Gravitation Astrometric Measurement Experiment

M. Gai - INAF-Osservatorio Astronomico di Torino

On some goals of Fundamental Physics achievable through astronomical techniques…

Goal of GAME: γ to 10^{-7}-10^{-8}; β to 10^{-5}-10^{-6}

GAME:

Gravitation → PPN parameters γ and β

Astrometric → Apparent star position variation

Measurement → Light deflection close to the Sun

Experiment → Space mission – small / medium

Approach:

build on flight inheritance from past missions

[SOHO, STEREO, Hipparcos, **Gaia**]

Outline of talk:

- ***Scientific rationale***
- The GAME implementation concept

Quick review of historical / scientific framework

Goal of GAME: γ to 10^{-7}-10^{-8}; β to 10^{-5}-10^{-6}

Classical tests of general relativity [Einstein, 1916]

1. Perihelion precession of planetary orbit [Mercury] ⇒ Eddington's parameter β

2. Light deflection by massive objects (Sun) ⇒ Eddington's parameter γ

3. Gravitational redshift / blueshift of light

GAME space

"Modern" tests:

Gravitational lensing; Equivalence principle;

Time delay of electromagnetic waves (Shapiro effect); ⇒ Cassini

Frame dragging tests (Lense-Thirring effect);

Gravitational waves; Cosmological tests (cosmic background);

…

Complementary GR tests: $\gamma + \beta$

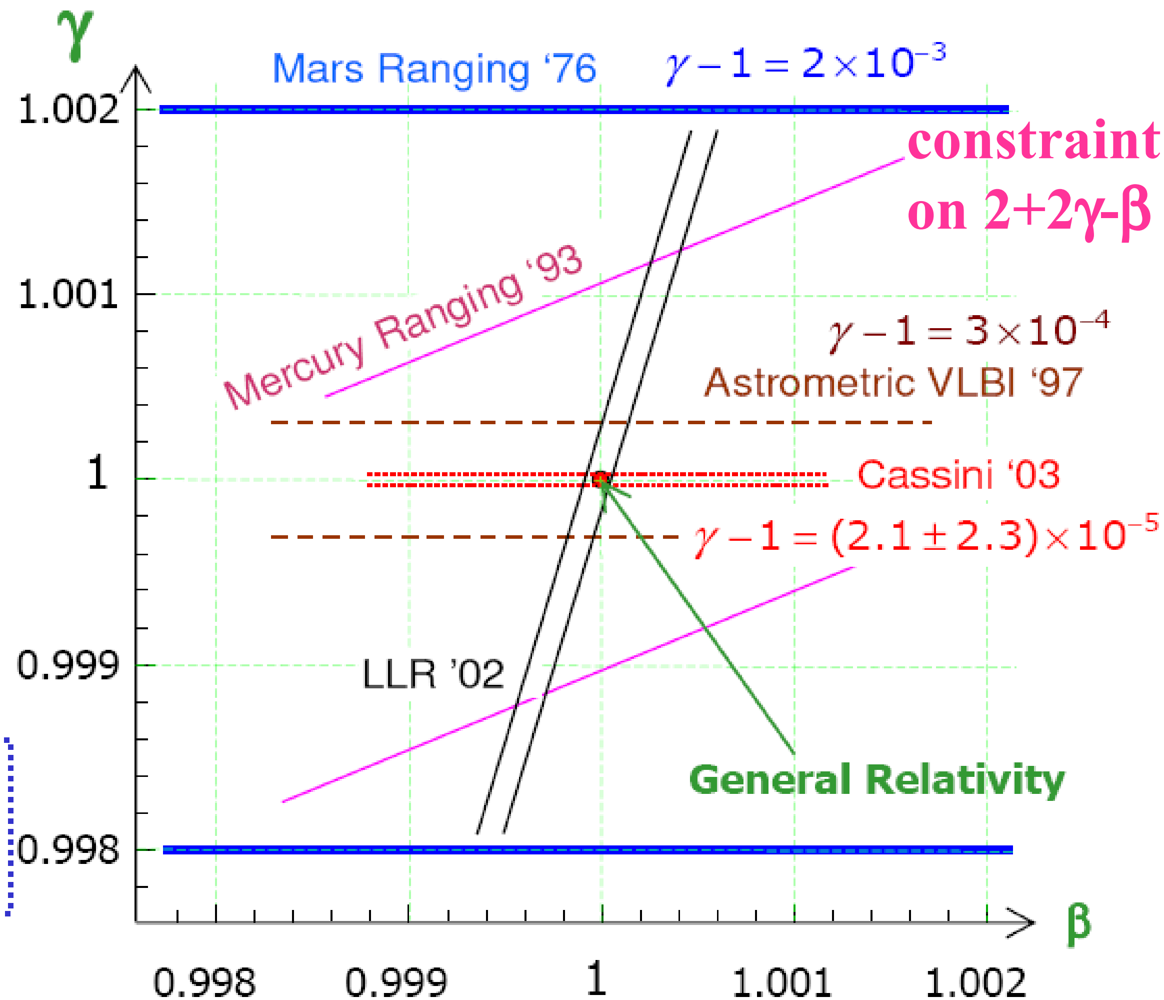
Current experimental bounds:

consistent with GR

$$|\gamma - 1| \leq 2 \times 10^{-5}$$

$$|\beta - 1| \leq 1 \times 10^{-4}$$

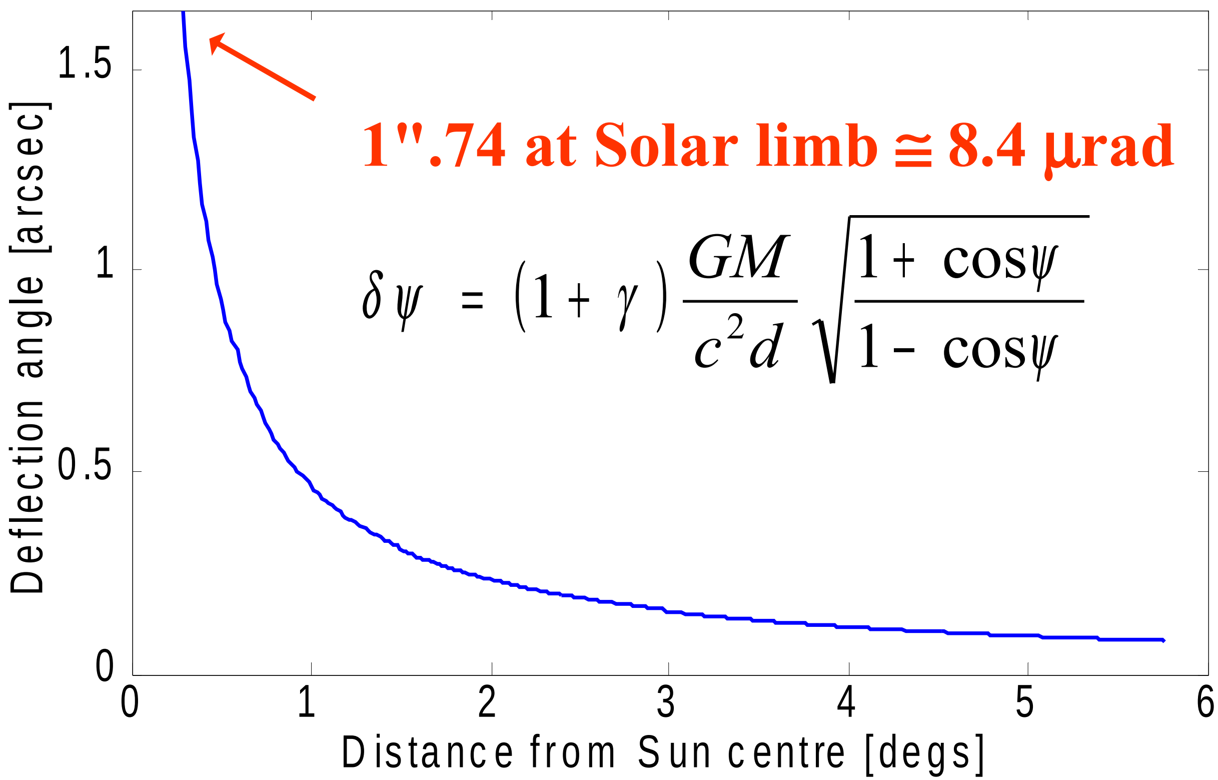
Same experiment ⇒ cross-calibration



S.G. Turyshev (JPL, NASA)

***Living Reviews in Relativity*, C.F. Will (2001)**

Spacetime curvature around massive objects



$$\delta\psi = (1+\gamma)\frac{GM}{c^2 d}\sqrt{\frac{1+\cos\psi}{1-\cos\psi}}$$

G: Newton's gravitational constant

d: distance Sun-observer

M: solar mass

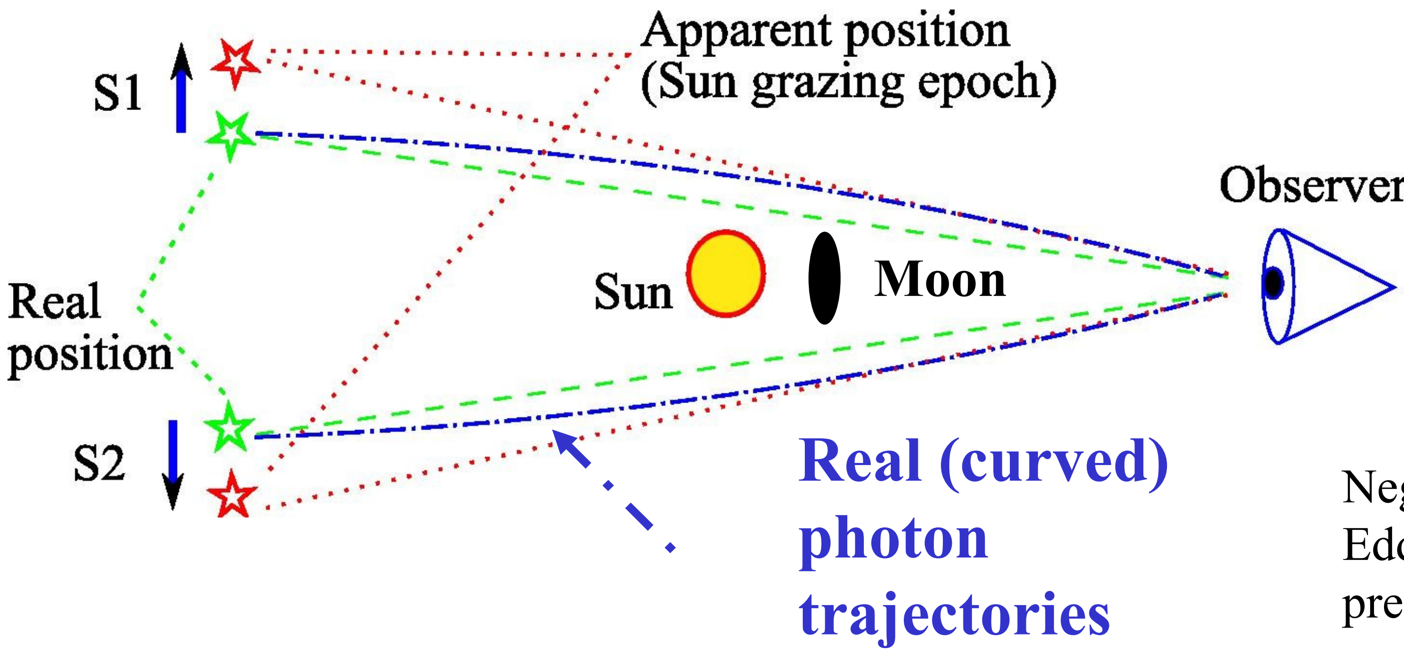
c: speed of light

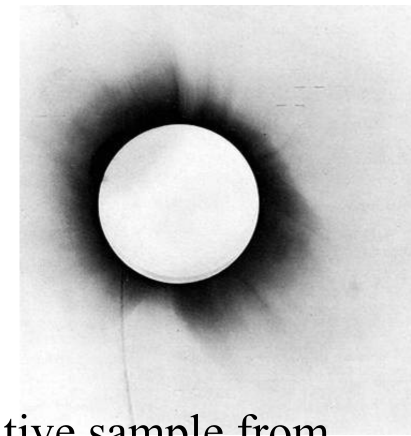
ψ: angular distance of the source to the Sun

Light deflection ⇔ Apparent variation of star position, related to the gravitational field of the Sun

⇔ γ in Parametrised Post-Newtonian (PPN) formulation

Dyson-Eddington-Davidson experiment (1919) - I





Negative sample from Eddington's photographs, presented in 1920 paper

First test of General Relativity by light deflection nearby the Sun

Epoch (a): unperturbed direction of stars S1, S2 (dashed lines)

Epoch (b): apparent direction as seen by observer (dotted line)

Dyson-Eddington-Davidson experiment (1919) - II

Repeated throughout XX century

Precision achieved: ~10%

Authors	Year	Deflection ["]
Dyson & al.	1920	1.98 ± 0.16
Dodwell & al.	1922	1.77 ± 0.40
Freundlich & al.	1929	2.24 ± 0.10
Mikhailov	1936	2.73 ± 0.31
van Biesbroeck	1947	2.01 ± 0.27
van Biesbroeck	1952	1.70 ± 0.10
Schmeidler	1959	2.17 ± 0.34
Schmeidler	1961	1.98 ± 0.46
TMET	1973	1.66 ± 0.19

[A. Vecchiato et al., MGM 11 2006]

Limiting factors:

- **Need for natural eclipses** → Short exposures, high background
- **Atmospheric turbulence** → Large astrometric noise
- **Portable instruments** → Limited resolution, collecting area

Cosmological implications

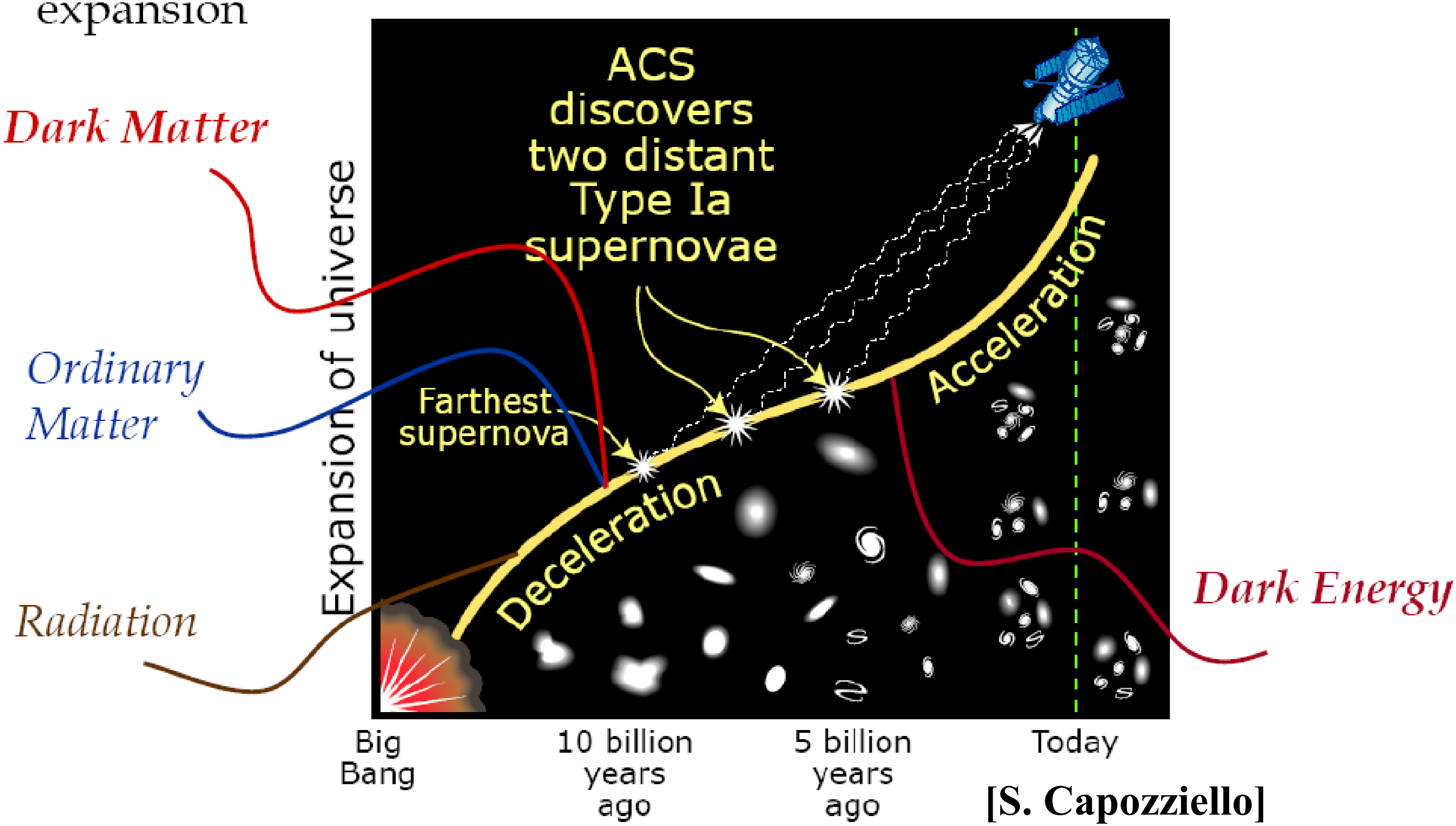
- Dark Matter and Dark Energy: explain experimental data
- Alternative explanations: modified gravity theories – e.g. *f(R)*
- Possible check: fit of gravitation theories with observations
- Check of modified gravitation theories *within Solar System*

Rationale:

replacement in Einsten's field equations of
source terms [⇔ **new particles**] on one side with
geometry terms [⇔ **intrinsic curvature**] on the other side

DE and DM from the Observations

- Universe evolution is characterized by different phases of expansion



[S. Capozziello]

Constraining the phase space of modified gravity

Taking advantage of PPN limit, e.g. for *f(R)* theories…

$$\gamma_R^{PPN} - 1 = \frac{-f''(R)^2}{f'(R) + 2f''(R)^2}, \quad \beta_R^{PPN} - 1 = \frac{1}{4}\left[\frac{f'(R)\cdot f''(R)}{2f'(R) + 3f''(R)^2} \cdot \frac{d\gamma_R^{PPN}}{d\phi}\right]$$

[Capozziello & Troisi 2005]

Alternative formulation:

$$\gamma_R^{PPN} - 1 = \frac{-\left(f''\dfrac{dR}{d\varphi}\right)^2}{Zf' + 2\left(f''\dfrac{dR}{d\varphi}\right)^2}, \quad \beta_R^{PPN} - 1 = \frac{1}{4}\left[\frac{f' \cdot f''\dfrac{dR}{d\varphi}}{2Zf' + 3\left(f''\dfrac{dR}{d\varphi}\right)^2} \cdot \frac{d\gamma}{dR} \cdot \frac{dR}{d\varphi}\right]$$

[Capone & Ruggiero 2010]

Check of gravitation theories within Solar System:

local measurements ⇒ cosmological constraints

Additional science topics - I

Fundamental physics experiments in the Solar System
⇔ planetary physics

Light deflection effects due to oblate and moving giant planets:
Jupiter and Saturn

- Monopole and quadrupole (till now undetected) terms of asymmetric mass distribution

Close encounters between Jupiter and selected quasars and stars

- "Speed of gravity" tests; link between dynamical reference system and ICRF

Mercury's orbit tracking / monitoring

- Perihelion precession determination
  ⇒ PPN β parameter

Additional science topics - II

Astrophysics of planet-star transition region

Upper limits on masses of known massive planets and brown dwarfs by astrometry

- Nearby (d < 30-50 pc), bright (4 < V < 9) stars, orbital radii 3-7 AU

Time resolved photometry on known transiting exo-planet systems

- Constraints on additional companions: mass, period, eccentricity

[Sample not conveniently observable by Gaia or Corot]

Additional science topics - III

Monitoring of Solar corona and asteroids

Observation in / through inner part of Solar System

- NEO orbits and asteroid dynamics (a few close encounters)
- Circumsolar environment transient phenomena (high resolution corona observations)

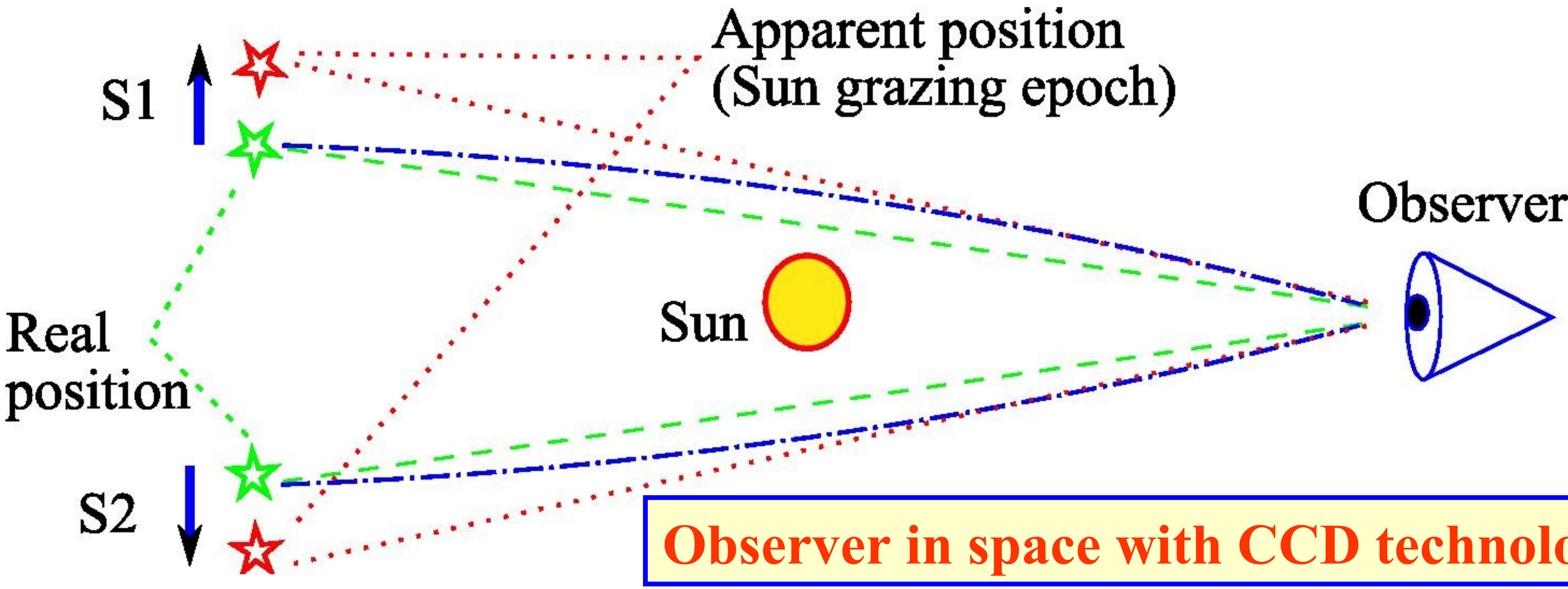
Outline of talk:

- Scientific rationale
- ***<u>The GAME implementation concept</u>***

Description focus on γ measurement

Goal of GAME: γ to 10^{-7}-10^{-8}; β to 10^{-5}-10^{-6}

The GAME concept (I)

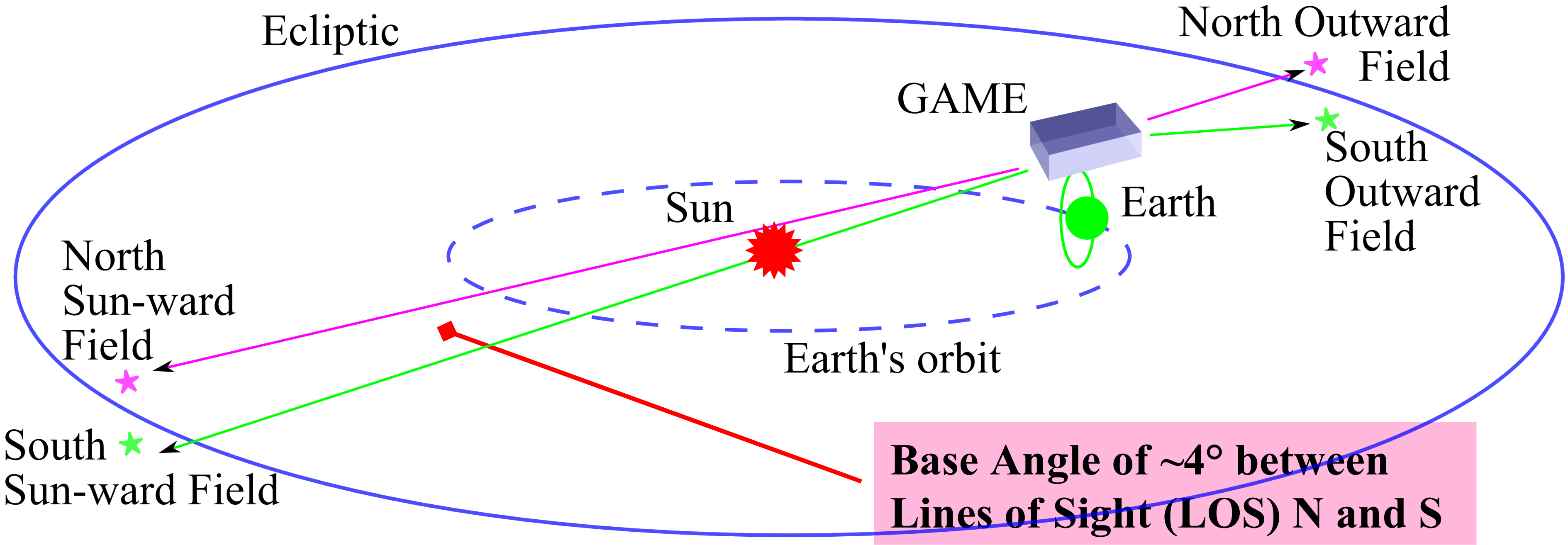


Observer in space with CCD technology

A space mission in the visible range to achieve

- long permanent artificial eclipses
- no atmospheric disturbances, low noise

The GAME concept (II)



Base Angle of ~4° between Lines of Sight (LOS) N and S

Experimental approach:

Repeated observation of fields close to the Ecliptic

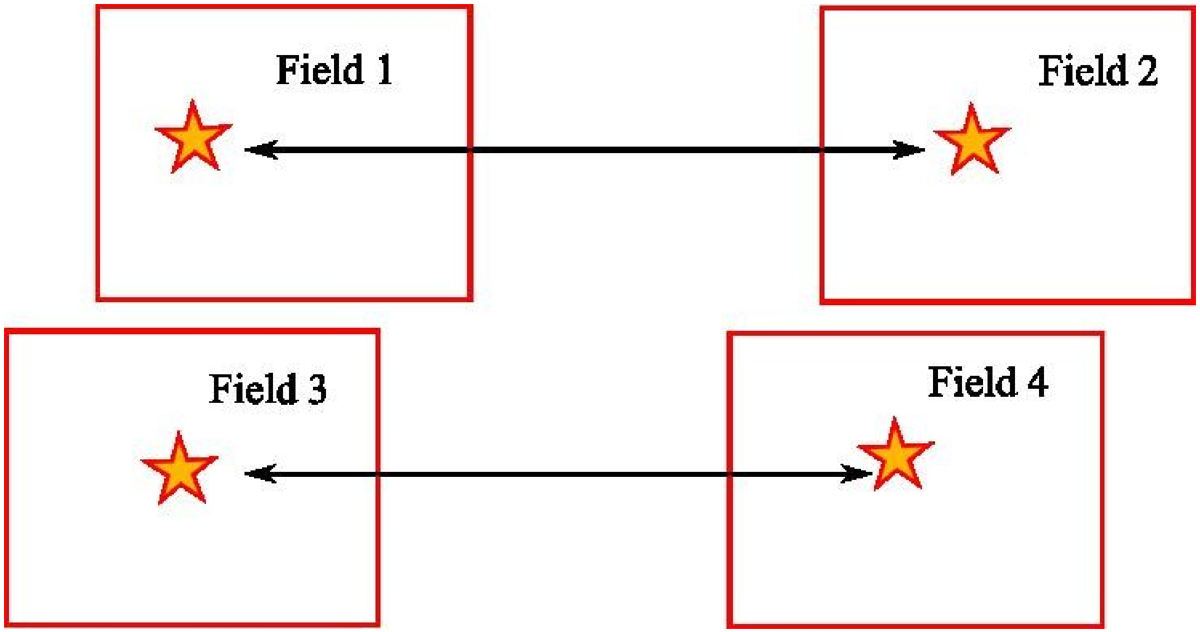
Measurement of angular separation of stars between fields

Track separation with epoch ⇔ distance to Sun

Key issues of GAME

- Multiple epoch observation sequence
- Differential measurement on superposed fields
- Systematic error control
- Precision on image location / separation
- The Fizeau interferometer / coronagraph
- Elementary astrometric performance
- **Photon limited mission performance**

Multiple epoch observation sequence



Deflection $\delta\psi$ measurement

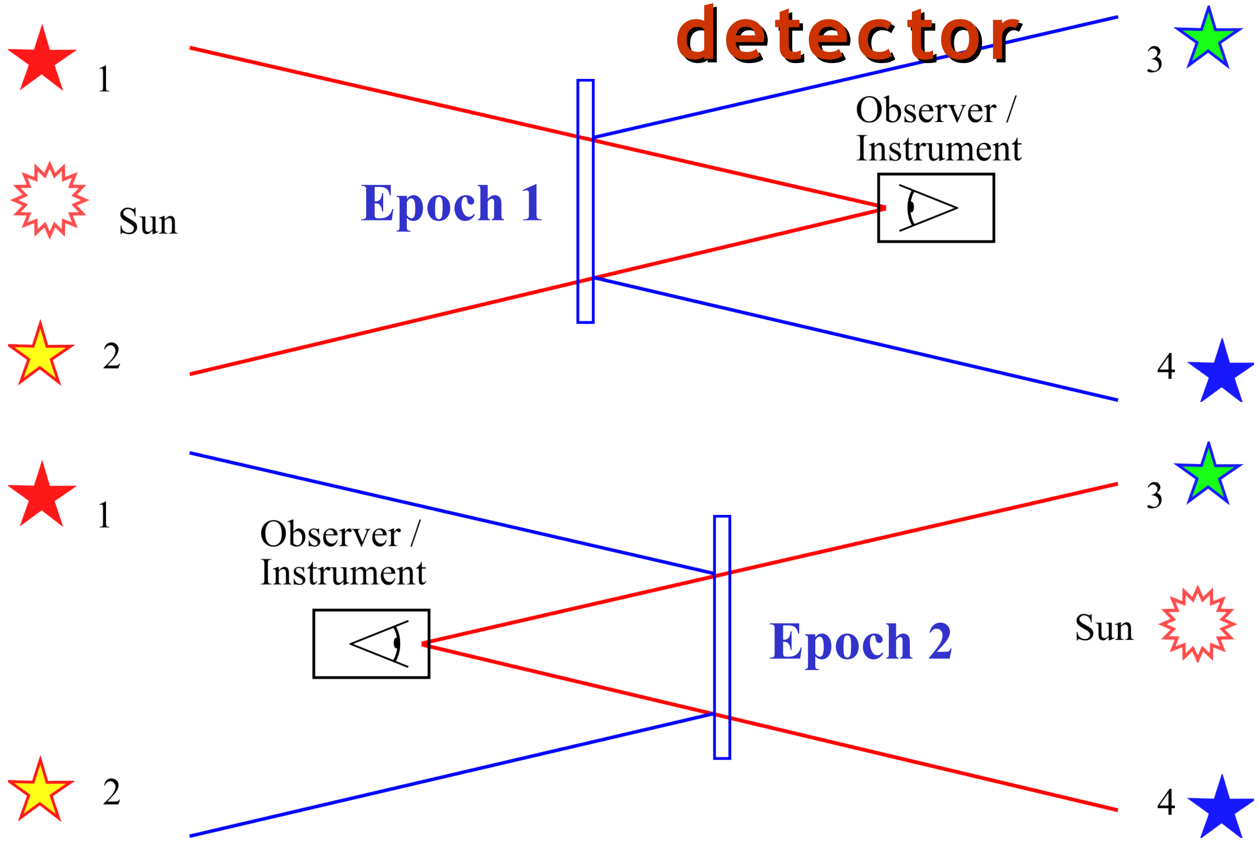
Calibration fields, $\delta\psi \cong 0$

Fields F1, F2 measured close to and away from the Sun:

2+ measurements epochs to <u>modulate</u> deflection
(Sun "switched" on/off)

Calibration fields: low deflection in all epochs

Multiple field multiplex on telescope + detector



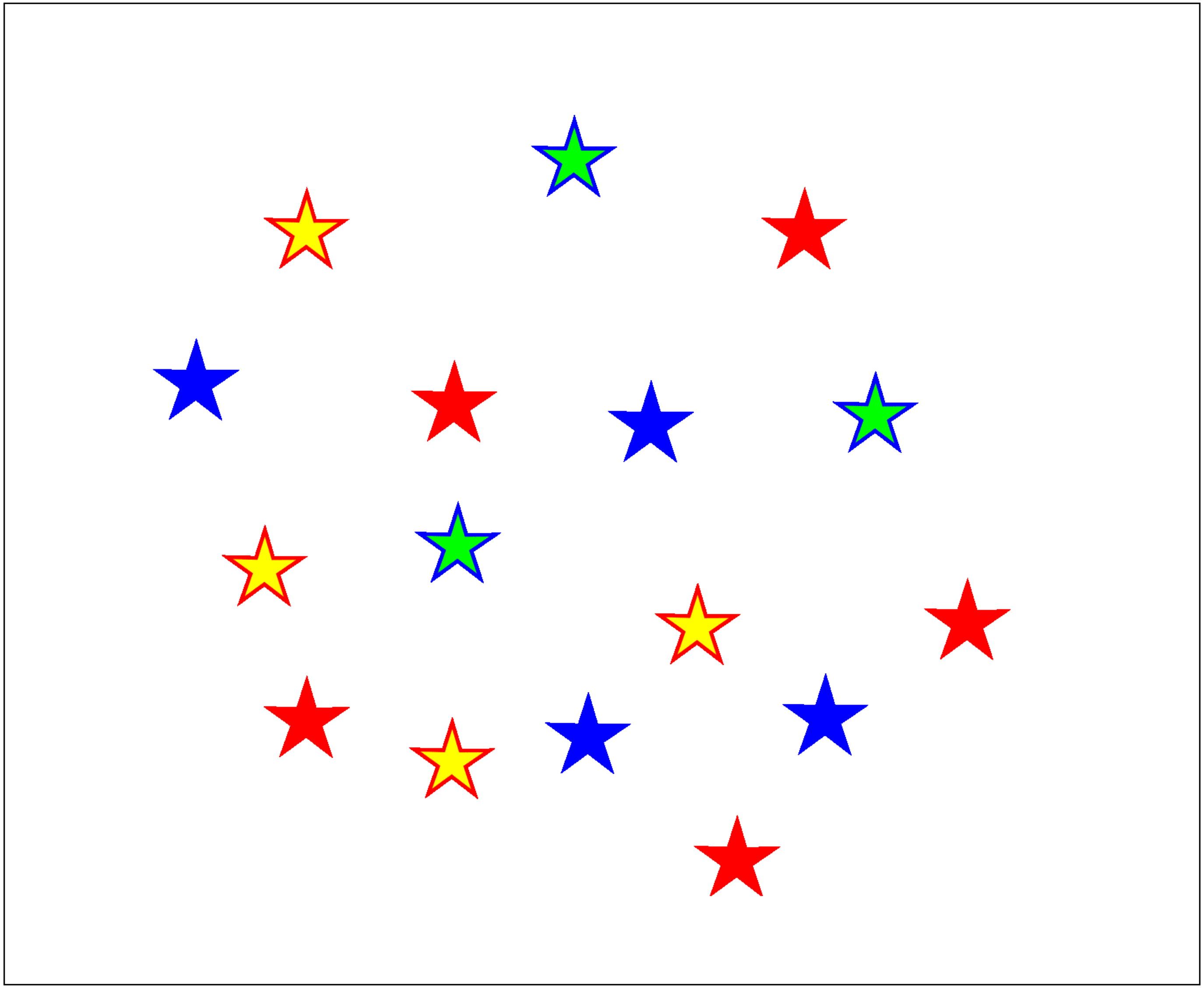
Epoch 1↔2:

deflection modulation switched between field pairs

Star separation variation: deflection ψ + instrument [base angle]

Additional epochs (calibration): low deflection on all fields

Multiple field superposition + epoch



Four epochs:

double differential measurement of deflection

+

astrometric calibration of stellar sample

Double differential measurement

Basic equations referred to stars in Fields 1, 2, 3, 4; Epochs 1, 2

$$[\xi(F1;E1) - \xi(F2;E1)] - [\xi(F1;E2) - \xi(F2;E2)] = \delta\psi(F1,F2) + \Delta\beta(E1;E2)$$

$$[\xi(F3;E2) - \xi(F4;E2)] - [\xi(F3;E1) - \xi(F4;E1)] = \delta\psi(F3,F4) - \Delta\beta(E1;E2)$$

Compensation among measurements of systematic error *Δβ*

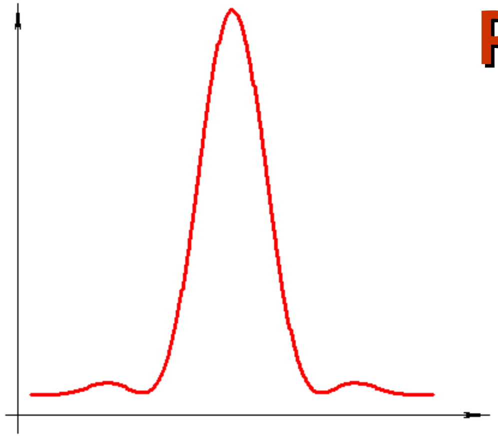
$$\delta\psi(F1,F2) + \delta\psi(F3,F4) =$$
$$[\Delta\xi(F1,F2;E1) - \Delta\xi(F1,F2;E2)] + [\Delta\xi(F3,F4;E2) - \Delta\xi(F3,F4;E1)]$$

Photon limited monitoring of base angle *β* variation

$$\Delta\beta(E1;E2) \cong [\Delta\xi(F1,F2;E1) - \Delta\xi(F1,F2;E2)] + [\Delta\xi(F3,F4;E1) - \xi(F3,F4;E2)]$$

⇒ Rationale for simultaneous Sun-ward + Out-ward observations

arXiv:1105.2740v1 [astro-ph.IM]



Precision on image location

$$\sigma = \alpha \frac{\lambda}{4\pi X} \cdot \frac{1}{SNR}$$

Diffraction (X) — Statistics (SNR)

σ: Standard deviation of image location

λ: Effective ***wavelength*** of observation

X: Root Mean Square size of the ***aperture***

$SNR \leq \sqrt{N}$

Signal to Noise Ratio ⇒ photons, RON, background

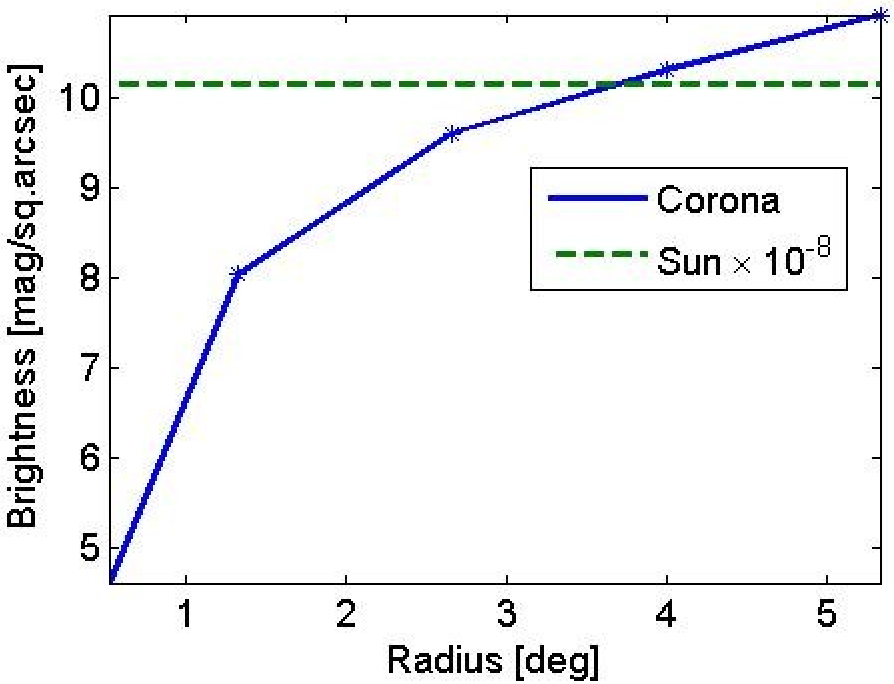
N: Number of photons collected

α>1: Instrumental factor of degradation (geometry, sampling, …)

σ can be a small fraction of pixel/image size

[Gai et al., PASP 110, 1998]

Sun disc and Coronal background



Steep decrease of Coronal background at increasing distance from Sun limb

Design trade-off: observation at 2° from Sun centre

Background: ~9 mag/square arcsec

Instrument: Fizeau interferometer + coronagraph

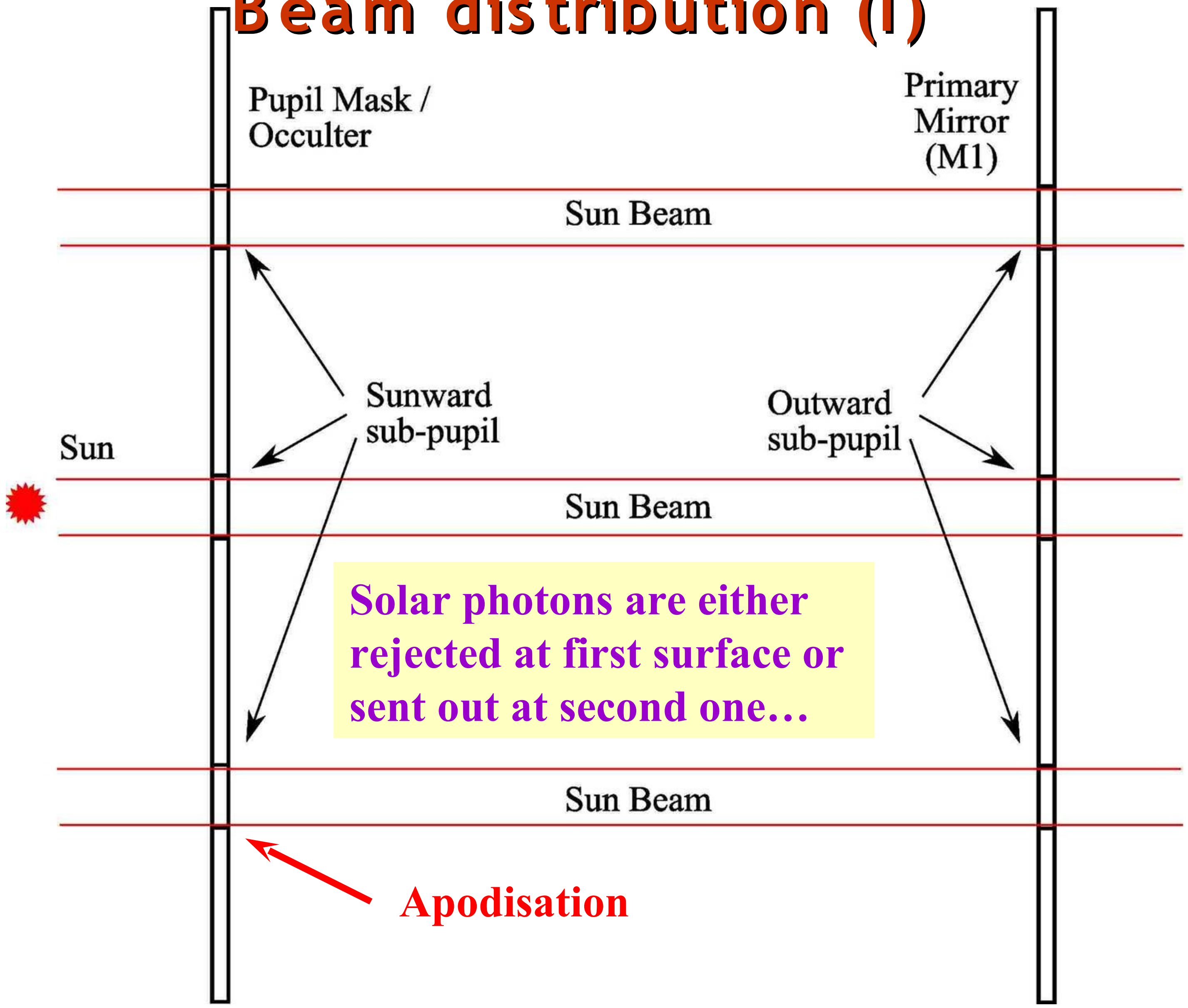
Goal: achieve higher resolution through small apertures

Fizeau interferometer implemented by Pupil Masking:
set of elementary apertures cut on pupil of underlying monolithic telescope ⇒ cophasing by alignment

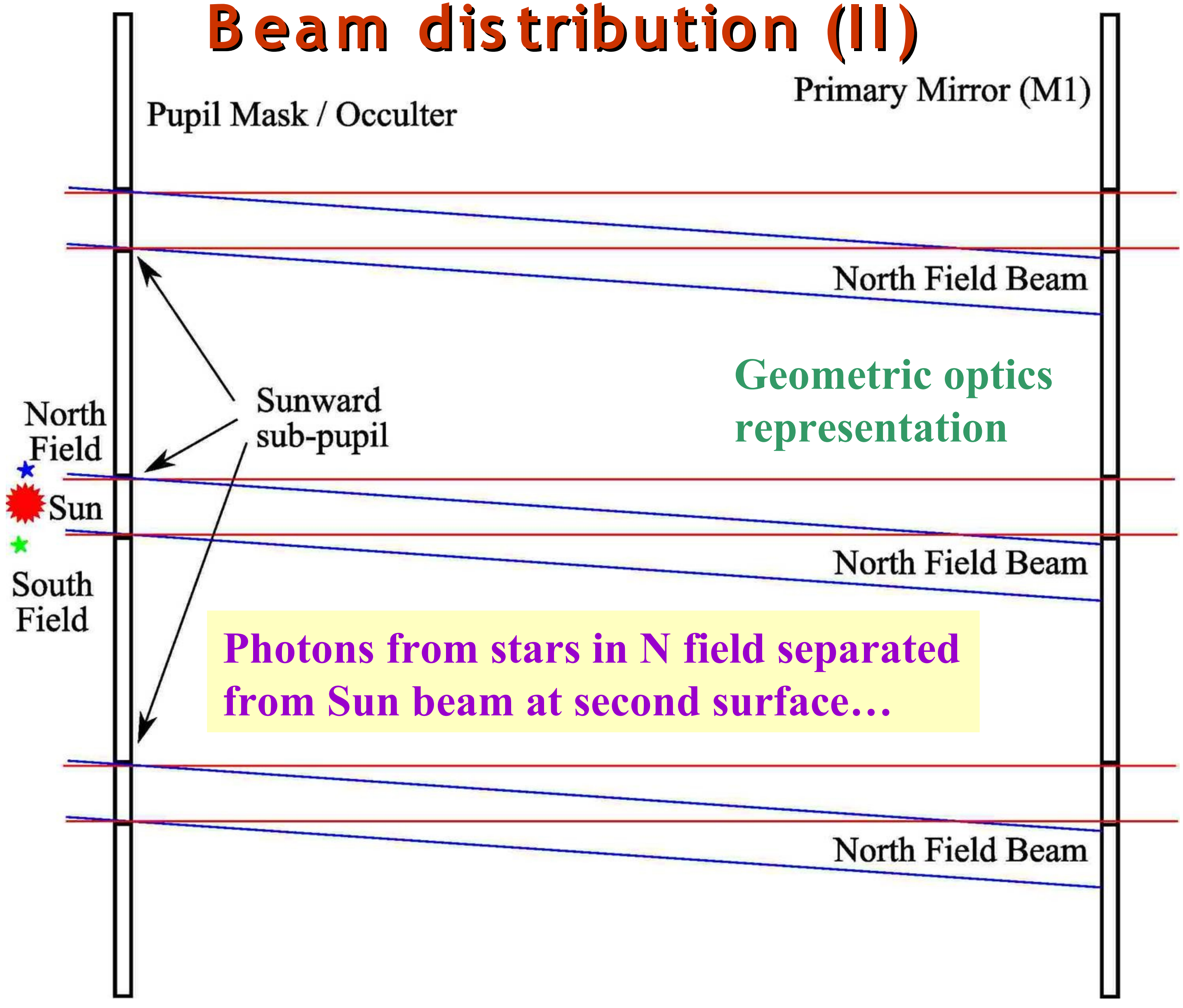
Coronagraphic techniques applied to each aperture ⇔ replication of individual coronagraphs in phased array

Geometry optimised vs. astrometry and background

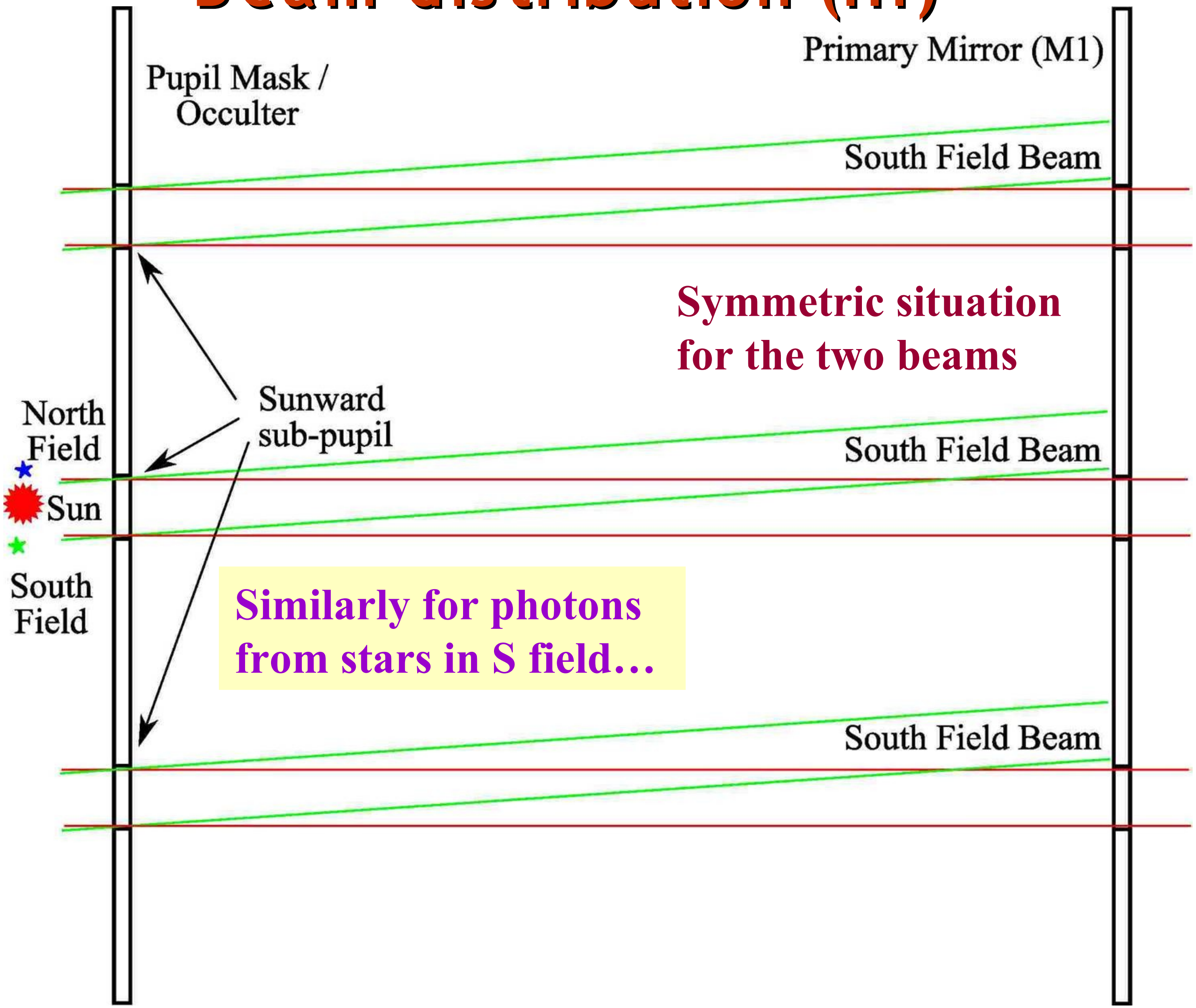
Beam distribution (I)



Beam distribution (II)



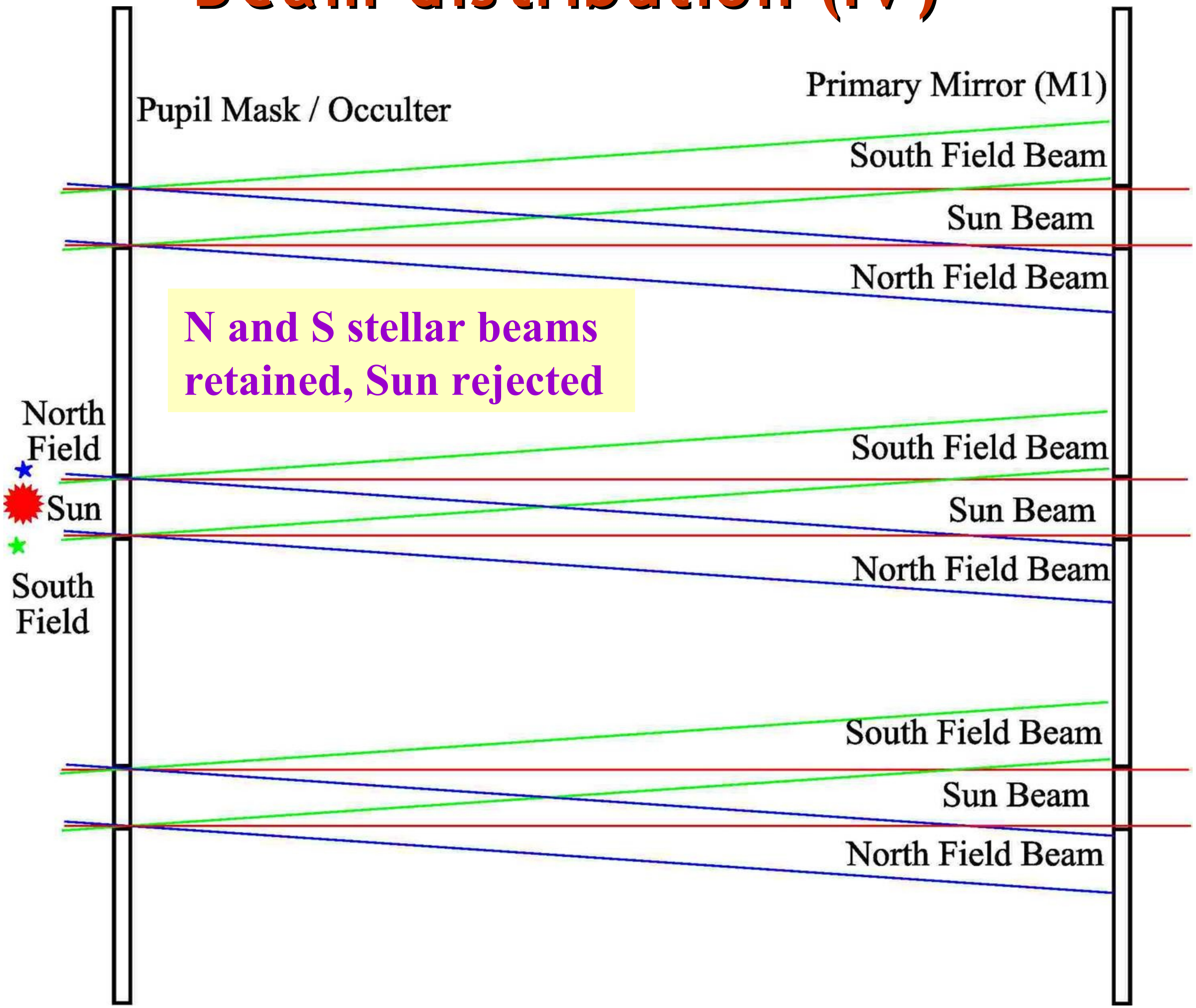
Beam distribution (III)



Symmetric situation for the two beams

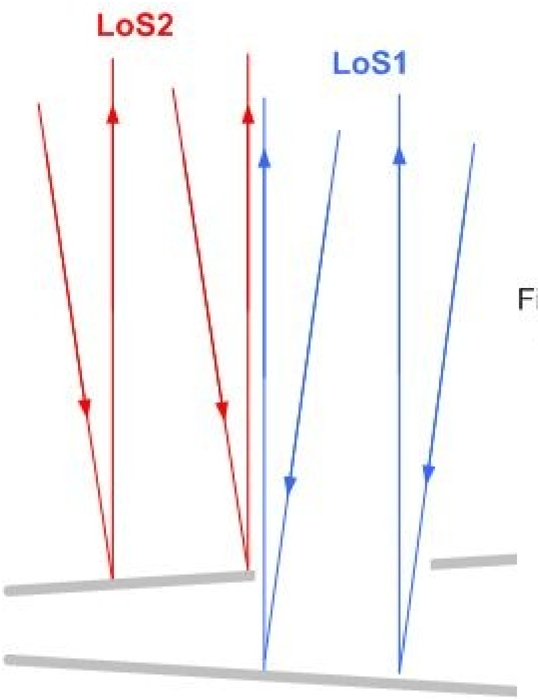
Similarly for photons from stars in S field…

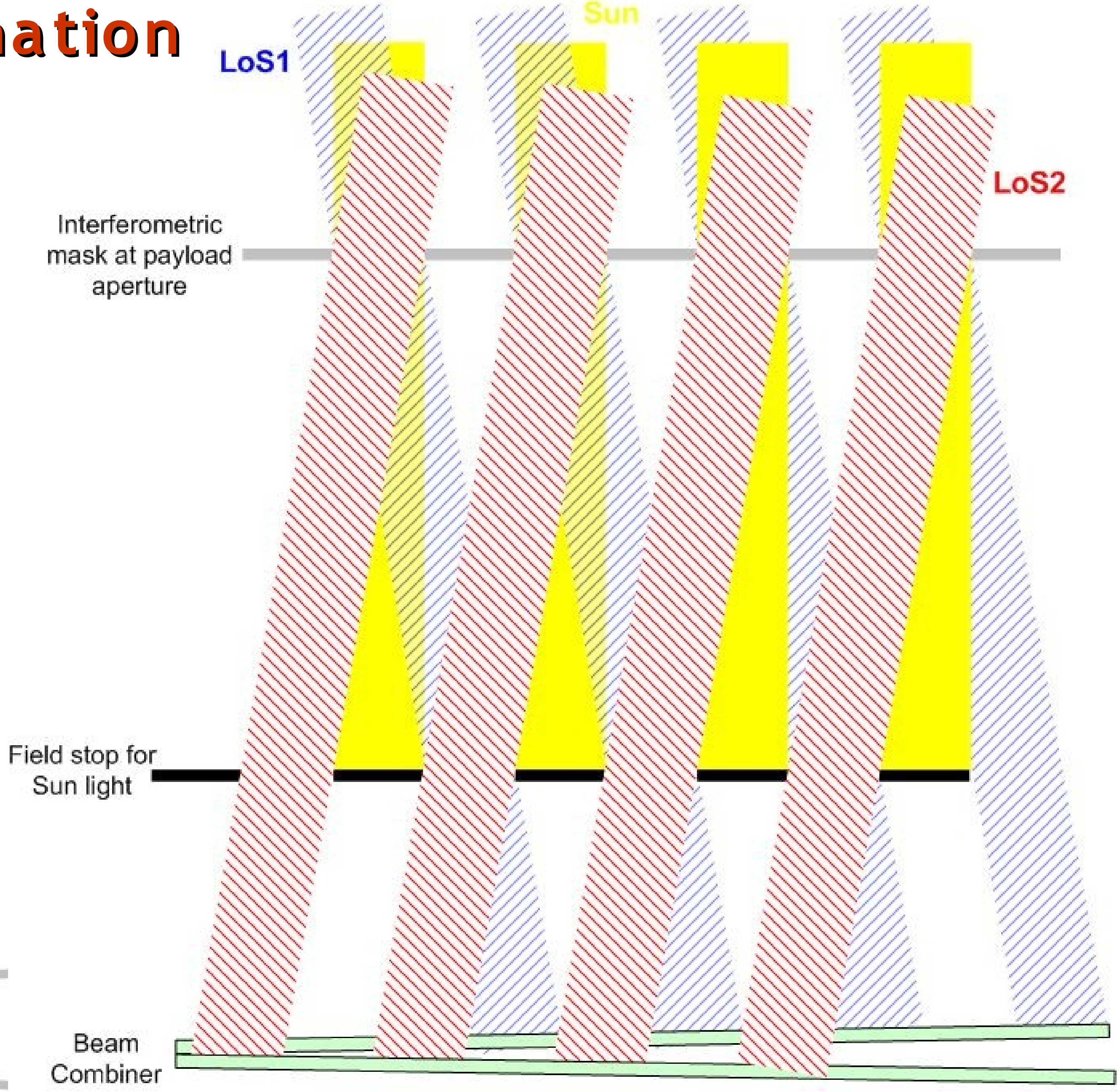
Beam distribution (IV)



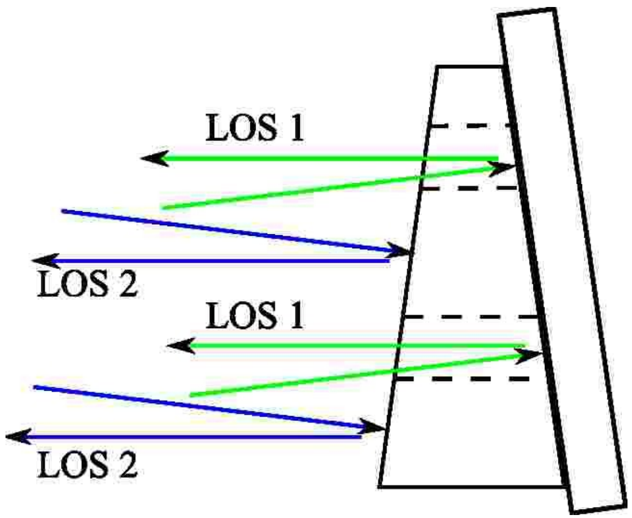
Beam Combination

N and S stellar beams folded onto telescope optical axis by beam combiner





Beam Combination

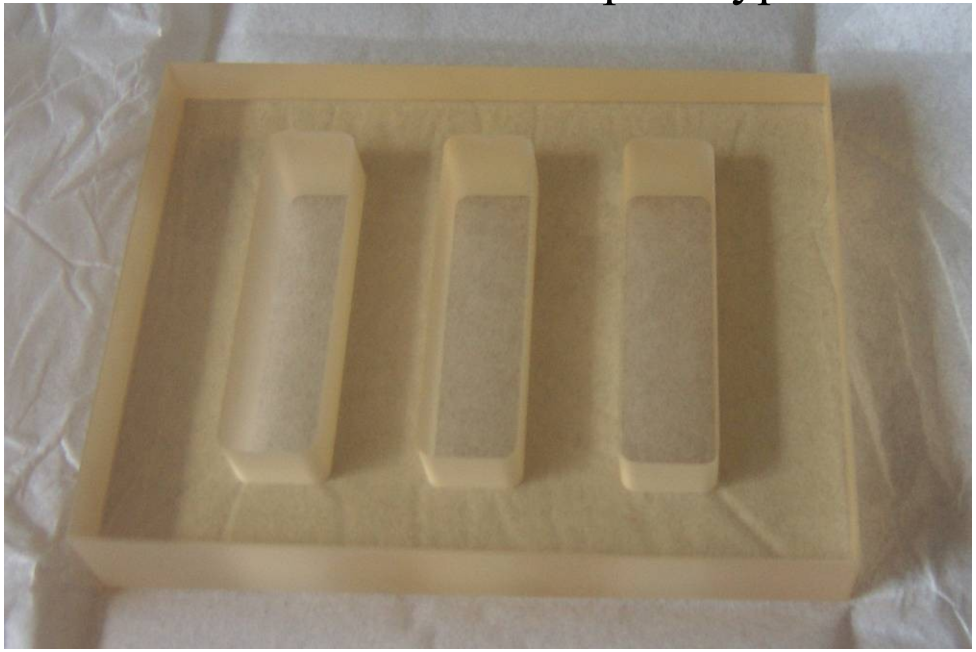


Requirements on Beam Combiner:

Two flat, pierced mirrors set at fixed angle

High dimensional stability over epochs

90×115 mm^2 Zerodur prototype

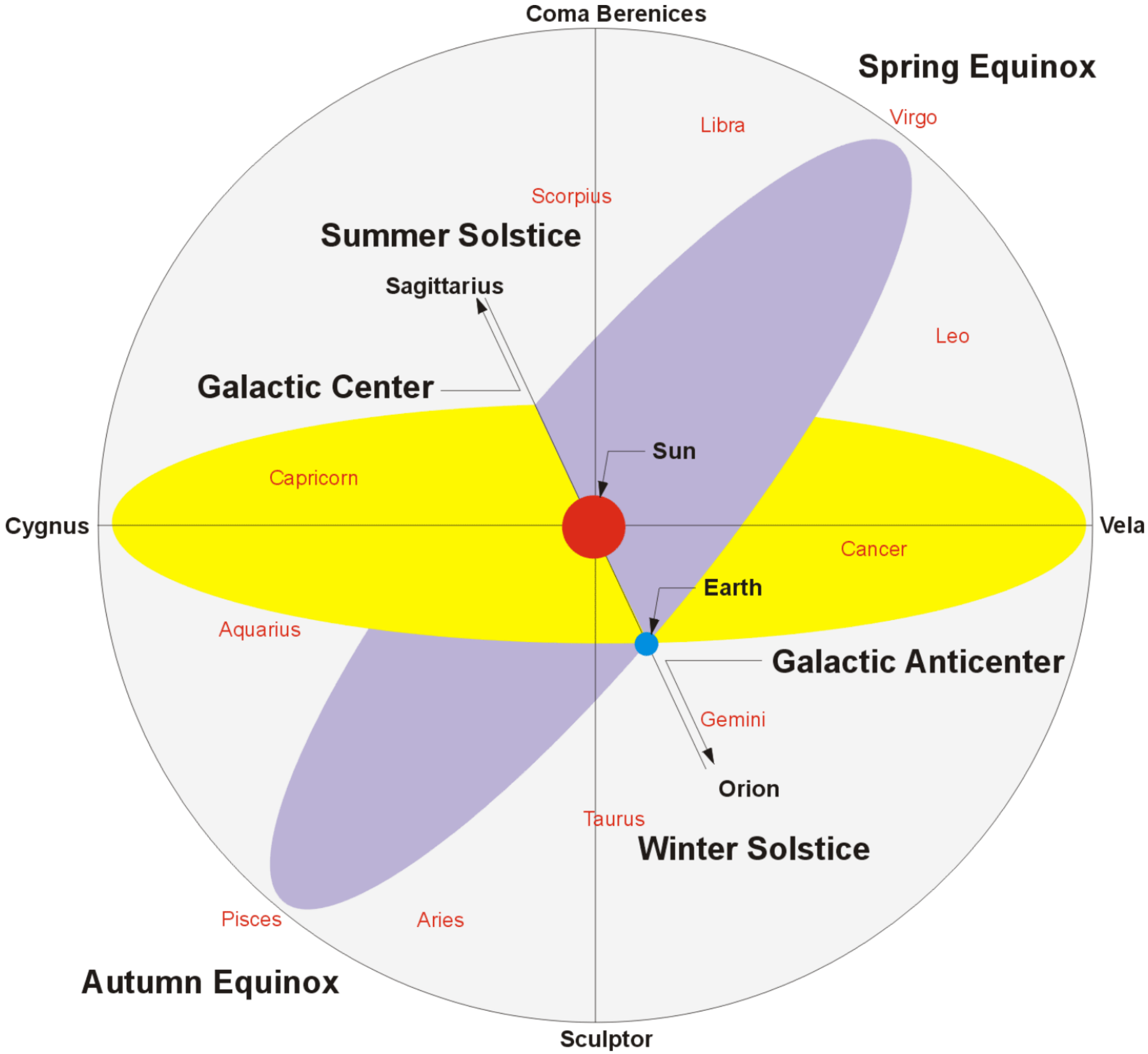


Proposed solution:

Pierced prism hosting one optical surface and supporting flat mirror e.g. by silicon bonding (LISA)

Near-monolithic assembly

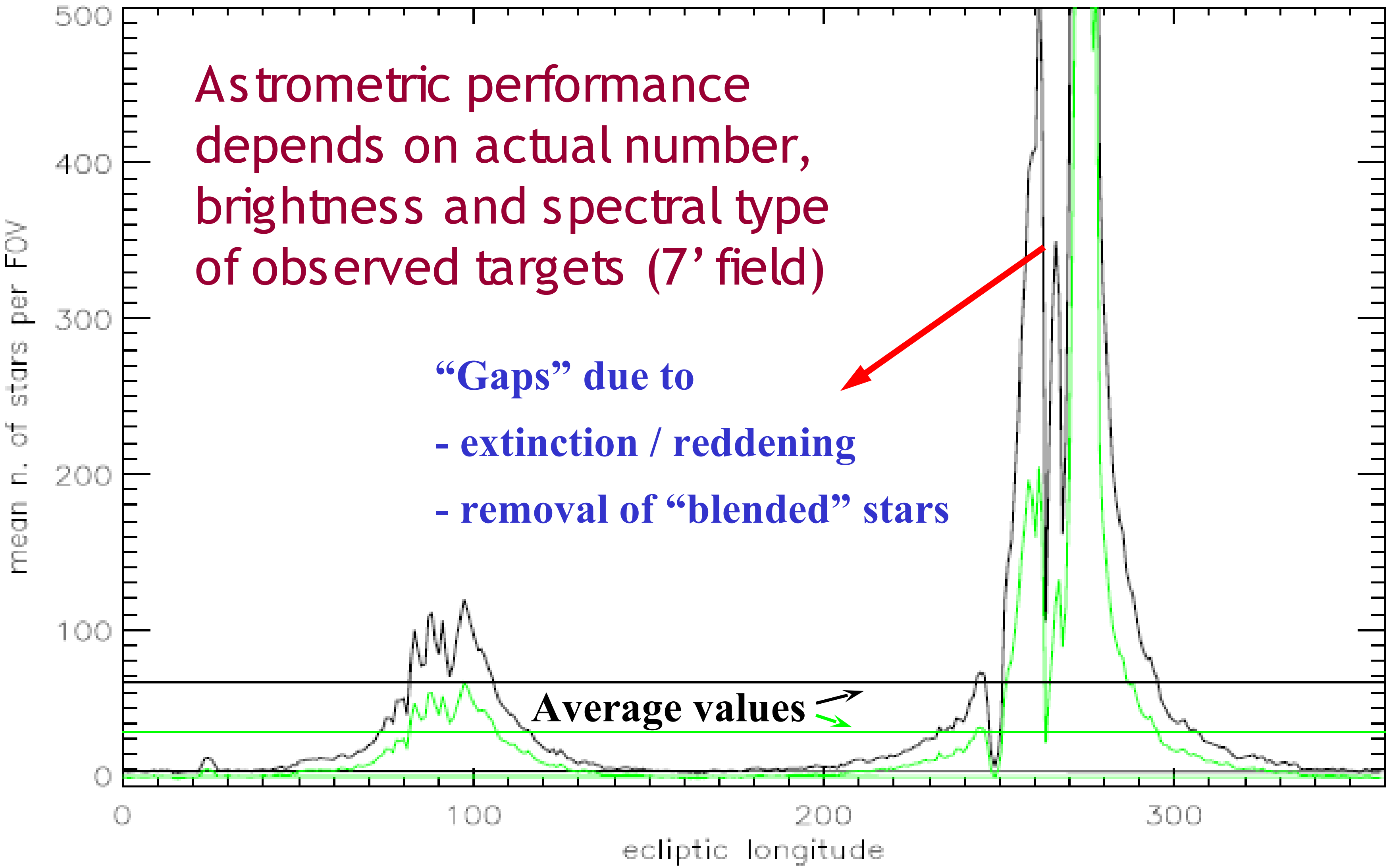
Convenient fields: Galactic plane Ecliptic



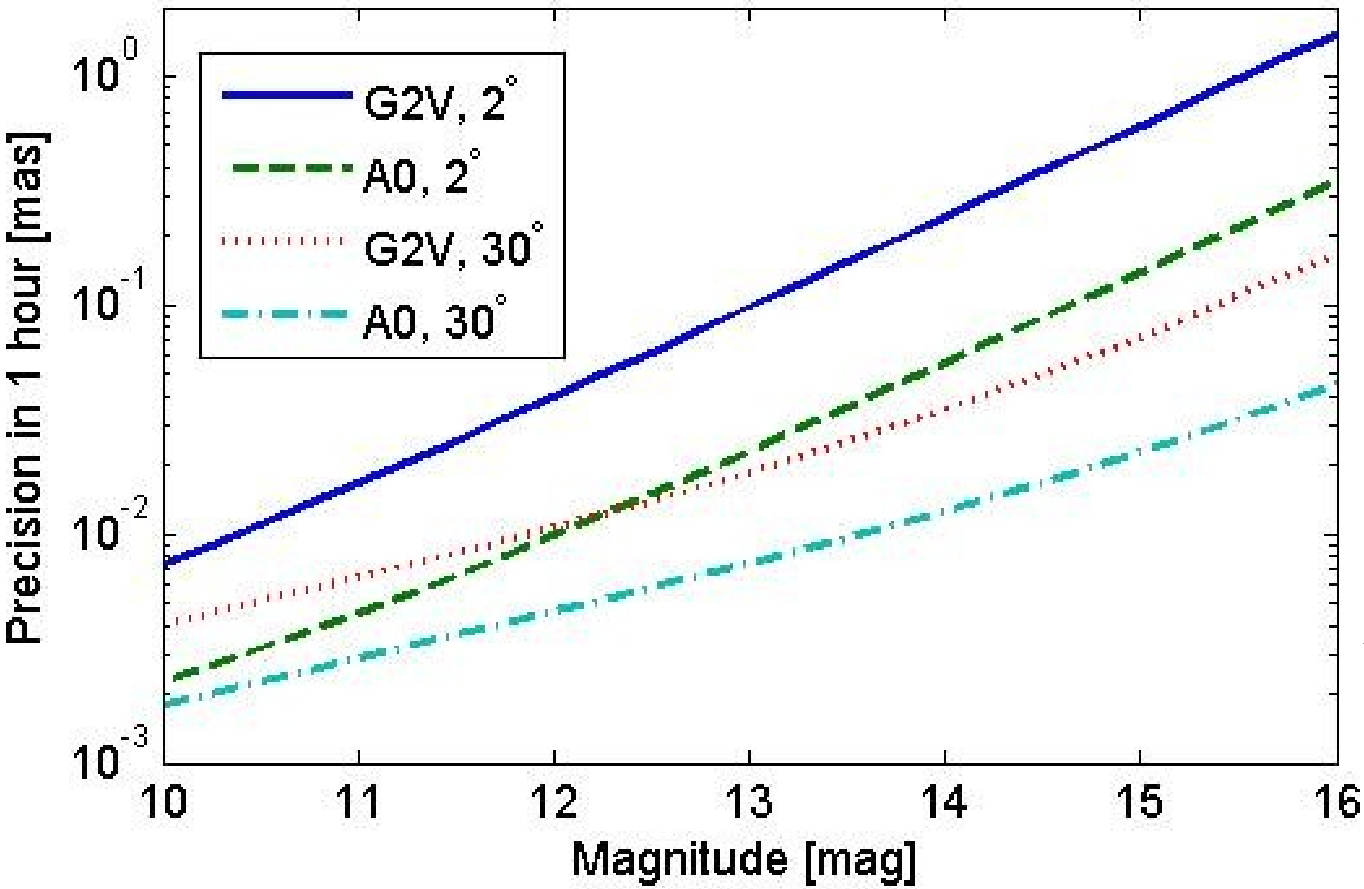
High stellar density regions:

intersection of Galactic and Ecliptic planes, toward Galactic centre / anti-centre

GSCII star counts along ecliptic plane



Elementary astrometric performance



Precision on a 15 mag star: < 1 mas_

Band:

$$\lambda_0 = 650\,nm$$

$$\Delta\lambda_{RMS} = 120\,nm$$

Performance depending on spectral type, background, …

Photon limited performance - small mission

1 million 15 mag stars required to achieve 1 μas cumulative

⇒2e-6 equivalent precision on γ

Observing time required: 20 + 20 days **[Gai et al., SPIE 2009]**

[on average Galactic plane stellar density from GSCII]

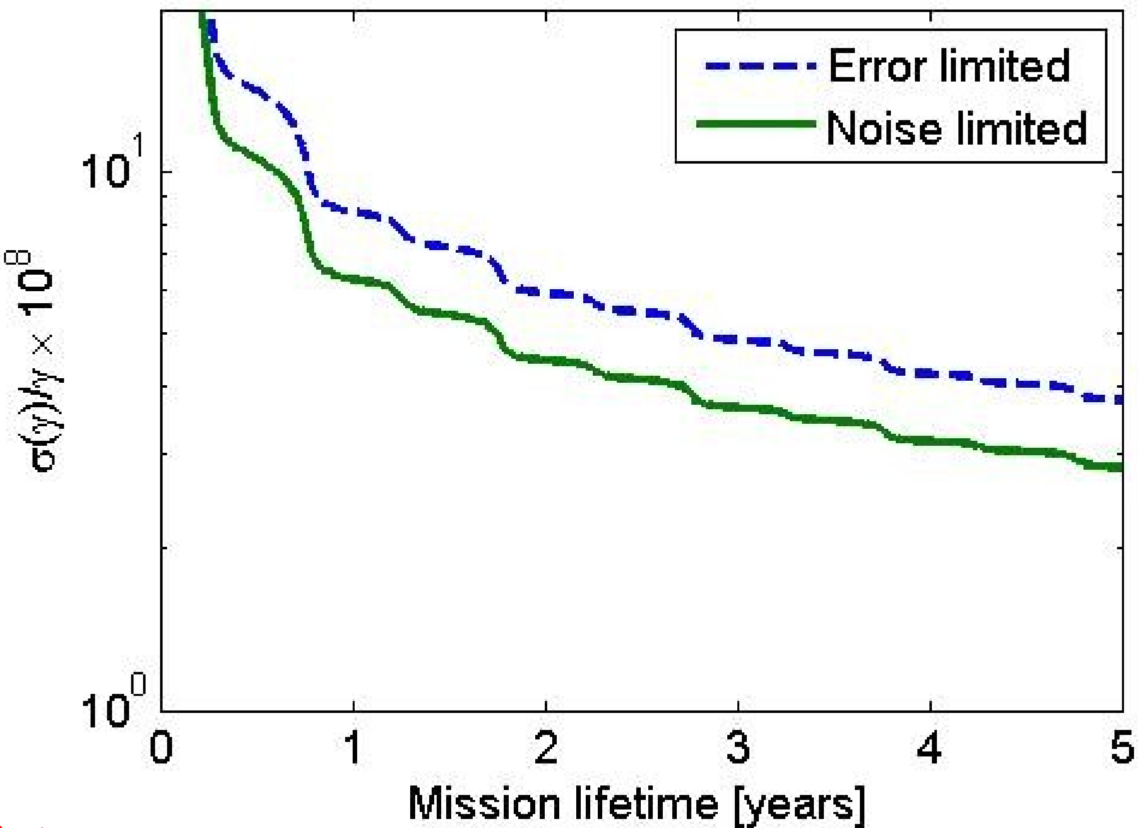
Observation focused on Galactic centre / anti-centre region:
3e-7 precision on γ ⇔ 2 + 2 months over 2 years

[Gai et al., COSPAR 2010;
Vecchiato et al., COSPAR 2010]

Photon limited performance - medium mission

Performance factors: ~diameter^2, (field of view)^{3/2}

5 years mission:
4e-8 precision on γ
5e-6 precision on β



ESA M3 proposal:
Cosmic Visions
2015-2025

Portugal: O. Bertolami & team

[Gai et al., Exp.Astr. 2011 (sub.)]

Concluding remarks

- ✓ Astronomical techniques ⇒ Fundamental Physics
- ✓ **GAME: Intrinsic mitigation of systematic errors**
- ✓ Double differential μas-level astrometry ⇒
  PPN γ to $10^{-7} – 10^{-8}$ range; PPN β to $10^{-5} – 10^{-6}$ range
- ✓ Efficient implementation on dedicated space mission
- ✓ Observation concentrated on few epochs, high density regions
- ✓ **Additional (astro-)physical topics achievable**
- ✓ Instrument based on proven concepts/technologies:
  coronagraphy + Fizeau interferometry

GAME [PRESENTATION] OVER

Open questions

What else can GAME do for you?

- either optimising observations with current configuration…
- adding additional secondary instruments…
- or optimising the main payload…

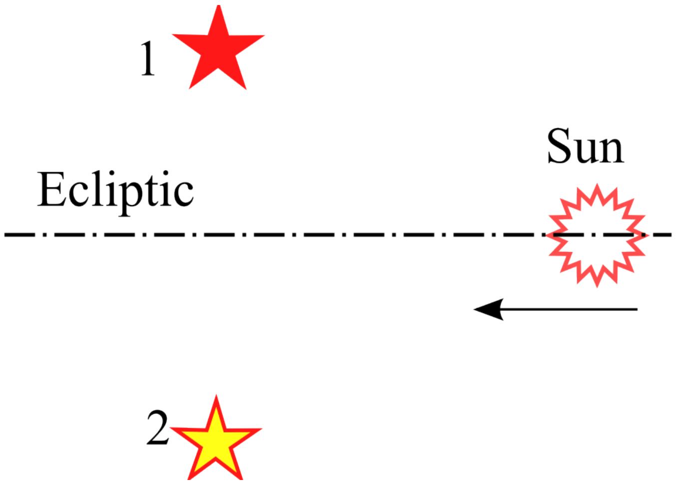
⇒ Concept dissemination within science community

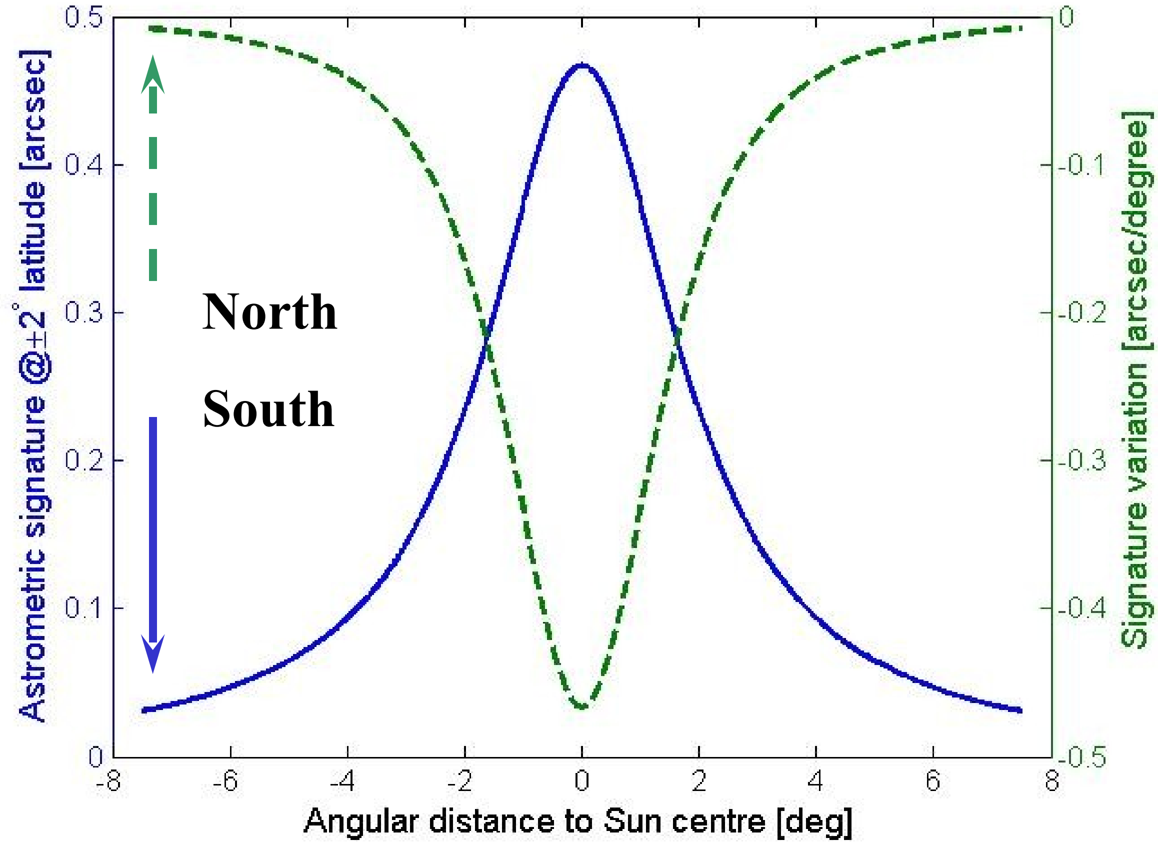
GAME vs. ESA Cosmic Vision "Grand Themes"

	Cosmic Vision Theme	GAME
1	What are the conditions for planet formation and the emergence of life?	10%
2	How does the Solar System work?	20%
3	**What are the fundamental physical laws of the Universe?**	**60%**
4	How did the Universe originate and what is it made of?	10%

Main science goal consistent with the Roadmap for Fundamental Physics in Space [by ESA appointed Advisory Team]

Astrometric signature at 2° ecliptic latitude

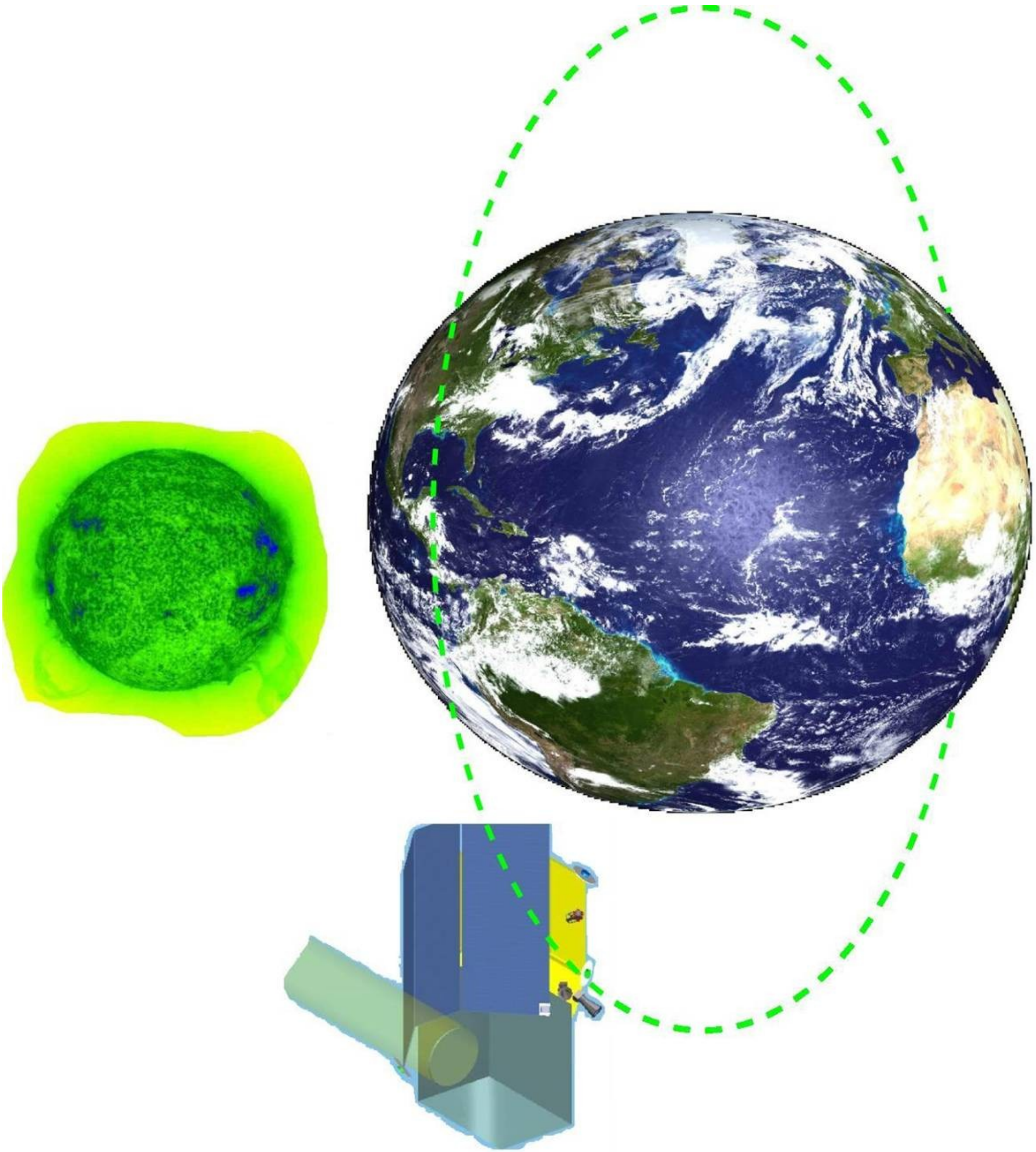




Peak displacement between stars @ ±2°: 466 mas

Largest signature over ±10° along the ecliptic, i.e. about ±10 days

Mission profile

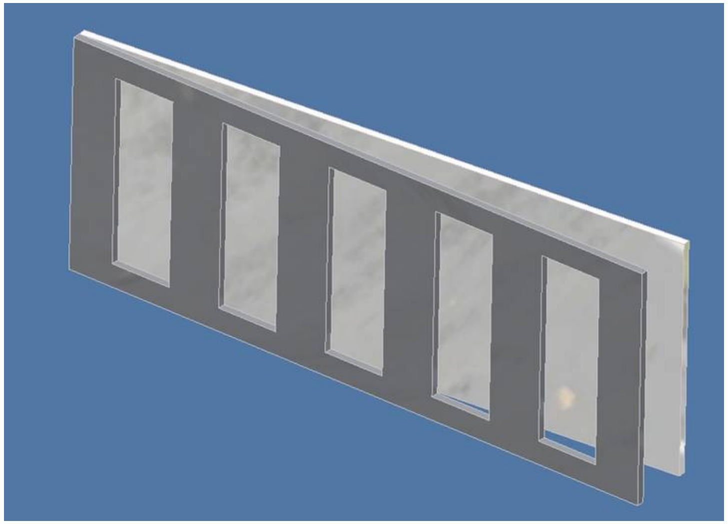


Sun-synchronous orbit, 1500 km elevation ⇒ no eclipse

100% nominal observing time

Stable solar power supply and thermal environment ⇒ instrument structural stability

Beam Combination aspects



Requirements on Beam Combiner:

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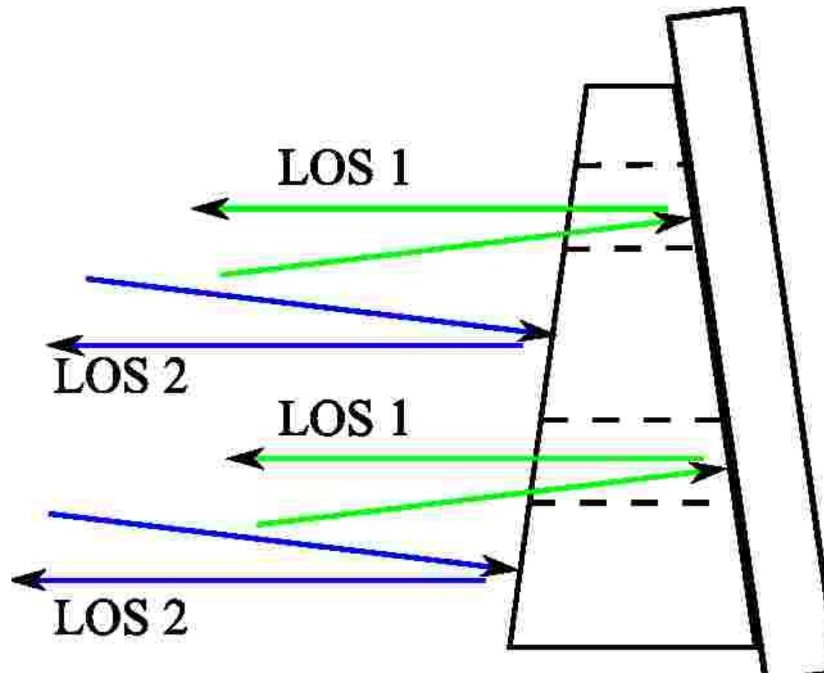
High dimensional stability over epochs

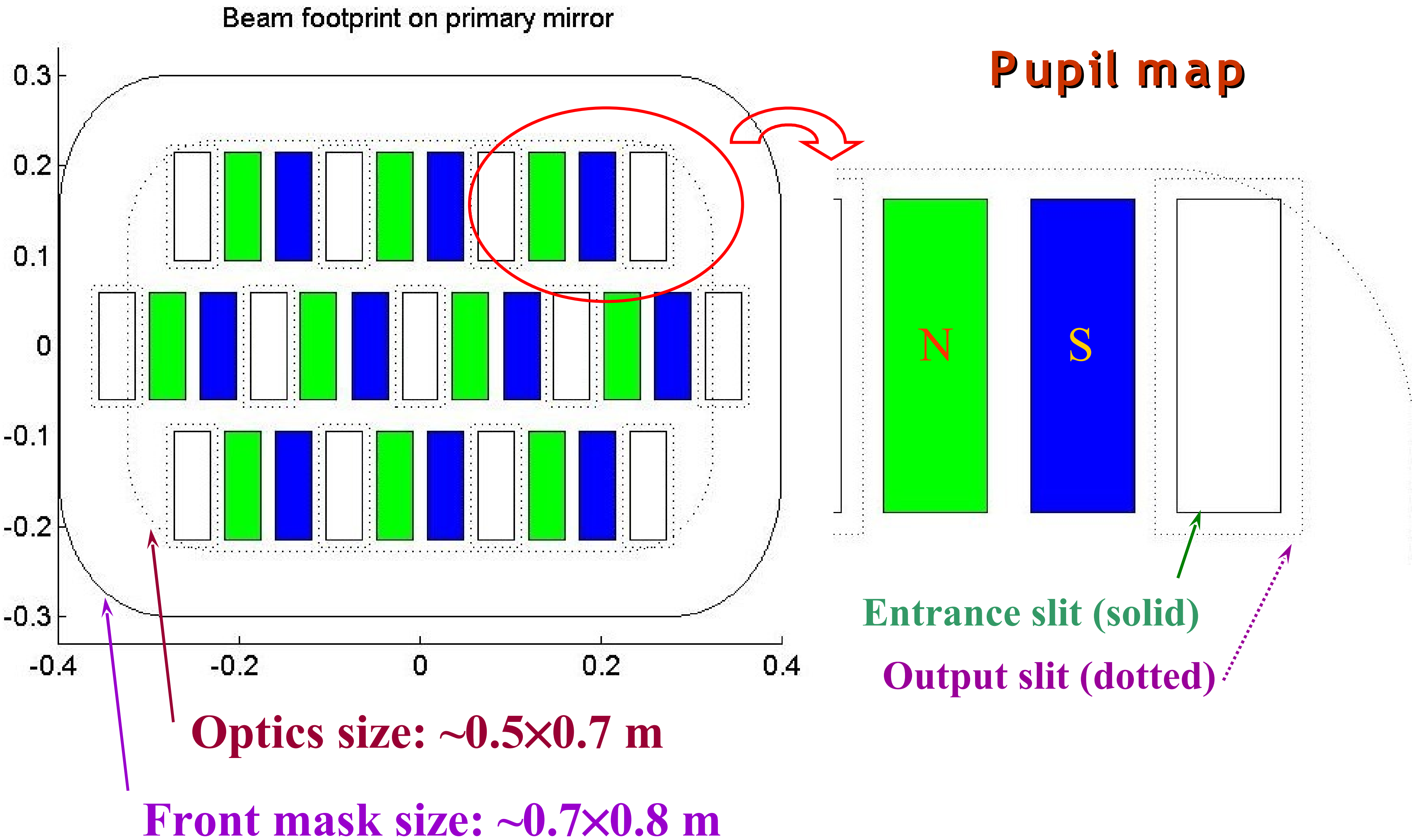
Proposed solution:

Pierced prism hosting one optical surface and supporting flat mirror e.g. by silicon bonding (LISA)

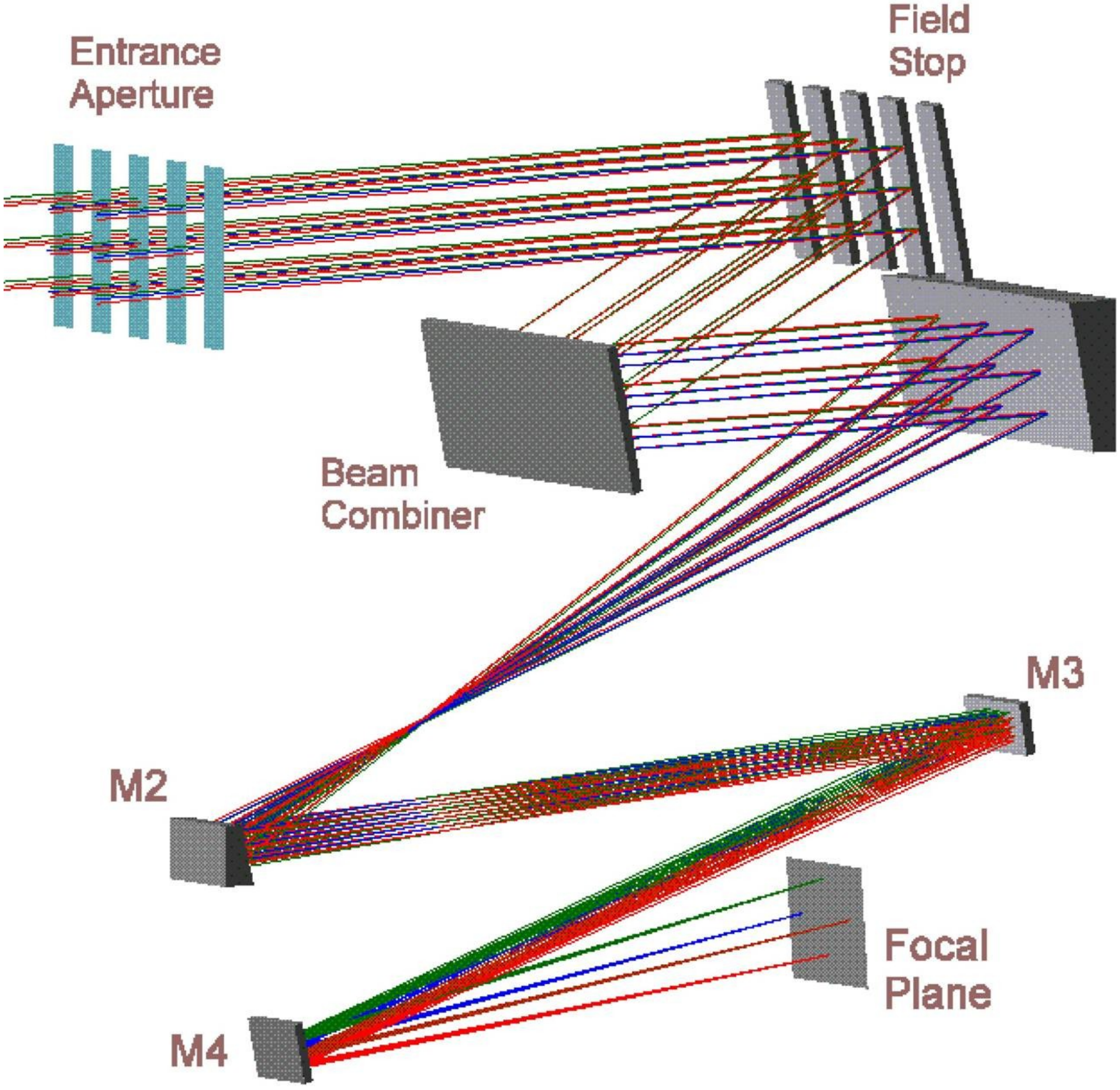
Near-monolithic assembly



Small mission version



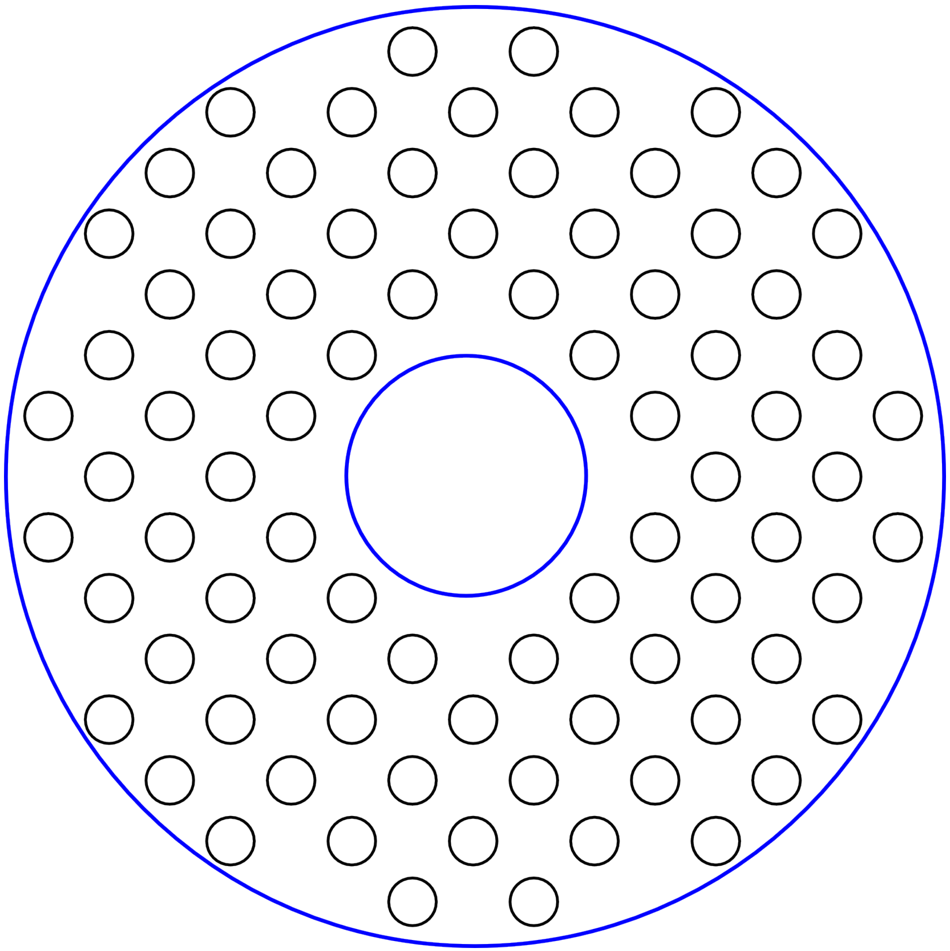
Optics layout



Korsch, 4 mirrors,
EFL = 19.50 m,
visibility > 95% over
20×20 arcmin field;
distortion < 1e-4

[Loreggia et al., SPIE 2010]

Medium mission version

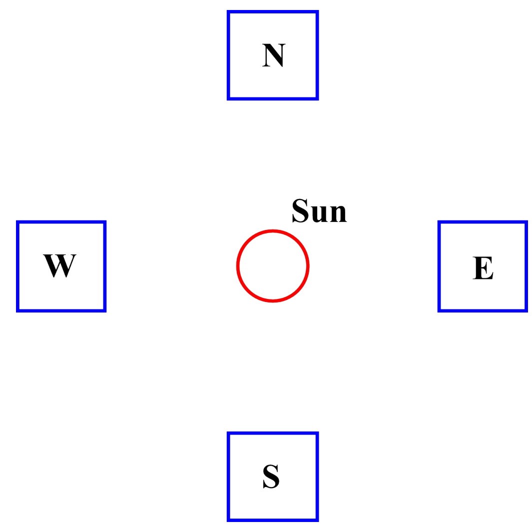


Pupil map

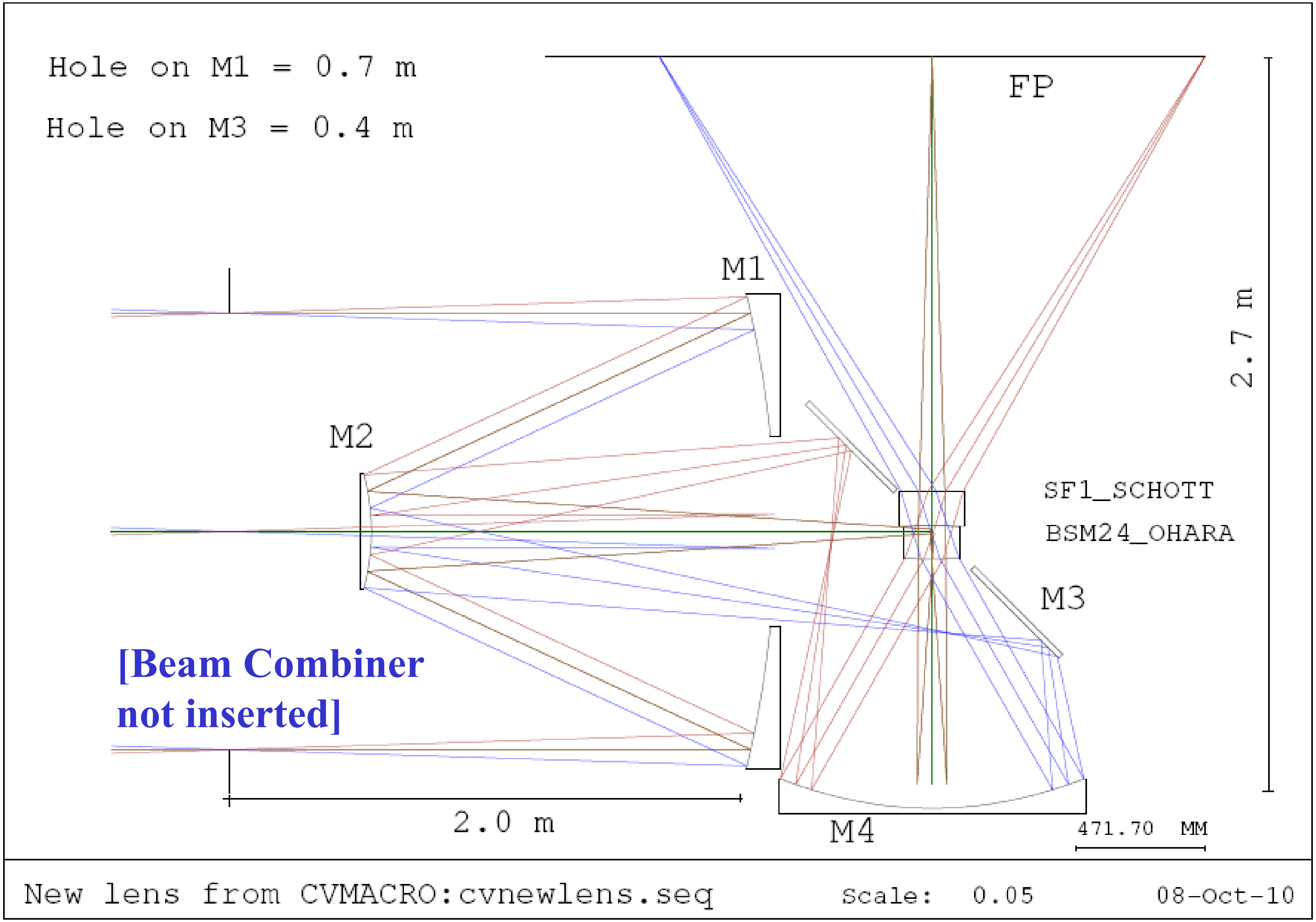
Overall diameter: ~1.5 m

Individual diameter: 7 cm

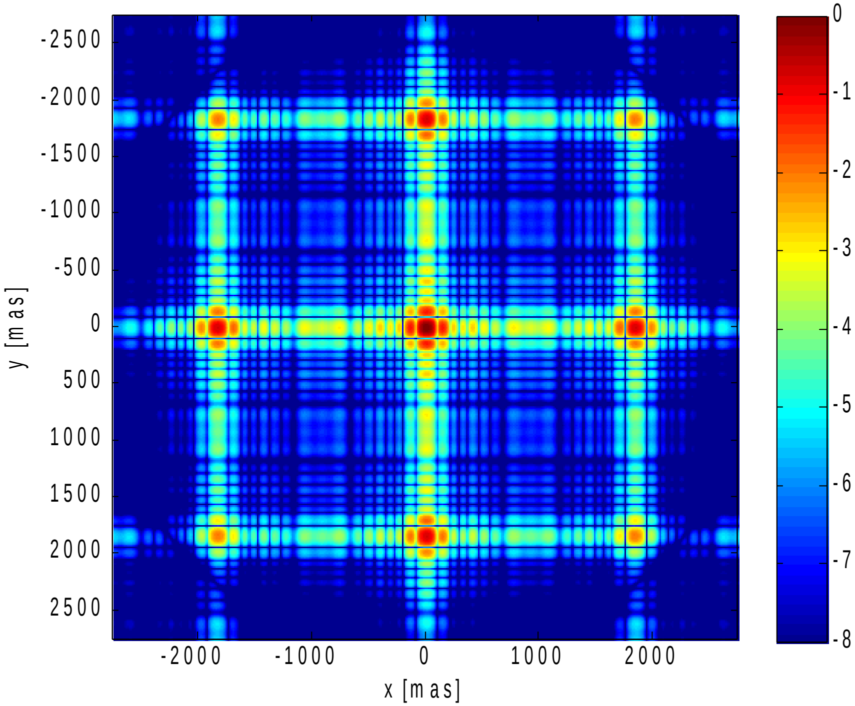
Simultaneous observation of 4 Sun-ward + 4 outward fields



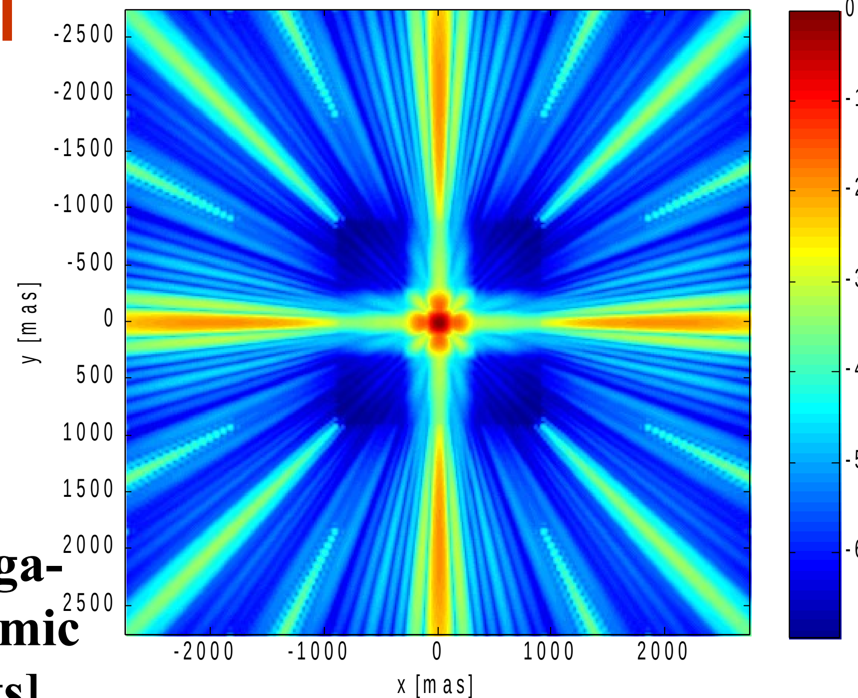
Preliminary optical design (unfolded)



Imaging performance: Aberration free PSF



[Loga-
rithmic
units]



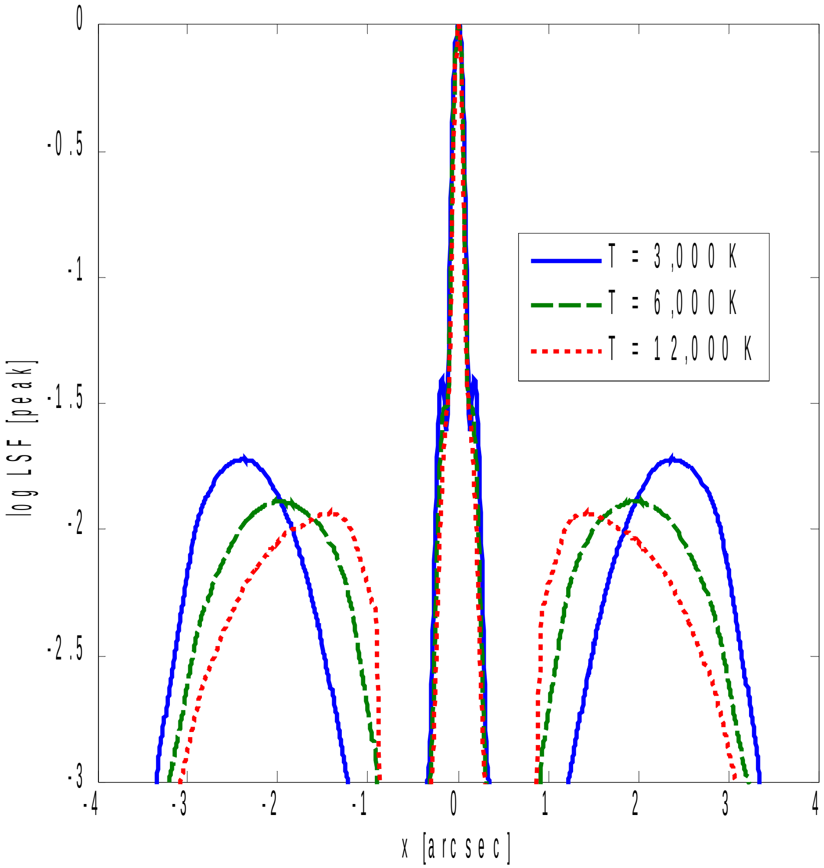
Monochromatic PSF
(λ = 600 nm)

Polychromatic PSF
(T = 6000 K)

~50% photons concentrated in central peak

~30% photons in main dispersed fringes ⇒ photometry

Photometry on PSF wings



Feasible in low background conditions (away from Sun)

Nearly independent from astrometry (central peak)

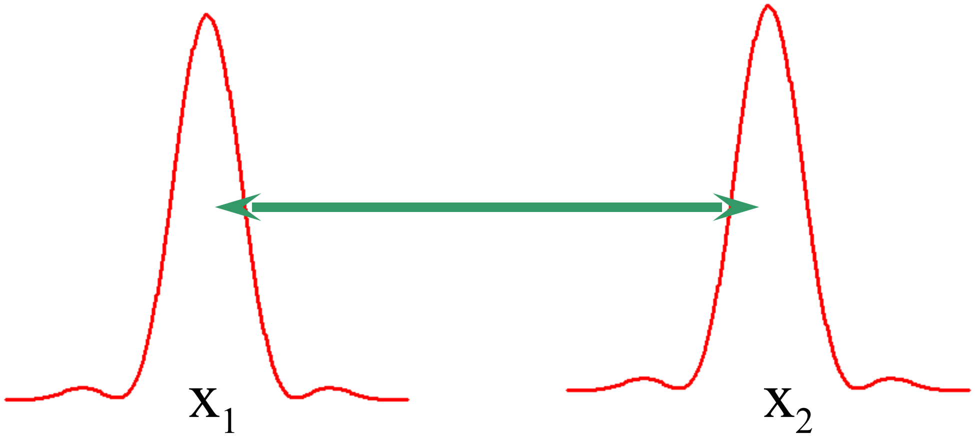
Crowding tolerant due to the four wings available [13% SNR loss / one wing]

…but most stars are already known from catalogue…

Basic optical / detector parameters

Elementary entrance aperture diameter:	6 cm diameter
Elementary output aperture diameter:	10 cm diameter
Main tube length (pupil mask to primary mirror):	2.5 m
Envelope diameter (M1, M2):	1.6 m
Effective focal length:	45 m (scale: 4.58 arcsec/mm)
Pixel size:	13.5 μm = 62 mas
Total field of view:	30×30 arcmin
Focal plane:	15×8 CCD mosaic
Detector: EEV CCD42-80	**2k×4k, 13.5 μm pixels**

Precision on image separation



Arc length defined by composition of individual locations

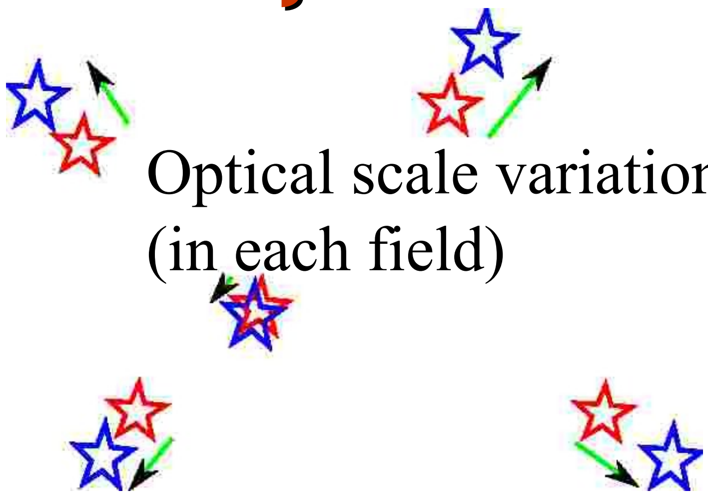
$$\sigma^2(x_1 - x_2) = \sigma^2(x_1) + \sigma^2(x_2)$$

Precision related to

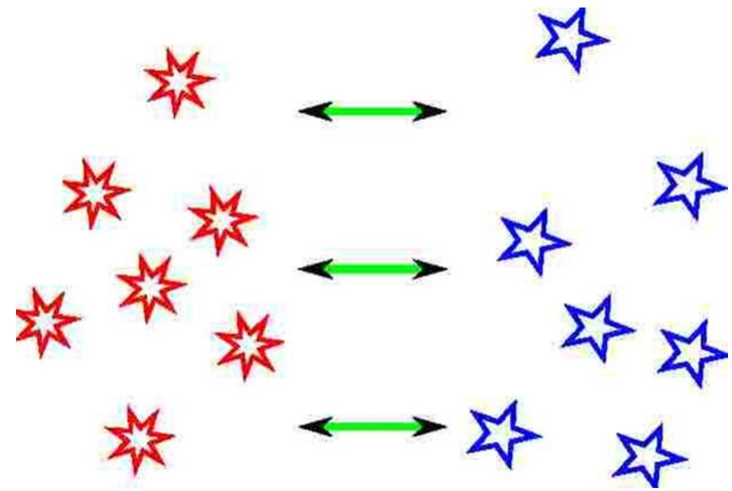
- ✓ Instrument resolution ⇒ Pupil size
- ✓ Source magnitude ⇒ Exposure time
- ✓ Average on # arcs ⇒ Field of view

} Observing strategy

Fully differential measurement (III)



Optical scale variation
(in each field)



Deflection between fields

Different **collective** effects on field images from

- instrument evolution (focal length, distortion)
- deflection (field displacement)

⇒ simple calibration of MULTIPLICATIVE terms

Why is space better than ground?

Atmospheric imaging limit without adaptive optics: **~1" [seeing]**

⇒ 10× degradation of individual location performance

Atmospheric coherence length in the visible: ~10"

⇒ **small differential deflection** ⇒ 100× degradation

Astrometric decorrelation noise ~0".1

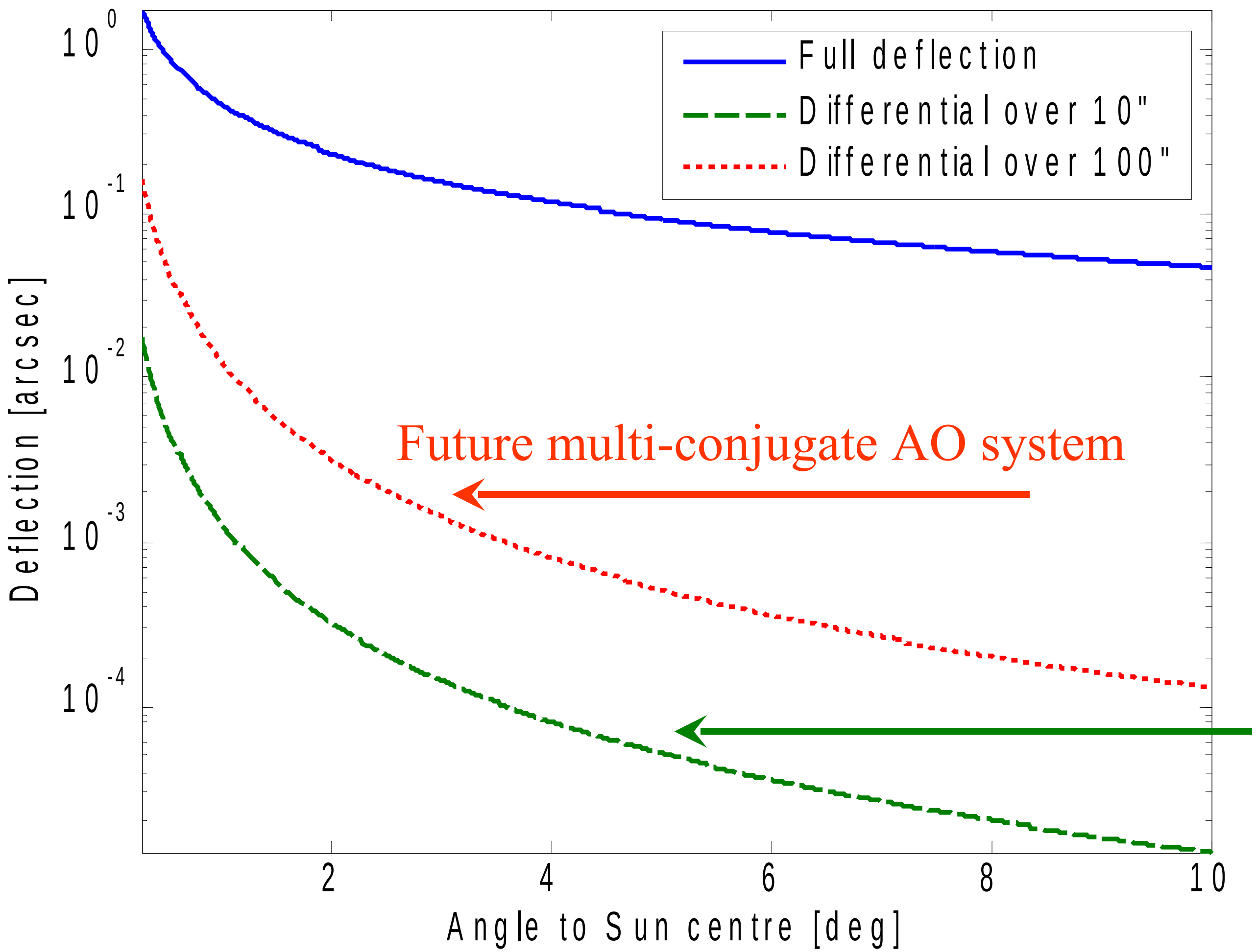
⇒ degraded statistics on stars ⇒ 10× degradation

Atmospheric diffusion of Sun light

⇒ increased background ⇒ 10÷100× degradation

Measurement performance loss vs. space case: 10^5 ÷10^6

Improvements achievable with adaptive optics

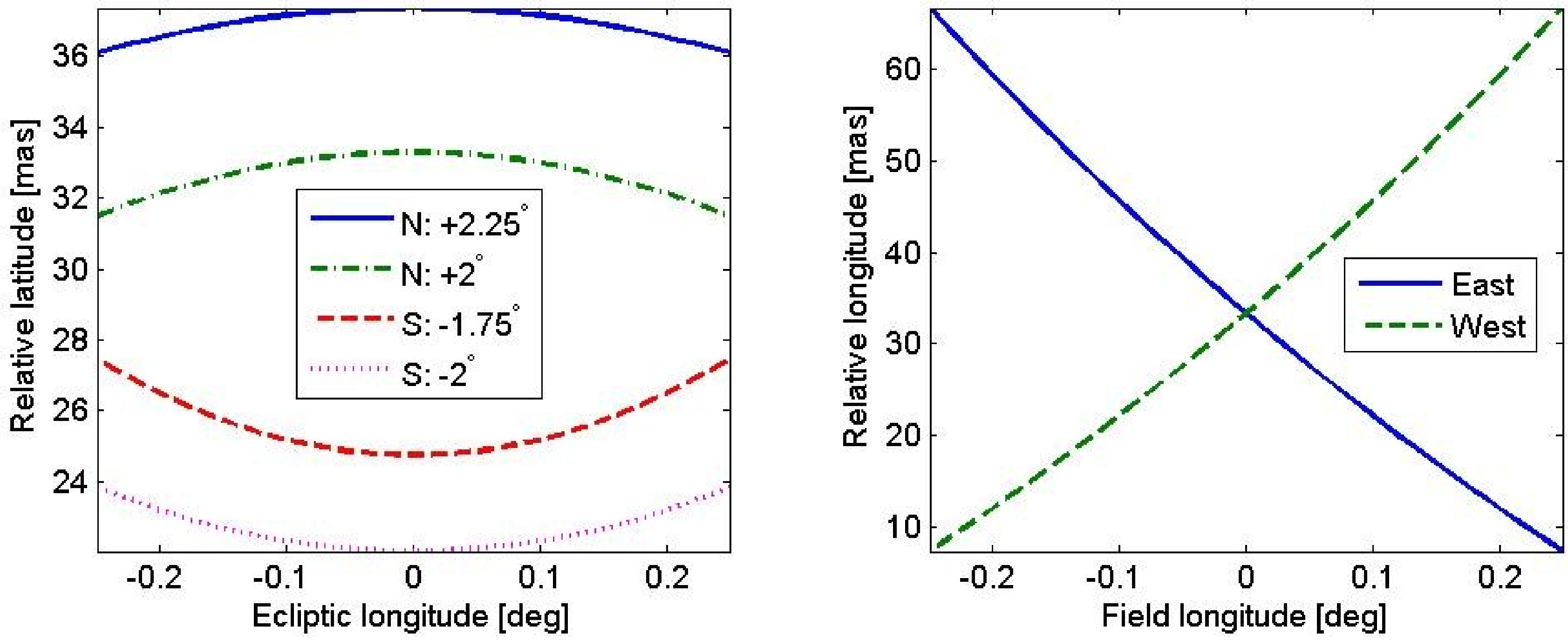


AO recovers <u>at most</u> 1-2 orders of magnitude

⇒ GAME needs space!

Large, state-of-the-art solar telescope equipped with high performance Adaptive Optics

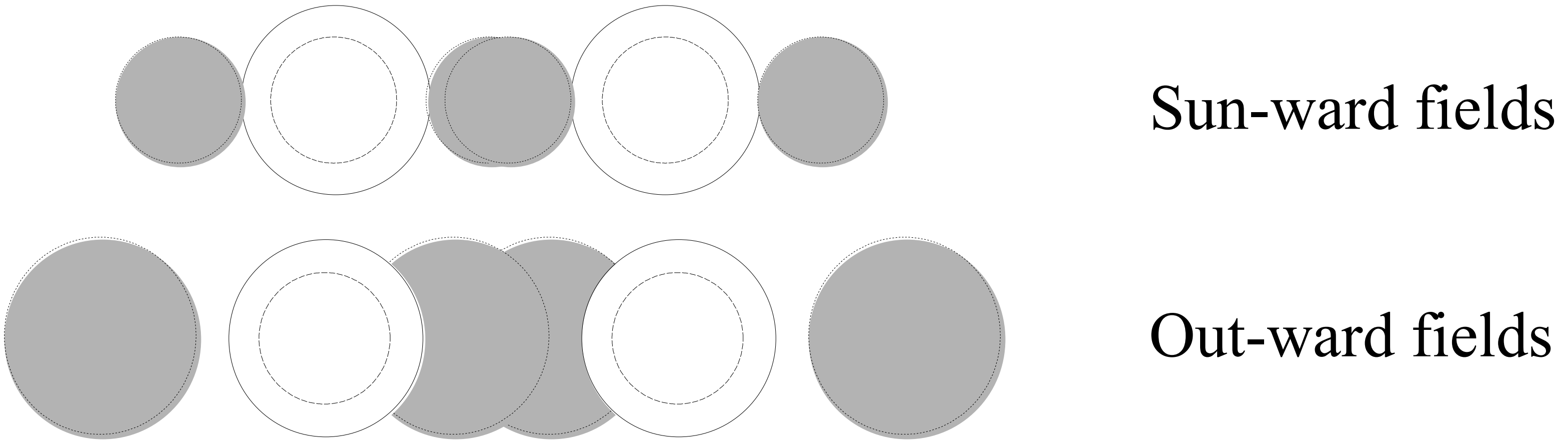
Field discrimination by deflection modulation

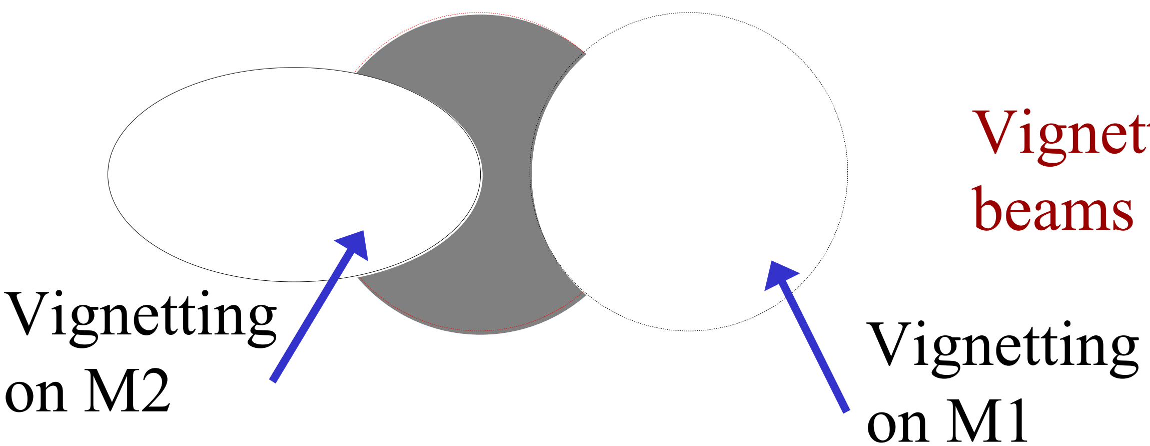


Deflection amplitude modulated by several mas along FOV transit

Additional orbital modulation:

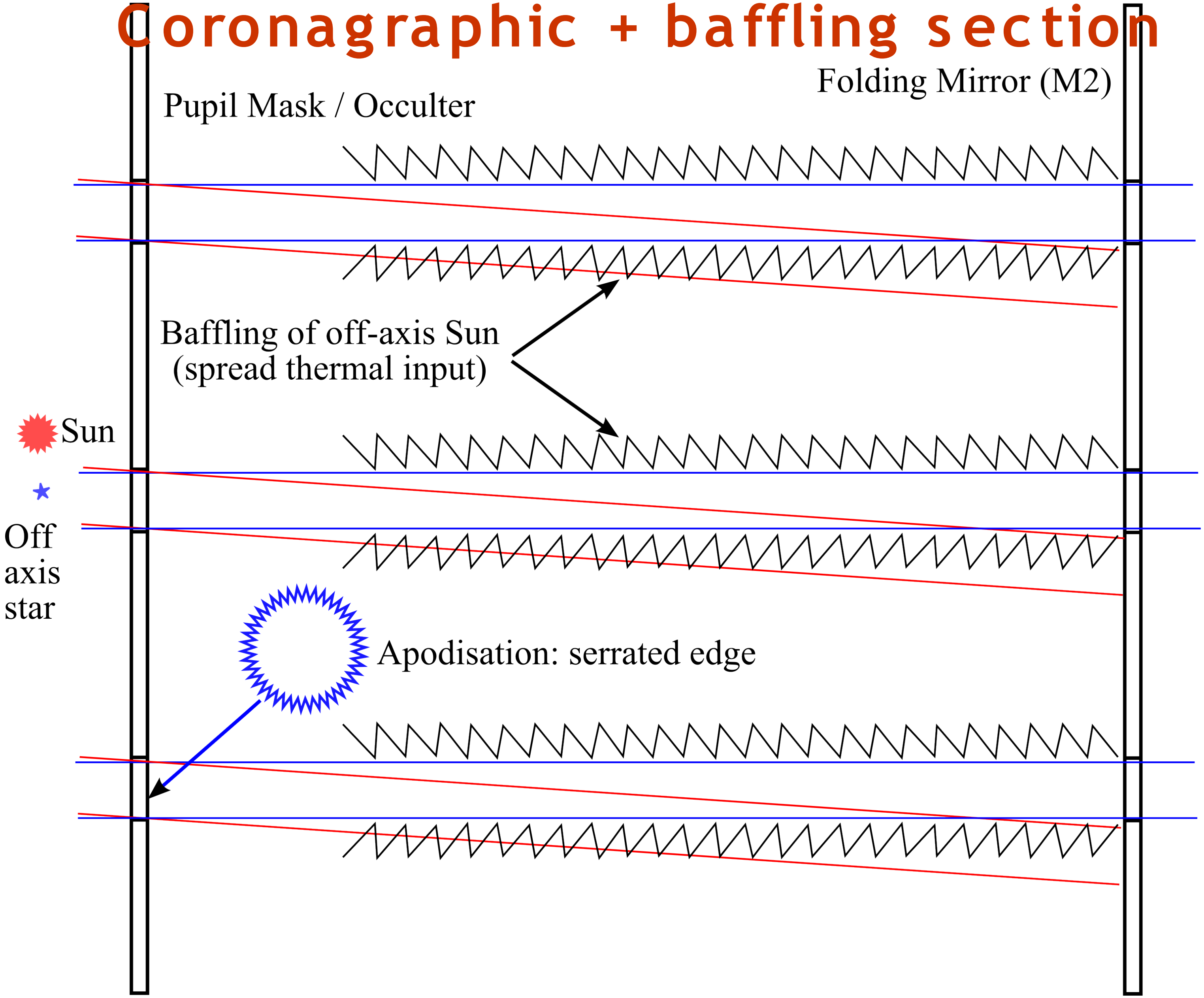
Beam footprint superposition on M1





Vignetting of out-ward beams on both M1 and M2

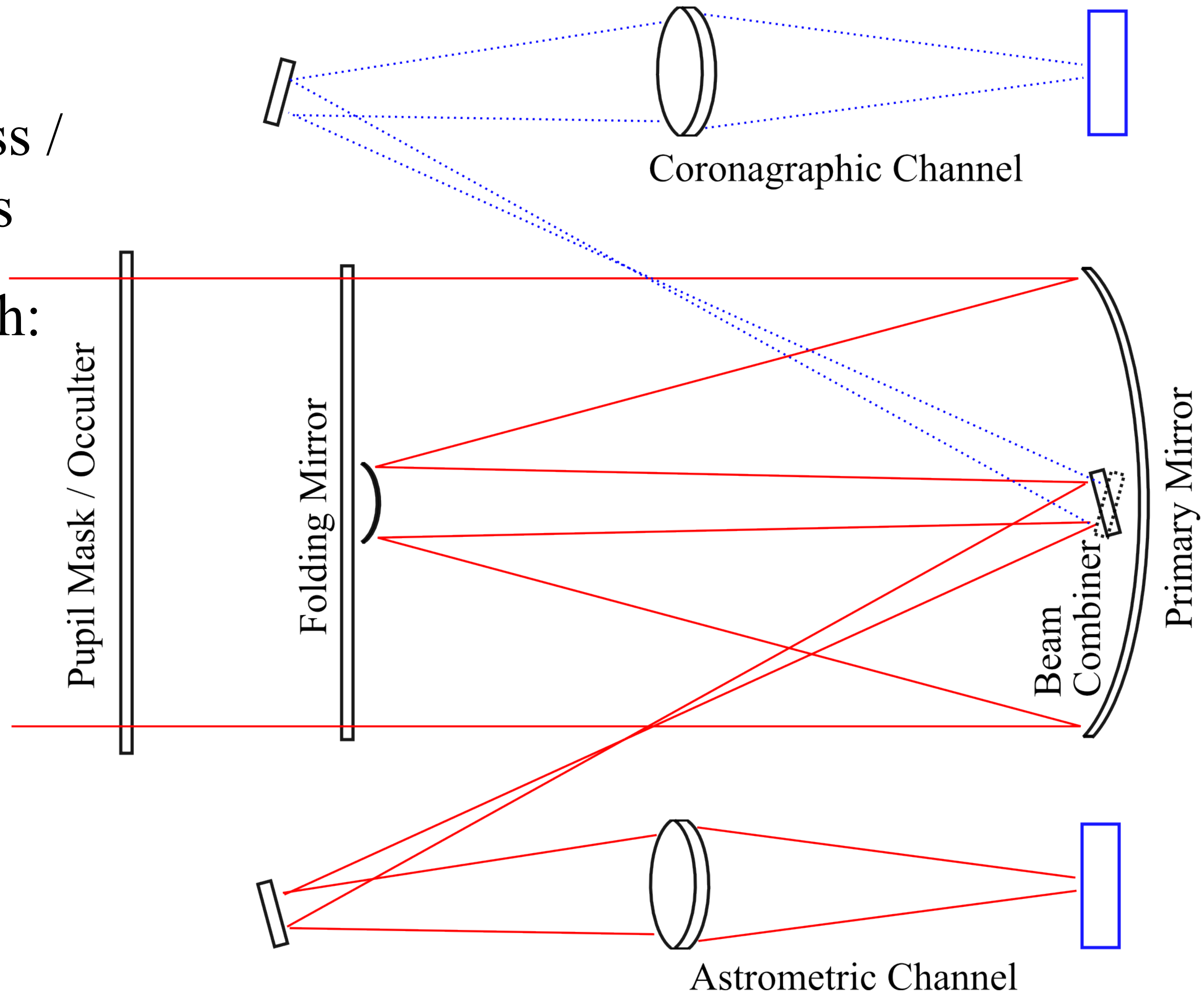
Coronagraphic + baffling section



Compatibility with additional payloads

Depending on mass / volume constraints

Most natural match: **Coronagraphic instrumentation**, also fed by main telescope



GAME vs. Gaia

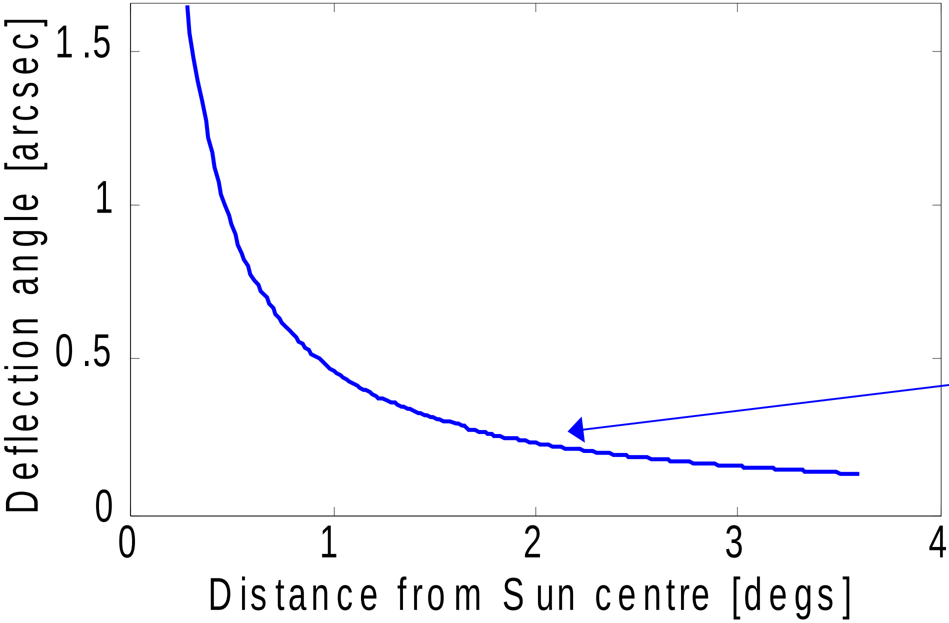
Commonality:

- Use of natural sources (**stars**) in two (or >2) fields of view
- Position measurement on CCD images
- Resolution (image size) ~200 mas

GAME peculiarity:

- Much more compact observing instrument, in low orbit
- **Payload optimised for γ and β measurement**
- **Fully differential**

Deflection range

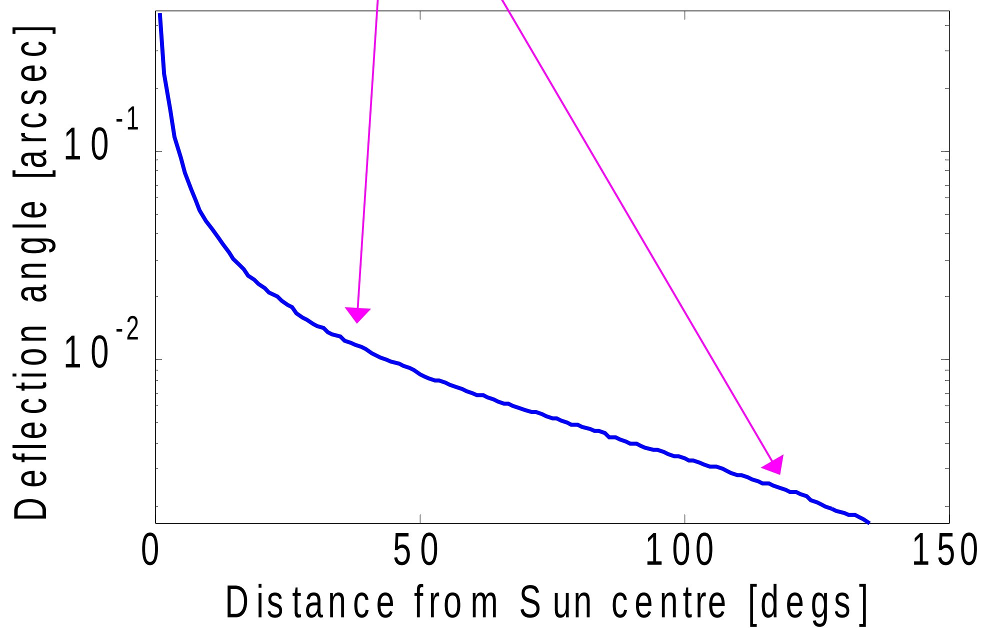


GAME: $\psi \sim 0.5$ arcsec

GAIA: $\psi \sim 2\text{-}20$ mas

GAME observes sky regions with deflection larger (by 10-100) than that seen by Gaia

Minimum correlation among variables



Sensitivity: amplitude of deflection / angular precision

$$S = \frac{\psi}{\sigma(\psi)}$$

Location precision @ V = 15 mag

Gaia: $\sigma(\psi) \sim 300$ μas ⇒ S = 7 ~ 70

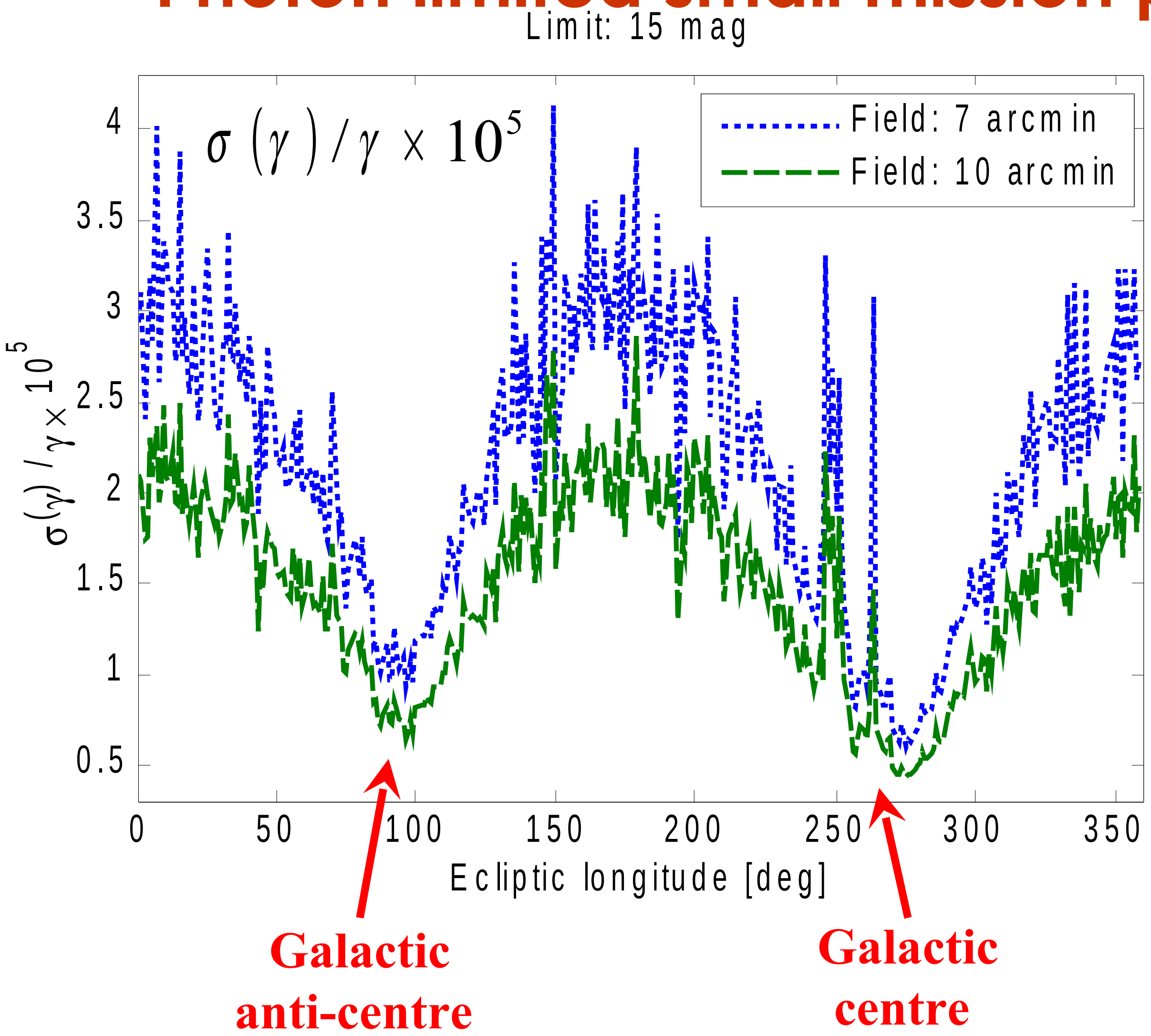
GAME: $\sigma(\psi) \sim 400$ μas ⇒ S = 1250

More than one order of magnitude of improvement

Lower number of measurements (stars) required by GAME

Lower sensitivity to systematic errors
(deflection signal ~0".5, ~ PSF size)

Photon limited small mission performance - I



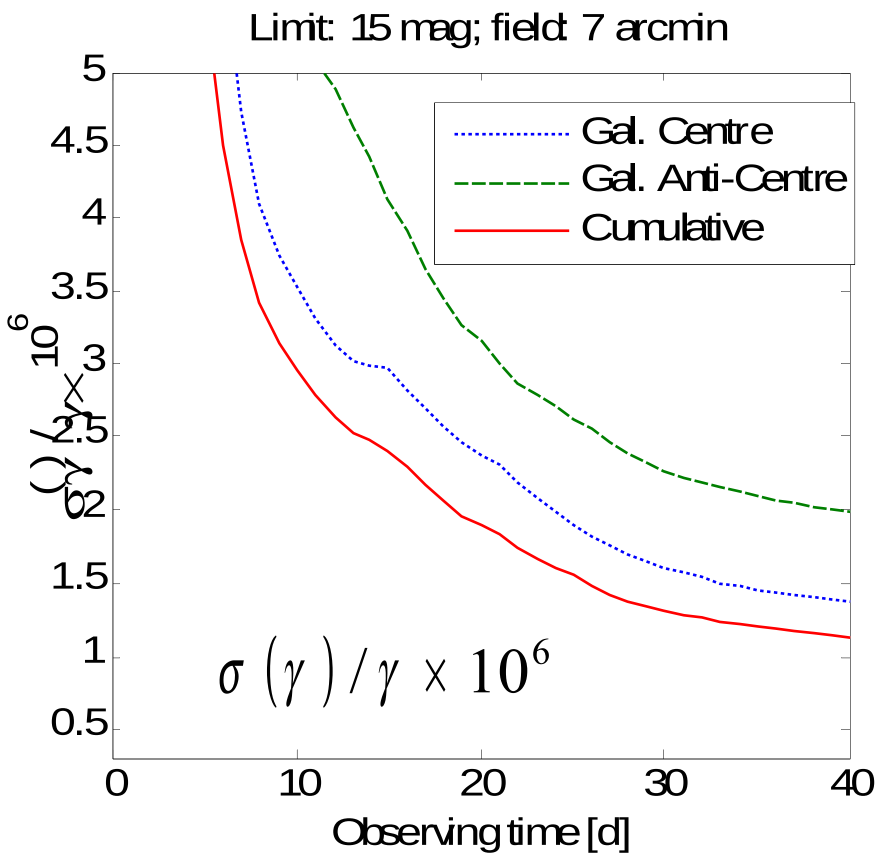
Precision averaged on 1° strip observations [~1 day]

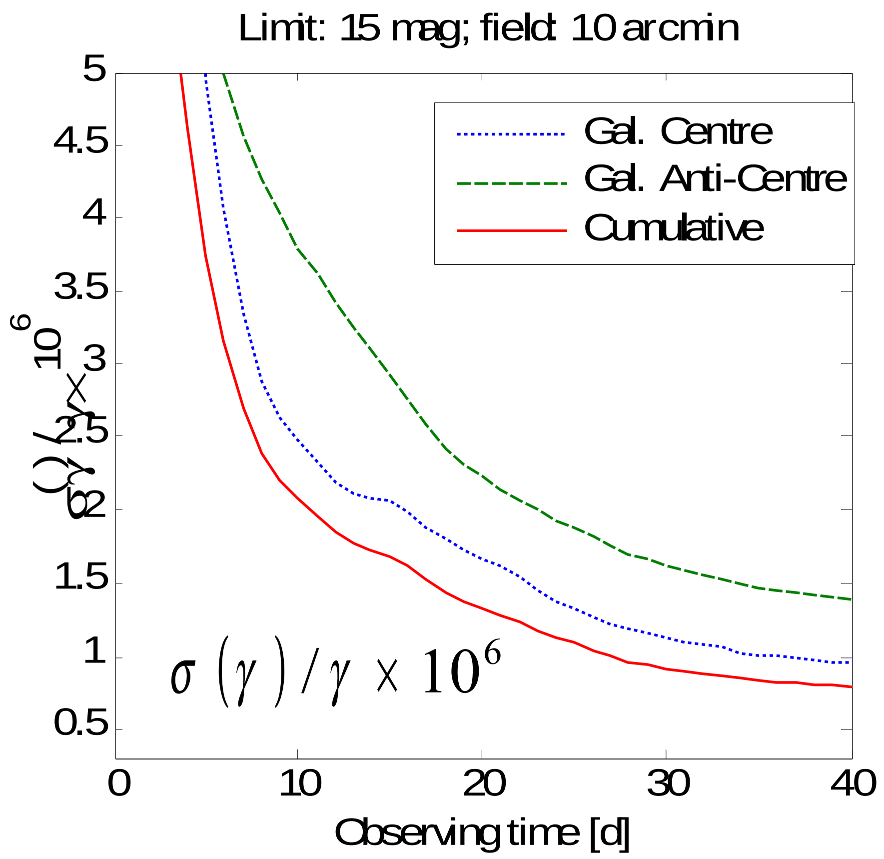
Field size: detector

7'×7': 2×2 CCD mosaic

10'×10': 3×3 CCD mosaic

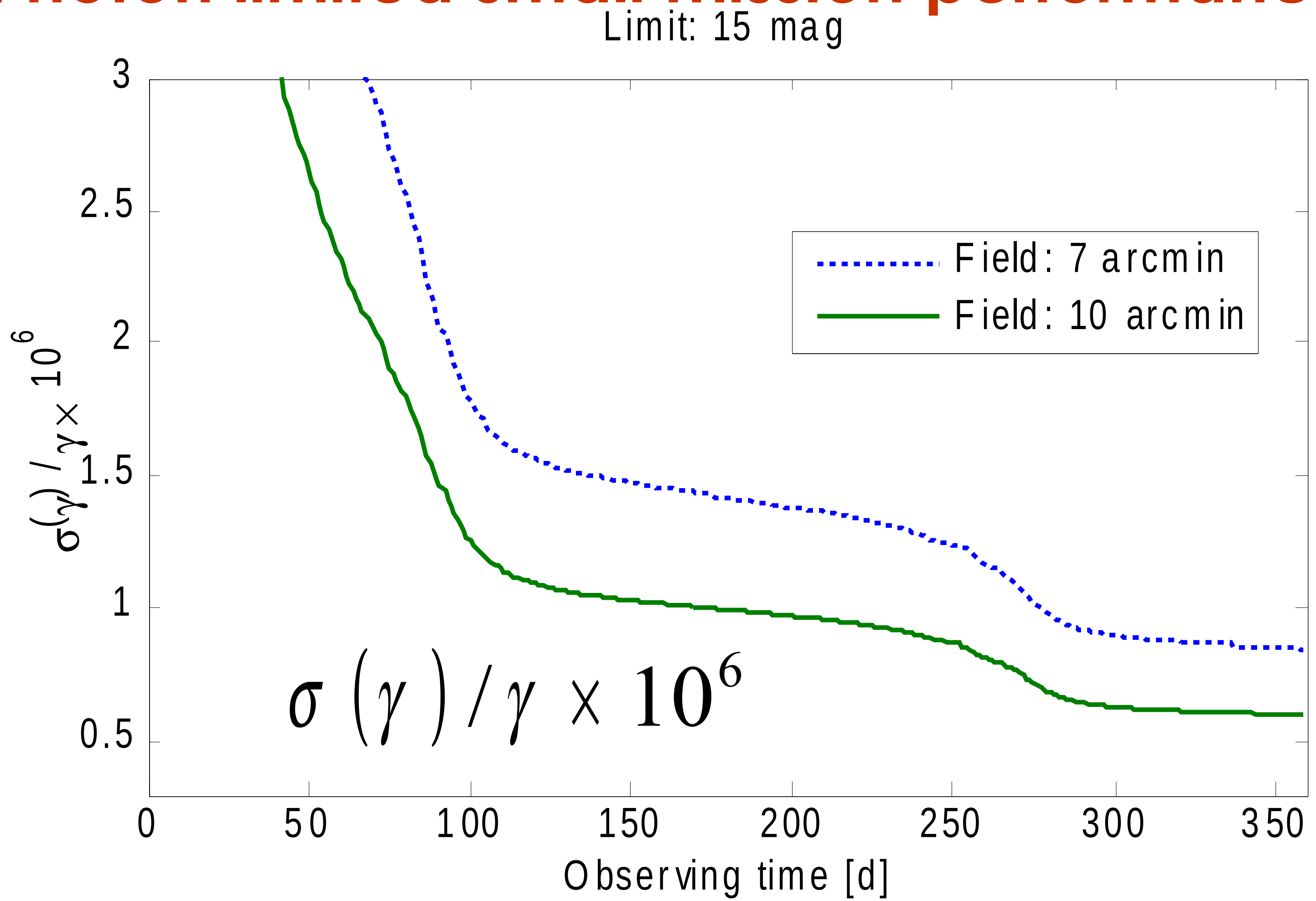
Photon limited small mission performance - II





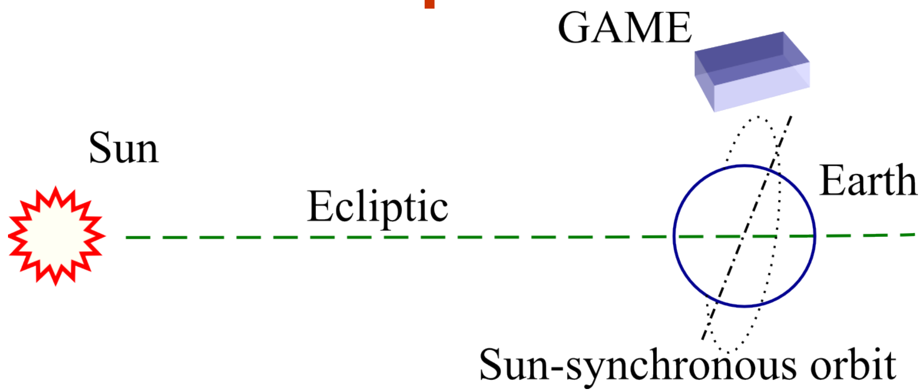
Cumulative precision < 10^{-6} with 10' field and >30 days observation

Photon limited small mission performance - III



Cumulative precision ~6×10^{-7}, 10' field,
1 year continuous observation per epoch

Orbital parallax for Solar System objects

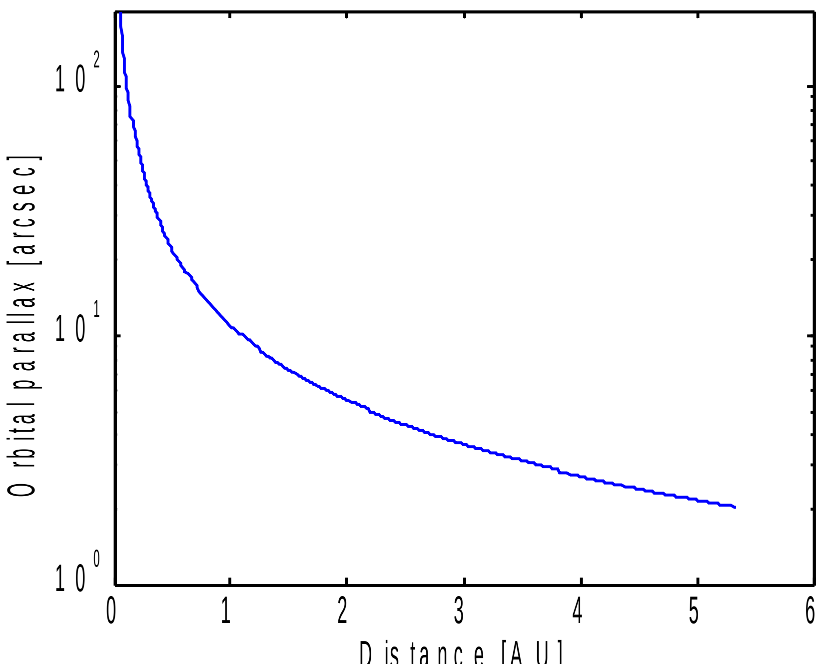


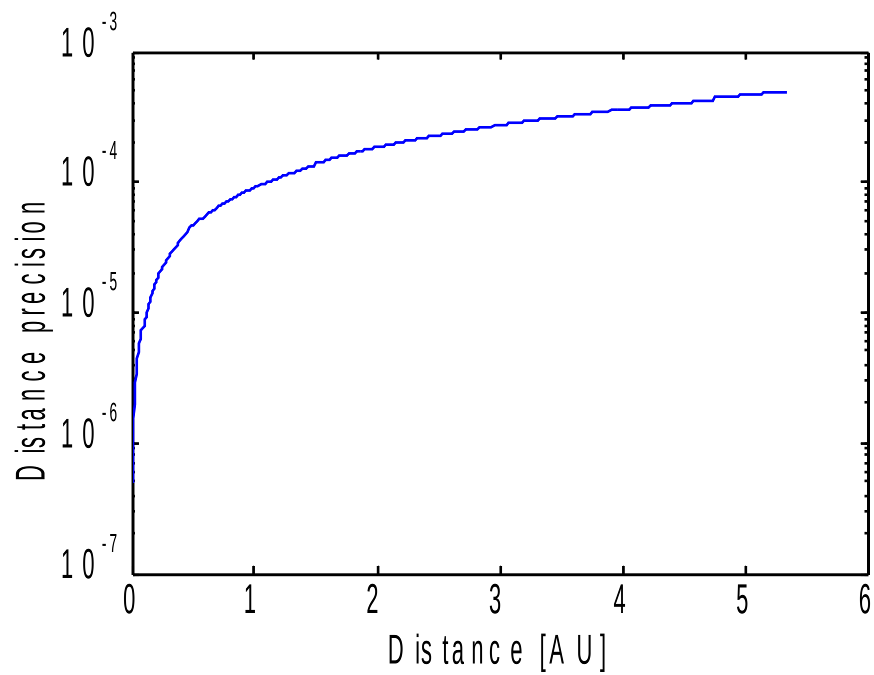
Satellite height: ~1500 km

Orbit radius: ~8000 km

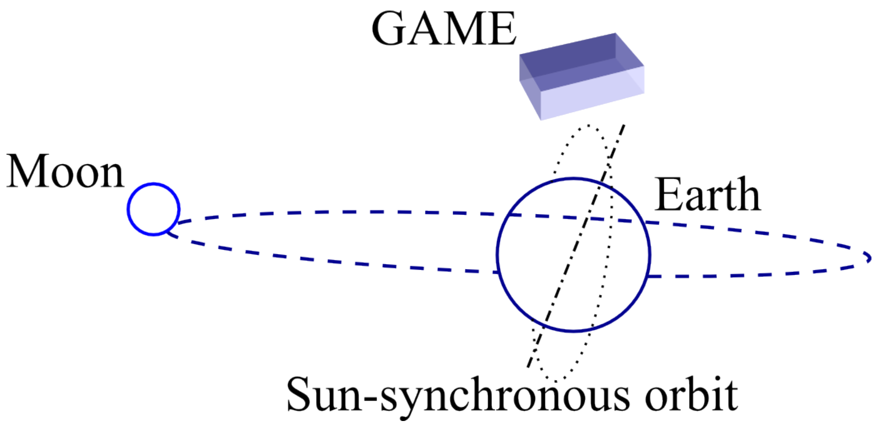
Orbit period: ~2 hours

Nearby objects affected by **orbital parallax** ⇒ distance estimate





Occultations as targets of opportunity…

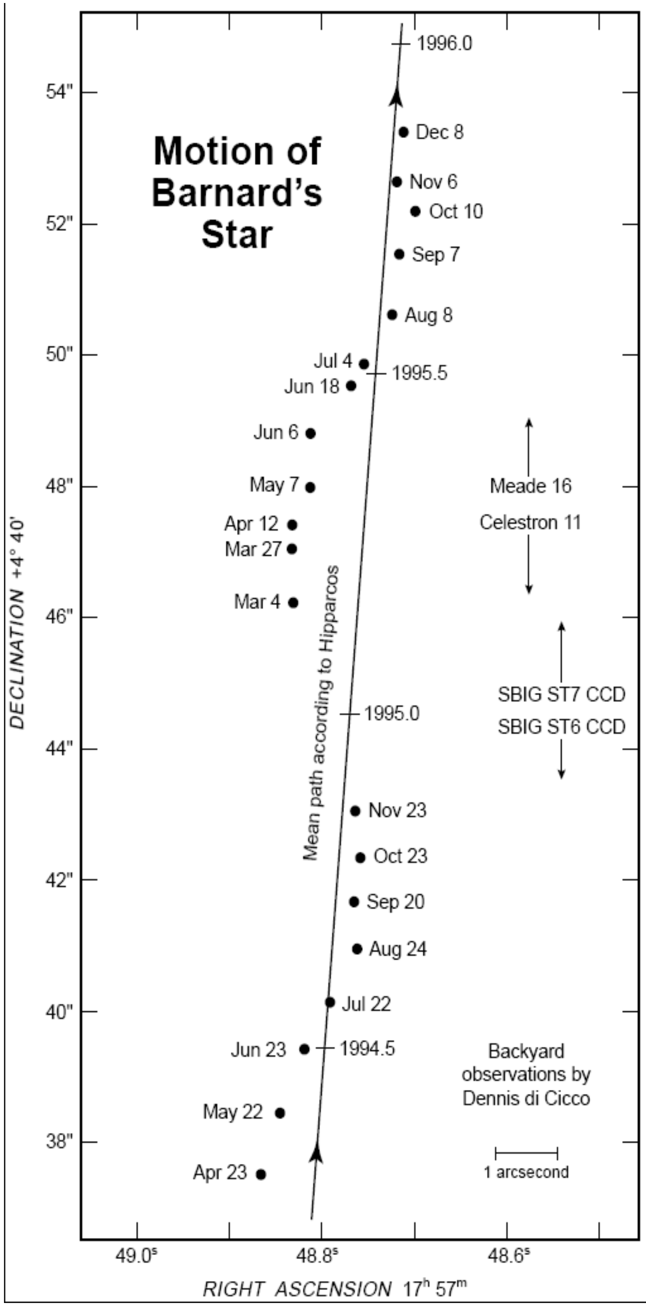


Apparent Moon motion induced by GAME orbit: ~1°.5 over ~2 hours

Slow repeated occultations in directions not sampled from ground
$\Rightarrow$ **independent information** + **high precision**

Observing mode: high cadence photometry on relevant sub-fields

Diameters and **binary separations** for a few thousand objects



Astrometric requirements

Position knowledge:
$\sigma(\psi) \cong 20$ mas

$$\delta\psi = (1+\gamma)\frac{GM}{c^2 d}\sqrt{\frac{1+\cos\psi}{1-\cos\psi}}$$

Better than GSC II, easy for Gaia

Individual star motion affects epoch modulation

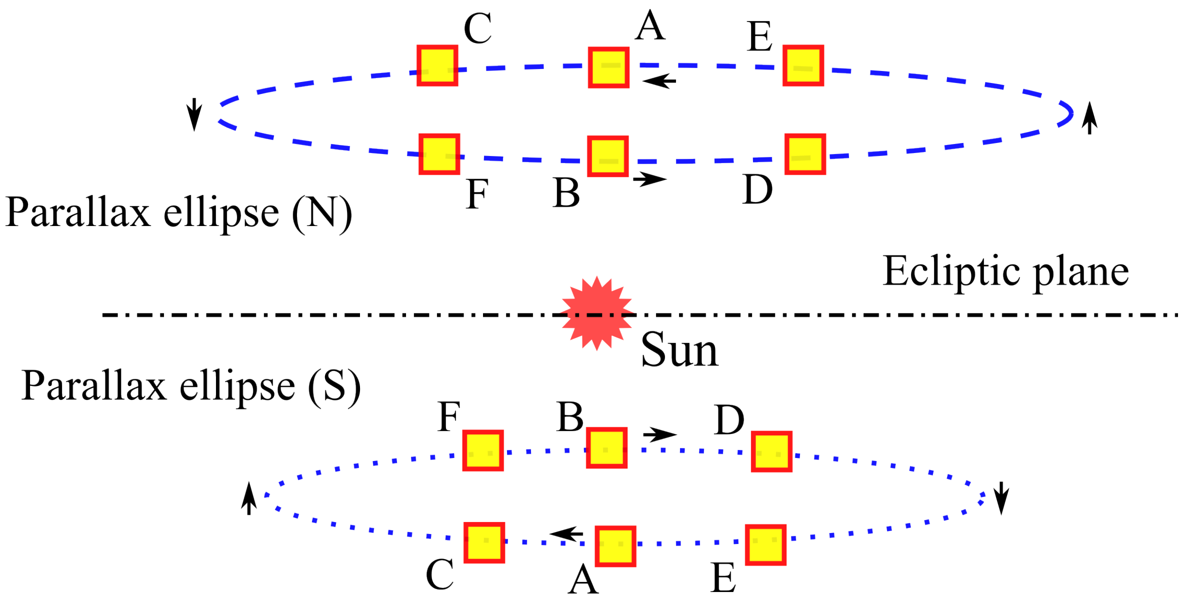
Precision required for $\sigma(\gamma)/\gamma \cong 10^{-8}$:

Proper motion: **few µas/year**

Parallax: **few µas**

Marginally compatible with nominal Gaia

Full astrometric solution: multi-epoch observation



{A,B}: deflection in phase with parallax

{C,D} and {E,F}: low deflection ⇒ determination of parallax

Observation sequence: {C,D}; {A,B}; {E,F} ⇒ 1+1+1 months

Sequence in complementary epoch: {D,C}; {B,A}; {F,E}

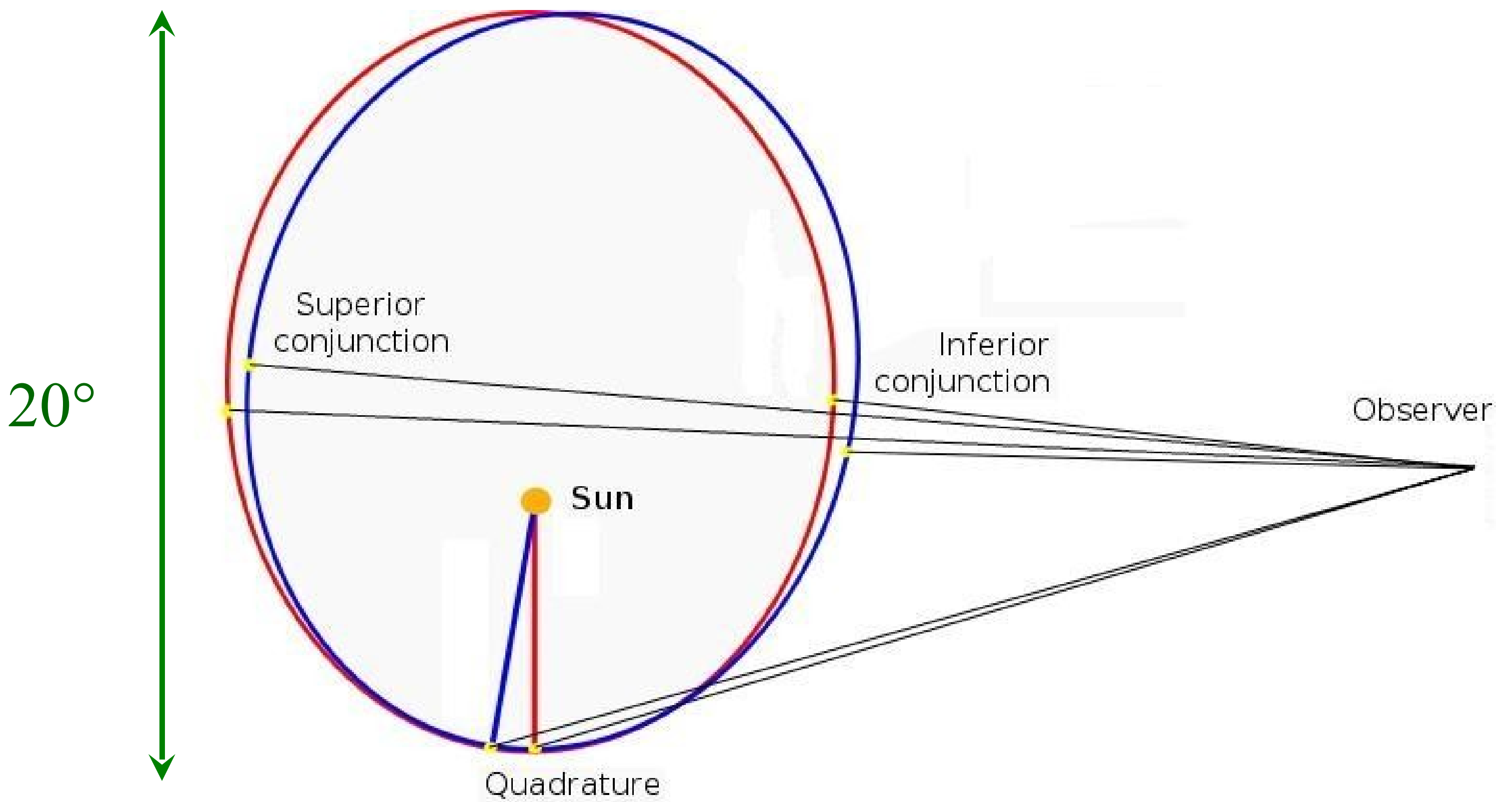
Total γ observations: 6 months/year

Side result: μas astrometric catalogue of stellar sample

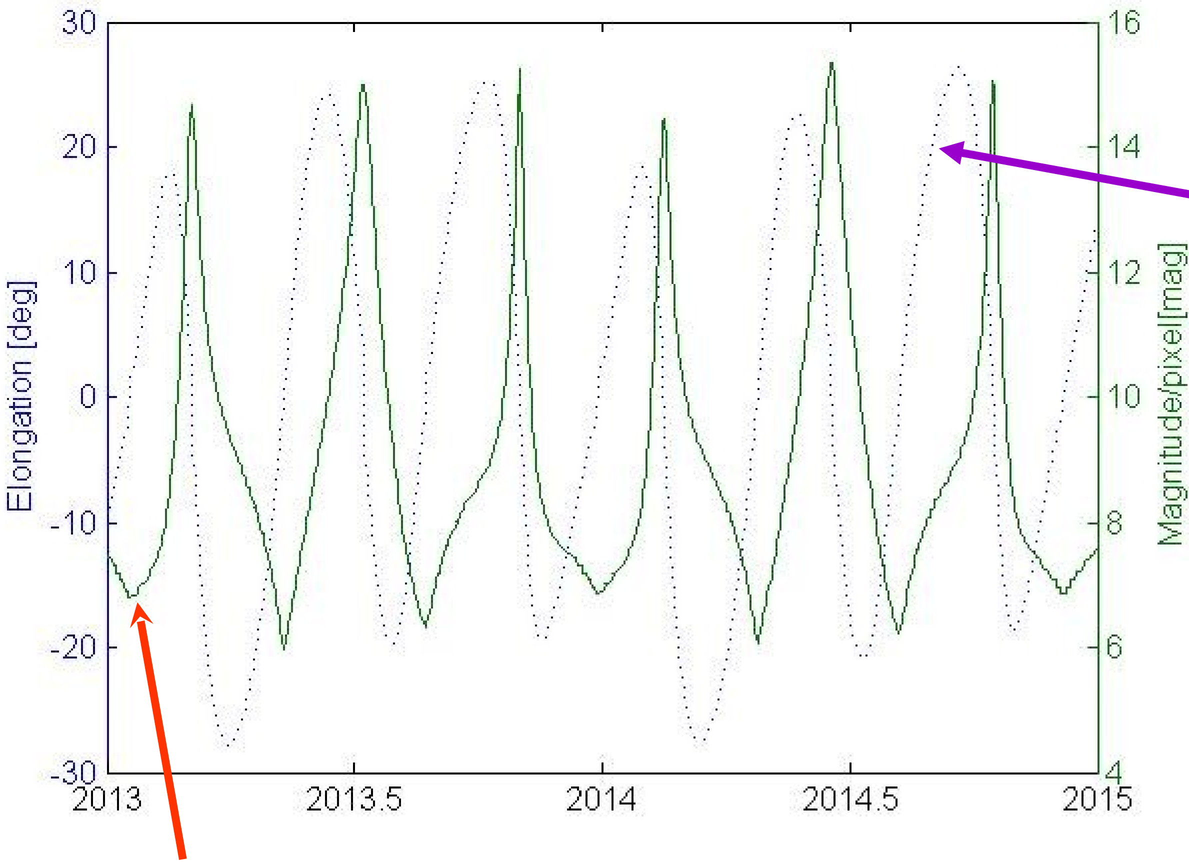
Classical GR test: Mercury's perihelion precession

Orbit reconstruction: standard astrometry task, but…

Mercury: difficult target for large telescopes, within 20° from Sun



Mercury observability by GAME



~three periods per mission year, four orbits (dotted line)

Orbit region accessible to GAME: up to 30° to Sun

Magnitude / pixel fits GAME dynamic range (scaling exposure time)

Performance assessment in progress