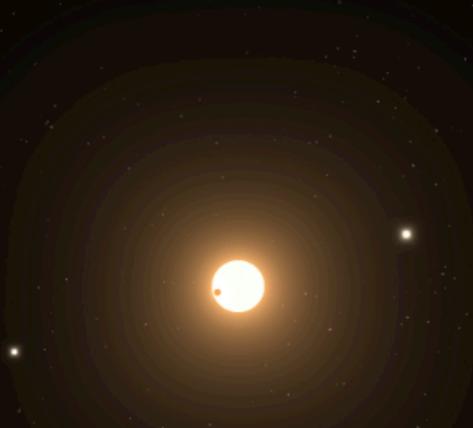
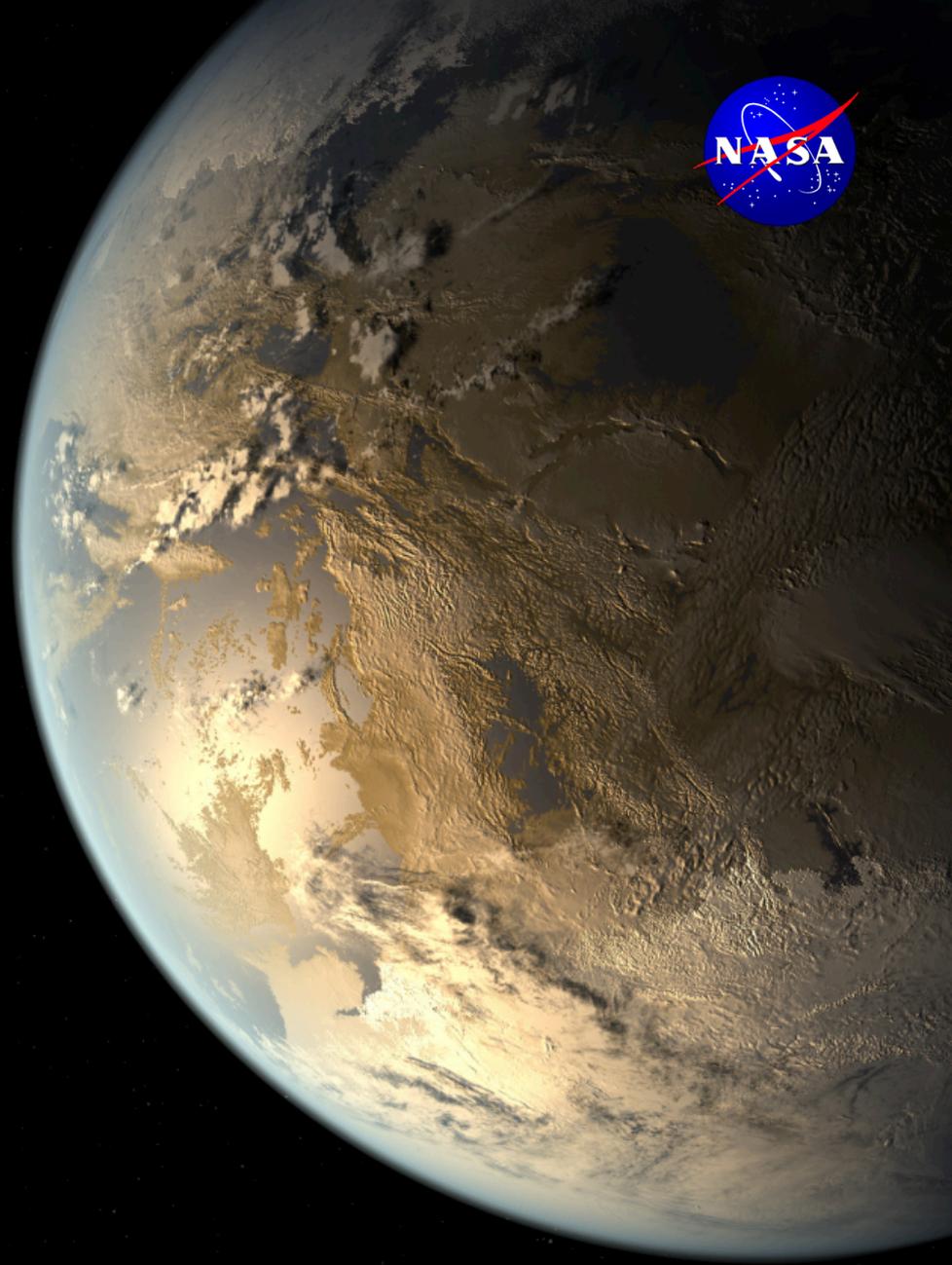
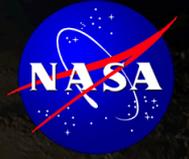


# SAG-12 Astrometry for exoplanet detection



# 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:**

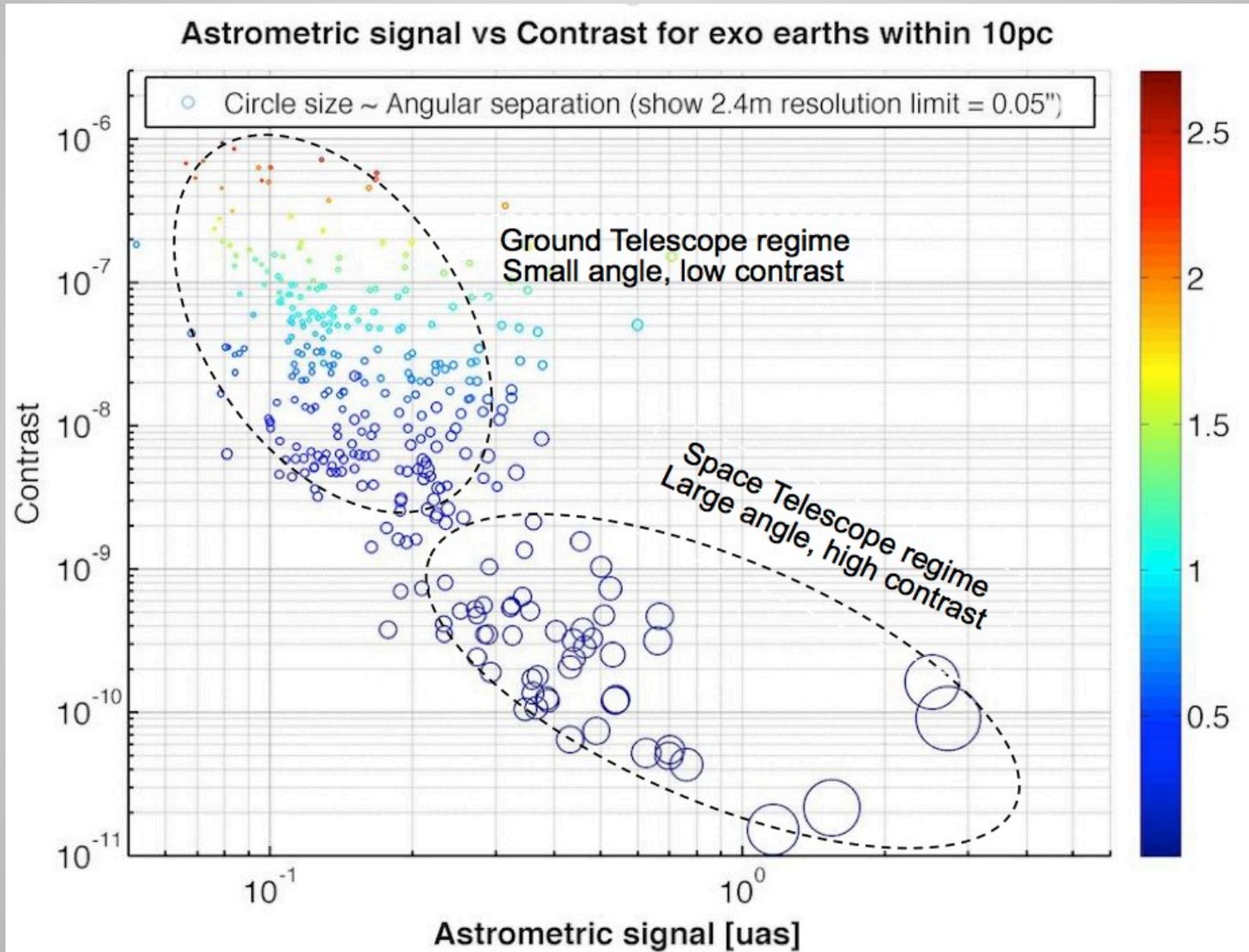
**1) What is the scientific potential of astrometry for different precision levels?** Which planet types, confirm planet candidates.

**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?

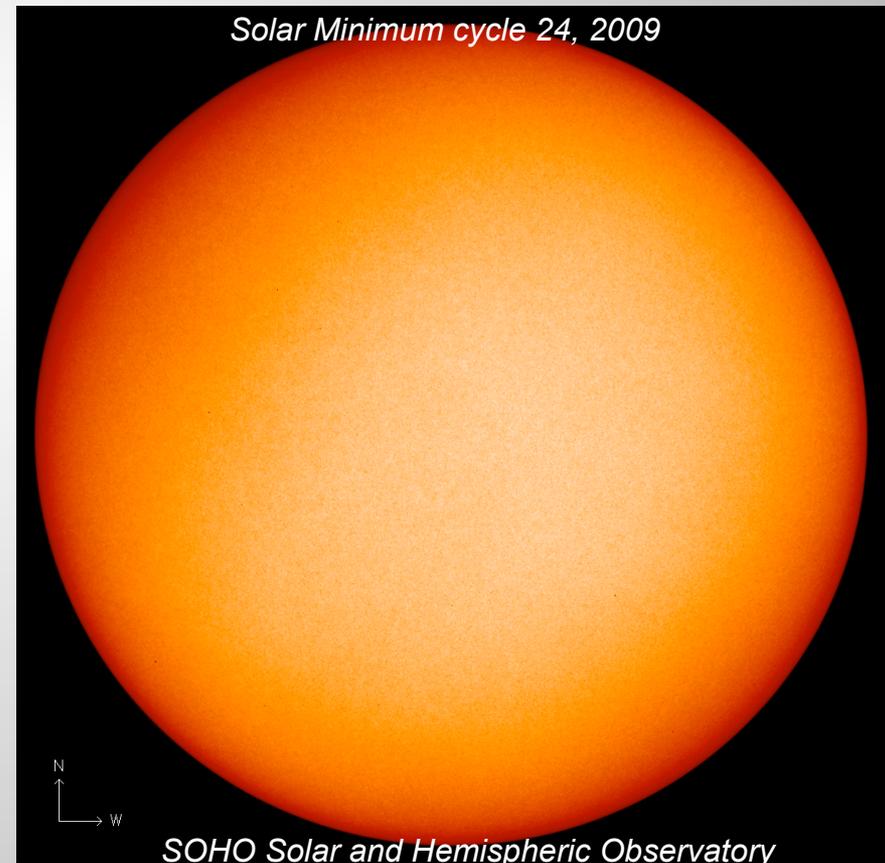
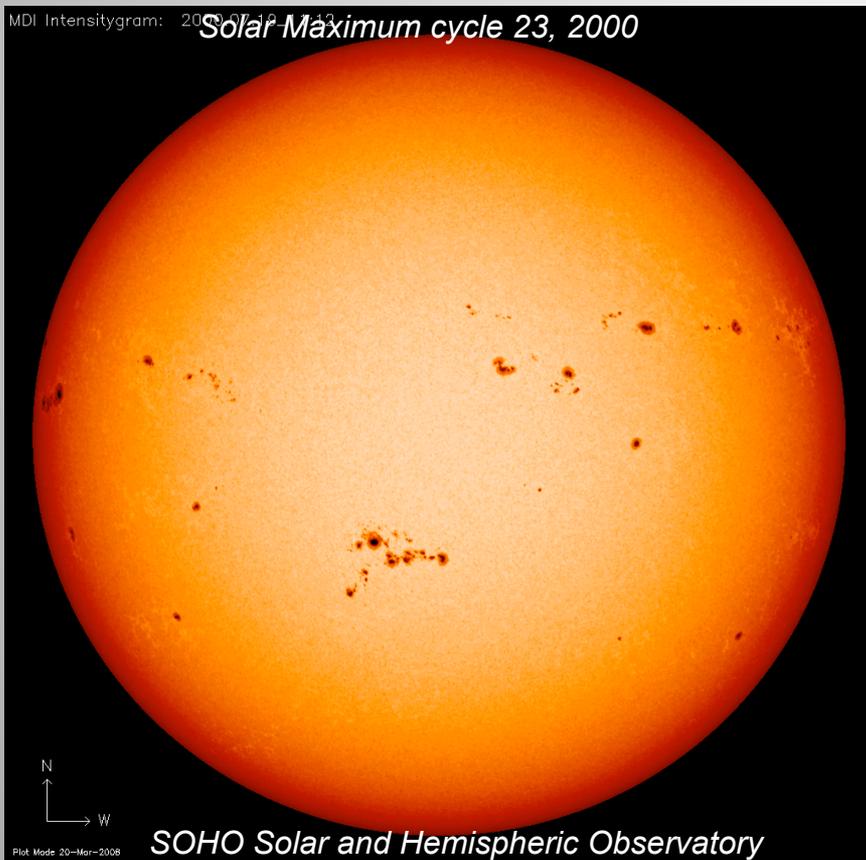
## 2: Exoplanet science



# 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



# 2: Astrometry Challenges

## Astrophysics:

Literature references:

- Sun-like stars at 10pc viewed from equator =  $0.087\mu\text{as}$  jitter  
Marakov et al 2009 (ApJ 707, L73)
- Similar study in 2011 is consistent =  $0.07\mu\text{as}$  RMS,  $0.2\mu\text{as}$  PV  
Lagrange et al 2011 (A&A 528, L9)
- Absolute astrometric jitter from solar data =  $0.52\mu\text{AU}$  jitter  
Marakov et al 2010 ApJ 717, 1202

Astrometric signal of an Earth-like planet in the HZ @ 10pc =  $0.3\mu\text{as}$

**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	
	$\eta_{\text{earth}}$ signal	Stellar noise	$\eta_{\text{earth}}$ signal	Stellar noise
Literature	0.3 $\mu\text{as}$	0.07 $\mu\text{as}$	3 $\mu\text{as}$	0.7 $\mu\text{as}$
Suggested Upper limit	0.3 $\mu\text{as}$	<0.7 $\mu\text{as}$	3 $\mu\text{as}$	<5 $\mu\text{as}$

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

# 2: Astrometry Challenges

## Astrophysics:

**Risk:** 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

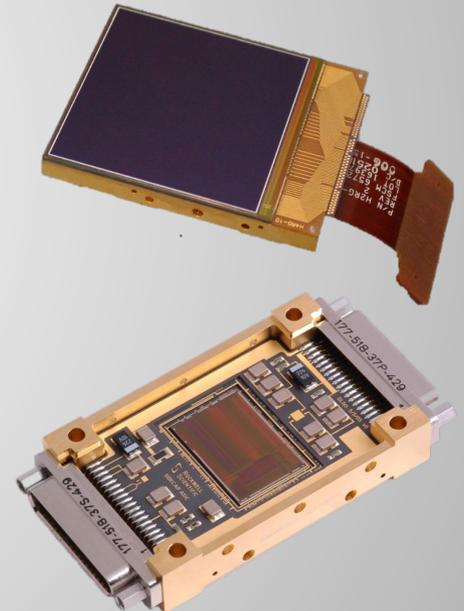
- Nonlinear response
- Sub-pixel response
- Inter-pixel capacitance
- Persistence
- Flux-dependent nonlinearity ("reciprocity failure")

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.



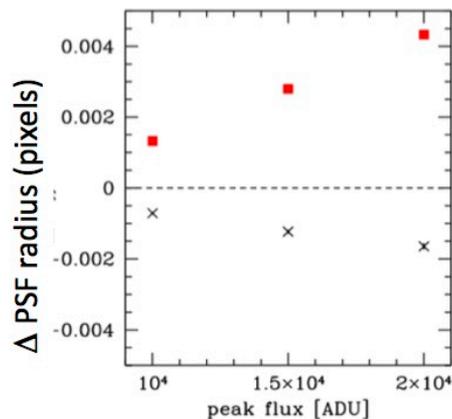
# 2: Astrometry Challenges

## 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.

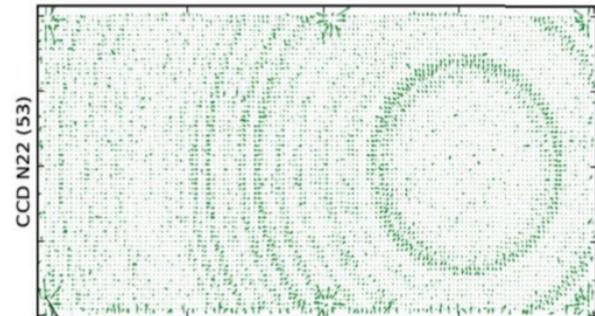
Red = Measurement

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  $\sim 0.06$  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.
- $0.01^{\circ}\text{K}$  gradient between extreme sides of the assembly can cause  $\sim 100\mu\text{as}$  errors

### Focal plane strain due to CTE mismatch.

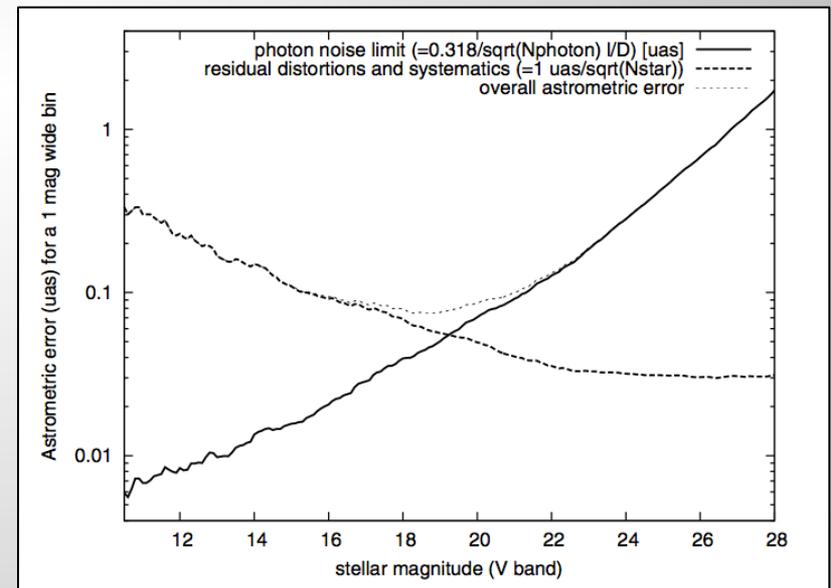
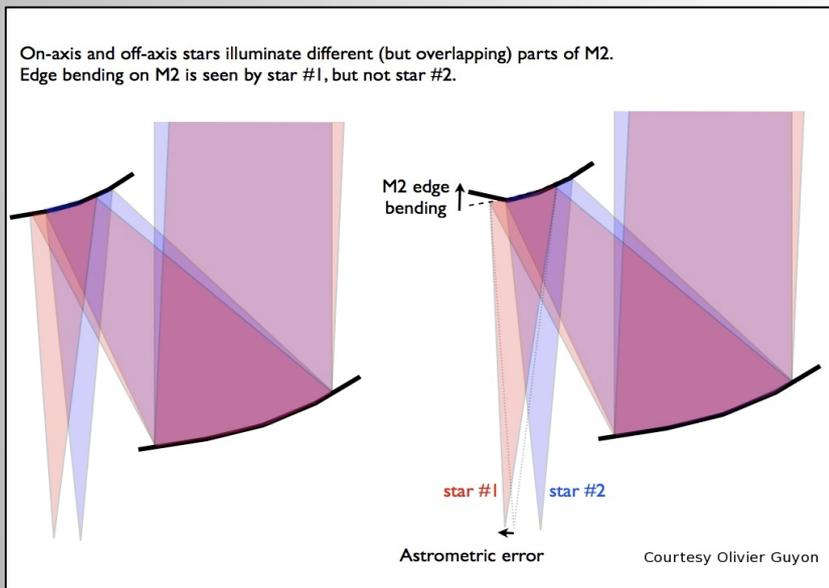
- SCA mounting holes might cause vertical deflections away from best focus
- Small correlated relative pixels shift in sensor plane

### 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

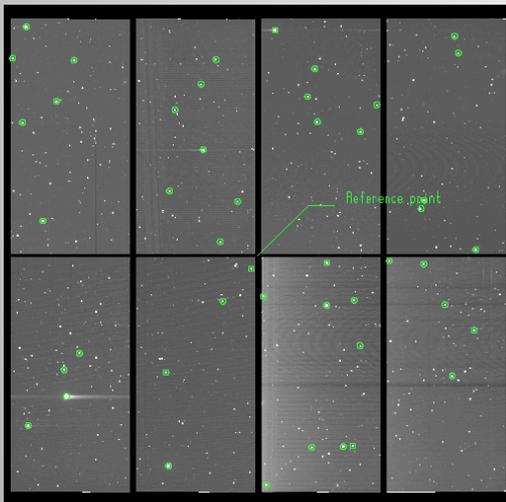
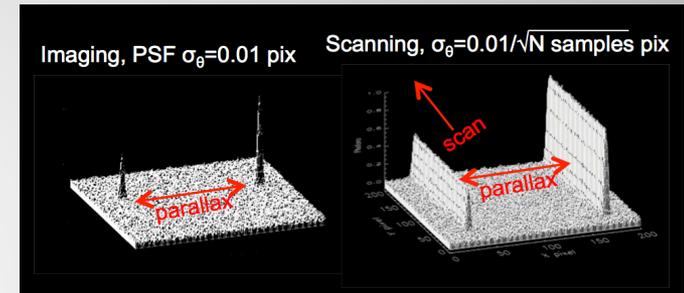
# 2: Astrometry Challenges

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

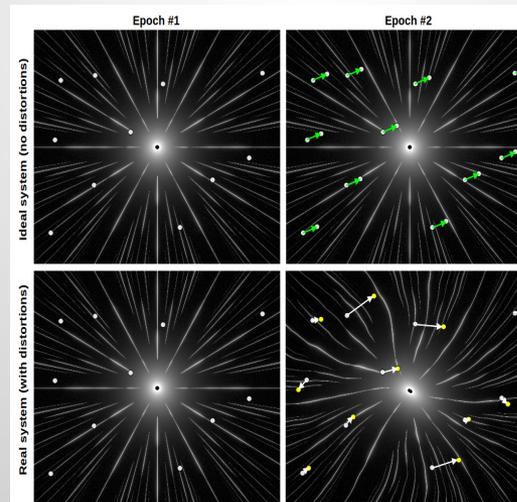


# 2: Astrometry Challenges

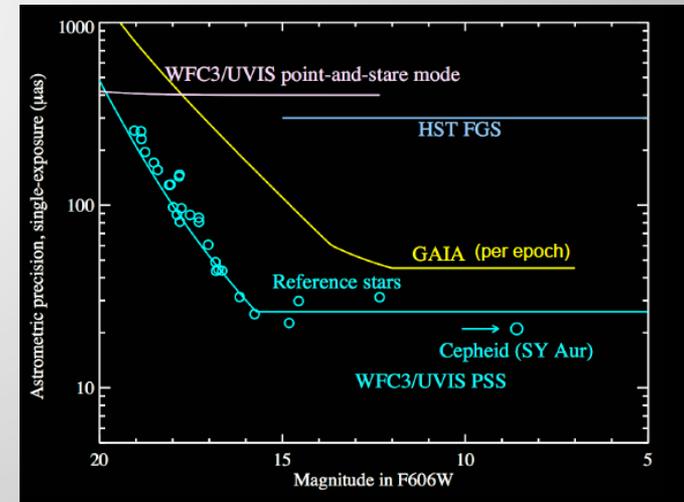
- Distortion mitigation strategies
  - Star cluster calibration
    - On sky, differential distortion after slewing to target, operations overhead
  - Diffractive pupil
    - Require dots on the mirror, permanent effect
  - PASS scanning
    - Operations impact



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]



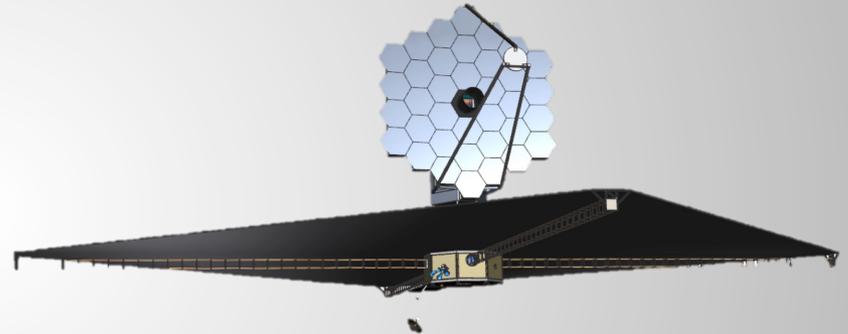
# 3: Astrometry missions

## 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

Aperture	LUVOIR FoV	
	4'	6'
8m	0.033 $\mu$ as	0.022 $\mu$ as
12m	0.012 $\mu$ as	0.007 $\mu$ as



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<sup>2</sup> 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 ( $\eta_{earth} = 10\%$ ) => 16 earth analogs**
- Measure masses or most know RV planets

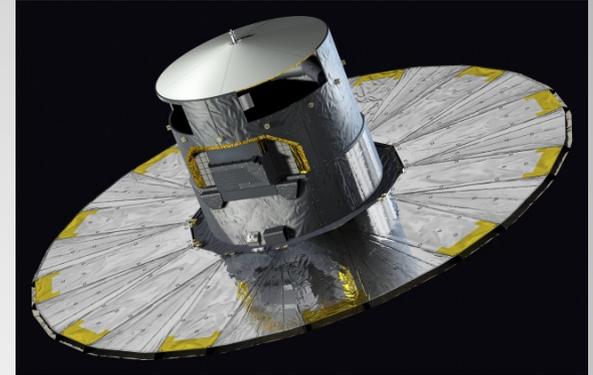
	Stars magnitude		
	V~7	V~10	V~15
Precision in 1hr	0.4 $\mu$ as	1.0 $\mu$ as	10.0 $\mu$ as

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

# 4: International Missions

## GAIA (Alessandro Sozzetti)

- Demonstrate 20 to 30 $\mu$ s 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



- **8 $\mu$ s for stars  $6 < m_v < 12$**
- **25 $\mu$ s 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

### 2) **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
- 0.3 $\mu$ s 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