Detector options for GaiaNIR

Guy Rixon, reprising an UKSA NSTP study from 2022, at
Science and technology roadmap for µas studies of the Milky Way, Lund, 2023

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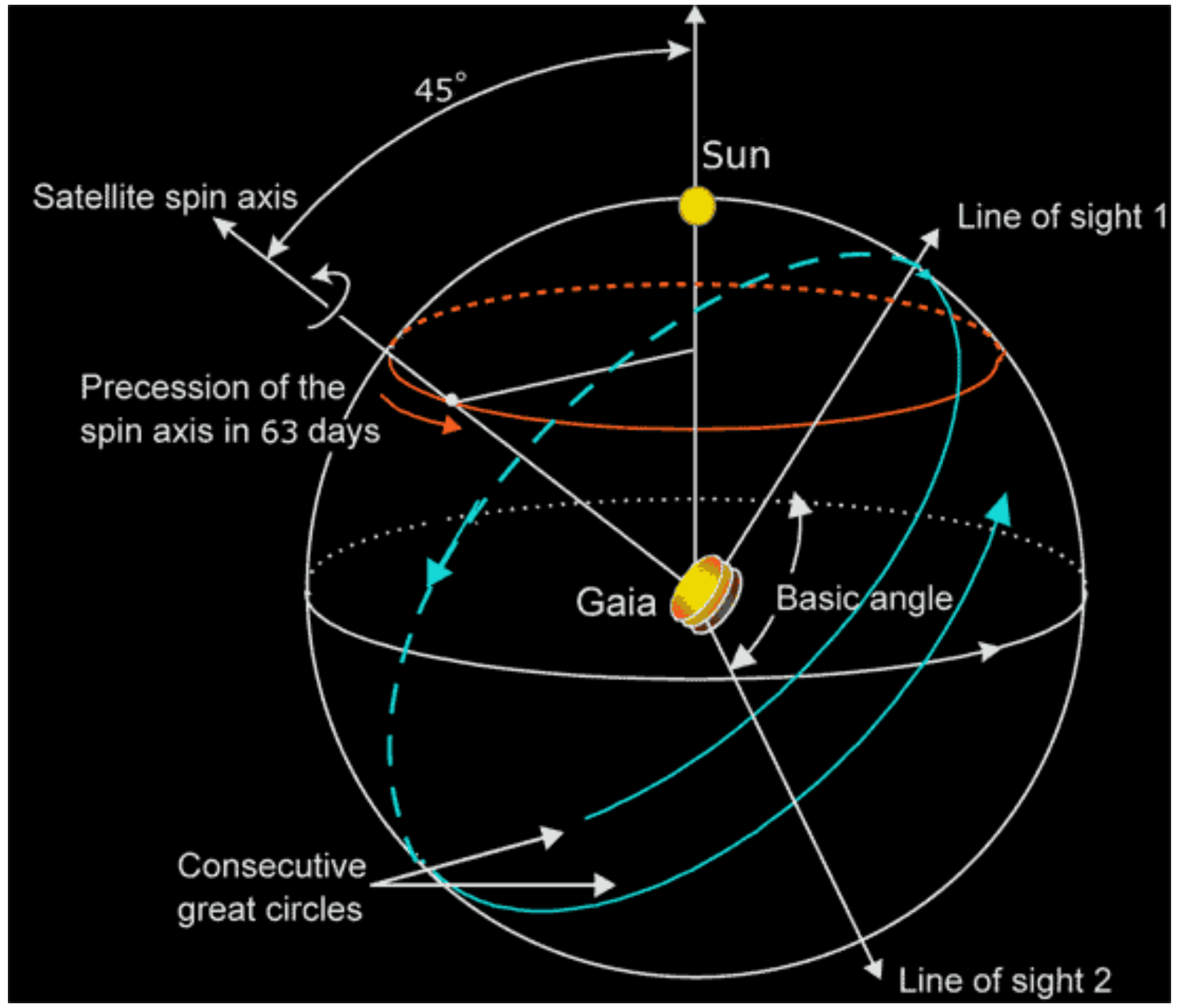
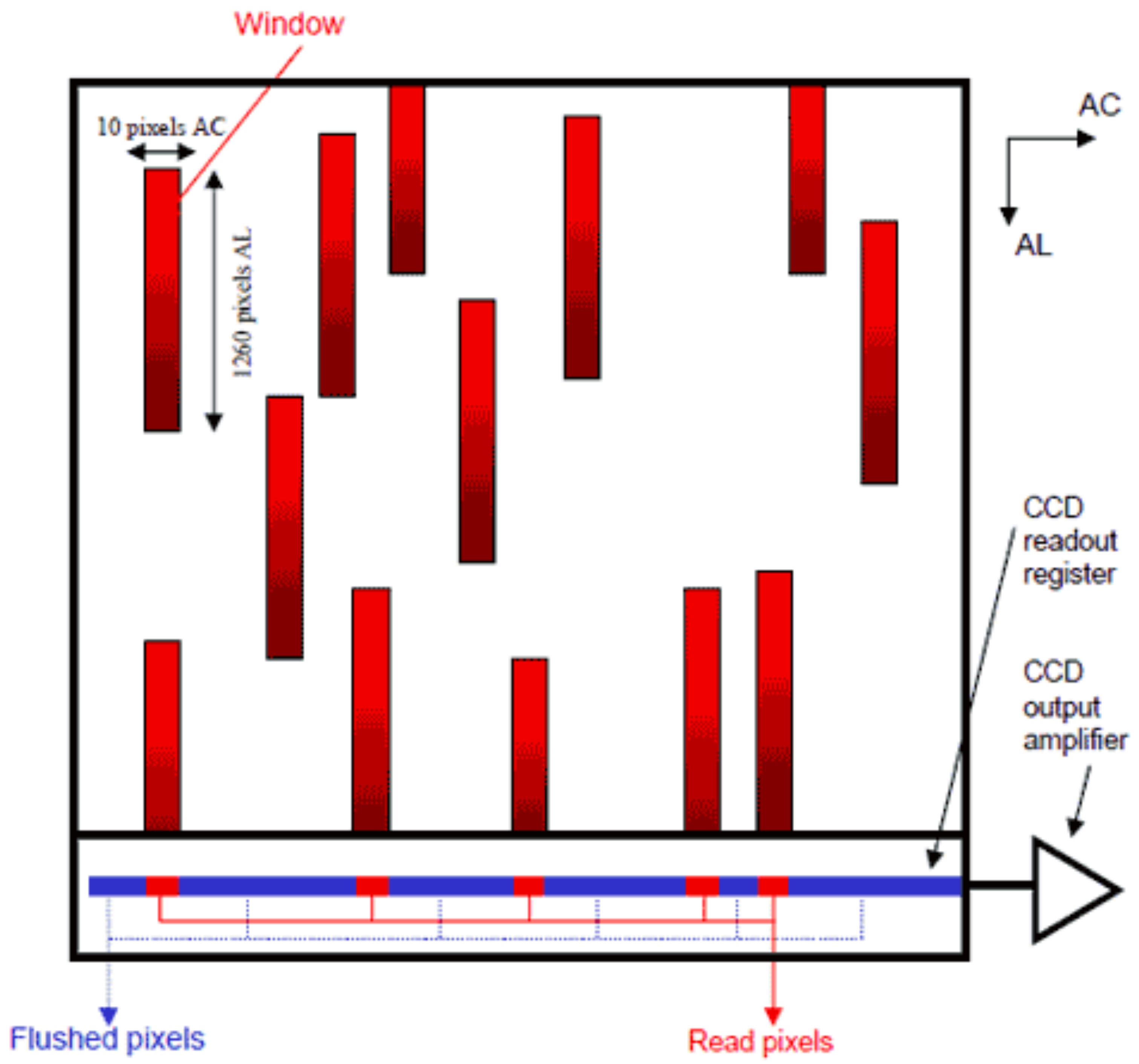
TDI on Gaia





Effective exposure is time for star to transit the CCD in along-scan (AL) direction

- Time Delay Integration allows observation with **fixed optics** from a rotating platform
    - Gaia does analogue TDI on the CCDs by clocking the charge across to match the spin rate.
    - Can also do digital TDI: shift and add short exposures in software
- But: “NIR detectors can’t do TDI” 😢 (consensus up to ~2022)

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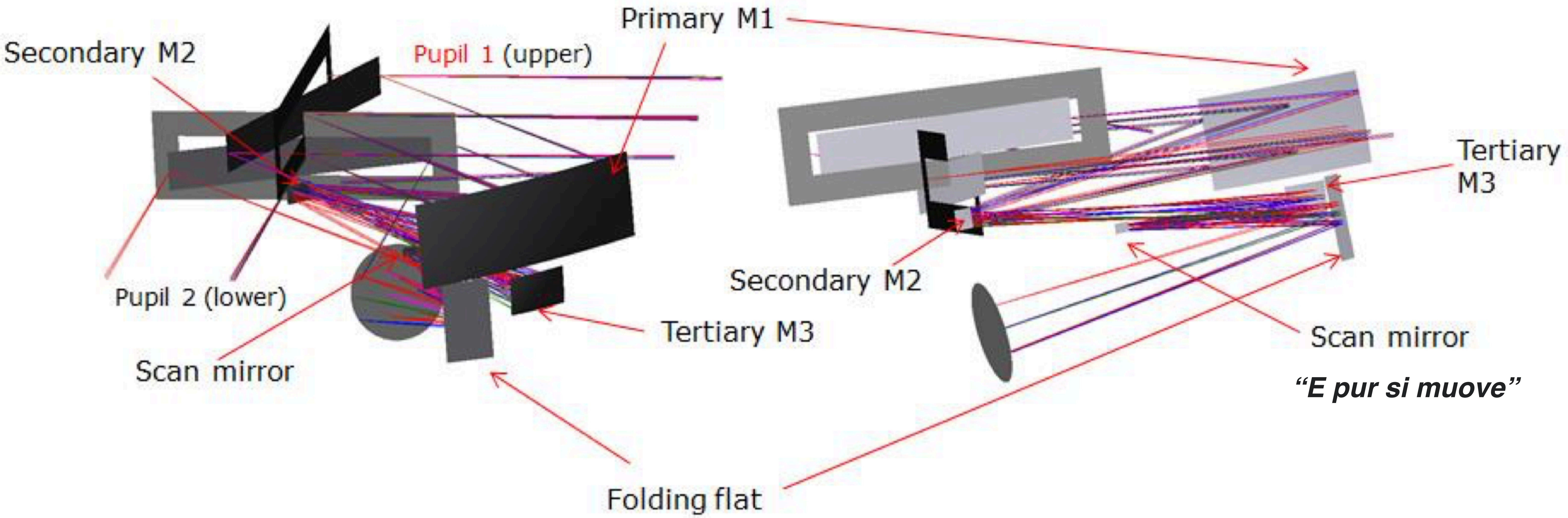
GaiaNIR without TDI



"E pur si muove"

- Opto-mechanical derotation proposal from Puig+ 2017, CDF Study Report on GaiaNIR
- The "scan mirror" tilts to counteract rotation of the FoV
- Solves the problem, but has trade-offs:
  - image quality, due to angle-dependent defocus;
  - Observations broken up by mirror fly-back time;
  - mission risk due to single point of failure in moving mechanism.
- TDI operation would be much simpler.

Our study

- Six-month initial study
    - Collaboration between IoA Cambridge, Leonardo UK, UK ATC, MSSL, University of Durham
    - Funded by UK Space Agency under New Space Technology Programme
- An existence proof for GaiaNIR based on TDI operation using LM-APD detectors
    - Examines only one family of detectors
    - Not a comparison of all available detectors
- Comparing predicable performance with Leonardo LM-APD detectors against science cases in *All-Sky Visible and Near Infrared Space Astrometry* white paper (Hobbs+ 2021)

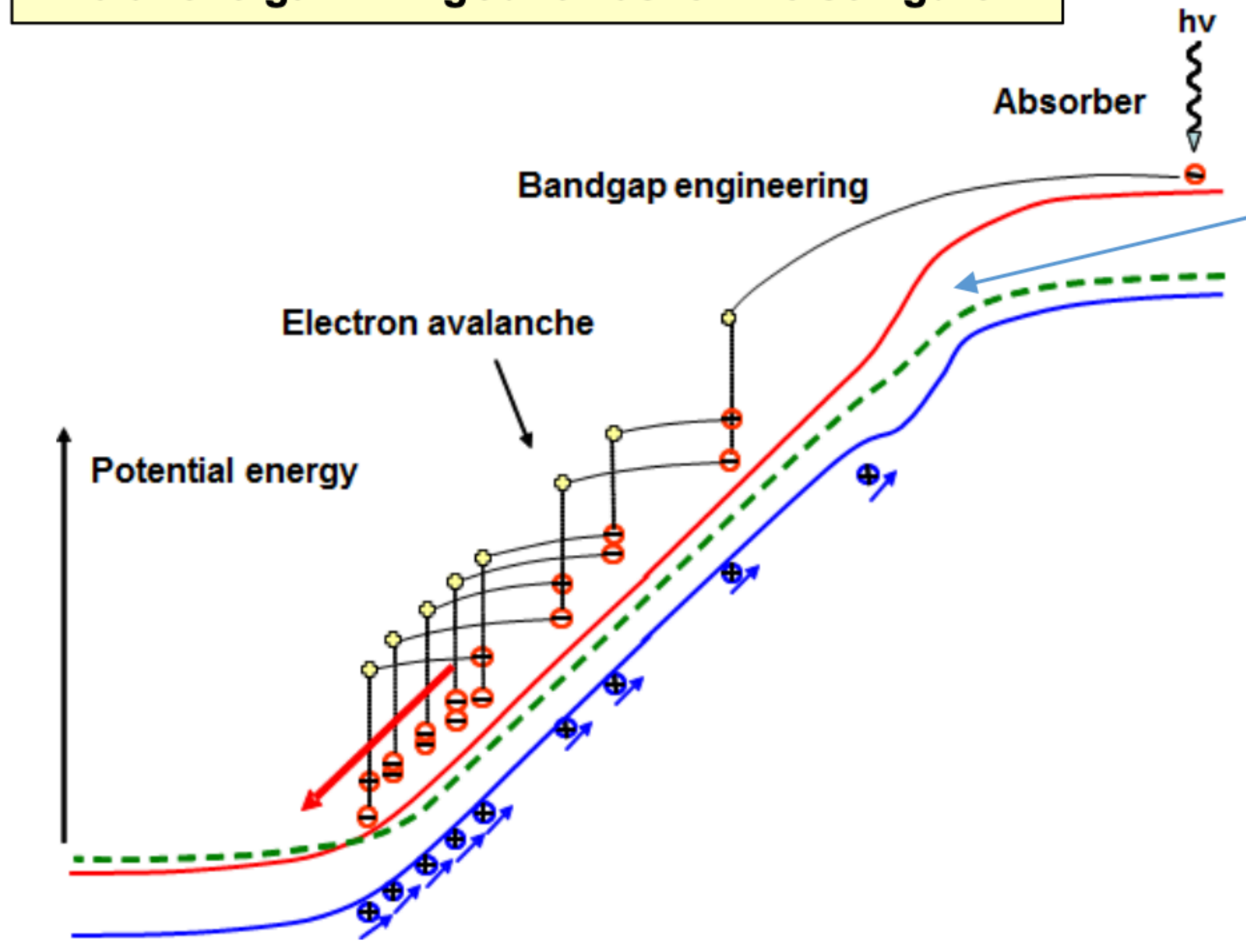
Constraints on detectors & focal-plane arrangement

- Constraints derived from mission goals in Hobbs+ 2021:
  - Survey limit to see MSTO in the galactic centre (affects detector width along scan)
  - End-of-mission accuracies (affects detector sensitivity, number of detectors and filling of focal plane):
    - Parallax: σ_π~12.5 μas for J=21, H=17.5, K=15.5
    - Proper motion: σ_μ~250 μas/yr at J=22.4, H=20, K=19.7
    - Proper motion: σ_μ~250 μas/yr at H=19.5, K=16.5
    - Proper motion: σ_μ~25 μas/yr at J=28.4 mag, H=13.8 mag, K=11.3
  - Enough spectral overlap with Gaia to cross-identify for long-baseline PM study (affects blue response)
  - Enough spectrophotometric ability to identify star types (affects range of detector types)
  - Enough dynamic range for mixed field of bright and faint stars
  - Affordable enough to fill the focal plane.

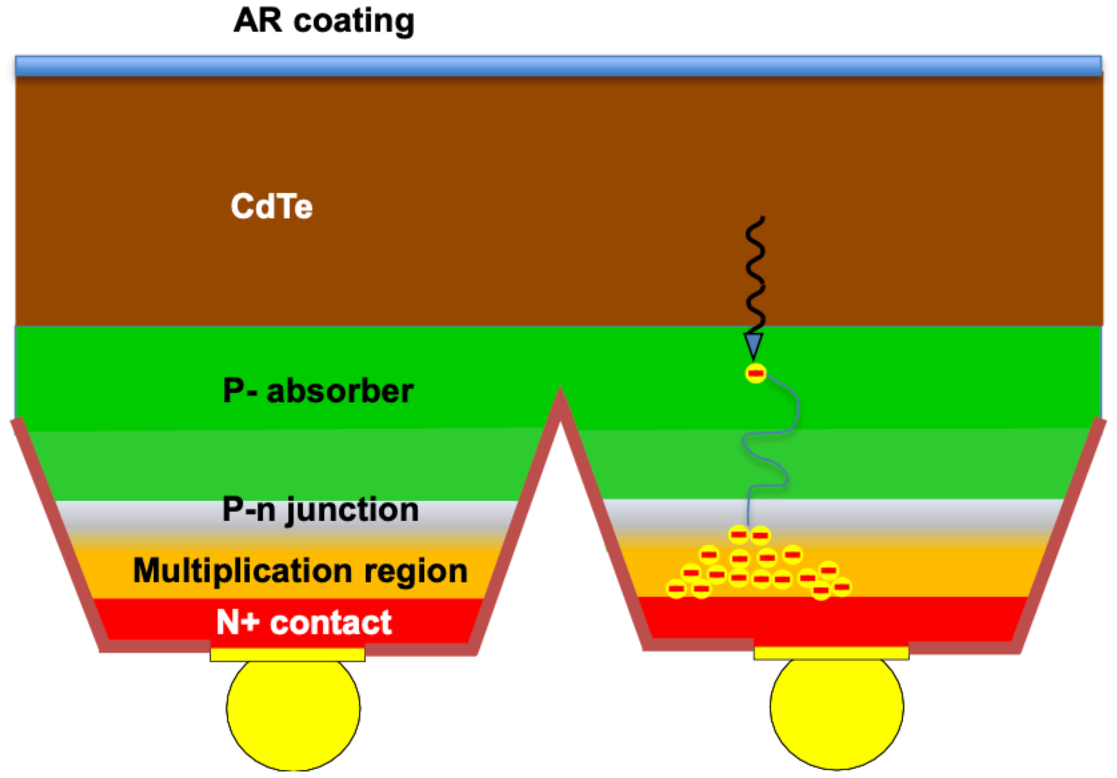
The detectors: technology

- Linear-mode Avalanche Photo Diode (LM-APD) detectors from Leonardo UK
- Existing technology, since 2001 (major advances in 2012)
- Basis of SAPHIRA, as used on VLT
- Photon counting, very low noise
- TDI achieved digitally, by Leonardo readout circuit (ROIC)
- Response 800..2500nm at >80% QE
- Specific detectors would be designed and made for GaiaNIR

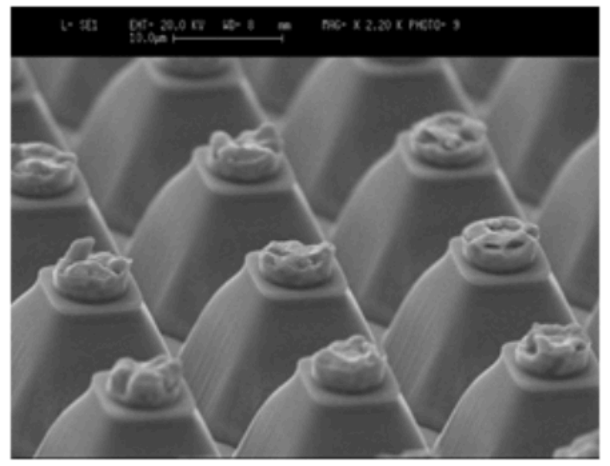
Avalanche gain in HgCdTe has low noise figure

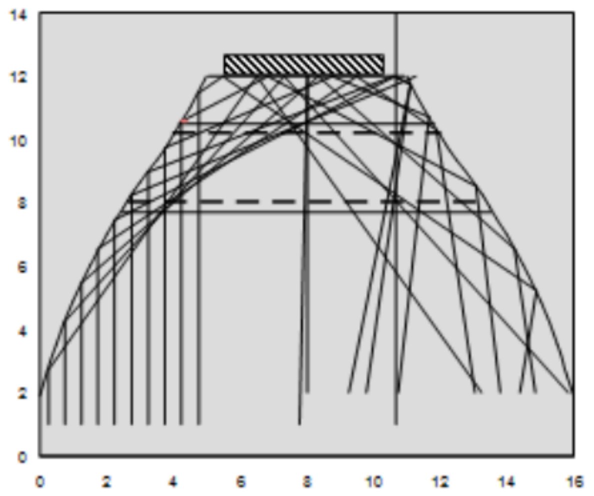


Bandgap engineering using MOVPE allows for widening of the bandgap in critical areas for good voltage tolerance for high gain at low photon flux



- **The absorption and fill factor is 100% in this structure**
- **The QE is typically 70-80% including top surface reflection of 8%.**





Low inter-pixel capacitance and near-ideal MTF and crosstalk

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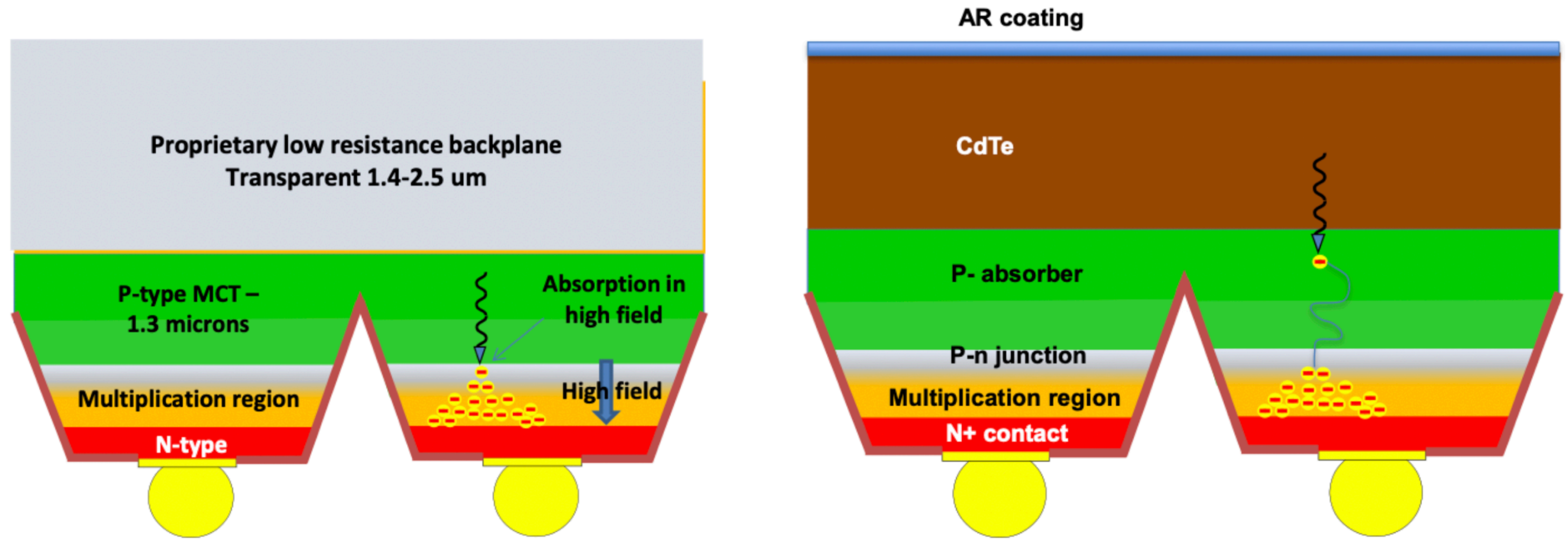
The detectors: wavelength response



1.45 - 2.5 um – internal QE – 100%

0.8 – 2.5 um – internal QE – 80-85%

- Two detector builds with different strengths
- Study was based on the 800-2500nm version
    - Better overlap with Gaia catalogue
    - Better spectrophotometry
- Surface coatings allow narrower bandpass than basic, common device

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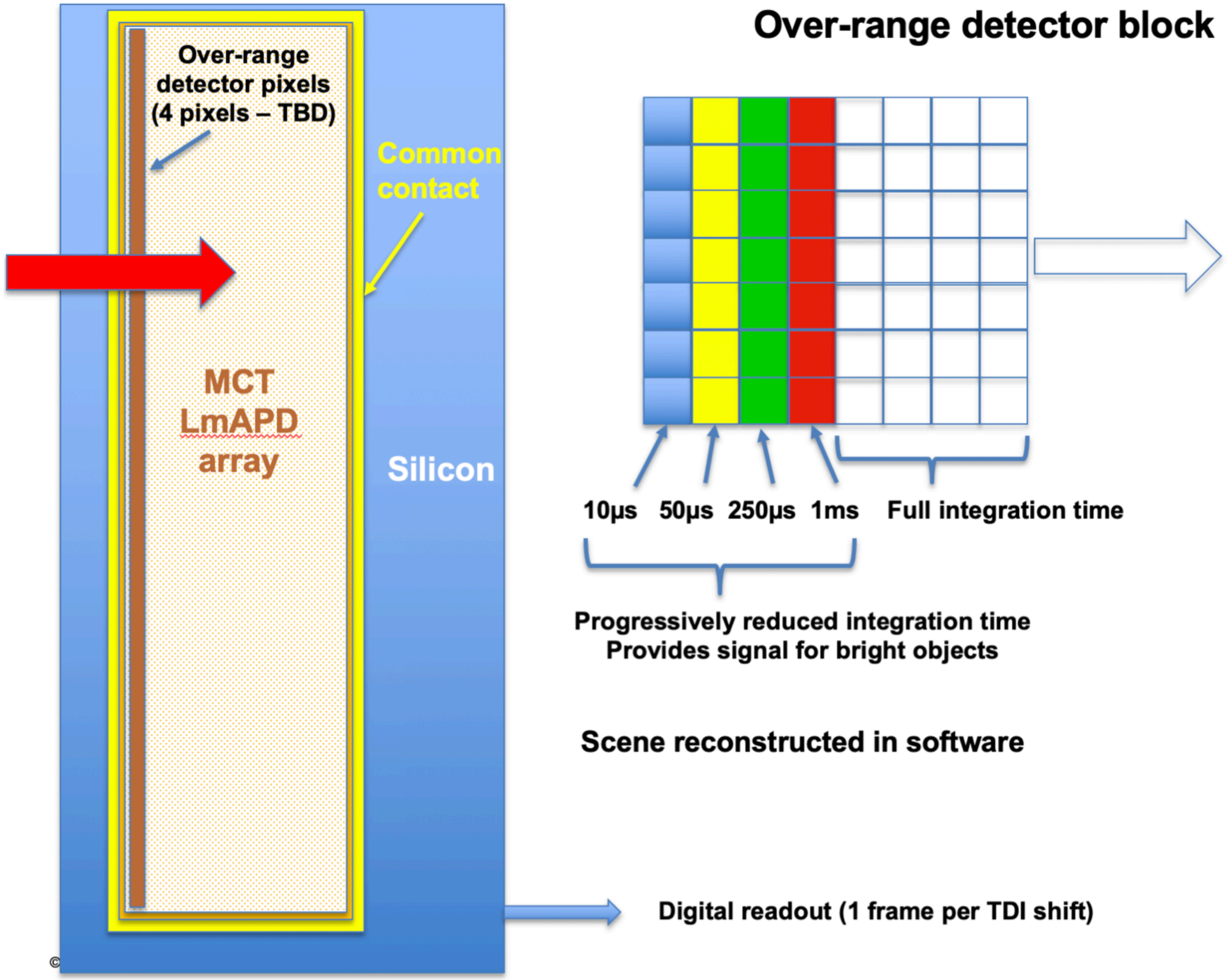
The detectors: dynamic range



- Native dynamic range of pixel is ~10^5
- Integration can vary between columns
- Proposed to have dedicated fast-r/o columns for bright objects while main array deals with faint population

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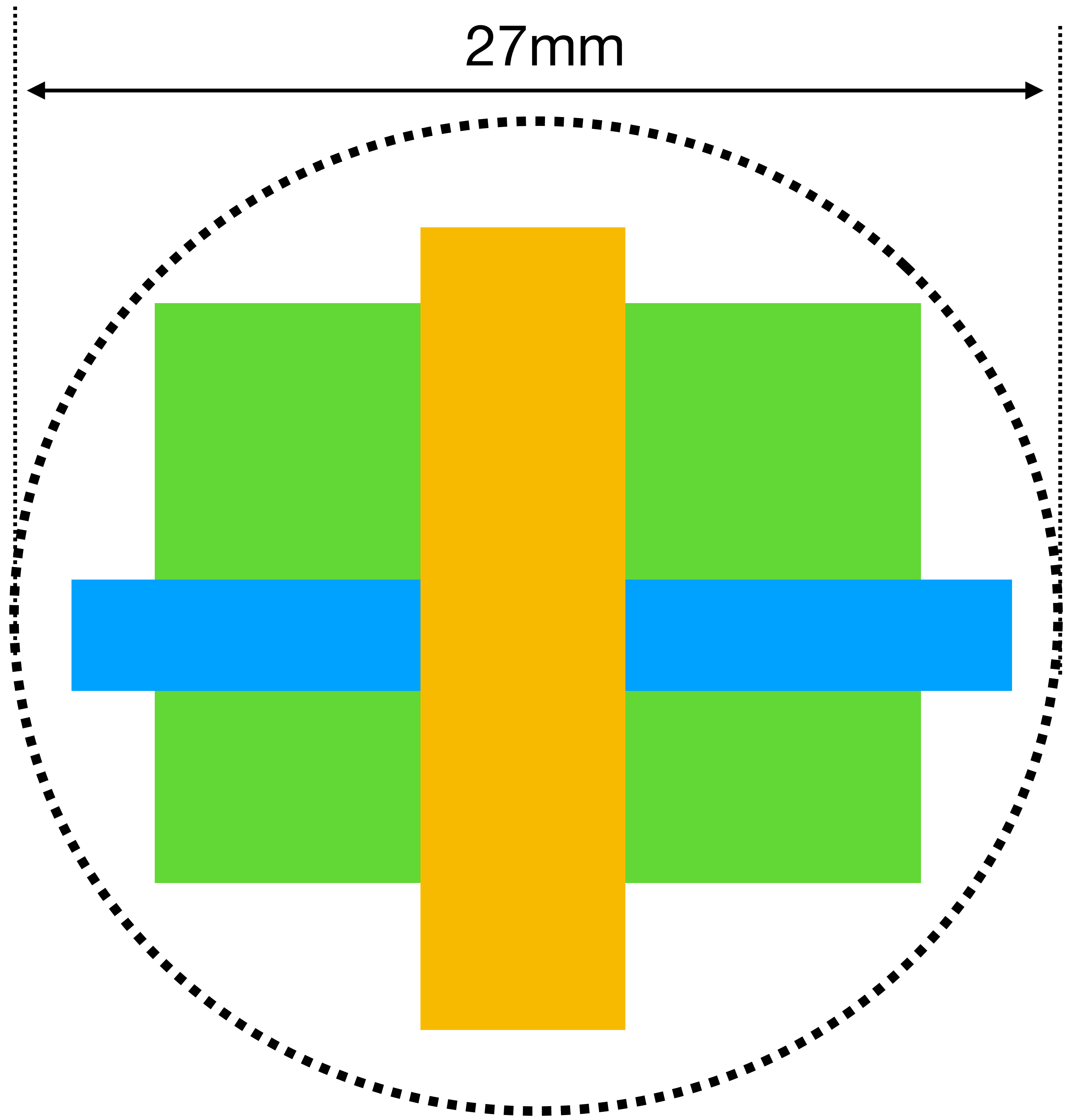
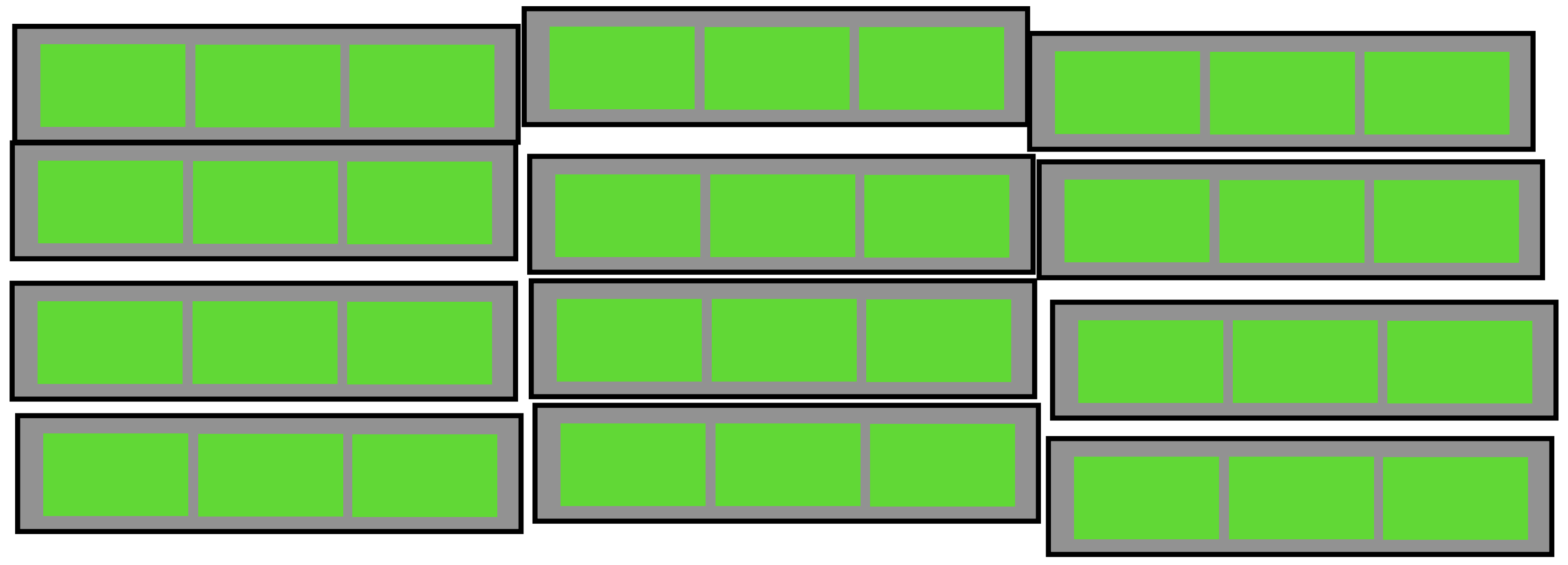
The detectors: size, shape and packaging



All aspect ratios possible within bounding circle



Detectors (green) are grouped into sub-modules (grey).
<0.1pixel alignment inside a sub-module.
Gaps ~mm between sub-modules.
Smaller gaps between detectors in a sub-module.

- Sub modules are effectively a wider detector in along-scan direction
- Can choose pixel size; minimum 15μm (c.f. Gaia 10μm); can be rectangular

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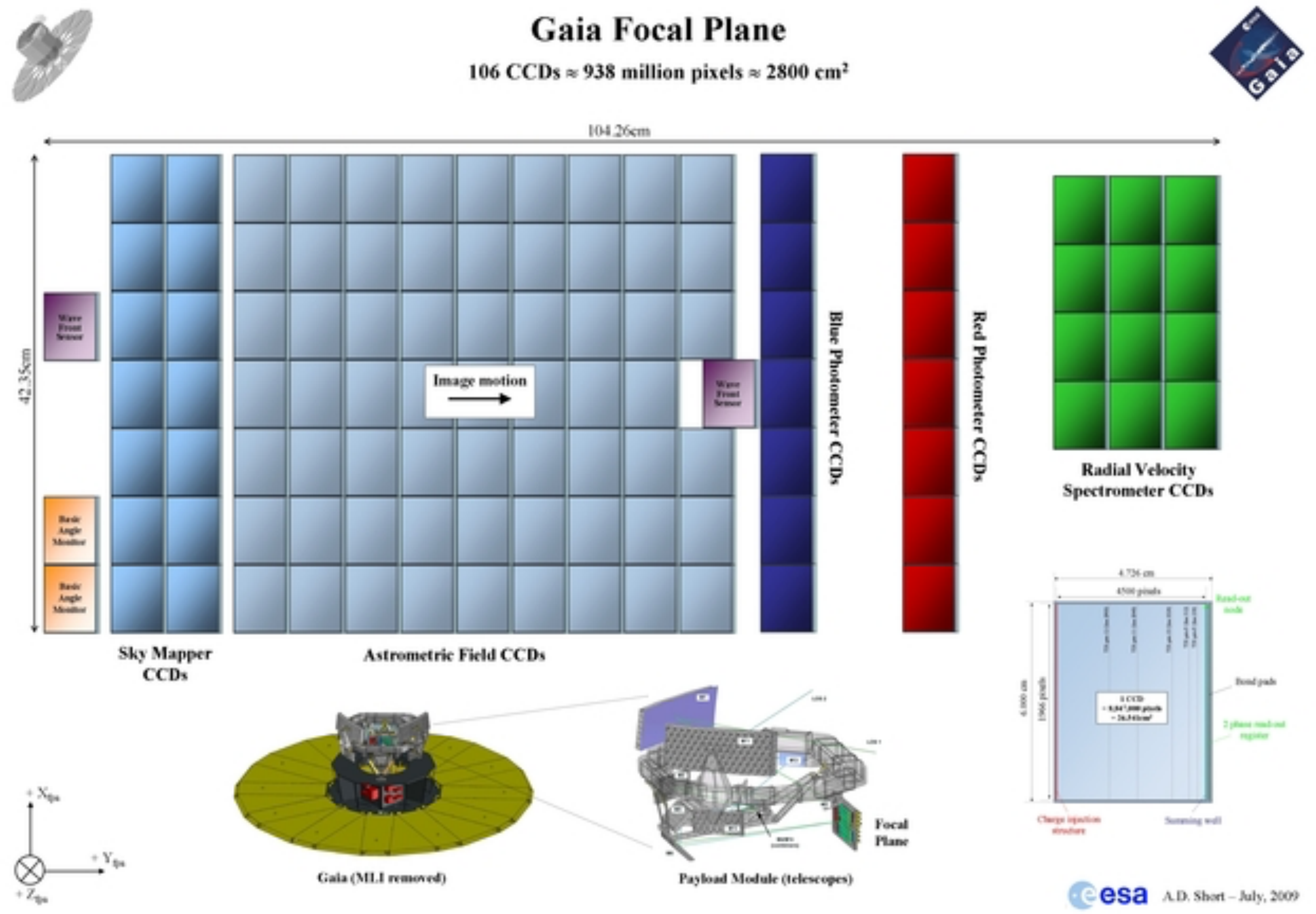
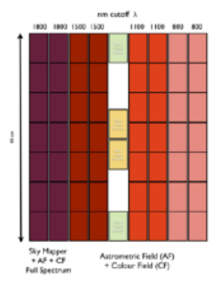
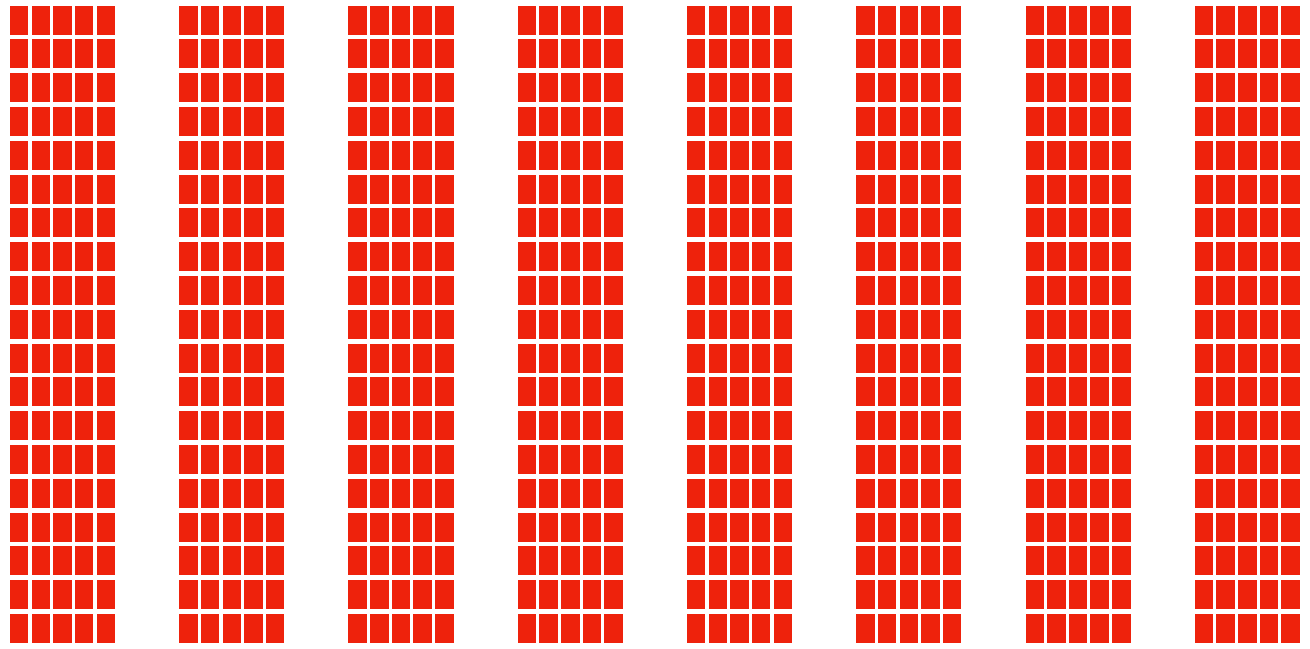
Tiling the focal plane



Gaia



GaiaNIR baseline (Hobbs+ 2021), rescaled (approx.) for max size of APD detectors



Legions of APD detectors to fill GaiaNIR's FP

Scenario	Detectors	Photon capture rel. Gaia	Error rel. Gaia
Baseline (Hobbs+ 2019)	8 x 7	0.082	3.5
Fill FP in AC only	8 x 21	0.24	2.0
Fill FP AC and half AL	20 x 21	0.61	1.3
Fill FP AC and AL	40 x 21	1.2	0.9

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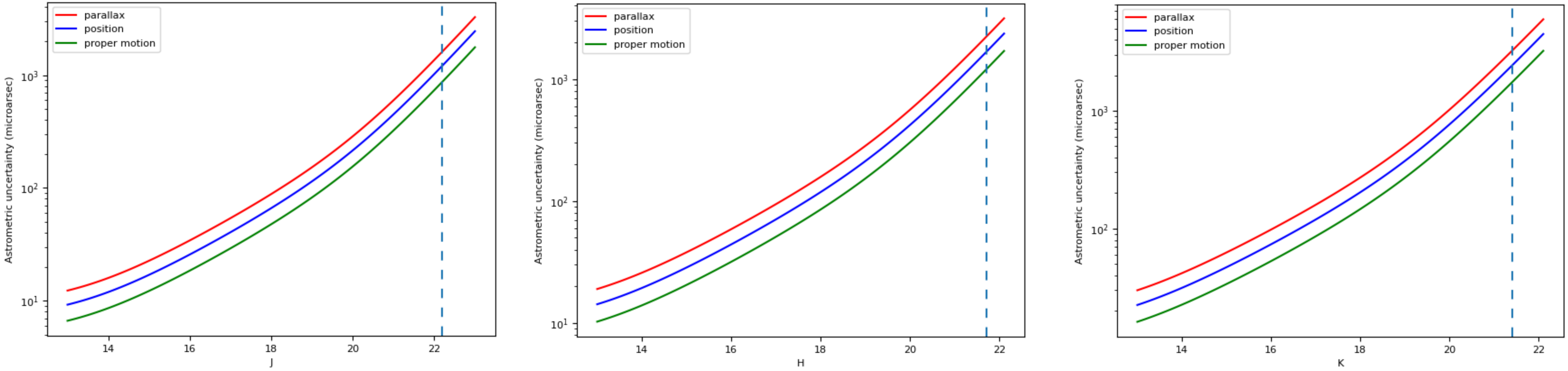
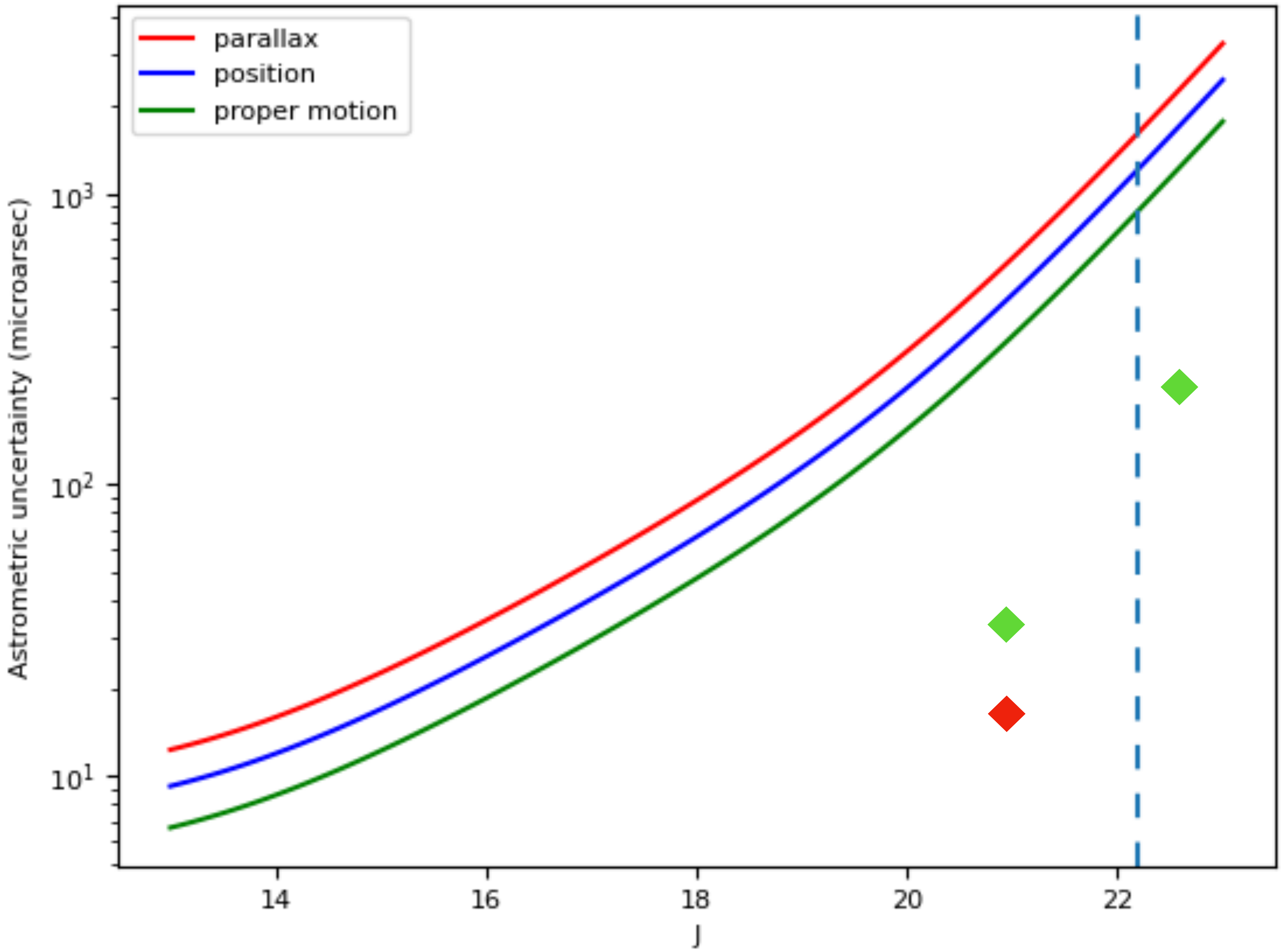
Predicted performance



Dashed lines are survey limits due to photon starvation

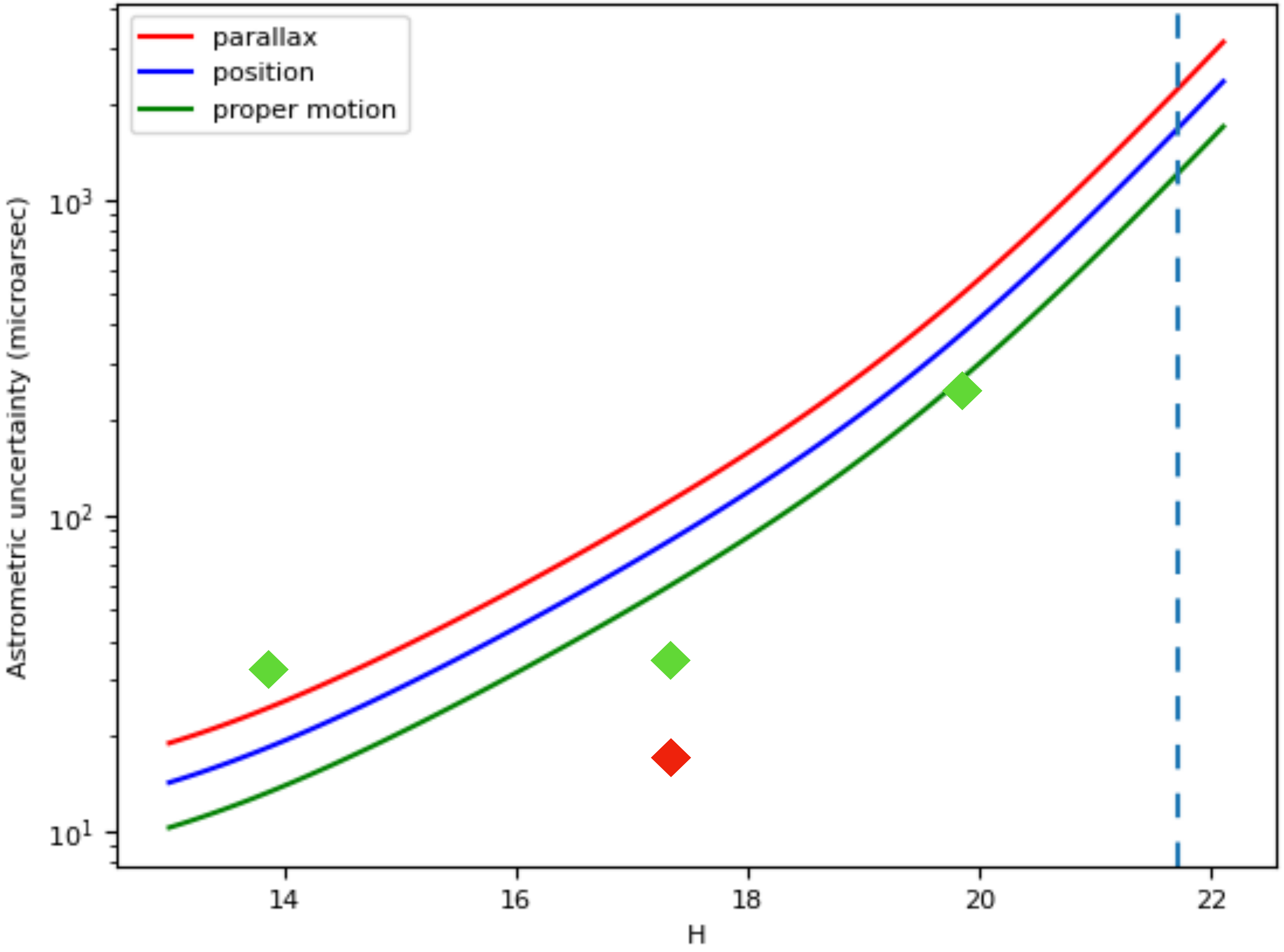
- Performance approaches requirements for science cases in H & K; poor in J.
- Numbers scaled from Gaia predictions for nominal mission, made at EDR3, accounting for wavelength difference and predicted photon capture; assumes focal plane filled with astrometric-mode detectors (no RVS) and sub-modules as wide as Gaia CCDs. Model neglects crowding and lower noise of LM-APDs.
- Changing fraction of focal plane covered changes end-of-mission accuracy but not survey limit
- Changing width of sub-module changes the survey limit but not end-of-mission accuracy

Predicted results in J



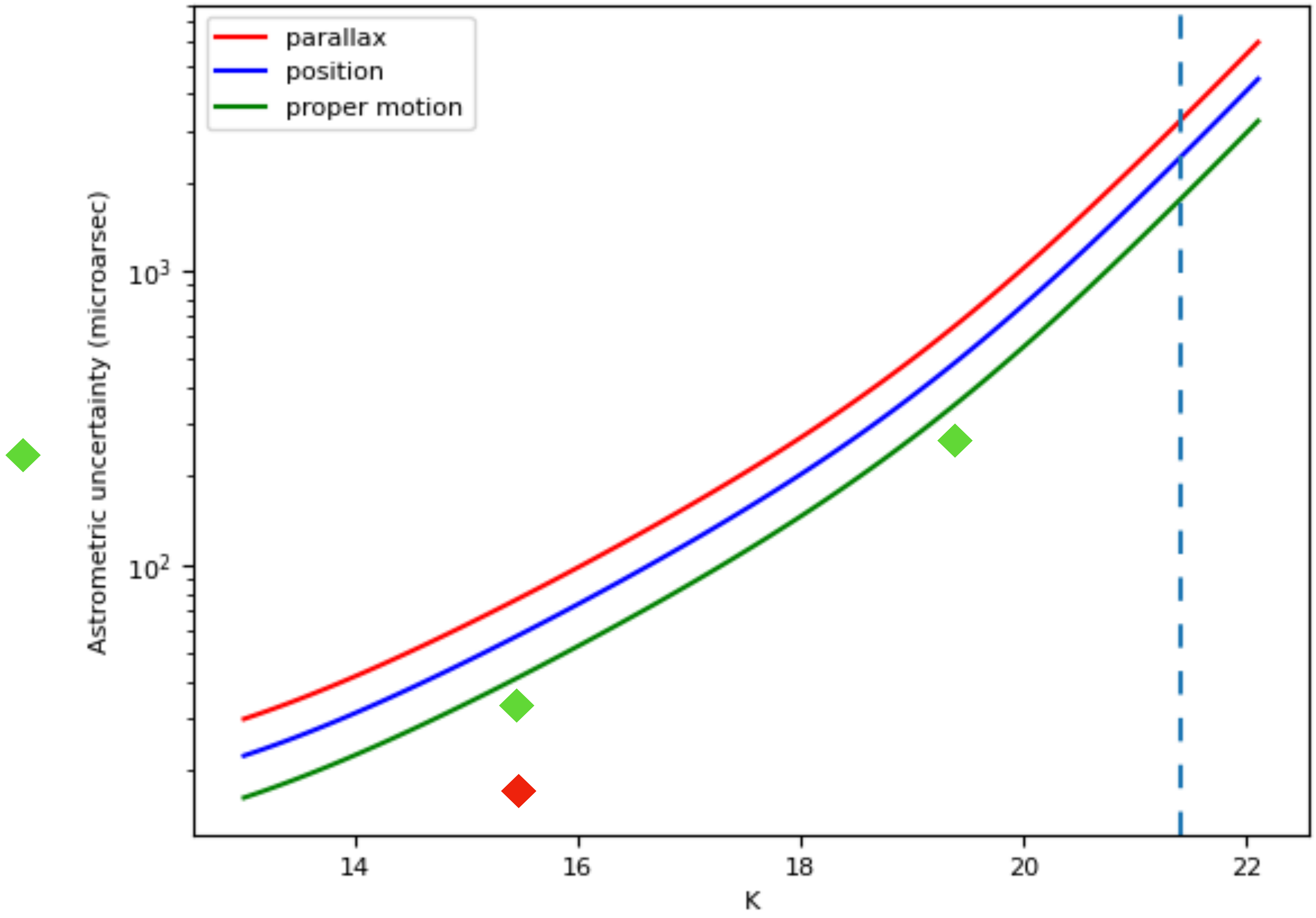
Diamonds indicate performance requested for science cases

Predicted results in H



Diamonds indicate performance requested for science cases

Predicted results in K



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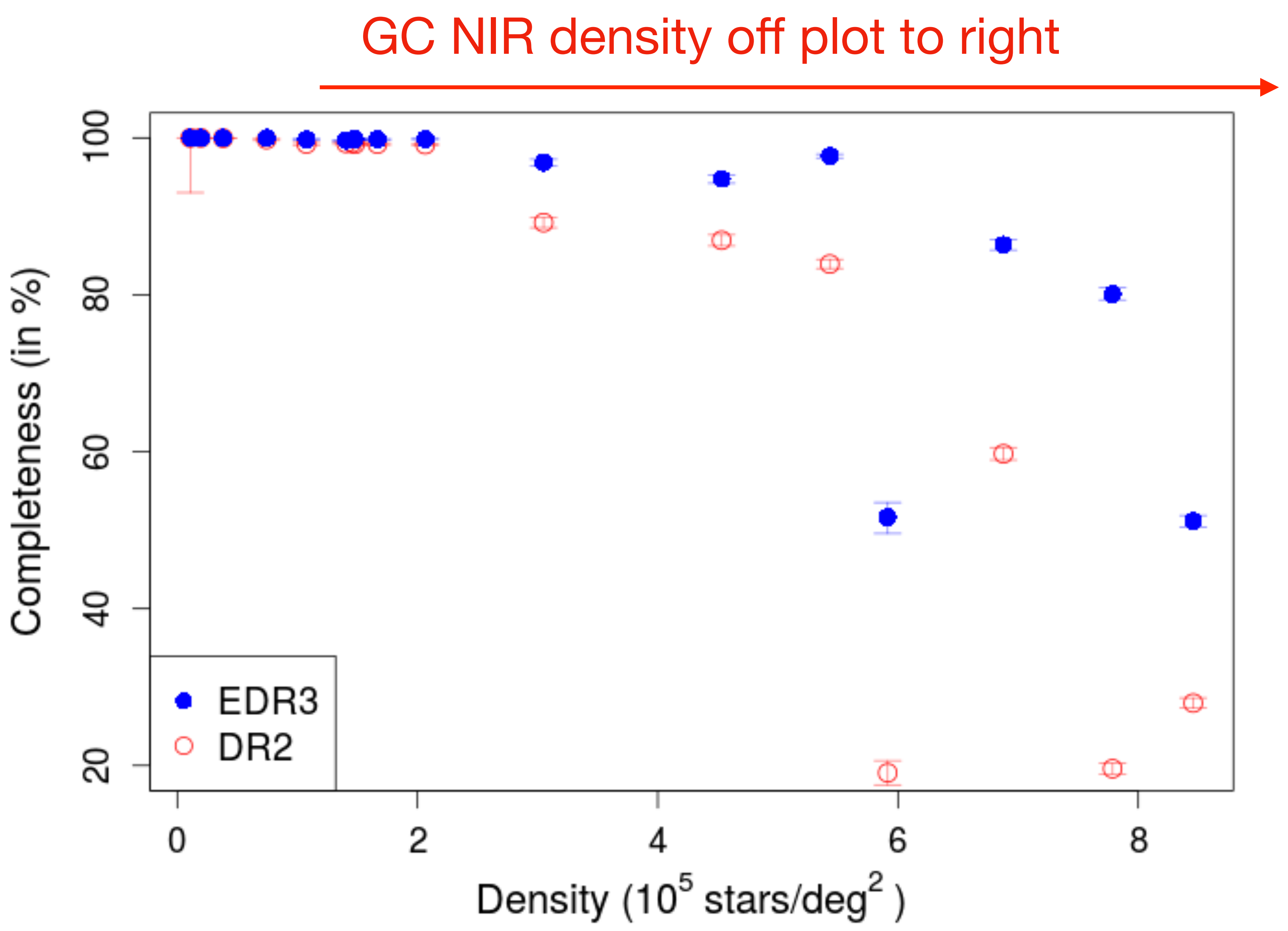
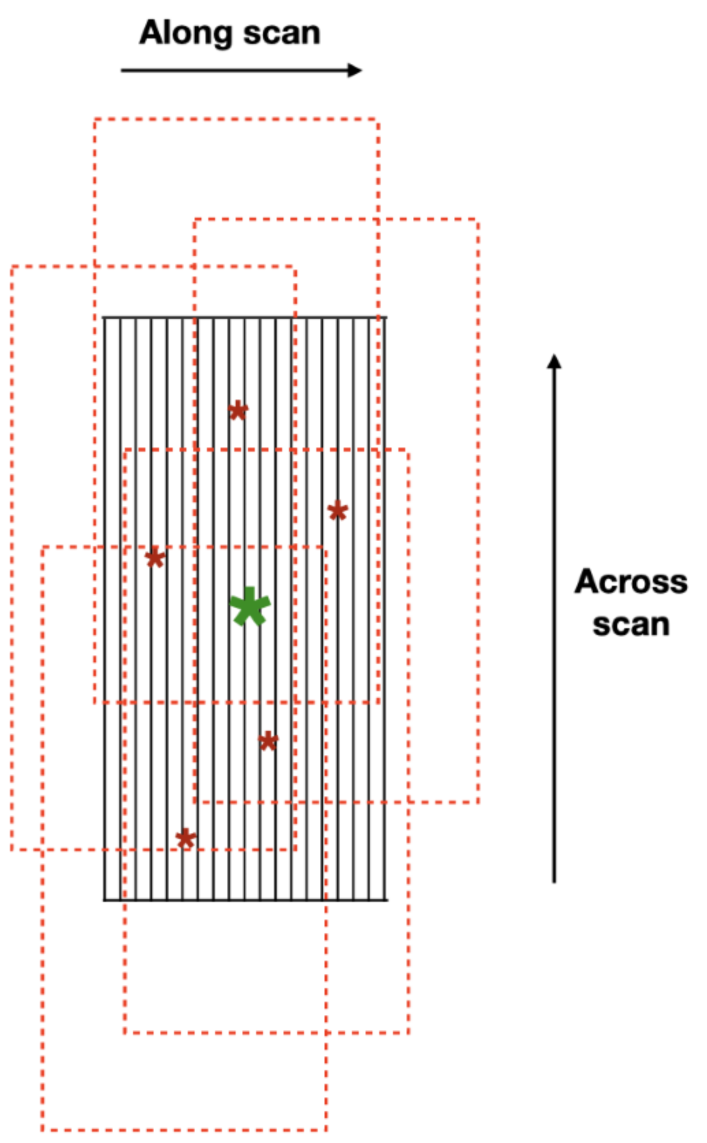
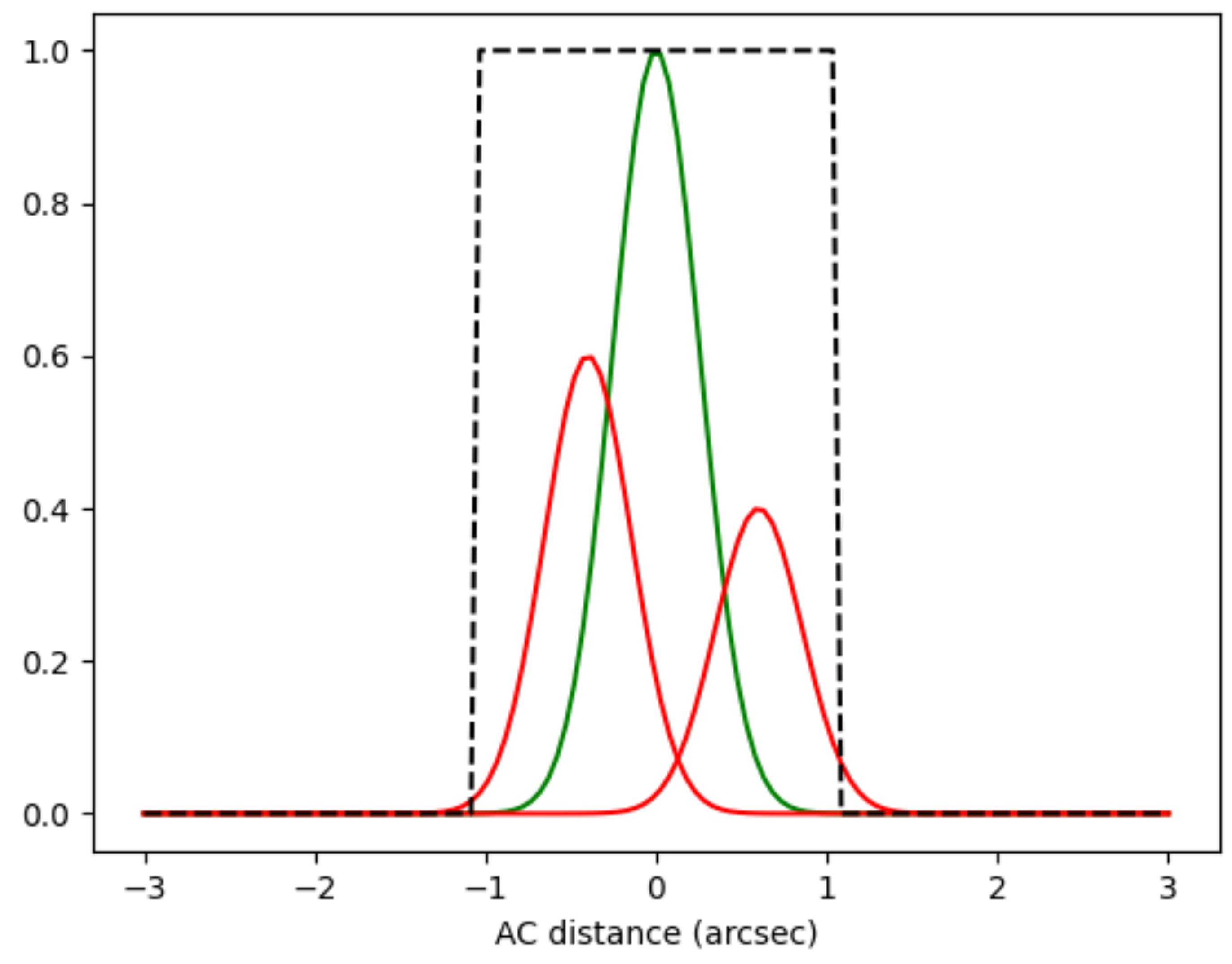
Crowding and incompleteness



Gaia incompleteness with density (from Fabricus+ 2020)



This is due to overlapping readout windows



Mitigated in GaiaNIR by profile fitting across scan instead of binning

- Must mitigate incompleteness due to crowding in order to meet science goals.
- => Profile-fitting across scan to resolve blended images
- Constrains the across-scan size of the detector pixels

Choices still to be optimised

- Size, shape and packing of detectors
- Pixel size, particularly in across-scan direction
- Wavelength range: how many of each band; do we want white-light detectors as well?
- Number of filter bands & can we live without dispersed spectra?
- How much of the focal plane can we use for the astrometric array?

2nd (larger) study pending

- Make prototype detectors to GaiaNIR parameters and evaluate in lab
  - Confirm detection of single photons at maximum gain
  - Measure dark current, noise properties, crosstalk etc.
- Investigate buttable detectors & sub-modules and best focal-plane layout
- Better model linking detector options to final performance of GaiaNIR → best detector options chosen
- Starting 4Q2023