Microarcsecond Astrometry with SIM Lite

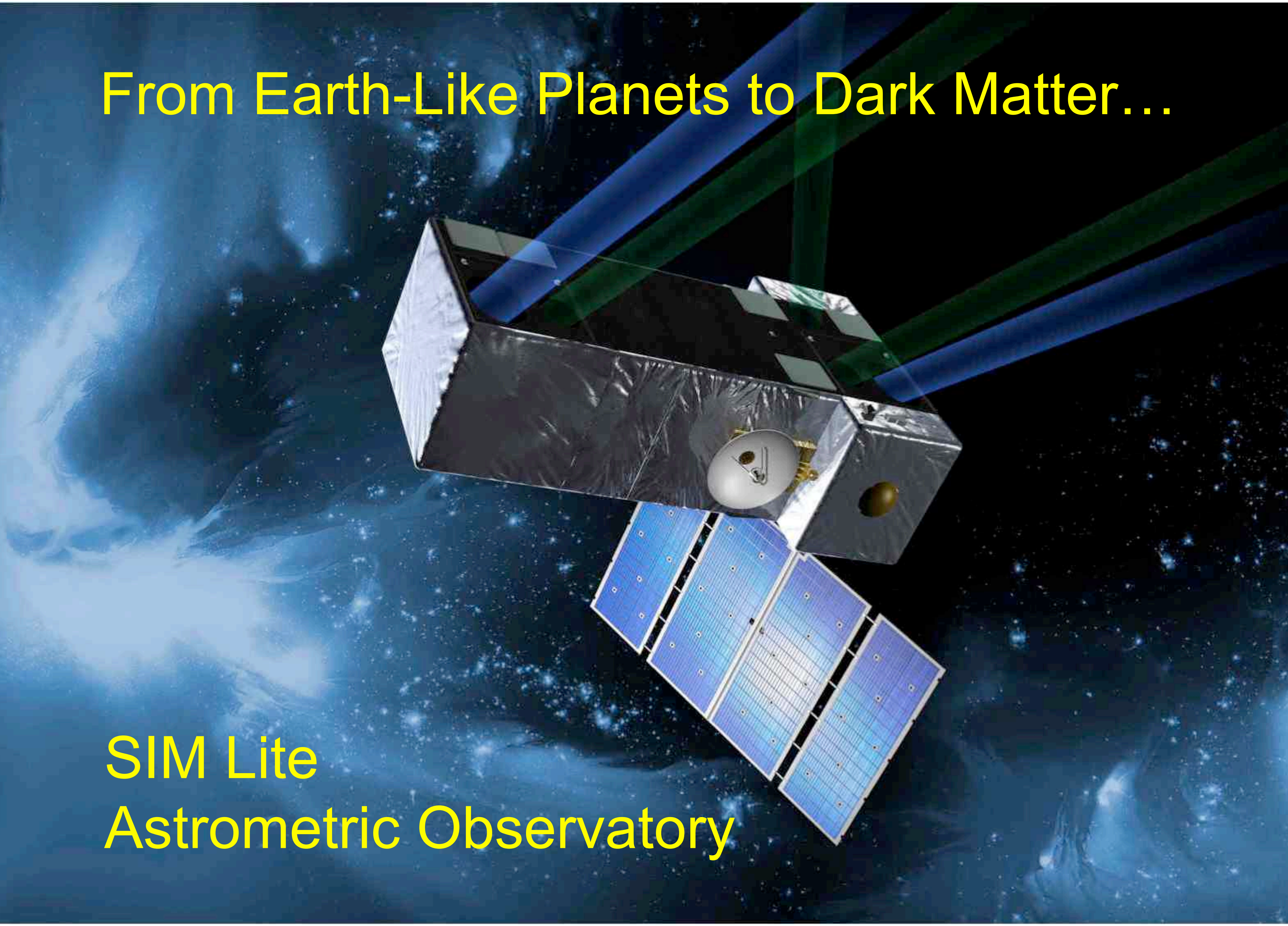
Stephen Unwin

SIM Deputy Project Scientist

New Science Enabled by Microarcsecond Astrometry

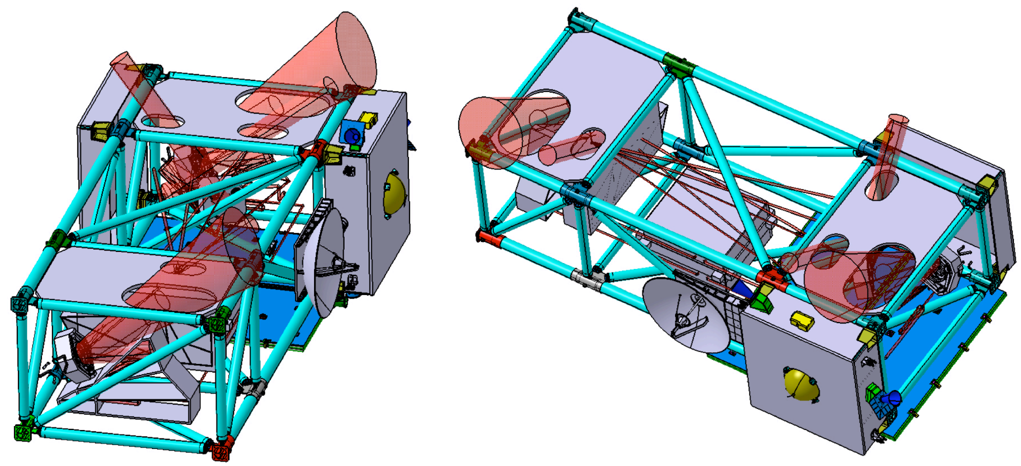
Socorro, New Mexico

July 21-23, 2009

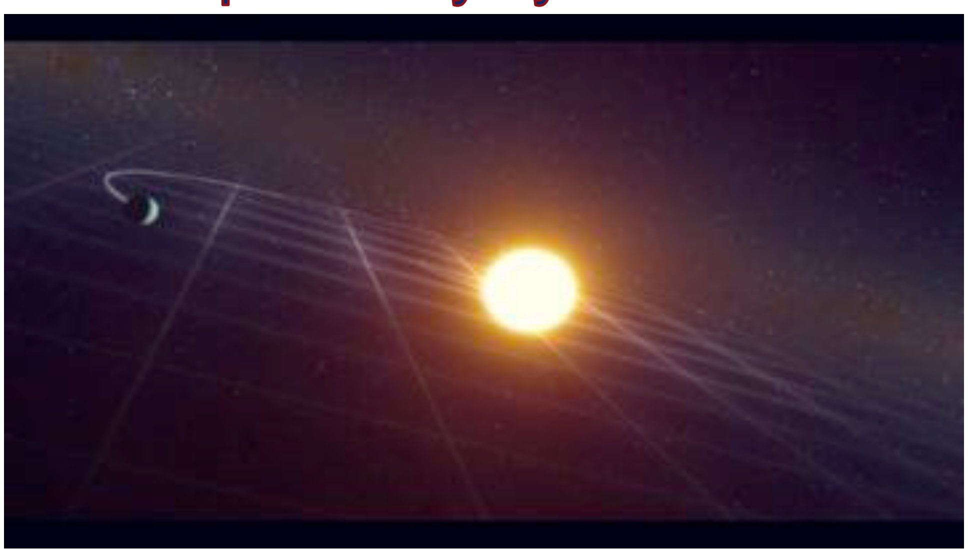

From Earth-Like Planets to Dark Matter…
SIM Lite
Astrometric Observatory

SIM Lite is an Engine for Dynamical Astronomy

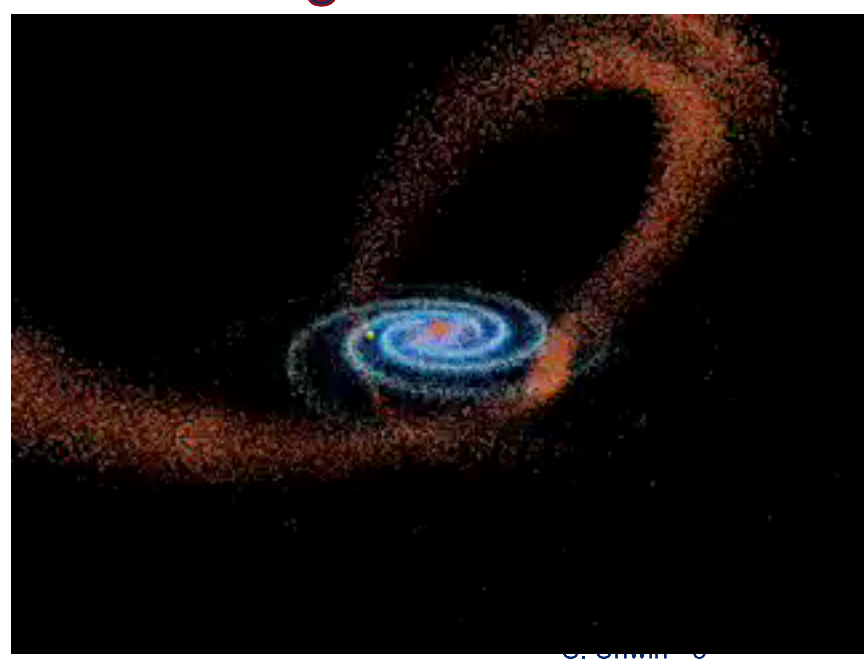
- Talk summary:
  - How SIM Lite works
  - SIM Lite programmatic status
  - SIM Lite science highlights
  - *General Observer* program



… on planetary system scales



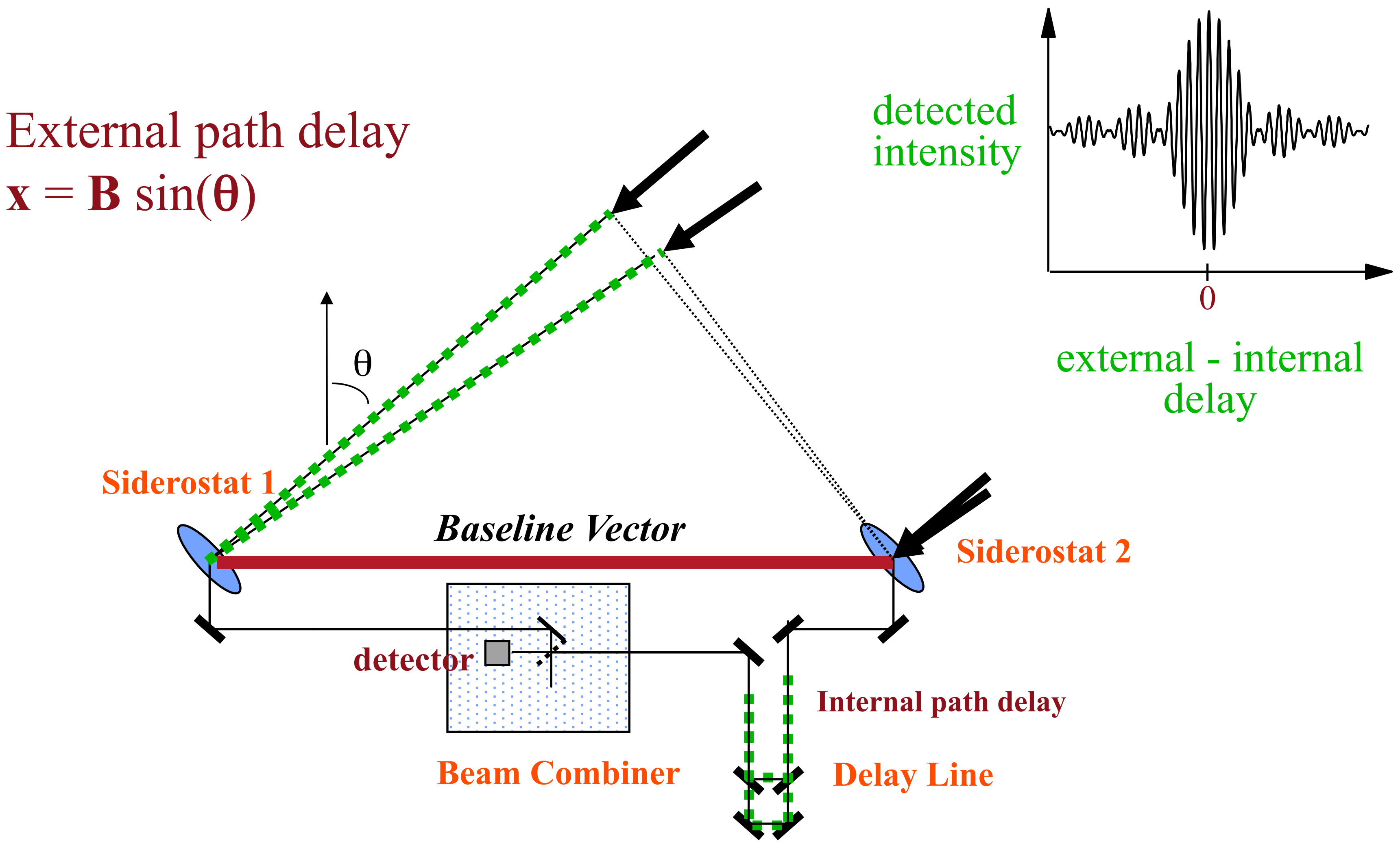
… on galactic scales



What is SIM Lite ?

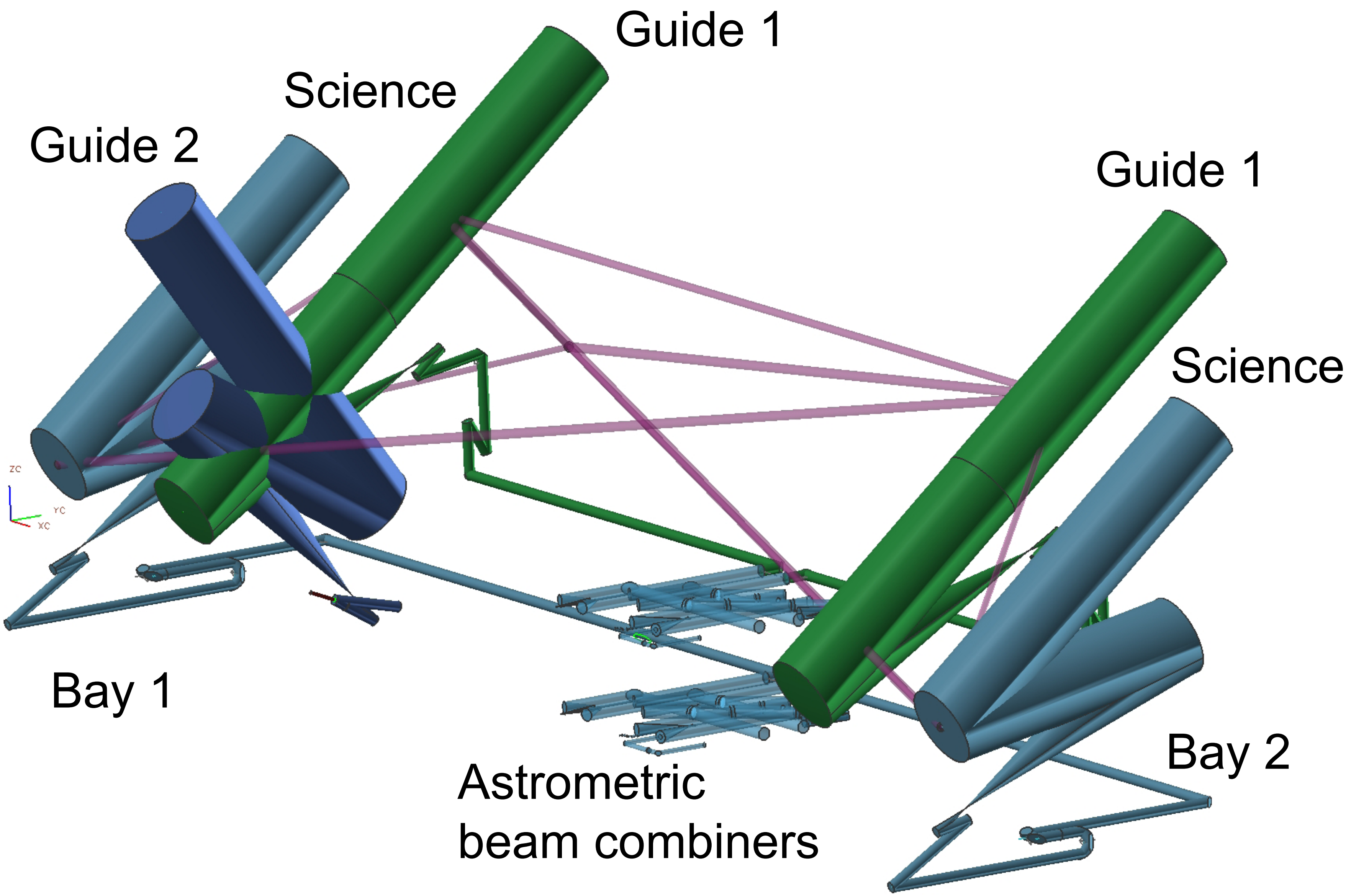
- Precision astrometry in the optical
  - 6-m Michelson Stellar Interferometer
  - 50 cm siderostats
  - Guide (bright star) interferometer used to stabilize instrument
  - Earth-trailing solar orbit
  - 5 year mission
- Performance
  - Wide-angle: 4.0 μas mission accuracy
    - Full precision from V = -1.4 to 20 (observing time limited)
  - Narrow-angle: 1.0 μas in a single measurement (1100 s)
    - Instrument noise ‘floor’ < 0.035 μas (mission accuracy)
    - Earth-Sun system at 10pc is 0.21 μas
- Observing
  - 36 % Awarded to SIM Science Team
  - 33 % Astrometric Grid (reference frame); slewing; calibration
  - 31% **General Observer time** (to be openly competed)

Astrometry with an Interferometer

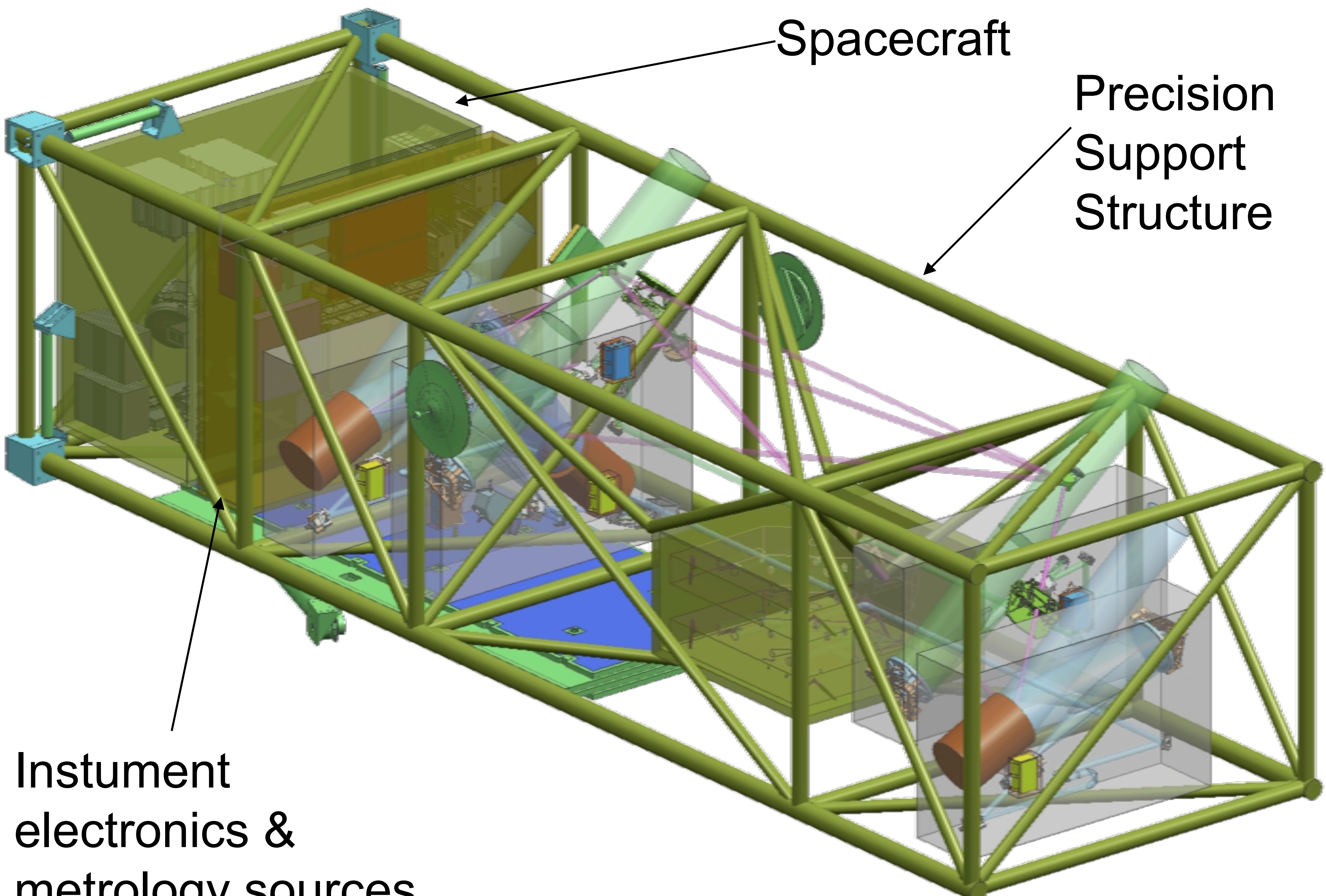


Astrometric quantity is the change in delay-line position between targets

Optical Prescription

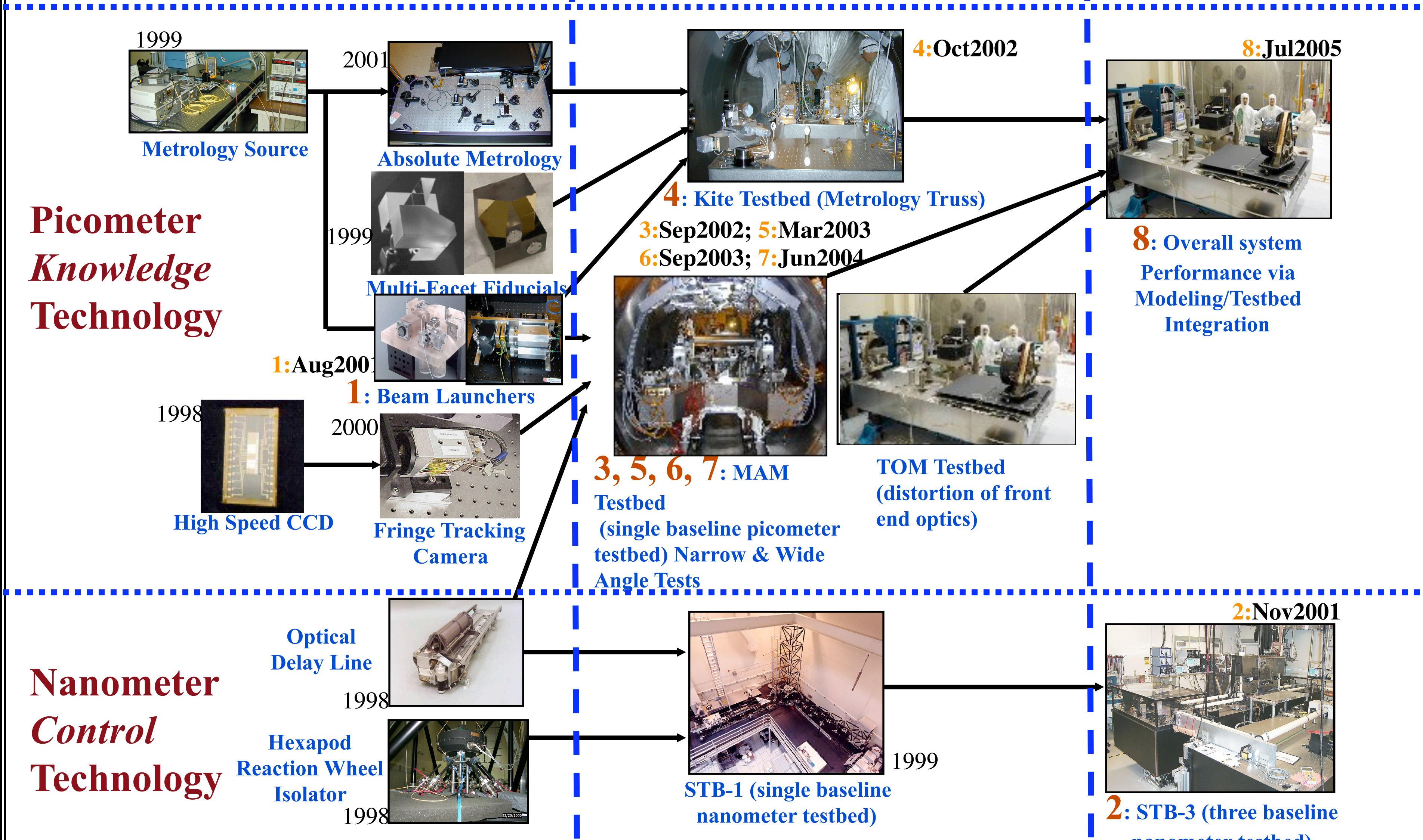


Configuration

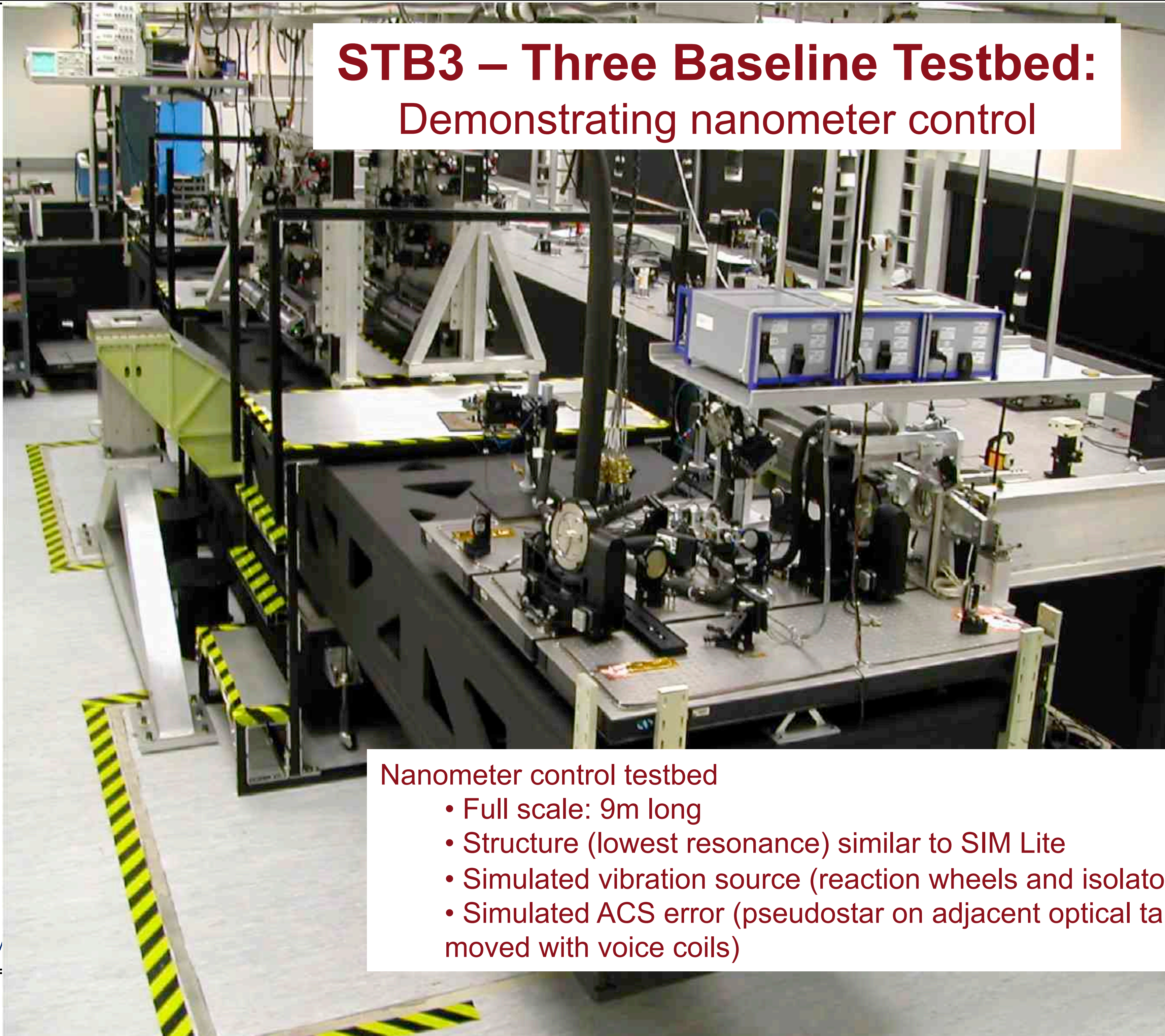


Technology Needed for SIM: Completed in 2005

Component Technology | **Subsystem-Level Testbeds** | **System-Level**

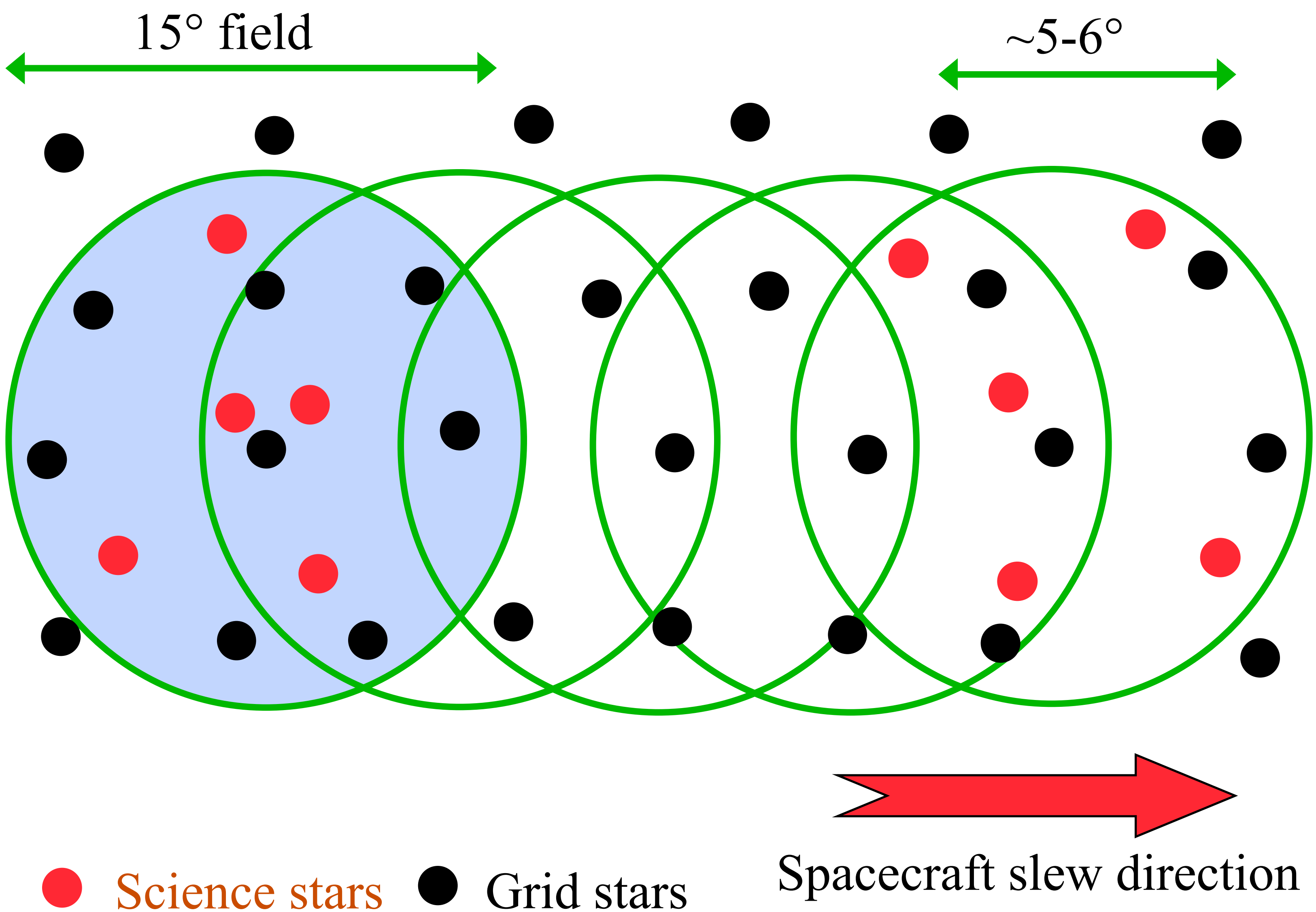


STB3 – Three Baseline Testbed:
Demonstrating nanometer control

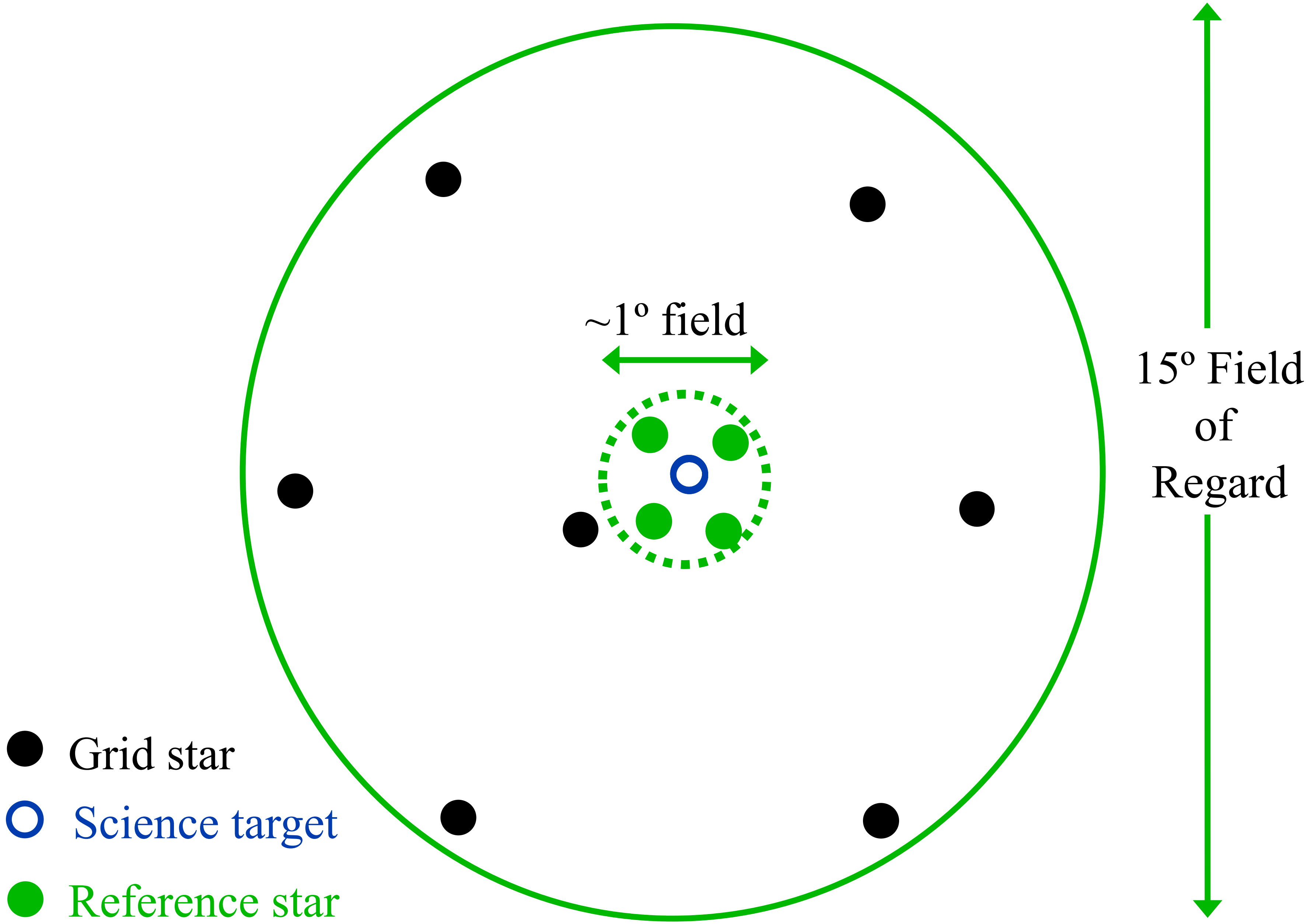


Nanometer control testbed
- Full scale: 9m long
- Structure (lowest resonance) similar to SIM Lite
- Simulated vibration source (reaction wheels and isolators)
- Simulated ACS error (pseudostar on adjacent optical table moved with voice coils)

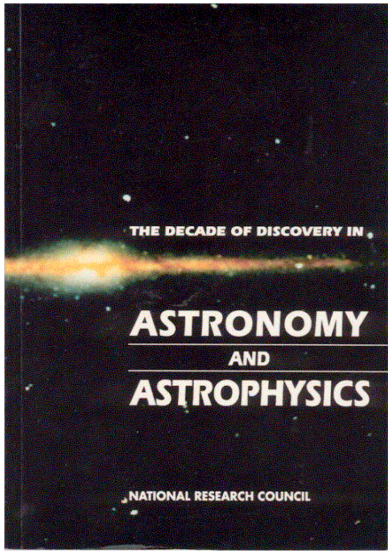
Global Astrometry Observing Scenario

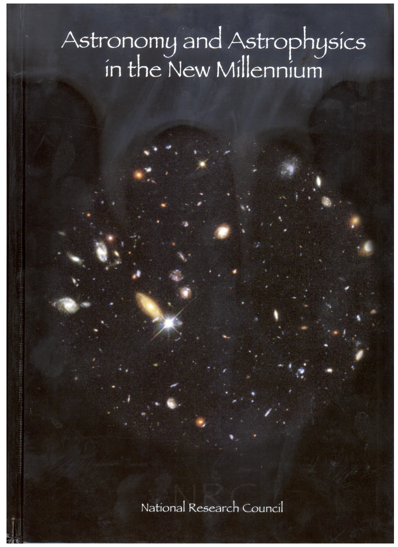


Planet Search Observing Scenario



Recommended by the National Academy of Sciences

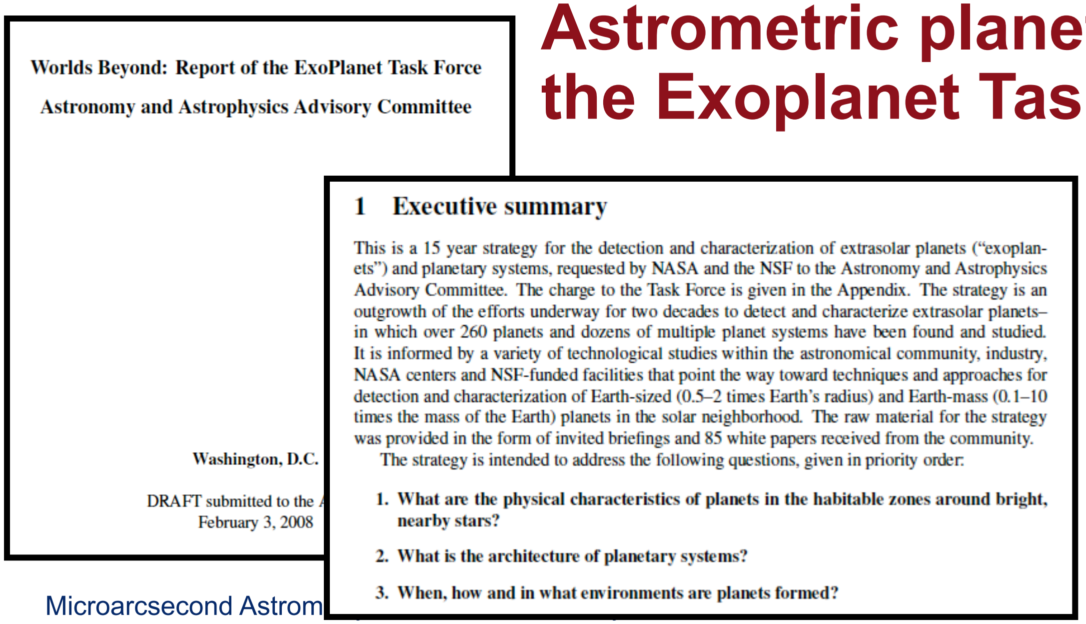




1990 and 2000 NRC Decadal Reviews

"…emphasized the *dual capability* of SIM, noting that this capability would enable "…both… detecting planets and … mapping the structure of the Milky Way and other nearby galaxies."

Astrometric planet search endorsed by the Exoplanet Task Force (AAAC 2008)


Worlds Beyond: Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

Washington, D.C.

DRAFT submitted to the

February 3, 2008

1 Executive summary

This is a 15 year strategy for the detection and characterization of extrasolar planets ("exoplanets") and planetary systems, requested by NASA and the NSF to the Astronomy and Astrophysics Advisory Committee. The charge to the Task Force is given in the Appendix. The strategy is an outgrowth of the efforts underway for two decades to detect and characterize extrasolar planets–in which over 260 planets and dozens of multiple planet systems have been found and studied. It is informed by a variety of technological studies within the astronomical community, industry, NASA centers and NSF-funded facilities that point the way toward techniques and approaches for detection and characterization of Earth-sized (0.5–2 times Earth's radius) and Earth-mass (0.1–10 times the mass of the Earth) planets in the solar neighborhood. The raw material for the strategy was provided in the form of invited briefings and 85 white papers received from the community.

The strategy is intended to address the following questions, given in priority order:

1. **What are the physical characteristics of planets in the habitable zones around bright, nearby stars?**
2. **What is the architecture of planetary systems?**
3. **When, how and in what environments are planets formed?**

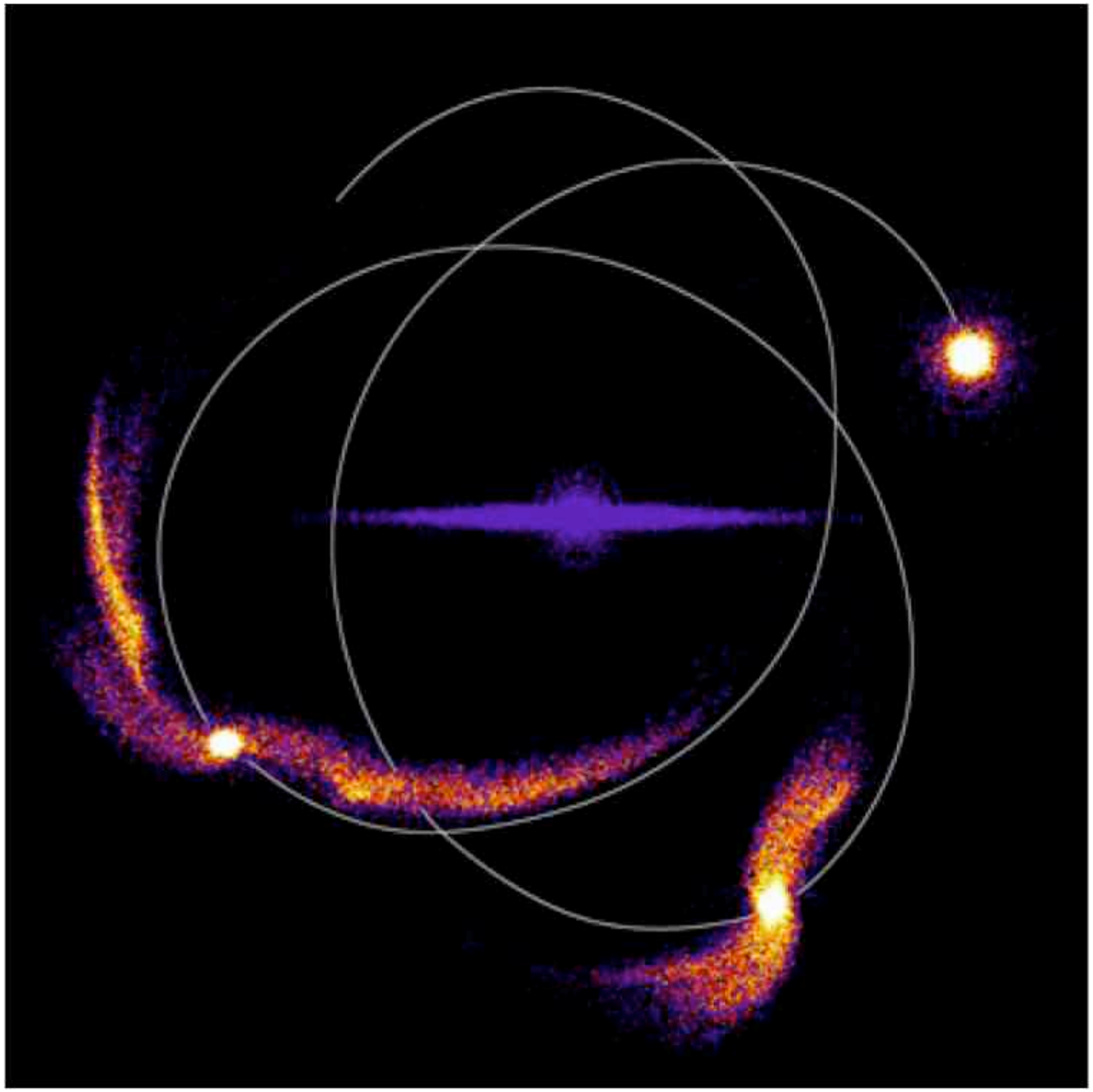
After careful consideration of 85 white papers & invited briefings, recommended:

Astrometry should precede direct detection

Where is SIM Lite now ?

- SIM Lite started ‘Pre-Phase A’ in 1996
- Technology Program completed in 2005
  - 8 milestones set by NASA HQ and independently reviewed
- Project slowed down in 2006
- Current status
  - SIM is currently in ‘Phase B’; phase B work is almost complete
  - Could begin construction of *flight instrument* in less than 2 years
  - Currently no official launch date
- Current activities
  - Performing Engineering Risk Reduction
  - Reducing the technical and cost risk prior to entry into Phase C
  - Science studies continue
- Under review by *Astro2010* – Decadal Survey
  - With a strong endorsement, SIM Lite could be rapidly on track to a launch in ~late-2015

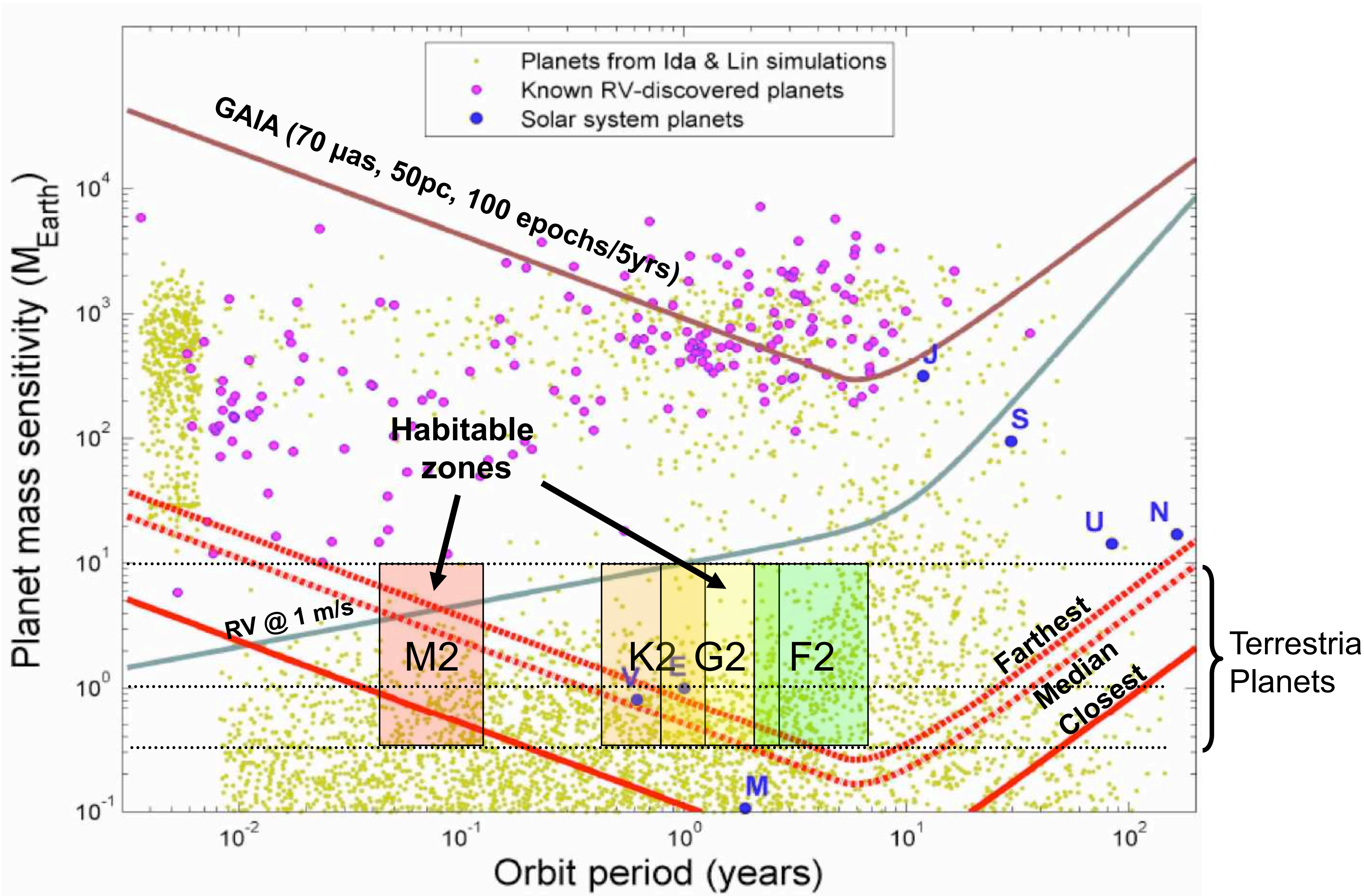
SIM Lite Science Highlights



SIM Lite will find and measure definitive masses of nearby Earth-like planets

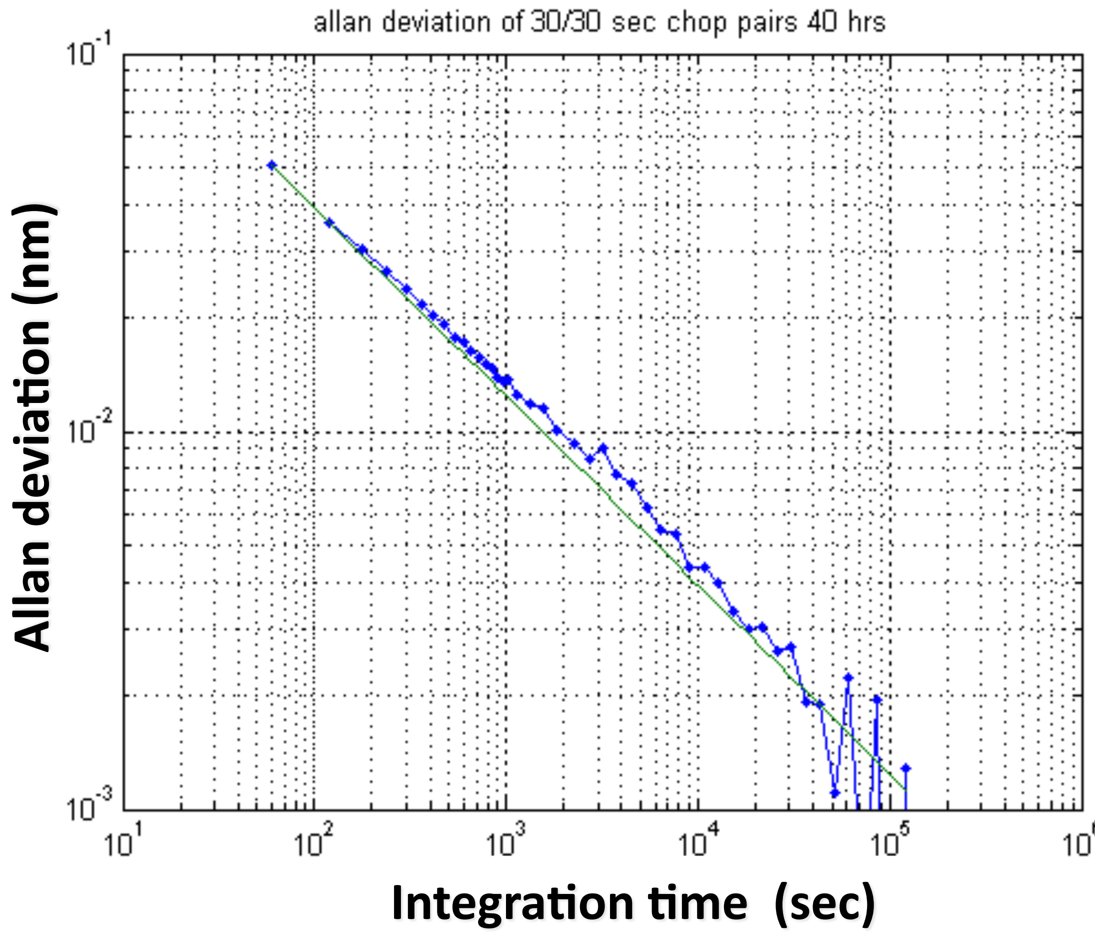
- A comprehensive search of Solar-type Stars in the Solar Neighborhood for Earth-like Planets
  - **Sensitivity is 1 Earth-mass around the nearest 60 FGK stars**
- This is a definitive search: planets cannot hide in the ‘glare’ of the parent star
- The result is a complete inventory of the local neighborhood FGK stars out to ~20 pc
- This is fundamental science on a topic of keen interest to astronomers and the general public
- SIM Lite’s legacy: the *Nearby Terrestrial Planet Catalog*
  - SIM Lite measures dynamical masses for all the planets it detects
  - SIM Lite measures orbital elements for every planet in multiple-planet systems
  - Critical information for understanding stability, formation and evolution

SIM Lite Earth-Analog Discovery Space

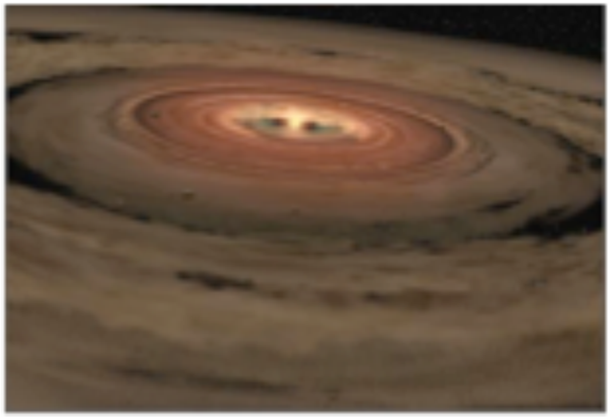


SIM Instrument Testbeds Demonstrate Planet Finding Capabilities

- Testbeds confirm SIM Lite performance models
- Testbed data average to less than <0.5 pm (<0.035 μas on 6-m baseline) with no floor, based upon longest data sets (42 hr) taken to date
- Modeling of thermal drift predicts in-orbit performance better than testbeds
- Field dependent and color dependent errors within budgeted allowances



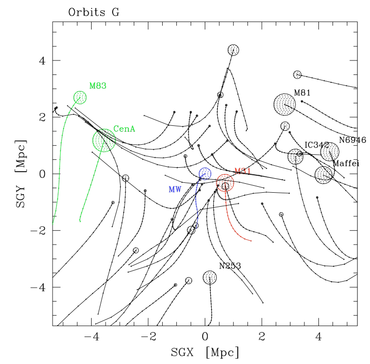
Observations of Young Planetary Systems



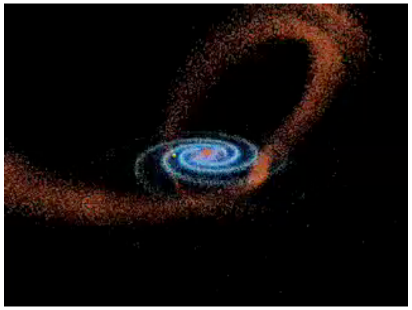
- Questions:
  - What fraction of young stars have gas-giants ?
  - Do gas-giant planets form at the “water-condensation” line ?
  - Does the distribution and orbital parameters of planets change with age & disk mass ?
  - How does orbital migration affect where, when, and how terrestrial planets form ?
- Astrometry can find gas giants in young-star systems
  - Orbits within 1-10 AU of parent stars at 25-150 pc
  - Jitter simulated to be a few μas, consistent with detecting gas giants
- Can’t do this science with RV, transits, or imaging
  - Variability, spectral jitter & rotation at >100 m/s
  - Disks preclude direct imaging at these radii
- Sample SIM Lite targets: nearby moving groups
  - Beta Pic (12 Myr, 35pc); AB Dor (50 Myr, 30pc)

SIM probes the dynamical effect of Dark Matter on scales up to 5 Mpc

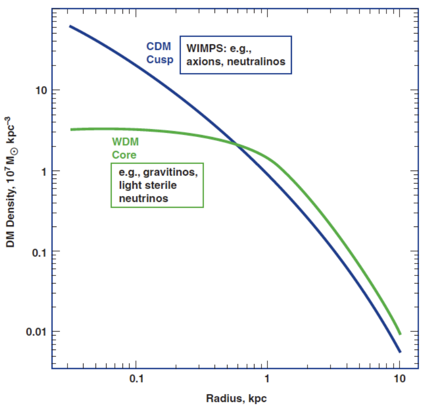
- Local Group galaxy motions
  - out to ~5 Mpc

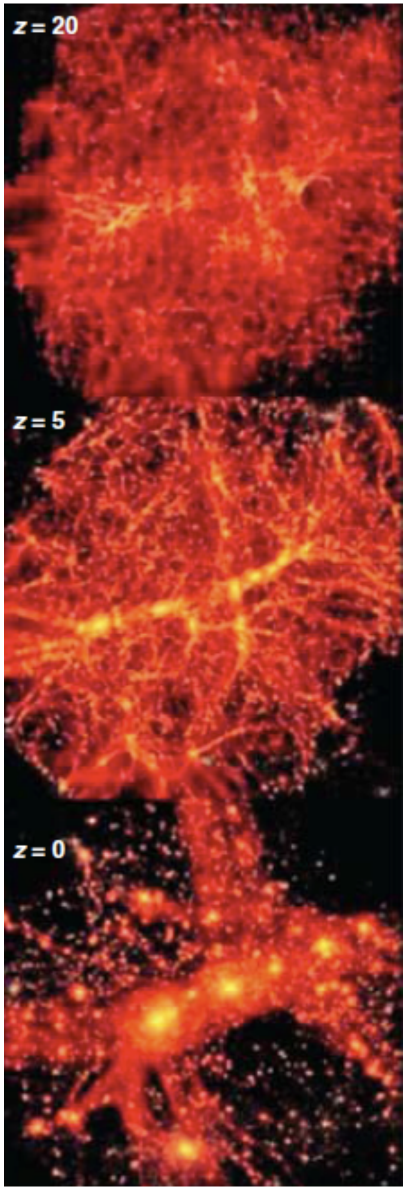


- ‘Tidal tails’ of disrupted dwarf spheroidal galaxies in the halo of the Milky Way
  - out to ~50 kpc



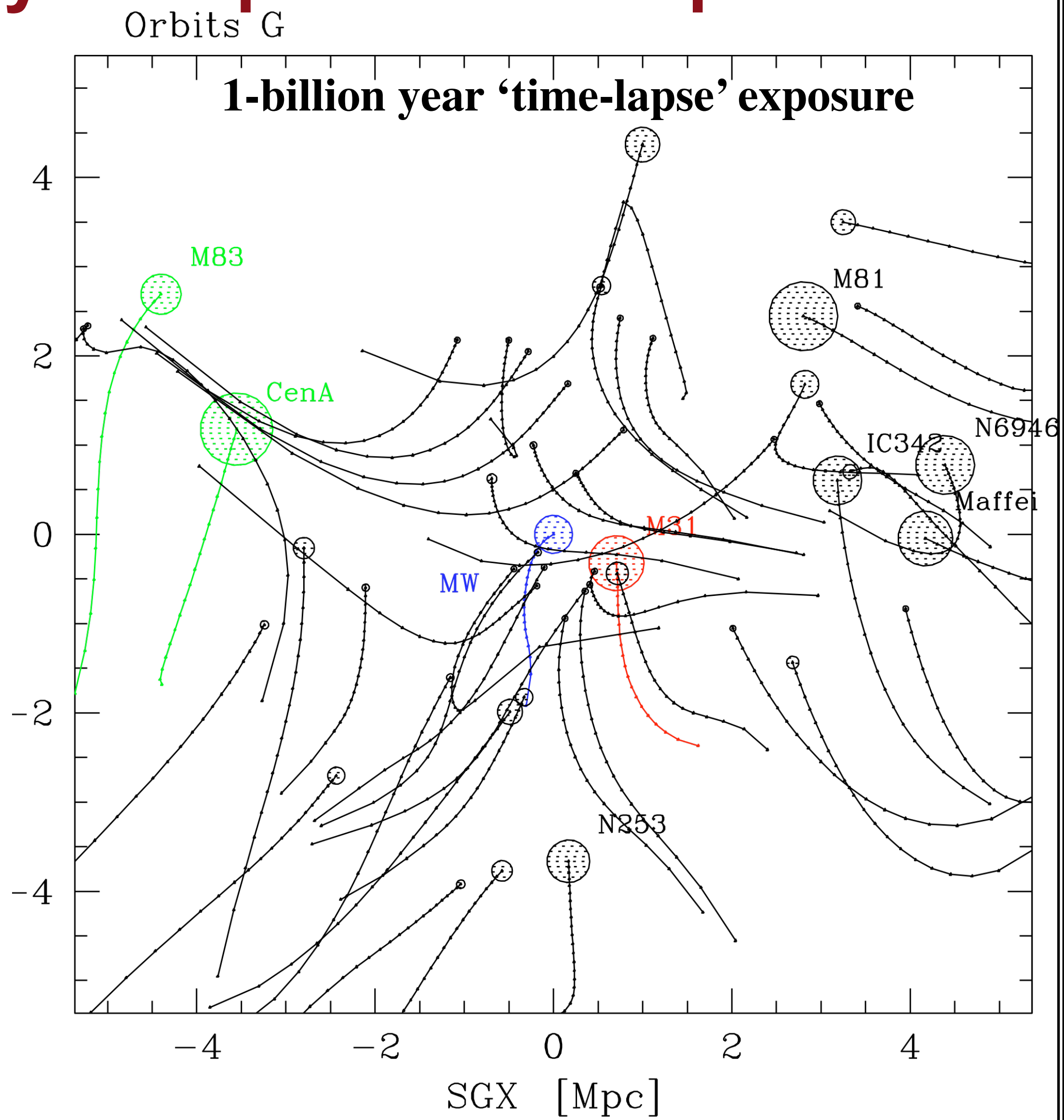
- Mass profiles of dwarf spheroidal galaxies – cusps or cores ?
  - on scales of ~1 kpc





Dynamics of Galaxy Groups within 5 Mpc

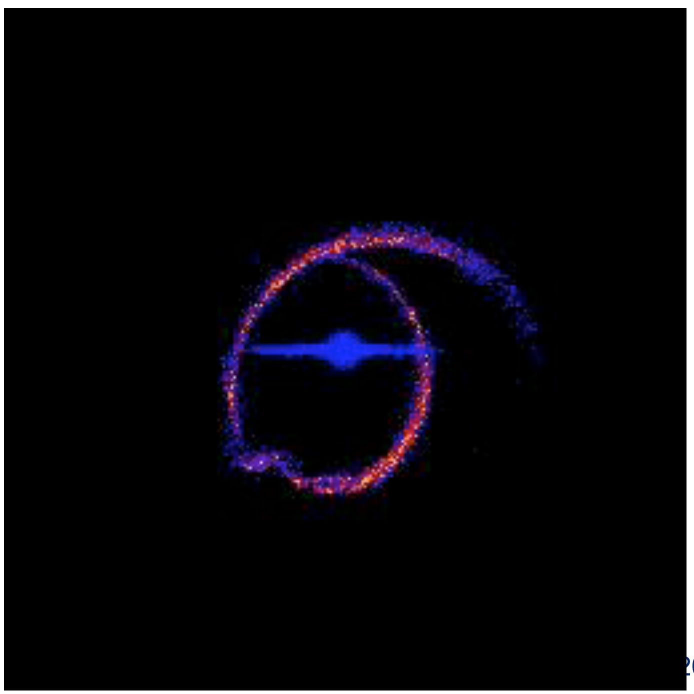
- Proper Motions are key to deciding among multiple solutions in Least Action and allow solutions for masses of individual galaxies, groups and mass distributions
- Probes the critical 1- 5 Mpc scale
- Constrains tidal fields from Virgo, GA, PP, and Local Void
- The properties of Dark Matter (Cold, Warm, and Hot) can be revealed by careful study of the motions of nearby galaxies
- Proper Motions can provide understanding of the state of groups and how they formed
- Required accuracy:
  - A few microarcsec/year absolute at V > 18mag



Trajectories of 30 nearby galaxies and groups from Numerical Action Method Calculations with M/L = 90 for spirals and 155 for ellipticals, $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$ (Shaya et al. 2009)

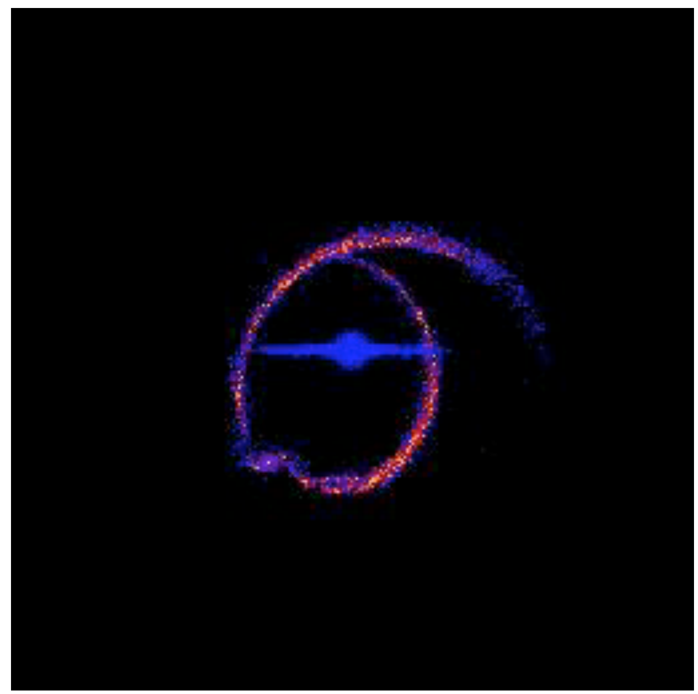
Mass distribution of the Galaxy using Tidal Tails

- Measure shape/orientation/density law/lumpiness of MW potential (Dark Matter)
- Tails ‘encode’ the infall trajectories of dwarf galaxies
- Dwarf spheroidal galaxies are dynamically ‘cold’
  - Don’t need many stars
- Need transverse velocities good to 10 km/s, which requires:
  - ~ 10 μas for satellites at ~250 kpc (Leo I, II, CanVen) for V~ 19.5 giant stars
  - ~ 20 μas for satellites at ~100 kpc (UMi, Dra, Car, …) for V~ 17.5 giant stars
  - Distant streams give better handle on mass distribution



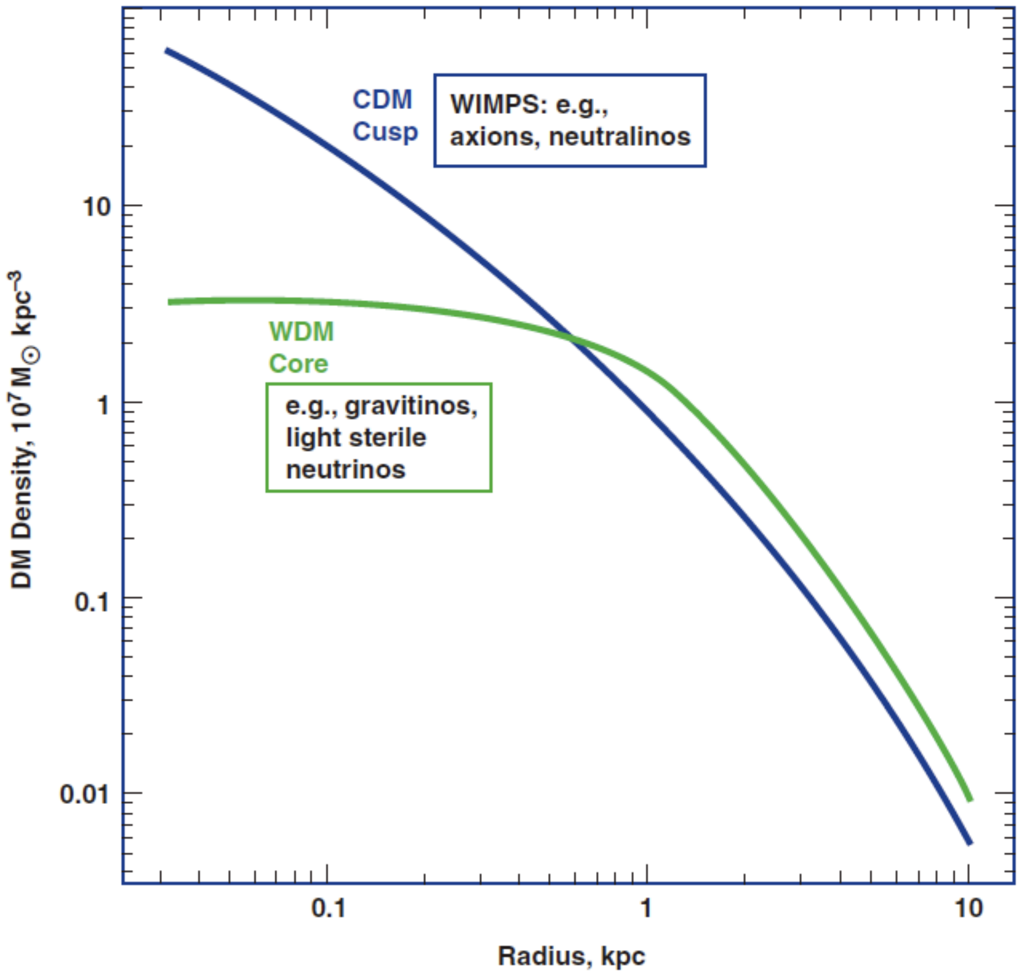
Which model has the correct potential?

We run the movie backwards



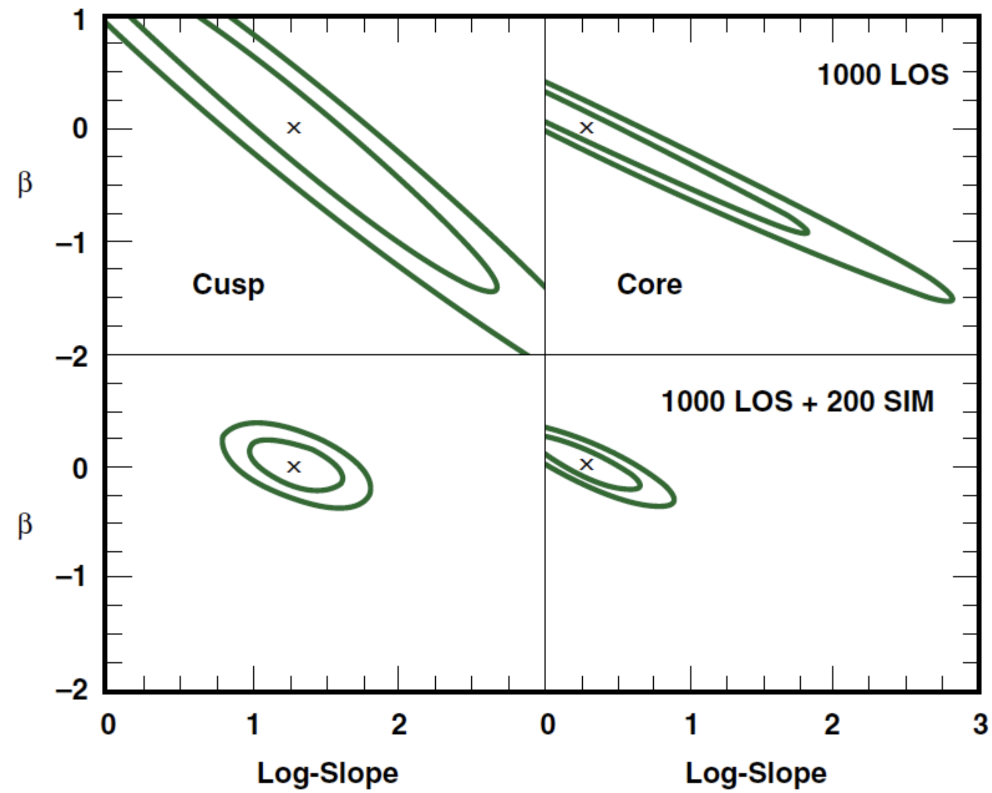
Dark Matter in Dwarf Spheroidal Galaxies

- Dwarf spheroidals are the best galaxies in which to study the particle nature of dark matter
  - Tremaine & Gunn 1979
  - Hogan & Dalcanton 2000
- Central density profile of a dwarf spheroidal galaxy is very sensitive to dark matter
- CDM particles characterized by low initial velocity dispersion and high phase space density (massive particle)
- Derive mass profile from the equilibrium Jeans equation
  - Steep profile 'cusp' is predicted by CDM
  - A much flatter 'core' is predicted by WDM



Dark Matter in Dwarf Spheroidal Galaxies

- Velocity anisotropy is degenerate with the (log) slope of the density profile
- Even 1000 radial velocities are not enough
- Need also to measure the velocity anisotropy β
- Measure ~200 transverse proper motions with SIM Lite to 5 km/s
- Distinguish between ‘cusp’ and ‘core’
  - **Fundamental constraint on dark matter particle**

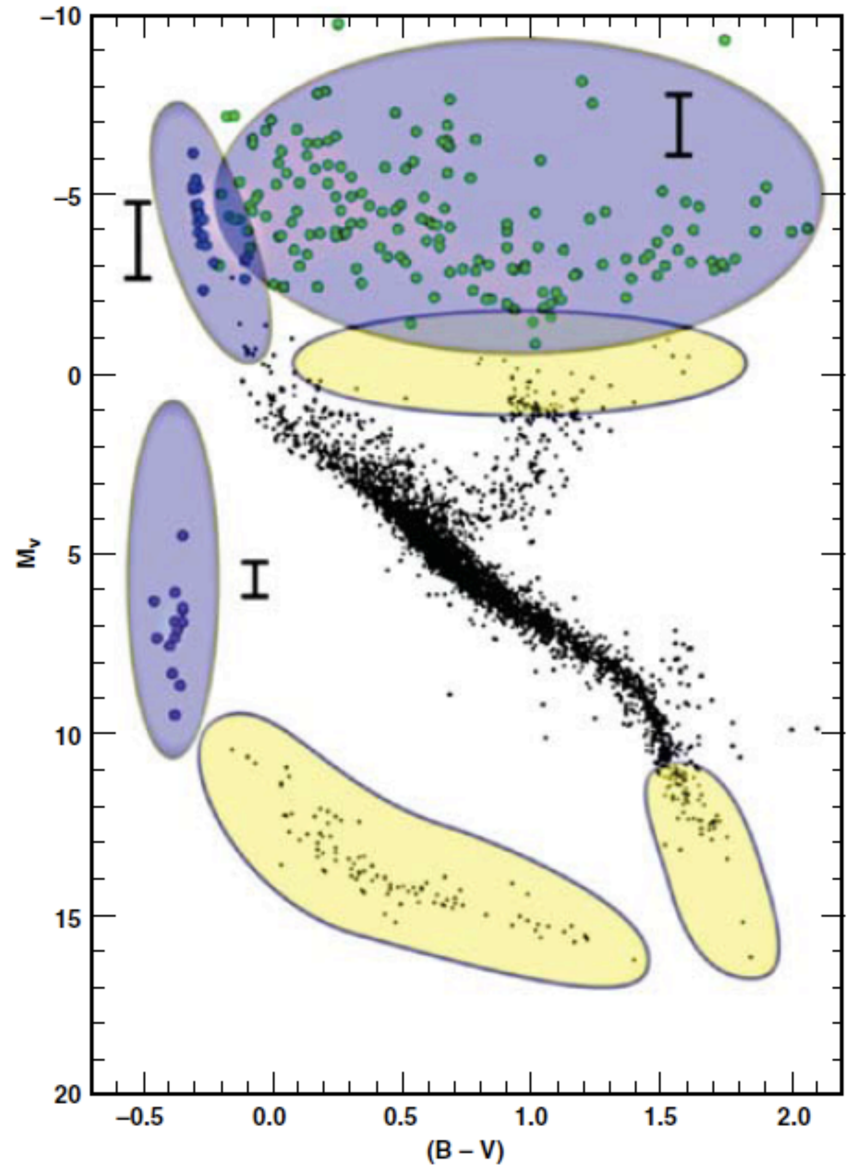


Model of density profile of a dwarf spheroidal galaxy at 2 r_{King}=0.4 kpc (Strigari et al. 2007)

Fundamental Stellar Astronomy: Bright, Faint, Rare

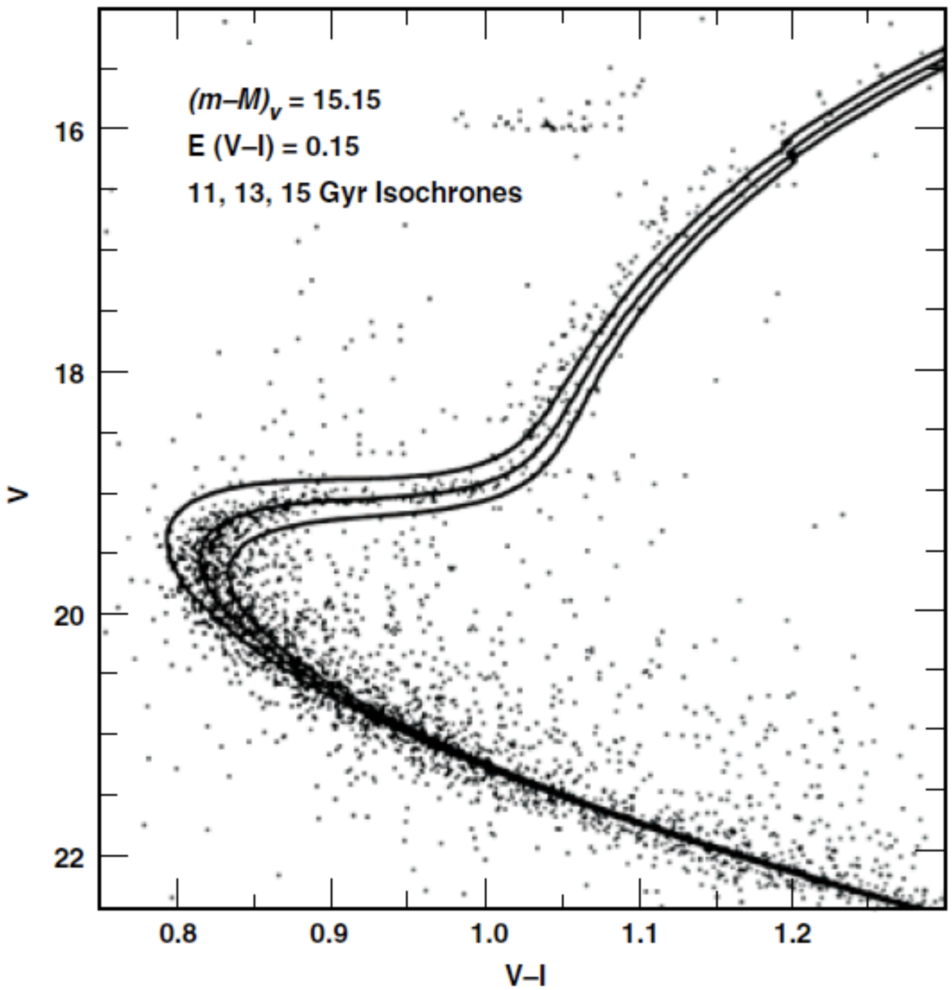
- Example: **supergiant stars**

- Nearby supergiants too bright for Gaia (V<6)
- Many are not in clusters
- 167 of 219 Hipparcos have luminosity errors >20%
- Need ~1% to understand:
  - Role of metallicity
  - Wind-momentum luminosity relation
  - Flux-weighted gravity luminosity relation
    - T. Henry et al. 2009



SIM Lite (blue) and Gaia (yellow) observations across the HR diagram

Formation of the Milky Way: Ages of Globular Clusters

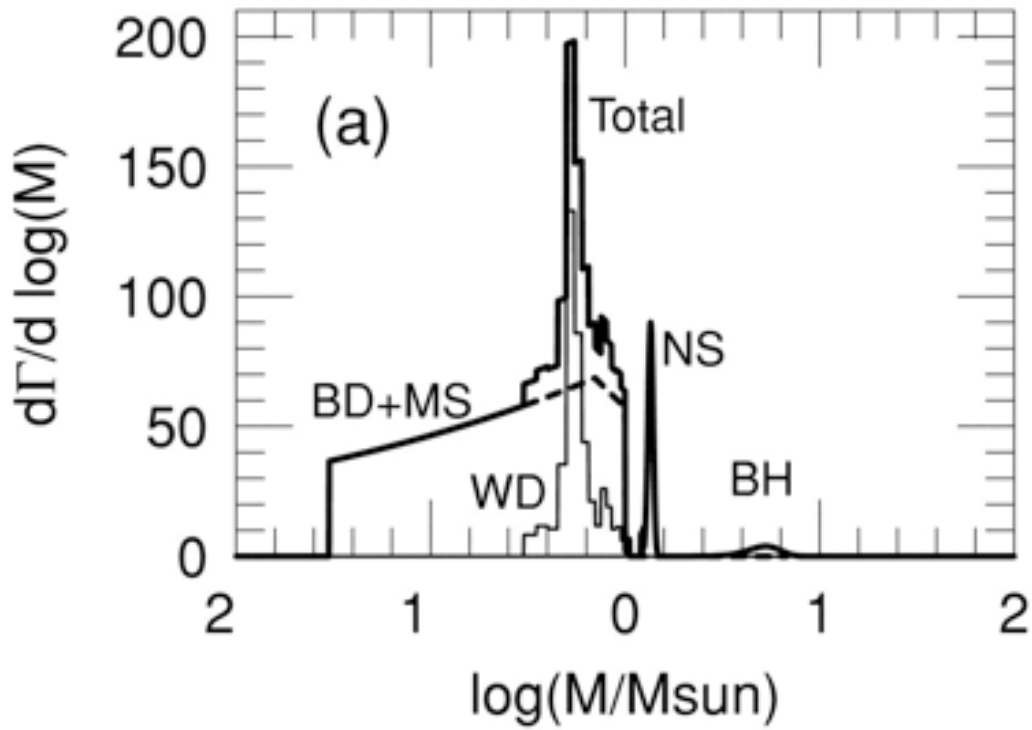


NGC6652 - Chaboyer et al. 2000

- Did GCs in spiral galaxies form rapidly, or slowly (accretion of satellites)?
  - **Need accurate ages**
- Universe is 13.7 Gyr old
  - WMAP; Spergel et al. 2007
- Best GC models have ages ~12 Gyr
  - Chaboyer 2002
- Applying the models requires more accurate luminosity (distance)
- SIM will measure ~20 clusters out to 12 kpc
  - Range of galactocentric radius
  - Metallicity
  - Halo class membership
- **SIM measures ages to 1 Gyr**
- And age *differences* of ~ 1 Gyr between populations

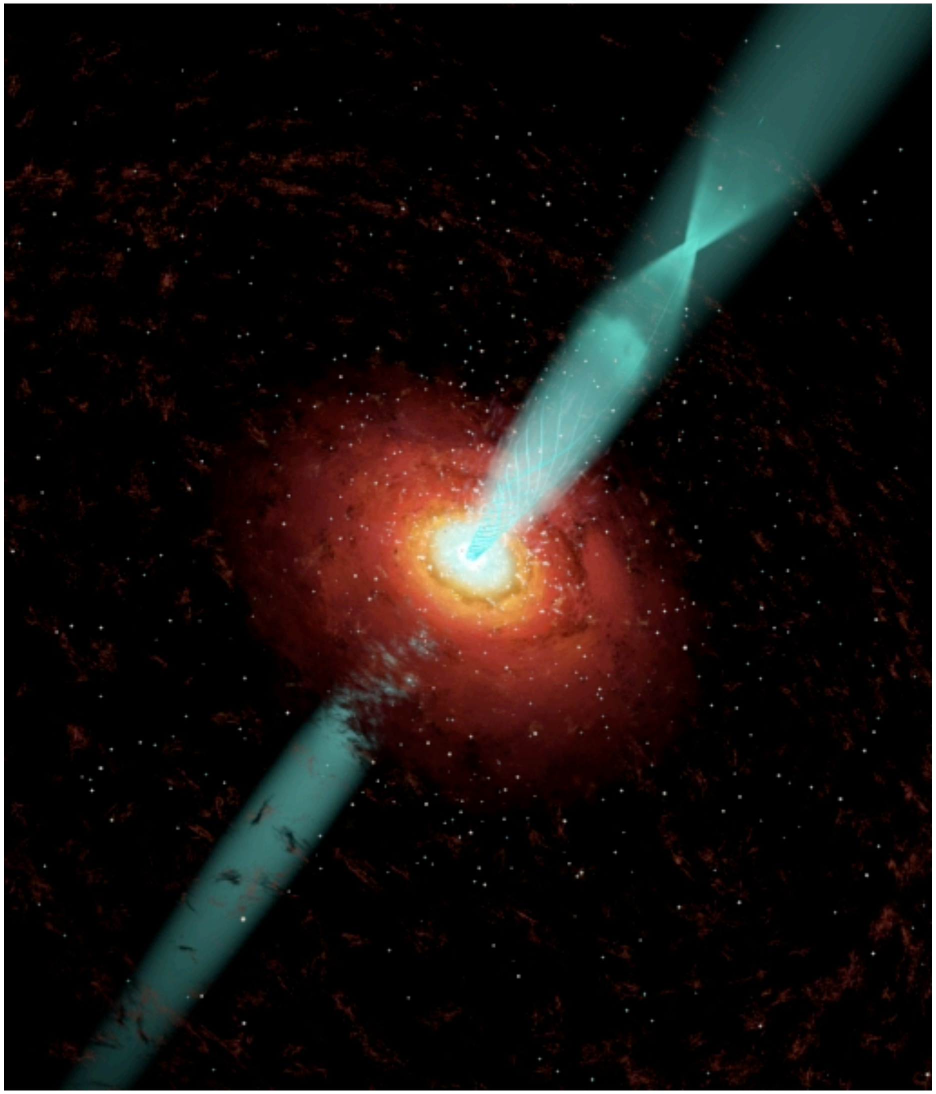
Using Gravitational Lensing to Probe Unseen Matter in the Milky Way

- For more detail, see Andy Gould's talk today:
  - *"Interpenetration of Astrometry and Microlensing"*



Galactic mass histogram

Astrometric Observations of Quasars with SIM Lite



One frame from a BL Lac simulation (W. Steffen, UNAM)

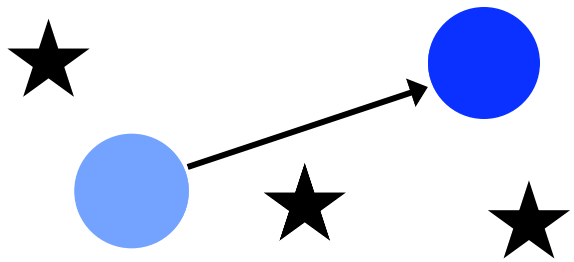
SIM Lite Quasar Astrophysics

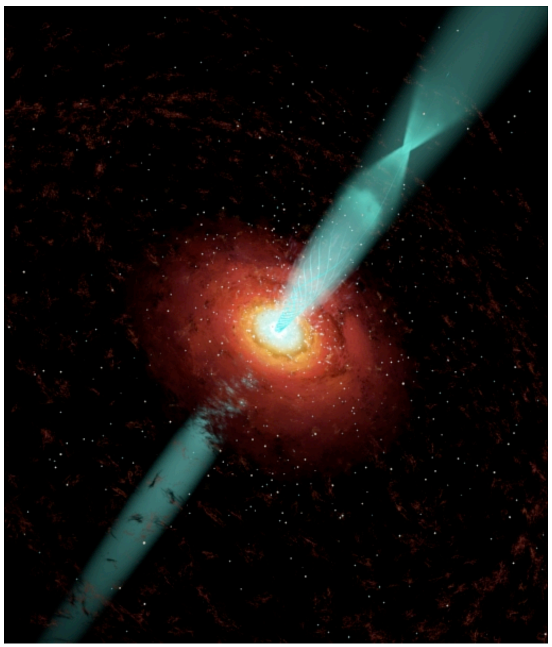
- Two SIM Lite Science Team Key Projects are devoted to AGN studies:

- Ken Johnston
  - *"Astrophysics of Reference Frame Tie Objects"*
- Ann Wehrle
  - *"Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby AGN and Quasars"*

- See Ann's talk on Thursday for much more detail:
  - *"Exploring the Inner 1-100 Microarcseconds of AGN using SIM Lite"*

What does SIM Lite Measure ?

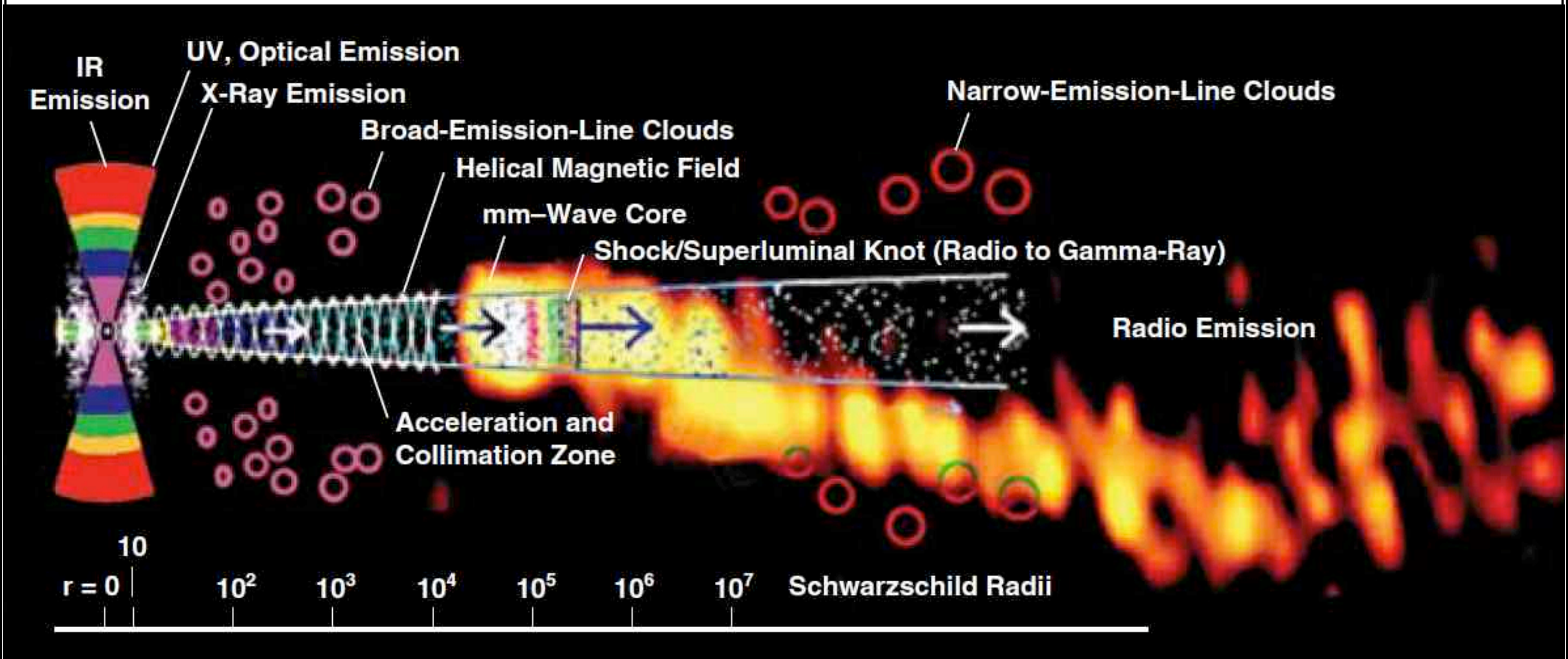




BL Lac simulation by W. Steffen (UNAM)

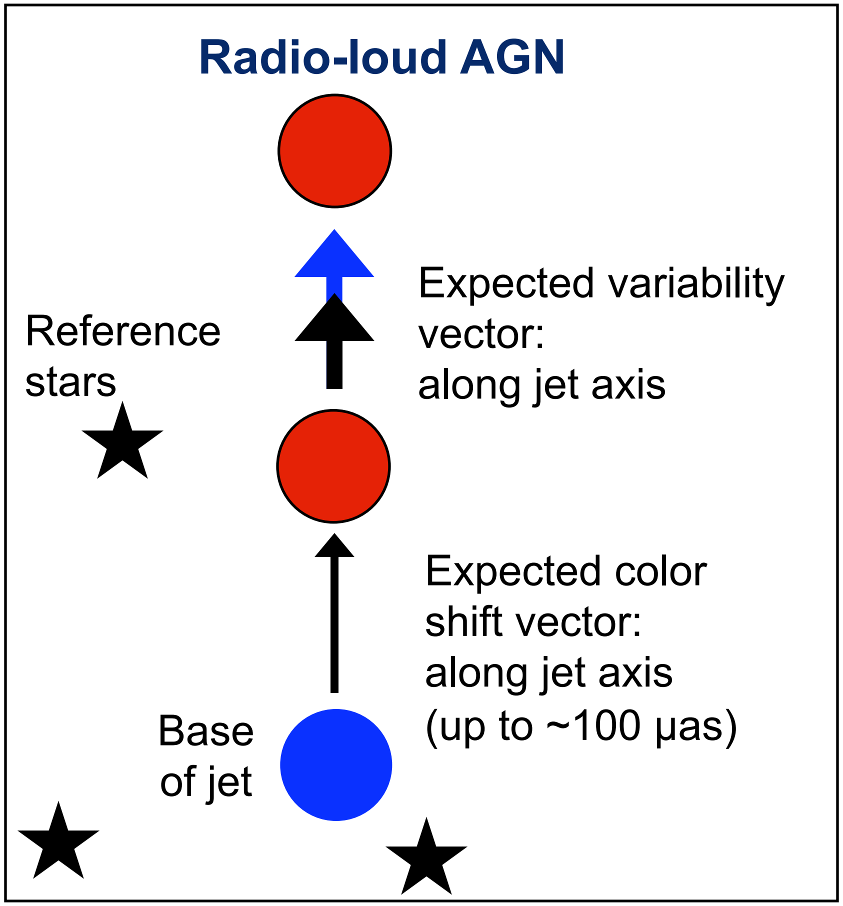
- SIM Lite measures the ‘center of light’ with a single measurement accuracy of
  - ~13 μas for V = 18 (~1200s integration)
  - Practical limit is ~ 20 μas at V = 20
- Measurements are relative to reference stars or other quasars
  - Directly detect motion in blazars
- Tie to global reference frame (ICRF) to ~3 μas and rotation ~ 2 μas/yr
- Measure position as a function of (optical) color
  - Structure information on scales of 10s of μas

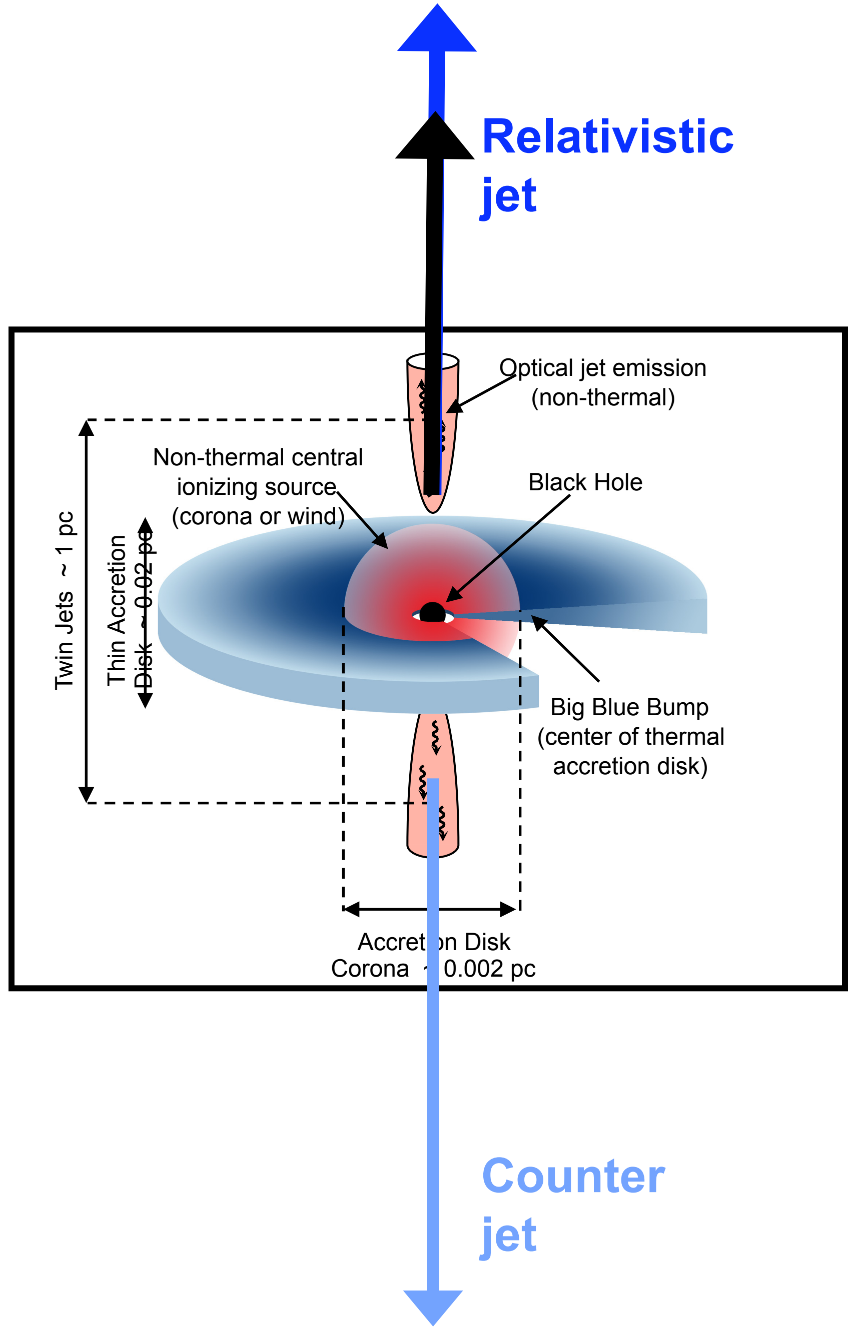
Astrometry Quasar Jets with SIM Lite



- SIM Lite should be able to detect optical components as they traverse the acceleration and collimation zone

Astrometric Motion in Quasars

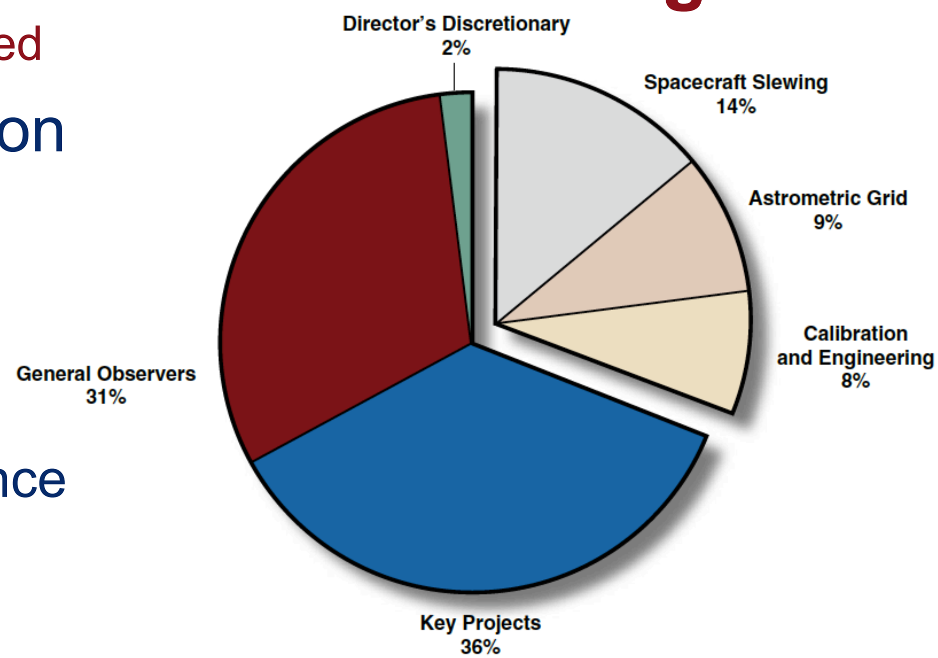




Future Opportunities: General Observer Program

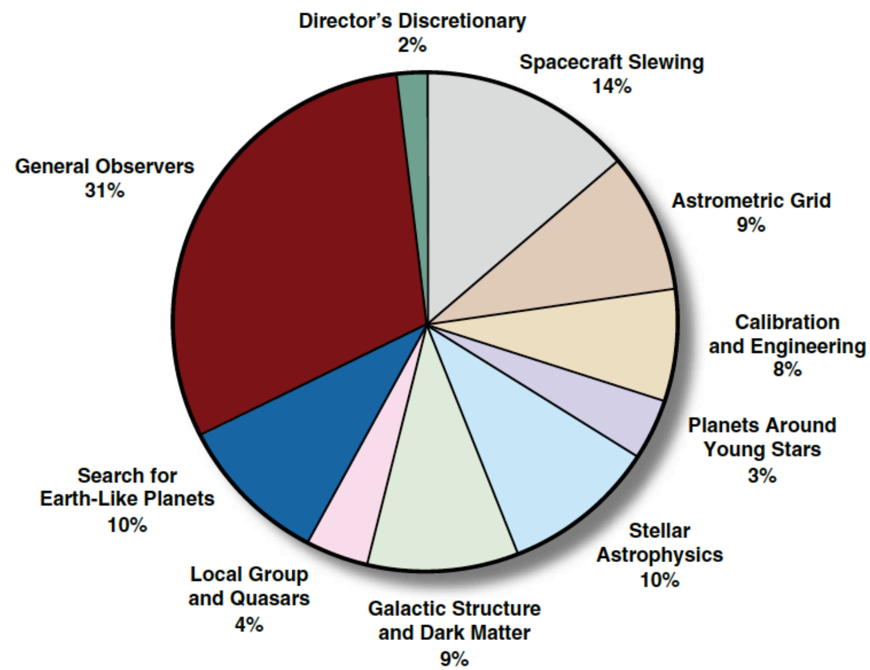
Unofficial: no promises expressed or implied

- All remaining observing time on SIM Lite will be competed through a *General Observer* (GO) Call
  - About 31% of 5 years
  - This about half of the total science time



- GO Program call will be issued 2-3 years before launch

- GO call will be completely open with respect to science topics
  - Peer review will determine the most promising science



SIM Lite's Legacy?

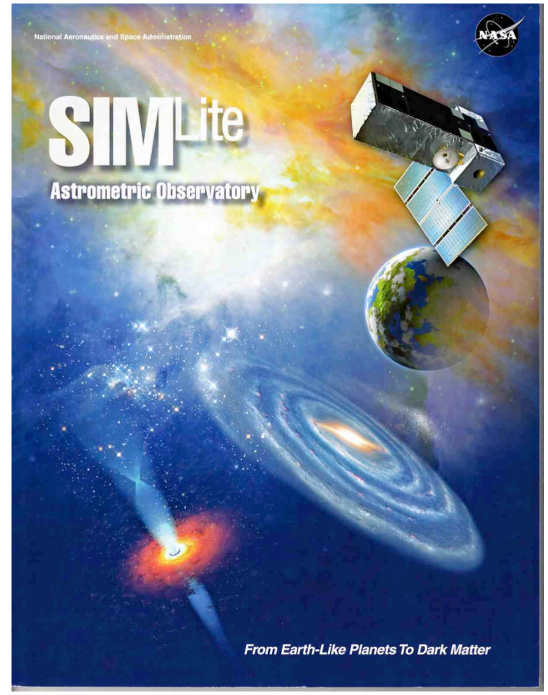
- The first catalog of Earthlike planets around nearby Sun-like stars
  - The only planets that can be probed for habitability with spectroscopy
  - Provides unambiguous mass and orbital addresses for direct detection missions
- The first catalog of planets down to Saturn-mass around young stars
  - There is much modeling and speculation (from debris disk images, etc.) but no actual data on the formation and evolution history of known planets around young stars
- A critical test of Cold Dark Matter on galactic and sub-galactic scales
  - The theory looks good on large scales; does it really break down on small scales?
- Masses, distances, and luminosities - instead of crude model-based estimates - for compact objects (neutron stars, black holes)
- Masses at the high end and low end of the main sequence, so that we can calibrate models of the ages of M stars and O stars
  - Current lack of precision masses is holding back both stellar evolution theorists, and astronomers who want to know how old their favorite M star is
- And much more!

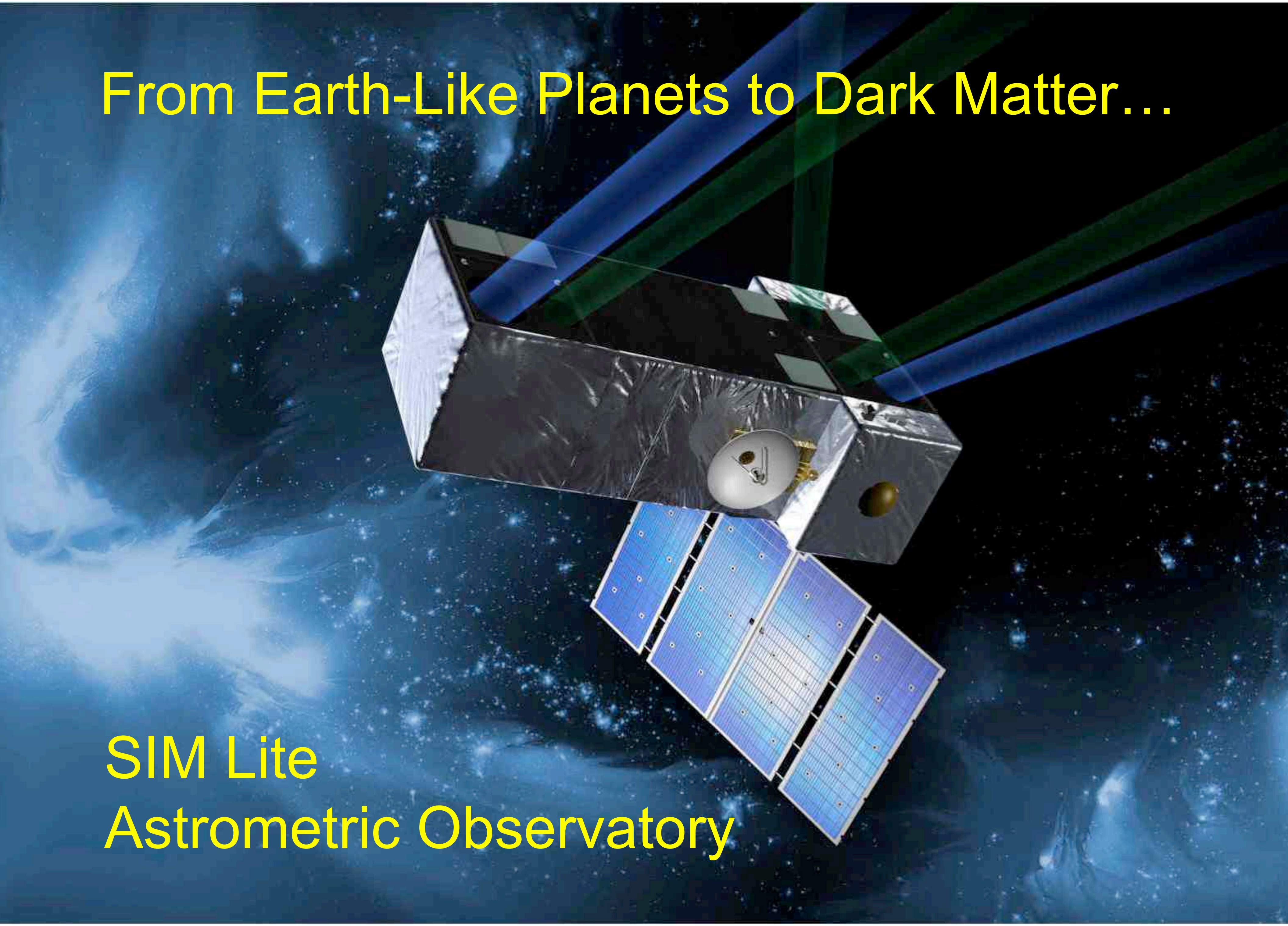
For more information on SIM Lite

- Read the *SIM Book* (published Feb 2009)
  - A comprehensive (~240 page) description of the science and the instrument
  - We can mail you a copy

- Visit the SIM Lite website at sim.jpl.nasa.gov
  - Recently revised and updated
  - Download submissions to *Astro2010*:
    - 12 science White Papers
    - RFI 'activity' paper

- Subscribe to: ***F R I N G E S - The Space Interferometry Mission Newsletter***
  - Published approximately quarterly
  - Current edition is Newsletter #48
  - Delivered by e-mail
  - Subscribe at sim.jpl.nasa.gov

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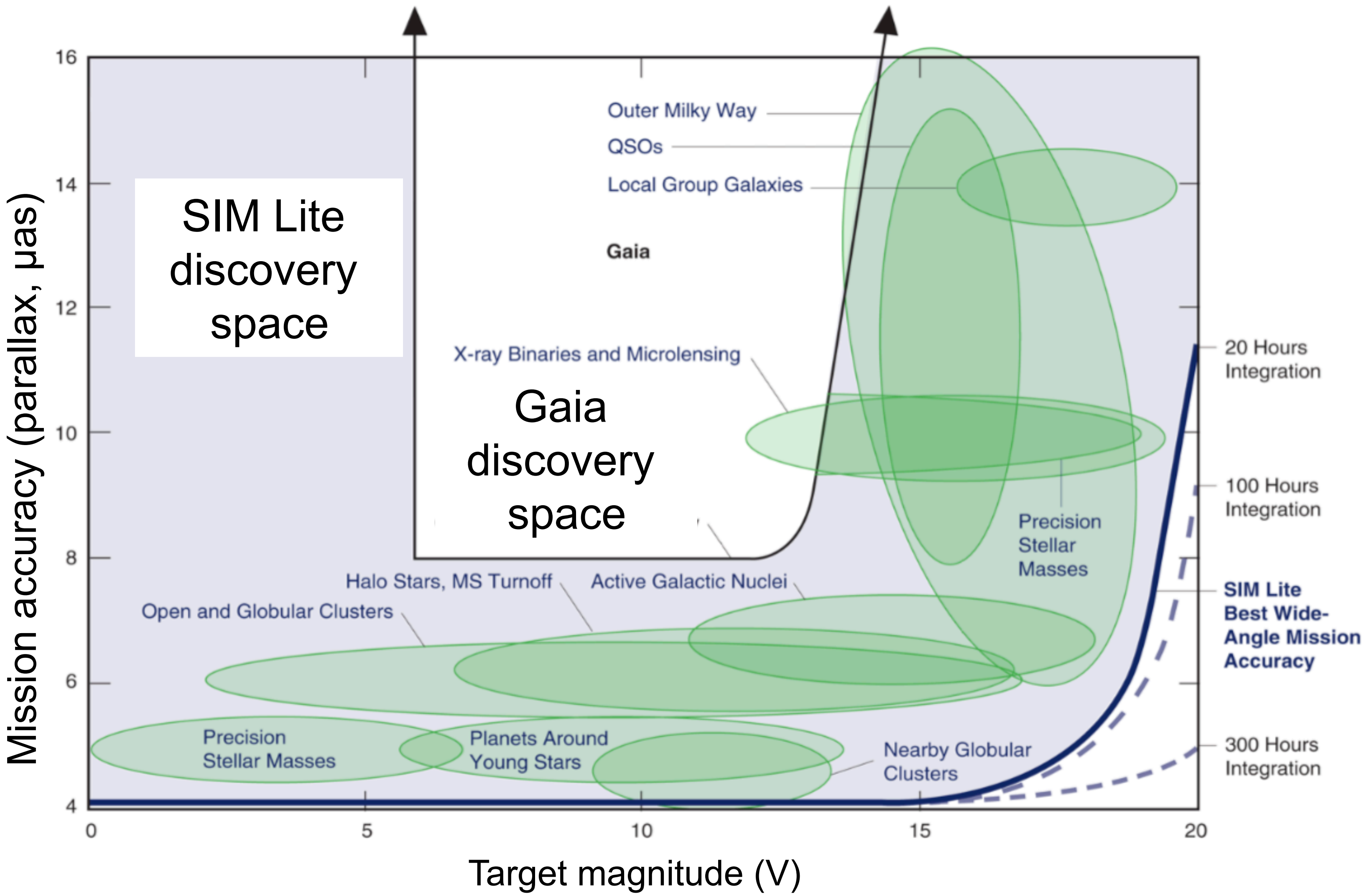
SIM Lite
Astrometric Observatory

Backup

SIM Lite and Gaia: Complementary Science



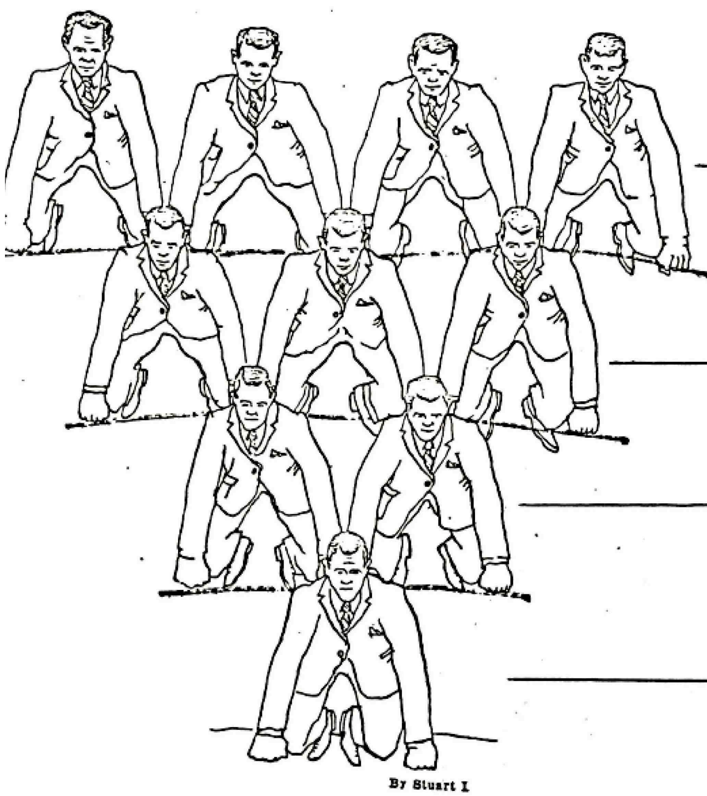
Note: SIM Lite science objectives have *always assumed* there is an astrometric survey mission (FAME or Gaia)

Hence, no experiments are planned for the 'survey' parameter space

Foundations of Astrophysics

THE ASTRONOMICAL PYRAMID

ILLUSTRATING THE INTERDEPENDENCE OF THE VARIOUS AREAS OF STUDY



COSMOLOGISTS, GENERAL RELATIVISTS, CRANKS, OTHER FUZZY-BRAINED PENCIL-PUSHERS.

ATMOSPHERES, INTERIORS, INTERSTELLAR MED. THEORISTS

SPECTROSCOPISTS PHOTOMETRISTS

ASTROMETRISTS

by Ron Probst, ~1978
While a grad student at UVa

GET BACK TO BASICS -- SUPPORT ASTROMETRY