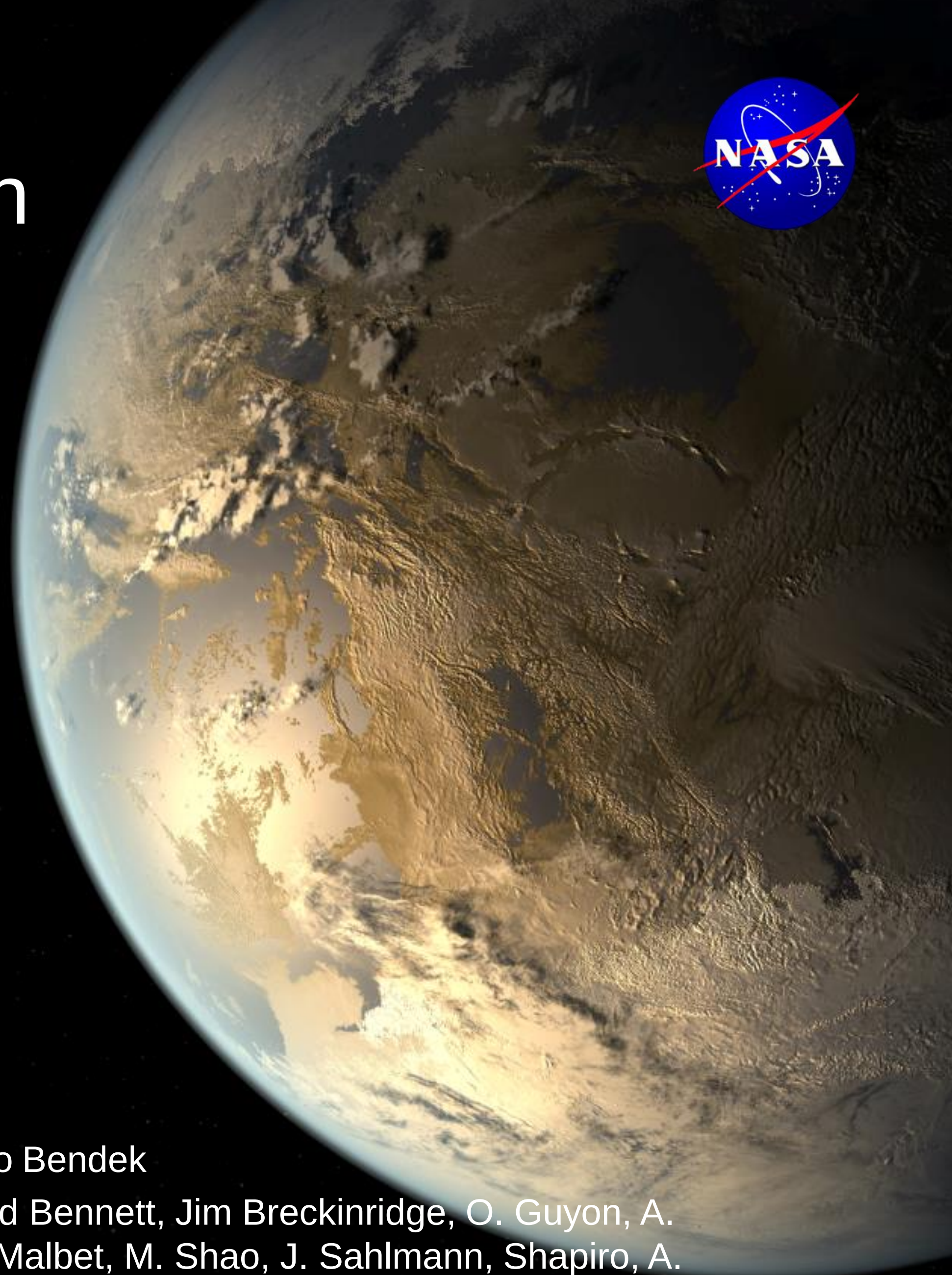
SAG-12 Astrometry for exoplanet detection



Closeout

SAG-12: Chair Eduardo Bendek

Contributions from: S. Mark Ammons, Rus Belikov, David Bennett, Jim Breckinridge, O. Guyon, A. Gould, T. Henry, S. Hildebrandt, J. Kuhn, V. Makarov, F. Malbet, M. Shao, J. Sahlmann, Shapiro, A. Sozzetti, D. Spergel.

Image Credit: NASA Ames *Kepler 186f*

SAG-12 Closeout

1) Review answers set by the SAG goals:

- What is the scientific potential of astrometry for different precision levels?
- What are the technical limitations to achieving astrometry of a given precision?
- Identify mission concepts that are well suited for astrometry, including synergy with European ones.
- Study potential synergies with ground based observatories

2) Deliverable:

- Written report
- Other requests?

Astrometry science and Link to NASA Roadmaps

NASA Science plan 2014, *"Discover and study planets around other stars, and explore whether they could harbor life" pg. 74,*

=> Mass measurements are necessary to answer this question

Astrophysics 2010– *New Worlds, New Horizons in Astronomy and Astrophysics*

- *"search for nearby, habitable, rocky or terrestrial planets with liquid water and oxygen… " pg. 11, 2020 Vision chapter*

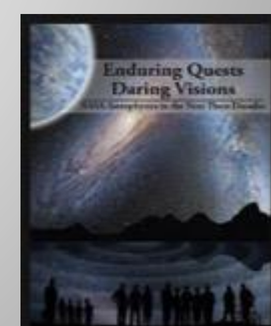
  => Mass measurements are necessary

- "Stars will then be targeted that are sufficiently close to Earth that the light of the companion planets can be separated from the glare of the parent star and studied" pg. 39 paragraph 1, On the threshold chapter

  => Focus on nearby stars, which is compatible with direct imaging and astrometry

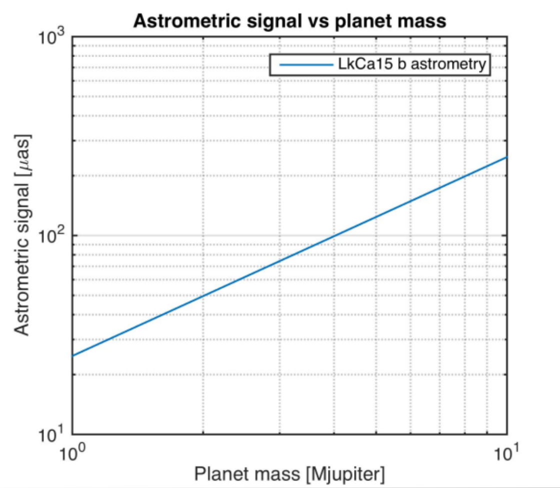
- *"the plan for the coming decade is to perform the necessary target reconnaissance surveys to inform next-generation mission designs while simultaneously completing the technology development to bring the goals within reach."* pg. 39 paragraph 2, On the threshold chapter

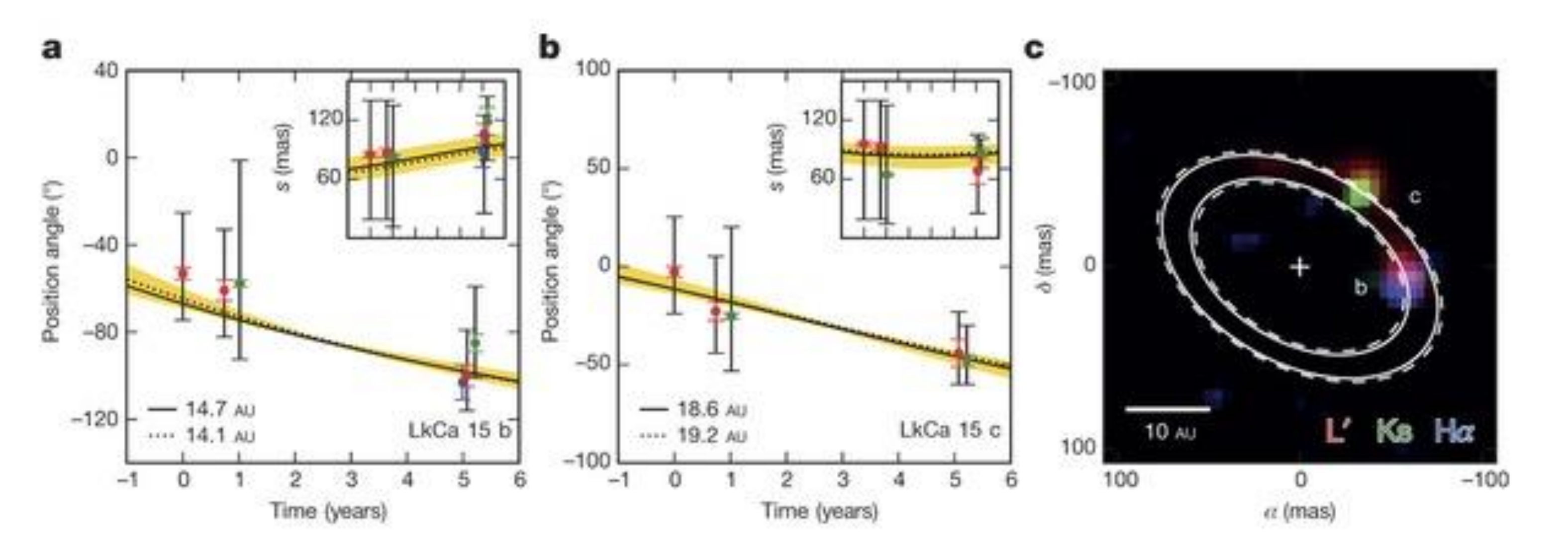
  => Need of measuring masses in advance of HABEX and LUVOIR and continue with the work with them



1: Science with Astrometry

- Exoplanet Detection
  - Mass determination
  - System inclination ambiguity
  - Confirm RV and transit detections
  - Distinguish zodi / dust from planets
  - Example LkCa 15 b
    - As ~ 100uas for 5Mj planet
    - GAIA data will help.





S. Sallum, et al., Nature 2015.

1: Science with Astrometry

- Characterization (With input from L. Rogers)

We need mass measurements to:

- Distinguish terrestrial planets from water-rich planets and mini-Neptunes (e.g., Grasset et al. 2009).

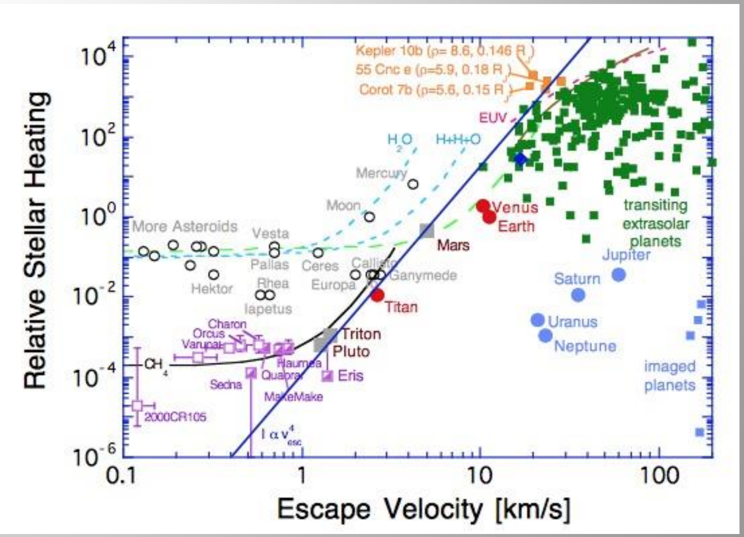
  "M-R measurements could be accurate enough to ascertain the discovery of an earth-like planet"

- Determine the planet's surface gravity (log g), which improves the retrieval of abundances from atmospheric spectra.

- Determine how oxygen is generated and retained (Zahnle 2016)
- Assess atmospheric loss rates

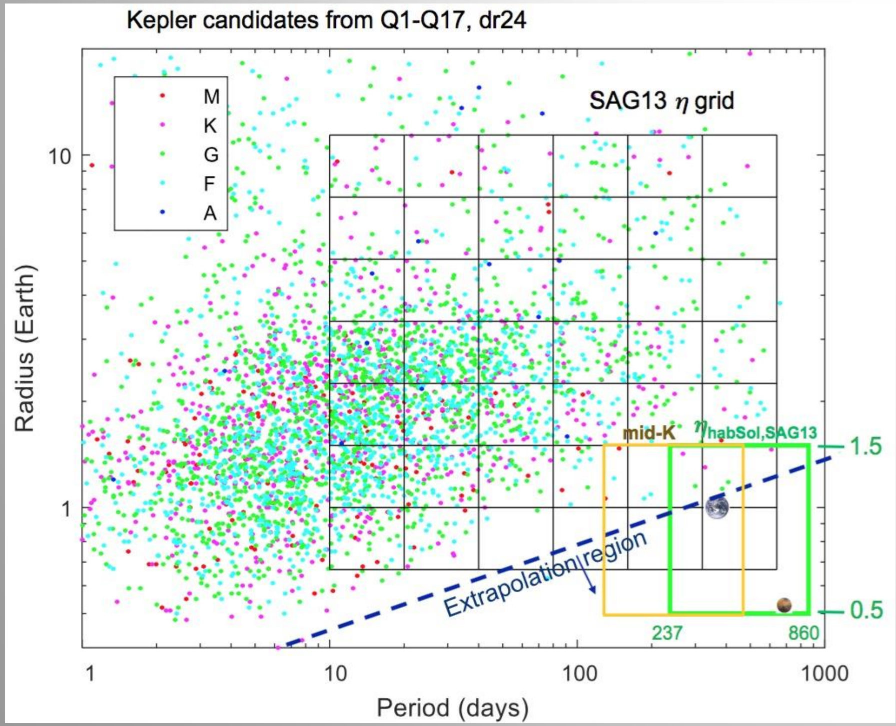
  Cosmic Shoreline (Zahnle & Caitling 2013)

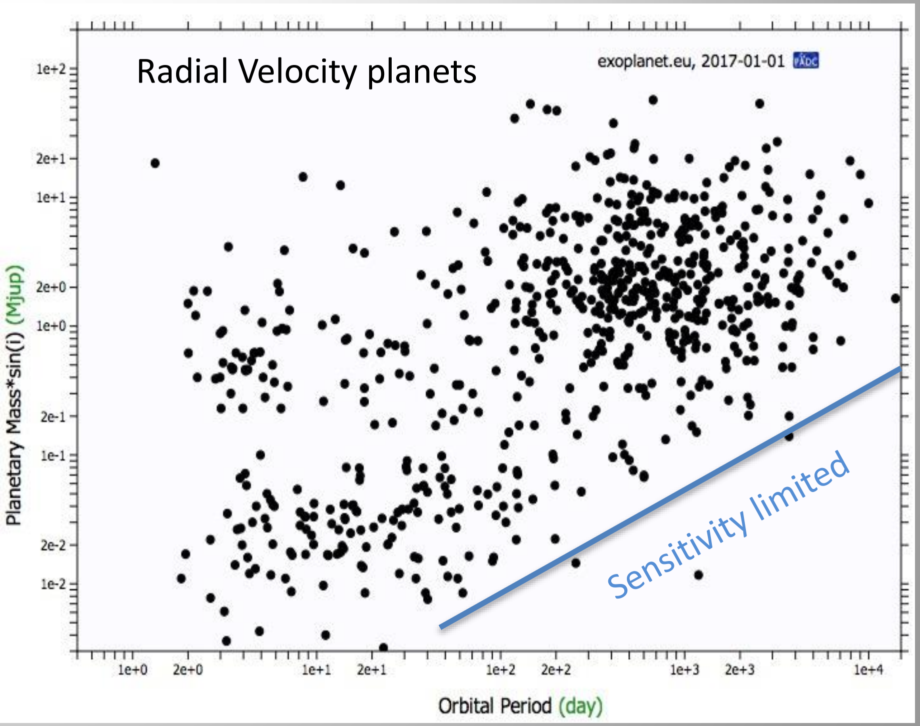
- Assess the planet's thermal evolution (e.g., likelihood of a dynamo magnetic field, geological activity).



1: Science with Astrometry

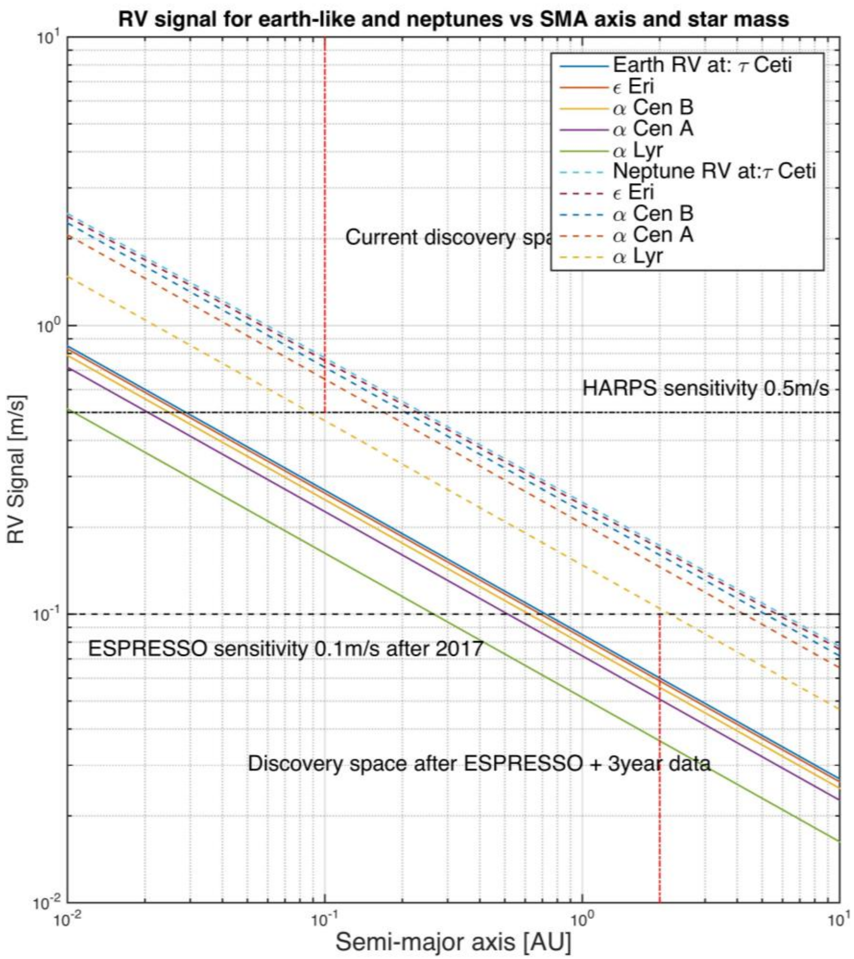
- Completeness
  - Need to explore the "extrapolation region", i.e. SAG-13 considers an extrapolation region The astrometry signal of those planets would range between 0.034uas and 21uas.
  - Search for long period planets (>1 year, FGK) around nearby stars (NWNH pg. 39)
  - Planetary formation around pre-main sequence stars
  - RV and Transit sensitivity goes down rapidly in this region

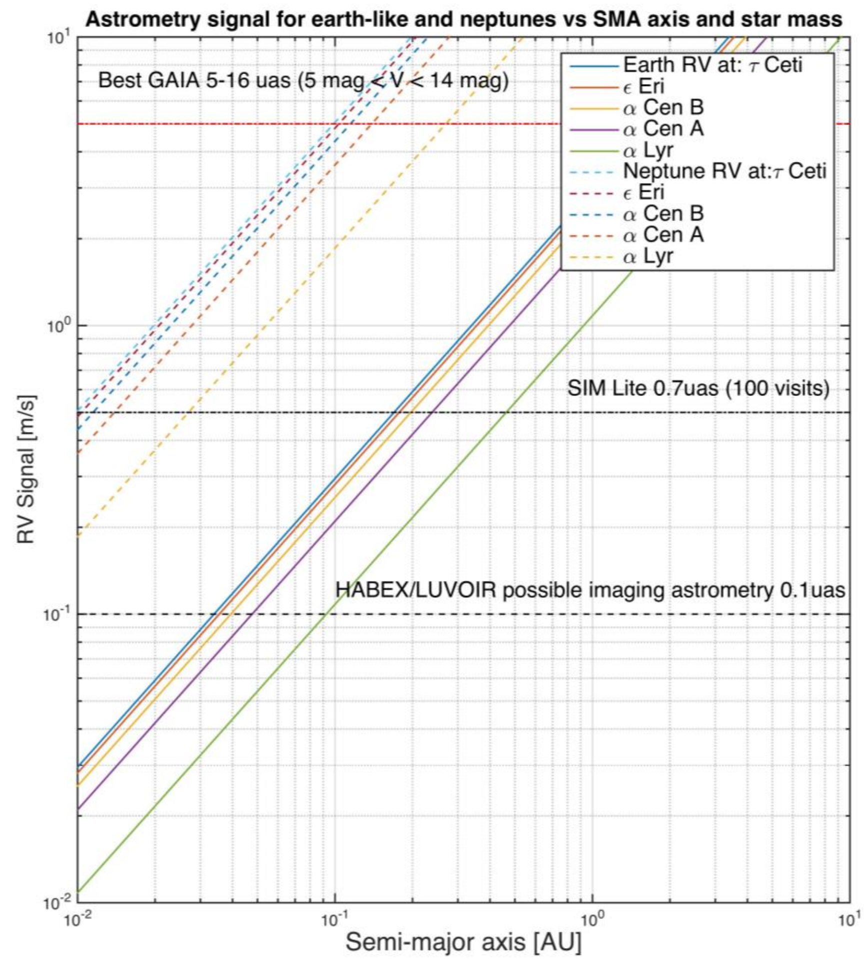




1: Science with Astrometry

- Astrometry expands RV's exploration envelope





2: Astrometry Limitations

Astrophysics: Stellar Jitter

Literature references:

- Sun-like stars at 10pc viewed from equator = 0.087μas jitter
  Marakov et al 2009 (ApJ 707, L73)
- Similar study in 2011 is consistent = 0.07μas RMS, 0.2μas PV
  Lagrange et al 2011 (A&A 528, L9)
- Absolute astrometric Jitter from solar data = 0.52μAU (0.11mR) jitter Marakov et al 2010 (ApJ 717, 1202)

Signal earth-like planet around the sun: 0.46mR = 2.17μAU = 0.3μas @ 10pc

- Peer reviewed literature agrees on a stellar astrometry jitter ~ <0.1uas
- New studies of sun jitter are being produced at this moment (led by J. Kuhn)
- **As of today, stellar jitter is NOT a showstopper for astrometry earth-like detection**

Mitigation strategies in case of noisier targets:

- Higher sampling avoiding stellar rotation period or its harmonics
- Observing in different wavelengths where spots and faculae is dimmer.

2: Astrometry Limitations

Instrumentation: Detectors

Known detector systematics to be characterized:

- nonlinear response, sub-pixel response, inter-pixel capacitance
- Persistence, flux-dependent nonlinearity ("reciprocity failure")
- SIDECAR systematics correlated read noise

Thermal/Mechanical (Rauscher/Shapiro)

Focal plane strain due to CTE mismatch.

- SCA mounting holes might cause vertical deflections away from best focus
- Small correlated relative pixels shift in sensor plane

Strain expected to be linear and repeatable function temperature

- Individual SCA temperature and frequent sampling needed for calibration
- Risk of small slips during vibe testing and launch. On-orbit subpixel shift might happen

Electrical distortions

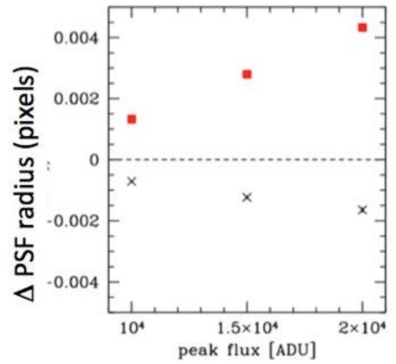
- 1/f noise and alternating column noise to be considered on centroiding algorithm
- Non-stationary noise

2: Astrometry Limitations

Instrumentation: Detectors

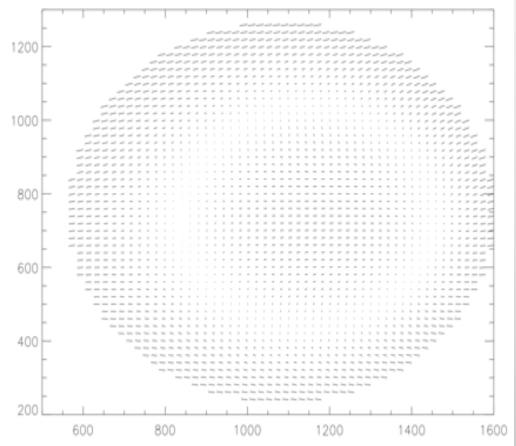
Known unknowns:

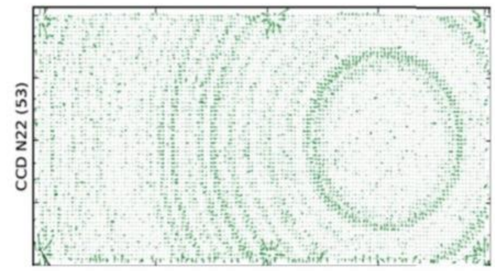
- Fluence-dependent PSF ("brighter-fatter effect”)
- inhomogeneity in electric field lines (e.g. edge effects or "tree-rings" in CCDs) causing astrometric errors
- These have not been investigated, and we don't know the scale of these effects in an H4RG. Tree-rings are probably specific to CCDs
- Brighter-fatter should theoretically be present in an H4RG.
- Nonlinear components of ShaneAO SHARCS distortion map, maybe caused by H2RG? Under investigation. (M. Ammons)



PSF radius change relative to stars with 5000 ADU peak.
Red = Measurement
Black X = After model correction

Image from Gruen et al. 2014





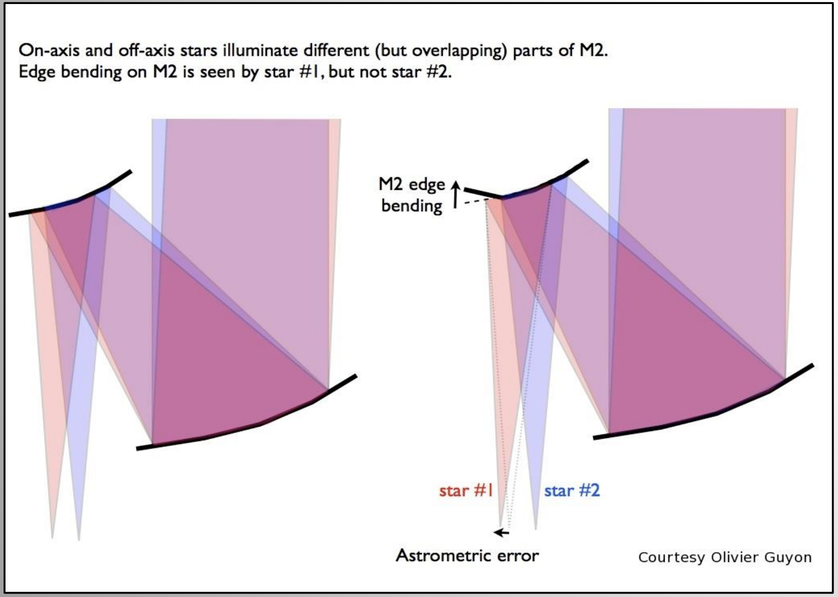
Green whiskers represent direction of astrometric errors, typical size ~0.06 pixels

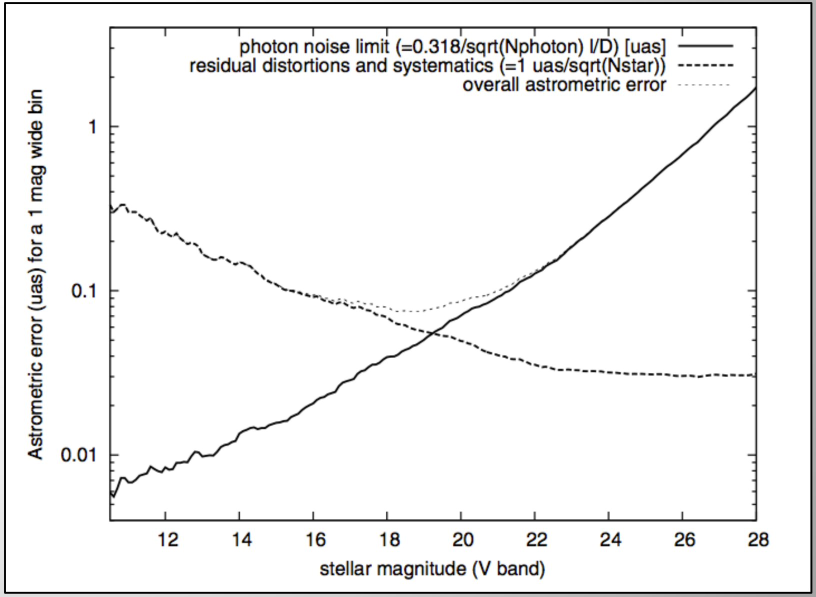
Image courtesy G. Bernstein, A. Plazas, DES Collaboration

2: Astrometry Limitations

Instrumentation: Distortion

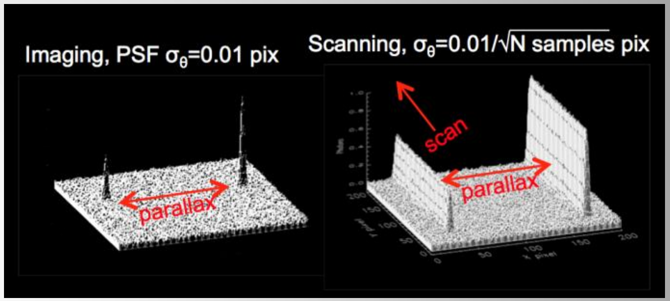
- Cause local plate scale changes
- Bias the astrometry measurements
- Impact on multi-epoch astrometry, very difficult long term calibration

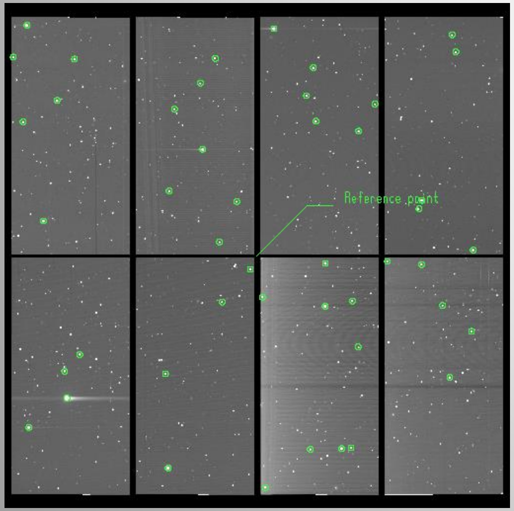




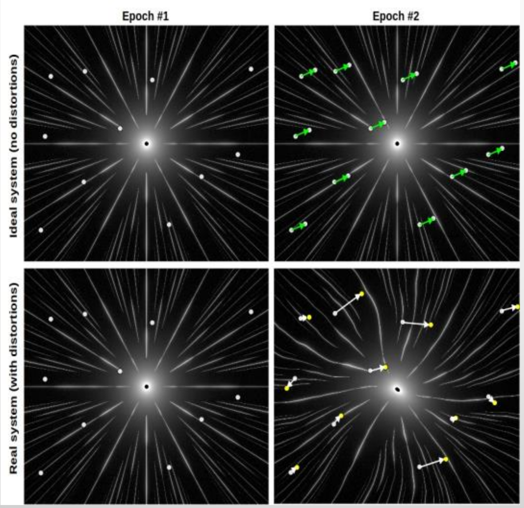
2: Astrometry Limitations

- Distortion mitigation strategies
  - Star cluster calibration
    - On sky, differential distortion after slewing
  - Diffractive pupil
    - Require dots on the mirror, permanent effect
  - Dithering, PASS scanning
    - Operations impact

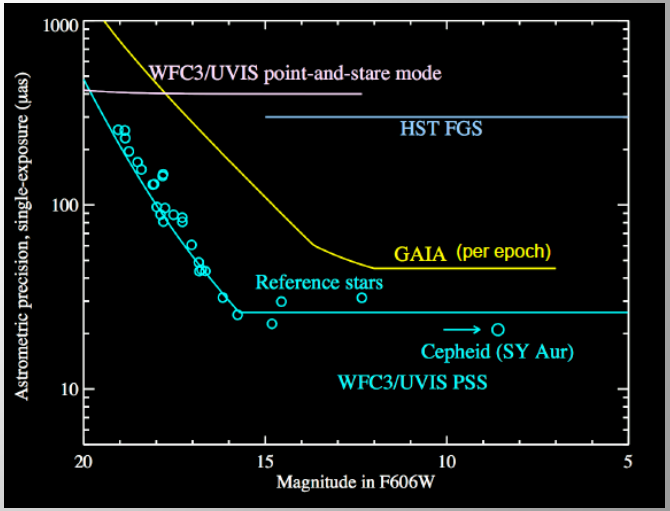




Cluster calibration



Diffractive pupil calibration



PASS scanning

Imaging astrometry TDEM work

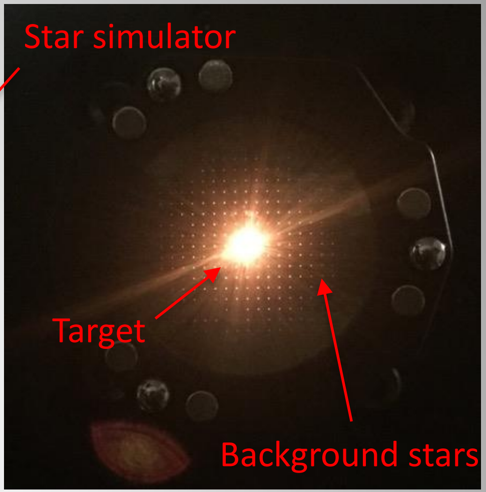
- **Milestone #1 Demonstrate 2.4x10^{-4} λ/D astrometric accuracy per axis**

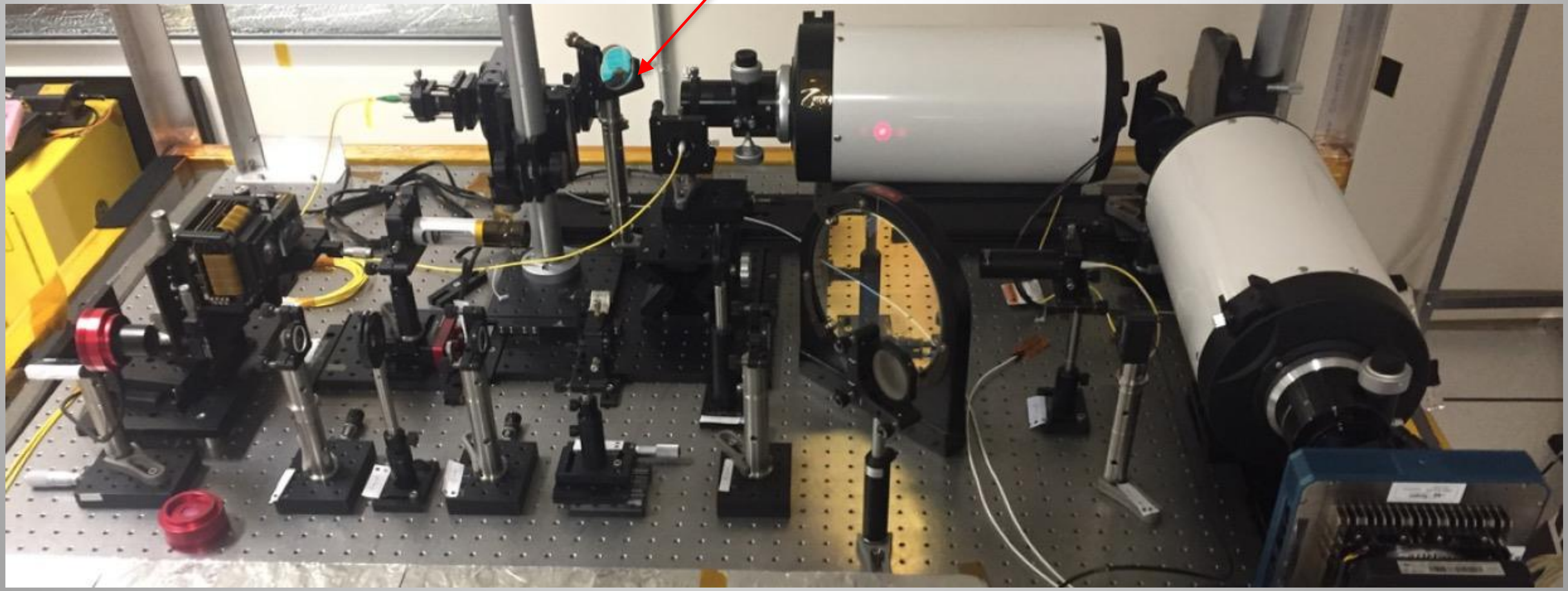
  X-axis: 5.6x10^{-5} λ/D ✔

- **Milestone #2: High-contrast imaging fed by the Diffractive Pupil primary**

  IWA (1.6 to 2.0λ/D) = 3.2x10^{-7} contrast ✔

  OWA (2.0 to 10λ/D) = 6.0x10^{-7} contrast

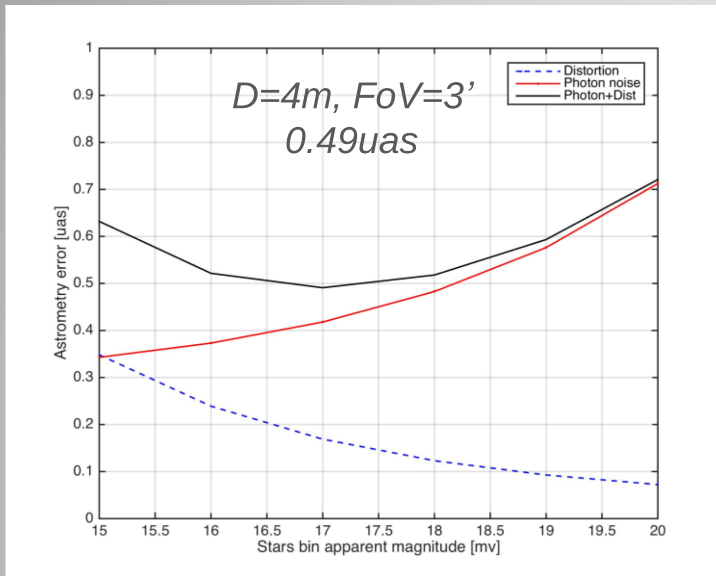




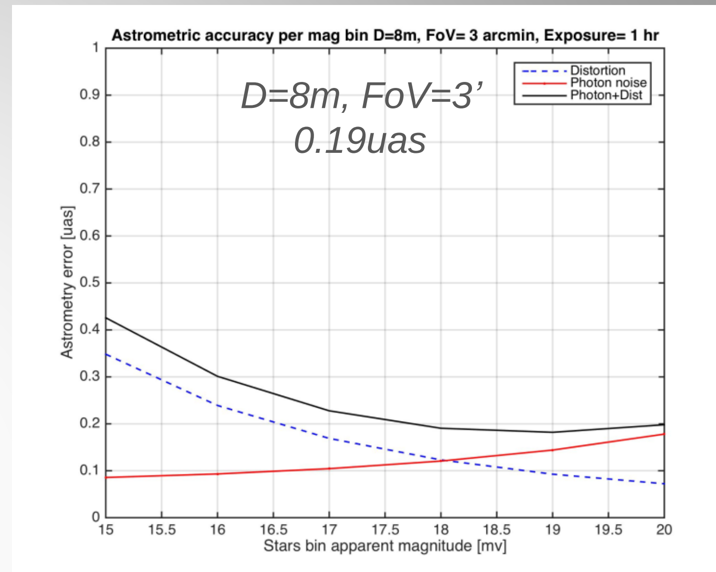
2: Astrometry Limitations

Description	Included	comments
Photon noise		
Photon noise (bg stars)	Yes	1/(Flux Star)^0.5
Sampling (bg stars)	Yes	(1/(Flux Star)^0.5)*(1/pi()+0.1*Sampling ^-1.2)
Polychromaticity (bg stars)	Yes	(1/(Flux Star)^0.5)*(1/pi()+0.1*Sampling ^-1.2)
Zodiacal light photon noise (bg stars)	No	To be included
Target star and Zodi photon noise	Approx	
Astrophysics		
Proper motion, parallax and companions (bg stars)	Approx	Assumed 0.1uas each and added as RSS
Target star proper motion and parallax	Yes	Subtracted
Target star jitter due to spots	Upper limit	0.1uas
Detector (calibration down 1e-4px)		
Uncalibrated errors flat field and geometry	Yes	Included in 1e-4px allocation
Pixel sensitivity time variations	Yes	Included in 1e-4px allocation
Detector geometry time variations	Yes	Included in 1e-4px allocation
Readout noise	No	Negligible with proper exposure time
Dithering or Roll to randomize detector error	Yes	Factor of 100 (x100 integration time) (x1 for roll)
Telescope and optics		
Telescope Jitter	No	Impact is very low
Distortion (Uncalibrated surface shape changes M2 and M3)	Yes	Cubic FoV normalized HST type optics + DC offset,

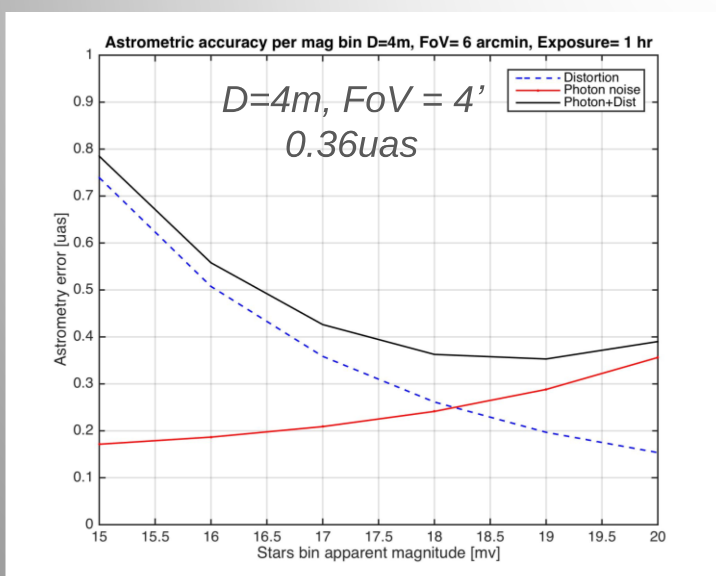
2: Astrometry Limitations

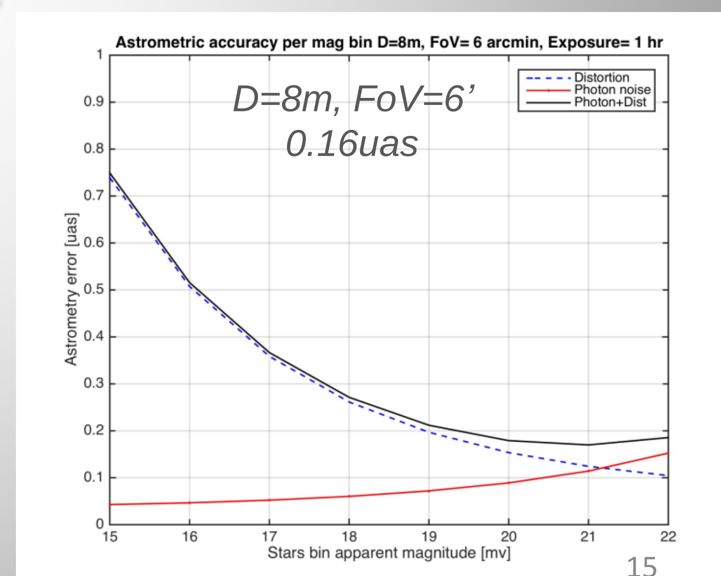


Grow in aperture Reduce photon noise



Grow in ***FoV*** *More stars, less distortion*





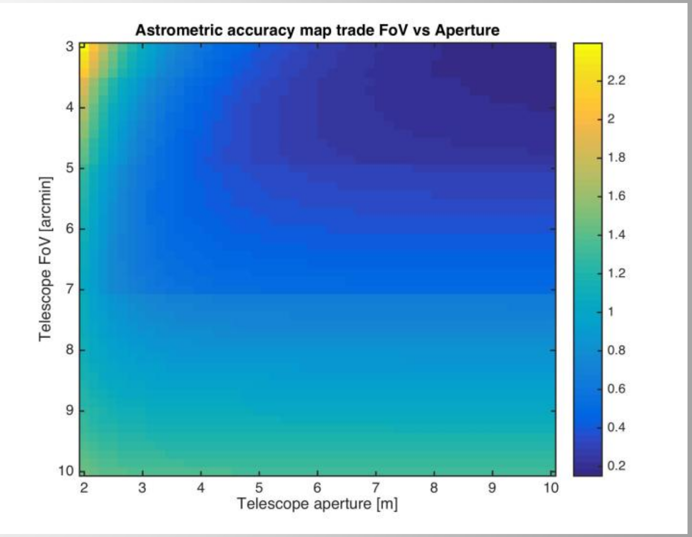
3: Mission Concepts

HABEX/LUVOIR Type mission astrometry error budget

- Flagship 8m class, 3'm FoV
- Imaging astrometry better than 0.2uas is possible with a 8m Telescope with 3' FoV
- Search 1000 stars for 0.5 earth mass or larger planets in the HZ in one year

Astrometry probe on ExoPAG report

- Probe-class astrometry mission < $1B cap
- ~1.2m astrometric telescope, with a 0.25 deg2 FOV
- Control systematic errors to near photon-limited
- Earth-mass planet detection around nearest stars (1pc)
- 25% time of a 5-year mission (η_{earth}= 10%) => 16 earth analogs
- Measure masses or most know RV planets



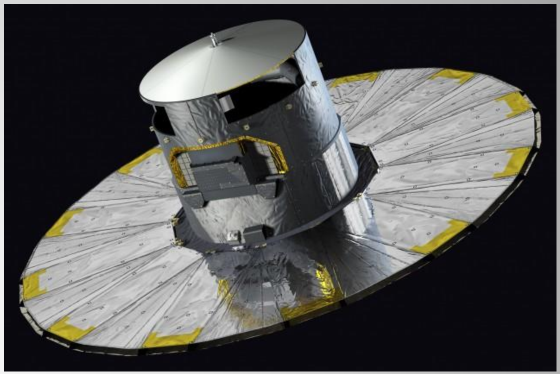
Assumption: *"..., which would use novel technologies to control systematic errors to near photon-limited performance."*

	Astrometry accuracy (1hr)		
Mission type	**V~7**	**V~10**	**V~15**
Probe (1m, 30'FoV)	0.4μas	1.0μas	10.0μas
Flagship (8m, 3FoV)	0.2μas	0.25μas	0.3μas

3: Mission Concepts

GAIA (Alessandro Sozzetti)

- Demonstrate 20 to 30µas single epoch for bright stars.
- 2 years of operations at L-2
- Issues detected during commissioning (Bruijine et al. 2015)
- Gaia Data Release 1 (GDR1) in September 2016



- **8µas for stars 6 < m_v < 12**
- **25µas for stars m_v = 15**
- 70 visits in 5 years.
- 1000 million stars, 30.000Ly range

1) **Stray light**, which periodically varies with time Increased noise levels lead to an irreversible degradation of the end-of-life astrometry

1) **Optics transmission degradation** with time (currently at a rate of ~40 mmag/100 days) due to water contamination
 Under control by (semi-) periodically heating the payload. ~10% end-of-life performance impact; (Included in the 20% "science margin")

3) **The intrinsic instability of the basic angle** – which separates the lines of sight of the two telescope is larger than expected.
 Basic-Angle-Monitor device (Mora et al., 2014) measures variations in the basic angle and inject this information into the astrometry global iterative solution (Lindegren et al, 2012)

3: Mission Concepts

THEIA (ESA M class mission) (Celine Boehm)

- Exoplanet census of earth-like planets in the HZ around the closest 50 FGK stars
- 0.3μas differential astrometry accuracy
- 0.8m, 0.6˚ FoV, TMA Korsch astrometric telescope
- Single imaging instrument at focal plane
- Interferometric metrology for Optics and Detectors
- Estimated cost of ~ $630M

EXPLORE (EXoPLanets ObseRvatory looking for nearby Earths) (Celine Boehm)

- Small astrometry mission
- Detect earth-like planets in the HZ of FGKM stars within 6pc
- 0.15m, 0.6˚ FoV, TMA Korsch astrometric telescope
- Precision not specified.

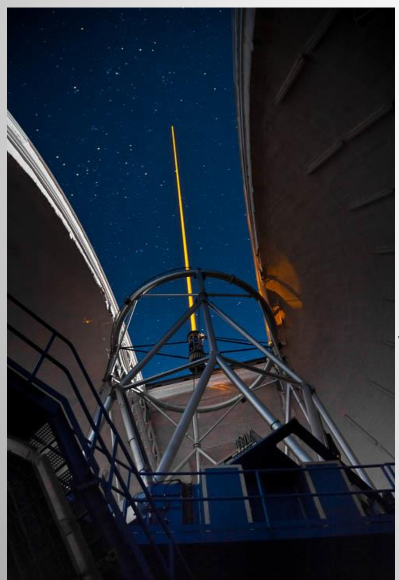
Binary stars concept (P. Tuthill, Sydney)

- Small astrometry mission specialized in binaries relative astrometry
- Capable of detecting earth-like planets in the HZ of aCen A&B
- Sparse/diffractive pupil aperture approach to spread light

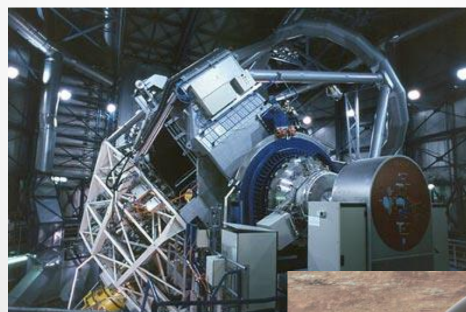
4: Ground based astrometry

Ground based telescopes astrometric performance

Observatory	Instrument	Performance	FoV	Comments	Ref
Gemini	GEMS+GSAOI	0.2mas monoepoch + 0.4 multi epoch	2'	Crowded wide	Neichel et al 2014 (MNRAS)
VLT	FORS	50µas	Narrow	Crowded	Lazorenko et al 2009 (A&A)
TMT	IRIS	25µas	17"x17"	Galactic center	Yelda et al 2013
EELT	MICADO	40µas	Narrow	Crowded	Trippe et al 2009



Gemini South, GEMS



VLT, FORS1, 2.

TMT, IRIS

EELT, MICADO

Conclusions:

Science:

- Exoplanet mass measurements is key to accomplish decadal survey scientific recommendations.
- Astrometry is very well suited to deliver those measurements

Limitations

- **Astrophysics:** Stellar jitter is important but not a showstopper for earth-like exoplanet science around nearby sun-like stars
- **Instrumental:** Detectors and distortion calibration makes uas imaging astrometry difficult, however multiple technologies solve those challenges

Missions

- Wide range of missions that could include and imaging astrometry instrument
- Trade between aperture and FoV enable cutting edge science on small apertures (1m class)

Ground Based

- 10m class and ELTs will deliver 10 to 20uas accuracy complementing GAIA
- Earth-like planet science needs to be done from space

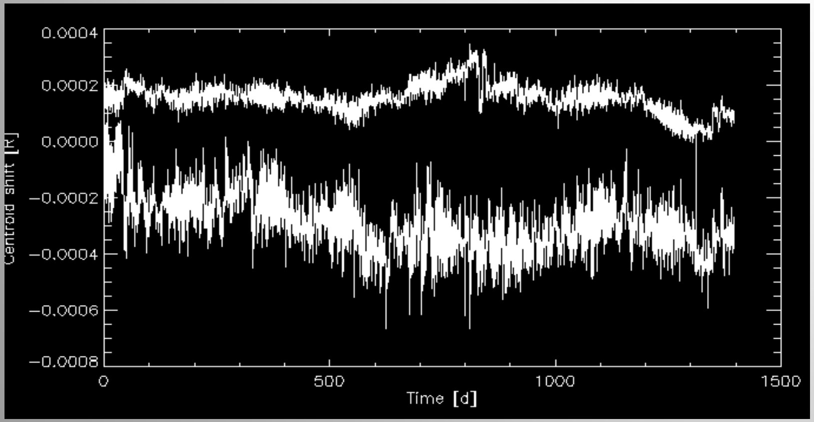
2: Astrometry Limitations

Astrophysics: Stellar Jitter

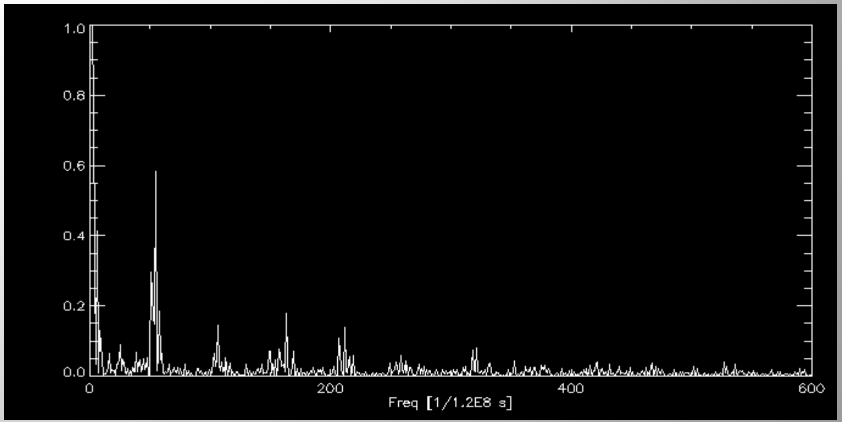
- Peer reviewed literature agrees on a stellar astrometry jitter ~ <0.1uas
- Factor of ~ 3 smaller than the planet signal at 10pc
- New studies of sun jitter are being produced at this moment and will be included in the report (led by J. Kuhn)
- As of today, stellar jitter does not seems to be a show stopper for earth-like planet mass determination around nearby stars.

Mitigation strategies in case of noisier targets:

- Higher sampling avoiding stellar rotation period or its harmonics
- Observing in different wavelengths where spots and faculae is dimmer.



The solar centroid variation in solar radius units over 1400 days from the outer 2% of the solar disk. E-W shift is lower curve, N-S is upper



Power spectrum of the solar centroid noise. Most of the centroid variance occurs at the solar rotation frequency and its harmonics.