The GaiaNIR mission and the hidden regions of our Galaxy
Overview and Status

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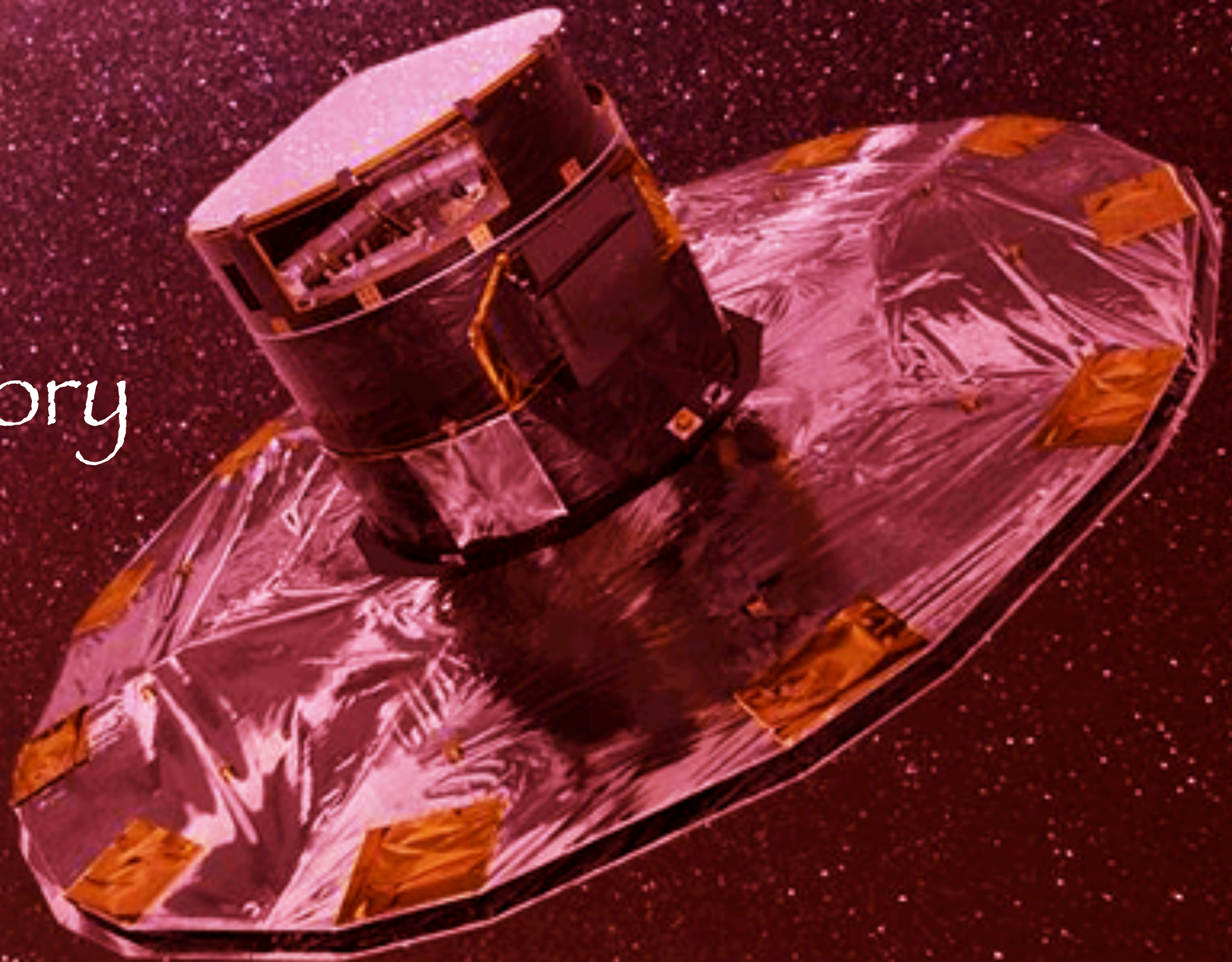
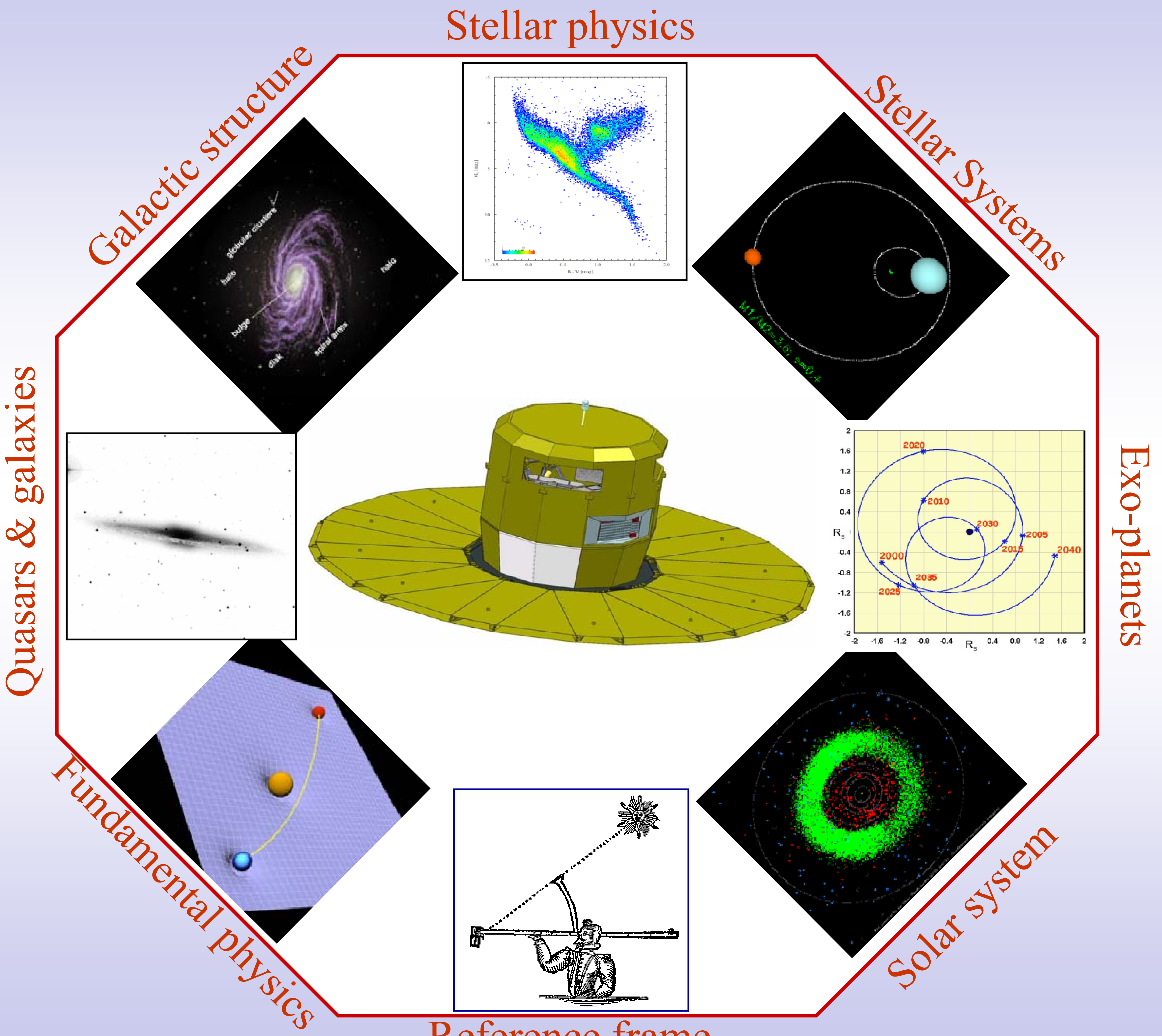


Gaia Science Objectives

GaiaNIR is similar but on a grander scale

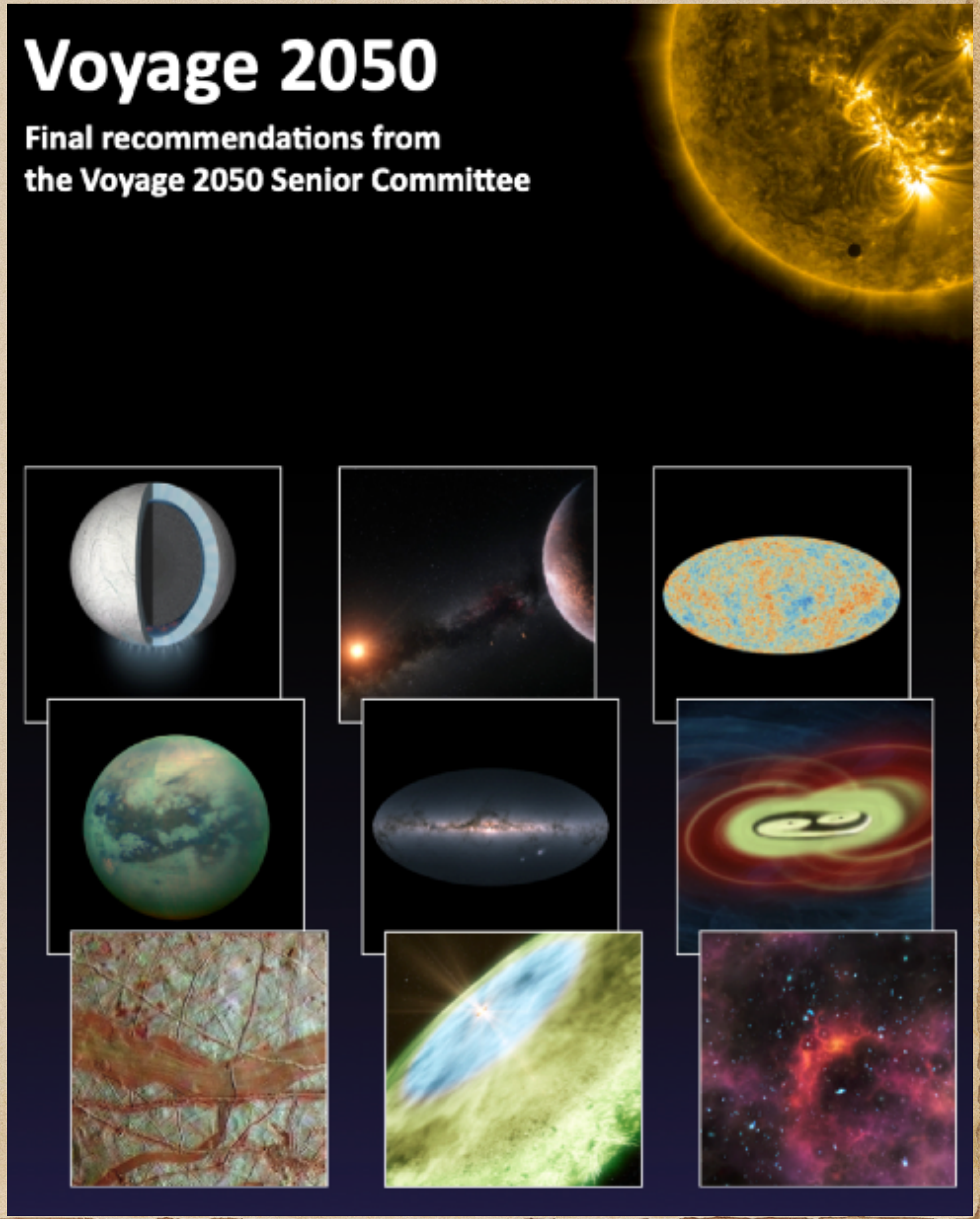


Science Cases

1. Adding NIR astrometry and photometry to probe the dynamically important hidden regions of the Galaxy giving at least 12 billion stars. Going deeper could give up to 75 billion stars (~25% of the Galaxy)
2. A combining GaiaNIR with ~2.0 billion common stars from Gaia with a 20 yr time gap would give much better PM's
3. Resetting the Gaia optical RF and catalogue. Expansion of the optical RF to the NIR is super important

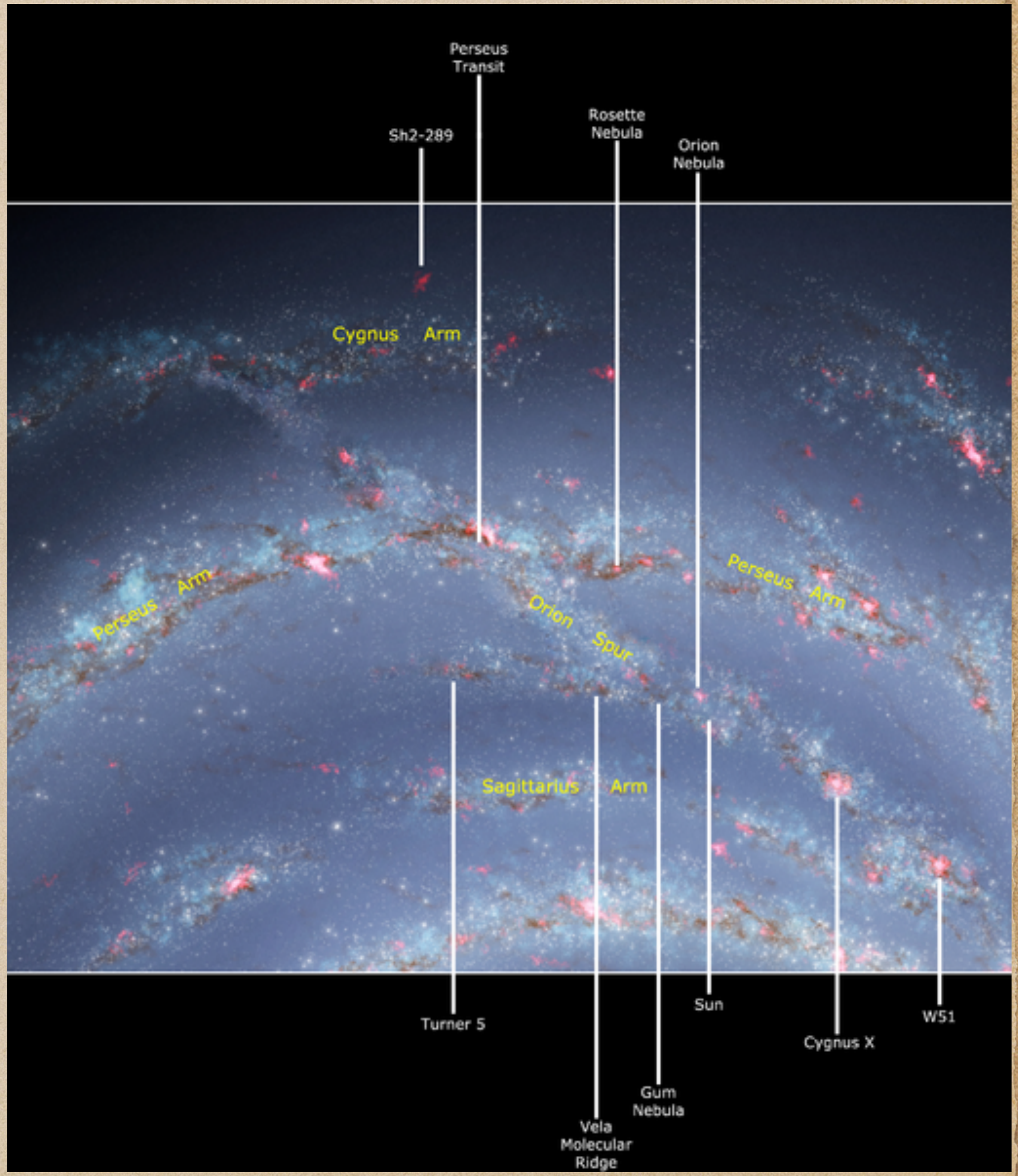
https://link.springer.com/article/10.1007/s10686-021-09705-z

4. Low resolution dispersion spectra for most of the stars
5. Adding a radial velocity spectrograph could give vast numbers of radial velocities - maybe a billion!



1. NIR Astrometry

- Dusty Bulge/bar region is dynamically important:
  - E.g. radial migration, bar perturbations of the bulge
- Probe DM in the thin and thick disc and spiral arms
- Unveil the inner disk which is not well known
- Map the dusty spiral arms - astrometry for billions 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.

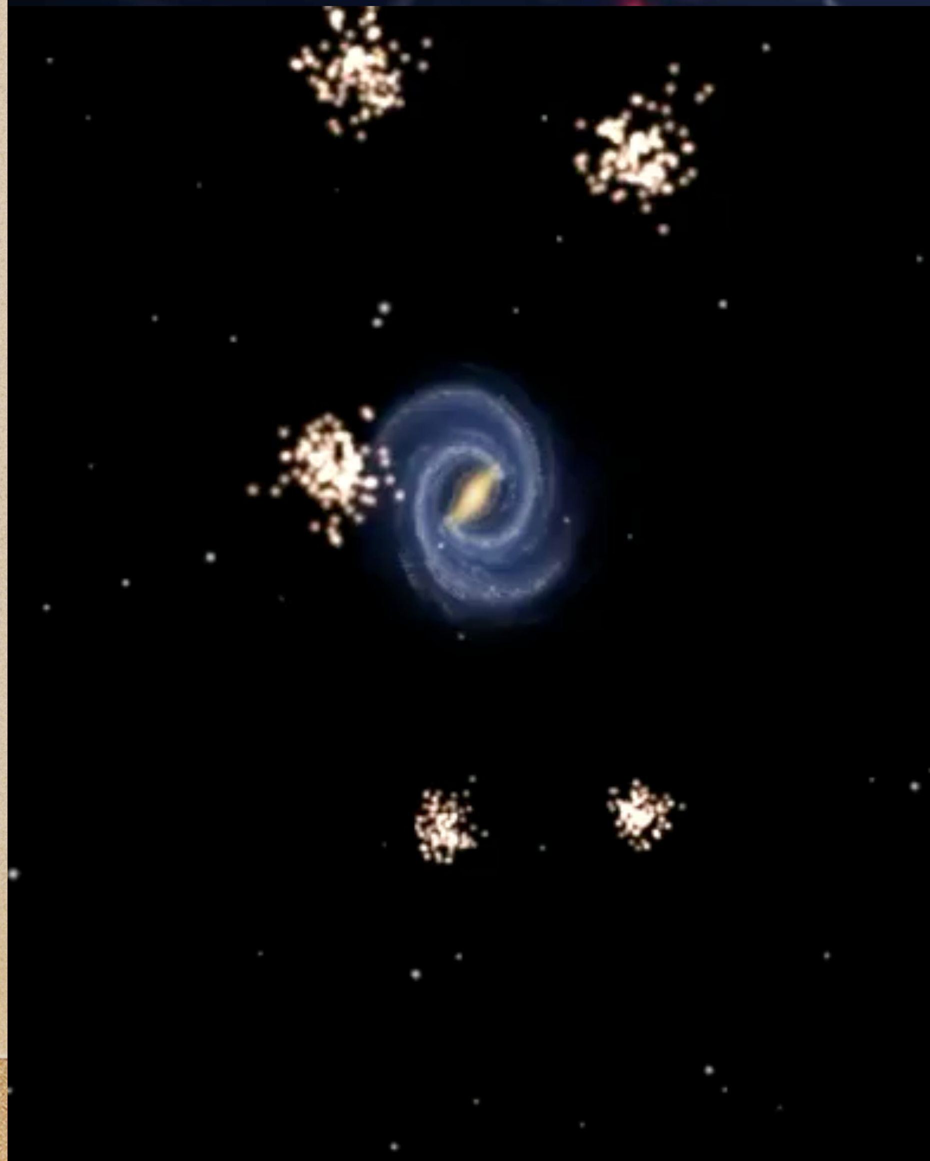


All of this for 10-75 billion new stars!

2. Improved Accuracy

- Improved PMs allow sub-structure in streams, dwarf galaxies and the Halo to be resolved
- Better estimates of our Galaxies mass
- Study the cusped/core (flat) dark matter density profile in clusters?
- Indirectly detect IMBH's in globular clusters?
- Internal dynamics of local group galaxies, dwarf sph., 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 periods up to 40 yr (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 at least 2 billion Gaia stars!



Nano-arcsec yr^{-1} PMs

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

$$\sigma_\mu = \frac{\left(\sigma_{\mathrm{pos}_N}^{-2} + \sigma_{\mathrm{pos}_G}^{-2}\right)^{-\frac{1}{2}}}{t_N - t_G}$$

$$\sigma_\mu = \frac{\left[\left(\frac{17.6}{\sqrt{2}}\right)^{-2} + \left(\frac{17.6}{\sqrt{2}}\right)^{-2}\right]^{-\frac{1}{2}}}{20+5+5} = 0.29\ \mu\mathrm{as\ yr}^{-1}$$

$$\sigma_\mu = \frac{\left[\left(\frac{15.4}{\sqrt{2}}\right)^{-2} + \left(\frac{15.4}{\sqrt{2}}\right)^{-2}\right]^{-\frac{1}{2}}}{20+5+5} = 0.26\ \mu\mathrm{as\ yr}^{-1}$$

Euclid, Roman, and JASMINE provide NIR stars

2055

2050

An earlier launch will decrease the PM accuracy

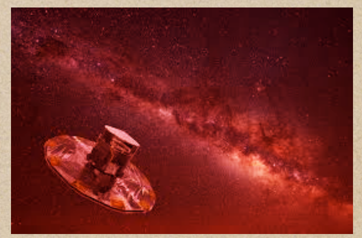
2045

A 20 year gap

2025

2020

2015



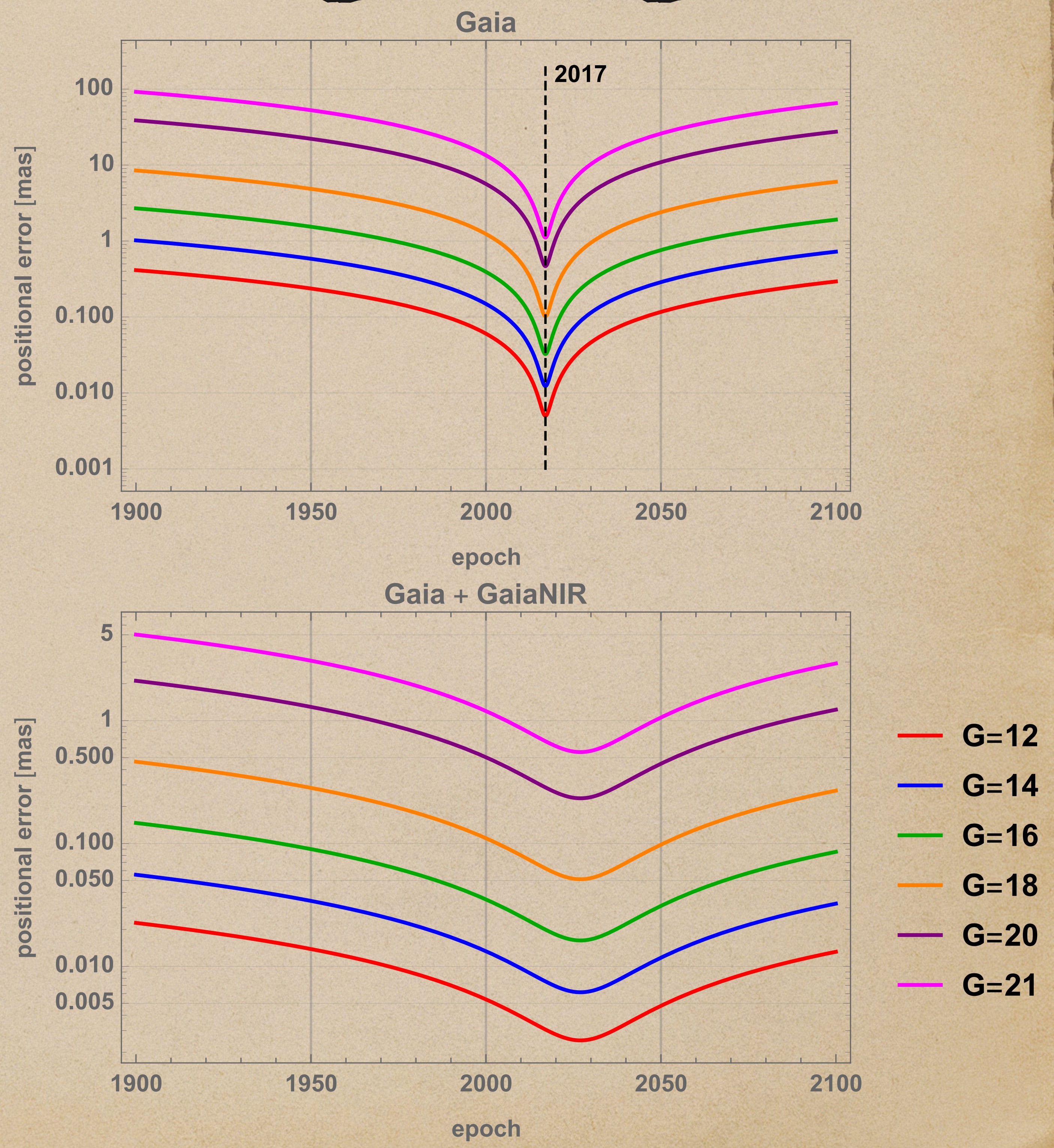
Second Epoch GaiaNIR 10yr (2050)

First Epoch Gaia 10yr (2020)

More than an order of magnitude improvement in PM's compared to Gaia DR4 giving nano-arcsec PMs for some common stars.

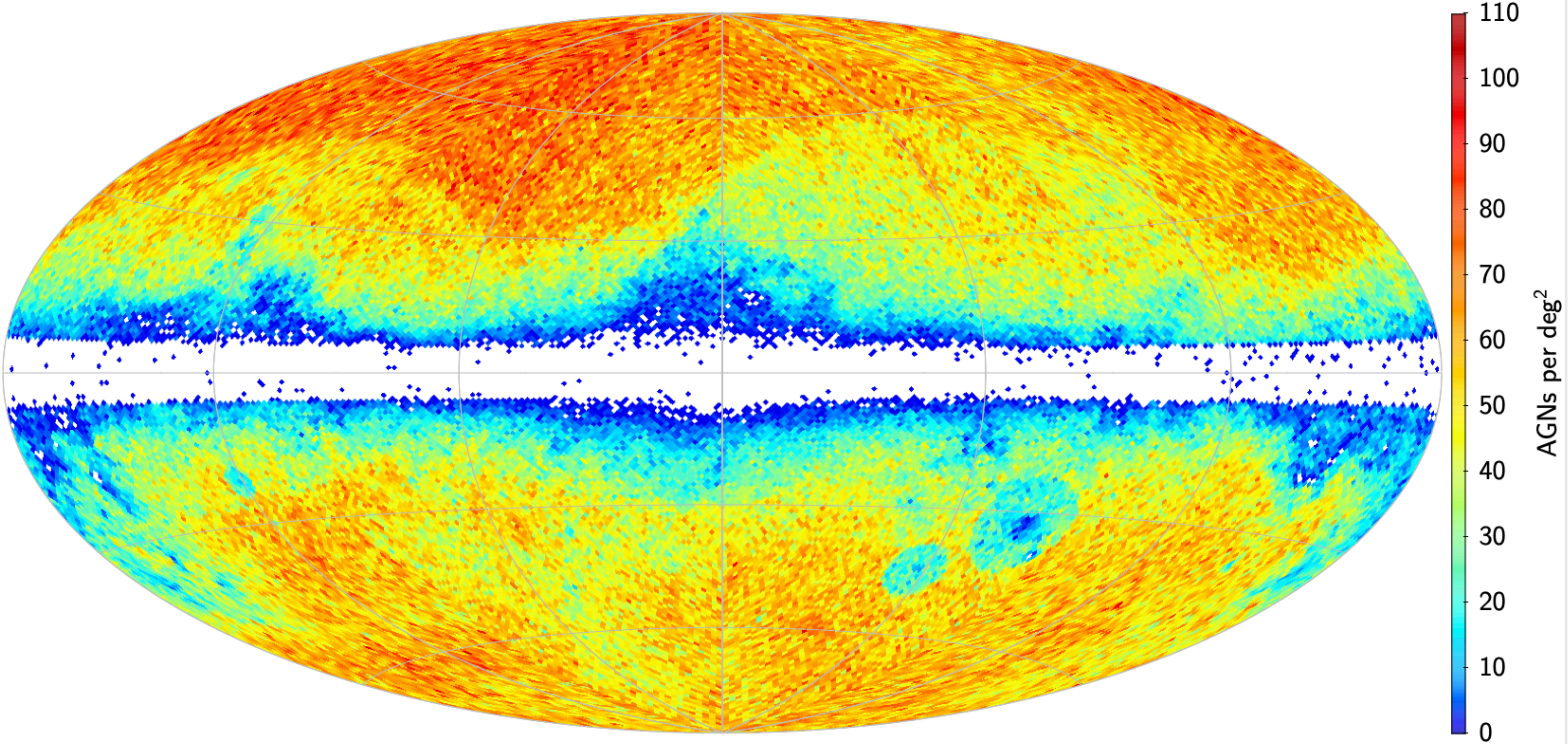
3. RF & Catalogue Ageing

- The RF degrades slowly (RF spin accurate to < 0.5 μas yr^{-1}) and will remain accurate for 100's of years
- The positional accuracy of the catalogue will degrade due to PM errors - requiring a new mission to correct 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
- Fundamental physics spin offs such as PM patterns, e.g. Galactic-centric acceleration of ~5.0 μas yr^{-1}, 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.

Gaia DR3: Sky distribution of the 1.6 million Gaia-CRF3 sources.

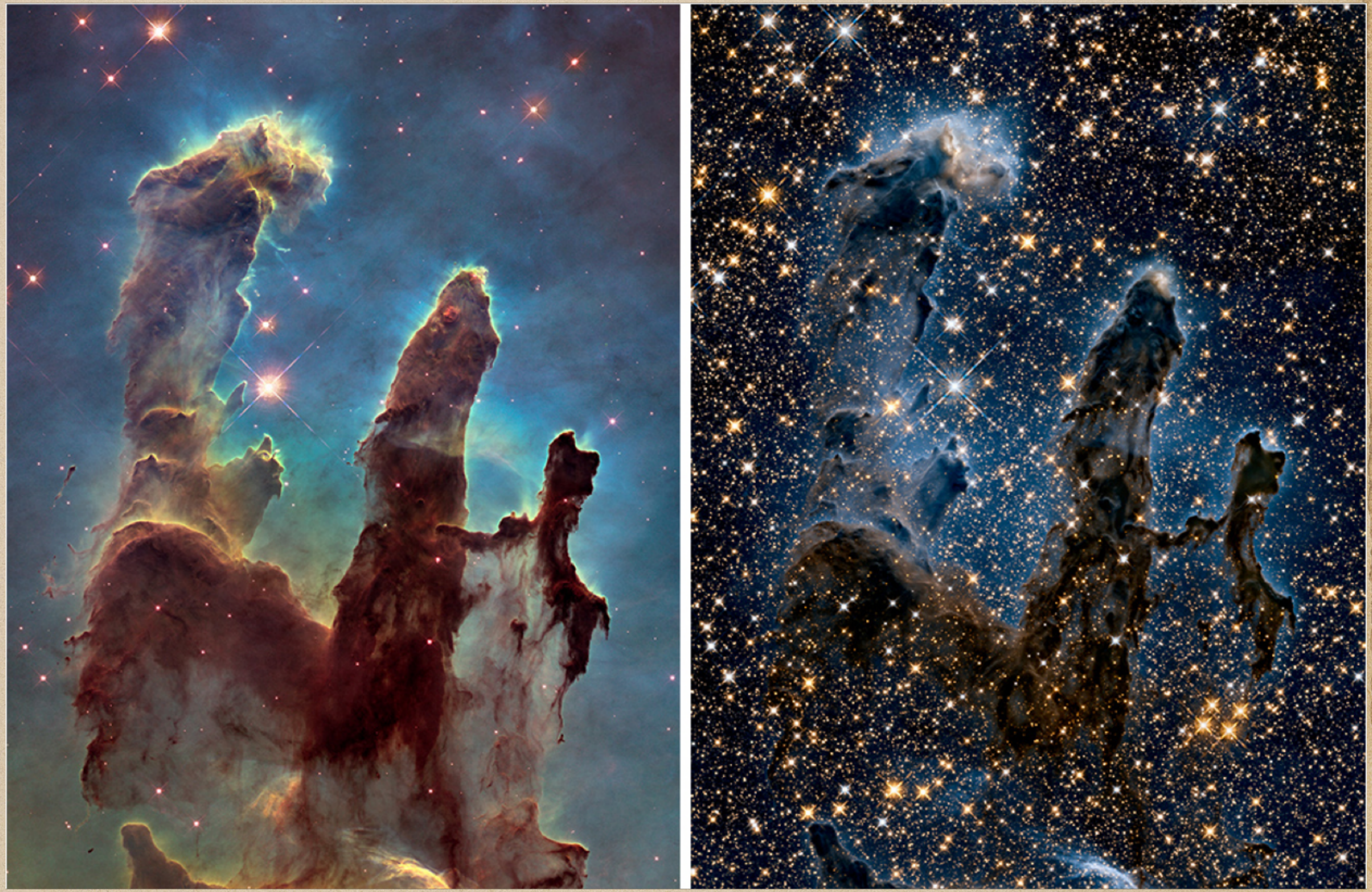


The big science questions!

- A new mission can measure the hidden stars not seen by Gaia!
- NIR science cases lie in the Galactic plane (Bulge/bar/disc) and star forming regions
  - Connections to early universe cosmology!
- Better PM accuracy will allow, for e.g.:
  - PMs of galactic streams can probe halo DM structure;
  - PMs in clusters can probe their halo DM;
- Long period binaries and exoplanets (solar system analogues)
- GaiaNIR will map the Galaxy and answer big science questions in many areas of astronomy!

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
- Each entrance pupil is at a flat folding mirror in front of the primary

GaiaNIR$_{Small}$

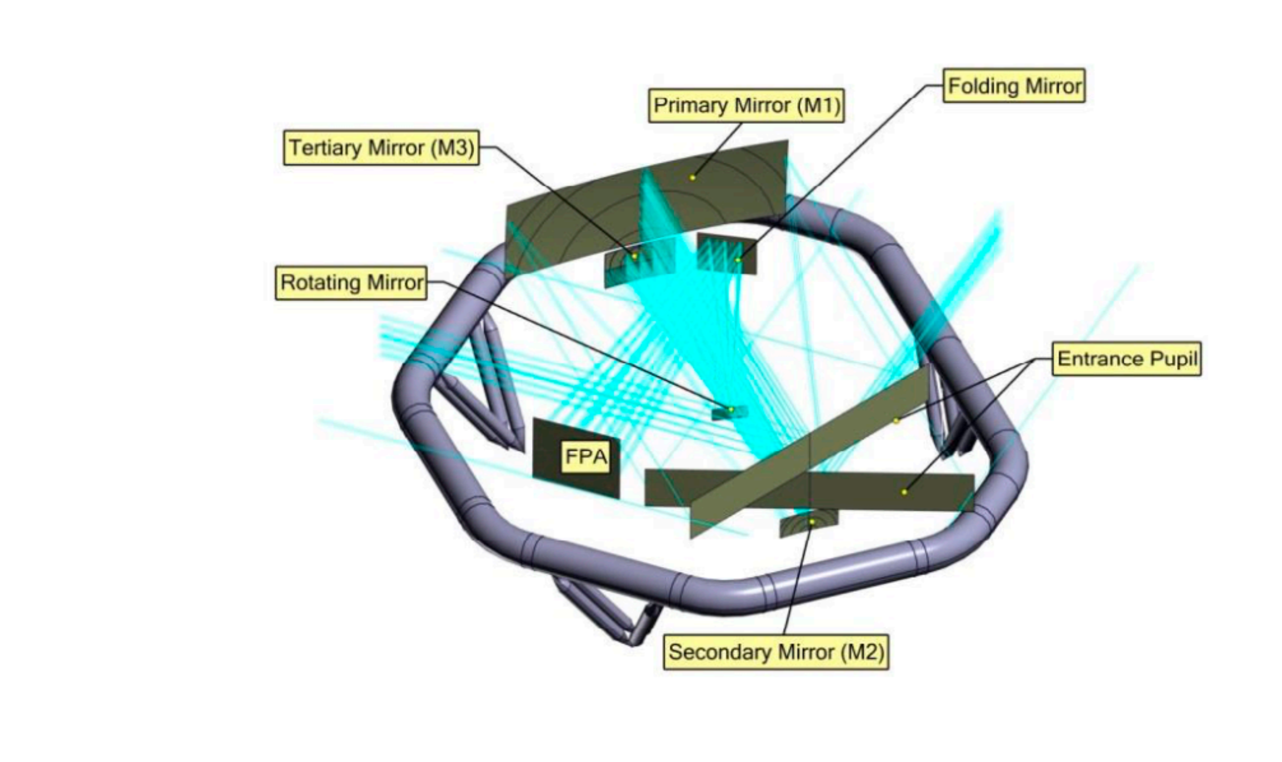


Figure 5-34: GaiaNIR optical surfaces and the light path

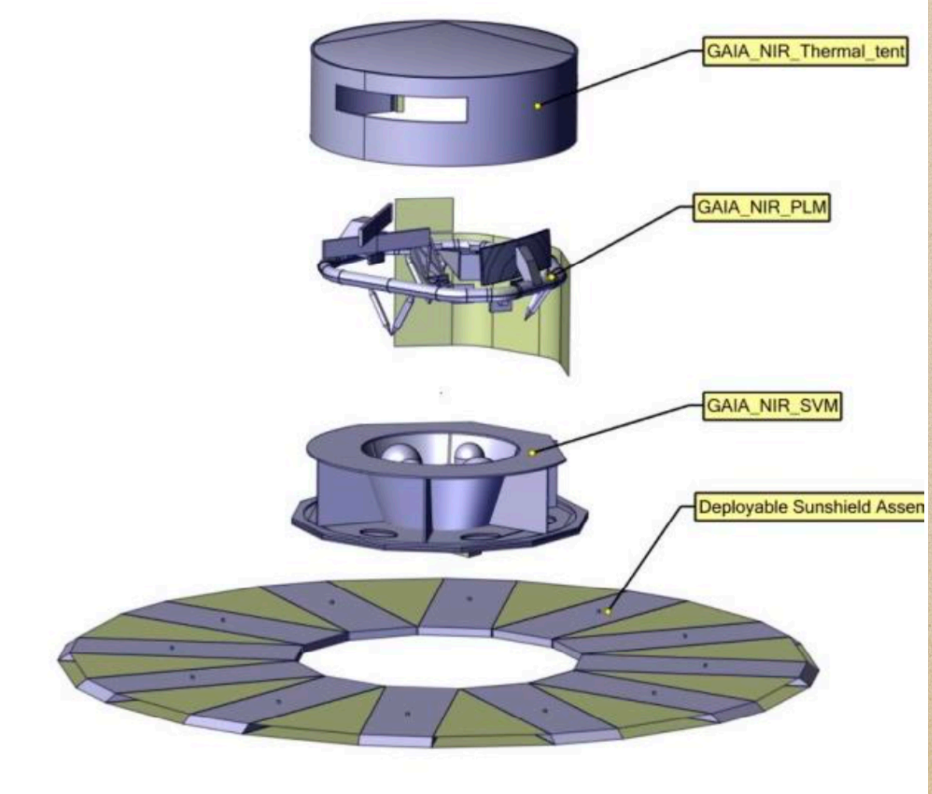


Figure 6-2: Gaia-NIR Spacecraft main elements

- 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)

GaiaNIR$_{Large}$

M1

D = 1.7m

D = 1.7m

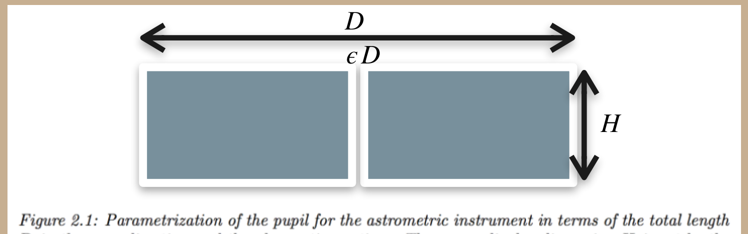


Figure 2.1: Parametrization of the pupil for the astrometric instrument in terms of the total length D in the scan direction and the obscuration ratio ϵ. The perpendicular dimension H is set by the (fixed) total area A = (1 − ϵ)DH.

New Design

Mission	Resolution
Gaia (λ_{mid}=700nm)	0.12“ with D=1.45m
GaiaNIR$_{Medium}$ (λ_{mid}=1600nm)	0.24” with D=1.7m
GaiaNIR$_{Large}$ (λ_{mid}=1600nm)	0.12” with D=3.5m

Drawing not to scale

Two Improvements:

- double the width of flat BA mirrors
- a segmented primary mirror

BA

D_{max} = 3.5m

The resolution and parallax errors are inversely proportional to the length of the primary mirror D_{max}

$$\sigma_\varpi \propto \frac{\lambda}{D\sqrt{N}\sin\xi}$$

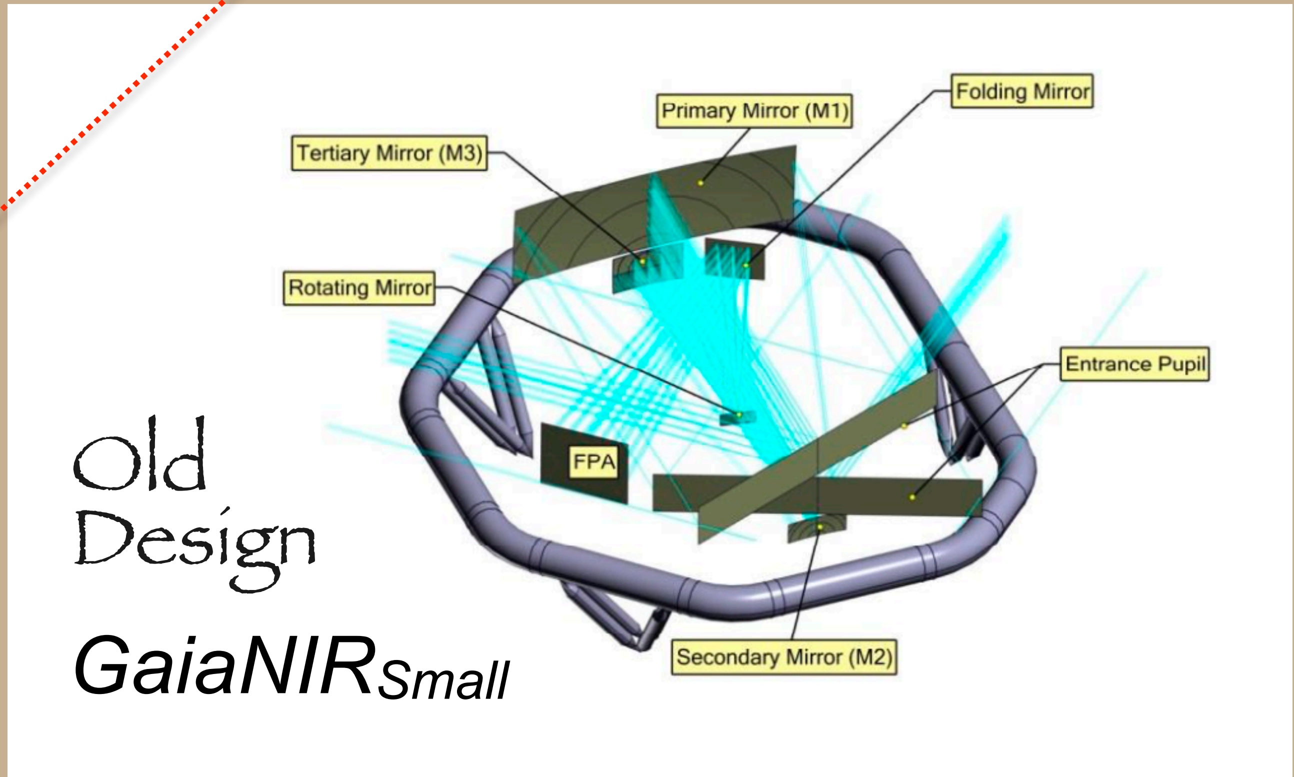


Figure 5-34: GaiaNIR optical surfaces and the light path

Detector Status

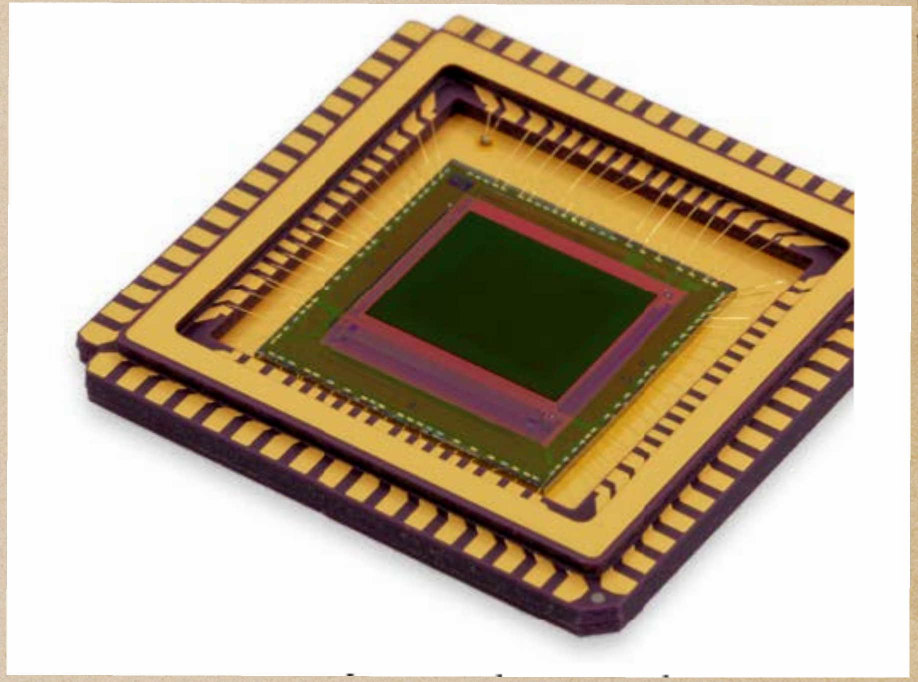
Italian owned Leonardo UK have small APDs with high frequency readout

APDs amplify and measure signals in photon starved environments

GHz variant high speed devices possible for TDI operation

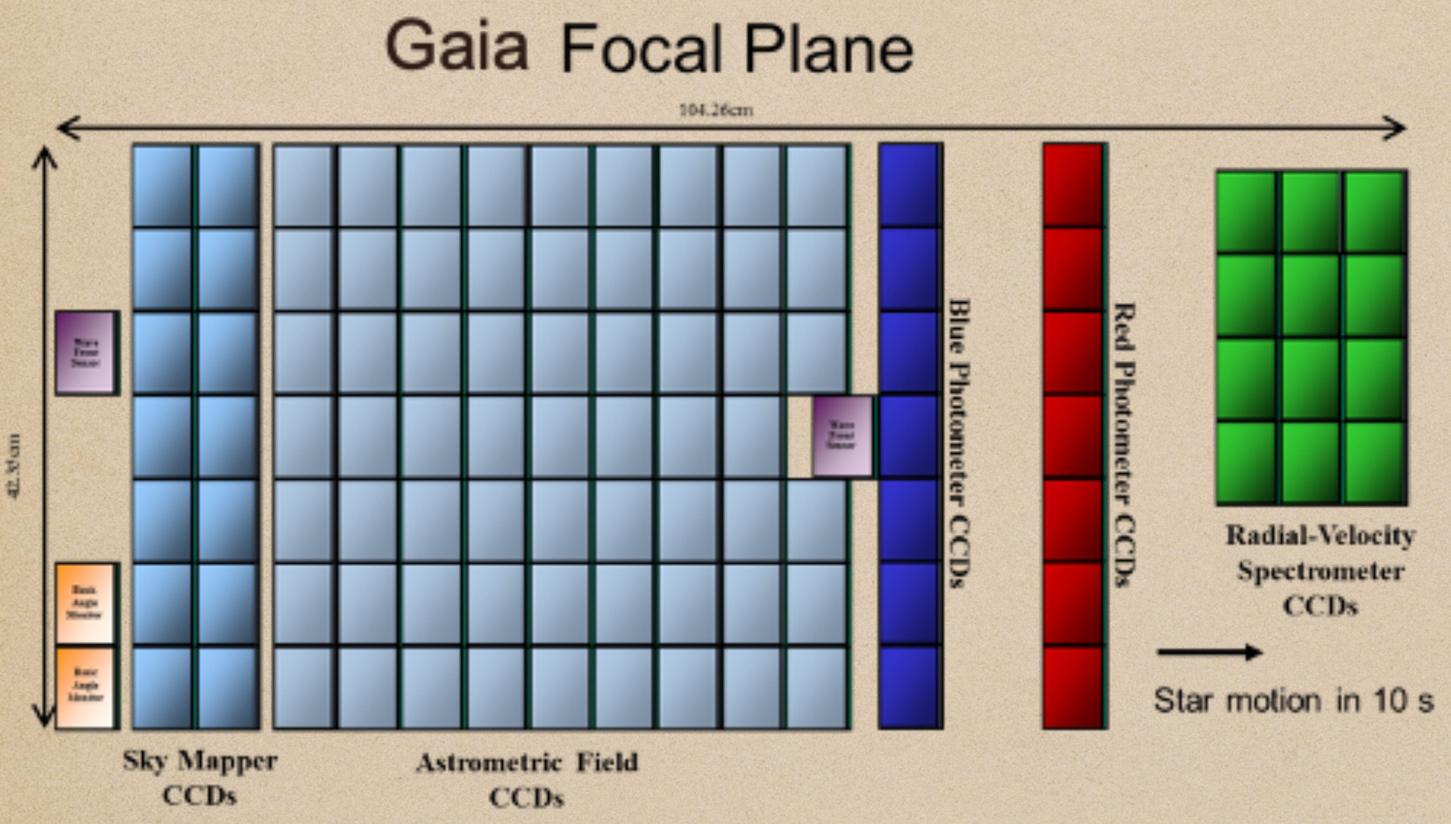
Noiseless signal amplification - perfect for faint astronomical applications

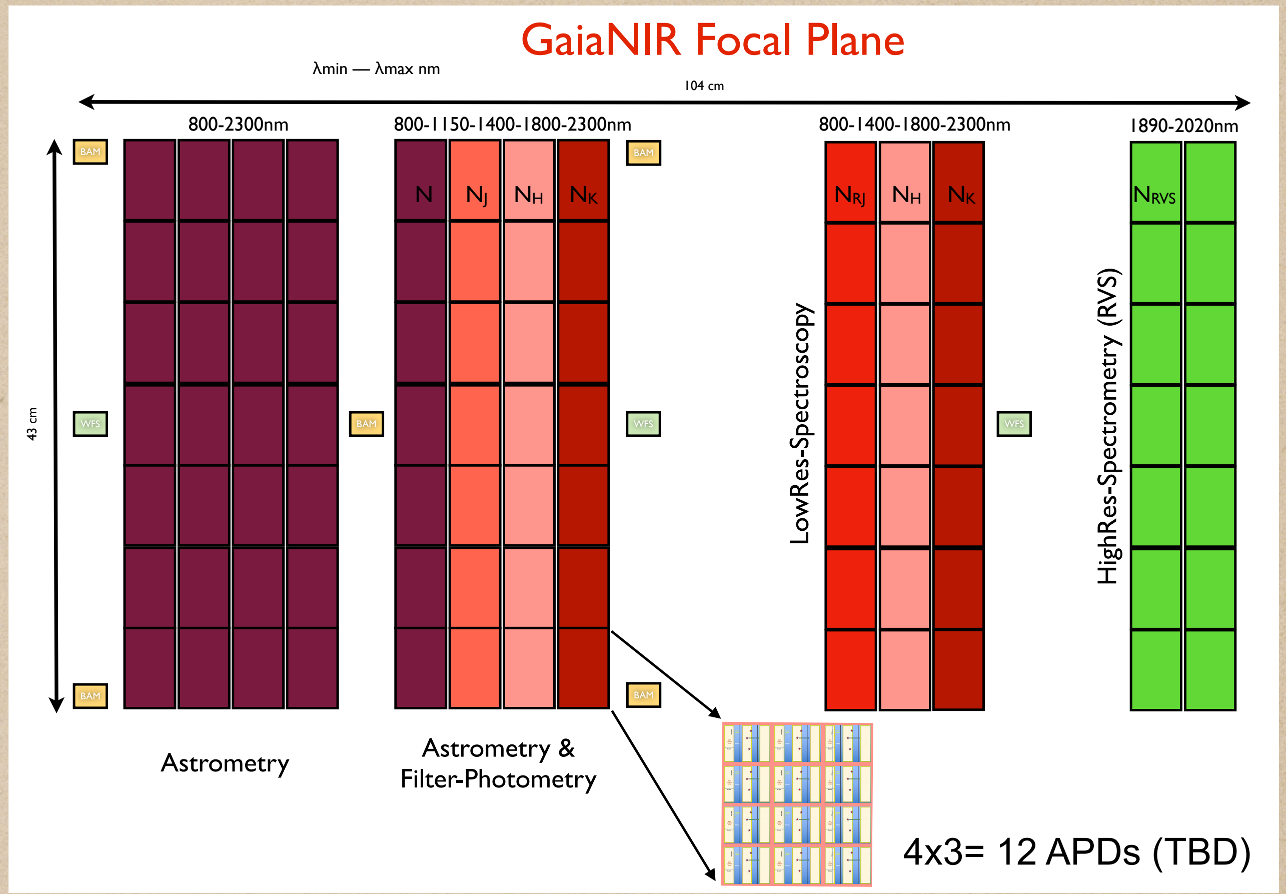
- For wavelength cutoff we have options for 2500nm or 3500nm
  - Few science cases above 2500nm
  - We start picking up thermal above 2000nm
  - Too much crowding and blending at long wavelengths
  - Too many stars to download - onboard processing needed!
- TDI mode is possible but for < 800nm studies are still needed
- Studies of the detectors are now ongoing in the UK



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

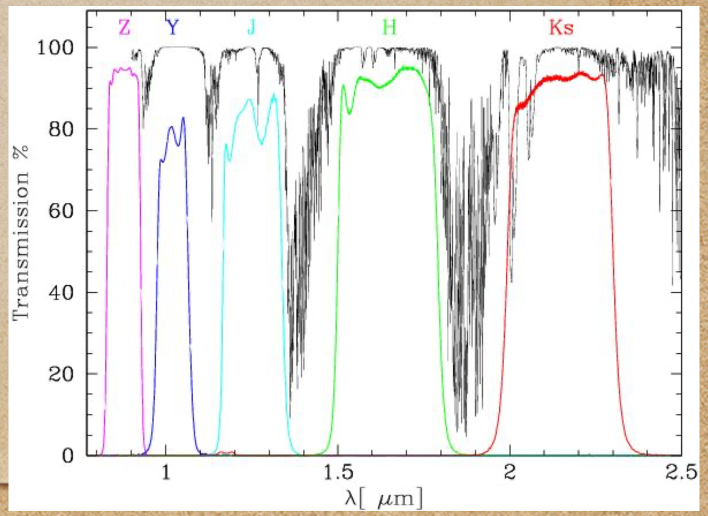




56 astro, 21 dispersion, 14 RV detectors

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 ~ 2300 nm, blue stars (<800nm) are more challenging
- 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?



Example from VVV

End Of Mission Accuracy

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

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%.

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

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

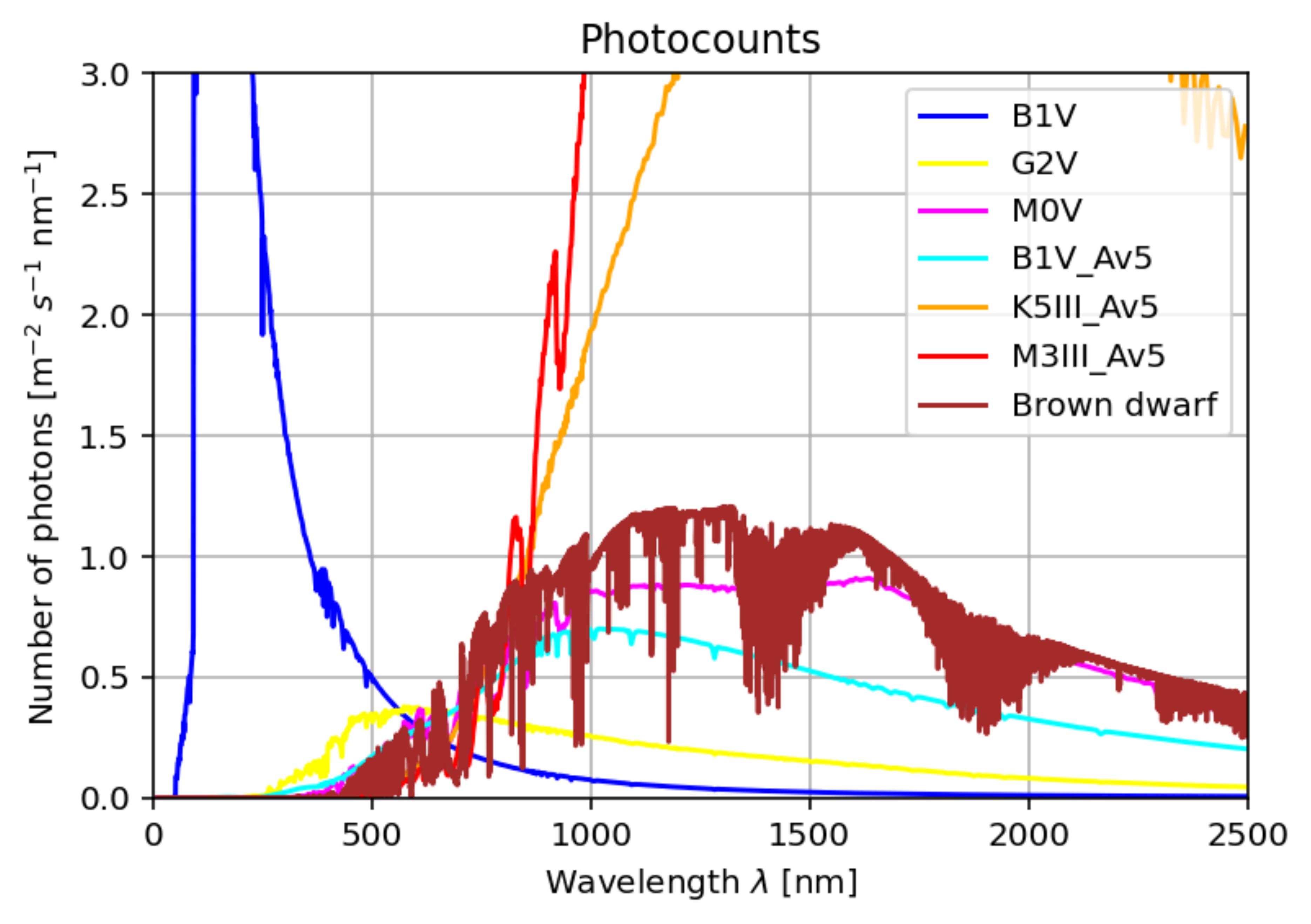
where

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−].

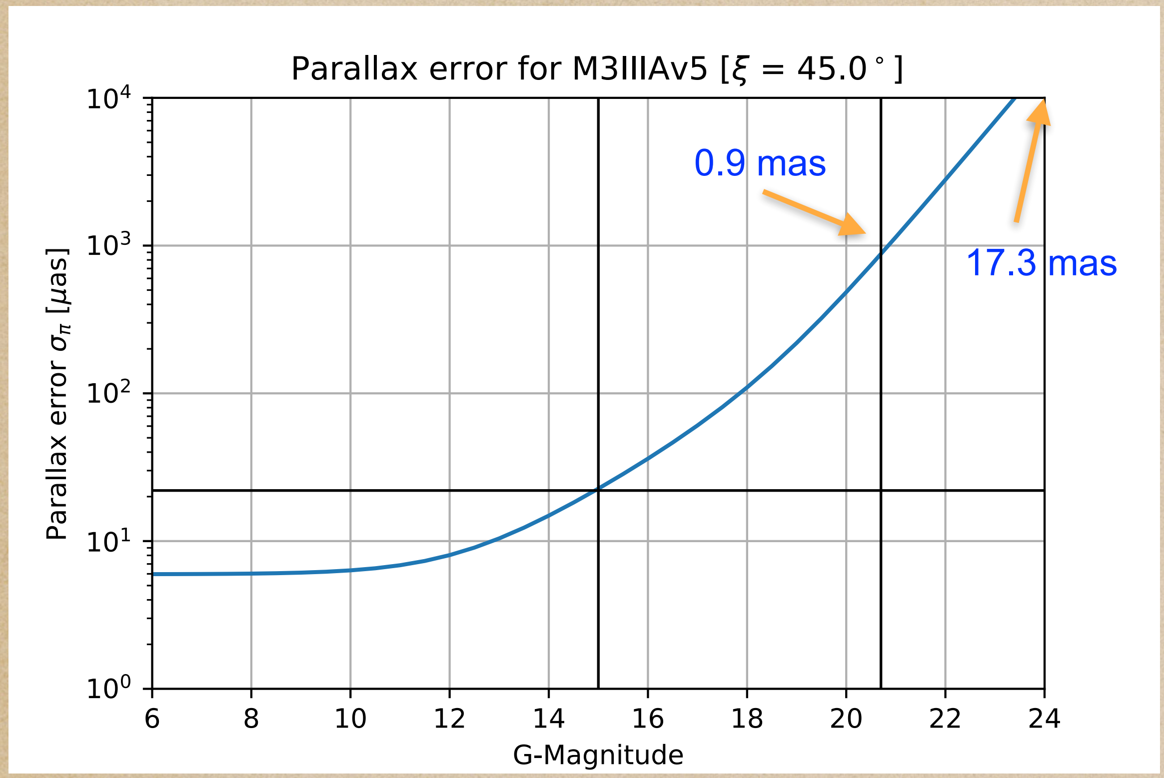
L = effective mission length (i.e. excluding dead time);

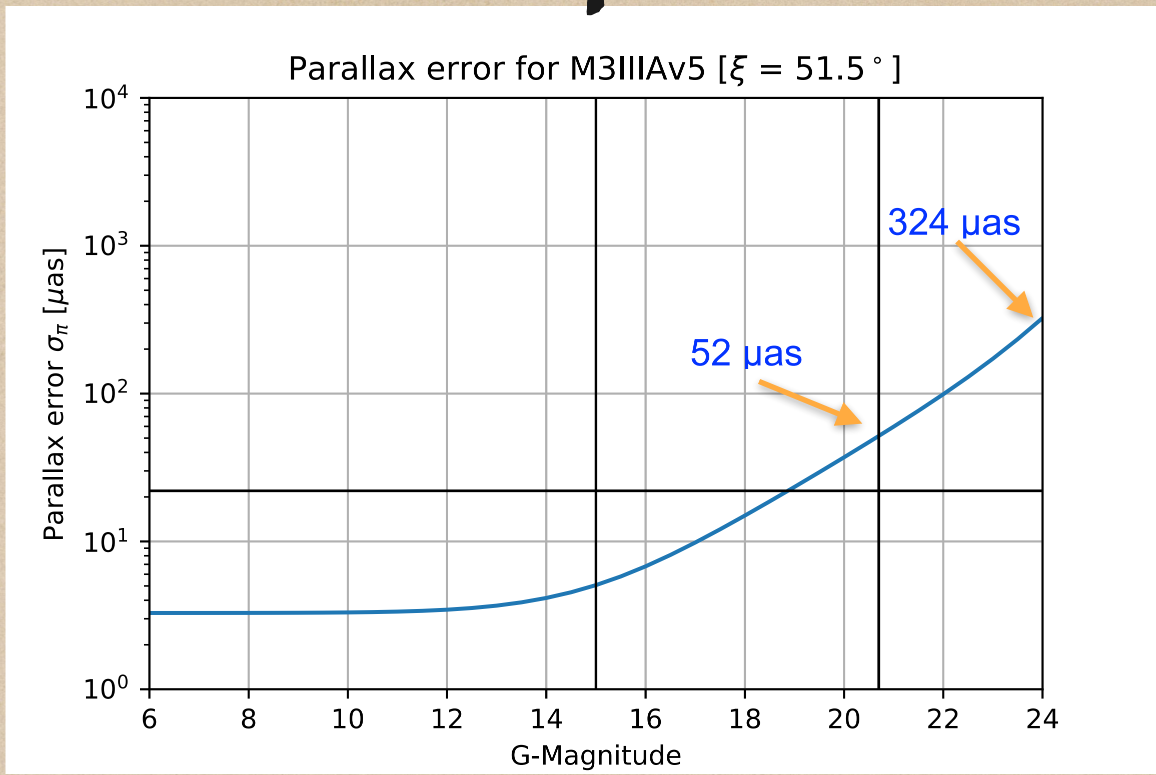
$\Omega = 1.2$ deg^2 = detector solid angle per instrument

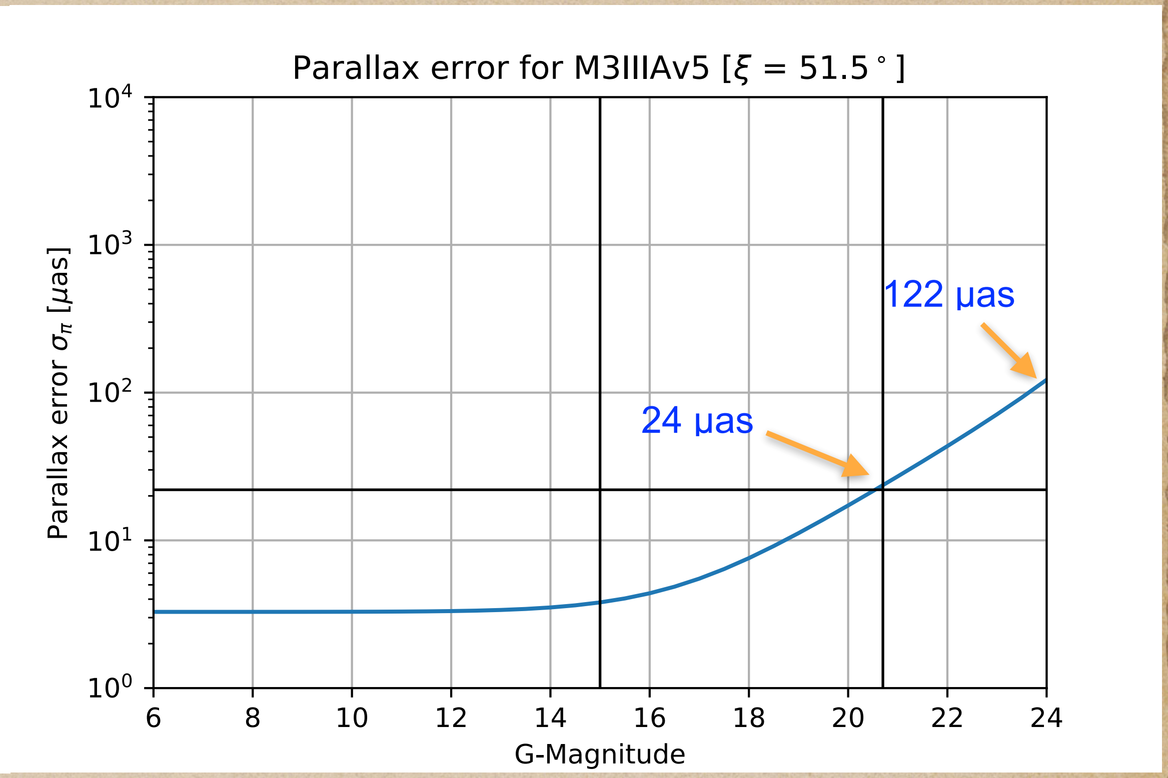
$g_{\varpi} = 1.47(sin\ \xi)^{-1}$ Sky averaged parallax factor

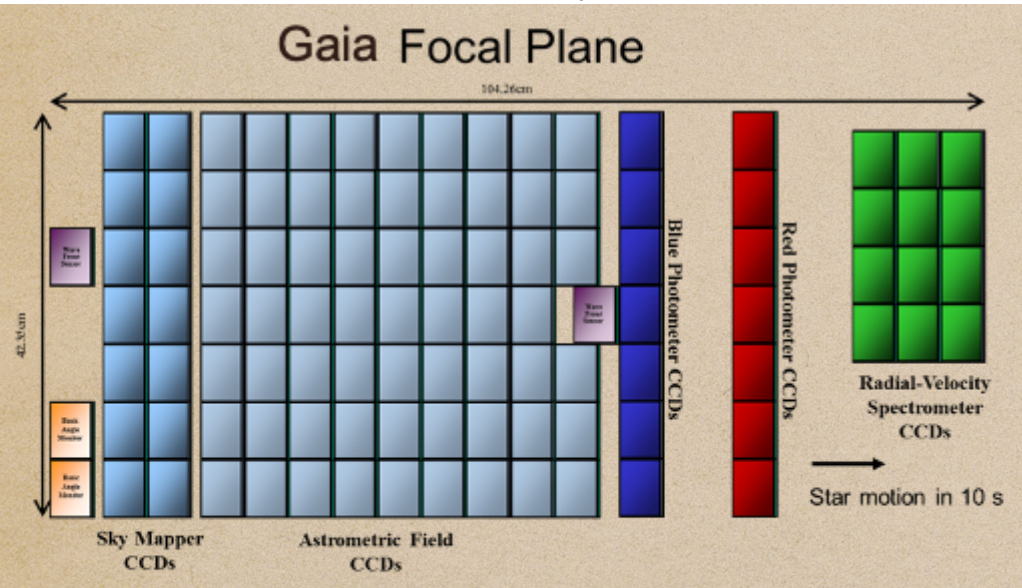


Detector Comparison (5-Yrs)

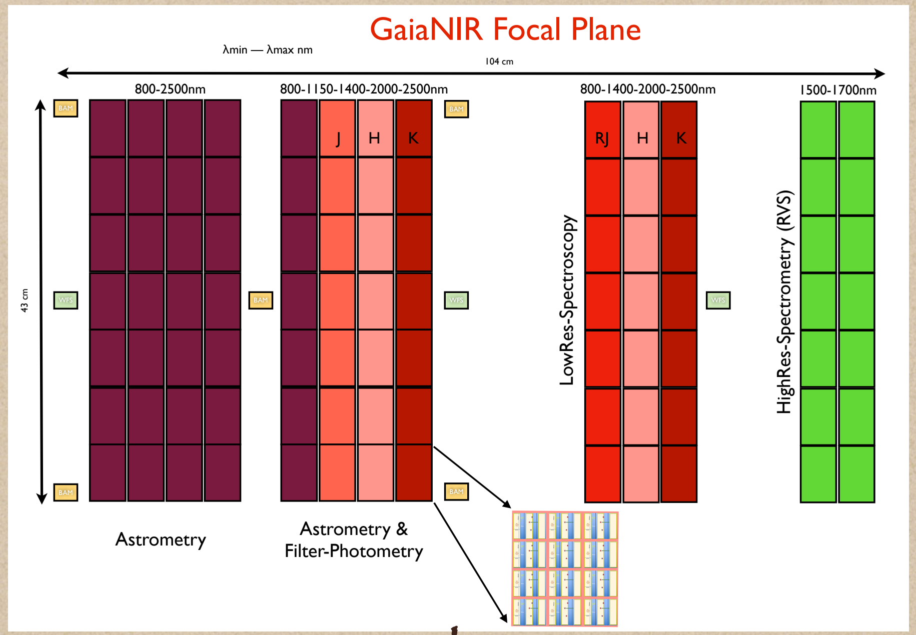








GaiaNIR$_{Medium}$ Optics

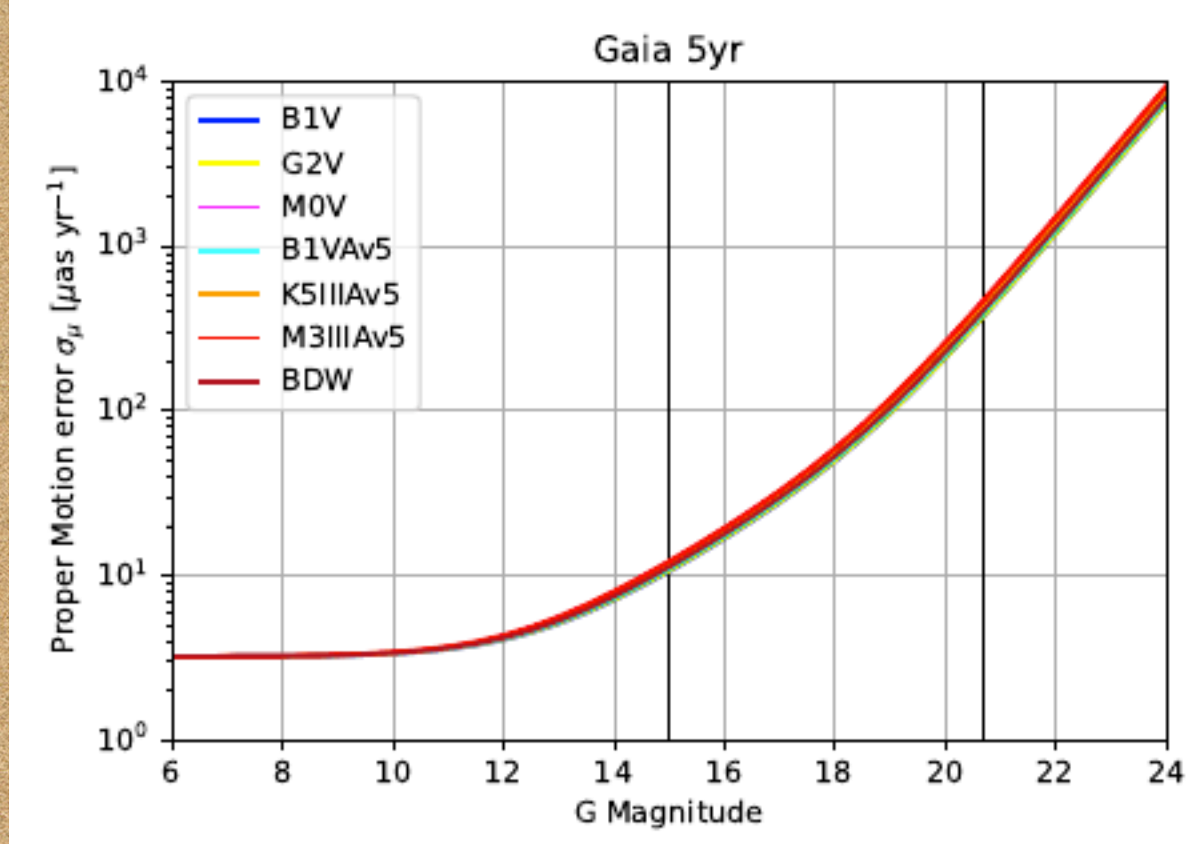


GaiaNIR$_{Large}$ Optics

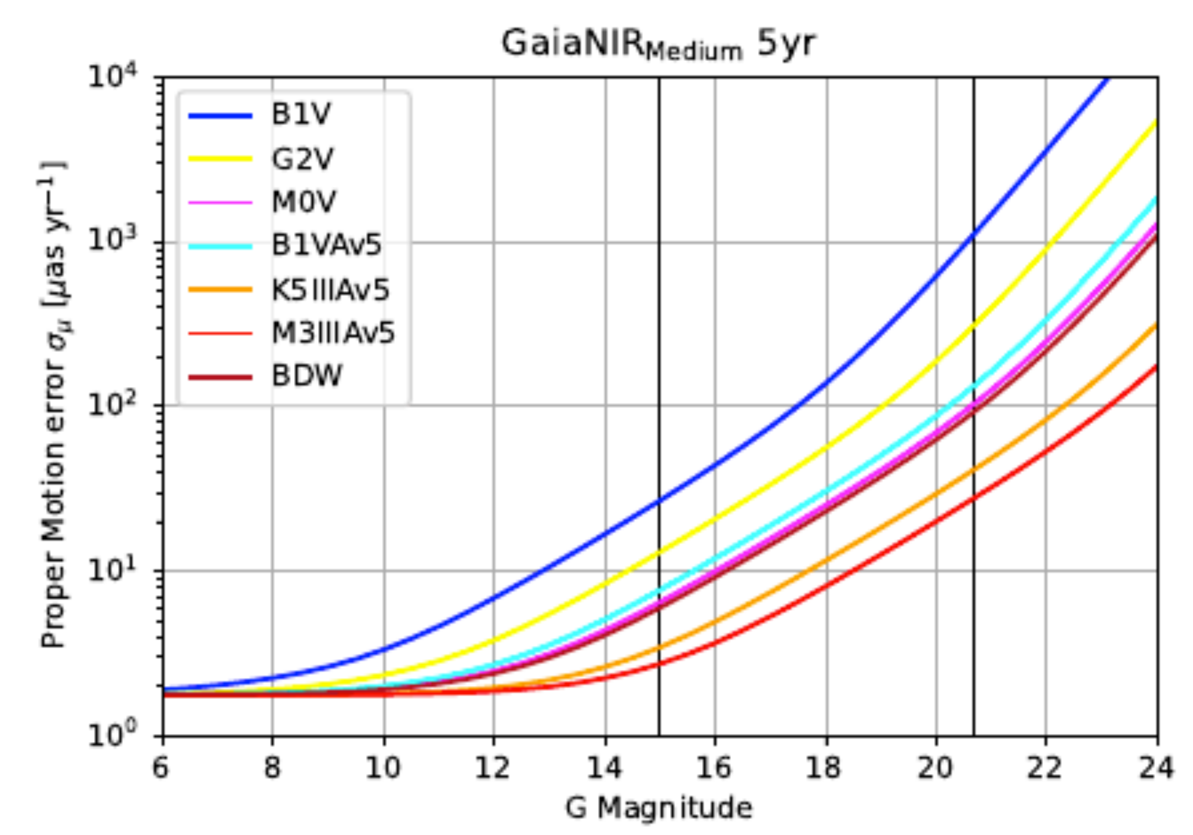
- Identical runs for M3III_Av5_T$_{eff}$3500_logg2.0_feh red giant giving a comparison between Gaia CCDs and GaiaNIR APD's
- APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs
- Separating photometry and low dispersion spectroscopy is better for astrometry and astrophysics!

EoM results PMs

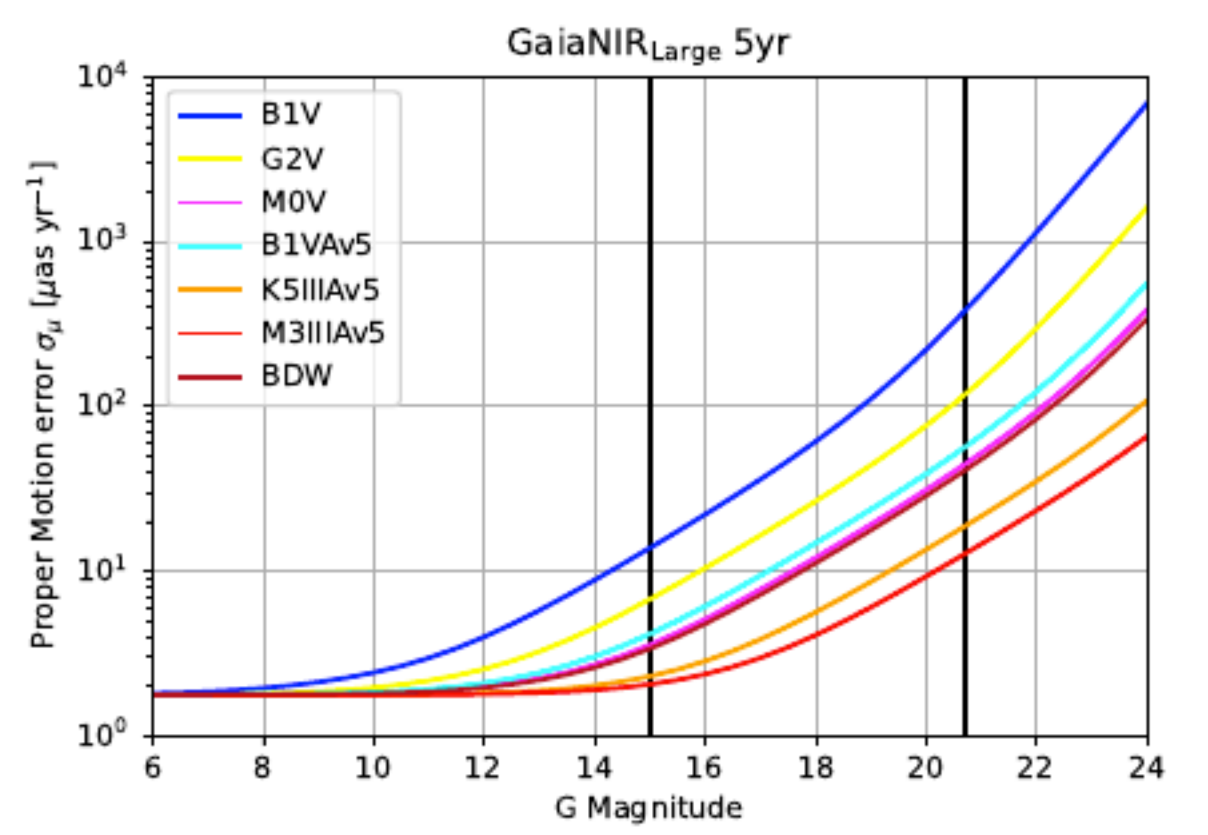
Gaia



GaiaNIR$_{\text{Medium}}$ Optics



GaiaNIR$_{\text{Large}}$ Optics



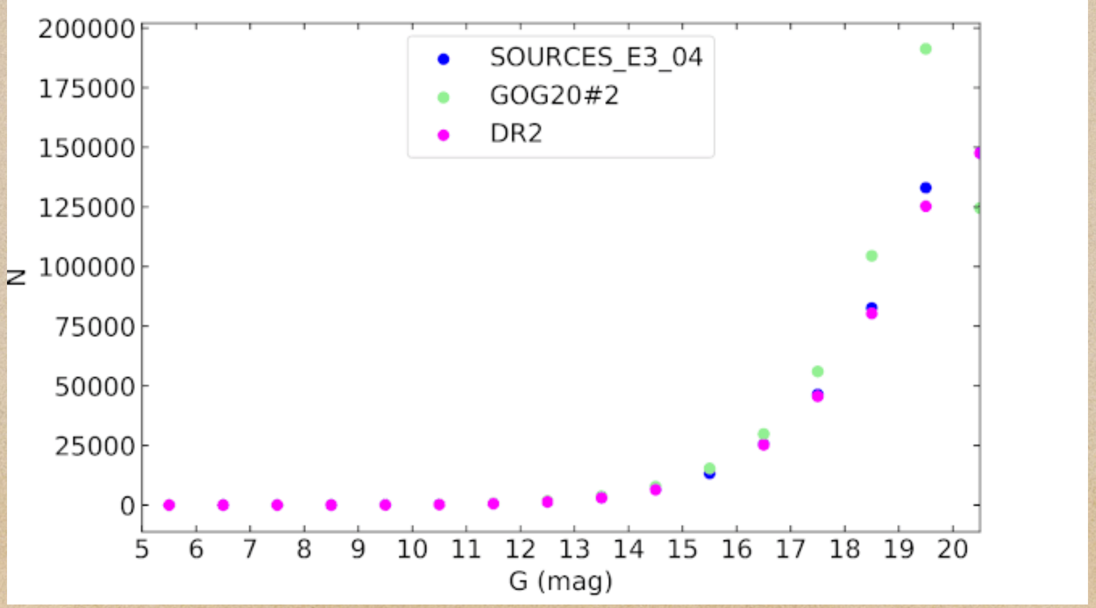
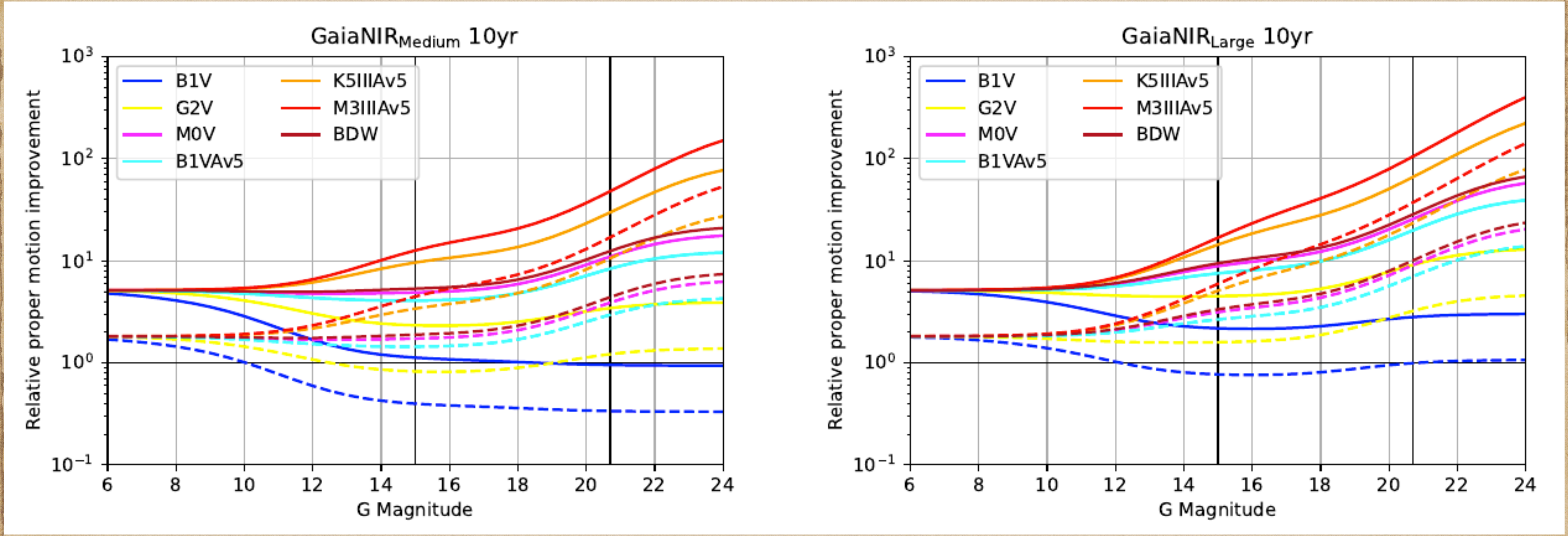


Figure 8.10: Average of the star counts over the whole sky as a function of magnitude, in Gaia EDR3 and Gaia DR2, compared to GOG20.

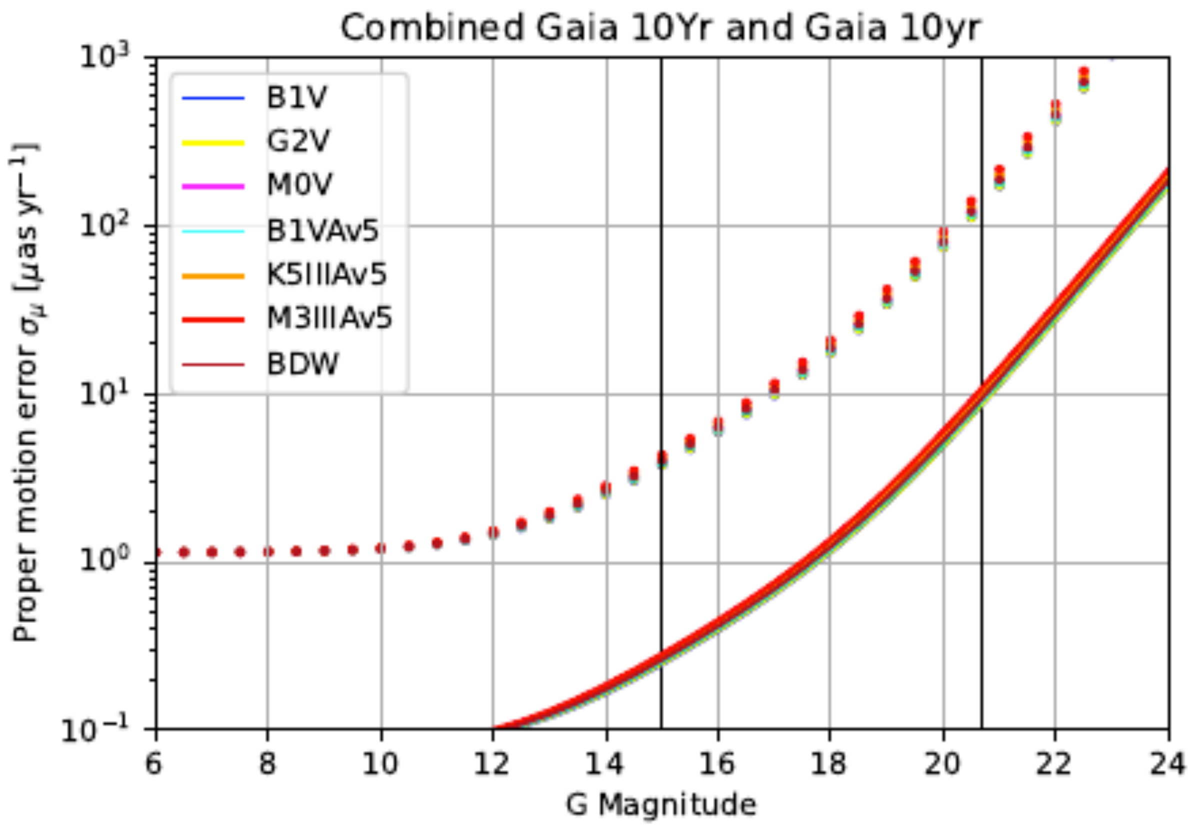
EoM resultsPM Relative Improvement



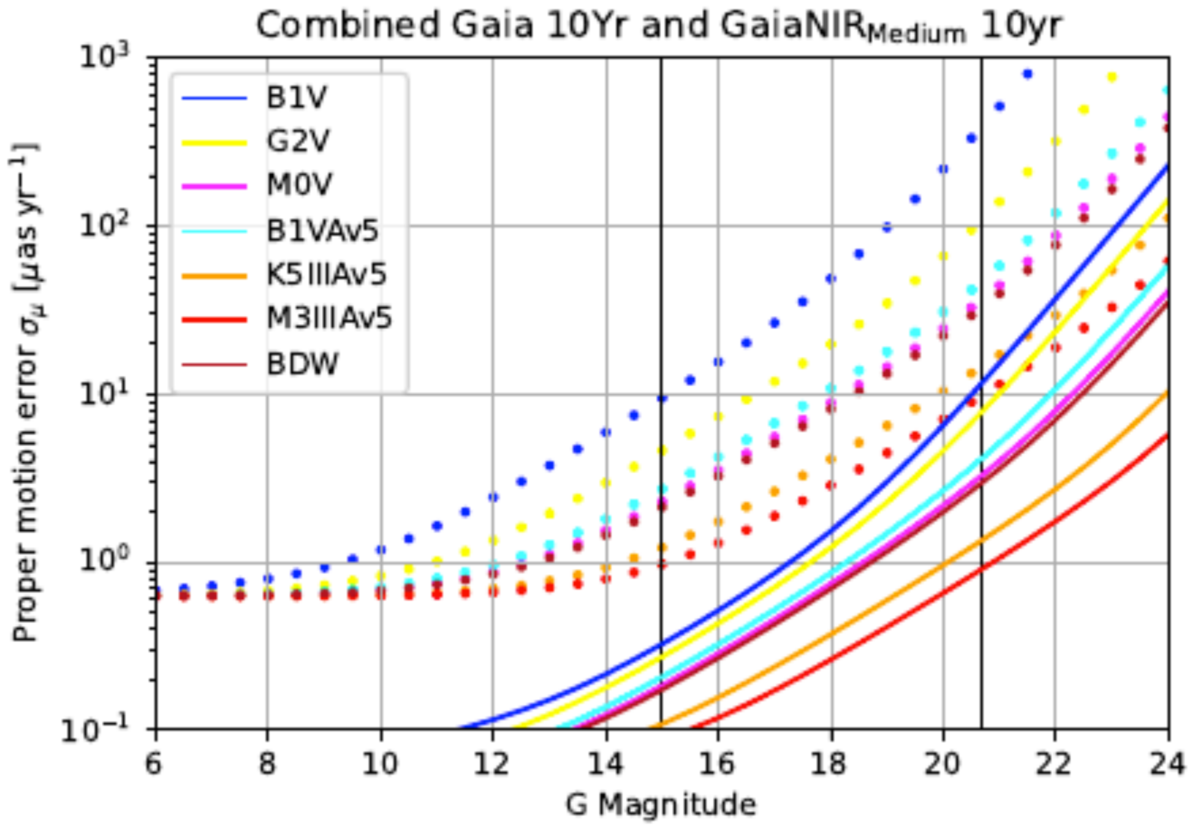
The relative improvement of individual *GaiaNIR* solutions compared to *Gaia*-DR4 (solid lines => 5 year) and DR5 (dashed lines => 10 year)

Joint EoM results PMs

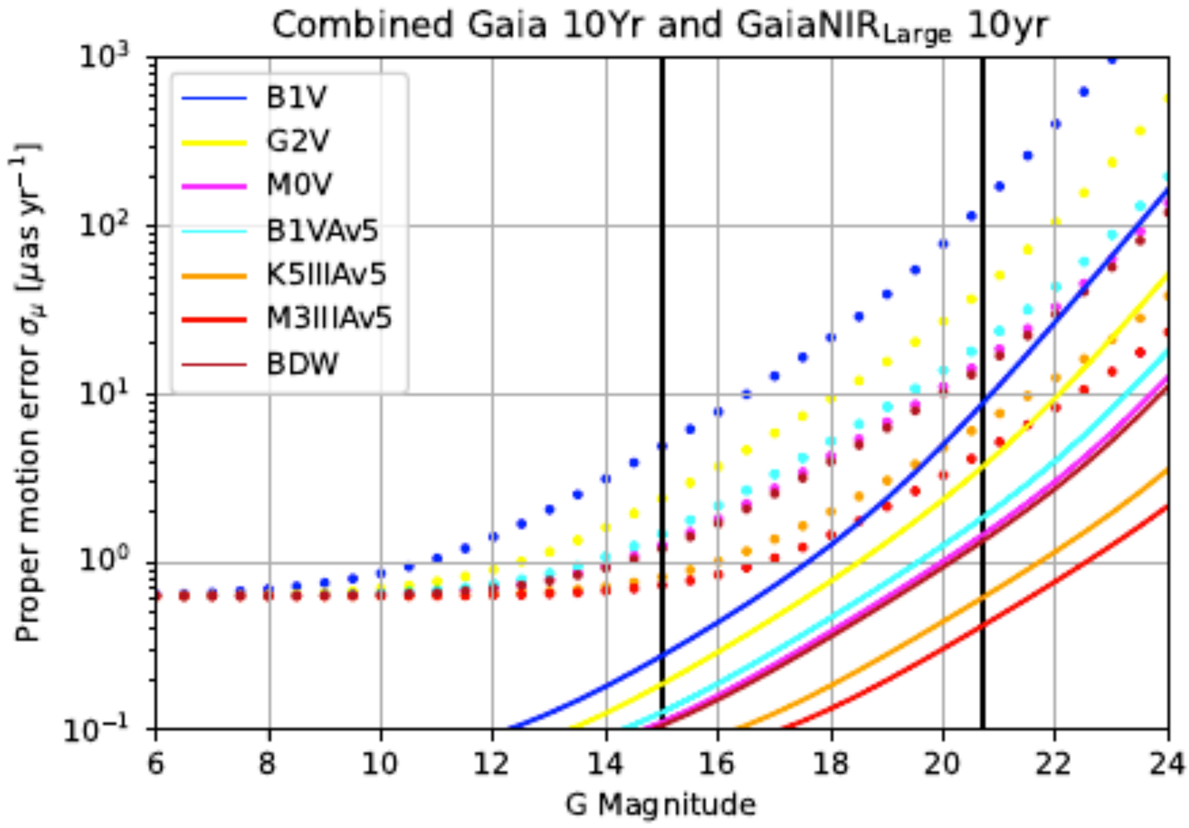
Gaia



GaiaNIR$_{\text{Medium}}$ Optics

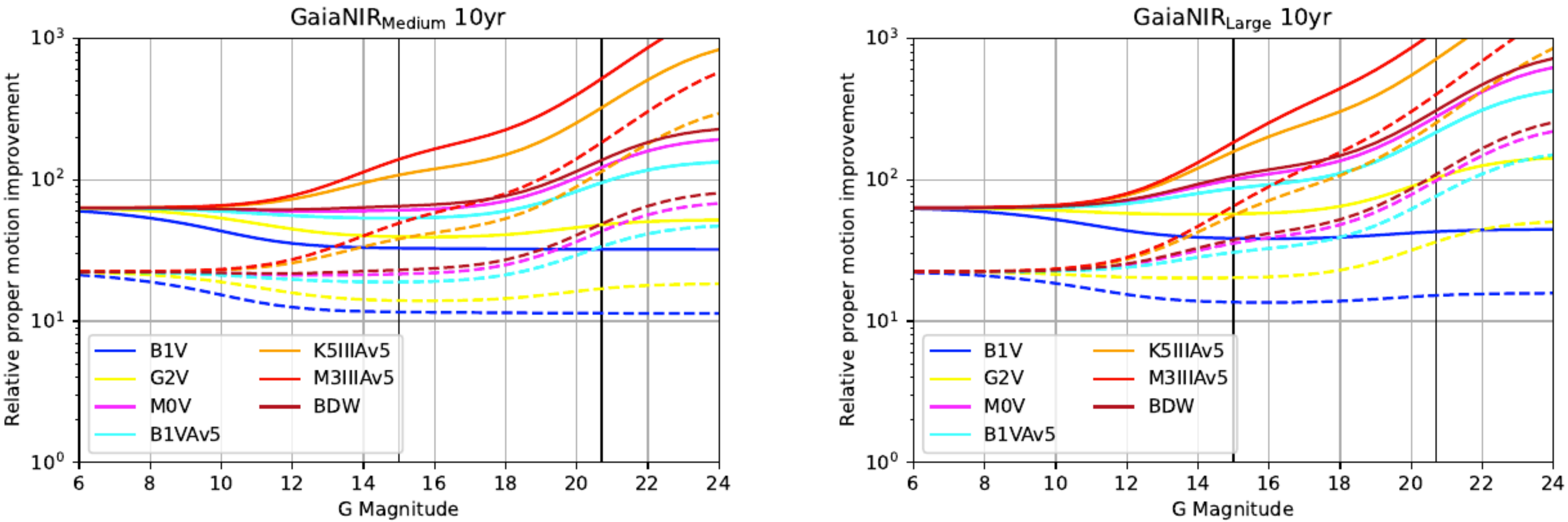


GaiaNIR$_{\text{Large}}$ Optics



The combined EoM proper motion accuracy estimates for a series of reference stars for *Gaia* (left), *GaiaNIR*$_{\text{Medium}}$ (centre) and *GaiaNIR*$_{\text{Large}}$ (right). Note that the corresponding dotted curves show the corresponding results from the individual missions without joint solutions.

Joint EoM results PM Relative Improvement



The relative improvement of joint *Gaia*-*GaiaNIR* solutions compared to *Gaia*-DR4 (solid lines => 5 year) and DR5 (dashed lines => 10 year)

GaiaNIR Summary

- For GaiaNIR APDs we get better astrometric performance for several reasons
  - Broader wavelength range more than compensates for longer observing wavelength
  - Segmented mirrors would double the resolution and collect more photons but at a cost!
  - Lower read noise and lower background noise are game changers for astrometry!
  - A massive improvement in accuracy at the faint end without joint solutions, i.e. for all stars
- The combinations of these improvements results in a new mission that can outperform Gaia!
- Including a spectrograph could give a deep RV survey for a billion objects?

Gaia Science Tree

Michael Perryman (v2, Jan 2025)
Essays 1-209 (Jan 2021-Dec 2024)
end nodes are hyperlinked to (Zenodo-hosted) essays

see also: michaelperryman.co.uk/essays

https://ui.adsabs.harvard.edu/abs/2024BAAS...56a.008P