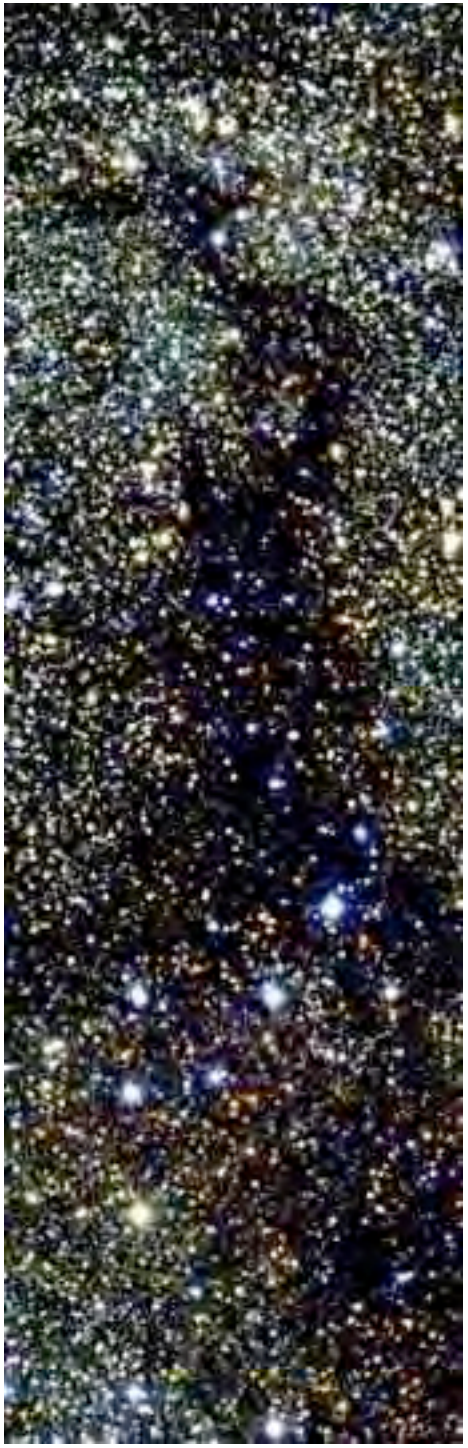


ASTROPHYSICS WITH MICROARCSECOND ACCURACY ASTROMETRY

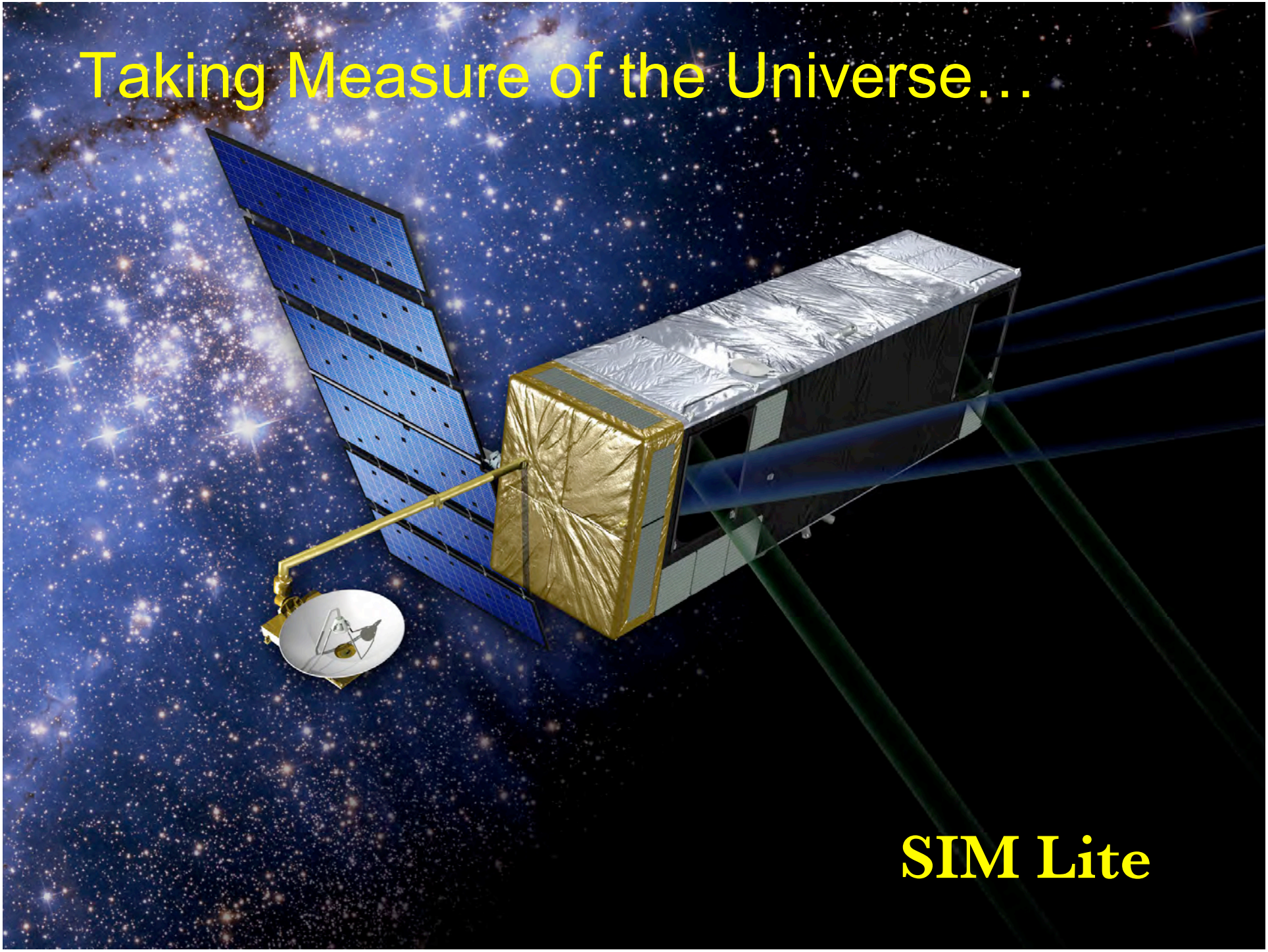
Stephen Unwin

Jet Propulsion Laboratory

California Institute of Technology

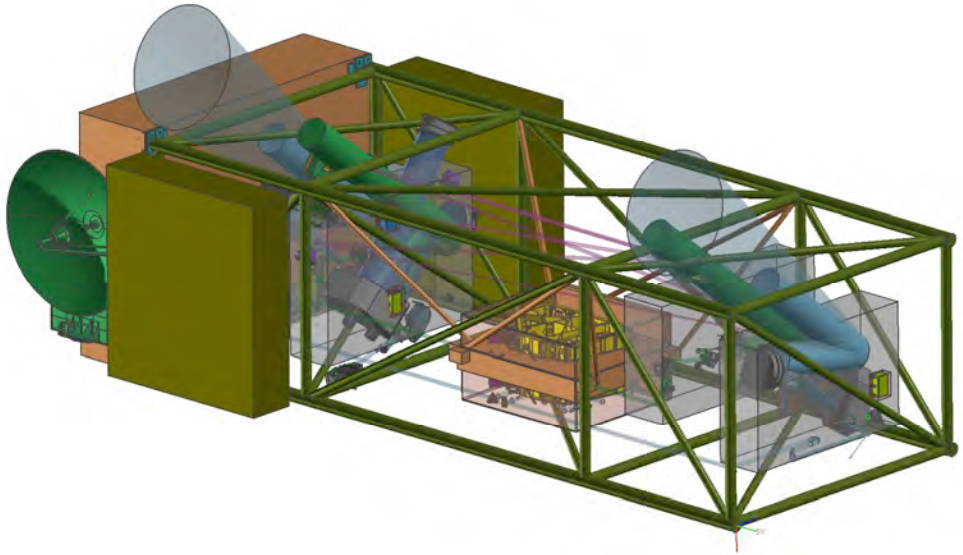
59th International Astronautical Congress

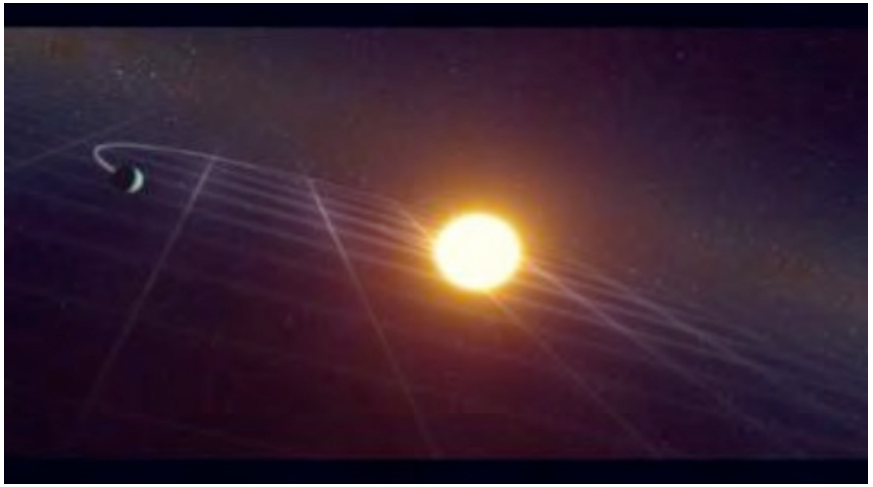
Glasgow, Sep 29-Oct 3, 2008

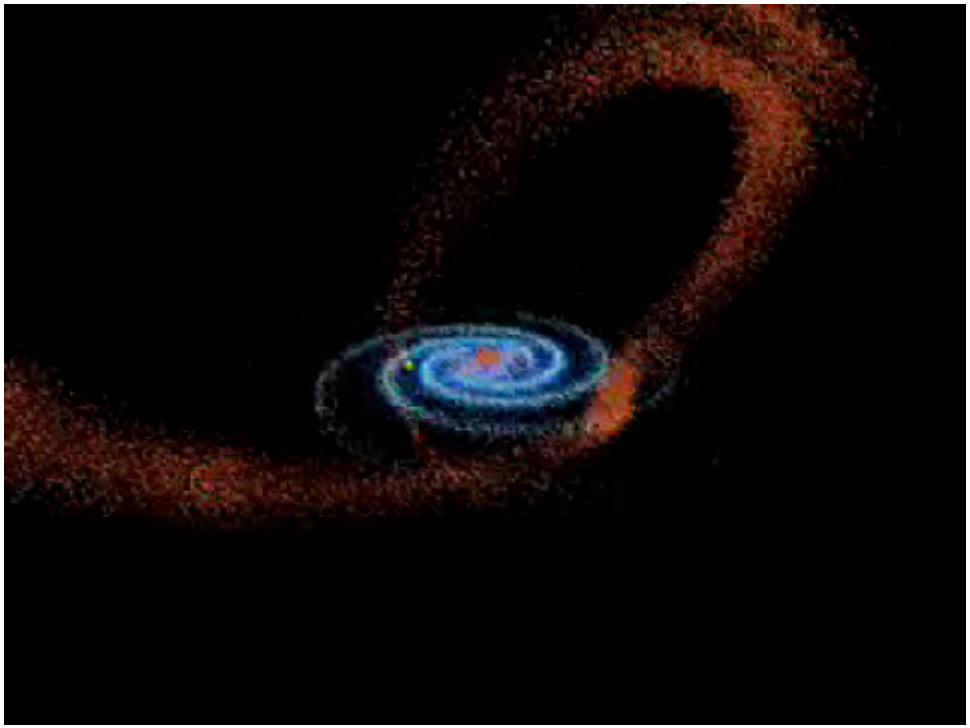

Taking Measure of the Universe…
SIM Lite

SIM Lite is an Engine for Dynamical Astronomy

- Science capability
- Science highlights
- Programmatic status and community review
- Next steps







Summary

- SIM Lite is a space-based interferometer for precision astrometry
  - Flexible scheduling: observations are tailored to science question
  - Limiting magnitude **V~19**
  - Wide angle accuracy **4 µas** (end of mission)
  - Narrow-angle accuracy **1 µas** *in a single measurement*
  - Noise floor is around **0.035 µas**
- SIM Lite is very mature and low-risk
- SIM Lite has almost completed NASA 'Phase B'
- Completed all needed technology in 2005
- SIM Lite is a mission 'ready to go' now that is capable of finding *one-Earth-mass planets* in the habitable zone of nearby sun-like stars
- SIM Lite can also tackle a broad array of questions in *stellar and galactic astrophysics*
- SIM Lite will have a substantial Guest Observer Program
  - Community participation is invited and encouraged

The School of Athens (Rafael, 1511)

"There are infinite worlds both like and unlike this world of ours... We must believe that in all worlds there are living creatures and planets and other things we see in this world."

Epicurius
c. 300 B.C

The year 1584

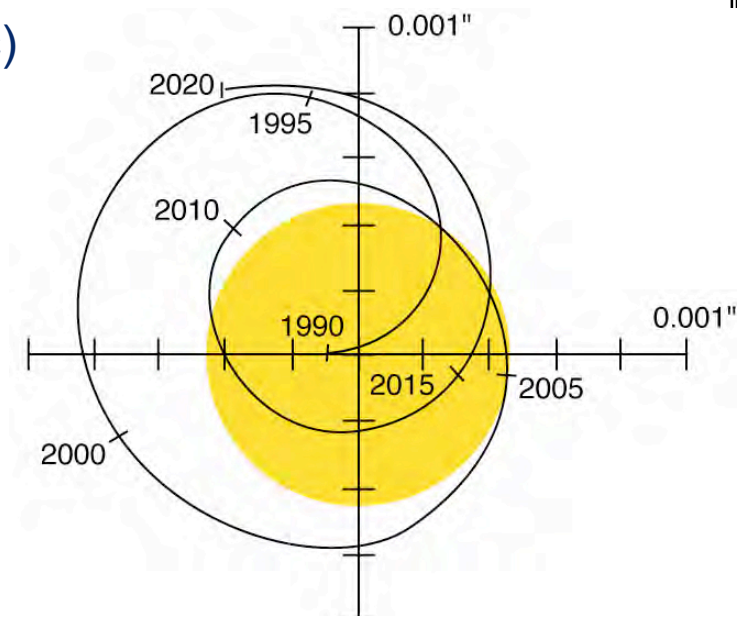
"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth"

Giordano Bruno

in De L'infinito
Universo E Mondi

Astrometric Detection of Terrestrial Planets

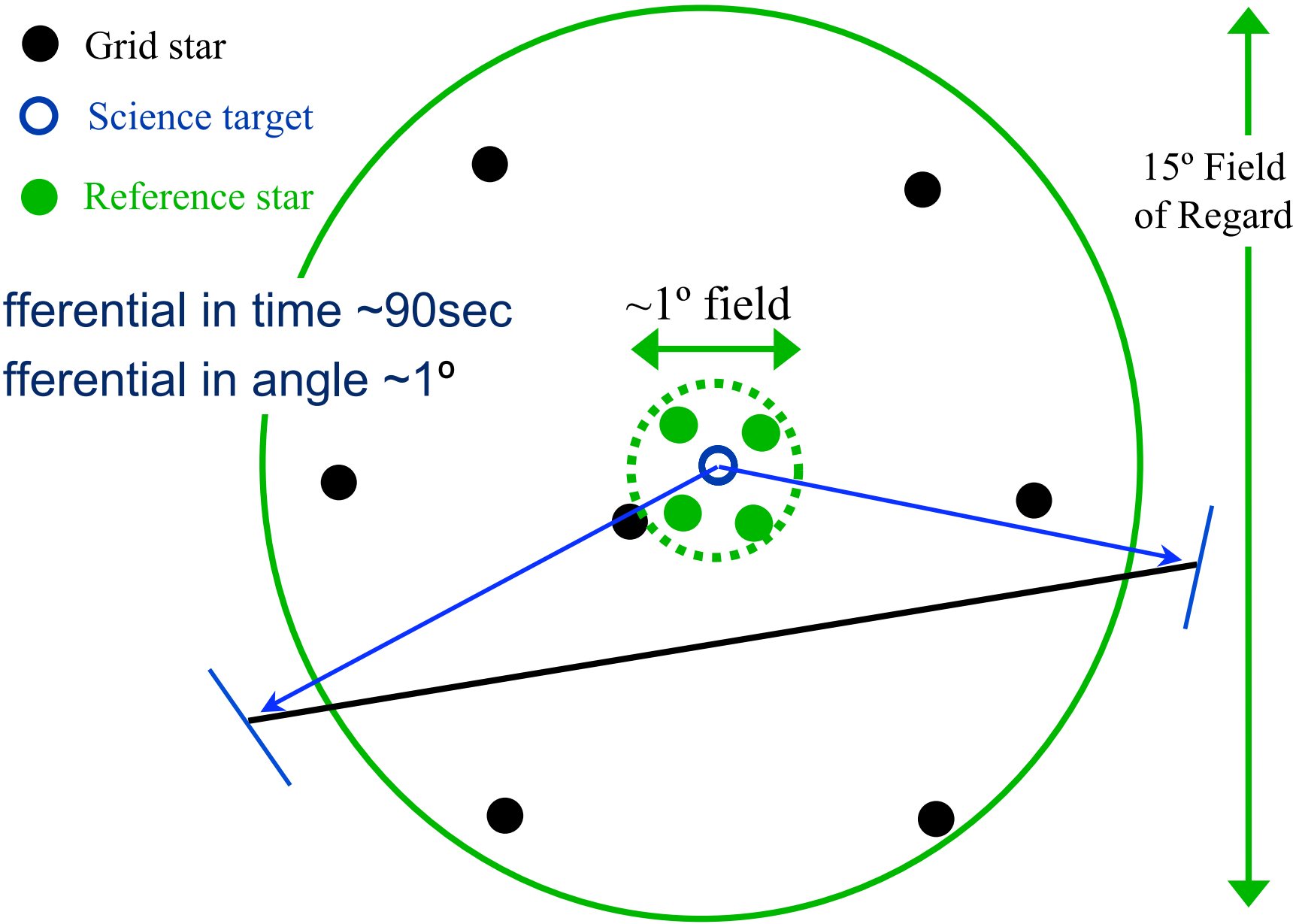
- Reflex motion α in microarcsec (μas):
  - Jupiter mass planet around a G2 star (at 10pc) has α = 500 μas
  - Earth-mass planet orbiting in the center of the 'habitable zone' (=1.0 AU) has α = 0.3 μas
- SIM Lite single measurement error is σ = 1 μas
- Threshold is $\alpha = 5.8\ \sigma\ N_{visits}^{-1/2}$
- SIM Lite "noise floor" is < 0.035 μas
- SIM Lite can detect a ~0.3 μas amplitude signal with $N_{visits}^{-1/2} \sim 400$
- Tailor the number of 'visits' to the star distance to achieve the desired mass sensitivity



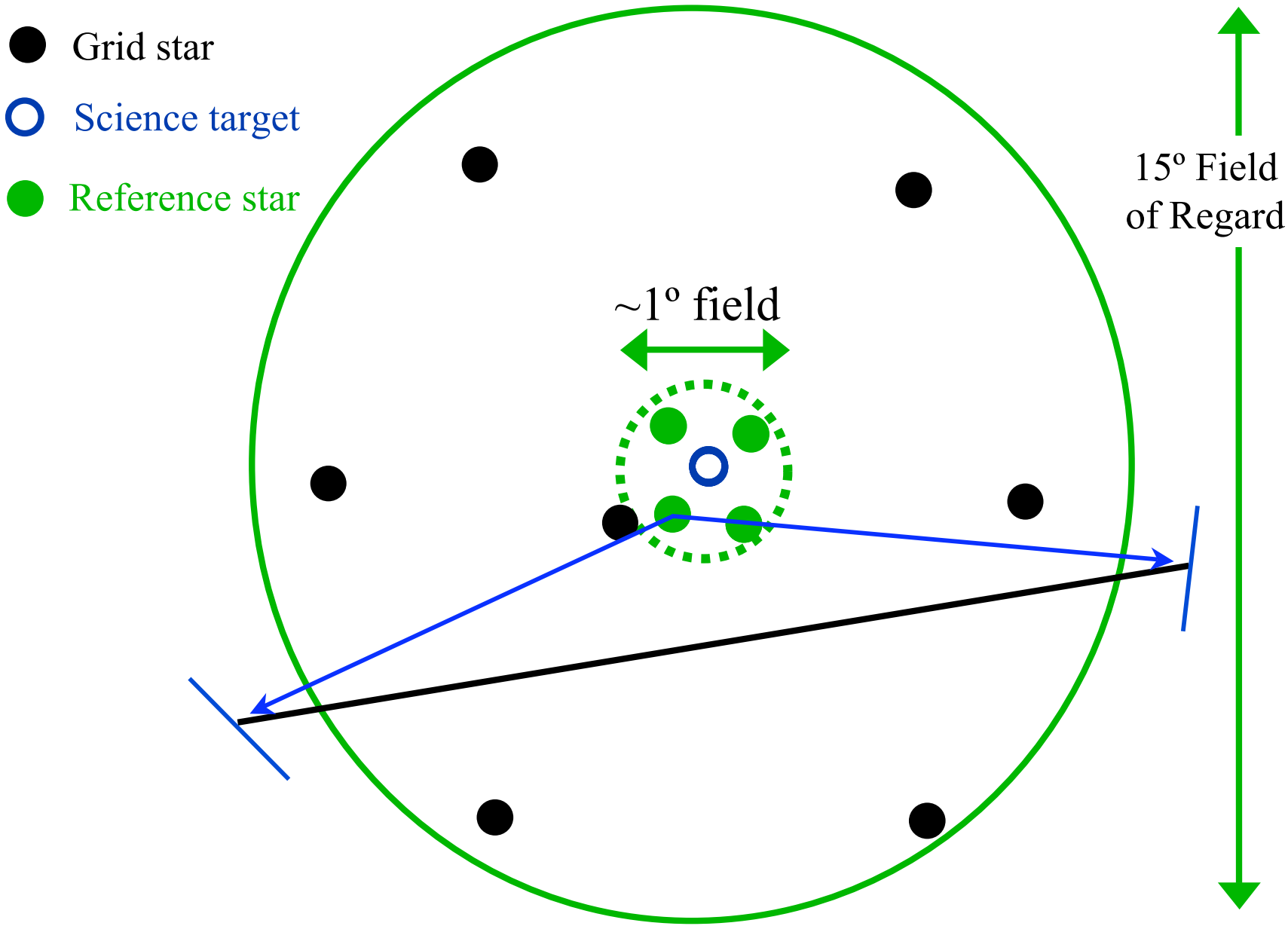
The Solar System at 10pc

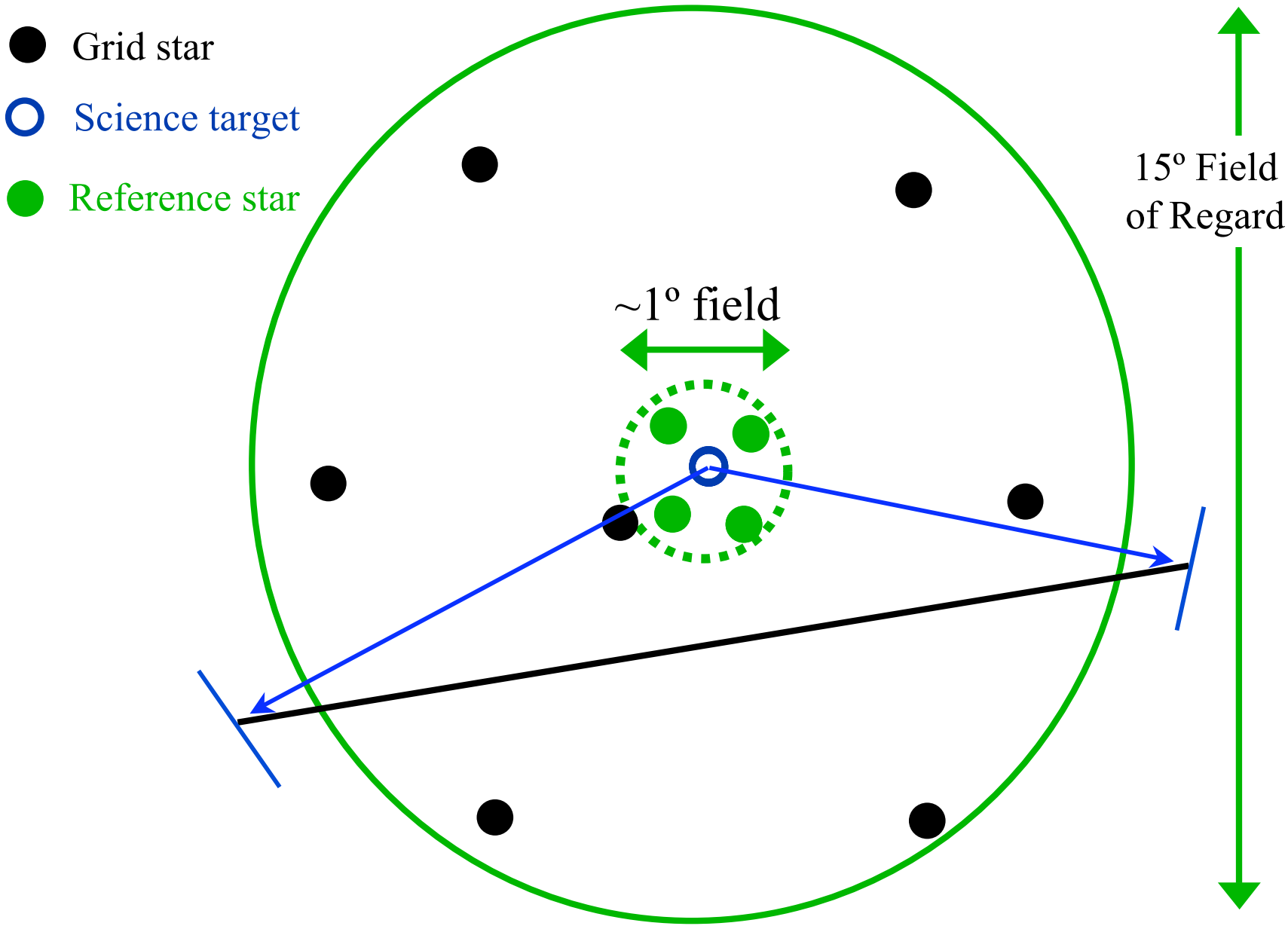
- **SIM Lite can survey at least 60 nearby FGK stars for Earth-mass planets**

Planet Search Observing Scenario



- Differential in time ~90sec
- Differential in angle ~1º


Grid star
Science target
Reference star
~1° field
15° Field
of Regard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Reference star
~1° field
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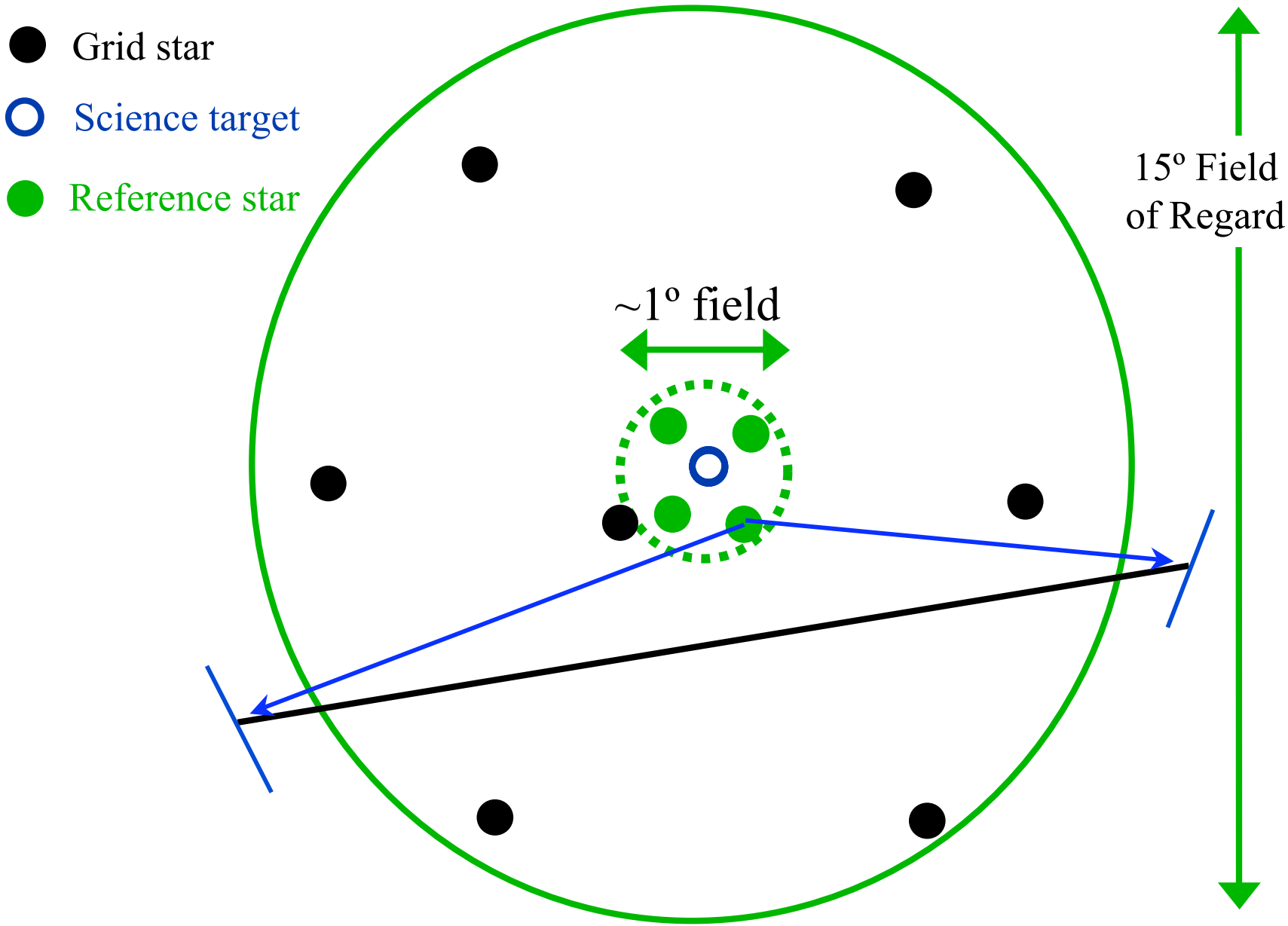
of Regard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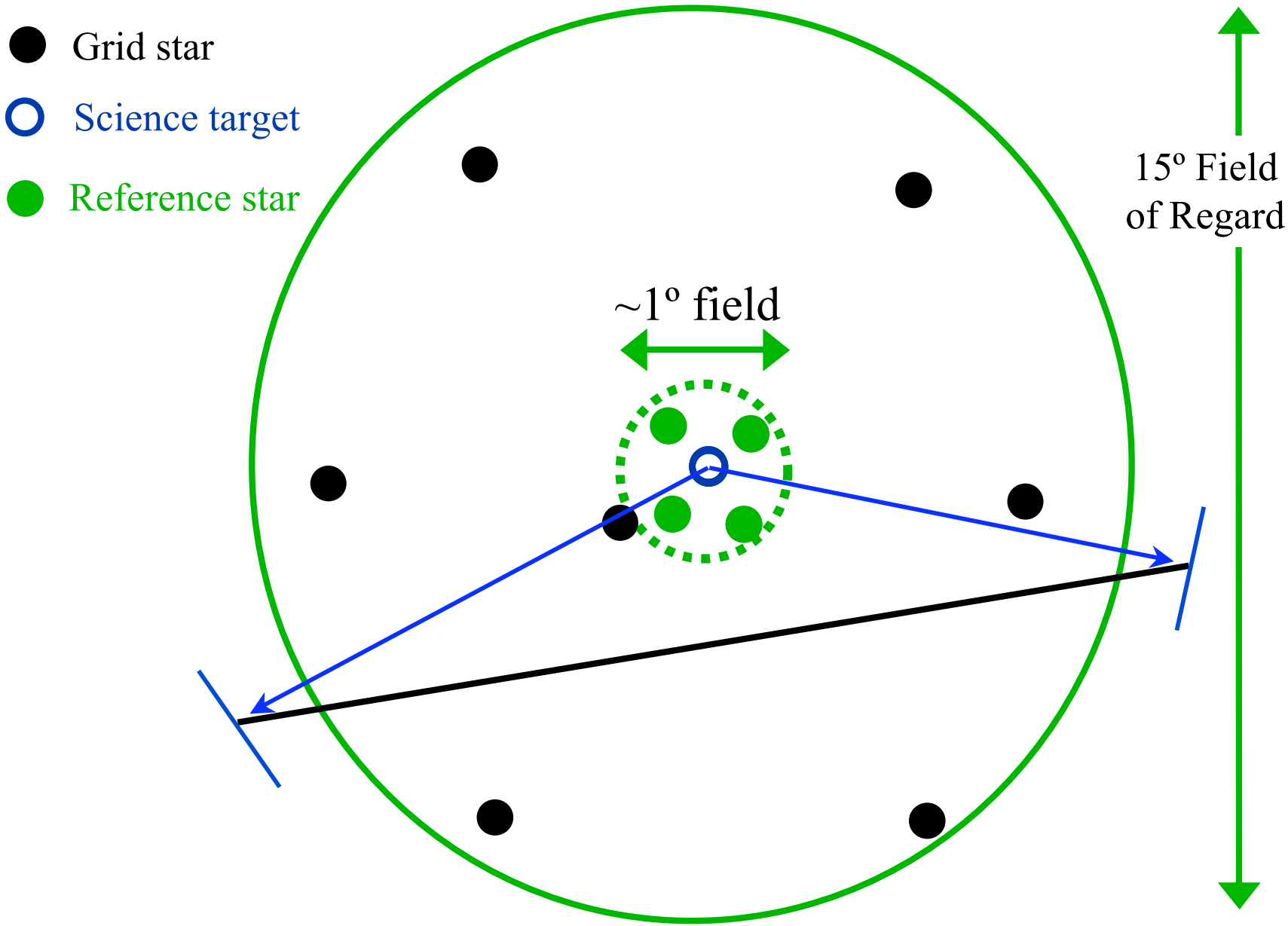
15° Field
of Regard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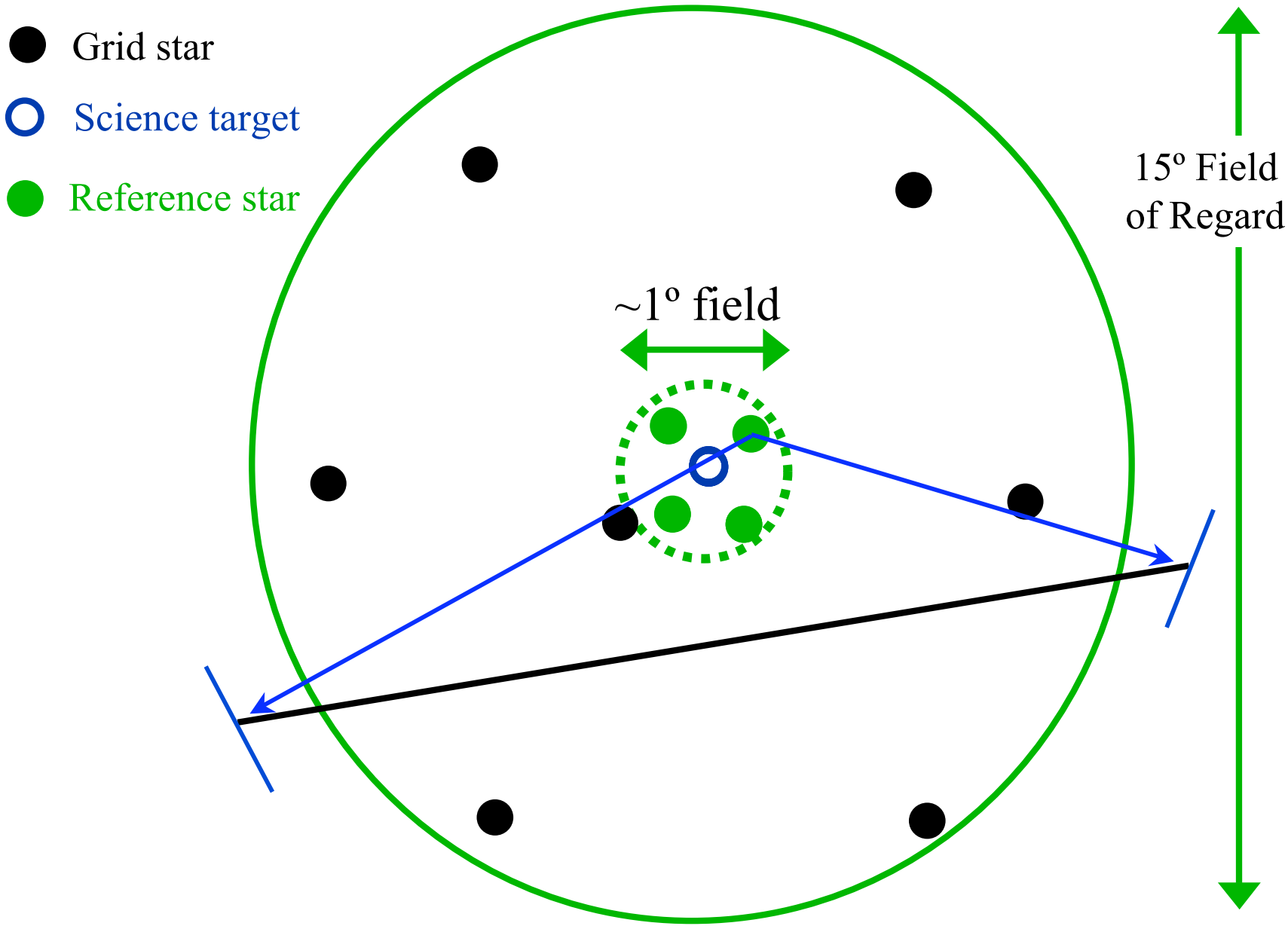
~1º field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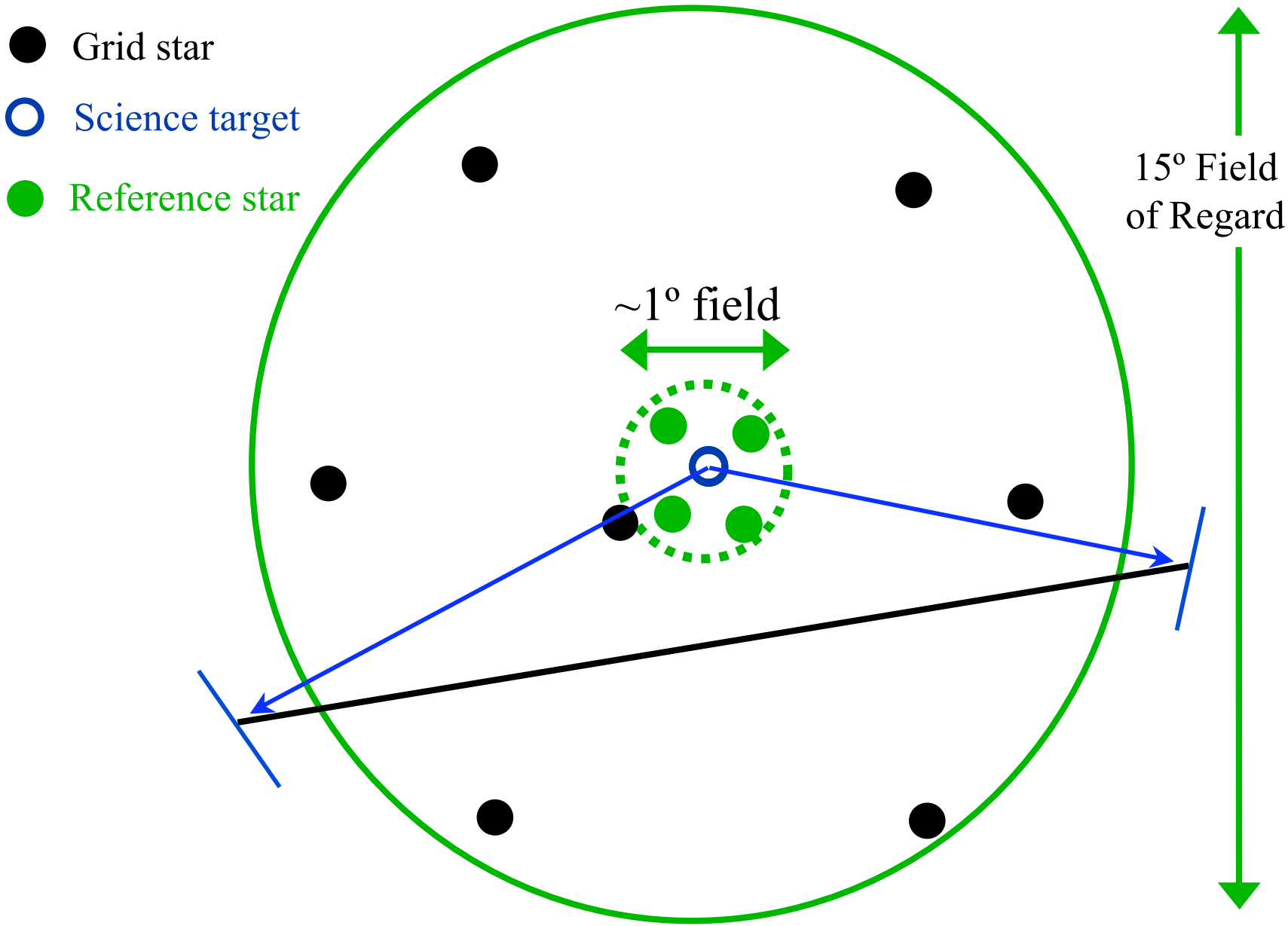
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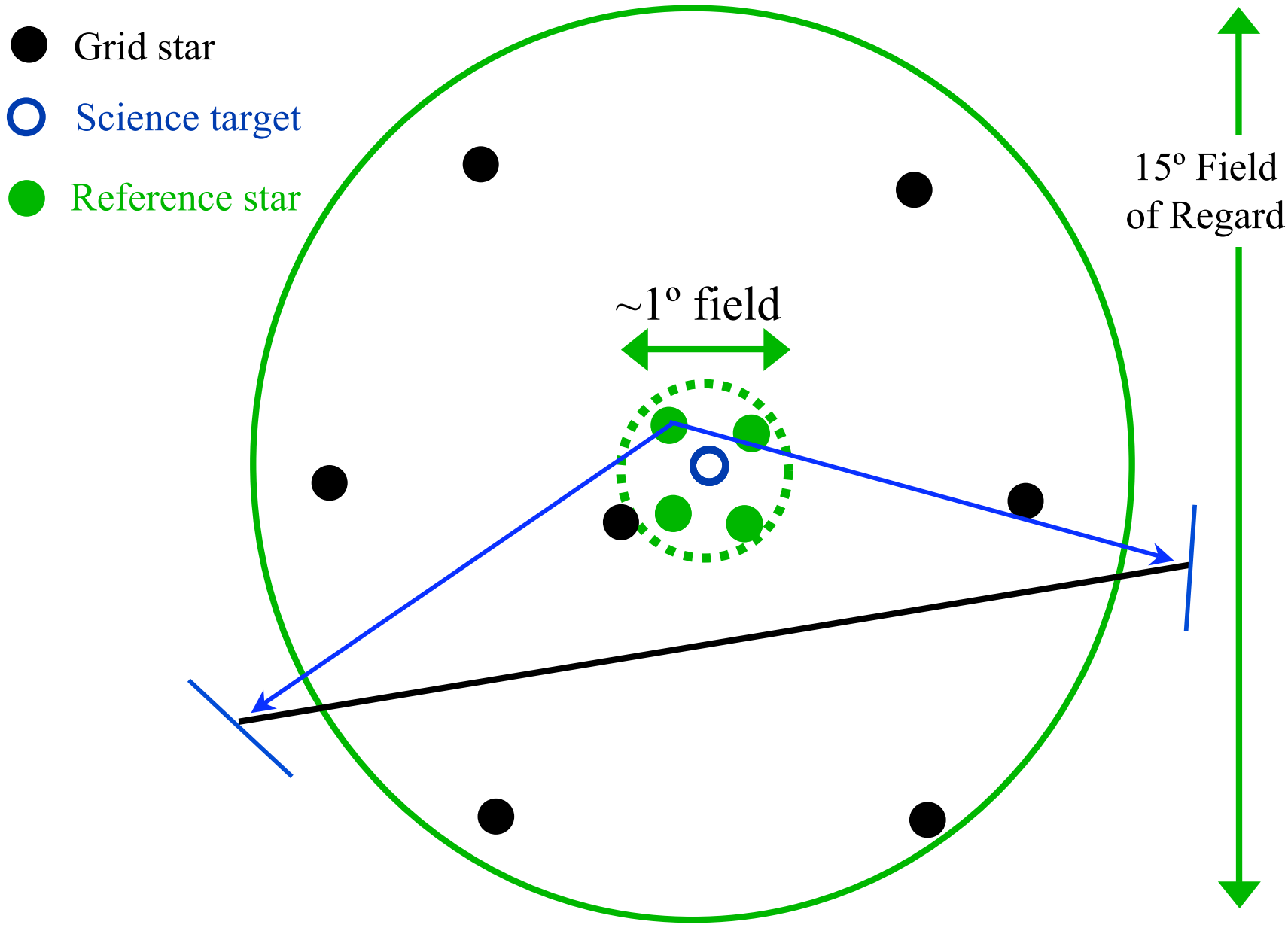
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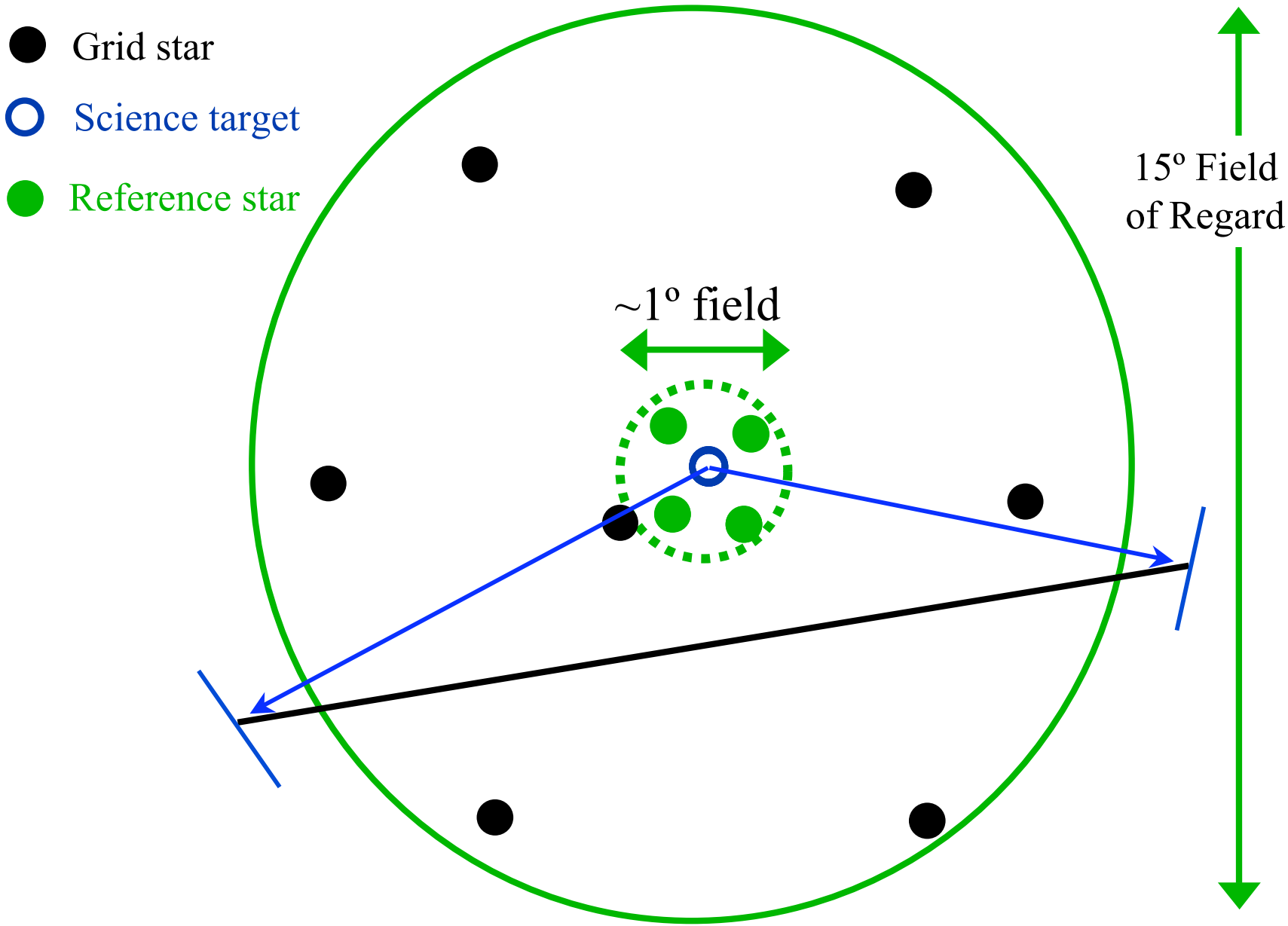
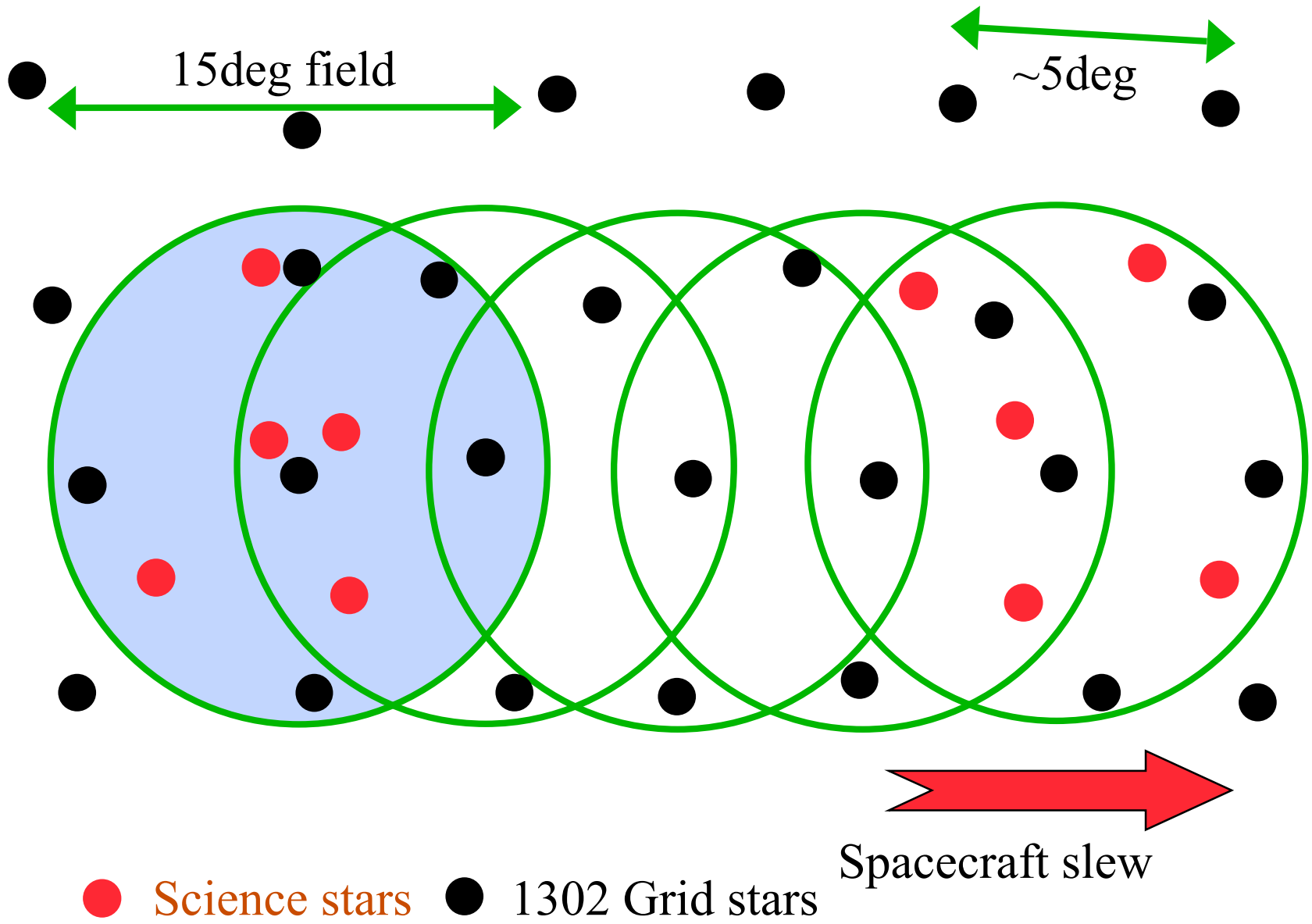
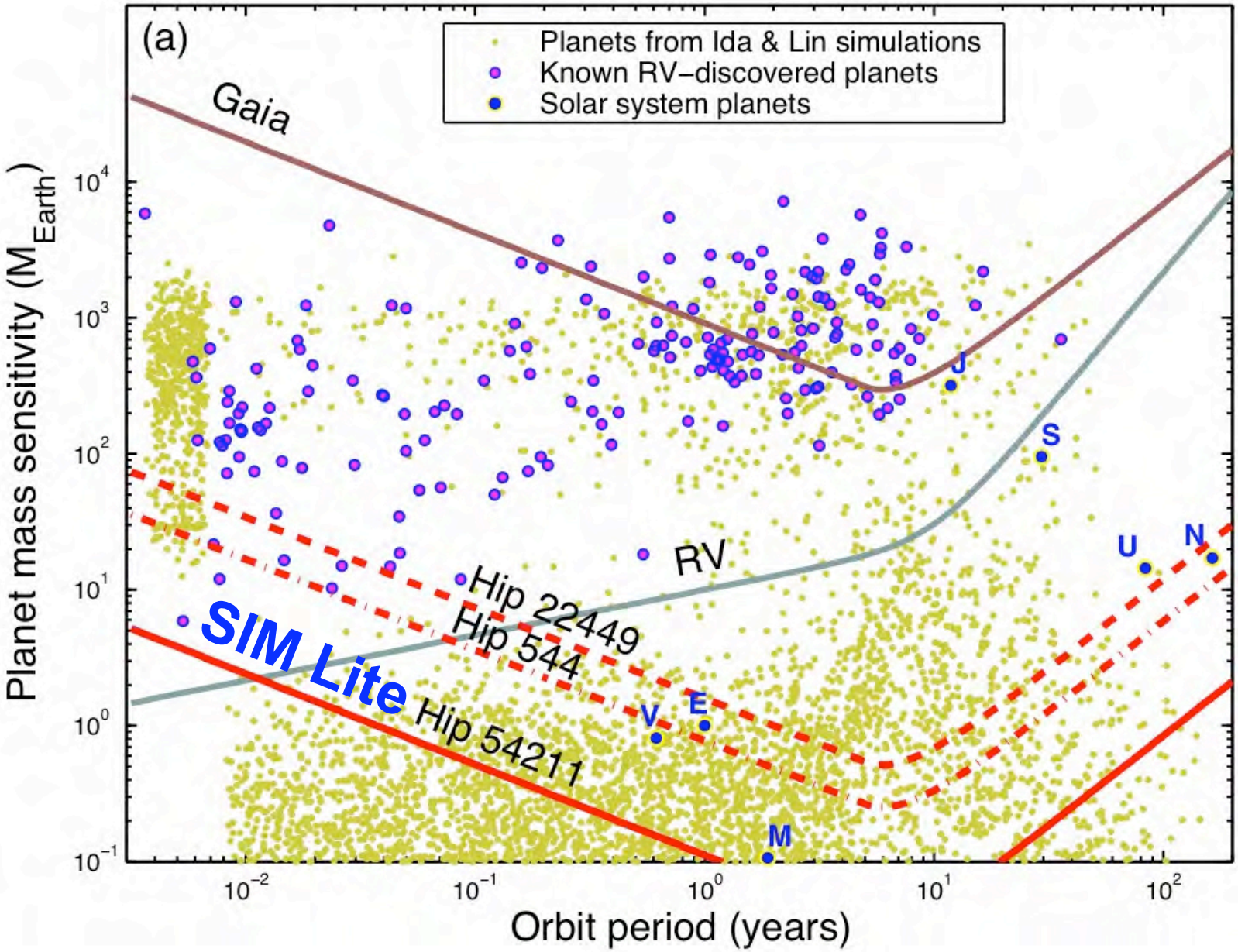

Grid star
Science target
Reference star
15º Field
of Regard
~1º field

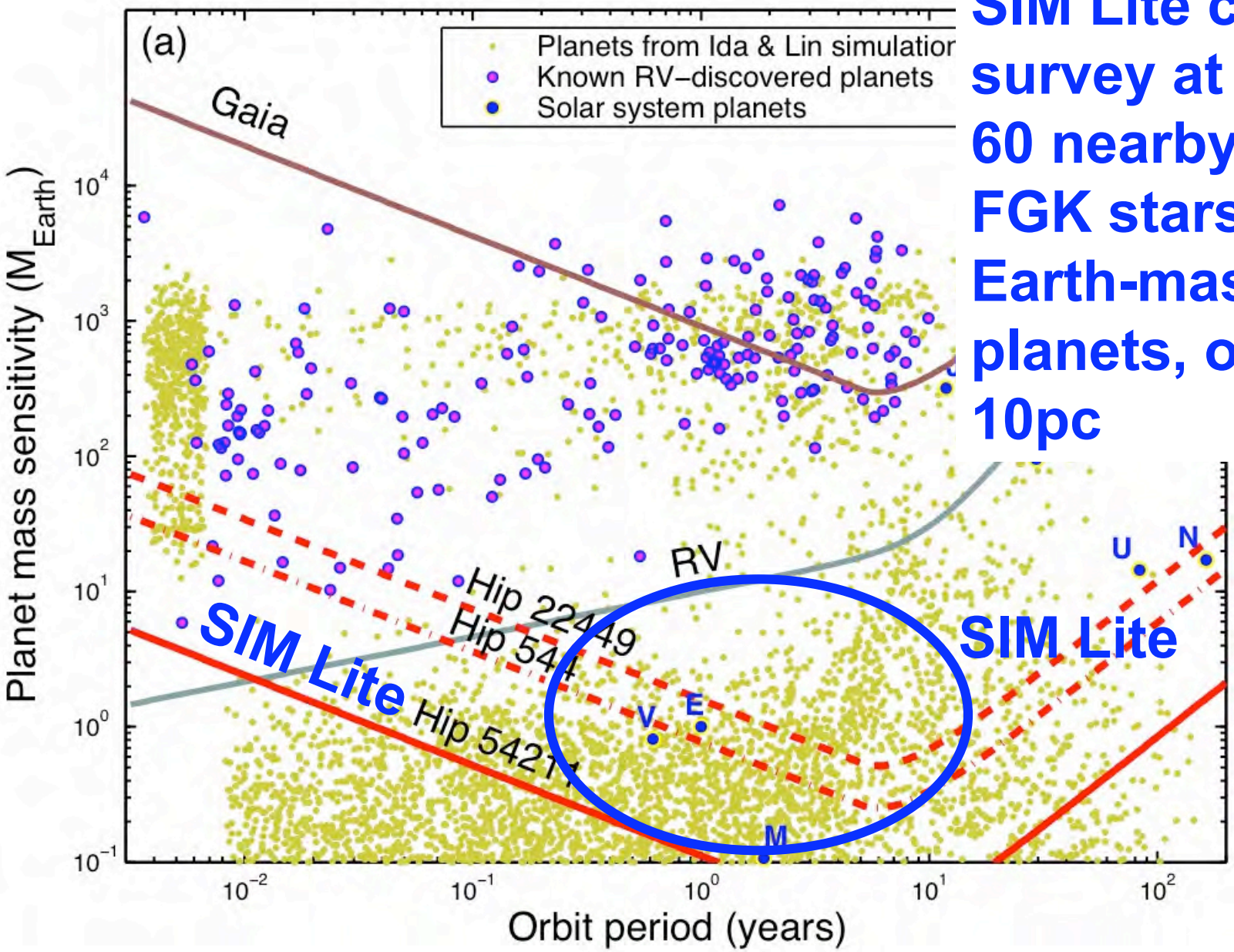
Combined grid star + science target observing scenario



SIM Lite Earth-Analog Discovery Space



SIM Lite Earth-Analog Discovery Space



SIM Lite can survey at least 60 nearby FGK stars for Earth-mass planets, out to 10pc

Exoplanets with SIM Lite:
Exploring a rich discovery space

- Earth-like planets in the Habitable Zone around *nearby* solar type stars
  - **Unambiguous, definitive (25 %) mass measurements**
  - Direct detection and spectroscopy are the obvious followups
- Rocky Planets and super-earths in 0.5 - 3 AU
  - Understanding the prevalence of rocky planets
- Architecture of Planetary Systems
  - Astrometry and radial velocity are *complementary* methods
  - Eliminate the major selection biases in the masses and periods
- Planets around early-type stars (A,F)
  - Do planetary systems around massive stars look different?
- A catalog of terrestrial planets around nearby stars
  - Exact locations of planets and when to look
  - These are critical data for follow-up spectroscopy missions
  - Direct-detection missions are very inefficient (esp. external ‘starshade’ occulters) and can likely be made smaller and cheaper

Understanding the dynamics of multiple-planet systems

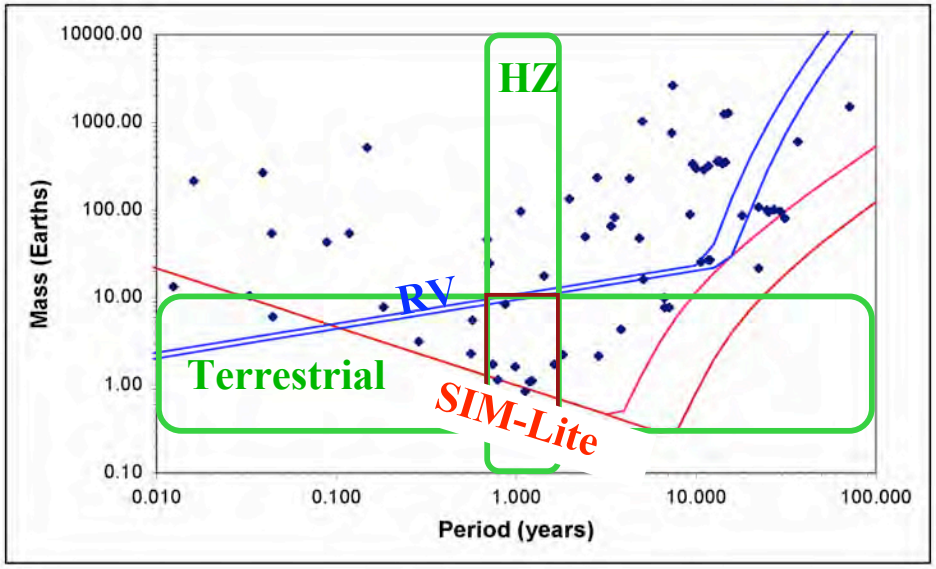
- Obvious candidates are many of the known multiple planet systems; many are very easy targets for SIM Lite
- SIM Lite provides **high-precision masses** (not lower limits or guesses based on models)
- SIM Lite **provides orbit inclinations** (no need to assume coplanar!) and full orbit parameters
  - These **do not currently exist**
  - You need them in order to study how systems came to have their current architectures
  - You need them to tell direct detection missions when and where to look
- Are multiple systems coplanar?
- How long are they stable?

Multiple-planet systems: A "Double-Blind" Study

- *Question: Can SIM-Lite, combined with radial-velocity data, detect Earths in multi-planet systems?*
- Seven-month double-blind study
  - Involved over thirty astronomers in 5 teams
- Teams worked independently on the simulated data for 48 planetary systems, *not knowing their contents of those systems*
  - 32 random
  - 8 Solar-system-analogs
  - 4 single terrestrial in HZ
  - 4 no-planets
- Answer: Yes!
  - Single-planet detection is *not degraded* by presence of other planets
  - Astrometry plus RV can find HZ Earths in multi-planet systems
  - Statistical testing methods need improvement: Study Phase 2

Completeness (did we miss some?)

- Define: completeness = #detected / #detectable
- There are 70 high SNR (>5.8) planets (plotted)
- 48 of these have a period shorter than 10 years
- We should have detected all of these, *and we did*

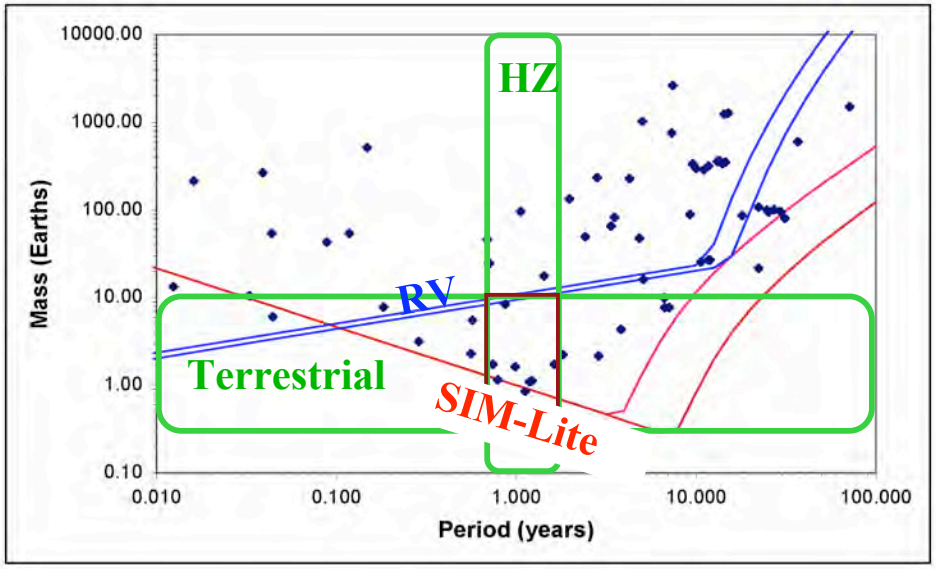


Detection limits for 70 planets with SNR > 5.8

Completeness	Team C1	Team C2	Team C4	Team C5
All	60%	91%	89%	95%
Terrestrial	28%	81%	81%	90%
In HZ	53%	84%	84%	100%
Terrestrial & in HZ	42%	71%	71%	100%

Reliability (were there false alarms?)

- Define: reliability = #detected / (#detected + false alarms)
- Astrometric & RV detection uses a periodogram in the presence of noise
  - A low threshold increases detections, but also increases false alarms
- Reliability: if we claim to see a planet, what is the probability that it is true?



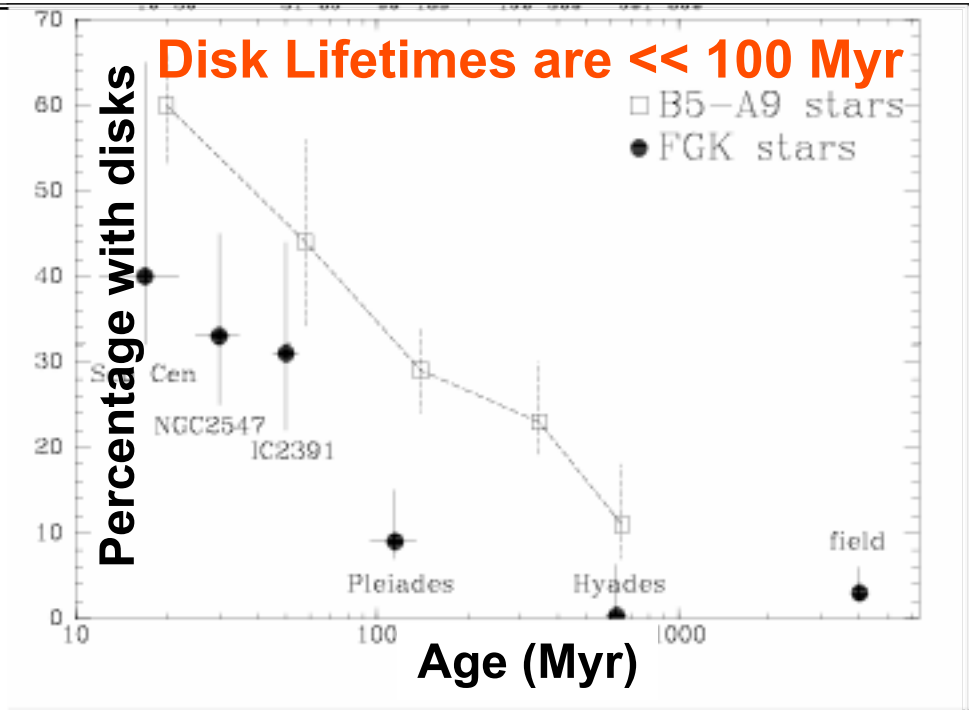
Detection limits for 70 planets with SNR > 5.8

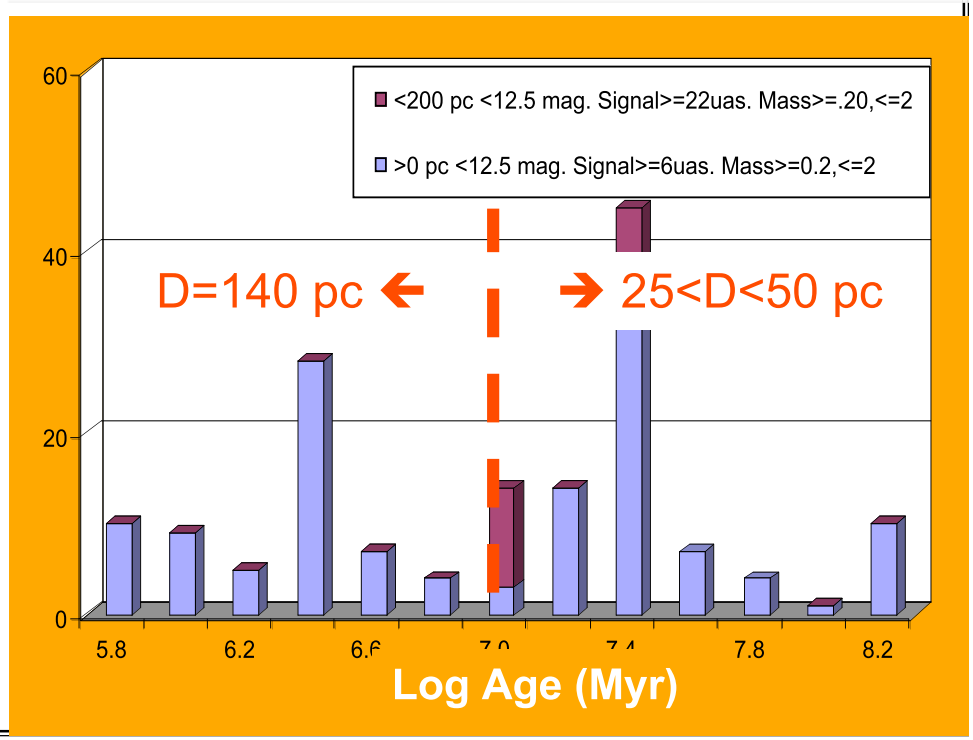
Reliability	Team C1	Team C2	Team C4	Team C5
All	70%	87%	89%	98%
Terrestrial	41%	86%	80%	96%
In HZ	44%	76%	79%	100%
Terrestrial & in HZ	40%	80%	71%	100%

How Do Planetary Systems Form & Evolve?

- What fraction of **young stars** have gas-giant planets?
- 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 do terrestrial planets form ?

- **SIM Lite will find gas giants within radii 1-10 AU of young stars (10-100 Myr) at distances of 25-150 pc**
  - Variability, spectral jitter & rotation of >100 m/s **preclude planet detection via RV or transits**





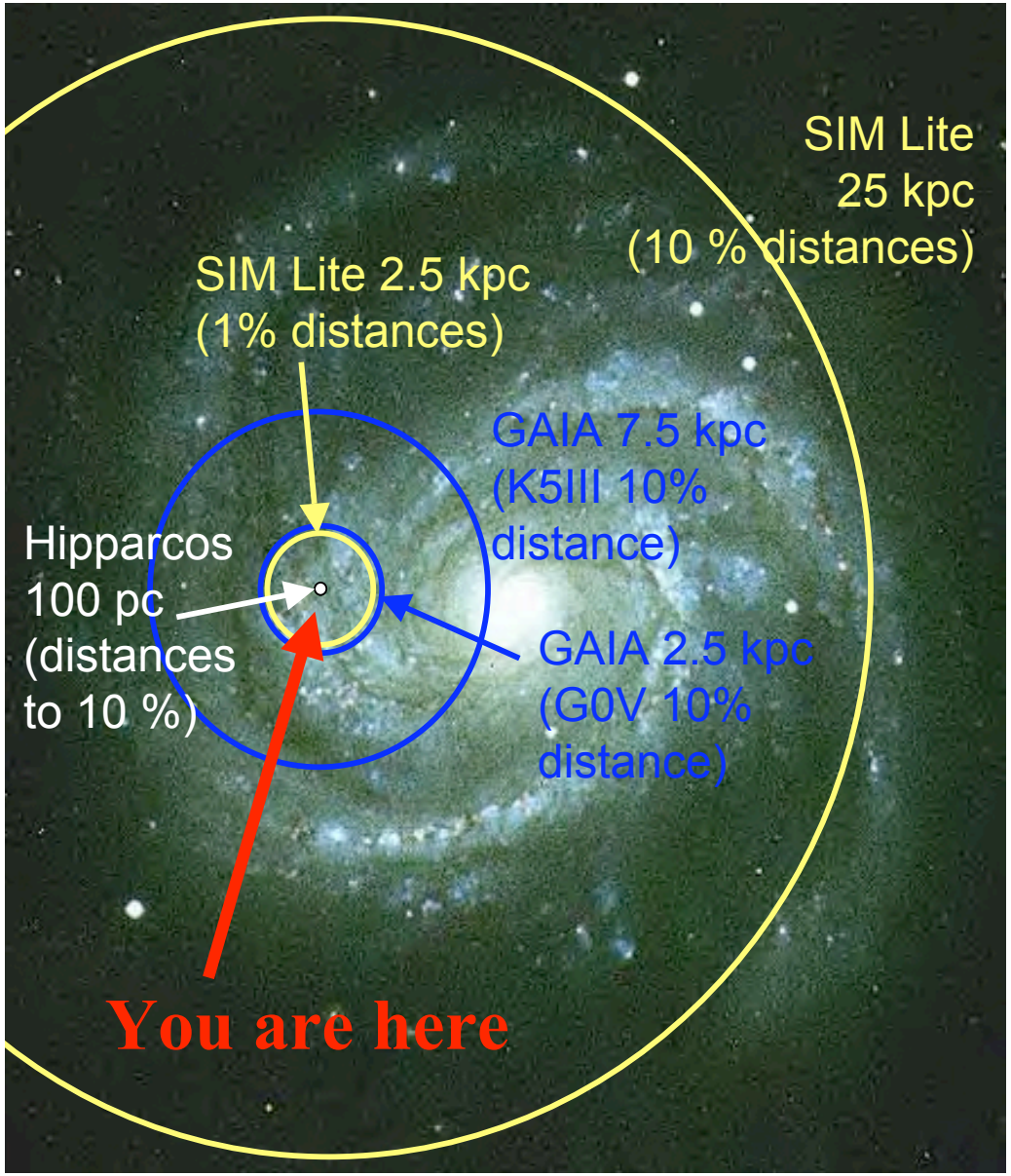
SIM Lite & Gaia: Mission Synergy

- *Gaia* is the Survey Machine
  - e.g. Palomar Sky Survey
  - e.g. Sloan Digital Sky Survey
- *SIM Lite* is the Observatory
  - e.g. Keck Observatory
  - e.g. Hubble Space Telescope
- *Gaia* will fly first, and open up a wide array of targets for followup with *SIM Lite*
- Missions are complementary:
  - Planets:
    - *Gaia* does a large survey for Jupiters
    - *SIM Lite* finds Earths around ~60-100 nearby stars
  - Galactic structure:
    - *Gaia* will study the bulge, bar, rotation curve
    - *SIM Lite* will study dark matter and 'assembly' of the Galactic halo, via tidal tails

SIM Lite's Reach Extends Across the Galaxy

What makes SIM Lite unique:

- Extreme astrometric precision
  - 4 μas (microarcsec) positions
  - 4 μas/yr proper motions
  - 1 μas differential positions
- Ability to observe faint targets
  - V <~ 19
  - bright limit V = -1.4
- Flexible scheduling
  - Optimize for *specific* science objectives
  - Targets of Opportunity
  - Microlensing

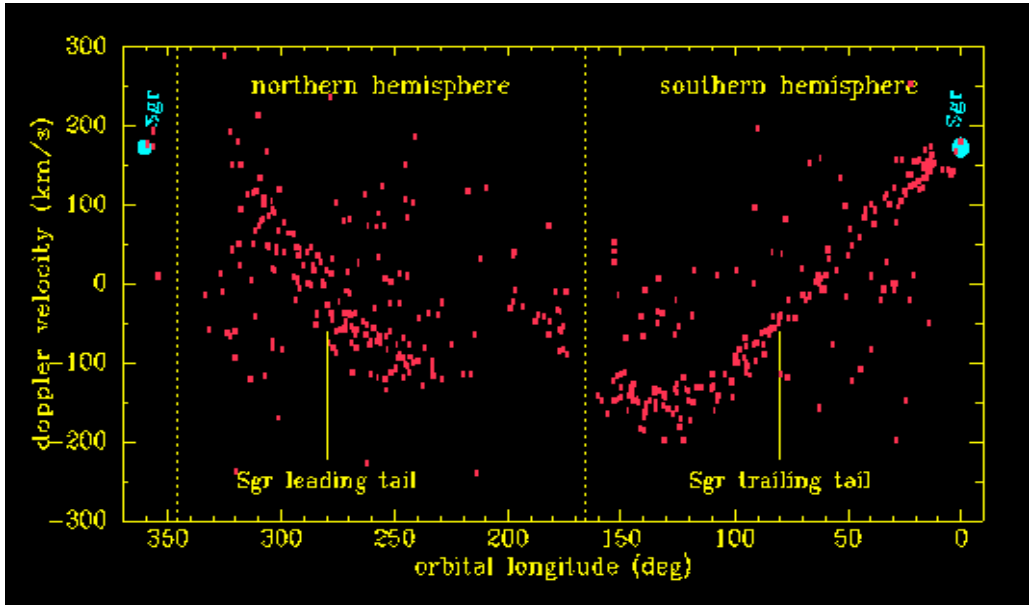


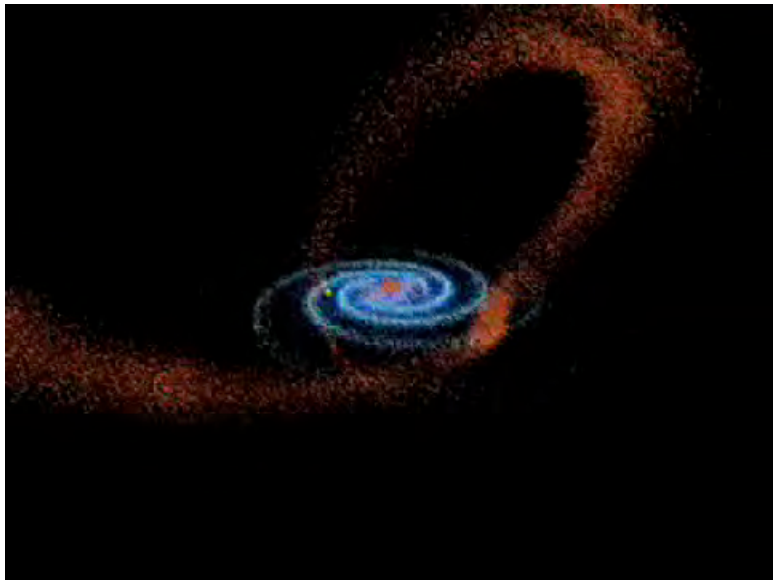
Galactic structure and formation: Near field cosmology on scales out to 5 Mpc

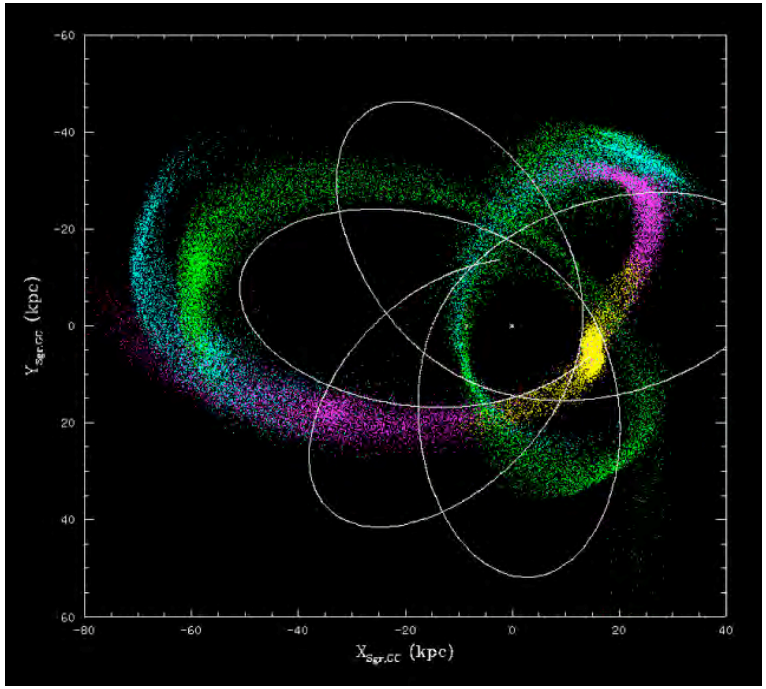
- Shape, orientation, density law and lumpiness of the dark halo of the Milky Way and other nearby galaxies
  - Tidal streams from the disruption of dwarf satellite systems
  - Hypervelocity stars catapulted from the core of the galaxy from encounters with massive objects
- Orbits of Galactic satellites
  - may be representative of late infall from the hierarchical formation of the Milky Way
- Distribution of angular momentum and orbital anisotropy of stars and globular clusters in the outer Galactic halo
  - clues to the early hierarchical formation of these systems
- Physical nature of dark matter by measuring the phase space density in the cores of nearby dSph galaxies
- Dynamical history of the Local Group through the determination of orbits and masses of its constituent galaxies

Sgr Dwarf Galaxy: Tracer of infall history

- Initial 2MASS work reveals >360deg arms
- Radial-velocity constraints help



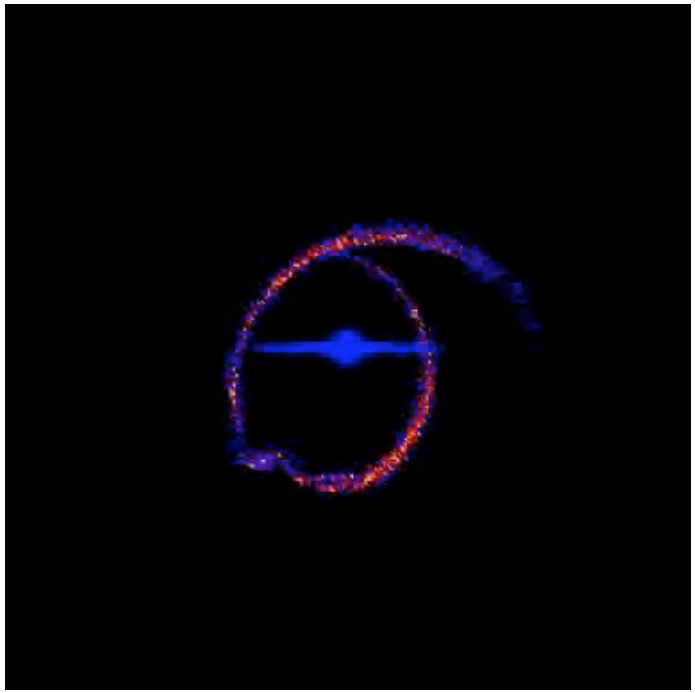


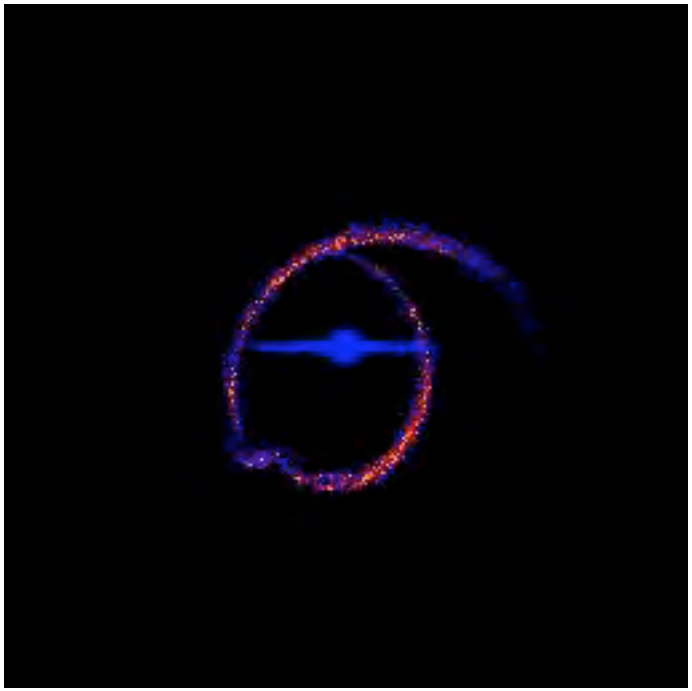


- With only 4-D constraints, problems/contradictions remain:
- Modeling of Sgr and Galactic halo
  - Leading Arm RVs “wrong”
  - Prolate vs. Oblate ambiguity

Mass distribution of the Galaxy using Tidal Tails: Run the movie backwards

- Dwarf spheroidal galaxies are dynamically ‘cold’
- Tails are very sensitive to the galactic mass distribution





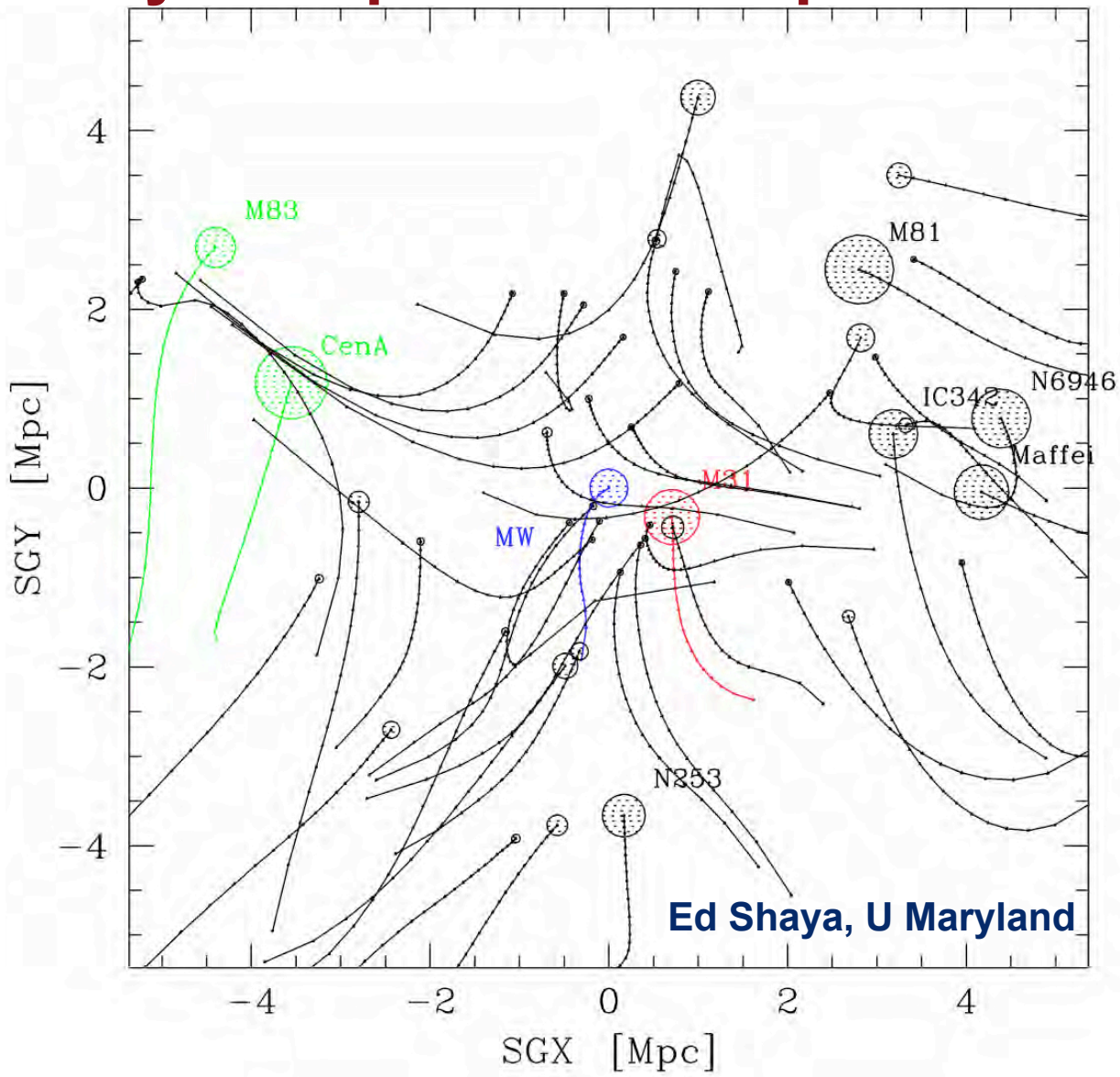
Dynamics of Galaxy Groups within 5 Mpc

Simulation from Numerical Action dynamical model

- Fidelity is limited because only 1-D velocity info is available (RV)

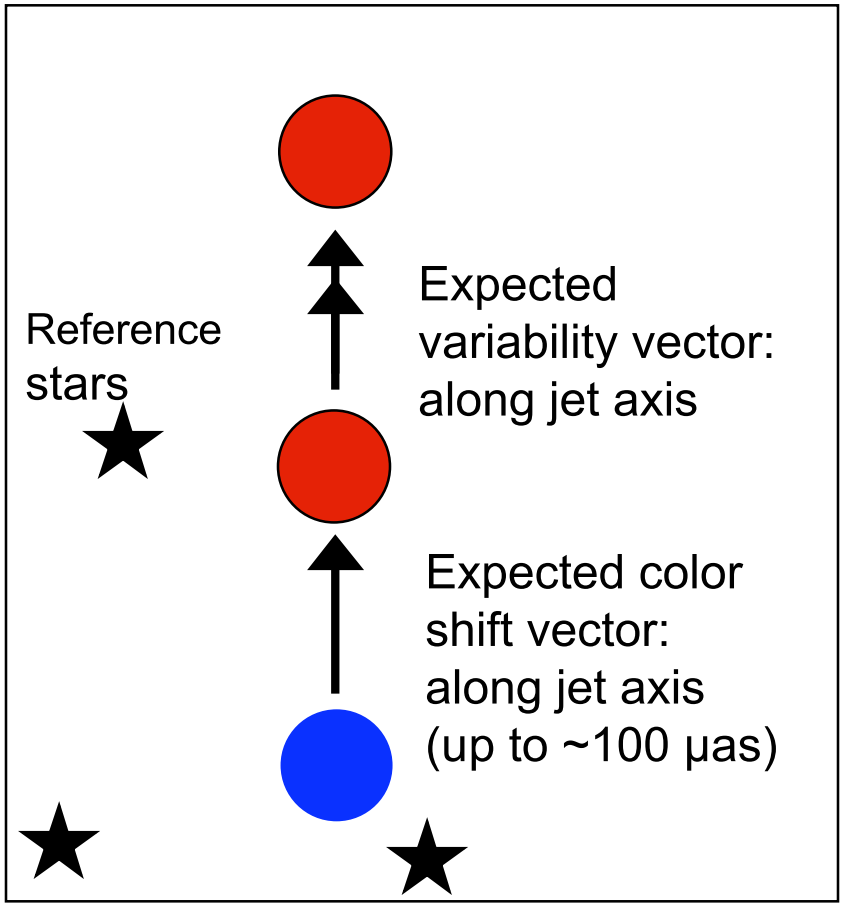
SIM Lite will test these models

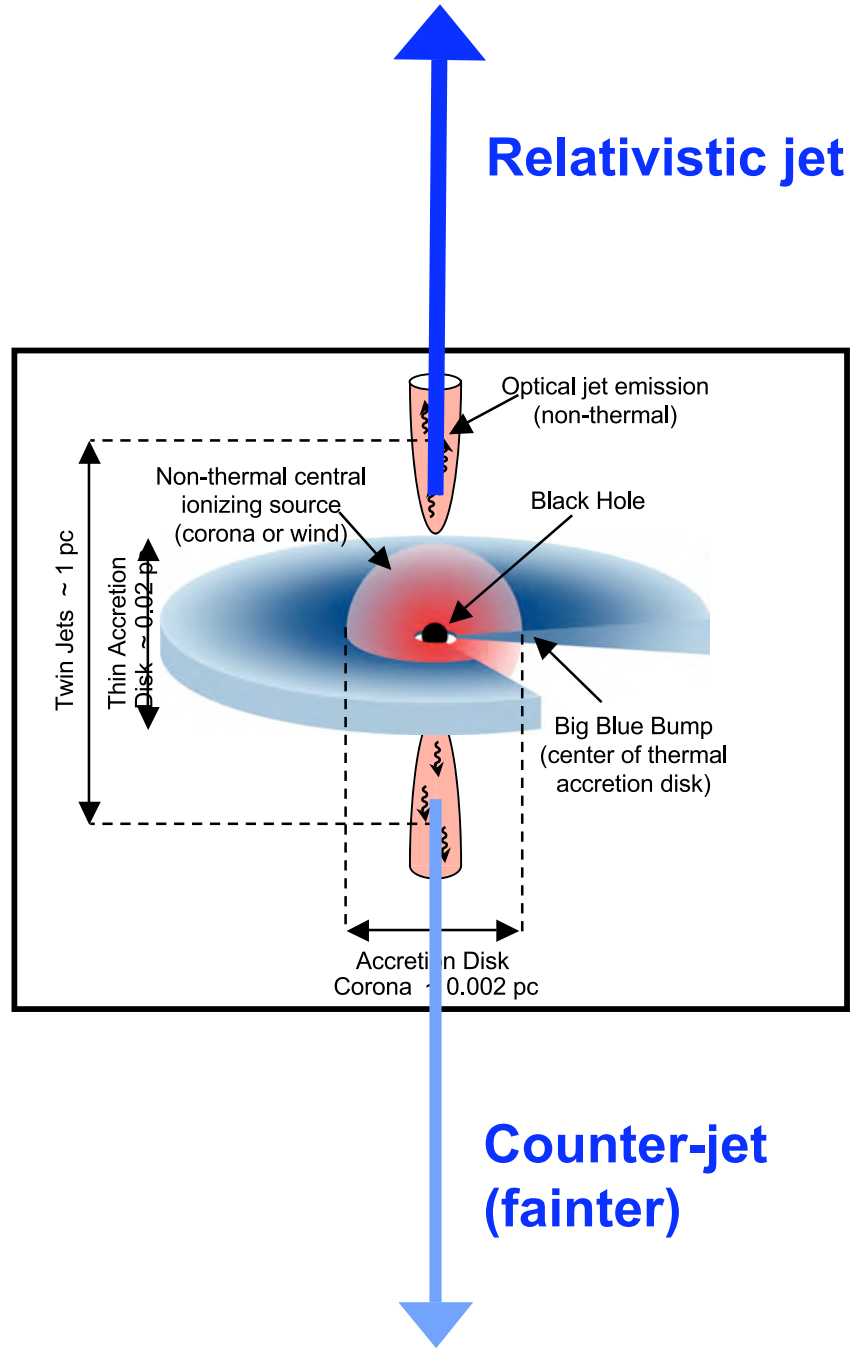
- SIM Lite will measure current transverse velocities
- Models will then sample the full 6-D phase space



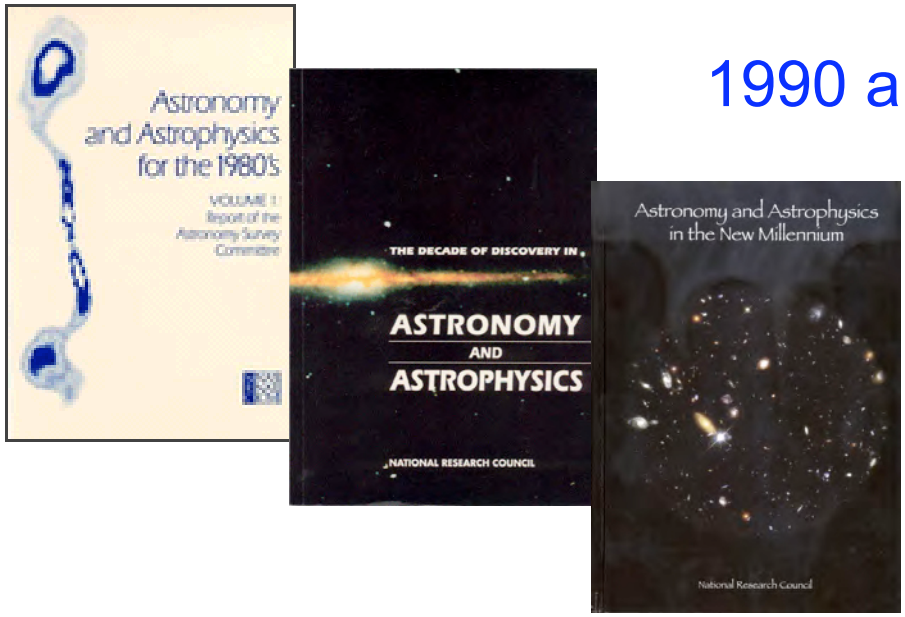
Simulated 'time-lapse' photo of 30 galaxies closest to our Milky Way (1-billion year exposure)

Astrometric Motion in Quasars





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."

Worlds Beyond: Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

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?**

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

"The only technique appropriate to survey the nearest hundred or so bright sun-like stars in the mid-term is space-based astrometry, and this is one cornerstone of the Task Force recommendations."

SIM PlanetQuest is now *SIM Lite*

- Effort in the past year to find a capable lower-cost precision astrometry mission resulted in *SIM Lite*
- Complexity, mass, and cost are reduced compared to SIM PlanetQuest
- Astrometric accuracy is maintained; some throughput loss
- Science Team's evaluation of science impact:
  - For planet searching, accuracy tailored to each target (according to star distance) by increasing the number of visits
    - Systematic noise floor is very low
  - For faint astrophysics targets, in photon-limited regime, larger collecting area compensates for shorter baseline
    - Where necessary, re-balance target list, to use fewer targets, or accept less accuracy
    - Re-optimization depends on the details of each specific study

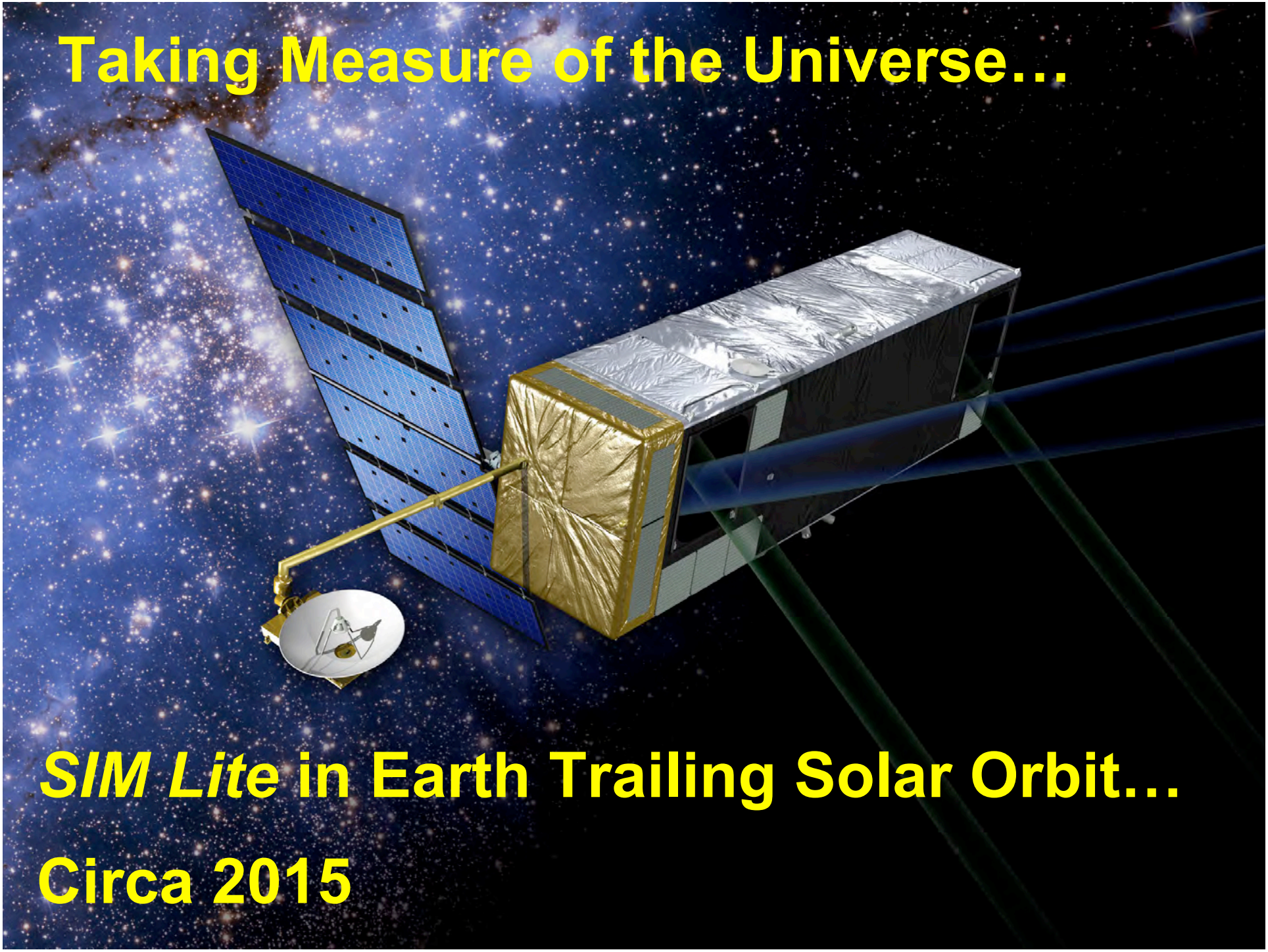
SIM Lite science is SIM science

- *SIM Lite* science has received endorsement from numerous community peer review committees
- It is the *same* broad-ranging science that has been evaluated and endorsed by independent committees:

- Greatly exceeds the objectives of the *1990 Decadal Survey*
- Meets the objectives of the *2000 Decadal Survey*
- Meets the objectives for extrasolar planet detection laid out by the *2008 Exoplanet Task Force*

Next Steps

- *SIM Lite Science Studies*
  - Exploratory studies of science that can be done with SIM Lite
  - **19 proposals were selected,** via peer-review, in July 2008
  - Open to all topics, especially Administered though *NASA Exoplanet Science Institute (NExSci)*
  - No SIM observing time; awards ~$50k for one year
  - Wide range of topics: exoplanets, stellar and galactic astrophysics, and innovative uses of astrometry
- Science Team is preparing a *SIM Book* describing the current and planned science program
- Review by the upcoming *Astronomy and Astrophysics Decadal Survey Committee* (Roger Blandford, Chair)


Taking Measure of the Universe…
SIM Lite in Earth Trailing Solar Orbit…
Circa 2015

End

SIM Meets National Academy Performance Goals

Report Name	Wide-Angle Astrometry (end of mission)		Narrow-Angle Astrometry (single measurement)				
	Requirement	Goal	Requirement	Goal	Magnitude Limit (V)	Nulling	Rotational Synthesis Imaging
1982 Decadal Survey	Space Optical Interferometer (SOI) with resolutions of 1 to 10 µas by early part of next century						
1991 Decadal Survey ('AIM')	30 µas	3 µas	not specified	not specified	20	No	No
2001 Decadal Survey ('SIM')	10 µas	4 µas	3 µas	1 µas	20	Yes	Full uv-plane from 1m to 10m
2002 CAA Letter Assessment of SIM	10 µas	4 µas	3 µas	1 µas	20	No	10m baseline
SIM-PQ Performance	2.4 µas *		0.7 µas *		20	No	9m and 6m baselines
Planet Hunter	none		1 µas *		10	No	6m baseline
SIM-Lite	**4 µas ***		**1 µas ***		**19-20**	**No**	**6 m baseline**

* Performance is Current Best Estimate (CBE) prediction, without margin, based upon SIM's completed technology development program and mature flight design

What About Kepler?

- Kepler is a transit mission that looks at ~10^5 stars in a 12° solid angle of sky in the direction of the Orion arm.
  - Stars at average distance of ~3 kpc
    - Too distant for follow up by direct detection
  - Transit requires alignment of the planetary plane with line of sight
    - 0.5% to 1% will be so aligned
  - Transit methods can give size, if stellar distance is accurately known, but not mass
- Kepler should provide a good measure of the frequency of habitable terrestrials
  - That will be useful in selecting the SIM Lite depth of search

What About Gaia?

- Gaia is a scanning astrometry mission like Hipparcos
  - Will achieve a mission accuracy of ~6 μas for stars between ~V = 7-12
- SIM Lite planet-search target stars will all be too bright for Gaia (V ≤ 7)
- Gaia's precision of 6 μas is not sufficient to detect HZ terrestrial planets

What About Ground RV?

- Radial velocity measures the Doppler shift in stellar spectrum resulting from the star's motion about the star-planet barycenter
  - Currently limited to ~1 m/s precision
  - Likely improving to high fractions of a m/s in coming decade
  - Can find HZ terrestrial planets only around coolest M-dwarfs
  - Can't reach terrestrial mass planets around FGK dwarfs in reasonable observation time
    - would take many 10's of thousands of nights to accomplish