Past and Future Impact of Interferometry

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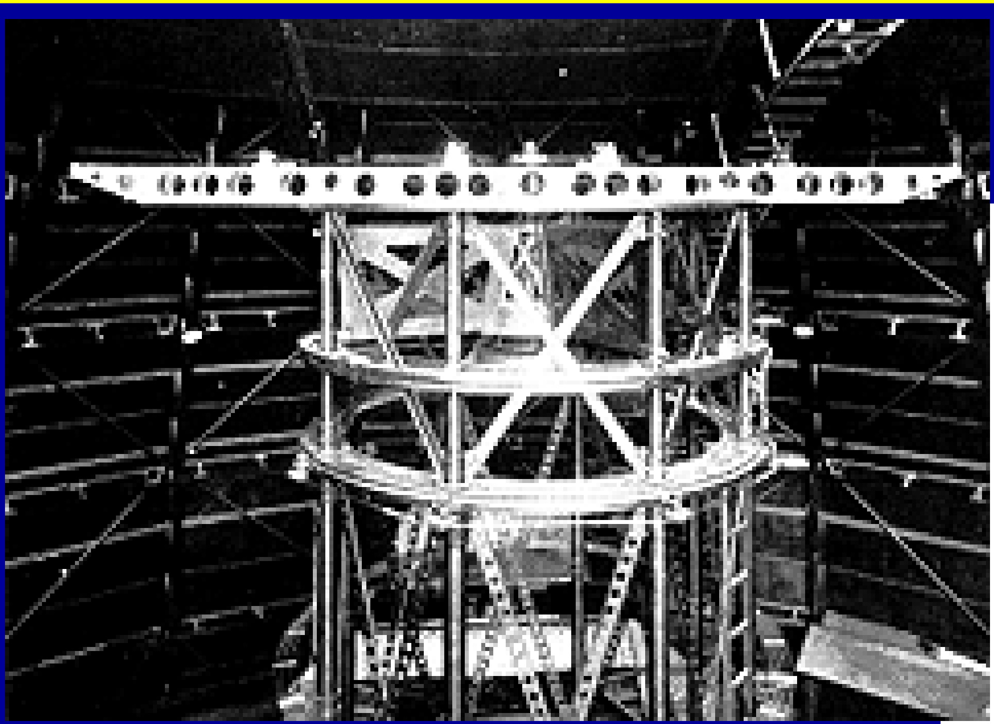
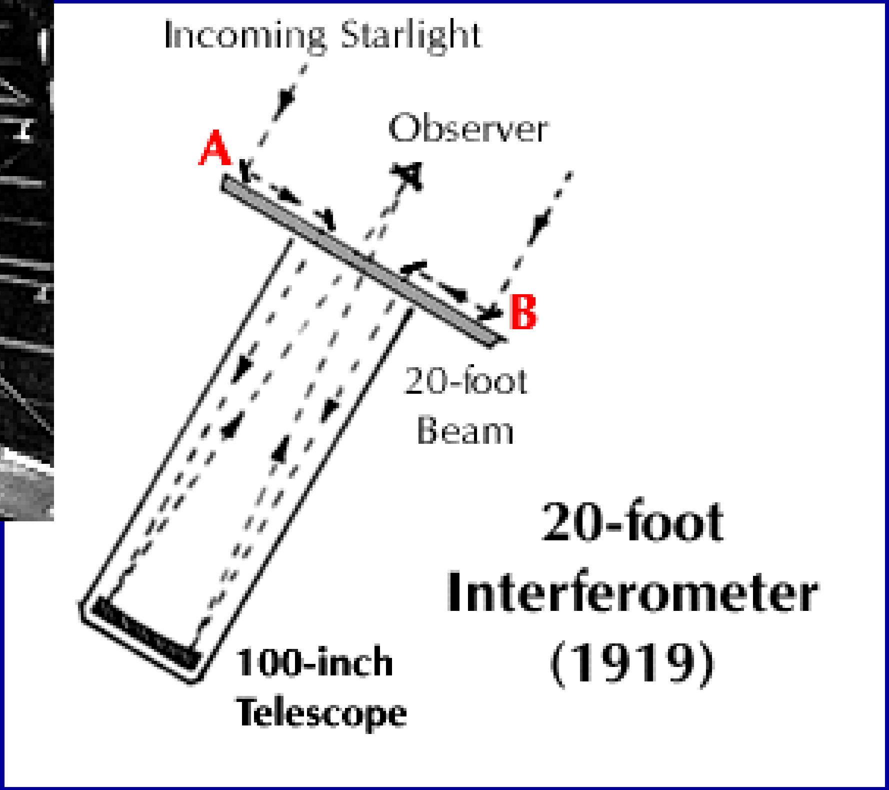
The VLT Interferometer

Why Build a Stellar Interferometer?

- To overcome the resolution limitations of conventional telescopes
- To measure the brightest and nearest stars
  - Angular diameters
  - Binary star orbits
  - Limb darkening
  - Stellar surface structure
  - Stellar positions and proper motions
  - Detection of planets
- To constrain theoretical models that describe stellar astrophysics.
- In the near future: also fainter objects (AGN etc.)

Michelson's 20 Foot Interferometer on Mt. Wilson





Observing in the Old Days

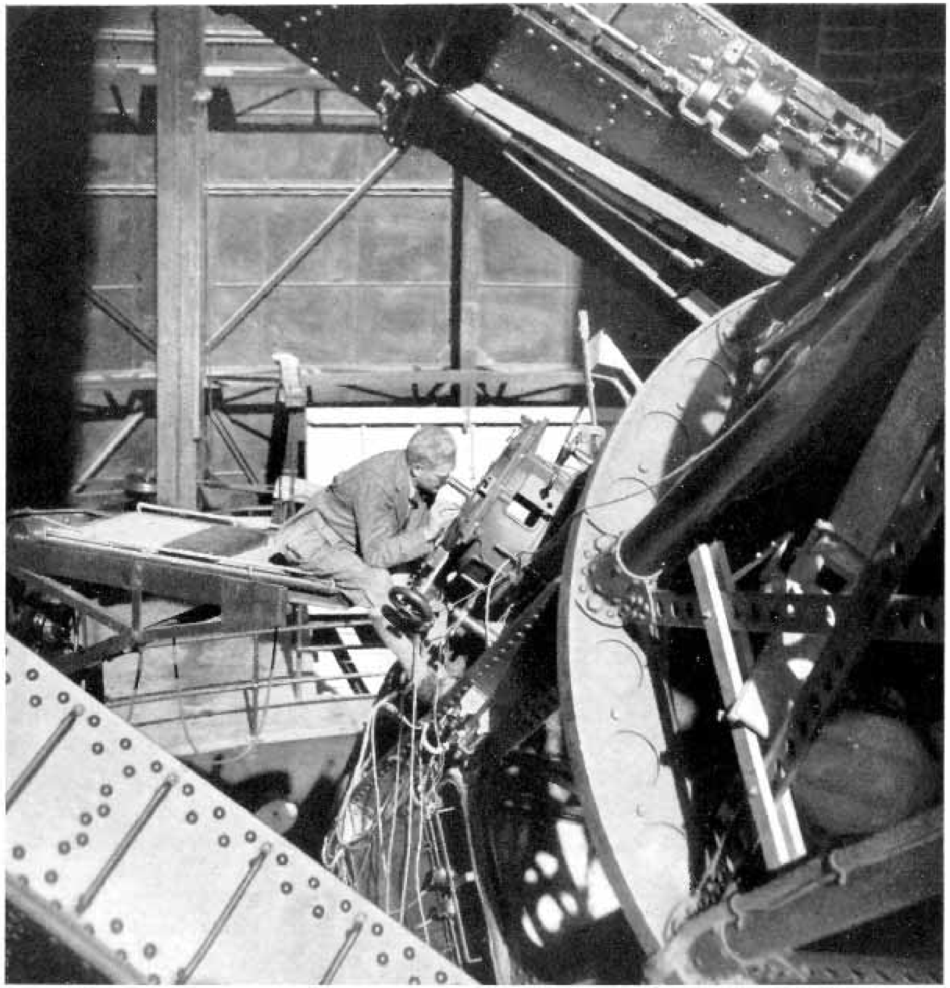
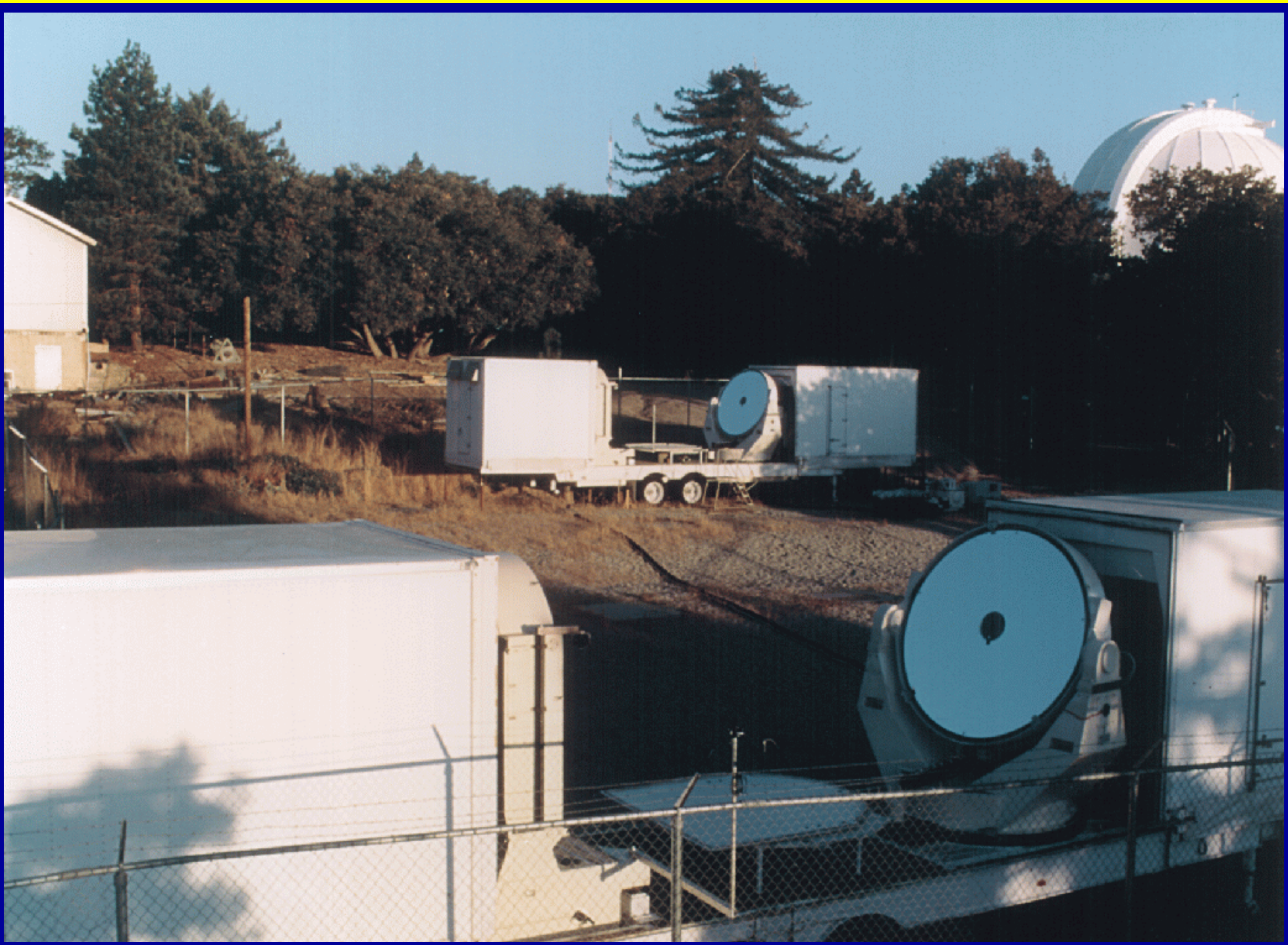
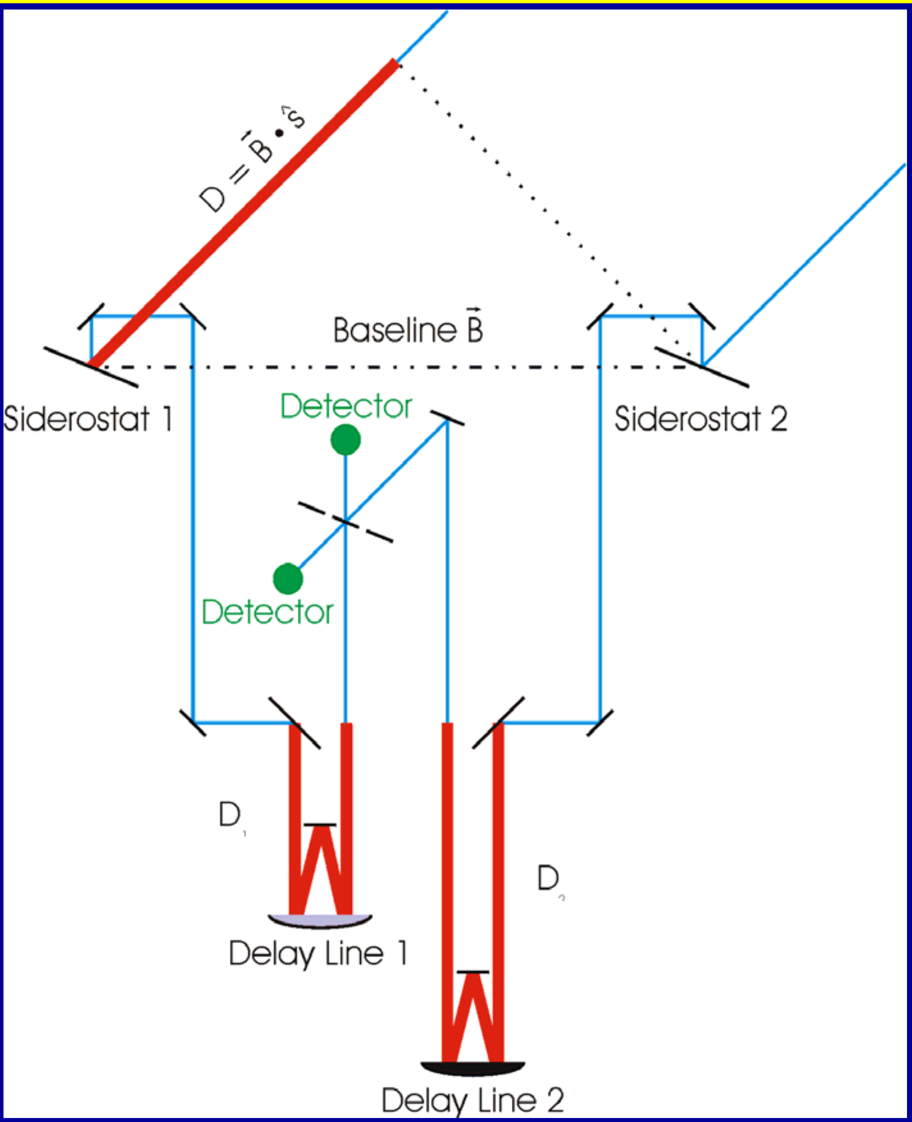


Abb. 3. Showing observer at eyepiece of 20 foot interferometer.

The ISI (Infrared Spatial Interferometer, Mt. Wilson)



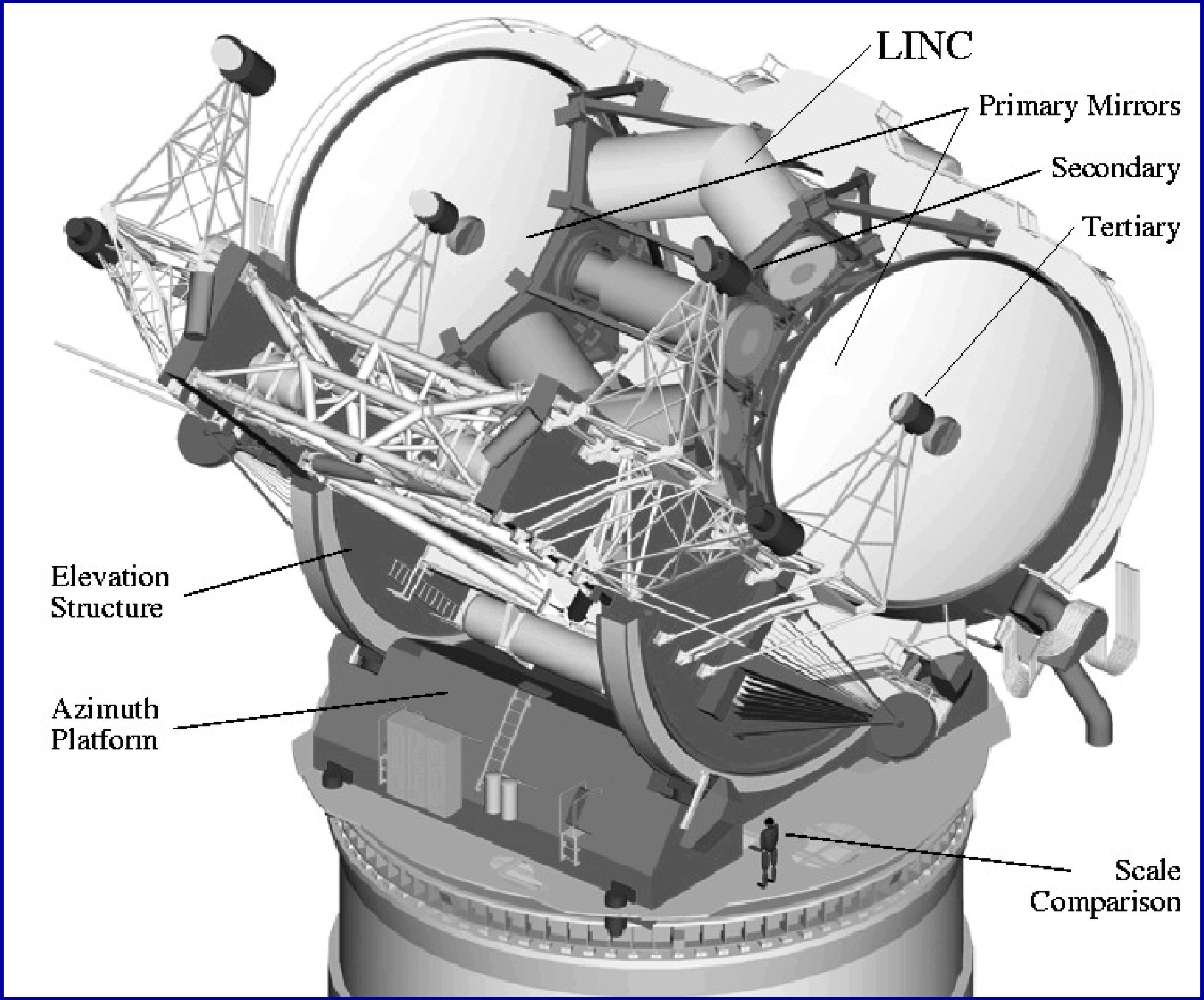
Schematic Layout of Michelson Interferometer



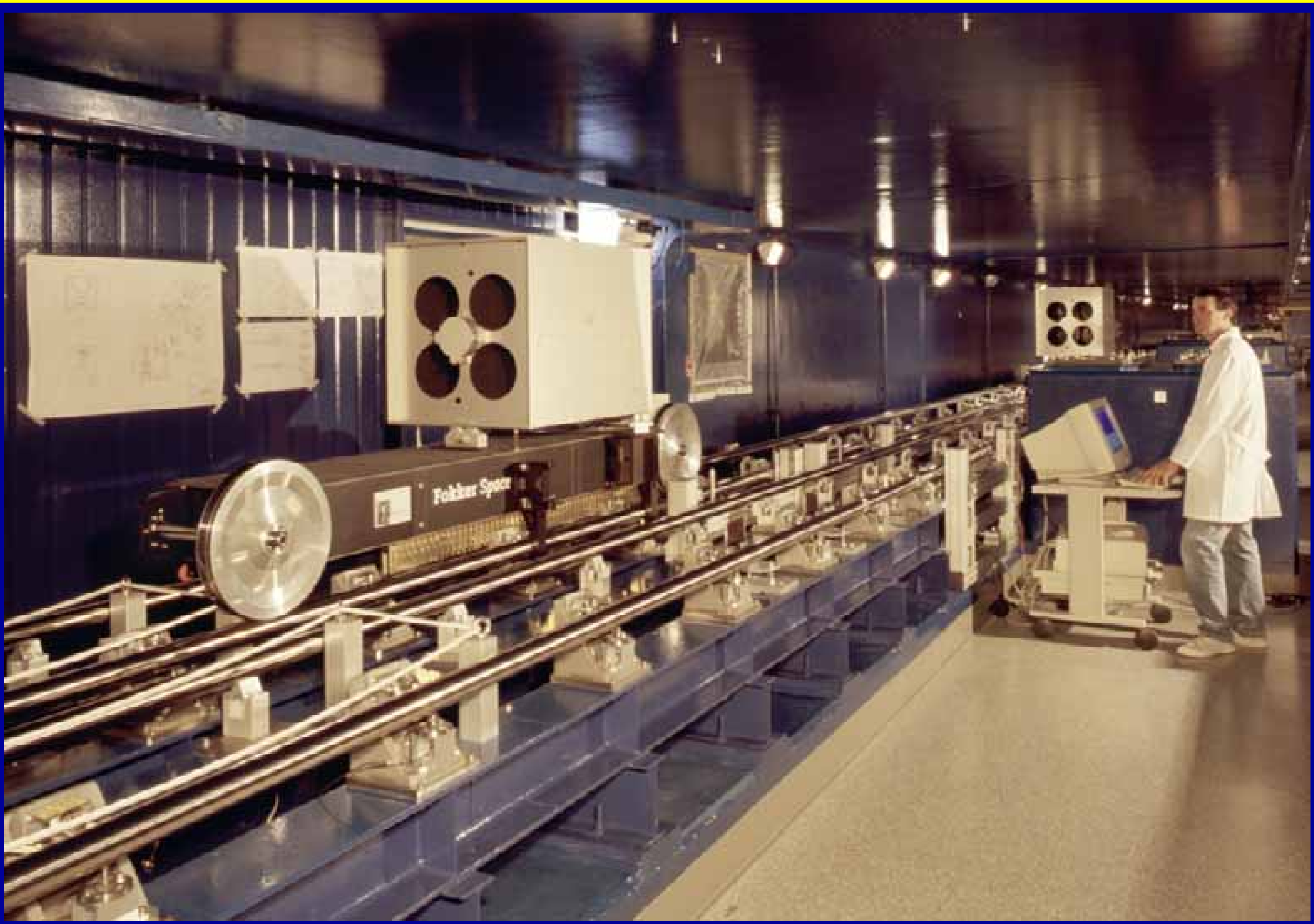
The Mark III Interferometer

The Twin Keck Telescopes on Mauna Kea (Hawaii)

The LBT (Large Binocular Telescope, Mt. Graham, AZ)

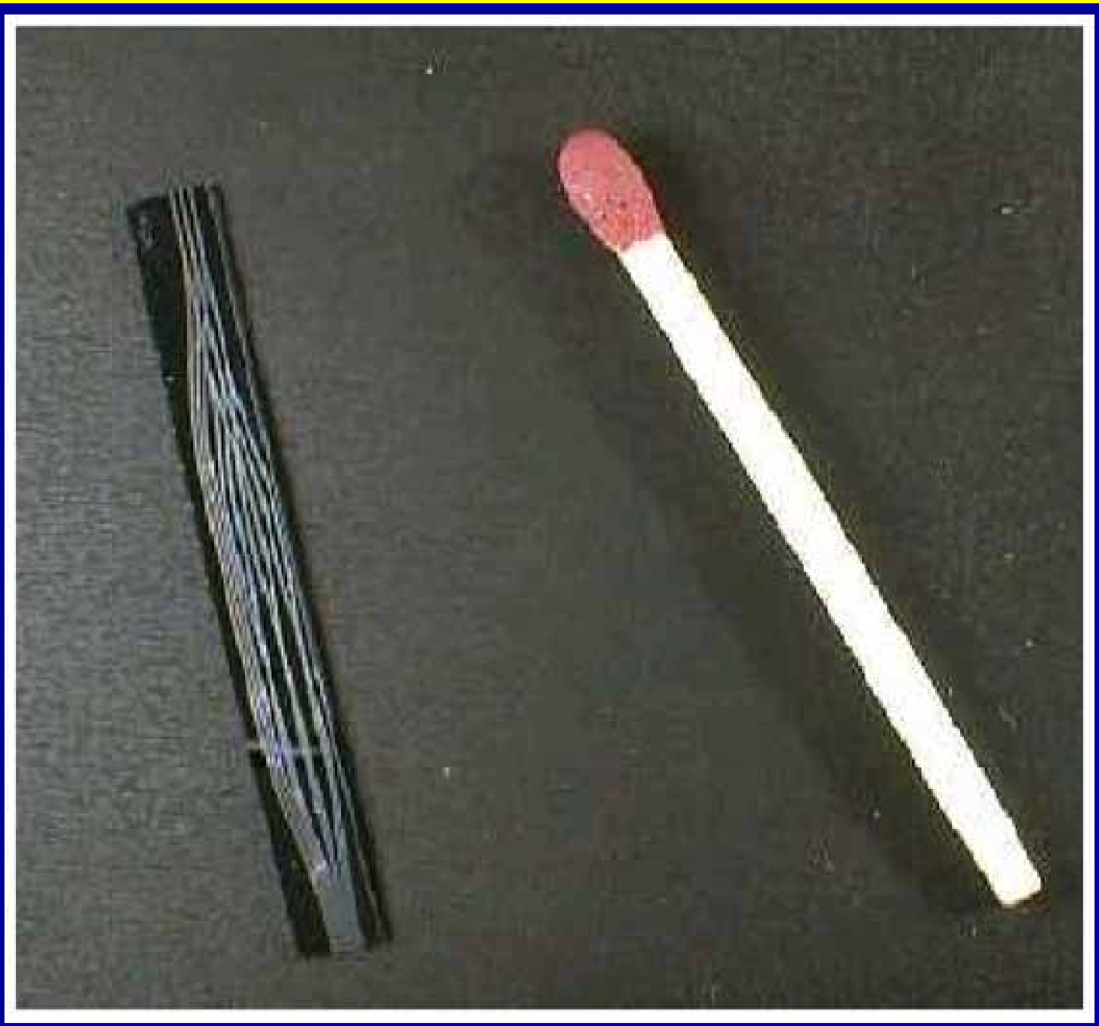


VLTI Delay Lines



NPOI Six-Way Beam Combiner

Integrated Optics Three-Way Beam Combiner



Produced by LETI with silica-on-silicon etching technique

Stellar Physics

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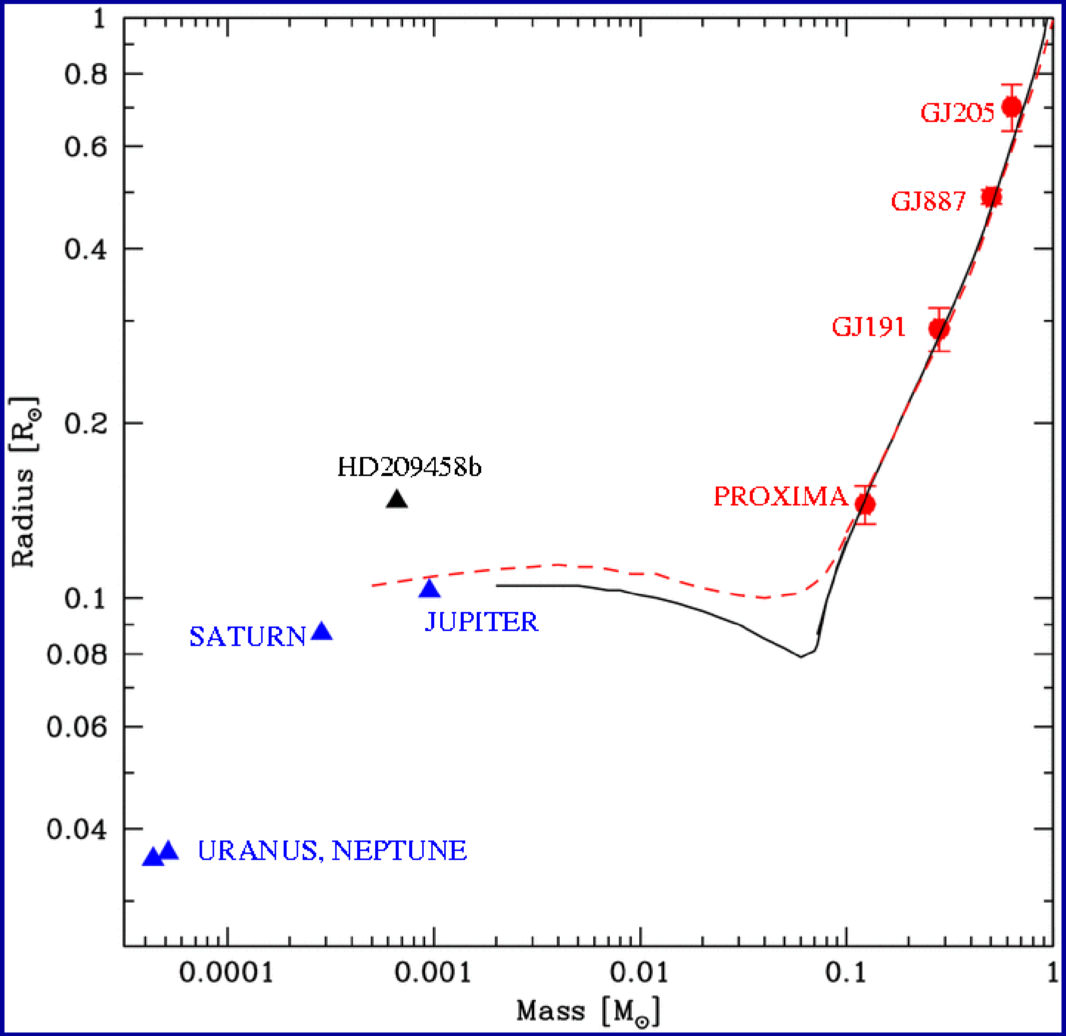
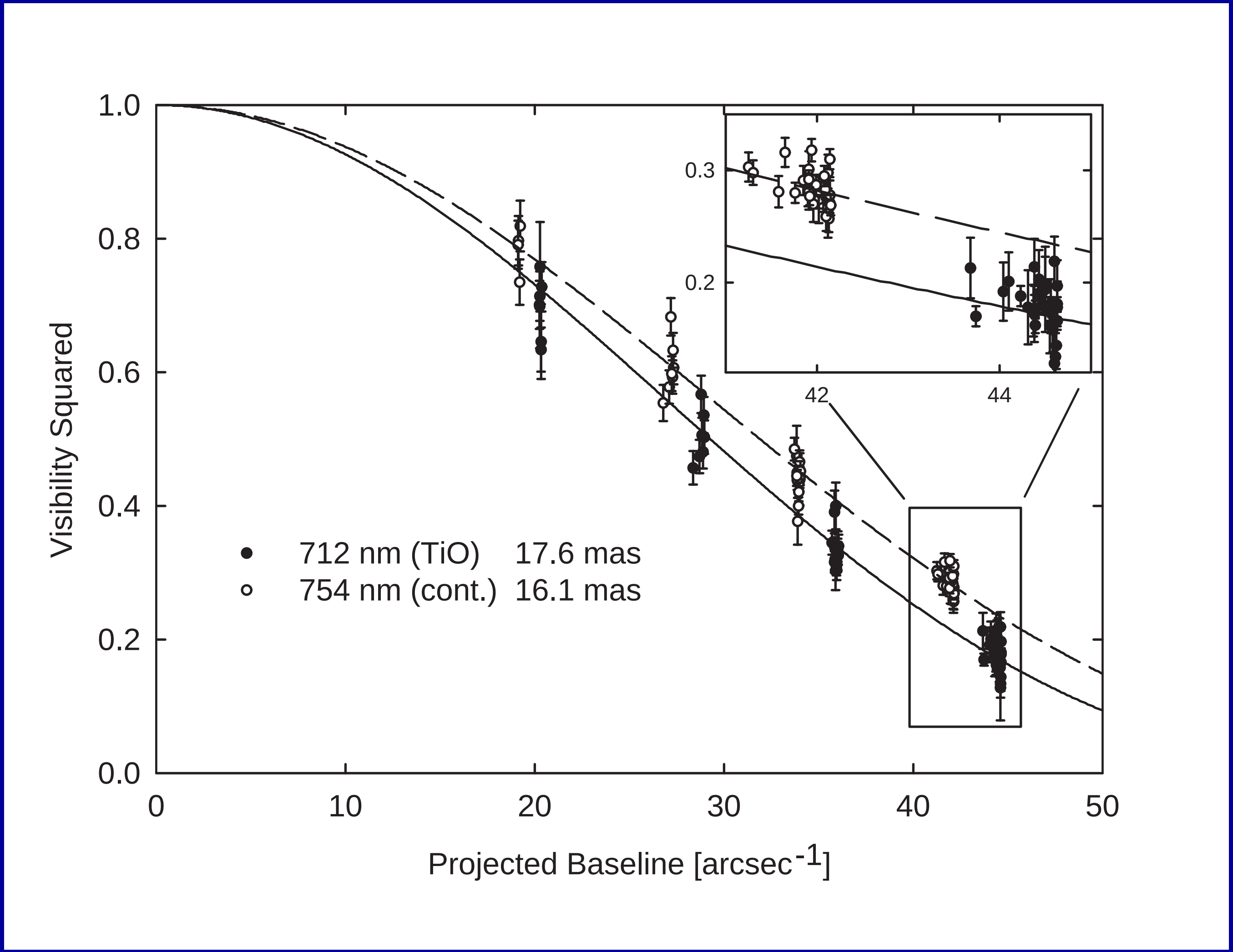
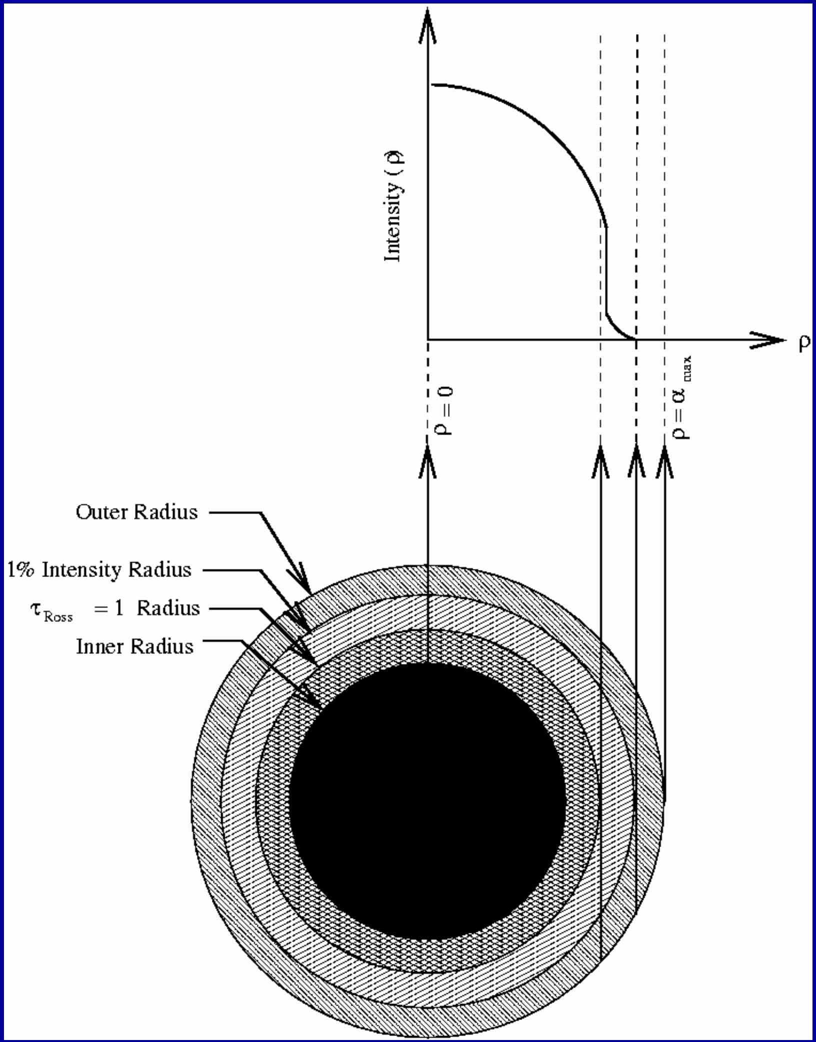
Mass-Radius Relation for Low-Mass Stars



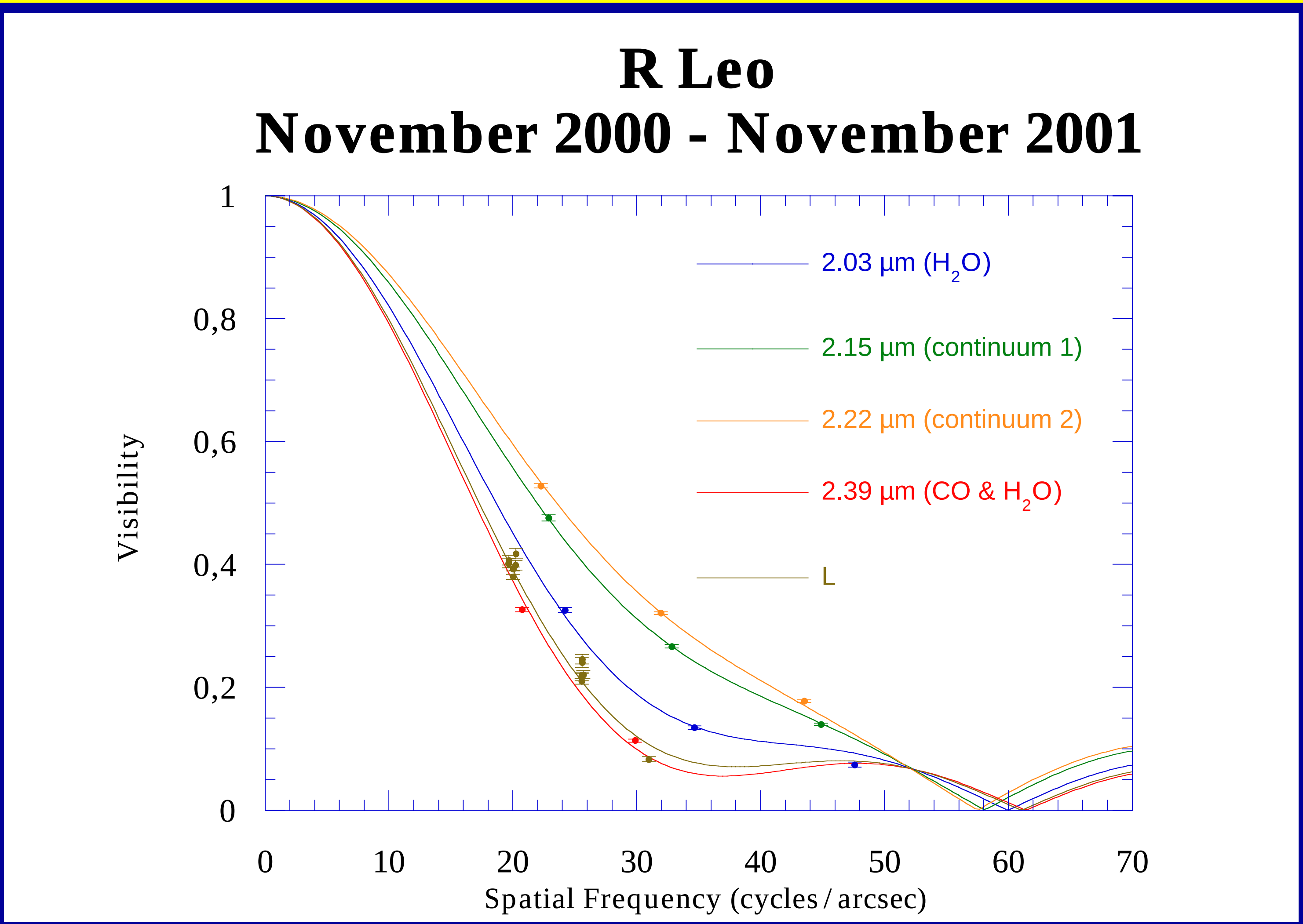
Mk III Diameter Measurements of the Giant Star β Pegasi



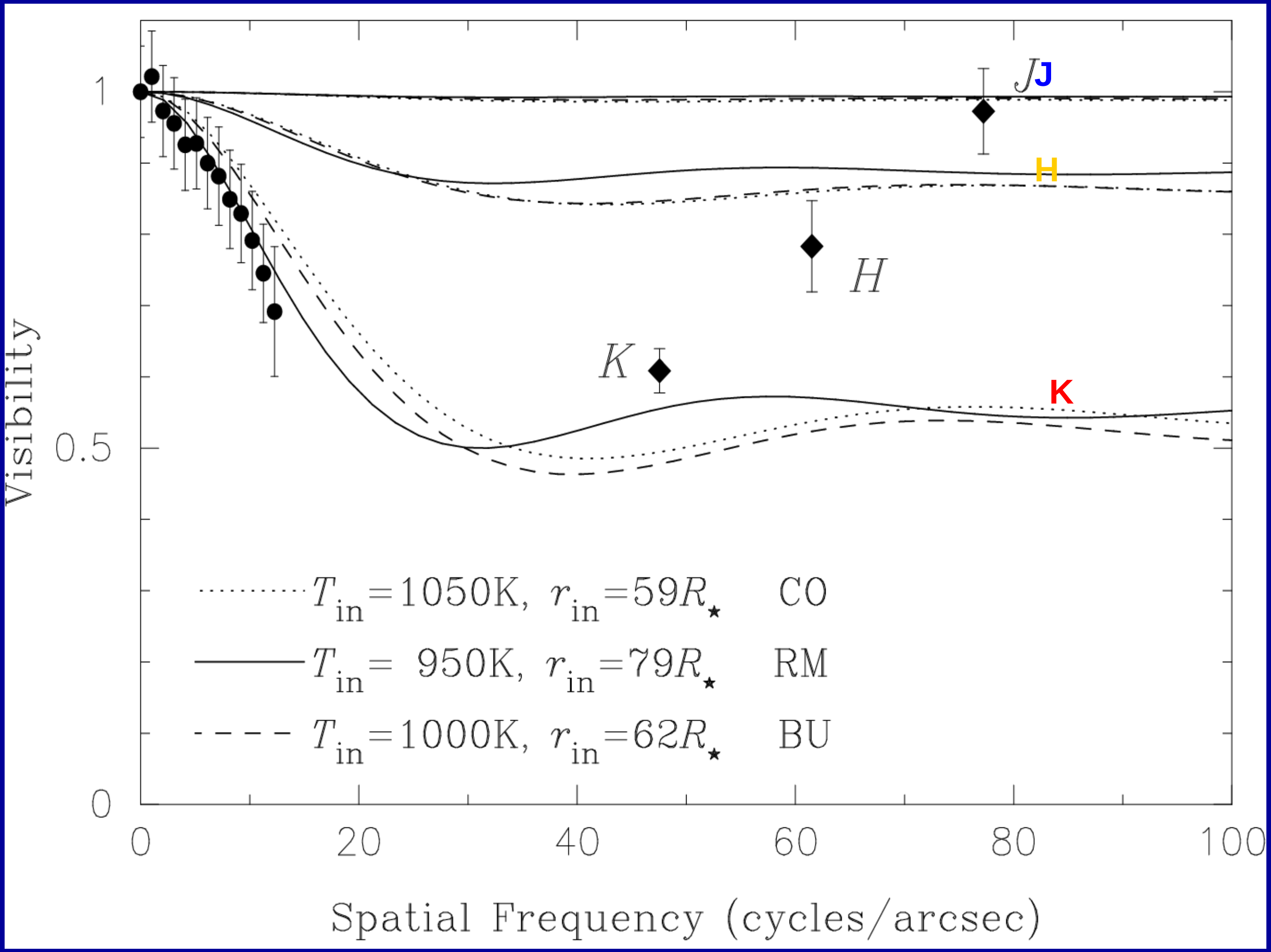
Schematic Model of Extended Stellar Atmosphere



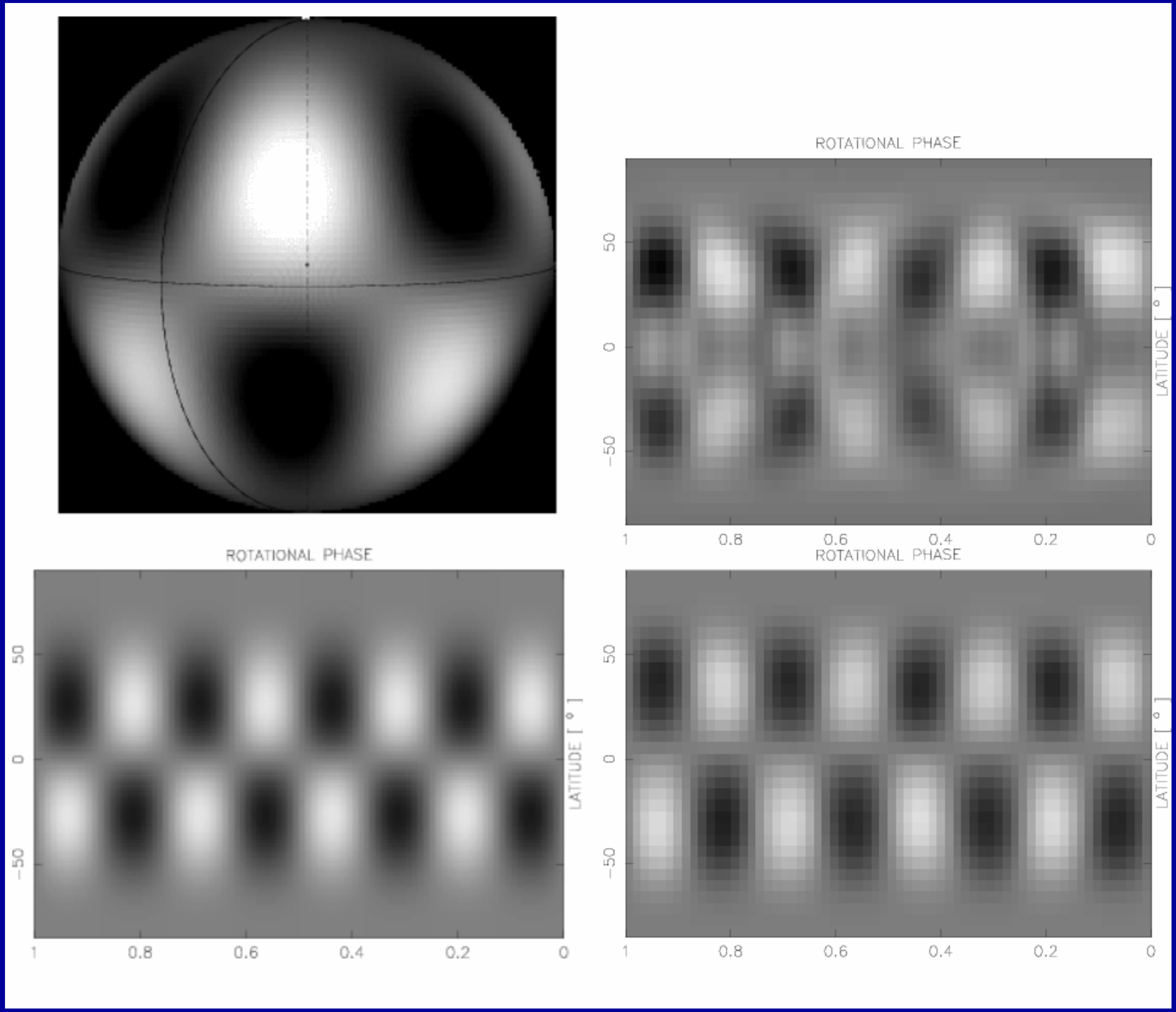
IOTA / FLUOR Data on the Mira Star R Leonis



IOTA and 6m SAO Speckle Data on R CrB (surrounded by dust)



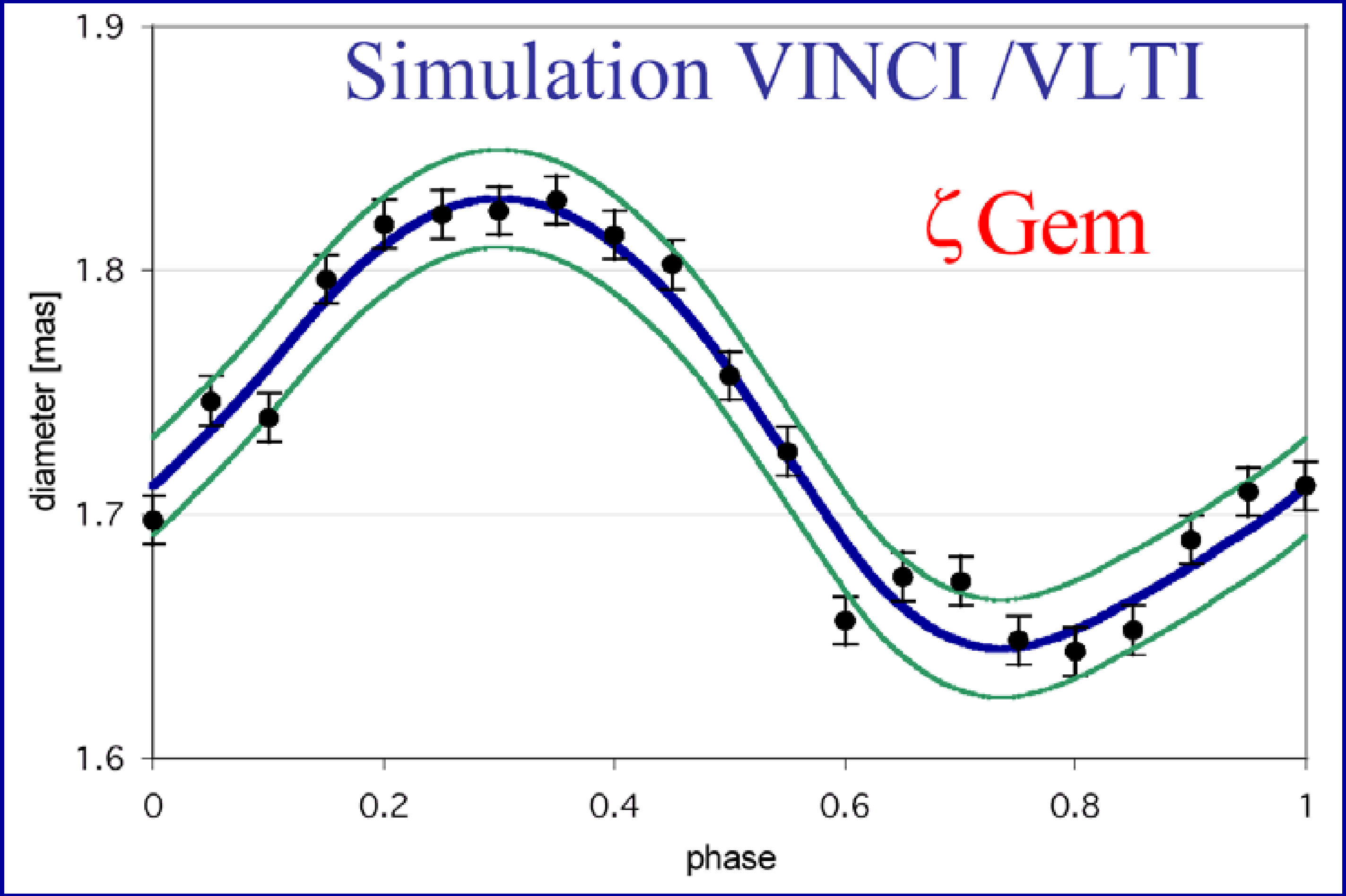
Mapping Pulsations with Doppler Tomography and Interferometry



Left: Model

Right: Simulated Reconstruction without and with interferometry

Cepheid Pulsations



Circumstellar Disks, Winds, and Outflows

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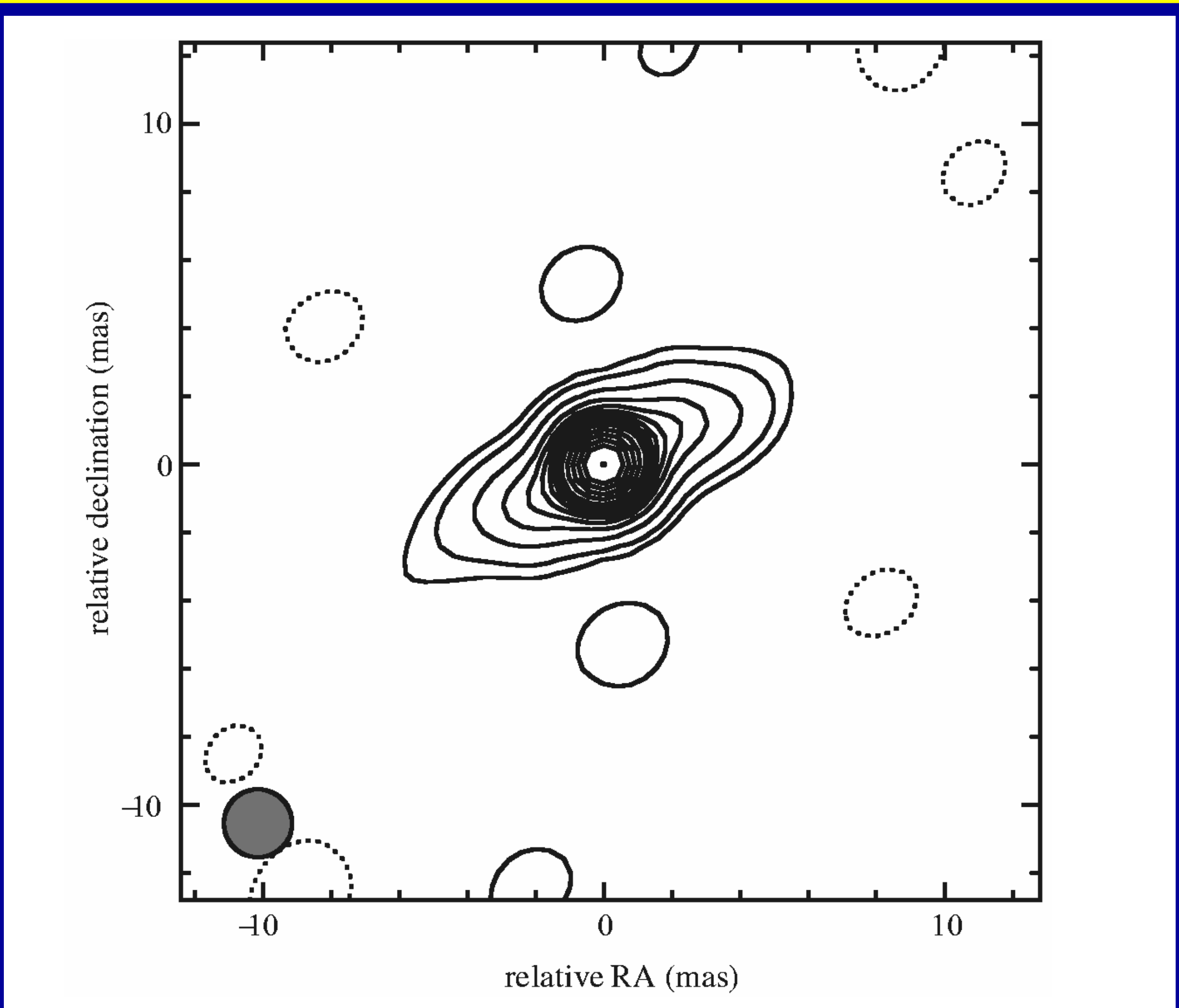
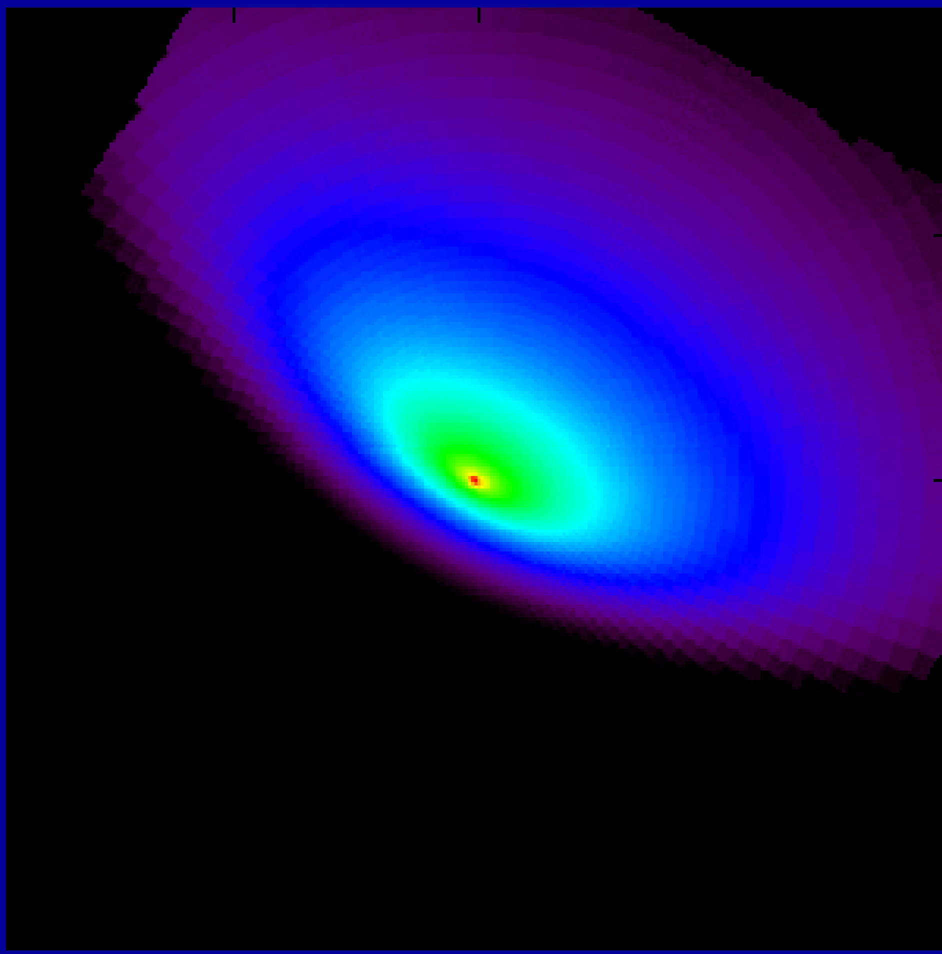
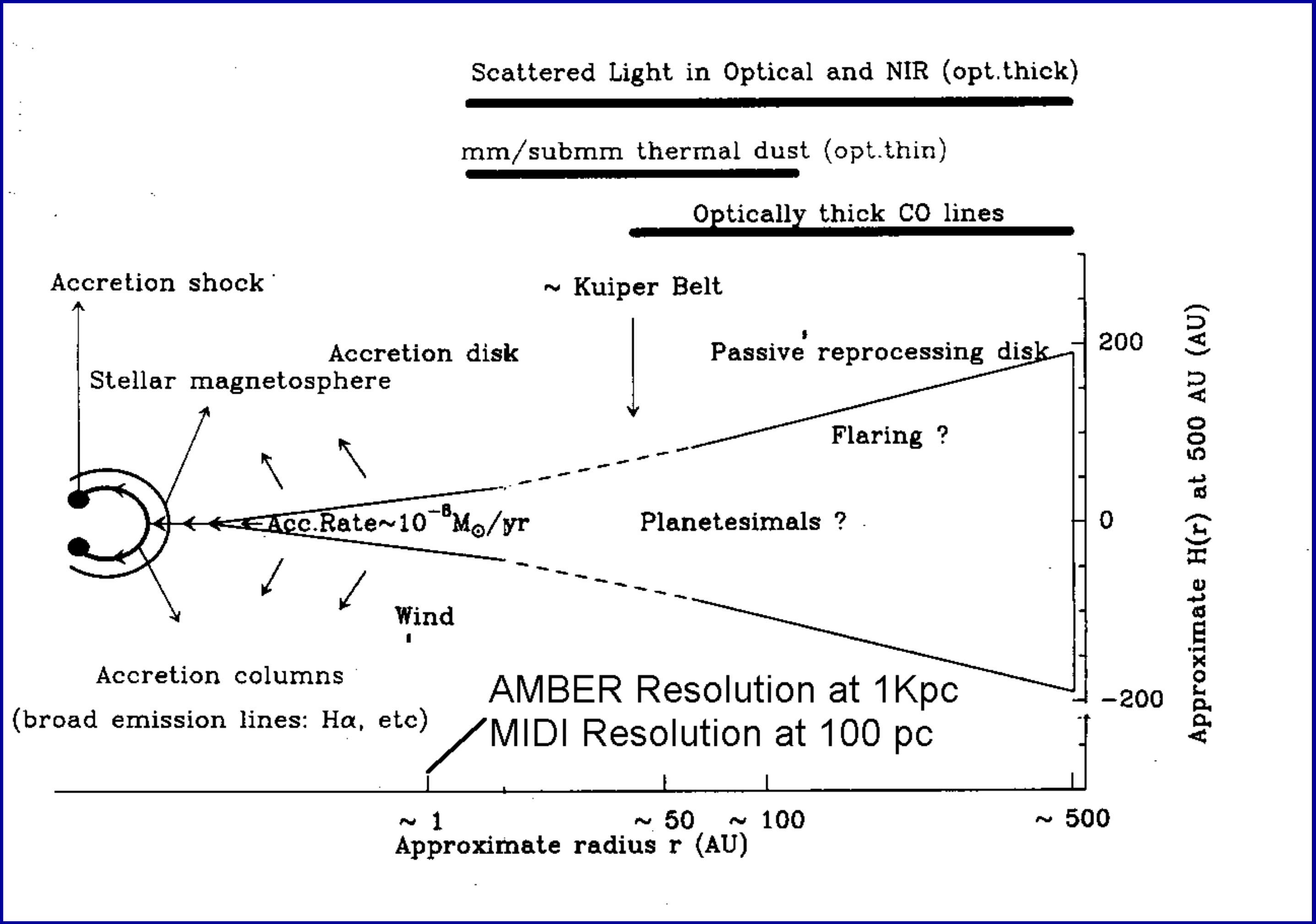
COAST Synthesis Image of the Be Star ζ Tauri



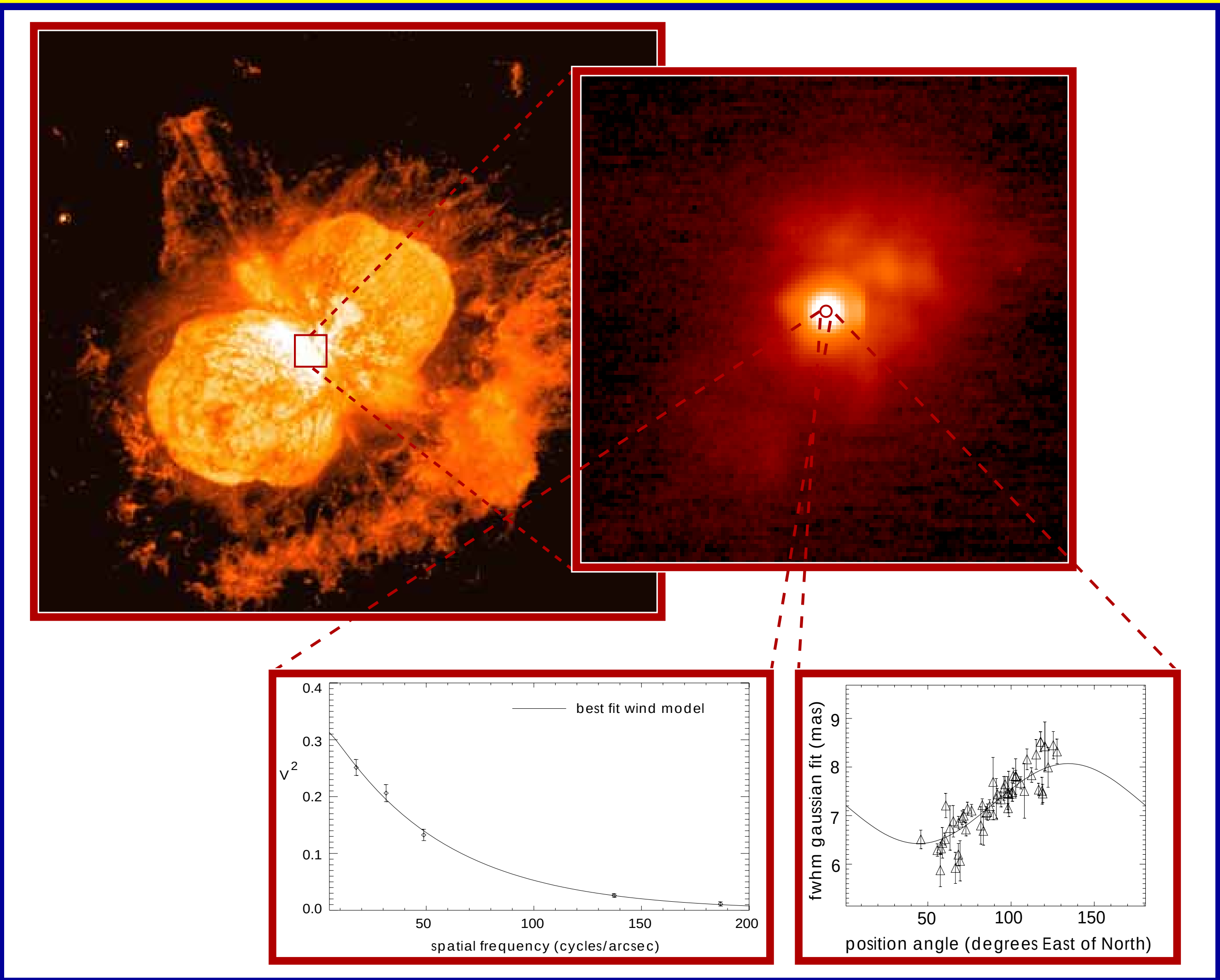
Model of a Main-Sequence Disk at 10 μm



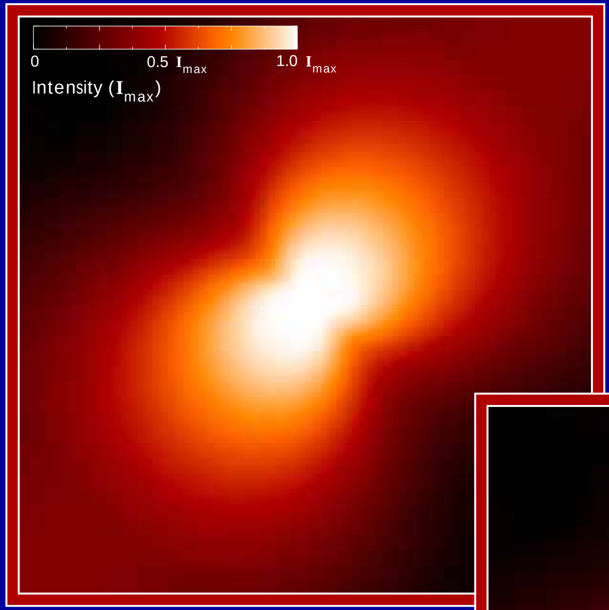
Schematic Diagram of Accretion Disk around a Proto-Star

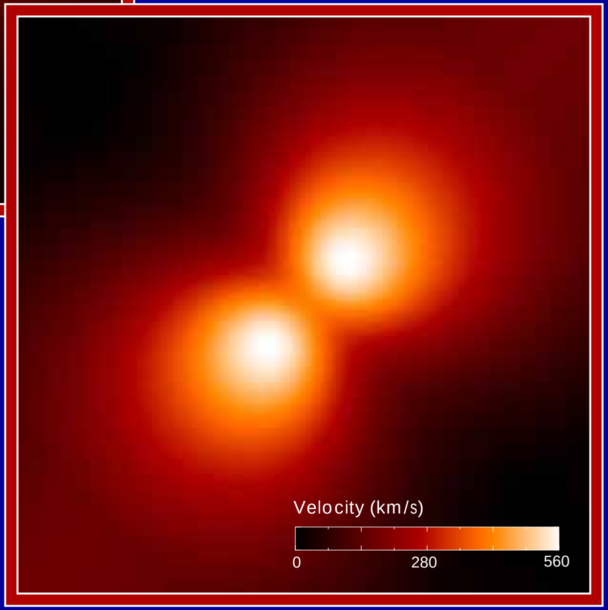


The η Carinae Nebula (WFPC2, NACO, VLTI)

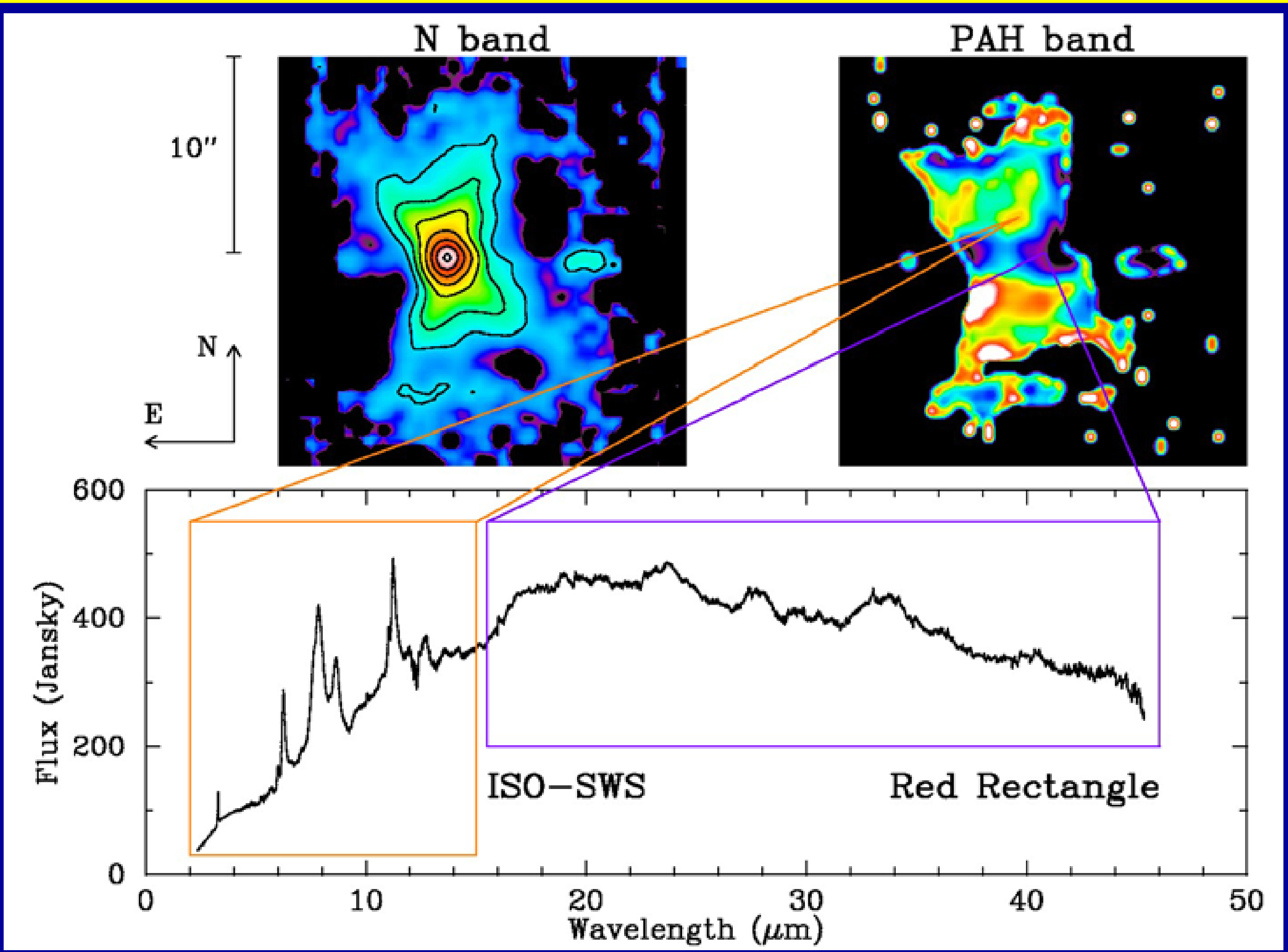


Model of η Carinae





ISO Spectrum of the Red Rectangle



Galactic Nuclei

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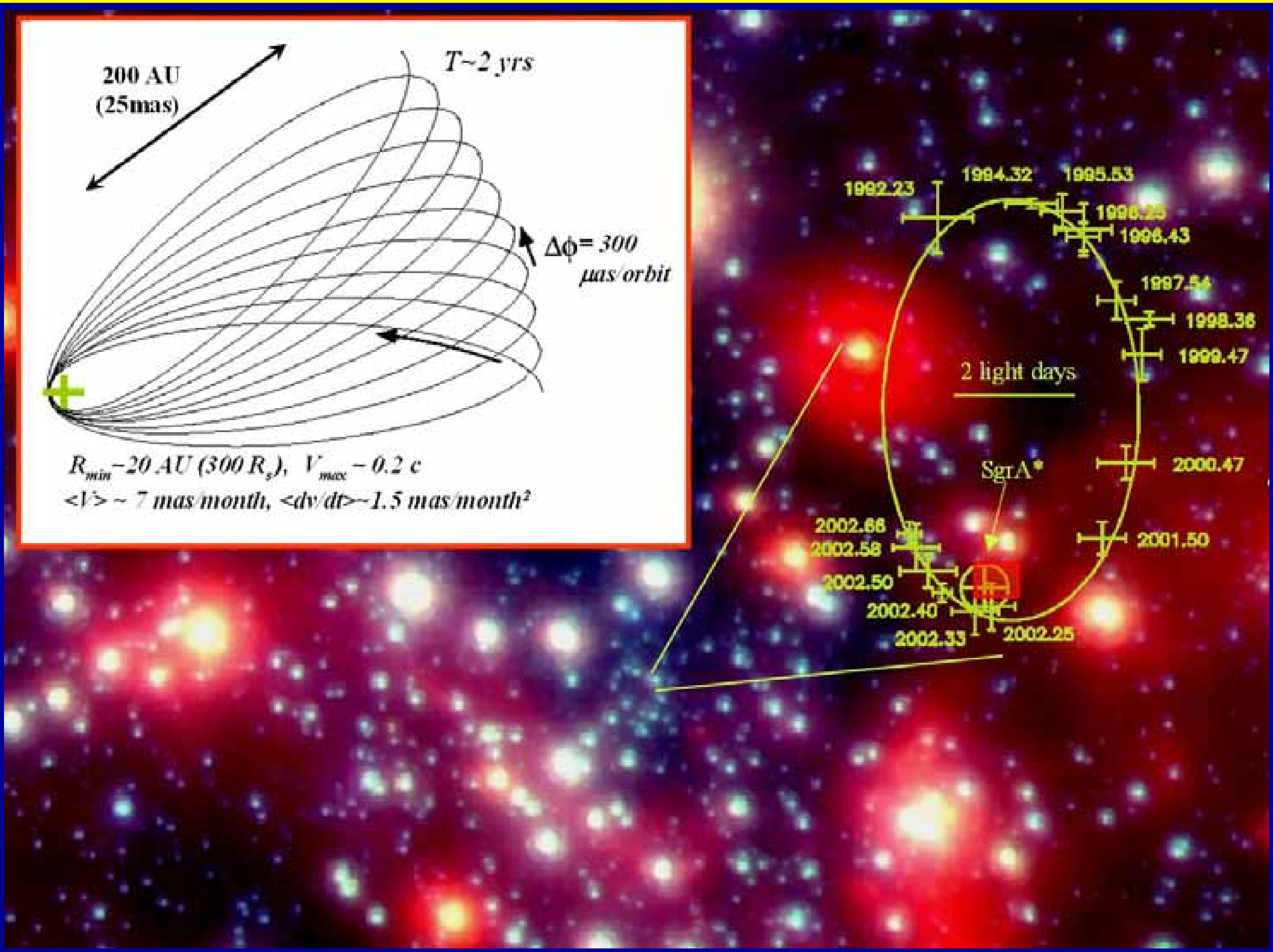
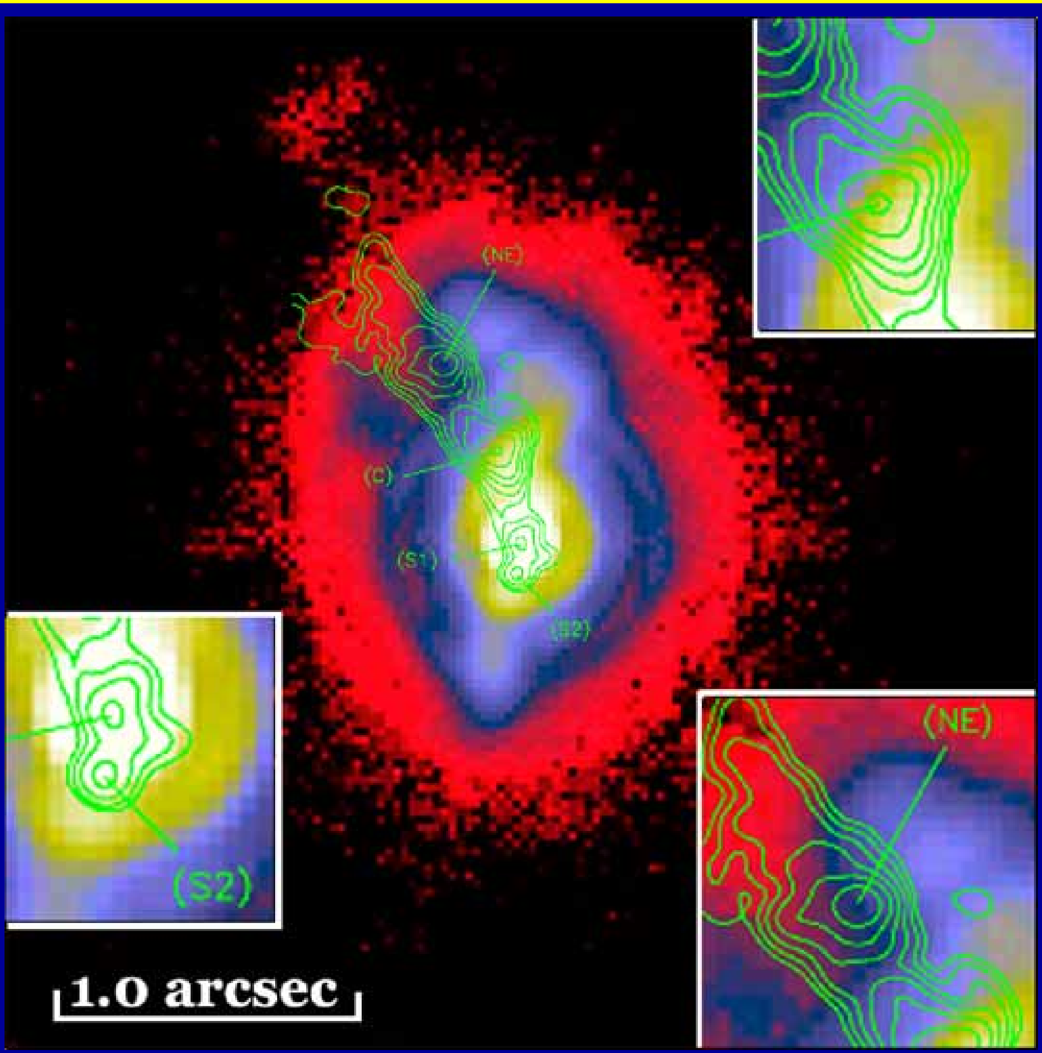
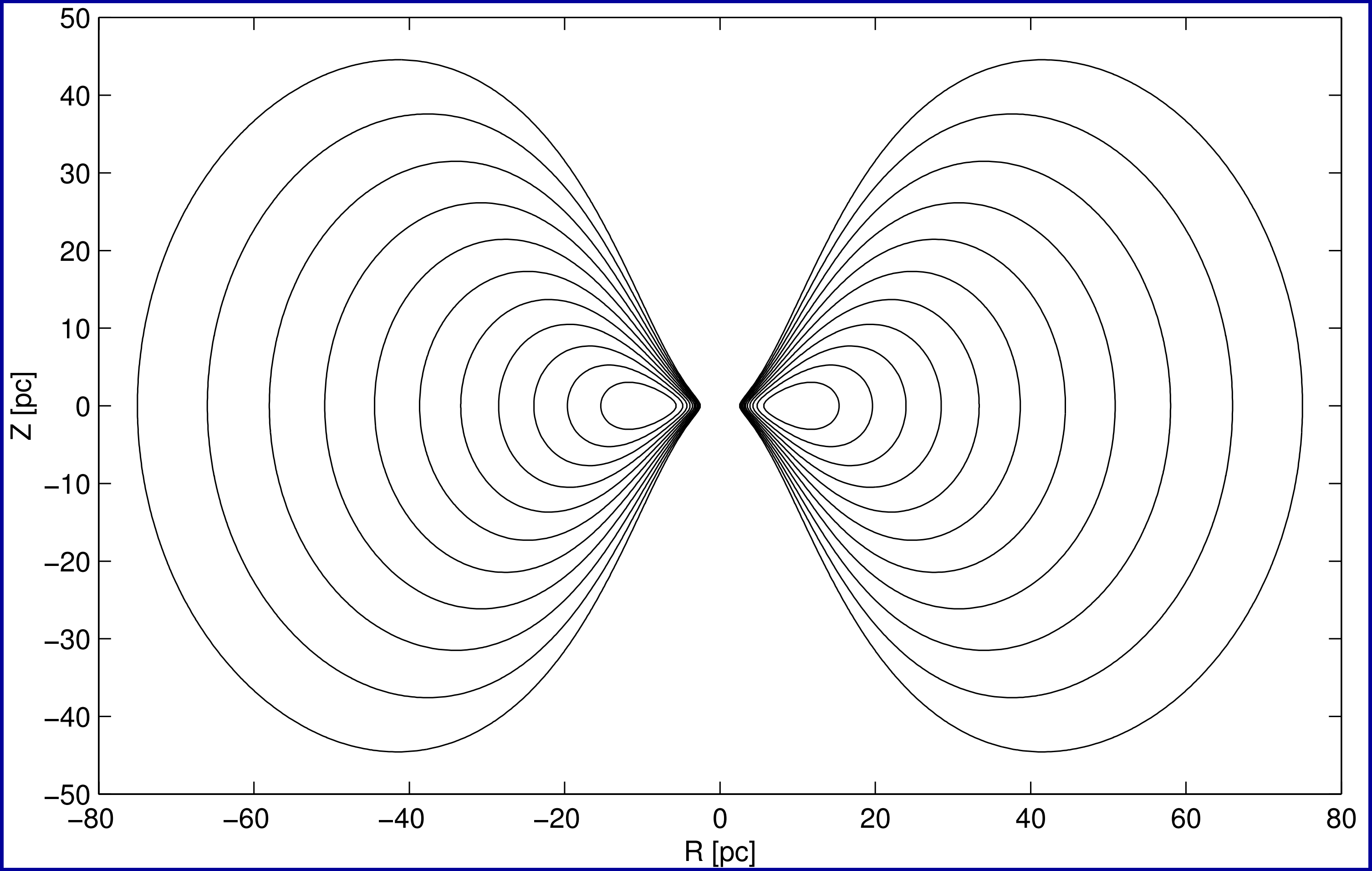
The Central Few Arcseconds of Our Galaxy



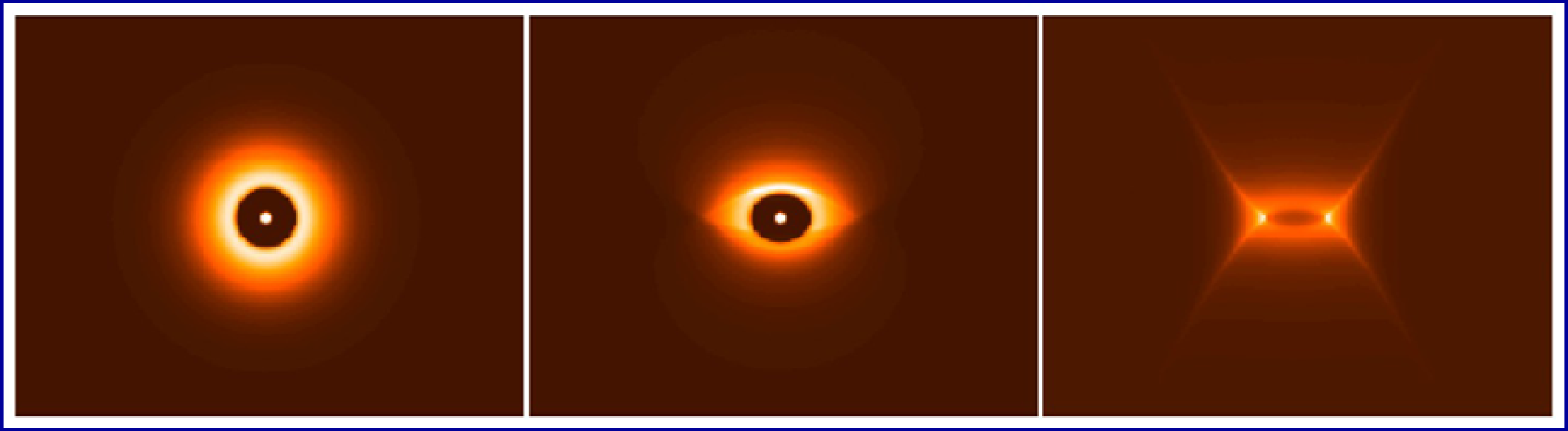
NGC 1068 as Seen in the Radio and by NACO at 5 μm



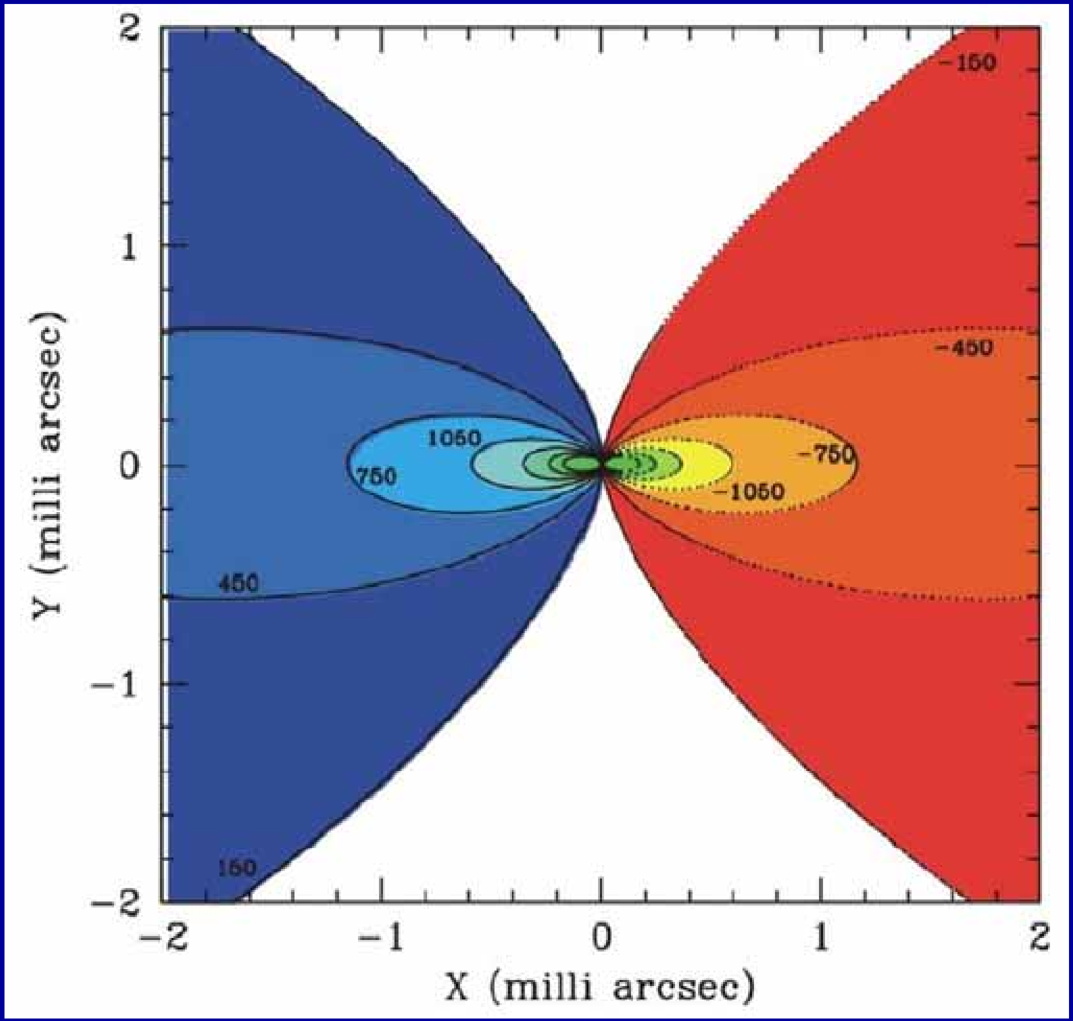
Model of an AGN Torus



Appearance of Torus as a Function of Inclination



Iso-Velocity Contours for Model of 3C273



Interferometric Astrometry

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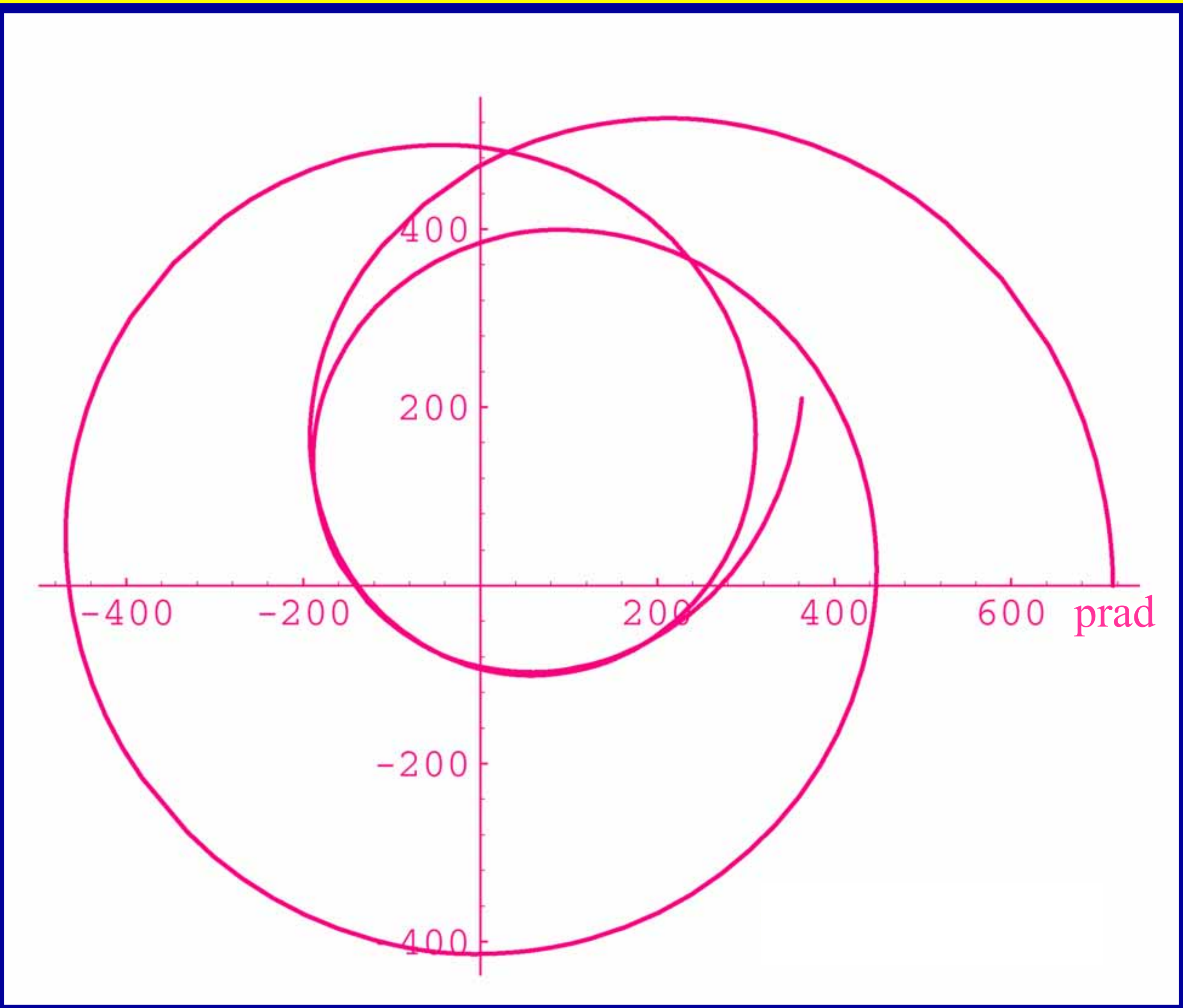
Motion of the Sun, Viewed Pole-on from 100 pc

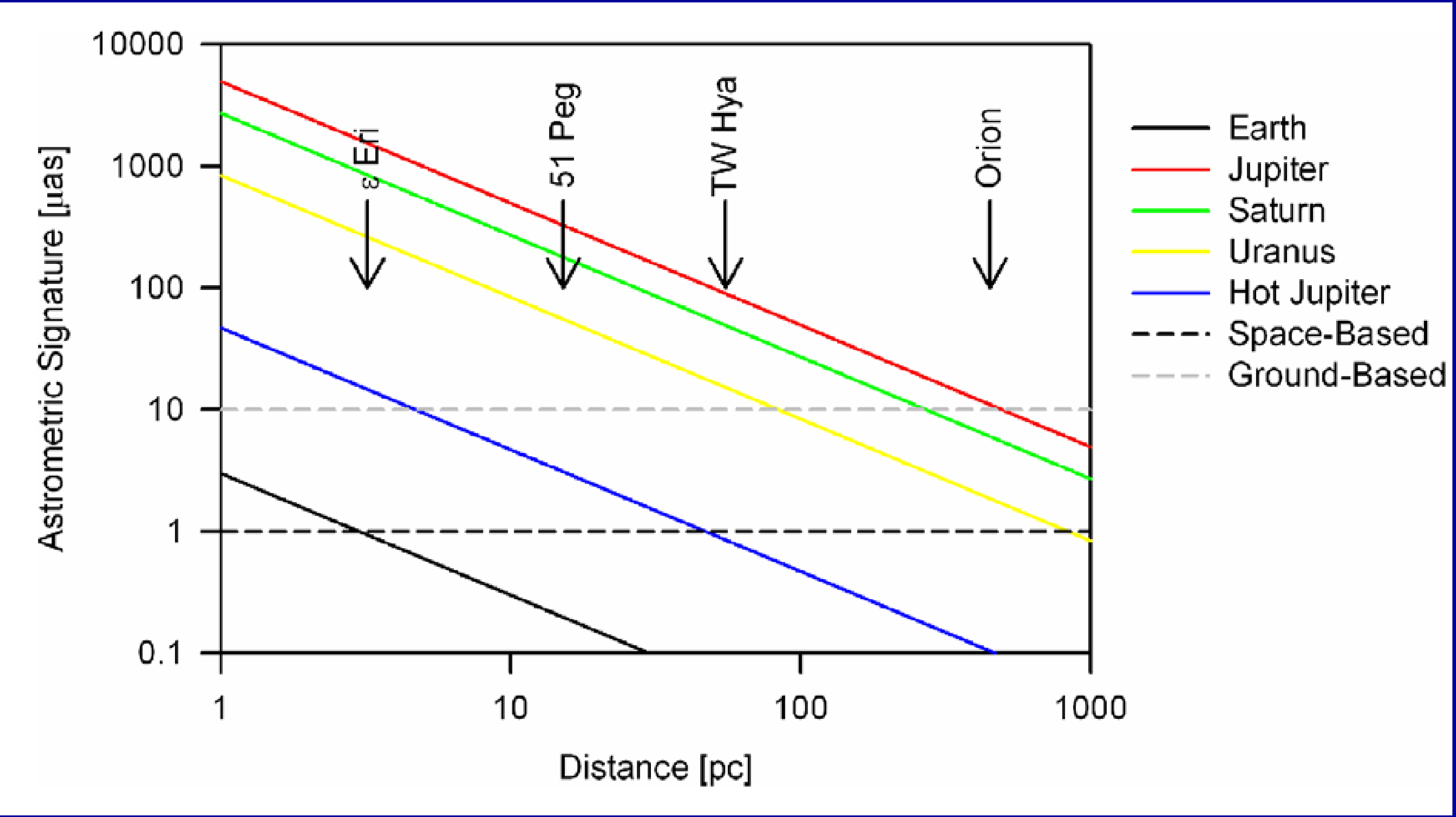


Amplitude:

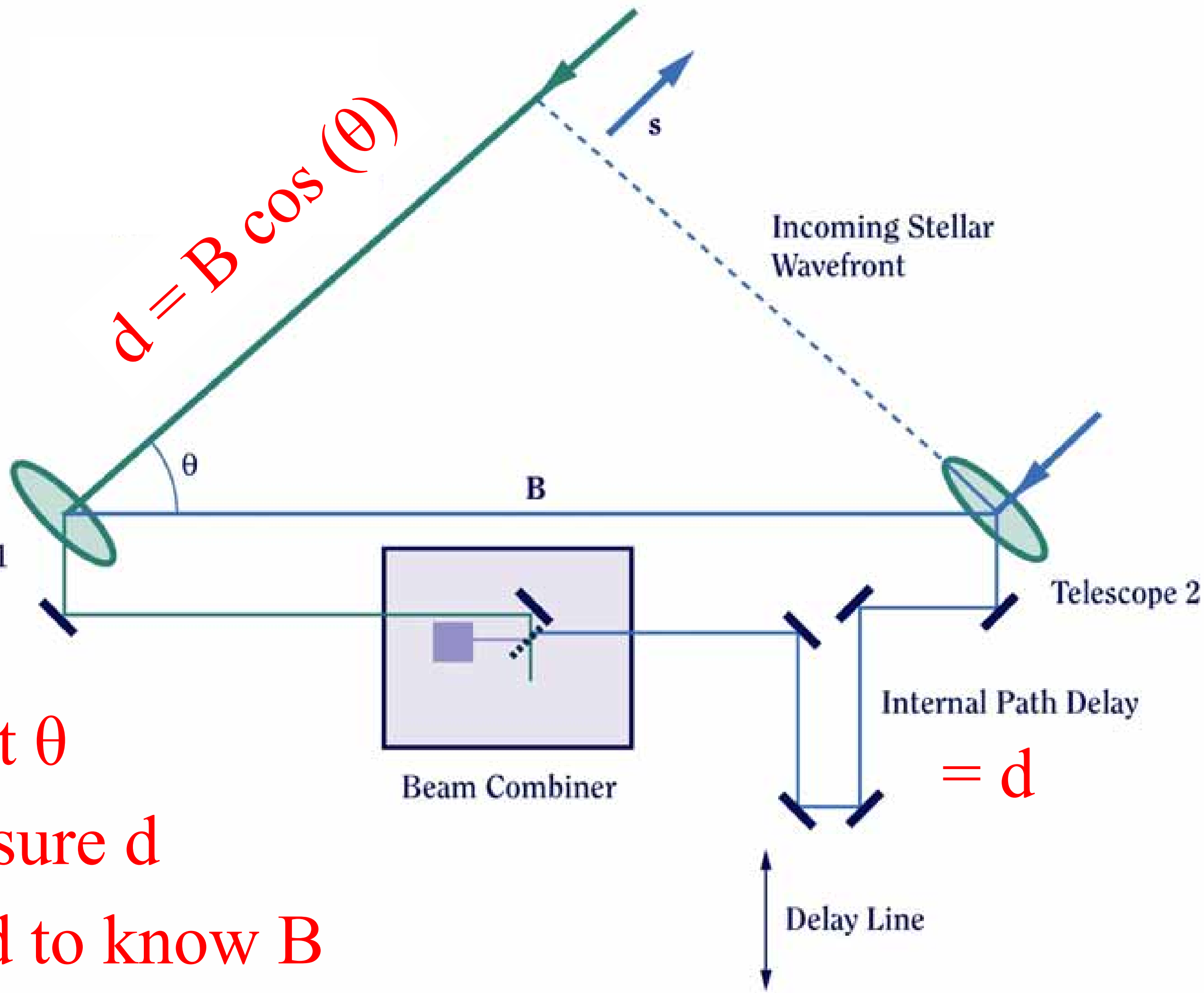
500 pico-radians

100 micro-arcsec

Requirements for Astrometric Planet Detection



Astrometric Measurement with an Interferometer

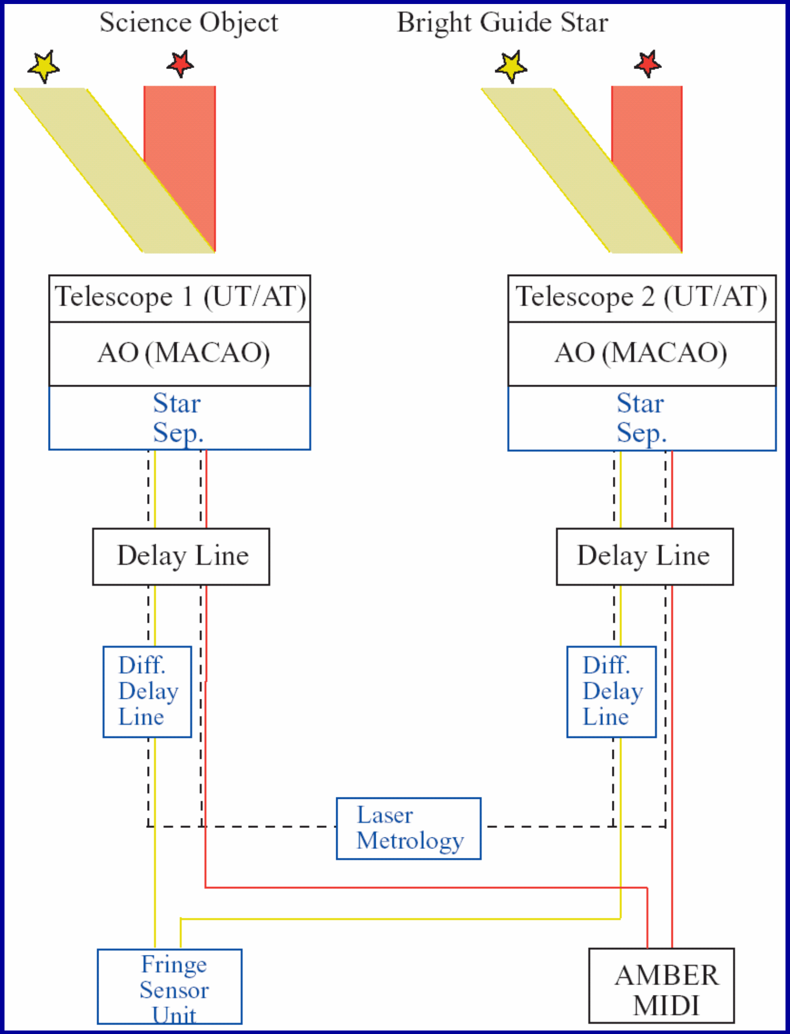


Want θ

Measure d

Need to know B

Dual-Star Interferometry

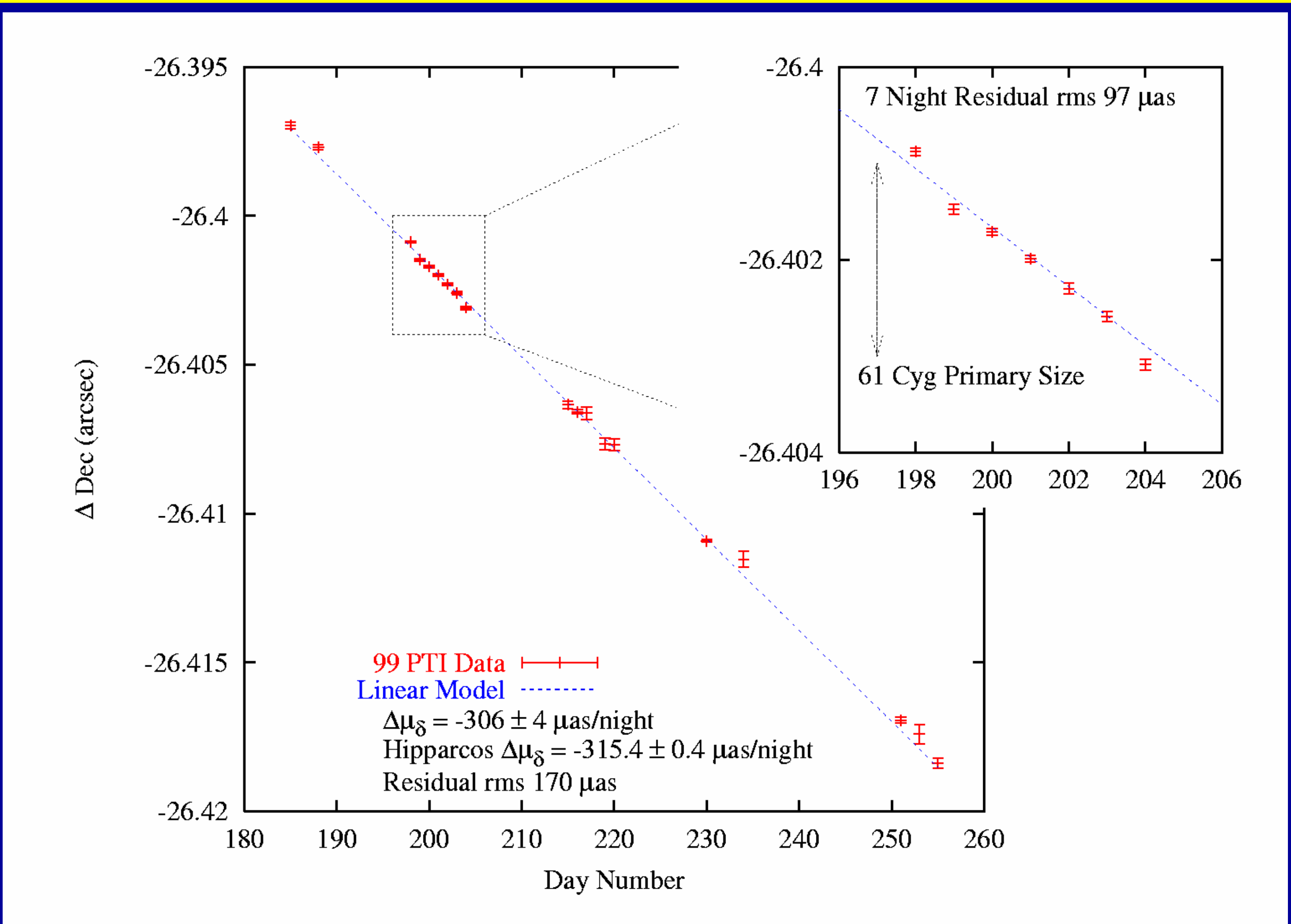


Goals of Astrometric Planet Surveys

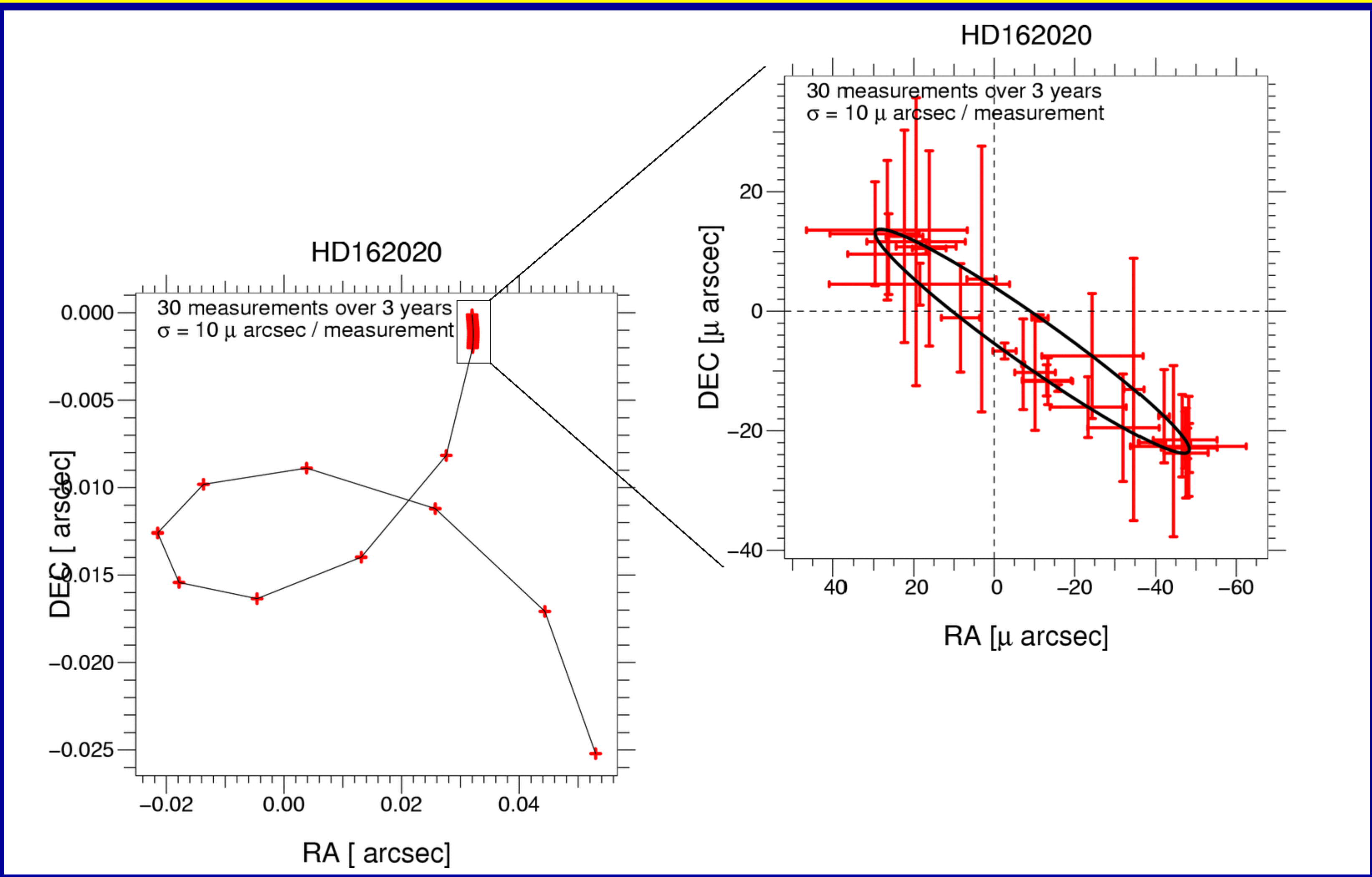
- Accurate mass determination for planets detected in radial-velocity surveys (no sin *i* ambiguity)
- Frequency of planets around stars of all masses
  - Relation between star formation and planet formation
- Gas giants around pre-main-sequence stars
  - Time scale of formation, test formation theories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

Palomar Testbed Interferometer (PTI)

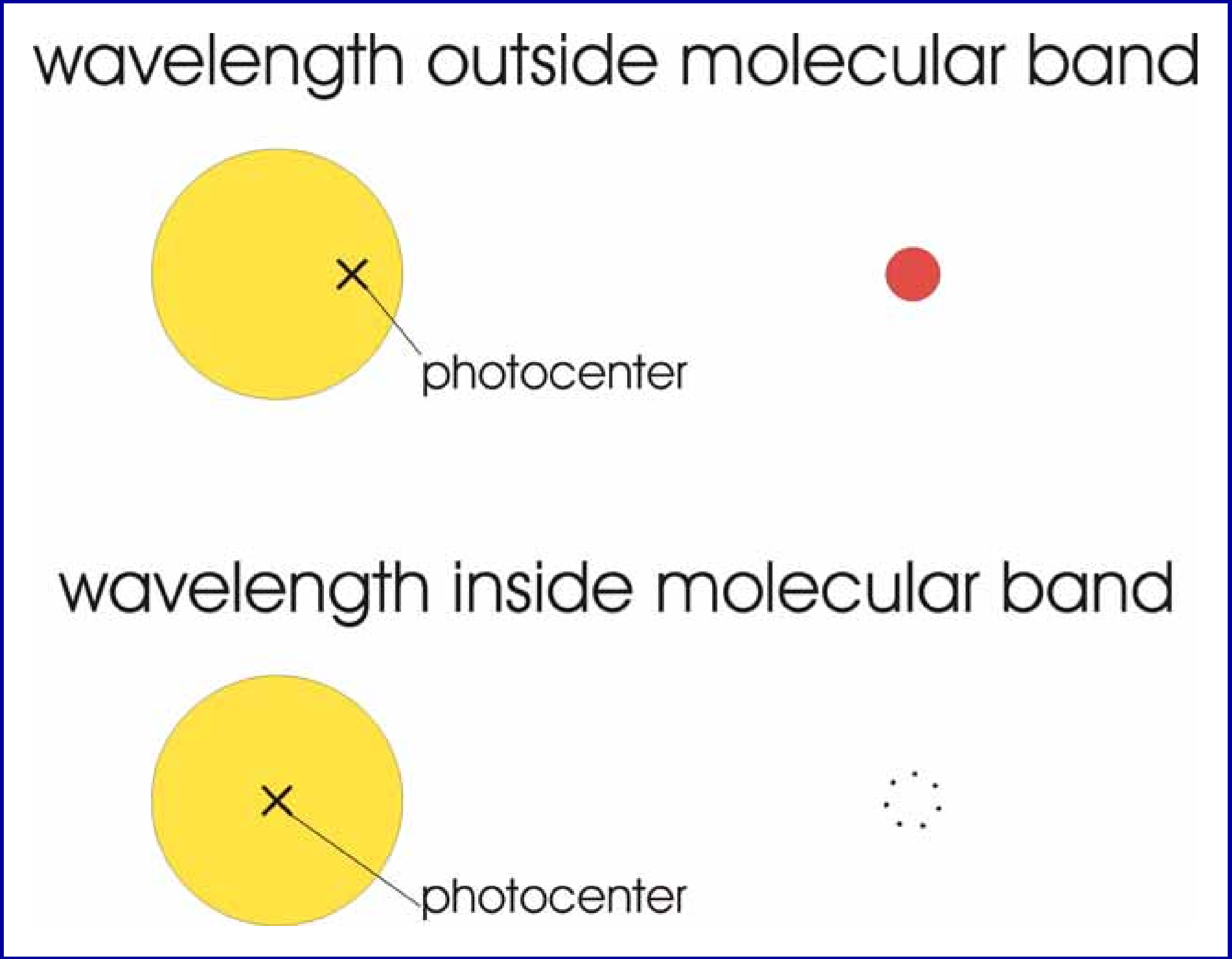
Astrometry Demonstration with Palomar Interferometer



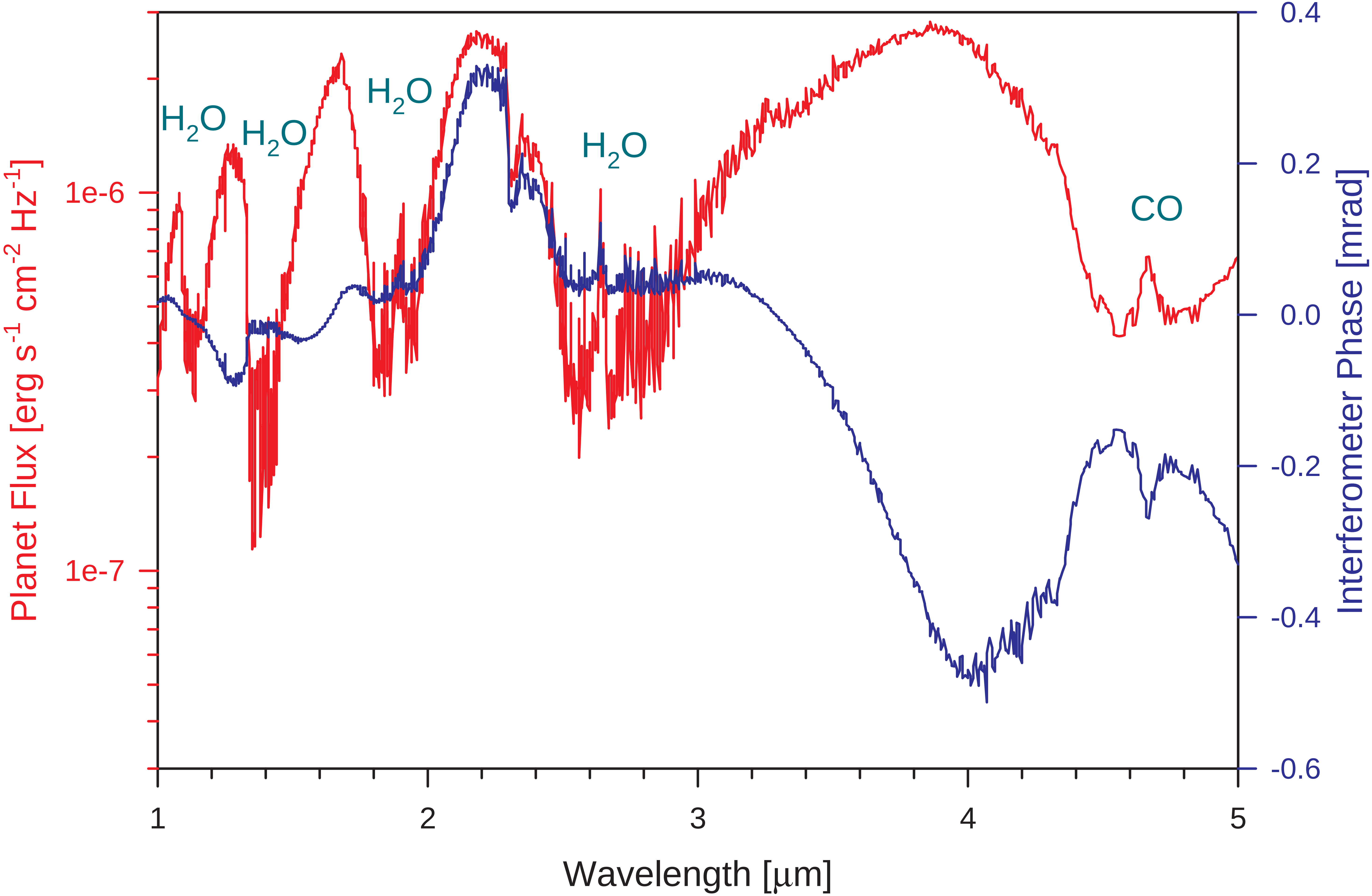
Simulation of Planet Observations with the VLTI



The Principle of Differential Phase Interferometry

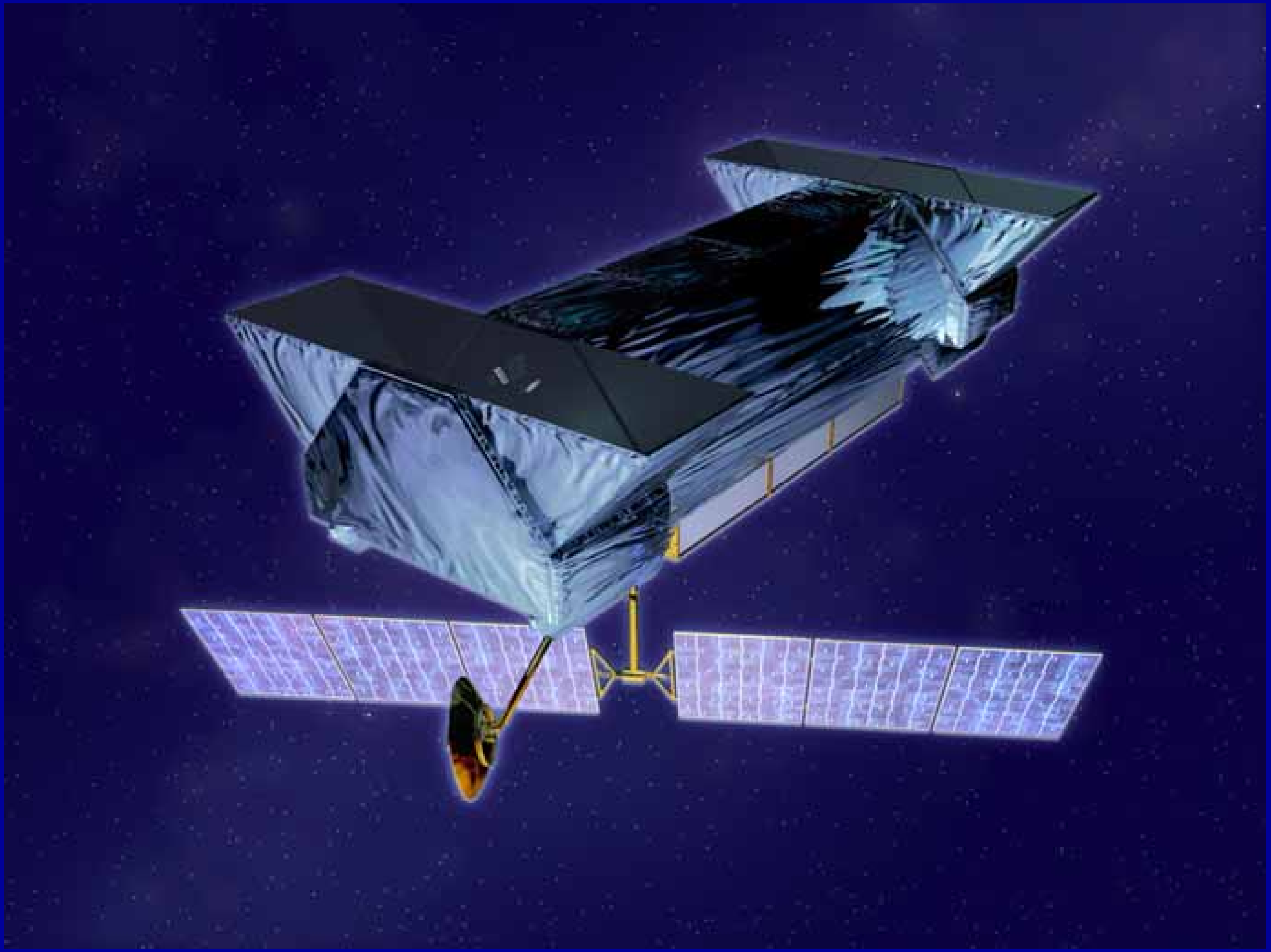


Spectrum of 51 Peg B and Phase on 100 m Baseline

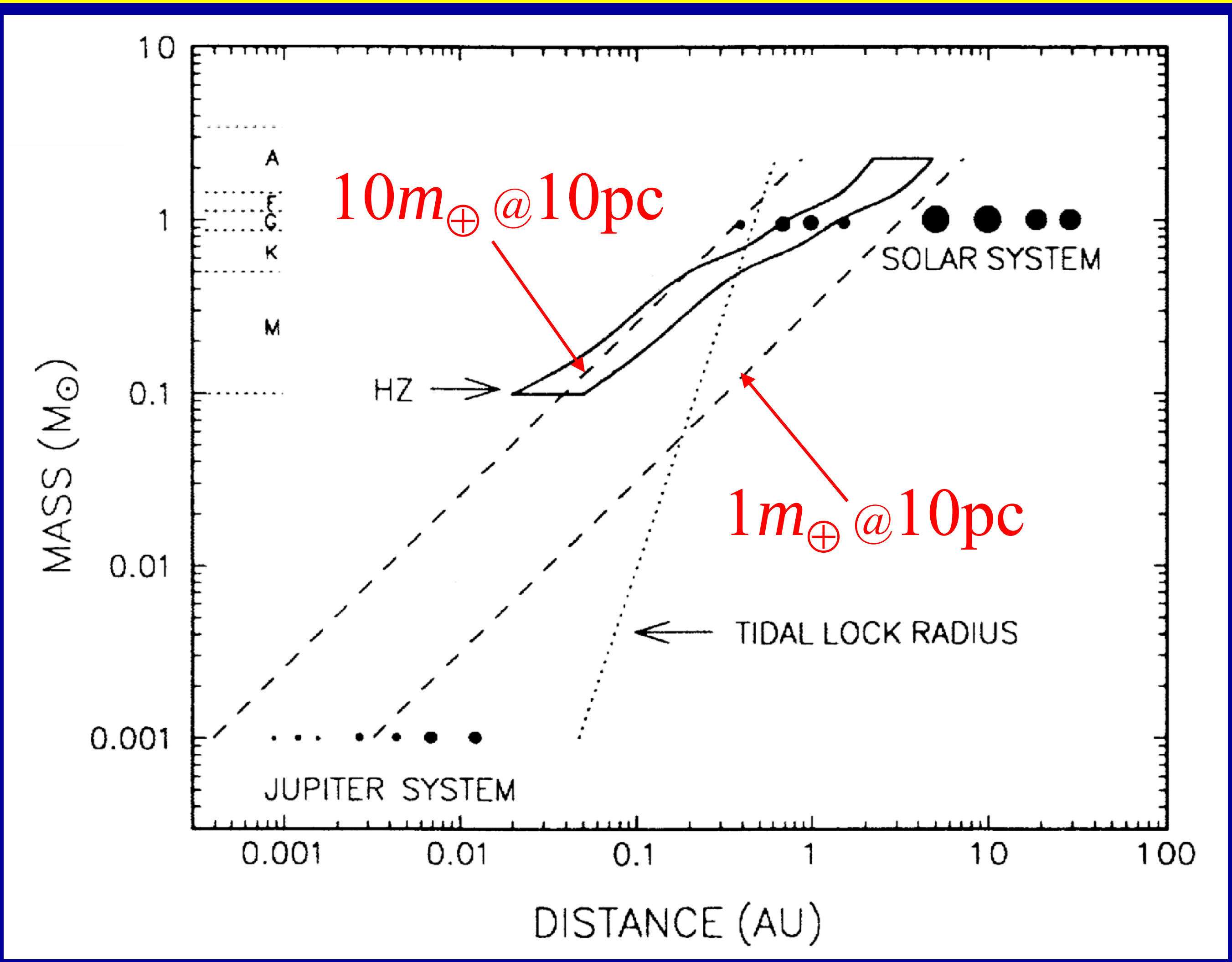


H_2O
H_2O
H_2O
H_2O
CO
1e-6
1e-7
Planet Flux [erg s^{-1} cm^{-2} Hz^{-1}]
0.4
0.2
0.0
-0.2
-0.4
-0.6
Interferometer Phase [mrad]
1
2
3
4
5
Wavelength [μm]

The Space Interferometry Mission (SIM)

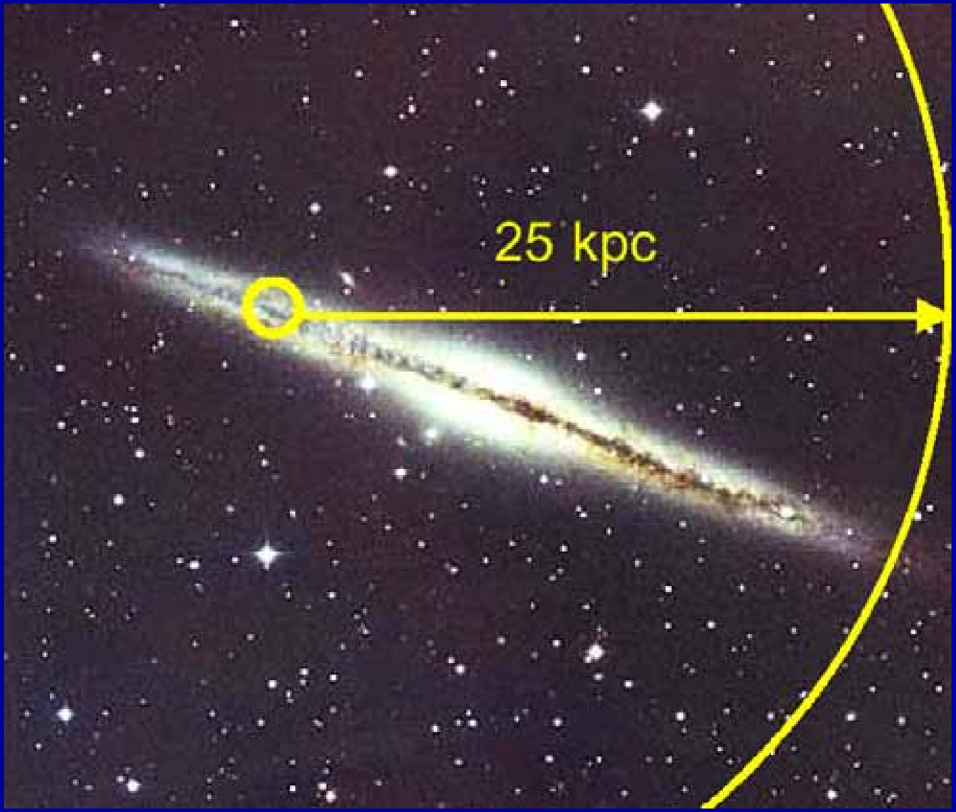


Planet Detection Capability for 1 μas Astrometric Sensitivity



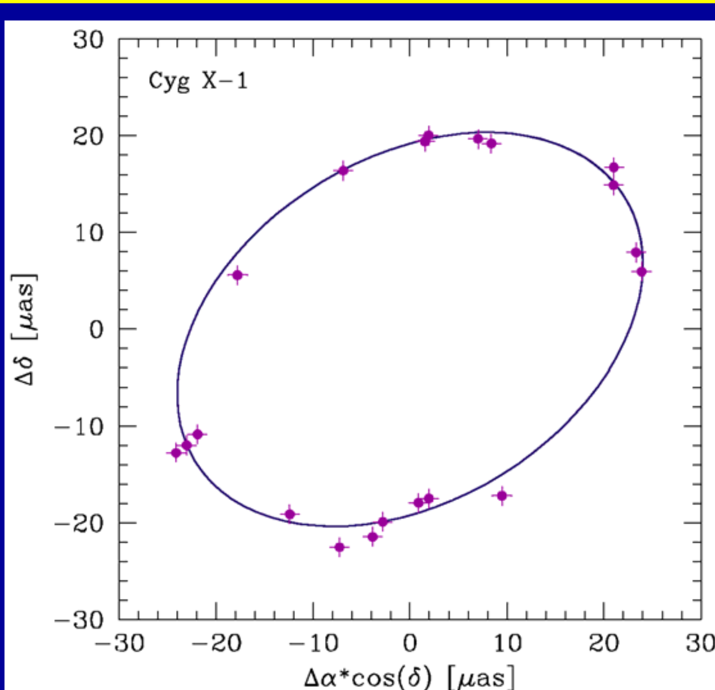
Distances in the Galaxy

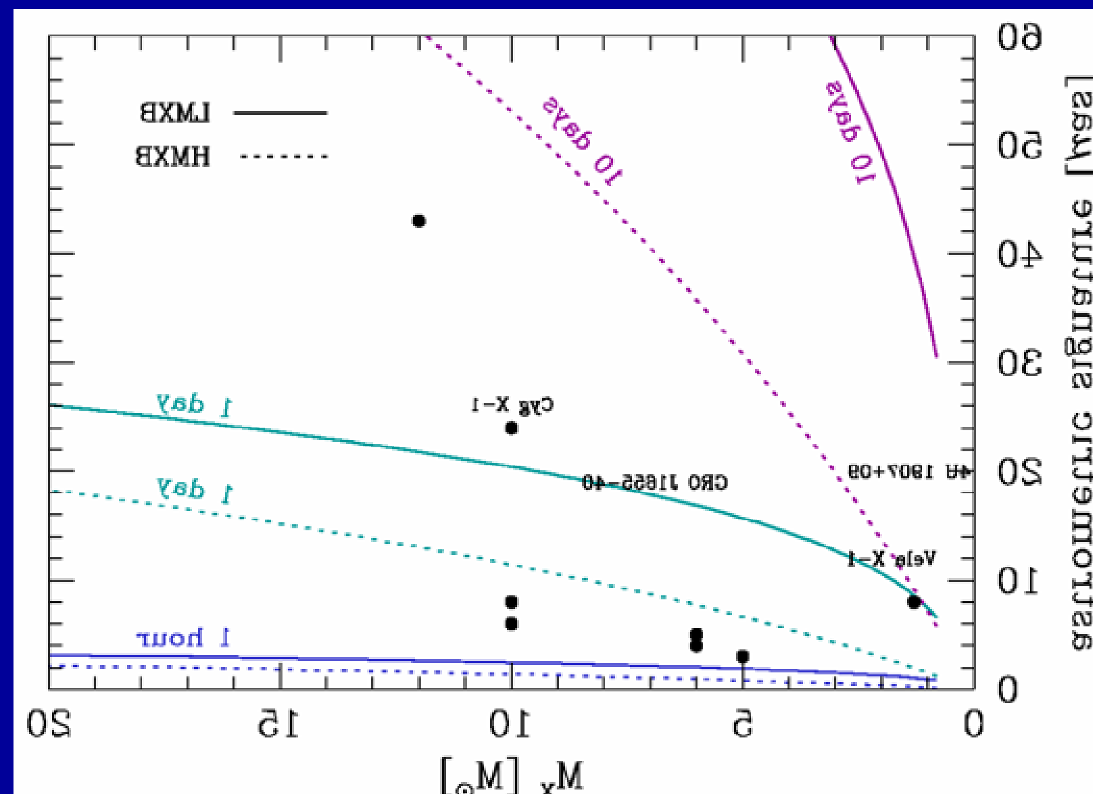
- Calibration of Cepheids and RR Lyrae stars
- Ages of globular clusters and metal-poor stars
- Luminosities of neutron stars and black hole candidates



10% accuracy at 25 kpc

Orbits of X-Ray Binaries



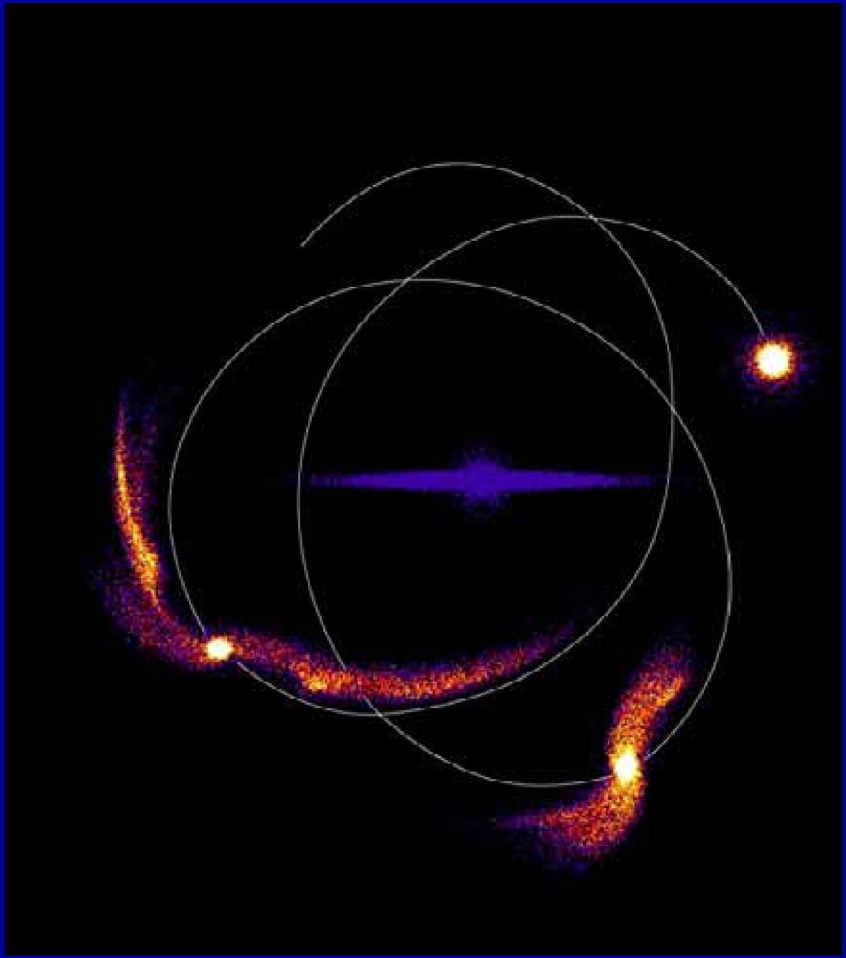


X-Ray Binary Science with SIM

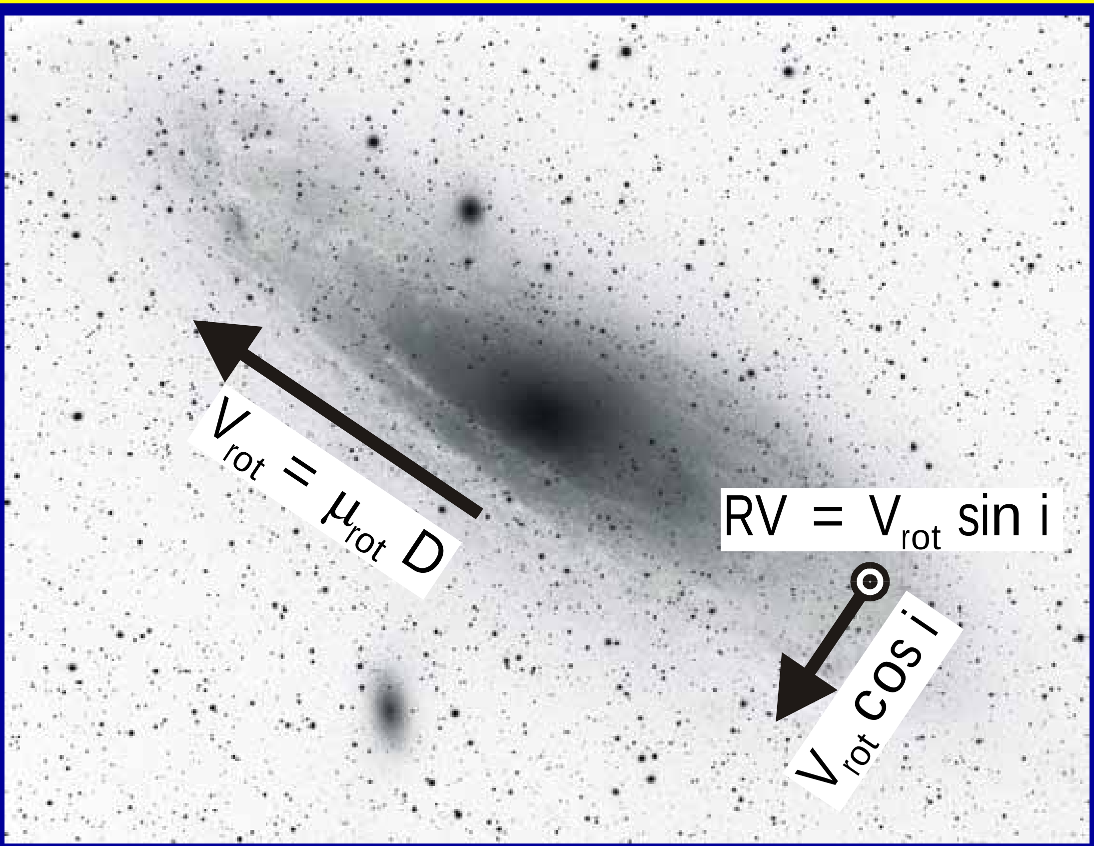
- Mass function of Black Hole Candidates
- Existence of black holes with $M \leq 5\ M_\odot$ formed via accretion-induced neutron star collapse?
- Existence of black holes with $M \geq 20\ M_\odot$ whose progenitors retained most of their mass until collapse?
- Mass of Neutron Stars: constraints on nuclear equation of state
- Luminosities from parallaxes: test of models (existence of event horizon in BHCs, ADAF 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

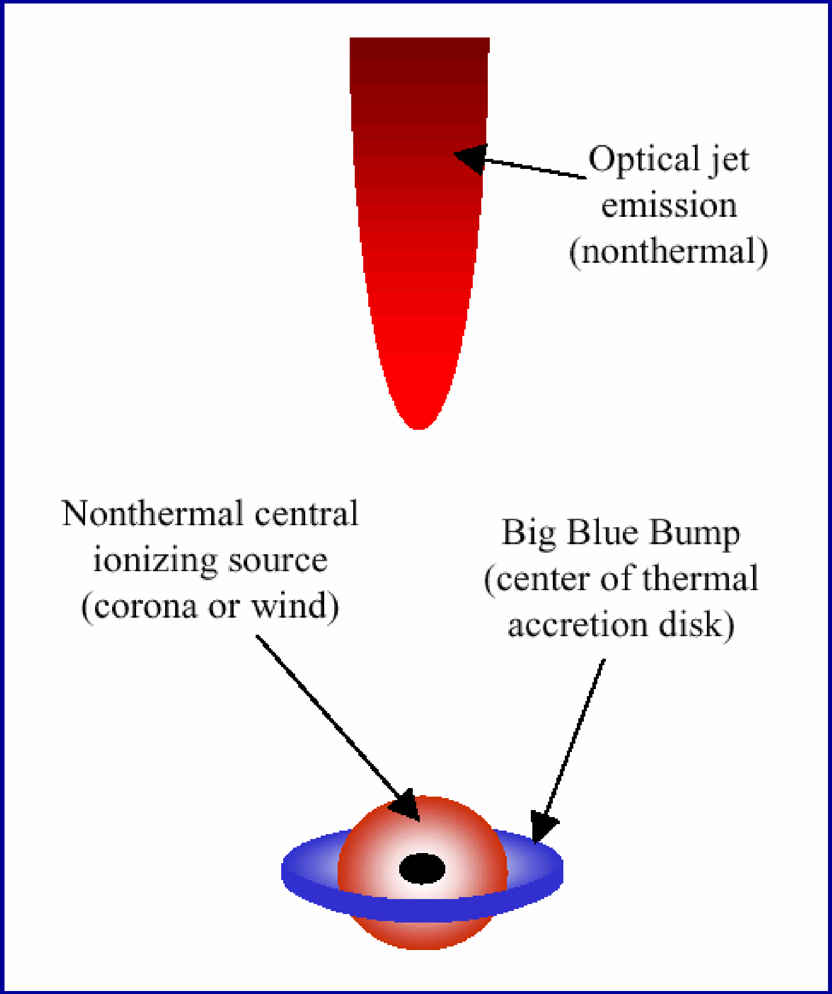


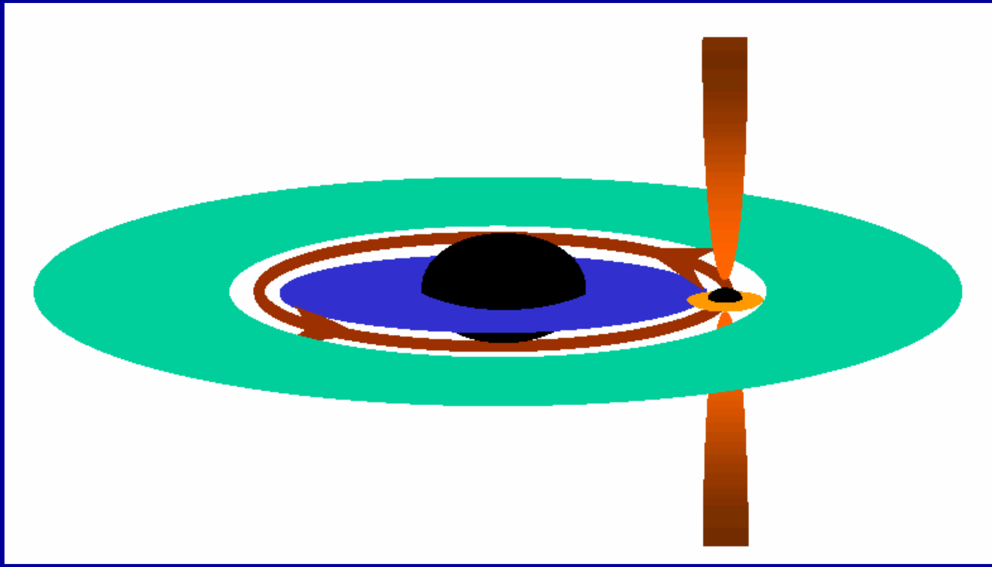
Rotational Parallax ⇒ Distance to Andromeda



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

"Proper Motion" of Quasars





Interferometric Imaging

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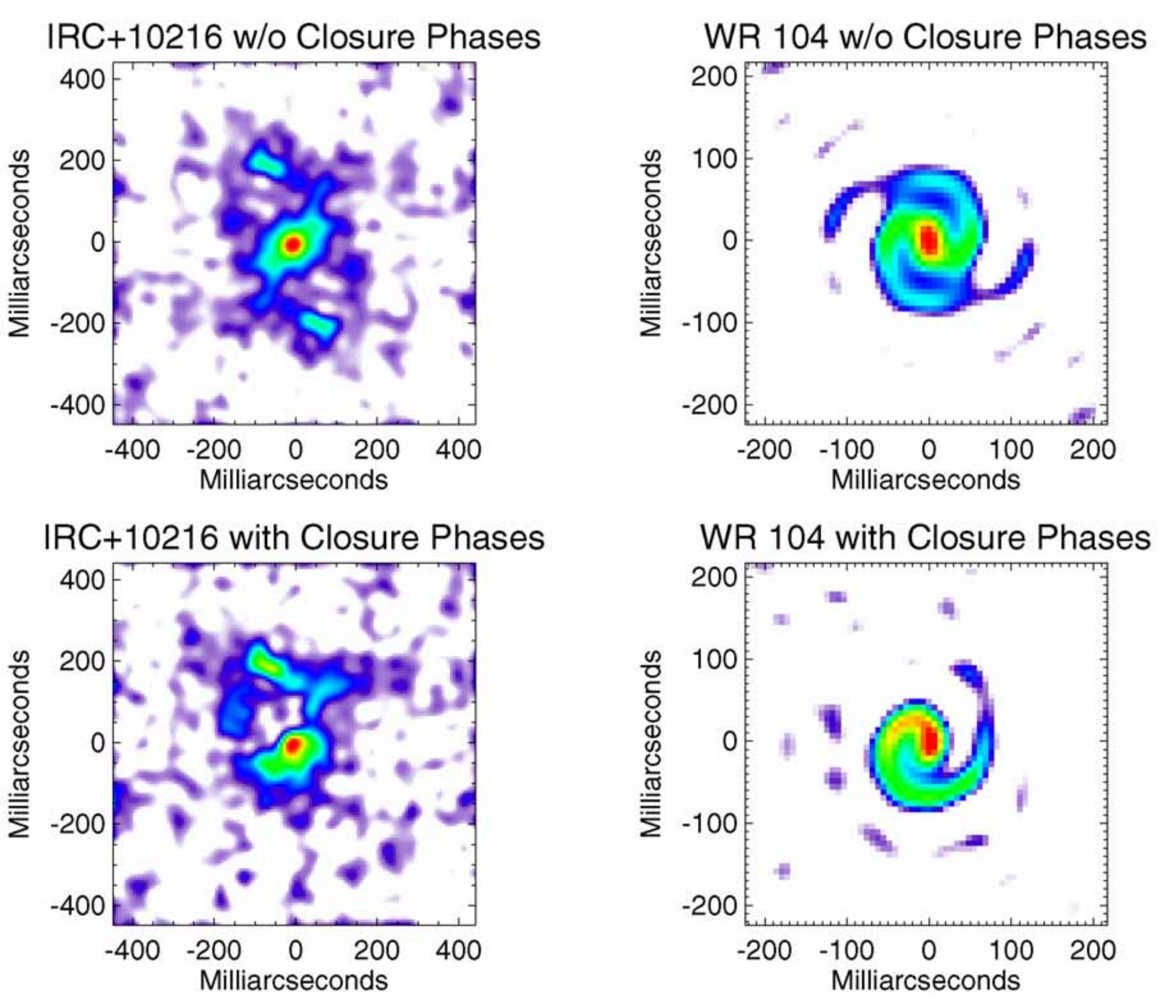
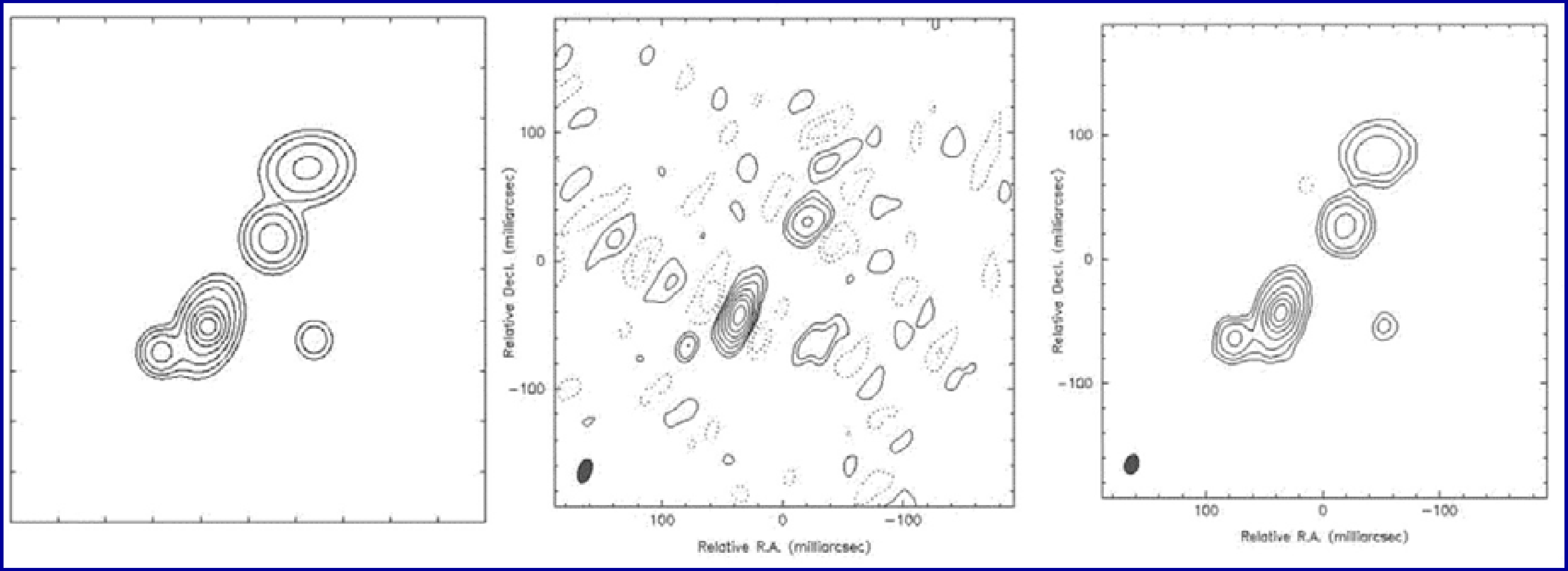
Images from Keck Aperture Masking (Tuthill et al.)

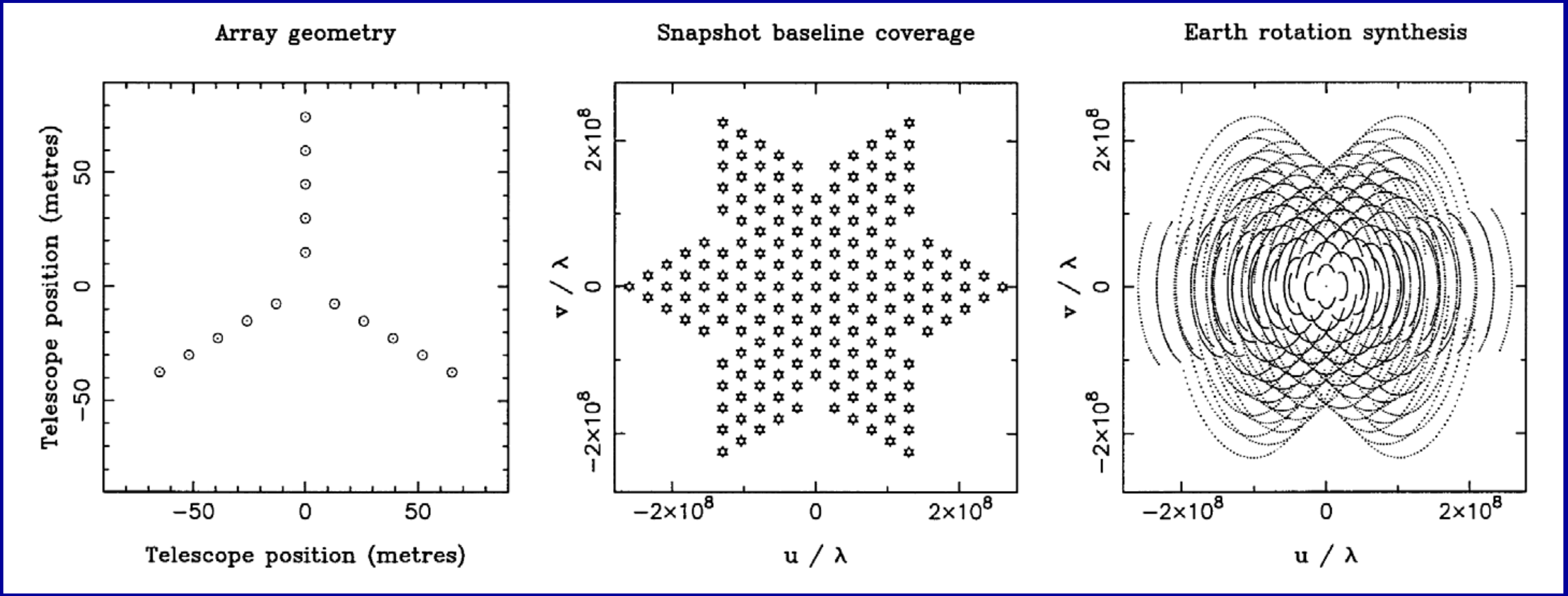


Phase information is needed to recover asymmetric structure.

VLTI Imaging Simulation with Four and Eight Telescopes



A Y-Shaped Configuration

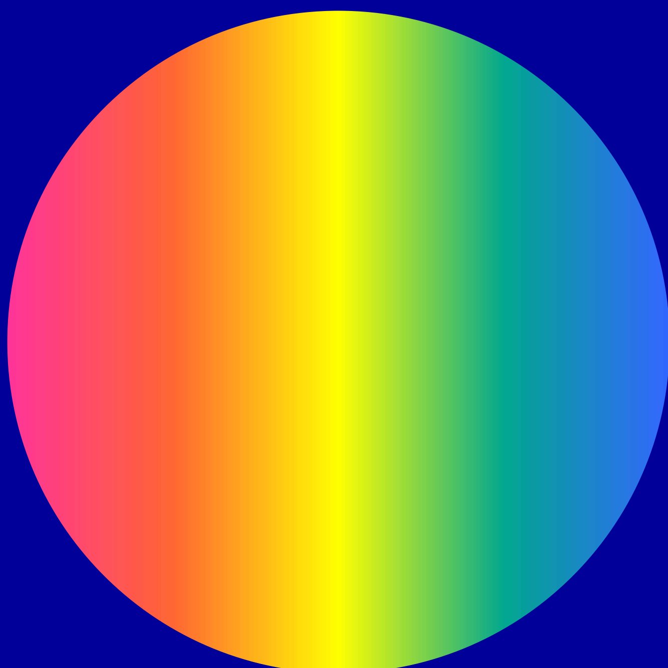


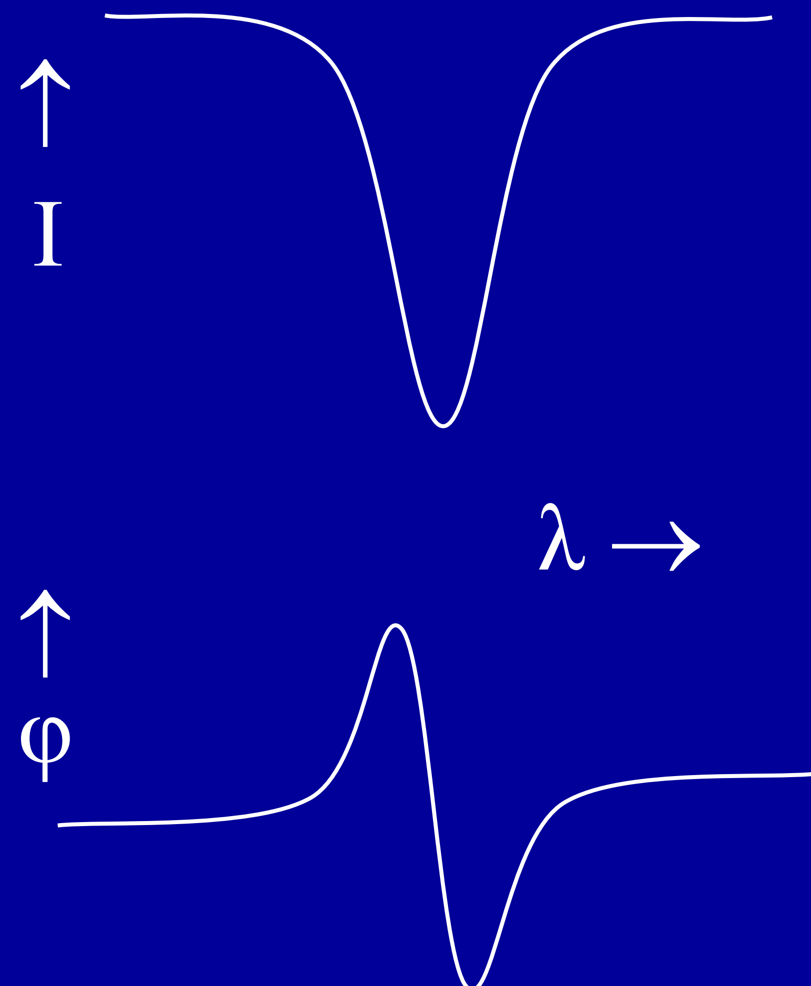
Aerial View of the NPOI Array

Interferometric High-Resolution Spectroscopy

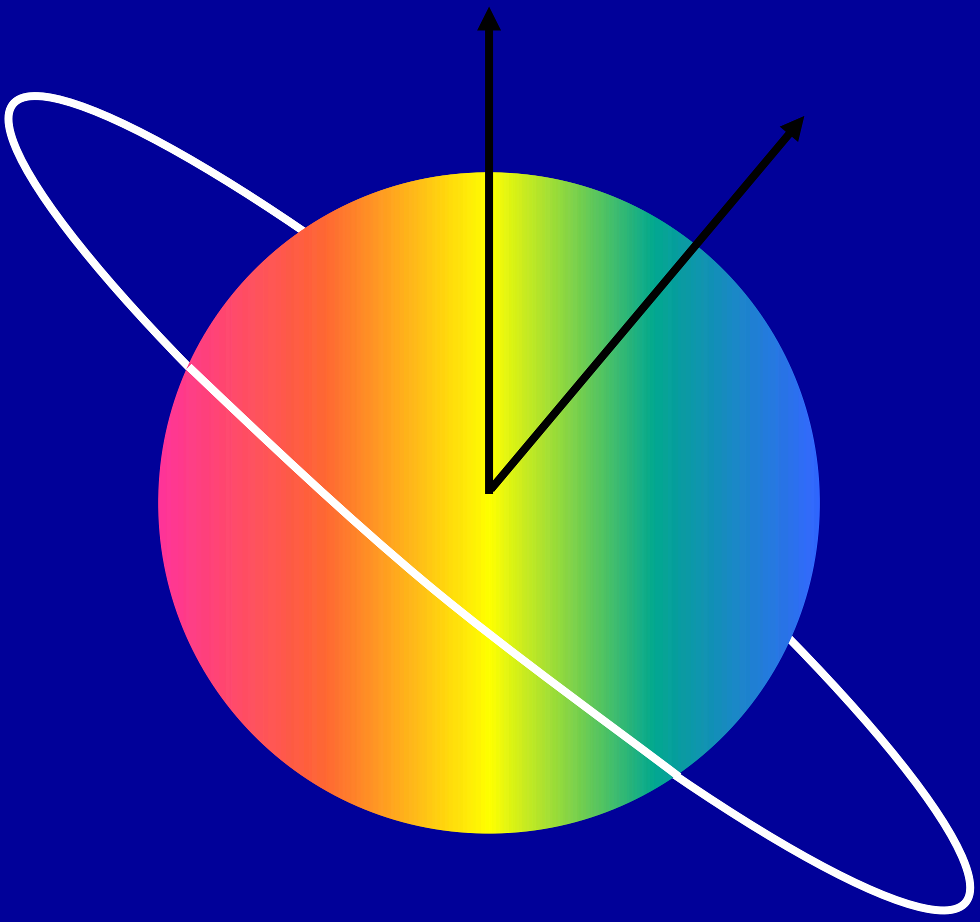
- Combination of interferometry with high-resolution spectroscopy is very powerful
  - Limb darkening profiles in absorption lines $\rightarrow$ tests of stellar atmospheres, calibration of projection factors in Cepheid measurements
  - Phase shift across absorption lines $\rightarrow$ orbits of very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

Interferometer Phase across Stellar Absorption Line





Combination of Astrometry with Spectro-Interferometry



Information from Orientation of Rotation Axis

- Alignment of components in wide binary systems
  - Mechanism of binary star formation
  - Angular momentum distribution in multiple systems
- Orientation of planetary orbit with respect to stellar rotation axis
  - Correlate with planetary masses, orbital eccentricities
  - Probe eccentricity pumping mechanisms

Spectroscopy of Extrasolar Planets

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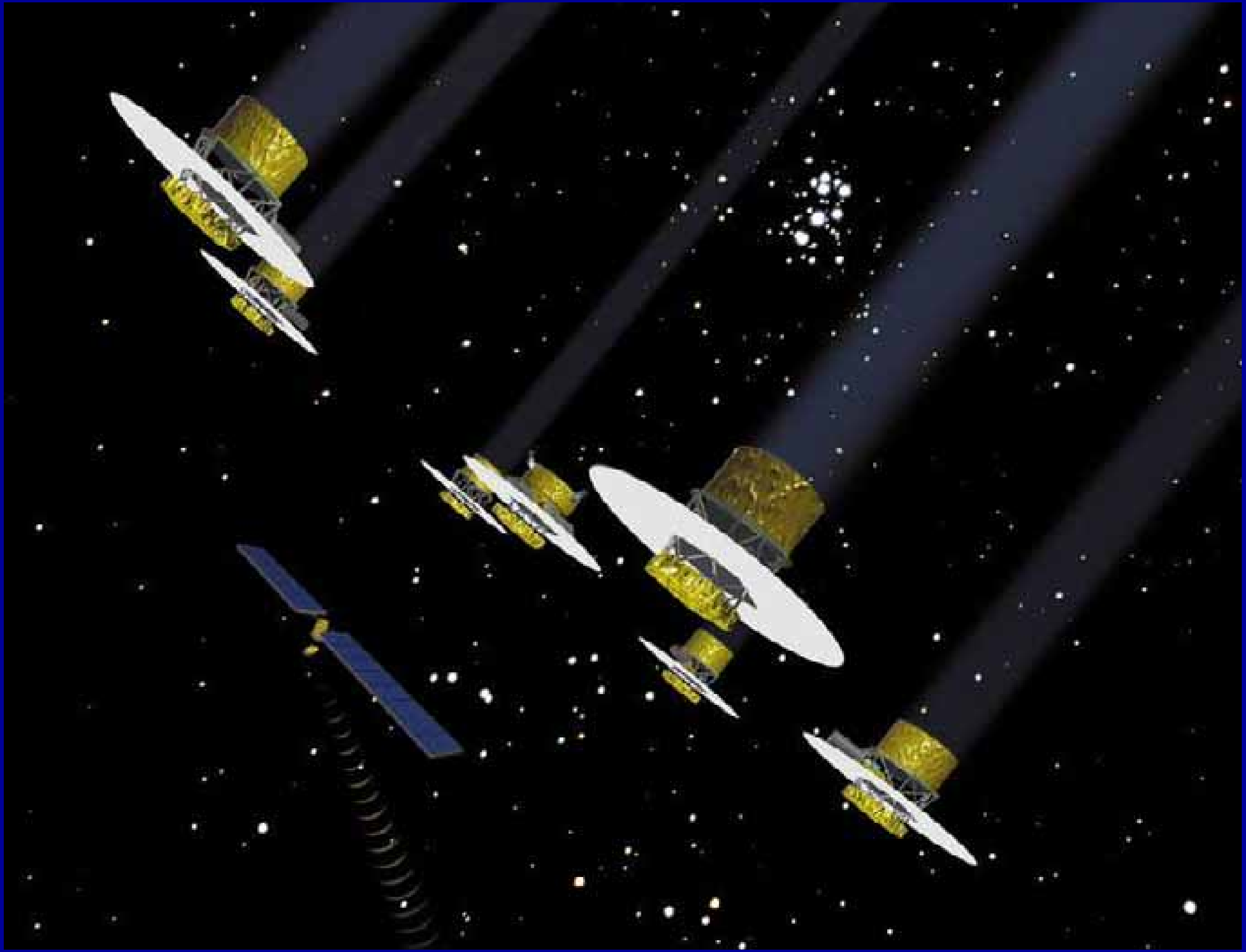
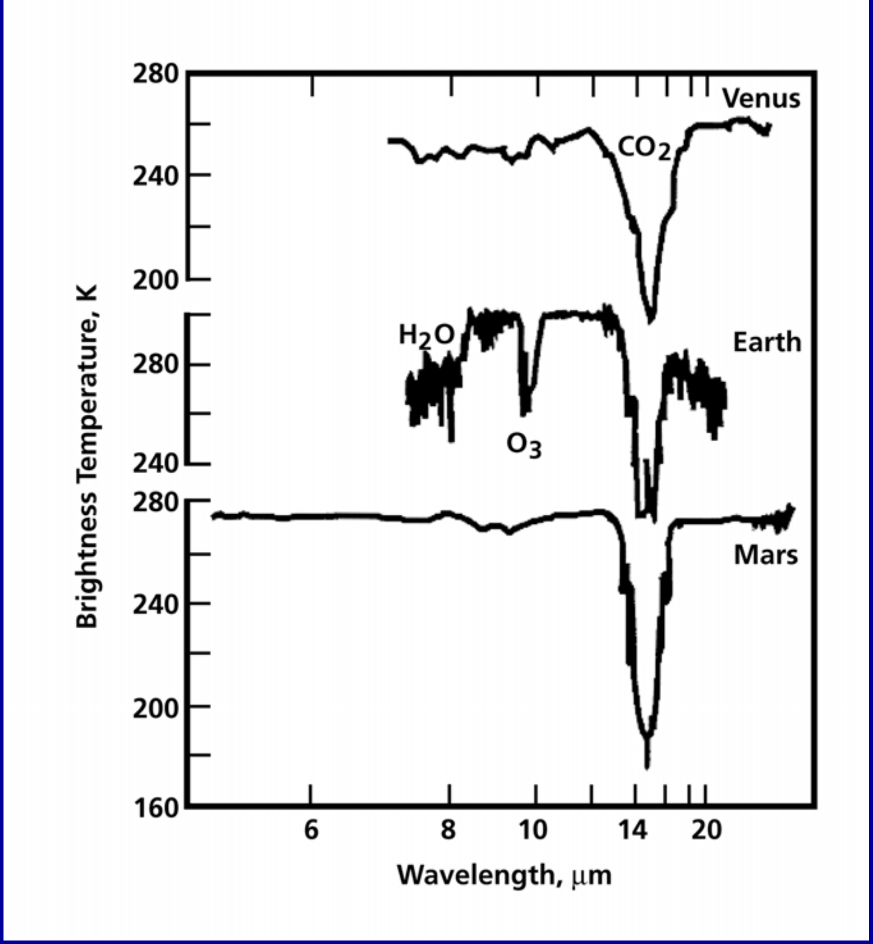
The DARWIN Interferometer (ESA, after 2012)

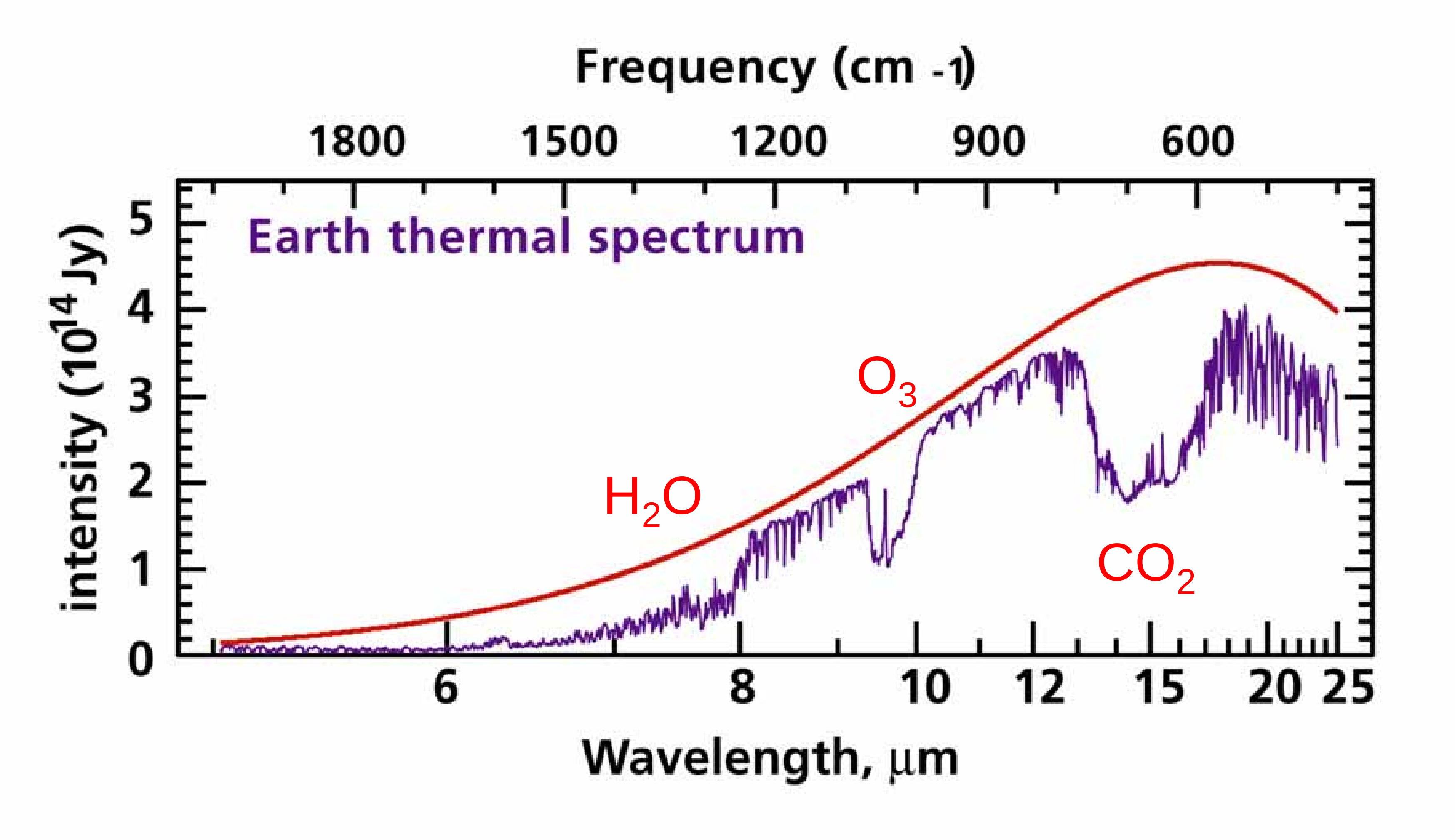


Infrared Spectra of Venus, Earth, and Mars

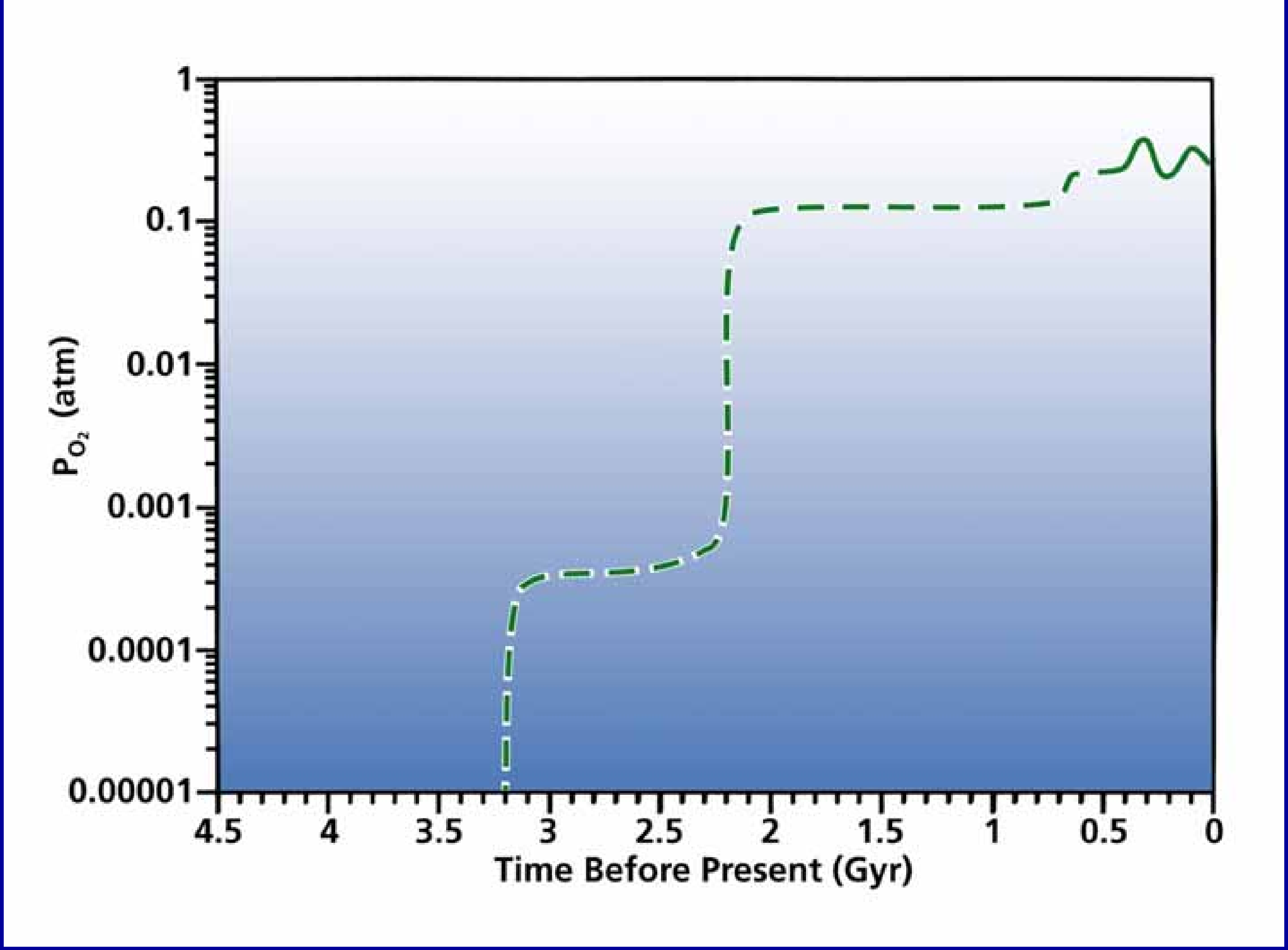
- Venus looks cold ⇒ cloud cover
- Mars is cold ⇒ no liquid water
- Earth is warm ⇒ liquid water and oxygen
- Note presence of CO_2 in all three cases



Infrared Spectrum of Earth

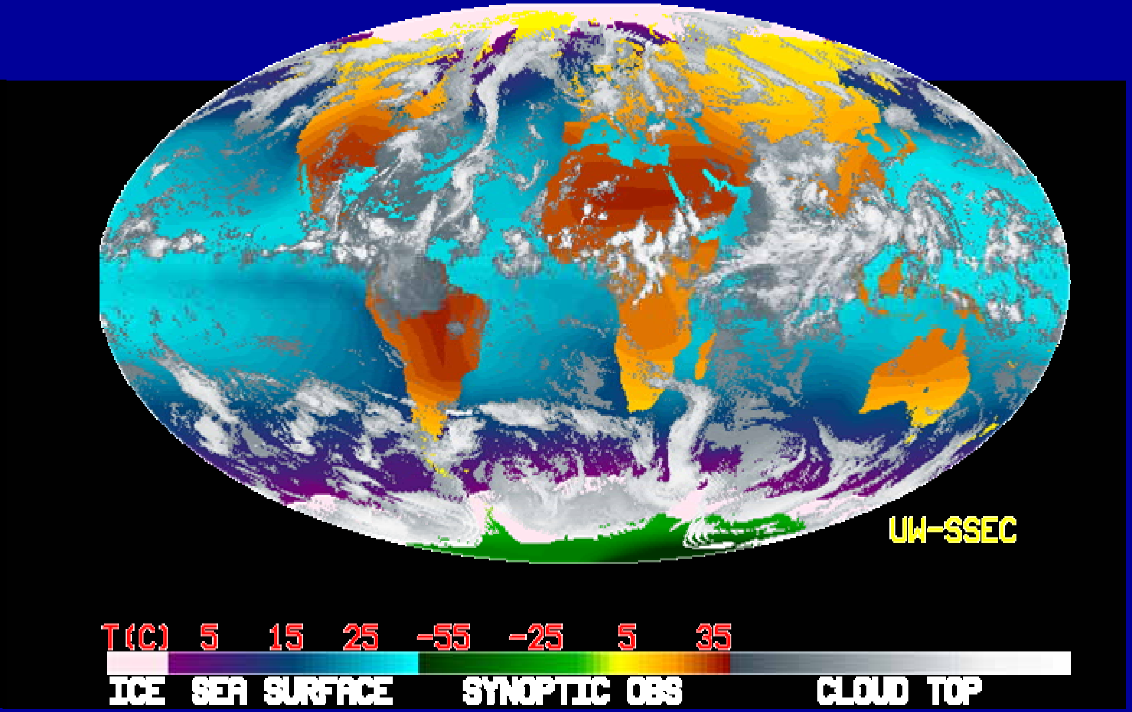


History of Oxygen in Earth's Atmosphere (Kasting et al.)

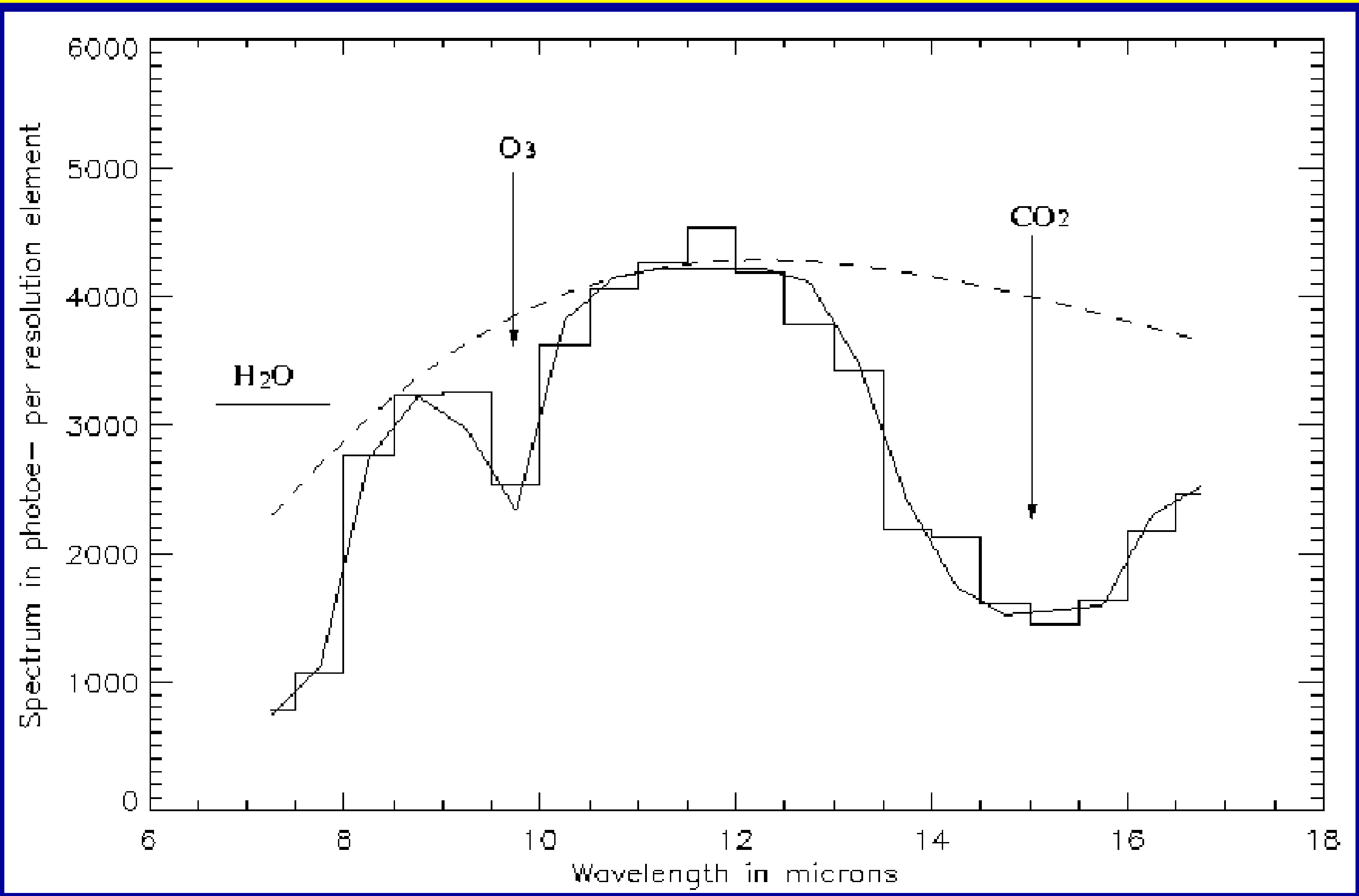


Temporal Variation

- Spectra will vary because of cloud variation, seasonal variation and rotational period; useful information might be derived from these variations.



Simulated Spectrum of Exo-Earth Observed with DARWIN



Dreams for the Future

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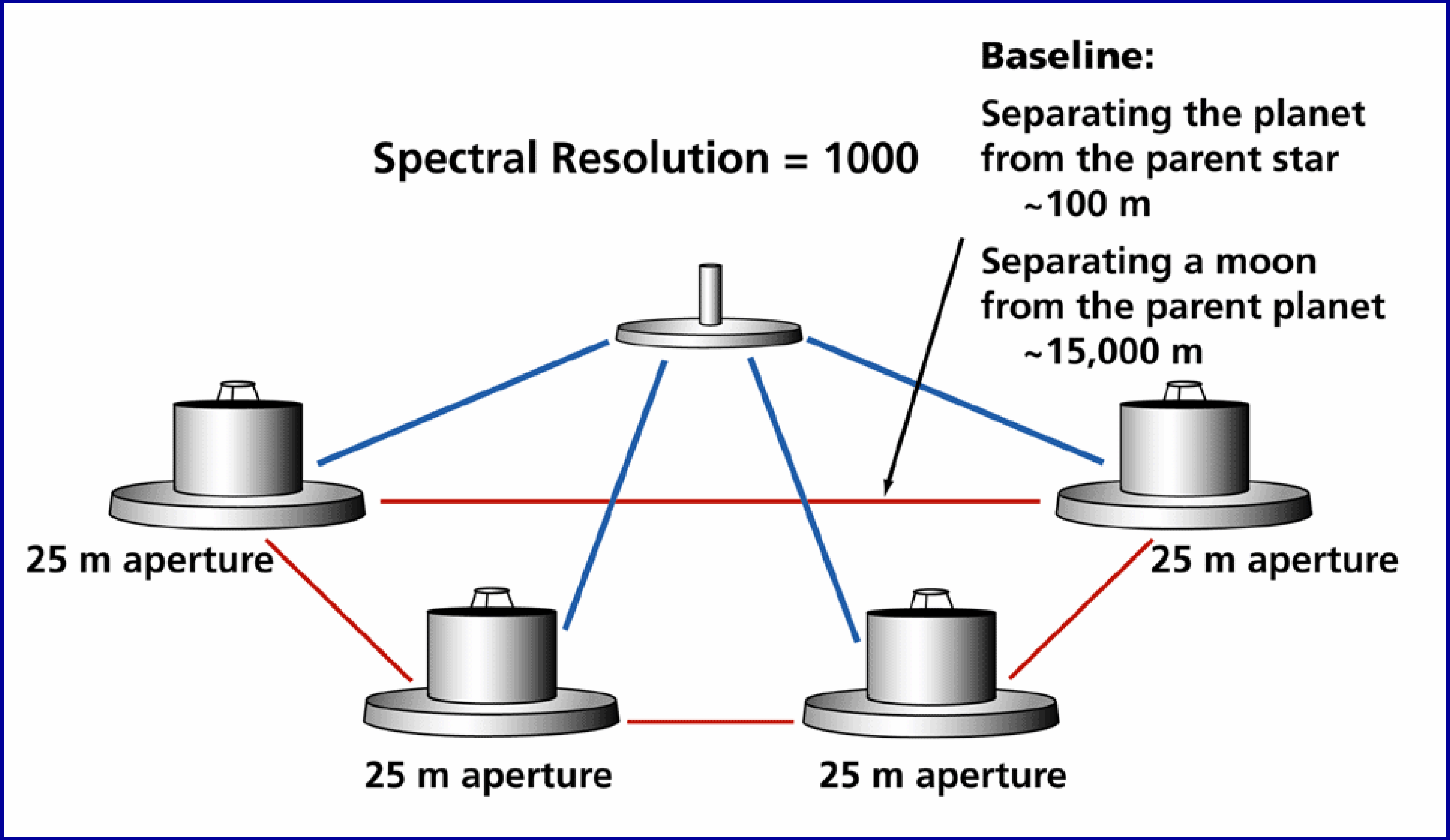
ELSA Concept

- Number of telescopes: 20
- Telescope diameter: 10 m
- Maximum baseline: 5 km
- Wavelength range: 500 nm … 20 μm
- Beam transport: Single-mode fiber bundles

ELSA Resolution: 20 μas at 500 nm

- 30,000 km at 10 pc
  - 4 pixels across Jupiter-size object
  - 40 pixels across Solar-type star
- 0.2 AU at 10 kpc
  - GR effects on stars very close to the Galactic Center
- 200 AU (1 light-day) at 10 Mpc
  - Images of AGN Broad-line regions
  - Expansion and light echoes of supernovae

Darwin / TPF ++



Baseline:
Separating the planet from the parent star ~100 m
Separating a moon from the parent planet ~15,000 m
Spectral Resolution = 1000
25 m aperture
25 m aperture
25 m aperture
25 m aperture

Exo-Earth Imager