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Exoplanetology and Gaia: Synergies in the Making

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We have, at last, evidence of the discovery of two planetary systems other than our own, and, what is more, these happen to be very near our own system. The suggestion naturally comes to mind that we may by similar means be able to find many more planetary systems in our galactic system, and the number of planetary systems in this universe may be quite large. It will be interesting in this connection to review briefly what theory has to say on this question.

On the tidal theories of Jeans³ and Jeffreys,⁴ planetary systems should indeed be rare. Taking the generally accepted age of the universe as of the order of 10^9 to 10^{10} years, and Jeans' estimate (1929) of the frequency of planetary systems on his theory—about one per 5000 million years—we have at the most two planetary systems in our galactic system. On Lyttleton's⁵ binary star collision theory, the probability of the formation of planetary systems is almost nil.

Sen (1943)

Alfven (1943)

Non-Solar Planetary Systems

IN discussing the significance of the two planet-like bodies which are now supposed to revolve around 61 Cygni and 70 Ophiuchi, Mr. Sen writes¹ that "we find that there can be at most two planetary systems in the galactic system, on Jeans's theory". If the true number were two, or anything like two, it would, of course, be out of the question to suppose that there could be three planetary systems so near to us in space. But I do not think that the true number is anywhere near to two; in a recent letter in NATURE², I calculated that something like one star in six might well be accompanied by planets, in which case the number of galactic planetary systems would not be two, but some tens of thousands of millions.

Jeans (1943)

Star	Mass	Distance of planet	
		Theory	Obs.
61 Cygni ²	0.56	2.9	2.4
70 Ophiuchi ³	1.1	5.7	6.8

The agreement indicates that these non-solar planets may have been formed in the same way as our planetary system.

The theory makes it probable that all stars are surrounded by planetary systems (more or less massive) of the same structure as ours. Planets corresponding to Jupiter will have the period

$$T = 11.9 M \text{ years.}$$

It may be worth while to look for disturbances with such periods.

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Sen (1944)

Non-Solar Planetary Systems

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BLUNDERS!!

70 Ophiuchi ³	1.1	5.7	6.8
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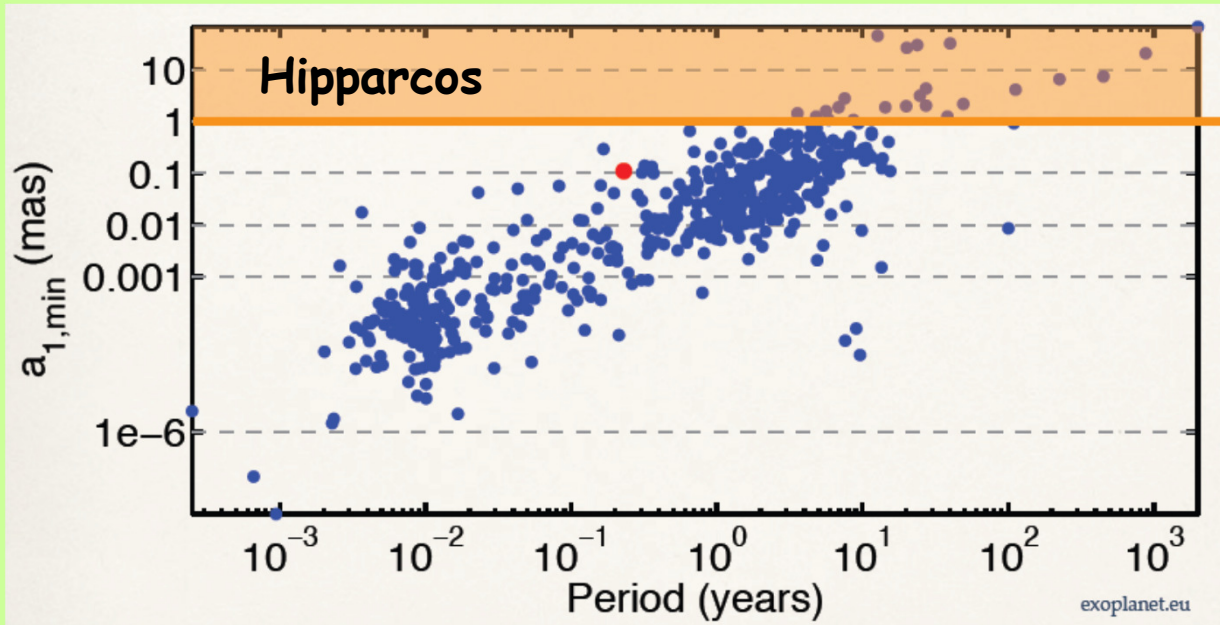
It may be worth while to look for disturbances with such periods.

Alfven (1943)



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μ as Astrometry: Challenges



Courtesy J. Sahlmann

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

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

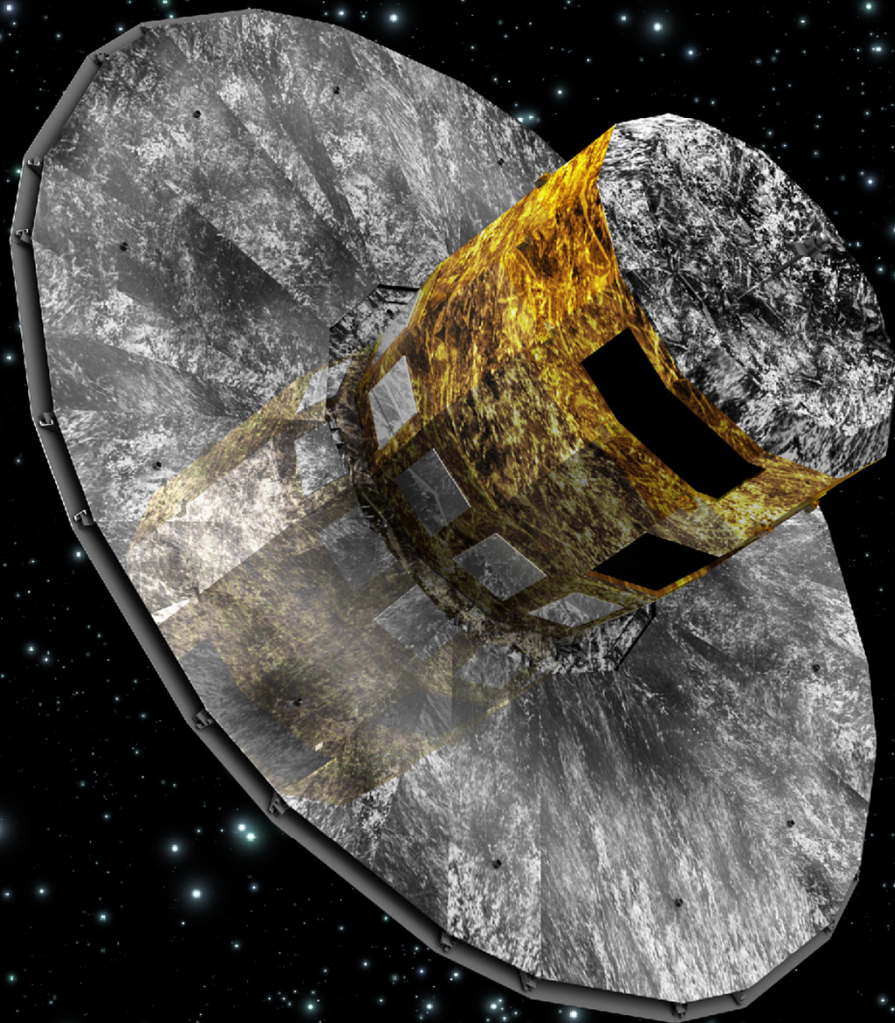
NOTE. — A $1 M_{\odot}$ star at 10 pc is assumed.

Sozzetti 2005

Like RV, it faces:

- technological challenges (achievable precision, ground vs. space, instrument configuration, choice of wavelength, calibrations, etc.)
 - astrophysical challenges (noise sources characterization)
 - data modeling challenges (orbital fits)
- See e.g. Sozzetti (2005, 2010)

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Micro-arcsec Astrometry Comes of Age!



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Up There and Cruising!



Successfully launched on
December 19th, 2013!

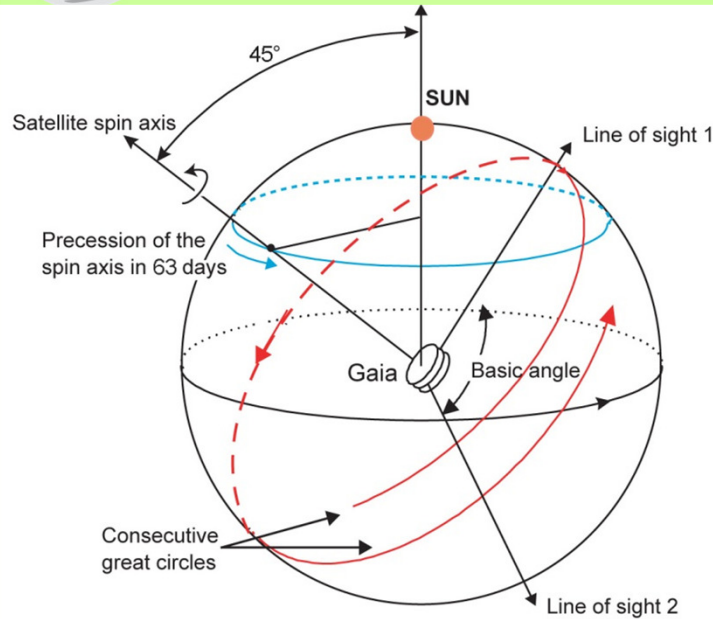


The Space Photometry Revolution – Toulouse, 08/07/2014

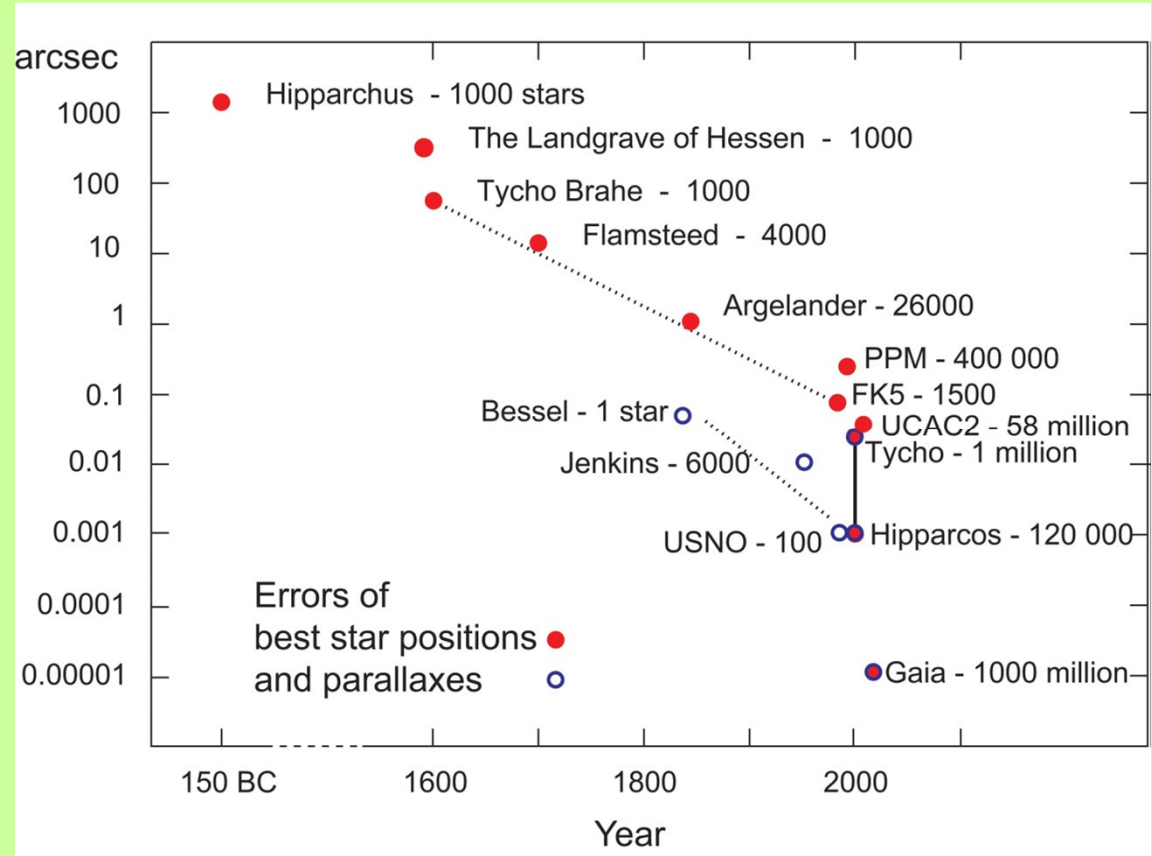
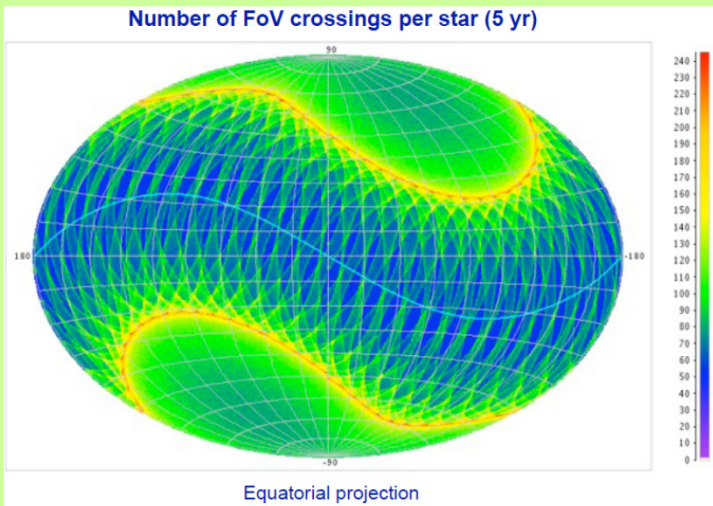


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A Space Astrometry Revolution!



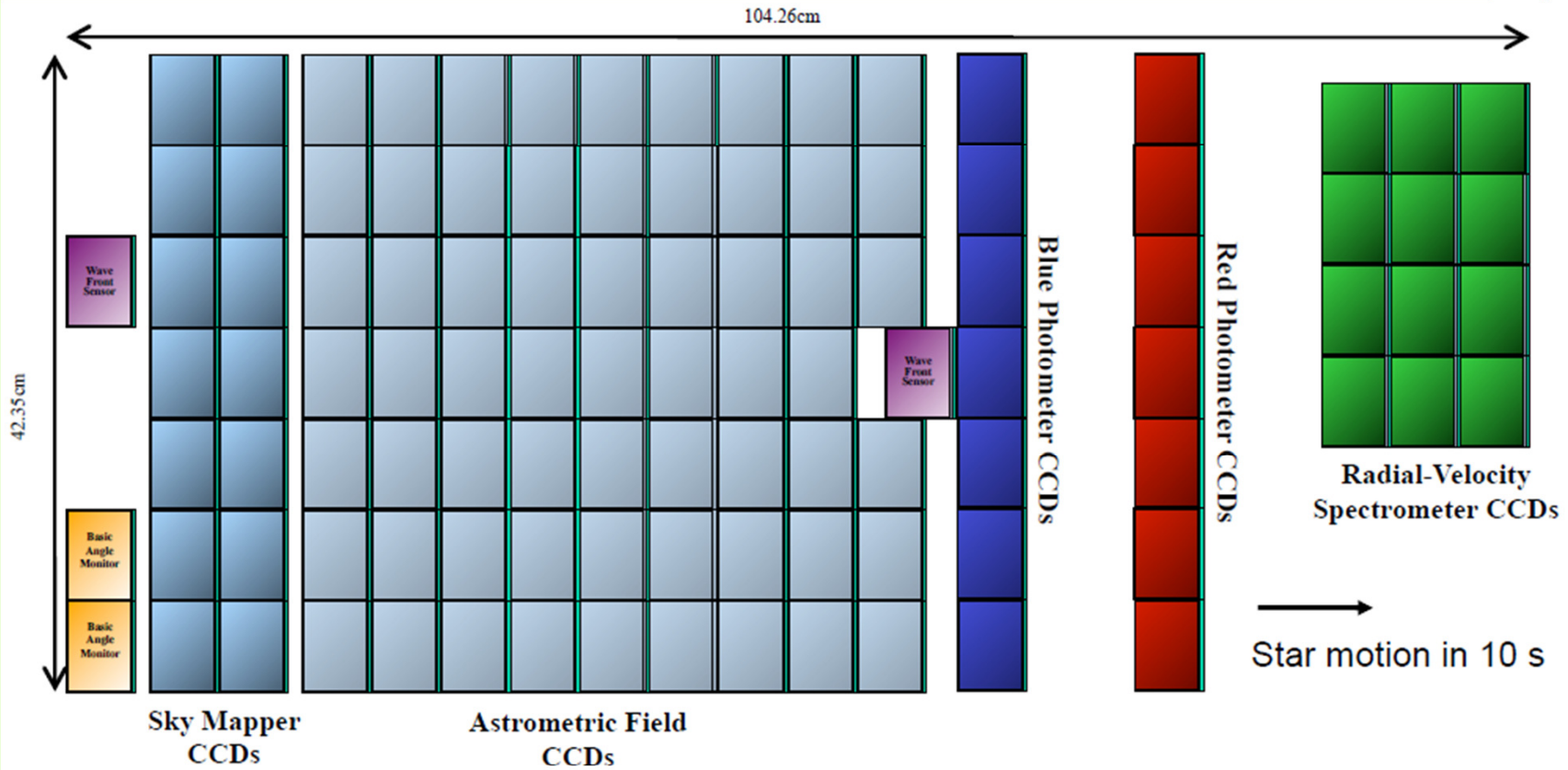
**At the V=20 survey limit:
1 billion stars observed!**





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Gaia Focal Plane



Total field:

- active area: 0.75 deg²
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 μm x 30 μm
= 59 mas x 177 mas

Sky mapper:

- detects all objects to 20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:

- total detection noise ~ 6 e⁻

Photometry:

- spectro-photometer
- blue and red CCDs

Spectroscopy:

- high-resolution spectra
- red CCDs



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Overall status post-commissioning

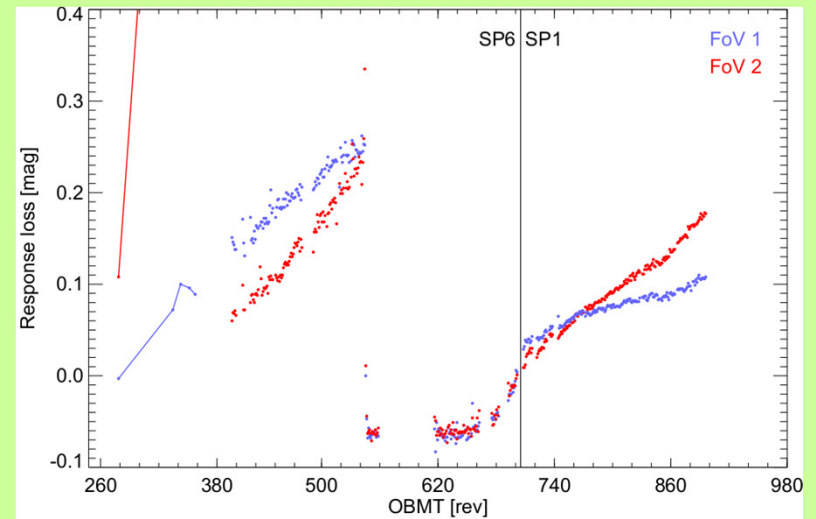


- Good launcher and excellent orbit insertion performance
 - ✓ plenty of propellant left for future manoeuvres **(TAKE THAT HIPPARCOS!)**
- Service module commissioning went smoothly
 - ✓ Chemical propulsion system for large manoeuvres
 - ✓ Micro propulsion system to maintain Gaia's spin rate and compensate solar radiation pressure torque
 - ✓ Attitude and Orbit Control System works well within specs; thermal control fine
 - ✓ Good link budget for phased array antenna \Rightarrow high data rates possible
- Rubidium atomic clock working to required accuracy at this stage
 - ✓ Validation of high accuracy time correlation pending
- Payload module
 - ✓ 106 CCDs and 106 backend electronics units all working fine
 - ✓ 7 on board computers managing the CCDs and electronics
 - ✓ Payload and data handling unit for storing and downlinking data
 - ✓ Telescope aligned and focused: very good image quality over full FPA
- Gaia \rightarrow ESOC \rightarrow DPAC/SOC \rightarrow AirbusDS chain working smoothly
 - ✓ Excellent flight control team at ESOC
 - ✓ DPAC operations teams calm and competent
 - ✓ About 40 DPAC Payload Experts analyzing the commissioning data
 - ✓ Many S/W patches and fixes but all in controlled manner



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The Unexpected News



- Gaia is a 'little' fainter than expected at L2
- Lower throughput than expected (icy materials)
- Stray light 'strikes' in
- BAM device sees large BA variations
- Lots of micrometeoroid hits



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Stray light science impact (G2V star)



Pre-launch predictions

V-magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
6 to 12	5-14 μas	4 mmag	1 km/s
15	24 μas	4 mmag	3 km/s
16.5			13 km/s
20	290 μas	40 mmag	

Stray light impact (noise contribution only)

6 to 12	5-14 μas	4 mmag	1 km/s
15	25 μas	5 mmag	13 km/s
16.5			
20	430 μas	60 (RP) – 80 (BP) mmag	

Calculations by: D. Katz, C. Jordi, L. Lindegren, J. de Bruijne



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Outlook on Gaia performances



- Stray light impact assessed with respect to extra noise
 - ▶ Systematics not accounted for
- On the assumption that BA variations and micro-meteoroid hits can be accounted for perfectly the stray light affected numbers provide an optimistic performance estimate
- Too early to provide quantitative estimates of the effects of
 - ▶ Basic Angle variations
 - ▶ Throughput loss (with corresponding optical quality degradation)
 - ▶ Micro-meteoroid hits
 - ▶ Radiation damage



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Gaia Data Releases (Pre-commissioning)



- Intermediate Data Release Scenario agreed with inputs from Data Release Policy and DPAC Operations Plan
 - Science Alerts as soon as possible
 - L+22m positions, G-magnitudes, proper motions to Hipparcos stars, ecliptic pole data
 - L+28m + first 5 parameter astrometric results, bright star radial velocities, integrated BP/RP photometry
 - L+40m + BP/RP data, some RVS spectra, astrophysical parameters, orbital solutions for short period binaries
 - L+65m + variability, solar system objects



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Impact on data release scenario



Impacts on data processing

- 3 months longer commissioning period
 - ▶ Later start of nominal operations and processing
- Extra development and processing effort needed to deal with:
 - ▶ Effect of future decontamination campaigns
 - ▶ Stray light effects
 - ▶ Change in RVS observing strategy
 - ▶ Account for basic angle variations through BAM measurements
 - ▶ Deal with high rate of micro-meteoroid hits
 - ▶ More complex data validation

First data release expected by mid-2016



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Next Steps



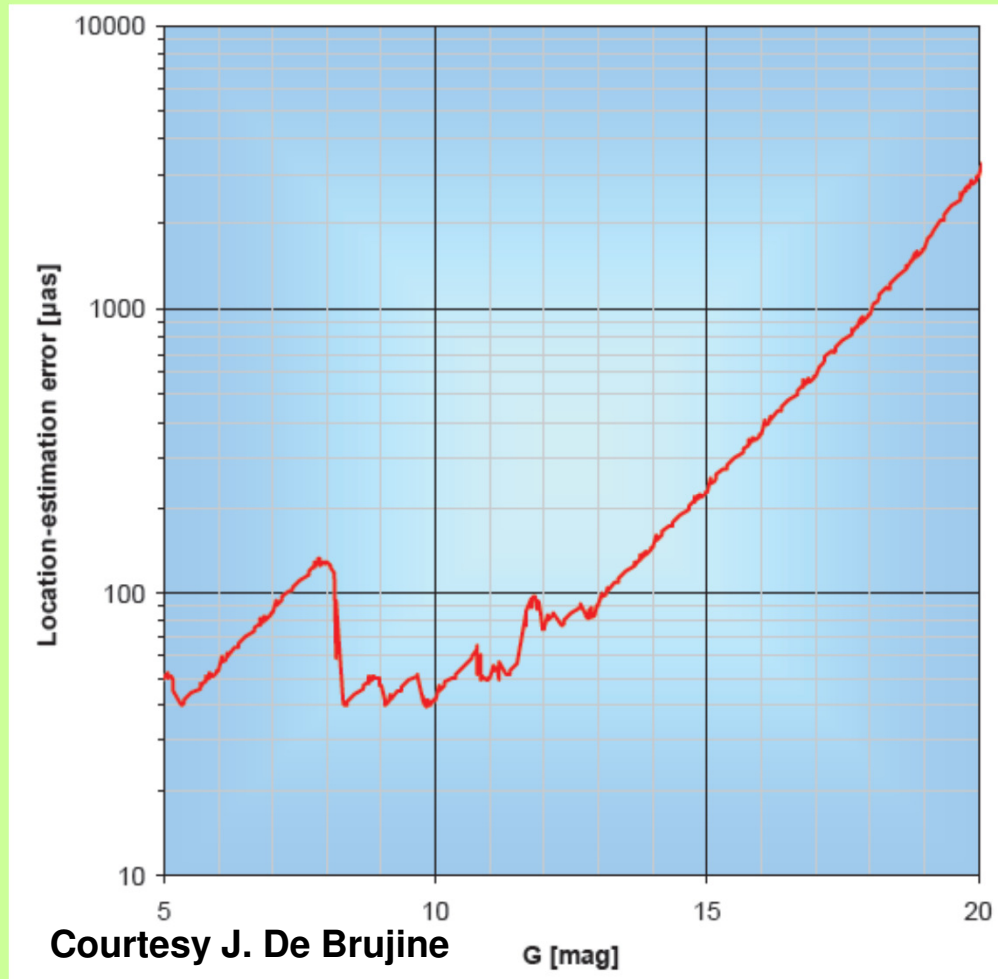
- Finish on-board parameter optimizations
- Around July 1: next decontamination and update of Central SW
 - ▶ possibly re-align telescopes after decontamination
- Start 28 days of undisturbed EPSL data collection around July 15
 - ▶ Start of nominal operations
 - ▶ NSL starts mid August

- In orbit commissioning review on July 18
 - ▶ Formal handover of Gaia
- Independent review of basic angle issue ongoing in parallel (ends July 2)
- Support contract with AirbusDS will be put in place to complete post-IOCR actions
 - ▶ Includes software updates for RVS observing strategy by end 2014



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CCD-level Location Estimation



Based on Monte Carlo simulations, including “everything”: e.g., CCD QE + MTF, telescope wave-front errors + transmission + optical distortion, LSF smearing due to attitude jitters + TDI motion, CCD noise + offset non-uniformity, radiation damage-induced charge loss + bias calibration, sky background, windowing/sampling, magnitude, extinction, spectral type, ...

Mind you: Pre-Commissioning!

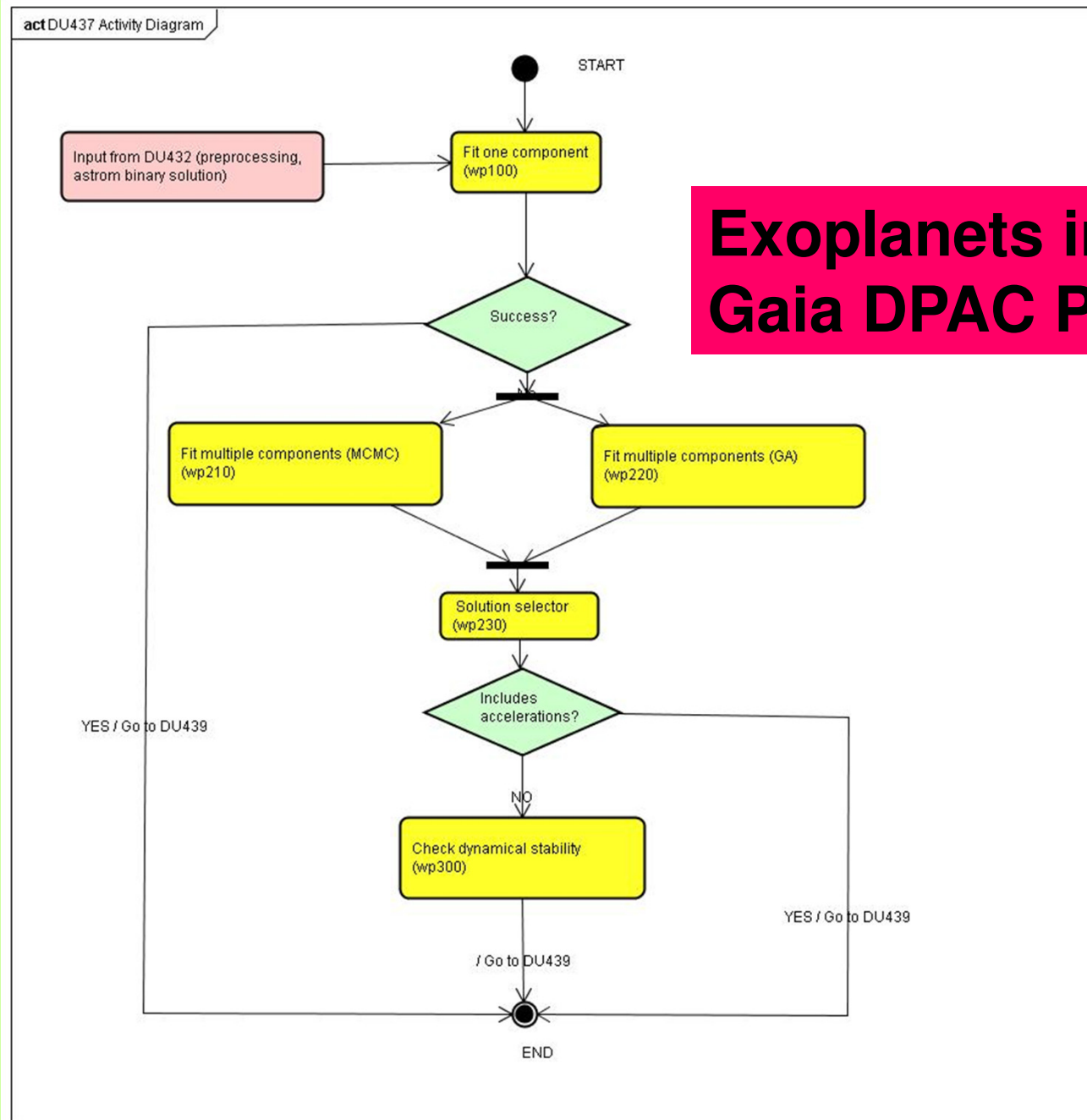
1. $2/3(\text{was } 6) < G < 12$: bright-star regime (calibration errors, CCD saturation)
2. $12 < G < 20$: photon-noise regime (sky-background and electronic noise at $G \sim 20$ mag)



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Exoplanets in the Gaia DPAC Pipeline





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Gaia transiting GP candidates?



- Required photometric precision not an issue
- Low-cadence of the observations a serious limitation
- It's not hopeless if you have the right tools! (Dzigan & Zucker 2012)
- It can work for early detections of (1000s?) short-period transiting GPs (and maybe ~100s BDs)
- It may require a dedicated follow-up network
- Confirmation efforts will likely be limited by target brightness (typically, $V > 14$ mag)

See Brandon Tingley's poster



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Gaia Discovery Space

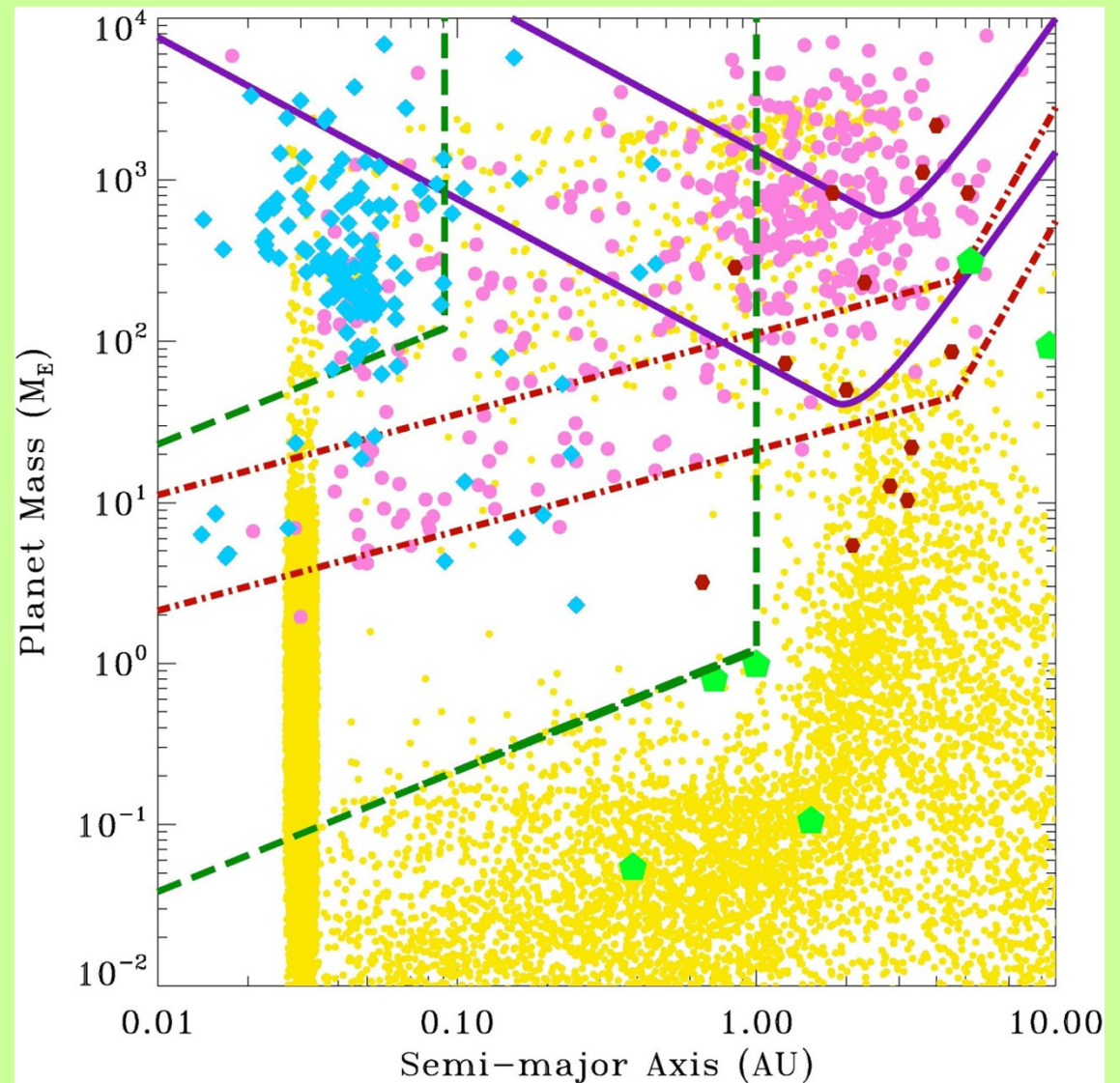


- 1) 2-3 M_J planets at $2 < a < 4$ AU are detectable out to ~ 200 pc around solar analogs
- 2) Saturn-mass planets with $1 < a < 4$ AU are measurable around nearby (< 25 pc) M dwarfs

For Gaia: $\sigma_A \sim 15-20 \mu\text{as}$

(Pending new assessment of systematic noise floor)

Sozzetti 2011



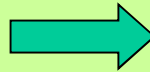


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How Many Planets will Gaia Find?



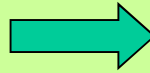
Starcounts ($V < 13$),
 $F_p(M_p, P)$ for F-G-K dwarfs,
Gaia completeness
limit



Δd (pc)	N_*	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

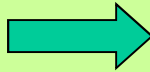
M dwarf starcounts ($V < 20$)



$2-3 \times 10^3$ additional giants (Sozzetti et al. 2014)

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 planet census of hundreds of thousands stars

of order of 10^4 NEW giant planets



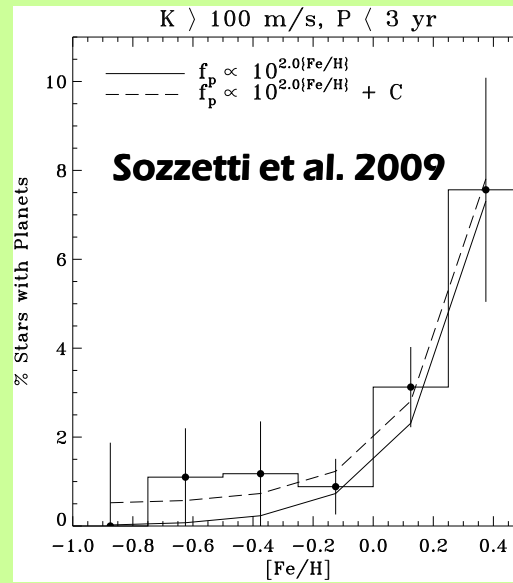
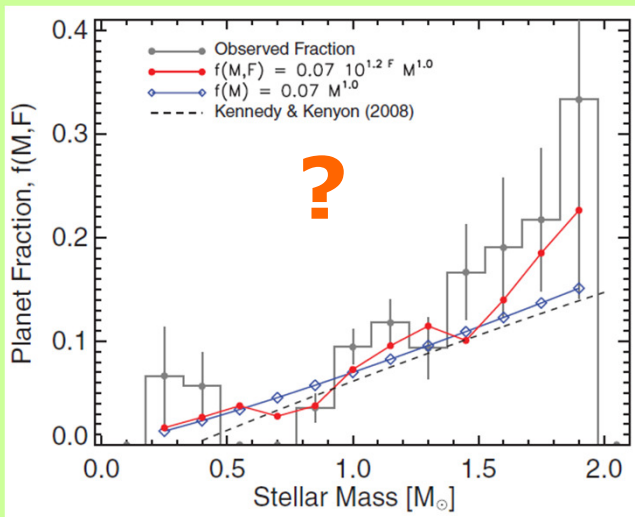
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The Gaia Legacy

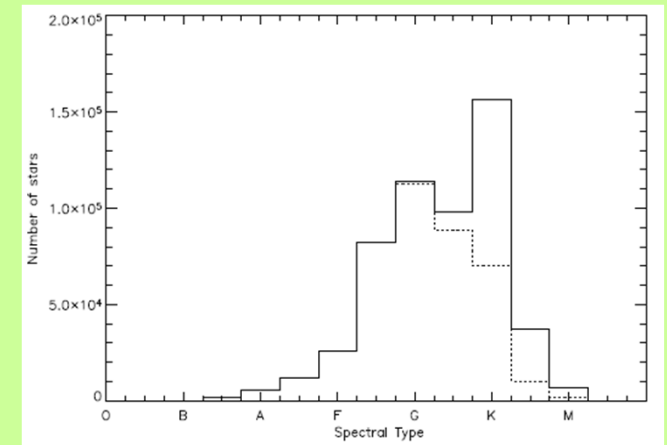


How do Planet Properties and Frequencies Depend Upon the Characteristics of the Parent Stars (also, What is the Preferred Mechanism of Gas Giant Planet Formation)?

Johnson et al. 2010



Casertano et al. 2008



↑

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

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

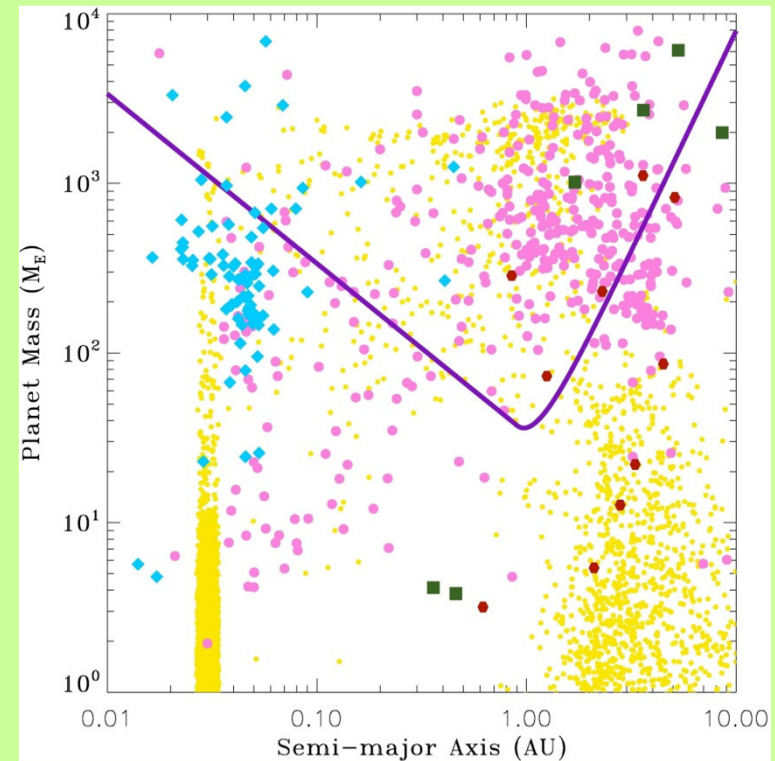
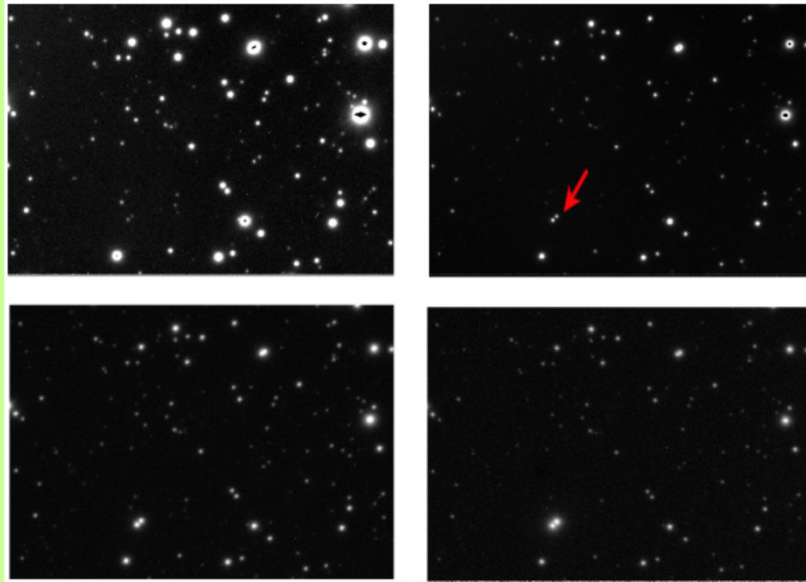


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Planets Around BDs



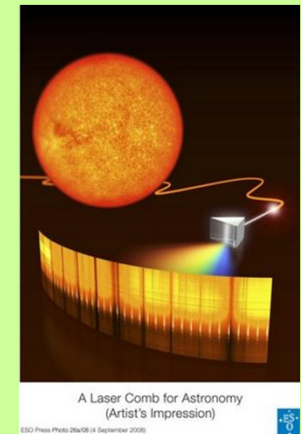
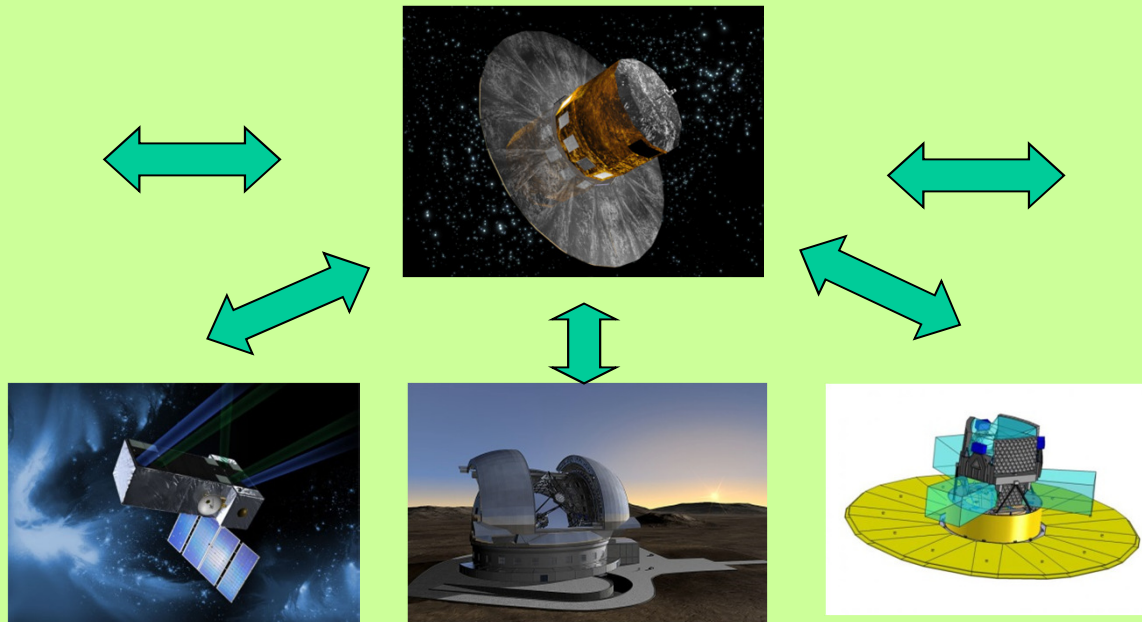
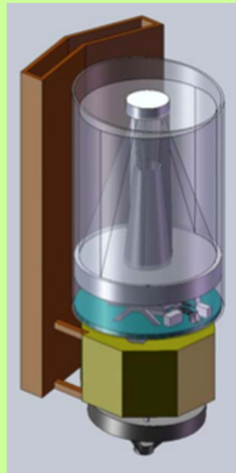
Gaia detection limits for Luhman 16 AB
(Boffin et al. 2014)



- Found so far only in microlensing events
- Gaia will see ~1000 BDs of all ages, with sufficient astrometric sensitivity to giant planets within 2-3 AU
- A fundamental test of planet formation! Sozzetti (arXiv:1406.1388)



Gaia - Synergies



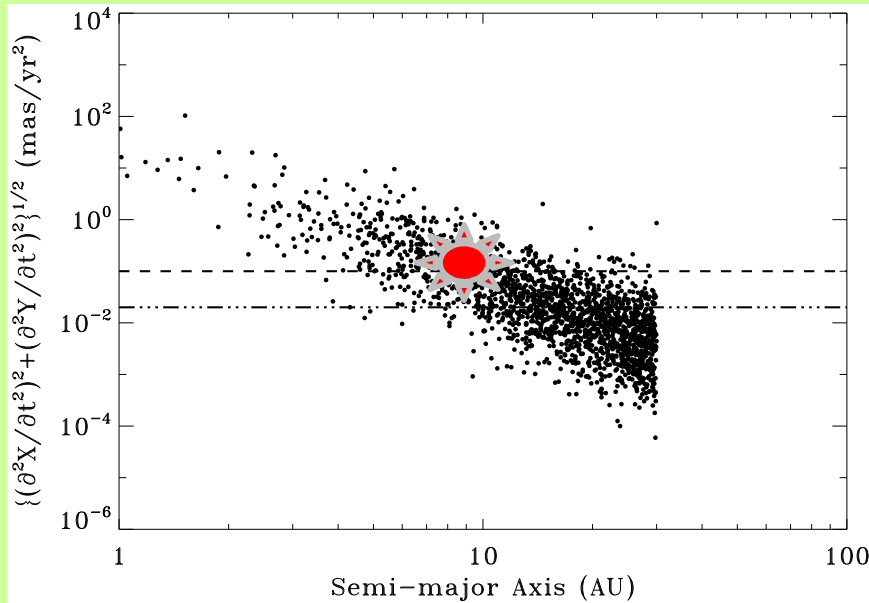
- **Gaia & spectroscopic characterization observatories (e.g., JWST)**
- **Gaia & transit surveys from the ground (e.g., WASP, HAT, MEarth, APACHE, NGTS) and in space (CoRoT, Kepler, TESS, PLATO)**
- **Gaia & direct imaging observatories (e.g., SPHERE/VLT, PCS/E-ELT)**
- **Gaia & RV programs (e.g., HARPS(-N), ESPRESSO, CARMENES, and the likes)**
- **Gaia & ground-based and space-borne astrometry**

Objectives of study within the GREAT RNP/ITN

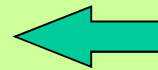


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Synergy with Direct Imaging



Accelerations in Gaia astrometry from giant planets orbiting the SPHERE GTO target sample

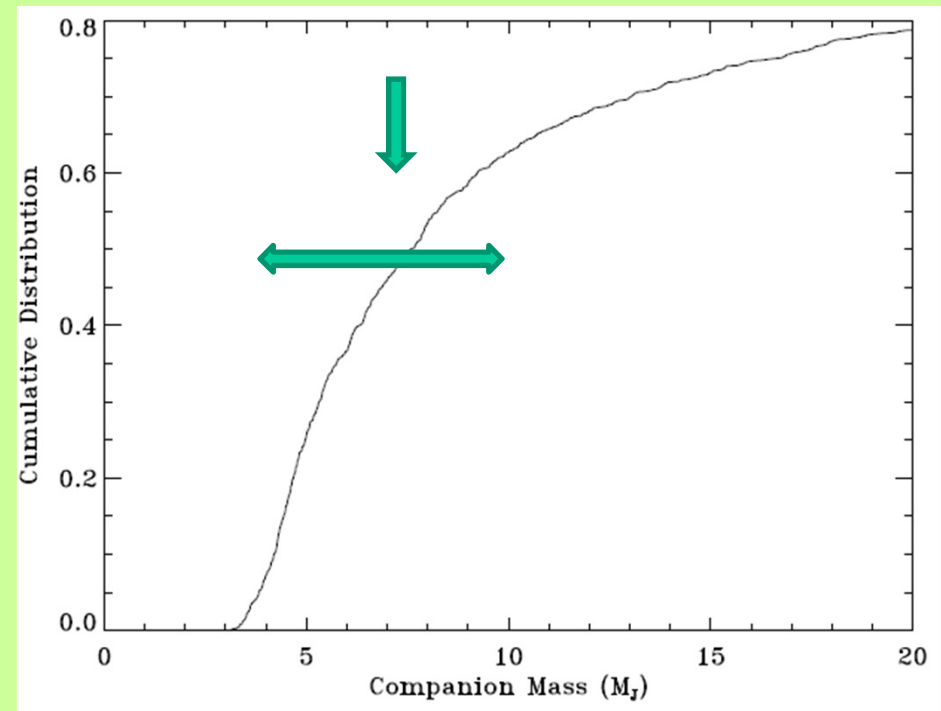


Sozzetti, Bonavita et al. in prep.

For β Pictoris:

$$a_x = 110 \mu\text{as}/\text{yr}^2 - a_y = 30 \mu\text{as}/\text{yr}^2$$

Mass CDF from Gaia measurements of the companion to β Pictoris





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Synergy with RVs



- Complete characterization of systems architectures across orders of magnitude in mass and orbital separation
- Refinement of known orbits (both ways)
- Complete dynamical stability studies in multiple systems
- Very important synergy with present (e.g., HARPS@ESO), starting (e.g., HARPS-N@TNG/GAPS), and upcoming (ESPRESSO@VLT, IR instruments) RV surveys



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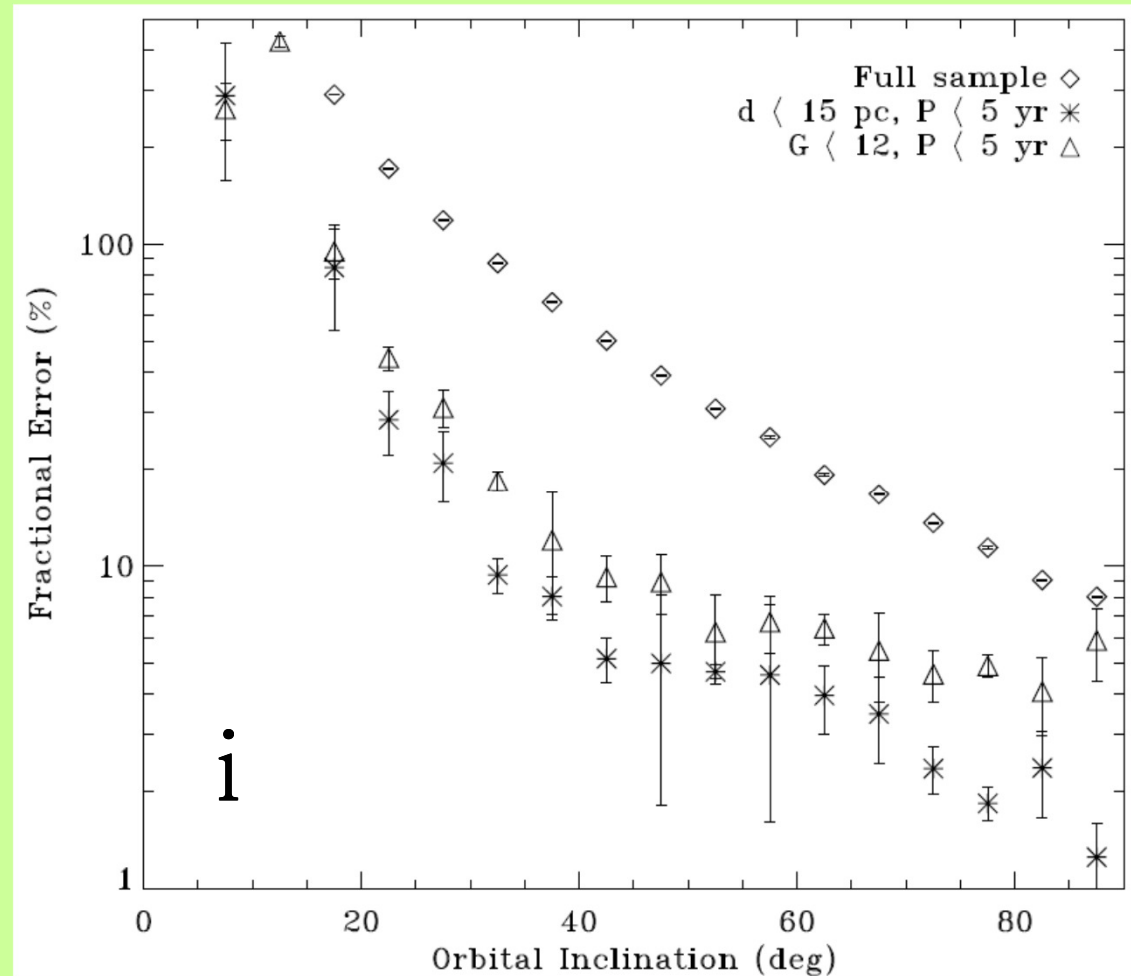
Finding Nearby Transiting Intermediate-Separation GPs



Sozzetti et al. 2014

For well-measured, quasi-edge-on orbits, i is accurate to $<3\%$

Gaia may find hundreds of candidate transiting giant planets around F-G-K-M dwarfs of all ages and $[Fe/H]$.
Some may be really transiting!



Follow-up efforts, possible targets for JWST

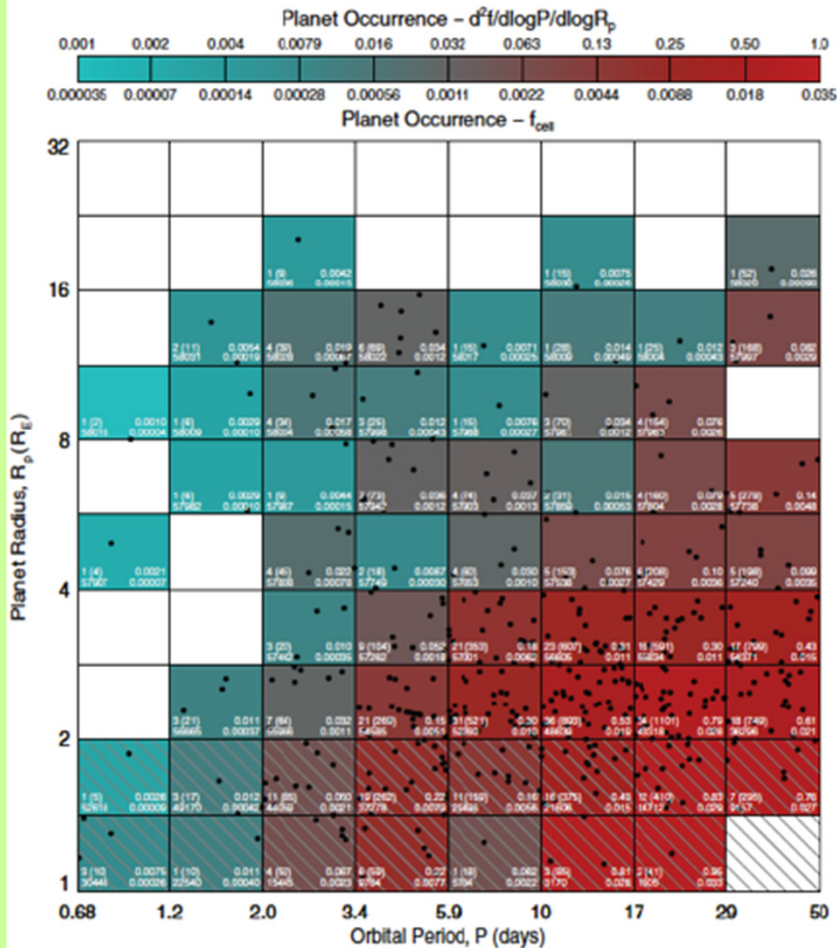


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Gaia – Kepler - HARPS-N



Howard et al. 2012



* Parallaxes of stars in the Kepler field released formally around mid-2016

* For a typical target with $V < 15$ at < 0.5 kpc, expect $\sigma(n)/n < 2-3\%$ from Gaia

* Re-calibrate absolute luminosities

* Re-determine the stellar radii to $< 5\%$ -> re-assess the planets' structural properties

A global statistical re-analysis of planetary properties and frequencies (including η_{\oplus}) in the Kepler field as a function of e.g. M_* , $[Fe/H]$

$$f_{\text{cell}} = \sum_{j=1}^{n_{\text{pl, cell}}} \frac{1/p_j}{n_{\star, j}}$$

$$p_j = (R_{\star}/a)_j$$

OBJECTIVE OF THE FP7-SPACE EARTH EARTH PROJECT

The Space Photometry Revolution – Toulouse, 08/07/2014



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Target Selection



- In Summer 2016, >90% of parallaxes for (well behaved?) stars observed by Gaia are delivered...
- Elected primary source of the TESS/PLATO input catalogs of $>2 \times 10^6$ bright dwarf stars (with negligible giant star contaminants)
- Significant reduction in astrophysical false positives (know thy neighbors!)



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The Take-Home Message



- **Providing the largest catalogue of 'new' astrometric orbits & masses of extrasolar planets and superbly accurate parallaxes is Gaia's defining role in the exoplanet arena**
- **Gaia will help to better characterize thousands of (old and new) planetary systems (in terms of both the planets and the hosts)**
- **The synergies between Gaia and ongoing and planned exoplanet detection and (atmospheric) characterization programs from the ground and in space are potentially huge**
- **Gaia's 'first' major release: L+28m (Middle of 2016)**