Space-Based Interferometers

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Michelson Summer School
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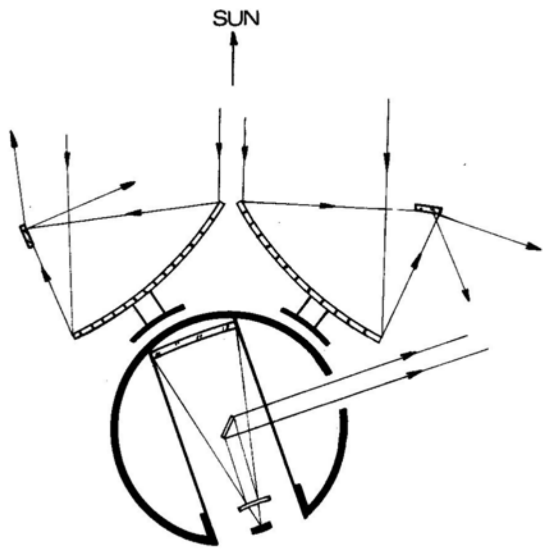
Outline

- Some History
  - Large Arrays meeting Cargese ’84
  - TRIO, COSMIC, Fiber-Linked COSMIC, SAMSI
  - OVLA (separate article)
  - Other
- SIM
  - Astrometry
  - SIM Instrument
- TPF
  - Nulling
  - TPF Instrument (several possibilities)
  - ST-3 precurser (2 s/c)
- LISA
  - Gravity Waves
  - LIGO
  - LISA Instrument

Reference for 20 yr old Ideas

- Colloquium on Kilometric Optical Arrays in Space, 23-25 October, 1984, Cargese, Corsica, France
- TRIO, Triangle, SAMSI, COSMIC, LAGOS

TRIO (Labeyrie et al)



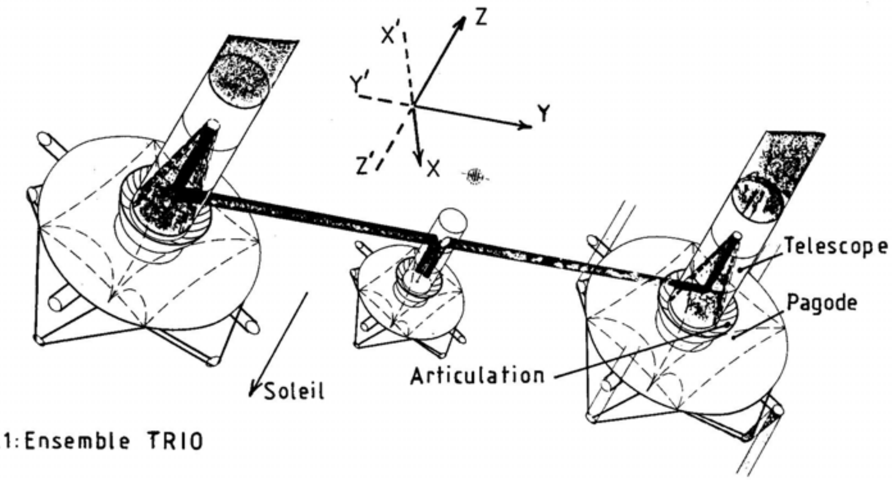


Fig 1: Ensemble TRIO

Figure 1: A- TRIO telescope with its solar sail and electrostatic mount. The sail has the shape of a pagoda roof, each side of which is an off-axis paraboloidal mirror. Their axis are maintained pointed towards the sun. Concentrated solar light in the focal regions is reflected by smaller mirrors or prisms, which may be tilted to vary the direction of the applied radiation force. Varied forces and torques can be applied to the spaceship by combining differently the action of the 4 "solar thrusters". B- Possible

Proc. Colloquium "Kilometric Optical Arrays in Space", Cargèse (Corsica), 23-25 October 1984 (ESA SP-226, April 1985)

A. Labeyrie, B. Authier, Th. De Graauw, E. Kibblewhite, G. Weigelt

TRIO Variants

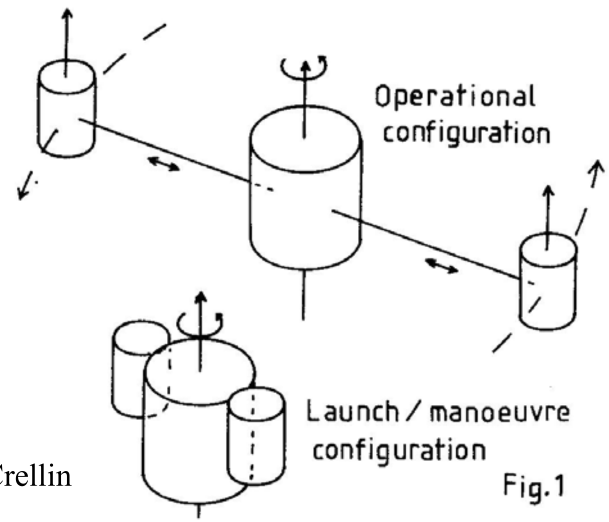


Fig.1

E. B. Crellin

The tethered concept has certain fairly obvious advantages when compared to the 'free-flying' concept. These are outlined below:

- a wide range of large baseline lengths (up to 10 km, say) can be achieved simply via deployment and retraction of the tethers;
- the baseline angle for any fixed baseline length varies through 2π due to the rotation (irrespective of the orbit chosen);
- attitude changes can be made with the tethers fully retracted and the telescopes attached to the central station (rigid configuration);
- attachment of the tethers to the telescopes can

P. Connes, C. Froehly, P. Facq

ABSTRACT.

We show that an appreciable simplification of Project TRIO may be obtained by the use of two equal-length single-mode fibers connecting the two telescopes to the central station. The price to be paid is mostly a reduction of base-length at the short wavelength end of the spectrum. The number of parameters to be accurately controled is much reduced : one merely has to guide telescopes and null path-difference. All motions of the central station become irrelevant. Star acquisition is performed in a docked configuration of all three elements. The necessary cables may also be used to feed power to the two telescopes ; hence these require neither power generating nor propulsion devices. Possible base line scanning methods either in high orbits (e.g. at the Lagrange points) or in low orbits are dis-

TRIANGLE version of TRIO (F. Vakili)

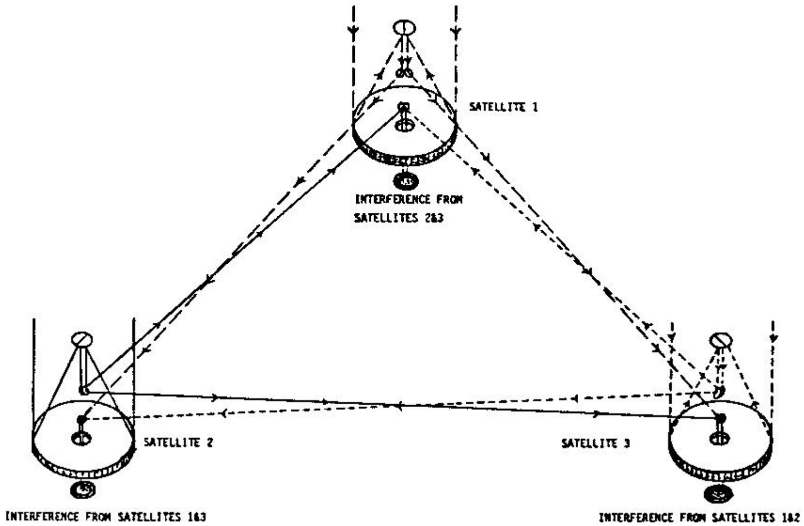


Figure 1. General view of TRIANGLE. Every satellite is the central station of the two others. Its telescope participates by half to the interferometric signal at each one of the two central stations. There are three different systems of fringes.

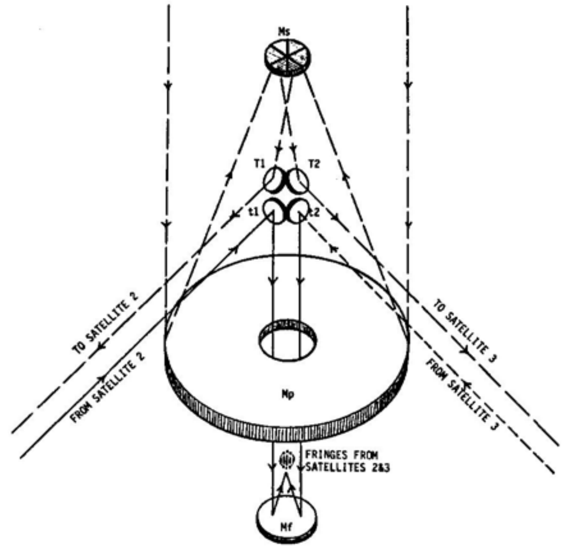


Figure 2. Configuration of a satellite for TRIANGLE. The light collected by the primary mirror Mp is split by a bi-mirror secondary Ms in two collimated beams and transmitted by two flat tertiaries, T1 and T2, in the direction of the two other satellites. The collimated beams from these satellites are reflected by two flat mirrors, t1 and t2, to a field mirror Mf which reimages the exit pupils for correct spacing of fringes.

COSMIC

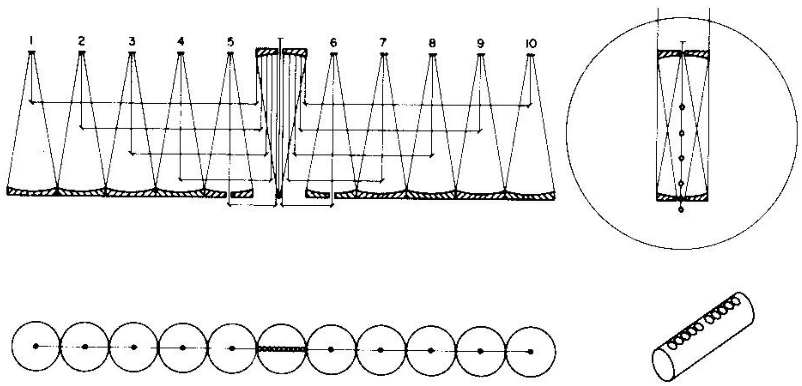


Figure 1. Schematic diagram showing light path within a single module of the COSMIC telescope array. Individual light-collecting telescopes numbered 1 to 10 each feed a central combining telescope via light paths which are of equal length. Side, end and top views are shown along with a reduced scale external view. To combine two or more modules end-to-end, the light paths would be arranged in a different fashion, so that no delicate manual adjustments would be needed during orbital assembly.

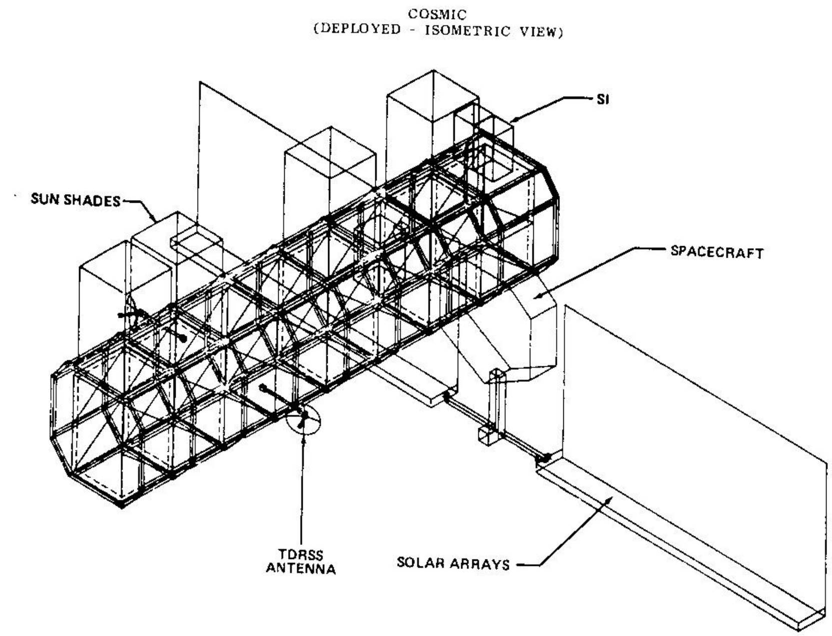
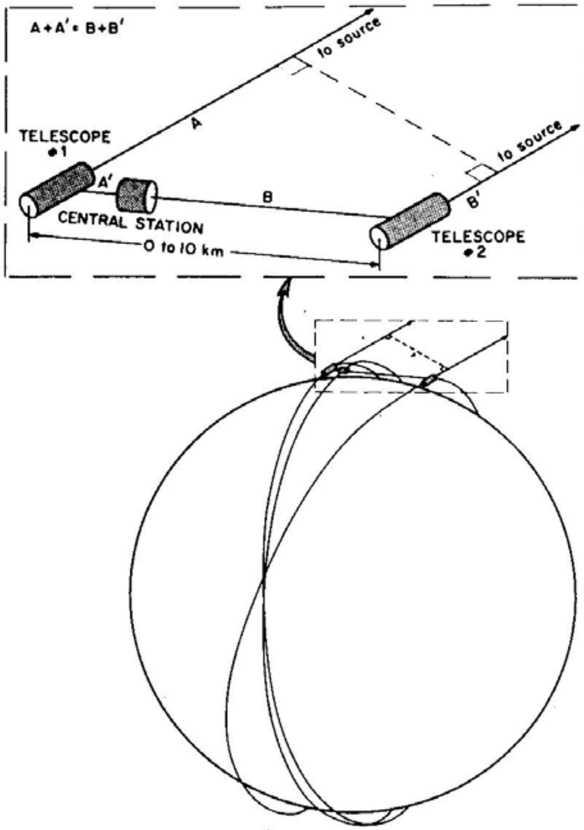


Figure 2. Fiber-composite optical support structure for a linear COSMIC, as developed at NASA-MSFC. The material and design are direct outgrowths of the Space Telescope program.

galactic pole. Of course, if the object to be

Spacecraft Array for Michelson Spatial Interfeormetry (SAMSI)



R. Stachnik and D. Gezari

Figure 1. Basic concept of the SAMSI multiple spacecraft stellar interferometer. For two telescopes in orbits which differ slightly in inclination but are otherwise identical, a third orbit exists which keeps the central station very close to the equi-optical-path position at all times.

LAGOS (early LISA)

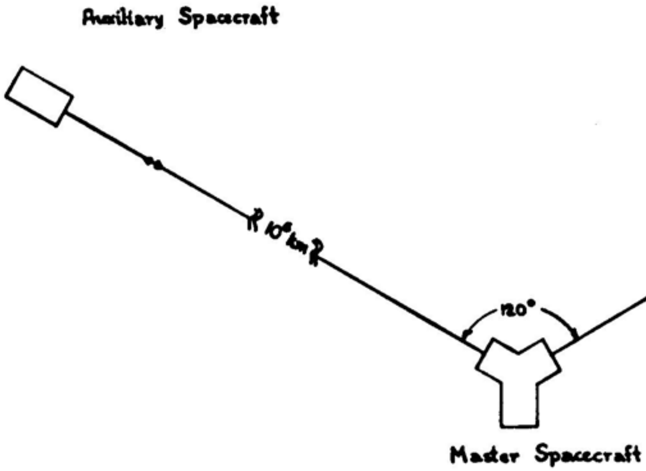


Figure 4. Gravitational-radiation space experiment.

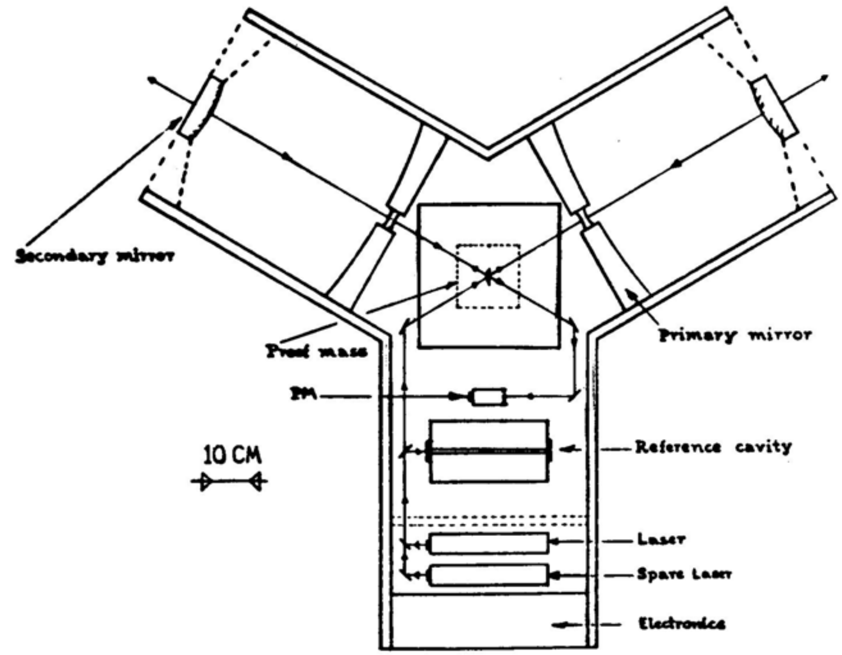


Figure 6. Central spacecraft instrument package.

J. Faller, P. Bender, J. Hall, D. Hils, M. Vincent

Lunar Optical Very Large Array (Labeyrie)

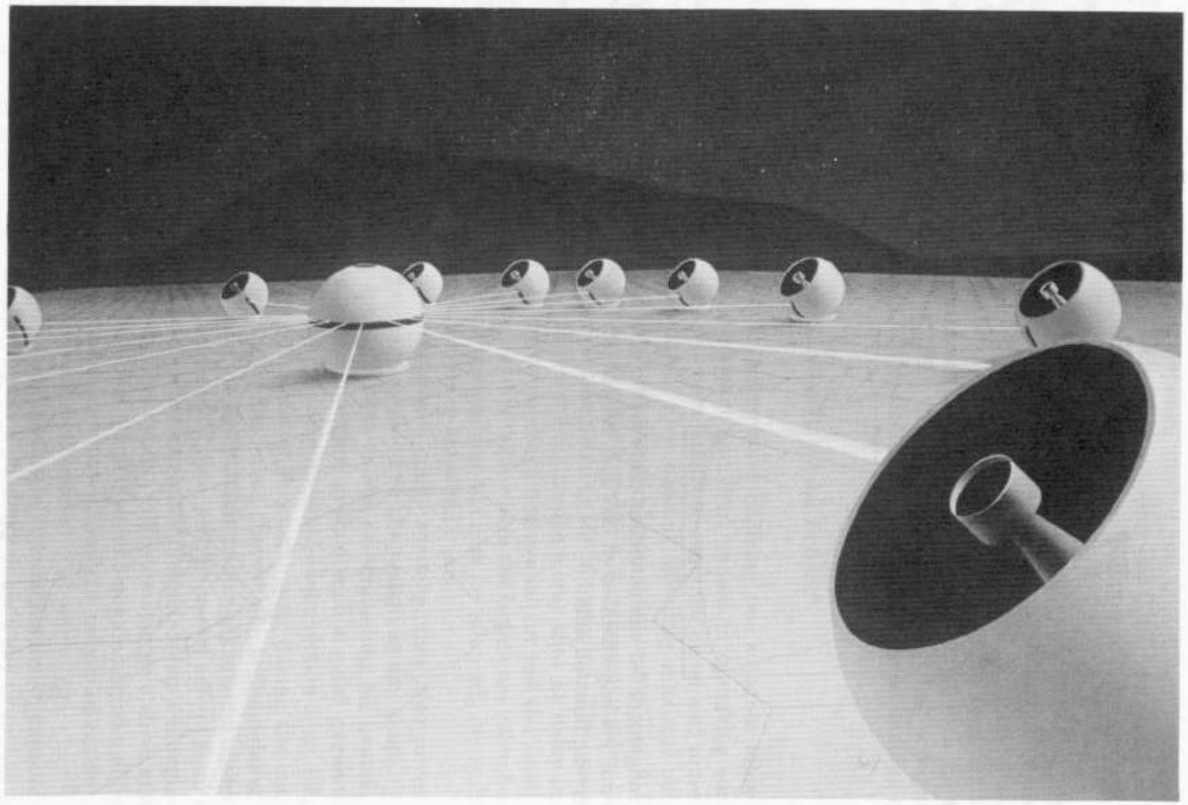


Figure 3: The Optical Very Large Array consists of many compact telescopes movable on a platform. The beams are recombined in a central station, using one of several interchangeable optical tables with different beam recombination systems. The telescopes move during the observation, so that delay lines be unnecessary. A sensitive system of laser beams keeps track of the telescope positions in three dimensions.

JPL Study: MUSIC

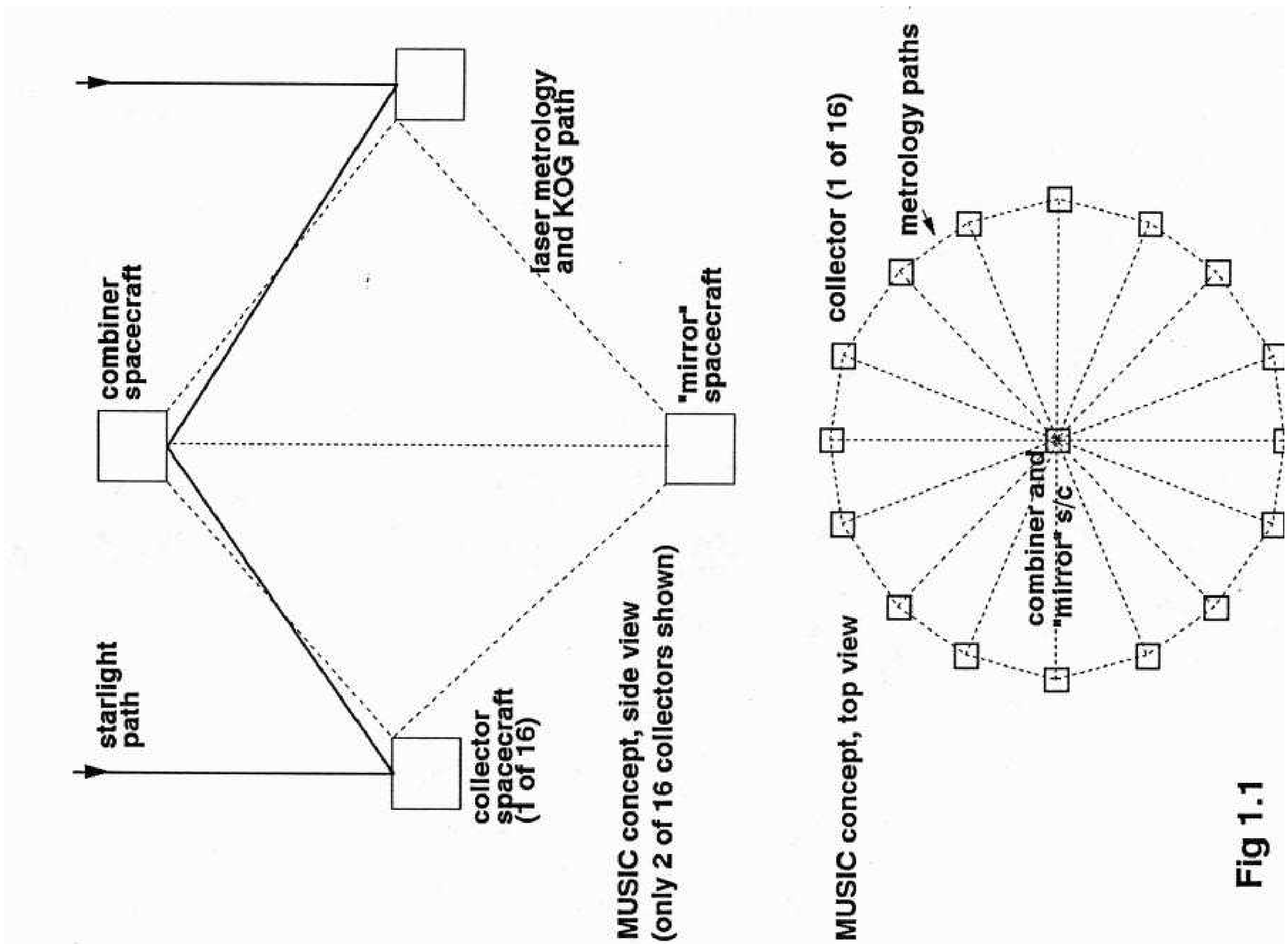
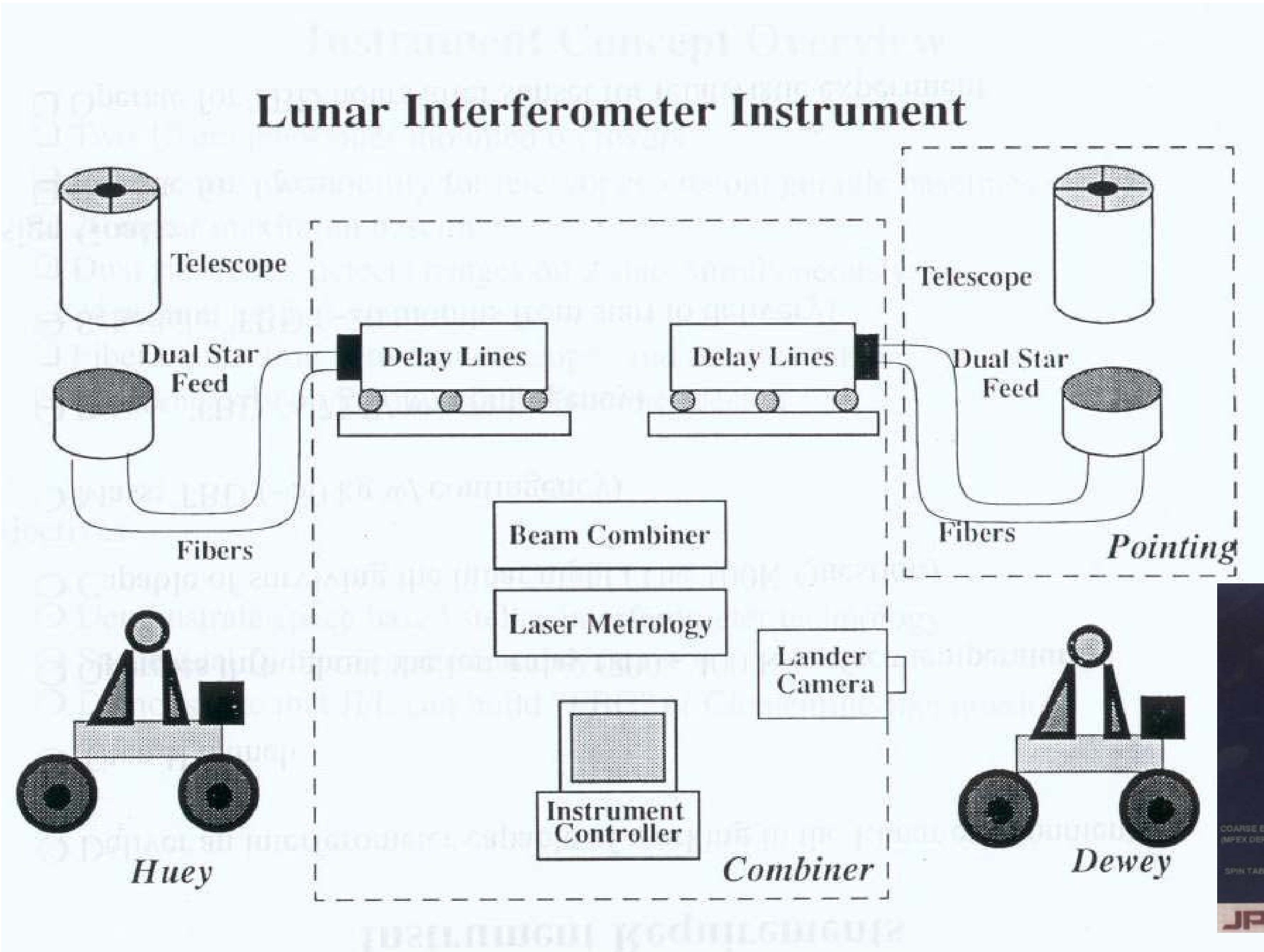
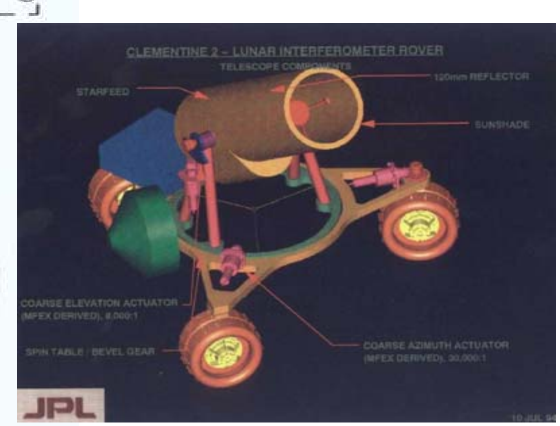


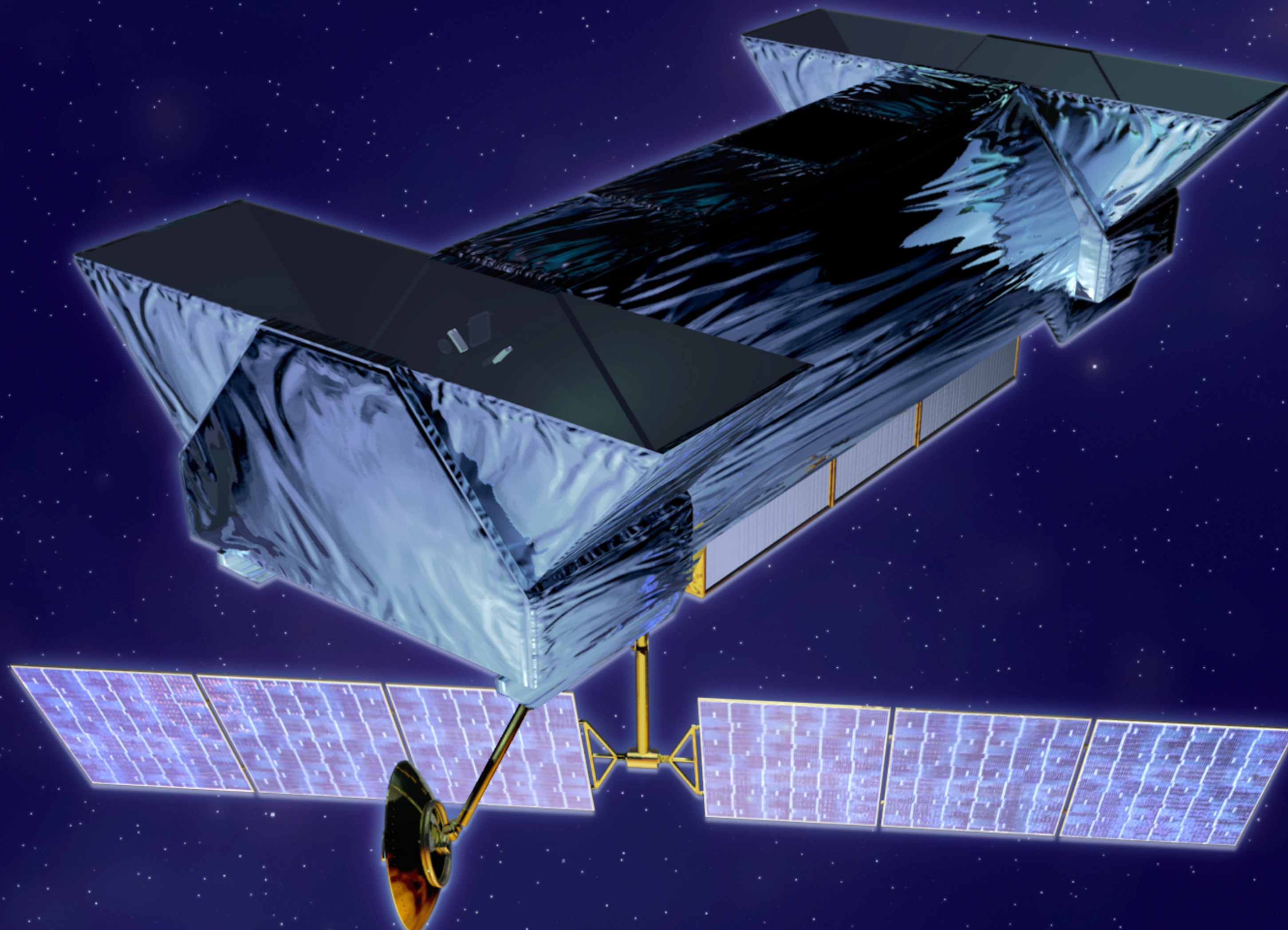
Fig 1.1

JPL Study: Clementine II Interferometer



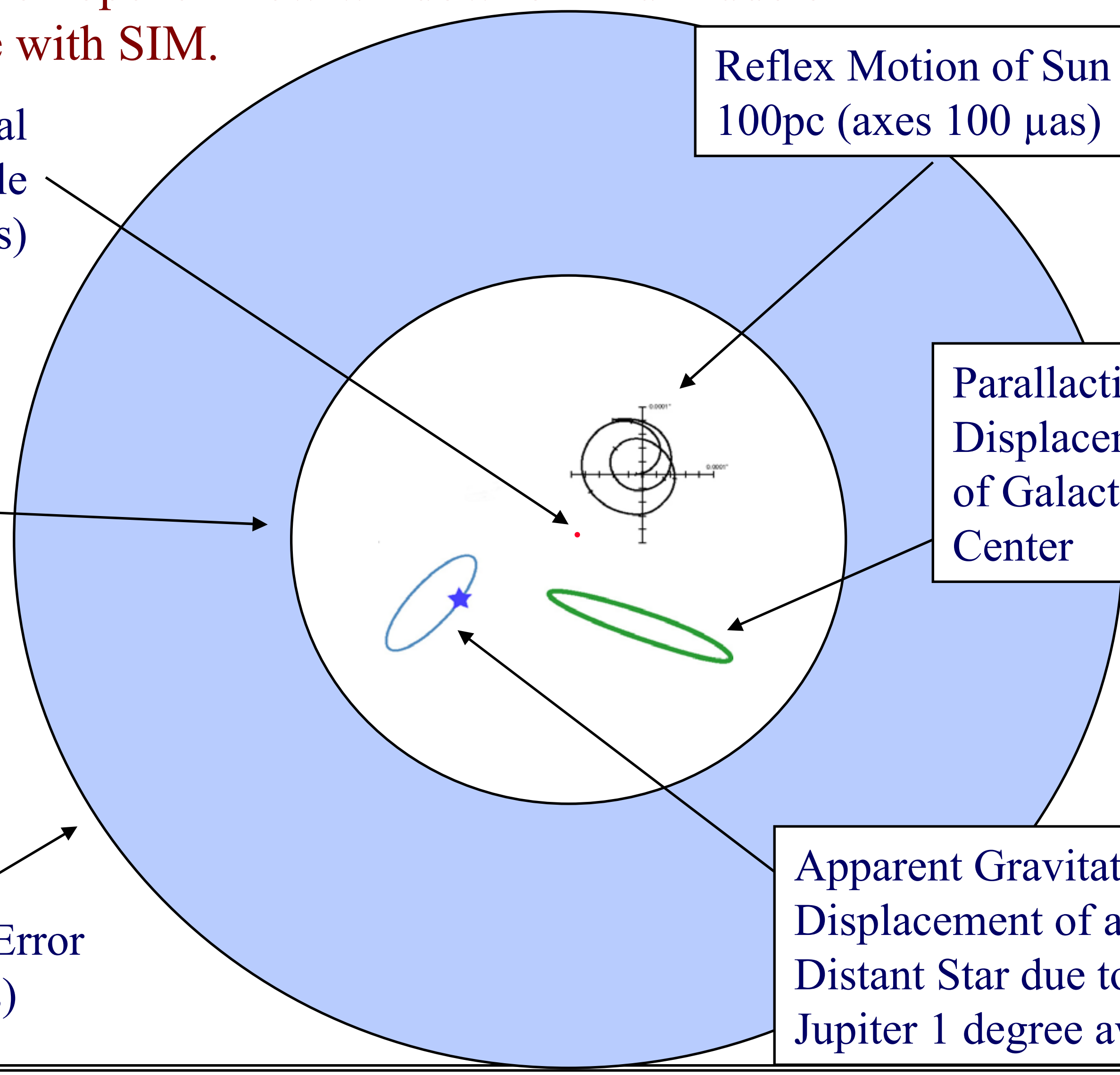


Space Interferometry Mission (SIM)



Science Objective - Astrometric Precision

Microarcsecond precision opens a new window to a multitude of phenomena observable with SIM.



SIM Positional Error Circle (4μas)

Reflex Motion of Sun from 100pc (axes 100 μas)

Hipparcos Positional Error Circle (0.64 mas)

Parallactic Displacement of Galactic Center

HST Positional Error Circle (~1.5 mas)

Apparent Gravitational Displacement of a Distant Star due to Jupiter 1 degree away

Science Objectives

- Perform a search for other planetary systems by surveying 2000 nearby stars for astrometric signatures of planetary companions

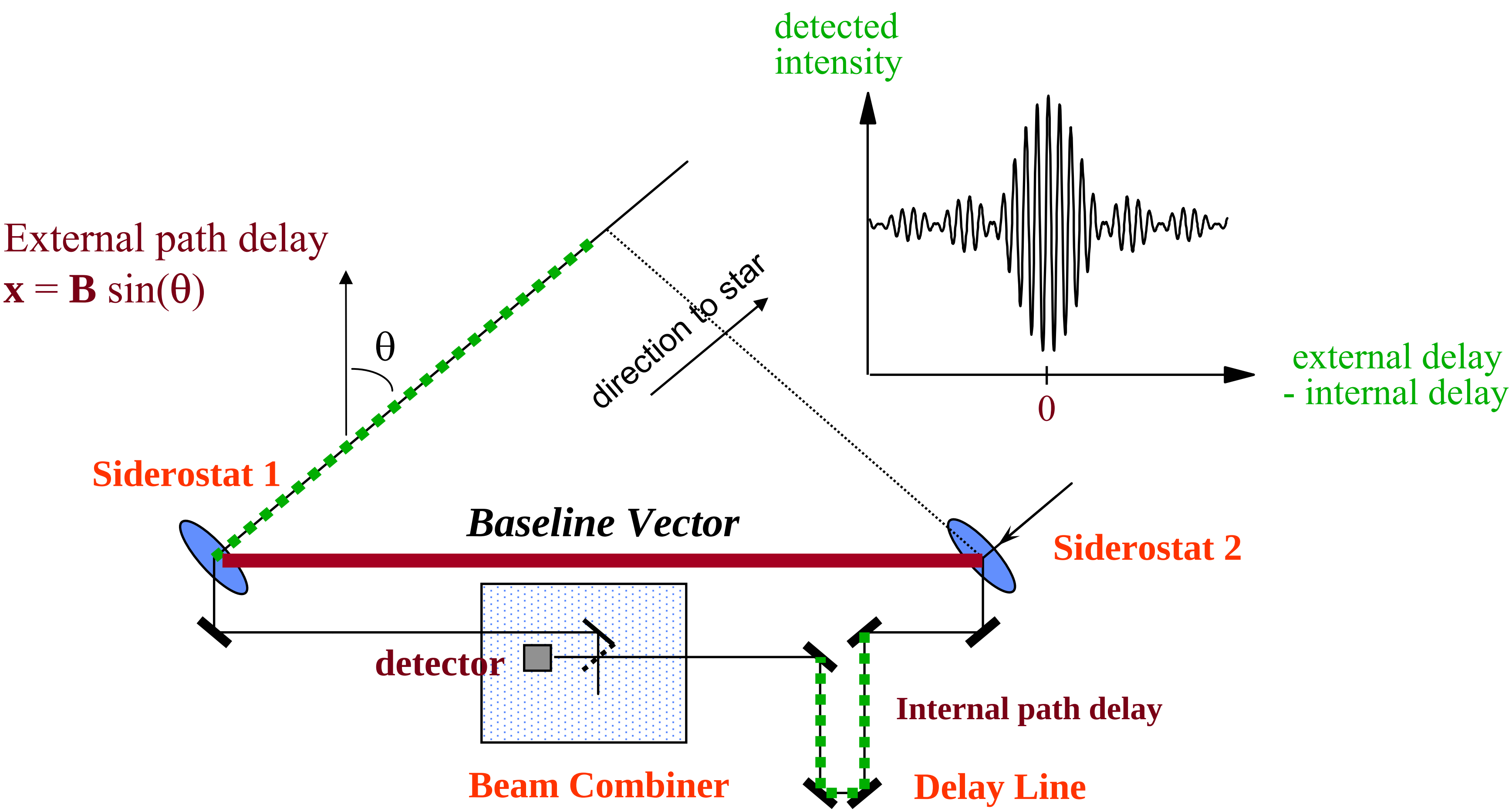
– Survey 200 nearby stars for orbiting planets down to terrestrial-type masses

- Improve best current catalog of star positions by >100x and extend to fainter stars to allow extension of stellar knowledge to include our entire galaxy

- Study dynamics and evolution of stars and star clusters in our galaxy to understand how our galaxy was formed and how it will evolve.

- Calibrate luminosities of important stars and cosmological distance indicators to improve our understanding of stellar processes and to measure precise distance in the distant universe

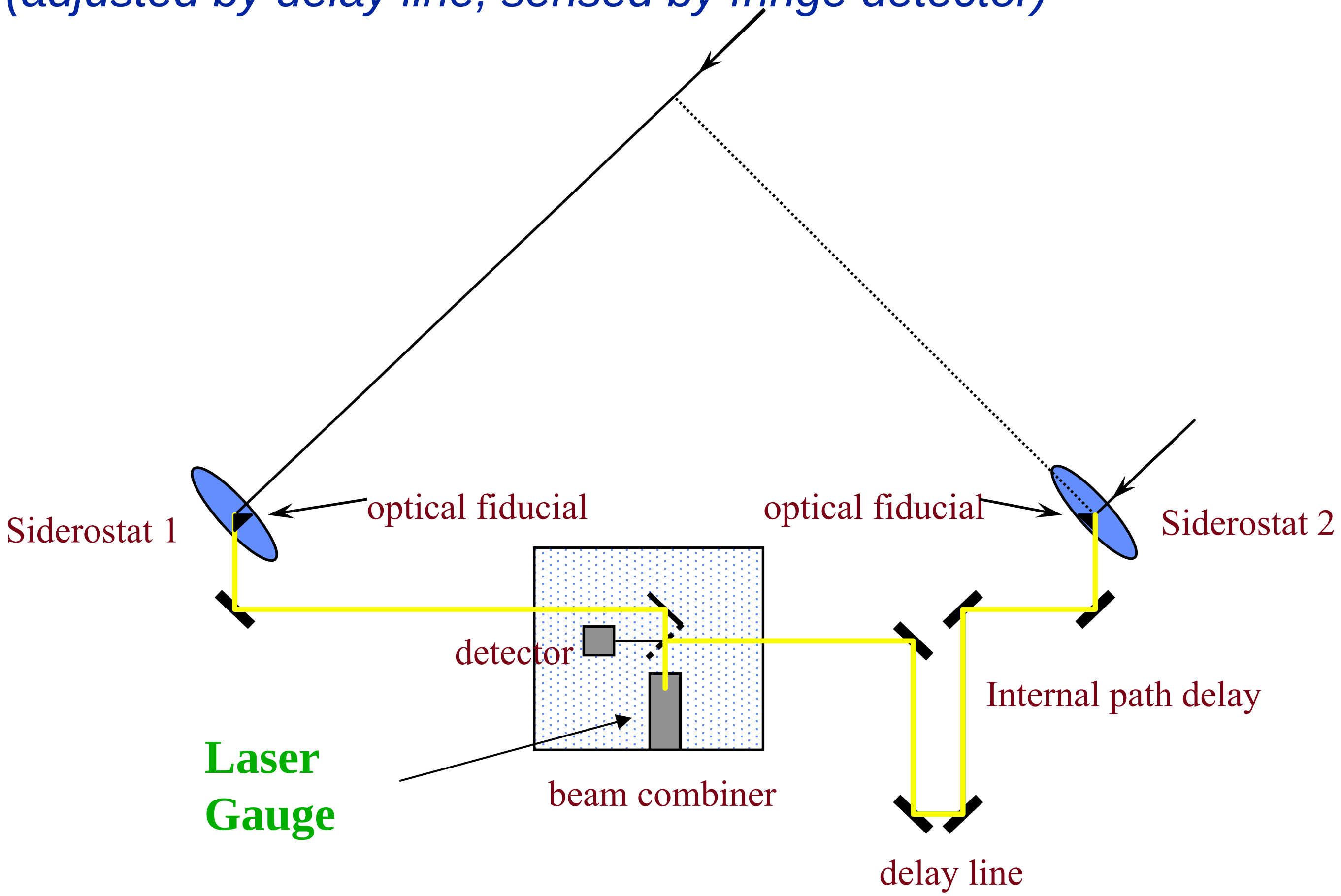
Measuring fringe positions with an Interferometer



The peak of the interference pattern occurs when the internal path delay equals the external path delay

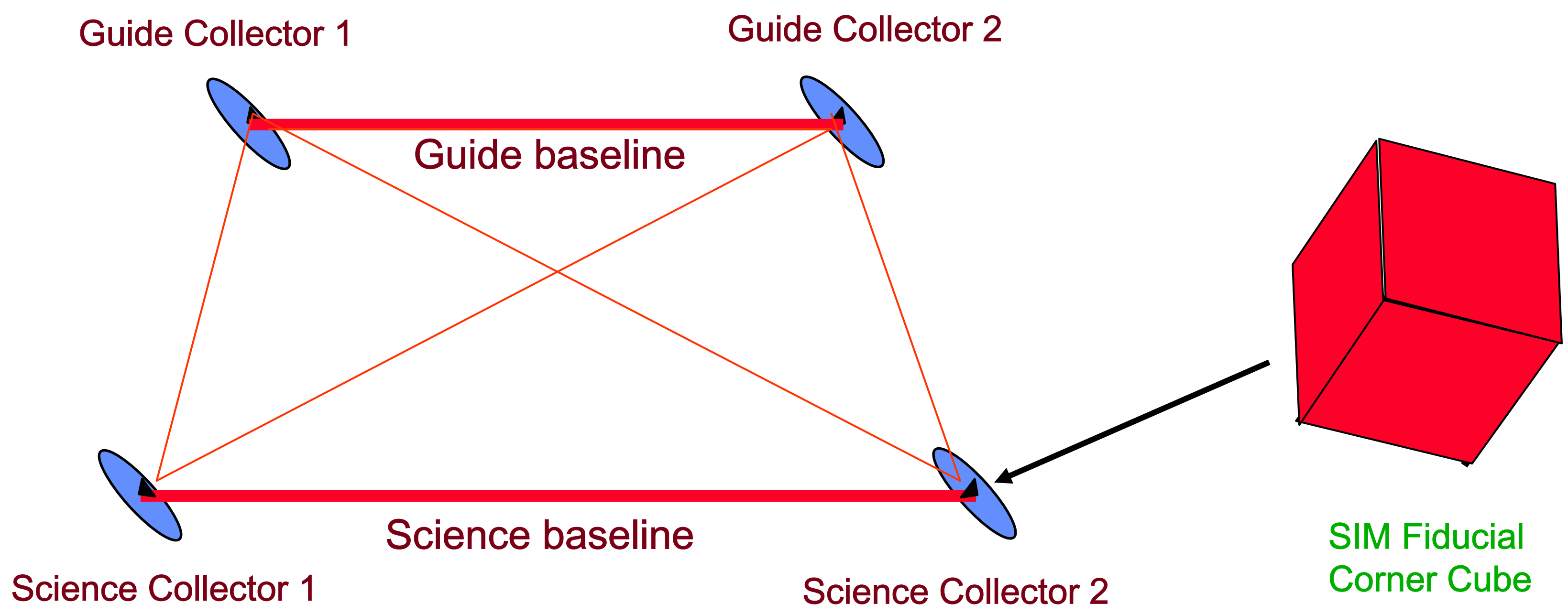
Internal Metrology

Laser metrology gauge measures internal delay (adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

External Metrology



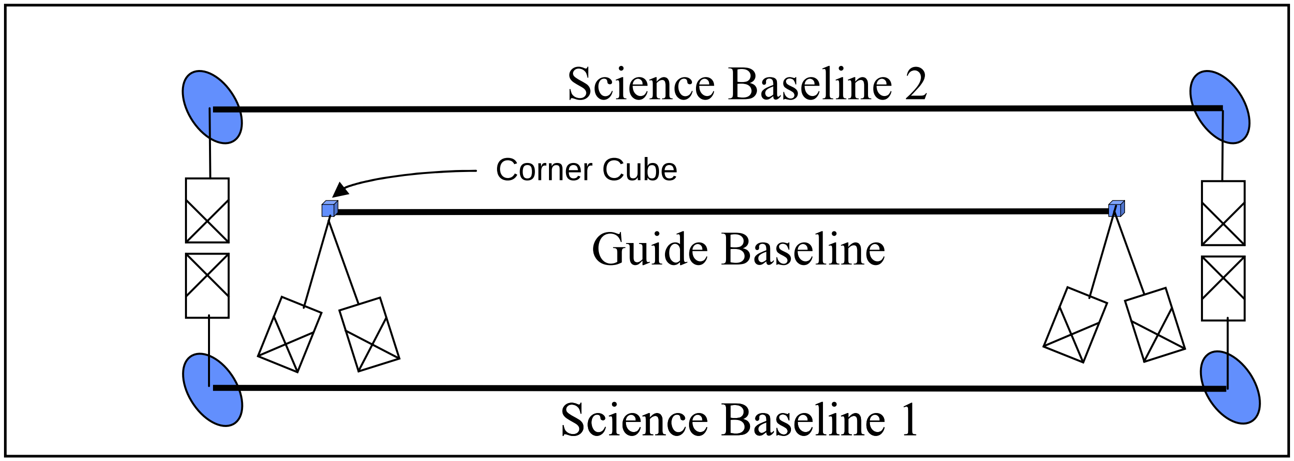
External metrology is used to measure

- *the science interferometer baseline with respect to the guide interferometer*
- *measure the science interferometer baseline length*

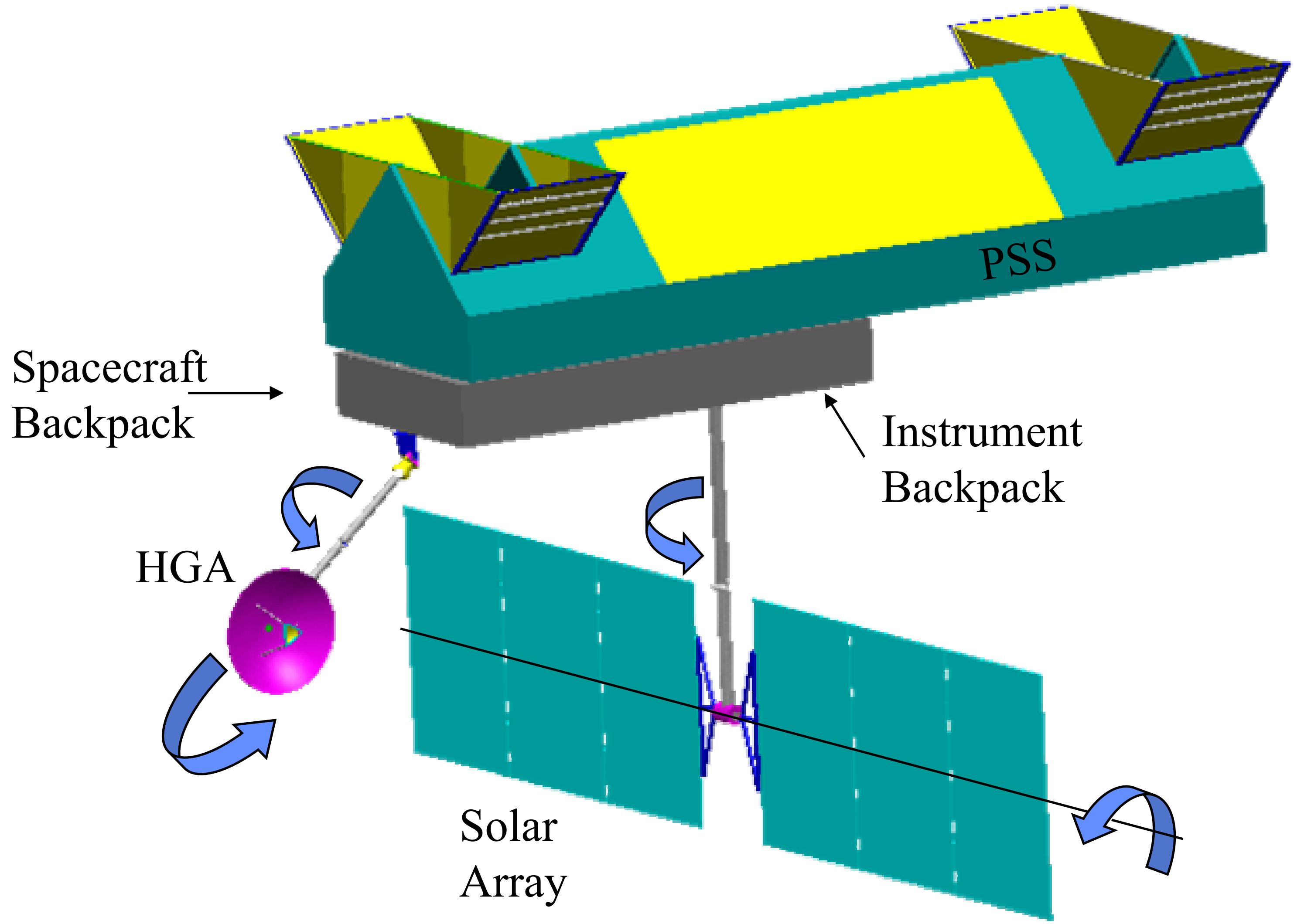
SIM ‘Shared Baseline’ Reference Design

- Continuing development of our Reference Design is a “work-in-progress”
- We are addressing the residual issues and looking for ways to reduce risk as we are moving out in our detailed design
- The design has two OPERATIONAL interferometer baselines
  - Two redundant science baselines
  - A shared guide baseline

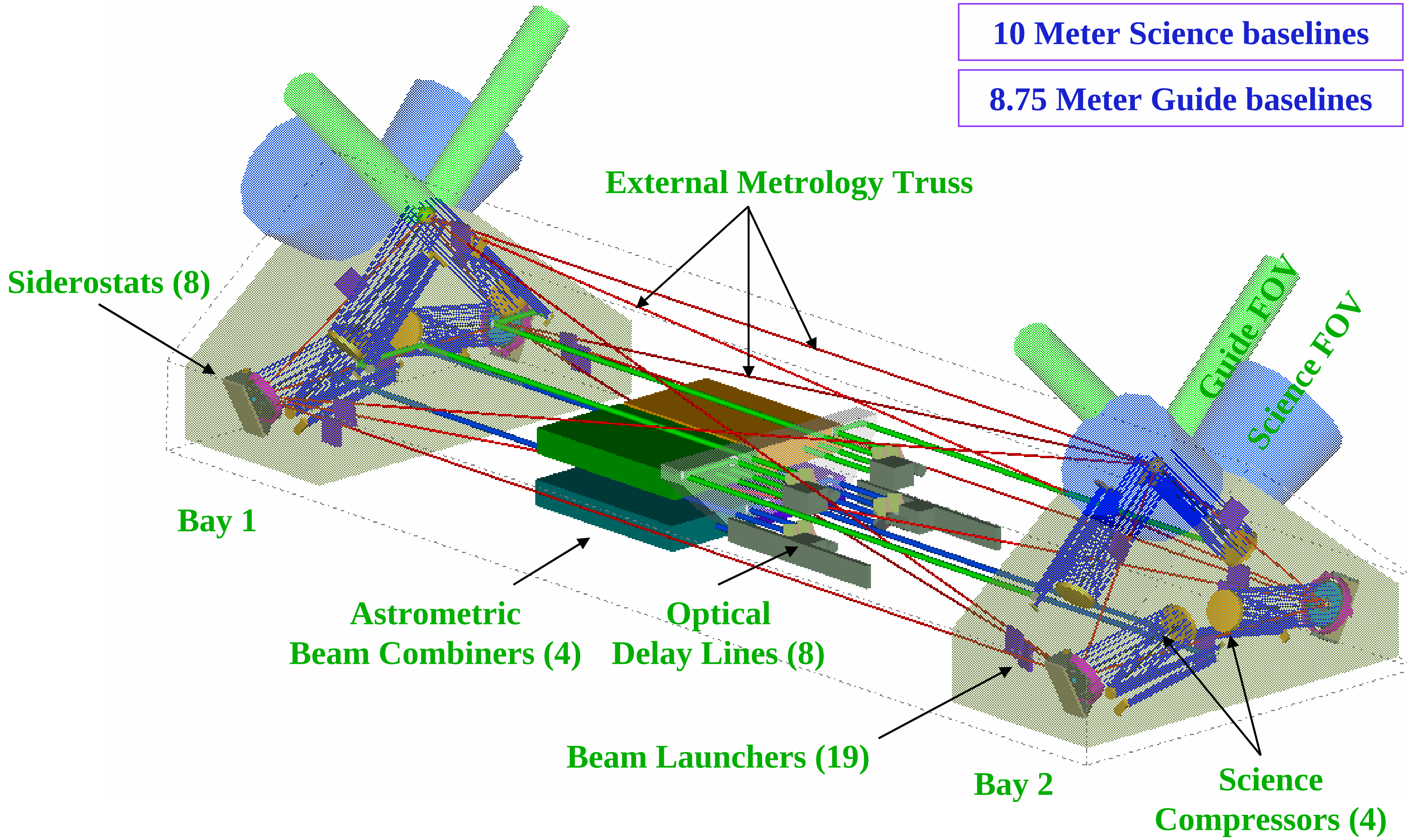
Current version (L15x) - Shared Baseline



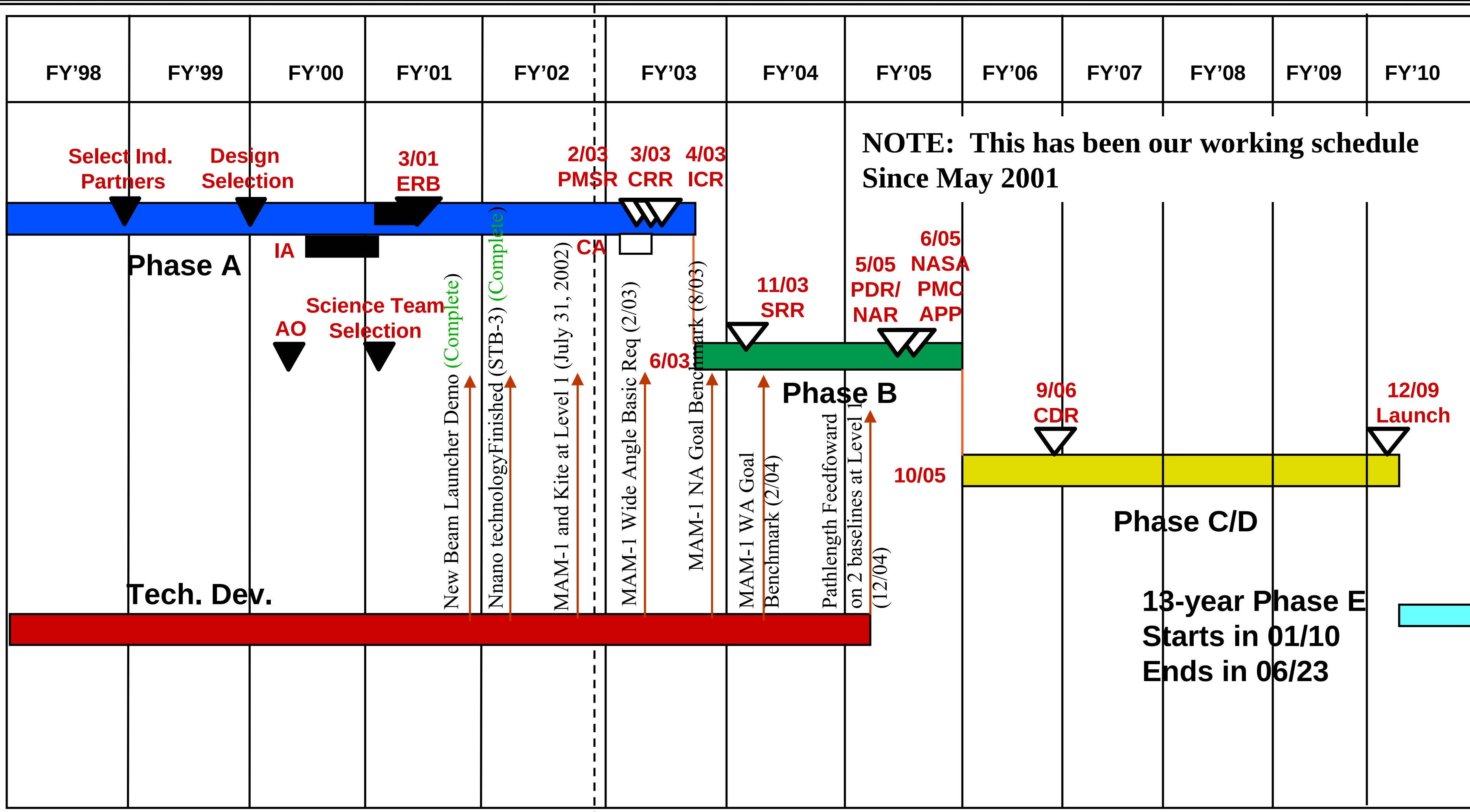
Flight System



Shared Baseline Interferometer Configuration



POP02 Option 1 Project Schedule
LRD 12/09



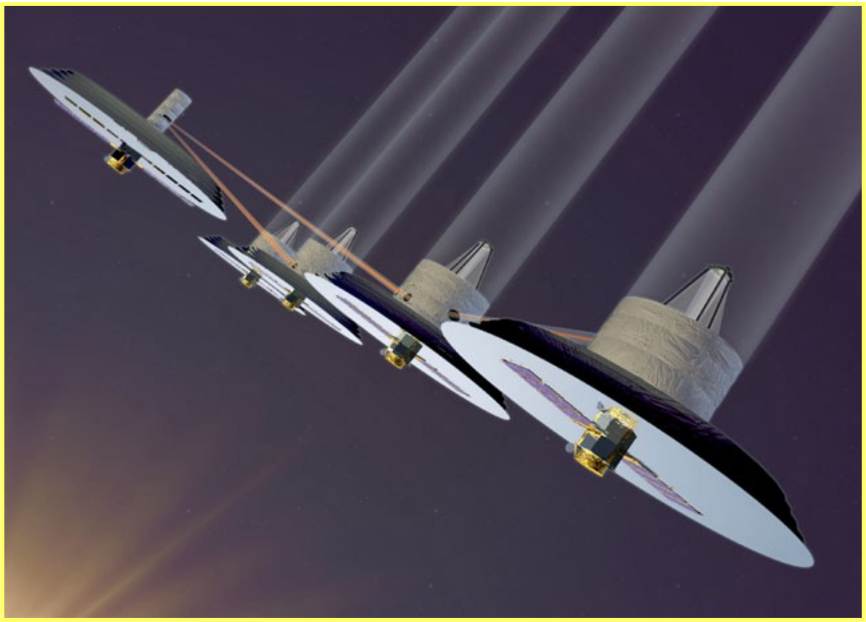
ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)

ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test

PMSR = Preliminary Mission & Systems Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)

SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Terrestrial Planet Finder

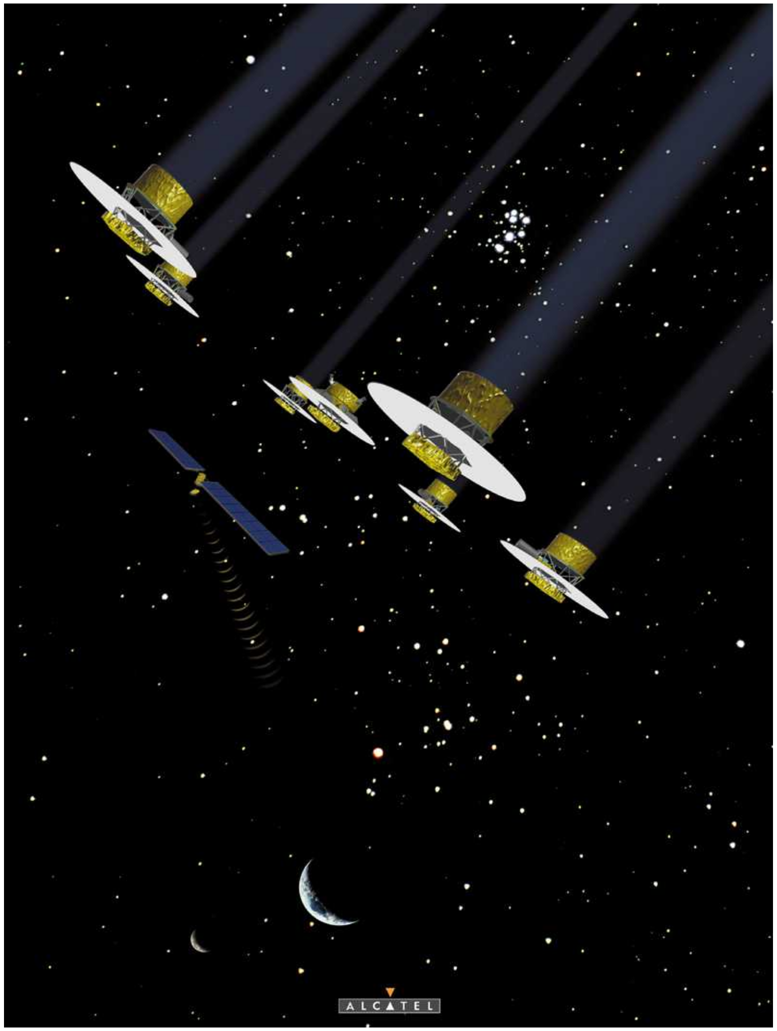


Formation Flying design shown here is one of three architectures currently being studied (also structurally connected mid-IR interferometer & visible coronagraph)

- Objectives:
  - Direct detection of earth-like planets
  - Imaging astrophysics
- Features:
  - Mid-IR nuller
  - Separations of ~ few meters to 1 km
  - 3.5 m primaries
  - L2 or Earth-trailing orbit

http://planetquest/TPF/tpf_index.html

DARWIN



- Objectives:
  - Direct detection of earth-like planets
  - Imaging astrophysics
- Features:
  - Mid-IR nuller
  - 6 x 1.5 m collectors
  - L2 orbit
- Similar goals to TPF

http://sci.esa.int/home/darwin/index.cfm

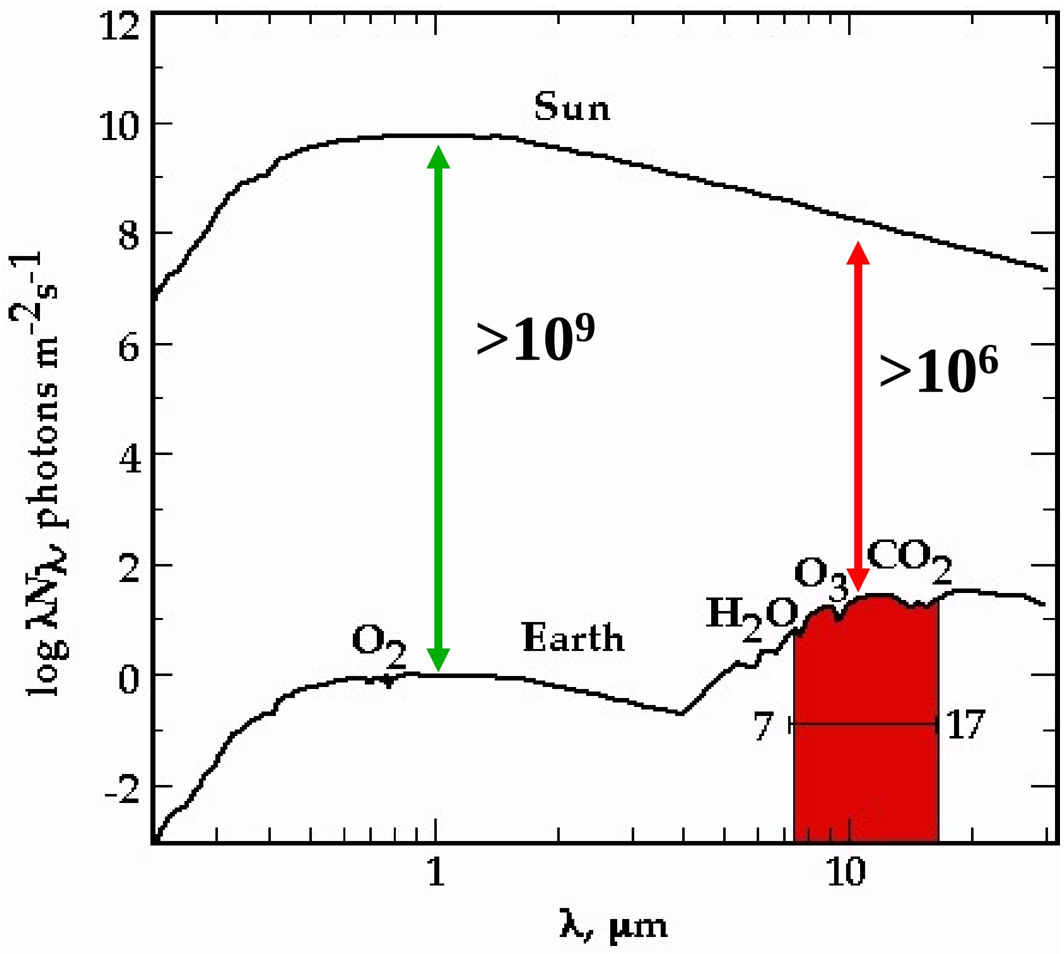
Goals for Terrestrial Planet Finder

- *Primary Goal*: Direct detection of *emitted* or *reflected* radiation from Earth-like planets located in the habitable zones of nearby solar type stars.
  - Determine orbital and physical properties
  - Characterize atmospheres and search for bio-markers
  - Search a statistically meaningful sample of stars (~150)
- *The Broader Scientific Context*: Comparative Planetology
  - Understand properties of all planetary system constituents, e.g. gas giant planets, terrestrial planets and debris disks.
- *Astrophysics:* An observatory with the power to detect an Earth orbiting a nearby star will be able to collect important new data on many targets of general astrophysical interest.

- This and subsequent TPF charts thanks to Chris Lindensmith of JPL!!

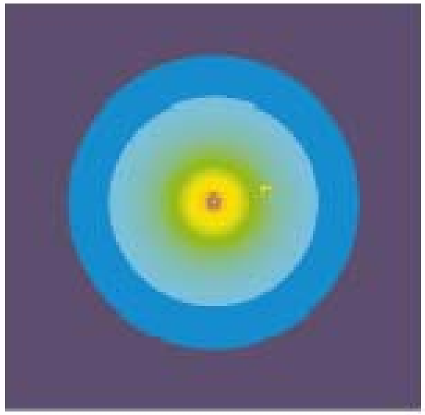
Terrestrial Planet Finder (TPF)

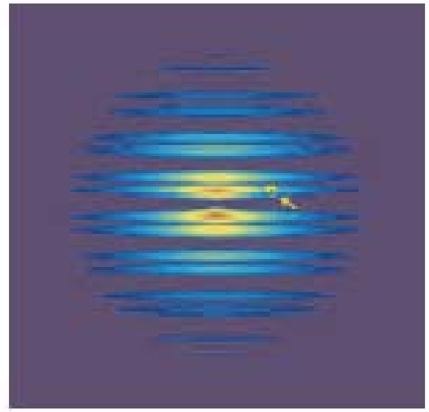
- Detecting light from planets beyond solar system is hard:
  - Planet signal is weak but detectable (few photons/sec/m^2)
  - Star emits million to billion more than planet
  - Planet within 1 AU of star
  - Dust in target solar system >300 brighter than planet
- Finding a firefly next to a searchlight on a foggy night



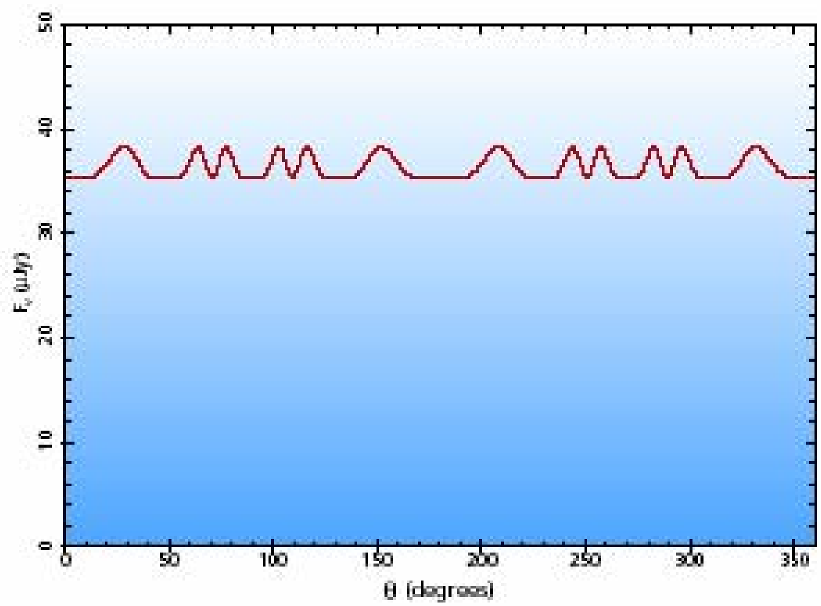
The TPF Synthesized Image

Signal: Star + Dust + Planet



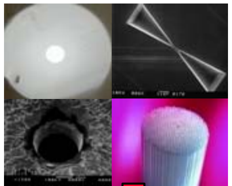


Interferometer fringes projected on the signal



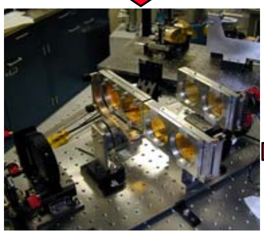
Response to a planet as the linear array is rotated through 360 degrees.

Interferometer Technology

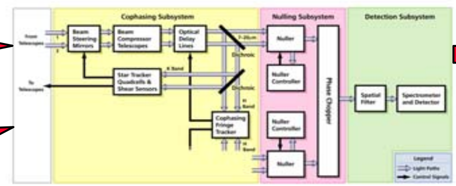


Mid-Infrared Spatial Filter Technology

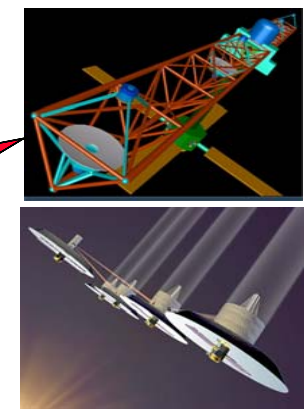
Achromatic Nulling Testbed



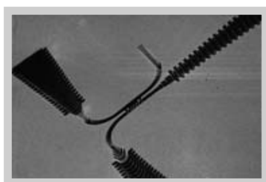
Phasing System Testbed



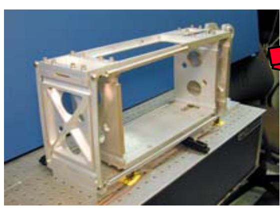
Interferometer Point Designs

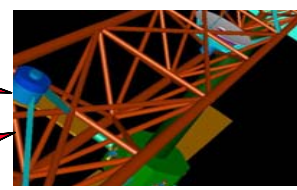


Advanced Nulling Technology

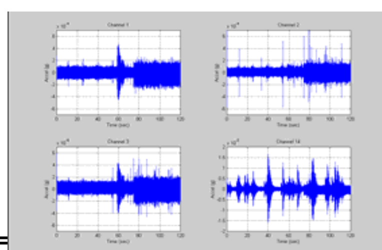


Cryogenic Delay Line



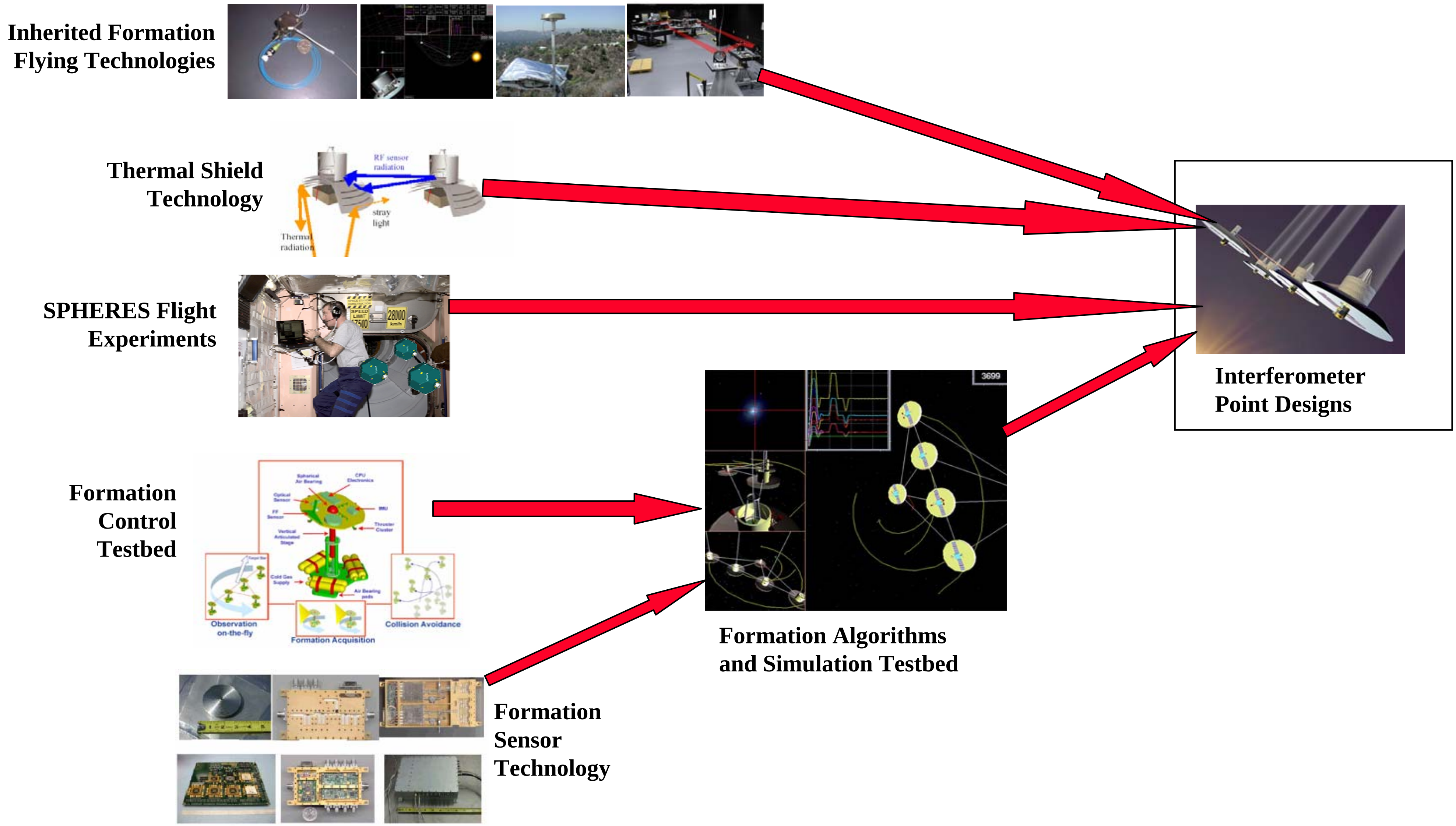


Structurally Connected Interferometer Testbed

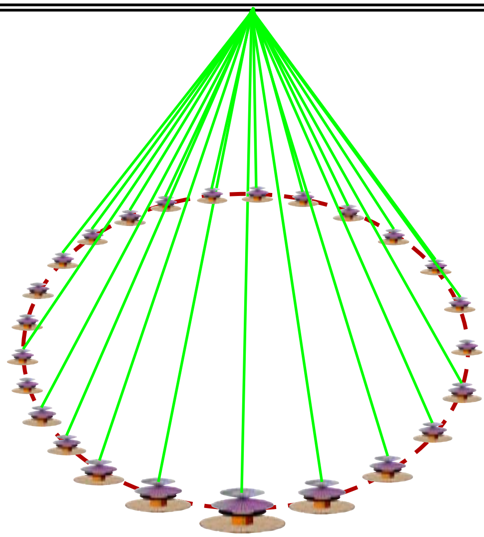


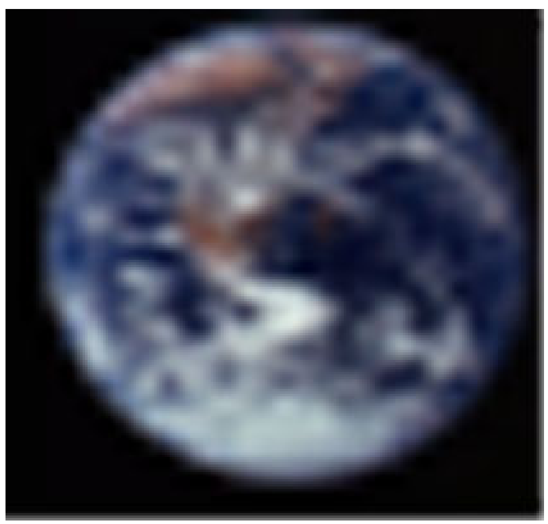
Cryogenic Structures and Modeling Technology

Formation Flying Technology

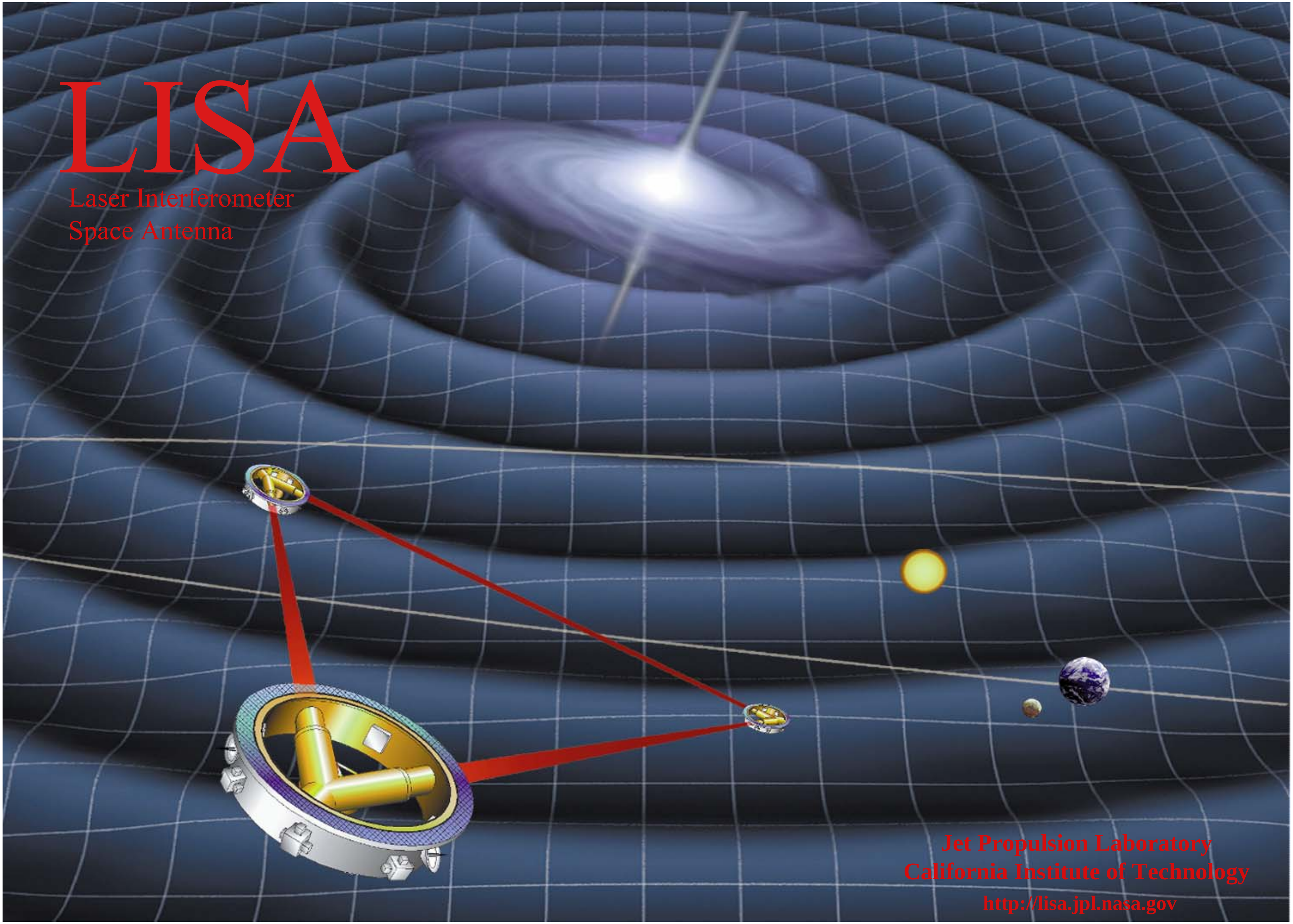


Life Finder, Planet Imager





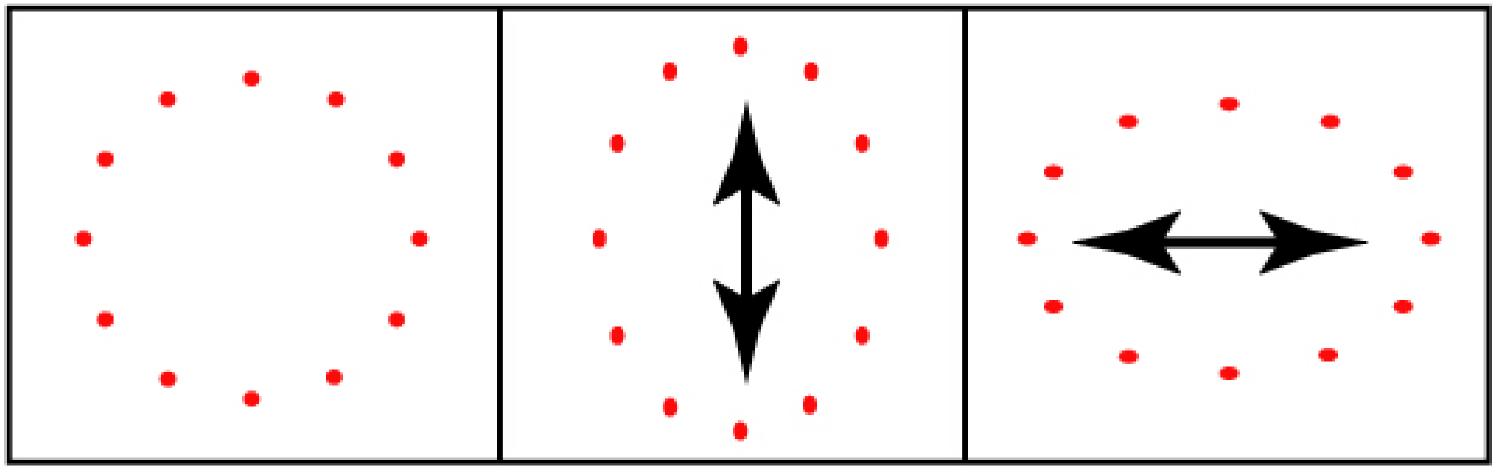
- Life Finder
  - Spectral features in planet atmospheres strongly indicative of life
  - 4 x 25 m apertures
  - 100 m baselines
- Planet Imager
  - 25 x 25 pixels over earth-like planet @ 10 pc
  - 25 x 40 m apertures
  - 400 km baselines


LISA
Laser Interferometer
Space Antenna
Jet Propulsion Laboratory
California Institute of Technology
http://lisa.jpl.nasa.gov

Gravitational Waves

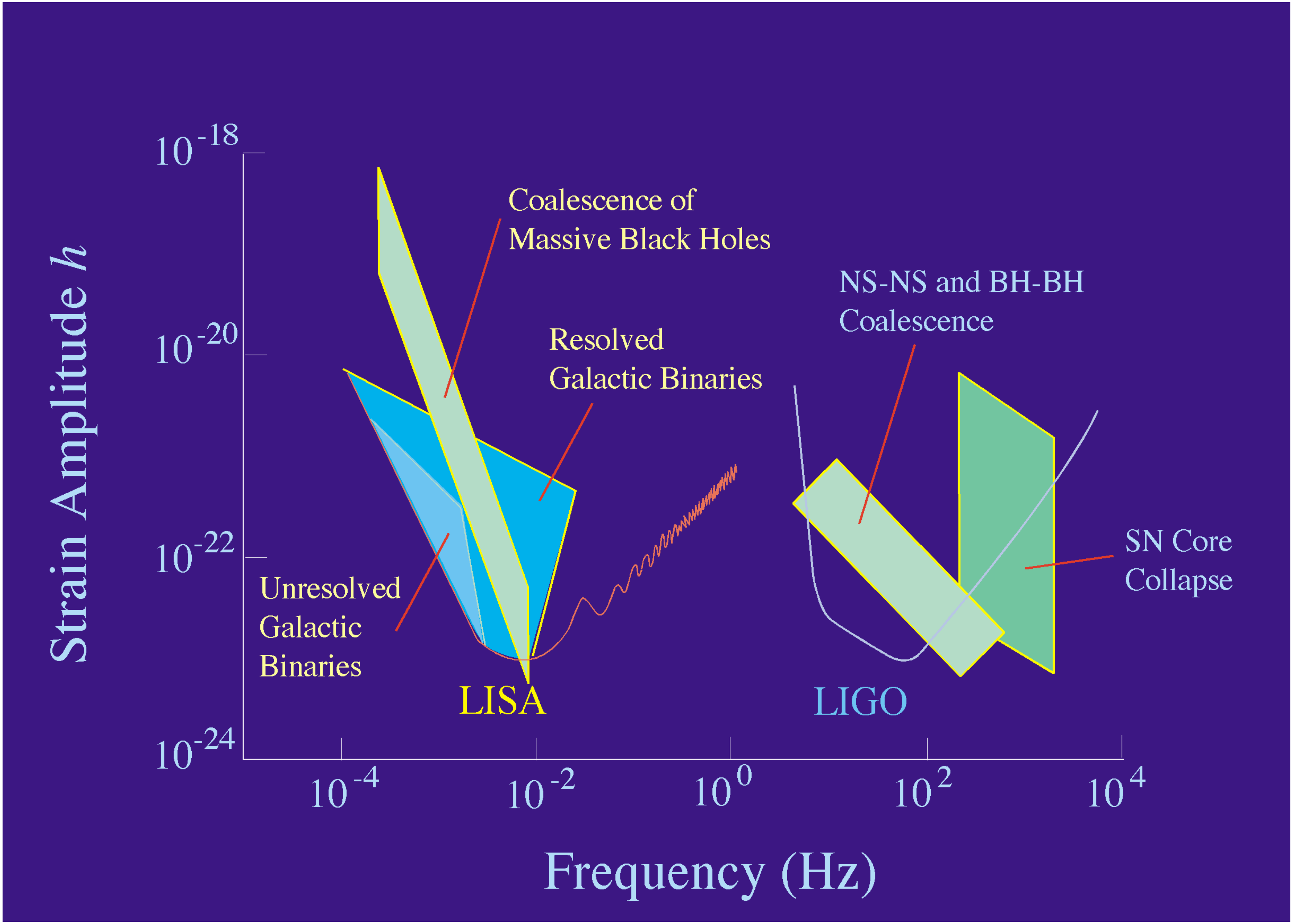
- Prediction of Einstein's General Theory of Relativity.
- GWs propagate through space-time at the speed of light
- Caused by catastrophic astronomical events
  - Super novae
  - Coalescing binary systems (neutron stars, massive black holes, etc)
  - Stochastic background (remnants of big-bang)
- **GWs have not yet been directly observed.**

The Effect of a GW on a Ring of Particles



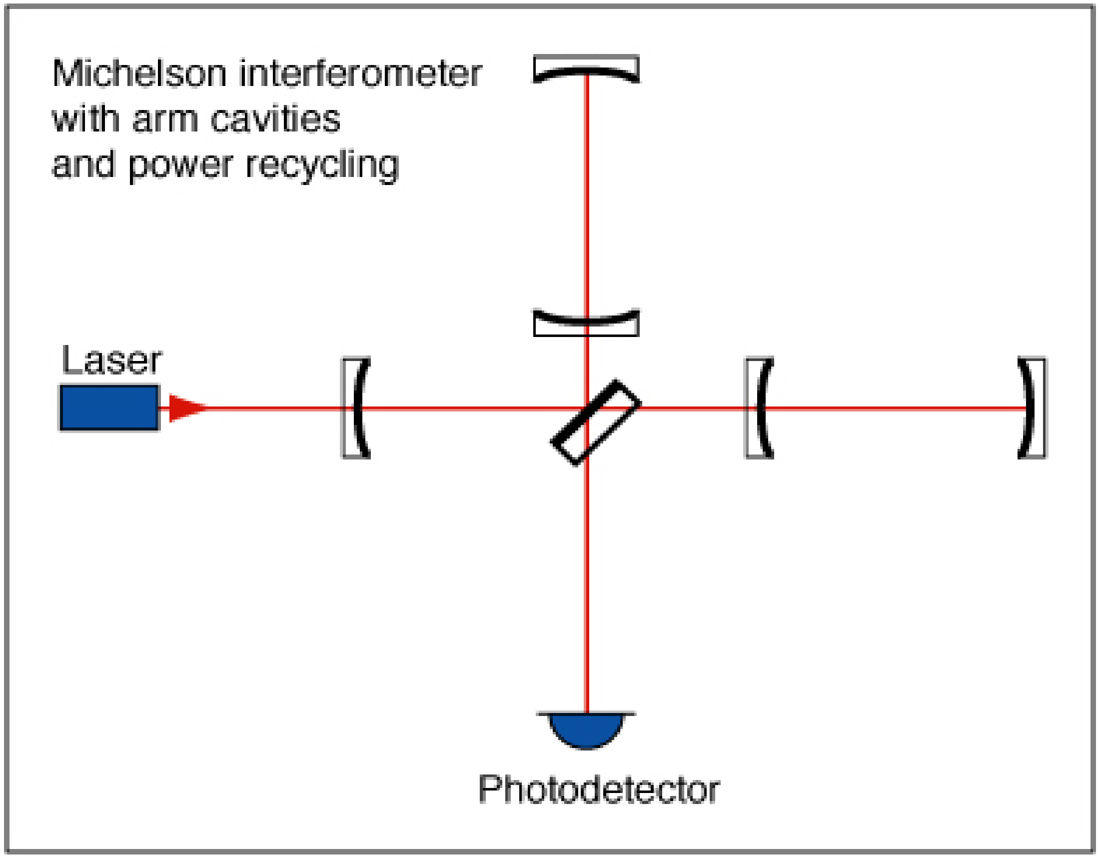
Space time is very, very stiff -> GWs contain enormous amounts of energy with very little observable results.

Fractional length change of space is termed "strain" and is expected to be of the order 10^{-21} to 10^{-23}.

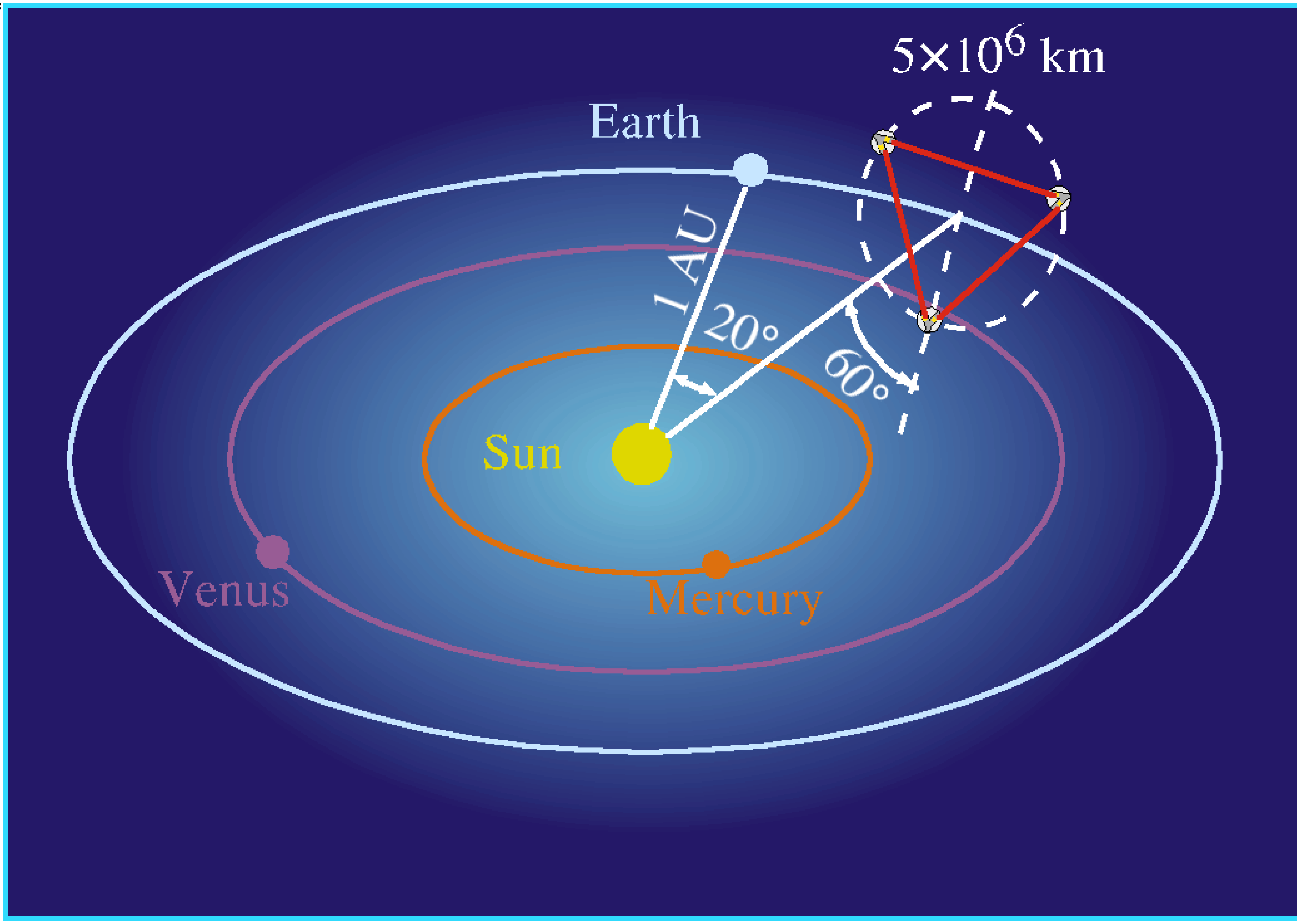


Strain Amplitude h
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
NS-NS and BH-BH Coalescence
SN Core Collapse
LISA
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

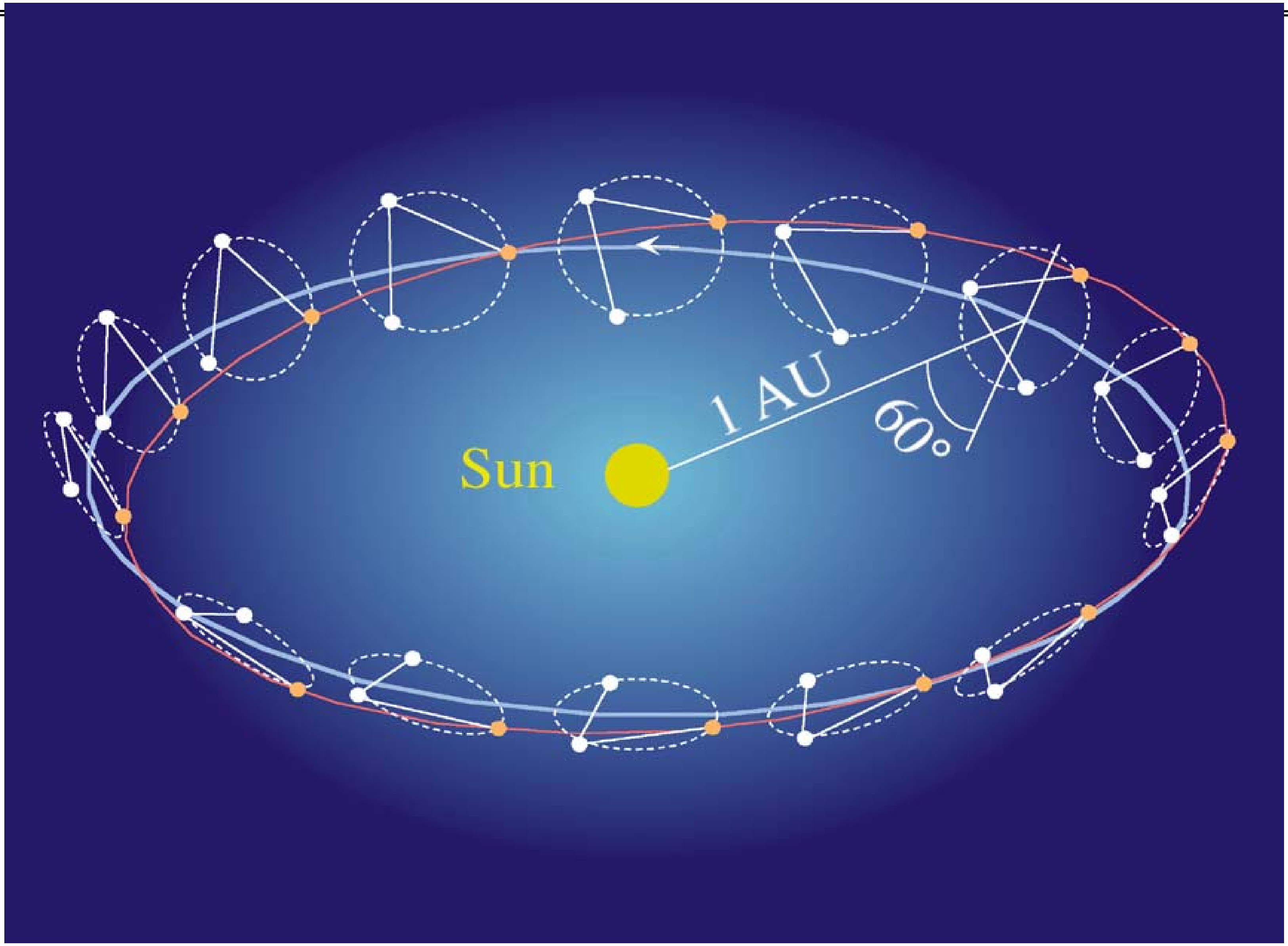
GW Detectors



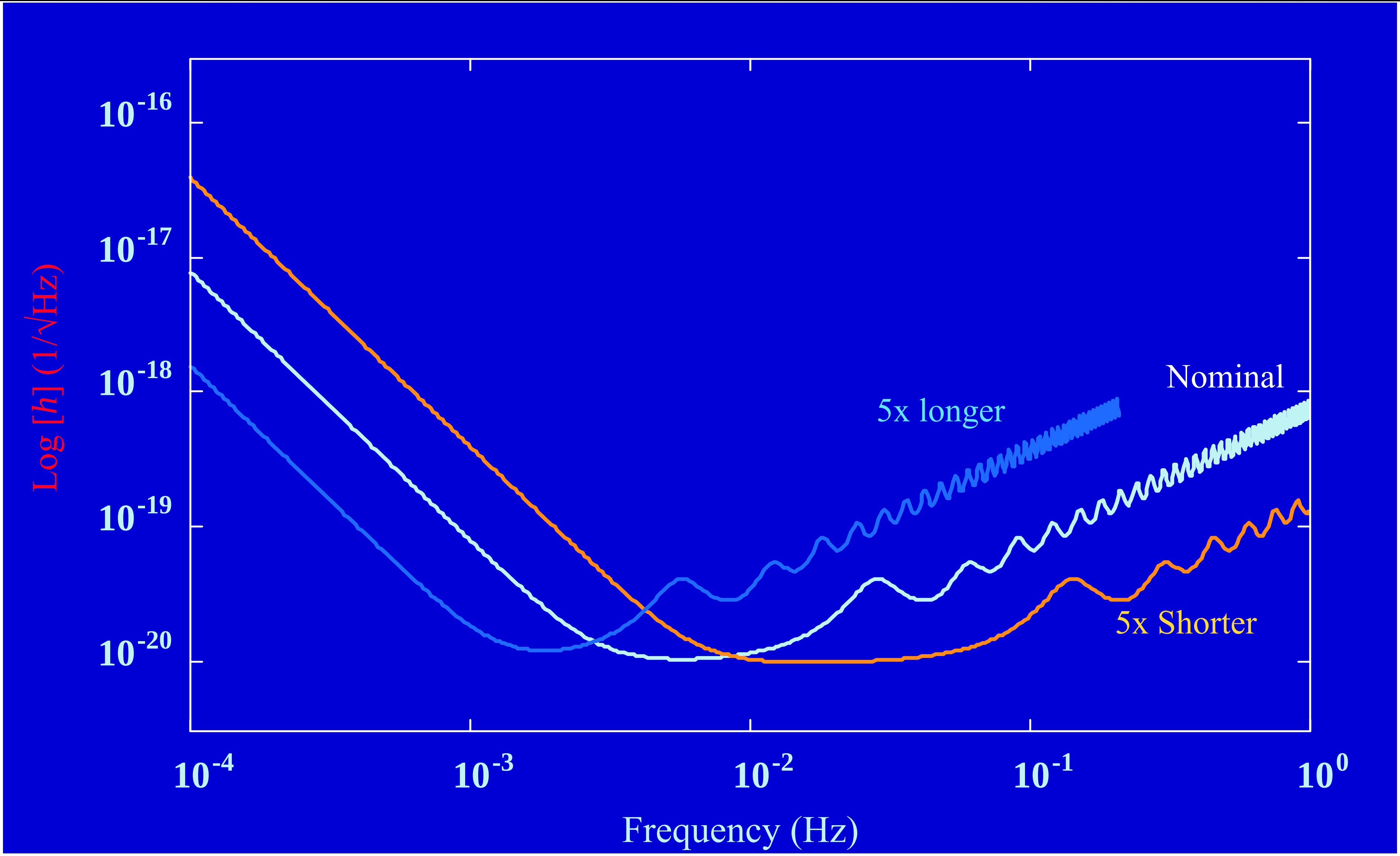
Spacecraft Formation



Spacecraft Orbits



Effect of Arm Length on Sensitivity

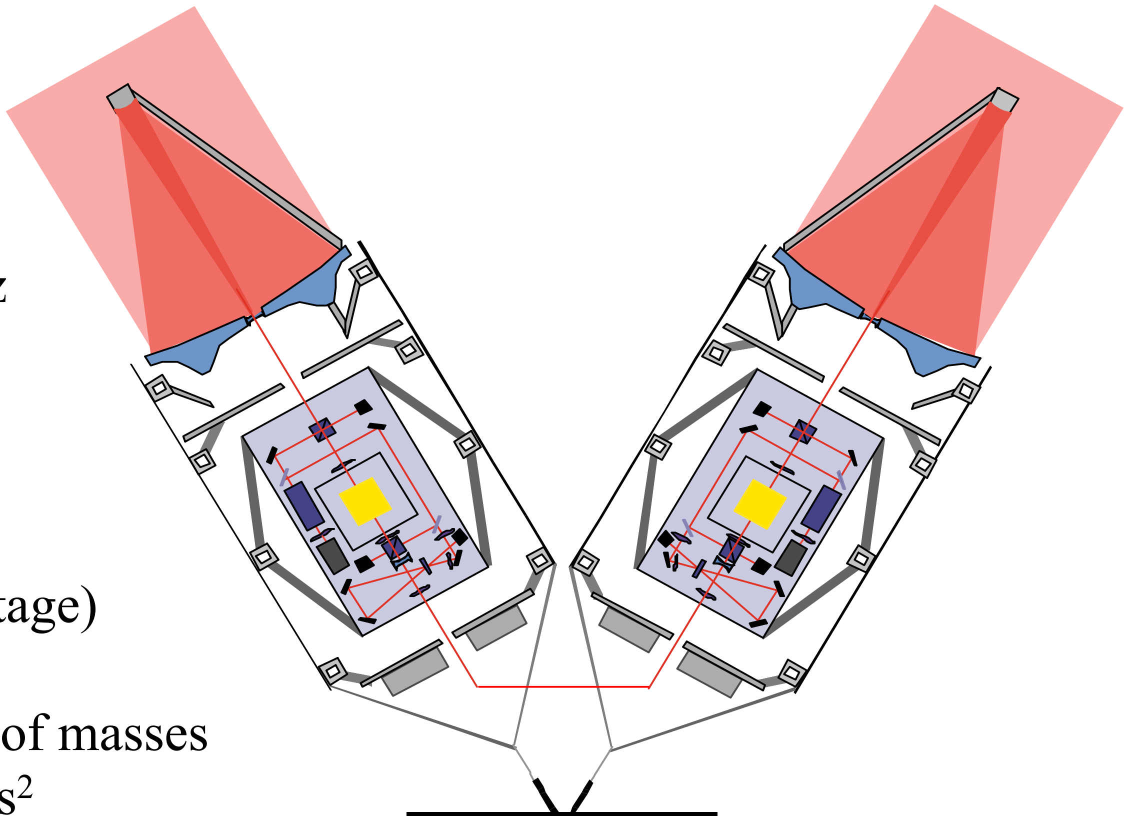


Payload Layout

- Two independent instruments
  - 30 cm telescopes, 1 W lasers
  - Measurement noise 20 pm/√Hz

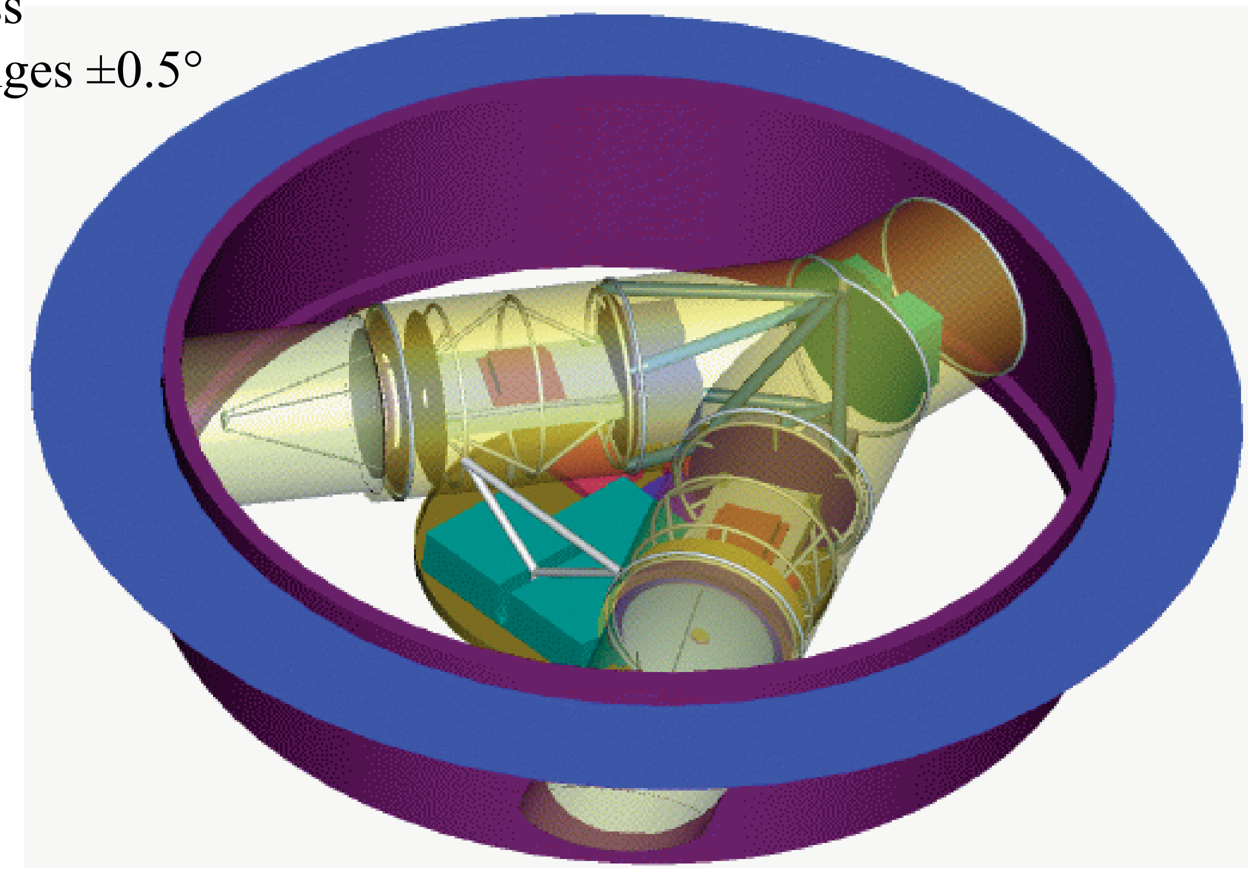
- Telescope pointing
  - Angle changes ±0.5° over year
  - Use flexures (HST heritage)
  - Steering mechanism (SIM heritage)

- Drag-free control law with two proof masses
  - Apply accelerations of 10^{-10} m/s^2



Spacecraft and Payload

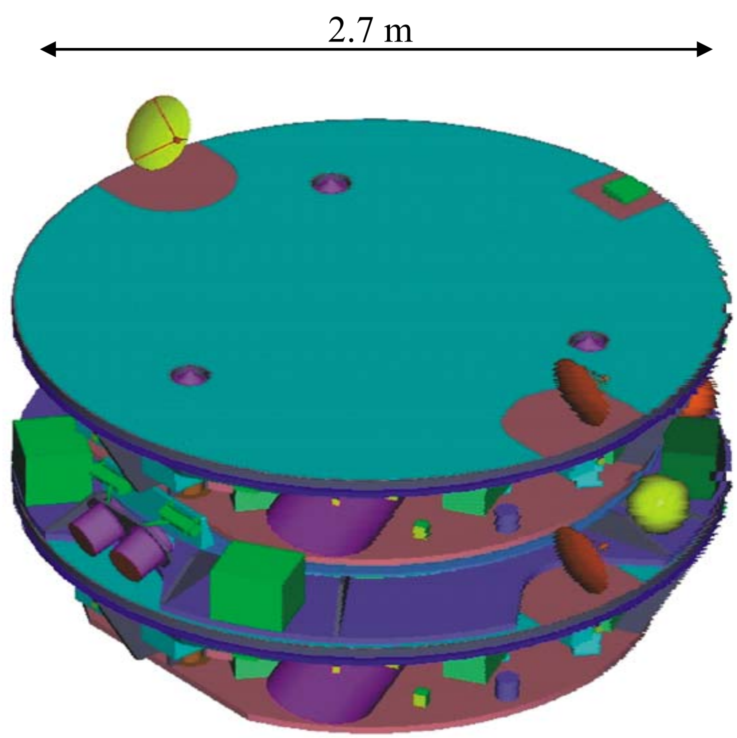
- Two independent instruments
  - 30 cm telescopes, 1 W lasers
  - Measurement noise 20 pm/√Hz
  - Freely-float test mass
- Telescope pointing changes ±0.5°

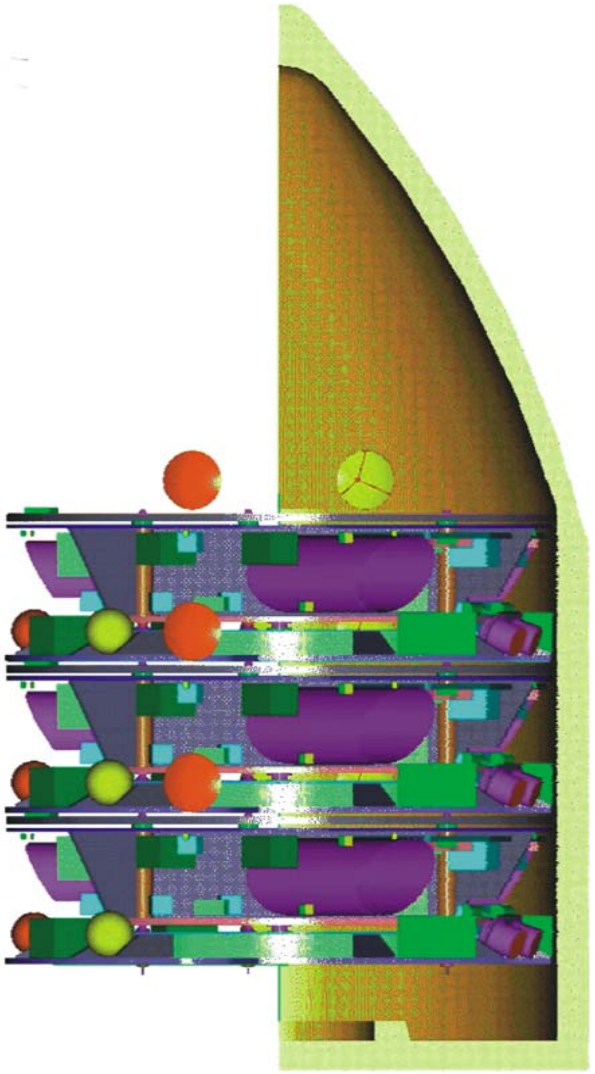


Launch Configuration

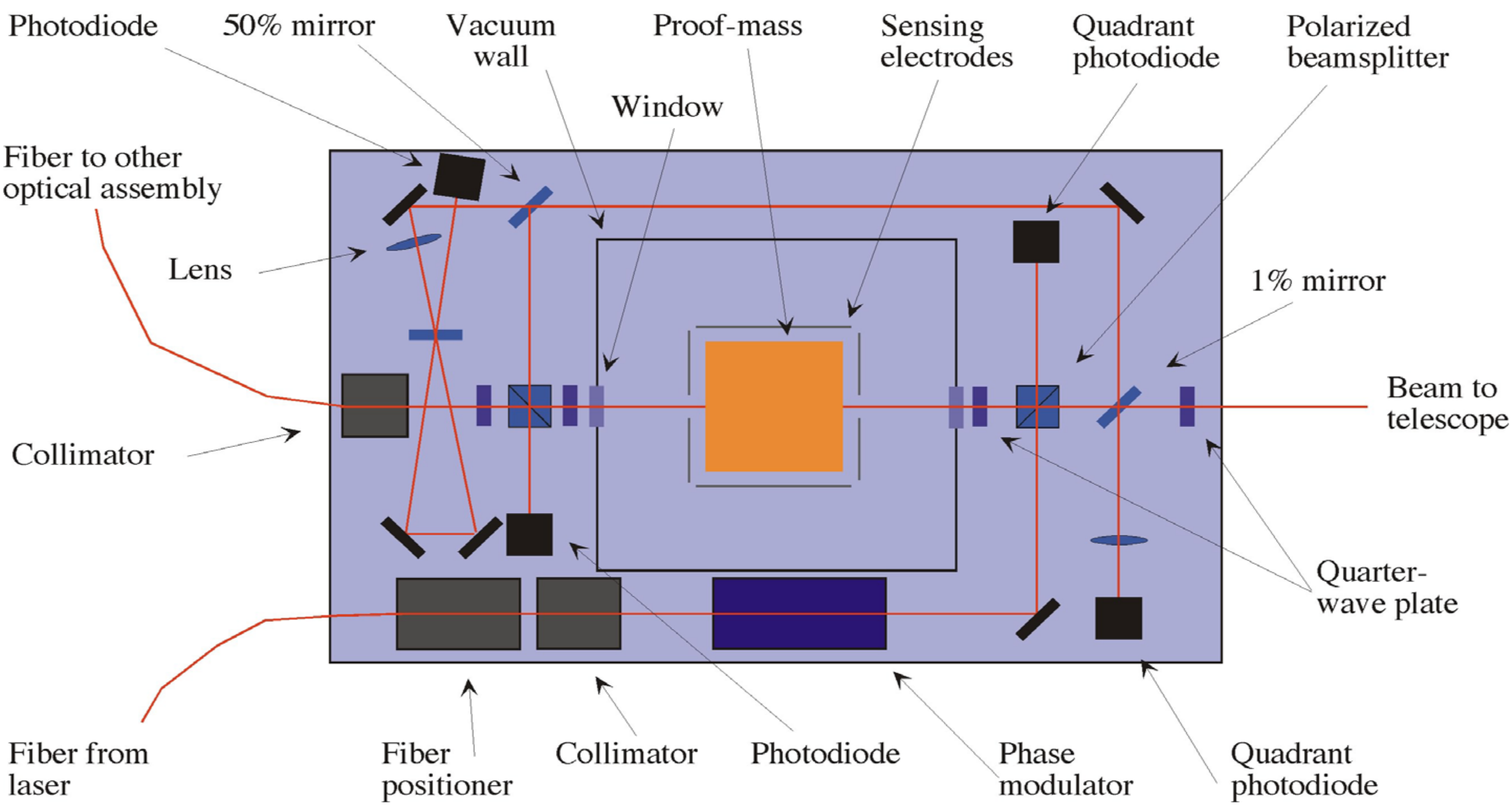
Spacecraft design constrained by volume of Launch vehicle shroud

Delta-II preferred because of lower cost





Optical Bench Layout



Conclusion

- 20 years ago, scientists foresaw general purpose interferometry missions, mainly imaging with ultra-high resolution (LAGOS/LISA is the exception)
- Current missions are focused:
  - SIM (2010 launch) will perform astrometry, with only limited imaging capability
  - TPF (~2015 launch) will search for and characterizes planets,
  - LISA (2011 launch) will measure gravity waves
- Development times are long
  - SIM started in 1990, TPF was first studied in ~ 1995, LISA in 1984
- What will the future hold? This depends on
  - The ultimate limits of ground-based technology (e.g. OHANA)
  - The questions opened by space interferometers
    - Will we detect Earth-like planets and signs of life?
  - How we view our place in the Universe
    - Planet imagers – what do the exo-planets look like?
    - Stellar imagers – what will be the fate of our solar system?
    - Different energy levels – what are the physical processes that we can only study with high resolution at X-ray, sub-millimeter, etc.