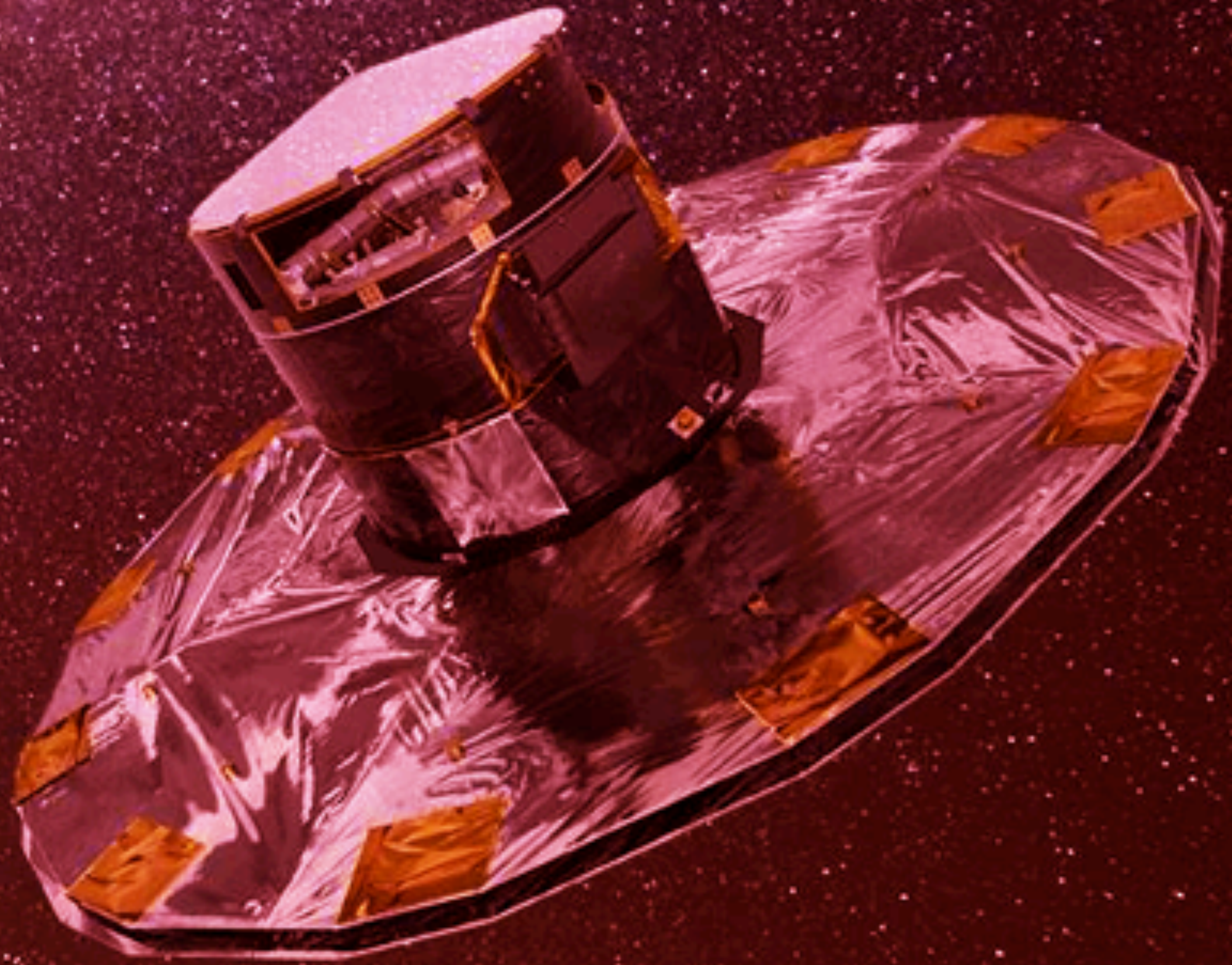
GaiaNIR

The Hidden Regions

Astrometry in the Near Infrared



David Hobbs
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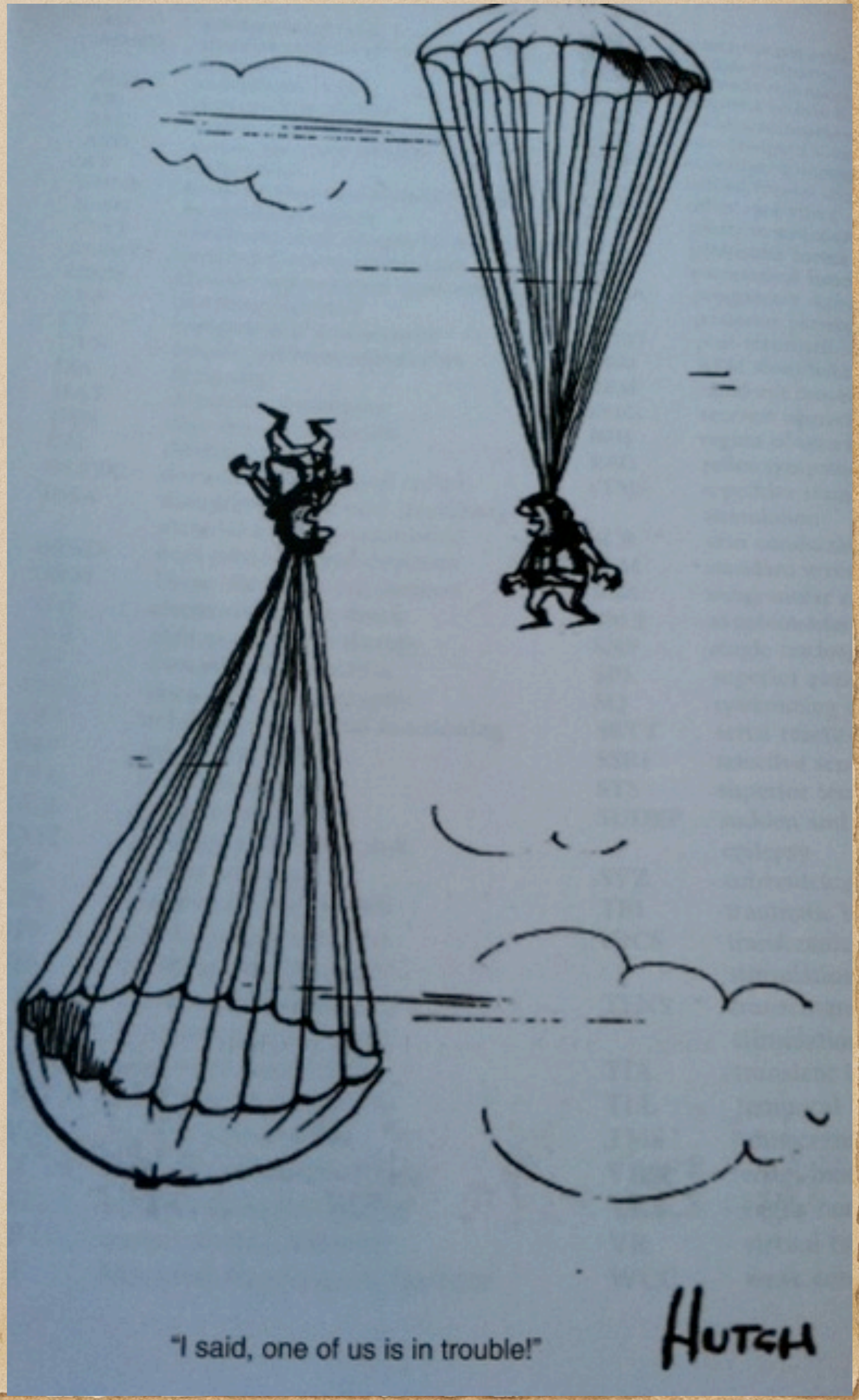
Which direction?

Future space astrometry can move in several directions:

- All-sky optical and NIR (Gaia-like μas) - known as GaiaNIR.
- Pointed relative astrometry in NIR (e.g. small-JASMINE) to add important regions such as the Galactic centre and spiral arms. Not very deep ($H_w < 15$ mag).
- Pointed relative astrometry missions (SIM, NEAT, Theia, ...), targeted ultra accurate (nas), aimed at specific questions on dark matter, exoplanets (e.g. exo-earths), etc.

Clearly there is overlap between science cases but global Gaia-like astrometry in the NIR can do more!



GaiaNIR Science Cases

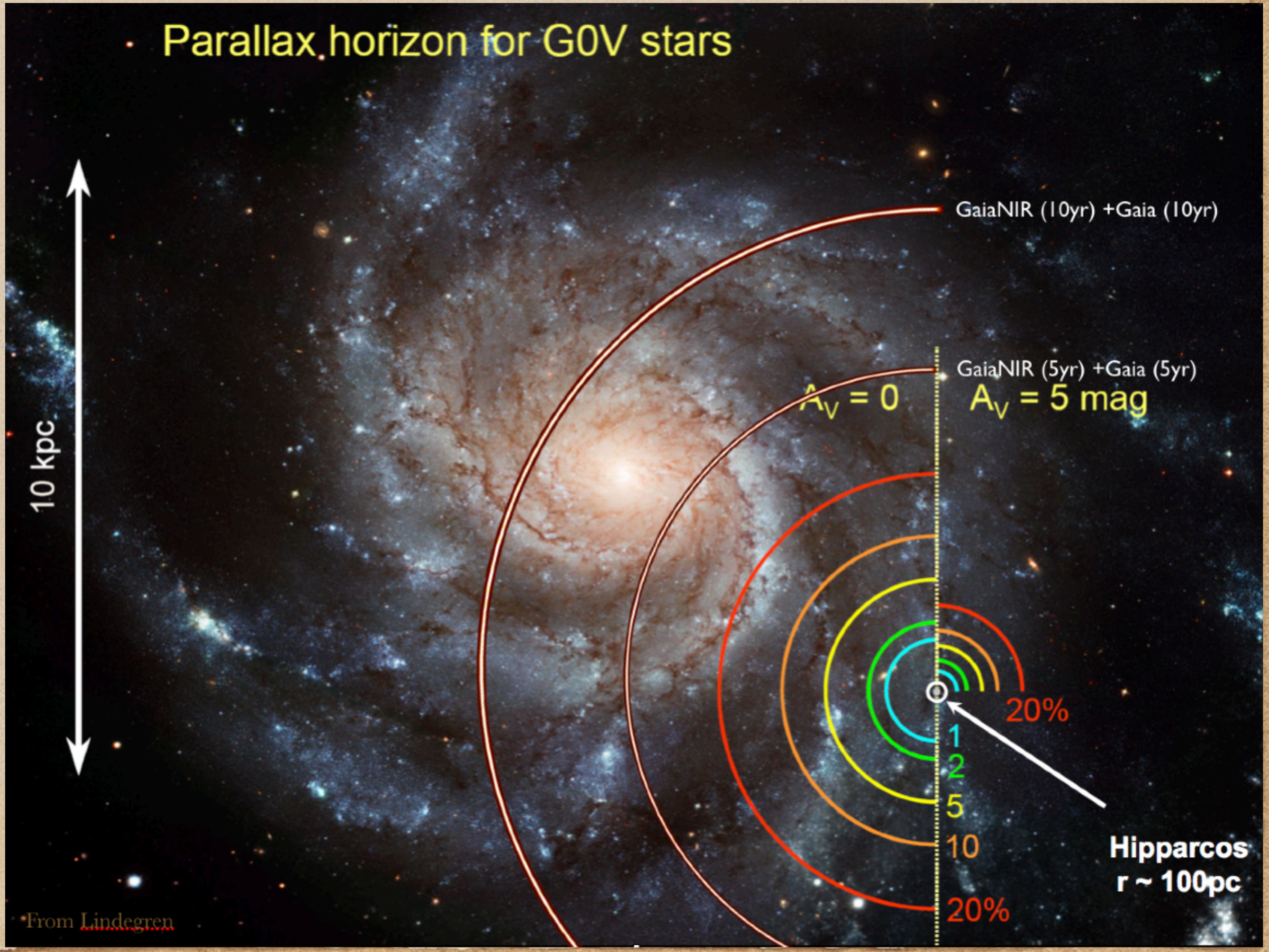
- Adding NIR astrometry and photometry to probe hidden regions of the Galaxy.
- A ~20 yr gap would give PMs 20 times better (compared to DR4) for common stars, opening many new science cases and the nano-arcsec regime.
- Resetting the Gaia optical RF and catalogue. Expansion of the optical RF to the NIR is super important.

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

Volume increase at the same accuracy

Parallax: $(\sqrt{2})^3 \approx 2.8$

Proper Motion: 10^3-$20^3 \approx 1000$-8000



From Lindegren

Nano-arcsec (yr^{-1}) PMs

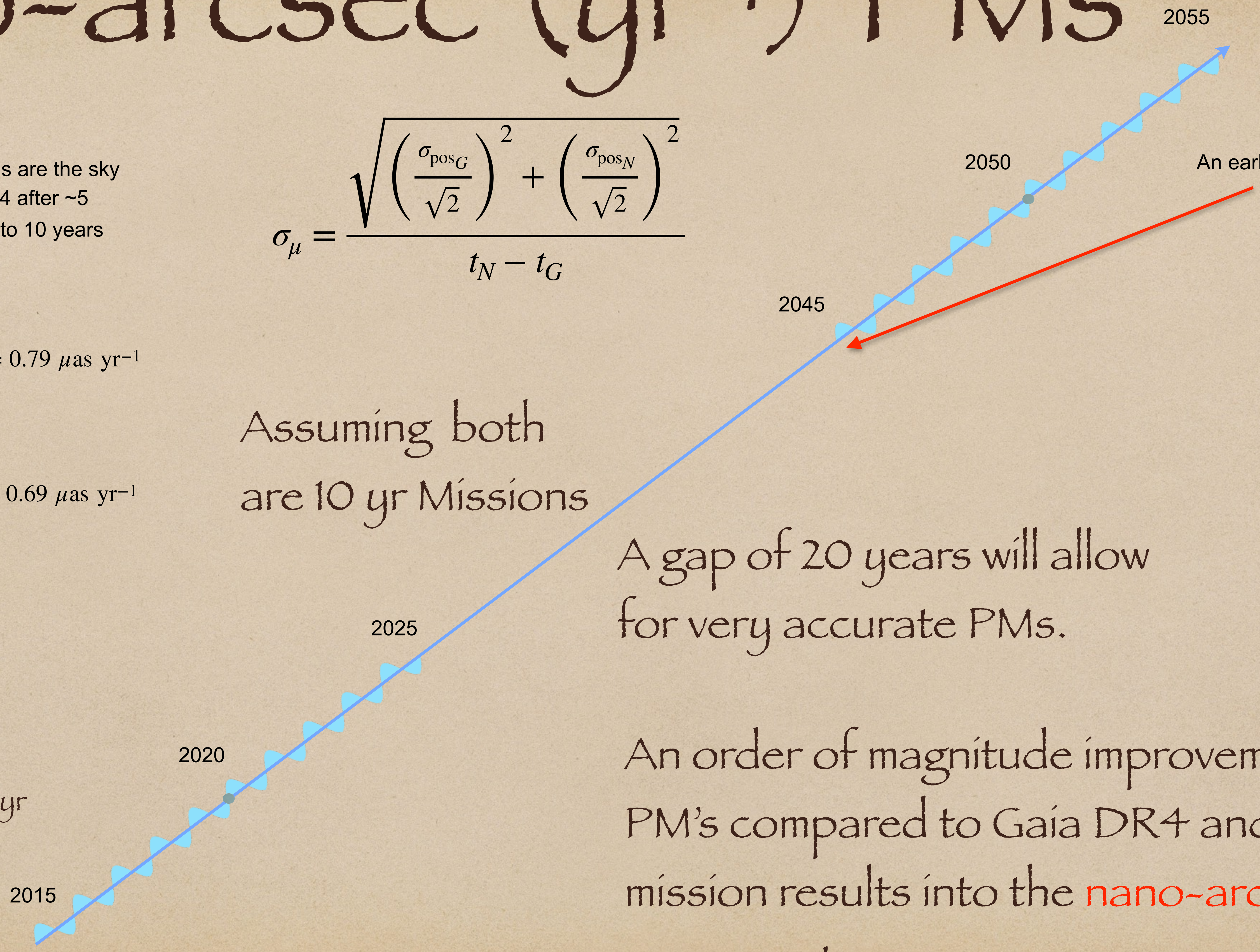
The numbers 23.6 and 20.6 μas are the sky averaged positions of Gaia DR4 after ~5 years and $\sqrt{2}$ is extrapolation to 10 years

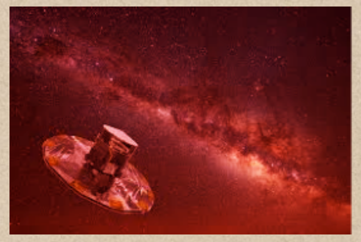
$$\sigma_\mu = \frac{\sqrt{\left(\frac{\sigma_{\mathrm{pos}_G}}{\sqrt{2}}\right)^2 + \left(\frac{\sigma_{\mathrm{pos}_N}}{\sqrt{2}}\right)^2}}{t_N - t_G}$$

$$\sigma_{\mu_{\alpha^*}} = \frac{\sqrt{\left(\frac{23.6}{\sqrt{2}}\right)^2 + \left(\frac{23.6}{\sqrt{2}}\right)^2}}{20+10} = 0.79\ \mu\mathrm{as\ yr^{-1}}$$

$$\sigma_{\mu_\delta} = \frac{\sqrt{\left(\frac{20.6}{\sqrt{2}}\right)^2 + \left(\frac{20.6}{\sqrt{2}}\right)^2}}{20+10} = 0.69\ \mu\mathrm{as\ yr^{-1}}$$

Assuming both are 10 yr Missions





Stars only seen in NIR will not benefit from this improvement

Second Epoch GaiaNIR 10yr (2050)

A gap of 20 years will allow for very accurate PMs.

An order of magnitude improvement (factor of 20) in PM's compared to Gaia DR4 and brings the combined mission results into the nano-arcsec regime for common stars.

First Epoch Gaia 10yr (2020)

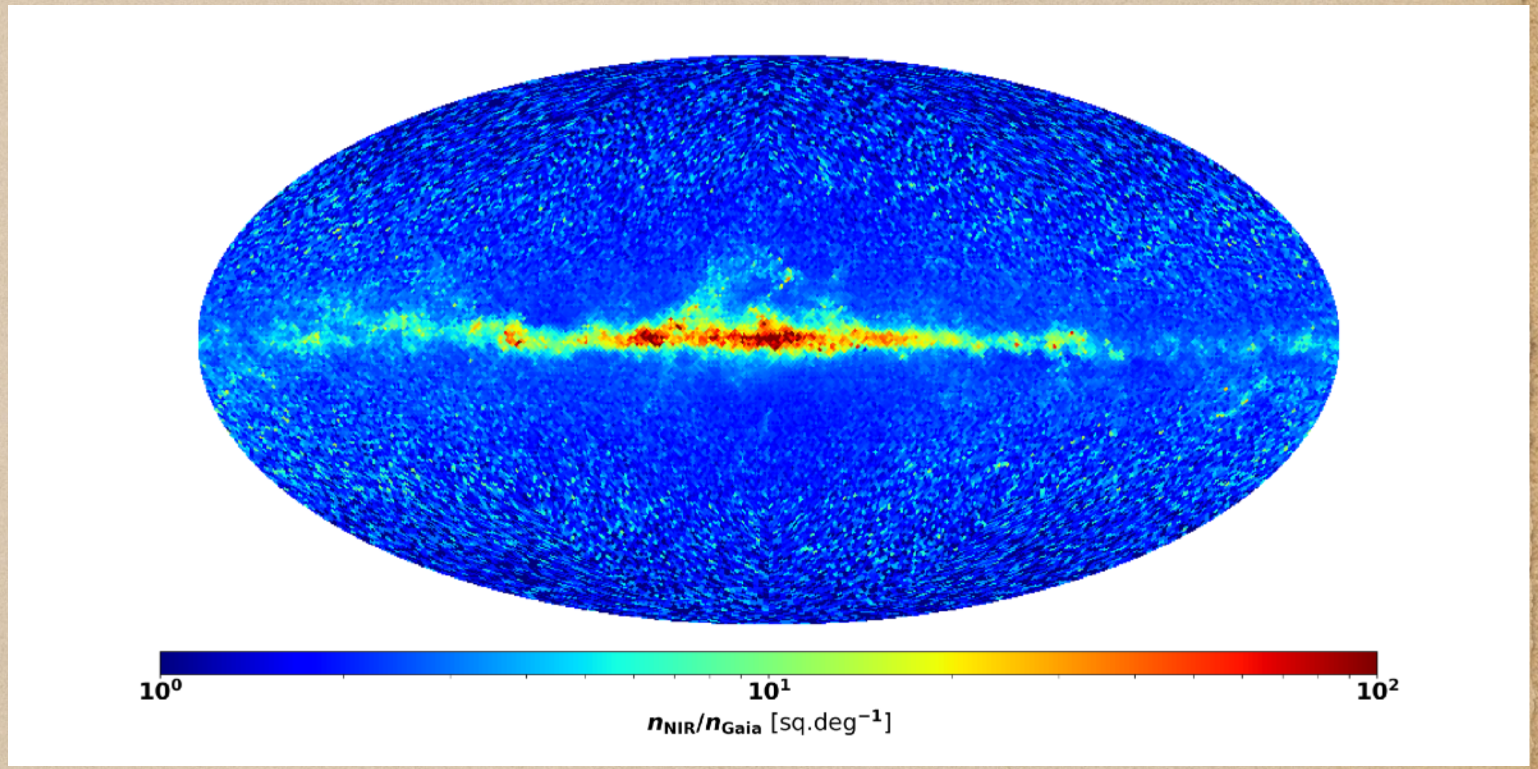
$\sigma_\mu = \sim 16\ \mu\mathrm{as\ yr^{-1}}$ is estimated at G = 15 for Gaia DR4

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 (older models give a ratio of 3 instead of 5).
- This uncertainty is a key science case in itself that cannot be resolved by Gaia alone.

GaiaNIR is not simply an increment on Gaia but will create an astrometric revolution in itself through it's 3 main science cases!

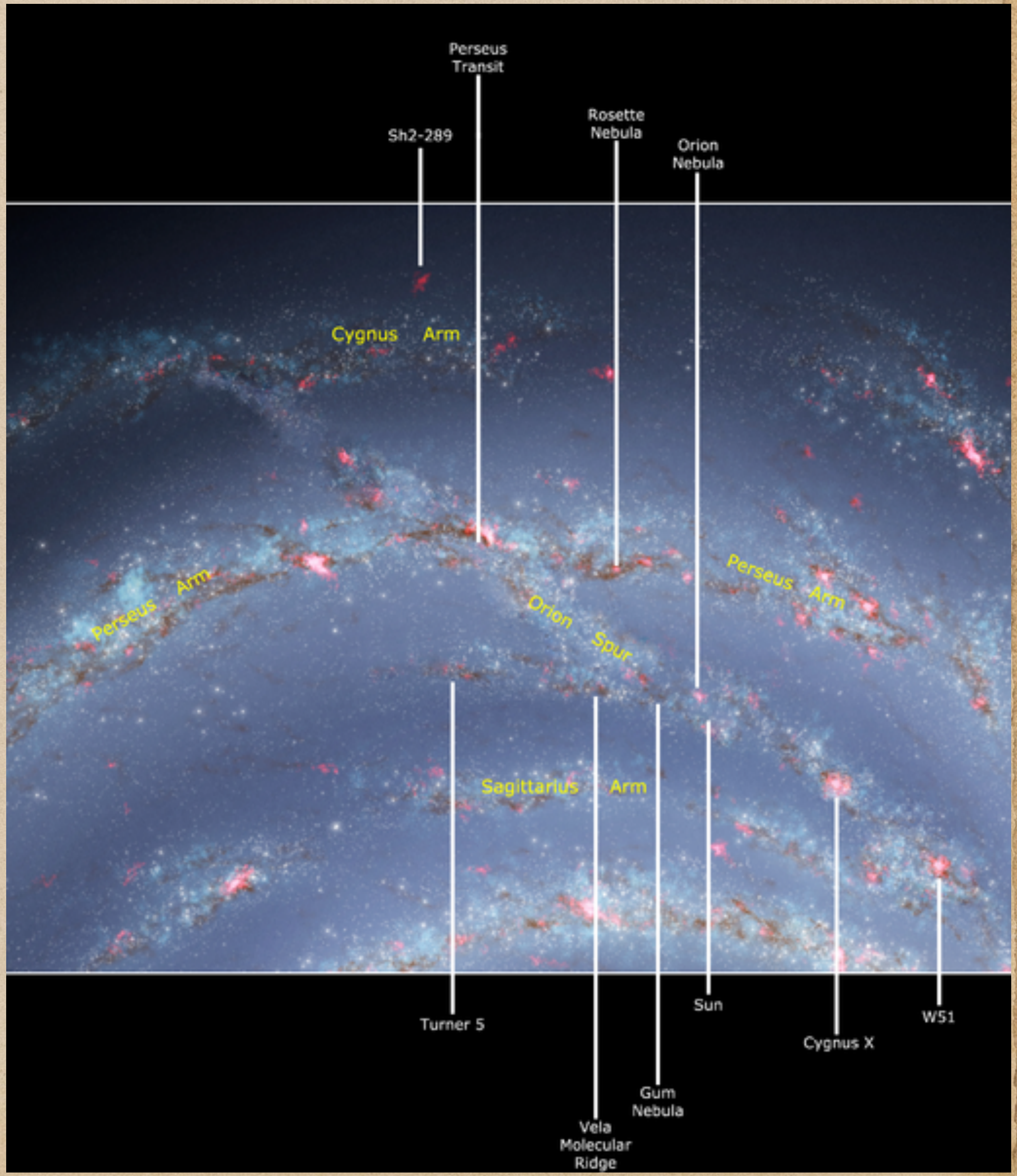
(H-band limit of 20th mag)



1. NIR Astrometry

- Dusty Bulge/bar region is dynamically important:
  - E.g. radial migration, bar perturbations of the bulge affecting DM density profile, etc.
- Unveil the inner disk which is not well known.
- Probe DM in the thin disc and spiral arms?
- Vastly improve measurements of the rotation curve.
- Map in detail the dusty spiral arms - astrometry for 100's of millions of objects.
- 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.

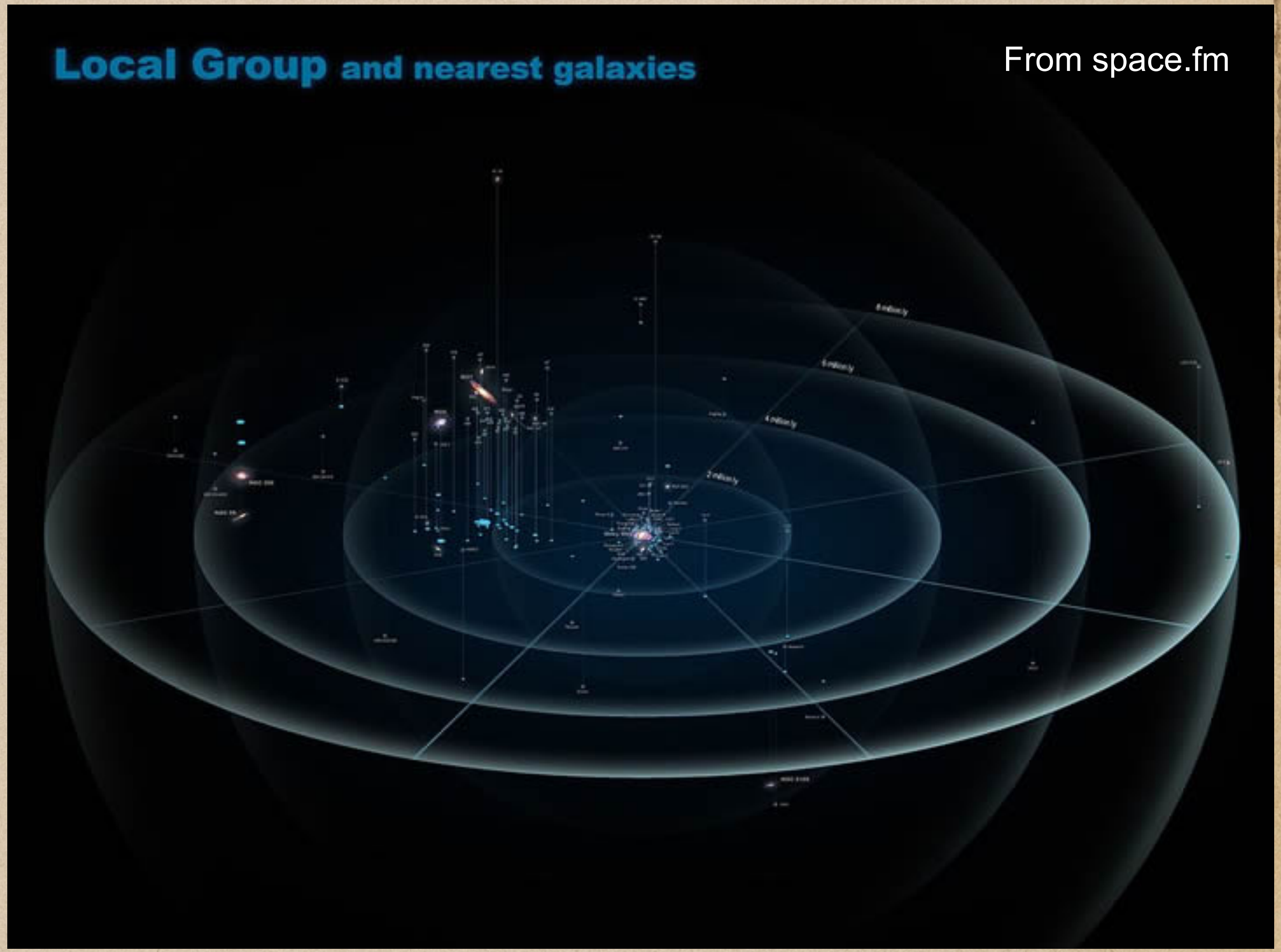
All of this for up to ~8-10 billion new stars!



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/flat dark matter Halo problem?
- 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).
- Exoplanets in dusty and star forming regions.
- Exoplanet community support is very important!
- Solar System orbits for >100,000 objects - greatly improved.

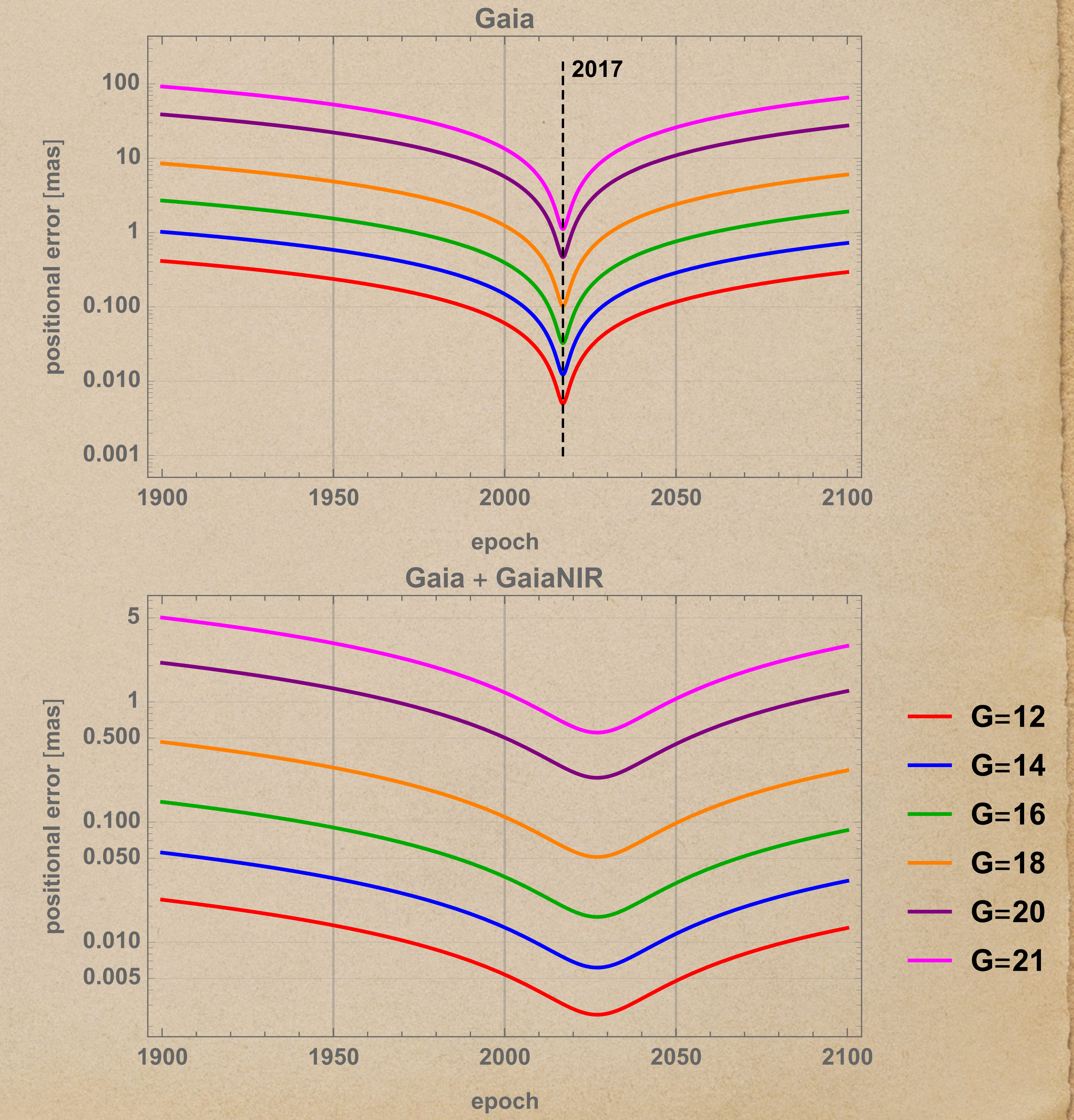
All of this for up to ~2 billion Gaia stars!



From space.fm

3. RF & Catalogue Ageing

- The RF degrades slowly (RF spin accurate to < 0.5 μas yr^{-1}) but other systematic PMs patterns will 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.

The big science question!

- A new mission can measure the hidden stars not seen by Gaia.
- It is analogous to comparing Hubble and James Webb
- A new mission can measure stars for the entire sky!
- The most important NIR science cases lie in the Galactic plane and star forming regions - Gaia cannot reach them, GaiaNIR can.
- Can we also get their RV's?

Comparison of the Carina Nebula in visible light (left) and infrared (right), both images by Hubble. In the infrared image, we can see more stars that weren't visible before. Credit: NASA/ESA/M. Livio & Hubble 20th Anniversary Team (STScI)

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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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
sion 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
olution, ☒ 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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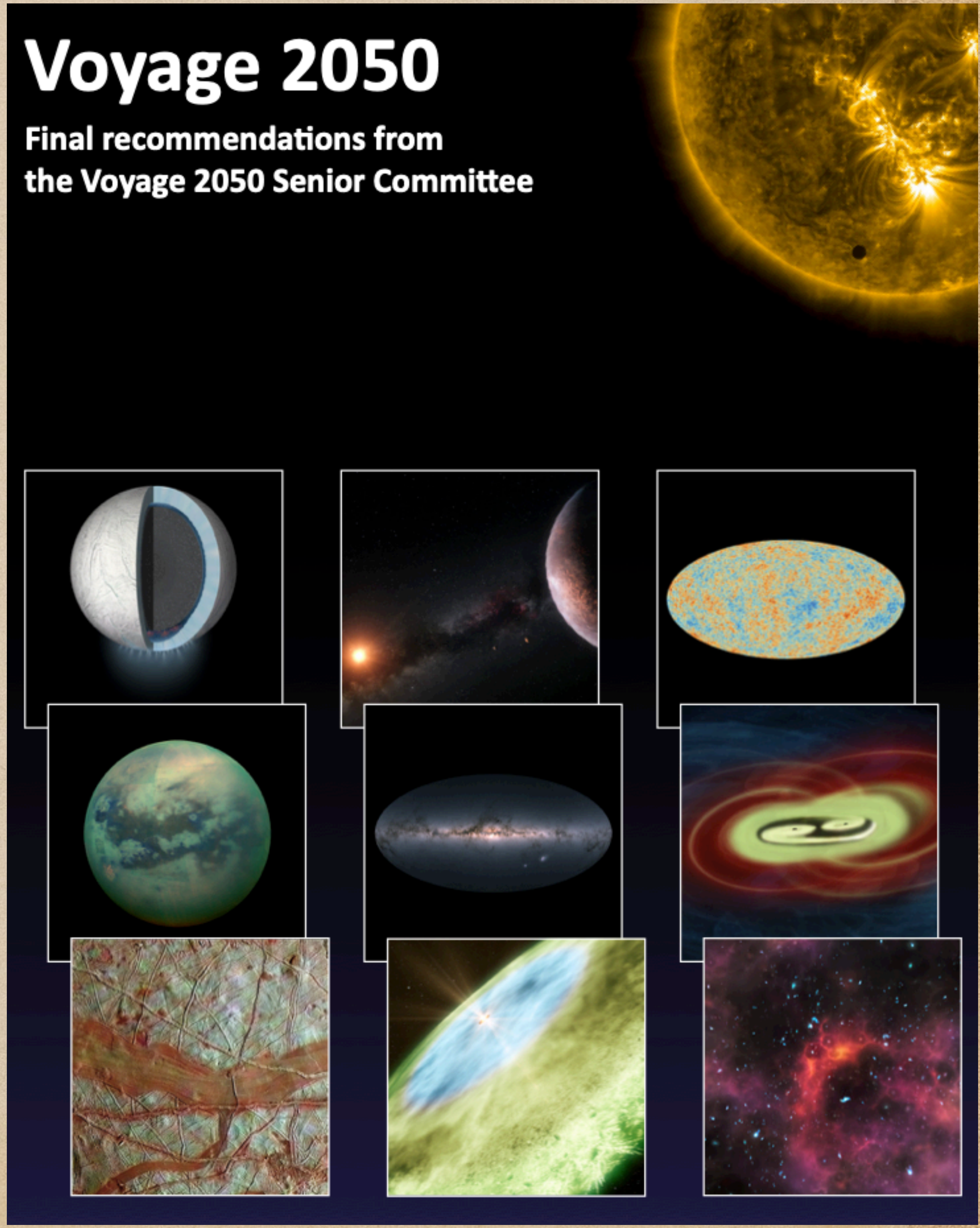
Voyage 2050 - Large class themes

Voyage 2050 identified two main themes:

- Exoplanets that may host life: "If it is found that at least 10 temperate exoplanets can be characterised and thus that a scientific breakthrough can be achieved in a feasible and affordable mission, then the committee recommends such a theme be selected for the third Large mission…"
- Hidden regions of our Galaxy: "If this is not the case, the committee instead recommends that ESA select the "Galactic Ecosystem with Astrometry in the Near-infrared" for a Large mission."
- "The compelling nature of the astrometry theme is also highlighted by its inclusion in the Medium mission recommendations." - International cooperation is needed in this case.



Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee

The US Astro-2020 survey suggests building a large space telescope to search for signs of exoplanets that might host life. The report calls for a mission in the 2040s and for cooperation with ESA.

It is logical for ESA to join efforts with the US on exoplanets.

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.

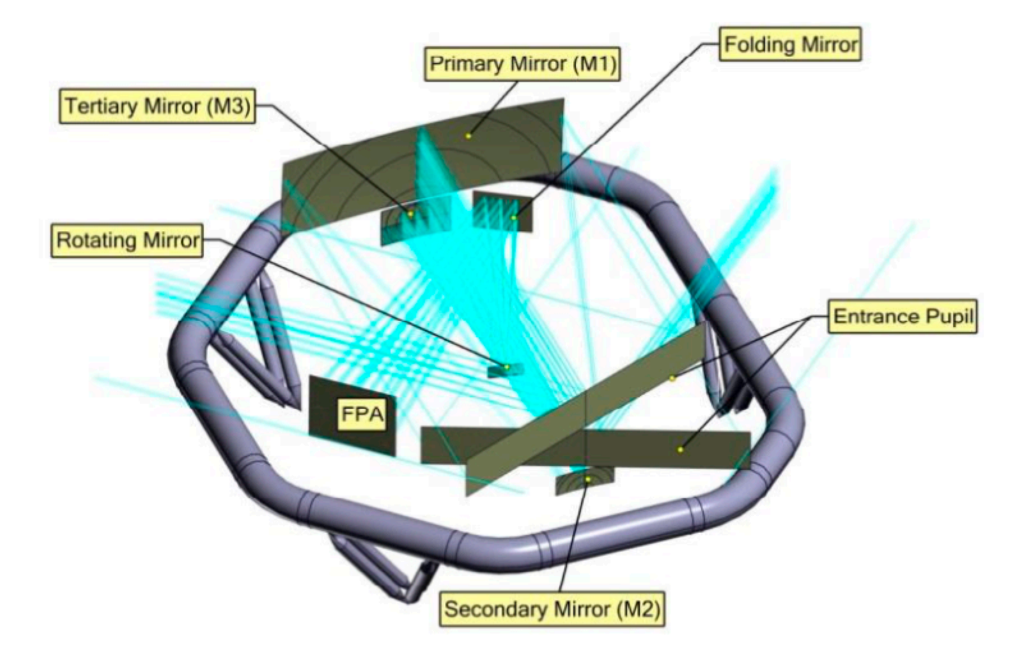


Figure 5-34: GaiaNIR optical surfaces and the light path

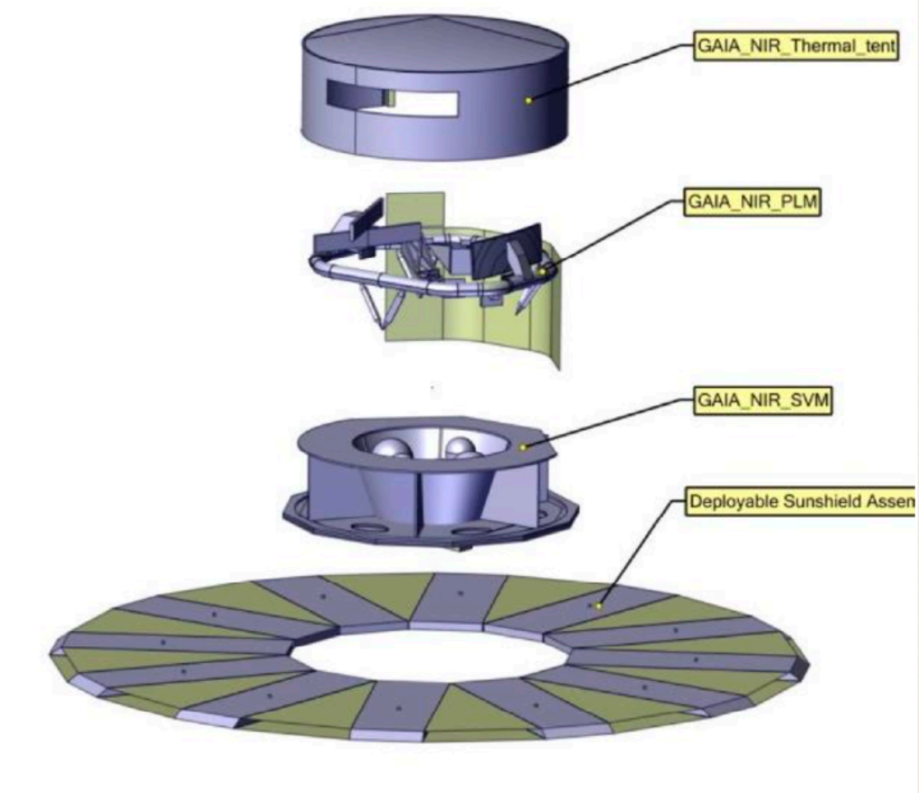


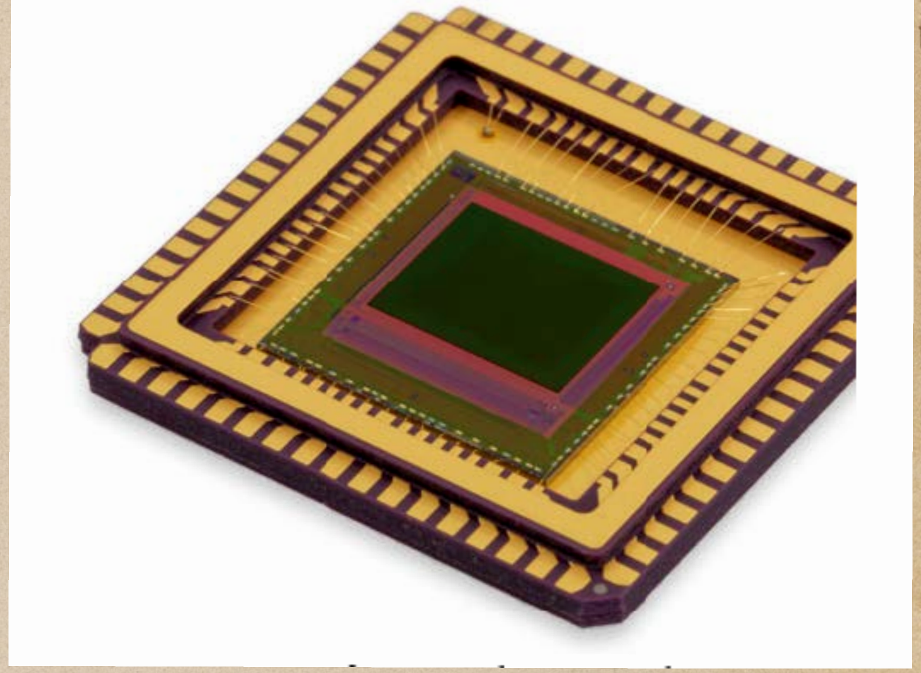
Figure 6-2: Gaia-NIR Spacecraft main elements

- 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 (UK) Leonardo have small APD's with high frequency readout making them ideal for a scanning (Time Delay Integration) telescopes

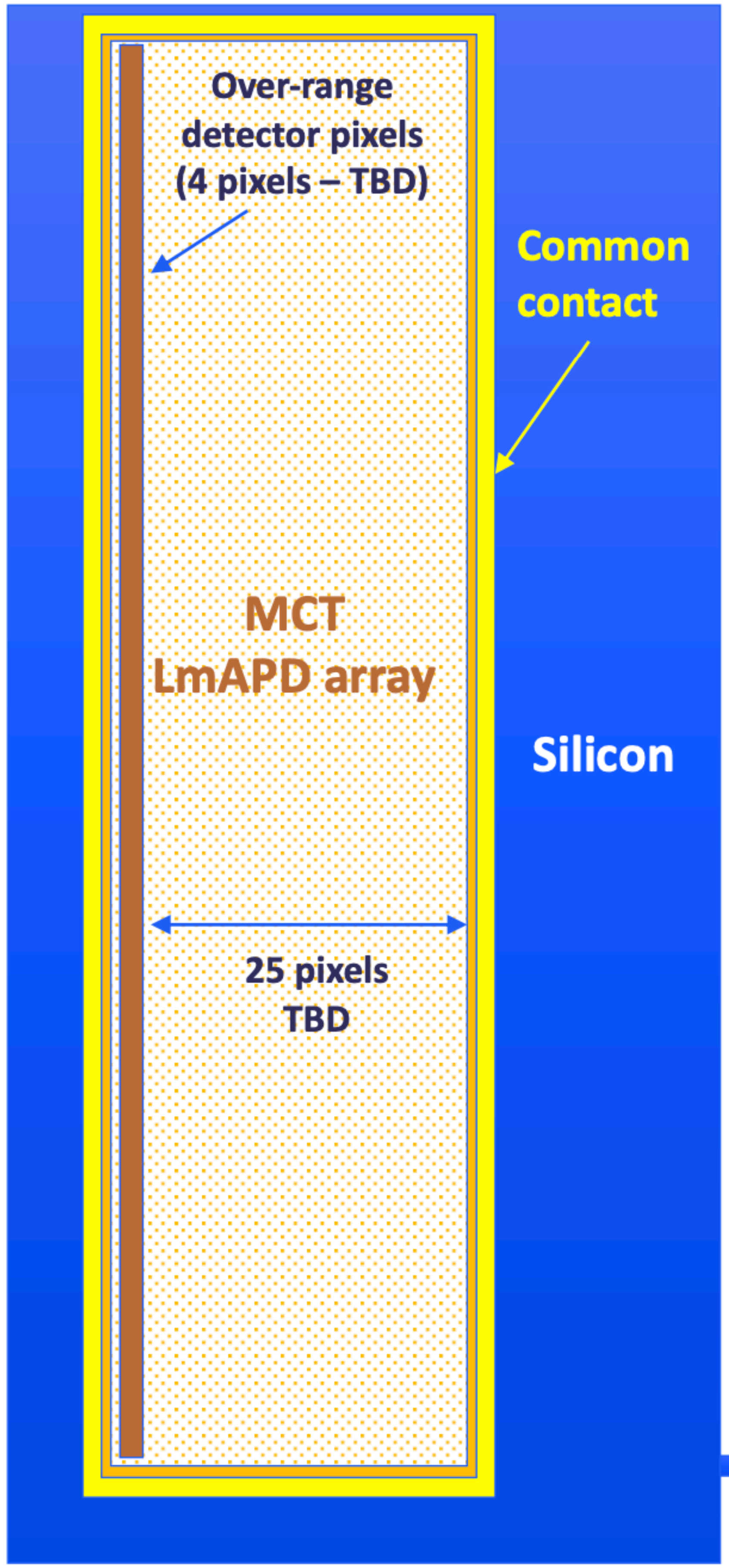
- Technical Readiness Level is relatively high
- Australian National University use them on ground telescopes and plan to deploy them on the ISS
- For wavelength cutoff we have options for 2500nm or 3500nm
  - Do we have important science cases above 2500nm?
  - Too much crowding and blending if we go to very long wavelengths.
  - Too many stars to download - onboard processing needed!
- TDI mode is possible but not for short (< 800nm) wavelengths



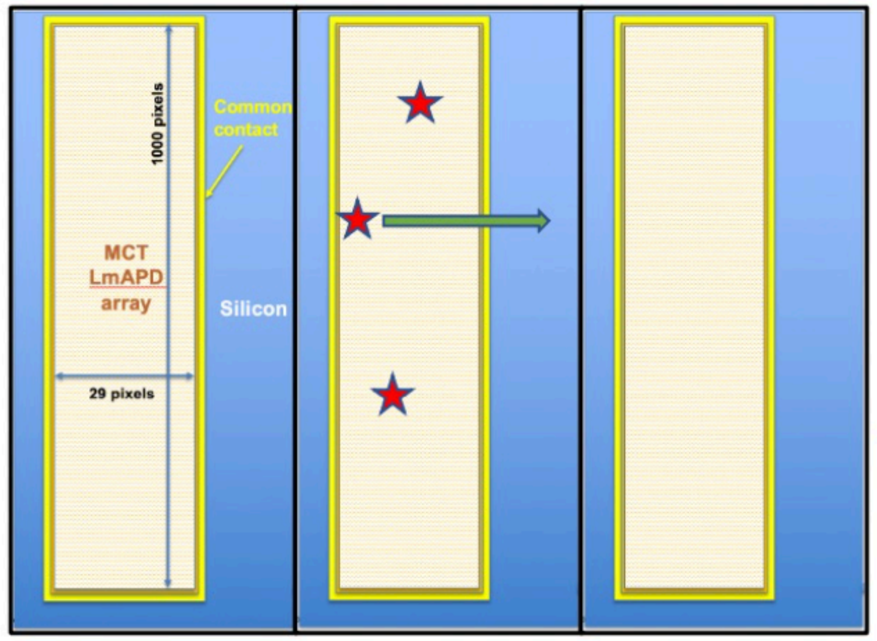
The SAPHIRA is a 320×256 pixel linear-mode avalanche photodiode array capable of 'noiseless' readouts via an upstream signal multiplication of several hundred.

The module concept

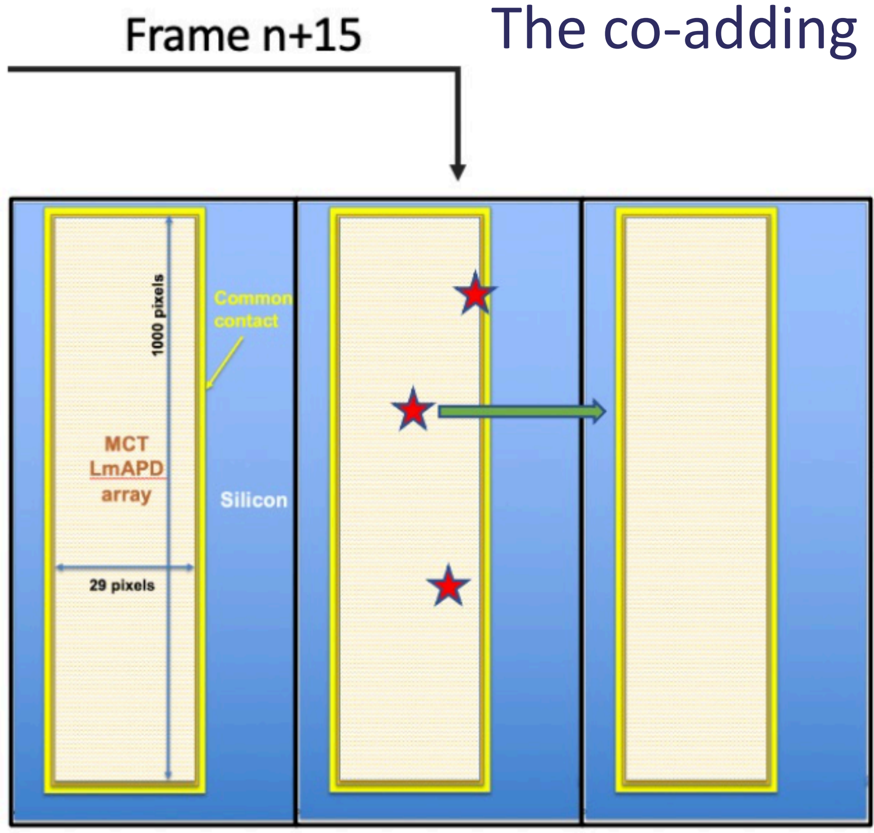
<— 25mm max —> i.e. 1600 pix max



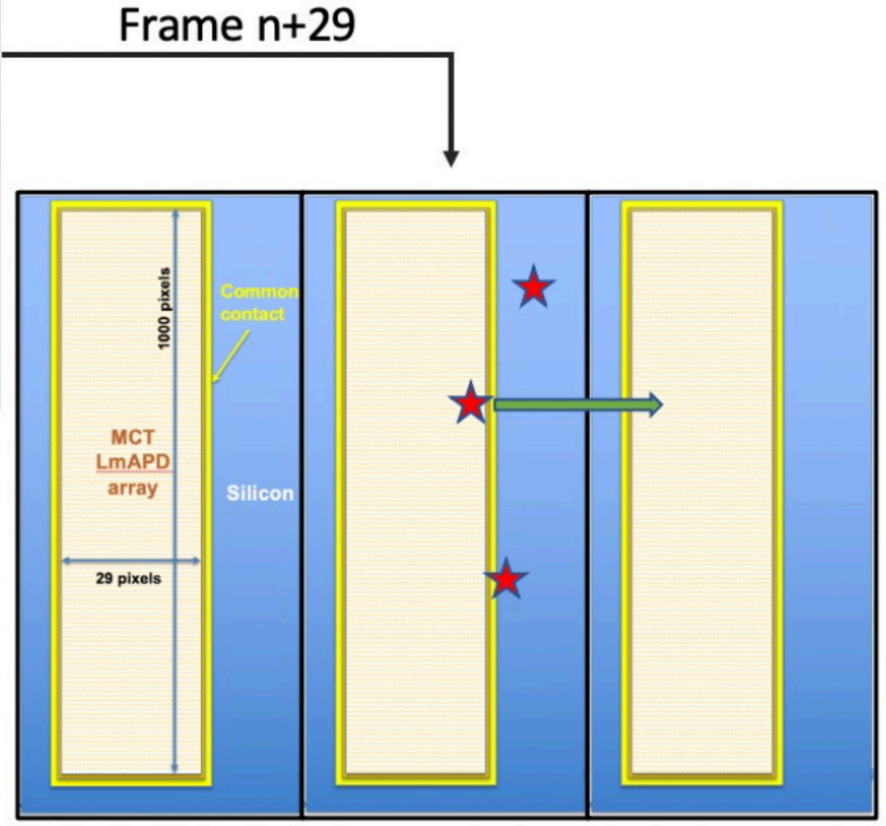
In Gaia with 10micron pixels along scan the dwell time and 4500 TDI stages, the integration time was 4.42s per CCD



The co-adding function is executed in software.



Over range pixels can be controlled to avoid saturate of bright stars and high density fields in the Galaxy!



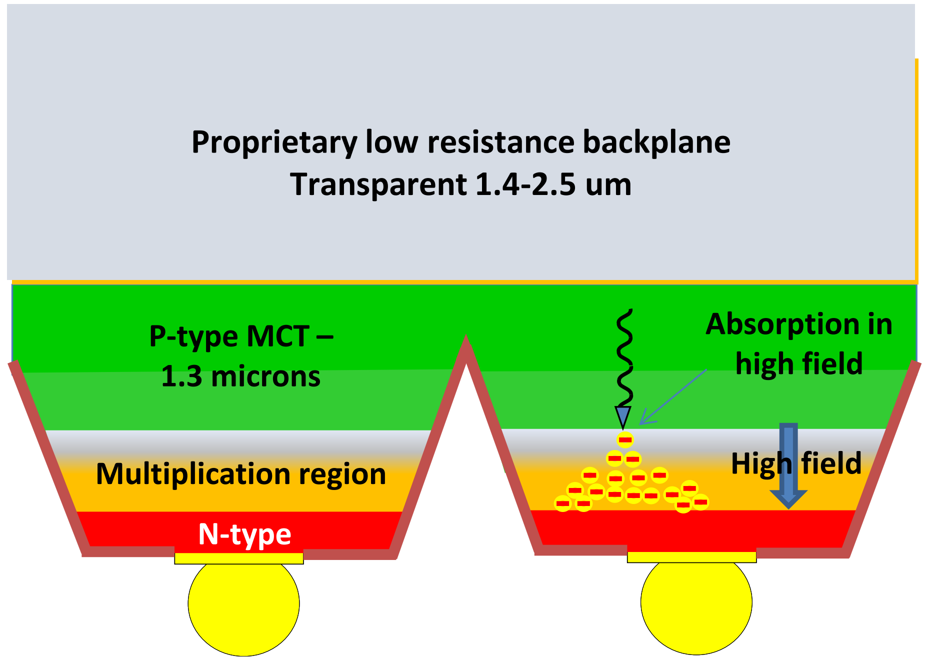
For example, in GaiaNIR, with 15micron pixels the array is read every 1.47ms and with 3000 total TDI stages the combined time is 4.42s is reached

Digital readout (1 frame per TDI shift)

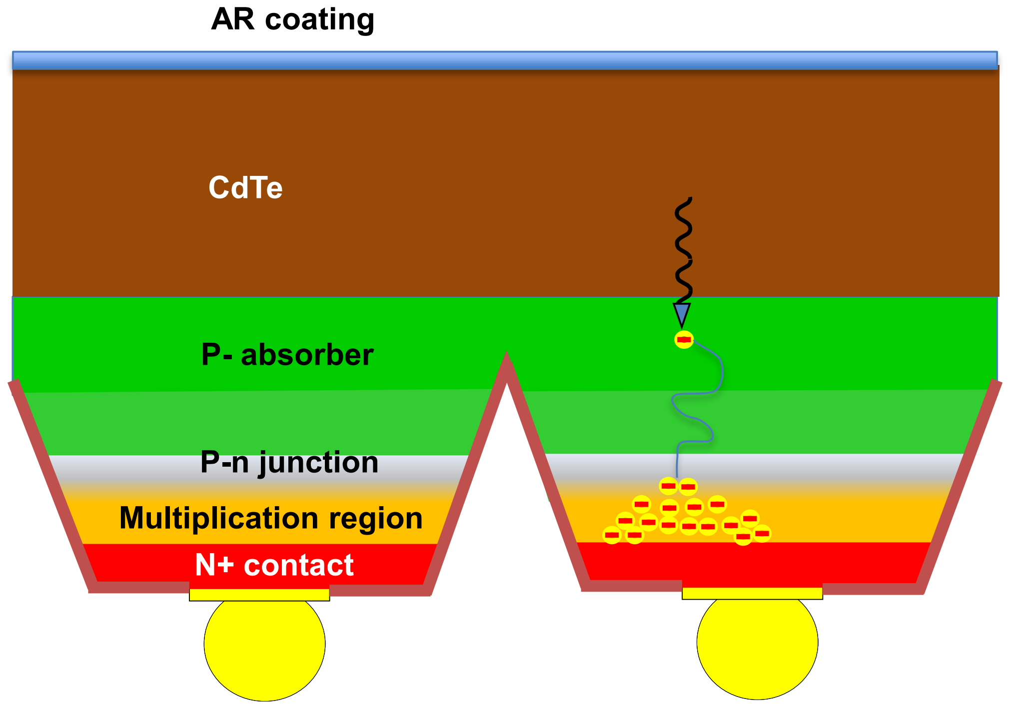
Credit: Oscar Gonzalez (UKATC, STFC-UKRI) Ian Baker (Leonardo)

Quantum Efficiency and wavelength range

Credit: Oscar Gonzalez (UKATC, STFC-UKRI) Ian Baker (Leonardo)



1.45 - 2.5 um – internal QE – 100%



0.8 – 2.5 um – internal QE – 80-85%

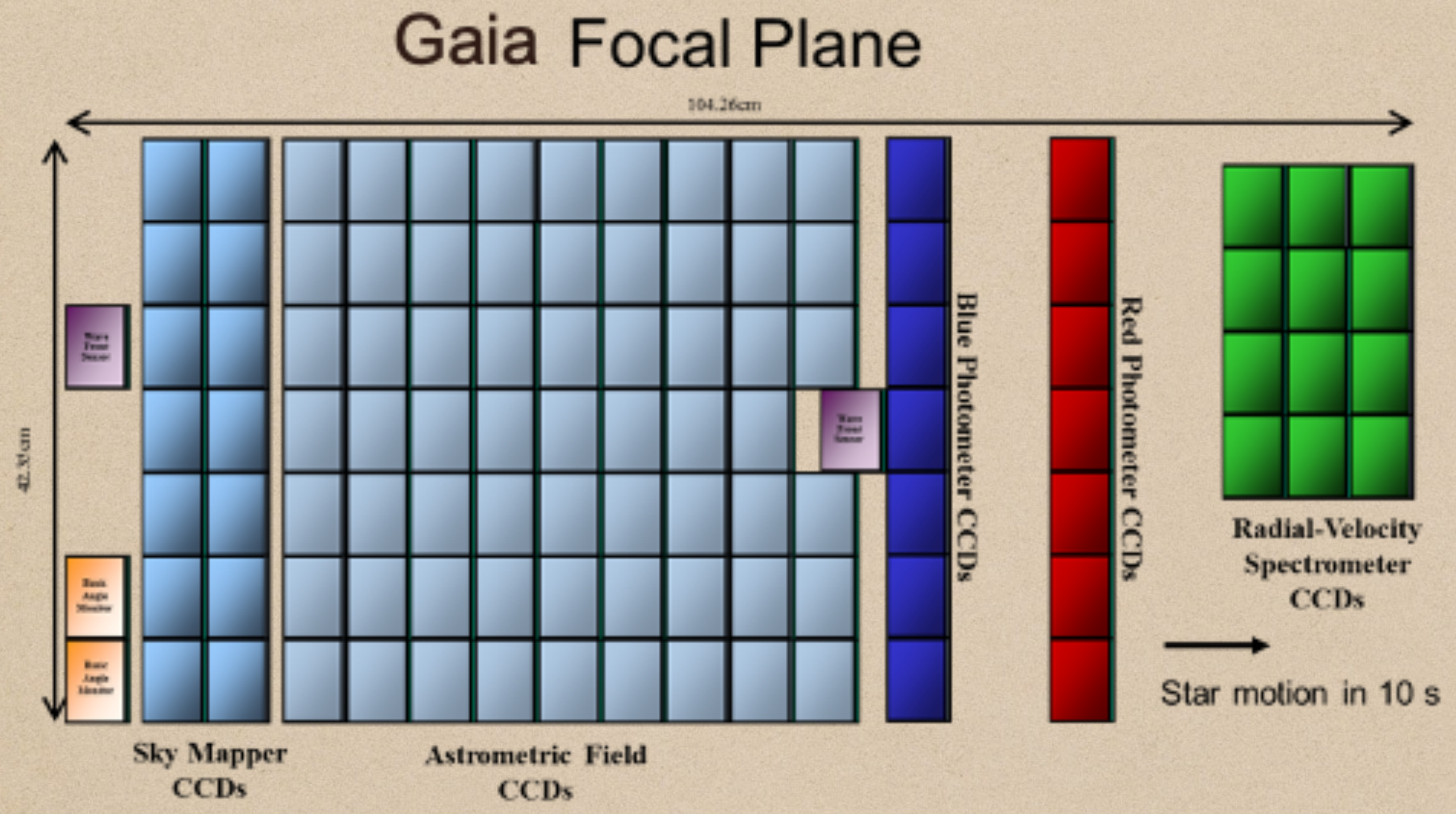
(can be extended to 3.5um)

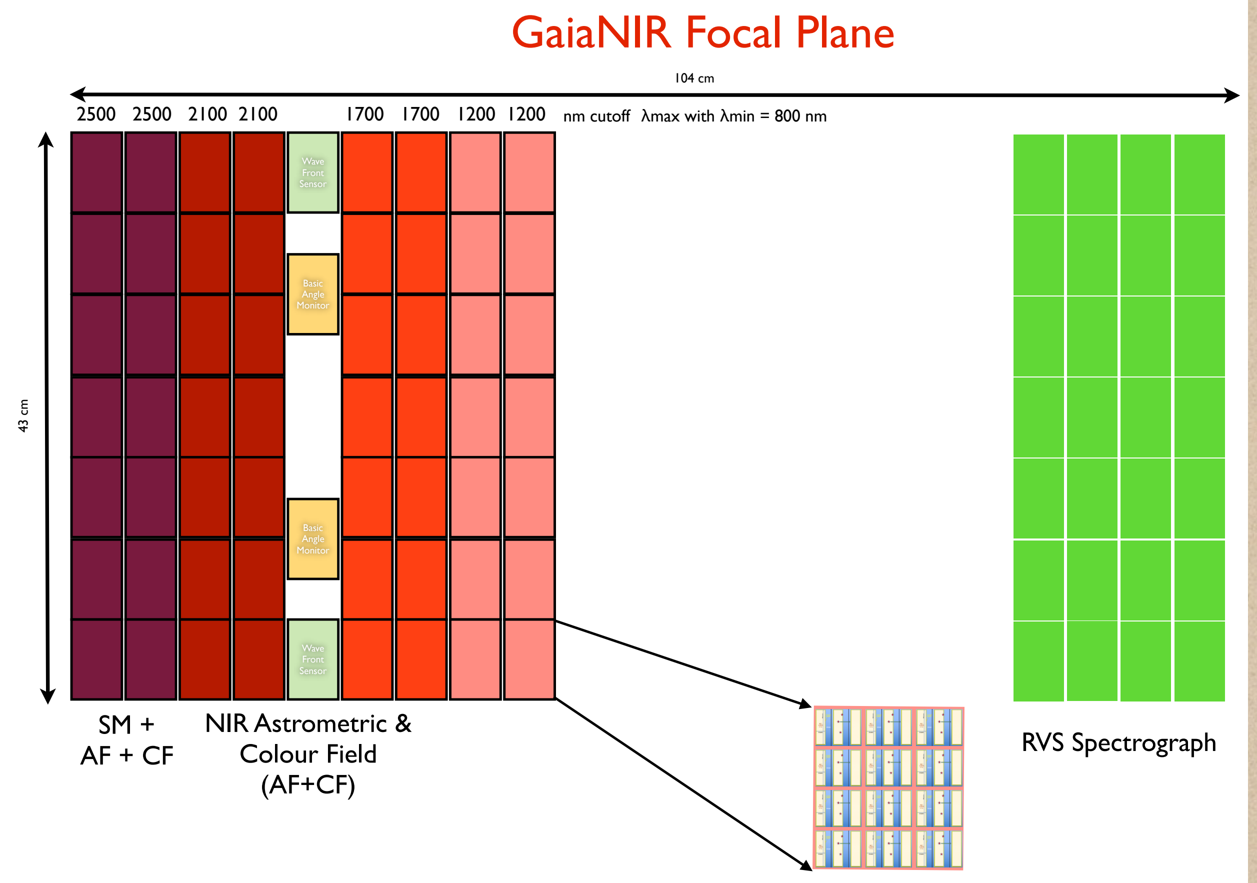
Other suitable coating options offer the possibility to handle wavelength cut-offs to define the Gaia-NIR bands without the use of filters.

Readout noise and dark current

Wavefront sensing applications have driven frames rates up to 200 kframes/s and avalanche gains to x600 achieving **read noise as low as 0.26 e- rms** and enabling single photon counting.
Work at the University of Hawaii and European Southern Observatory has demonstrated dark currents in the **4-10 electrons/hour** range and, with avalanche gain, offers the prospect of much higher science return from ground-based and space-based astronomical telescope projects.

The Focal Plane & Filters





4x3x3= 36 APDs (TBD)

- Linear Mode APDs are the most promising detector for GaiaNIR
- Cooling strategy must be passive (~90K)
- We can live with poorer astrometry for blue stars (<800nm)
- Max wavelength - 2500 nm
- Filter photometry with different λ cutoffs can be achieved in manufacture or by depositing filter material
- No SMs - track motion of stars instead to determine the FoV
- An RVS Spectrograph is a great opportunity? - space is available for more full wavelength detectors!

End Of Mission Accuracy

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

p_{det} is the detection probability in a single transit;

σ_ξ angular uncertainty AL from one CCD transit [rad];

σ_{cal} accuracy of astrometric or photometric calibration [rad];

N_i is the number of instruments and m is a safety factor of 20%.

$$\tau = \frac{L\Omega}{4\pi} = \text{Total integration time on object per source[s]}$$

$$\tau_1 = \frac{N_\xi \Delta\xi}{\omega} = \text{Integration time per CCD[s]}$$

where

ω is the scan speed [rad s^{-1}];

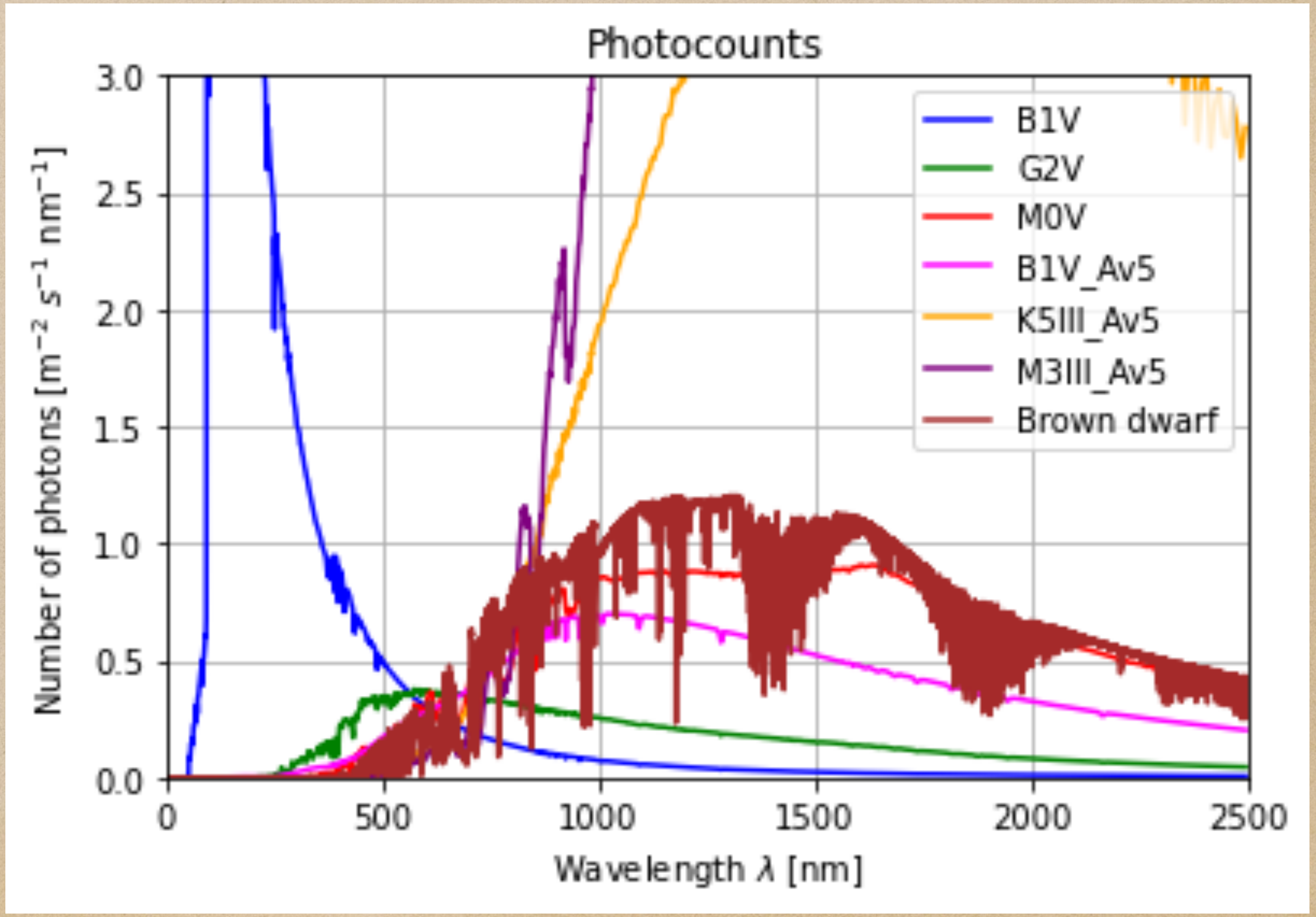
$\Delta\xi$ is the angular pixel size along scan [rad] and;

N_ξ is the number of pixels per CCD in the scan direction [e−].

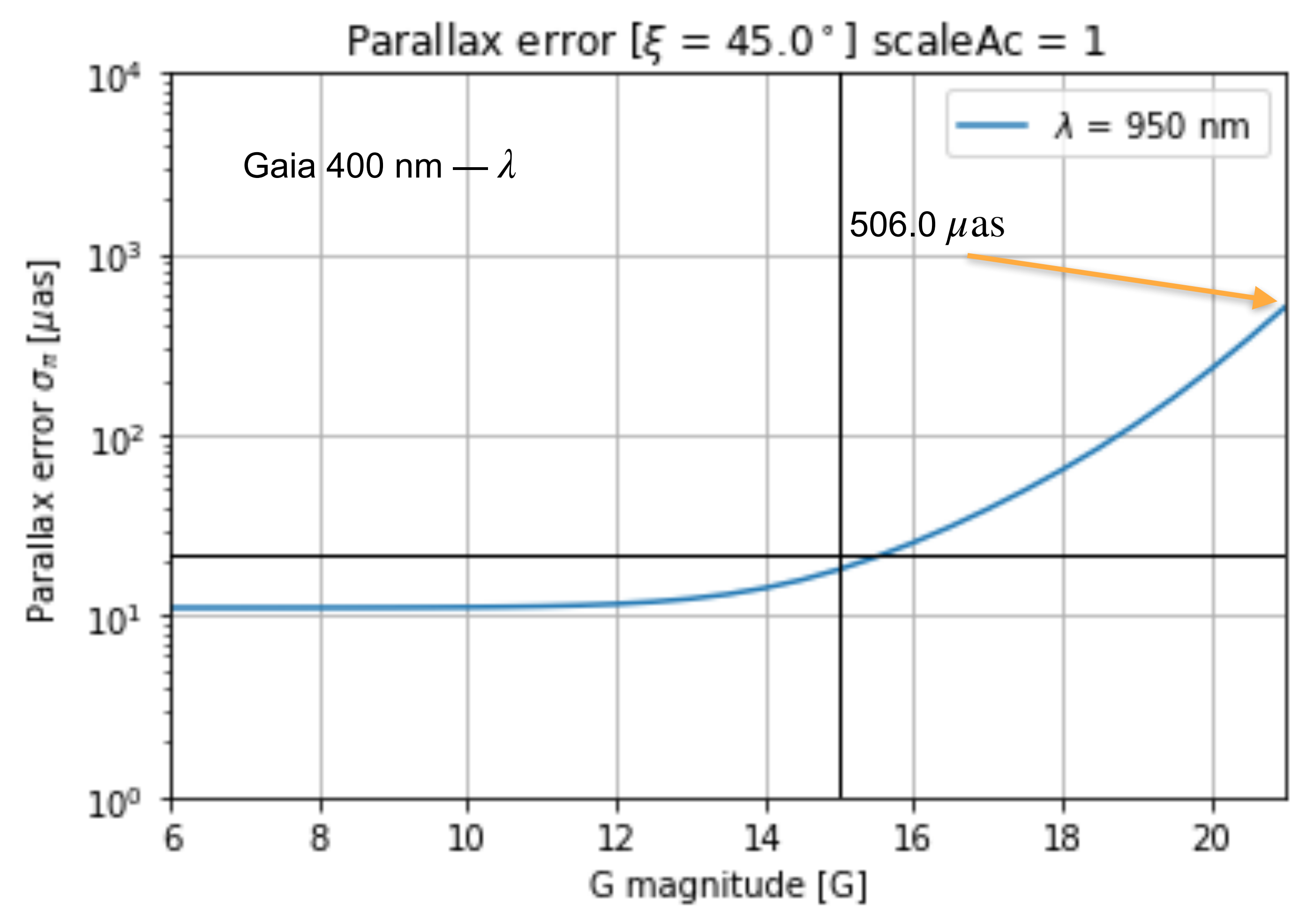
L = effective mission length (i.e. excluding dead time);

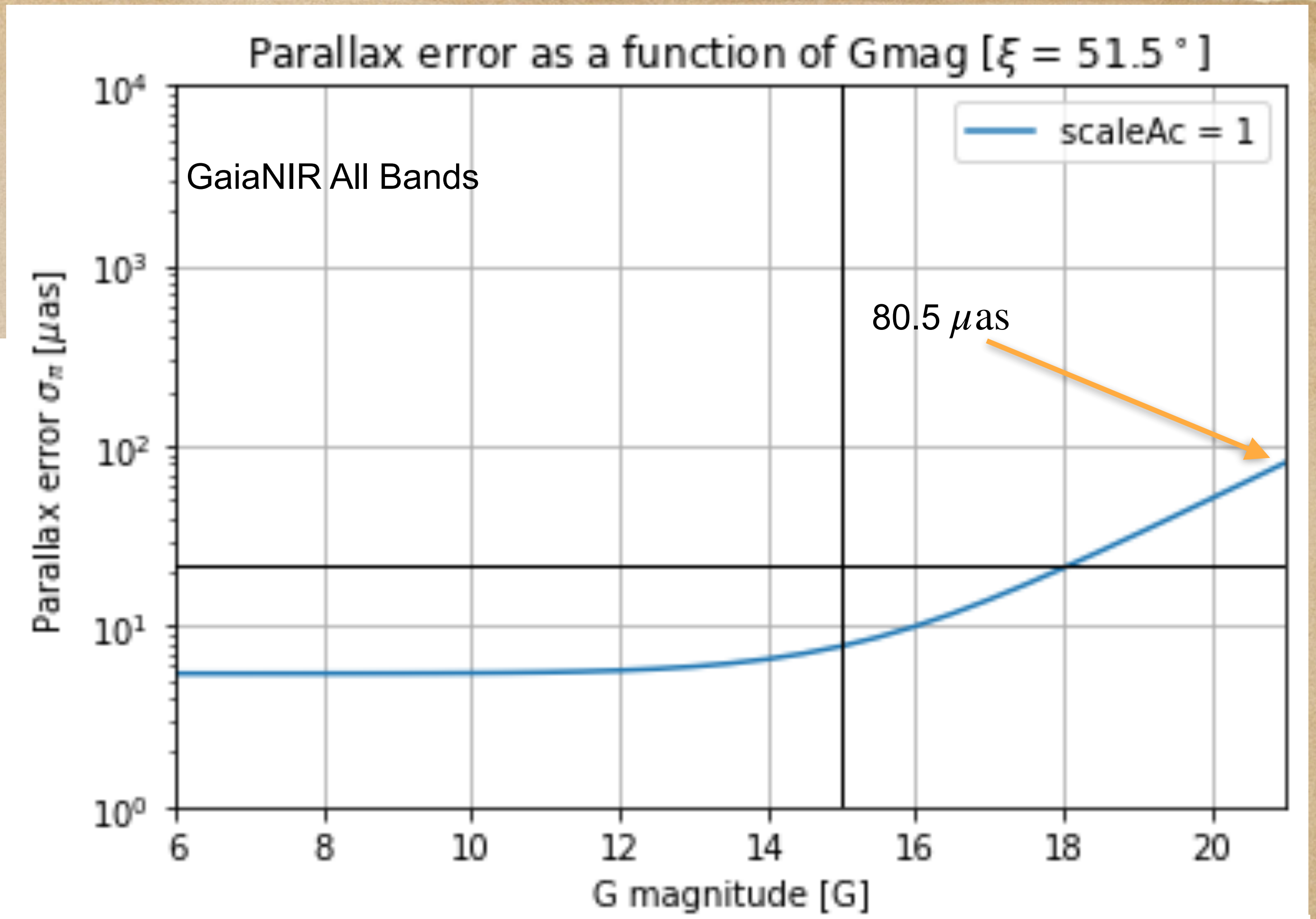
$\Omega = 1.2\ \mathrm{deg}^2$ = detector solid angle per instrument

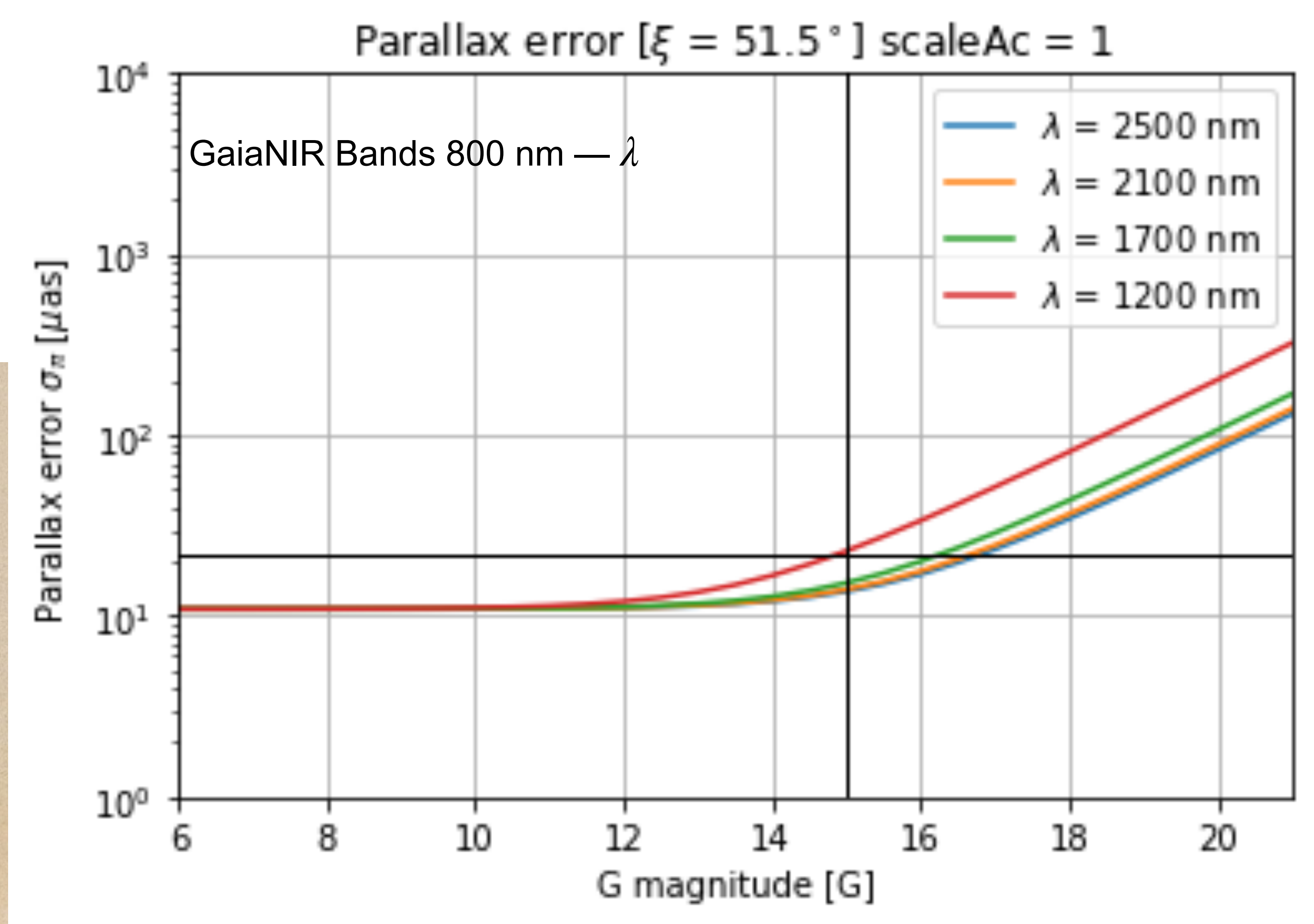
$g_\varpi = 1.47(sin\ \xi)^{-1}$ Sky averaged parallax factor



Detector Comparison

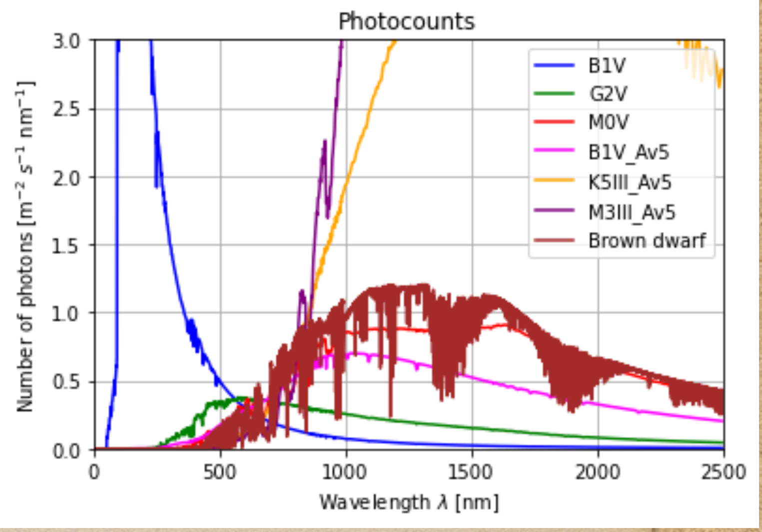






- Identical runs for M3III_Av5_T_{eff}3500_logg2.0_feh giving a comparison between Gaia CCDs and GaiaNIR.
- APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs

GaiaNIR vs Gaia



Faint red stars are better in GaiaNIR compared to Gaia

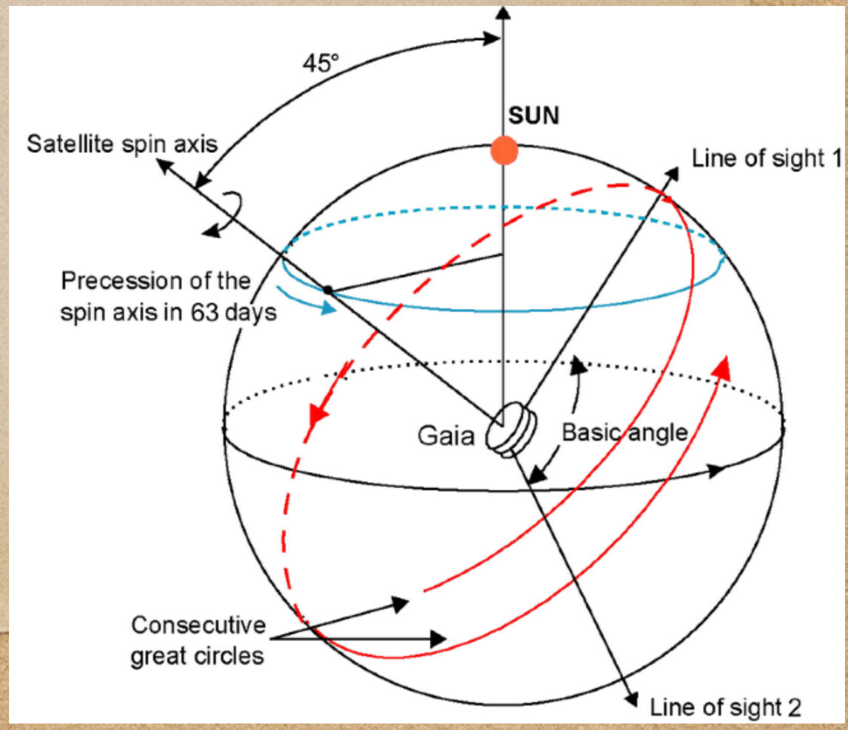
- Lower read noise gives a linear increase with magnitude and helps faint stars most
- Most stars are faint!
- Red star long wavelength range helps recover good accuracy!
- Blue stars still work but are less accurate!

ξ=51.5°	**B1V**	**G2V**	**M0V**	**B1V Av5**	**K5III Av5**	**M3III Av5**	**Brown Dwarf_{2000K}**
Bright ✮ G= 6	2.0	2.0	2.0	2.0	2.0	2.0	2.0
G=15 mag	0.4	0.7	1.2	1.1	2.0	2.3	1.3
G=21 mag	0.6	1.3	2.6	2.2	4.7	6.3	2.7

Can we get billions of RV's?

RV's are super important for Galactic dynamics

- The RV spectrograph was avoided to fit in a Medium-class mission. A downside is that it would increase the costs the data rate significantly but the science return could be outstanding
- However, if we slow the scan rate for part of the mission we could get large numbers of RV's - e.g. 2 yrs Astrometry + 2 yrs Spectroscopy, etc.
- A slow scan rate would also allow a deeper survey
- A long baseline still gives good astrometry as gaps in the normal scanning law do not matter much
- All this could allow a deep RV survey for billions of objects (at a € cost)



Summary

Conclusions of comparison of Gaia CCDs and GaiaNIR APDs

- For Gaia CCDs we reproduce the nominal accuracy (slightly better due to simple models)
- 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 (~23rd 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 could give a deep all-sky astrometric and RV survey for billions of objects!

The Hera Mission - Creation of the Milky Way

One legend explains how the Milky Way was created. Zeus was fond of his son, who was born of the mortal woman Alcmene.

He let the infant Heracles suckle on his divine wife Hera's milk when she was asleep, an act which would endow the baby with godlike qualities.

When Hera woke and realized that she was breastfeeding an unknown infant, she pushed him away and the spurting milk became the Milky Way.

The Birth of the Milky Way - Peter Paul Rubens (1577–1640)