Interferometric Astrometry from Space

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Outline

- Space Astrometry with stellar interferometers (not scanning telescopes, GAIA)

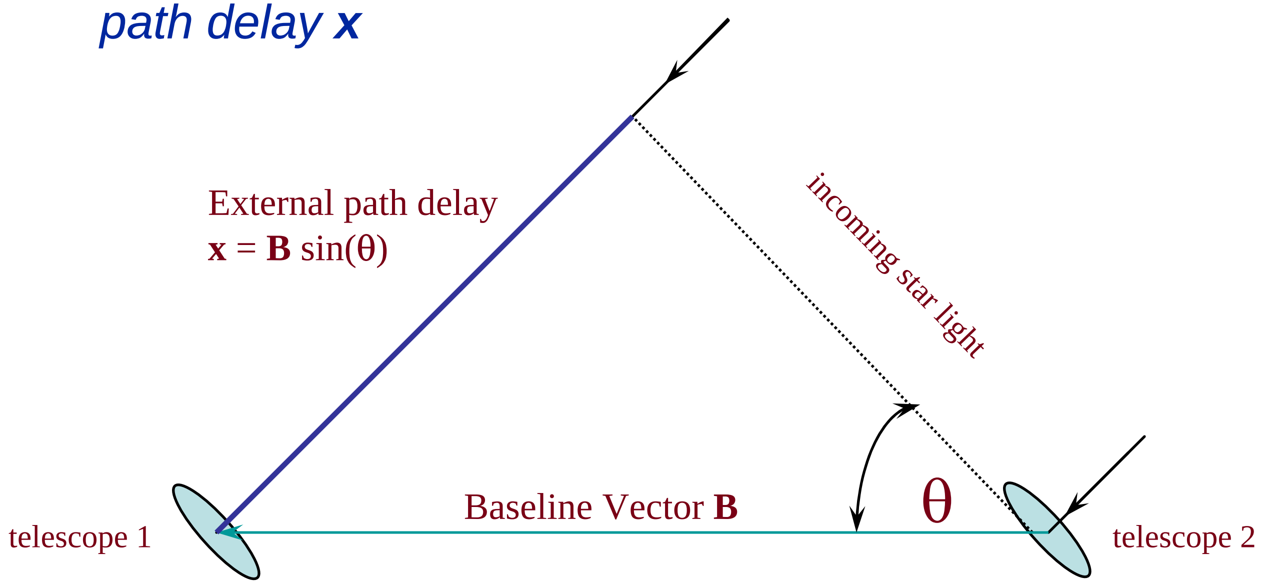
- Basics of astrometry with a space interferometer (SIM)

- Pointed, or targeted observations

- Two modes of operation
  - Narrow angle astrometry (1 uas single epoch, 0.1 uas mission average)
  - Global astrometry (4uas mission average for grid)

Basics of Interferometric Astrometry
Star-Baseline Geometry

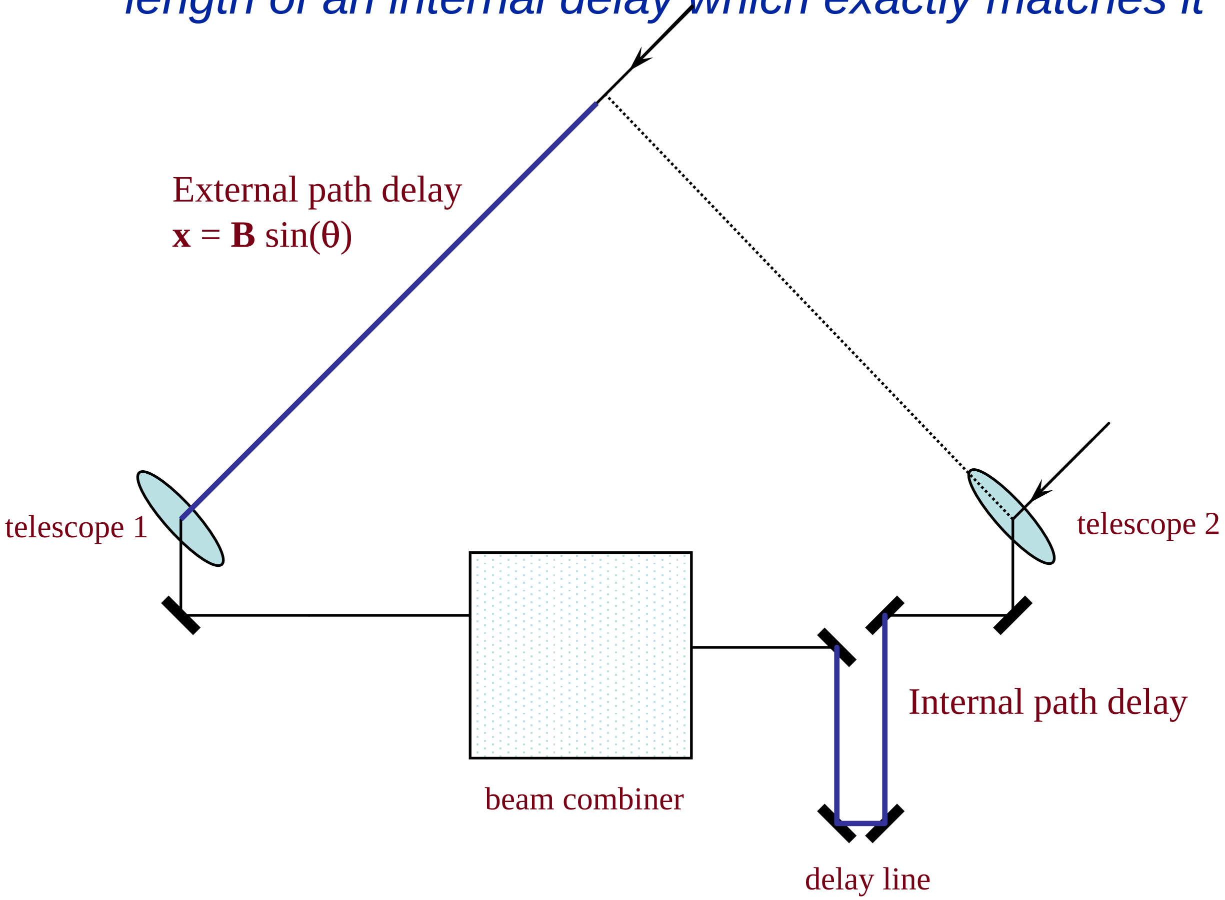
*The angle between the star and baseline creates an external path delay **x***



*If we know **B**, and can determine **x**, we can solve for the relative star position θ*

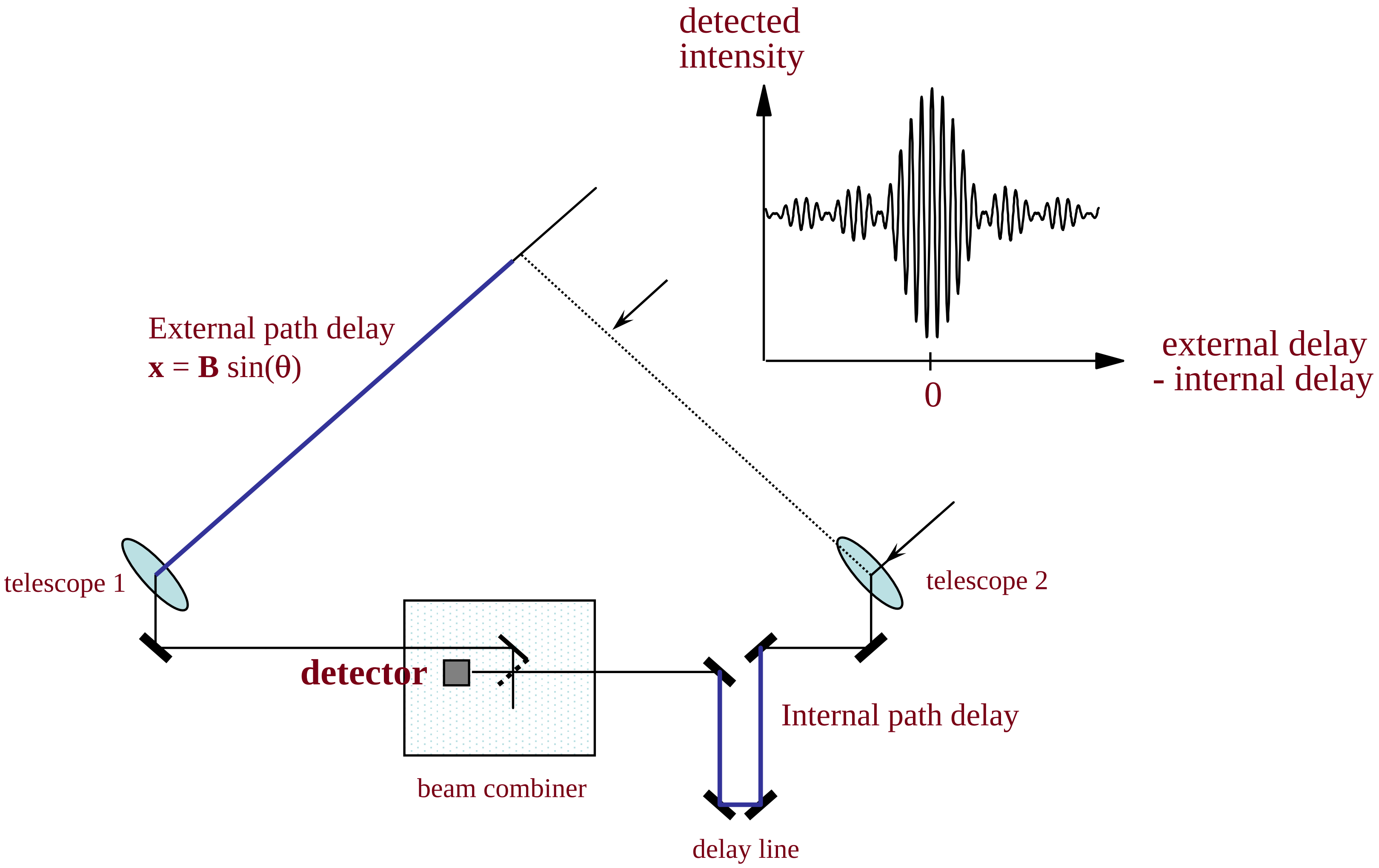
Determining the External Delay

We determine the external delay by measuring the length of an internal delay which exactly matches it



Optical delay lines are used to vary the internal delay

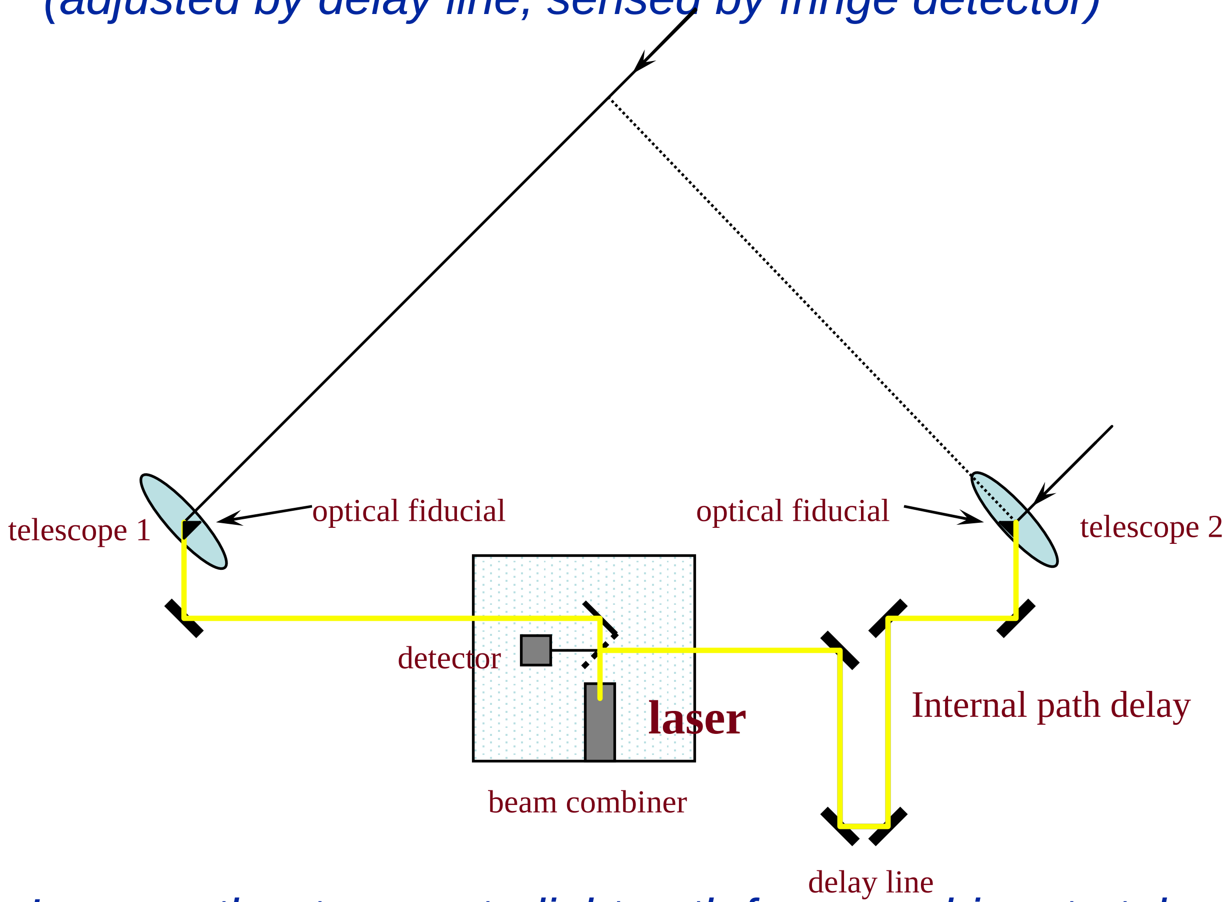
Fringe Position as a Measure of Pathlength Equality



The peak of the interference pattern occurs when the internal path delay equals the external path delay

Internal Metrology

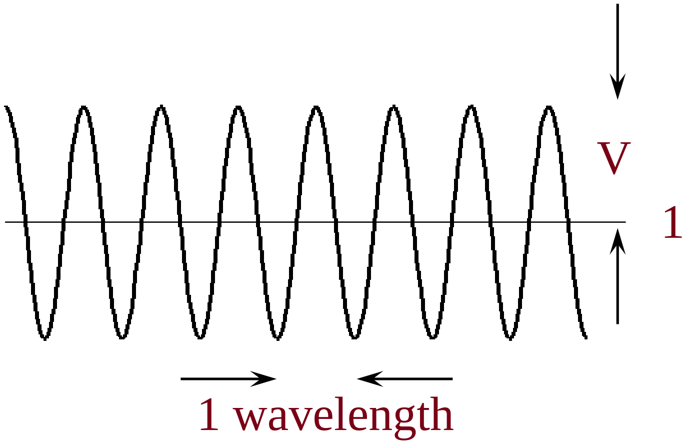
Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

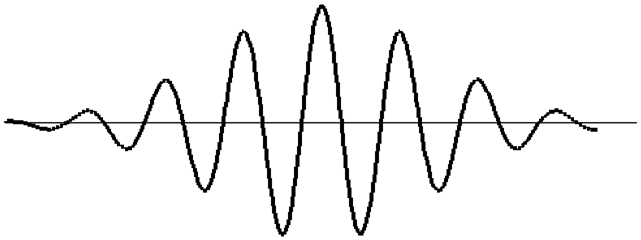
About Fringes

Narrowband (laser) fringe
$\Delta\lambda \sim 0$



-Fringes at all delays

Wideband (white light) fringe
$\Delta\lambda >> 0$



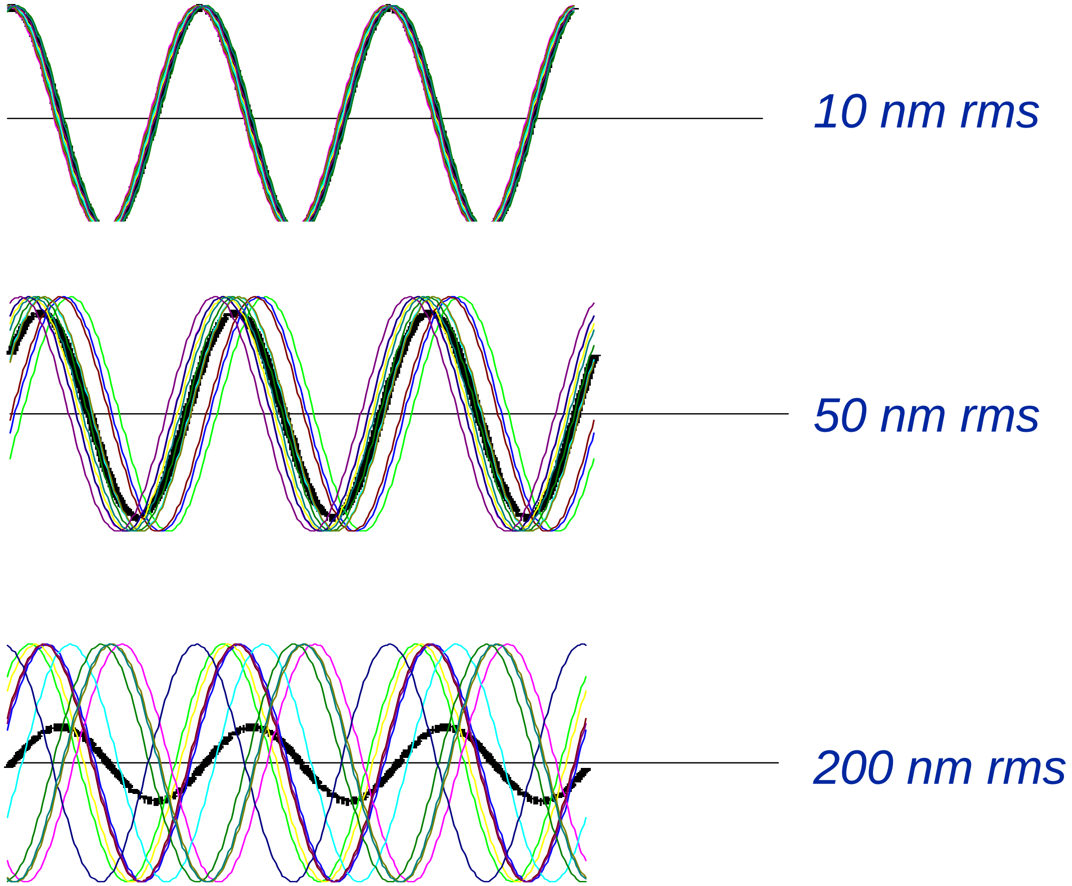
-Number of fringes ~ $\Delta\lambda/\lambda$
-There is a well defined central fringe

-Fringe position tells us about position of source

-Fringe visibility tells us about structure of source
(extended sources have reduced fringe visibility)

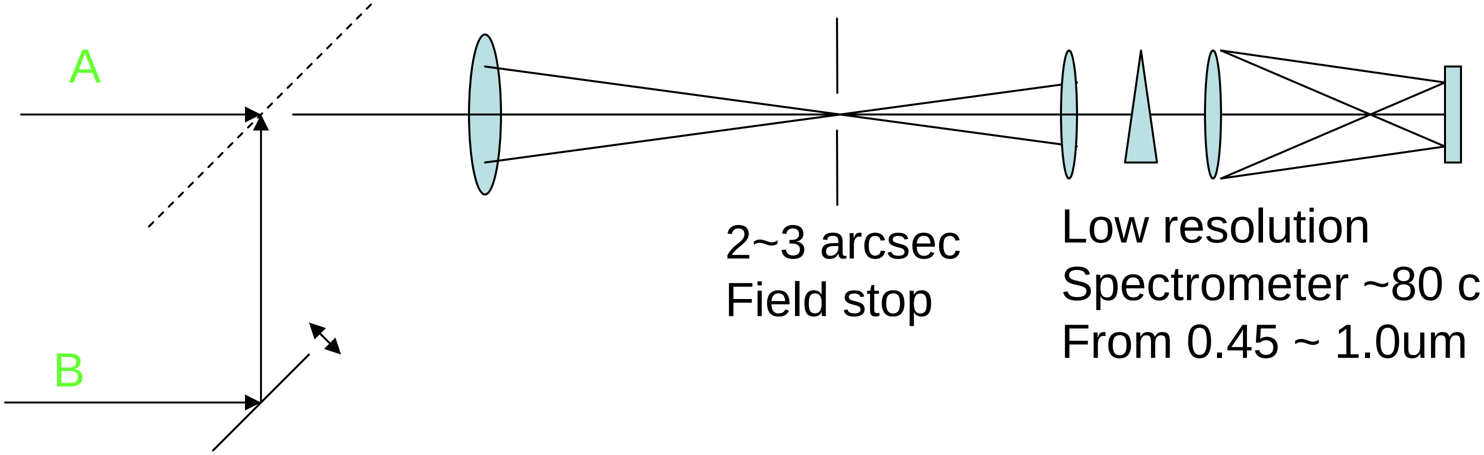
Requirements on Fringe Stabilization

Vibrations blur out the fringe



Need real-time control of pathlength to ~10 nm (λ/50) for high fringe visibility

SIM Fringe Detector
(conceptual schematic)



Light is combined

2~3 arcsec
Field stop

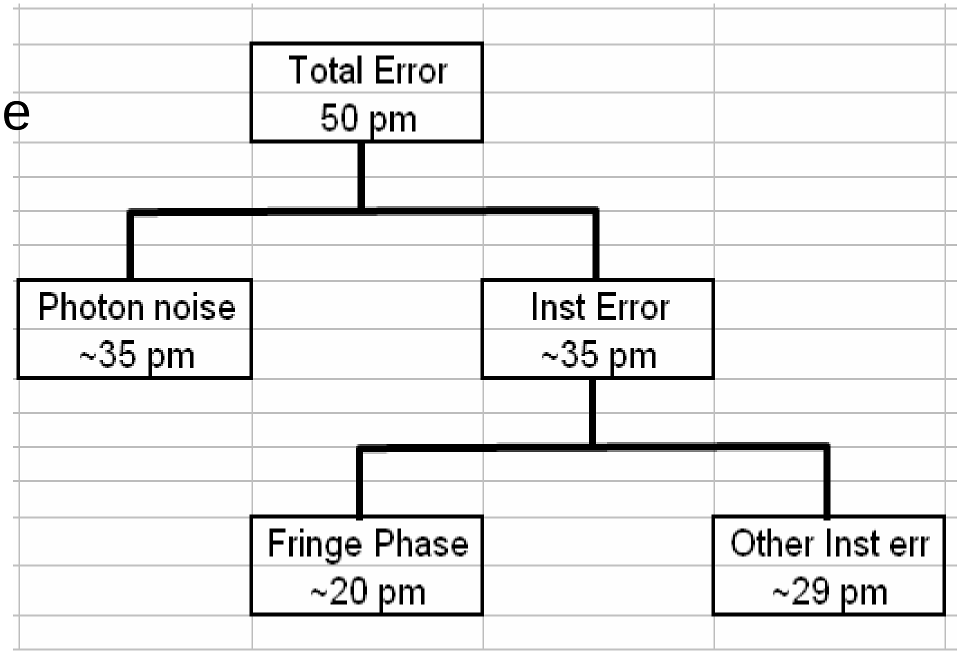
Low resolution
Spectrometer ~80 channels
From 0.45 ~ 1.0um

Vibrating mirror
250Hz triangle wave 1um
CCD read out @ 8 samples/um

One Laser metrology system measures the optical path diff (A-B) from the combining beam splitter to optical fiducials at siderostat that defines the baseline vector.

Accurate White Light Fringe Phase Measurement

- 1 uas accuracy with a 10m baseline => optical path accurate to ~50pm.



- The allocation to white light fringe measurement is ~ 20pm or a required accuracy of $\lambda/30{,}000$
- Normal opd dither modulation and demodulation isn't accurate enough

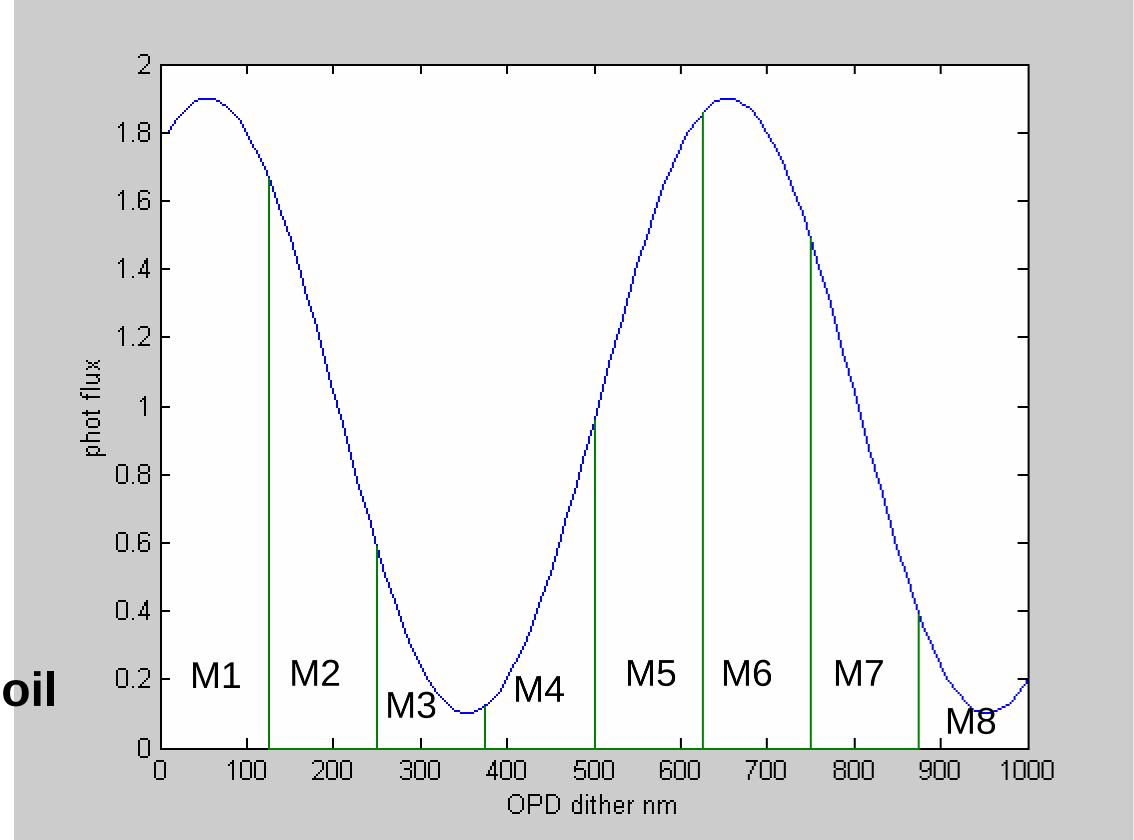
- Inten = $1+\text{vis}*\sin(2\pi X/\lambda + \phi)$ in monochromatic light

White Light Fringe Phase 2

$\mathrm{Inten} = 1+\mathrm{vis}*\sin(2\pi X/\lambda + \phi)$

Measuring Inten(1-8), one then solve for in a least sq's sense, ϕ , vis etc.

Errors in the knowledge of X produces both random and Systematic errors



Systematic errors are due to
- **non-linearities in PZT/voicecoil**
- **hysteresis in PZT**
- **vibrations at the modulation freq or harmonics**

Random errors from
- **vibration at freq other than the modulation freq**

Errors in our knowledge of X result 1:1 in errors in $\phi*\lambda//2\pi$

Random errors in X will average down ~sqrt(N), but systematic errors won't (and often the systematic errors can be ~ $\lambda/50$ or larger

White Light Fringe Phase 3

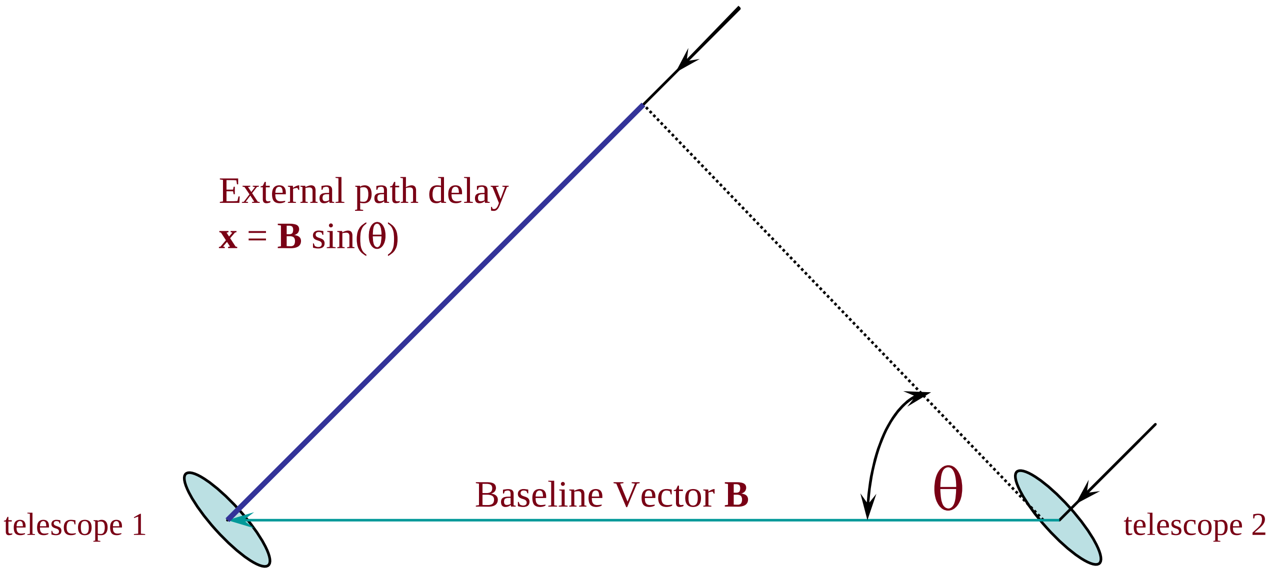
- By measuring the modulator motion with laser metrology with systematic errors < 10pm, and random noise < 10pm/sqrt(hz) white light fringe measurements can be extremely accurate.
  - However, the metrology data must be used when demodulating the whitelight fringe.
  - Normally we solve for the phasor components of the whitelight fringe, in a least squares fashion
    - [Vis*sin(phi), Vis*cos(phi), DC] = pseudo_inv * [M1…M8]
    - The brute force approach to using the metrology data is to calculate a diff pseudo_inverse for every modulator stroke based on the X's measured.
      - However a much more computationally efficient route is possible is the modulation waveform is highly repeatable.
- Fundamental limits (beside stellar photon noise) to w.l. measurements are due to
  - errors in the metrology system
  - Errors in the timing of the metrology and ccd measurements.

Some Numbers

- Metrology detectors ~3Mhz bw 1e-12 W/rthz, ~30 nw received signal power. ~ 5 pm/rt_hz, two arms total ~7pm/rthz
- 1usec timing uncertainty (met vs CCD) ~0.5nm/sample ~ 11pm/rt_hz
- Theoretically SIM starlight fringe detector (infinitely bright star) should be capable of 13pm (in 1 sec) ~ 50 nano-arcsec in a 30 sec integration observation. Actual performance is ~< 300 nano-arcsec.
  - Other error sources dominate the ~ 1uas error budget.

Star-Baseline Geometry

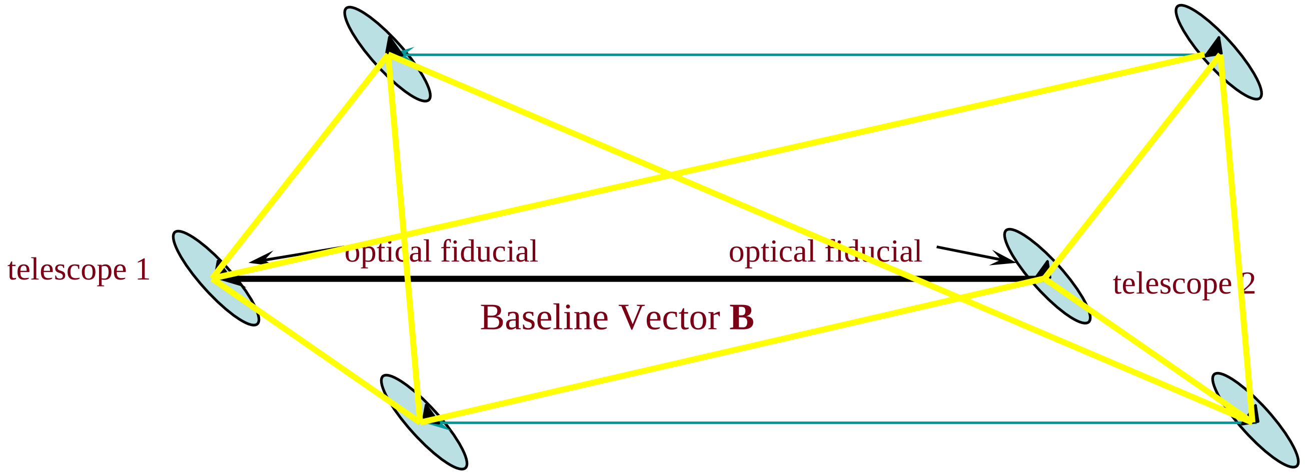
We now know x; what about B?



External Metrology

SIM uses 2 guide interferometers looking at two guide stars (7 mag) to define an inertial frame to < 1uas/1hr

External laser metrology measures the relative baseline vectors of The two guide interferometers wrt the science interferometer



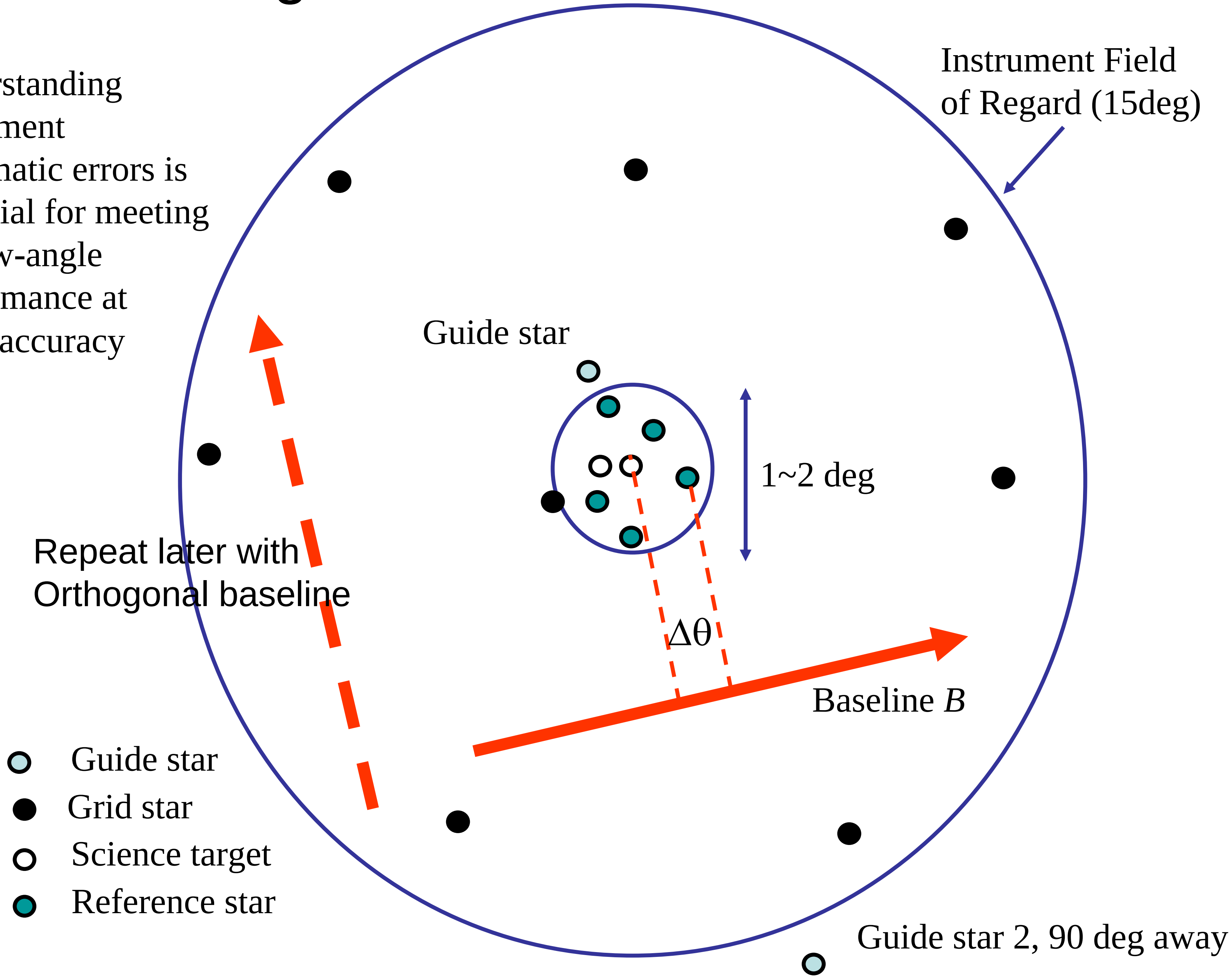
Guide 1 near
Center of field (15 deg)

Guide 2 ~90 deg away

The physical baseline of SIM will move ~ 0.1 arcsec on a time scale of ~30 sec. In data reduction, we define a “regularized” baseline that is fixed in inertial space to < 1uas over ~ 1hr by using information from both guide interferometers and the external laser metrology truss.

Narrow-angle Astrometric Observations

Understanding instrument systematic errors is essential for meeting narrow-angle performance at 1 μas accuracy



Instrument Field of Regard (15deg)

Guide star

1~2 deg

Δθ

Repeat later with Orthogonal baseline

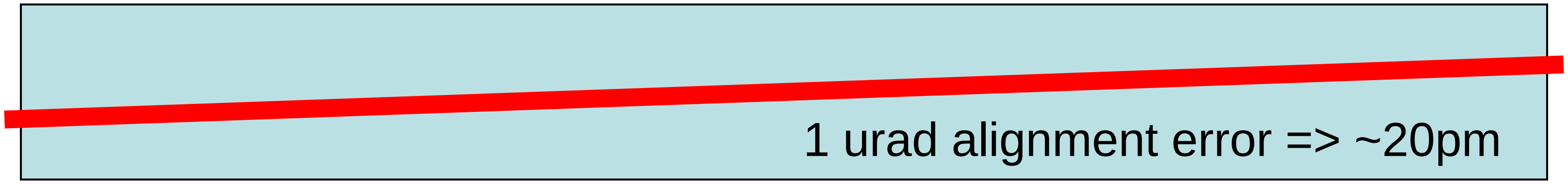
Baseline *B*

Guide star 2, 90 deg away

- ○ Guide star
- ● Grid star
- ○ Science target
- ● Reference star

Error Sources and Observation Design

- Thermal drift (time dependent biases)
  - The laser measures the optical path at the center of the starlight beam in a direction very close to parallel to the starlight.
  - Change in the curvature of the starlight optics can produce errors
  - Change in the alignment of the metrology wrt starlight => errors
  - Change in temp of transmissive optics will change the dispersion of the glass (1.32um metrology vs 0.6um starlight)



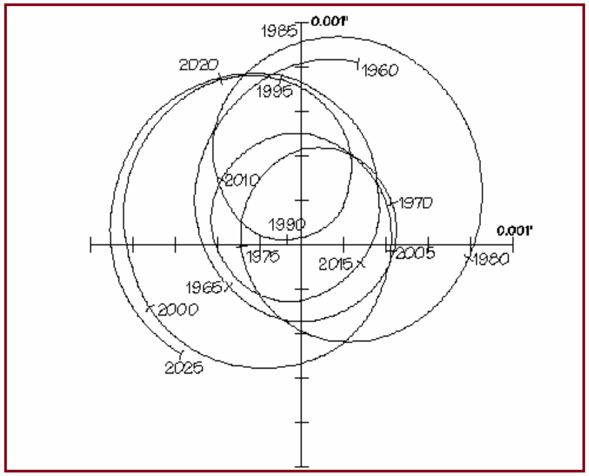
1 urad alignment error => ~20pm

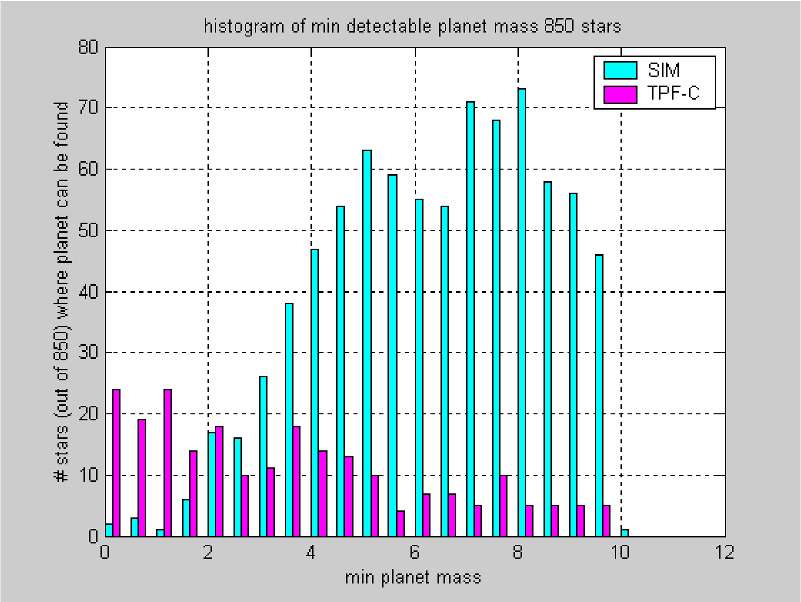
- Field dependent biases
  - Beam walk (when the siderostat articulates, the starlight footprint on the mirror changes) Same for laser footprint on CC.
  - Bi-linear errors (static misalignment * field dependent offset or field dependent misalignment *static beam offset)
  - CC polarization errors, CC dihedral errors

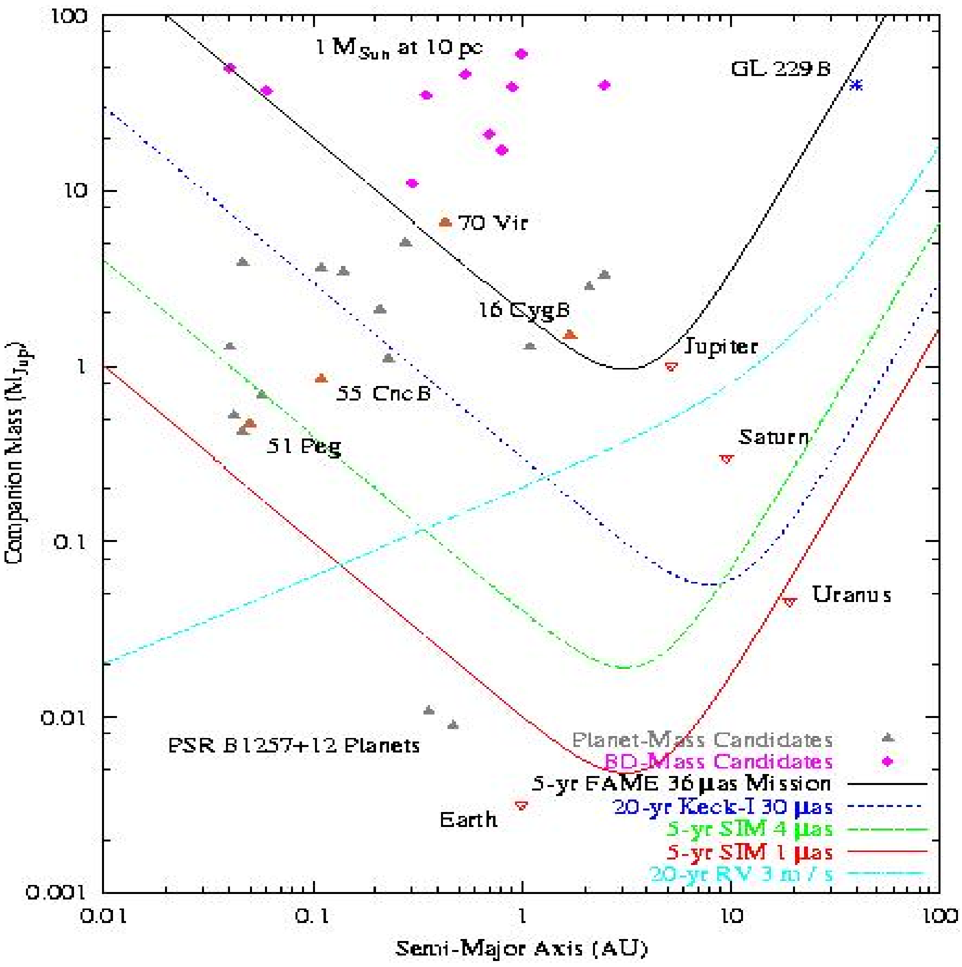
Observation Planning Around Systematic Errors

- To reduce the effect of temporal drifts, chop between target and ref stars.
  - R1-T-R2-T-R3-T-R4-T-R1-T-R2-T-R3-T-R4-T-R1-T-R2-T-R3-T-R4
- Relative astrometry (wrt ref stars) use the ref stars to define the local frame’s zero point, and X-scale and Y-scale
  - Grid stars are used to determine the orientation of the local frame
  - 1st Field dependent errors that matter are 2nd order
- To reduce the effect of field dependent errors limit the field of view to ~ 1 deg radius.
- To reduce the photon noise contribution, use 10 mag or brighter stars.

Application of Narrow Angle Astrometry Planet Detection



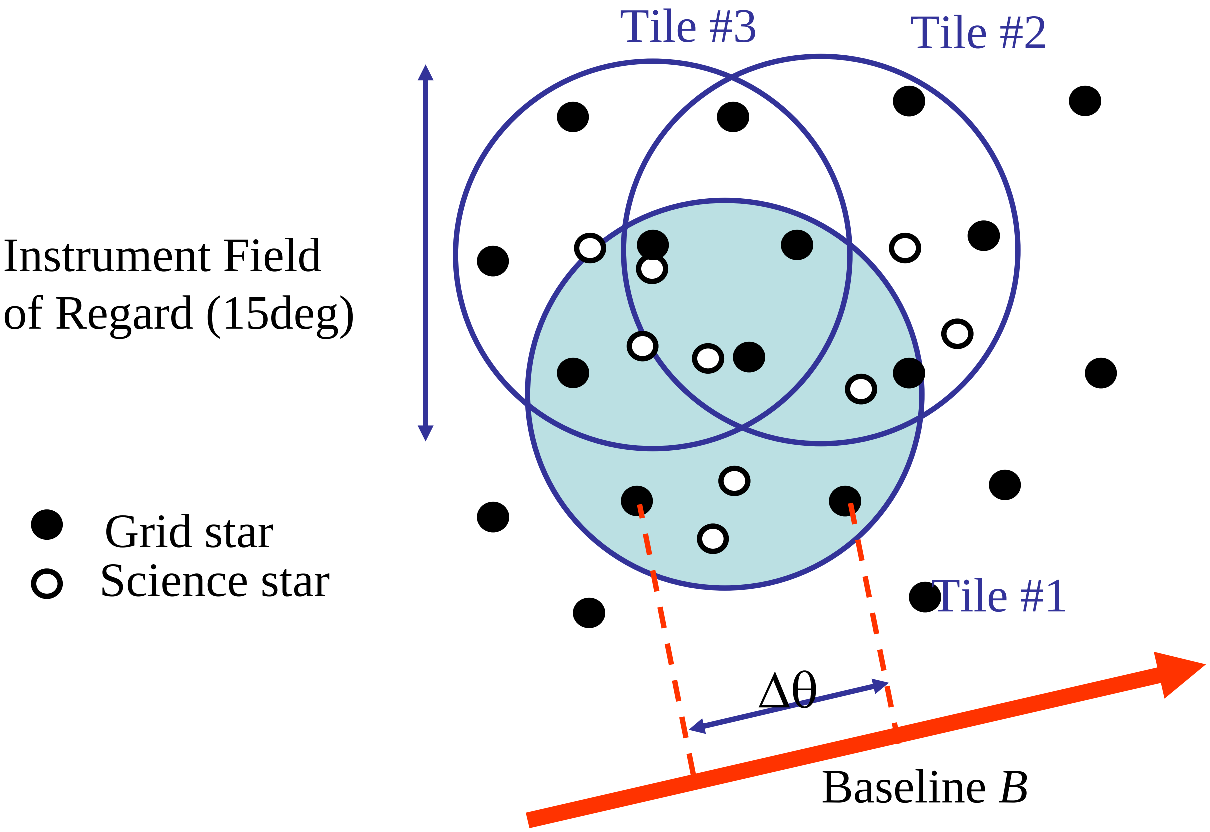




Detection Limits
SIM: 1 µas over 5 years (mission lifetime)

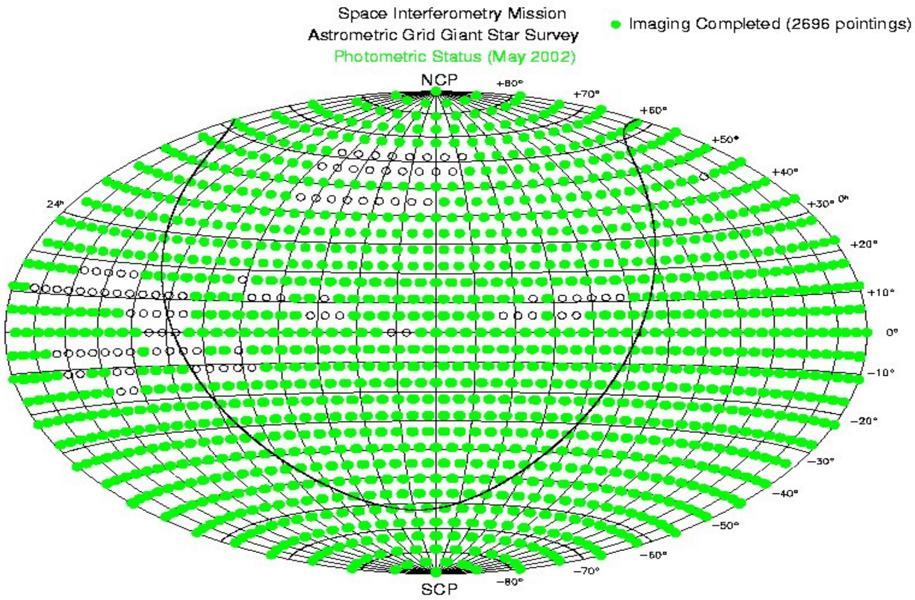
Global Astrometry

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



What is the Grid?

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



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

Solving the Simple Grid

- Each tile has ~7 grid stars, 7 delay measurements.
- There are ~1300 overlapping tiles (per orange peel)
- 2 baseline orientation per tile
- 22 orange peels in a 5 year mission
- The 5 yr grid has ~400,000 measurements
- Astrometric variables (RA, Dec, PM_RA, PM_Dec, Prlx) ~6500
- Nuisance parameters (regularized baseline vectors xyzc) ~175,000
- Large least squares fit
- Approx results
  - Position accuracy ~ 4uas (for single epoch accuracy 10uas)
  - Proper motion accuracy ~ 2.5uas/yr
  - Absolute Prlx accuracy ~ 4.5 uas

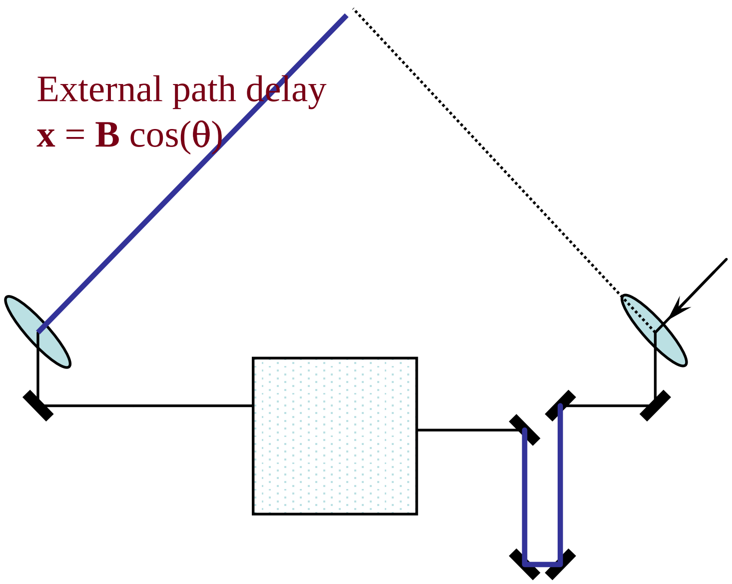
More on the Grid

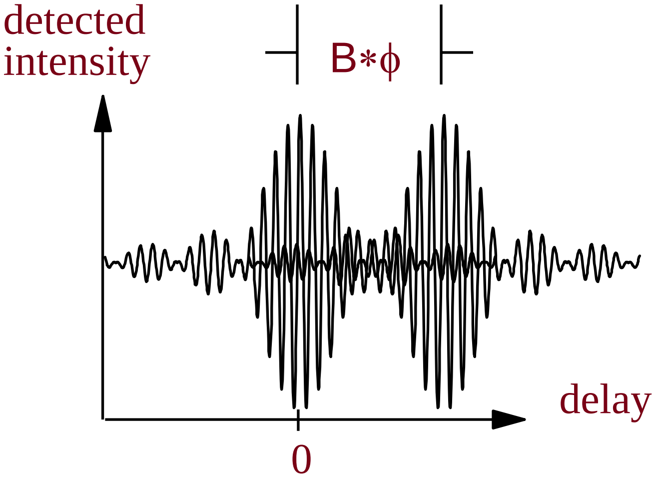
- Time doesn’t permit me to more than mention some additional issues being studied by the SIM project
- Zonal errors, the errors in parallax (or PM or position) from star to stars have both a random and systematic component. (assuming the actual delay measurements themselves are totally random)
  - This limits the ability to for example determine the distance to an extra galactic object by averaging the parallaxes of N stars in that object
- Solving for field dependent biases. Many (most?) of the field dependent biases in SIM will be stable over very long time scales. In addition to solving for the baseline vector, per tile, it may be possible to solve for field dependent biases. (numerical experiments have shown this is possible if the field dependent errors are stable for several 100 hrs.
- Using QSO’s. Todate numerical simulations have only looked at a stellar grid. The use of a number of QSO’s may avoid some of the zonal errors that arise from a star-only grid.

Astrometry of Multiple Stars with SIM

If instead of 1 star, there are two stars, separate by a small angle ϕ

There will then be two fringe patterns, one from each star.

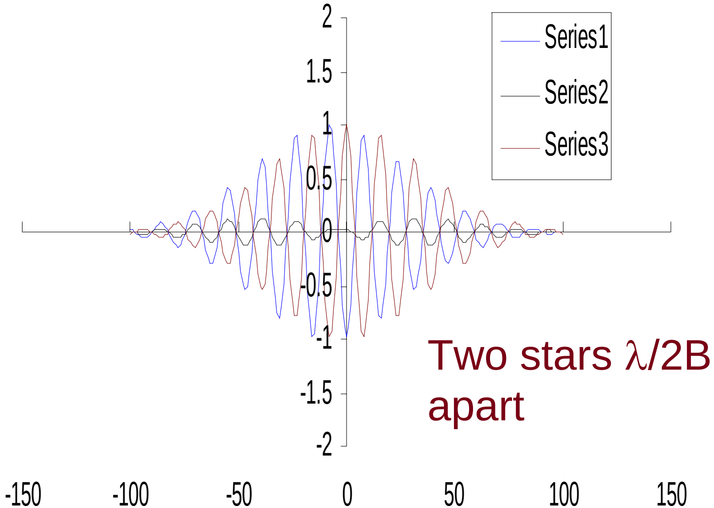




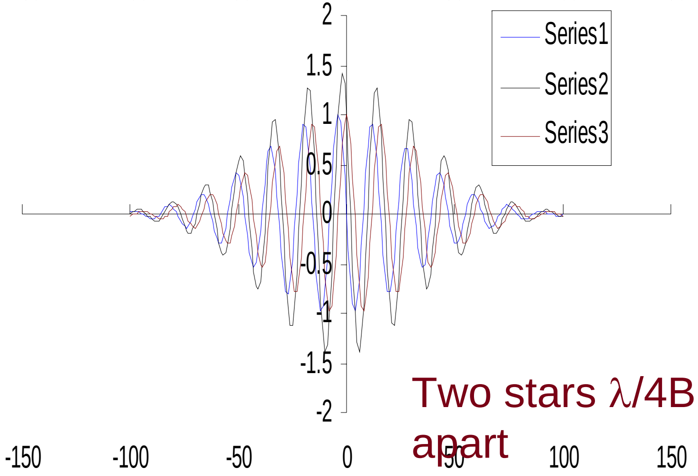
The two fringe patterns, will be superimposed on each star.

If the two patterns are only $\lambda/2$ apart, they will cancel each other.

Spatial Coherence



Two stars $\lambda/2B$ apart



Two stars $\lambda/4B$ apart

The fringe pattern seen at the combiner is the sum of the fringe patterns of all the objects in the field of view.

In monochromatic light, The sum, can be expressed as:

$I(\text{delay}) = \Sigma\, I(\theta)*\cos((2\pi\theta\lambda\ /B)+\text{delay})$

$I(\theta)$ is the source brightness distribution

Using the fringe Vis and phase as a function of baseline orientation and length to reconstruct the spatial distribution of a complex source is call synthetic aperture imaging.

SIM's ability to do synthetic aperture imaging is limited by having just 1 (possibly 2) baseline lengths.

Astrometry of Multiple Star Systems

- However if the object is composed of a few point sources, a modest number of baseline orientations are all that's needed to make rather accurate relative astrometric and photometric measurements.
- Multiple stars (all within ~2 arcsec, the field stop on SIM) are immune to time dependent errors (all objects are observed simultaneously), the have very small field dependent errors. (arcsec versus 1 deg field of view) The main noise will be photon noise and random errors in the fringe measurement. Unfortunately photon noise is ~sqrt(2) of the total error for nominal targets (10 mag for narrow angle astrometry).
- Significant improvement over the nominal ~1 uas accuracy of narrow angle measurements are possible for multiple stars, only if the objects are significantly brighter than 10 mag. (or the astronomer is willing to spend a lot of integration time.)

Astrophysical Errors or

One person’s signal is another person’s noise

- Binary stars (for ref stars or grid stars)
- Planets around ref stars or grid stars
- Star spots (on target or ref stars)

- There is no one solution for all these problems
- Grid, ref stars
  - Extensive RV survey to eliminate all stellar companions and some planetary companions.
  - Solve for companion orbits
  - The issue of astrophysical noise on the grid has been the most studied, with detailed monte carlo simulations of binary and planetary companion’s effect on the grid’s accuracy after RV vetting of potential grid stars.
- Spots, photometric monitoring. Modeling the astrometric effects with multi-color astrometric measurements.

SIM Science Team

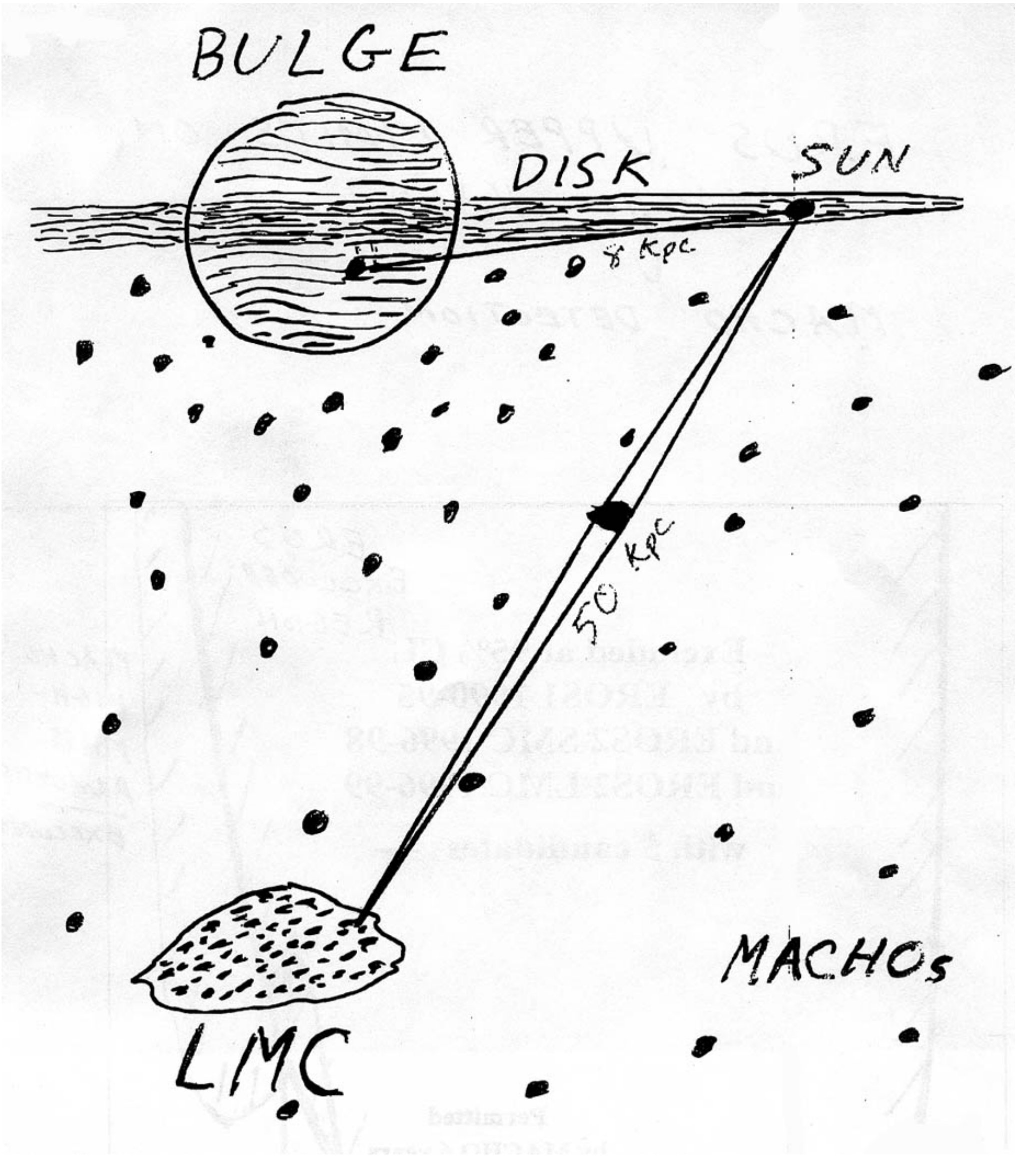
Key Science Projects

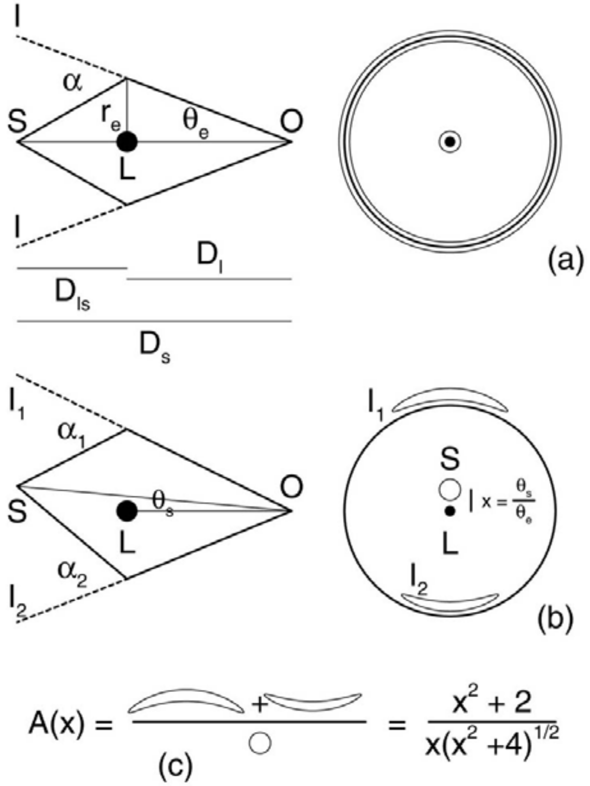
Names	Institutions	Topic
Dr. Geoffrey Marcy	University of California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corporation	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Cluster Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	NASA/JPL	Active Galactic Nuclei

Mission Scientists

Dr. Guy Worthey	University of Washington	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	University of California, San Diego	Data Scientist
Dr. Stuart Shaklan	NASA/JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	California Institute of Technology	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Institute	Synthesis Imaging Scientist

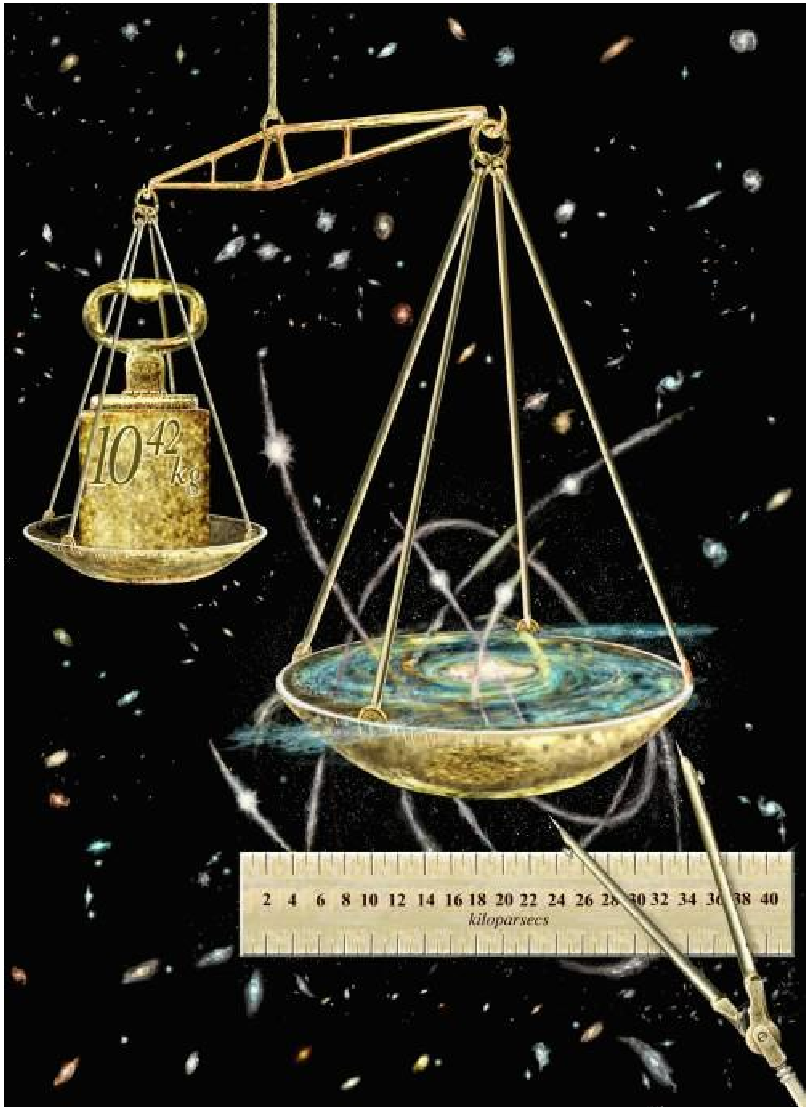
Galactic Structure from Microlensing



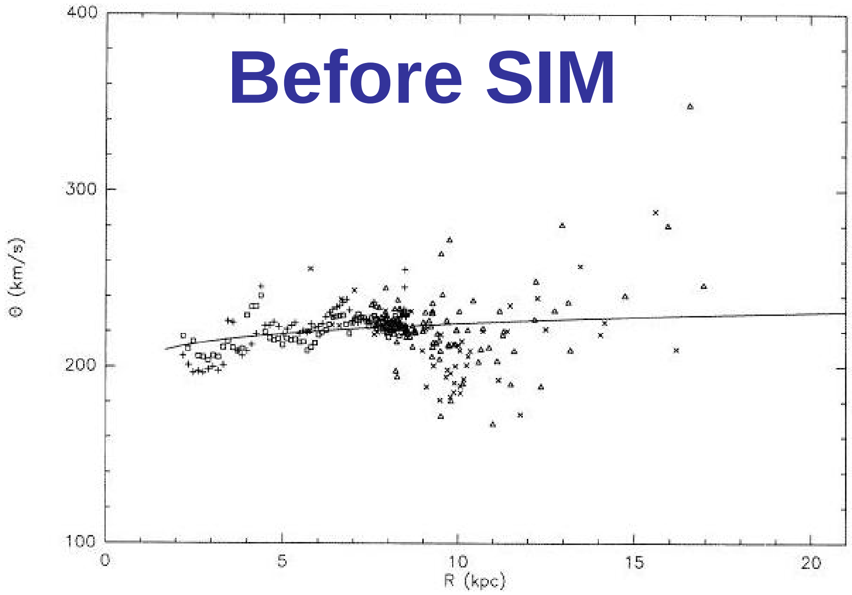


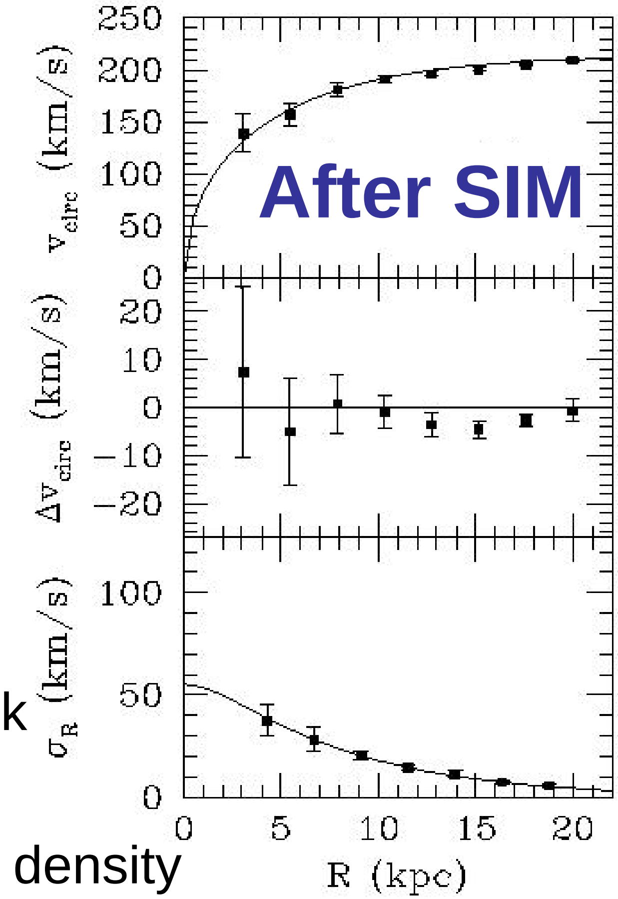
Taking the Measure of the Milky Way

- *Unique, legacy, measurements* of fundamental parameters of the Milky Way:
    - Mass scale → Total mass
    - Distance scale → Size
    - Dynamical scale → Rotation curve



Probe of Inner Galactic Potential



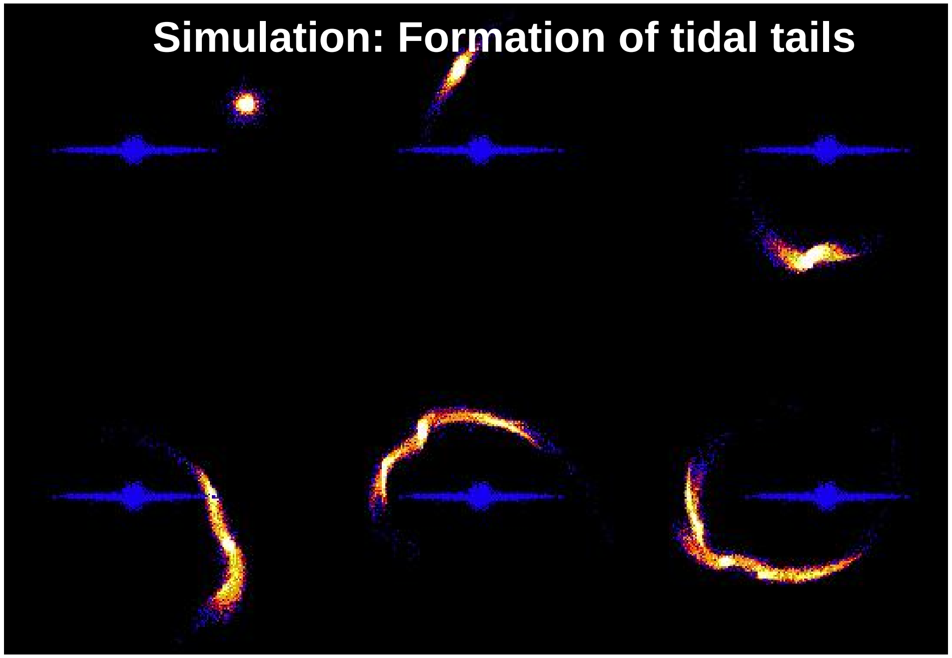


- SIM will measure:
  - Galactic rotation curve across entire disk
  - $V_{circ}(R) \rightarrow$ disk potential to 2-3% $\leq 2R_o$
  - Local mass volume density and column density
  - Amplitude, pattern speed, shape, wavelengths, phase for large non-axisymmetries:
    - bars, warps, spiral arms

Mass of the Galaxy (Dark Halo)

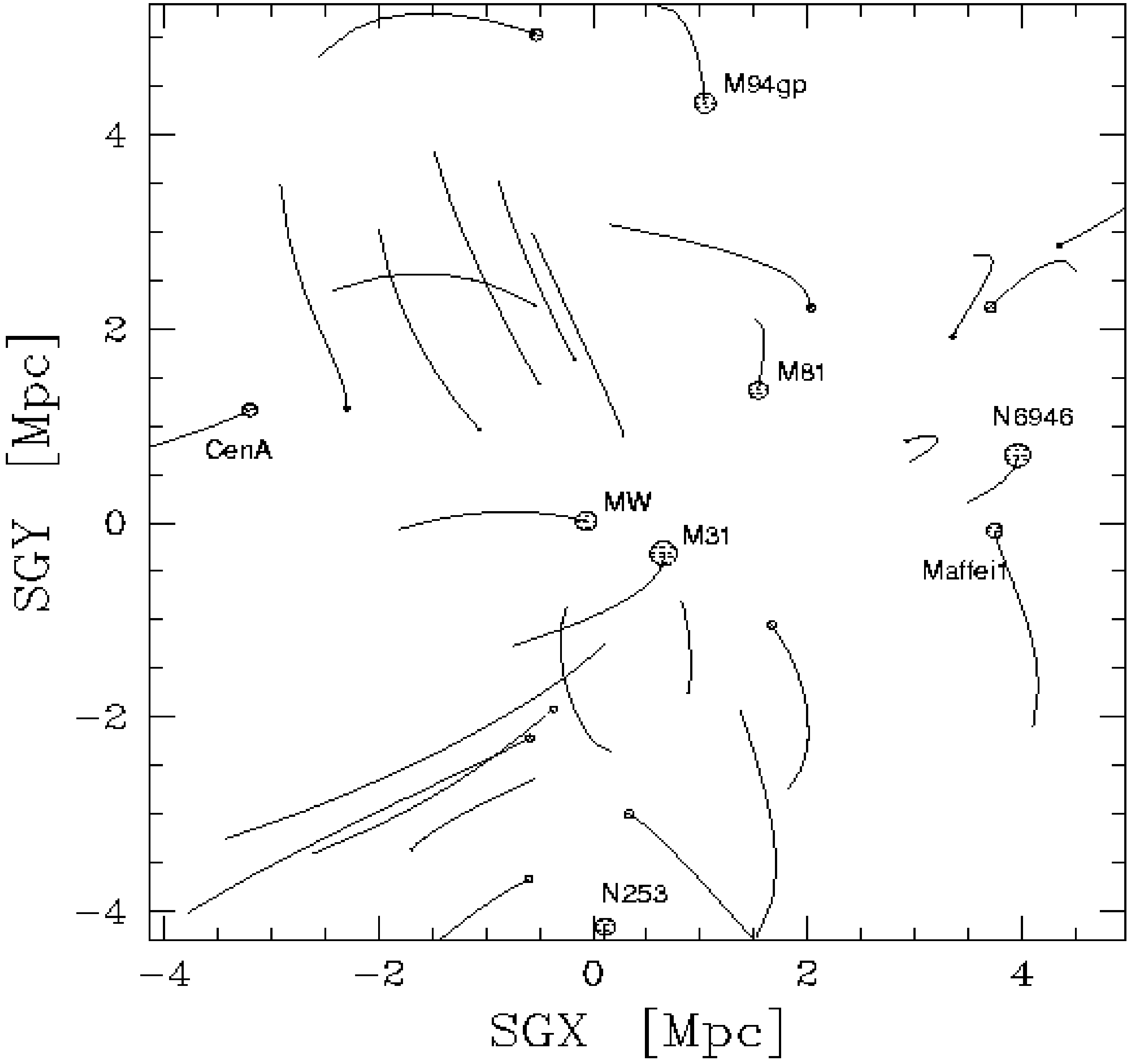
- SIM is the only means for obtaining precision velocities in outer Galaxy
- SIM can determine mass vs. radius to *R* > 200 kpc via complementary methods:
  - **Jeans Equation**: ~1000 random field giants, Galactic globulars and satellite galaxies
  - Stars in **tidal streams** (e.g., Sagittarius): Milky Way potential from true 3-D orbits

Polar ring galaxies:
proven gravitational laboratories



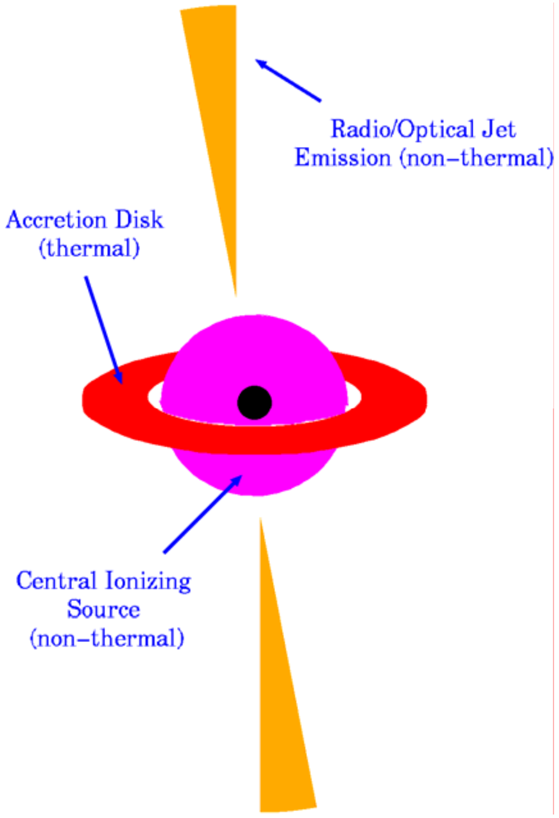
Simulation: Formation of tidal tails

Dynamics of the Local Universe



Physics of Active Galactic Nuclei

- Does the most compact non-thermal optical emission from an AGN come from an *accretion disk* or from a *relativistic jet* ?
- Do the cores of galaxies harbor *binary supermassive black holes* remaining from galaxy mergers ?
- Can AGNs be used to ‘anchor’ the SIM astrometric reference frame (the grid) ?



Stellar Astrophysics Goals

- Precise Masses and Luminosities
  - Open clusters
  - Selected classes of objects

- Population II Distance Scale
  - Ages of globular clusters
  - RR Lyraes as standard candles
  - MS turnoff stars and subgiants in the halo

- Dynamics
  - Black hole and RS CVn binary emission
  - Paths of neutron stars and OB stars