On the Gaia Exoplanet Discovery Potential

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Astrometry: Blunders

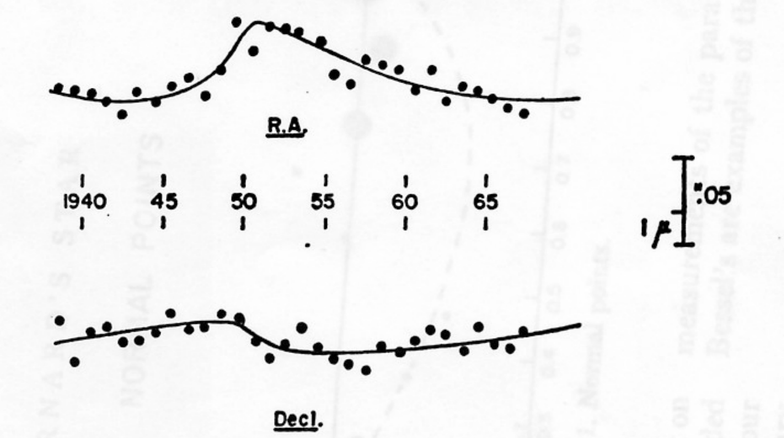


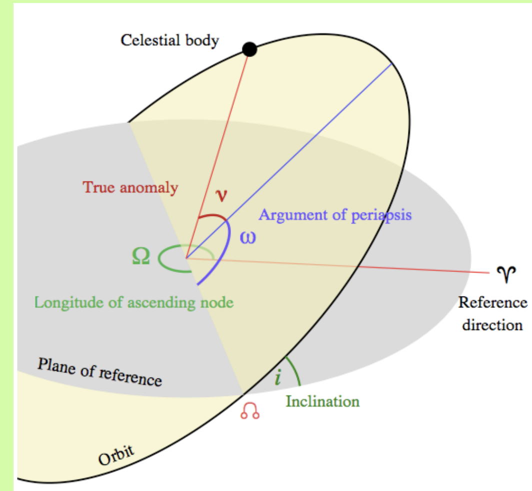
FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time-displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

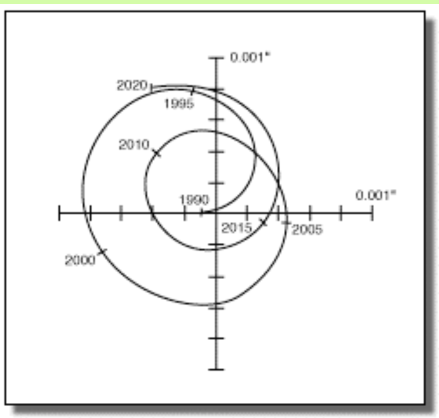
1940's: Strand, Reuyl & Holmberg (61 Cyg, 70 Oph)
1960's: Lippincott,Hershey (Lalande 21185)
1960's-80's: Van de Kamp (Barnard's Star)
1980's: Gatewood (Lalande 21185, again)
2001: Han et al. (some 20 RV planets)
2009: Pravdo & Shaklan (VB10b)

mas-precision astrometry is usually not enough for planet detection

Astrometric Orbits

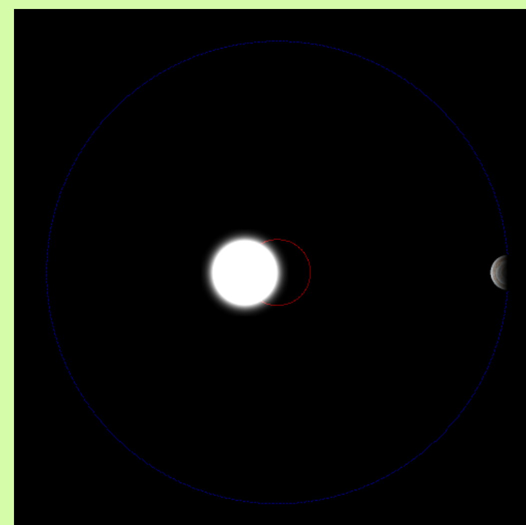
- Astrometry measures stellar positions and uses them to determine a binary orbit projected onto the plane of the sky
- measures all 7 parameters of the orbit, in multiple systems it derives the relative inclination angles between pairs of orbits, regardless of the actual geometry. Mass is derived given 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.

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



µas Astrometry: Challenges

Two main directions for improvement:

1) Monolithic configurations (optical)
2) Diluted configurations (optical/near IR)

- Narrow-angle, relative astrometry: both from the ground and in space (VLTI/PRIMA,???)

- Global astrometry: only in space (Gaia)

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

Like RV, it faces:

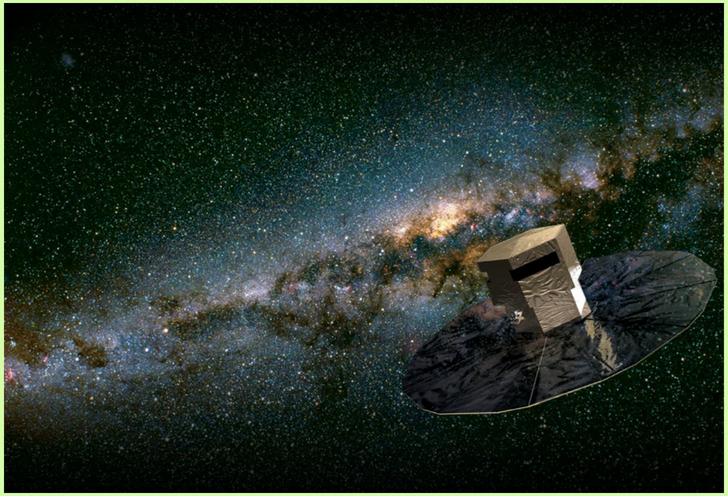
- technological challenges (achievable precision, ground vs. space, instrument configuration, choice of wavelength, calibrations, etc.)

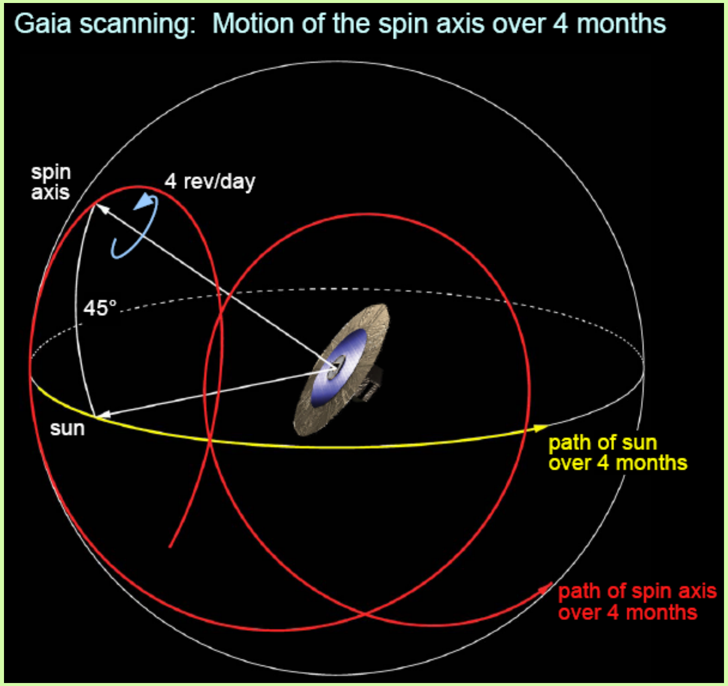
- astrophysical challenges (noise sources characterization)

- data modeling challenges (orbital fits)

See e.g. Sozzetti (2005, 2010)

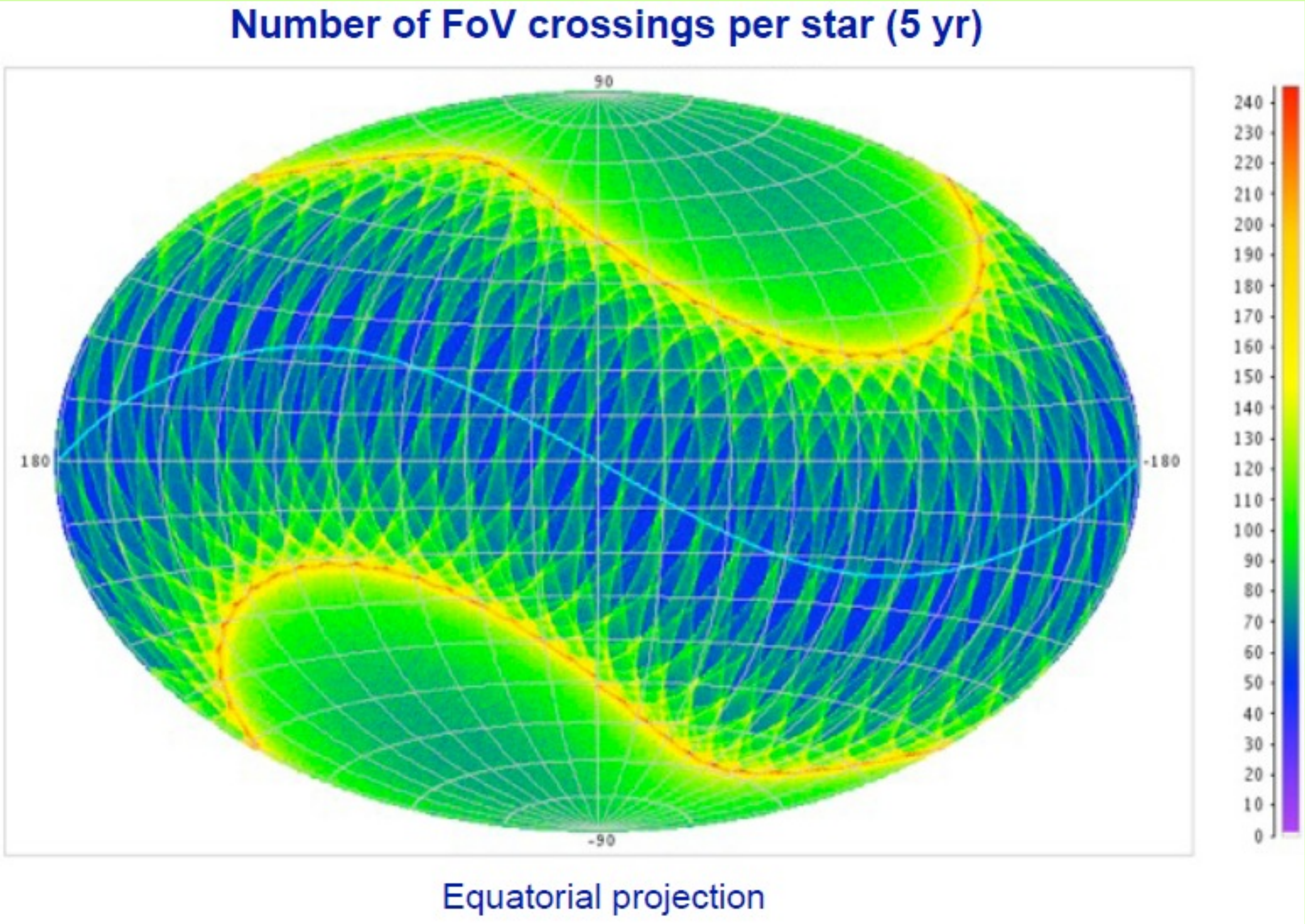
gaia





Gaia in a nutshell

- ESA mission building on the Hipparcos heritage
- Astrometry, Photometry and Spectroscopy
- Satellite, including the payload, by industry (Astrium, Toulouse), operations by ESA and data processing by scientists (DPAC)
- Launch October 2013
- Science Alerts early on
- First intermediate data release 22 months after launch


Number of FoV crossings per star (5 yr)
90
180
-180
-90
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Equatorial projection

Gaia vs. Hipparcos

- Magnitude limits:
  - Hipparcos <12 mag
  - Gaia 6 - 20 mag
- Number of objects: 120,000 => 10^9
- Accuracy: milliarcsec => µarcsec
- Radial velocity: none => 150 million
- Pre-selected => Unbiased survey

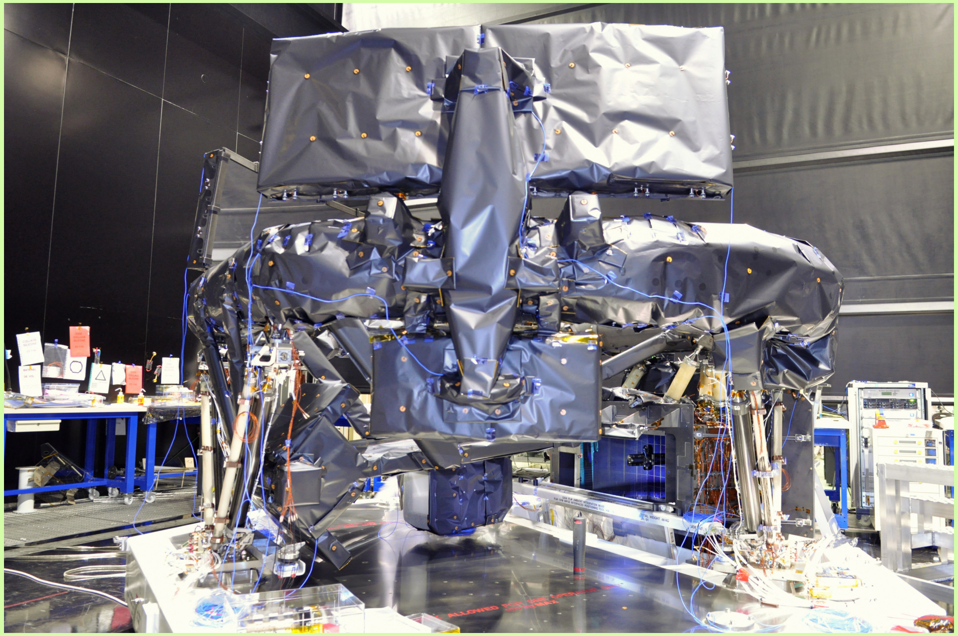
It's Almost Ready!

* Gaia Protoflight Payload Module fully integrated

* Spacecraft level assembly starting early 2013 leading to launch in October

* Galileo launch in October 2011 successful and with mechanical loads as anticipated

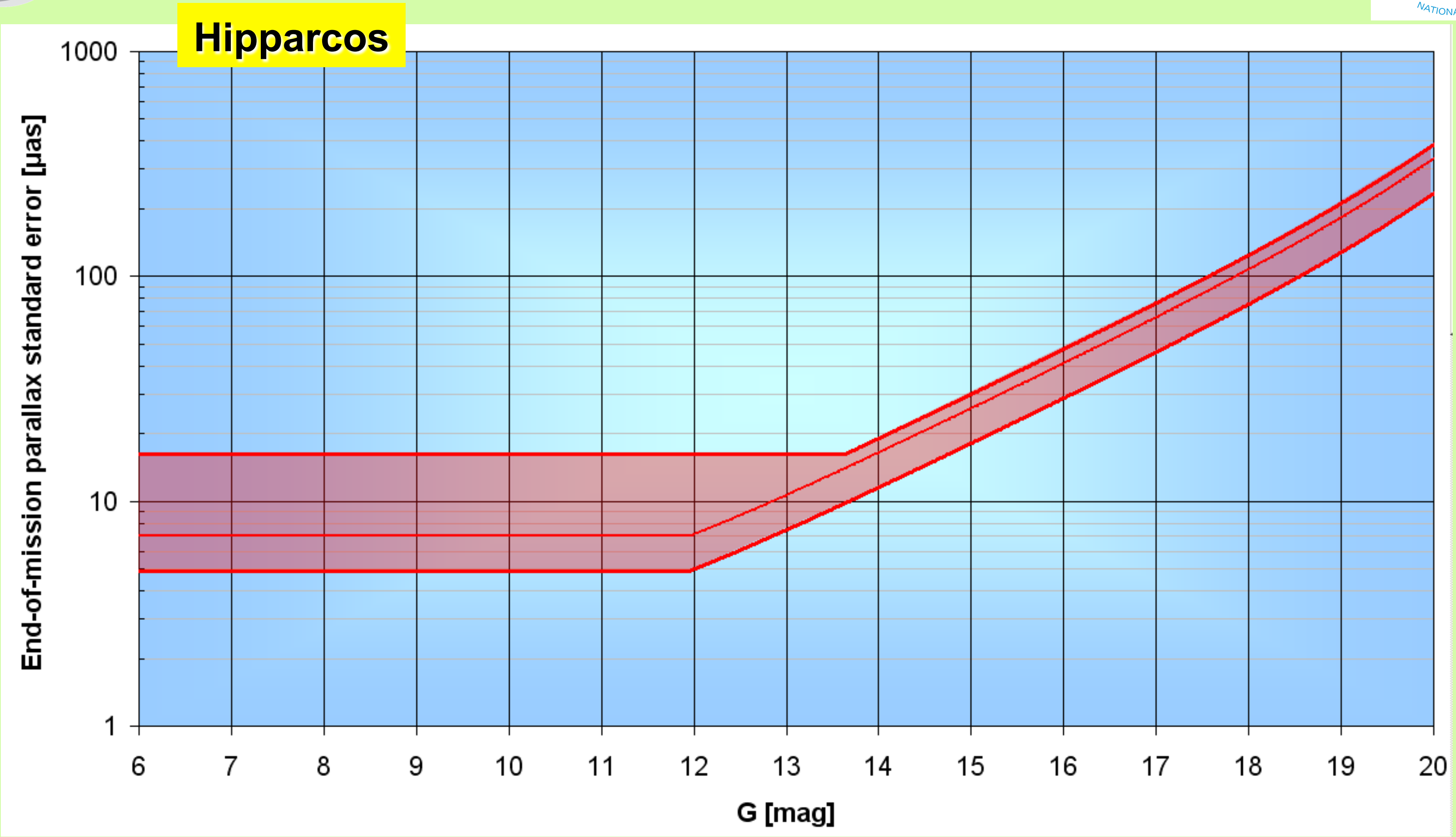
* Gaia launcher manufacturing started (ahiahi, Soyuz rocket Sz-013!)



Intermediate Data Releases

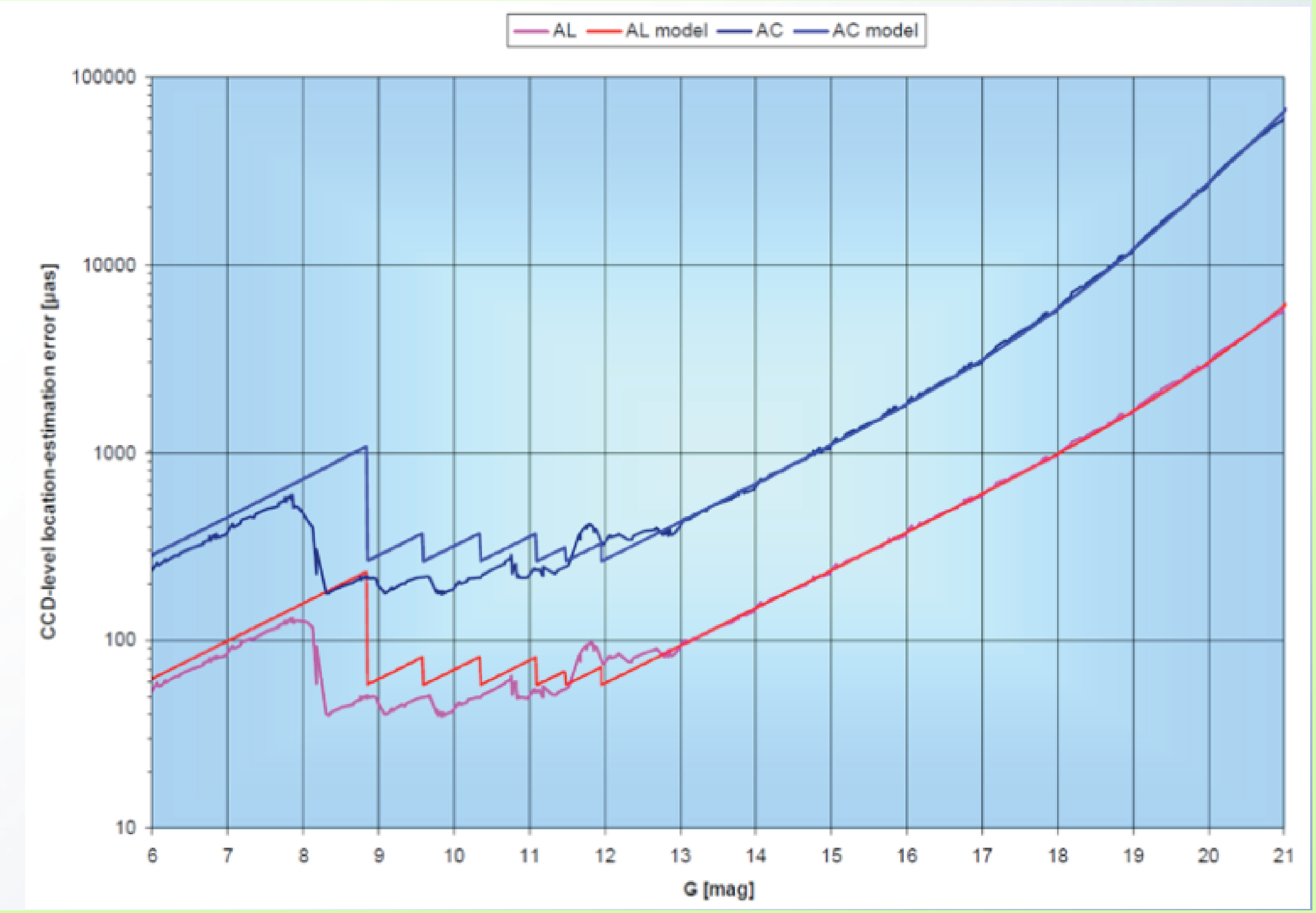
- Intermediate Data Release Scenario agreed with inputs from Data Release Policy and DPAC Operations Plan
  - Science Alerts as soon as possible
  - L+22m positions, G-magnitudes, proper motions to Hipparcos stars, ecliptic pole data
  - L+28m + first 5 parameter astrometric results, bright star radial 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

Gaia Astrometric Precision



1. 6 < G < 12: bright-star regime (calibration errors, CCD saturation)
2. 12 < G < 20: photon-noise regime (sky-background and electronic noise at G ~ 20 mag)

CCD-level Location Estimation



gaia 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

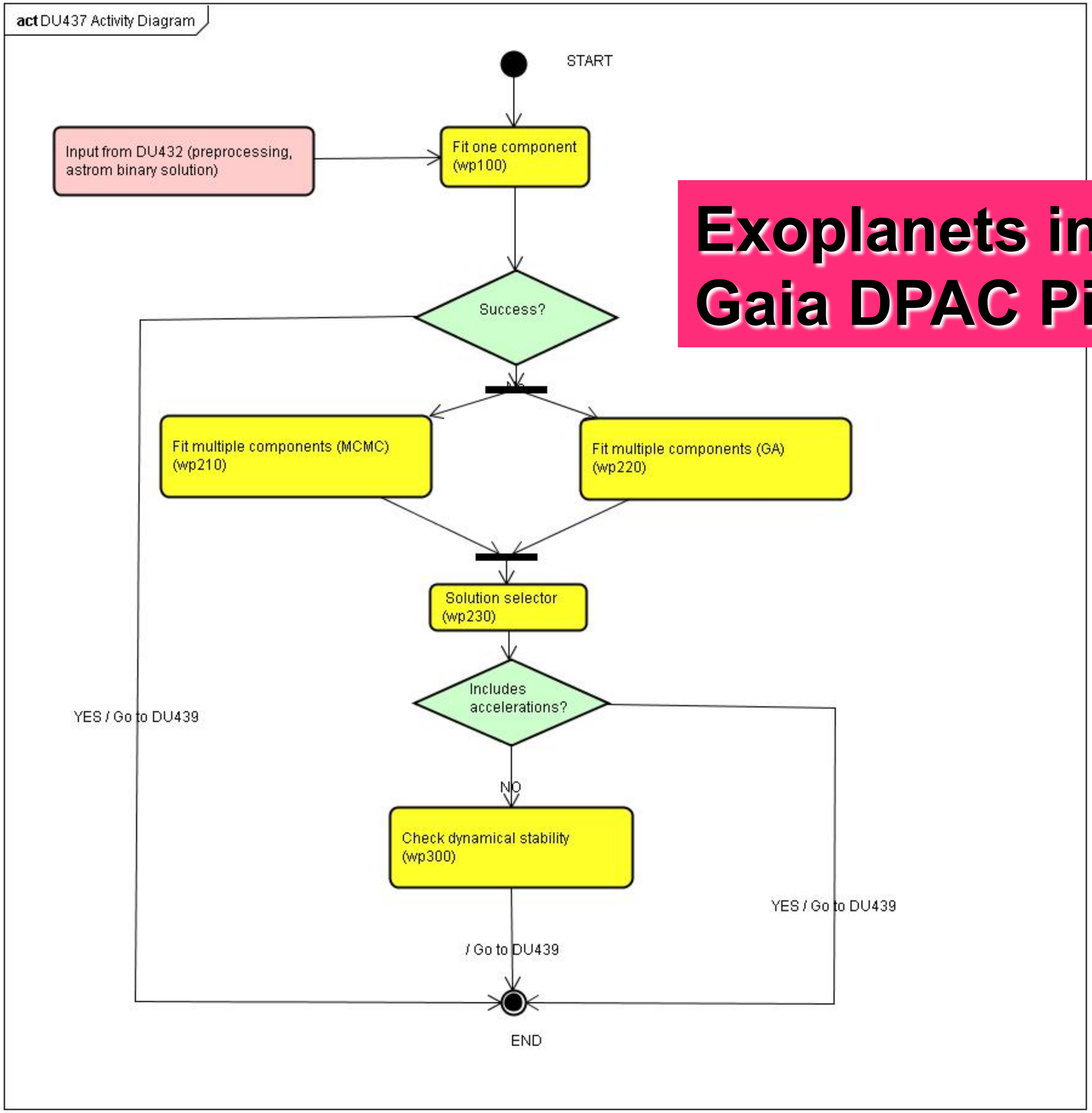
- Global searches (grids, Fourier decomposition, genetic algorithms, Bayesian inference +MCMC) must be coupled to local minimization procedures (e.g., L-M)

- 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
- Memento lessons learned from RV surveys, with disagreement on orbital solution details, and sometime number of planets!!

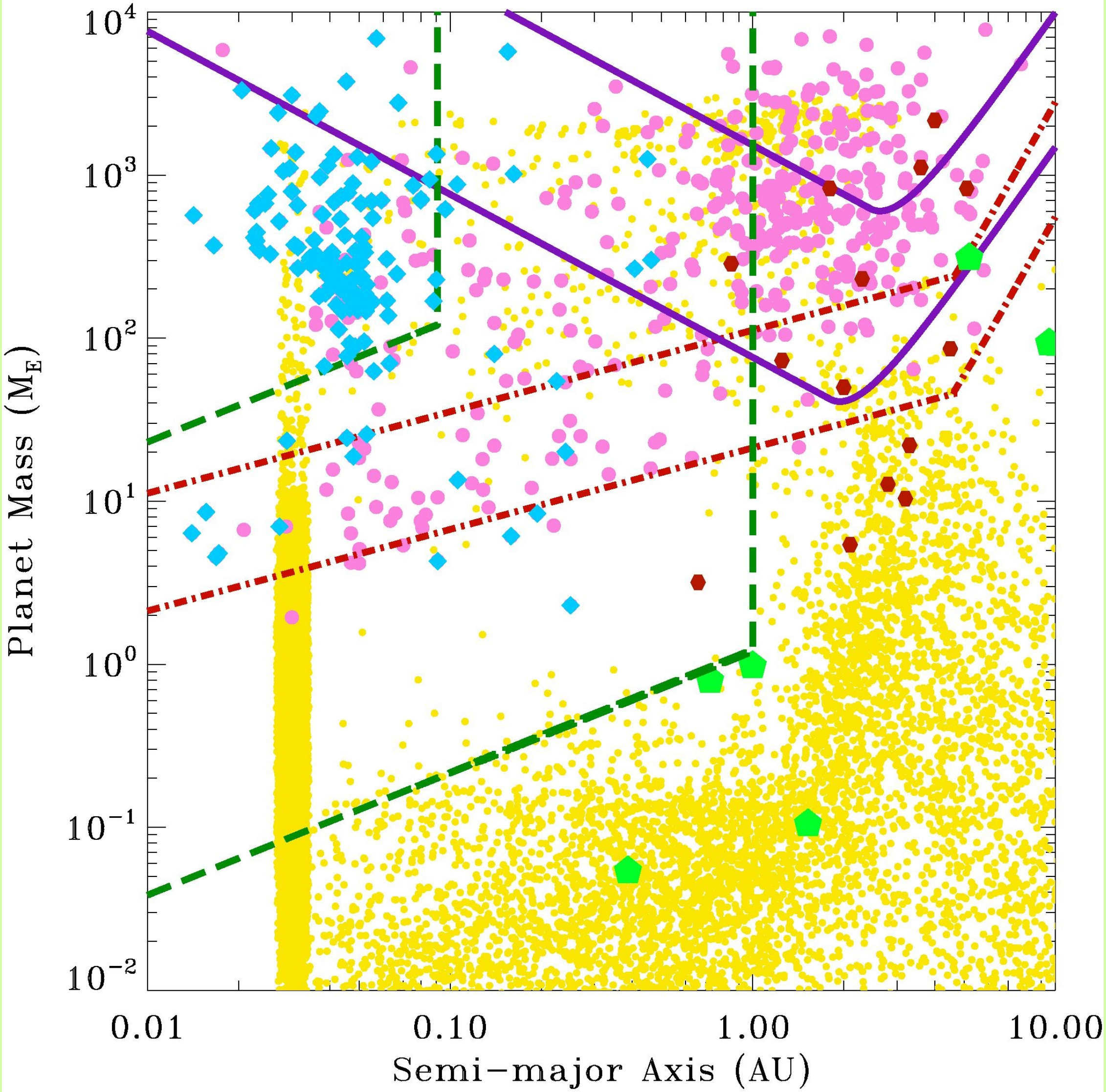
Exoplanets in the Gaia DPAC Pipeline



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 ~ 20 μas



Sozzetti 2011

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

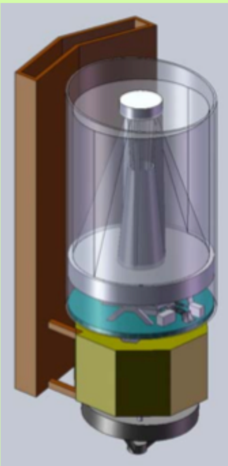
How Many Multiple-Planet Systems will Gaia find?

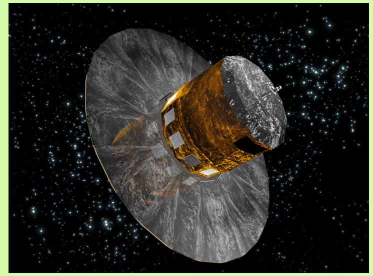
Star counts (V<13),
$F_{p,mult}$,
Gaia detection limit

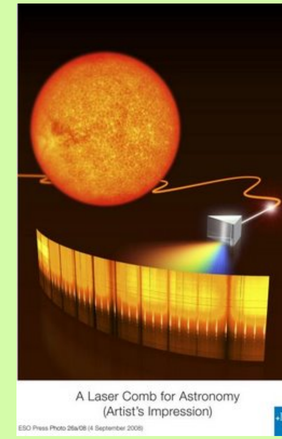
Case	Number of Systems
Detection	~ 1000
Orbits and masses to better than 15-20% accuracy	~ 400 – 500
Successfull coplanarity tests	~ 150

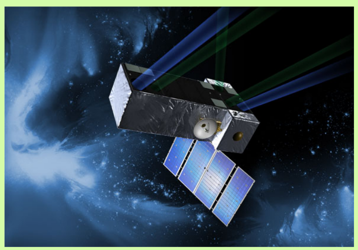
Unbiased, magnitude-limited planet census of hundreds of thousands stars

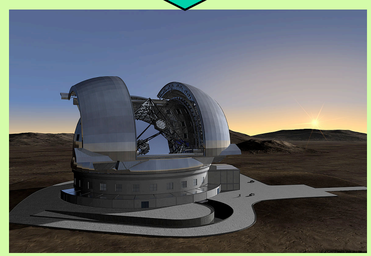
Gaia - Synergies

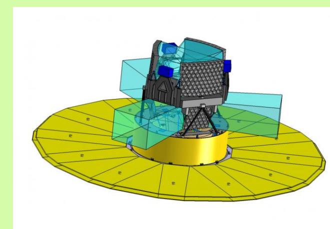












- **Gaia & spectroscopic characterization observatories (e.g., EChO)**
- **Gaia & transit surveys from the ground (e.g., WASP) and in space (CoRoT, Kepler)**
- **Gaia & direct imaging observatories (e.g., SPHERE/PCS)**
- **Gaia & RV programs (e.g., HARPS(-N), ESPRESSO, CARMENES, and the likes)**
- **Gaia & ground-based and space-borne astrometry**

Objectives of study within the GREAT RNP/ITN

Focusing on M Dwarfs

(Sozzetti et al., A&A submitted)

Cool, nearby M dwarfs within a few tens of parsecs from the Sun are now the focus of dedicated experiments in the realm of exoplanets astrophysics.

WHY?

* Shifting theoretical paradigms in light of new observations

* Improved understanding of the observational opportunities for planet detection and characterization provided by this sample.

WHAT CAN Gaia CONTRIBUTE?

* Gaia, in its all-sky survey, will deliver precision astrometry for a magnitude-limited sample of M dwarfs, providing an inventory of cool nearby stars with a much higher degree of completeness (particularly for late sub-types) with respect to currently available catalogs.

SIMULATION SCHEME

1) Basis: The Casertano et al. (2008, A&A, 482, 699) simulation setup

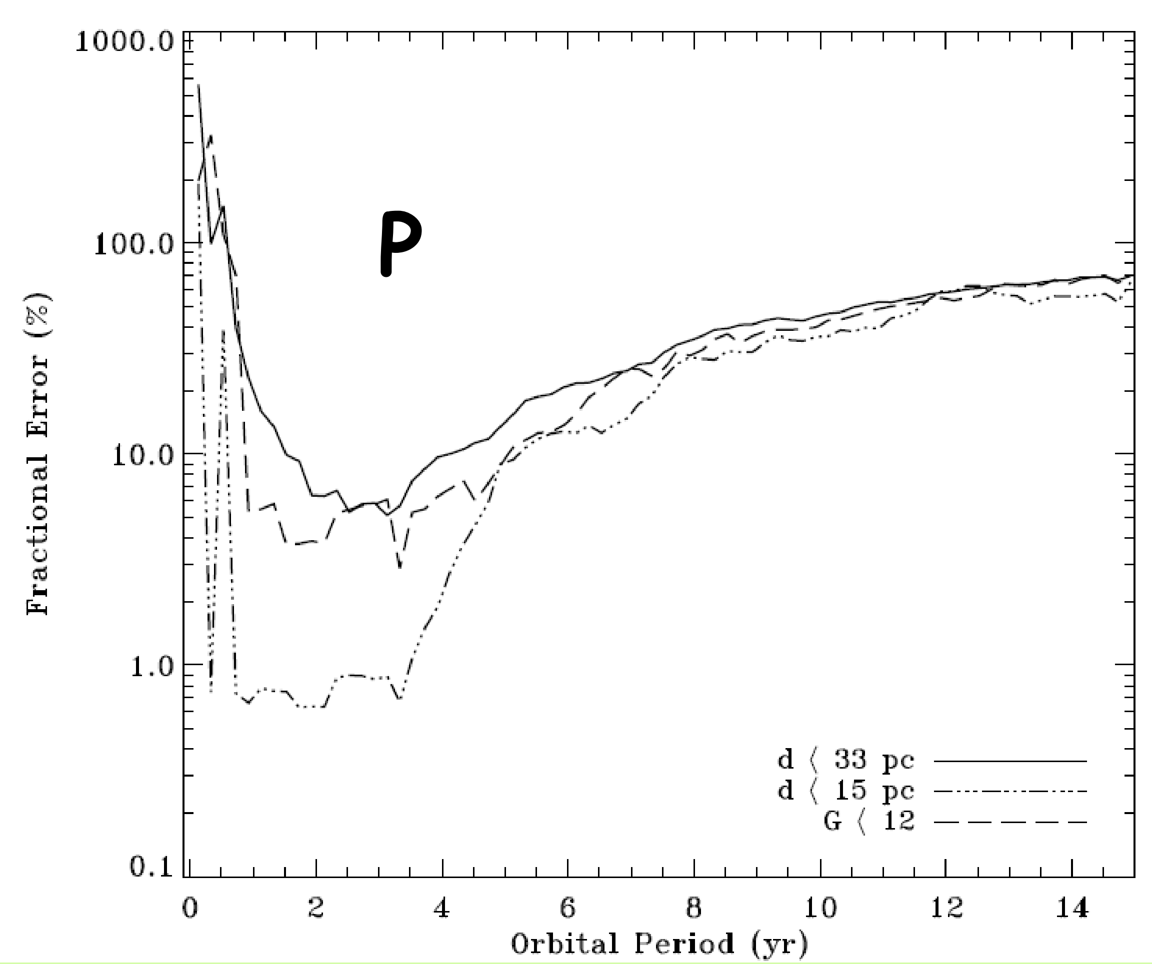
2) Updated Gaia scanning law. *T*=5 yr nominal mission duration

3) Up-to-date error model as a function of Gaia *G*-band mag (inclusive of gate scheme for 20% of bright [*G*< 12] stars). Single-measurement errors are typically σ_m~100 μas

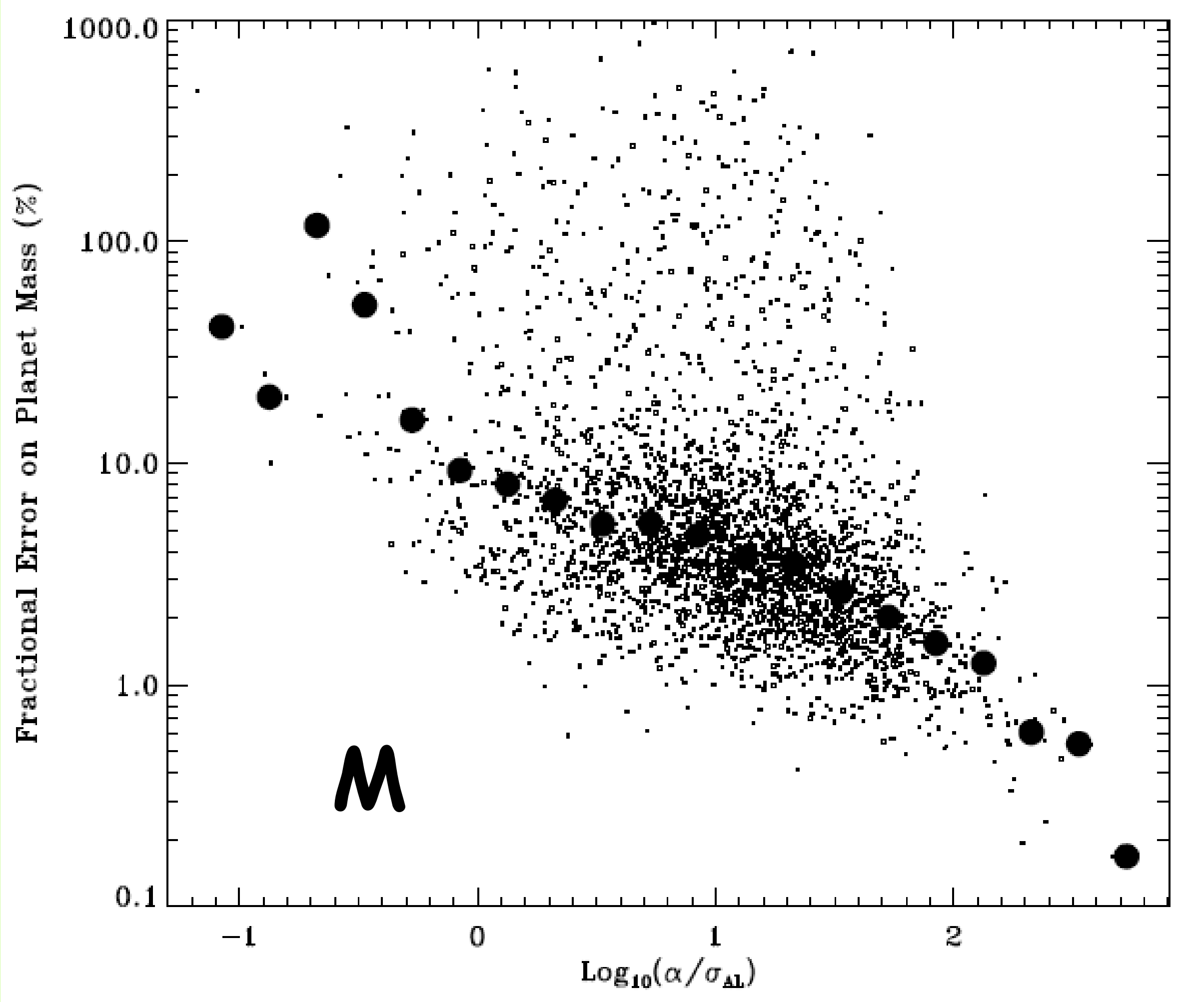
4) Actual list of targets: 3150 M dwarfs (0.09-0.6 M_{SUN}) within 33 pc from the Sun from the LSPM-North Catalog (Lépine 2005, AJ, 130, 1680), with average *G*~14.0 mag and M_*~0.3 M_{SUN}

5) 1 M_{JUP} companions, orbital periods $P < 3T$, moderate eccentricities (e<0.6), all other orbital elements uniformly distributed within their respective ranges

Determining Giant Planets Orbits (1)



Determining Giant Planets Orbits (2)



How Many Giants?

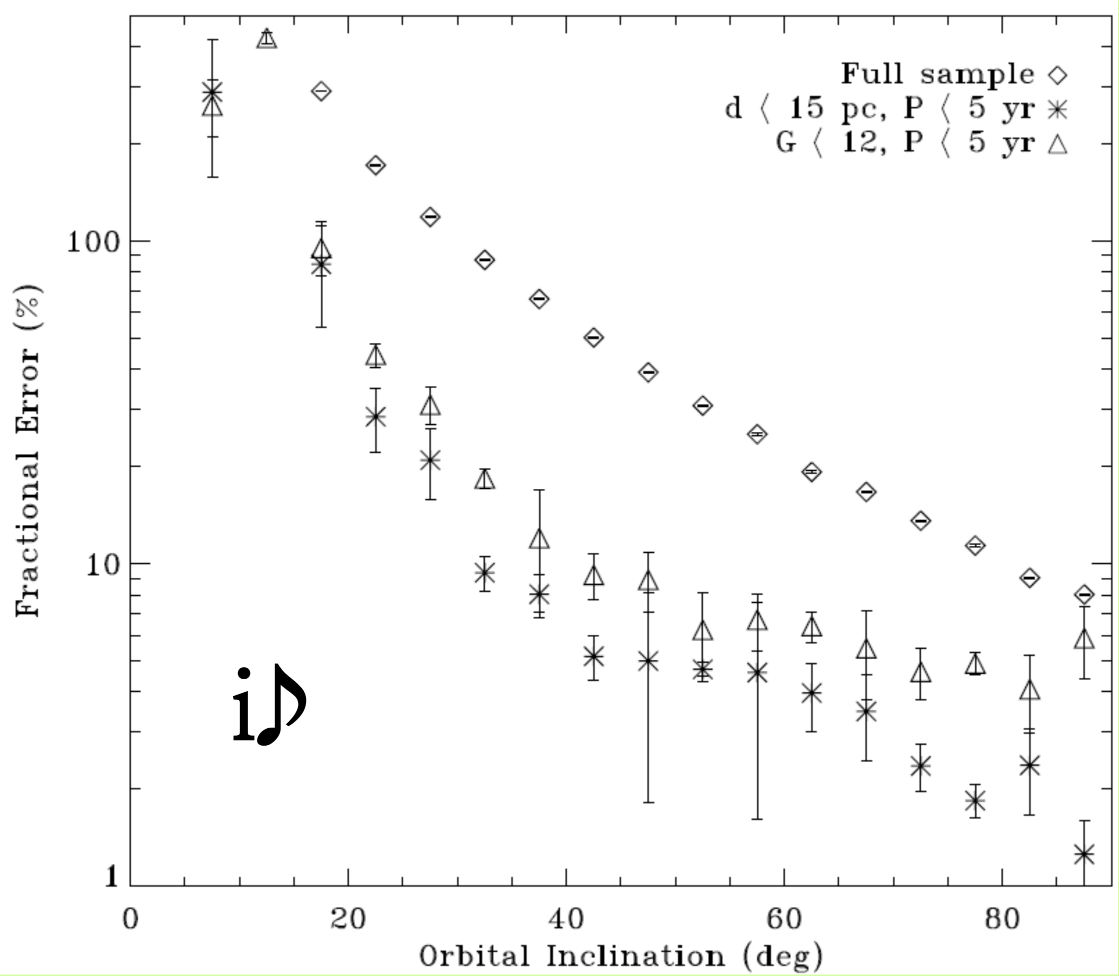
- Present-day estimates from RV surveys imply f_p~3-4% (within 3 AU)
- Gaia could identify ~100 giant planets around this sample, an order-of-magnitude increase
- For approximately 50% of them, accurate orbit reconstruction will be possible
- The sample size is such that f_p will be put on much more solid statistical grounds
- Very important synergy with present (e.g., HARPS@ESO), starting (e.g., HARPS-N@TNG), and upcoming (ESPRESSO@VLT) RV surveys

Finding Nearby Transiting Wide Separation Giants…

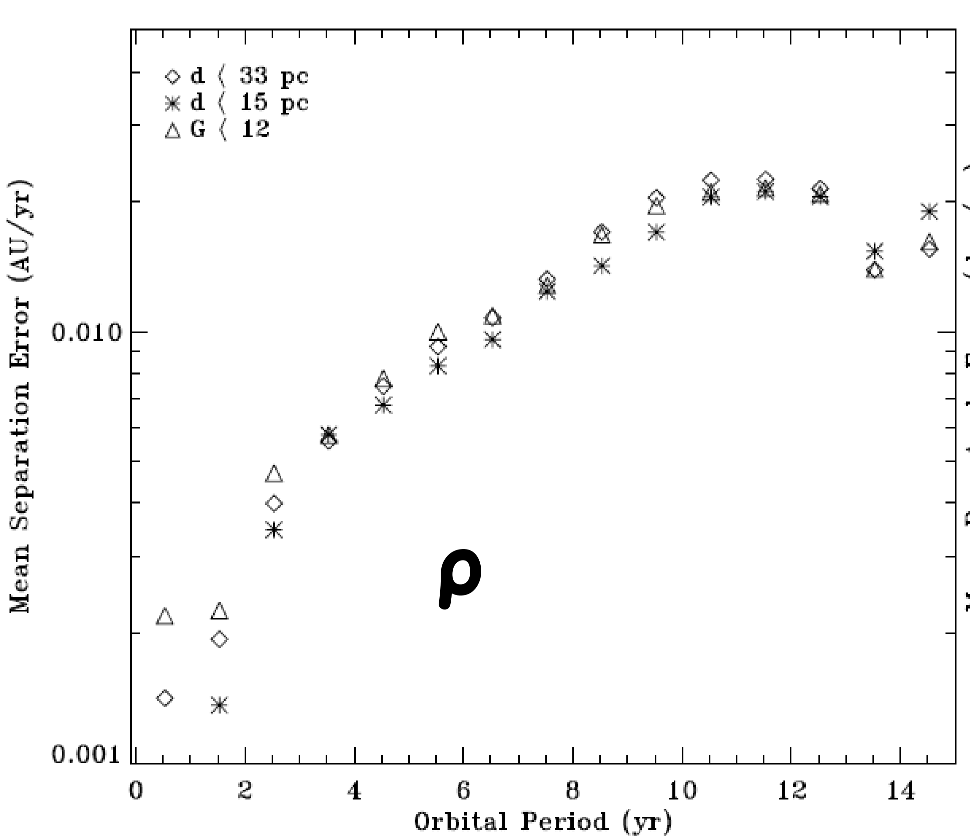
For quasi-edge-on orbits, i is measured to ~3%

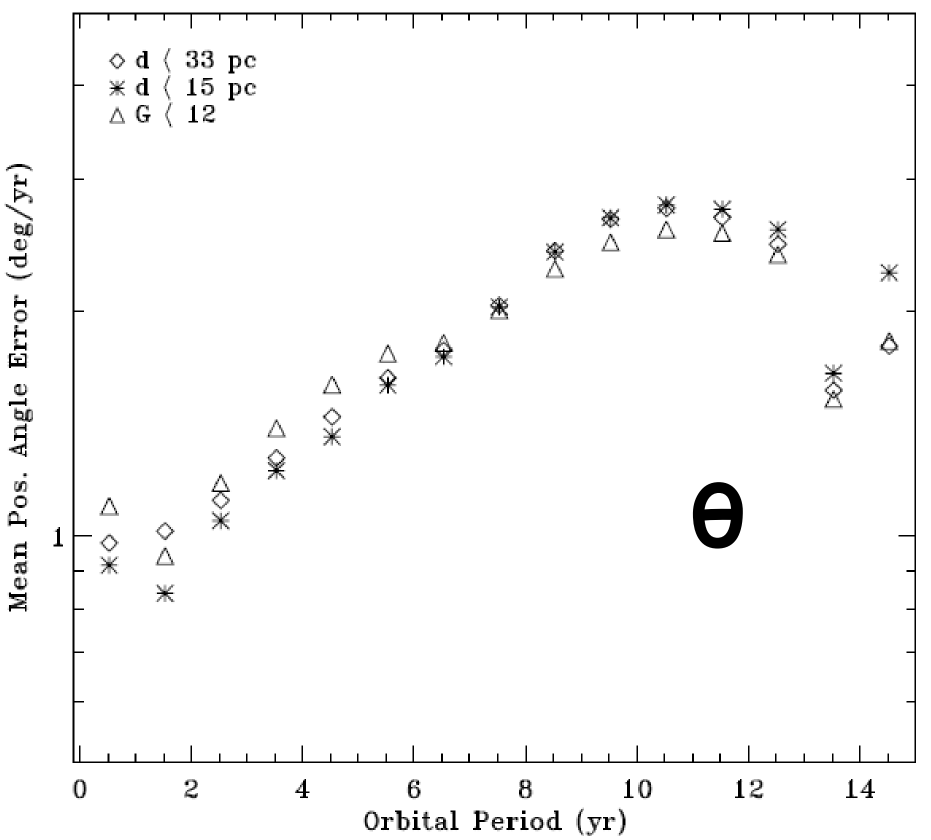
Gaia may find hundreds of giant planets around M dwarfs (and thousands around F-G-K dwarfs). Some may be transiting!

Obvious synergy with ground-based transit work!



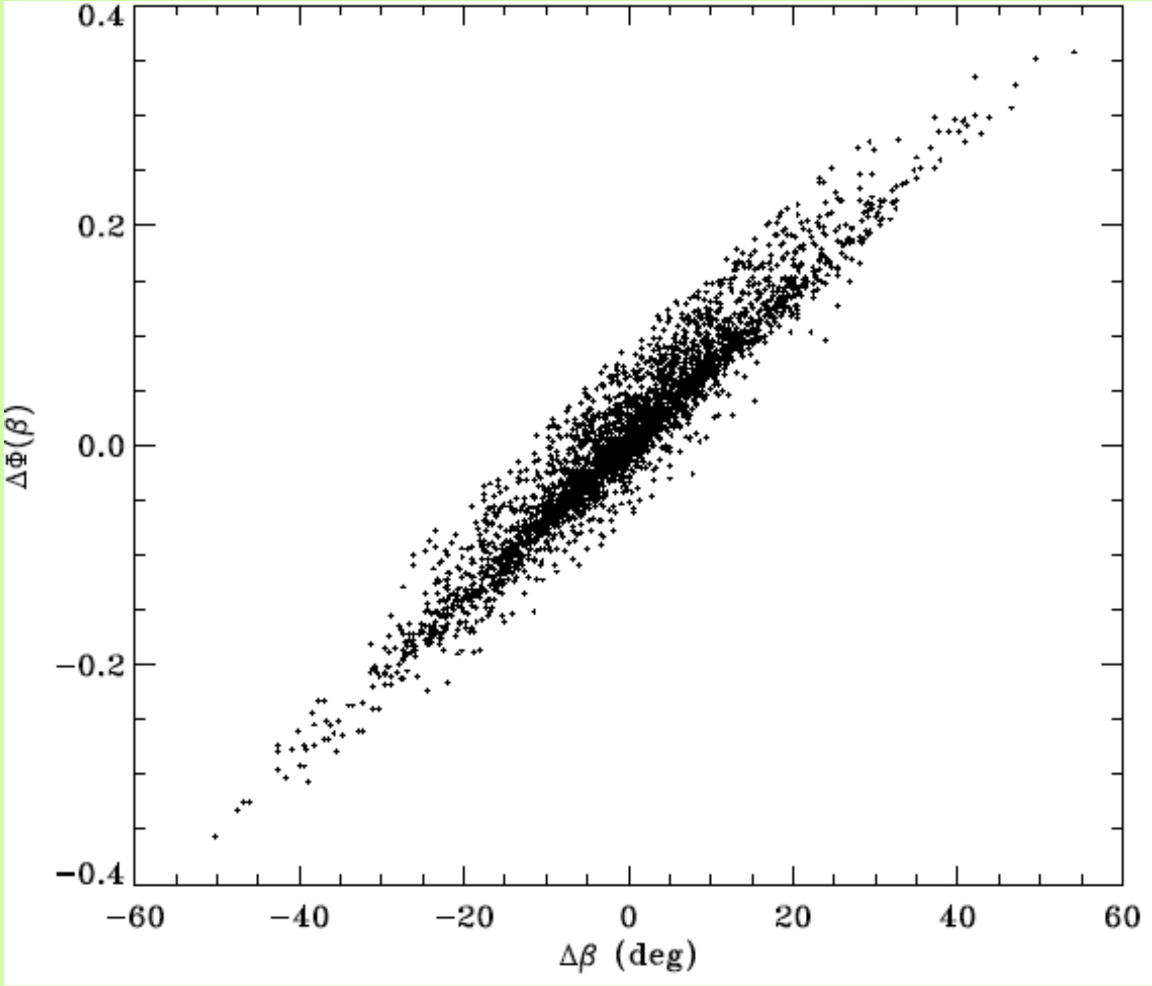
Predicting Their Location…





For well-sampled orbits (P<T), Δρ < 0.01 AU/yr and Δθ < 2 deg/yr
(Over an order of magnitude better than HST/FGS predictions for ε Eri!)

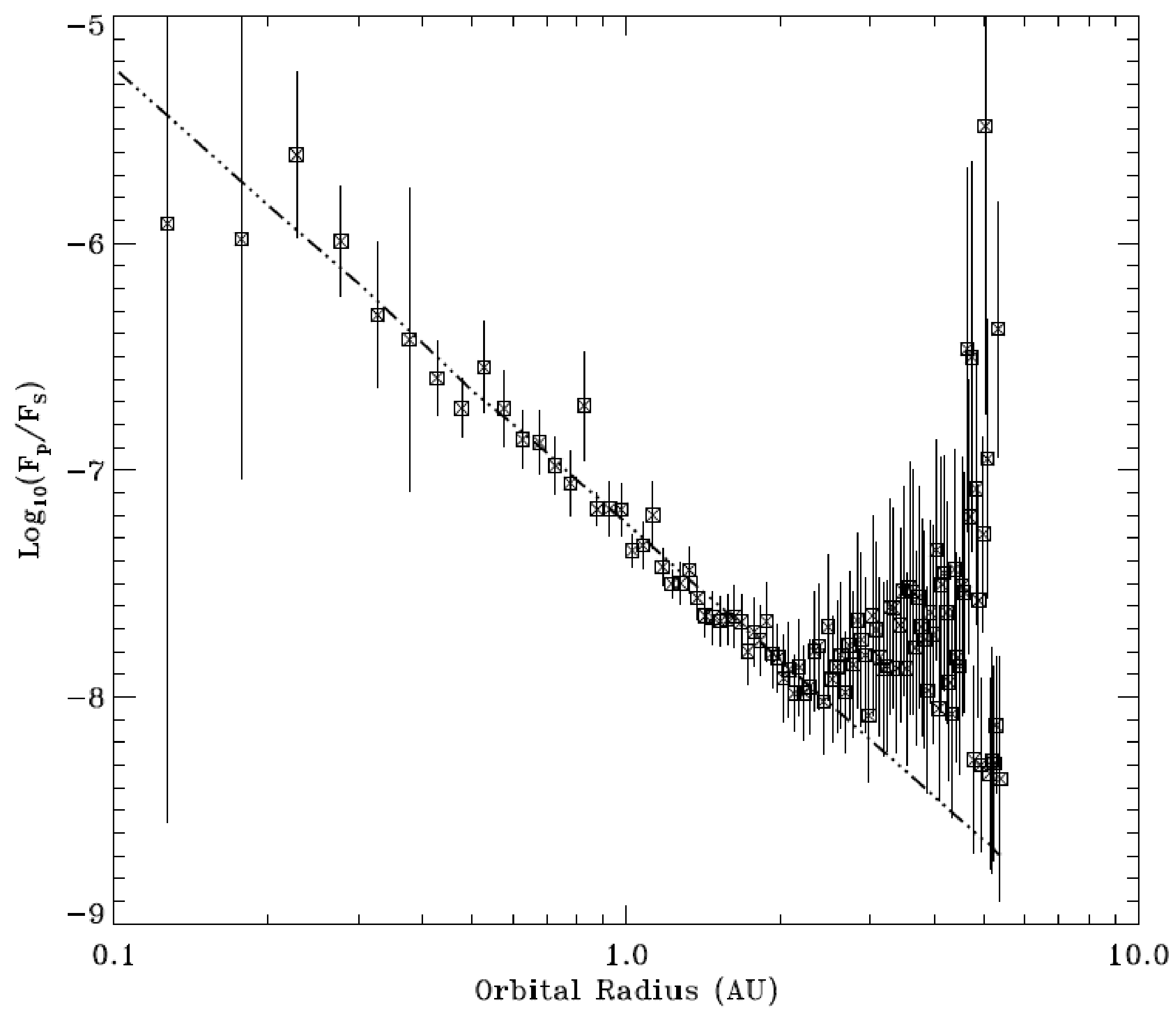
...Their Phases...



Assuming Φ(β) of a Lambert sphere, typically Δβ ~ several deg, ΔΦ(β)~0.1

...and telling how bright they are!

For 0.3<a<3.0 AU, uncertainties in the emergent flux will typically be 10-15%



Potential synergy with direct imaging, reflected light and atmospheric characterization measurements

Re-Calibrating the Hosts

- ALL parallaxes of this M dwarf sample released formally around mid-2016 (not to mention the improvement in completeness levels down to V=20!)
- For a typical target with V~14 at d~ 20 pc, expect $\sigma(\pi)/\pi<0.1\%$
- Re-calibrate absolute luminosities
- Derive trigonometric gravities to ~0.03 dex
- Re-determine the stellar radii to <3%
- Great synergy with ongoing (MEarth), starting (APACHE), and upcoming (NGTS) ground-based surveys, as well as space-based observatories (e.g., EChO)

The Message (take it home!)

- 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.

- The synergies between Gaia and ongoing and planned exoplanet detection and (atmospheric) characterization programs from the ground and in space are potentially huge

- This was a snippet of the Gaia potential on the sample of nearby low-mass M dwarfs

- Gaia’s ‘first’ release: L+22m (Summer 2015)

- Gaia’s ‘first’ major release: L+28m (Beginning of 2016)

- Gaia’s ‘first’ complete catalog release: L+40m (Early 2017)