Astrometric Gravitation Probe (AGP)

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Prevously a.k.a. GAME:
Gravitation Astrometric Measurement Experiment

AGP: Astrometric Gravitation Probe

→ Apparent star position measurement

→ **1) Light deflection close to the Sun**
[e.g. PPN parameters γ and $\boldsymbol{\beta}$]

2) High precision dynamics in Solar System

→ **Medium** Space mission

Mission design driver: light bending around the Sun

Approach:

build on flight inheritance from past / current missions

[**Gaia, Solar Orbiter**]

Talk outline

Science goal: review of context

Mission implementation concept

Expected performance

ESA M4 Call for mission

AGP Science goals

*** Characterisation of weak field gravity in the Solar System:**

- Parametrised Post-Newtonian parameters γ, β
- Relativistic effects of oblate and moving giant planets
- Solar system dynamics [High precision ephemerides]

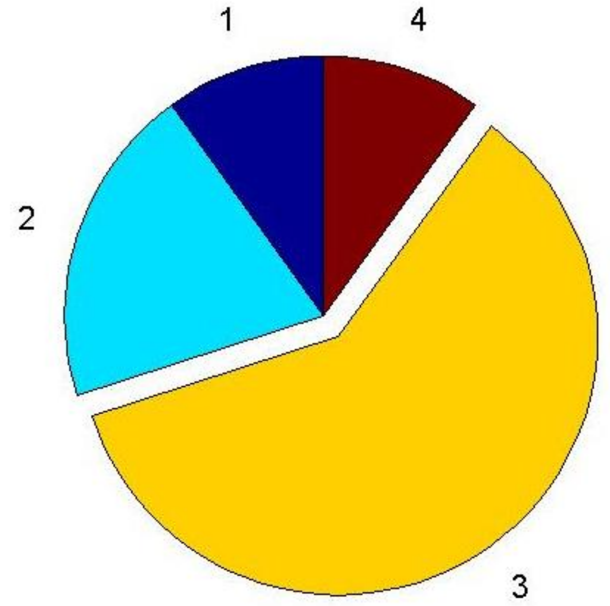
*** High resolution Corona polarimetry**

*** Science bonus:**

- Extra-solar Planetary systems
- Stellar astrophysics topics
- Upper limits on some Lorentz-violating SME parameters

AGP 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?**	**30%**
3	**What are the fundamental physical laws of the Universe?**	**50%**
4	How did the Universe originate and what is it made of?	10%



Main science case:

Astrometric tests of General Relativity in Solar system

Science case (I): Gravitation tests ⇒ themes 2, 3, and 4

Classical tests of general relativity [Einstein, 1916]

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

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

AGP space

3. Gravitational redshift / blueshift of light

"Modern" tests:

Gravitational lensing; Equivalence principle;

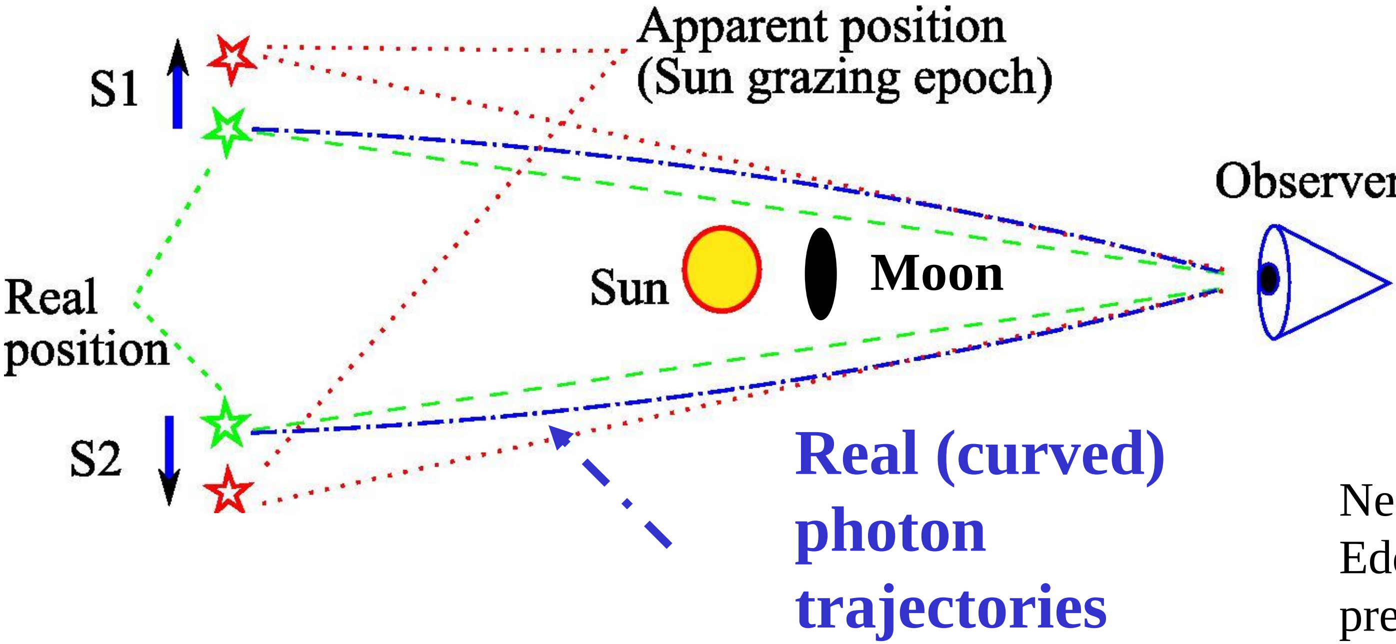
Time delay of electromagnetic waves (Shapiro effect); ⇒ Cassini

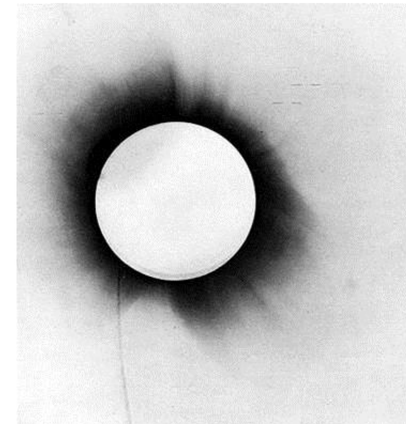
Frame dragging tests (Lense-Thirring effect);

Gravitational waves; Cosmological tests (cosmic background);

…

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%

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

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

Limiting factors:

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

Freundlich's attempts to verify relativity theory (I)

[D. Dravins, 2012]

End of 1911–Oct. 1912: Examination of available plate data from solar eclipse expeditions for evidence of light deflection in the sun's gravitational field; plates not sharp enough.

1912–1913: Comments on possible daytime observations of stars near the sun; but too much scattered light.

1913: Analyses of binary stars: Test of the axiom c = constant of the special theory of relativity versus RITZ's emission theory of light.

1914: Analysis of FRAUNHOFER-line measurements by EVERSHED (1913) and FABRY & BUISSON [1910] with the view toward possible gravitational redshift; Results: redshift is present. But already in 1914 SCHWARZSCHILD publishes new data that rather speak against gravitational redshift.

1914: Expedition to the Crimea exclusively to verify light deflection during a solar eclipse; due to the outbreak of war, the members of the expeditions are taken into custody and their instruments confiscated.

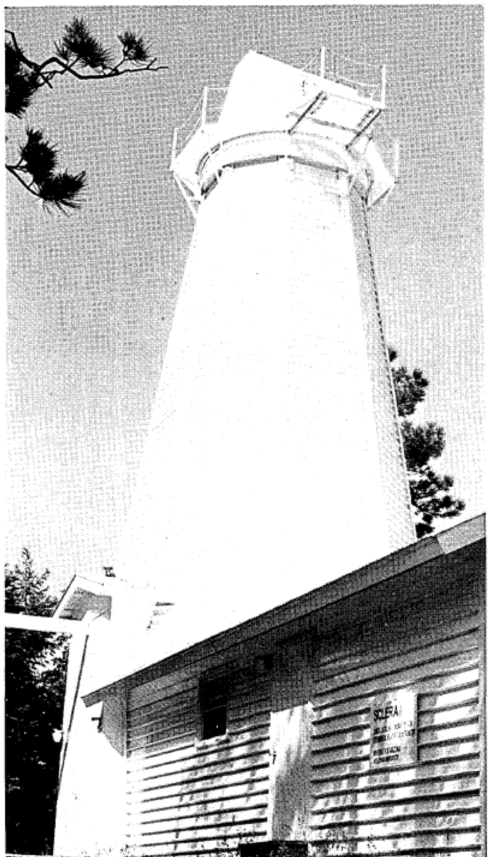
Erwin Finlay Freundlich (1885-1964) worked to experimentally verify the predictions from Einstein's theory of relativity and the effects of gravity on light.

Klaus Hentschel: *Erwin Finlay Freundlich and Testing Einstein's Theory of Relativity*, Archive for History of Exact Sciences **47**, 243 (1994)

SCLERA: an Astrometric Telescope for Experimental Relativity

APPLIED OPTICS / Vol. 13, No. 1 / January 1974

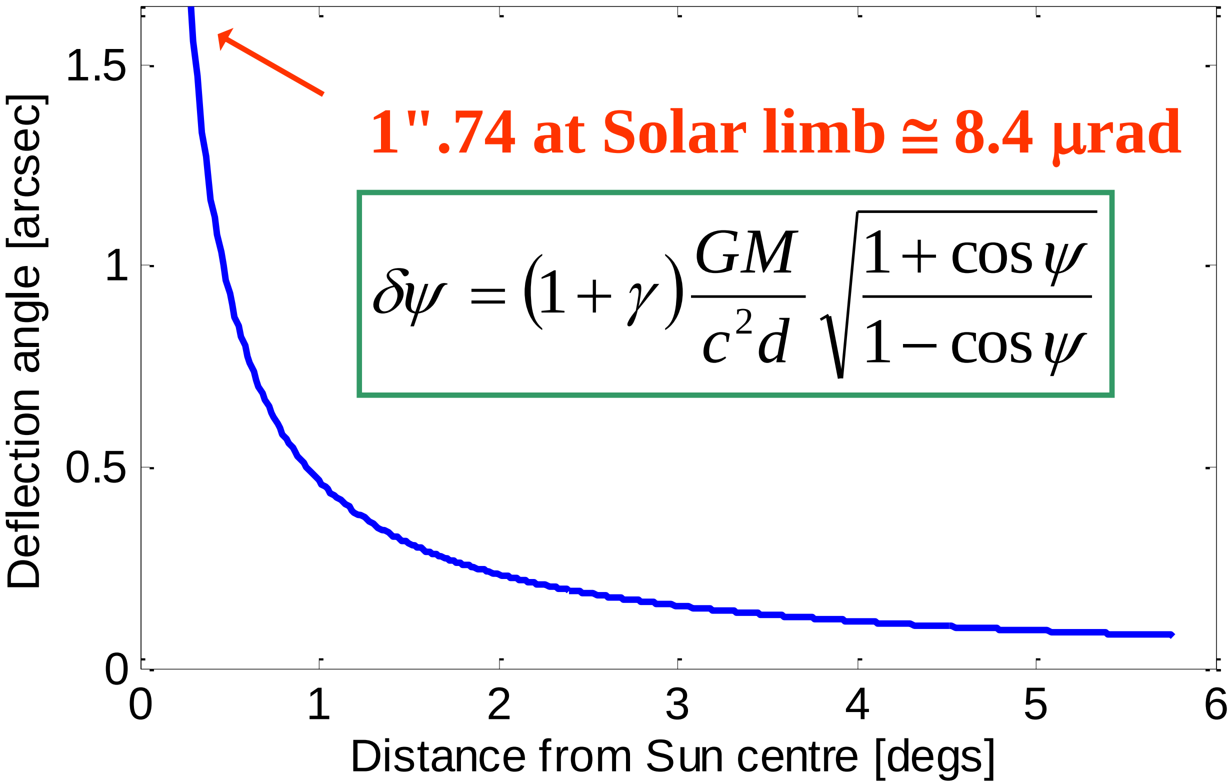
J. R. Oleson, C. A. Zanoni, H. A. Hill, A. W. Healy, P. D. Clayton, and D. L. Patz



An $f/100$, 12.2-m focal length photoelectric telescope designed specifically for daytime astrometry of objects near the sun is now operative at its Tucson, Arizona, site. The design goal was to achieve accuracies of order 0.001 sec of arc in field position measurements of stars. To accomplish this, many features reducing systematic and random errors are employed, including Schupmann medial telescope optics, compensation for lateral color aberration, apodization for reduction of diffracted light, and use of an accurately measured solar diameter for calibrating the field.

Precision limitations from ground at the few milli-arcsec level…

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

⇔ **ASTROMETRY**

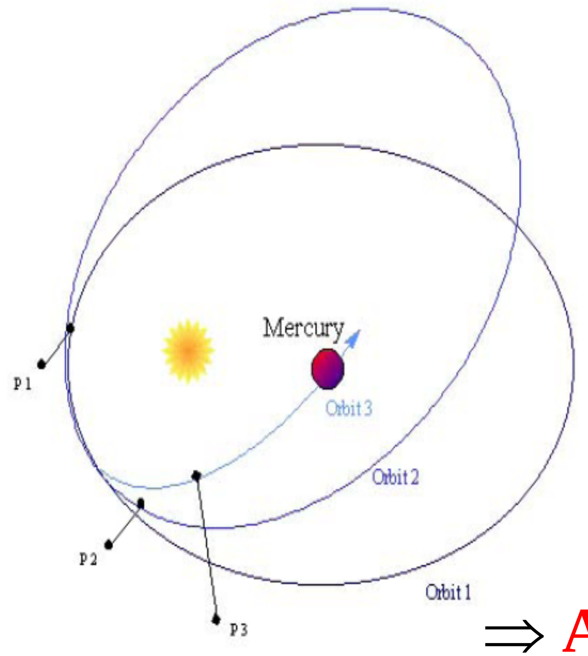
Classical GR test: Mercury's perihelion precession

Total observed precession of Mercury: 574 arc-seconds per century

Newtonian contribution: 531 arc-seconds per century

General Relativity term: 43 arc-seconds per century

- The effect of the perihelion shift excess depends on a combination of both γ and β (and other PPN parameters).



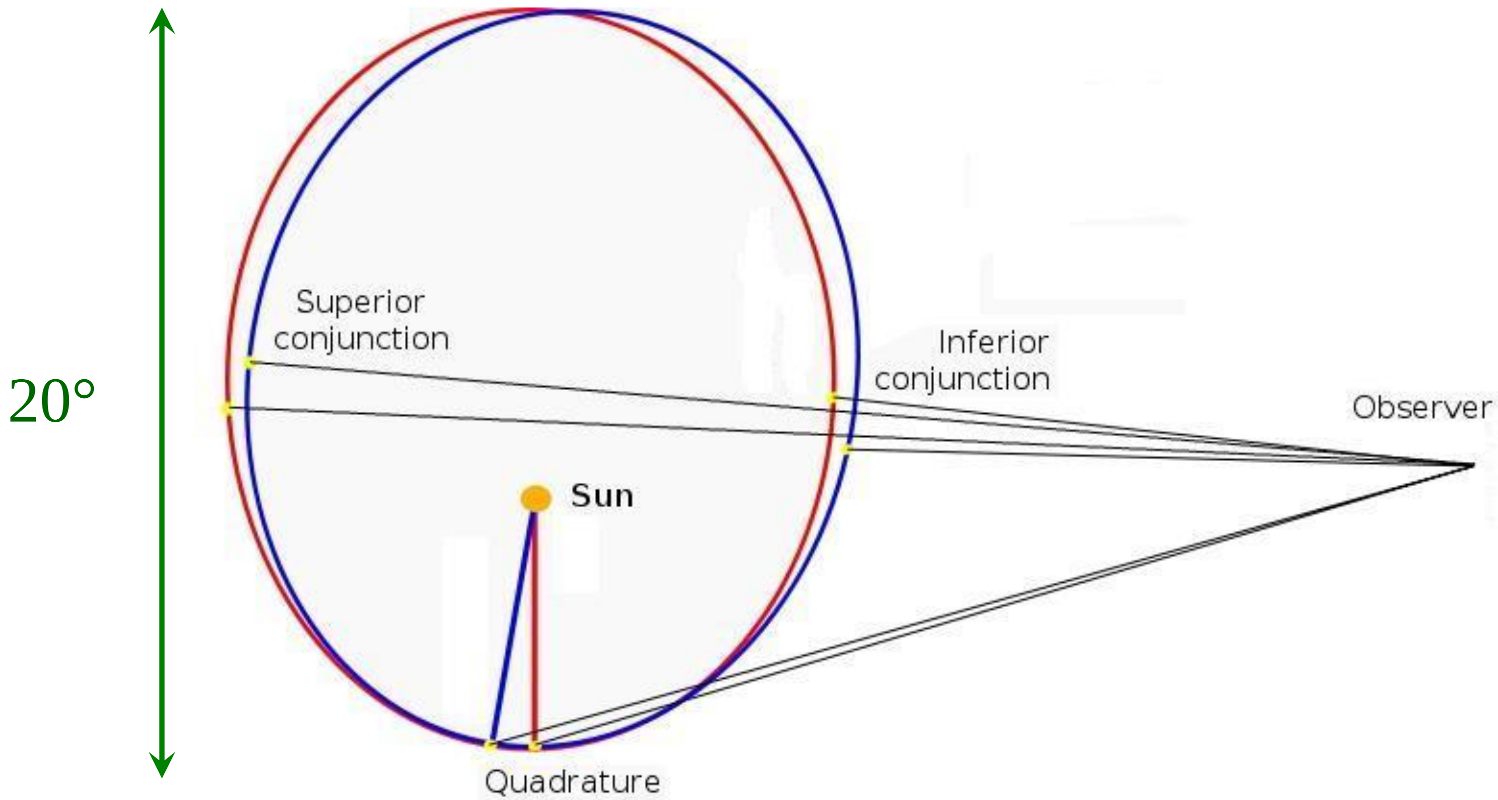
$\Rightarrow$ **ASTROMETRY**

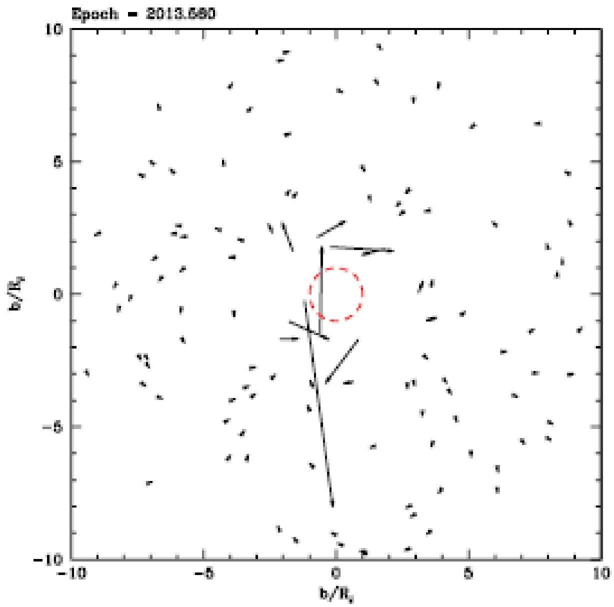
$$\Delta\omega = \frac{6\pi m}{a\left(1-e^2\right)}\left[\frac{1}{3}\left(2+2\gamma-\beta\right)+f\left(\alpha_1,\alpha_2,\alpha_3,\zeta_2,J_2\right)\right]$$

Test implementation constraints

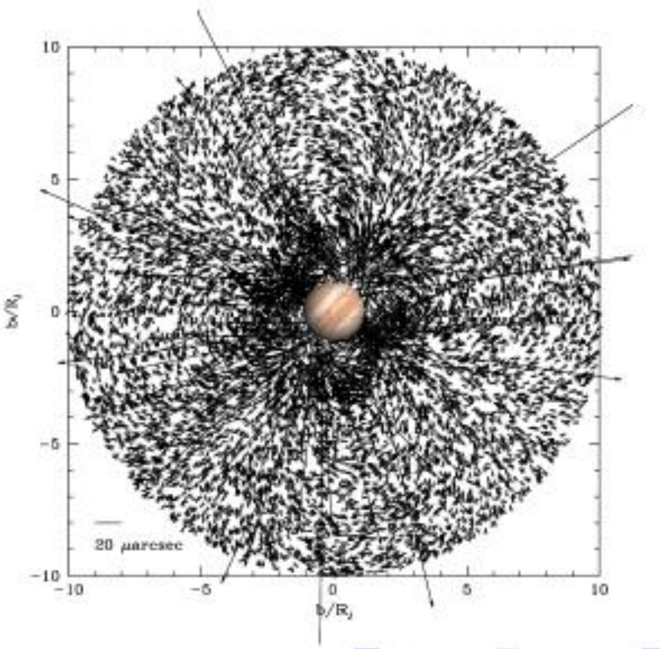
Orbit reconstruction: standard astrometry task, but…

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





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



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

Measure of the amount of quadrupole deflection as test of GR

⇒ **ASTROMETRY**

Upper limits on Lorentz-violating SME parameters

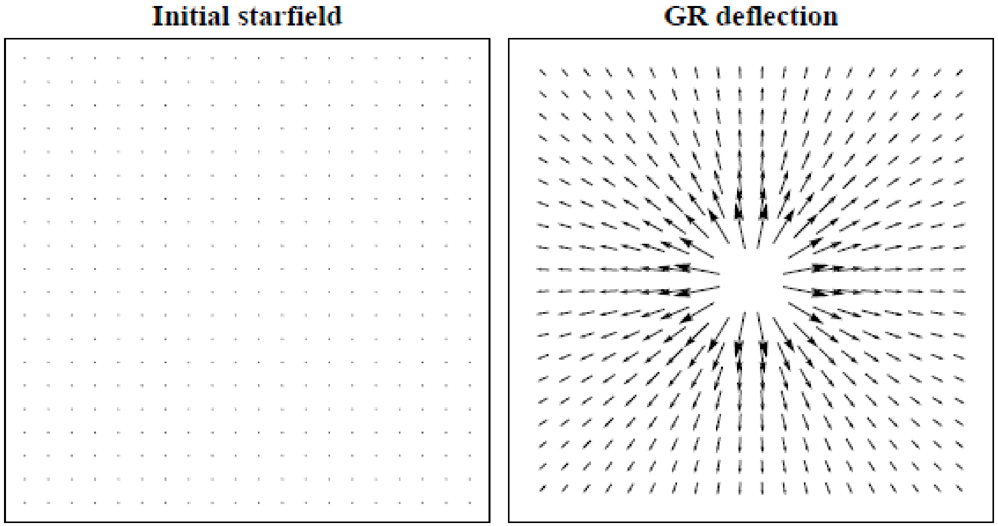


FIG. 2: Initial uniform star field (left). Apparent shift of distant light in the standard general relativity case (right).

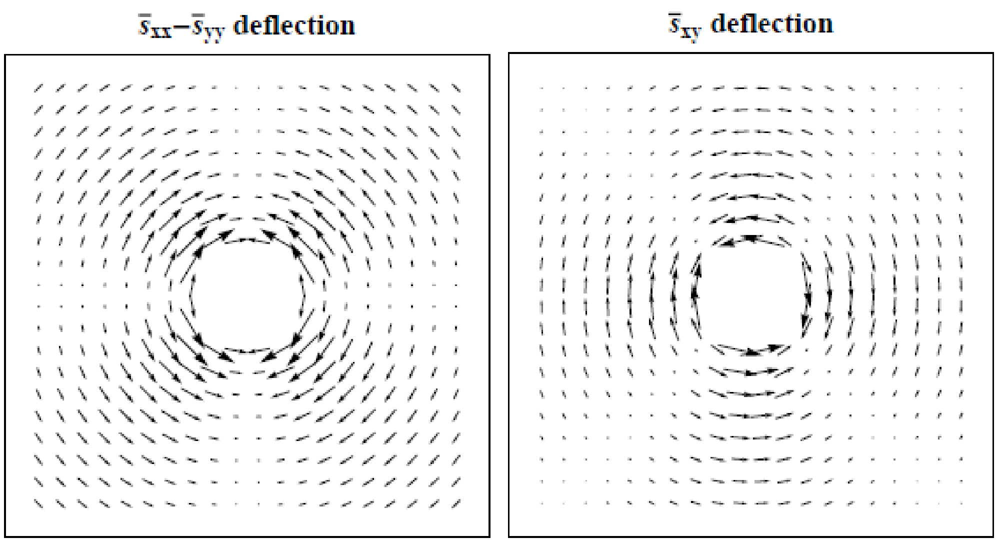


FIG. 3: Anisotropic apparent shift of star field due to the $\bar{s}_{xx} - \bar{s}_{yy}$ coefficients (left) and the $\bar{s}_{xy}$ coefficients (right). The local x coordinate runs horizontally and y is vertical.

GR: isotropic effect

Lorents invariance violation effects associated to anisotropy of light bending may be detected

⇒ **ASTROMETRY**

[Tso and Bailey, Phys. Rev. D, 2011]

Additional science topics - I

Fundamental physics in the Solar System ⇔ planetary physics

Planetary orbit tracking / monitoring + Grand Fit

- **Mercury's perihelion precession determination**

  ⇒ PPN β parameter

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**

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]

Gaia + AGP: 10+ year temporal baseline astrometry

- **Sensitivity to "true" Saturn+Sun systems [20+ yr period]**

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)**

Instrument and operation concepts compatible with simultaneous observation of deflection (astrometry) + corona (polarimetry)

Current experimental results on light deflection…

Hipparcos

Different observing conditions: ***global astrometry***, estimate of full sky deflection on survey sample

Precision achieved: 3e-3

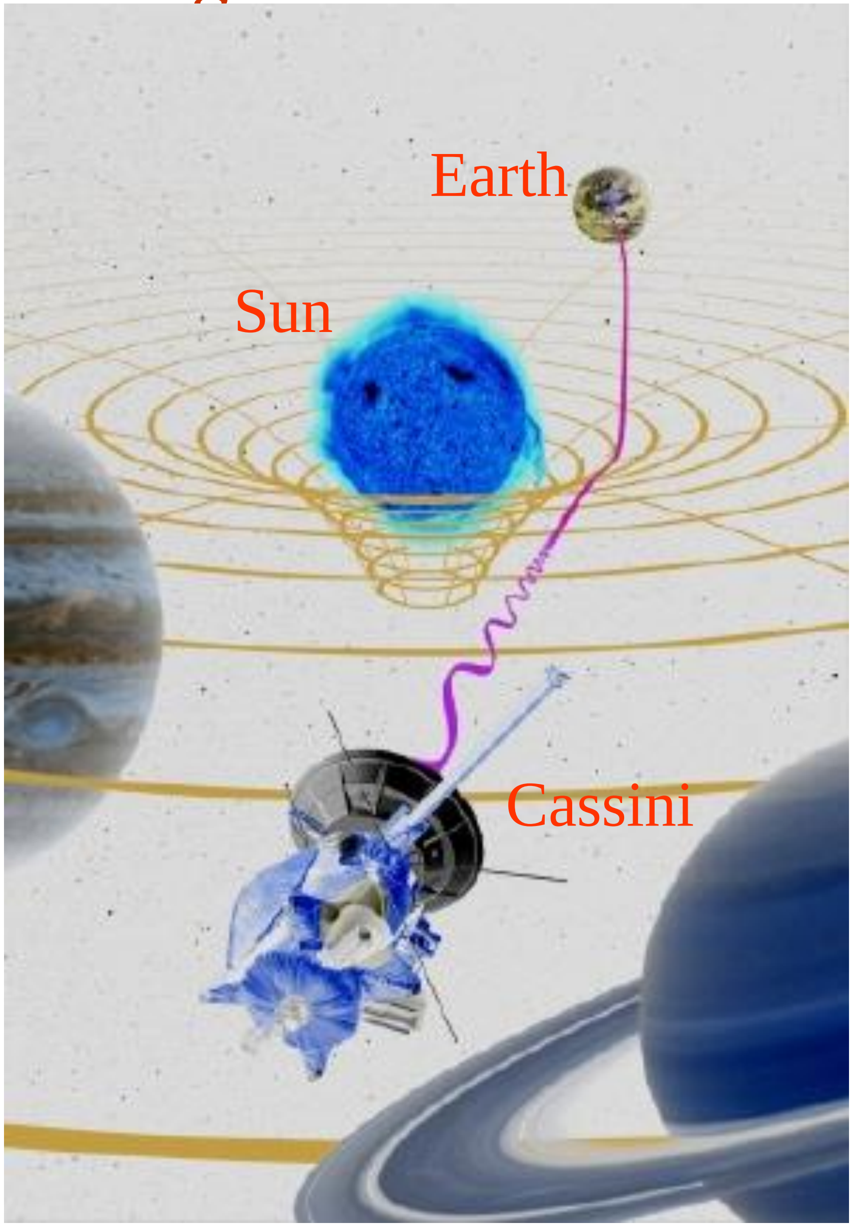
Cassini

Radio link delay timing, δν/ν~1e-14

(similarly for Viking, VLBI: Shapiro delay effect, "temporal" component)

[B. Bertotti et al., Nature 2003]

Precision achieved: 2e-5



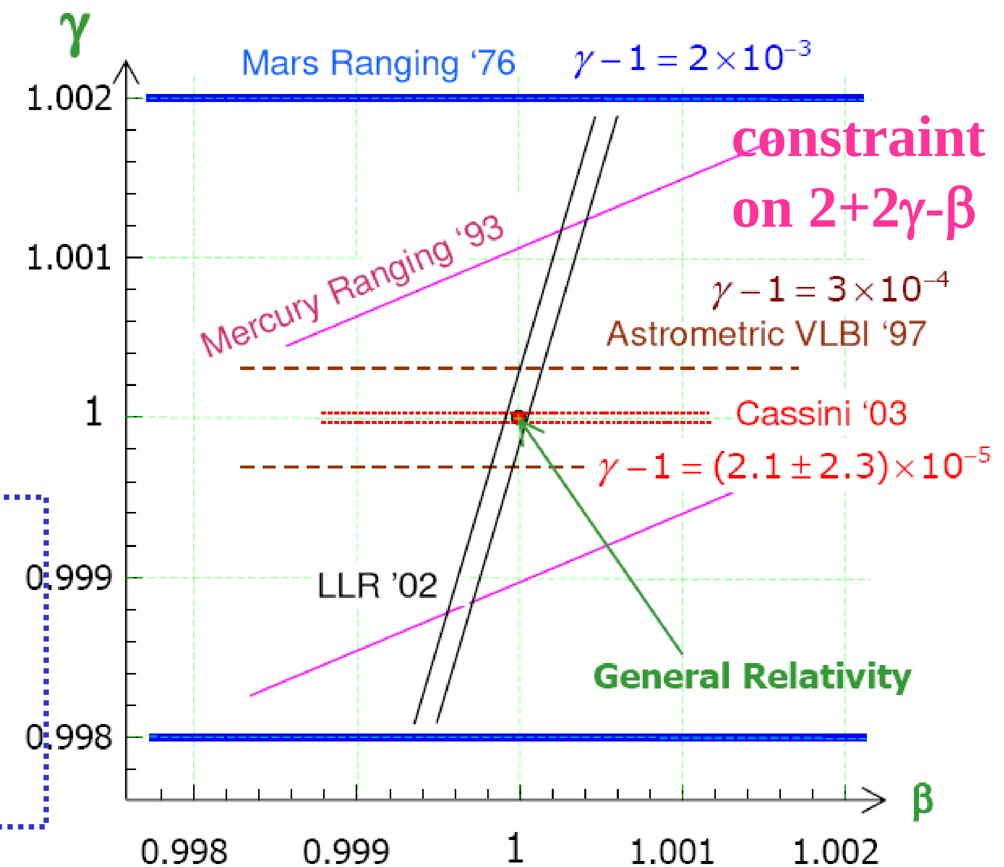
Why testing GR through γ (+ β)?

Current experimental bounds:

consistent with GR

$$|\gamma - 1| \le 2 \times 10^{-5}$$
$$|\beta - 1| \le 1 \times 10^{-4}$$

Parametrised Post-Newtonian (PPN) formulation allows comparison of competing gravitation theories



S.G. Turyshev (JPL, NASA)

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

Deviation range expected:

$$\mathbf{10^{-5} - 10^{-7}}$$

Cosmological implications

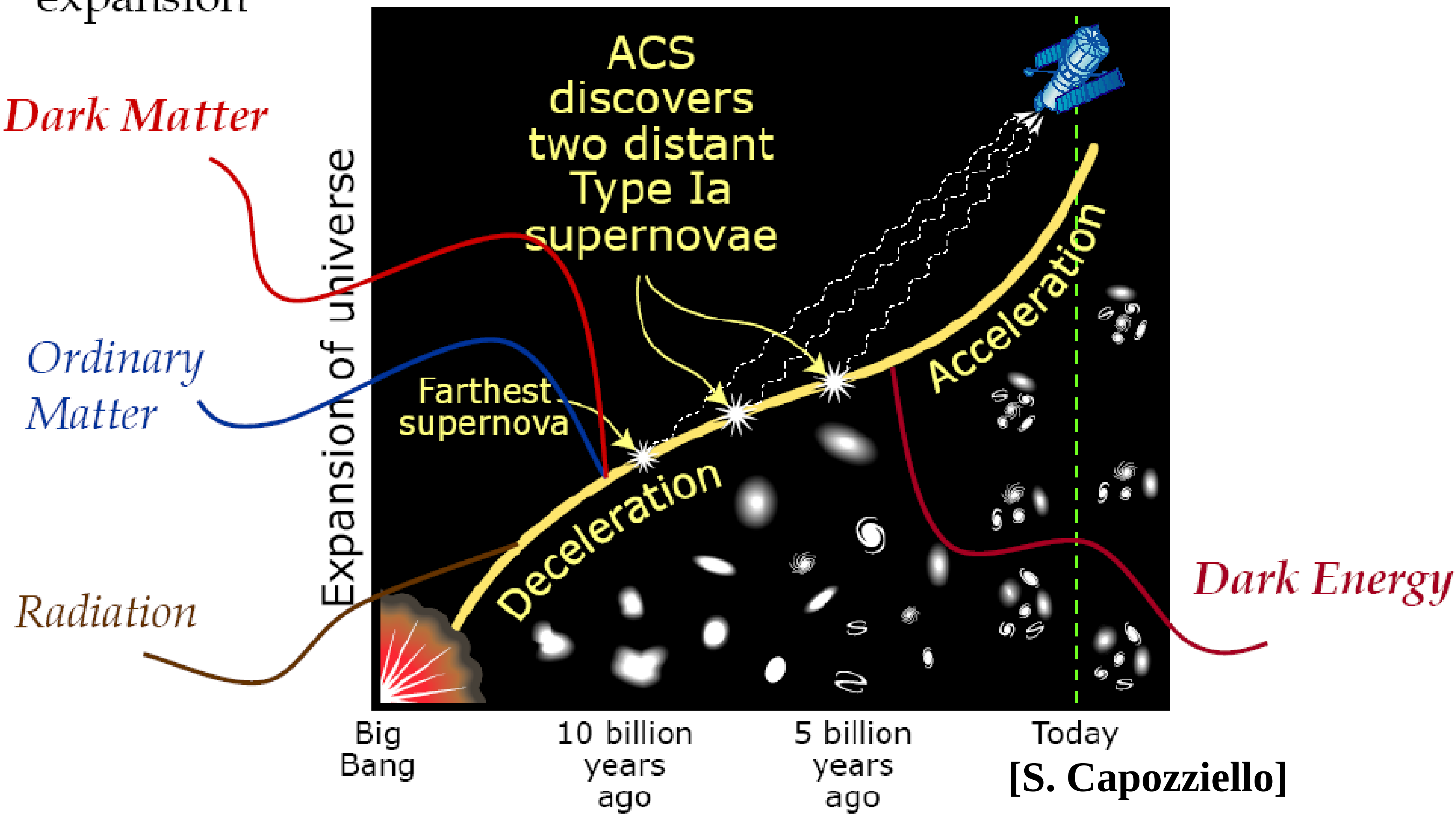
- Dark Matter and Dark Energy: explain experimental data
- Alternative explanations: modified gravity theories – e.g. *f(R)*
- Possible check: fit of gravitation theories with observations
- Check of modified gravitation theories ***within Solar System***

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:

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

[Capone & Ruggiero 2010]

Similar constraints for e.g. MOND

Check of gravitation theories within Solar System:

local measurements ⇒ cosmological constraints

Scientific requirements for mission design

Main driver: measurement of light bending to 10^{-7} – 10^{-8} level

Amplitude of deflection at 1° from Sun centre: **±0.5 arcsec**

Final measurement precision required: **0.1 – 0.01 µas**

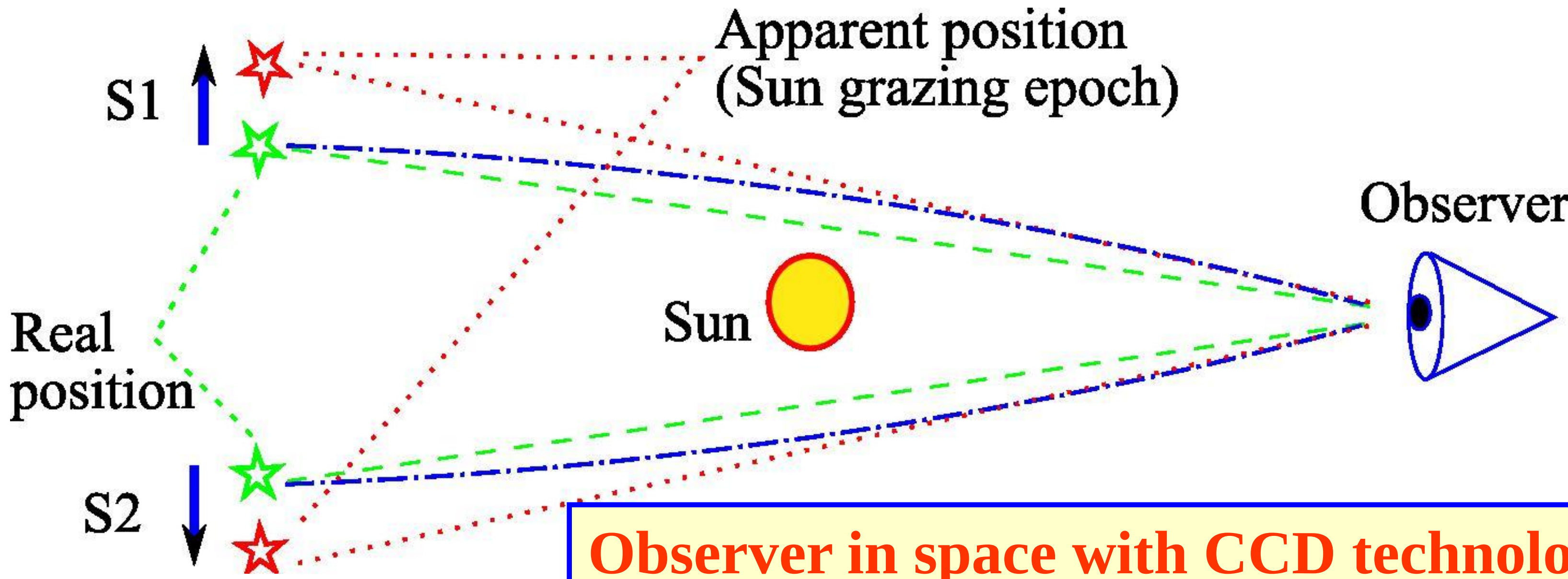
Challenging!

Mitigation: average ~10^6 measurements

Individual measurement precision required: **100 – 10 µas**

Remark: control of systematic errors

The AGP concept (I)



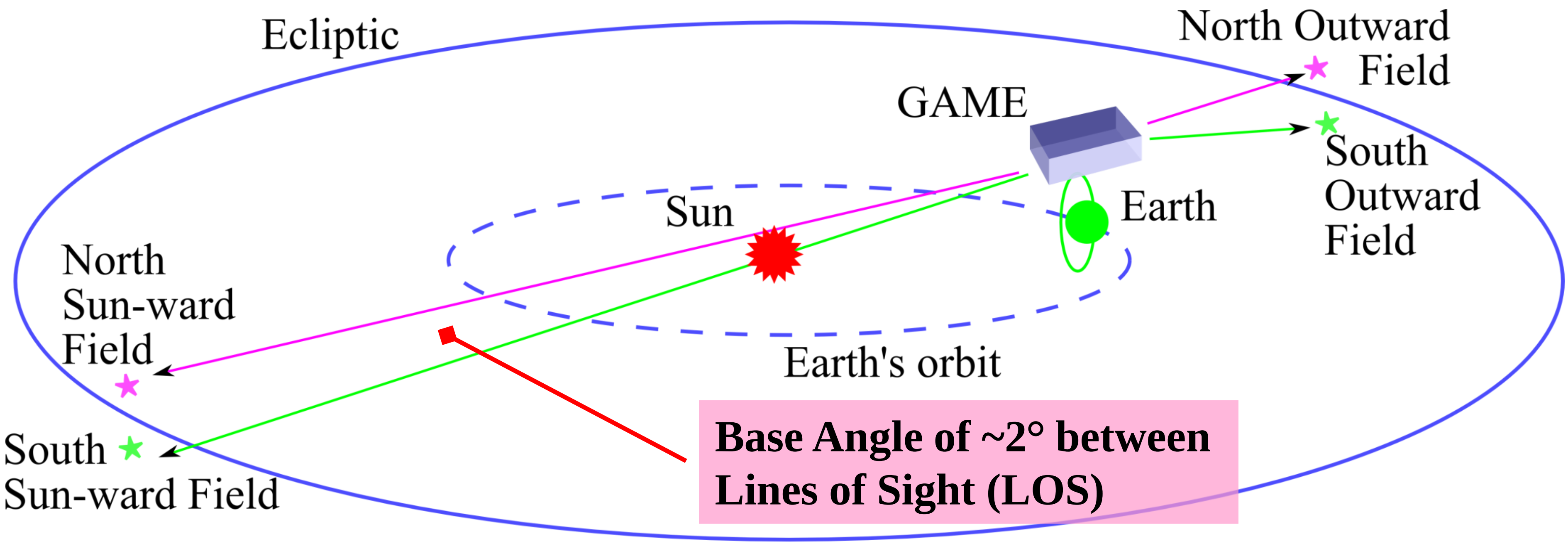
Observer in space with CCD technology

A space mission in the visible range to achieve

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

Differential measurement for systematic error control

The AGP concept (II)



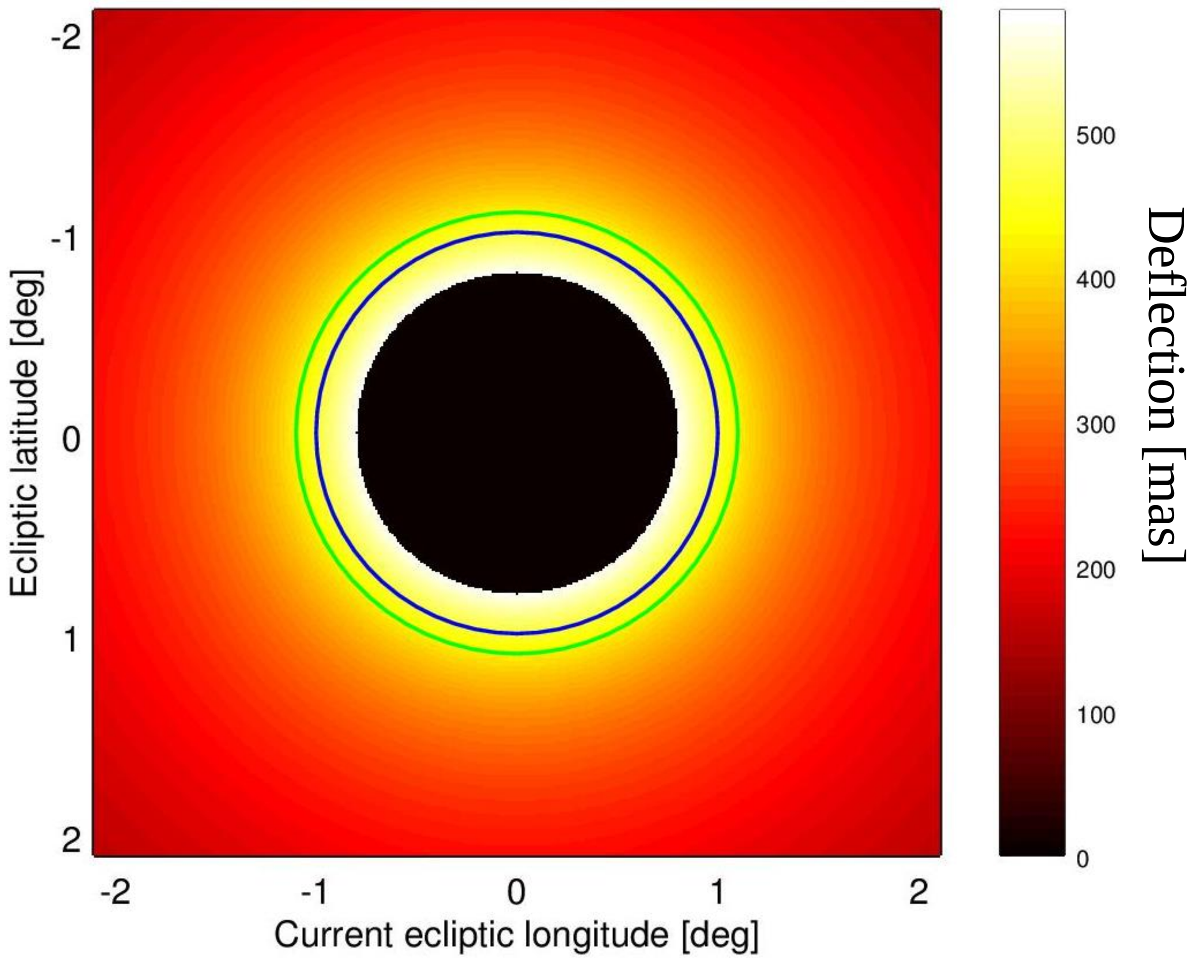
Experimental approach:

Repeated observation of fields close to the Ecliptic

Measurement of angular separation of stars between fields

2 epochs to modulate deflection (Sun gravity “switched” on/off)

Deflection distribution in observed region



Case of observation between 1º and 1º.2 (blue / green rings)

Deflection:
1º: 466.62 mas
1º.2: 388.84 mas
Variation: 78 mas

Deflection at 179º: 35.6 μas

Space: minimization of systematic errors

Permanent “eclipse” by coronagraphy → long exposures

No atmospheric turbulence

Quiet environment (to be preserved!)

Low disturbance to measurables

Light **refraction** at wavelength λ, distance ρ to Sun centre, due to electron density N(ρ)

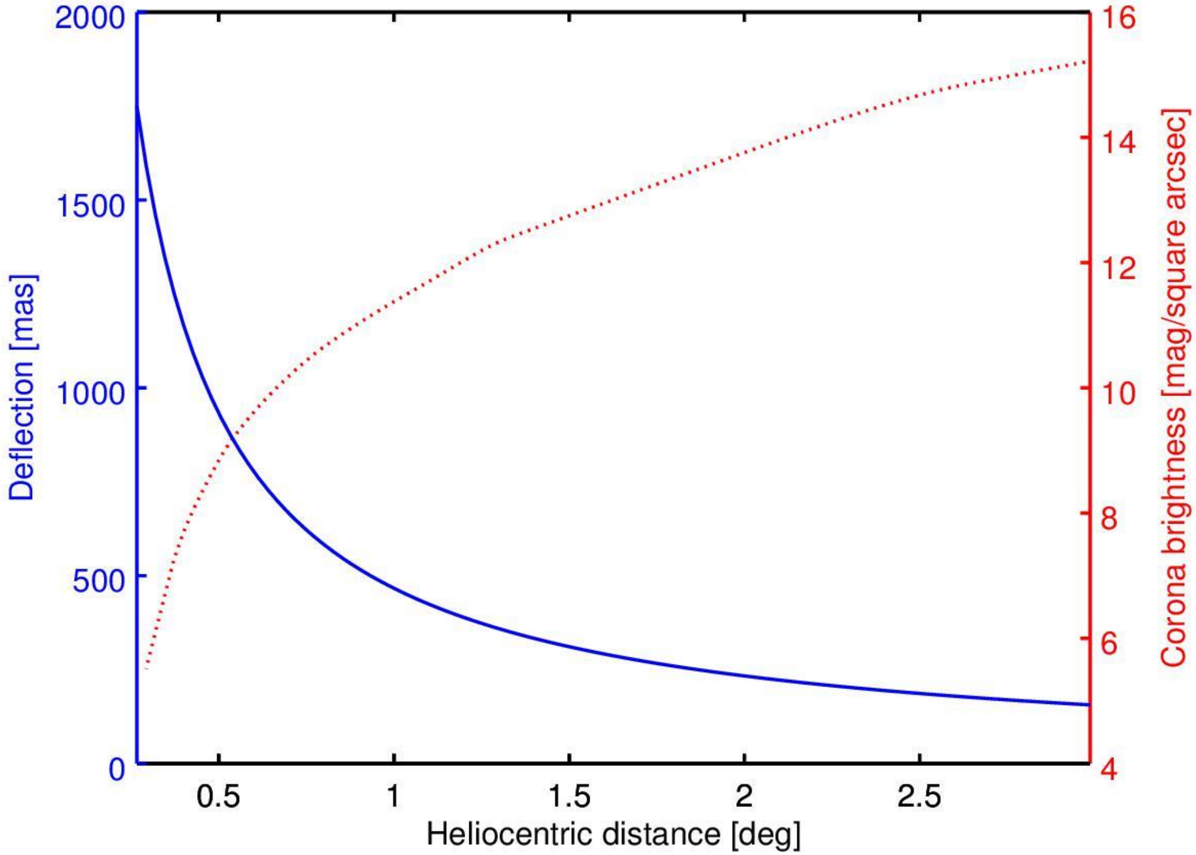
$$\Delta\alpha \propto \lambda^2 N(\rho)$$

Radio @ ρ = 4 R_Sun [Cassini]: **≈0.1 arcsec**
[Bliokh et al. 1969; Gnedin et al. 1996]

Visible @ ρ = 1.2 R_Sun [~limb]: **<1e-9 arcsec**
[Argence 1944]

AGP: no need for refraction correction

Sun disc straylight and Coronal background



Increasing distance from Sun limb:

Decrease of background from Corona and disc diffraction

Decrease of deflection angle ⇔ astrometric signal

Design trade-off: observation at 1° -2° from Sun centre

Background still high: ~9-11 mag/square arcsec

Higher spatial resolution ⇒ lower background per star

Multiple field observation (I)

Multiple field multiplex on telescope + detector

Technical requirement: field of many degrees at high resolution difficult for both optics & detector

Scientific benefit: simplify differential measurement

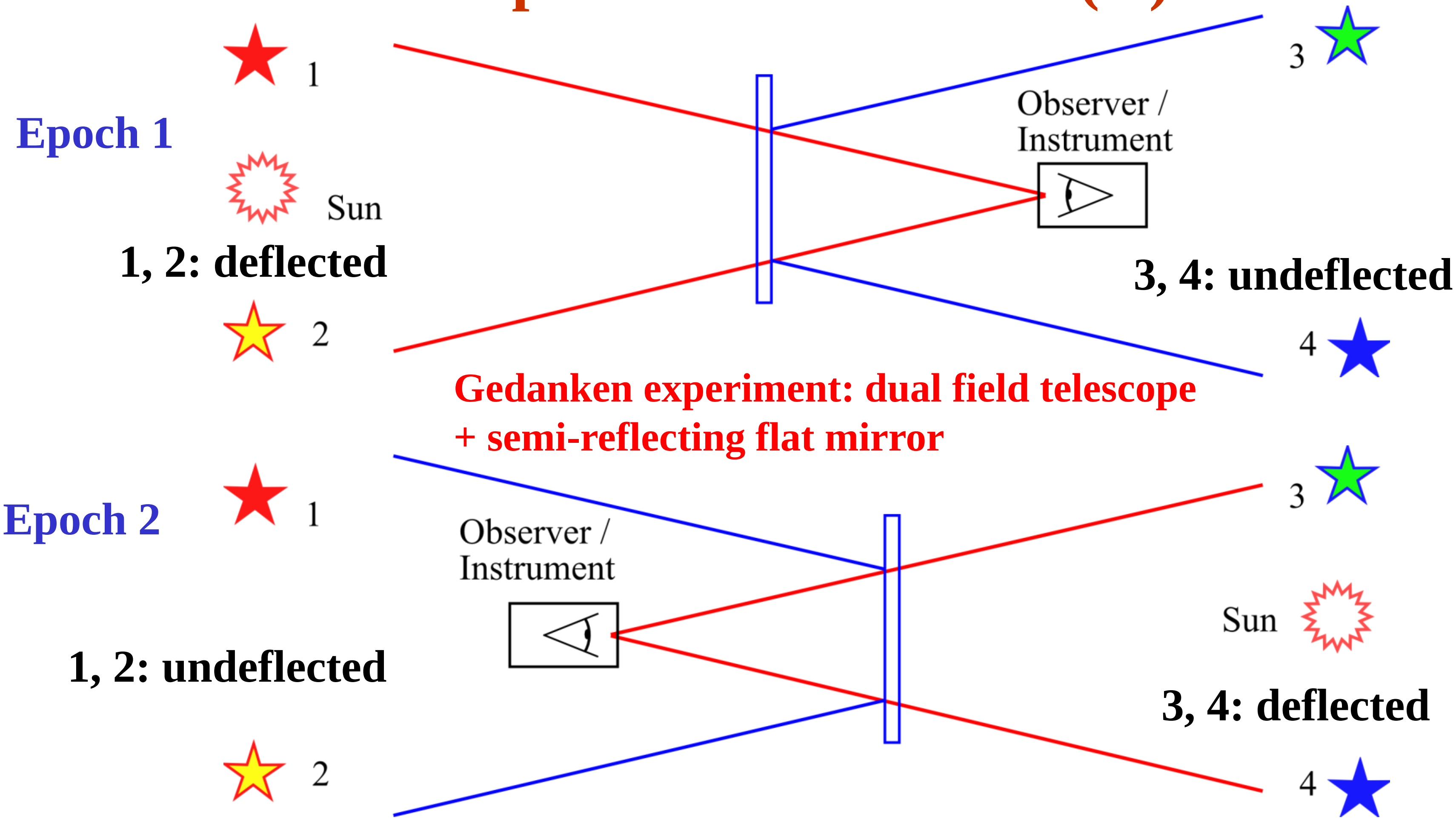
Epoch 1↔2: deflection modulation switched between field pairs

Additional epochs (calibration): low deflection on all fields

Star separation variation: due to

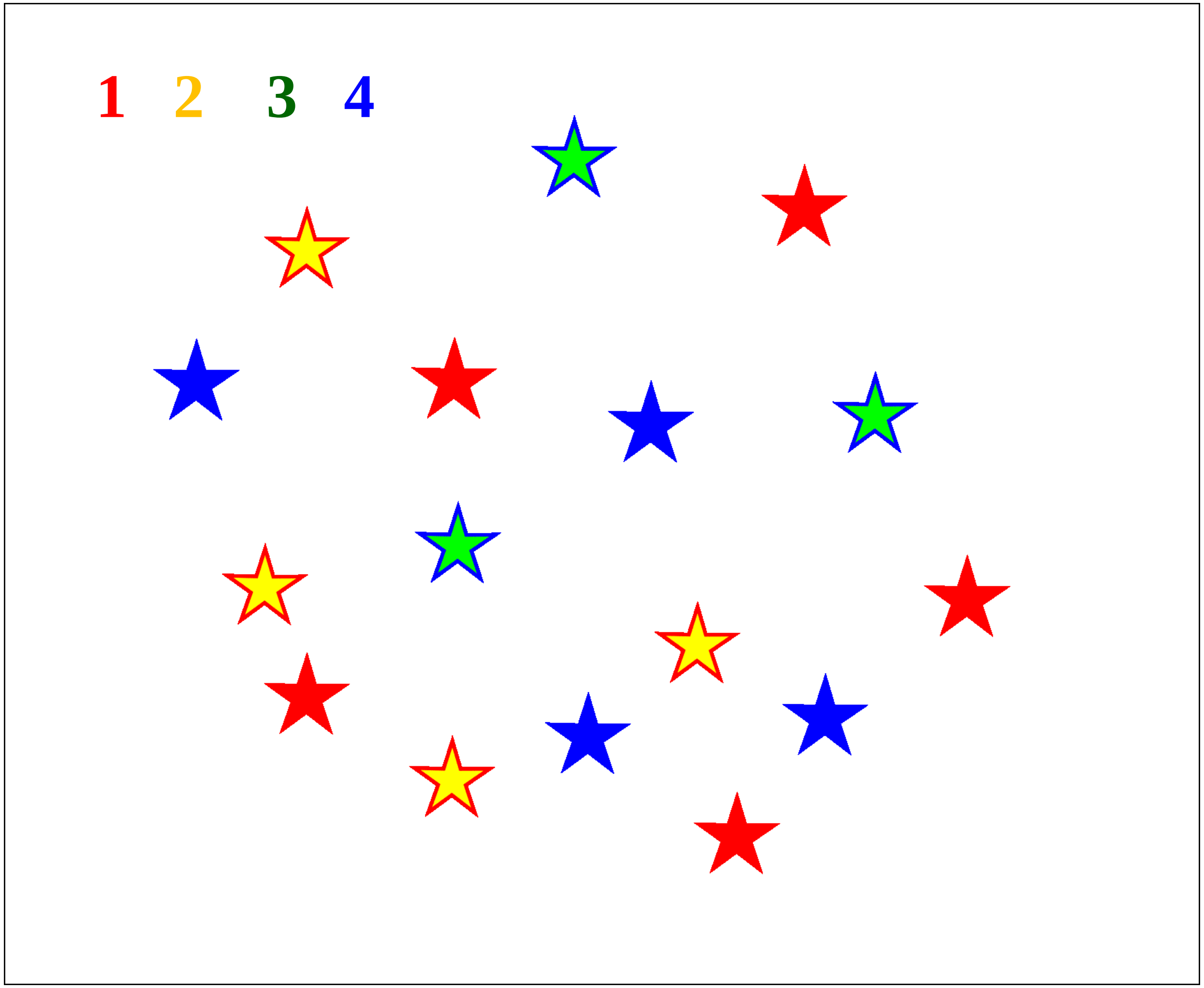
- deflection quantity to be measured
- instrument systematic error [e.g. base angle variation]

Multiple field observation (II)



Epoch 1↔2: deflection modulation switched between field pairs

Multiple field superposition + epoch modulation



Two epochs:

differential measurement of deflection on stellar sample

+

astrometric calibration on undeflected fields

Instrument errors mostly common mode to all fields

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*

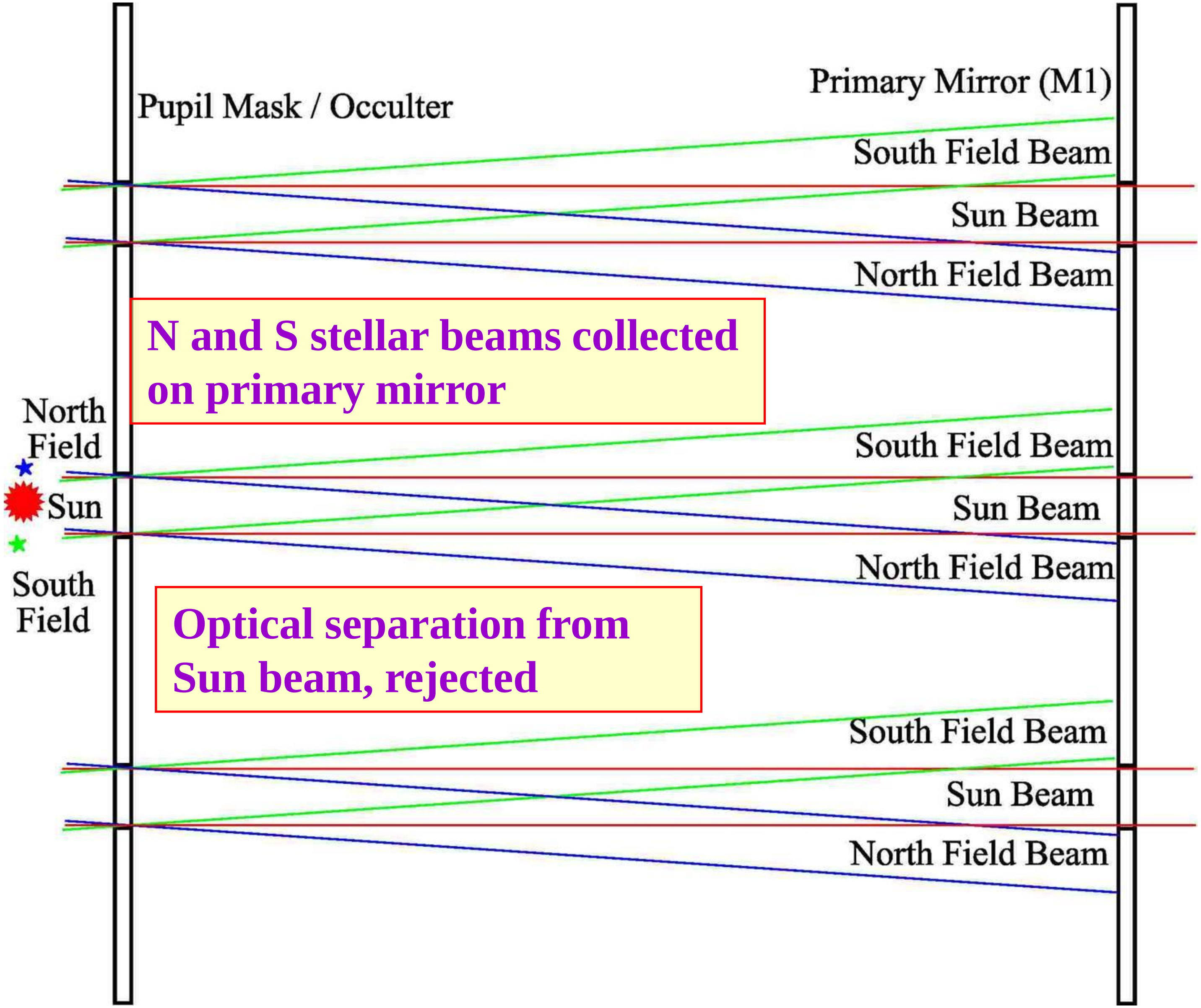
$$\boxed{\begin{array}{l}\delta\psi(F1,F2)+\delta\psi(F3,F4)=\\ {[\Delta\xi(F1,F2;E1)-\Delta\xi(F1,F2;E2)]+[\Delta\xi(F3,F4;E2)-\Delta\xi(F3,F4;E1)]}\end{array}}$$

Photon limited monitoring of base angle *β* variation

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

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

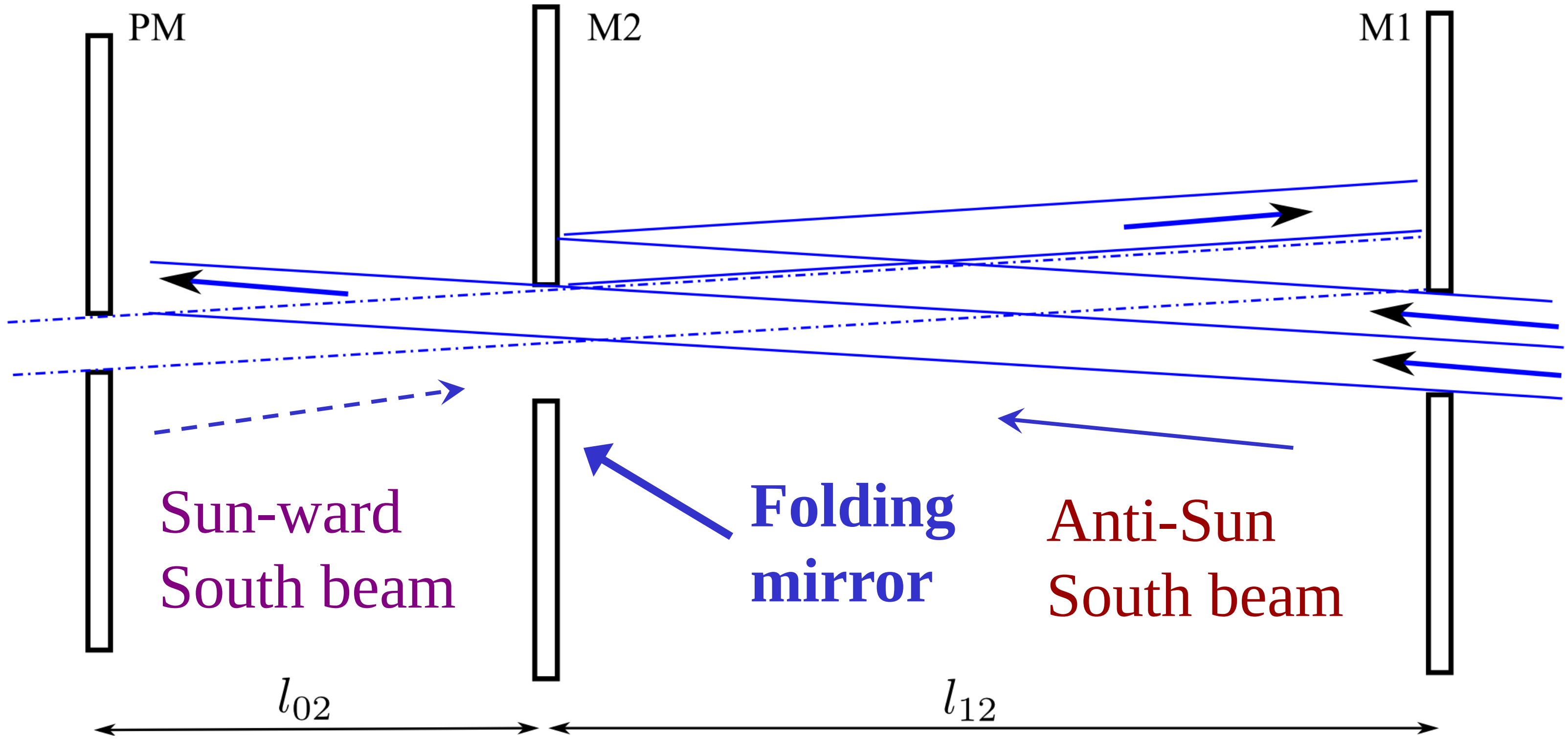
Injection of Sun-ward fields



N and S stellar beams collected on primary mirror

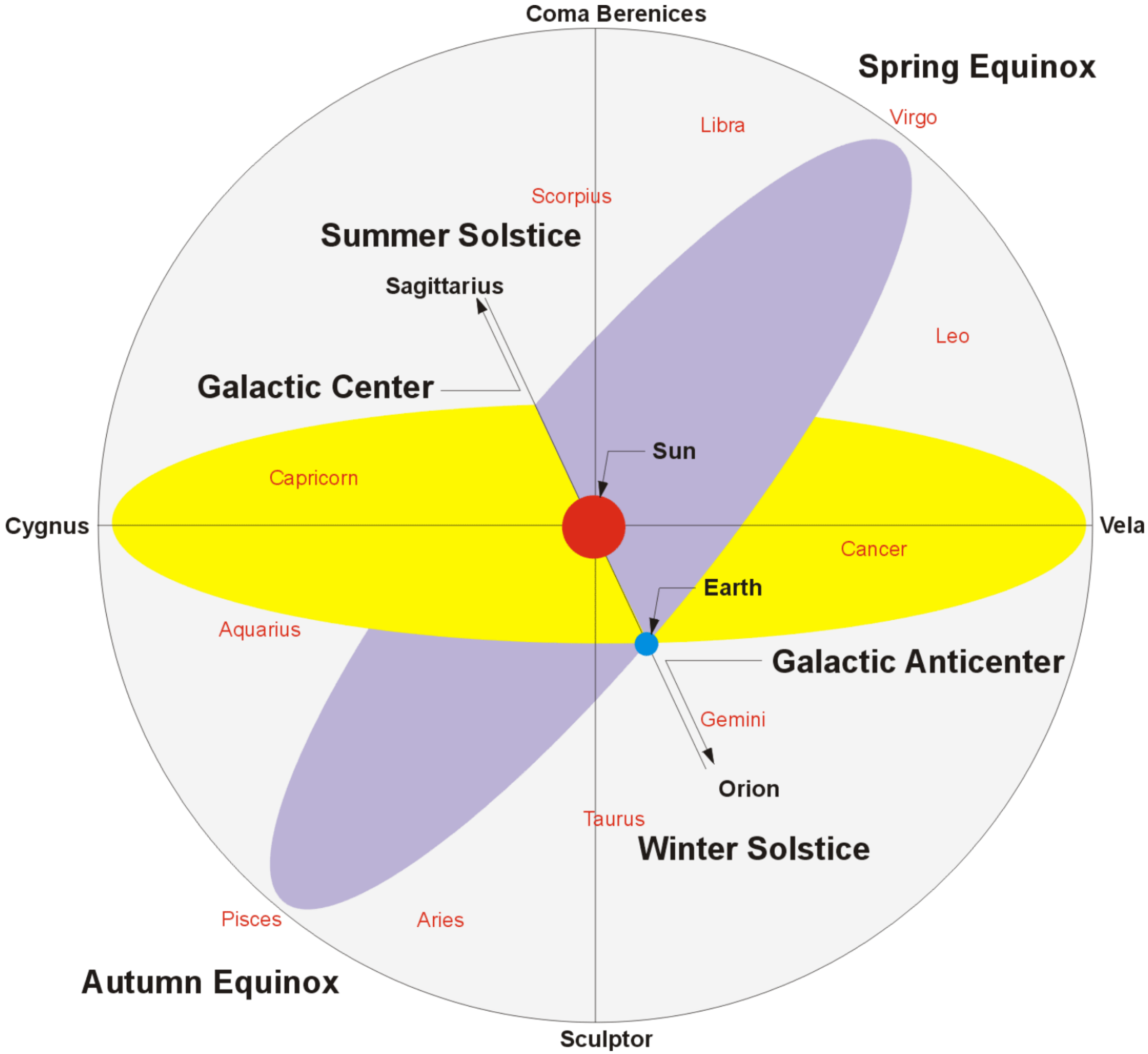
Optical separation from Sun beam, rejected

Injection of anti-Sun fields @ 180°



(Larger) beams from anti-Sun directions **±β/2** injected into the telescope with acceptable vignetting

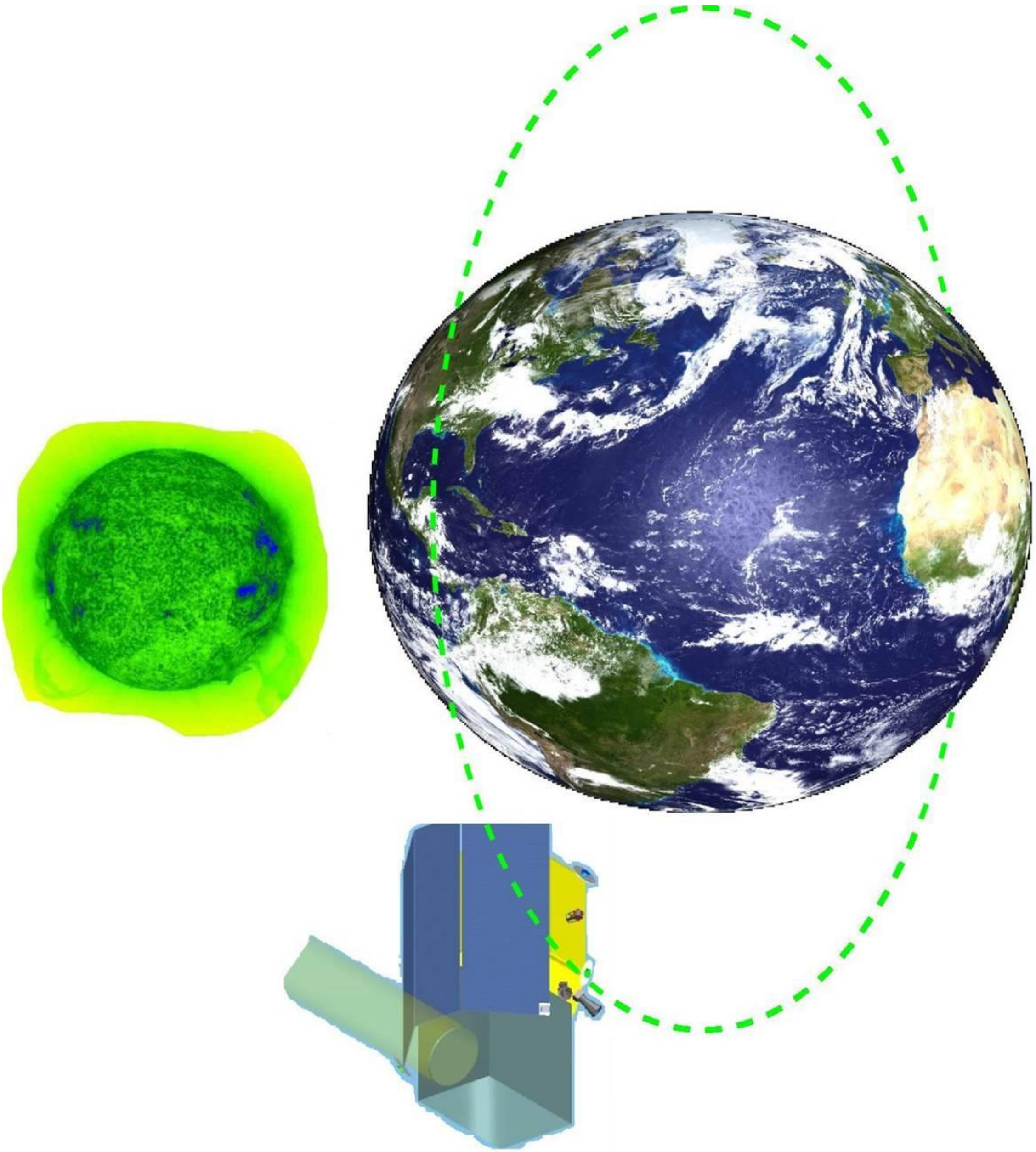
Convenient fields: Galactic ∩ Ecliptic plane



High stellar density regions:

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

Mission profile



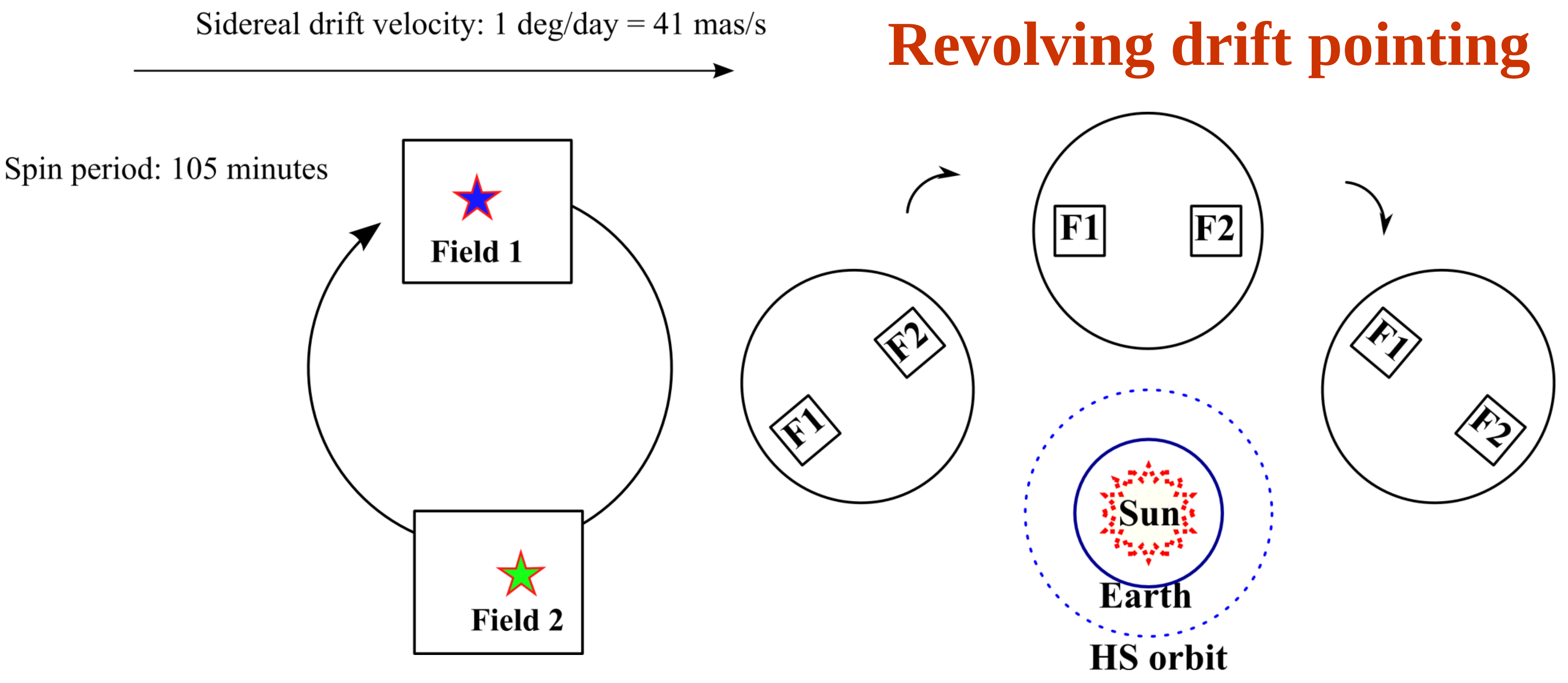
Sun-synchronous orbit, 1000 km elevation ⇒ no eclipse

105 minute orbit period

100% nominal observing time

Stable solar power supply and thermal environment ⇒ instrument structural stability

Revolving drift pointing

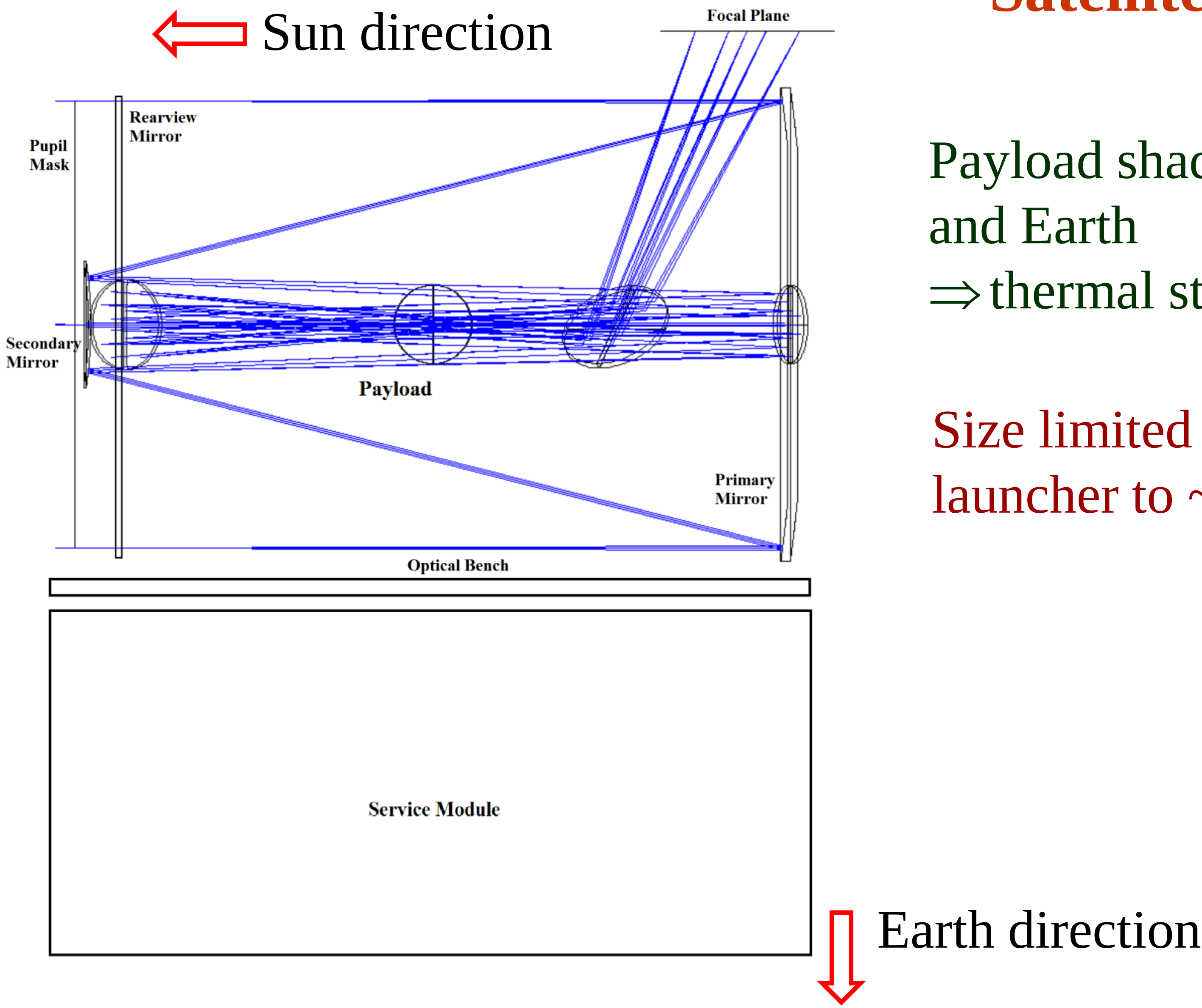


Field rotation around the Sun synchronous with orbital motion

System rationale: preserve satellite orientation vs. Earth (nearly stable thermal environment)

Science rationale: average instrument response among channels (strenghten calibration)

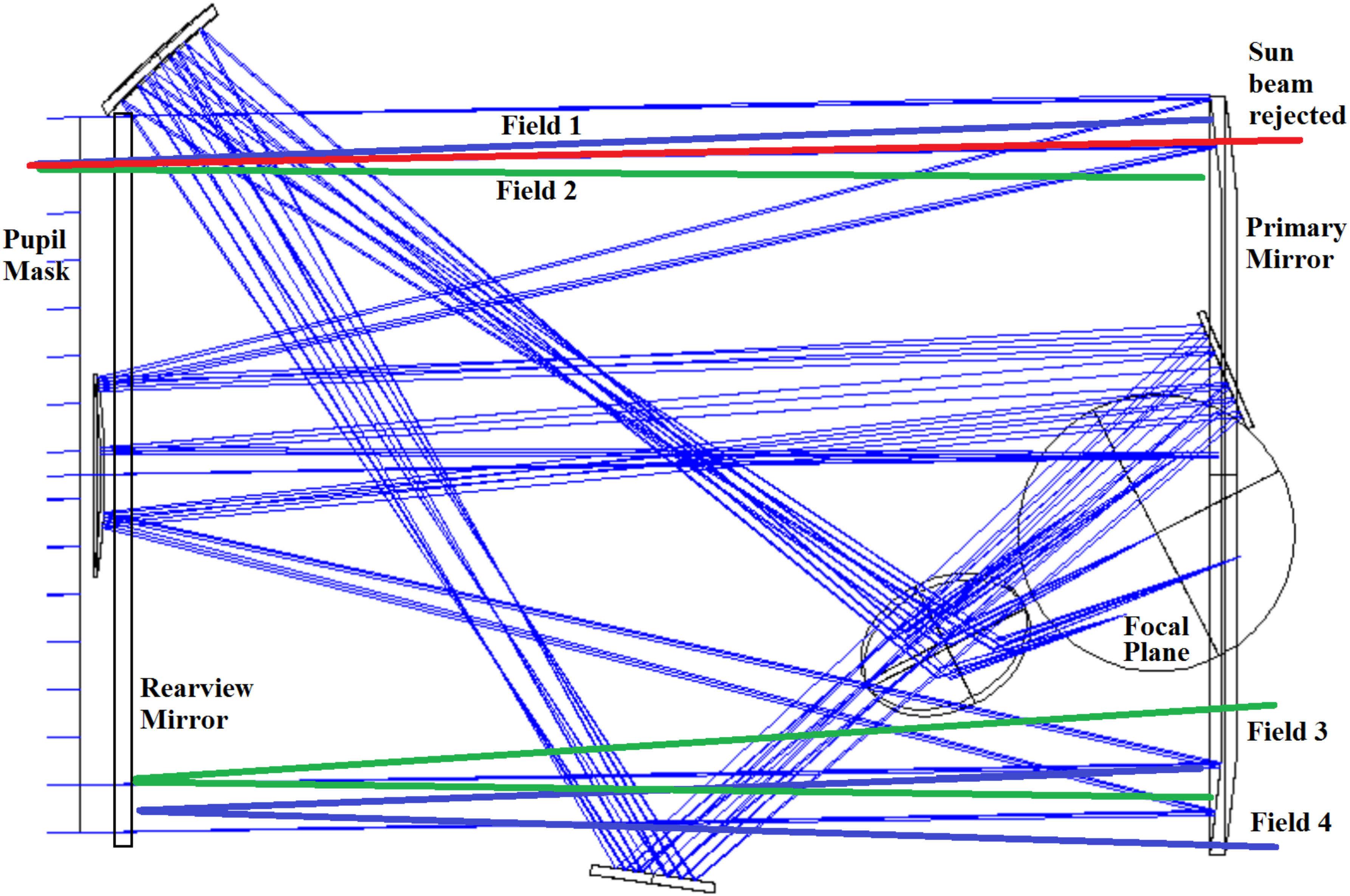
Satellite geometry



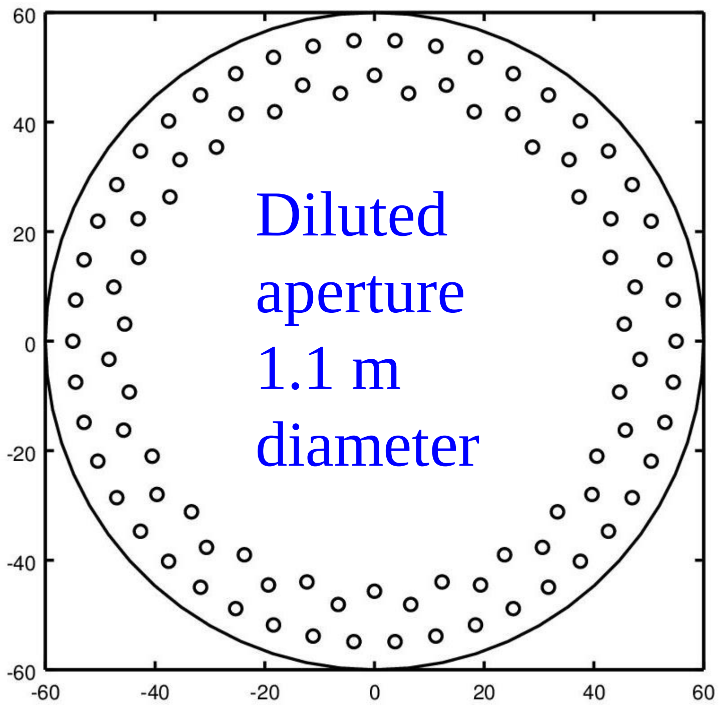
Payload shaded vs. Sun and Earth
$\Rightarrow$ thermal stability

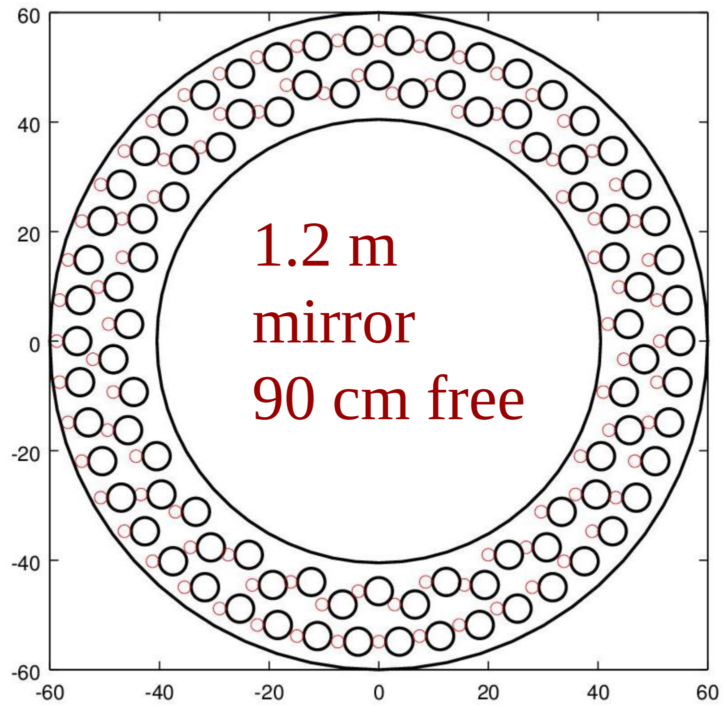
Size limited by Vega launcher to ~2 m

Payload concept (I): multiple field telescope



Payload concept (I): imaging Fizeau interferometer





Collecting area

Sun direction: 375 cm^2

Anti-Sun direction: 1574 cm^2

Observation

On deflected fields

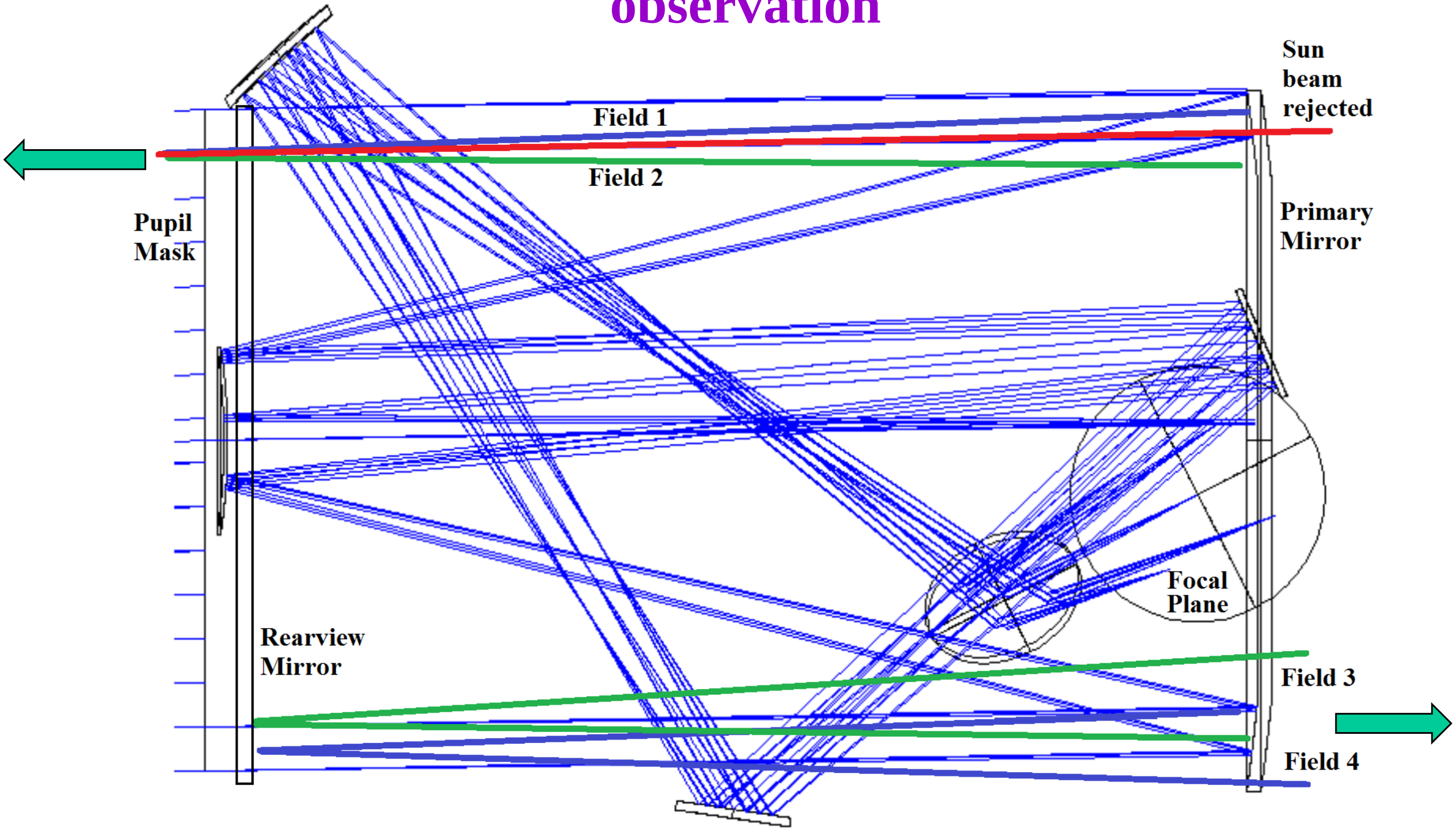
Sun direction

Simultaneous observation

Calibration

On undeflected fields

Anti-Sun direction



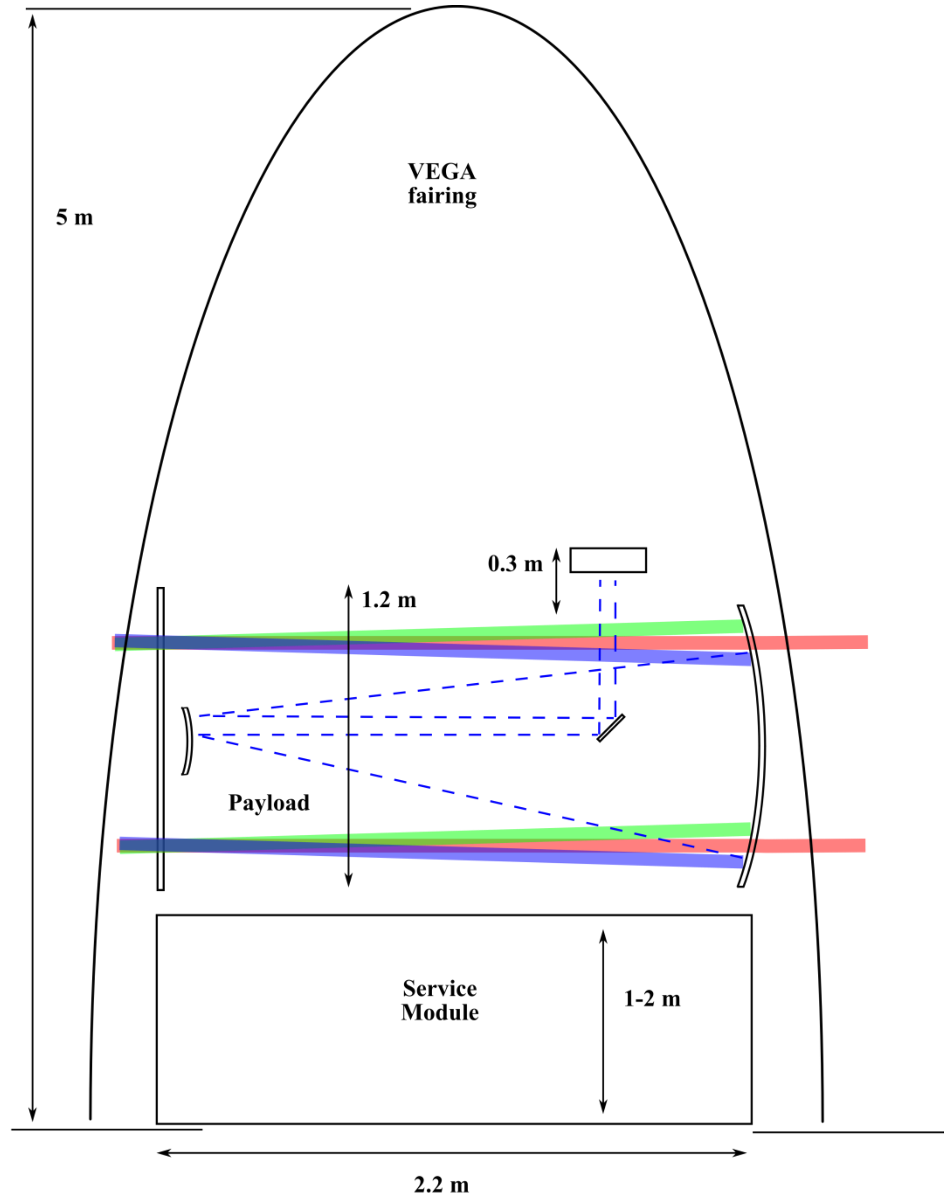
Fairing volume usage

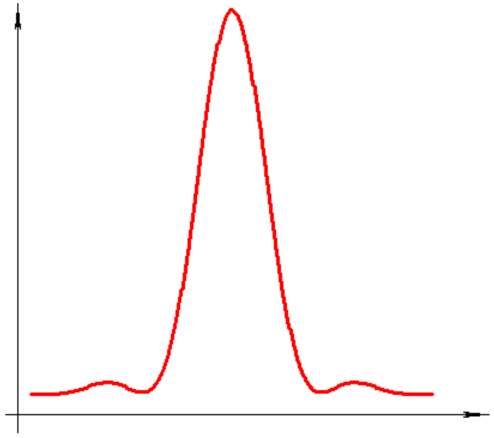
Spacecraft / payload diameter: 2.2 m

Height (without interface): ~3 m

No deployable subsystems

Compatible with small additional payloads





Precision on single image location

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

Statistics

Diffraction

s: Standard deviation of image location

l: Effective ***wavelength*** of observation

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

$SNR \leq \sqrt{N}$

Signal to Noise Ratio $\Rightarrow$ photons, RON, background

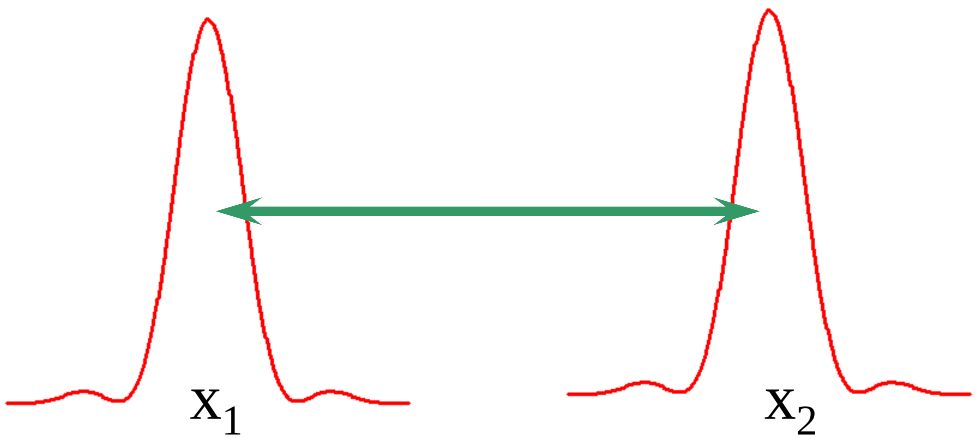
N: Number of photons collected

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

σ can be a small fraction of pixel/image size

[Gai et al., PASP 110, 1998]

Precision on image separation



Arc length defined by composition of individual locations

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

Precision related to

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

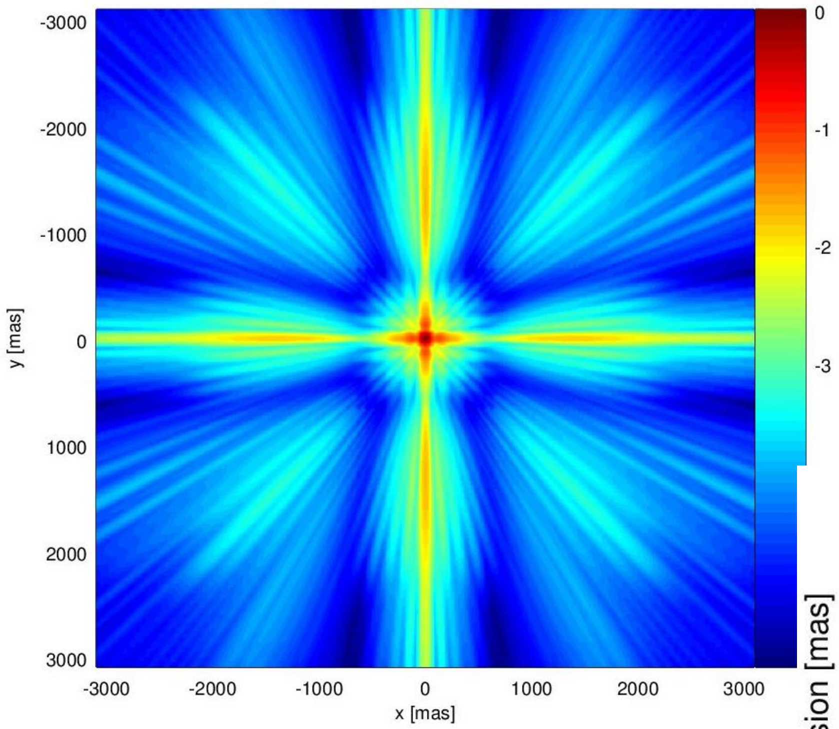
Observing strategy

Individual imaging and location performance

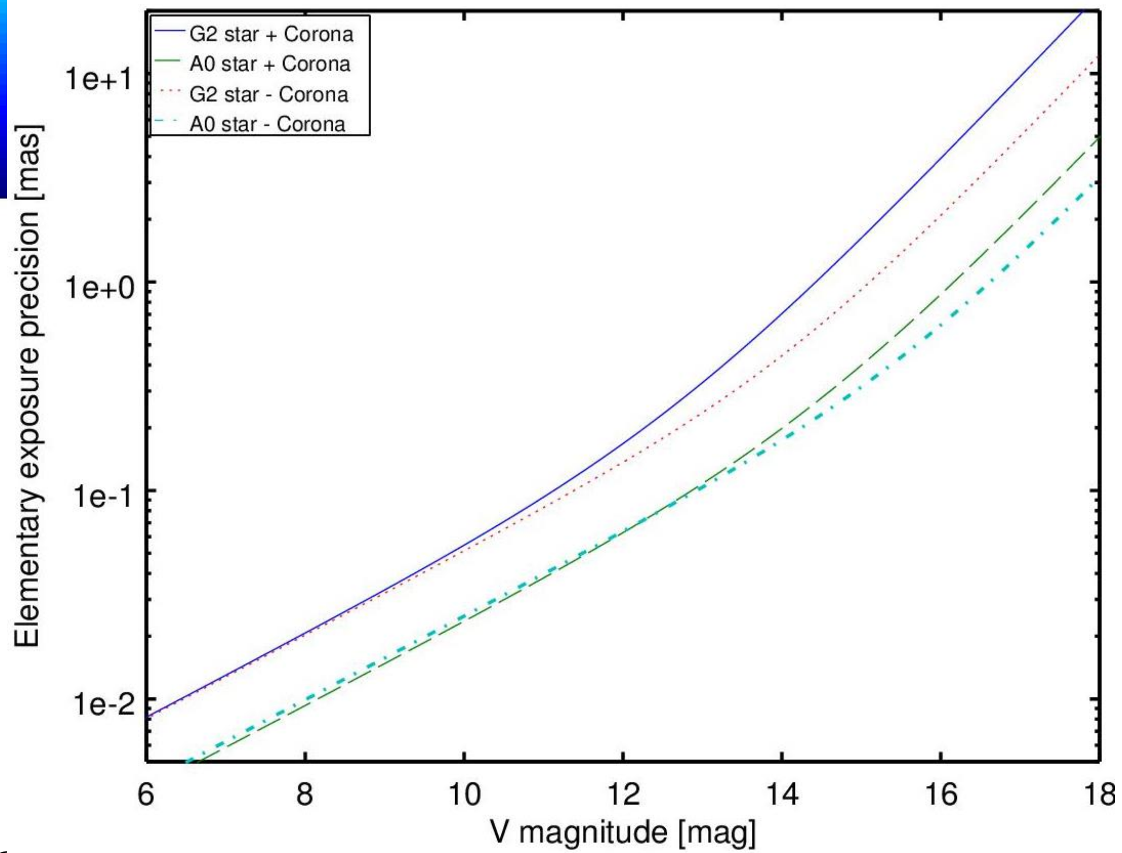
High resolution images: ~0.2 arcsec peak

Underlying structure: spoiler detection

Photometry on side wings at <1%



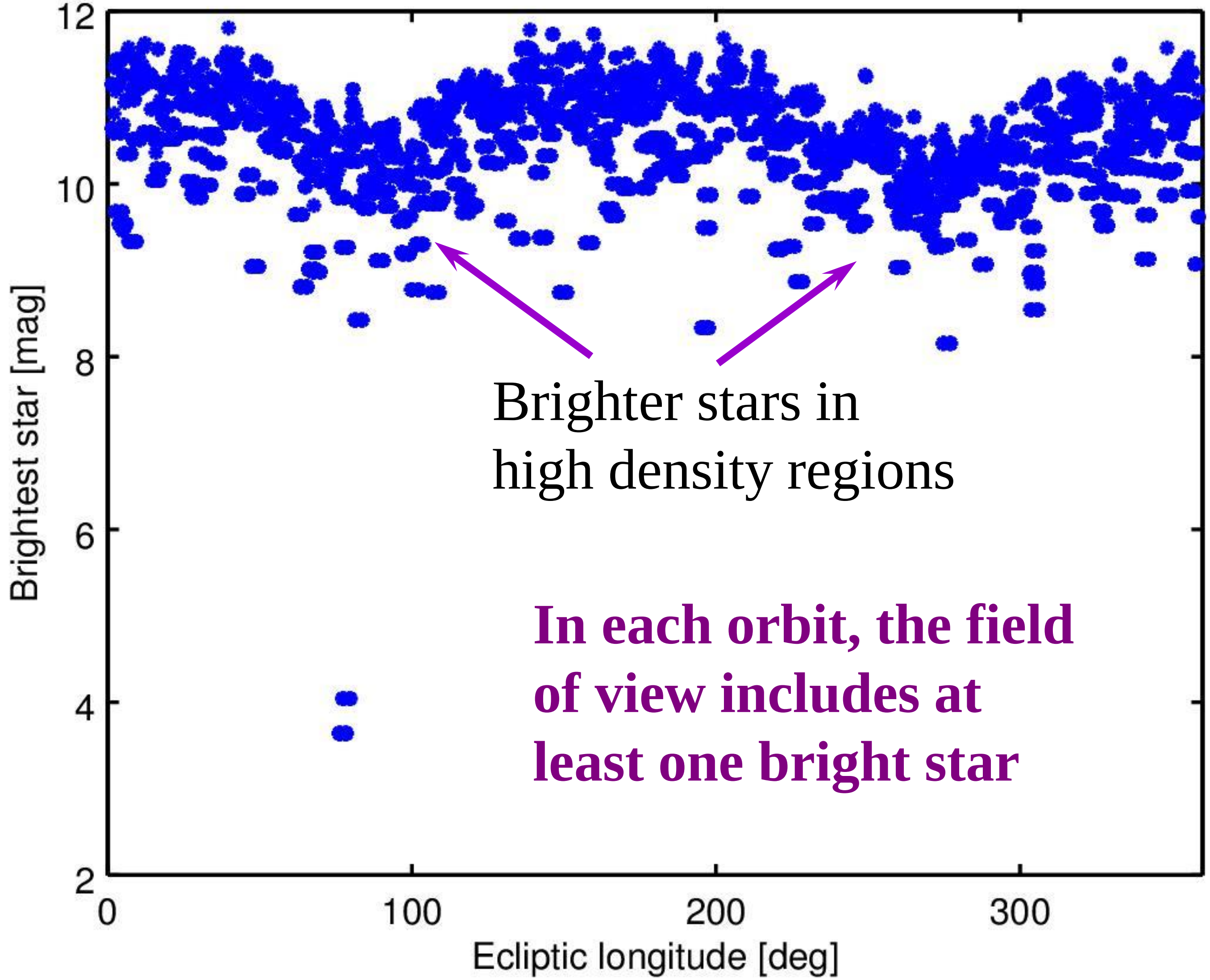
Near-solar unresolved star [log intensity]



Elementary precision on

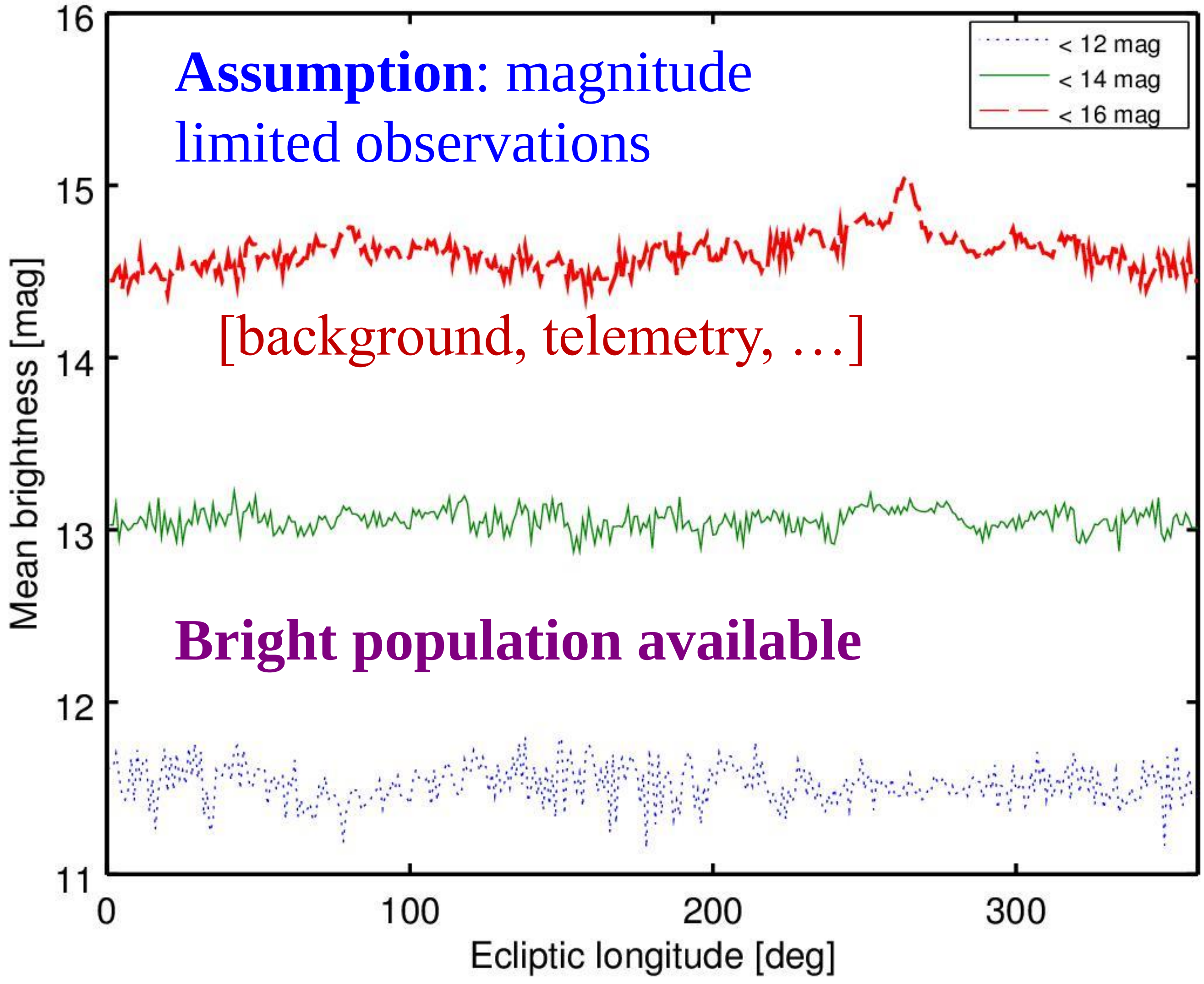
location in 1 min. integration

Observations (I): availability of bright stars

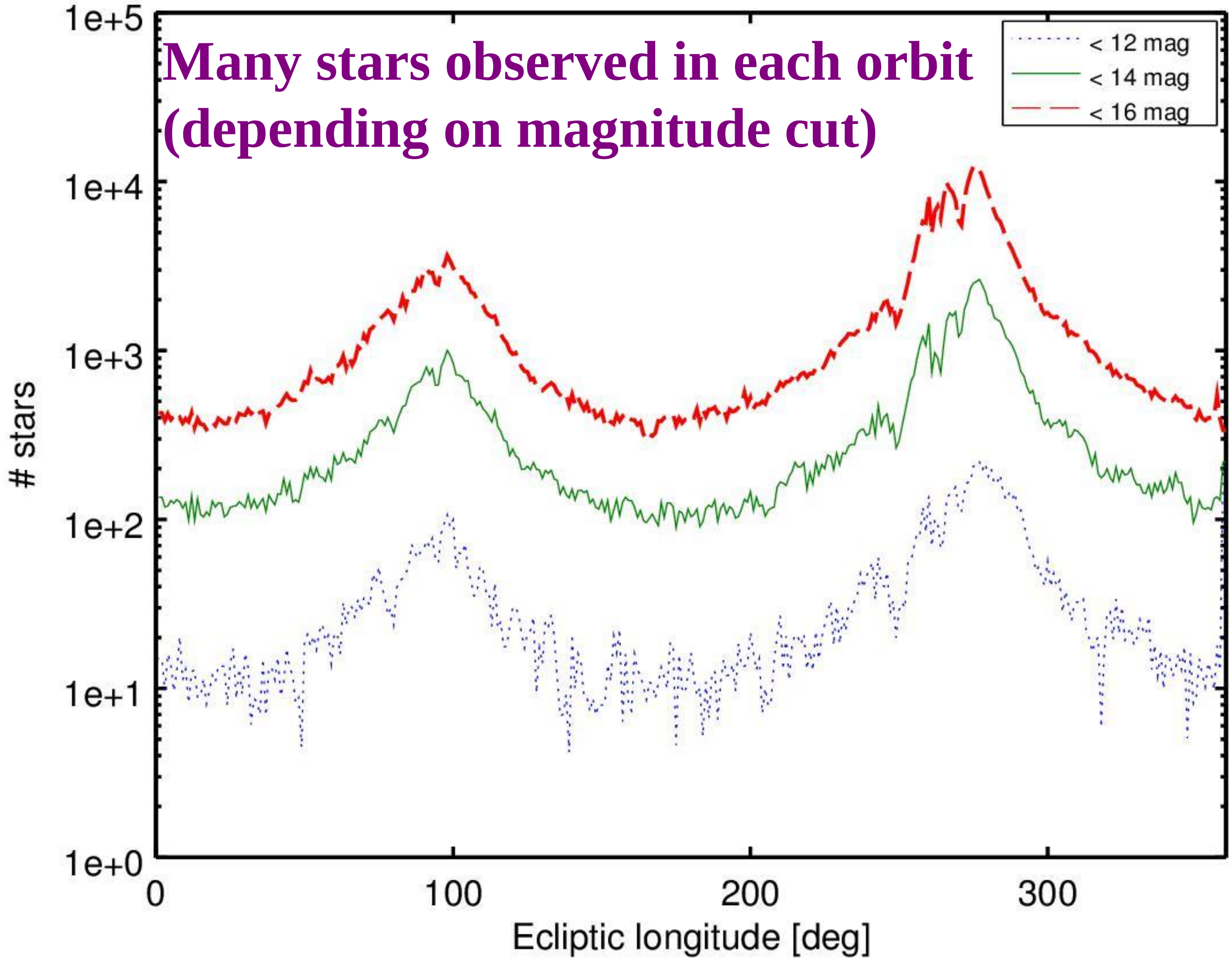


In each orbit, the field of view includes at least one bright star

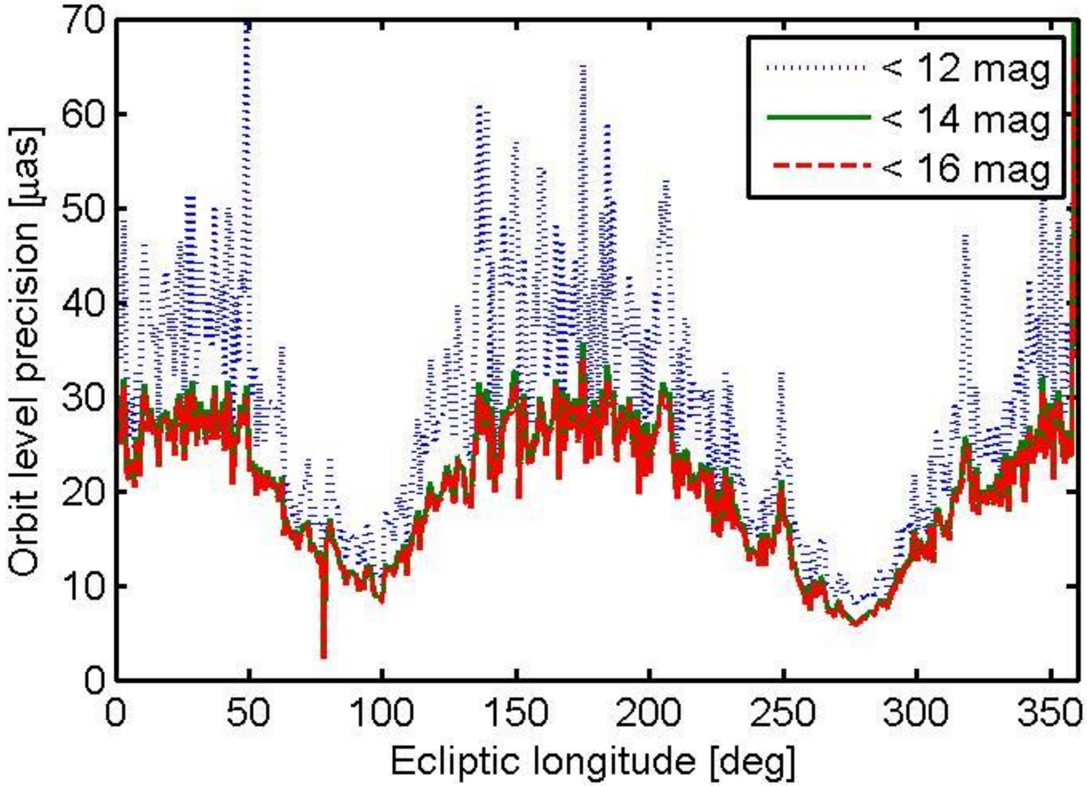
Observations (II): mean brightness of stellar sample



Observations (III): size of stellar sample



Precision per orbit

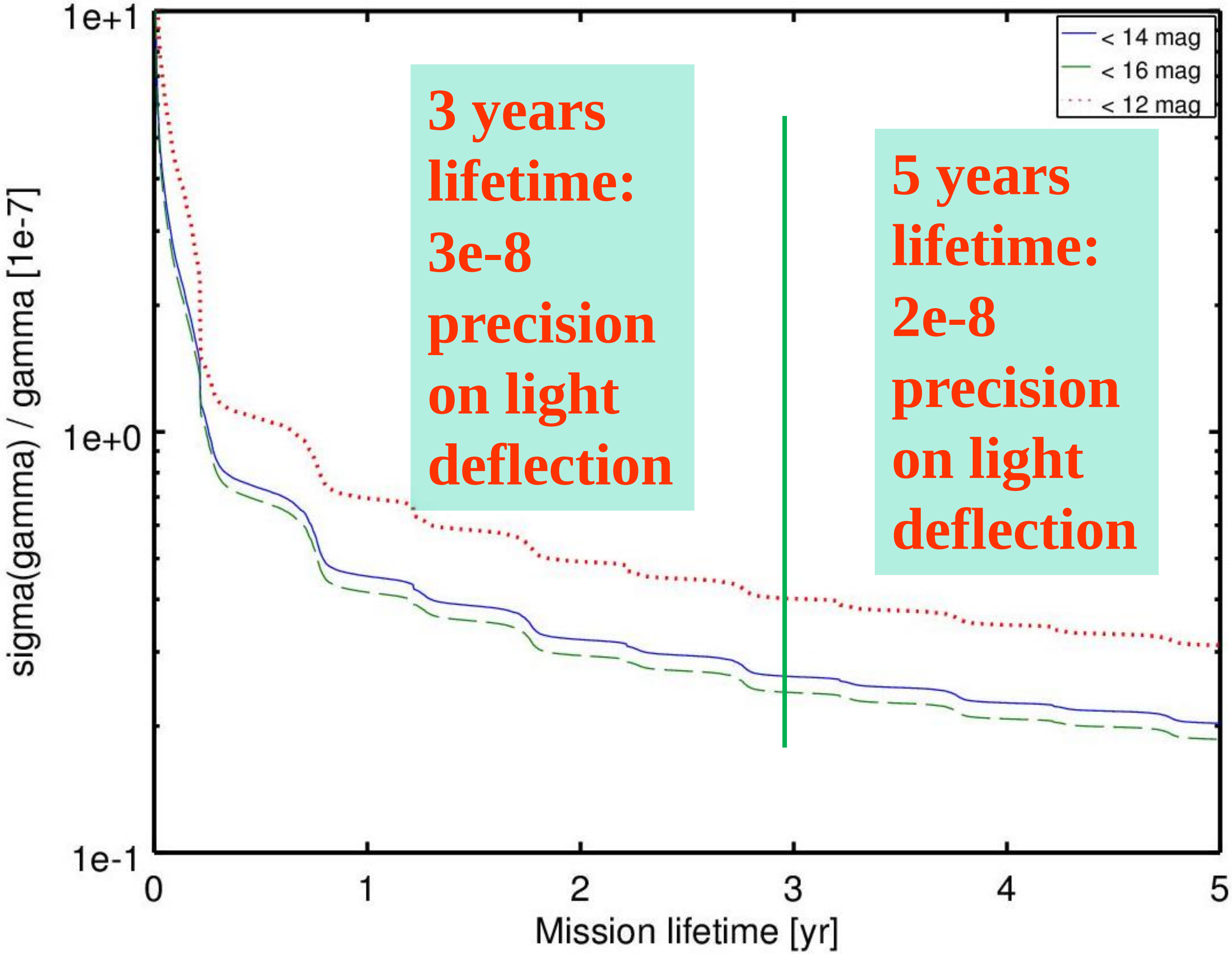


Each orbit (<2 hr) cumulates the precision of all observed stars

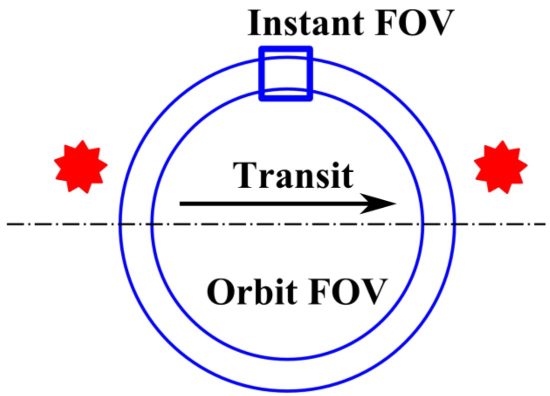
Stars fainter than ~14 mag provide negligible improvement

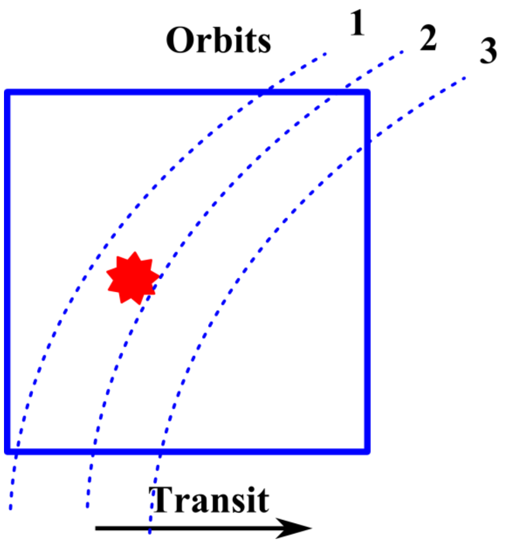
Photon limited performance – 3-5 year mission

Performance factors: ~diameter^2, (field of view)^{3/2}, time^{1/2}



Astrometry on main planets (I)





"Epoch": transit of the planet on both "sides" of the field of view

Each transit: ~3 orbital passes

Standard FOV exposure: ~3 min

Observation in both optical channels

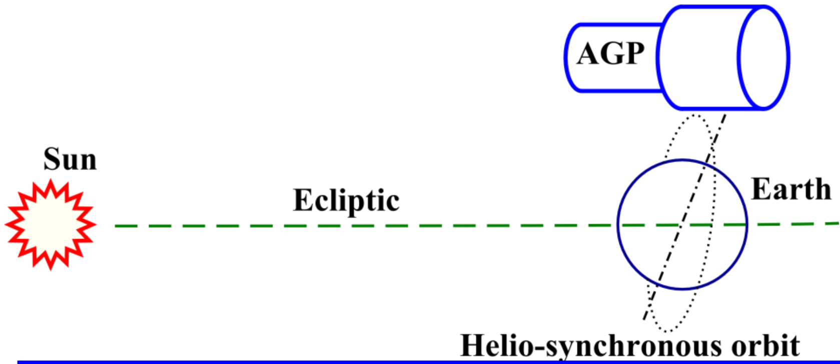
Sampling: 6 exposures, one every ~52 min

Transit separation: ~2 days (on Ecliptic)

Astrometry on main planets (II)

	Magnitude / pixel [mag]	SNR level / 1e3	Transit Precision [µas]	Epoch Precision [µas]	Velocity Precision [µas/day]
Mercury (superior conjunction)	**6.84**	**356**	**3.65**	**1.58**	**1.05**
Venus (superior conjunction)	**7.38**	**619**	**4.66**	**2.02**	**1.34**
Mars (conjunction)	**10.5**	**51.4**	**19.7**	**8.55**	**5.67**
Mars (opposition)	**11.2**	**269**	**26.8**	**11.61**	**7.69**
Jupiter (conjunction)	**12**	**223**	**38.8**	**16.88**	**11.19**
Jupiter (opposition)	**11.8**	**406**	**35.5**	**15.40**	**10.21**
Saturn (conjunction)	**13.5**	**52.2**	**80.3**	**34.94**	**23.16**
Saturn (opposition)	**12.4**	**119**	**48.7**	**21.27**	**14.10**
Uranus (conjunction)	**14.7**	**6.47**	**147**	**64.04**	**42.46**
Uranus (opposition)	**14.5**	**8.62**	**137**	**59.70**	**39.58**

Orbital parallax for Solar System objects

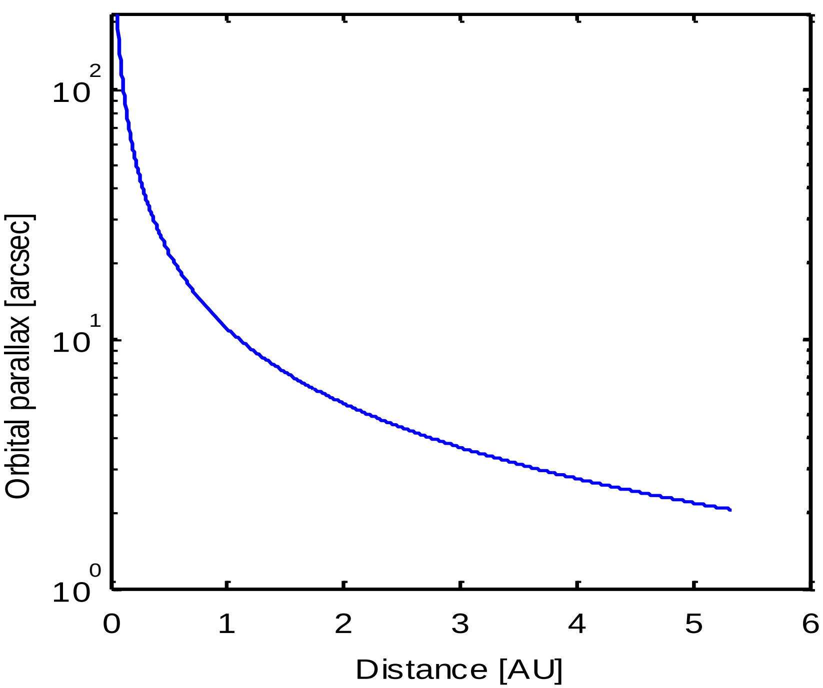


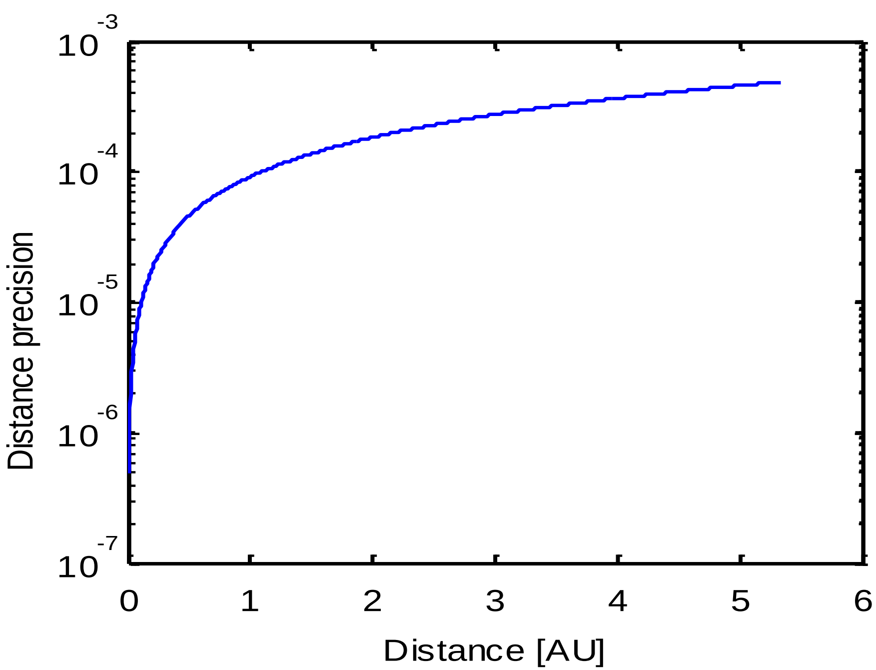
Satellite height: ~1000 km

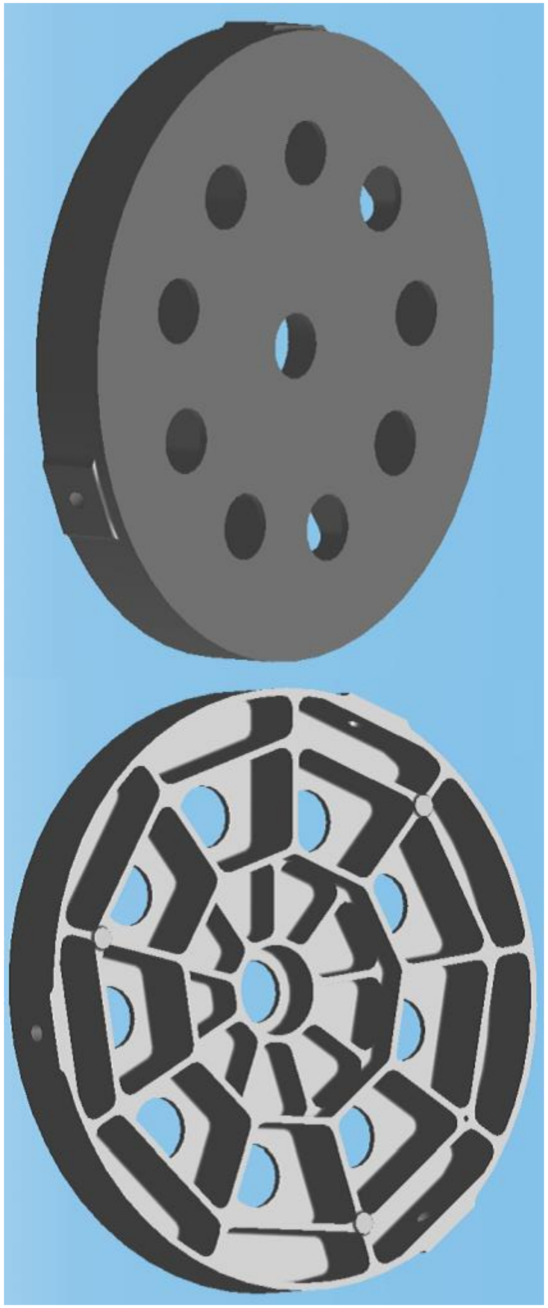
Orbit radius: ~7500 km

Orbit period: ~105 min

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







Laboratory prototype - I

Diluted SiC Mirror Demonstrator

Pupil mask [shading the telescope]

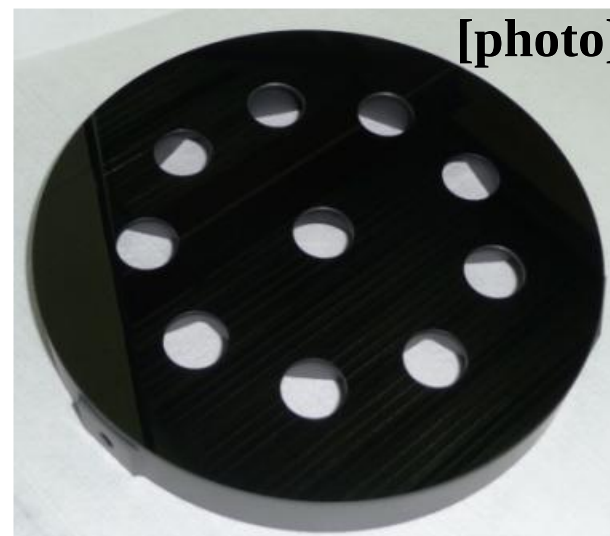
9+1 apertures, ∅ 20 mm

Outer diameter: 20 cm

Manufacturer: **Boostec** (Bazet, F)

Qualification tests at ADS Intl. (LC)

Requirements:
Static & dynamic load compatible with e.g. Soyuz launcher



Review of M4 Call "boundary conditions" (I)

Cost ceiling: 450M€

Preparation phase: 2018 (3.5 yrs), **Implementation phase**: 2025 (7 yrs)

TRL: 5-6 before the starting of the implementation phase (2018)

International collaborations: M mission can be entirely European or European-led with junior participation by international partners

Endorsement by national funding agencies needed for the submission

Review of M4 Call "boundary conditions" (II)

Proposal structure (suggested):

- Front cover (1 page)
- Back cover (1 page)
- Executive summary (2 pages)
- Science case (10 pages)
- Scientific requirements (5 pages)
- Proposed scientific instruments (15 pages)
- Proposed mission configuration and profile (10 pages)
- Management scheme (5 pages)
- Costing (2 pages)
- Bibliography (encouraged)

HARD LIMIT ON TOTAL PAGE COUNT

Deadlines and schedule:

Activity	Date
Release of Call for M4 mission	August 19, 2014
Letter of Intent submission deadline	September 16, 2014 (12:00 CEST)
Briefing meeting (ESTEC)	September 26, 2014 (TBC)
Proposal submission deadline	January 15, 2015 (12:00 CET)
Selection of missions for study	March 2015

Standard Procurement scheme:

ESA: spacecraft; launcher; launch services and operations

Payloads: responsibility of scientific consortia funded by member state agencies, with a varying degree of ESA involvement

Deviations are possible:

ESA taking charge of whole payload (Gaia) or large subsystems (PLATO: focal plane detectors; Euclid: telescope assembly and optical detectors)

Ground segment: shared responsibility of ESA and member States

Specific procurement scheme of AGP to be discussed

Concluding remarks

- ✓ Astronomical techniques ⇒ Fundamental Physics
- ✓ **AGP: light deflection to 10^{-8} range**
- ✓ Early development phase: flexible sub-system split

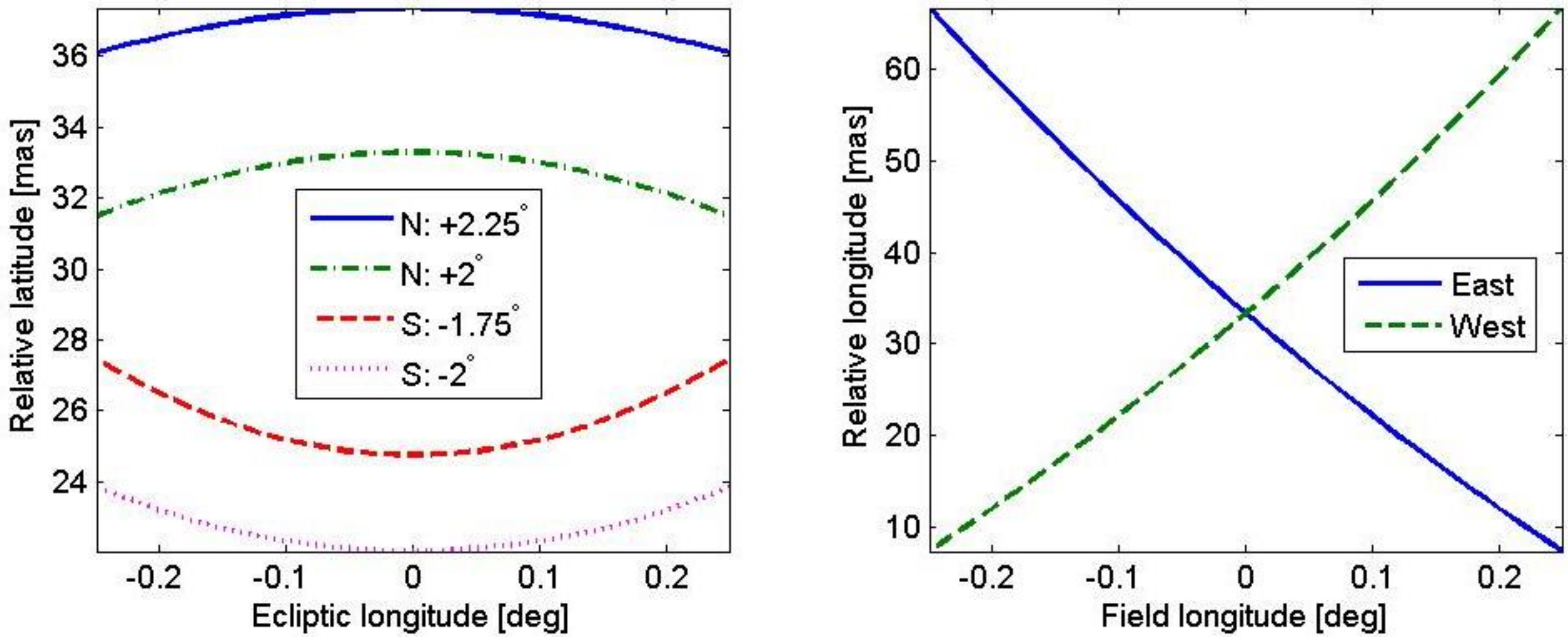
Possible collaboration areas:

- ➢ Device and principle tests in lab and on sky
- ➢ Operations and data processing
- ➢ Selected sub-systems of payload and spacecraft
- ➢ Participation to data reduction and analysis consortium
- ➢ High angular resolution Solar coronagraphy

GAME OVER

…NOW AGP!

Field discrimination by deflection modulation



Deflection amplitude modulated by several mas along FOV transit

Additional orbital modulation: different position of the Sun

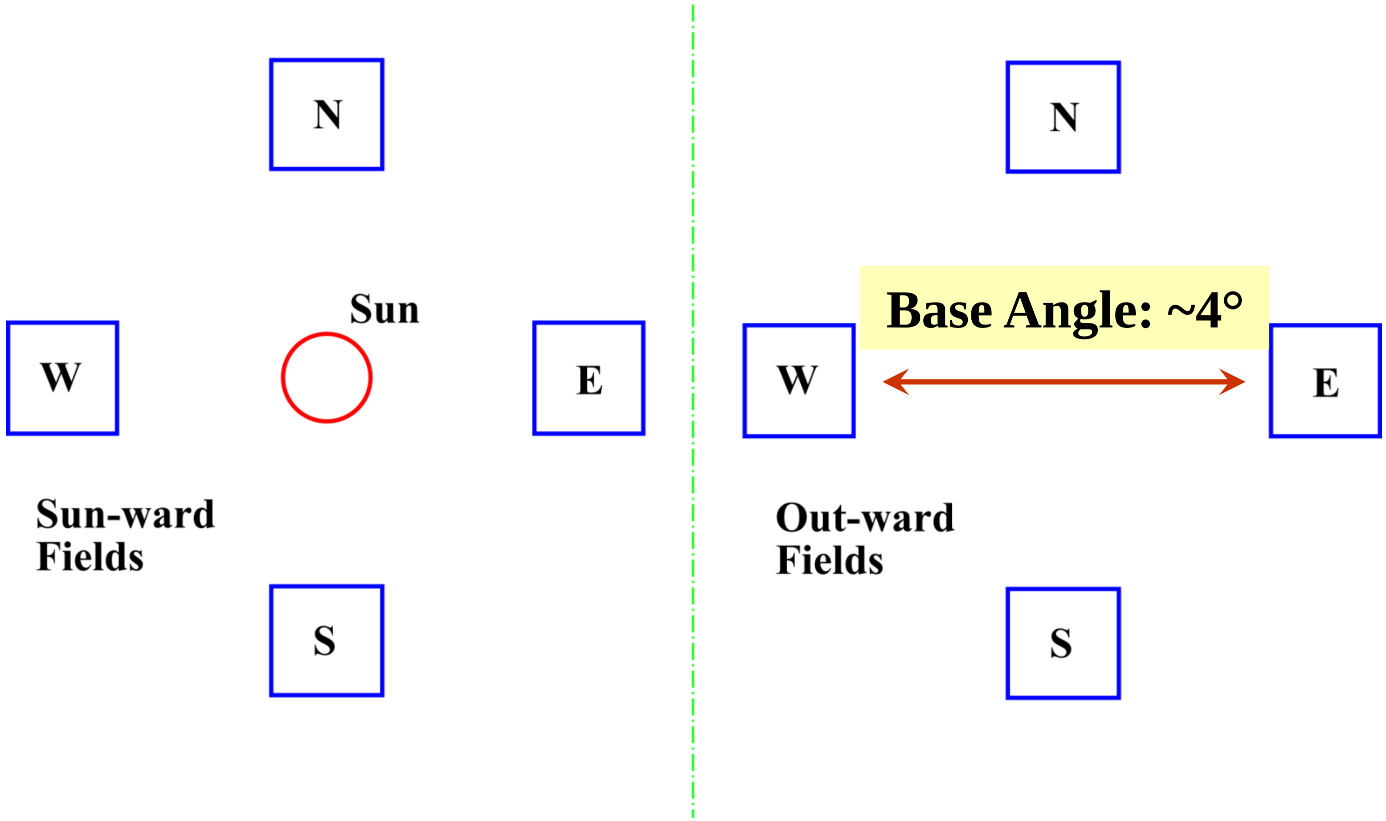
Gravitational redshift?

$$z = \left(1 - \frac{2GM}{rc^2}\right)^{-1/2} - 1$$

Redshift of starlight at the edge of the Sun: 3×10^{-6}

Detectability TBD…

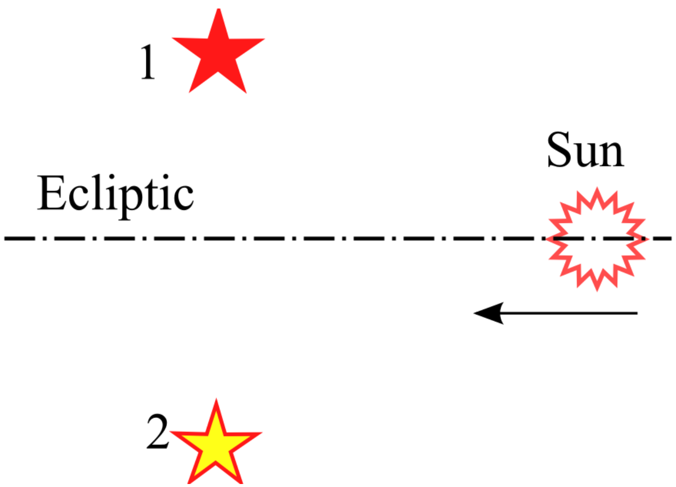
Field multiplicity: 4 Sun-ward + 4 Out-ward

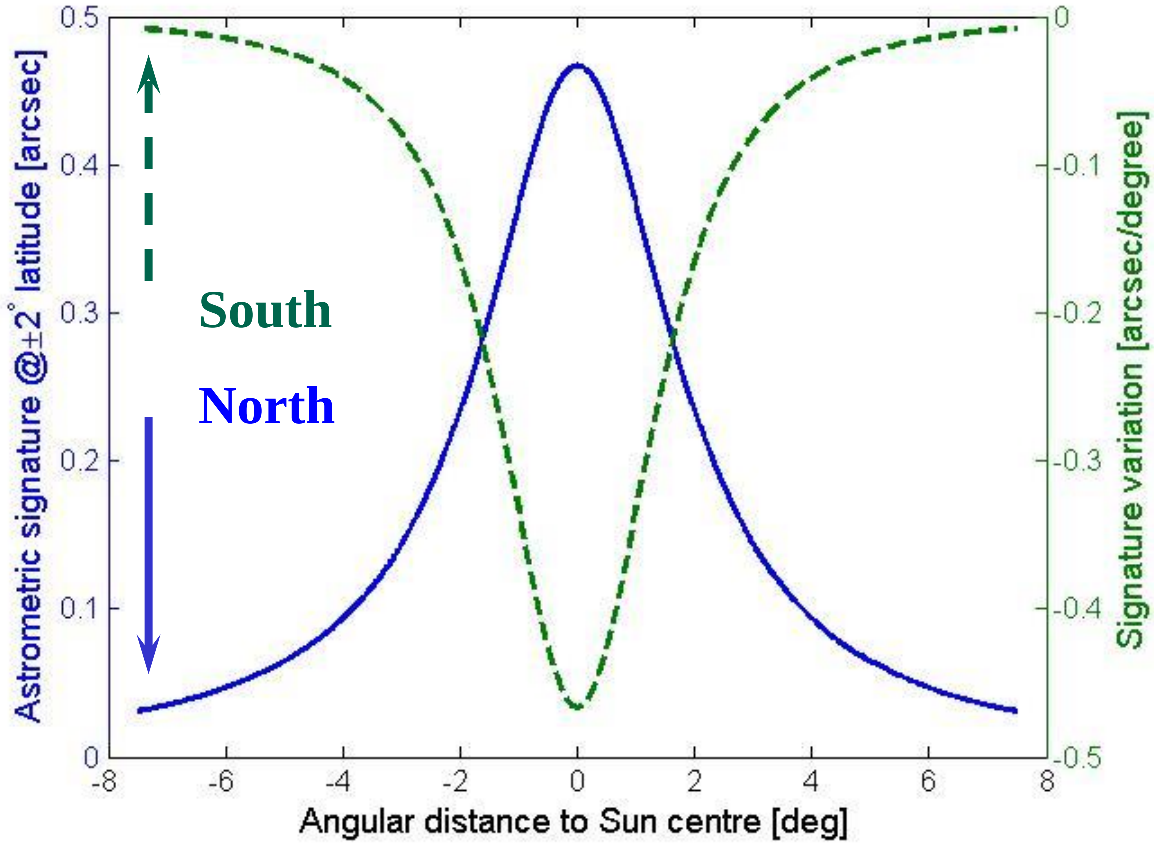


Multiplexing of 4+4 beams within telescope

Field superposition onto CCD detector (4× Corona background)

Astrometric signature at ±2° ecliptic latitude





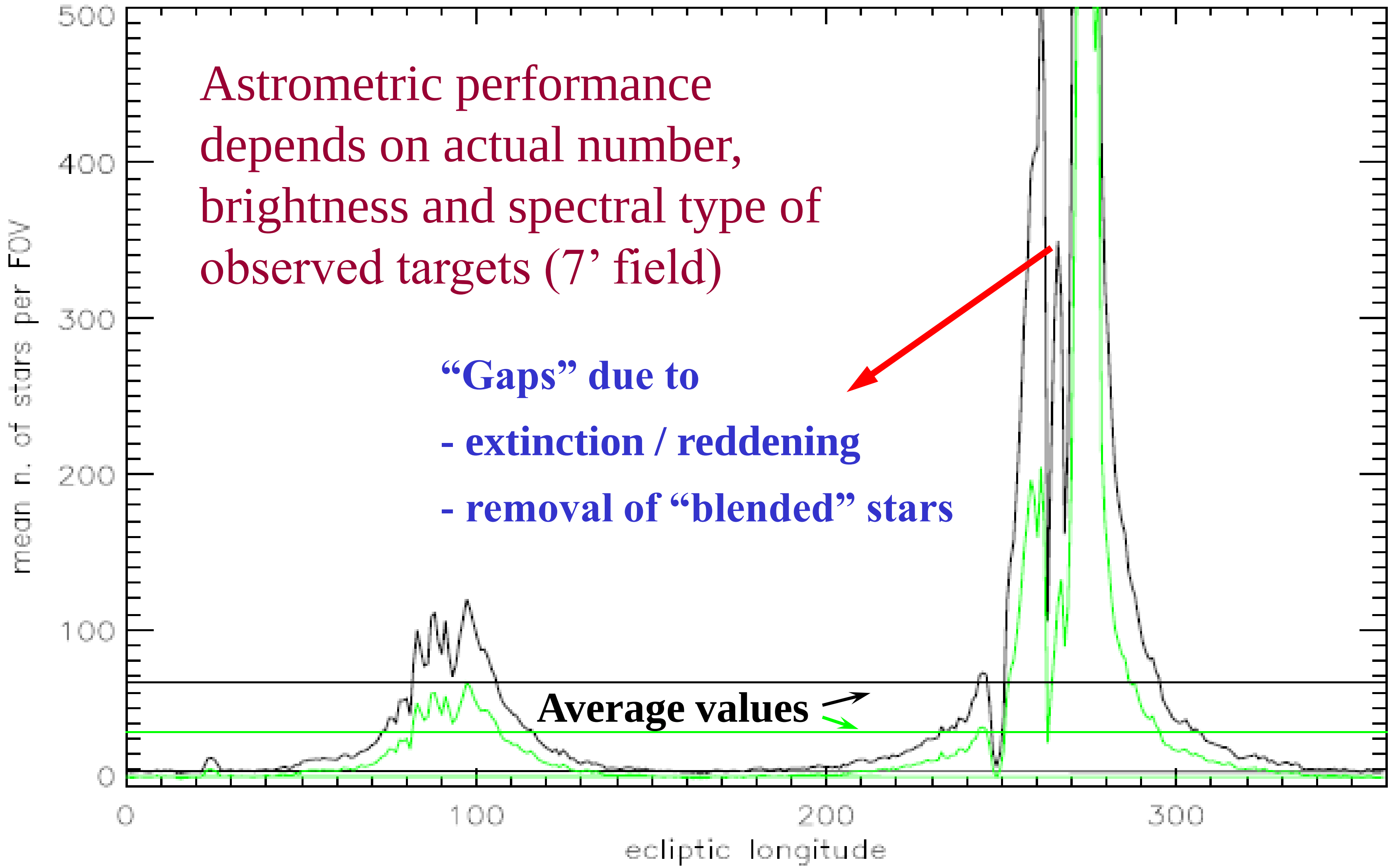
Peak displacement between stars @ ±2°: 466 mas

[when crossing the Sun]

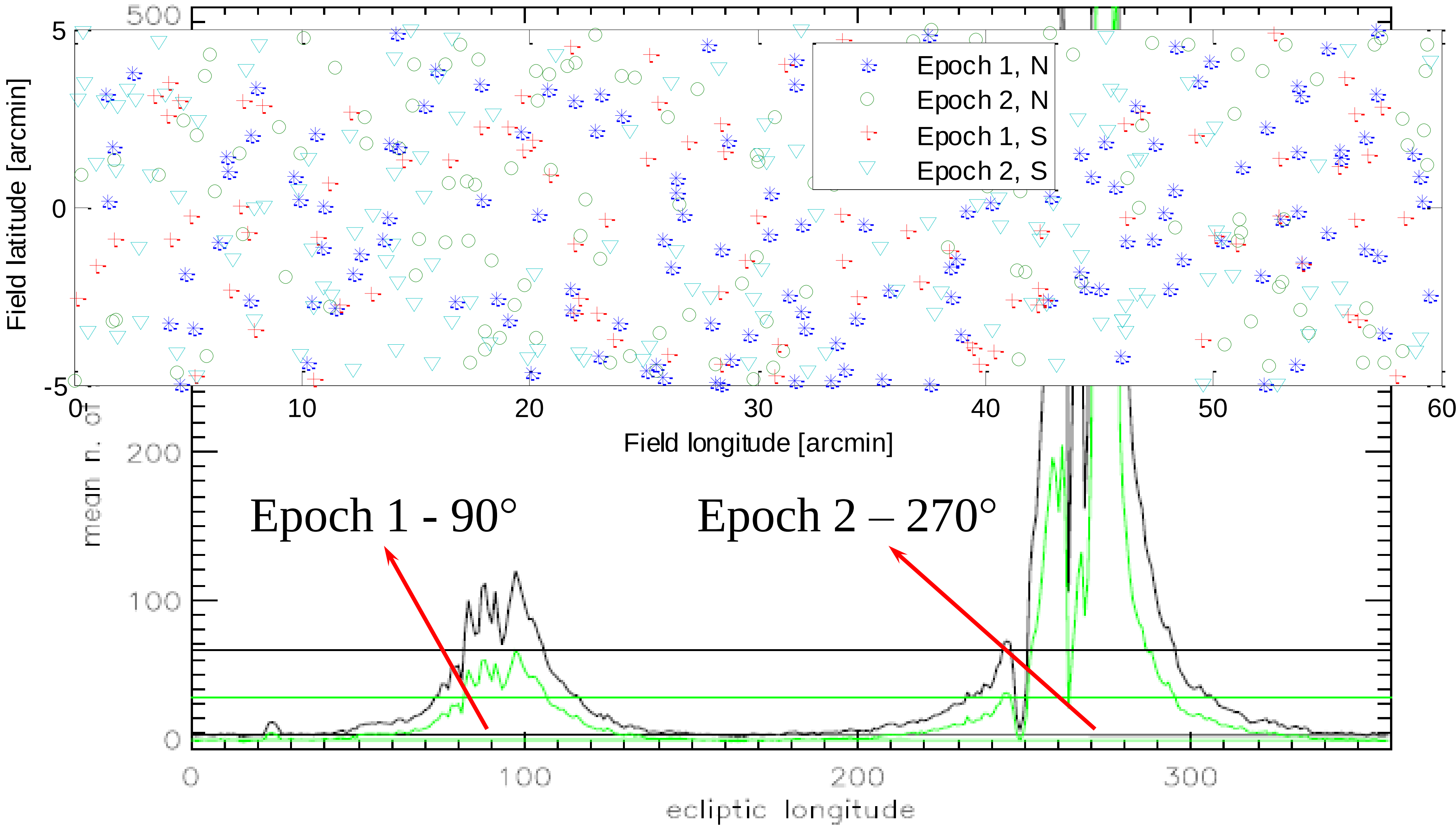
Largest signature over ±10° along the ecliptic, i.e. about ±10 days

Light bending ⇔ Gravitational lensing

GSCII star counts along ecliptic plane



Crowding on GC/GAC regions, V ≤ 15 mag



AGP vs. Gaia

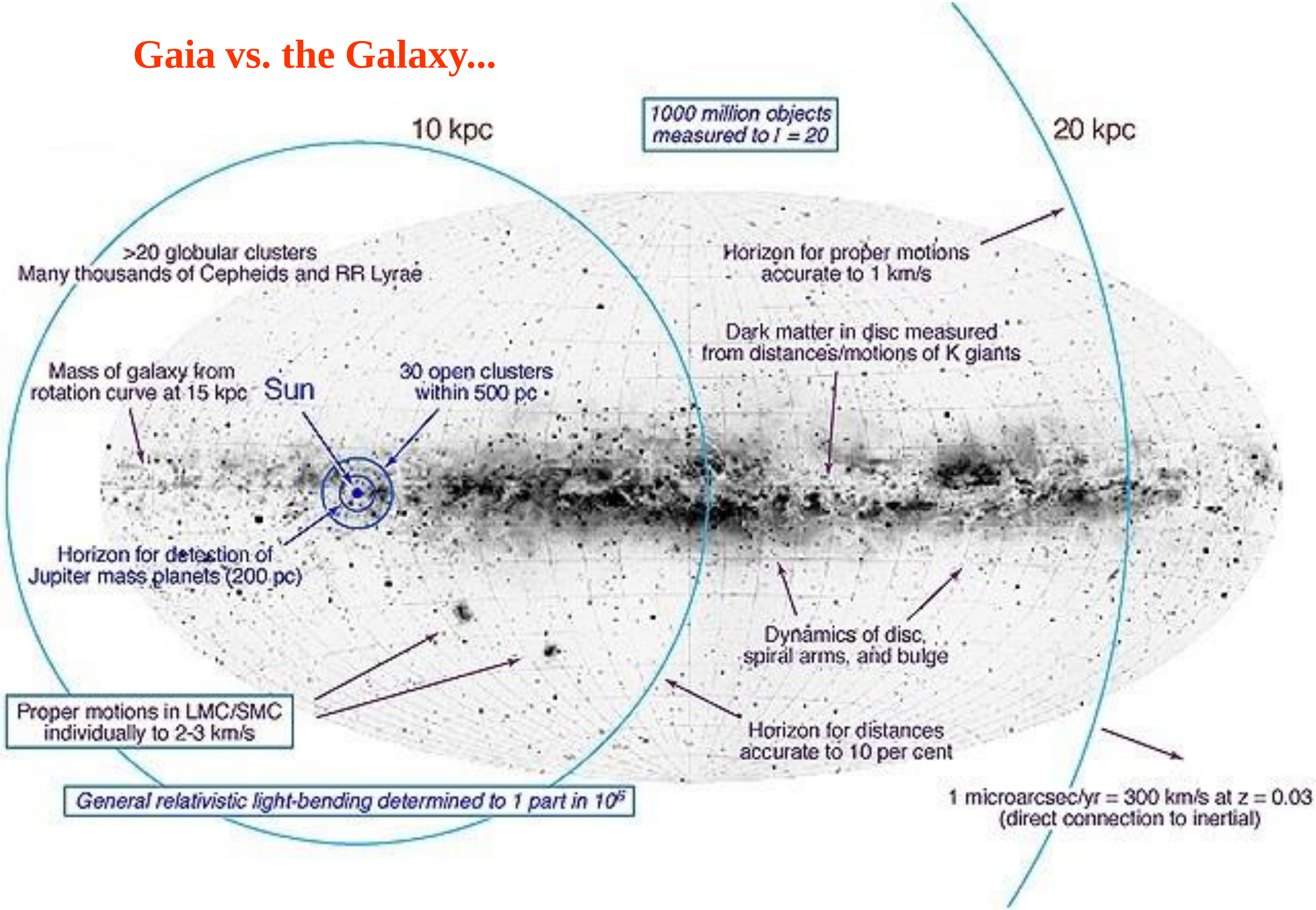
Commonality:

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

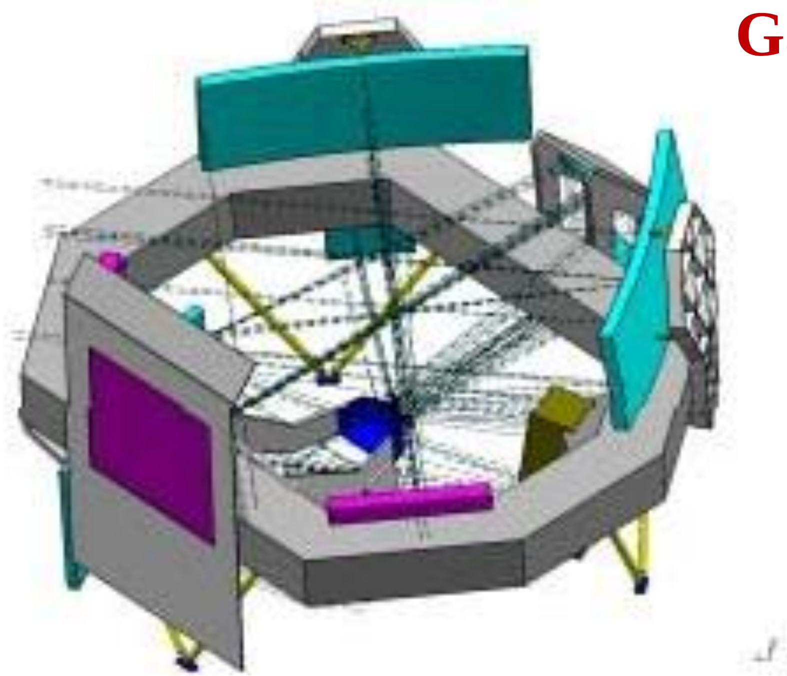
AGP peculiarity:

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

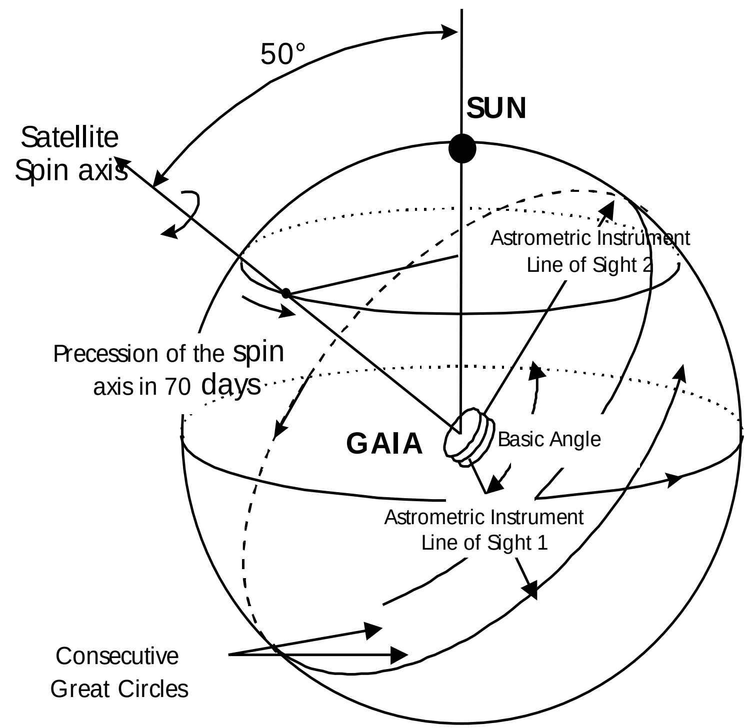
Gaia vs. the Galaxy...



Gaia Instrument and Observations



Wide-angle simultaneous observation by two telescopes pointing along different directions, separated by a ***basic angle*** which must remain stable to within the mission requirements



One-dimensional measurements along current *great circle* composed to get the desired bidimensional measurement on the celestial sphere:

2 angular positions;

parallax;

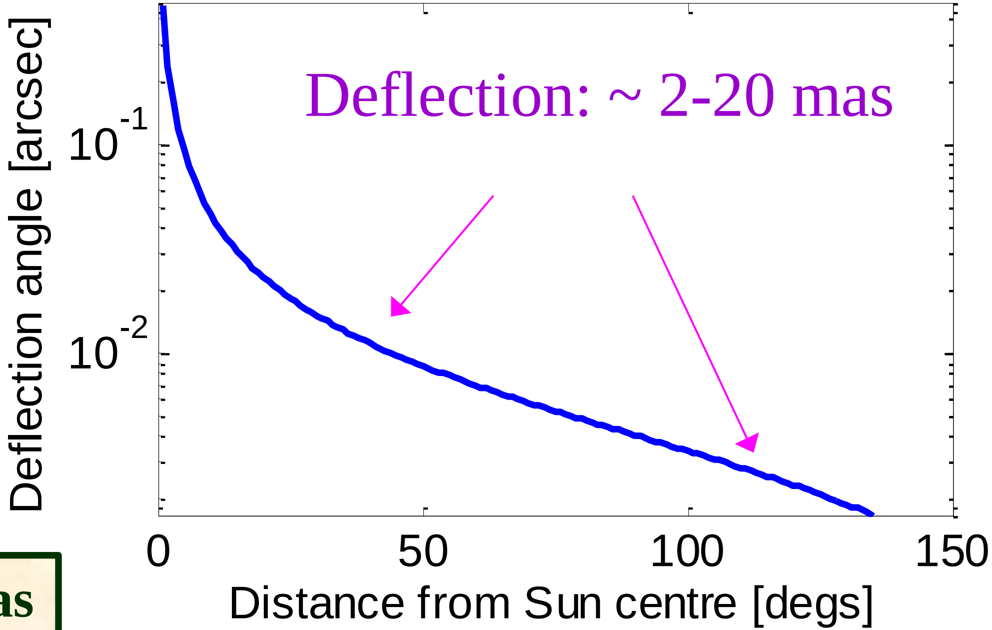
2 (tangential) proper motions

Visible light bending experiments in space

Hipparcos [1997] demonstrated ~10^-3 (0.1%) precision

Gaia [launch at end 2013]

aims at ~10^-6 precision on γ

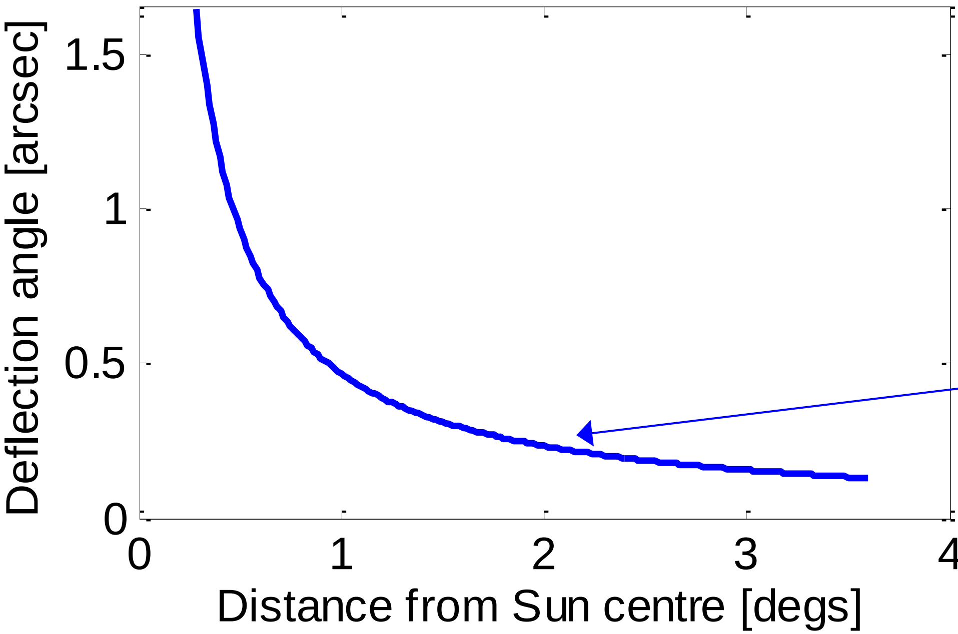


Astrometric precision: a few 10 μas on a few million stars

Technique: astrometric measurement of apparent displacement of a large number of stars at <u>large angular distance</u> to the Sun

γ determination as byproduct of full-sky astrometric reduction

Deflection range

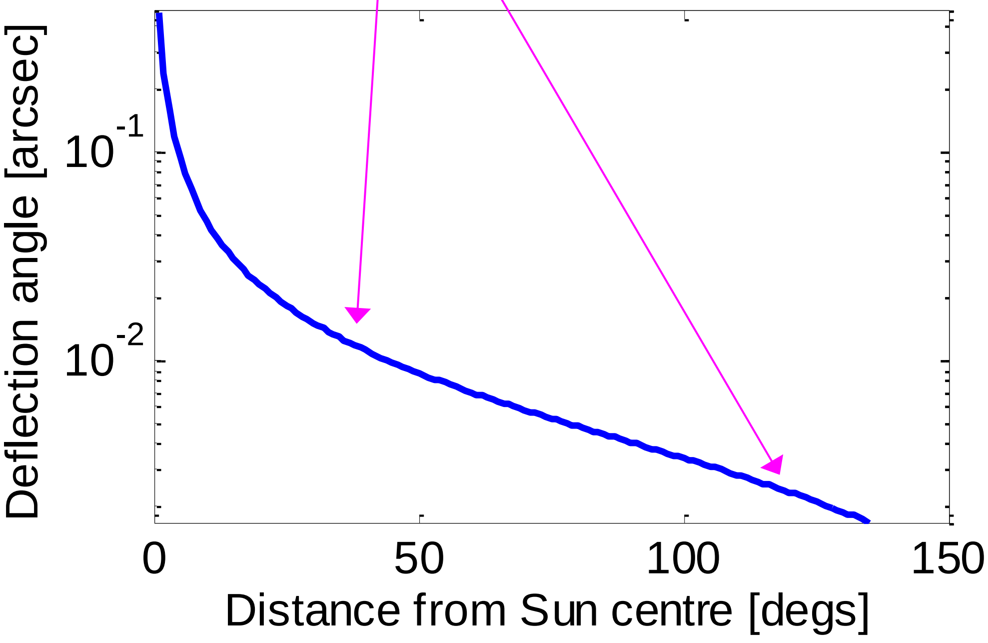


AGP: $\psi \sim$ 0.5 arcsec

GAIA: $\psi \sim$ 2-20 mas

AGP 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

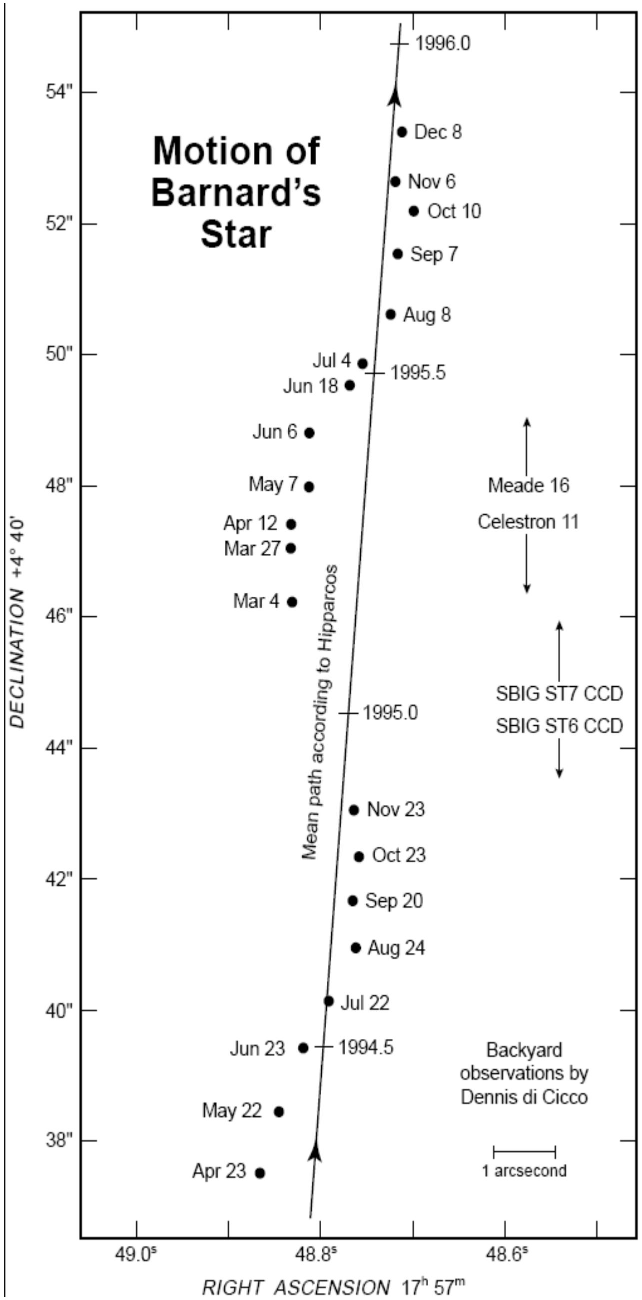
Gaia: $\sigma(\psi) \sim 300$ μas $\Rightarrow$ S = 7 ~ 70

AGP: $\sigma(\psi) \sim 400$ μas $\Rightarrow$ S = 1250

More than one order of magnitude of improvement

Lower number of measurements (stars) required by AGP

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



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**

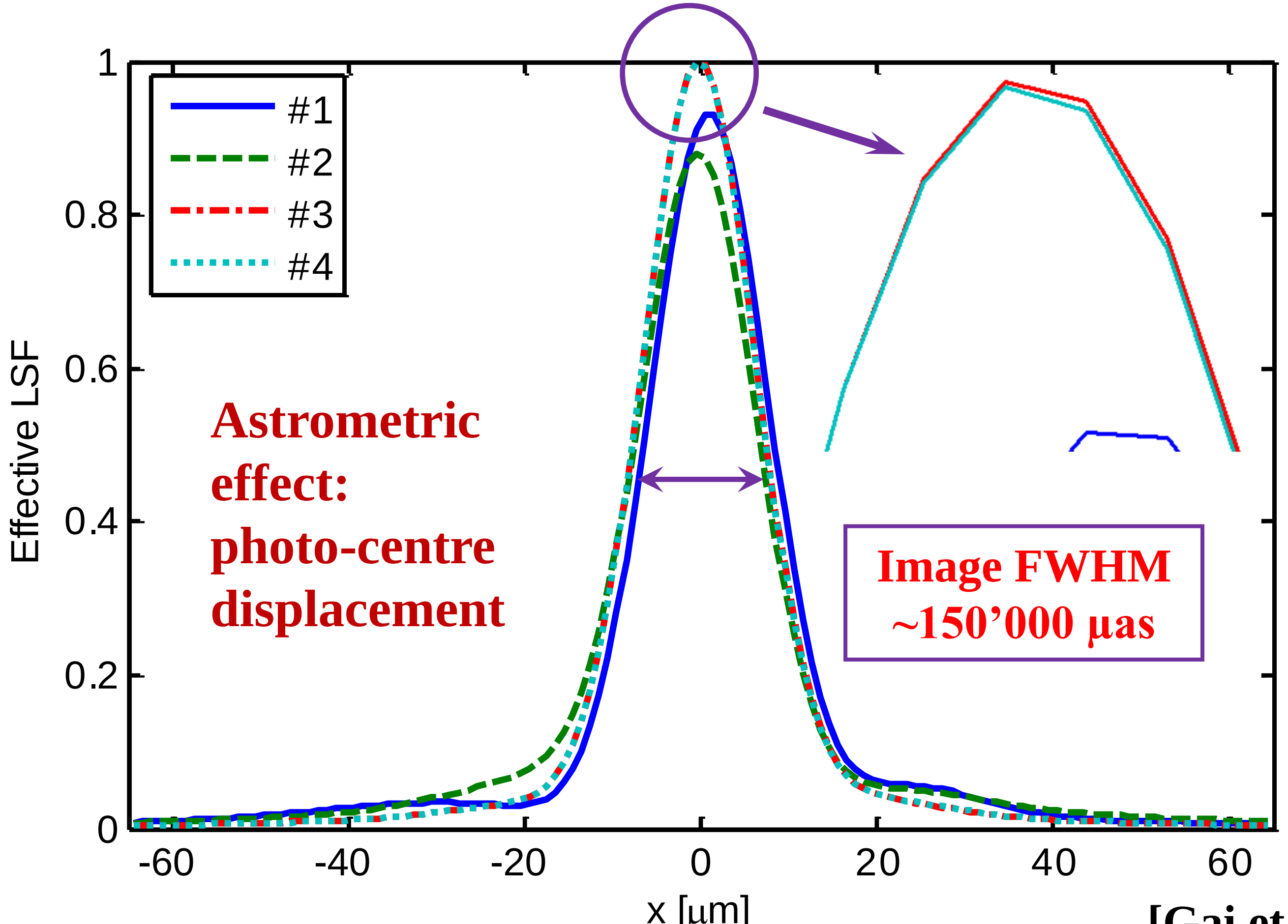
Parallax: **few µas**

Barnard's star: spectral type M4,
distance ~6 ly ≅ 1.8 pc
proper motion ~10 arcsec/year!

Realistic detected LSF: tiny effects relevant at μas level!

Need for convenient description tool of one-dimensional signal

Profile affected by source spectrum AND instrument response

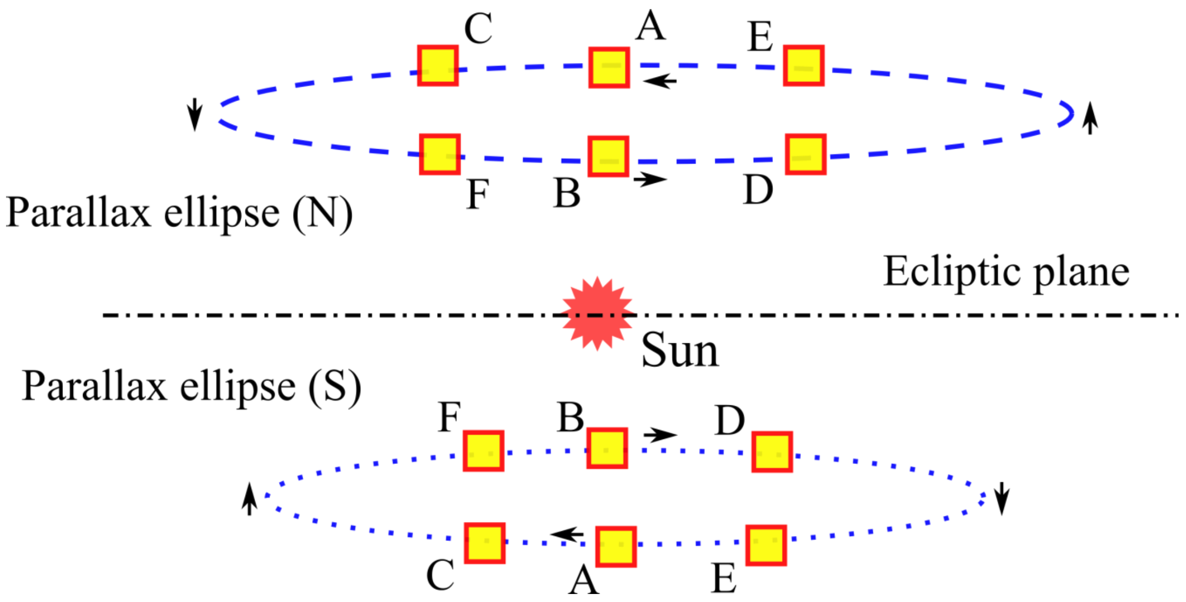


Profile model ⇒ location and parameter estimate

Minimise astrometric error induced by fit residual

[Gai et al., PASP 2013]

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

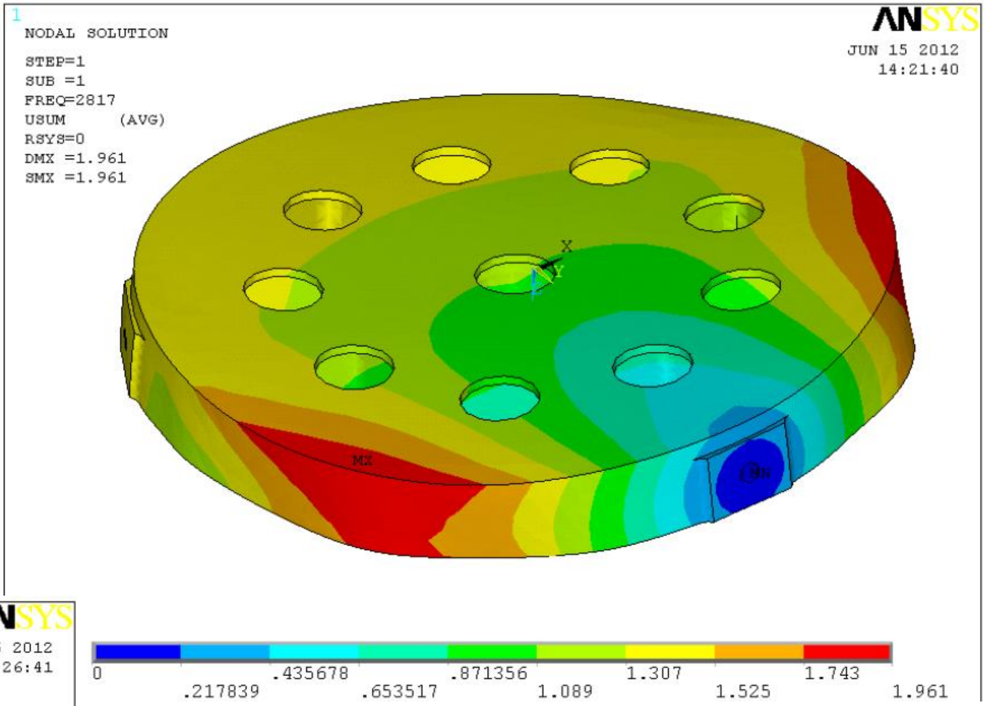
Side result: μas astrometric catalogue of stellar sample

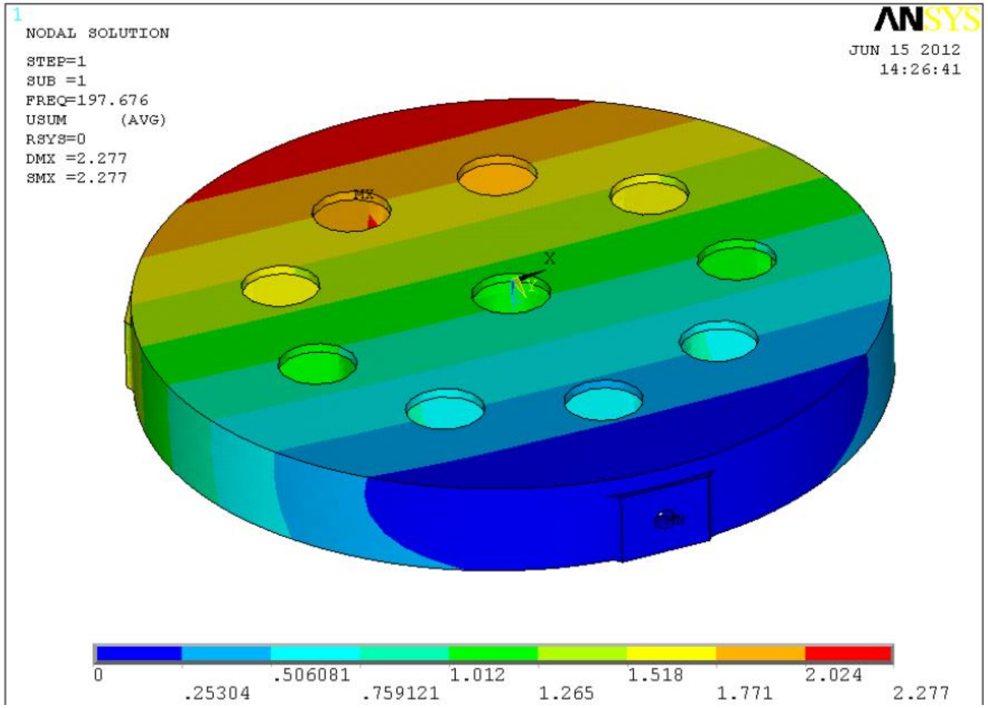
Laboratory prototype - II

Dynamic analysis (example)

3 clamping areas

First mode: 2817 Hz



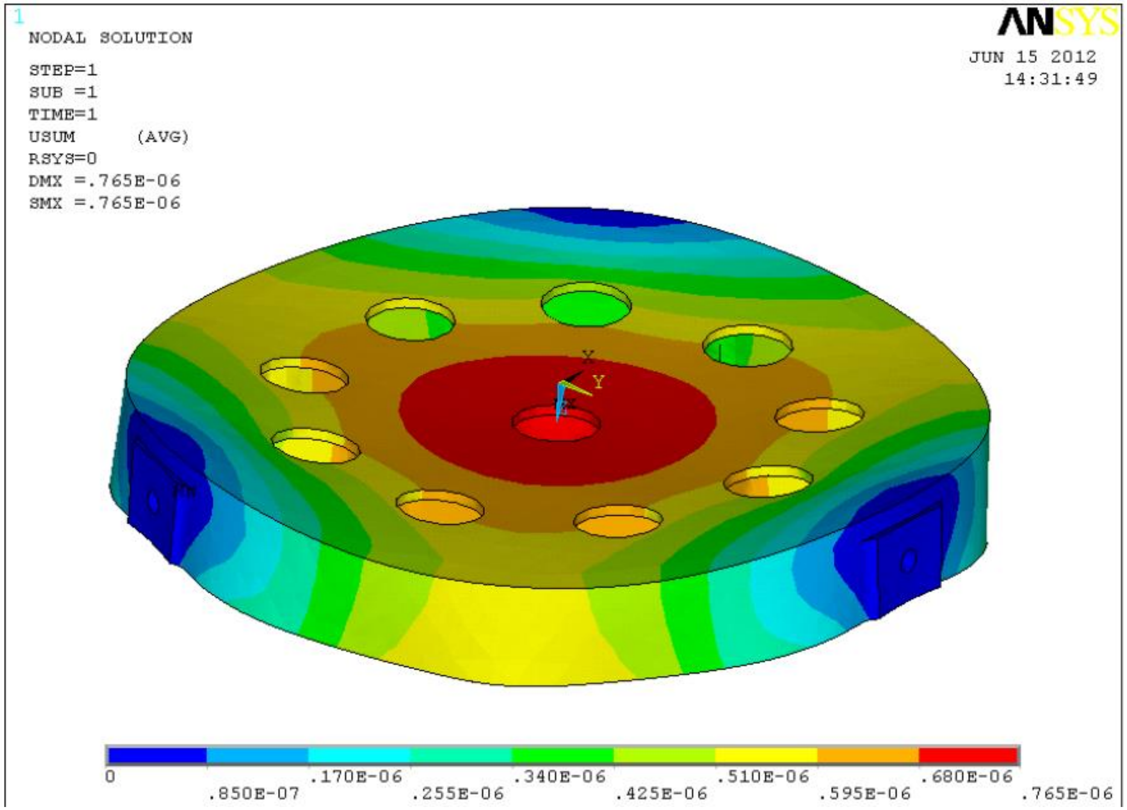


1 clamping area

First mode: 198 Hz

Tests by ADS Int.l

Laboratory prototype - III



Static analysis (example)

30 g load
Deformation acceptable

Test requirements fulfilled

Design scalable to small / medium mission class

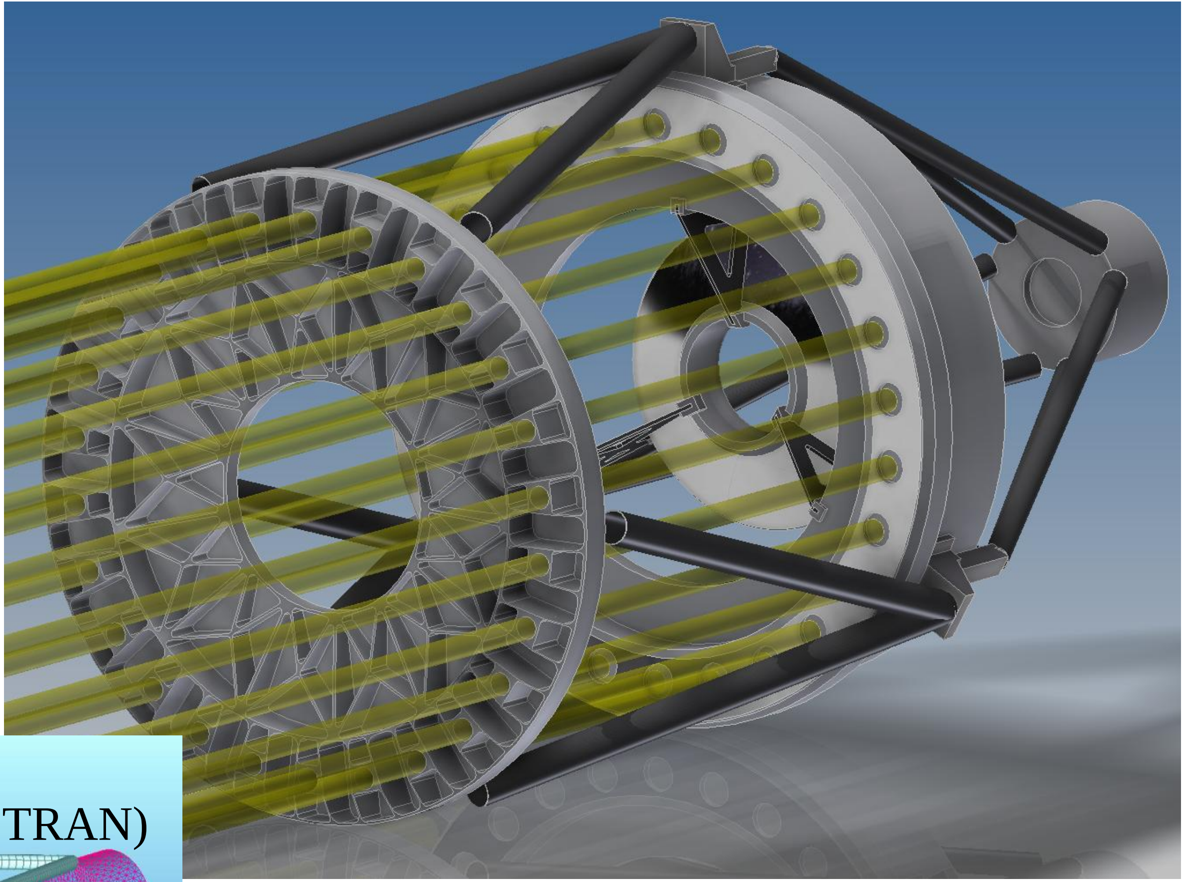
Analysis of medium mission class payload

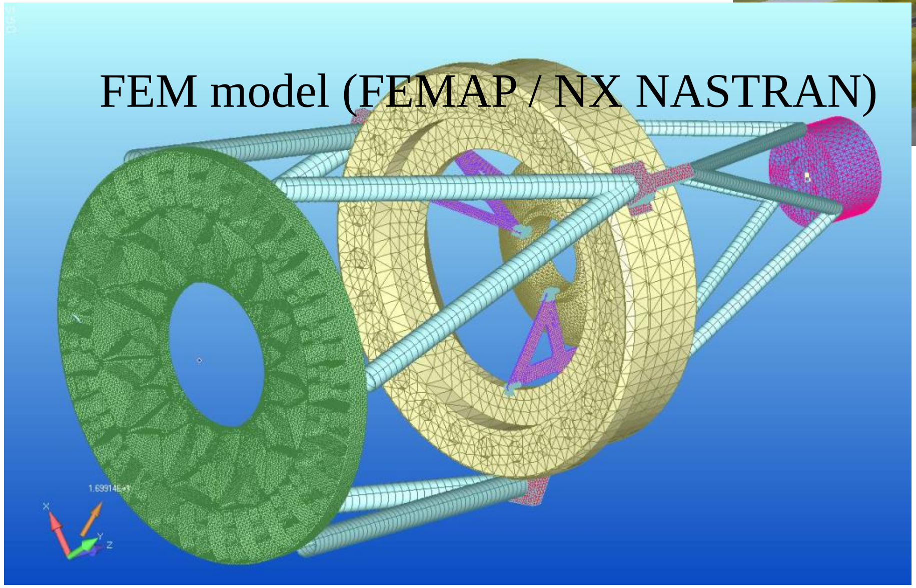
Telescope class: 1.5 m ∅

Trusses: CFRP

Optics: SiC

Invar clamps





FEM model (FEMAP / NX NASTRAN)

Preliminary mass budget: 577 kg

Scaling to small mission size: 72 kg

Only pupil mask lightweighted

Additional lightweighting feasible

Roadmap: from balloon (ISAS) to satellite (AGP)

Gravitation Astrometric Measurement Experiment – AGP

Concept initially investigated for the satellite version

Main goal: Fundamental Physics (General Relativity tests);

Secondary goal: astrophysics by astrometry (solar system; exoplanets; …)

Current investigation: Precursor on stratospheric balloon

Science goal: astrometry of Solar System (major) planets

Technical goal: demonstration of main AGP concepts

Interferometric Stratospheric Astrometry for Solar system - ISAS