Astrometry & Exoplanets: Gaia, and Beyond

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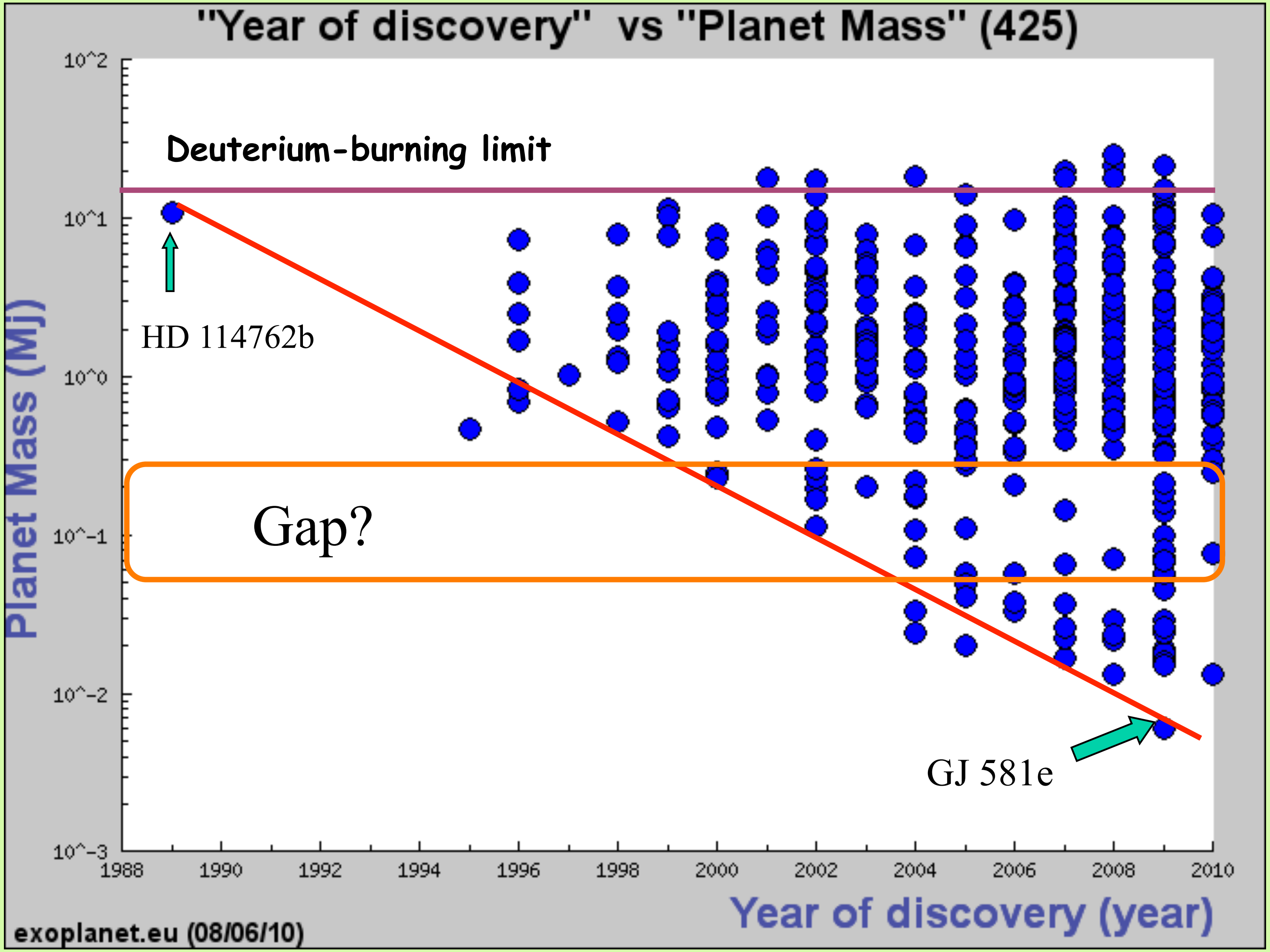
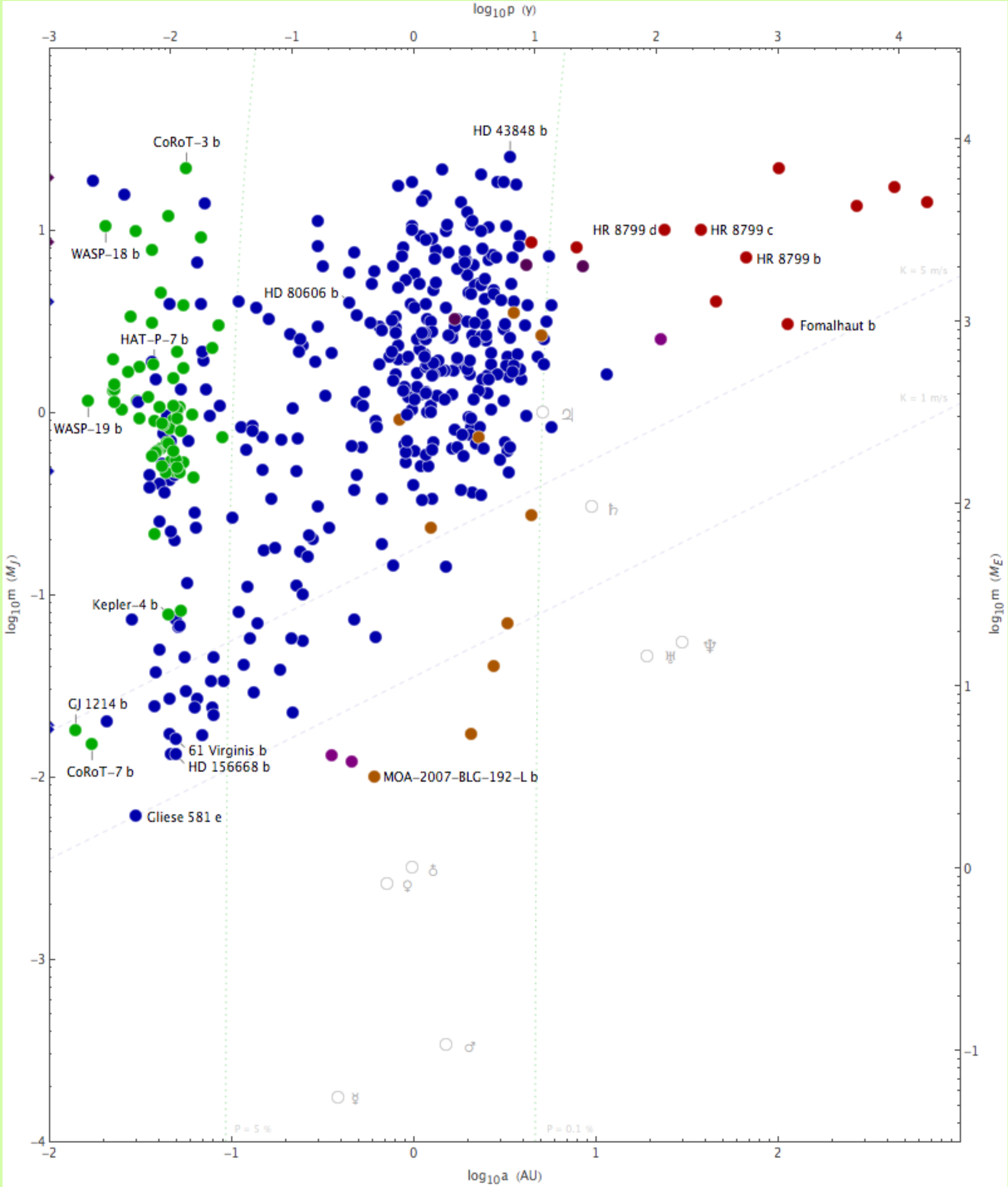


Today: f_p~10% (M_p < 15 M_J, a < 4 AU), >30% host multiple systems

Detection/Characterization

- **Indirect detection (Visible):**
  - Doppler spectroscopy (95%)
  - Transit photometry (14%)
  - Gravitational microlensing (2%)
  - Pulsar/pulsation timing (1.5%)
  - Astrometry (0/454)
- **Direct detection (Visible)**
  - imaging (0.3%, still debatable)
- **Indirect characterization (Visible/IR):**
  - Transit timing
  - Transmission spectroscopy
  - Rossiter-McLaughlin effect
- **Direct characterization (Visible/IR):**
  - Reflected light
  - Infrared emission



Comparative Planetology

- 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

→ **Putting our Solar System in Context!**

And, for those X-Files fans: Finding and Characterizing Earth analogs!

Low-Precision Astrometry…

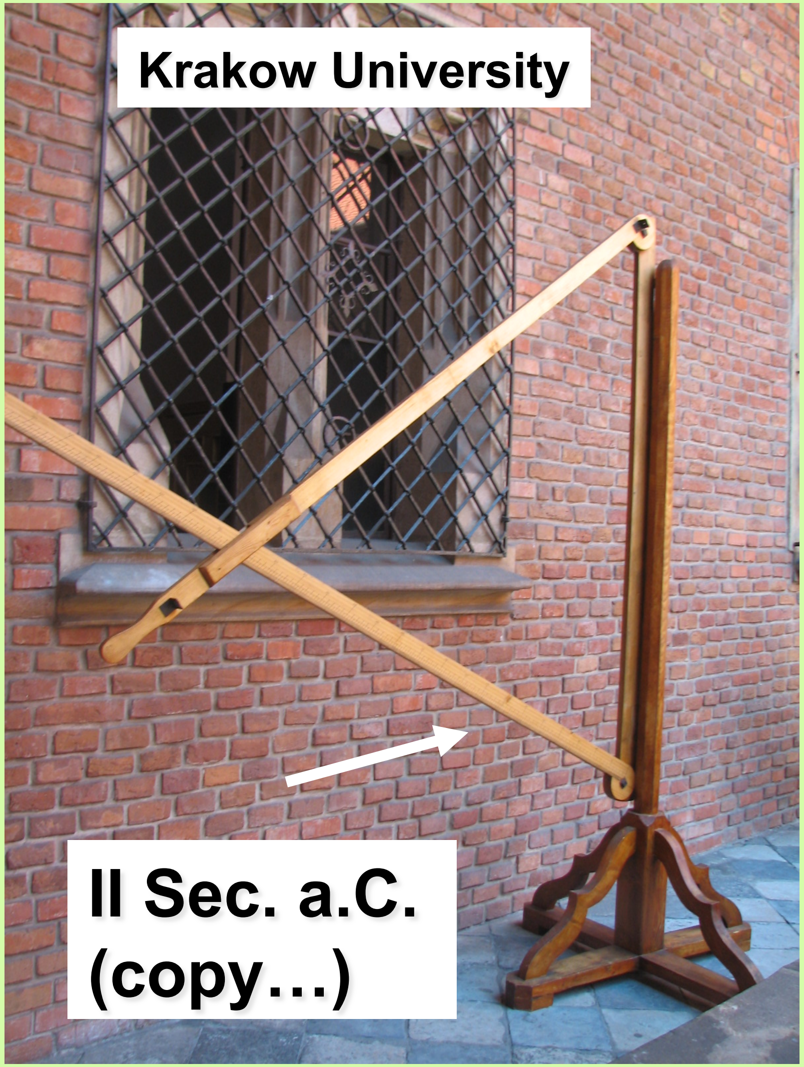


TABLE 1
PARALLAX, PROPER MOTION, AND ASTROMETRIC SIGNATURES INDUCED BY PLANETS OF VARIOUS MASSES AND ORBITAL RADII

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

Ptolemy's Triquetrum (arcmin precision) is not enough for planet detection!

Astrometry: Blunders

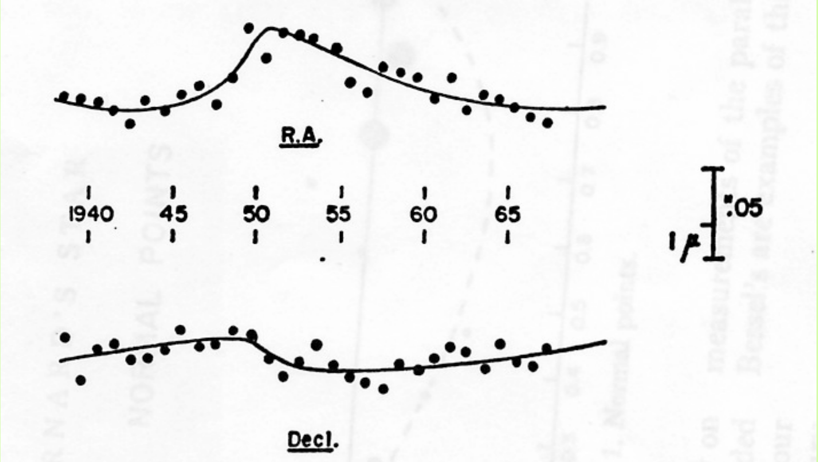


FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time-displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

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

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

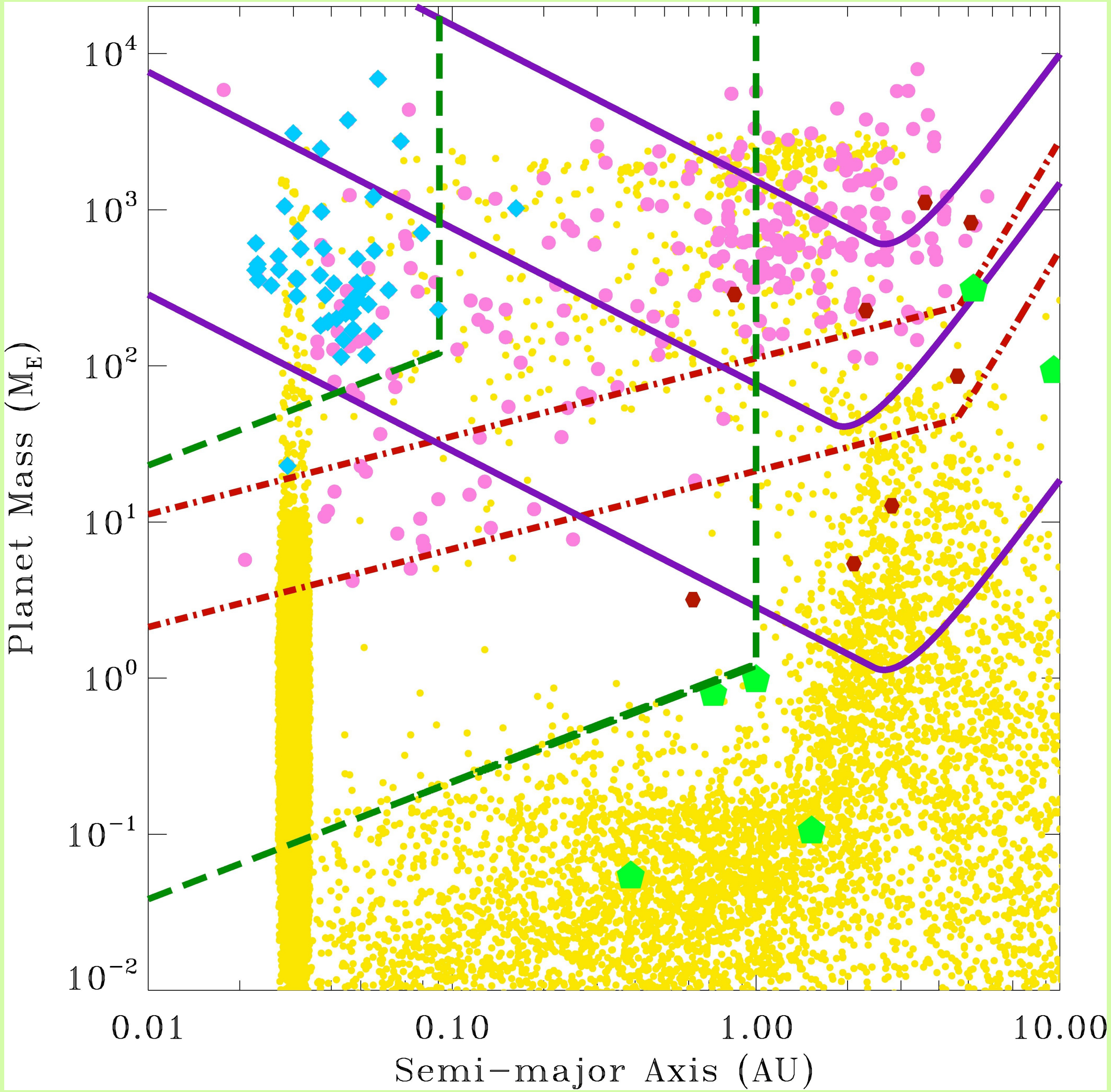
Notes:

- 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

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: σ_A ~ 10-15 µas



Sozzetti 2009

Gaia DPAC Data Processing & Analysis Consortium

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

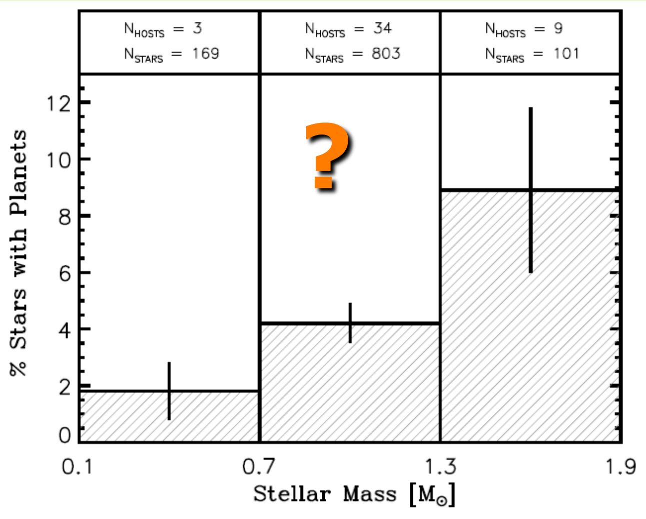
Case	Number of Systems
Detection	~ 1000
Orbits and masses to better than 15-20% accuracy	~ 400 – 500
Successfull coplanarity tests	~ 150

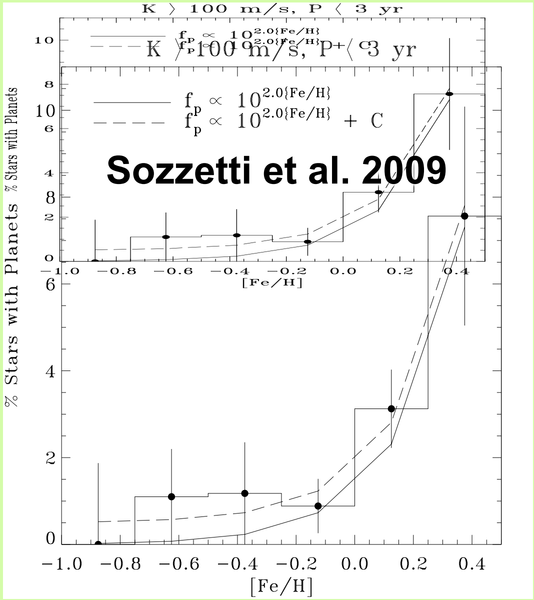
Unbiased, magnitude-limited planet census of hundreds of thousands stars

The Gaia Legacy (1)

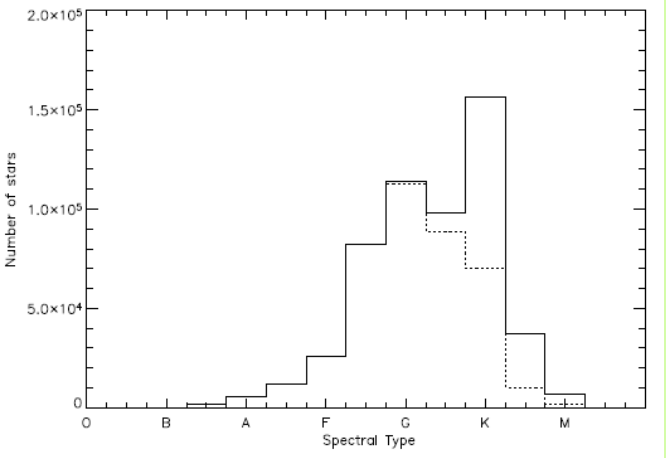
How do Planet Properties and Frequencies Depend Upon the Characteristics of the Parent Stars (also, What is the Preferred Mechanism of Gas Giant Planet Formation?)?

Johnson 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

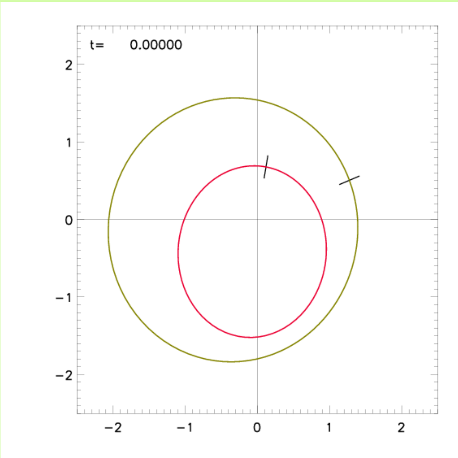
10^4 stars per 0.1 M_{Sun} bin!

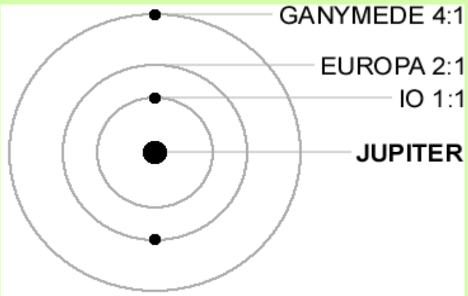
The Gaia Legacy (2)

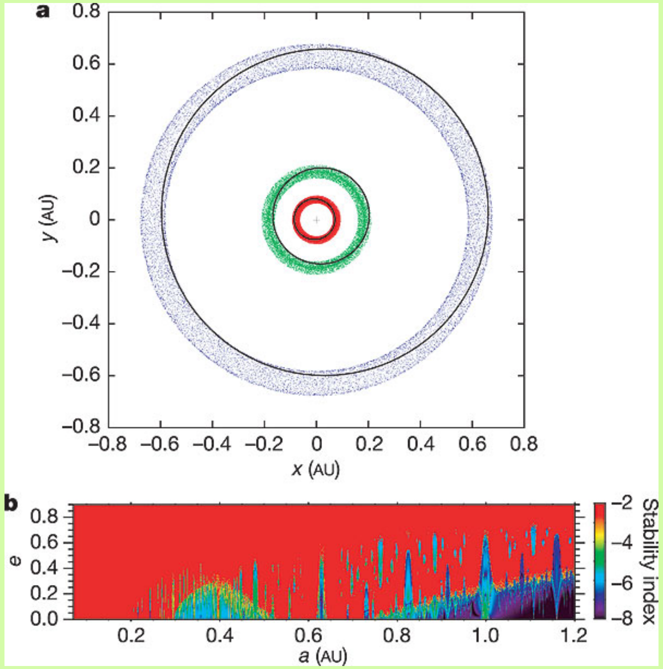
What is the Evolution of the Various Architectures of Planetary Systems?

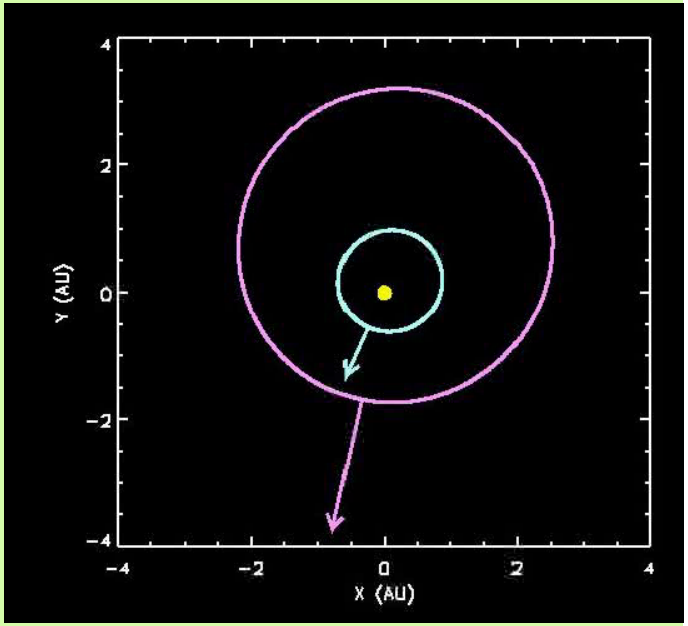
1) What is the richness of the dynamical families?
2) What is the relative role of many proposed mechanisms of dynamical interaction?
3) Are there regions of stable, habitable orbits?

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





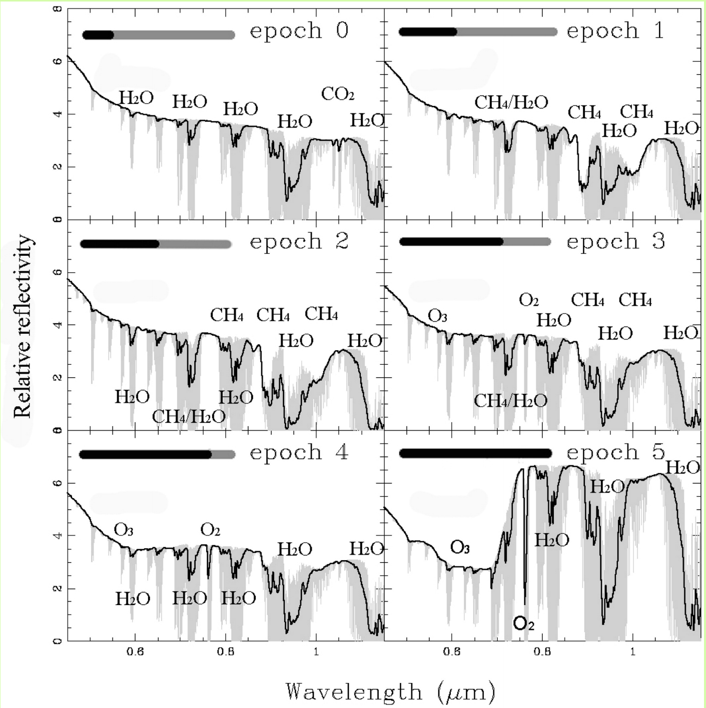




The Gaia Legacy (3)

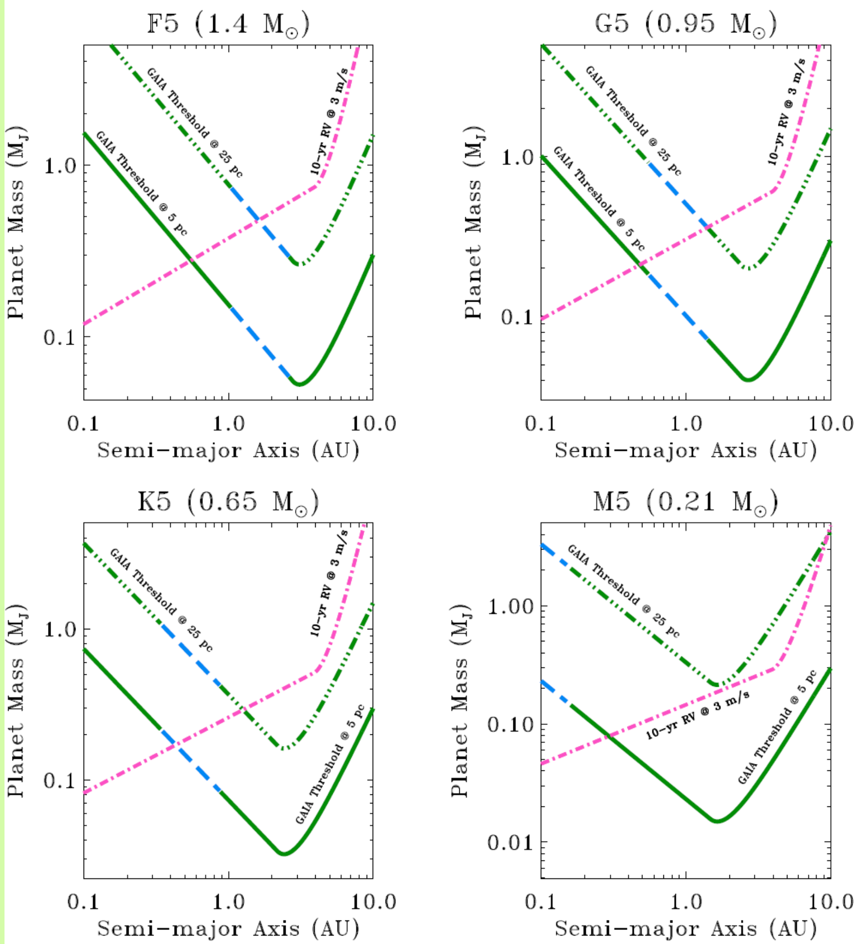
Where Are the Earth-Like Planets, and What Are Their Characteristics?

Kaltenegger et al. 2007



Nearby stars: THE targets.

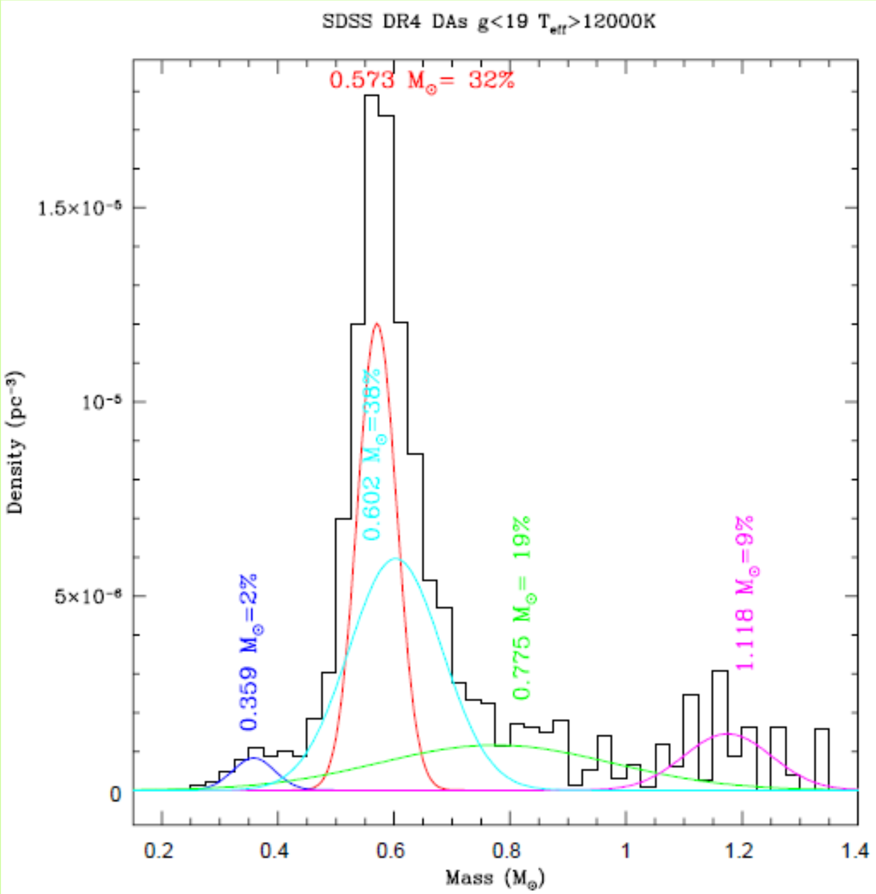
Study them as best as you can



Gaia will provide important supplementary data for the optimization and characterization of targets, e.g., by screening all stars within ~25 pc (including large numbers of M dwarfs) for Jupiter- and Saturn-sized planets out to several AUs.

Sozzetti et al. 2003

Gaia & Post-MS Stars



White dwarfs in the solar neighborhood

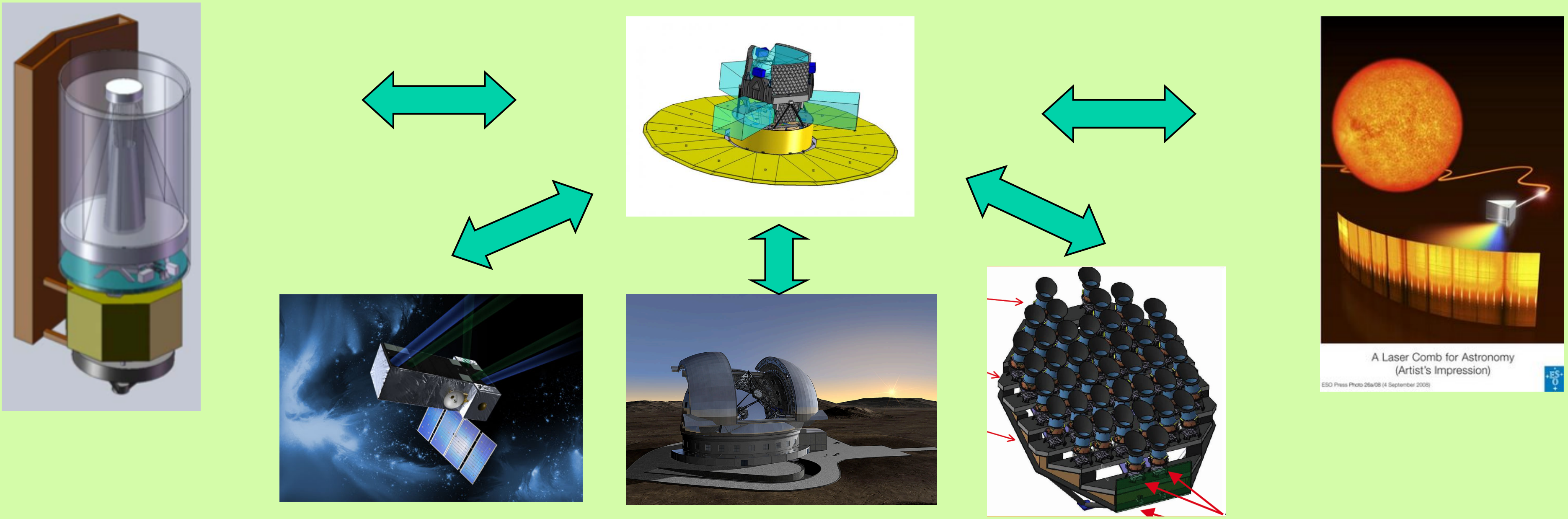
Good to within a factor 2…

	D<100 pc	D<200 pc
R<13	50	400
R<14	200	1600
R<15	800	6400

Sozzetti, Silvotti, & Lattanzi, in prep.

Gaia will perform THE observational test of theoretical predictions related to: A) post-MS planet evolution & B) 2nd generation planet formation

Gaia - Synergies



- **Gaia & THESIS (Tessenyi, Tinetti, Sozzetti et al., in prep.)**
- **Gaia & Plato**
- **Gaia & SPHERE/EPIC**
- **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 Planetary Systems 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 will be required

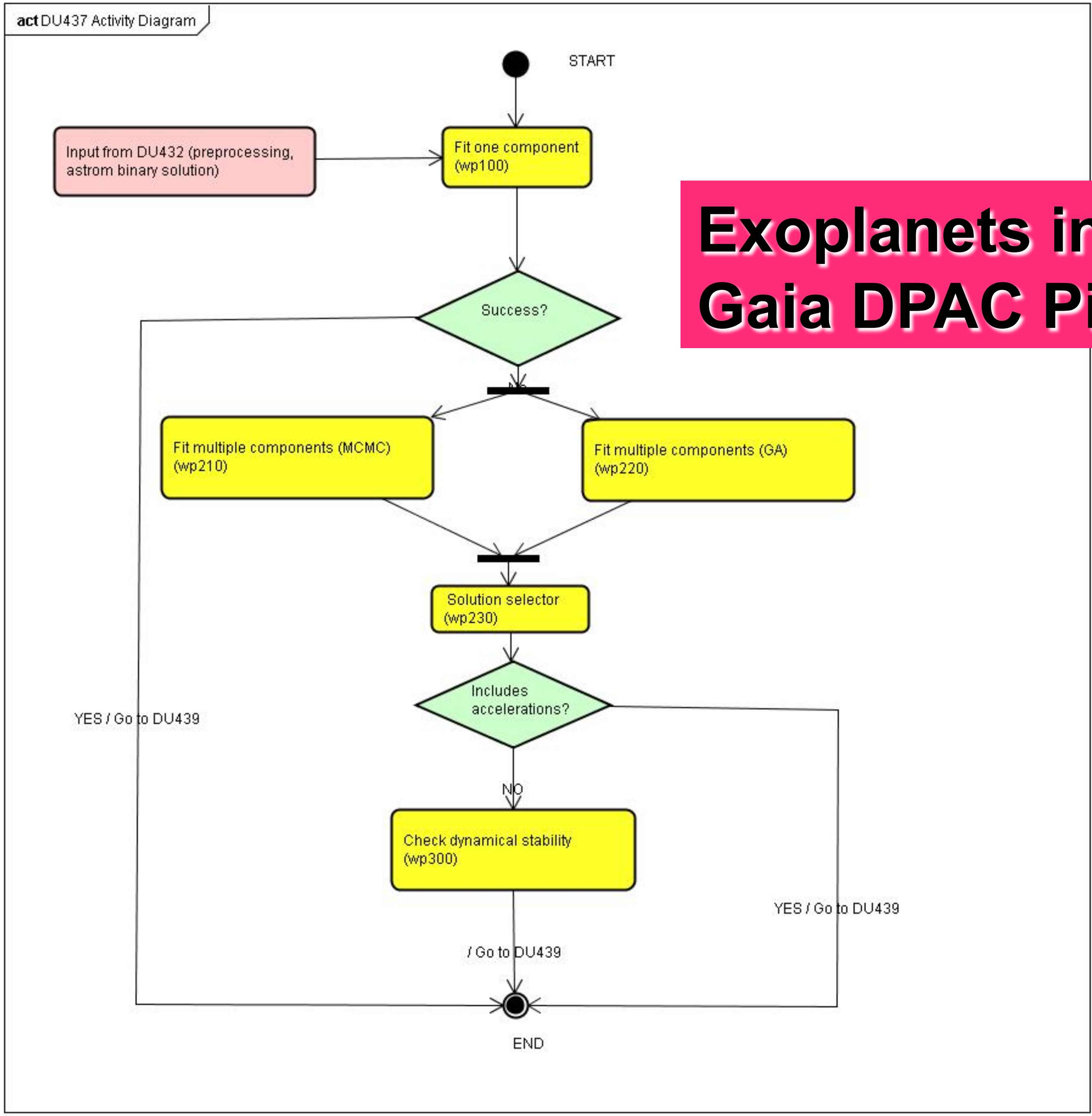
Assessing Detections

- 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?

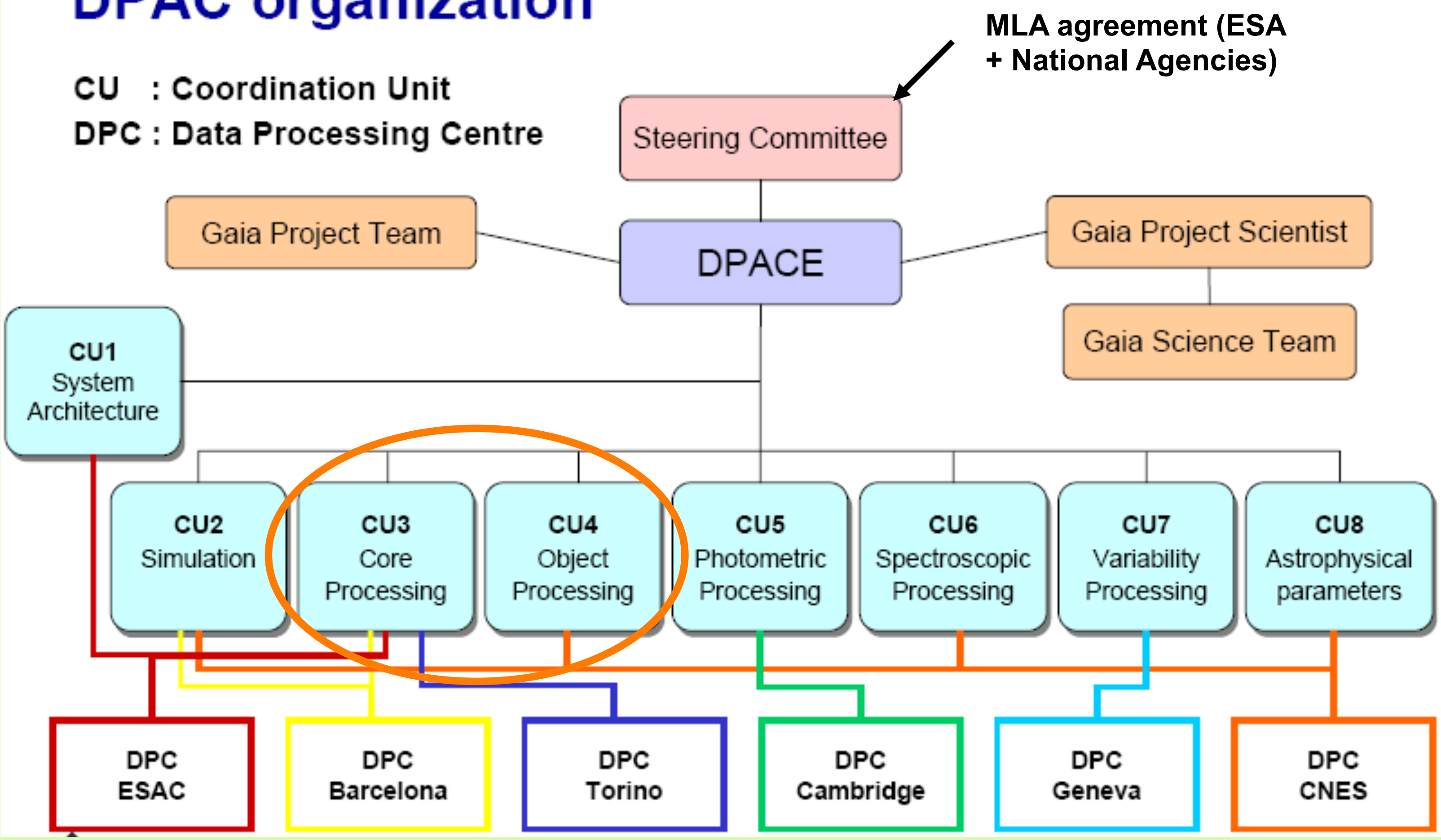
- Importance of consistency checks between different solution algorithms (see lessons learned from RV surveys)

Exoplanets in the Gaia DPAC Pipeline

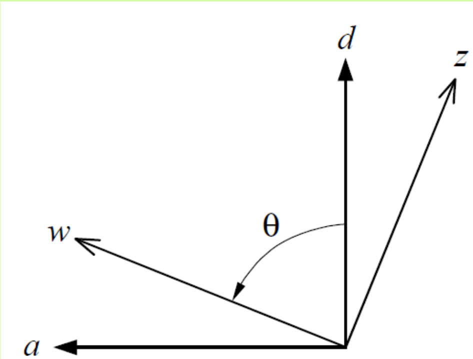


DPAC organization

CU : Coordination Unit
DPC : Data Processing Centre



Warning: In the Local Plane…



$$a = w\sin\theta - z\cos\theta$$
$$d = w\cos\theta + z\sin\theta$$

$$s = \sin\theta,\ c = \cos\theta$$

$$w = \quad s a_T + c d_T + (t-T)s\mu_{\alpha*} + (t-T)c\mu_\delta + f_w\pi + XcA + XsB + YcF + YsG$$
$$z = -c a_T + s d_T - (t-T)c\mu_{\alpha*} + (t-T)s\mu_\delta + f_z\pi + XsA - XcB + YsF - YcG$$

The position angle of the scan knows it all!

It REQUIRES the best possible calibrations…

Gaia DPAC
Data Processing & Analysis Consortium

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	10.4	…..	…..	…..	…..	…..	…..	344	µas

Notes:

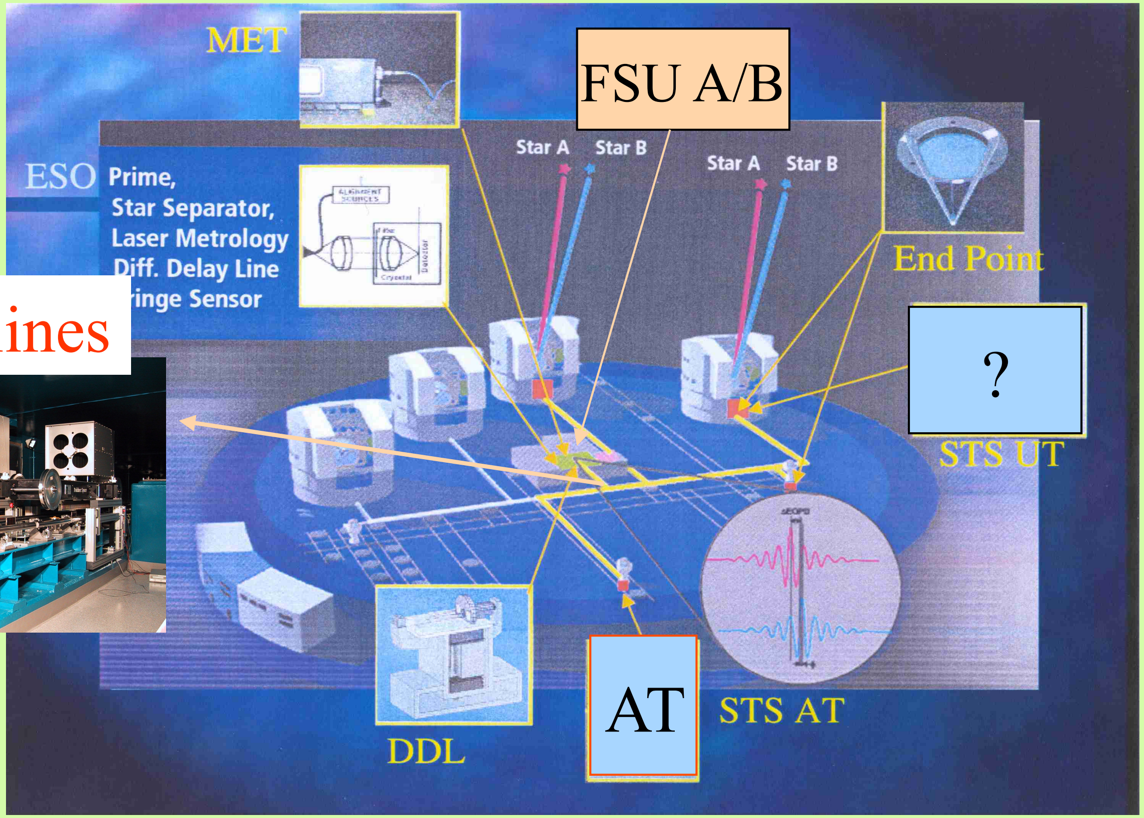
- Estimates calculated with the Gaia Accuracy Tool (courtesy J. de Bruijne, ESA)
- Radiation-damage effects on CCDs ~~not fully~~ taken into account
- Estimates include a 20% margin (factor 1.2) for unmodelled errors

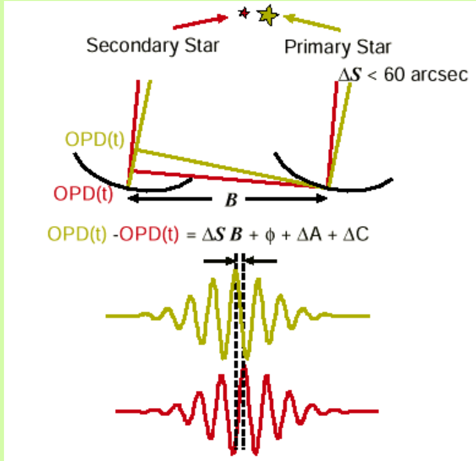
A Word of Caution…

$\sigma_\psi{}^a$ (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

VLTI/PRIMA & ESPRI



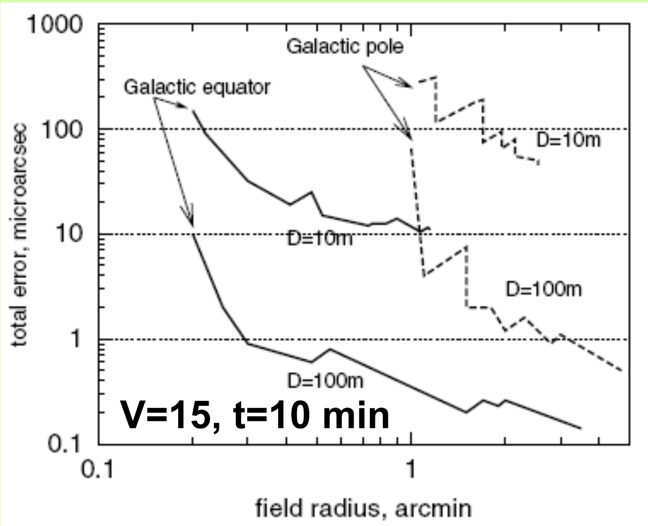


Expected to reach the atmospheric limiting precision of ~10-20 μas

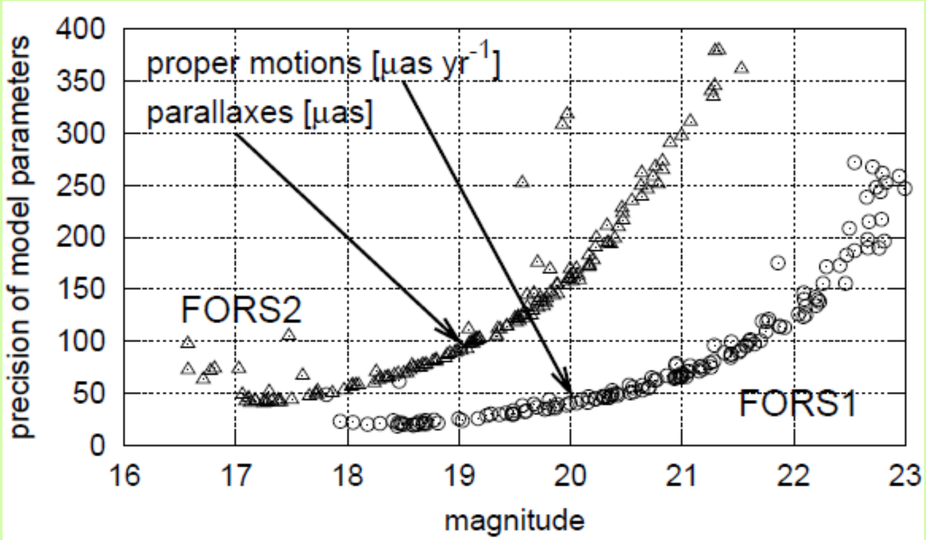
- Instrument under commissioning since quite a while…
- ESPRI will carry out a two-fold program (~100 targets envisioned)

Adaptive Optics Astrometry

AO + symmetrization of the reference frame to remove low-f components of the image motion spectrum and improve image centroid.



Lazorenko 2006

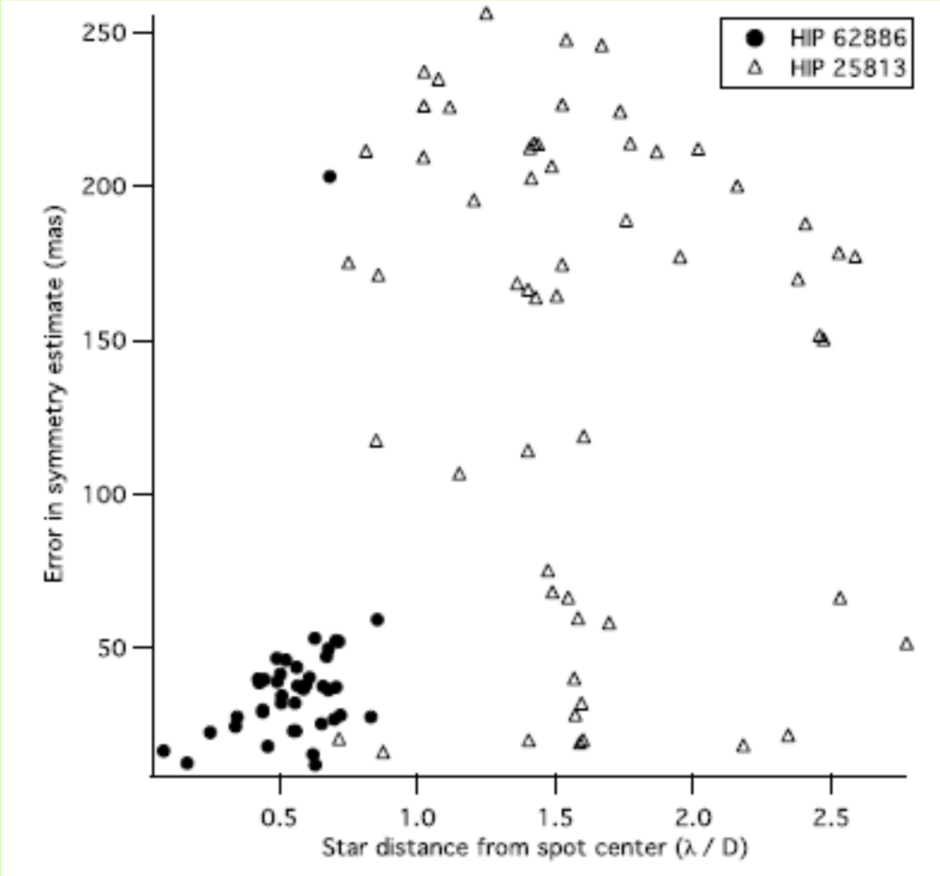


Lazorenko et al. 2009

Presently limited to very faint objects, dense stellar fields

•See also poster by Roell et al.

Coronagraphic Astrometry

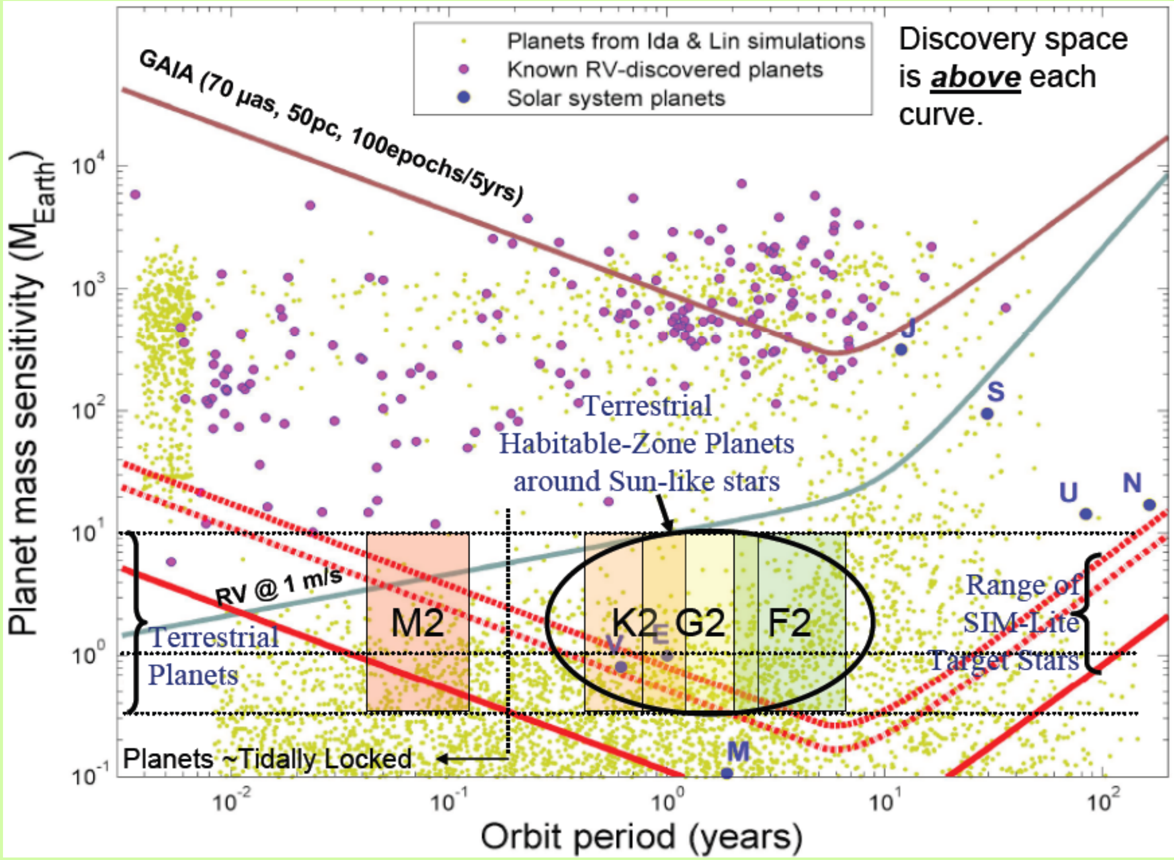


Digby et al. 2006

Predicting the star location with respect to the occulting spot from image centroid, instrument feedback, or PSF symmetry still results in mas precision at best

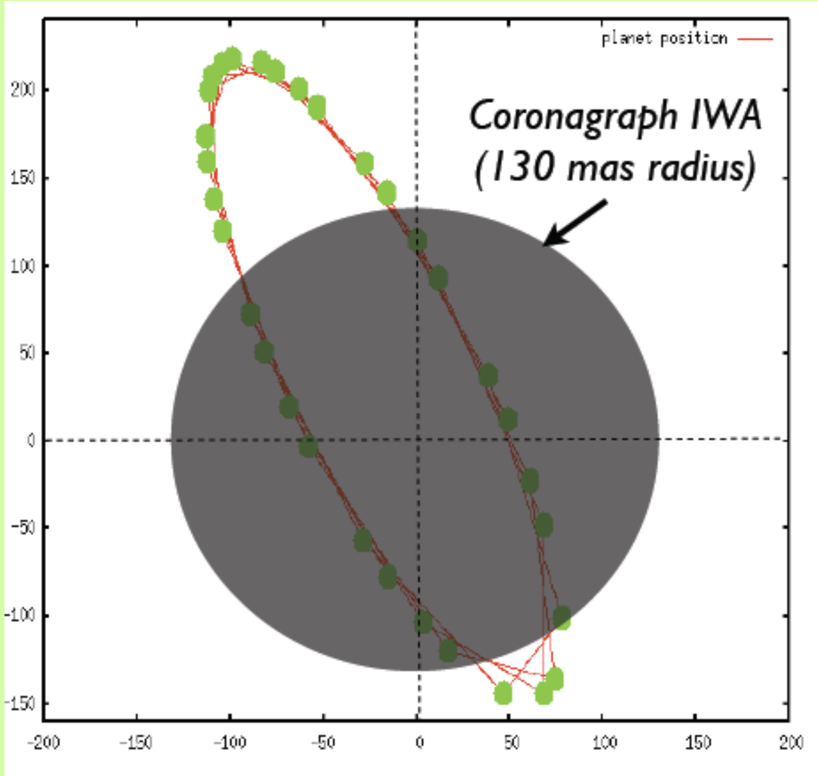
1 μas Relative Astrometry in Space

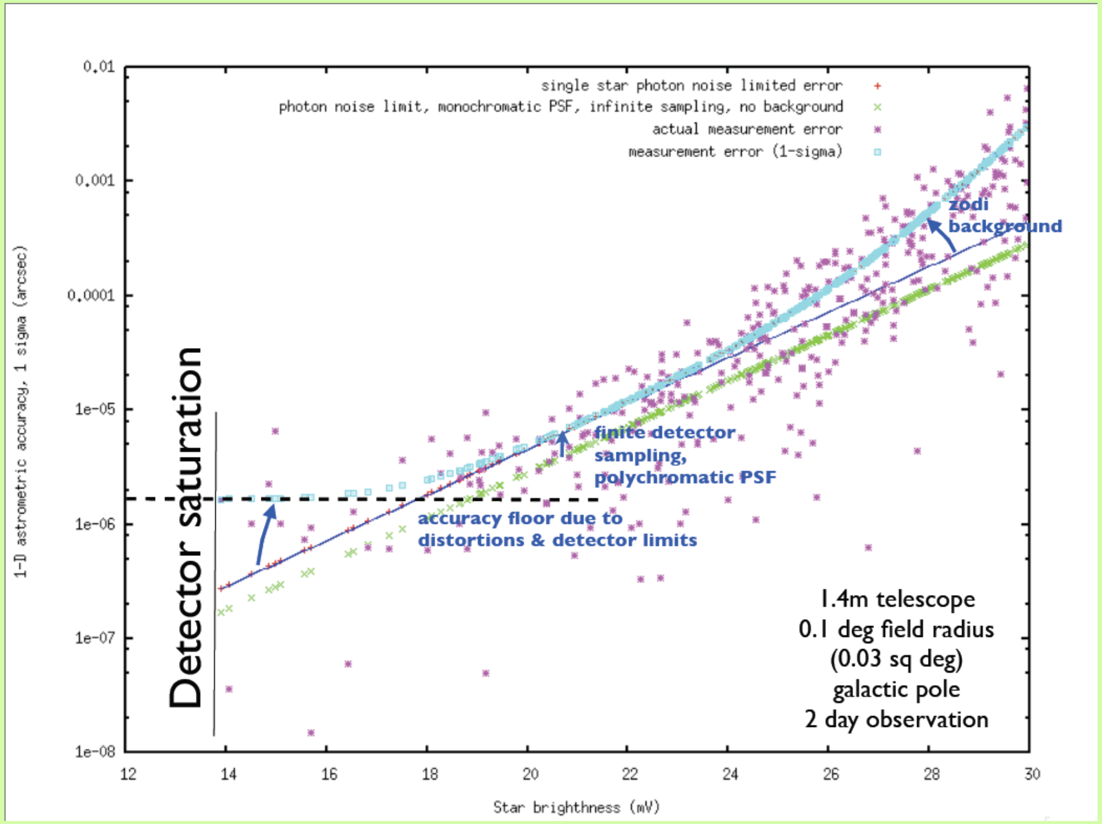
NASA's SIM-Lite observatory will determine the positions of ~1000 stars 10 times more accurately than Gaia, helping to pin-point Earth-sized planets around the nearest stars.



However, SIM-Lite's fate is pending…

Space Astrometry + Coronagraphy?





Guyon & Shao 2010

Conclusions

- Gaia holds promise for crucial contributions to many aspects of planetary systems astrophysics (formation theories, dynamical evolution), in combination with present-day and future extrasolar planet search programs
- Providing the largest catalogue of 'new' astrometric orbits of extrasolar planets is Gaia's defining role in the exoplanet arena.
- If Gaia cannot do it, no one will!
- Save the bright stars! They're a tiny fraction of the lot, but they hold some of the lowest hanging 'super-science' fruits!