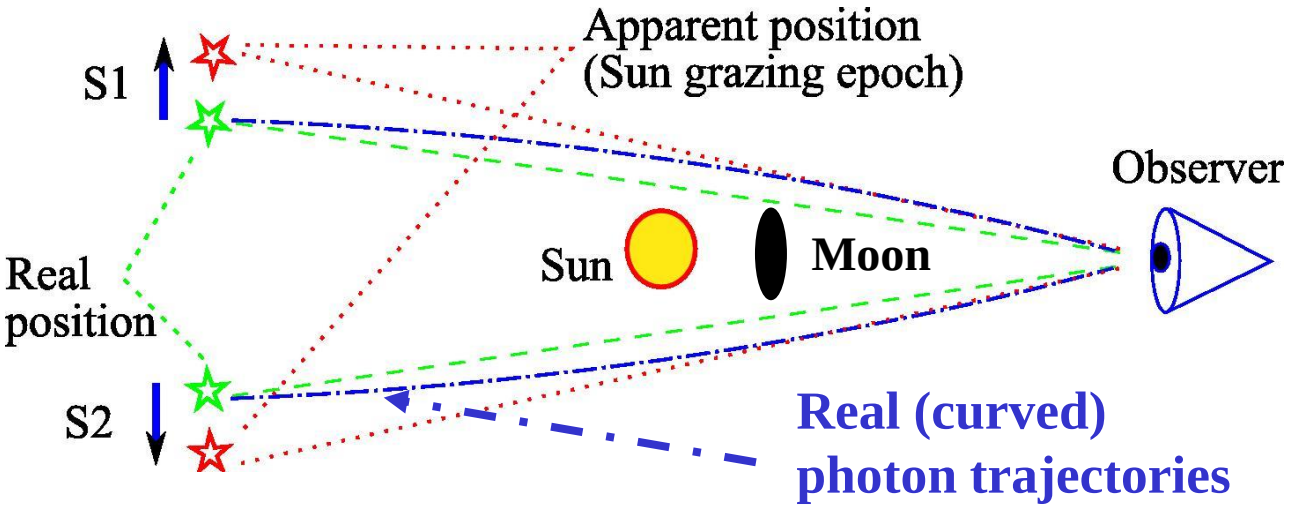
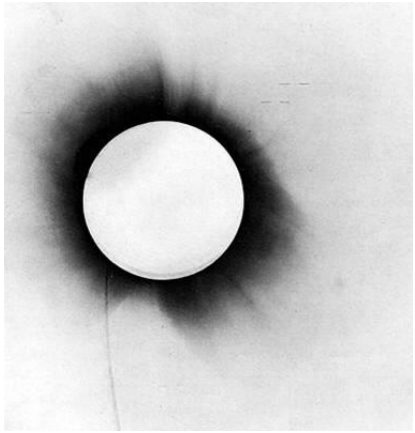
Gravitation astrometric tests in the internal Solar System: the Astrometric Gravitation Probe mission goals

M. Gai, A. Vecchiato, A. Riva, D. Busonero, M.G. Lattanzi
Istituto Nazionale di Astrofisica [INAF]
Osservatorio Astrofisico di Torino [OATo]

High precision astrometry as a tool for Fundamental Physics

Dyson-Eddington-Davidson experiment (1919)





Negative sample from original plates [1920 paper]

First test of General Relativity by light deflection nearby the Sun

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

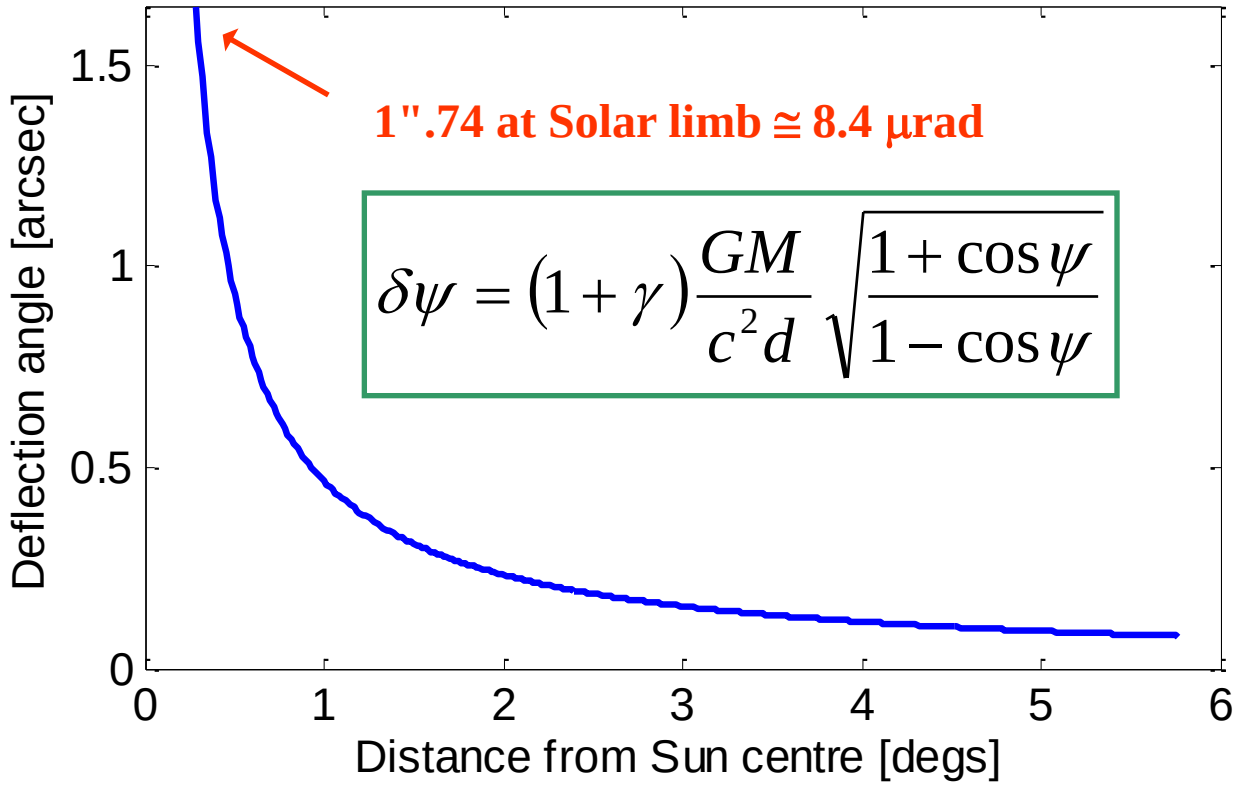
Epoch (b): apparent direction as seen by observer (dotted line)

Micro-arcsec astrometry:

1 arcsec (1″) ≅ 5 μrad

1 micro-arcsec (1 μas) ≅ 5 prad

Spacetime curvature around massive objects



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**

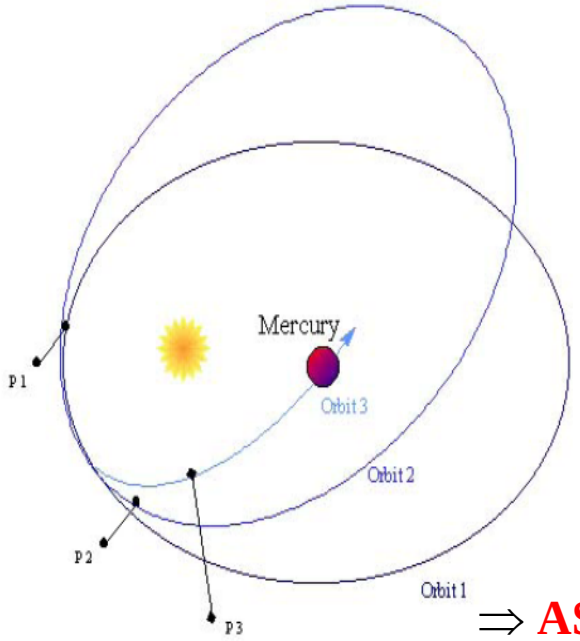
Classical GR test: Mercury's perihelion precession

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**

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

Aftermath of 1919 eclipse experiment…

Repeated throughout
most of 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)

…and previous, less fortunate attempts

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.

[D. Dravins, 2012]

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)

Current experimental results on light deflection…

Hipparcos

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

Precision achieved: 3e-3

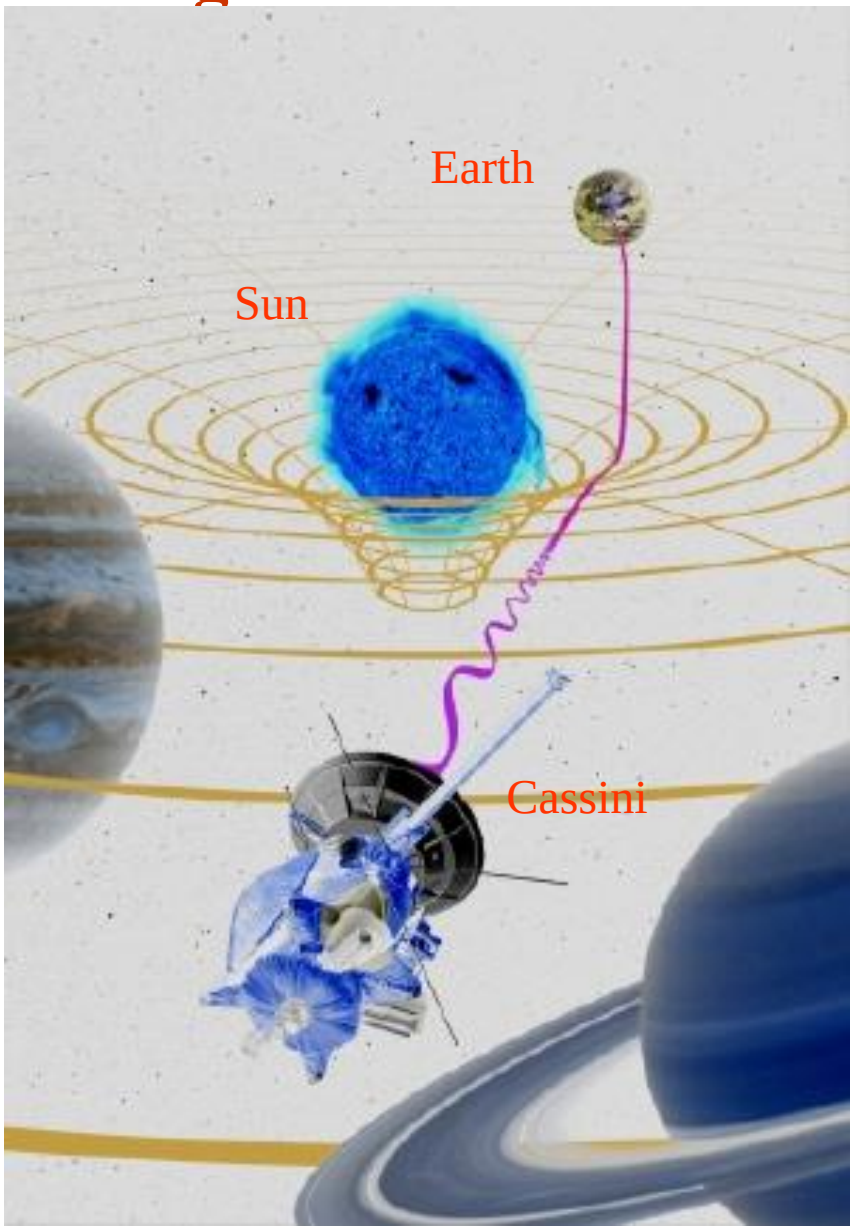
Cassini

Radio link delay timing, $\delta\nu/\nu$~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)?

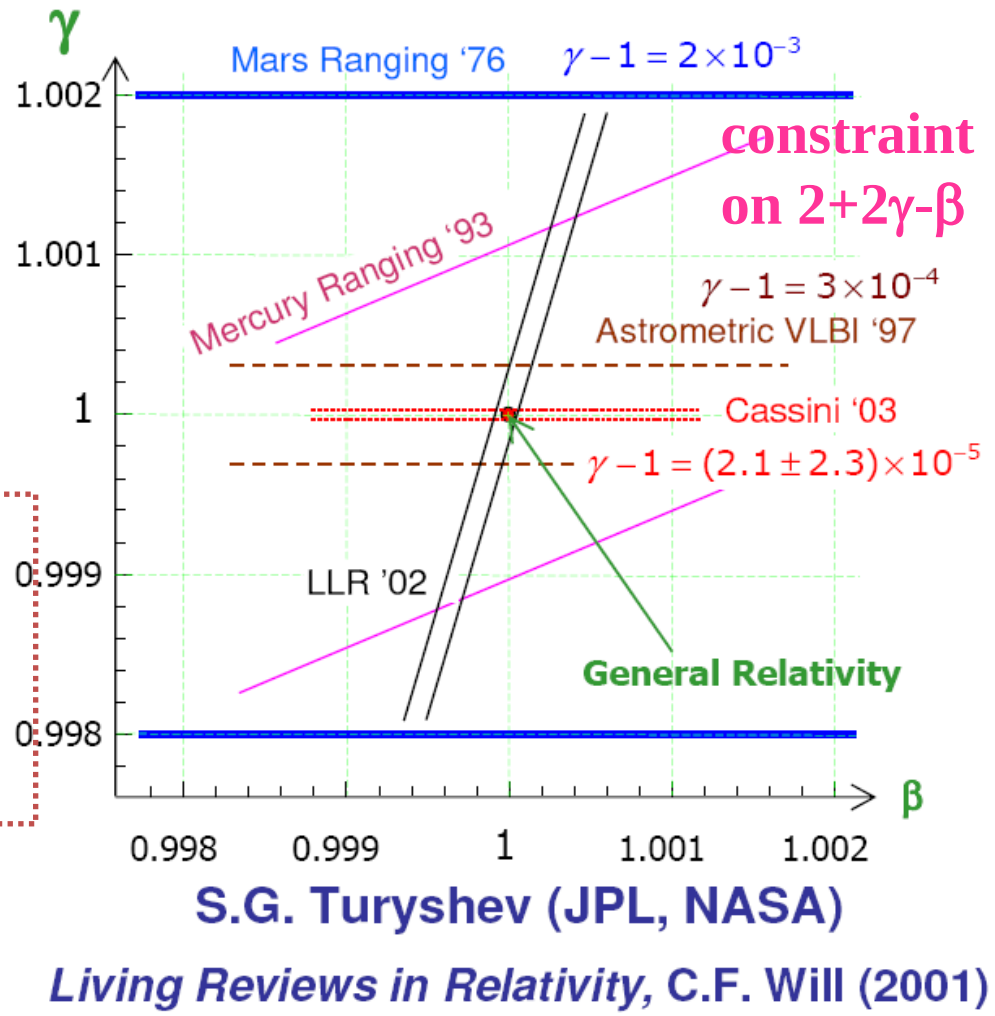
Current experimental bounds:

consistent with GR

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

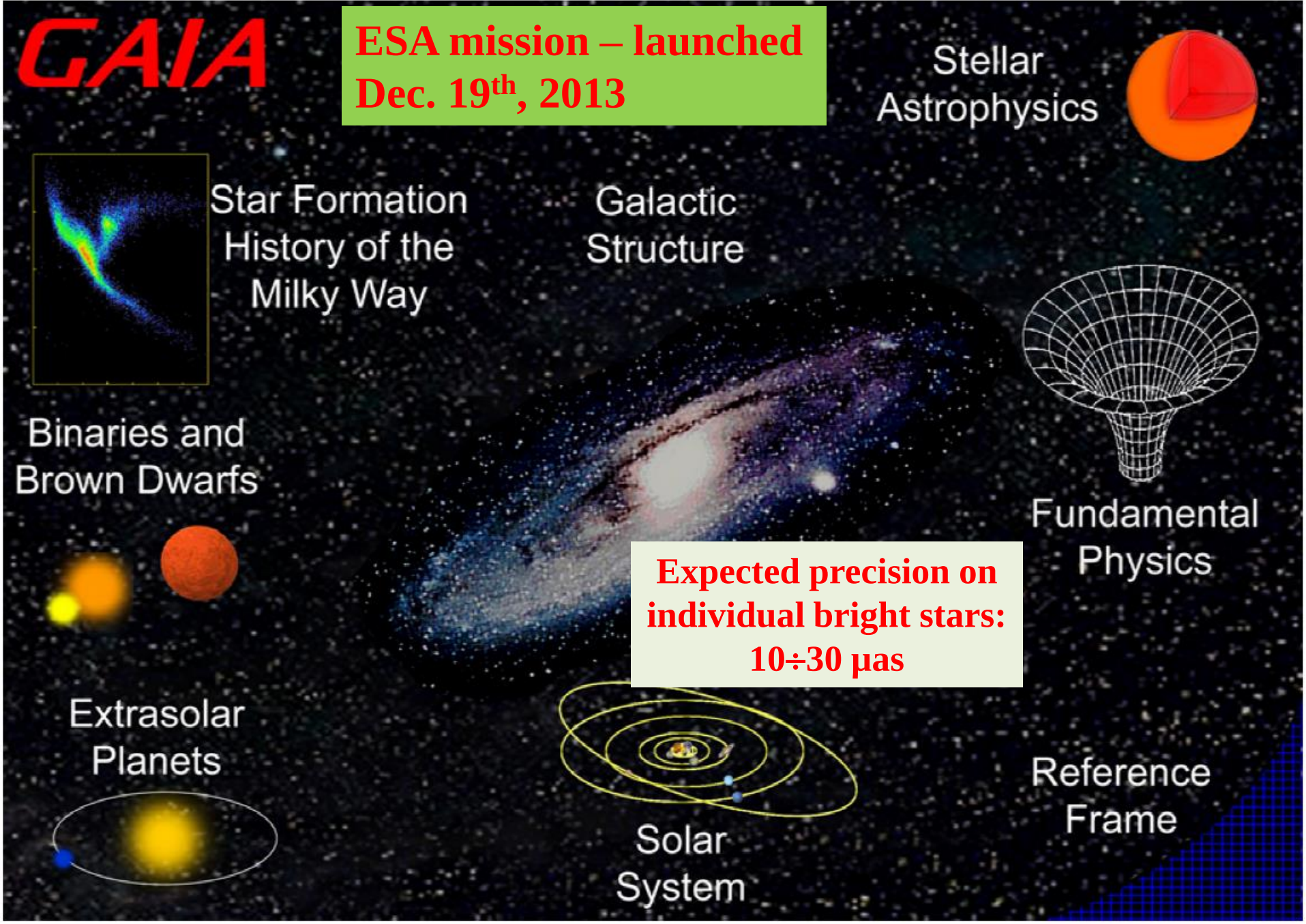
$$|\beta - 1| \leq 1 \times 10^{-4}$$

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



Deviation range expected:

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


GAIA
ESA mission – launched
Dec. 19th, 2013
Stellar
Astrophysics
Star Formation
History of the
Milky Way
Galactic
Structure
Binaries and
Brown Dwarfs
Fundamental
Physics
Expected precision on
individual bright stars:
10÷30 μas
Extrasolar
Planets
Reference
Frame
Solar
System

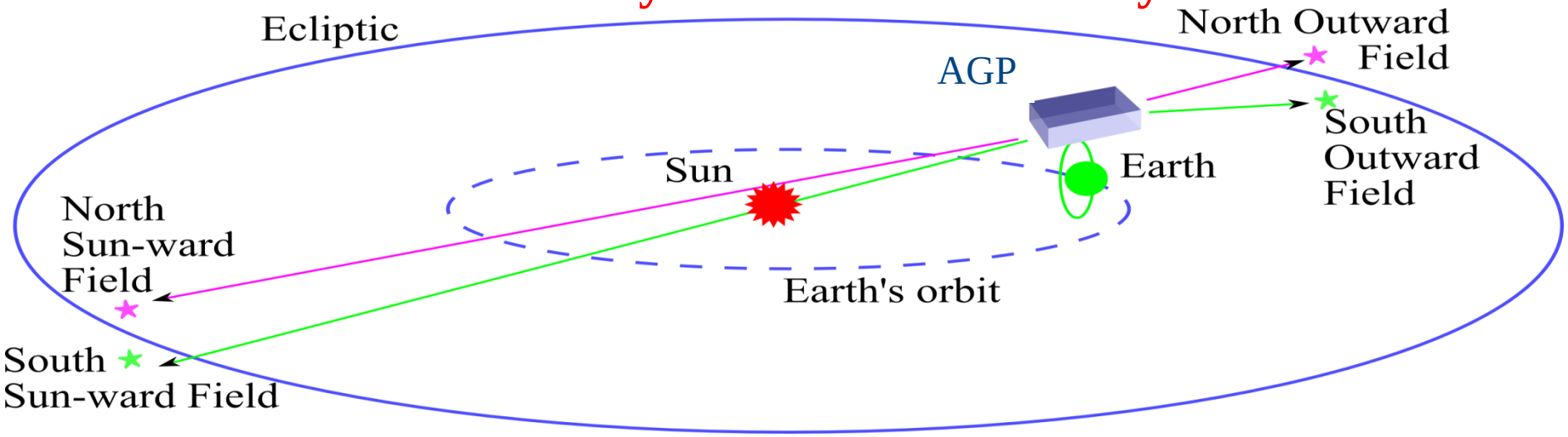
Precision astrometry for Fundamental Physics – Gaia

1. Light deflection
   - Monopole deflection from the Sun: $\sigma_\gamma \sim 10^{-6}$ (systematic errors remain a difficult challenge)
   - First detection of a number of subtle deflection effects from the planets: monopole, quadrupole, gravitomagnetic
2. Motion of the solar system: perihelion and node precessions, quadratic deviations in the mean longitudes

$$\sigma_\beta \sim 10^{-3}\,, \quad \sigma_{J_2^{\rm Sun}} \sim 10^{-7}\,, \quad \sigma_{\dot{G}/G} \sim 10^{-12}\,{\rm yr}^{-1}\,, \quad \sigma_\eta \sim 10^{-3}$$

3. Local Lorentz Invariance: Gaia is a kind of Michelson-Morley experiment
4. Pattern matching in proper motions and epoch astrometry:
   - Solar system acceleration $\sigma_a/a < 0.1$
   - Improved estimates of the stochastic background of primordial low frequency gravitational waves
5. Astrometric information for the optical components of some objects that are important for other relativistic tests

Precision astrometry for Fundamental Physics – AGP



A = Apparent star position measurement

G = Testing gravitation in the solar system

1) Light deflection close to the Sun

2) High precision dynamics in Solar System

P = Medium size space mission - ESA M4 (2014)

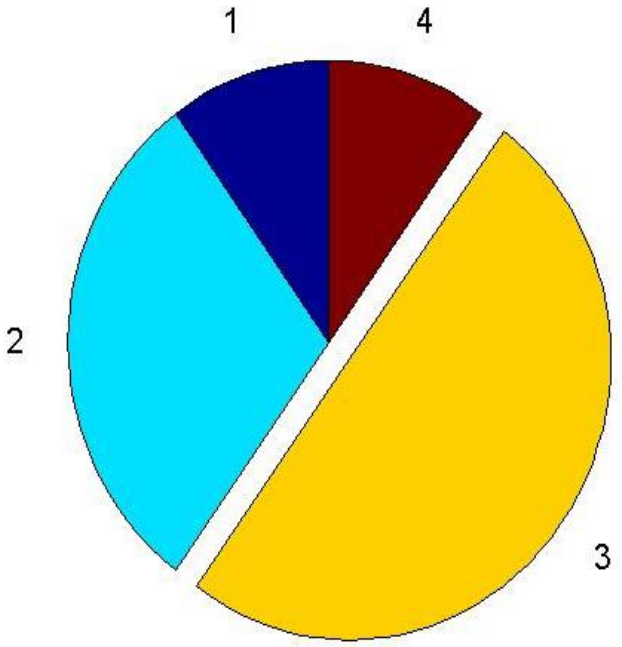
AGP:
Astrometric
Gravitation
Probe

Design driver: light bending around the Sun @ μas fraction

Previously proposed for ESA M3 (2010) as GAME – Gravitation Astrometric Measurement Experiment

AGP vs. ESA Cosmic Vision "Grand Themes"

	Cosmic Vision Theme	AGP
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%

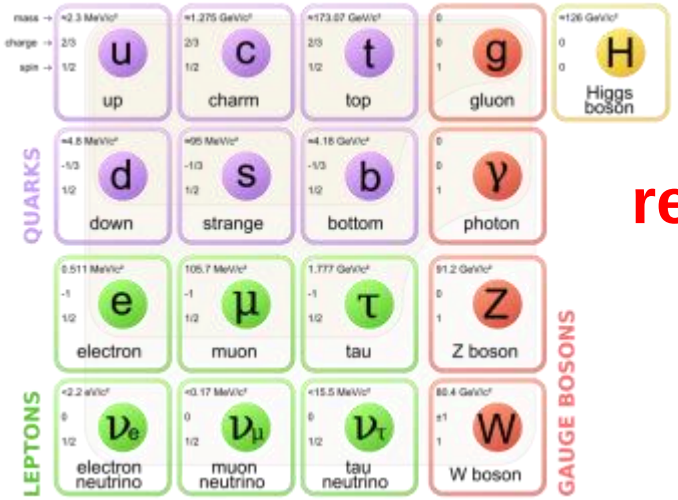


Next ESA Call for Medium size mission: M5 - 2016

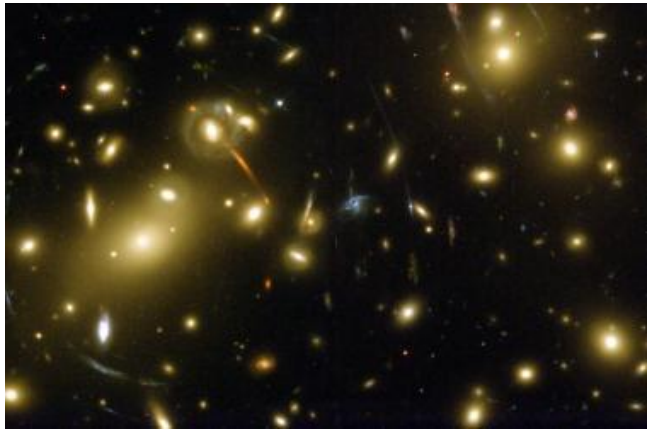
Context in Fundamental Physics : Standard model and General Relativity

Particle physics: Standard Model

3 forces, families of fermions and bosons



Gravitation: General Relativity



Very well tested, but… residual problems:

- ❑ **Hierarchy problem: why is gravity so weak compared to the other forces?**
- ❑ **Unification of gravity with electroweak and strong forces?**
- ❑ **ΛCDM: what are dark energy and dark matter?**
- ❑ **…**

Extra scalar field theories coupled to matter/CDM (dilaton, chameleon...)

Modified gravity theories: scalar-tensor theories; f(R); ISL, Yukawa

Predicted deviations from General Relativity may be measurable at laboratory / Solar System scale

AGP Science goal - 1

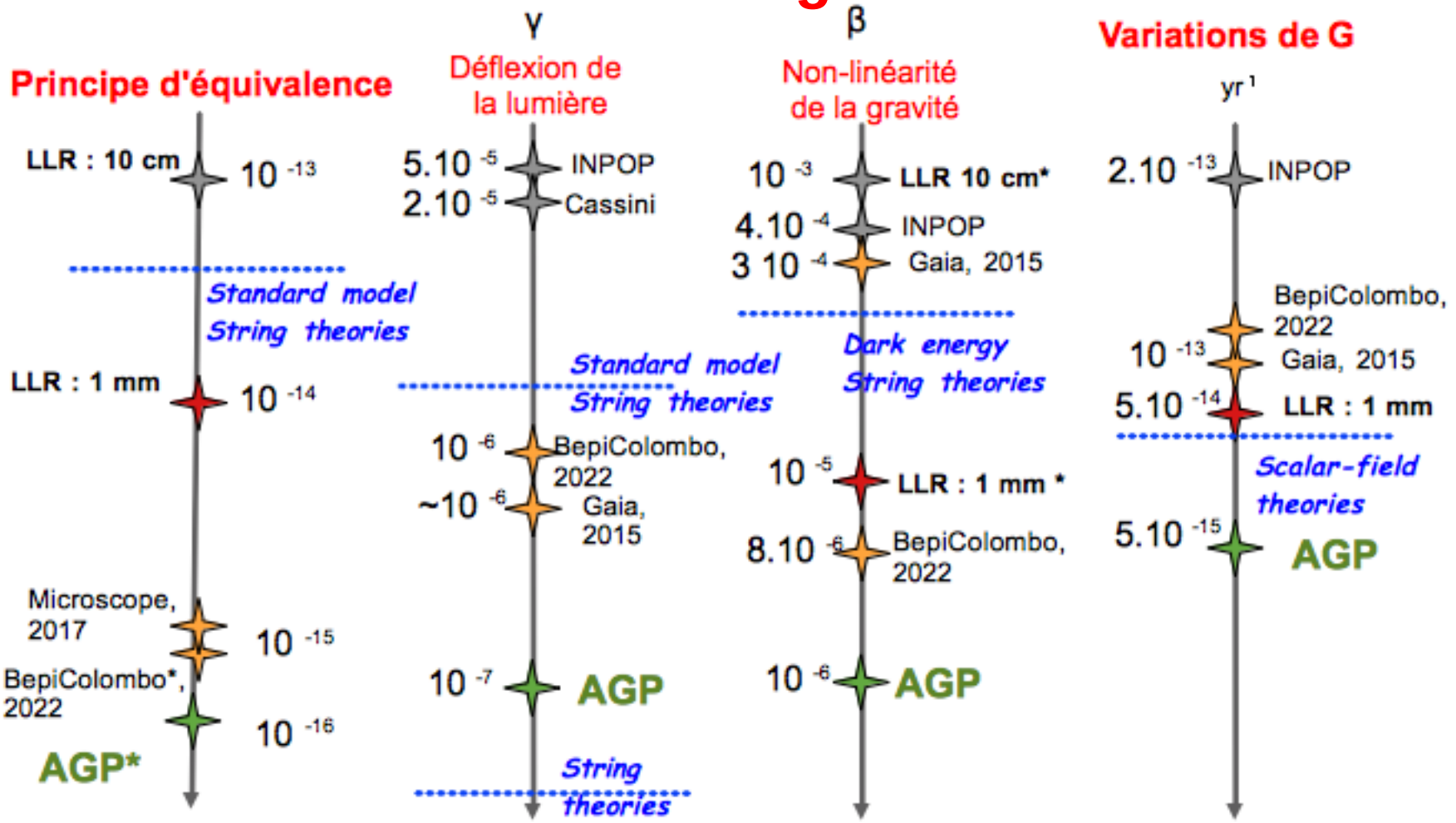
Characterisation of weak field gravity in the Solar System

- Deflection of light in the solar system
- Non-linearity of gravity, preferred frame
- Relativistic effects of oblate and moving giant planets
- Solar system dynamics [High precision ephemerides]

- **Detection limit of dilaton**
- **Limits for Lorentz invariance**
- **Preferred frame detection**
- **Anisotropy of light deflection**

→ **Exclusion / validation of alternative theories of gravity**

AGP science goal - 2

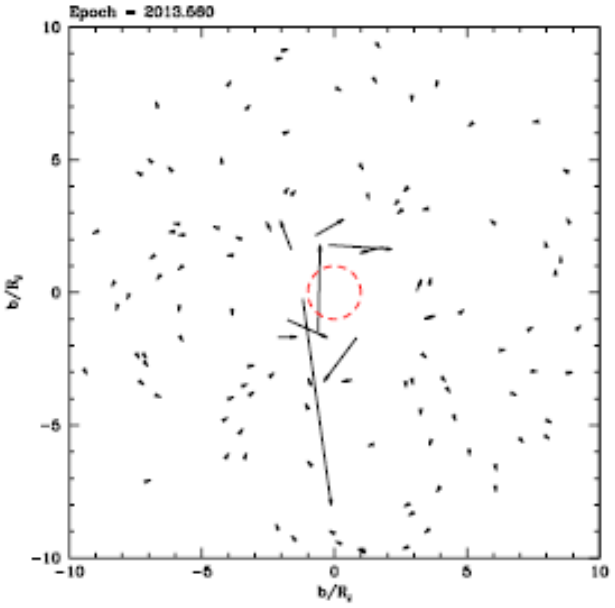


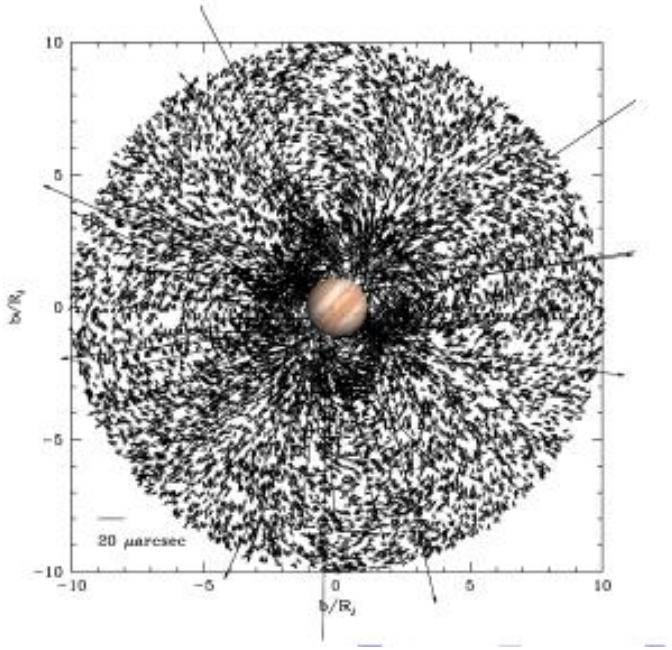
Light bending to 10^{-7} – 10^{-8} level

1 μas accuracy (α,δ) planet

→ Final collective accuracy (α,δ): 0.1 to 0.01 μas

→ Individual precision: σ_{star}~ 100 to 10 μas





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

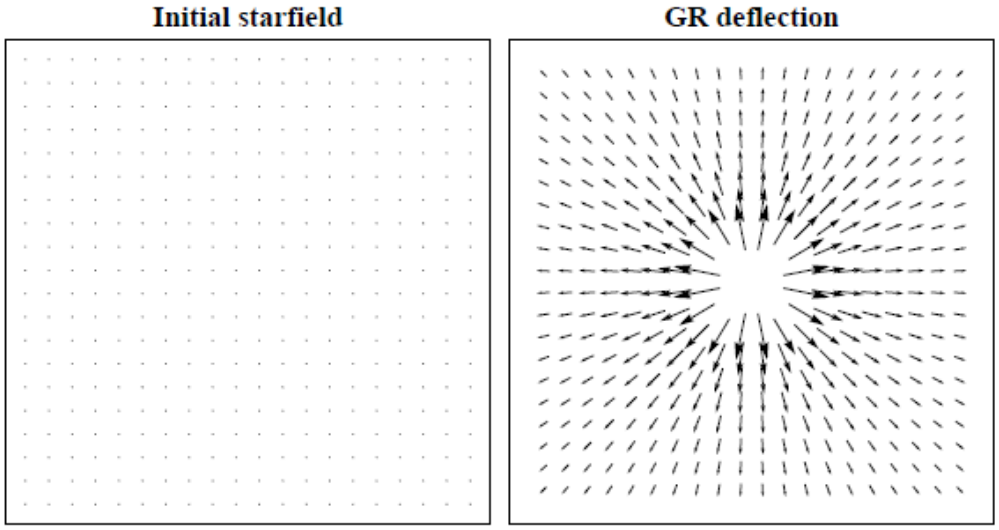


FIG. 2: Initial uniform star field (left). Apparent shift of distant light in the standard general relativity case (right).

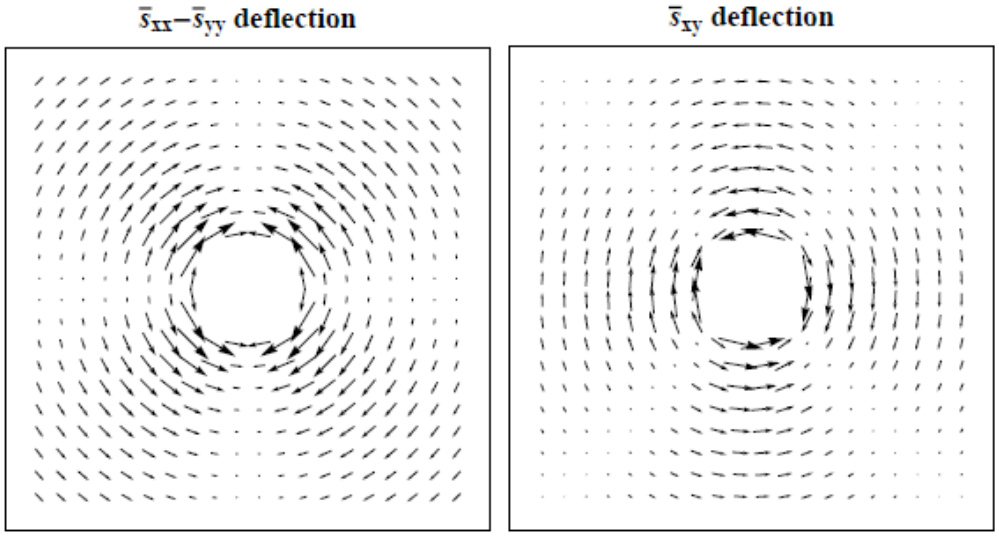


FIG. 3: Anisotropic apparent shift of star field due to the $\bar{s}_{xx} - \bar{s}_{yy}$ coefficients (left) and the $\bar{s}_{xy}$ coefficients (right). The local x coordinate runs horizontally and y is vertical.

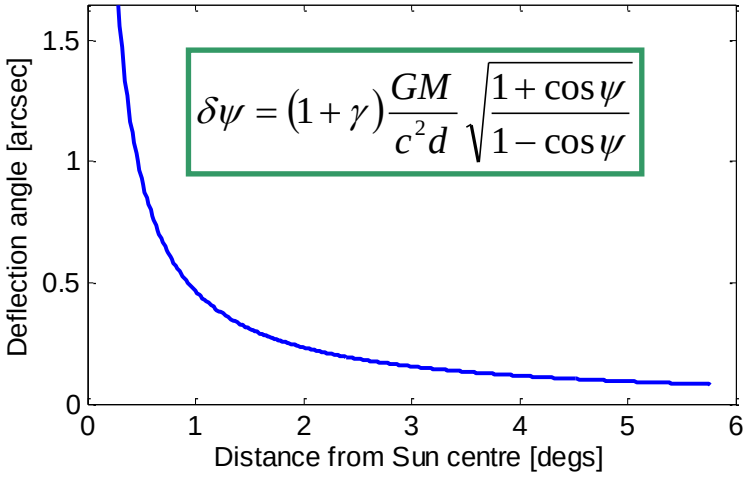
Upper limits on Lorentz-violating SME parameters

GR: isotropic effect

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

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

AGP scientific requirements – driven by light deflection case

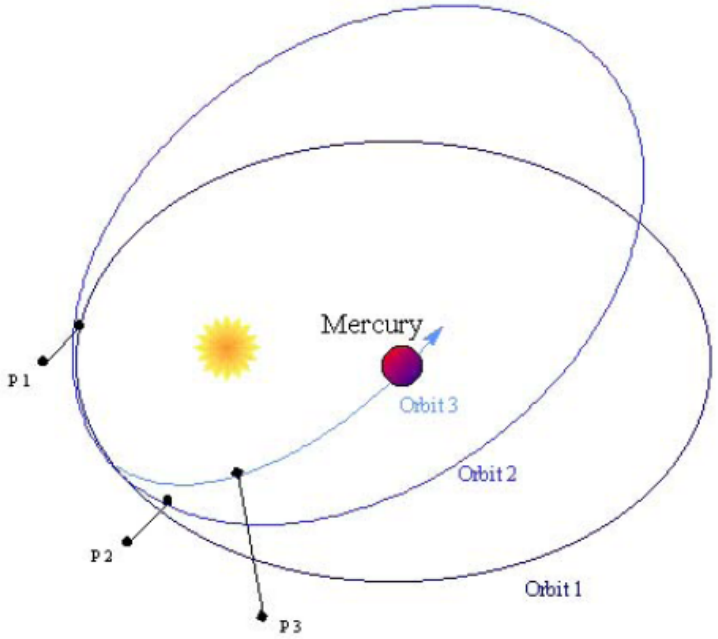


1) Measurement of light bending to 10^{-7}-10^{-8}

2) Non-linearity of gravity to 10^{-6}

Measurement precision required:

Final accuracy: 0.1 – 0.01 μas for star sample and ~1 μas for Mercury



Differential astrometry: between perturbed and un-perturbed fields

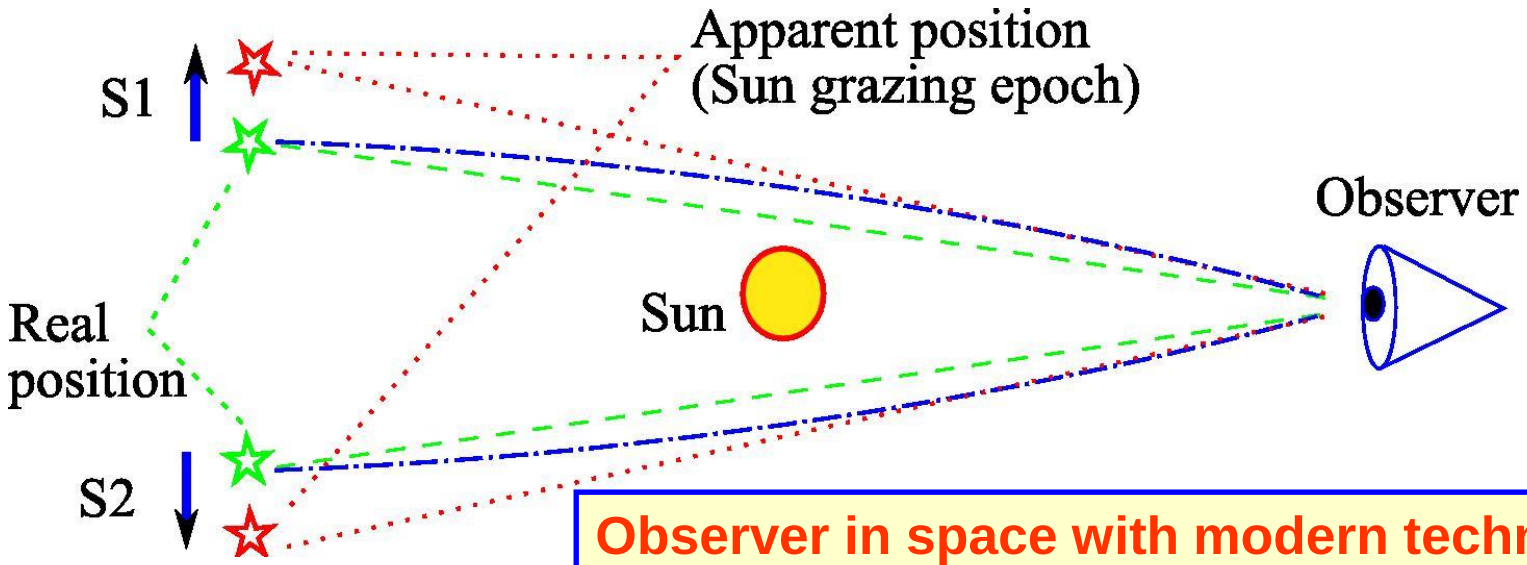
→ astrophysical and PSF errors control

Mitigation: average ~10^6 measurements

→ individual σ ~100 to 10 μas

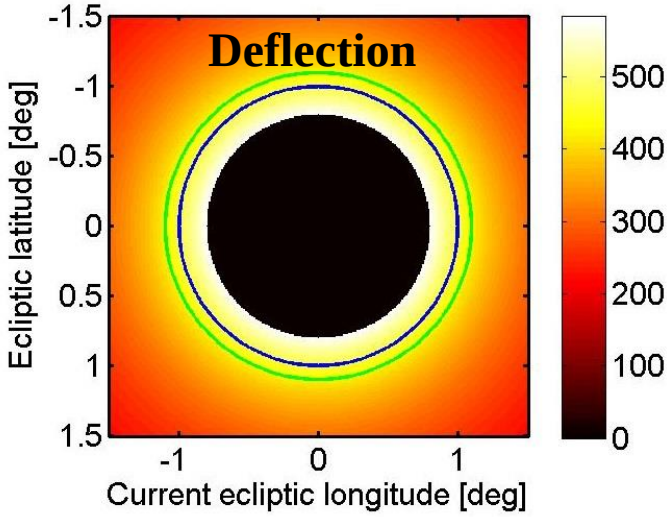
good metrology and calibration techniques

AGP concept: Dyson-Eddington-Davidson experiment (1919)



Observer in space with modern technology

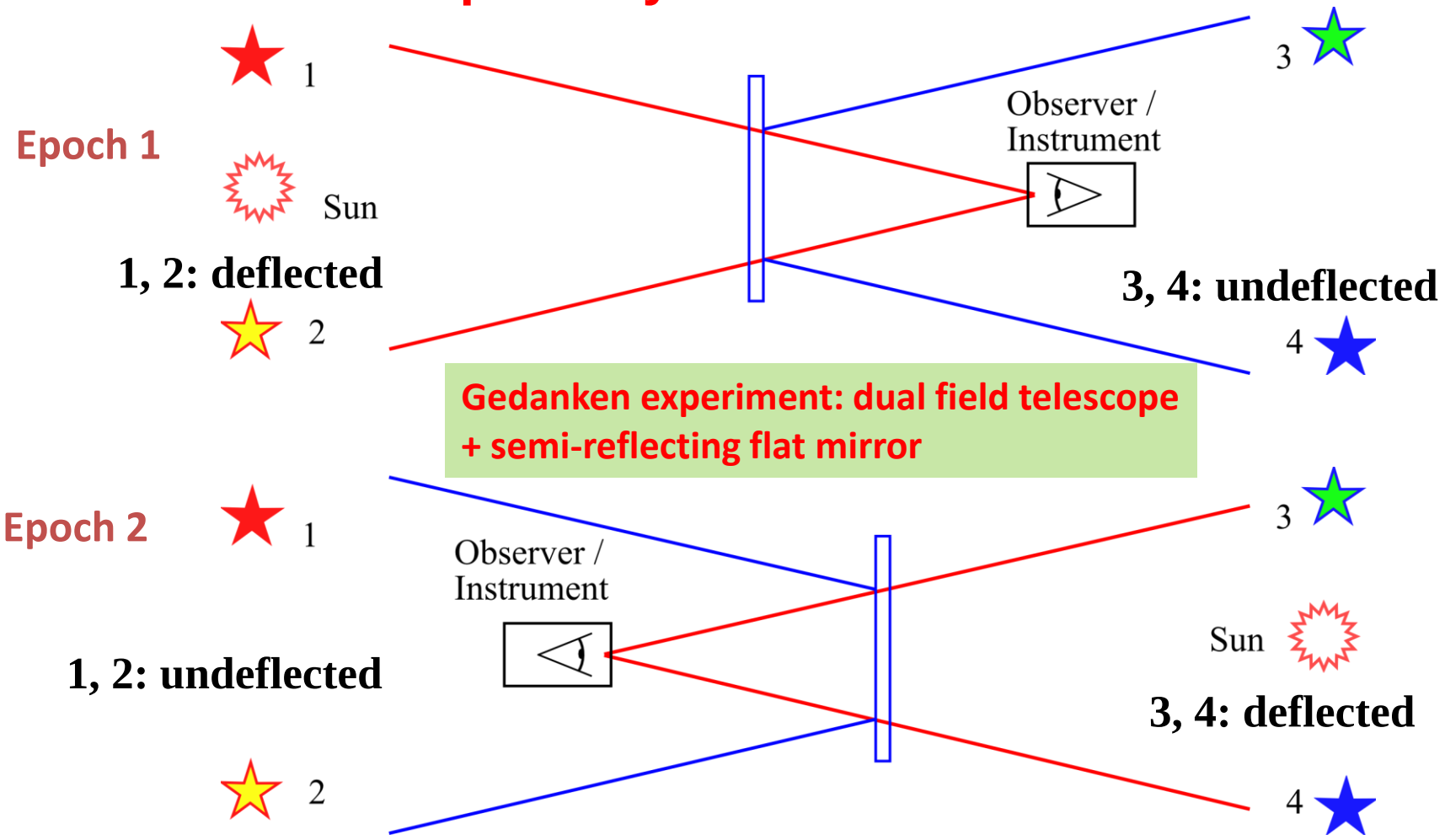
A space mission in the visible range to achieve



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

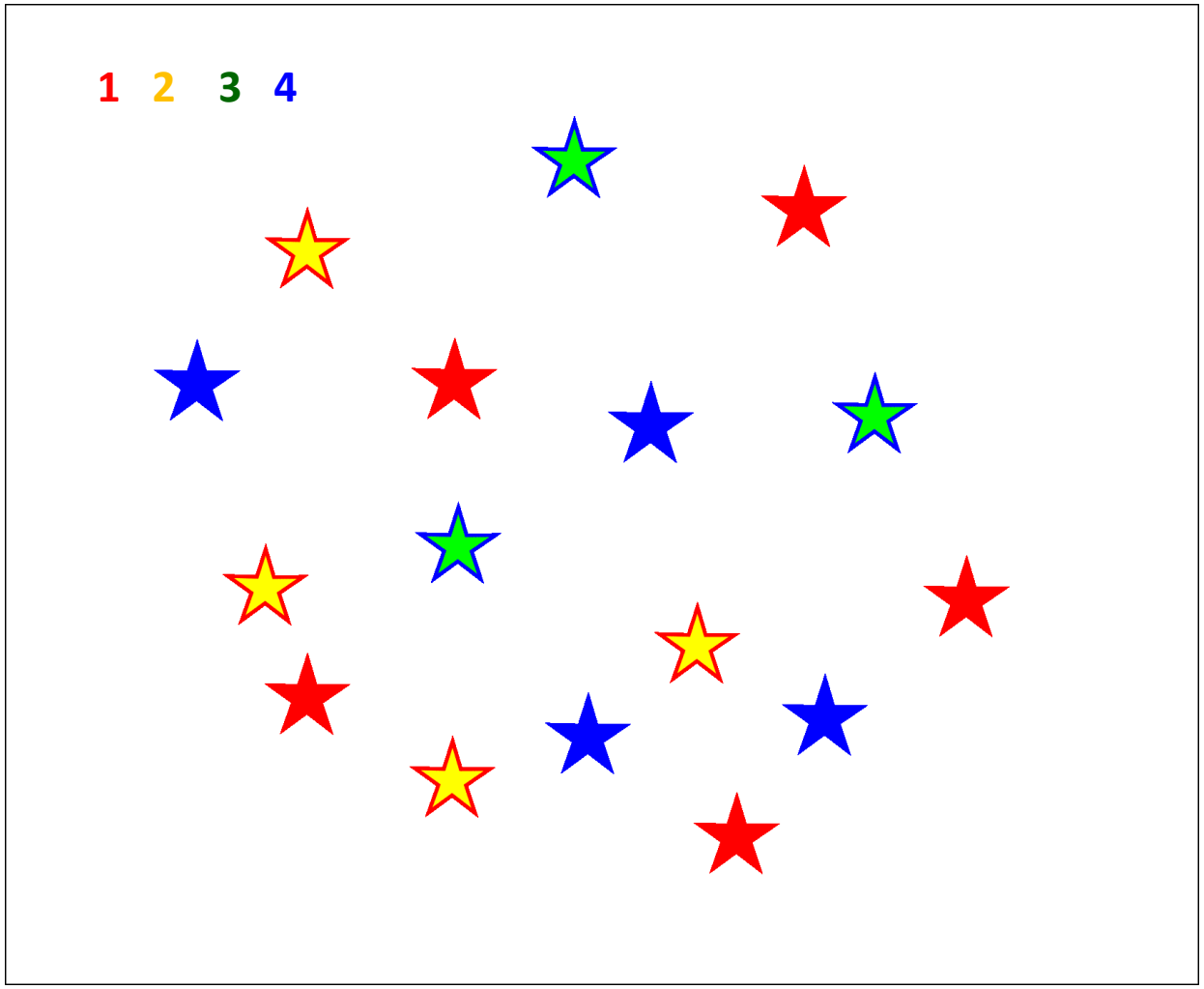
Differential measurement for systematic error control

AGP concept for systematic error control



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

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

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

Compensation among measurements of systematic error $\Delta\beta$

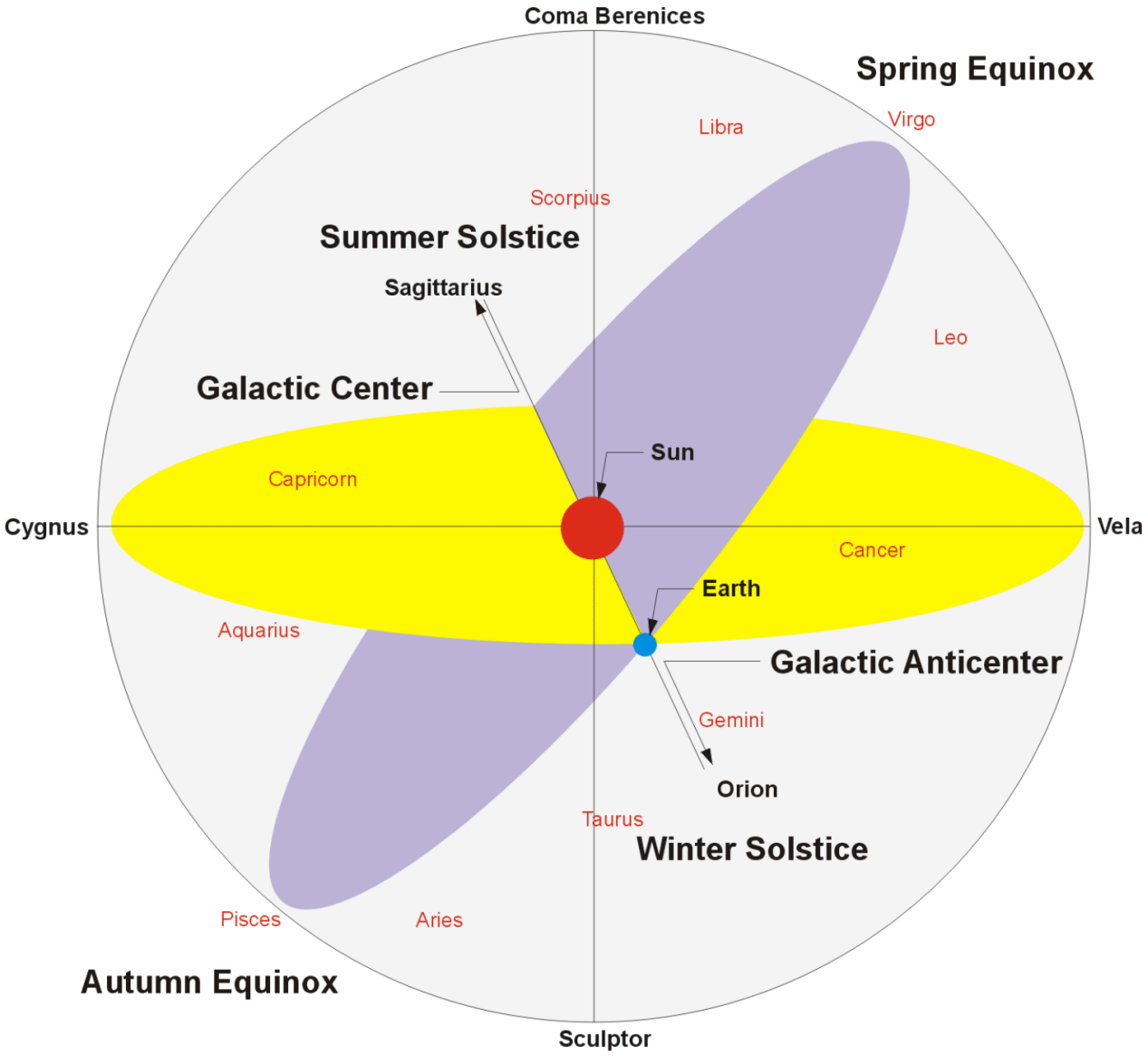
$$\delta\psi(F1,F2)+\delta\psi(F3,F4)=$$
$$\left[\Delta\xi(F1,F2;E1)-\Delta\xi(F1,F2;E2)\right]+\left[\Delta\xi(F3,F4;E2)-\Delta\xi(F3,F4;E1)\right]$$

Photon limited monitoring of base angle β variation

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

$\Rightarrow$ Rationale for simultaneous Sun-ward + Out-ward observations

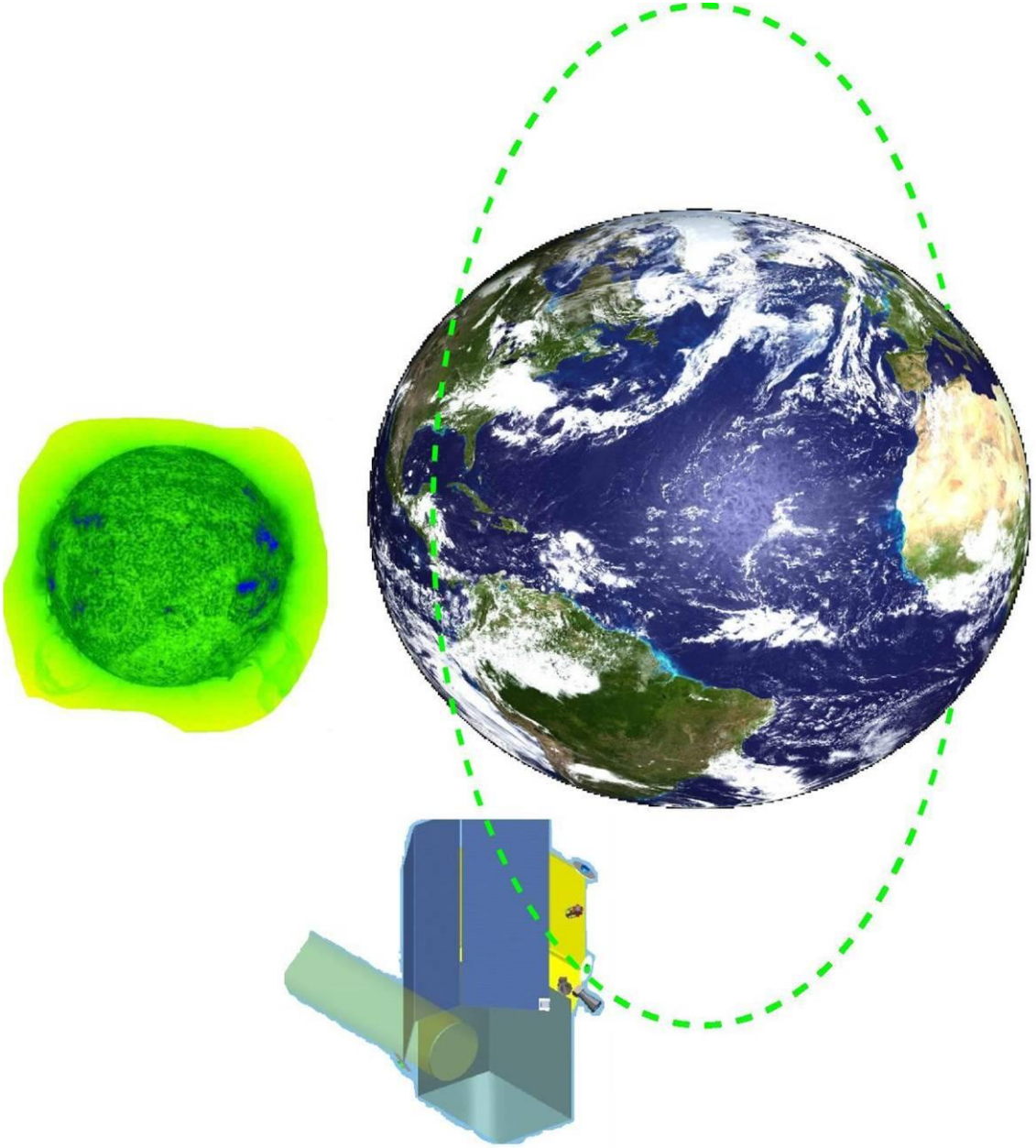
Convenient fields: Galactic ∩ Ecliptic plane



High stellar density regions:

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

Mission profile



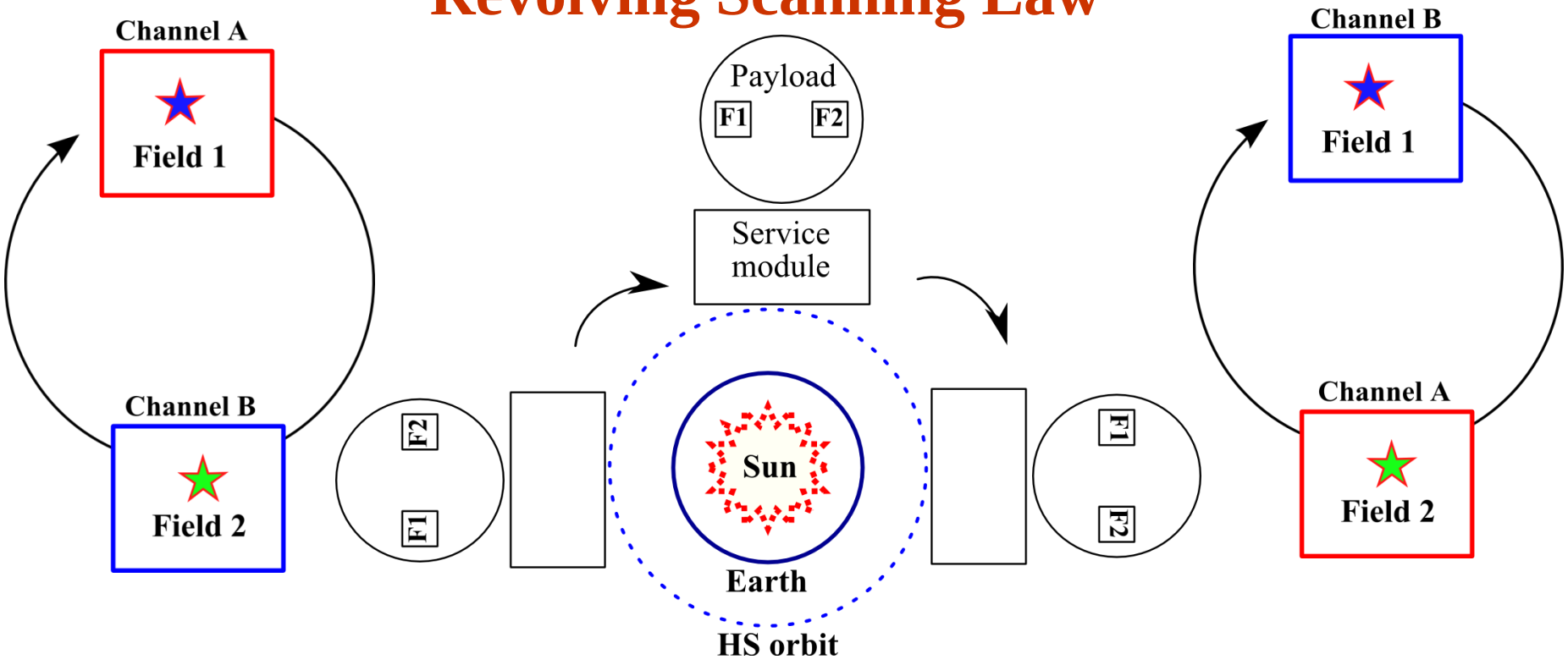
Sun-synchronous orbit, 1000 km elevation ⇒ no eclipse

105 minute orbit period

100% nominal observing time

Stable solar power supply and thermal environment ⇒ instrument structural stability

Revolving Scanning Law



Field rotation around the Sun synchronous with orbital motion

System rationale:

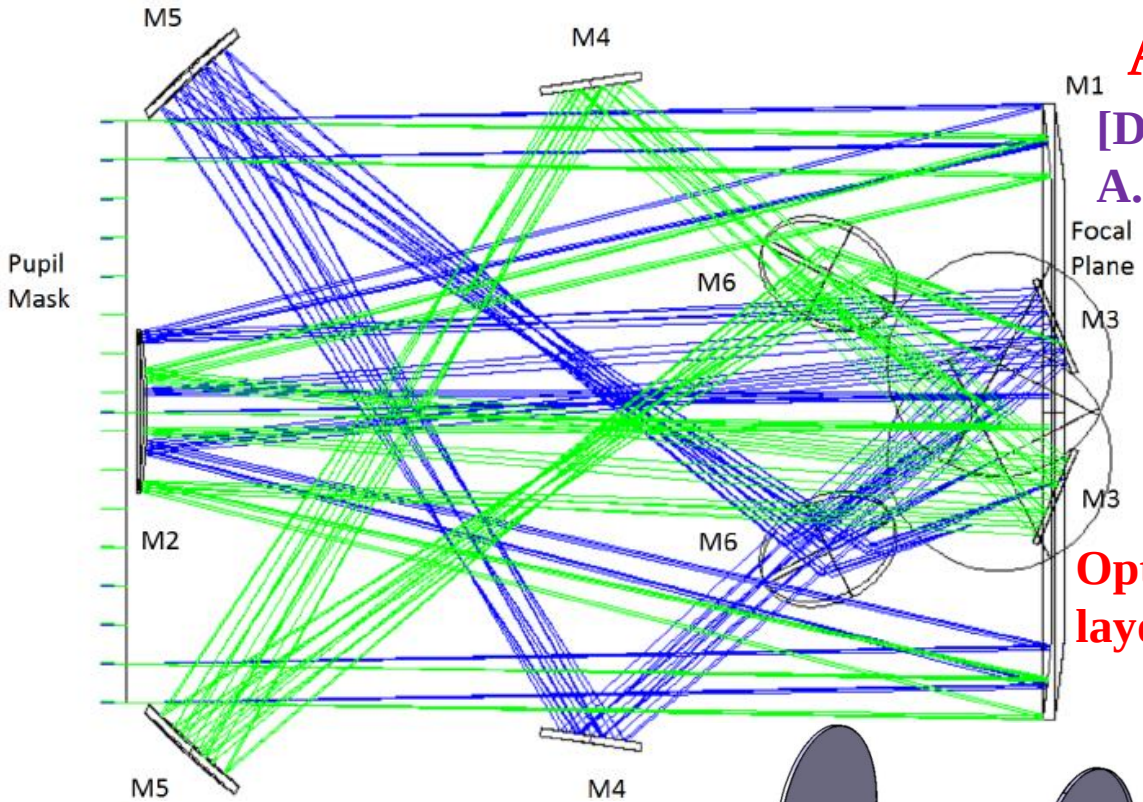
preserve satellite orientation vs. Earth (stable thermal environment)

Science rationale:

switch stars between channels (strenghten calibration)

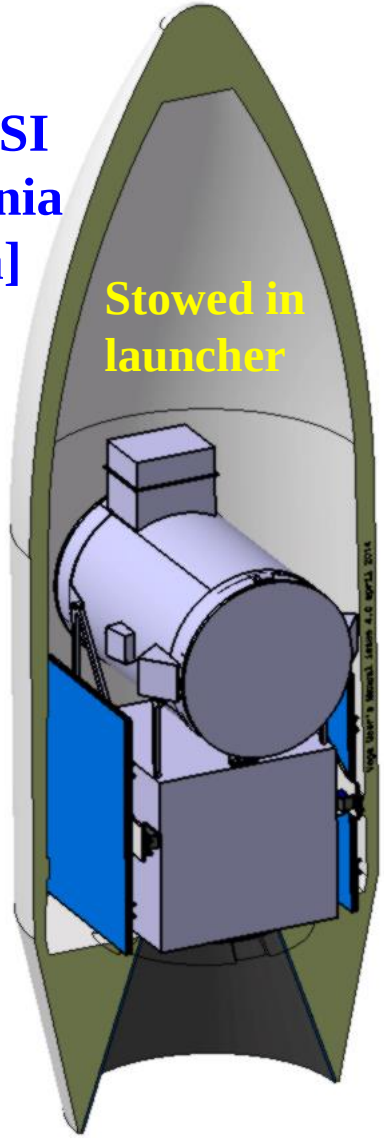
AGP Payload Allocation

[Design: A. Riva]

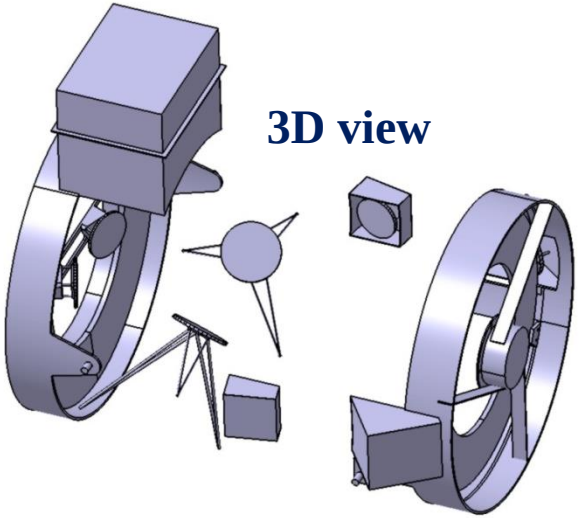


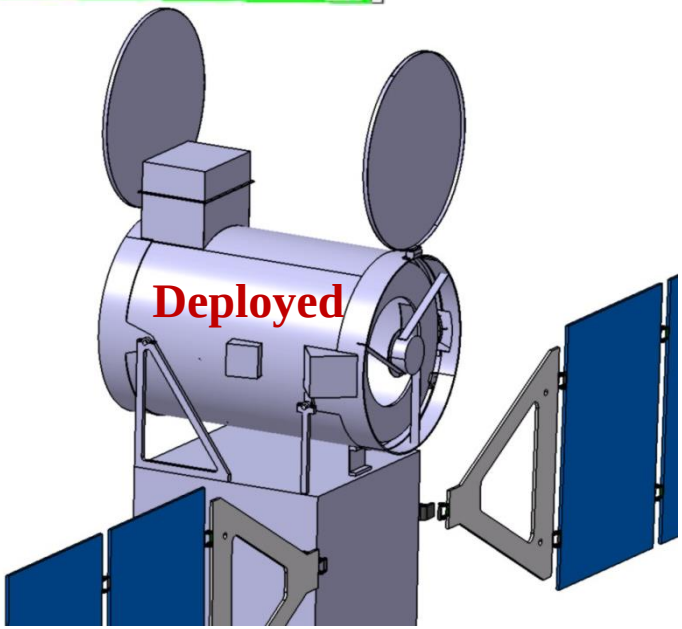
Optical layout

Layout: TASI [Thales Alenia Space Italia]

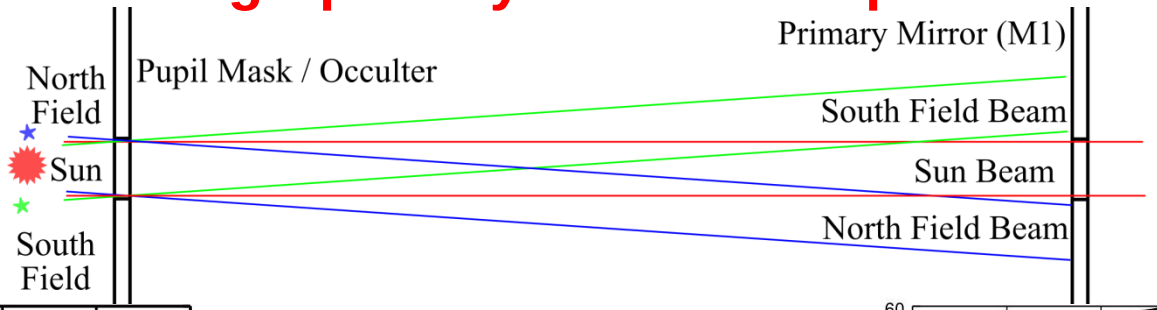


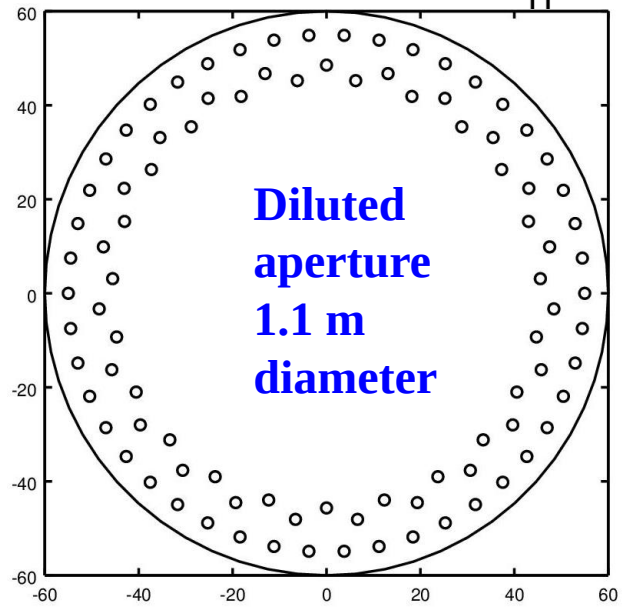
3D view





AGP Payload: Coronagraphic system – multiple inverted occulter

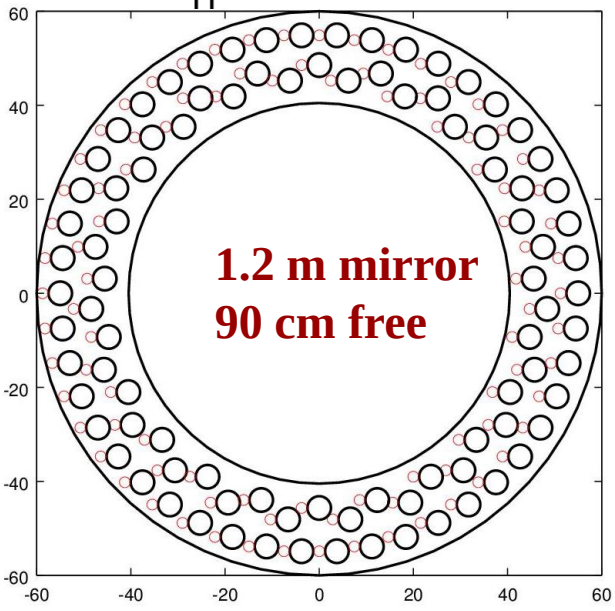


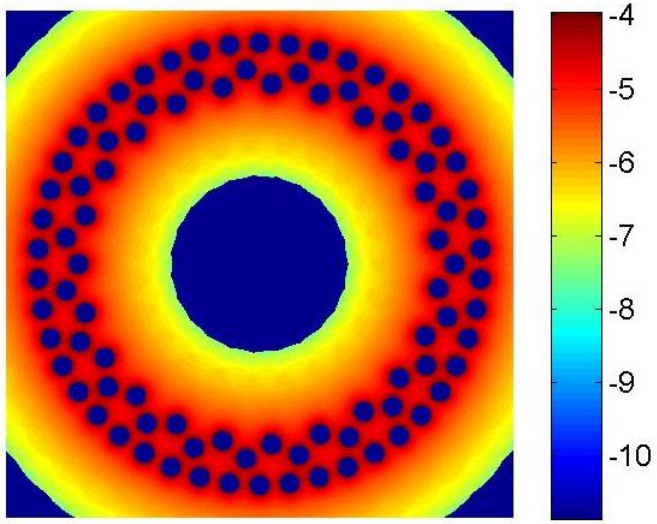


Collecting area

Sun direction: 375 cm^2

Anti-Sun direction: 1500 cm^2





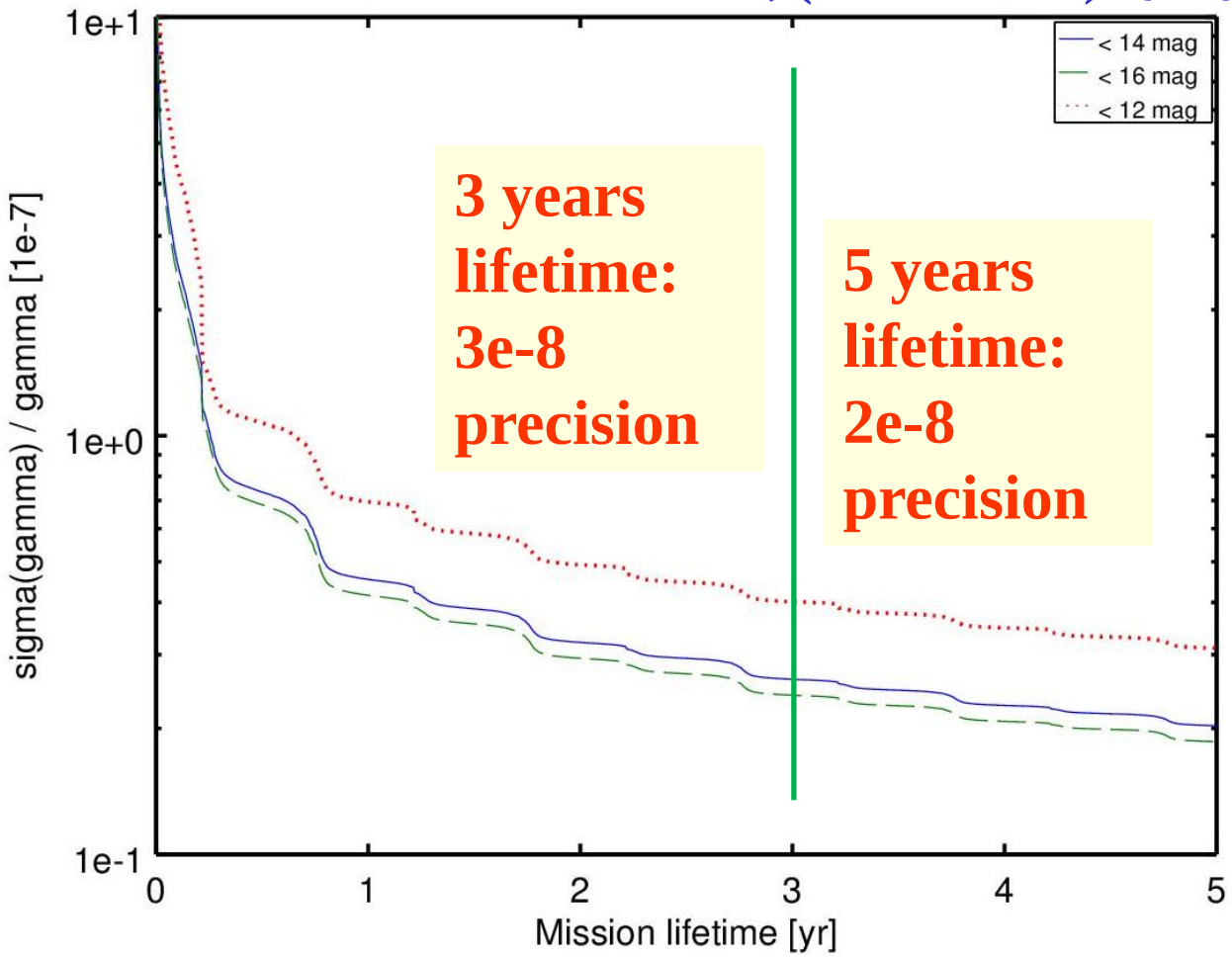
Diffraction on primary mirror [log units]

[F. Landini]

Background on focal plane: ~10^{-7} B_{Sun}

Mission performance on light deflection

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



Deflection measurements averaged over ~5000 orbits/year

Simultaneous estimate of star and planet astrometric parameters

Precision ⇒ accuracy: calibration, metrology

…but performance on orbits scales as time^{3/2}: factor >2

AGP Mission profile vs. ESA M4 Call specifications

Baseline launcher:	Vega
Sun-Synchronous orbit (SSO, i=99.48°), elevation:	1000 (1500) km
Useful mass (satellite + payload):	1140 (1000) kg
Spacecraft dry mass (incl. payload and propulsion systems)	~ 800 kg
Payload mass	~ 300 kg
In-orbit operations	3-5 years
Science telemetry:	S band (~600 kbps); X band (20 – 200 Mbps)
Telescope primary diameter:	1.15 m
Effective Fizeau pupil diameter:	1.10 m
Payload envelope:	2.1 m diameter x 1.5 m height
Detector:	CCD mosaic @ -20 C
Main science focal plane:	8 x 4 CCDs - 2kx4k
Auxiliary (pointing) focal plane:	1 x 2 CCDs - 2kx4k

Laser corner cube for high precision satellite ranging? (F)

Corona polarimetry at high spatial resolution? (I)

Conclusions

High precision astrometry: tool for Fundamental Physics

Discrimination of gravitation theories on Solar System scale

Differential measurement concept: improve result reliability

Implementation concept: astrometry + coronagraphy

Space mission design consolidated (to be improved)

Contributions on science case and mission development welcome!