SAG-12 Astrometry for exoplanet detection

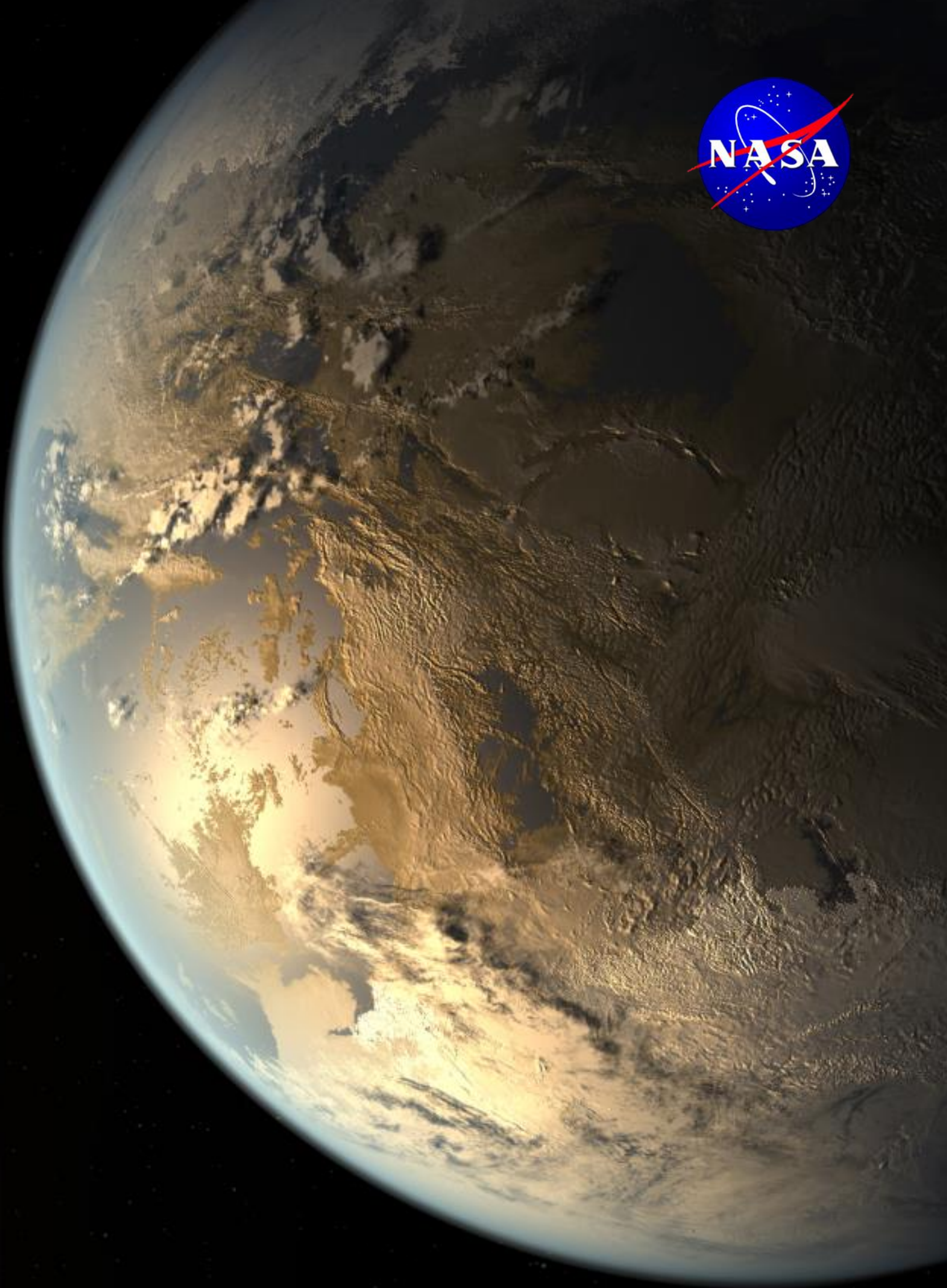


Image Credit: NASA Ames *Kepler 186f*

SAG-12: Report structure

1. Introduction and goals
2. Exoplanet Science with Astrometry
3. Astrometry Challenges
    1. Astrophysical
    2. Technical
        1. Detector
        2. Optics/distortion
        3. Long term stability
4. Astrometry missions
    1. WFIRST
    2. LUVOIR
    3. Astrometry Probe
5. International
6. Ground Based

1: Goals and question

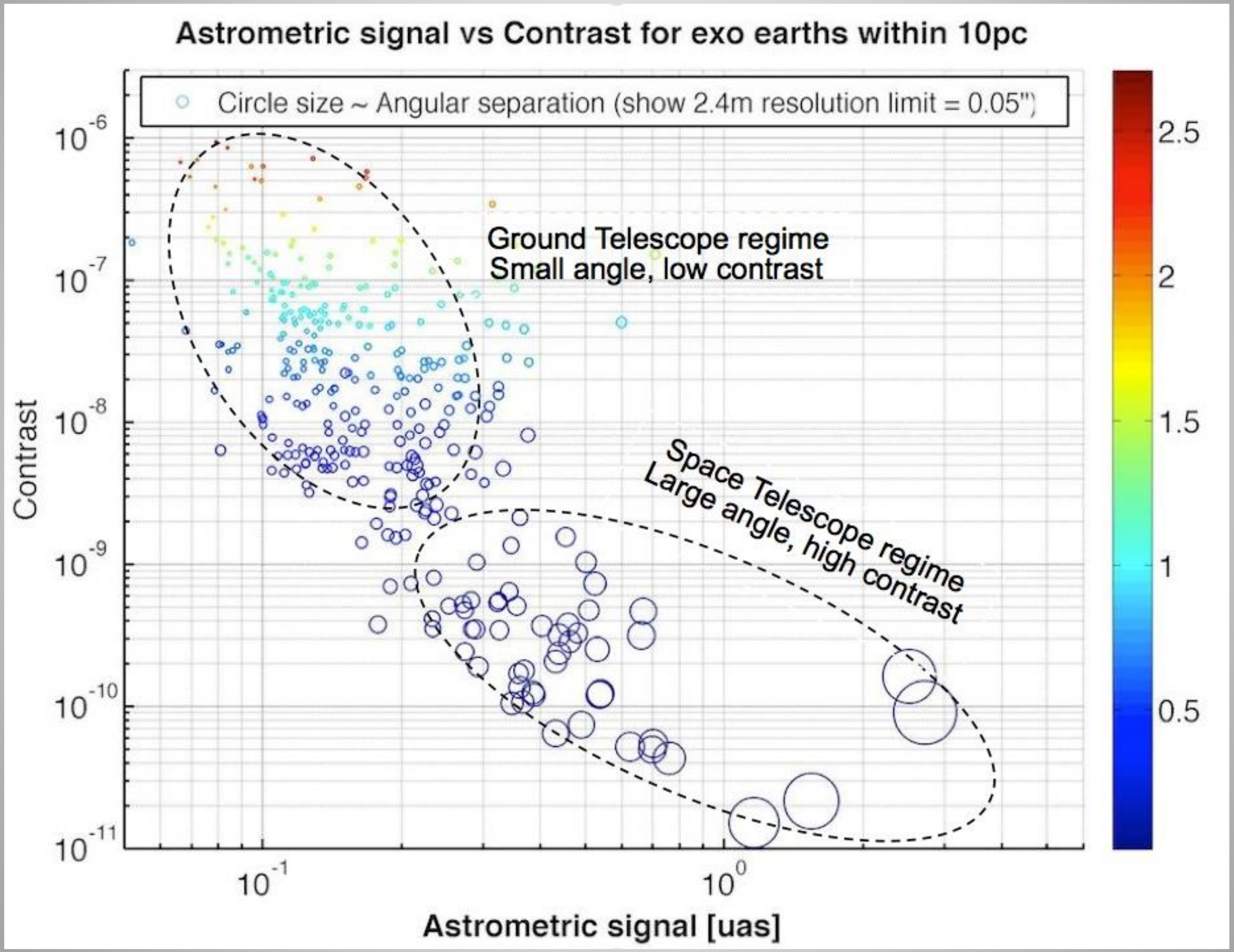
Key questions and goals that this group will address are: 1) What is the scientific potential of astrometry for different precision levels? Which planet types, confirm planet candidates.

2) What are the technical limitations to achieving astrometry of a given precision? Technical challenges, observational strategies or post processing to improve the astrometry.

3) Identify mission concepts that are well suited for astrometry. Next mission after GAIA that will make exoplanet science possible? What are the requirements for such a mission?

4) Study potential synergies with current and future European astrometry missions. What are the available astrometric facilities to follow-up on GAIA (exoplanet-related) discoveries? Are they sufficient?

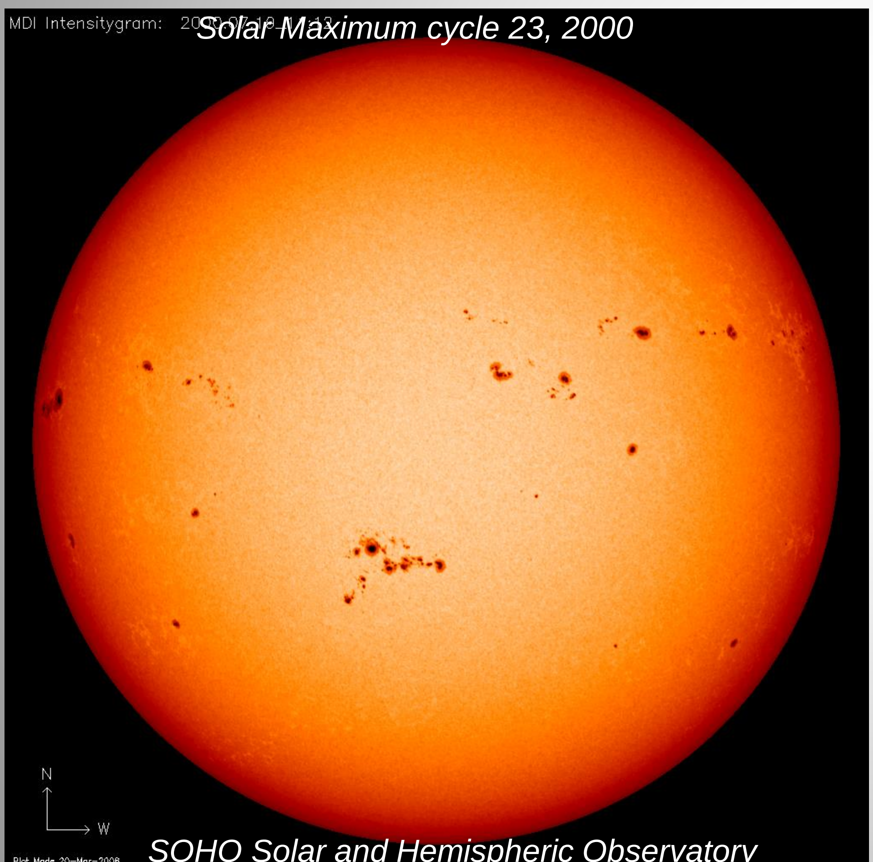
2: Exoplanet science



2: Astrometry Challenges

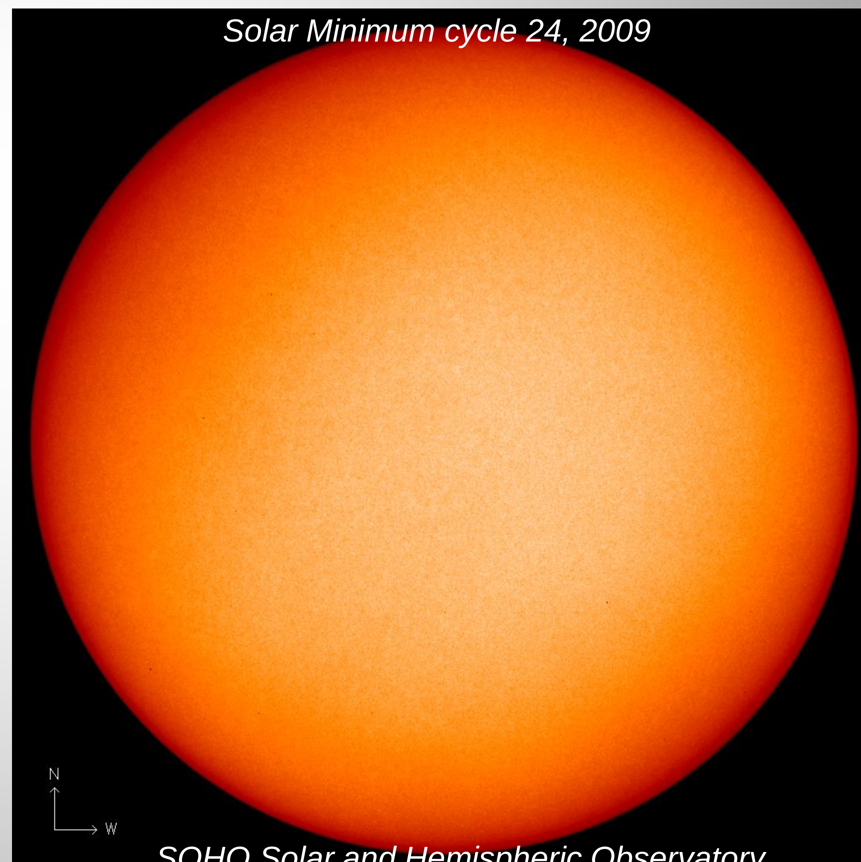
Astrophysics:

- Stellar jitter due to star spots: VERY IMPORTANT!
- This is the *astrophysical limit* of astrometry accuracy
- Temporal and star to star variability



Solar Maximum cycle 23, 2000

SOHO Solar and Hemispheric Observatory



Solar Minimum cycle 24, 2009

SOHO Solar and Hemispheric Observatory

2: Astrometry Challenges

Astrophysics:

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 jitter
  Marakov et al 2010 ApJ 717, 1202

Astrometric signal of an Earth-like planet in the HZ @ 10pc = 0.3μas

Summary: Peer reviewed literature agrees on:
Stellar astrometry jitter ~ factor of 5 smaller than the planet's signal.
=> Not a lot of margin

2: Astrometry Challenges

Astrophysics:

Risk: Stellar jitter higher than expected will prevent earth-like planet detection.

- Some solar/stellar astronomers suggest that the stellar jitter could be up to 10 times larger (Kuhn, Ayres).

- aCen example:

  Why? Because it would be the largest astrometric signal possible for an earth-like planet in the HZ of a sun-like star.

	Sun-like star @ 10pc		**aCen A&B**	
	η_{earth} signal	Stellar noise	η_{earth} signal	Stellar noise
Literature	0.3µas	0.07µas	3µas	0.7µas
Suggested Upper limit	0.3µas	<0.7µas	3µas	<5µas

Even If the stellar jitter is 5 times higher, it would be really difficult to detect an earth-like planet.

2: Astrometry Challenges

Astrophysics:

<u>Risk:</u> Stellar jitter higher than expected will prevent earth-like planet detection.

⇒ Action to reach a consensus and/or perform more observations and modeling

⇒ Stellar cycles variability may make stars suitable for astrometric detection seasonally
  - Requires operations planning and/or mission launch timing for target focused missions (i.e. aCen)

⇒ Mitigation strategies:
  - If the noise is comparable (x5), longer observation campaigns to obtain more samples
  - Ground based campaign might be necessary

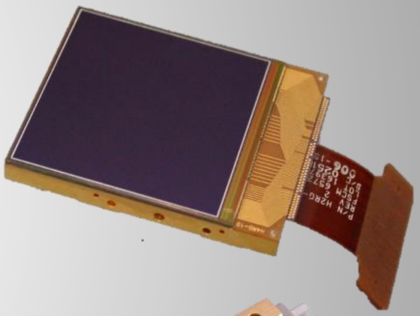
2: Astrometry Challenges

Detectors:

Primary concern (C. Shapiro) – Not enough experience with CMOS devices; experience with analysis and systematics mitigation is based on CCDs.

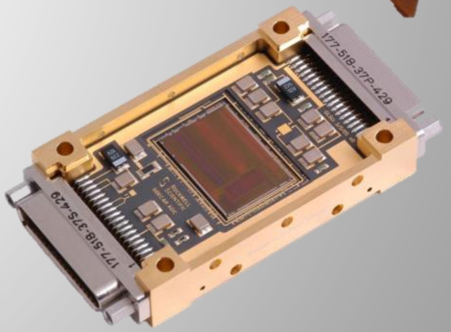
Known detector systematics which need to be characterized

- Nonlinear response
- Sub-pixel response
- Inter-pixel capacitance
- Persistence
- Flux-dependent nonlinearity ("reciprocity failure")



Known SIDECAR systematics

- Correlated read noise



Known unknowns – we don’t know their scale

- Fluence-dependent PSF ("brighter-fatter effect")
- Inhomogeneity in electric field lines
  (e.g. edge effects or "tree-rings" in CCDs) causing astrometric errors.

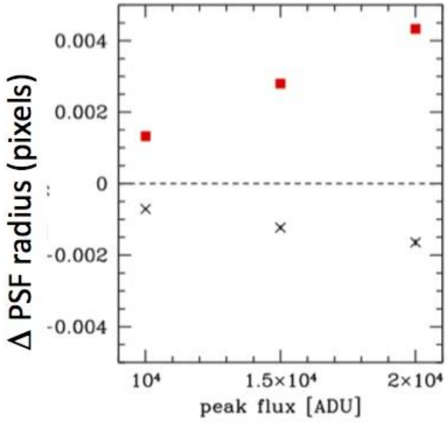
2: Astrometry Challenges

CCD* anomalies discovered by Dark Energy Survey during commissioning

(Slide from C. Shapiro)

Brighter-fatter effect

- Detector PSF size increases with signal
- Cause: Repulsion of photo-charge from bright pixels
- Magnitude of effect varies across devices
- Complicates PSF calibration of (faint) galaxy images from (bright) star images

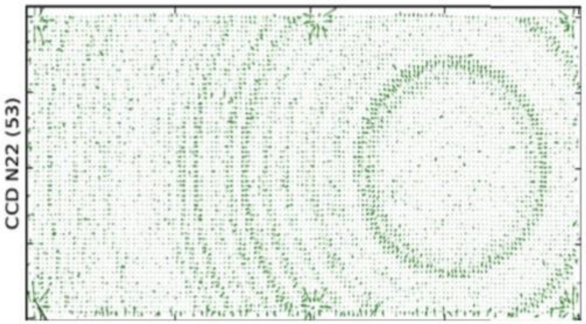


PSF radius change relative to stars with 5000 ADU peak.
Red = Measurement
Black X = After model correction

Image from Gruen et al. 2014

Tree-rings *(CCD specific)*

- Non-random pattern of astrometric errors
- Cause: charge deflection by inhomogeneous electric field in detector



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

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

* CCDs are mature devices

2: Astrometry Challenges

Recent surprises in NIR detectors

(Slide from C. Shapiro)

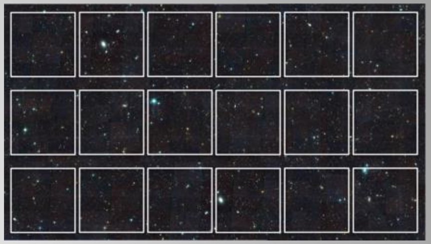
- **JWST**: Spontaneous development of hot pixels
  - Caused by impurity diffusion into the pixel contacts near indium bumps.
  - Discovered on flight detectors in storage. Further pre-flight degradation was feared, and all devices were re-procured
- **WFC3**: Scintillation by high energy particles
  - Discovered pre-launch as splashes of light in long dark frames
  - Scintillation originates in the CdZnTe substrate
  - Fabrication process was modified, leading to “substrate removal”, creating other benefits
- **NICMOS and WFC3**: “Reciprocity failure”
  - Photometry explicitly depends on source flux, not just FLUX*TIME → Degrades photometric accuracy
  - **Discovered in flight** as a discrepancy between photometric calibrations of CCD and NIR arrays
  - Cause not well-understood; may be related to charge trapping/persistence – research ongoing (R. Smith et al.)
- **SIDECAR**: Correlated read noise
  - Requires complex measurements to allow optimal reference pixel subtraction (Moseley, Rauscher et al.)

These issues were discovered by conventional tests.

What will we find in PSF-based tests?

2: Astrometry Challenges

Thermal/Mechanical (Rauscher/Shapiro)



Detector motion due to detector array assembly thermal distortion

- 25cm wide SiC (CTE 4ppm) focal plane.
- 0.01˚K gradient between extreme sides of the assembly can cause ~100μas errors

Focal plane strain due to CTE mismatch.

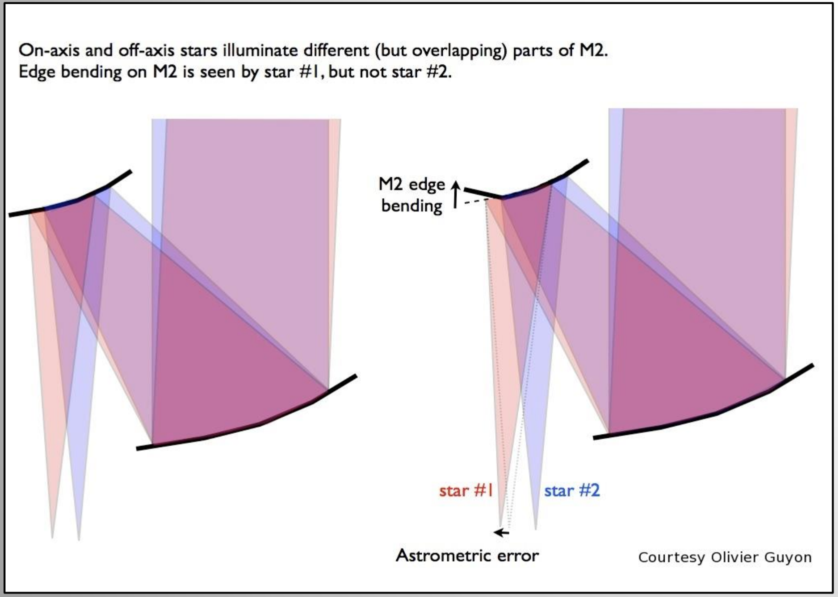
- SCA mounting holes might cause vertical deflections away from best focus
- Small correlated relative pixels shift in sensor plane

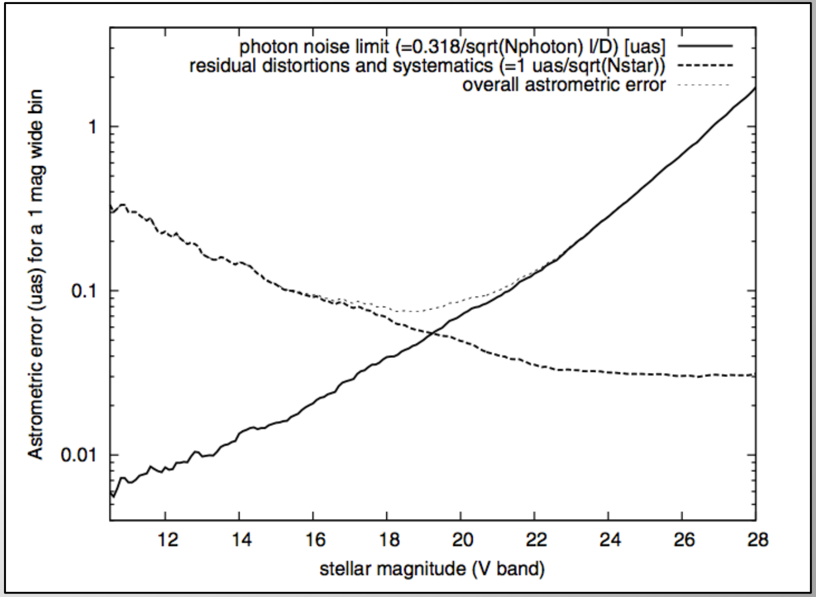
Strain expected to be linear and repeatable function temperature

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

2: Astrometry Challenges

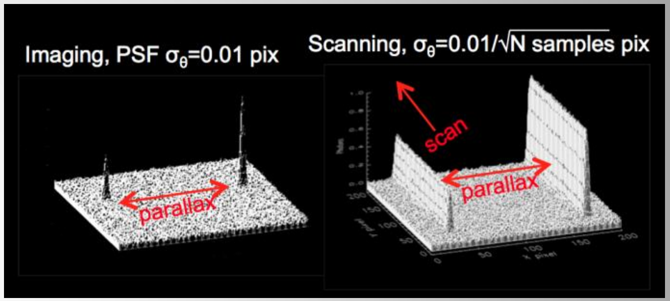
- Distortions
  - Cause local plate scale changes
  - Bias the astrometric measurements
  - Impact on multi-epoch astrometry

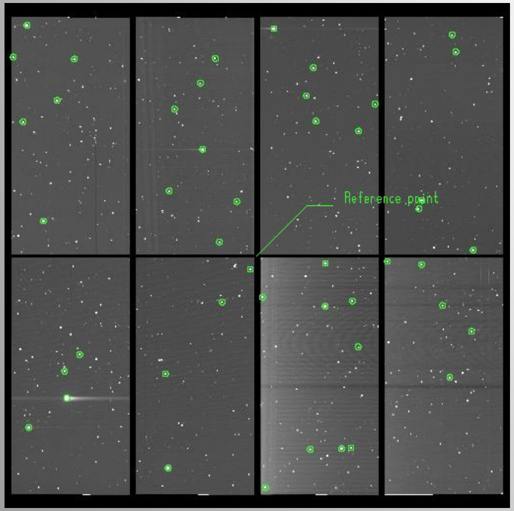




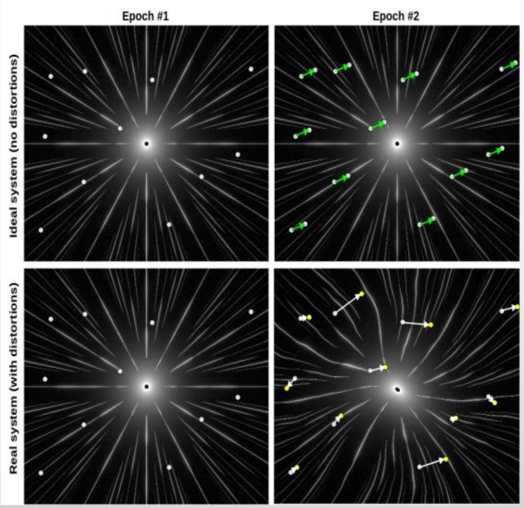
2: Astrometry Challenges

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

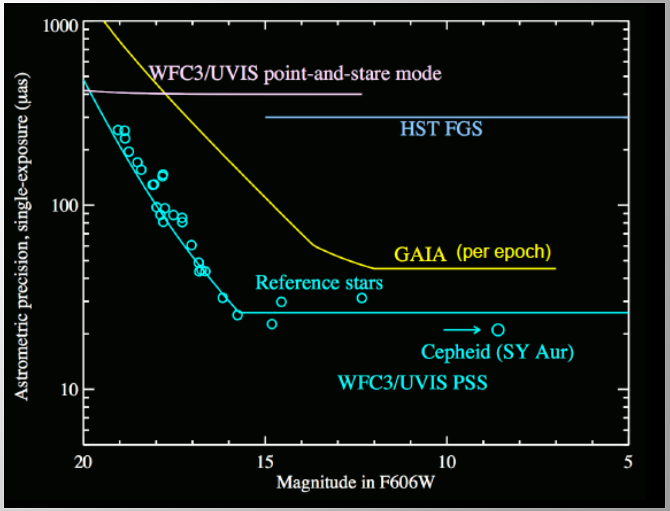




Cluster calibration



Diffractive pupil calibration



PASS scanning

3: Astrometry missions

- WFIRST
  - SITs and Working groups taking over
  - Astrometry group
    - Robyn Sanderson [Columbia] - FSWG Co-Chair
    - Andrea Bellini [STScI] - Science Center Co-Chair
    - Jessica Lu [Hawaii] - Milky Way GO SIT liaison
    - Jay Anderson [STScI] - MicroSIT team member
    - David Bennett [NASA/GSFC] - FSWG, MicroSIT Deputy PI
    - Jason Rhodes [JPL]
    - Scott Gaudi [OSU] - FSWG, MicroSIT PI
    - Raja GuhaThakurta [UCSC, UCO/Lick Obs]
    - Michael Fall [STScI] - STScI AWG liaison
    - Peter Melchior [Princeton]
    - Stefano Casertano [STScI]

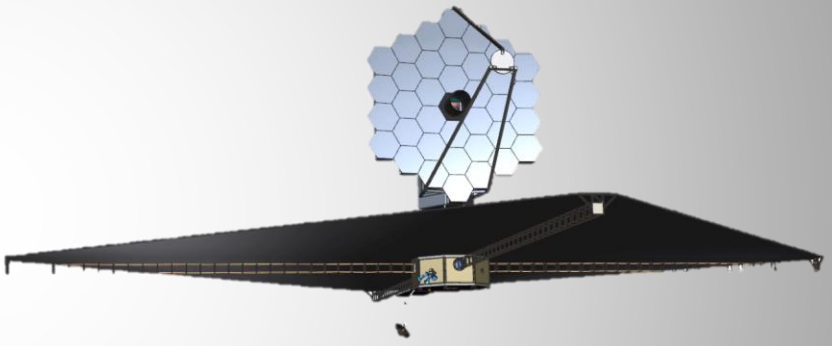
3: Astrometry missions

Astrometry with LUVOIR: (M. Shao's contribution)

Assumptions: 12m aperture, 8x8' FoV calibration floor at 1e-6px

- Photon noise dominated by fainter reference stars. The table gives photon limited accuracy in 1hr

	LUVOIR FoV	
Aperture	**4'**	**6'**
8m	0.033µas	0.022µas
12m	0.012µas	0.007µas



Over a year LUVOIR can:

- Search 230 stars for 0.1 earth mass or bigger planets in the HZ
- Search 1000 stars for 0.5 earth mass or larger planets in the HZ

- Likely to be constrained by stellar jitter.

3: Astrometry missions

Astrometry probe on ExoPAG report

- Probe-class astrometry mission < $1B cap to be studied before 2020 DS
- ~1.2m astrometric telescope, with a 0.25 deg^2 FOV
- Control systematic errors to near photon-limited performance
- Enable earth-mass planet detection around nearest stars (10pc)
- **25% time of a 5-year mission (η_{earth}= 10%) => 16 earth analogs**
- Measure masses or most know RV planets

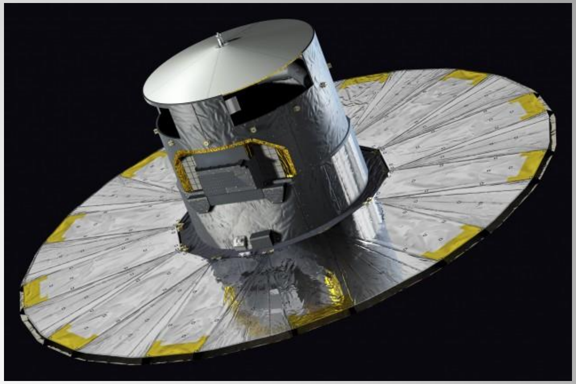
	Stars magnitude		
	V~7	**V~10**	**V~15**
Precision in 1hr	0.4μas	1.0μas	10.0μas

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

4: International Missions

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) is scheduled for the end of Summer 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 telescopes is larger than expected
   Basic-Angle-Monitor device (Mora et al., 2014) measures variations in the basic angle and injects this information into the astrometry global iterative solution (Lindegren et al, 2012)

4: International Missions

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