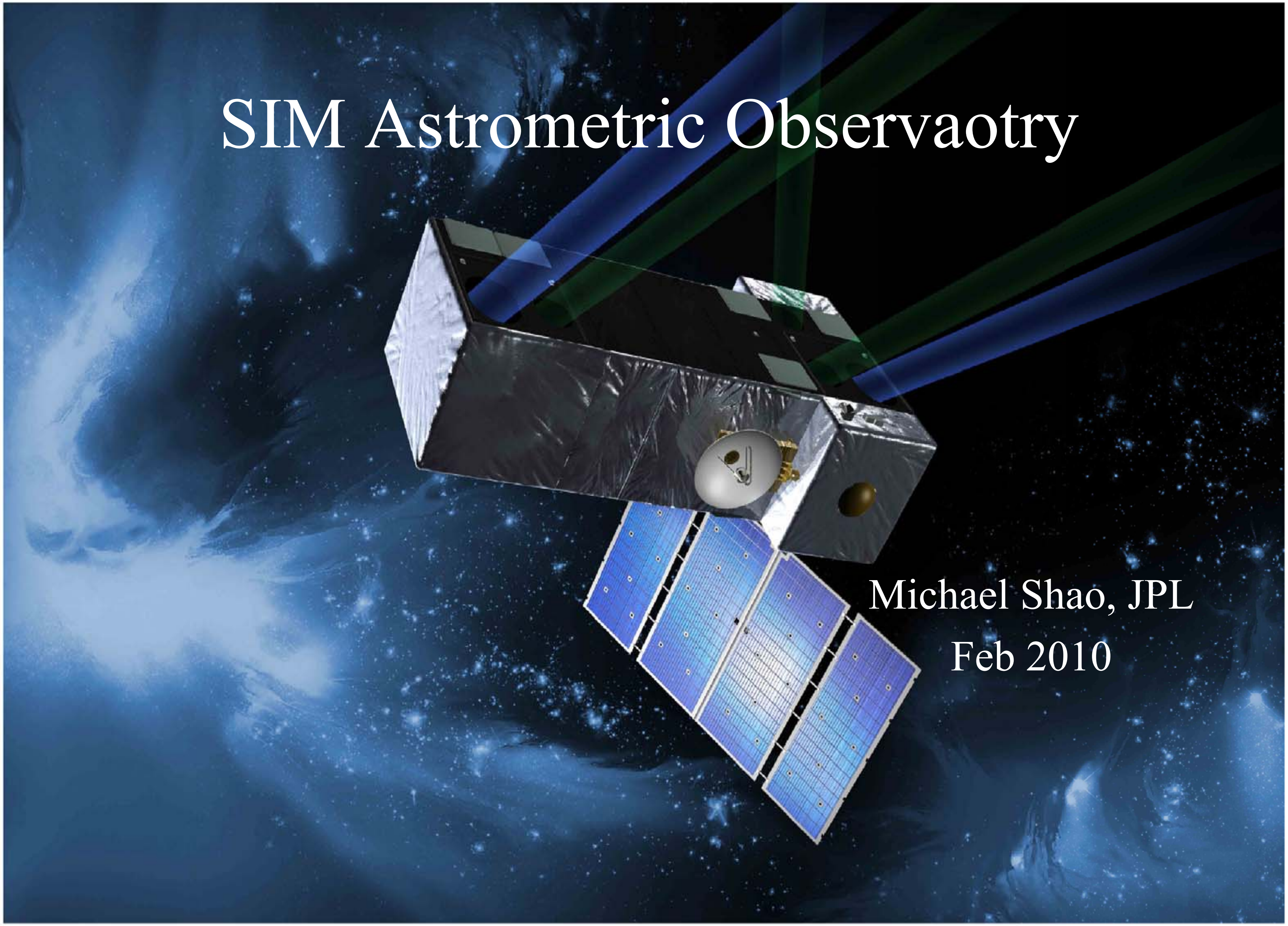
SIM Astrometric Observaotry



Michael Shao, JPL

Feb 2010

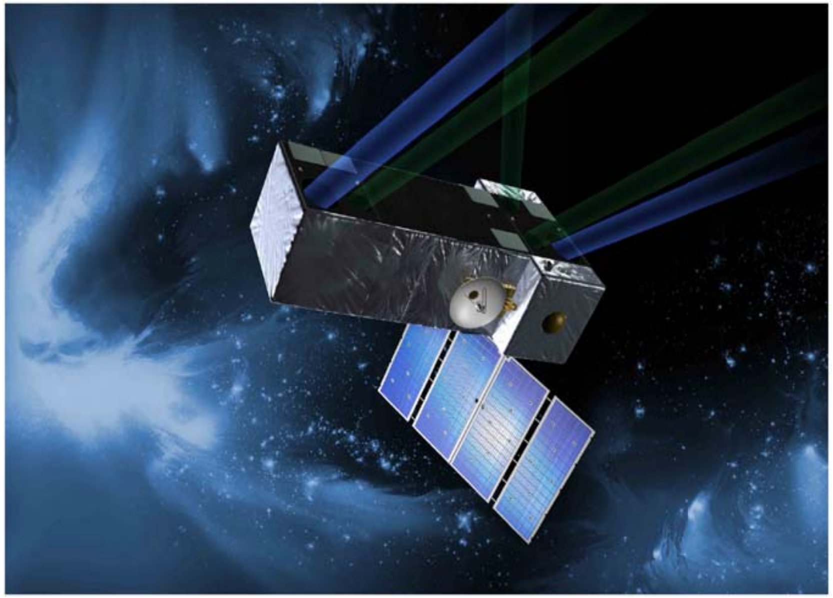
Outline

- How SIM works
- SIM Science
- Technology Development
- Engineering Risk Reduction
- Detecting Earths in multiple planet systems

SIM Lite Astrometric Observatory Overview

Salient Features

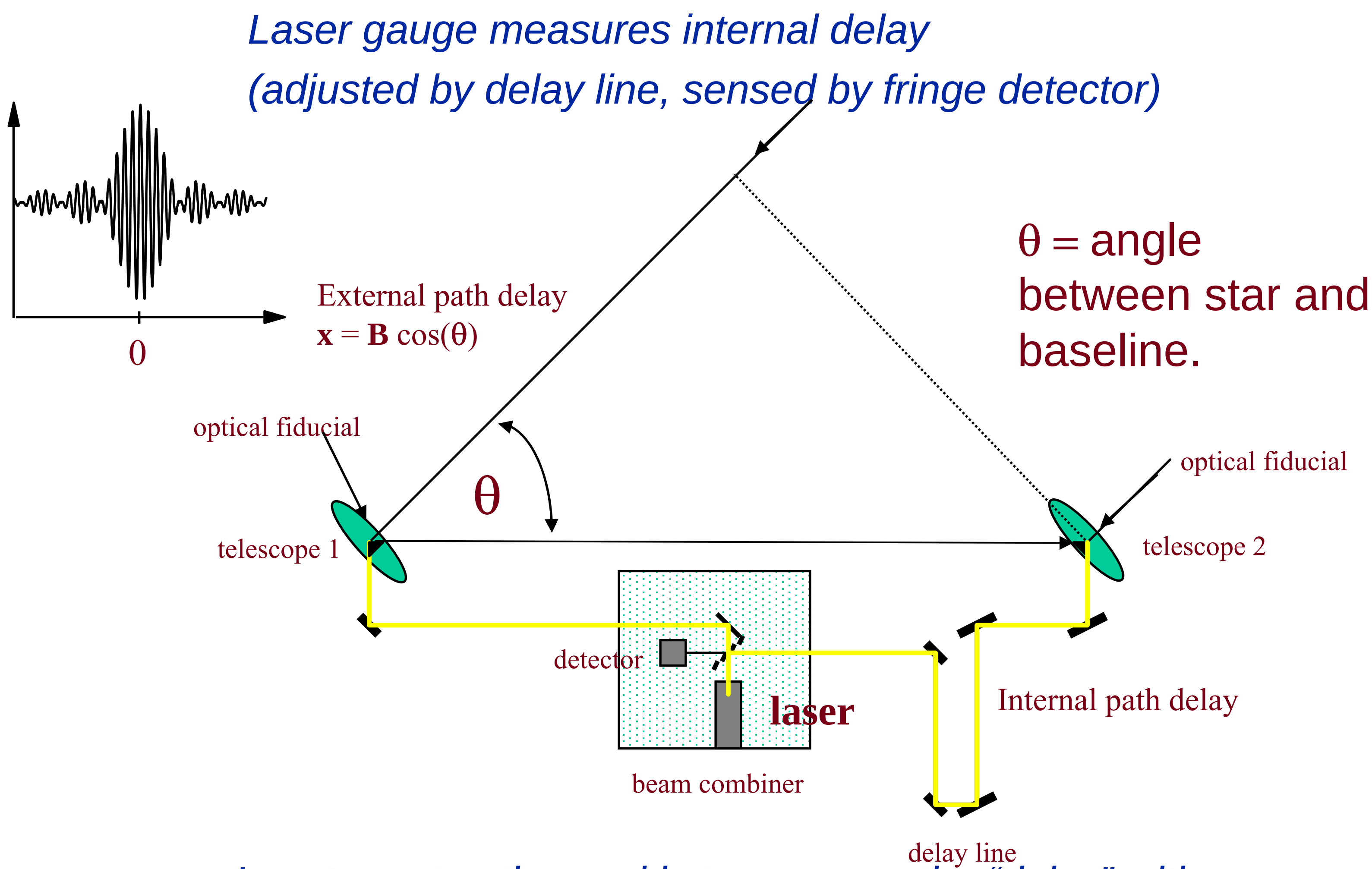
- One 6 meter science Michelson Stellar Interferometer (MSI) with 50 cm siderostats
- One 4m Michelson Stellar interferometer and one 30cm telescope as Guides
- Visible wavelengths
- Earth-trailing solar orbit, 5 year mission
- SIM is a JPL, Caltech, NGAS, KSC, and SIM Science Team partnership



Science

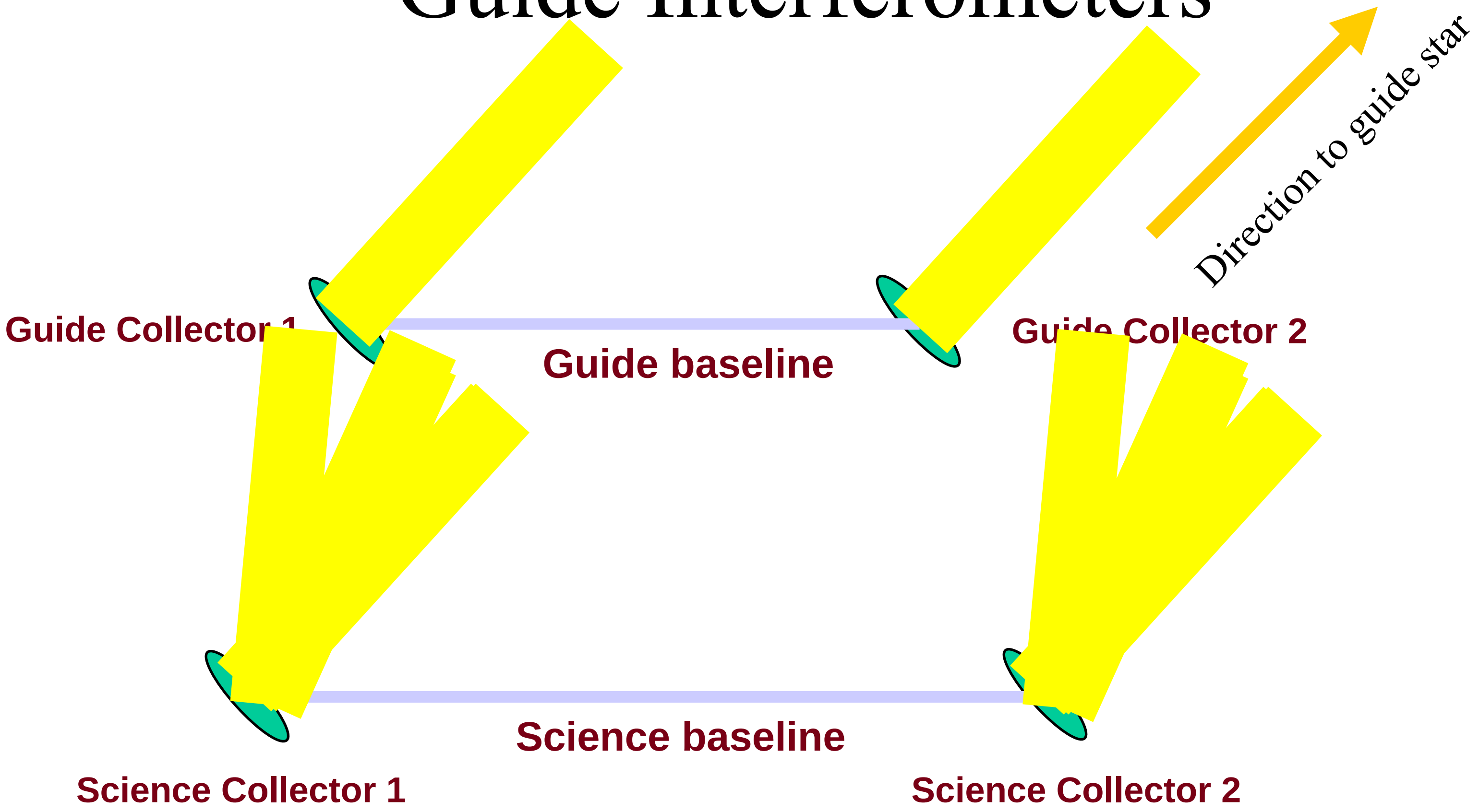
- **Finding Earths** – Reveal the population, masses, and orbits of terrestrial and giant planets around nearby stars, and the formation, evolution, and architecture of planetary systems.
- **Dark Matter & Galaxy Assembly** – Determine the age of and probe the hierarchical formation history of the Milky Way. Map the distribution of local dark matter, and place limits on the mass of the dark matter particle. Include rotational parallaxes.
- **Precision Stellar Astrophysics** – Precision measurements of the masses and luminosities of the highest and lowest mass stars allow testing of models of stellar evolution, from brown dwarfs to black holes.
- **Supermassive Black Hole Astrophysics** – Understand how black holes accelerate jets, for masses from stellar to galaxy central engines.

Astrometry, the Position/Motion of Stars



In astrometry, the goal is to measure the "delay" with an accuracy that is << λ. 1uas ~ 30pm, ~λ/20,000

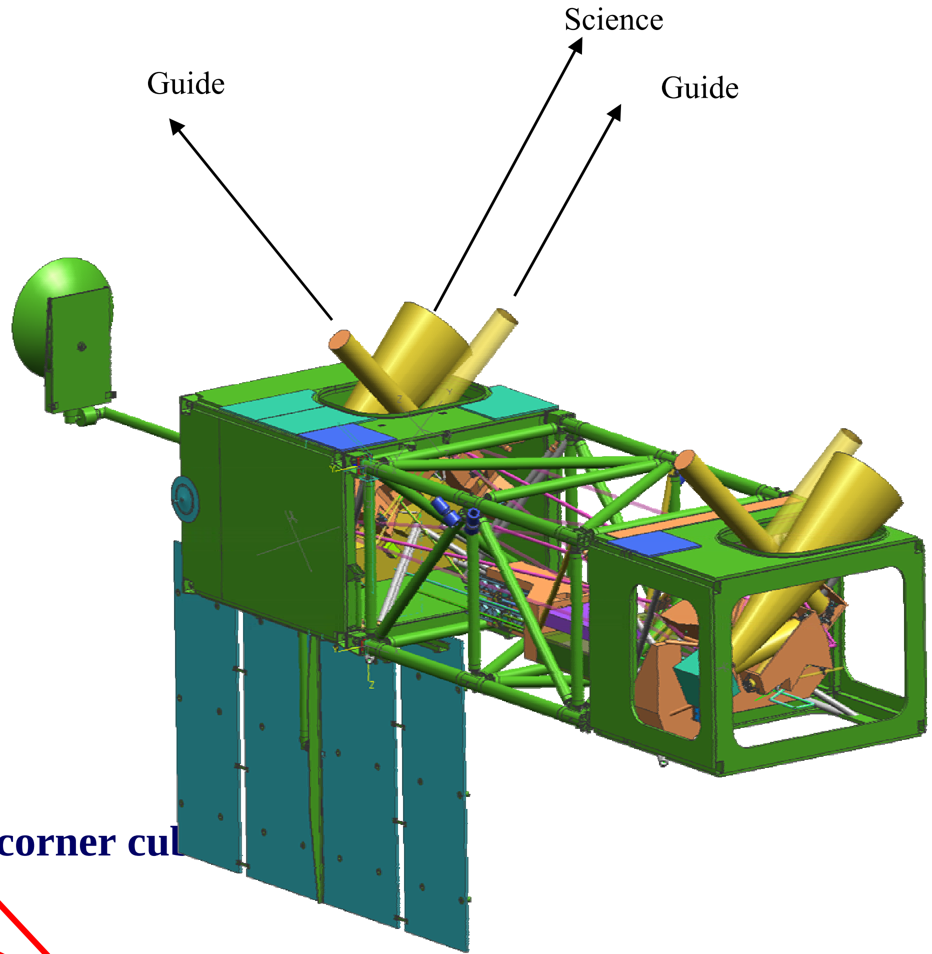
Guide Interferometers

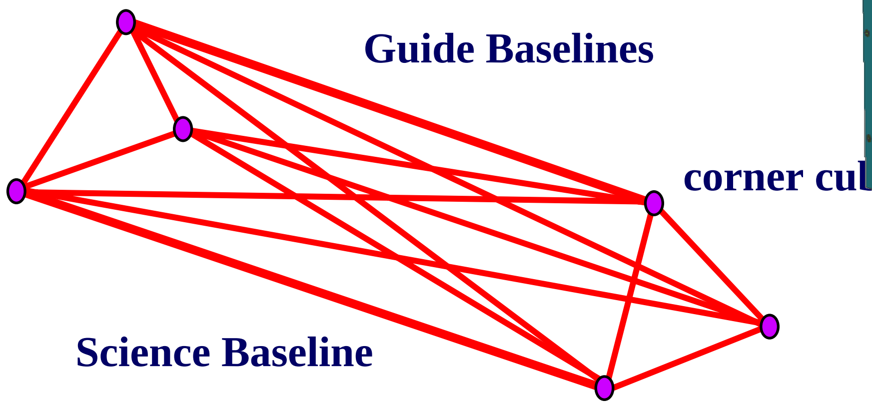


Guide interferometers are used to determine the attitude of the guide interferometer baseline

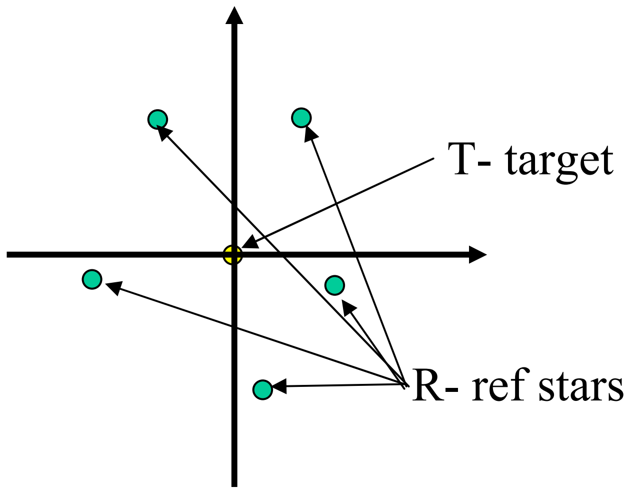
SIM Optical Truss

- SIM has 3 interferometers
  - Two guide interferometers that measure changes in the spacecraft attitude (at uas level)
  - The 3rd interferometer sequentially measures the position of N stars in the field of regard, in 2 ~orthogonal baseline orientations
  - Metrology to “tie” 3 interferometers together





Narrow Angle Astrometry (relative astrometry)



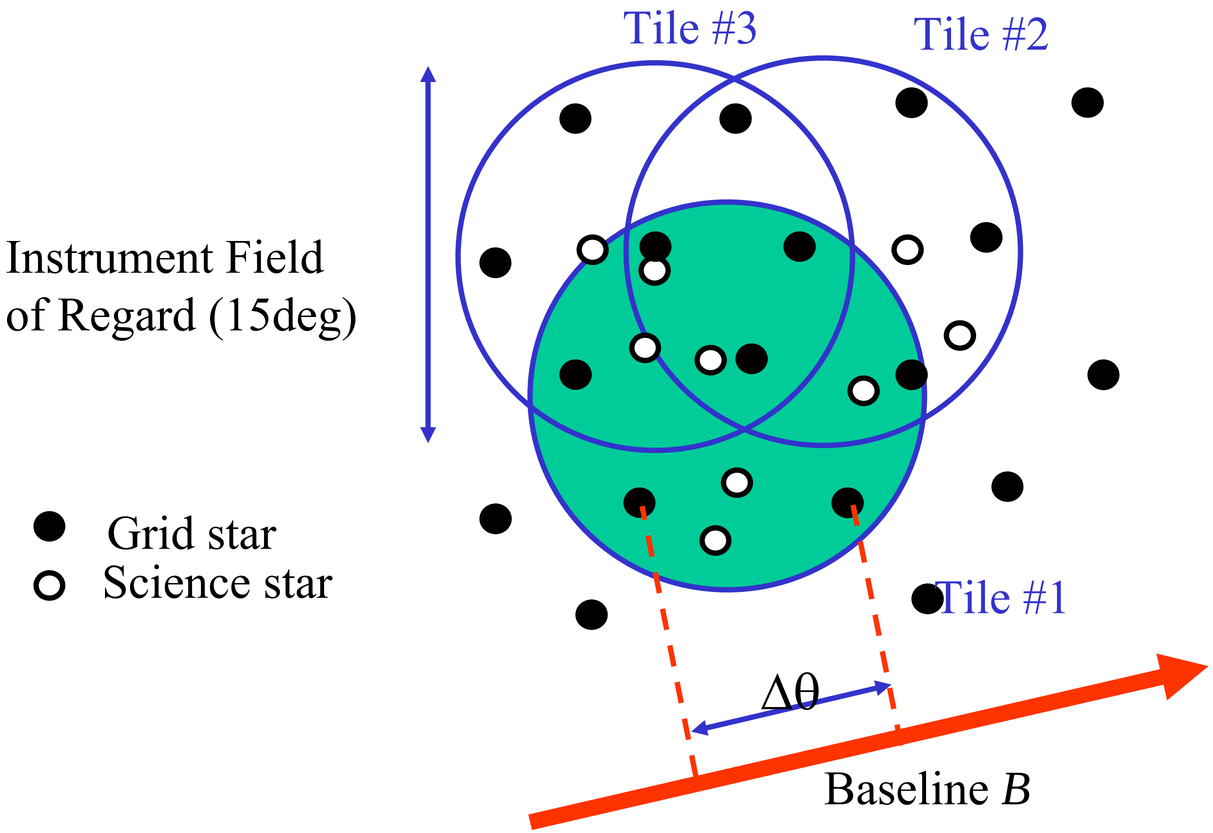
Observing Sequence
Baseline 1 T-R1-T-R2-T-R3-T-R4-T-R5
T-R1-T-R2-T-R3-T-R4-T-R5
Baseline 2 T-R1-T-R2-T-R3-T-R4-T-R5
T-R1-T-R2-T-R3-T-R4-T-R5

Baseline motion is monitored by guide interferometers, and compensated in data analysis.

- Relative Astrometry: the position of a target star with respect to adjacent “nearby” stars
- Typically 4~5 ref stars within ~1 deg of the target
  - 10 mag or brighter
  - Distant K giant (600~1Kpc)
- Baseline length and orientation derived from observation of Grid stars. (sed Global Astrometry description)
- Solve for PM and relative parallax of Target(t) <u>and</u> ref stars
  - Ref star motion modeled by parallax, prop mot, & relativity

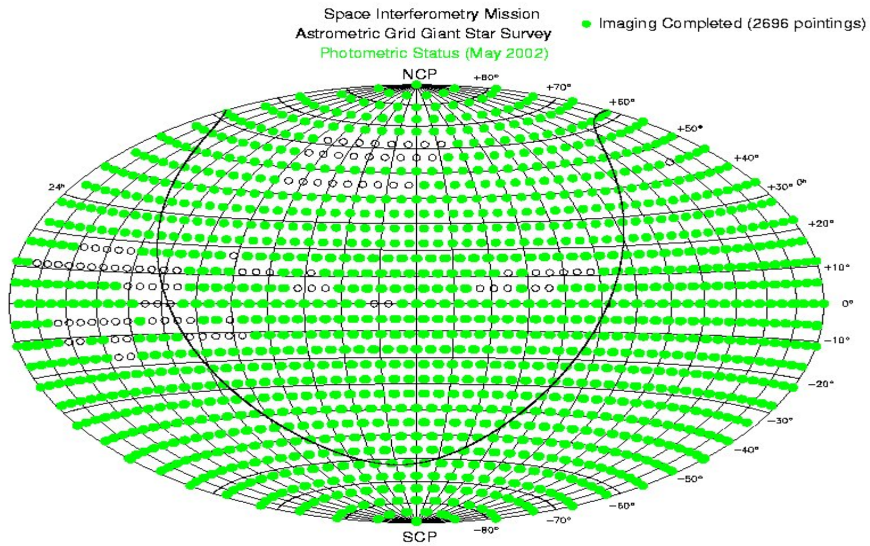
Global Astrometry

At any one time, SIM's field of regard is 15 deg. In order tie the whole sky together, SIM makes measurements over 4π in a series of overlapping tiles.



SIM Grid, Global Astrometry

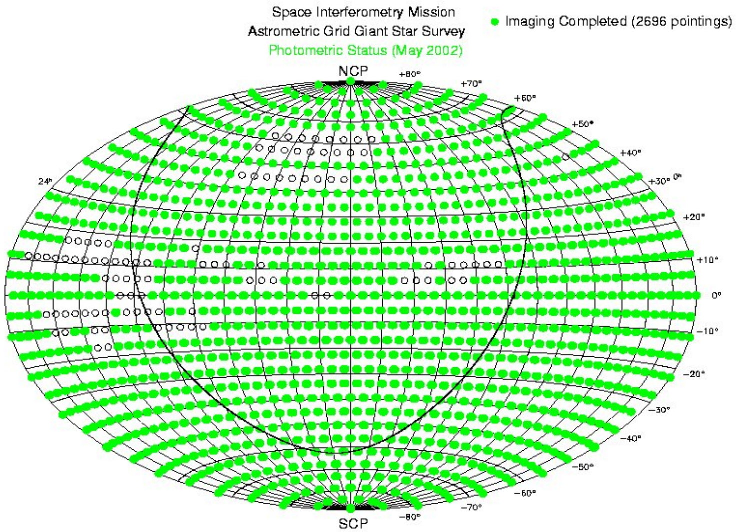
- A regularly spaced set of 10~12 mag stars that cover the whole sky, along with 25~50 QSO's that form a reference frame for SIM global and narrow angle observations.



- Grid stars: Moderately bright (11 mag) ~1300 stars in a regular grid pattern
  - K giants were chosen because they are intrinsically bright, hence distant, 1~2 Kpc
  - At such a distance jovian planets would in general would produce non-linear motions over 5 years < 4 uas.

Grid Wide Angle Observing Scenario

Placeholder

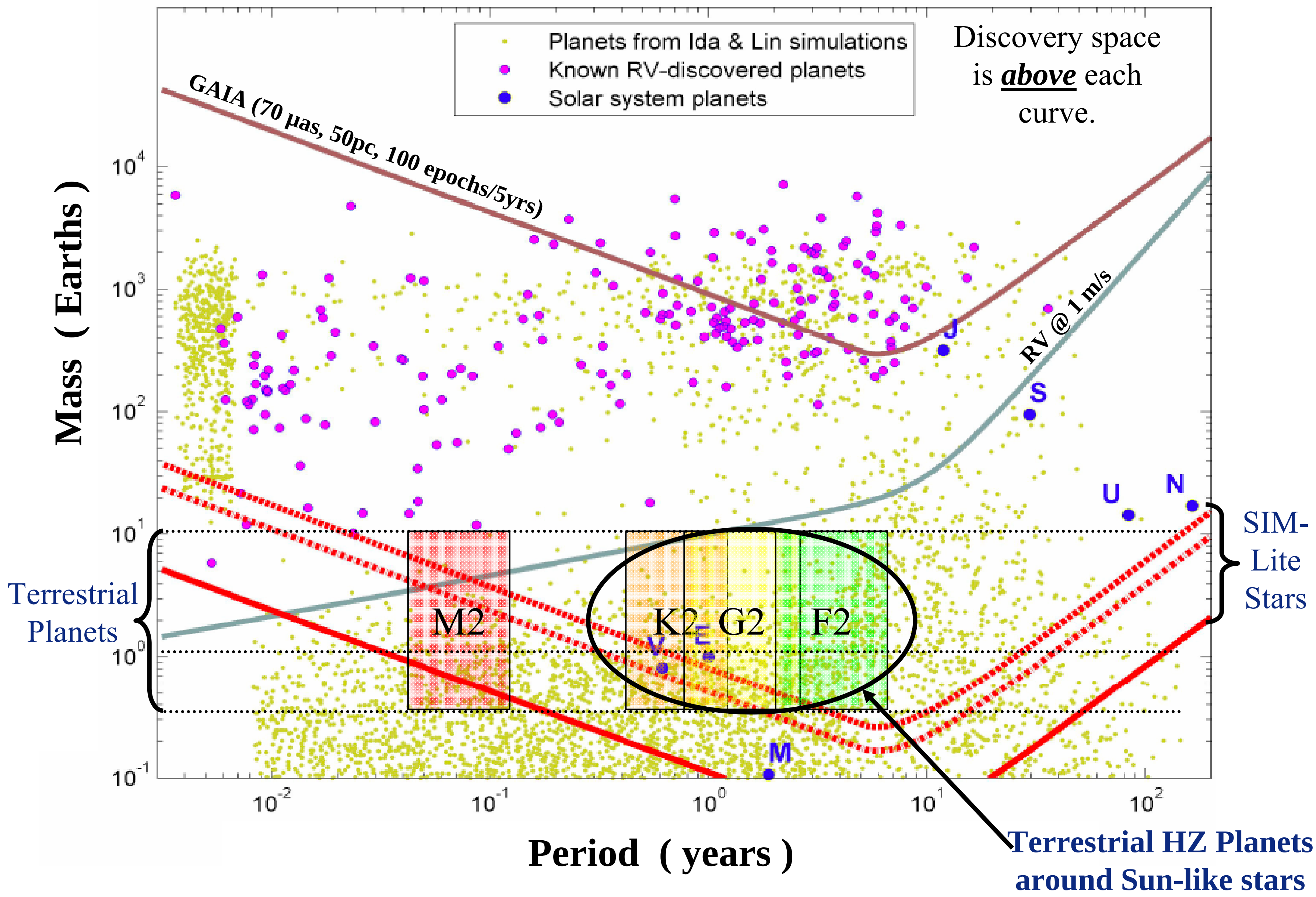


- Astron[illegible] measurements are ma[illegible]
  - 6-7 grid stars are measured along with other science targets
  - grid stars are measured ~ 220 times during the 5 year mission
- Tiles are measured using an Sun, anti-Sun orange peel scan
  - care is taken to keep out of the Sun avoidance region
- Positions, proper motions, and parallaxes are derived from the ~ 40000 to 50000 observations
- A global least squares solution is used to extract both stellar parameters and instrument parameters
  - Solving from instrument parameters allows one to relax requirements on timescales greater than 1tile observing time (~ 1 hour)

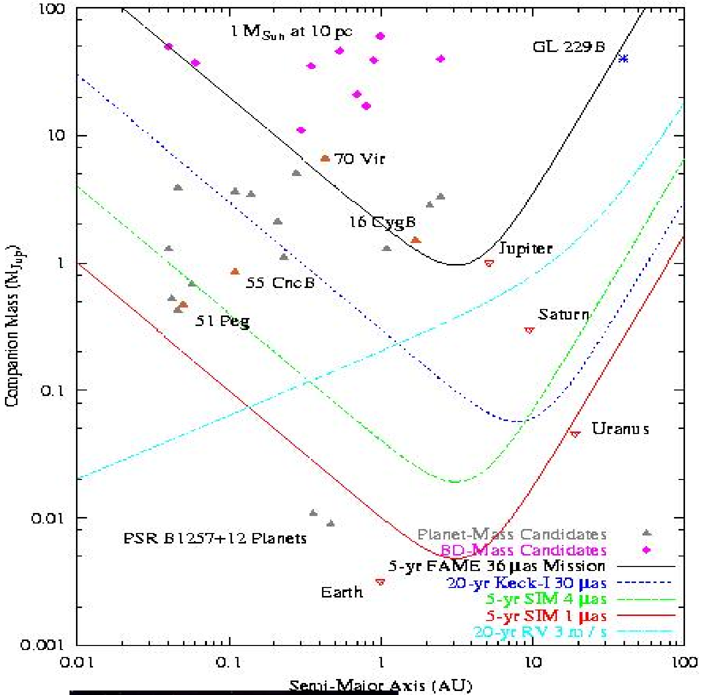
SIM Science Overview

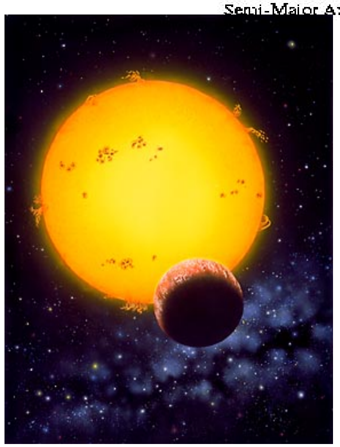
- Exoplanets
  - Earth clones (1 M_e, 1 AU) (60~100 nearest stars)
  - Planetary system architecture (~1000 stars) multiple systems, coplanar orbits, # planets vs stellar type
  - Young planets, (< 100 Myr) planetary systems before they have reached dynamical steady state.
- Dark Matter
  - In the galactic halo
  - In nearby dwarf galaxies
  - Local group
- Astrophysics of stellar mass objects
  - Extend precise mass luminosity relation to all stellar types
  - Masses of neutron stars and black holes

Astrometric & RV Sensitivities



Is Our Solar System of Planets Typical?



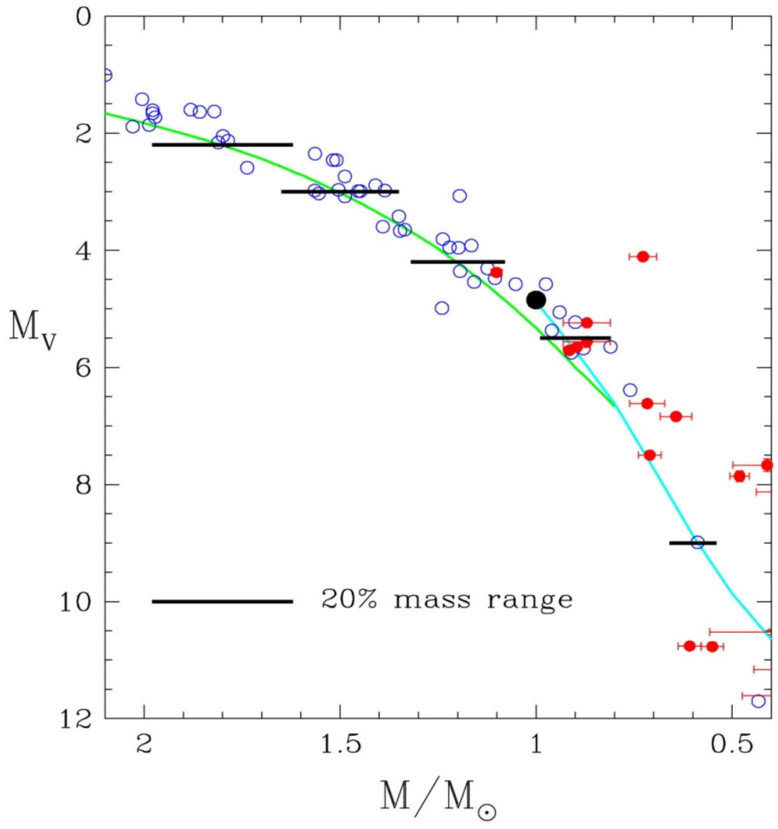


51 Peg
Hot Jupiter
@0.05 AU

- ~160 planets have been found outside the solar system in the last 10 years since the discovery of the Jupiter sized planet around 51 Peg
- ~7% of solar like stars are known to have planets (Jupiter ~ Neptune mass)
- The most striking result of research is that the vast majority of exoplanets found todate look nothing like our solar system.
  - Gas Giants in the outer solar system, rocky planets <2AU.
- Radial velocity searches, responsible for virtually all exoplanets found biased against planetary systems like our own.
- SIM's broad survey of ~2000 stars for planets to ~Neptune mass will answer the question, "**Is our solar system typical or are we rare perhaps unique**?"

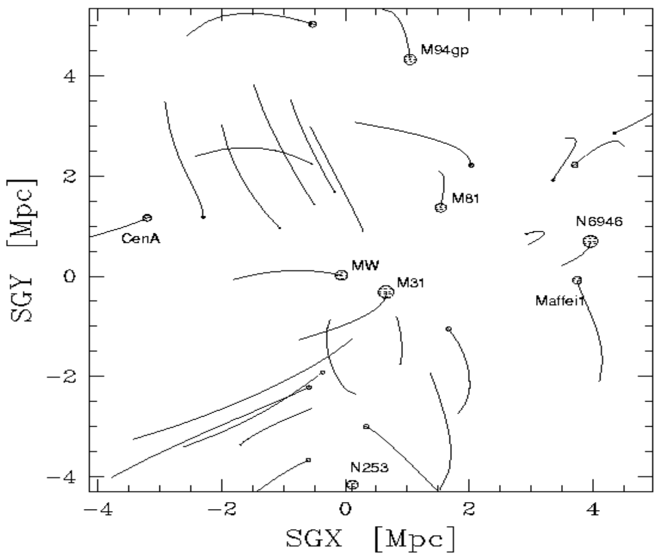
Stellar Astrophysics

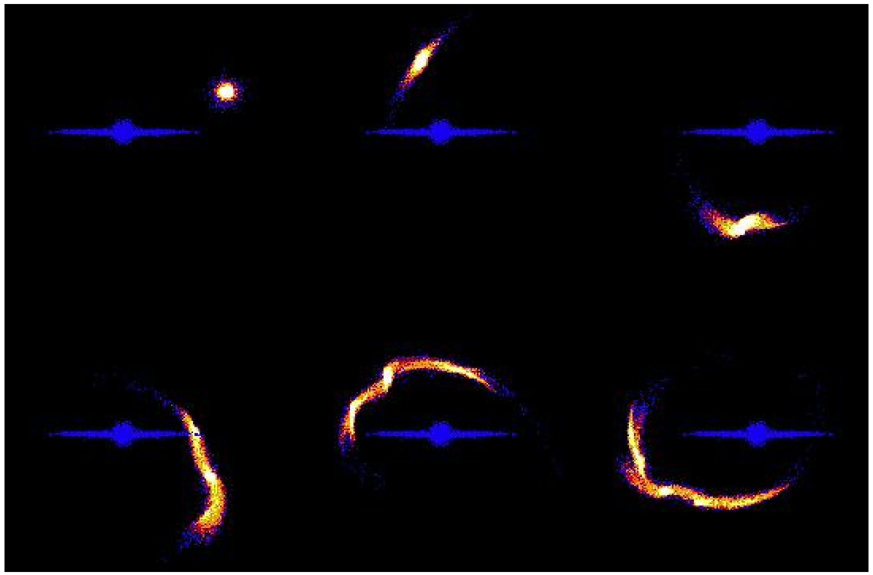
- The most important property of a star is its mass. The motion of objects orbiting each other is the most direct way to measure the mass.
- SIM will enable very precise tests of stellar models for “normal” stars. (200 times more precise than Hipparcos)
- SIM will also be able to, for the first time, directly measure the mass of objects at end of the stellar evolution process, **Neutron stars and stellar mass black holes**.



Dark Matter, (What we see, stars, galaxies are represent only ~5% of the matter in the universe)

- 3 of SIM's key science projects address the issue of Dark Matter
- Dark matter in dwarf galaxies, CDM vs WDM
- Dark Matter in the galactic halo
- Dark Matter in the local group of galaxies

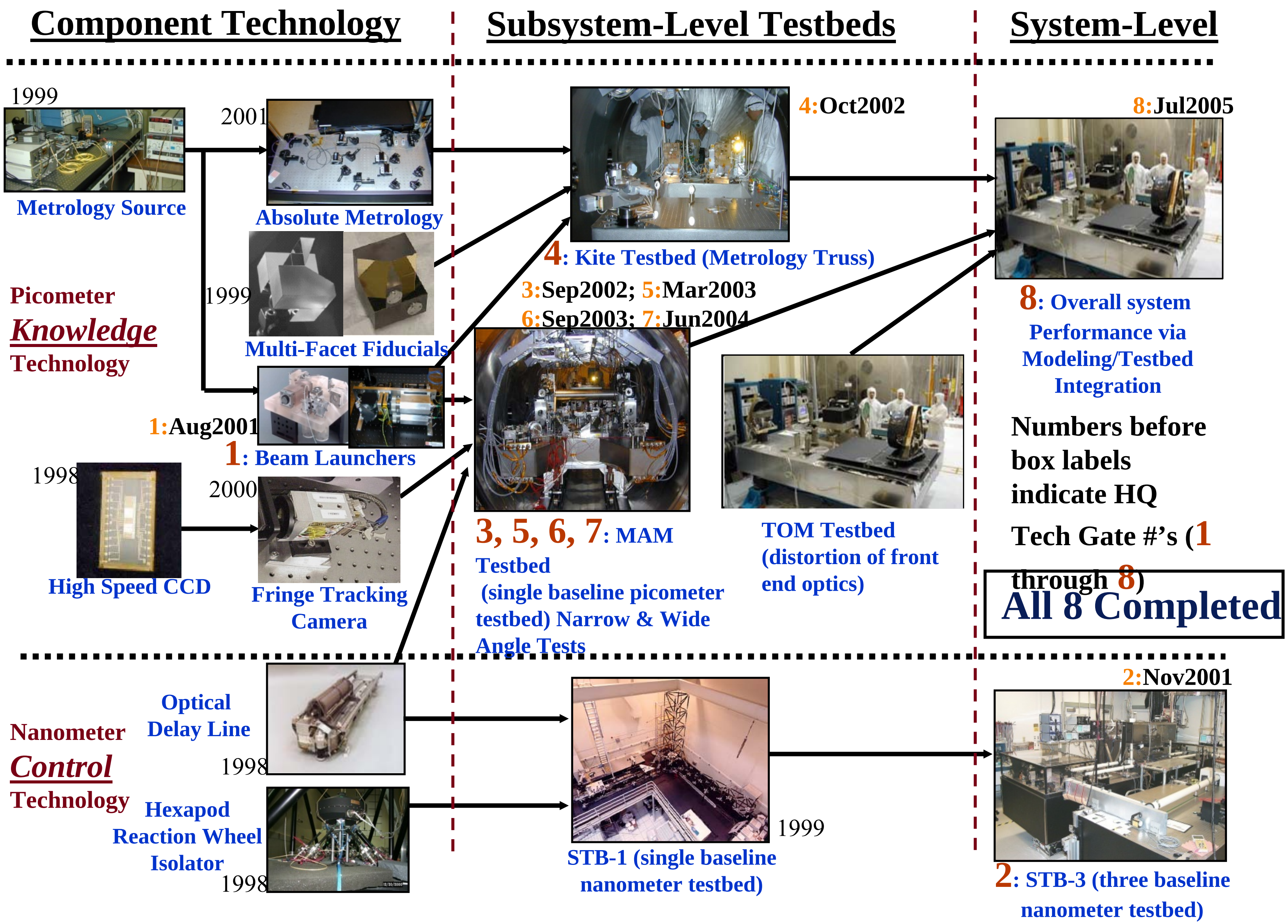




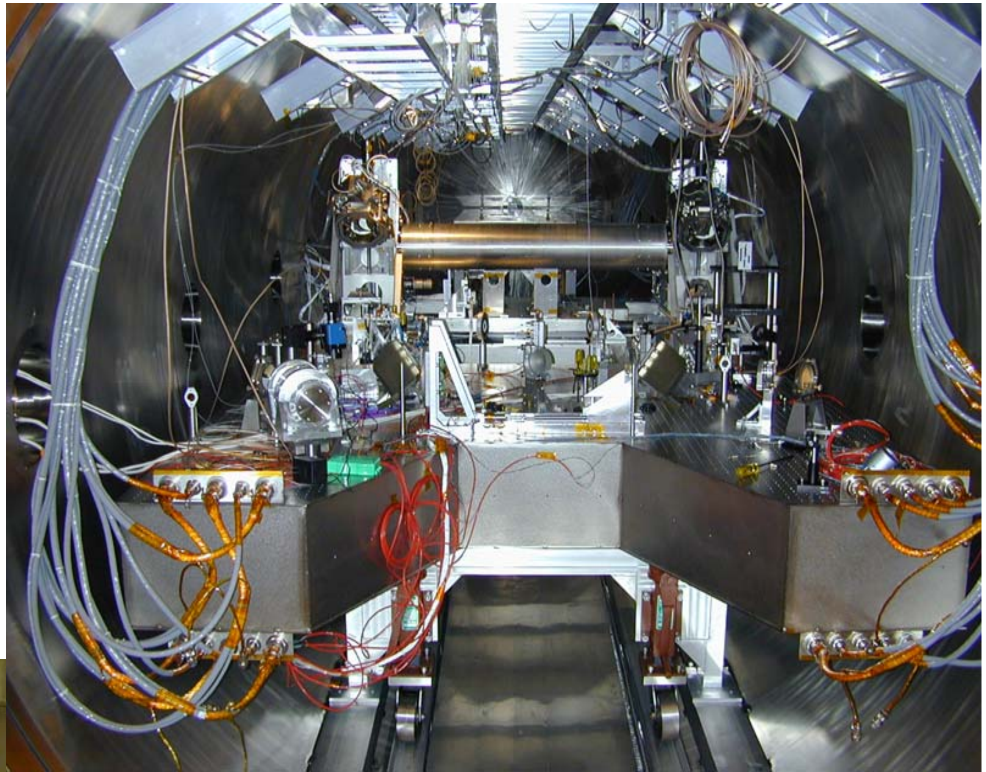
Technology Dev for SIM

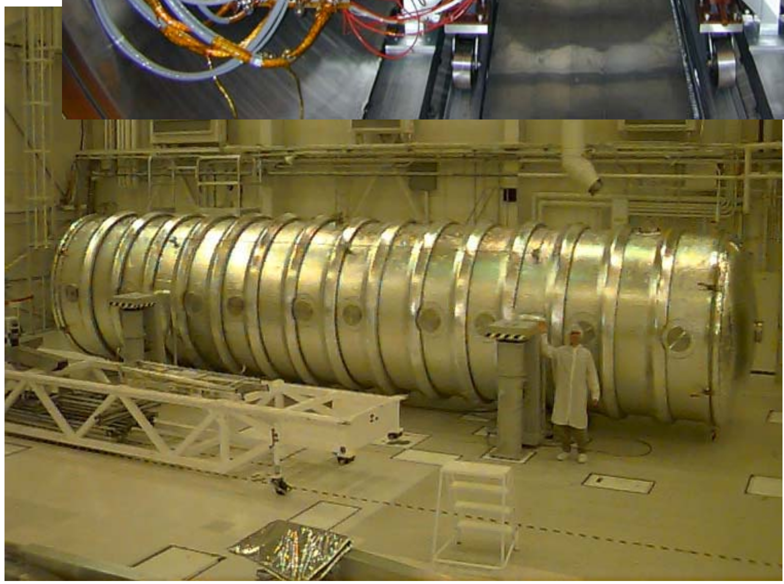
- Technology development for SIM was needed in two areas
  - **Nanometer control**, optical paths had to stable ~10nm for high fringe visibility observation of faint targets)
  - **Picometer knowledge**, 1 uas is a 30 pm (picometer) change in optical path for a 6 m baseline interferometer.
- NASA asked JPL to create a list of technology milestones, the technology milestone had to be met (reviewed by NASA appointed external review panel) before starting the design of the flight hardware.
  - A set of 8 technical milestones were created and the last one reviewed in 2006.
  - Since then the project has undertaken a series of “engineering risk reduction efforts”, to build flight qualifable components and subsystems

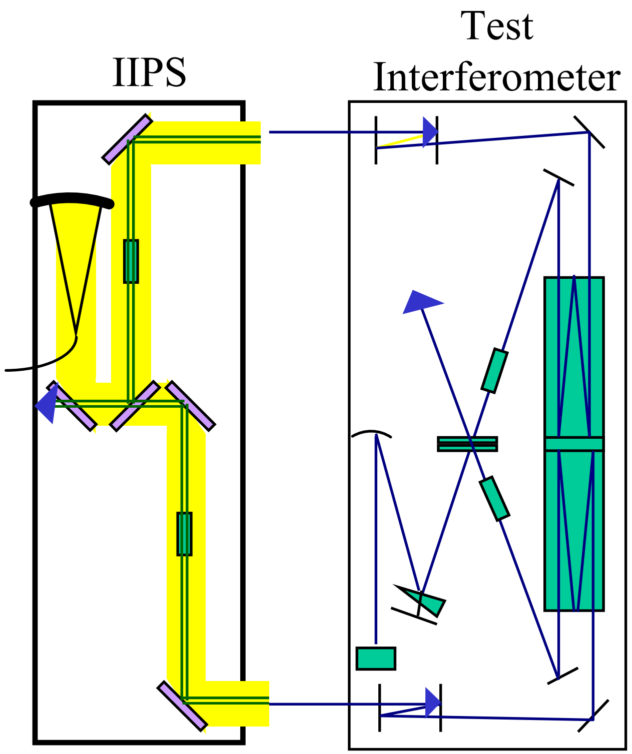
SIM Technology Flow



The Micro Arcsec Metrology Testbed







SIM Technology Gates -- Summary

Technology Gate	Description	Due Date	Complete Date	Performance
1	Next generation metrology beam launcher performance at 100pm uncompensated cyclic error, 20pm/mK thermal sensitivity	8/01	8/01	Exceeded objective
2	Achieve 50dB fringe motion attenuation on STB-3 testbed (demonstrates science star tracking)	12/01	11/01	Exceeded objective
3	Demonstrate MAM Testbed performance of 150pm over its narrow angle field of regard	7/02	9/02	Exceeded objective
4	Demonstrate Kite Testbed performance at 50pm narrow angle, 300pm wide angle	7/02	10/02	Exceeded objectives
5	Demonstrate MAM Testbed performance at 4000pm wide angle	2/03	3/03	Exceeded objective
6	Benchmark MAM Testbed performance against narrow angle goal of 24pm	8/03	9/03	Exceeded objective
7	Benchmark MAM Testbed performance against wide angle goal of 280pm	2/04, 5/04*	6/04	Met objective
8	Demonstrate SIM instrument performance via testbed anchored predicts against science requirements	4/05	7/05	Met objective

<u>Legend</u>

pm = picometer

mK = milliKelvin

dB = decibel (50dB = factor of 300)

* HQS directed a scope increase (by adding a numerical goal to what had been a benchmark Gate) and provided a 3 month extension when performance fell short

Technology and Engineering Milestones Status

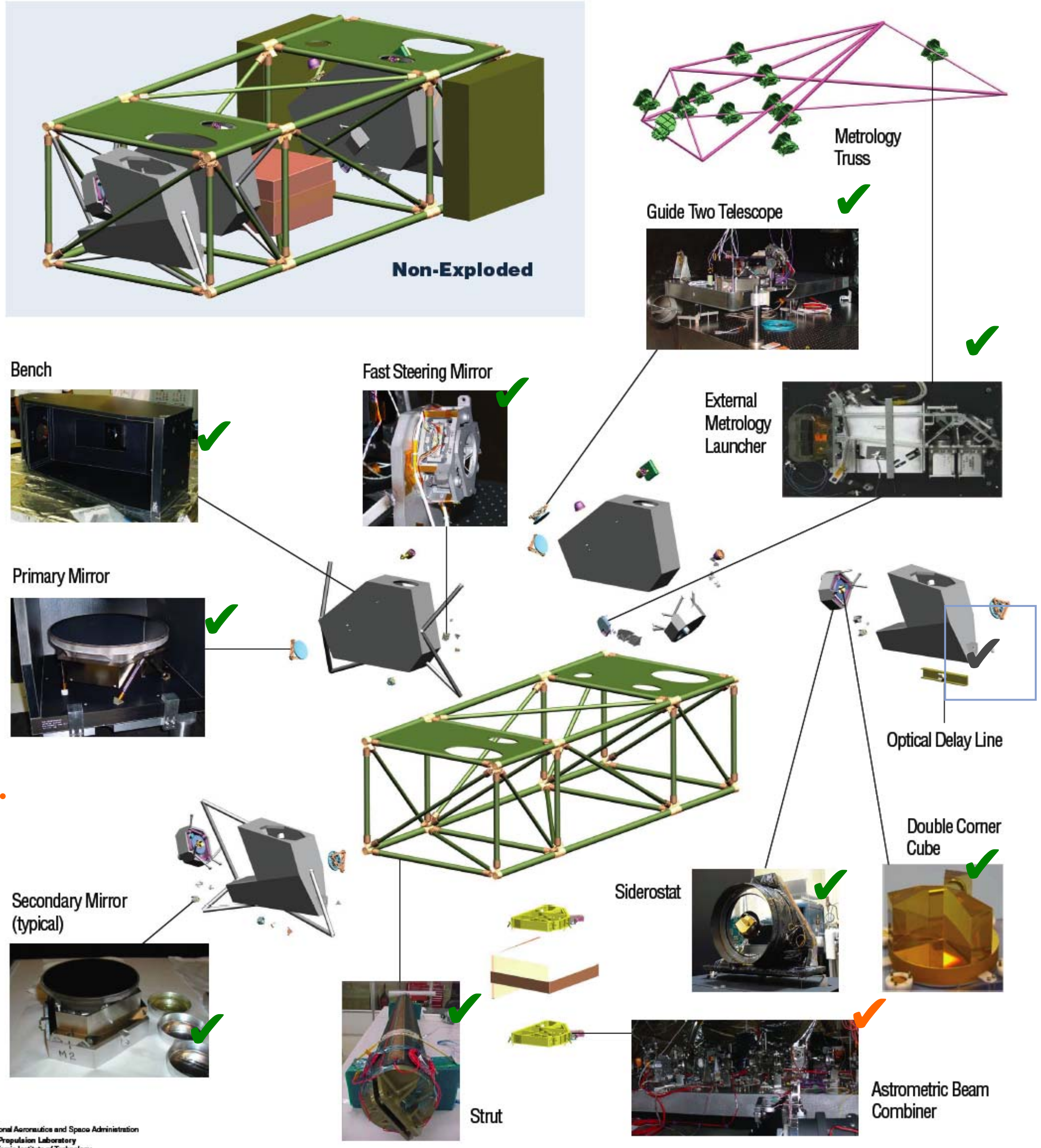
- Last SIM Technology milestone completed: Jun 2005 (end-to-end performance through stitching together of testbeds)
- SIM Technology Program completion final signoff: Mar 2006

Engineering Milestone	Description	Due Date	Complete Date	Performance
Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded Objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	4/30/06	5/3/06**	Exceeded Objective
EM-3	Metrology Source Assembly Validation (meet Qual environmental and allocated performance)	6/30/06	6/28/06	Exceeded Objective
EM-4	Spectral Calibration Development Unit (SCDU) (demo flight-traceable fringe error calibration methodology and validate model of wavelength-dependent measurement errors)	8/30/07	12/10/07	Met Objectives
EM-5	Instrument Communication H/W & S/W Architecture Demo (validate SIM's multi-processor communications system using two brassboard instrument flight computers, ring bus, and flight software version 2.0 with specific S/W functions as listed)	4/1/07	3/5/07	Met Objectives

- Since Dec 2007 Project has been performing engineering risk reduction activities by building brassboards
  - Brassboards are form, fit & function to flight and subjected to qualification-level environmental tests.

SIM Lite Brassboard Status - Today

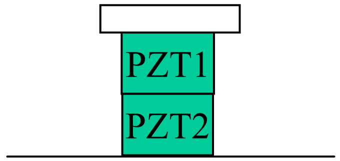
- **Brassboards – form, fit and function to flight**
- **Completed:**
  - **Guide-2 Telescope.**
  - **Internal & External Metrology beam launchers.**
  - **Fine Steering Mirror.**
  - **Beam Compressor & Bench.**
  - **Modulation Optical Mechanism (not shown).**
  - **Pathlength Optical Mechanism (not shown).**
  - **Double Corner Cube.**
  - **30 cm Siderostat mirror.**
  - **Precision Structure Strut.**
- **In process now:**
  - **Astrometric Beam Combiner (next page).**
  - **Metrology source pump diode assembly (not shown).**
- **Planned but not yet started:**
  - **Optical Delay Line**
  - **Siderostat gimbal mechanism.**



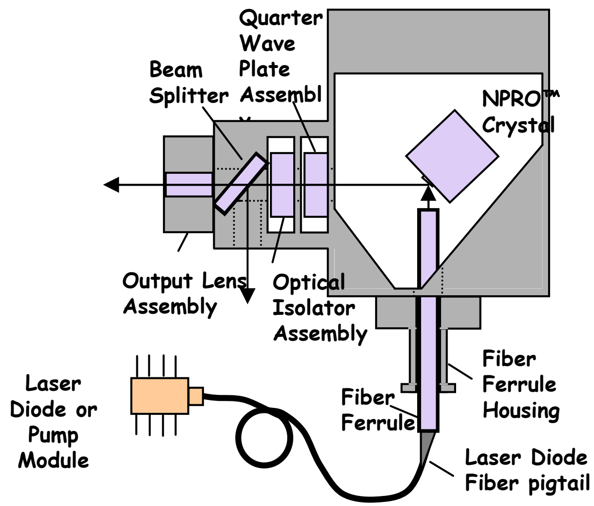
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Example of What's Done During Engineering Risk Reduction

- Lifetime testing. Class A/B missions have a requirement that mechanisms have a 99.7% probability of working throughout the mission (5yrs) AND there is a backup.
  - Eg a PZT actuator will be designed with 2PZTs
  - Laser lifetime.



- The laser used for metrology on SIM is a diode pumped YAG laser (NPRO geometry). Producing ~250mw of 1.319um output. The lifetime limiting component are the pump laser diodes. It is not possible to achieve 99.7% prob that a single pump diode would last 5.5yrs. Several schemes using multiple pump diodes were investigated.
- Most of the other engineering tasks had to do with building the components to survive launch and work in space.



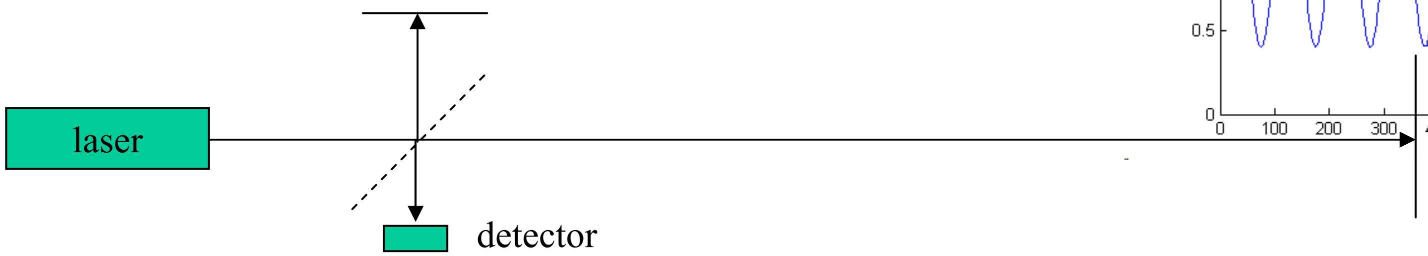
Laser Metrology in SIM

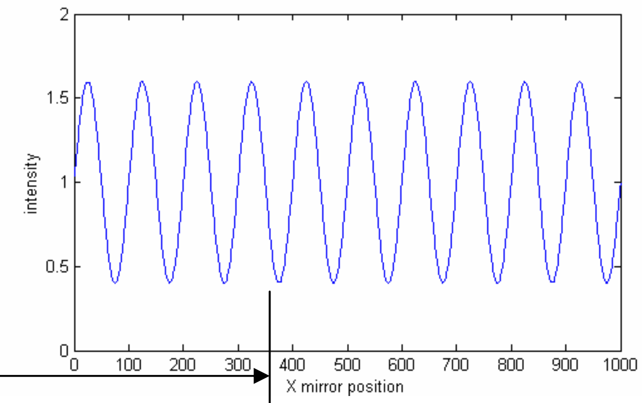
- Basic heterodyne interferometer concept
- Laser source
- Laser gauge
- Phase meter (electronics)

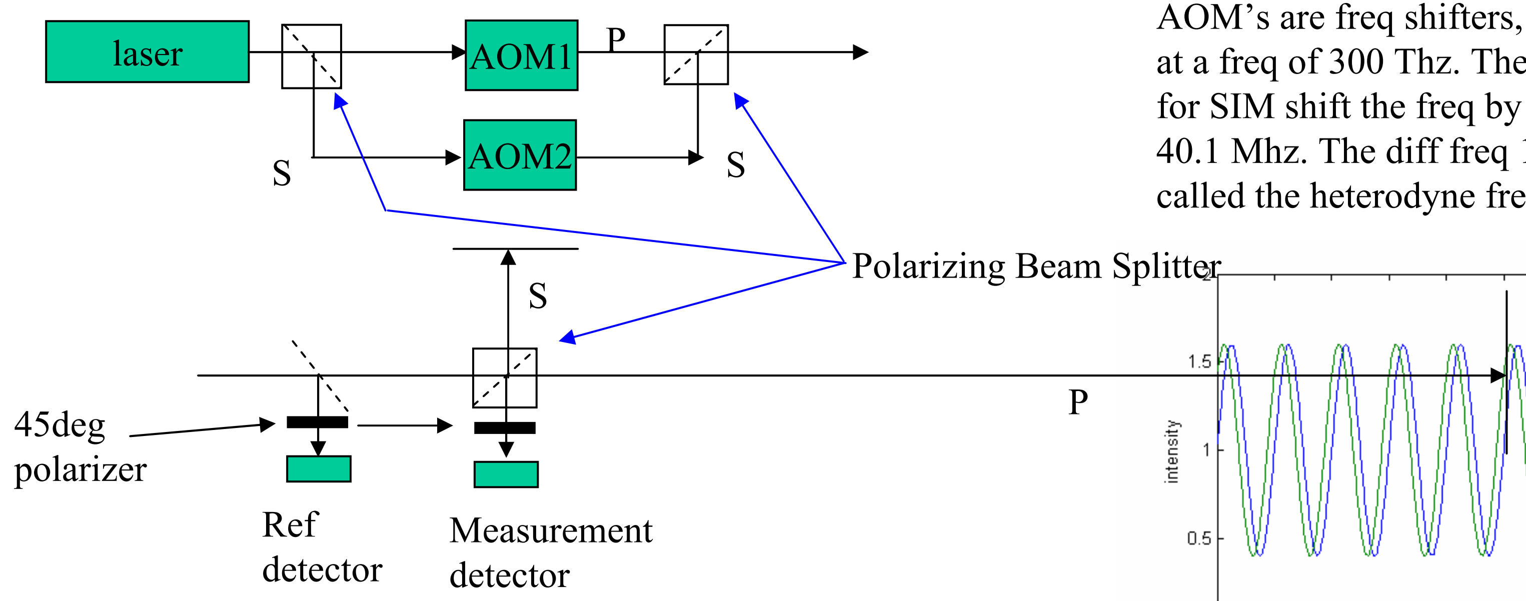
Heterodyne Interferometry

for distance measurement

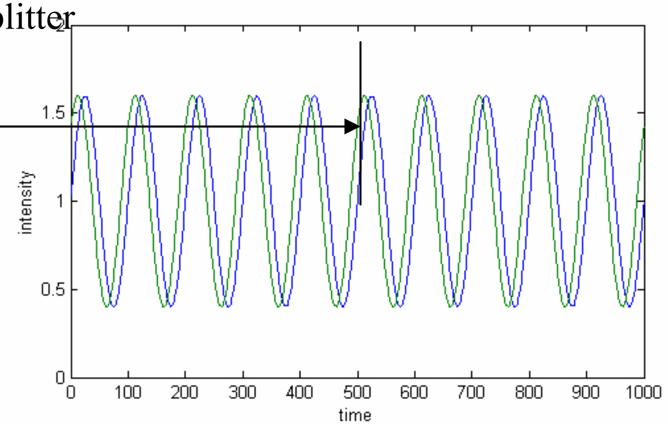
- Michelson interferometer vs heterodyne interferometer





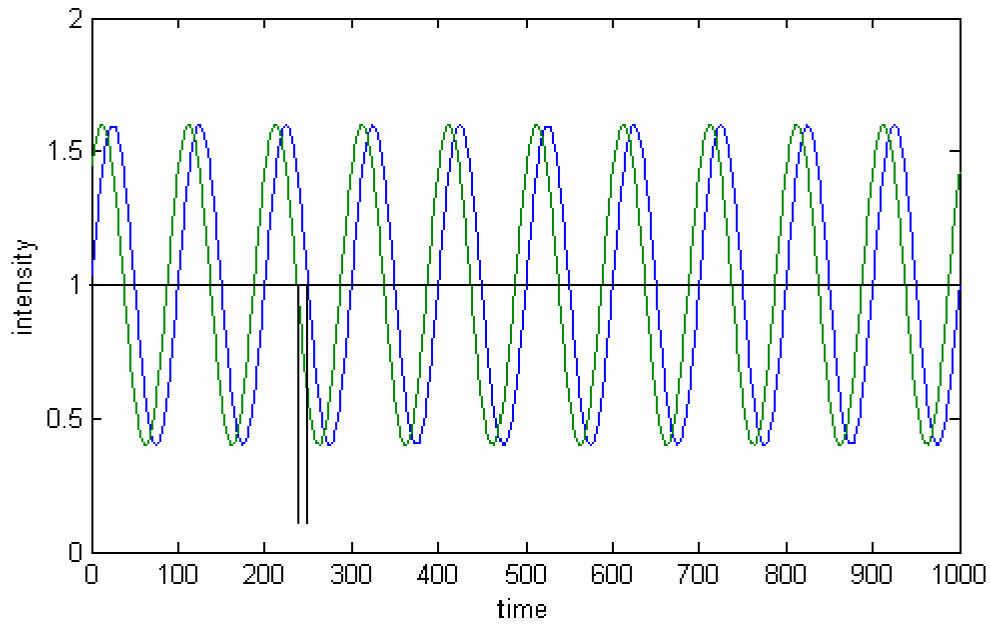


AOM's are freq shifters, a 1um laser is at a freq of 300 Thz. The freq shifters for SIM shift the freq by 40 Mhz and 40.1 Mhz. The diff freq 10~100 Khz is called the heterodyne freq.



Advantages of Heterodyne Interferometry

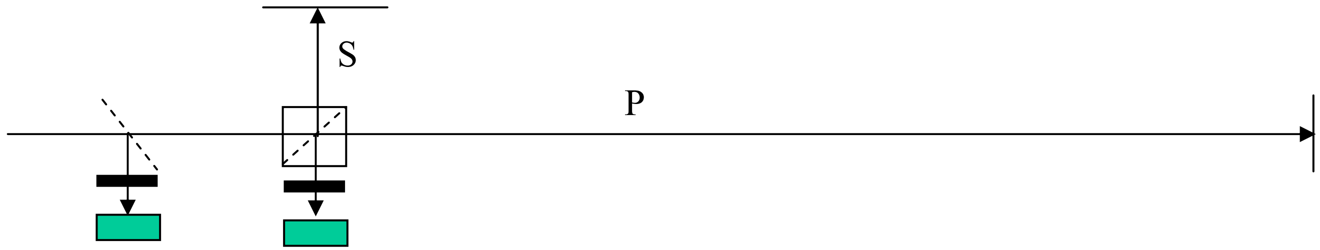
- Signal is AC, mostly immune to dc room light, 60hz flicker etc.
  - Relaxed calibration of DC levels and gain of detector/amp
- Turns length measurement into a time measurement



Time delay measured with high speed clock.
10Khz het-freq, & 500Mhz high speed clock means
the signal is digitized to λ/50,000

Systematic Errors

- The polarization based heterodyne interferometer was commercially introduced by Hewlett Packard (now Agilent Corp) in the 1980's? It is widely used in the semi-conductor fab industry. However it has relatively large systematic (cyclic) errors (~ $\lambda/200$) that arise because of imperfect polarization components (or improperly aligned components)

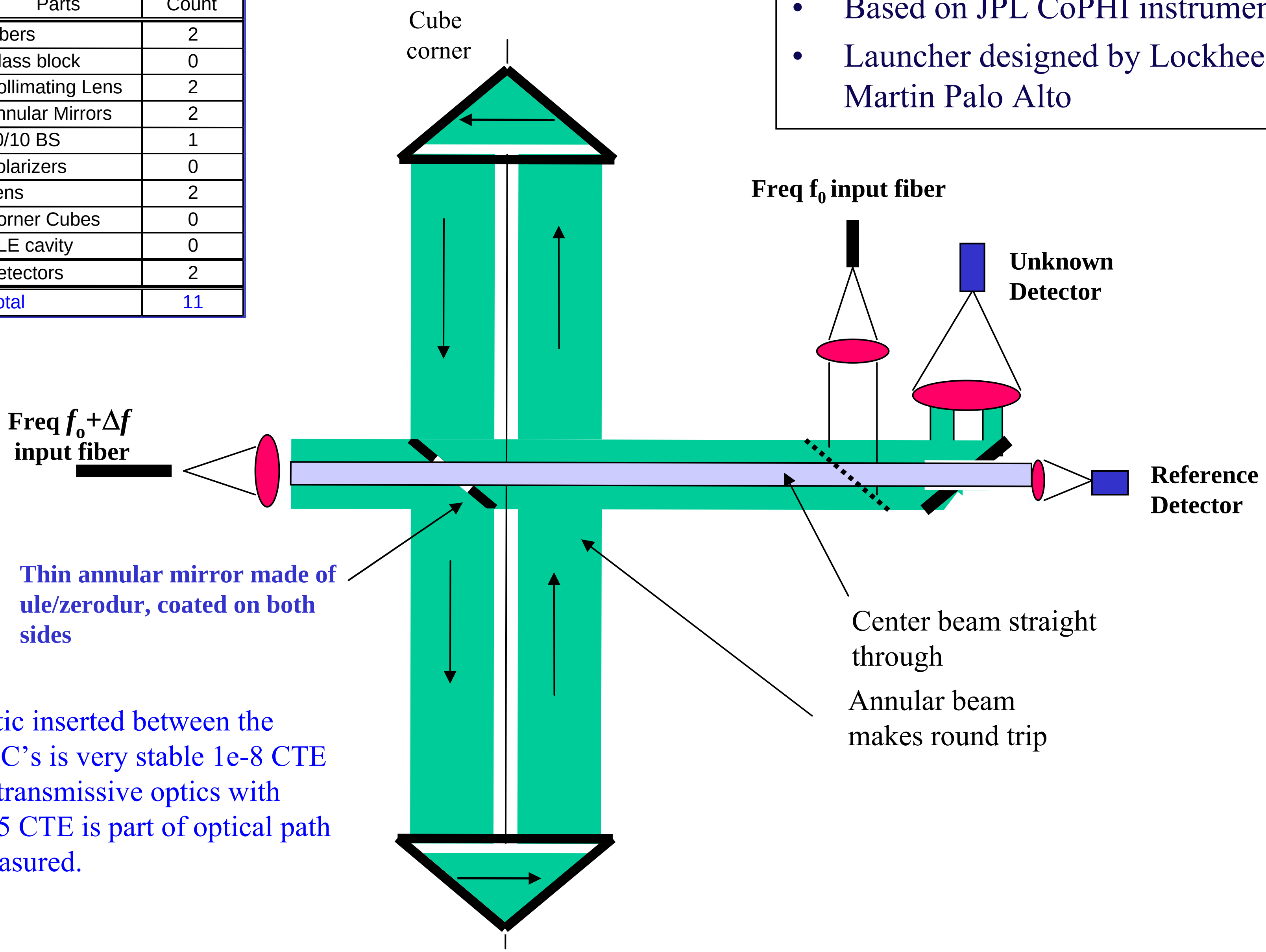


- On SIM we've adopted the spatially separated beam launcher laser gauge. This gauge comes in a variety of configurations.
  - Gauge measures difference in OPD between 2 arms of a stellar interferometer,
  - Gauge measures the distance between two optical fiducials, with the gauge between the two fiducials.
  - Gauge measures the distance between two optical fiducials, with the gauge outside the two fiducials.

Spatially Separated Heterodyne Gauge

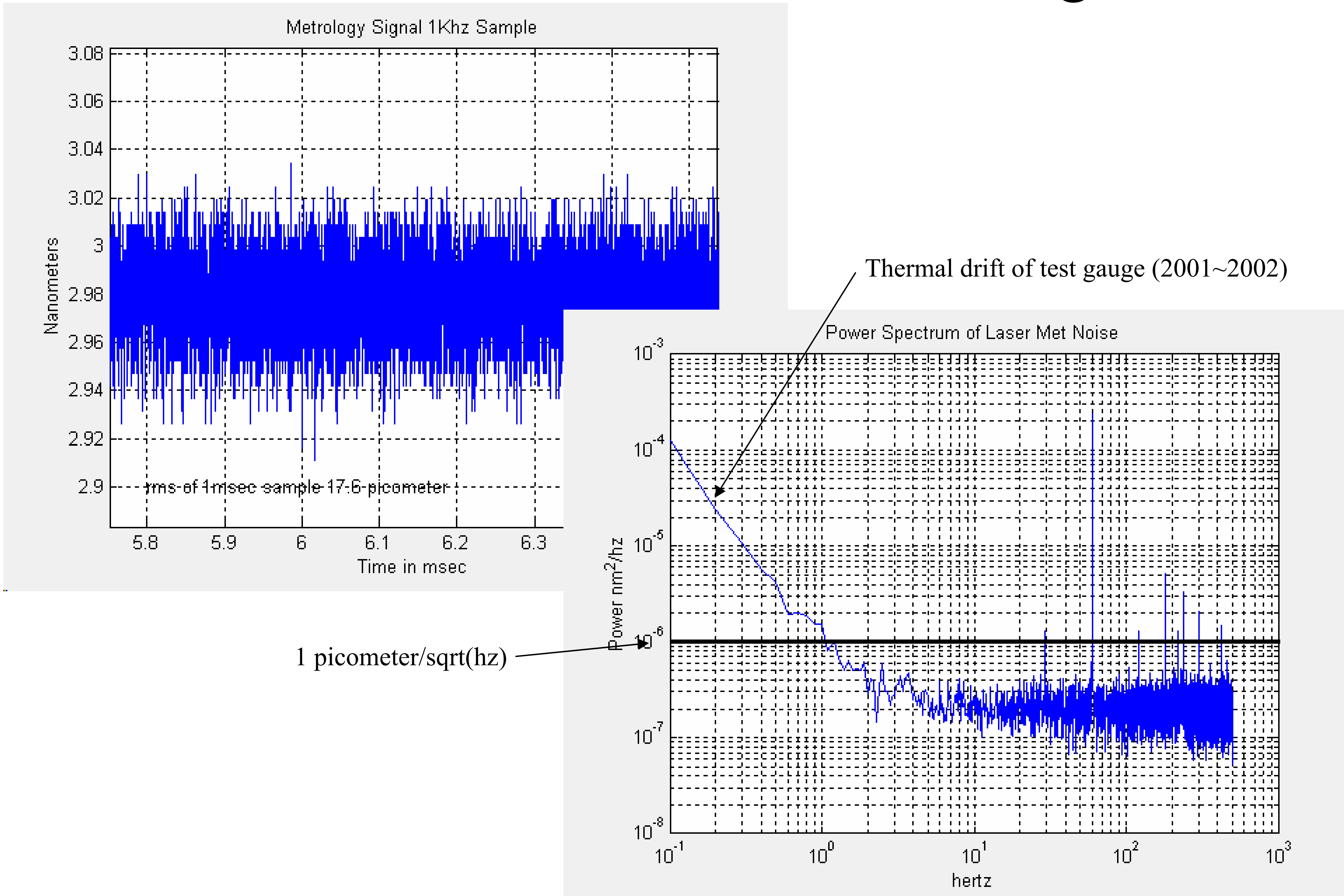
Parts	Count
Fibers	2
Glass block	0
Collimating Lens	2
Annular Mirrors	2
90/10 BS	1
Polarizers	0
Lens	2
Corner Cubes	0
ULE cavity	0
Detectors	2
Total	11

- Based on JPL CoPHI instrument
- Launcher designed by Lockheed-Martin Palo Alto



Optic inserted between the 1 CC's is very stable 1e-8 CTE no transmissive optics with 1e-5 CTE is part of optical path Measured.

SIM Laser Gauge Noise



Thermal drift of test gauge (2001~2002)

1 picometer/sqrt(hz)

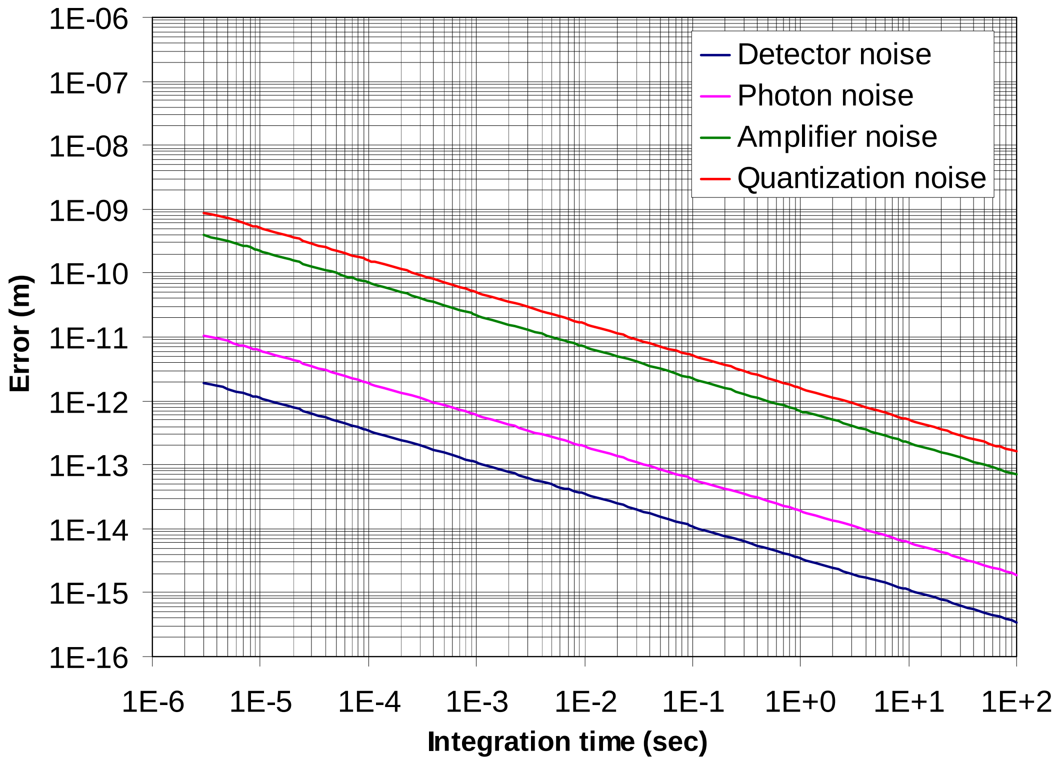
Random Noise Sources (SIM Internal Gauge)

Detector noise	$\varepsilon = \lambda \cdot NEP \cdot \dfrac{\sqrt{B}}{4\pi\eta P}$
Photon noise	$\varepsilon = \dfrac{1}{4\pi}\sqrt{\dfrac{2hc\lambda B}{\eta P}}$
Amplifier noise	$\varepsilon = \dfrac{\lambda}{2\pi}\dfrac{\sqrt{4kTRB}}{\eta PR}$
Phase meter quantization noise	$\varepsilon = \dfrac{\lambda}{\sqrt{12}}\dfrac{f_{het}}{f_{clock}}$

- P=200nW
- NEP=5x10^{-15} W/sqrt(Hz),
- R=100kΩ,
- heterodyne f_{het}=300kHz,
- clock f_{clock}=128MHz,
- bandwidth B=540kHz,

- Use higher laser power
- Use lower heterodyne frequency
- Use longer integration time (averaging)

$$\langle \delta x \rangle = \frac{\varepsilon}{\sqrt{N}} = \frac{\varepsilon}{\sqrt{f_h \tau}}$$

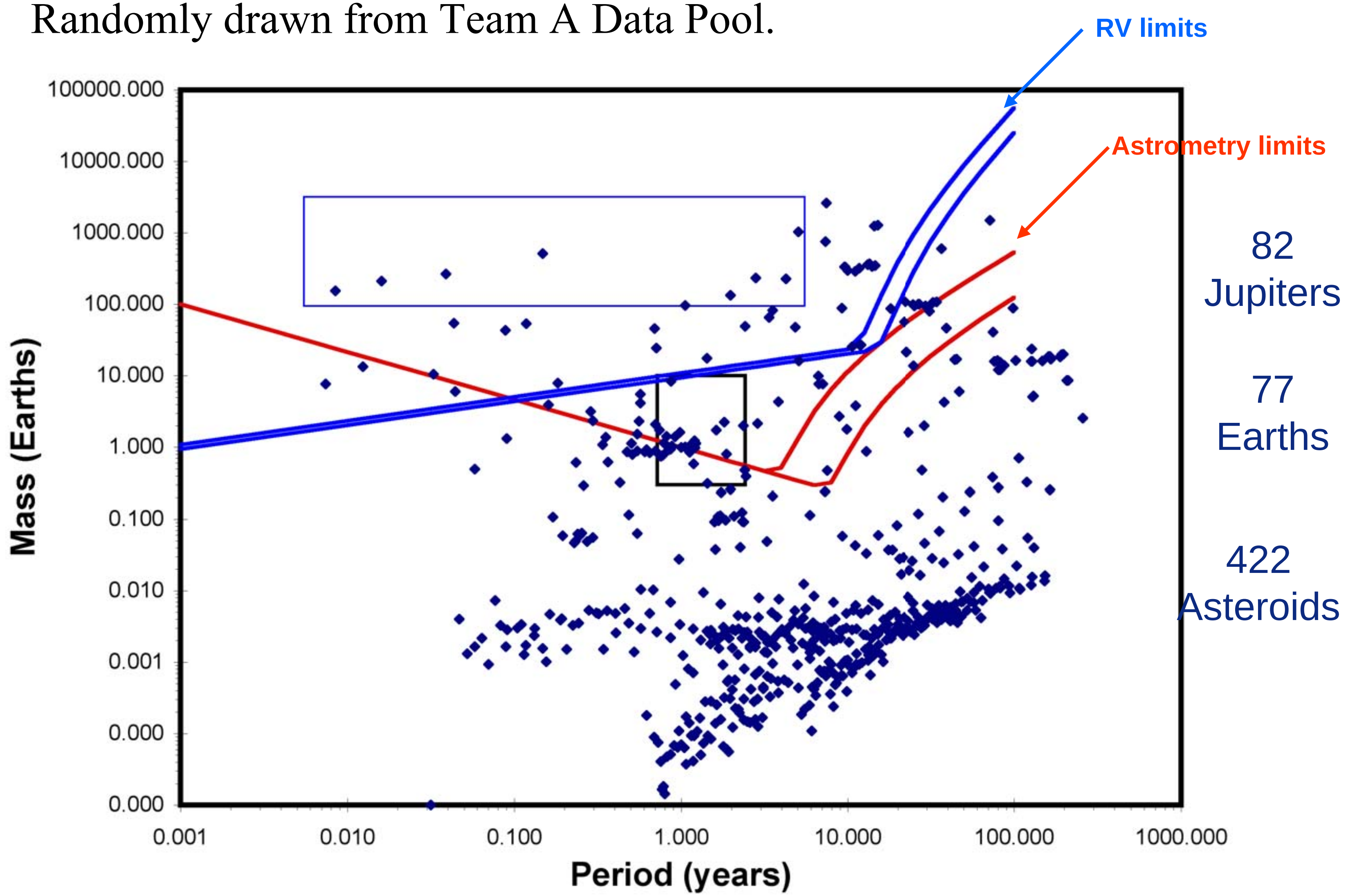


Short Skip Back to SIM Science

- In early 2008, NASA asked if astrometry could detect an Earth in a multiple planet system, where other planets had astrometric signatures much larger than the Earth.
- The project conducted a double blind study, where 1 team generated fake planetary systems, their astrometric and radial velocity signatures with noise, and 5 separate teams attempted to "solve" for the planets.
  - Team A's Generated planetary systems
  - Team B Randomized orbit (orbit phase and orientation of system) and generated the data (with noise)
  - Team C's Solved for the planets

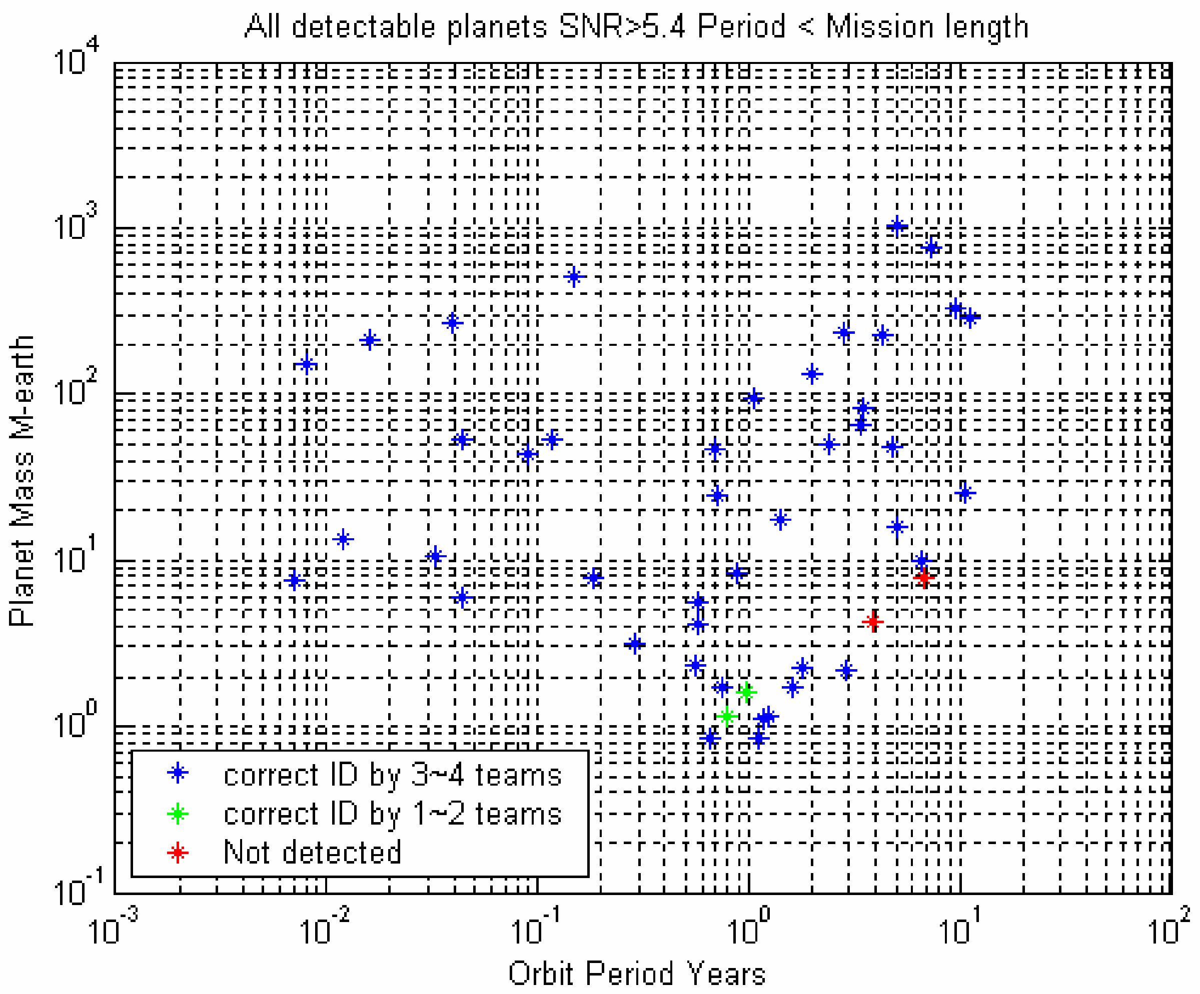
Blind Test Data: 48 stars and 581 objects

- Randomly drawn from Team A Data Pool.



Completeness,

What fraction of reasonably detectable planets were detected?



Define SNR>5.8 as Threshold for detectability

All planets, period < 5,10yr There are 48 reasonably detectable planets (out of 95 total planets)

Relevant Statistics

- Criteria for a successful solution. The solution had to have the correct planet period AND the correct planet mass. (to +/- 2 sigma, where sigma is the Cramer Rao bound)
- When judging how well the team C's did in finding Exo-Earths there are two important statistics
  - **Completeness** How many planets were found, that should have been found (had SNR> 6)?
  - **Confidence** Of the planets that were reported to have been found, how many of them were real?

Confidence of Detection = # det/(#det + # false_positives)

Completeness = #det/(# detectable planet (solor))

	All planets	Hab Zone	0.3~10Me	Earths
Confidence	98%	100%	96%	100%
Completeness	96%	100%	91%	100%

Summary

- The SIM-Lite observatory is designed to search 60~100 nearby stars for Earth clones (down to 1 Mearth mass, in the middle of the habitable zone).
- In addition it has a strong astrophysics science component, dark matter, QSO's, Neutron stars and BH's.
- The technology program for SIM is complete
- We're investigating other uses for the metrology, such as for GG.

SIM Beam Launcher (circa 2000)

Parts	Count
Fibers	2
Glass block	2
Spherical Mirror	2
PBS (regular)	2
90/10 BS	1
Polarizers	2
Lens	2
Corner Cubes	0
ULE cavity	0
Detectors	2
Total	15