Astrometric Detection of Terrestrial Exoplanets

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Navigator Forum-2007: Small- and Mid-Scale Exoplanet Space Missions

Astrometry: Deep and Broad

- Astrometry (like radial velocity) is a broad technique
  - Sensitive to a wide range of masses and orbit radii
- Astrometric signal *increases* with orbital period
  - Astrometry and radial velocity are *complementary*
- Astrometry measures:
  - Masses (a key attribute of a planet)
  - Inclinations of multiple planet systems (a key diagnostic of planetary origins)
- Planet location (orbit) will greatly motivate follow-up and characterization
  - Ground based follow-up
  - Increase efficacy of TPF

Astrometry from Space

- Scientific objective:
  - Detection of Earth-like planets
    - around Sun-like Stars
    - in the Habitable Zone
    - for stars out to ~10 pc
- Measurement to meet this requires:
  - **~1 μas** single-measurement accuracy

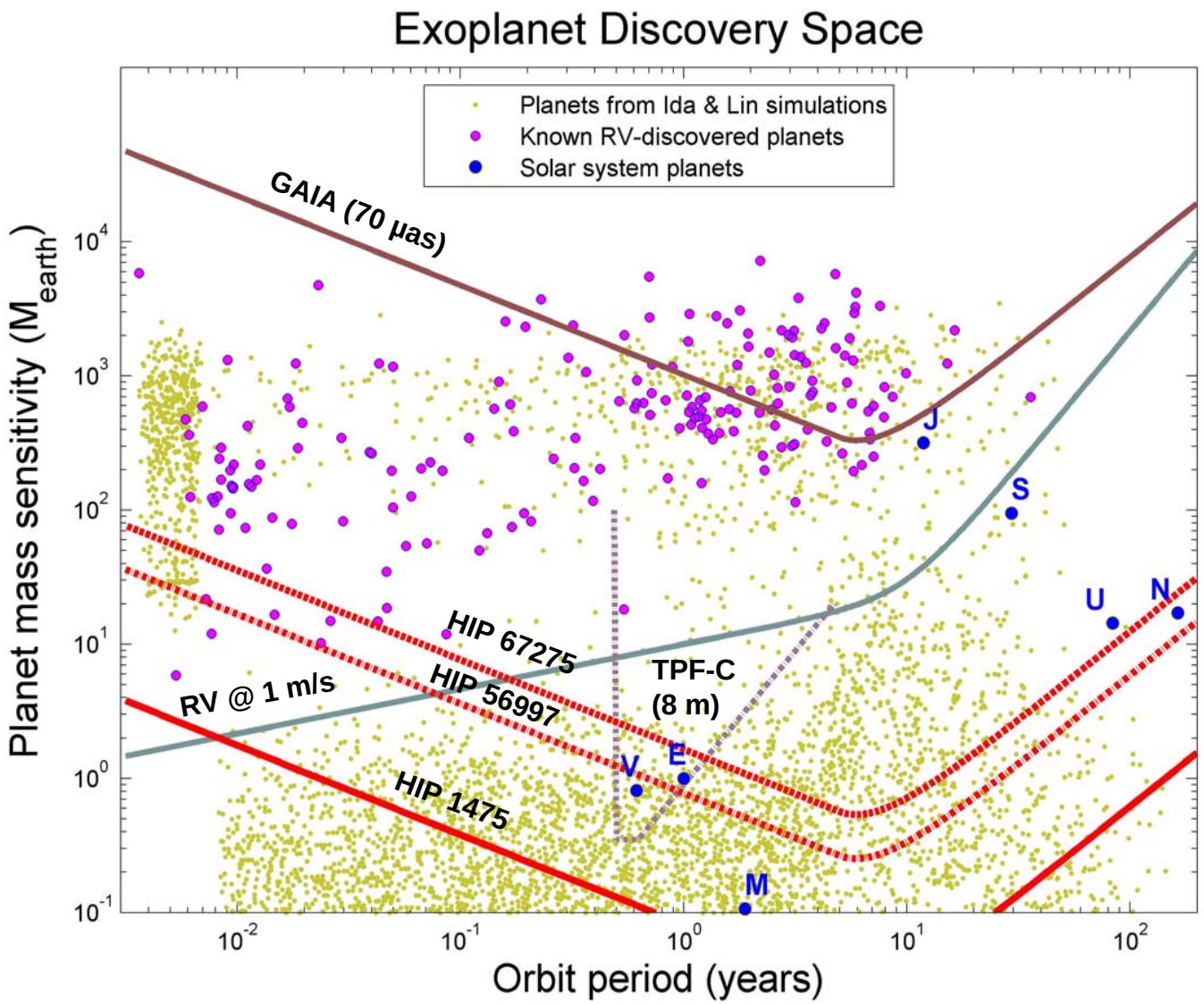
Science Goals of Microarcsecond Astrometry: Deep and Broad Surveys

- Earth-like planets around Sun-like Stars and in Habitable Zone
- Planets around early type stars (O,B,A, early F)
- Planets around young stars
- Planetary Masses and Inclinations
- Truly complementary exploration of thousands of stars (planetary diversity) from RV discoveries
- Complete architecture of systems with transit-discovered planets

Three Astrometric Planet Surveys

- Earth Analog Survey
- Broad Survey
- Young Star Survey

Earth Analog Survey



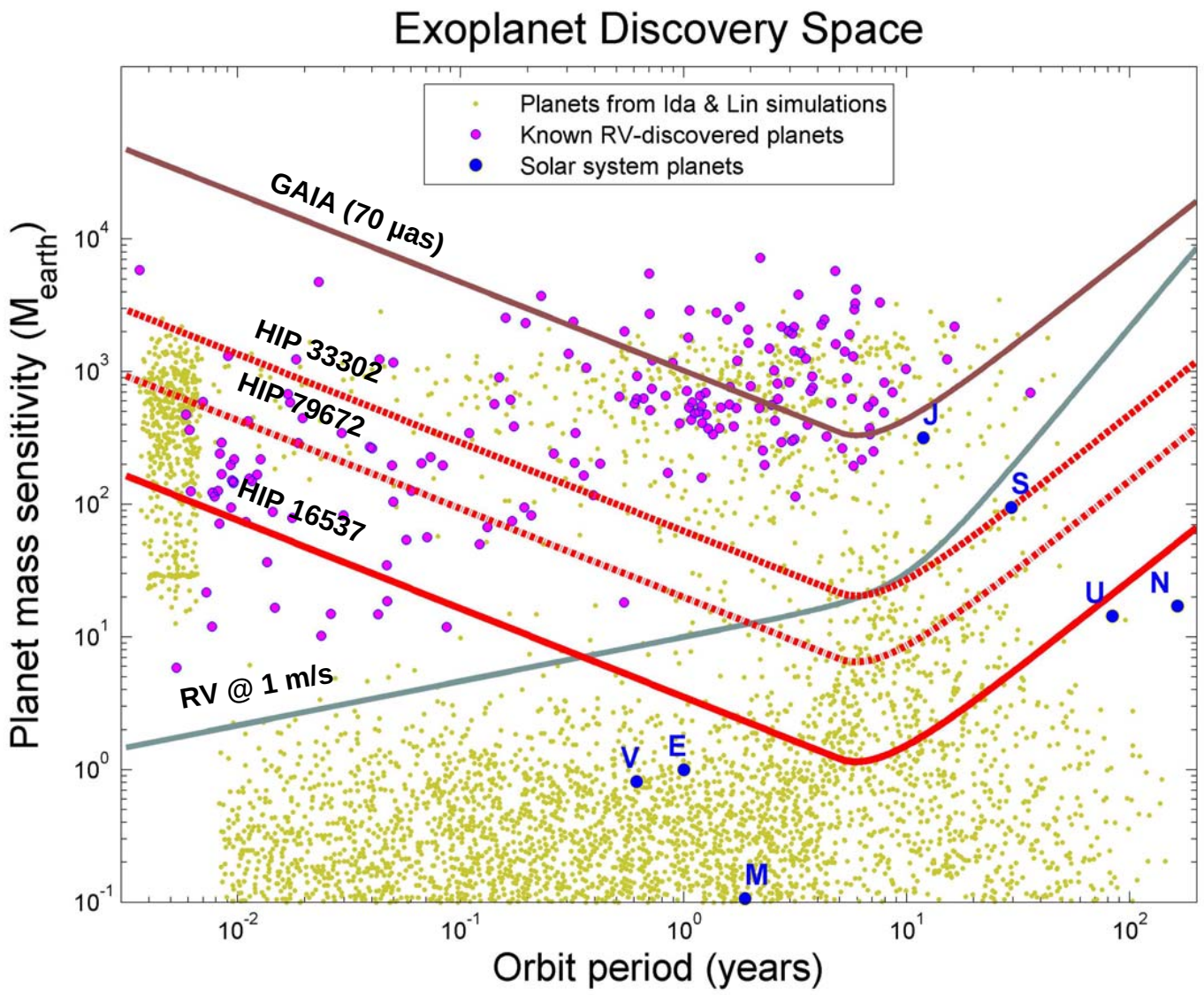
Red curves: best, median, and worst of 69 Earth Analog Survey targets, labeled by HIPPARCOS catalog number

1 μas Habitable Planet Survey

Mass sensitivity at mid-habitable zone	**1 $M_\oplus$**	**2 $M_\oplus$**	**3 $M_\oplus$**
# of target stars that can be surveyed using 40% of mission time	69	160	259
# of target stars that can be surveyed using 75% of mission time	101	233	360

- Design observations of each target to achieve a specified *mass sensitivity*
  - A pointed astrometric mission is flexibly scheduled
- Table shows three cases, optimized for 1, 2, or 3 M⊕
  - Assumes five year mission duration

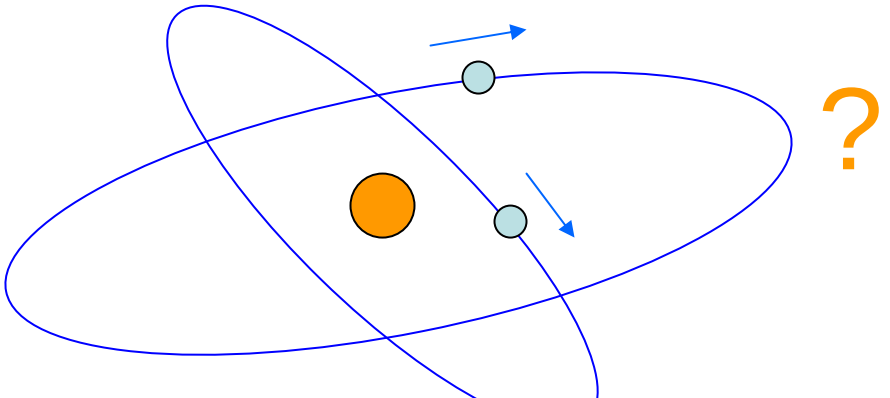
Broad Survey



Red curves: best, median, and worst of 2100 Broad Survey targets, labeled by HIPPARCOS catalog number

Survey ~2100 Stars for System Architectures

- Comprehensively survey ~2100 stars to probe for terrestrial-mass planets and larger to periods of 4 – 5 years as a function of metallicity, absence/presence of debris disks, and presence in binary systems
- Mutual inclinations are essential to understanding multiple planet systems
  - *only astrometry can do this*
- Search for planets around stars not probed by RV
  - star types O, B, A, early F, white dwarfs

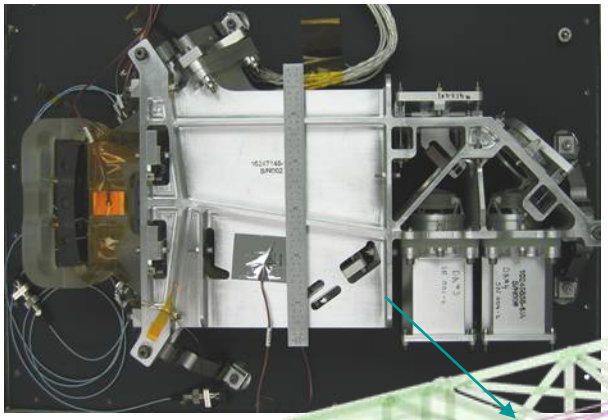


Formation and Evolution of Planetary Systems

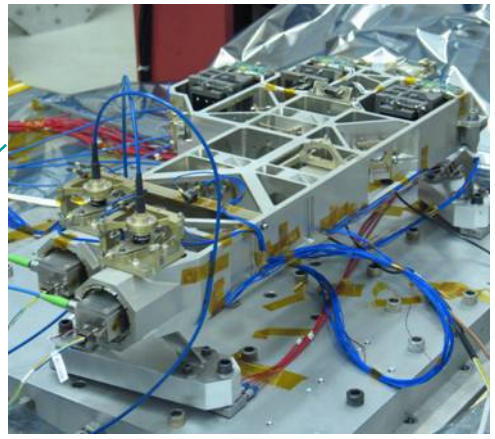
- Probe for planets around ~200 **young** stars and thus provide insight into the *evolution* of planetary systems
- Radial velocity measurements of young stars are degraded by a factor of 100 or more compared to mature stars by rotation, line veiling, starspots and other sources of photospheric variability: 100-500 m/s (at best!) vs. 1 m/s
- Sensitivity and angular resolution limits of coronagraphy and interferometry preclude direct detection of Jupiters in the critical region of the “snowline”, 1-10 AU
- Uniquely detect Jupiter/Saturn mass planets around stars with ages of 1-100 Myr at distances of 25-140 pc
  - Astrometric sensitivity limit is set by jitter due to starspots of a few micro arcsec, but still adequate for finding gas giants

SIM PlanetQuest

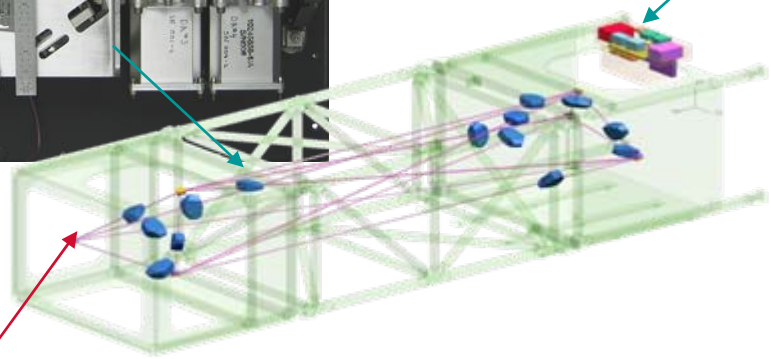
Ready to build!

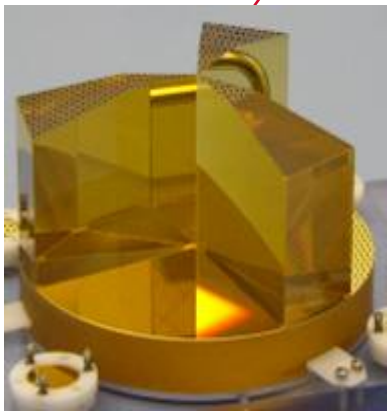


External
Metrology
Launcher



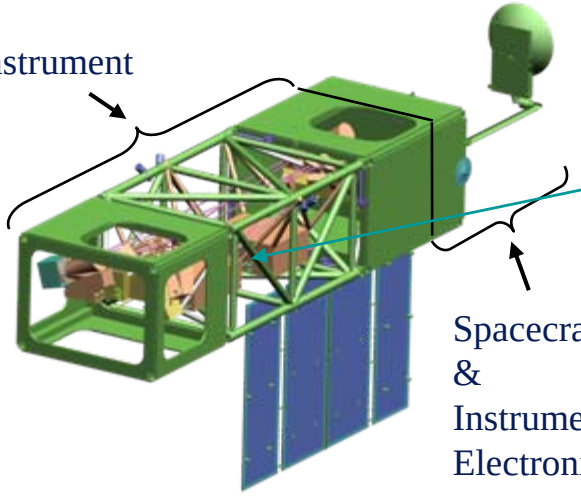
Metrology
Source



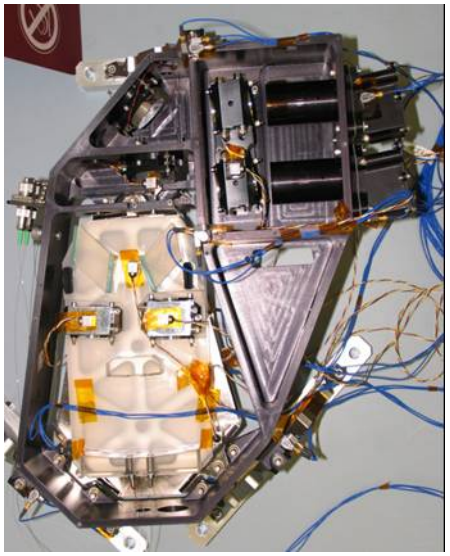


Double Corner
Cube

Instrument



Spacecraft
&
Instrument
Electronics



Internal Metrology
Launcher

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

SIM PlanetQuest Technology Gates: All Completed and Reviewed by 2005

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

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

* NASA HQ 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

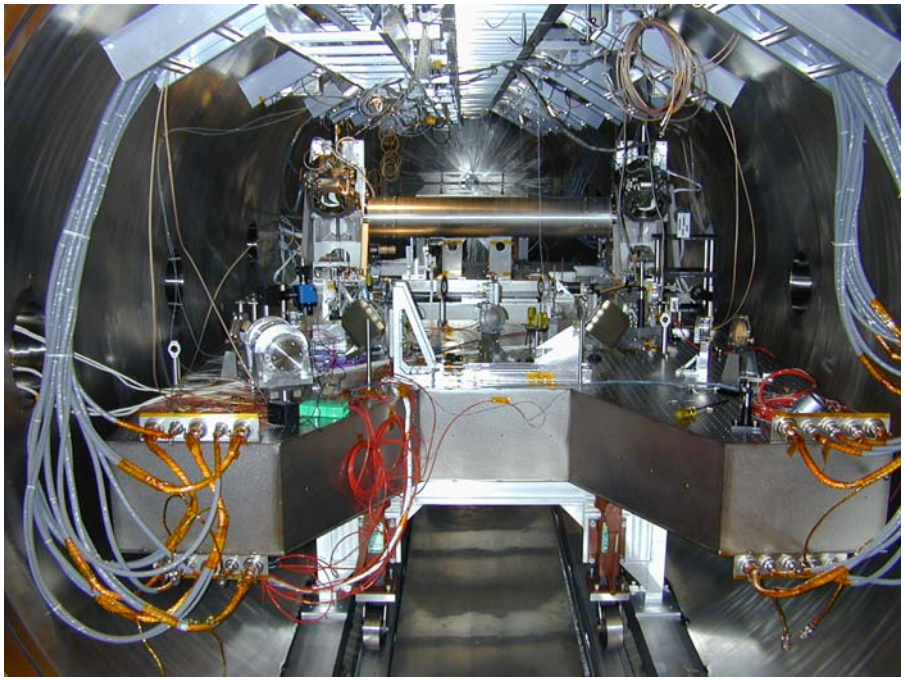
Engineering Milestones – On Track

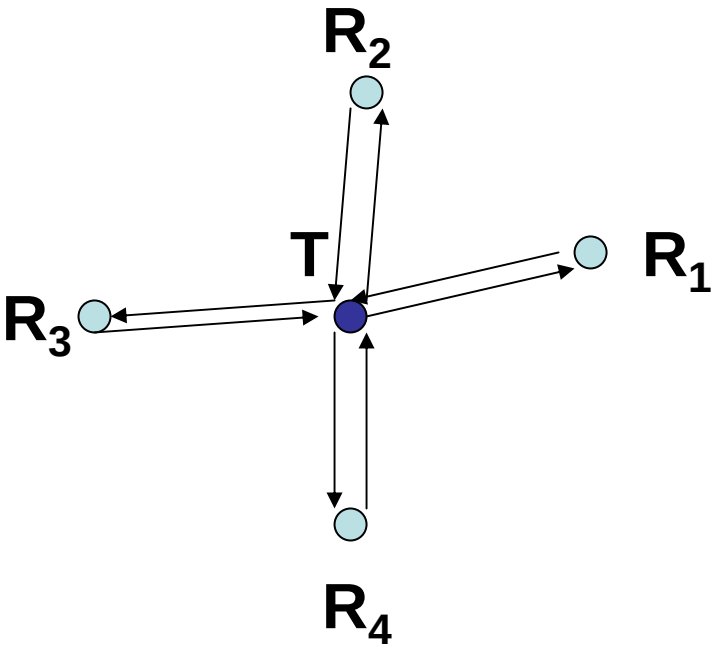
Engineering Milestone	Description	Due Date	Complete Date	Performance
Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental 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	In test	
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
Implementation Phase				
EM-6	Engineering Models for Metrology Fiducials (double and triple corner cubes fully meeting SIM flight requirements)	9/30/2007*		
EM-7	Metrology Source Engineering Models (optical bench; fiber splitters; fiber switches; fiber distribution assembly; laser pump module: all fully meeting SIM flight performance requirements per table).	9/30/2008*		
EM-8	Instrument/Mission Performance Prediction (update Tech Gate #8 using latest hardware results).	9/30/2008*		
EM-9	Integration of S/C FSW build-1 with phase-1 of the S/C engineering model testbed (demonstrates specific S/W functions)	10/1/2008*		

* Completion dates deferred indefinitely due to FY07 NASA decision to delay SIM indefinitely.

** Actual signoff by NASA HQ delayed until 12/12/06 due to requests for additional thermal testing by the TAC and EIRB boards.

Laboratory Demonstration

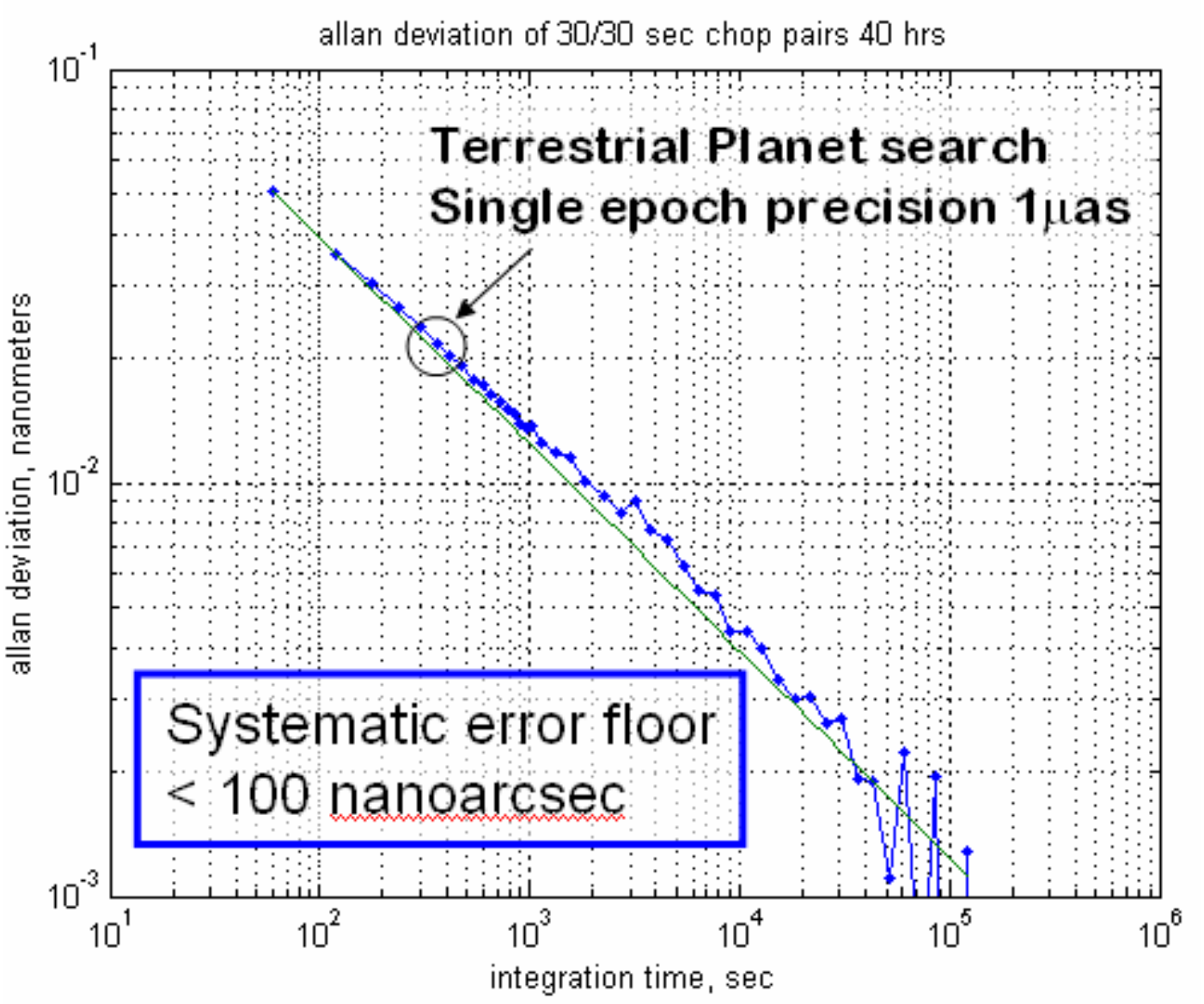




MicroArcsecond Metrology Testbed

- SIM science interferometer
- Pseudostar + metrology connecting pseudostar to interferometer

- Narrow-angle chopping sequence:
- $T – R_1 – T – R_2 – T – R_3 – T – R_4$
  - Repeated twice


allan deviation of 30/30 sec chop pairs 40 hrs
Terrestrial Planet search
Single epoch precision 1μas
Systematic error floor
< 100 nanoarcsec
allan deviation, nanometers
integration time, sec
10^-1
10^-2
10^-3
10^1
10^2
10^3
10^4
10^5
10^6

SIM PlanetQuest: Proven, Timely, & Synergistic

- Demonstrated sub-microarcsecond precision
  - This series of lab demos define the heart of the mission
- The SIM Project has:
  - met all Technical Milestones
  - undergone multiple reviews of mission costs
- SIM has been validated by two Decadal Reports and two roadmap studies
- SIM is ready to fly as early as 2013
- SIM could make 2013-2023 the decade of extra-solar planets
  - SIM & COROT and Kepler
  - SIM & GAIA
  - SIM & GSMT, EELT
  - SIM & TPF/Darwin

SIM & Other Missions

- SIM will complete the architecture for stars with planets identified by Kepler and CoROT
  - Kepler/CoROT ... Rocky planets
  - SIM … Giant planets (not perfectly co-planar)
- SIM will provide high quality parallaxes (and thus angular diameters) of stars around which planets have been detected by transits
  - Resolves the current biggest uncertainty in determining planetary radii from transits
- SIM provides location of planet in sky which is critical for any follow up program including GSMT and TPF

GAIA

(charts provided by
Michael Perryman, ESA)

Gaia (ESA)

Launch: Dec 2011

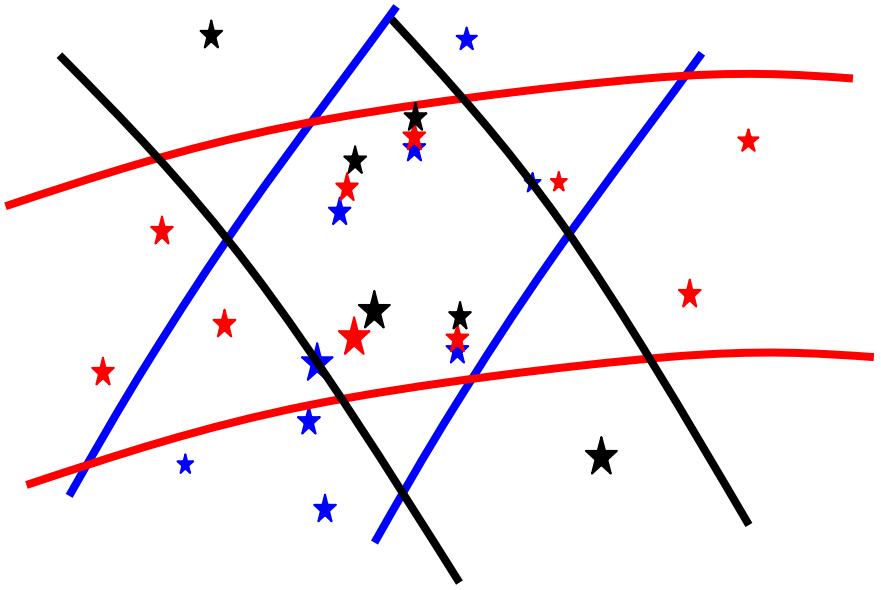
http://www.rssd.esa.int/GAIA

Method:

- astrometry, Hipparcos principles
- two 1.45 × 0.5 m^2 mirrors + 7 × 9 CCDs
- continuous ‘revolving’ sky scanning
- 5-year observations: 100 epochs per star

Objectives:

- distances + motions for 10^9 stars
- originally (2000) 10 μas at 15 mag
- structure and evolution of Galaxy



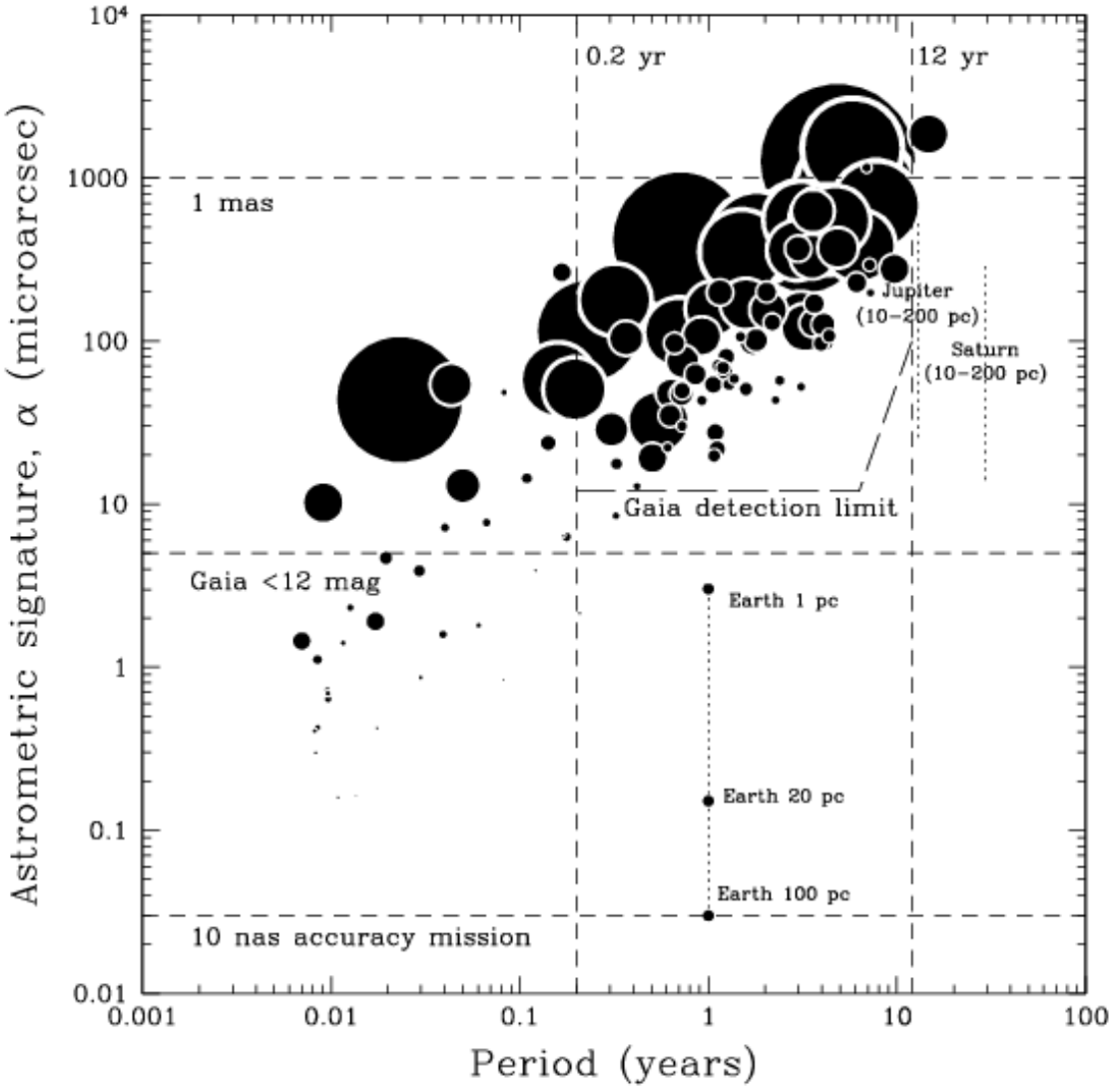
… and their resulting astrometric signatures

$$\alpha = \left(\frac{M_p}{M_s}\right)\left(\frac{a_p}{d}\right)$$

...α in arcsec if *a* in AU
and *d* in pc

At 10 pc:

Jupiter: 500 μarcsec
10 Earth: 3 μarcsec
Earth: 0.3 μarcsec



Gaia: Expected Astrometric Discoveries

- Large-scale detection and physical characterisation (10μas):
  - complete census to 150–200 pc; P=2–9 yr, primarily Jupiter-type systems
  - detection of ~10,000 planetary systems (standard assumptions)
  - masses, rather than lower limits (M × sin i), down to 10 M_{Earth} to 10 pc
  - orbits for ~1000 systems + multiple systems: relative inclinations
- Photometric events: transits of ~4000 'hot-Jupiters' possible but TBC
- Still uncertain effects of CCD radiation damage:
  - astrometric effects (CTI) classified as: charge loss + image smearing
  - current accuracies at 15 mag are around 20μas, including only charge loss
  - bright star accuracies are formally around 7 μas at 10–12 mag
  - no full characterisation of smearing versus history, charge injection, etc
  - PDR in June 2007; launch in 2011 is close to solar max (delays are good!)
- 10 nas mission concept is in Cosmic Vision (Earths at 100 pc)

SIM and GAIA Mission Comparison

	SIM	GAIA
Narrow Angle single-visit accuracy goal	1 μarcsec	~70 μarcsec
Wide angle end-of-mission absolute accuracy goal	4 μarcsec	10 - 300 μarcsec
Operation mode	Pointed observations of science targets plus reference grid	All-sky scanning survey
Other functionality	Interferometric imaging (selected sources)	Concurrent photometry, radial velocity
GO program	Yes	No
Limiting magnitude	V ~20	V = ~20
Bright limit	V = -1.4	V = +6
Phase/Launch	B/2013 ?	B/2011

Astrometric Planet Hunter

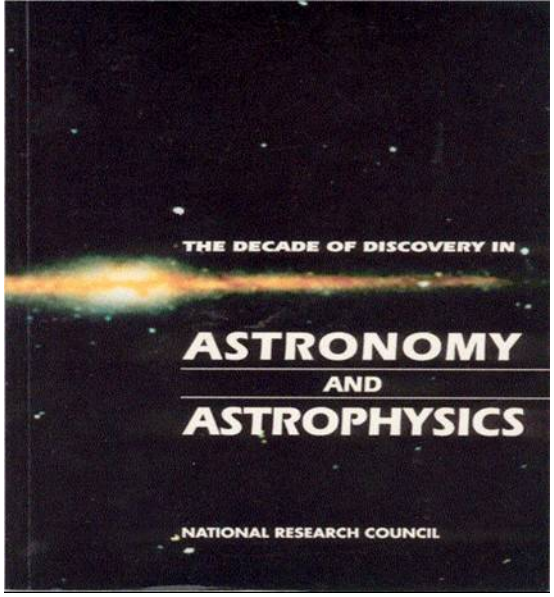
Astrometric Planet Hunter

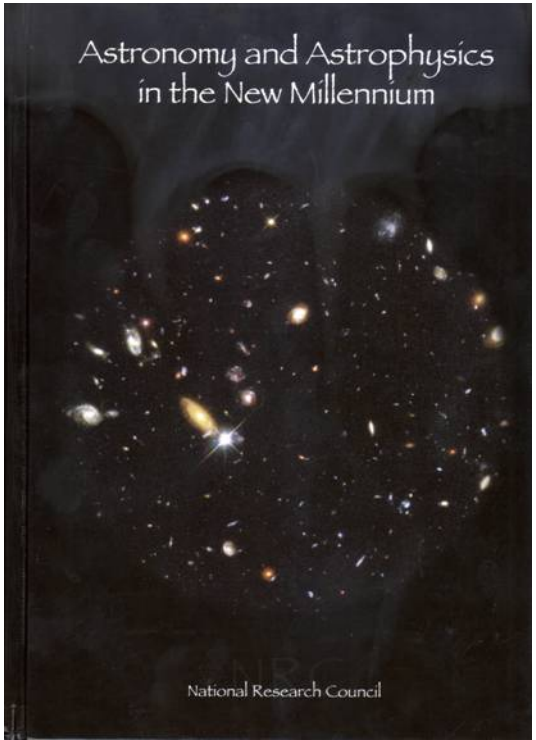
- Objective:
  - Exoplanet discovery and characterization
  - Detection of *terrestrial* exoplanets
- Mission concept:
  - Precision optical astrometry to detect reflex motion of planet
- Instrument performance:
  - Single measurement in the microarcsecond range
- Mission capability:
  - Capable of finding Earth-mass planets in the Habitable Zone around an F, G or K star
  - Definitive planet mass measurements
  - Solar system architectures

Rationale and Approach for Astrometric Planet Hunter

- NASA budget constraints leading to more emphasis on small and mid-scale missions
- Goal is to develop a probe-scale planet-search mission
- Mission will have a very focused science goal: finding planets around relatively bright stars
- Approach:
  - Make effective use of completed SIM technology at the component and subsystem level
  - Reduces risk by using years of SIM expertise and experience
  - Instrument architecture, mission design, mission operations will be sized to minimize cost for the science
  - Enhances the effectiveness of smaller TPF missions by vetting potential target stars and providing full orbital parameters for interesting targets
- Status:
  - Currently under study - complete by July 2007

Backup

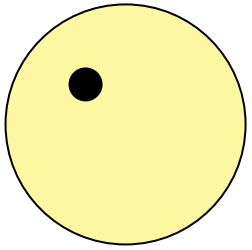




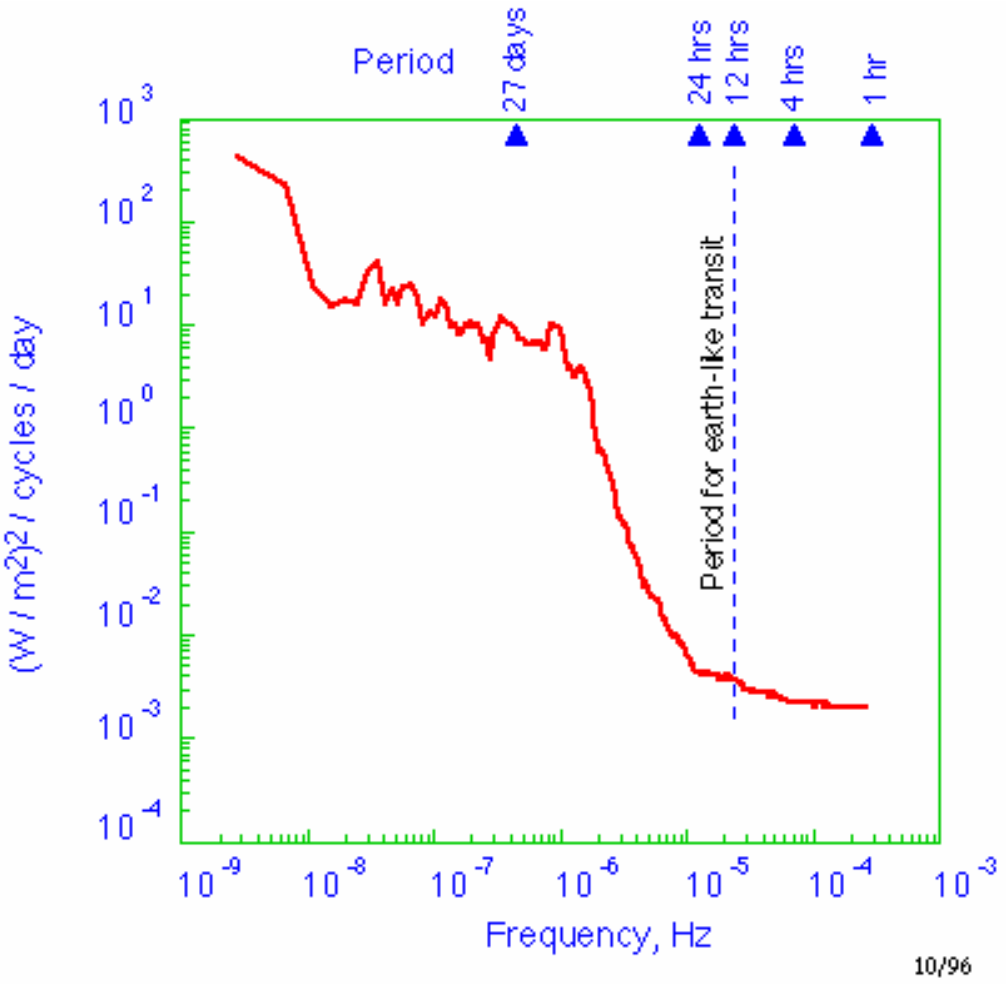
SIM Predicted Performance Exceeds NRC Goals

Concept	Wide-Angle Astrometry		Narrow-Angle Astrometry				
	Require-ment (μas)	Goal (μas)	Require-ment (μas)	Goal (μas)	Magni-tude Limit (V)	Null-ing?	Synthesis Imaging?
1991 AASC (AIM)	30	3	-	-	20	No	No
2001 AASC (SIM)	10	4	3	1	20	Yes	Full UV plane from 1 to 10 m
2002 CAA Assess-ment	30	4	3	1	20	No	10 m baseline only (plus rotation)
Current Perform-ance	2.4 μas		0.8 μas		20	No	9 m baseline only (plus rotation)

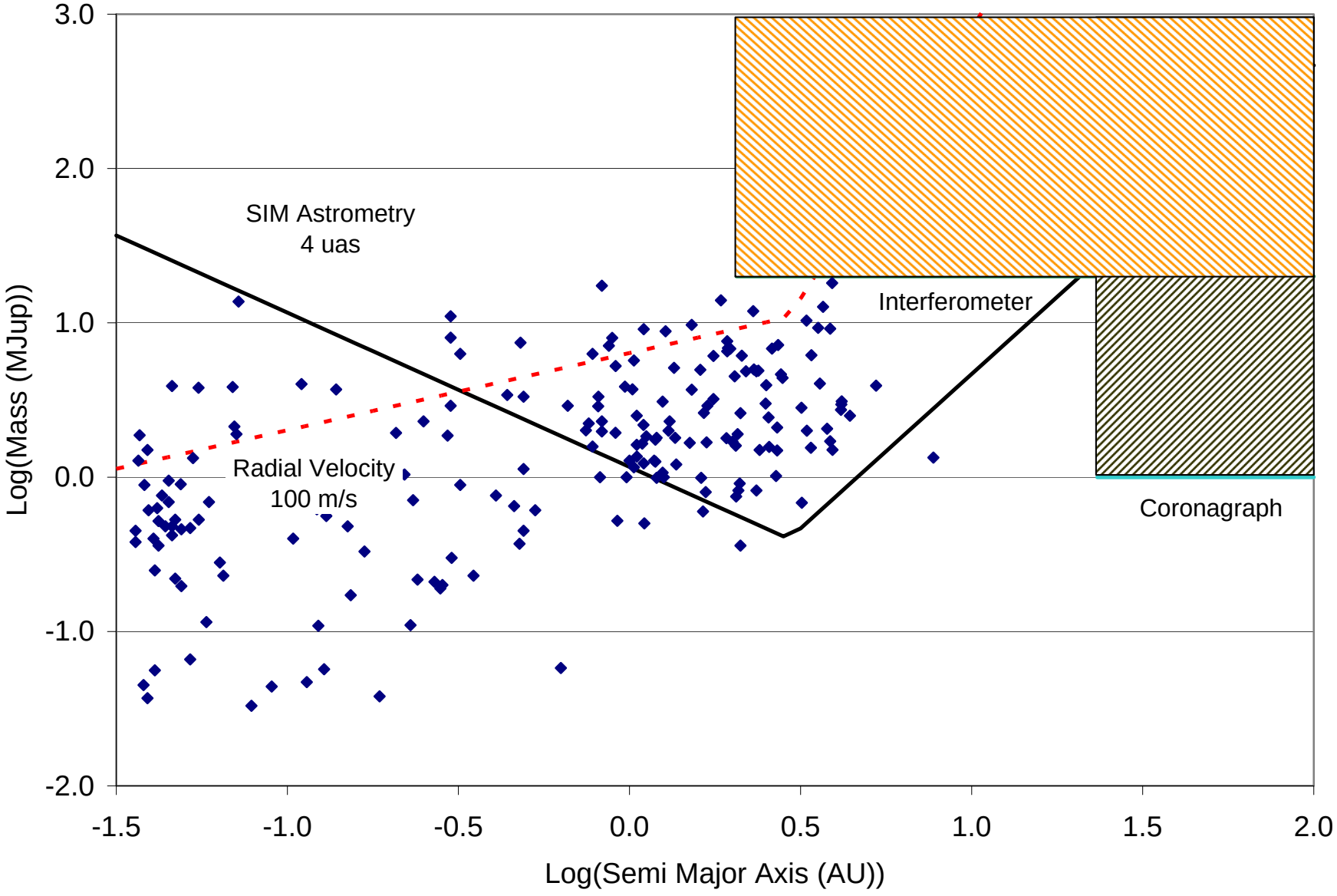
Star Spots



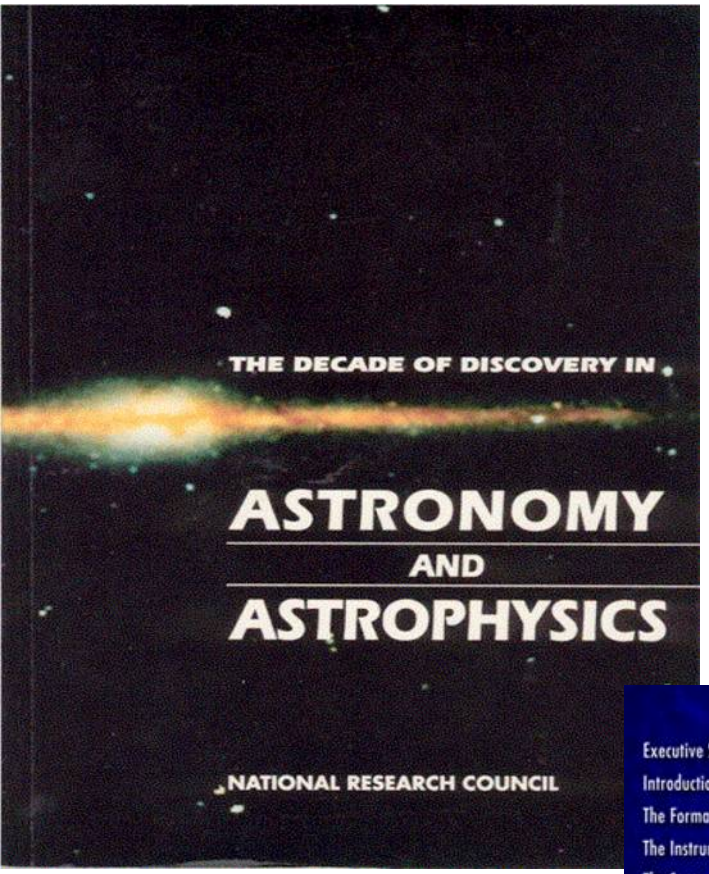
- “Spots” produce both astrometric and RV biases.
- For G2 star a 10^{-3} spot will create bias of
  - 0.25 μas with no modeling
  - 1m/s RV with no modeling

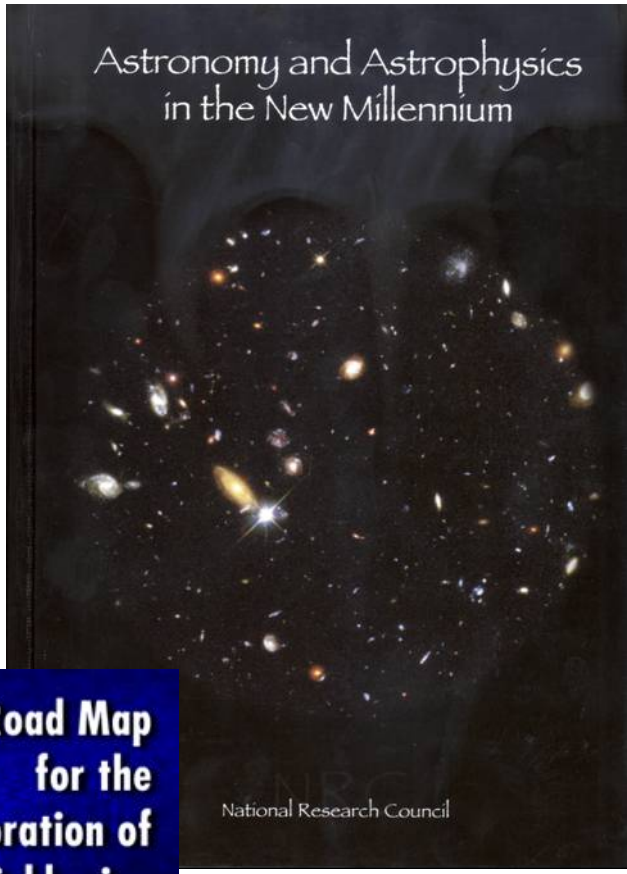


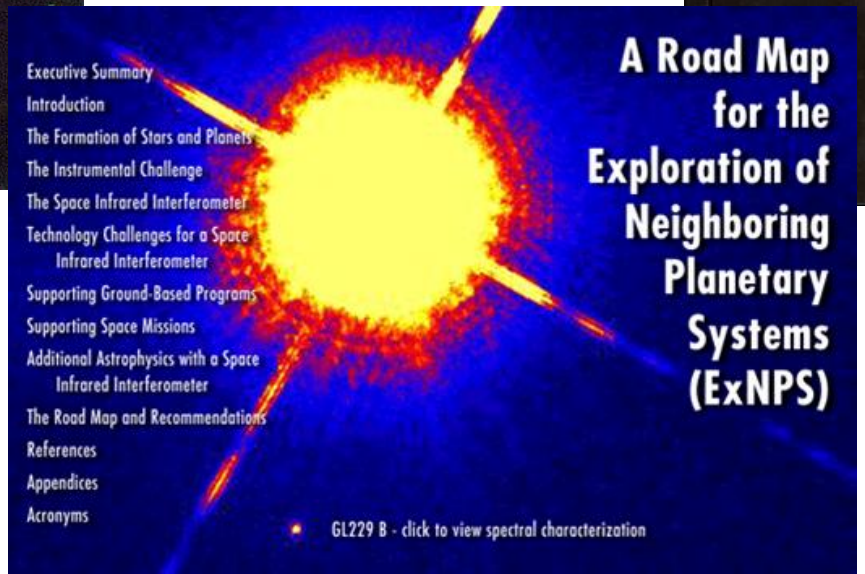
SIM will Find Jupiters Orbiting Young Stars



1990 & 2000 Decadal Reviews Endorse SIM





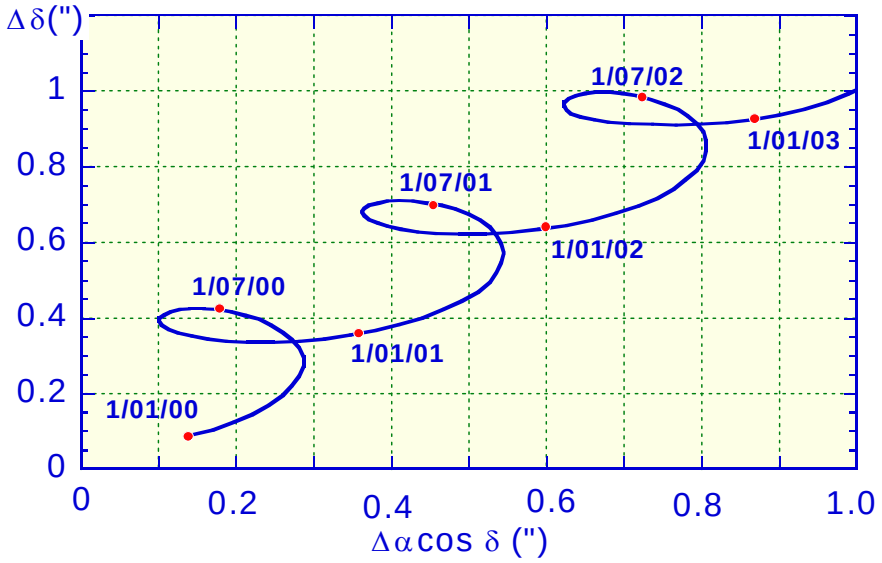


Gaia: Planet Motions

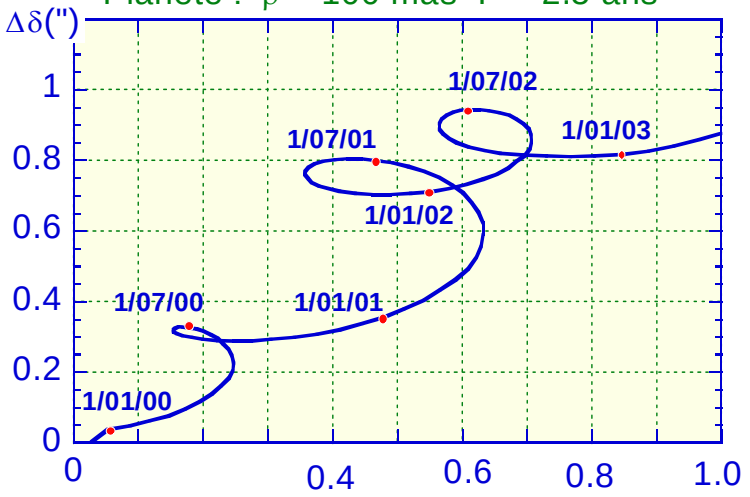
$\mu \sim 250$ milliarcsec/year

$\pi \sim 100$ milliarcsec

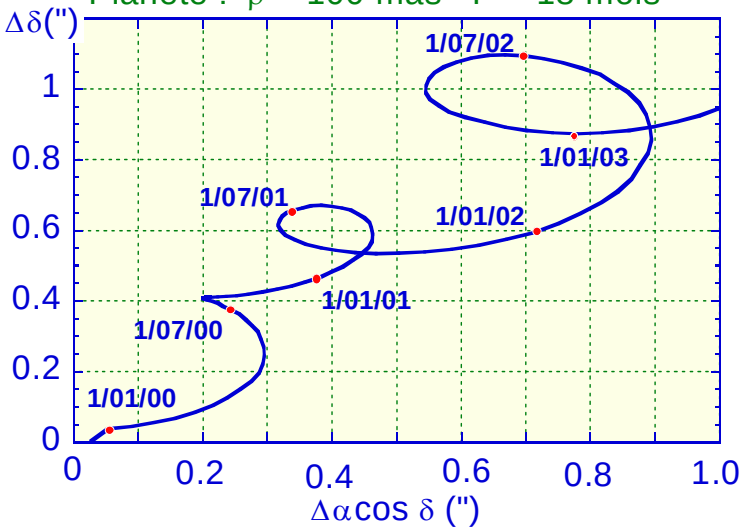
Single star

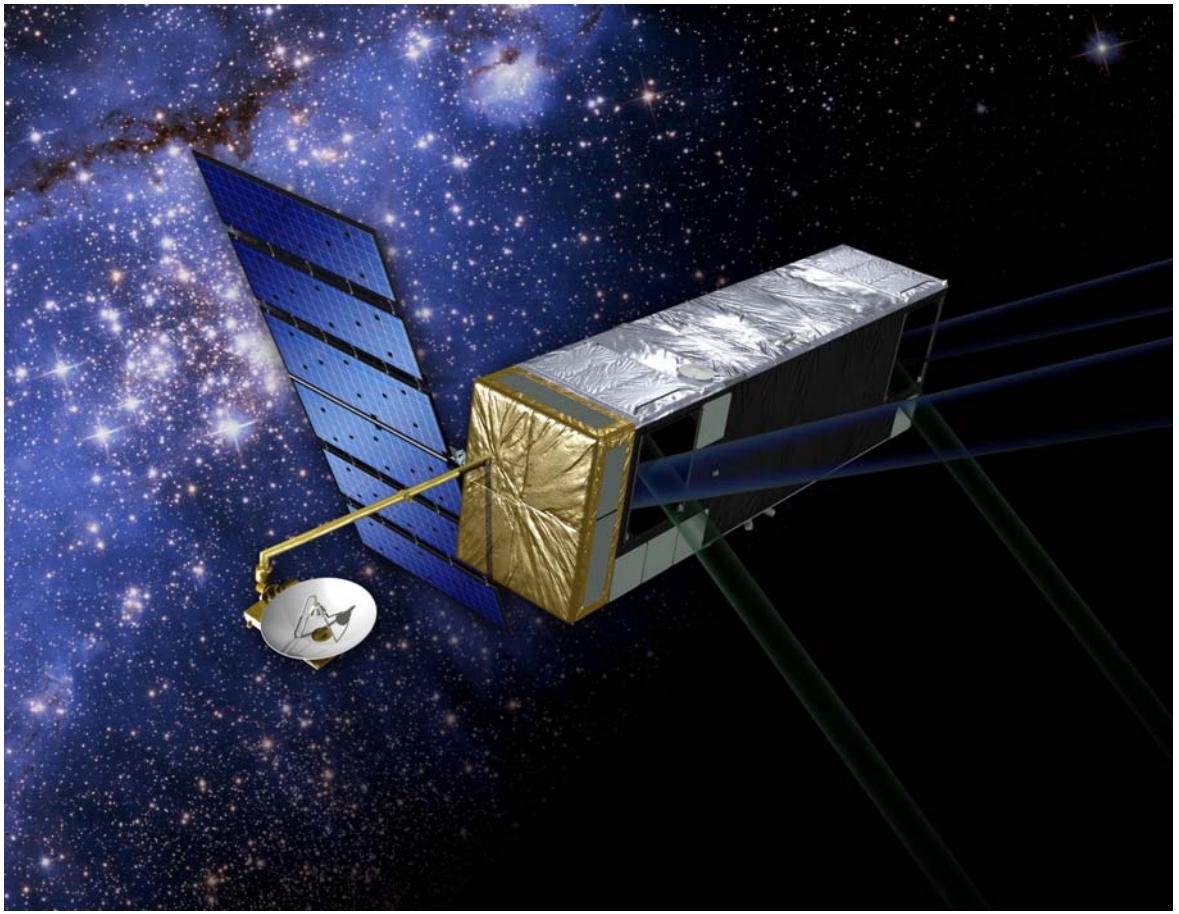


Planète : ρ = 100 mas P = 2.5 ans



Planète : ρ = 100 mas P = 18 mois





Narrow angle astrometry **1 μas** (single visit)

Global astrometry (5 yr mission)

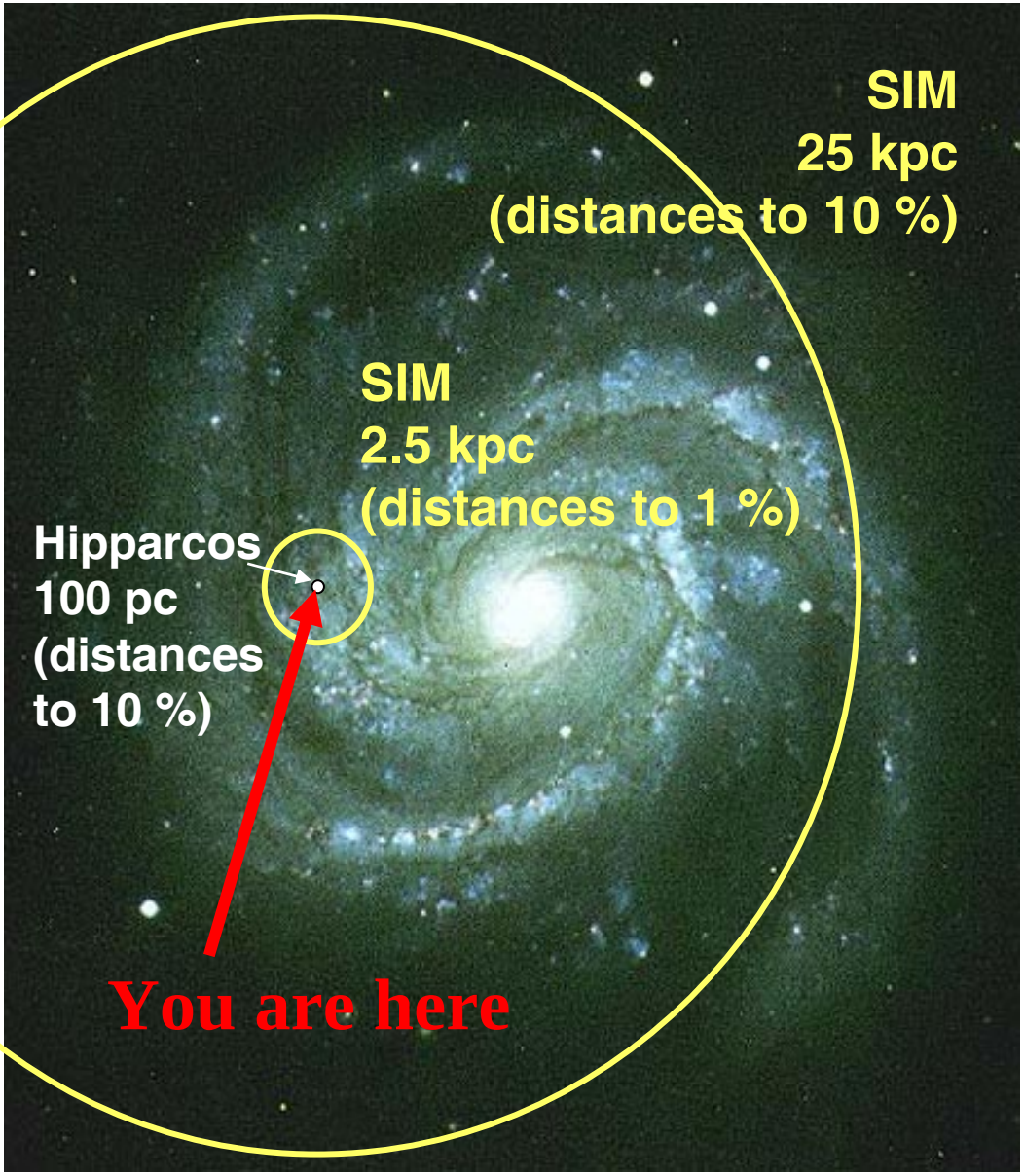
- **4 μas** position (reference to QSOs)
- **2.5 μas/yr** proper motion
- **4 μas** parallax

SIM & Unique Astrophysics

SIM's Reach Extends Across our Entire Galaxy to do "Precision Astrophysics"

What makes SIM unique:

- Extreme astrometric precision
  - 4 μas (microarcsec) positions
  - 4 μas/yr proper motions
  - 1 μas differential positions
- Ability to observe faint targets
  - V <~ 20
- Flexible scheduling
  - optimize for specific science objectives



SIM: Unique Astrophysics

- Masses of stars
  - Accurate dynamical masses for neutron stars and black holes - no more rough estimates
- The Galaxy and star clusters
  - Ages of globular clusters; ages and evolution of open clusters
  - Mass distribution of dark matter through microlensing and tidal tails
- Nearby galaxies
  - Mass distribution, including dark matter, of the Local Group - directly measure galaxy motions
- Cosmology
  - Unambiguous geometric distances to nearby galaxies; calibrate standard candles
  - H_o to 2% - strongly constrain the equation of state of dark energy