“NEAT/Theia/Stare”

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THE UNIVERSITY OF SYDNEY

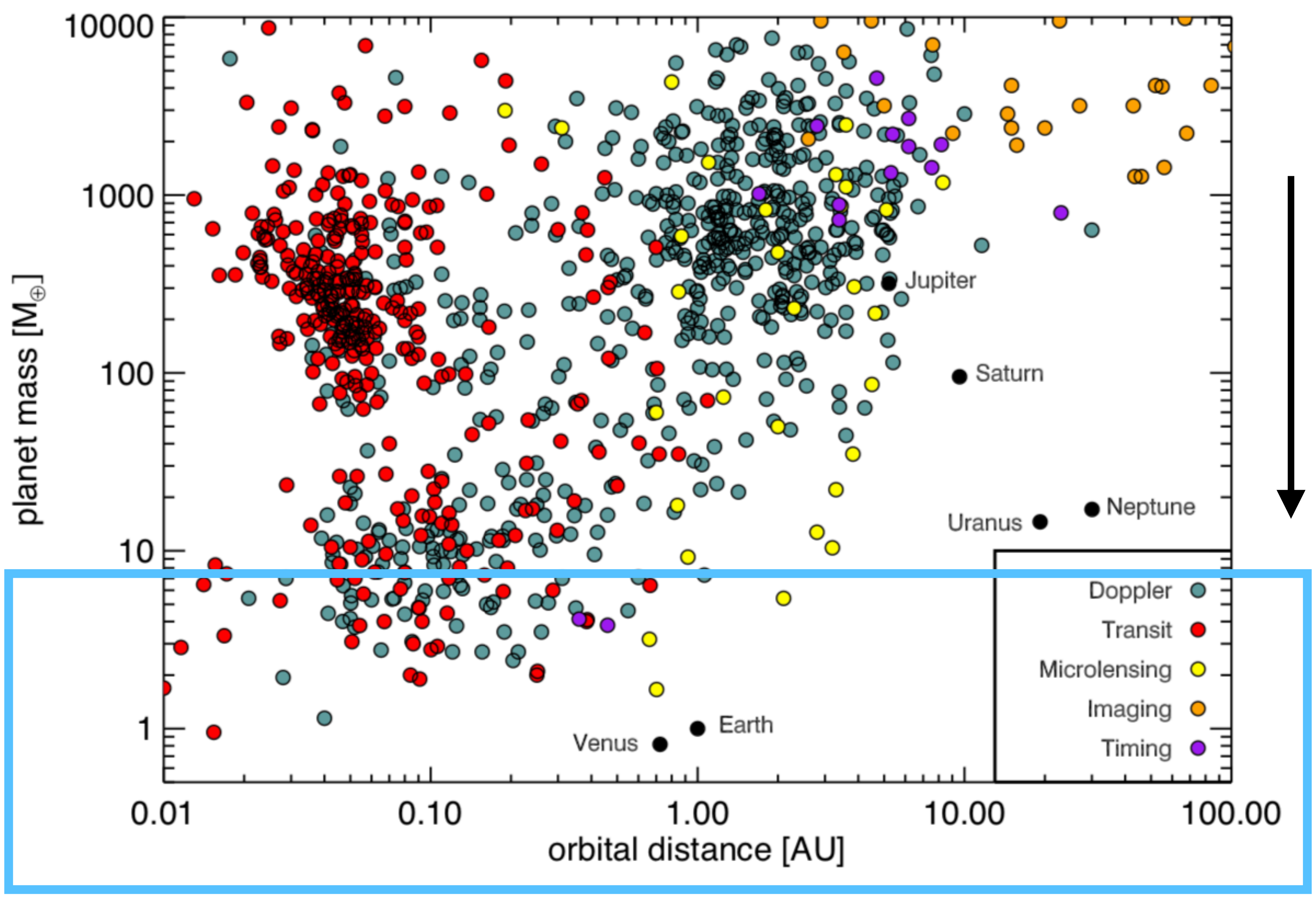
IPPP, Durham,
CNRS, Annecy

Rome, Breakthrough initiatives, Nov 2018

Common purpose of these 3 missions

Motivation number 1: search for exoplanets

arXiv:1410.4199

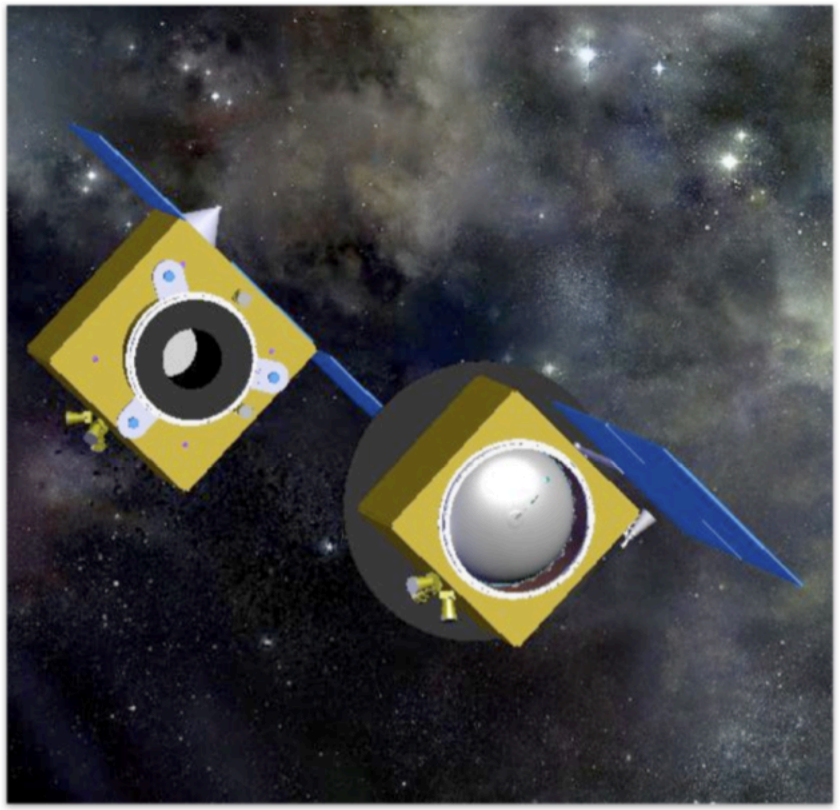


Focus as competition becomes tougher

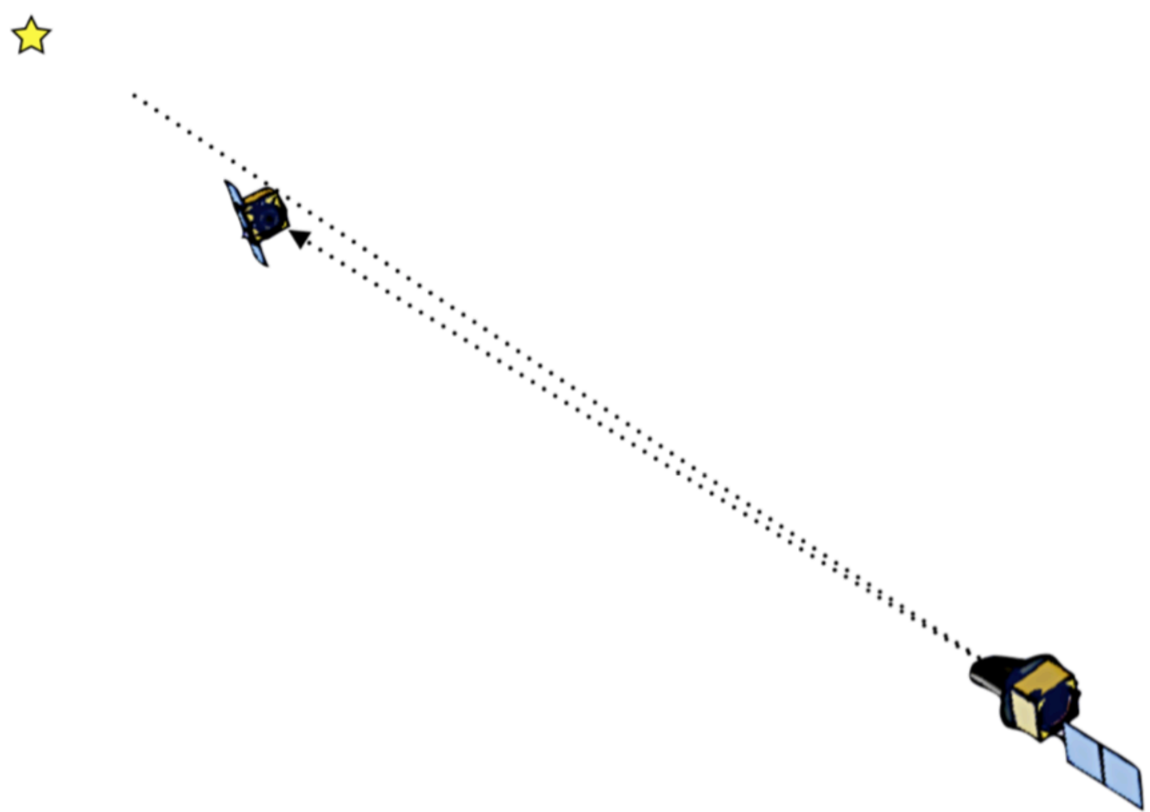
Figure 1 Approximate masses and orbital distances of known planets, based on an October 2014 query of the `exoplanets.eu` encyclopedia (Schneider et al. 2011). This plot does not consider selection biases and glosses over many important details. For Doppler planets, the plotted mass is really $M_p \sin i$. For imaging planets, the plotted mass is based on theoretical models relating the planet's age, luminosity, and mass. With microlensing, the planet-to-star mass ratio is determined more directly than the planet mass. For microlensing and imaging planets, the plotted orbital distance is really the sky-projected orbital distance. For transiting planets, thousands of candidates identified by the *Kepler* mission are missing; these have unknown masses, but many of them are likely to be planets. For timing planets, many are dubious cases of circumbinary planets around evolved stars (see § 6.2).

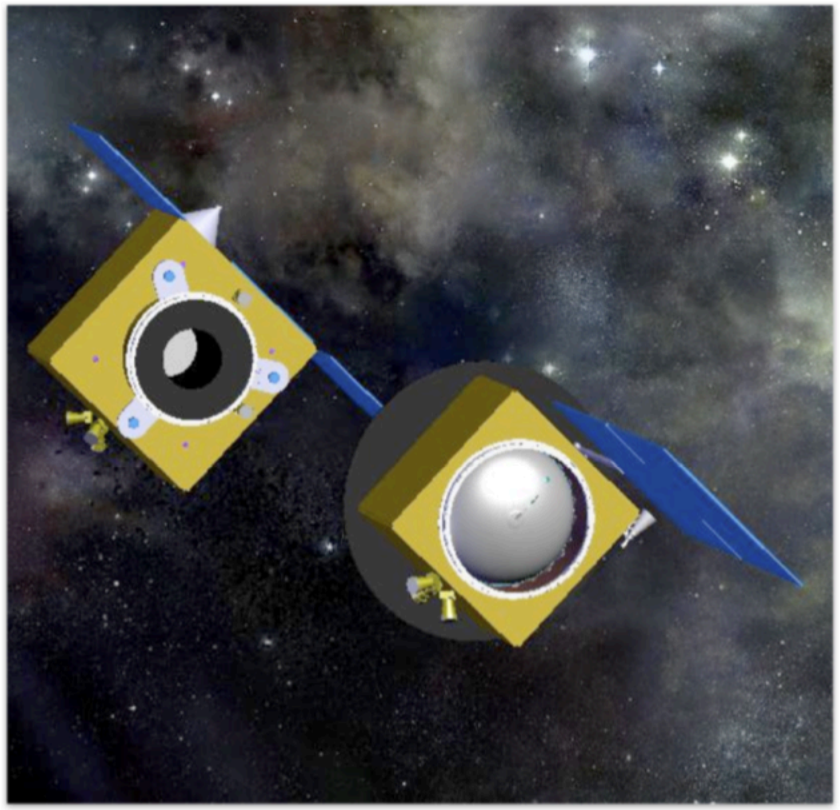
The different missions

NEAT



Formation in flight





Proposed to answer the ESA M4 call.
Main focus: a census of all exoplanets around 50 closest stars

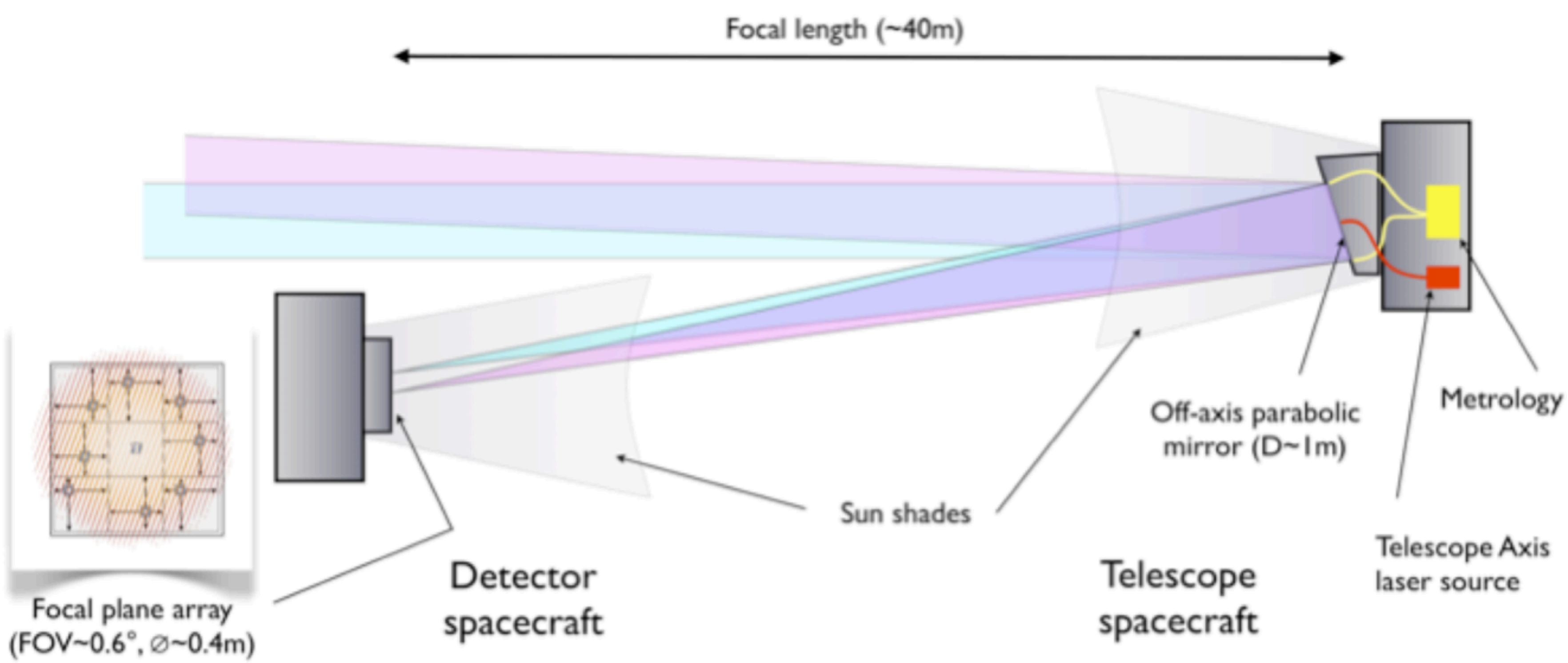


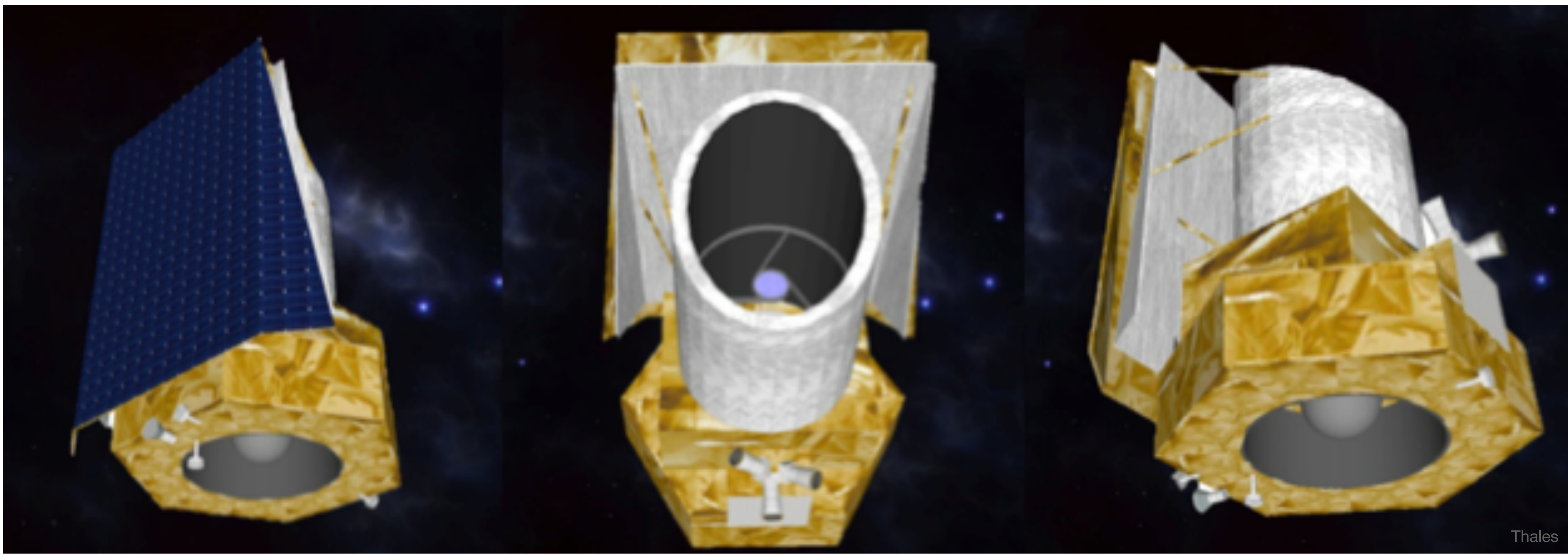
Figure 5 *NEAT instrumental concept with two satellites: the telescope satellite (right) that carries the parabolic primary 1m mirror and the source for the metrology, and the detector satellite which carries the focal plane that is illuminated once every minute by Young's fringes to calibrate the position of all CCDs.*

Table 1: *Science impact from NEAT scaling*

Mission name	***Mirror diameter***	***Focal length***	***Field of view diameter***	***Focal Plane size***	***DMA in 1h***	***# targets for a given mass limit***		
	(m)	(m)	(deg)	(cm)	(μas)	0.5M⊕	1 M⊕	5 M⊕
NEAT plus	1.2	50	0.45	40	0.7	**7**	**100**	**200**
NEAT	1.0	40	0.56	40	0.8	**5**	**70**	**200**
NEAT light	0.8	30	0.71	35	1.0	**4**	**50**	**200**
EXAM	0.6	20	0.85	30	1.4	**2**	**35**	**200**

1-m telescope and 40-m focal length

Theia

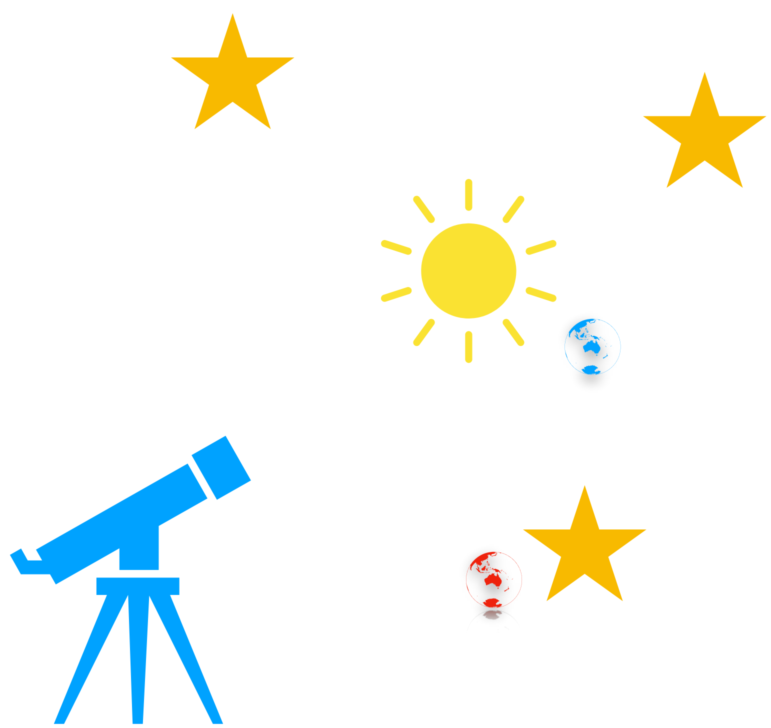


Proposed to answer the ESA M5 call.
Main focus: Dark Matter (70%) ; Earth-like exoplanets (20%)

Too much competition:
Let us focus on Earth-like exo-planets

At **10 pc**, the astrometric signature of an Earth-like planet in the HZ of a Sunlike star is **0.3 μas**.

Exo-planets should be near bright stars (no mag limits) but these are sparse

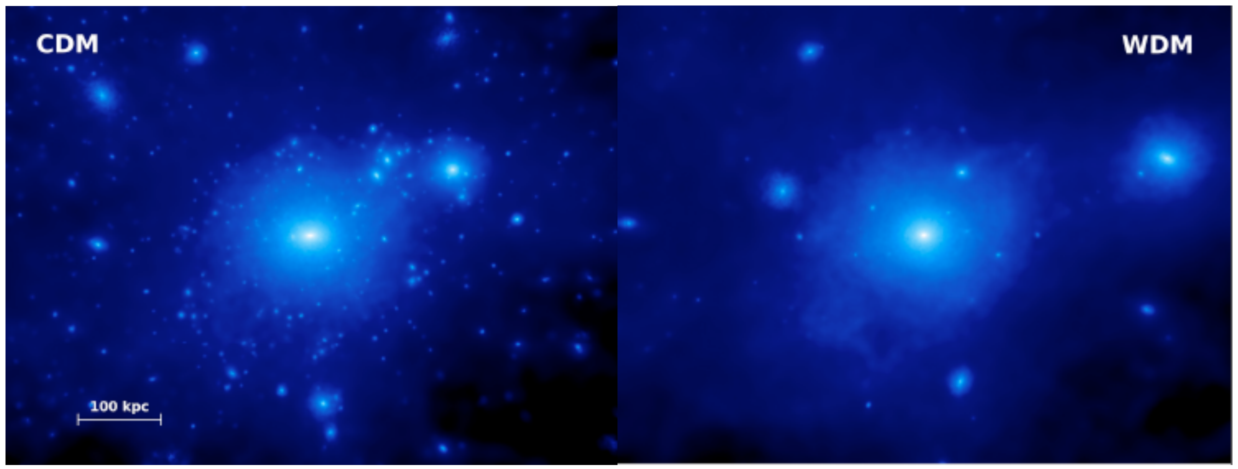


wide angle astrometry + ultra high precision

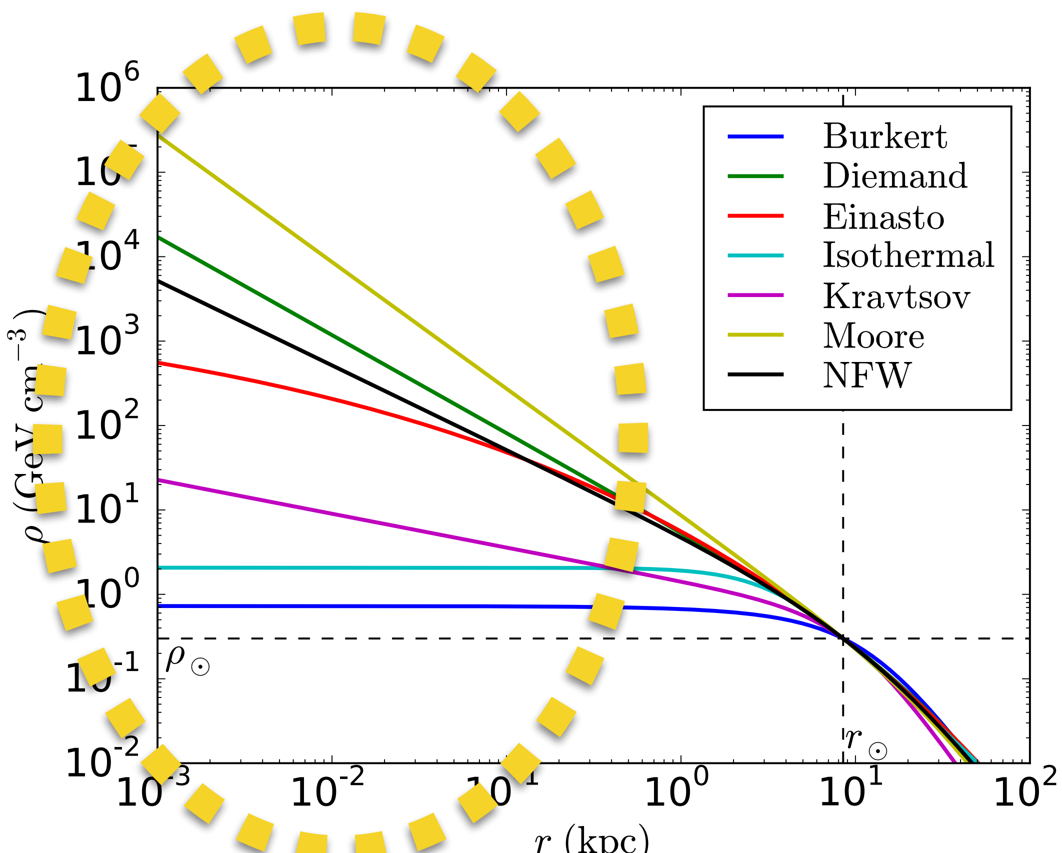
This means a great instrument for only 20% of observational time

Dark Matter

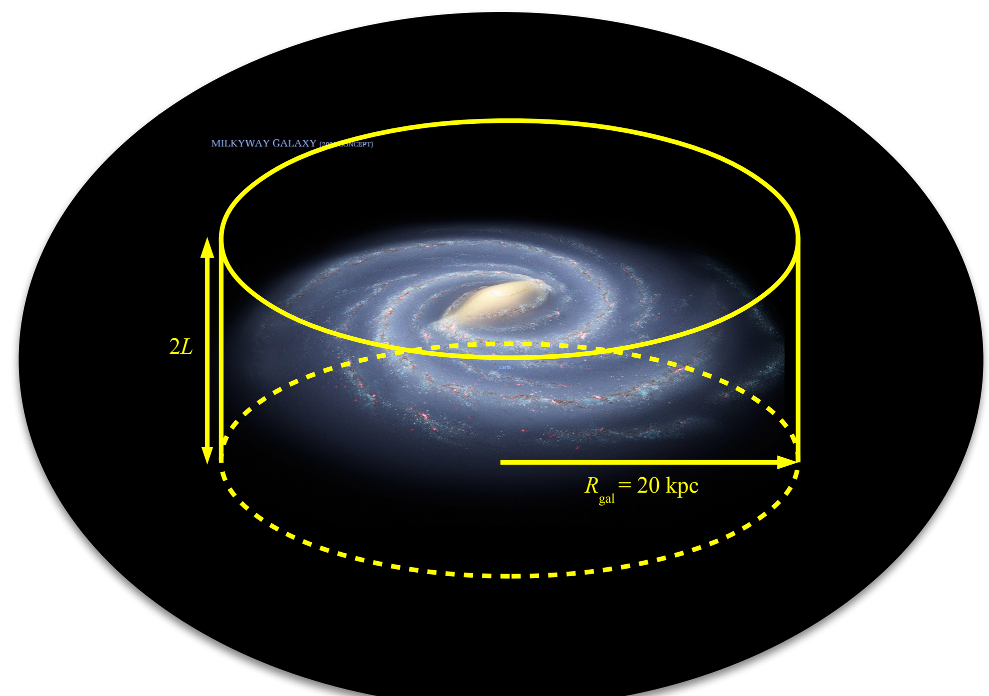
Testing LCDM



Mass of the smallest DM halos

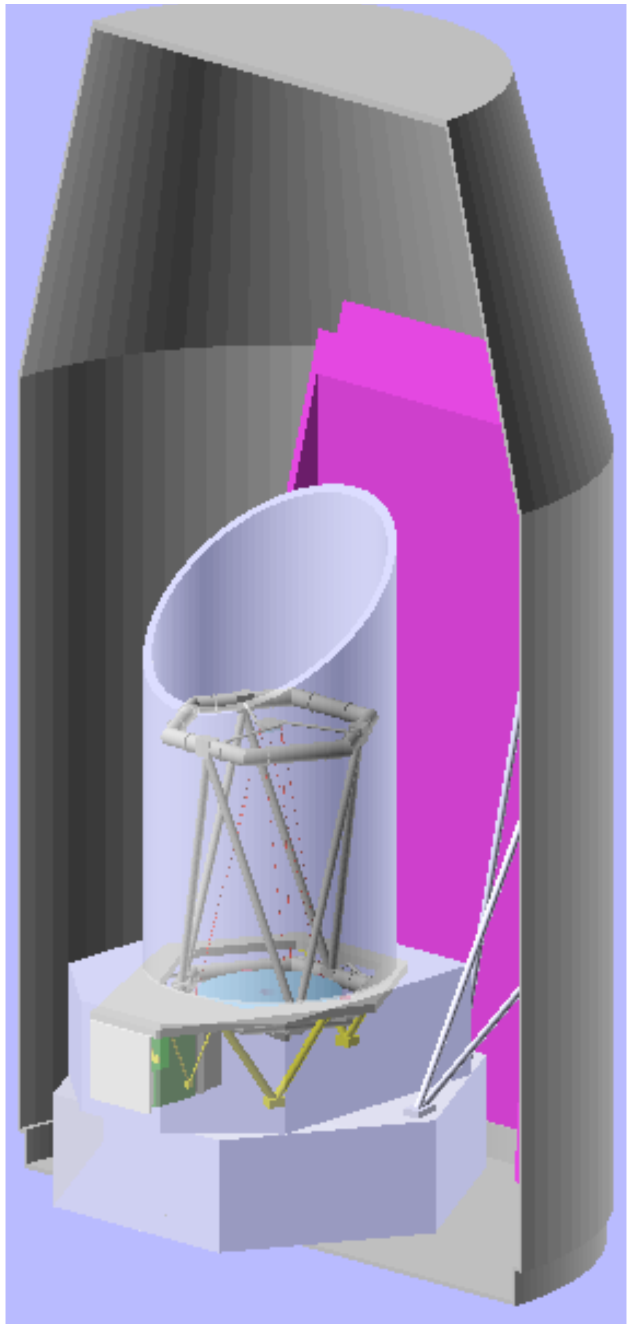


DM distribution in dwarf galaxies

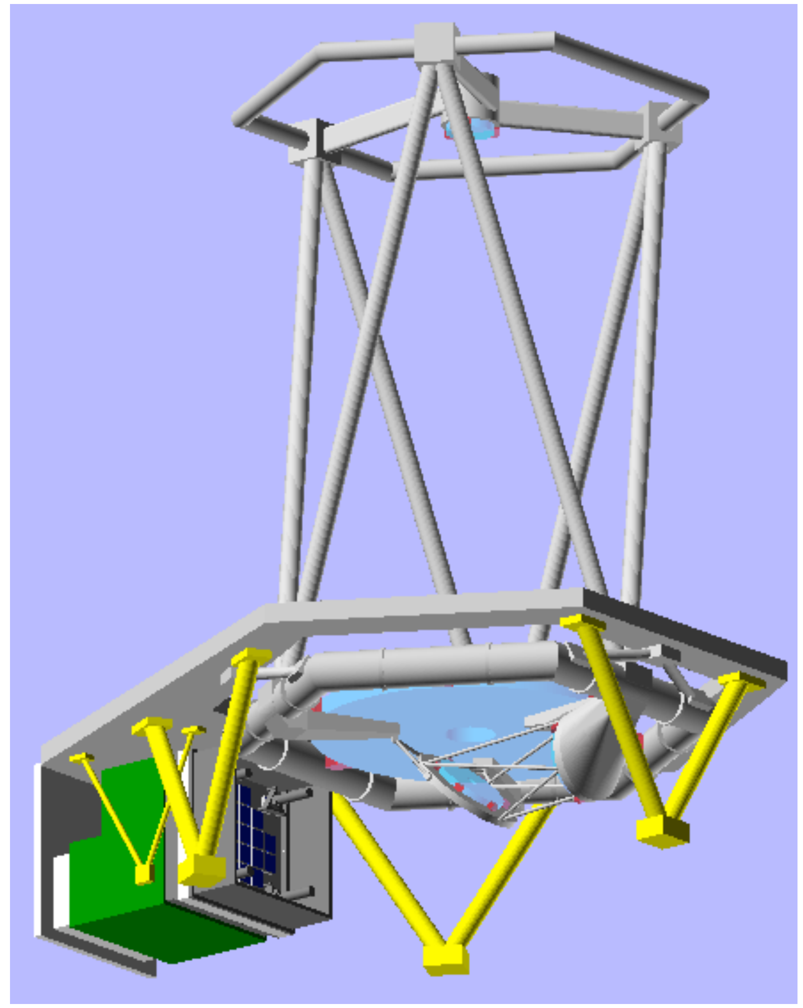


shape of the MW halo oblate/prolate

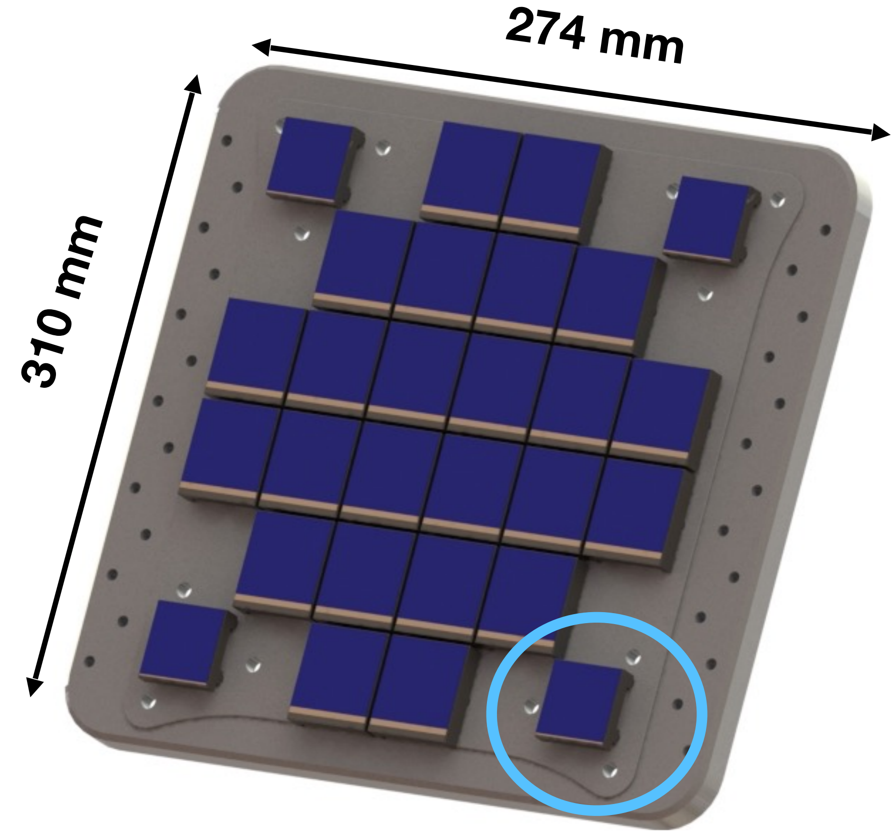
TMA + camera with a 0.6 deg FoV



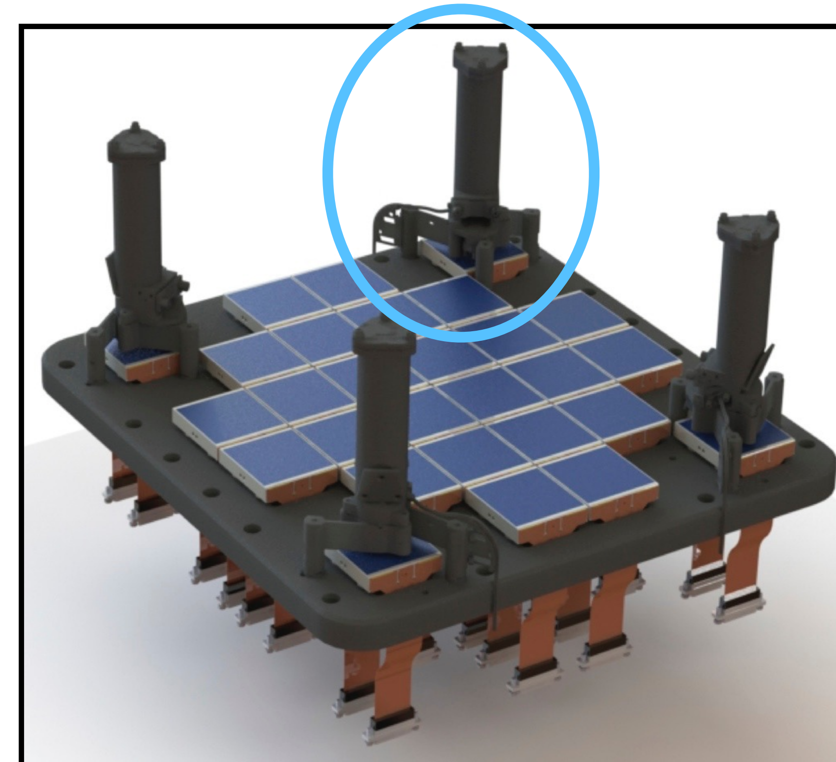
Soyuz -> Ariane 6



Detectors:
-FPA: 24 e2V 4k^2 CCD
-WFS: 4 e2V 4k^2 CCD



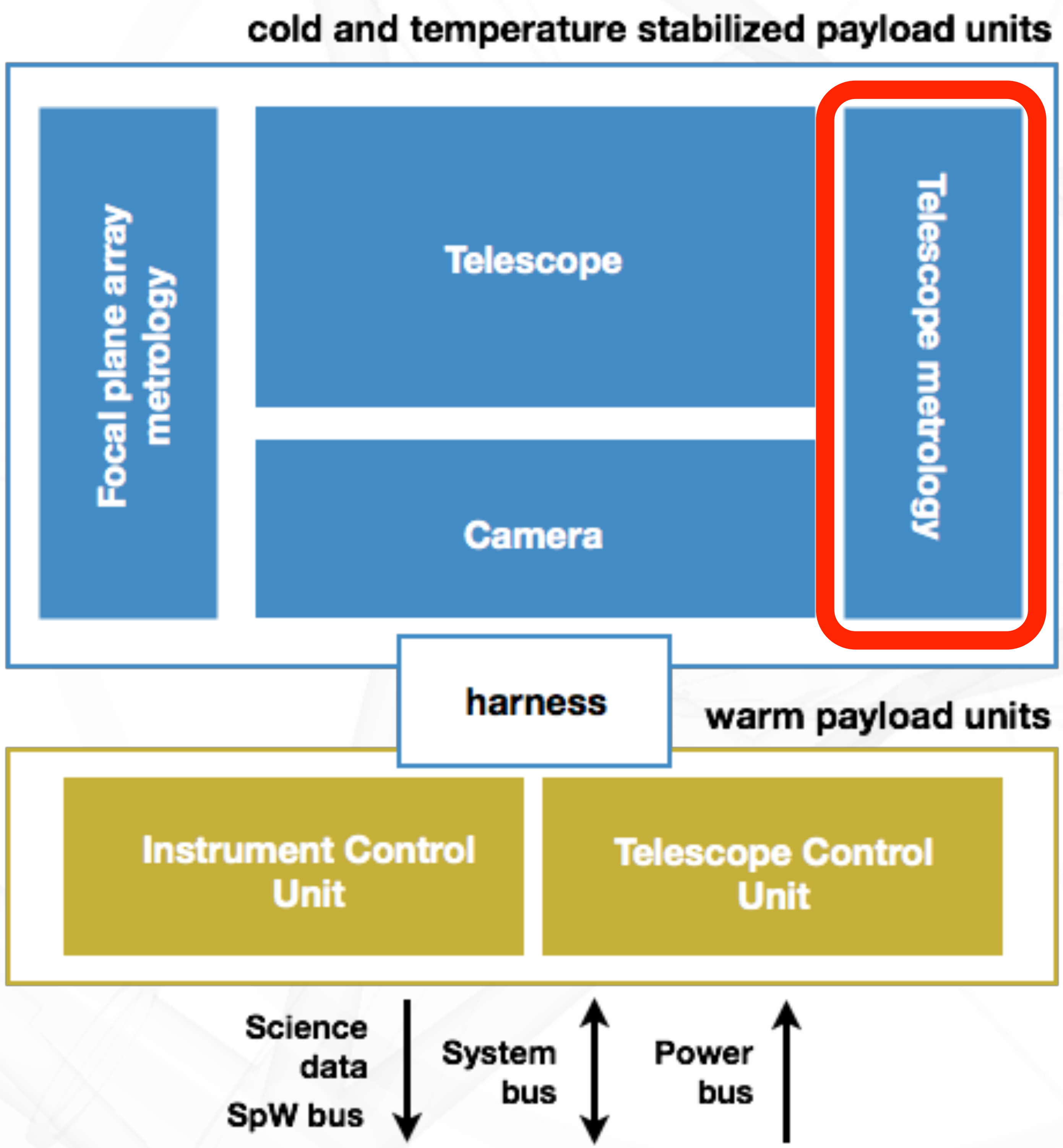
Wavefront sensor (WFS) detectors



6x6 Elliptical FoV Science Array of 4k vs. 4k Detectors

THEIA

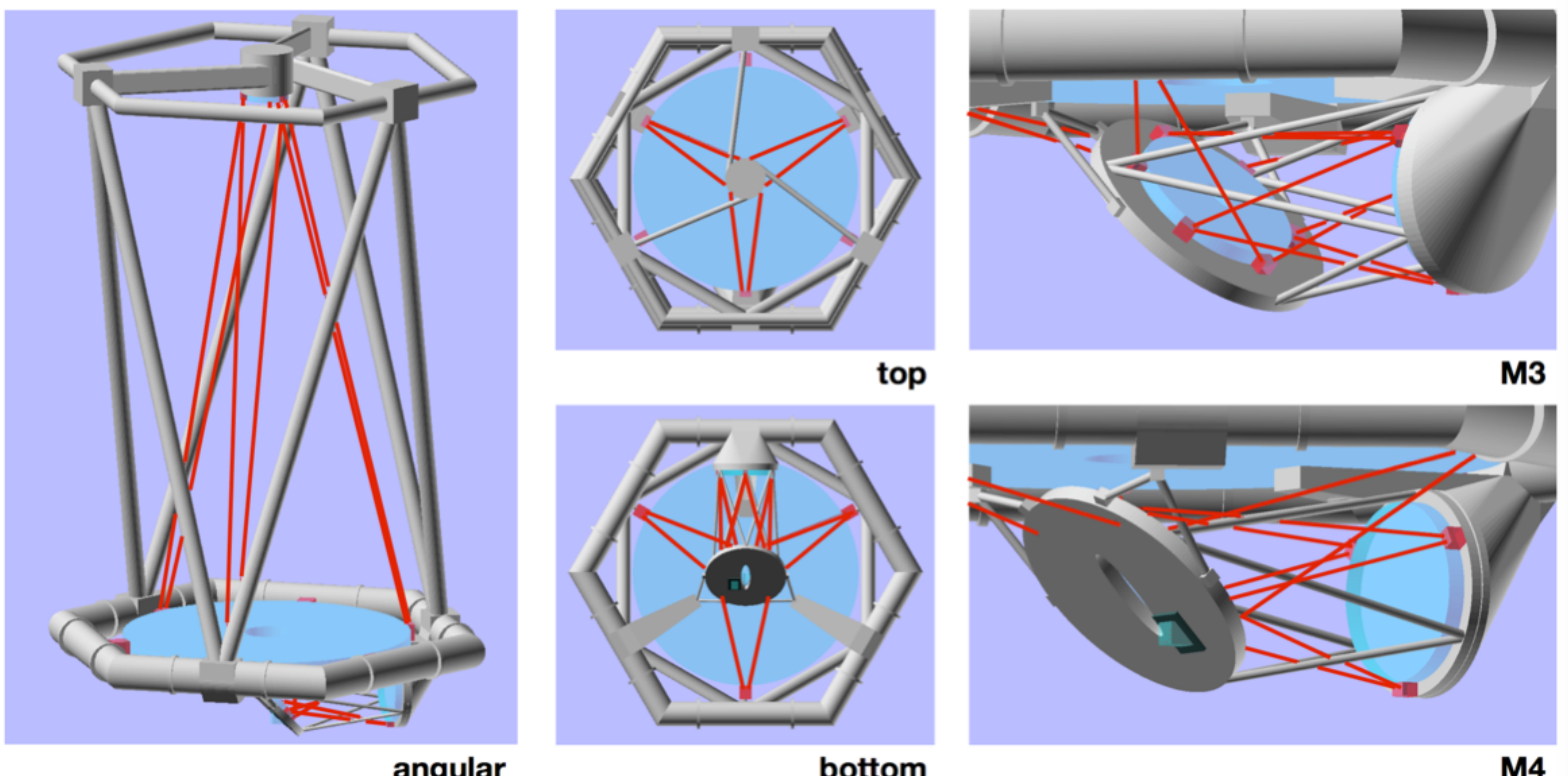
Microarcsecond Astrometric Observatory



Theia : *the new Astrometry frontier*

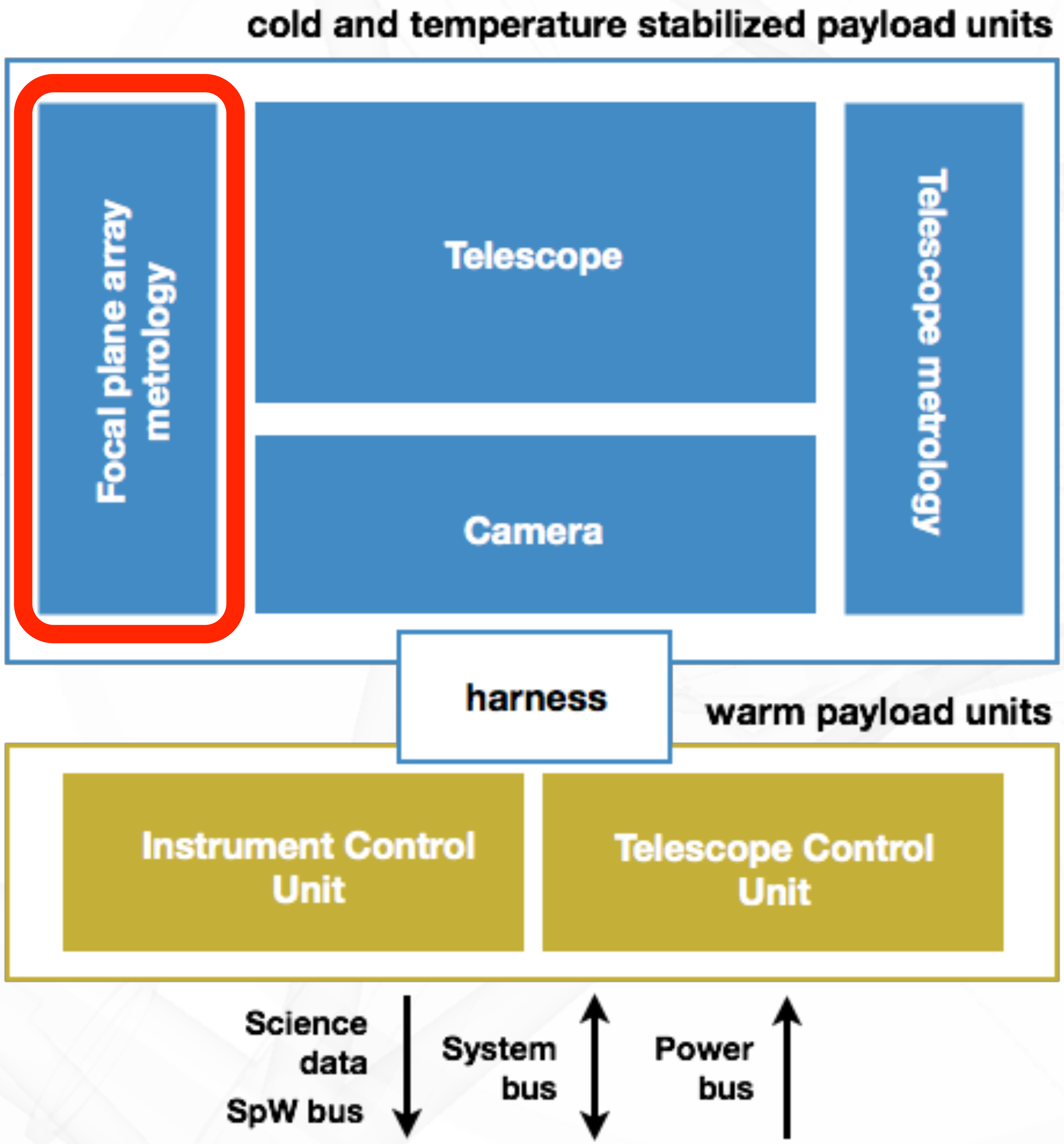
Outstanding precision requires metrology

Lesson from Gaia :: Monitor, monitor, monitor



Interferometers for instrument monitoring and astrometric corrections.

Theia : *the new Astrometry frontier*



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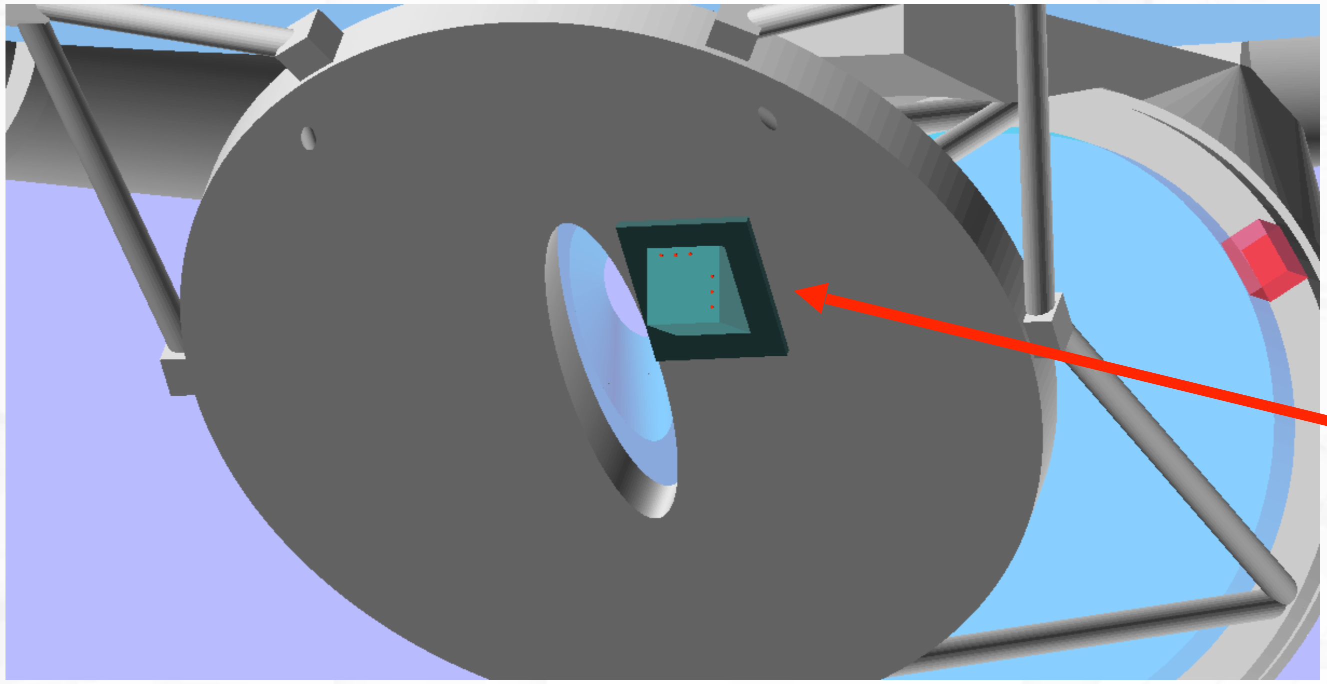


Prototype DICE @ IPAG reached 5×10^{-5} pixel size

Interferometric FPA callibration

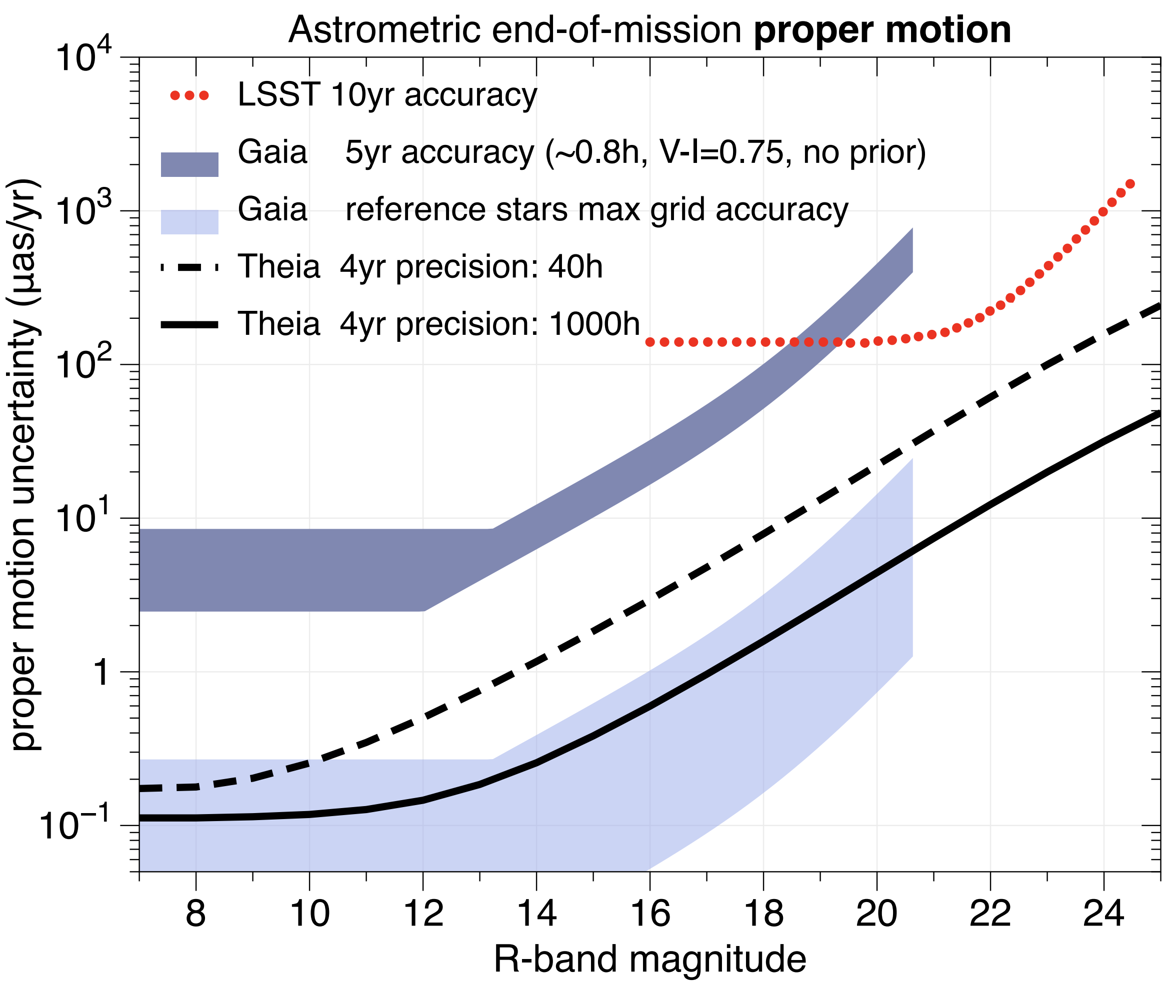
Main observational targets	• dwarf spheroidals & ultra-faint dwarf galaxies, hyper-velocity stars; • nearby A, F, G, K, M stellar systems; • neutron stars in X-ray binaries; • Milky Way disc + open observatory targets.
Payload	• Korsch on-axis TMA telescope with controlled optical aberrations; • Primary mirror: $D = 0.8\,\mathrm{m}$ diameter; • Long focal length, $f = 32\,\mathrm{m}$; • FoV ∼0.5 deg, with 4 to 6 reference stars with magnitude $R \leq 10.8\,\mathrm{mag}$; • Focal plane with 24 CCD detectors (∼402 Mpixels, 350nm-1000nm); • Nyquist sampling of the point-spread-function; • Metrology calibration of the focal plane array: relative positions of pixels at the micropixel level using Young's interferometric fringes; • Interferometric monitoring of the telescope: picometer level determination; of the telescope geometry using laser interferometric hexapods.
Spacecraft	• Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg; • Attitude Control System: synergistic system with hydrazine, reaction wheels and cold-gas thrusters. RPE: 20 mas rms in a few minutes (1σ); • Thermal Control System: active thermal control of telescope; dedicated radiator for the payload; • Telecommand, Telemetry and Communication: Ka-band, ∼95 GBytes of science data per day. High Gain Antenna and 35m stations.
Launcher and operations	• Ariane 6.02. Lissajous orbit at L2. Launch in 2029; • Nominal mission: 4 yrs + 6 months transit, outgassing & commissioning; • MOC at ESOC, SOC at ESAC.
Data policy	• Instrument Science Data Centers at consortium member states; • Short proprietary period and 2 data releases.

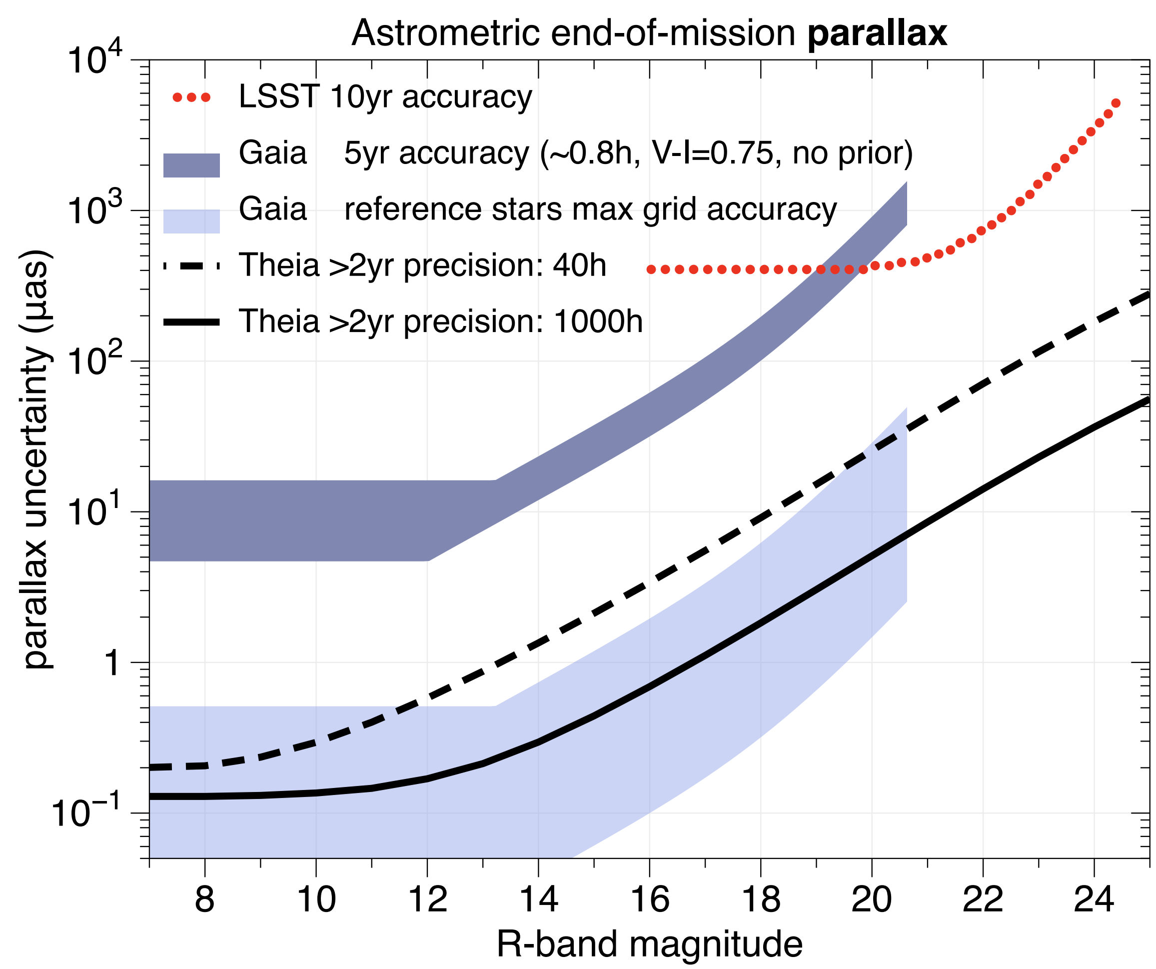
THEIA

Microarcsecond Astrometric Observatory

Relative Astrometry ; point and stare

+ photometry (optical, 350-1000nm)





30-100 times better than Gaia

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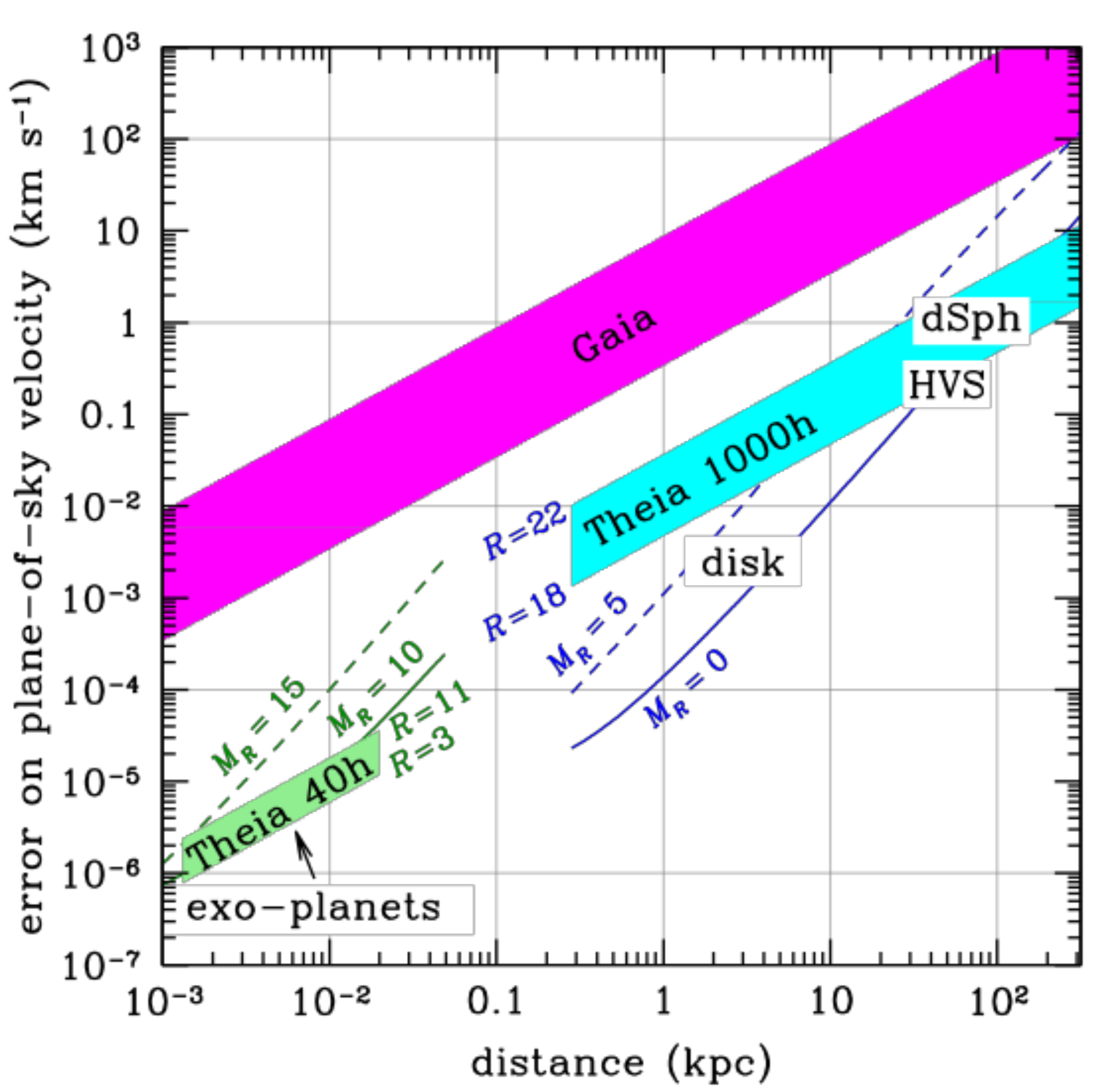
Microarcsecond Astrometric Observatory



The 1000 brightest stars in Draco have magnitudes R = 17.5 to 20.5

Draco seen in one single shot

R < 22 stars in dwarfs such as Draco and Ursa Minor

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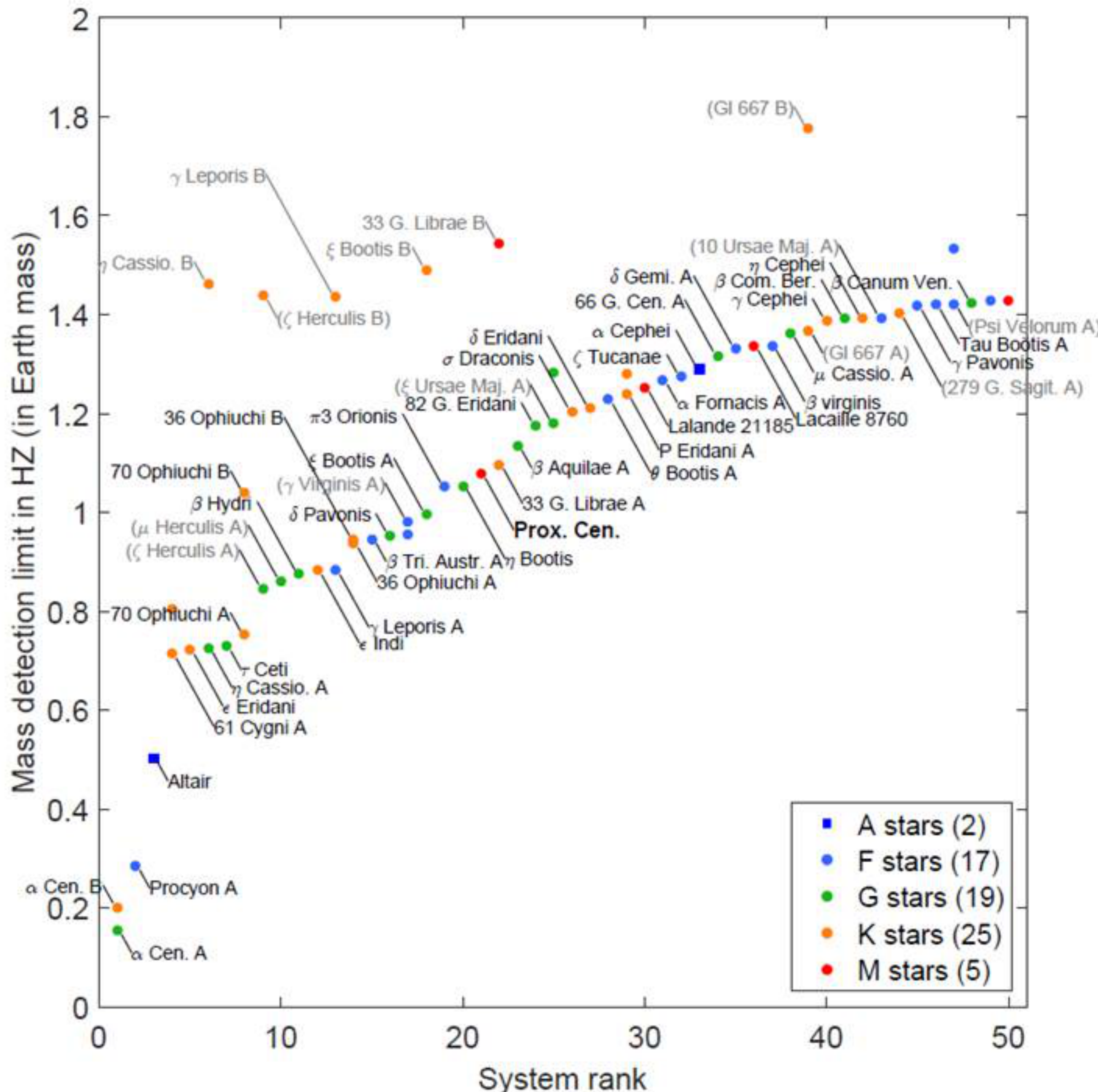
Microarcsecond Astrometric Observatory

Exoplanets

Complete census of exo-Earths and superEarths orbiting our 50 nearest stars



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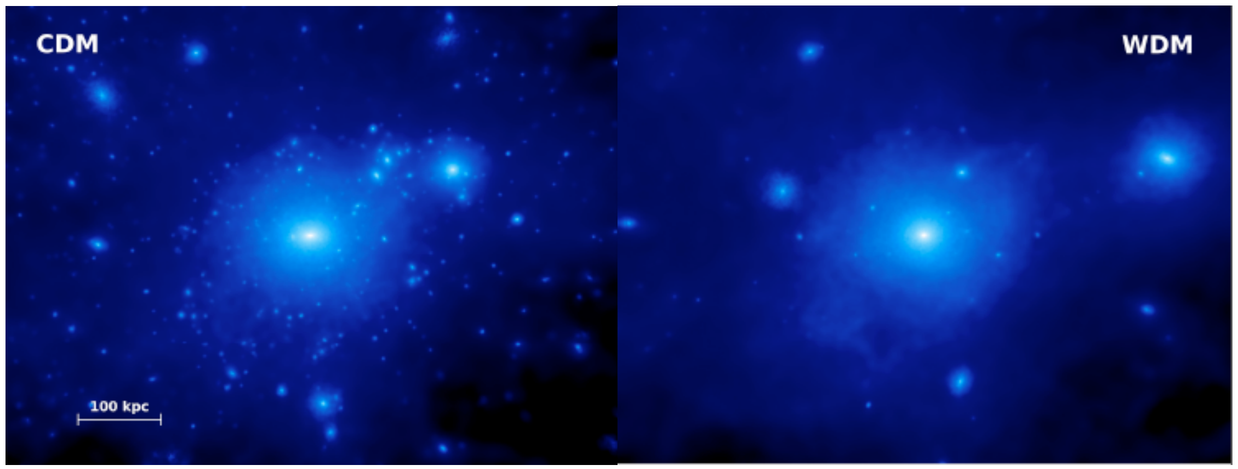
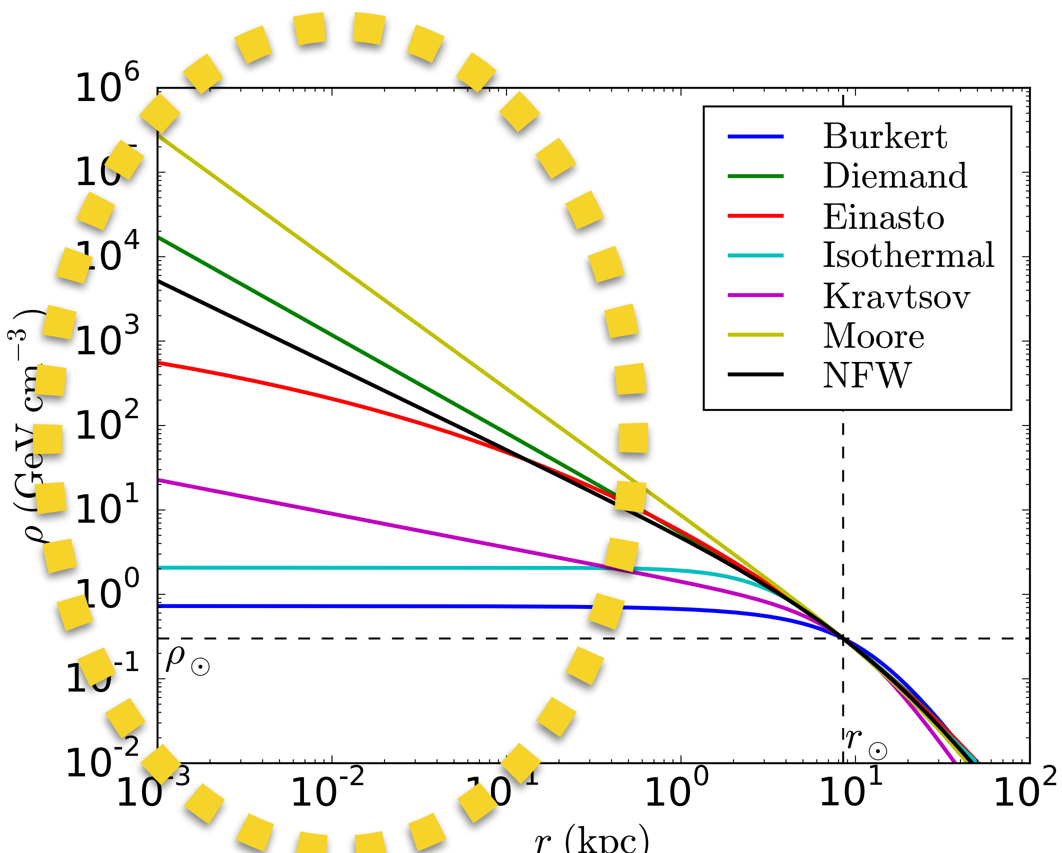
Microarcsecond Astrometric Observatory

Dark Matter

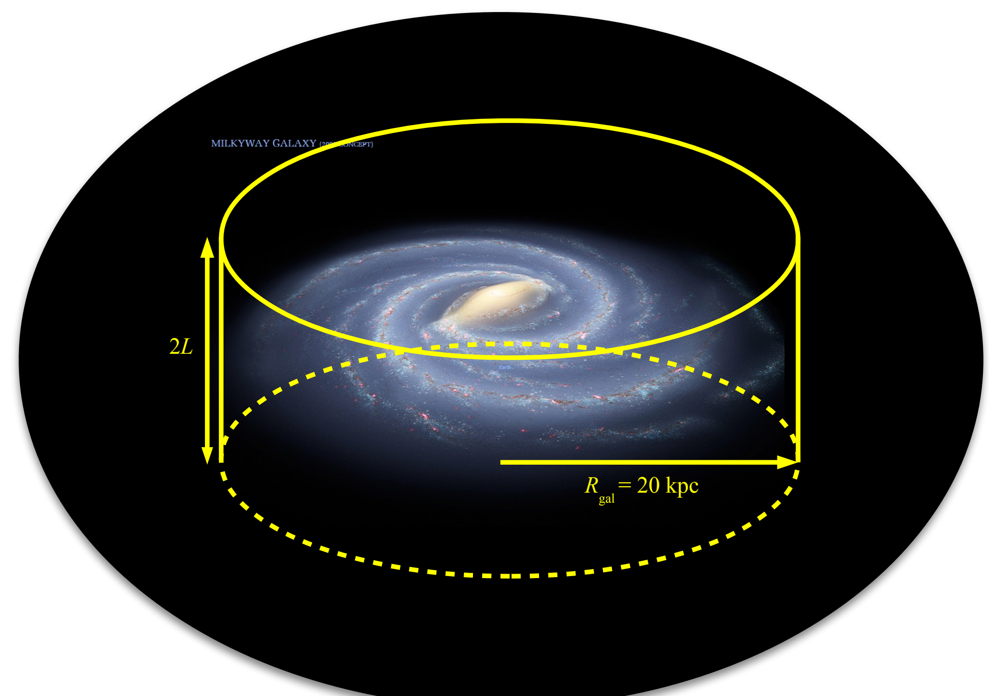
Testing LCDM



Mass of the smallest DM halos



DM distribution in dwarf galaxies



shape of the MW halo oblate/prolate

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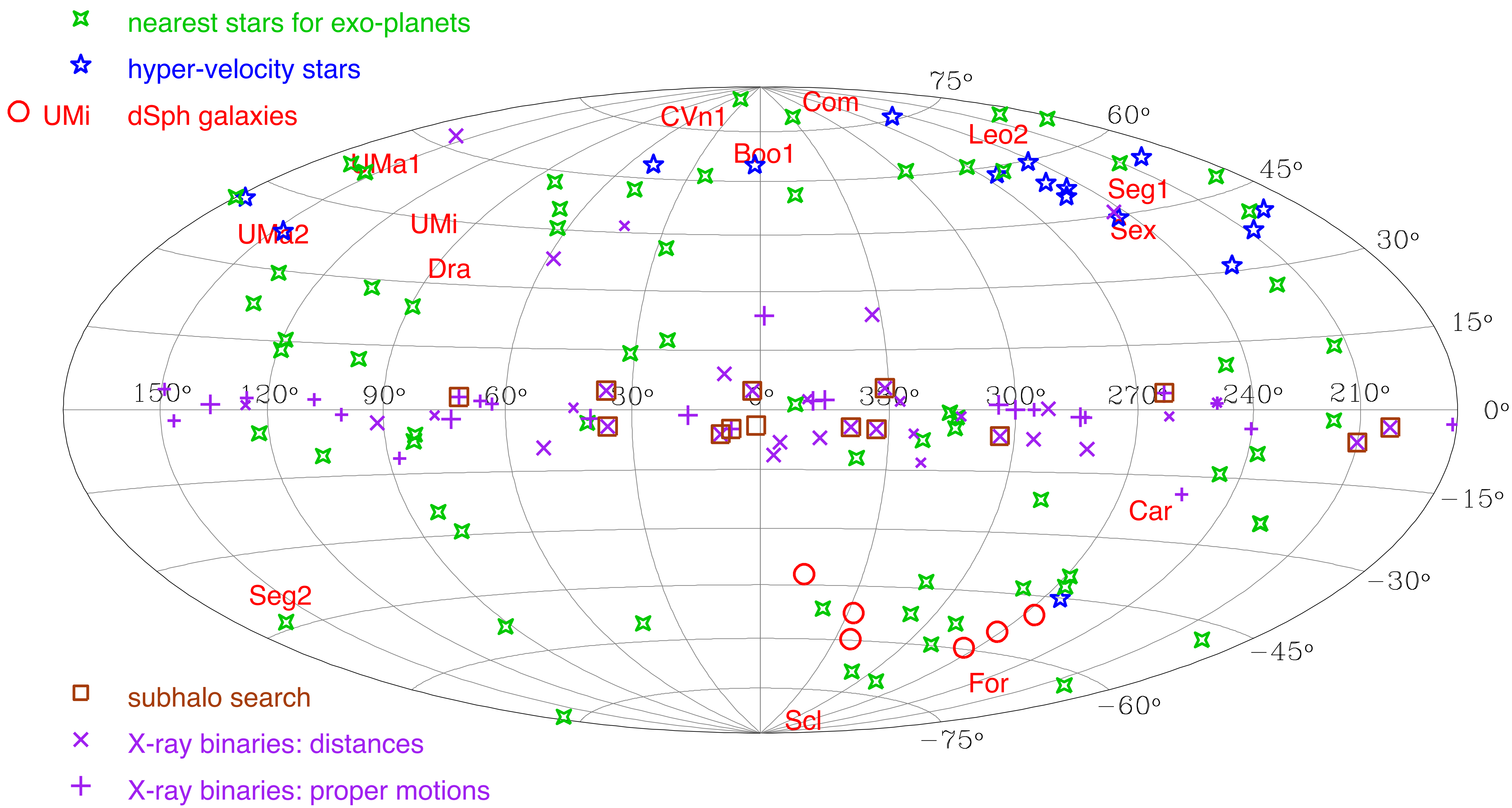


In optimal mission configuration

THEIA

Microarcsecond Astrometric Observatory

Pessimistic case (CCDs)

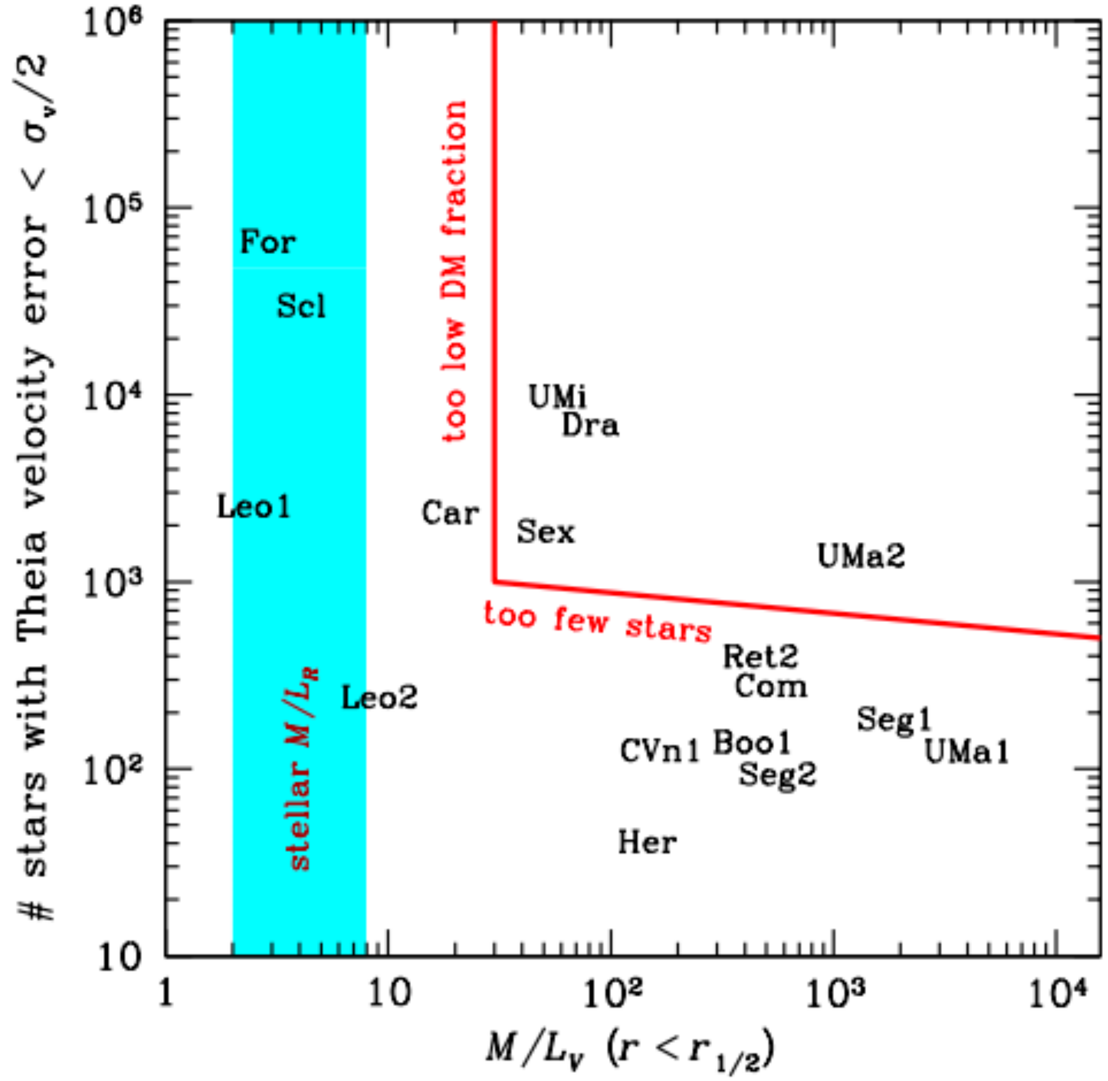


Fig. 2.1: Number of dwarf spheroidal galaxy stars within the *Theia* field with expected plane-of-sky errors lower than half the galaxy's velocity dispersion as a function of the galaxy's estimated mass-to-light ratio within the effective (half-projected-light) radius of the galaxy. Luminosities and total masses within the half-light radii are mainly from Walker et al. (2009).

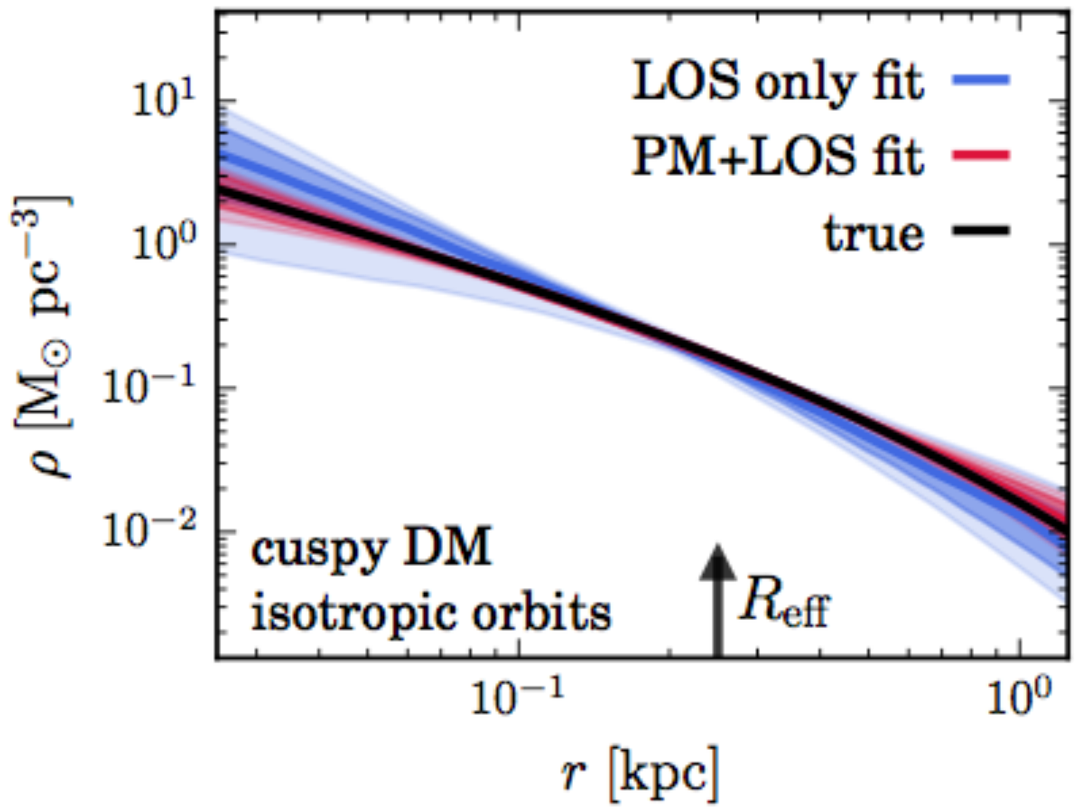
Degeneracy between the radial DM profile and orbital anisotropy quantifies whether stellar orbits are more radial or more tangential in the Jeans equation (Binney & Mamon 1982).

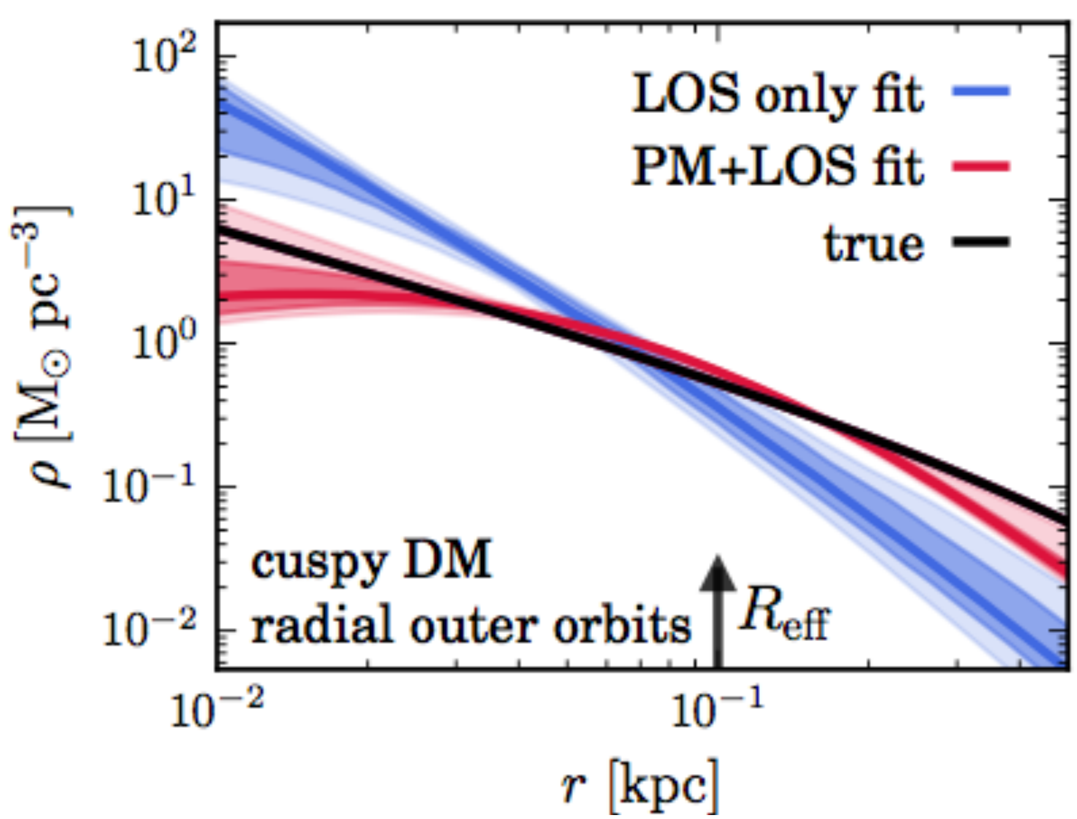
Adding proper motions can help removing these degeneracies!

THEIA

Microarcsecond Astrometric Observatory

Dark Matter in dSphs





CDM halos can be heated by bursty star formation inside the stellar half light radius *R*1/2, if star formation proceeds for long enough.

Some **dSphs like Fornax** have formed stars for almost a Hubble time and so **should have large central dark matter cores,** while others, like **Draco and Ursa Major2 should retain their steep central dark matter cusp**.

But it depends on the DM nature.

We can tell how DM is distributed and discriminate between cusp/core distributions

Theia can probe self-interactions

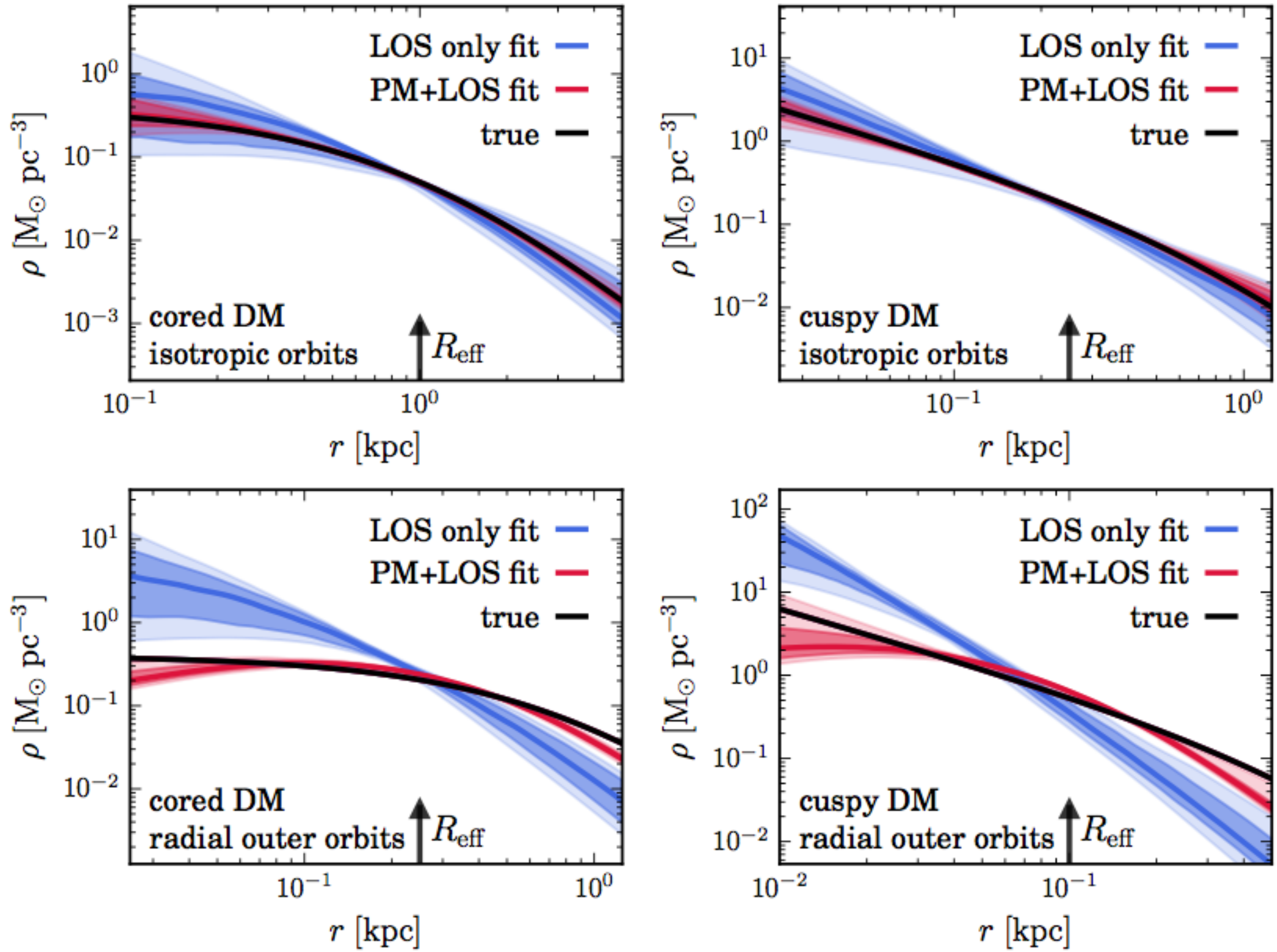
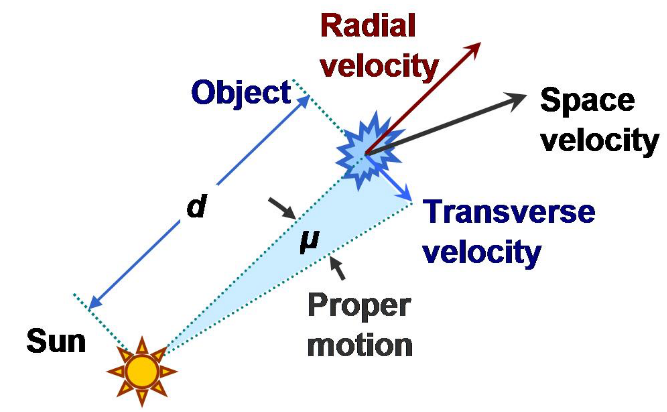


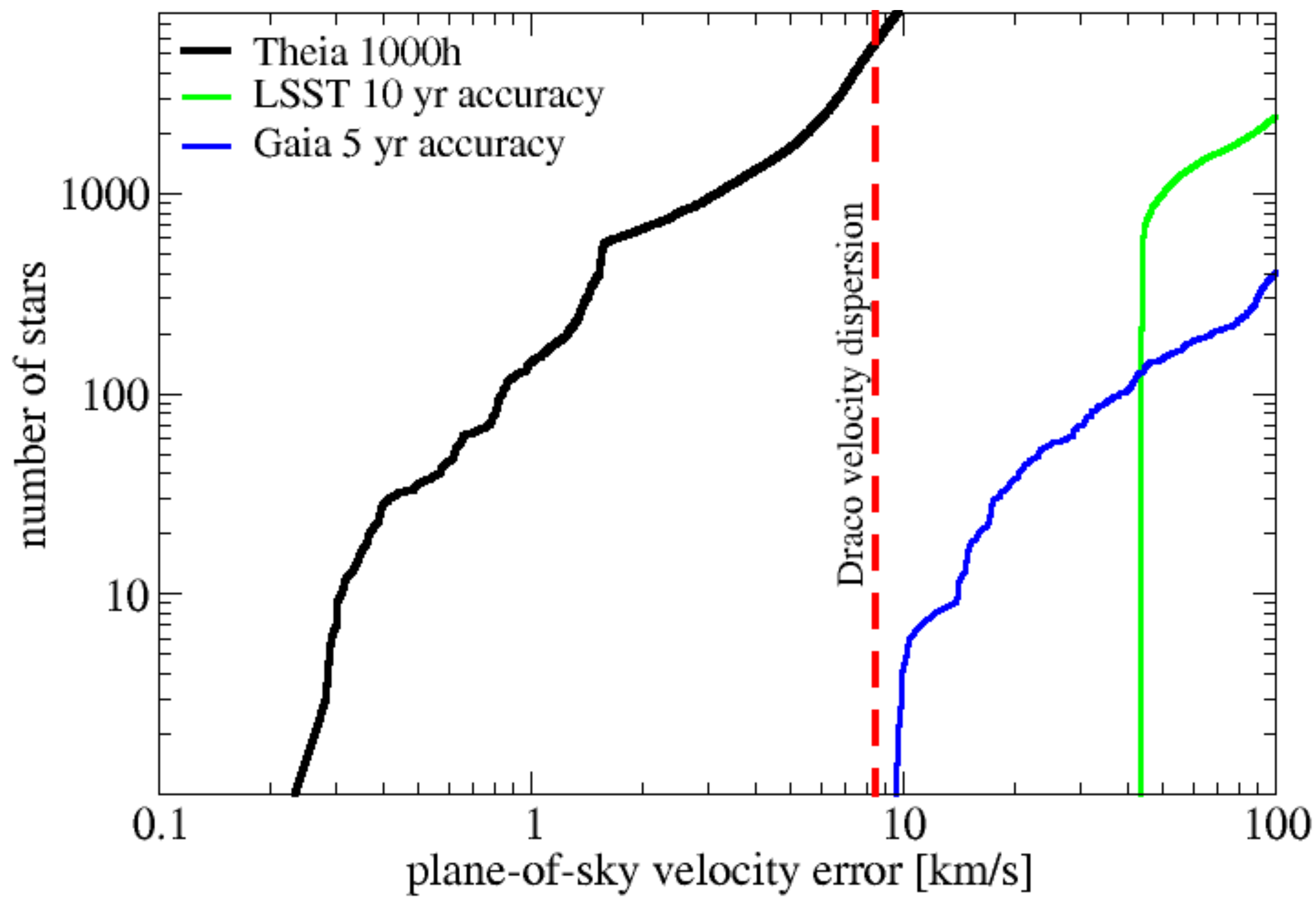
Fig. 2.2: Reconstruction of the DM halo profile of the Draco dSph without (*blue*) and with (*red*) proper motions using the mass-orbit modeling algorithm of Watkins et al. (2013). Four mocks of Draco were used, with cored (*left*) and cuspy (*right*) DM halos, and with isotropic velocities everywhere (*top*) or only in the inner regions with increasingly radial motions in the outer regions (*bottom*). The effective (half-projected light) radii of each mock is shown with the *arrows*. The stellar proper motions in the mocks were given errors, function of apparent magnitude, as expected with 1000 hours of observations spread over 4 years. Only with proper motions can the DM density profile be accurately reconstructed, properly recovering its cuspy or cored nature.

THEIA

Microarcsecond Astrometric Observatory

Pessimistic case (CCDs)



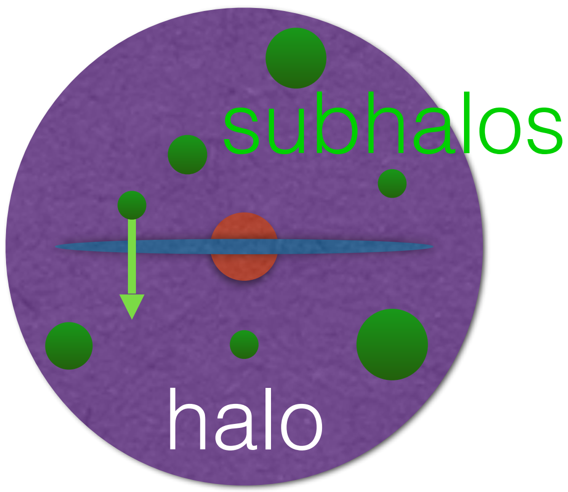


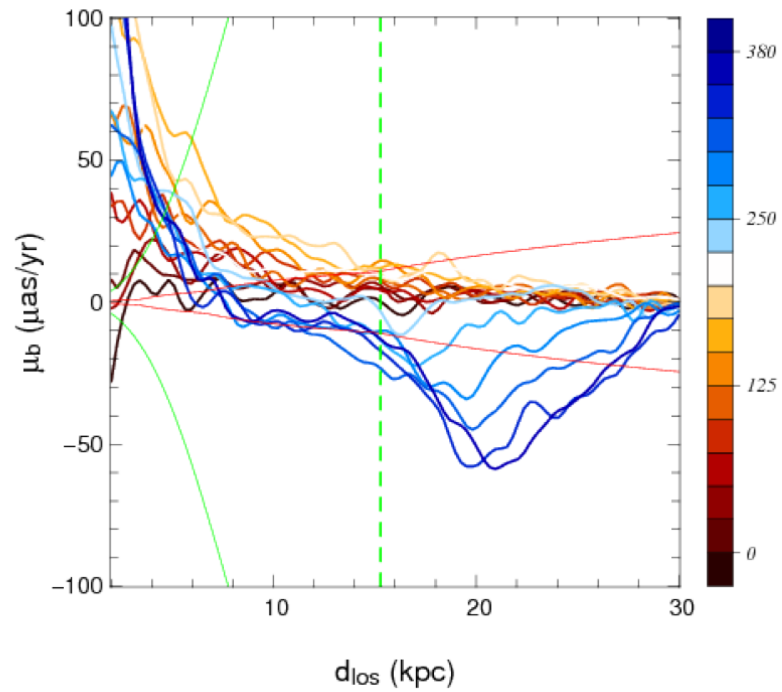
Theia is sensitive to the inner DM profiles of Dwarf galaxies

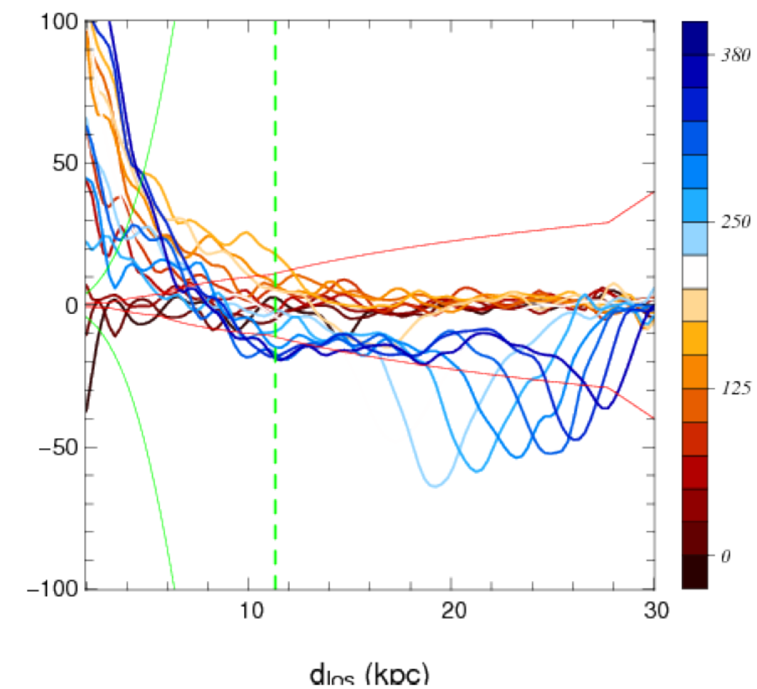
THEIA

Microarcsecond Astrometric Observatory

Dark Matter
Masses of sub halos

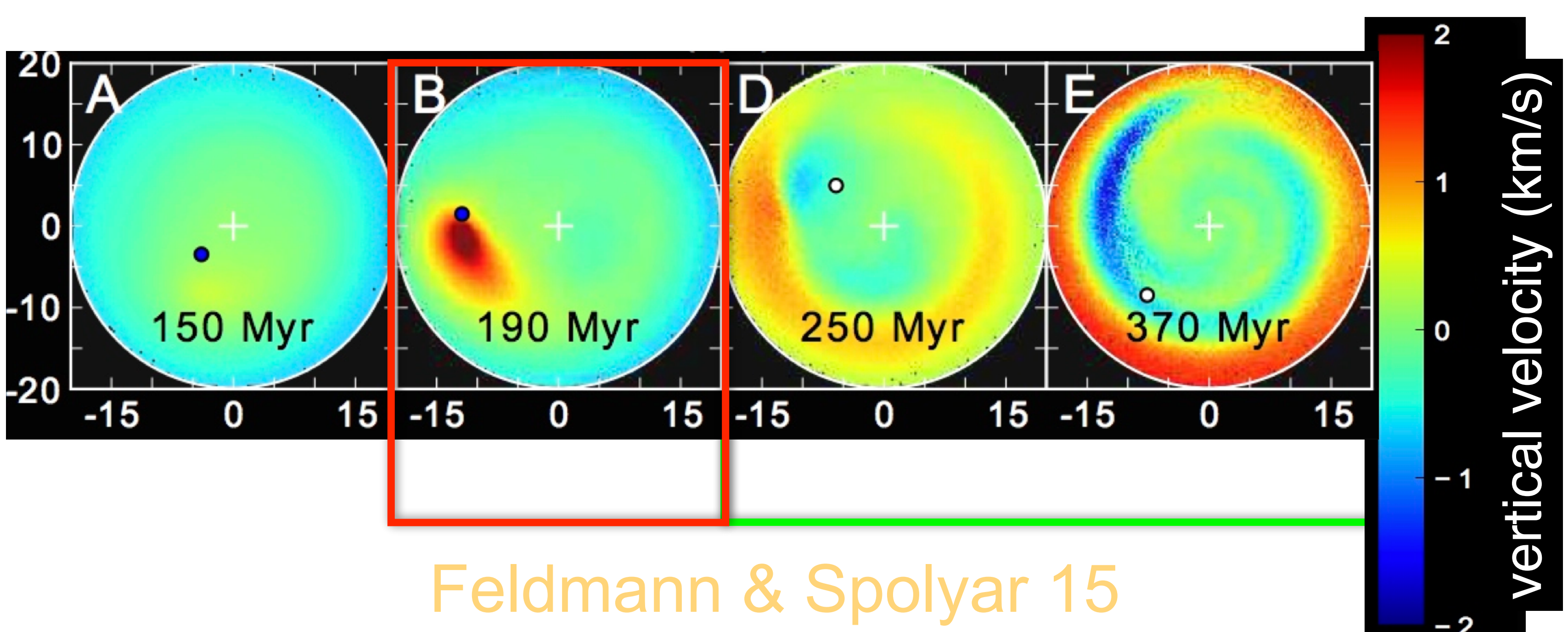




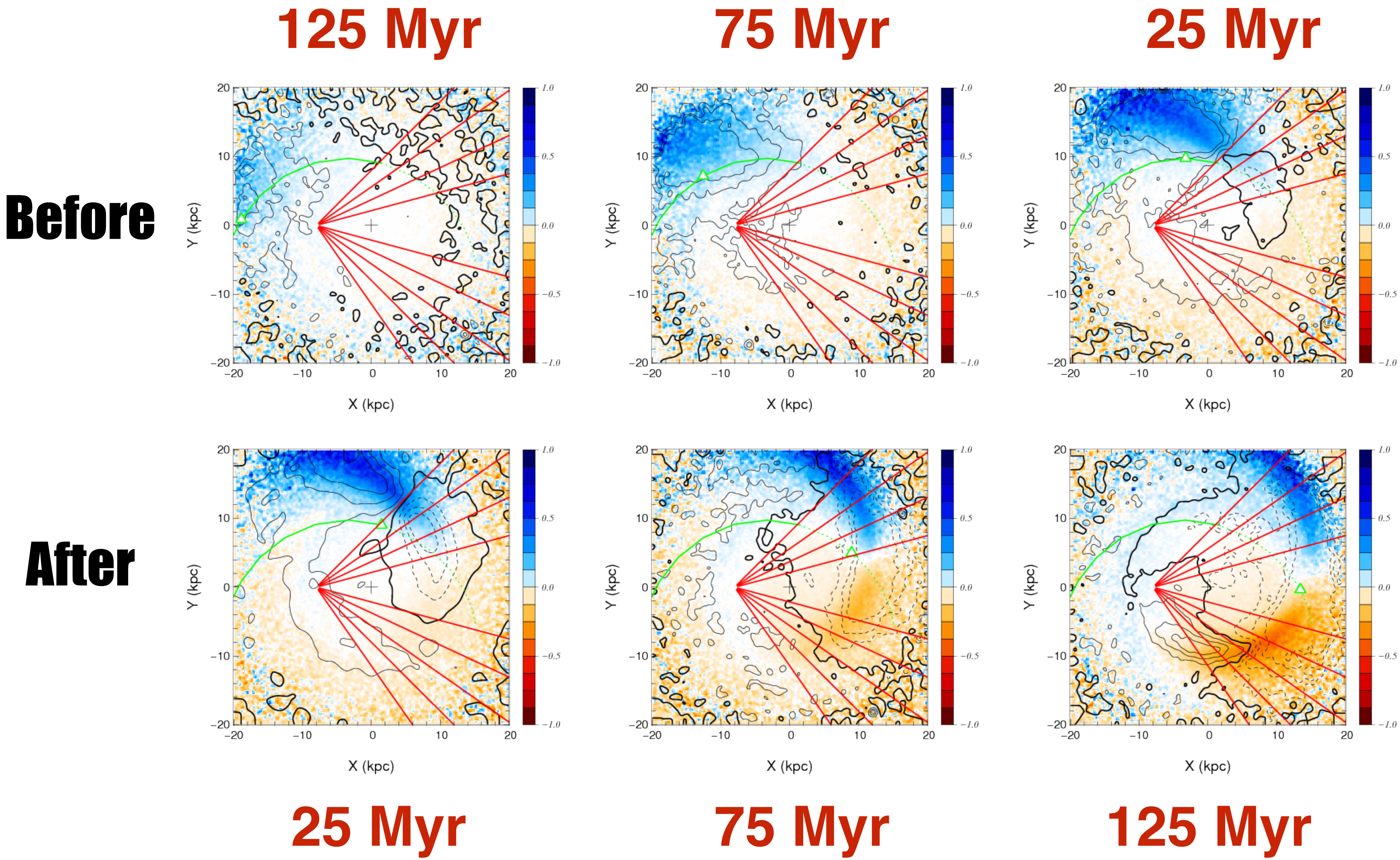


Largest effect when subhalo passes through disk

still visible after 1st passage



Feldmann & Spolyar 15



Colorbar: mean displacement
contours amplitude of bending modes in velocity space
plain line = +; dashed lines = -
triangle = actual location of sub halos

A dynamically young and perturbed Milky Way disk

T. Antoja, A. Helmi, M. Romero-Gómez, D. Katz, C. Babusiaux, R. Drimmel, D. W. Evans, F. Figueras, E. Poggio, C. Reylé, A. C. Robin, G. Seabroke & C. Soubiran

Nature **561**, 360–362 (2018) | Download Citation

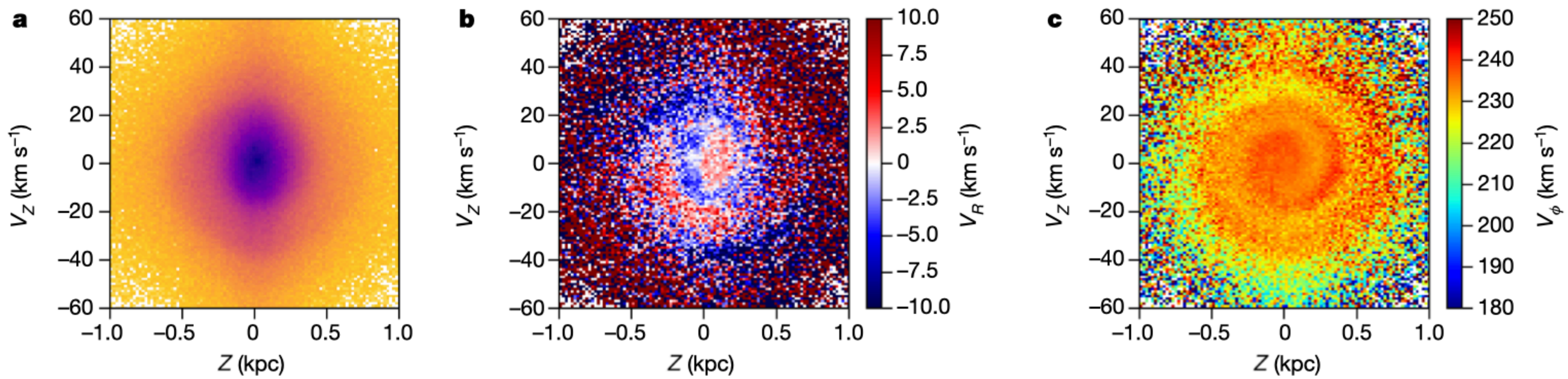


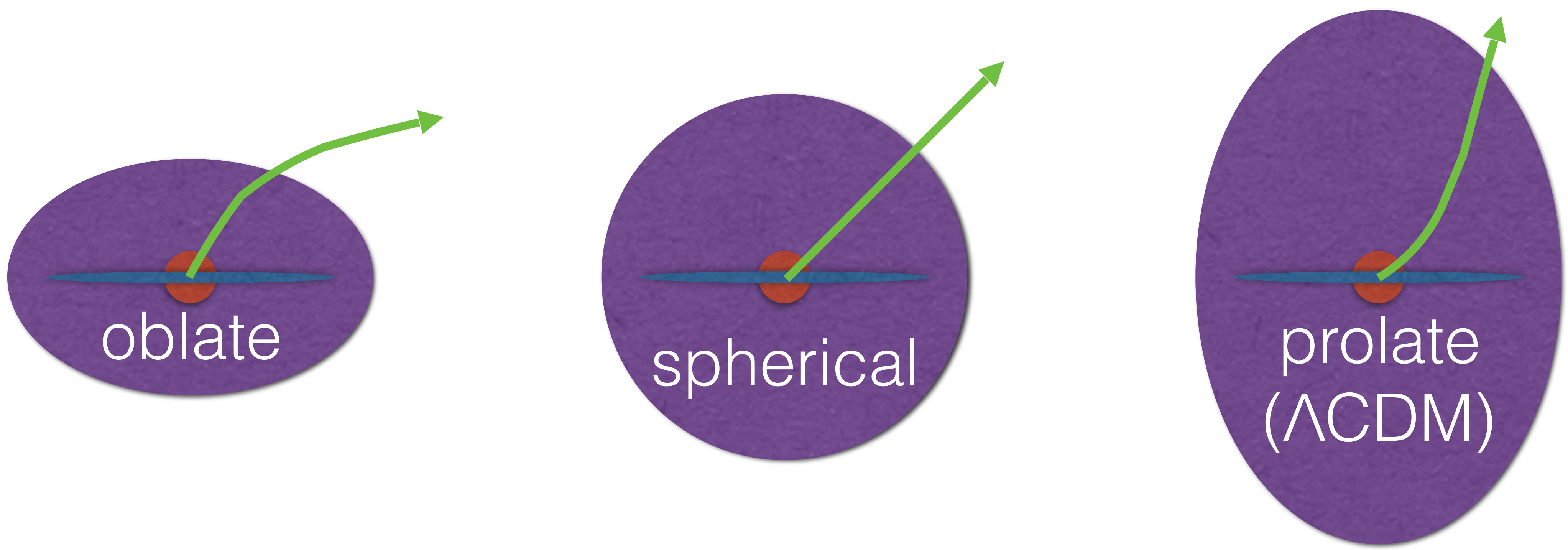
Fig. 1 | Vertical positions and velocities of the stars. The plots show the distribution of stars in the vertical position–velocity (Z–V_Z) plane from our sample of Gaia data for stars with Galactocentric radii of 8.24 kpc $< R <$ 8.44 kpc. **a**, Two-dimensional histogram in bins of $\Delta Z = 0.02$ kpc and $\Delta V_Z = 1$ km s^{-1}, with the darkness of the colour scale proportional to the number of stars. **b**, Z–V_Z plane coloured as a function of median radial velocity V_R in bins of $\Delta Z = 0.02$ kpc and $\Delta V_Z = 1$ km s^{-1}. **c**, Same as **b**, but for the azimuthal velocity V_ϕ. V_R and V_ϕ are positive towards the Galactic anticentre and the direction of Galactic rotation, respectively.

Dark Matter Triaxiality of halos

Hypervelocity stars

- $v > v_{esc} \sim 500$ km/s
- > 20 known today
- Too far/too faint to be seen by Gaia
- Likely originate from Galactic Center

⇒ trajectories (transverse motions) measure shape of MW potential



10 μas/yr accuracy required Gnedin+05
Theia → axis ratios to $\Delta(c/a) = 0.05$

THEIA

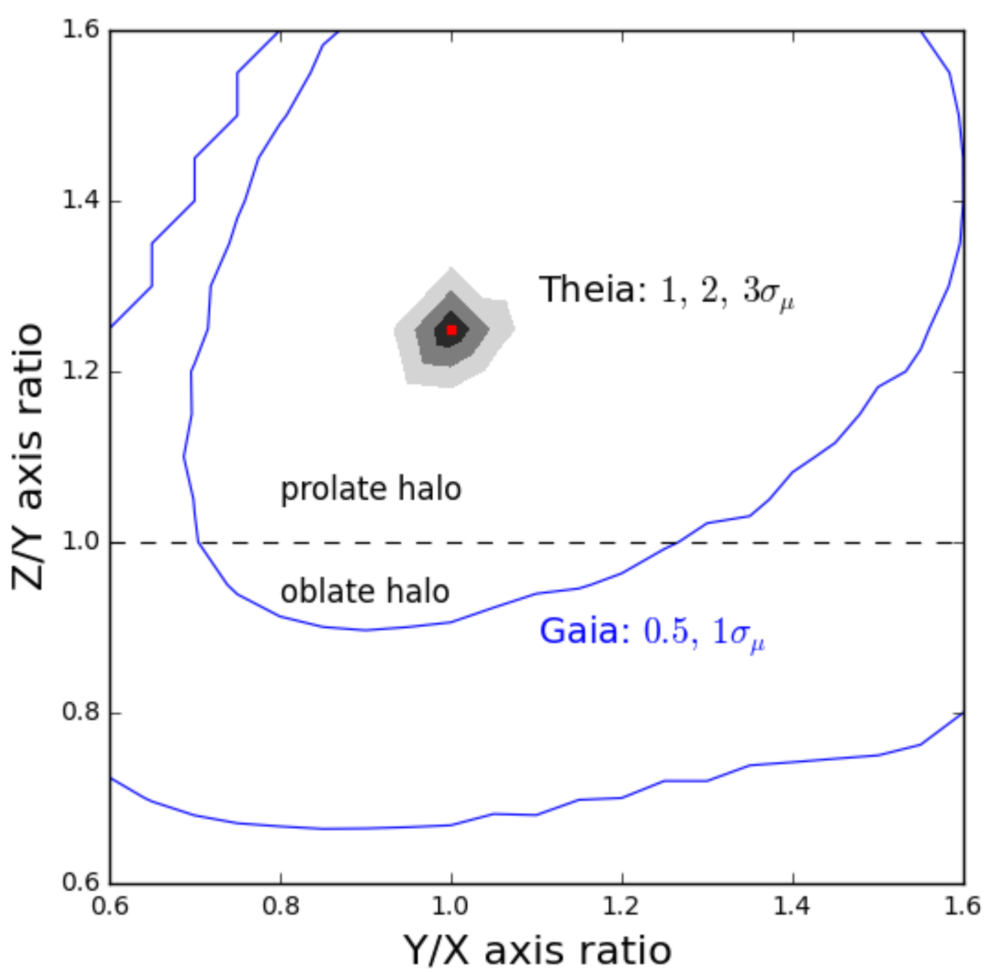
Microarcsecond Astrometric Observatory

Dark Matter Triaxiality of halos

proper motions precision of 5 -15 µas/yr for a typical R=17-19 mag of HVS for 125 ours of observation in 1 year.

5 HVS over 4 years, for a total of 2500 h.

Theia offers a unique window of opportunity; measurement cannot be done from the ground. Laser-AO imagers have FoV of less than 1 arcmin, even smaller than HST, which at high Galactic latitudes contain few quasars



Will help to determine if HVS from a three-body interaction and ejection from the deep potential well of SgrA*

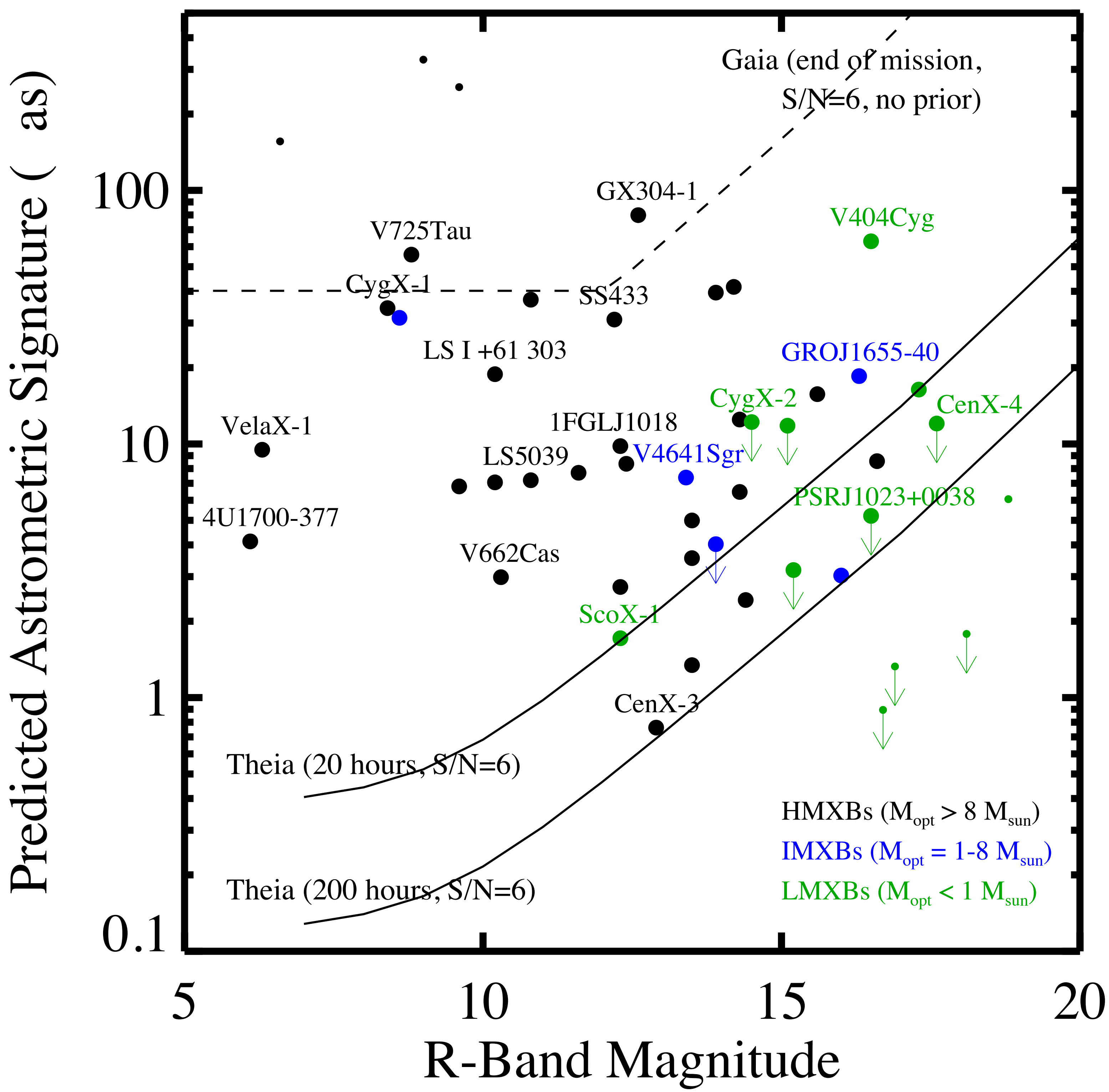
The assumed proper motions correspond to a prolate model with $qX = qY = 0.8\ qZ$, marked by a *red square*.

THEIA

Microarcsecond Astrometric Observatory

Compact objects

Measurements of orbits and distances

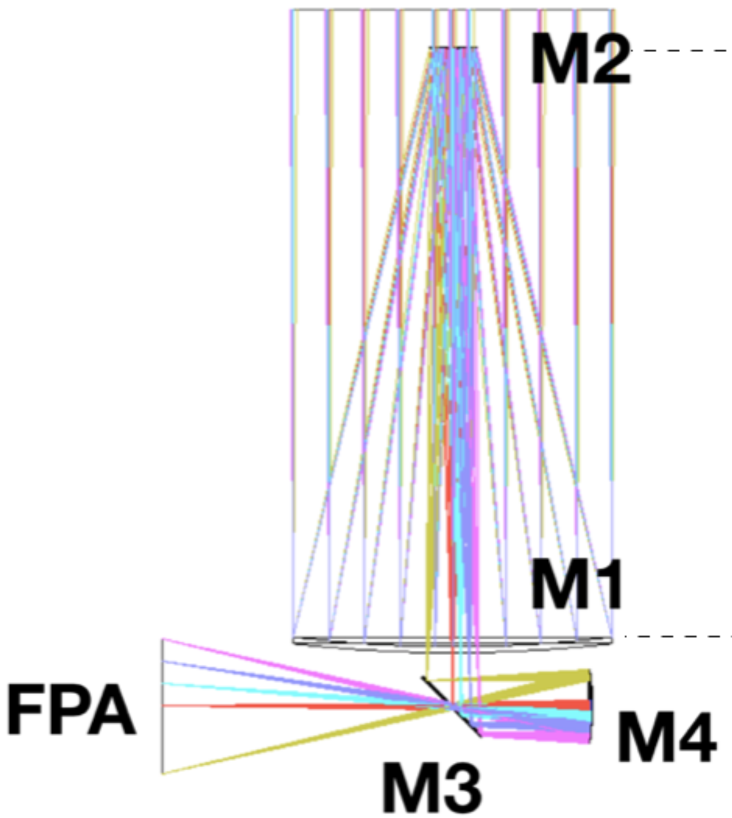


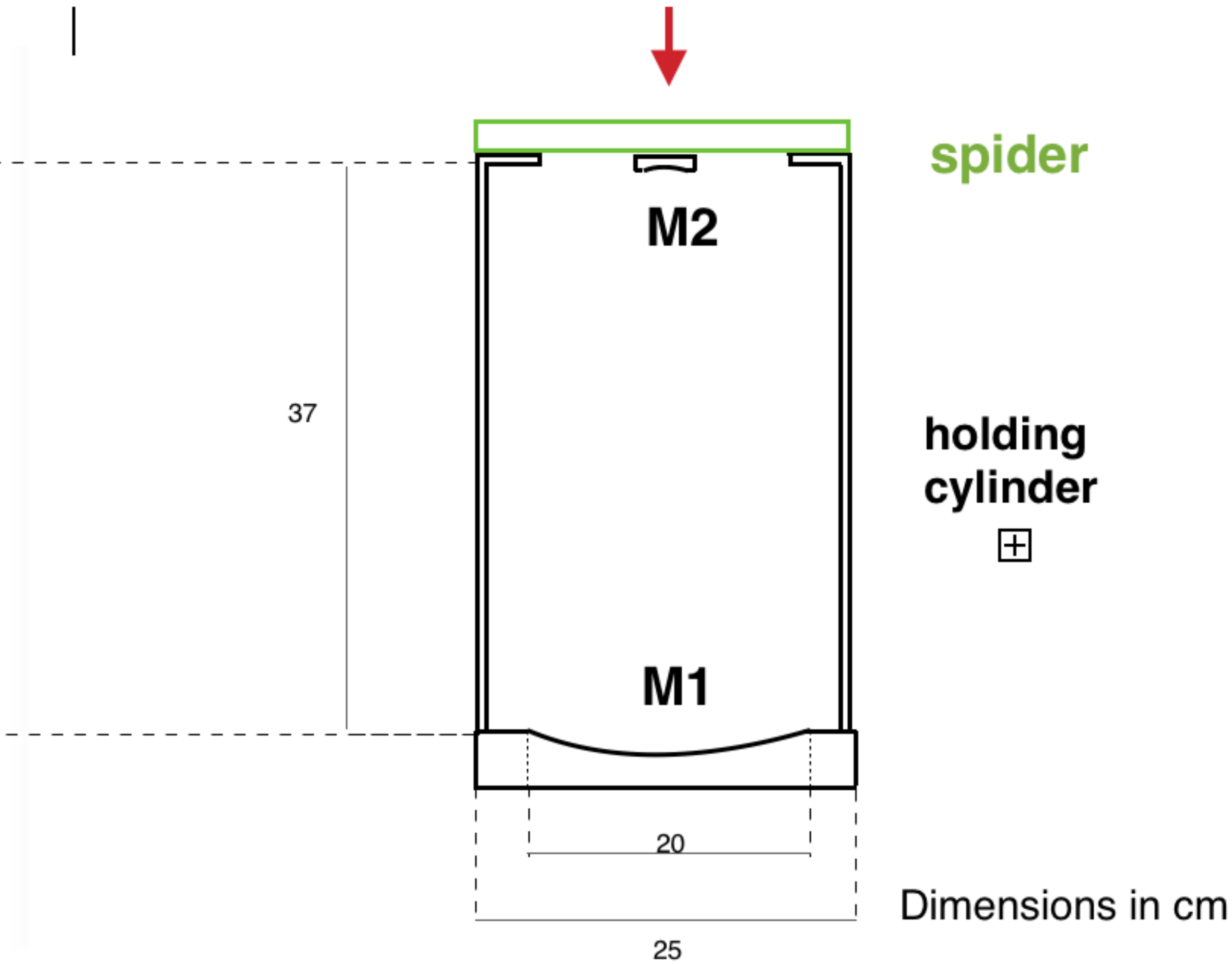
Explore Concept
(mini Theia to study alpha Cen)

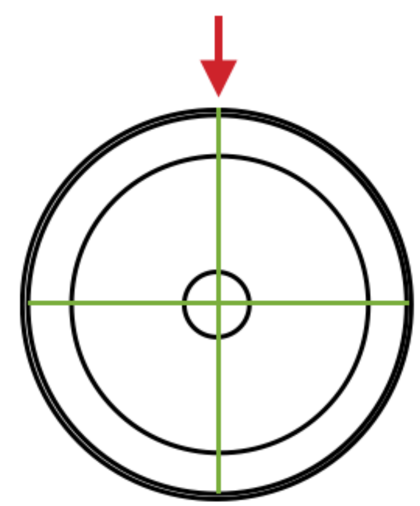
α Cen is at 1.3 pc;
An Earth-like planet signature around α Cen A&B is ~ 2.5μas
α Cen A & B are separated by several arcseconds on the sky

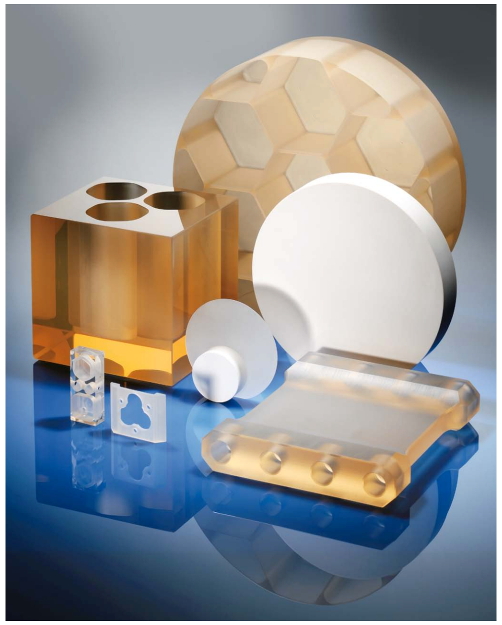
The EXPLORE telescope

TMA





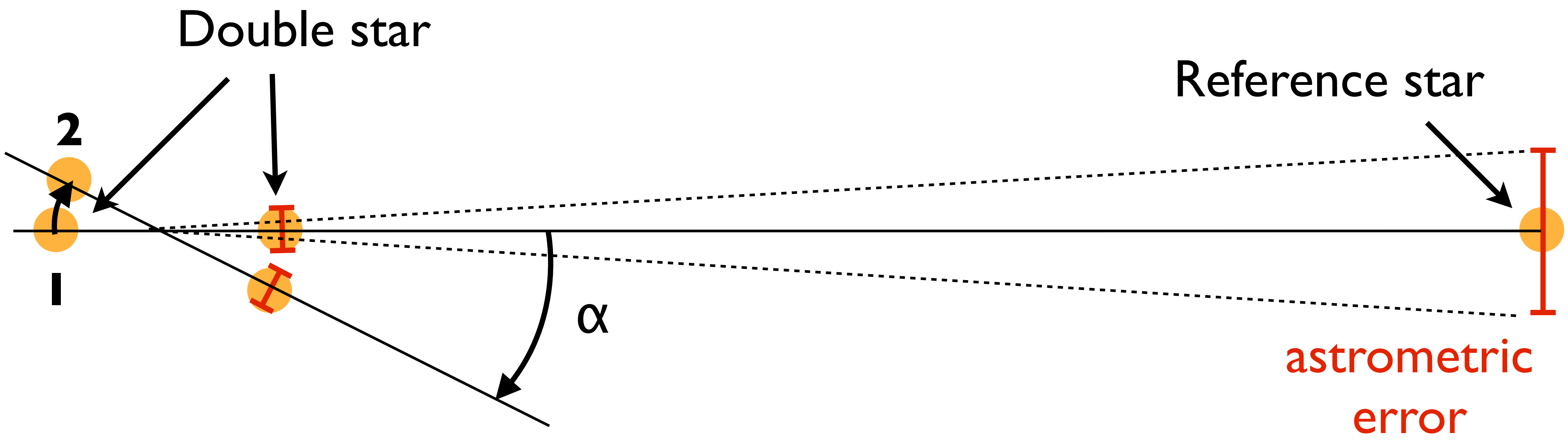




Baseline instrument

Possible M1-M2 holding all in Zerodur

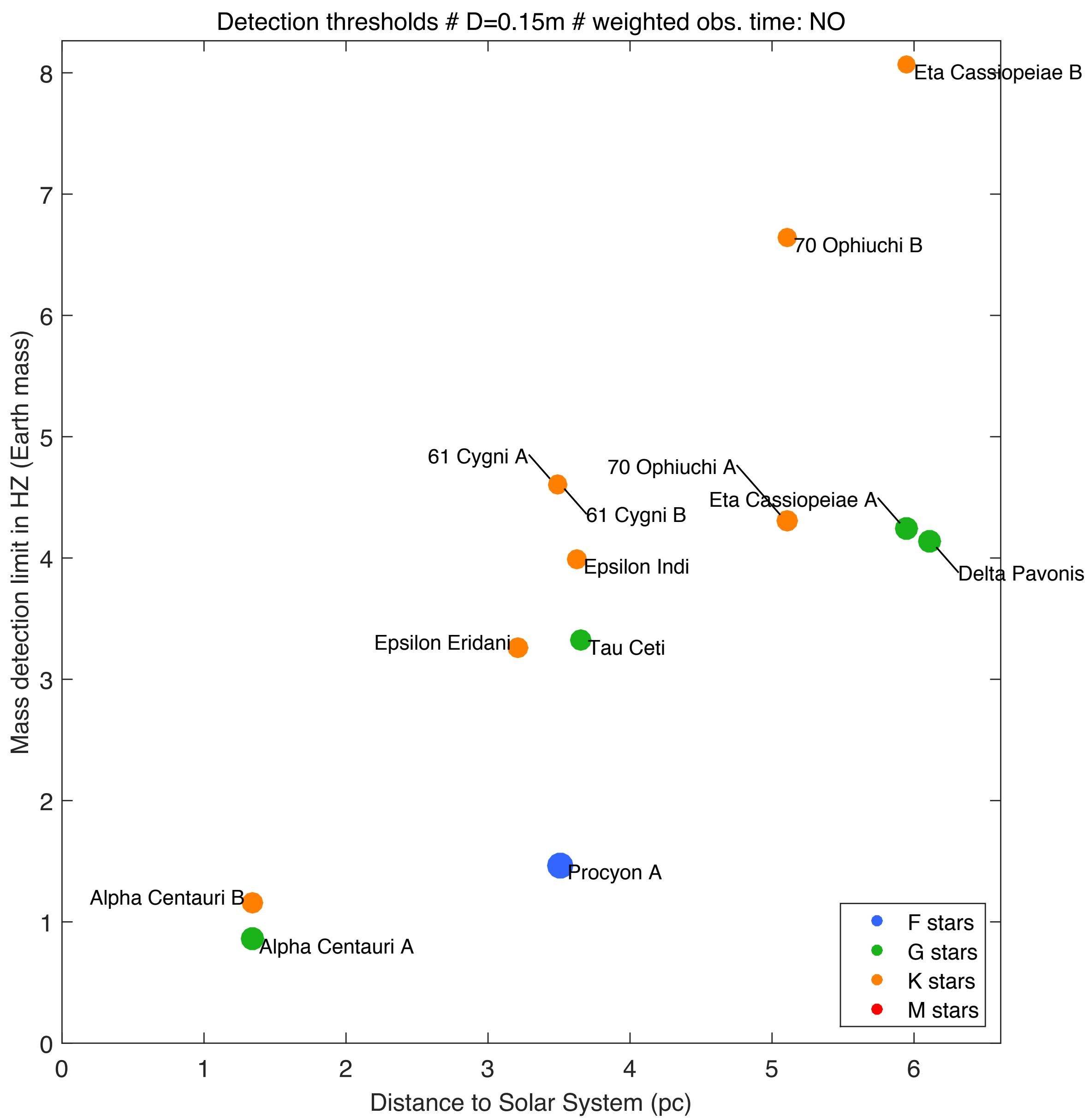
Using reference stars

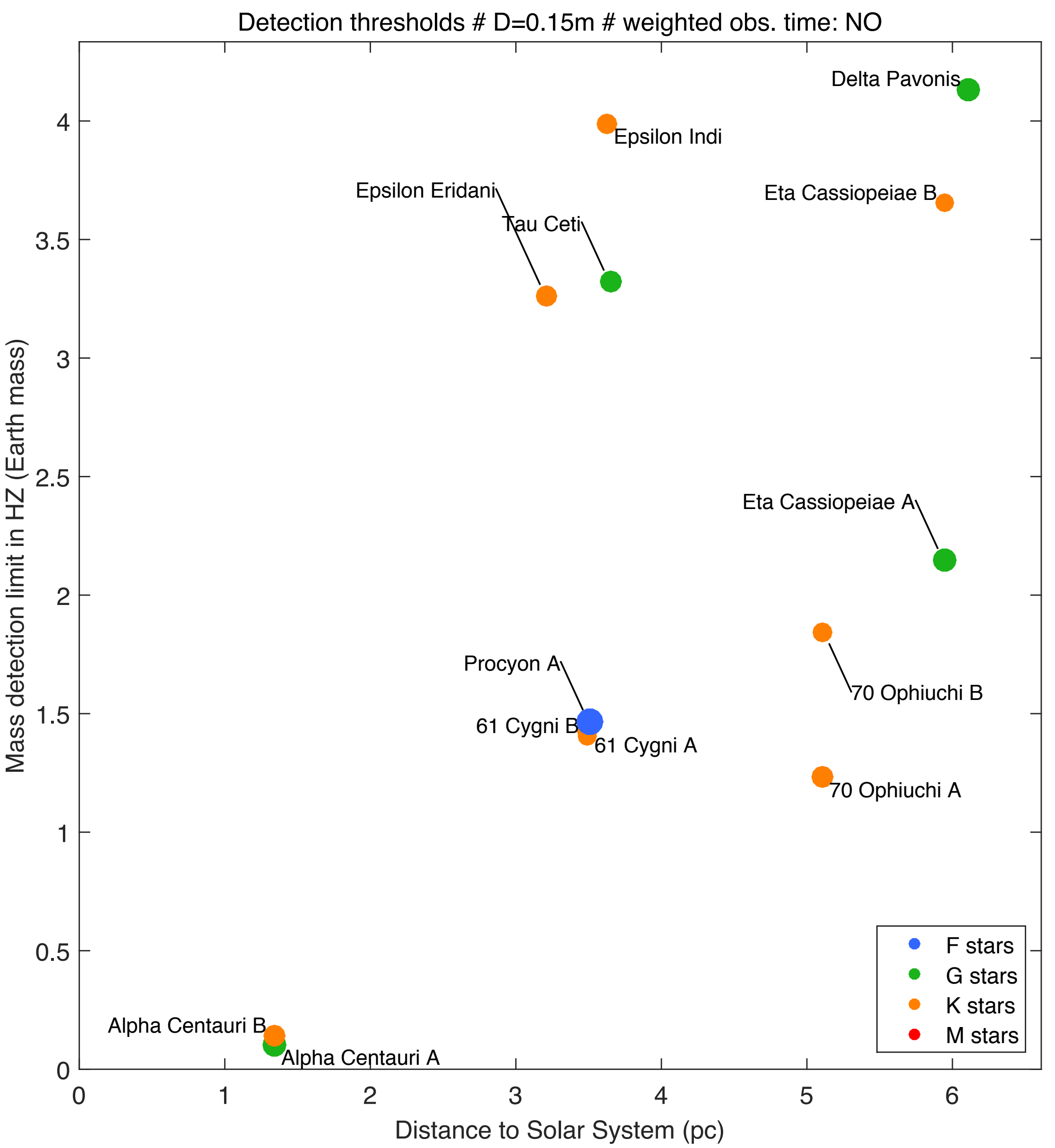


Use of reference stars could be a good way to do the platescale,
without any need for additional calibration equipment on the payload.

EXPLORE capabilities

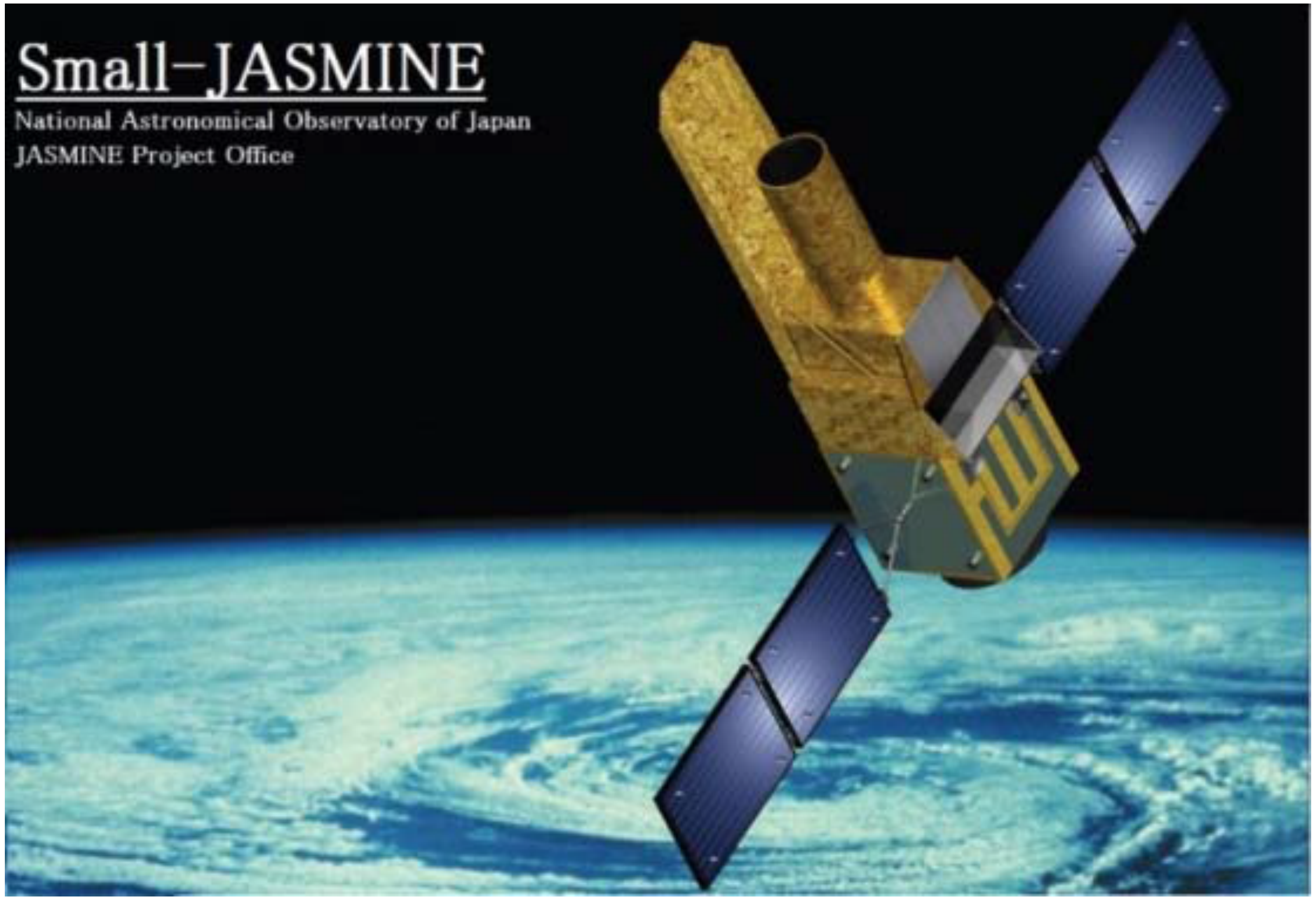
15 (20, 25,30) cm mirror; capable of staring at all nearby FGKM stars.

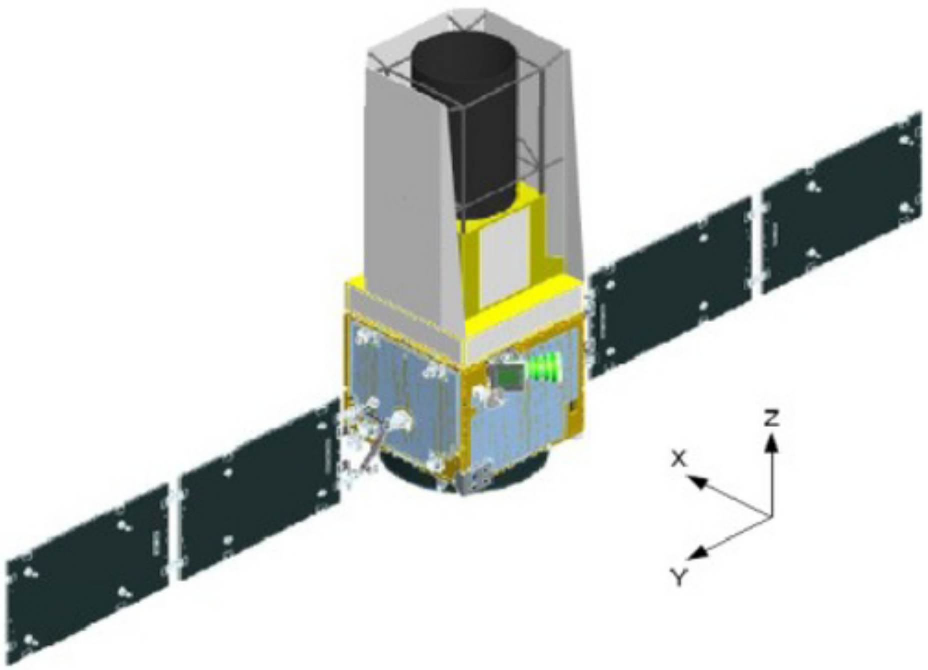


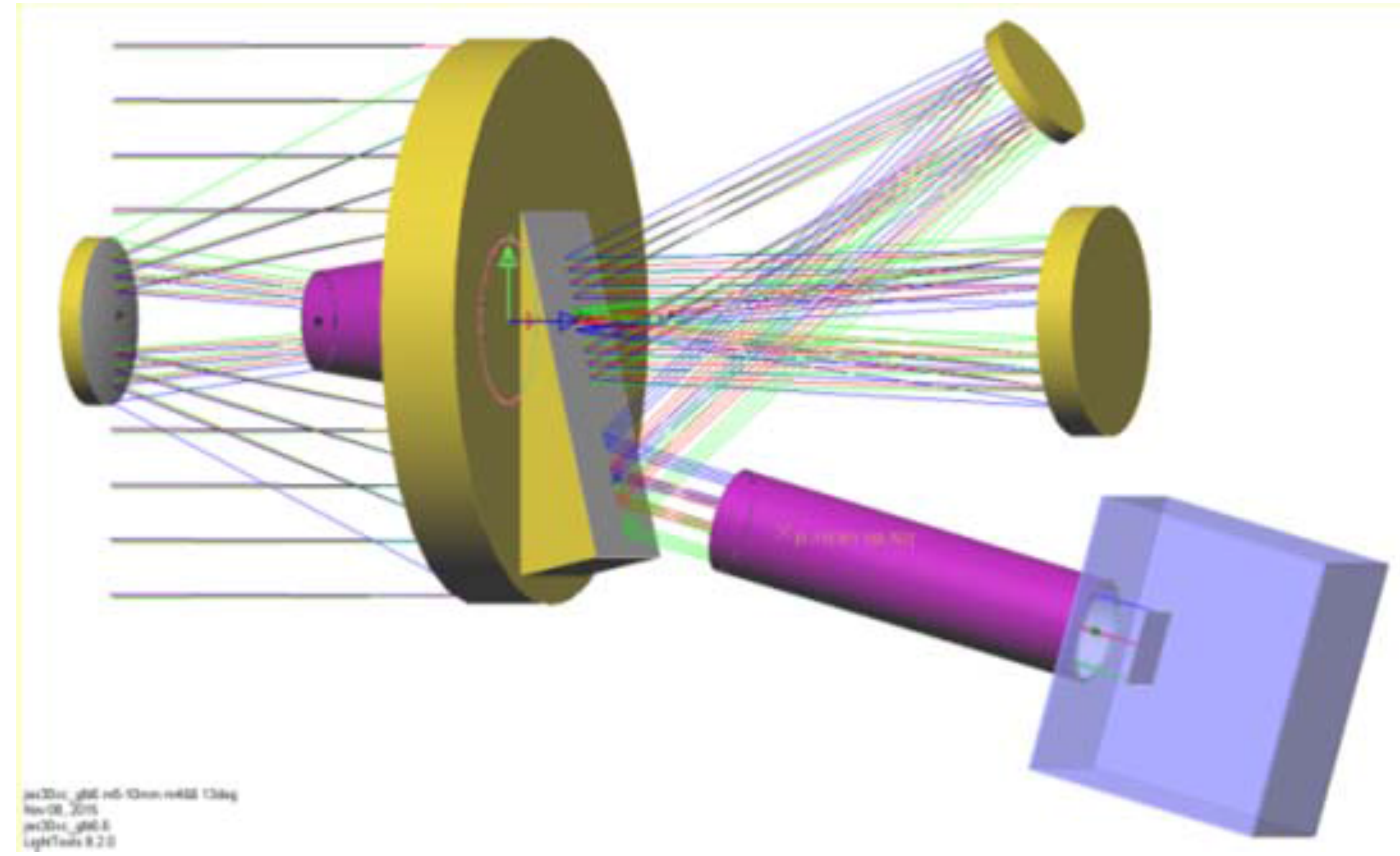


binary gain

Small-Jasmine





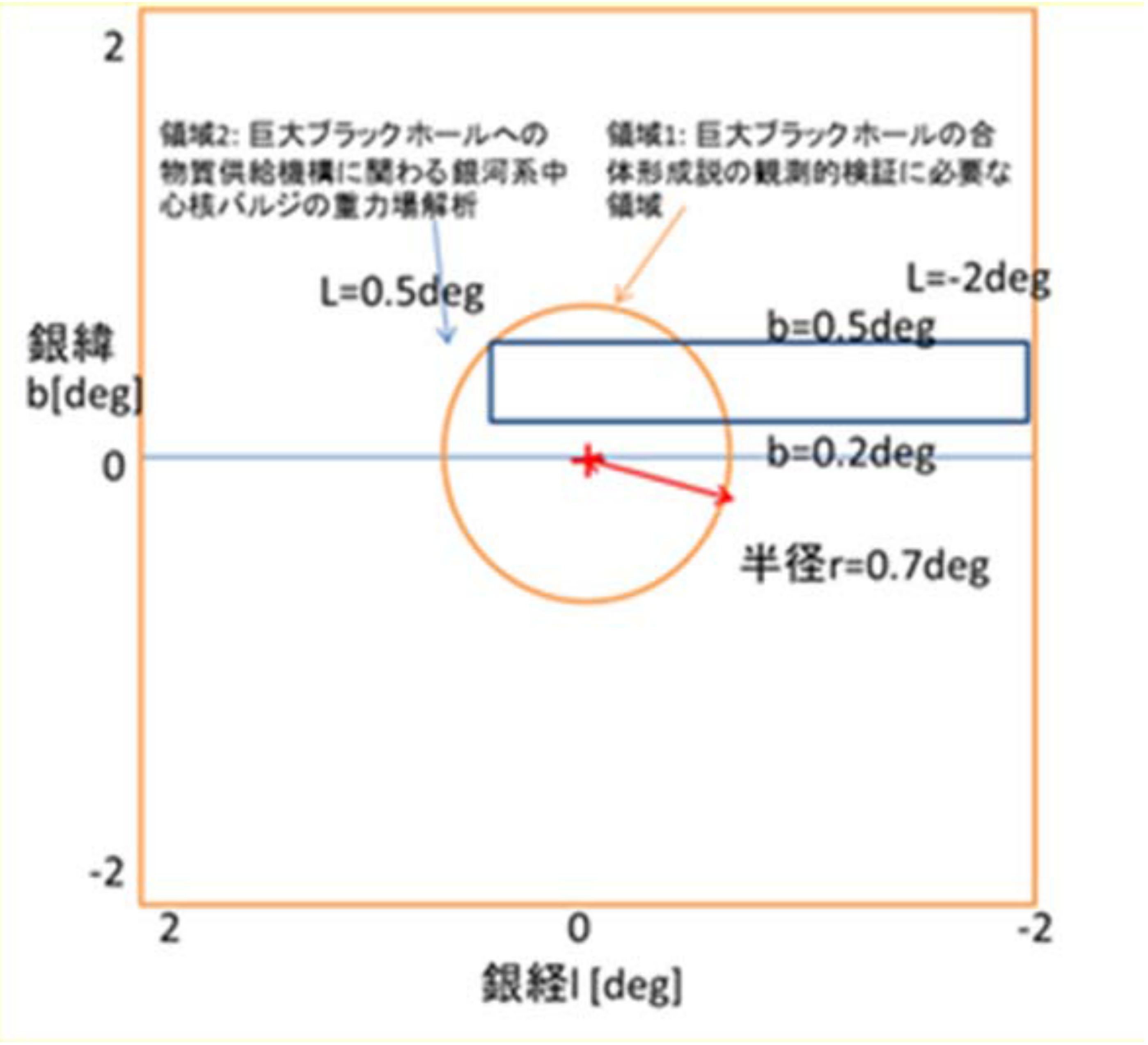


Astrometric Measurement in **Hw-band (1.1 µm - 1.7µm)**

Infrared astrometry to survey the Galactic nuclear bulge, hidden by interstellar dust in optical bands

Small-Jasmine's Science case

Main survey: Focus on nuclear bulge around the Galactic center



Second survey:

- X-ray binaries (e.g. CygX-1),
- γ-ray binaries,
- Planetary systems of brown dwarfs,
- Star-forming regions besides the area near the center

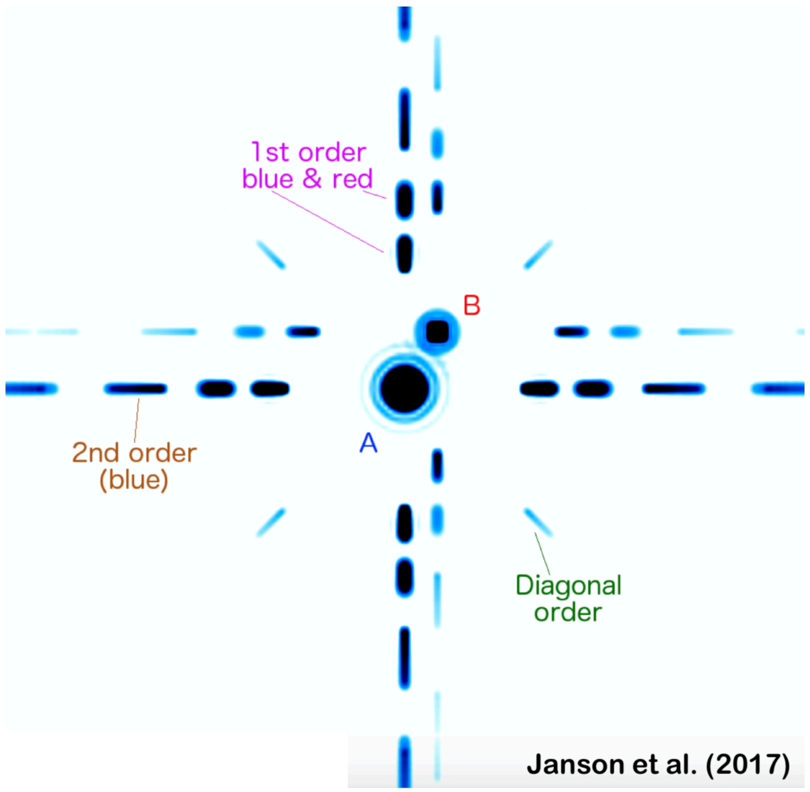
The Stare concept

Swedish proposal focus on alpha cen

Stare

small-aperture telescope (12.5 cm diameter)

Source	Time	Sensitivity
α Cen	When the sat is not behind the Earth ~ 20 min per ~ 90 min orbit	1 $M_{\rm Earth}$ in the HZ of α Cen A and B.
61 Cygni	Same as above	6 $M_{\rm Earth}$ in the HZ



Telescope	Detector
Optical components will be made in Zerodur	sCMOS detectors less sensitive to cosmic ray hits
The pre-camera part of the telescope will be kept thermally stable to a ~ 1 K-level precision	chip of 2 k*2 k pixels, read out in global shutter mode at a 50 Hz rate (20 ms per frame)
split up wavefront of the incoming light prior to the focusing optics using a form of transmissive phase grating, which produces dispersive first- and second-order PSF features at fixed angular separations from the nondispersive zero-order features of the two stars	The detector is strongly oversampled (a factor 20 relative to the FWHM) which partly serves to average out flat field-related errors, and along with the high frame rate, it keeps the targets comfortably within the linear response regime of the detector.
wedge filters are used to produce a transmission profile which is close to 1 between 450 and 550 nm and between 650 and 750 nm and zero elsewhere. Each spectrum is split up into a blue and a red spot.	

Conclusion

Mission summary

Missions/ purpose	NEAT	Theia	Explore	Small-Jasmine	Stare
Exo-planets	✓	✓	✓	✓	✓
Dark Matter	✗	✓	✗	✗	✗
Neutron stars	✗	✓	✓	✓	✗
GC	✗	✓	✓	✓	✗
Other	✗	✓	✓	✓	✗

Cannot see faint stars

Mission summary

Missions/ purpose	NEAT	Theia	Explore	Small-Jasmine	Stare
Telescope	Formation fly	TMA	TMA	Modified Korsch	Cassegrain
Size	1m + 40m	80 cm	10/20/30 cm	30 cm	12.5 cm
Camera	CCD	CCD/ CMOS	CMOS	CMOS	CMOS
FoV	0.6 deg	0.6 deg	0.6 deg	0.6 deg	Small
Orbit	L2	L2	Geo	SSO	Leo
Astrometry	Relative/ pointed	Relative/ pointed	Relative/ pointed	Survey	Stare
Precision	~ 0.1 µas/yr	~ 0.1 µas/yr	~20 µas/yr	~ 20 µas/yr	~ µas/yr
Band	Visible	Visible	Visible	Infrared	Visible
Collaboration	ESA/ International	ESA/ International	Subset Theia	Jaxa	Sweden

Mission Component	What is included	Effort needed + Cost
Mission Architect and "Mission Owner"	Mission Assessment study	14 man month
	Mission Requirement Document	27 man month
	Public Outreach	8 man month
	Sub total	**49 man months**
Spacecraft Launch	Launch Agency price tag	12 M€
	(Internal) Procurement cost	2 man month
	Launch campaign	8 man month 40 k€
	Sub total	**10 man months 12 M€**
Spacecraft Architect	System engineering & Mission Analysis	72 man month
	Project communication and interaction with "Mission Owner"	5 man months
	Overall assembly, integration and testing	81 man months 1.2M€
	Sub total	**160 man months 1.2 M€**
Spacecraft Platform Excluding: * Payload and Geometry Control (some part or all of the AOCS/GNC) * *Relative sensor system	AOCS / GNC minus the Payload & Geometry Control "soft" capabilities, minus the Modular vision based sensors. Adaptation work (Design, Implementation, Test, Test & Verification environment/s) Equipment Price tags (internal) procurement costs.	113 man months 3.5 M€
	Mechanical & Structure. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment Price tags. (internal) procurement costs	23 man month 0.8 M€
	Electrical, DHS & ISL & Power. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment Price tags. (internal) procurement costs	41 man month 4.0 M€
	Thermal. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment Price tags. (internal) procurement costs	14 man month 0.1 M€
	S/C to Ground COM design and components. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment Price tags (internal) procurement costs	23 man month 3.0 M€
	Propulsion system. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment Price tags. (internal) procurement costs	32 man months 5.5 M€
	Sub total	**246 man months 17.0 M€**

piggyback ~ 5 millions?

perhaps still at 1.2

Swedish:8 Millions...

246 ESA man months -> normal price

Payload and Geometry Control	Payload and Geometry Control, Adaptation work (Design, Implementation, Test, Test & Verification environment/s, documentation)	27 man month 0.15 M€
Modular Vision based sensor suite	Modular Vision based sensor suite. Adaptation work (Design, Implementation, Test, Test & Verification environment/s). Equipment price tags. (internal) procurement costs	27 man month 3.0 M€
	Sub total	**54 man months** **3.15 M€**
Mission Operations	Setup and prepare for Mission Planning & Control including Flight Dynamics Adaptation work (Definition, Implementation and Testing of equipment, tools, processes and procedures) (covers the time up to and including launch)	27 man months 30 k€
	Mission Planning & Control including Flight Dynamics covers the time from LEOP and onwards	97 man months
	Setup and prepare for Operations including preparations and training, Adaptation work (Definition, Implementation and Testing of equipment, tools, processes, procedures, procedures and procedures) (covers the time up to and including launch)	36 man months 30 k€
	Operations (covers the time from LEOP and onwards)	162 man month
	Up/Downlink Antenna Stations (provided by ...)	2.2 M€
	Primary Data storage	50 k€
	Sub total (up to and including launch)	**62 man months** **0.06 M€**
	Sub total (post launch)	**260 man months** **2.25 M€**
Transportation		140 k€
TOTAL	**Mission Cost, excluding Payload**	**841 man month** **35.7 M€**
Payload	**See Table K.2**	**26.4 M€**

cheaper as there will be only 1 module

cheaper for geo than L2

cheaper for geo than L2

between 14-20 ??

Now possibly reduced to 14 -20 (with instrument)?

Payload	Cost (M€)
FP electronics, power	6
Detectors	5
Metrology	5
Mirror + PTZ control	2
Carrier interface	4
Payload subtotal	22
Payload margin (20%)	4.4
Payload subtotal with margins	26.4

probably cheaper
because a much simpler
configuration

CMOS, single tile
1 module
(not 2 like for microNEAT!)

The Explore telescope

1 block Zerodur telescope

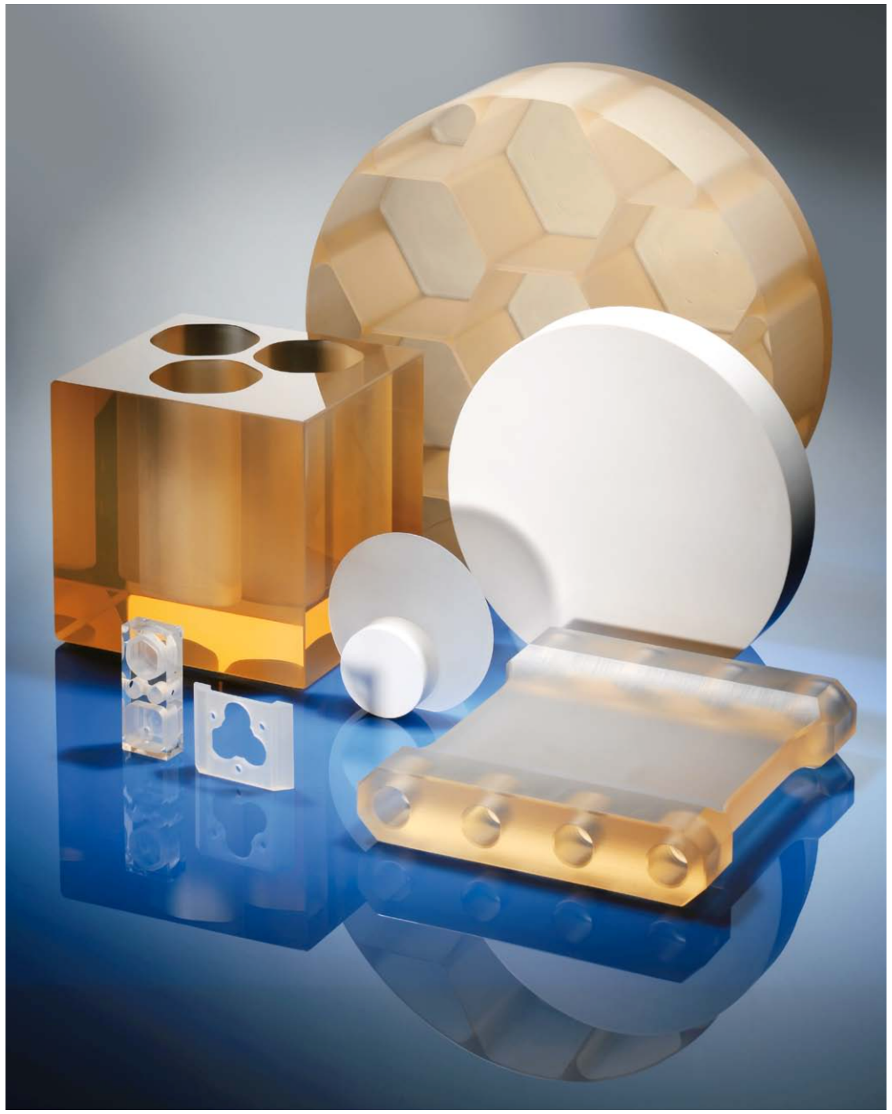
Zerodur features (Schott company)

- low ETC = **0 +/- 0.02 10^-6 K^{-1}**
  => no need for sophisticated thermal regulation

- machinable

- mechanical stress
  - < 10 G Pascal (usual)
  - < 50 G Pascal (polished, or acid etching)

Question: can it stand space qualification?



Surviving launch ?

Requirements

1. stand static acceleration : 100 g
2. stand 30 g at f = 30 Hz
3. Eigen vibration frequencies: all > 200 Hz

Check of 1.

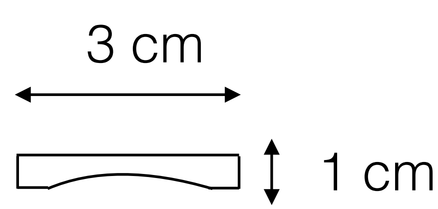
- Mirror M2 + spider

  $V_{M2} = \pi/4\ (3)^2\ 1 \quad [cm^3]$

  $\varrho = 2.53\ g/cm^3$

  $M_{M2} \approx 20\ g$

  assume $M_{spider} = M_{M2}$ => **40 g**



- M1 - M2 holder (cylinder)

  e = 0.3 cm, H = 37 cm, M_{holder} = **550 g**

Can it stand static 100 g?

<u>Holder</u>

base section = 0.3 x 37… = 5.9 cm²

$P_{stress} = (M_{holder} / sect) * 100\ g$

$= 9.1\ 10^5$ Pascal

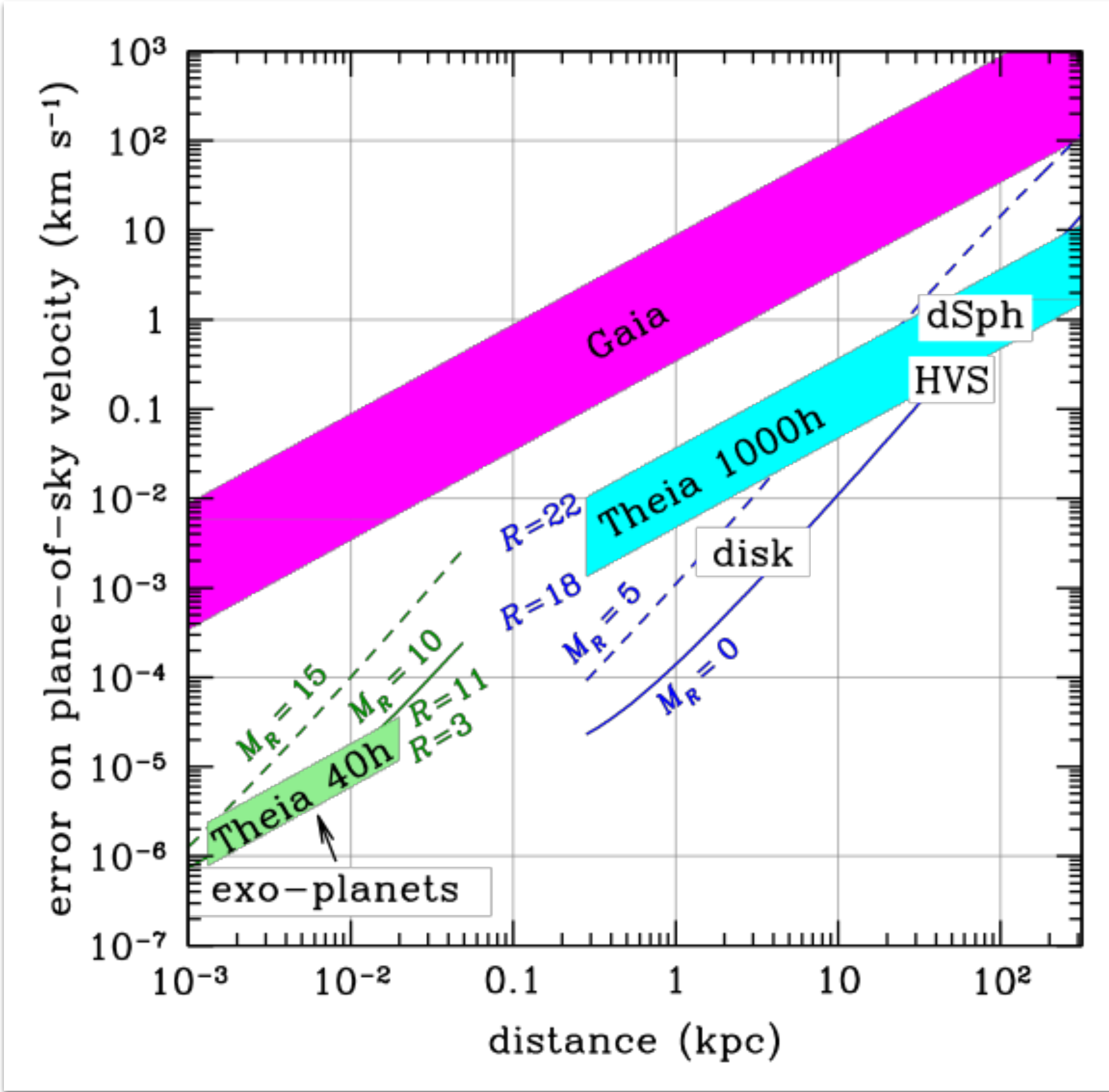
≈ 1 M Pascal <—> OK

<u>Spider</u>

TBD, but should be easy to design

THEIA

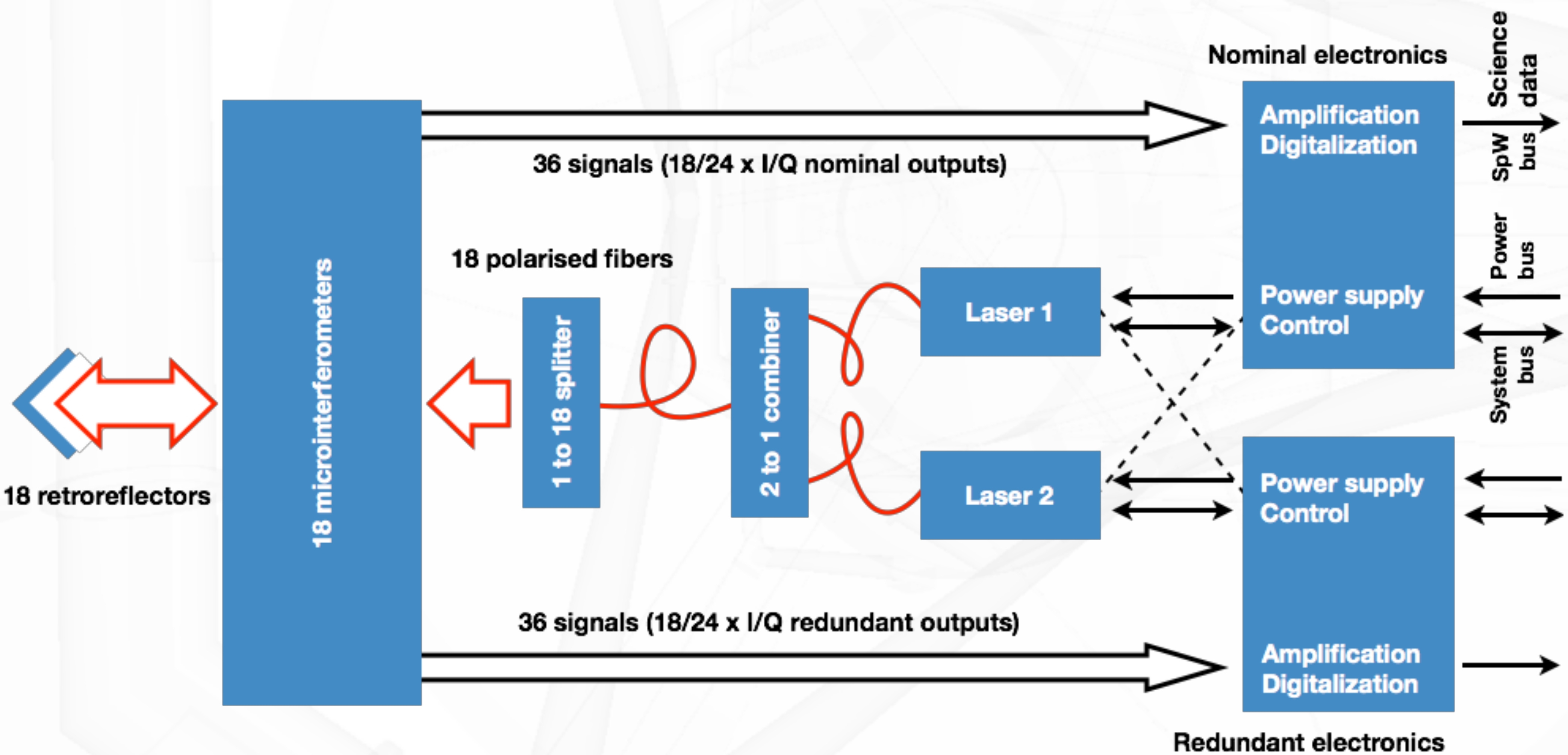
Microarcsecond Astrometric Observatory



	Gaia post-launch	Theia	improvement
Telescope Aperture	1.45 x 0.5 = 0.73 m^2	0.8 m → 0.40 m^2	**0.55**
Field of view		0.5 deg	
Coverage	Survey	*Pointed*	
Astrometry	Global	*Differential*	
Exposure time per field	76 x 9 (CCD) x 4.4 sec = 0.84 hr	25 x 40 hr = 1000 hr	**1200**
Additional factors	2D vs 1D astrometry: 1.4, Gaia Stray light: 1.9		
Proper motion accuracy *G*=10 star	3.5 µas/yr	0.11 µas/yr	**30**
Proper motion accuracy *G*=15 star	14 µas/yr	0.4 µas/yr	**35**
Proper motion accuracy *G*=20 star	330 µas/yr	5 µas/yr	**66**

Theia : *the new Astrometry frontier*

Lesson from Gaia :: Monitor, monitor, monitor

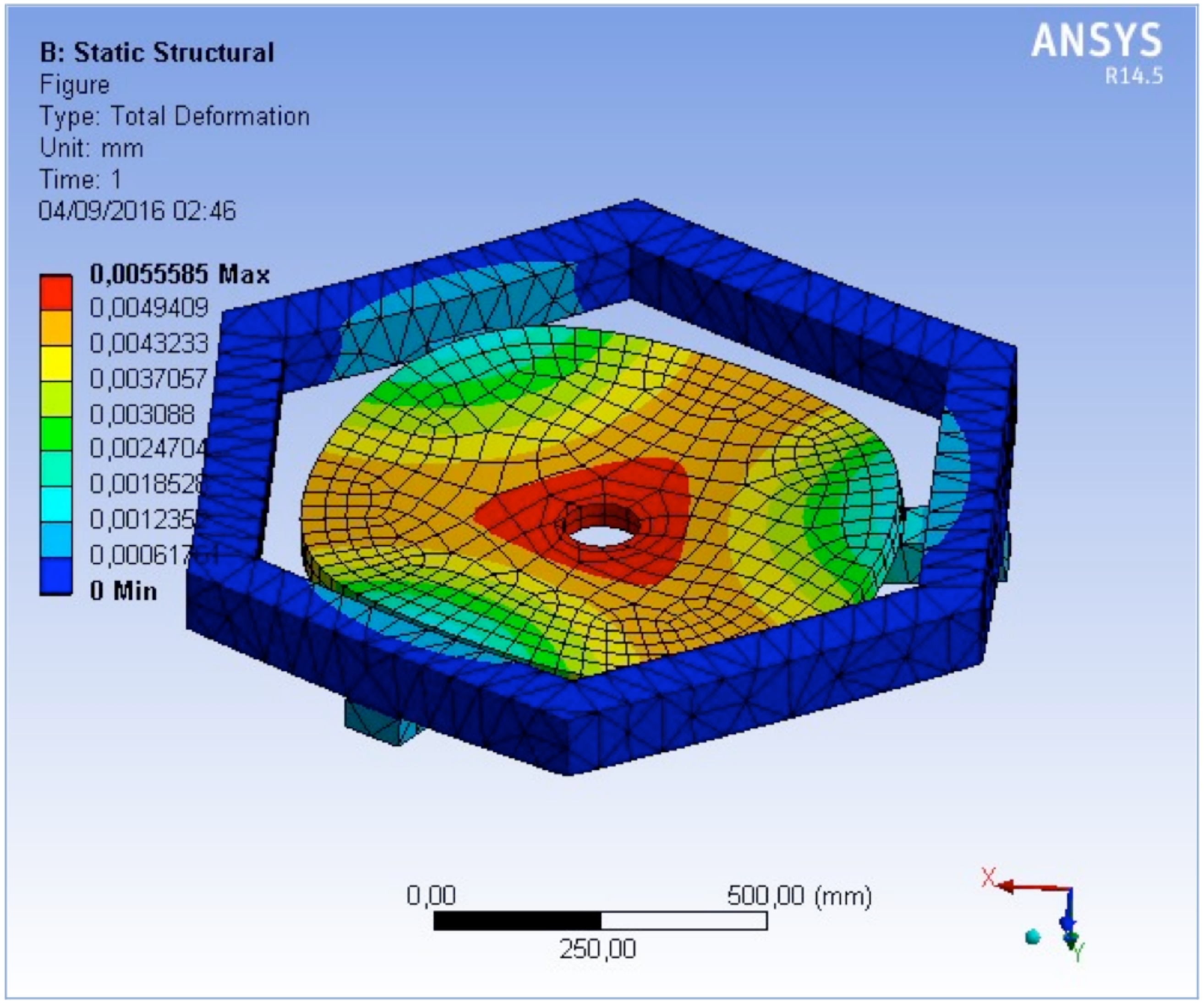


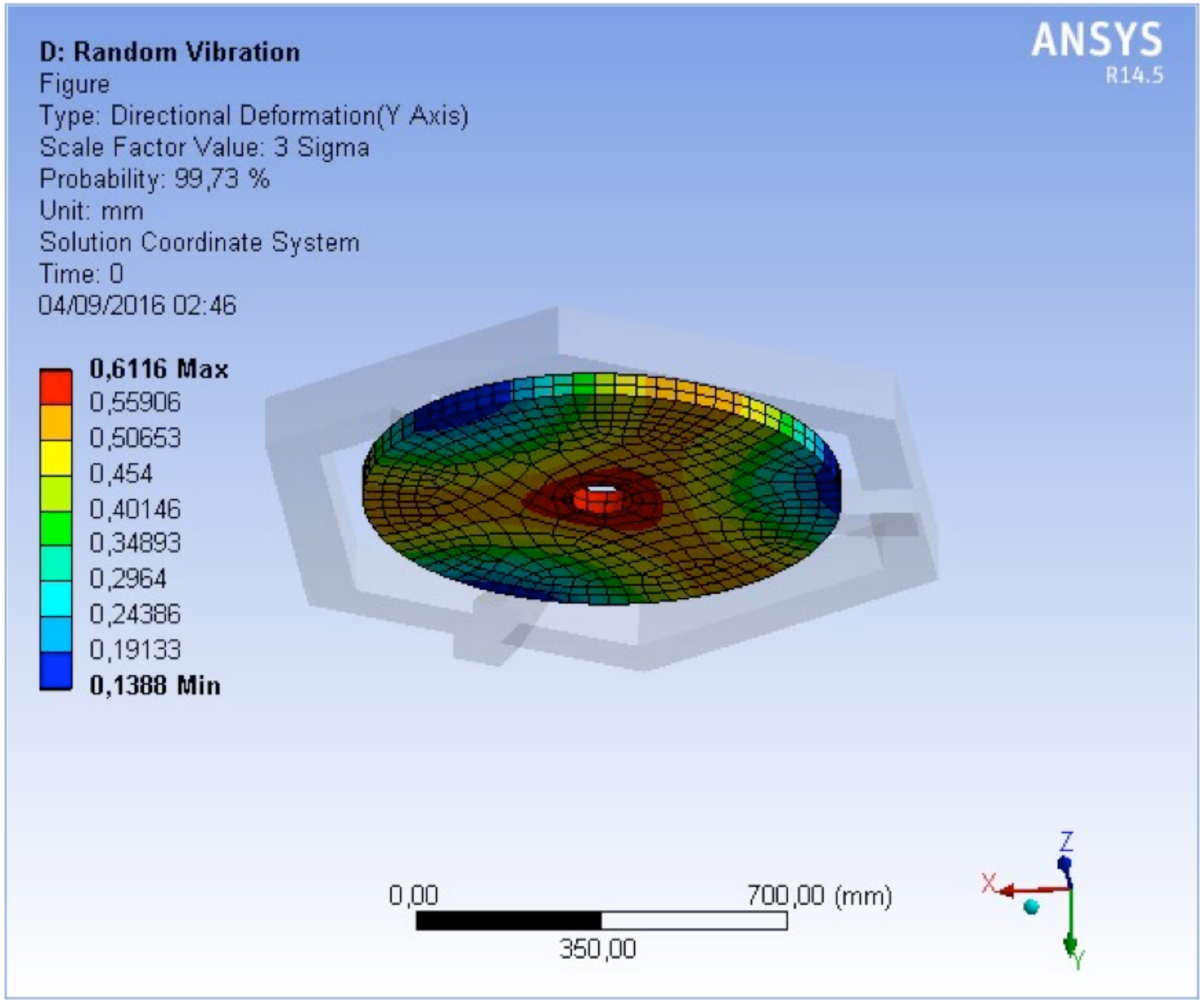
Interferometers for instrument monitoring and astrometric corrections.

Theia : *the Universe in motion*

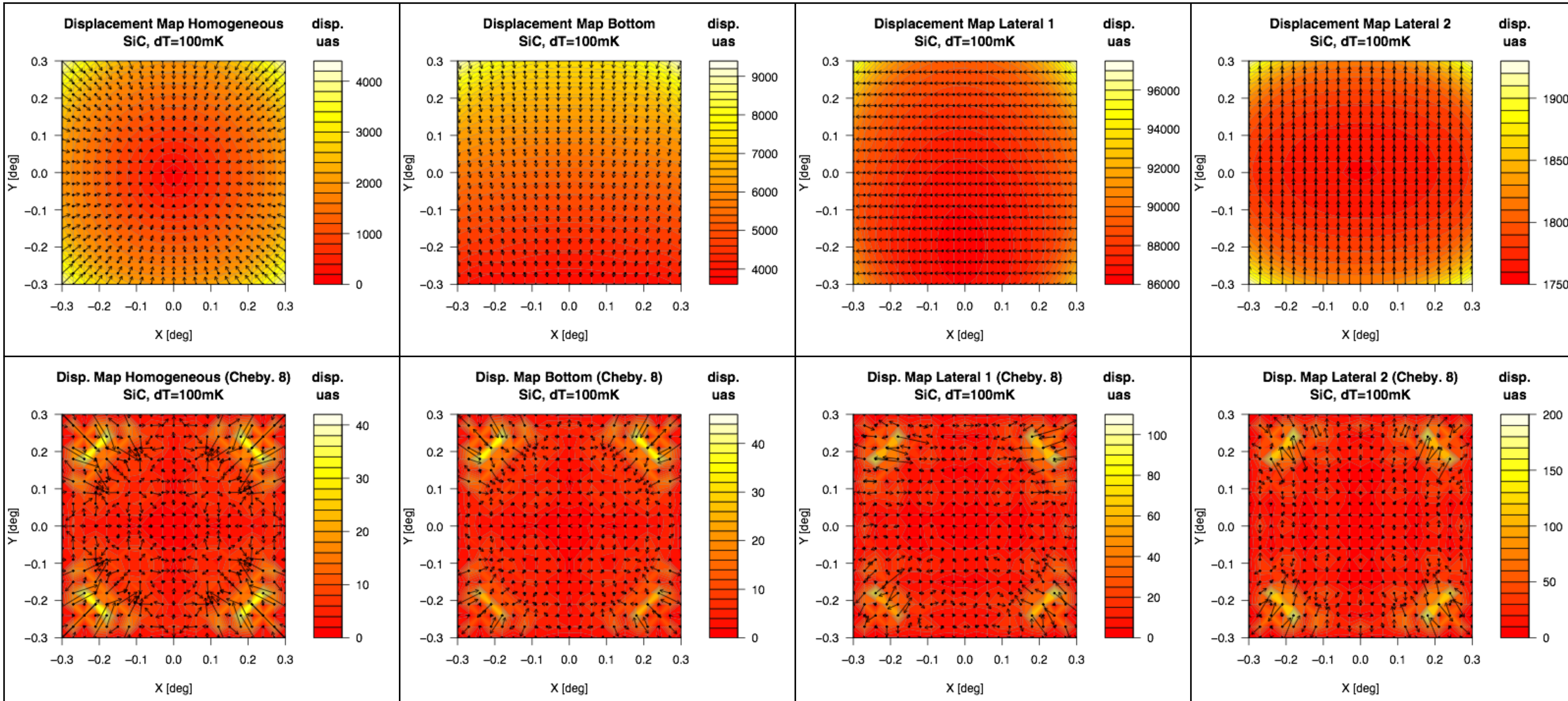
Theia::Modifications for the proposal

Mechanical verification of the deformations on the primary mirror due to the M1 supporting fingers for Soyuz-like launch conditions





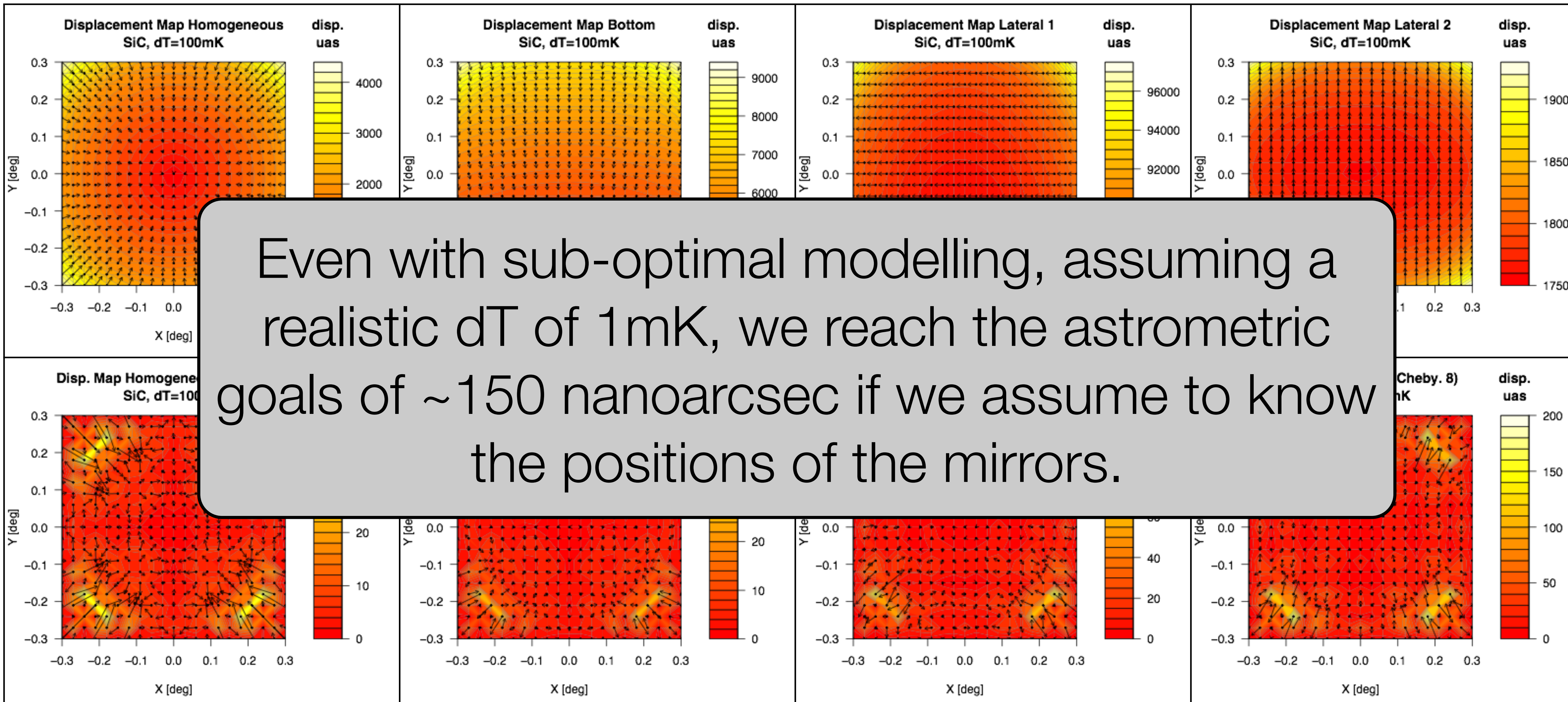
Astrometric displacement scenarios for the pessimistic 100mK dT and SiC structure



median of the residuals after the simple modelling with a Cheby. pol. of order 8			
3.57 uas	3.31 uas	12.63 uas	26.37 uas

Assuming a 10x lower dT is realistic. Gaia has <100x dT.

Astrometric displacement scenarios for the pessimistic 100mK dT and SiC structure

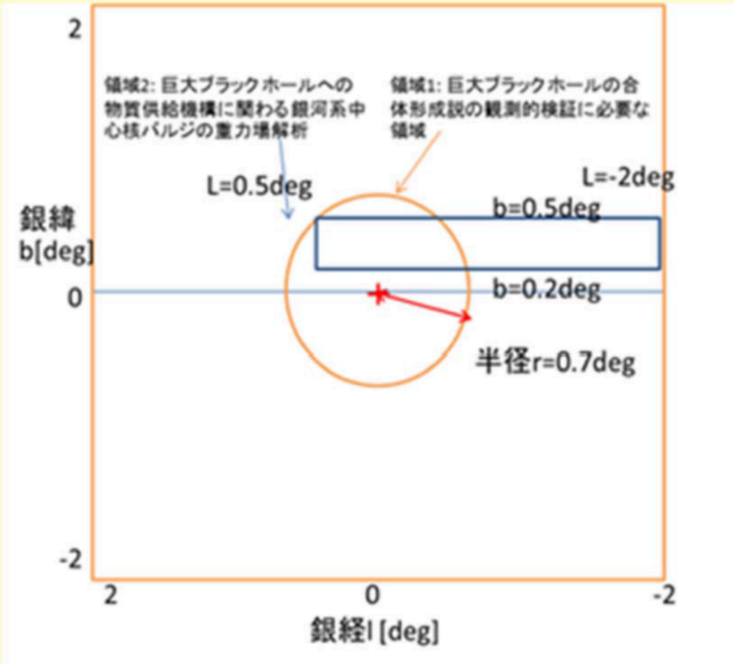


Even with sub-optimal modelling, assuming a realistic dT of 1mK, we reach the astrometric goals of ~150 nanoarcsec if we assume to know the positions of the mirrors.

median of the residuals after the simple modelling with a Cheby. pol. of order 8			
3.57 uas	3.31 uas	12.63 uas	26.37 uas

27th July 2016 - Early draft **Assuming a 10x lower dT is realistic. Gaia has <100x dT.** ON-AXIS DESIGN, LONG-LONG

★The details of the survey mode for the key project (toward the Galactic nuclear bulge)



Survey region 1:

the circle with the radius of 0.7 degree (〜100pc) around the Galactic center

・the number of observable stars

bulge stars: ~5000(Hw<12.5mag)

(disk stars:〜3500(Hw<12.5) common with stars measured by Gaia)

➡ This survey region makes it possible to determine whether or not relatively small supermassive black holes merge to form the supermassive black hole at the Galactic center. Please refer to the scientific objective A-1.

Survey region 2:

Survey region: Galactic longitude -2.0〜0.5 degree

Galactic latitude 0.2〜0.5 degree

・the number of observable stars

bulge stars: ~5000 (Hw<12.5mag)

(disk stars:〜1600 (Hw<12.5))

➡ This survey region makes it possible to determine whether an inner bar exist. Please refer to the scientific objective A-2

The different concepts