The GaiaNIR mission and the hidden regions of our Galaxy

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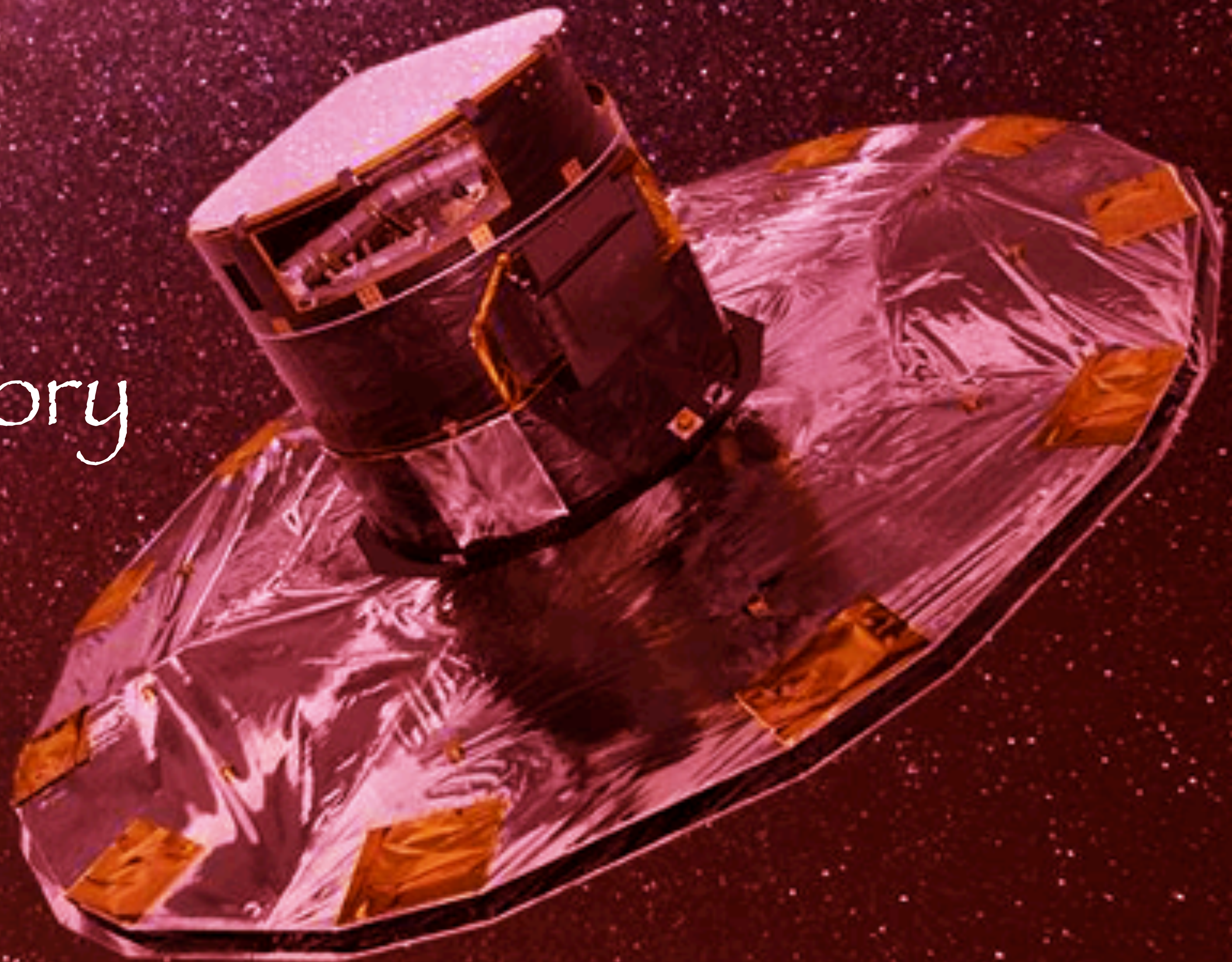


Science Cases

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!

GaiaNIR is a discovery mission designed to unveil the nature of our Galaxy - Voyage 2050

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

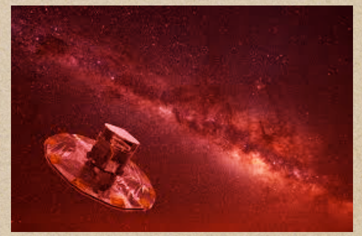
2045

2025

2020

2015

A 20 year gap



Second Epoch GaiaNIR 10yr (2050)

First Epoch Gaia 10yr (2020)

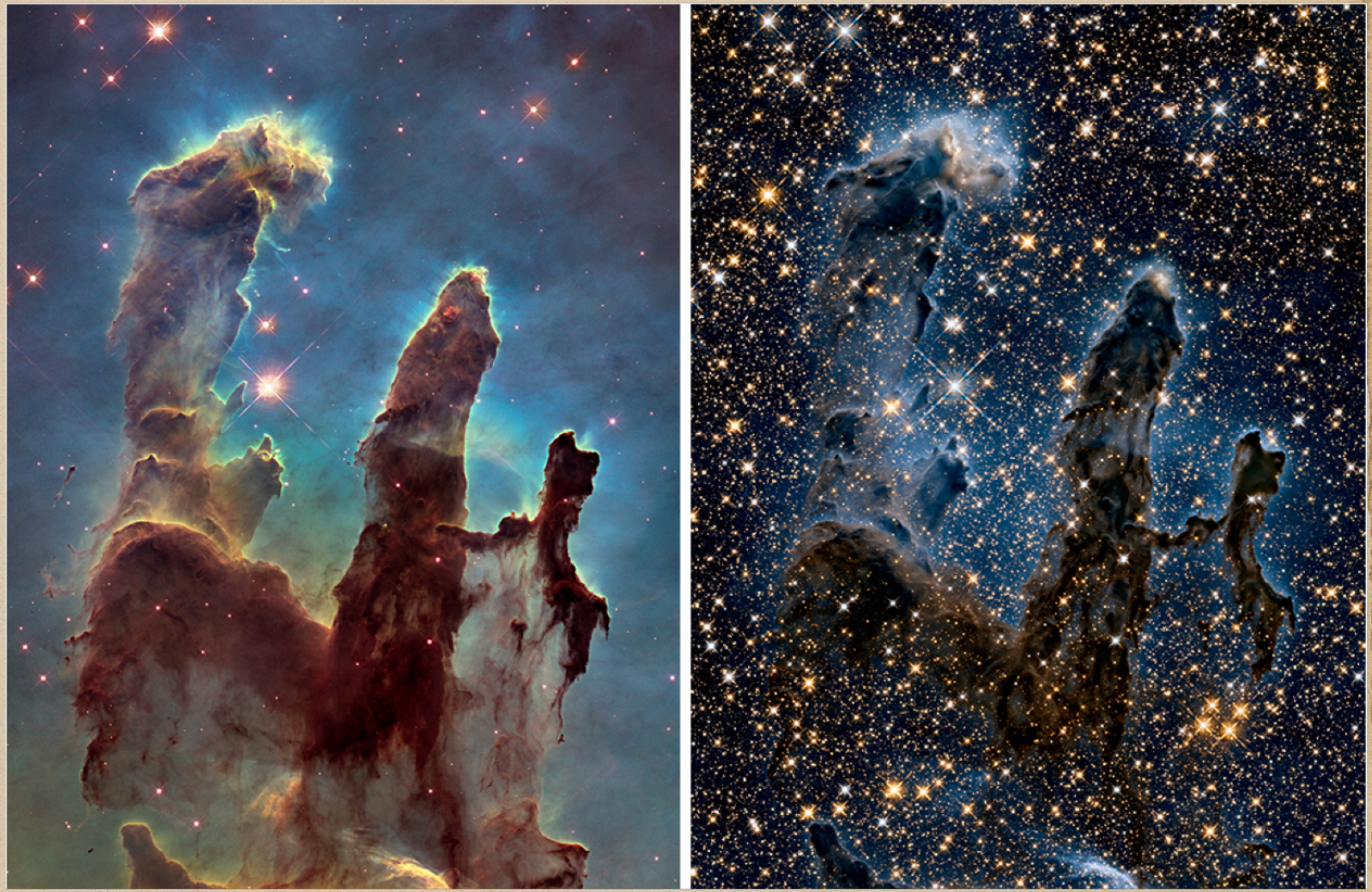
More than an order of magnitude improvement in PM's compared to Gaia DR4 giving nano-arcsec PMs for some common stars.

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

GaiaNIRSmall

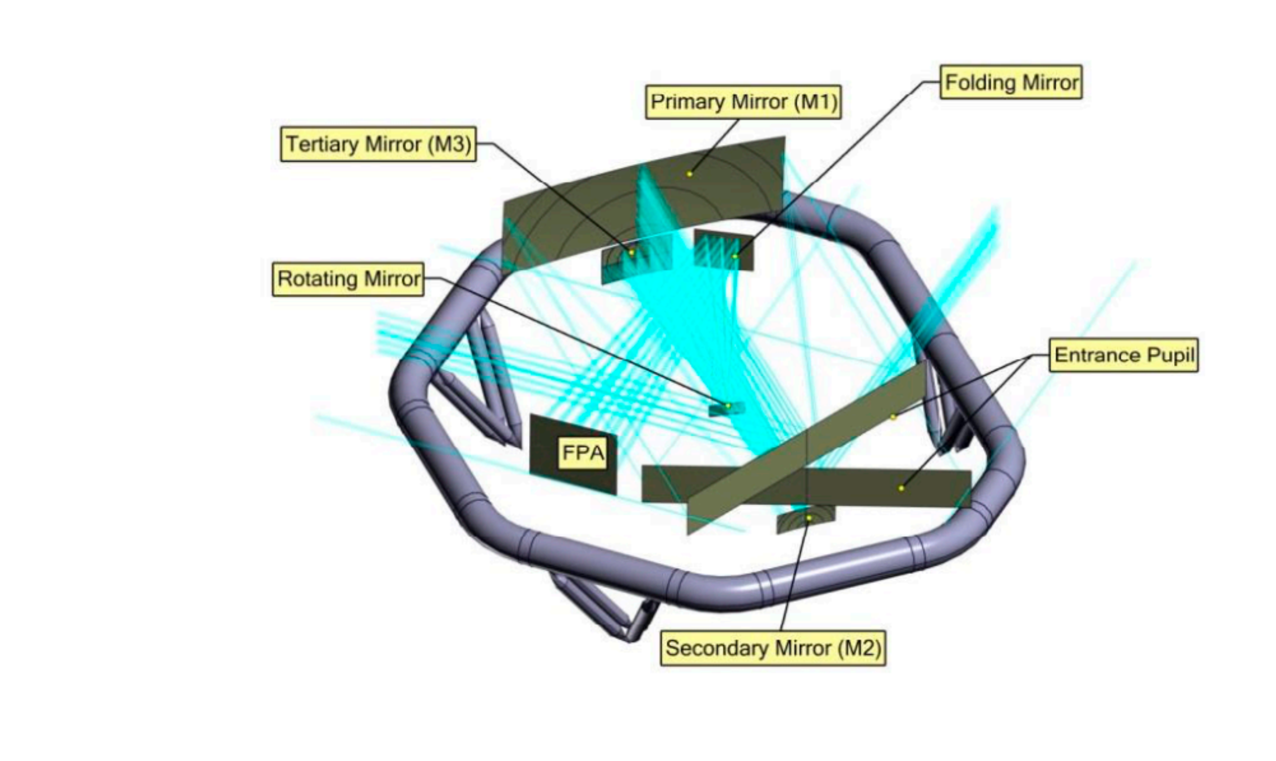


Figure 5-34: GaiaNIR optical surfaces and the light path

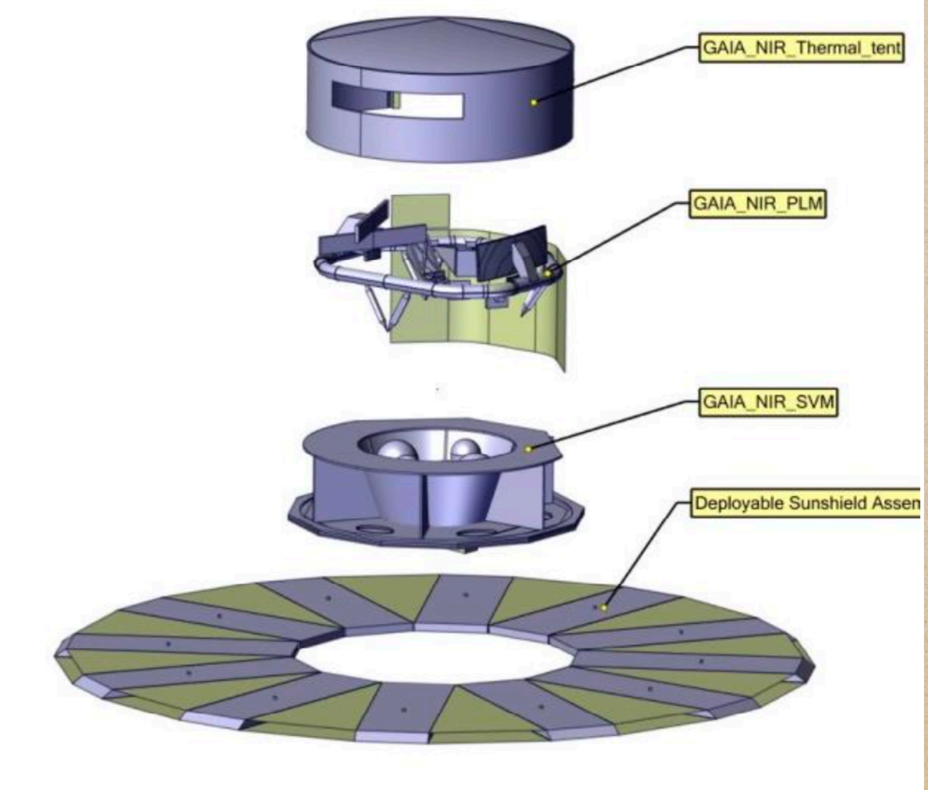


Figure 6-2: Gaia-NIR Spacecraft main elements

- 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)

New Design

GaiaNIR$_{Large}$

M1

D = 1.7m

D = 1.7m

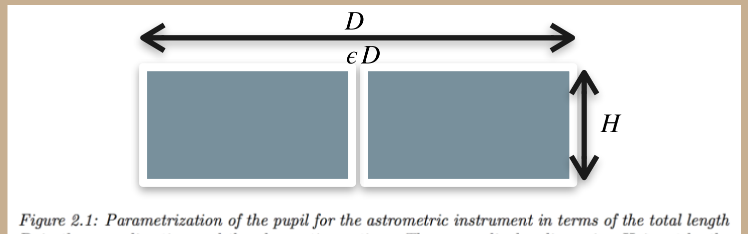


Figure 2.1: Parametrization of the pupil for the astrometric instrument in terms of the total length D in the scan direction and the obscuration ratio ε. The perpendicular dimension H is set by the (fixed) total area A = (1 − ε)DH.

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:

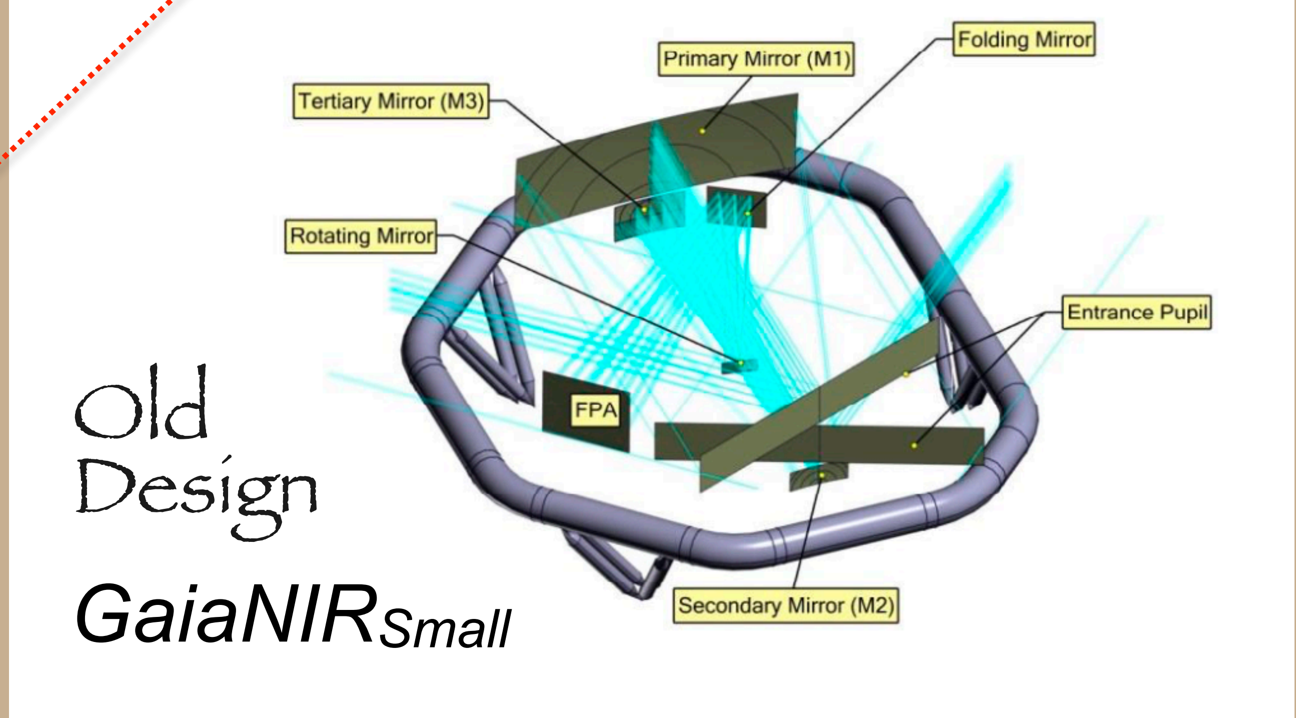
- double the width of flat BA mirrors
- a segmented primary mirror

BA

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

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

D_{max} = 3.5m



Old Design

GaiaNIR$_{Small}$

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

Detector Status

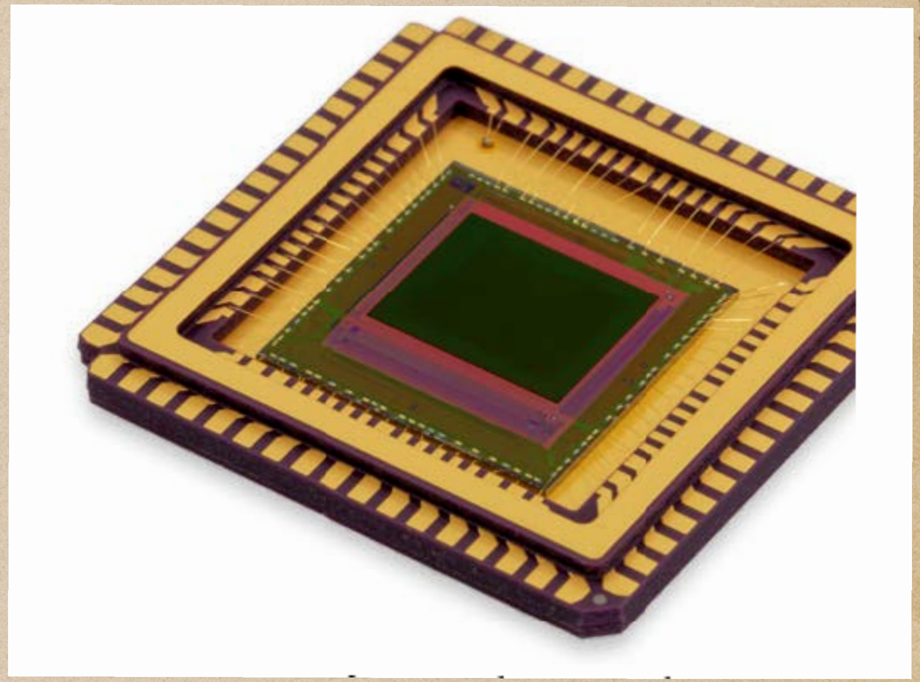
Italian owned Leonardo UK have small APDs with high frequency readout.

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 IR
  - 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.

MVGaiaDN Detector Meeting

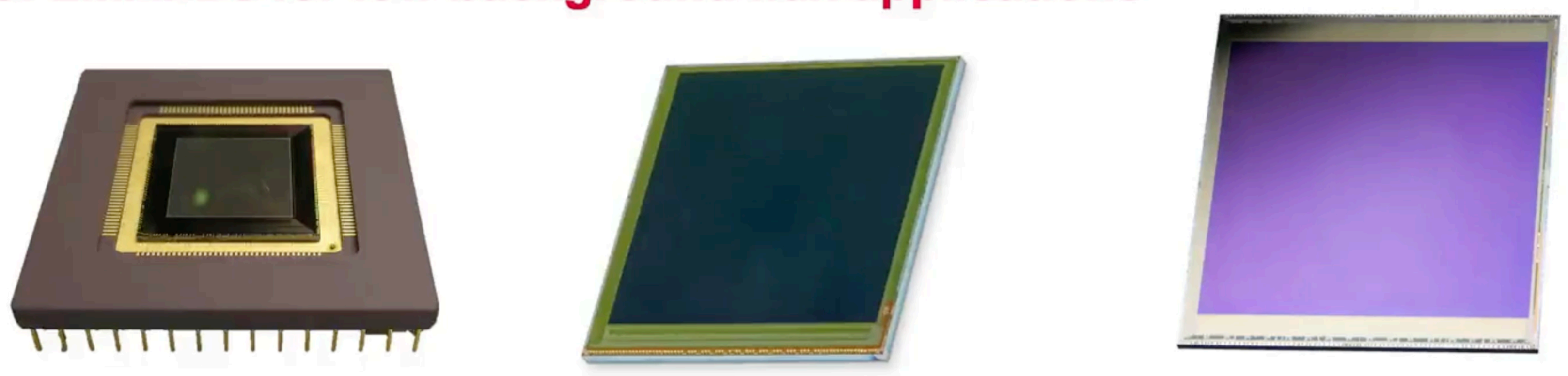
Meeting being held in Cambridge in July 15-16th to discuss technology for GaiaNIR

Technical challenges of space-based astronomy

https://indico.ast.cam.ac.uk/event/8/overview

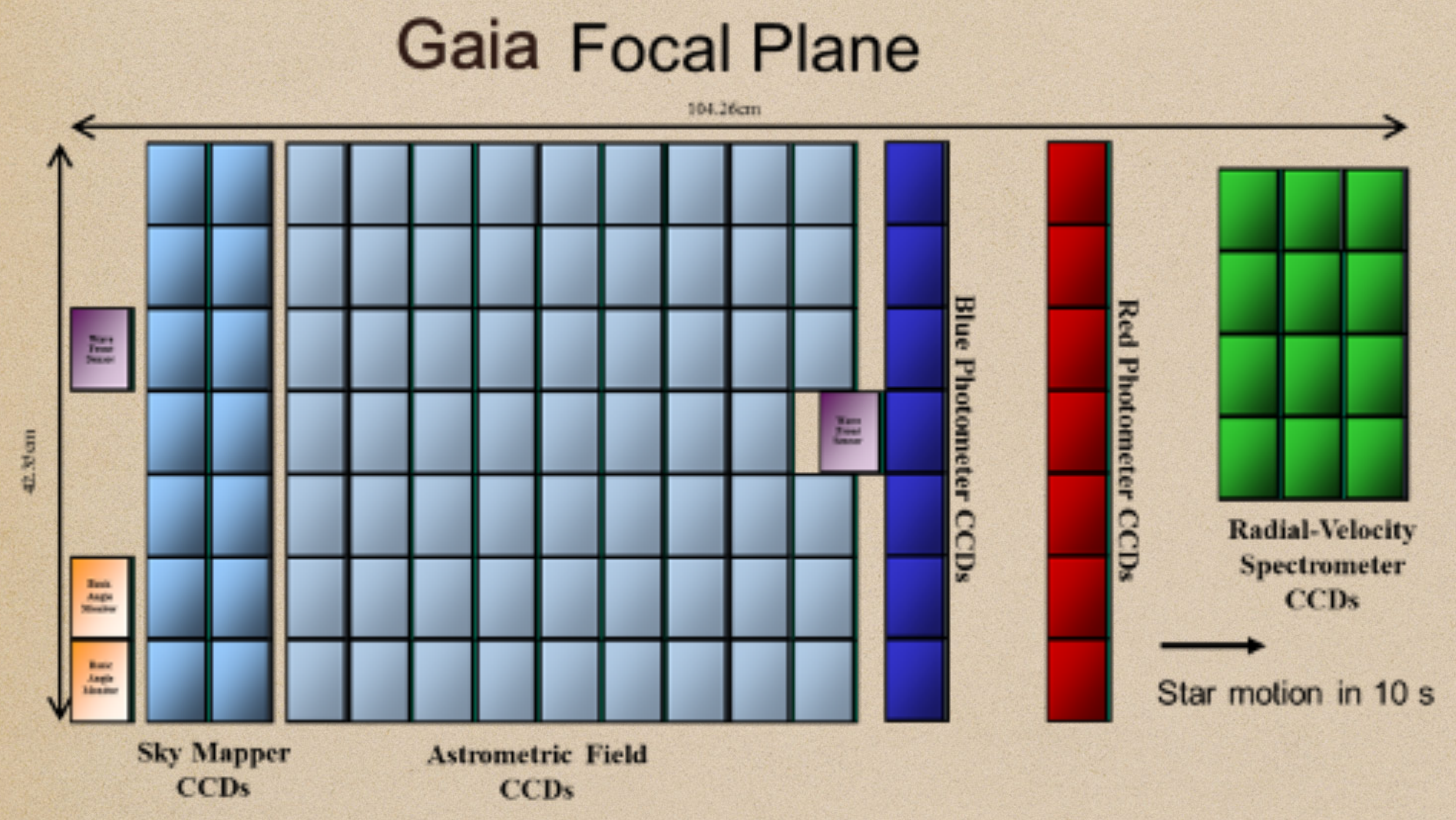
Industrial partners like Leonardo UK will attend and all people interested are welcome

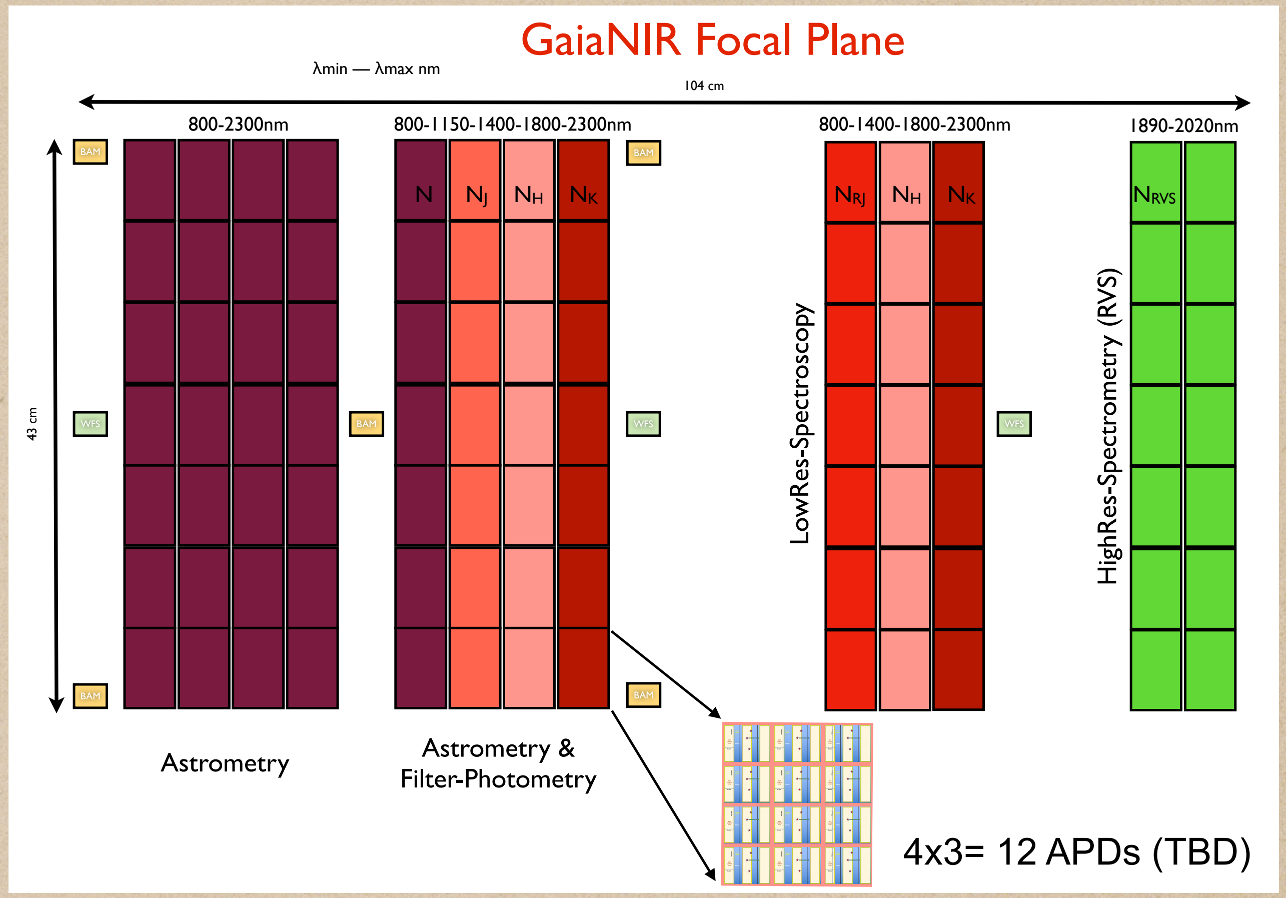
Update of LmAPDs for low background flux applications



	Large Saphira	Ike-Pono	IBEX
Dimensions	512x512/24µm	1024x1024/15µm	2048x2048/15µm
Status	Detectors provided to consortium partners for evaluation and system development.	First science grade devices under assessment – see **Charles-Antoine Claveau** talk tomorrow for further details.	Prototype arrays manufactured
Collaborator	ESO, Max Planck and NCR	NASA APRA ROSES, University of Hawai'i	ESA
Current Planned Uses	Wavefront sensing for extreme Adaptive Optics (AO) Over 2000 frames per second.	Extreme low dark current applications	Earth Observation

The Focal Plane & Filters

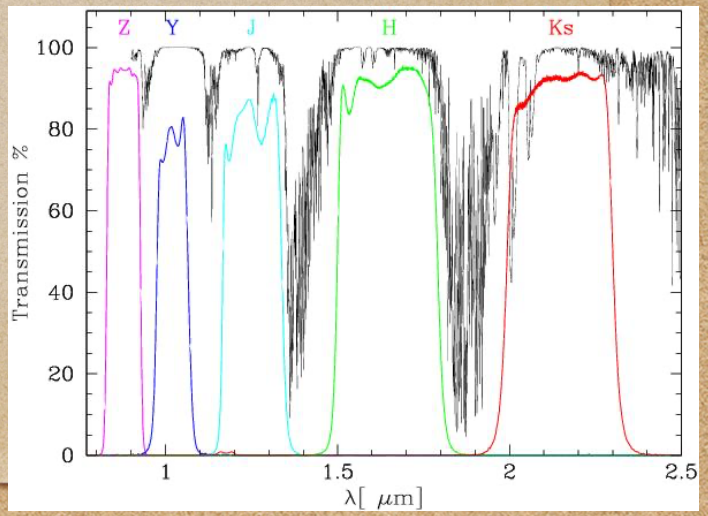




- Linear Mode APDs are the most promising detector for GaiaNIR
- Cooling strategy must be passive (~90K)
- Max wavelength ~ 2300 nm, blue stars (<800nm) are more challenging
- No SMs - track motion of stars instead to determine the FoV
- Filter photometry on astrometric field by depositing filter material on detectors
- Low resolution spectra on a dedicated field for astrophysical parameters
- An RVS Spectrograph is a great opportunity?

56 astro, 21 dispersion, 14 RV detectors

A modular concept uses small detectors to form larger ones



Example from VVV

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%.

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

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

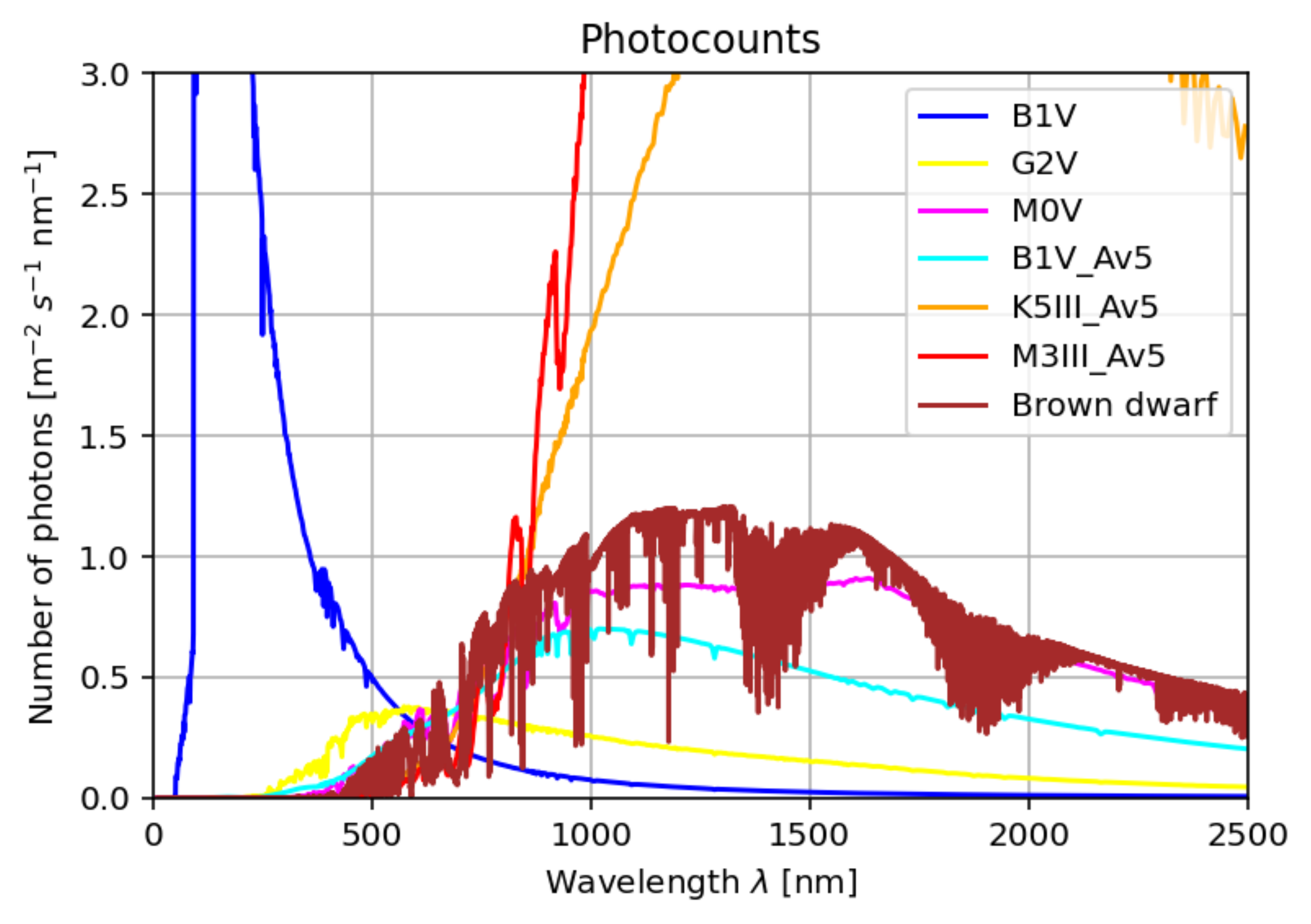
where

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−].

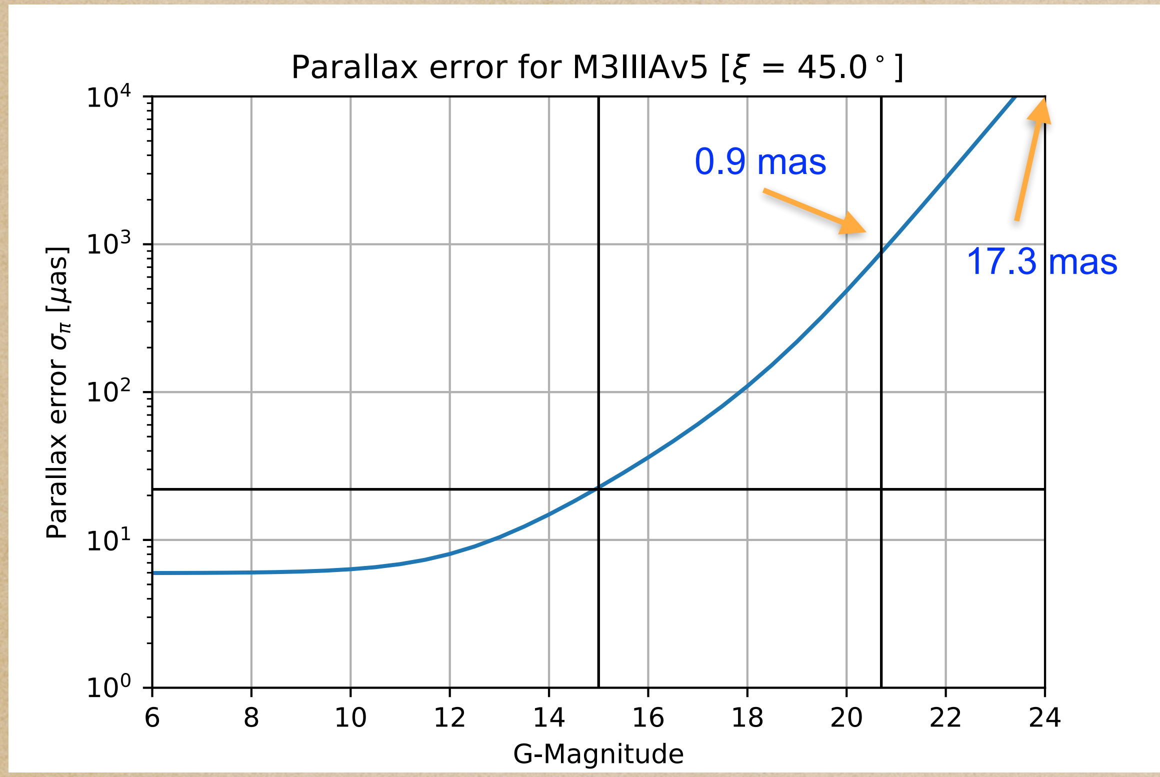
L = effective mission length (i.e. excluding dead time);

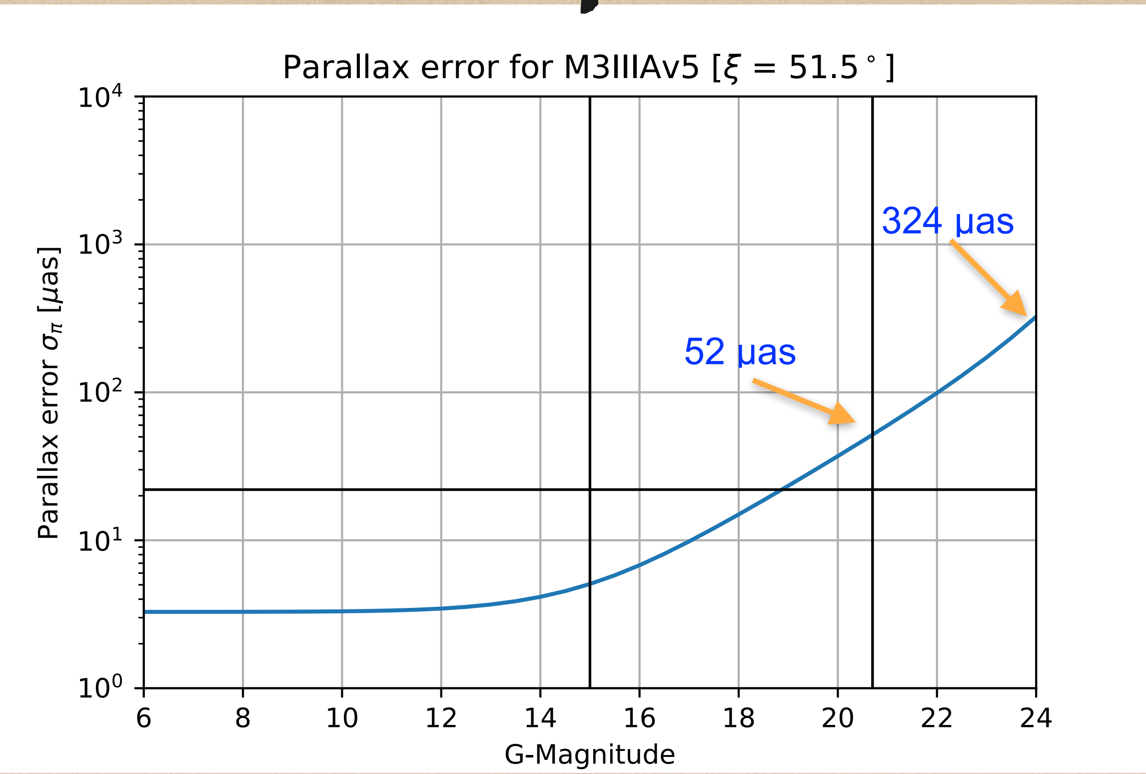
$\Omega = 1.2$ deg^2 = detector solid angle per instrument

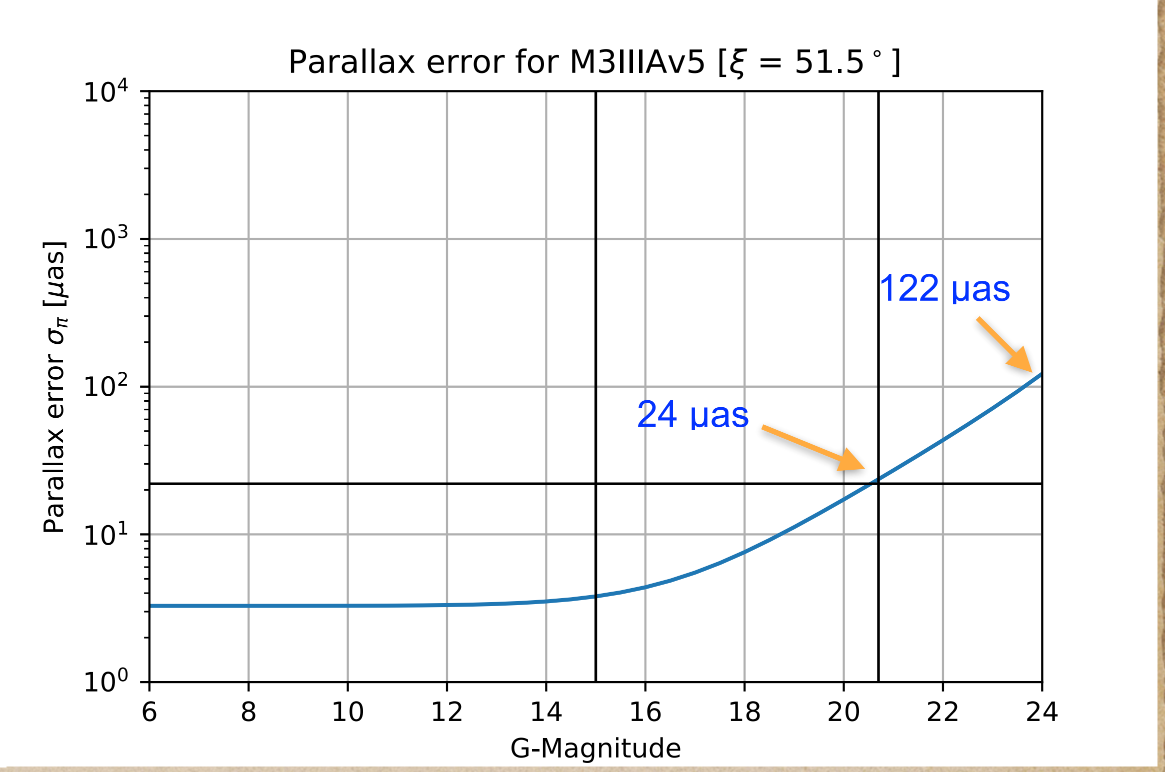
$g_\varpi = 1.47(sin\ \xi)^{-1}$ Sky averaged parallax factor



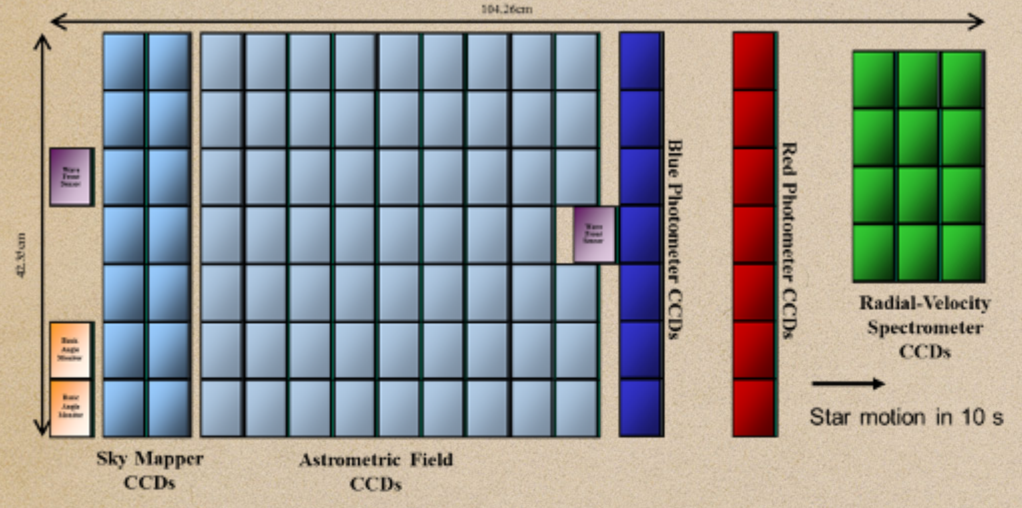
Detector Comparison (5-Yrs)



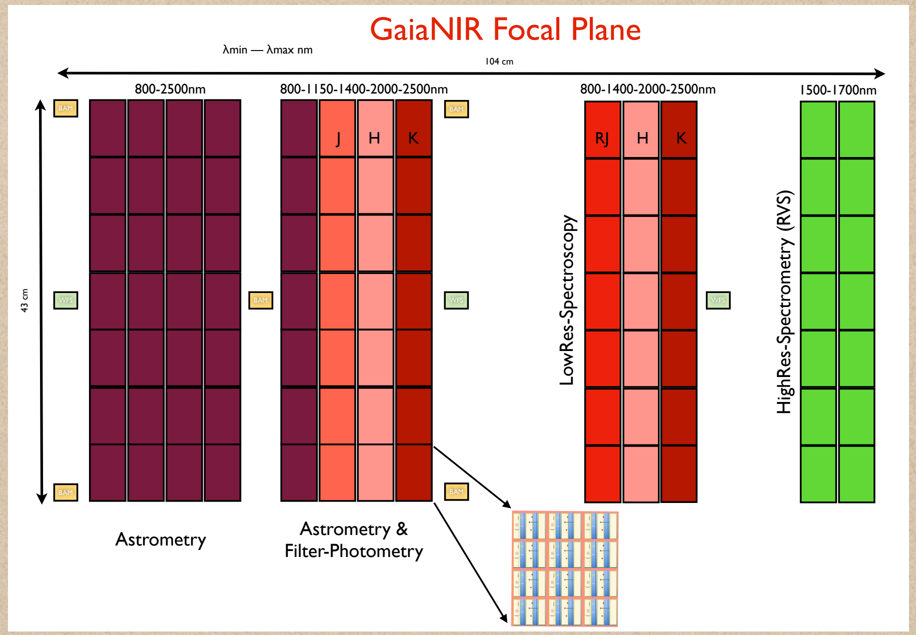




Gaia Focal Plane



GaiaNIR$_{Medium}$ Optics

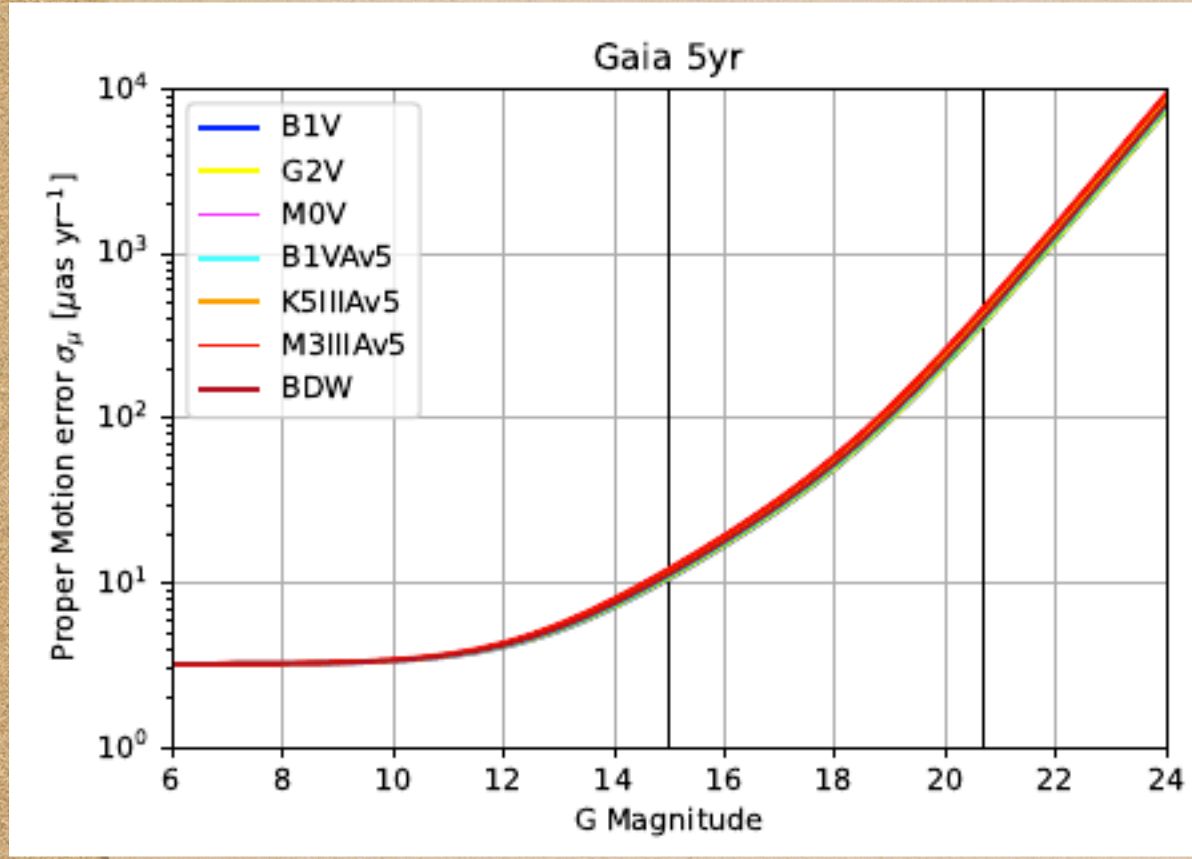


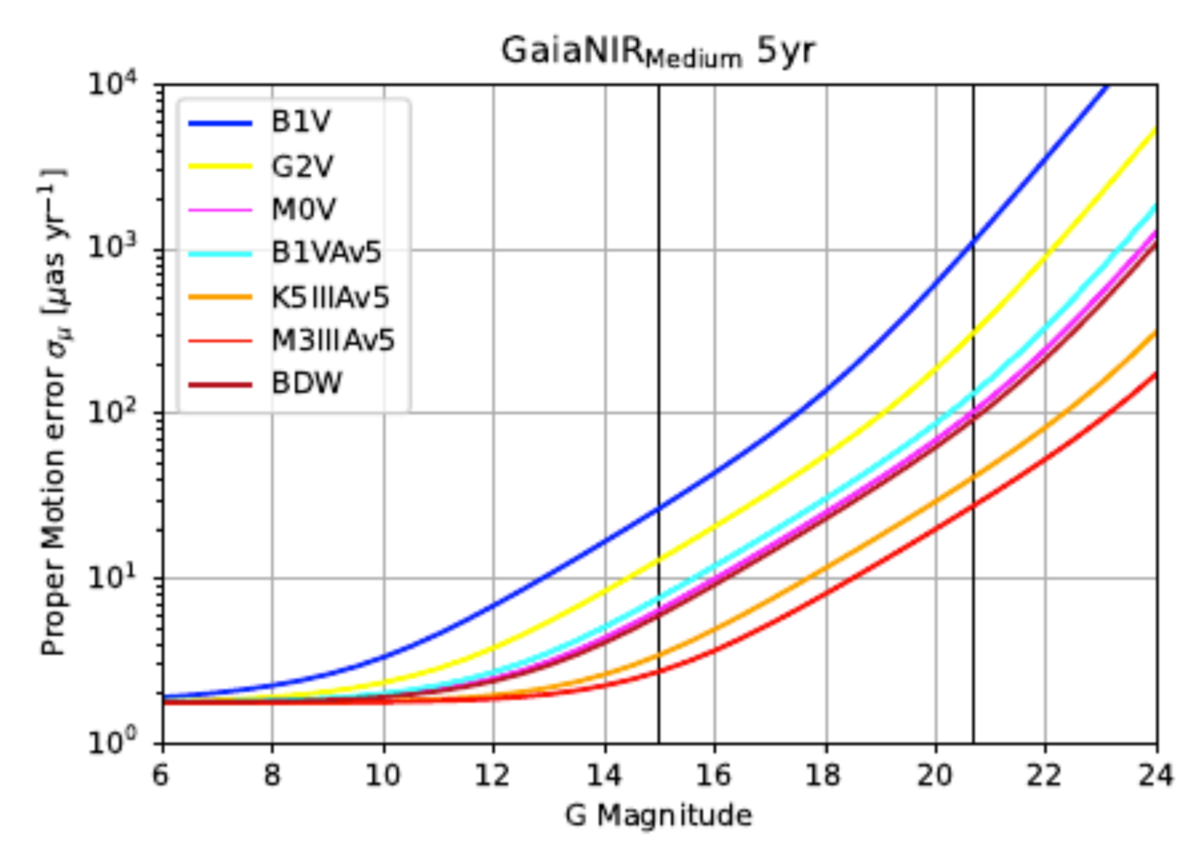
GaiaNIR$_{Large}$ Optics

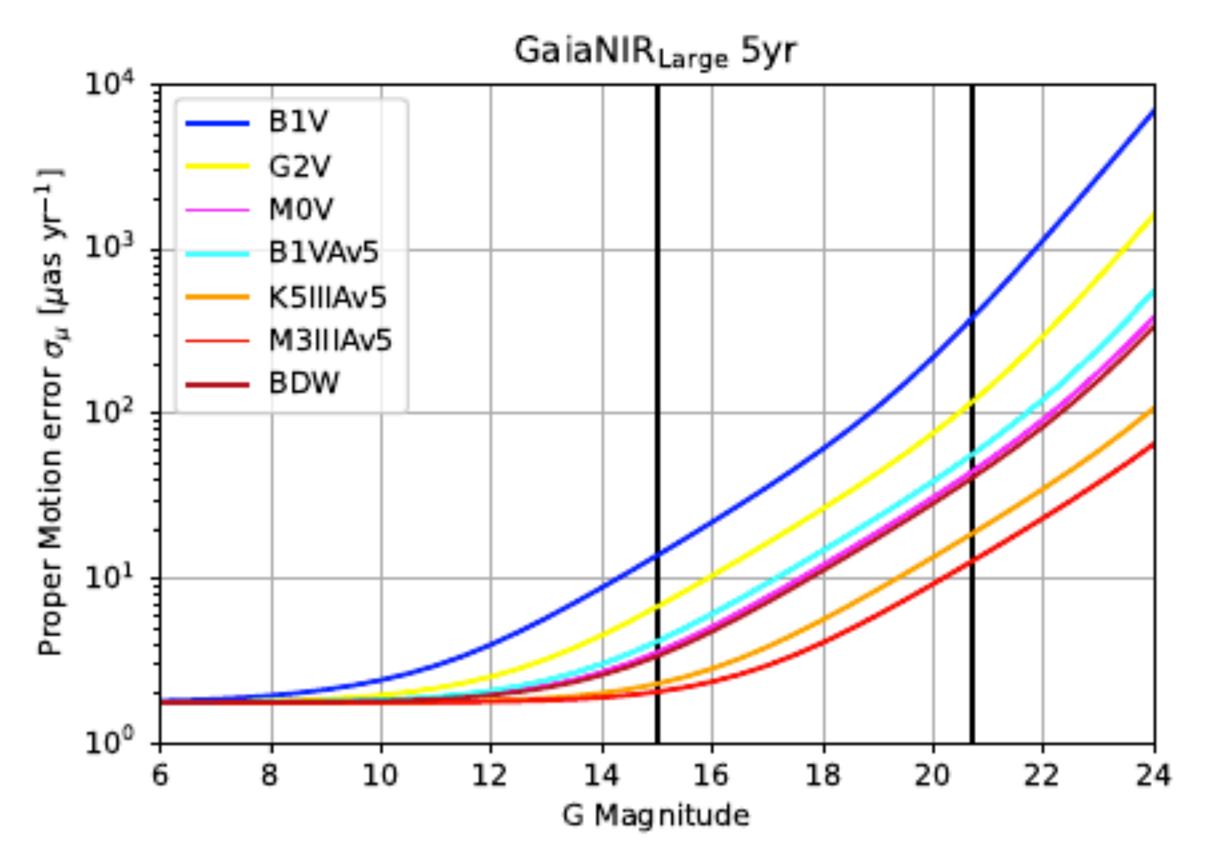
- Identical runs for M3III_Av5_T$_{eff}$3500_logg2.0_feh red giant giving a comparison between Gaia CCDs and GaiaNIR APD's
- APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs

EoM results PMs

Gaia | *GaiaNIR*$_{\text{Medium}}$ Optics | *GaiaNIR*$_{\text{Large}}$ Optics







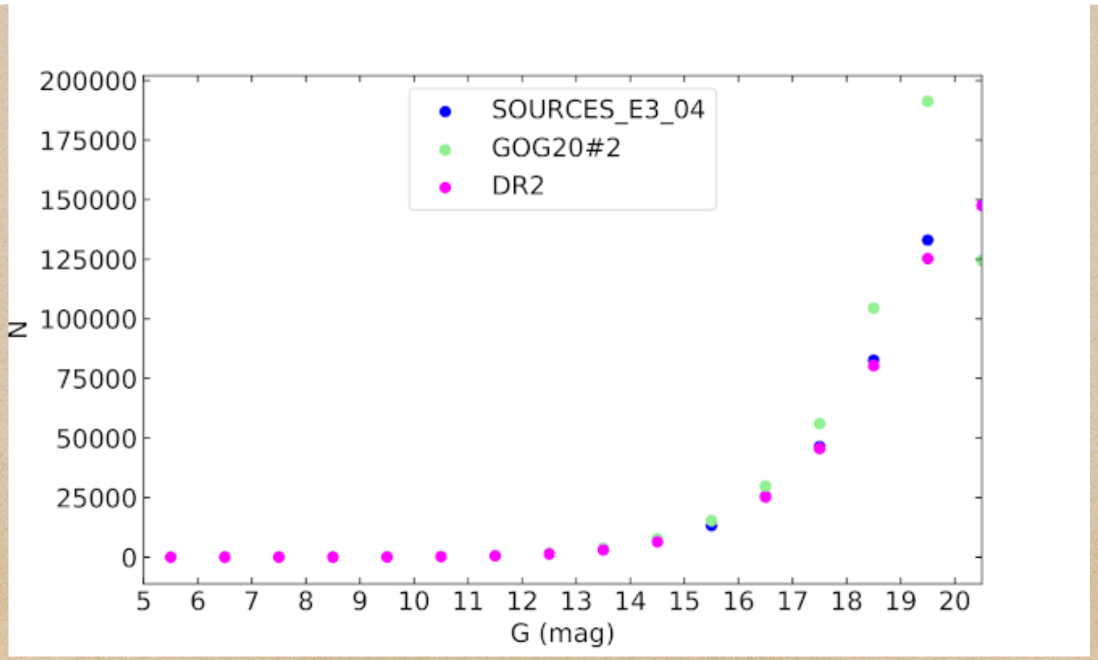
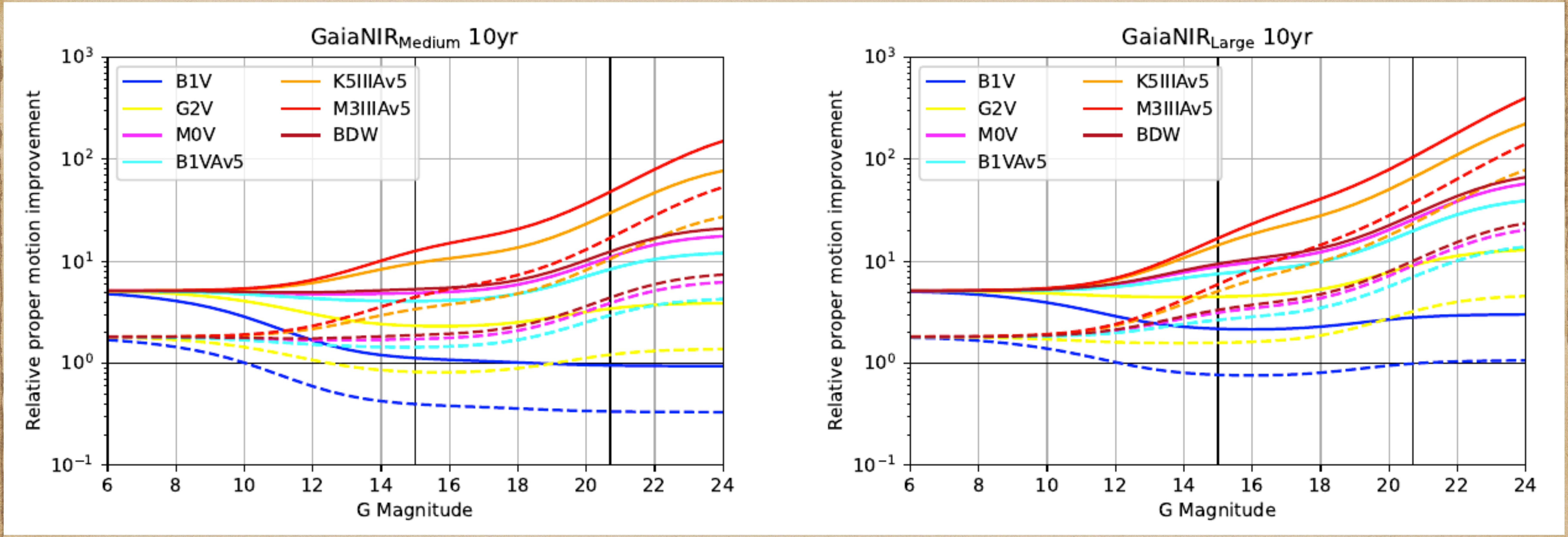


Figure 8.10: Average of the star counts over the whole sky as a function of magnitude, in Gaia EDR3 and Gaia DR2, compared to GOG20.

EoM resultsPM Relative Improvement



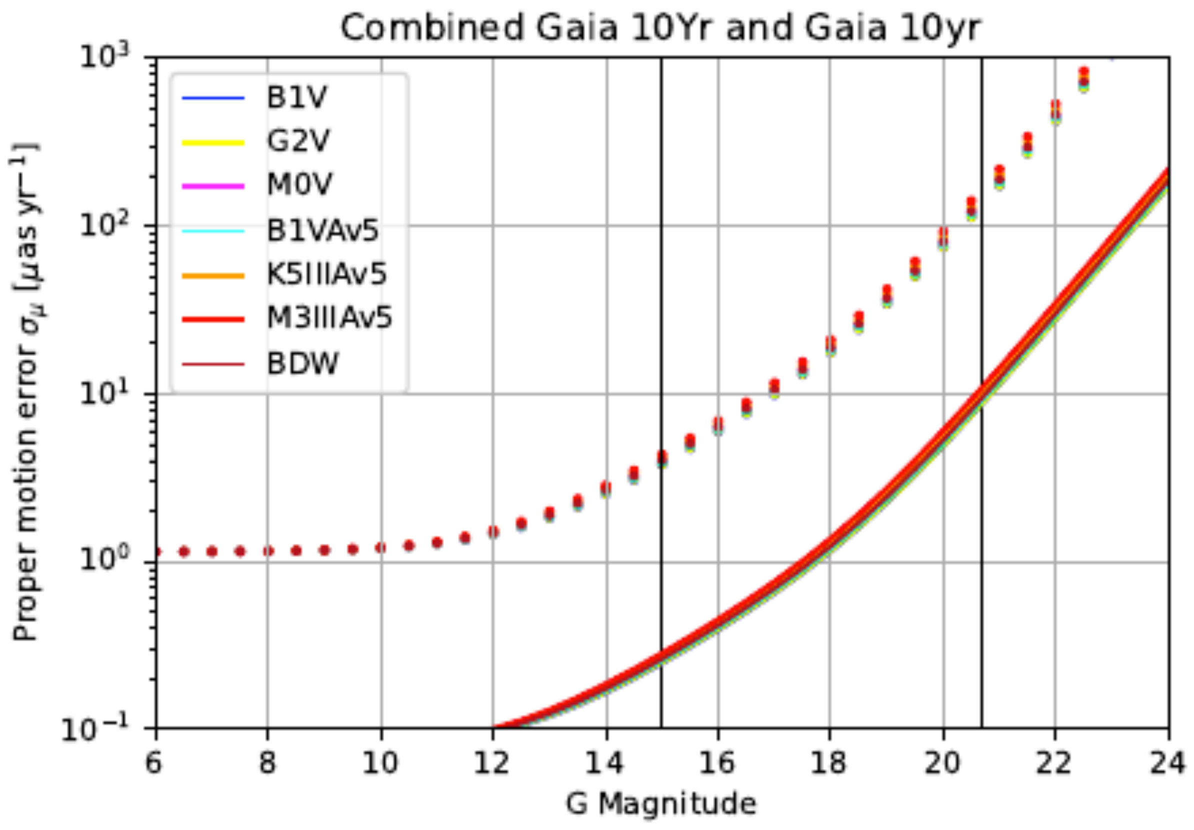
The relative improvement of individual *GaiaNIR* solutions compared to *Gaia*-DR4 (solid lines => 5 year) and DR5 (dashed lines => 10 year)

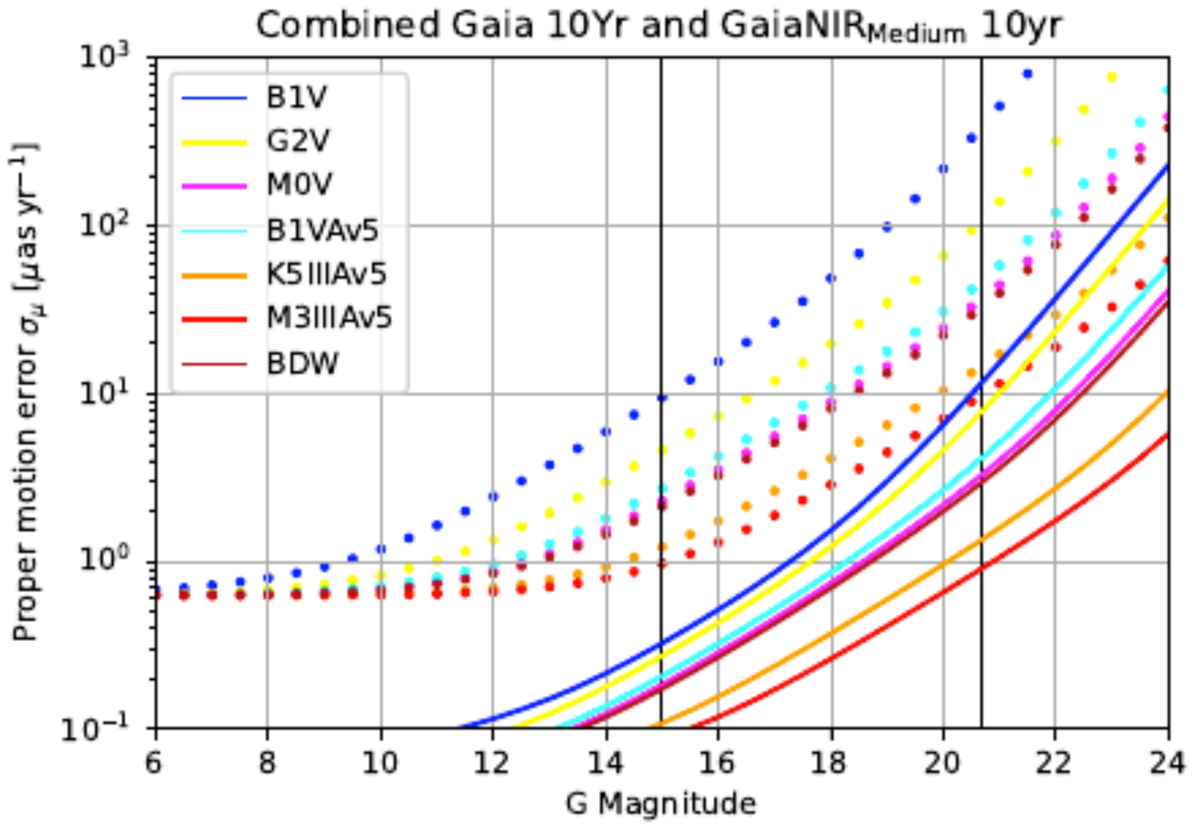
Joint EoM results PMs

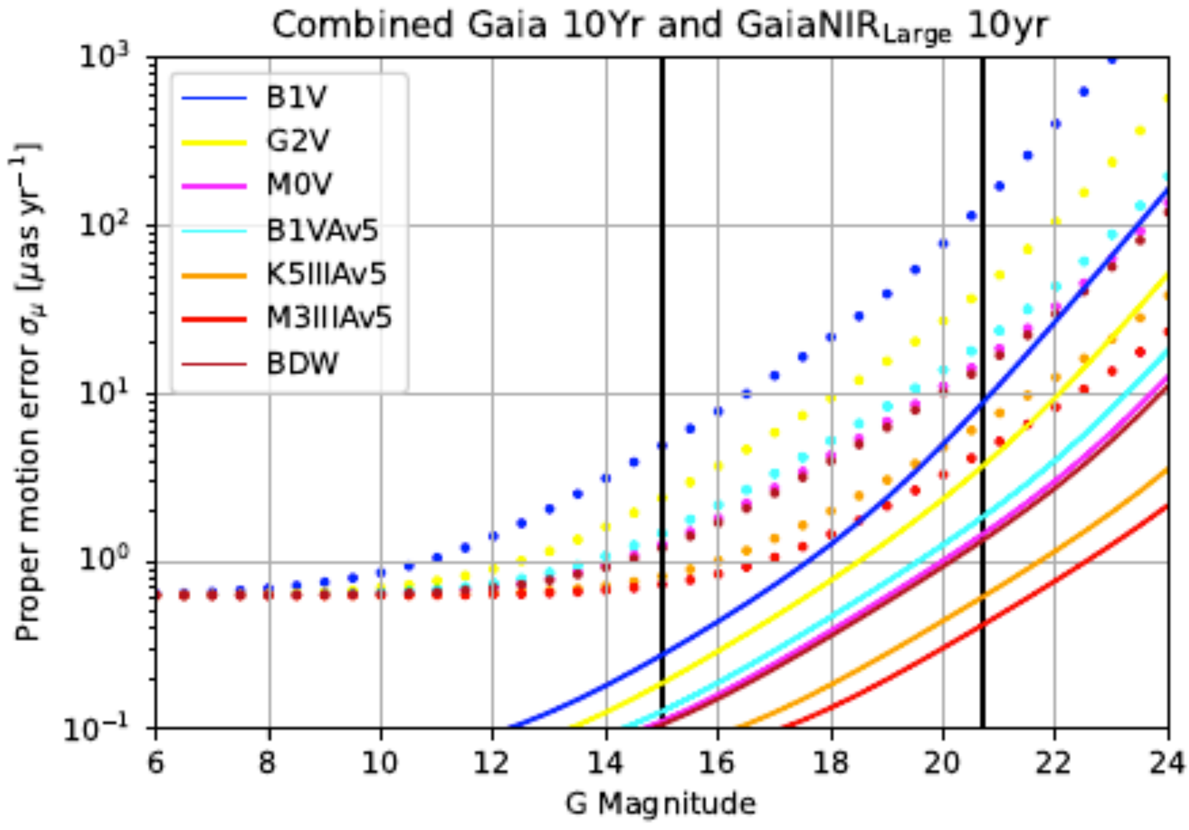
Gaia

*GaiaNIR*Medium Optics

*GaiaNIR*Large Optics

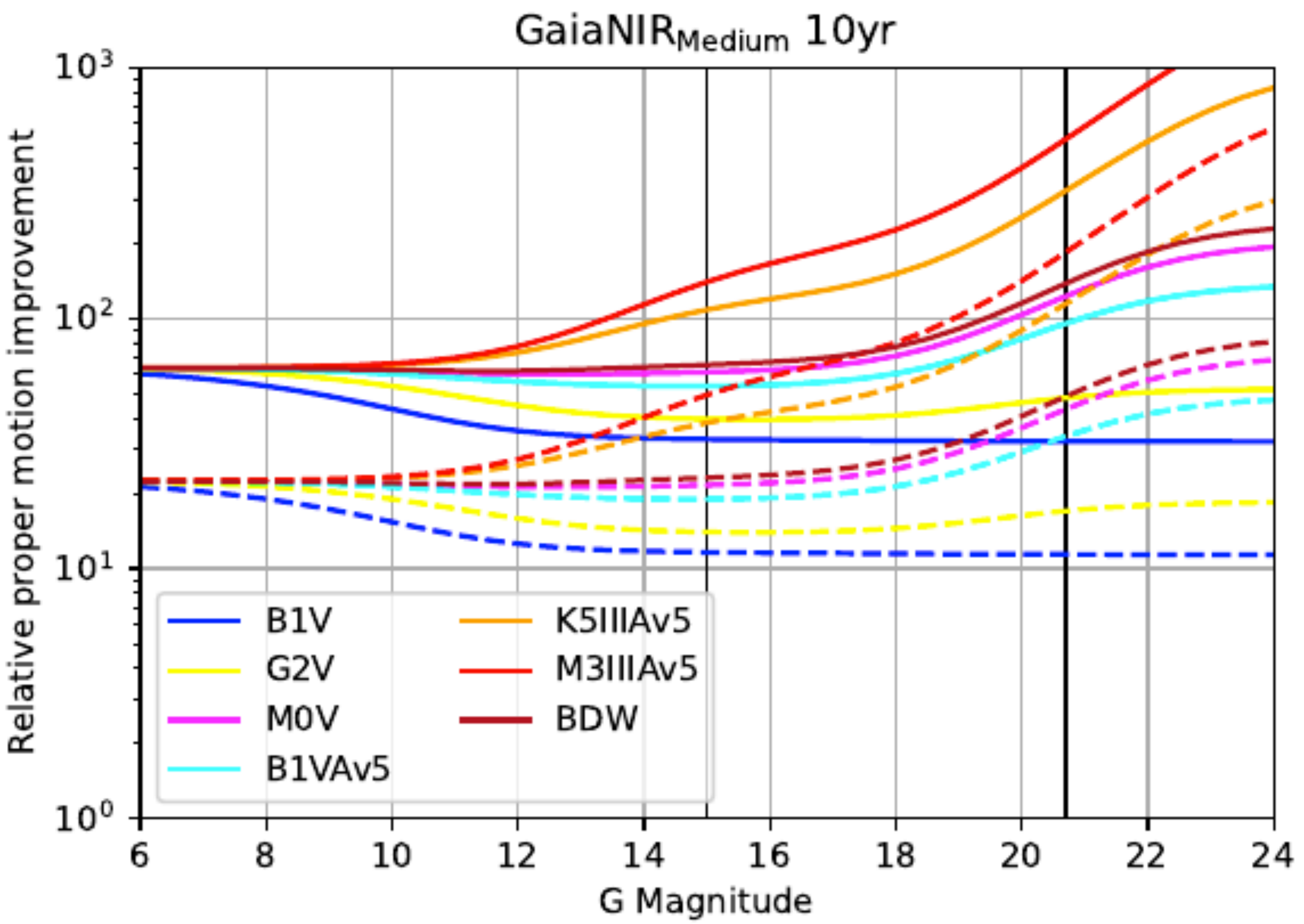


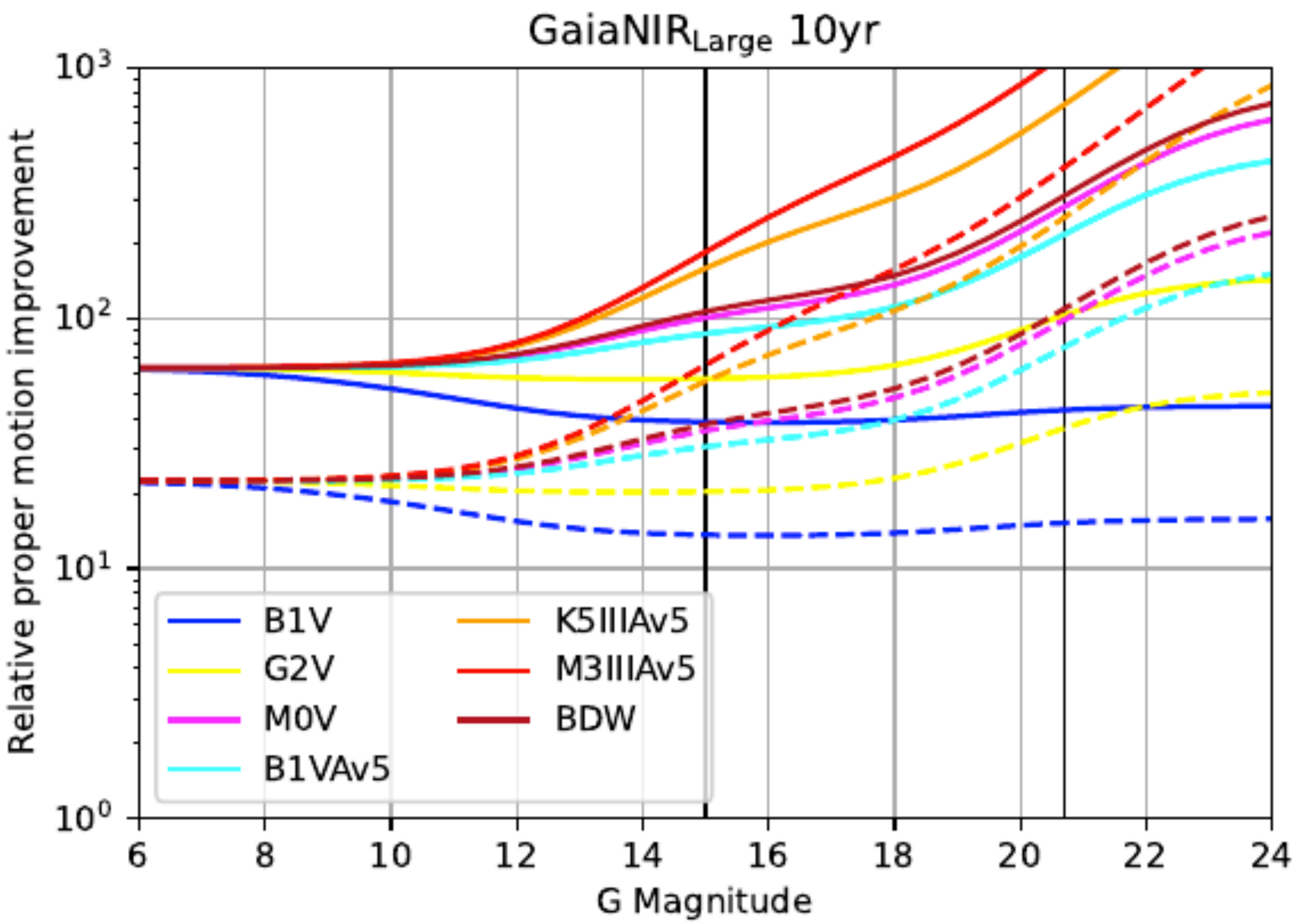




The combined EoM proper motion accuracy estimates for a series of reference stars for *Gaia* (left), *GaiaNIR*Medium (centre) and *GaiaNIR*Large (right). Note that the corresponding dotted curves show the corresponding results from the individual missions without joint solutions.

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