SIM PlanetQuest Science & Technology:

A Status Report

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Проблемы Современной Астрометрии,
Всероссийская конференция-школа для молодых ученых
Звенигород, Россия - 22-26 октября 2007

Scales for comparison – food for thought

Space Interferometry Mission

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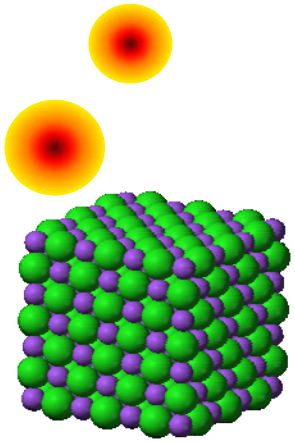
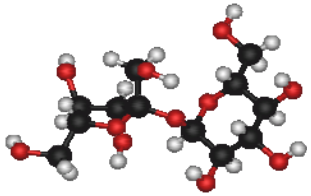
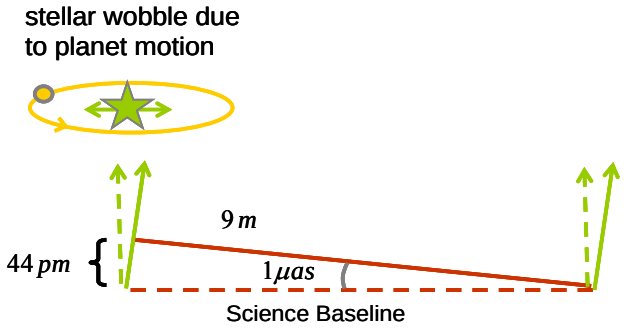
- Hydrogen atom “radius” ~ 26 pm
- Helium atom “radius” ~ 31 pm



- Salt crystal cell width ~ 560 nm



- Sucrose (table sugar) cell width ~ 1 nm
- Delay change for 1 mas angle ~ 44 pm



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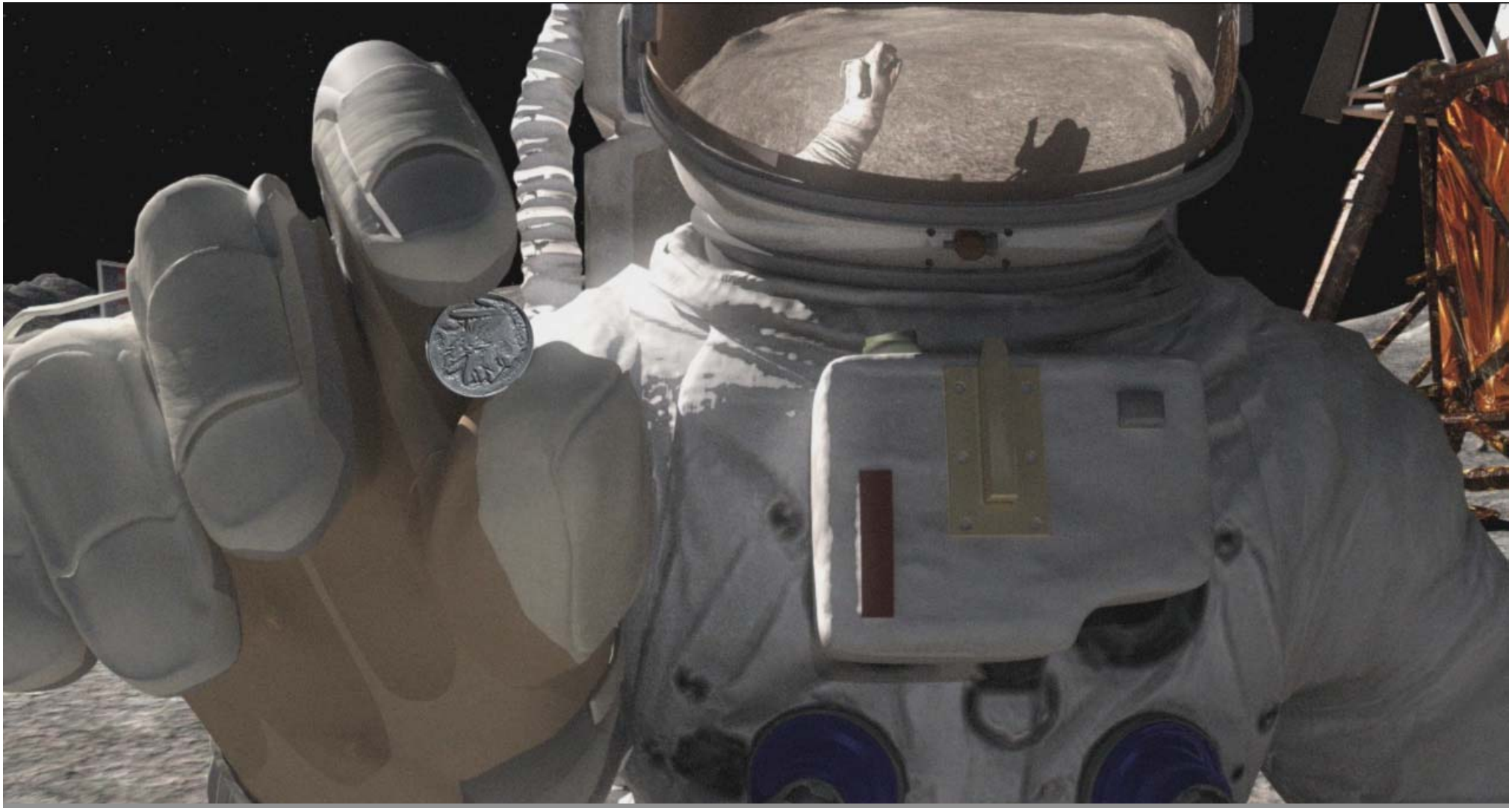
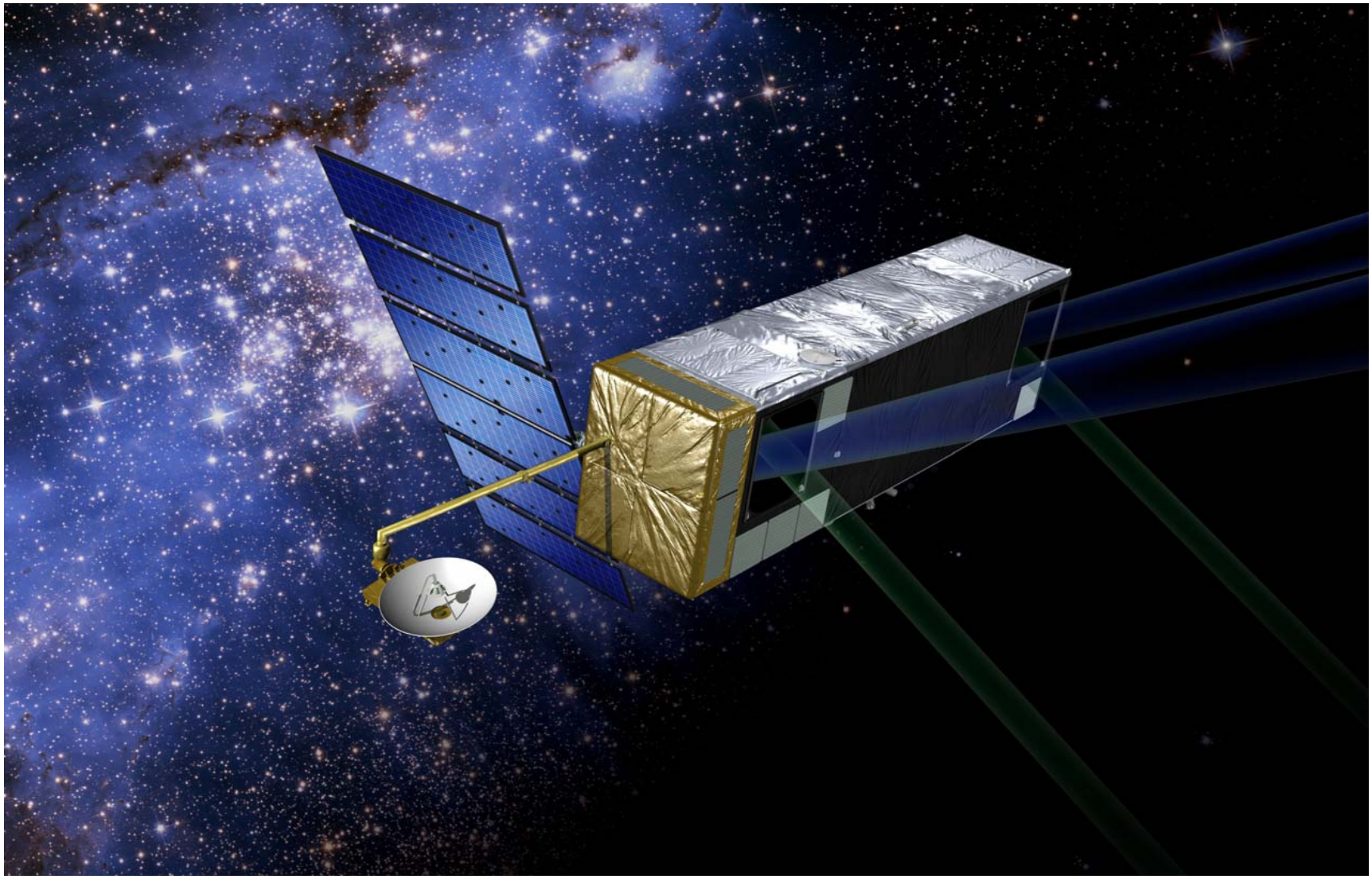
1 μas = the ***thickness*** of a nickel on the Moon, as seen from Earth



- **Hydrogen atom “radius” ~ 26 pm**
- **Delay change for 1 μas angle ~ 44 pm**

How to measure fringes?



Space Interferometry Mission

SIM

With SIM PlanetQuest!

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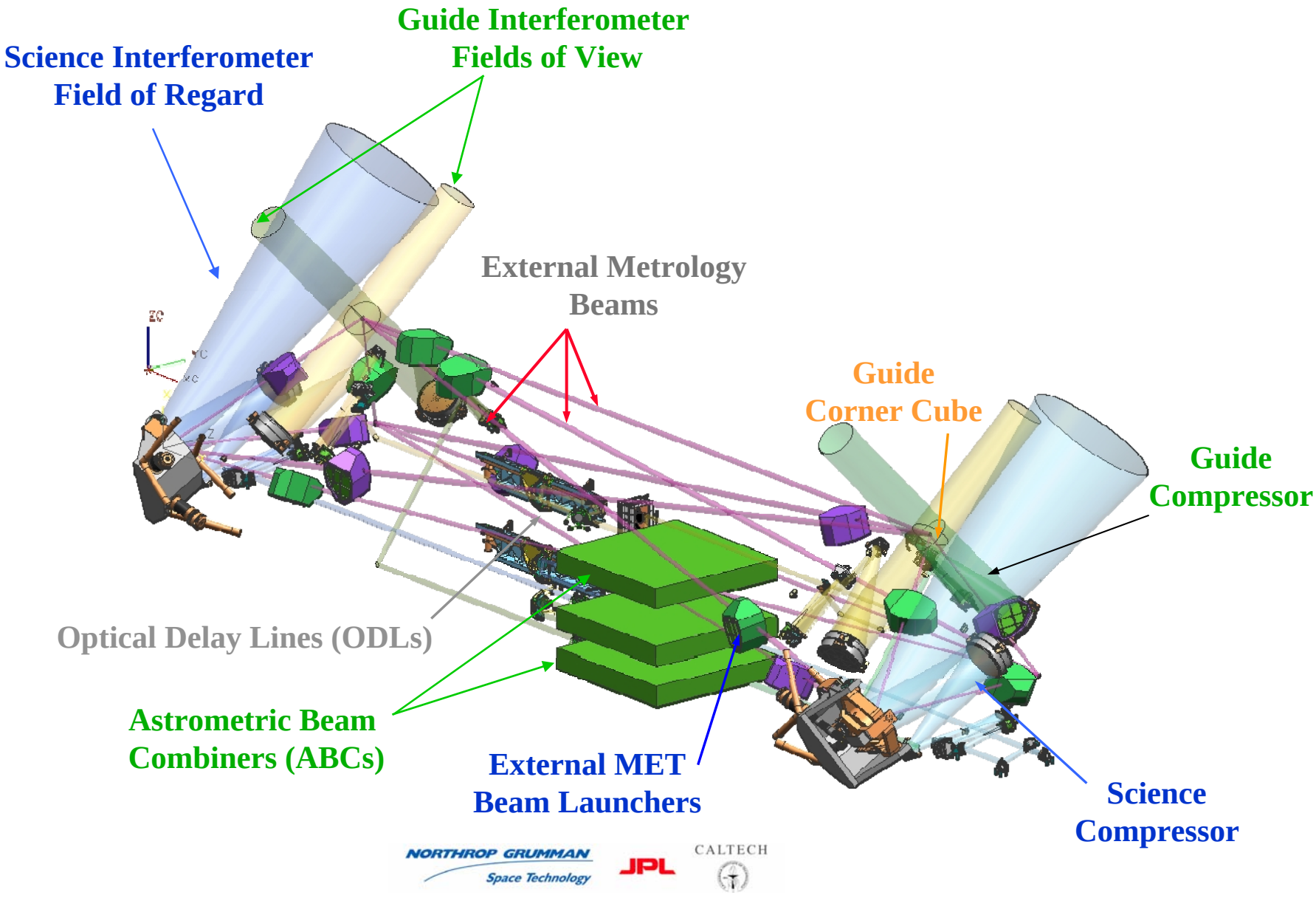
Its size

~12 m

SIM Configuration



Space Interferometry Mission

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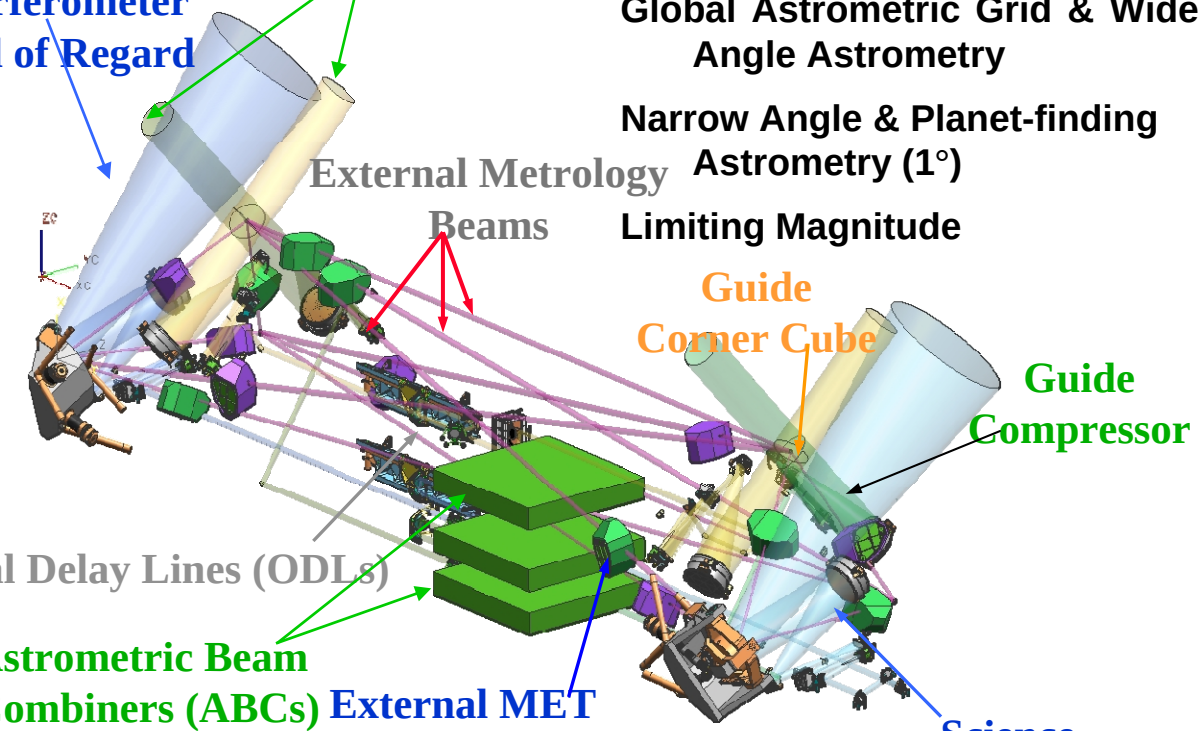
SIM Configuration

Space Interferometry Mission

SIM

Science Interferometer Baseline	9 m
Guide Interferometer Baselines	7.2 m
Wavelength range	0.4 – 1.0 mm
Telescope Aperture	0.30 m diameter
Astrometric Field of Regard	15 degrees
Narrow Angle Field of Regard	1 degree
Detector	Si CCD
Orbit	Earth-trailing solar orbit
Science Mission Duration	5 years
Global Astrometric Grid & Wide Angle Astrometry	4 μas mission accuracy
Narrow Angle & Planet-finding Astrometry (1°)	1 μas single measurement accuracy
Limiting Magnitude	20 mag



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SIM PlanetQuest Design and Performance

Science Interferometer Baseline	9 m
Guide Interferometer Baselines	7.2 m
Wavelength range	0.4 – 1.0 mm
Telescope Aperture	0.30 m diameter
Astrometric Field of Regard	15 degrees
Narrow Angle Field of Regard	1 degree
Detector	Si CCD
Orbit	Earth-trailing solar orbit
Science Mission Duration	5 years
Global Astrometric Grid & Wide Angle Astrometry	4 μas mission accuracy
Narrow Angle & Planet-finding Astrometry (1°)	1 μas single measurement accuracy
Limiting Magnitude	20 mag

- *More information on SIM is available at: http://sim.jpl.nasa.gov*

Space Interferometry Mission

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What's An Orange Peel?

Space Interferometry Mission

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"Orange peel" coverage means that the celestial sphere is covered in a spiral pattern that moves from one side of the sphere to the opposite side.

Escher

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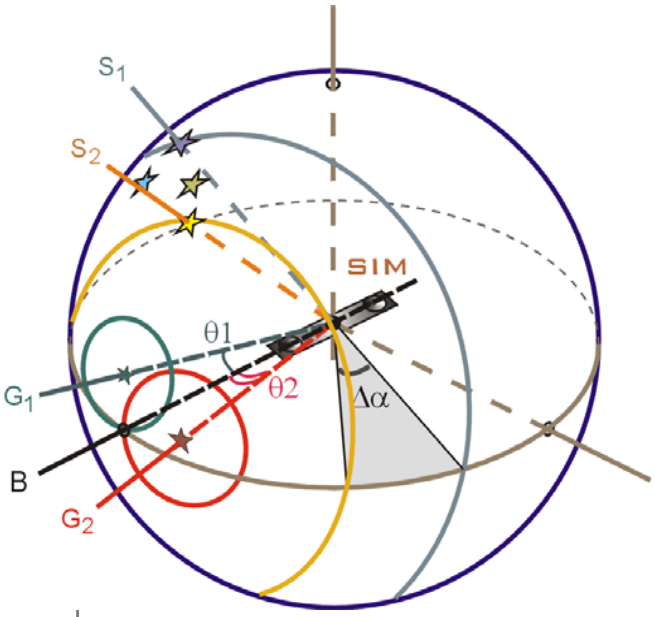
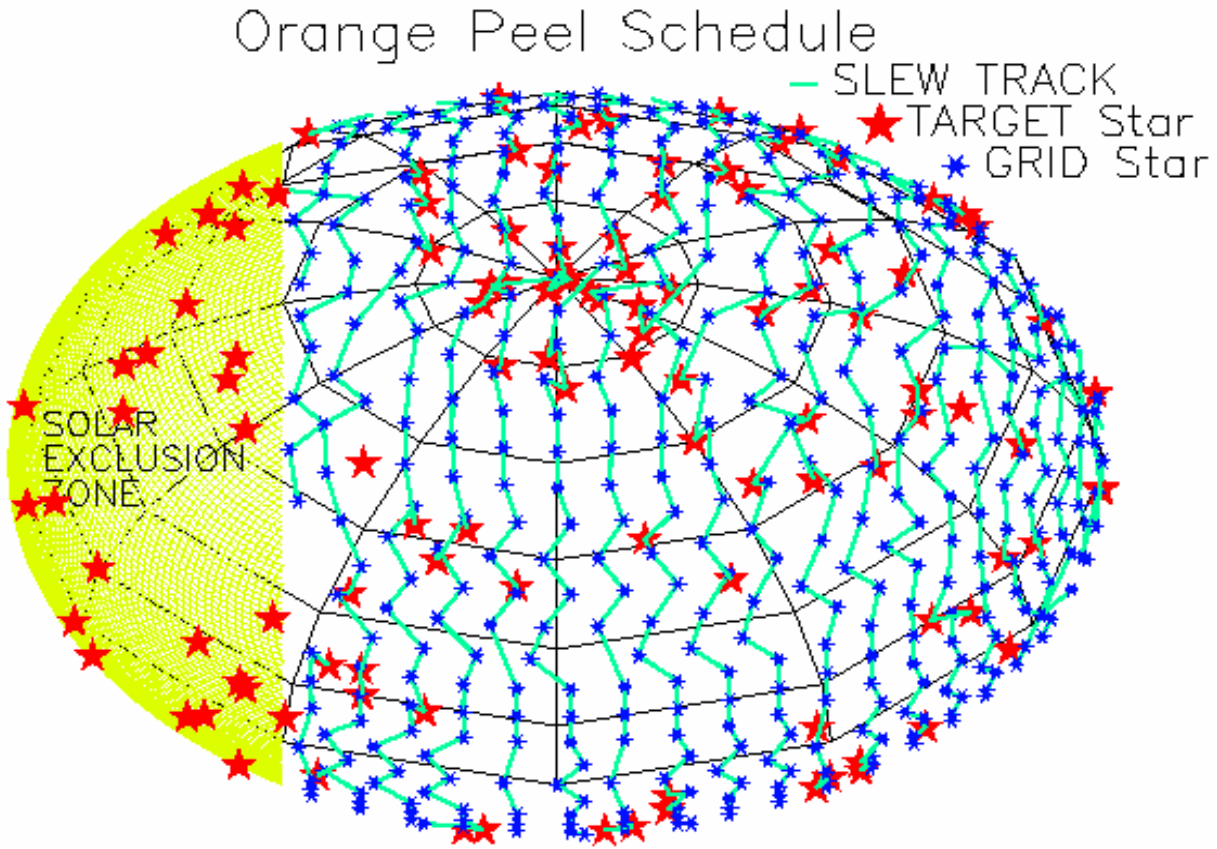
Observing scenario – containing objects of interest





Space SIM

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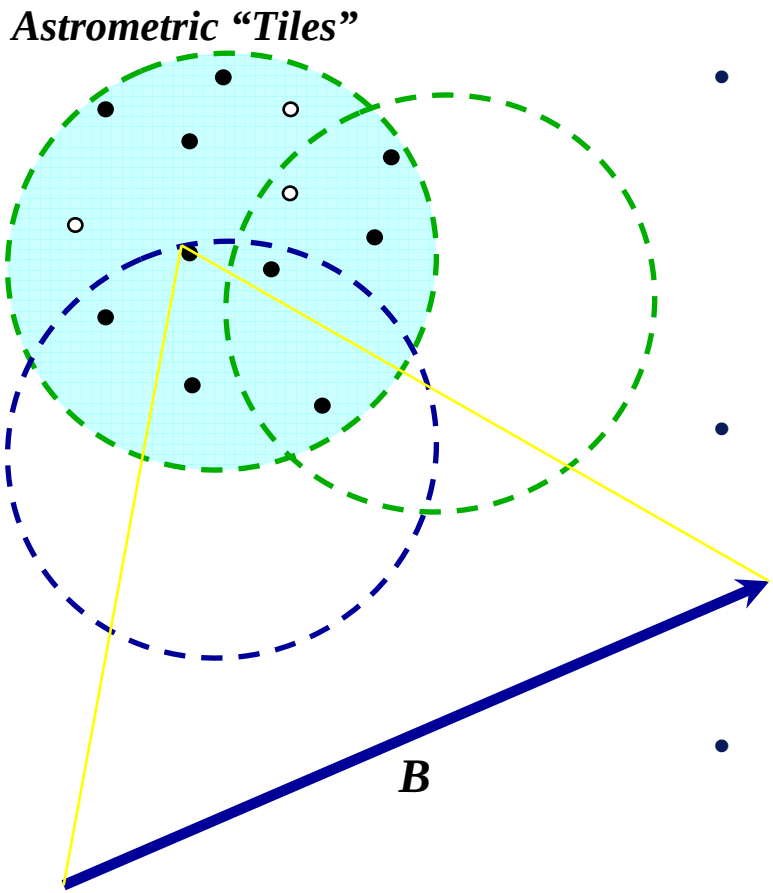
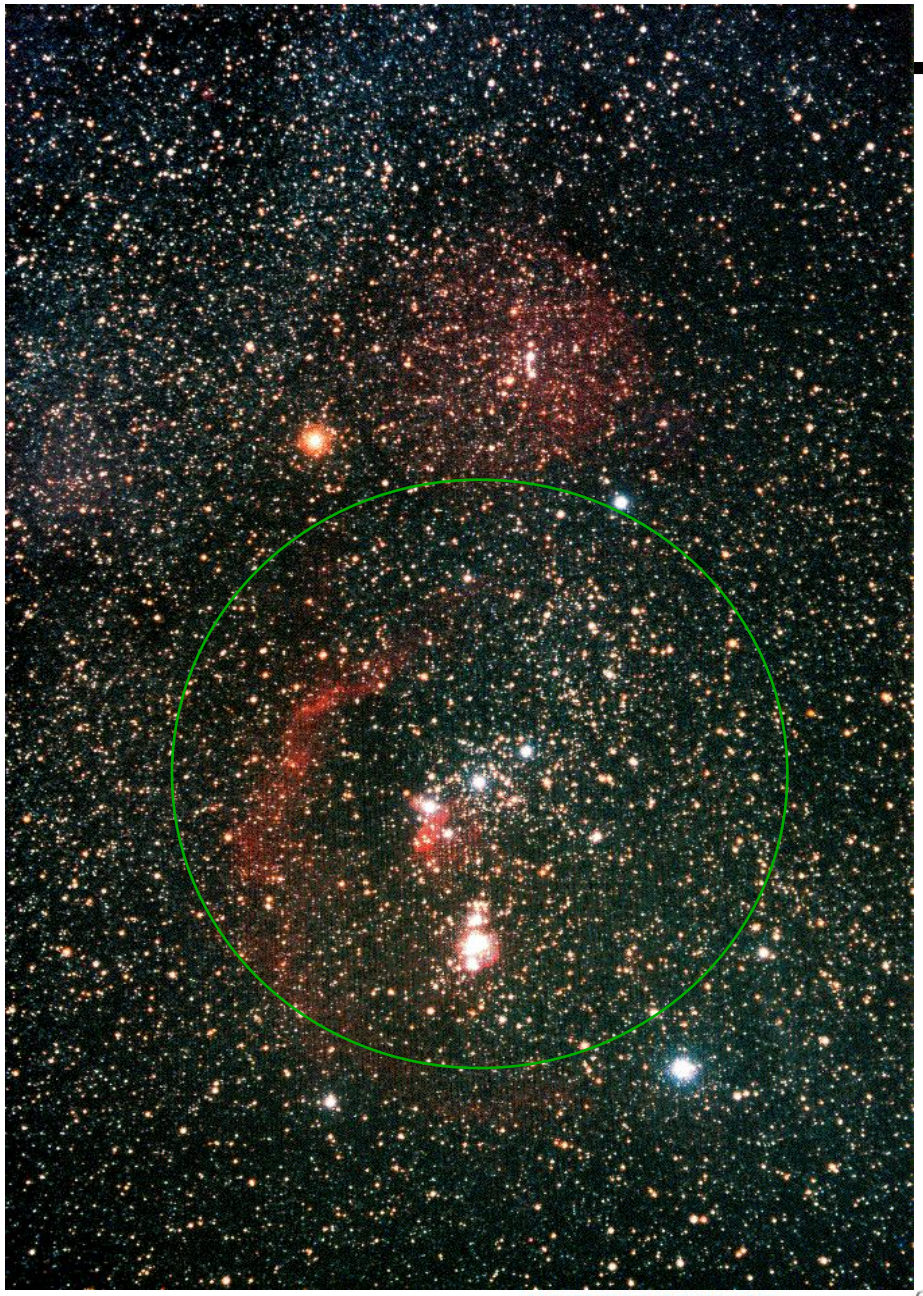
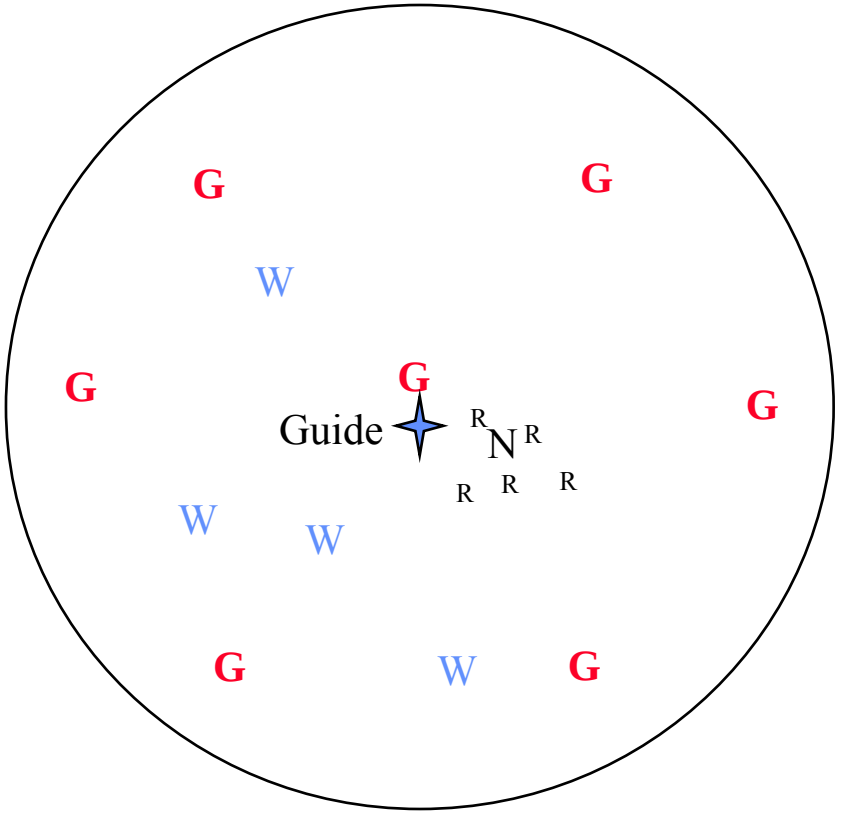
SIM Astrometric Measurements



$$d = s \bullet B + c$$

- Grid of stars is measured over entire sky
  - **Grid is referenced to extra galactic objects**
  - **Position, parallax, proper motion are measured for all grid stars**
  - **Science targets are measured wrt grid**
- Grid is subdivided into 15 degree tiles
  - **6-8 grid stars per tile**
  - **Up to 50 additional science targets**
  - **Tiles centered on grid stars**
  - **Tiles overlap**
- SIM measures angle between stars in a grid.
  - **S/C attitude is held fixed**
  - **Instrument scans over 15 degree tile**





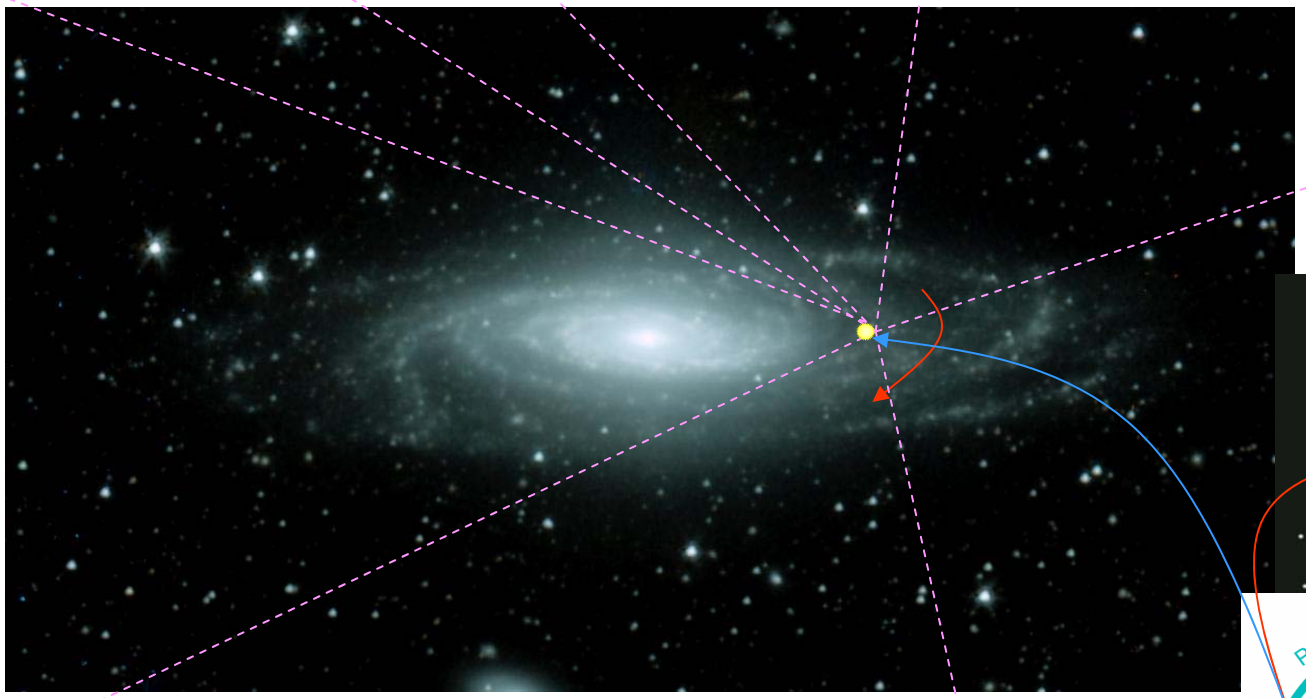
The Field Of Regard covers Orion. 1302 red giants form the grid of reference stars.

All objects are moving, twisting and turning, so what is “fixed”?

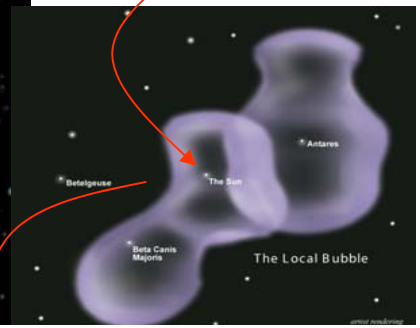
QSO

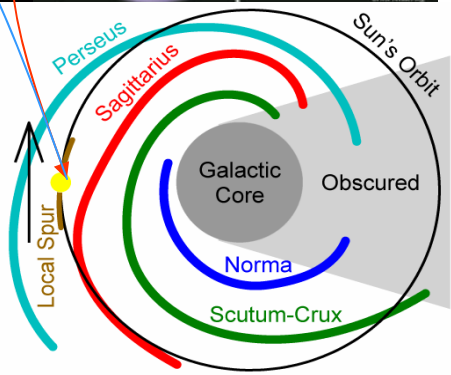
Space Interferometry Mission

SIM



We are here♠





♠Border of alpha & beta quadrants according to *Star Trek* world

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How Precise is SIM?

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

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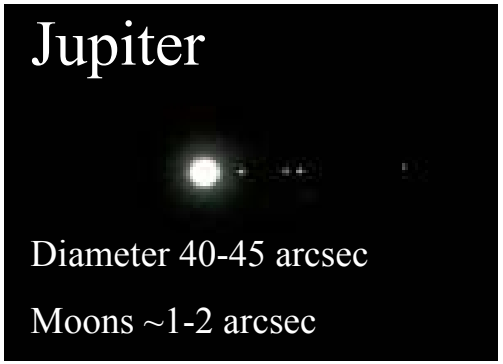

SIM Positional Error Circle (4 μas)

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

Parallactic Displacement of Galactic Center

Hipparcos Positional Error Circle (0.64 mas)

HST Positional Error Circle (~1.5 mas)

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

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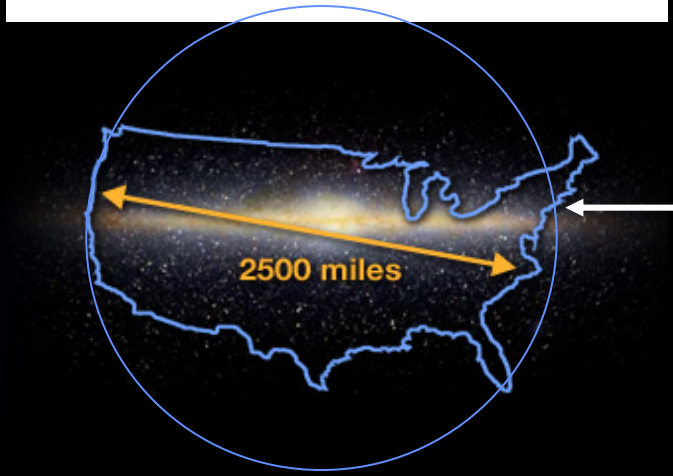
Cosmic scales

Our whole Solar System

would be this big

Our Milky Way Galaxy



would be the size of the United States.

And the neighborhood

where we've found new planets would only be the size of Manhattan.

Peer Reviewed Technology Gates – Managing Technology Development

Accomplishment of Technology Gates Against Original Due Dates Stated in May 2001 Letter

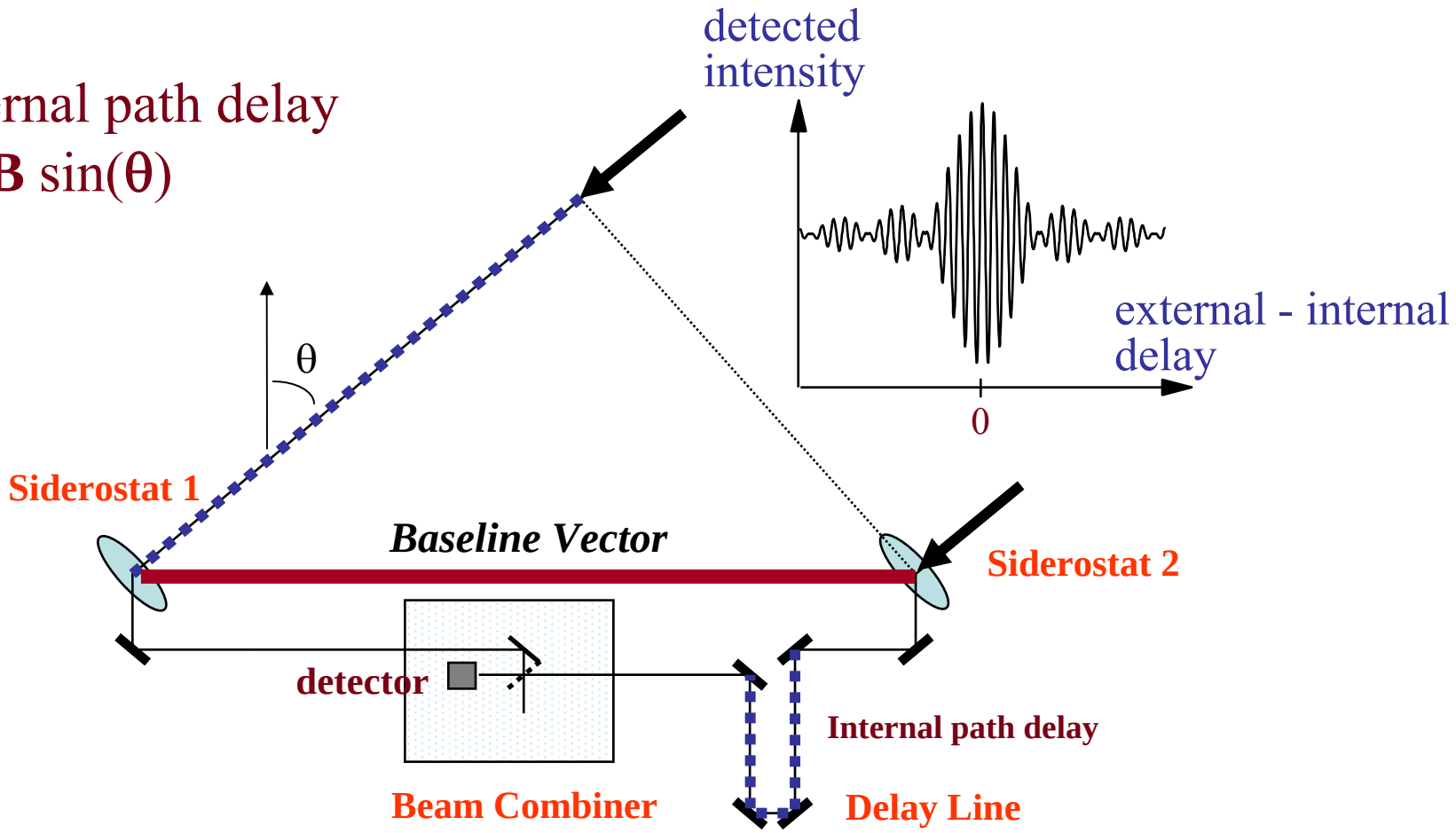
Technology Gate	Description	Due Date	Complete Date	Performance
1	Next generation metrology beam launcher performance at 100pm uncompensated cyclic error, 20pm/mK thermal sensitivity	8/01	8/01	Exceeded objective
2	Achieve 50dB fringe motion attenuation on STB-3 testbed (demonstrates science star tracking)	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

Legend
pm = picometer
mK = milliKelvin
dB = decibel (50dB = factor of 300)

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

Astrometry with an Interferometer

External path delay
x = B sin(θ)

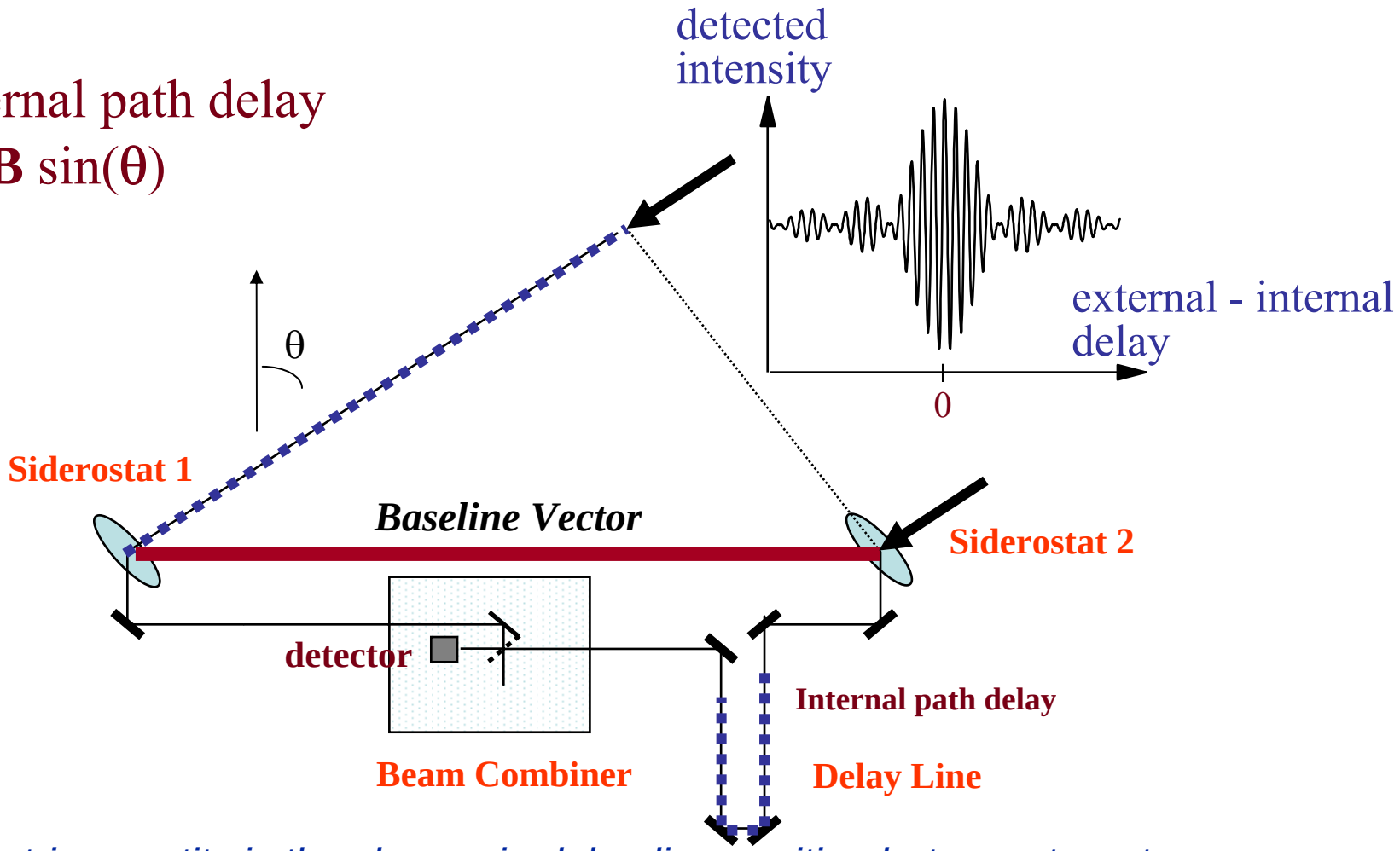


Astrometric quantity is the change in delay-line position between targets

Astrometry with an Interferometer

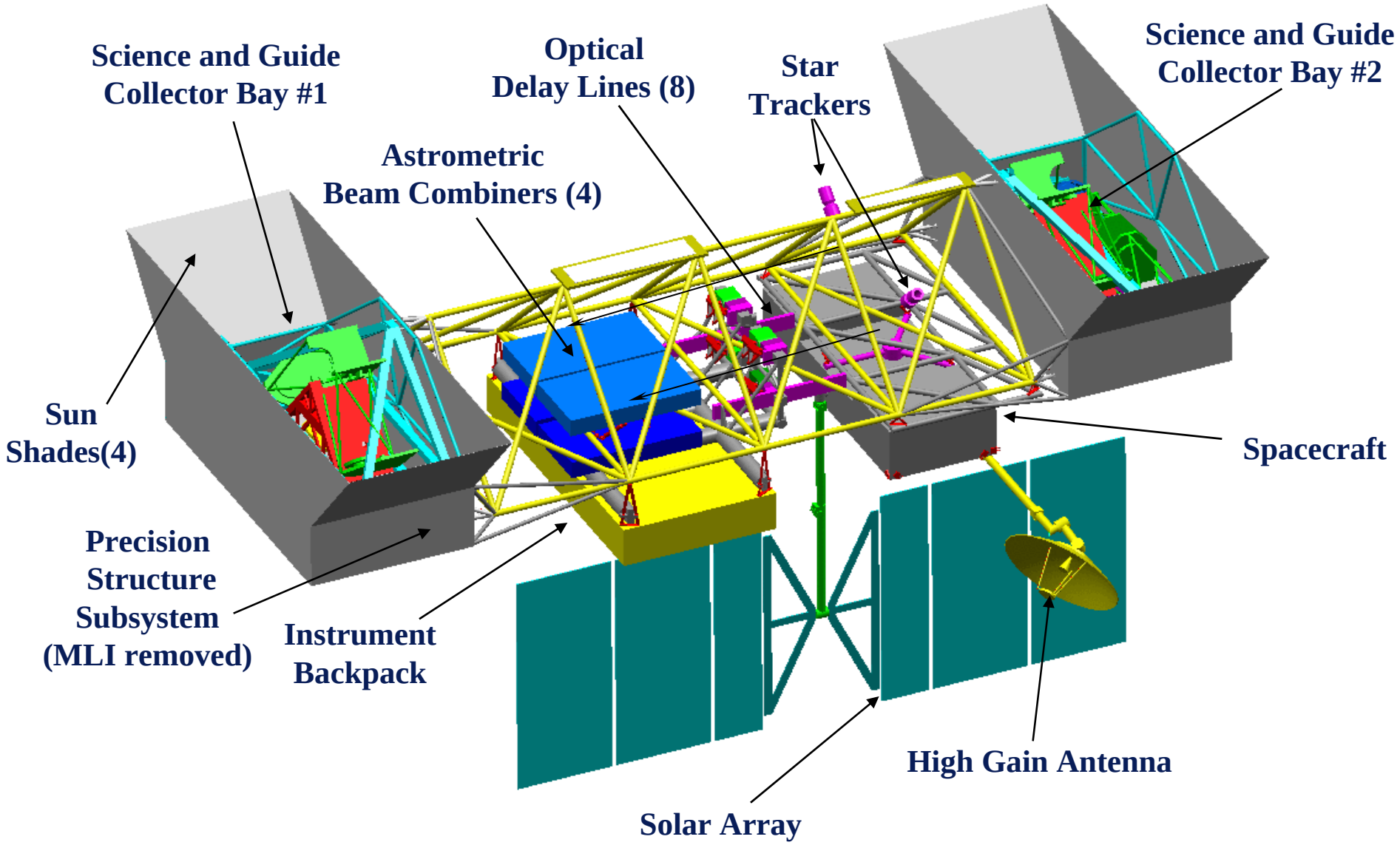
External path delay

$\mathbf{x} = \mathbf{B}\sin(\theta)$

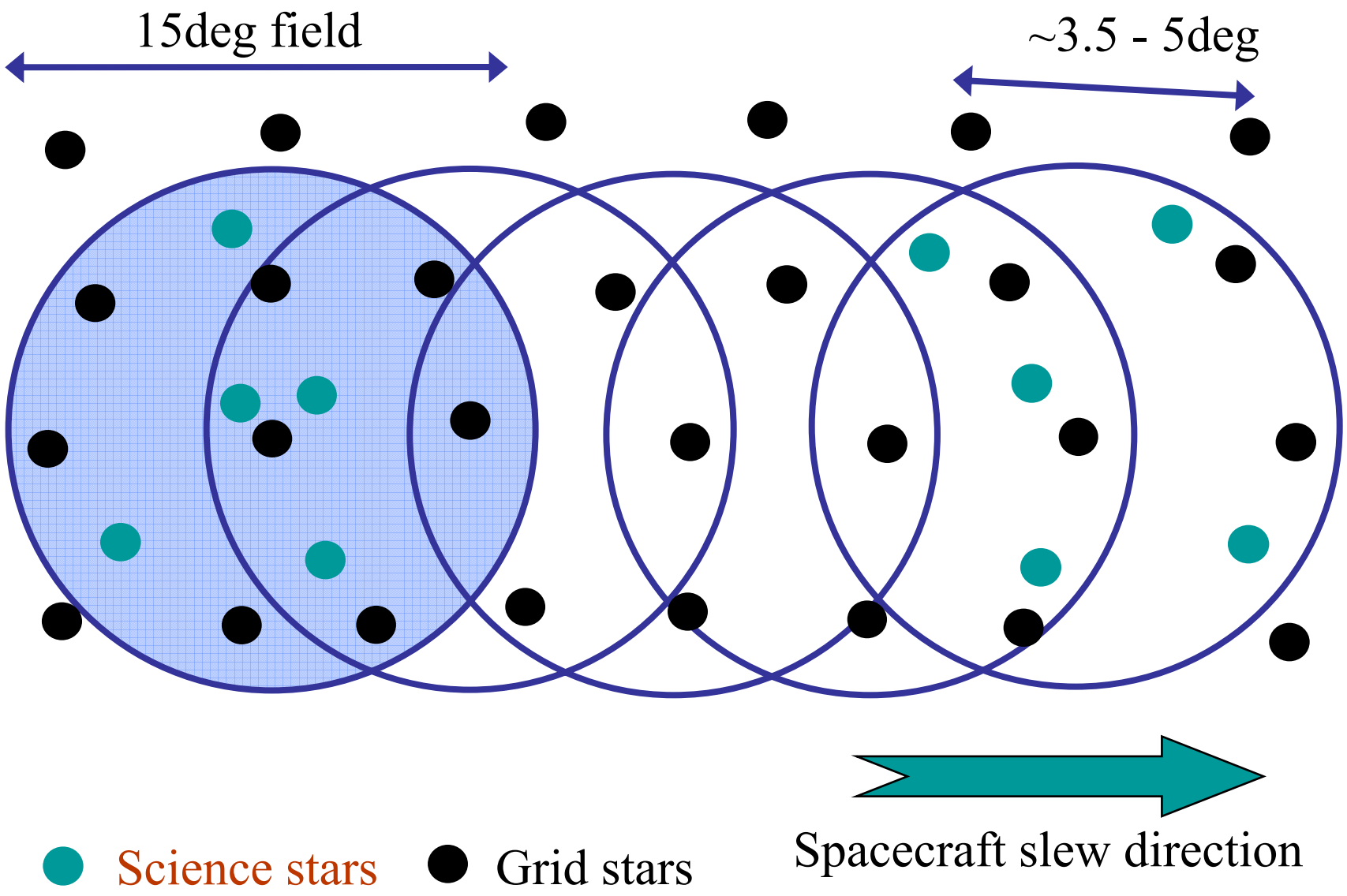


Astrometric quantity is the change in delay-line position between targets

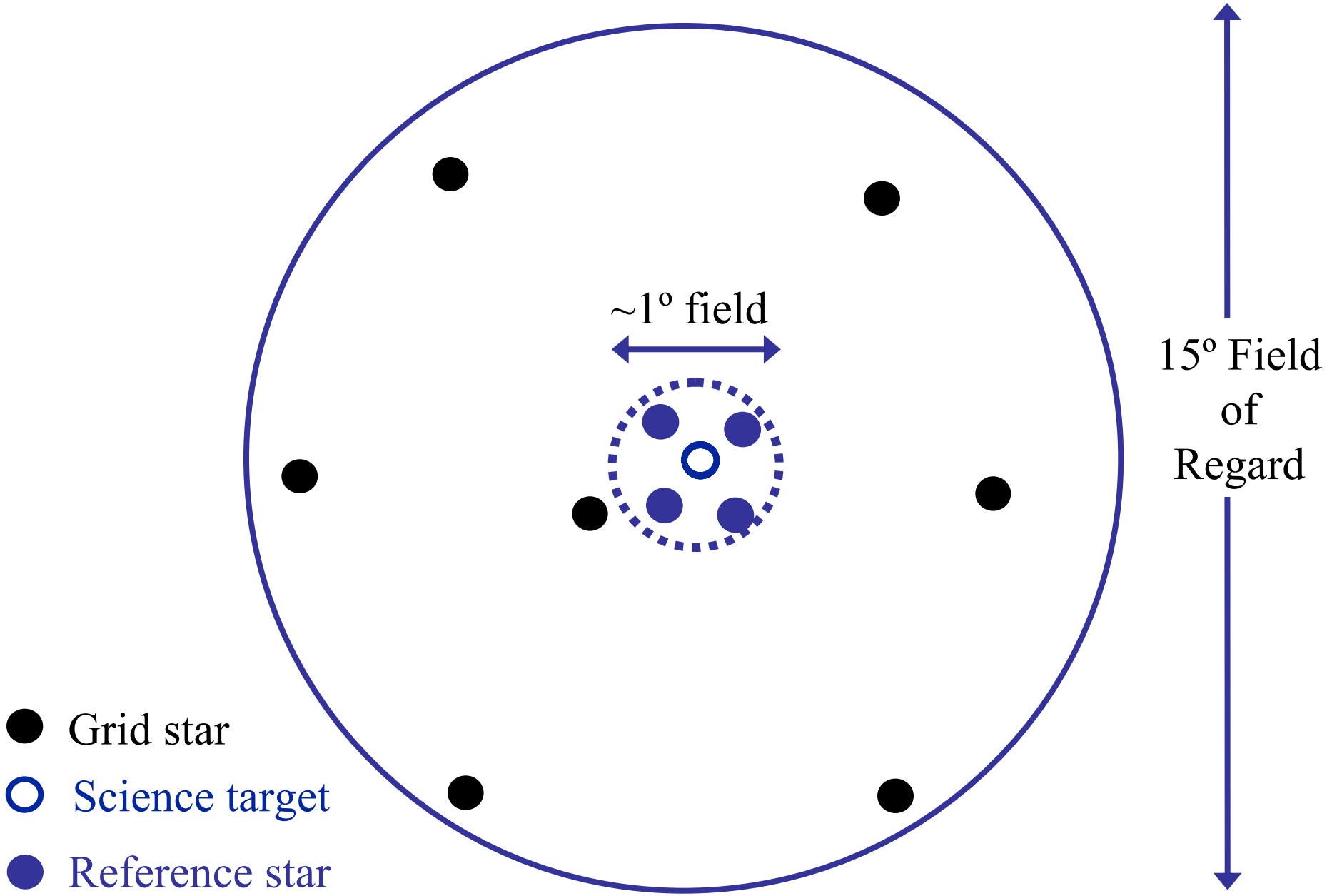
SIM PlanetQuest Flight System Architecture



Global Astrometry Observing Scenario

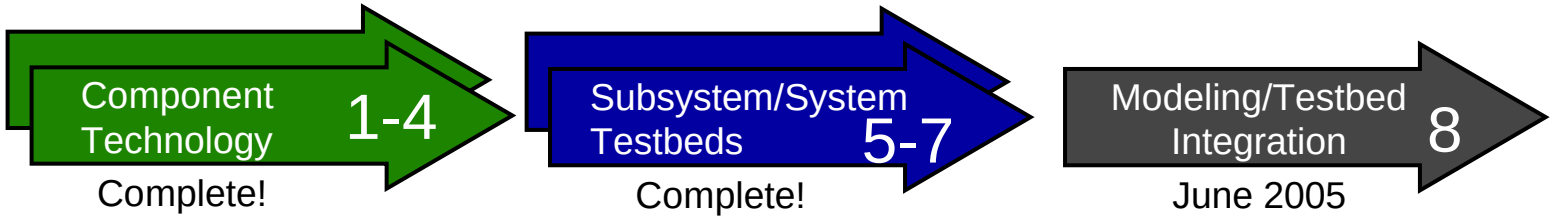


Planet Search Observing Scenario



SIM Technology Nearly Complete

- NASA HQ and SIM project laid out 8 Technology Milestones in 2001
  - 4 Milestones prior to Phase B start
  - 4 more Milestones prior to Phase C/D start
- Technology is on schedule! One Milestone remains…



Goal-level performance has already been demonstrated in the SIM Testbeds!

Technology Milestone 8

MAM

KITE

Subsystem-level Testbeds

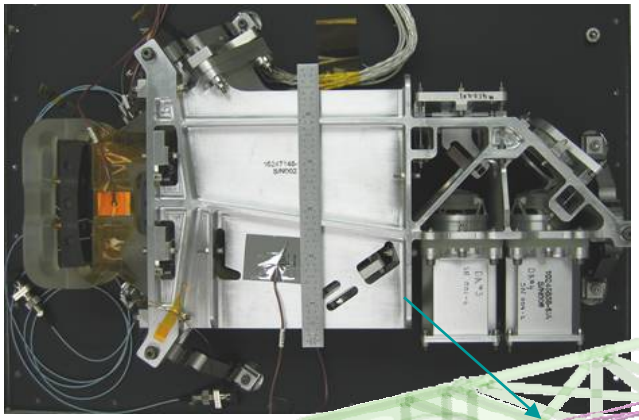
STB-3

System-level Testbed

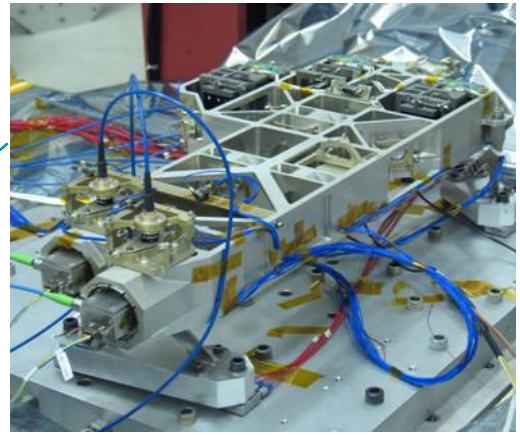
TOM-3

Modeling/Testbed Integration

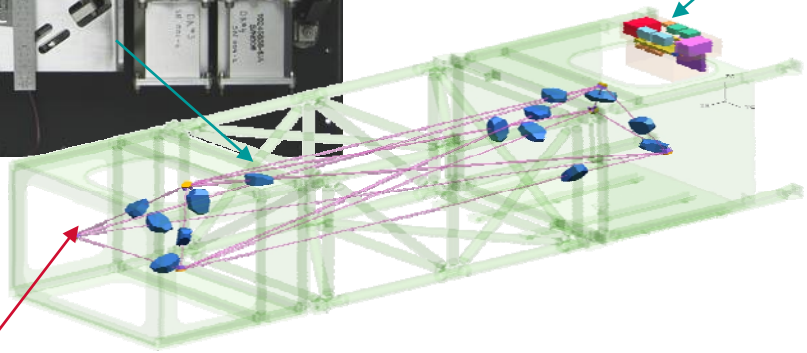
Ready to build!

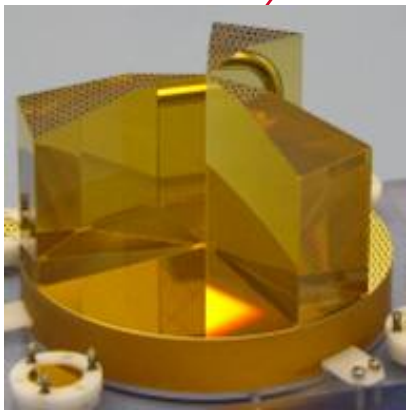


External
Metrology
Launcher

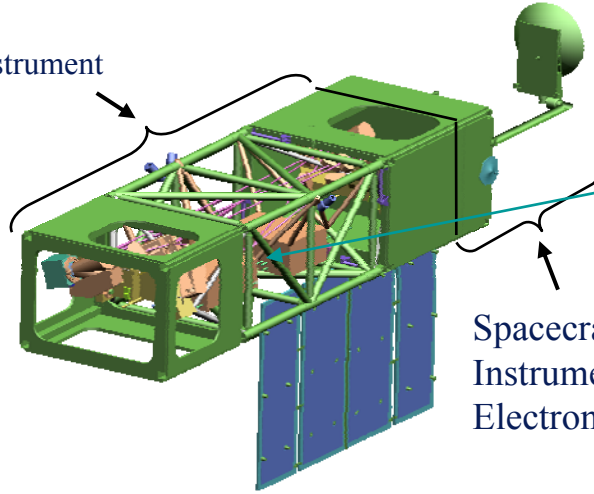


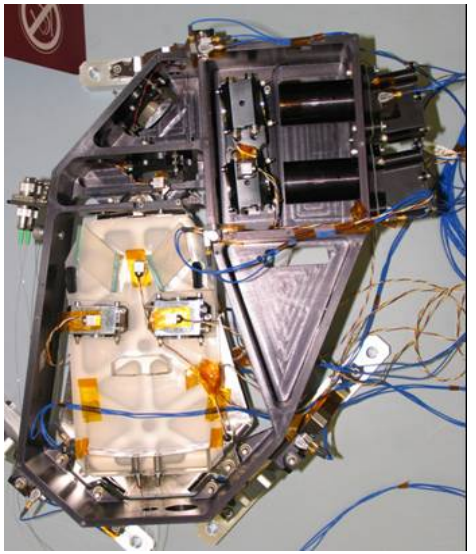
Metrology
Source





Double Corner
Cube



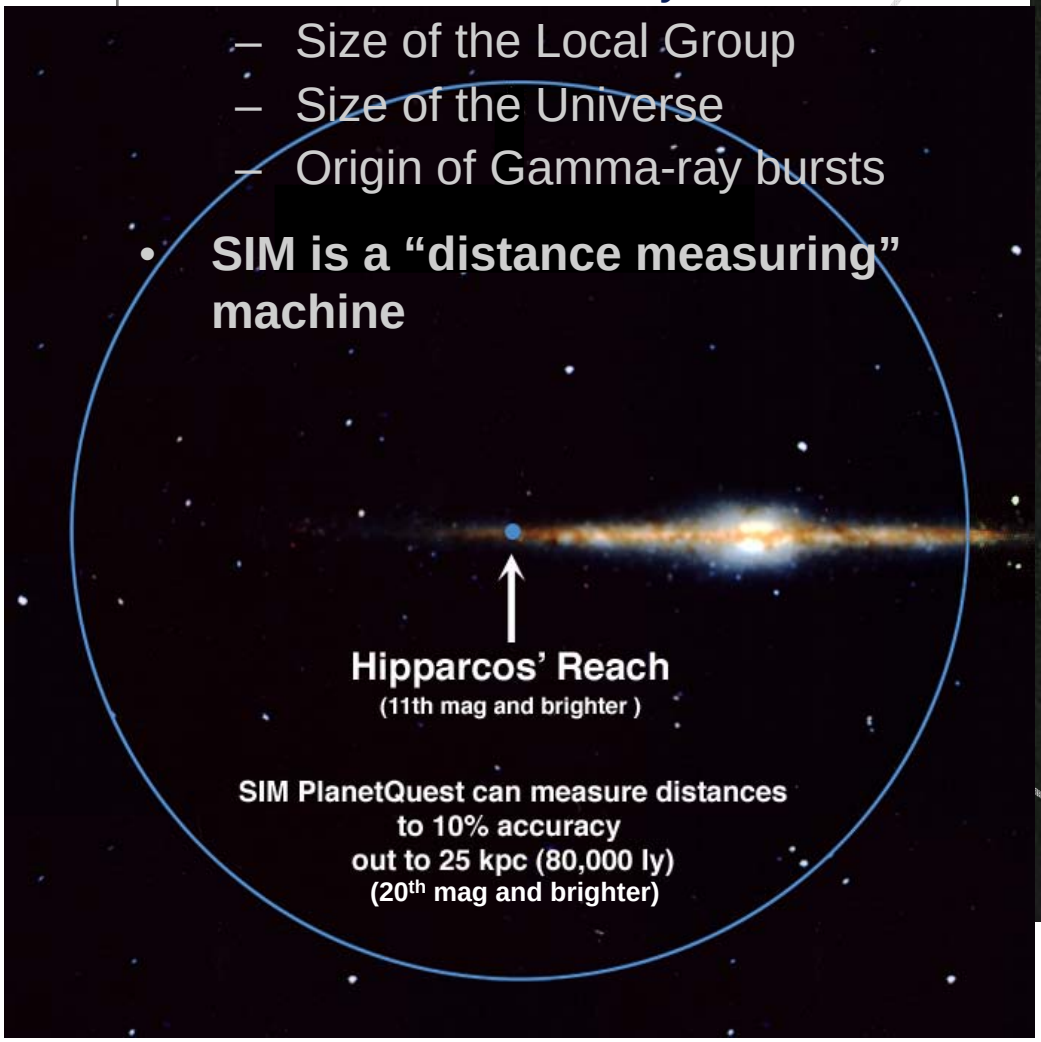


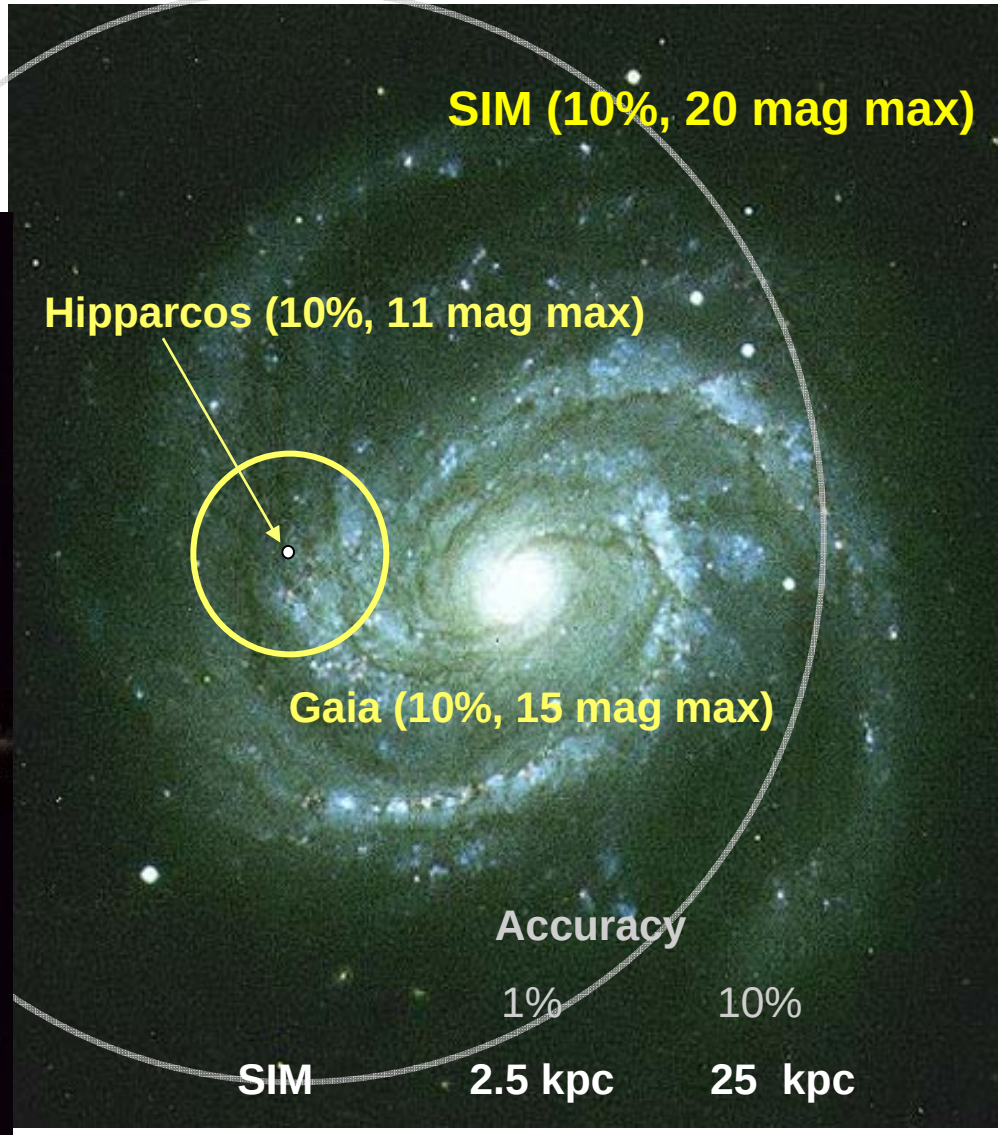
Internal Metrology
Launcher

Nanometer Control & Picometer Knowledge: Flight Ready Hardware
(**TRL6 since 2005**)

SIM Covers the Galaxy

- **The history of astronomy is entwined with the determination of reliable distances**
  - Size of the Galaxy
  - Size of the Local Group
  - Size of the Universe
  - Origin of Gamma-ray bursts
- **SIM is a "distance measuring" machine**





	Accuracy 1%	10%
SIM	2.5 kpc	25 kpc
GAIA	0.4 kpc	4 kpc
Hipparcos	0.010 kpc	0.1 kpc

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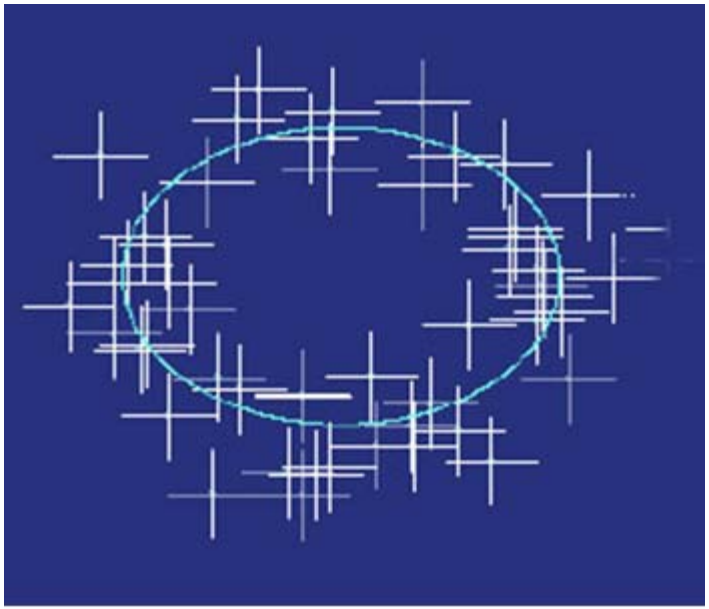
Principle of Astrometric Planet Detection

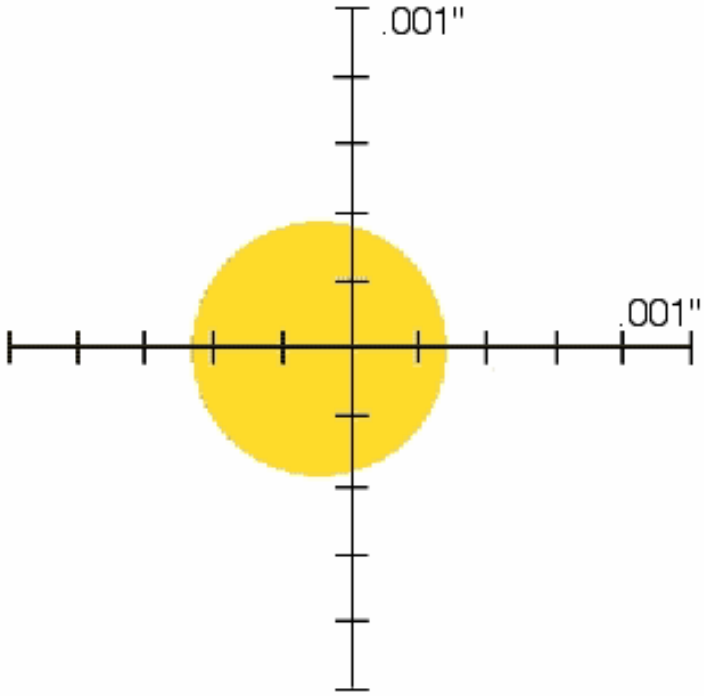
How Much Wobble?



SIM Simulation:

detecting a planetary orbit with a series of 2-D measurements

Orbit parameter	Planet Property
Mass	Atmosphere?
Semi-major axis	Temperature
Eccentricity	Variation of temp
Orbit Inclination	Coplanar planets?
Period	



"The wobble effect": our Solar System as seen at 10 pc distance

- 1 tick mark = 200 μas
- SIM accuracy = 1 μas (single meas.)
- Sun-Jupiter wobble = 500 μas
- Sun-Earth wobble = 0.3 μas

Space Interferometry Mission

SIM

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Space Technology

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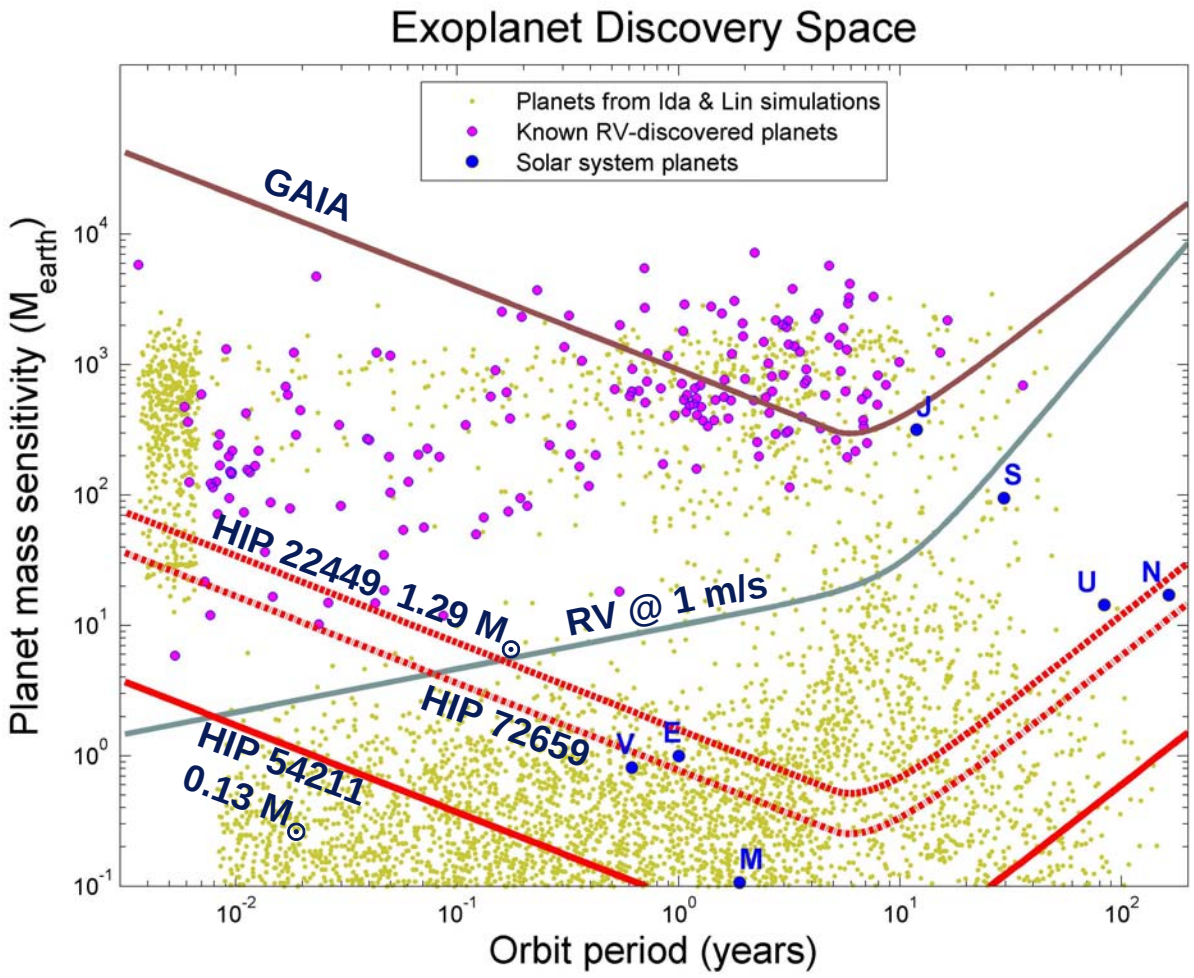
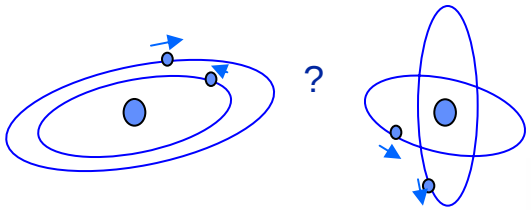
SIM Earth Analog Discovery Space



After Ida & Lin (2004, ApJ, 604, 388)



- **Current harvest of 200 planets by Radial Velocity (RV): Adds empirical constraints to planetary system formation.**
- **Jupiter & Neptune appear to be the tip of the "planetary iceberg"**
- **Radial velocity (RV) will press on icy planets and close-in planets**
- **Transit & Microlensing will provide statistical census of rocky planets**
  - eg. Kepler, 1 kpc
  - eg. Microlensing, 5 kpc
- SIM: uniquely probes
  - **1~10 M_{Earth} (0.4~6.0AU) for nearby stars**
  - **Orbital parameters and mass for RV planets**

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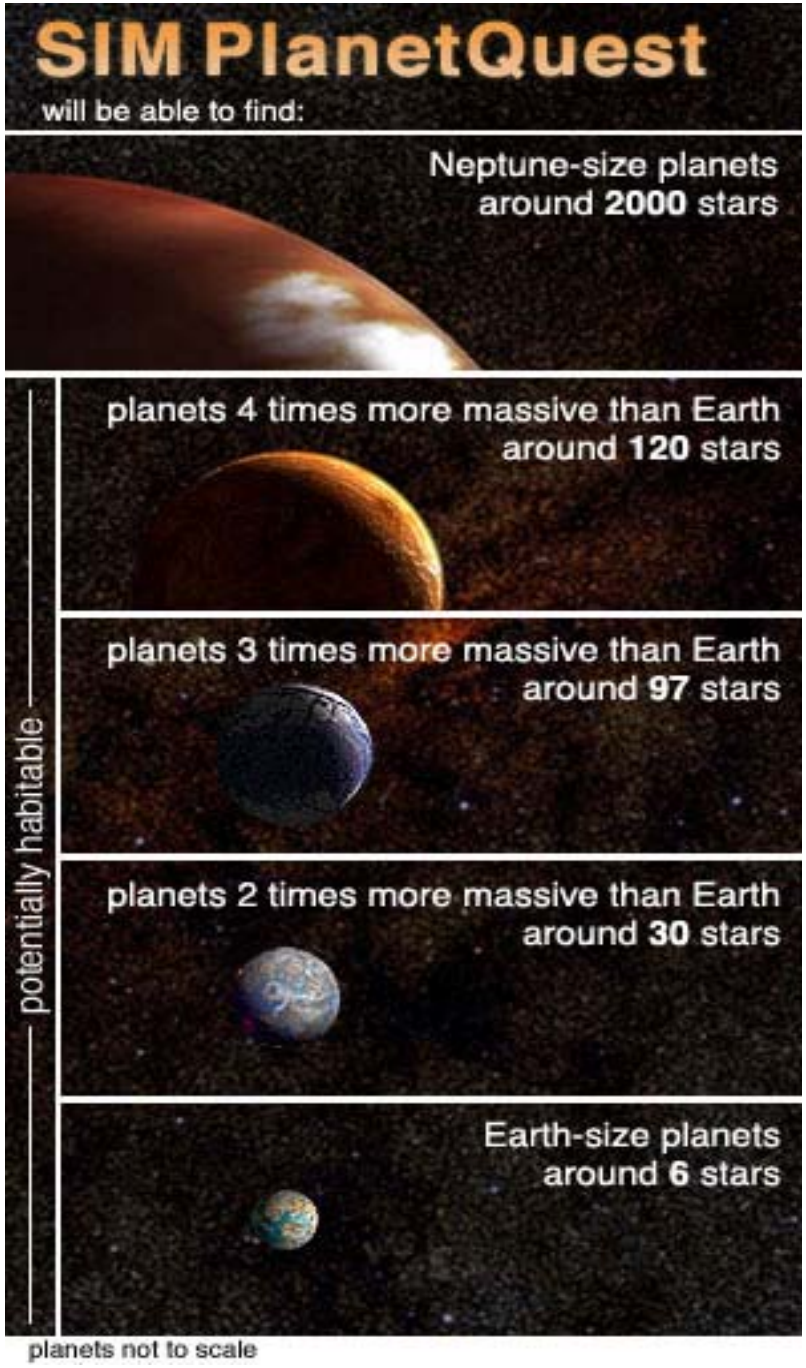
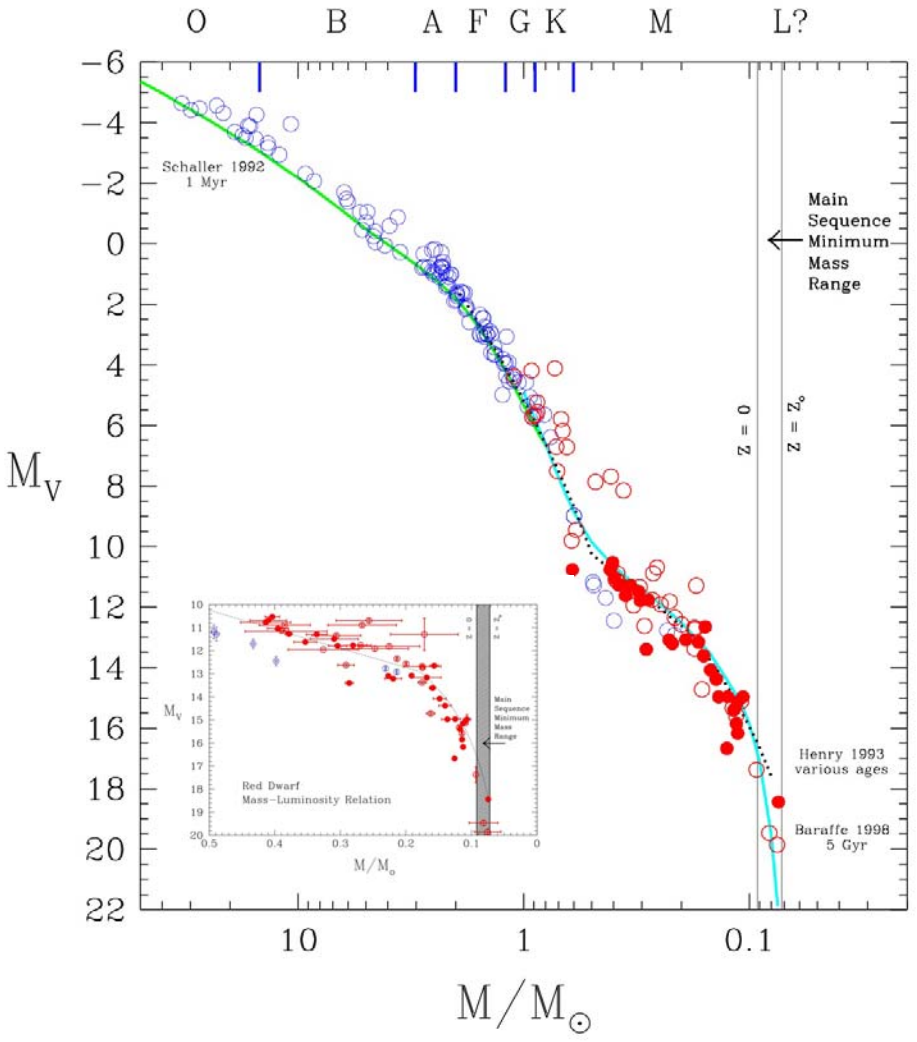
SIM Planet Finding Capabilities

- Potentially Habitable Planets are defined as:
  - Terrestrial planets in the habitable zone, where HZ = (0.7 to 1.5)$(L_{star}/L_{sun})^{0.5}$ AU
  - Mass: 0.33 $M_{\oplus}$ to 10 $M_{\oplus}$
  - Radius: 0.5 $R_{\oplus}$ to 2.2 $R_{\oplus}$
  - Orbit: $e \leq 0.35$
- Deep search of 120 nearby stars within 30 parsecs
- Based on a 5 year science mission with
  - 1 μas single measurement accuracy with a 1.4 μas differential measurement in ~ 20 minutes, and
  - An allocation of 17% of SIM mission observing time



How Do Stars Evolve?

- **SIM will permit 1% mass measurements over the whole range of stellar types, including**
  - Black holes, OB stars to brown dwarfs, and white dwarfs.
- **SIM can obtain precision masses for stars in clusters covering a range of ages (1 Myr -- 5 Gyr) and a variety of metallicities**
- **SIM will use astrometry and photometry of micro-lensing events to determine physical properties of lensing stars**



Space Interferometry Mission

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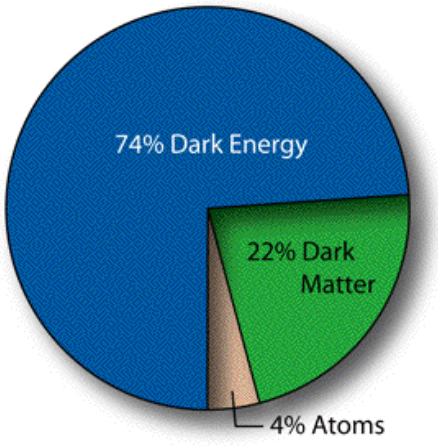
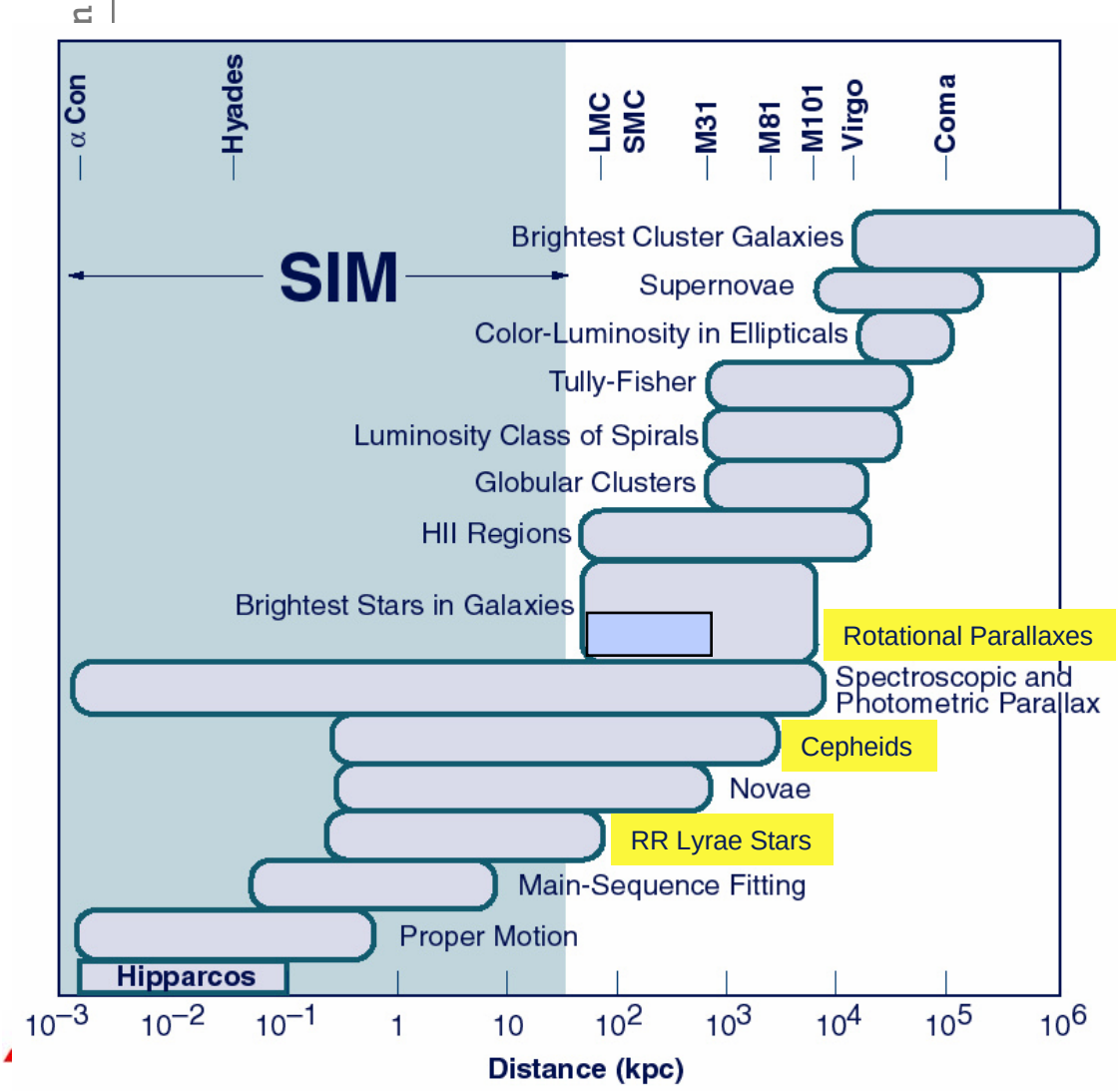
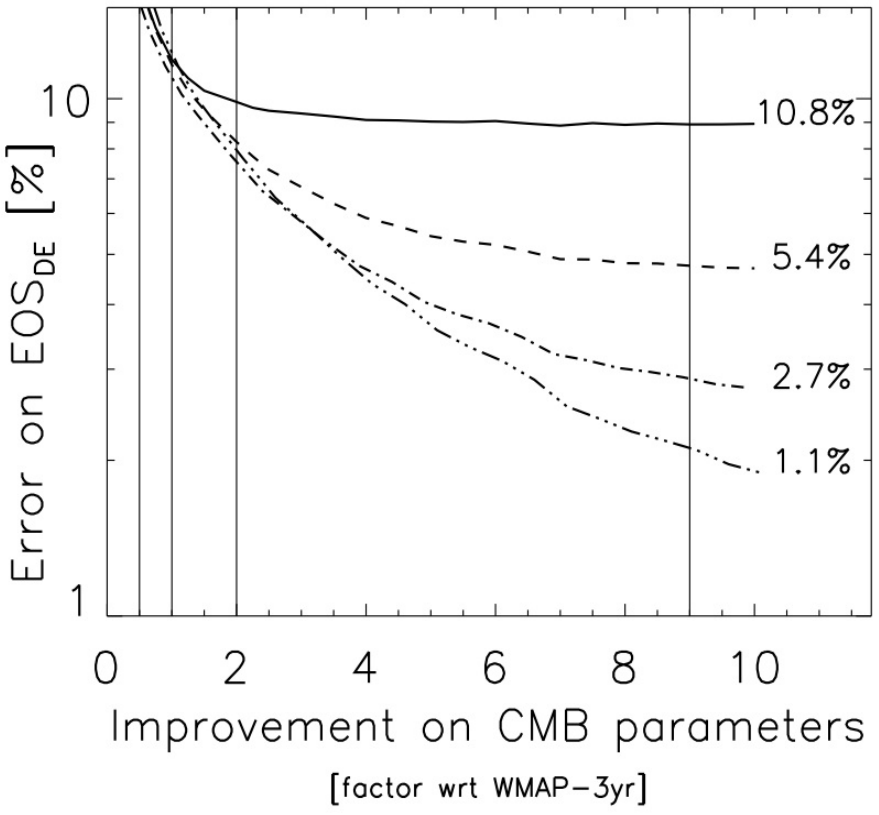
Calibrating the Cosmic Distance Scale

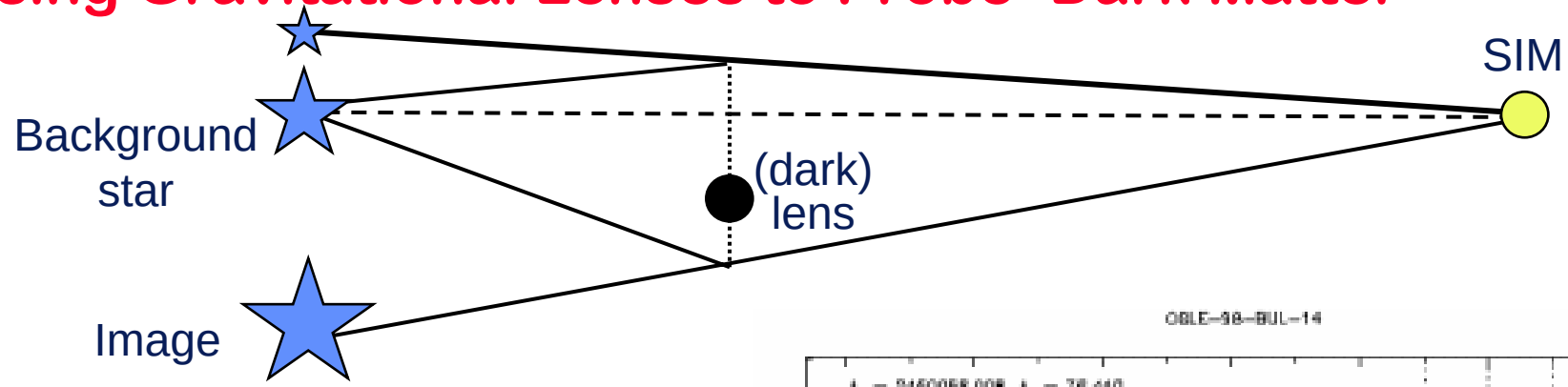
- **Current parallax measurements reach only to about 100 pc.**
- **SIM can improve the value of the Hubble Constant, H_0, to between 1-2%.**



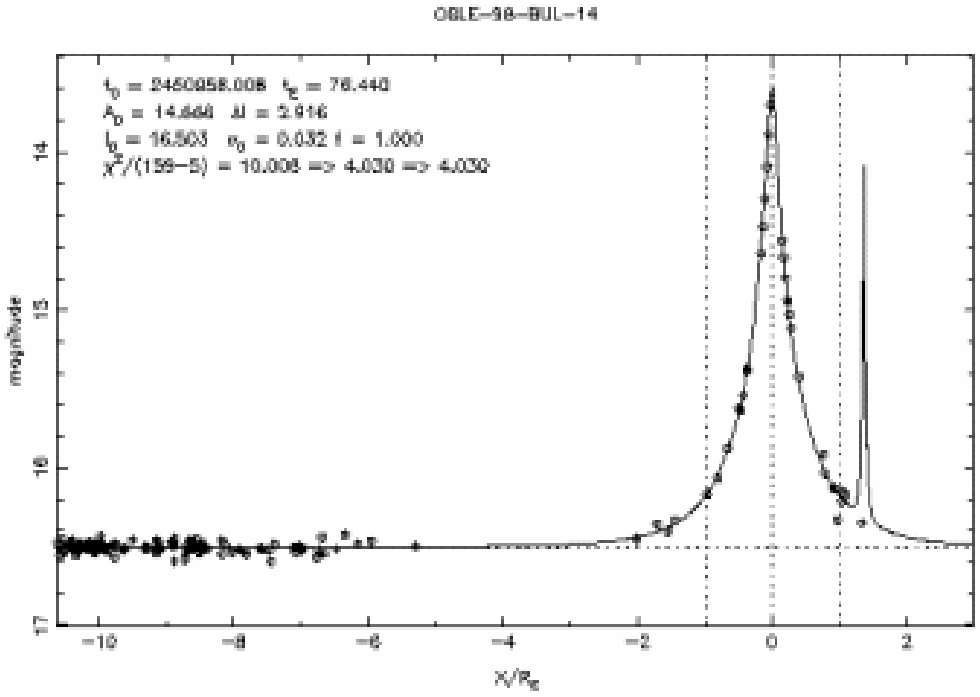




Using Gravitational Lenses to Probe 'Dark Matter'



- Events are detected by
  - Brightness enhancement (~days) – ground based
  - Astrometric perturbation (~weeks to months) – SIM, ~100 μas
- Symmetry of track 'broken' by Earth orbit motion due to lens parallax
  - Hence: distance to lens
- Derive: mass, distance, and velocity of the lensing object



Determine the Mass Spectrum of the Milky Way

Space Interferometry Mission

SIM

JPL

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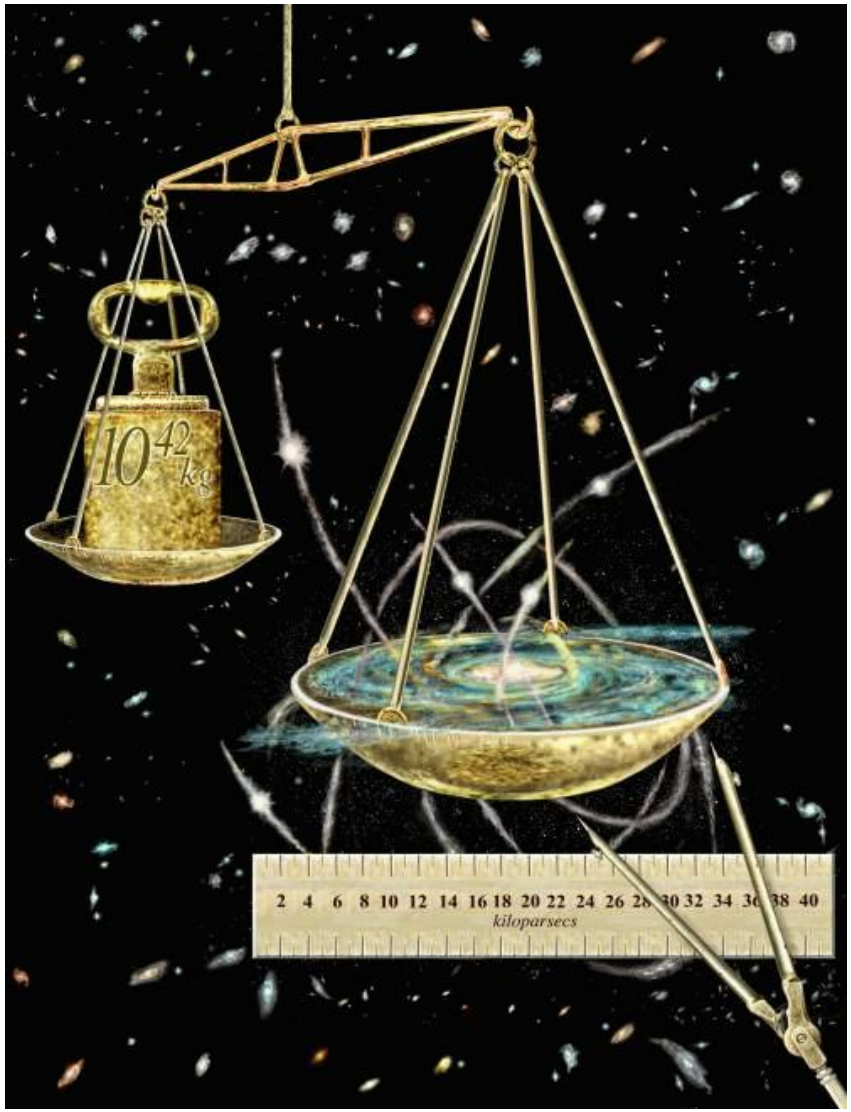
Taking Measure of the Milky Way

- **SIM will probe the structure of our Galaxy:**
- **Fundamental measurements of:**
  - Total mass of the Galaxy
  - Distribution of mass in the Galaxy
  - Rotation of the Galactic disk
  - Bar and spiral structure
  - Mixing in the Milky Way's halo
- **How?**
  - By observing samples of stars throughout the Galaxy
  - By sampling different star populations



Cover page from S. Majewski Key Project proposal

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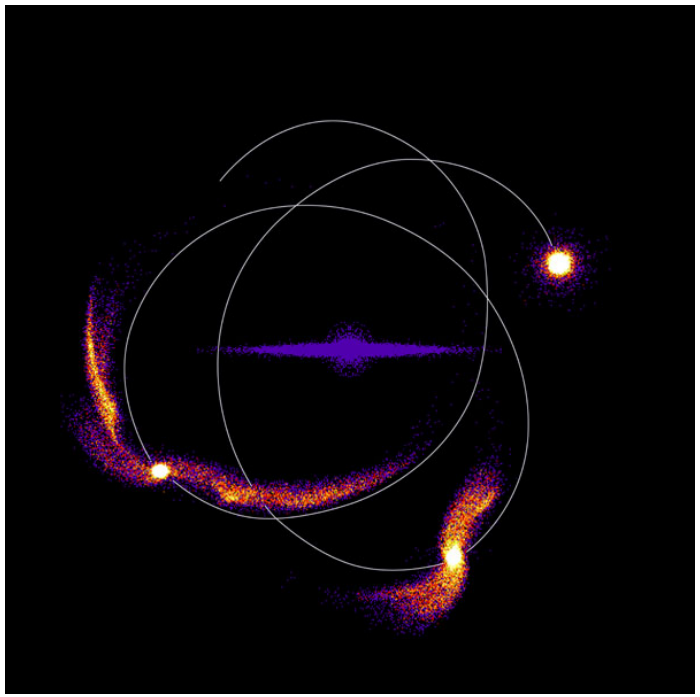
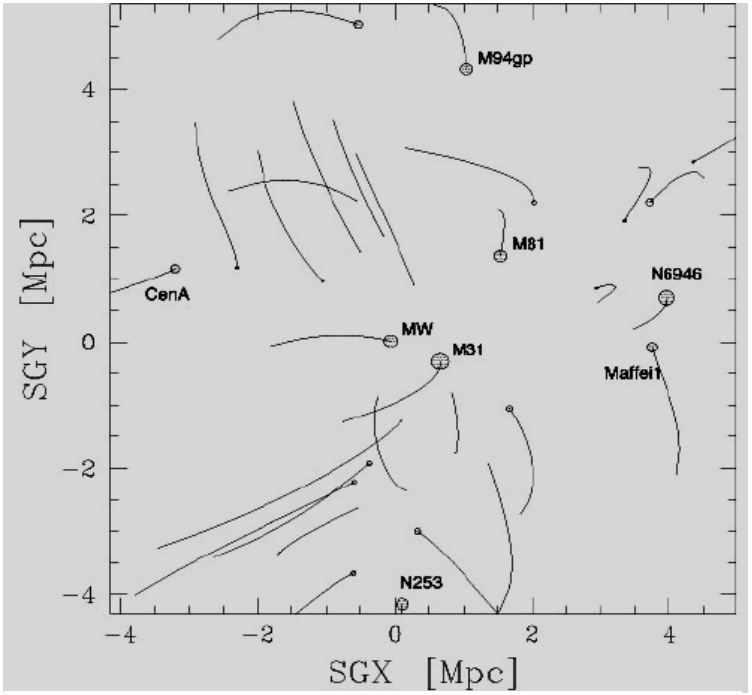
Matter Distribution: Galaxy & Local Group

- SIM's precision is needed to understand the dynamics & mass/energy distribution in our Galaxy and in the Local Group. This will enable accurate time reversal simulations to understand how halo objects and our Local Group evolved with time.
- SIM's microlensing measurements will yield the true mass spectrum of the Galaxy.
- SIM will also obtain accurate masses for black holes and neutron stars, which are laboratories for strong gravity, jet formation, and dense matter.



Tidal disruption of a Milky Way companion.



Simulated 1 Gyr trajectories of our neighbors.

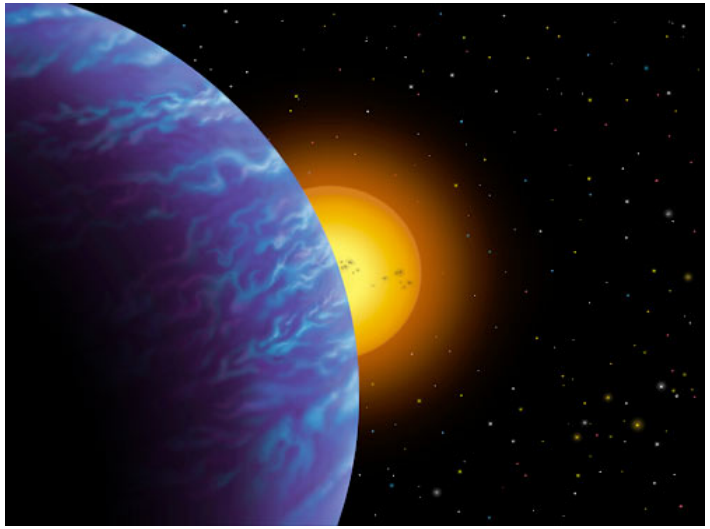
Extrasolar planetary systems: a growing and diverse field

- Discovery of first extrasolar planets around normal stars in 1995 started a renaissance of interest in the field
- Many instruments and missions bring key pieces to the overall picture:
  - Ground-based radial velocities (RV)
  - Ground-based transit and microlensing searches
  - KI and LBTI - debris disks in the 'habitable zone'
  - HST - transits, and images of debris disks around planet-forming stars
  - Spitzer - profiles of dust disks through spectroscopy (and transits!)
  - JWST - direct imaging and spectroscopy of warm Jupiters
  - Kepler - statistics of terrestrial planet frequency
- Terrestrial planets around nearby stars:
  - SIM PlanetQuest
  - TPF-C
  - TPF-I

Searching for Terrestrial Planets with SIM

What We Don't Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - **Only astrometry measures planet masses unambiguously**
- Are there low-mass planets in 'habitable zone' ?



A Broad Survey for Planets

- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2,000 stars within ~25 pc with sensitivity <<Jupiter mass

A Deep Search for Earths

- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Detection limit of ~3 M_e at 10 pc
- Sensitivity limit of ~1 M_e at 3 pc

Evolution of Planets

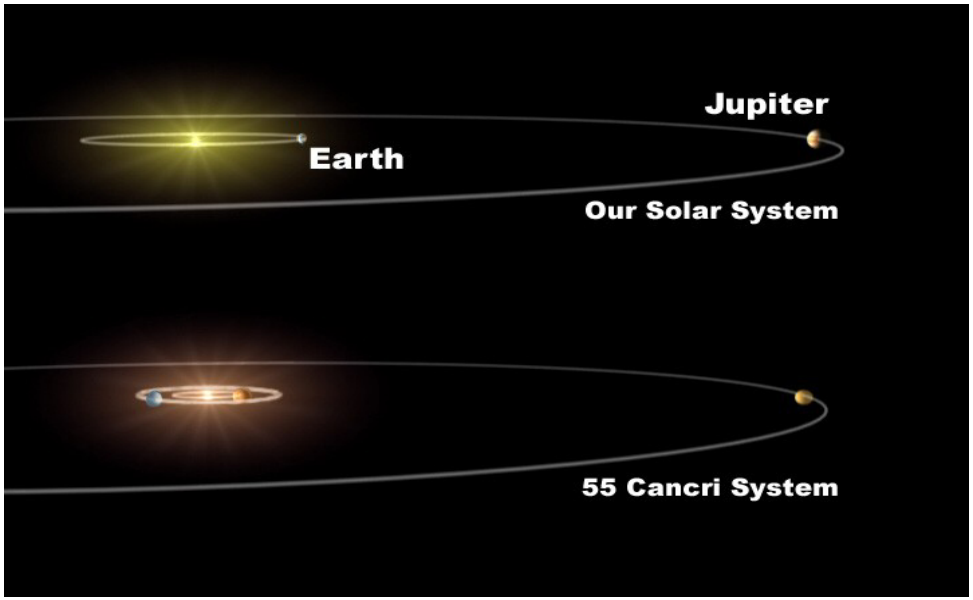
- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?

Broad Survey of Planetary Systems

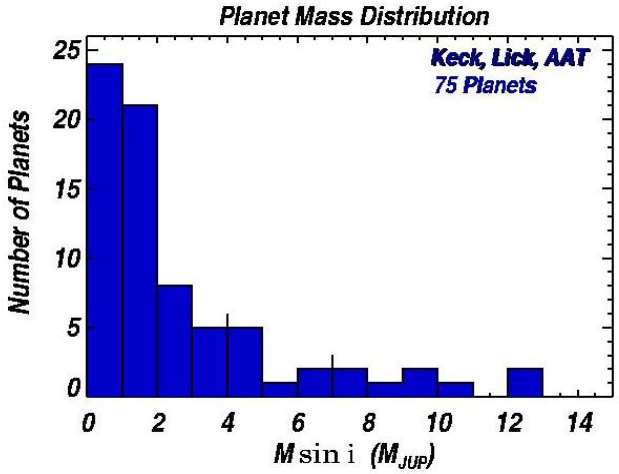
- Sample ~2000 stars within ~25 pc with sensitivity << Jupiter mass

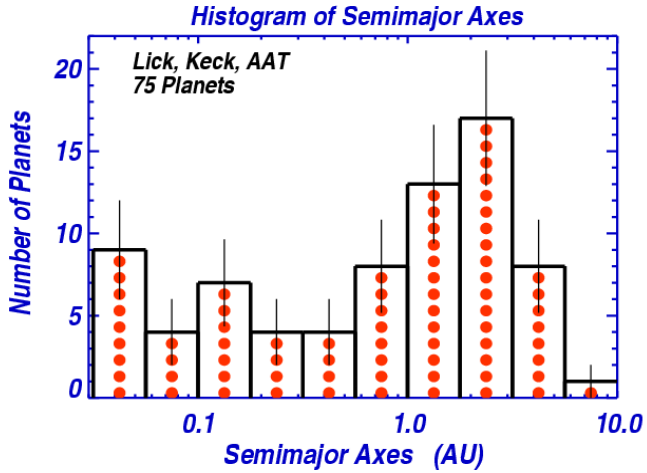
Questions:

- Is our solar system typical or unusual?
- Are planets more common around sun-like stars?
- What are the 'architectures' of other planetary systems



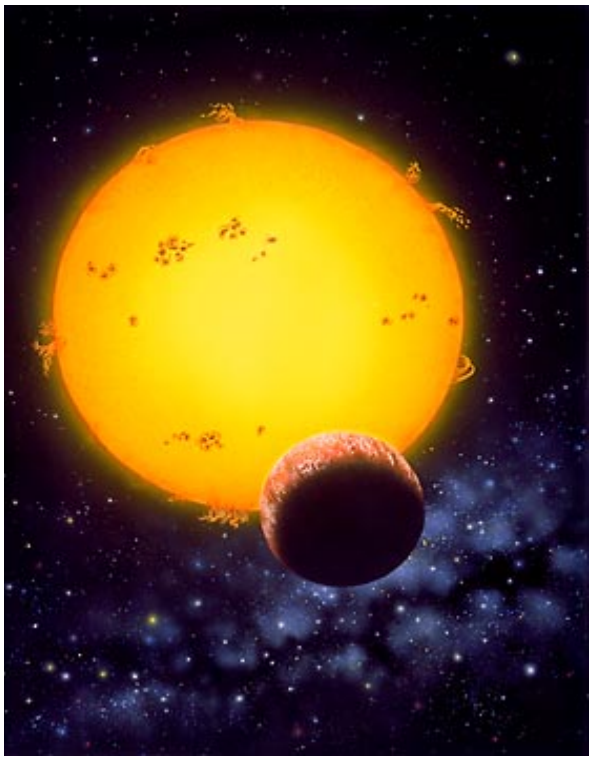
55 Cancri: a planetary system like our own?





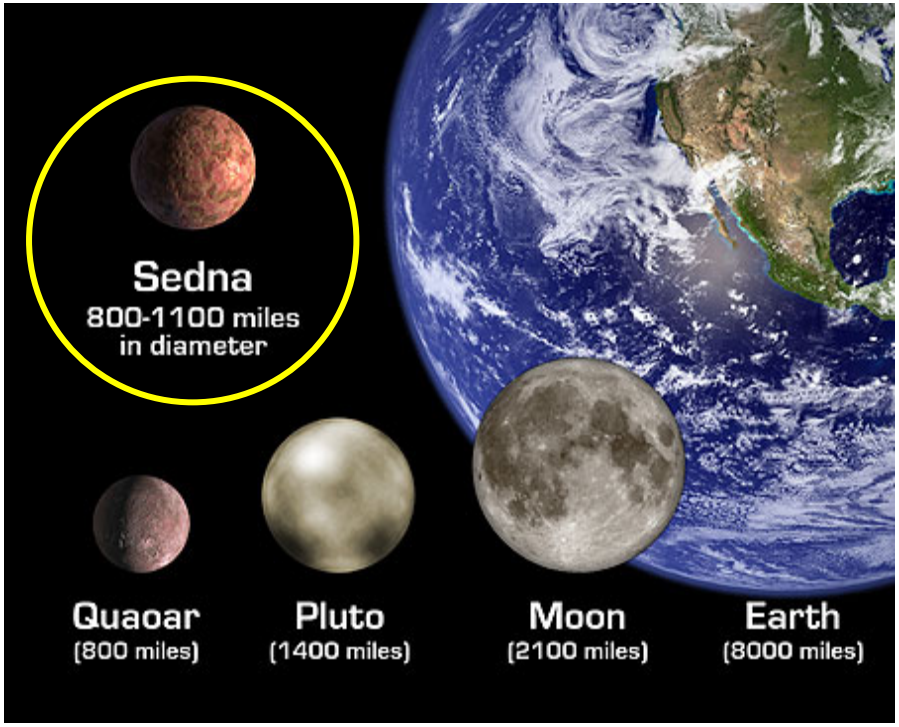
Planets around Young Stars

- What fraction of young stars have gas-giant planets?
  - Only SIM astrometry can find planets around young stars since active stellar atmospheres and rapid rotation preclude radial velocity or transit searches
- Do gas-giant planets form at the "water-condensation" line?
  - SIM will survey ~200 stars to a level adequate to find Jovian or smaller planets on orbits <1 AU to >5 AU around stars from 25-150 pc
- Does the incidence, distribution, and orbital parameters of planets change with age and protostellar disk mass?
  - Study of clusters with ages spanning 1-100 Myr to test orbital migration theories
  - Correlate with Spitzer results on disks (at 4-24 μm)
- Where, when, and how do terrestrial planets form ?
  - Understand the formation and orbital migration mechanisms of the giant planets
- ***No other technique before and possibly including TPF (RV, AO imaging, IR interferometry) can credibly claim to find***



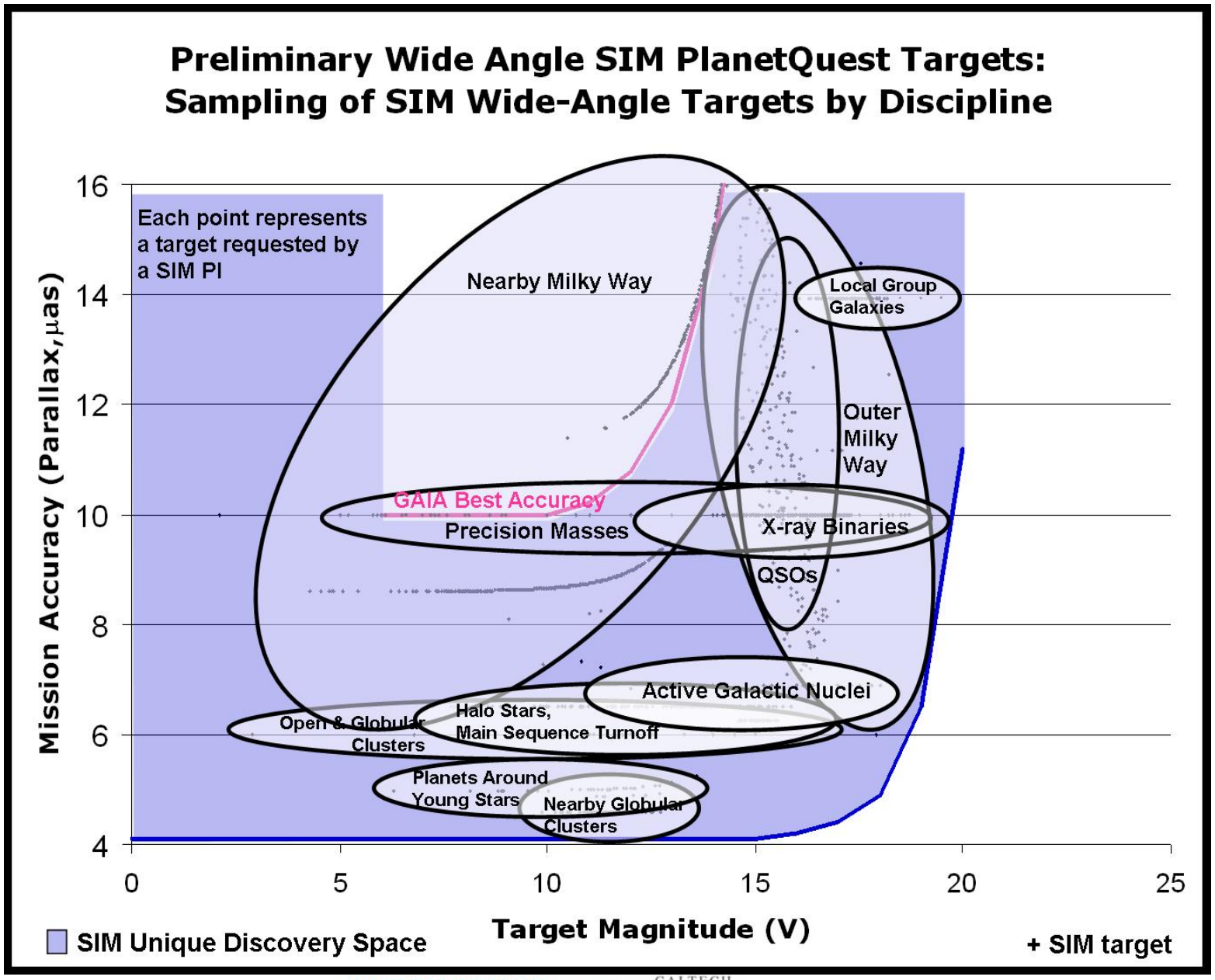
What Will We Learn About Other Earths?

- Orbital Parameters (SIM)
  - Stable orbit in habitable zone
- Characteristics for habitability
  - Mass (SIM)
  - Temperature (TPF)
  - Temperature Variability (SIM)
  - Radius (TPF)
  - Albedo (TPF)
  - Surface gravity (SIM+TPF)
  - Composition (TPF)
  - Atmospheric conditions (TPF)
  - Presence of water (TPF)
  - Temporal variability (TPF)
- Solar System Characteristics
  - Influence of other planets (SIM)
  - Presence of comets or asteroids (TPF)



- Indicators of Life (TPF)
  - Multiple spectral lines in different wavebands confirm initial detections and extend physical interpretation
  - For planets with atmospheres (and modest cloud cover), IR characterizes atmosphere while visible sees planetary surface

SIM Astrophysics Targets



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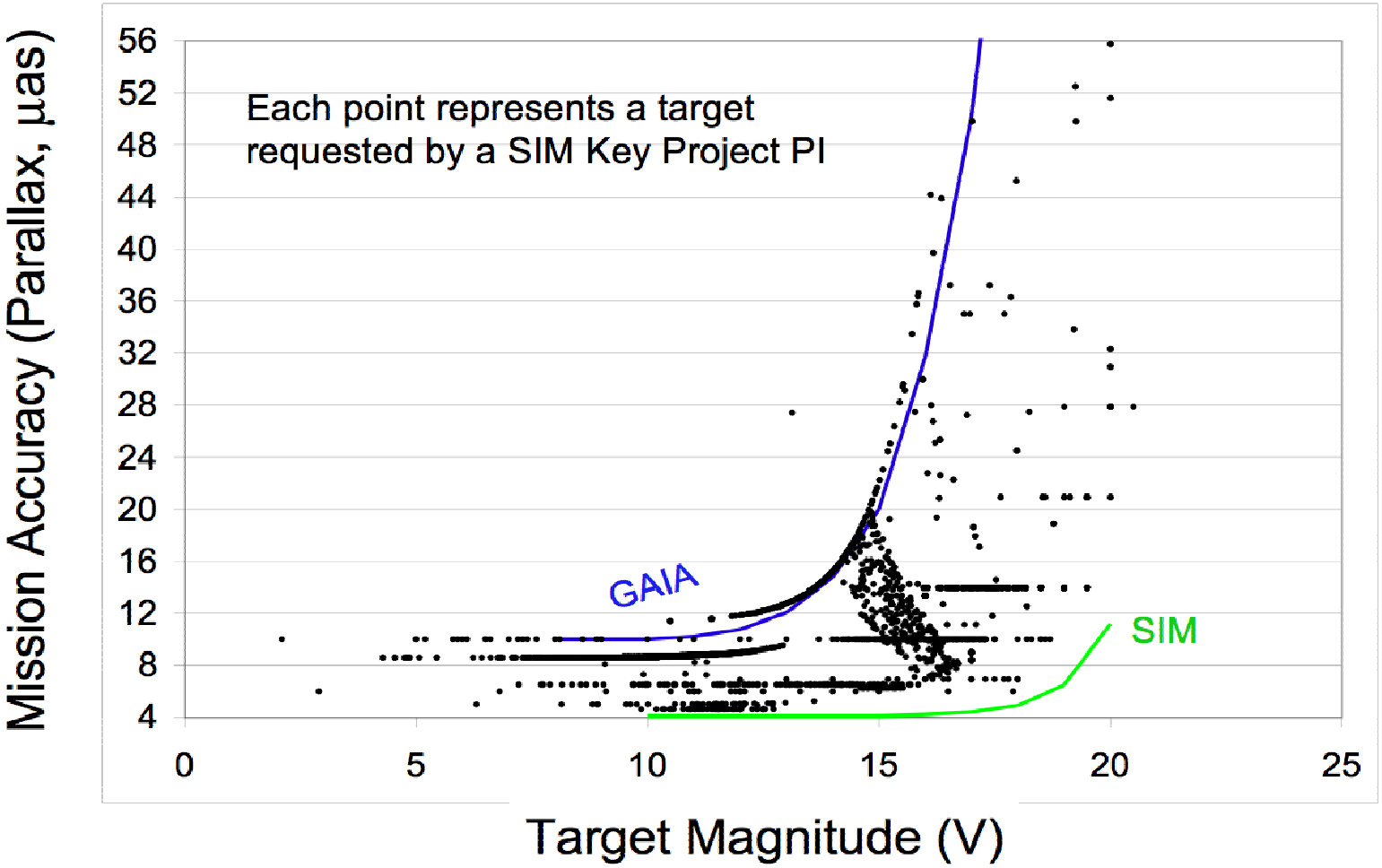
SIM and GAIA: Different Science



Virtually all SIM Science Team targets are beyond the reach of GAIA's capability

SIM Science (and fraction accomplished by GAIA)

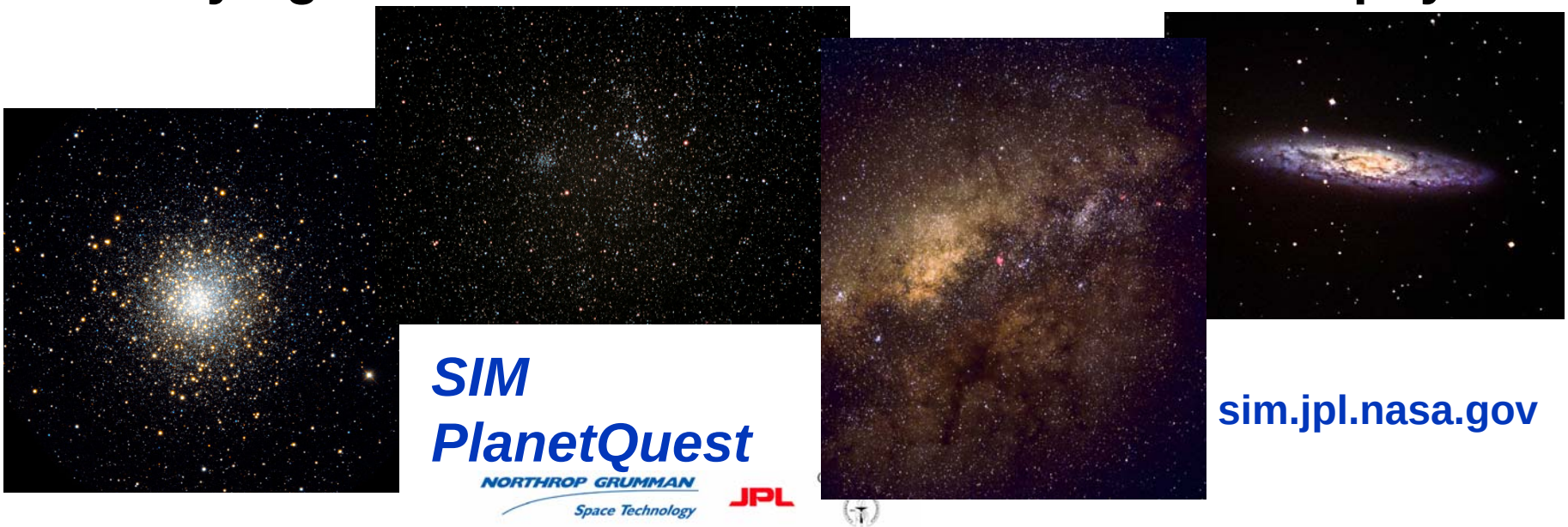
Key SIM Science Project Objectives	GAIA %
Find candidate habitable planets	0%
Reconnaissance of young planetary systems	~0%
Exo-Planetary system contents census	>Jupiter
Unbiased galactic mass function (from micro-lensing)	0%
Local Galaxy group mass distribution (from motions)	8%
Age of galaxy (from globular clusters and stellar models)	20%
Star masses to 1% (SIM program emphasizes difficult types)	~0%
Structure of Galaxy (size, spiral arms, tidal streams, bulge, halo)	~50%
Motion in/of QSO's, AGN's	0%
Coordinate frame tie to cosmological standard of rest (QSO's)	~90%

SIM: Searching for Other Earths...

Space Interferometry Mission

SIM

...Studying the Foundations and Frontiers of Astrophysics



SIM PlanetQuest

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