Gaia-inspired suggestions to TOLIMAN

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Potential contributions to TOLIMAN

Instrument and operation design - forward analysis

Lessons learned from Gaia – Astrometric Verification Unit [INAF-OATo]

and from LISA metrology telescope [INRIM]

Calibration, data reduction and analysis packages

Metrology analysis and possible solutions

Independent implementation option:

Three-way Resolved Imaging [for] Nearby Earth Twins Investigation [TRINETI]

Basic considerations…

Expected astrometric signal from planet: **~0.1 μas on star**

Time scale: few days to ~1 year (Earth twins)

Alpha Cen very bright, A: V = 0 mag – B: V = 1.34 mag

Flux in Gaia broad band, on a 30 cm full aperture

A: ~1e9 photons/s – B: ~3e8 photons/s

Reference CCD pixel, 10×10 μm ⇒ full well capacity ~1e5 electrons

Need to bridge a dynamics gap by a factor 1e4!

Signal to be "spread out" preserving astrometric performance ⇒ Toliman

Project-wide option: fast imaging (sCMOS) ⇔ relaxed attitude requirements

Flexible read-out mode on Gaia CCDs: windowing on AF, BAM

Option: usage of full spectral band

Rationale:

Preliminary mitigation of input photon flux, retaining all photons (efficiency)

Larger spectral bandwidth ⇒ smaller telescope OR fainter limiting magnitude

TOLIMAN proposal: ~10% bandwidth; Gaia-like broad band: ~300 nm

~5× photon flux, compatible with

~2× smaller telescope diameter ⇒

~8× lower telescope volume

⇒ impact on cost and/or stability

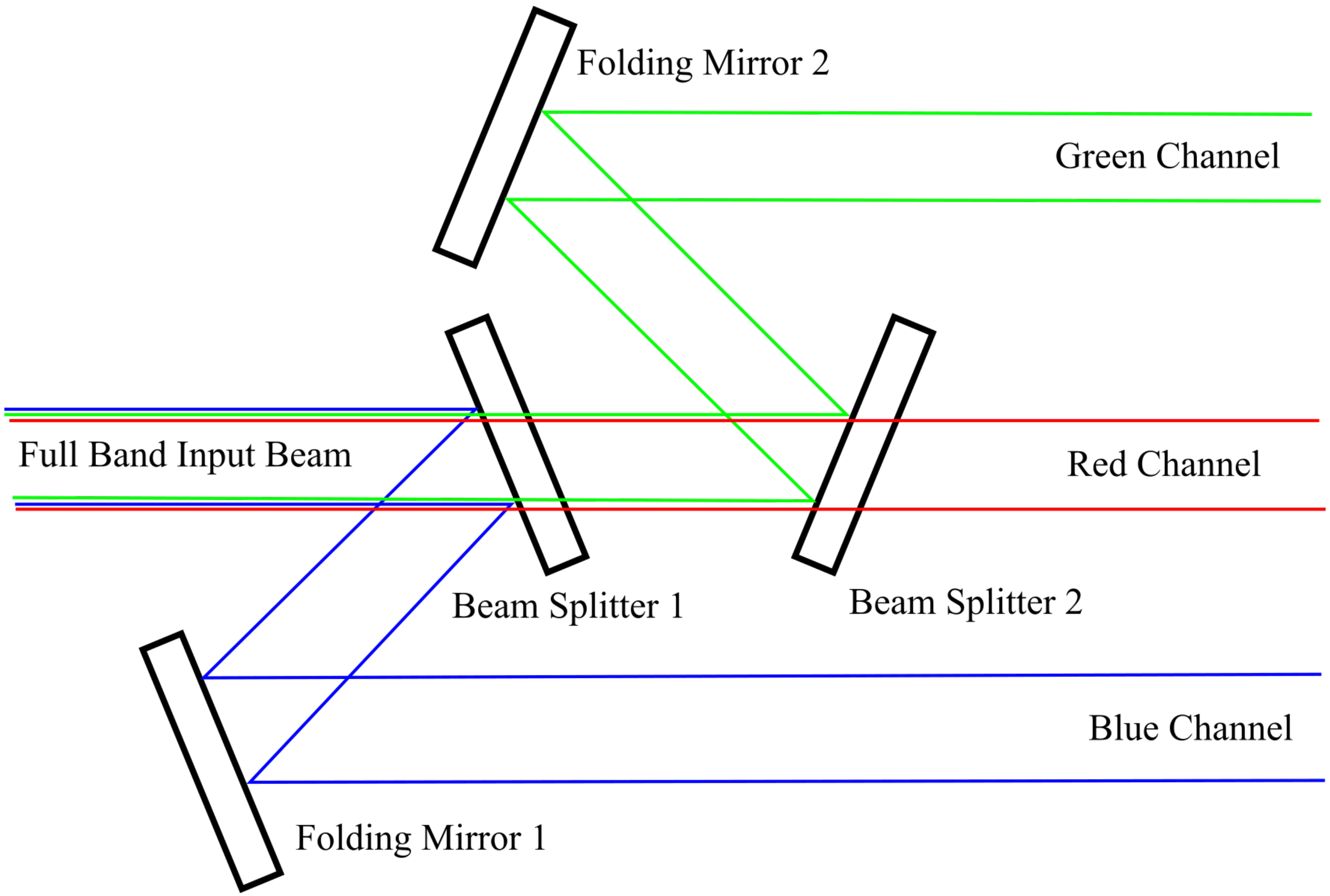
OR ~2 mag fainter limiting magnitude

⇒ impact on accessible sources and/or precision

Option: spectral band splitting

Implications:

Limited band channels have less stringent technical constraints (simplification)



Separate channels may be “packages” allocated to consortium teams

Cross-calibration may help identification of systematic errors

Beam splitter / folding mirror pairs: compatible coating specifications

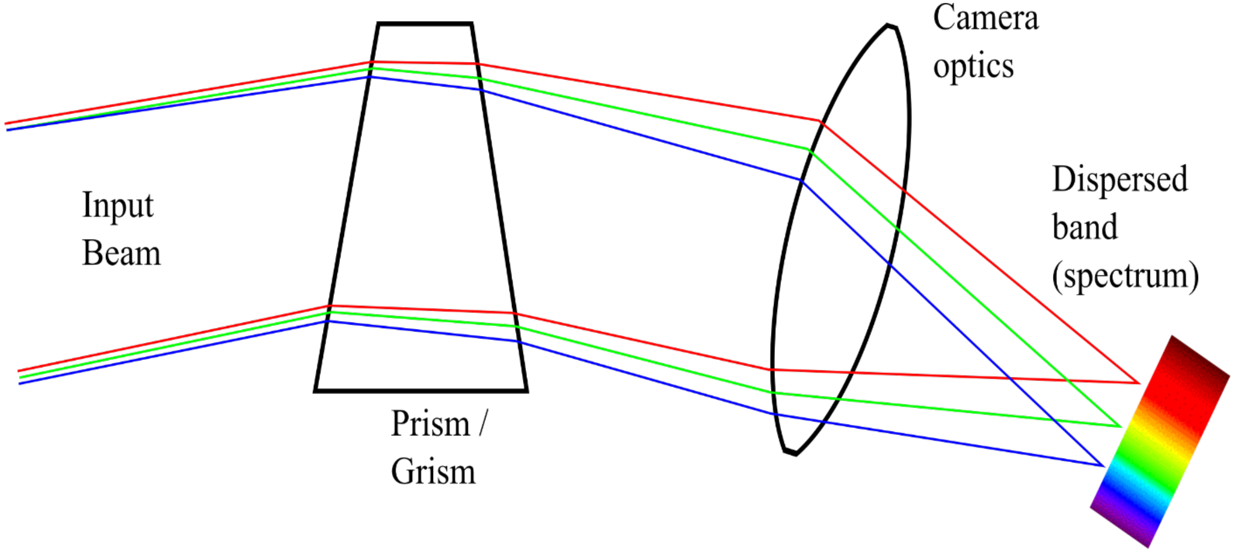
Dispersion as efficient trade-off between astrometry and spectro-photometry

Slitless spectroscopy:

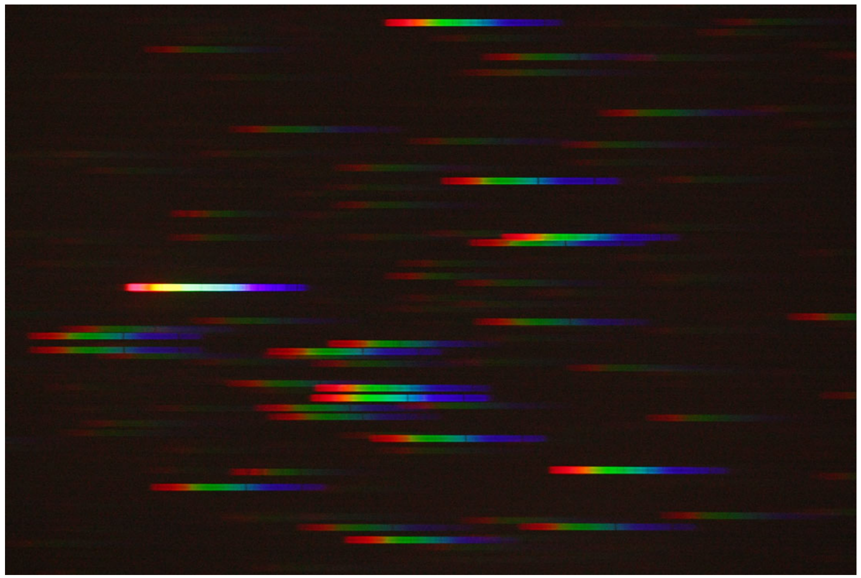
- **Retains 1D spatial resolution across dispersion**
- **Operates on all field objects (2!)**

Field required: <1 arcmin

Sources: pair of isolated stars (few arcsec separation)



Hyades, Objective Prism



Previous proposition of combined astrometry and spectro-photometry

Issue: spatial resolution / sampling dependent on wavelength

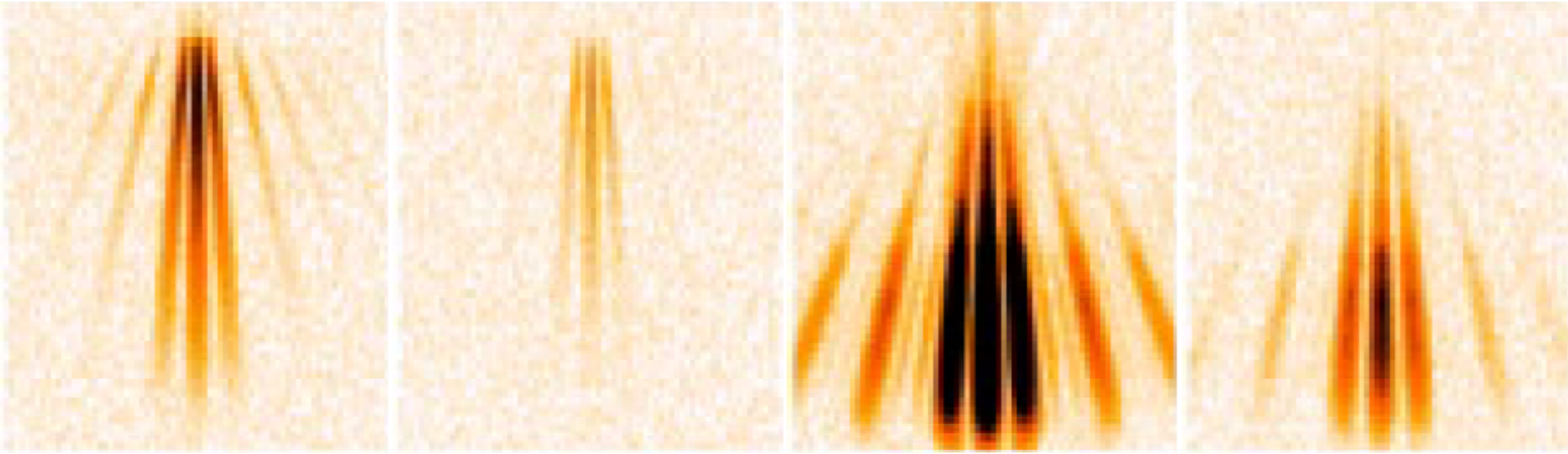
Option investigated in detail for the proposed space mission DIVA:

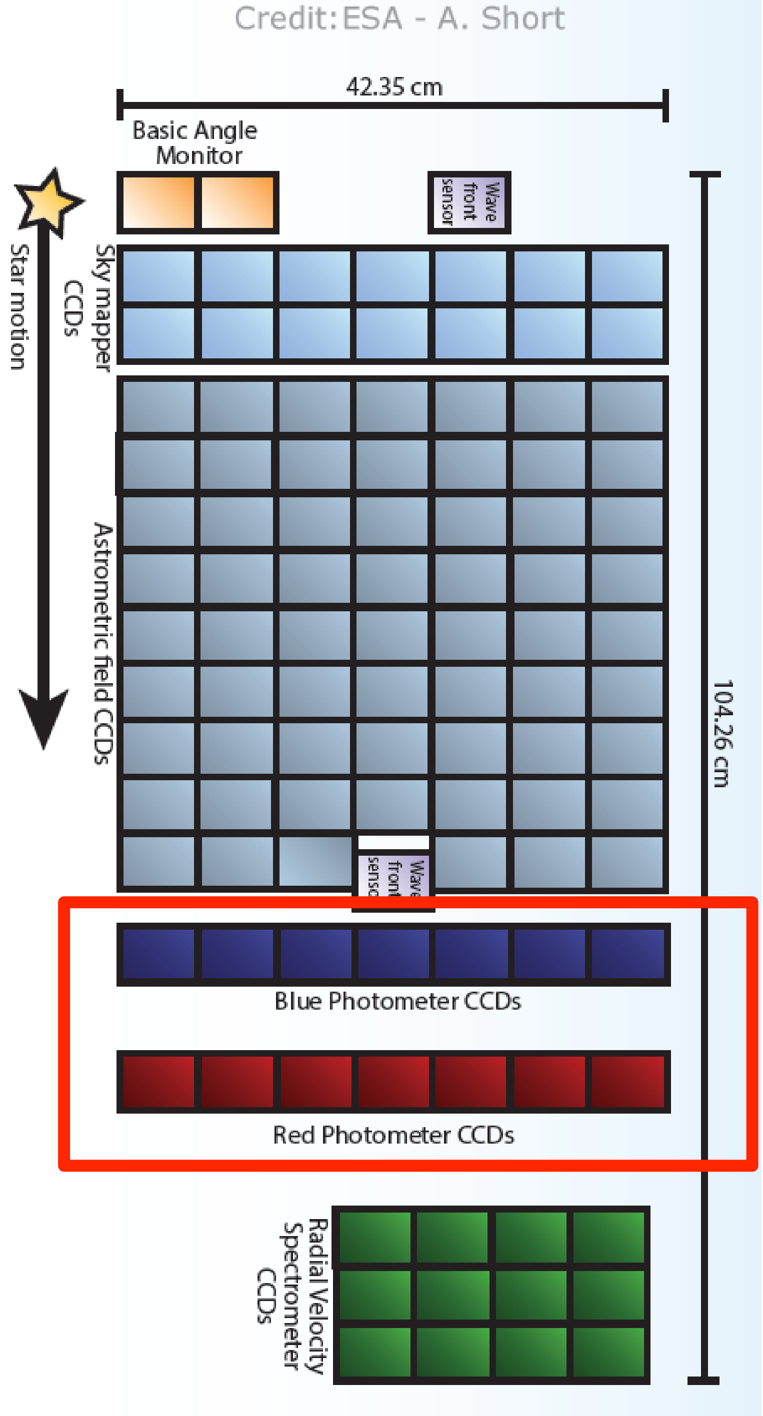
small Fizeau stellar interferometer with dispersed wide band fringes

[Röser et al. (1997), Bastian & Scholz (1997), Bastian & Scholz (1997), Willemsen et al. (2003)]

Feature: large sampling variation over spectral range

B1-V star, V = 7.5 | B1-V star, V = 10.0 | M5-V star, V = 7.5 | M5-V star, V = 10.0





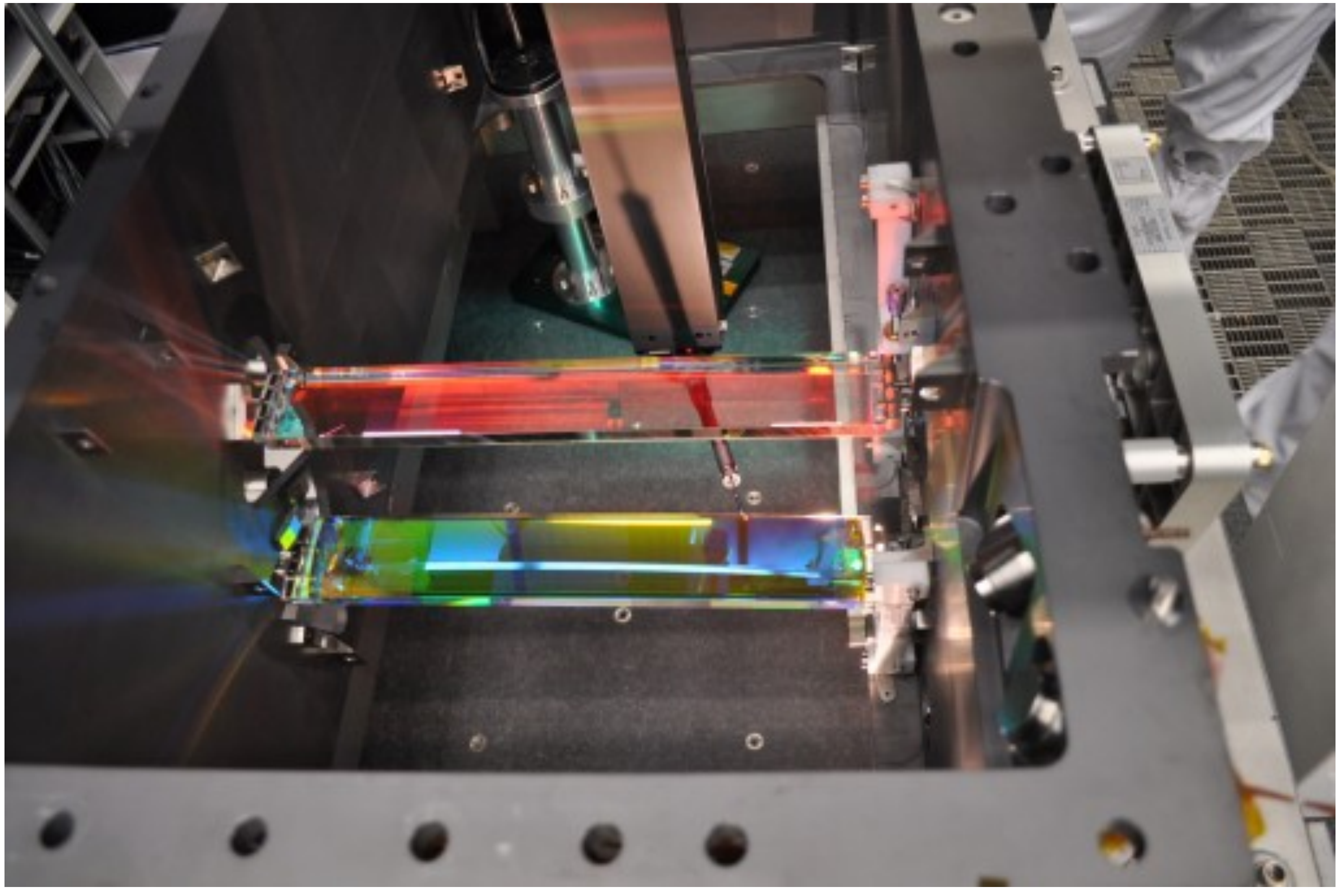
In-flight dispersed images: Gaia Red/Blue Photometer (I)

Simple implementation by two prisms in front of detectors

7 (BP) +7 (RP) dedicated CCDs

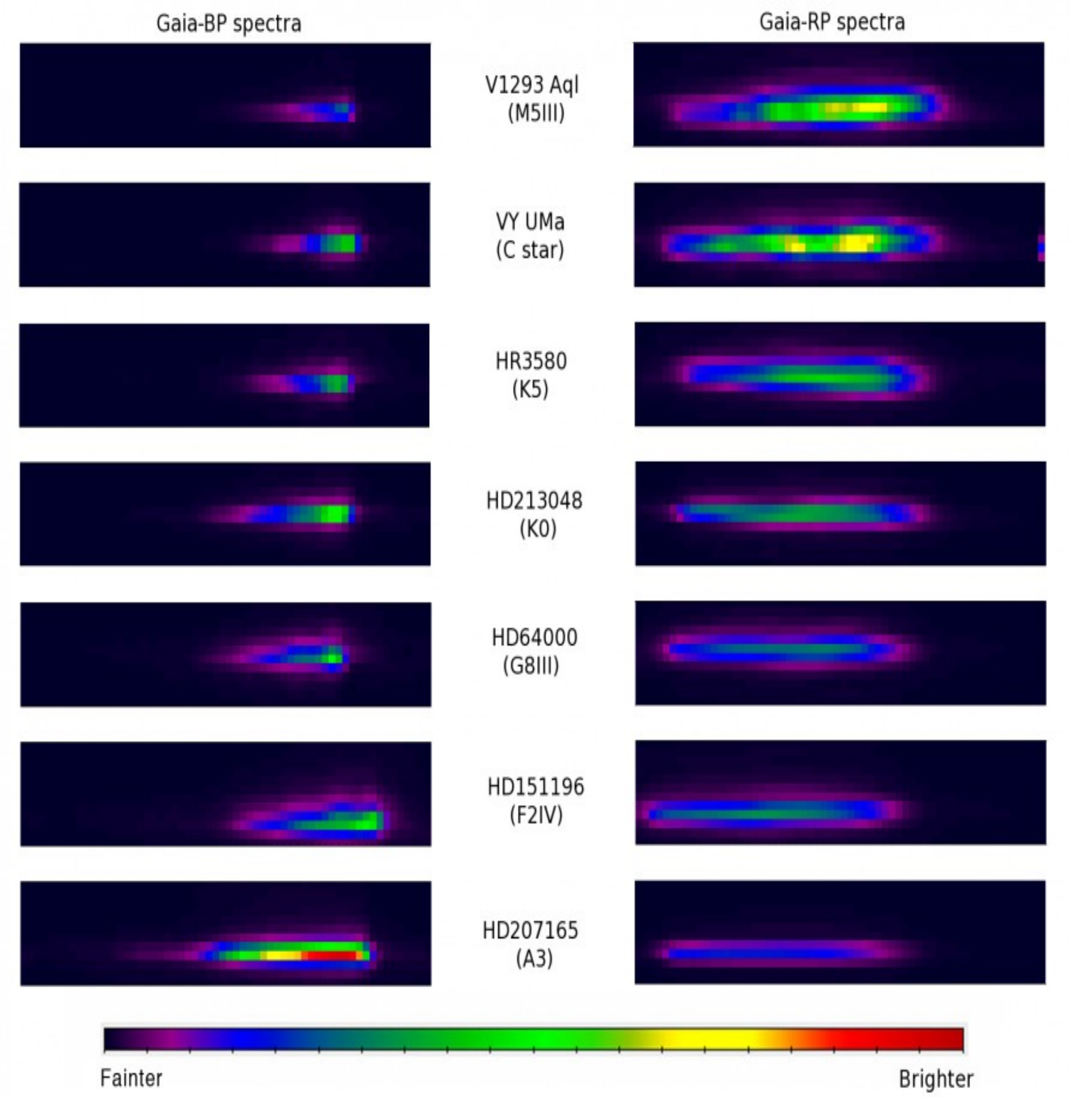
DR2: 1.3+ billion objects, keeps counting

[Evans et al., 2018]



In-flight dispersed images: Gaia Red/Blue Photometer (II)

Gaia BP/RP data for seven bright stars.
Credits: ESA/Gaia/DPAC/Airbus DS

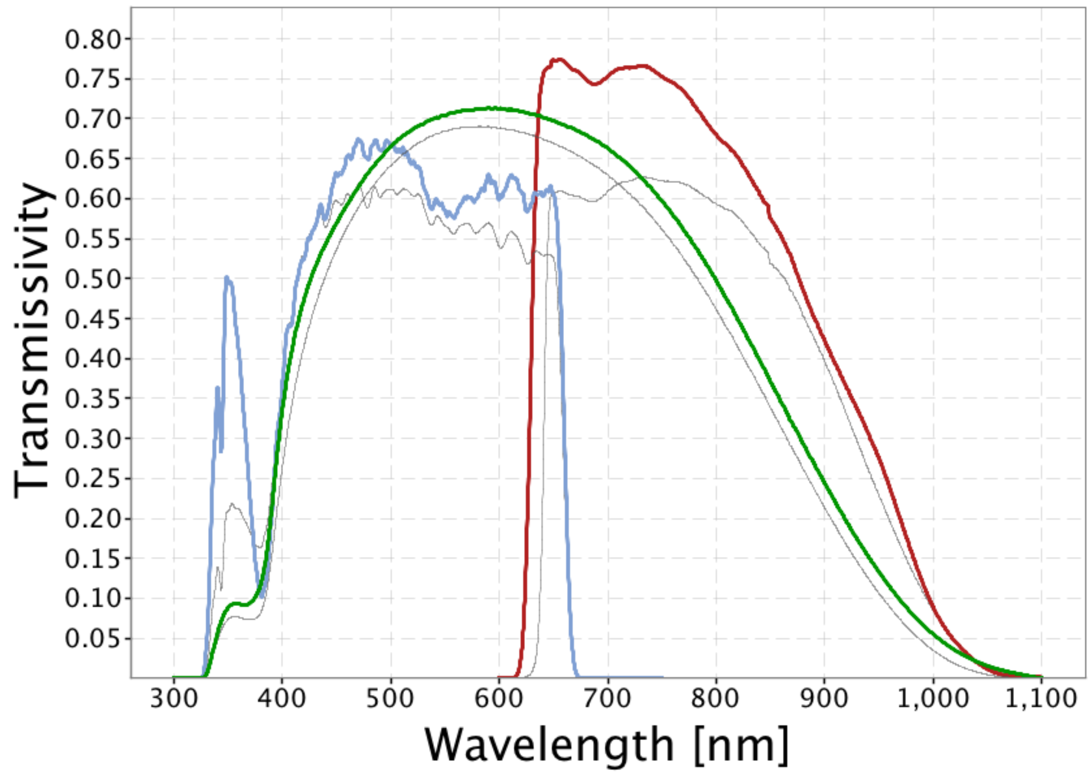


Used for photometry only

Cross-calibration vs. astrometry

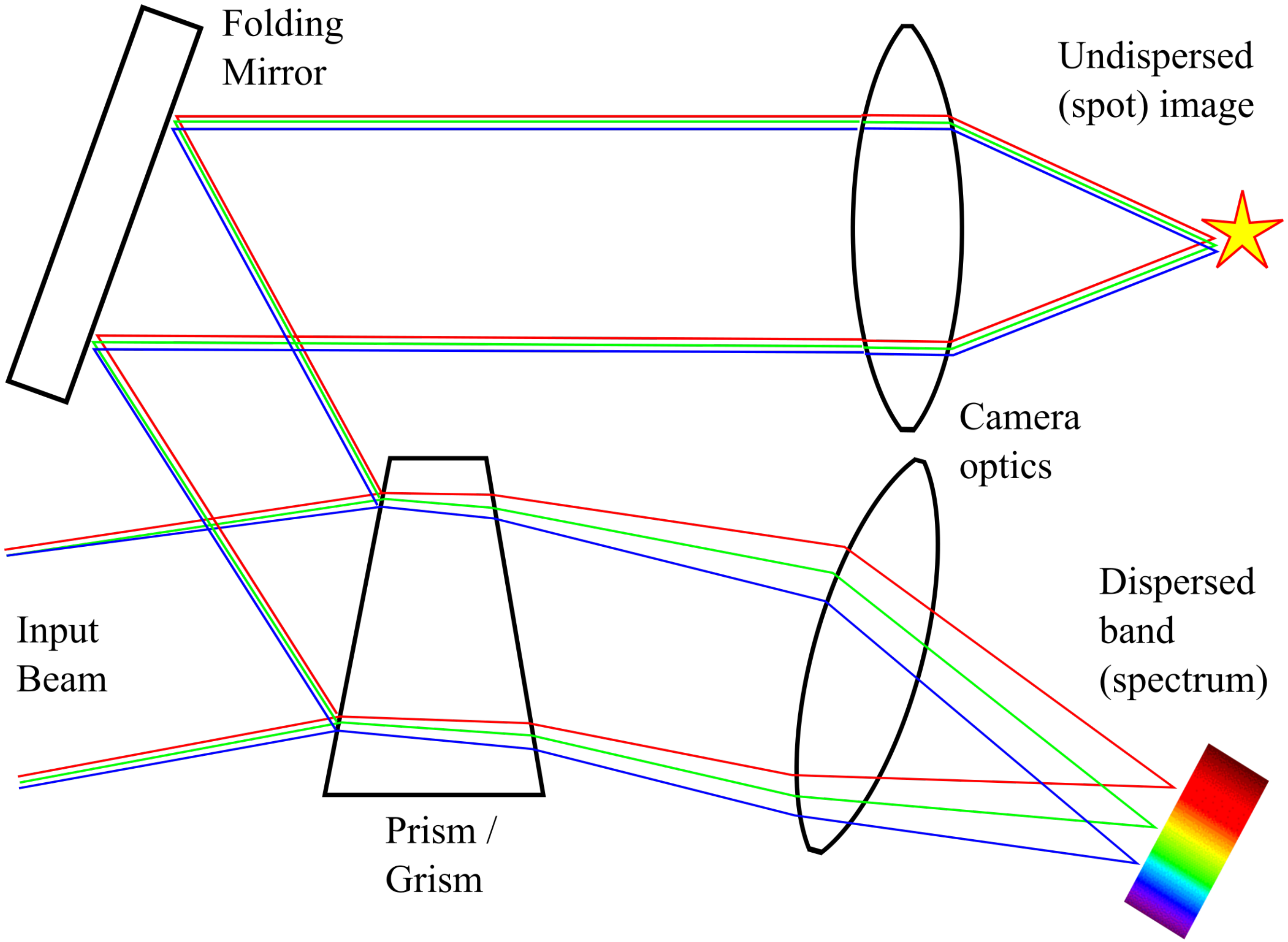
[Data Release 1: A&A 595, A1 (2016);

Data Release 2: A&A 616, A1 (2018)]



Option: using both dispersed and undispersed images

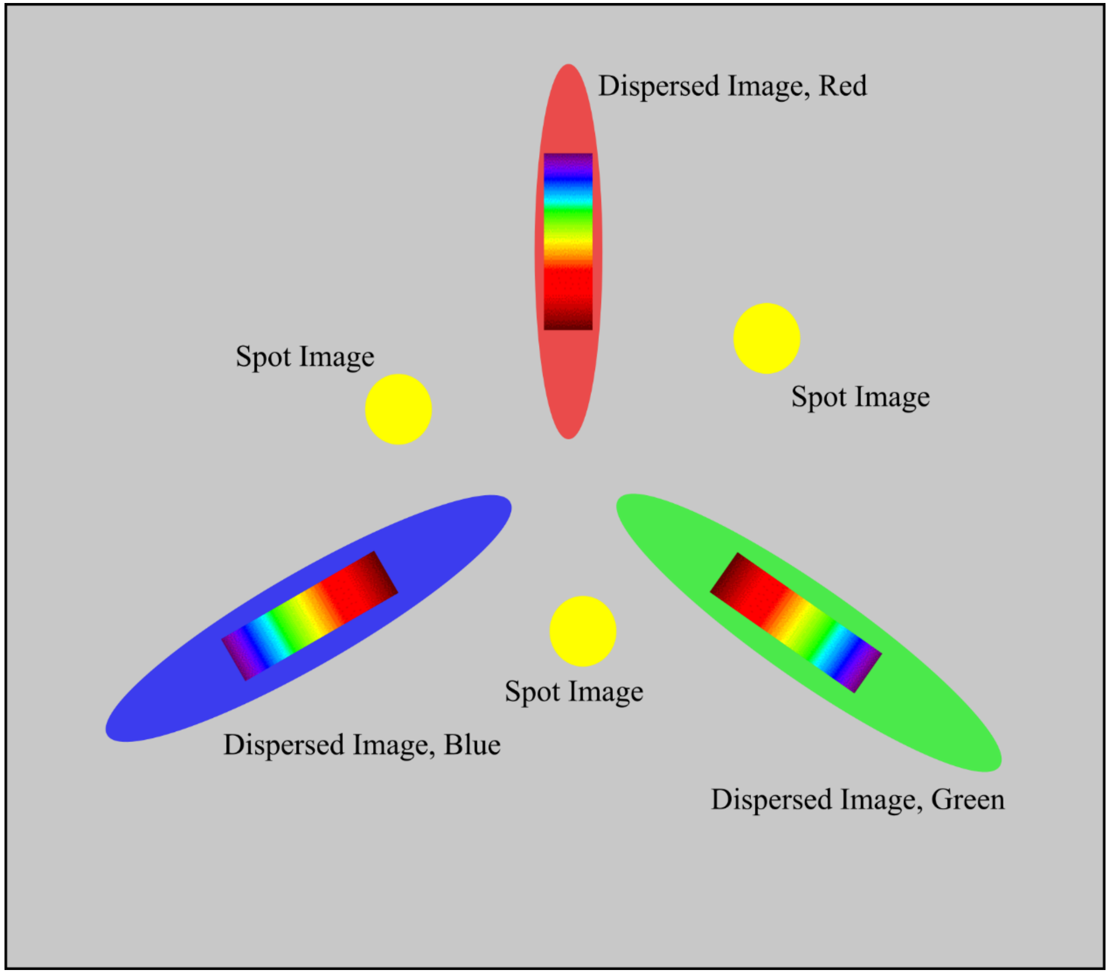
Reflection "loss" of (transmissive) disperser (or folding mirrors) can be used to get a zero-order spot image



Strengthen correlation among channels

Solve ambiguity between astrometry and photometry

A possible on-chip allocation of dispersed and focused images…



Efficient spread of source photons over detector

Dispersion in different directions on sky preserves bidimensional astrometric measurement

Trade-off between **common** or **separate** detectors

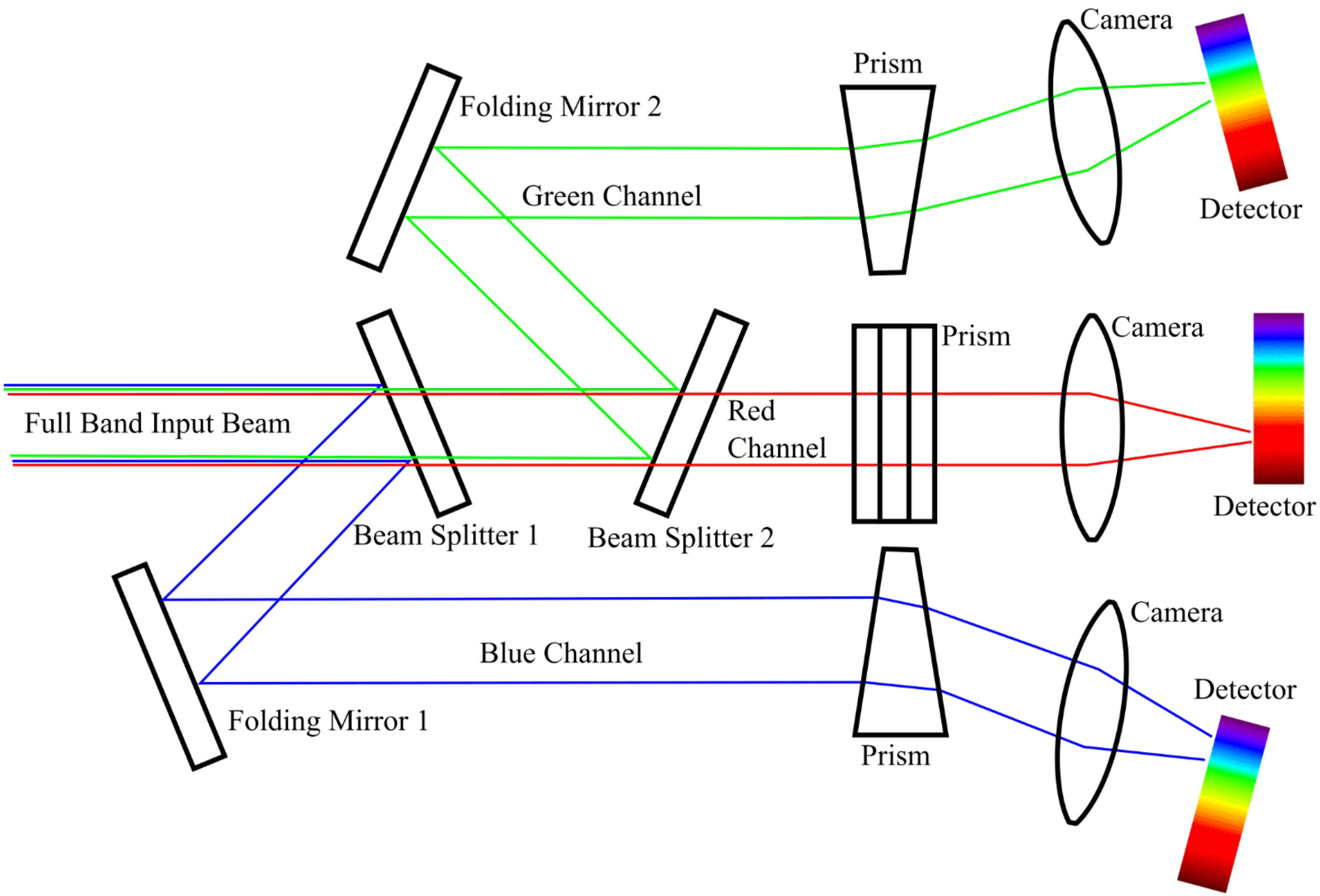
Three channels ⇒ minimum redundancy

Bidimensional astrometric measurement preserved independent of source orientation vs. dispersers

Potential use of all source photons instead of limited (~10%) bandwidth

Conceptual scheme of dispersed image system

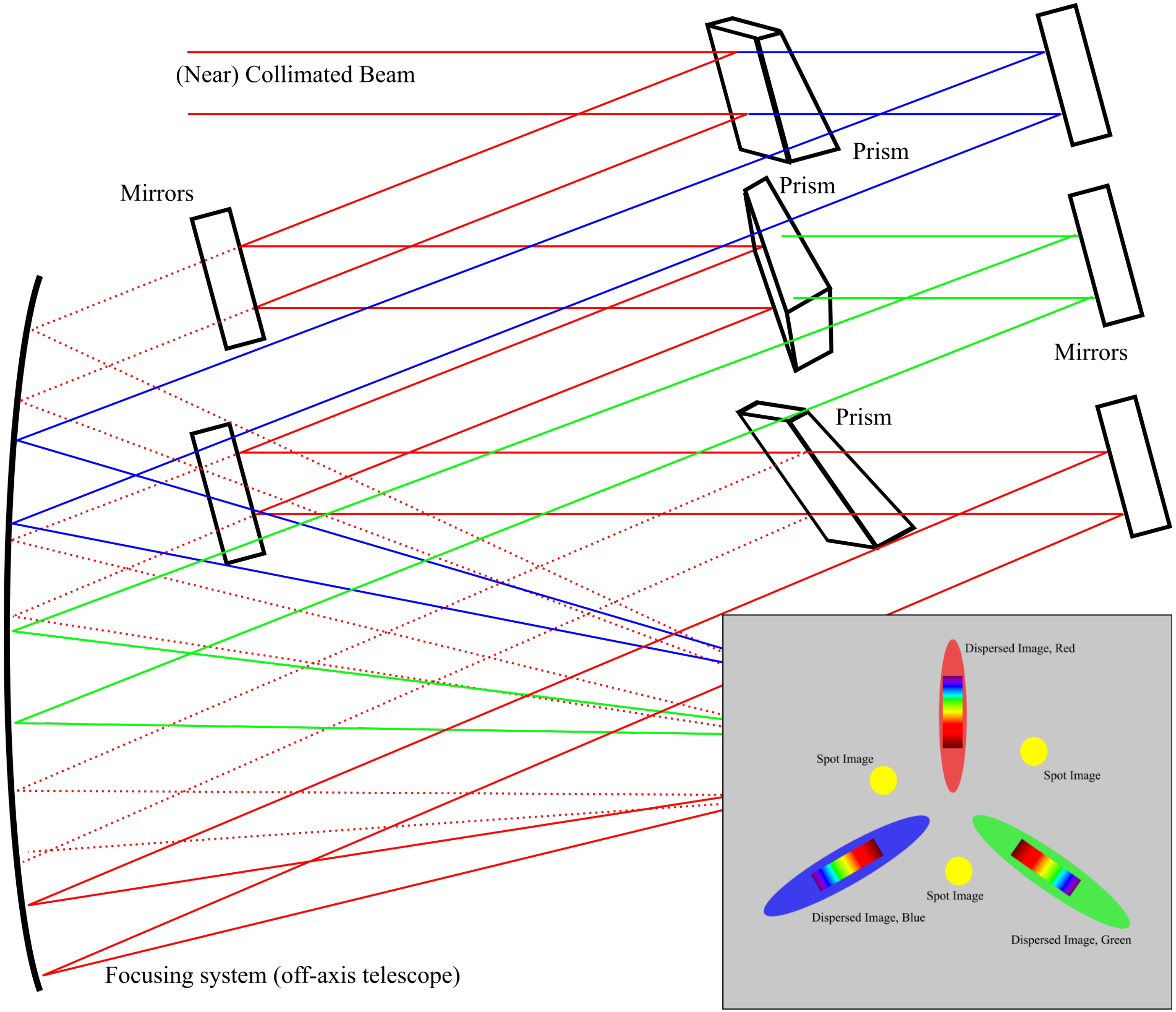
Separate chromatic optimisation of channel optics characteristics



Folding mirrors etc. may be included in actual optical layout

Dispersing elements: prisms, grisms, gratings, …

Concept of common detector scheme



Channels aligned onto camera by folding mirrors

Off-axis focusing telescope (layout deployed in 3D)

Trade-off between common or split detection system

Trade-off on spectral bands

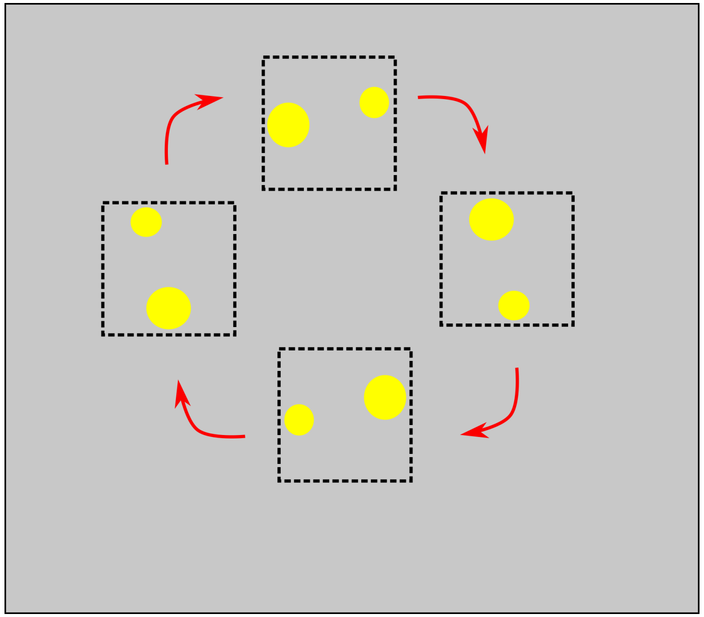
Detector response issue mitigation by scanning operation

Line of sight ~centered on observed field

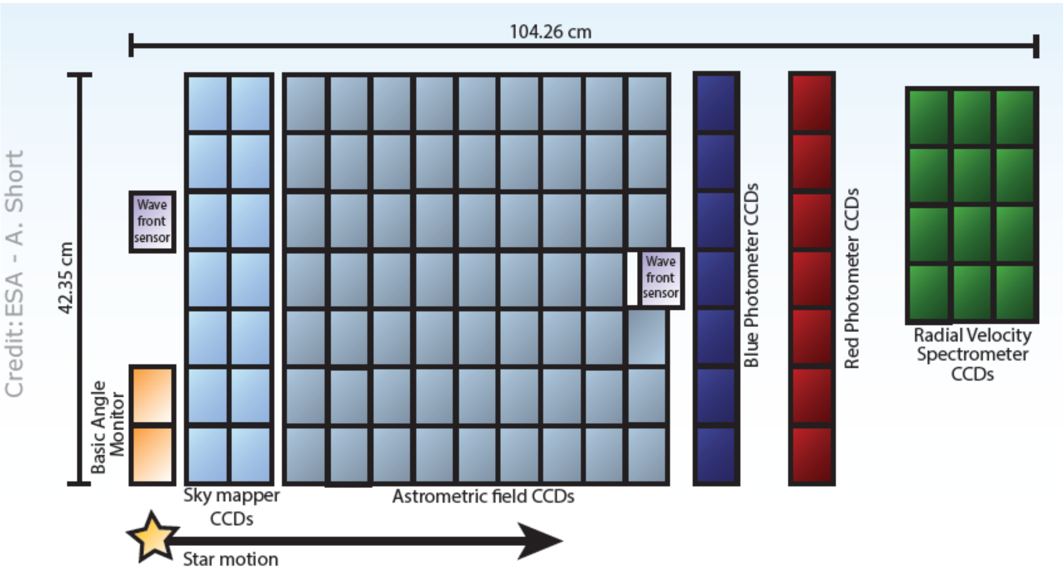
⇒ Field image rotates over detector through revolution

Both targets observed subsequently by same set of pixels

Pixel response averaged over many pixels AND common mode



Gaia: transit on 9 CCDs



"Dithering" among subsequent positions

Little displacement between frames

Fast imaging, frame period ≤1 s

Mitigation of attitude requirements

Compatible with TOLIMAN GEO orbit

Option: Sun-synchronous orbit

Payload back side kept always toward Sun

Benefit: stable power supply and thermal input

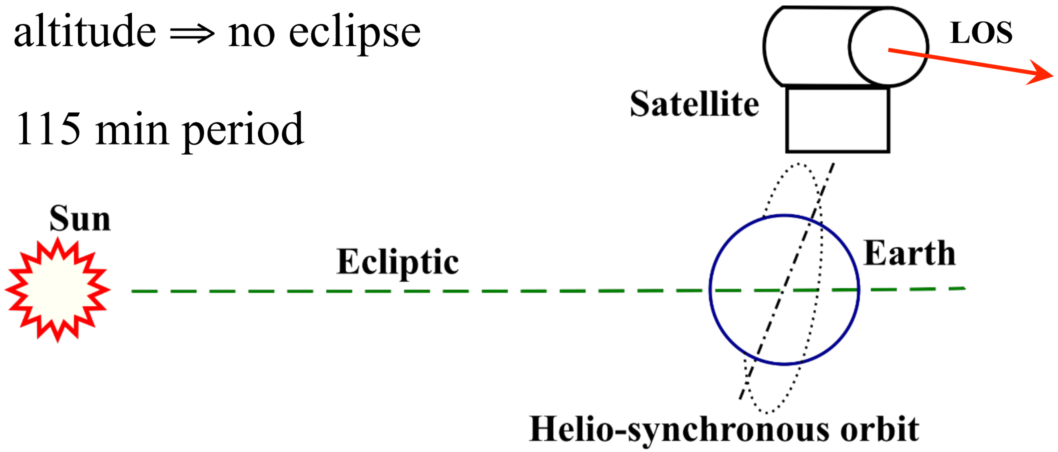
⇒ instrument structural stability

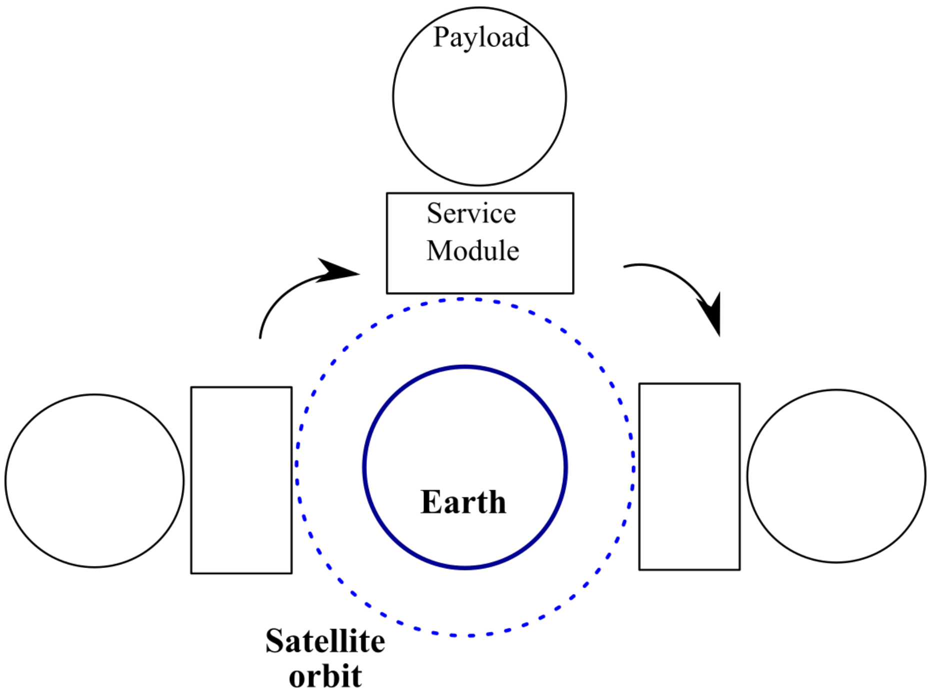
100% nominal observing time

Alternative to TOLIMAN GEO orbit

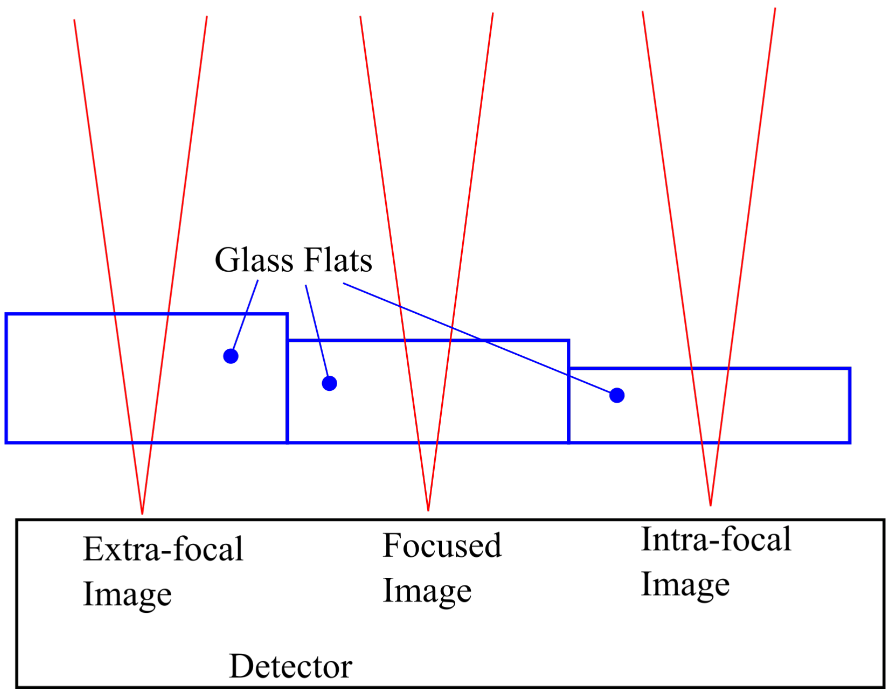
Sun-synchronous orbit, 1500 km altitude ⇒ no eclipse

115 min period





Option: Effective focal length monitoring on undispersed images



Effective focal length (EFL) is the gauge between pixels and sky

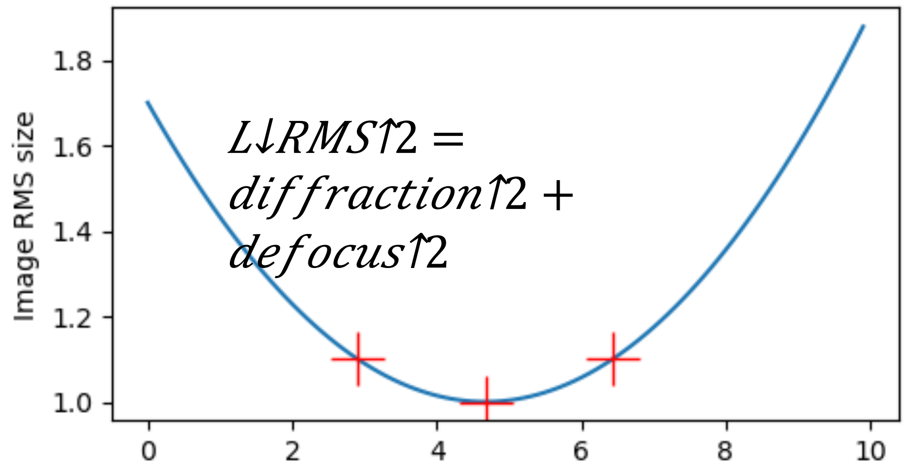
Simple implementation: tuning of optical path by monolithic glass flats

Slight defocus (e.g. +10% image size) **preserves** most of astrometric performance

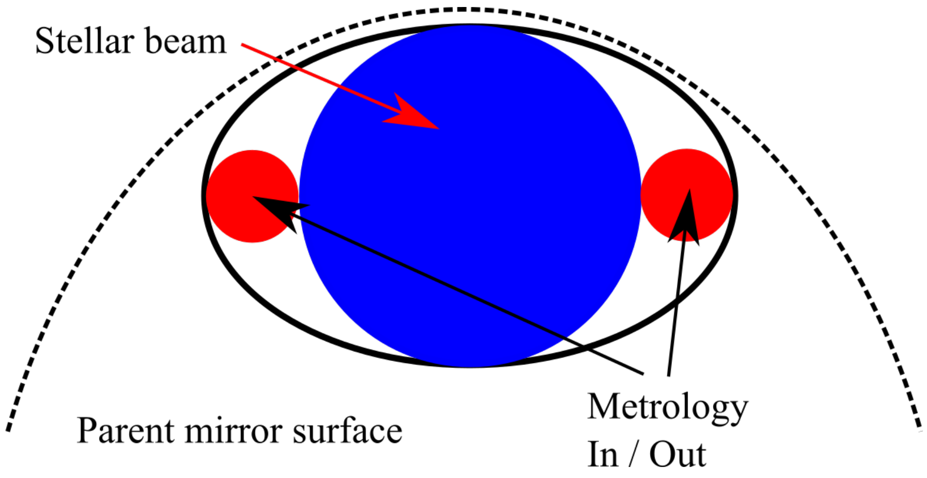
EFL variation ⇒ correlated change in image size

Gaia: monitoring of optical response variation over focal plane and time [AVU: D. Busonero]

Intrinsic calibration of basic measurement scale



First stage: beam compressor



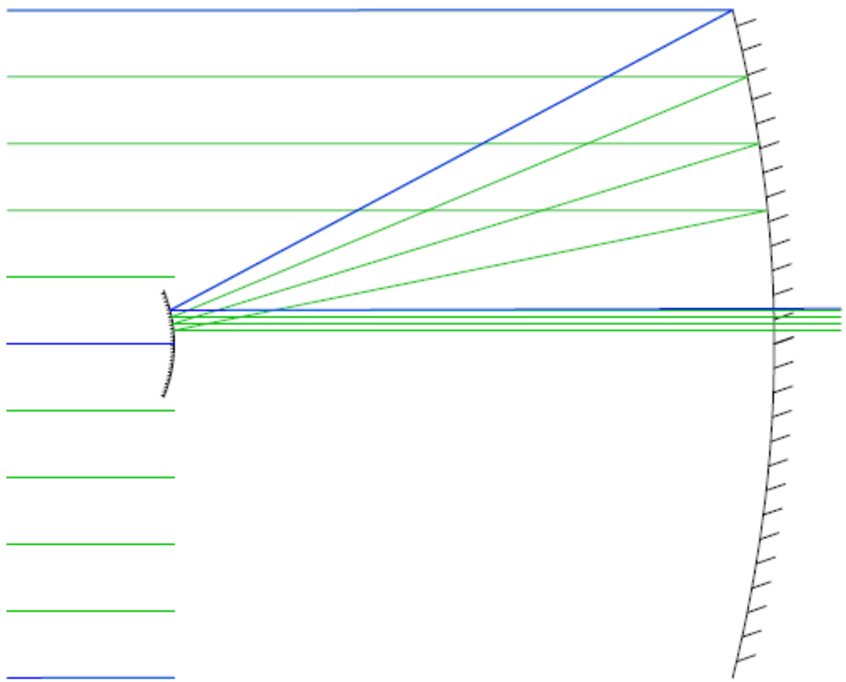
Simple off-axis design (decentered sub-pupil of centered configuration)

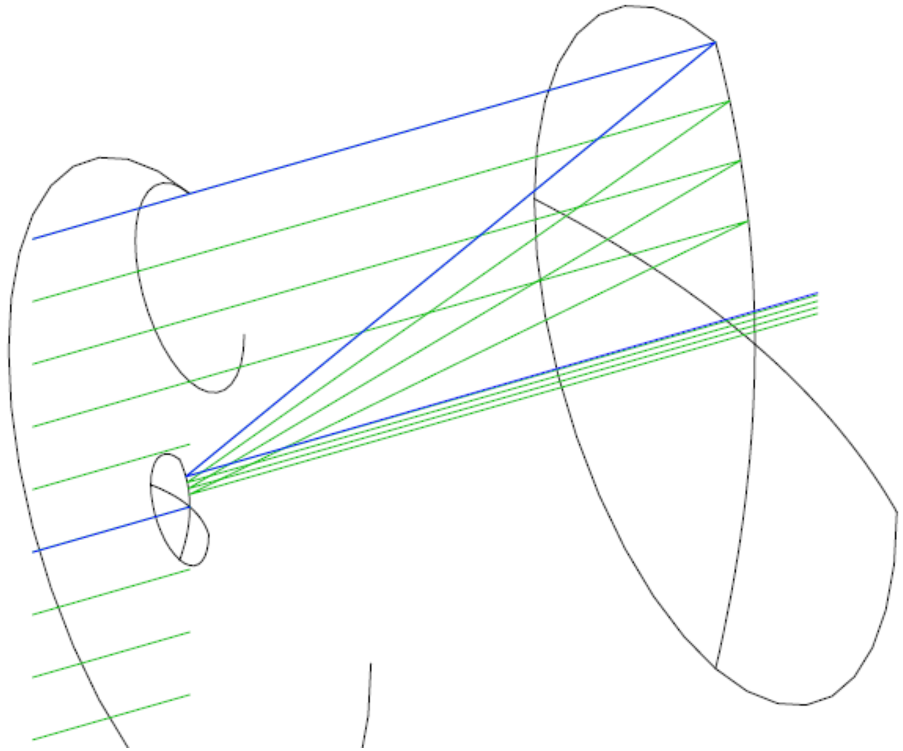
Clear aperture => clean PSF

Simple access to metrology beam injection / extraction

Simple, well defined optical cavity

[Sasso et al. 2018]

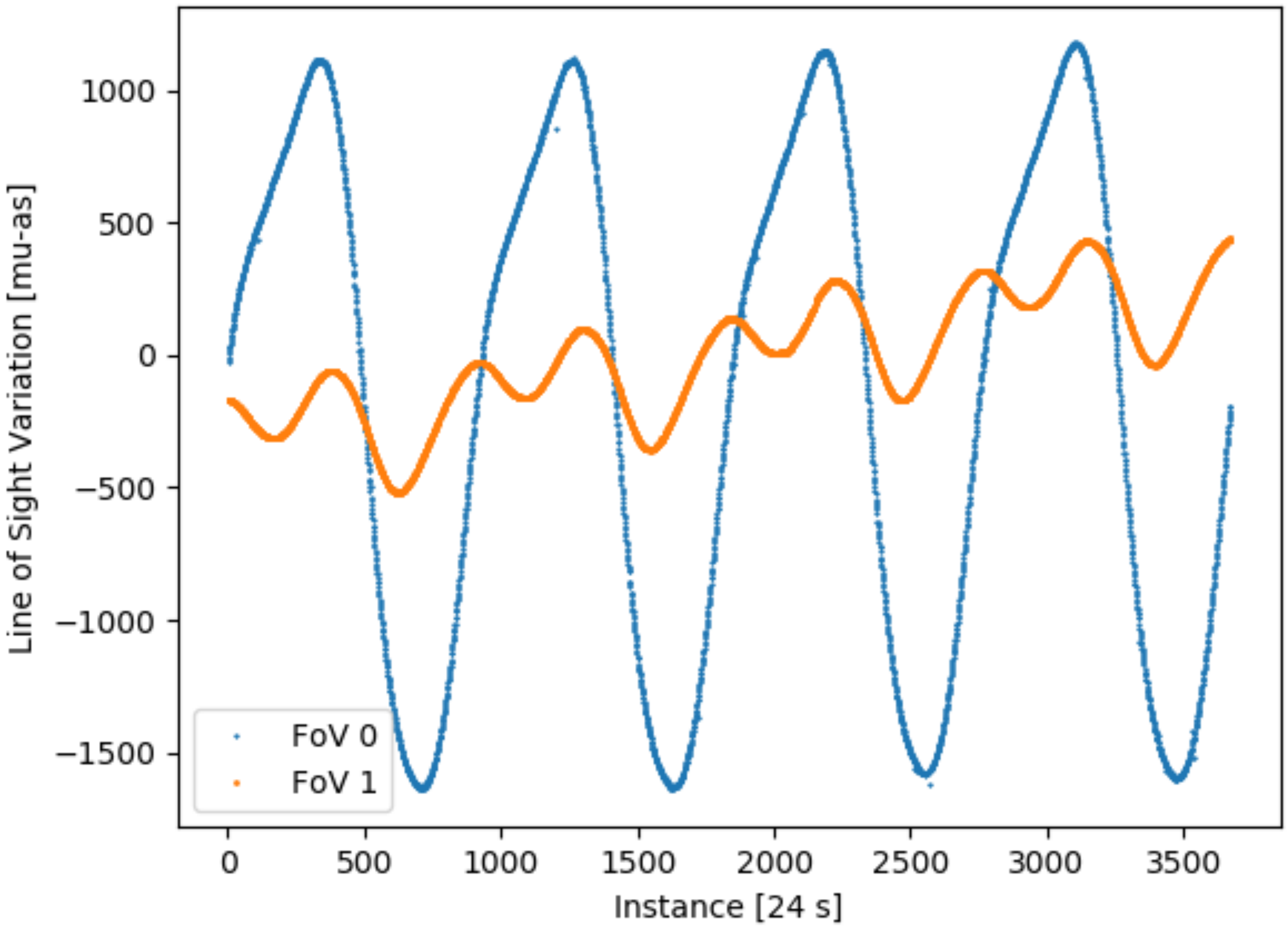




Gaia Basic Angle Monitoring as metrology inspiration

Satellite revolution ⇒ 6 hour "breathing", ~2 milli-arcsec peak to valley

BAM measurement noise ~20 μas on 24 s period

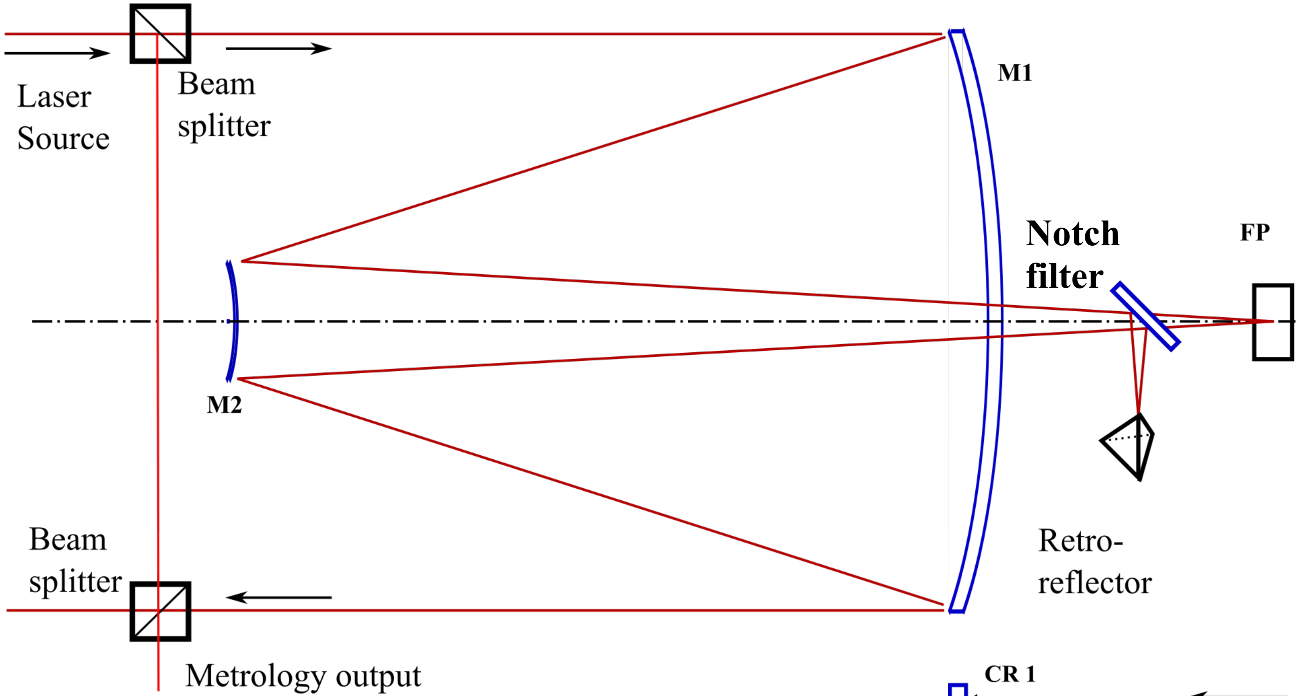


Noise averaging over 1 day (3600 samples): 0.33 μas

Close to TOLIMAN requirements

Monitoring of Basic Angle variation over time [Gaia AVU BAM: A. Riva]

Option: Telescope metrology configurations



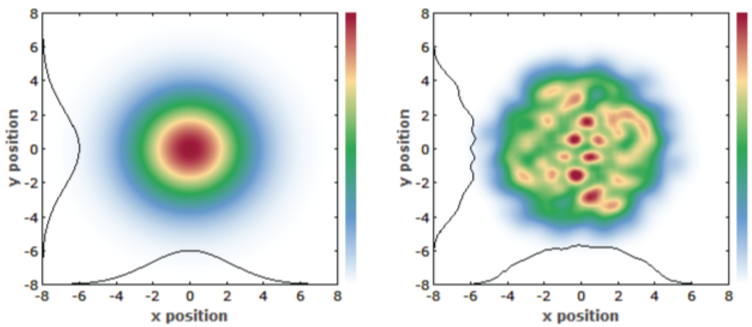
Goal: monitor alignment and main telescope characteristics **(EFL)**

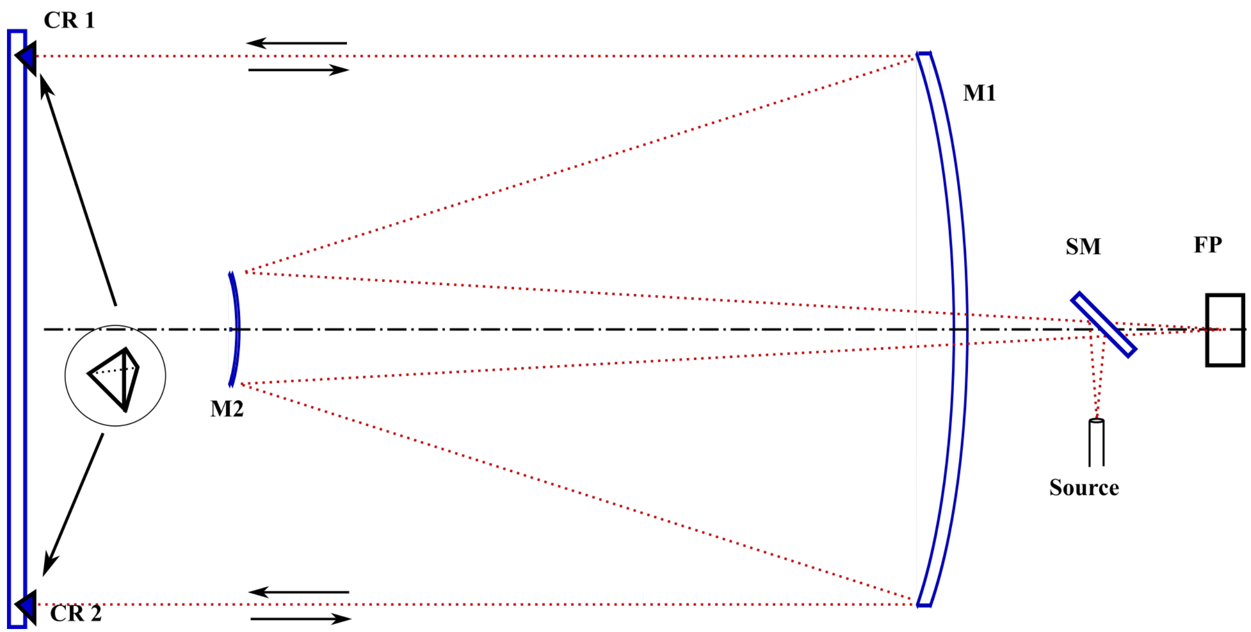
Short to medium term calibration

Applicable to whole telescope OR sub-systems

Independent of source

Laser beam profiler (CCD camera) for response / alignment monitoring





Roadmap toward larger survey…

Extension to

- <u>Fainter</u> sources (6-7 mag)

- <u>Single</u> (non-binary) sources

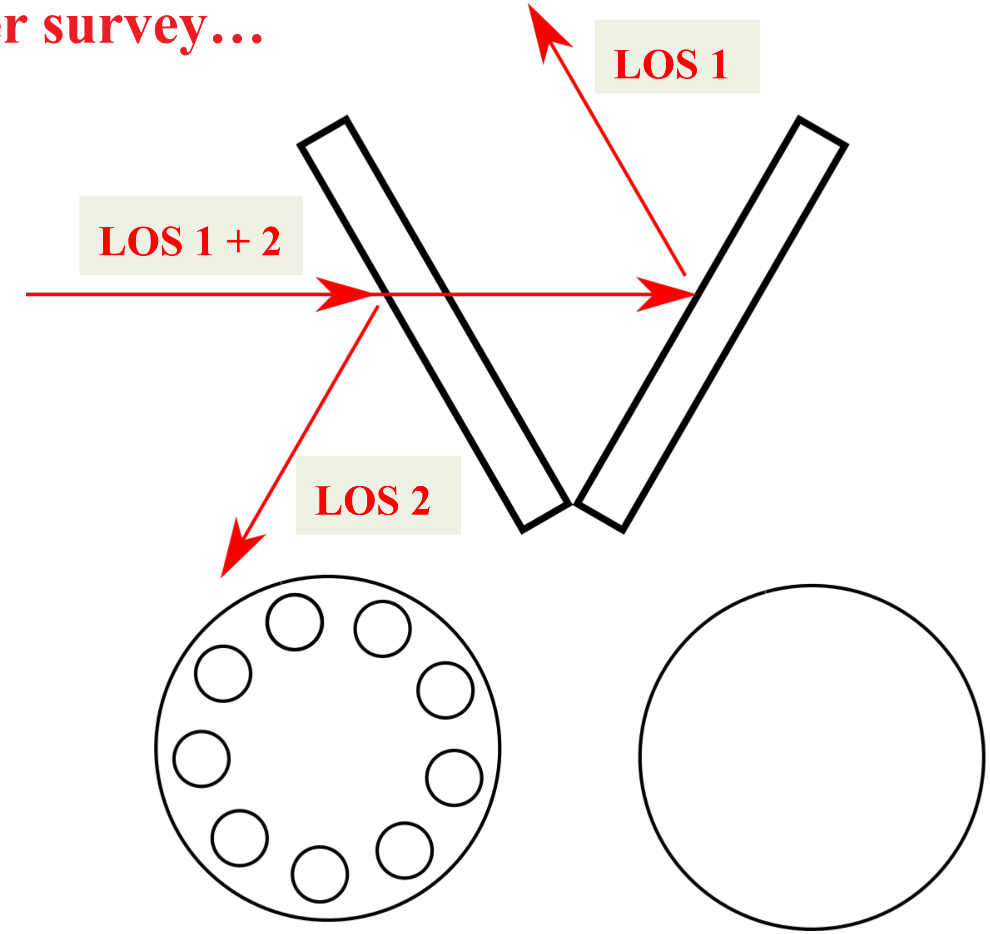
Large angle measurement between bright sources

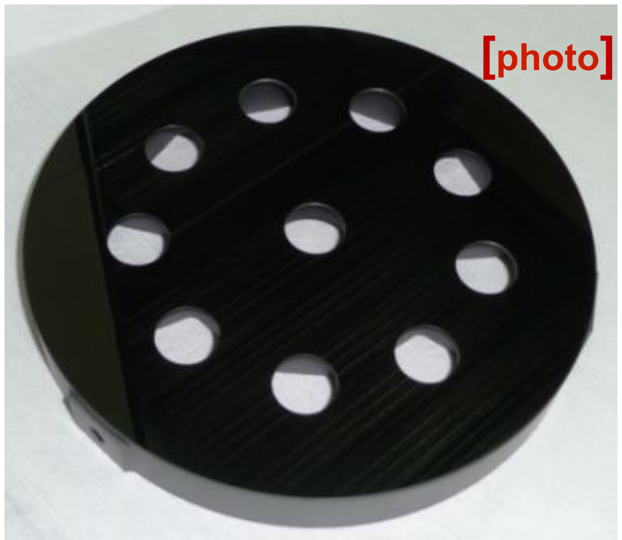
Possible solution: Hipparcos-like beam combiner

“Diffractive” (diluted) pupil solution possible

Active solution: tuneable basic angle

Metrology required to consolidate basic angle





SiC prototype, ~0.2 kg, ∅ 200 mm

9+1 apertures, ∅ 20 mm

Manufacturer: Boostec (Bazet, F)

Additional science: Jupiter quadrupole

Reference: GAREQ experiment in Gaia

Goal: measurements of light deflection due to Jupiter's quadrupole moment

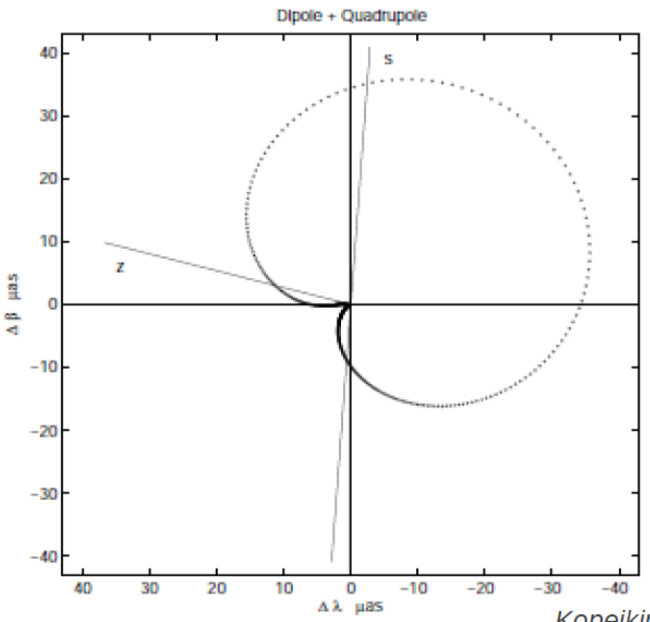
Jupiter magnitude: V = -2.8 to -1.6 mag

Diameter: 30 to 50 arcsec

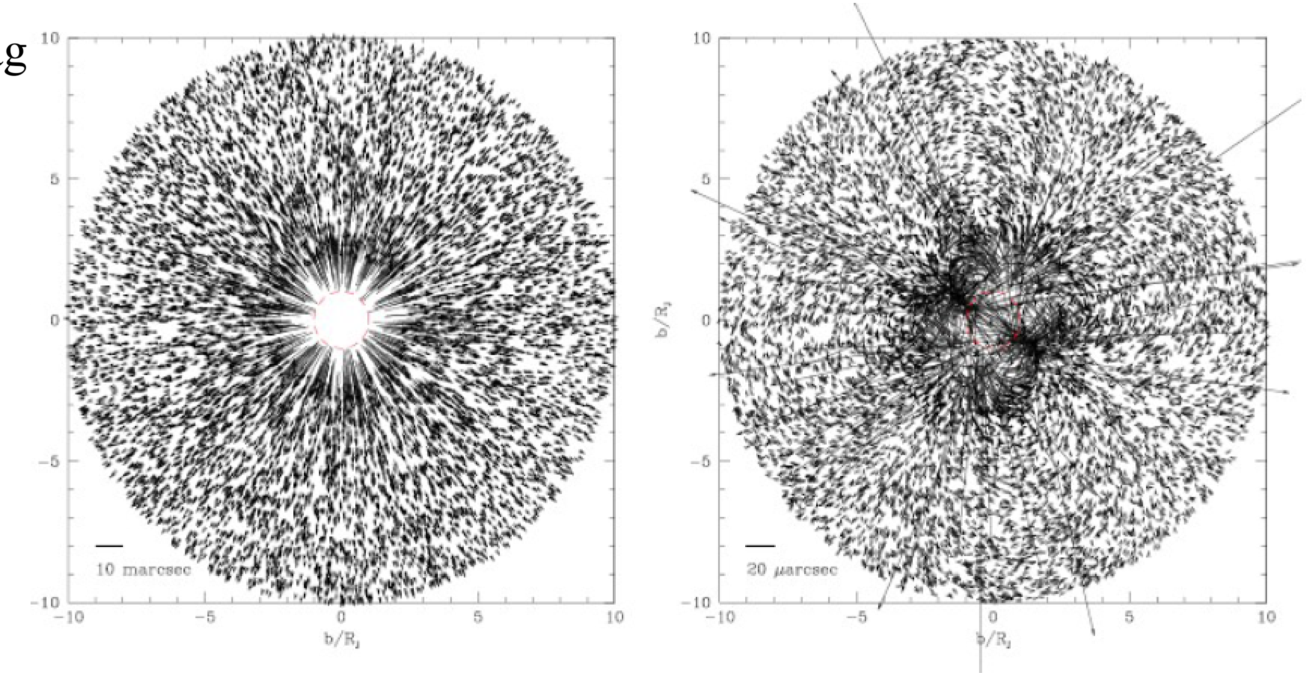
Magnitude per arcsec: V = 5.4 to 5.5 mag

Magnitude on 0.2 arcsec pixels: V = 9 mag

Observable by TRINETI on long exposures



Kopeikin & Makarov 2007



Monopole (left) and Quadrupole (right) stellar vector fields

Conclusions

Lessons learned from Gaia – Astrometric Verification Unit

Implementation options

Possible collaborations on e.g.

- **Instrument and operation design - forward analysis**
- **Calibration, data reduction and analysis packages**
- **Metrology analysis and possible solutions**

Basic considerations…

Alpha Cen magnitude very bright

A: V = 0 mag – B: V = 1.34 mag

Flux in Gaia broad band, on a 30 cm full aperture

A: ~1e9 photons/s – B: ~3e8 photons/s

Reference CCD pixel, 10×10 μm ⇒ full well ~1e5 electrons

Need to bridge a gap by a factor 1e4!

Signal to be spread out without exceeding astrometric loss

Side options: fast imaging; good PSF sampling

Motivation: sure detection

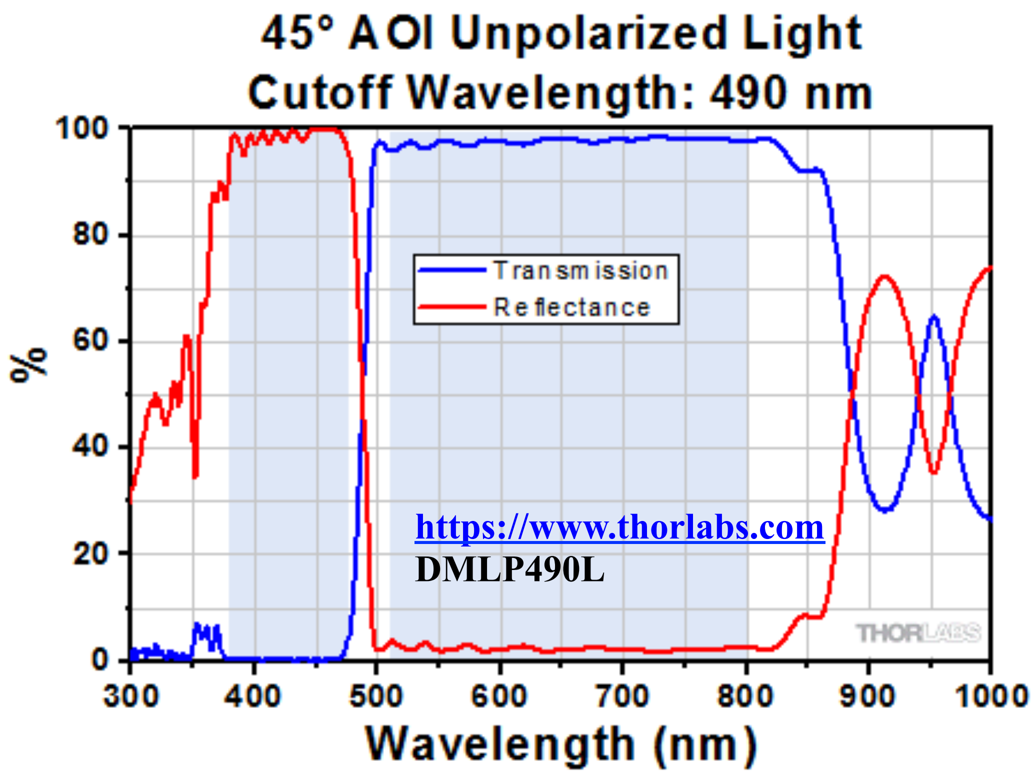
An Earth-mass planet orbiting α Centauri B [Dumusque et al. 2012]

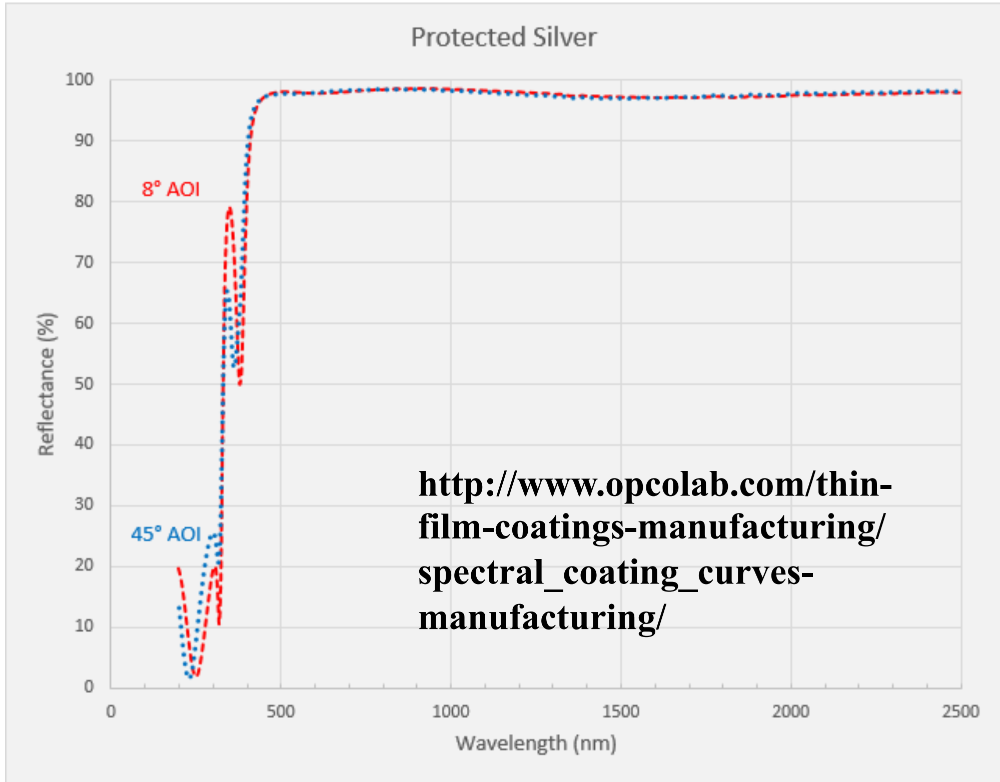
Period ~3 days, distance to parent star ~0.04 AU, mass ~1.13 M_Earth

Expected astrometric signal: ~30 mas (planet) ⇒ **0.12 μas on star**

Flexible band selection

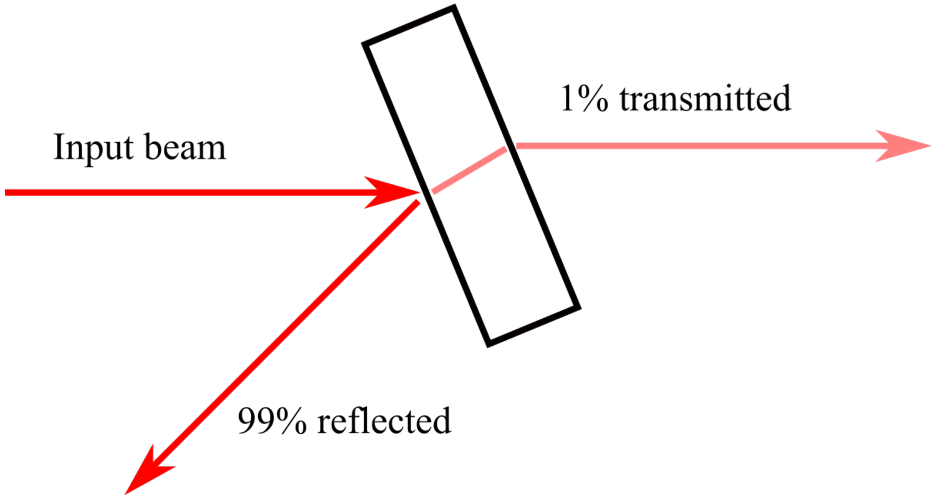
Coating design can be tailored on cutoff wavelength requirements





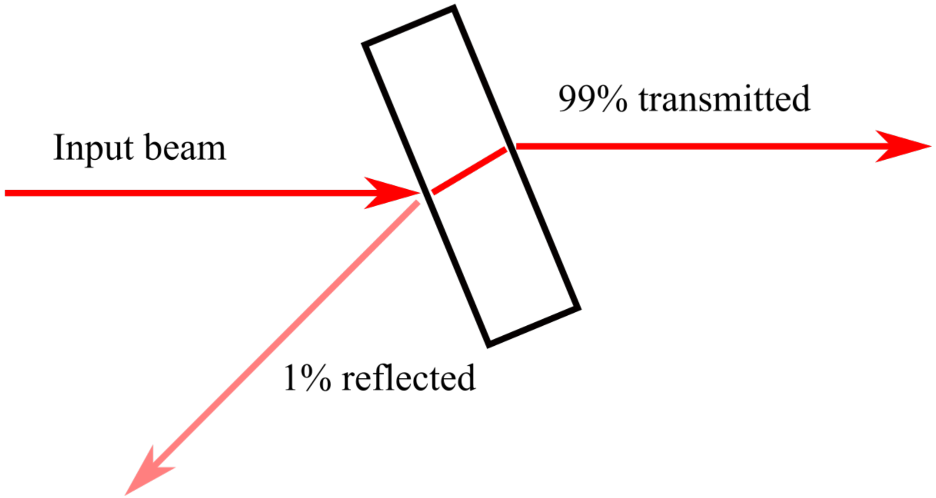
Pick-up of attenuated “white light” beams

Rationale: detect undispersed (zero order) images



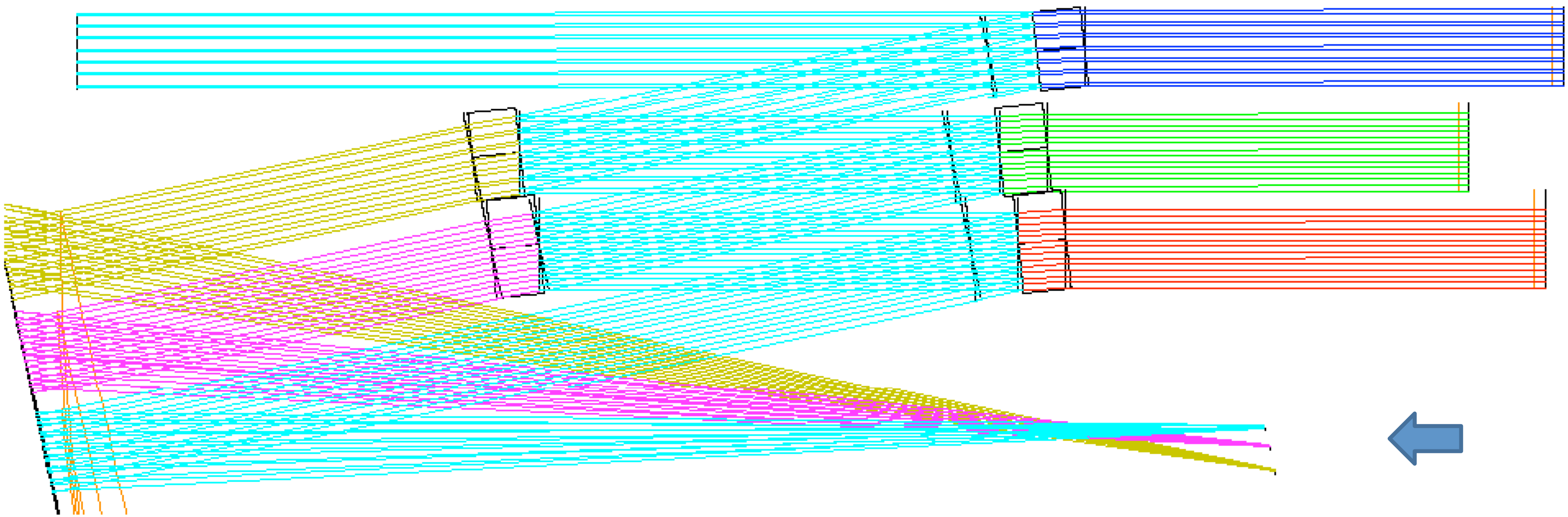
Pick-up from folding mirrors or front surface of prisms

Beams can be focused onto separate detectors, or folded onto a common detector

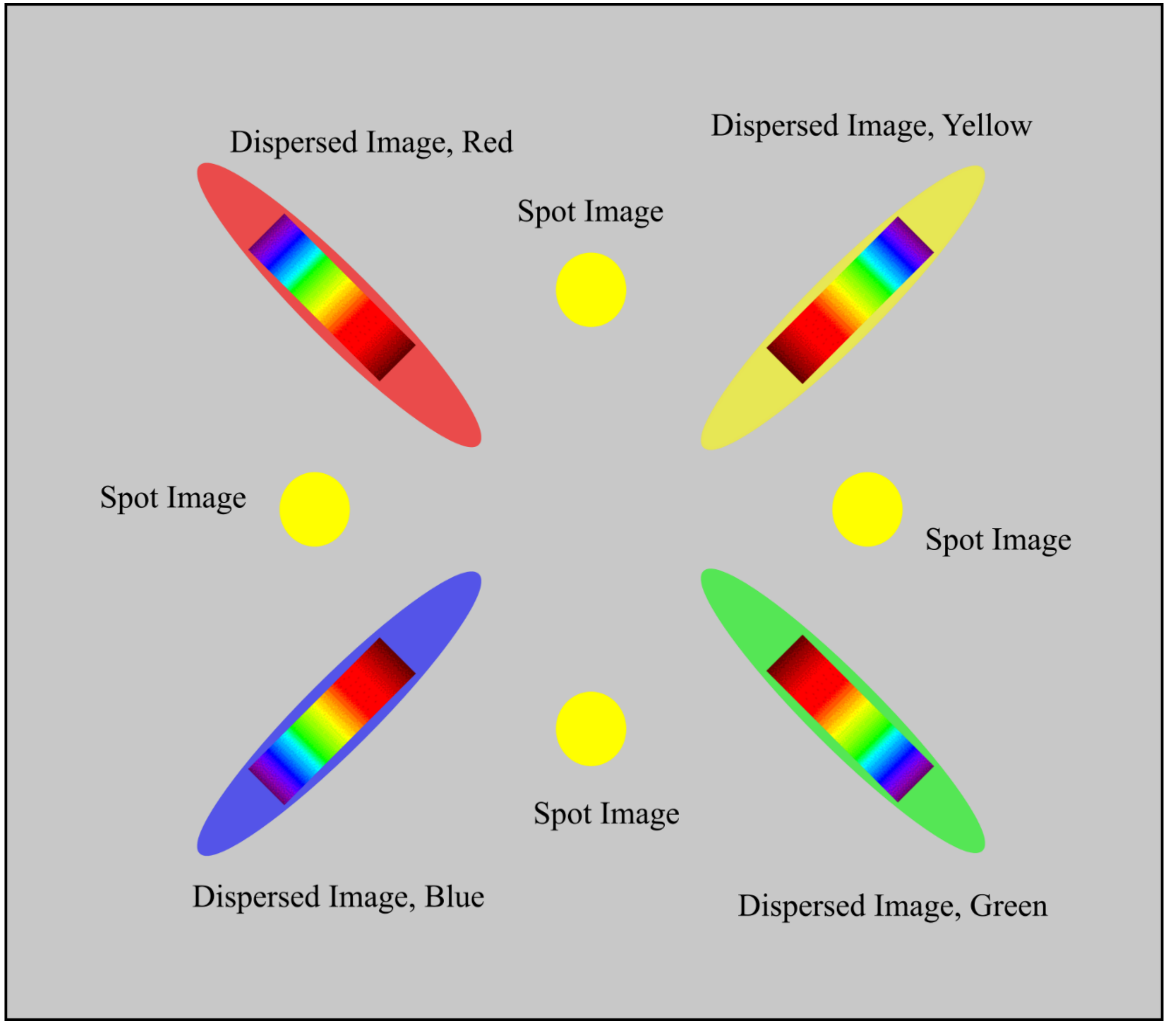


Ray tracing example (Zemax)

Remark: only camera path of undispersed images shown in figure



Four band version…



Design adjustable vs. number of bands