Gaia
(It's that simple!)

Alessandro Sozzetti

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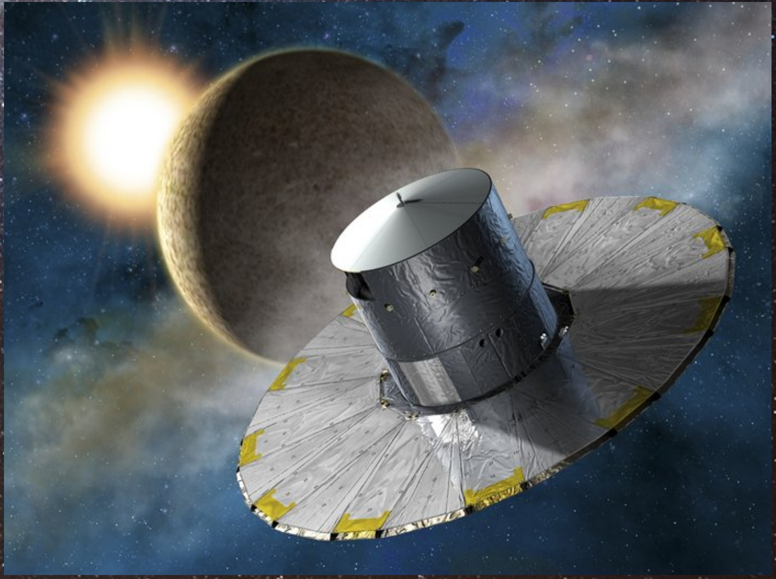

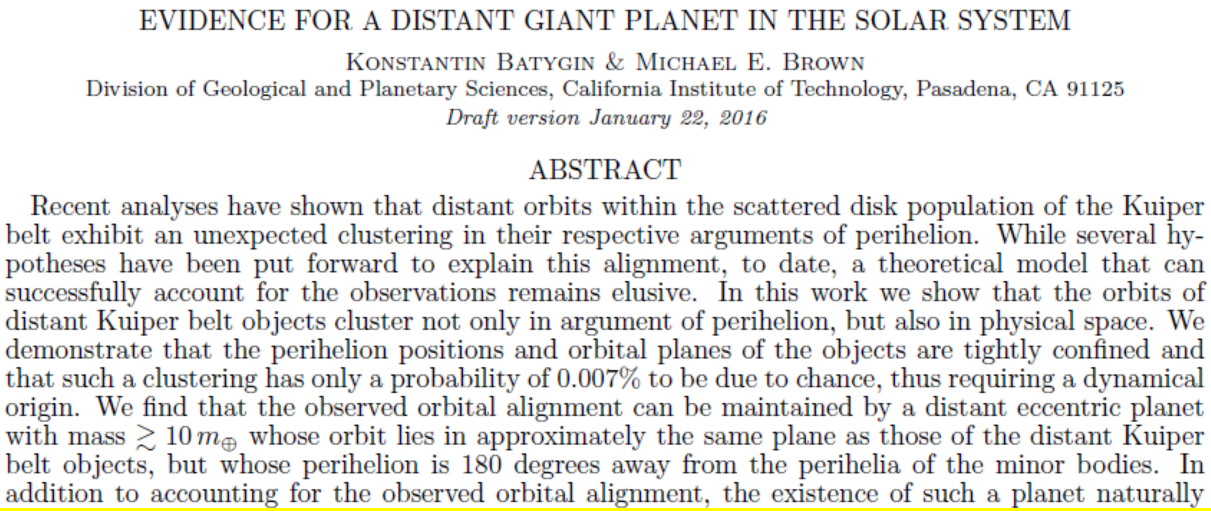

EVIDENCE FOR A DISTANT GIANT PLANET IN THE SOLAR SYSTEM

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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

La

n??

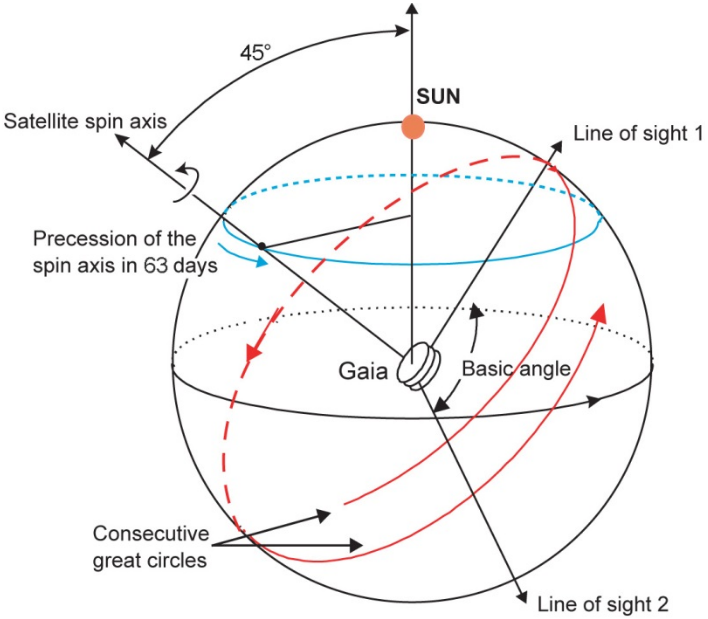
Will it last?

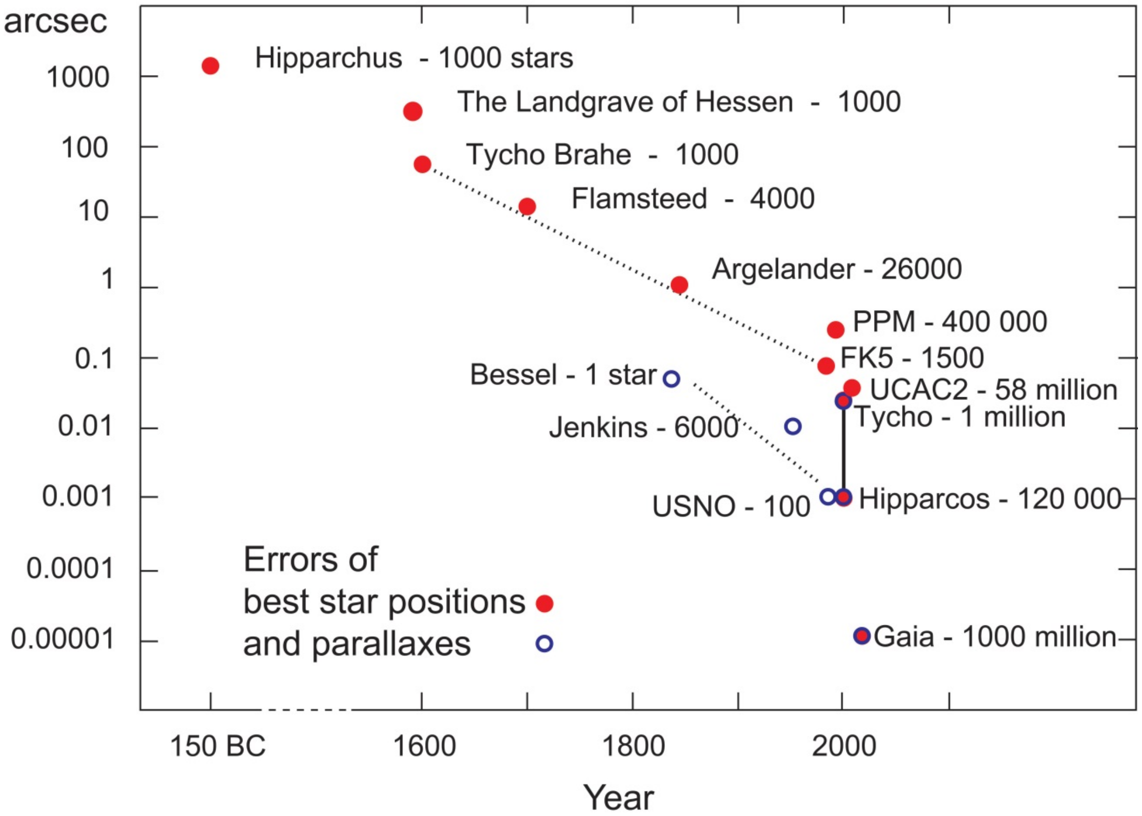
“Simulations show that for most study designs and settings, it is more likely for a research claim to be false than true.“

(Ioannidis, PLoS Med 2005)

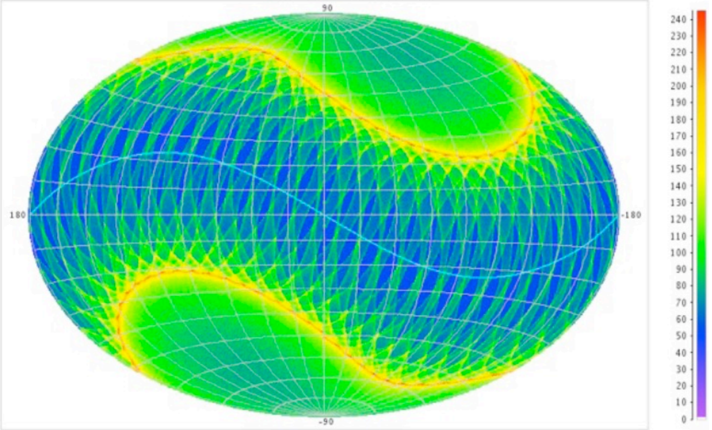
A Space Astrometry Revolution!

At Gaia's G=20.7 survey limit: >1.5x10^9 stars





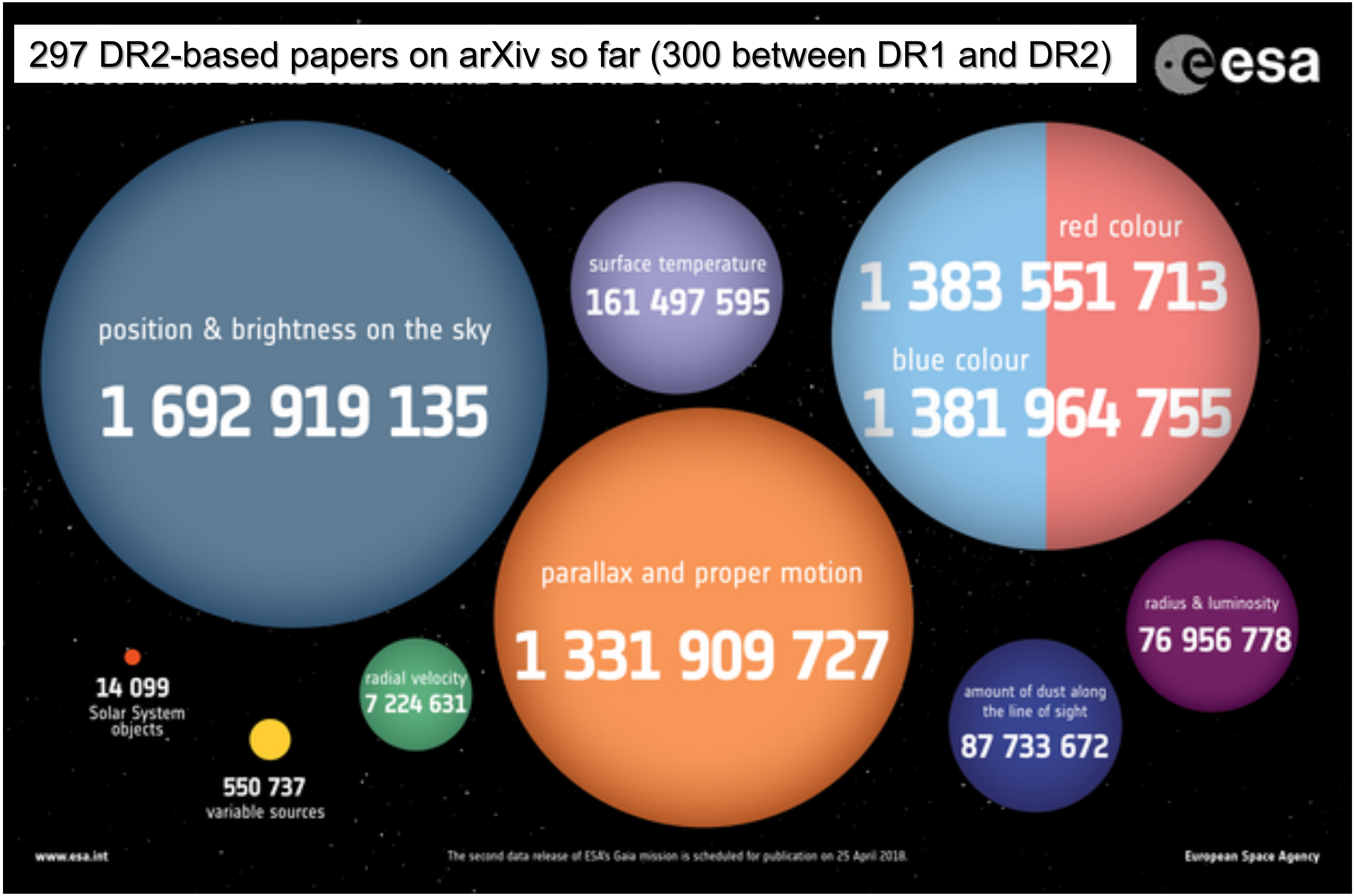
Number of FoV crossings per star (5 yr)



Equatorial projection

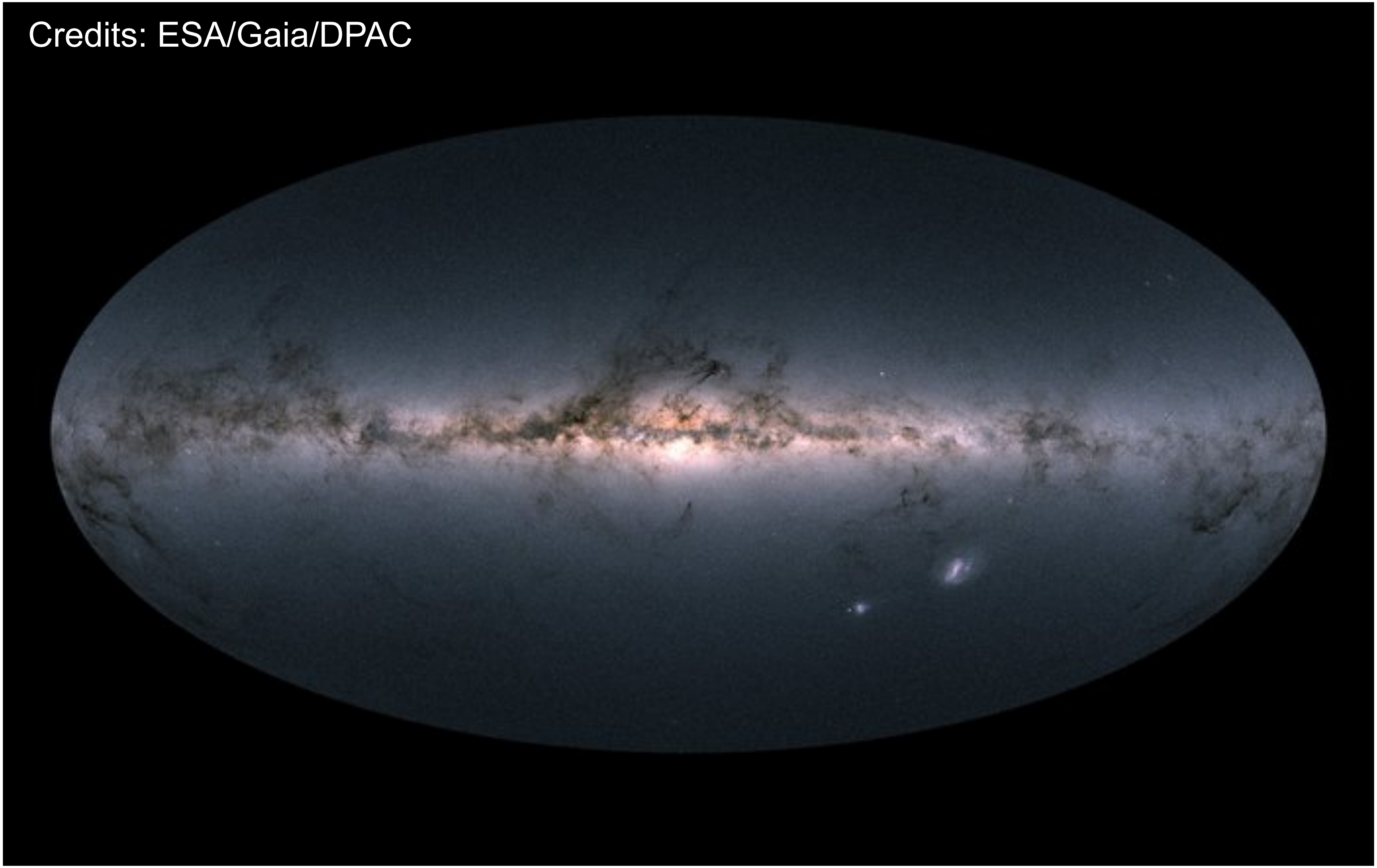
*** 1462 days of routine operations**
*** >105 billion transits observed**

Gaia DR2: 25 April 2018



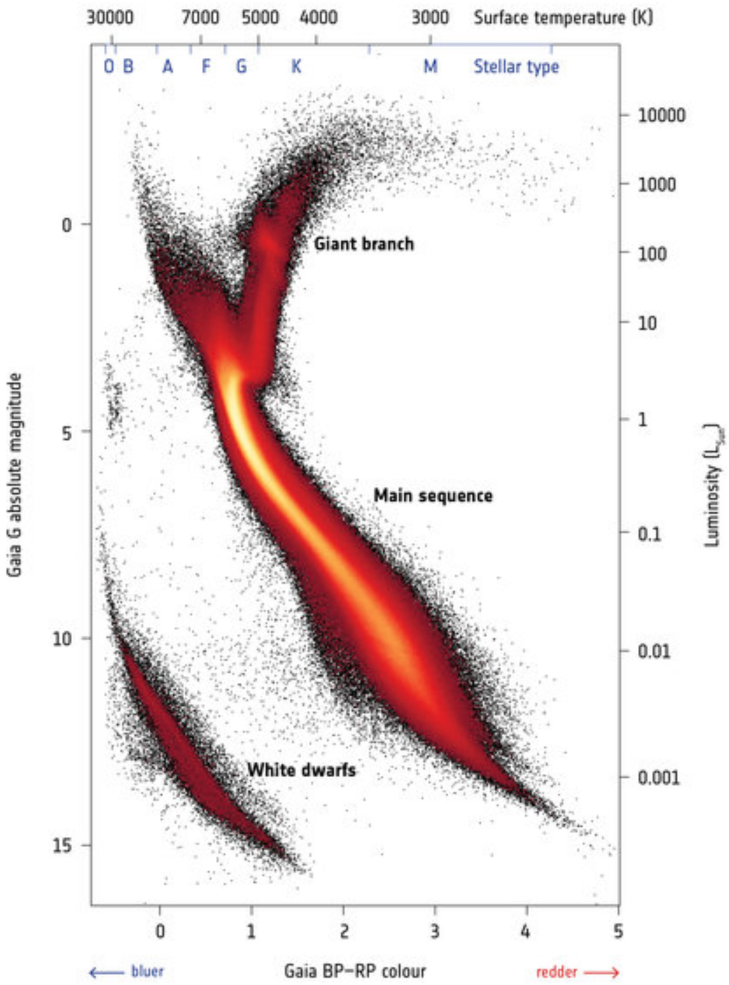
297 DR2-based papers on arXiv so far (300 between DR1 and DR2)

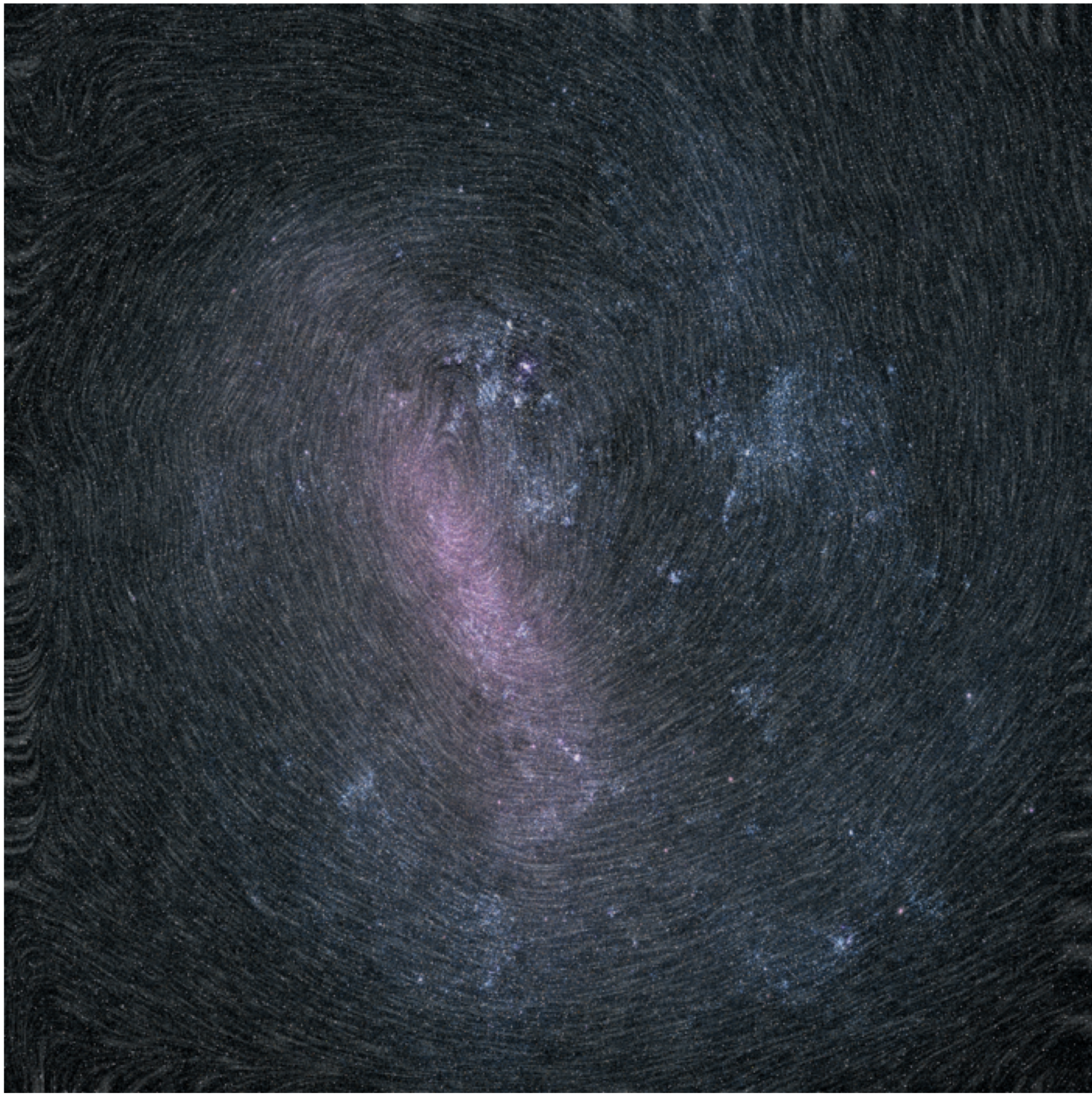
Credits: ESA/Gaia/DPAC



https://www.cosmos.esa.int/web/gaia

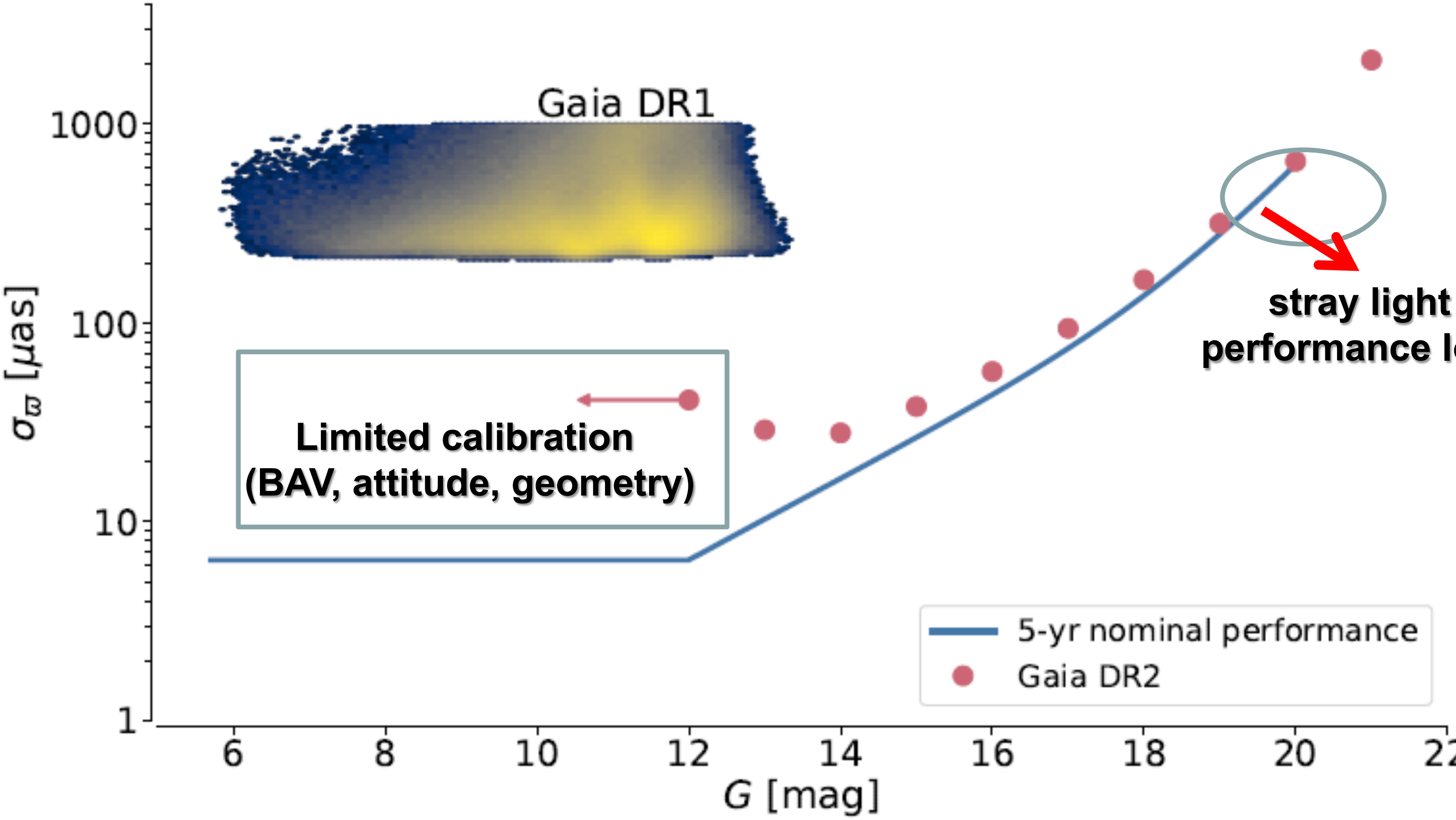
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM





Credits: ESA/Gaia/DPAC

Gaia DR2 – Astrometry (22 months of data)



Limited calibration (BAV, attitude, geometry)

stray light performance loss

Gaia Collaboration et al. 2018

After Gaia DR2

LESSONS LEARNED:

- Complex interfaces between DPAC elements
- Need to produce catalogues providing scientifically significant steps forward
- This hampers the possibility to have DRs on a yearly basis
- Orbit fitting algorithms about to start running on Gaia astrometry

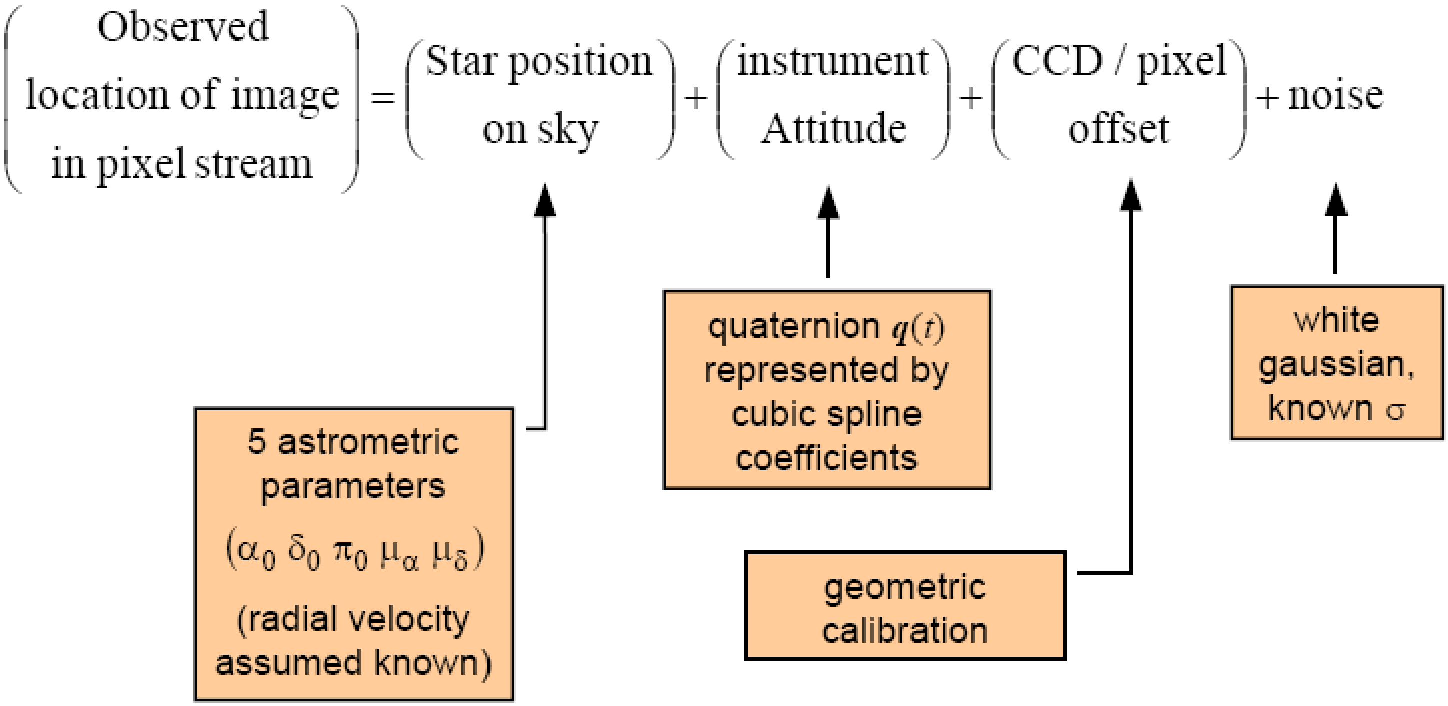
THEREFORE, NOMINALLY:

- DR3 scheduled for late 2020 (first DR with orbital solutions)
- Final DR in 2022 (three yrs after end of mission, with exoplanet catalog)
- See https://www.cosmos.esa.int/web/gaia/release

MISSION EXTENSION:

- End of 2017 approved extension for mid-2019-20
- End of 2018 preliminary scientific extension approval for 2021-22

Astrometric solution for Gaia: Formulation



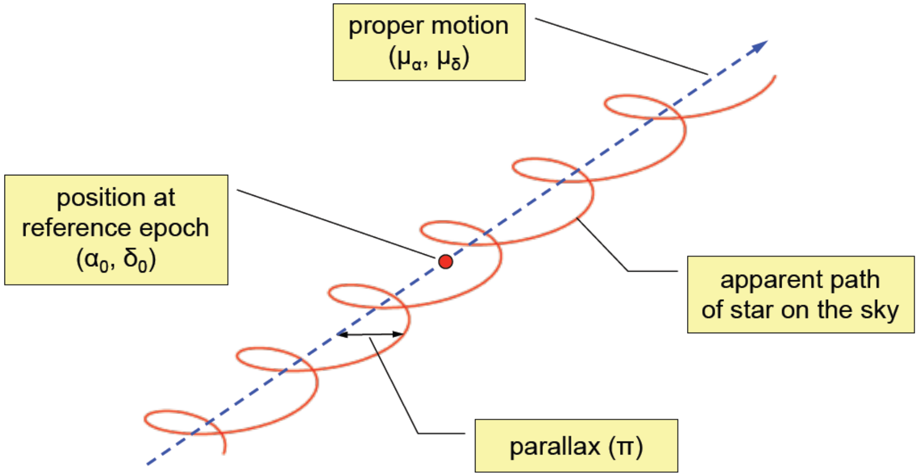
$$\begin{pmatrix}\text{Observed}\\ \text{location of image}\\ \text{in pixel stream}\end{pmatrix} = \begin{pmatrix}\text{Star position}\\ \text{on sky}\end{pmatrix} + \begin{pmatrix}\text{instrument}\\ \text{Attitude}\end{pmatrix} + \begin{pmatrix}\text{CCD / pixel}\\ \text{offset}\end{pmatrix} + \text{noise}$$

5 astrometric parameters
$(\alpha_0\ \delta_0\ \pi_0\ \mu_\alpha\ \mu_\delta)$
(radial velocity assumed known)

quaternion $q(t)$ represented by cubic spline coefficients

geometric calibration

white gaussian, known σ



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

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

> 5 billion unknowns!
> 100 billion measurements already, whew!

Astrometric Signal

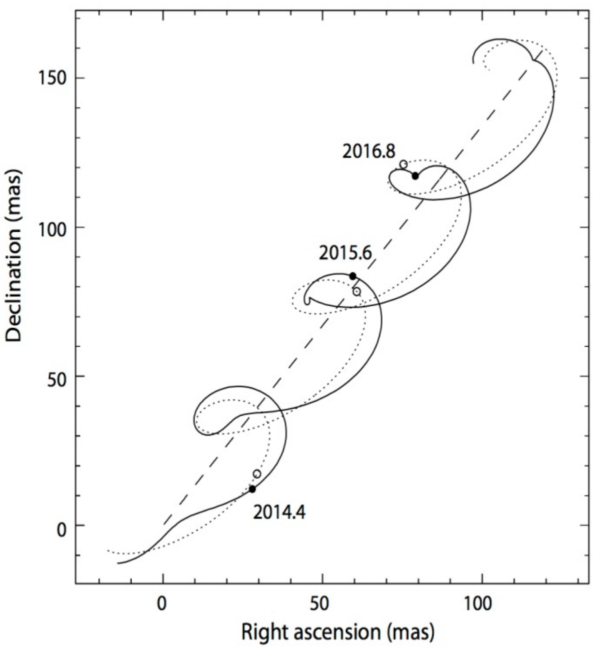
- Higher-order effect superposed to proper motion and parallax effects
- The measured amplitude of the orbital motion (in milli-arcsec) is:

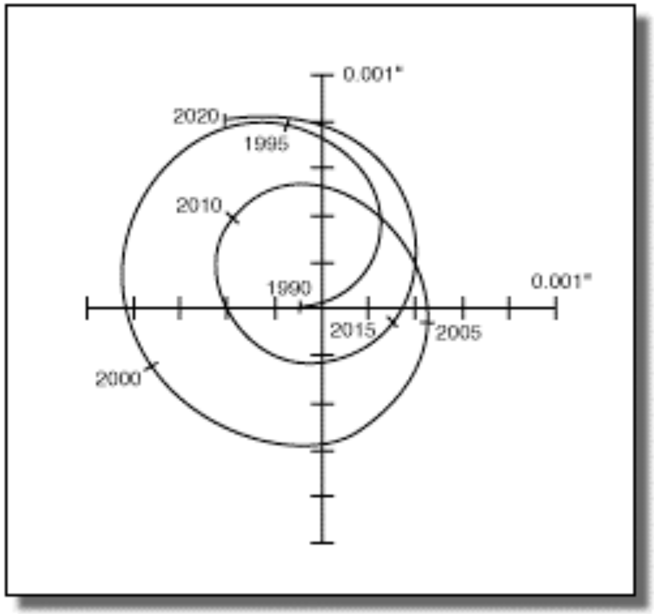
$$\Delta\theta = 0.5\left(\frac{q}{10^{-3}}\right)\left(\frac{a}{5AU}\right)\left(\frac{d}{10pc}\right)^{-1}$$

With $q=M_p/M_*$

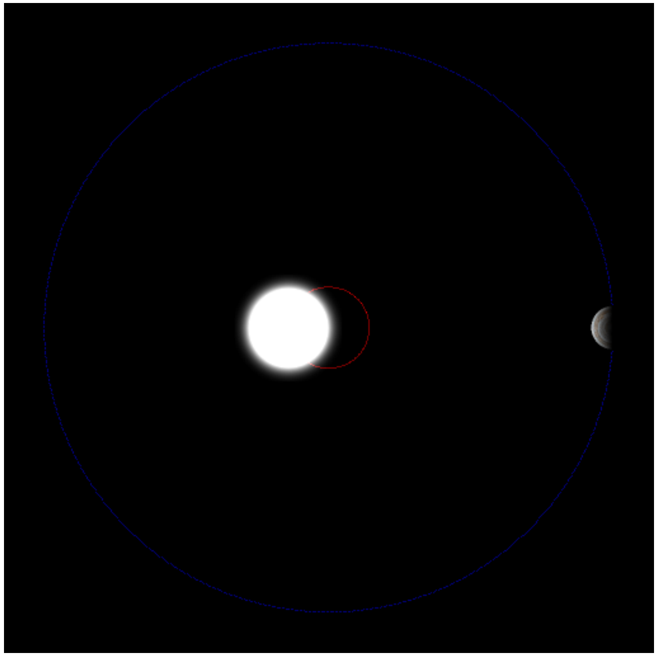
-> Given a guess for the primary, one derives the planet's actual mass

-> In multiple systems, the mutual inclination angle can be measured

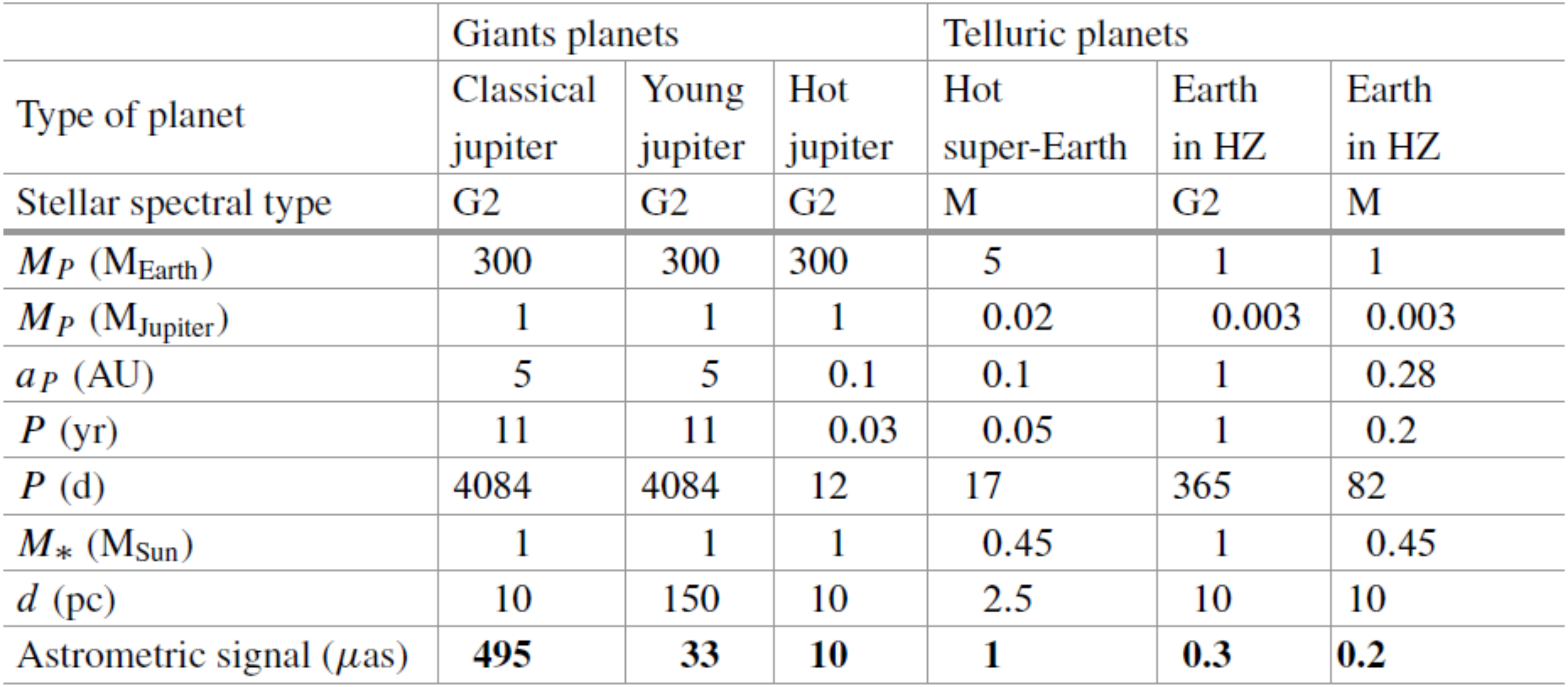




Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.



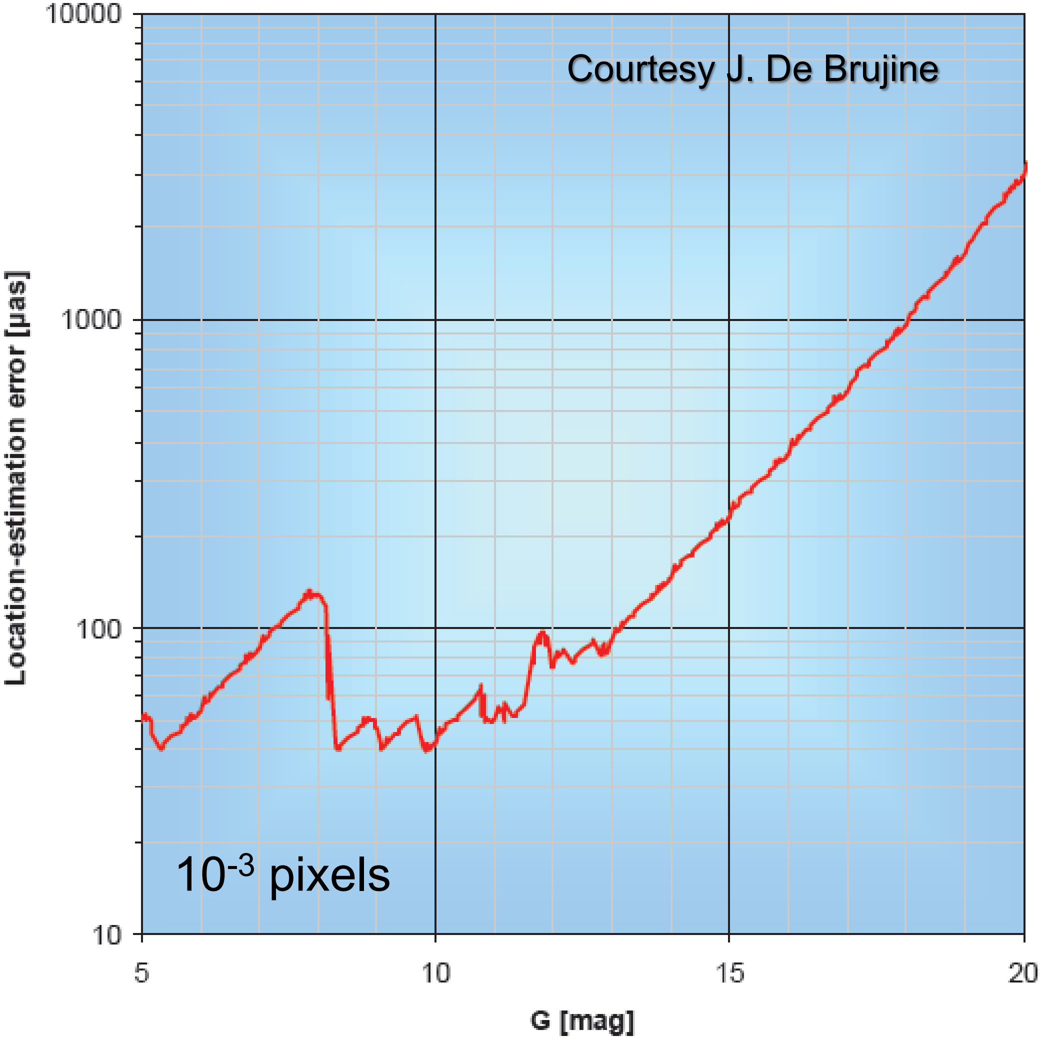
Habitable Earths: Not Gaia’s Thing?



	Giants planets			Telluric planets		
Type of planet	Classical jupiter	Young jupiter	Hot jupiter	Hot super-Earth	Earth in HZ	Earth in HZ
Stellar spectral type	G2	G2	G2	M	G2	M
M_P ($M_{\rm Earth}$)	300	300	300	5	1	1
M_P ($M_{\rm Jupiter}$)	1	1	1	0.02	0.003	0.003
a_P (AU)	5	5	0.1	0.1	1	0.28
P (yr)	11	11	0.03	0.05	1	0.2
P (d)	4084	4084	12	17	365	82
M_* ($M_{\rm Sun}$)	1	1	1	0.45	1	0.45
d (pc)	10	150	10	2.5	10	10
Astrometric signal (μas)	**495**	**33**	**10**	**1**	**0.3**	**0.2**

Malbet & Sozzetti 2018

Single-Measurement Error

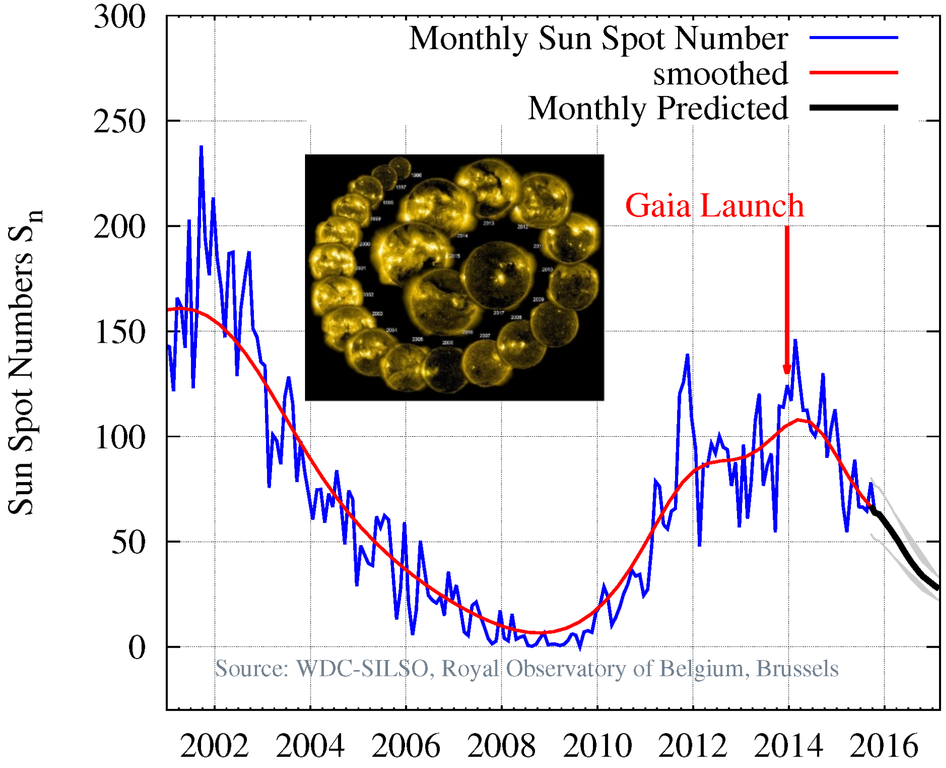


Based on Monte Carlo simulations, including “everything”: e.g., CCD QE + MTF, telescope wave-front errors + transmission + optical distortion, LSF smearing due to attitude jitters + TDI motion, CCD noise + offset non-uniformity, radiation damage-induced chargeloss + bias calibration, sky background,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

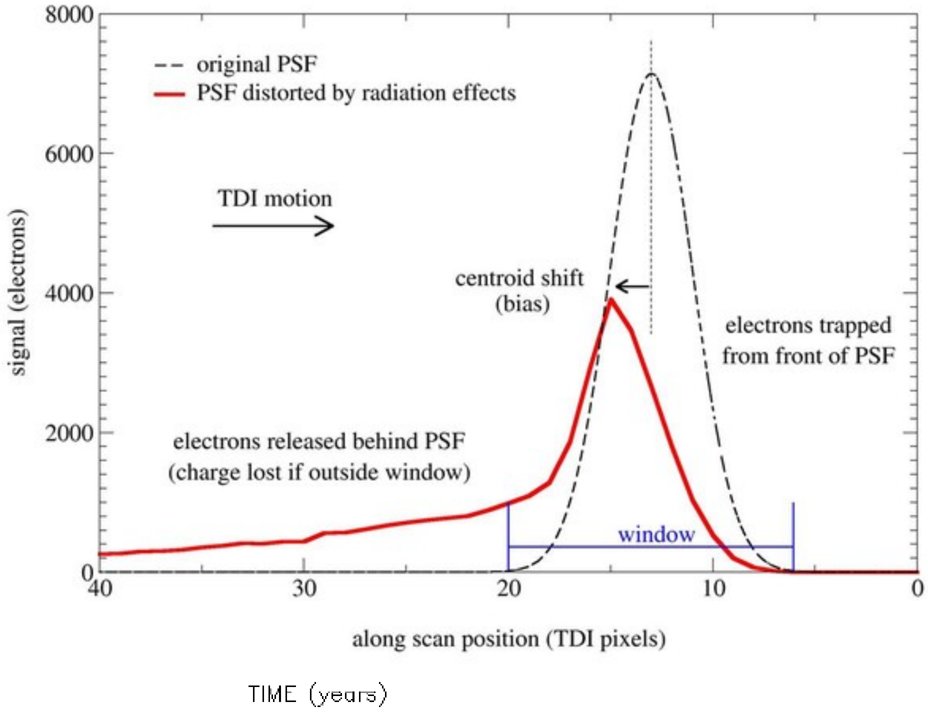
$$\sigma_A = \sqrt{\sigma^2{}_\eta + \sigma^2{}_{att} + \sigma^2{}_{cal}}$$

For G < 13 mag: σ_A ~ 15-20 µas (there are 9 CCDs in a transit measurement)

The Solar Cycle Impact



Source: WDC-SILSO, Royal Observatory of Belgium, Brussels



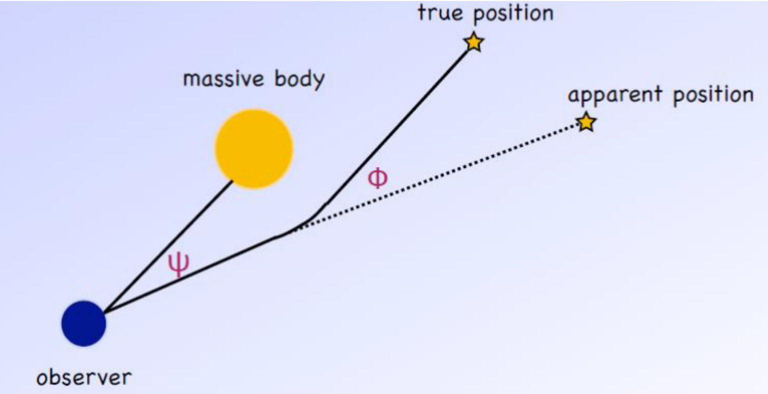
Solar radiation damage creates permanent electron traps in the CCD

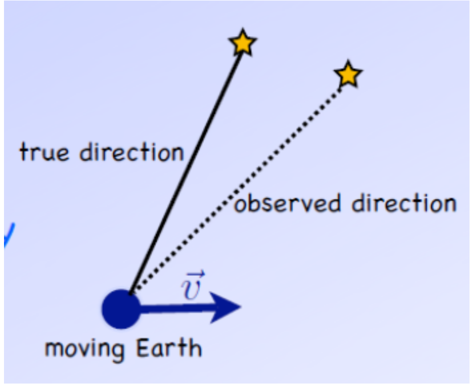
These systematically distort the PSF and reduce the collected signal

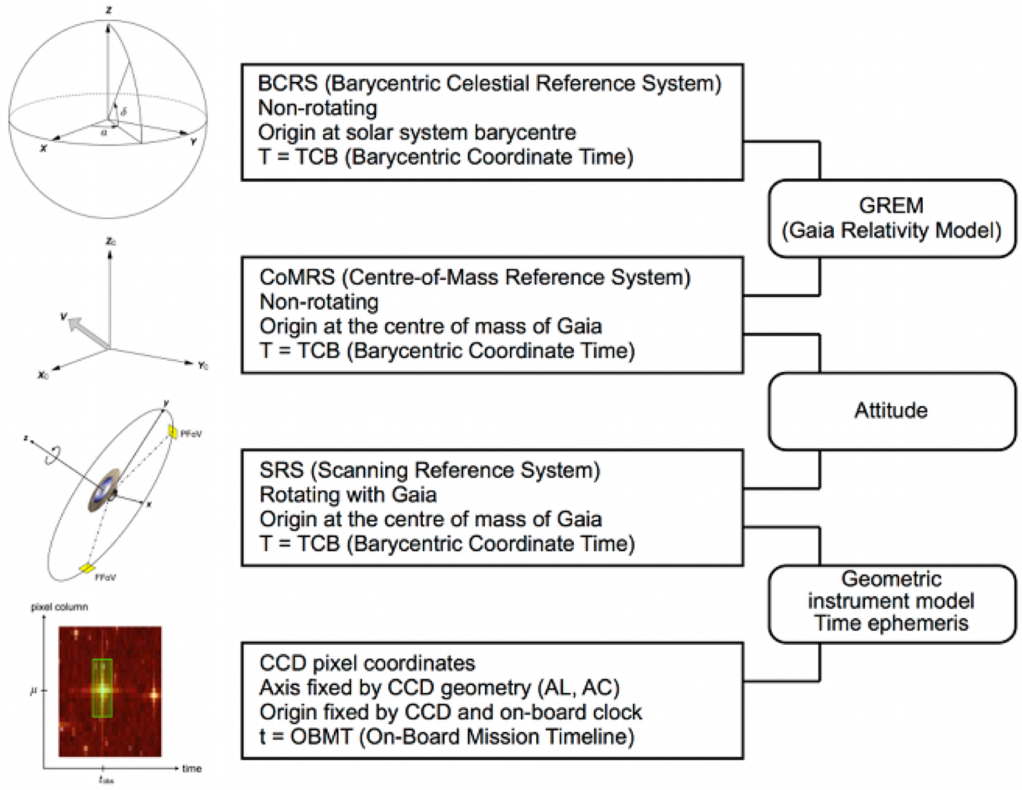
PSF distortion induces position biases → on-ground calibration

Residual errors degrade the astrometric performance by ~5–10%

Light Deflection / Aberration







BCRS (Barycentric Celestial Reference System)
Non-rotating
Origin at solar system barycentre
T = TCB (Barycentric Coordinate Time)

GREM
(Gaia Relativity Model)

CoMRS (Centre-of-Mass Reference System)
Non-rotating
Origin at the centre of mass of Gaia
T = TCB (Barycentric Coordinate Time)

Attitude

SRS (Scanning Reference System)
Rotating with Gaia
Origin at the centre of mass of Gaia
T = TCB (Barycentric Coordinate Time)

Geometric
instrument model
Time ephemeris

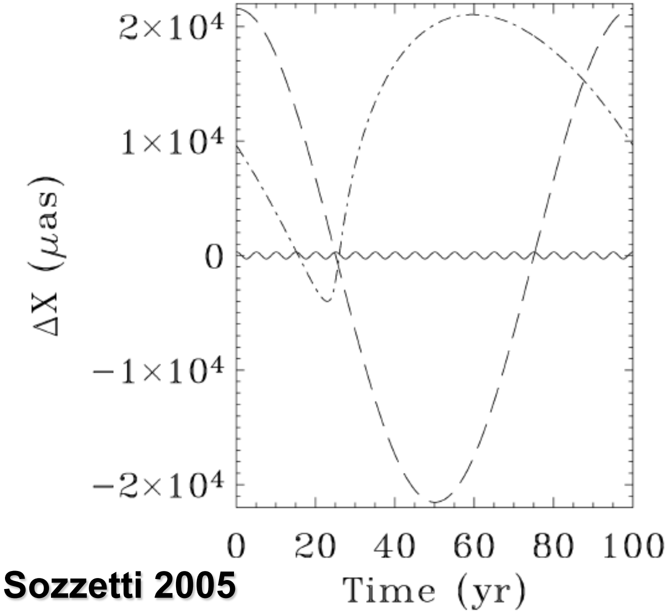
CCD pixel coordinates
Axis fixed by CCD geometry (AL, AC)
Origin fixed by CCD and on-board clock
t = OBMT (On-Board Mission Timeline)

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

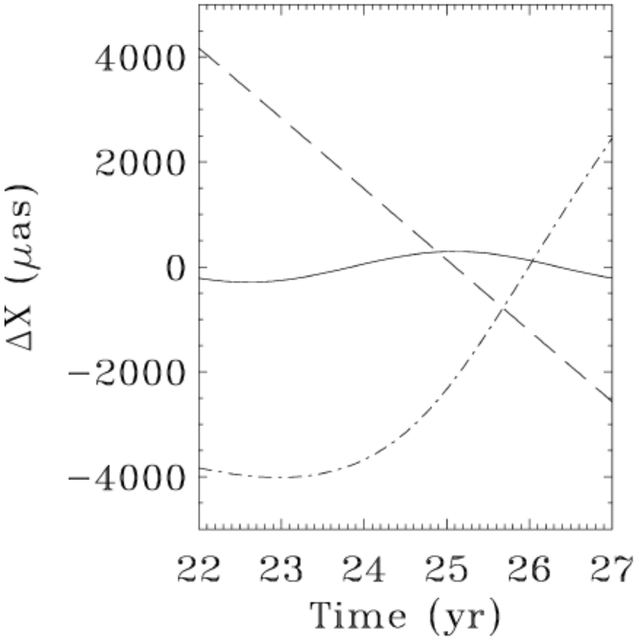
$$\alpha_{\mathrm{defl}} = \frac{(1+\gamma)GM}{R_0 c^2}\cot\frac{\psi}{2},$$

Sozzetti 2005

Stellar Binaries / Surface Structures

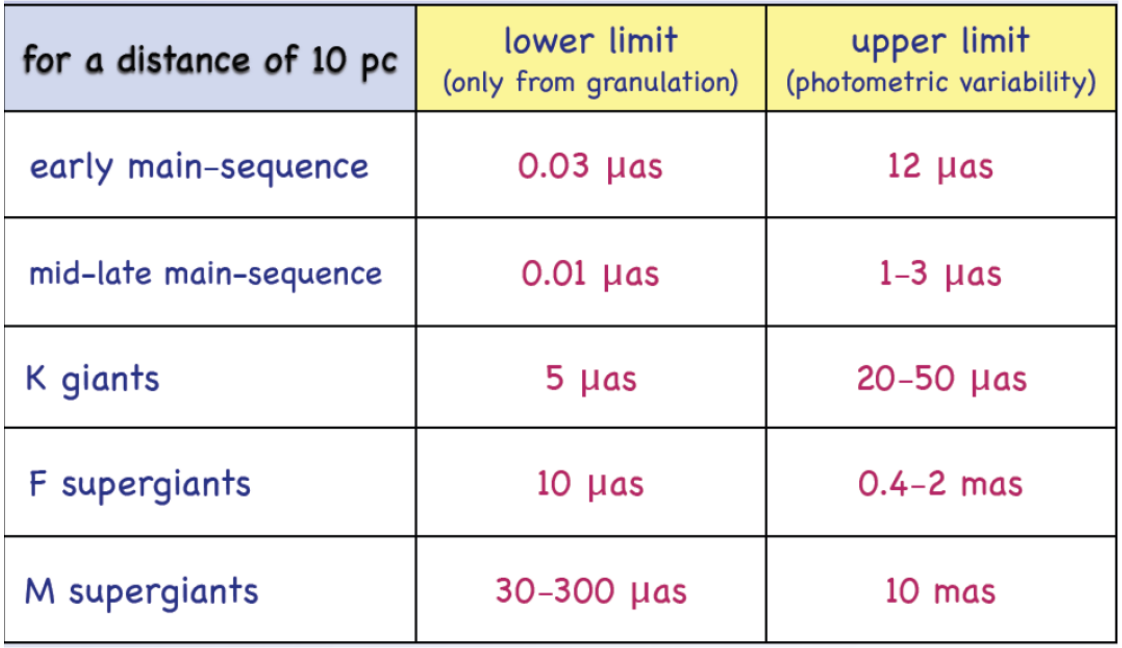


Sozzetti 2005



And Stellar Rotation?
No problem, whew!

Activity-induced astrometric Jitter



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

Orbits with Gaia

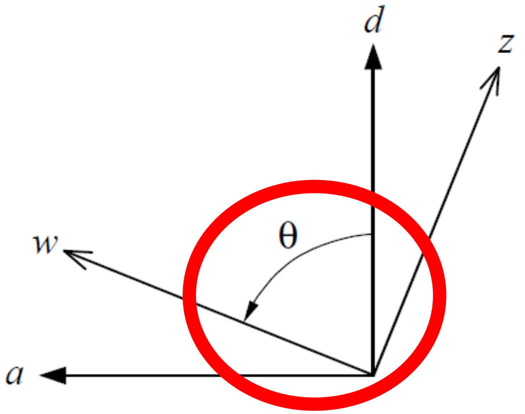
In the plane of the sky:

Astrometric parameters **Planet parameters**

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

Rotate by a scanning angle:

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



Solve for:

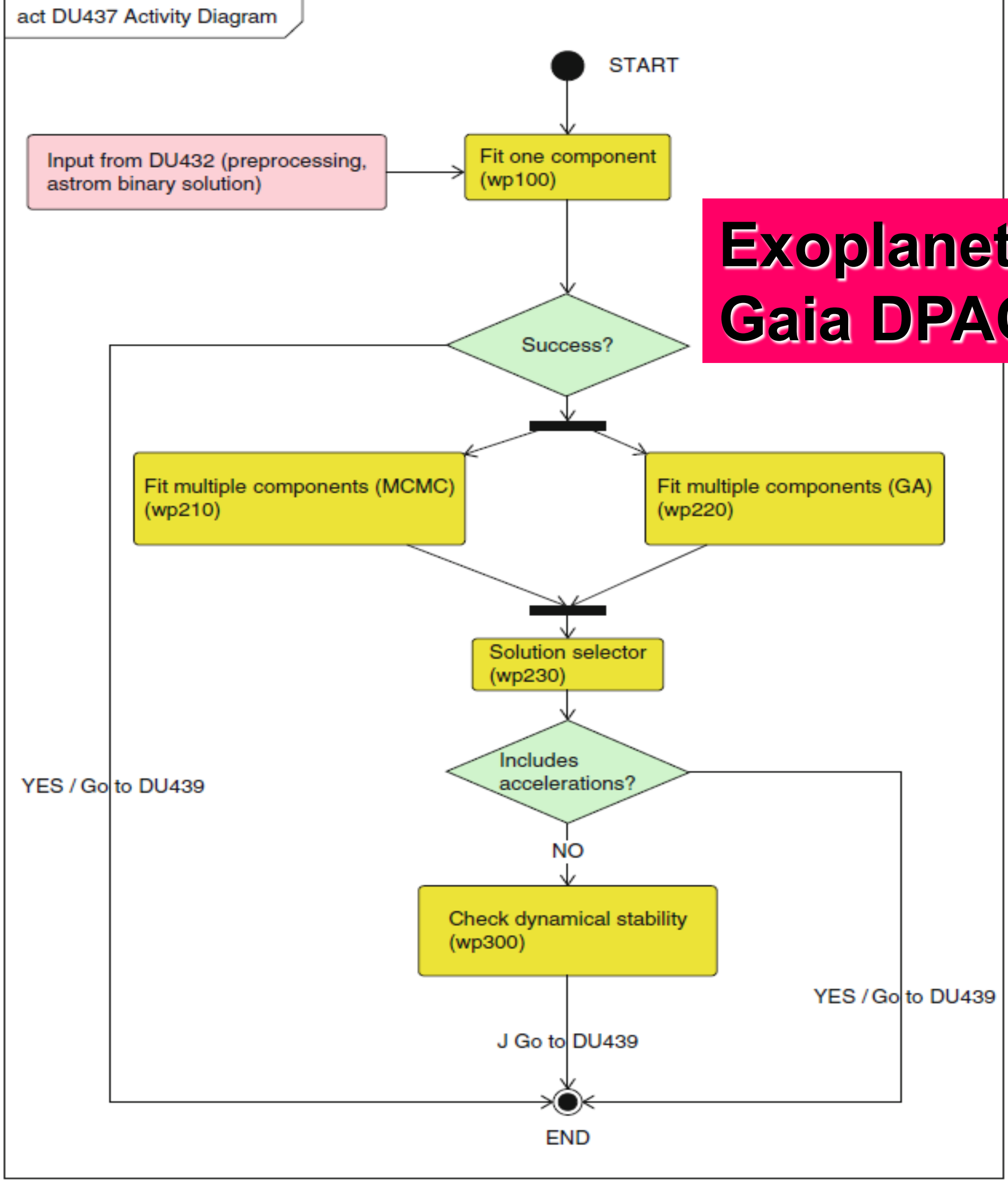
$$\left.\begin{aligned} w &= sa_T + cd_T + (t-T)s\mu_{\alpha*} + (t-T)c\mu_\delta + f_w\pi + XcA + XsB + YcF + YsG \\ z &= -ca_T + sd_T - (t-T)c\mu_{\alpha*} + (t-T)s\mu_\delta + f_z\pi + XsA - XcB + YsF - YcG \end{aligned}\right\}$$

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

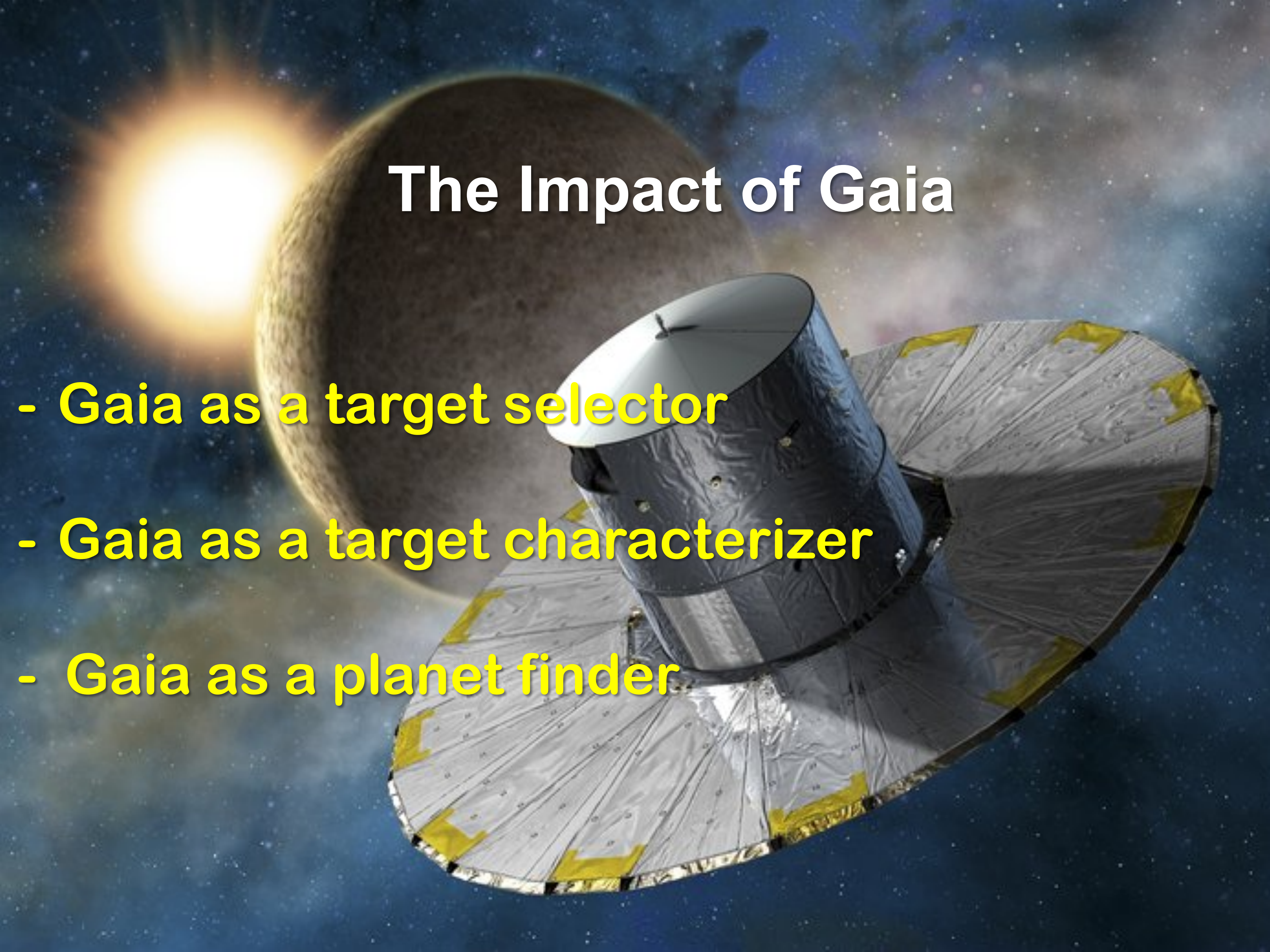
Planetary Systems Orbits

- Highly non-linear fitting procedures, with a large number of model parameters (at a minimum, N_p=5+7*n_{pl}).
  -> Redundancy requirement: $N_{obs} \gg N_p$
- 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
- Confidence in an n-component orbital solution: FAPs, F-tests, MLR tests, statistical properties of the errors on the model parameters, BIC, AIC, BF… You name it!
- Importance of consistency checks between different solution algorithms (Memento lessons learned from RVs!)

Exoplanets in the Gaia DPAC Pipeline



The Impact of Gaia



- Gaia as a target selector

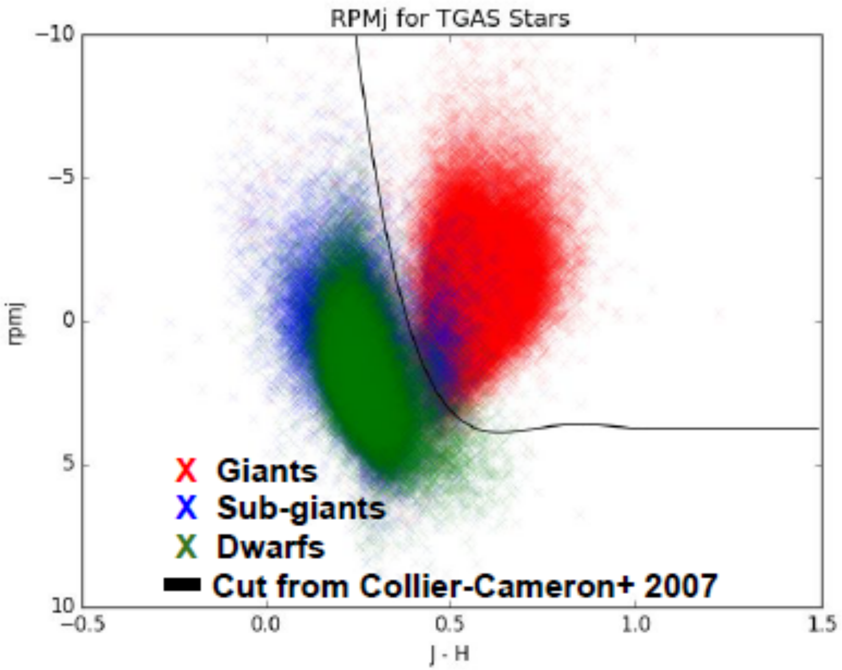
- Gaia as a target characterizer

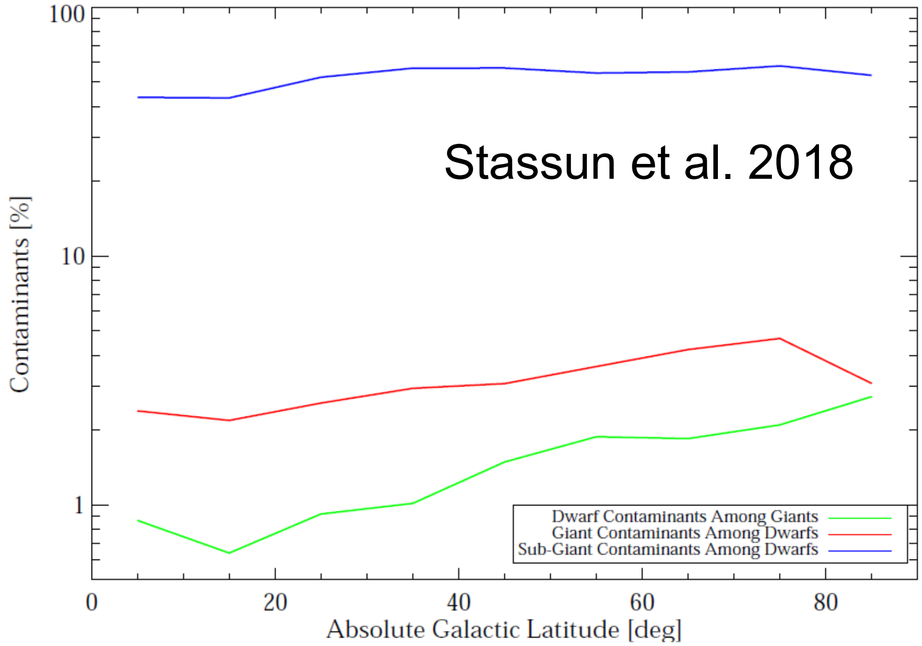
- Gaia as a planet finder

Populating the TIC/PIC

- Gaia is the primary source for target selection in the input catalogs of both TESS (launched April 18th, 2018) and PLATO (coming a little later…)

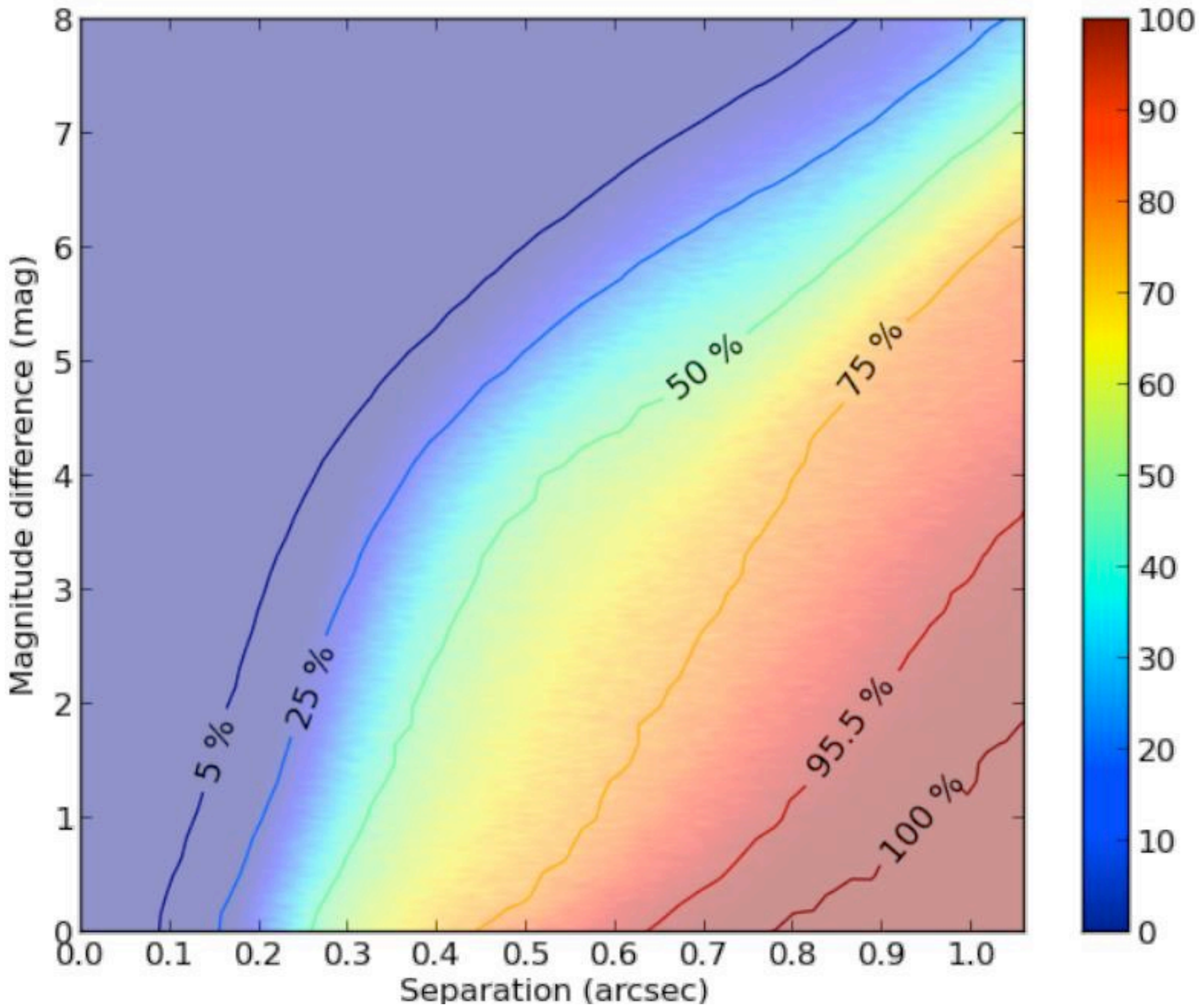
- Using G mag, parallax, Teff/logg info will allow to limit 'contaminants' (unwanted spectral classes) to <0.1% (with ALL later than F5V stars identified)





Stassun et al. 2018

Know what's in thy pixels



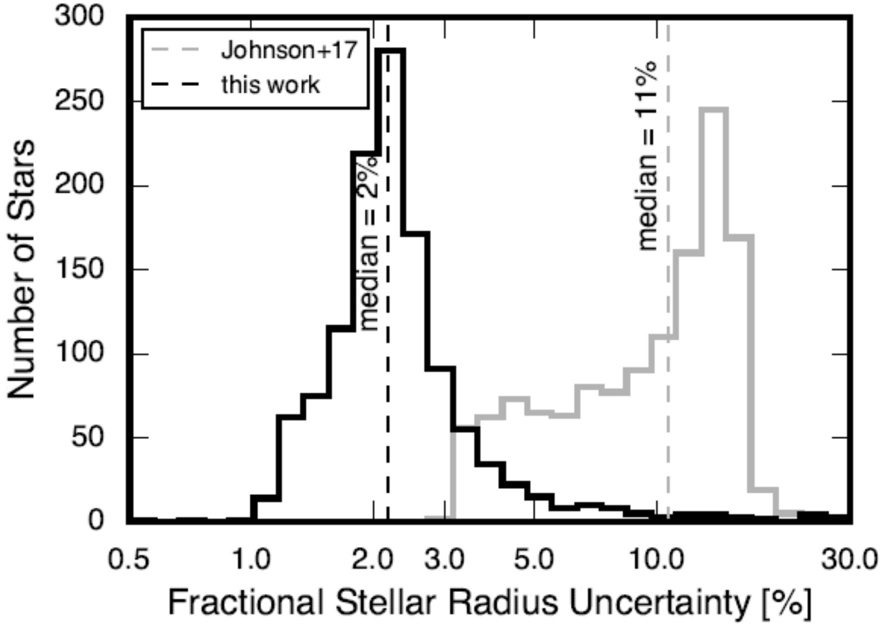
Fundamental insights on a variety of classes of contaminants causing false positives and transit depth dilution

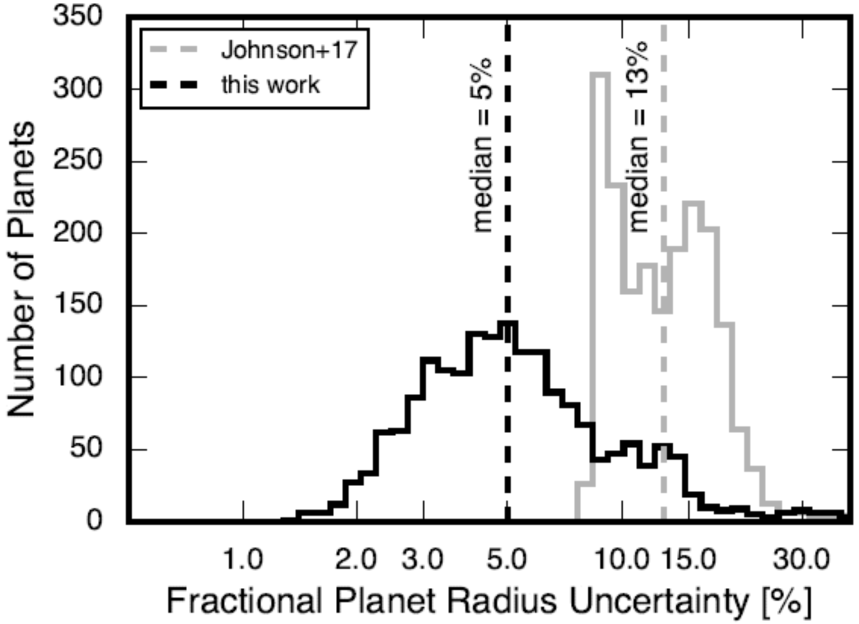
Mind you:
Independent of magnitude of the primary

de Brujine et al. 2015

Calibration of the Hosts

Take Gaia parallaxes, and then do it your way!



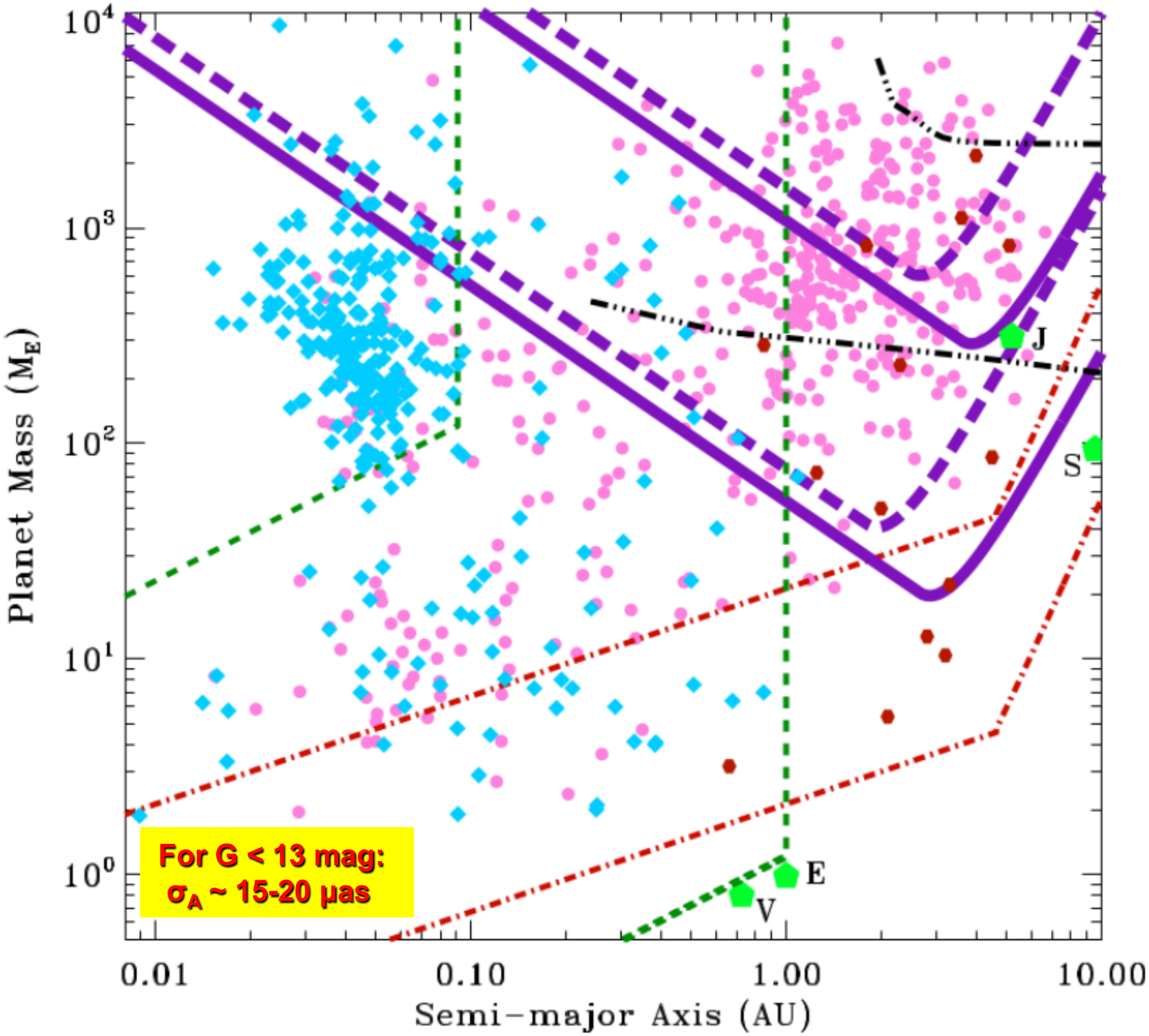


Fulton & Petigura 2018

DR2:
Bright (V<13) F-G-K stars (D<300-400 pc) and not very faint (V<16) M dwarfs (D<50-60 pc) have distances determined to 5%, or better

➡ **Derive 'accurate' stellar (and planetary) radii to within 5% or better**

Gaia Discovery Space



For G < 13 mag: σ_A ~ 15-20 μas

Unbiased, magnitude-limited planet census of maybe 10^6-10^7 stars

>10^4 NEW gas giants (< 15 M_{JUP}) around A through M dwarfs Numbers might as much as triple for a 10-yr mission

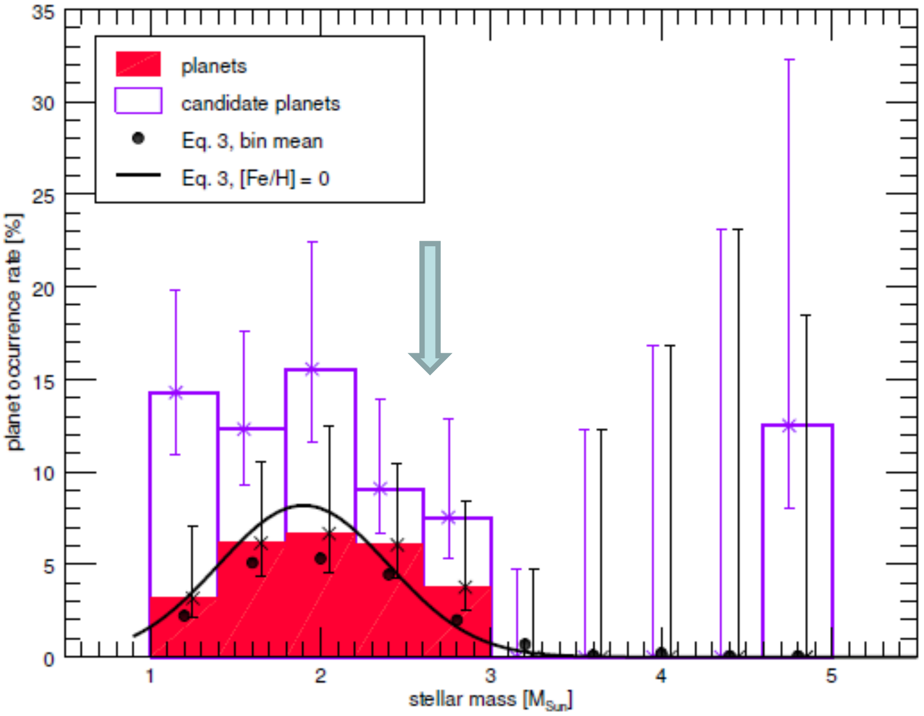
Lattanzi et al. 2000,
Sozzetti et al.2001
Casertano et al. 2008
Perryman et al. 2014
Sozzetti et al. 2014
Sahlmann et al. 2014

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, age, and multiplicity with unprecedented resolution

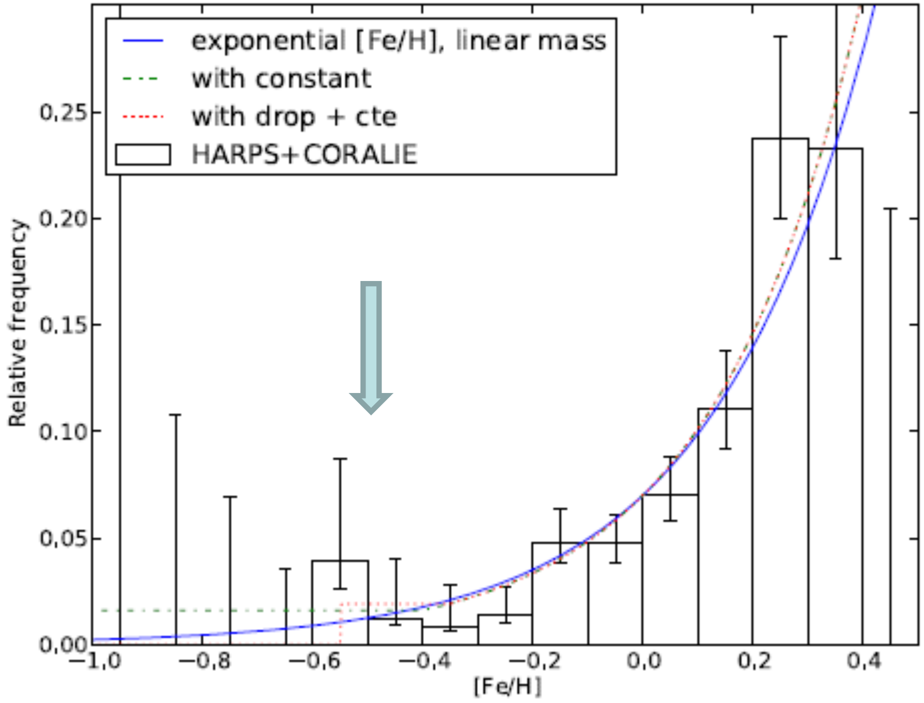
M_*, [Fe/H]: Frequencies

Gaia: 10^4 stars in a bin!

Today: 10^2 stars in a bin!

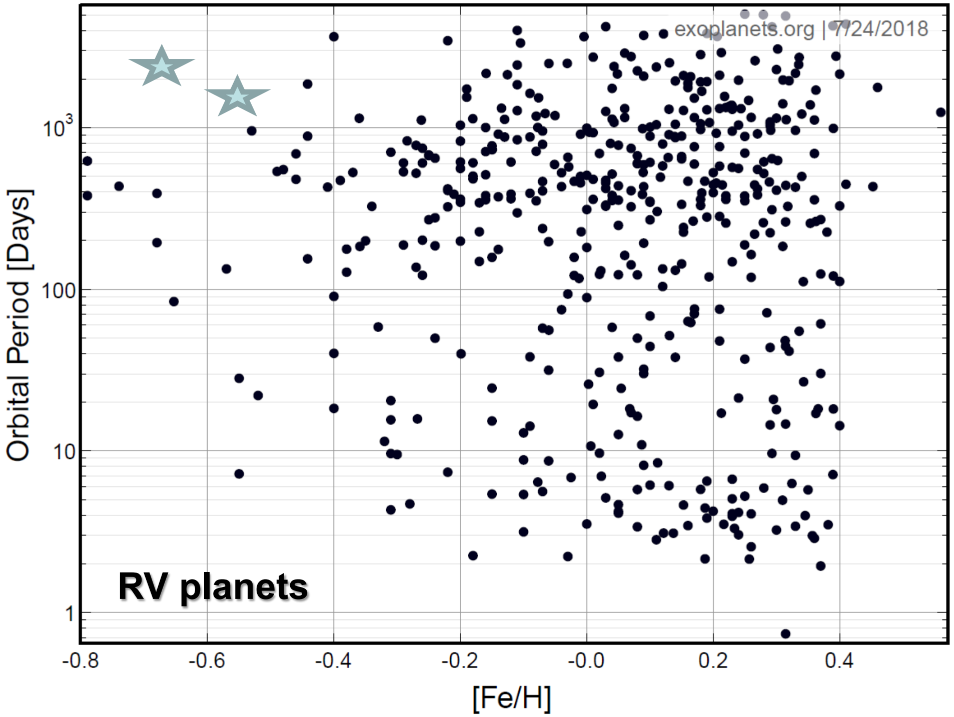


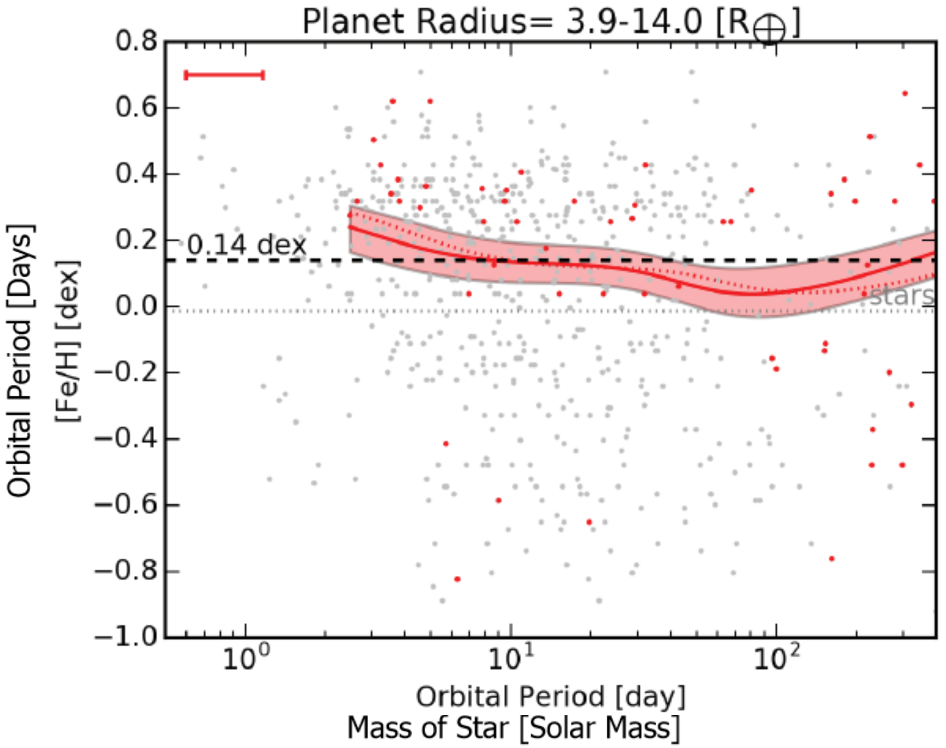
Johnson et al. 2010, Reffert et al. 2015



Mortier, Santos, Sozzetti et al. 2012, Mortier et al. 2012

M_*, [Fe/H]: Correlations



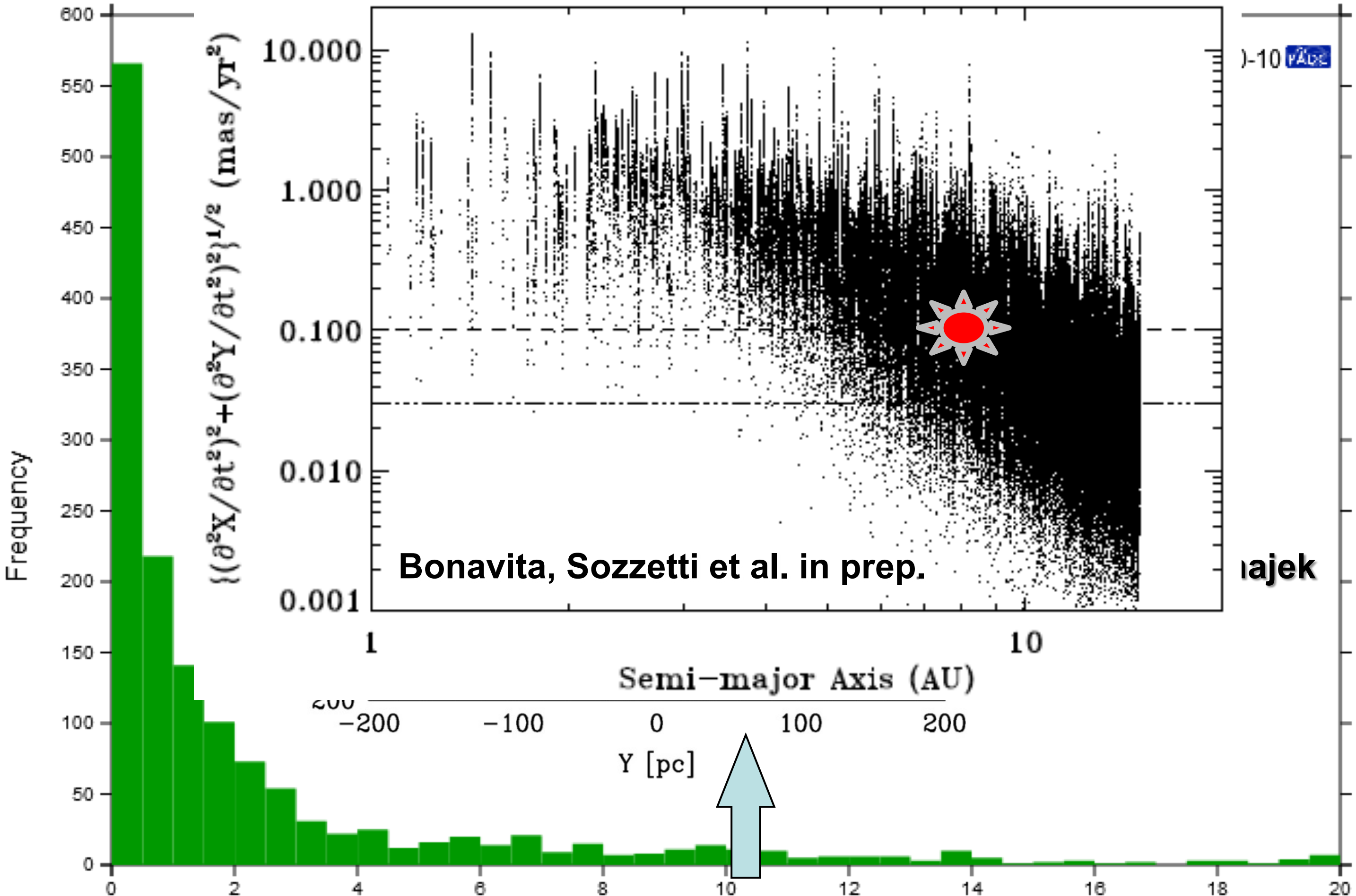


Santos et al. 2017 **Thorngren et al. 2016** **Sozzetti 2004** **Mulders et al. 2016**

- Are more massive planets preferentially found around more massive primaries?
- Do lower- and higher-mass star only host longer-period companions?
- Are more massive planets preferentially found around low-[Fe/H] primaries?
- Do low-[Fe/H] stars host longer-period companions?
- What is the actual [Fe/H] limit for giant planet formation?

Gaia will allow you to answer with 10x more planets!

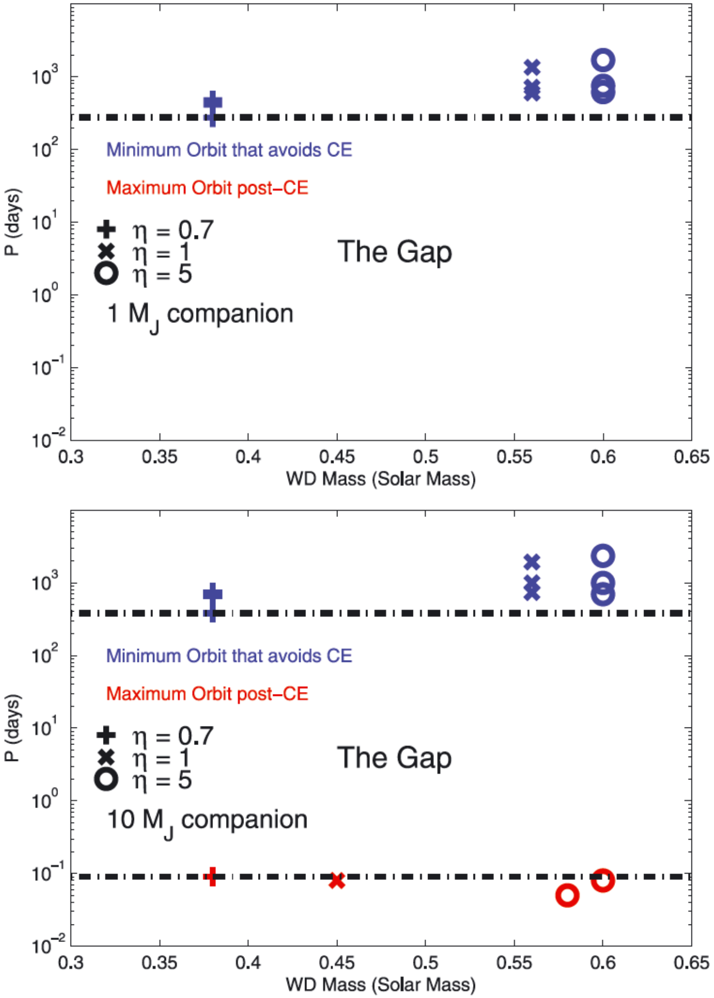
Gaia and Young Stars



Accelerations in Gaia astrometry from companions orbiting the SPHERE GTO target sample with V < 12, d < 50 pc

Unique explorat **anions to**
1000s of young **accesible to DI**

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

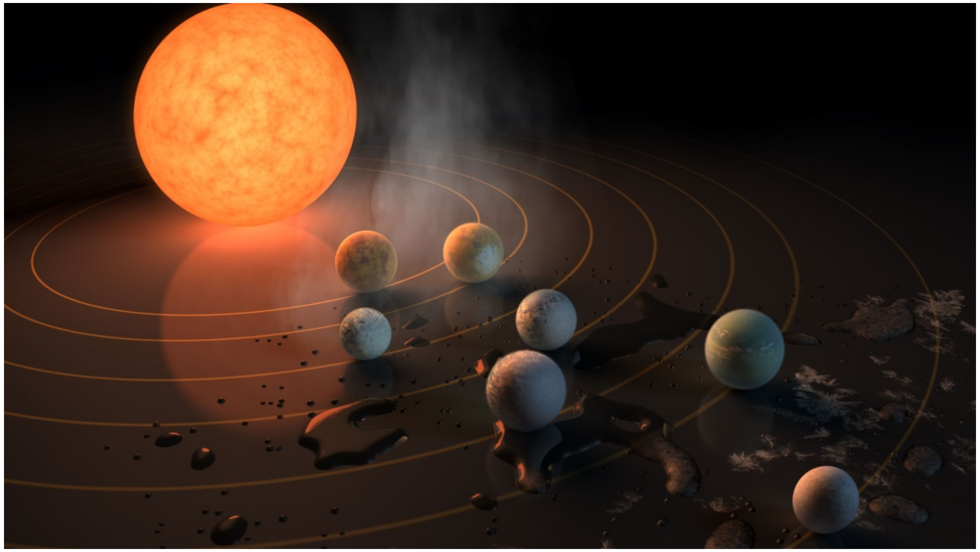
Silvotti, Sozzetti, & Lattanzi, 2015

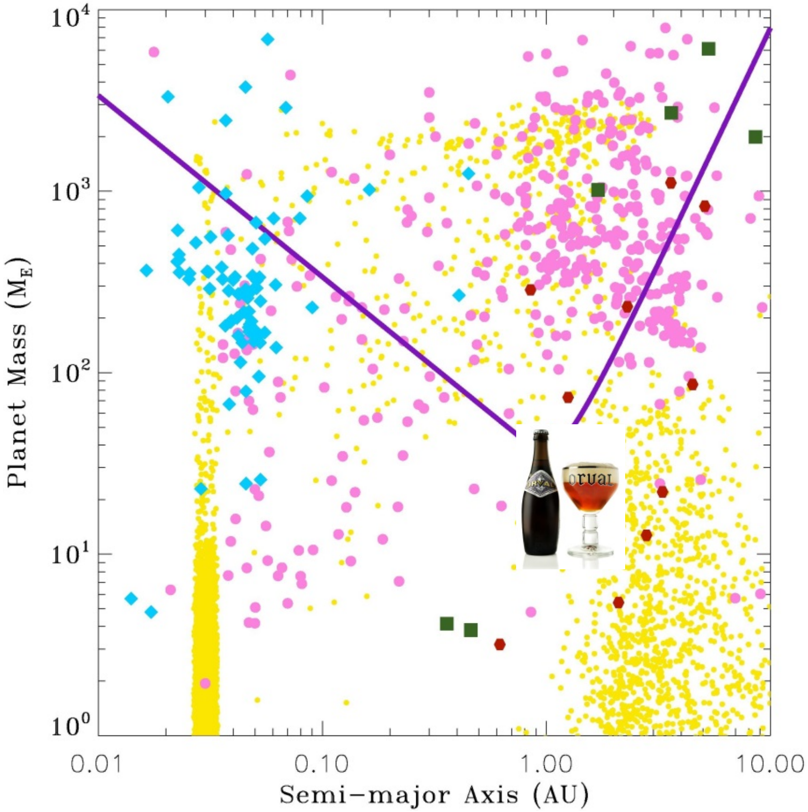
Gaia will perform THE observational test of theoretical predictions related to: A) post-MS planet evolution & B) 2nd generation planet formation

Gaia & UCD Planets

Gaia detection limits for Luhman 16 AB

Trappist-1 is 1.5 mag brighter:
Gaia might be sensitive to cold Neptunes!

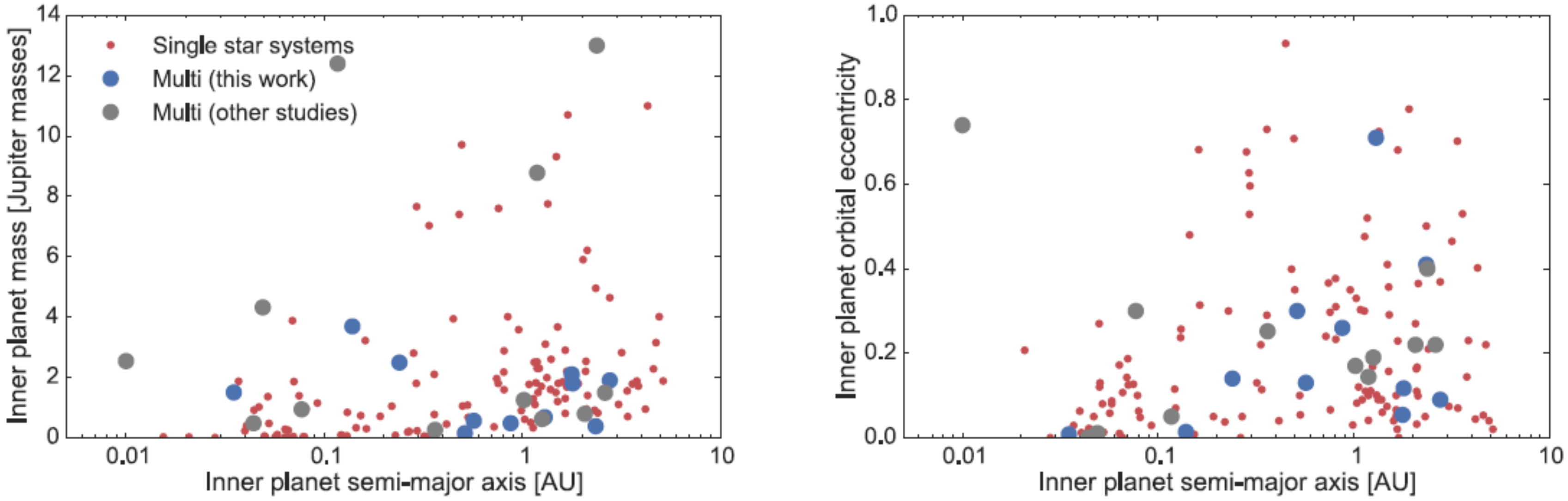




- Found so far only in microlensing events
- Gaia will see ~1000 UCDs of all ages, with sufficient astrometric sensitivity to giant planets within 2-3 AU
- A fundamental test of planet formation!

Sozzetti (Mem. SAIt, 2014)

Gaia and Planets in Binaries



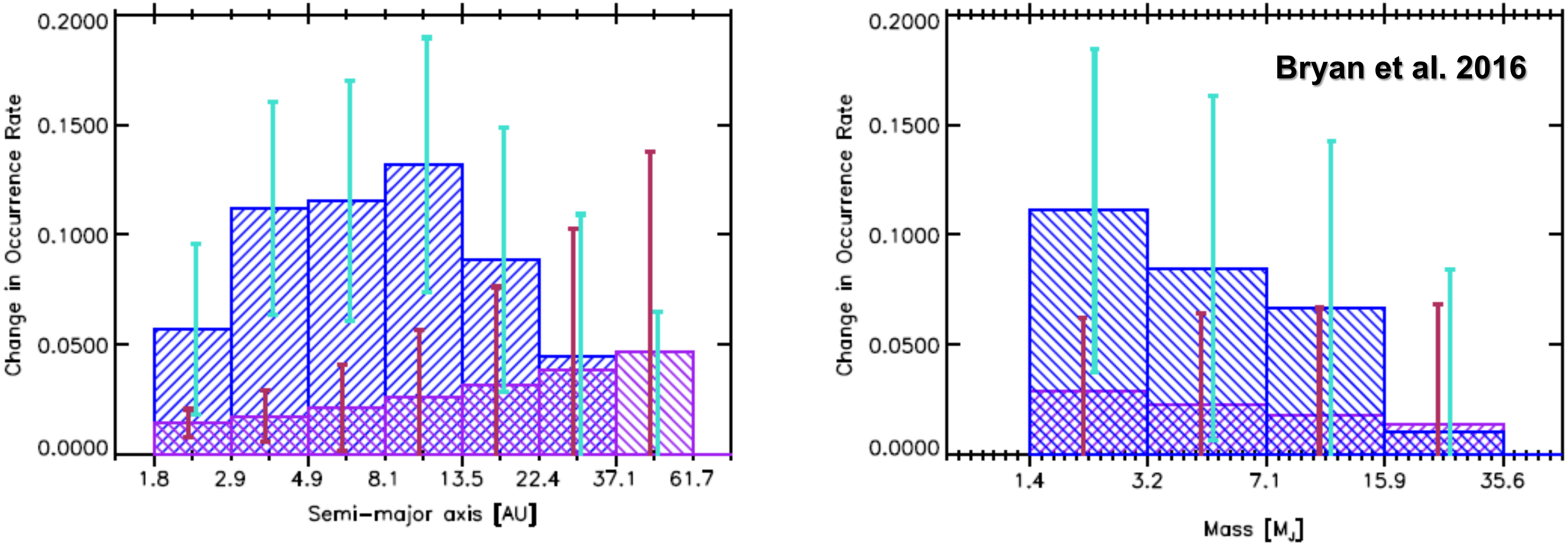
Ngo et al. 2017, but see Moutou et al. 2017

- Are orbital elements distribution of planets in binaries and around single stars the same?
- Are the orbital architectures of giant planet systems in binaries the same as those of planets around single stars?
- How do frequencies depend on binary separation?
- What about all these questions in the circumbinary case?

Gaia is sensitive to giant planets around >10^6 stars: > 50% will be binaries!

Gaia & Multiple Systems

>50% of 1-GP systems has additional massive companions



Bryan et al. 2016

- Combine Perryman et al. (2014) and Casertano et al. (2008) results:
- $T_{mission}$= 5 yr:
  >2500 two-planet systems with σ(M)<15%-20%, some 250 I_{rel} measurements
- $T_{mission}$= 10 yr:
  >6000 two-planet systems with σ(M)<15%-20%, some 600 I_{rel} measurements

Gaia Astrometry And Transiting Giant Planets

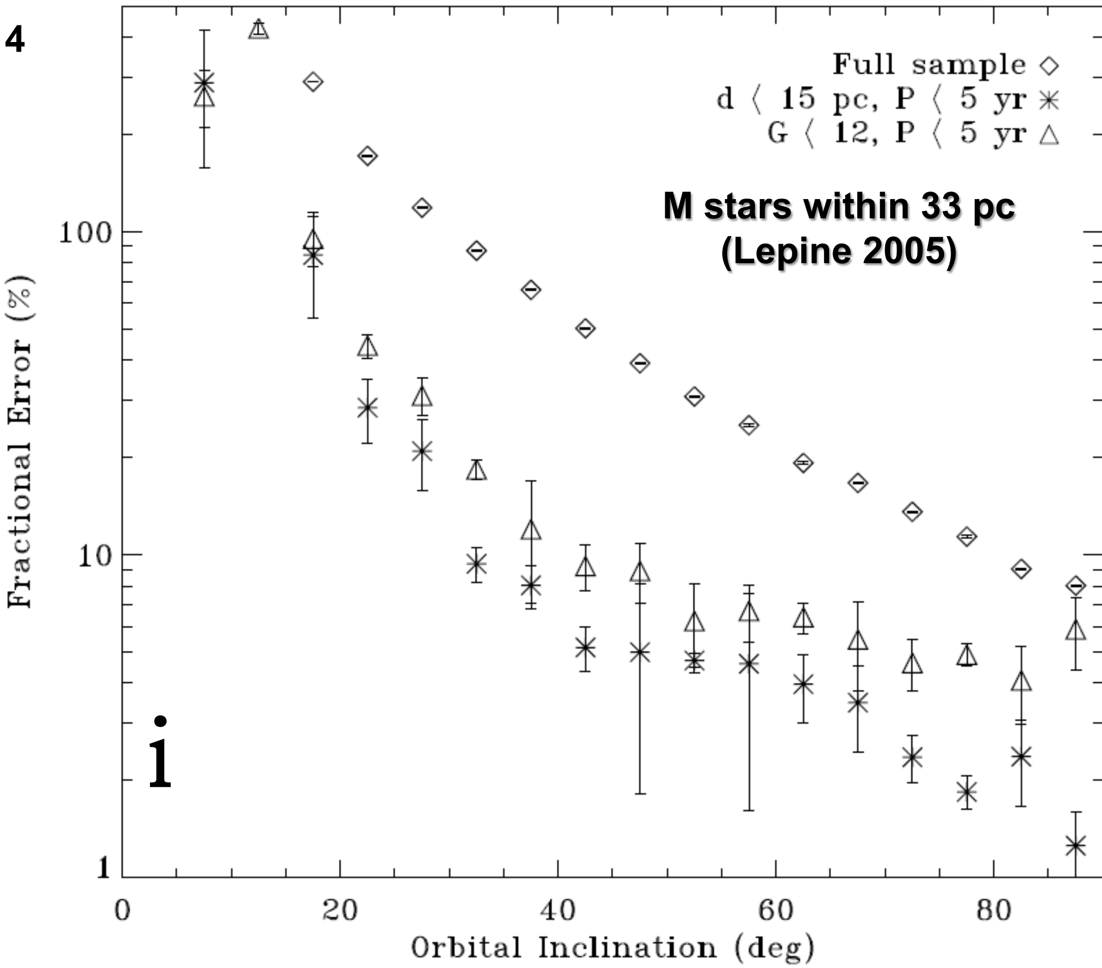
Sozzetti et al. 2014, Perryman et al.2014

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!

RV follow-up will be KEY

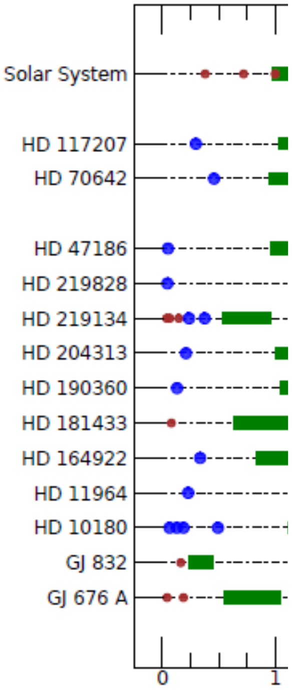
And don't rule out Gaia's help for Kepler, K2, TESS, and PLATO single transit events

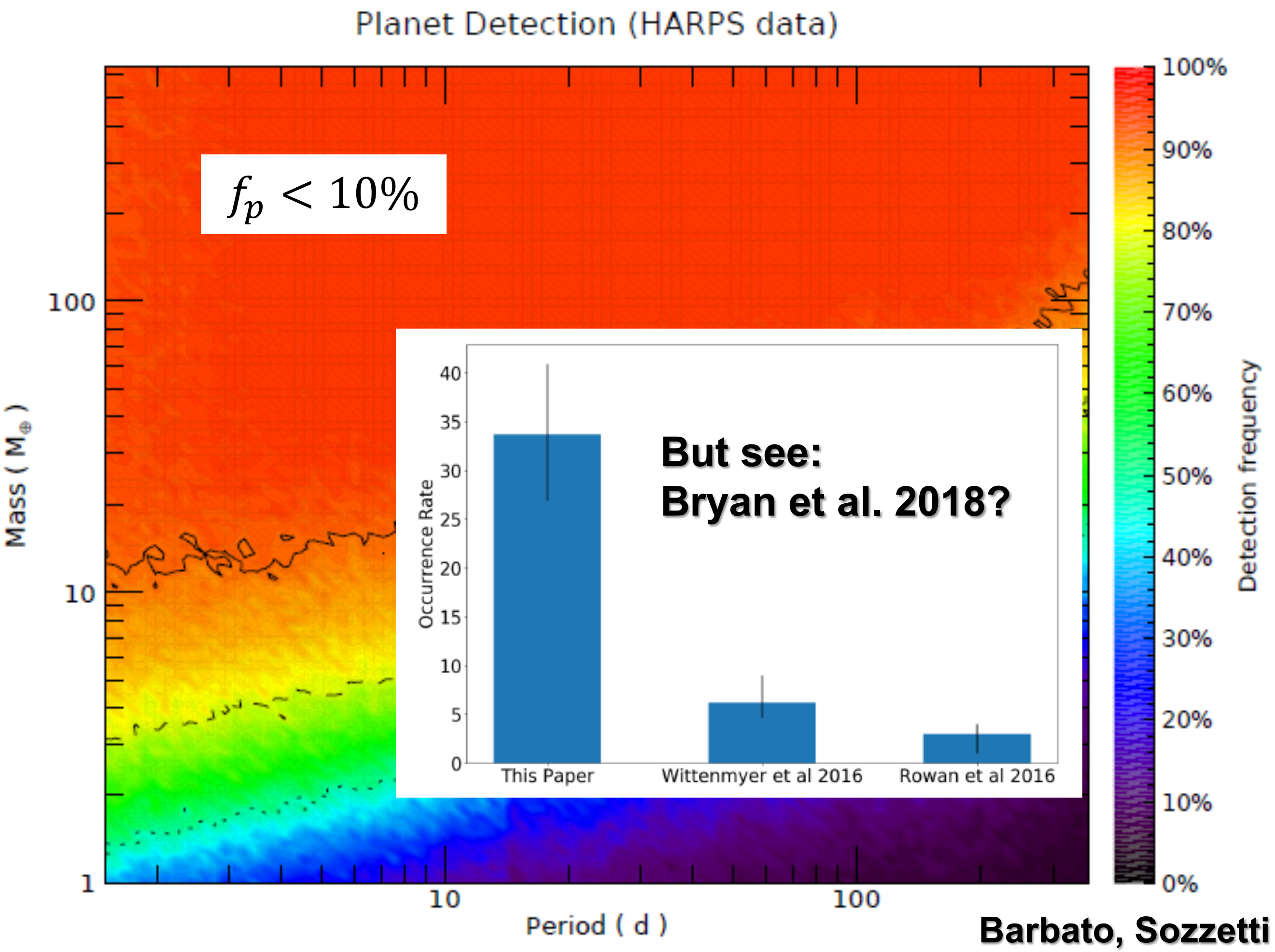


M stars within 33 pc (Lepine 2005)

Follow-up efforts, possible targets for JWST

η_E and Solar System analogs





$f_p < 10\%$

But see:
Bryan et al. 2018?

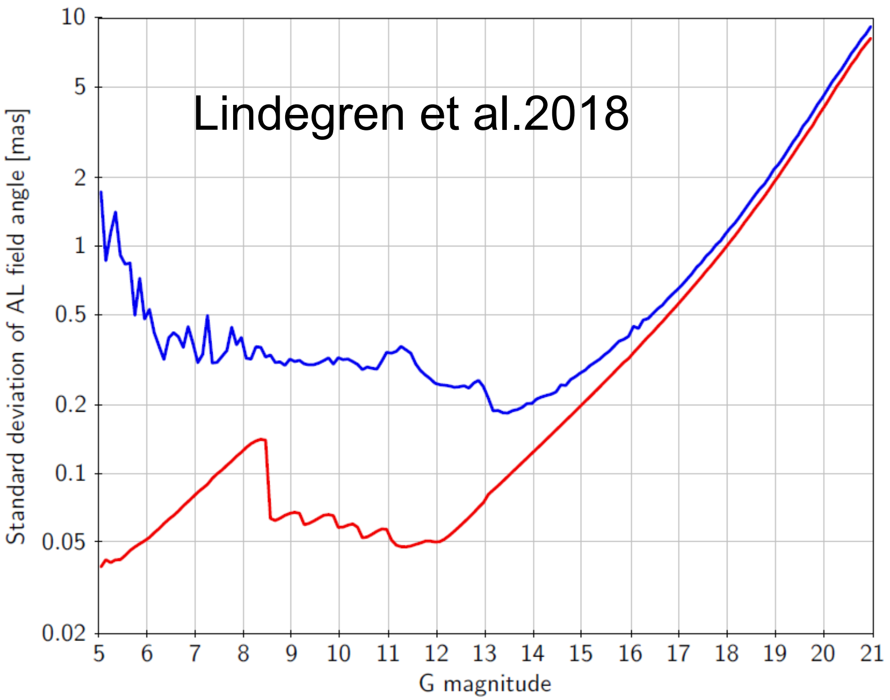
nets"

e	Reference
	1
	2
	3
	4
	5
	6
	7
	8
	9

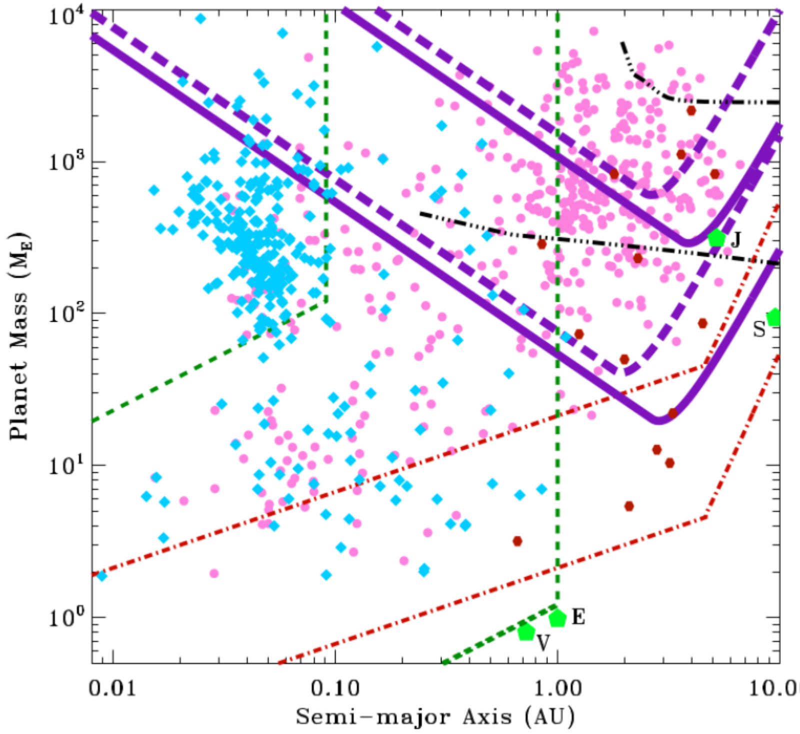
Barbato, Sozzetti et al. 2018

A 10-yr Gaia mission could provide a census of > 1 M_{Jup} analogs around most of TESS and PLATO targets (planet hosts and not)

A Word of Caution



Lindegren et al.2018



*** G < 13 mag: typical σ_A ~ 20 μas**
*** BUT: systematic errors ~ 100 μas**
*** Calibration of bright stars limited**

For Gaia, G < 13 mag:
σ_A ~ 15-20 μas

Critical to improve significantly the bright-star performance:

- At G < 13 mag exoplanet detections maximize the Gaia impact and synergy potential
- At G > 13 mag exoplanet detections will primarily have only a statistical value

Gaia, Stars, and Exoplanets

The impact of Gaia on our knowledge of stars and the planets they host:

- Critical for clean target sample selection
- Crucial for accurate determination of stellar properties
- Diversified across orders of magnitude in mass and separation of companions, encompassing all ranges of stellar mass, chemical composition, age, multiplicity

Multi-faceted and far-reaching, i.e. revolutionary!

Exoplanetology with Gaia will seriously begin with DR3 (2020)