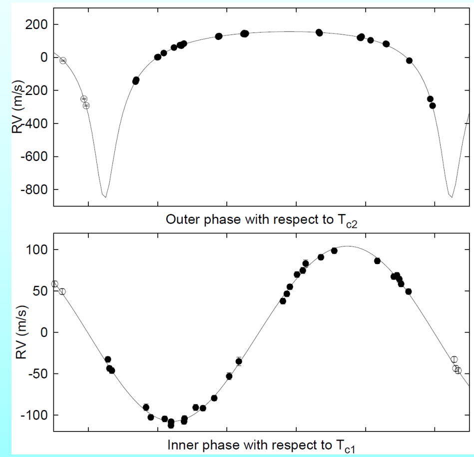
$$\Delta t \simeq \frac{45\pi}{16}\left(\frac{M_2}{M_*}\right)P_1\alpha_e^3\left(1-\sqrt{2}\alpha_e^{3/2}\right)^{-2}$$



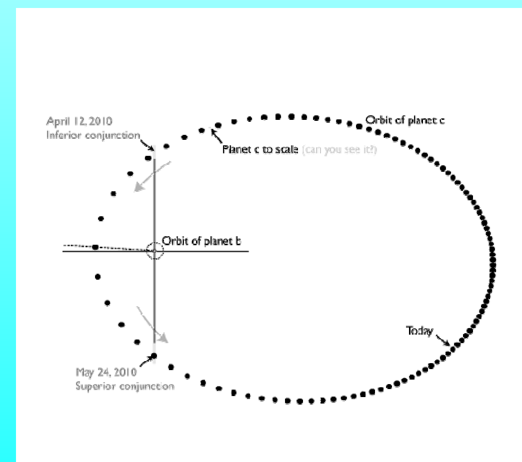
SYSTEMS WITH TRANSITING PLANETS



HAT-P-13



CoRoT-7



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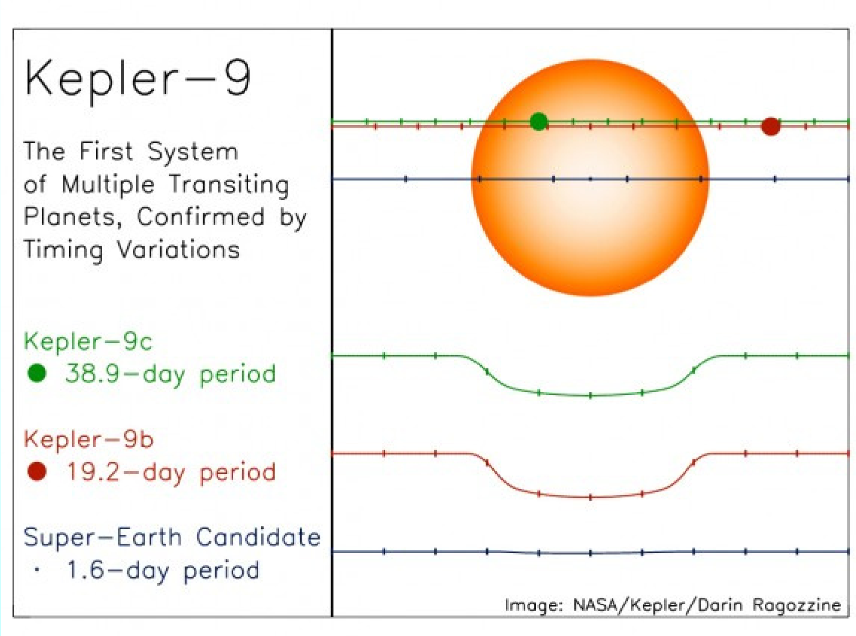

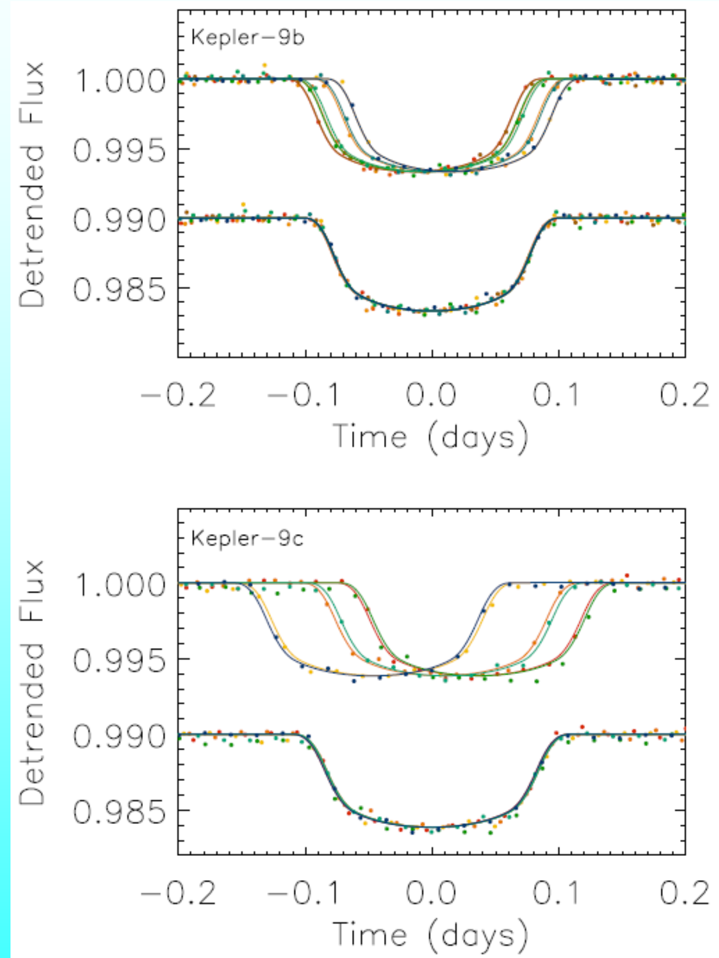

Two Saturn-sized, Saturn-mass planets orbiting a sun-like star

Close to a 2:1 resonance

Small mutual inclination (<10 deg)

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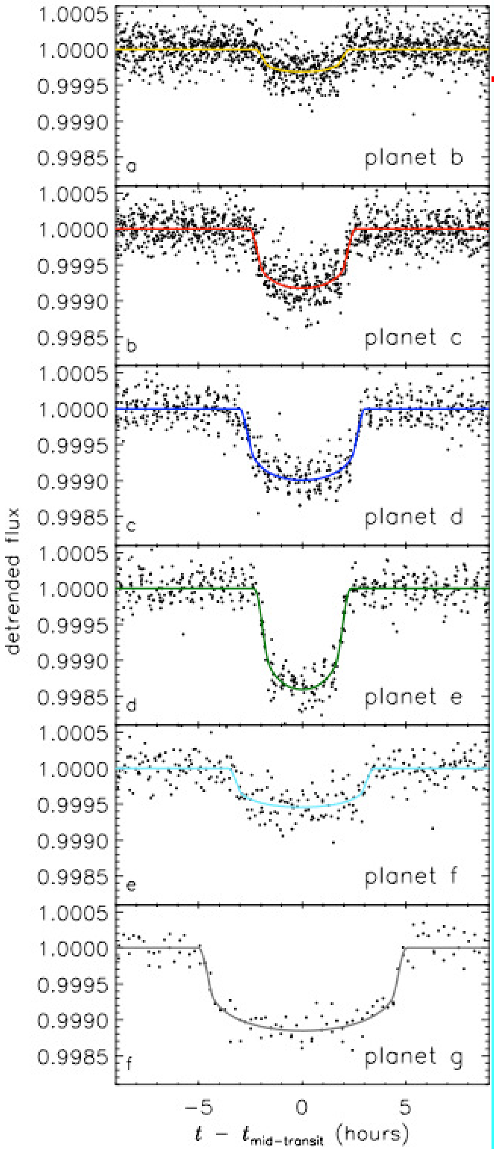
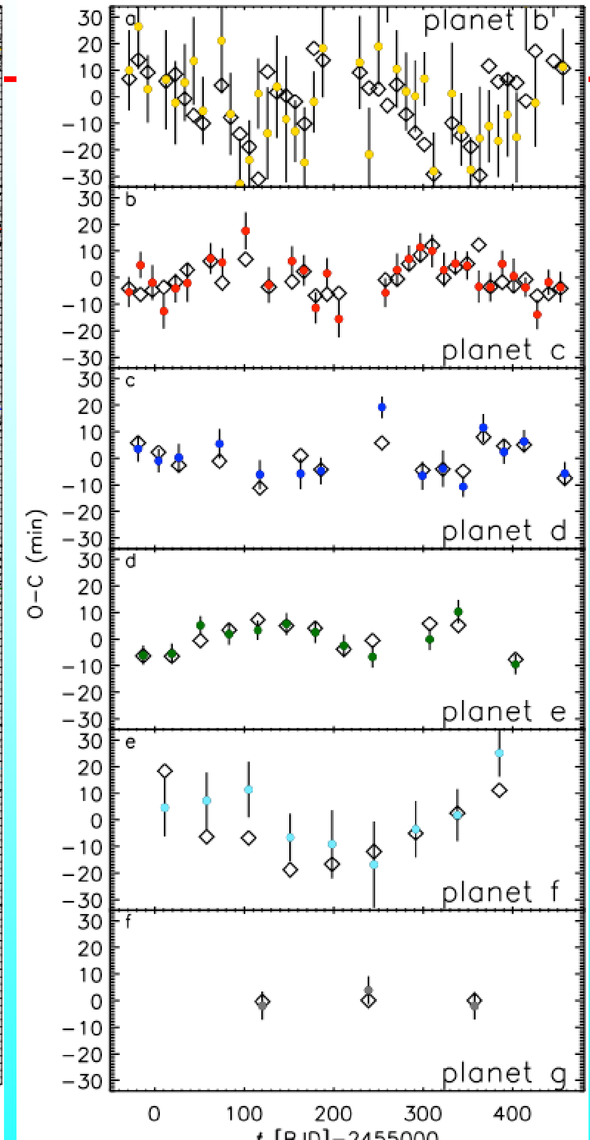
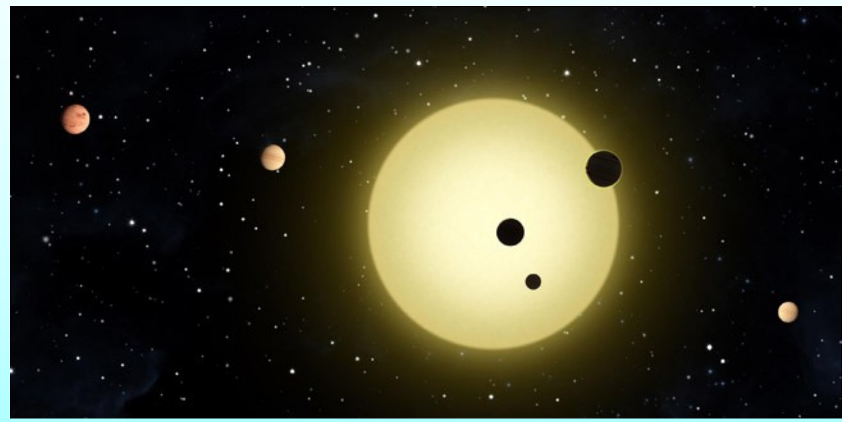
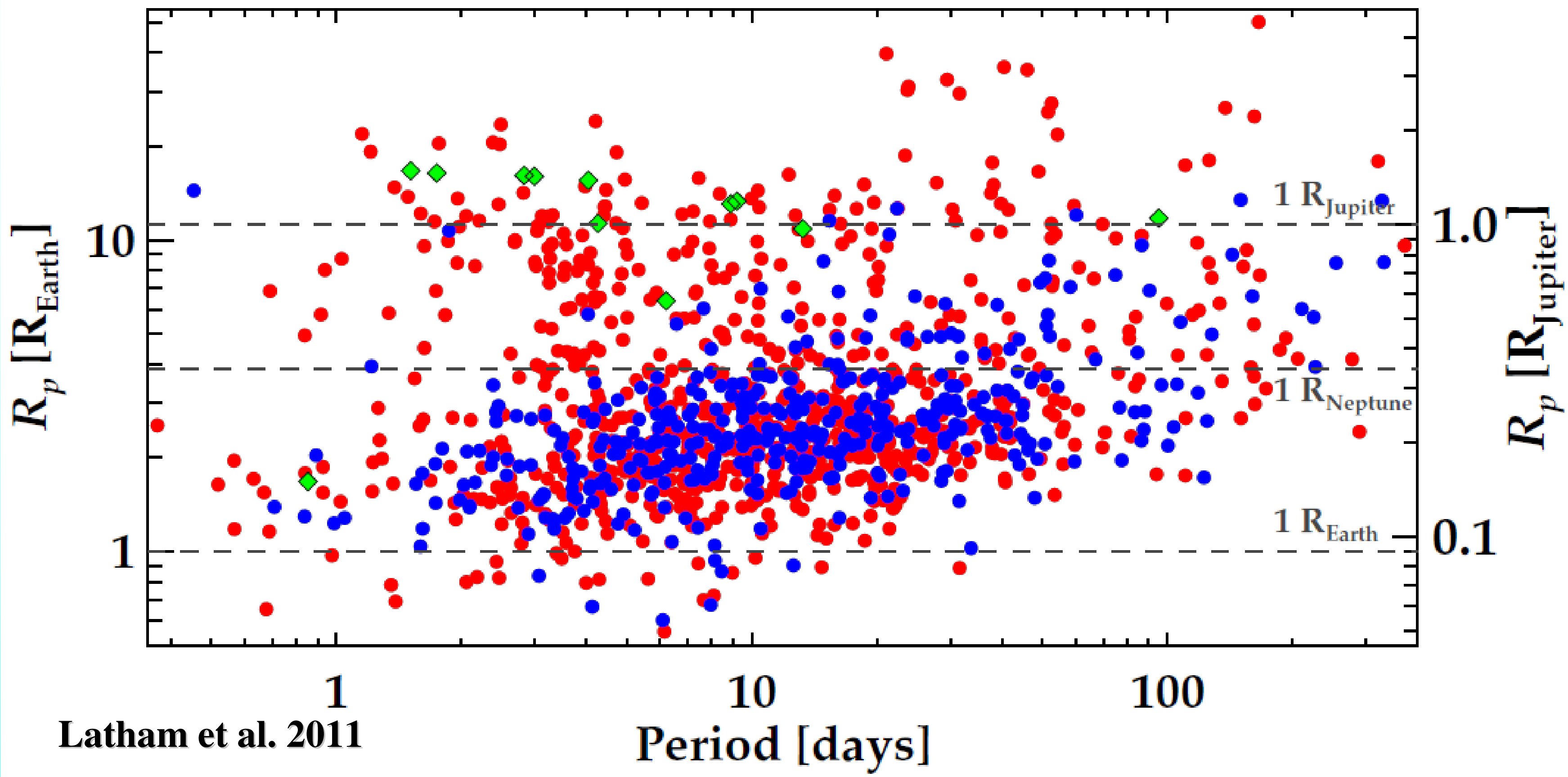
The Kepler-11 System





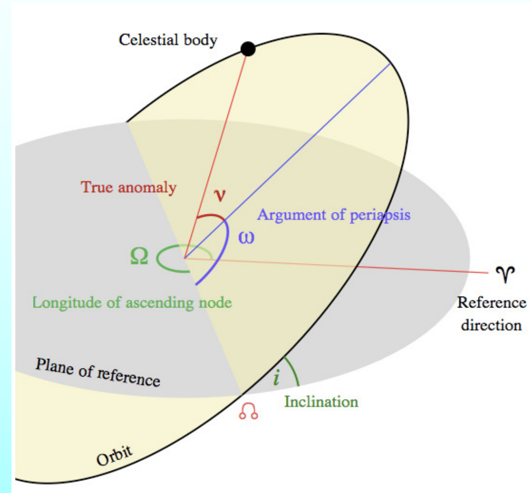




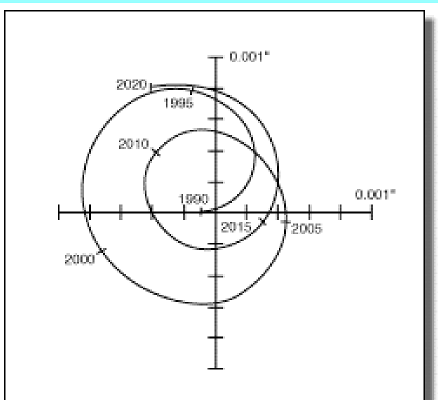
Latham et al. 2011

Multiple "flat" systems tend not to have gas giants

What About Astrometry?

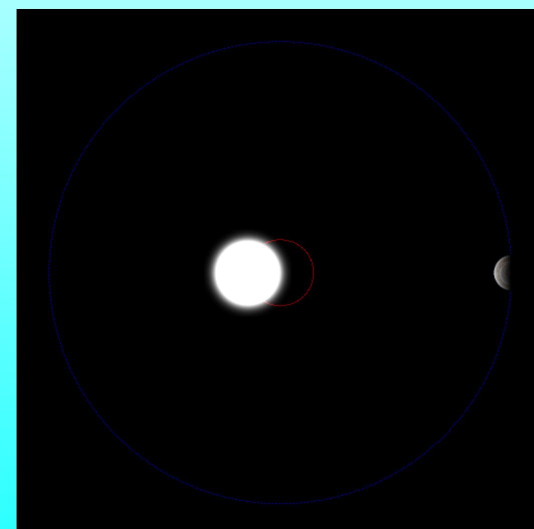


- measures stellar positions and uses them to determine a binary orbit projected onto the plane of the sky
- measures all 7 parameters of the orbit, in multiple systems it derives the relative inclination angles between pairs of orbits, regardless of the actual geometry. Mass is derived given a guess for the primary's.
- In analysis, one has to take the proper motion and the stellar parallax into account
- The measured amplitude of the orbital motion (in mas) is:



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

$$\Delta\theta = 0.5\left(\frac{q}{10^{-3}}\right)\left(\frac{a}{5AU}\right)\left(\frac{d}{10pc}\right)^{-1}$$



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PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

With the completion of the great radial-velocity programmes of the major observatories, the impression seems to have gained ground that the measurement of Doppler displacements in stellar spectra is less important at the present time than it was prior to the completion of R. E. Wilson's new radial-velocity catalogue.

I believe that this impression is incorrect, and I should like to support my contention by presenting a proposal for the solution of a characteristic astrophysical problem.

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun. K. A. Strand's[1] discovery of a planet-like companion in the system of 61 Cygni, which was recently confirmed by A. N. Deitch[2] at Poulkovo, and similar results announced for other stars by P. Van de Kamp[3] and D. Reuyl and E. Holmberg[4] have stimulated interest in this problem. I have suggested elsewhere that the absence of rapid axial rotation in all normal solar-type stars (the only rapidly-rotating G and K stars are either W Ursae Majoris binaries or T Tauri nebular variables,[5] or they possess peculiar spectra[6]) suggests that these stars have somehow converted their angular momentum of axial rotation into angular momentum of orbital motions of planets. Hence, there may be many objects of planet-like character in the galaxy.

But how should we proceed to detect them? The method of direct photography used by Strand is, of course, excellent for nearby binary systems, but it is quite limited in scope. There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.

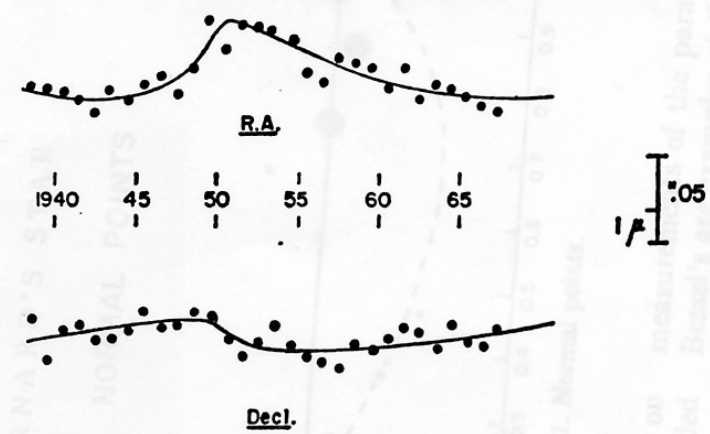

FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

1940's: Strand, Reuyl & Holmberg (61 Cyg, 70 Oph)
1960's: Lippincott,Hershey (Lalande 21185)
1960's-80's: Van de Kamp (Barnard's Star)
1980's: Gatewood (Lalande 21185, again)
2001: Gatewood et al. (some 20 RV planets)
2009: Pravdo & Shaklan (VB10b) ?

mas-precision astrometry is not enough for planet detection

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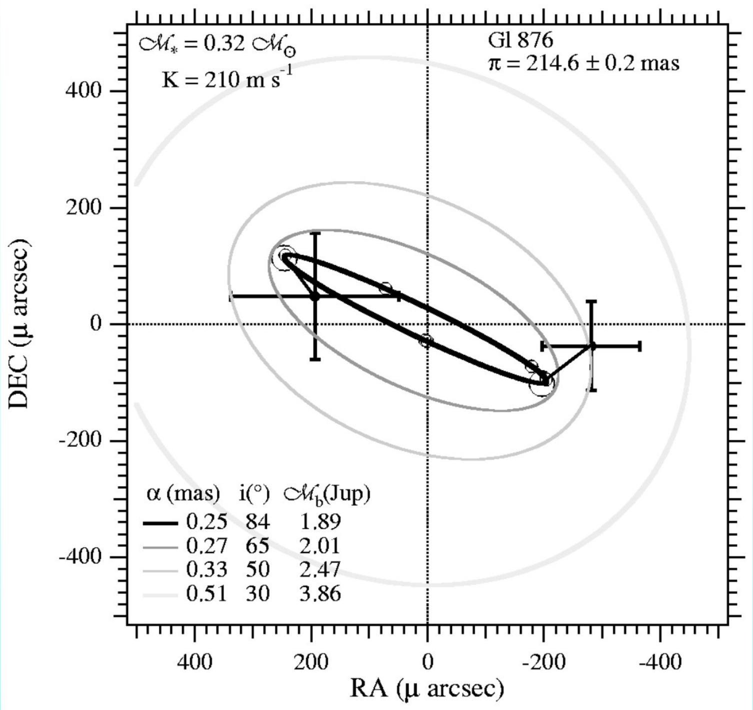
Success: HST Follow-up Studies



- *A mass for GJ 876c*
- *A mass for ε Eri b*
- Not a planet but an M dwarf: HD 33636b
- Not planets but brown dwarfs: HD136118b, HD 38529c

$$\frac{a \sin i}{\pi_*} = \frac{PK\sqrt{1-e^2}}{2\pi(4.7405)}$$

Benedict et al. 2002, 2006, 2010
Martioli et al. 2010

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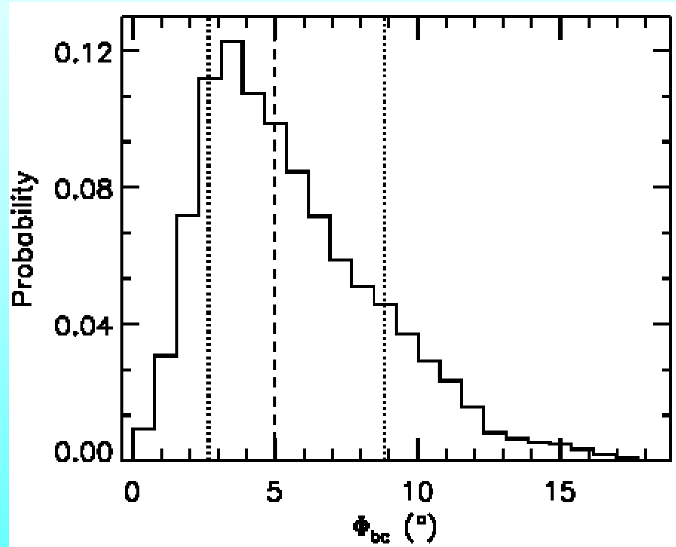
mas Astrometry: Coplanarity Measurements

$$\cos i_{\rm rel} = \cos i_{\rm in} \cos i_{\rm out} + \sin i_{\rm in} \sin i_{\rm out} \cos(\Omega_{\rm out} - \Omega_{\rm in})$$

Targets - HST Data in Hand							
Companion	$\mathcal{M}_*$ ($\mathcal{M}_\odot$)	Sp.T.	d(pc)	ecc	$\mathcal{M}$ sini ($\mathcal{M}_{Jup}$)	αsini (mas)	P(d)
HD 47536 b	1.1	K1 III	12.1	0.2	7	0.8	712
HD 136118 b	1.21	F9 V	52.3	0.36	11.8	0.4	1209
HD 168443 c	1.05	G6 IV	37.9	0.2	17.4	1.3	1739
HD 145675 b	1.00	K0 V	18.1	0.38	4.9	0.8	1796
HD 38529 c	1.45	G4 IV	42.4	0.33	13.1	0.8	2207
Coplanarity Targets for HST Cycle 16-17							
HD 128311 b	0.79	K0 V	16.6	0.3	2.6	0.8	458
HD 128311 c	0.79	K0 V	16.6	0.29	3.2	0.3	928
HD 202206 b	0.90	G6 V	46.3	0.44	17.4	0.5	256
HD 202206 c	0.90	G6 V	46.3	0.27	2.4	0.2	1383
μ Ara b	1.15	G3 IV	15.3	0.31	1.7	0.3	630
μ Ara c	1.15	G3 IV	15.3	0.57	3.1	0.5	2490
γ Cep Ab	1.18	K1IV+M4V	13.7	0.11	1.4	0.8	2207

McArthur et al 2009, in prep.



Bean & Seifahrt 2009

v And c,d are mutually inclined by ~30 deg

μas Astrometry

Like (and worse than) RV, it faces:

- **technological challenges** (achievable precision, ground vs. space, instrument configuration, choice of wavelength)

- **astrophysical challenges** (noise sources characterization)

- **data modeling challenges** (orbital fits)

TABLE 1
PARALLAX, PROPER MOTION, AND ASTROMETRIC SIGNATURES INDUCED BY PLANETS OF VARIOUS MASSES AND ORBITAL RADII

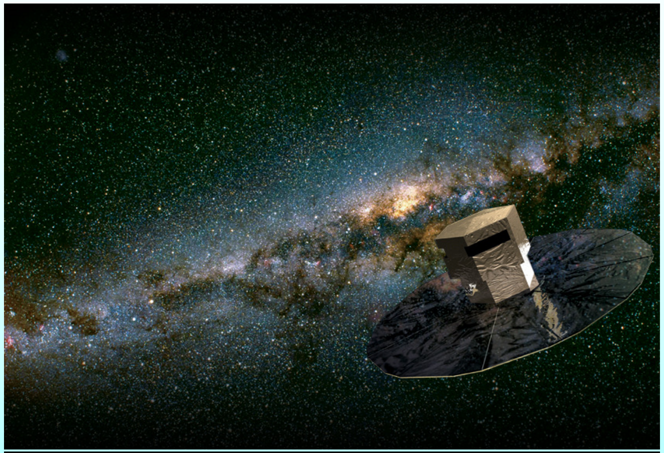
Source	α
Jupiter at 1 AU (μas)	100
Jupiter at 5 AU (μas)	500
Jupiter at 0.05 AU (μas)	5
Neptune at 1 AU (μas)	6
Earth at 1 AU (μas)	0.33
Parallax (μas)	1×10^5
Proper motion (μas yr^{-1})	5×10^5

NOTE.—A 1 $M_{\odot}$ star at 10 pc is assumed.

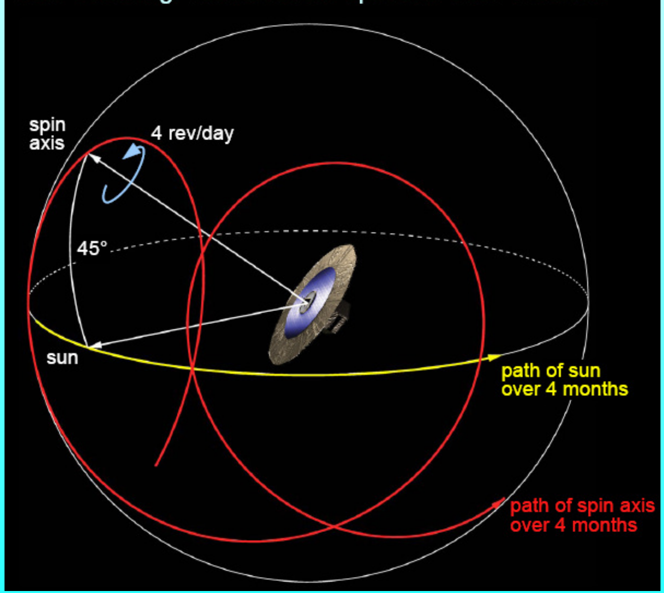
Sozzetti 2005

See e.g. Sozzetti (2005, 2009)

10 μas Astrometry: 2012-2017



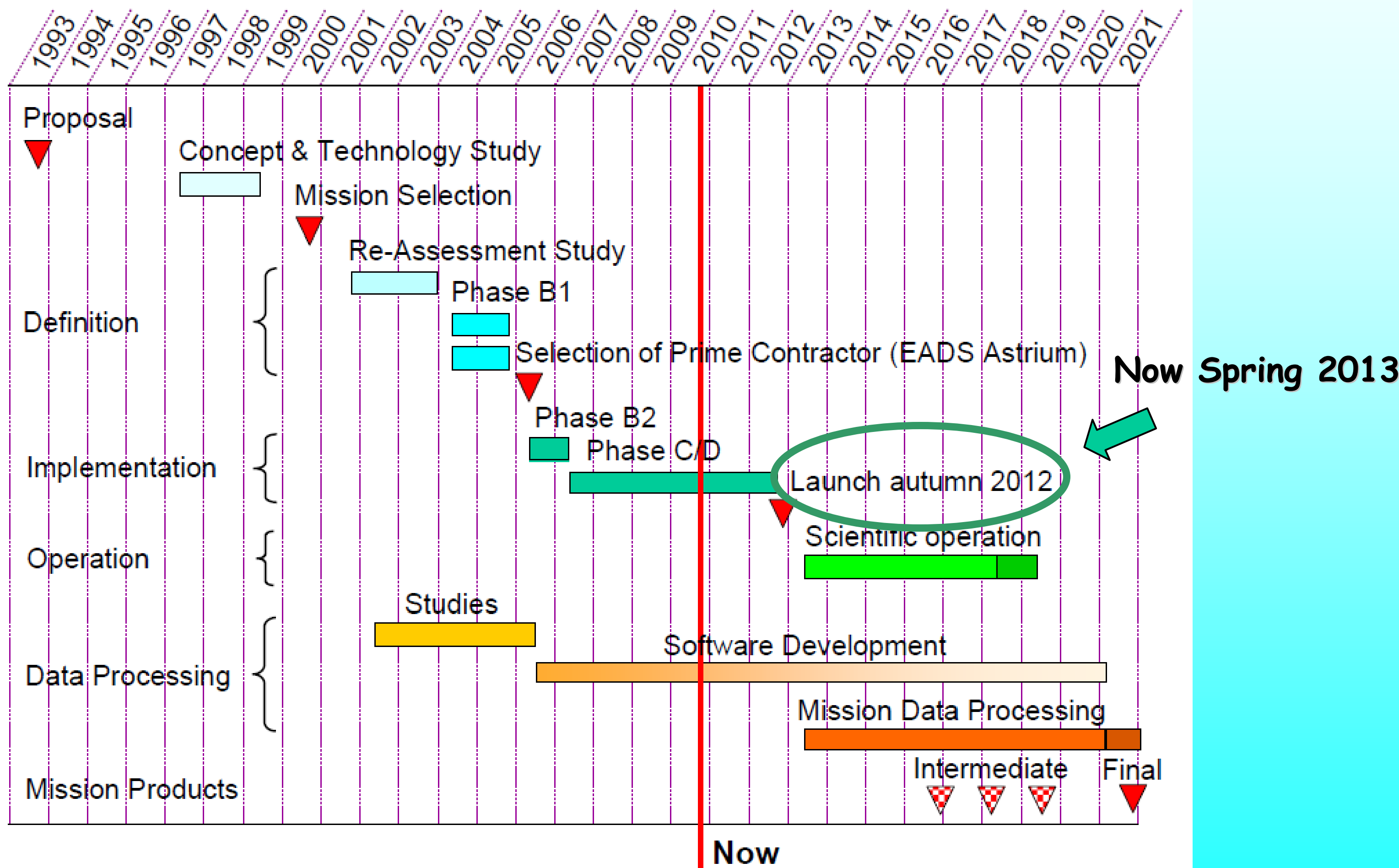
Gaia scanning: Motion of the spin axis over 4 months



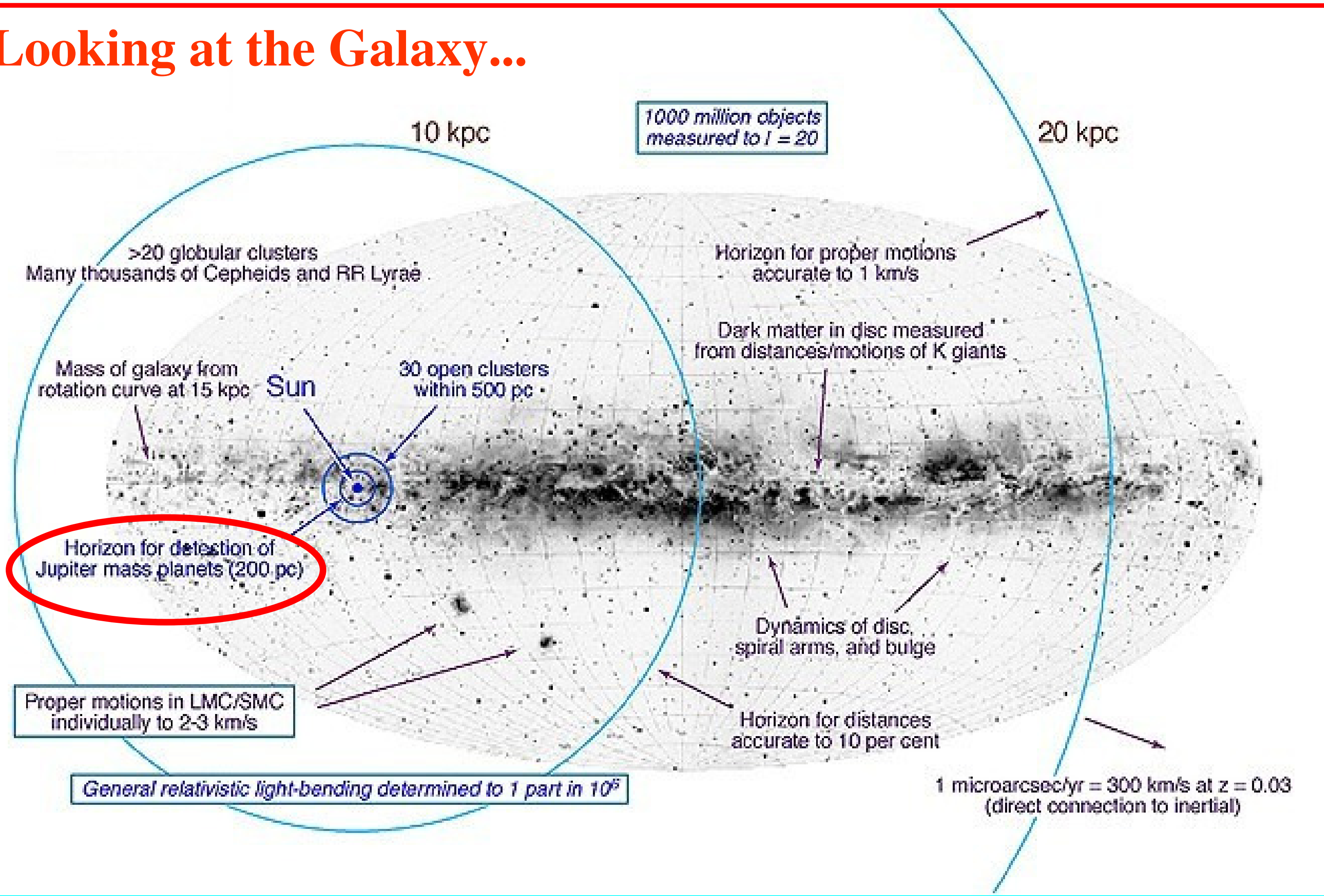
Gaia in a nutshell

- All-sky astrometric survey carried out 2012 – 2017
  - ⇒ final results around 2020
- All point objects between magnitude 6 and 20
  - ⇒ stars, asteroids, quasars, extragalactic supernovae, etc
  - ⇒ about 10^9 objects
- Using Hipparcos principle (continuous scanning, two fields of view)
  - ⇒ stellar astrometric parameters α, δ, ϖ, μ_α, μ_δ
- Positional accuracy from 6 μas (bright stars) to 200 μas (faint)
  - ⇒ tied to the extragalactic frame via ~500,000 quasars
- Complementary spectrophotometry and spectroscopic radial velocity

Project schedule



Looking at the Galaxy...



10 μas Global Astrometry: The Gaia challenge

Predicted astrometric accuracies

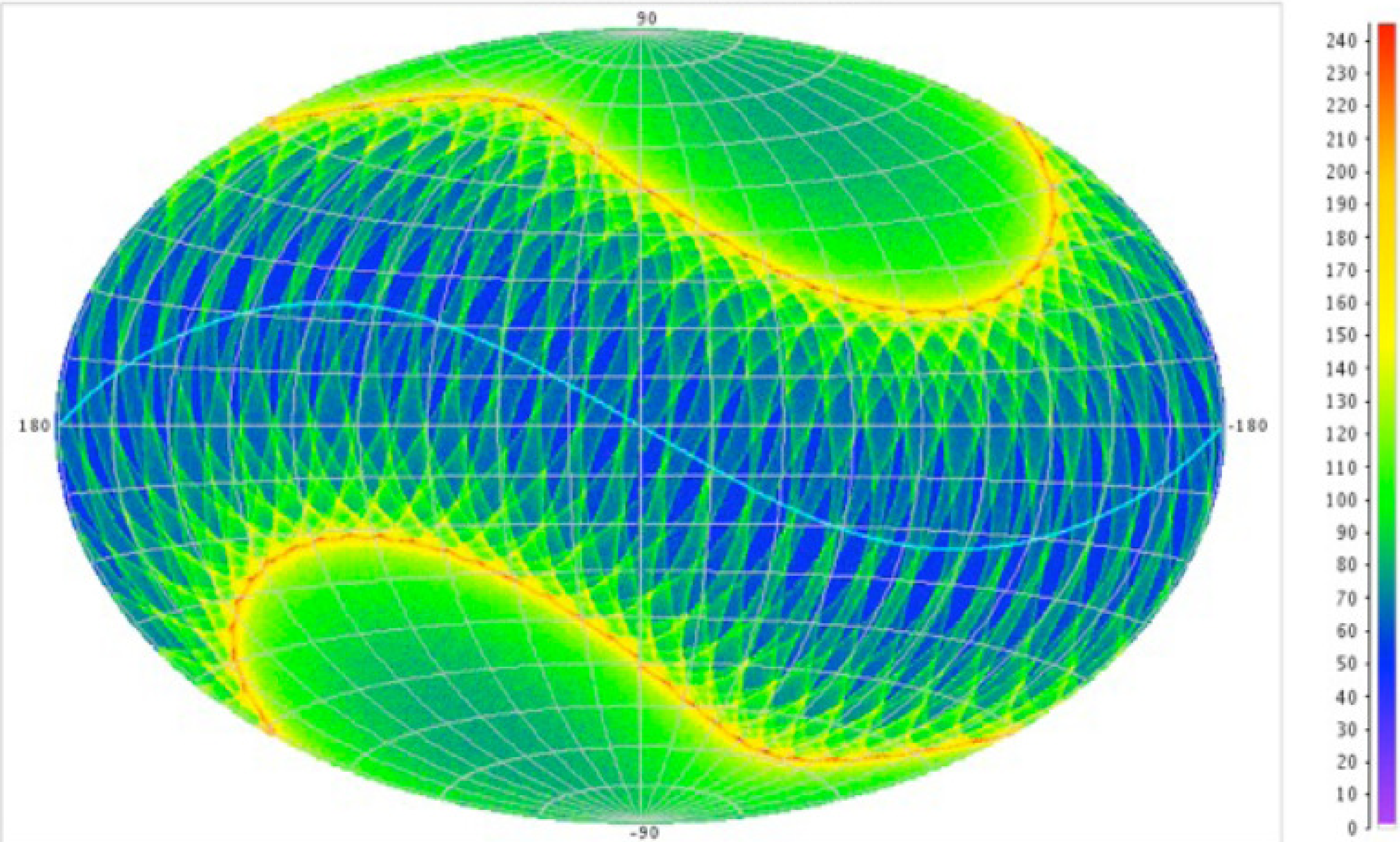
Sky-averaged standard errors for G0V stars (single stars, no extinction)

V magnitude	6 - 13	14	15	16	17	18	19	20	mag
Parallax	8	13	21	34	55	90	155	275	μas
Proper motion	5	7	11	18	30	50	80	145	μas / yr
Position @2015	6	10	16	25	40	70	115	205	μas

Notes:

- Estimates calculated with the Gaia Accuracy Tool (courtesy J. de Bruijne, ESA)
- Radiation-damage effects on CCDs not fully taken into account
- Estimates include a 20% margin (factor 1.2) for unmodelled errors

Number of FoV crossings per star (5 yr)

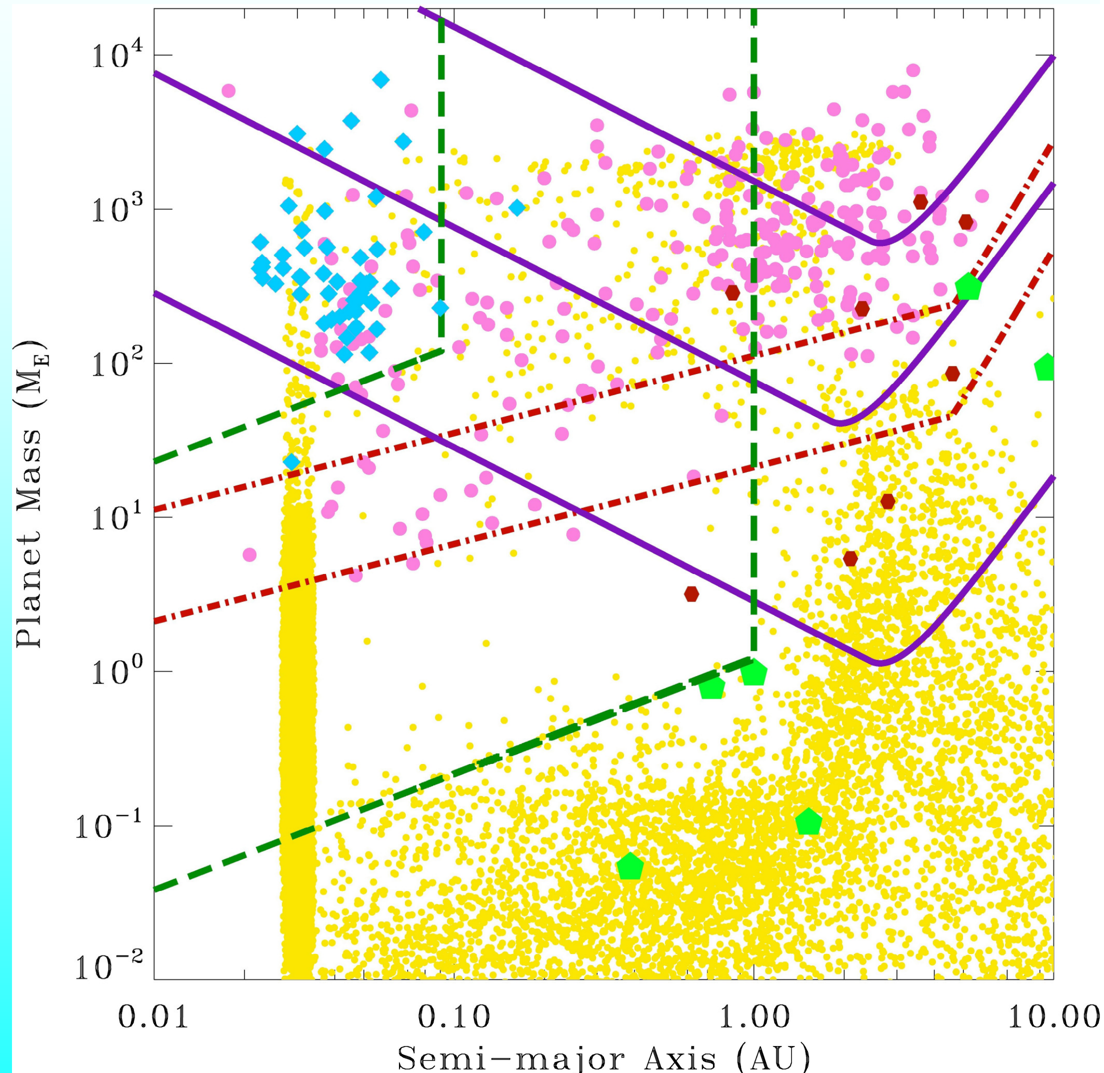


Equatorial projection

Gaia: Discovery Space

1) 2-3 M_J planets at 2<a<4 AU are detectable out to~200 pc around solar analogs
2) Saturn-mass planets with 1<a<4 AU are measurable around nearby (<25 pc) M dwarfs

Critical assumption:
σ_A ~ 15 µas (6<V<13)



Sozzetti 2010

How Many Planets will Gaia find?

Star counts (V<13), $F_p(M_p,P)$, Gaia completeness limit →

Δd (pc)	$N_\star$	Δa (AU)	ΔM_p (M_J)	N_d	N_m
0-50	~10 000	1.0 - 4.0	1.0 - 13.0	~ 1400	~ 700
50-100	~51 000	1.0 - 4.0	1.5 - 13.0	~ 2500	~ 1750
100-150	~114 000	1.5 - 3.8	2.0 - 13.0	~ 2600	~ 1300
150-200	~295 000	1.4 - 3.4	3.0 - 13.0	~ 2150	~ 1050

Casertano, Lattanzi, Sozzetti et al. 2008

How Many Multiple-Planet Systems will Gaia find?

Star counts (V<13), $F_{p,mult}$, Gaia detection limit →

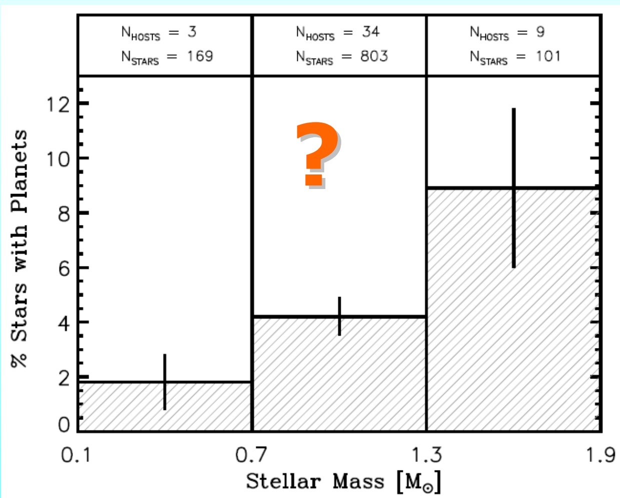
Case	Number of Systems
Detection	~ 1000
Orbits and masses to better than 15-20% accuracy	~ 400 – 500
Successfull coplanarity tests	~ 150

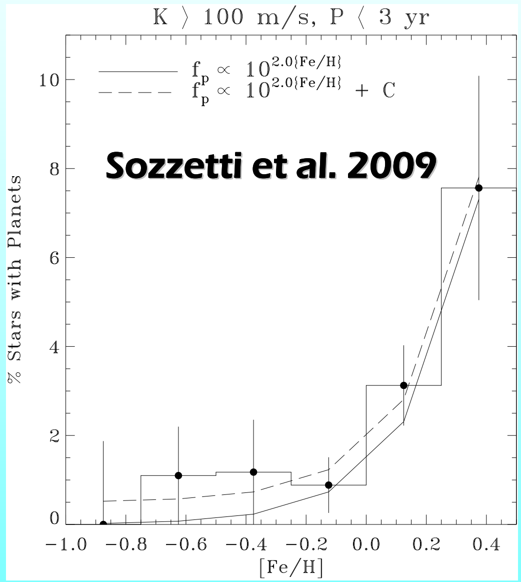
Unbiased, magnitude-limited census of hundreds of thousands stars

How do Planet Properties and Frequencies Depend Upon the Characteristics of the Parent Stars (also, What is the Preferred Mechanism of Gas Giant Planet Formation?)?

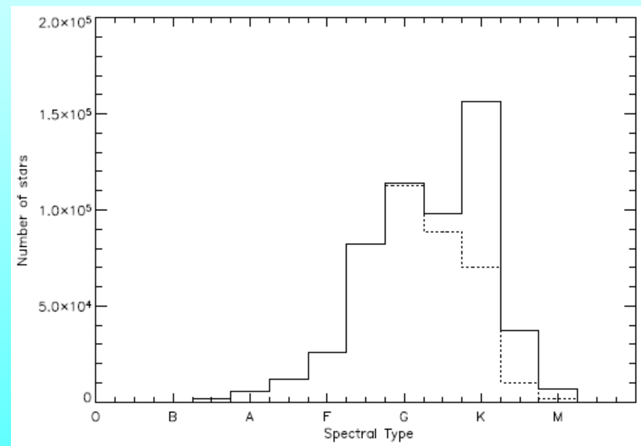
The Gaia Legacy (1)

Johnson 2007





Casertano et al. 2008



Gaia will test the fine structure of giant planet parameters distributions and frequencies, and investigate their possible changes as a function of stellar mass, metallicity, and age with unprecedented resolution

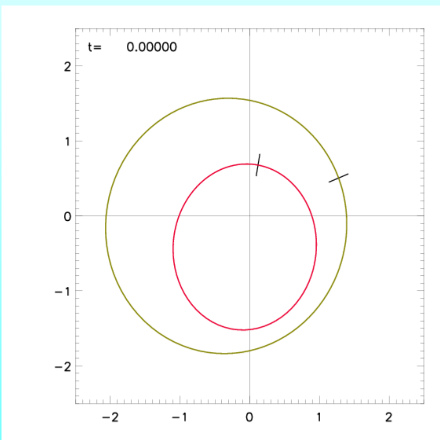
10^4 stars per 0.1 M_{Sun} bin!

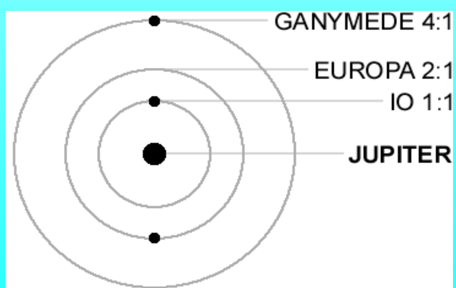
What is the Evolution of the Various Architectures of Planetary Systems?

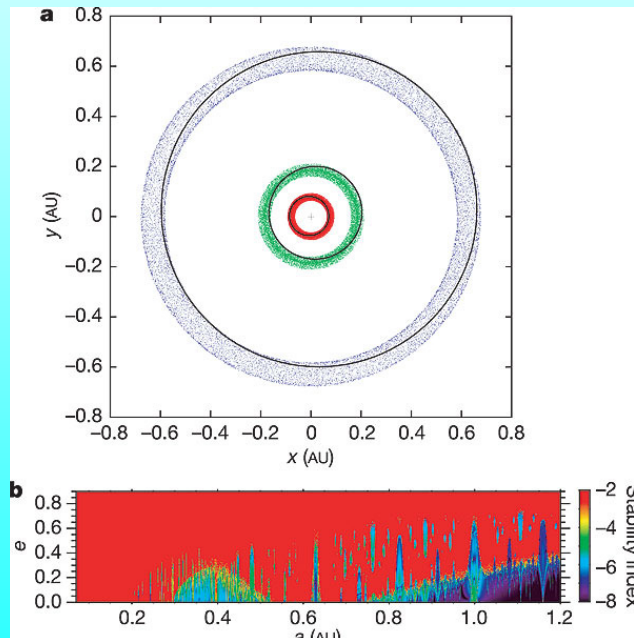
1) What is the richness of the dynamical families?
2) What is the relative role of many proposed mechanisms of dynamical interaction?
3) Are there regions of stable, habitable orbits?

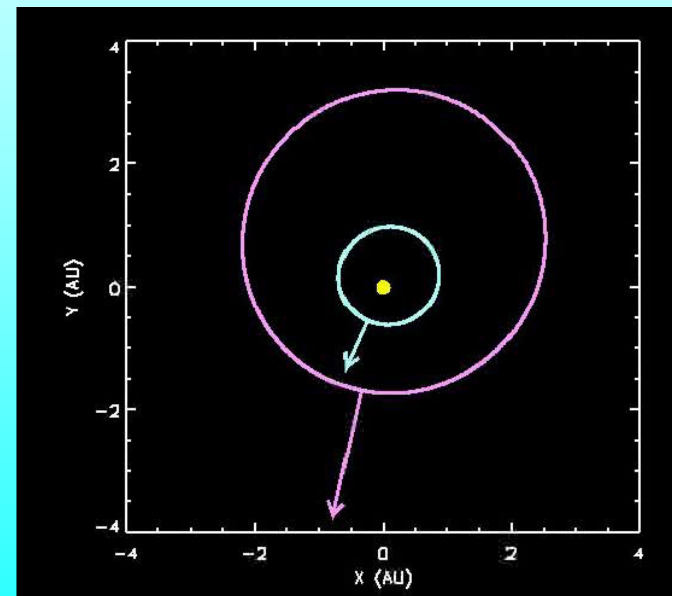
The Gaia Legacy (2)

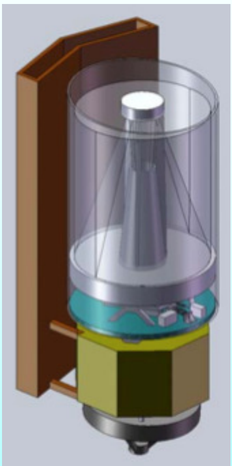
Gaia coplanarity tests will help answering these questions in a statistical sense, not just on a star-by-star basis.

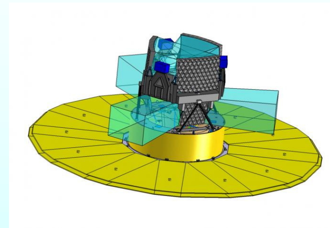


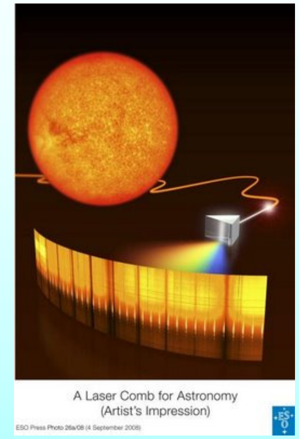


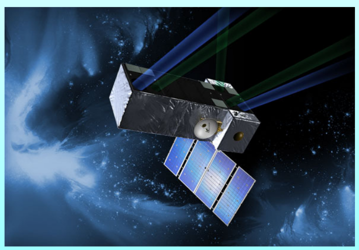


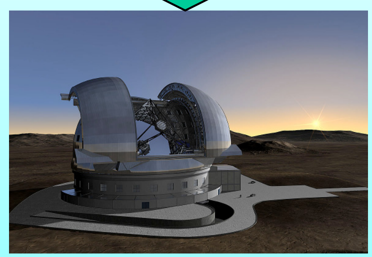


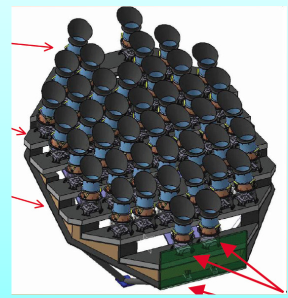












- **Gaia & EChO (Tessenyi, Tinetti, Sozzetti et al., in prep.)**
- **Gaia & PLATO/other transit surveys**
- **Gaia & SPHERE/EPICS**
- **Gaia & RV surveys, ground-based and space-borne astrometry**

Currently under study within the GREAT RNP/ITN (WGC1)

Gaia & Exoplanets: RV follow-up

- **High-res, high-precision spectroscopy of Gaia-discovered systems (four-fold aim)**
- **Both visual and IR wavelengths, depending on targets**
- **Need for quasi-dedicated visible-IR spectrographs on 4-m class telescopes**
- **What of lower-class facilities for follow-up of transit candidates (must evaluate the relevance of the science case)?**

Fitting Multiple-Planet Orbits

- Highly non-linear fitting procedures, with a large number of model parameters (at a minimum, $N_p=5+7*n_{pl}$, not counting references)

- Redundancy requirement: $N_{obs} >> N_p$

- Global searches (grids, Fourier decomposition, genetic algorithms, Bayesian inference +MCMC) must be coupled to local minimization procedures (e.g., L-M)

- For strongly interacting systems, dynamical fits using N-body codes may be required

Astrometry + RV Orbital Fits

- **The lesson from RV surveys: it is not uncommon to find disagreement between solutions (and sometimes number of planets detected!) presented by different teams.**

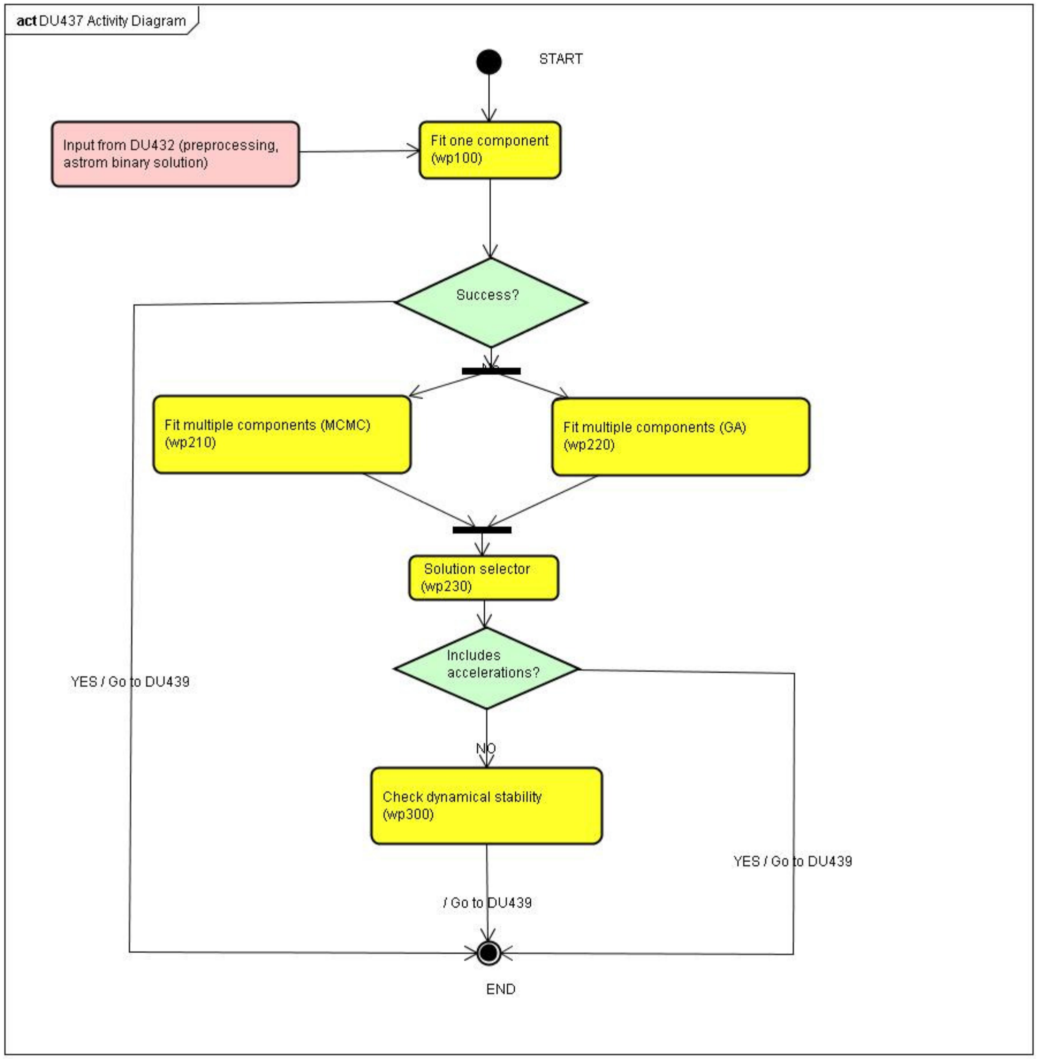
- **Simultaneous orbital fits: fully exploit the redundancy constraints from both types of data to strengthen the determination of orbital elements and masses of the companions**

$$\chi^2_{\rm comb} = \chi^2_{\rm astr} + \chi^2_{\rm spec} = \sum \left(\frac{x^M - x^\star}{\sigma_{\rm x}} \right)^2 + \sum \left(\frac{y^M - y^\star}{\sigma_{\rm y}} \right)^2 + \sum \left(\frac{RV^M - RV^\star}{\sigma_{\rm RV}} \right)^2$$

Assessing Detections

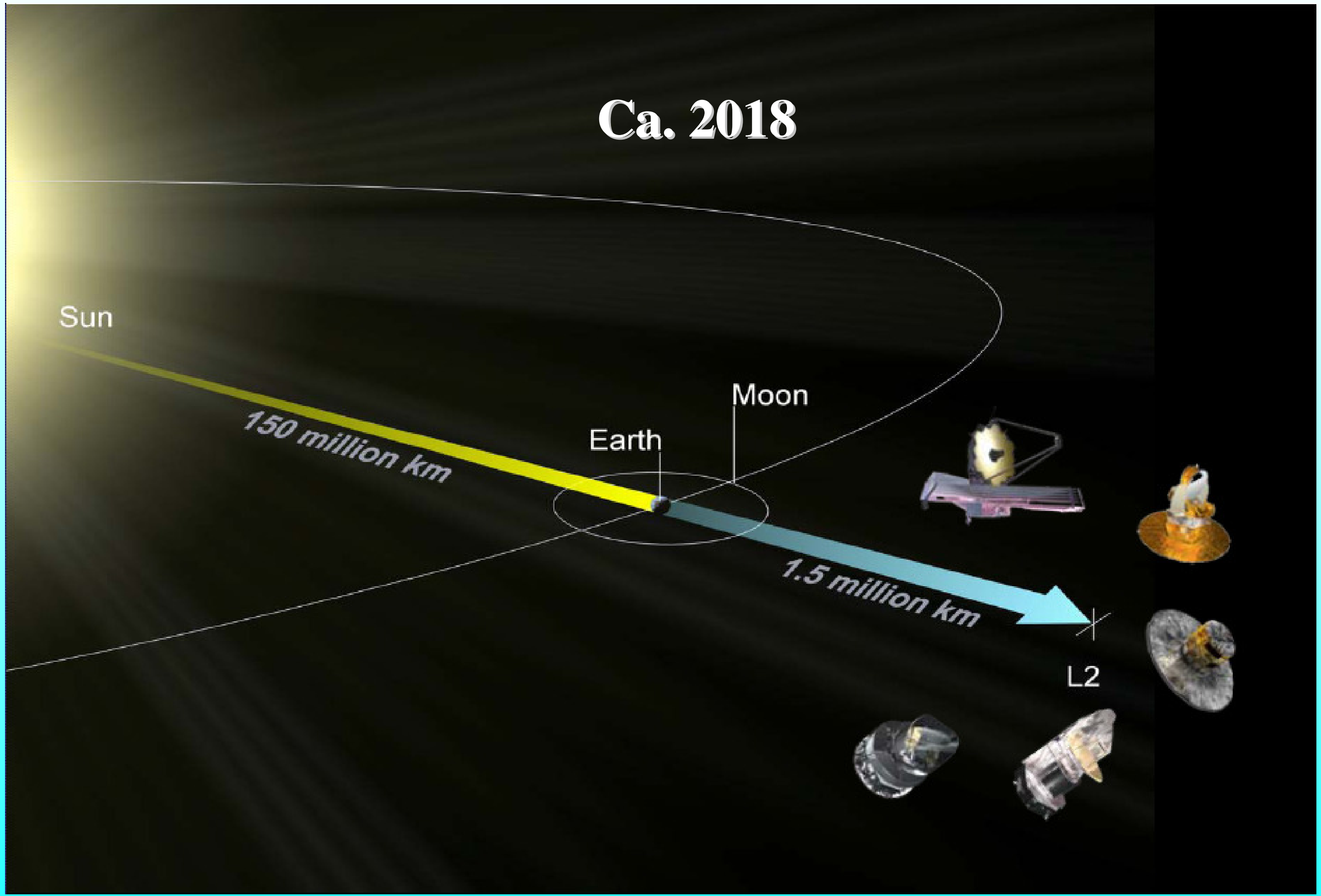
- **Errors on orbital parameters: covariance matrix vs. χ^2 surface mapping vs. bootstrapping procedures**

- **Confidence in an n-component orbital solution: FAPs, F-tests, MLR tests, statistical properties of the errors on the model parameters, others?**



Exoplanets in the Gaia DPAC Pipeline

Sozzetti, Segransan, et al. in prep.


Ca. 2018
Sun
150 million km
Earth
Moon
1.5 million km
L2

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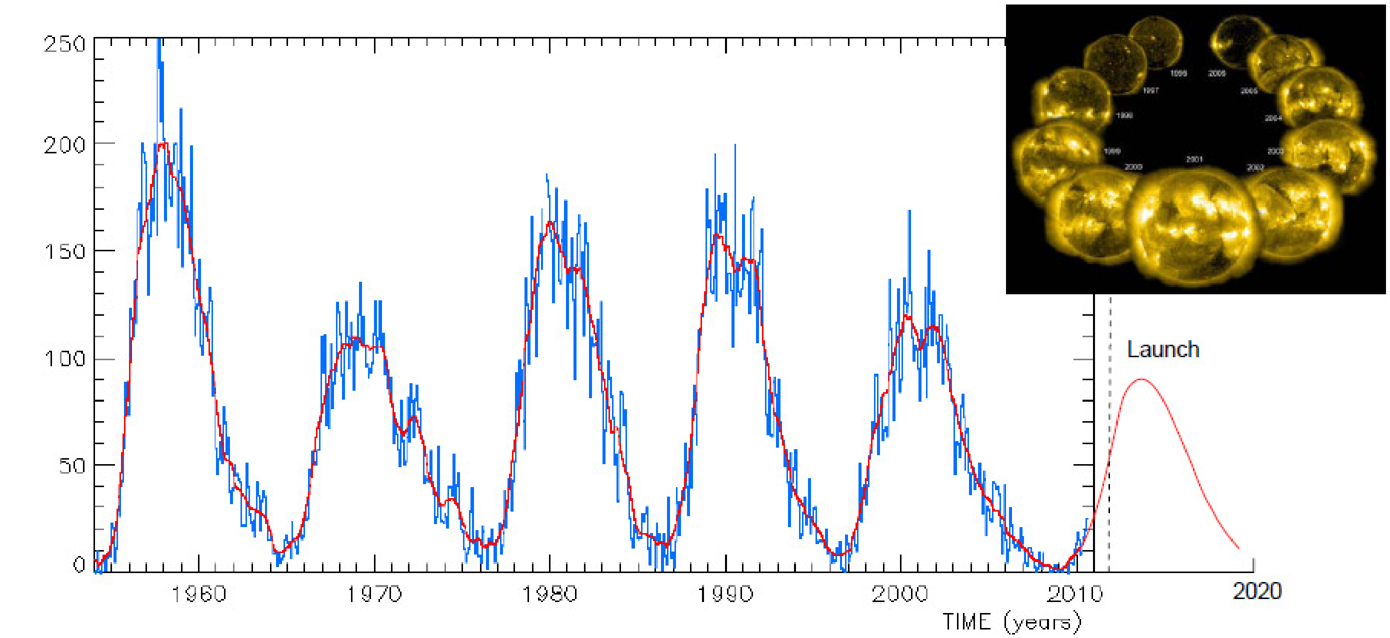
Radiation Damage: the Solar Cycle



- Solar radiation damage creates permanent electron traps in the CCD
- These systematically distort the PSF and reduce the collected signal
- PSF distortion induces position biases → on-ground calibration
- Residual errors degrade the astrometric performance by ~5–10%

A Word of Caution...

$\sigma_\psi{}^a$ (μas)	$N_\star{}^b$	$N_d{}^c$	$N_m{}^d$	$N_{d,mult}{}^e$	$N_{m,mult}{}^f$	$N_{copl}{}^g$
11	500 000	8000	4000	1000	500	159
16	148 148	2370	1185	296	148	47
22	62 500	1000	500	125	62	19
27	18 519	296	148	37	18	5
60	4000	64	32	8	4	1
100	500	8	4	1	0	0

If the single-measurement precision degrades significantly, exoplanets could disappear from the Gaia science case

Ongoing re-assessment of Gaia's exoplanet science potential

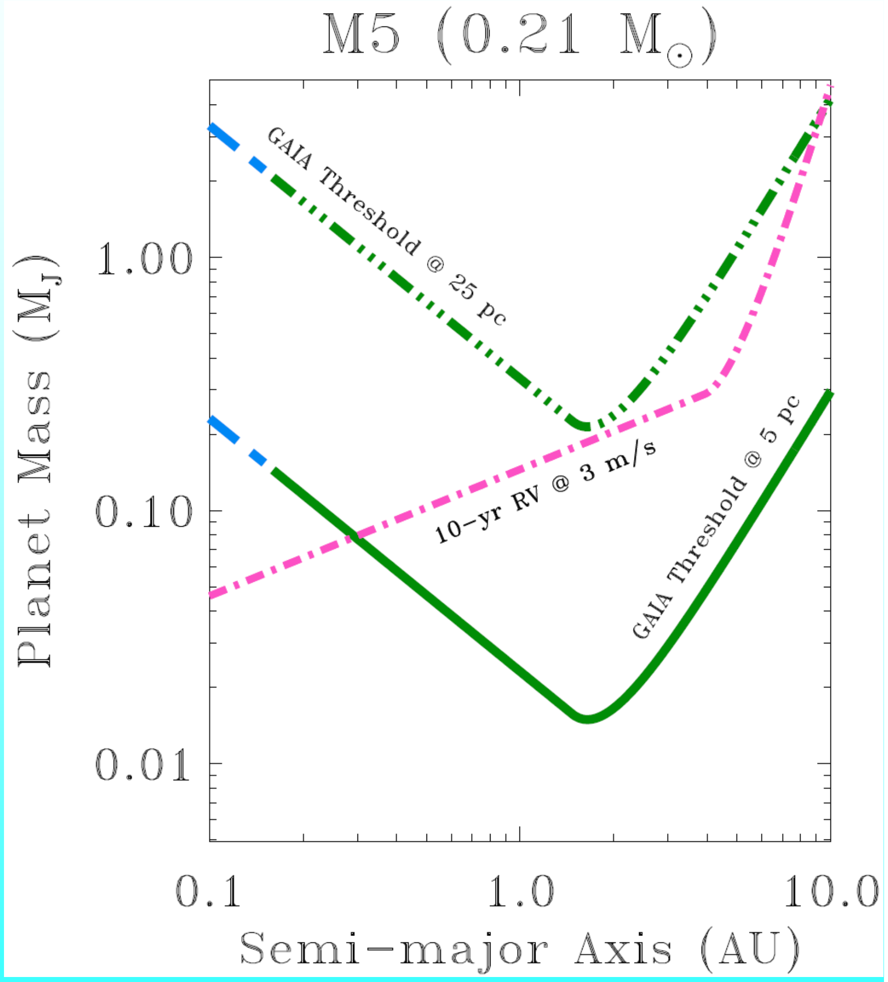
Gaia & the M dwarfs

- Nearby stars: the best reservoir to search for planetary systems with low-mass components

- Select a sample of several thousands nearby (<30 pc) M dwarfs from the Lepine catalogue

- Assess Gaia sensitivity to planetary systems architectures based on the latest error budget estimates

- Discuss results in the context of other planet-related observations of nearby stars



Sozzetti et al., in prep.

Summary

- Planetary SYSTEMS are common, and many more are going to be discovered in the near future
- They are great laboratories for studies of planet formation and evolution
- Compared to other techniques, μas astrometry is hard, but not impossible! Future programs from the ground (e.g., VLTI/PRIMA) and in space (Gaia) hold promise for crucial contributions to many aspects of planetary systems astrophysics (formation theories, dynamical evolution)
- It's almost coming of age: stay tuned!