The Laser Astrometric Test Of Relativity Mission

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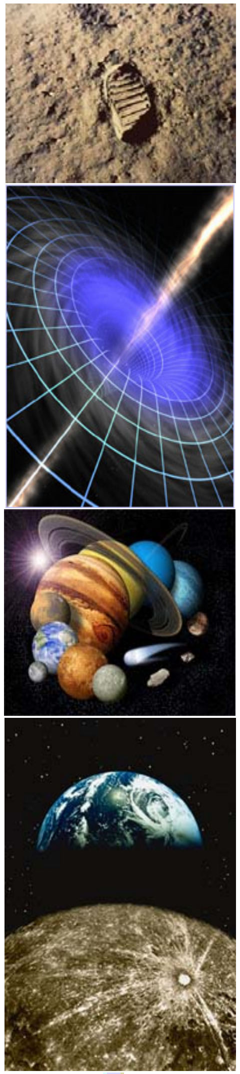
Meeting on “Beyond Einstein: From the Big Bang to Black Holes”
Stanford Linear Accelerator Center, Stanford University, 12-15 May 2004

The Purpose:

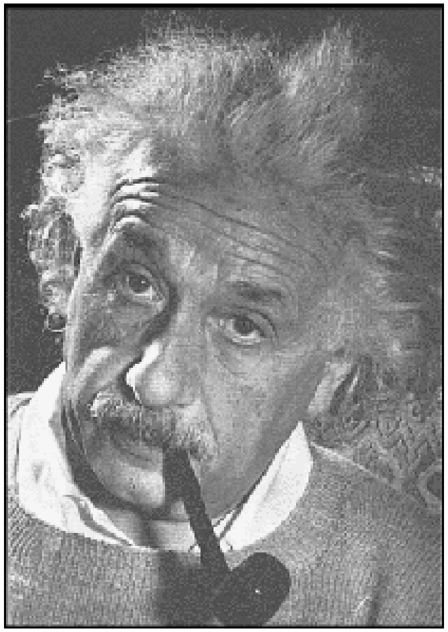


New Gravitational Experiment in Space:

The Laser Astrometric Test Of Relativity (LATOR) Mission

Talk will cover:

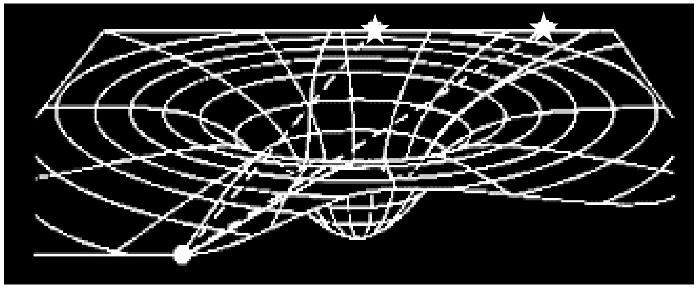
- Gravity Experiments in the Solar System
  - Brief History & Motivations
- The LATOR Mission concept:
  - Science & Technologies of LATOR
  - Relevance to *"Moon, Mars and Beyond"* Initiative



Take-Away Message:

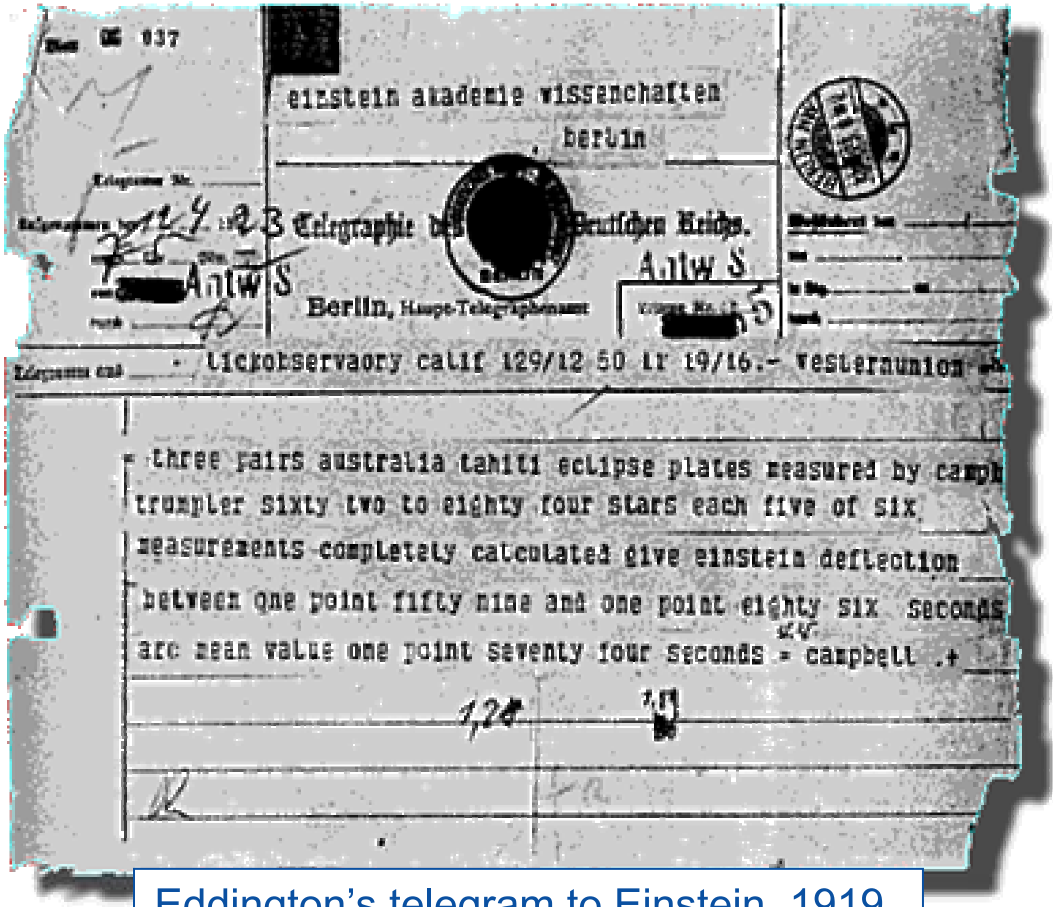
LATOR will lead to robust advances in Fundamental Physics.
LATOR mission is technologically feasible and economically sound.
LATOR experiment is unique and it must be done!
May be a critical part of Nav/Comm space infrastructure.

The First Test of General Theory of Relativity



Gravitational Deflection of Light:

Solar Eclipse 1919



einstein akademie wissenschaften
berlin

Telegraphie des Deutschen Reichs.

Berlin, Haupt-Telegraphenamt

Antw S

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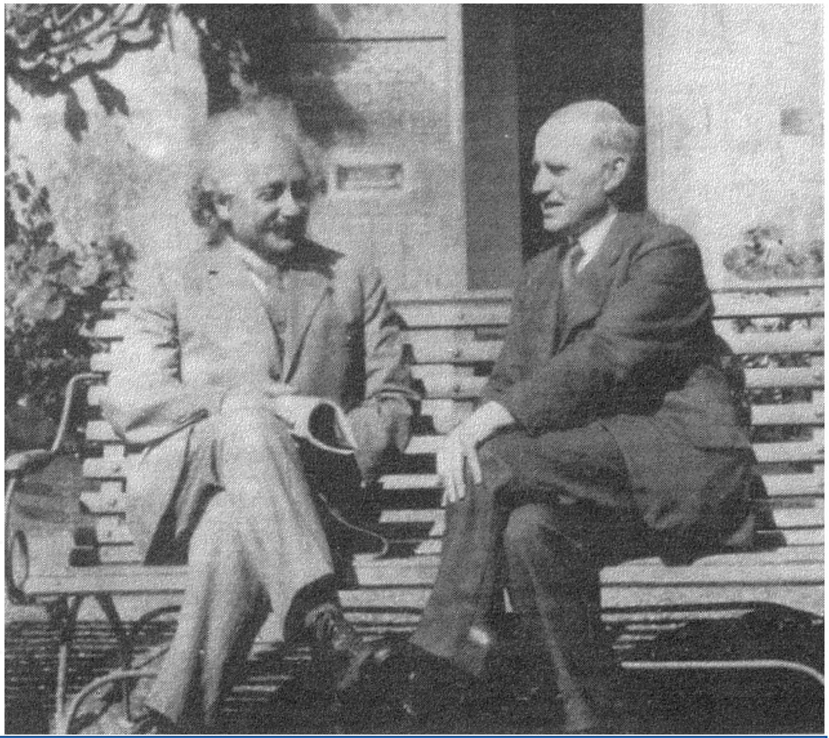
three pairs australia tahiti eclipse plates measured by camp
trumpler sixty two to eighty four stars each five of six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell .+

Eddington's telegram to Einstein, 1919

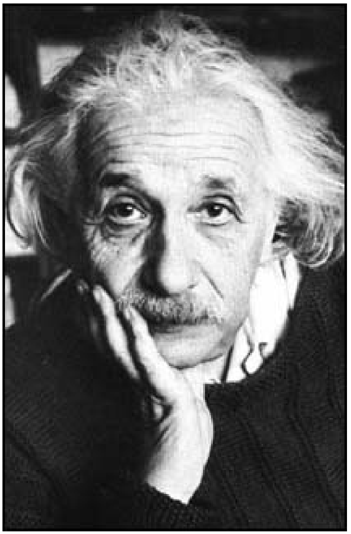
Possible outcomes in 1919:

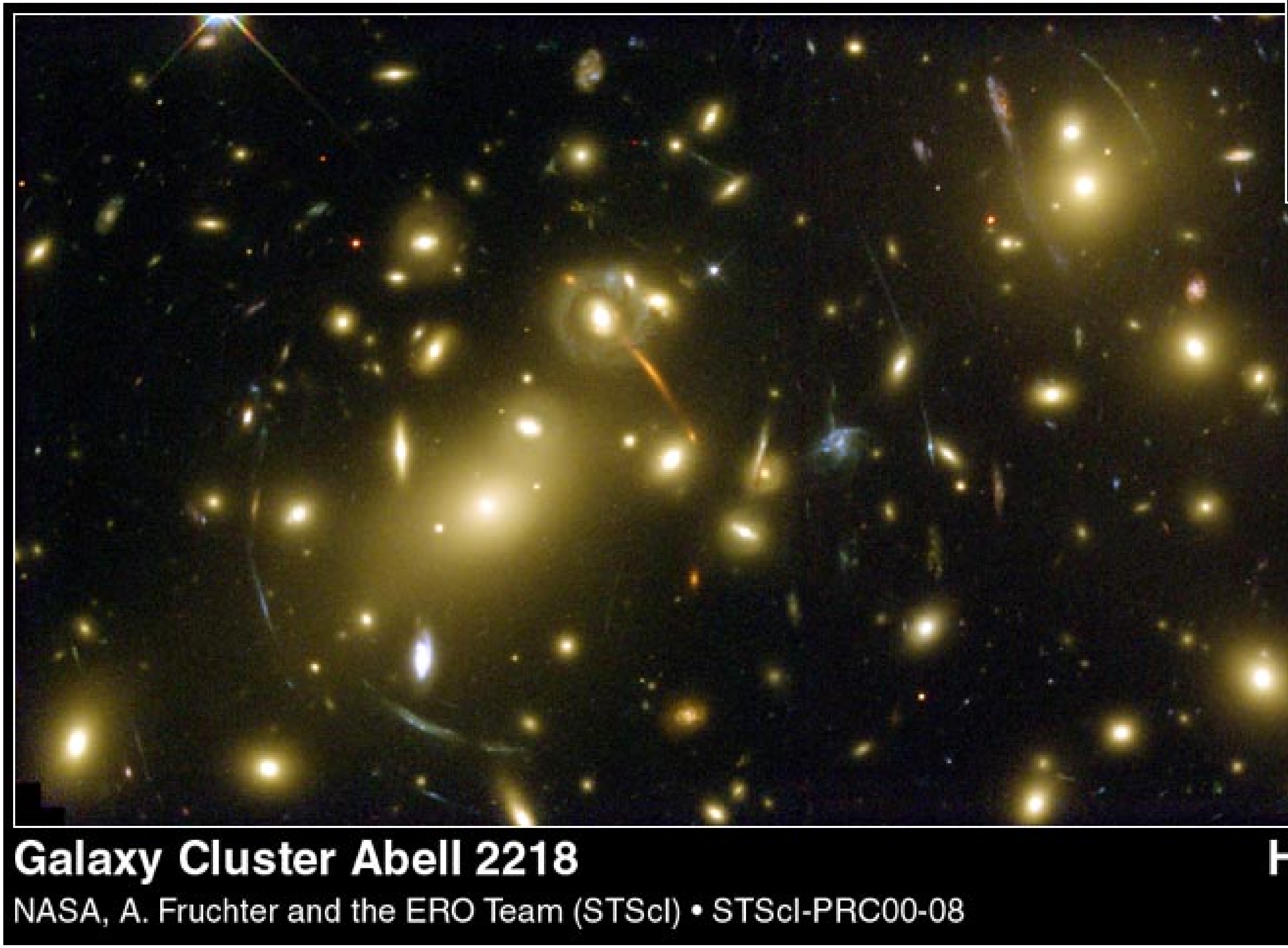
Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec



Einstein and Eddington, Cambridge, 1930

Gravitational Deflection of Light is a Well-Known Effect Today





Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

35 Years of Relativistic Gravity Tests

Techniques for Gravity Tests:

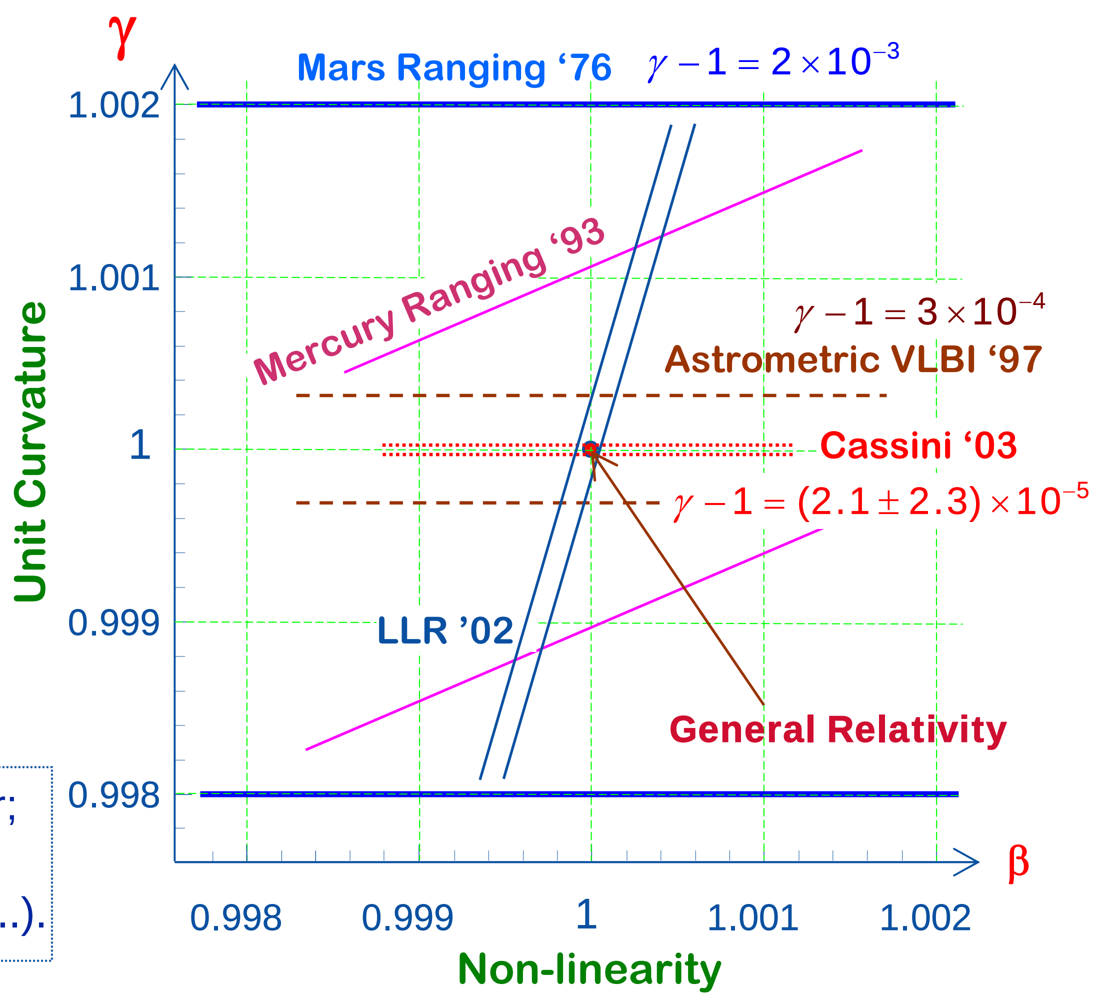
- Spacecraft Doppler & range, planetary ranging;
- VLBI, LLR, SLR, GPS, etc.

Designated Gravity Missions:

- LLR (1969 - on-going!!)
- GP-A, ’76; LAGEOS, ’76,’92; GP-B, ’04; LISA, 2012

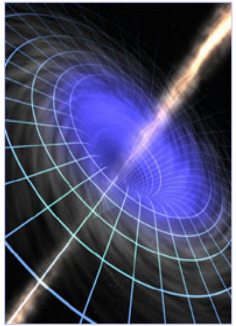
New Engineering Discipline – Applied General Relativity:

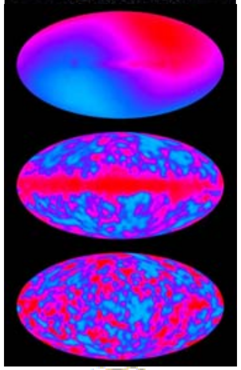
- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, GAIA,....).

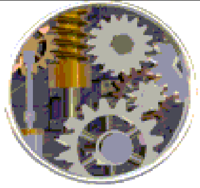


A factor of 100 in 35 years is impressive, but is not enough for the near future!

Challenges to General Relativity







Fundamental Physics Challenges:

- Appearance of space-time singularities;
- Classical description breaks down in large curvature;
- Quest for Quantum Gravity → GR modification;
- Cosmology: accelerating Universe, *dark energy?!*

Alternative Theories of Gravity:

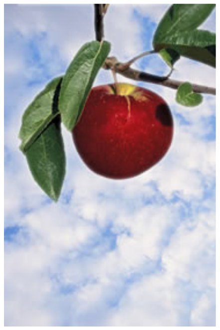
- Grand Unification Models, Standard Model Extensions;
- Inflationary cosmologies, strings, Kaluza-Klein theories;

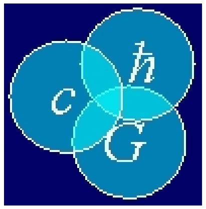
Common element:

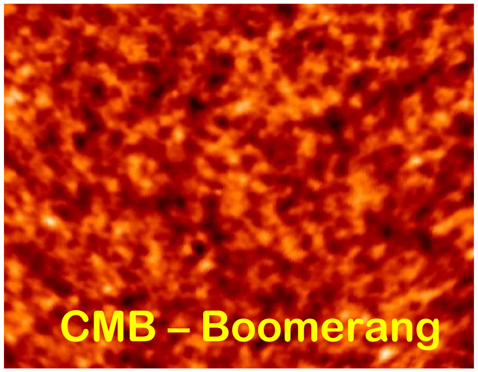
scalar partners – dilaton, moduli fields…

If scalar exists, how to observe it?

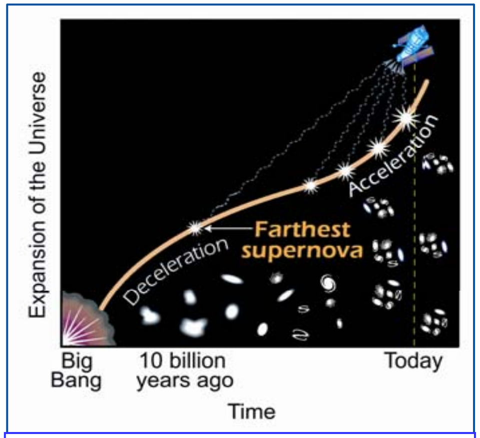
- Search for violations of the Equivalence Principle;
- Look for modification of large-scale gravity phenomena;
- Test for variability of fundamental constants (G, α, …);
- Search for gravity anomalies [short/solar system scales]







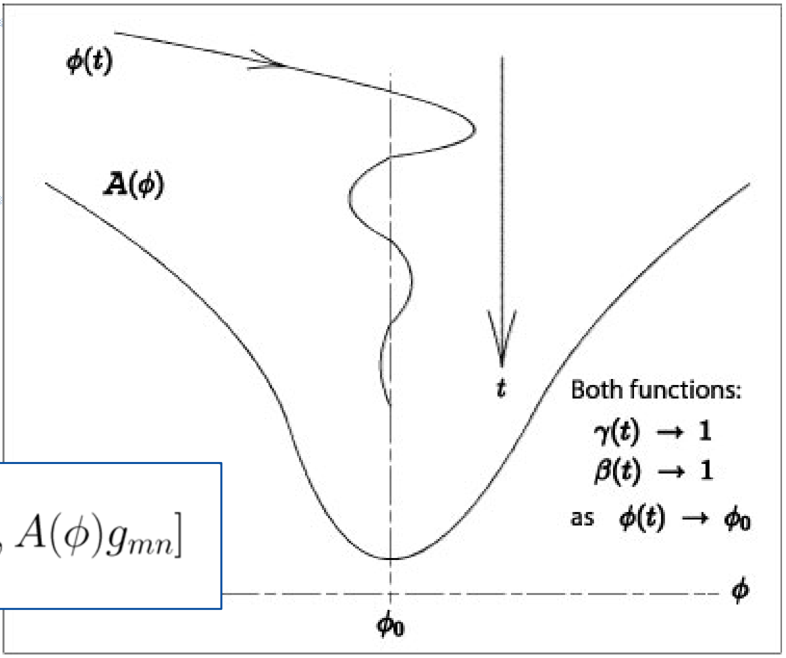
CMB – Boomerang



1998 SN Ia evidence for accelerating Universe

As a fundamental theory, GR must be tested to the highest level

Theoretical Motivation for New Gravity Tests



Long-range massless [or low-mass] scalar:

The low-energy limit of the String Theory in 'Einstein Frame' (Damour-Nordtvedt-Polyakov 1993) suggests:

$$S = -\frac{1}{16\pi G}\int dx^4\sqrt{-g}\Big(R - 2g^{mn}\nabla_m\phi\nabla_n\phi\Big) + S_M[\psi_M, A(\phi)g_{mn}]$$

Expansion *A(ϕ)* around background value ϕ_0 of the scalar leads:

$$\ln A(\varphi) = \ln A(\varphi_0) + \alpha_0(\varphi - \varphi_0) + \frac{1}{2}k_0(\varphi - \varphi_0)^2 + \mathcal{O}(\Delta\varphi^3)$$

Slope α_0 measures the coupling strength of interaction between matter and the scalar.

$$\gamma - 1 \;=\; \frac{-2\alpha_0^2}{1+\alpha_0^2} \simeq -2\alpha_0^2$$

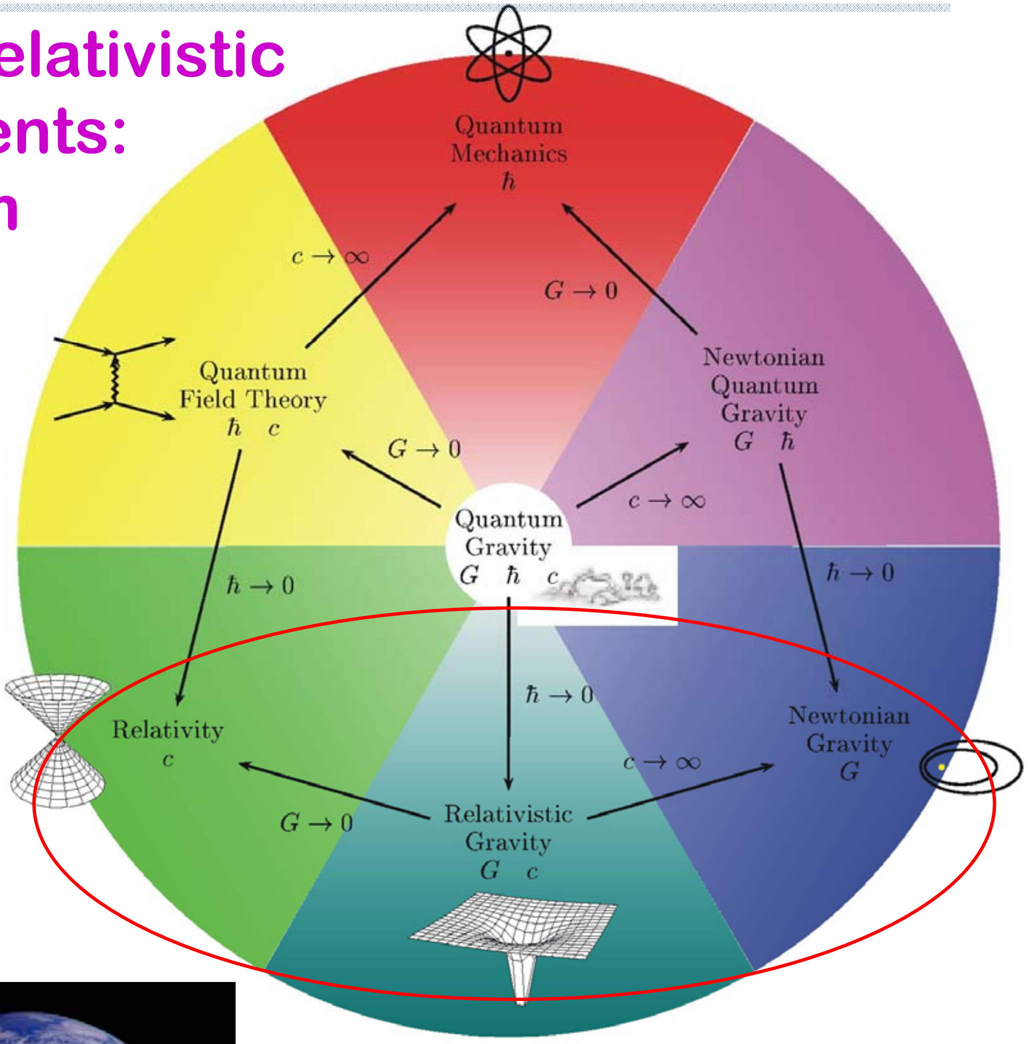
$$\beta - 1 = \frac{1}{2}\frac{\alpha_0^2 k_0}{(1+\alpha_0^2)^2} \simeq \frac{1}{2}\alpha_0^2 k_0 \simeq \frac{1}{4}(1-\gamma)k_0$$

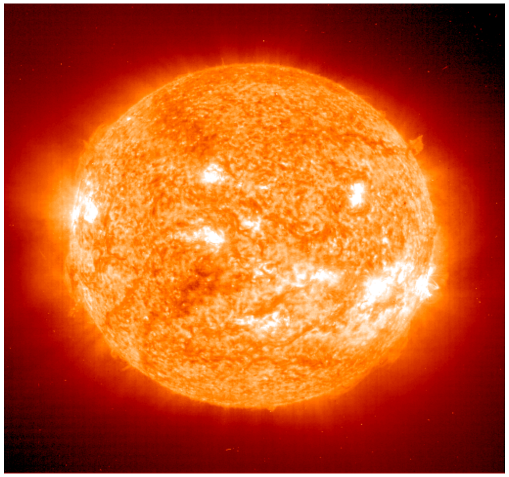
Scenario for cosmological evolution of the scalar (Damour, Piazza & Veneziano 2002):

$$\gamma - 1 \sim 7.3 \times 10^{-7}\left(\frac{H_0}{\Omega_0^3}\right)^{\frac{1}{2}} \quad \Rightarrow \quad \boxed{\gamma - 1 \sim 10^{-5} - 10^{-7}}$$

The unit curvature, PPN parameter γ – the most important quantity to test

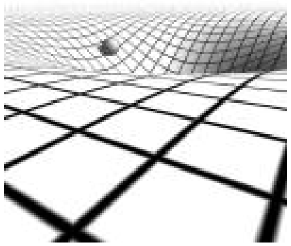
Laboratory for Relativistic Gravity Experiments: Our Solar System





Strongest gravity potential

$$\frac{GM_{\odot}}{c^2R_{\odot}} \sim 10^{-6}$$



$$\frac{GM_{\oplus}}{c^2R_{\oplus}} \sim 10^{-9}$$

Most accessible region for gravity tests in space:

- ISS, LLR, SLR, free-fliers

Cassini 2003: Where Do We Go From Here?

Cassini Conjunction Experiment 2002:

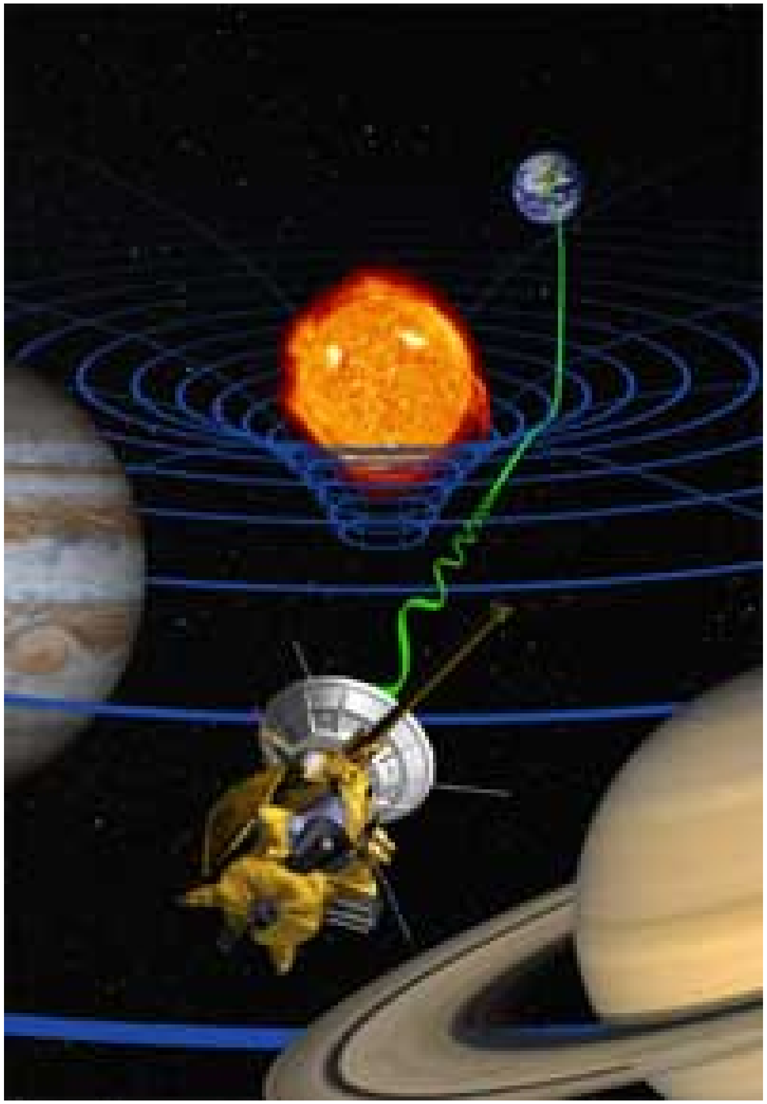
- Spacecraft—Earth separation > 1 billion km
- Ranging: X~7.14GHz & Ka~34.1GHz
- Result: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

Possible with Existing Technologies?!

- VLBI [current 3×10^{-4}]: in 5 years $\sim 8\times10^{-5}$:
  - # of observations (1.6M to 16M → factor of 3)
- LLR [current 4×10^{-4}]: in 5 years $\sim 3\times10^{-5}$:
  - mm accuracies [APOLLO] & modeling efforts
- Microwave ranging to a Lander on Mars $\sim 6\times10^{-6}$
- Astrometry [current 3×10^{-3}]: SIM $\sim 1\times10^{-6}$ (2012)

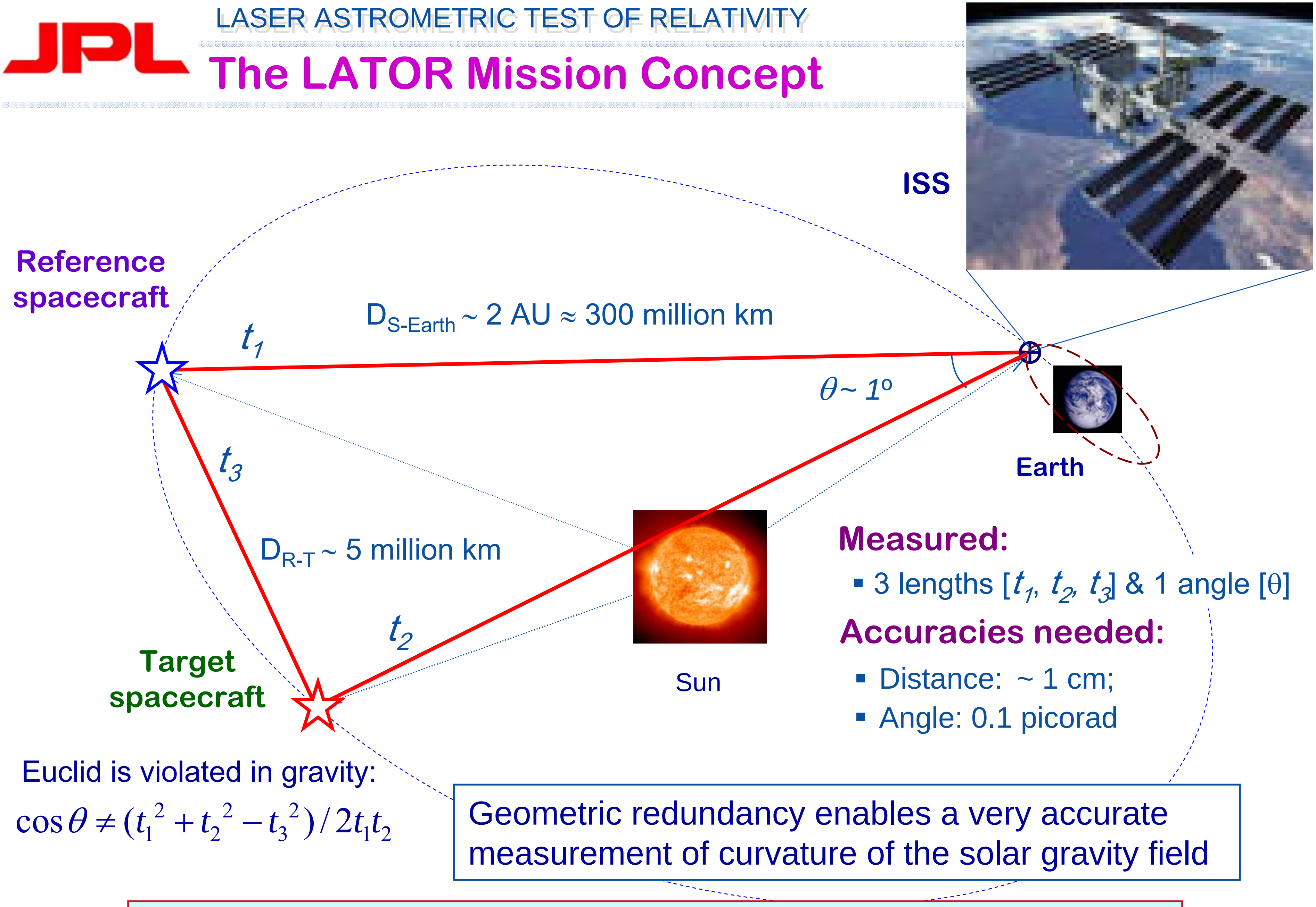
The tests at $\sim G^2$ offer New Science:

- Cosmologically evolved scalar field, etc.
- Gravity modifications [$\sim R^{-n}$ terms, Carroll 2003]



We need a designated mission to explore accuracies better than 10^{-6}

The LATOR Mission Concept



Measured:

- 3 lengths [t_1, t_2, t_3] & 1 angle [θ]

Accuracies needed:

- Distance: ~ 1 cm;
- Angle: 0.1 picorad

Euclid is violated in gravity:

$$\cos\theta \neq (t_1{}^2 + t_2{}^2 - t_3{}^2)/2t_1t_2$$

Geometric redundancy enables a very accurate measurement of curvature of the solar gravity field

Accurate test of gravitational deflection of light to 1 part in 10^8

Sizes of the Effects & Needed Accuracy

Effect	Analytical Form	Deflection Value (μas)	B=100 m Value (pm)
First Order	$2(1+\gamma)\frac{M}{R}$	1.75×10^6	8.487×10^8
Second Order	$([2(1+\gamma)-\beta+\frac{3}{4}\delta]\pi-2(1+\gamma)^2)\frac{M^2}{R^2}$	3.5	1702
Frame-Dragging	$\pm 2(1+\gamma)\frac{J}{R^2}$	± 0.7	± 339
Solar Quadrupole	$2(1+\gamma)J_2\frac{M}{R^3}$	0.2	97

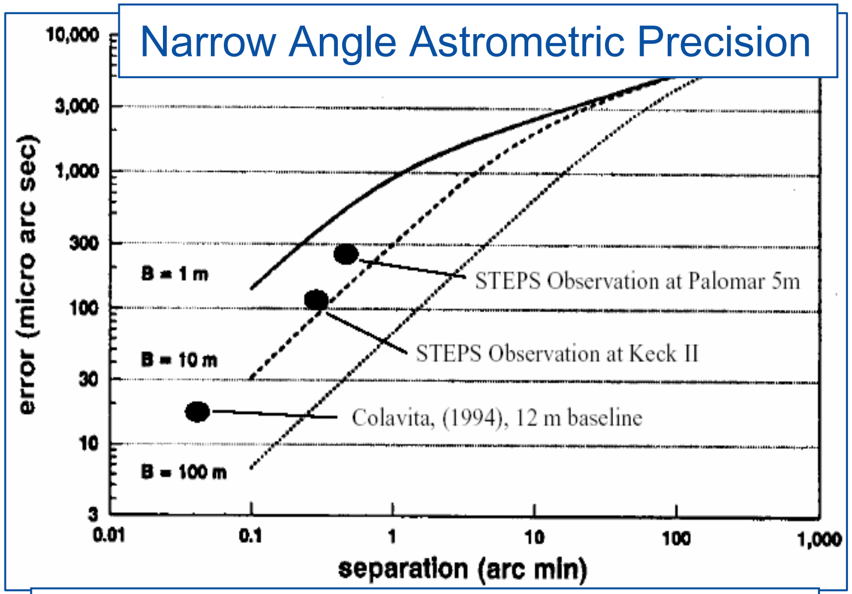
LATOR 1994 Proposal:

- Ground-based interferometer [B = 30km]
- Limited capabilities due to atmosphere

$(M/R)^2$ term ~0.2% accuracy [B =100 m]:
0.02 μas ⇒ 0.1 picorad ~10pm

LATOR 2004 (all in space):

- Interferometer on the ISS [B = 100m]
- Technology exists as a result of NASA investments in astrometric interferometry

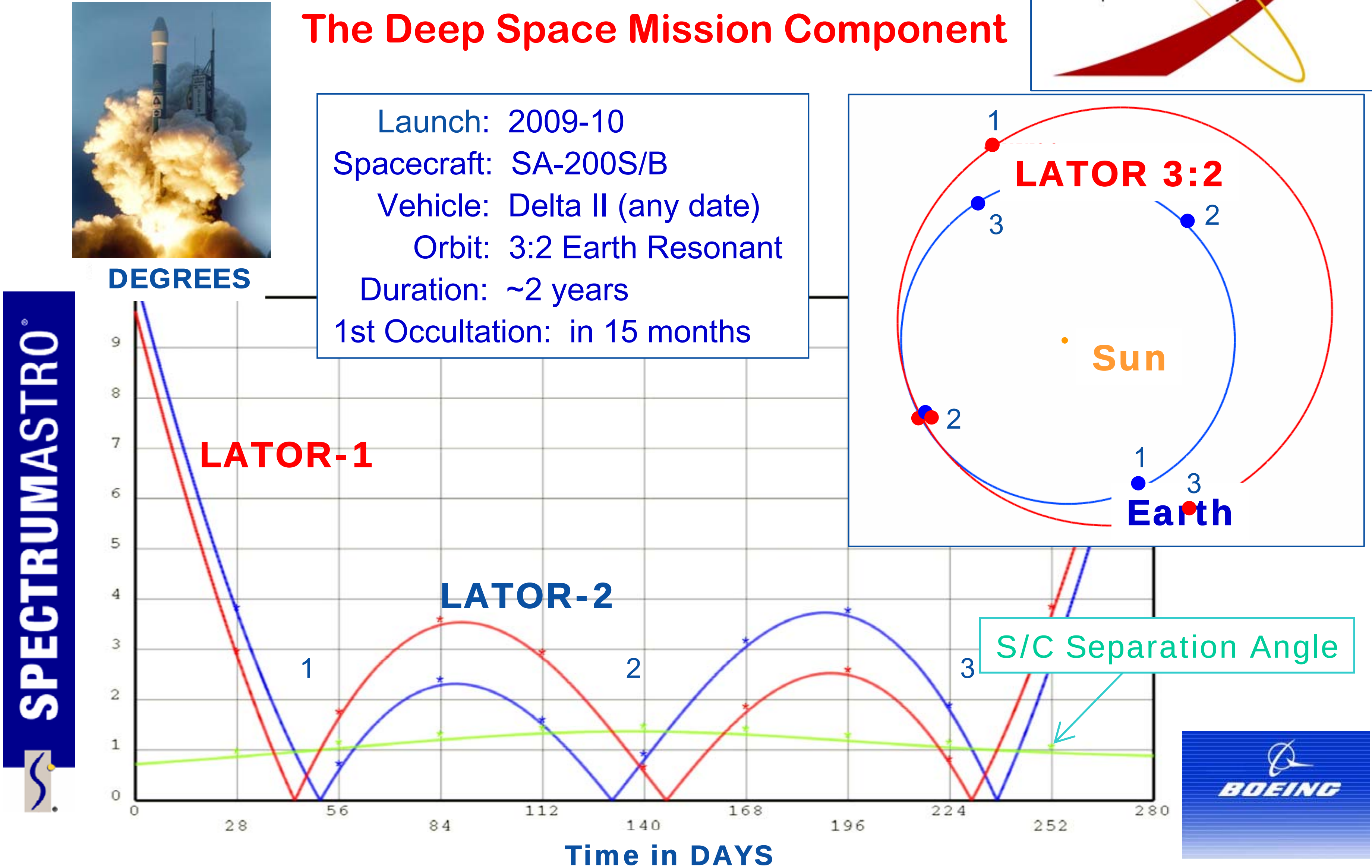

Narrow Angle Astrometric Precision

1 hour integration in 0.5 arcsec seeing

The key technologies are already available – SIM, TPF, Starlight, KI

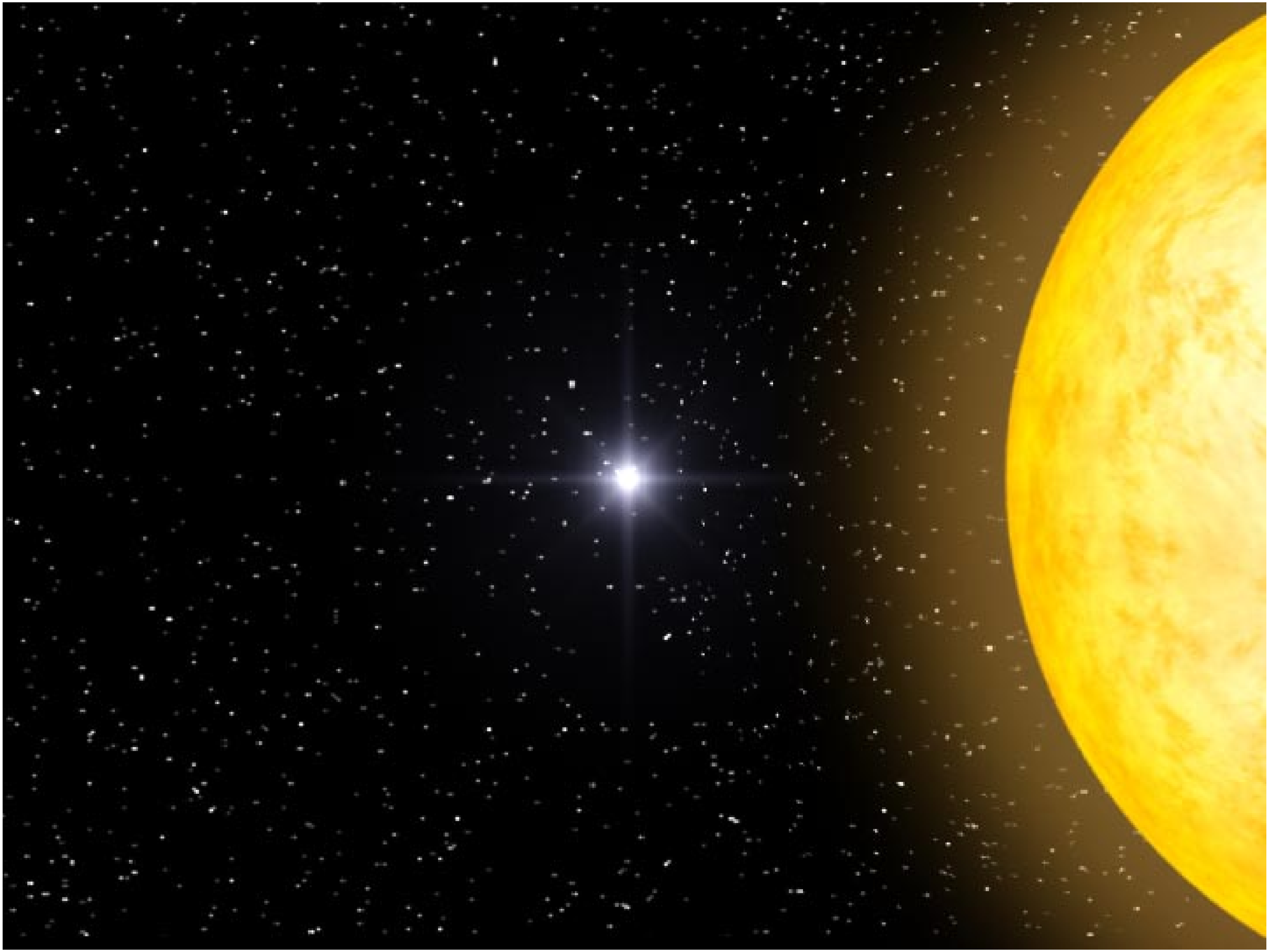
Recent JPL Team X Mission Study:

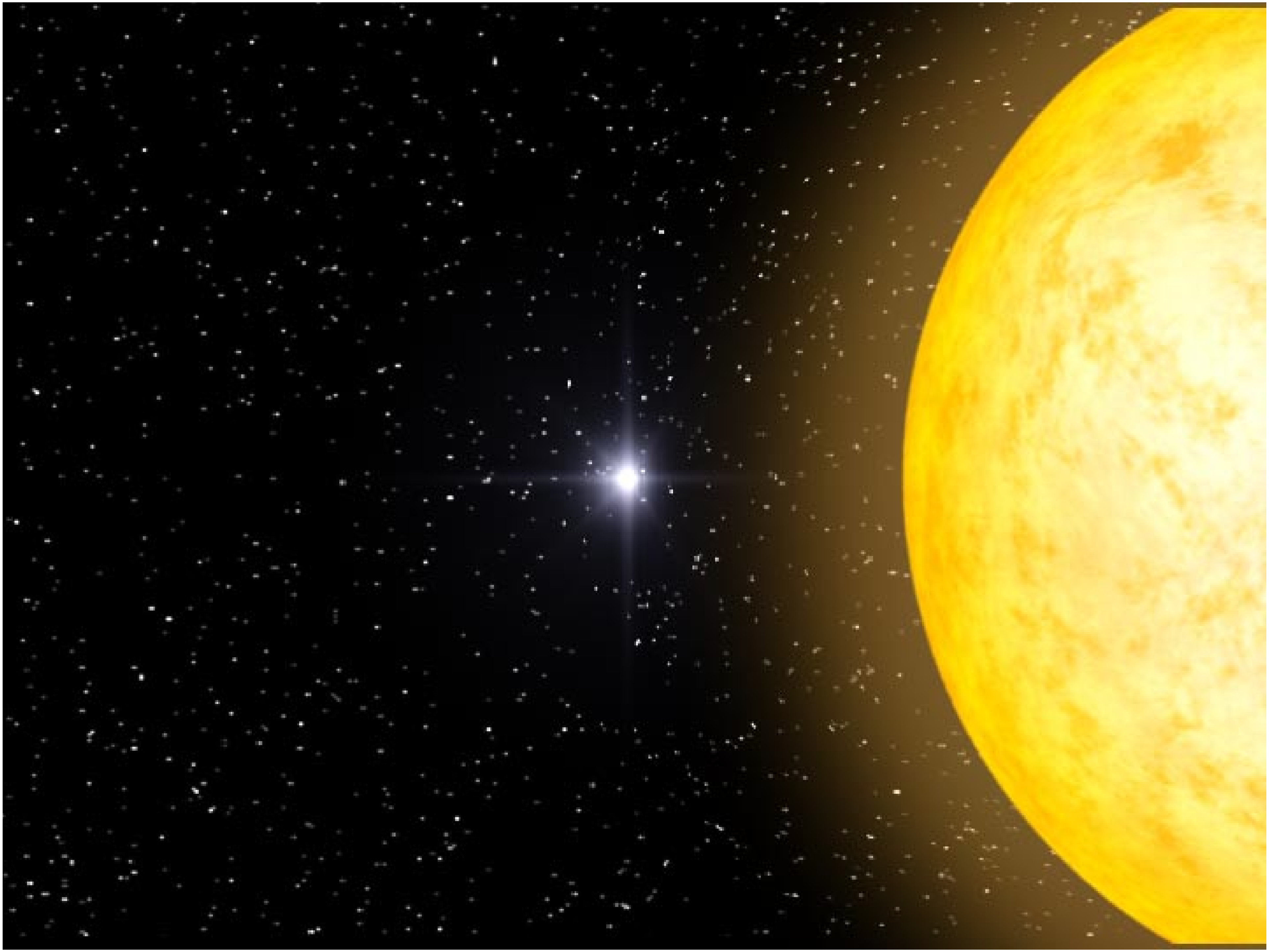
The Deep Space Mission Component

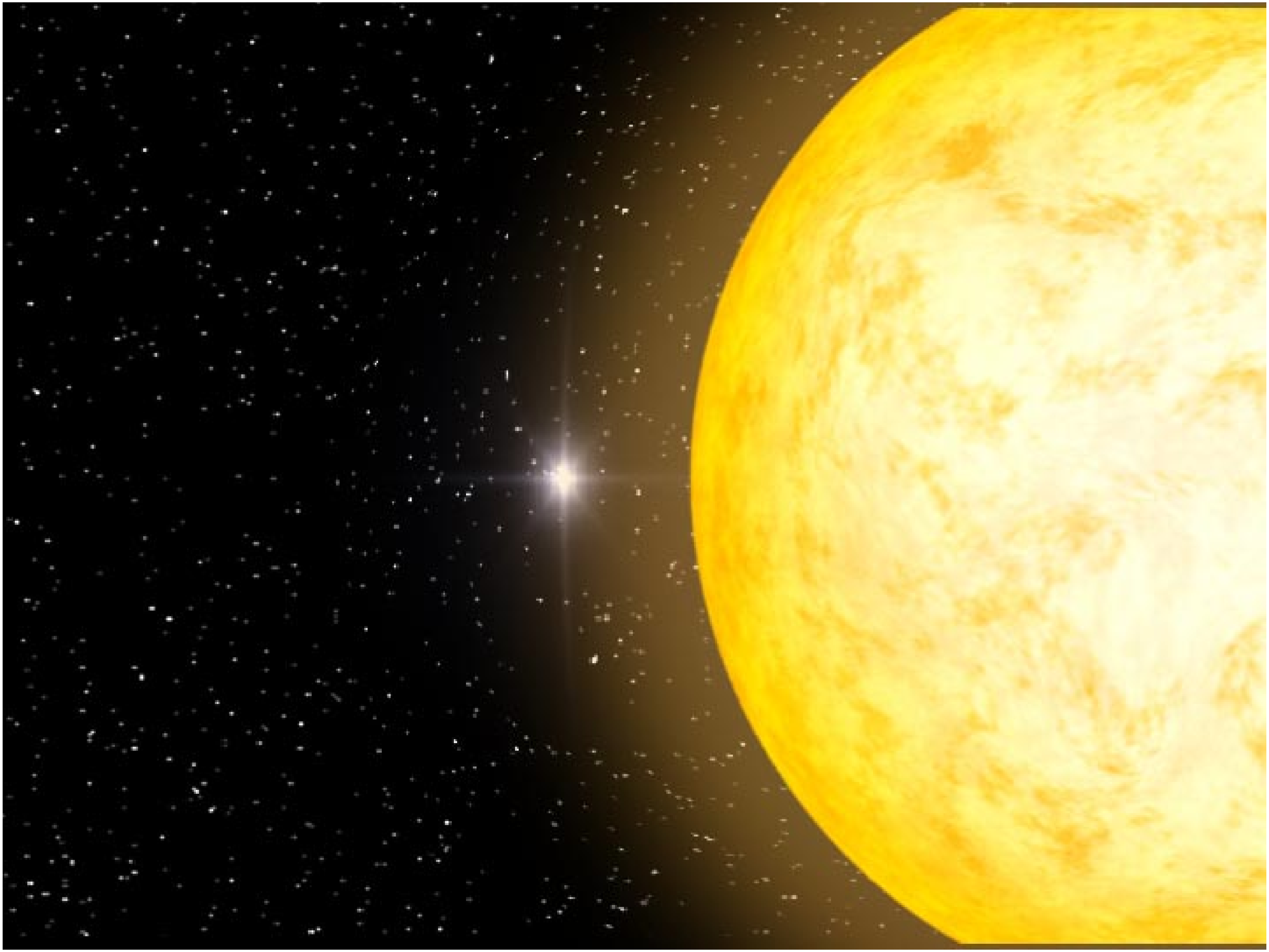


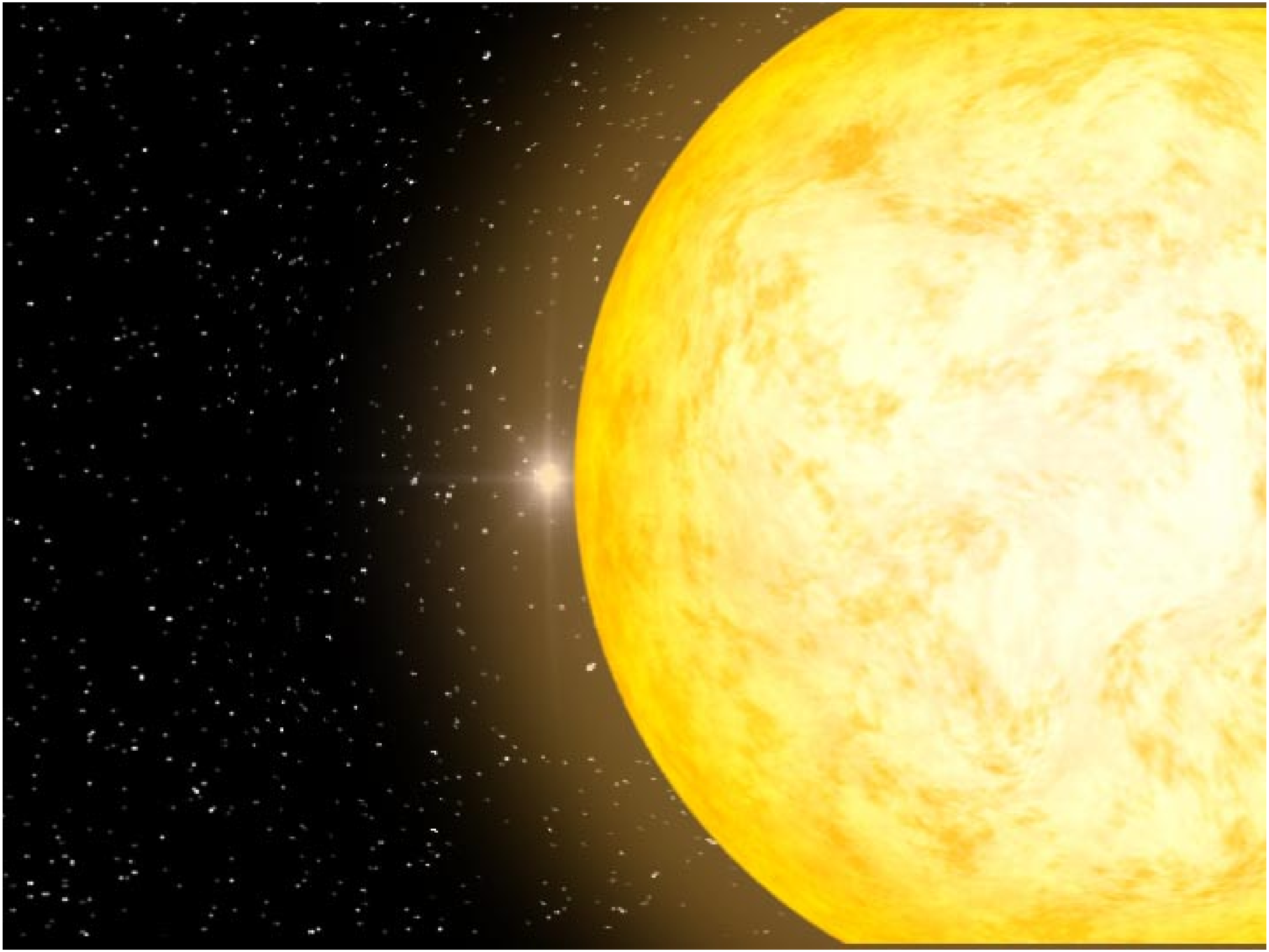
Launch: 2009-10
Spacecraft: SA-200S/B
Vehicle: Delta II (any date)
Orbit: 3:2 Earth Resonant
Duration: ~2 years
1st Occultation: in 15 months

JPL Team X study demonstrates feasibility of LATOR as a MIDEX

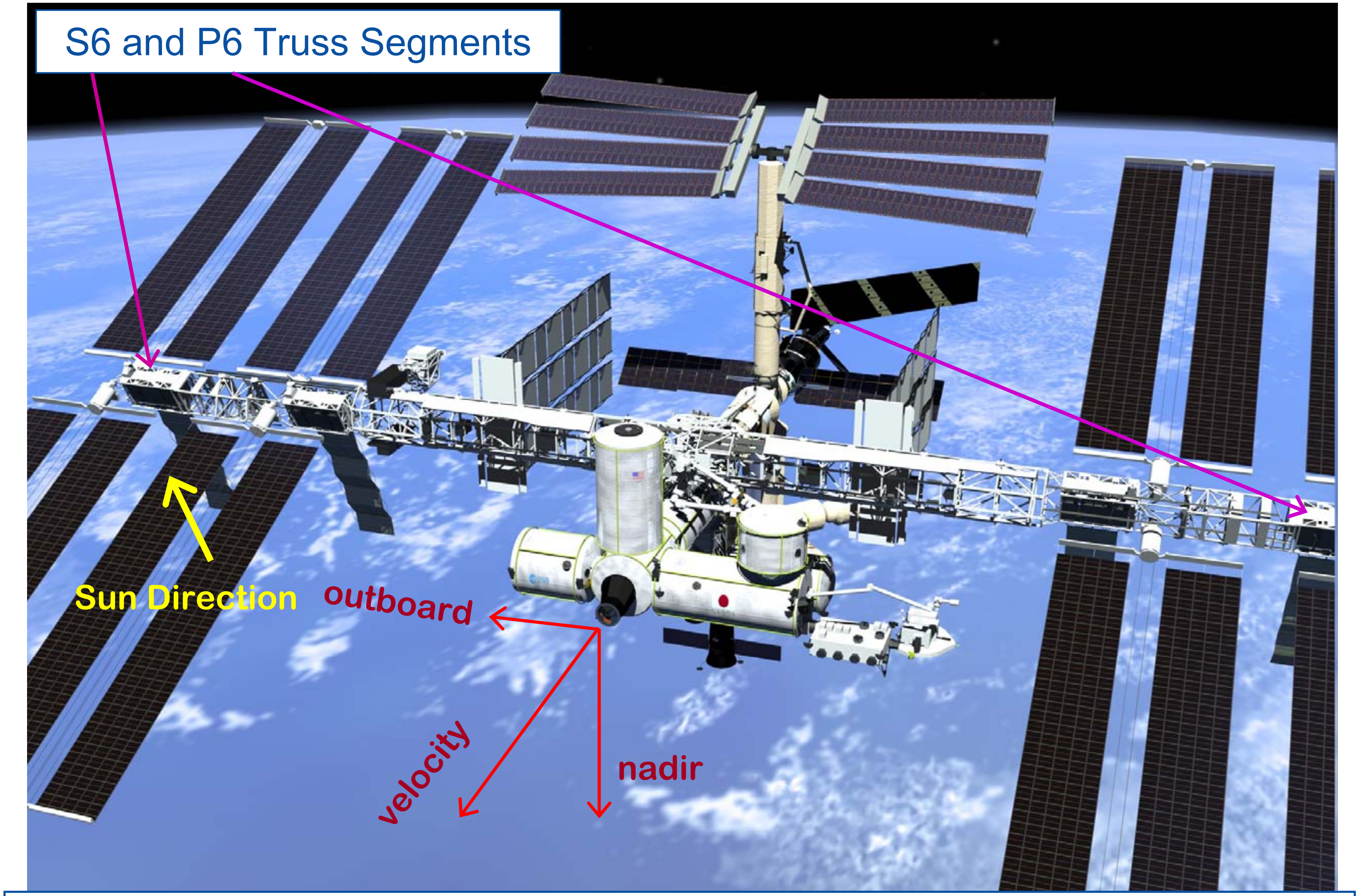








LATOR Interferometer on the ISS



To utilize the inherent ISS sun-tracking capability, the LATOR optical packages will be located on the outboard truss segments P6 & S6 outwards

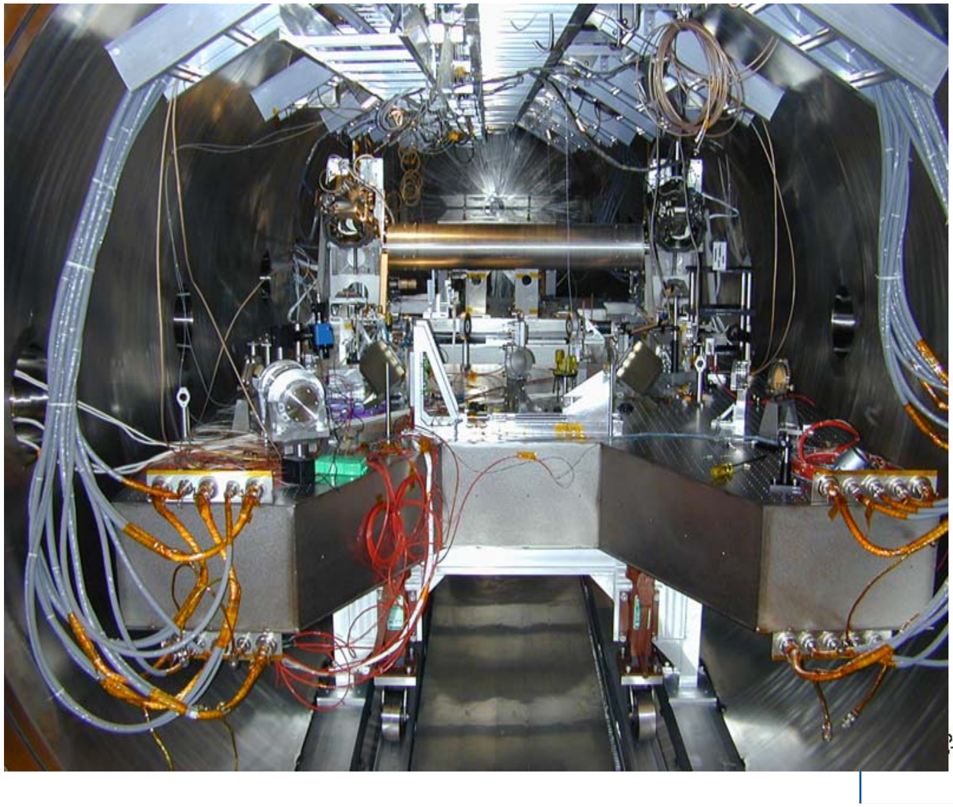
Success of SIM Enables LATOR: MAM Testbed

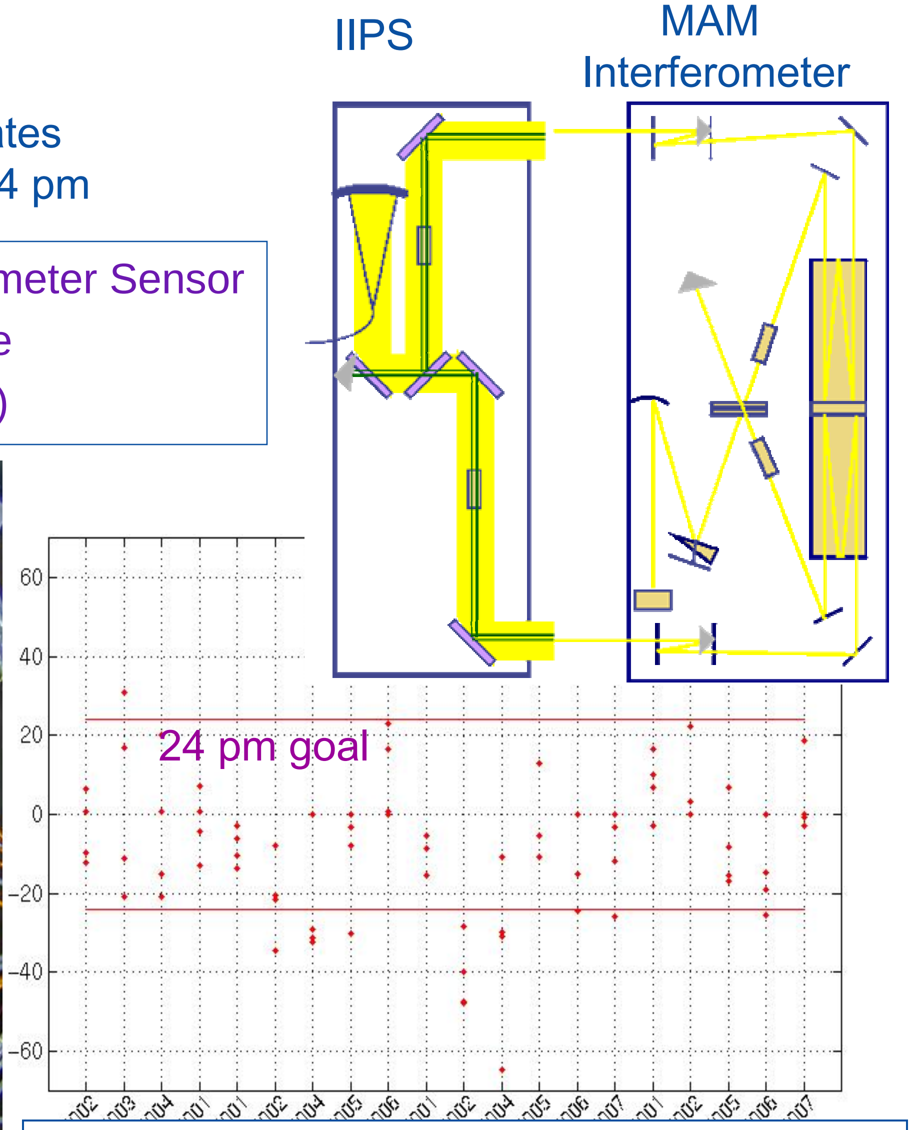
SIM is in Phase B: Aug 2003

- After passing all 6 NASA technology gates
- Goal for Narrow Angle performance ~24 pm

MAM is a demonstration of SIM's Interferometer Sensor

- Single baseline interferometer test article
- Inverse Interferometer Pseudostar (IIPS)

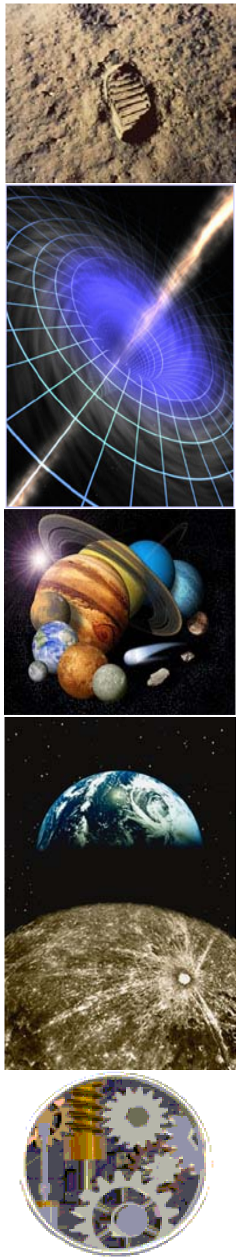




Performance of Microarcsecond testbed:
75.3% of data with uncertainty below 24 pm

Why is LATOR Orders of Magnitude

More Sensitive & Less Expensive



Optical vs. Microwave:

- Solar plasma effects decrease as λ^2: from 10cm (3GHz) to 1 μm 300 THz is a 10^{10} reduction in solar plasma optical path fluctuations

Orbit Determination (OD):

- No need for drag-free spacecraft for LATOR
- Redundant optical truss – alternative to ultra-precise OD: LATOR is insensitive to s/c buffeting from solar wind & solar radiation pressure

A Low Cost Experiment:

- Existing technologies, laser components and spacecraft
- 1W lasers w/ freq stability and >10 years lifetime already developed for telecom; and flight qualified for SIM
- Optical apertures ~10-20cm – sufficient; high SNR ~1700
- Options exist for <u>NO</u> motorized moving parts

AstroAccel resoltn: 10^{-9}g in 7 sec integrtn

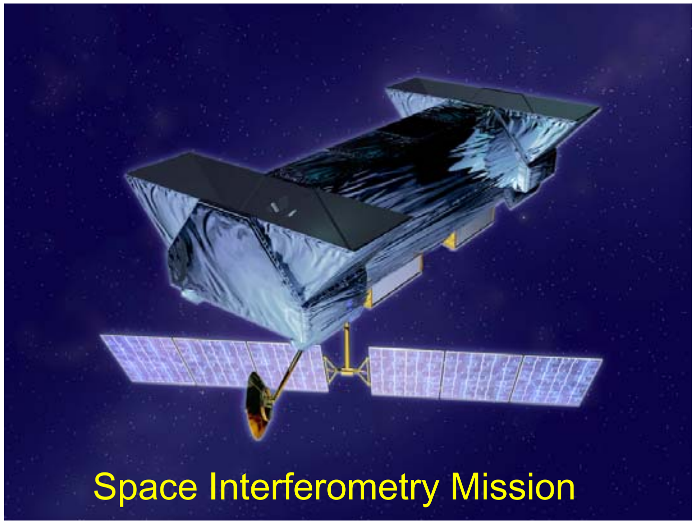
LATOR Mission: ISS Concept

Primary Objective:

To measure curvature of the solar gravitational field with accuracy of 3,000 times better than currently possible

LATOR Experiment uses:

- Two spacecraft @ 1AU, heliocentric orbit & laser transponders;
- Optical interferometer to measure angles between the spacecraft

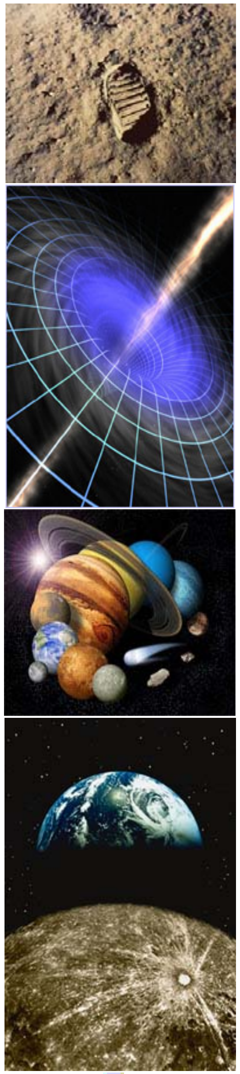


Space Interferometry Mission

- Laser Transponders [λ = 1064 nm]:
  - Pointing & range at 2AU with accuracy ~1 cm
  - Target acquisition with solar background
  - X-band will also be used
- Angle Measurement Accuracy:
  - Optical interferometer on the ISS with B = 100m
  - Laser metrology accuracy ~10 pm

SIM demonstrated laser metrology repeatability <10pm (~0.03 Hz)

Fundamental Physics with LATOR:



A 21st Century version of Michelson-Morley Experiment

Only <u>Existing Technology</u> is needed:

- Laser Nav/Comm over interplanetary distances
- Redundant optical truss for Nav and attitude control
- Precise spatial acquisition, tracking and fine beam-pointing
- Signal acquisition on a noisy background (i.e. Sun)
- Vibration isolation for extended structures at a picometer level

Relevance to the Space Exploration Initiative:

- Beacon station / Interferometer on the Moon (or ISS)
- Optical Technology Demonstration Testbed, and
- Precise Nav/Comm over interplanetary distances (~20 cm telescope):
  - Spacecraft: 10 uas on approach to Mars/Jupiter; 1 cm ranging

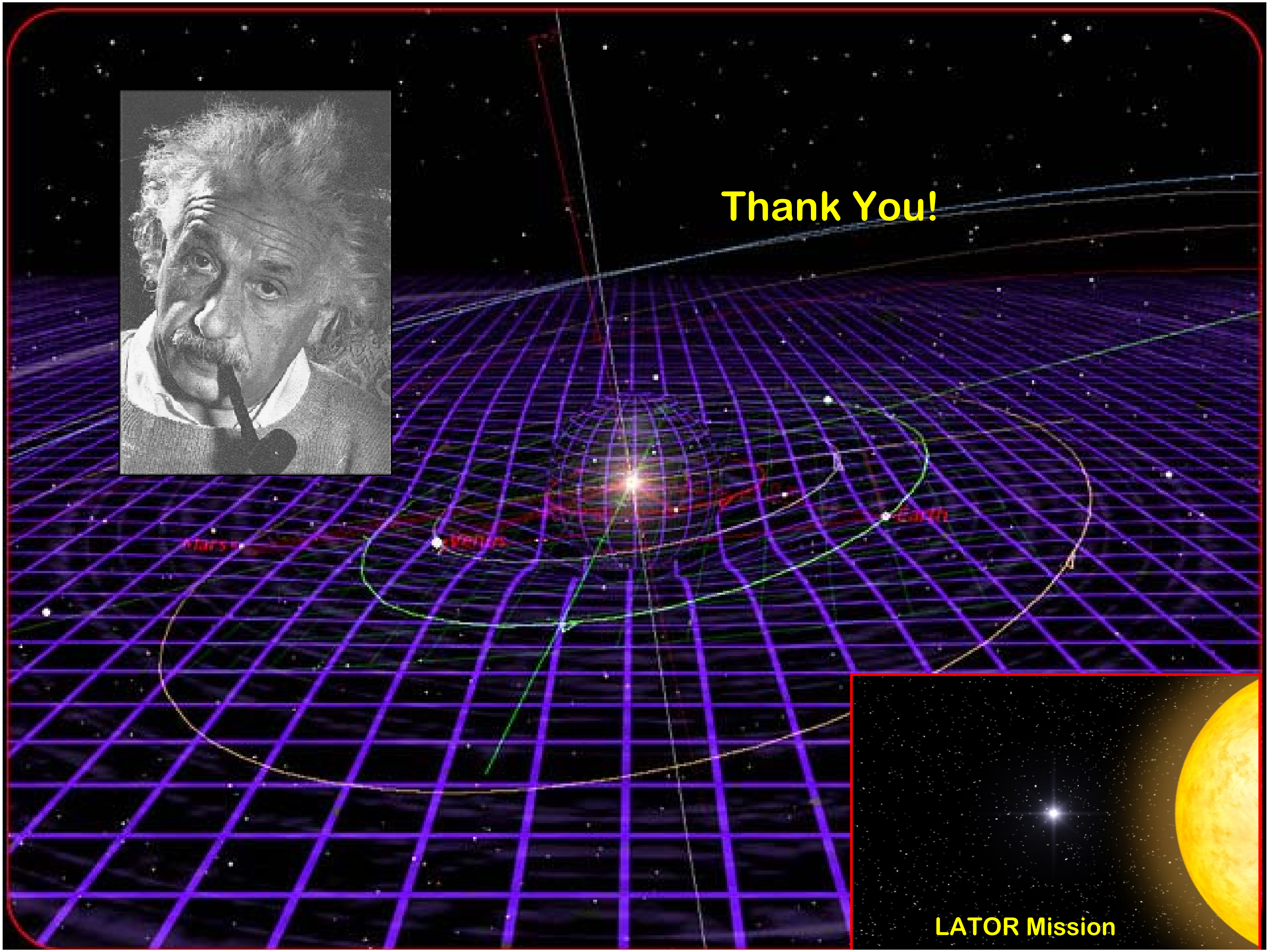
LATOR is the ultimate test of GR in the Solar System:

A factor of 3,000 improvement in the light deflection tests

- PPN parameters: γ to 1 part in 10^8; direct measure of β to 1%
- Solar physics: solar J2 (~10%); mass, atmosphere
- Will search for cosmological remnants of scalar field

The LATOR Mission is important and it should be done!

Thank You!



LATOR Mission