TMT+IRIS: A High-Precision Astrometry Tool for Exoplanet Follow-Up and Discovery

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Luhman 16AB / Janella Williams / PSU

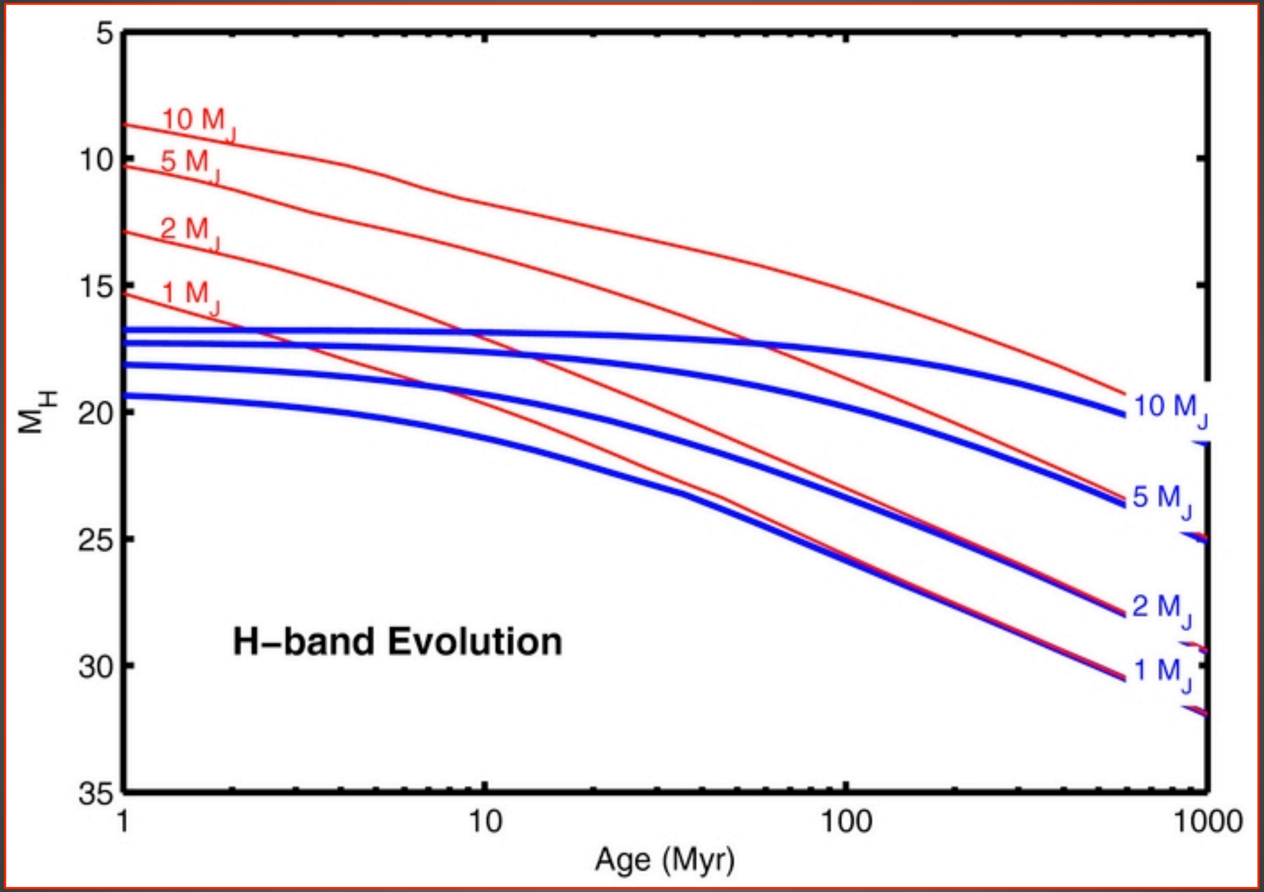
Astrometry Exoplanet Science Cases for TMT

1. Mass Measurement of Directly Imaged Exoplanets with TMT IRIS

2. An Astrometric Search for Exoplanets Orbiting L/T Brown Dwarfs

3. Using GAIA Accelerations to Sort PFI Target Lists

Exoplanet Masses and Luminosities Constrain Planetary Formation Models

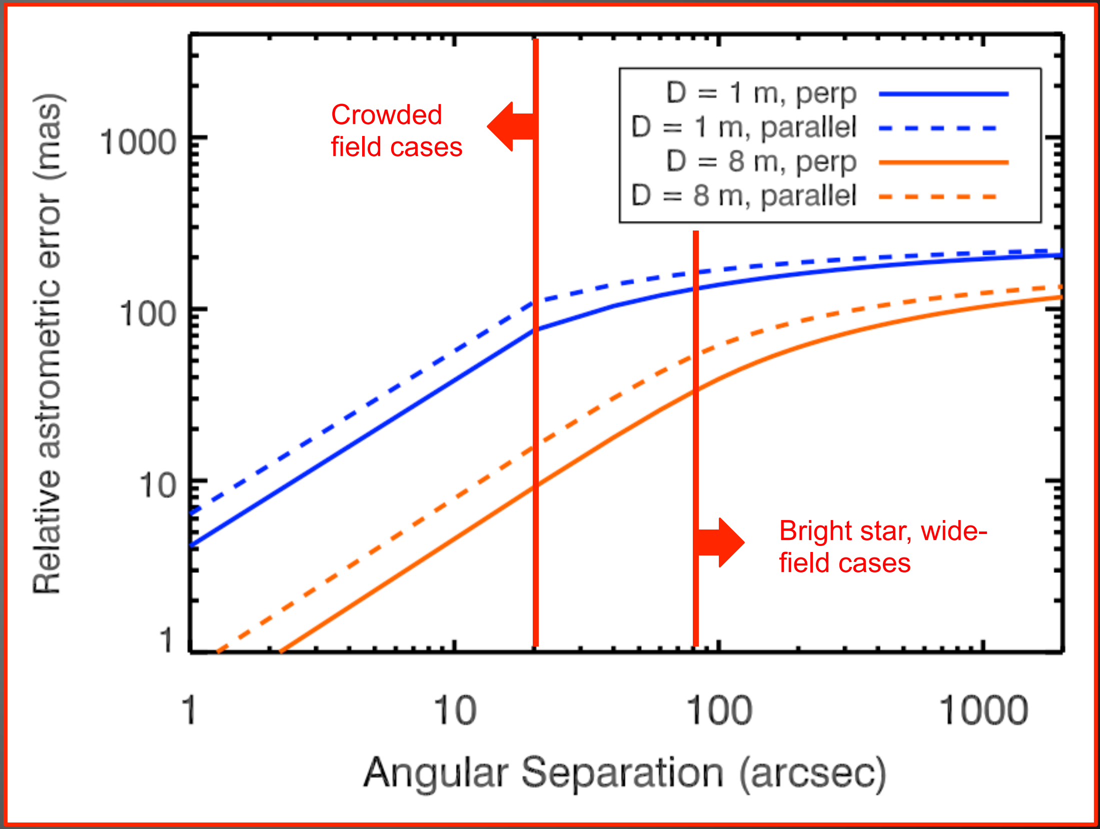


Spiegel and Burrows 2012

- Measurements of exoplanet mass will help distinguish between "hot start" and "cold start" planetary formation models

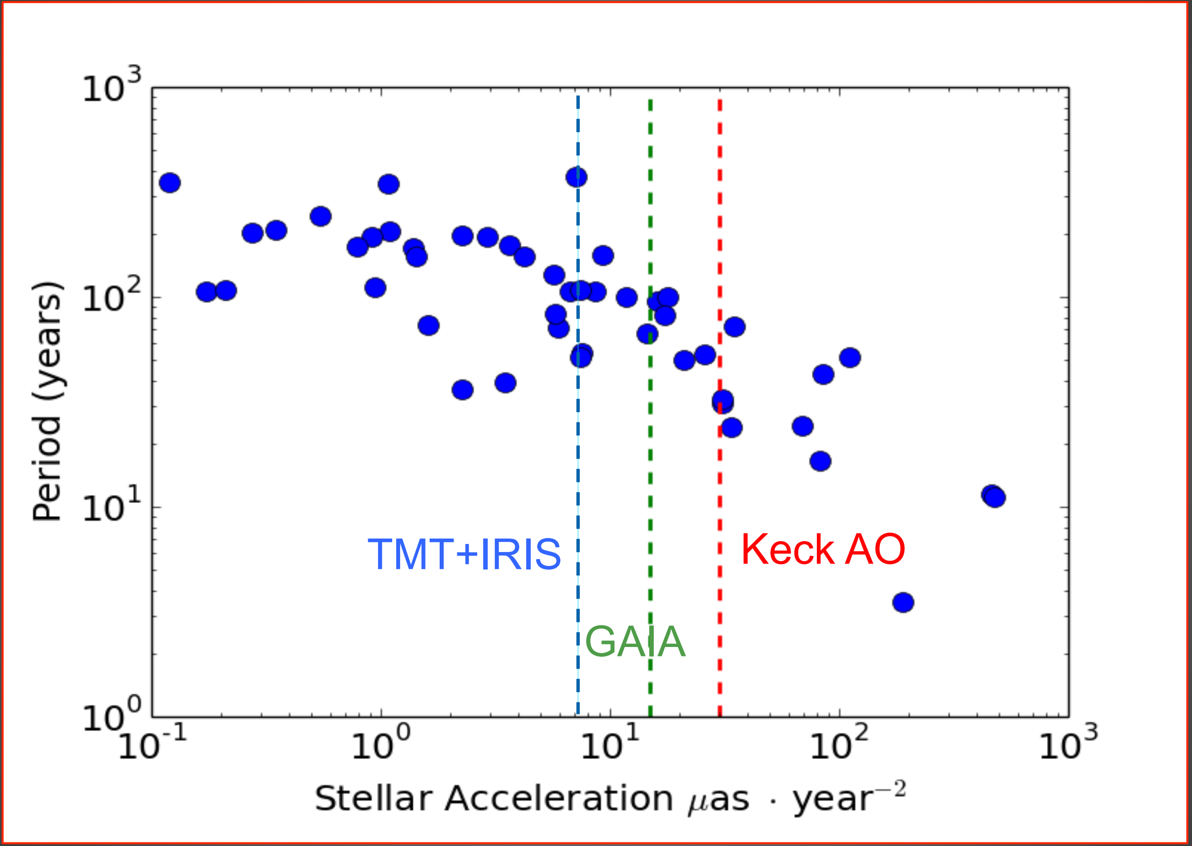
For Wide-Field AO, Atmospheric Tip/Tilt Jitter is a Major Error Term

- Differential Tip/Tilt Jitter is the error in measuring relative positions of stars due to high-altitude atmosphere
- MCAO *actively cancels DTTJ: Use MCAO*
- *DTTJ improves as* D^{-1}



Relative astrometric error between two stars due to DTTJ

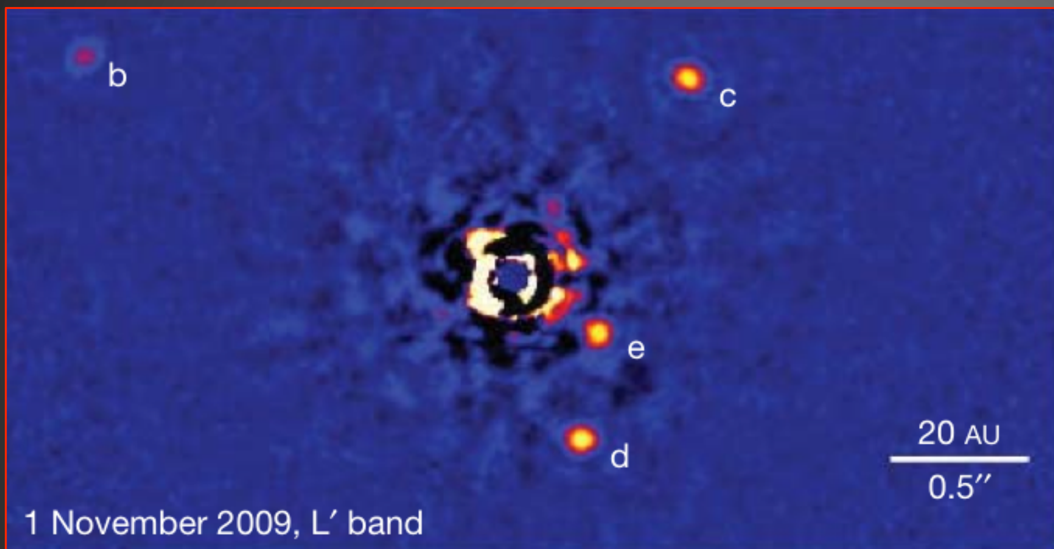
Precision Astrometry with TMT+IRIS Enables Exoplanet Mass Measurement

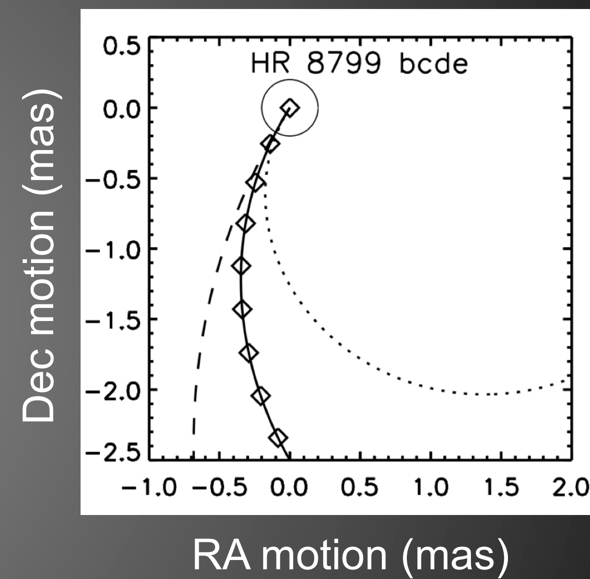


Credit: D Savransky

- Stellar accelerations induced by simulated GPI exoplanets
- ~1/3 have masses measurable by current ground-based capabilities (~0.1 mas)
- ~1/2 measurable with TMT IRIS (0.02-0.03 mas)

HR 8799c+d+e Mass Measurable with TMT+IRIS





C. Marois

- Total astrometric signal on HR 8799 dominated by three innermost planets ($F \sim r^{-2}$)
- Measured acceleration is nonlinear function of *c, d, e* masses
- Could detect unseen planet interior to HR 8799*e*

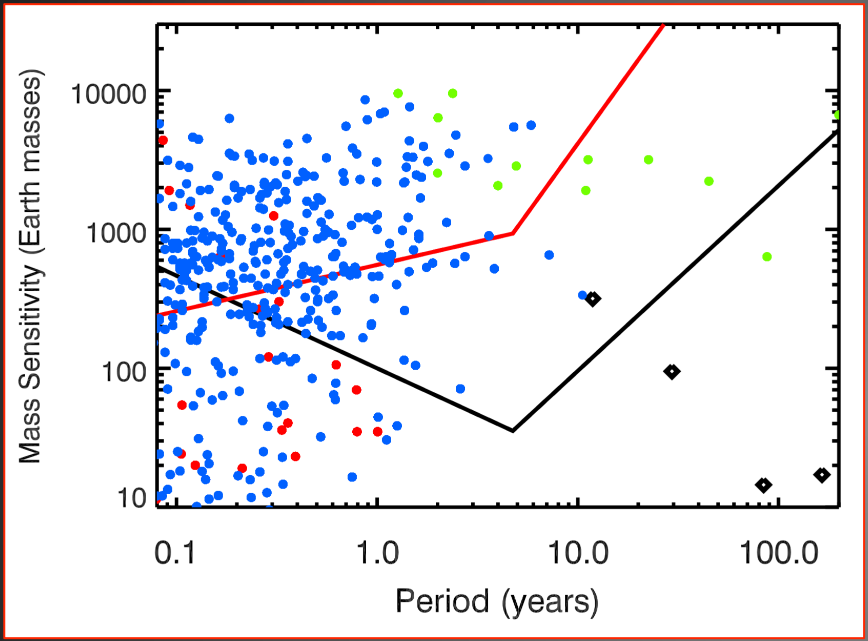
How Precise is TMT Sparse-Field Astrometry?

TMT astrometry error budget																			
v 25 July 2014		Differential Astrometry relative to field stars						Differential Astrometry science objects relative to each other						Absolute Astrometry					
	N_{ref}	1		3		100		0		3		100		0		3		100	
	N_{sci}	1		1		1		2		2		2		1		1		1	
	N_{field}	1		3		100													
	r_{sep} [arcsec]	1		1		1		1		1		1		30		15		15	
			[uas]		[uas]		[uas]		[uas]		[uas]		[uas]		[uas]		[uas]		[uas]
6.7	Telescope optics	D-2	7.1	D-2	5.8	D-2	5.0	D-1	7.1	D-1	7.1	D-1	7.1	A-2	5.0	A-1	5.8	A-1	5.0
6.8	Rotator errors	D-2	4.2	D-2	3.5	D-2	3.0	D-1	4.2	D-1	4.2	D-1	4.2	A-2	3.0	A-1	3.5	A-1	3.0
6.9	Actuators, diffr. spikes	D-2	1.4	D-2	1.2	D-2	1.0	D-1	1.4	D-1	1.4	D-1	1.4	A-2	1.0	A-1	1.2	A-1	1.0
6.10	Vibrations	D-2	7.1	D-2	5.8	D-2	5.0	D-1	7.1	D-1	7.1	D-1	7.1	A-2	5.0	A-1	5.8	A-1	5.0
6.11	Coupling with atm. effects	D-2	4.2	D-2	3.5	D-2	3.0	D-1	4.2	D-1	4.2	D-1	4.2	A-2	3.0	A-1	3.5	A-1	3.0
	Subtotal		**69.7**		**16.6**		**14.5**		**69.7**		**20.3**		**20.3**		**2000.1**		**16.6**		**14.5**
Atmospheric refraction errors																			
7.1	Achromatic differential refraction	D-2	2.8	D-2	2.3	D-2	2.0	D-1	2.8	D-1	2.8	D-1	2.8	A-2	2.0	A-1	2.3	A-1	2.0
7.3	Dispersion: object spectra	D-2	7.1	D-2	5.8	D-2	5.0	D-1	7.1	D-1	7.1	D-1	7.1	A-2	5.0	A-1	5.8	A-1	5.0
7.4	Dispersion: atm. conditions	D-2	7.1	D-2	5.8	D-2	5.0	D-1	7.1	D-1	7.1	D-1	7.1	A-2	5.0	A-1	5.8	A-1	5.0
7.5	Dispersion: ADC position	D-2	1.4	D-2	1.2	D-2	1.0	D-1	1.4	D-1	1.4	D-1	1.4	A-2	1.0	A-1	1.2	A-1	1.0
7.6	Dispersion: variability	D-2	2.8	D-2	2.3	D-2	2.0	D-1	2.8	D-1	2.8	D-1	2.8	A-2	2.0	A-1	2.3	A-1	2.0
	Subtotal		**10.9**		**8.9**		**7.7**		**10.9**		**10.9**		**10.9**		**7.7**		**8.9**		**7.7**
Residual turbulence errors																			
8.2.1	Diff. TTJ: plate scale	D-2	0.2	---	0	---	0	D-1	0.2	---	0	---	0	A-2	4.7	---	0	---	0
8.2.2	Diff. TTJ: higher order	D-2	4.7	D-2	3.8	D-2	3.3	D-1	4.7	D-1	4.7	D-1	4.7	A-2	3.3	A-1	3.8	A-1	3.3
8.3	PSF irregularities	D-2	2.5	D-2	2.0	D-2	1.7	D-1	2.5	D-1	2.5	D-1	2.5	A-2	1.7	A-1	2.0	A-1	1.7
8.4	Halo effect	D-2	4.2	D-2	3.5	D-2	3.0	D-1	4.2	D-1	4.2	D-1	4.2	A-2	3.0	A-1	3.5	A-1	3.0
8.5	Turb. conditions variability	D-2	1.4	D-2	1.2	D-2	1.0	D-1	1.4	D-1	1.4	D-1	1.4	A-2	1.0	A-1	1.2	A-1	1.0
	Subtotal		**6.9**		**5.7**		**4.9**		**6.9**		**6.9**		**6.9**		**6.8**		**5.7**		**4.9**
Reference object and catalog errors																			
9.1	Position errors	PS-1	33.3	PS-2	33.3	PS-2	5.8	PS-1	33.3	PS-2	33.3	PS-2	5.8	PS-1	1000.0	PS-2	58.8	PS-2	10.2
9.2	Proper motion errors	PS-1	16.7	PS-2	16.7	PS-2	2.9	PS-1	16.7	PS-2	16.7	PS-2	2.9	PS-1	500.0	PS-2	29.4	PS-2	5.1
9.4	Aberration, grav. deflection	PS-1	0.0	PS-2	0.0	PS-2	0.0	PS-1	0.0	PS-2	0.0	PS-2	0.0	PS-1	1.0	PS-2	0.1	PS-2	0.0
9.5	Other	PS-1	0.0	PS-2	0.0	PS-2	0.0	PS-1	0.0	PS-2	0.0	PS-2	0.0	PS-1	1.0	PS-2	0.1	PS-2	0.0
	Subtotal		**37.3**		**37.3**		**6.5**		**37.3**		**37.3**		**6.5**		**1118.0**		**65.7**		**11.4**
	Total		**81**		**43**		**21**		**81**		**46**		**28**		**2291**		**69**		**22**

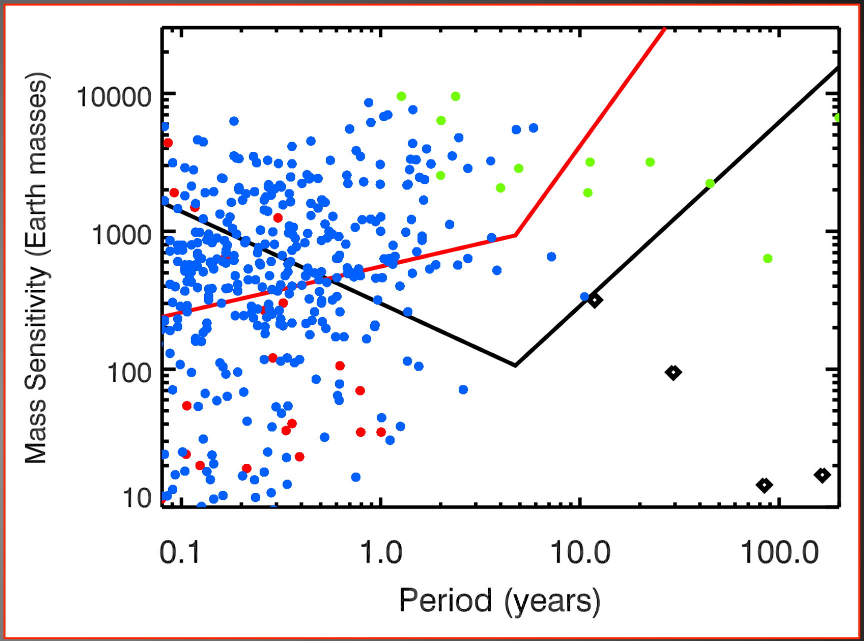
- We use Schoeck et al. 2014 error budget
- Includes
  - DAR
  - DTTJ
  - S/N
  - Optical distortion
  - Calibration errors
- 20-30 µas single-epoch precision per axis for
  - $V < 10$
  - 15 min. exposure
  - $b < 60°$

- Primary advantages of TMT astrometry over radial velocity and GAIA are:
  - Faint, red stars (M stars, red dwarfs)
  - Young FGK stars with RV jitter

Comparison to Radial Velocity for Young FGK Hosts



10 pc



30 pc

- Young stars targeted for direct image surveys have increased stellar jitter (50 m/s)
- Astrometry has major advantage over RV for P > 2 months
- Astrometry yields two projected components of acceleration vector (RV yields one)

Four Regimes: Astrometric Follow-up Strategies

If Absolute Astrometry Measurement is…	And Direct Imaging Status is….	Then I can
Significant acceleration detection	No detection	Favor wedge of image, rotate dark hole, etc
Acc. Detection with rotation	No detection	Fit period, favor wedge of image
Acc. Detection	Marginal single-epoch	Fit period / weakly constrain exoplanet mass
Acc. Detection	Multi-epoch detection	Joint fit of orbital parameters – stronger constraint of companion mass

- Astrometry enables exoplanet mass measurement and improves:
  - direct imaging detection SNR
  - SNR on orbital parameters

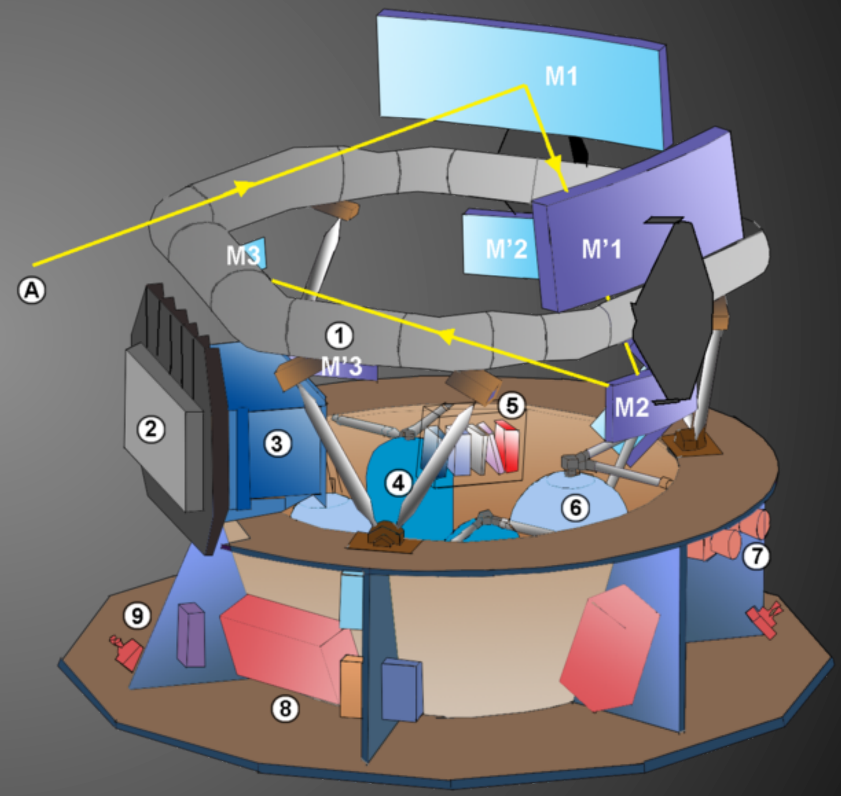
GAIA provides sub-mas absolute astrometry over the entire sky

Telescope and Instruments Description

- Two 1.5 x 0.5 m TMA telescopes anchor long separations (106 deg separation)
- 106 CCDS of 4500 x 1966 pixels
    - Drift scanning, 60 x 180 mas pixels
- Radial Velocity Spectrometer provides > 1 km/s RV precision

Mission Objectives

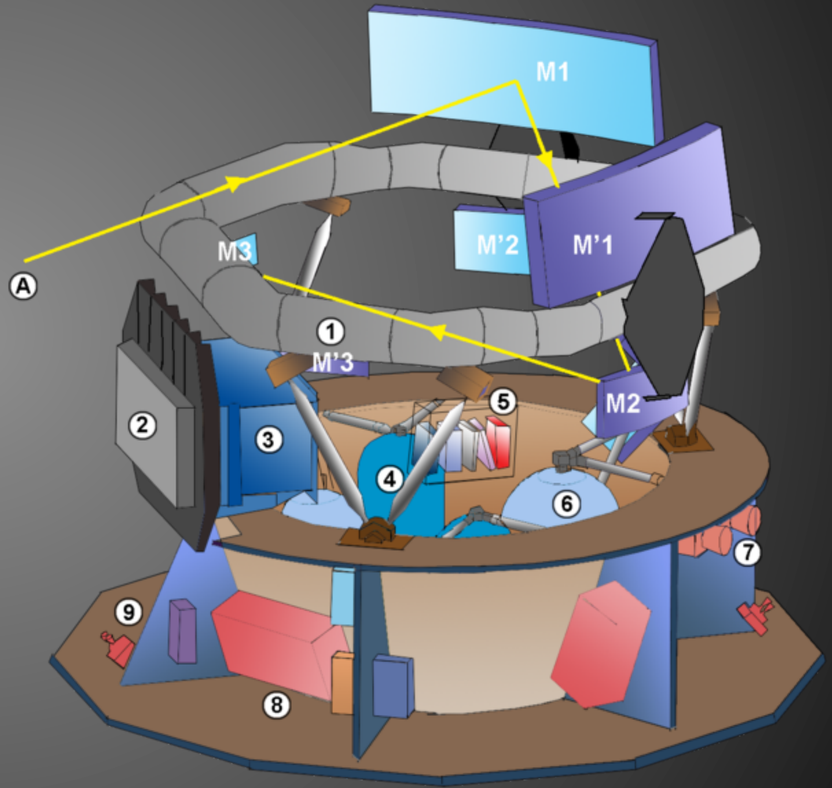
- Determine 5-parameter astrometic solution (parallax, position, proper motion) at 20 uas precision at V = 15 over 5 years
- Measure atmospheric parameters (log g, [Fe/H], T_{eff}) for V < 15
- Measure orbits and inclinations of 1000 extrasolar planets



GAIA provides sub-mas absolute astrometry over the entire sky

System Status

- Telescope launched Dec 2013 and reaches L2 in Jan 2014
- Stray light caused by unexpected ice deposits
  - diffracts sunlight around the edge of the sunshield
- Larger fluctuation in Basic Angle Monitor (BAM) than expected ~ 1 mas
  - Measures angular separation of telescopes
- Saturation will be avoided for 3 < G < 12 with shorter integration times using Time-Delayed Integration mode (TDI)
- Effective short exposures (~1 millisecond) prevents star saturation for bright stars

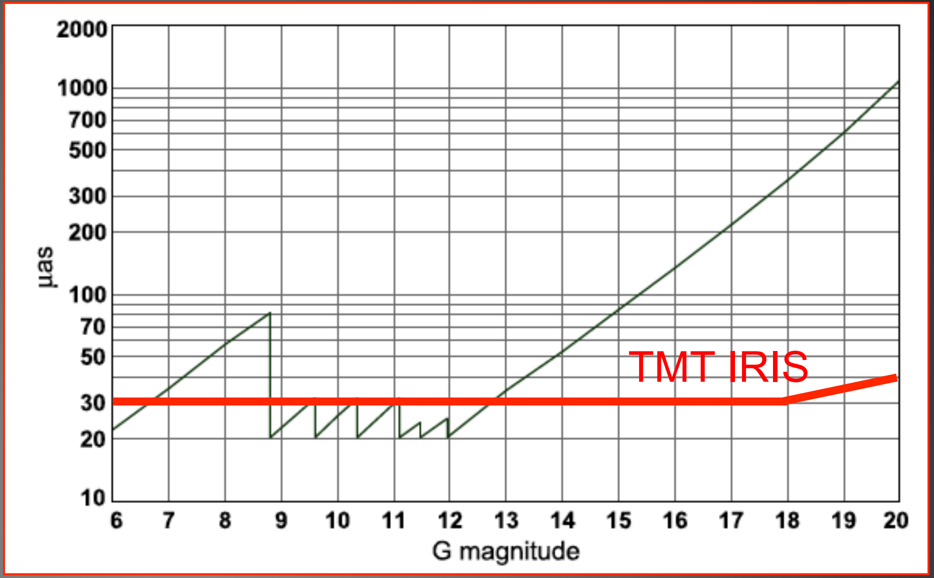


GAIA Astrometric Precision

Error budget has been updated to include transmission loss and stray light, but not increased BAM noise

Major advantage of TMT +IRIS is at faint magnitudes (G > 13)

Single-Epoch Precision



Mignard 2011 Fig 1, TMT+IRIS from Schoeck+14 error budget, 900 second exposure, b=20°

End of Mission Precision

	B1V	G2V	M6V
V-I$_C$ [mag]	-0.22	0.75	3.85
Bright stars	5-14 µas (3 mag < V < 12 mag)	5-14 µas (3 mag < V < 12 mag)	5-14 µas (5 mag < V < 14 mag)
V = 15 mag	26 µas	24 µas	9 µas
V = 20 mag	600 µas	540 µas	130 µas

http://www.cosmos.esa.int/web/gaia/science-performance

Astrometry Exoplanet Science Cases for TMT

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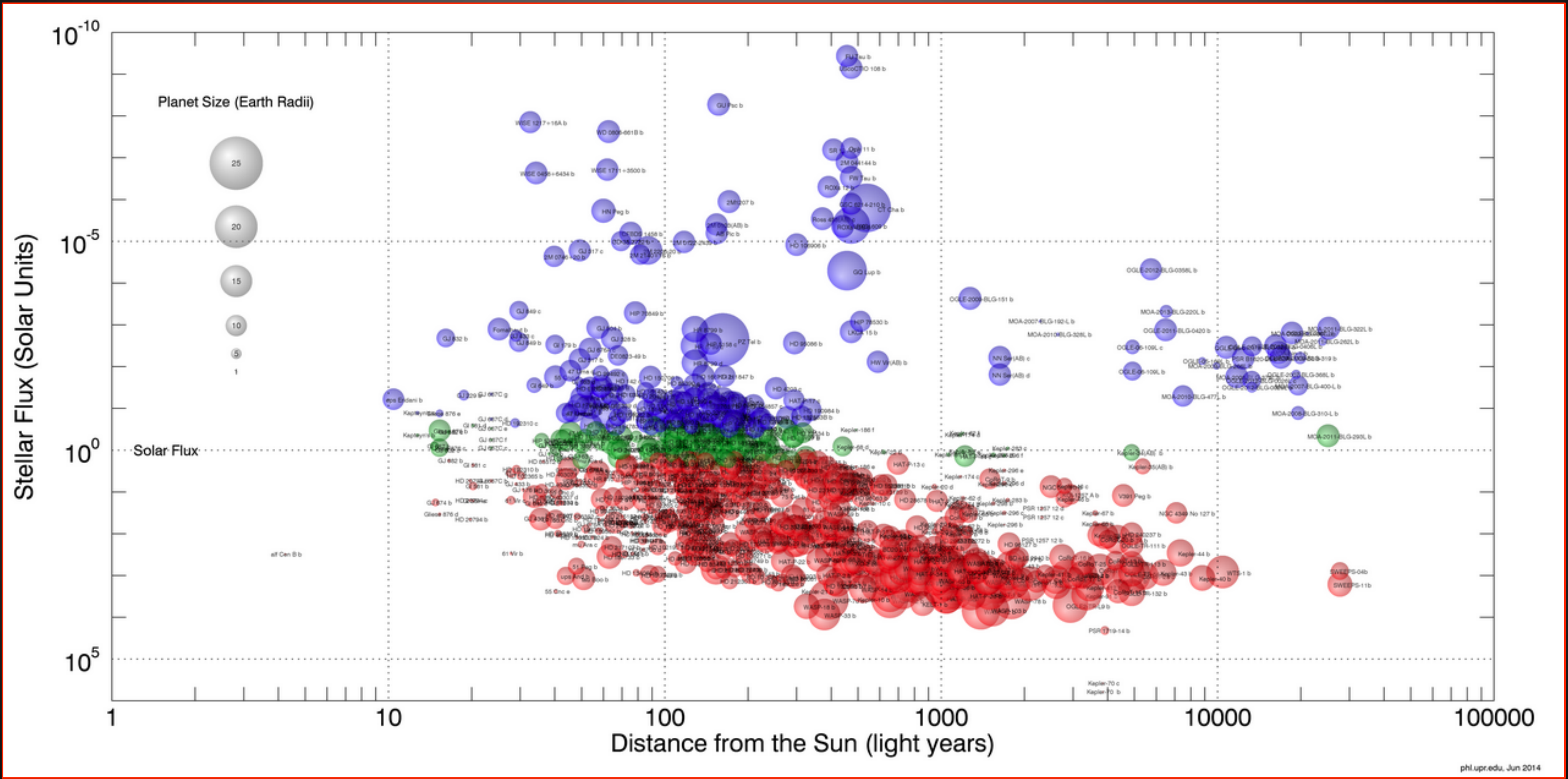
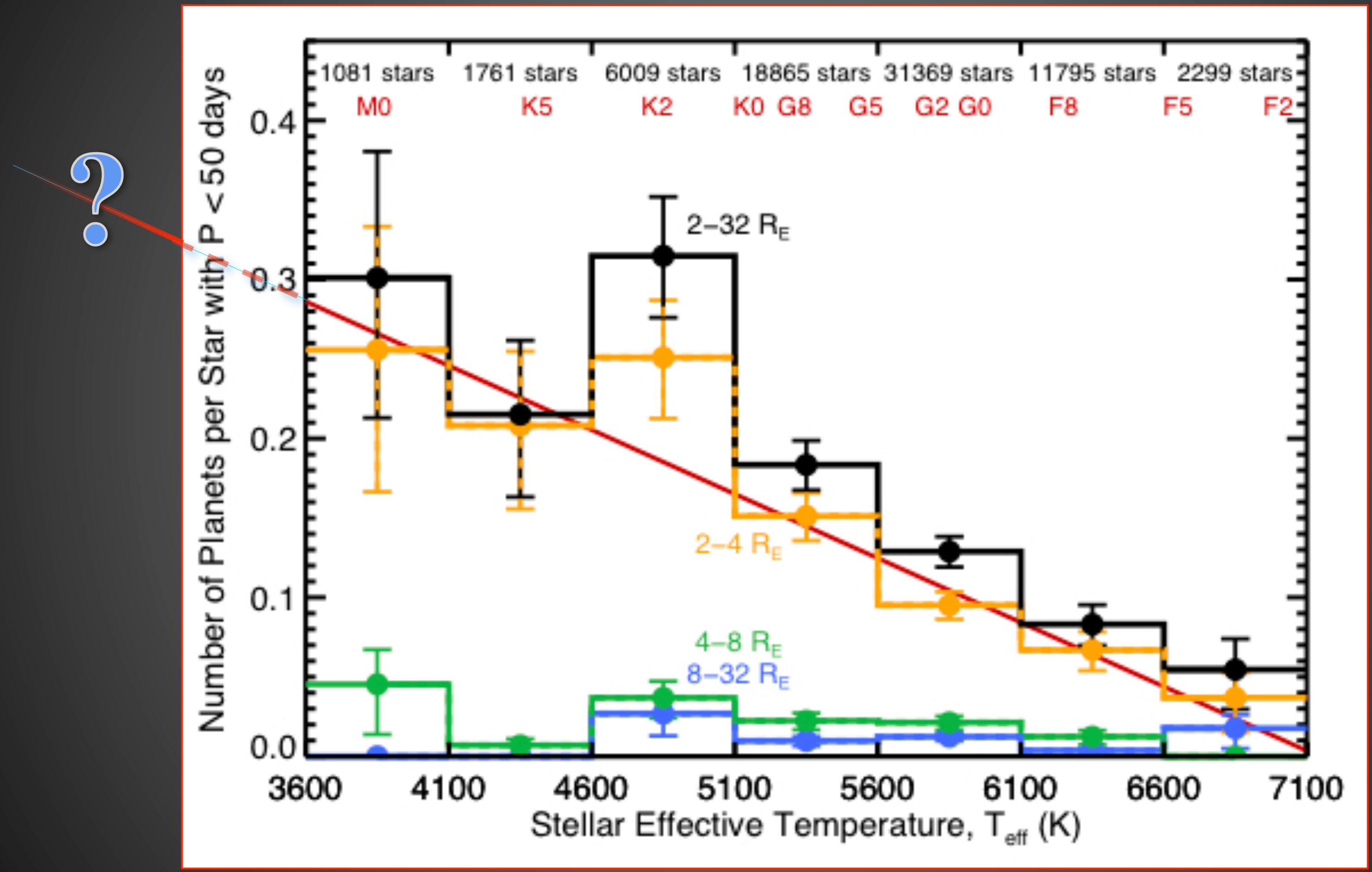
Exoplanet Occurrence Rate for L/T Dwarf Hosts Unknown



Phl.upr.edu, Jun 2014

- Planet occurrence rates for substellar hosts unknown
- Majority of planets are at high incident stellar flux or self-heated

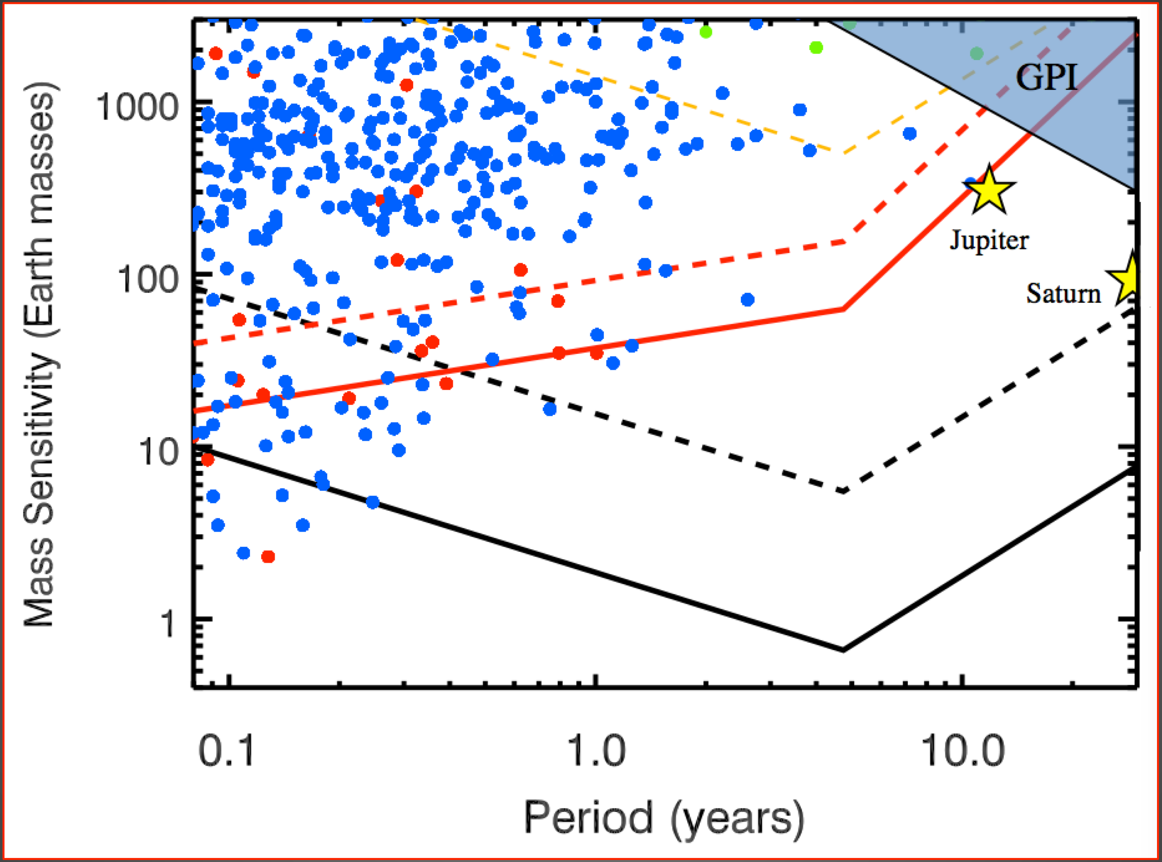
Short-Period Occurrence Rate around M Dwarfs is High



Howard et al. 2012

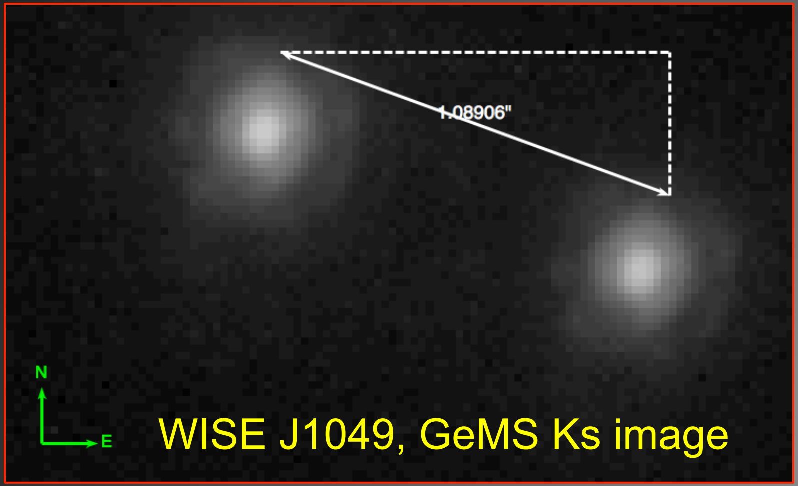
- Number of planets per stars is 2-3x greater for M dwarfs than for FGK stars
- Occurrence rate for brown dwarf hosts is unknown

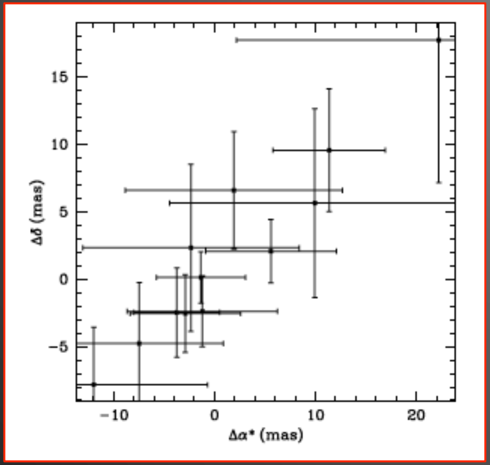
Precision Astrometry Enables Surveys of Brown Dwarfs



- Exoplanet mass sensitivity curves (5-sigma) for a 5-year astrometric survey for exoplanets orbiting brown dwarfs
- Distance = 2-20 pc
- 0.02 – 0.04 mas TMT+IRIS precision
- 200 m/s RV precision (brown dwarf hosts)

Test Case: Closest Known Binary Brown Dwarf WISEJ1049

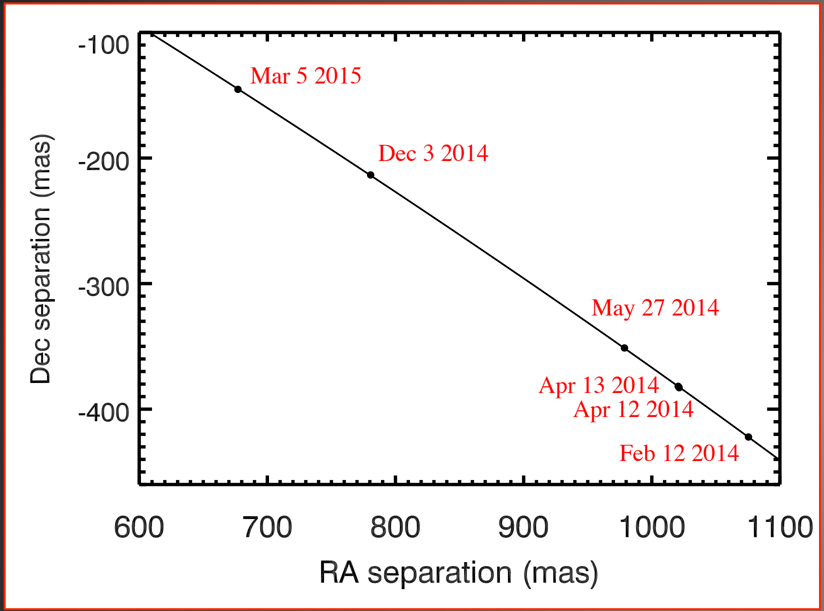


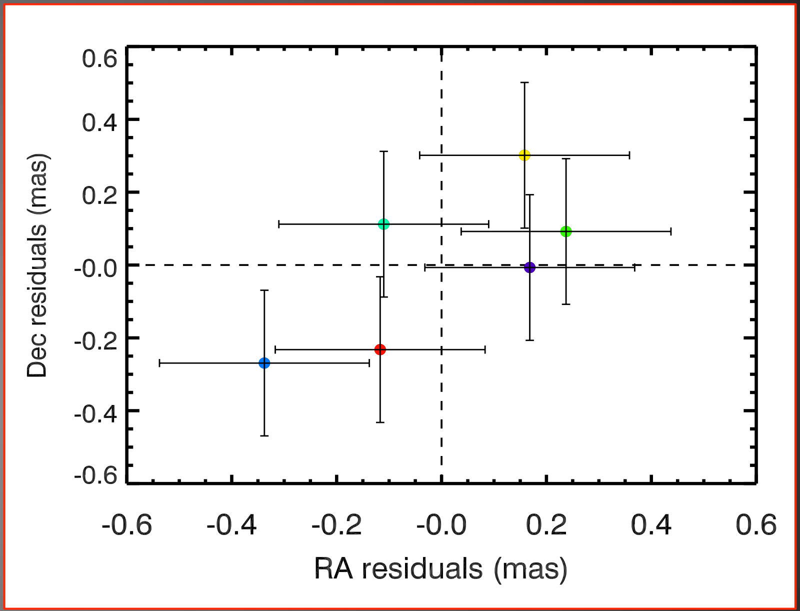


Boffin+14 astrometric residuals (2 months baseline)

- Closest known binary brown dwarf system – 2.02 pc
  - Luhman et al. 2013
- Exoplanet announced orbiting one of the dwarfs
  - Boffin et al. 2014
  - Uses ~4-5 mas precision astrometry
- Good trial system for GeMS astrometry
  - 1 arcminute field needed for absolute reference stars
  - Can improve astrometry by 20x over Boffin+14 data

MCMC Keplerian Orbit Fits GeMS Data to Within 0.22 Milliarcseconds (No Obvious Planet Seen…)



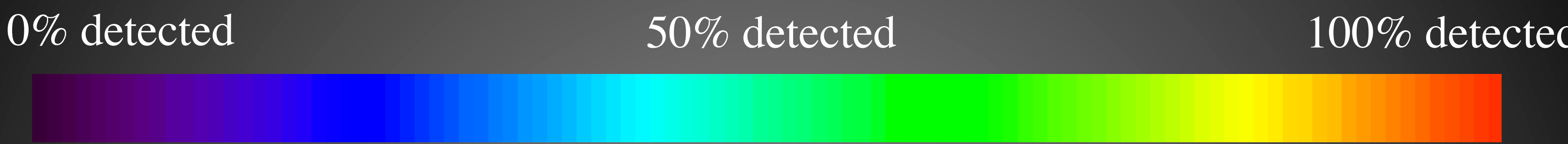


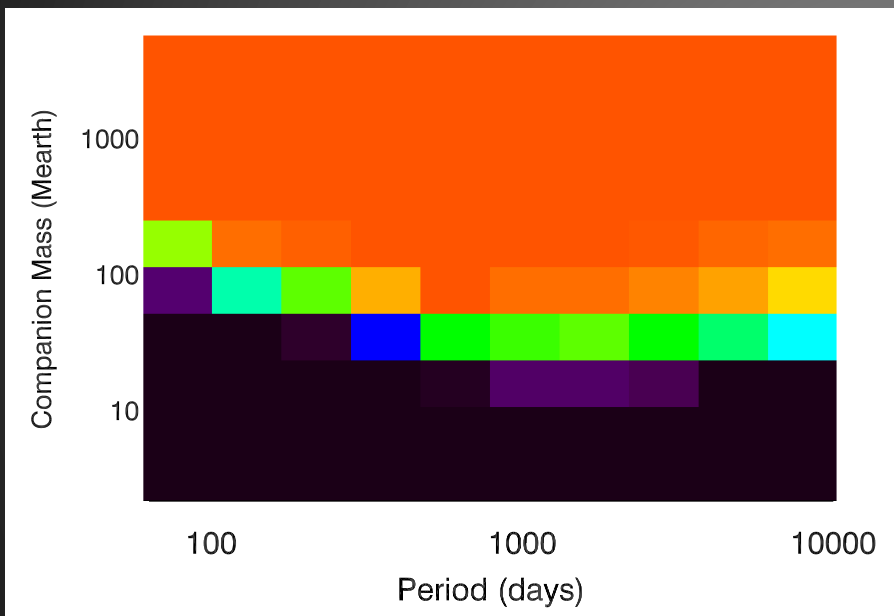
6 epochs of astrometry obtained over 13 months

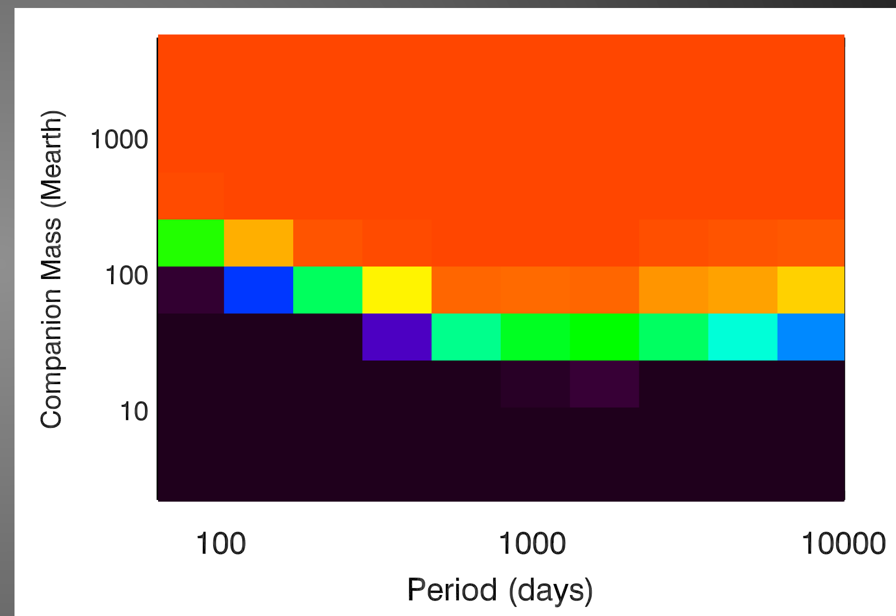
Astrometric residuals = 0.22 mas for Keplerian orbit

- GeMS delivers narrow-angle stability of ~0.2 mas over months
- GeMS' larger field needed for reference stars!
- *Inconsistent with planet proposed in Boffin et al. 2014*
- Total open shutter time ~ 20 minutes

GeMS Places Neptune-Mass Limits on Companion Mass







T dwarf companion limits (3-σ)

L dwarf companion limits (3-σ)

- Monte Carlo simulation of planet detectability, given epoch timing

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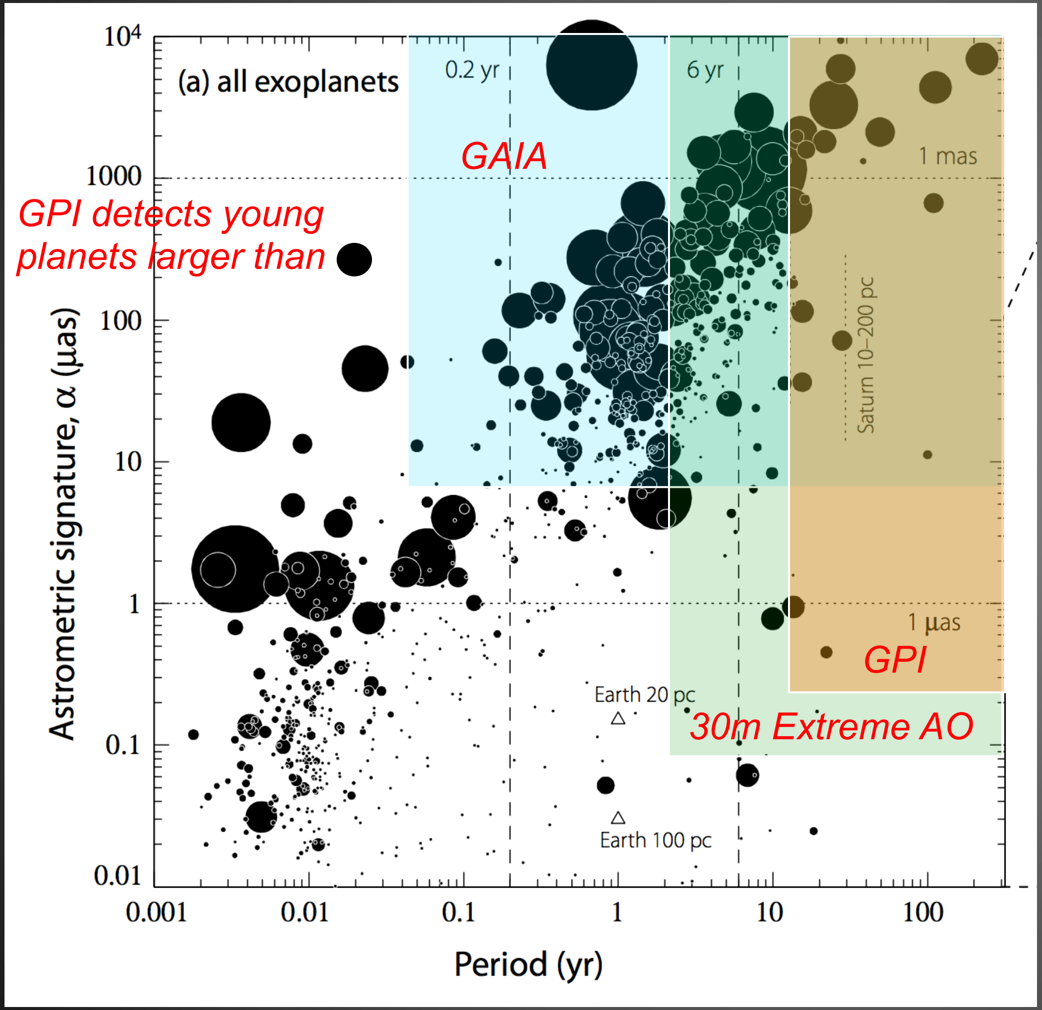
GAIA Will Discover 21,000 Exoplanets Over 5 Years

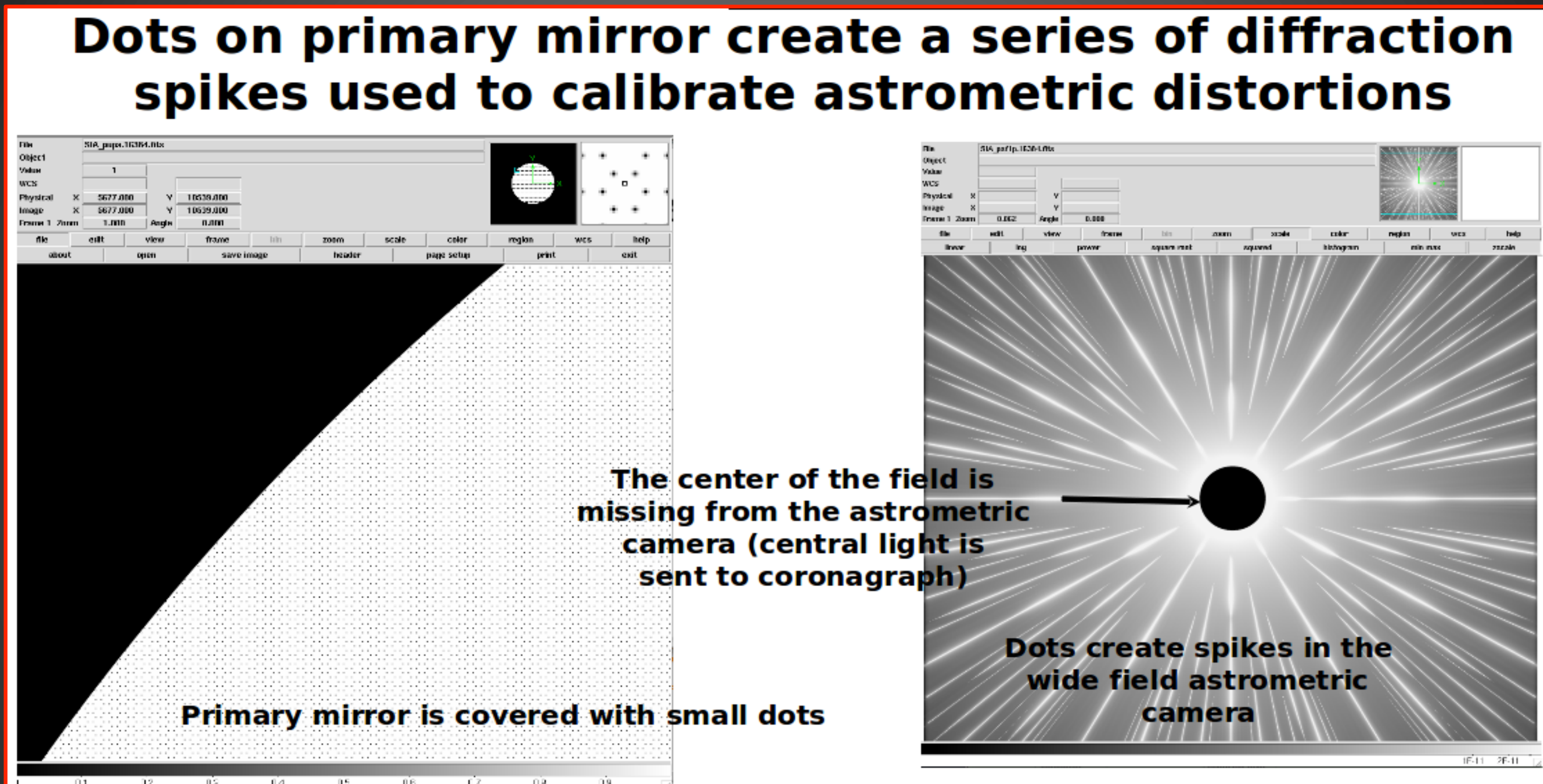


Perryman et al. 2014 Fig 1a. Plots known exoplanets only. Symbol size proportional to planet mass.

- GAIA will measure stellar acceleration for all stars
- GAIA will produce 10-100 young (age < 300 Myr) candidates with trending, long-period acceleration
- TMT+Extreme AO will follow-up GAIA-identified "trending" candidates
- TMT+Extreme AO has ~4x improvement in inner working distance over GPI
  - ~8x improvement in period

Diffractive Pupil for TMT IRIS

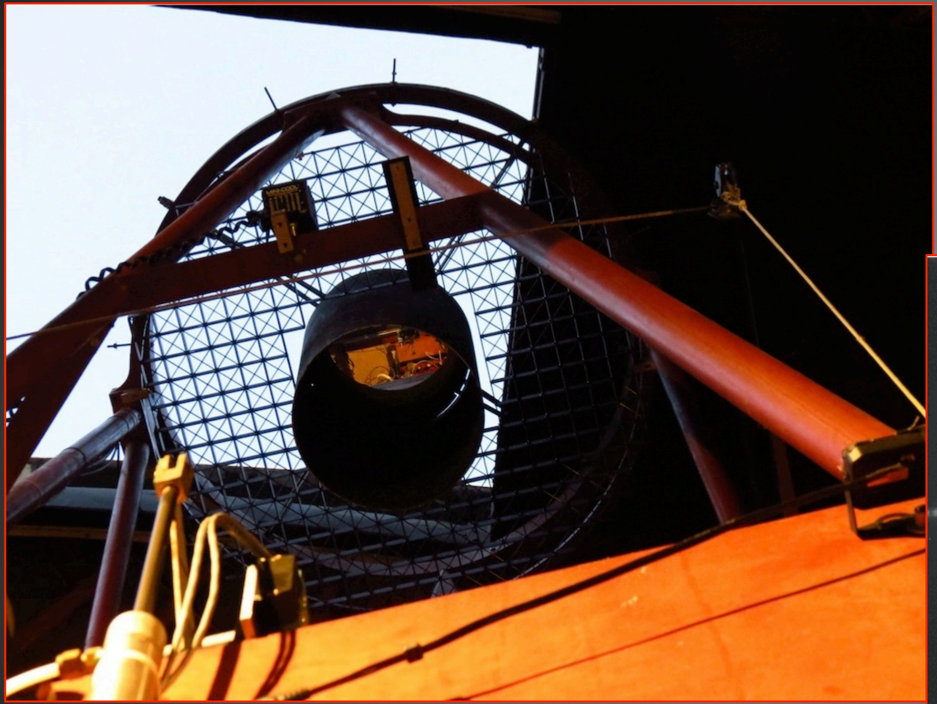
Improving Astrometric Precision with the *Diffractive Grid*



Olivier Guyon

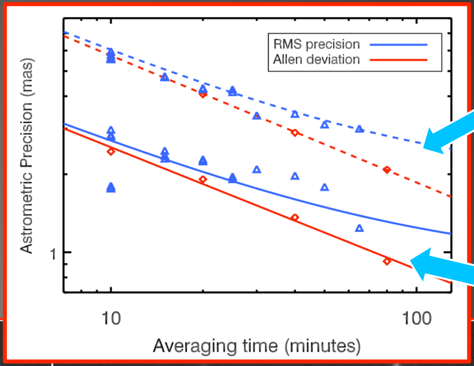
All astrometric distortions (due to change in optics shapes and deformations of the focal plane array) **are common to the spikes and the background stars**. By referencing the background star positions to the spikes, the astrometric measurement is largely immune to large scale astrometric distortions.

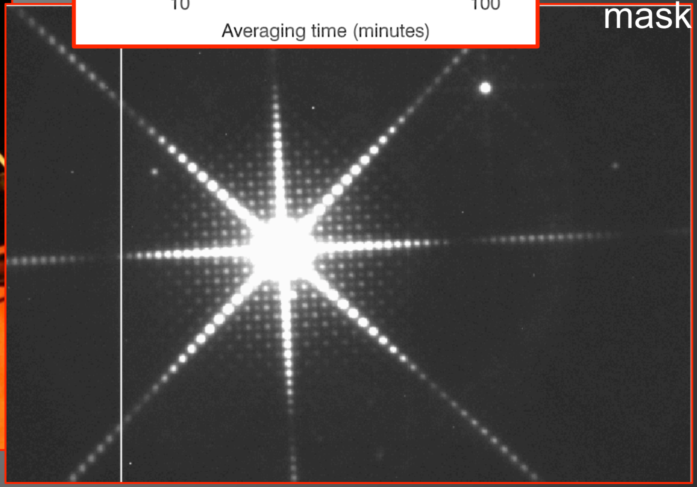
Diffractions Spikes Map Optical Distortion, Prevent Star Saturation



Carbon mask installed on Nickel Telescope (Credit: E. Bendek)

Ammons et al. 2013



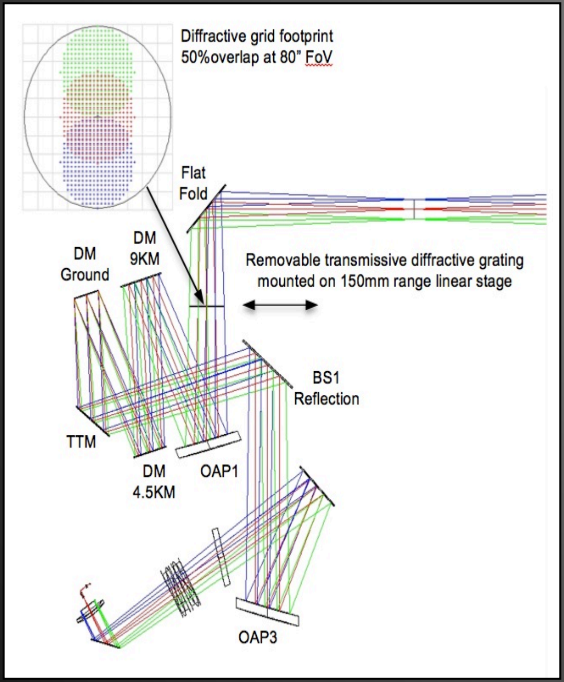


51 Per

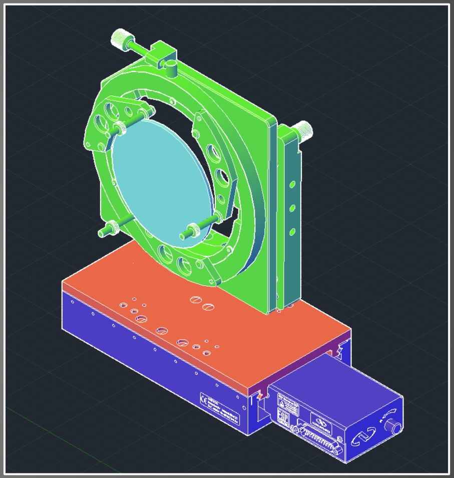
- Stiff CFRP honeycomb mounted at secondary produces diffraction spikes that map changing optical distortion
- Experiment designed to average down random errors and reveal systematics
- Final generation mask manufactured in San Jose and designed by Eduardo Bendek

A Diffractive Mask for GeMS

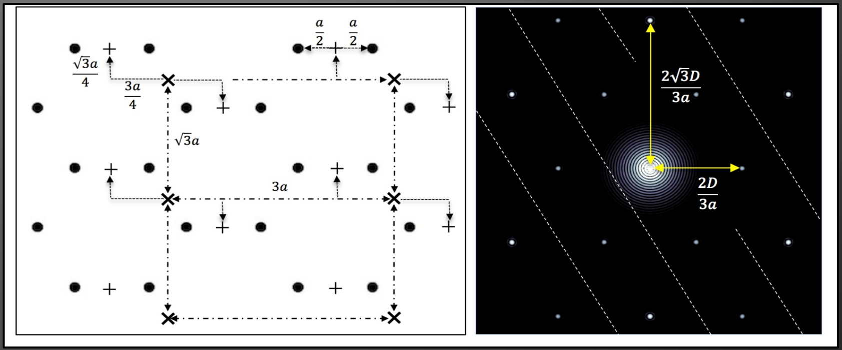
- An LLNL-led visitor instrument for GeMS
- Engineering support from NASA Ames (Eduardo Bendek)
- Procurement in FY15; Installation and testing complete by summer 2016



Optical design within GeMS



AutoCAD drawing of insertion mechanism



Dot Matrix Pattern Imprinted on Mask

Summary

1. TMT IRIS can measure masses of half of exoplanets directly imaged by GPI/SPHERE/SCExAO

2. TMT IRIS can measure an exoplanet occurrence rate for L/T brown dwarf hosts

3. TMT PFI can follow up 10-100 young “trending” candidates discovered with GAIA