PRIMA and Next Generation VLTI Instrumentation

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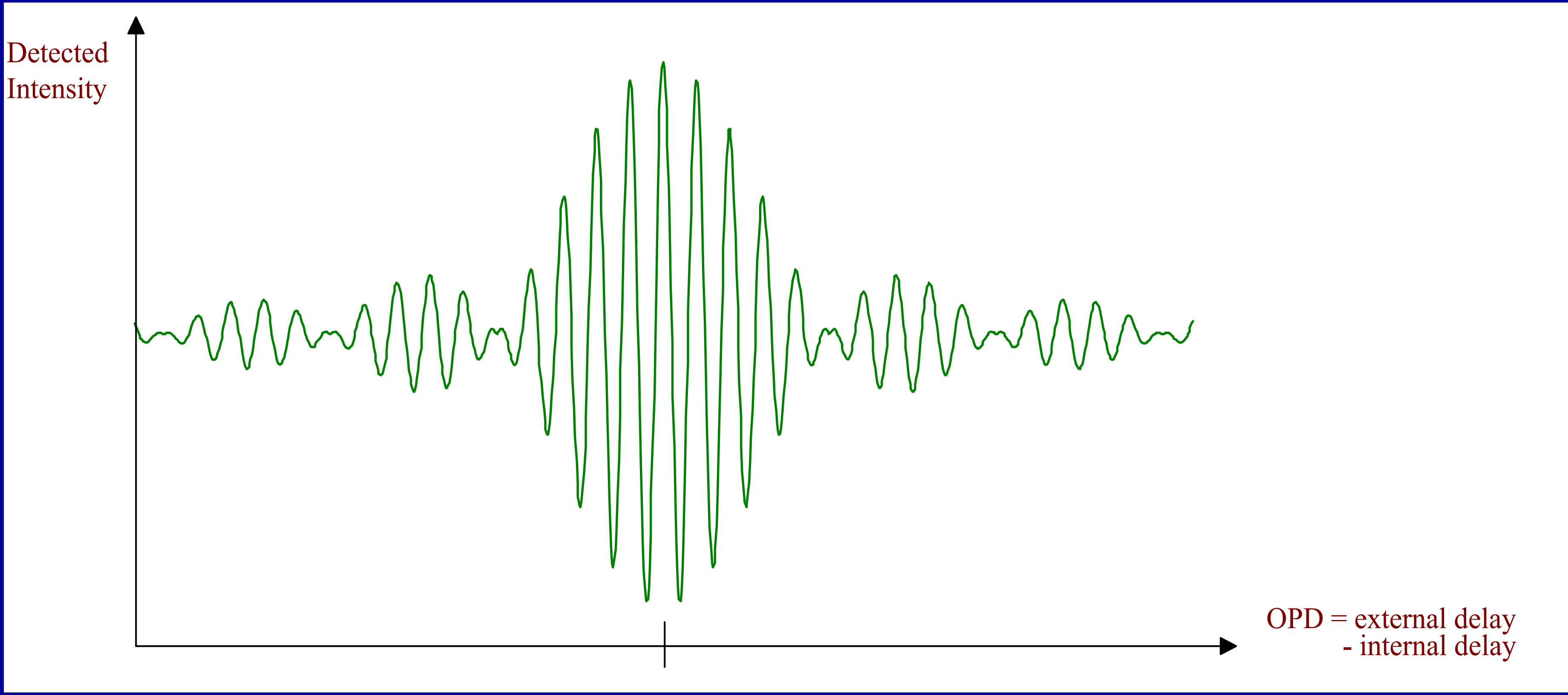
Scanning the Delay Line through the Fringe Packet



Fringe Scanning and Phase Coherent Interferometry

- VLTI currently uses scans through fringe packet for visibility measurements and delay line adjustments (coherencing)
- Planned fringe trackers will allow stabilization of fringes to better than 1 radian
  - Better sensitivity (no time lost off-fringe)
  - Enables many advanced interferometric techniques (astrometry, phase-referenced imaging, nulling, differential-phase measurements)

The Potential of Phase Referencing

- Astrometry
  - Limit set by atmosphere is 10 μas over 10″ arc
- Faint-source observations
  - Once array is co-phased, point-source sensitivity is similar to single large telescope
  - Needs nearby bright reference star
  - Fails on fuzzy objects
- Imaging of bright resolved objects
  - No need for baseline bootstrapping

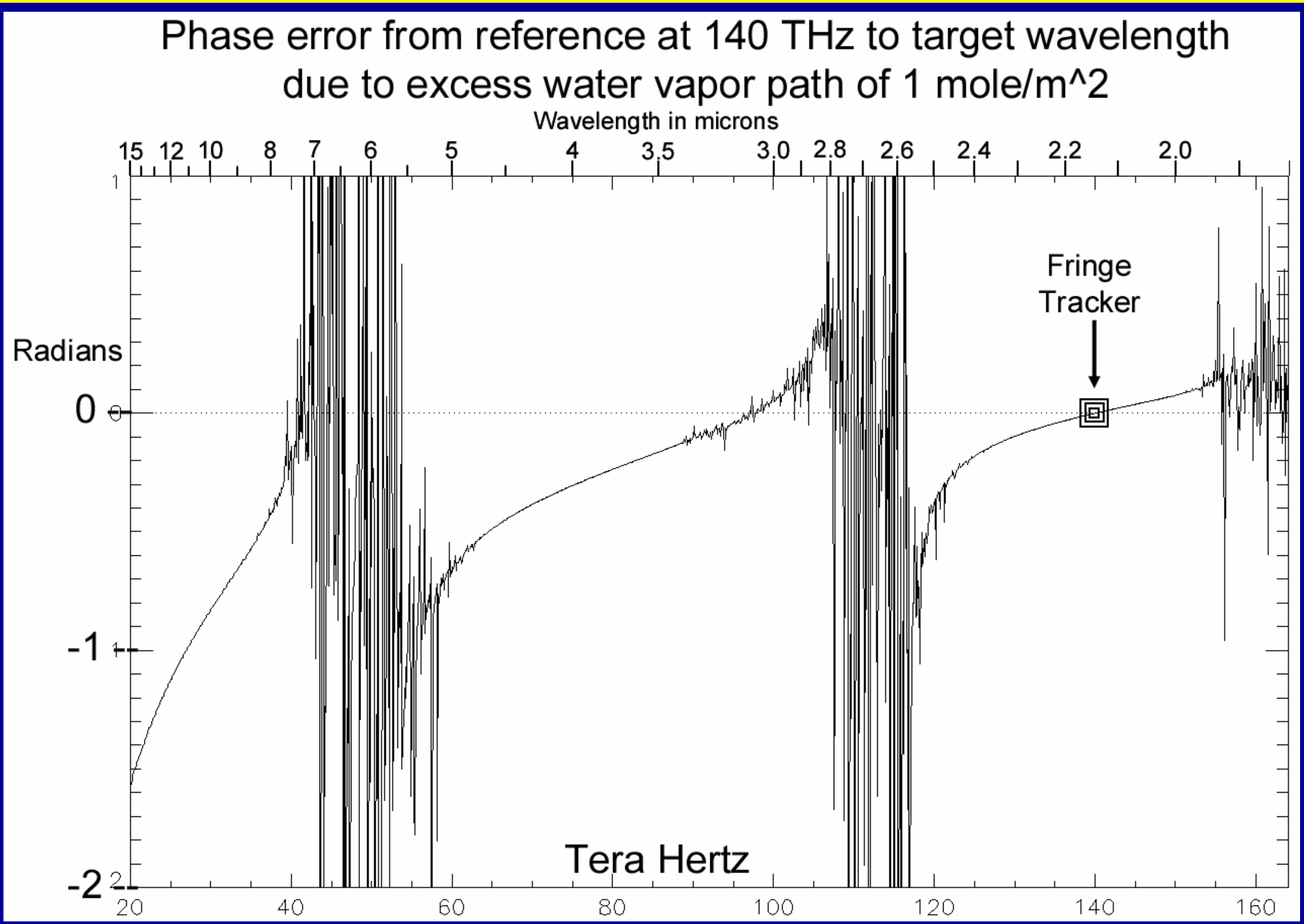
Scientific Drivers of Faint-Source Interferometry

- Obscuring tori and emission line regions in Active Galactic Nuclei
- Faint binaries (X-ray binaries, cataclysmic variables)
- Clusters (globulars, Galactic Center etc.)
- Circumstellar environment of young and very old stars
  - At 10µm, many of them are too faint for fringe tracking, but may be self-referenced in K band
- Stars in external galaxies (including LMC)

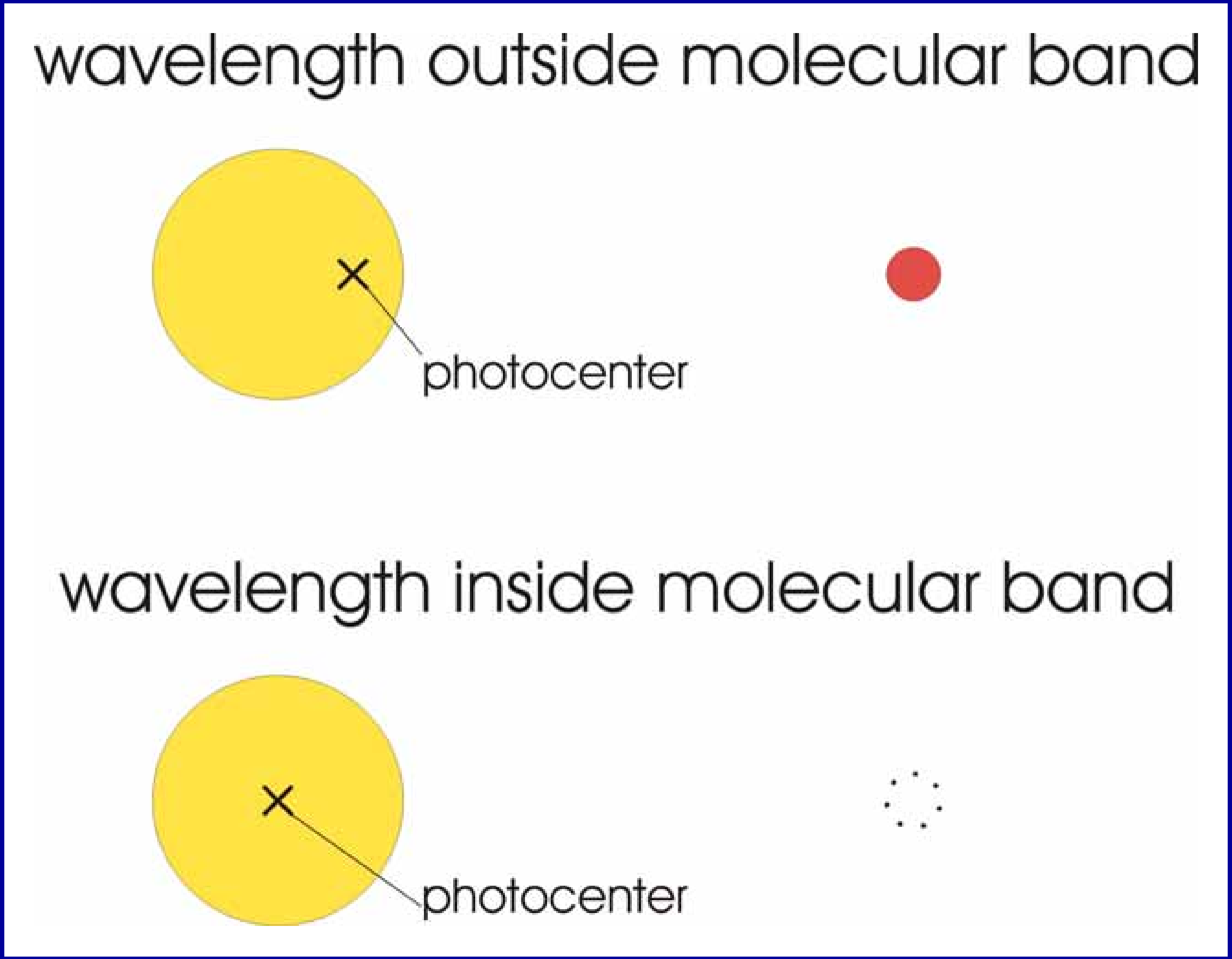
Coming to Terms with Dispersion

- Random OPD fluctuations (turbulence with zero mean) are not completely achromatic
  - Dispersion of dry air
  - Water vapor dispersion (important in the infrared)
  - Pressure balance limits dry air fluctuations $\Rightarrow$ relative fluctuations of water vapor are larger
- Air delay lines cause systematic delay-dependent dispersion
  - Decorrelation of referenced visibilities
  - Systematic astrometric and phase errors

Dispersion of Water Vapor (Courtesy Jeff Meisner)

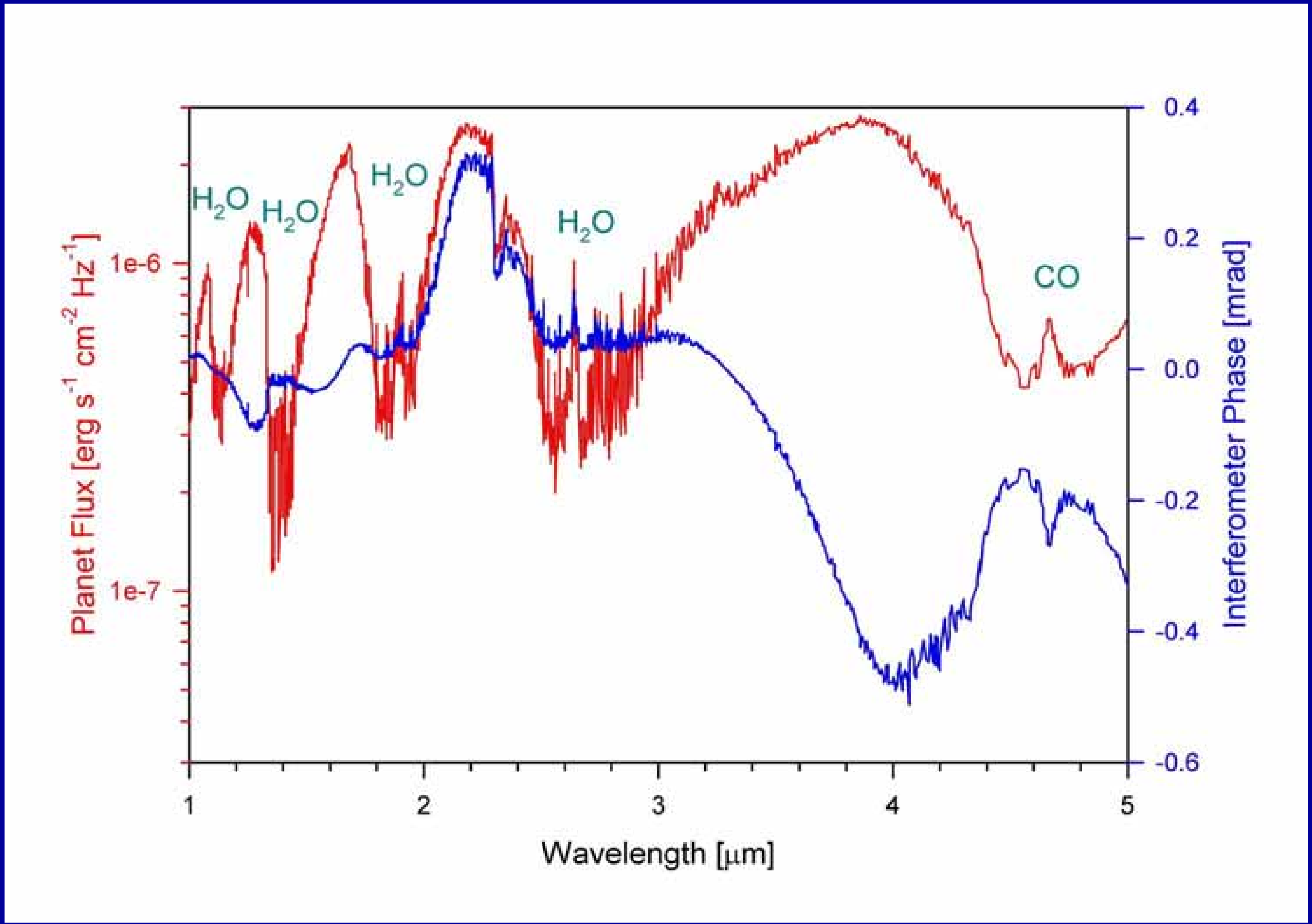


The Principle of Differential Phase Interferometry



Need about 0.1 mrad phase accuracy for hot Jupiters

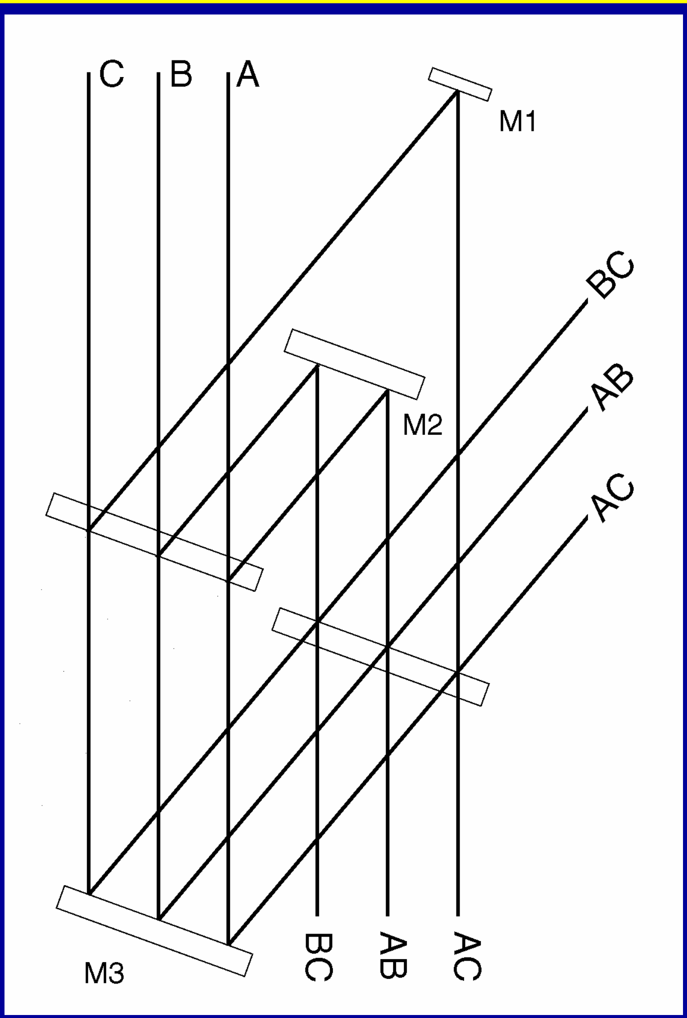
Model Spectrum of 51 Peg B, and Phase on 100 m Baseline

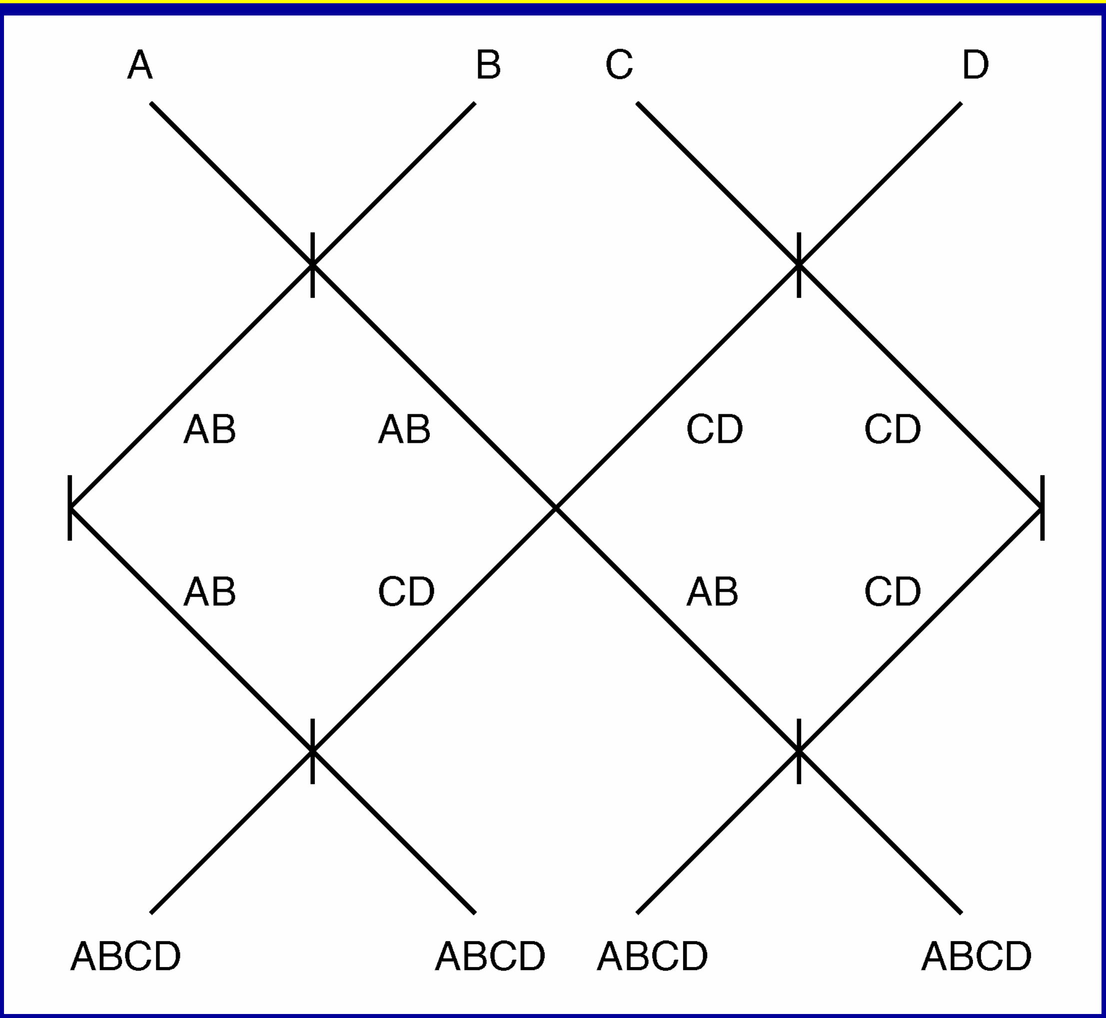


Multi-Telescope Closure-Phase Imaging

- Currently four UTs and four ATs funded, but only one three-way instrument (AMBER)
- Six-way or eight-way beam combination is a logical next step
- Proven concept with bulk optics, low risk
  - Integrated optics is a promising alternative
- Strong scientific potential on short time scale
  - Circumstellar disks
  - Stellar surfaces

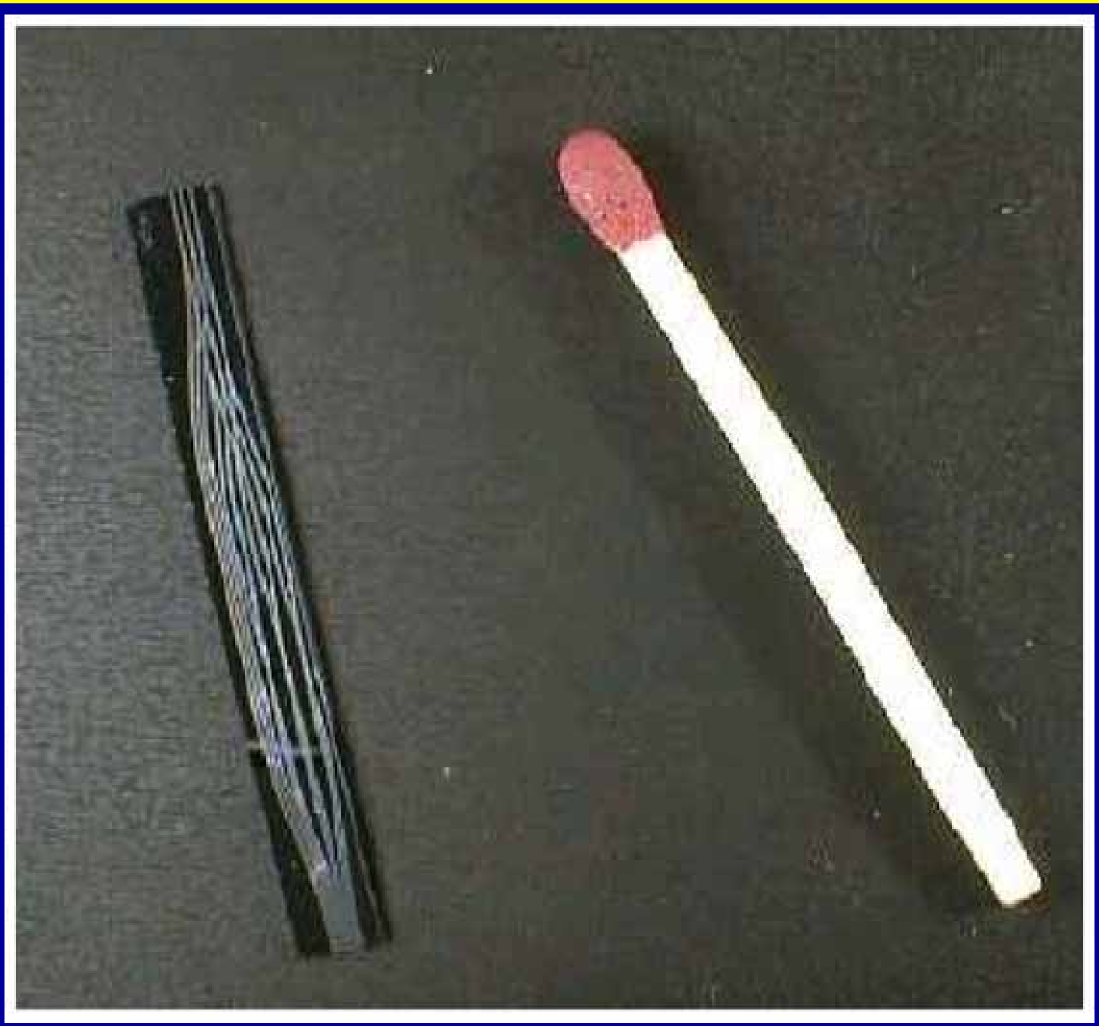
Multi-Baseline Pupil Plane Beam Combination





NPOI Six-Way Beam Combiner

Integrated Optics Three-Way Beam Combiner



Produced by LETI with silica-on-silicon etching technique

Extending the Wavelength Range

- MIDI extension to 20 μm (in progress)
- Current gap between 2.2 μm and 10 μm could be filled by GENIE (depends on trade-offs)
- Good reasons to go to visible wavelengths
  - Higher angular resolution
  - Stronger emission lines
- Adaptive optics requirements are demanding
  - $d\,/\,r_0$ in visible at ATs similar to near-IR at UTs
  - But faster (by $\lambda^{6/5}$) and fewer photons (by $\lambda^{18/5}$)

Four-Telescope Combination in the Mid-IR (10 and 20μm)

- Compelling scientific drivers
  - Mass-loss and dust formation in AGB stars
  - Disks of young stellar objects
  - Geometry of obscuring material in Seyfert nuclei
- Takes advantage of a unique capability of the VLTI (4 large telescopes)
- Does not depend much on adaptive optics
- Logical successor of MIDI

Interferometric High-Resolution Spectroscopy

- Combination of interferometry with high-resolution spectroscopy is very powerful
  - Limb darkening profiles in absorption lines $\rightarrow$ tests of stellar atmospheres, calibration of projection factors in Cepheid measurements
  - Phase shift across absorption lines $\rightarrow$ orbits of very close binaries, direct measurement of stellar rotation
  - Surface structure of chemically peculiar stars
  - Trace shocks in Mira atmospheres
- Need $R \approx 20{,}000 \ldots 100{,}000$

Can We Take Advantage of the VLT Instrument Suite?

- Building VLTI instruments from scratch is time-consuming and expensive
- Feeding existing VLT instruments with fibers from interferometer lab is an attractive alternative
- Prime candidates for this approach are the high-resolution spectrographs UVES and CRIRES (R up to 100,000 in visible and near-IR)

Interferometric Modes for CRIRES and UVES

- VLTI will have fringe tracking units soon $\Rightarrow$ phase-stable output beams available
- Construct beam combiner that outputs four signals (fringe at 0º, 90º, 180º, 270º)
- Feed these four signals to UVES and CRIRES with fibers (no phase-stability required after beam combiner)
- For spectrograph, interferometric mode is "transparent" (signal looks like four stars)

CRIRES-I and UVES-I

- Current UVES spectrograph can be fed by 8 fibers for multi-object spectroscopy $\Rightarrow$ similar fiber feed from the VLTI (2 baselines at a time)
- CRIRES fiber feed can be integrated in calibration unit
- Beam combiner table is the only hardware needed in interferometry lab $\Rightarrow$ uses little real estate
- No new detector, electronics, dewar, …

Polarimetry with the VLTI

- Polarization carries a lot of information, in particular about scattering processes
- Polarized signal frequently increases with angular resolution
  - E.g. stellar limb, averaged out in integrated light because of symmetry
- Many oblique reflections in beam path $\Rightarrow$ high instrumental polarization
- Polarimetric interferometry has never been tried seriously (some experiments at MkIII, NPOI, GI2T)
  - Modeling of VLTI is better than for any other interferometer
  - Opportunity for a unique niche

The Case for Wide-Field Interferometric Imaging

- Mostly fields consisting of many point sources
  - Extended emission has a surface brightness problem
- Physical properties of stars in clusters
  - Requires interferometric spectroscopy
- Motions of stars in clusters
  - Requires astrometric integrity of imaging system
- Prominent example: Galactic Center cluster
  - Mosaicing of $10'' \times 10''$ field is possible only if instantaneous field is at least $2'' \times 2''$

Challenges of Wide-Field Interferometry

- Near-IR detector real estate and performance (need 2048 × 2048 pixels at fairly fast read rate)
  - Spectroscopic mode difficult to implement
- Output pupil of interferometer must be scaled replica of input pupil (“homothetic mapping”)
  - Tight tolerances
- Distortions compromise astrometric integrity
  - Variable curvature mirror in delay line focal plane is hard to calibrate

Interferometric Astrometry

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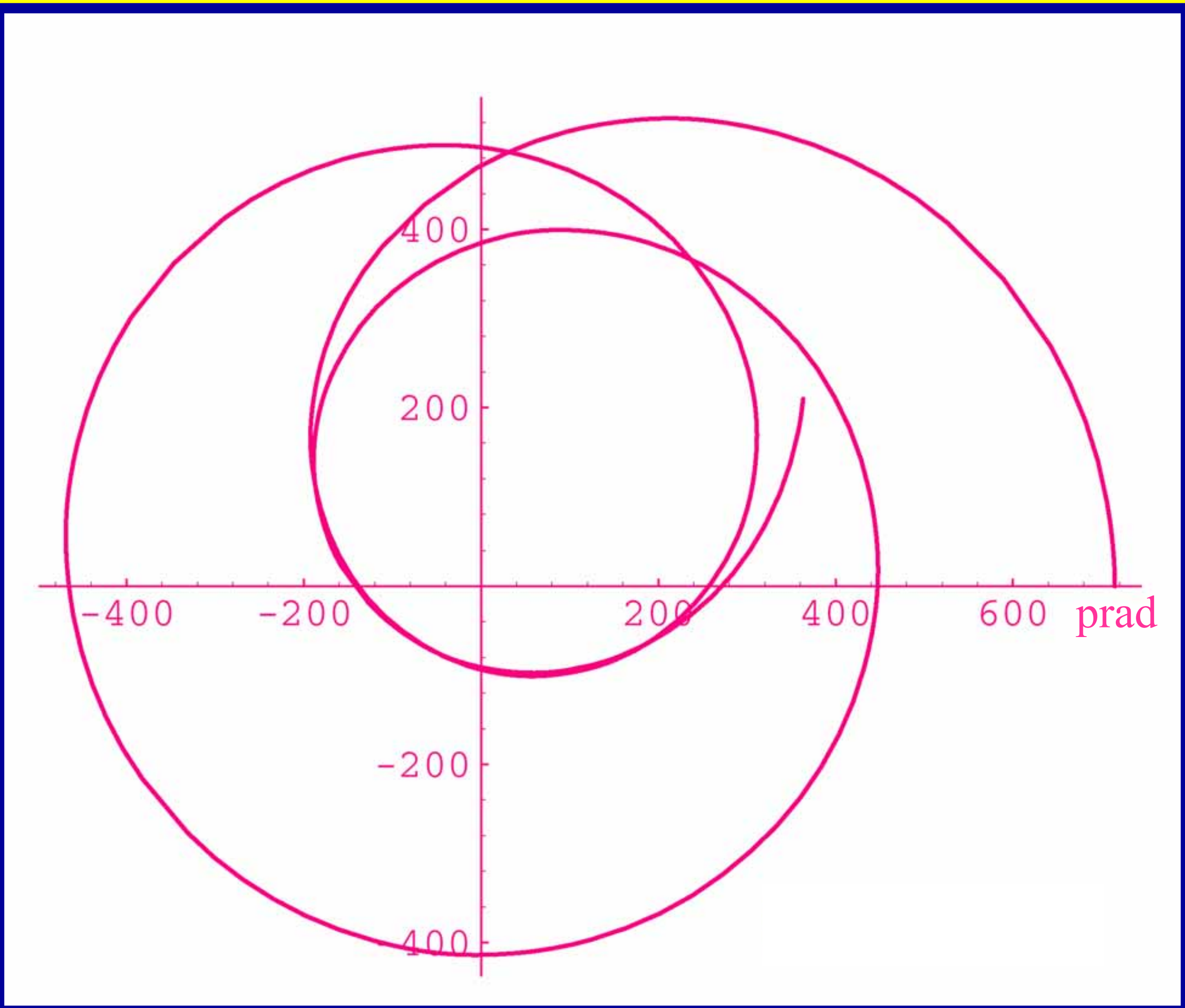
Motion of the Sun, Viewed Pole-on from 100 pc

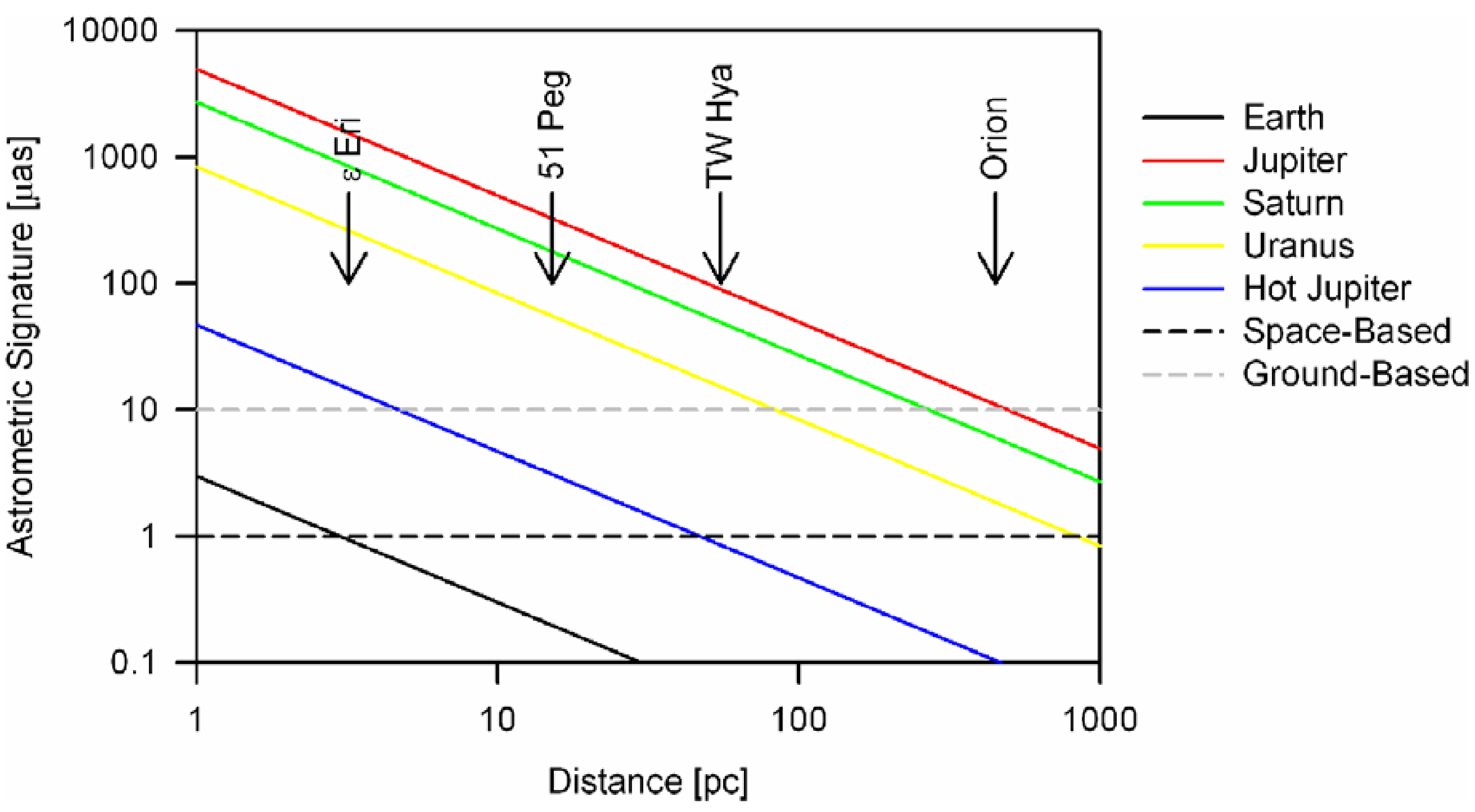


Amplitude:

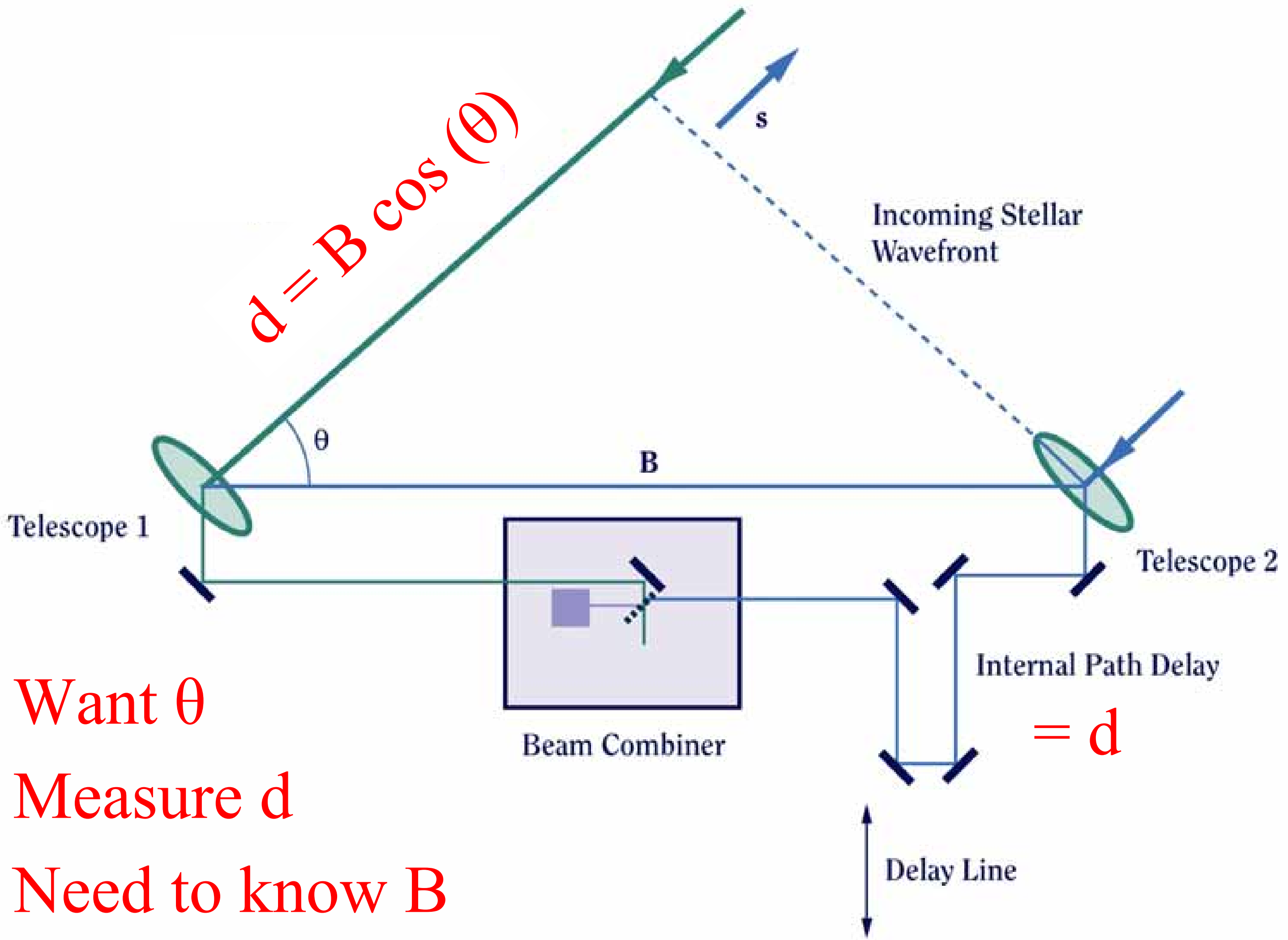
500 pico-radians

100 micro-arcsec

Requirements for Astrometric Planet Detection



Astrometric Measurement with an Interferometer

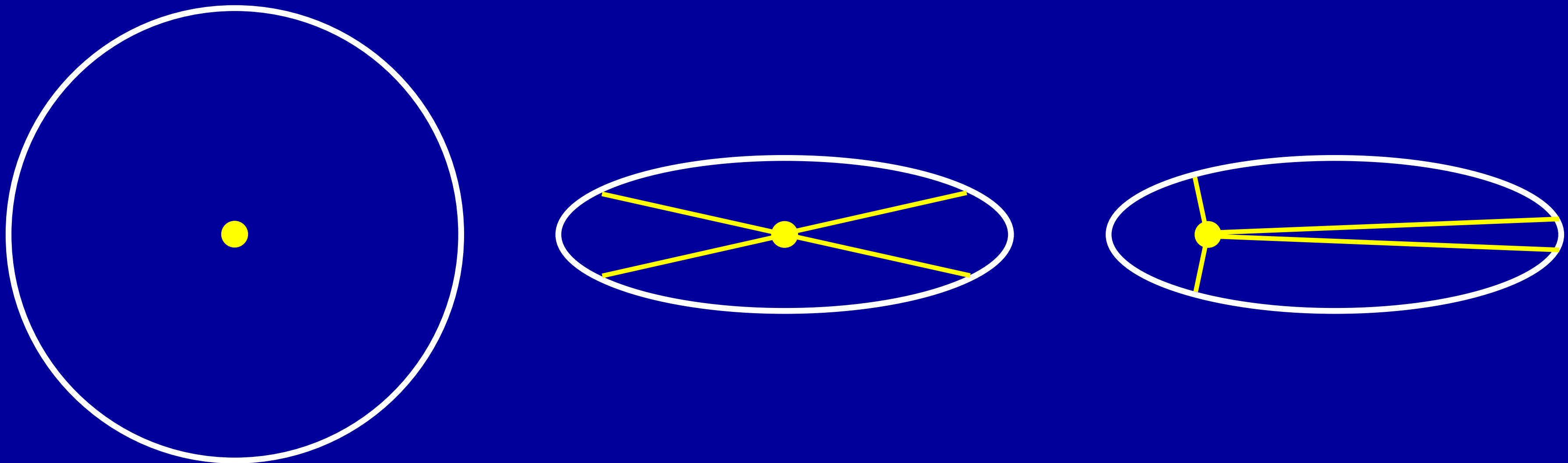


Want θ

Measure d

Need to know B

Deriving Inclination from Astrometric Observations

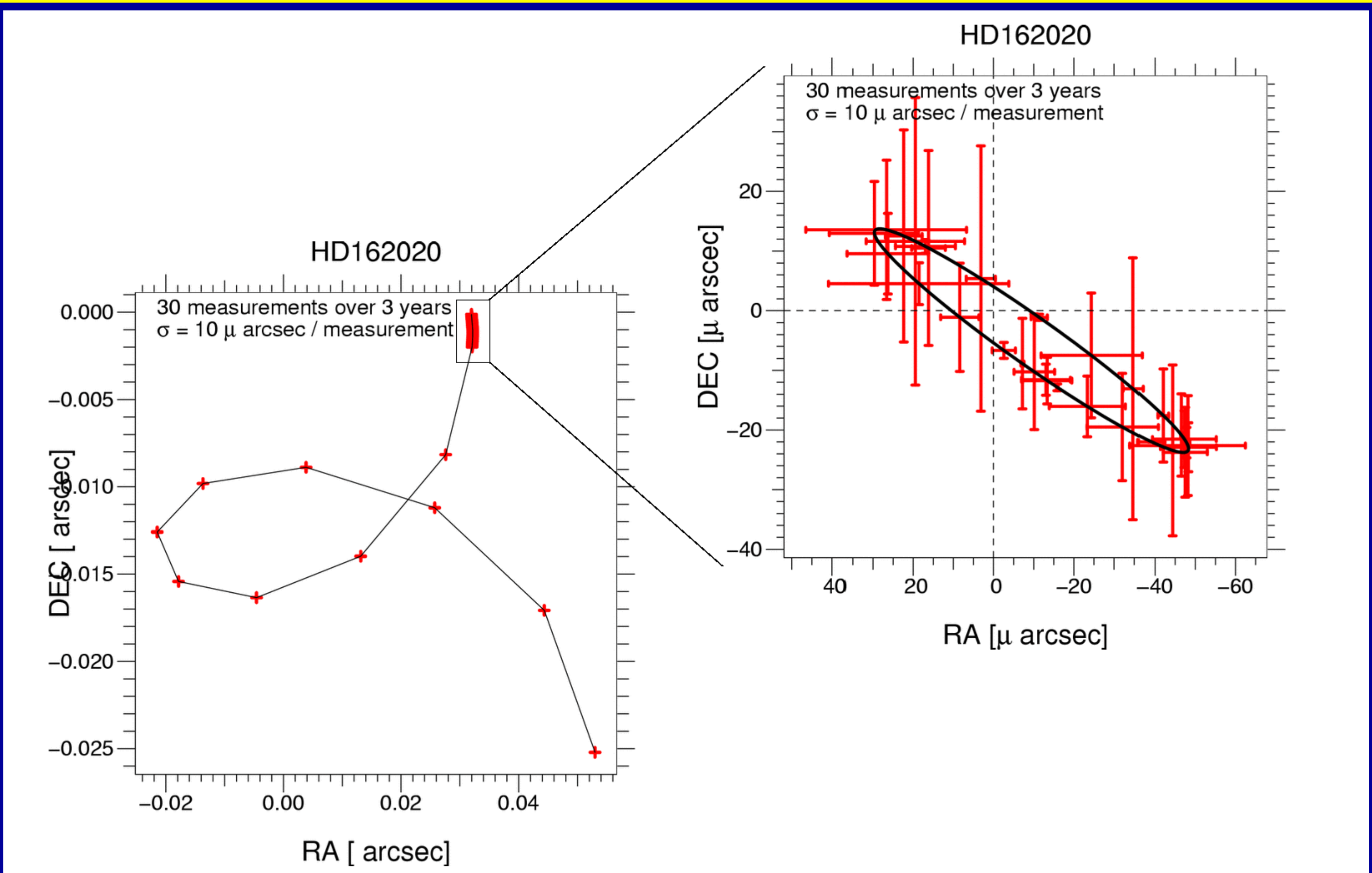


Circular Orbit Face-on	Inclined Circular Orbit	Elliptical Orbit Face-on

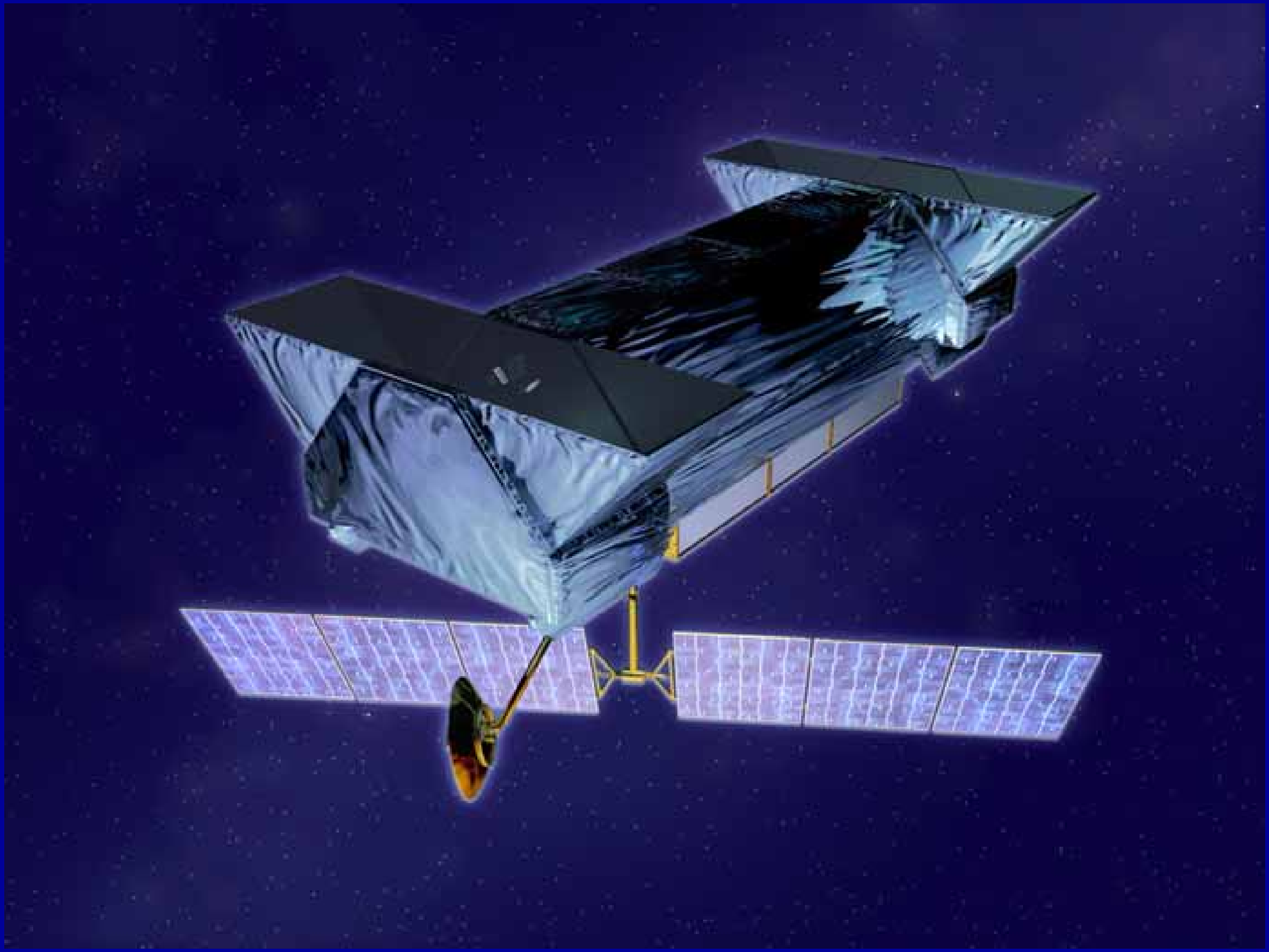
Goals of Astrometric Planet Surveys

- Accurate mass determination for planets detected in radial-velocity surveys (no sin *i* ambiguity)
- Frequency of planets around stars of all masses
  - Relation between star formation and planet formation
- Gas giants around pre-main-sequence stars
  - Time scale of formation, test formation theories
- Coplanarity of multiple systems
  - Test interaction and migration theories
- Search for Solar System analogs
  - Detection of icy or rocky planets

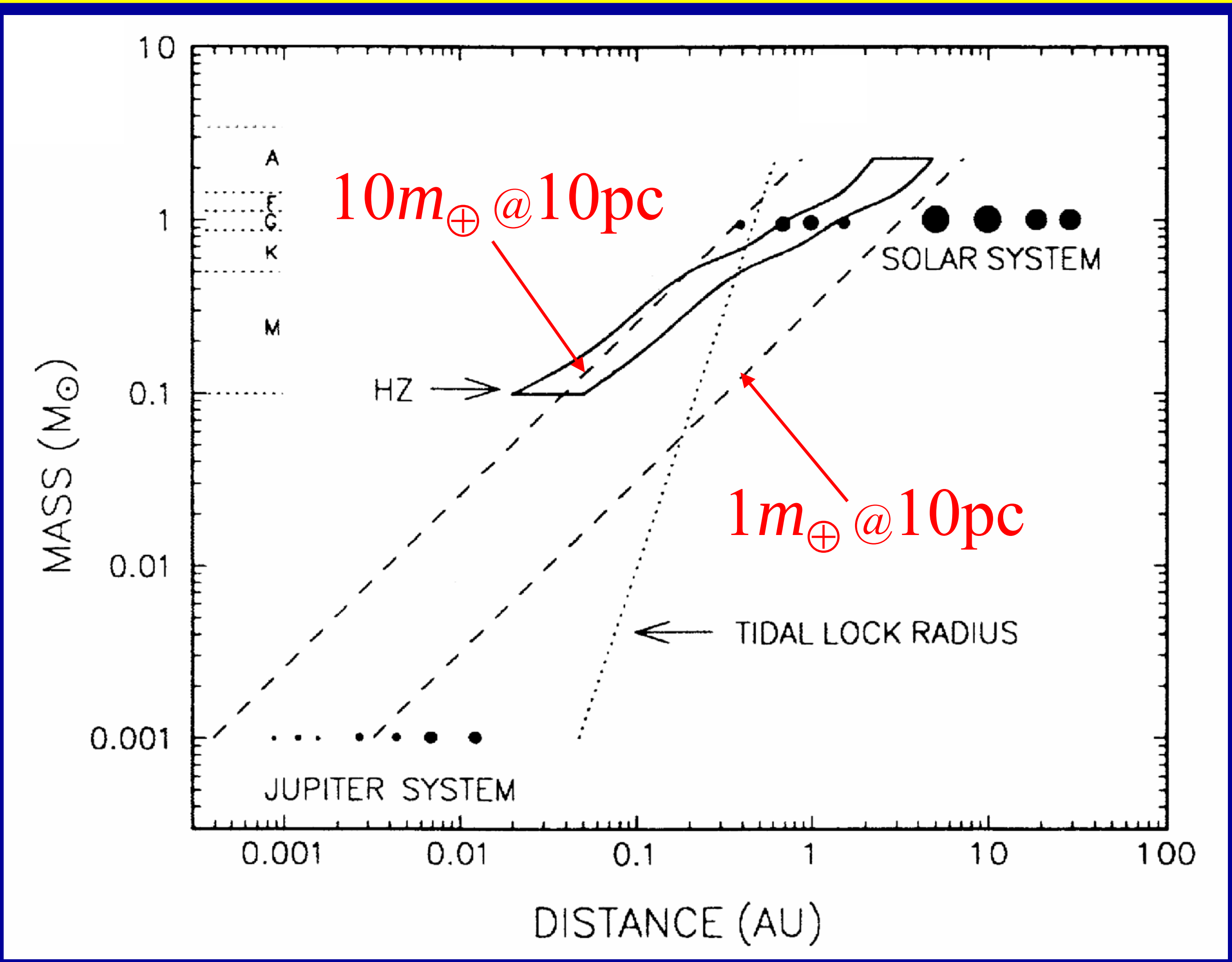
Simulation of Planet Observations with the VLTI



The Space Interferometry Mission (SIM, NASA 2009)

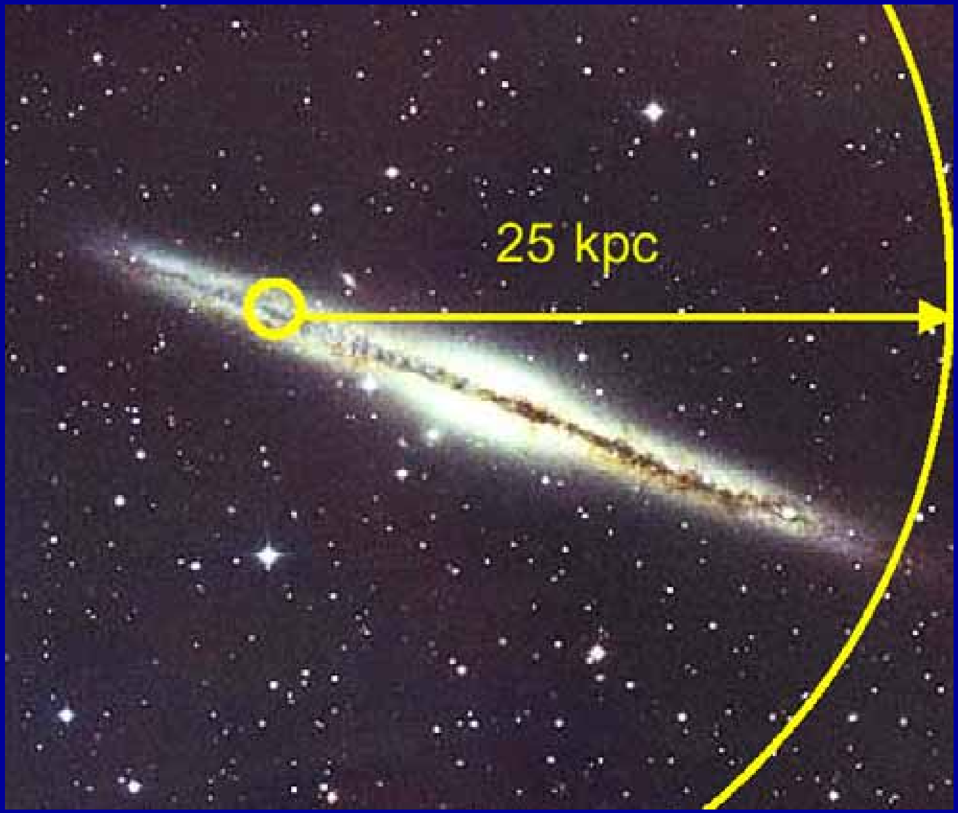


Planet Detection Capability
1 µas Astrometric Sensitivity



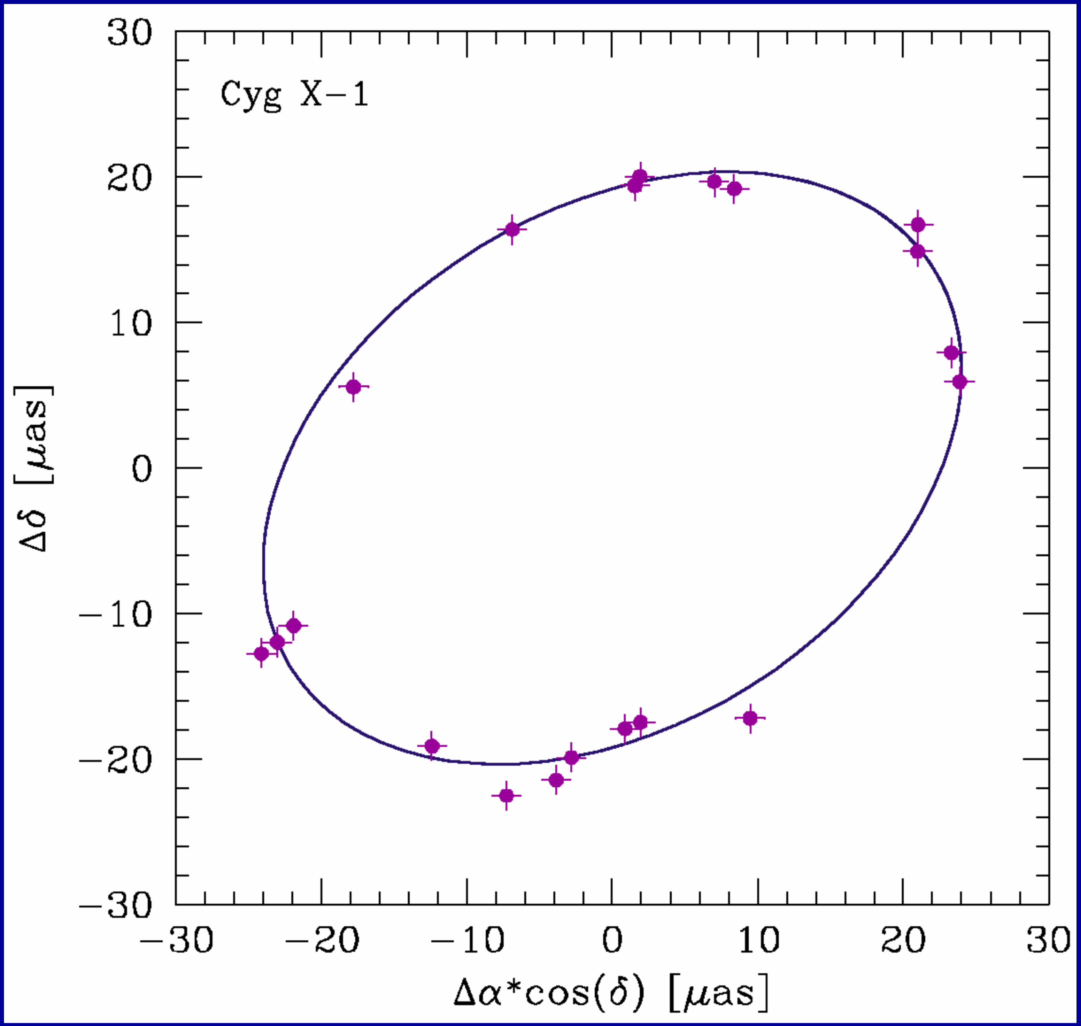
Distances in the Galaxy

- Distance calibration of Cepheids and RR Lyrae stars
- Ages of globular clusters and metal-poor stars
- Luminosities of neutron stars and black hole candidates



10% accuracy at 25 kpc

Simulated SIM Observations of the X-Ray Binary Cyg X-1

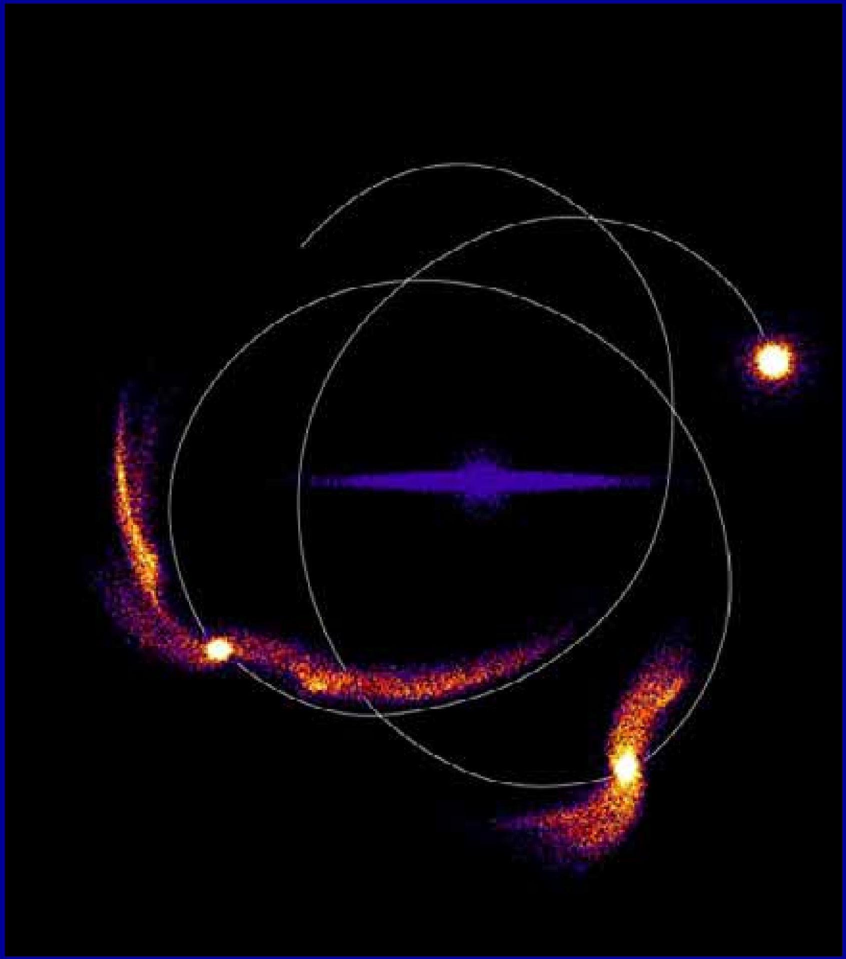


X-Ray Binary Science with SIM

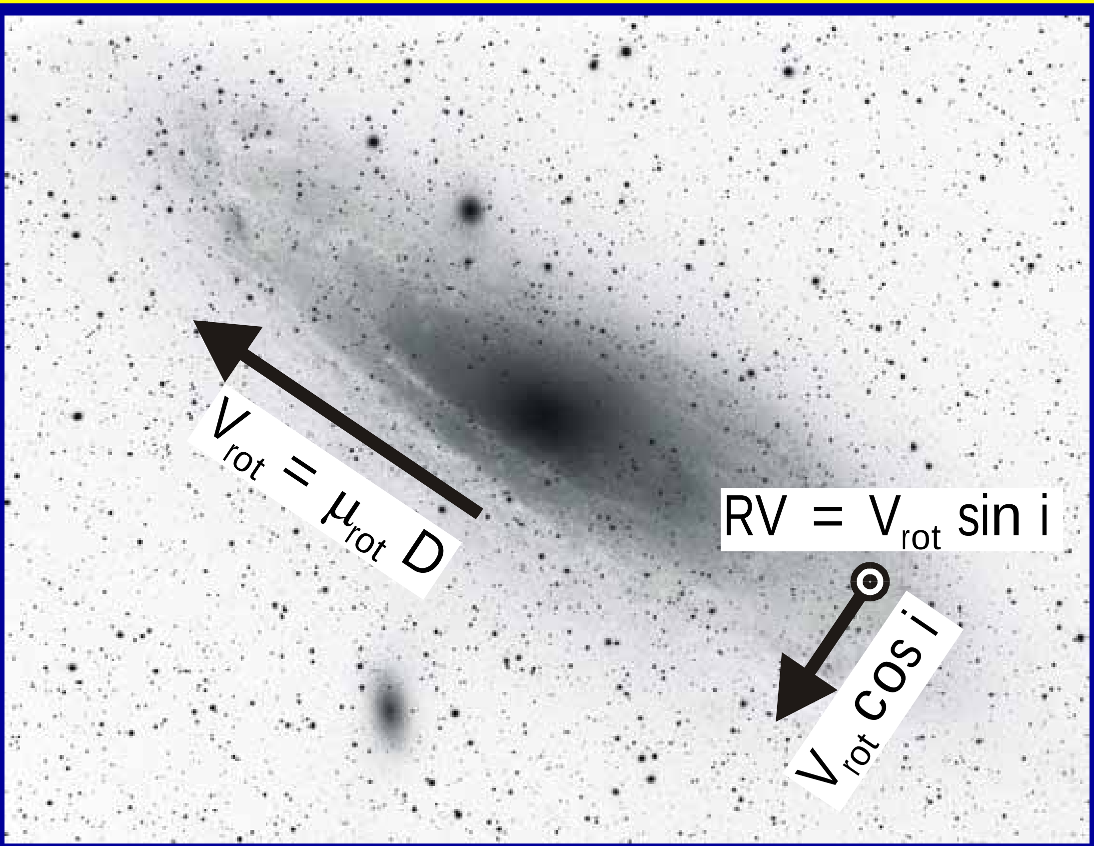
- Mass function of Black Hole Candidates
- Mass of Neutron Stars: constraints on nuclear equation of state
- Luminosities from parallaxes: test of models (existence of event horizon in Black Hole Candidates, Advection-Dominated Accretion Flow models)

Measuring the Potential of the Galaxy

- Dwarf galaxy is disrupted in potential of the Galaxy
- Measure 6-dim phase space for stars in coherent structures (debris tails)
- Integrate orbits backwards $\Rightarrow$ must retrieve compact dwarf galaxy
- Adjust assumed galactic potential until this is achieved

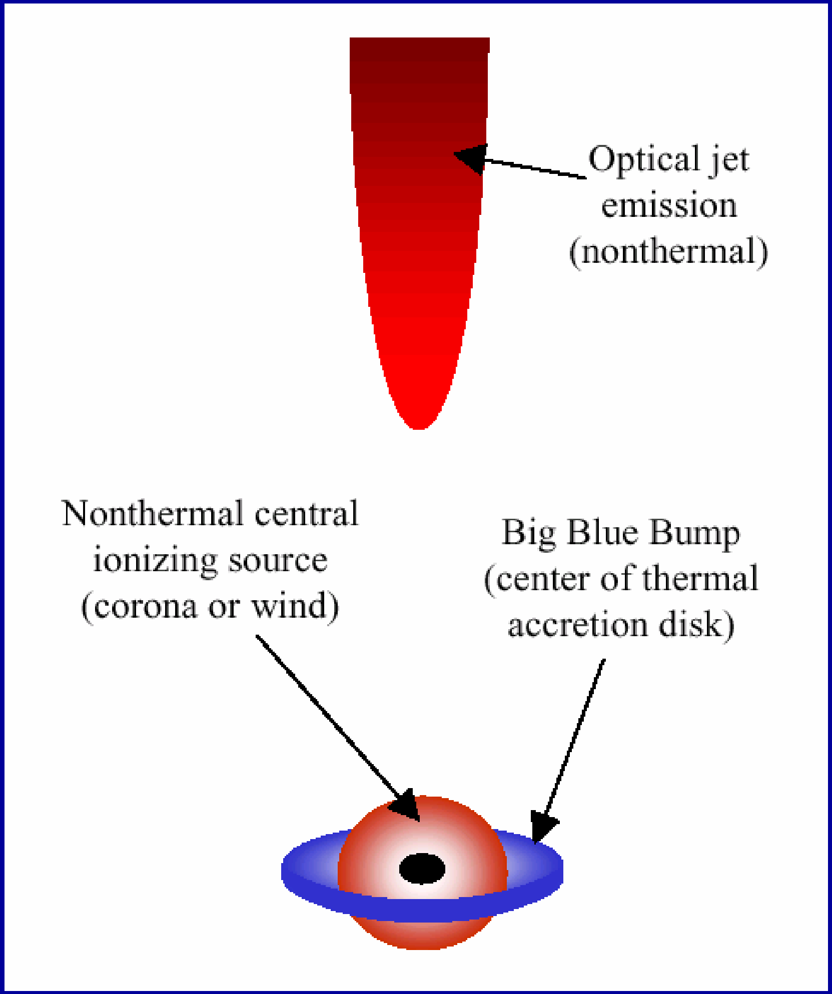


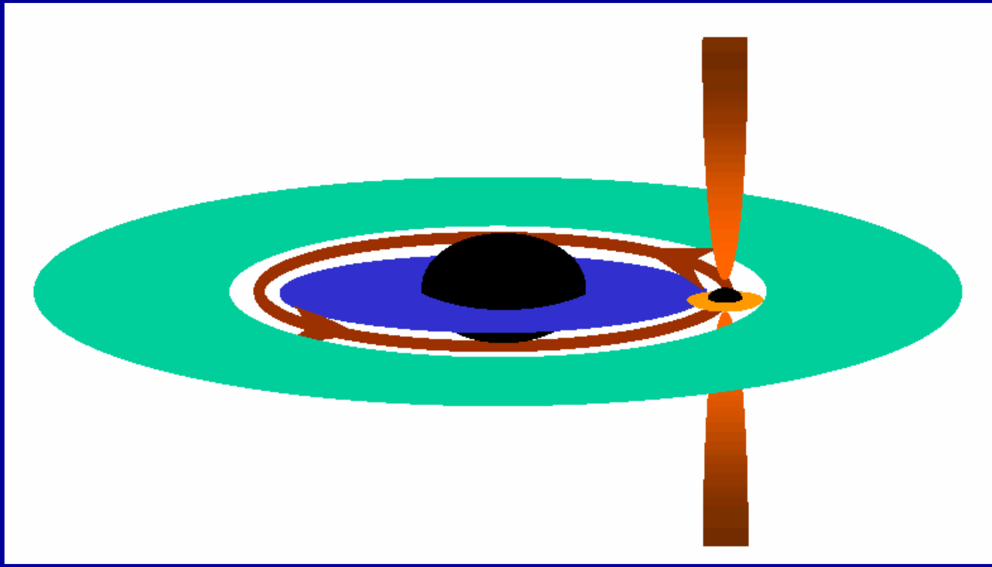
Rotational Parallax ⇒ Distance to Andromeda



- Observe radial velocity, two proper motions
- Solve for D, i, and V_{rot}

“Motion” of Quasars





Priorities for the VLTI (My Personal Opinion!)

1. Science with the first-generation instruments
   - Environment and mass-loss of young and old stars
   - A few Active Galactic Nuclei
2. Develop phase-coherent methods
   - Astrometry and Phase-referenced imaging
   - Nulling
3. Complete the full VLTI array
   - Second-generation instruments
   - Full complement of 8 ATs and 8 delay lines
   - Dual-star modules and AO at all telescopes

Summary: Concepts for 2nd-Generation Instruments

- Multi-telescope near-IR imager
- UVES-I
- Four-way mid-IR instrument (MIDI successor)
- Interferometric polarimeter
- Wide-field imager (homothetic mapping)
- Facility upgrades
  - Vacuum delay lines
  - STJ-based fringe tracker
  - Visible-light adaptive optics