Gaia and Exoplanets: Promises and Synergies

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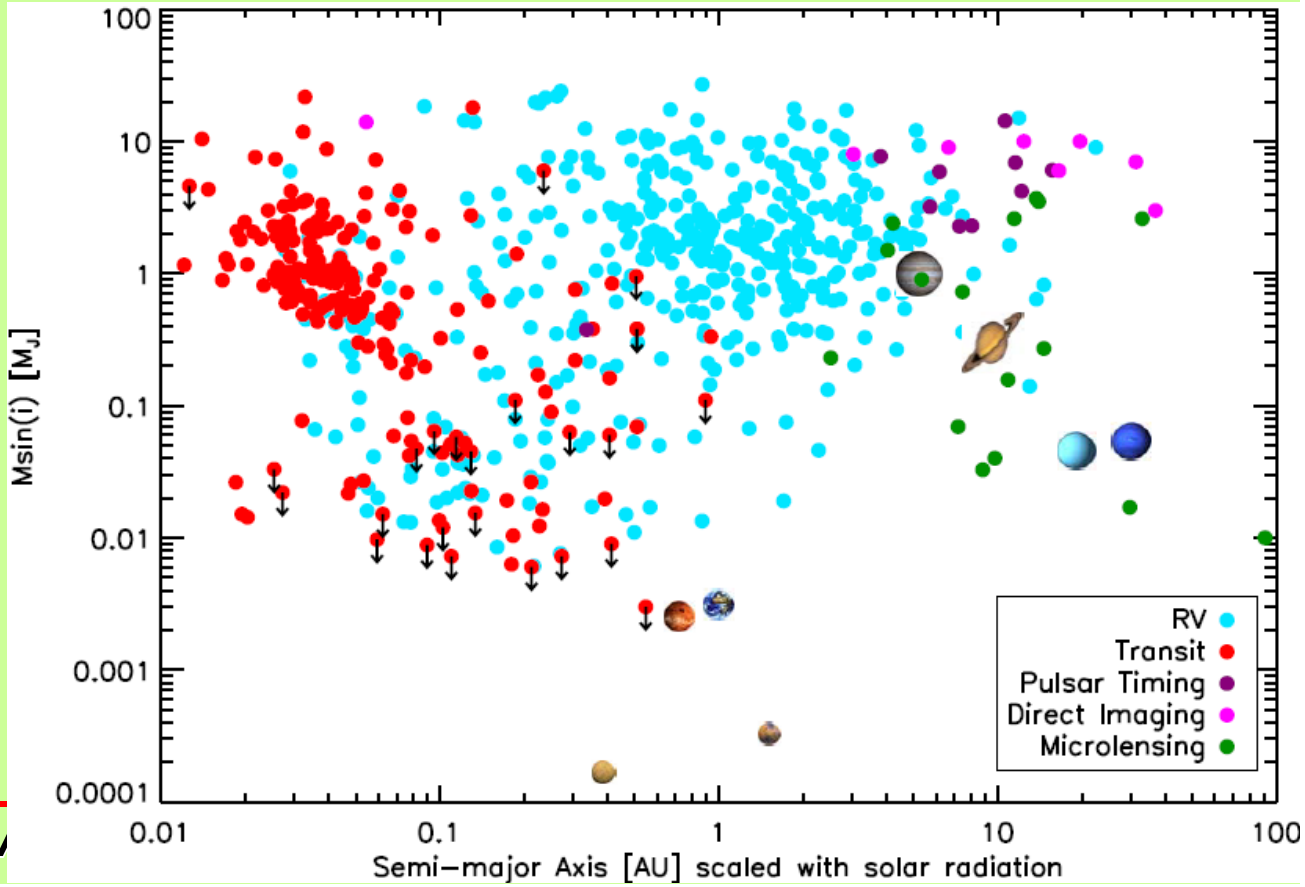
X^th Rencontres du Vietnam: Exoplanetary Science – Quy Nhon, 25/04/2014

Detection/Characterization

- Detection (Visible):
  - Doppler spectroscopy (92%)
  - Transit photometry (44%)
  - Gravitational microlensing (2%)
  - Pulsar/pulsation timing (2%)
  - imaging (4%)

- Characterization (Visible/IR):
  - Transit timing
  - Transmission spectroscopy
  - Rossiter-McLaughlin effect
  - Reflected light
  - Infrared emission

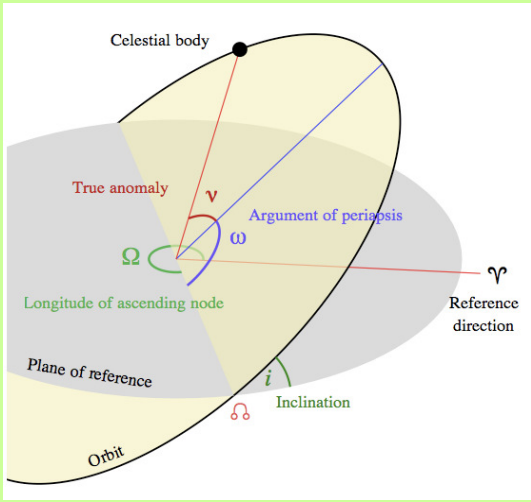


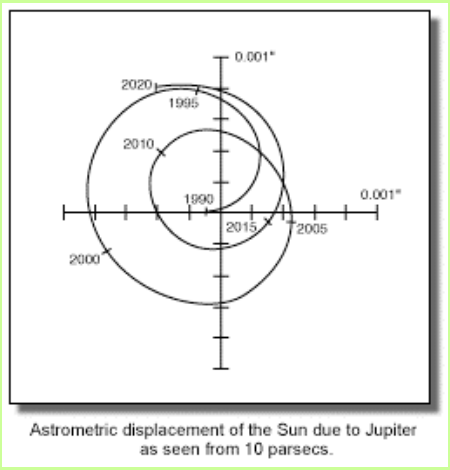
1779 Exoplanets known today, in 1102 systems

460 in multiple-planet systems

Astrometric Orbits

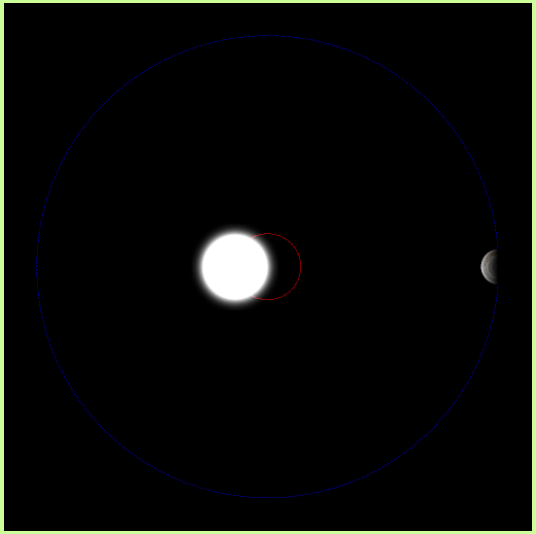
- Astrometry measures stellar positions and uses them to determine a binary orbit projected onto the plane of the sky
- measures all 7 parameters of the orbit, in multiple systems it derives the relative inclination angles between pairs of orbits, regardless of the actual geometry. Mass is derived given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

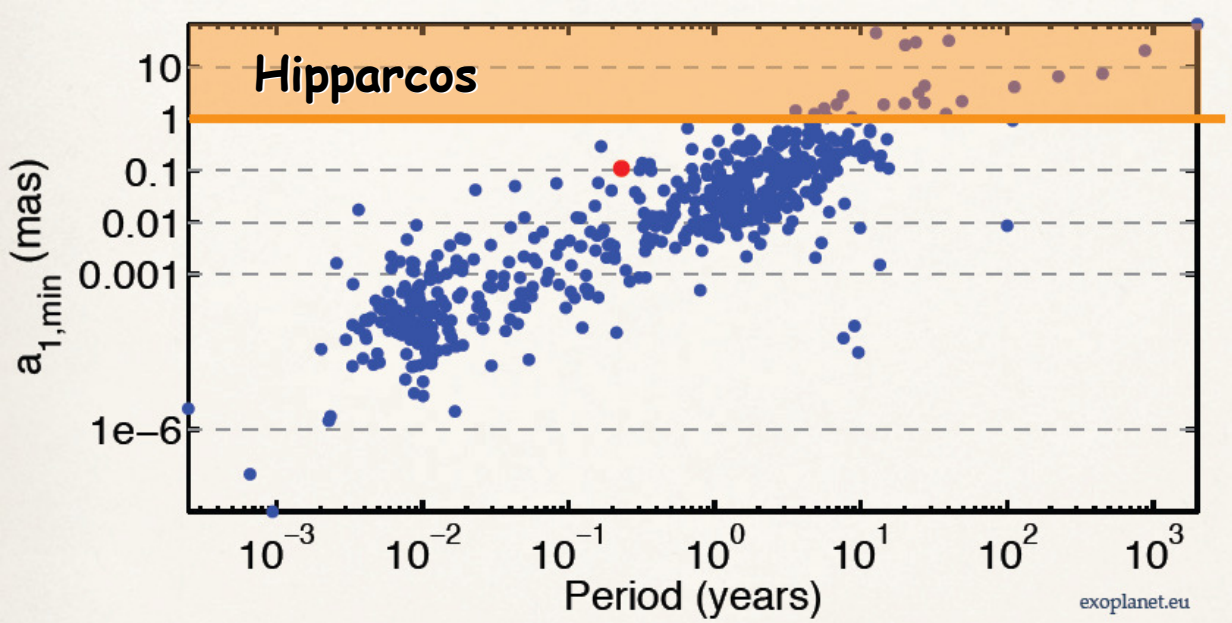


TABLE 1
PARALLAX, PROPER MOTION, AND ASTROMETRIC SIGNATURES INDUCED BY PLANETS OF VARIOUS MASSES AND ORBITAL RADII

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.

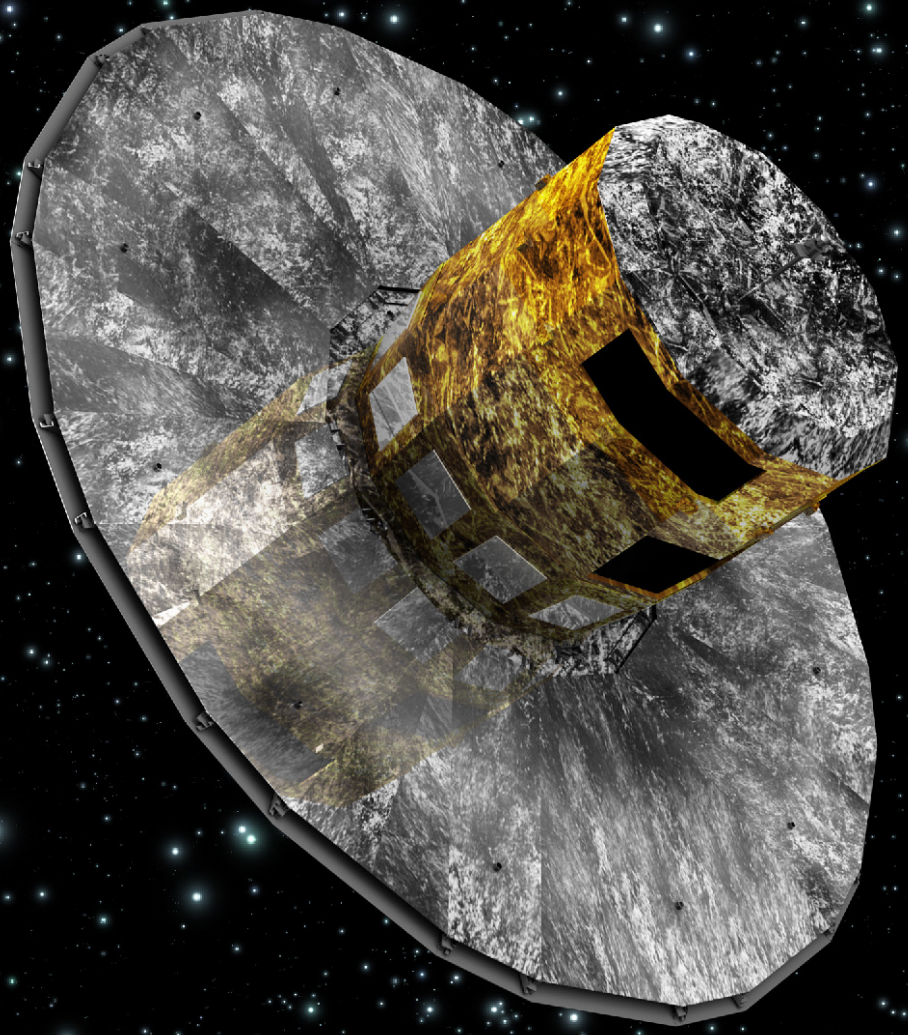
Sozzetti 2005

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)

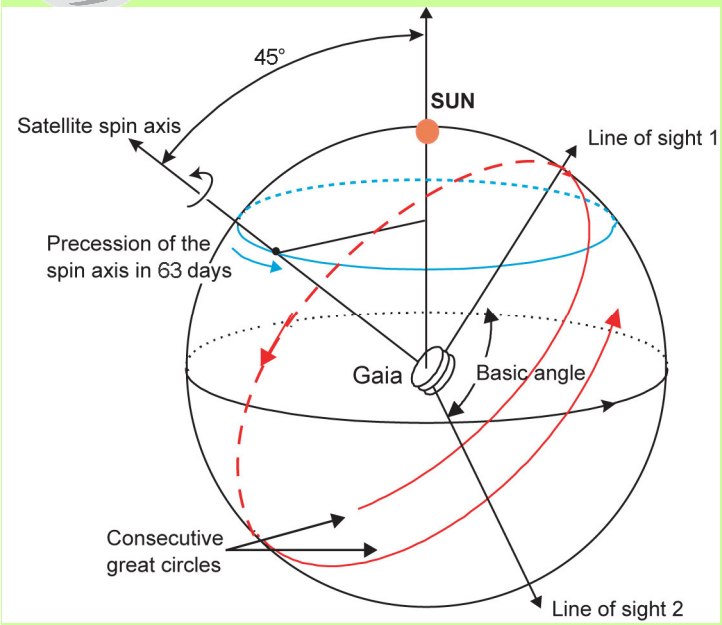
See e.g. Sozzetti (2005, 2010)

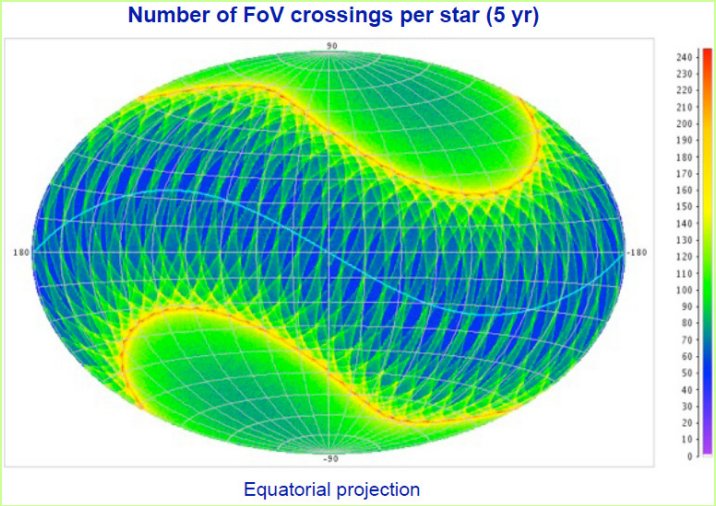
Gaia



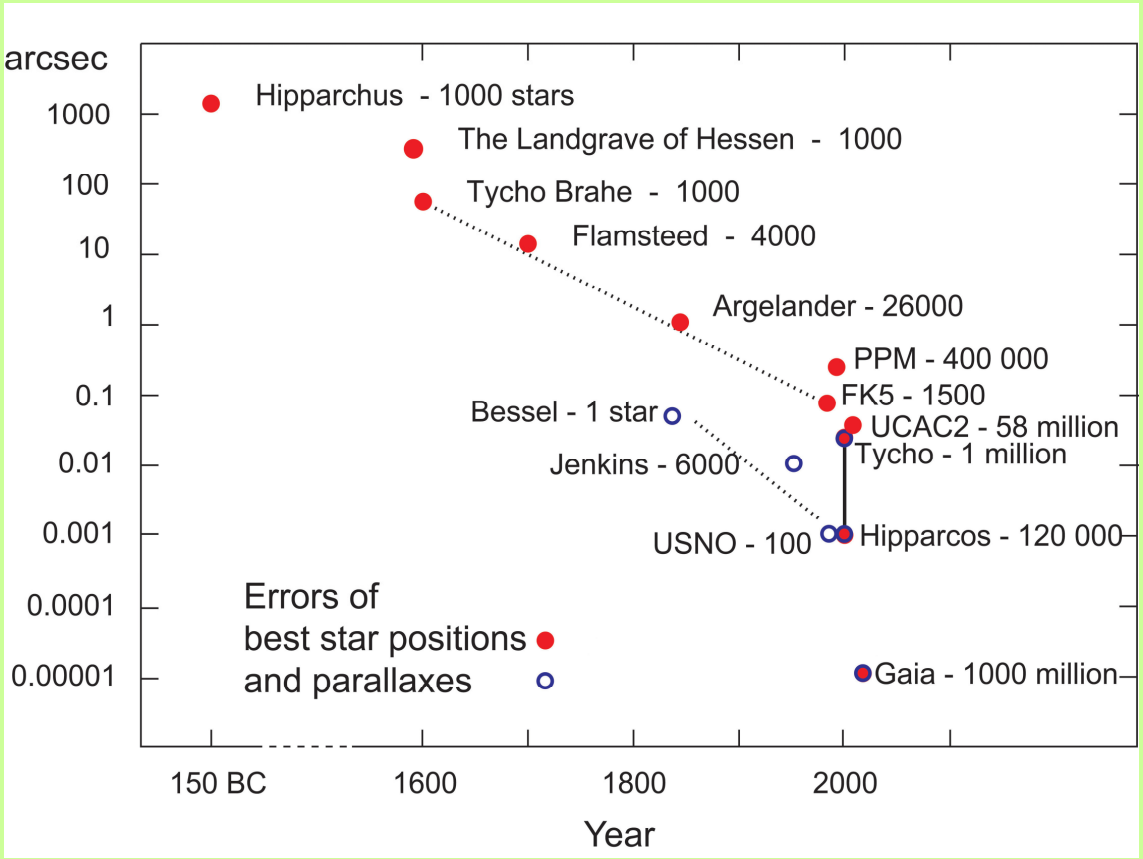
Micro-arcsec Astrometry Comes of Age!

Gaia: a 10 μas machine!





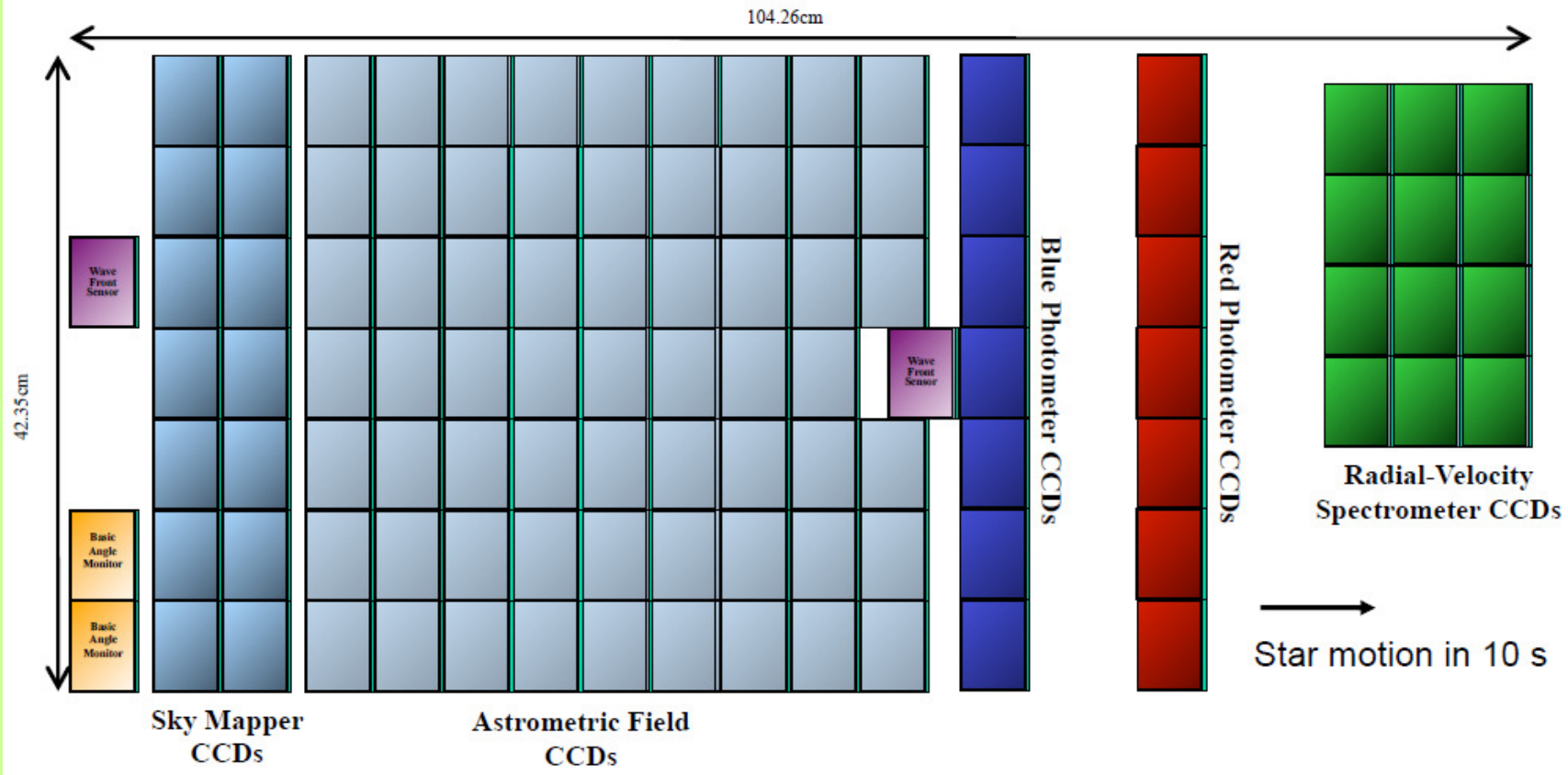
At the V=20 survey limit:
1 billion stars observed!



gaia Up There and Cruising!

Successfully launched on December 19th, 2013!

Gaia Focal Plane



Total field:

- active area: 0.75 deg^2
- 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:

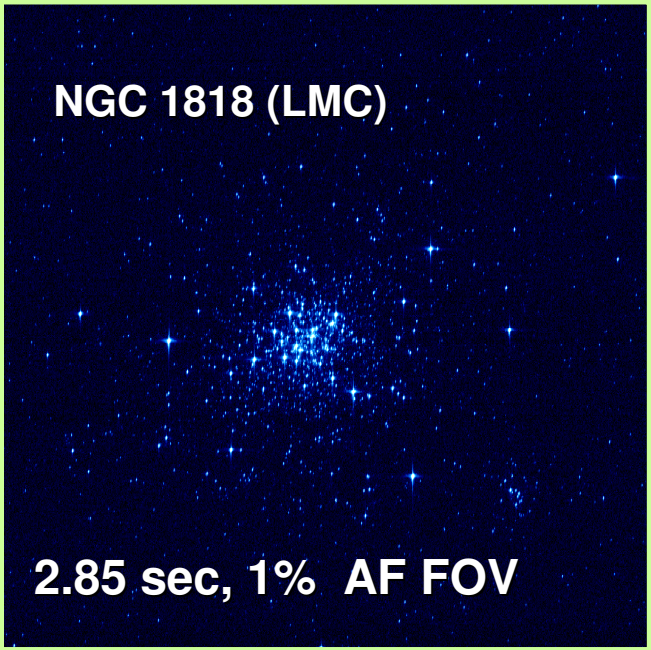
- spectro-photometer
- blue and red CCDs

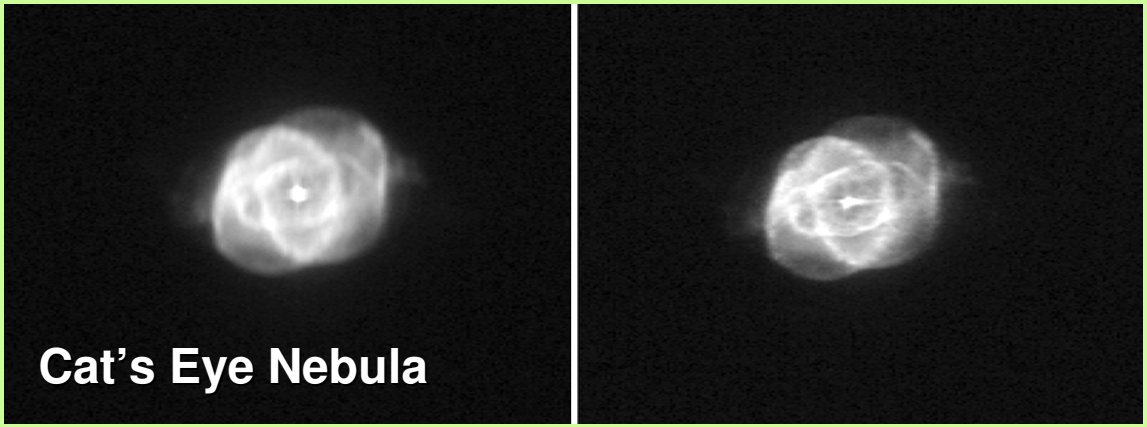
Spectroscopy:

- high-resolution spectra
- red CCDs

The Good News

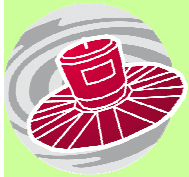
- **Perfect L2 orbit insertion (take that, Hipparcos!)**
- **Excellent image quality (focus and SL tuning up)**





The Unexpected News

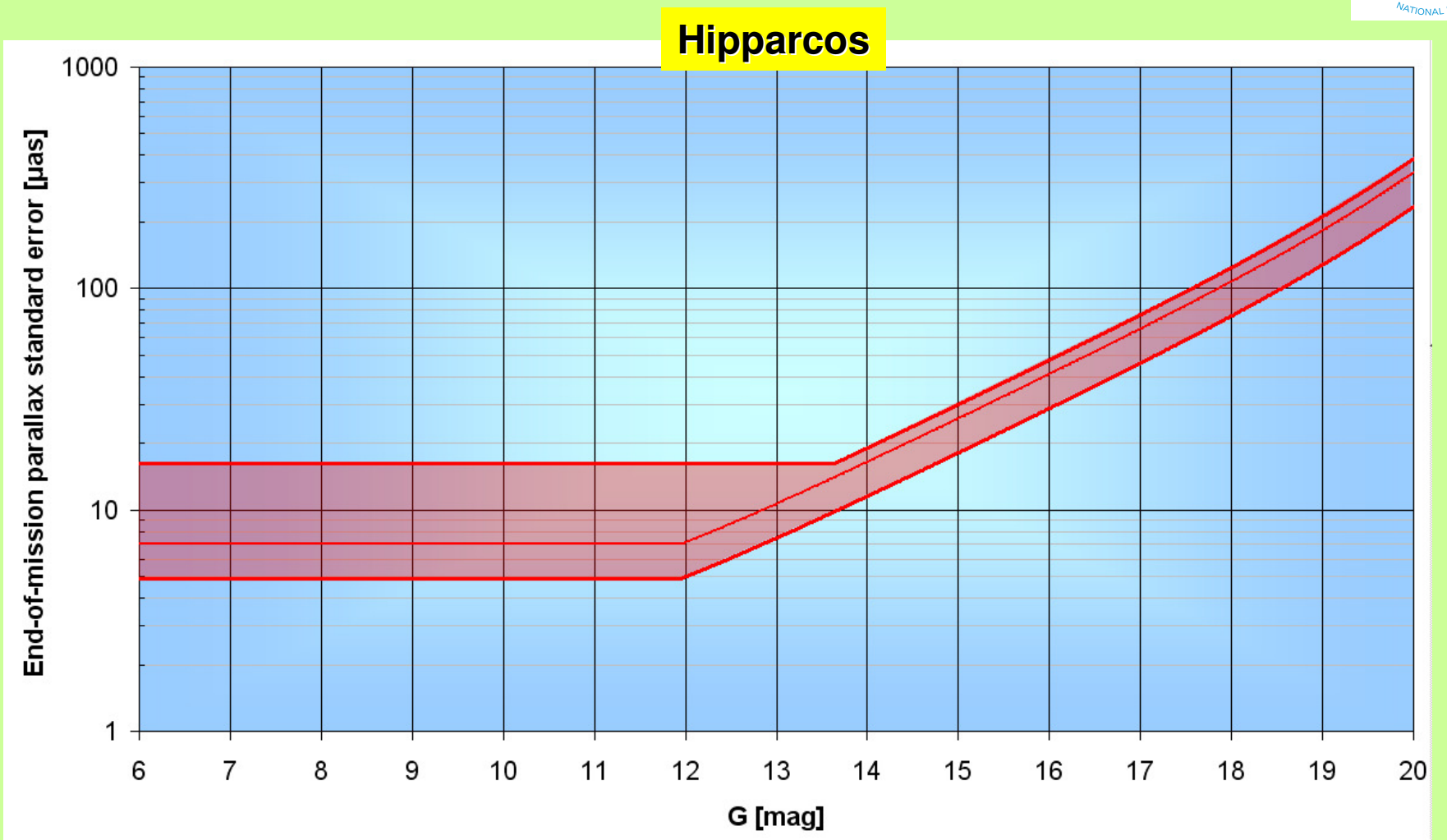
- Gaia is a ‘little’ fainter than expected at L2
- Stray light ‘strikes’ in
- A few other glitches to fix…



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

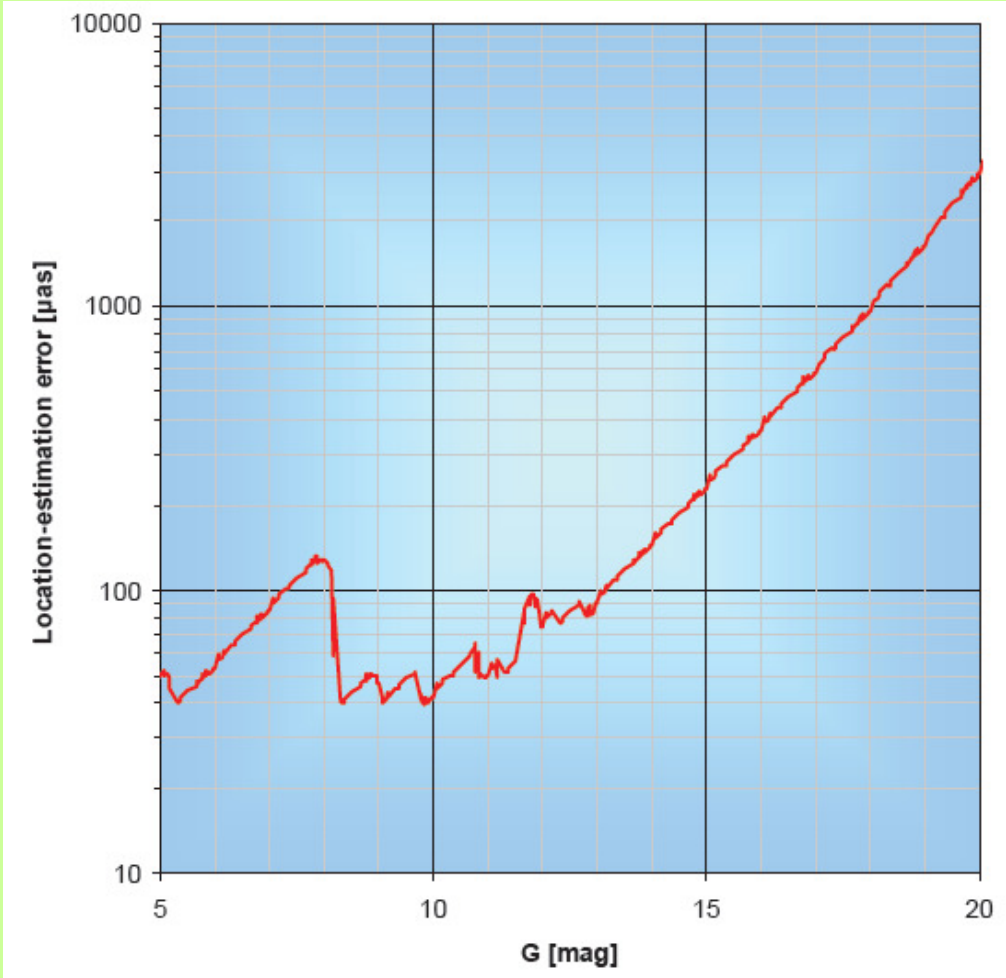
gaia



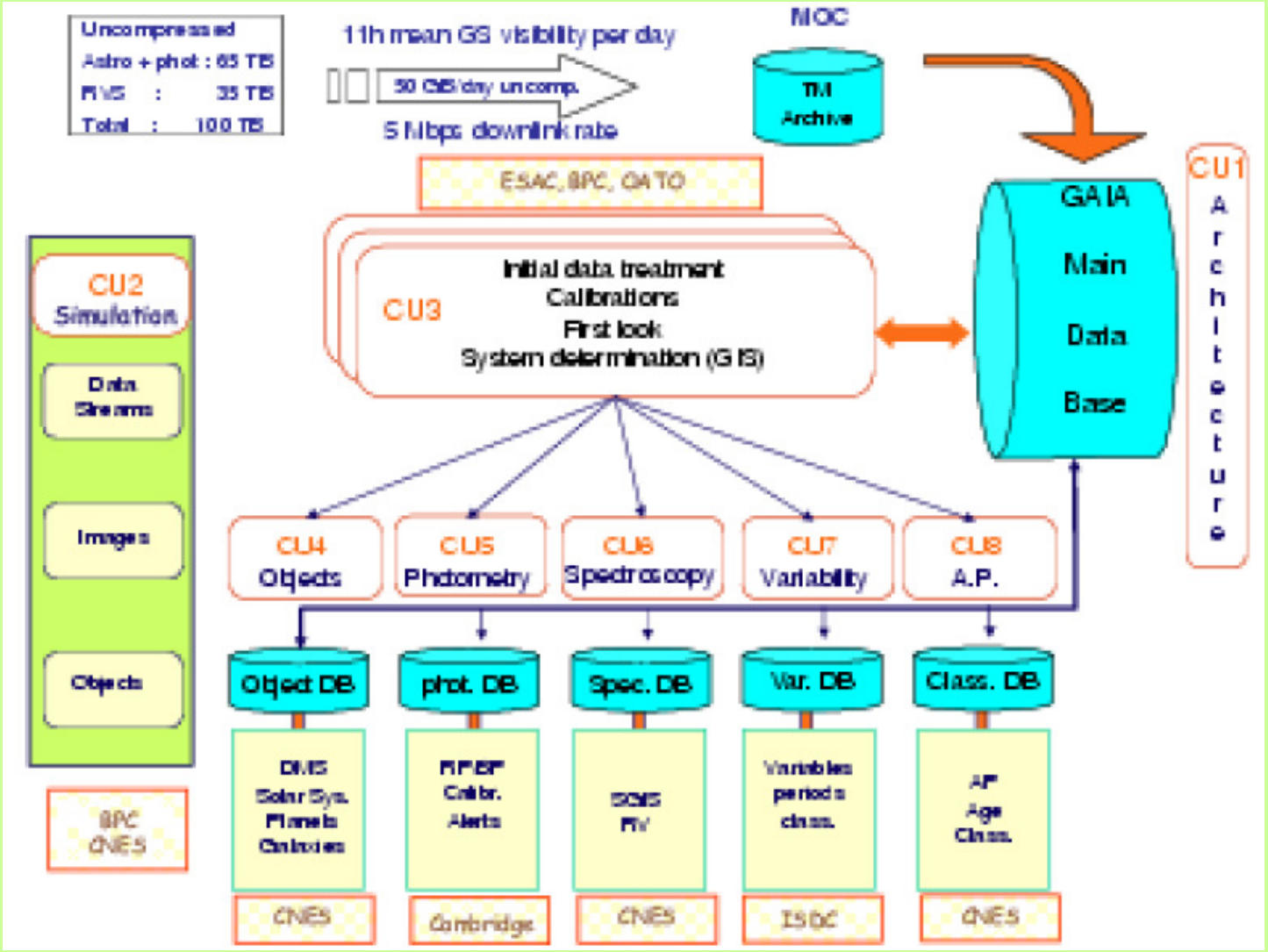
1. 2(was 6) < G < 12: bright-star regime (calibration errors, CCD saturation)
2. 12 < G < 20: photon-noise regime (sky-background and electronic noise at G ~ 20 mag)

gaia

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 chargeloss + bias calibration, sky background, windowing /sampling, magnitude,extinction, spectral type, …

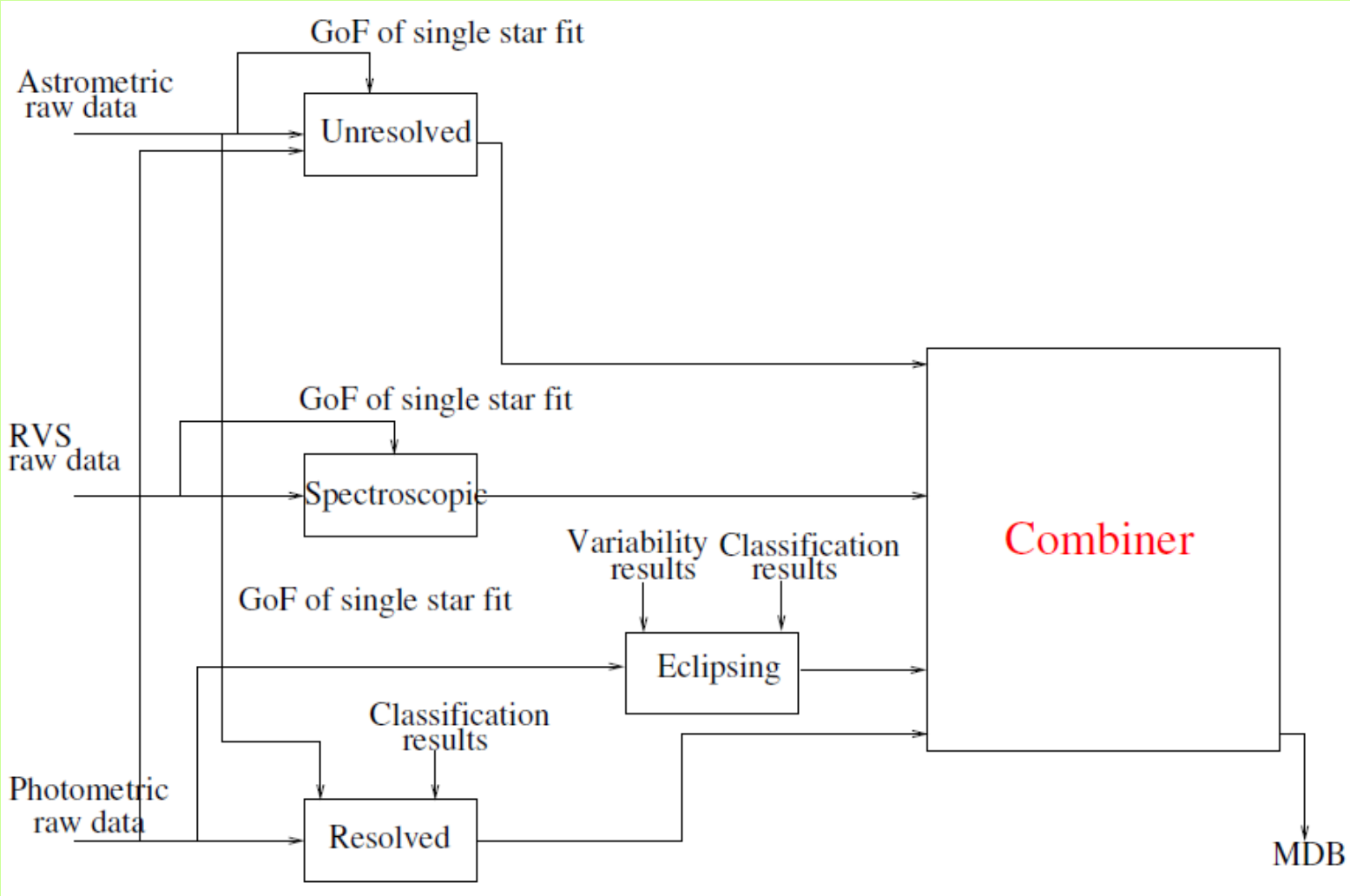

Uncompressed
Astro + phot : 65 TB
RVS : 35 TB
Total : 100 TB
11h mean GS visibility per day
50 GB/day uncomp.
5 Mbps downlink rate
MOC
TM Archive
ESAC, BPC, OATO
CU1 Architecture
GAIA Main Data Base
CU2 Simulation
Data Streams
Images
Objects
BPC CNES
CU3
Initial data treatment
Calibrations
First look
System determination (GIS)
CU4 Objects
CU5 Photometry
CU6 Spectroscopy
CU7 Variability
CU8 A.P.
Object DB
phot. DB
Spec. DB
Var. DB
Class. DB
DMS Solar Sys. Planets Galaxies
PIPEP Calibr. Alerts
DDAS PIV
Variables periods class.
AP Age Class.
CNES
Cambridge
CNES
ISDC
CNES

CU4 NSS WBS

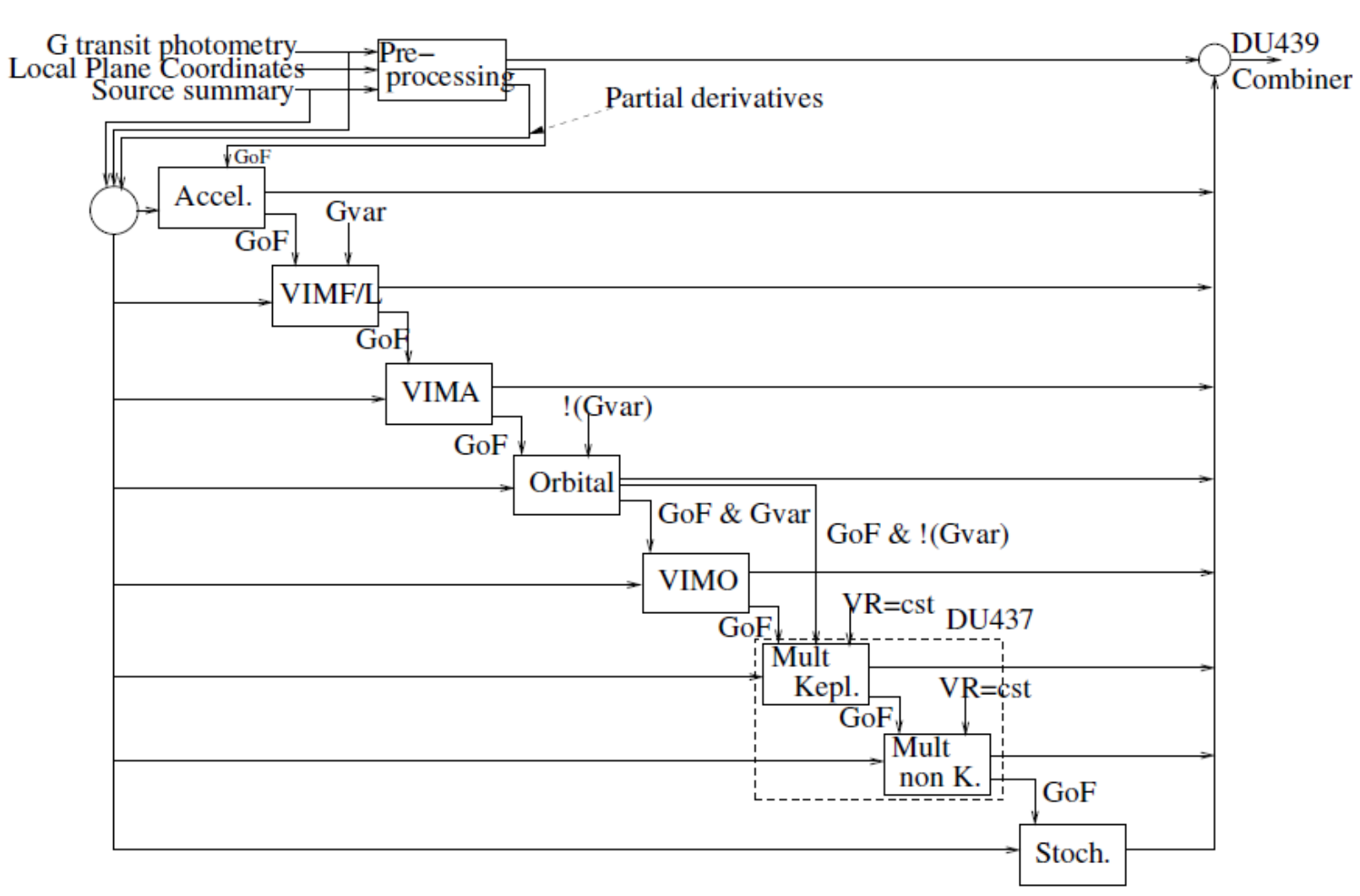
CU4, Object processing, in charge of Non Single Stars. A total of 80 man-years manpower spread over several Development Units:

- DU 432: Unresolved NSS
- DU 433: Resolved NSS
- DU 434: Spectroscopic NSS
- DU 436: Eclipsing
- DU 437: Extrasolar planets
- DU 438: NSS simulation
- DU 439: Solution combiner

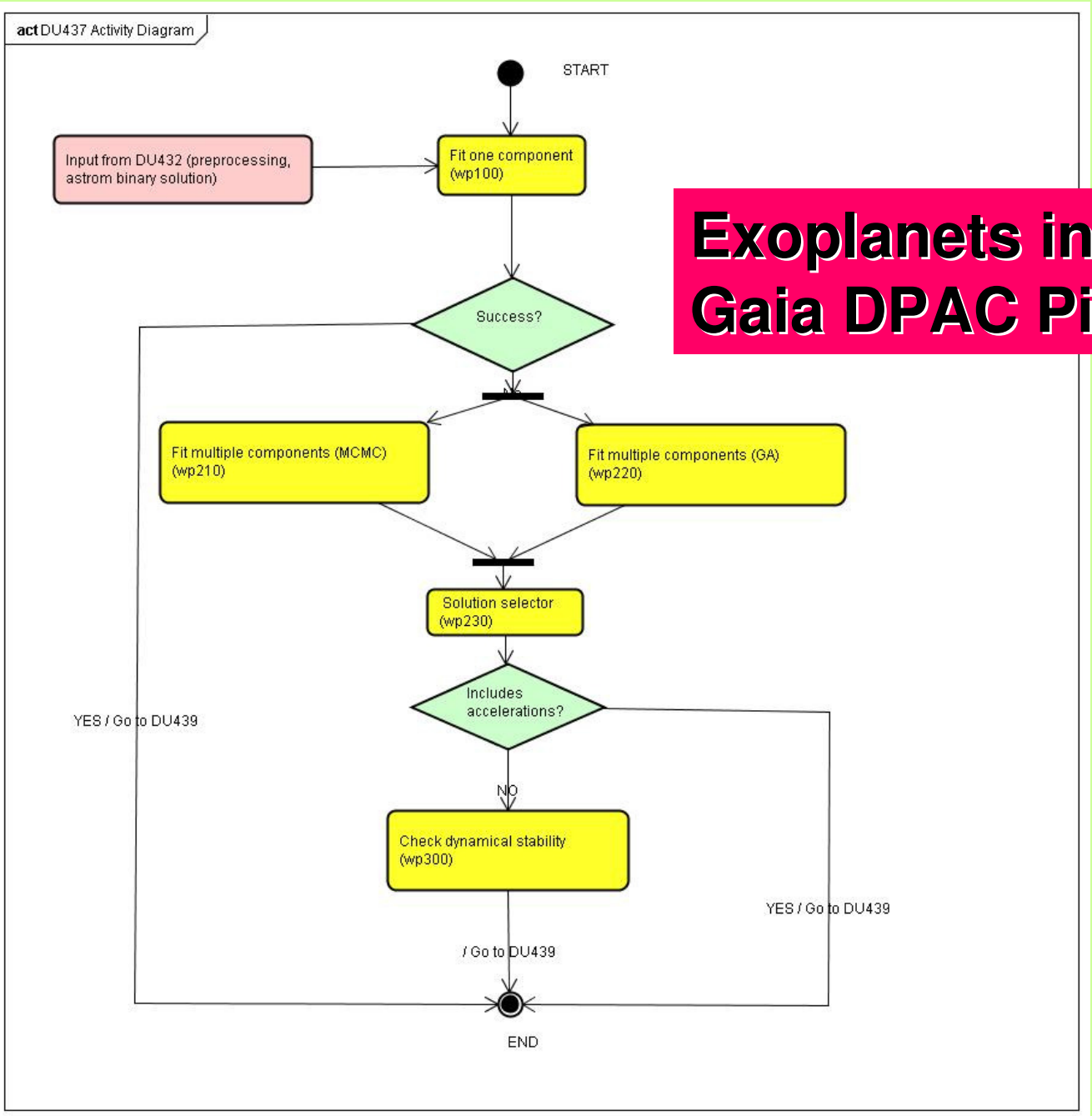
Gaia CU4 – NSS Treatment



Gaia CU4 – Astrometric NSS Treatment



Exoplanets in the Gaia DPAC Pipeline



gaia 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 (1000?) short-period transiting GPs (and maybe ~100 BDs)

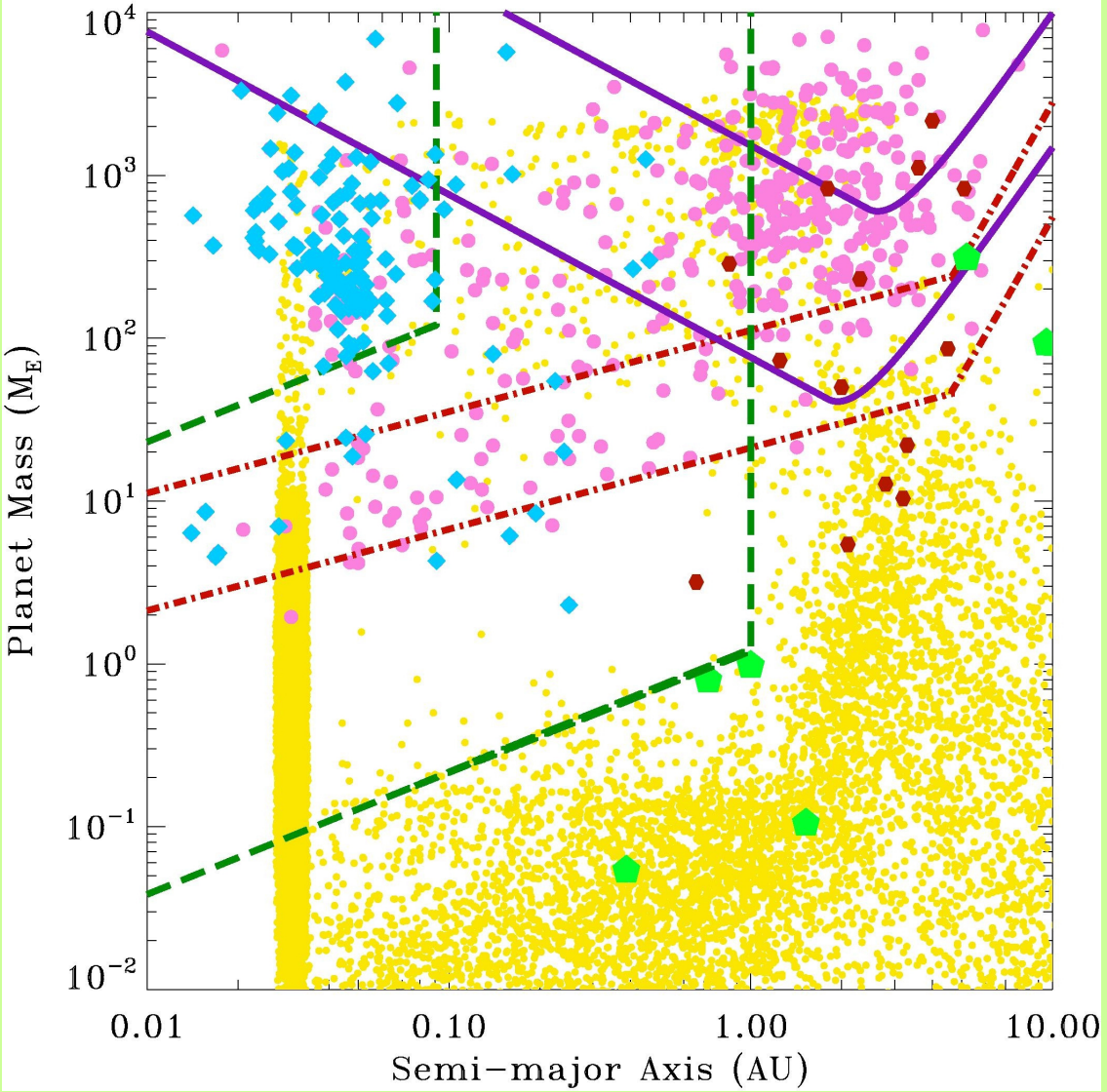
- It may require a dedicated follow-up network

- Confirmation efforts will likely be limited by target brightness (typically, V > 14 mag)

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 ~ 15-20 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

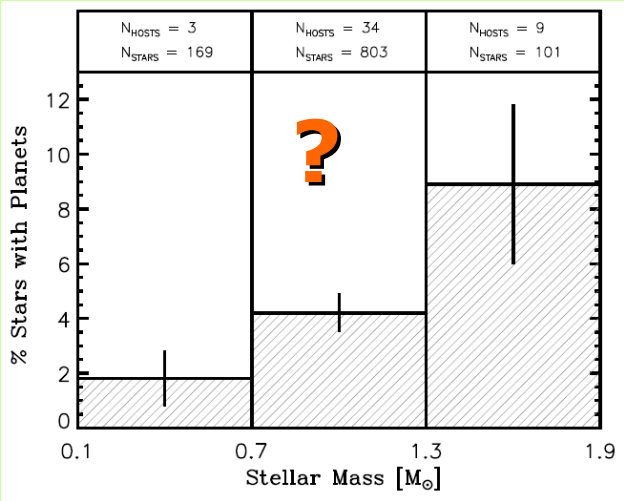
Case	Number of Systems
Detection	~ 1000
Orbits and masses to better than 15-20% accuracy	~ 400 – 500
Successfull coplanarity tests	~ 150

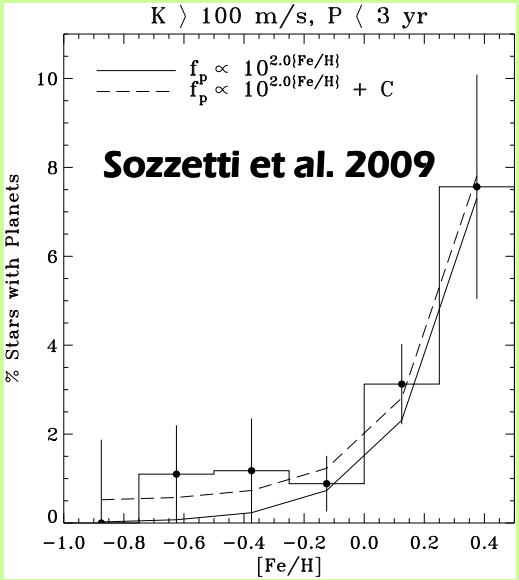
Unbiased, magnitude-limited planet census of hundreds of thousands stars

The Gaia Legacy

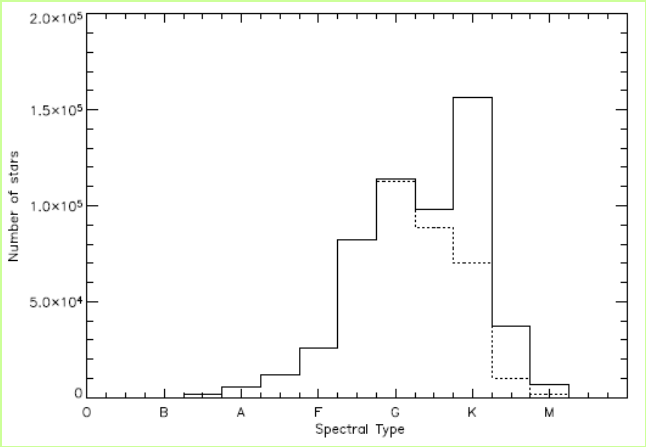
How do Planet Properties and Frequencies Depend Upon the Characteristics of the Parent Stars (also, What is the Preferred Mechanism of Gas Giant Planet Formation?)?

Johnson 2007





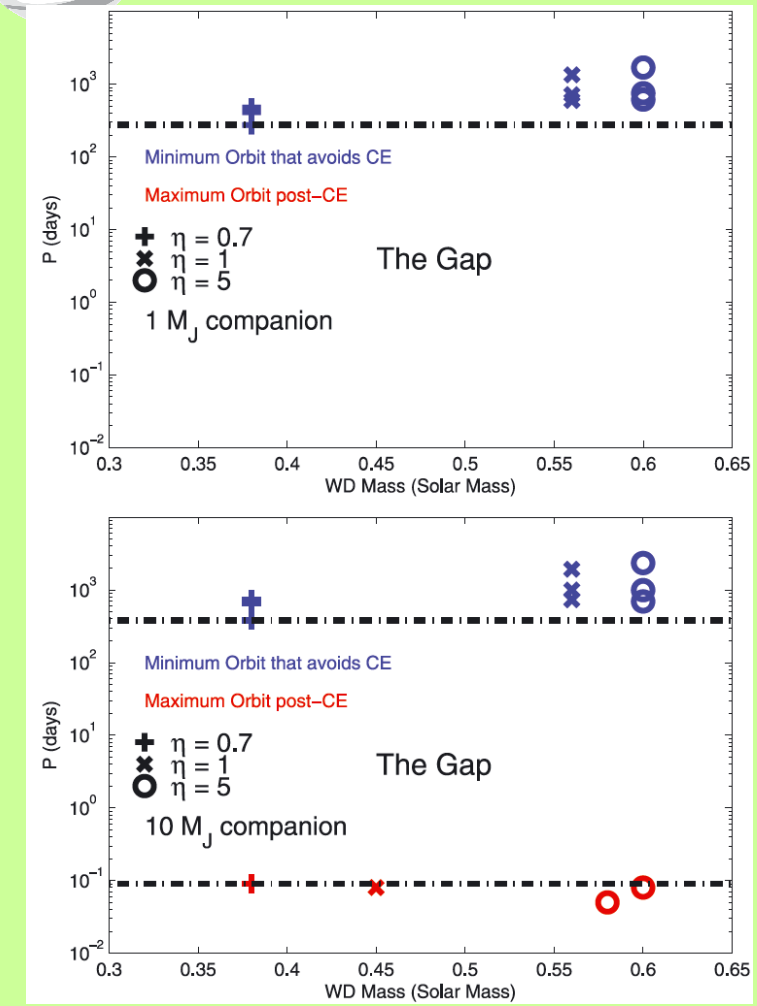
Casertano et al. 2008



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!

Gaia & Post-MS Stars



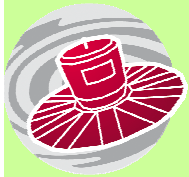
White dwarfs in the solar neighborhood

Good to within a factor 2…

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

Silvotti, Sozzetti, & Lattanzi, AIP

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



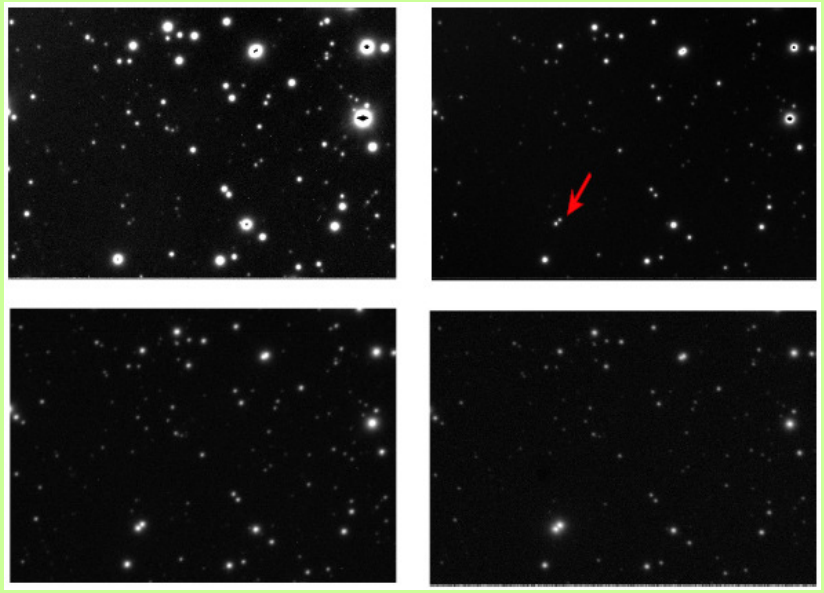
Gaia and the BD Desert

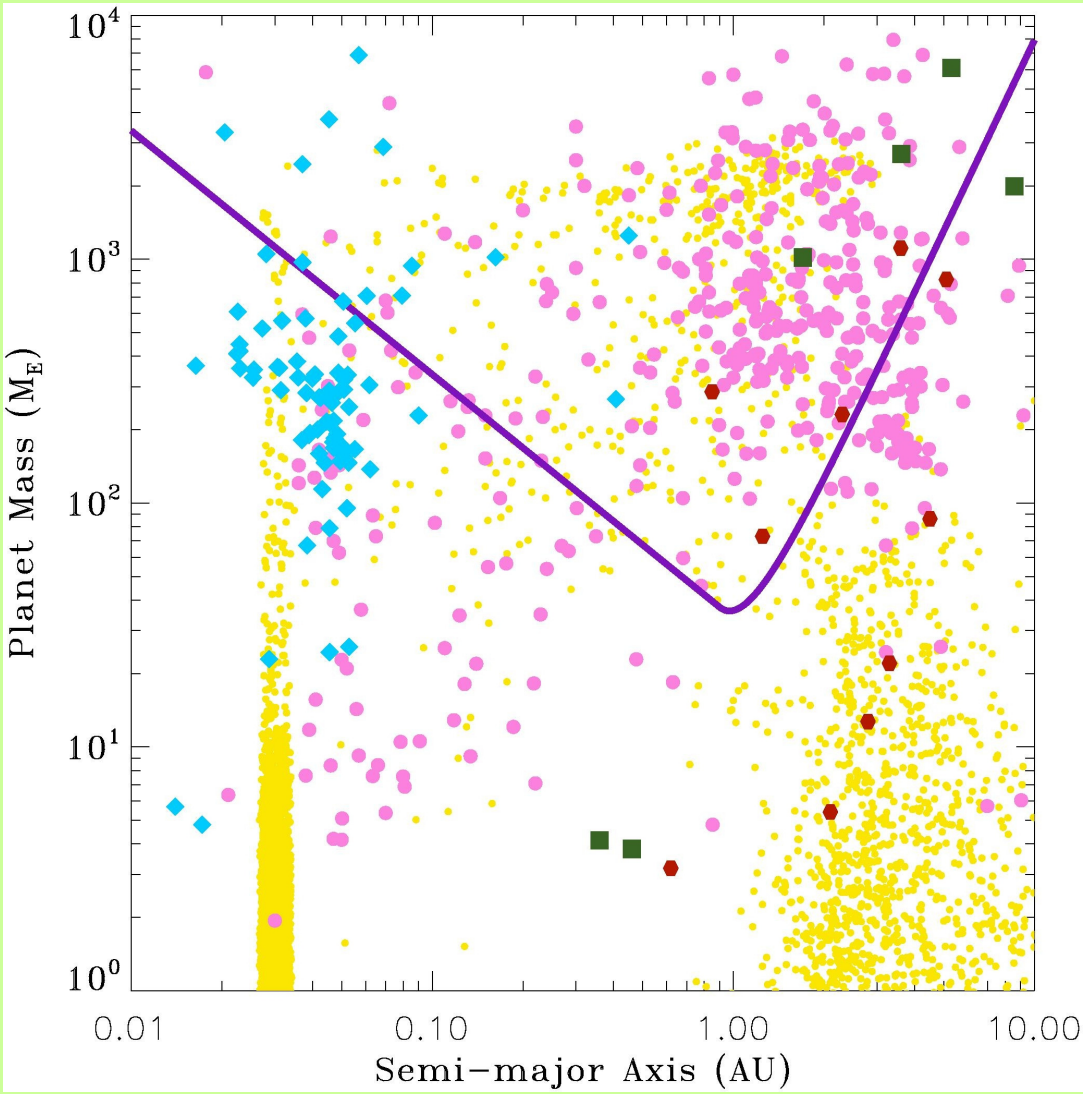
- **Close (a<3-4 AU) BD companions to Sun-like stars are rare (<1%)**
- **Short-period, medium-mass gap, different eccentricity distributions. Evidence for different formation mechanisms?**
- **Occurrence rates have best-case uncertainties of 30% (some 60 objects known)**
- **Gaia will be sensitive to BD companions around ~10^6 stars, up to a 10^4-fold increase in target sample! -> 1000s of detections…**
- **It will completely characterize the BD desert, with fine structure analysis of its dependence on stellar properties (mass, metallicity) -> probe of BD formation mechanism**

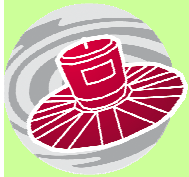
Sozzetti, Mem. Sait in press

gaia

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



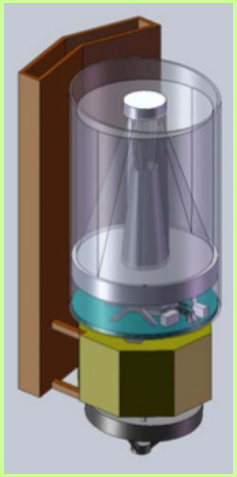


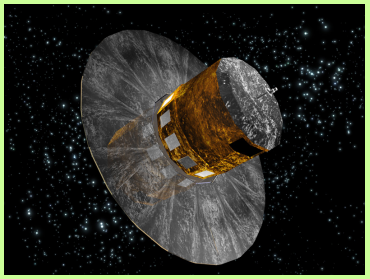


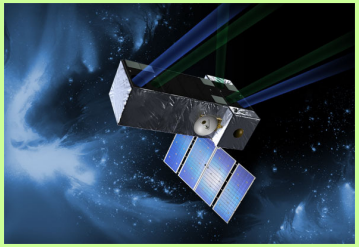
Planets Around BDs

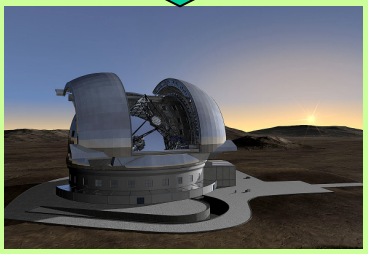
- **Found so far only in microlensing events**
- **Gaia will see ~1000 BDs of all ages (and more if G=21 mag achieved, but beware of stray light!), with sufficient astrometric sensitivity to giant planets within 2-3 AU**
- **A fundamental test of planet formation!**

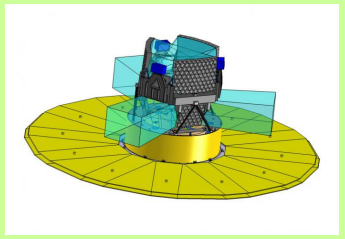
Gaia - Synergies

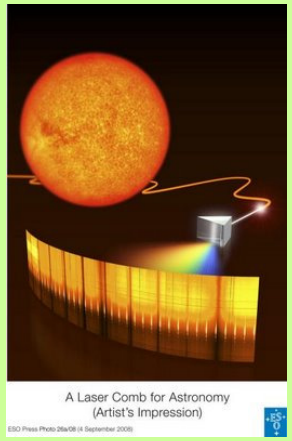












- **Gaia & spectroscopic characterization observatories (e.g., JWST)**
- **Gaia & transit surveys from the ground (e.g., WASP, HAT, MEarth, APACHE, NGTS) and in space (CoRoT, Kepler, TESS, PLATO)**
- **Gaia & direct imaging observatories (e.g., SPHERE/VLT, PCS/E-ELT)**
- **Gaia & RV programs (e.g., HARPS(-N),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

Objectives of study within the GREAT RNP/ITN

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

Gaia & M Dwarfs

- Present-day estimates from RV surveys imply f_p~3-4% (within 3 AU)
- Gaia could identify ~100 giant planets around the Lepine (2005) sample of d<30 pc M dwarfs, an order-of-magnitude increase
- Extrapolations based on Besancon model (d < 100 pc): 2600 detected giants, > 1000 measured with high accuracy. The sample size is such that f_p will be put on much more solid statistical grounds (Sozzetti et al. 2014)
- Very important synergy with present (e.g., HARPS@ESO), starting (e.g., HARPS-N@TNG/GAPS), and upcoming (ESPRESSO@VLT) RV surveys

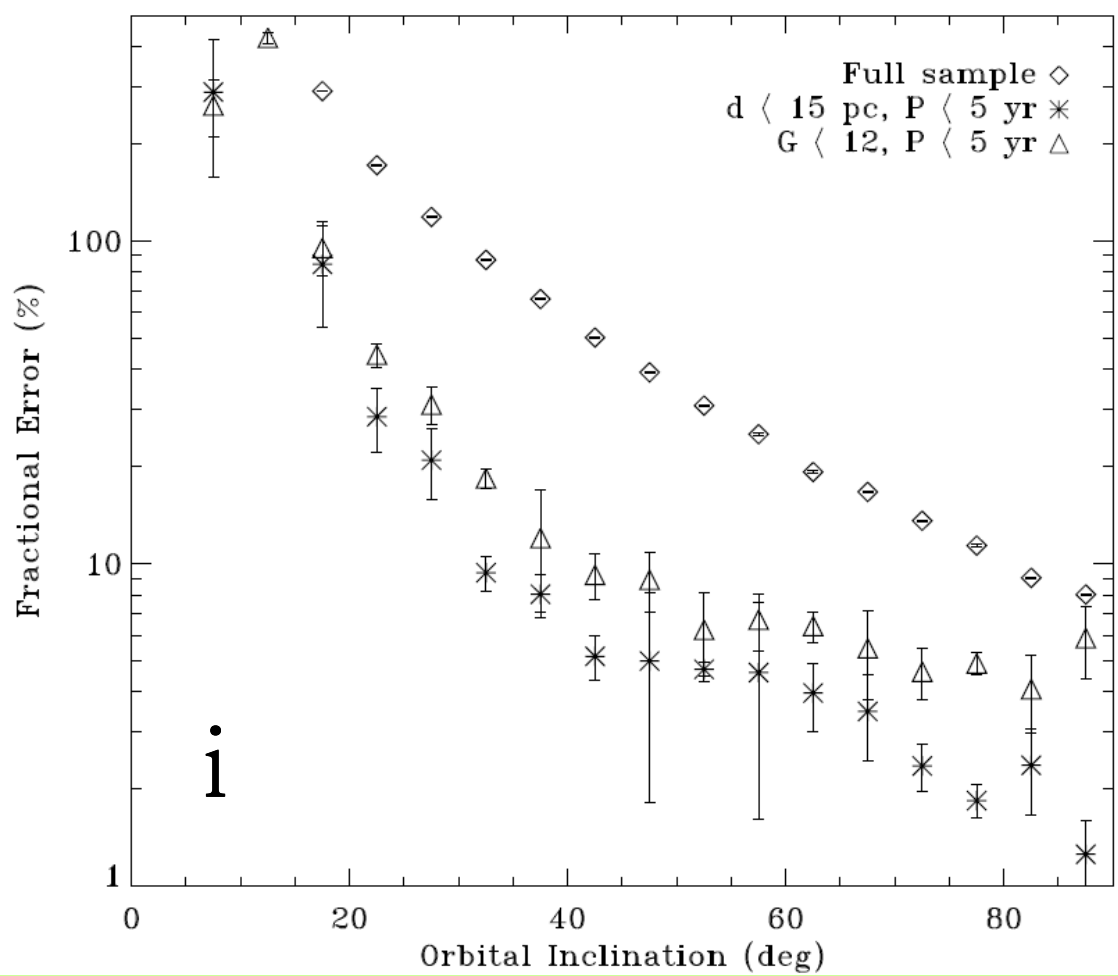
Finding Nearby Transiting Intermediate-Separation GPs

Sozzetti et al. 2014

For well-measured, quasi-edge-on orbits, i is measured 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!

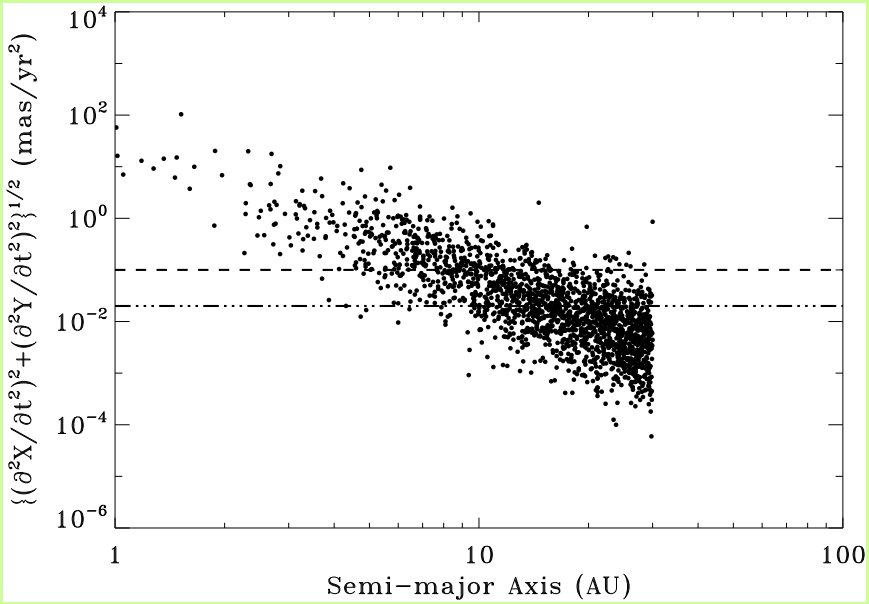


Follow-up efforts, possible targets for JWST

Target Selection

- Revised proper motions of Hipparcos stars available as early as late-2015
- Six months later, >90% of parallaxes for all stars observed by Gaia are delivered…
- Elected primary source of the TESS/PLATO input catalogs of >2x10^6 bright dwarf stars (with negligible contamination from giants)
- Significant reduction in astrophysical false positives (know thy neighbors!)

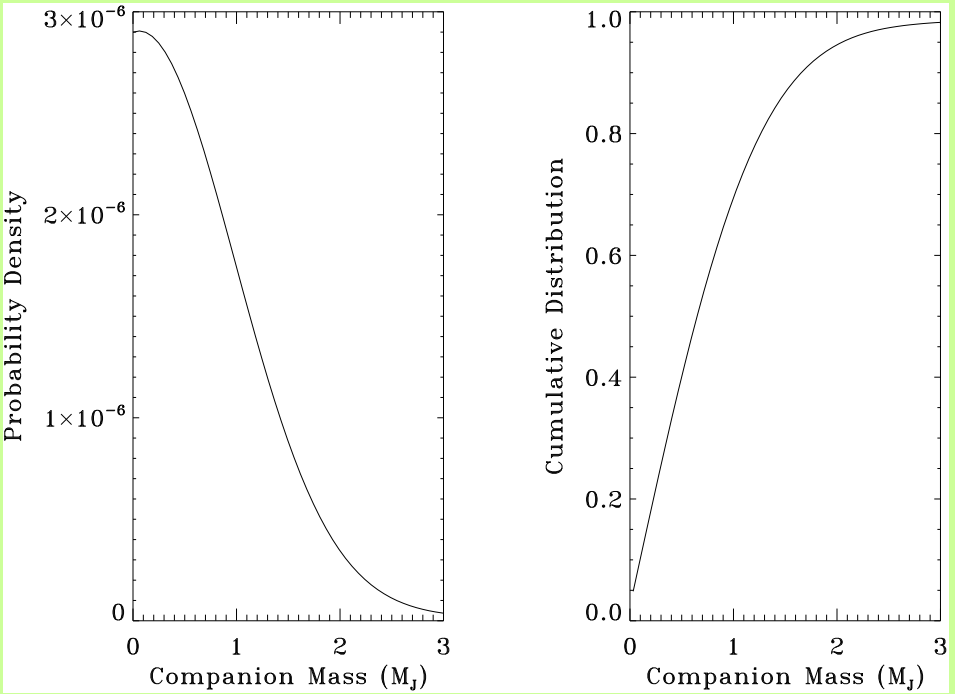
Synergy with Direct Imaging



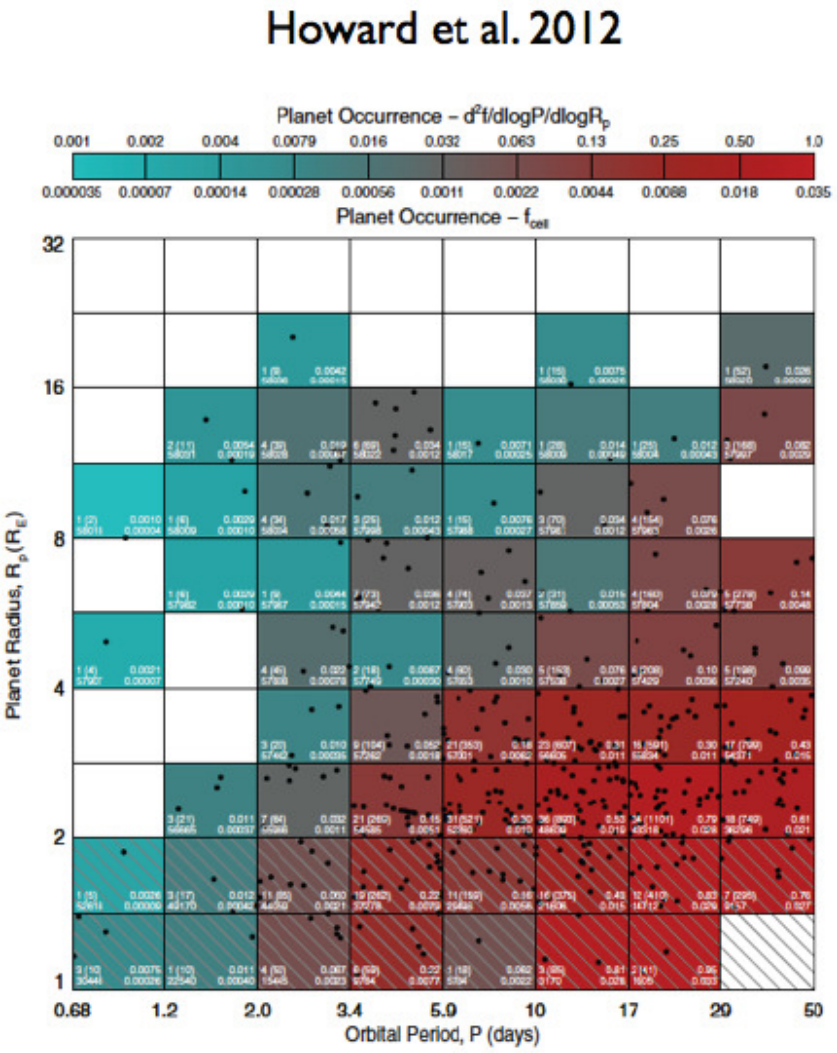
Sozzetti, Bonavita et al. in prep.

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

Estimated mass distribution from Gaia measurements of of the companion to β Pictoris



Gaia – Kepler - HARPS-N



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

*** For a typical target with V<15 at <0.5 kpc, expect σ(π)/π<2-3% from Gaia**

*** Re-calibrate absolute luminosities**

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

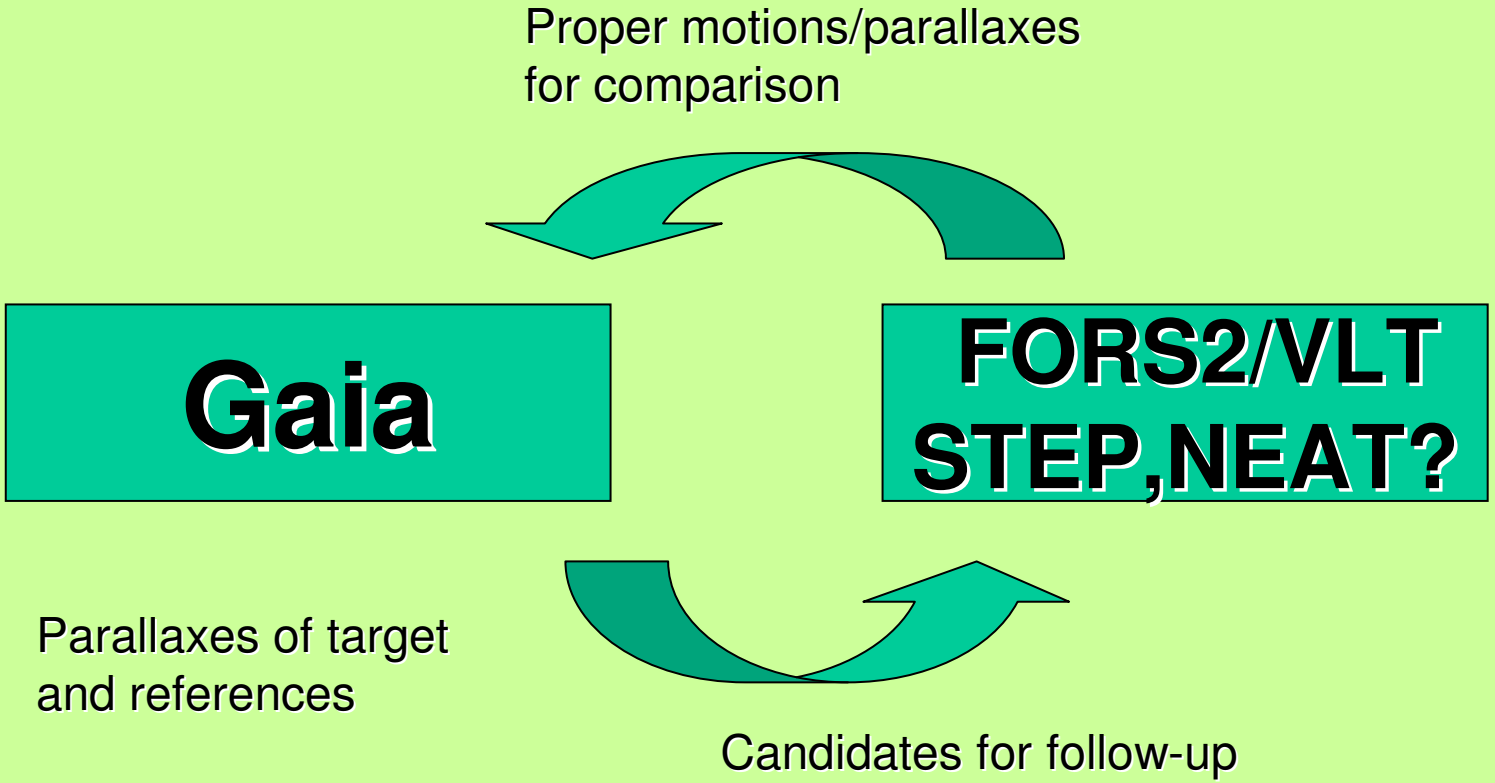
A global statistical re-analysis of planetary properties and frequencies (including $\eta_\oplus$) in the Kepler field as a function of e.g. M_*, [Fe/H]

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

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

OBJECTIVE OF THE FP7-SPACE ETAEARTH PROJECT

Gaia & Ground-Space Astrometry



Combined analyses can profit from large time baseline, particularly when Gaia intermediate astrometry data will become available

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 (orbital architecture, atmospheric) characterization programs from the ground and in space are potentially huge**
- **This was a snippet of the Gaia potential in the exoplanets arena**
- **Gaia's 'first' release: L+22m (Late 2015)**
- **Gaia's 'first' major release: L+28m (Middle of 2016)**
- **Gaia's 'first' complete catalog release: L+40m (Middle of 2017)**