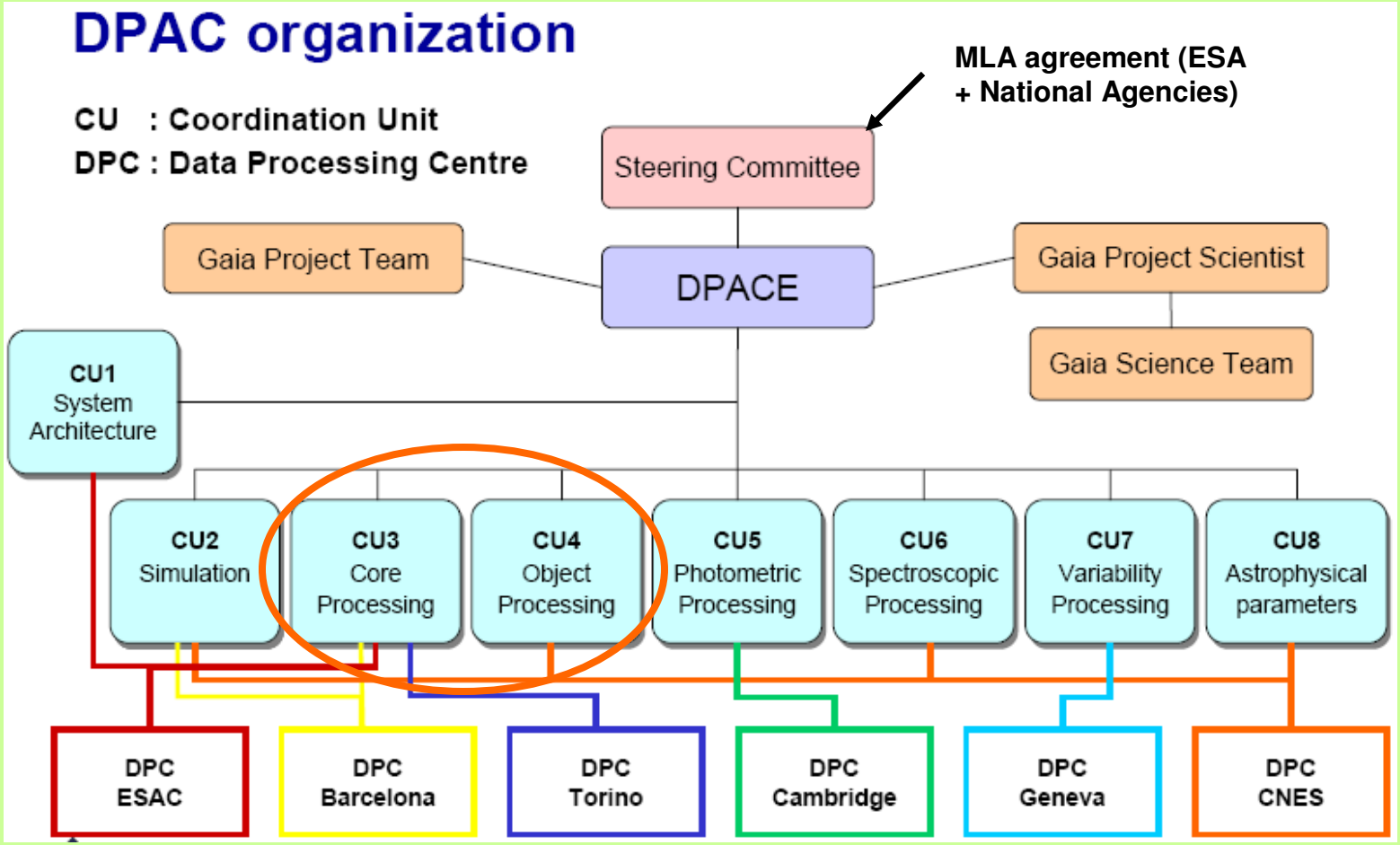
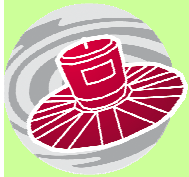
Gaia NSS Processing: Star+BD, BD+planet systems

A. Sozzetti

INAF – Osservatorio Astrofisico di Torino


DPAC organization
CU : Coordination Unit
DPC : Data Processing Centre
MLA agreement (ESA + National Agencies)
Steering Committee
Gaia Project Team
DPACE
Gaia Project Scientist
Gaia Science Team
CU1 System Architecture
CU2 Simulation
CU3 Core Processing
CU4 Object Processing
CU5 Photometric Processing
CU6 Spectroscopic Processing
CU7 Variability Processing
CU8 Astrophysical parameters
DPC ESAC
DPC Barcelona
DPC Torino
DPC Cambridge
DPC Geneva
DPC CNES



gaia

Astrometric solution for Gaia: The problem

- The basic measurement is the "time of observation" for each star's crossing a CCD
  - ⇒ 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)
  - ⇒ 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
  - ⇒ astrometric solution needs 5×10^{8} unknowns

Astrometric solution for Gaia: Formulation

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

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

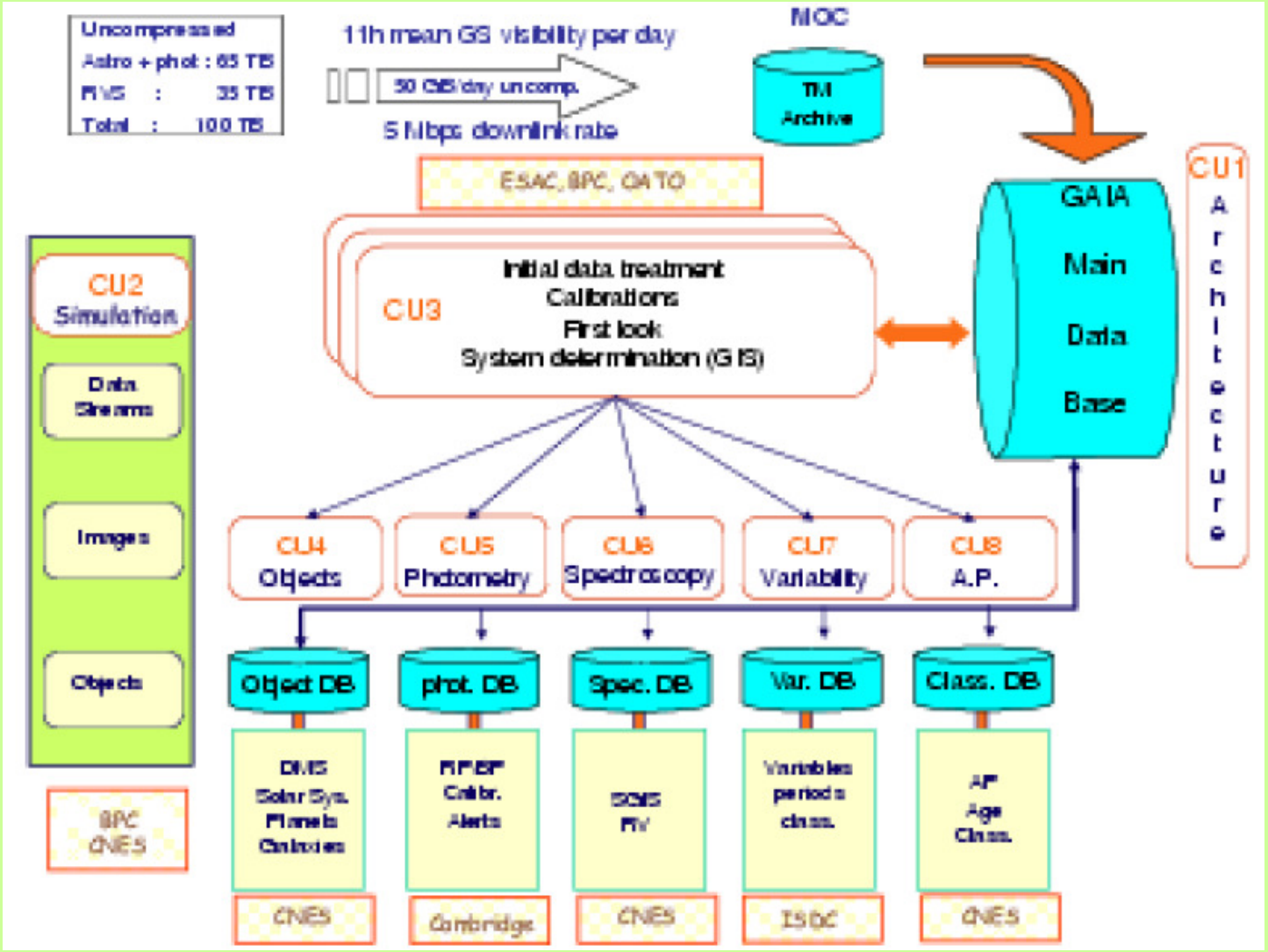
quaternion $q(t)$ represented by cubic spline coefficients

geometric calibration

white gaussian, known σ

Symbolically: $\boldsymbol{O} = f(\boldsymbol{S}, \boldsymbol{A}, \boldsymbol{C}) + \boldsymbol{n}$

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

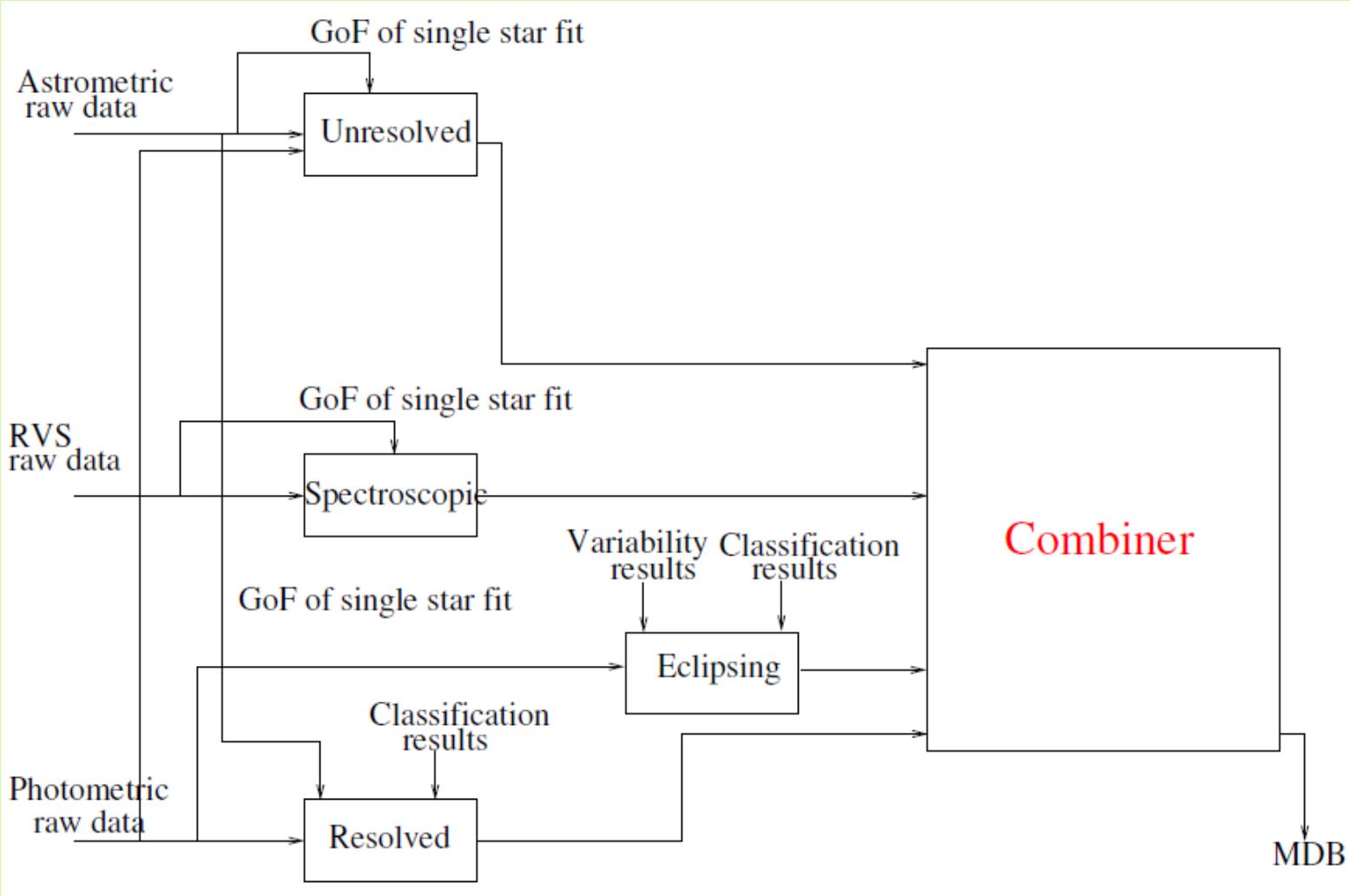

Uncompressed
Astro + phot : 65 TB
RVS : 35 TB
Total : 100 TB
11h mean GS visibility per day
50 GB/day uncomp.
5 Mbps downlink rate
MOC
TM Archive
ESAC, BPC, OATO
GAIA Main Data Base
CU1 Architecture
CU2 Simulation
Data Streams
Images
Objects
BPC CNES
CU3
Initial data treatment
Calibrations
First look
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

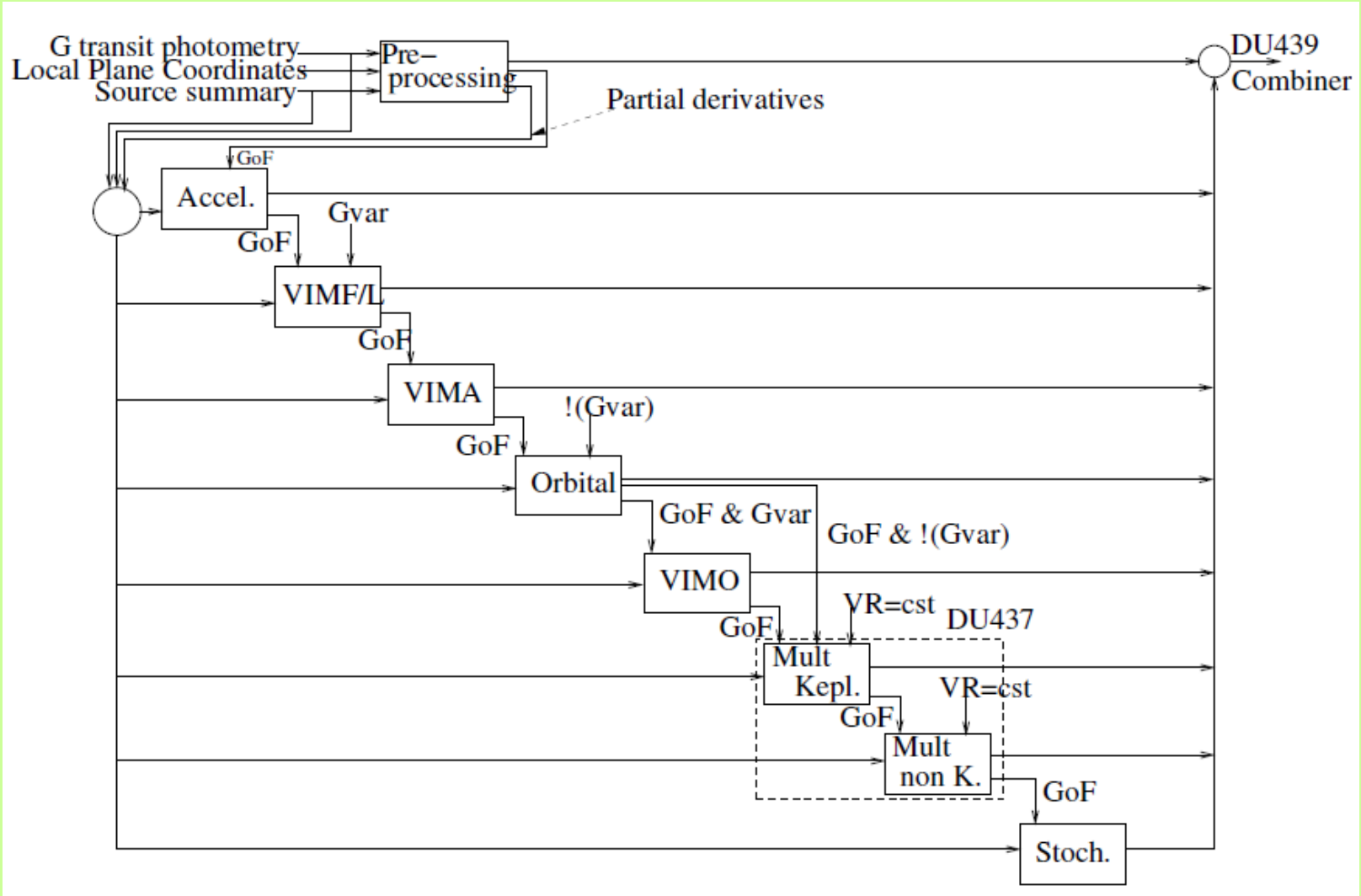
CU4, Object processing, in charge of Non Single Stars. A total of 80 man-years manpower spread over several Development Units:

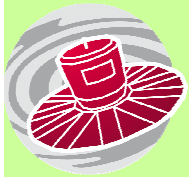
- DU 432: Unresolved NSS
- DU 433: Resolved NSS
- DU 434: Spectroscopic NSS
- DU 436: Eclipsing
- DU 437: Extrasolar planets
- DU 438: NSS simulation
- DU 439: Solution combiner

Gaia CU4 – NSS Treatment



Gaia CU4 – Astrometric NSS Treatment





gaia

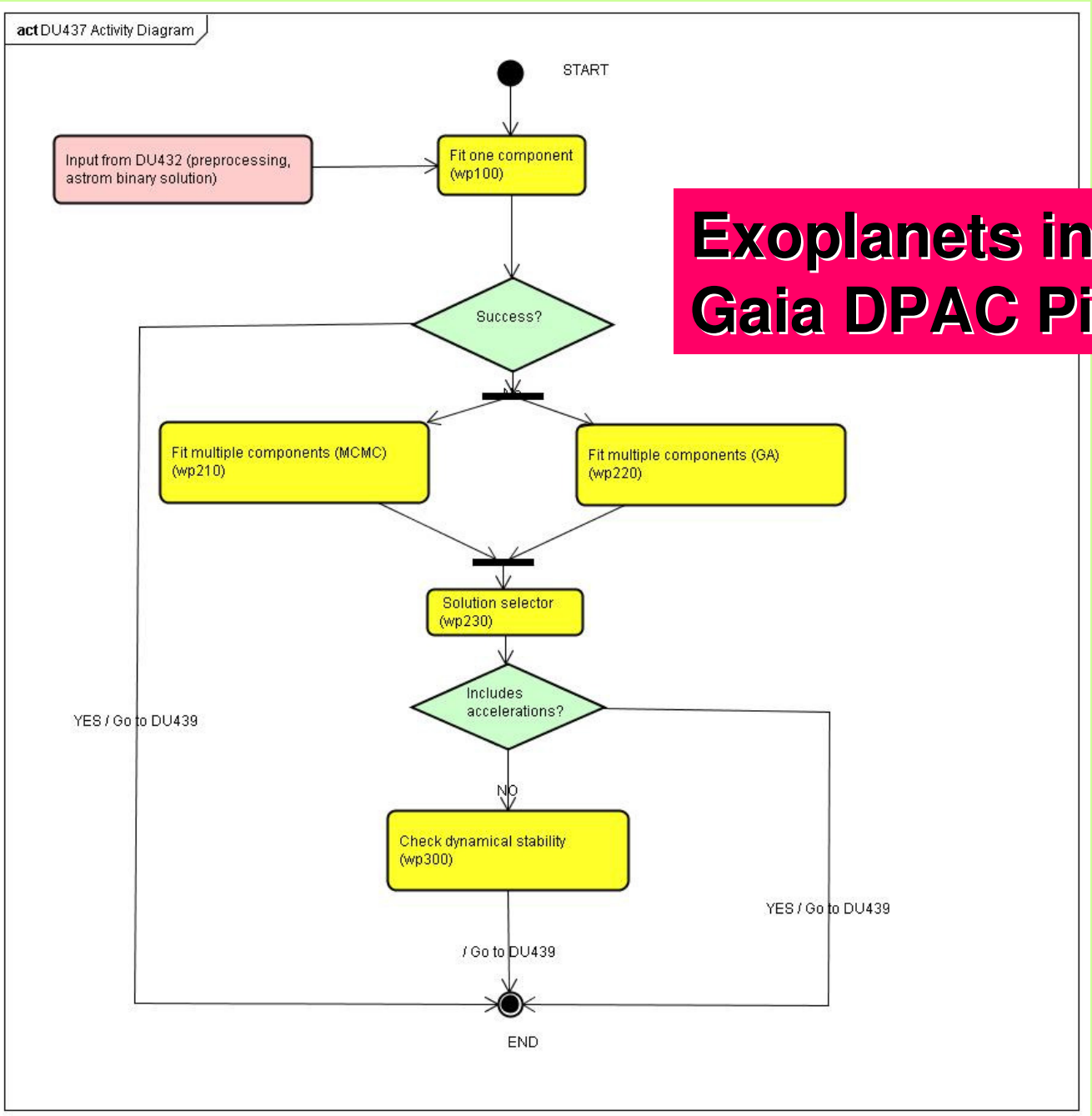
Fitting Astrometric Orbits

- 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) 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



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

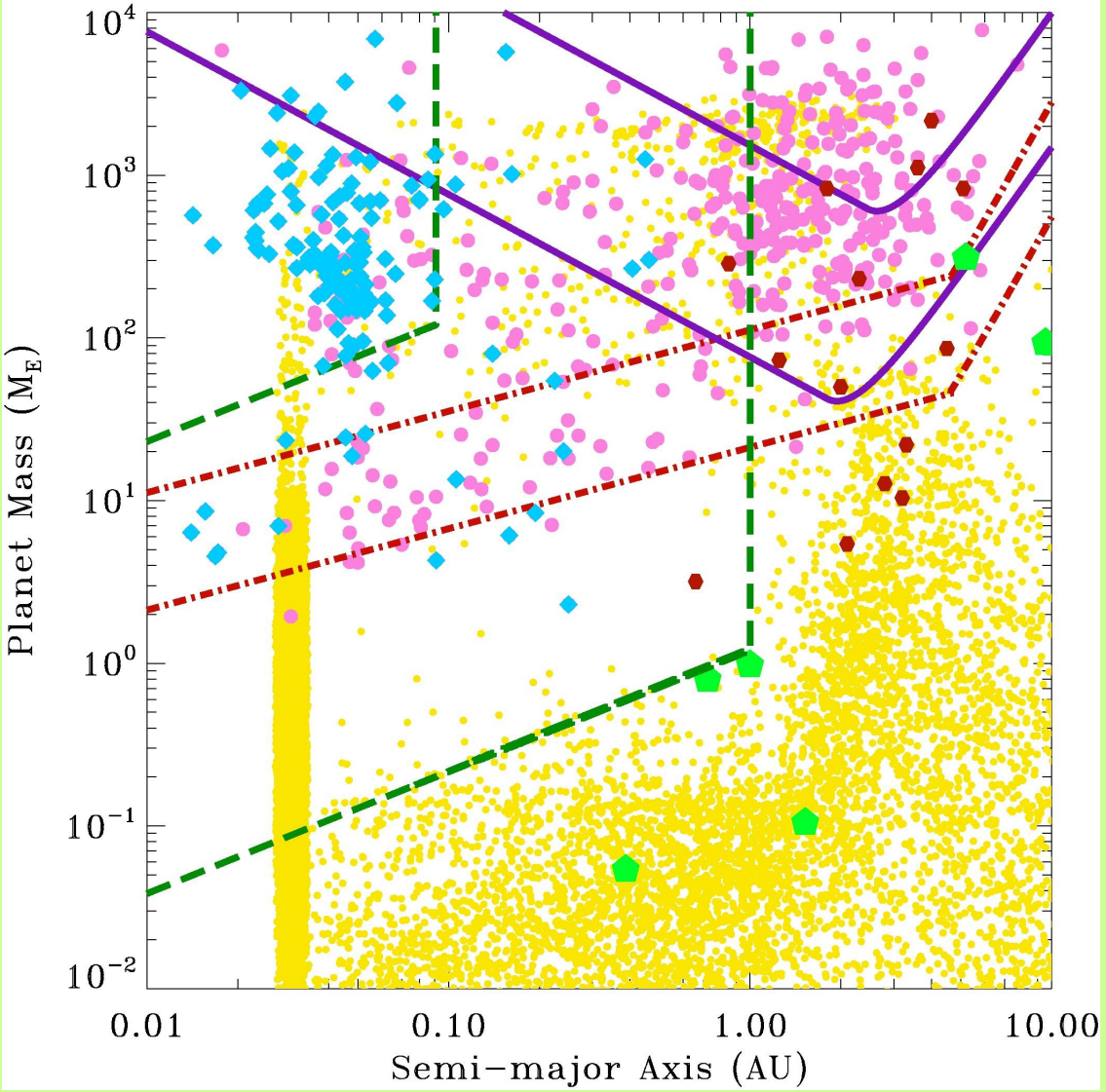
Gaia transiting BD candidates?

- Required photometric precision not an issue
- Low-cadence of the observations a serious limitation
- It's not hopeless if you have the right tools!
- It can work for early detections of (a few hundred?) short-period transiting BDs
- It may require a dedicated follow-up network
- Confirmation efforts might be limited by V mag (typically, V > 14 mag), although not as severely as for transiting giant planet candidates
- See e.g. Dzigan's and Bouchy's talks, Bonomo's poster

Gaia Discovery Space

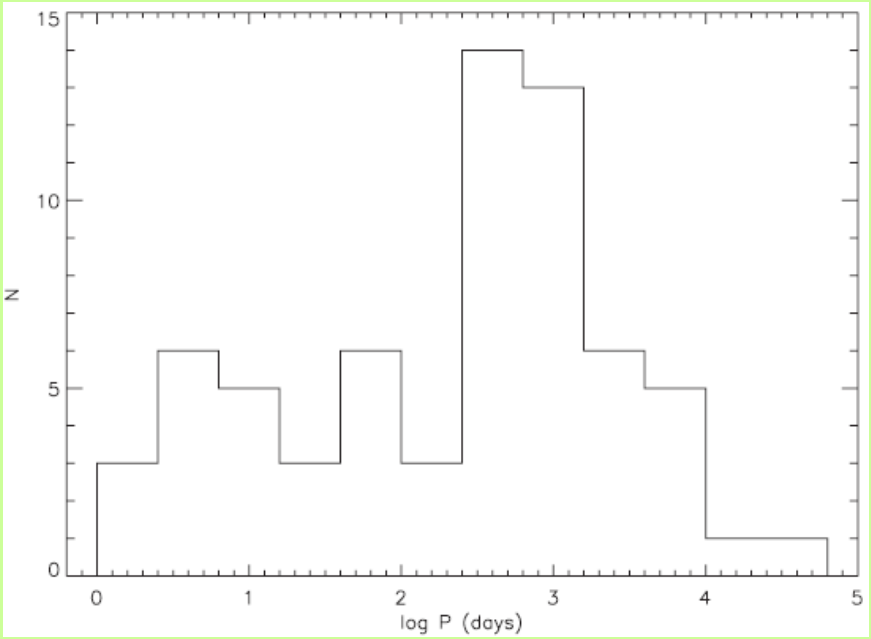
1) 2-3 M_J planets at 2<a<4 AU are detectable out to~200 pc around solar analogs
2) Saturn-mass planets with 1<a<4 AU are measurable around nearby (<25 pc) M dwarfs

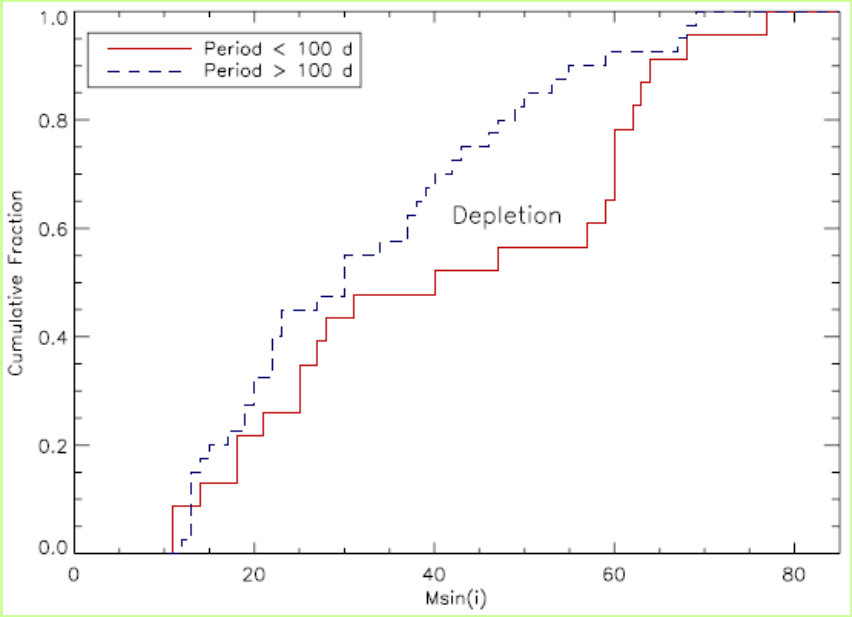
For Gaia: σ_A ~ 15-20 μas

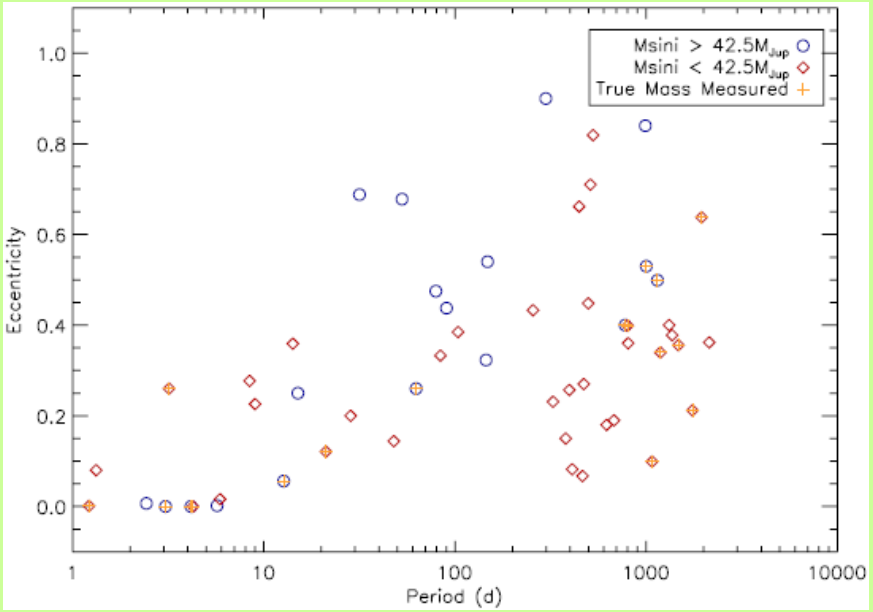


Sozzetti 2011

Ma & Ge 2014


N
log P (days)


Period < 100 d
Period > 100 d
Depletion
Cumulative Fraction
Msin(i)


Msini > 42.5M_Jup
Msini < 42.5M_Jup
True Mass Measured
Eccentricity
Period (d)

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% (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 (Parker's talk)

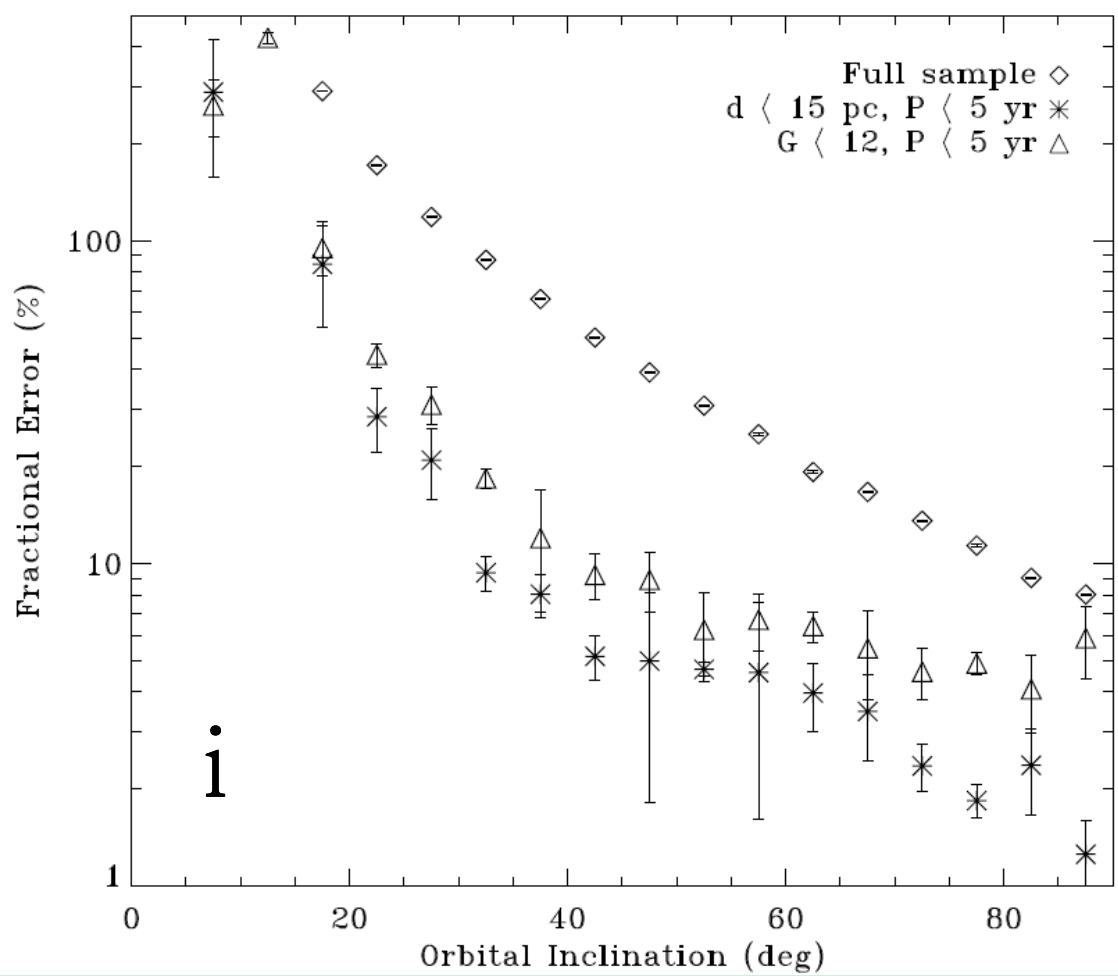
Finding Nearby Transiting Intermediate-Separation BDs

Sozzetti et al. 2014

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

Gaia may find hundreds of candidate transiting brown dwarfs around F-G-K-M dwarfs of all ages and [Fe/H].

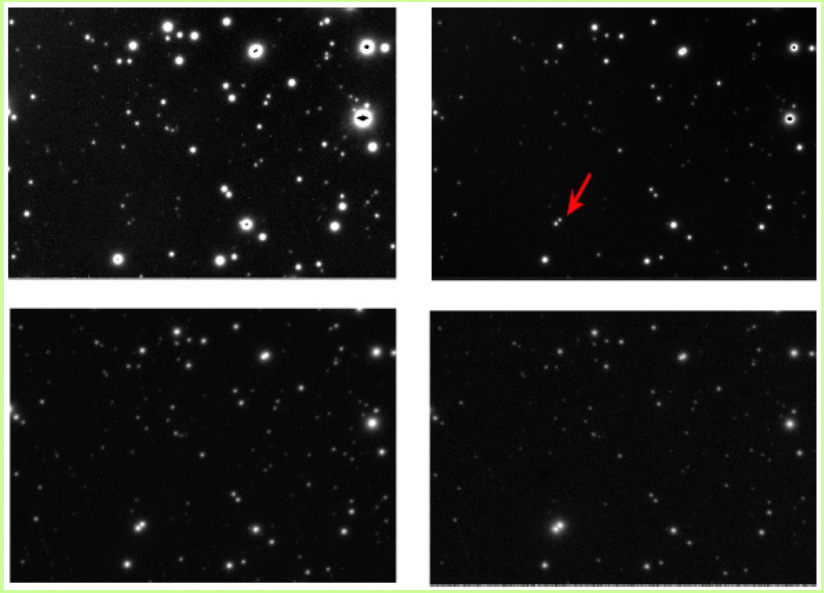
Some may be really transiting!

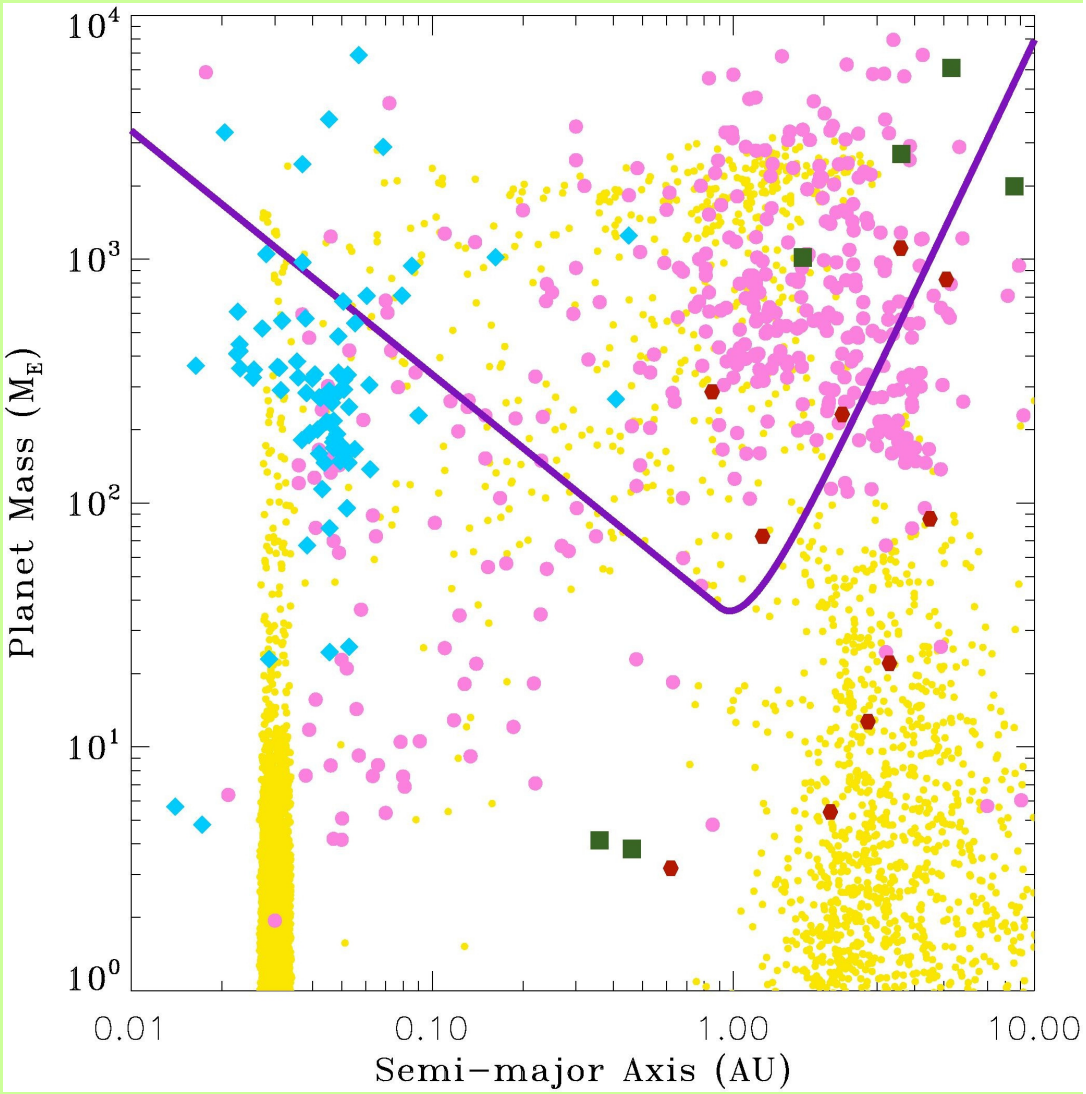


Follow-up efforts, possible targets for JWST

gaia

Gaia detection limits for WISE J104915.57-531906.1 (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!

Summary

Gaia astrometry and photometry will give the coolest results when applied to the coolest objects in the Solar neighborhood!

Synergistic efforts with other ground-based and space-borne programs the other fundamental element of the Gaia legacy to address many key questions in BD astrophysics (see talks by Dzigan, Sahlmann, Bouchy, Kirkpatrick, Joergens)