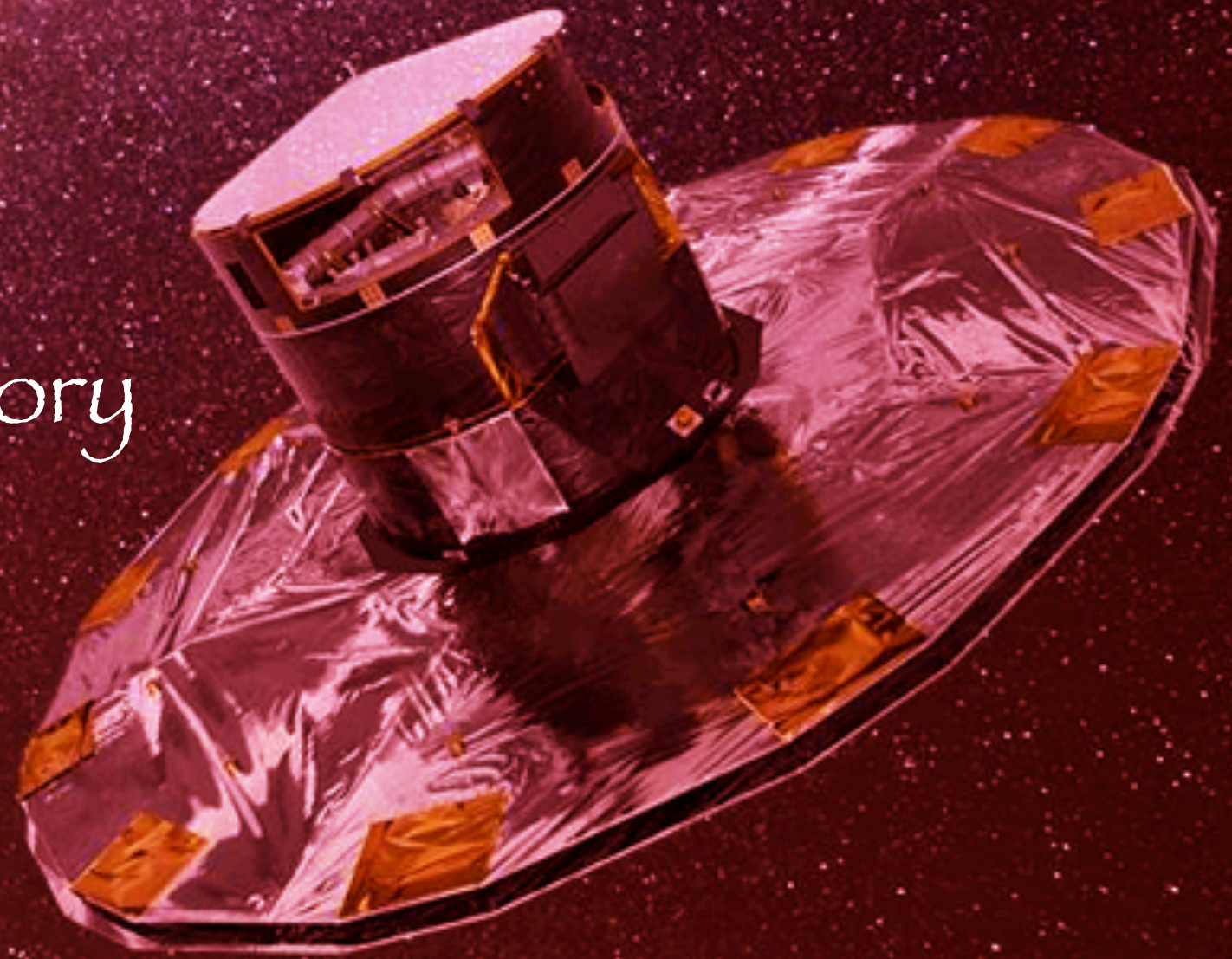


The GaiaNIR mission and the hidden regions of our Galaxy

Overview and Status

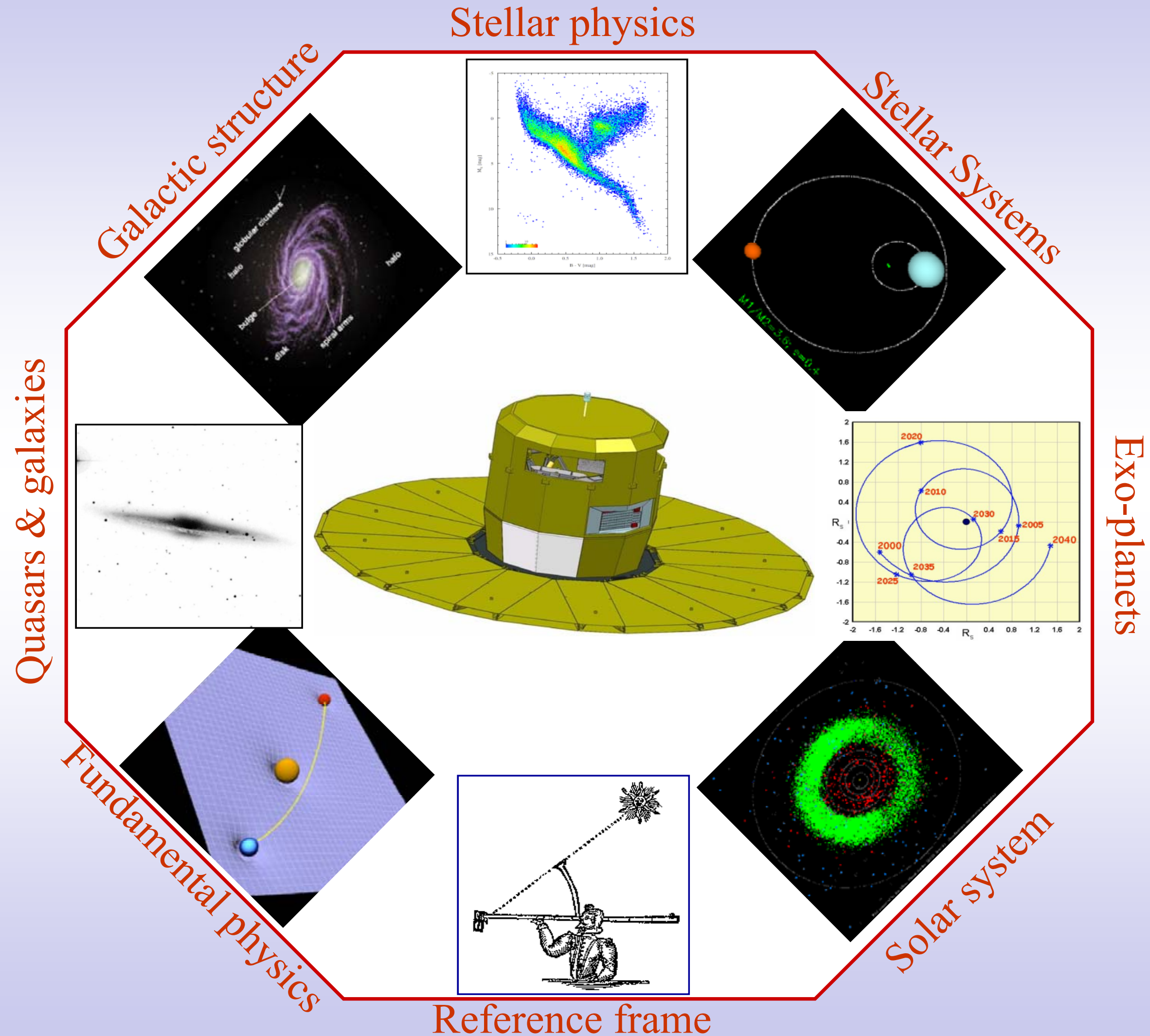
David Hobbs
Lund Observatory
Sweden



Old Gaia
Science
Objectives

GaiaNIR is
similar but

on a
grand
scale



Science Cases

1. Adding NIR astrometry and photometry to probe the dynamically important hidden regions of the Galaxy. Going deeper than Gaia this would 50+ billion stars when crowding is accounted for (~25% of the Galaxy)
2. Combining GaiaNIR with up to 2.5 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>

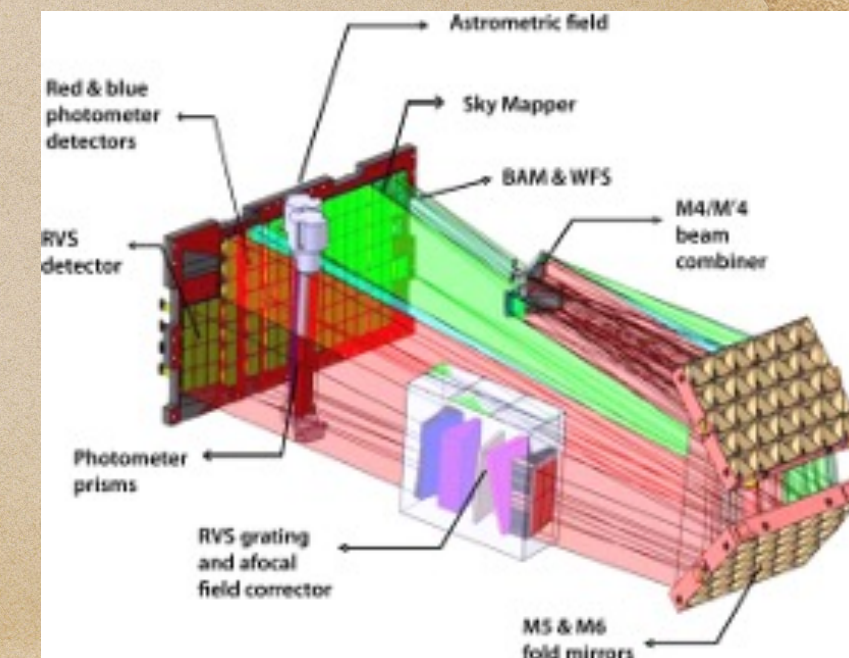
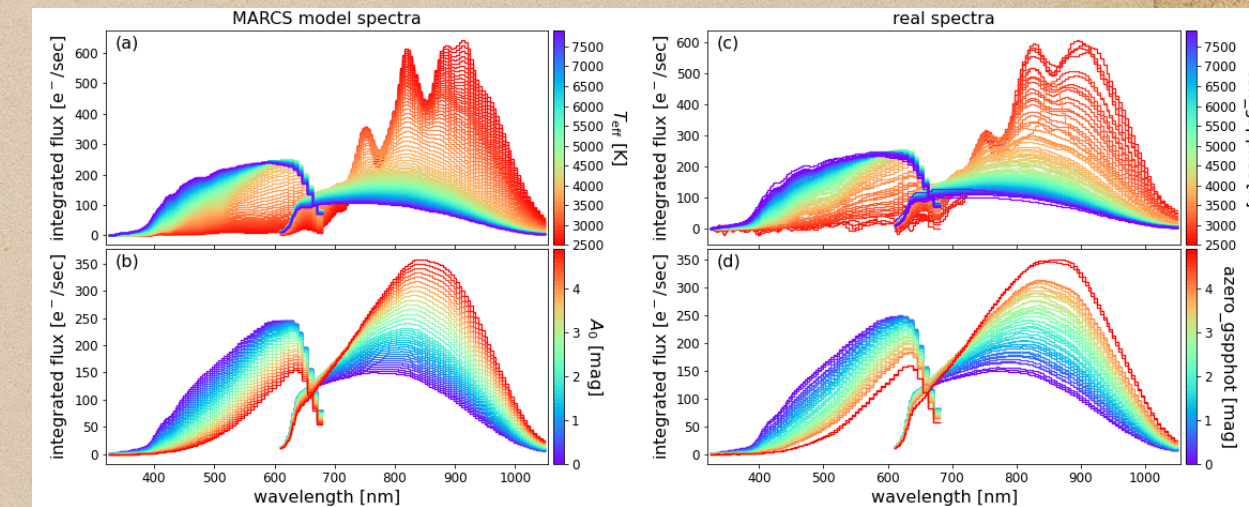
Voyage 2050

Final recommendations from
the Voyage 2050 Senior Committee



Billions of Spectra and RV's?

- ◆ Uniform all-sky low resolution dispersion spectra for most stars
- ◆ Abundances are a key tool to unravel our Galactic merger history
- ◆ RV's give an outstanding science case for Galactic dynamics but their lack is a major unresolved problem
- ◆ How to increase the dept of the survey (for RVS and dispersion spectra)
 - A slower scan rate
 - Wider detectors
 - Lower read noise



A deep survey with 50+ billion low dispersion spectra and ~1 billion RVs

(at a € cost)

Nano-arcsec yr⁻¹ PMs

For Gaia DR5 after ~10 years (assuming GaiaNIR has the same accuracy)

Positions
12.8=0.8σ_π and 11.2=0.7σ_π μas

Proper motions
4.64=0.29σ_π and 4.0=0.25σ_π μas

The combined uncertainty with ΔT=20+5+5 is

$$\sigma_{\mu 0} = \frac{(\sigma_{posN}^2 + \sigma_{posG}^2)^{1/2}}{\Delta T}$$

When using a joint solution we get the weighted mean of all three measures.
σ_{μ0} is also independent as positions are independent in their respective catalogues

$$\sigma_{\mu} = \left(\sigma_{\mu 0}^{-2} + \sigma_{\mu N}^{-2} + \sigma_{\mu G}^{-2} \right)^{-1/2}$$

$$\sigma_{\mu_{\alpha}^*} = 0.59 \mu\text{as yr}^{-1}$$

$$\sigma_{\mu_{\delta}} = 0.52 \mu\text{as yr}^{-1}$$

First Epoch Gaia 10yr
(2020)



2015

2020

2025

2045

2050

2055

Euclid, Roman,
and JASMINE
provide NIR stars

A 20 year gap

An earlier launch will increase the PM uncertainty



Second Epoch
GaiaNIR 10yr (2050)

A factor of 21 times better for PM's
compared to Gaia DR4 and a factor of
8 times better than Gaia DR5 giving
nano-arcsec PMs for common stars

Early Gaia-GaiaNIR Joint PM Catalogues

For Gaia DR5 after ~10 years (assuming GaiaNIR has the same accuracy)

Positions
 $12.8=0.8\sigma_{\pi}$ and $11.2=0.7\sigma_{\pi} \mu\text{as}$

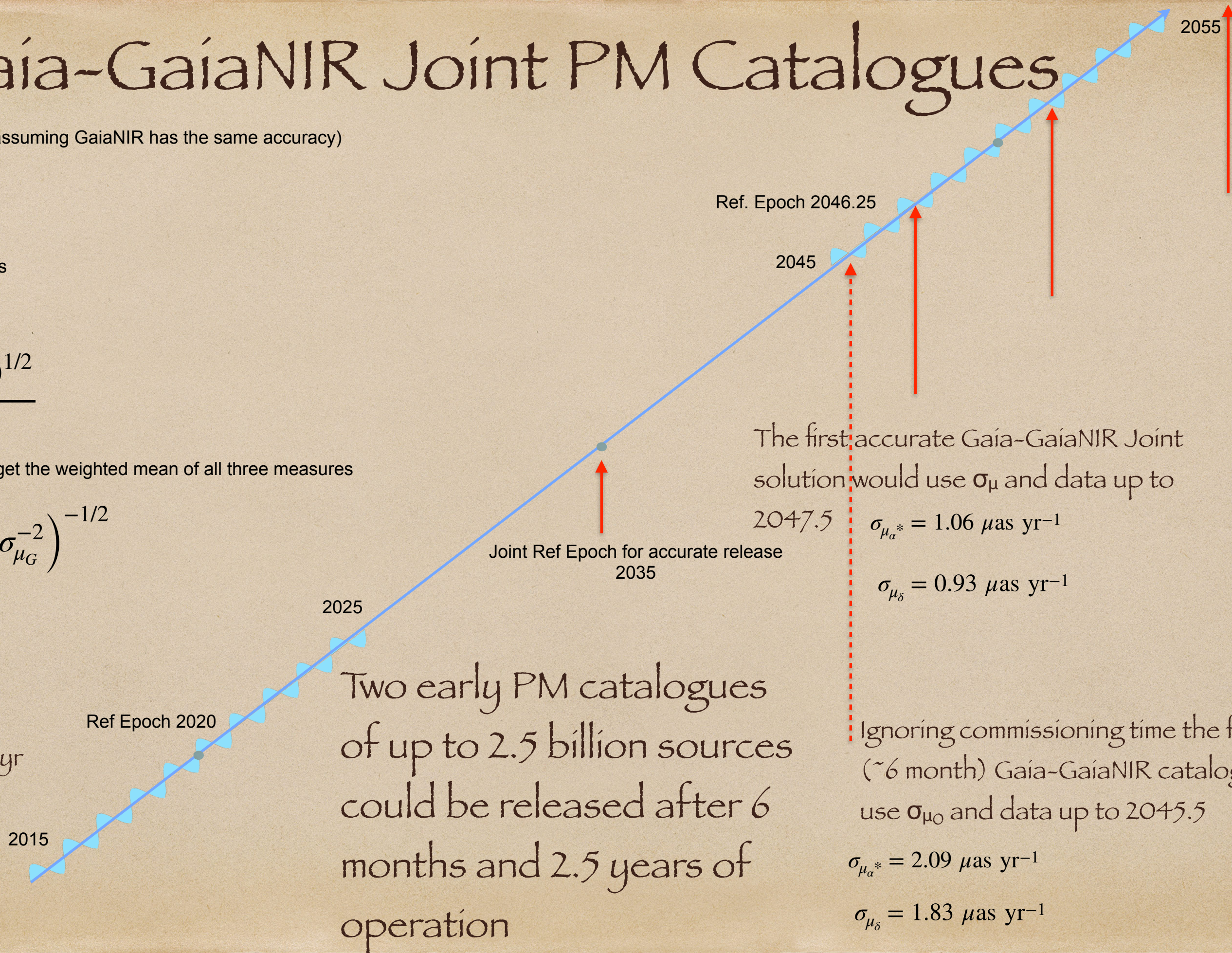
Proper motions
 $4.64=0.29\sigma_{\pi}$ and $4.0=0.25\sigma_{\pi} \mu\text{as}$

$$\sigma_{\mu 0} = \frac{(\sigma_{posN}^2 + \sigma_{posG}^2)^{1/2}}{\Delta T}$$

When using a joint solution we get the weighted mean of all three measures

$$\sigma_{\mu} = \left(\sigma_{\mu 0}^{-2} + \sigma_{\mu N}^{-2} + \sigma_{\mu G}^{-2} \right)^{-1/2}$$

First Epoch Gaia 10yr
(2020)



Two early PM catalogues
of up to 2.5 billion sources
could be released after 6
months and 2.5 years of
operation

The first accurate Gaia-GaiaNIR Joint
solution would use σ_{μ} and data up to
2047.5

$$\sigma_{\mu_{\alpha}^*} = 1.06 \mu\text{as yr}^{-1}$$

$$\sigma_{\mu_{\delta}} = 0.93 \mu\text{as yr}^{-1}$$

Ignoring commissioning time the first crude
(~6 month) Gaia-GaiaNIR catalogue would
use $\sigma_{\mu 0}$ and data up to 2045.5

$$\sigma_{\mu_{\alpha}^*} = 2.09 \mu\text{as yr}^{-1}$$

$$\sigma_{\mu_{\delta}} = 1.83 \mu\text{as yr}^{-1}$$

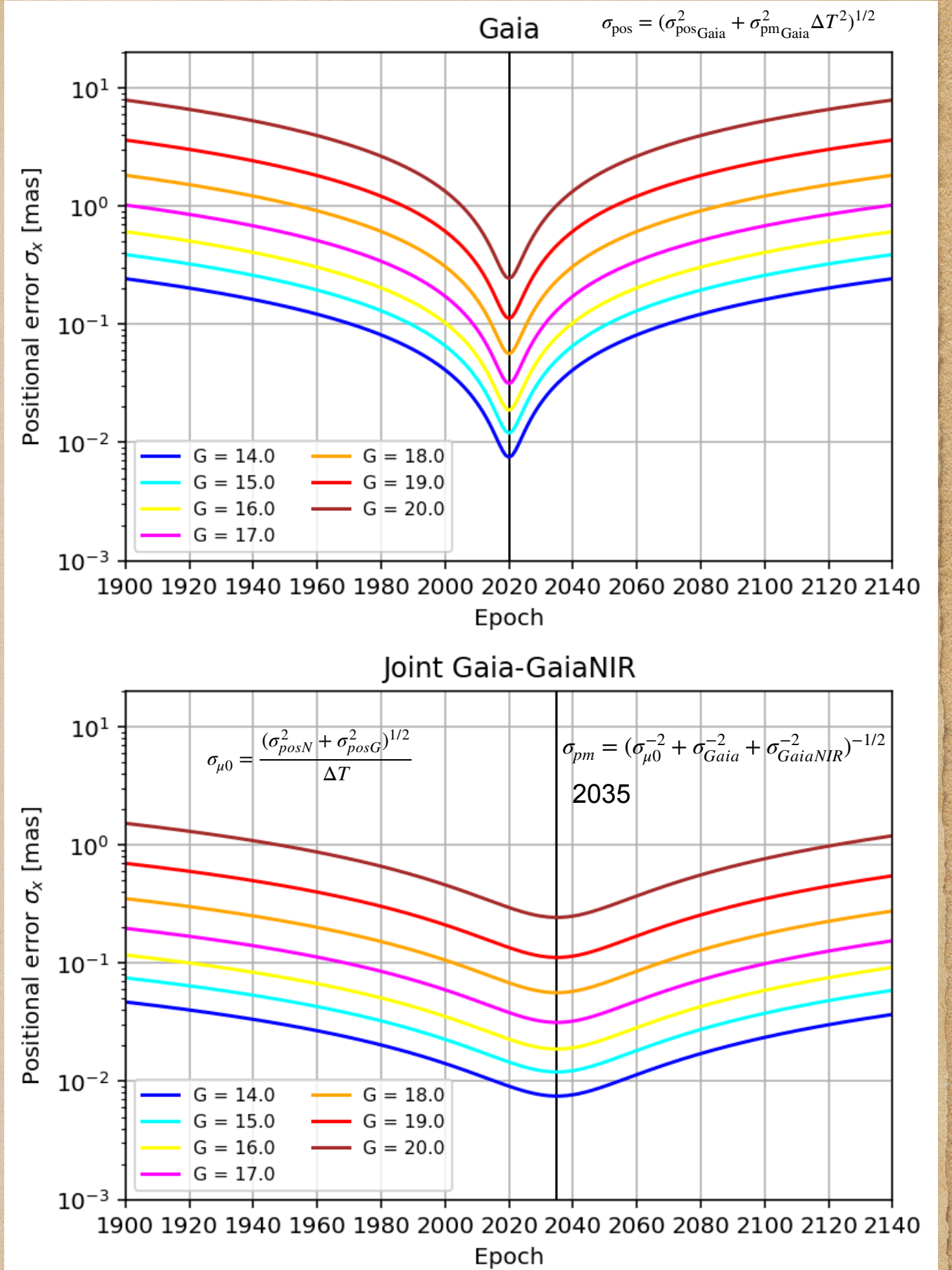
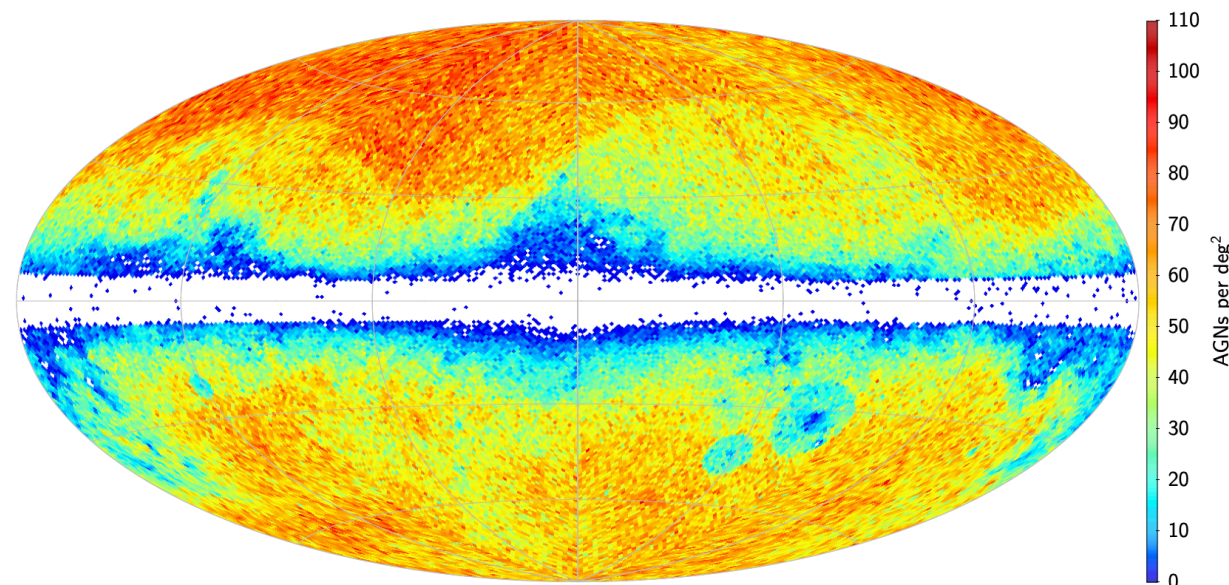


Second Epoch
GaiaNIR 10yr
(2050)

Catalogue Ageing

- ◆ The positional uncertainty of the catalogue will degrade due to PM errors - requiring a new mission to correct the catalogue.
- ◆ Without GaiaNIR astronomy will be held back after 20 years
- ◆ 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

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



Degradation of the astrometric uncertainty 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)



University of Sydney, The Sydney Institute for Astronomy (SIfA)

“Without question, the major stumbling block to constructing a believable dynamical model of the Milky Way, the only galaxy where we can hope to observe the full stellar inventory, ***is the presence of dust.*** We need an infrared version of Gaia to extend significantly beyond where we are today.”

Hunstead Lectures 2022: “Our Galaxy in the era of Gaia” by James Binney

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 uncertainty 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_{Small}

GaiaNIR is based on a off-axis $f=35\text{m}$ 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

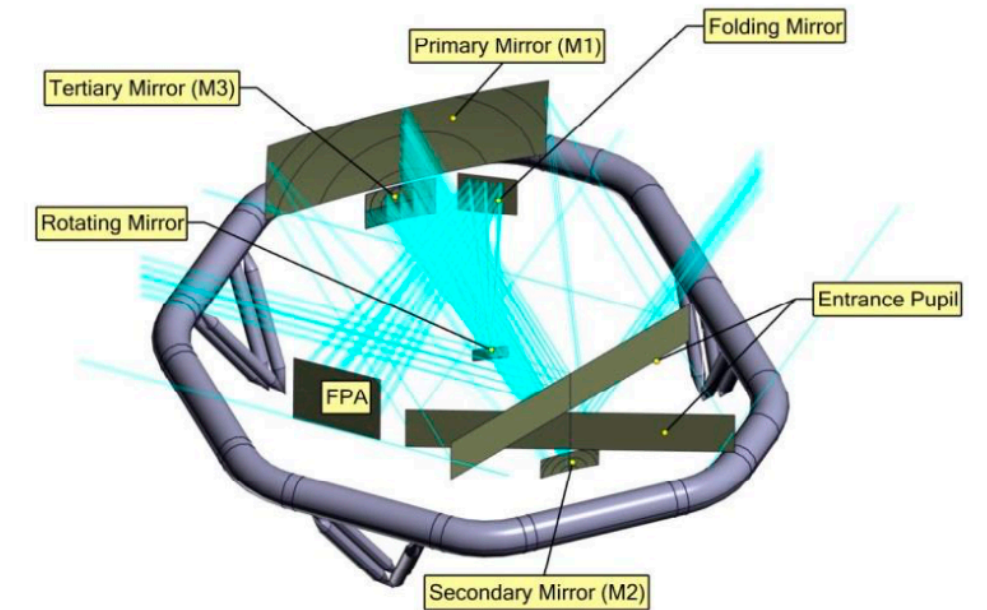


Figure 5-34: GaiaNIR optical surfaces and the light path

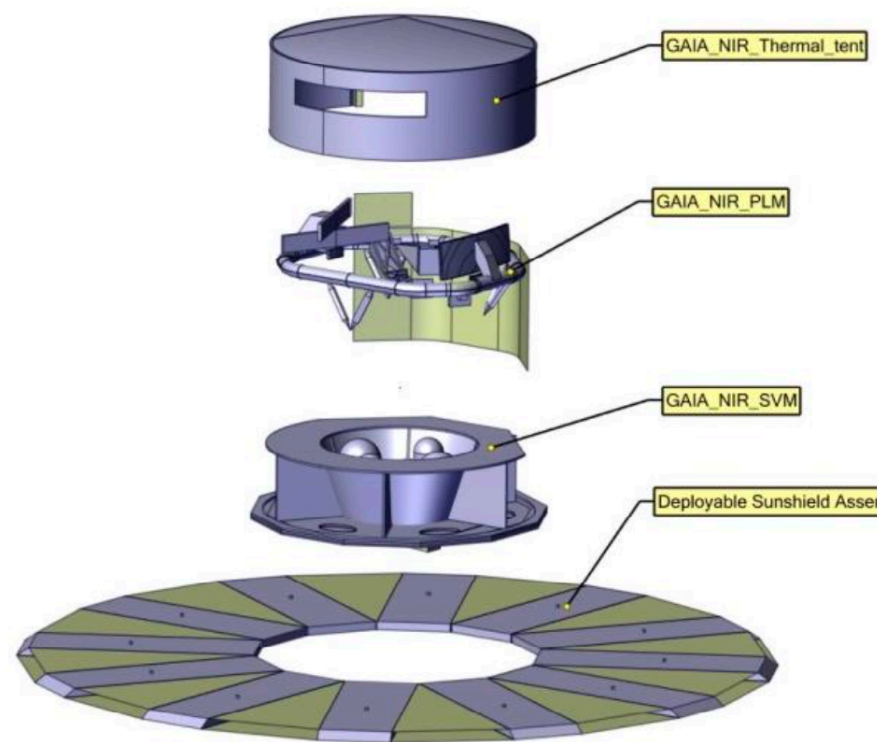


Figure 6-2: Gaia-NIR Spacecraft main elements

- ◆ 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}

D = 1.7m M1 D = 1.7m

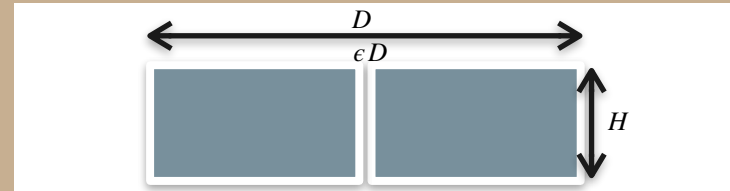


Figure 2.1: Parametrization of the pupil for the astrometric instrument in terms of the total length D in the scan direction and the obscuration ratio ϵ . The perpendicular dimension H is set by the (fixed) total area $A = (1 - \epsilon)DH$.

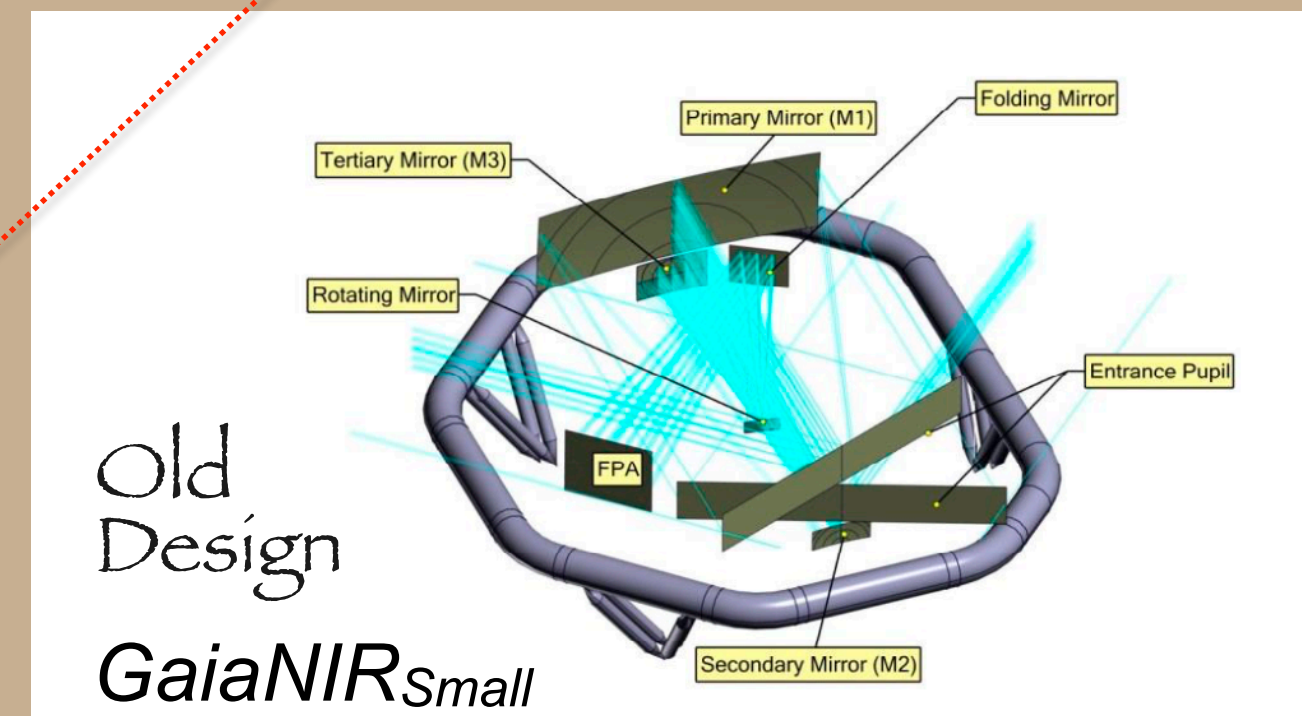
Mission	Resolution
Gaia ($\lambda_{mid}=700nm$)	0.12" with $D=1.45m$
<i>GaiaNIR_{Medium}</i> ($\lambda_{mid}=1550nm$)	0.24" with $D=1.7m$
<i>GaiaNIR_{Large}</i> ($\lambda_{mid}=1550nm$)	0.11" with $D=3.5m$

BA

Two Improvements:

GaiaNIR_{Medium}
double the height of the primary and BA mirrors

GaiaNIR_{Large}
double the width of the primary as a segmented mirror



Old Design

GaiaNIR_{Small}

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

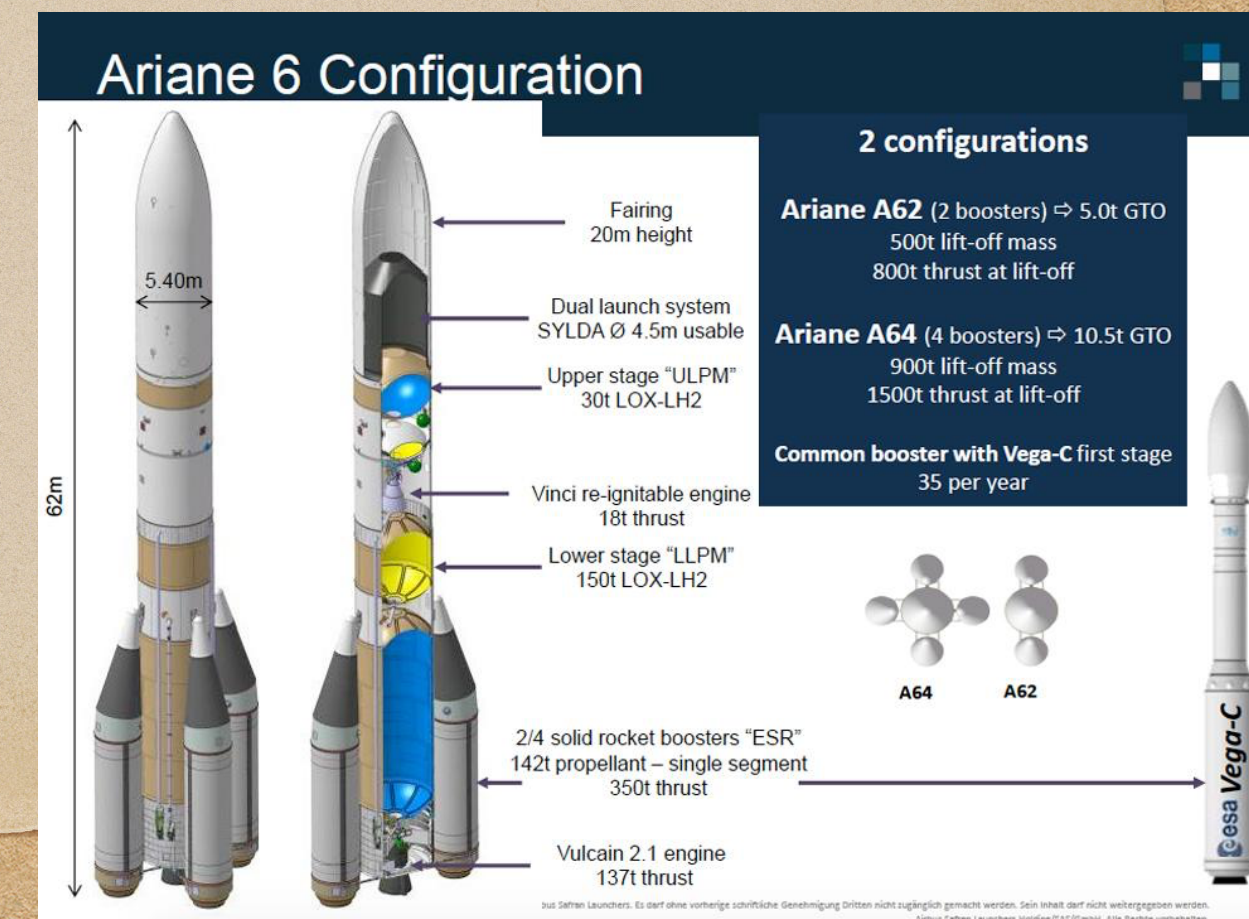
The resolution and parallax errors are inversely proportional to the length of the primary mirror D_{max}

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

$D_{max} = 3.5m$

We will propose GaiaNIR_{Large}

- ◆ A primary mirror of 3.5 m may mean a larger taurus than for Gaia
 - ◆ Gaia has two 1.45 m primary mirrors sides by side so not much smaller
 - ◆ Gaia had a diameter of 10 meters (with the sunshield deployed)
 - ◆ When stowed for launch, Gaia was much smaller, measuring 4.4 meters tall and **3.8 meters** in diameter
 - ◆ Aim for launch on Ariane 6
- ◆ Gaia 3.8 m
 - ◆ GaiaNIR ? m
 - ◆ Falcon Heavy 3.7 m
 - ◆ Soyuz Fregat-MT 3.8 m
 - ◆ Soyuz Fregat-SB 3.875 m
 - ◆ **Ariane 6 5.4 m**
 - ◆ SpaceX's Starship 9 m



Detector Status

Leonardo UK have small APDs with high frequency readout

GHz readout devices are possible for TDI operation

LmAPDs amplify (avalanche gain of $>100\times$) and measure signals in photon starved environments and are perfect for faint astronomical applications

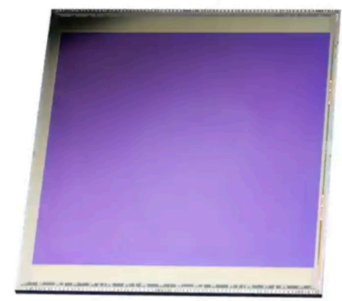
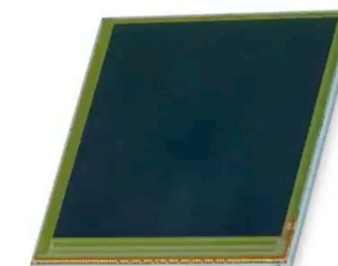
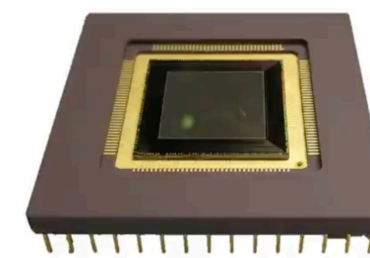
For wavelength cutoff we choose 800-2300nm to avoid thermal noise

Studies of the detectors are now ongoing in the UK

GaiaNIR requires a high frequency readout which is only possible with the Saphira type of detector

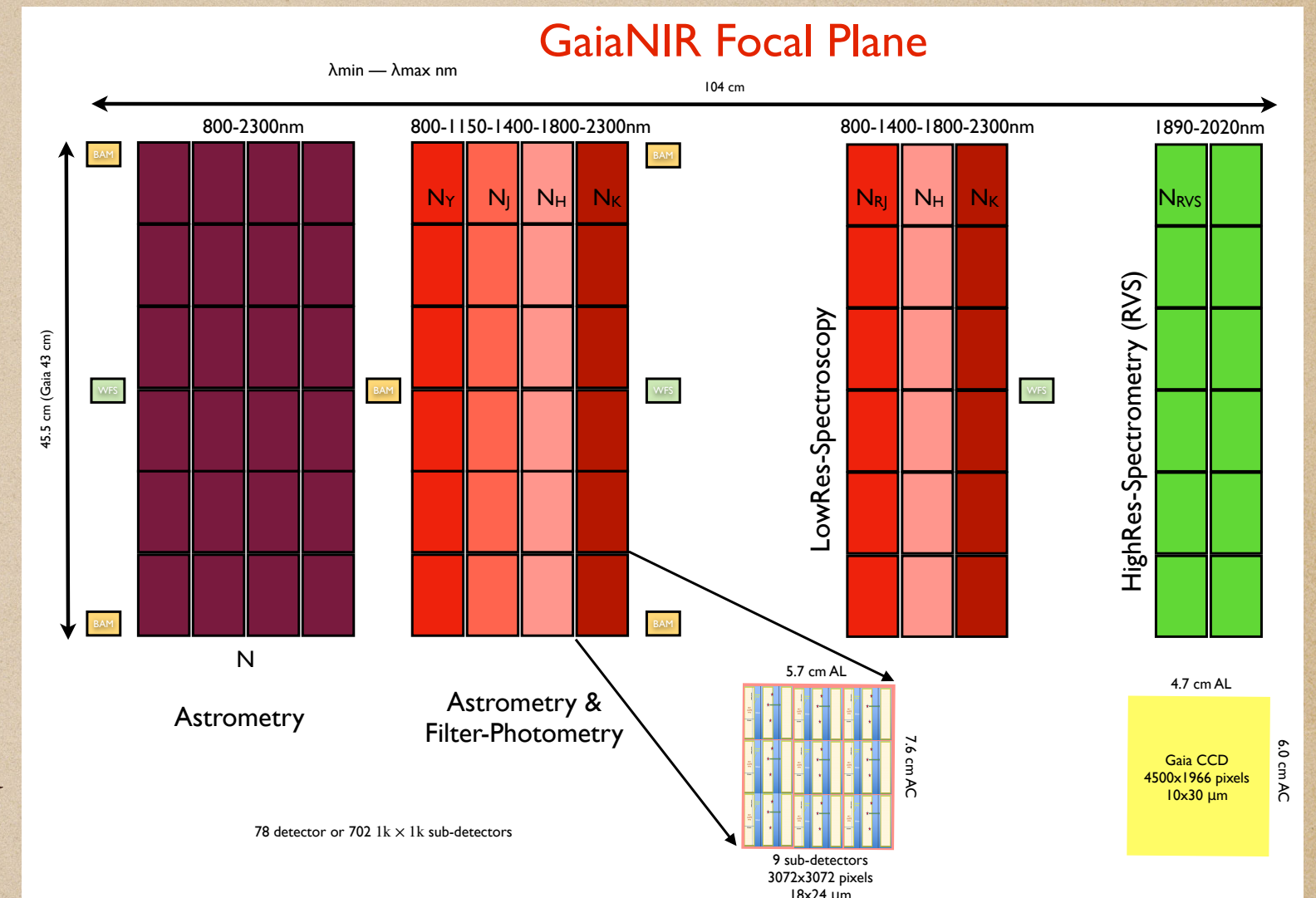
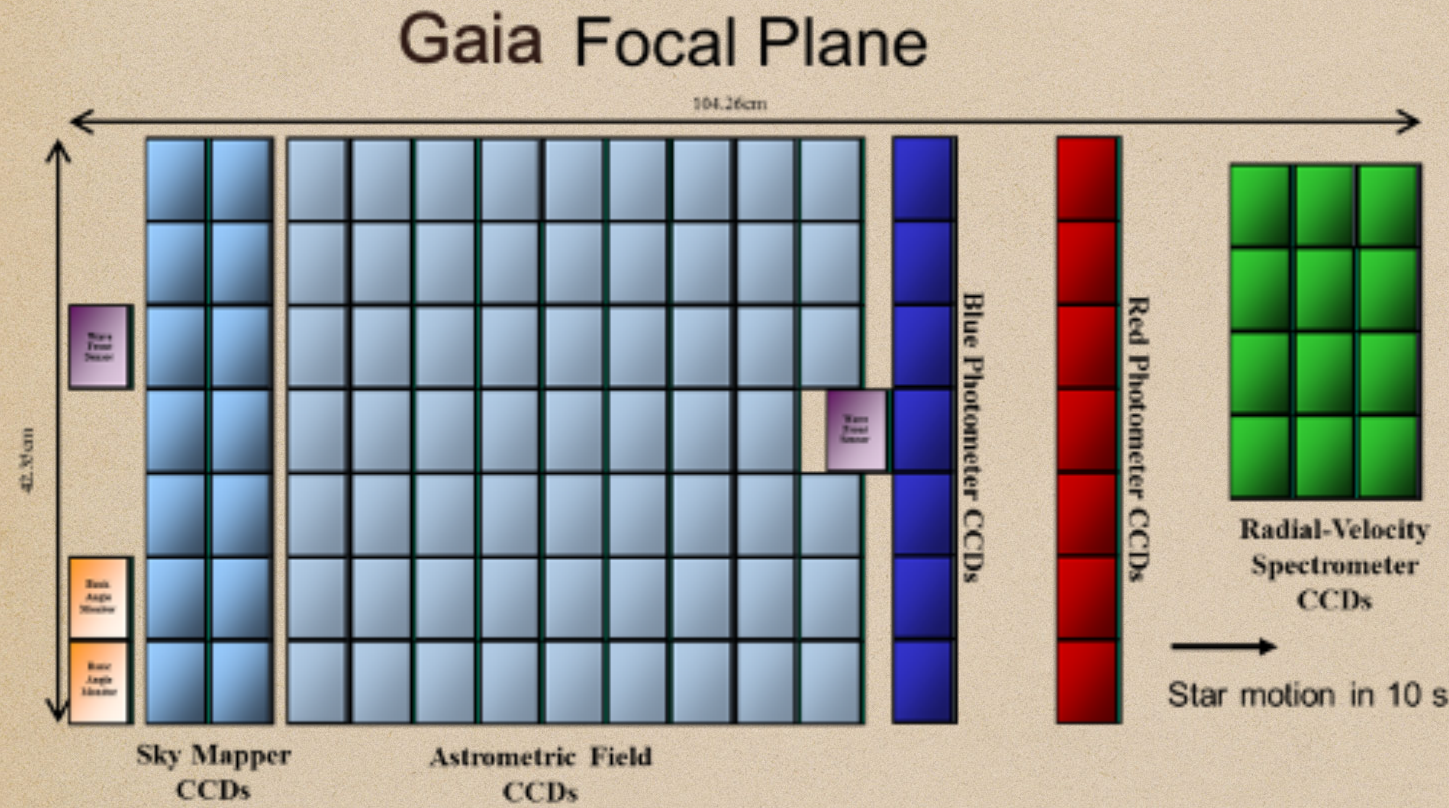
Detectors can be connected in sequence and use image stacking

Update of LmAPDs for low background flux applications



	Large Saphira	Ike-Pono	IBEX
Dimensions	512x512/24 μm	1024x1024/15 μm	2048x2048/15 μm
Status	Detectors provided to consortium partners for evaluation and system development.	First science grade devices under assessment – see Charles-Antoine tails.	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

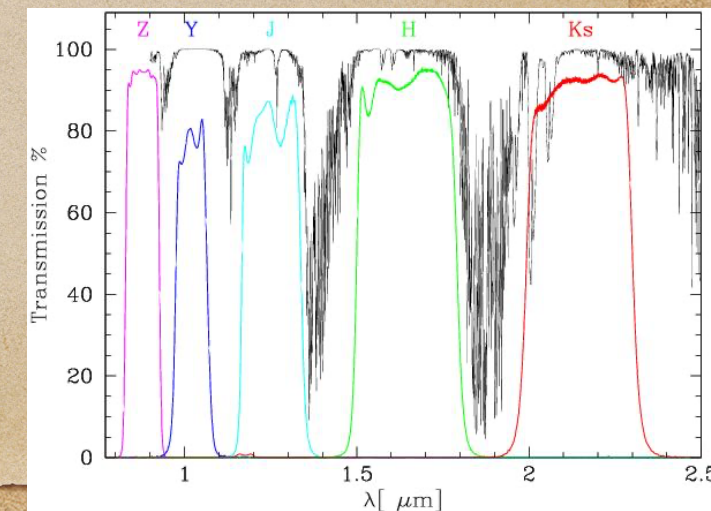


- ◆ Linear Mode APDs are the most promising detector for GaiaNIR
- ◆ Cooling strategy must be passive (~90K)
- ◆ Max wavelength - 2300 nm, blue stars (<800nm) are more challenging
- ◆ No SMs - track motion of stars instead to determine the FoV
- ◆ Filter photometry on astrometric field by depositing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

48 astro, 18 dispersion, 12 RV detectors

A modular concept uses small detectors to form larger ones

FoV=0.72°x0.72°



Example from VVV

End Of Mission Uncertainty

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

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}];

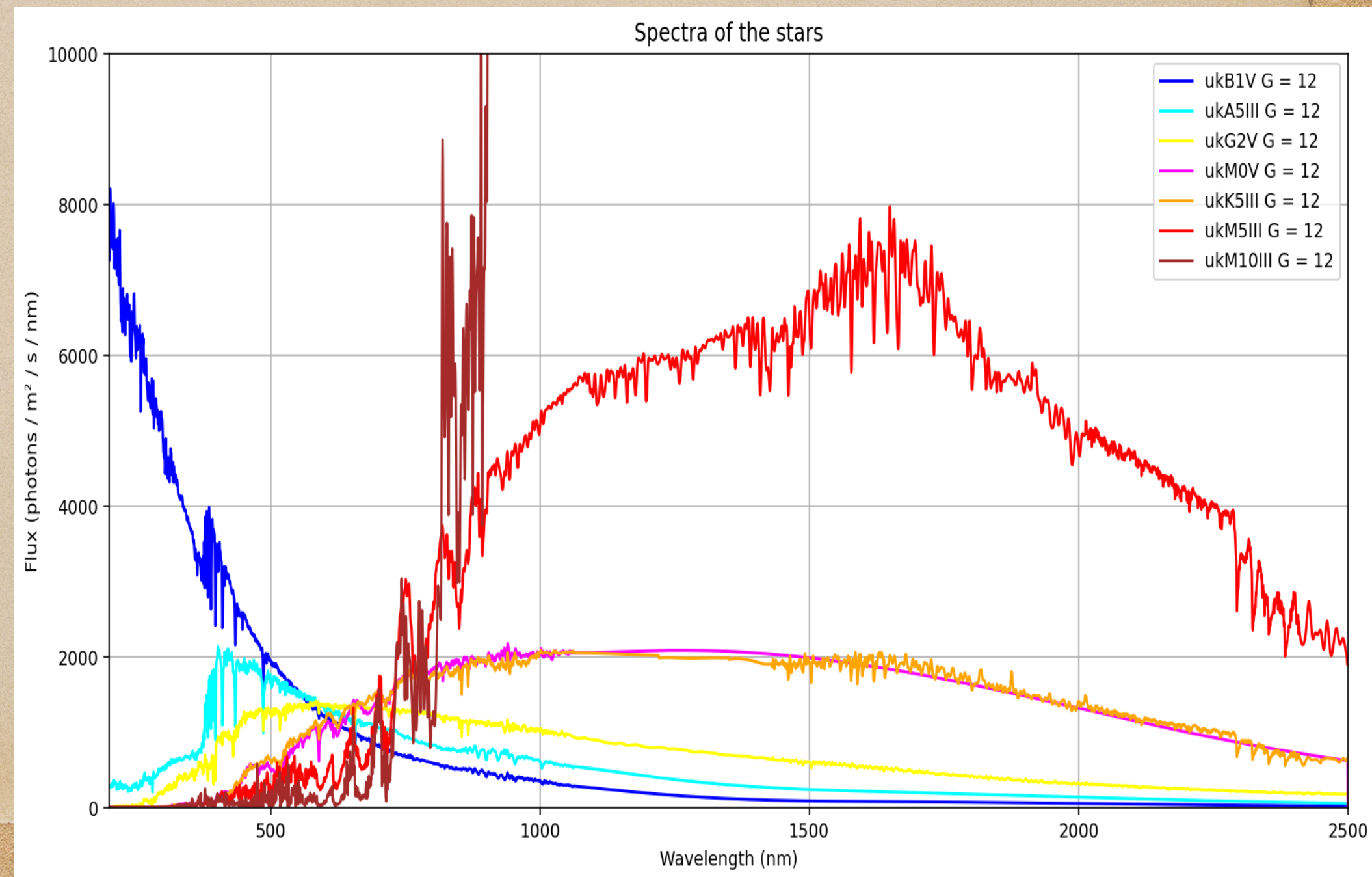
$\Delta \xi$ is the angular pixel size along scan [rad] and;

N_{ξ} is the number of pixels per CCD in the scan direction [e-].

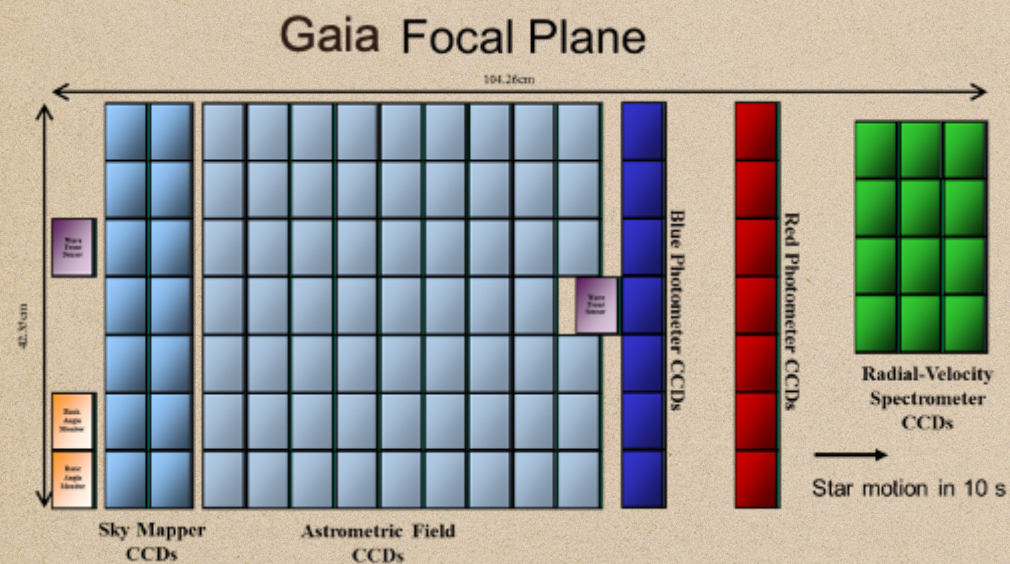
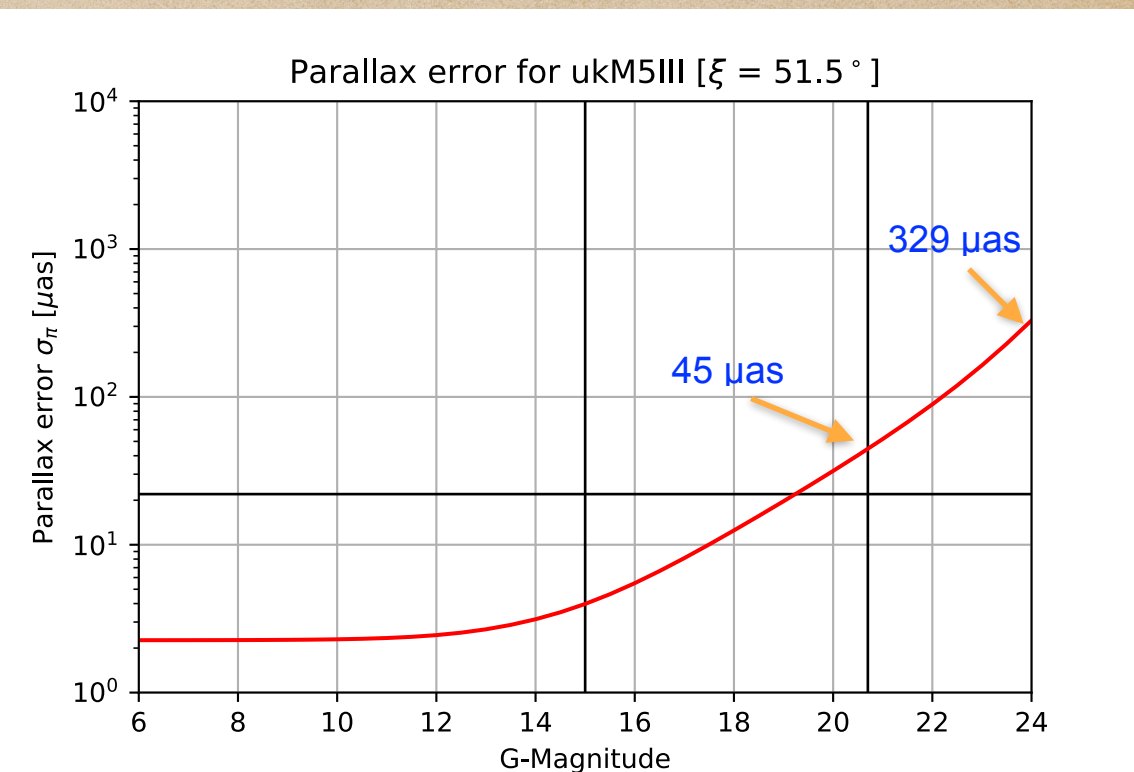
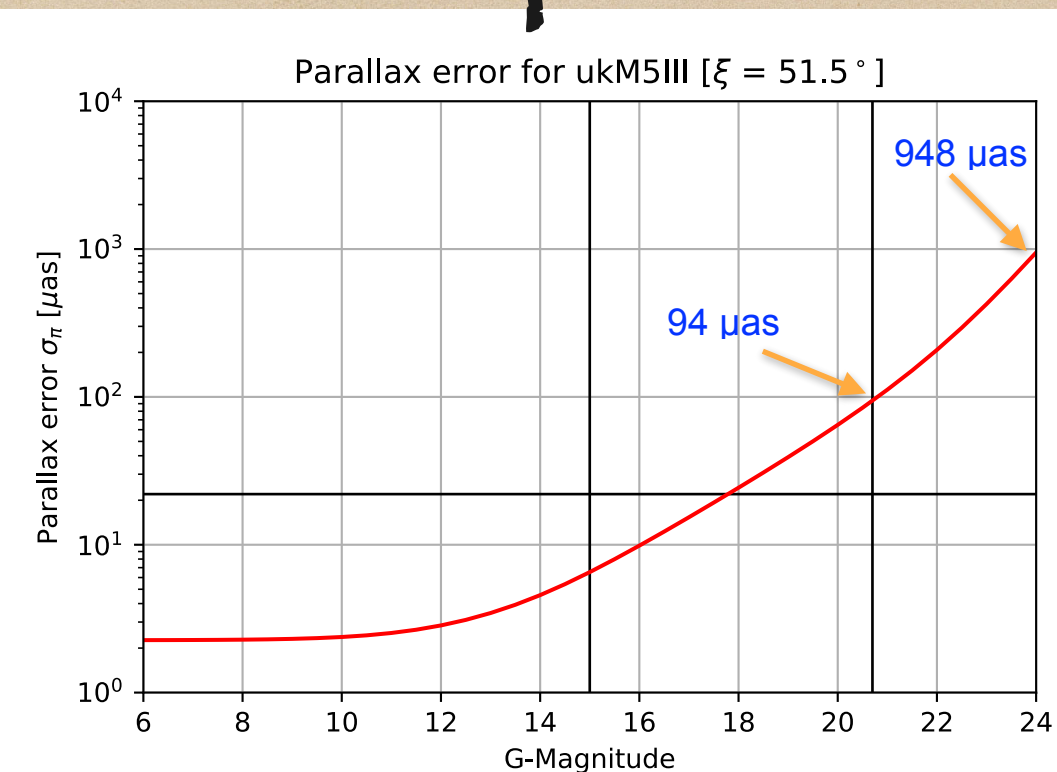
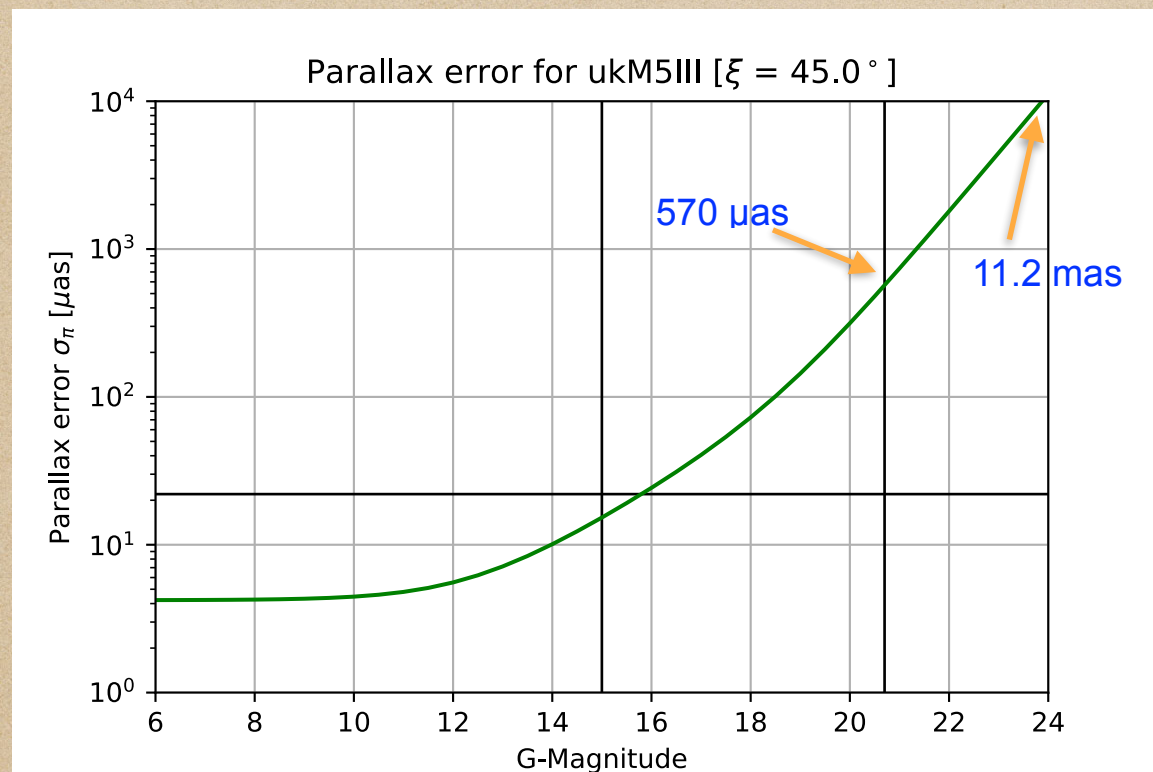
L = effective mission length (i.e. excluding dead time);

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

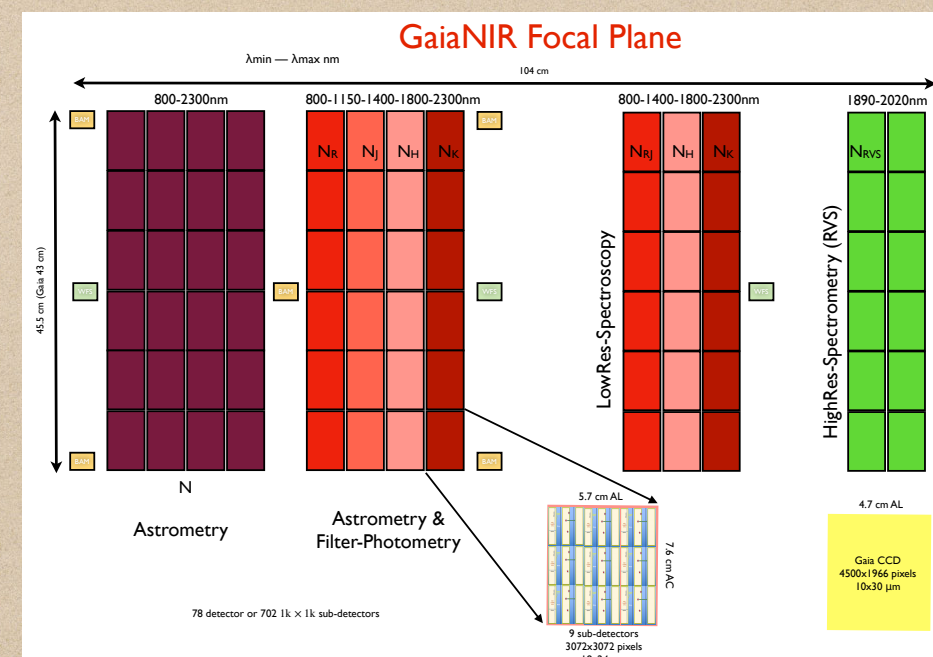
$g_{\varpi} = 1.47 (\sin \xi)^{-1}$ Sky averaged parallax factor



Detector Comparison (10-Yrs)



GaiaNIR_{Medium} Optics



GaiaNIR_{Large} Optics

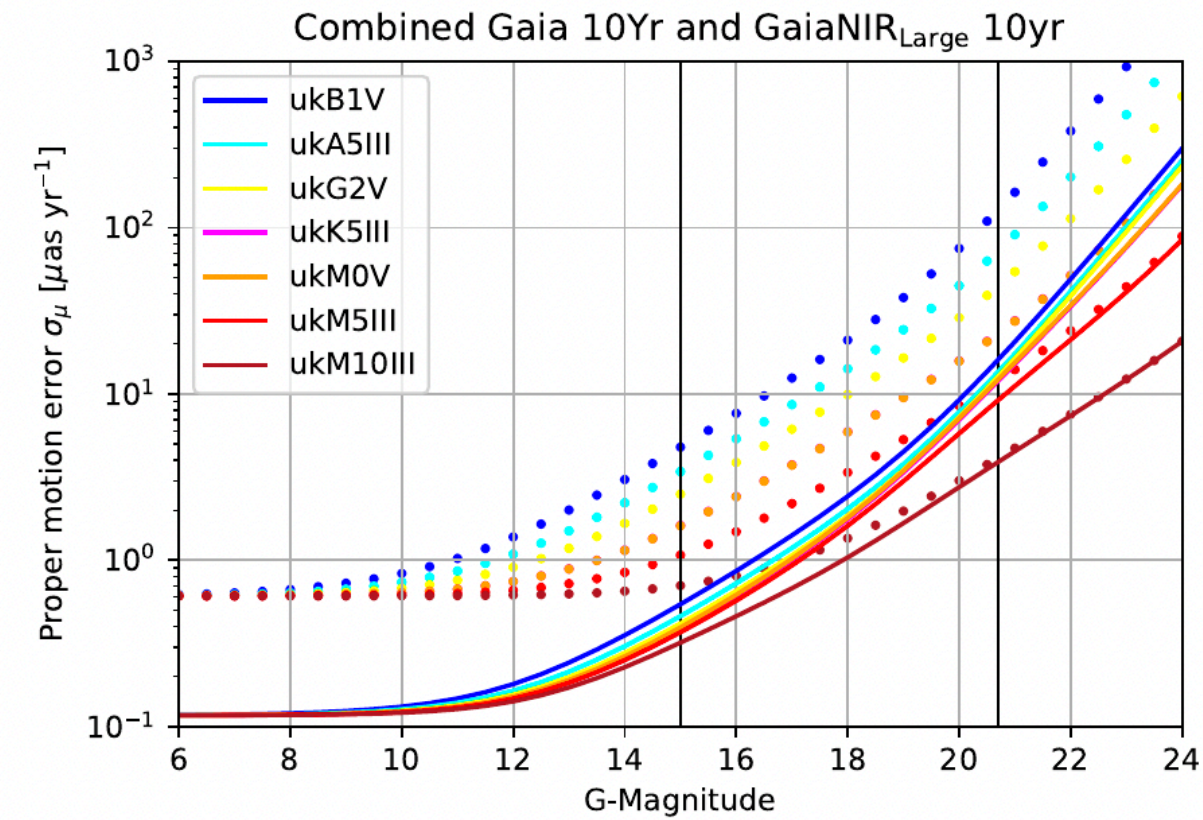
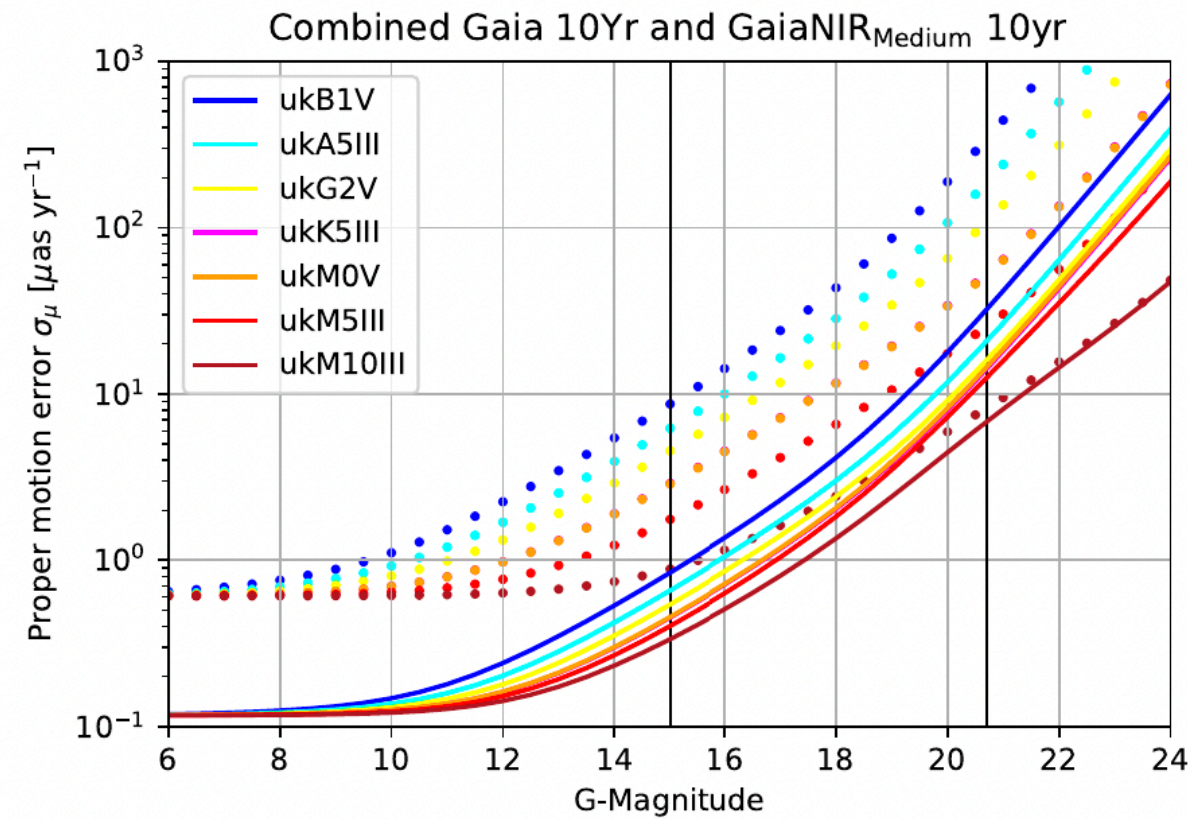
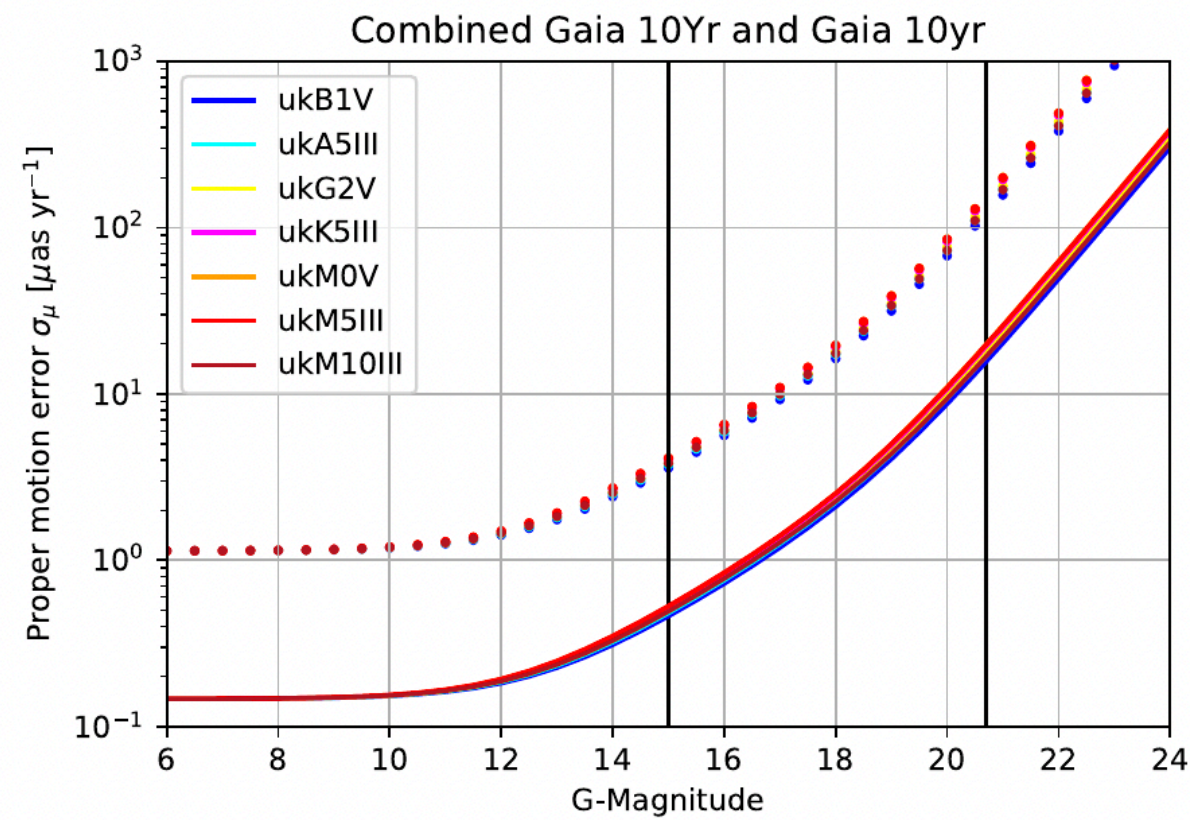
- ◆ Identical runs for **M5III** cool, luminous red giant giving a comparison between Gaia CCDs and GaiaNIR APD's
- ◆ APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs

Combined EoM PMs

Gaia

*GaiaNIR*_{Medium} Optics

*GaiaNIR*_{Large} Optics



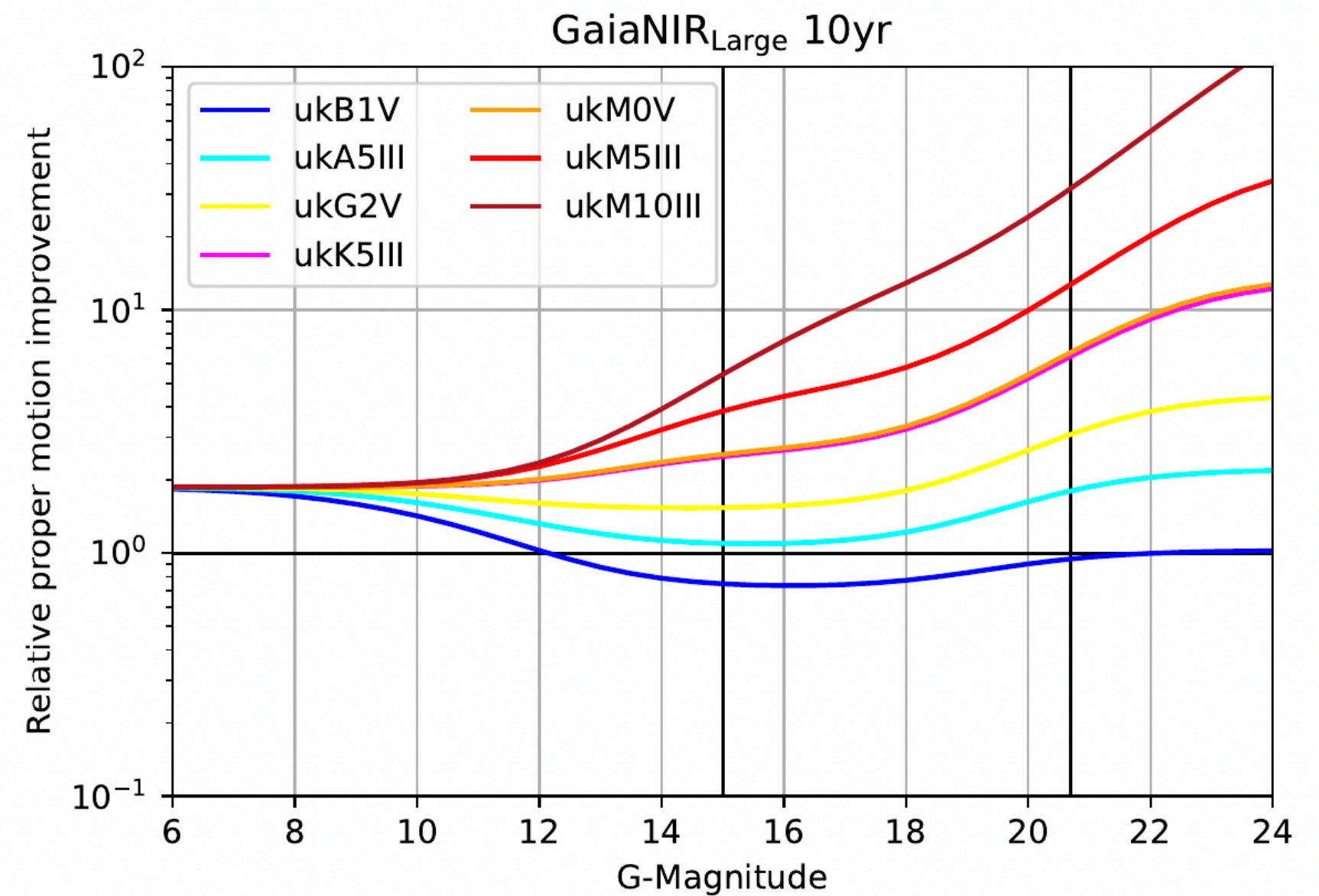
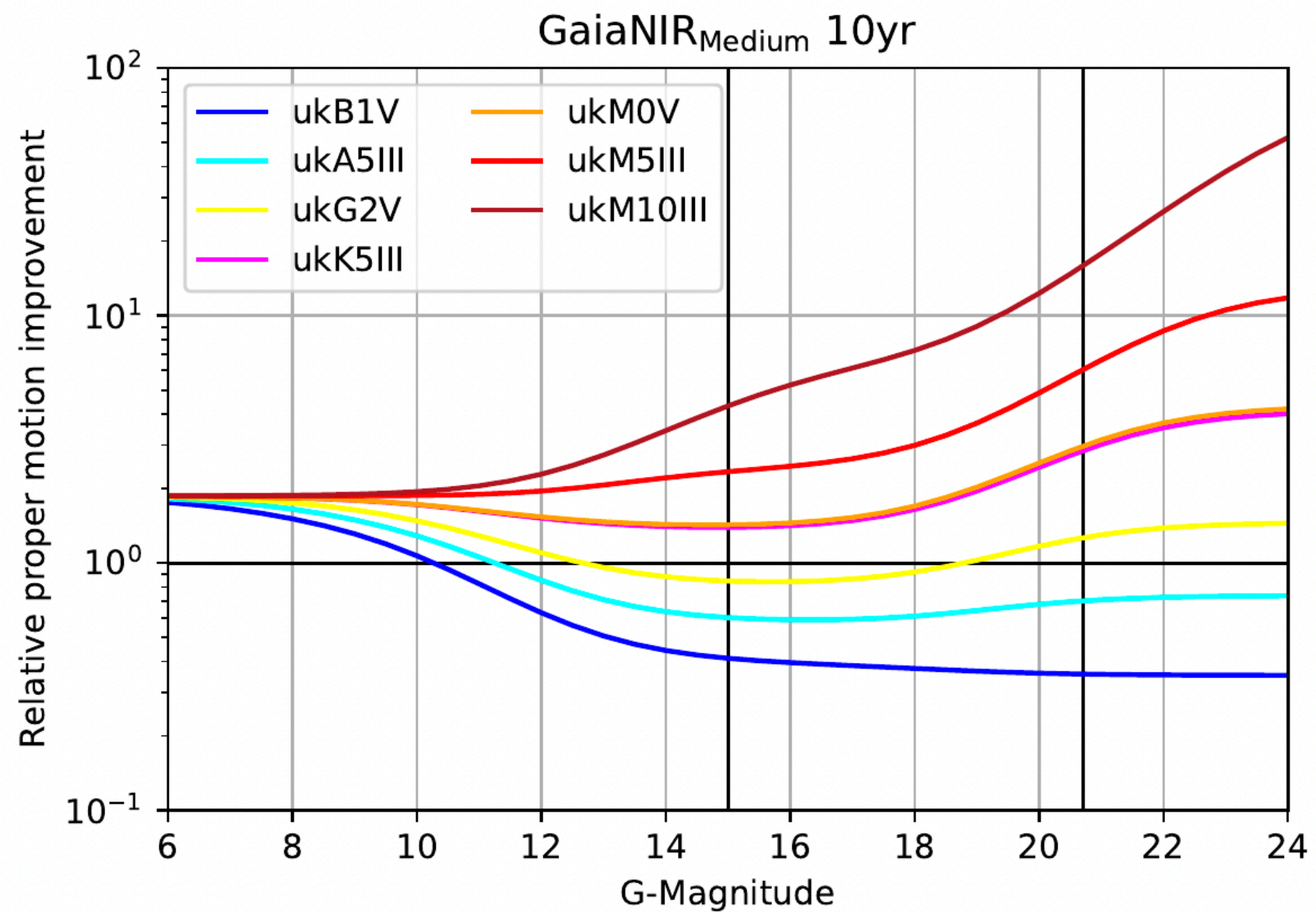
$$\sigma_{\mu 0} = \frac{(\sigma_{posN}^2 + \sigma_{posG}^2)^{1/2}}{\Delta T}$$

$$\sigma_\mu = \left(\sigma_{\mu 0}^{-2} + \sigma_{\mu N}^{-2} + \sigma_{\mu G}^{-2} \right)^{-1/2}$$

The combined EoM proper motion uncertainty 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.

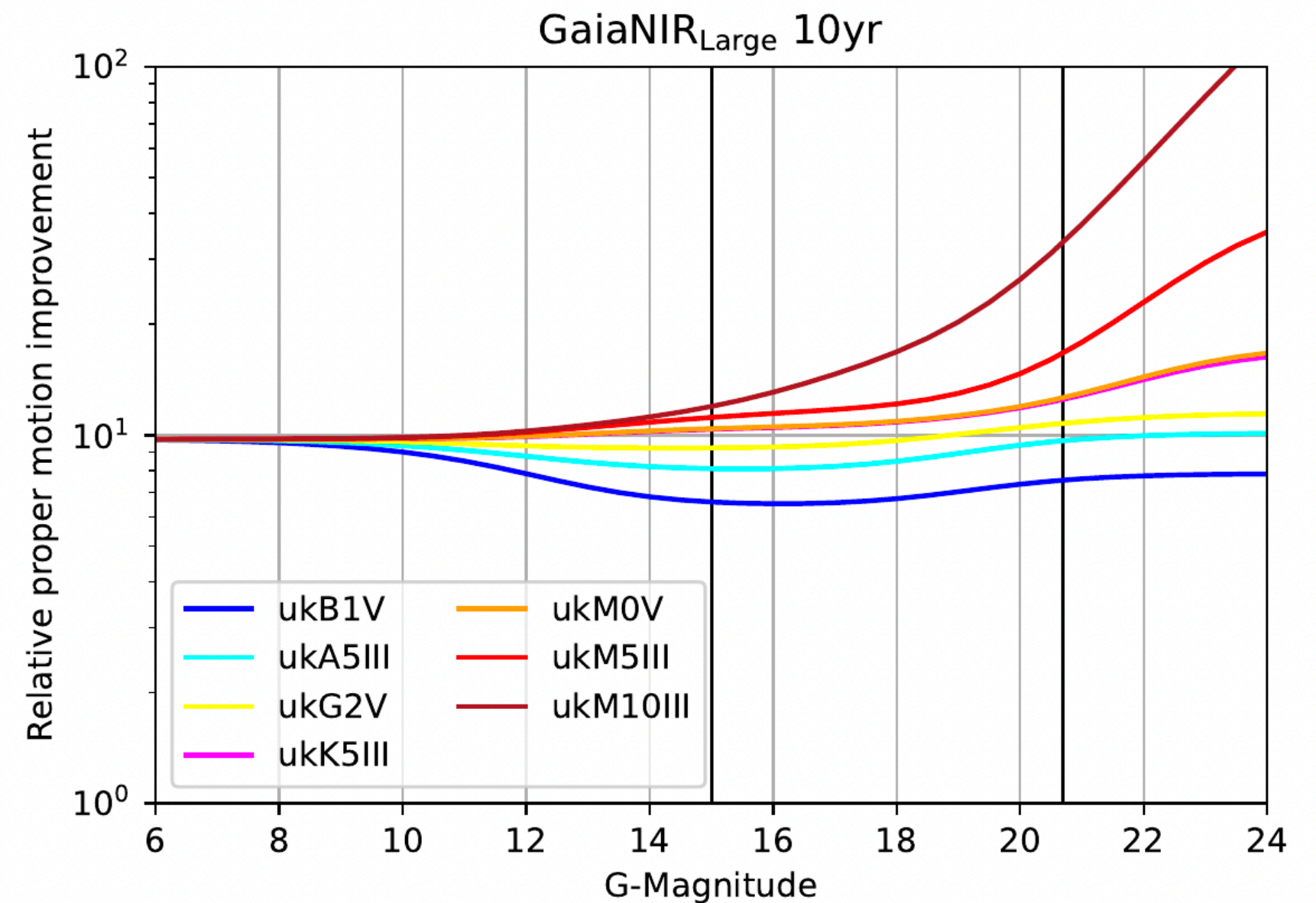
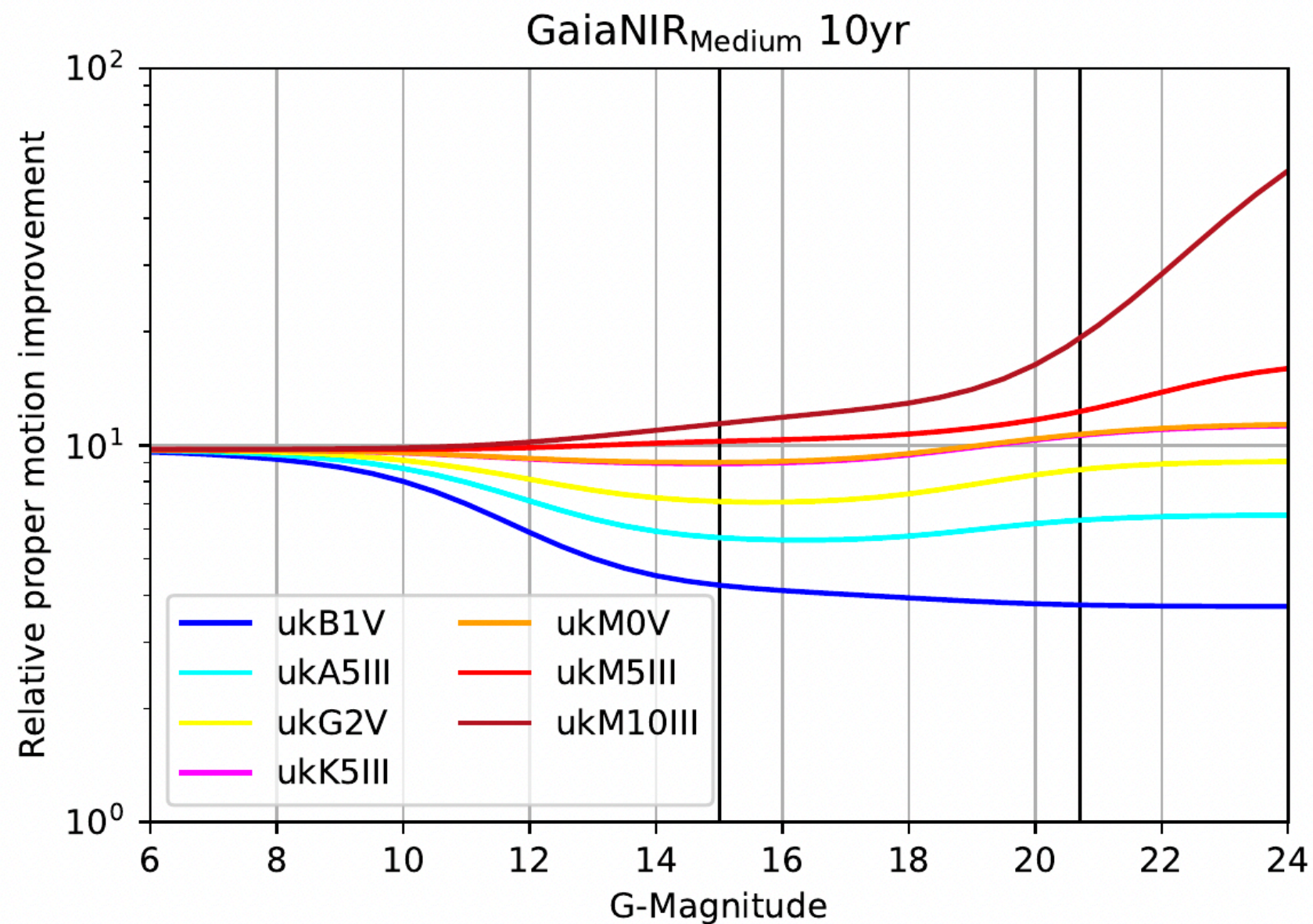
At least an order of magnitude improvement from combined solutions!

Relative PM Improvement of individual solutions



The relative improvement of individual *GaiaNIR* solutions compared to *Gaia-DR5*
For 50+ billion sources

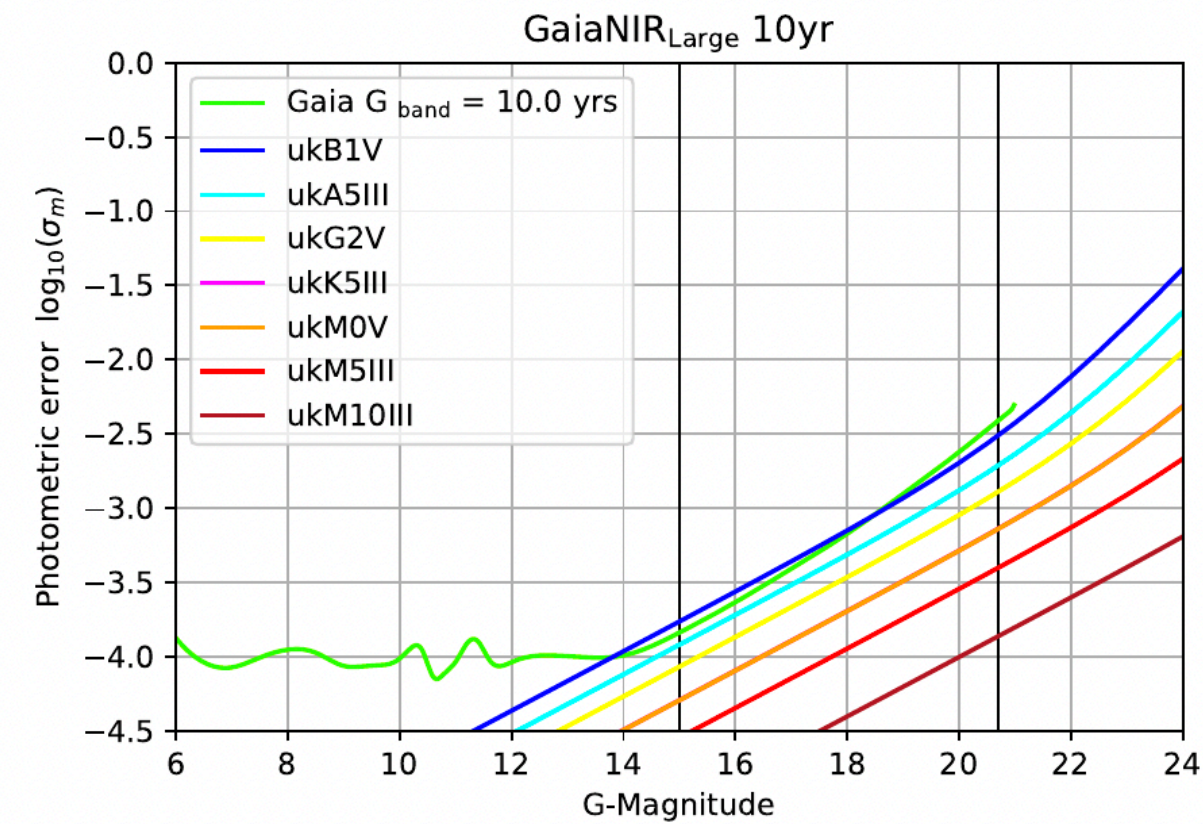
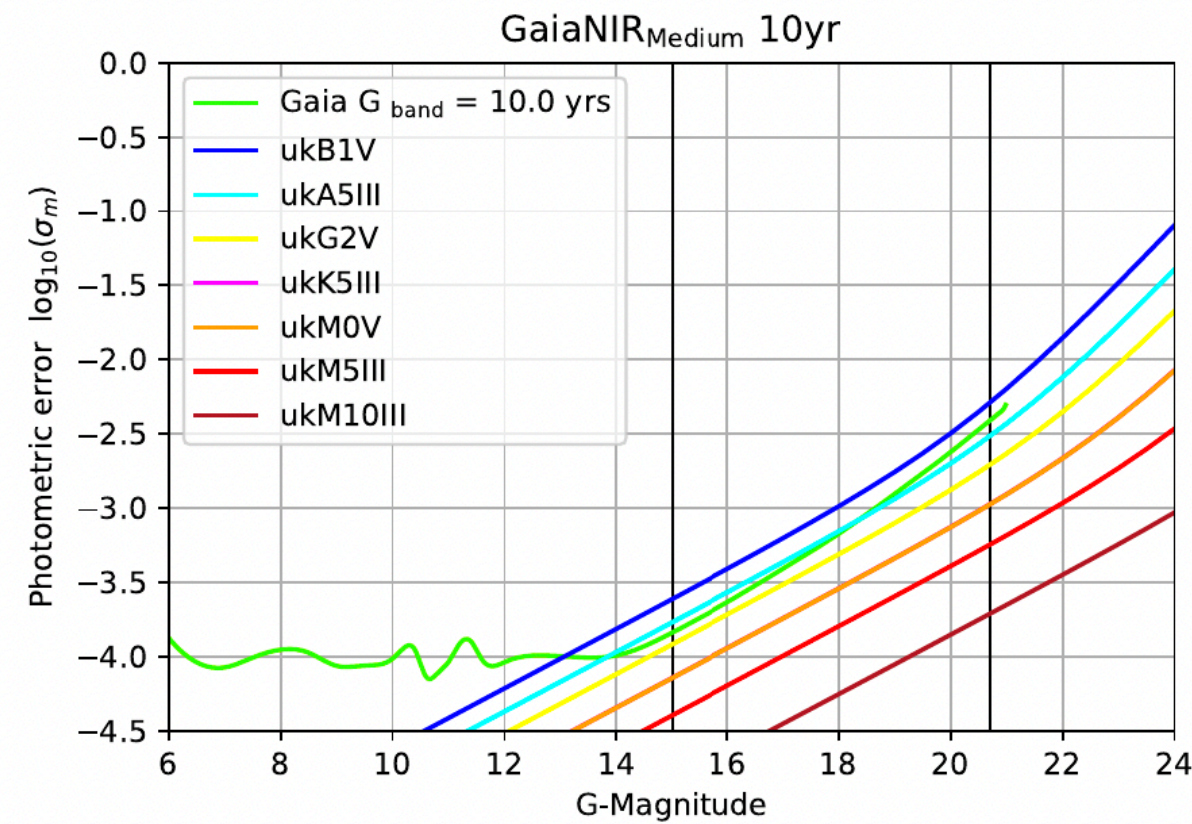
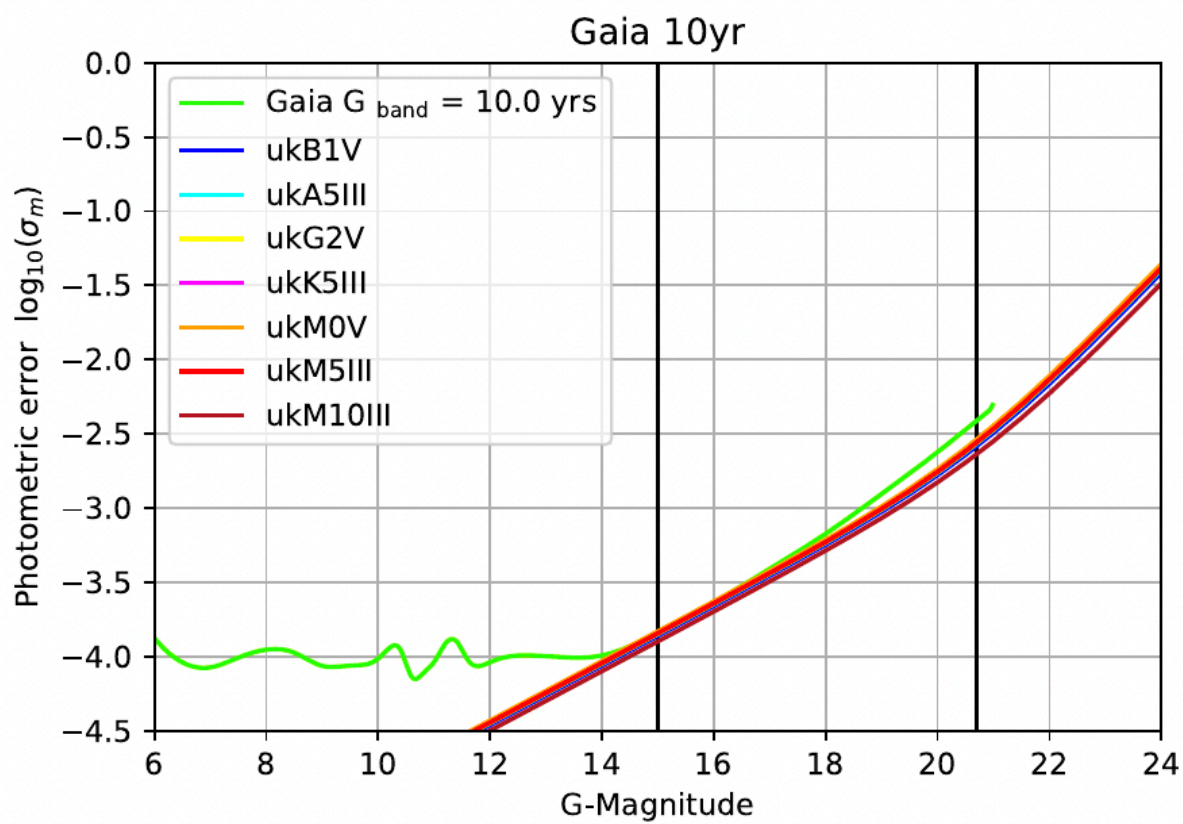
Relative PM Improvement of Joint solutions



The relative improvement of joint *GaiaNIR* solutions with *Gaia*-DR5
For up to 2.5 billion sources

Photometry

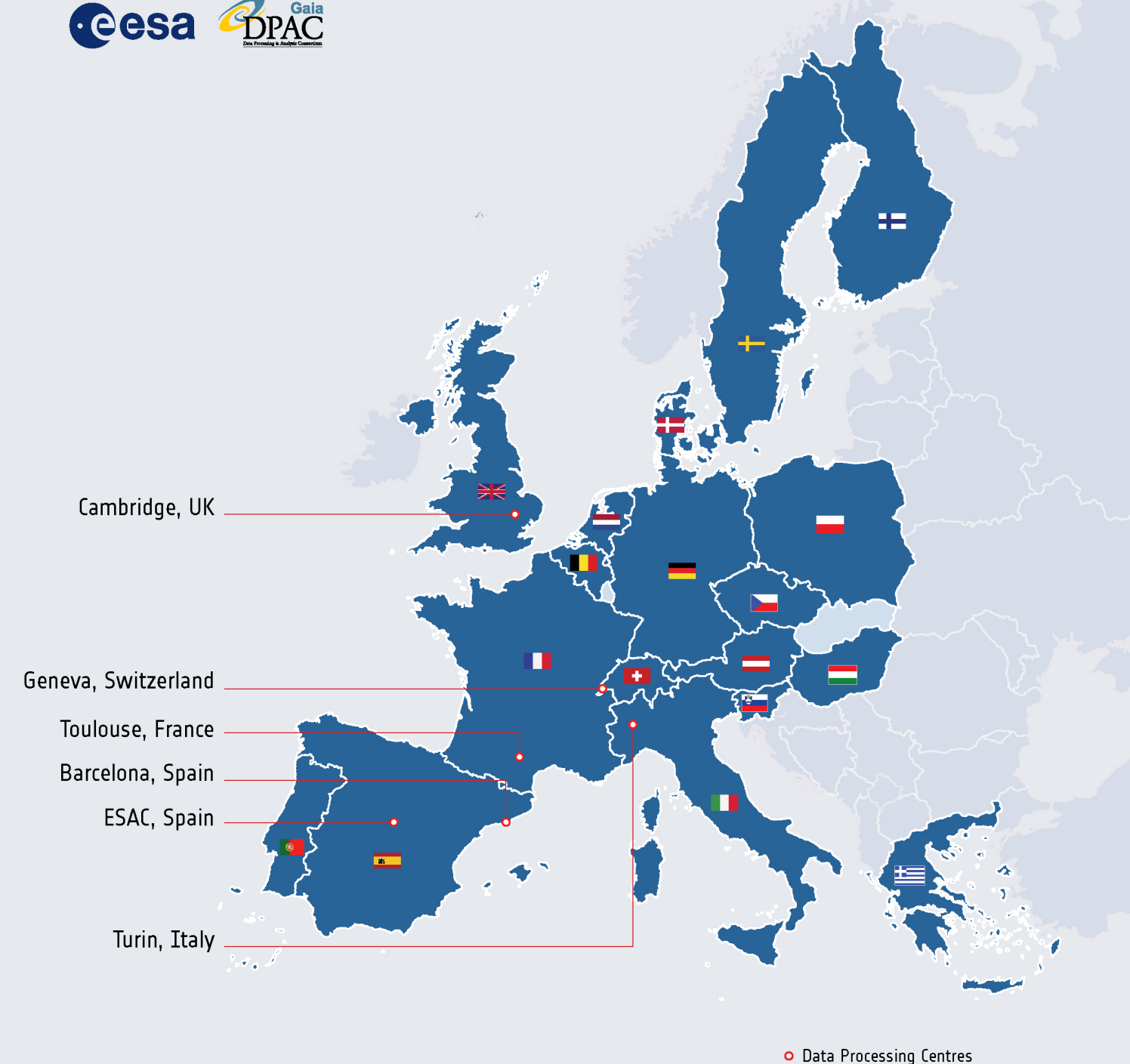
The formalism developed in Lund also allows a least squares estimate of the photometric uncertainty



The results broadly agree with the independent work of J. M. Carrasco
For 50+ billion sources

A GaiaNIR Consortium

- ◆ The ESA Ministerial Council meeting was in November 2025 and ESA got its new budget!
- ◆ We may have to make a proposal in 2028 for GaiaNIR
- ◆ Currently we are working on a new White Paper focused on technical performance of GaiaNIR
- ◆ Each country will have at least one co-PI (S, M, L)
- ◆ The co-PI must interact with the funding agencies and SPC representatives to put GaiaNIR on the map



Small external contributions from: Algeria, Brazil, Chile, China, Israel, United States, European Southern Observatory

Gaia DPAC - 2017 - all countries in dark blue participate in Gaia DPAC

GaiaNIR Working Groups

- ◆ Galactic Structure and Dynamics
- ◆ Relativity & Fundamental Physics
- ◆ AGN & Reference Frame
- ◆ Extragalactic
- ◆ Solar Neighbourhood
- ◆ Stellar Physics & Stellar Types
- ◆ Grouping, clouds, associations & clusters
- ◆ Exoplanets
- ◆ Binaries
- ◆ Solar System
- ◆ Technology - Detectors
- ◆ Low dispersion Spectro.
- ◆ Spectroscopy - RV
- ◆ Photometry
- ◆ Astrometry
- ◆ Crowding
- ◆ Variables
- ◆ Transients
- ◆ Dark Matter
- ◆ Cosmology
- ◆ Multi-messenger
- ◆ White papers
- ◆ Proposals
- ◆ Webpage
- ◆ Outreach

GaiaNIR DPAC

What are the lessons learned from Gaia's organisation?

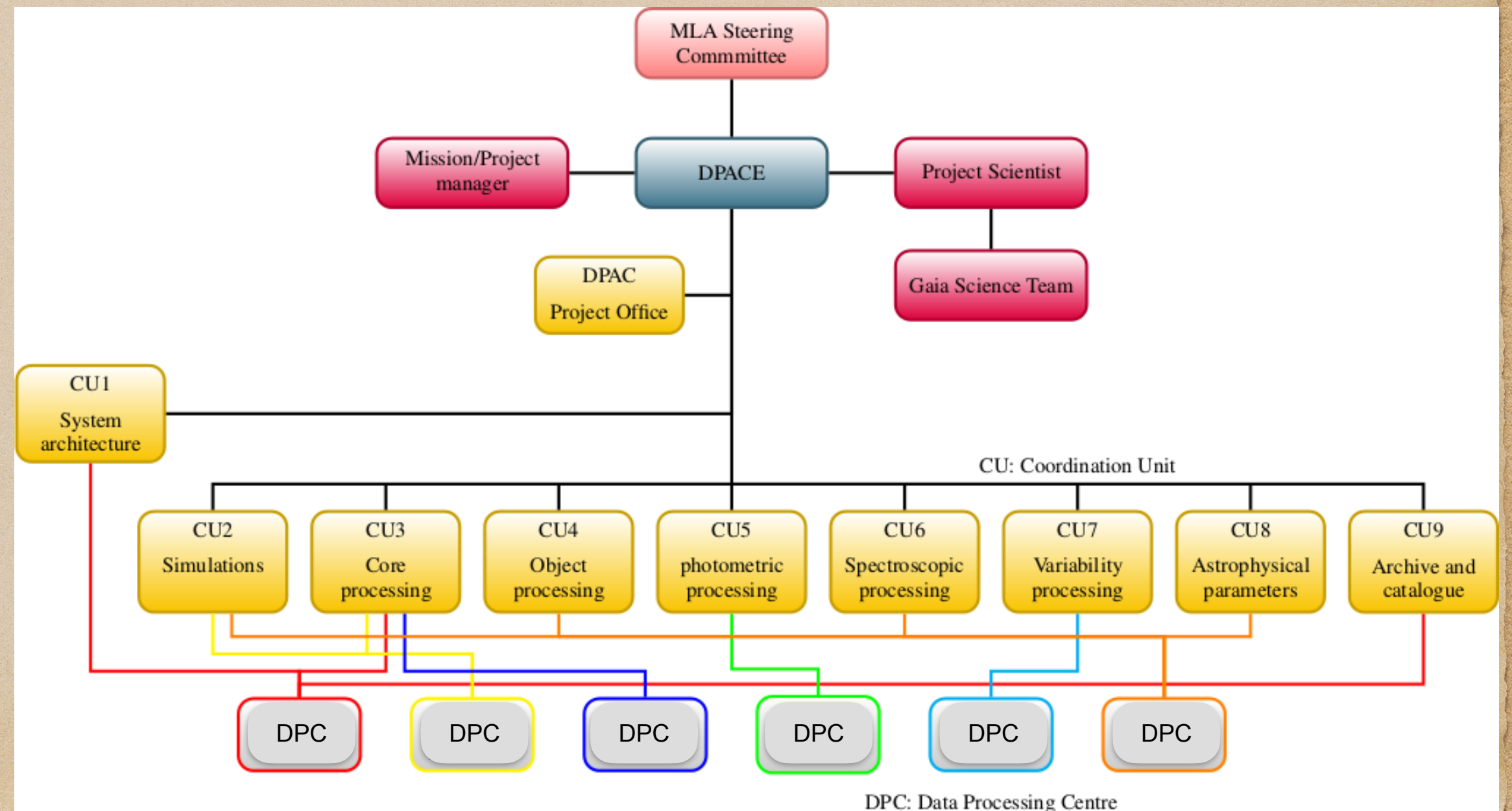
What do we want to change?

What do we want to keep?

International partners?

How do we integrate

International partners?



DPC: Data Processing Centre

GaiaNIR Summary

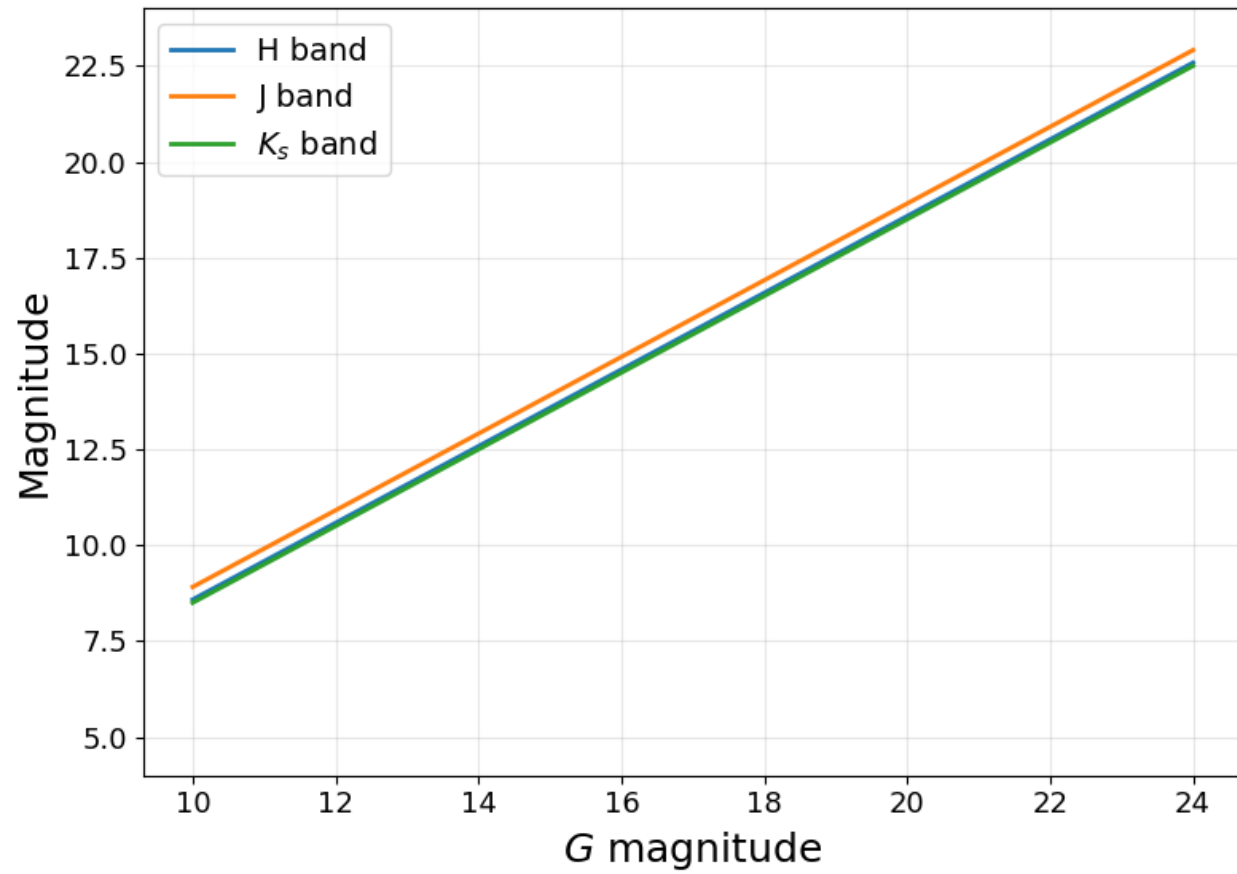
- ◆ For GaiaNIR APDs we get better astrometric performance for several reasons
 - Broader wavelength range more than compensates for longer observing wavelength
 - Segmented mirrors would double the resolution and collect more photons but at a cost!
 - Lower read noise and lower background noise are game changers for astrometry!
 - A massive improvement in uncertainty at the faint end without joint solutions, i.e. for all stars
 - A deep RV, chemistry and abundance survey for a billions of objects
- ◆ These improvements result in a new mission that significantly outperforms Gaia!

You can register your interest in GaiaNIR here: <https://www.astro.lu.se/GaiaNIR/consortium>

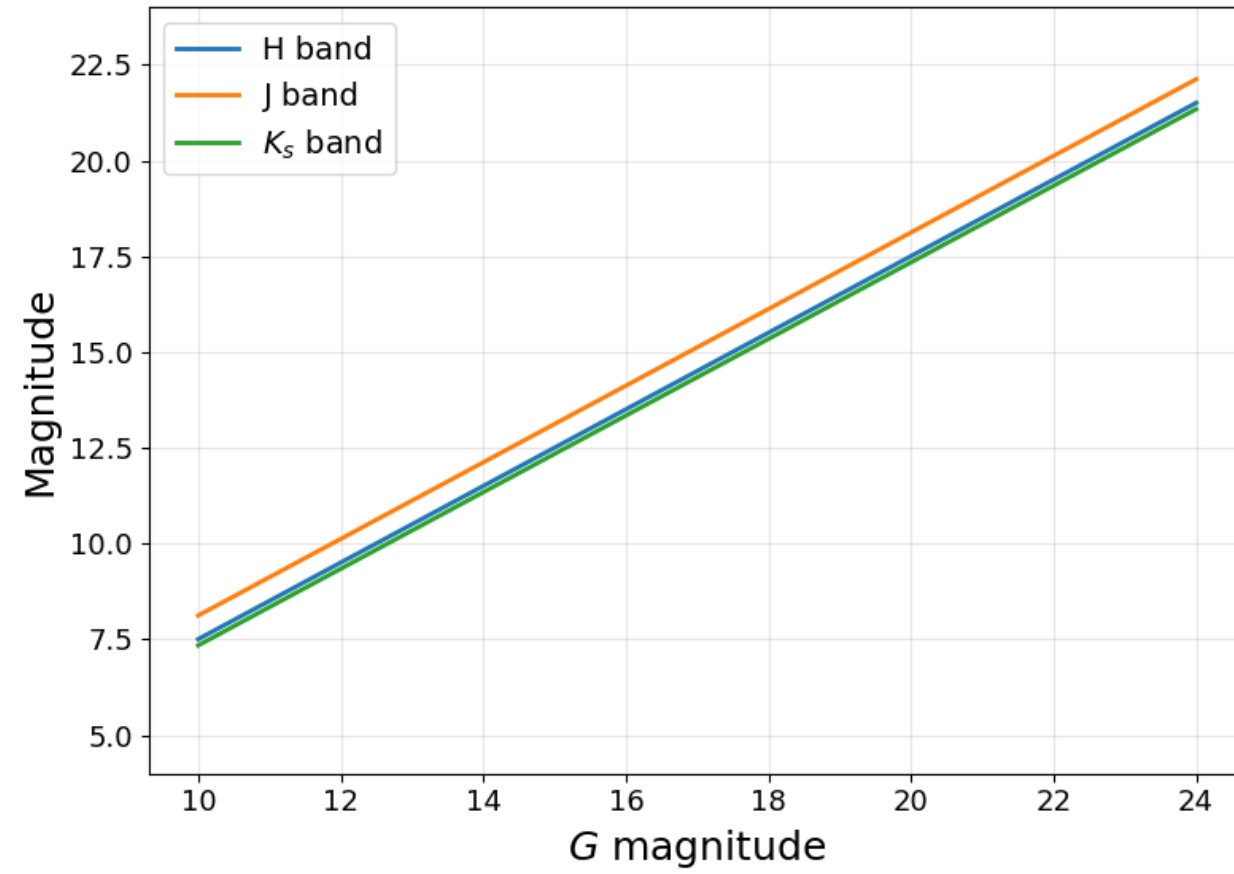
Isabella Henum - PhD Student

Band Conversions

G2V



K5V



M5V

