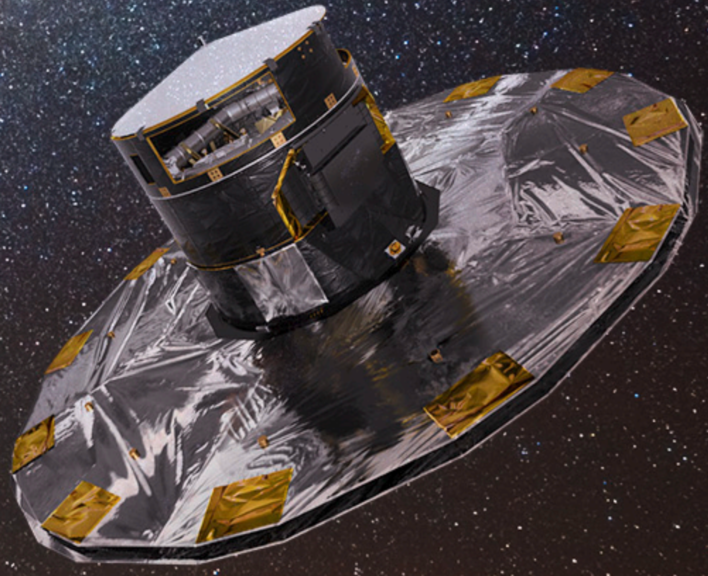
Astrometry & the Promise of Gaia
(Techniques, Challenges, and Science)

Alessandro Sozzetti
(INAF – Osservatorio Astrofisico di Torino)

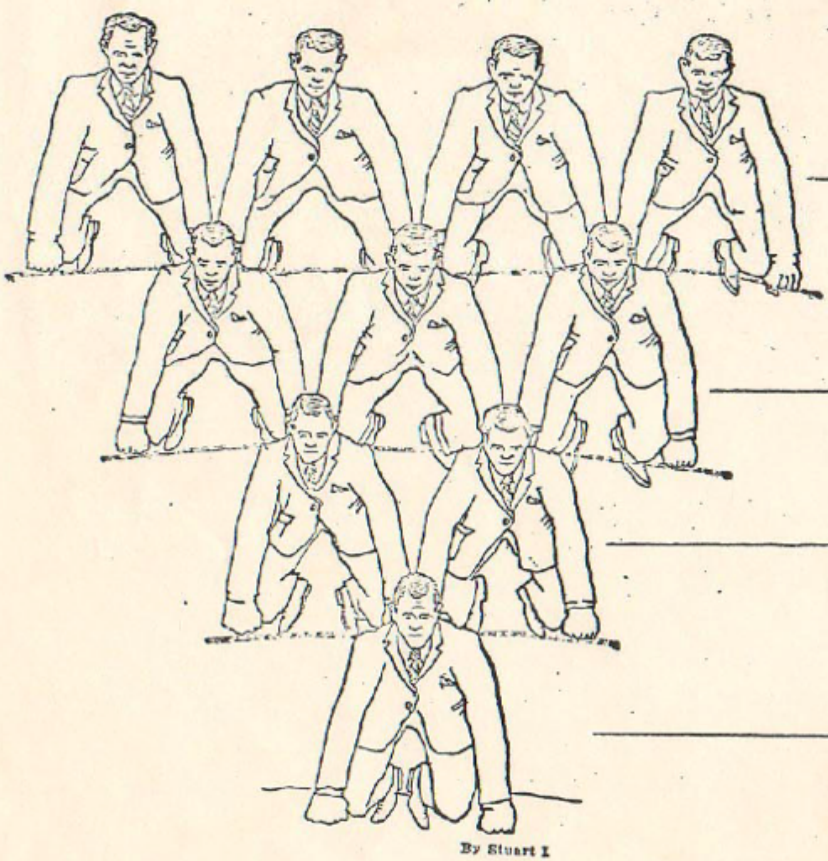


Recommended Readings

1) M.A.C. Perryman,
   'Astronomical Applications of Astrometry', Cambridge University Press
2) W. Van Altena, Ed.:
   'Astrometry for Astrophysics', Cambridge University Press

THE ASTRONOMICAL PYRAMID

ILLUSTRATING THE INTERDEPENDENCE OF THE VARIOUS AREAS OF STUDY



COSMOLOGISTS, GENERAL RELATIVISTS, CRANKS, OTHER FUZZY-BRAINED PENCIL-PUSHERS.

ATMOSPHERES, INTERIORS, INTERSTELLAR MED. THEORISTS

SPECTROSCOPISTS PHOTOMETRISTS

ASTROMETRISTS

GET BACK TO BASICS -- SUPPORT ASTROMETRY

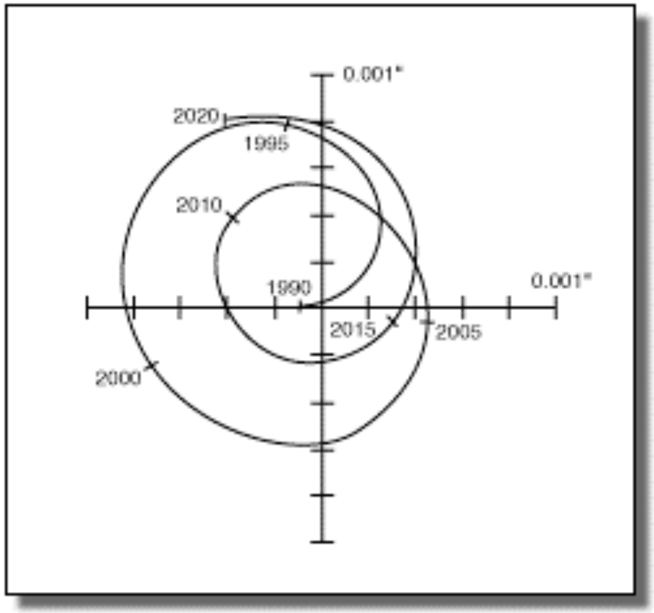
Ron Probst, ca. 1974

Astrometric Signature

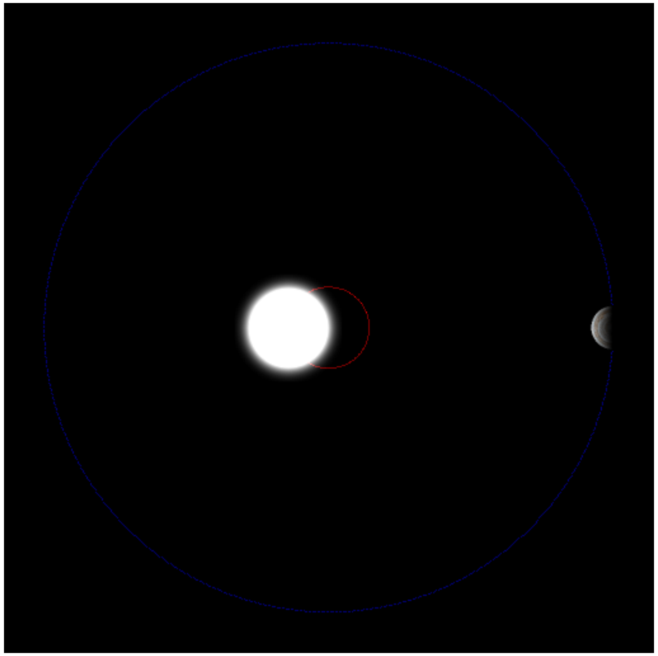
The measured amplitude of the orbital motion (in milli-arcsec) is:

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

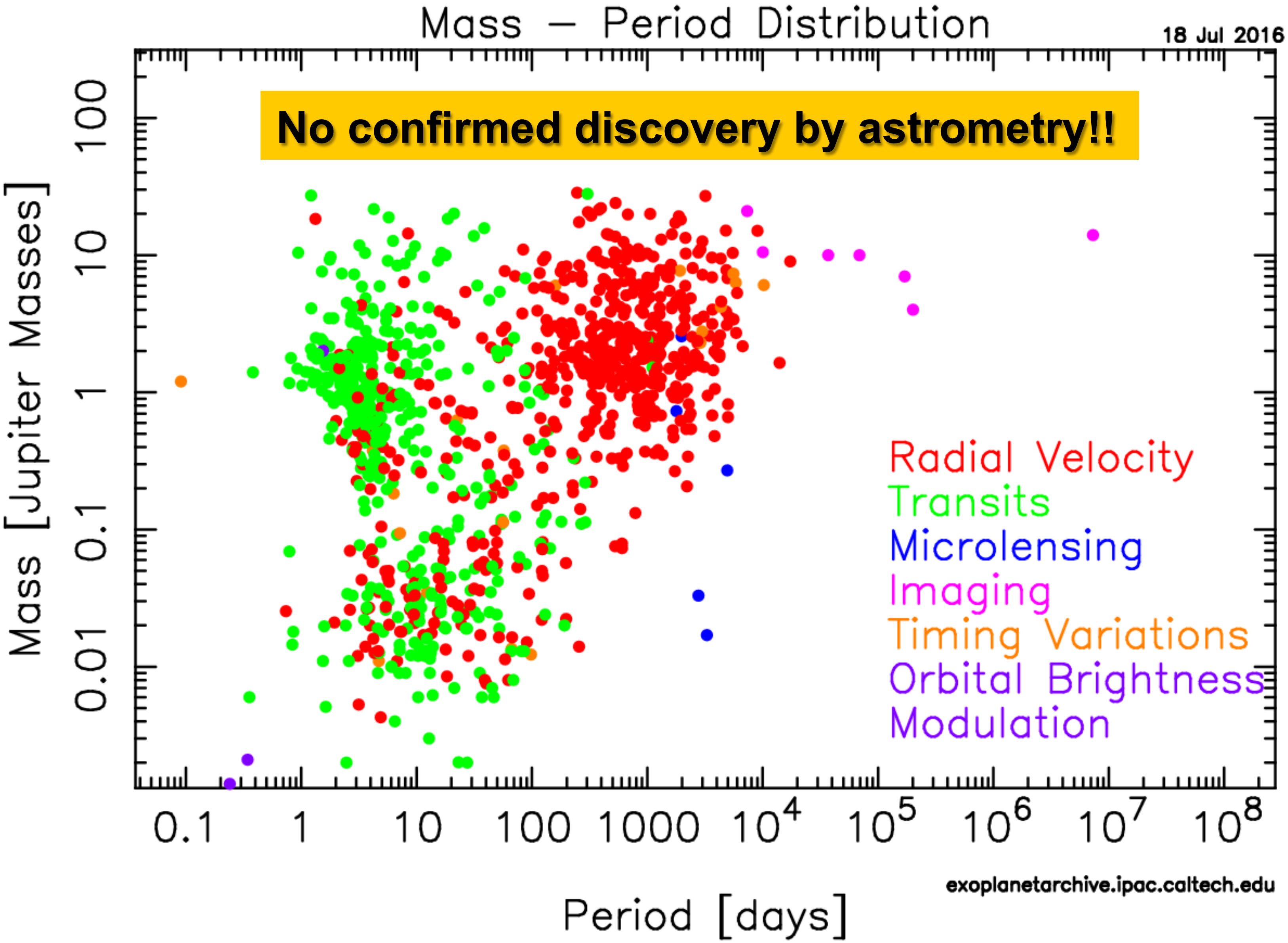
Where $q=M_p/M_*$ -> Given a guess for the primary, one derives the planet's actual mass



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



20+ Years of Exoplanets



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 Jeans[3] 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's[5] binary star collision theory, the probability of the formation of planetary systems is almost nil.

H. K. Sen (Phys. Rev. 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 writes[1] 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 NATURE[2], 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.

Sir J. Jeans (Nature, 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

$$T = 11{\cdot}9\,M \text{ years.}$$

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

H. Alfven, Nobel Prize (Nature, 1943)

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

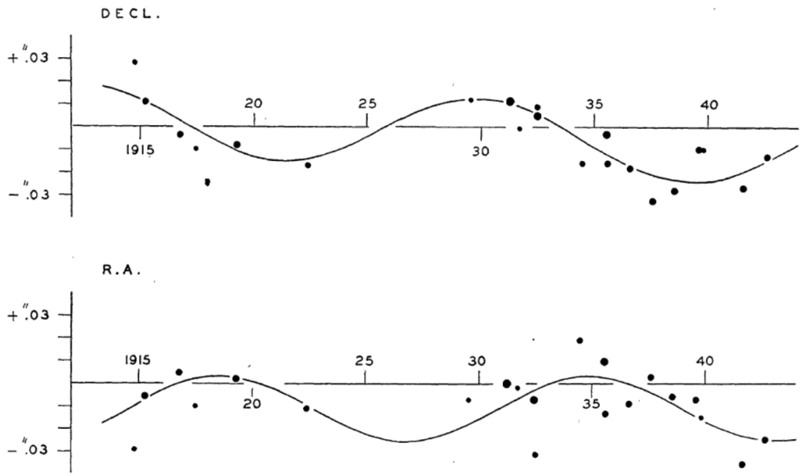
Simulations show that for most study designs and settings, it is more likely for a research claim to be false than true."

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.

A.D. 1952

Astrometry ‘Tragic’ Tale



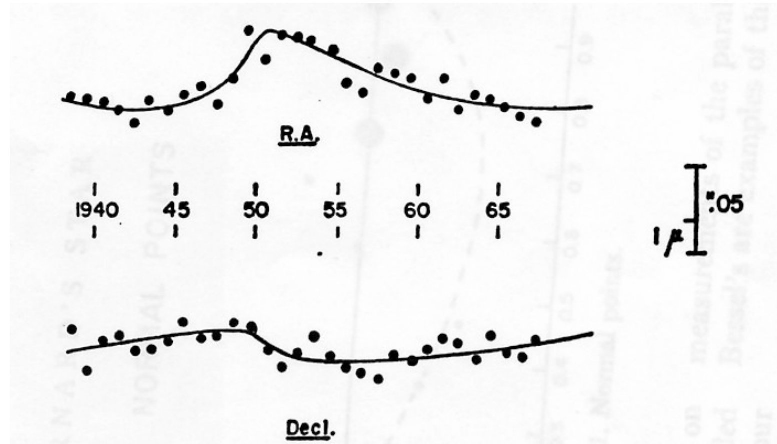
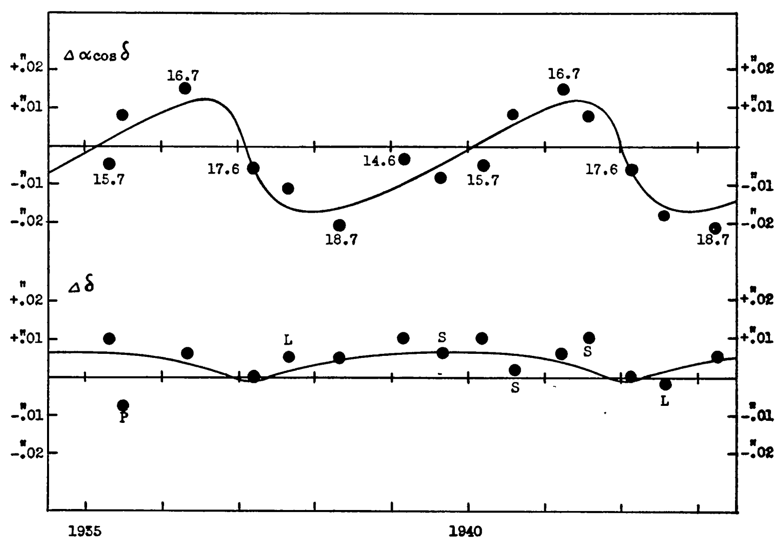


FIG. 1. Barnard’s star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.



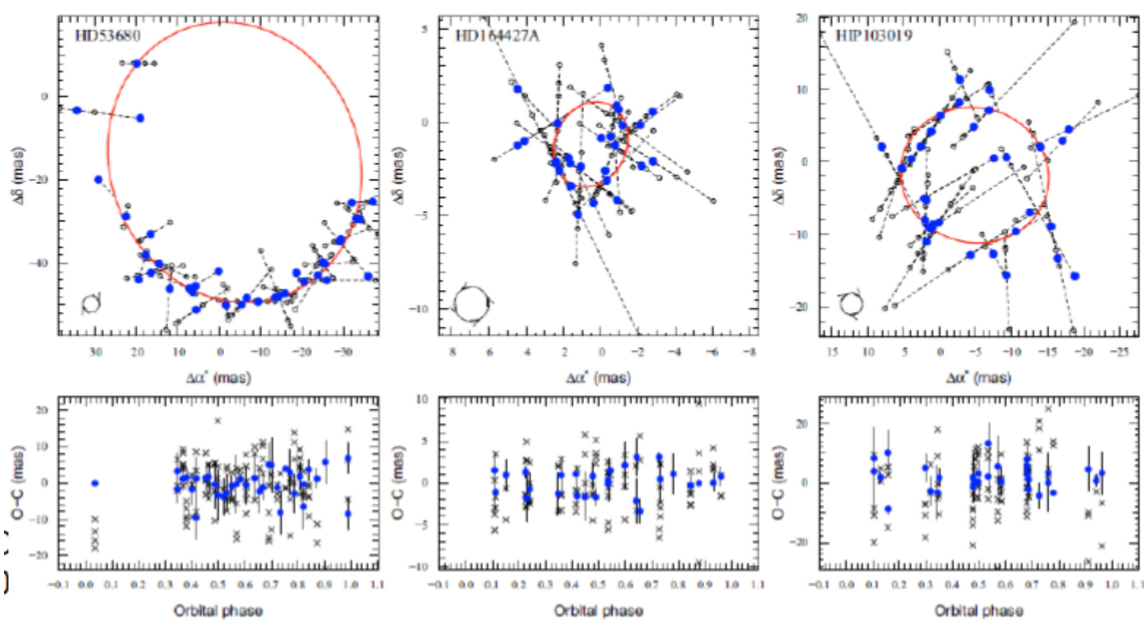
1940’s: Strand, Reuyl & Holmberg (61 Cyg, 70 Oph)
1960’s: Lippincott, Hershey (Lalande 21185)
1960’s-80’s: Van de Kamp (Barnard’s Star)
1980’s: Gatewood (Lalande 21185, again)
2001: Han et al., Gatewood et al. (some 30 RV planets)
2009: Pravdo & Shaklan (VB10b)

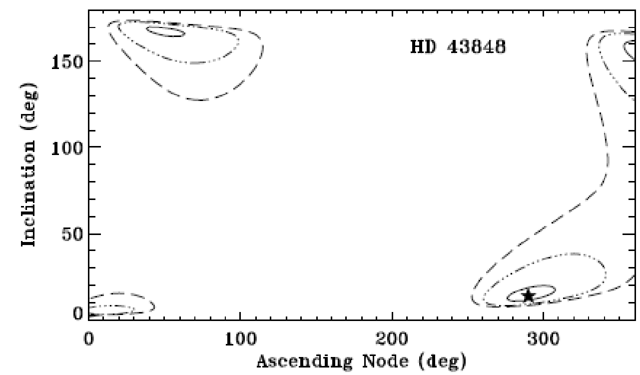
Undisputed (?) Results

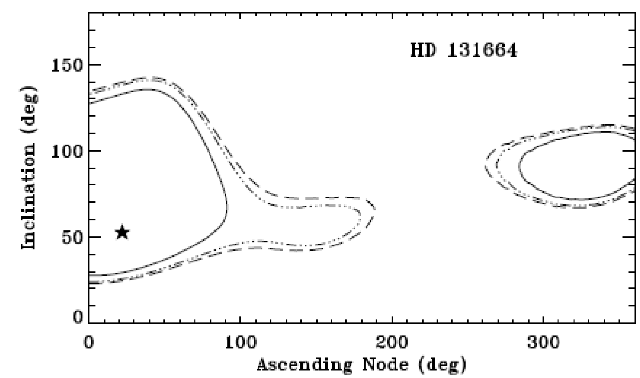
Perryman et al. 1996, Reffert & Quirrenbach 2006, Sozzetti & Desidera 2010, Reffert & Quirrenbach 2011, Sahlmann et al. 2011

Many ~2-3σ upper limits (and some orbits) in the BD and stellar regime

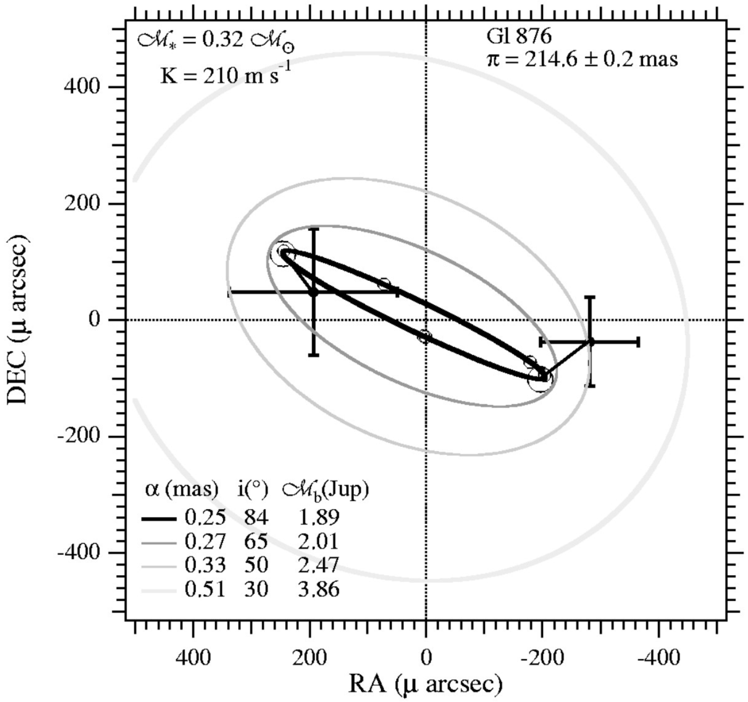
Several 'confirmed' planets at the 2-3σ level



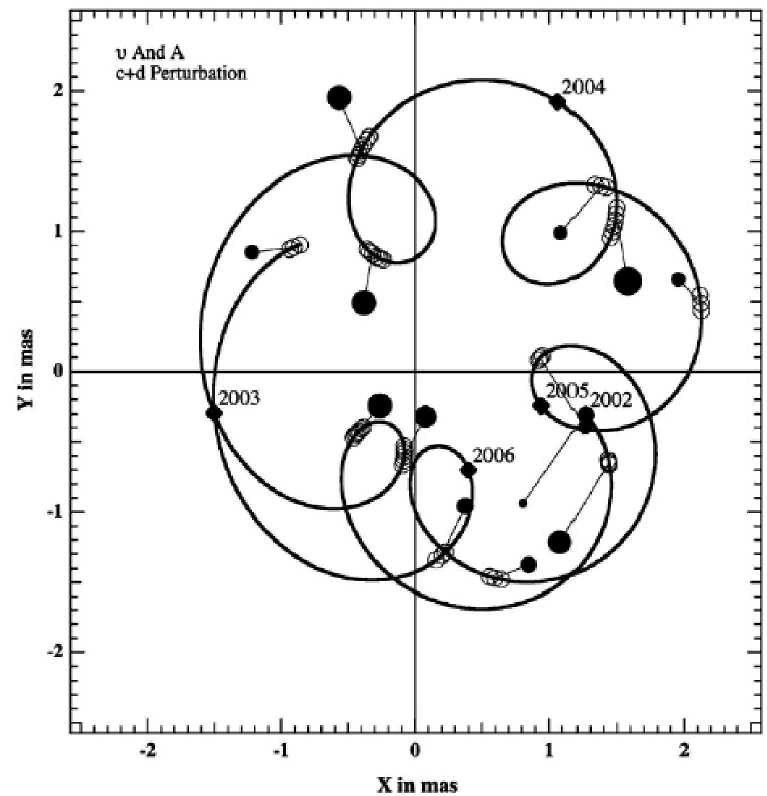




Success: HST Follow-up



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



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

- A mass for GJ 876c
- A mass for ε Eri b
- A mass for HD128311c
- Not a planet but an M dwarf: HD 33636b
- Not planets but brown dwarfs: HD136118b, HD 38529c
- Coplanarity measurement for υ And c,d

Benedict et al. 2002, 2006, 2010, Martioli et al. 2010, McArthur et al. 2010, 2014

PHASES

- The now-completed Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) used phase-referenced long-baseline interferometry to monitor 51 sub-arcsec binary systems with some 100 micro-arcsecond measurement precision

- The PHASES observations have been able to exclude tertiary companions with masses as small as a few Jupiter masses with a < 2 AU in several binary systems (Muterspaugh et al. 2006).

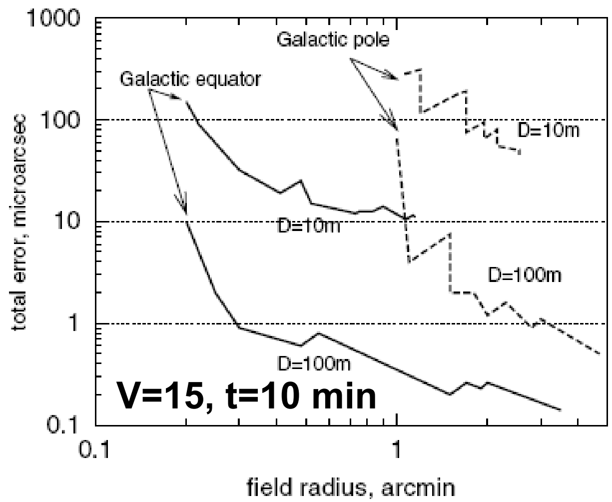
- Muterspaugh et al. (2010) announced 6 candidate substellar companions around PHASES targets, one with a nominal mass of 1.5+/-0.3 M_J and a~2AU.

Utmost caution is conveyed by the team in the paper. The jury is still out!

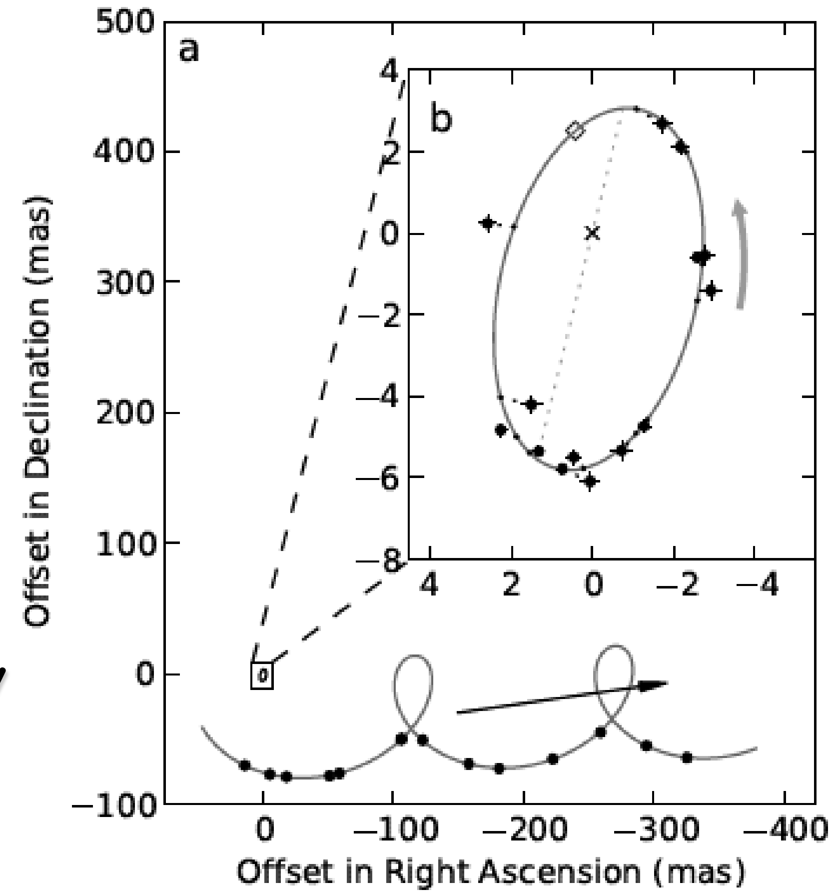
Only Gaia might tell...

VLT/FORS2

AO + symmetrization of the reference frame to remove low-f components of the image motion spectrum and improve image centroid (10-m class required).



Lazorenko 2006



(Sahlmann et al. 2013)

100-200 μas single measurement accuracy allows to detect a low-mass companion to an ultra-cool dwarf:

M ~ 28+/-2 M_J, P=246 d, e=0.34

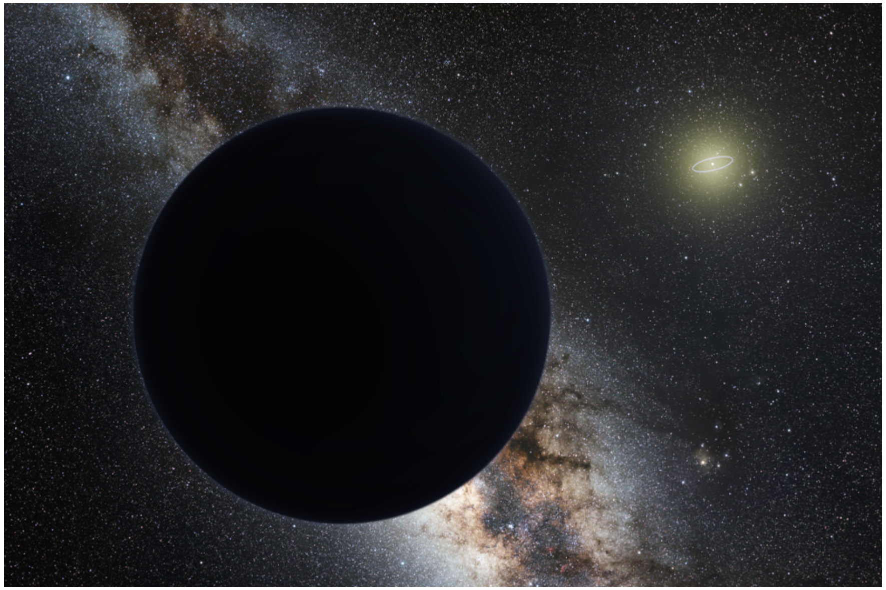
EVIDENCE FOR A DISTANT GIANT PLANET IN THE SOLAR SYSTEM

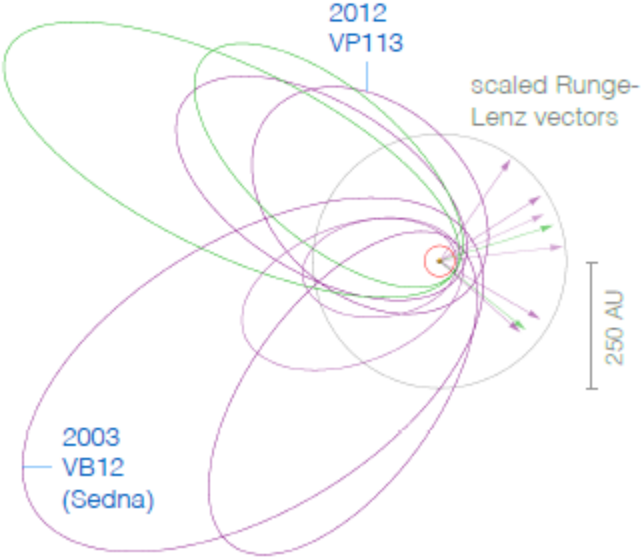
Konstantin Batygin & Michael E. Brown
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125
Draft version January 22, 2016

ABSTRACT

Recent analyses have shown that distant orbits within the scattered disk population of the Kuiper belt exhibit an unexpected clustering in their respective arguments of perihelion. While several hypotheses have been put forward to explain this alignment, to date, a theoretical model that can successfully account for the observations remains elusive. In this work we show that the orbits of distant Kuiper belt objects cluster not only in argument of perihelion, but also in physical space. We demonstrate that the perihelion positions and orbital planes of the objects are tightly confined and that such a clustering has only a probability of 0.007% to be due to chance, thus requiring a dynamical origin. We find that the observed orbital alignment can be maintained by a distant eccentric planet with mass $\gtrsim 10\, m_{\oplus}$ whose orbit lies in approximately the same plane as those of the distant Kuiper belt objects, but whose perihelion is 180 degrees away from the perihelia of the minor bodies. In addition to accounting for the observed orbital alignment, the existence of such a planet naturally explains the presence of high perihelion Sedna-like objects, as well as the known collection of high semimajor axis objects with inclinations between 60 and 150 degrees whose origin was previously unclear. Continued analysis of both distant and highly inclined outer solar system objects provides the opportunity for testing our hypothesis as well as further constraining the orbital elements and mass of the distant planet.

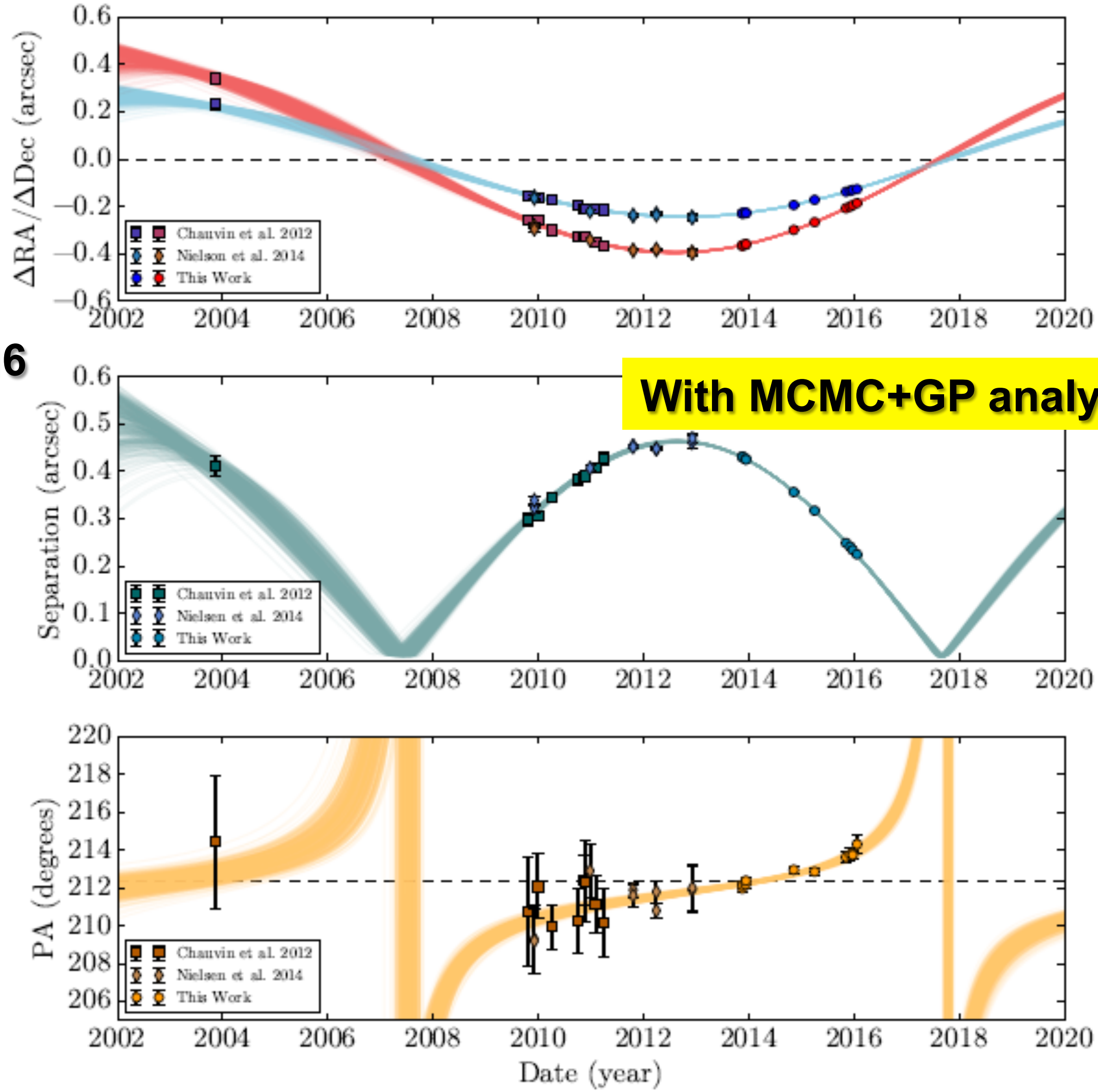
Latest success of mas astrometry: **A Super Earth at 150-250 AU from the Sun??**





Sagan summer workshop 2016 – caltech, 21/07/2016

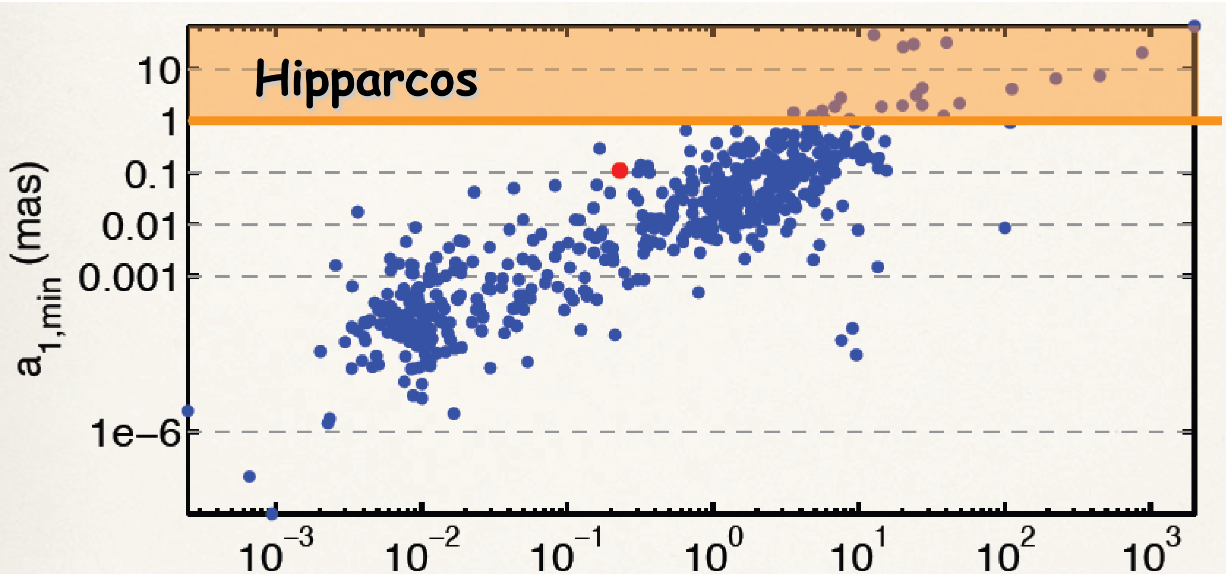
Wang et al. 2016



With MCMC+GP analysis, mind you...

REALLY latest success of mas astrometry: **β Pictoris b will not transit!**

µas 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 (μas)	100
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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

mas-precision astrometry is not enough for planet discovery

Like RV, it faces:

- technol… …t configur…

- astroph…

- data mo… challenges (orbital fits)

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

- Global astrometry: only in space (Gaia)

So What do We Need?

Observable Model

- The angular position of a star as measured by a given instrument in its local frame of reference
- 1-d: Hipparcos, Gaia (one sensitive direction), interferometers (optical path-length difference between the two arms)
- 2-d: two coordinates at the focal plane of the instrument (monolithic telescopes, HST/FGS)

What does it contain?

- Location and motion of the target (and reference stars if applicable)
- Location and motion of the instrument (on the ground), attitude of the spacecraft (in space)
- The number, masses, and orbital parameters of companions to the target (and reference stars, where applicable)
- Any physical effects that modify the apparent positions of stars.

For Hipparcos/Gaia

Sozzetti 2005

$$Z = AS_*.$$

S* = object position in the barycentric frame
Z = object position in the instrument frame
A = 3x3 rotation matrix continuous function of time that specifies the spacecraft attitude

Ground-based Monopupils

Sozzetti 2005

$$r = Mp. \qquad M = \begin{pmatrix} s_1 & s_2 & 1 & 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & s_1 & s_2 & 1 & \dots \end{pmatrix}.$$

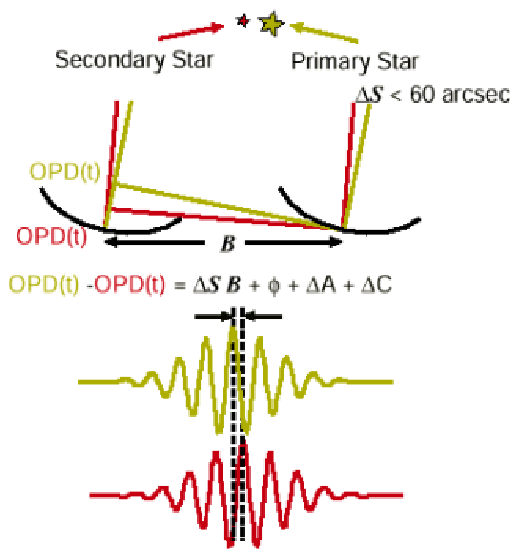
r = 2-d coordinates in the sky
s = 2-d coordinates in the detector frame
p = a column vector containing the plate constants.
A minimum of six is required to describe scale and rotation factors and offsets of coordinate origins between the two frames of reference (but also focal plane tilt and other optical distortion terms, in addition to magnitude dependent terms and color index of the star observed).

Interferometers

In general

$$d_* = B \cdot S_* + C.$$

Sozzetti 2005



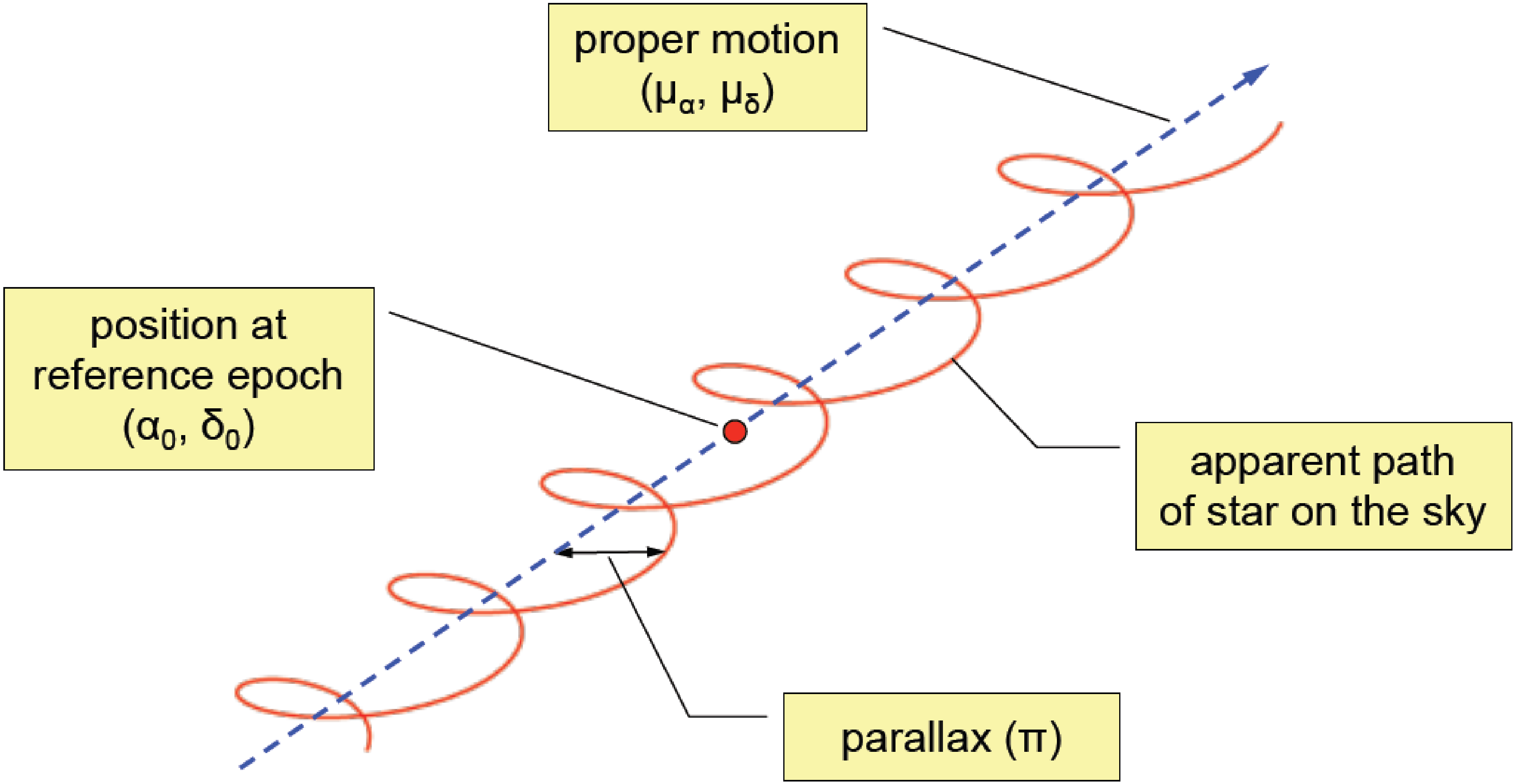
Narrow-angle mode

$$\Delta d_{*,j} = B \cdot (S_* - S_j).$$

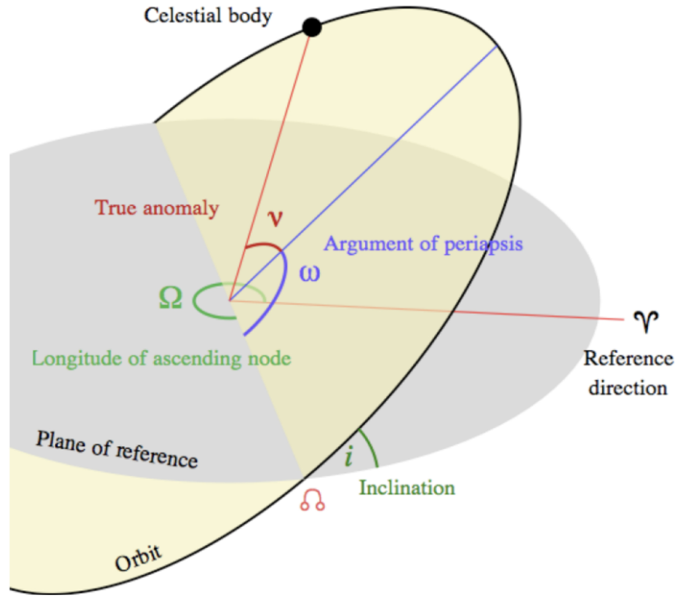
One measures the instantaneous three-dimensional position of the target on the sky projected onto the interferometer baseline:

d_* = optical pathlength delay
B: describes the spacecraft attitude or interferometer motion/location
C: a constant term representing residual internal optical path differences.

First Gotta Model This…



Planet Parameters



Companions to the target object (and reference stars, where applicable) are described in terms of their masses and orbital elements.

The Keplerian orbit of each companion is described by seven parameters: semimajor axis ***a*** with respect to the center of mass of the system, period ***P***, eccentricity ***e***, inclination ***i***, position angle of the line of nodes **Ω**, argument of pericenter **ω**, and epoch of pericenter passage ***τ***.

$$\left.\begin{aligned} a(t) &= a_T + (t-T)\mu_{\alpha*} + f_a(t)\pi + BX(t) + GY(t) \\ d(t) &= d_T + (t-T)\mu_\delta + f_d(t)\pi + AX(t) + FY(t) \end{aligned}\right\}$$

Linear Component

$$\begin{aligned}
\mathrm{T}_1 &= a(\cos\omega\cos\Omega - \sin\omega\sin\Omega\cos i) \\
\mathrm{T}_2 &= a(-\sin\omega\cos\Omega - \cos\omega\sin\Omega\cos i) \\
\mathrm{T}_3 &= a(\cos\omega\sin\Omega + \sin\omega\cos\Omega\cos i) \\
\mathrm{T}_4 &= a(-\sin\omega\sin\Omega + \cos\omega\cos\Omega\cos i)
\end{aligned}$$

Non-Linear Component

$$X = \cos E - e$$

$$Y = \sqrt{1 - e^2}\sin E$$

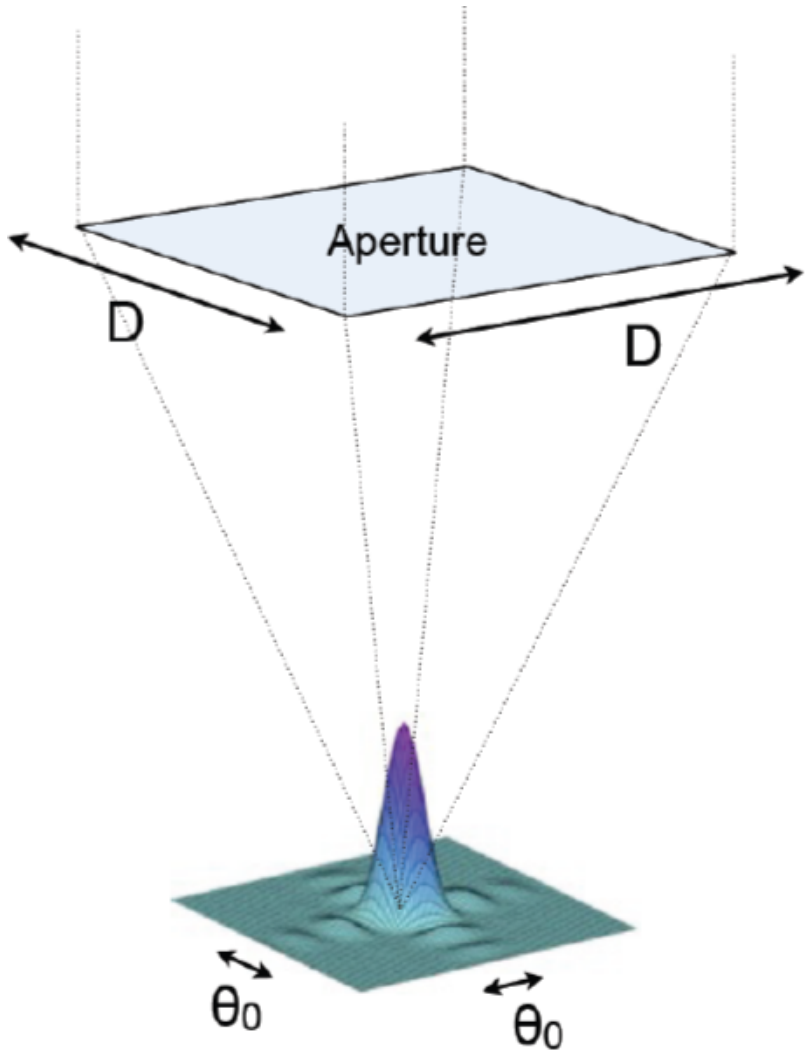
Obtained by solving Kepler's Equation: $E - e\sin E = \frac{2\pi}{T}(t - \tau) \equiv M$

Noise Model

- Astrometric data contain correlated and uncorrelated instrumental, atmospheric (if operating from the ground), and astrophysical noise

- The noise model describes these uncertainties for use in the estimation process

The Fundamental Diffraction Limit



$$\sigma_\theta = \frac{\sqrt{3}}{2\pi}\frac{\lambda_{\rm eff}}{D}\frac{1}{\sqrt{N}}$$

$$N \propto D^2 \times T \times \Delta\lambda$$

$$\sigma_\theta \propto \lambda_{\rm eff}\,\Delta\lambda^{-1/2}\,D^{-2}\,T^{-1/2}$$

Example:

Resolution

$D = 1$ m
$\lambda_{eff} = 500$ nm
$\} \Rightarrow \theta_0 = 0.1$ arcsec

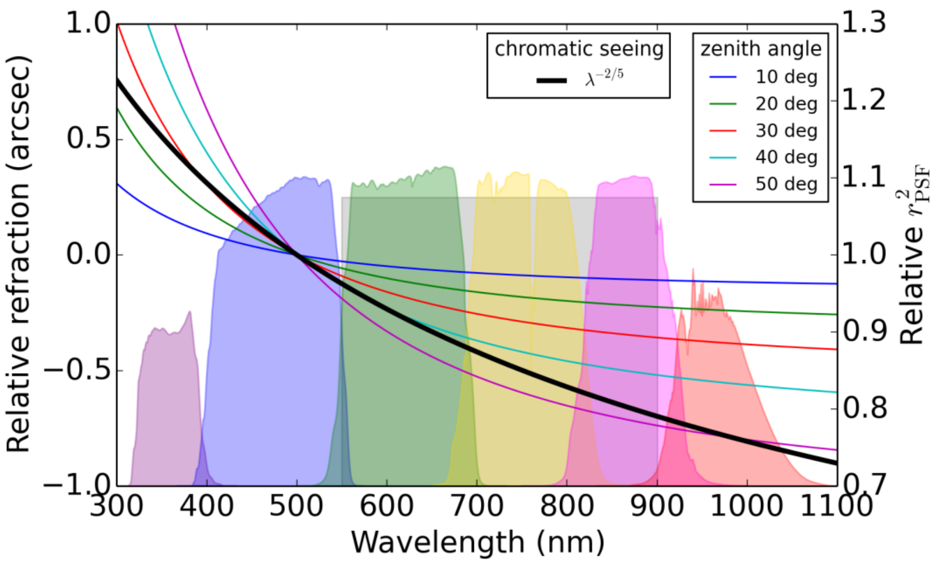
$\Delta\lambda = 200$ nm
$T = 100$ s
$V = 15$ mag
$QE = 0.5$
$\} \Rightarrow \{$ $N = 10^6$, $\sigma_\theta = 30$ μas

Credits: L. Lindegren

Differential Chromatic Refraction

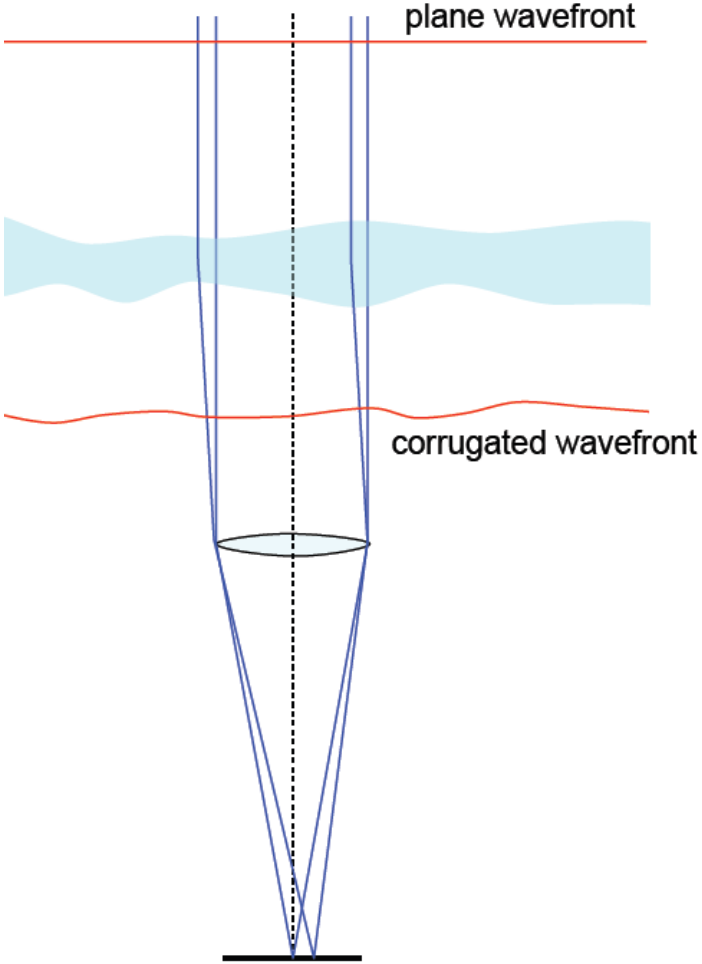
- Refraction itself is not a problem if it's the same for all stars
- But if it's different for individual stars, it matters!
- DCR depends on the color of the star -> need to correct for that
- Need temperature, pressure, humidity, and star color
- Easier to correct for smaller bandpass -> use narrow filters
- Also, size of DCR wavelength dependent
- Often the limiting factor for ground-based astrometry!

Credits: S. Reffert



$$\sigma_{\mathrm{DCR}} \approx 1\text{–}3\ \mathrm{mas}$$

Atmospheric Limitations



Kolmogorov's theory of turbulence (1941) and the phase-screen approximation gives the statistics of wavefront errors:

$$\left\langle \left| W(\boldsymbol{r}+\boldsymbol{\Delta r}) - W(\boldsymbol{r}) \right|^2 \right\rangle = C|\boldsymbol{\Delta r}|^{5/3}$$

Lindegren (1980) derived relations for the time-averaged RMS deviation:

$$\sigma_\theta \simeq 0.24'' \, T^{-1/6} \quad (T \text{ in s})$$

and the RMS relative deviation:

$$\sigma_{\Delta\theta} \simeq 0.06'' \, \theta^{1/3} \, T^{-1/2} \quad (\theta \text{ in arcmin})$$

Credits: L. Lindegren

e.g.: θ = 10 arcsec, T = 1000 s ⇒ $\sigma_{\Delta\theta}$ = 0.001 arcsec (1 mas)

Use various tricks (AO, multi-λ obs., refs. choice) to improve by up to a factor 10

Other Systematic Errors

Monolithic Configurations

Sozzetti 2005

$$\sigma_{\rm sys} = \sqrt{\sigma^2_{\rm CCD} + \sigma^2_{\rm OP}}.$$

State-of-the-art: centroiding to 1/100 of a pixel, Gaia strives to do <1/500 of a pixel

For Gaia: σ_{sys} = 15-20 μas

Diluted Configurations

Sozzetti 2005

$$\sigma_{\rm sys} = \sqrt{\sigma^2_1 + \sigma^2_B}. \qquad \sigma_1 = \delta l/B \qquad \sigma_B = (\delta B/B)\vartheta$$

The most critical element: calibration errors from the monitoring of the OPD

For GRAVITY: σ_{sys} = 50-100 μas

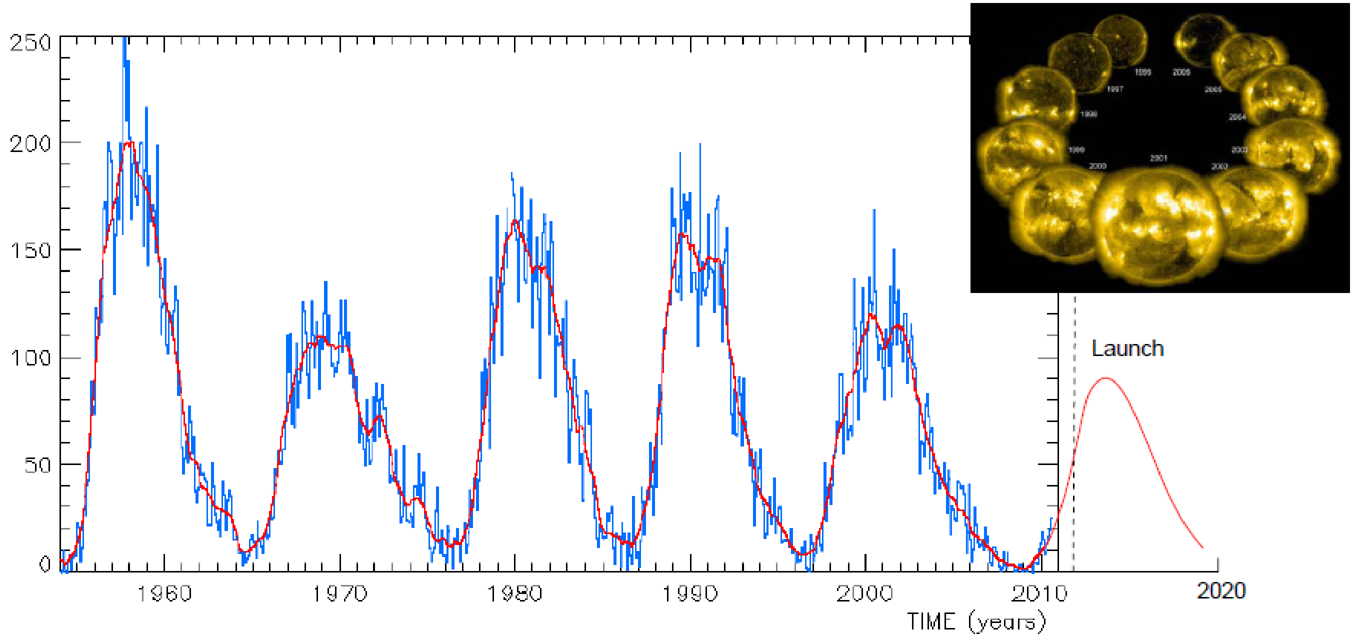
And MORE….

- Additional random and systematic error sources that are introduced by the satellite operations and environment must be taken into account: **Attitude Errors**

- **Attitude errors** can occur due to perturbations produced by the **solar wind, micrometeorites, particle radiation, and radiation pressure. Thermal drifts and spacecraft jitter** can also induce significant errors in attitude determination.

- **Very hard to quantify a priori in a general fashion. Detailed error models must be developed case by case**

… and MORE: 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%

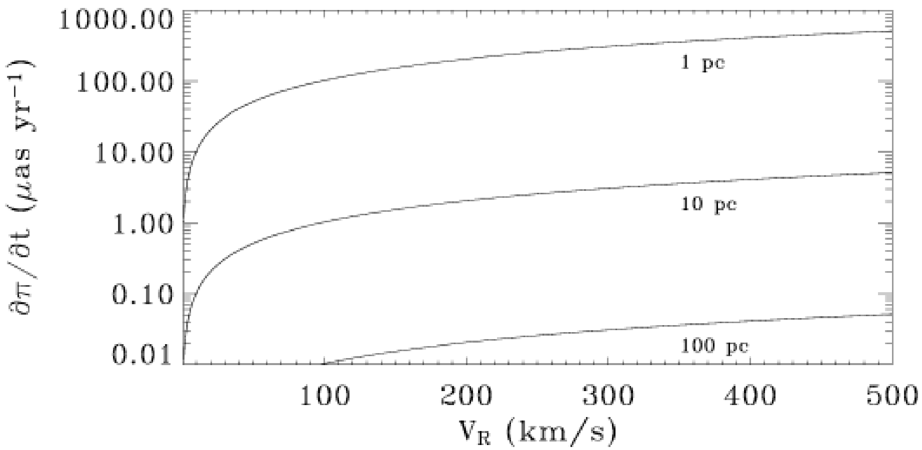
Astrophysics: ‘Effects’ and ‘Noise’

- Secular changes in the target motion (perspective accelerations)
- Relativistic corrections due to:
  a) the observer's motion (aberration) and
  b) the gravitational fields in the observer's vicinity (light deflection)
- Astrophysical ‘jitter’ intrinsic to the target (e.g., spots), and due to environment (disks, stellar companions)

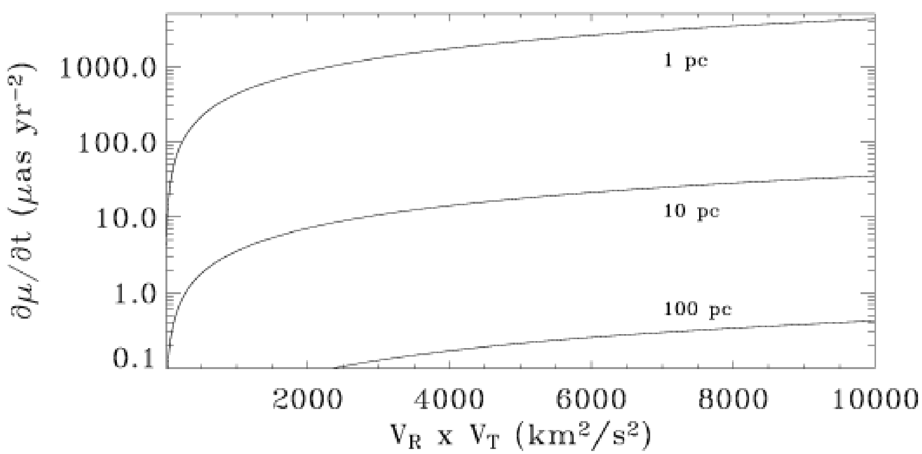
Secular Changes: μ and π

$$\frac{d\mu}{dt} = -\frac{2v_r}{\mathrm{AU}}\mu\pi,$$

$$\frac{d\pi}{dt} = -\frac{v_r}{\mathrm{AU}}\pi^2.$$



Sozzetti 2005



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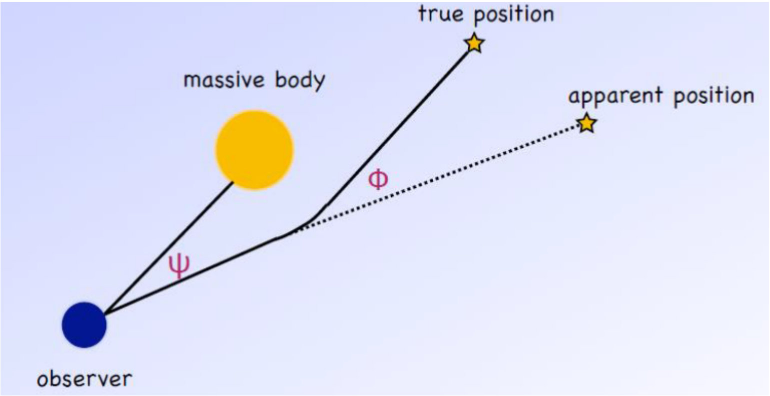
NOTE.—A 1 $M_\odot$ star at 10 pc is assumed.

Light Deflection



$$\alpha_{\mathrm{defl}} = \frac{(1+\gamma)GM}{R_0 c^2} \cot \frac{\psi}{2} ,$$

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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.

TABLE 2
RELATIVISTIC LIGHT-DEFLECTION EFFECTS OF VARIOUS SOLAR SYSTEM OBJECTS

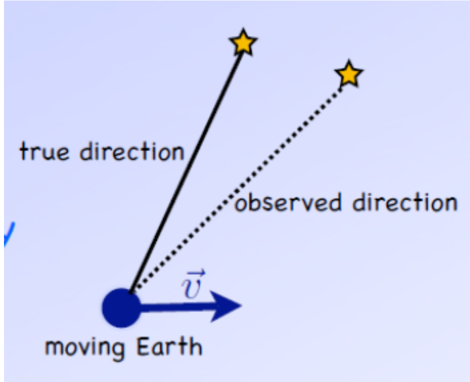
Source	α (μas)	δ_{min} (1 μas)
Sun	1.75×10^6	180°
Mercury	83	9′
Venus	493	4°.5
Earth	574	178°/123°
Moon	26	9°/5°
Mars	116	25′
Jupiter	16,270	90°
Saturn	5780	17°
Uranus	2080	71′
Neptune	2533	51′
Ganymede	35	32″
Titan	32	14″
Io	31	19″
Callisto	28	23″
Europa	19	11″
Triton	10	0″.7
Pluto	7	0″.4

Sozzetti 2005

Aberration

$$\alpha_{\rm aberr} \simeq \frac{v}{c}\sin\vartheta - \frac{1}{4}\frac{v^2}{c^2}\sin 2\vartheta + \frac{1}{6}\frac{v^3}{c^3}\sin\vartheta(1+2\sin^2\vartheta) + O(c^{-4}),$$

Klioner 2003



The magnitude of the classic aberration term (first order in *v*/*c*) is ~20"–30"

The second-order relativistic correction amounts to 1–3 mas.

Targeting a measurement precision of 1 μas, $(v/c)^3$ terms must be retained

NOTE 1: *for relativistic stellar aberration to be properly accounted for, the spacecraft's velocity will need to be determined to an accuracy of <20 mm/s*

NOTE 2: *write your data processing pipeline in a fully relativistic environment, and you'll be fine. Gaia, for good measure, does it twice!*

Stellar Binaries:

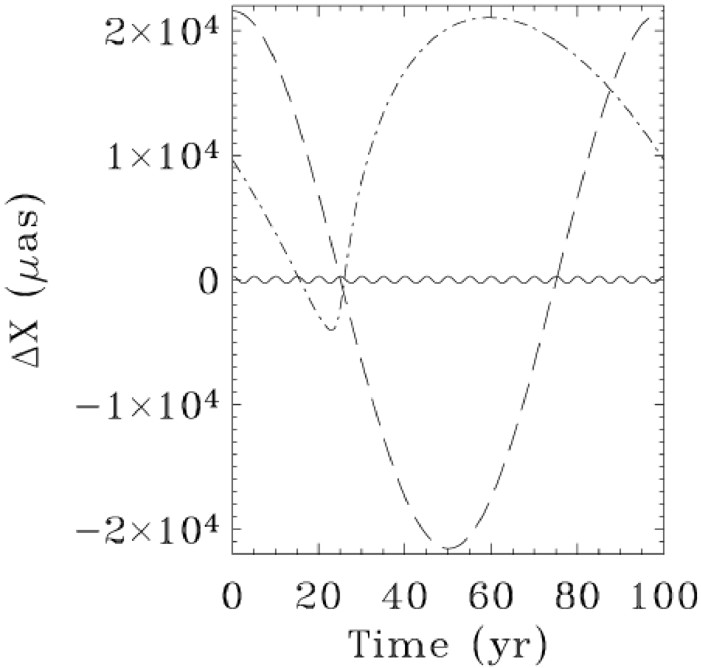
Yet Another Nuisance!

TABLE 1

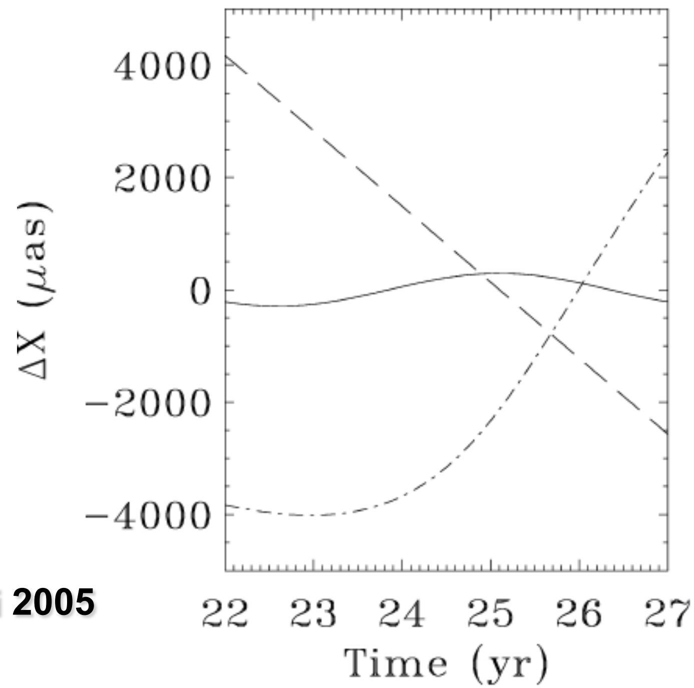
PARALLAX, PROPER MOTION, AND ASTROMETRIC SIGNATURES INDUCED BY PLANETS OF VARIOUS MASSES AND ORBITAL RADII

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

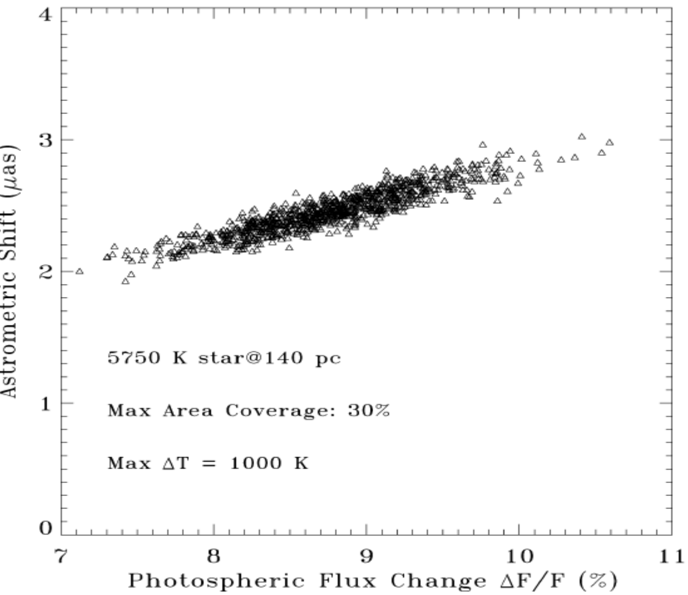
NOTE.—A 1 $M_\odot$ star at 10 pc is assumed.



Sozzetti 2005



Stellar Surface Structures



Sozzetti 2005

And Stellar Rotation?

No problem, dude!

Astrometric Jitter Size

for a distance of 10 pc	lower limit (only from granulation)	upper limit (photometric variability)
early main-sequence	0.03 μas	12 μas
mid-late main-sequence	0.01 μas	1-3 μas
K giants	5 μas	20-50 μas
F supergiants	10 μas	0.4-2 mas
M supergiants	30-300 μas	10 mas

Lagrange et al. 2011

Circumstellar Disks

- Gravitationally unstable circumstellar disks

$$\Delta\theta \approx 100 \left(\frac{r_{\rm grav}}{25\ {\rm au}}\right) \left(\frac{d}{100\ {\rm pc}}\right)^{-1} \mu{\rm arcsec}$$

Rice et al. 2003

$$\tau \approx 50 \left(\frac{r_{\rm grav}}{25\ {\rm au}}\right)^{3/2} {\rm yr}.$$

- Disks' variable illumination due to orbiting planets can induce peak-to-peak photocenter variations of 10–100 μas

Takeuchi et al. 2005

- Disks' inhomogeneities and asymmetries can also produce (wavelength-dependent) effects on the order of 0.1-10 μas

Kral et al. 2016

Estimation Process

- The estimation process finds parameter values that produce the closest agreement between the observable model estimates and the data, in light of the noise model.

Planetary Systems Orbits

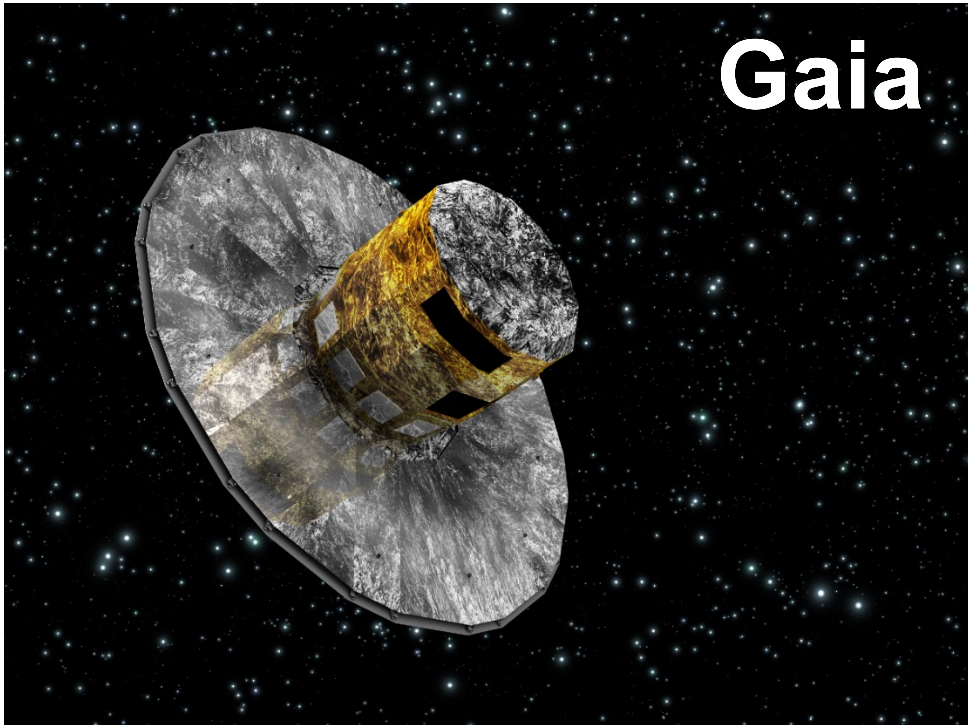
- Highly non-linear fitting procedures, with a large number of model parameters (at a minimum, $N_p=5+7*n_{pl}$)
- Redundancy requirement: $N_{obs} >> N_p$
- Global searches (grids, Fourier decomposition, genetic algorithms, Bayesian inference +MCMC) can be coupled to local minimization procedures (e.g., L-M)
- For strongly interacting systems, dynamical fits using N-body codes may be required

Assessing Detections

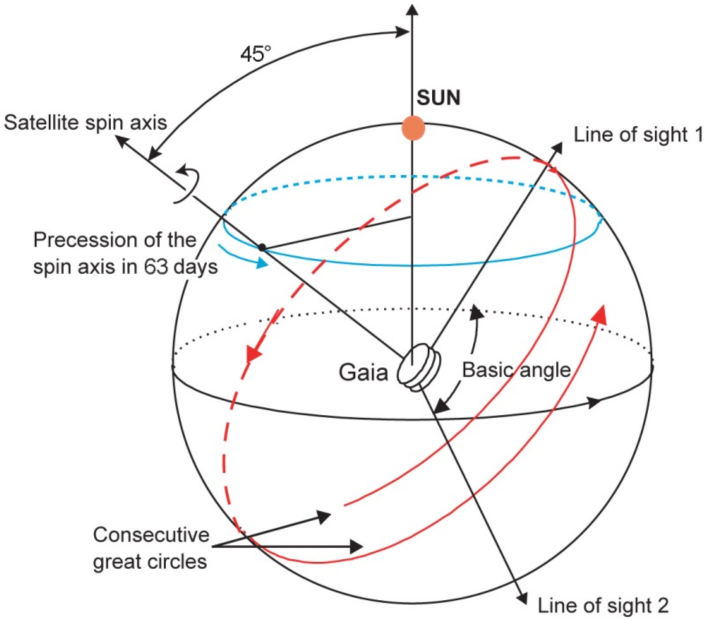
- Errors on orbital parameters: covariance matrix vs. χ^2 surface mapping vs. bootstrapping procedures
- Confidence in an n-component orbital solution: FAPs, F-tests, MLR tests, statistical properties of the errors on the model parameters, BIC, AIC, BF, others? You name it!
- Importance of consistency checks between different solution algorithms
- Memento lessons learned from RV surveys, with disagreement on orbital solution details, and sometime number of planets! See previous speakers' talks…

Enter Gaia

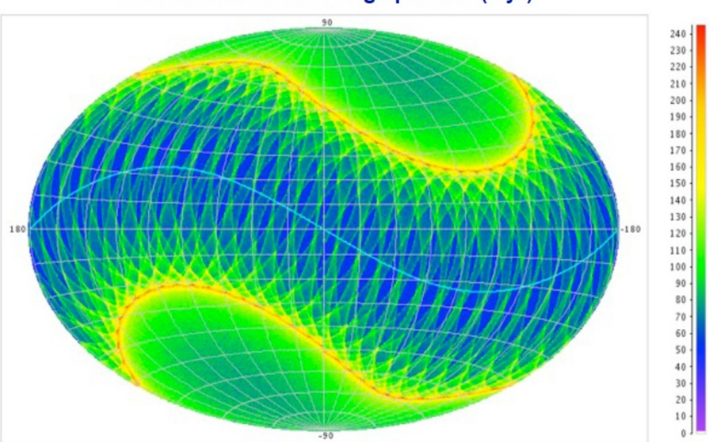
Successfully launched on December 19^{th}, 2013!



A Space Astrometry Revolution!



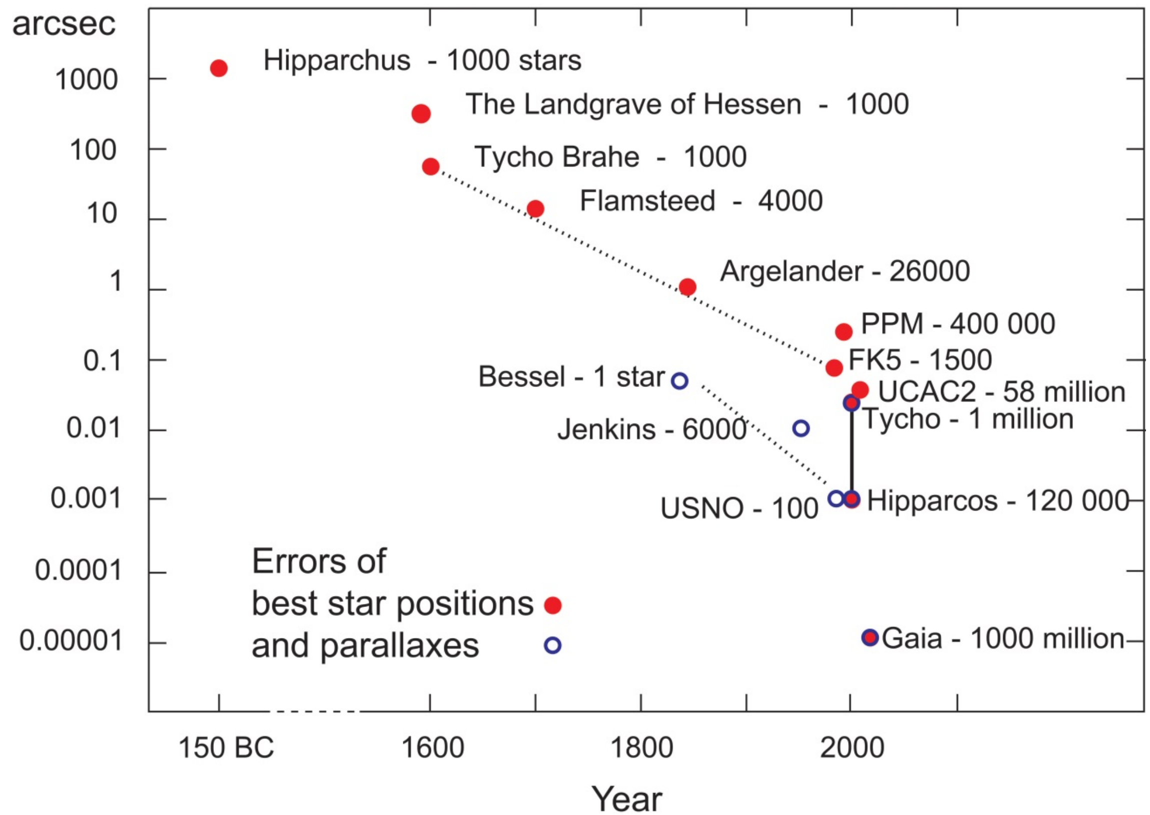
Number of FoV crossings per star (5 yr)



Equatorial projection

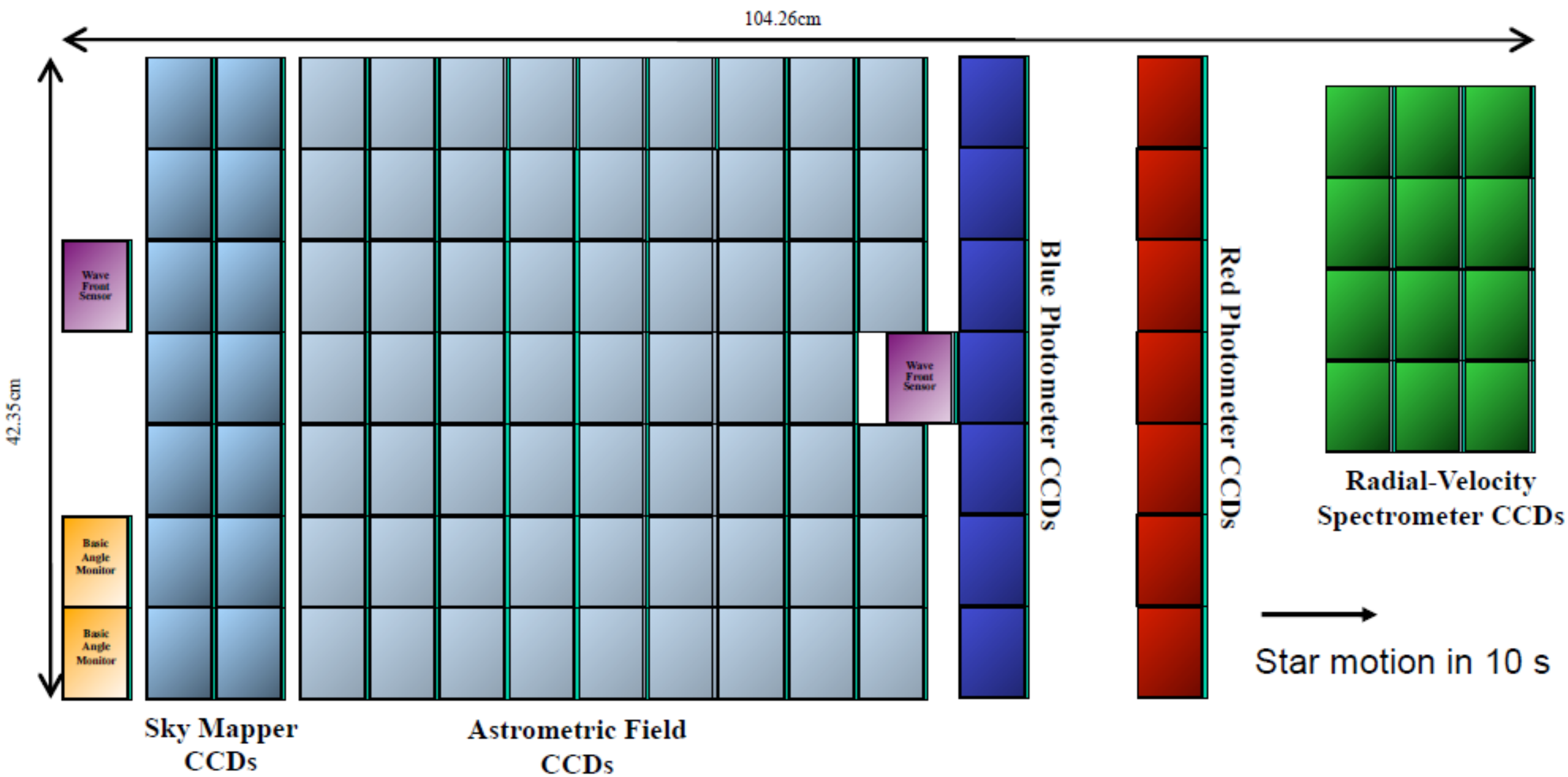
Typically 70 observations in 5yrs

At Gaia's G=20.7 survey limit: 2×10^9 stars



μas astrometry comes of age...

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

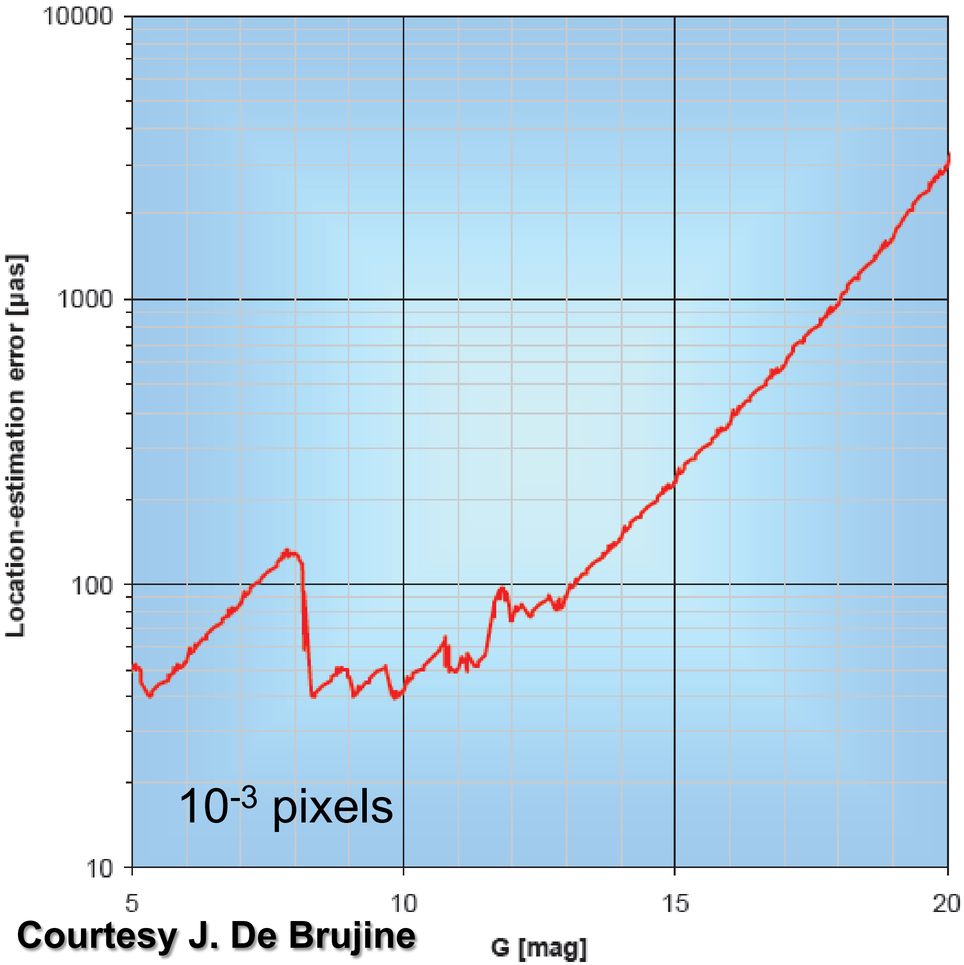
Gaia: Routine Operations

- In 5-year routine phase since 18 July 2014
- Nominal scanning law optimised for Jupiter quadrupole moment general relativity experiment
- Data collection: **May 2015**
  - 225 billion astrometric measurements
  - 45 billion photometric measurements
  - 4.4 billion spectra
- Magnitude limits
  - Astrometry and photometry between $2 < G < 20.7$ mag
  - Stars brighter than $G = 3$ mag captured with Sky Mapper imaging
  - Spectra till $G_{RVS} = 16.2$ mag (and $G > 2$ mag)

Unwanted Surprises

- Stray light both from astronomical sources and the Sun
  - Sun stray light due to scattering of fibres at the edge of the Sun shield
  - Impacts faint sources especially in spectroscopy
- Transmission loss due to continuing contamination of mirrors by water
  - Water source not yet exhausted although contamination rate much less than during commissioning
- Basic Angle variation larger than expected
  - Variation measured by on-board metrology device and verified at milliarsec level by astronomical sources
- Attitude disturbances
  - Micro-meteoroids taken into account in pre-launch work
  - At small impact levels many micro-clanks observed

CCD-level Location Estimation



Courtesy J. De Brujine

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, …

1. 3(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)

Science Performance

For unreddened Solar type (G2V) star

V-magnitude	*Astrometry (parallax)*	*Photometry (BP/RP integrated)*	*Spectroscopy (radial velocity)*
3 *to 12*	*5-14 μas*	*4 mmag* *G = 1.4 mmag*	*1 km/s*
15	*25 μas*	*5 mmag* *G = 1.5 mmag*	*13 km/s*
20	*540 μas*	*60 (RP) – 80 (BP) mmag* *G = 4.0 mmag*	

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

Astrometric solution for Gaia: The problem

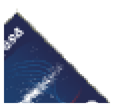
- The basic measurement is the "time of observation" for each star's crossing a CCD
  $\Rightarrow$ 10^{12} measurements in total
- Unknown parameters to estimate:
  - 5 astrometric parameters per star
  - attitude (celestial orientation) of instrument as function of time
  - instrument calibration parameters (basic angle, CCD positions, etc)
  - possibly additional parameters (incl. PPN-γ)
  $\Rightarrow$ 5×10^{9} unknowns in total
- Not all stars are suitable for simple modelling (binaries, etc)
  - a subset of "primary stars" is used for the astrometric solution
  - aim to use at least 100 million primary stars (10% of all)
  - the rest are "secondary stars", can be treated offline
  $\Rightarrow$ astrometric solution needs 5×10^{8} unknowns

Remember: people can fit an elephant with three unknowns...

Astrometric solution for Gaia: Formulation

$$\begin{pmatrix}\text{Observed}\\ \text{location of image}\\ \text{in pixel stream}\end{pmatrix} = \begin{pmatrix}\text{Star position}\\ \text{on sky}\end{pmatrix} + \begin{pmatrix}\text{instrument}\\ \text{Attitude}\end{pmatrix} + \begin{pmatrix}\text{CCD / pixel}\\ \text{offset}\end{pmatrix} + \text{noise}$$

- Star position on sky ← 5 astrometric parameters $(\alpha_0\ \delta_0\ \pi_0\ \mu_\alpha\ \mu_\delta)$ (radial velocity assumed known)
- Instrument Attitude ← quaternion $q(t)$ represented by cubic spline coefficients
- CCD / pixel offset ← geometric calibration
- noise ← white gaussian, known σ



Symbolically: $O = f(S, A, C) + n$

Block-iterative least-squares solution + alignment with the ICRS

Purely frequentist approach, live with it!

Data Release Scenario (http://www.cosmos.esa.int/web/gaia/release)

- First release: September 14 2016 – 1000th day of the Gaia mission!
  - **Positions** (α, δ) and **G magnitudes** for all stars with acceptable formal standard errors on positions (based on generic priors on μ, π and Bayes' rule)
  - **Photometric data** of **RR Lyrae and Cepheids** from high-cadence measurements (from 1-month EPSL operations)
  - The **five-parameter astrometric solution** - positions, parallaxes, and proper motions - for stars in **common between the Tycho-2 Catalogue and Gaia** (TGAS), with prior information (constraints) from Tycho-2 positions

- Second release summer 2017 - Potentially:
  - **Five-parameter astrometric solutions** of objects with single-star behaviour
  - Integrated **BP/RP photometry,** for sources where basic astrophysical parameter estimation has been verified
  - **Mean radial velocities** will be released for "well behaved objects"

DR1 Astrometric Content

- **Primary Dataset:** 2 086 766 objects mainly $m_V < 11.5$ (no $m_V \leq 6$)

- What's provided for every source:
  - 5 astrometric parameters $\alpha, \delta, \mu_\alpha, \mu_\delta, \pi$ @ J2015.0 plus variances and correlations (10% parallax accuracy at 300 pc)
  - number of FOV transits used in solutions, number of accepted and rejected CCD observations
  - excess noise ε representing modelling errors, ideally zero for primary sources, actually ~ 0.5 mas for most sources

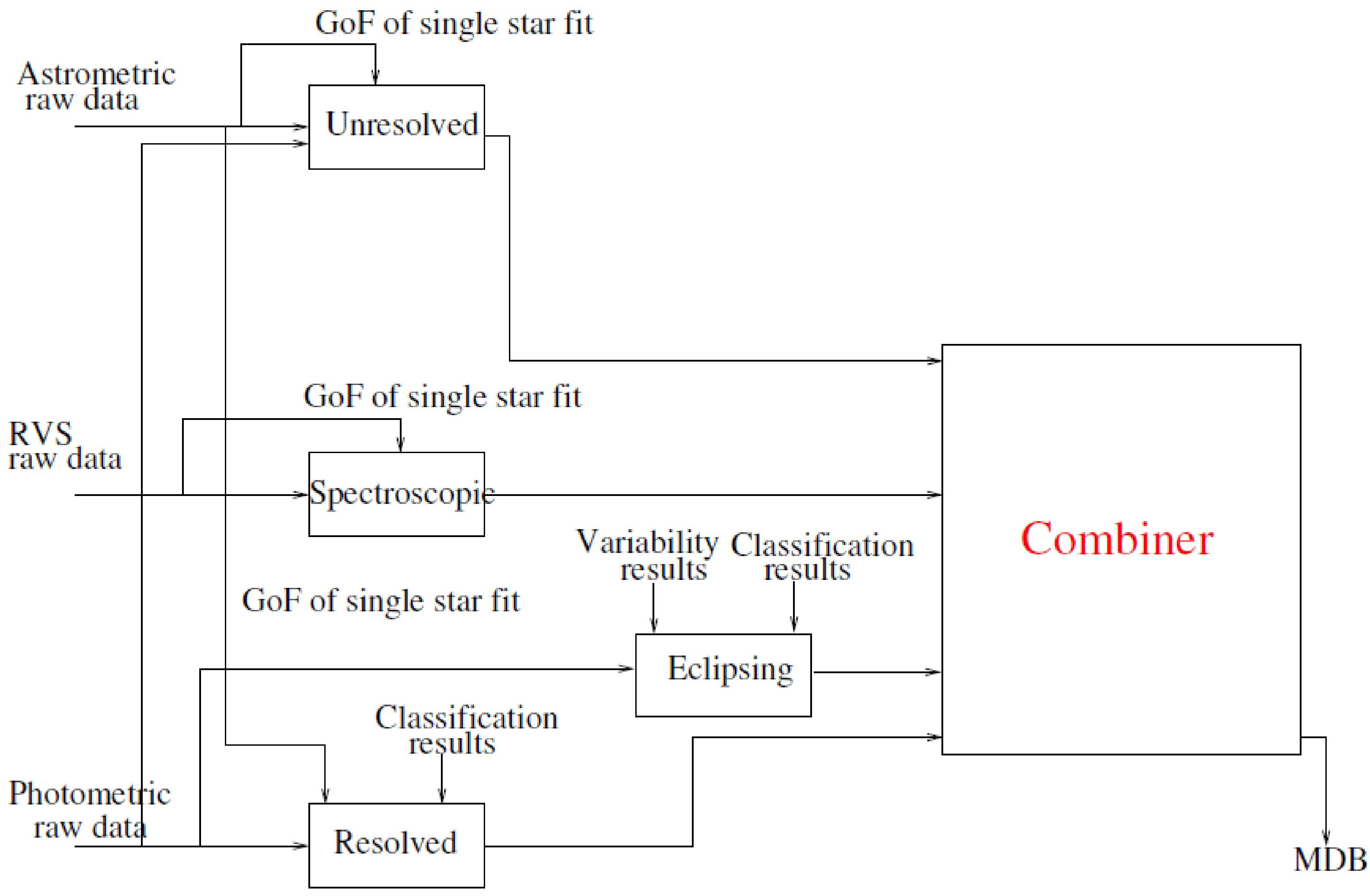
  → presence of attitude and instrument modelling errors (BAV, microstuff...).

- **Secondary Dataset:** 1.467 billion objects (stars + extragalactic) with $m_G < 20.7$

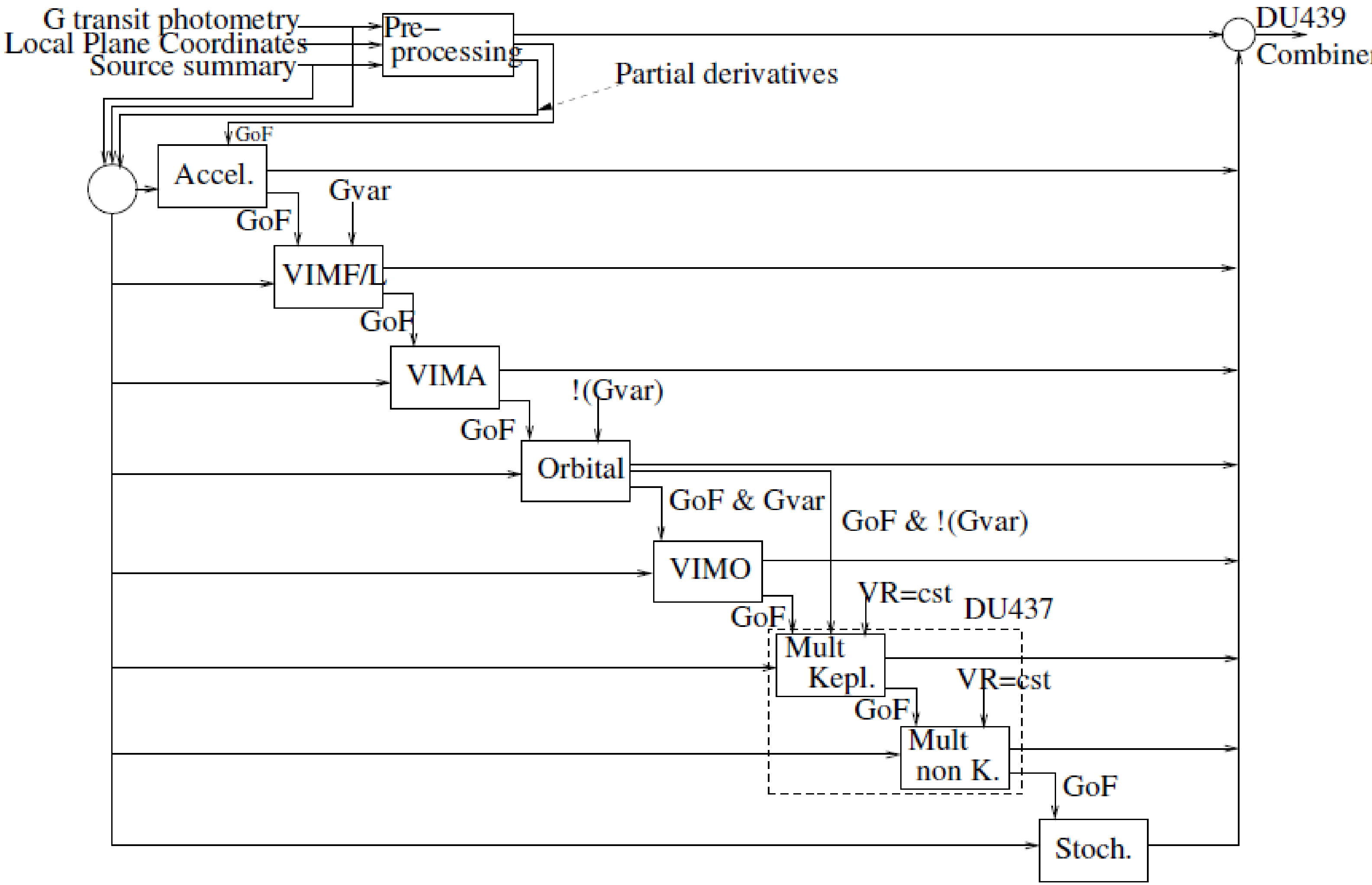
- Derived using *secondary solution (calibration parameters taken from primary solution).* Effects of parallax and proper motions 'neglected'

  → Positional accuracy limited to a few mas or larger

Gaia CU4 – NSS Treatment



Gaia CU4 – Astrometric NSS Treatment



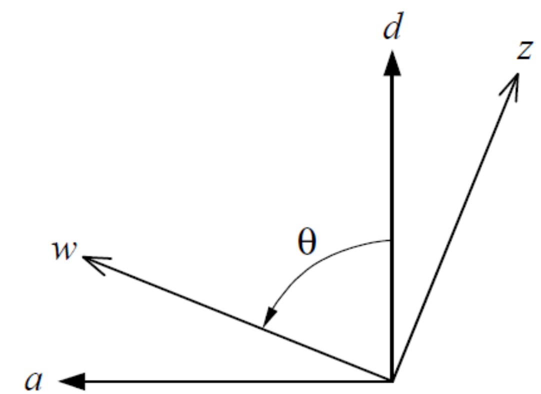
Orbits with Gaia

In the plane of the sky:

$$\left.\begin{aligned} a(t) &= a_T + (t-T)\mu_{\alpha*} + f_a(t)\pi + BX(t) + GY(t) \\ d(t) &= d_T + (t-T)\mu_\delta \;\; + f_d(t)\pi + AX(t) + FY(t) \end{aligned}\right\}$$

Rotate by a scanning angle:

$$\left.\begin{aligned} w &= \quad a\sin\theta + d\cos\theta \\ z &= -a\cos\theta + d\sin\theta \end{aligned}\right\}$$

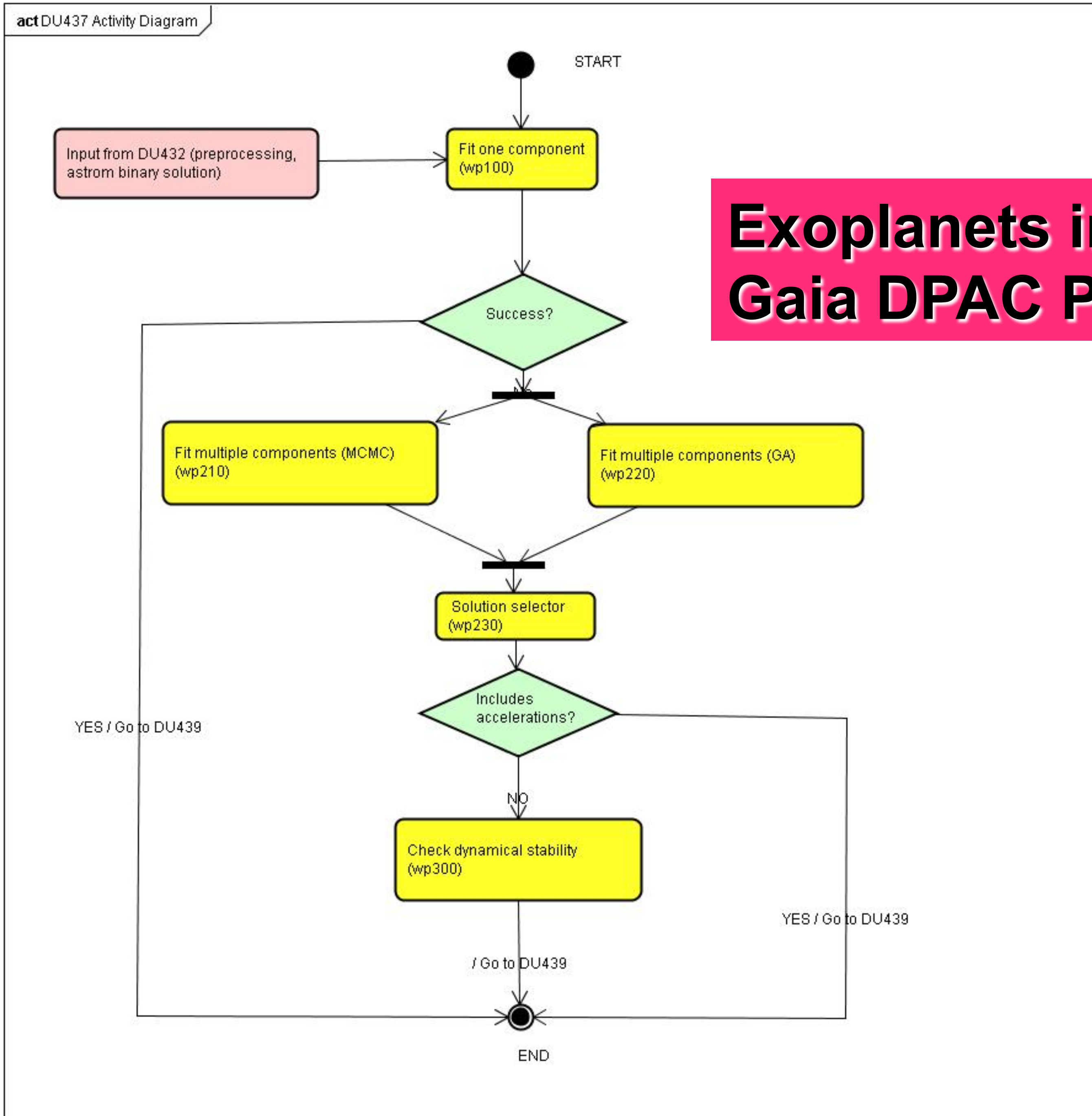


Solve for:

$$\left.\begin{aligned} w &= \quad sa_T + cd_T + (t-T)s\mu_{\alpha*} + (t-T)c\mu_\delta + f_w\pi + XcA + XsB + YcF + YsG \\ z &= -ca_T + sd_T - (t-T)c\mu_{\alpha*} + (t-T)s\mu_\delta + f_z\pi + XsA - XcB + YsF - YcG \end{aligned}\right\}$$

In practice, only w is useful (z known 5 times worse)

Exoplanets in the Gaia DPAC Pipeline



So Let's Assume We Can Get It to Work

What's Gaia Going to Give us for Exoplanets?

Gaia Photometry: Transiting GP candidates

- Required photometric precision (a few mmag) not an issue

- Low-cadence of the observations a serious limitation

- It's not hopeless if you have the right tools! (Dzigan 2012)

- It can work for early detections of (1000?) short-period transiting GPs (and 100s of BDs)

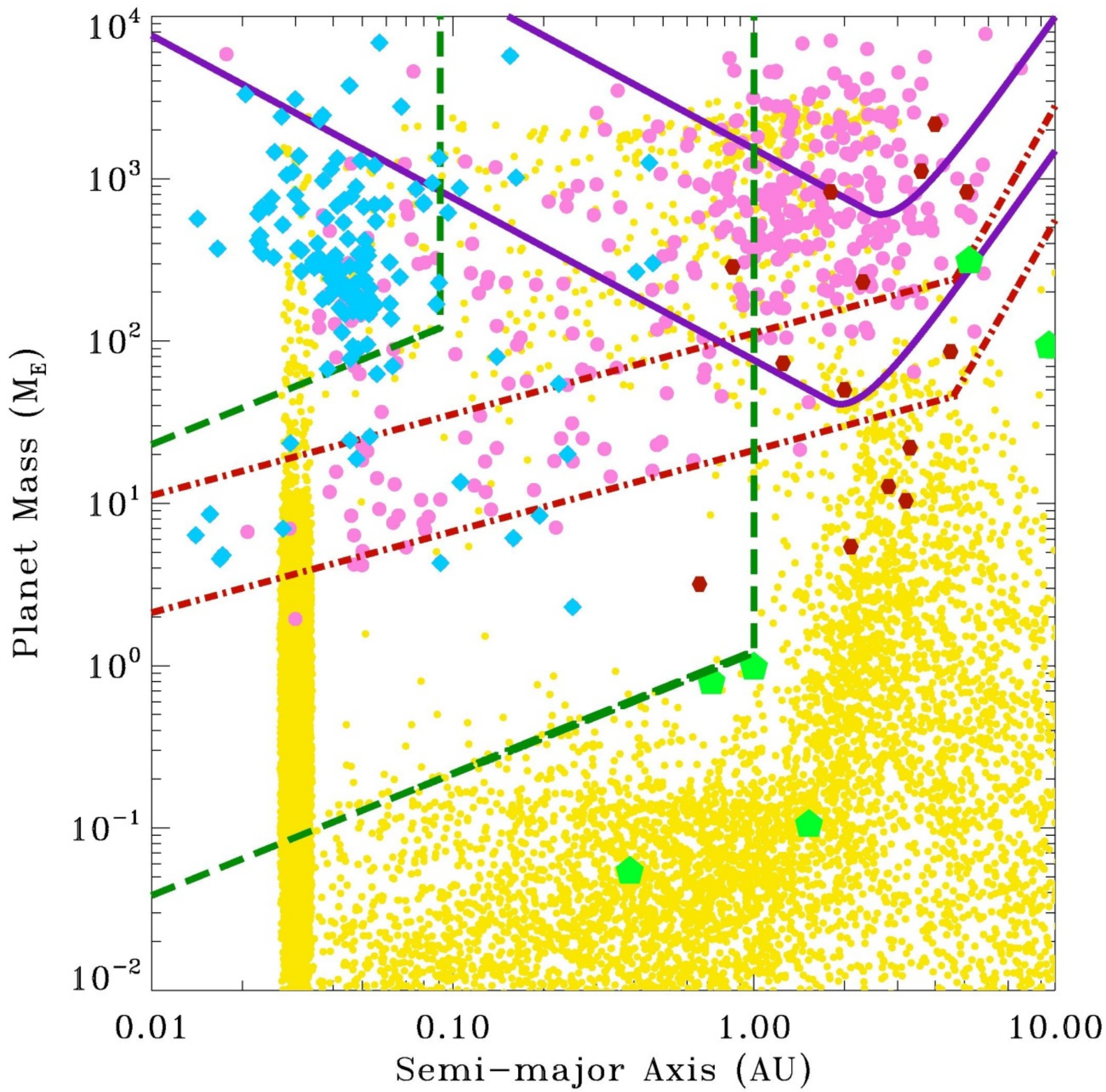
- It may require a dedicated follow-up network

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

Gaia Discovery Space

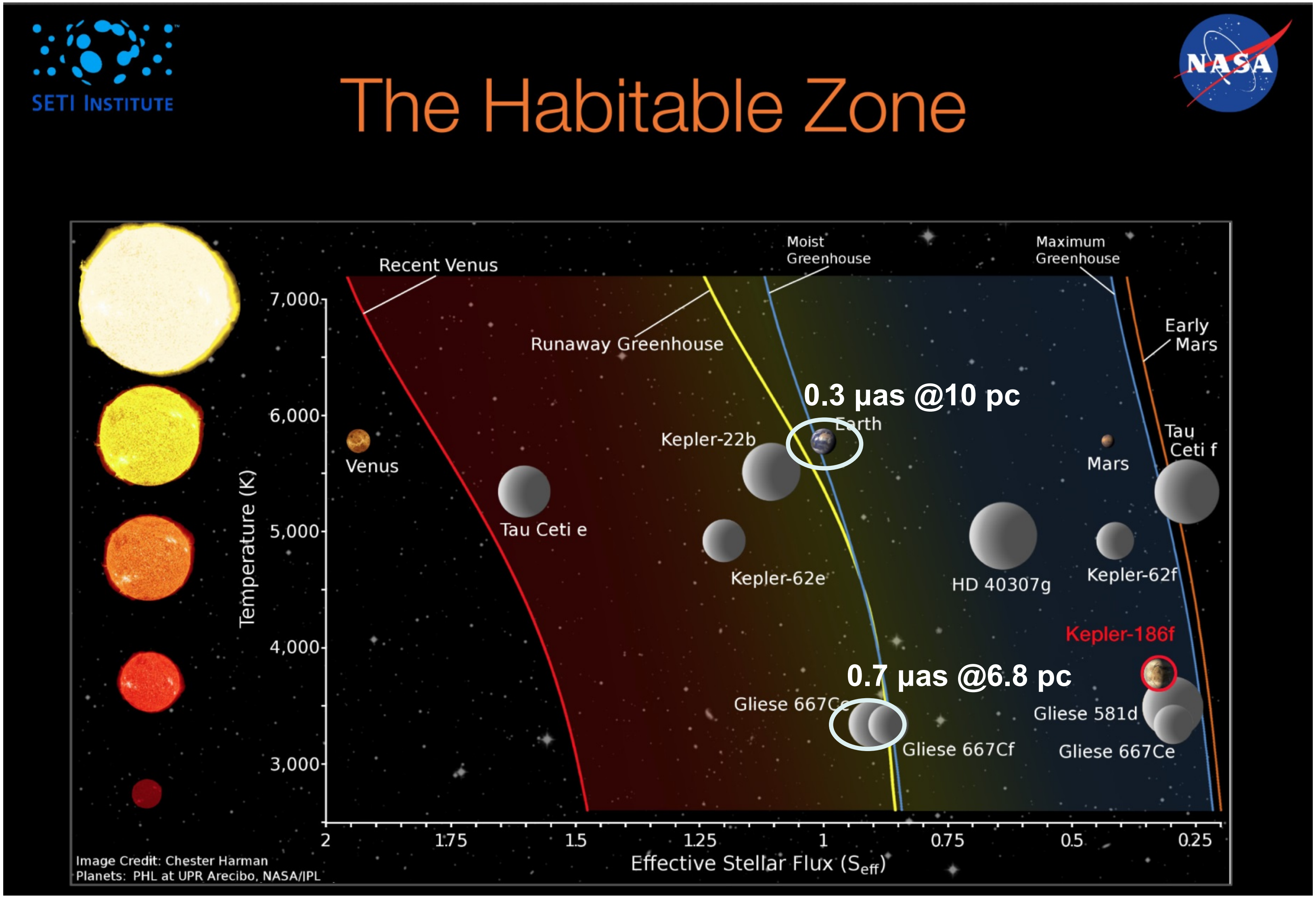
1) 2-3 M_J planets at 2<a<4 AU are detectable out to~200 pc around solar analogs
2) Saturn-mass planets with 1<a<4 AU are measurable around nearby (<25 pc) M dwarfs

For Gaia: σ_A ~ 15-20 μas



Sozzetti 2011

Habitable Earths: Not Gaia's Thing



The Gaia Exoplanet Yield

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

M dwarf starcounts (G<20) → **2-3x10^3 additional giants (Sozzetti et al. 2014)**

All spectral types (G<17.5) → **2x10^4 new gas giants (Perryman et al. 2014)**

Close binaries within 200 pc → **100s circumbinary giants (Sahlmann et al. 2014**

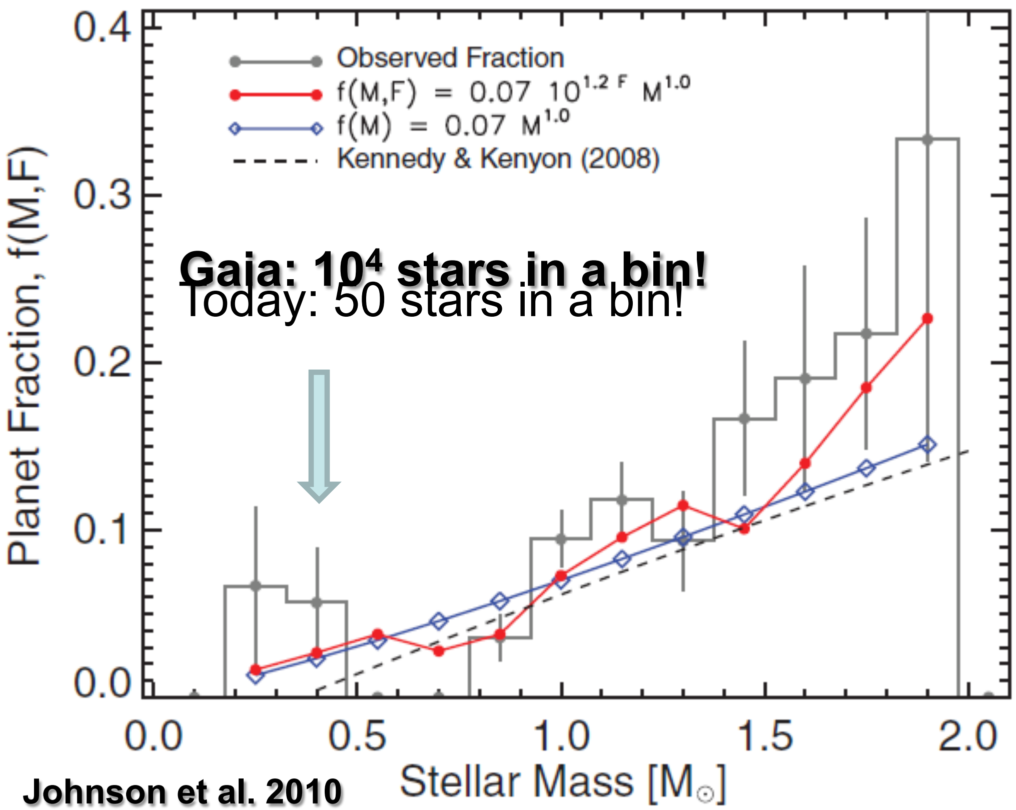
Unbiased, magnitude-limited planet census of possibly millions of stars

On the order of 10^4 NEW giant (< 15 M_{JUP}) planets

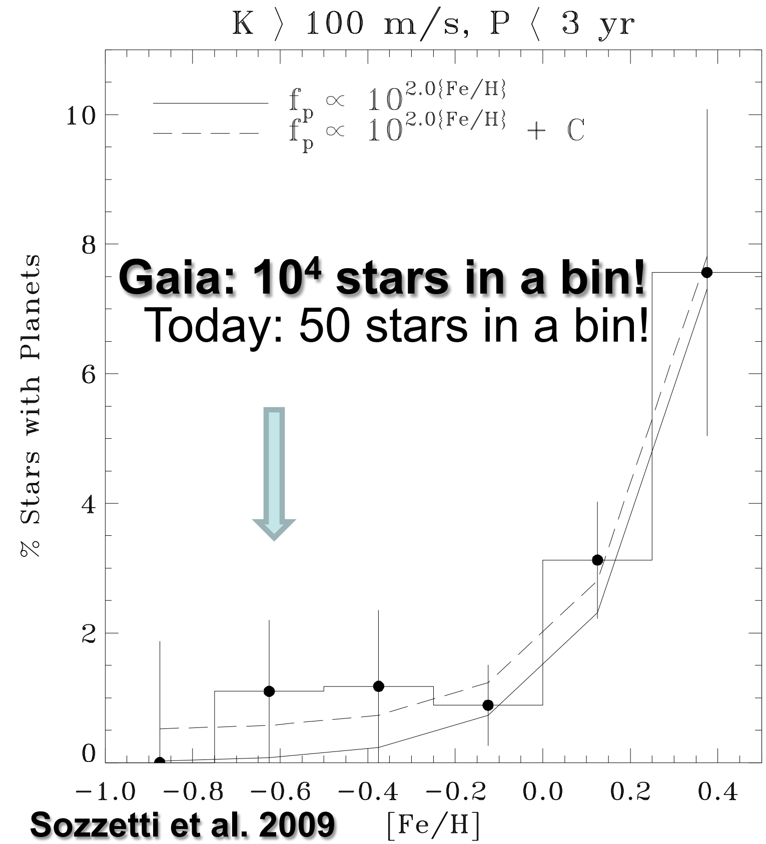
Final catalogue: around 2022, pending extension

The Gaia Legacy

How do giant planets properties (mass, orbit) depend on those of the host stars?



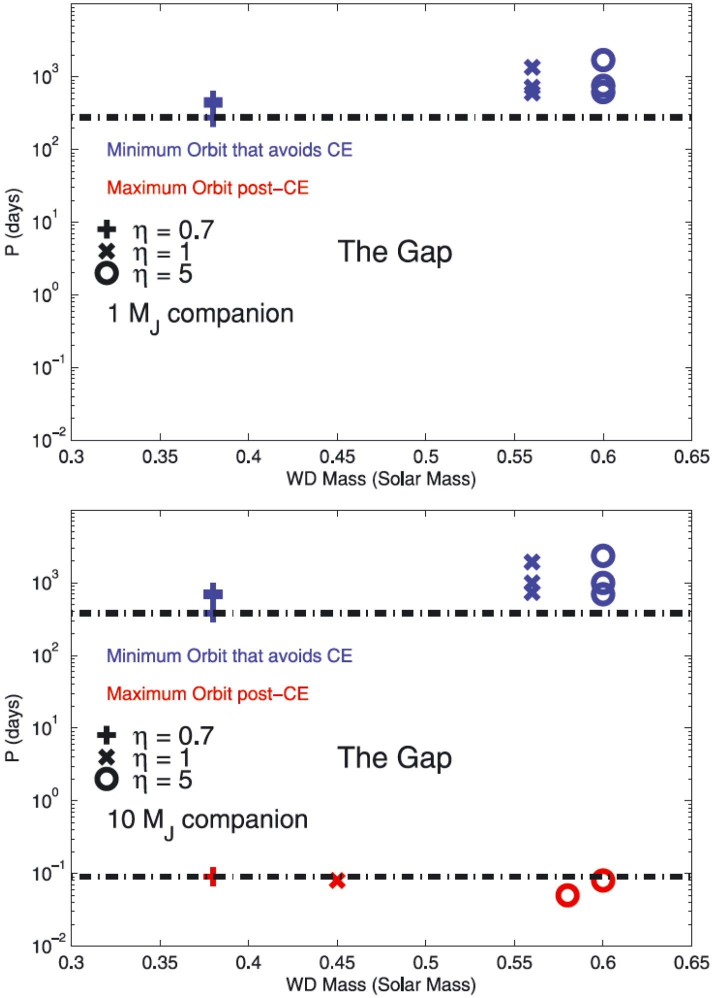
Johnson et al. 2010



Sozzetti et al. 2009

Gaia will test the fine structure of GP parameters distributions and frequencies (including the GP/BD transition), and investigate their changes as a function of stellar mass, metallicity, and age with unprecedented resolution

Gaia & Post-MS Stars



White dwarfs in the solar neighborhood

Good to within a factor 2…

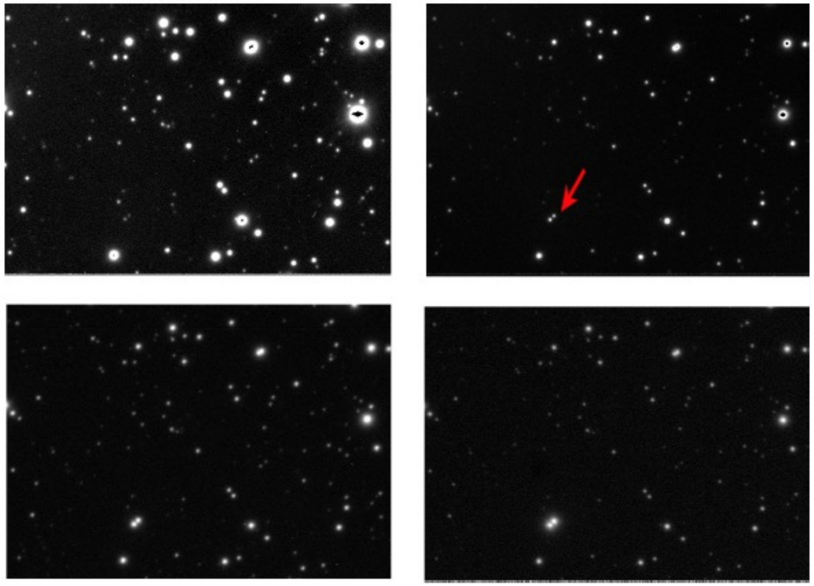
	D<100 pc	D<200 pc
R<13	50	400
R<14	200	1600
R<15	800	6400

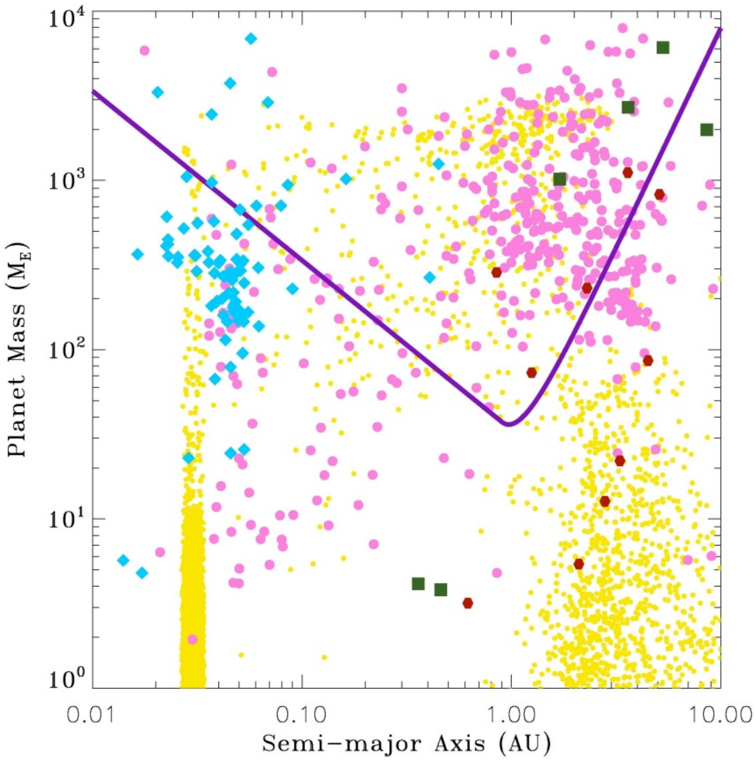
Silvotti, Sozzetti, & Lattanzi, AIP

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

Planets Around BDs

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

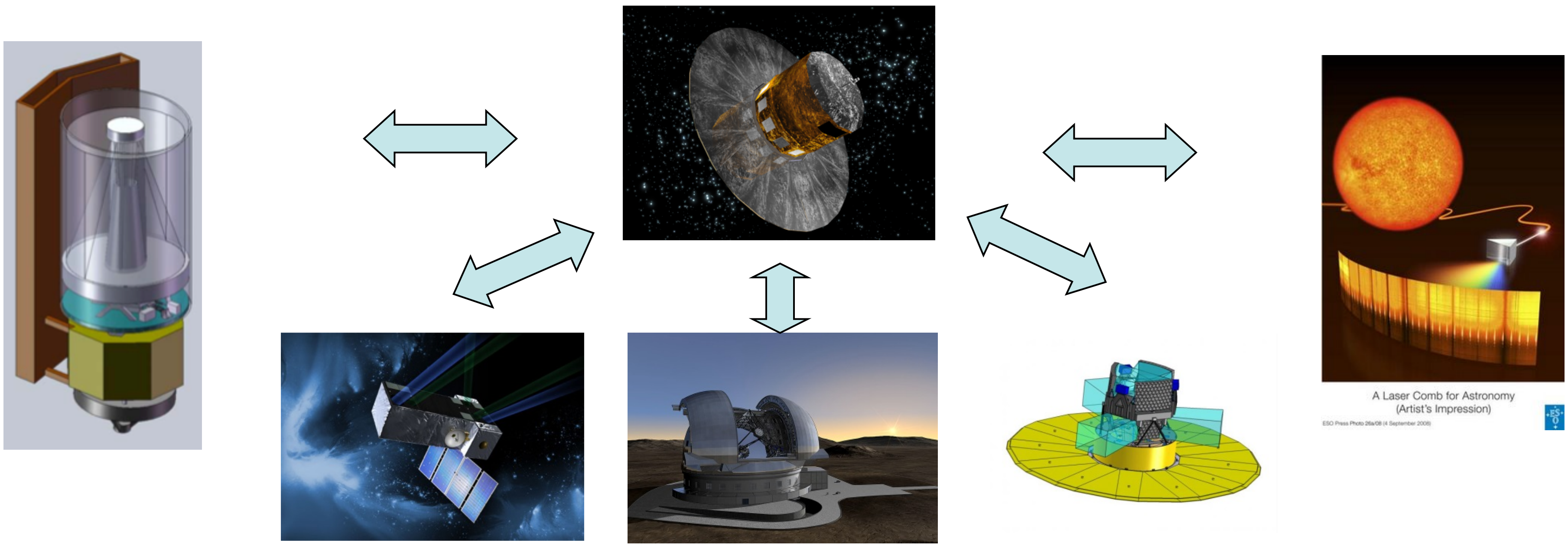




- Found so far only in microlensing events
- Gaia will see ~1000 BDs of all ages, with sufficient astrometric sensitivity to giant planets within 2-3 AU
- A fundamental test of planet formation!

Sozzetti (arXiv:1406.1388)

Gaia - Synergies



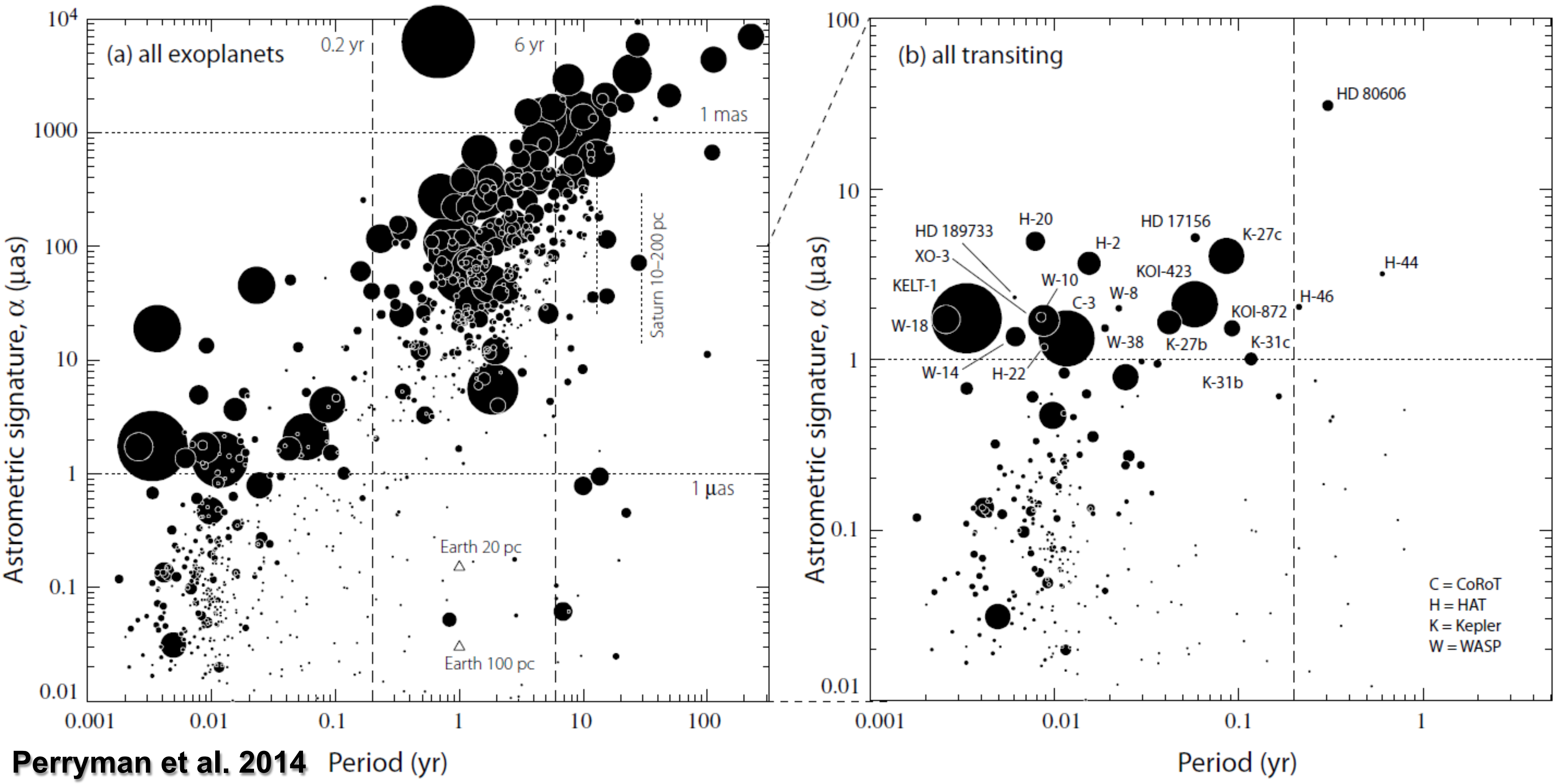
- Gaia & spectroscopic characterization observatories (e.g., JWST, E-ELT)
- Gaia & transit surveys from the ground (e.g., WASP, HAT, APACHE, NGTS) and in space (CoRoT, Kepler, K2, TESS, PLATO)
- Gaia & direct imaging observatories (e.g., SPHERE/VLT, PCS/E-ELT, WFIRST)
- Gaia & RV programs (e.g., HARPS(-N), ESPRESSO, CARMENES, and the likes)
- Gaia & ground-based and space-borne astrometry

Synergy with RVs

- Complete characterization of systems architectures across (some) 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, HARPS-N@TNG, Keck/HIRES), and upcoming (ESPRESSO@VLT, IR instruments) RV surveys

Combined analyses can profit from large time baseline, particularly when Gaia intermediate astrometry data will become available (> 2022)

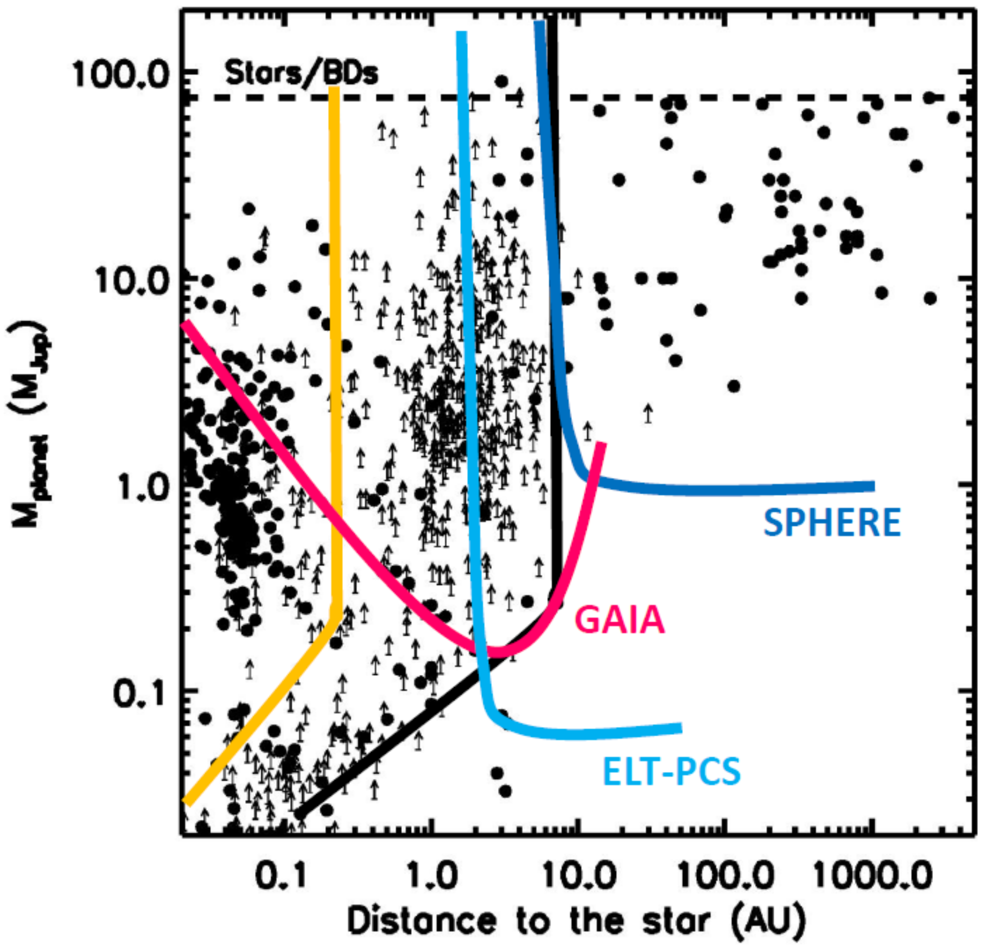
Gaia & Known Planets



Perryman et al. 2014

Astrometry + Direct Imaging

- Direct imagers to-date sensitive to young giants at wide separations
- Mass estimates rely on models, ages have big uncertainties
- Dynamical constraints on mass are difficult, but highly desirable
- Full astrometric orbits improve phase function and light-curve modeling
- RV amplitudes are small at large separations, and young stars are trouble
- Youth not an issue for astrometry, signal amplitudes increase at large a



Gaia astrometry + direct imaging: an ideal synergy!

Finding Nearby Transiting Intermediate-Separation GPs

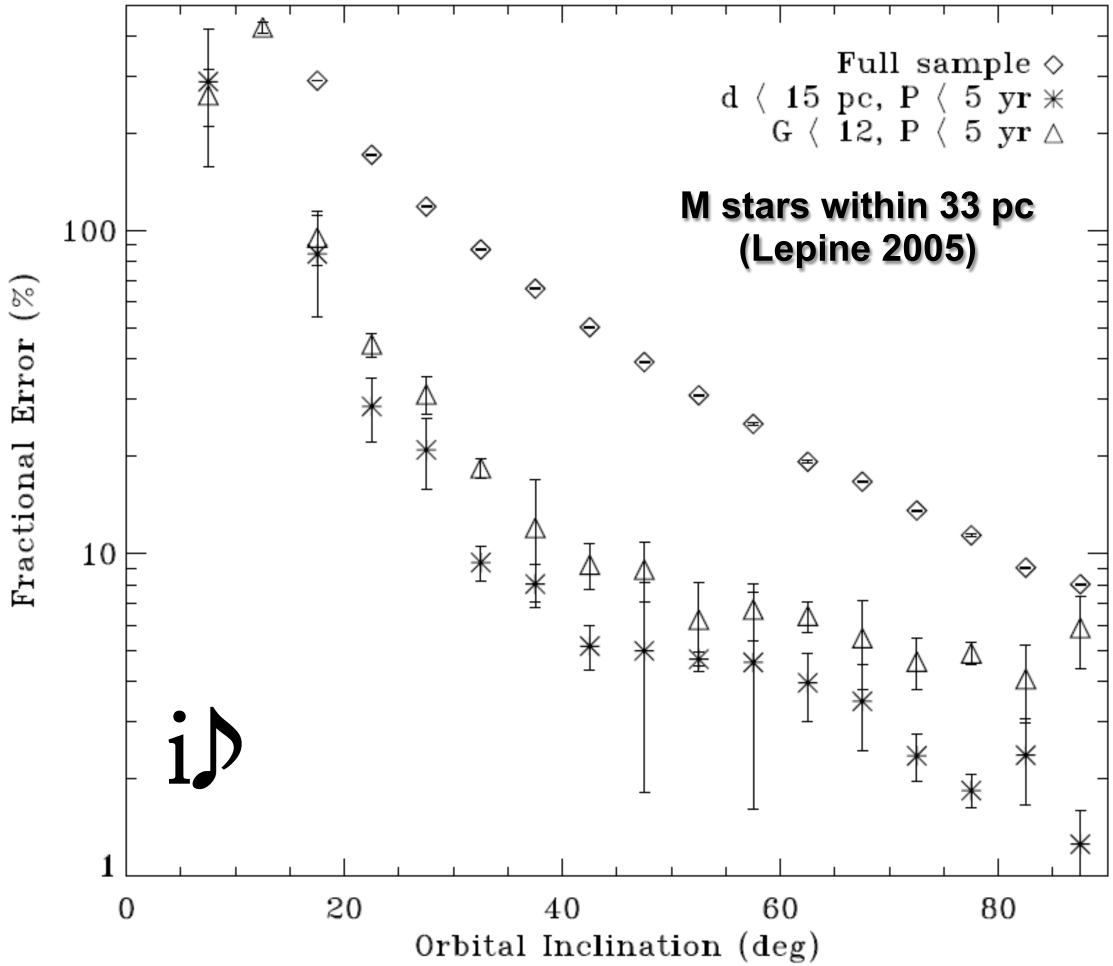
Sozzetti et al. 2014

For well-measured, quasi-edge-on orbits, i is measured to 2-3%

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!

And don't rule out Gaia's help for TESS's single transit events



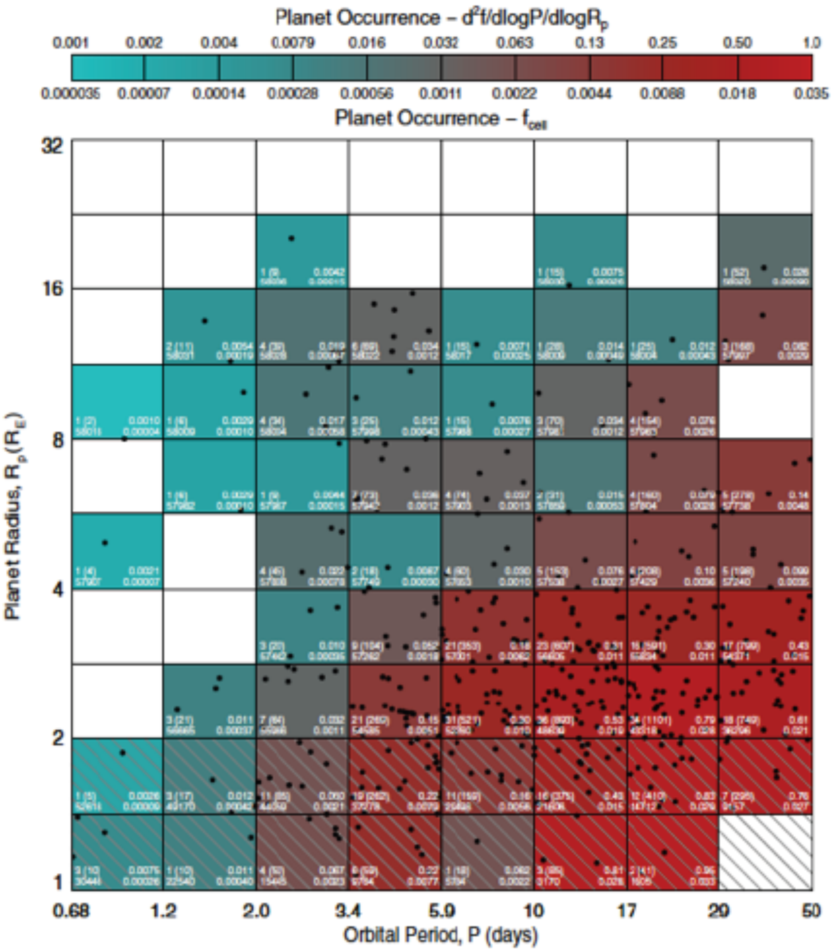
Follow-up efforts, possible targets for JWST

Target Selection

- Parallaxes of Tycho-2 stars available end of summer 2016
- One year later, >90% of parallaxes for all stars observed by Gaia are delivered…
- Elected primary source of the TESS/PLATO input catalogs of $>2\times10^6$ bright dwarf stars (with negligible contamination from giants)
- Significant reduction in astrophysical false positives (know thy neighbors!)

Gaia – Kepler - HARPS-N

Howard et al. 2012



* **ALL parallaxes of stars in the Kepler field released formally around mid-2017**

* **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]

$$f_{\rm cell} = \sum_{j=1}^{n_{pl,cell}} \frac{1/p_j}{n_{\star,j}}, \qquad p_j = (R_\star/a)_j$$

OBJECTIVE OF THE INAF-LED FP7-SPACE ETAEARTH PROJECT

Gaia & Ground-Space Astrometry

Proper motions/parallaxes
for comparison

Gaia

FORS2/VLT,STEP(?), Theia(?),WFIRST

Parallaxes of target
and references

Candidates for follow-up

Combined analyses can profit from large time baseline, particularly when Gaia intermediate astrometry data will become available (> 2022)

The Take-Home Message

- **Exoplanetary science is a fast-developing, highly interdisciplinary field**
- **Astrometry is REALLY hard, but there's hope and promise!**
- **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 data release: September 14th 2016.**
- **Expect the first orbital solutions by mid-2018. GET READY!**