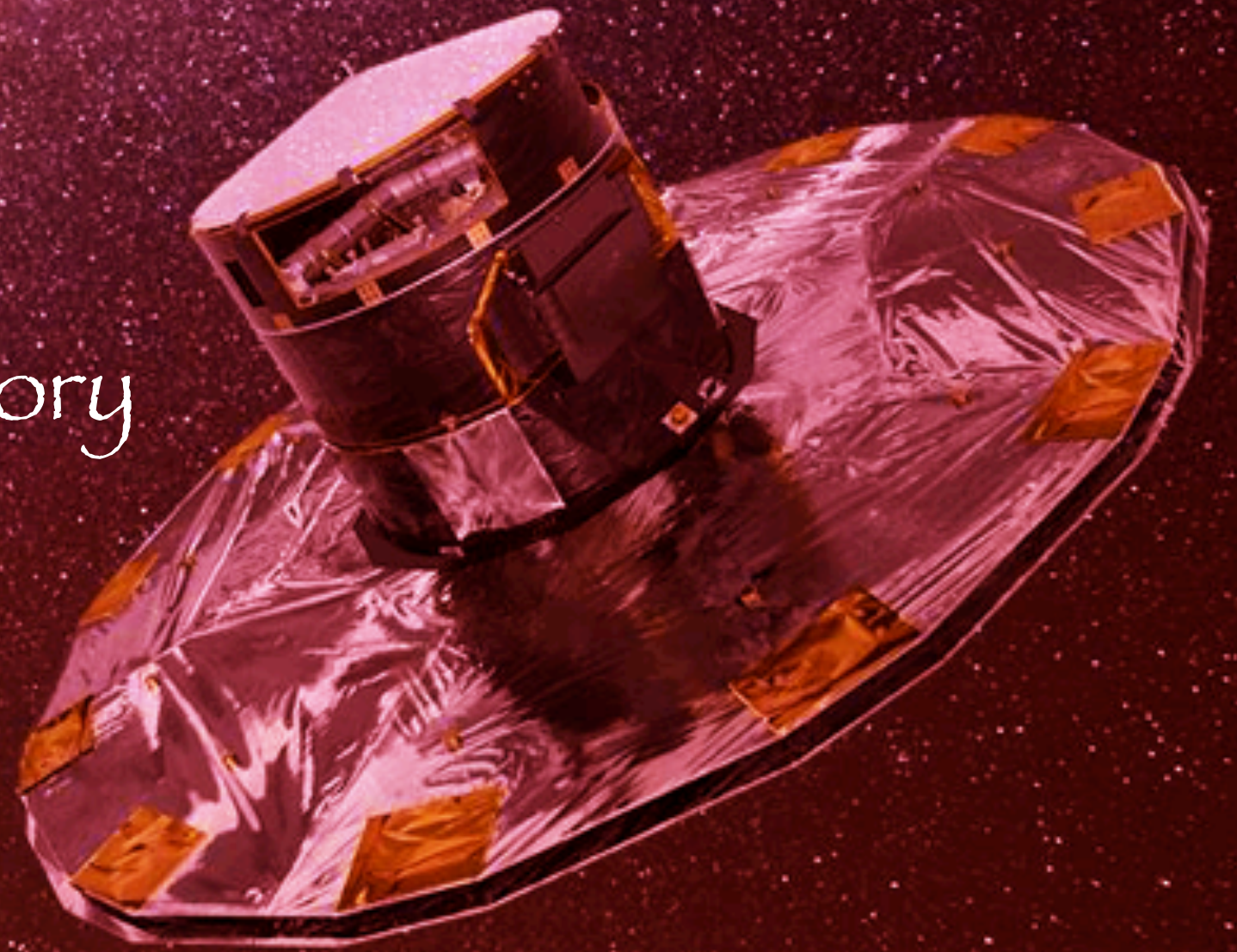


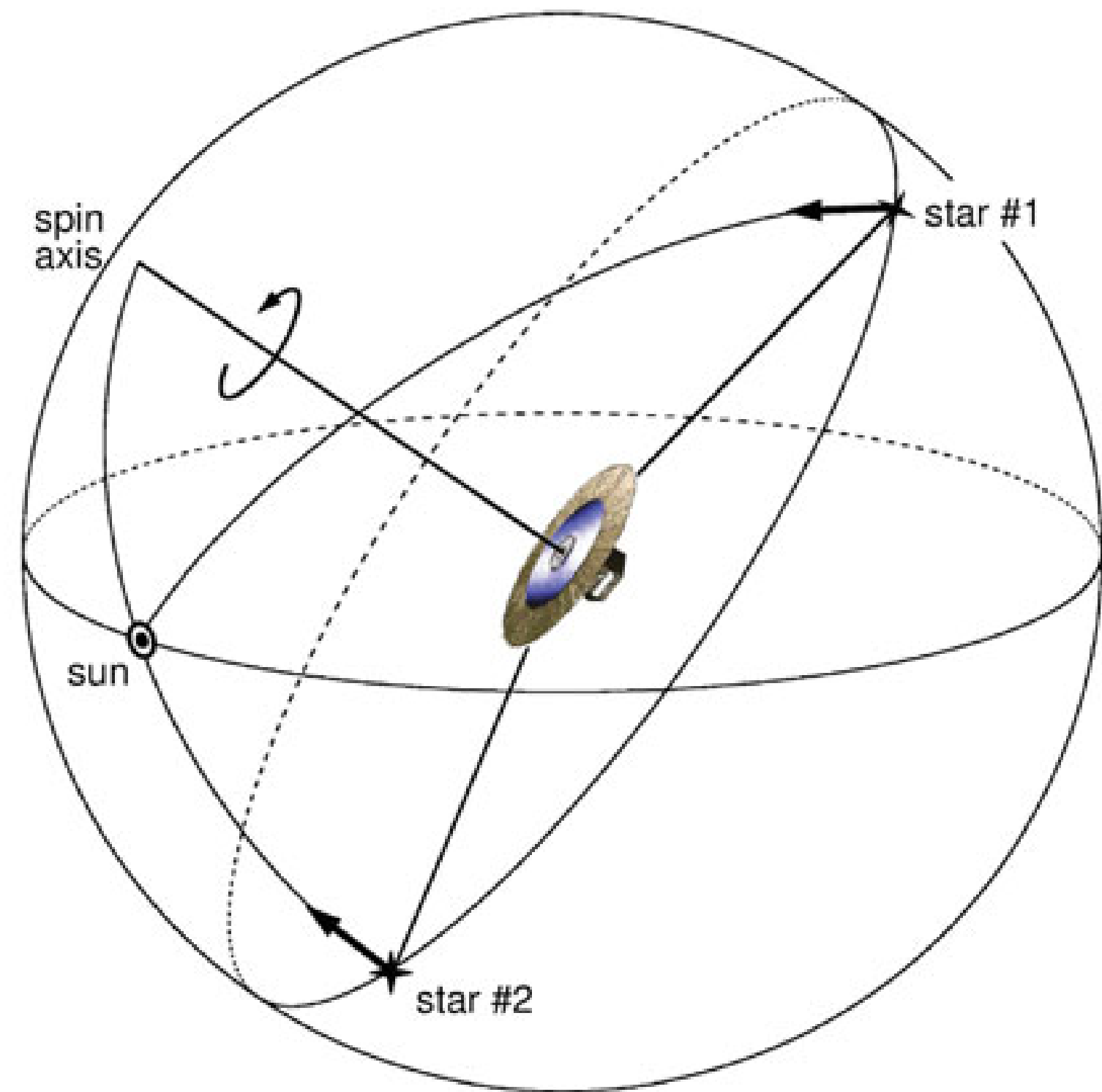
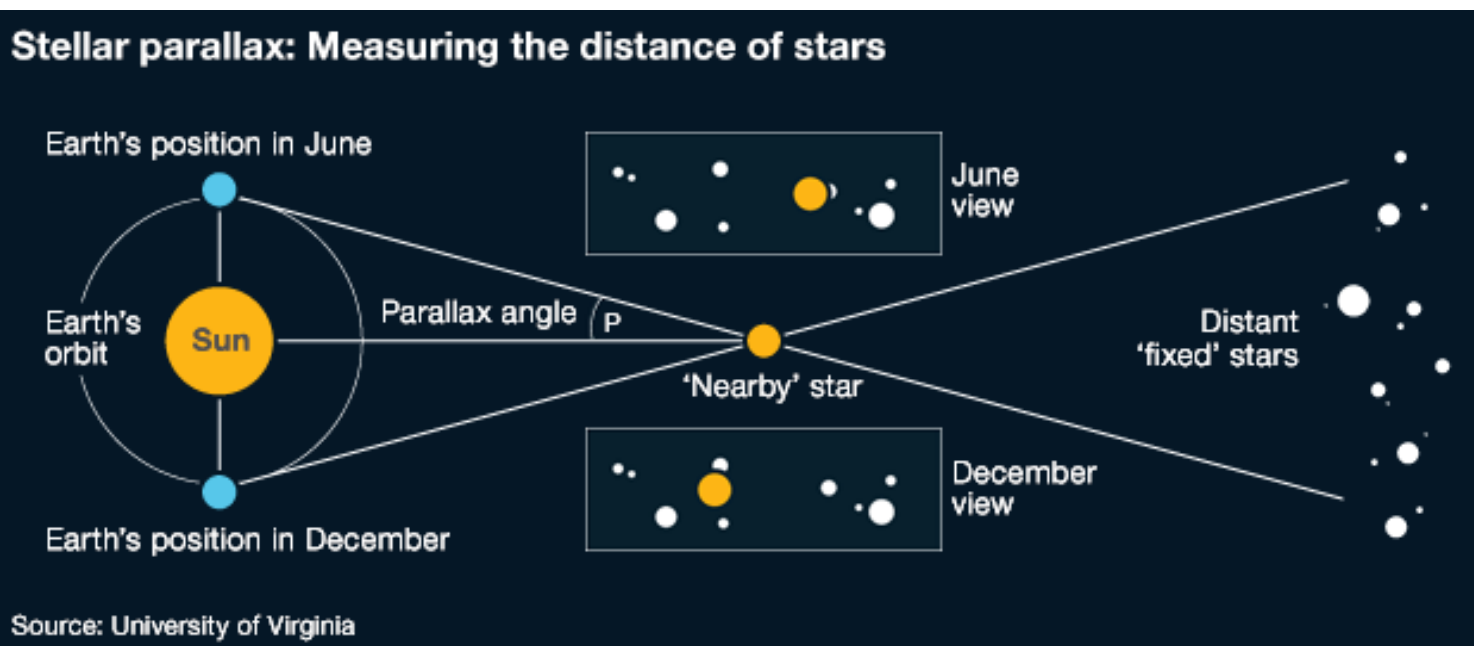
The GaiaNIR mission and the hidden regions of our Galaxy

Overview and Status

David Hobbs
Lund Observatory
Sweden

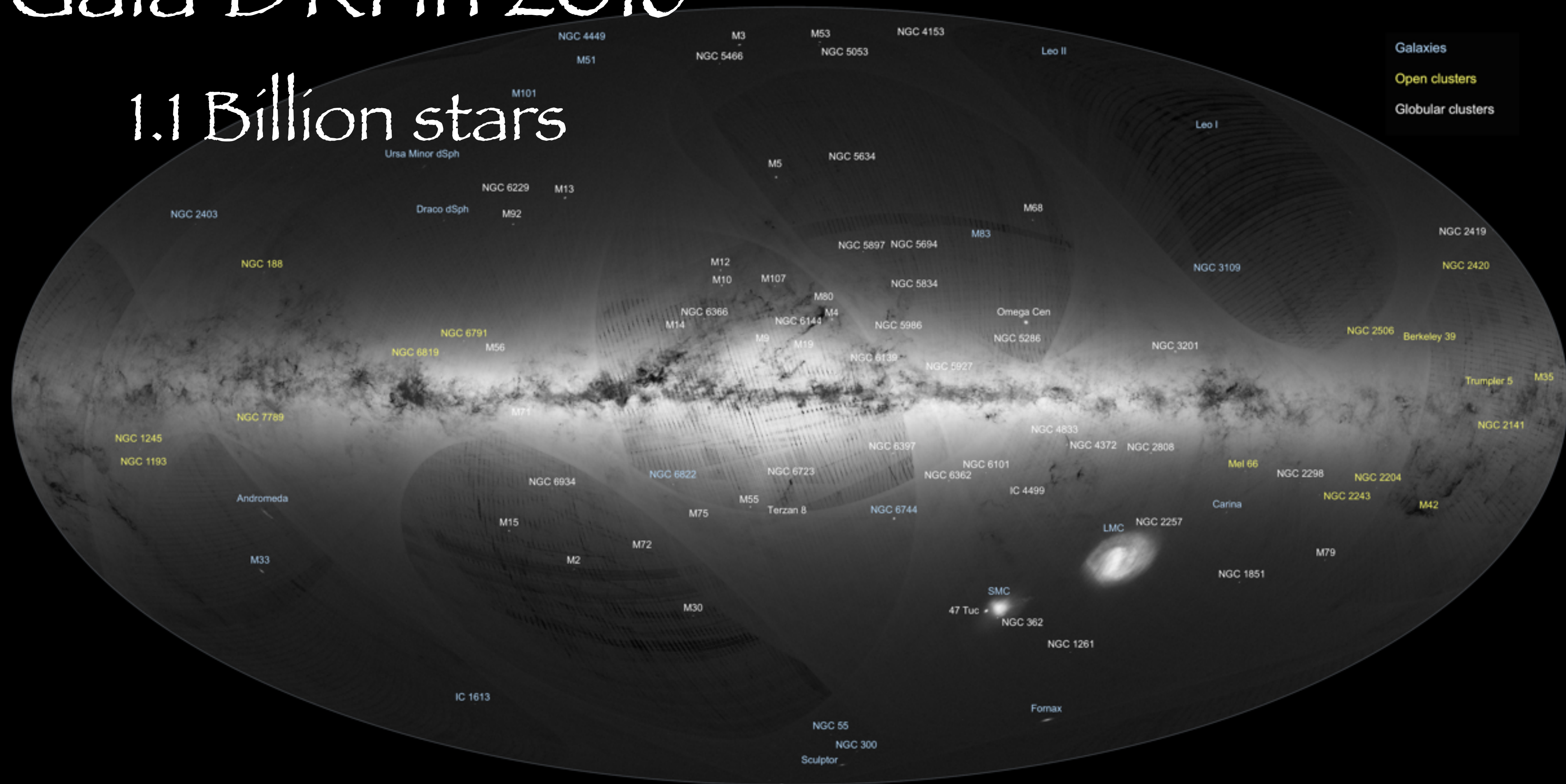


Gaia Measures Absolute Parallaxes



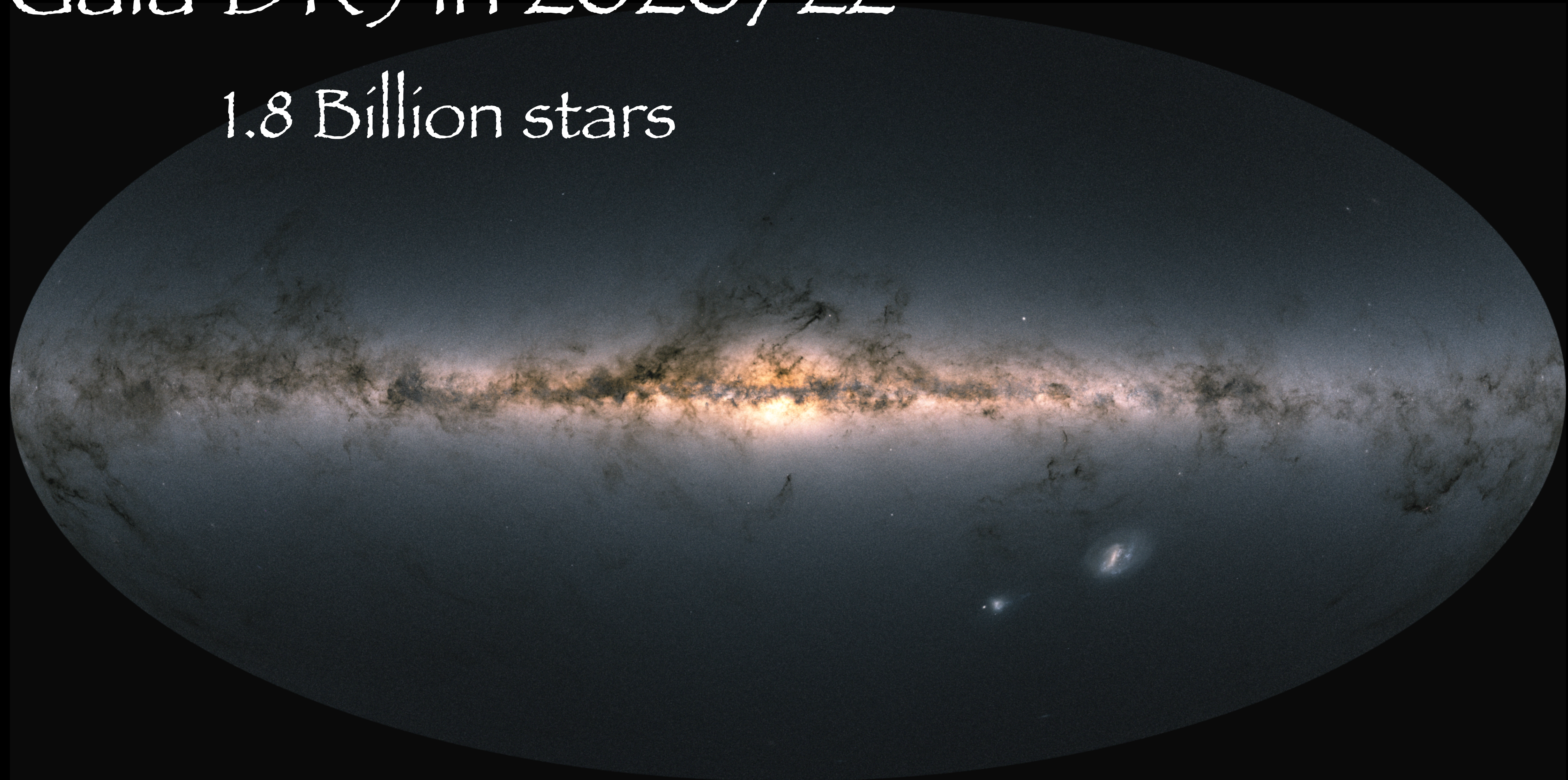
Parallax is directed along a great-circle from the star to the Sun. Generally, the observed angle depends on both parallaxes but for some measurements it depends on the parallax of #1, but is independent of the parallax of #2. This allows absolute values to be disentangled.

1.1 Billion stars ^{M101}



Gaia DR3 in 2020/22

1.8 Billion stars



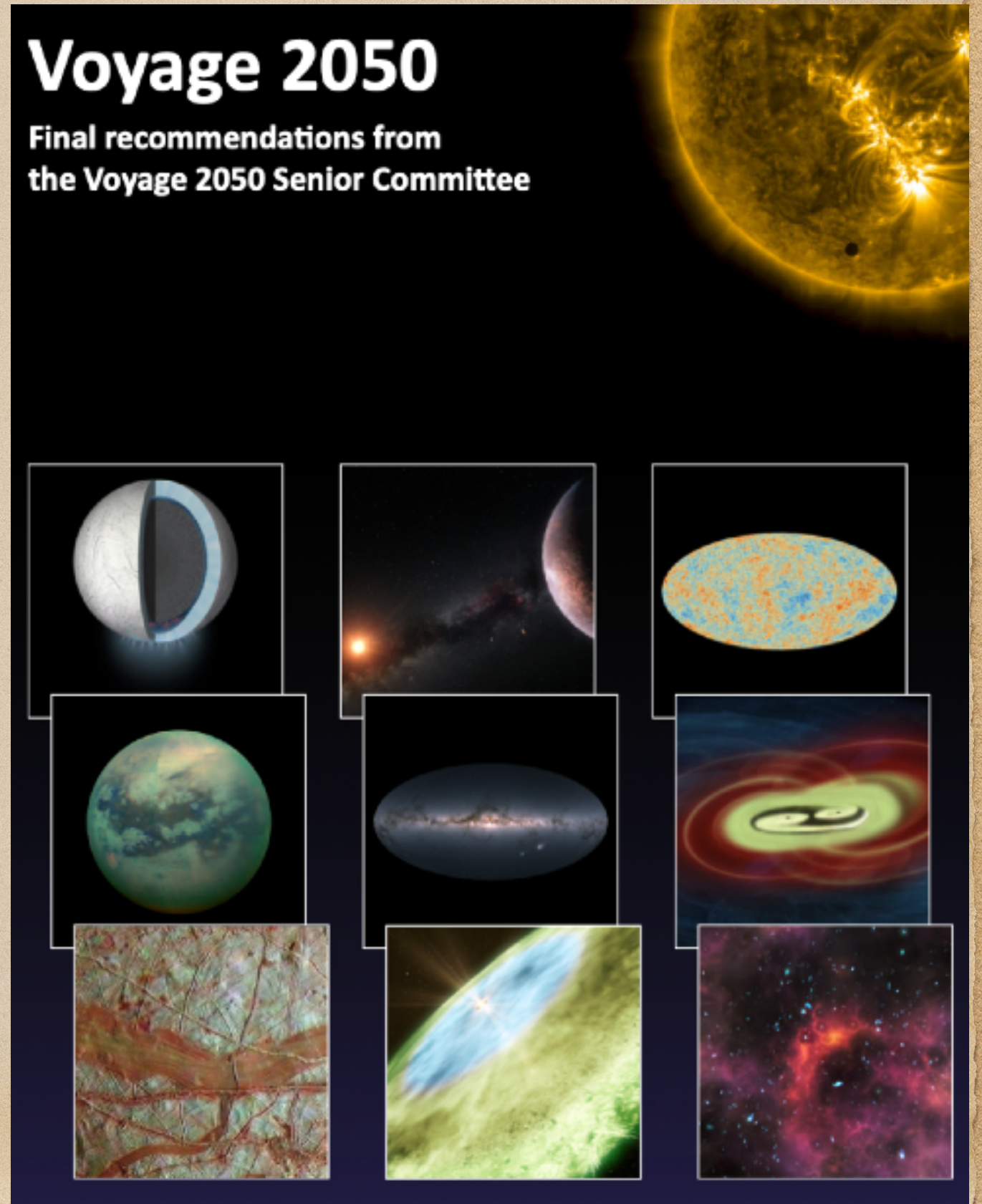
Science Cases

1. Adding NIR astrometry and photometry to probe the dynamically important hidden regions of the Galaxy giving up to 15 billion stars. Going deeper could give 50+ billion stars (~25% and the most detailed map 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



Science Cases

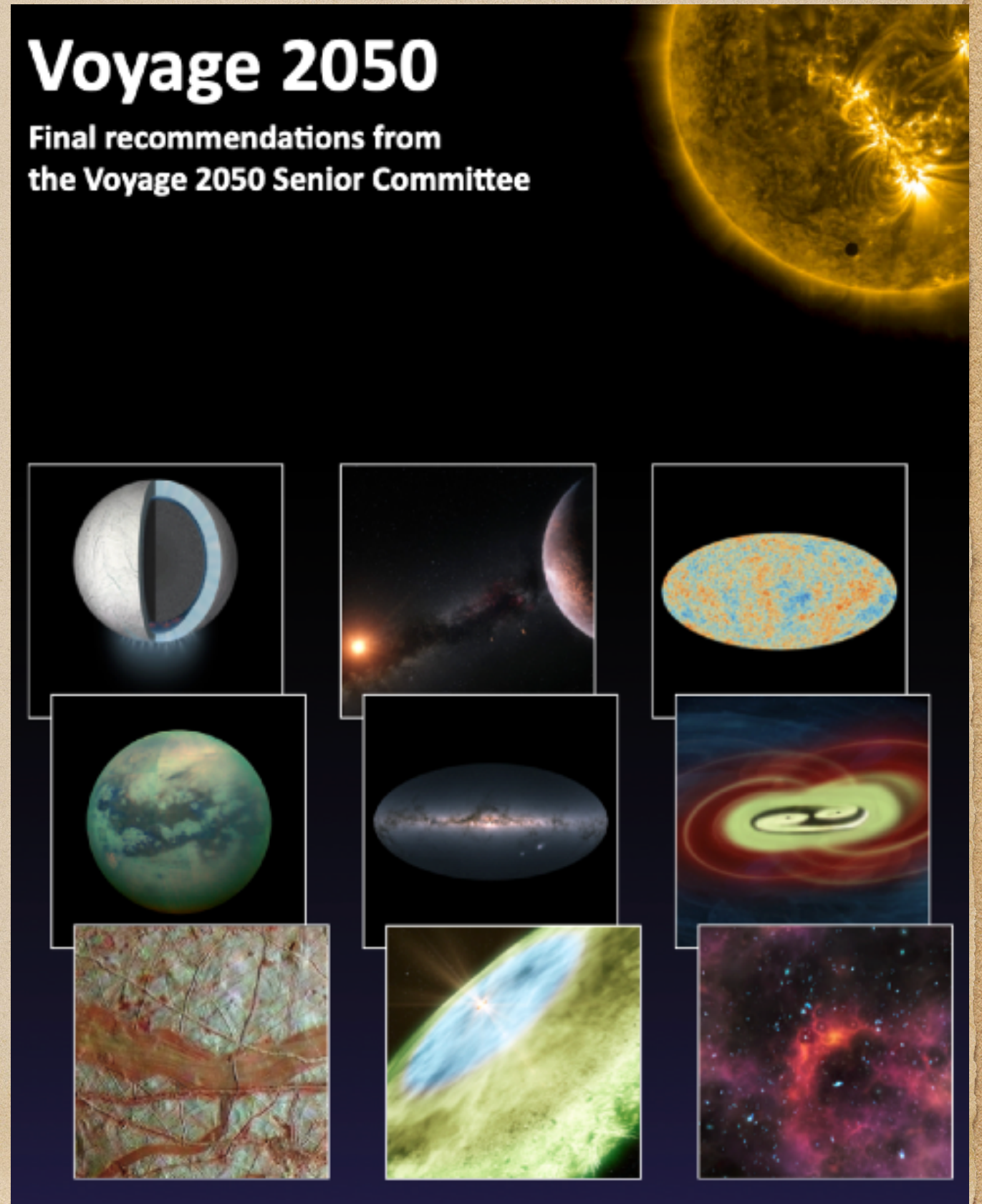
<https://link.springer.com/article/10.1007/s10686-021-09705-z>

1. Low resolution dispersion spectra for most of the stars
2. Adding a radial velocity spectrograph could give vast numbers of RV's. A lack of RVs is one of the biggest observational issue in Galactic astronomy but would increase the costs and data rate significantly

A deep RV survey of a billion objects (at a € cost)

Voyage 2050

Final recommendations from
the Voyage 2050 Senior Committee



Nano-arcsec yr⁻¹ PMs

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

Positions

12.8=0.8 σ_{π} and 11.2=0.7 σ_{π} μ as

Proper motions

4.64=0.29 σ_{π} and 4.0=0.25 σ_{π} μ as

The combined uncertainty with $\Delta T=20+5+5$ 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.

$\sigma_{\mu 0}$ 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)



Euclid, Roman,
and JASMINE
provide NIR stars

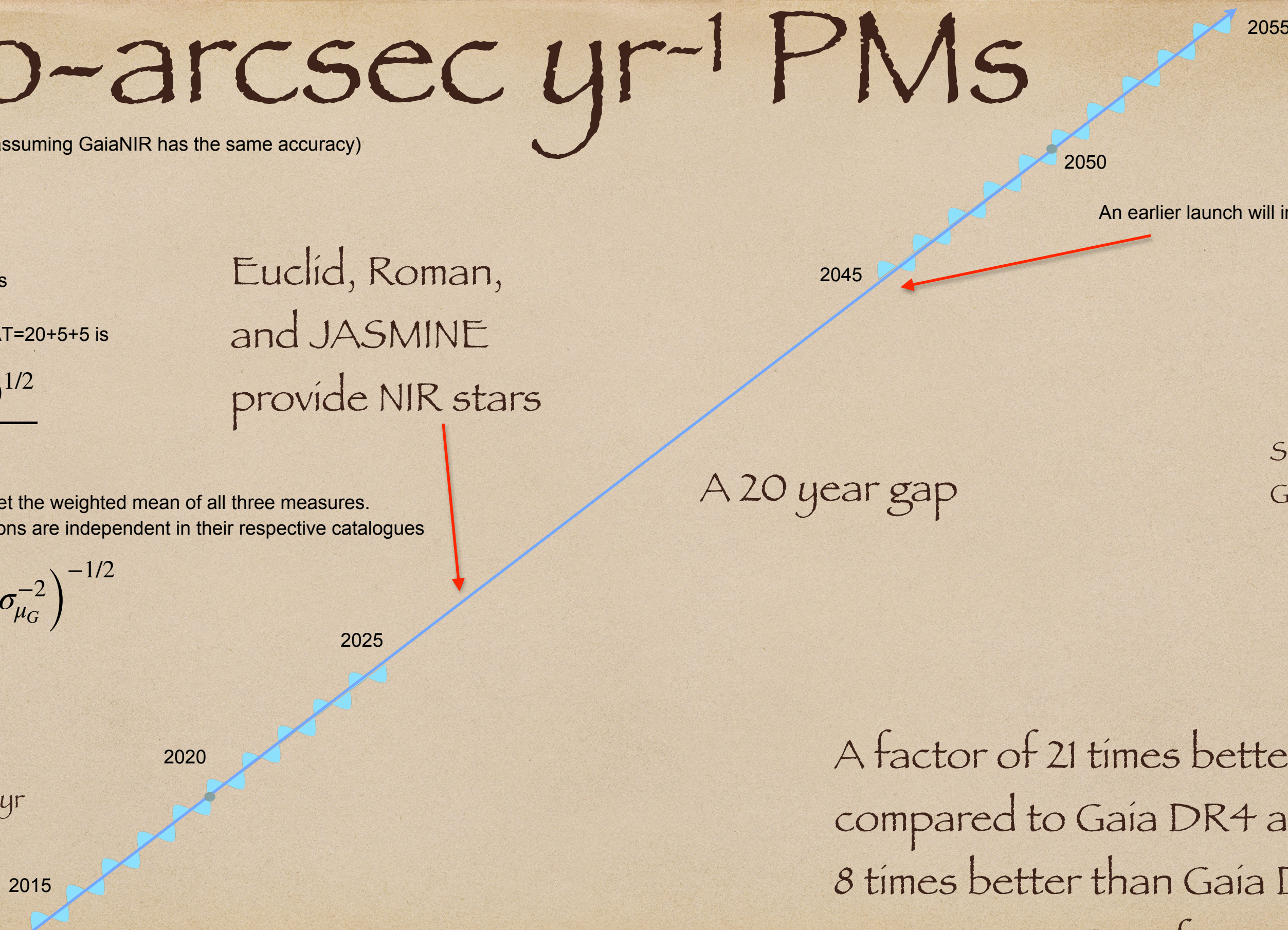
A 20 year gap

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 $11.2=0.7\sigma_\pi \mu\text{as}$ but scaled to 2.5 years

Proper motions

$4.64=0.29\sigma_\pi$ and $4.0=0.25\sigma_\pi \mu\text{as}$ but scaled to 2.5 years

The combined uncertainty with $\Delta T=20+5+1.25$ 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

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

First Epoch Gaia 10yr
(2020)



2015

Ref Epoch 2020

2025

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

Euclid, Roman,
and JASMINE
provide NIR stars

Ref. Epoch 2046.25

2045

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

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

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

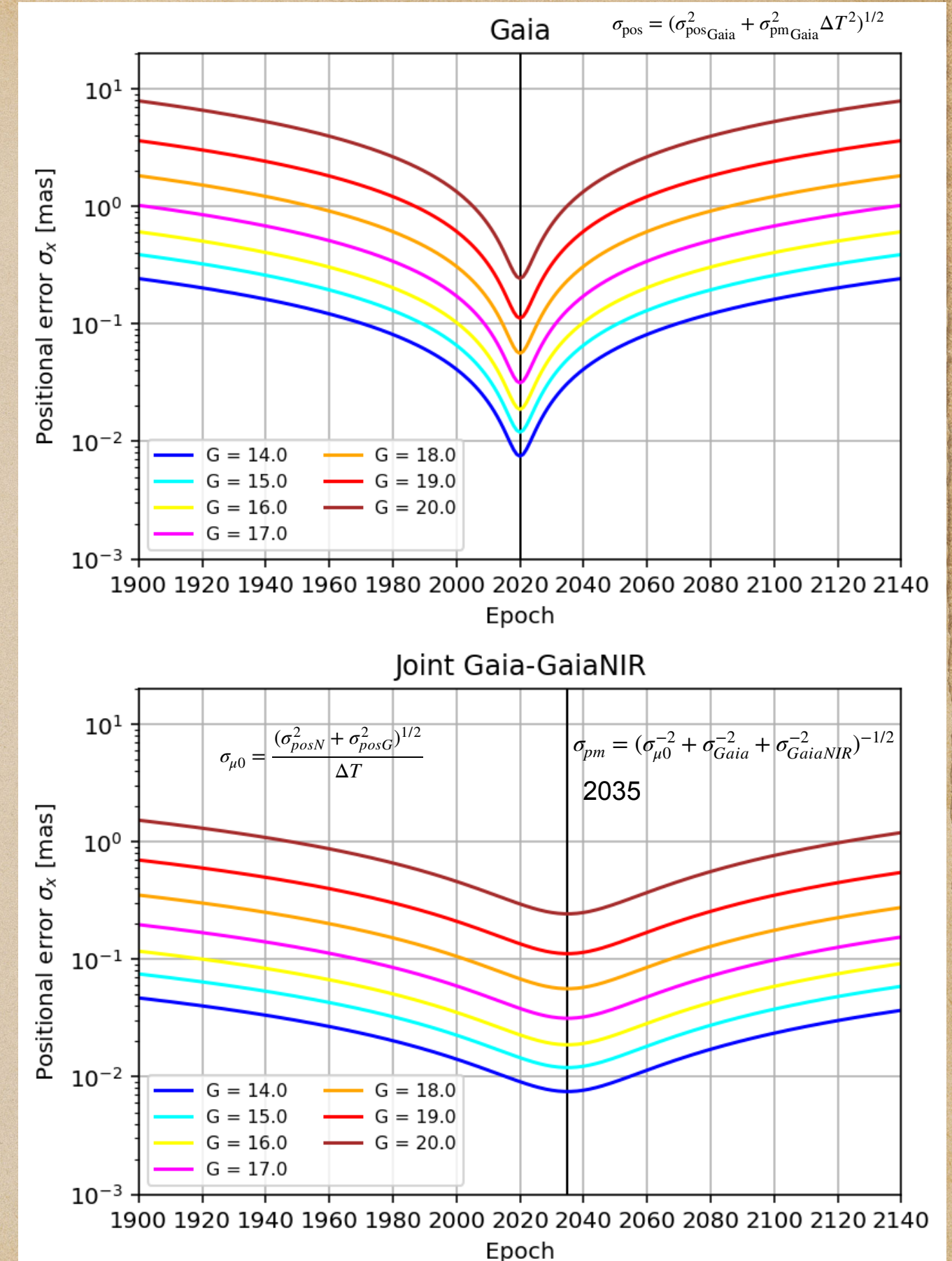


Second Epoch
GaiaNIR 2.5yr (Ref
Epoch 2046.25)

2055

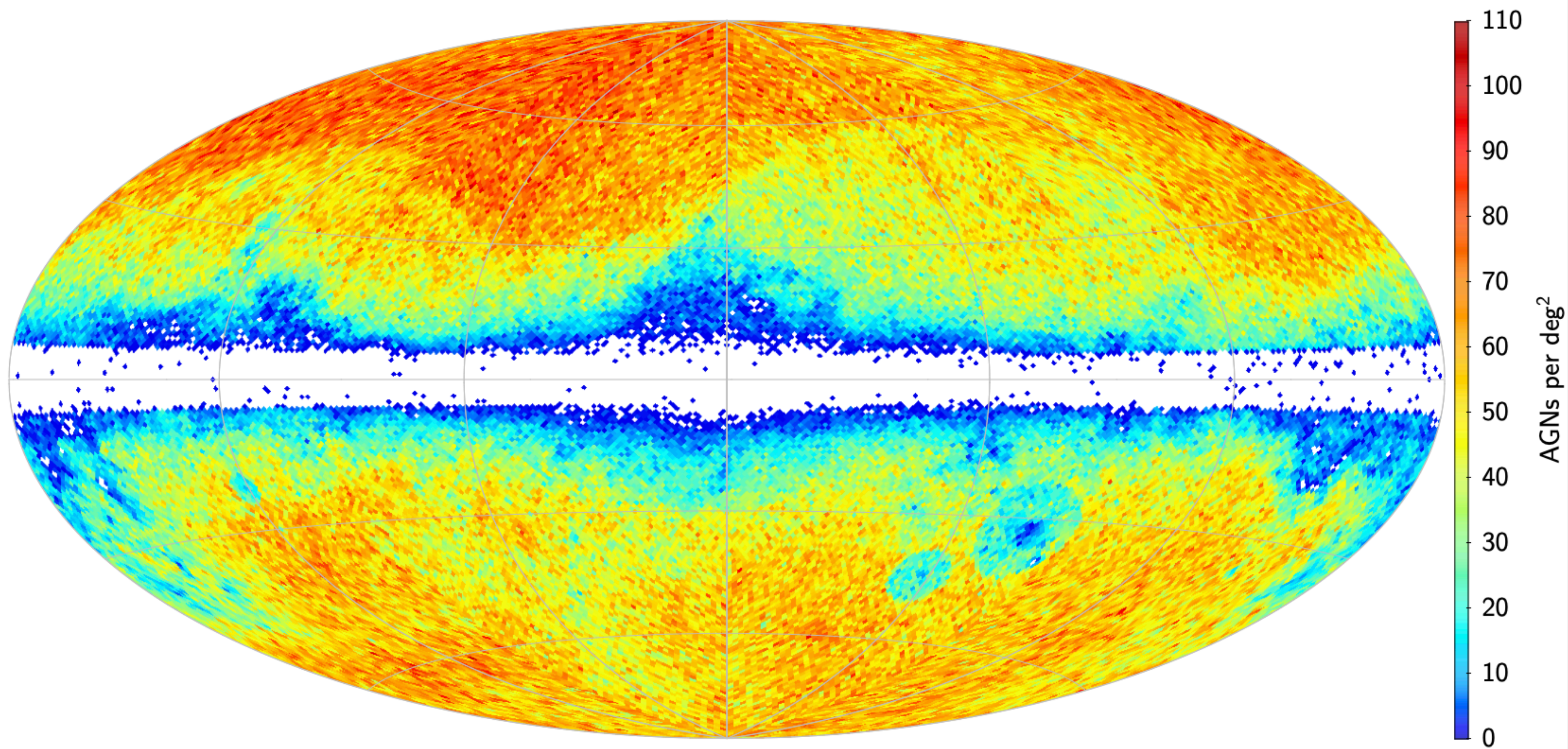
Catalogue Ageing

- ◆ 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



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)

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





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

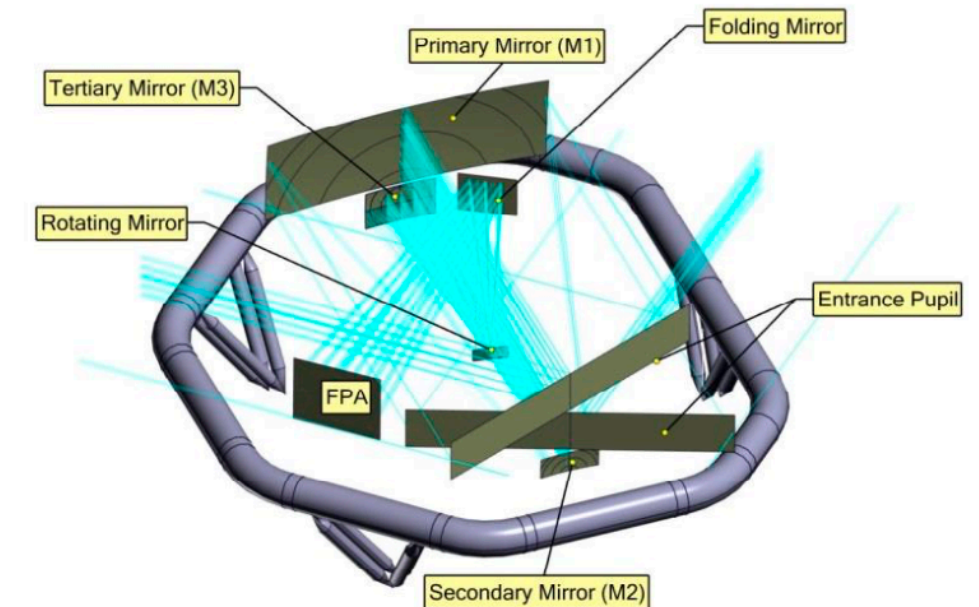


Figure 5-34: GaiaNIR optical surfaces and the light path

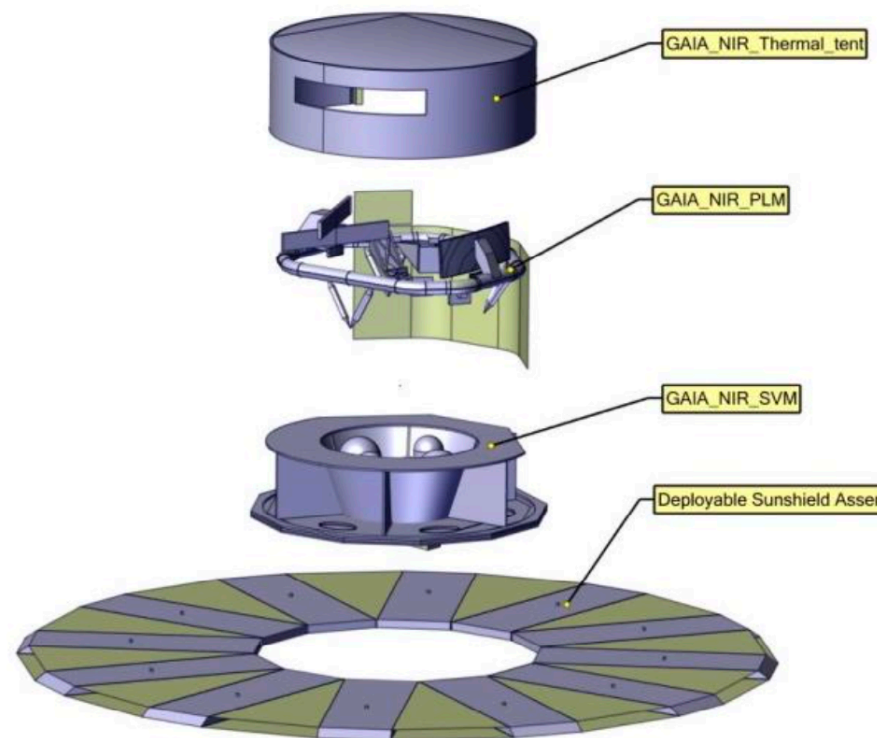


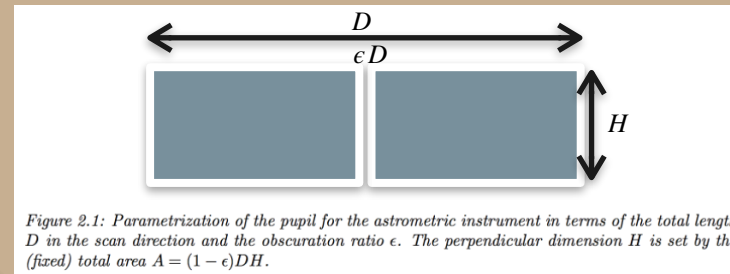
Figure 6-2: Gaia-NIR Spacecraft main elements

- ◆ 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

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

D = 1.7m M1 D = 1.7m



BA

Drawing not to scale

Two Improvements:

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

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

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

$D_{\text{max}} = 3.5\text{m}$

Old Design

*GaiaNIR*_{Small}

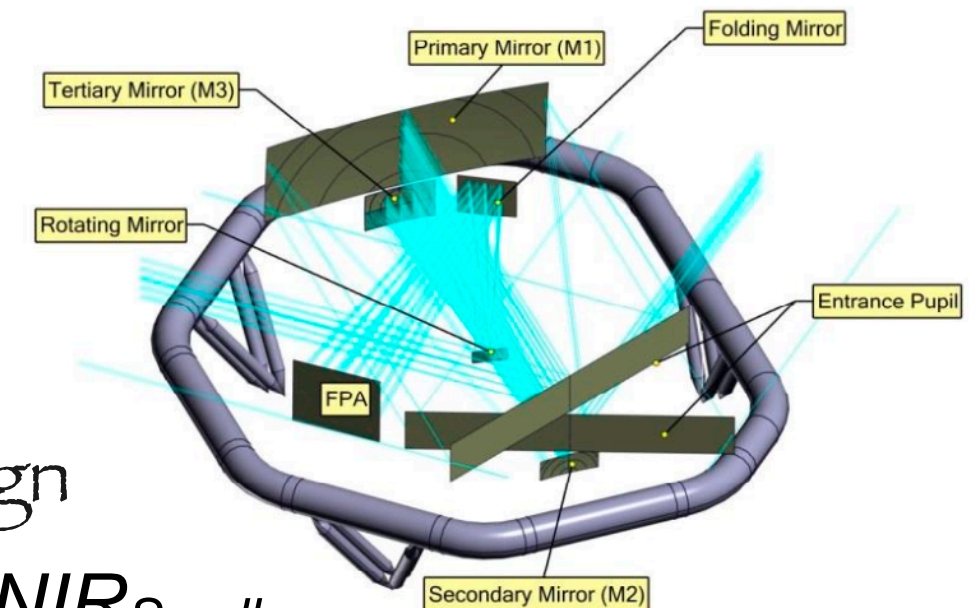
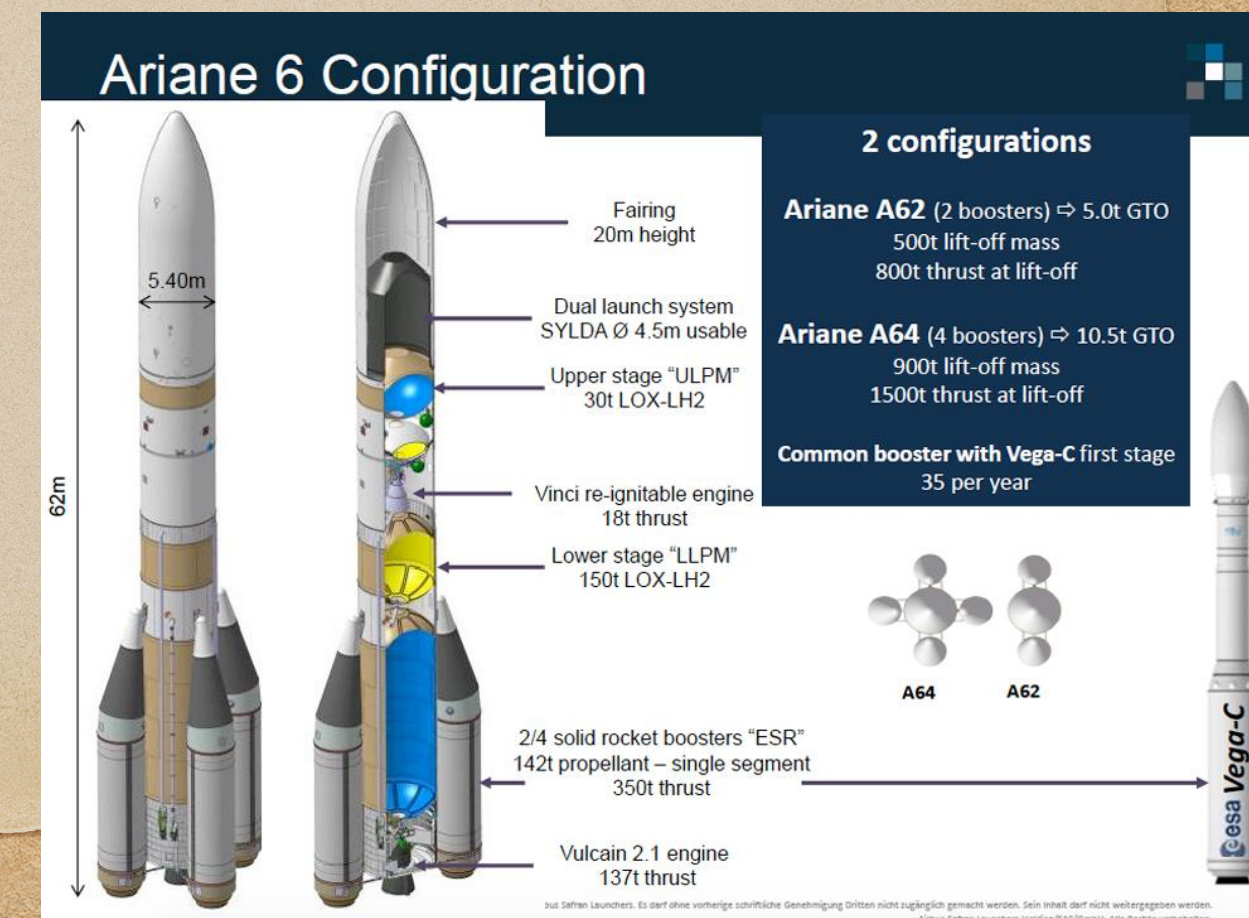


Figure 5-34: GaiaNIR optical surfaces and the light path

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 launch diameter (with the sunshield deployed) of approximately 10 meters
- ◆ 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

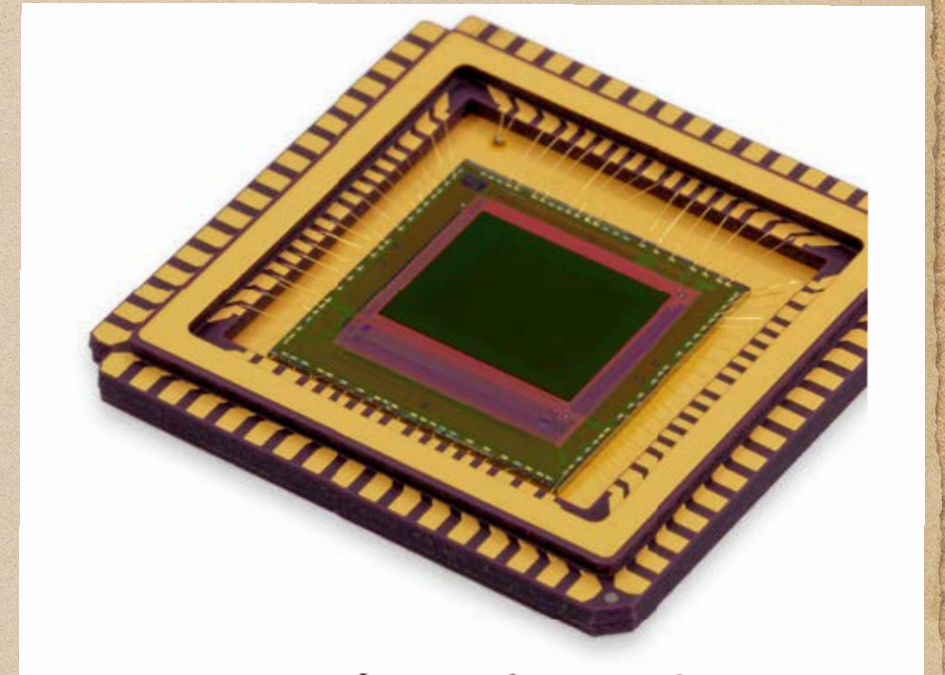
Italian owned Leonardo UK have small APDs with high frequency readout

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

GHz readout devices are possible for TDI operation but we only need kHz

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

Studies of the detectors are now ongoing in the UK



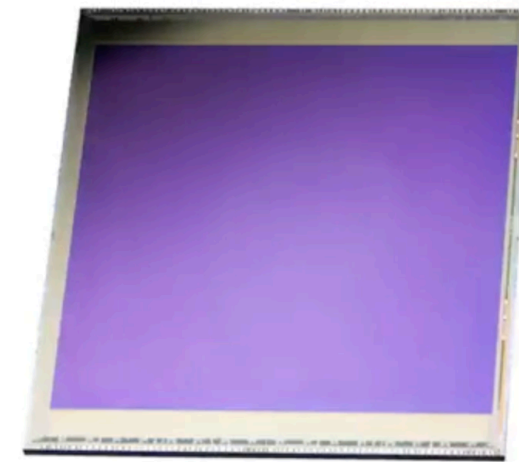
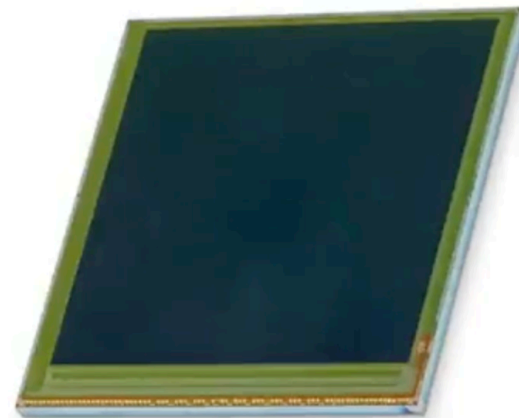
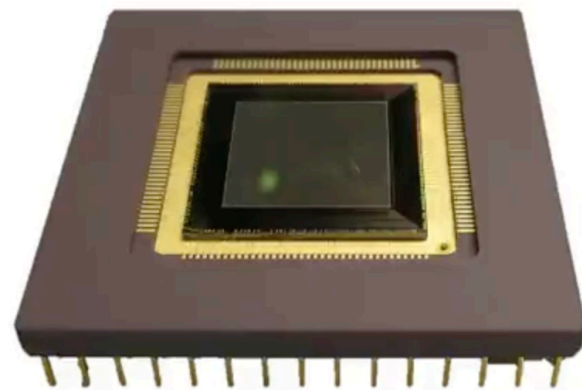
The SAPHIRA is a 320×256 pixel linear-mode avalanche photodiode array capable of 'noiseless' readouts via an upstream signal multiplication of several hundred.

Leonardo Detectors

Leonardo make a range of different detectors

GaiaNIR requires a high frequency readout which is only possible with the Saphira type but we require a detector of about 3×1024 pixels ($18 \times 24\mu\text{m}$) so they need to be connected in sequence and use image stacking in software.

Update of LmAPDs for low background flux applications



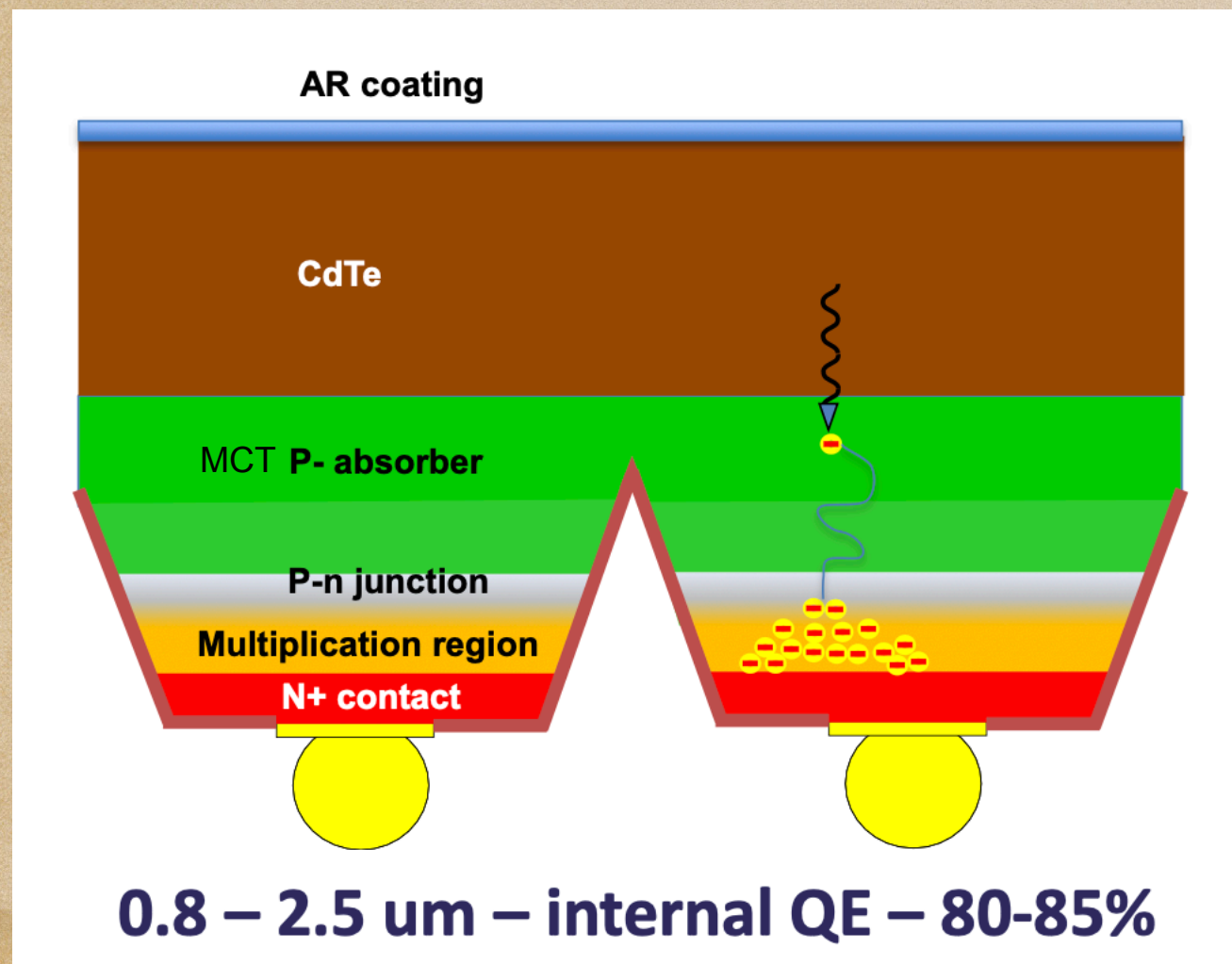
	Large Saphira	Ike-Pono	IBEX
Dimensions	512x512/24 μm	1024x1024/15 μm	2048x2048/15 μm
Status	Detectors provided to consortium partners for evaluation and system development.	First science grade devices under assessment	Prototype arrays manufactured
Collaborator	ESO, Max Planck and NCR	NASA APRA ROSES, 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

Leonardo Module Concept

Digital readout can be implemented allowing TDI by co-adding data in software or hardware

1 Detector with 9 LmAPD sub-detectors
3072x3072 pixels
18 x 24 μm

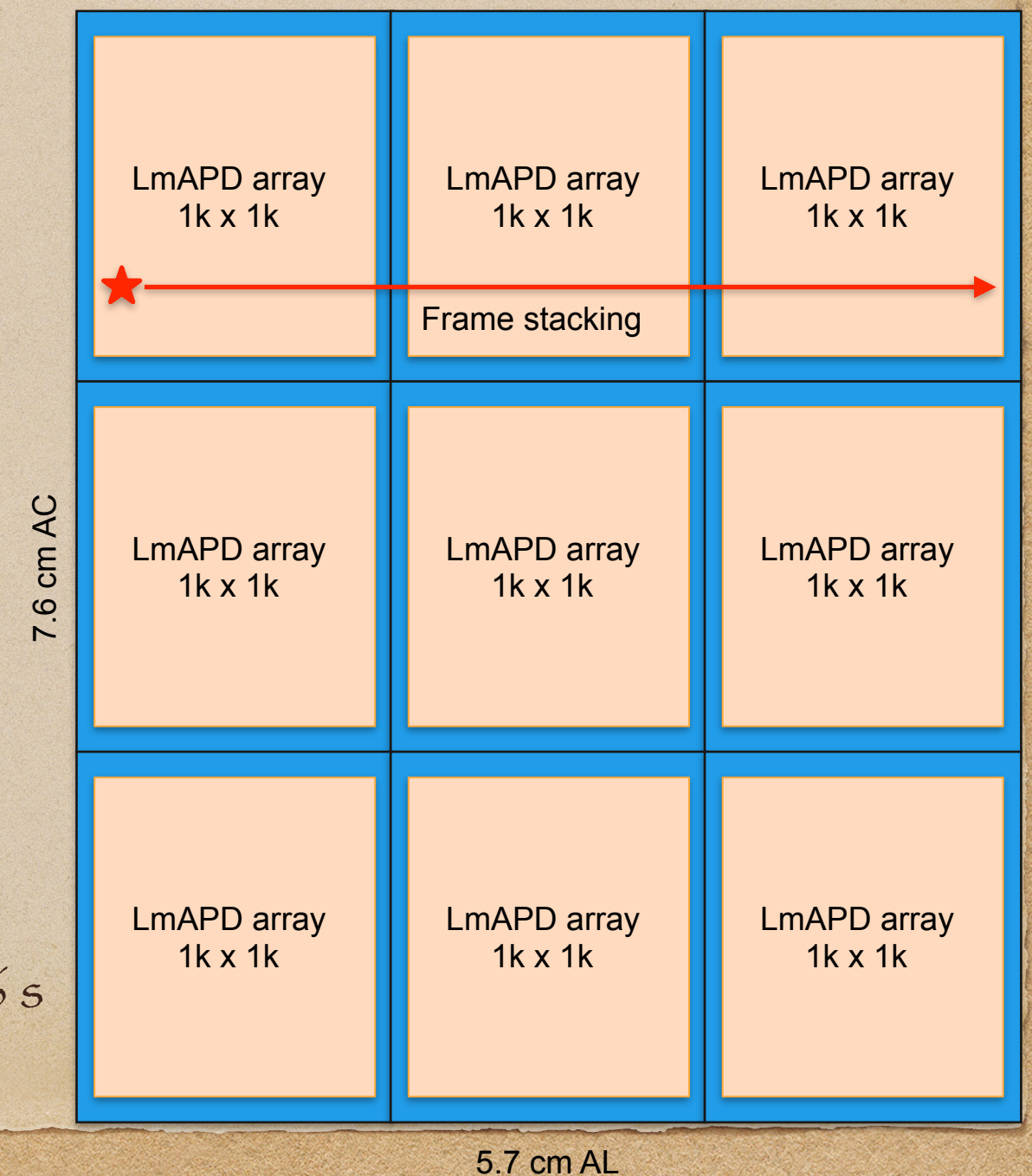
Quantum Efficiency and wavelength range



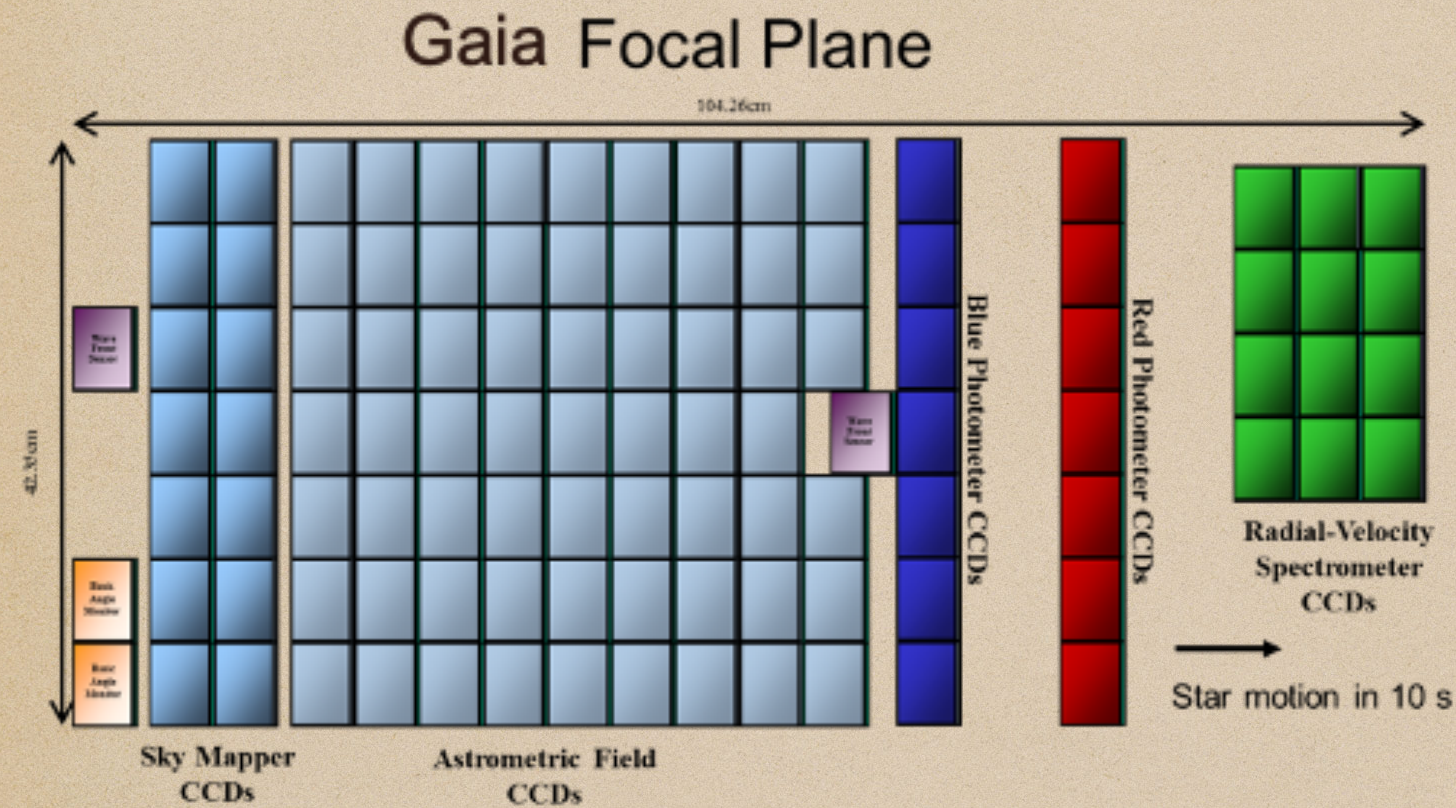
Bright stars might be handled
in S/W to avoid saturation?

No need for over-range block?

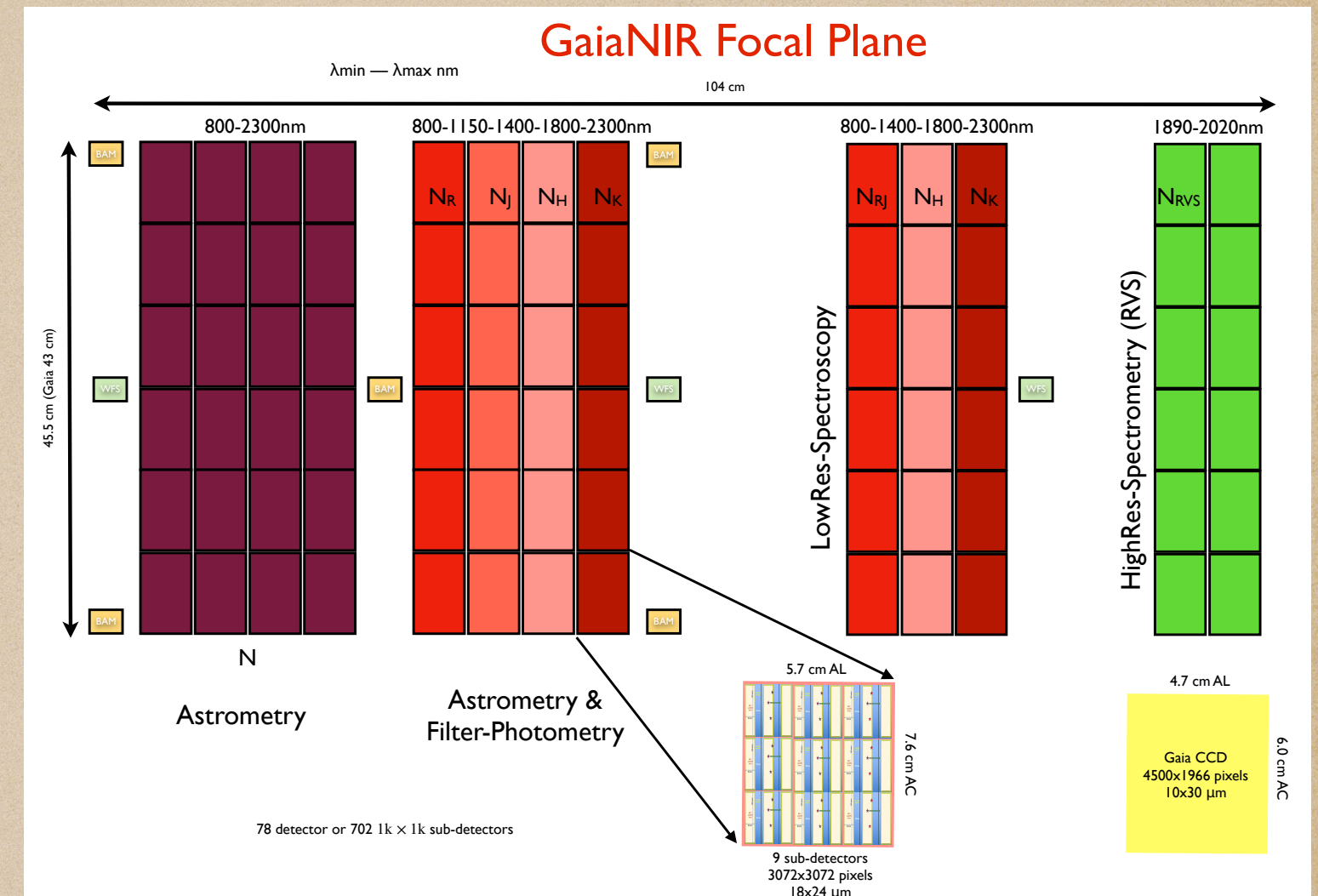
For GaiaNIR with 18 micron pixels is read
every 1.81 ms (or 552.5 Hz) and with 3072
total TDI stages the combined time is 5.56 s



The Focal Plane & Filters



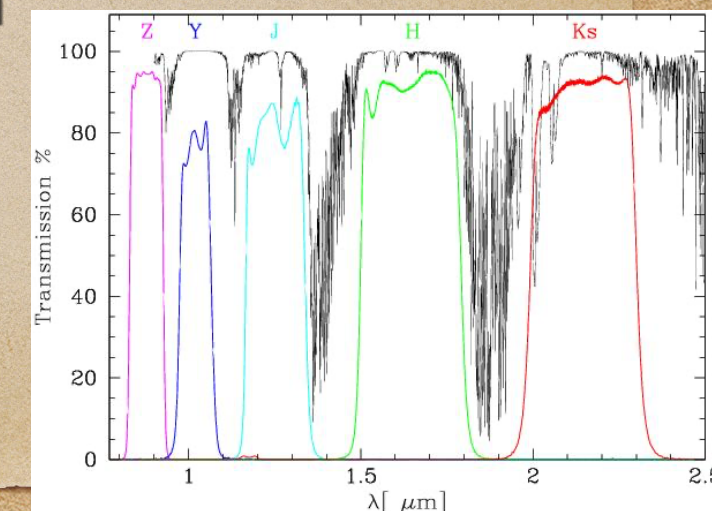
- ◆ Linear Mode APDs are the most promising detector for GaiaNIR
- ◆ Cooling strategy must be passive (~90K)
- ◆ Max wavelength ~ 2300 nm, blue stars (<800nm) are more challenging
- ◆ No SMs ~ track motion of stars instead to determine the FoV
- ◆ Filter photometry on astrometric field by depositing 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

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

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%.

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

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

where

ω is the scan speed [rad s^{-1}];

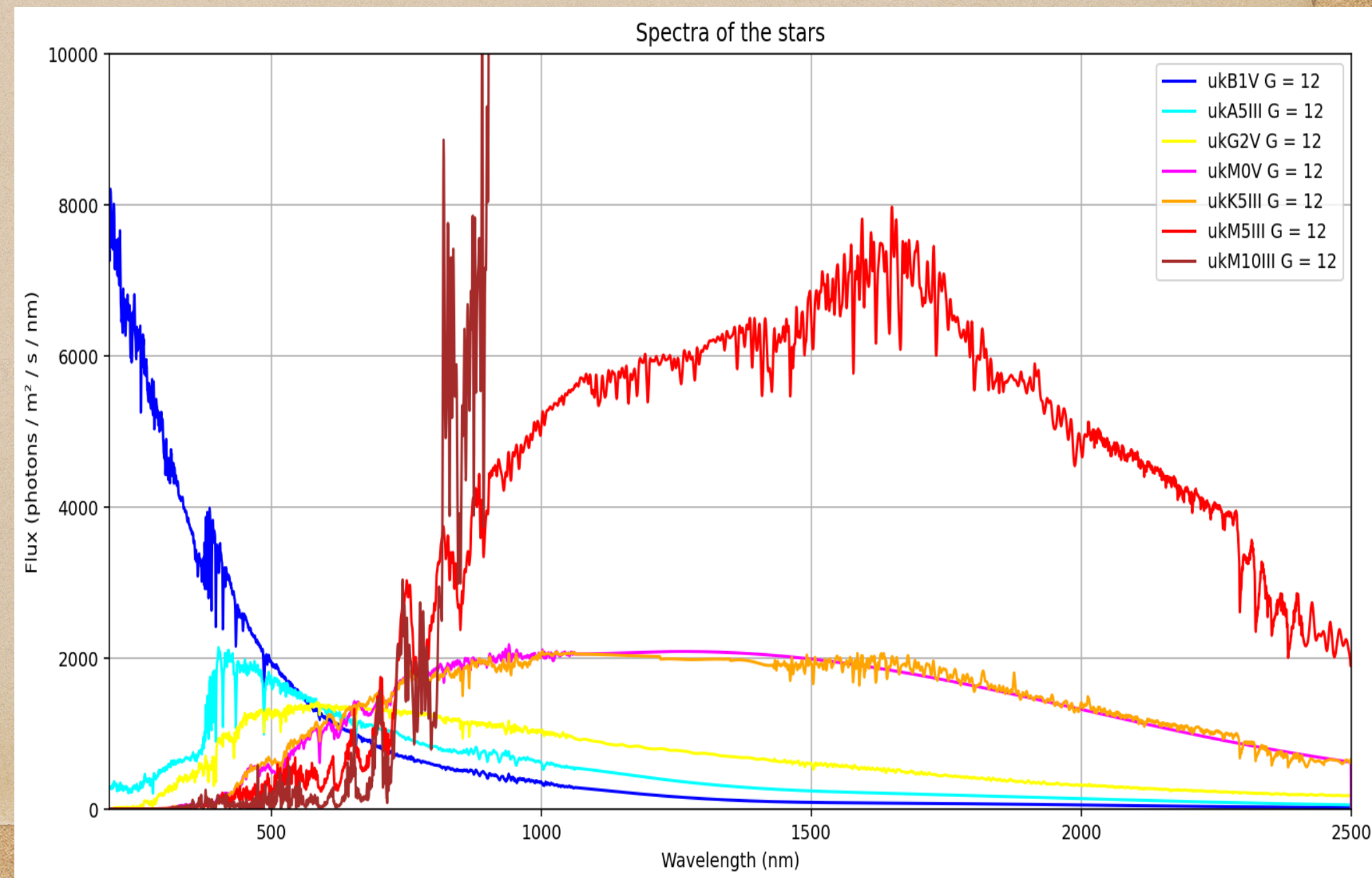
$\Delta \xi$ is the angular pixel size along scan [rad] and;

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

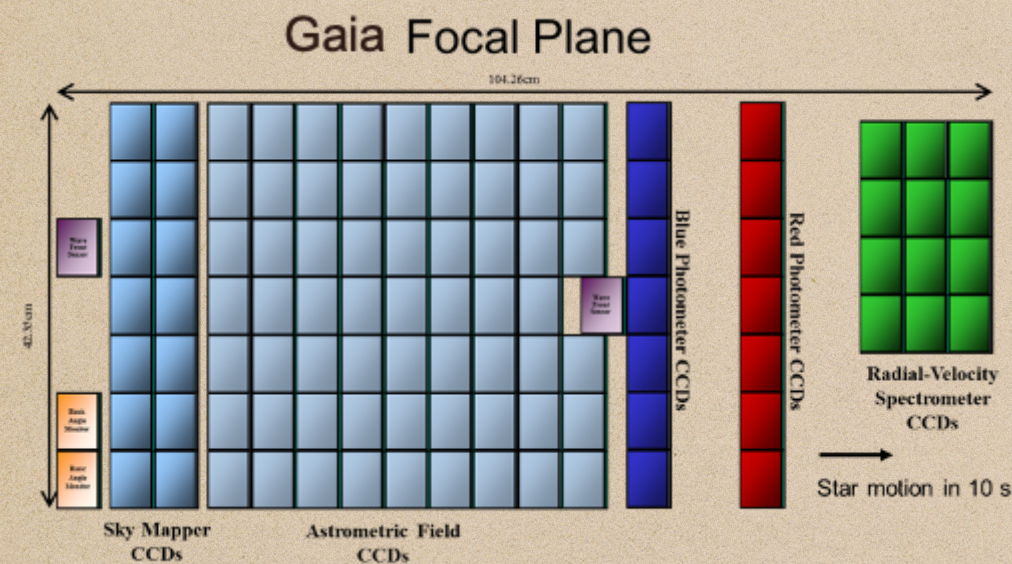
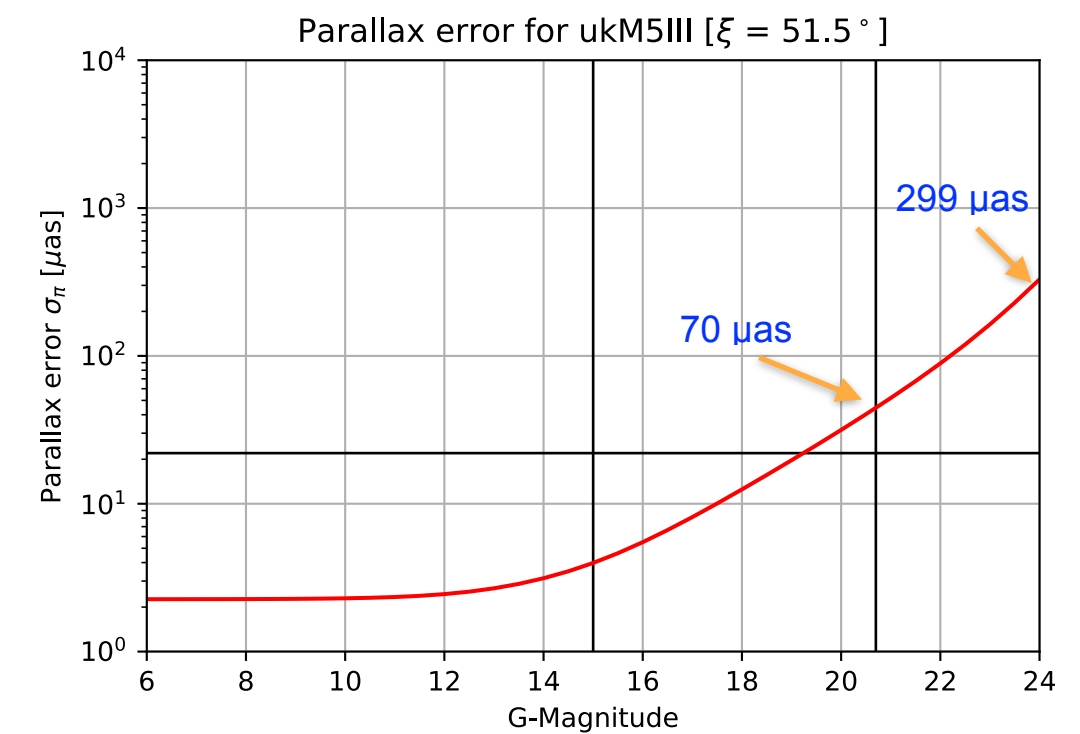
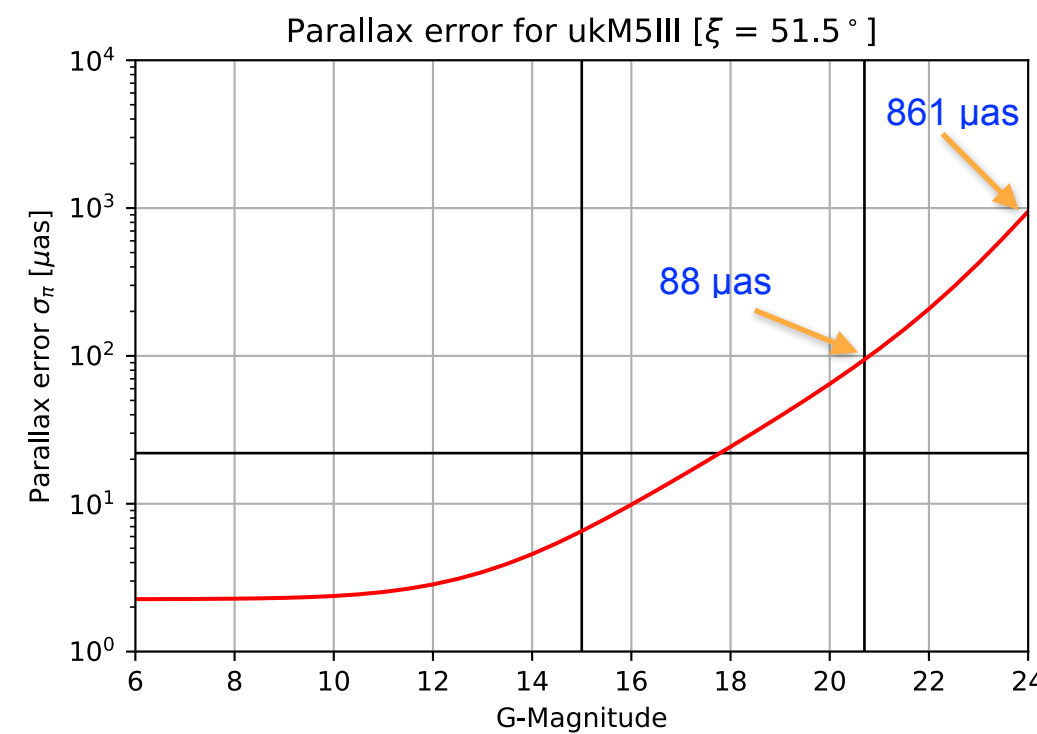
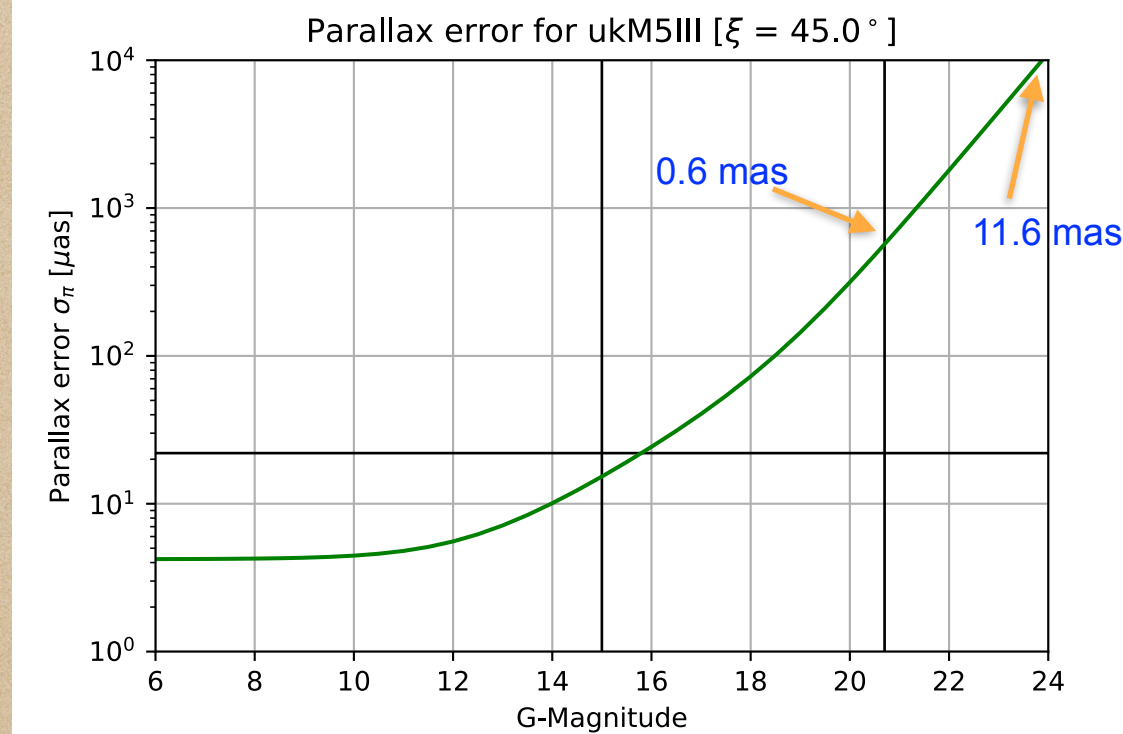
L = effective mission length (i.e. excluding dead time);

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

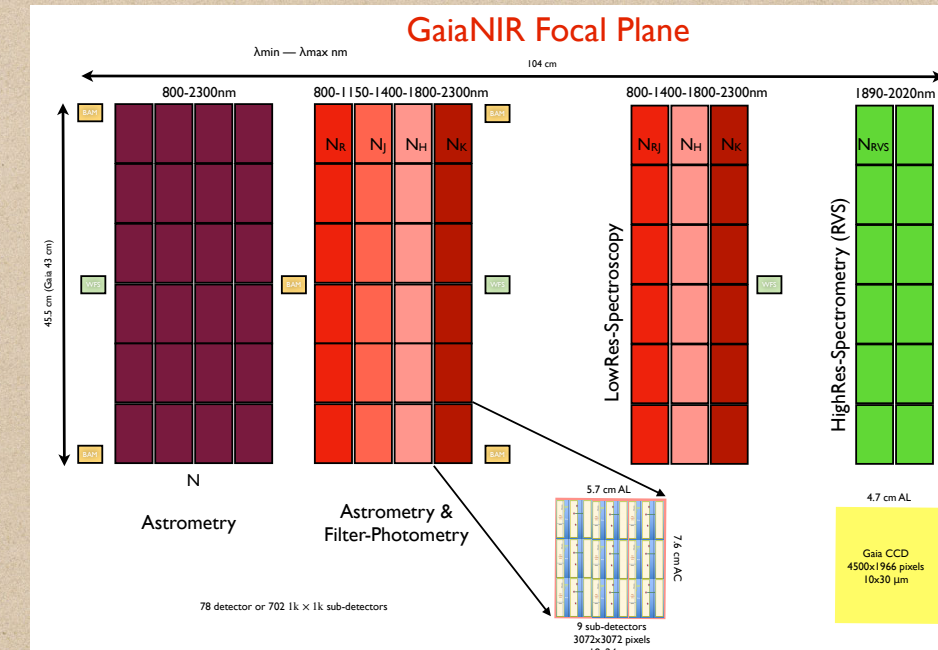
$g_{\varpi} = 1.47 (\sin \xi)^{-1}$ Sky averaged parallax factor



Detector Comparison (10-Yrs)



GaiaNIR_{Medium} Optics



GaiaNIR_{Large} Optics

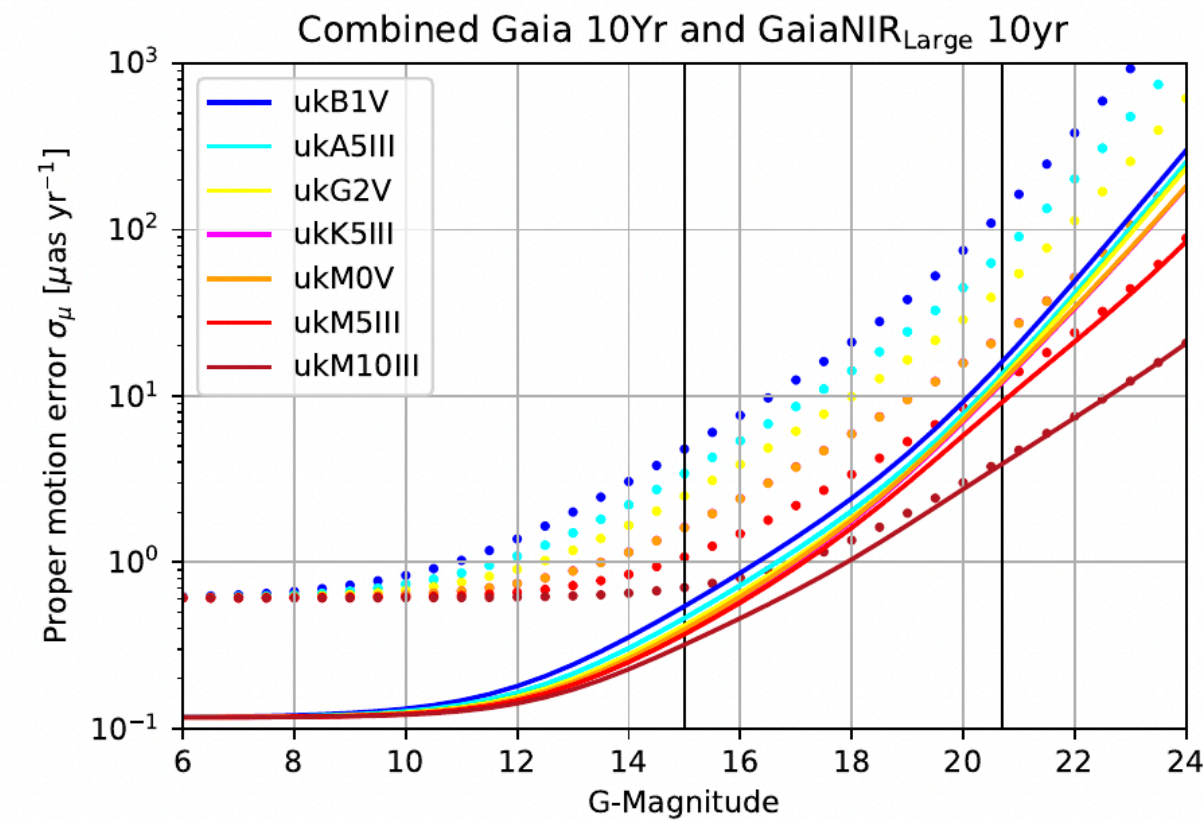
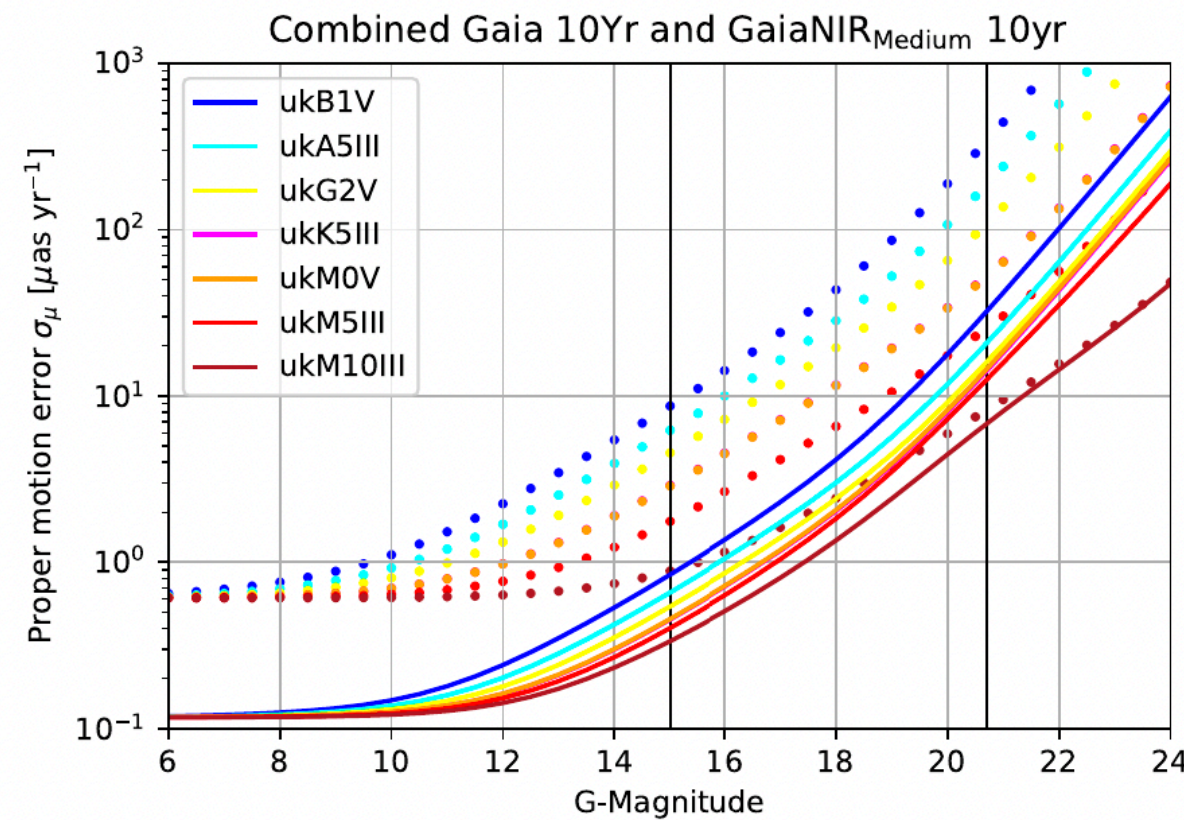
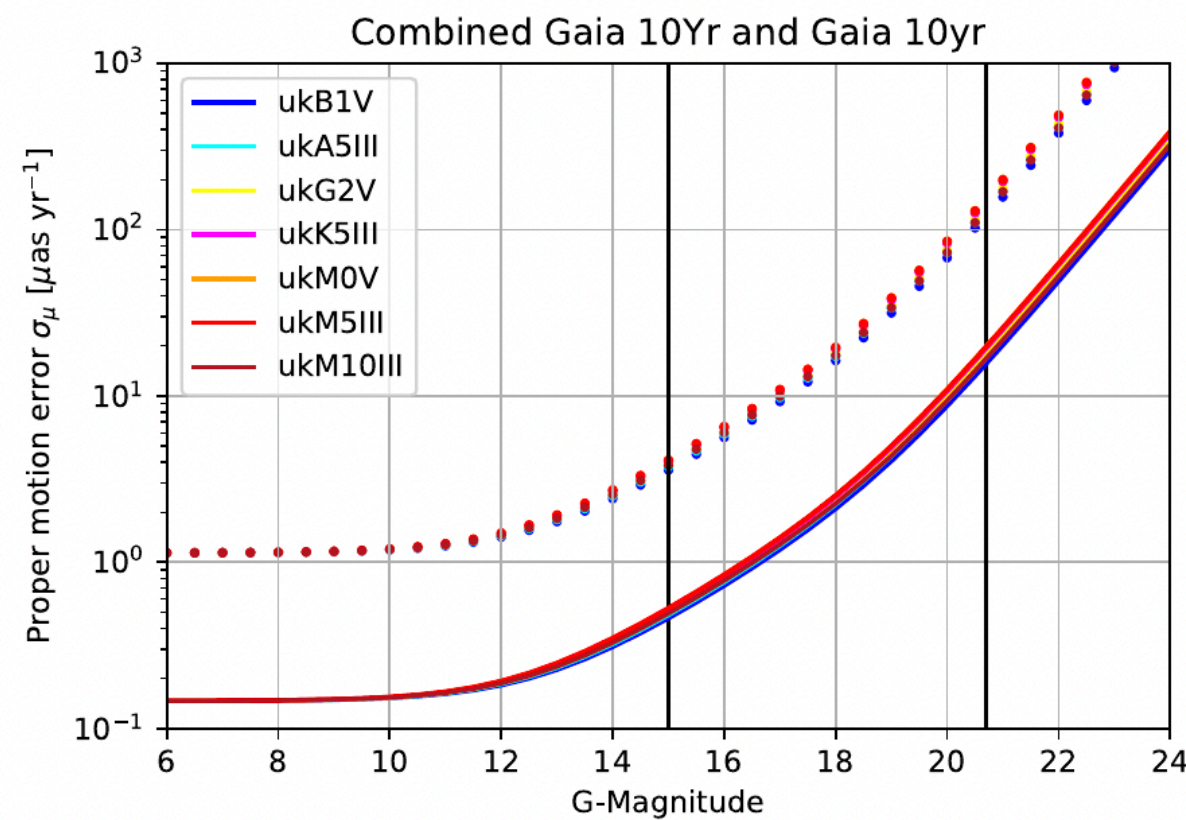
- Identical runs for **M5III** cool, luminous red giant giving a comparison between Gaia CCDs and GaiaNIR APD's
- APDs shows a linear (log) increase in error with magnitude compared with an exponential increase in CCDs

Combined EoM PMs

Gaia

*GaiaNIR*_{Medium} Optics

*GaiaNIR*_{Large} Optics



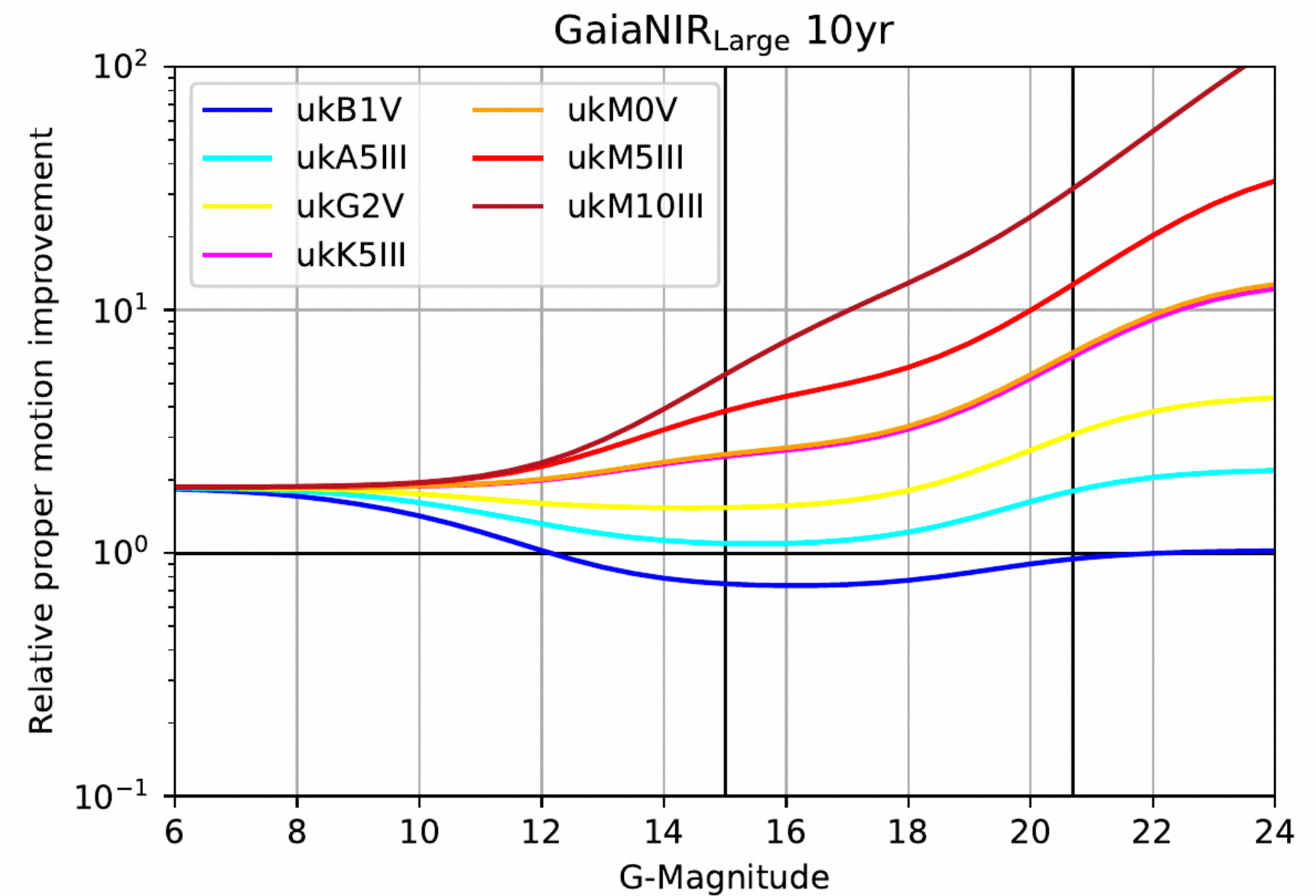
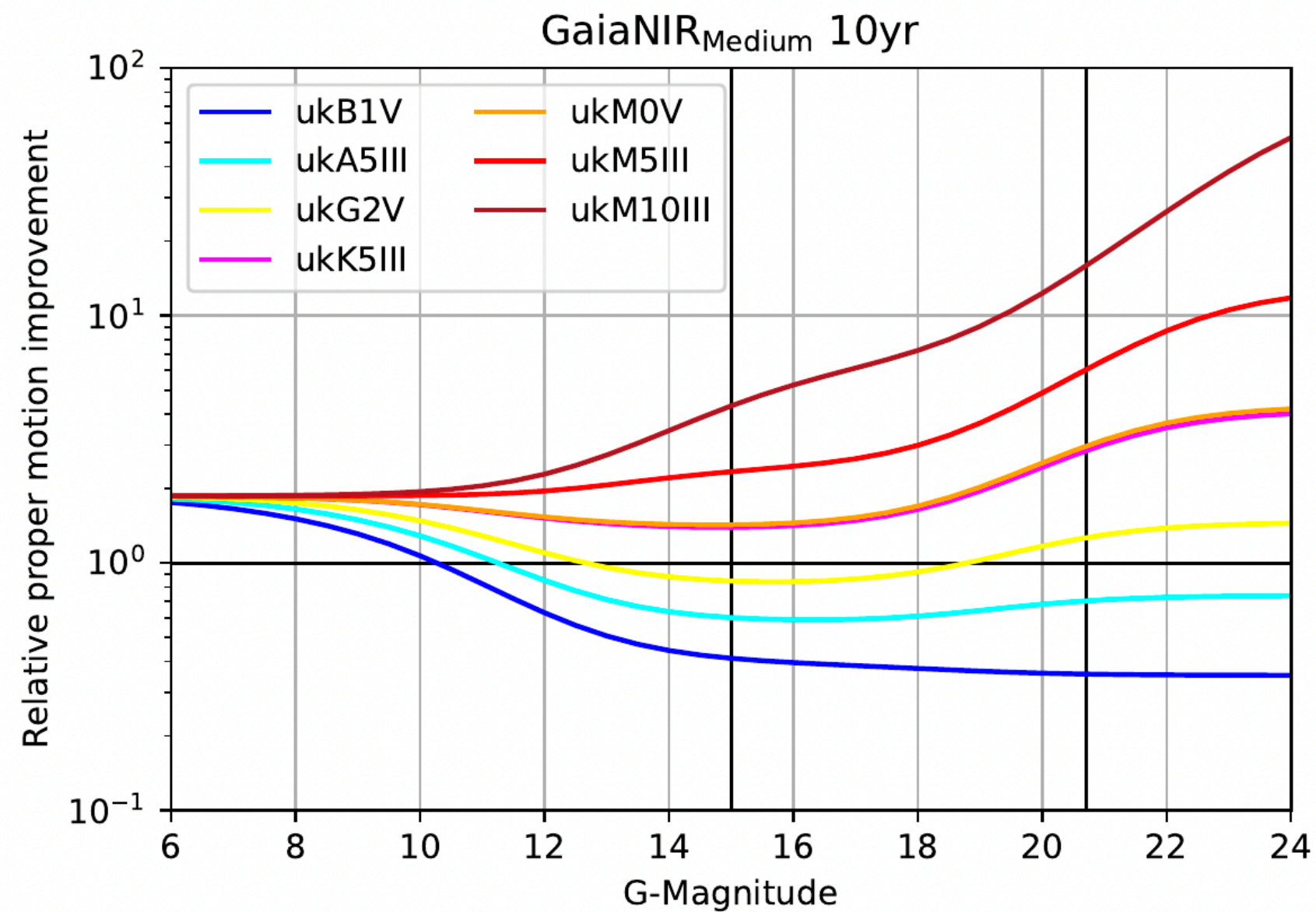
$$\sigma_{\mu 0} = \frac{(\sigma_{posN}^2 + \sigma_{posG}^2)^{1/2}}{\Delta T}$$

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

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.

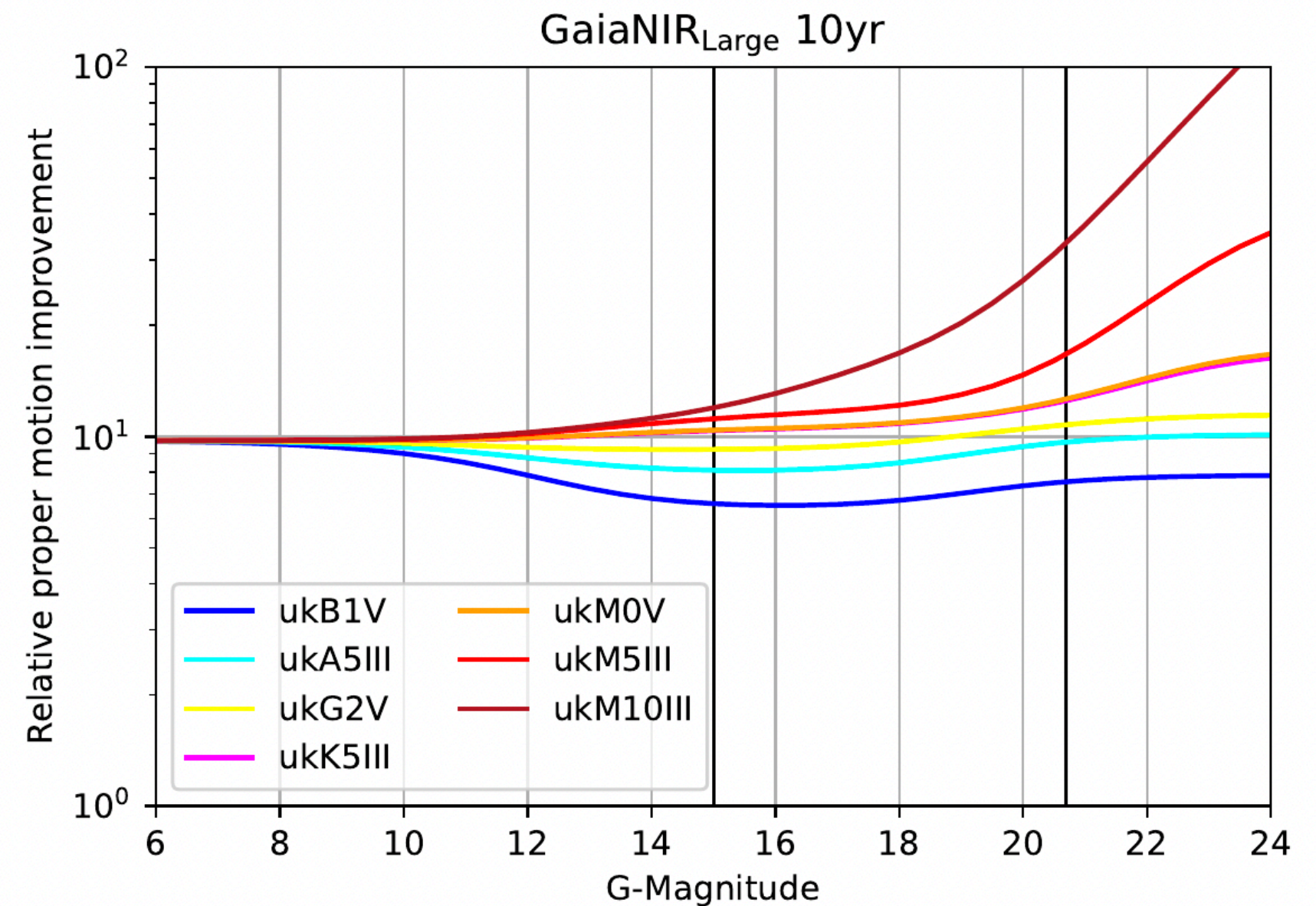
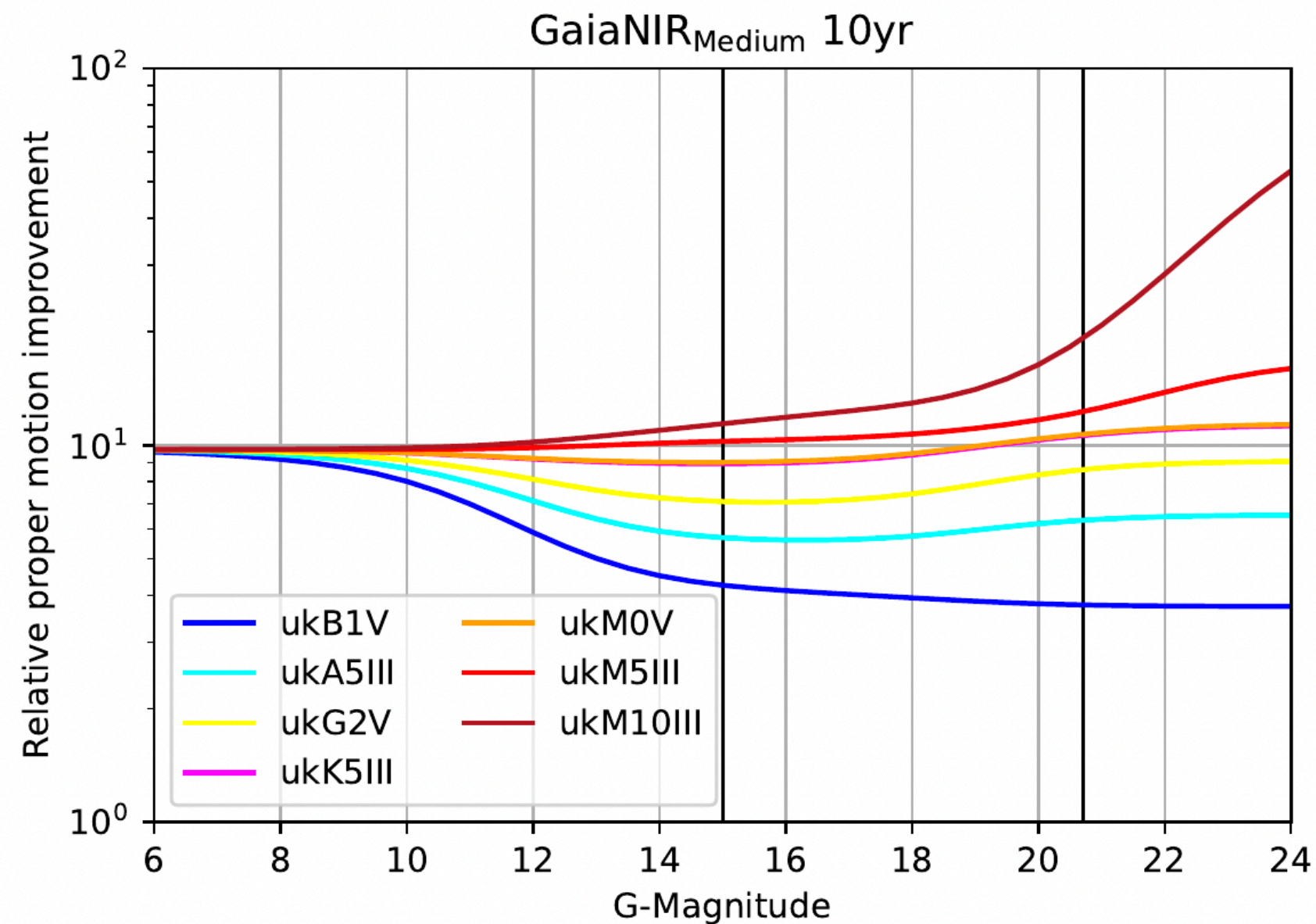
At least an order of magnitude improvement from combined solutions!

Relative PM Improvement of individual solutions



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

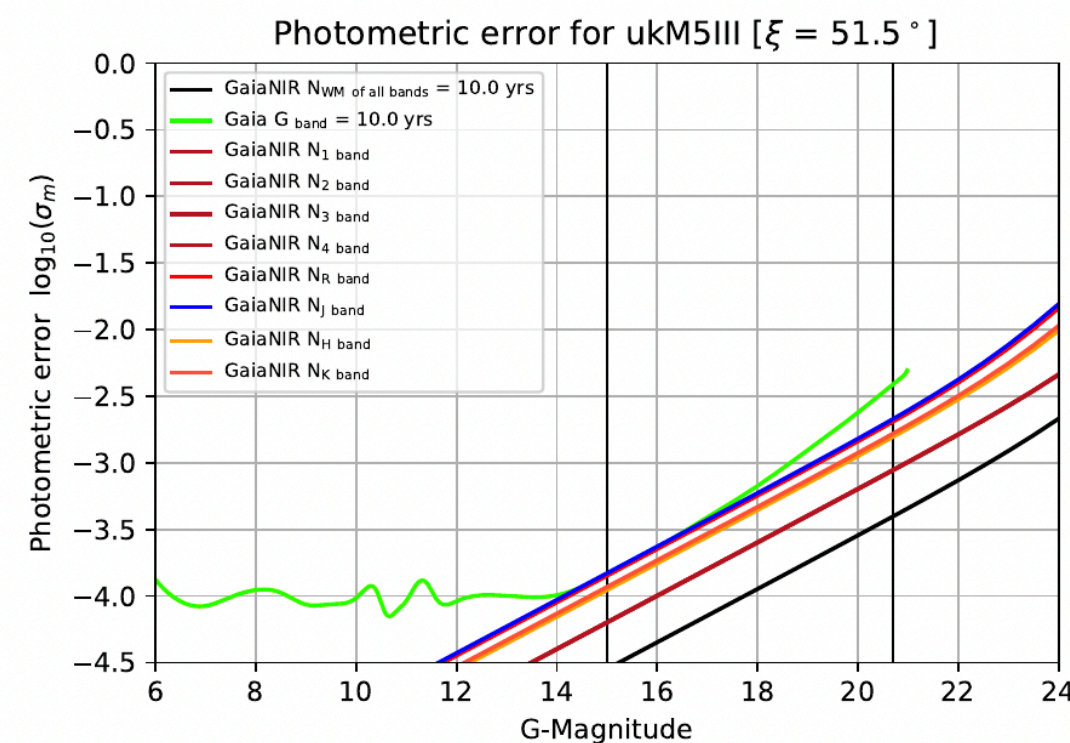
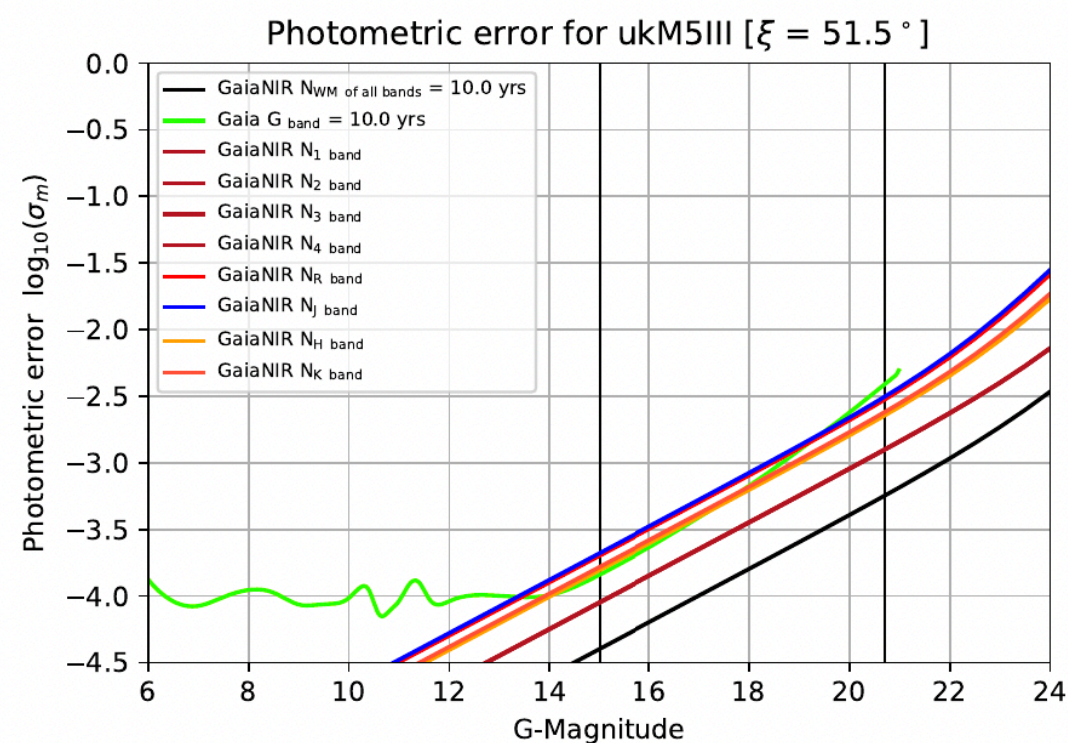
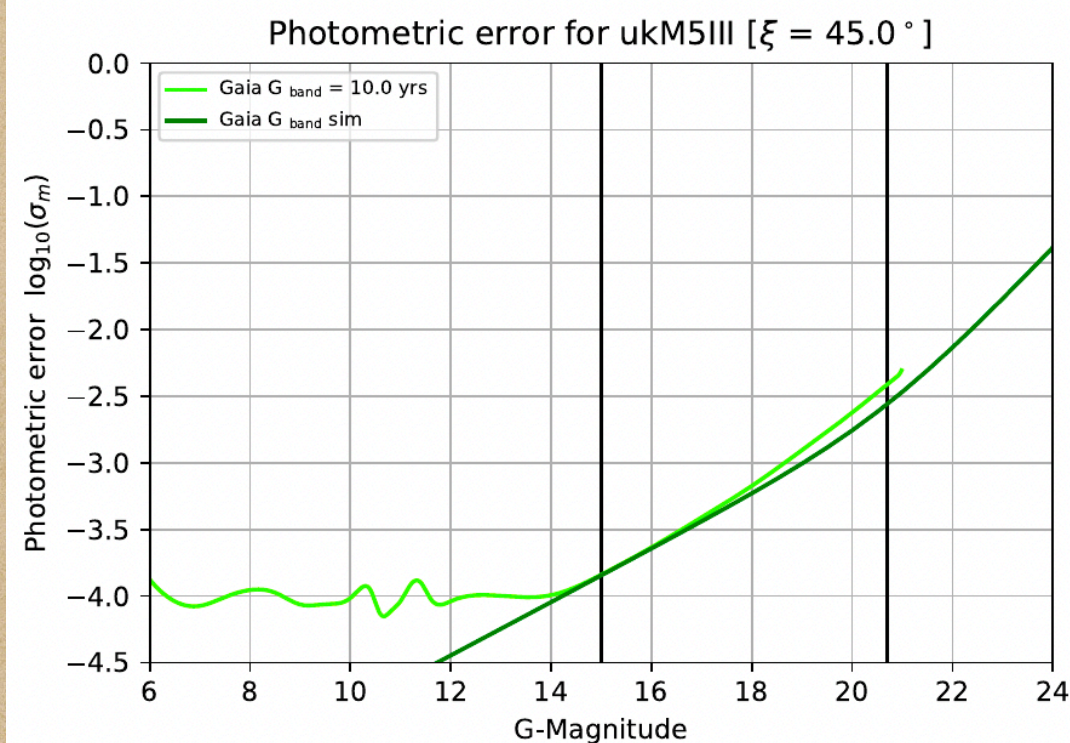
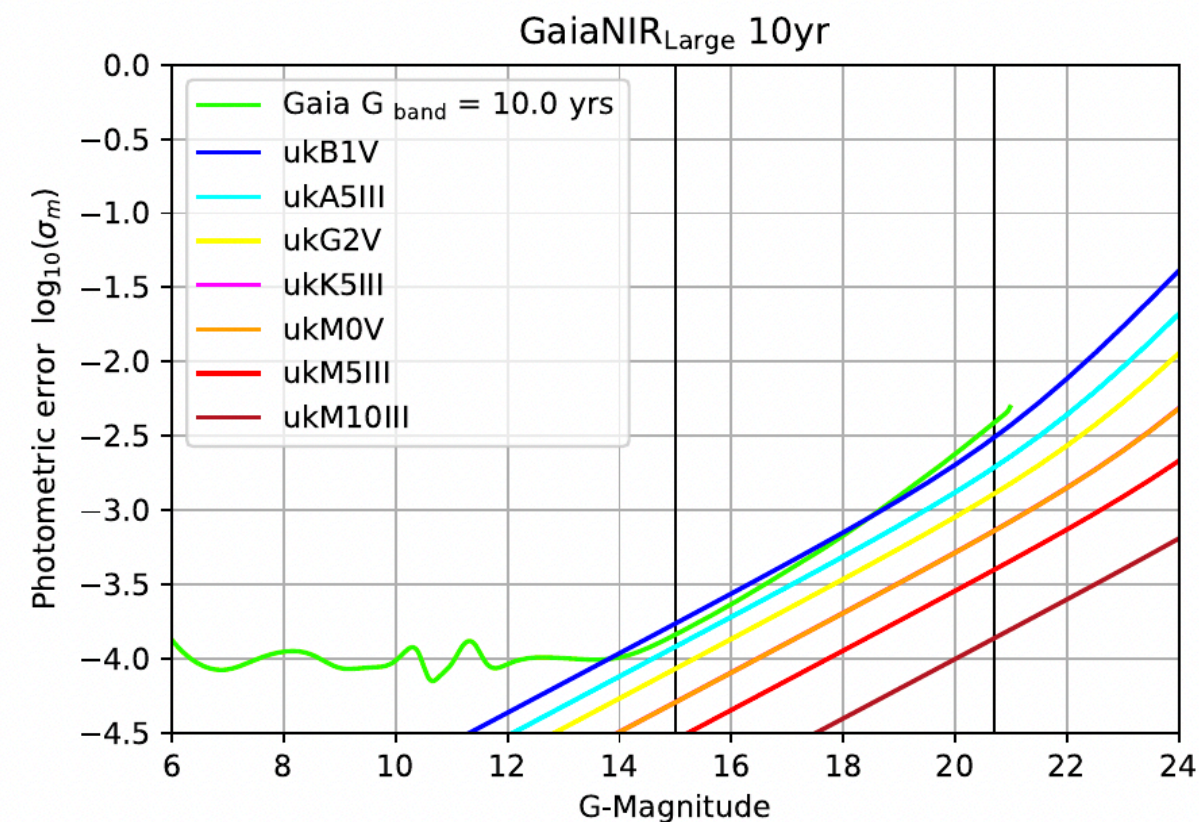
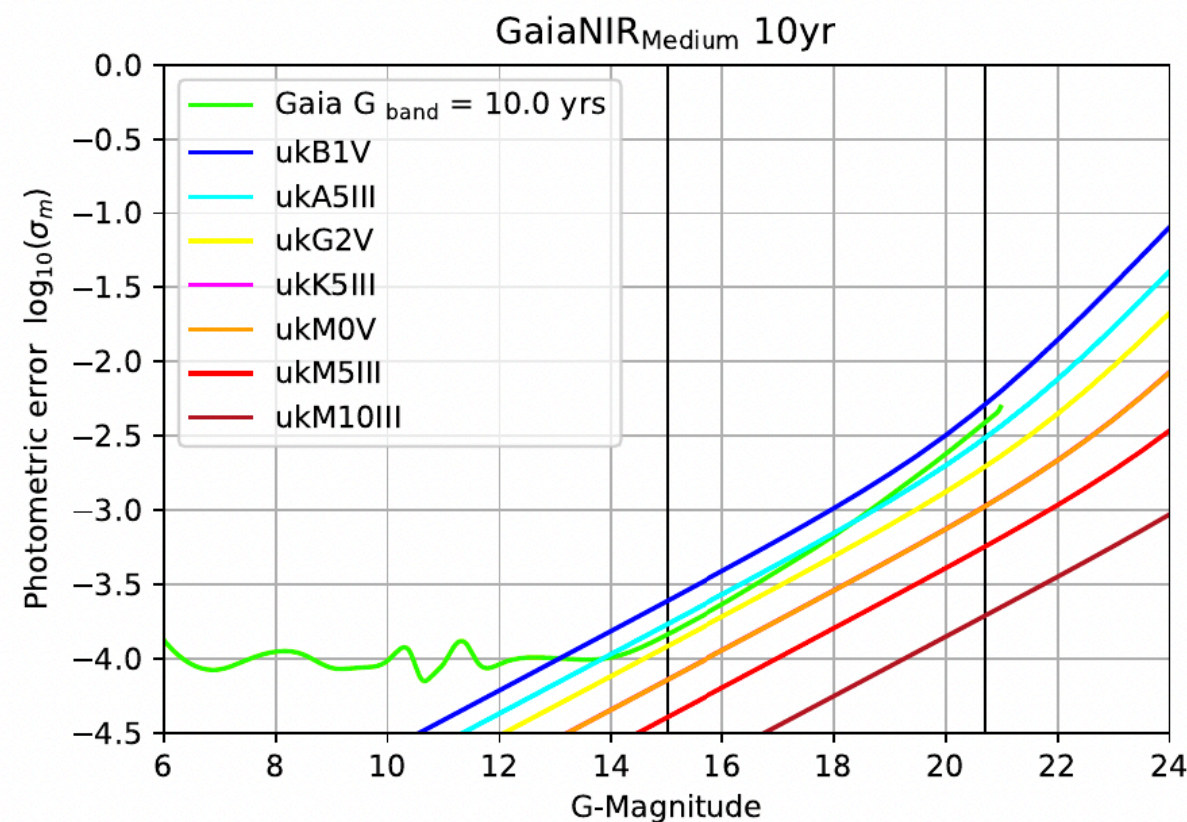
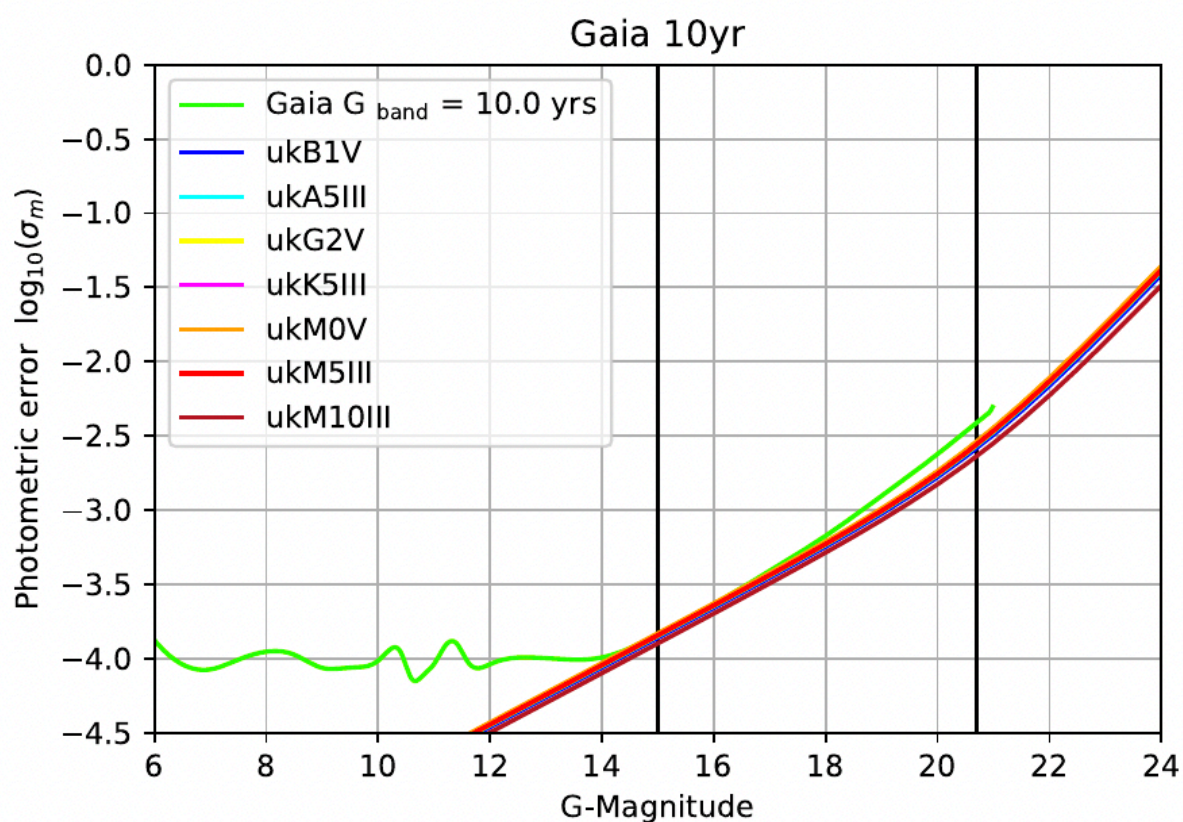
Relative PM Improvement of Joint solutions



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

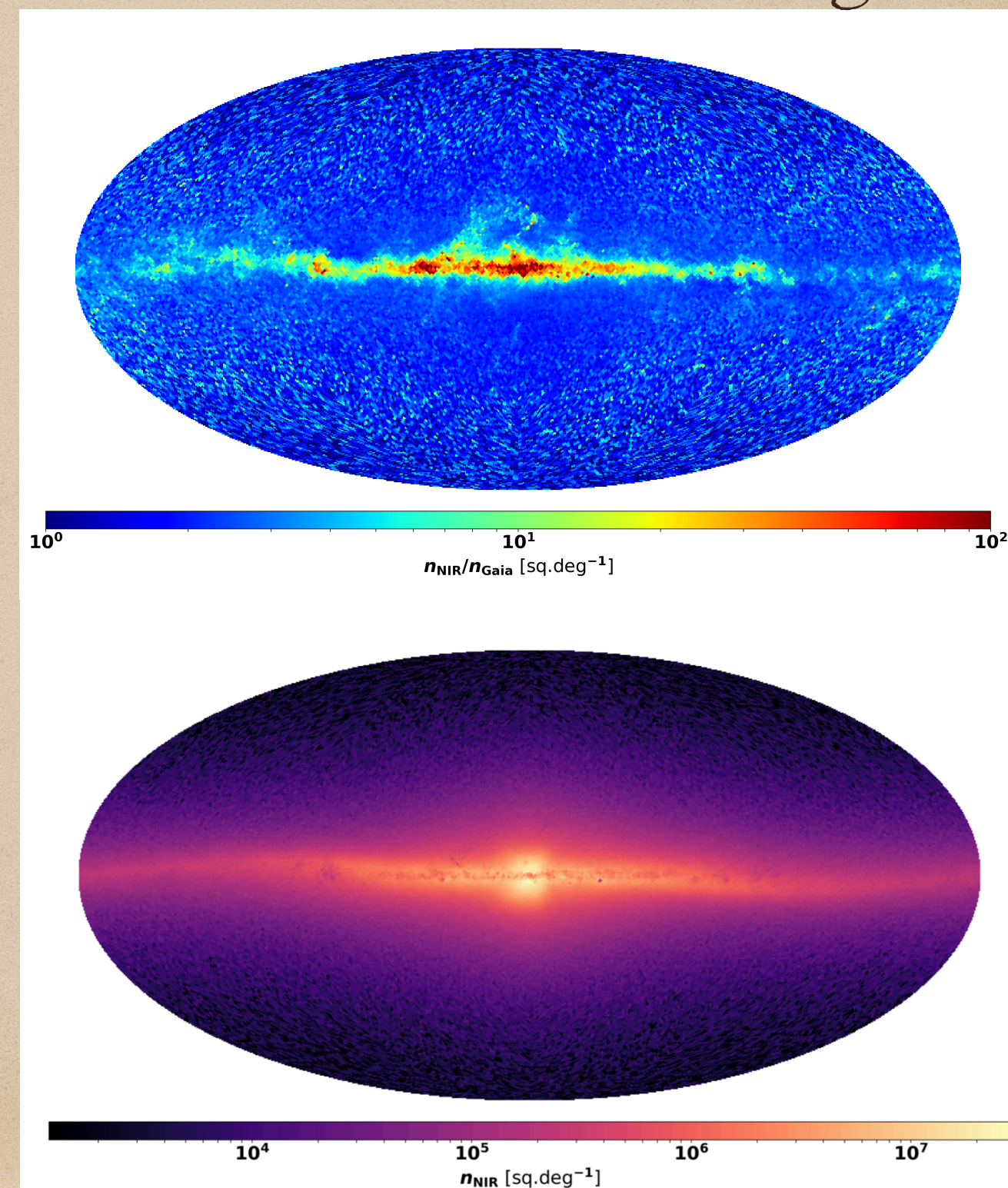
For 50+ billion sources

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
 - So 12.5 to 15 billion stars for H or K-band cut-off's
 - A K-band cutoff with 15 billion stars makes more sense!
 - If we go 2 magnitudes deeper than Gaia this would yield up to 95 billion stars or 50+ billion stars when crowding is accounted for
- ◆ The star count ratio estimates are currently being updated but the galactic centre may have up to 10 million stars/deg²

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)



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
- ◆ 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?

Isabella Henum - Band Conversions

