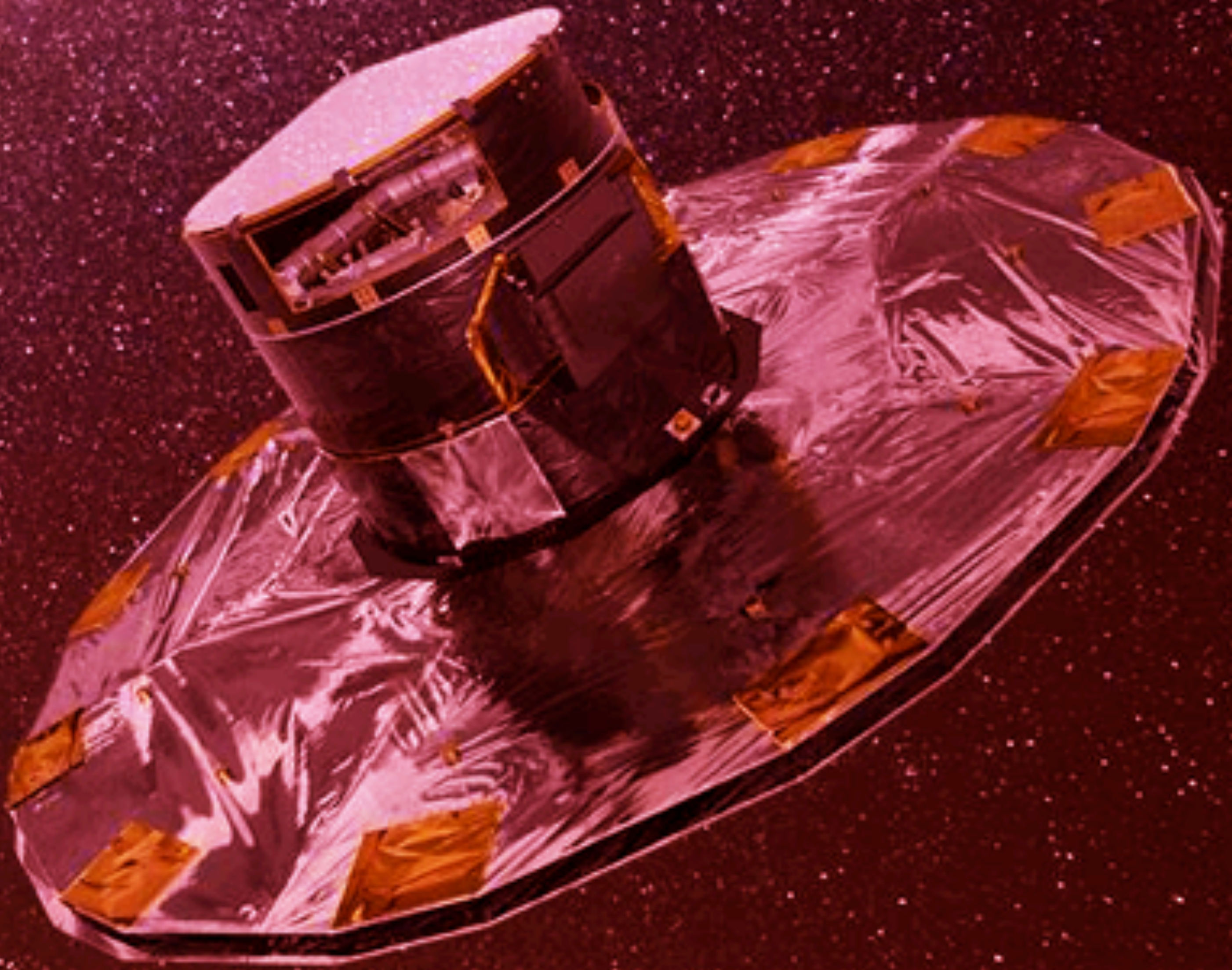
GaiaNIR

The GaiaNIR mission

Future Space Astrometry in the Near Infrared



David Hobbs
Lund Observatory
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Science Cases

- Adding NIR astrometry and photometry to probe the dynamically important hidden regions of the Galaxy
- A new mission, combined with ~2 billion common stars from Gaia with a 20yr time gap would give PM's 15 times better and open many new science cases
- Resetting the Gaia optical RF and catalogue. Expansion of the optical RF to the NIR is super important

https://link.springer.com/article/10.1007/s10686-021-09705-z

- Adding a radial velocity spectrograph could give vast numbers of radial velocities!

GaiaNIR is a discovery mission designed to unveil the nature of our Galaxy

Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee

White Papers

- In 2016 ESA announced a call for new and innovative science ideas for future space missions.
- 26 proposals were received and 3 were selected for further study - including NIR global astrometry.
- In late 2017 ESA conducted a Concurrent Design Facility (CDF) study of our proposal and the results were published in early 2018.
- In 2019 a science and a technical white paper were submitted to Astro 2020 for a US-EU collaboration on all-sky NIR astrometry.
- A Voyage 2050 science case white paper was submitted August. 2019.
- Voyage 2050 sets sail: ESA chooses future science mission themes, June 2021

Proposal title: GaiaNIR
Combining optical and Near-Infra-Red (NIR) capabilities with Time-Delay-Integration (TDI) sensors for a future Gaia-like mission.

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M. Davidson	University of Edinburgh, UK.
Proposal writers:	See Appendix A.
Other supporting scientists:	See Appendix B and Appendix C.
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1: Left is an IR image from the Two Micron All-Sky Survey (image G. Kopan, R. Hurt) while on the right an artist's concept of the Gaia ssion superimposed on an optical image, (Image ESA). Images not to scale.

Astro2020 Science White Paper

All-Sky Near Infrared Space Astrometry

hematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation ☒ Formation and volution of Compact Objects ☒ Cosmology and Fundamental Physics ☒ Stars and Stellar volution, ☒ Resolved Stellar Populations and their Environments ☒ Galaxy Evolution Multi-Messenger Astronomy and Astrophysics

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Astro2020 Activity, Project of State of the Profession Consideration (APC) White Paper:

Title: All-Sky Near Infrared Space Astrometry

State of the Profession Considerations: Development of Scanning NIR Detectors for Astronomy

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Voyage 2050 White Paper

All-Sky Visible and Near Infrared Space Astrometry

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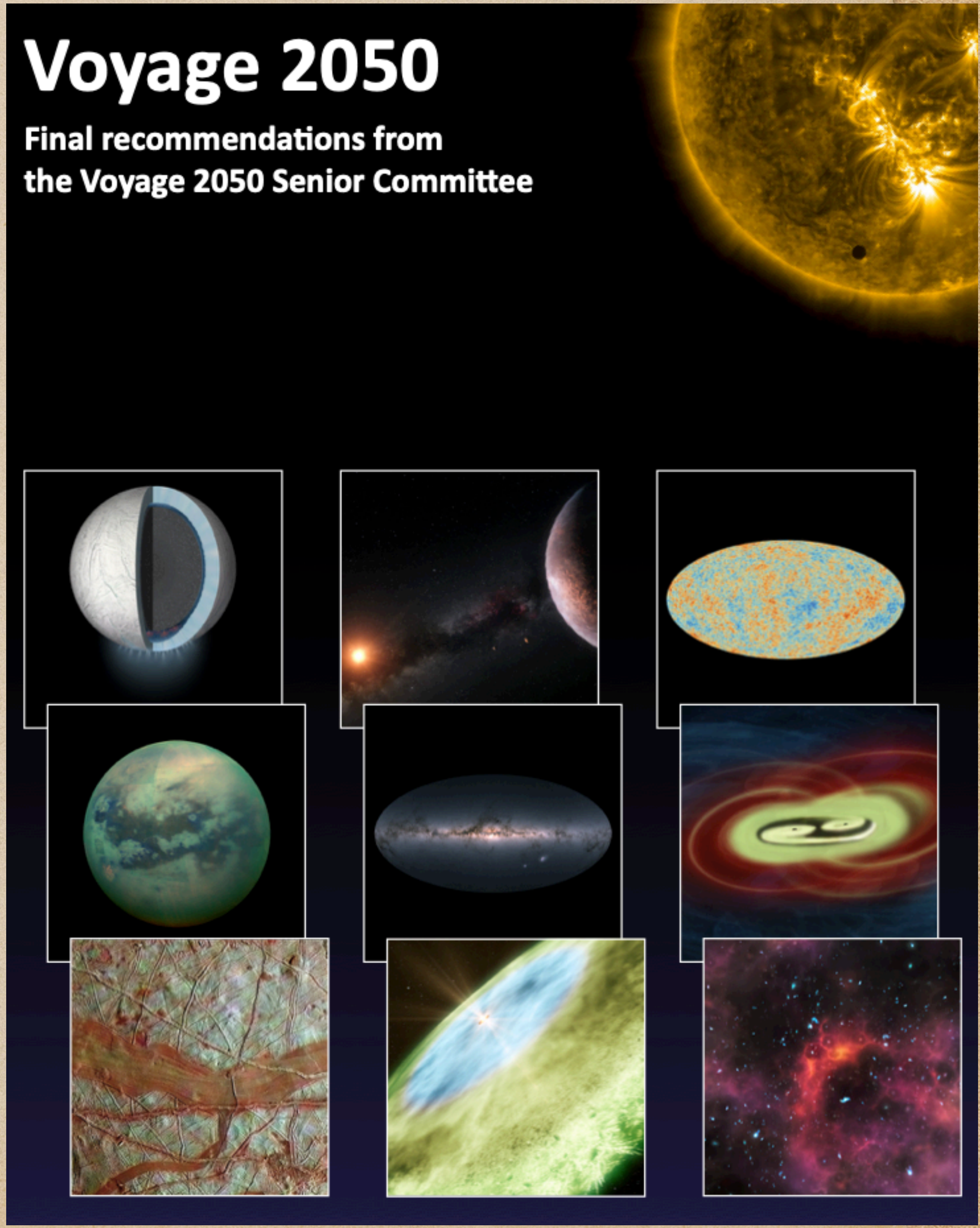
Voyage 2050

- Close to 100 proposals (I counted 95)
- Purpose was to:
  - recommend science themes for the next three large-class missions
  - identify potential themes for future medium-class missions
  - recommend areas for long-term technology development beyond Voyage 2050
- The themes were selected by ESA's Science Programme Committee on 10 June 2021
- Voyage 2050 identified two main themes:
  - Exoplanets that may host life
  - Hidden regions of our Galaxy in Near Infrared
- The missions will be selected when ESA issues individual calls for mission proposals



Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee

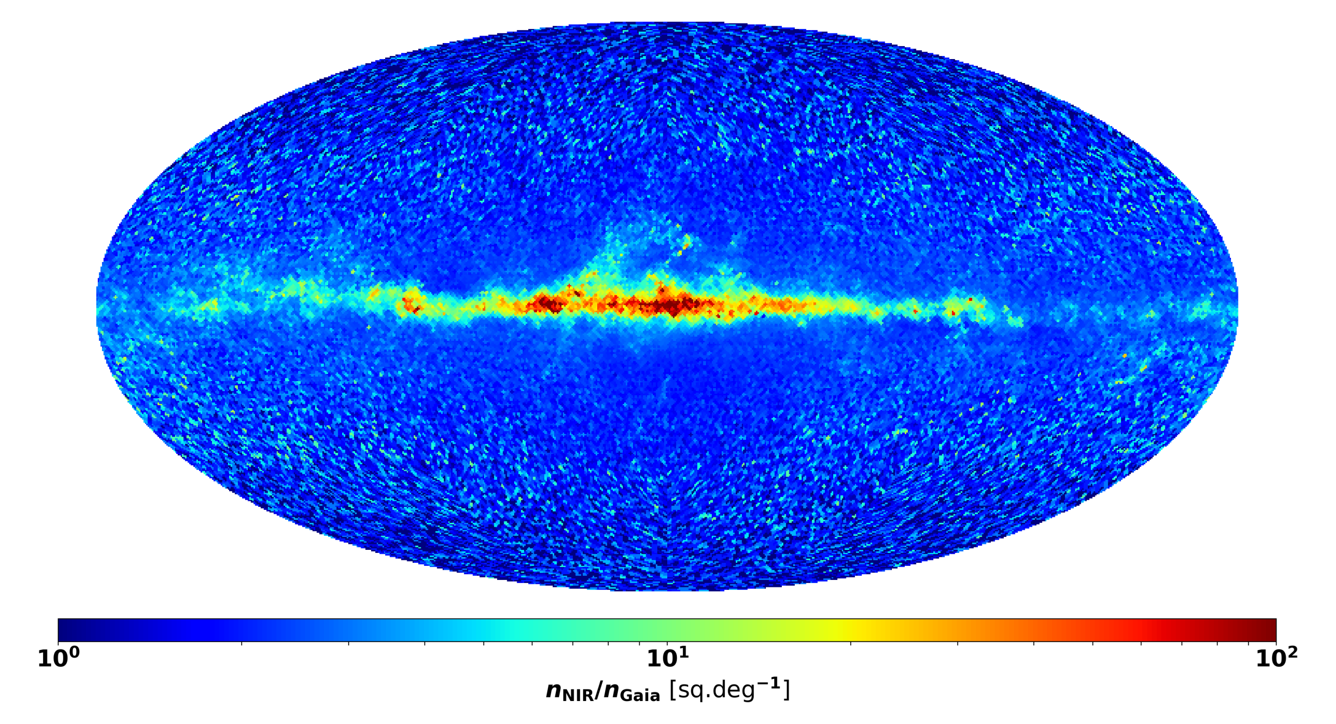
What will GaiaNIR Observe?

- Star count ratio between GaiaNIR and Gaia gives 5 times more stars for a H-band limit of 20th mag and 6 times more stars for a K-band limit of 20th mag
  - About 10 or 12 billion stars for H or K-band cut-off's
  - A K-band cutoff with 12 billion stars makes more sense!

- The star count ratio in the disk is uncertain due the extinction model used which is a key science case in itself

GaiaNIR is not simply an increment on Gaia but will create an astrometric revolution in itself through it's main science cases!

(H-band limit of 20th mag)



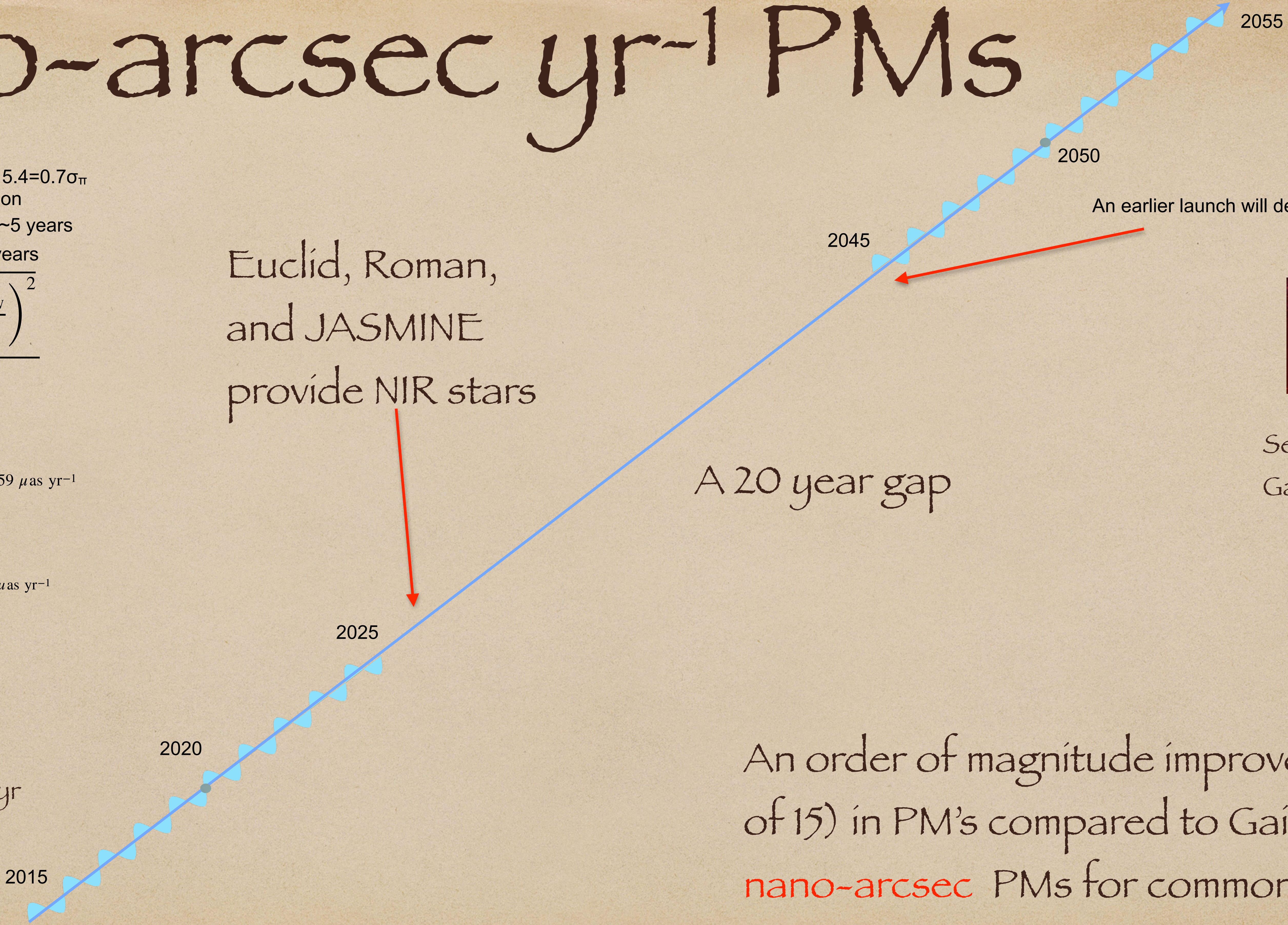
Nano-arcsec yr^{-1} PMs

The numbers $17.6=0.8\sigma_\pi$ and $15.4=0.7\sigma_\pi$ μas are the sky averaged position components of Gaia DR4 after ~5 years and $\sqrt{2}$ is extrapolation to 10 years

$$\sigma_\mu = \frac{\sqrt{\left(\frac{\sigma_{\mathrm{pos}_G}}{\sqrt{2}}\right)^2 + \left(\frac{\sigma_{\mathrm{pos}_N}}{\sqrt{2}}\right)^2}}{t_N - t_G}$$

$$\sigma_{\mu_{\alpha*}} = \frac{\sqrt{\left(\frac{17.6}{\sqrt{2}}\right)^2 + \left(\frac{17.6}{\sqrt{2}}\right)^2}}{20+10} = 0.59\ \mu\mathrm{as\ yr}^{-1}$$

$$\sigma_{\mu_\delta} = \frac{\sqrt{\left(\frac{15.4}{\sqrt{2}}\right)^2 + \left(\frac{15.4}{\sqrt{2}}\right)^2}}{20+10} = 0.51\ \mu\mathrm{as\ yr}^{-1}$$



An earlier launch will decrease the PM accuracy

Euclid, Roman, and JASMINE provide NIR stars

A 20 year gap

Second Epoch
GaiaNIR 10yr (2050)

First Epoch Gaia 10yr
(2020)

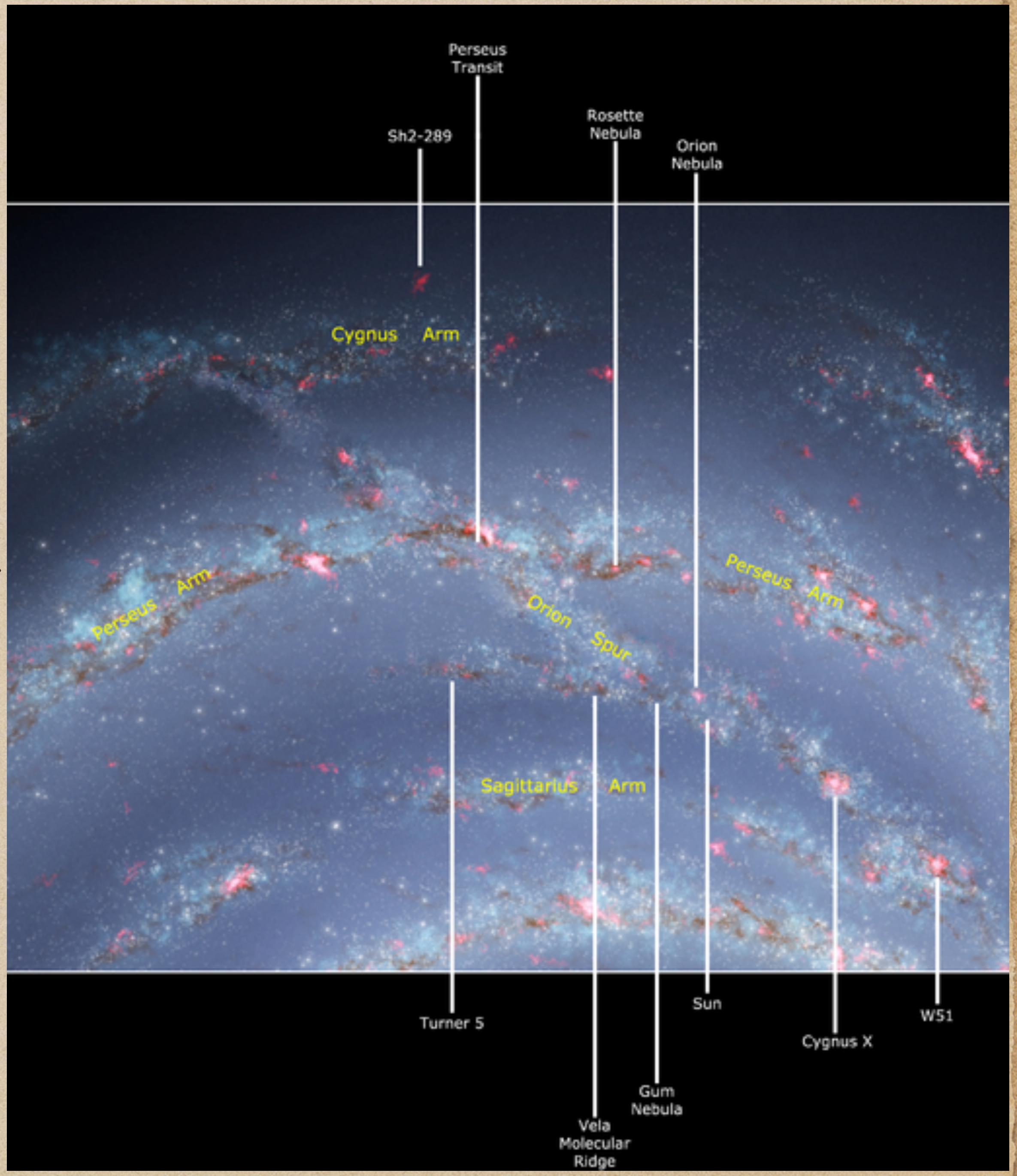
$\sigma_\mu = \sim 11.9 = 0.54\sigma_\varpi$ μas yr^{-1} is estimated at G = 15 for Gaia DR4

An order of magnitude improvement (factor of 15) in PM's compared to Gaia DR4 giving nano-arcsec PMs for common stars.

1. NIR Astrometry

- Dusty Bulge/bar region is dynamically important:
  - E.g. radial migration, bar perturbations of the bulge.
- IMBH's in embedded clusters may be detected?
- Probe DM in the thin and thick disc and spiral arms?
- Unveil the inner disk which is not well known.
- Map in detail the dusty spiral arms - astrometry for 100's of millions of objects.
- Vastly improve measurements of the rotation curve.
- Exoplanets in dusty and star forming regions.
- Study internal & bulk dynamics of young clusters.
- Many other science cases: brown dwarfs, M-dwarfs, cool white dwarfs, free floating planets, PL relations of red Mira's, etc.

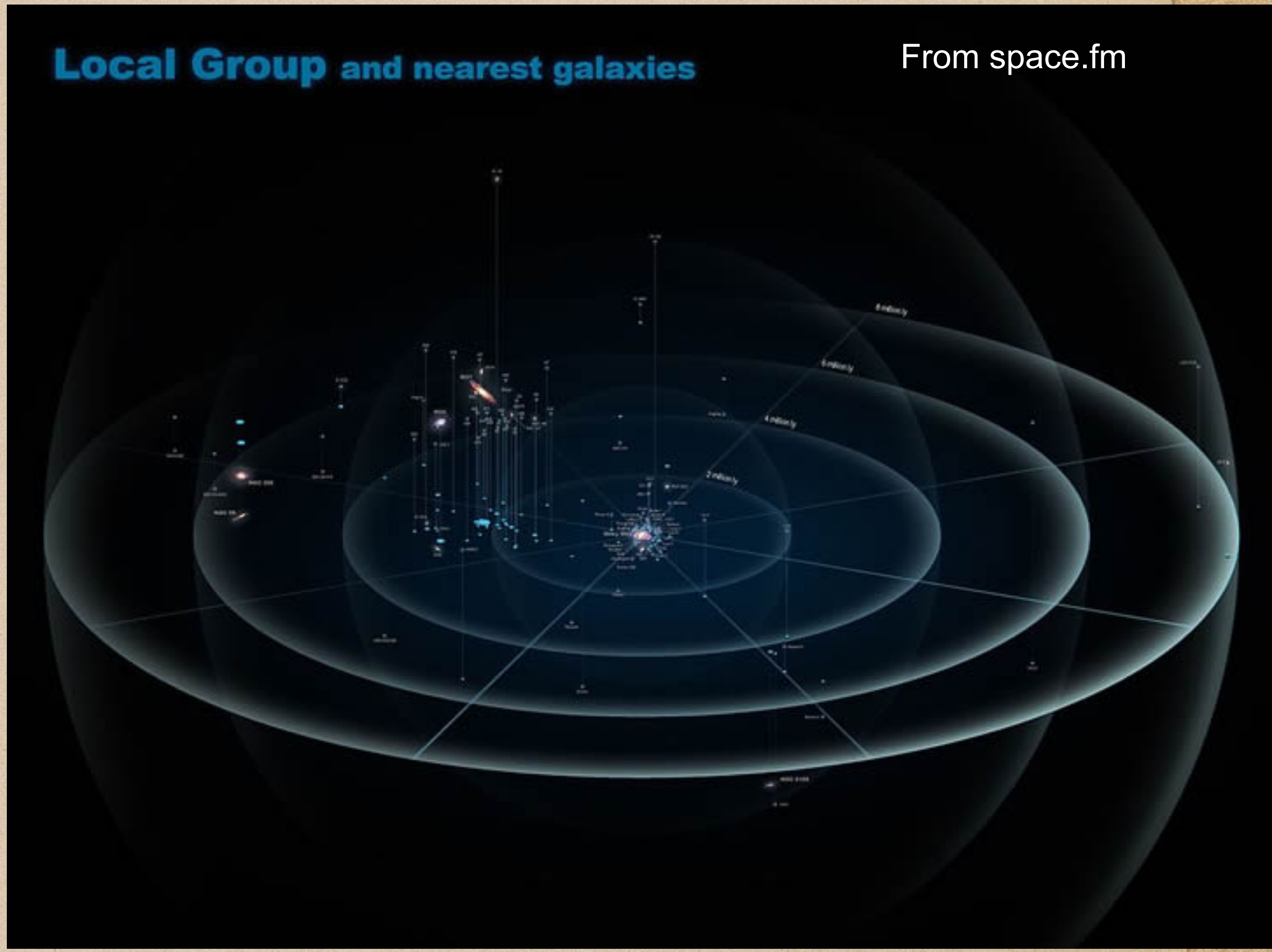
All of this for ~10 billion new stars!



2. Improved Accuracy

- Improved PMs allow sub-structure in streams, dwarf galaxies and the Halo to be resolved.
- Better estimates of Galaxy mass and help resolve the cusped/core (flat) dark matter Halo problem?
- IMBH's in globular clusters like M54 or Omega Centauri may be indirectly detected?
- Internal dynamics of local group galaxies, dwarf spheroids, globular clusters, LMC & SMC.
- Map the DM sub-structure in the local group.
- PMs of hyper-velocity stars to trace their origin and constrain triaxial models.
- Exoplanet & binary detectable periods up to 40 yr with Gaia + GaiaNIR (Saturn P=29 yr). Solar system analogue survey!
- Wide binaries are probes of DM theories.
- Solar System orbits for >100,000 objects - greatly improved.

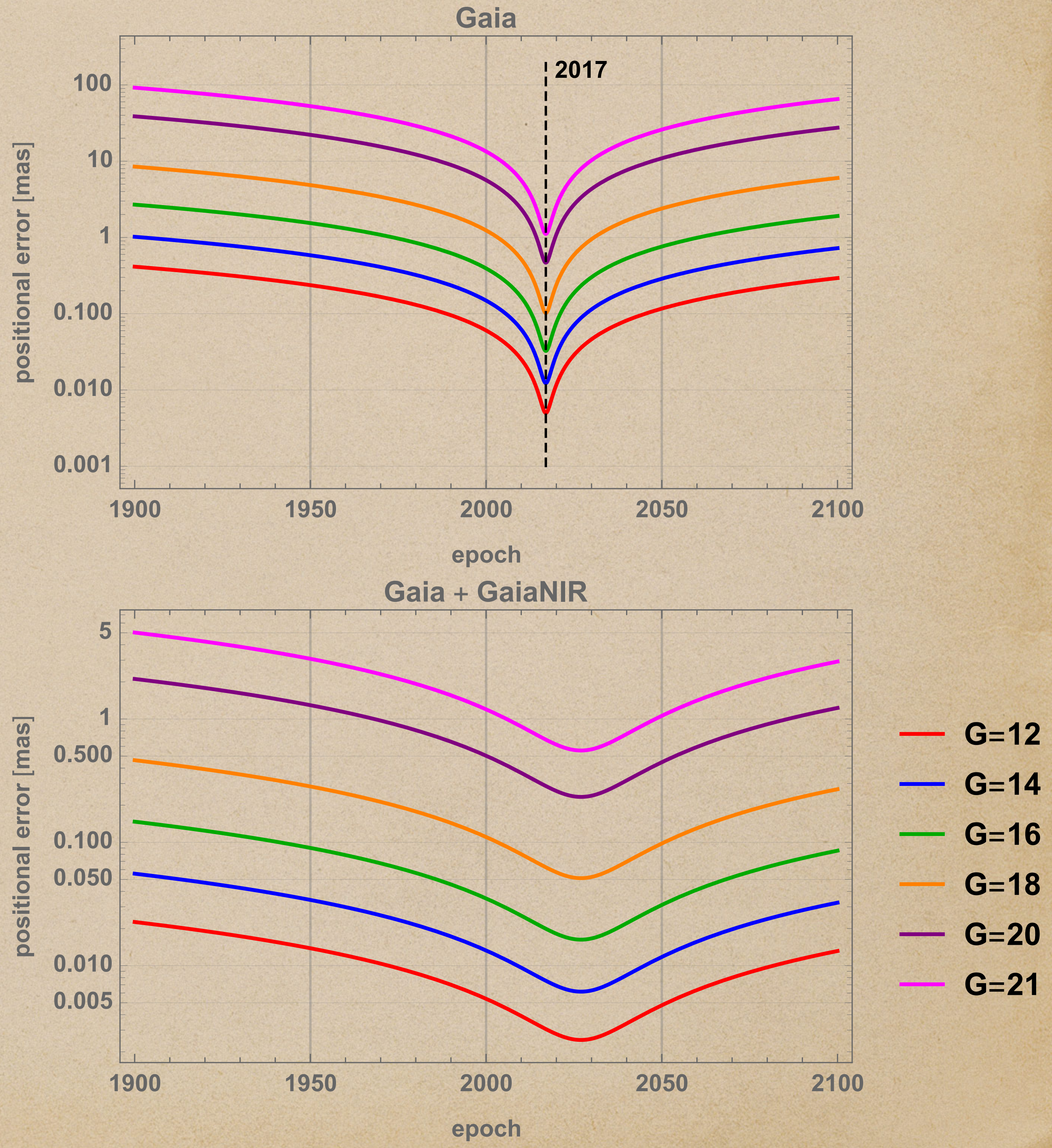
All of this for ~2 billion Gaia stars!



From space.fm

3. RF & Catalogue Ageing

- The RF degrades slowly (RF spin accurate to $< 0.5\ \mu$as yr^{-1}) but other systematic PMs patterns show up, e.g. Galactic-centric acceleration of ~5.0 μas yr^{-1}.
- The positional accuracy of the catalogue will degrade due to PM errors - requiring a new mission to update the catalogue.
- A strong science case is to expand the Gaia RF to the NIR increasing its density in obscured regions for use in future observational astronomy.
- Spin offs such as PM patterns and GW constraints are improved due to better PMs



Degradation of the astrometric accuracy of the individual sources in the Gaia catalogue (top pane) and of the common solution using 10 years of Gaia and 10 years of GaiaNIR data (bottom pane), Image S. Klioner.

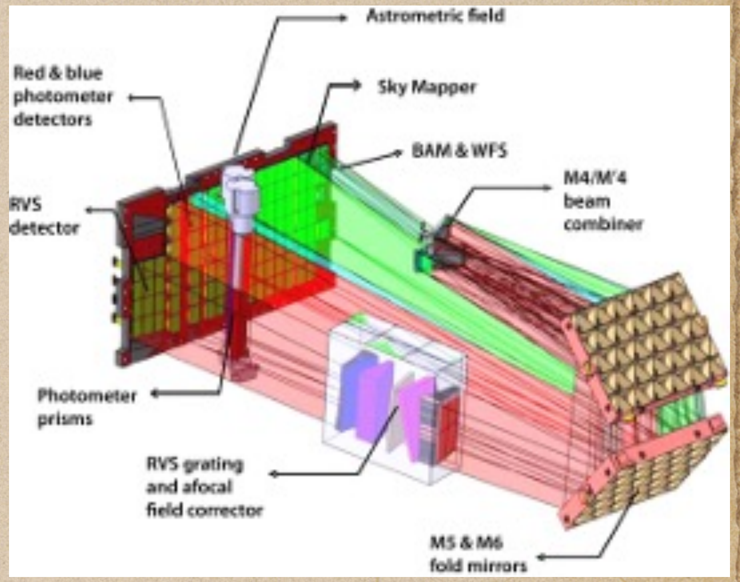
4. Can we a billion RV's?

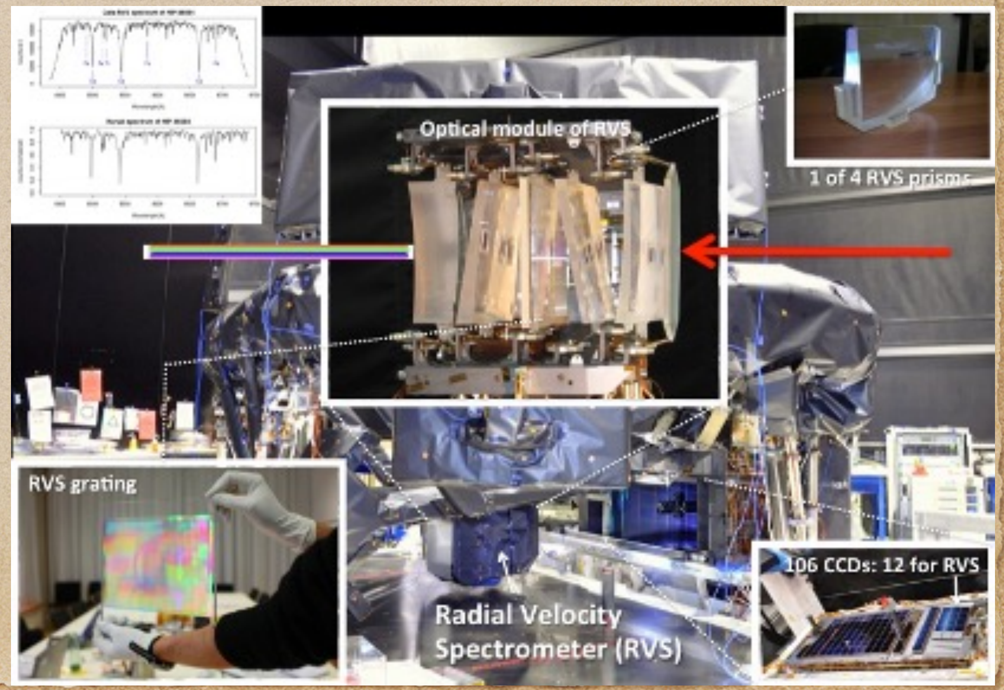
RV's are super important for Galactic dynamics

- The RV spectrograph was avoided to fit in a Medium-class mission
- RV would increase the costs and data rate significantly
- RV would give an outstanding science return
- How to increase the dept of the survey - A slow the scan rate or wider detectors would allow a deeper survey
- A long baseline still gives good astrometry

All this could allow a deep RV survey for billions of objects

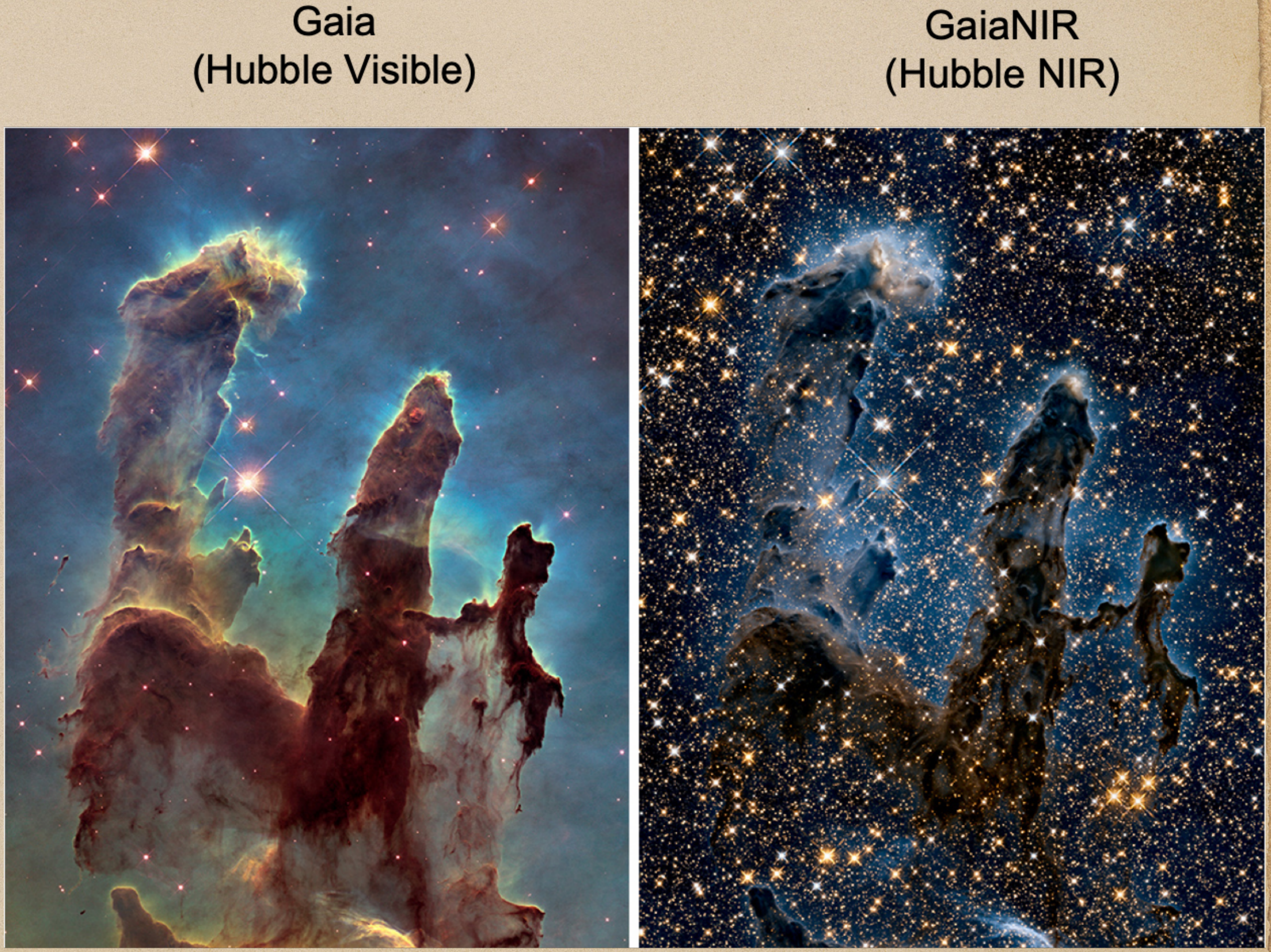
(at a € cost)





The big science question!

- A new mission can measure the hidden stars not seen by Gaia for the entire sky!
- A comparison between visible and NIR is shown!
- The most important NIR science cases lie in the Galactic plane (bulge/bar) and star forming regions
  - E.g. long period binaries can reveal BH's or probe gravity; IMBH's in clusters.
- As a new science case - can an we also get their RV's?


Gaia (Hubble Visible)

GaiaNIR (Hubble NIR)

The Pillars of Creation in the Eagle Nebula. Image NASA.

ESA's GaiaNIR Design

- GaiaNIR is based on a off-axis f=35m Korsch telescope as is Gaia, but differs in:
- The mirror surfaces are simple conics to simplify manufacturing, alignment and test.
- Entrance pupil is at a flat folding mirror in front of the primary instead of on the primary mirror itself.

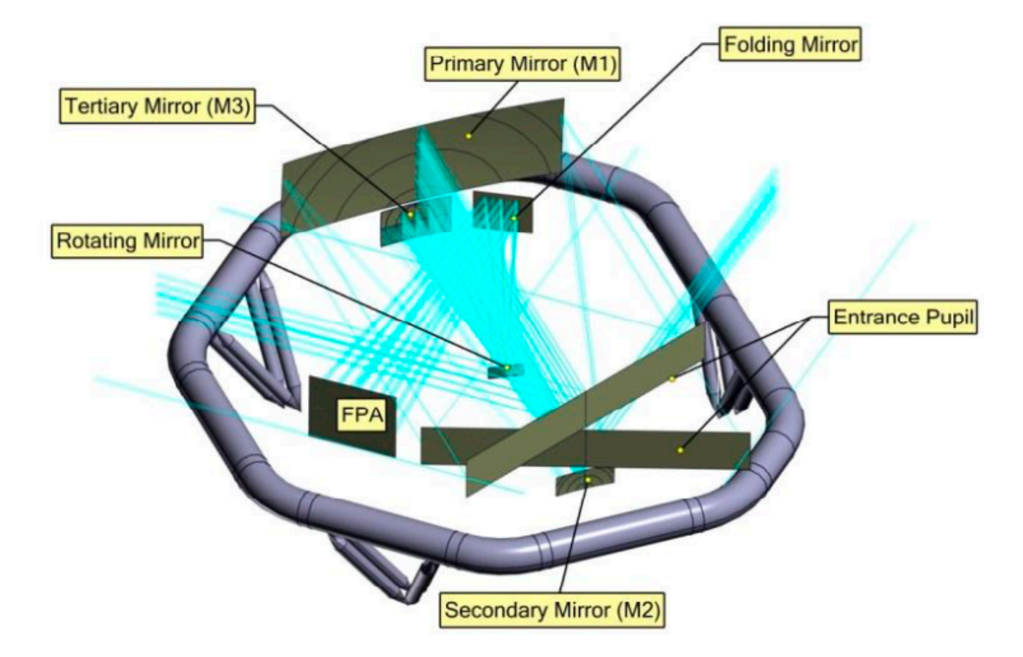


Figure 5-34: GaiaNIR optical surfaces and the light path

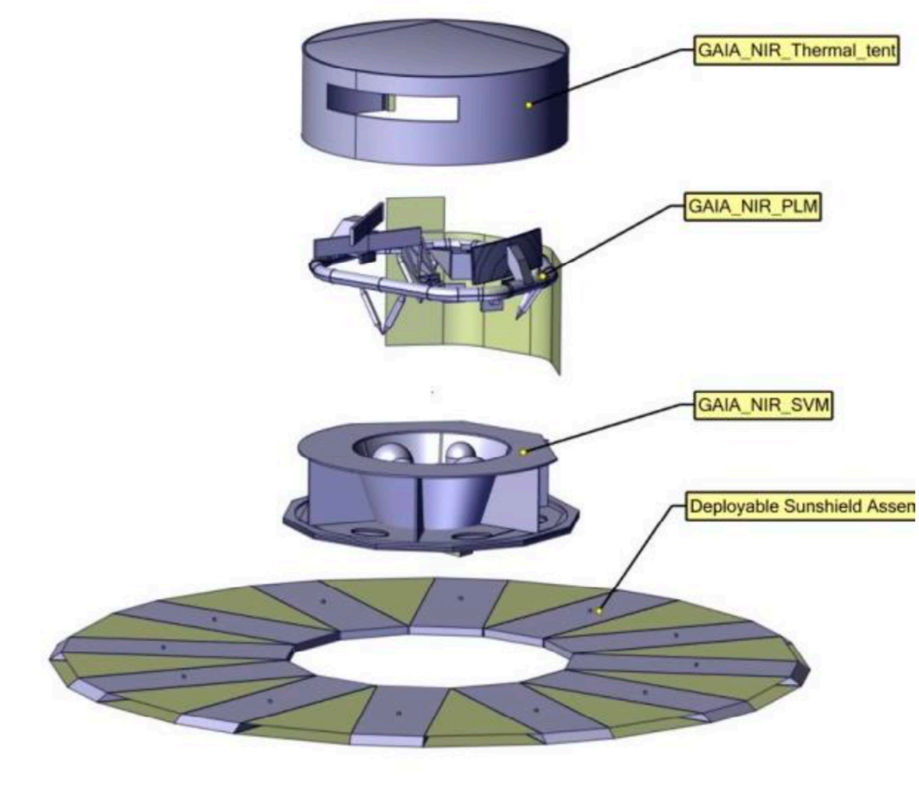


Figure 6-2: Gaia-NIR Spacecraft main elements

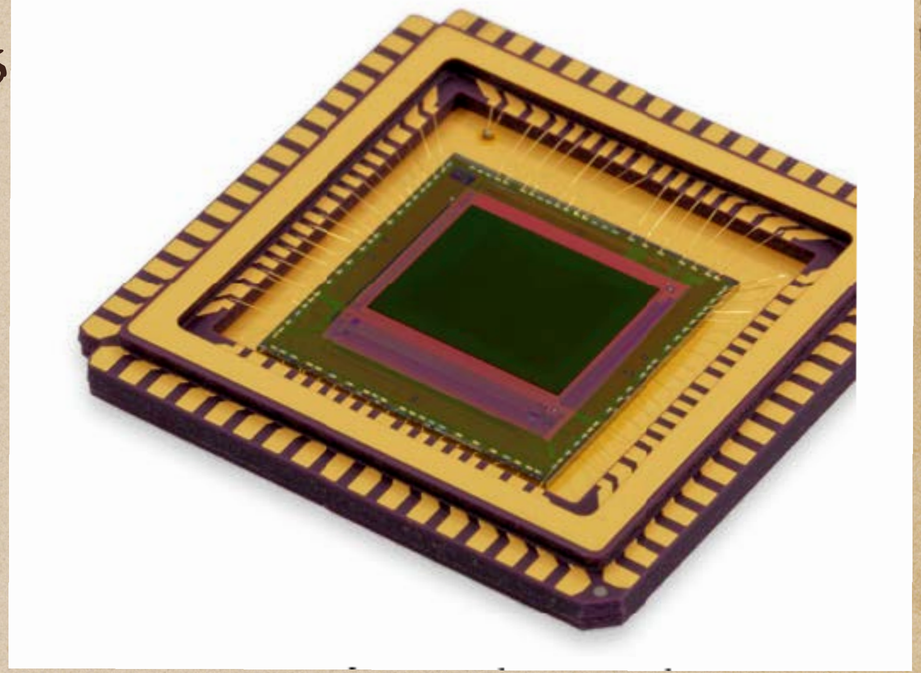
- The optical path of the telescope is composed of:
- Primary mirror
- Secondary mirror
- Tertiary mirror
- 4x Flat mirrors:
  1. At the entrance pupil (2 defining the BA)
  2. Folding mirror (after the exit pupil)
  3. At the exit pupil (de-spin mirror)

Detector Status

Italian owned Leonardo UK have small APDs with high frequency readout.

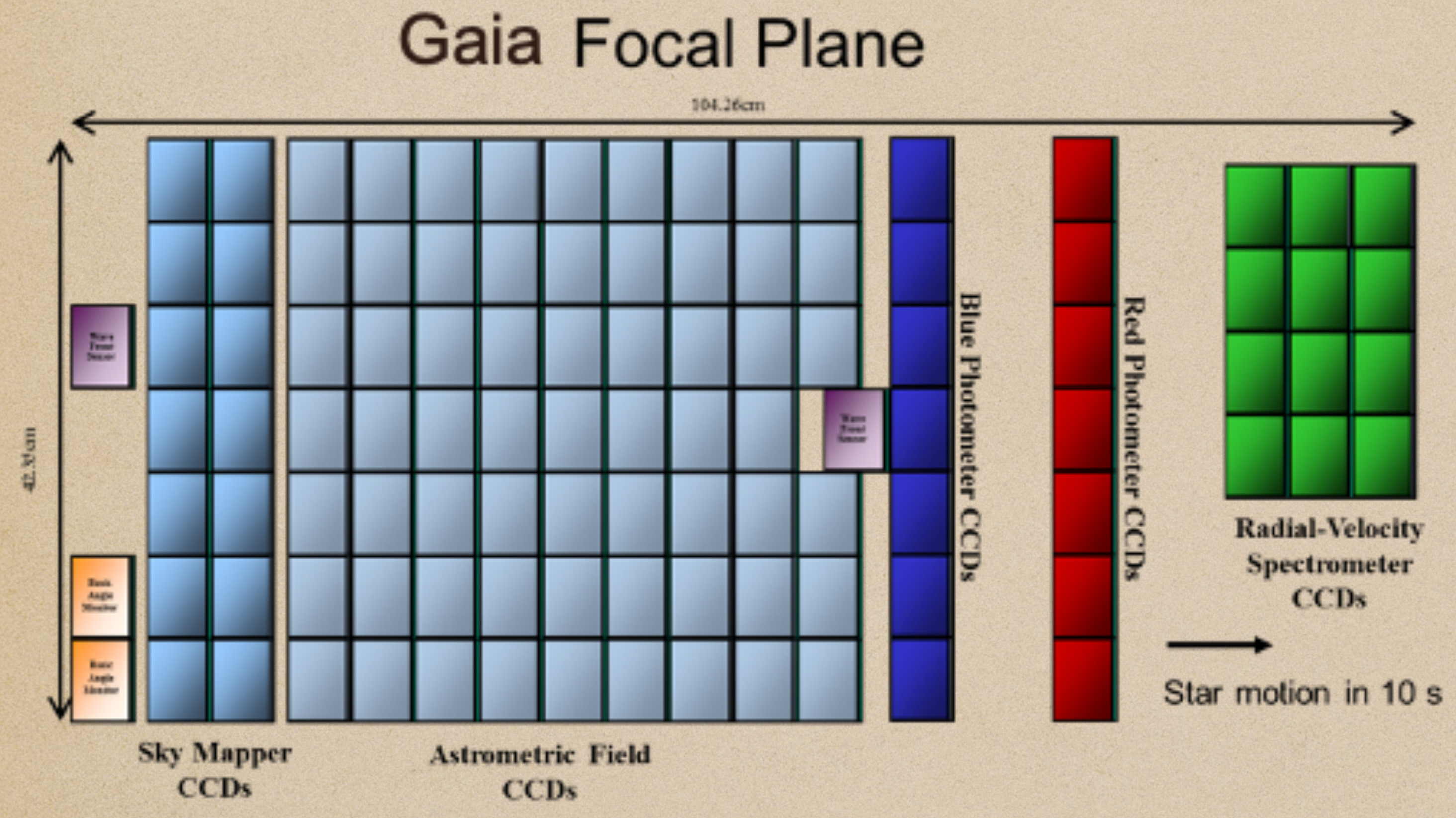
This makes them ideal for TDI operation and they can form larger detectors

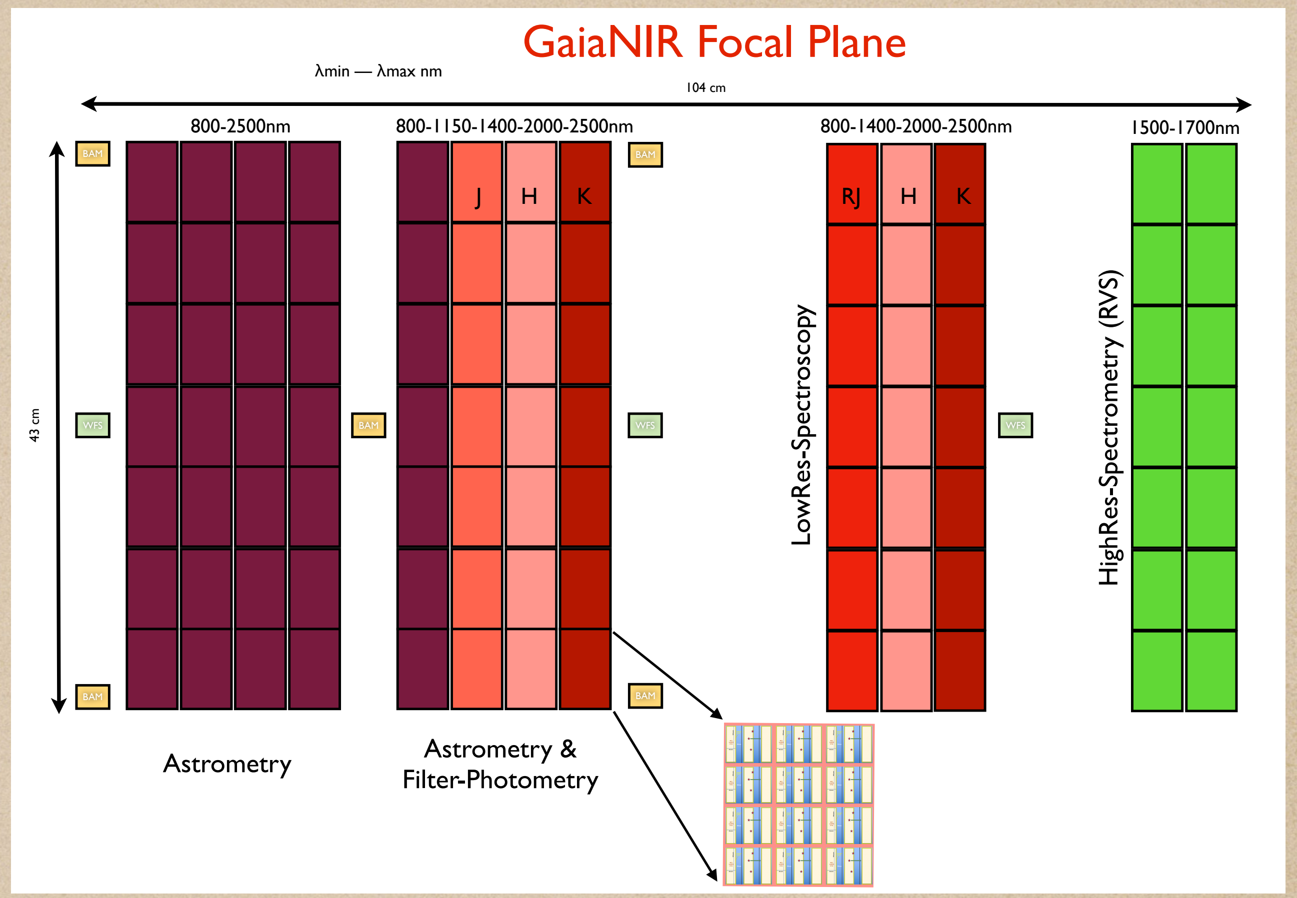
- Technical Readiness Level is relatively high
- ANU use APDs on ground telescopes and will deploy on ISS
- For wavelength cutoff we have options for 2500nm or 3500nm
  - Do we have science cases above 2500nm?
  - Would we get too much crowding and blending at long wavelengths
  - Too many stars to download - onboard processing needed!
- TDI mode is possible but for < 800nm studies are still needed



The SAPHIRA is a 320×256 pixel linear-mode avalanche photodiode array capable of 'noiseless' readouts via an upstream signal multiplication of several hundred.

The Focal Plane & Filters

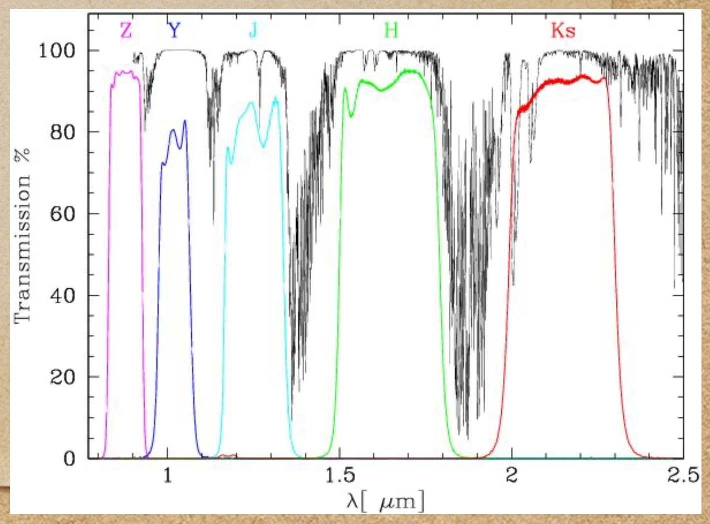




4x3= 12 APDs (TBD)

A modular concept uses small detectors to form larger ones

- Linear Mode APDs are the most promising detector for GaiaNIR
- Cooling strategy must be passive (~90K)
- Max wavelength - 2500 nm, blue stars (<800nm) are more challenging – studies ongoing
- No SMs - track motion of stars instead to determine the FoV
- Filter photometry on astrometric field by depositing filter material on detectors
- Low resolution spectra on a dedicated field for astrophysical parameters
- An RVS Spectrograph is a great opportunity? - space is available for more full wavelength detectors!



Example from VVV

Wavelength Range

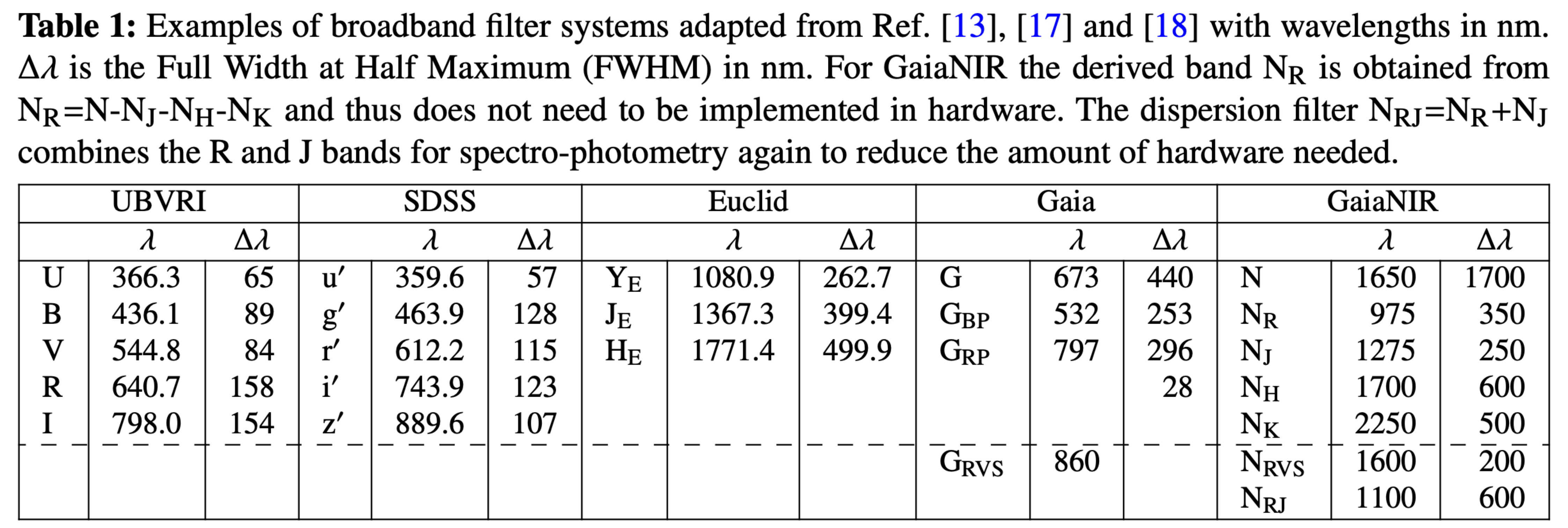
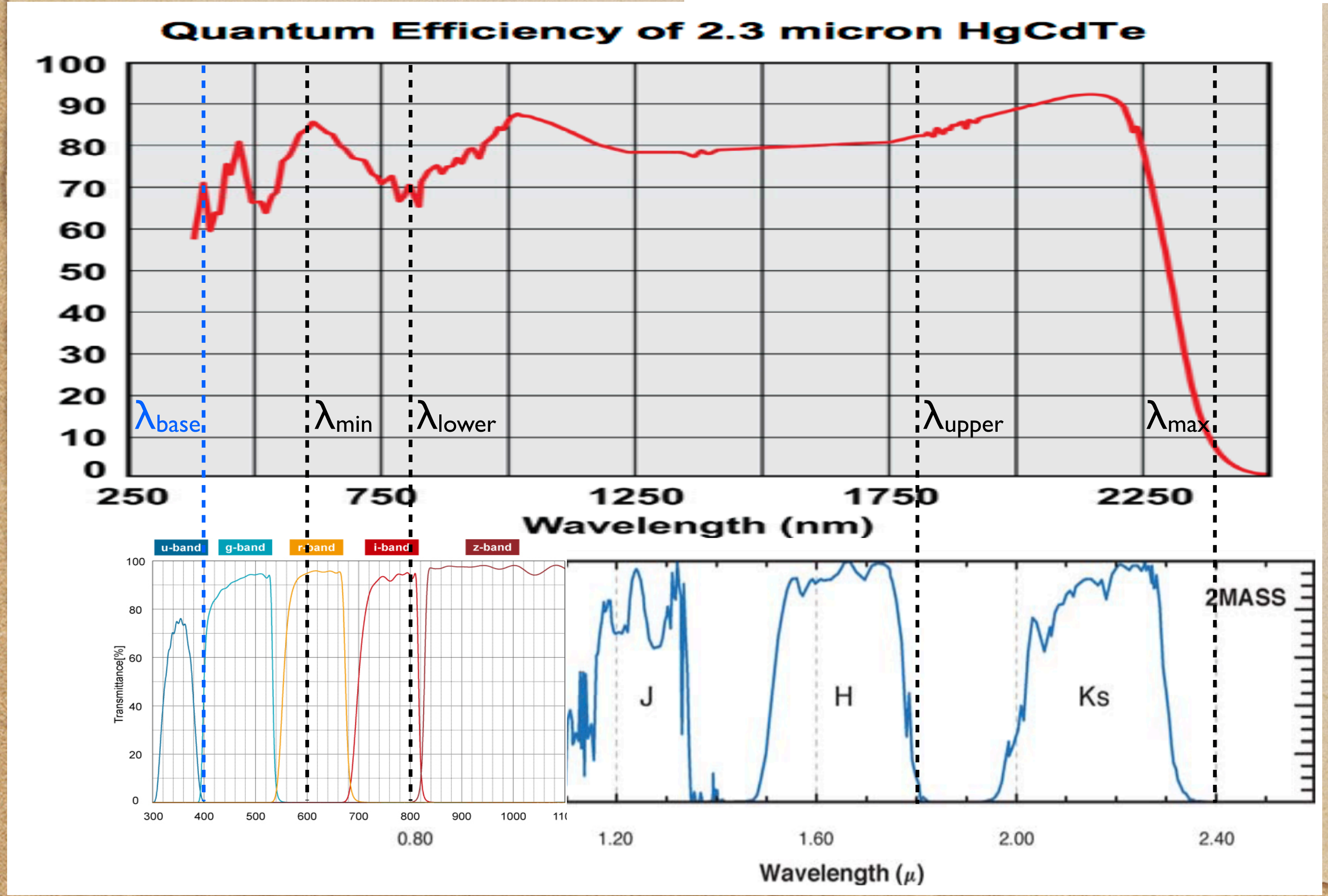


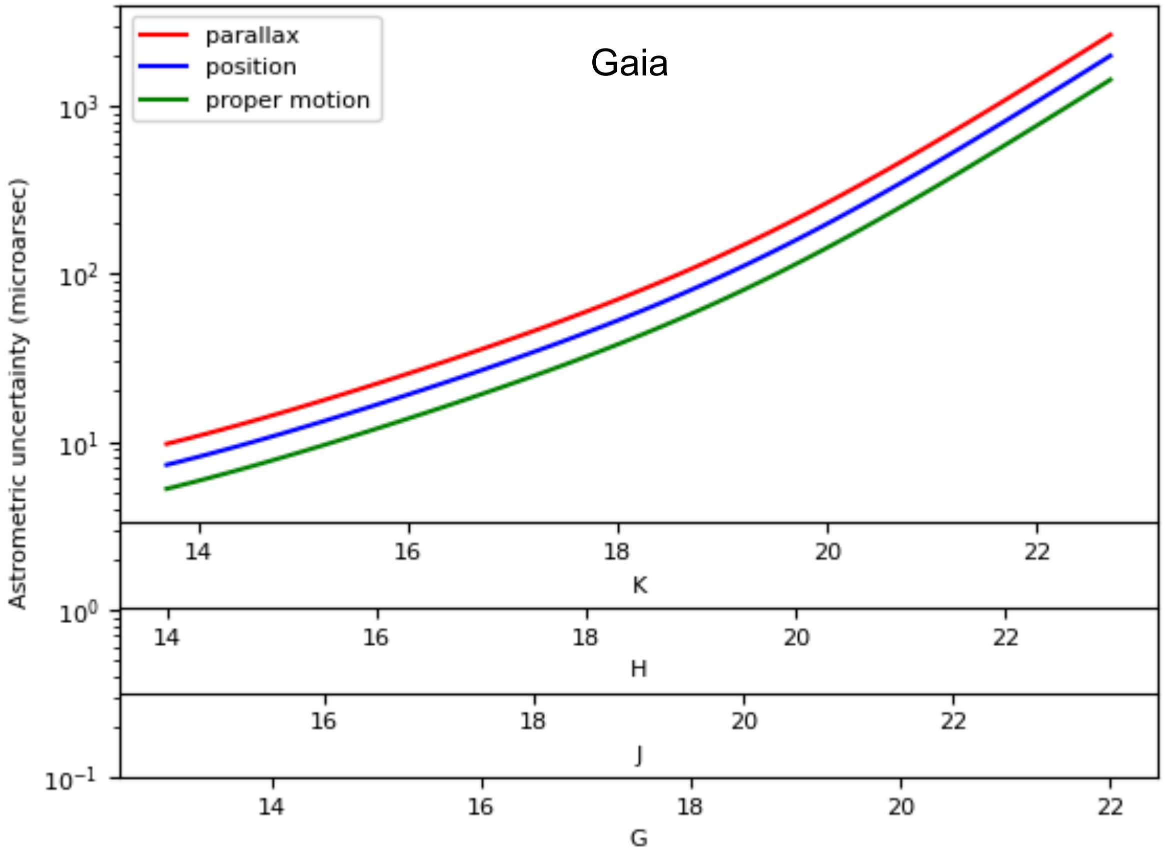
Table 1: Examples of broadband filter systems adapted from Ref. [13], [17] and [18] with wavelengths in nm. $\Delta\lambda$ is the Full Width at Half Maximum (FWHM) in nm. For GaiaNIR the derived band N_R is obtained from N_R=N-N_J-N_H-N_K and thus does not need to be implemented in hardware. The dispersion filter N_{RJ}=N_R+N_J combines the R and J bands for spectro-photometry again to reduce the amount of hardware needed.

UBVRI			SDSS			Euclid			Gaia			GaiaNIR		
	λ	$\Delta\lambda$		λ	$\Delta\lambda$		λ	$\Delta\lambda$		λ	$\Delta\lambda$		λ	$\Delta\lambda$
U	366.3	65	u′	359.6	57	Y_E	1080.9	262.7	G	673	440	N	1650	1700
B	436.1	89	g′	463.9	128	J_E	1367.3	399.4	G_{BP}	532	253	N_R	975	350
V	544.8	84	r′	612.2	115	H_E	1771.4	499.9	G_{RP}	797	296	N_J	1275	250
R	640.7	158	i′	743.9	123						28	N_H	1700	600
I	798.0	154	z′	889.6	107							N_K	2250	500
									G_{RVS}	860		N_{RVS}	1600	200
												N_{RJ}	1100	600



Patched together illustration of possible filter bands (Sloan and 2MASS) and quantum efficiency (Teledyne) and the various cut-off wavelengths.

Going to as low a wavelength as possible would give more overlap with Gaia but is incompatible with NIR detectors!



Effective Modulated Transfer Function

1-D detector signal
OTF≈MTF

Charge diffusion across
the pixel boundaries

Aberrations reduce peak intensity of
the PSF: characterised by Strehl ratio

$$U(u) = M_\xi(u) M_\tau(u) M_\omega(u) \frac{\int_{\lambda_{min}}^{\lambda_{max}} M_0(u,\lambda) M_d(u,\lambda) S_\lambda Q_\lambda T_\lambda f_\lambda d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} Q_\lambda T_\lambda f_\lambda d\lambda}$$

Pixel width modulation

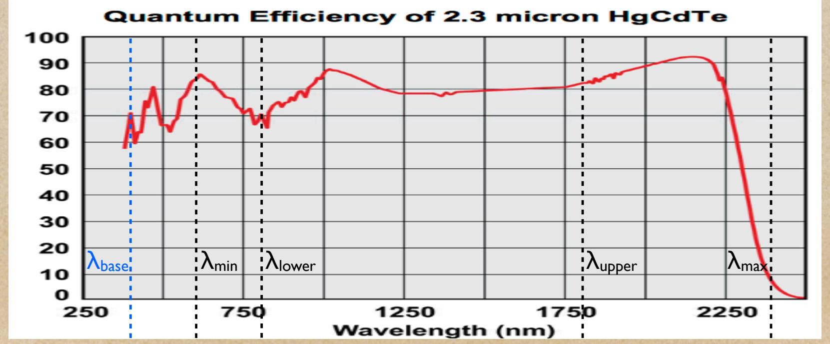
TDI smearing

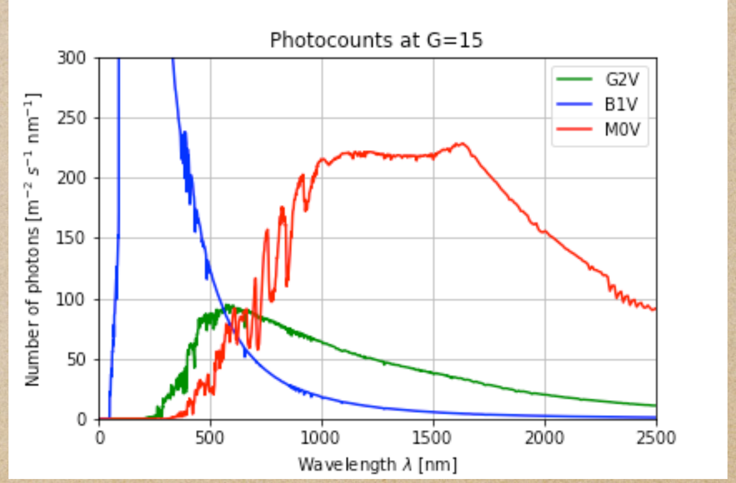
Rate & attitude errors

Detector QE

Transmittance

Stellar
photon flux





u is the AL scan spatial
frequency [rad^{-1}]

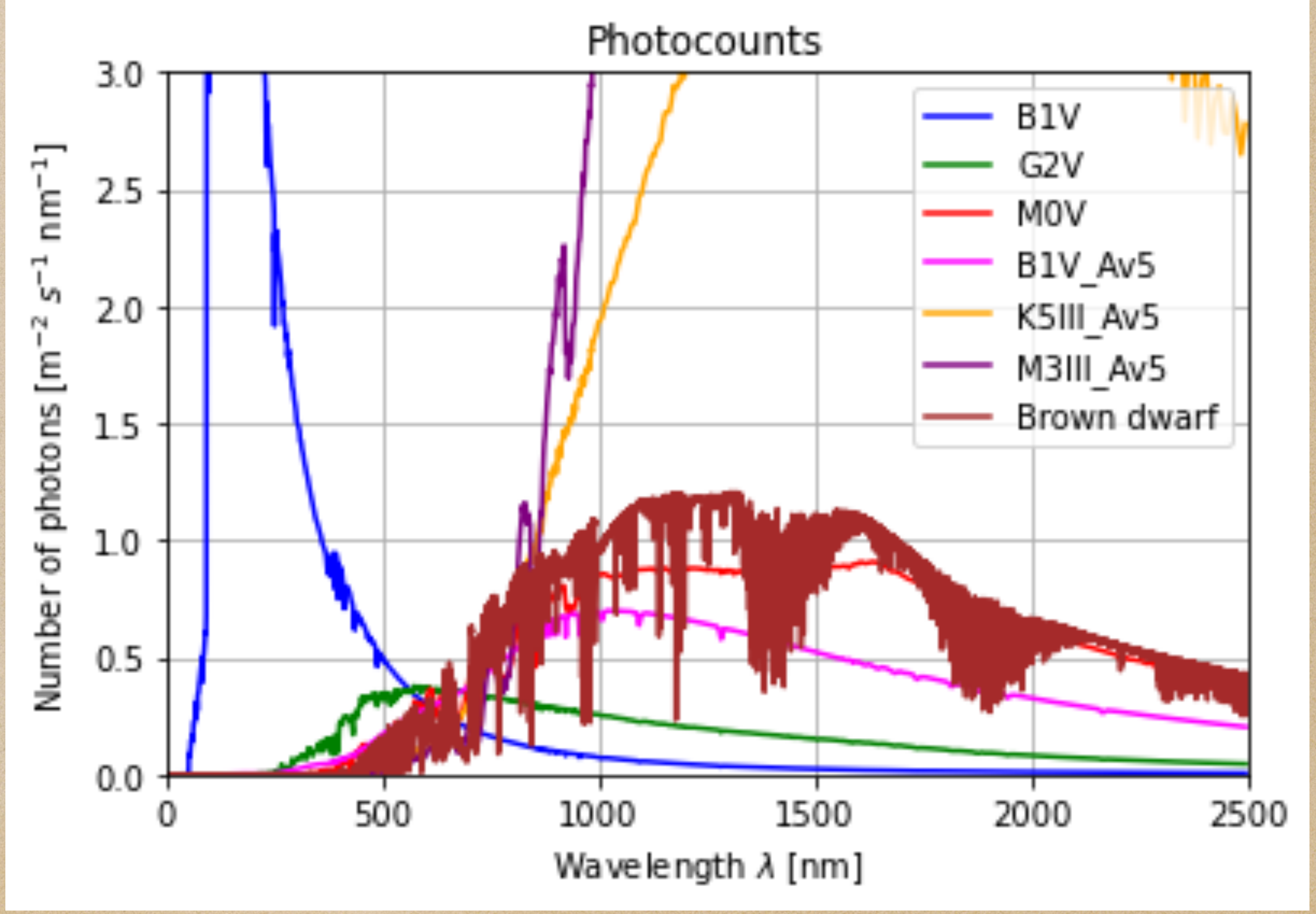
End Of Mission Accuracy

$$\sigma_\varpi = m g_\varpi \left[\frac{\tau_1}{N_i \tau p_{\rm det}(G)} \left(\sigma_\xi^2 + \sigma_{\rm cal}^2\right) \right]^{1/2}$$

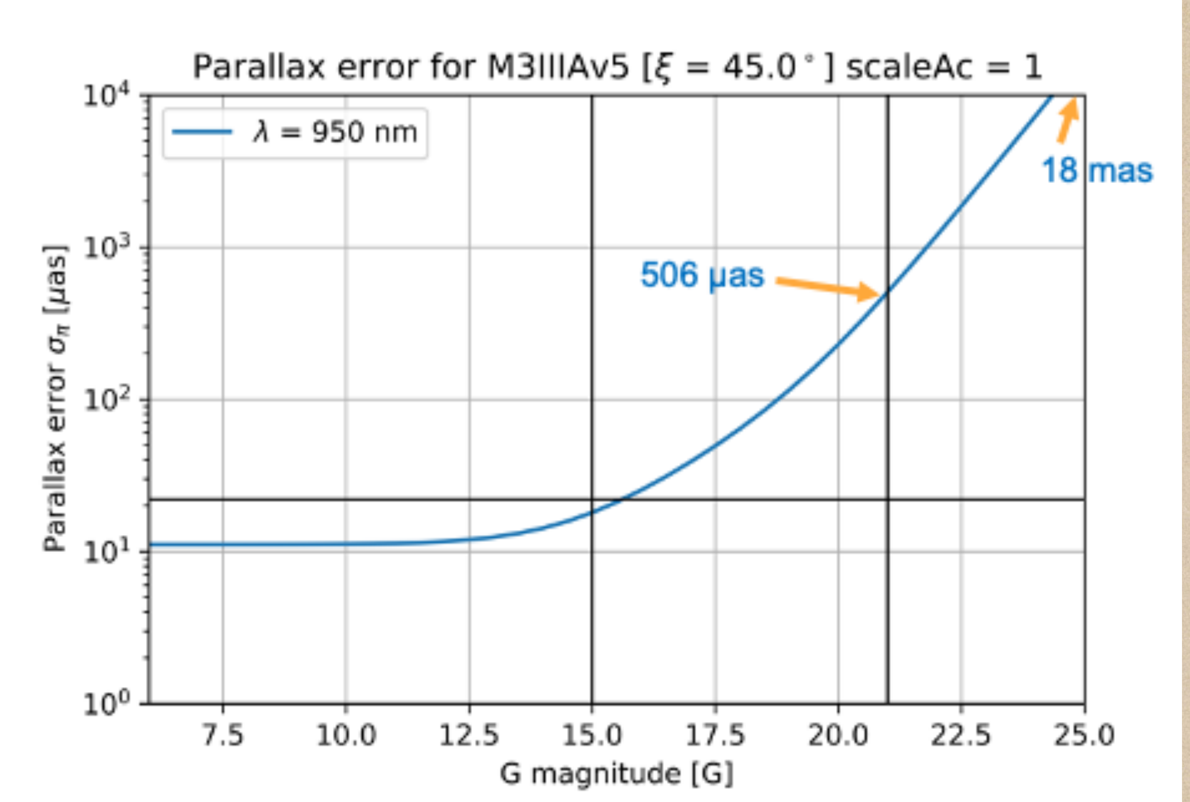
p_{det} is the detection probability in a single transit;
σ_ξ angular uncertainty AL from one CCD transit [rad];
$\sigma_{\rm cal}$ accuracy of astrometric or photometric calibration [rad];
N_i is the number of instruments and m is a safety factor of 20%.

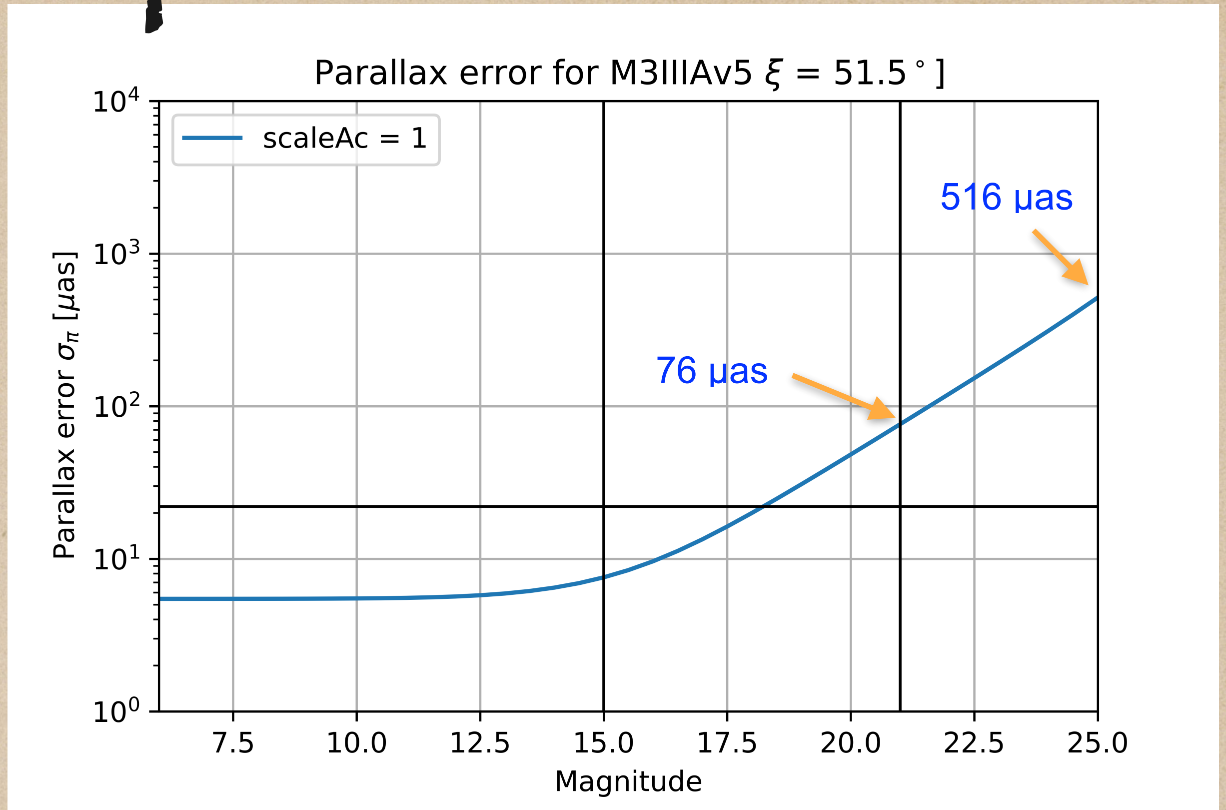
$\tau = \frac{L\Omega}{4\pi}$ = Total integration time on object per source[s]
$\tau_1 = \frac{N_\xi \Delta\xi}{\omega}$ = Integration time per CCD[s]
where
ω is the scan speed [rad s^{-1}];
$\Delta\xi$ is the angular pixel size along scan [rad] and;
N_ξ is the number of pixels per CCD in the scan direction [e−].

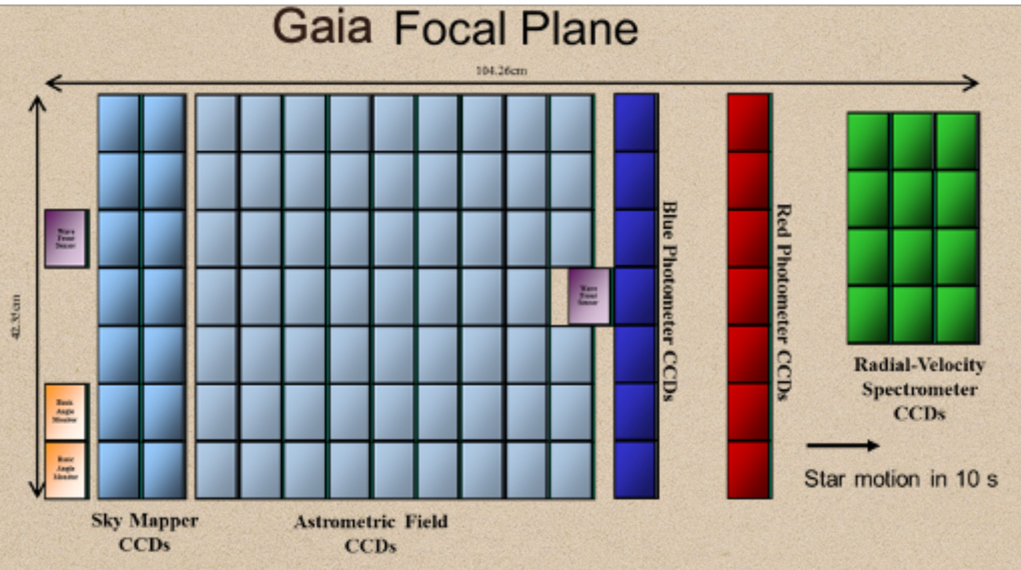
L = effective mission length (i.e. excluding dead time);
$\Omega = 1.2\ \mathrm{deg}^2$ = detector solid angle per instrument
$g_\varpi = 1.47(sin\ \xi)^{-1}$ Sky averaged parallax factor

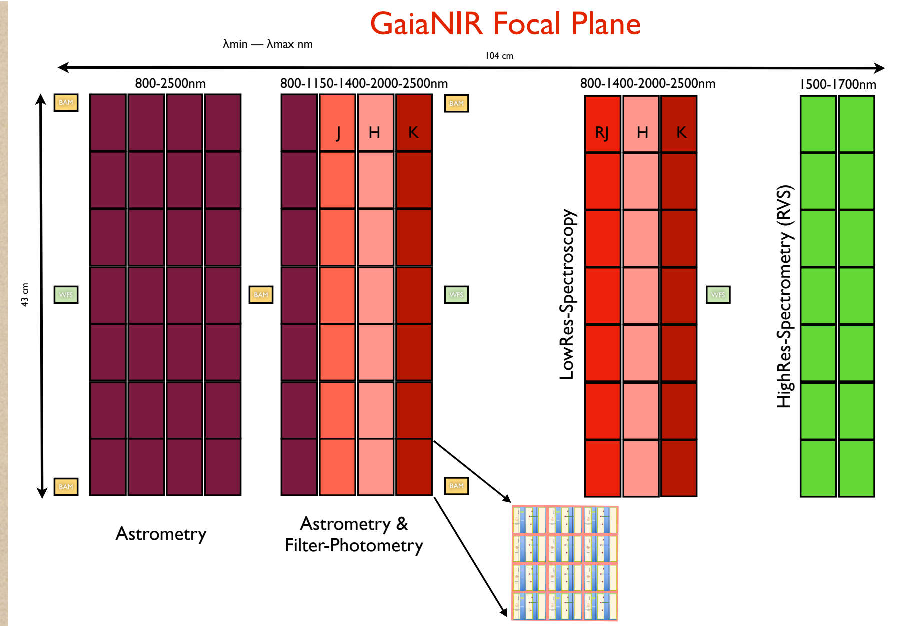


Detector Comparison





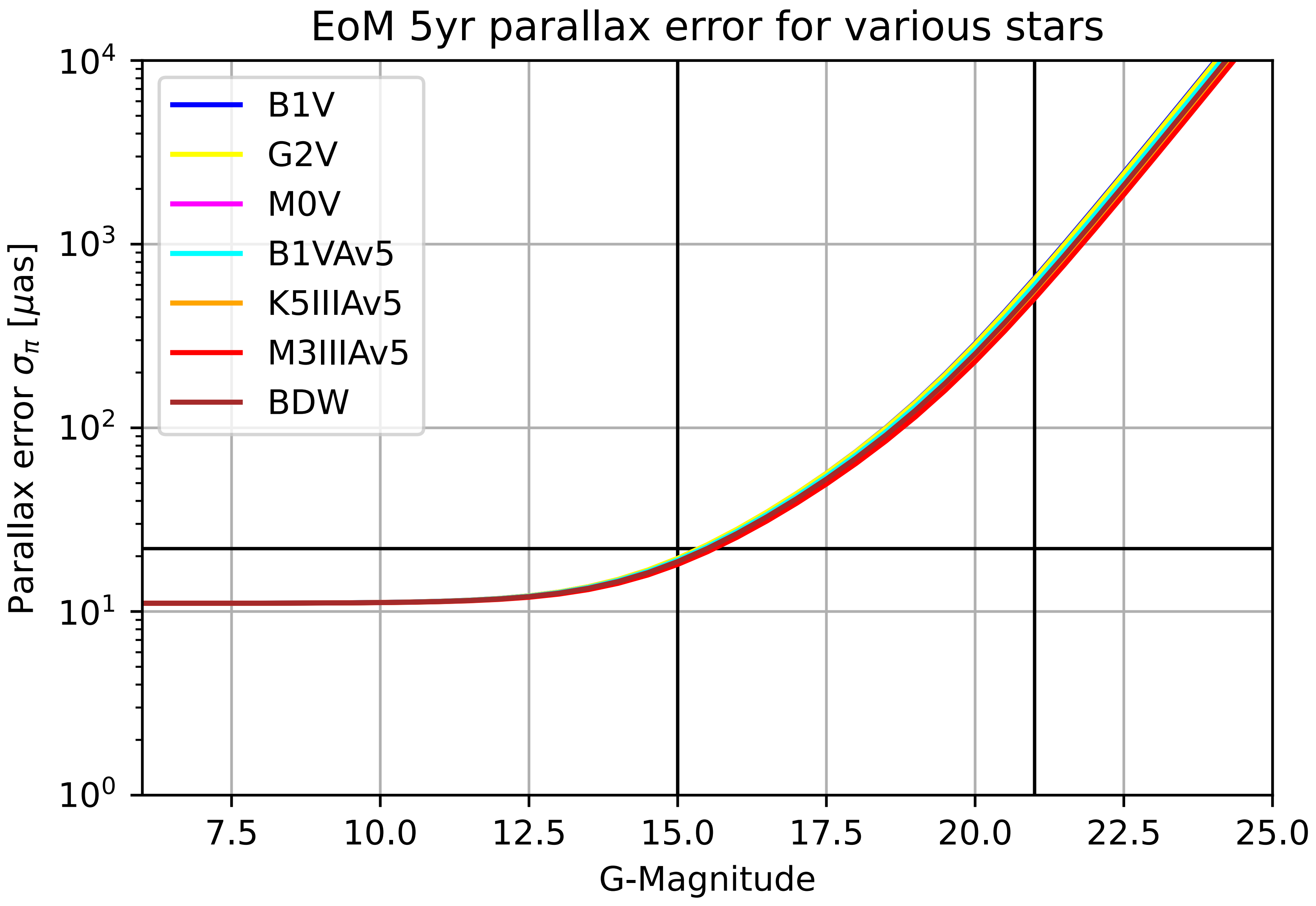




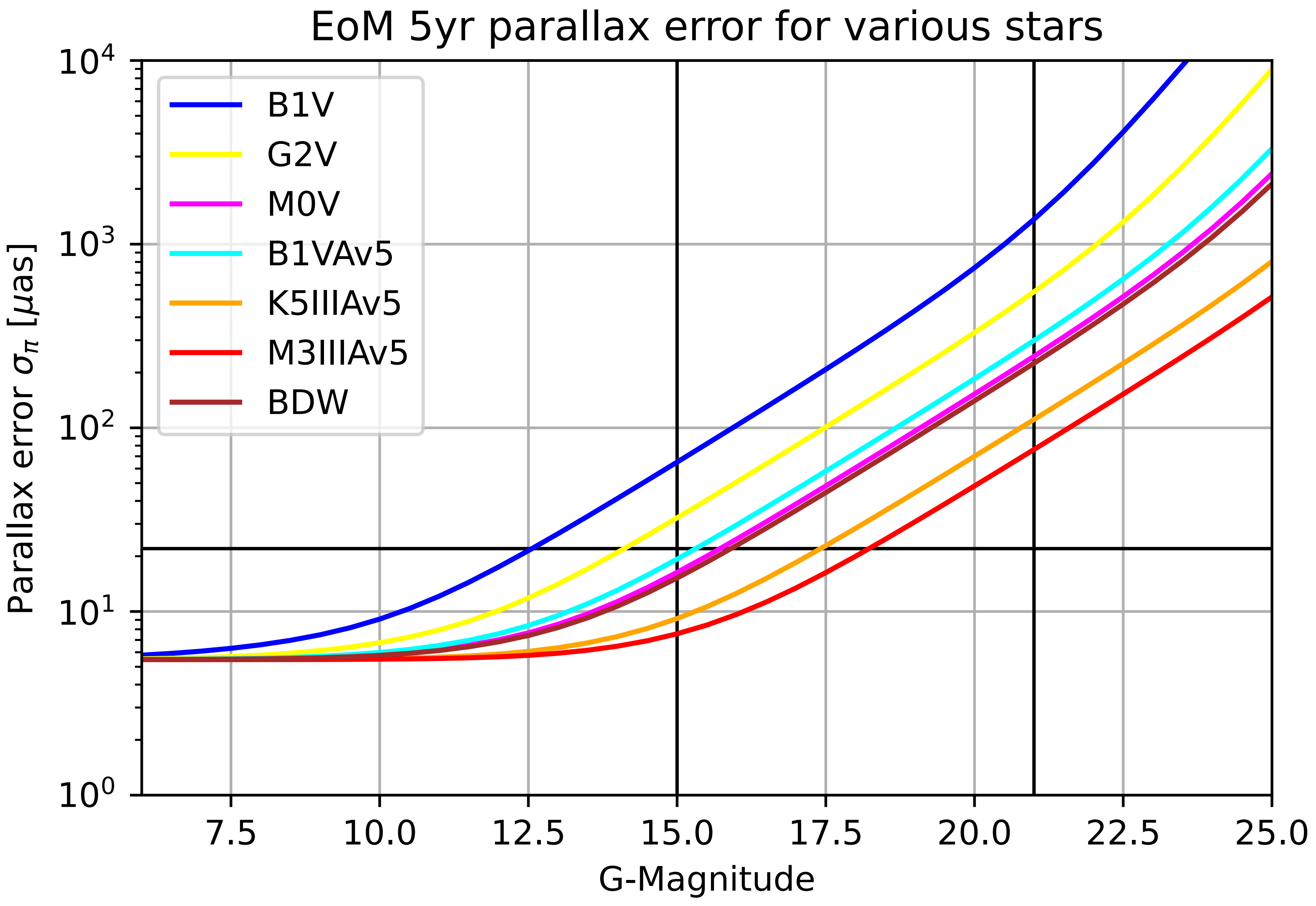
- Identical runs for M3III_Av5_T_{eff}3500_logg2.0_feh red giant giving a comparison between Gaia CCDs and GaiaNIR APD's
- APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs
- Separating AF and CF is better for astrometry and astrophysics!

Eom Results For Various Stars

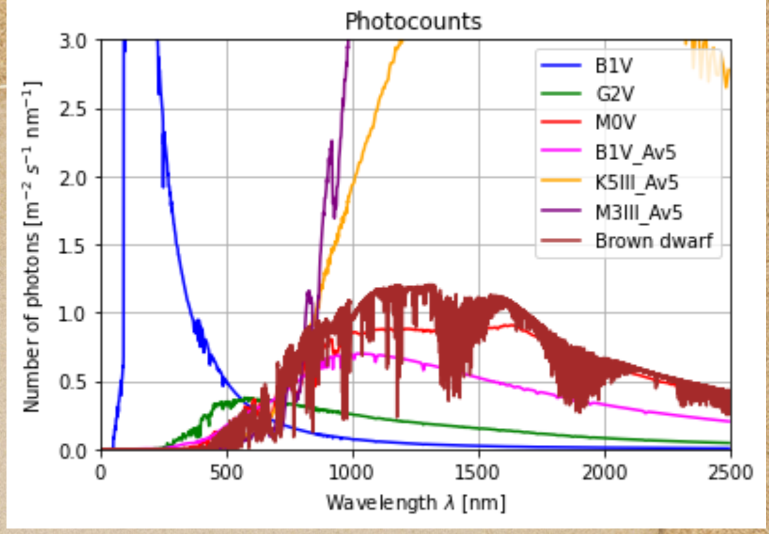
Gaia



GaiaNIR



GaiaNIR vs Gaia



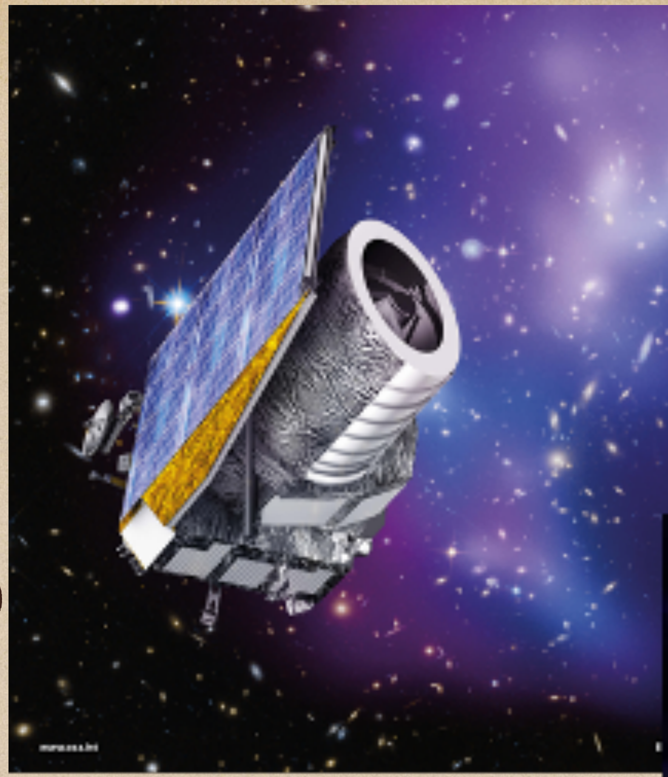
Faint red stars are better in GaiaNIR compared to Gaia

- Lower read noise gives a linear increase with magnitude and helps faint stars most
- Most stars are faint!
- Red star long wavelength range helps recover good accuracy!
- Blue stars still work but are less accurate!

Yes, I don't think I have persuaded everyone how game-changing APDs are for GaiaNIR
Ian Baker, Leonardo, UK

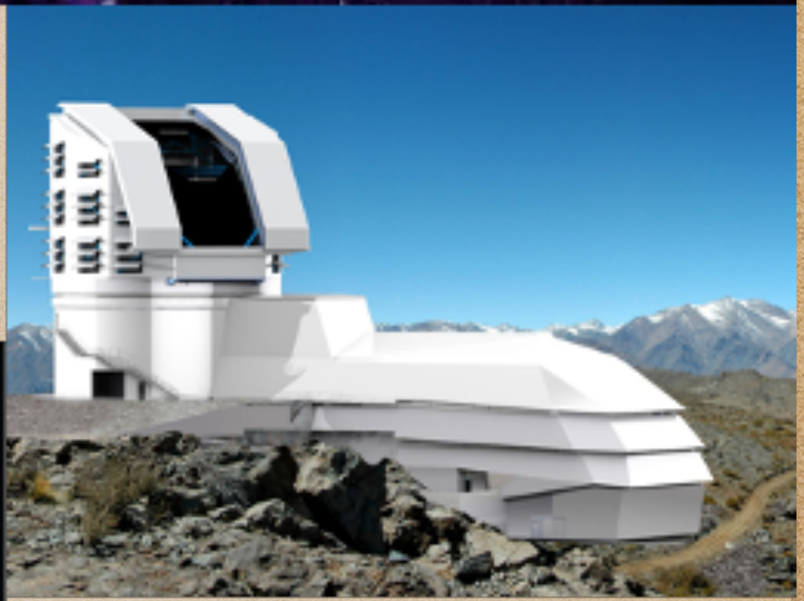
ξ=51.5°	B1V	G2V	M0V	B1V Av5	K5III Av5	M3III Av5	Brown Dwarf$_{2000K}$
G=15 mag	0.3	0.6	1.2	1.0	**2.0**	**2.4**	1.2
G=21 mag	0.5	1.2	**2.4**	**2.0**	**4.8**	**6.6**	**2.5**
G=25 mag	0.7	**2.7**	**9.0**	**6.6**	**23.8**	**35.1**	**9.6**

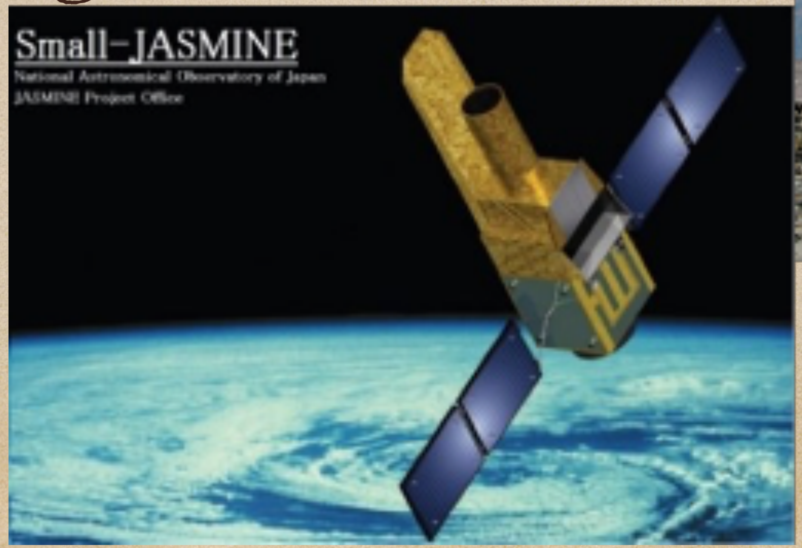
Synergies



- ESA's Euclid (~2023) (0.55–2.0 µm and H-mag ~24.5)
- Vera C. Rubin Observatory (LSST) (~2024) (0.3–1.1 µm and V-mag ~25)
- NASA's Roman Space Telescope (~2026) (0.5–2.3 µm and H-mag ~24.5)
- JAXA's JASMINE (Japan) (~2028) (1.1–1.7 µm and H-mag ~15)

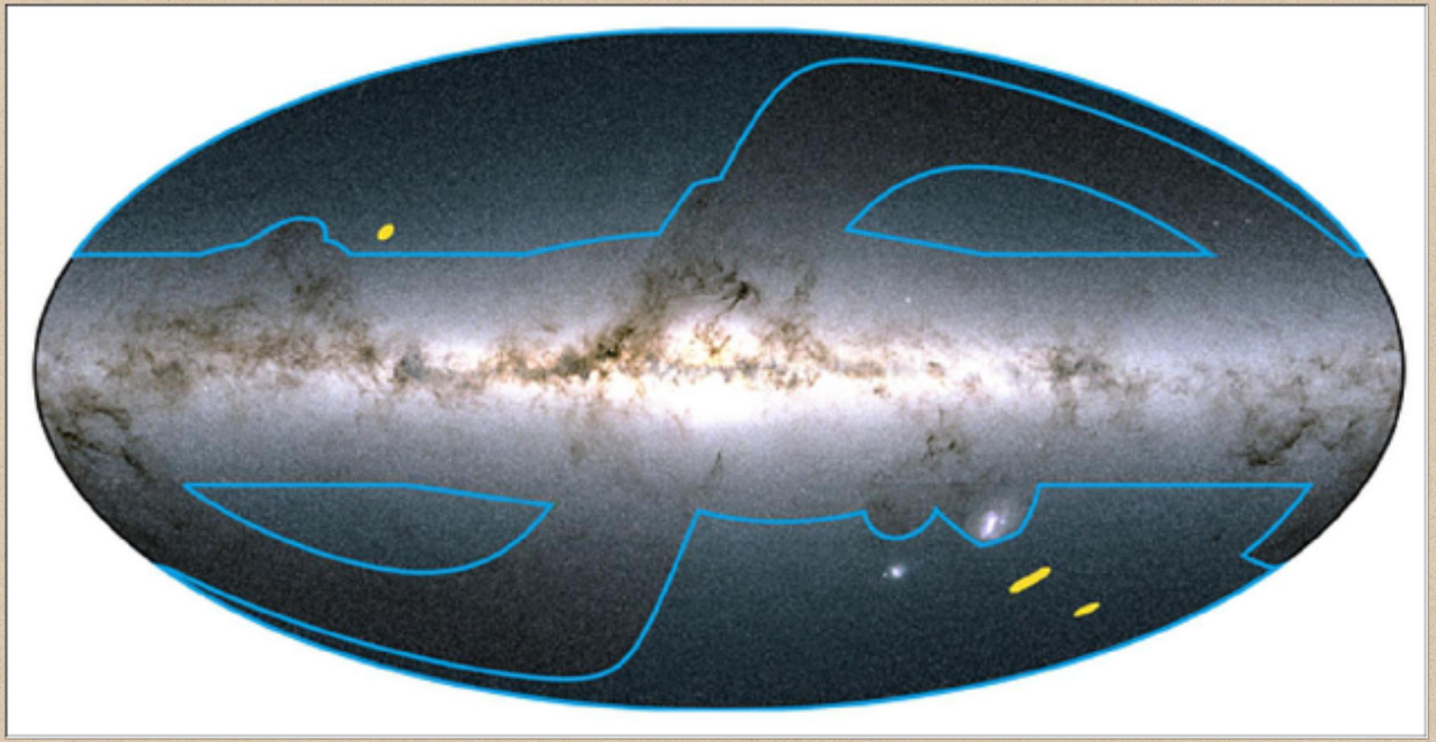
ESA's GaiaNIR (~2045) (0.8–2.5 µm and G-mag 23.5?)





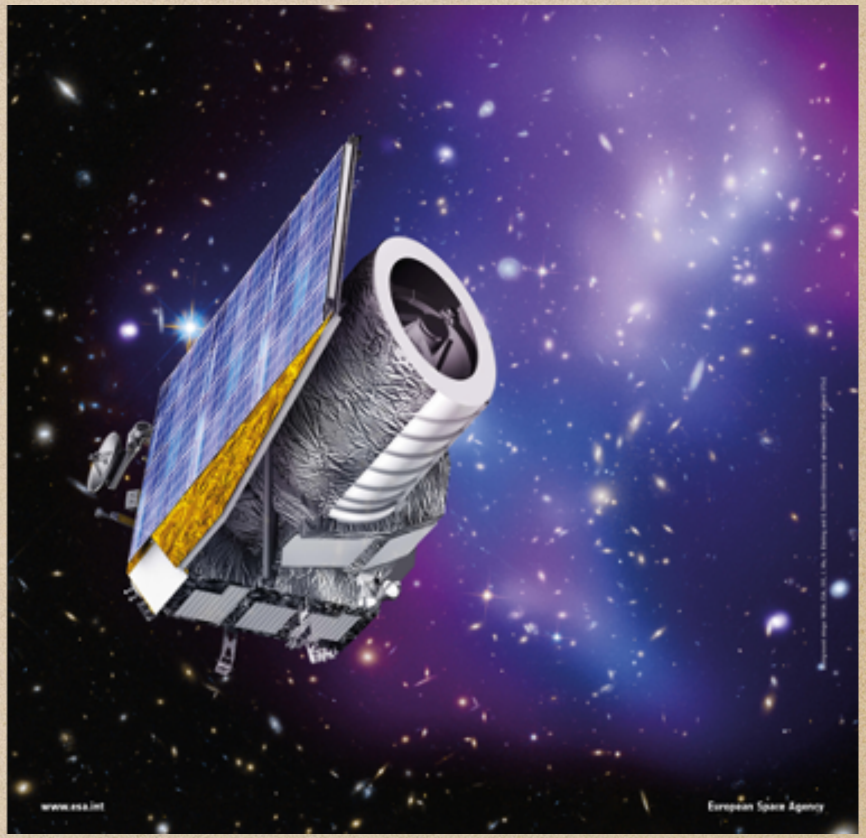
Synergies with Euclid

- Euclid will study dark matter and dark energy.
- Points out of the Galactic plane and will see stars in the halo



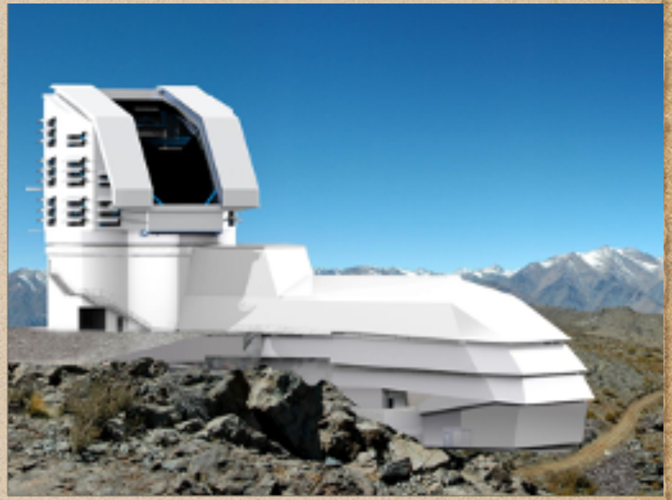
ESA's Euclid (~2023) (0.55–2.0 μm and mag ~24.5)

The Euclid wide and deep surveys (image credit: ESA/Euclid Consortium)

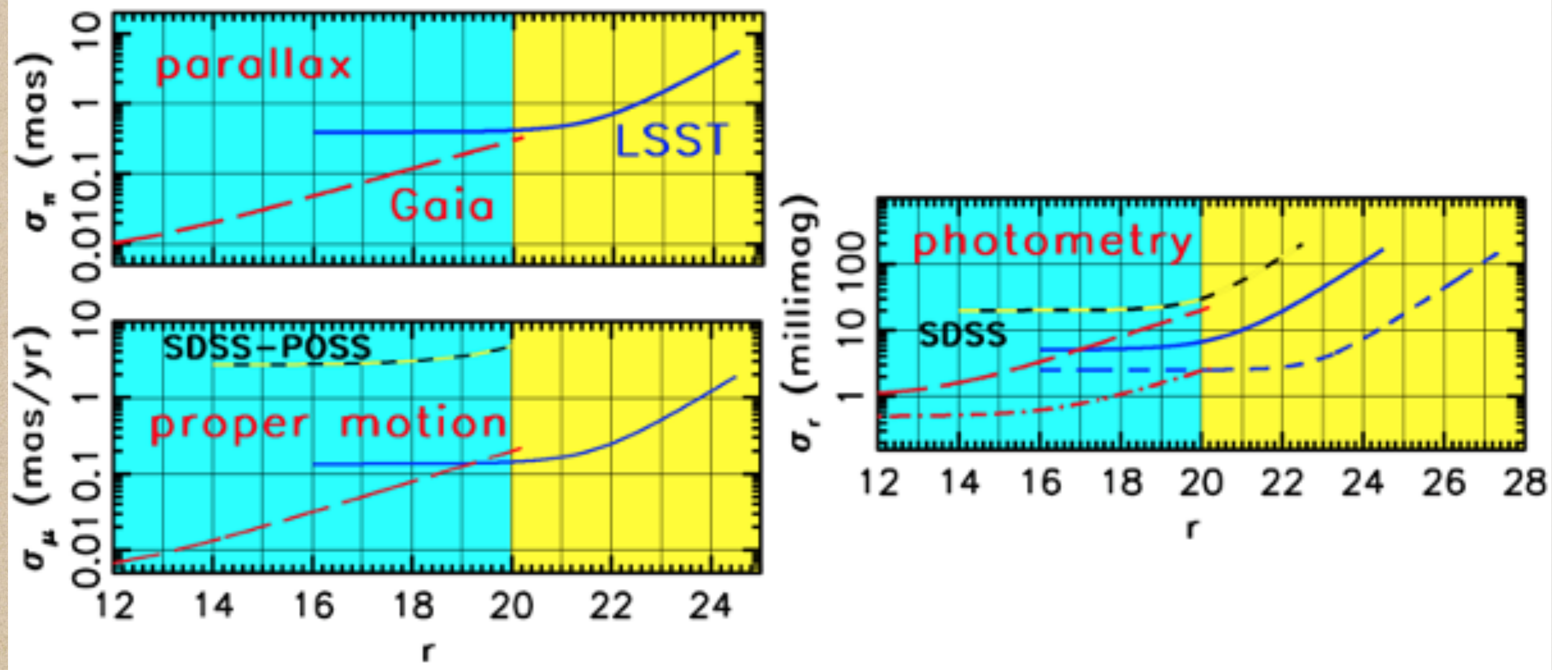


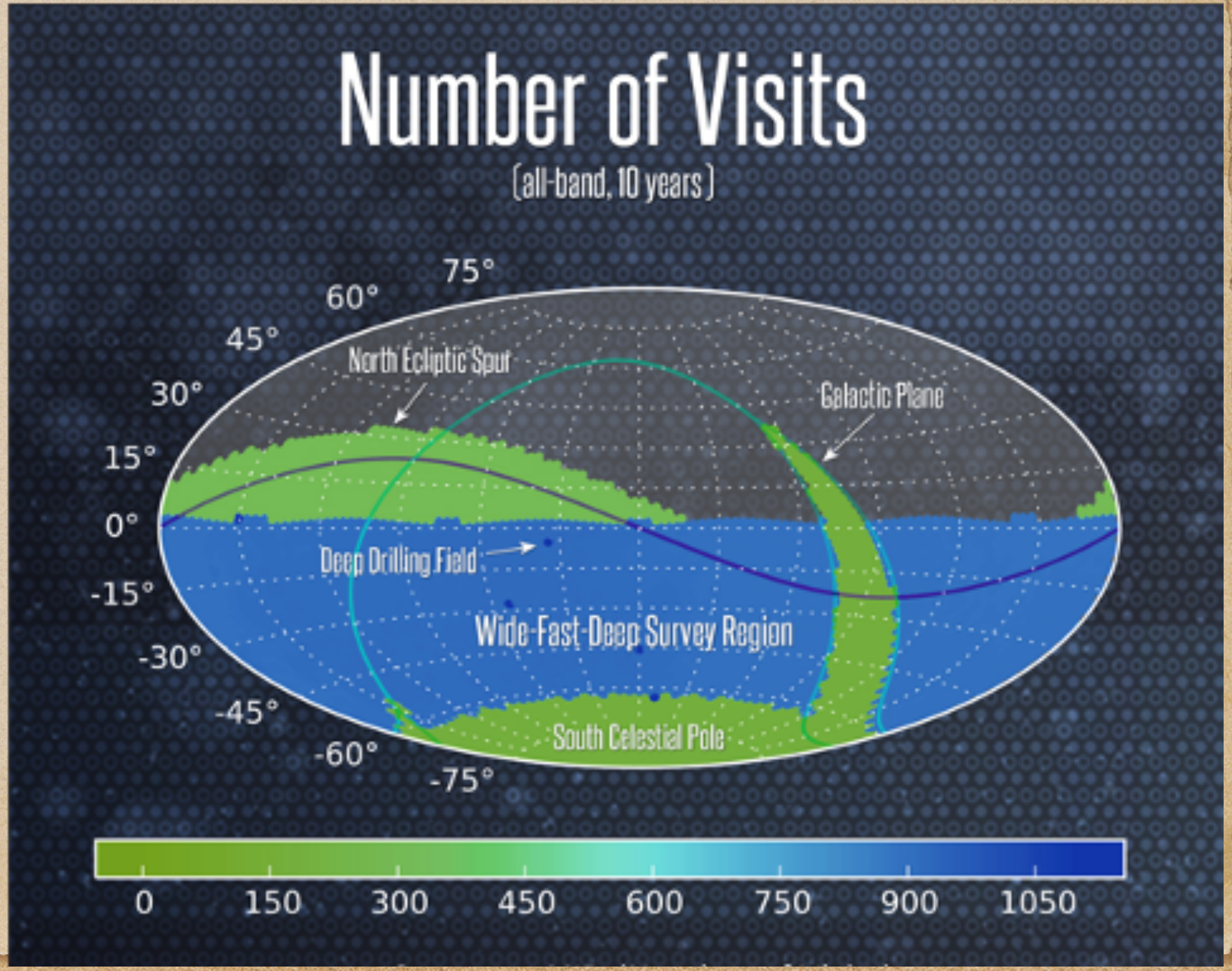
- Combined with Gaia/GaiaNIR to improve PMs
- Fewer NIR stars in this sky survey (15,000 deg^2) but it is still useful!

Synergies with Rubin



- The Vera C. Rubin Observatory (LSST) is a wide-field telescope with an 8.4-meter primary mirror (320–1060 nm).
- Covers 18,000 deg^2
- Less accurate down to 20th magnitude but goes much deeper than Gaia, about mag ~25)





- Very complementary to Gaia and GaiaNIR

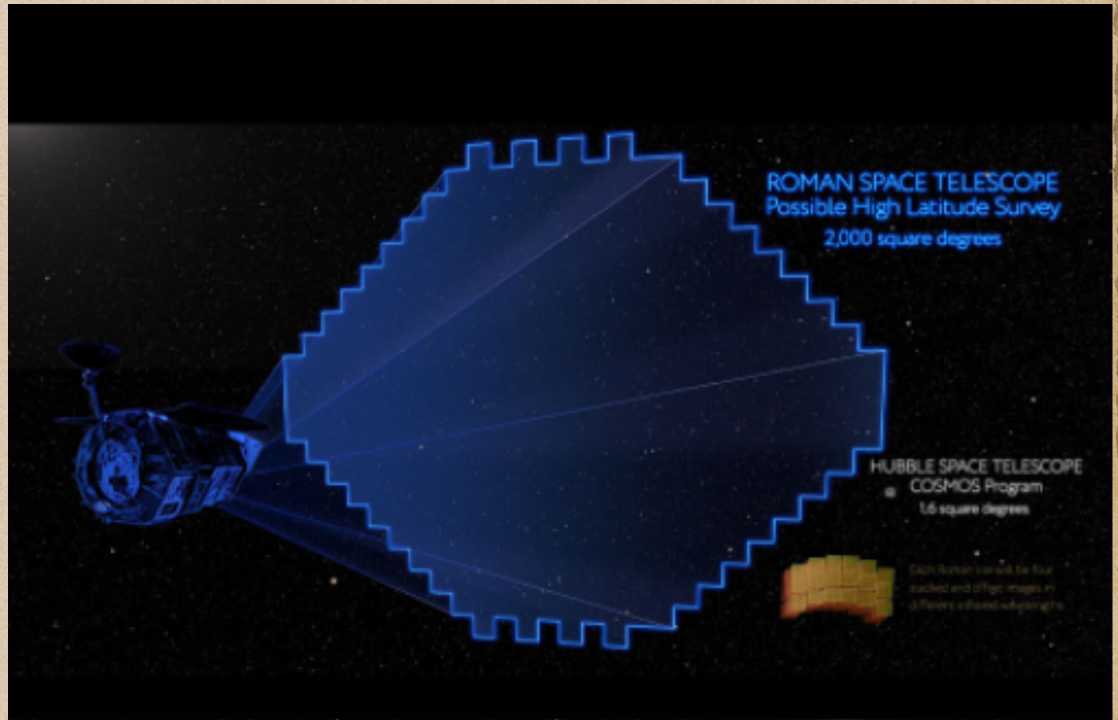
Synergies with Roman

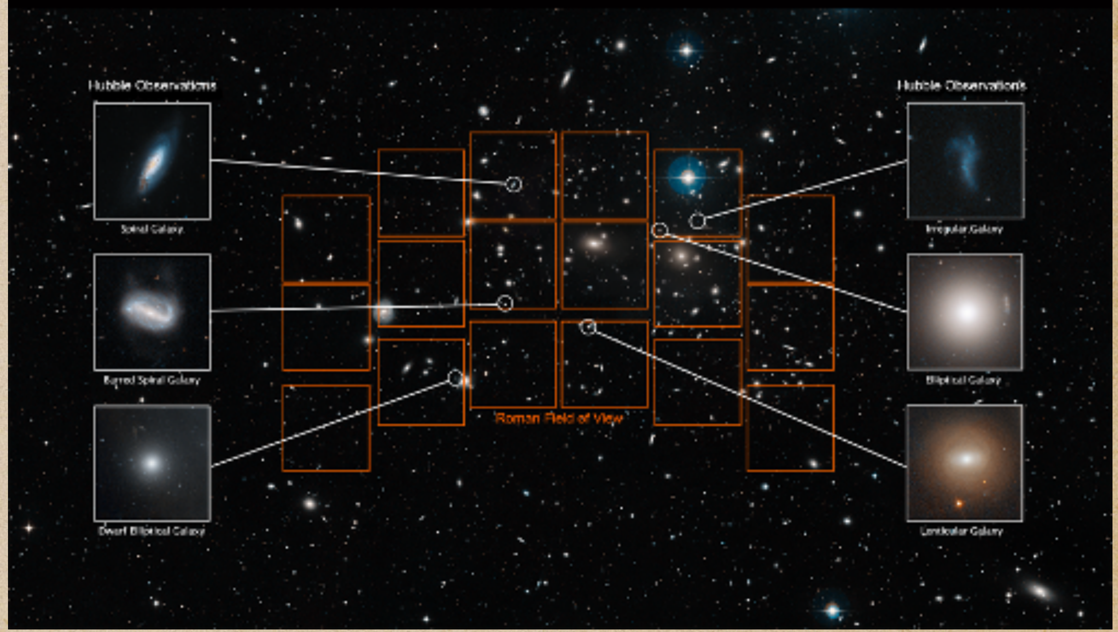
- NASA's Nancy Grace Roman Space Telescope (~2026) targets dark matter and dark energy, exoplanets and NIR astrophysics at L2

- FoV is 100 times > Hubble's
  - A High Latitude Survey is planned (2000 deg^2)
  - Galactic Bulge Time Domain Survey - exoplanet detection with microlensing and transits (~2 deg^2)
  - Recent proposal NANCY: All-sky NIR astrometry (two epochs - no parallax)

- NANCY would be a useful first epoch when combined with GaiaNIR to give 10 billion PMs with sub-µas accuracy

- Do they have enough fuel (to despin RWs) for 2 x 41,253 deg^2 ?
- Each all-sky scan would cost 204 days and interfere with the main survey!

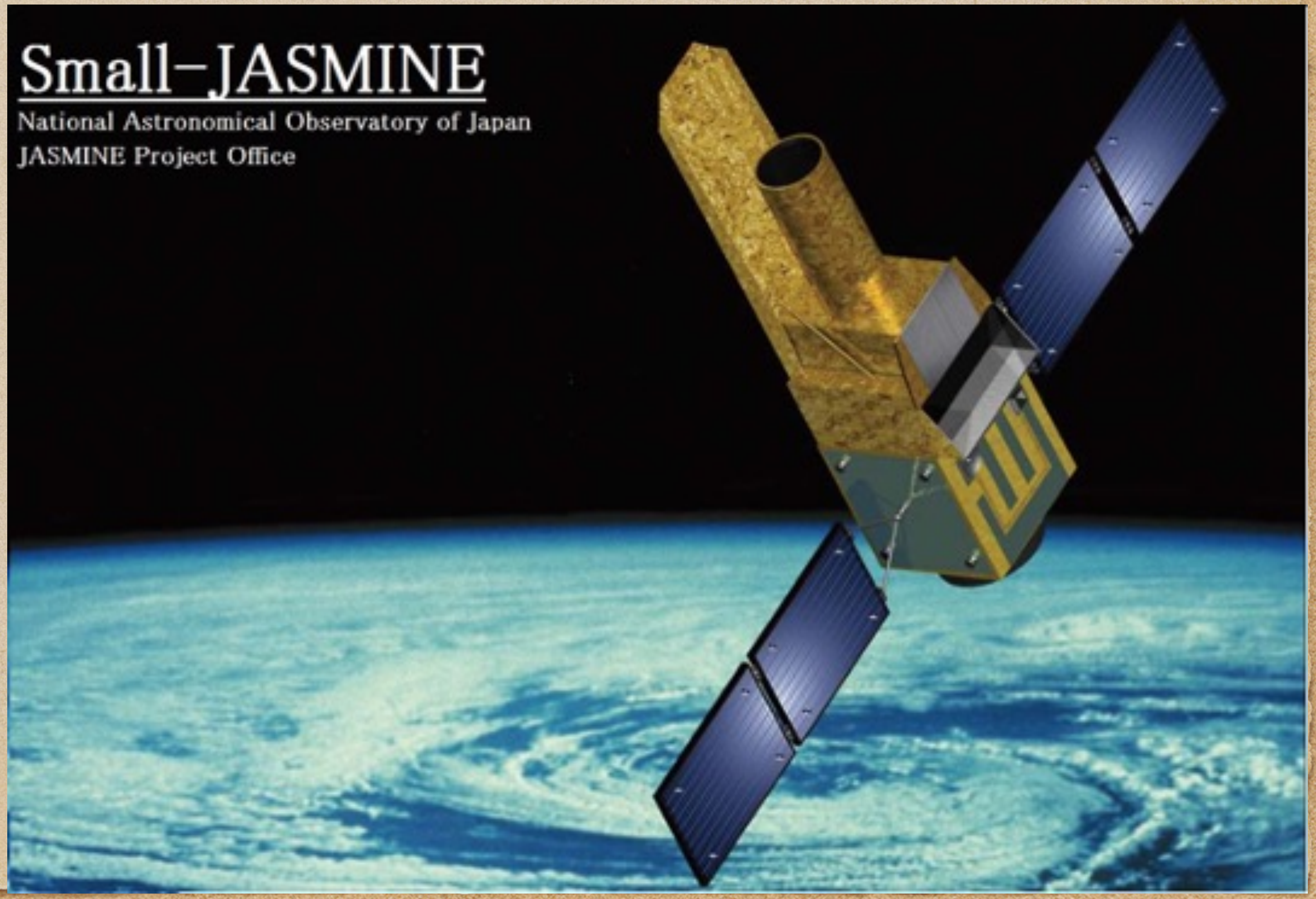




Synergies with JASMINE

- The JASMINE (Japan) (~2028) (1.1–1.7 μm and mag ~15) and bright (Hw< 15 mag) stars
- NIR relative (to Gaia) astrometry within ~100 pc from the GC mainly the Galactic nuclear bulge
- Exoplanets for M-type main sequence stars using photometry

Excellent pathfinder for GaiaNIR



Summary

- For GaiaNIR APDs we get better astrometric performance for several reasons
  - Reverting back to optimal scanning law parameters (e.g. sun aspect angle, scan rate, etc.)
  - Broader wavelength range more than compensates for longer observing wavelength
  - Lower read noise and lower background noise are game changers for astrometry!
  - Instead of going to longer wavelengths it is better to go fainter (~23-24 mag)!
- The combinations of these improvements results in a new mission that can outperform Gaia!
- Including a spectrograph and a slow scan rate for part of the mission or elongated detectors could give a deep all-sky astrometric and RV survey for a billion or more objects!