Introduction to Optical / Infrared Interferometry

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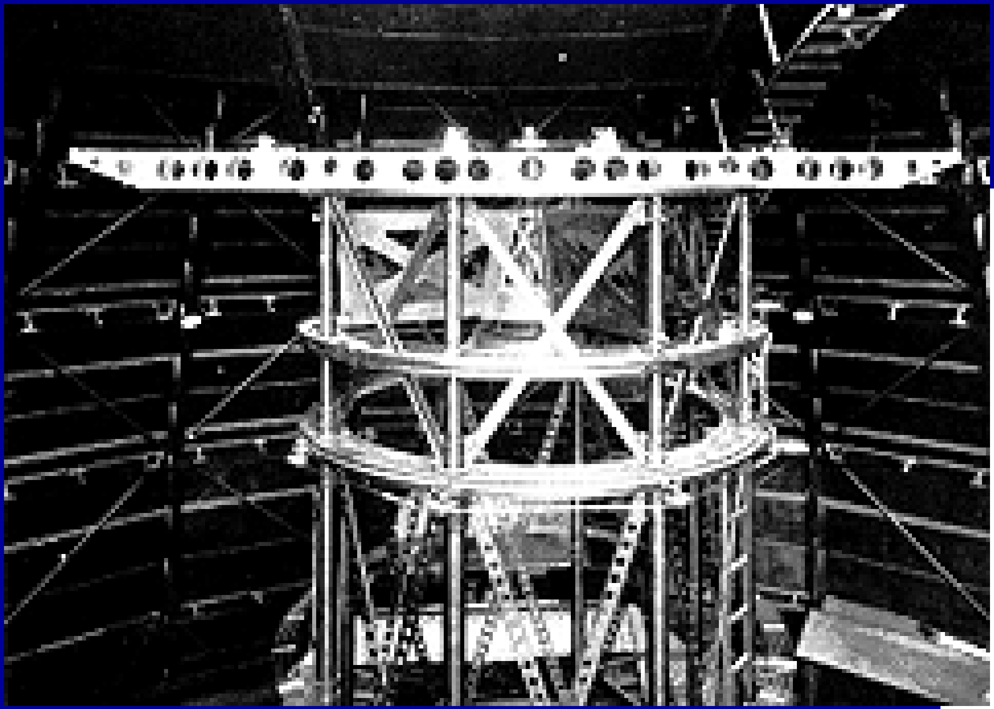
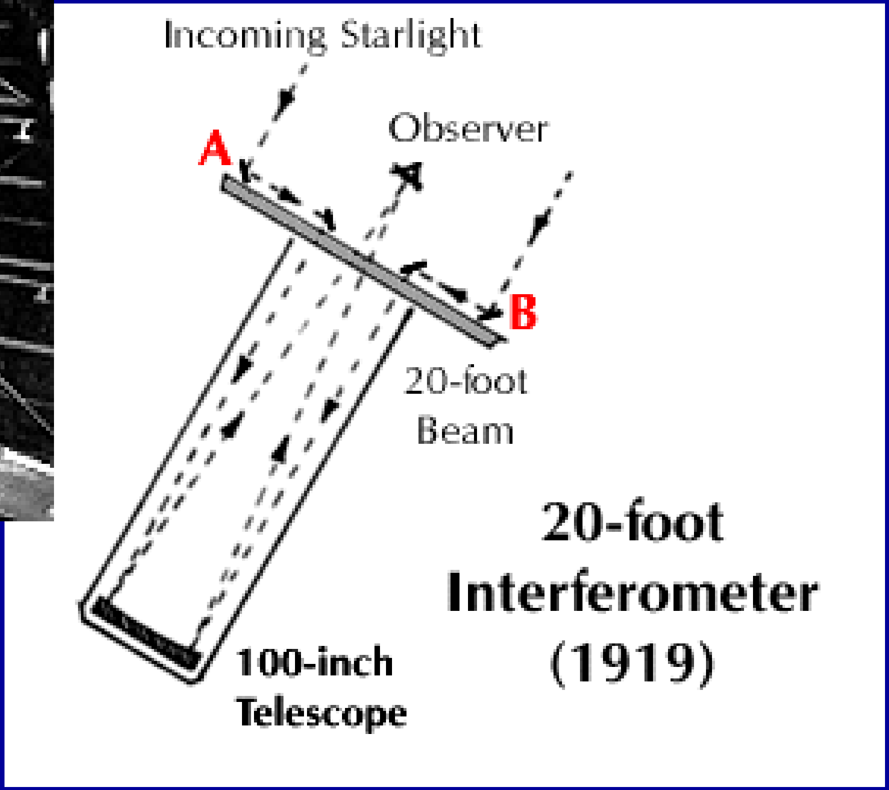
Why Build a Stellar Interferometer?

- 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.
- Now also fainter objects (AGN etc.)

Michelson's 20 Foot Interferometer on Mt. Wilson





Observing in the Old Days

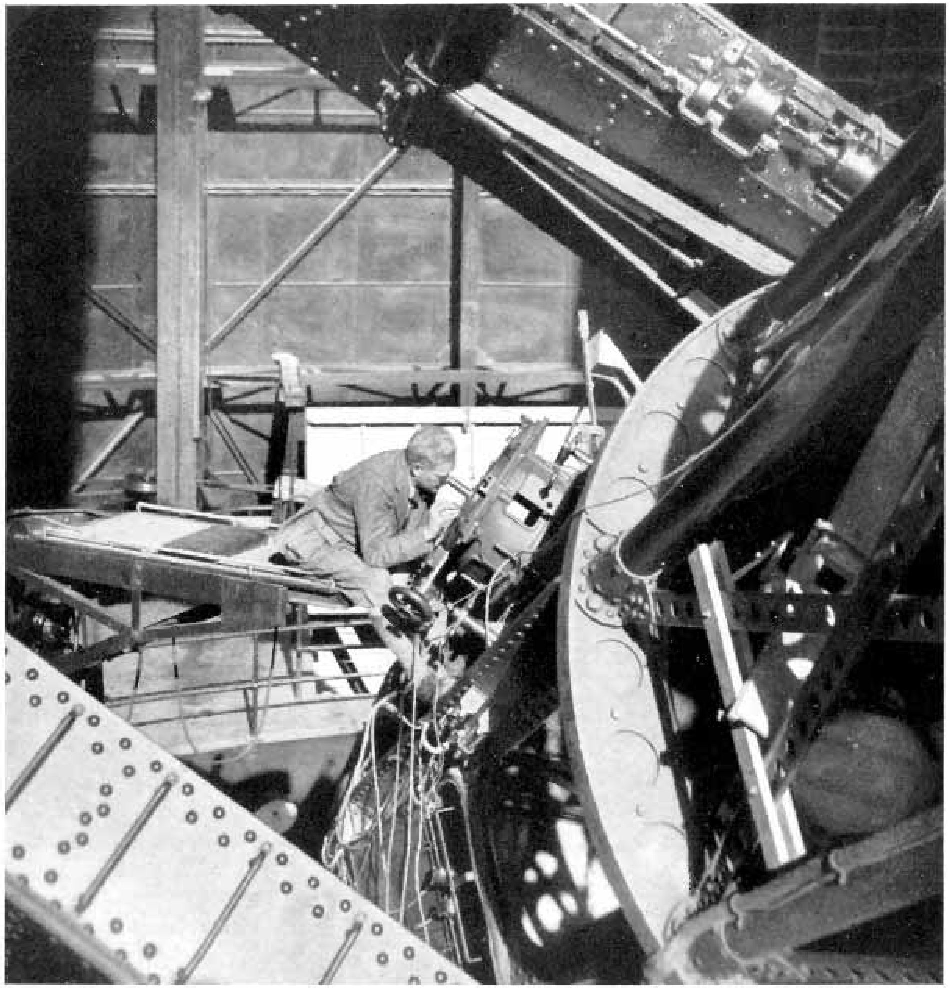
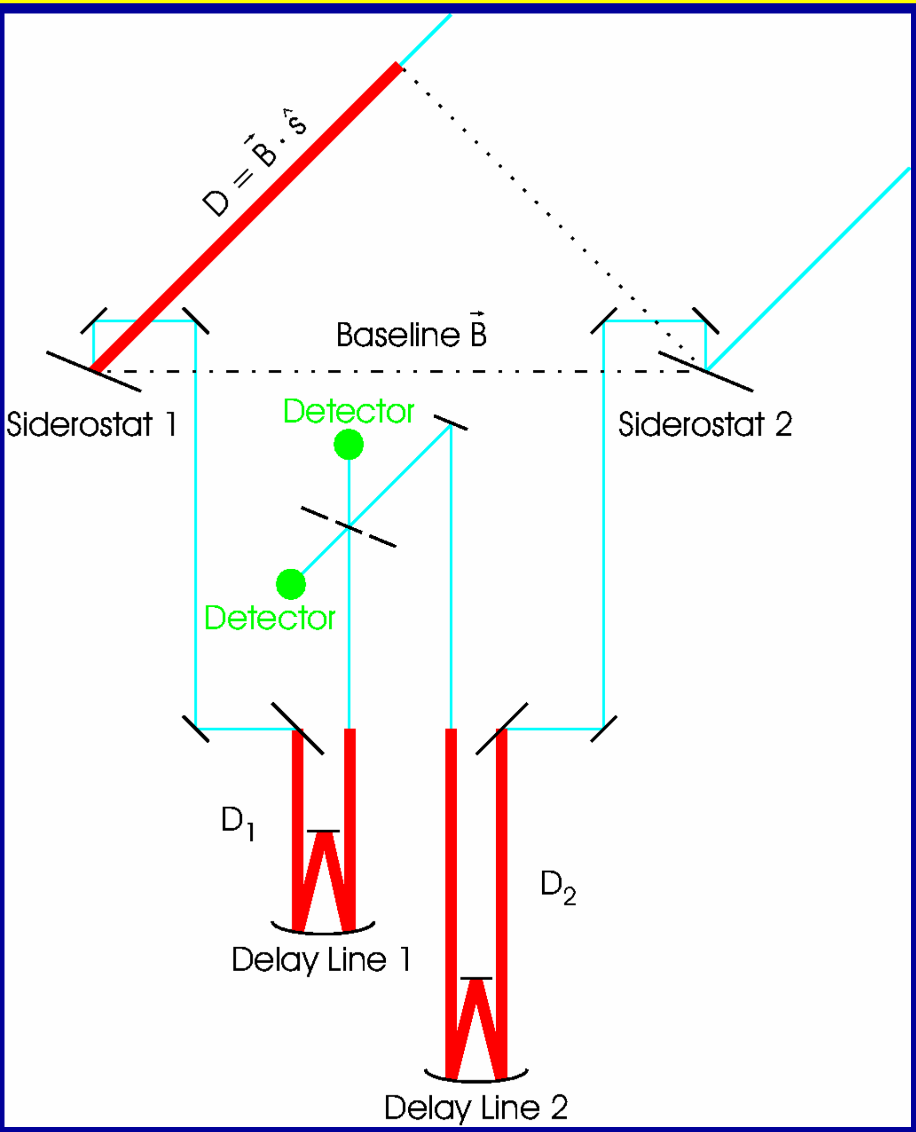


Abb. 3. Showing observer at eyepiece of 20 foot interferometer.

Schematic Layout of Michelson Interferometer

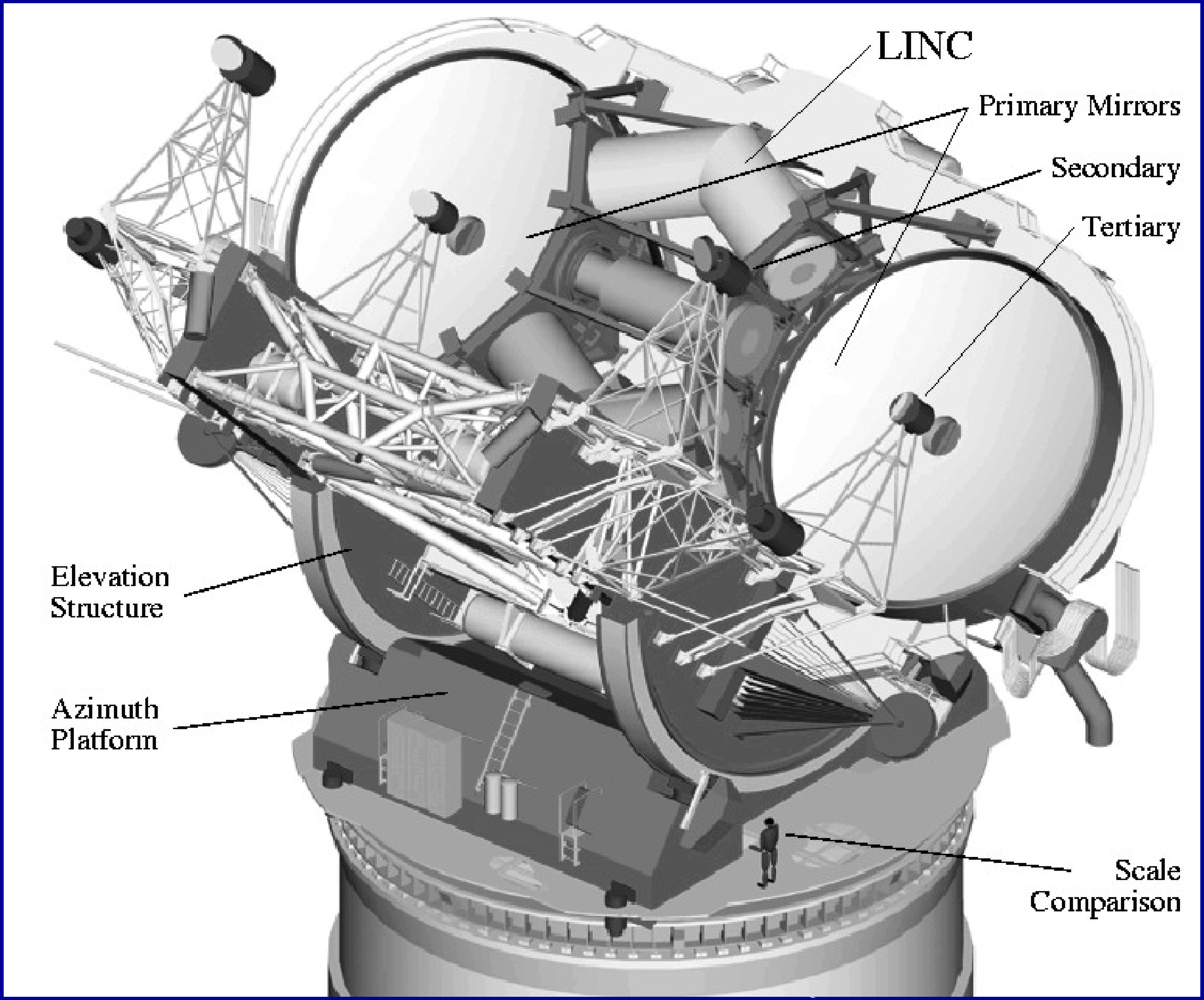


The Mark III Interferometer

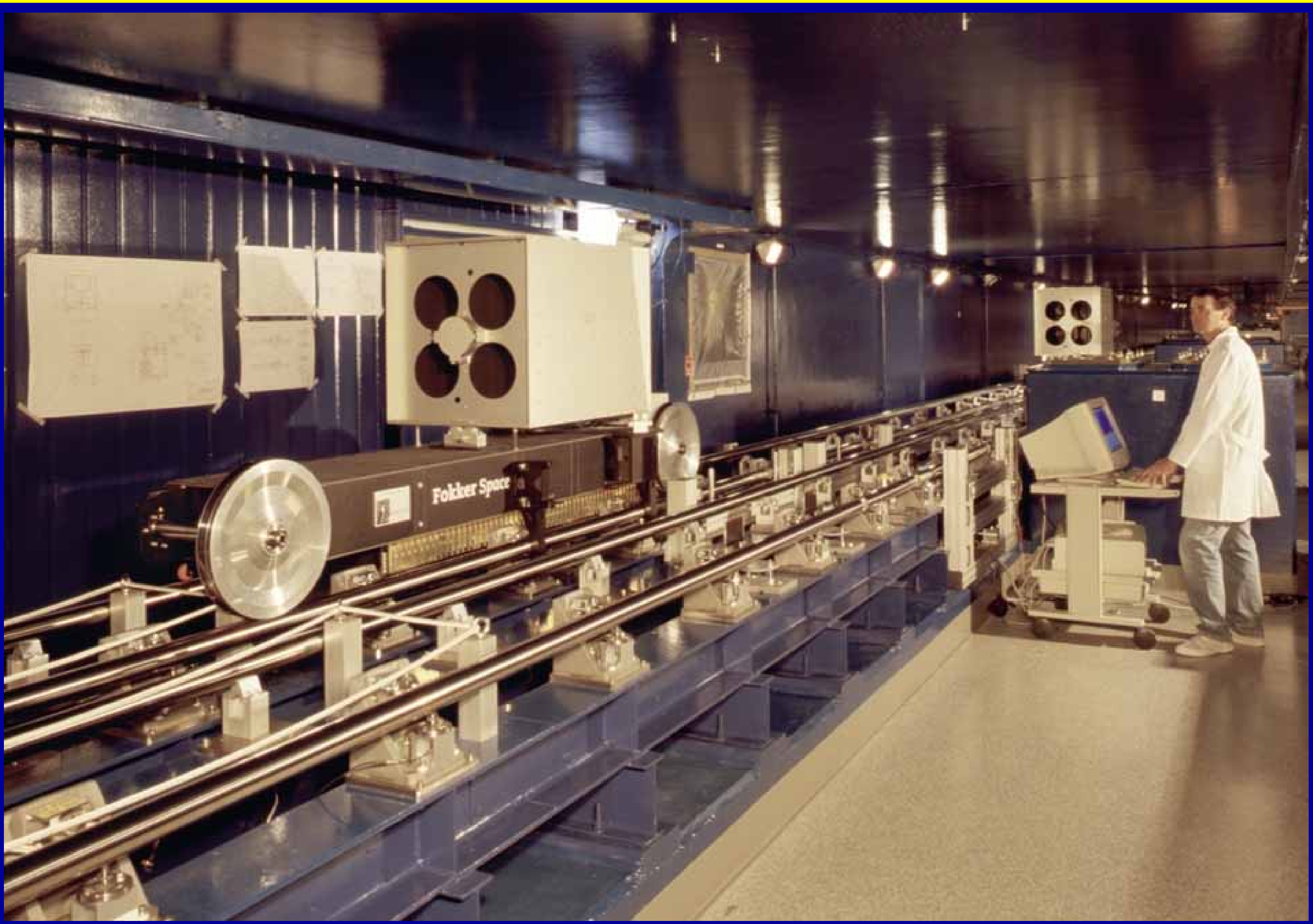
The Twin Keck Telescopes on Mauna Kea (Hawaii)

The VLT Interferometer

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



VLTI Delay Lines



Fringes and Fringe Detection

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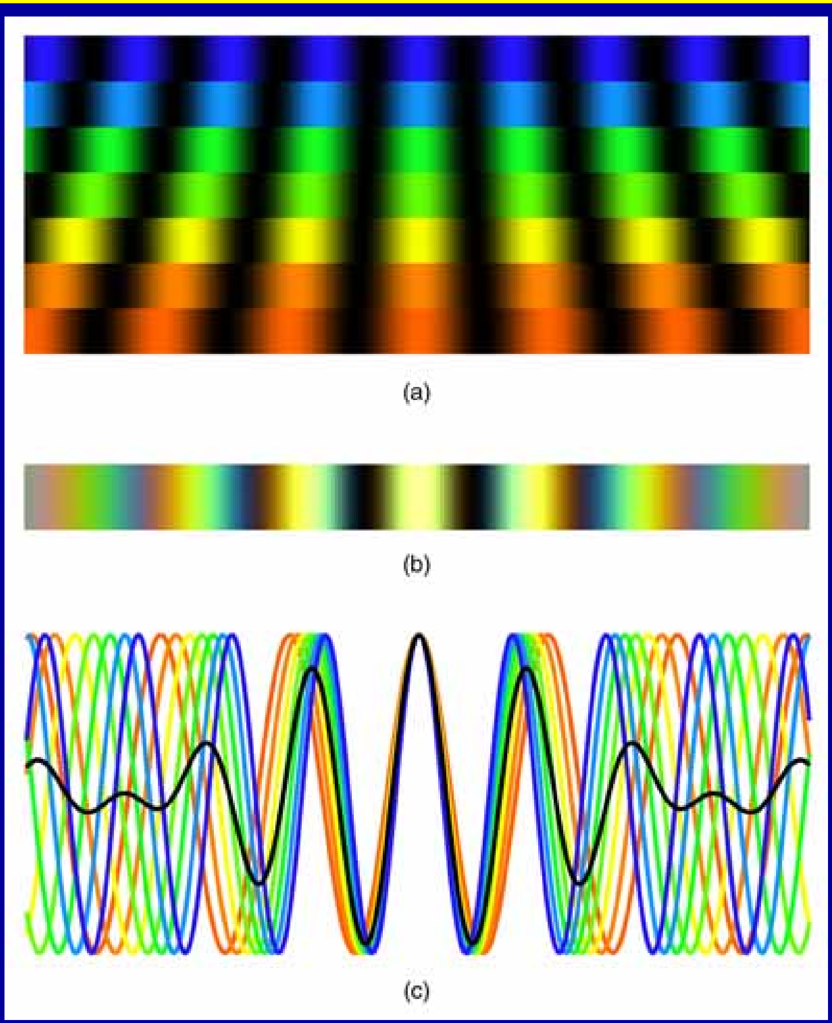
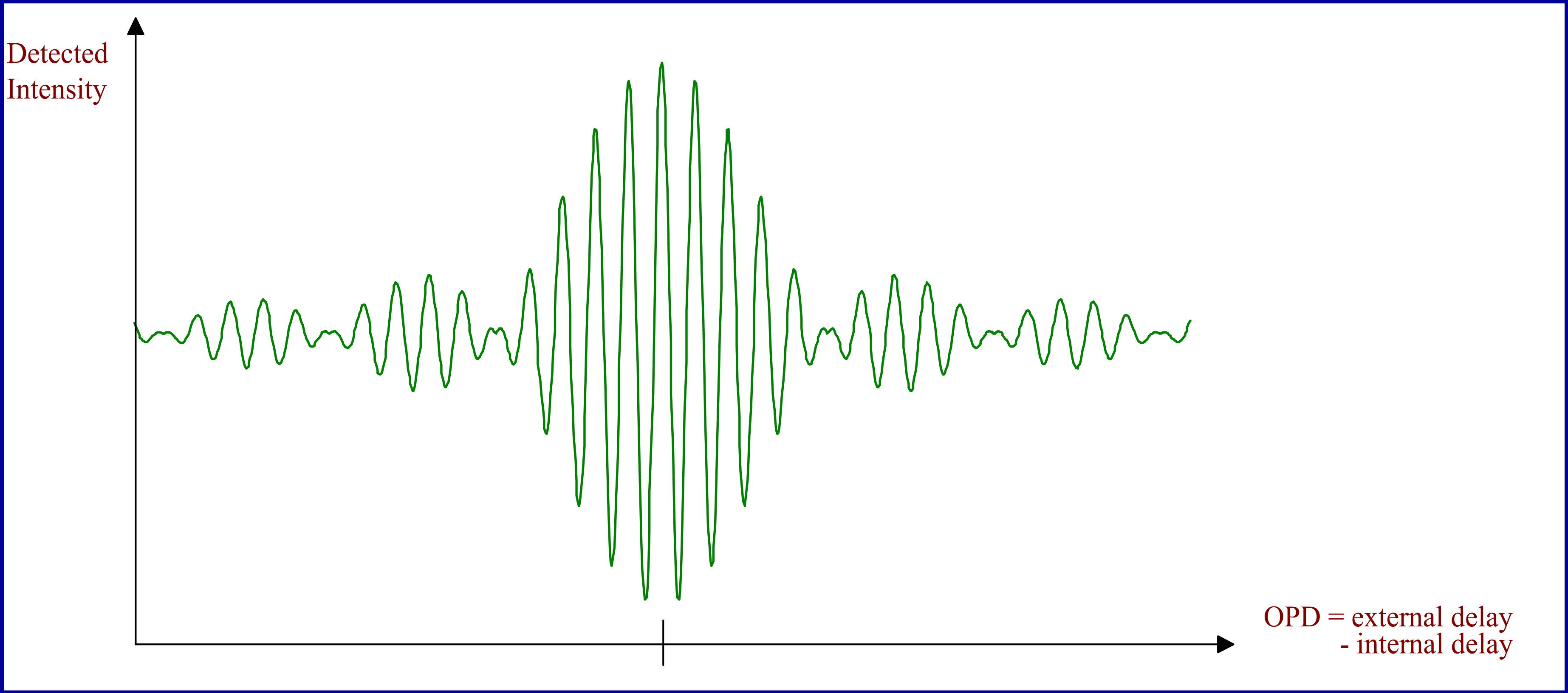
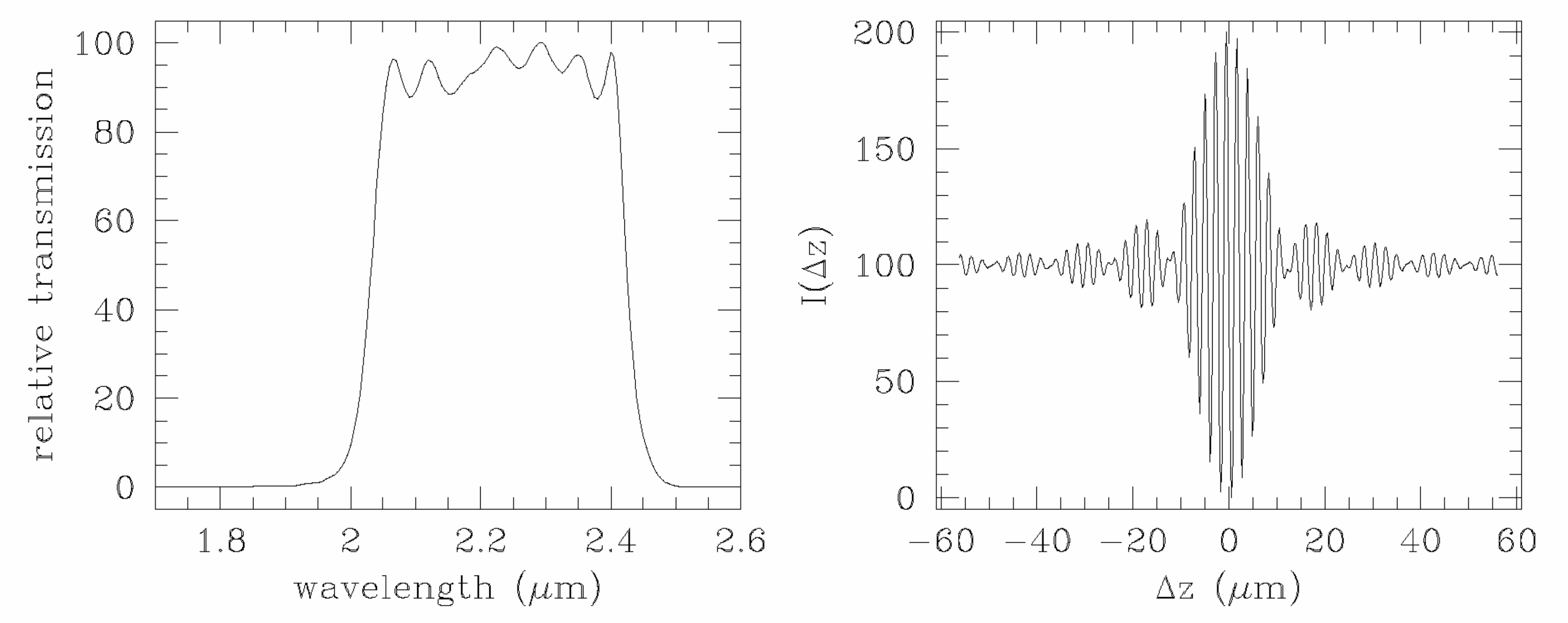
Channeled Spectrum and White-Light Fringes



Scanning the Delay Line through the Fringe Packet

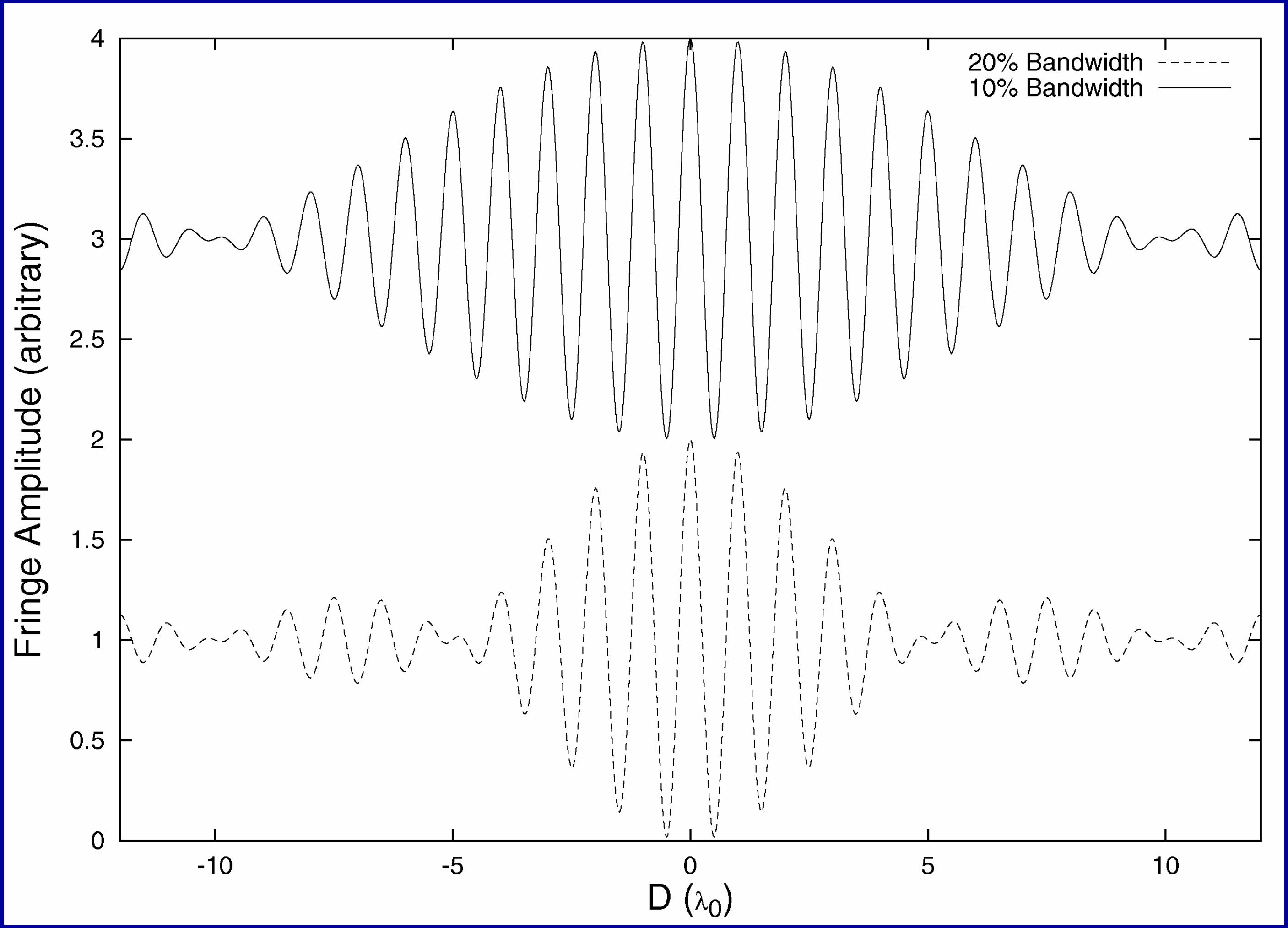


Fringe Envelope is Fourier Transform of Spectrum

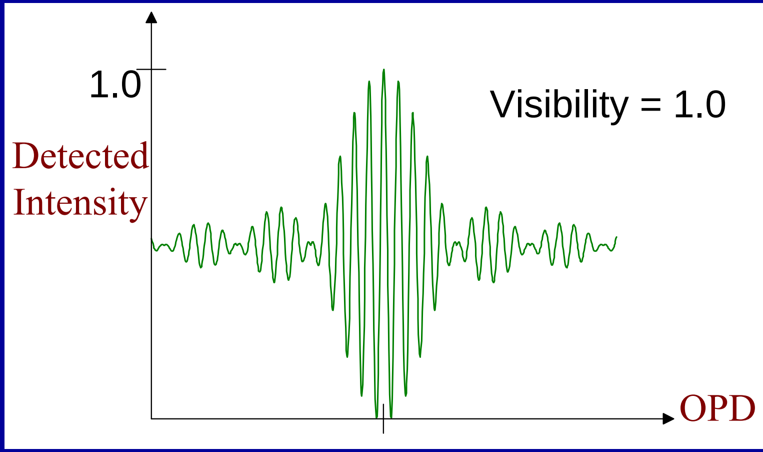


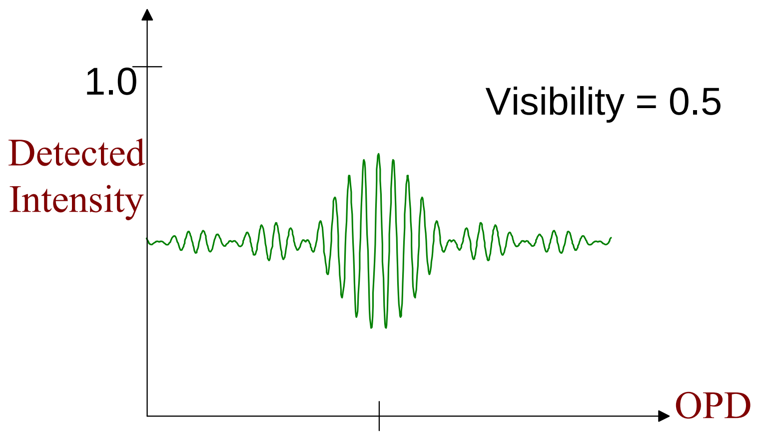
Nearly rectangular bandpass ⇒ sinc modulation

Effect of Bandwidth on Fringe Envelope



Visibility Amplitude





- Visibility amplitude is related to size of object and baseline length (Fourier relation).
- Visibility can be reduced by imperfections in the interferometer ⇒ need for calibration.

Fringe Visibility Defined

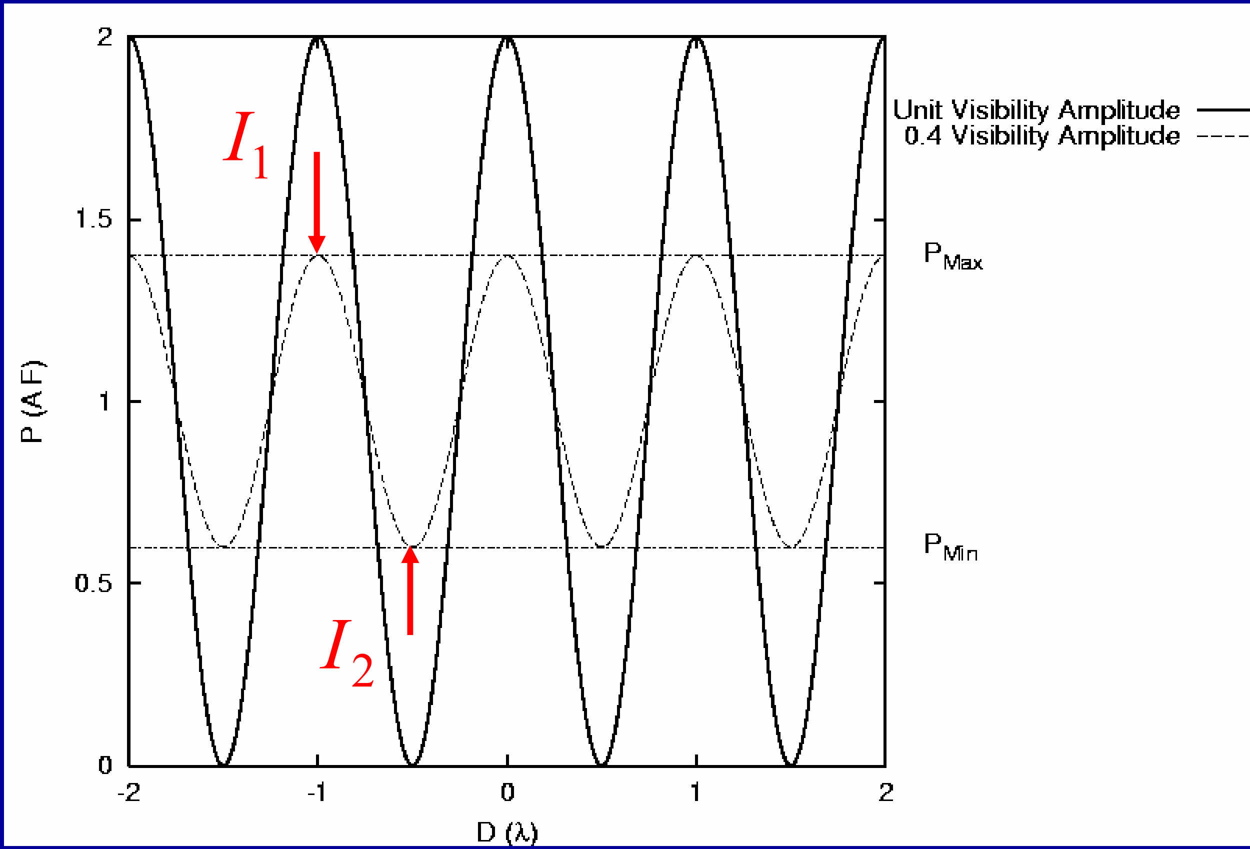
Visibility:

$$V = \frac{I_1 - I_2}{I_1 + I_2}$$

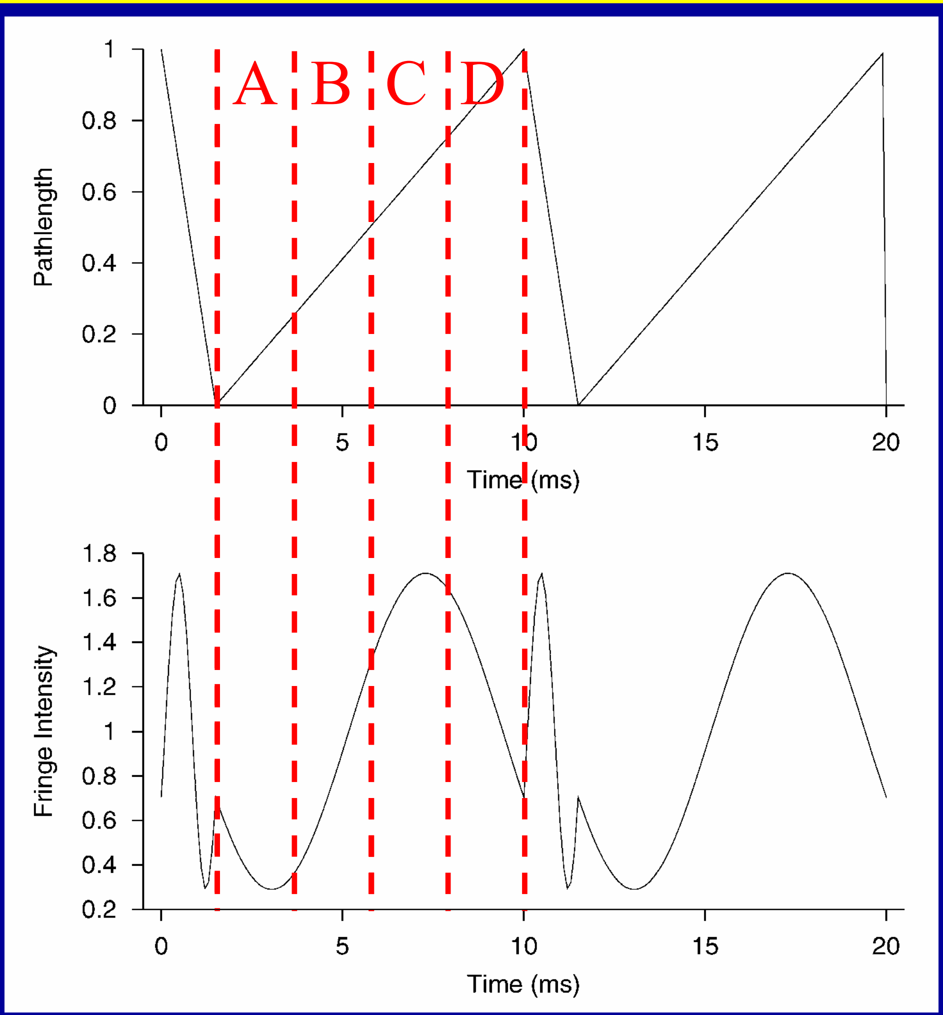
$I_1 =$ bright fringe

$I_2 =$ dark fringe

The visibility is a measure of the fringe contrast.



Example: Sawtooth Fringe Scanning



$$X := A - C$$

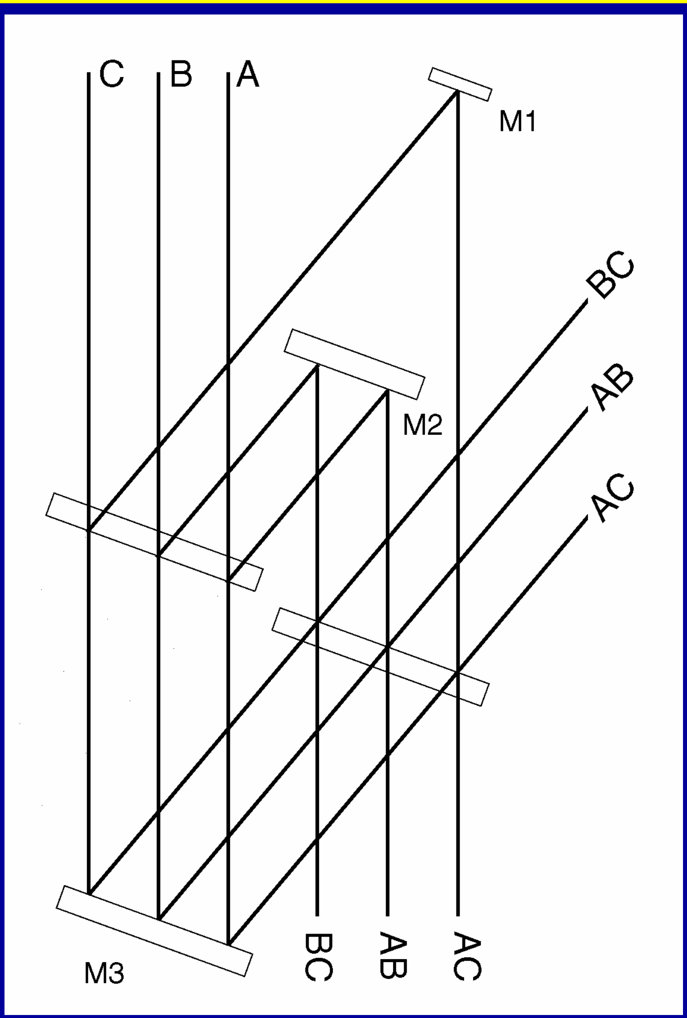
$$Y := B - D$$

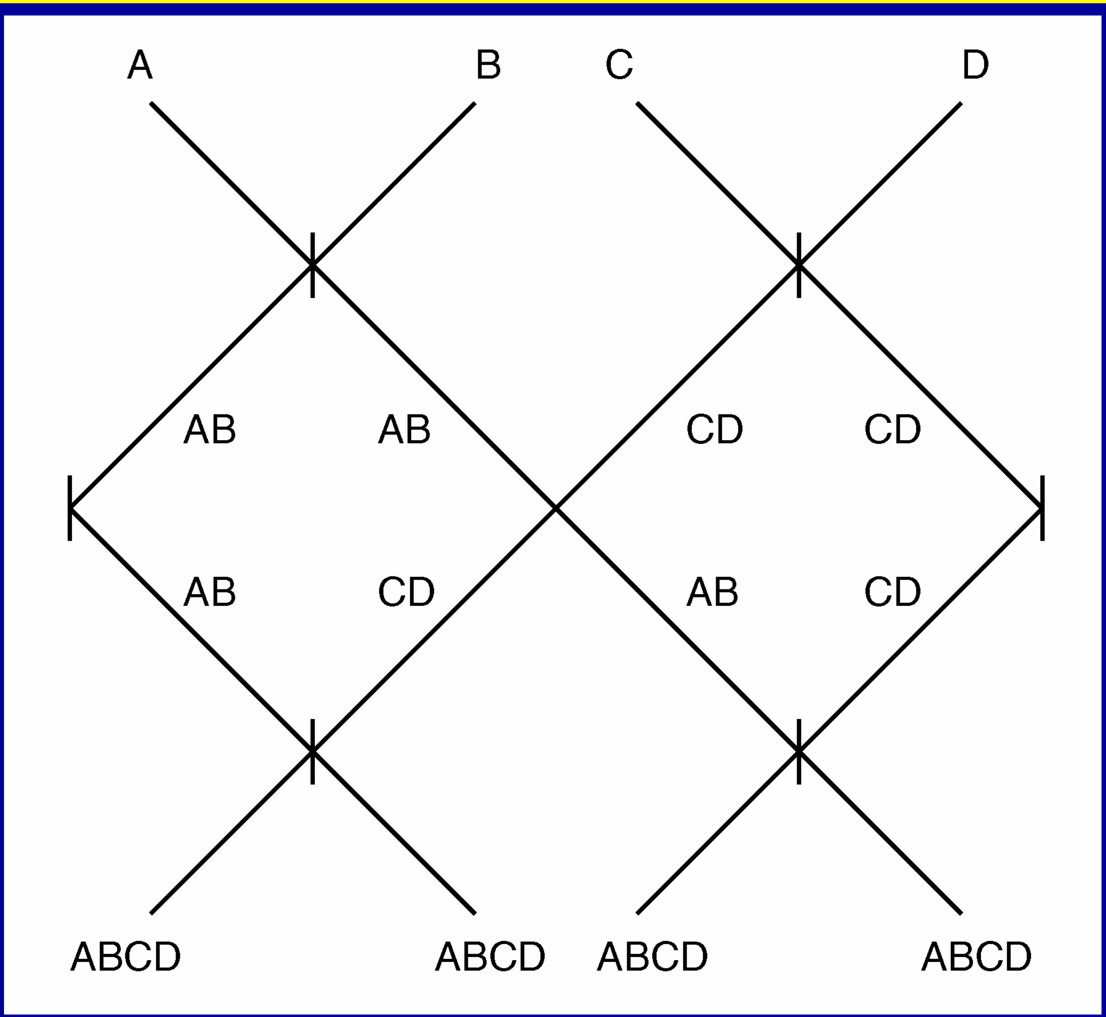
$$N := A + B + C + D$$

$$V^2 = \frac{\pi^2}{4} \frac{\left\langle X^2 + Y^2 - N \right\rangle}{\left\langle N - N_{dark} \right\rangle^2}$$

$$\varphi = \arctan \frac{Y}{X} - \frac{\pi}{4}$$

Multi-Baseline Pupil Plane Beam Combination





NPOI Six-Telescope Beam Combiner

Integrated Optics Three-Way Beam Combiner

Produced by LETI with silica-on-silicon etching technique

Bandwidth and Interfero-metric Field-of-View

- For monochromatic light, the interferometer response is:

$$F = \cos\left(\frac{2\pi D}{\lambda}\sin\theta\right) = \cos\left(\frac{2\pi D\xi}{\lambda}\right) \quad .$$

- For a rectangular bandpass with width $\Delta\nu$, the response is:

$$F(\nu_0) = \frac{1}{\Delta\nu}\int_{\nu_0-\Delta\nu/2}^{\nu_0+\Delta\nu/2} \cos\left(\frac{2\pi D\xi\nu}{c}\right) d\nu$$

$$= \cos\left(\frac{2\pi D\xi\nu_0}{c}\right) \cdot \frac{\sin(\pi D\xi\Delta\nu/c)}{\pi D\xi\Delta\nu/c} \quad .$$

- This bandwidth smearing limits the field-of-view; the maximum size of the field is of order $R = \nu_0/\Delta\nu$ resolution elements.

Measurements of Source Properties

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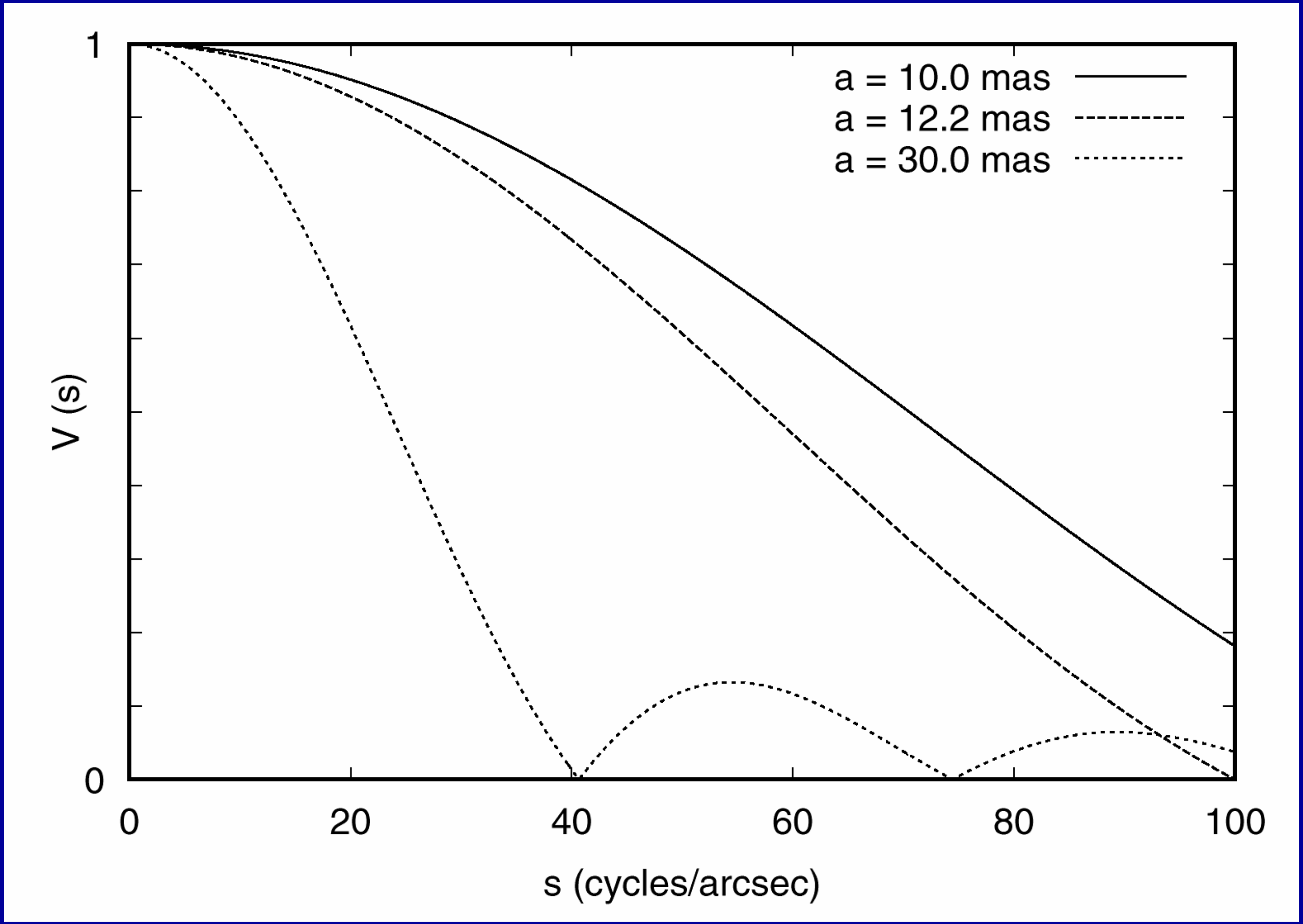
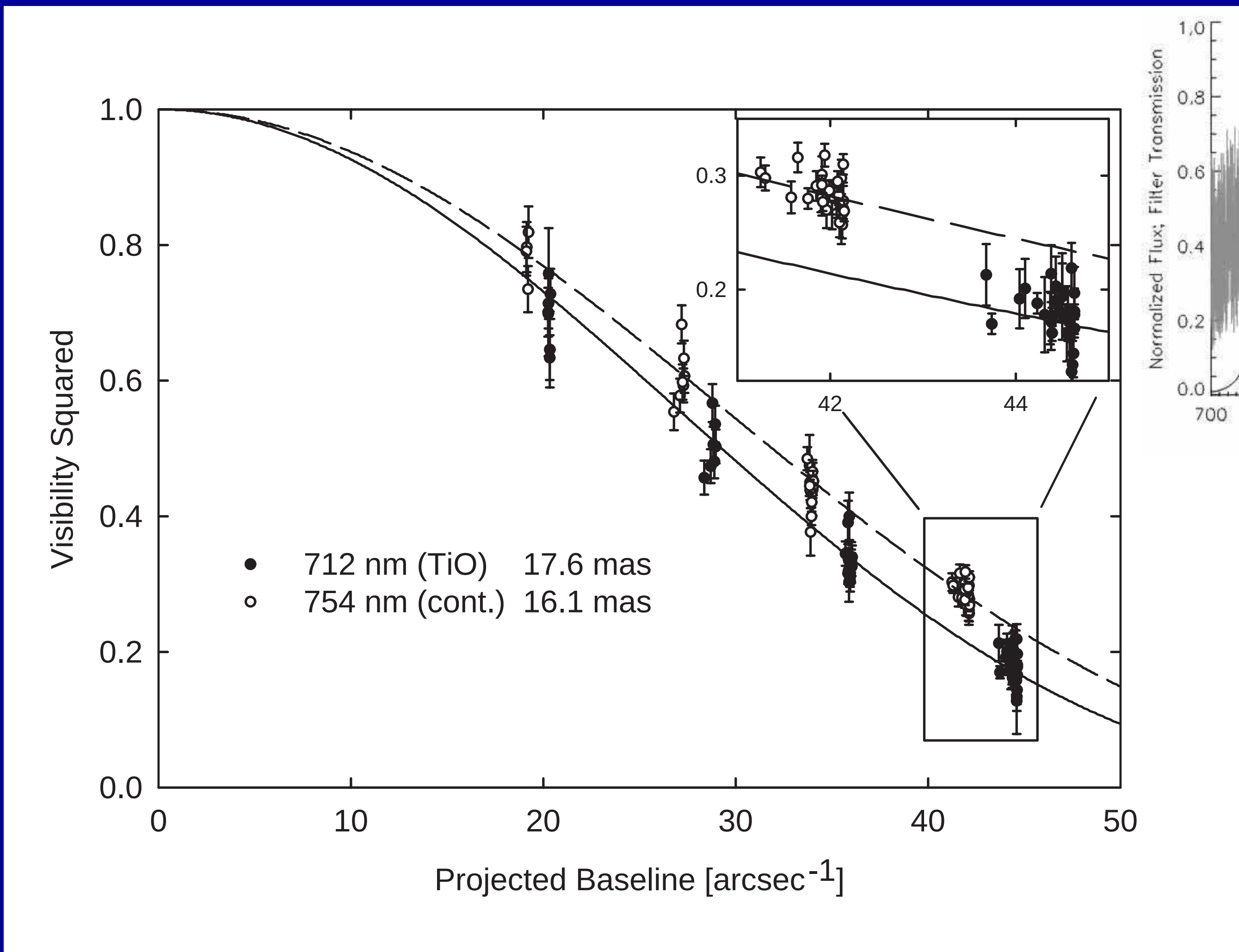
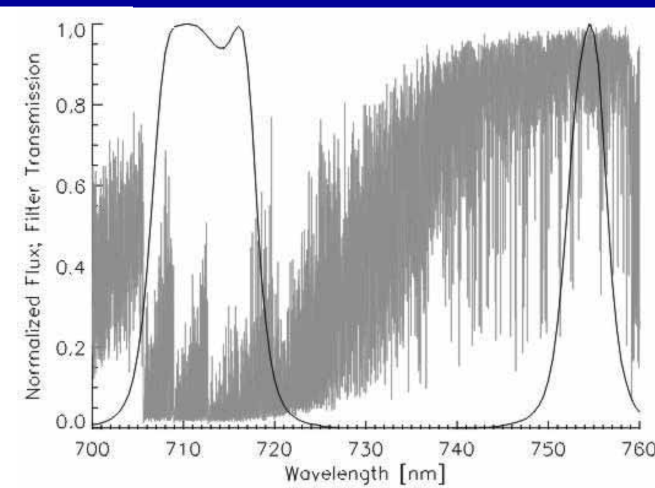
Example: Uniform Disks



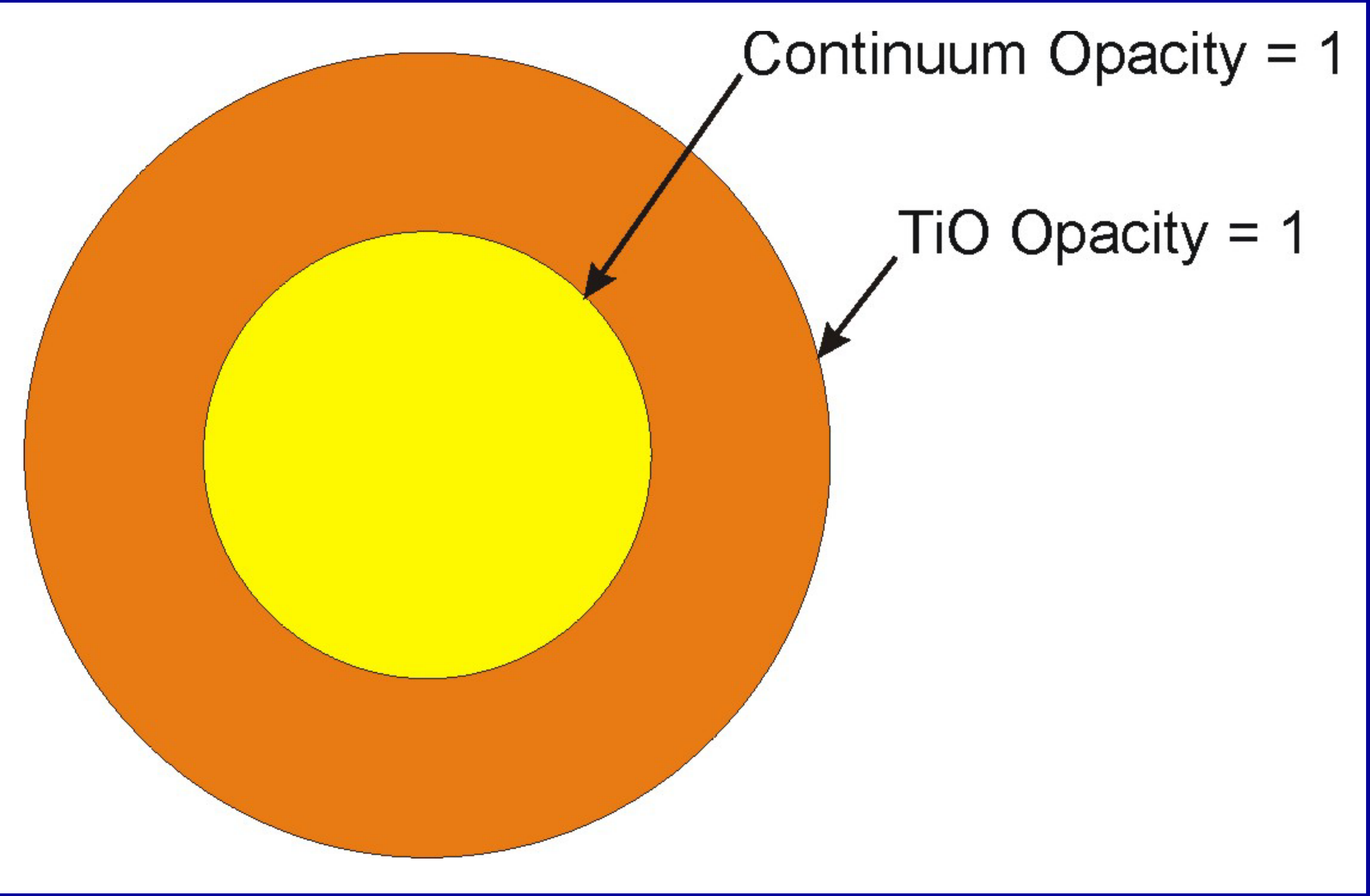
Mk III Diameter Measurements of the Giant Star β Pegasi



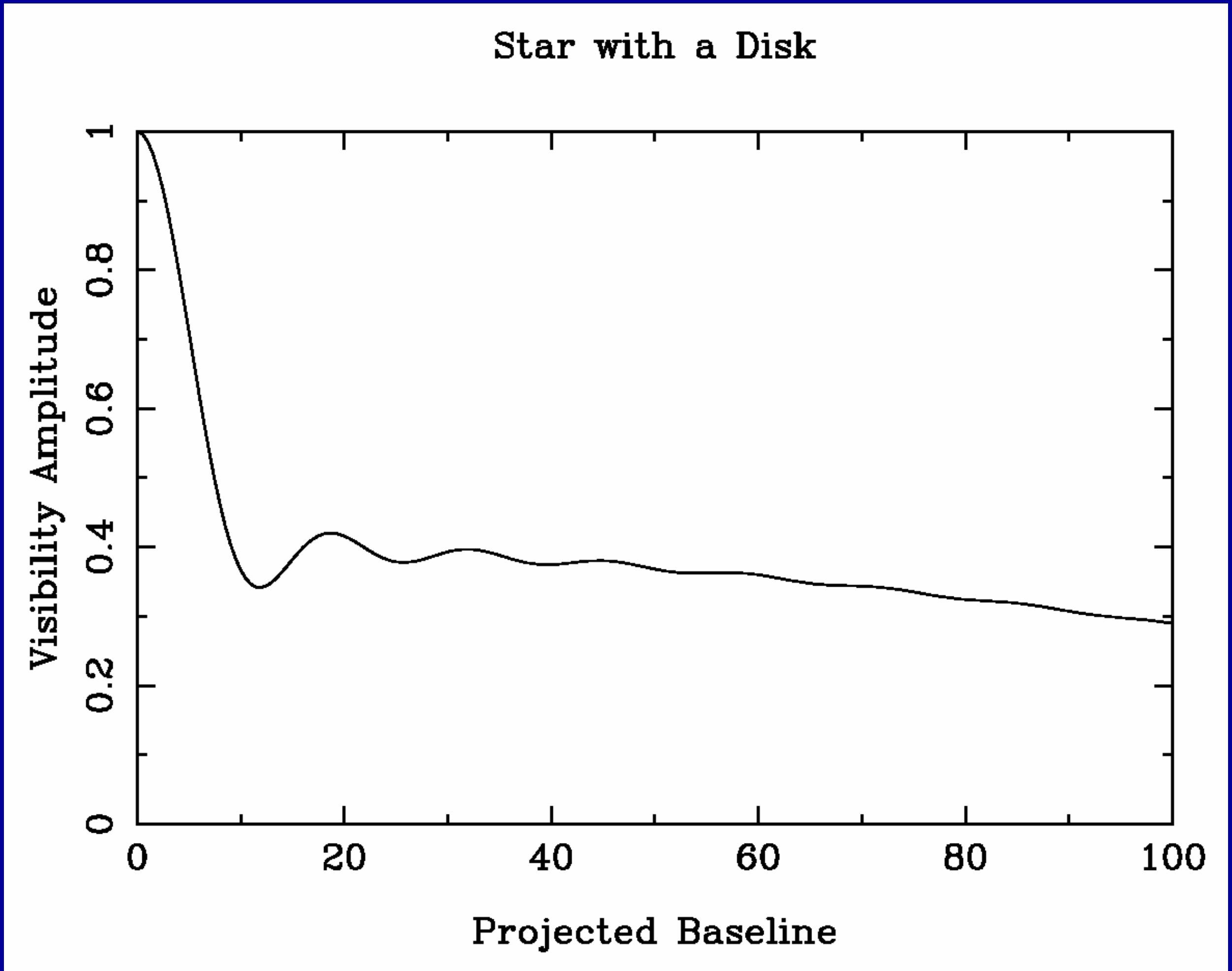


Quirrenbach et al.

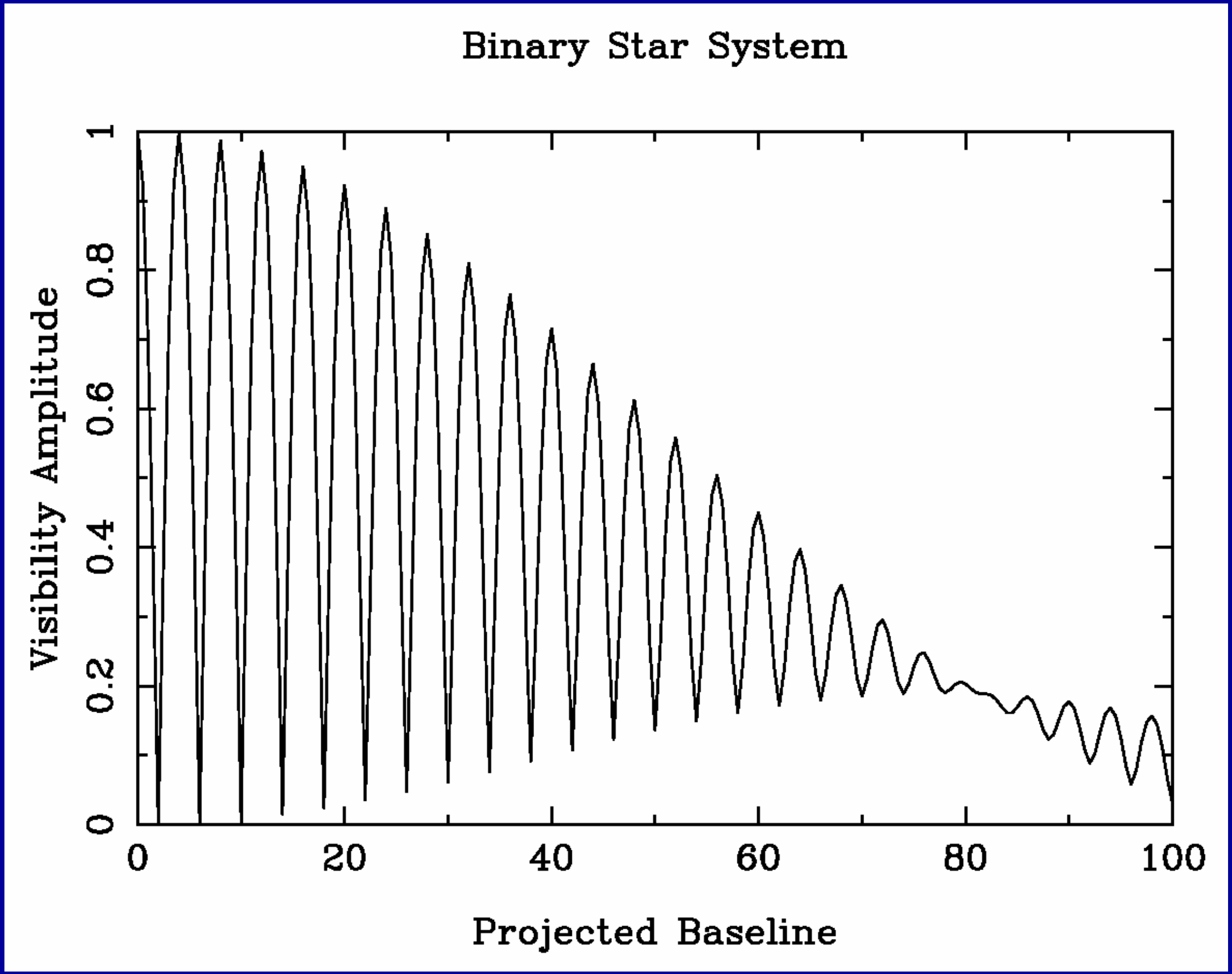
Schematic Model of Extended Stellar Atmosphere



Visibility of a Star with a Disk



Visibility Curve of a Binary Star



Information from Binary Stars

- Most important are double-lined spectroscopic binaries (SB2s)
- Spectroscopy gives all system parameters except inclination
- Interferometry can measure inclination ⇒ can derive masses for both components
- Spectroscopy measures orbit in km/s, interferometry in mas ⇒ combination gives distance (dynamical parallax)

NGC1068: A Galactic Nucleus

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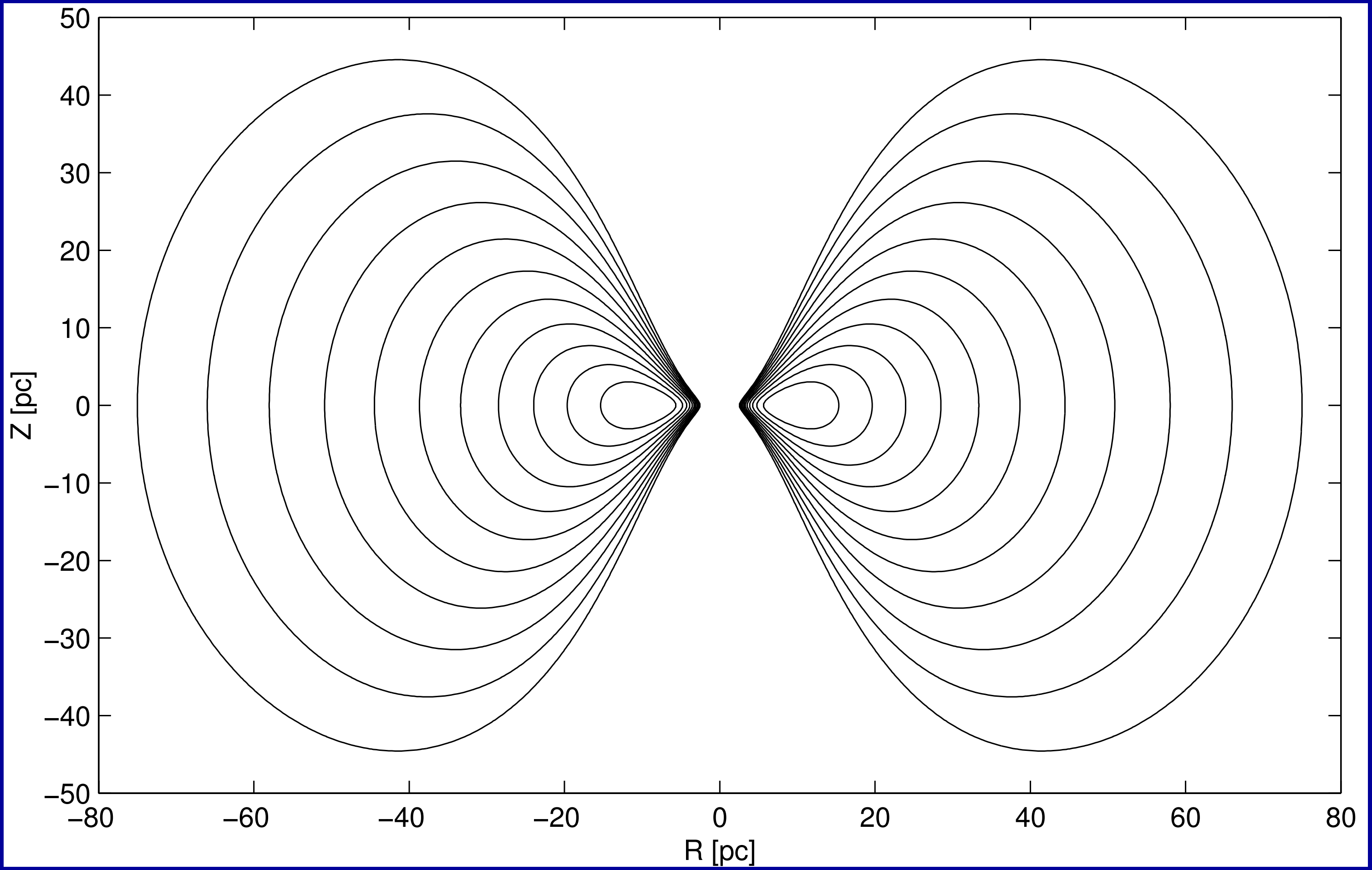
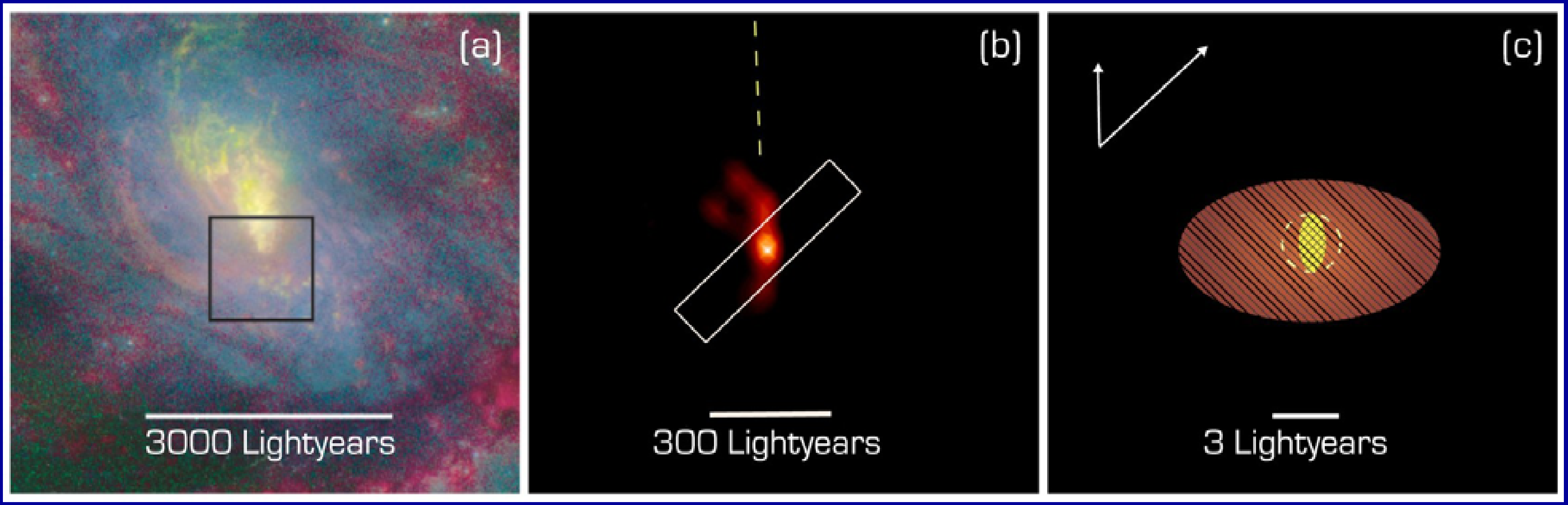
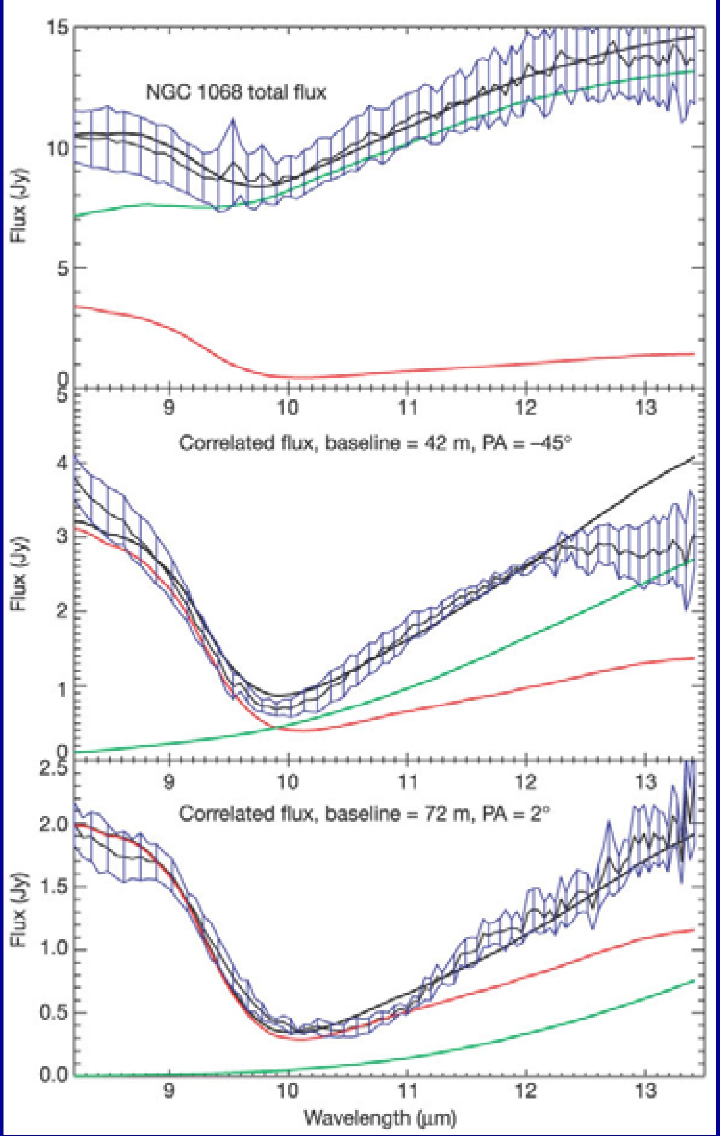
Model of a Dust Torus around an Active Galactic Nucleus



Zoom into Innermost Region of the Active Galaxy NGC 1068



Observed Spectra and Model for the Nucleus of NGC 1068



Atmospheric Turbulence

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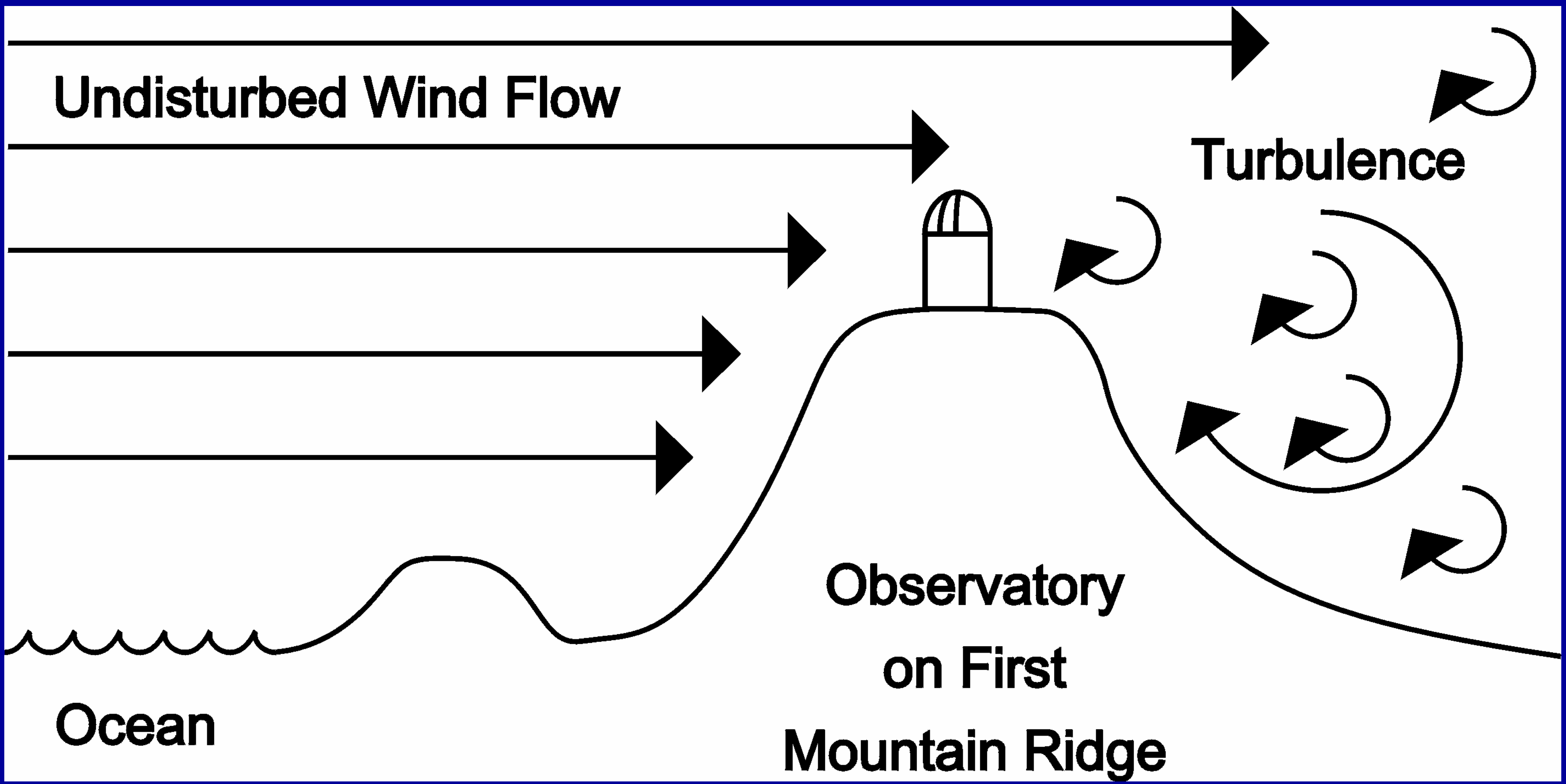
Turbulence Generation



Kolmogorov Theory of Atmospheric Turbulence

- The Reynolds number $Re \equiv VL/v$ for atmospheric flows is of order $Re \geq 10^6$, i.e, the atmosphere is highly turbulent.
- Turbulent energy is generated on a large "outer" scale L_0, and dissipated on a small "inner" scale l_0.
- In the "inertial range" between l_0 and L_0, there is a universal description for the turbulence spectrum, which can be calculated from simple scaling arguments.

Significance of the Fried Parameter r_0

- r_0 describes the turbulence strength
- The effective resolution of long exposures through the atmosphere is the same as the resolution with a telescope of diameter r_0.
- The phase variance over an aperture with diameter r_0 is approximately 1 rad^2.
- The wavelength dependence is $r_0 \propto \lambda^{6/5}$; this leads to an image size $\alpha \propto \lambda / r_0 \propto \lambda^{-1/5}$.
- At good sites, typical values for r_0 at $\lambda = 500$ nm are in the range 10…20 cm; this corresponds to $\alpha = 0.5'' \ldots 1''$.

Temporal Variations and the Taylor Hypothesis

- The time constant for changes in the turbulence pattern is usually assumed to be much longer than the time it takes the wind to blow the turbulence past the telescope aperture.
- Atmospheric turbulence is often dominated by a single layer.
- The temporal behavior of the turbulence can therefore be characterized by a time constant $\tau_0 \equiv r_0/V$, where V is the wind velocity in the dominant layer.

Anisoplanatism

- The light from two stars separated by an angle θ passes through different patches of the atmosphere and therefore experiences different phase variations.
- It can be shown that the variance of the phase difference between the two stars is given by:

$$\langle \sigma_\theta^2 \rangle = \left(\frac{\theta}{\theta_0} \right)^{5/3}$$

- In this relation, the isoplanatic angle θ_0 is given by:

$$\theta_0 = 0.314 \ \cos z \ \frac{r_0}{H}$$

Consequences of Seeing for Interferometry

- Single apertures have to be phased. For apertures larger than $\sim 3r_0$ adaptive optics is needed.
- Fringe tracking has to be performed with a servo bandwidth larger than $1/\tau_0$.
- Phase referencing is possible only over angles smaller than θ_0.
- The $\lambda^{6/5}$ scaling of these quantities strongly favors operation at longer wavelengths.

Air Dispersion

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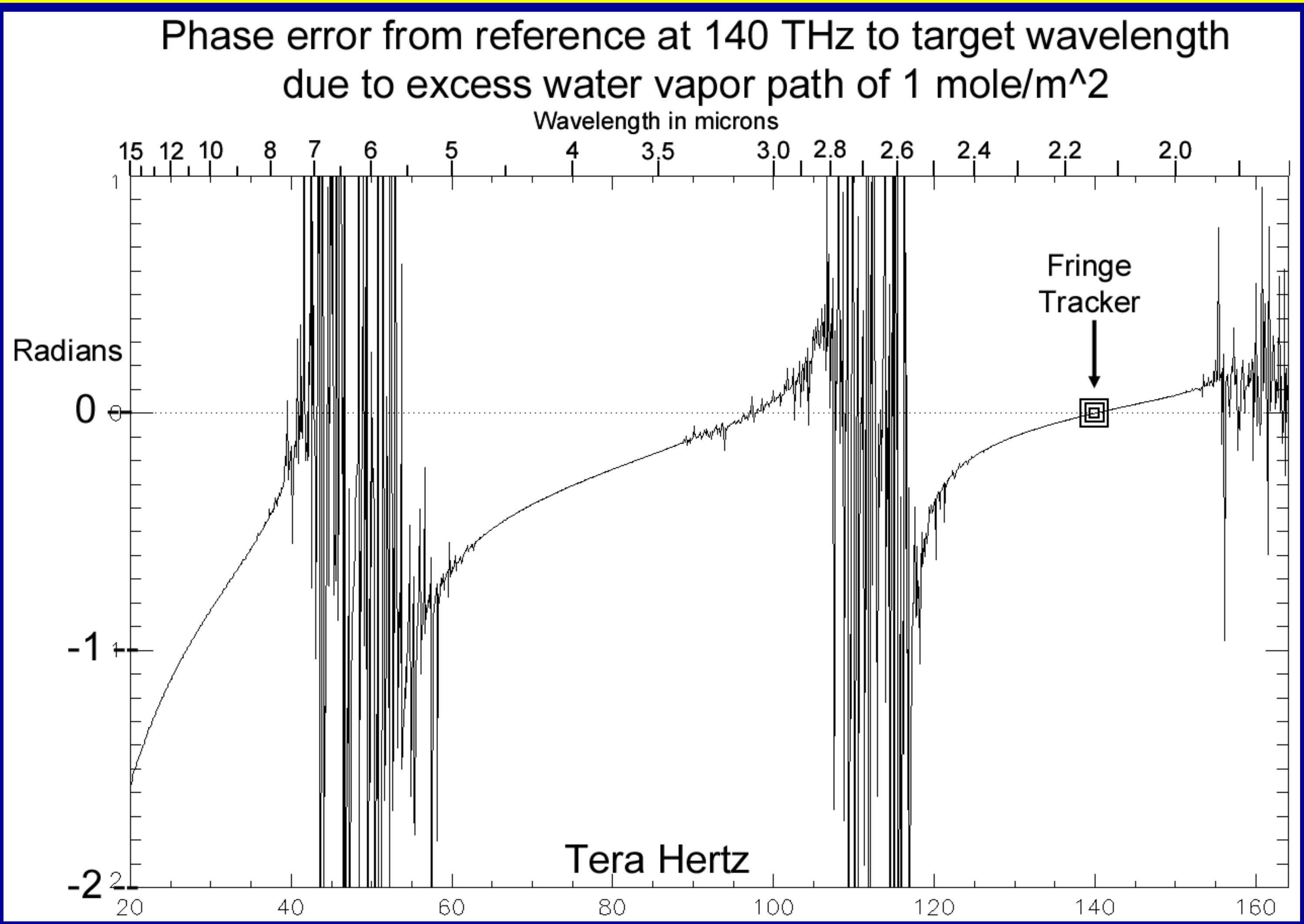
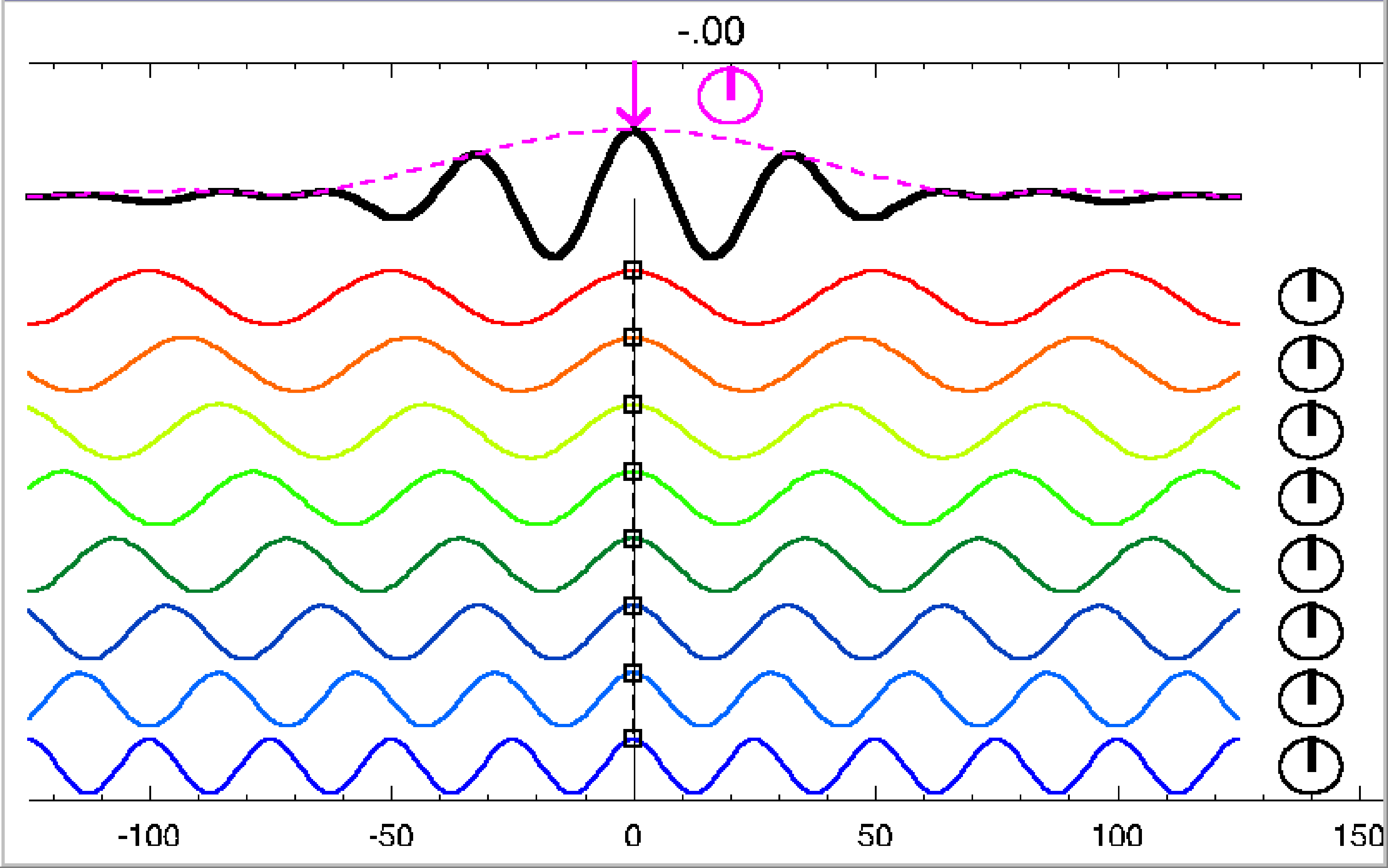
Causes of Dispersion

- 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

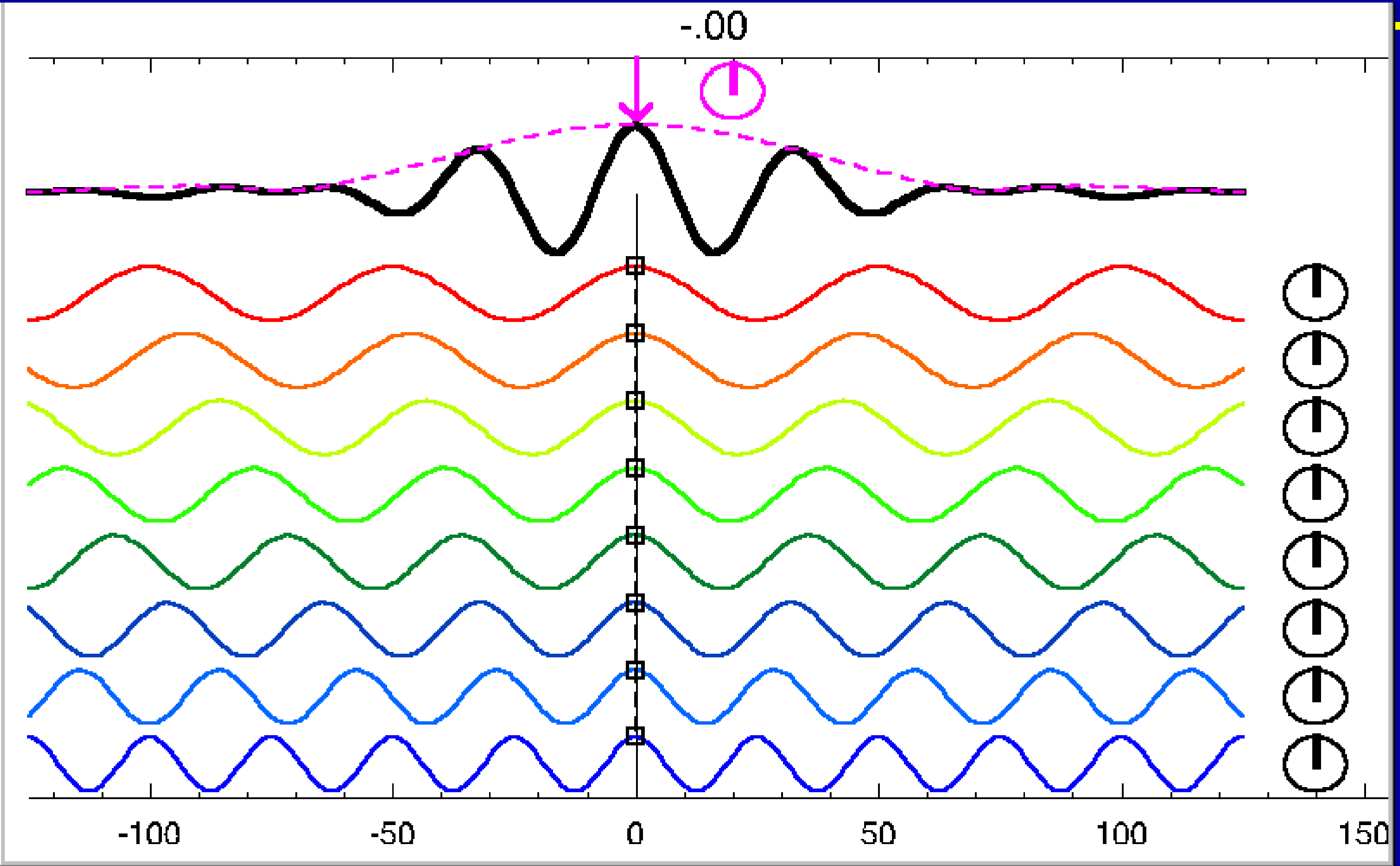
Dispersion of Water Vapor (Richard Mathar / Jeff Meisner)



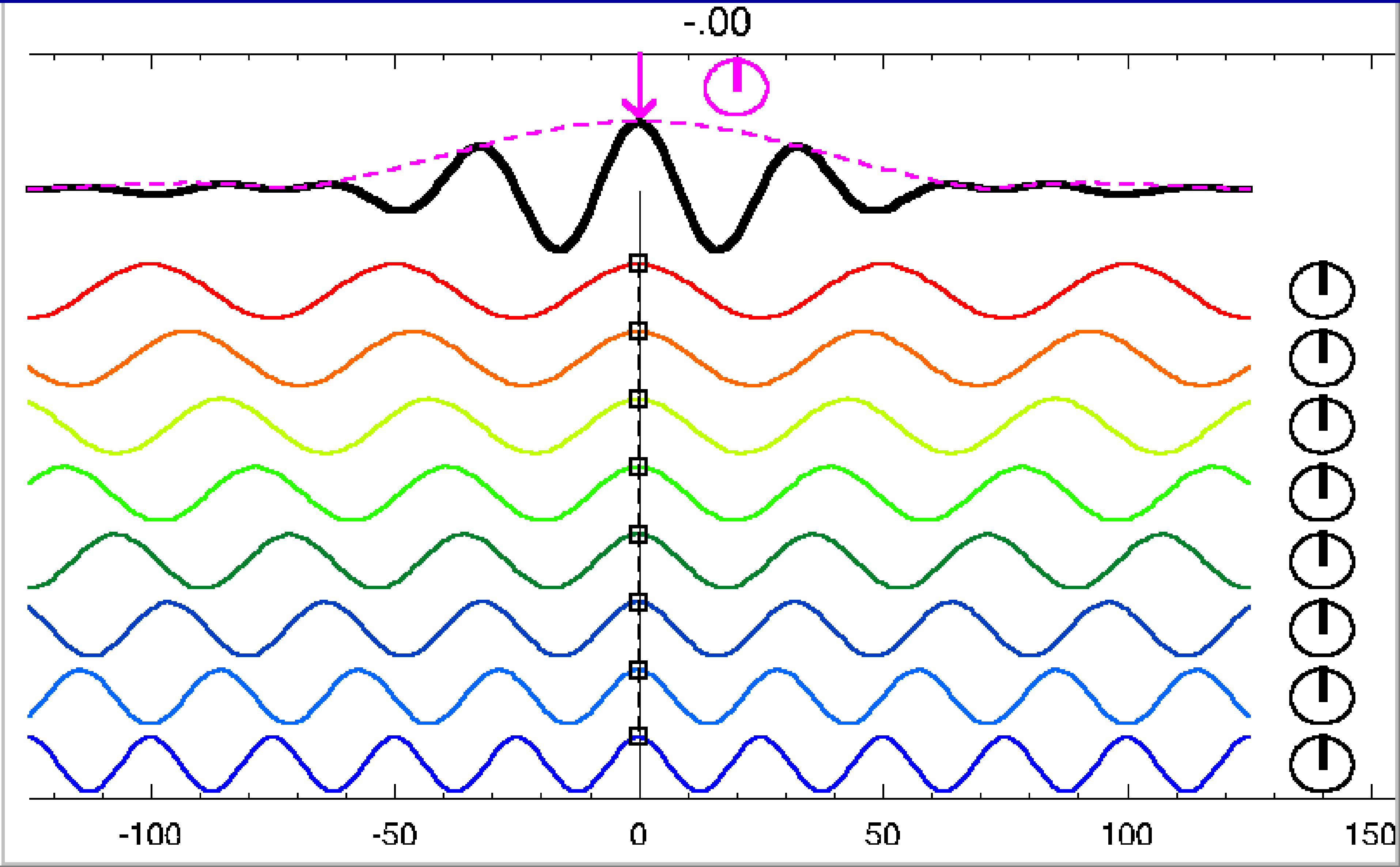
- Achromatic differential delay
- Phase delay same for all optical frequencies
- Phase at each frequency: $\varphi = 2\pi \cdot \nu \cdot \tau$ (where τ is phase delay)



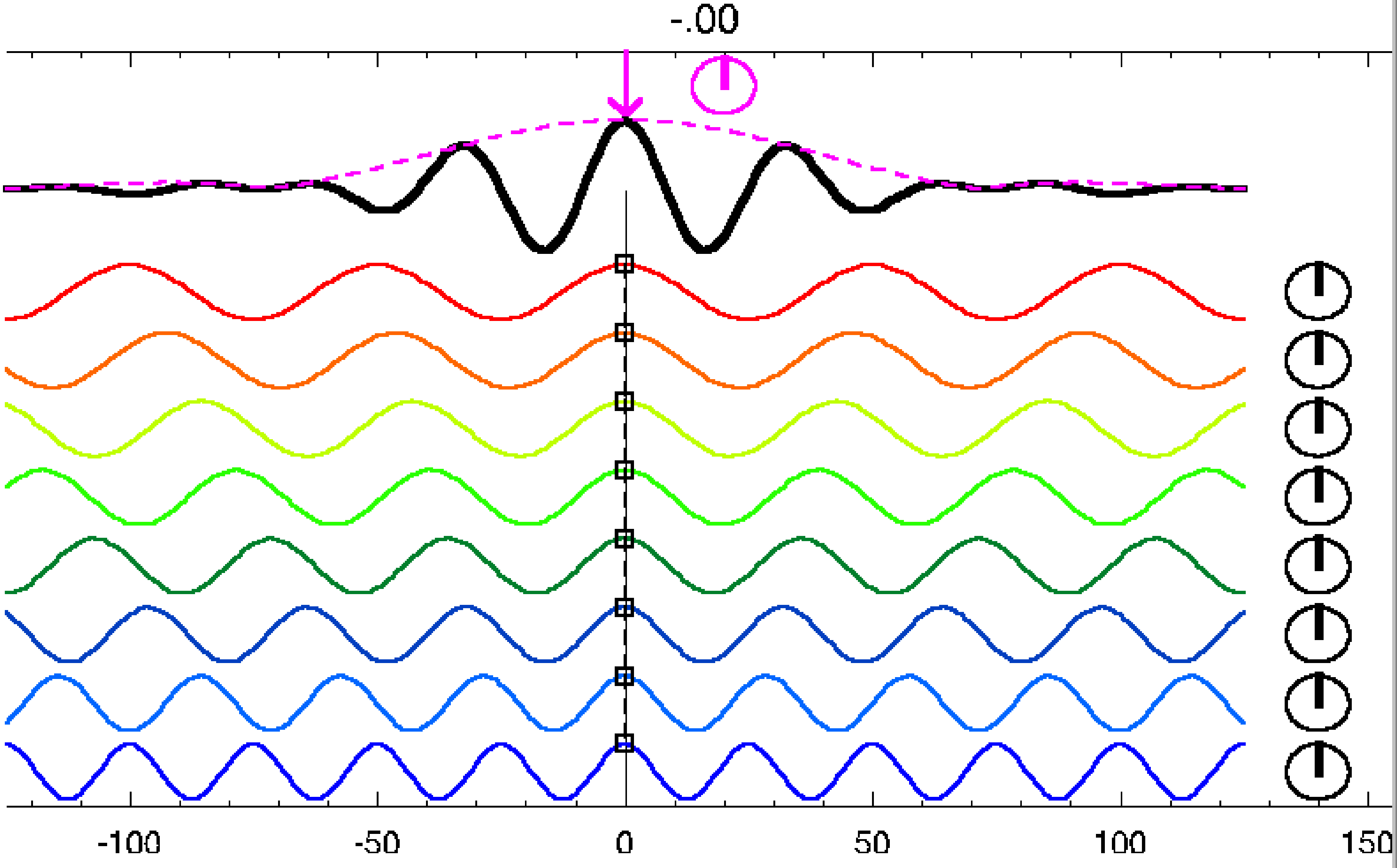
- Non-achromatic delay from water vapor exhibiting *First Order Dispersion*
- Phase delay at each optical frequency proportional to refractivity at that wavelength



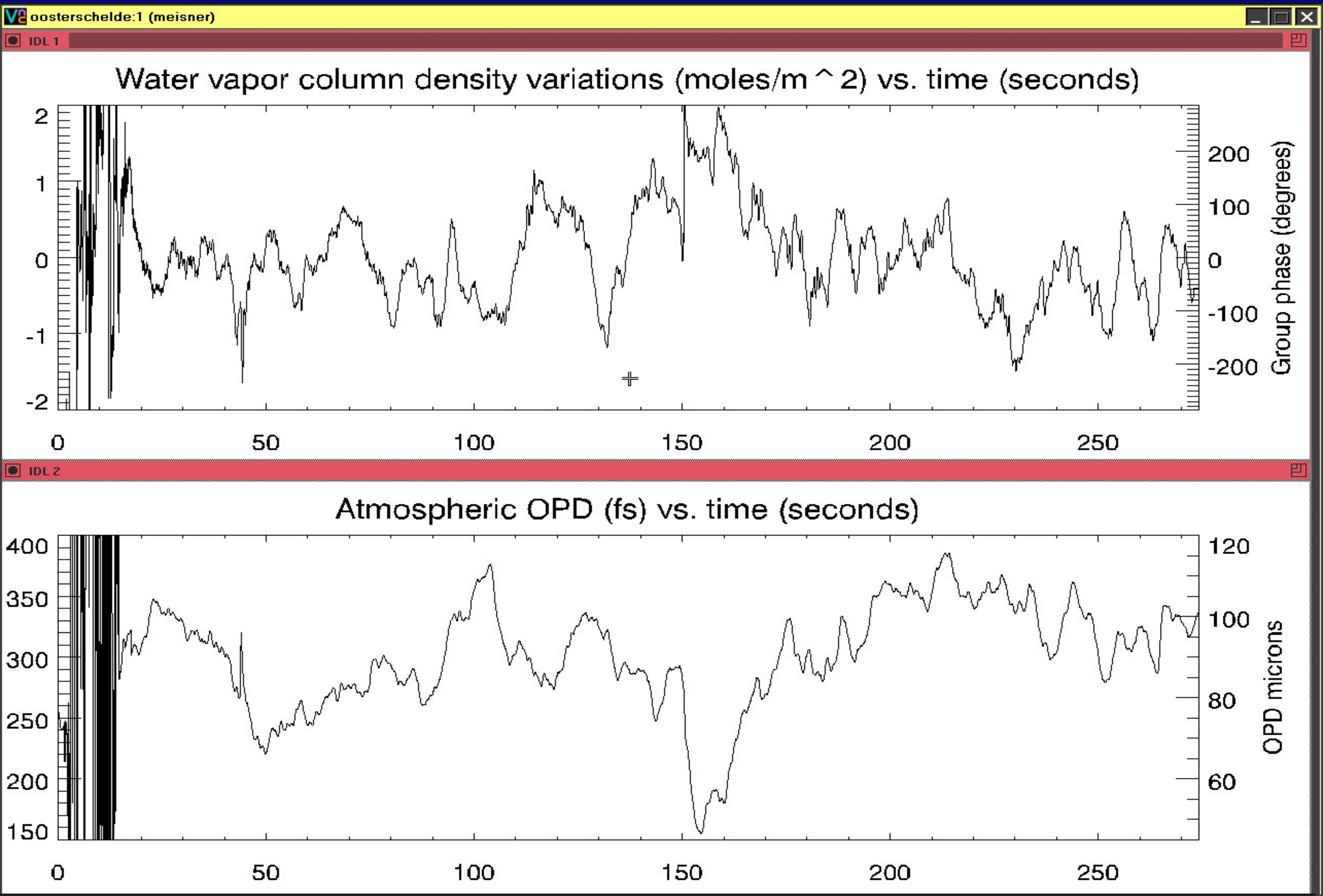
- Non-achromatic delay from water vapor exhibiting *First Order Dispersion*
- Viewed at phase of center frequency, envelope ("group delay") shifts w/r/t phase



- Non-achromatic delay from water vapor exhibiting *First Order Dispersion*
- Tracking the "group delay" we see the fringe phase go from 0 to 2π and repeat!

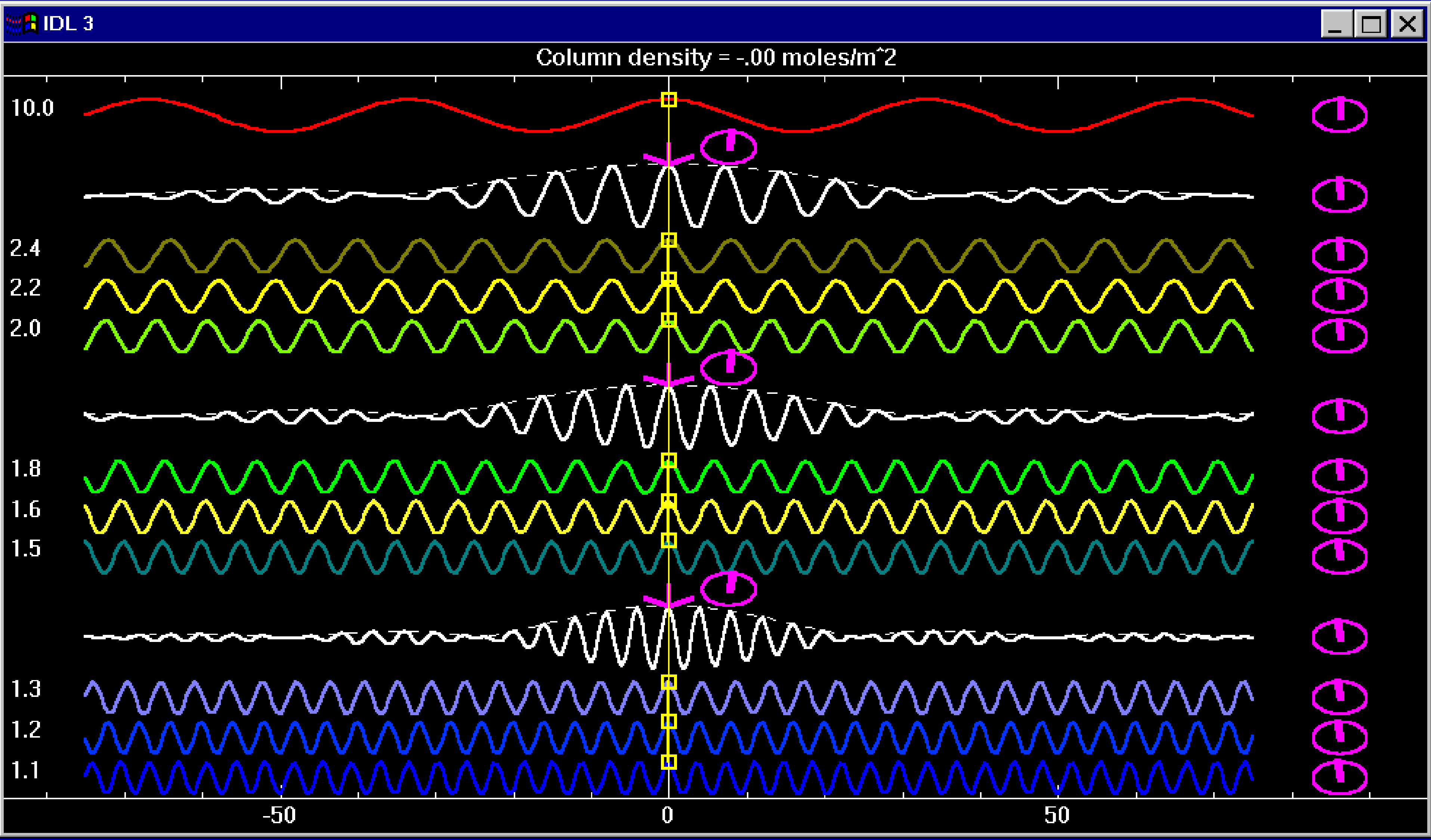


MIDI observation, tracking atmospheric (?) OPD and water vapor



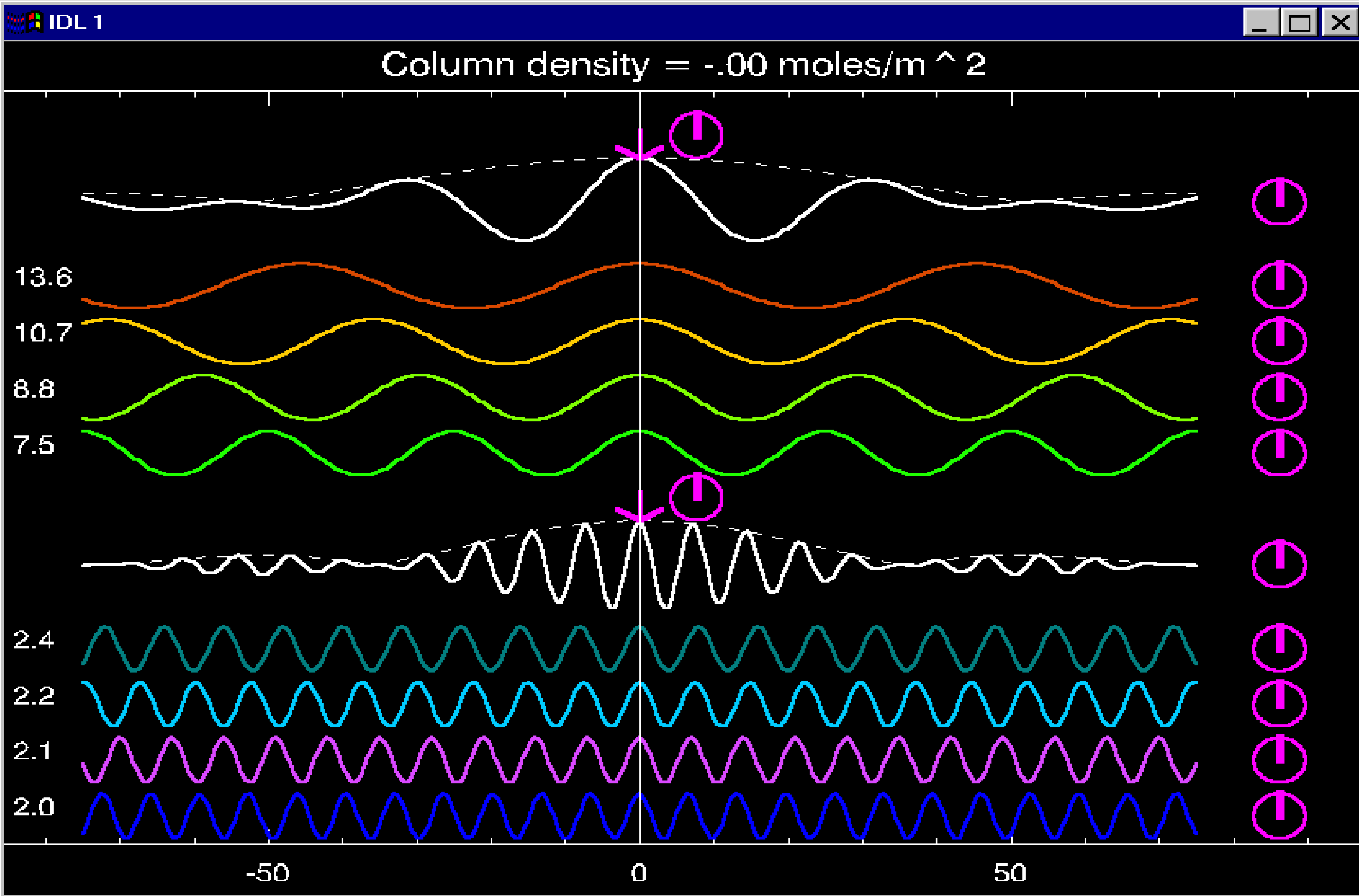
Dispersive effect between (and within) bands due to 0 – 600 moles/m² of additional dry air. (= 20 meter delay-line offset)

Note that dispersion from dry air increases rapidly at short wavelengths



(Tracking at the group-delay in K band)

Water Vapor dispersion, with phase-tracking at K band
0 – 5 moles/m^2 (typical p-p value due to atmosphere)



Water Vapor dispersion, with phase-tracking at K band
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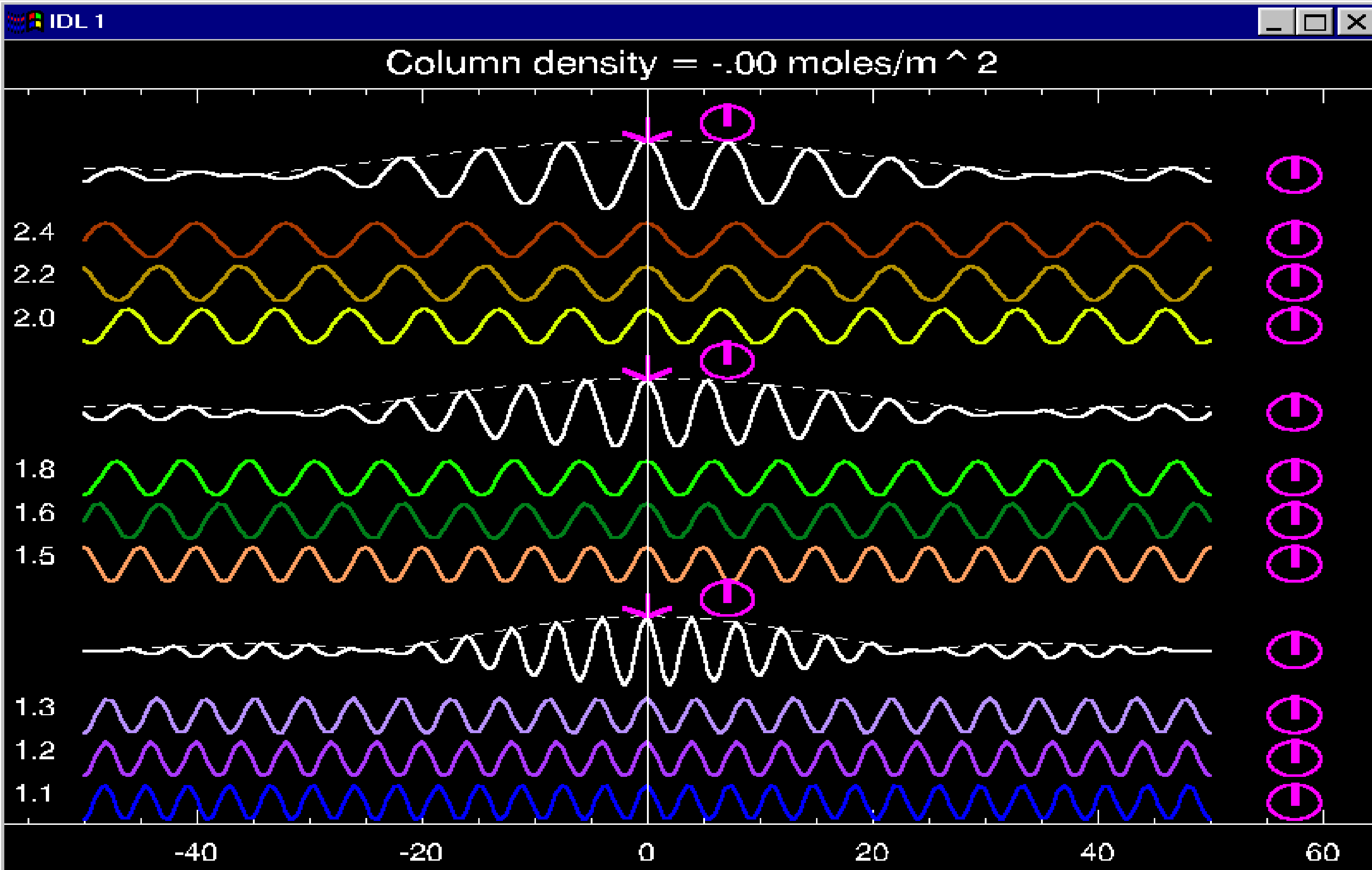

Phase-Coherent Interferometry

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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)

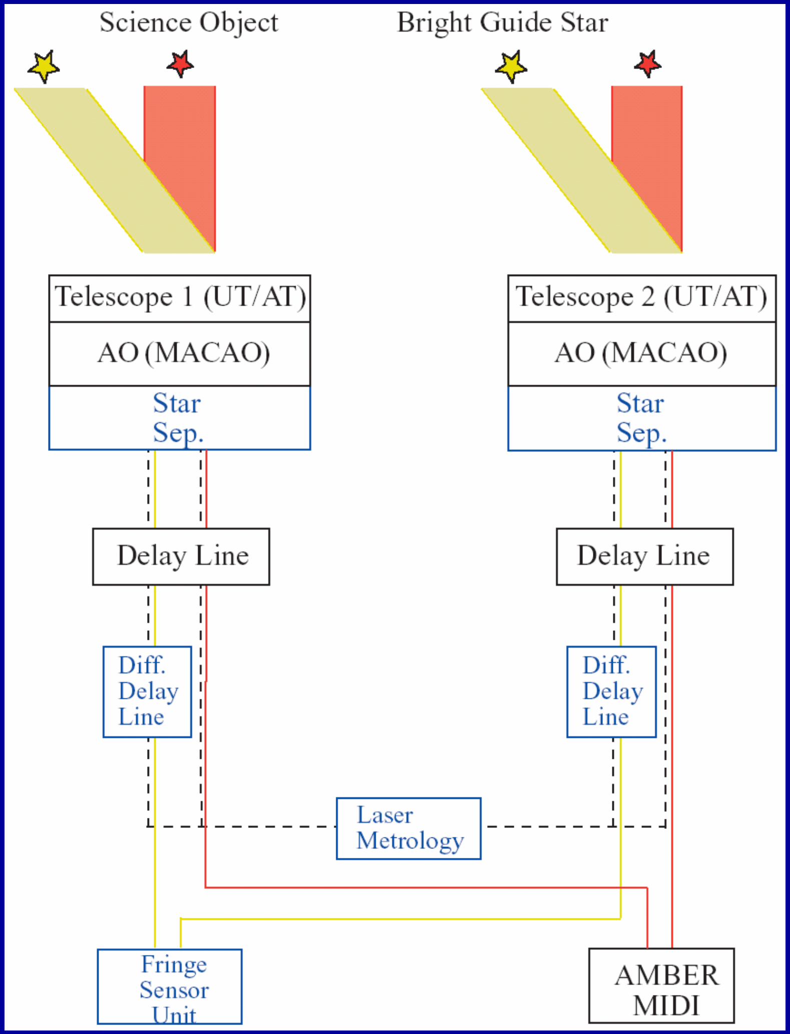
The Potential of Phase Referencing

- 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

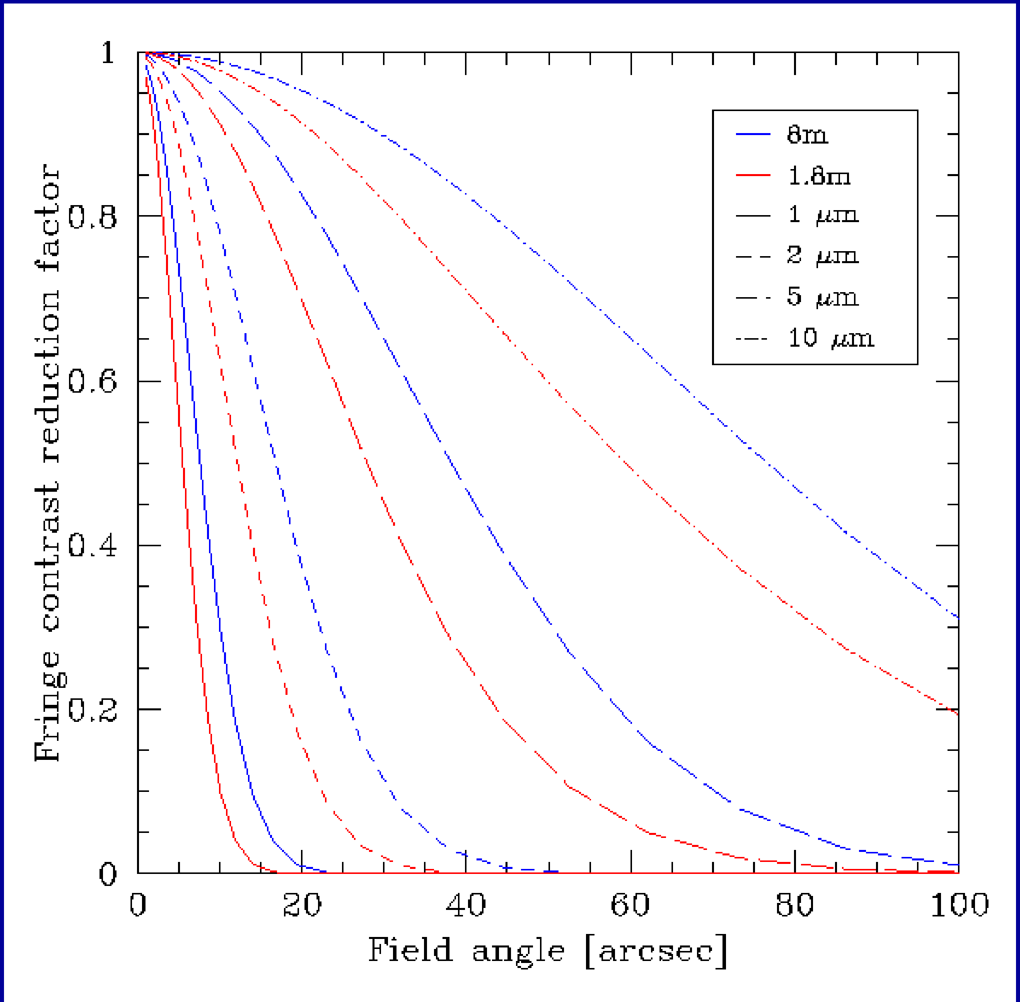
Scientific Drivers of Faint-Source Interferometry

- 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)

Dual-Star Interferometry



Effect of Anisoplanatism (for Cerro Paranal)



Interferometric Astrometry

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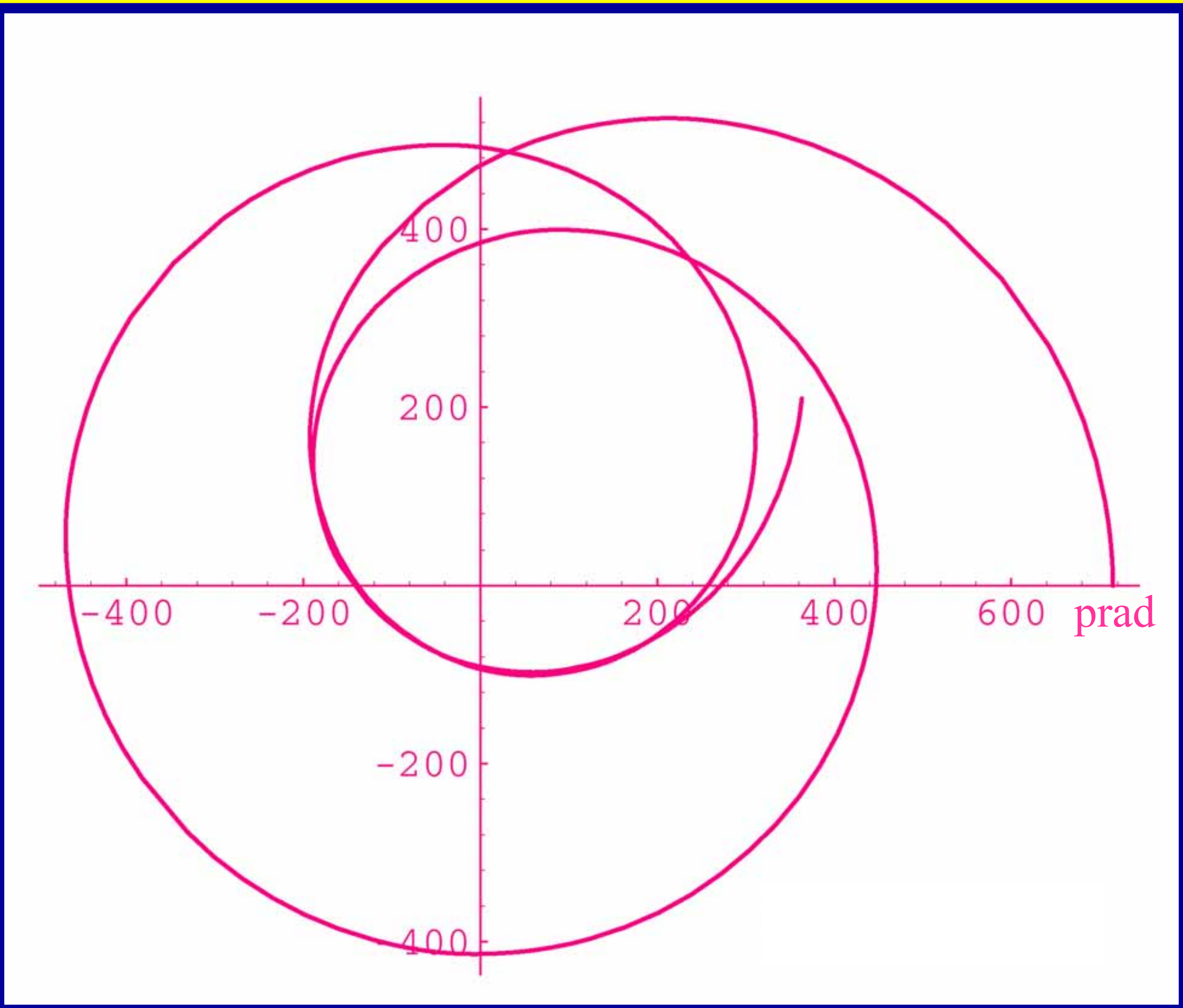
Motion of the Sun, Viewed Pole-on from 100 pc

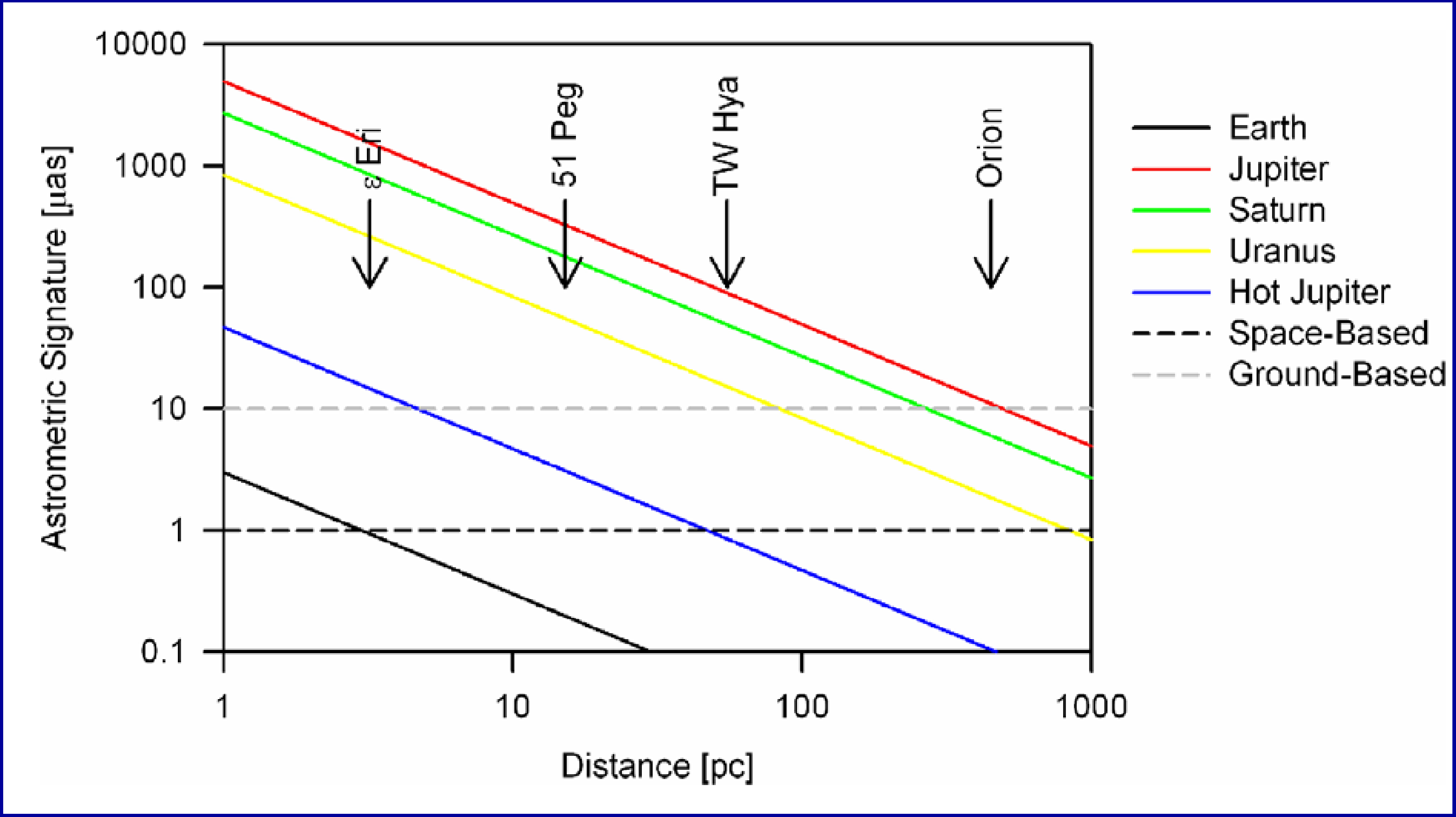


Amplitude:

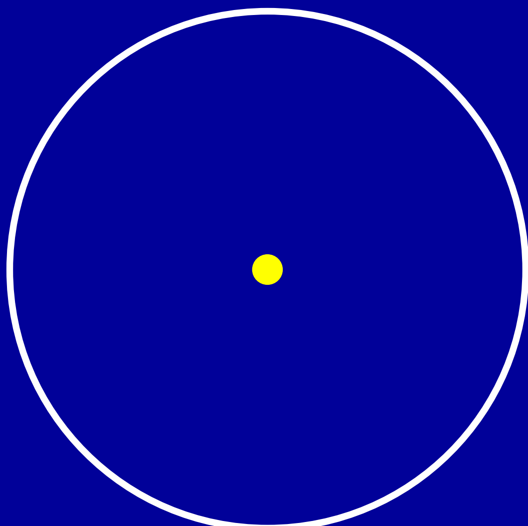
500 pico-radians

100 micro-arcsec

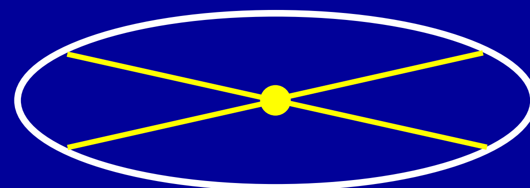
Requirements for Astrometric Planet Detection



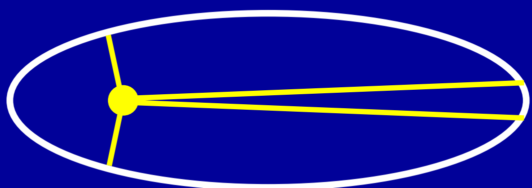
Deriving Inclination from Astrometric Observations



Circular Orbit
Face-on



Inclined
Circular Orbit

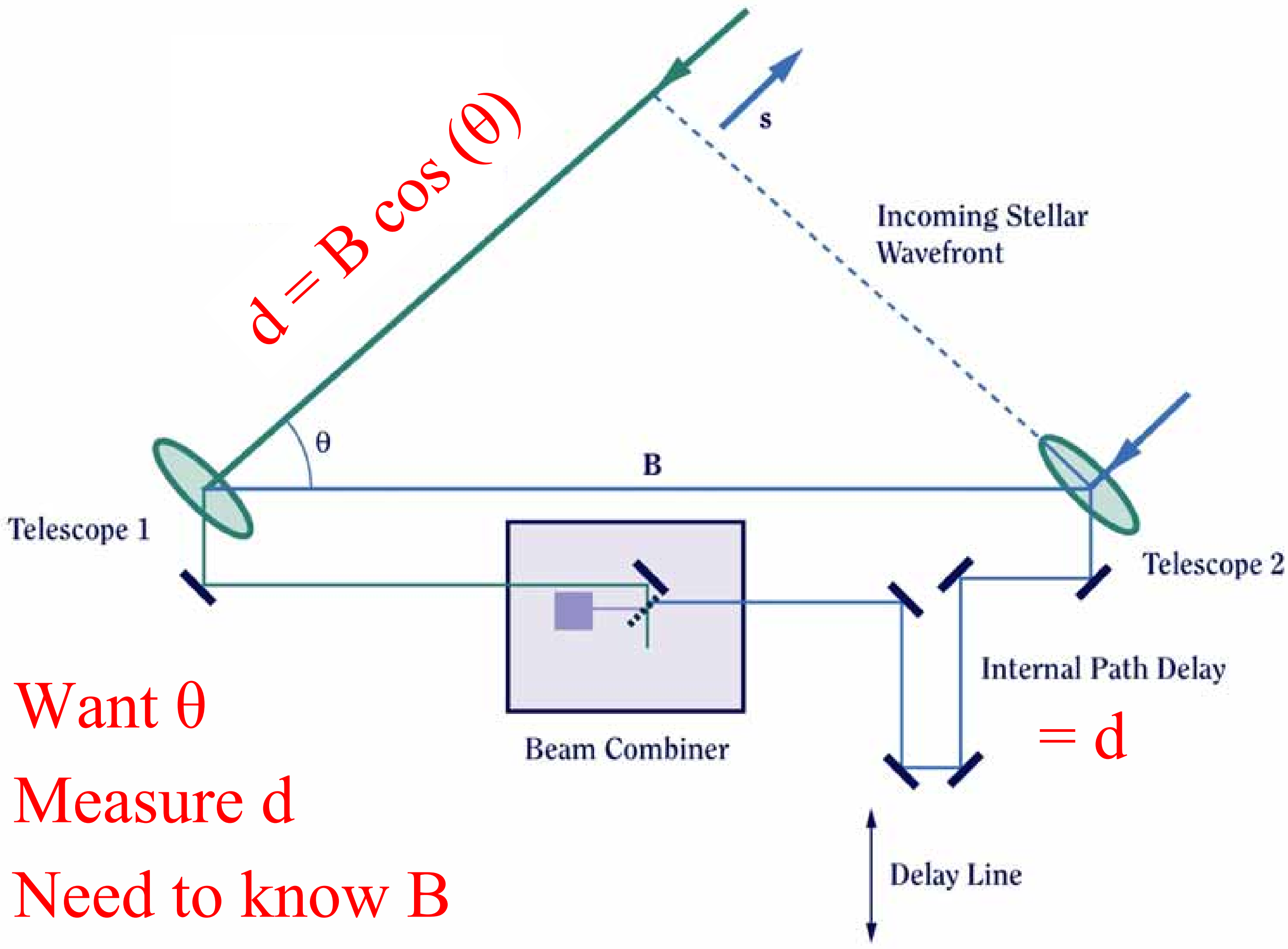


Elliptical Orbit
Face-on

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

Astrometric Measurement with an Interferometer

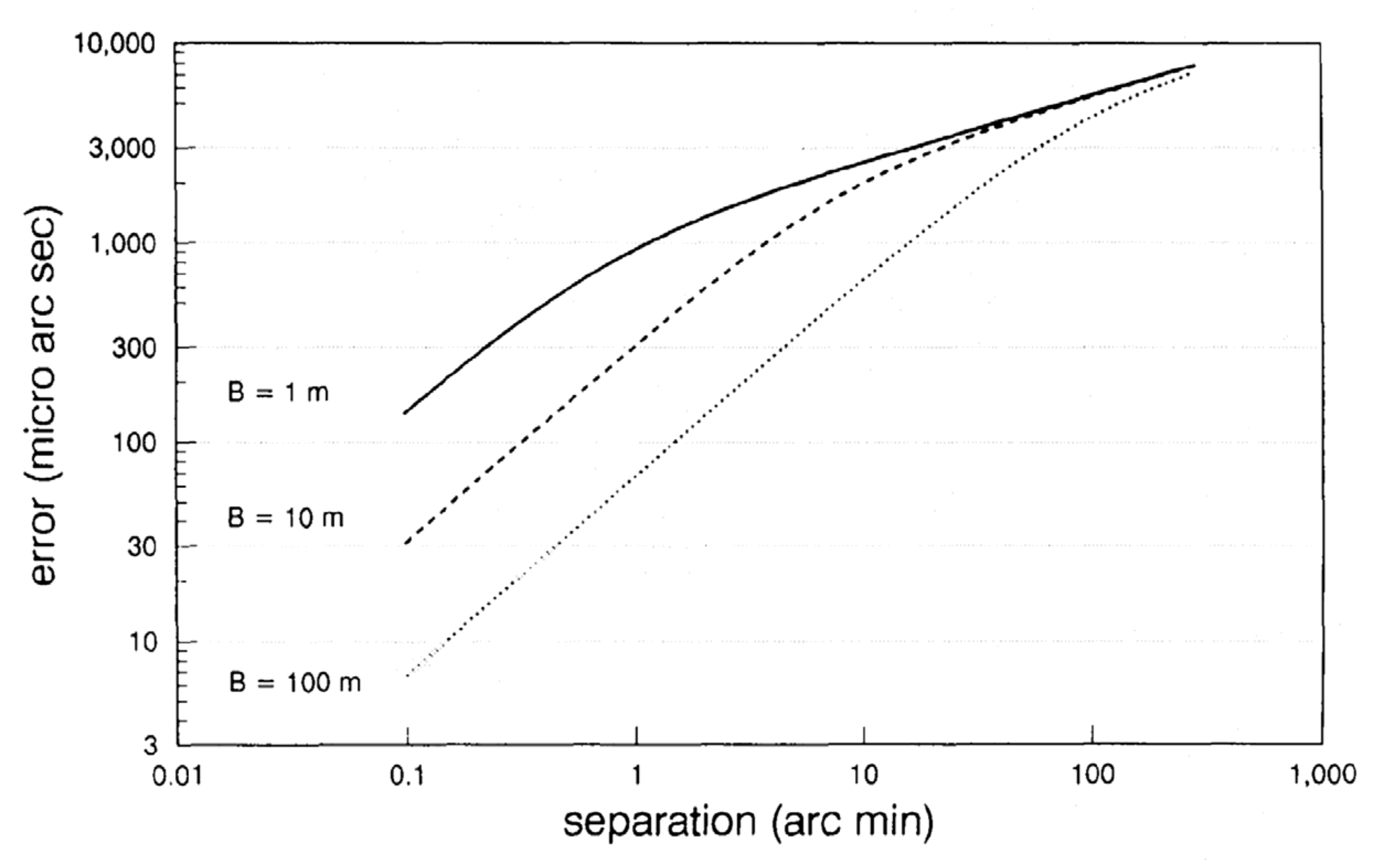


Want θ

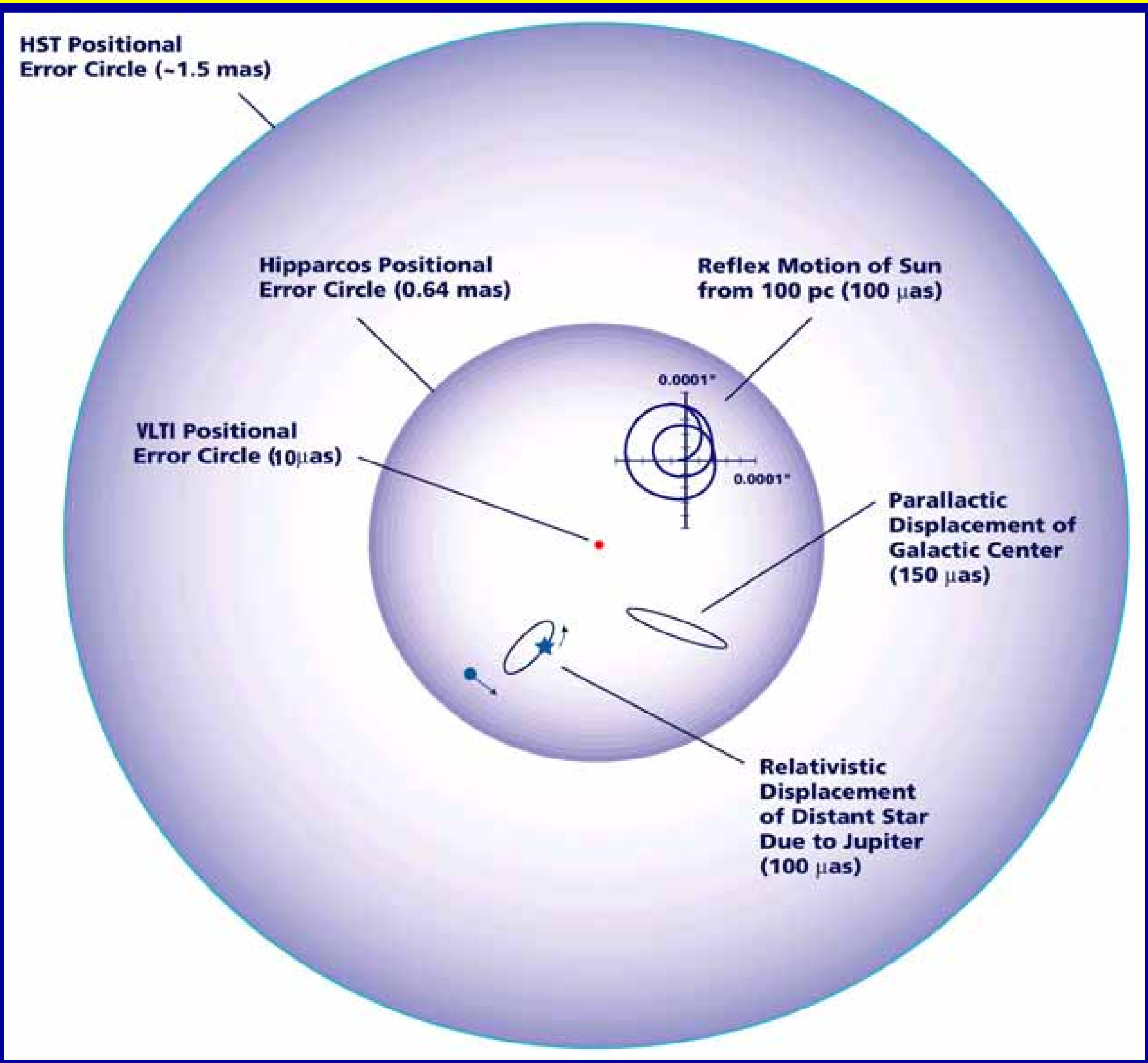
Measure d

Need to know B

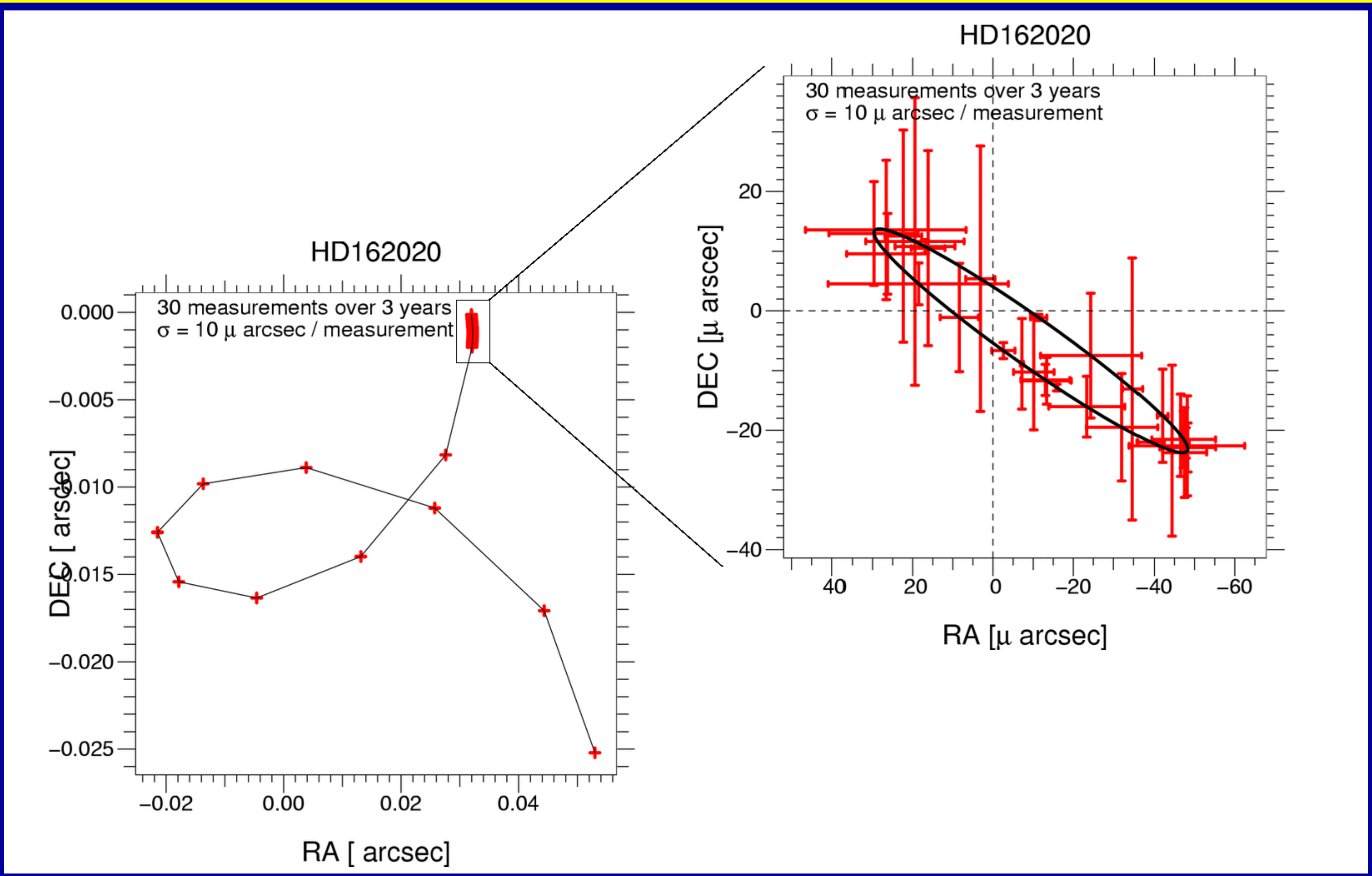
Atmospheric Limitation of Narrow-Angle Astrometry



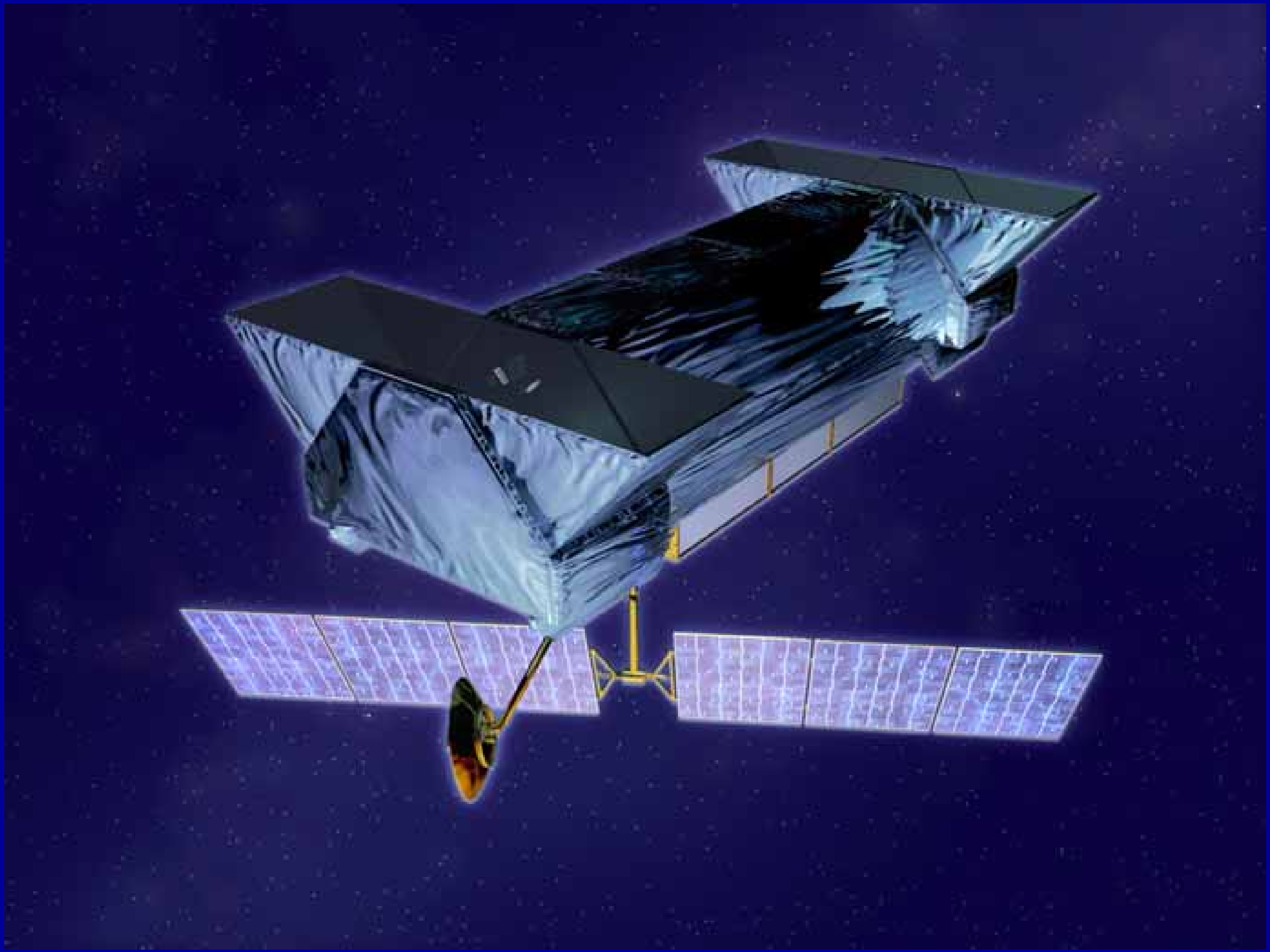
Comparison with Present Capabilities



Simulation of Planet Observations with the VLTI

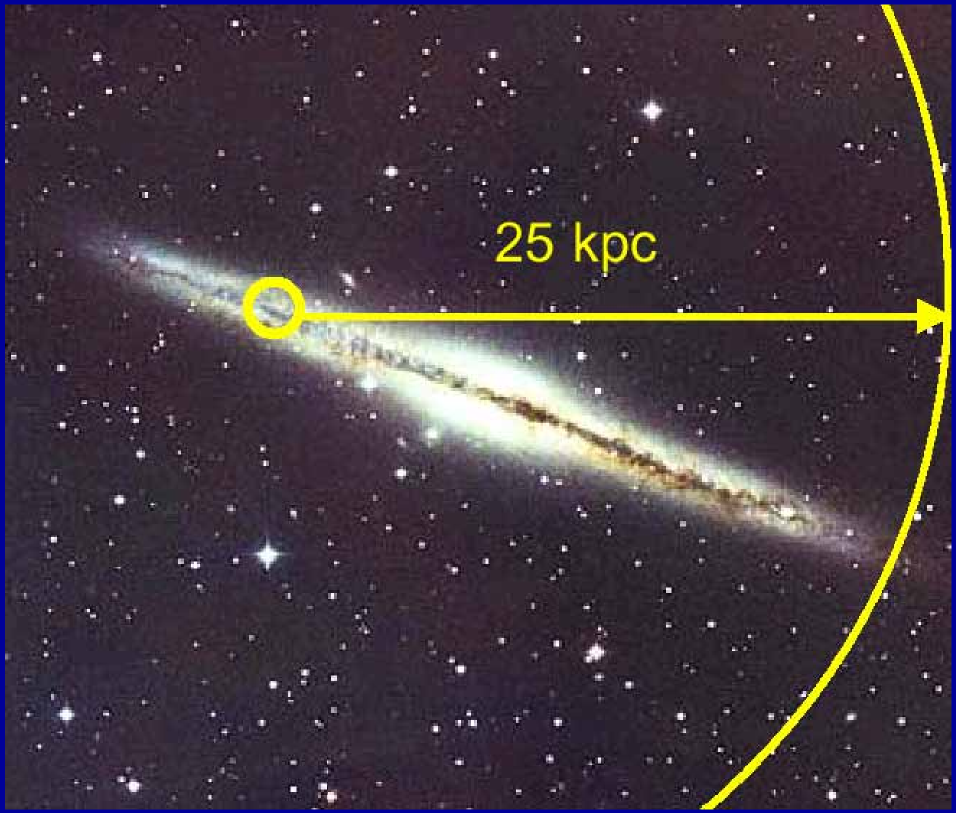


The Space Interferometry Mission (SIM)



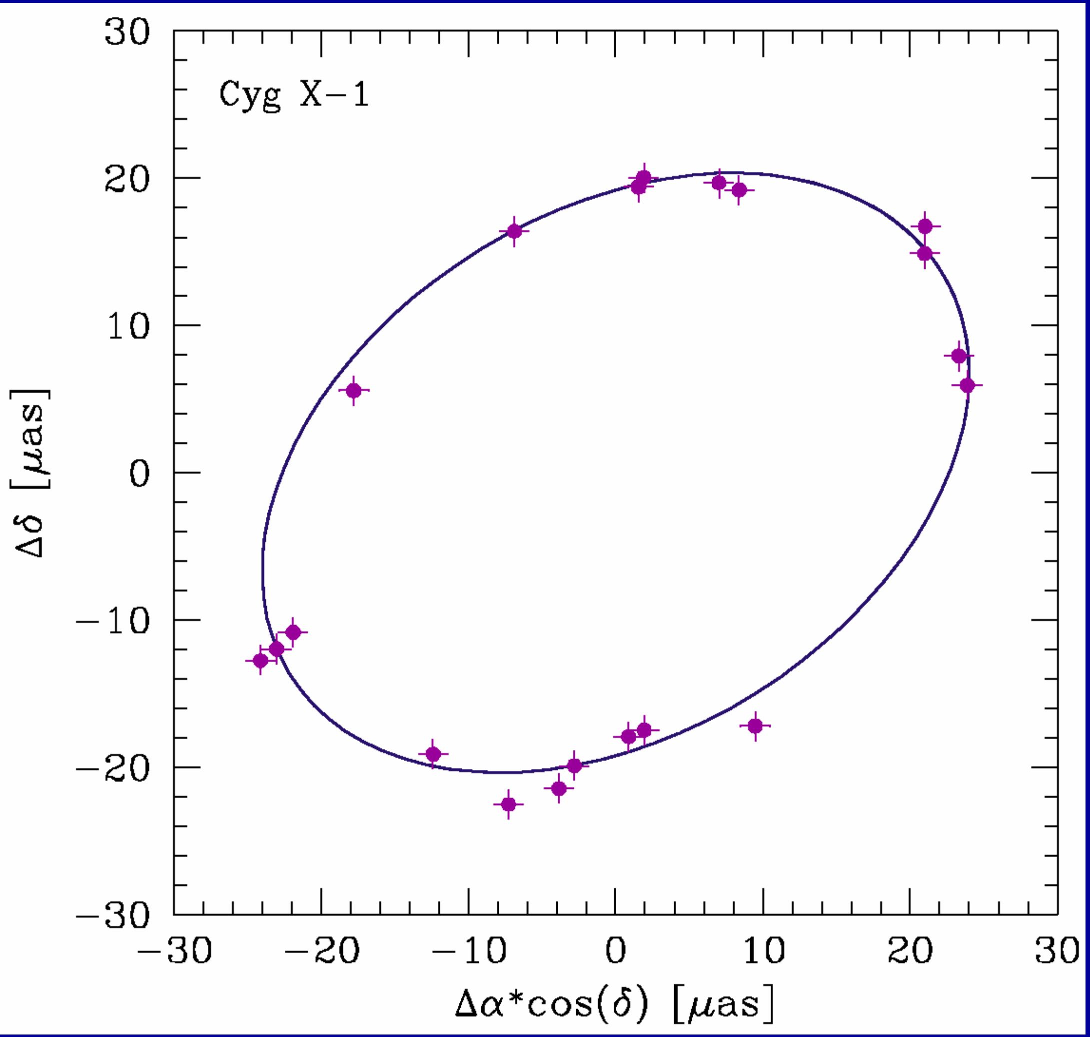
Distances in the Galaxy

- 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

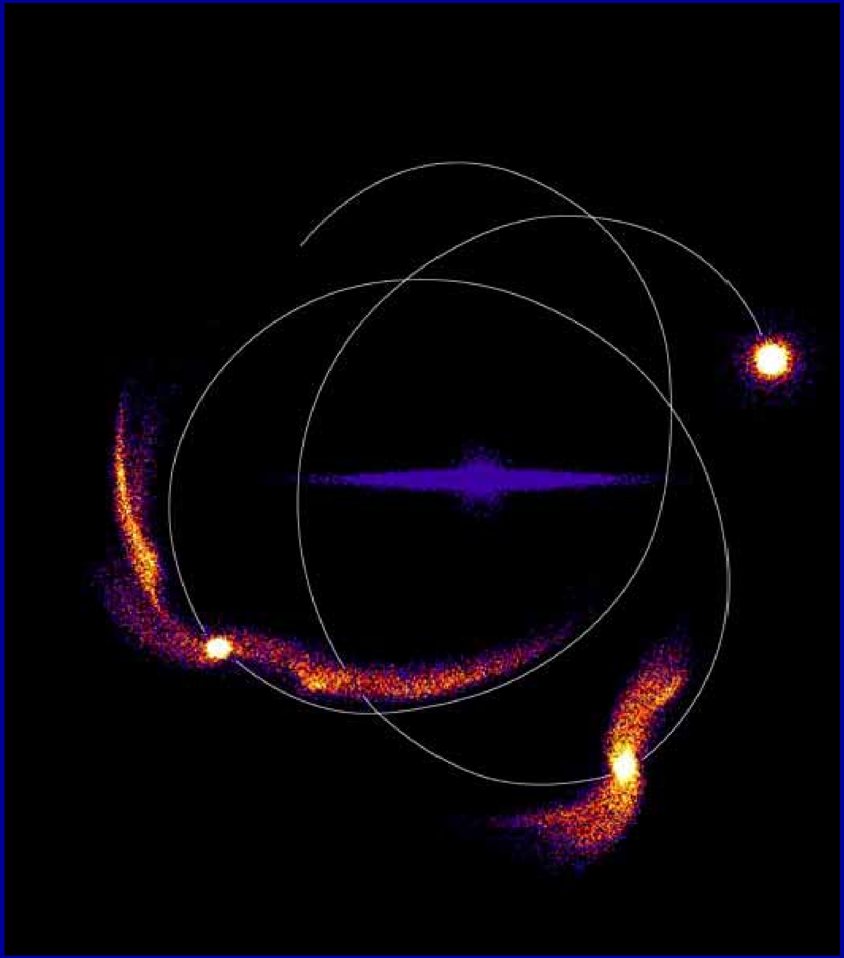


X-Ray Binary Science with SIM

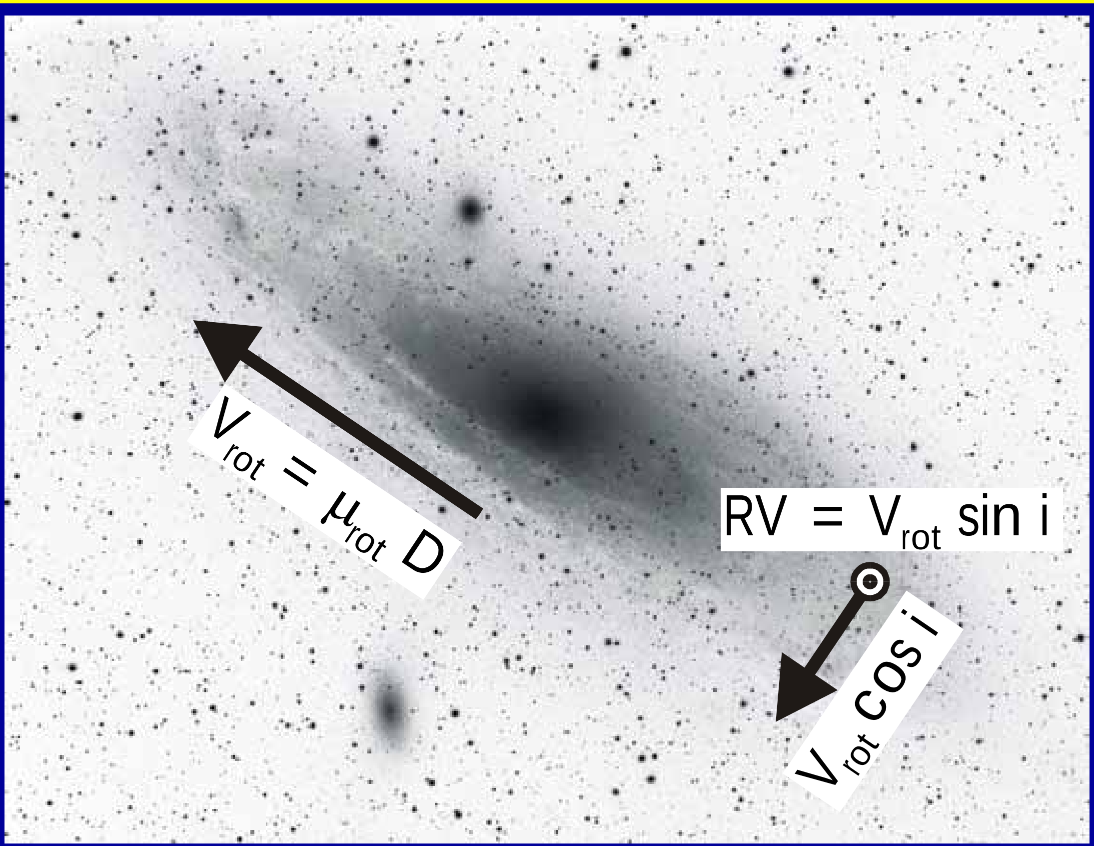
- Mass function of Black Hole Candidates
- Existence of black holes with $M \leq 5\ M_{\odot}$ formed via accretion-induced neutron star collapse?
- Existence of black holes with $M \geq 20\ M_{\odot}$ whose progenitors retained most of their mass until collapse?
- Mass of Neutron Stars: constraints 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



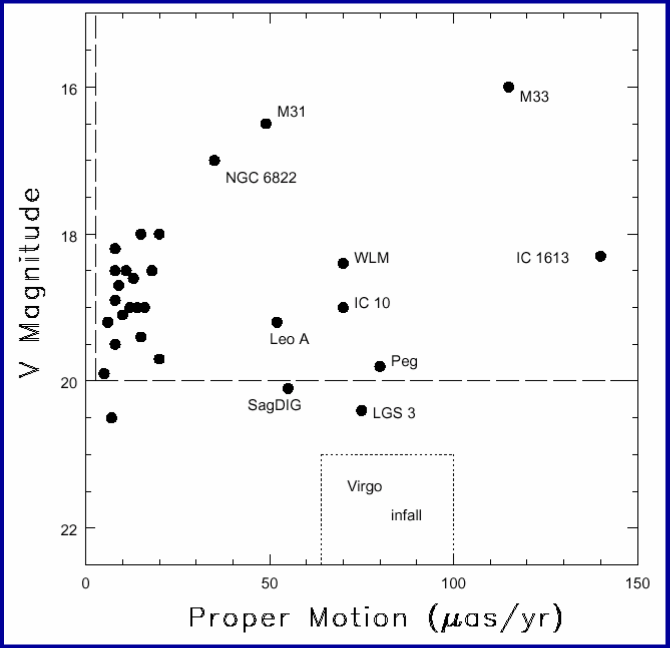
Rotational Parallax ⇒ Distance to Andromeda

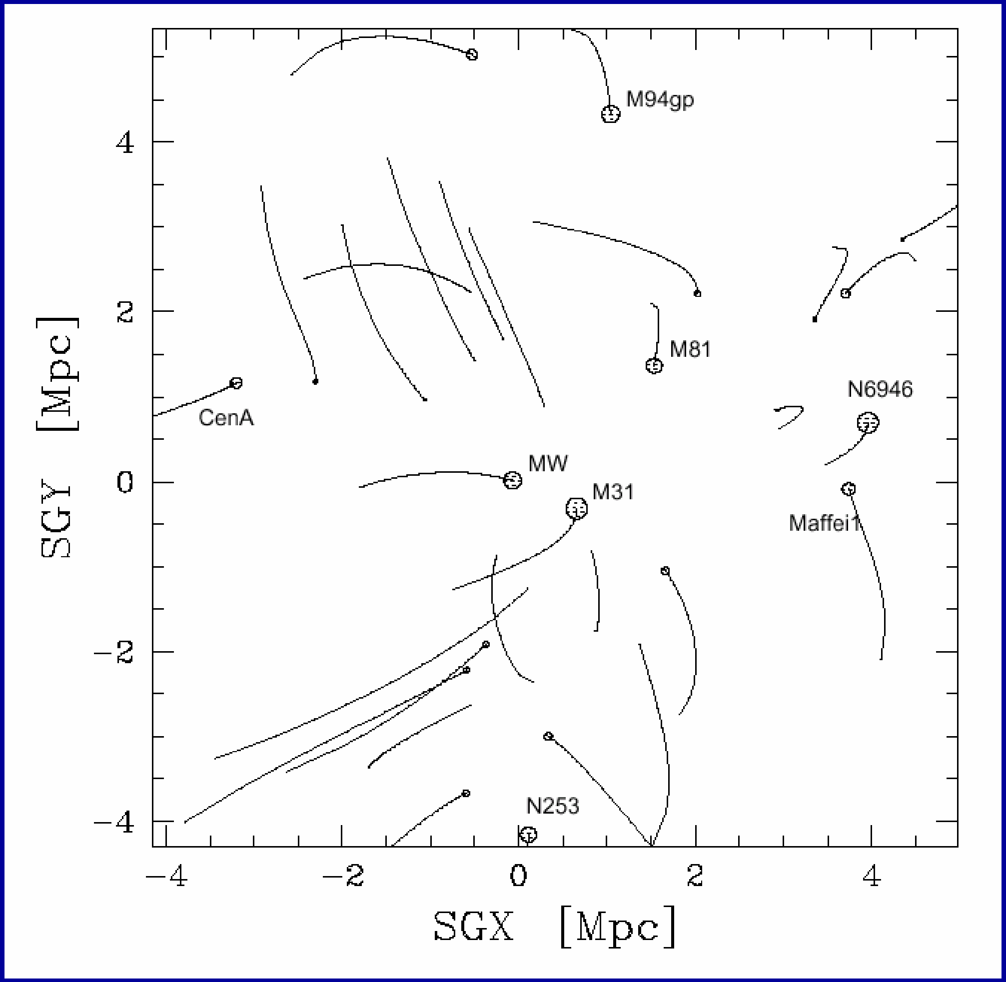


- Observe radial velocity, two proper motions
- Solve for D, i, and V_{rot}

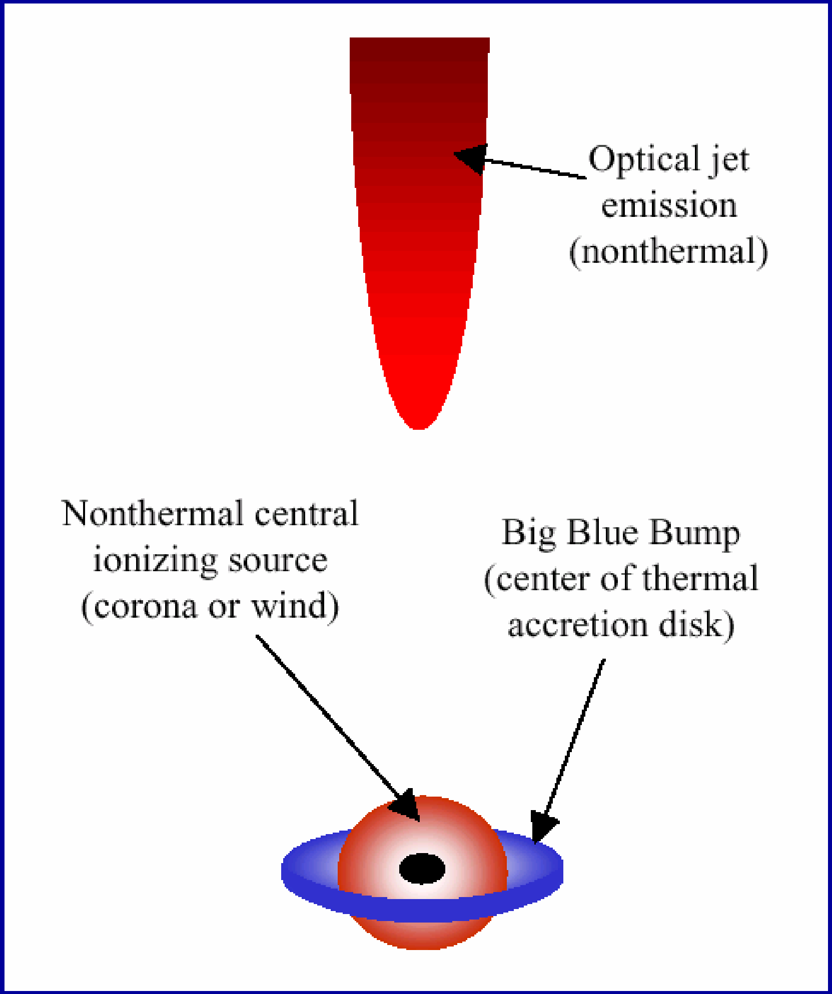
Dynamics of the Local Universe

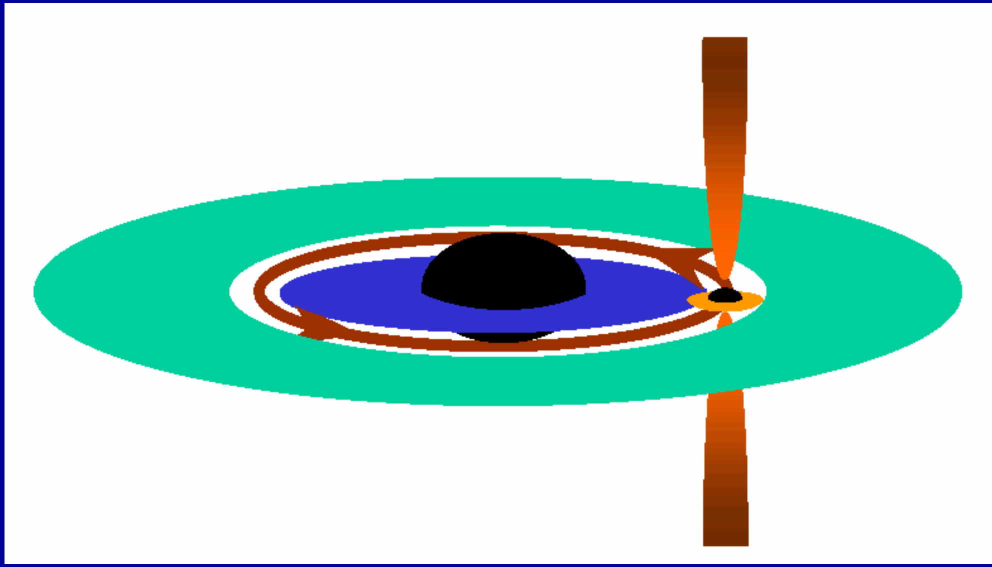
2 µas/yr ≡ 10 *d* km/s where *d* is the distance in Mpc





“Proper Motion” of Quasars

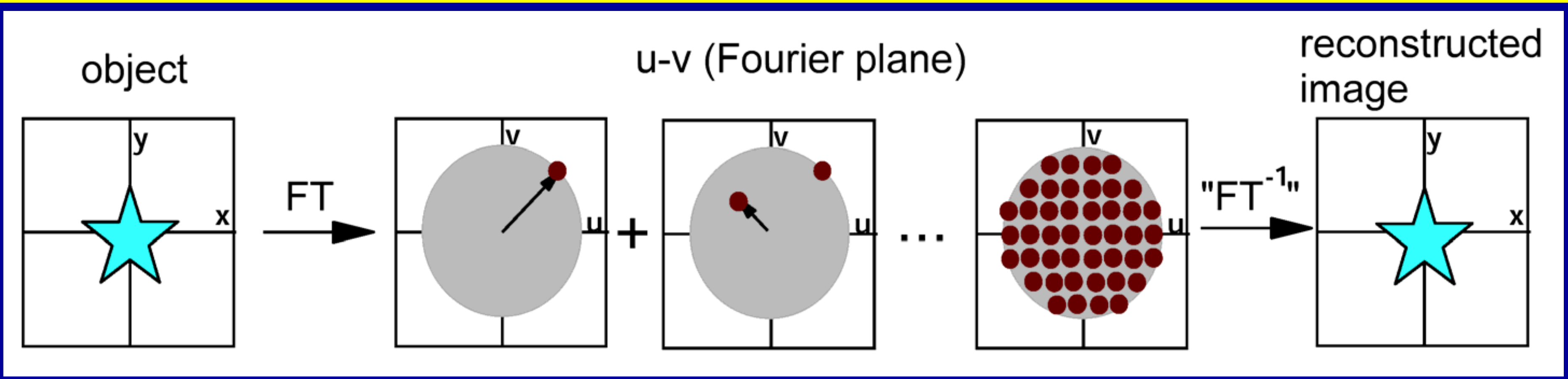




Interferometric Imaging

Andreas Quirrenbach
Sterrewacht Leiden

Aperture Synthesis Imaging

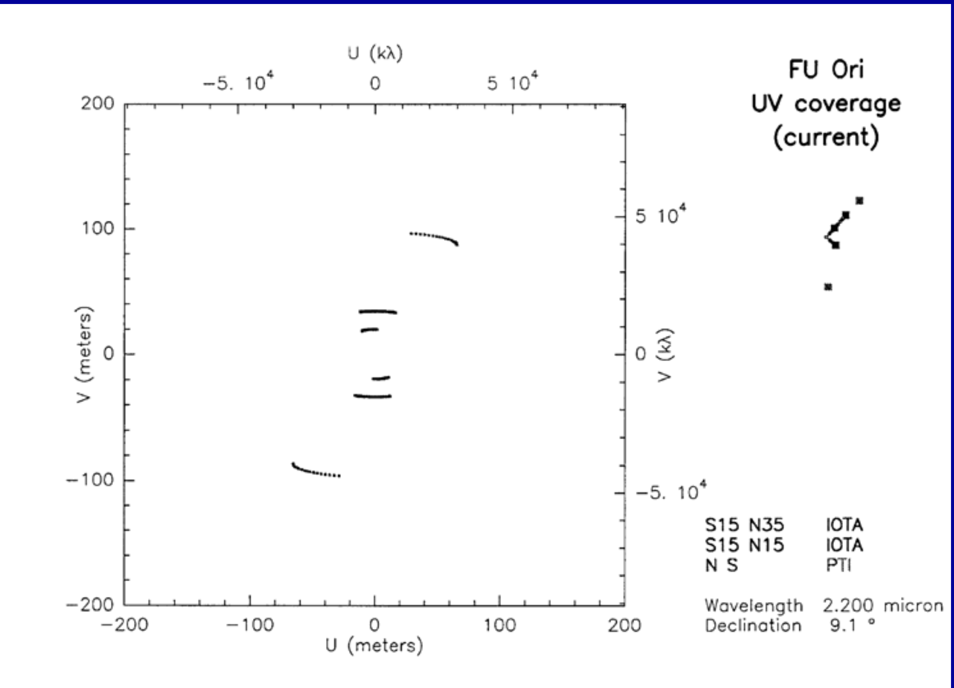


- Each observation measures one Fourier component of the sky brightness distribution.
- <u>Complex</u> visibilities (i.e. fringe amplitude and phase) are needed for Fourier inversion.

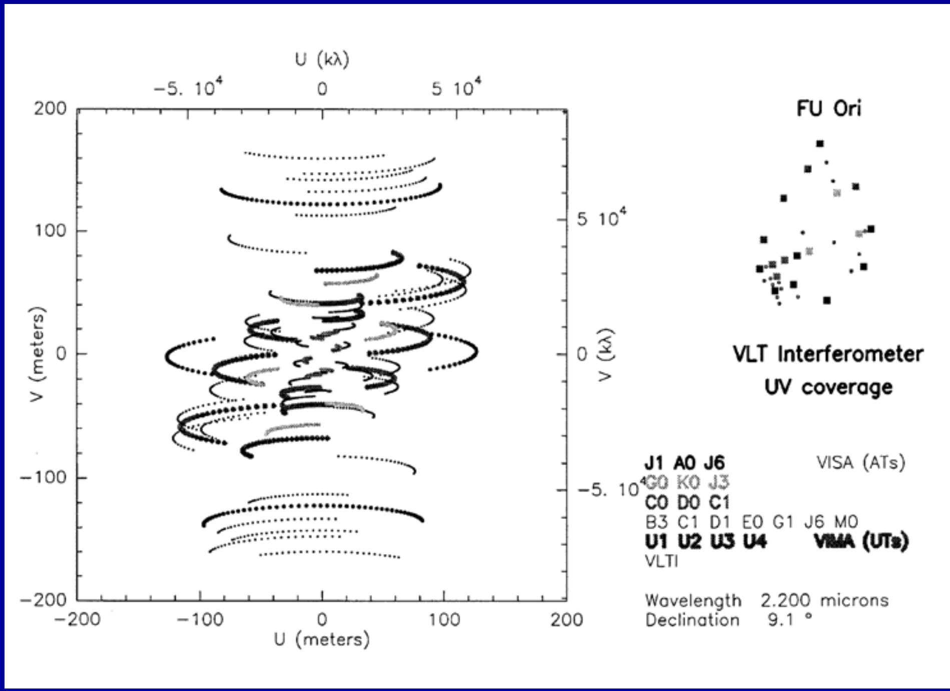
Coverage of the uv Plane

- As for any signal, the Nyquist sampling theorem applies.
- The longest baselines determine the resolution of the observations.
- The shortest baselines determine the field-of-view that can be synthesized.
- All intermediate Fourier components have to be sampled adequately.

Comparison of Present uv Coverage with VLTI

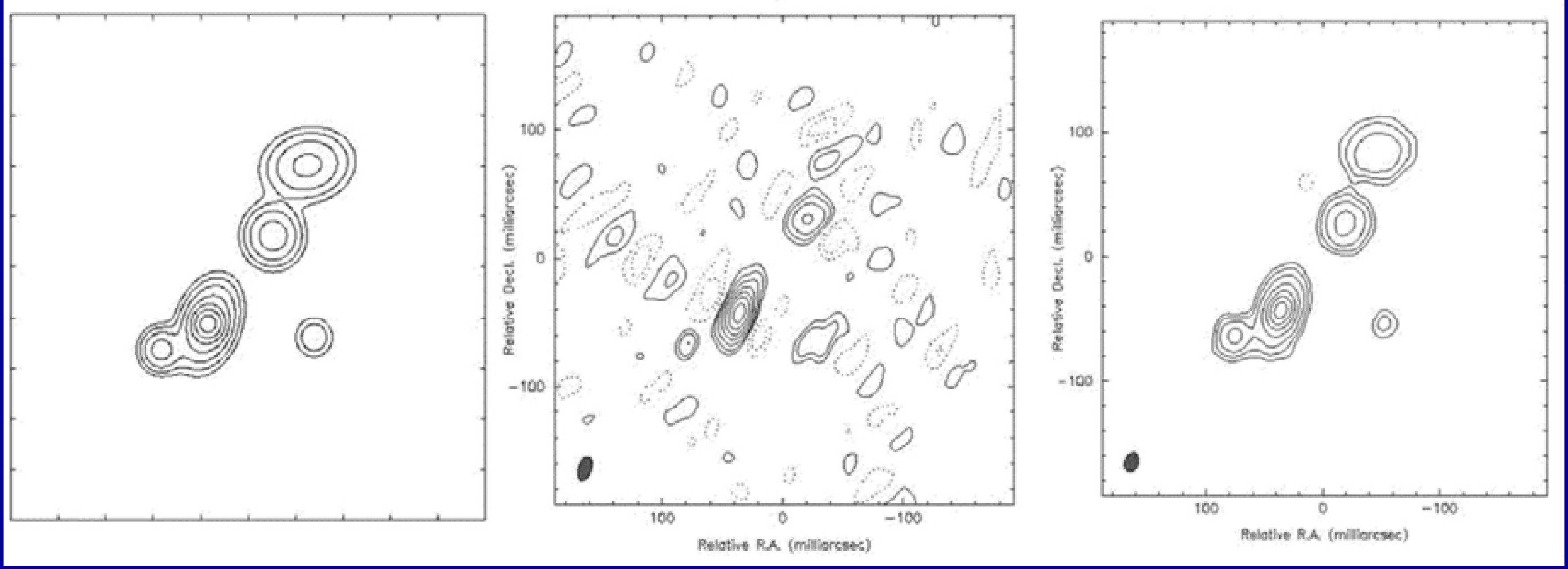


single baselines (no phases)

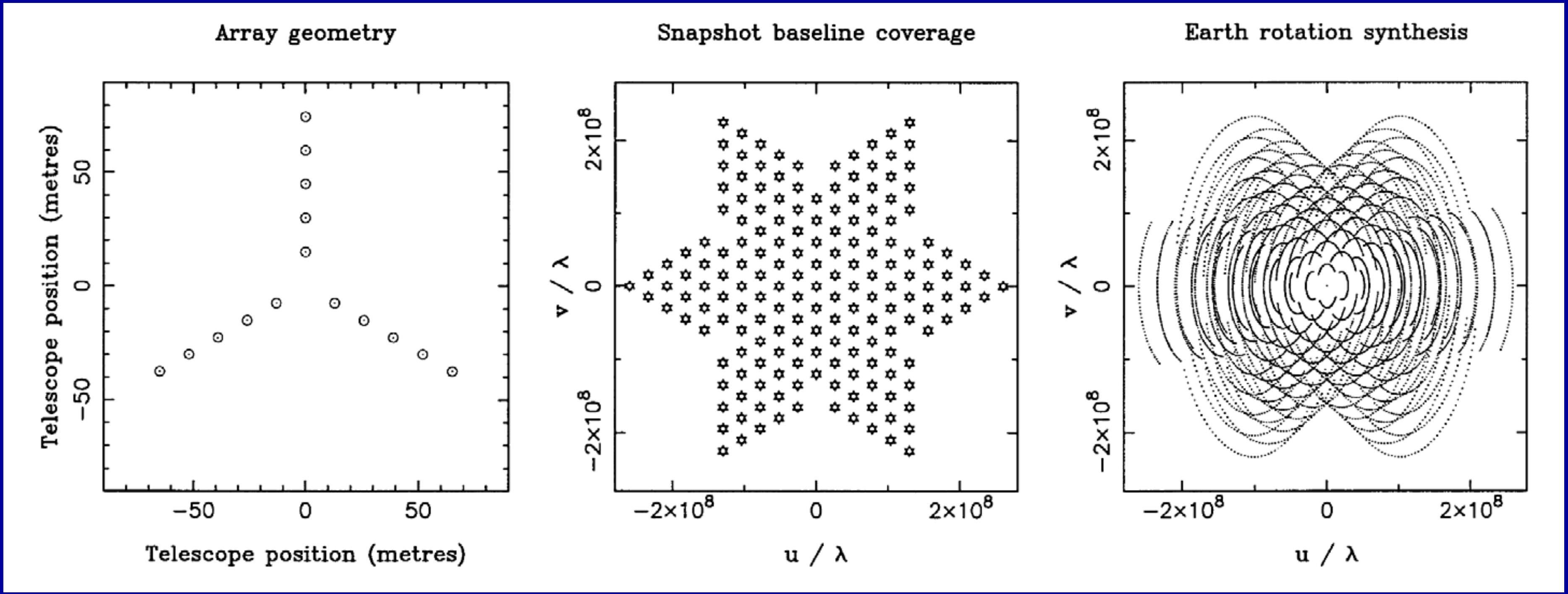


multiple baselines (closure phases)

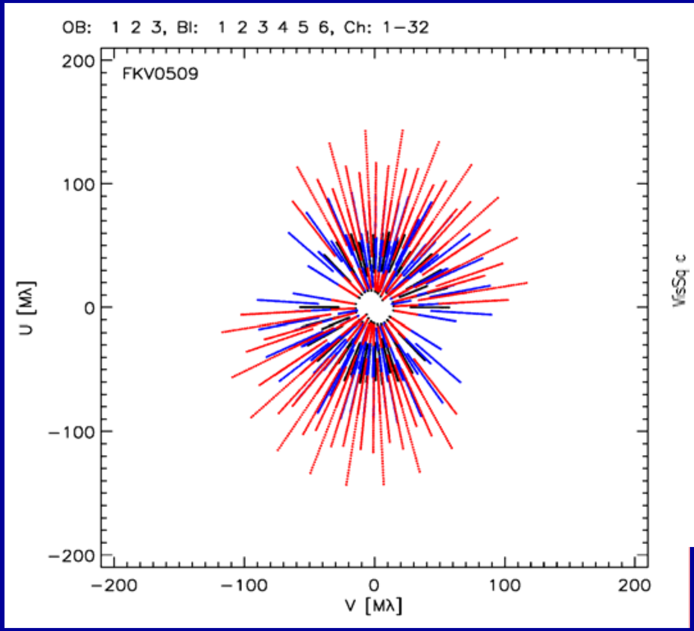
VLTI Imaging Simulation with Four and Eight Telescopes

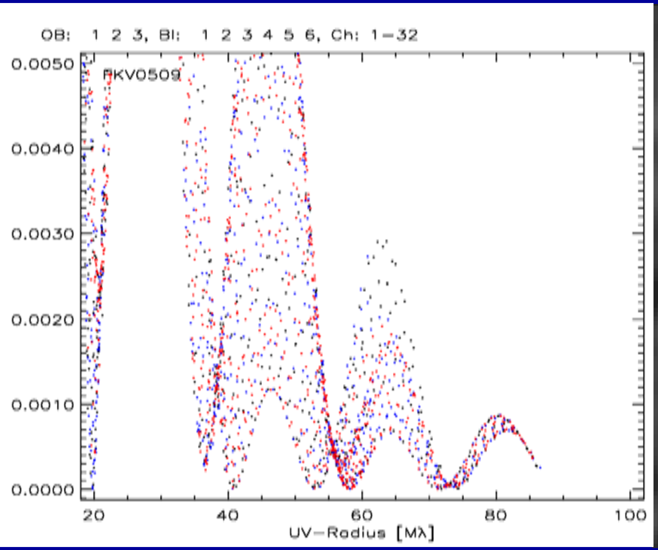


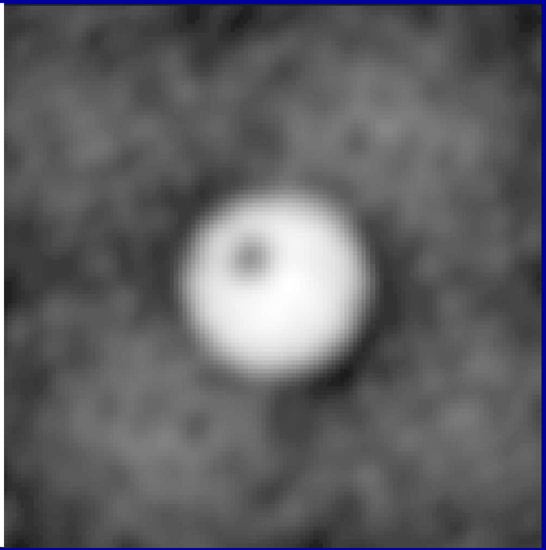
A Y-Shaped Configuration



Interferometric Imaging Simulation





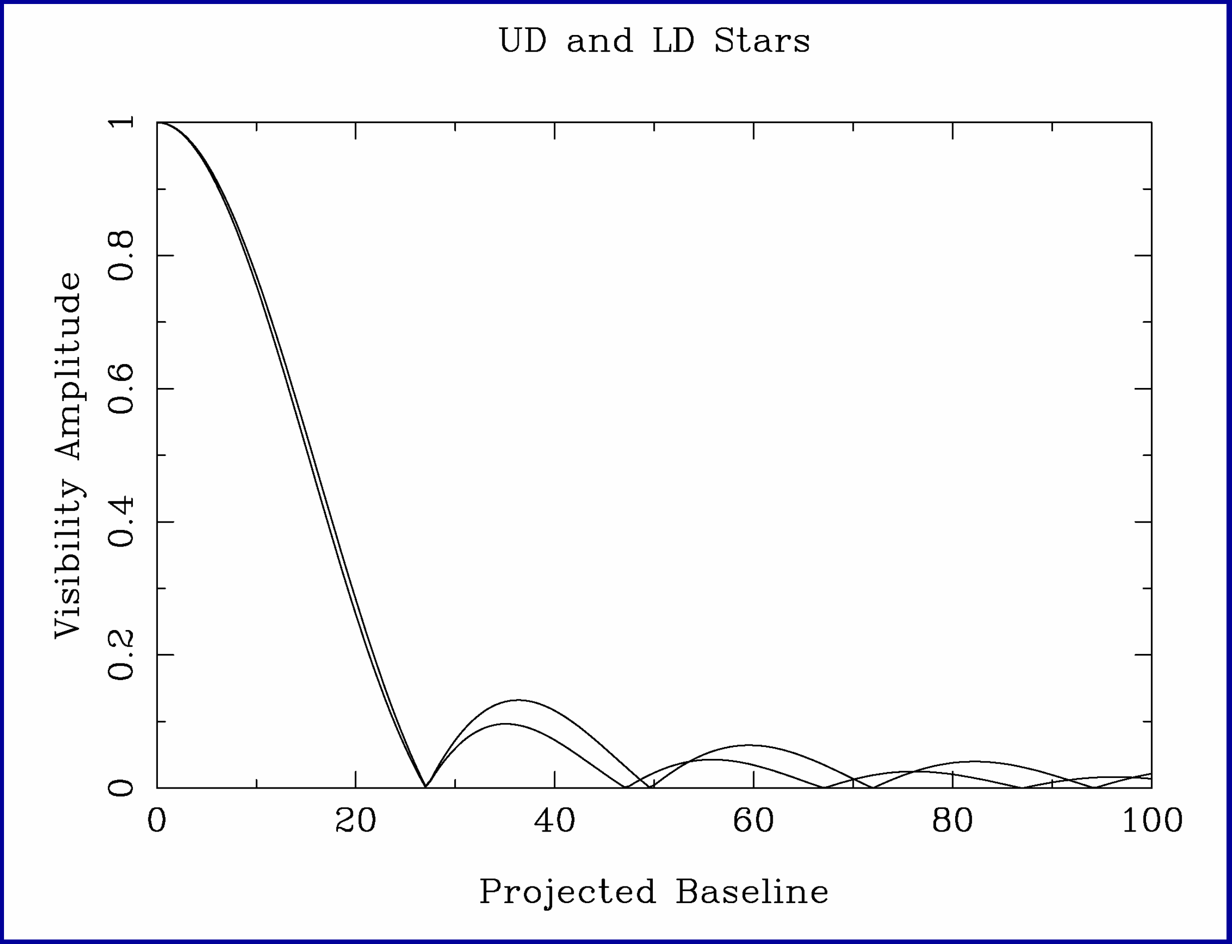


uv plane coverage

data (V^2)

restored image

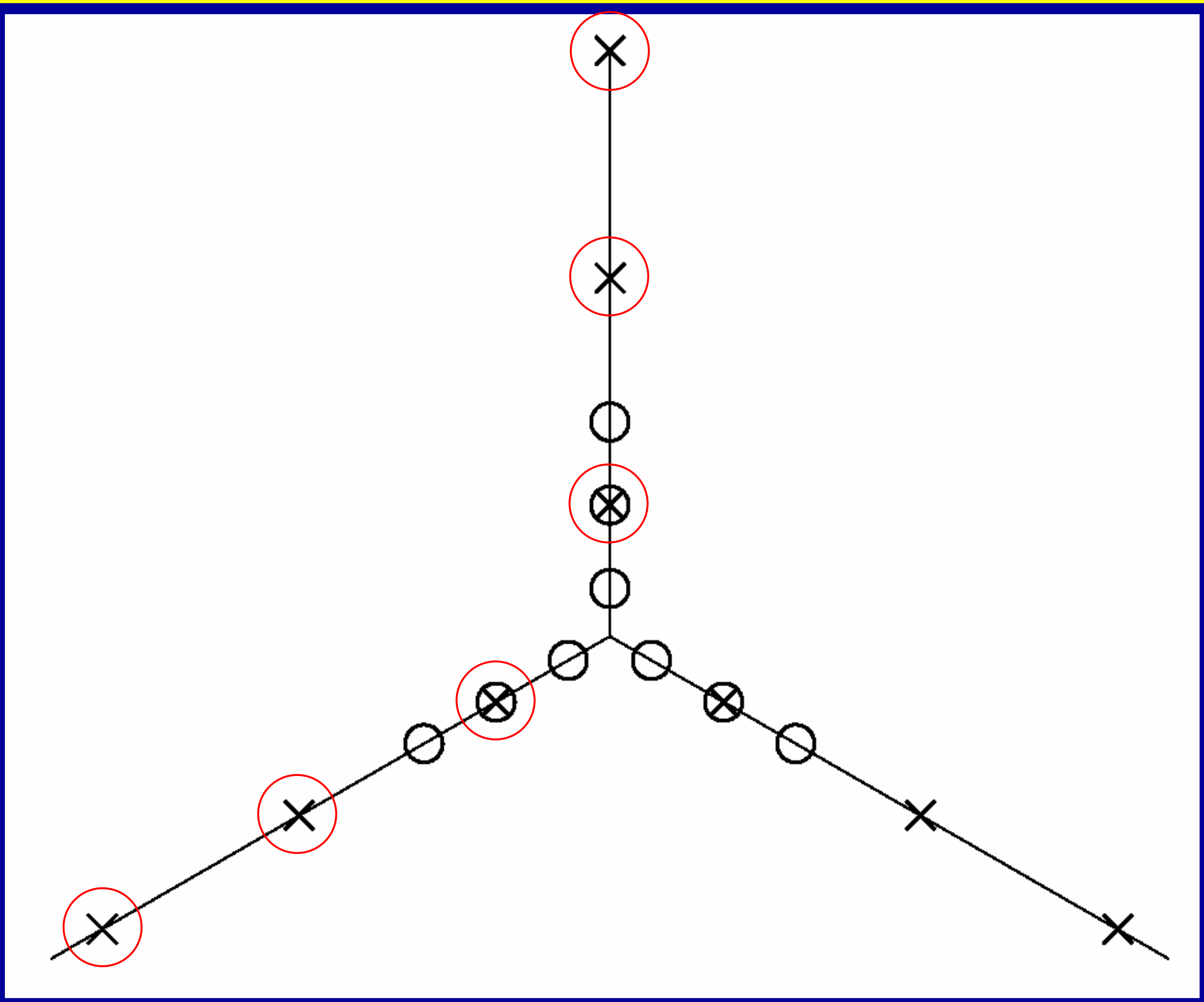
Visibility for Uniform and Limb-Darkened Disk



Most interesting Information is on long baselines, where visibilities are low and fringe tracking is difficult (SNR $\propto V^2$).

Aerial View of the NPOI Array

Layout of NPOI Optimized for Baseline Bootstrapping



Phase Errors

- Atmospheric turbulence corrupts phase above each telescope in interferometer array.
- The observed phase φ' is given by the sum of the true phase φ, and the phase errors ψ at the two telescopes (with correct signs):

$$\varphi'_{12} = \varphi_{12} + \psi_1 - \psi_2$$

- The errors are frequently much larger than 1 radian, which makes phase data useless.

Closure Phase

- Look at phase disturbance on triangle of baselines. The phase errors cancel in the sum:

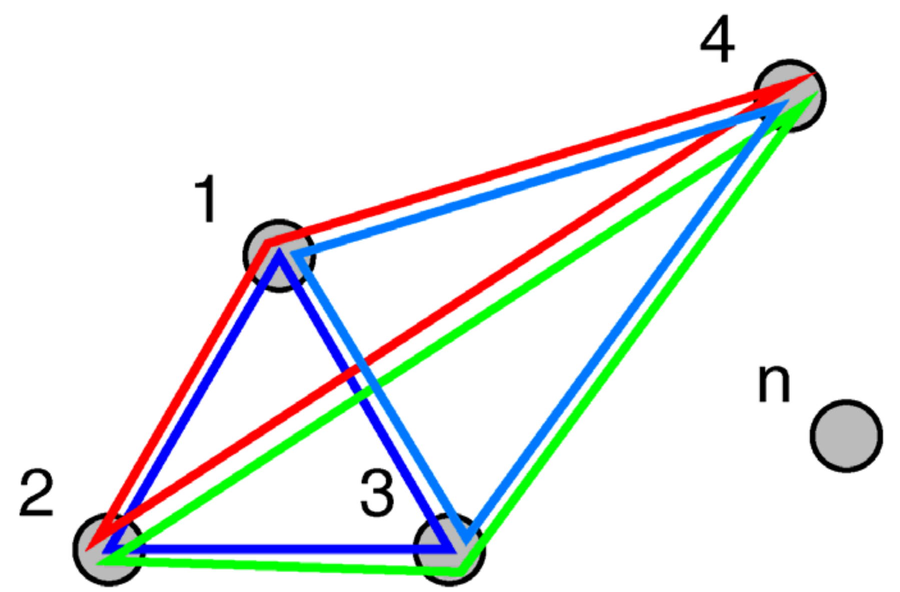
$$\varphi'_{12} = \varphi_{12} + \psi_1 - \psi_2$$

$$\varphi'_{23} = \varphi_{23} + \psi_2 - \psi_3$$

$$\varphi'_{31} = \varphi_{31} + \psi_3 - \psi_1$$

$$\varphi_{123} \equiv \varphi'_{12} + \varphi'_{23} + \varphi'_{31} = \varphi_{12} + \varphi_{23} + \varphi_{31}$$

Relation Between Closure Phases



$$\Phi(1\text{-}2\text{-}3) = \Phi(1\text{-}2\text{-}4) + \Phi(4\text{-}2\text{-}3) + \Phi(1\text{-}4\text{-}3)$$

In General:

$$\Phi(1\text{-}2\text{-}3) = \Phi(1\text{-}2\text{-}n) + \Phi(n\text{-}2\text{-}3) + \Phi(1\text{-}n\text{-}3)$$

Number of Closure Phases

- The total number of closure phases is:

$$\binom{N}{3} = \frac{N(N-1)(N-2)}{3 \cdot 2}$$

- The number of independent closure phases is:

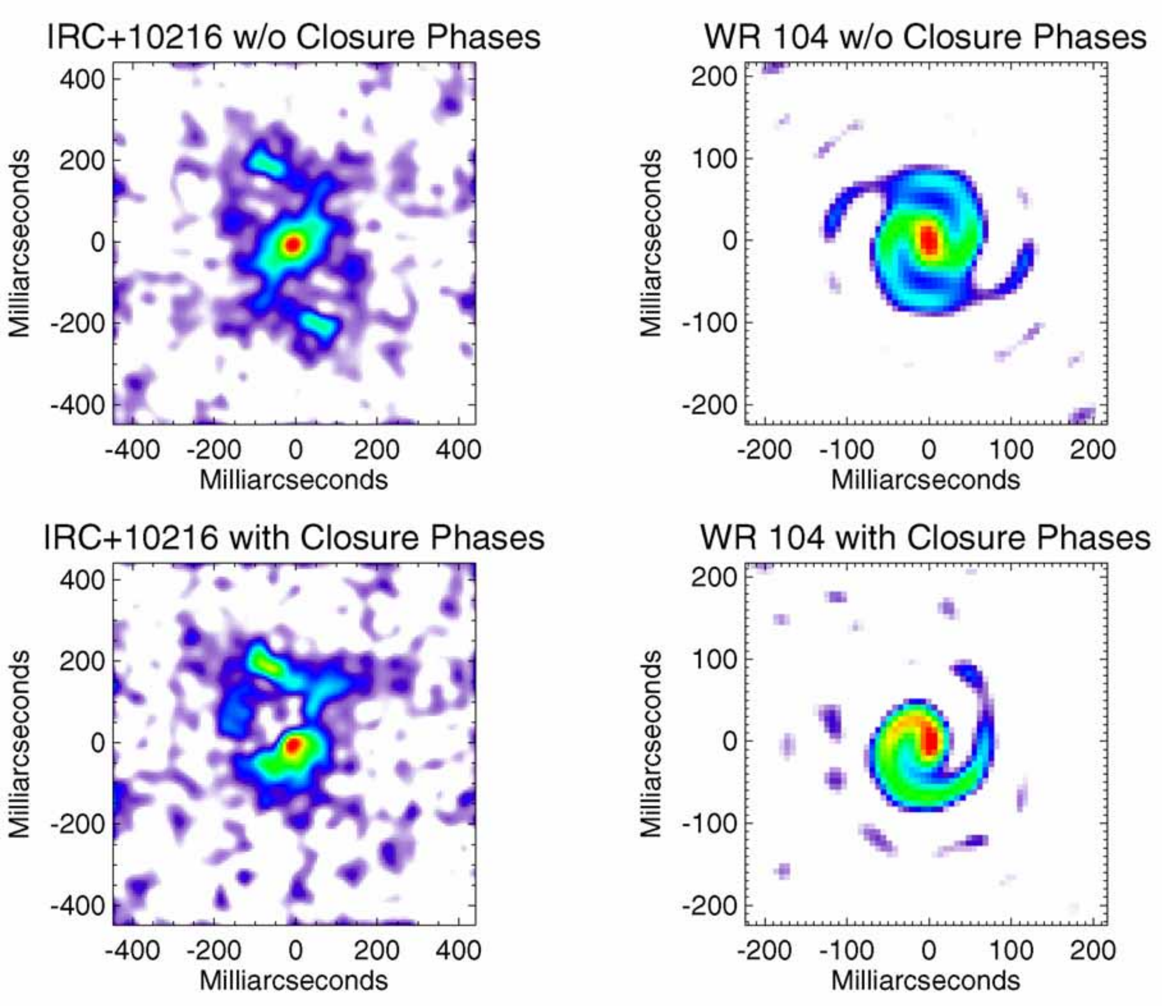
$$\binom{N-1}{2} = \frac{(N-1)(N-2)}{2}$$

- This is equal to the number of baselines minus (*N-1*) arbitrary phases.

Information Content in Closure Phases

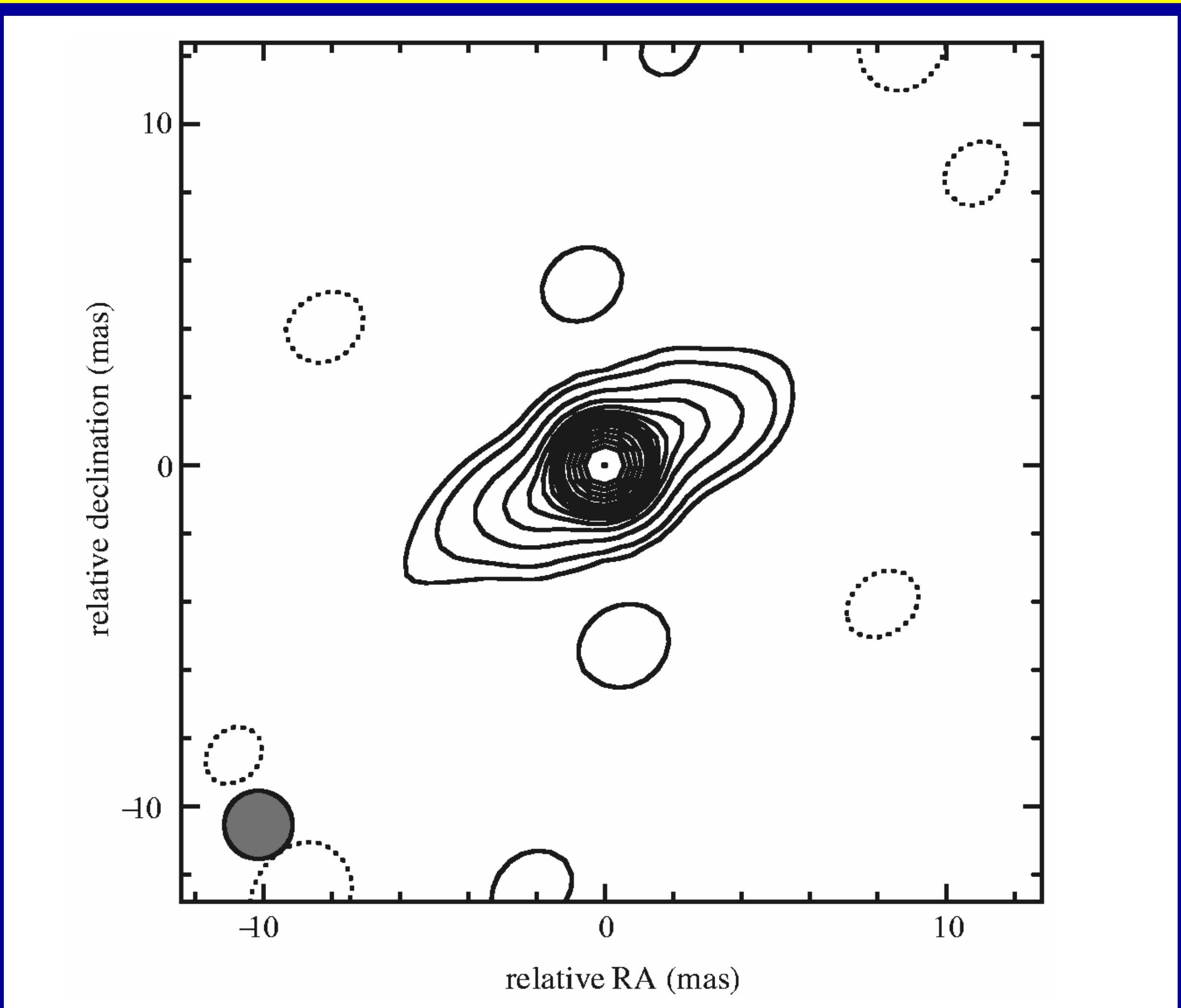
Number of Telescopes	Number of Fourier Phases	Number of Closing Triangles	Number of Independent Closure Phases	Percentage of Phase Information
3	3	1	1	33%
7	21	35	15	71%
21	210	1330	190	90%
27	351	2925	325	93%
50	1225	19600	1176	96%

Images from Keck Aperture Masking (Tuthill et al.)



Phase information is needed to recover asymmetric structure.

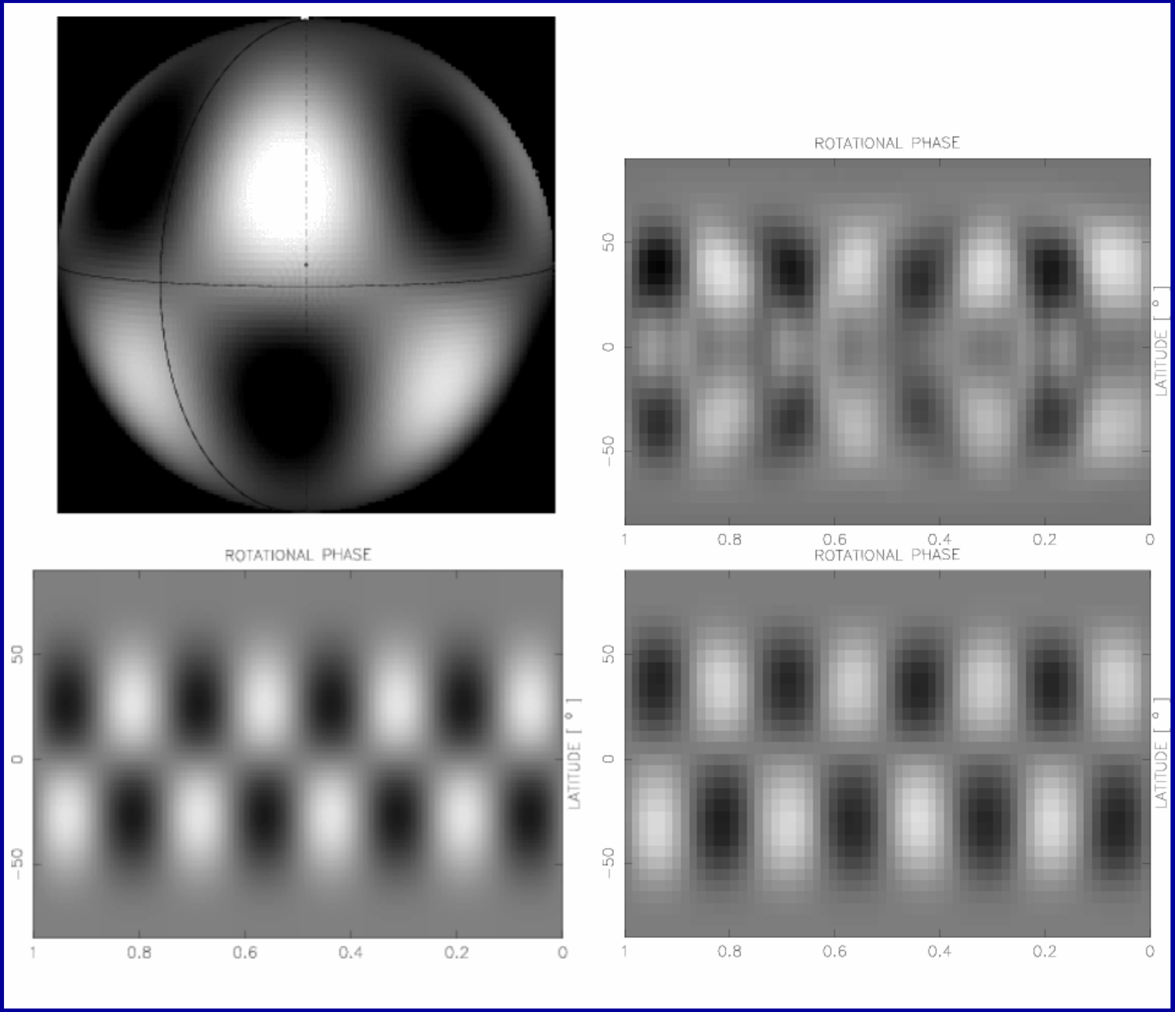
COAST Synthesis Image of the Be Star ζ Tauri



Interferometric High-Resolution Spectroscopy

Andreas Quirrenbach
Sterrewacht Leiden

Mapping Pulsations with Doppler Tomography and Interferometry



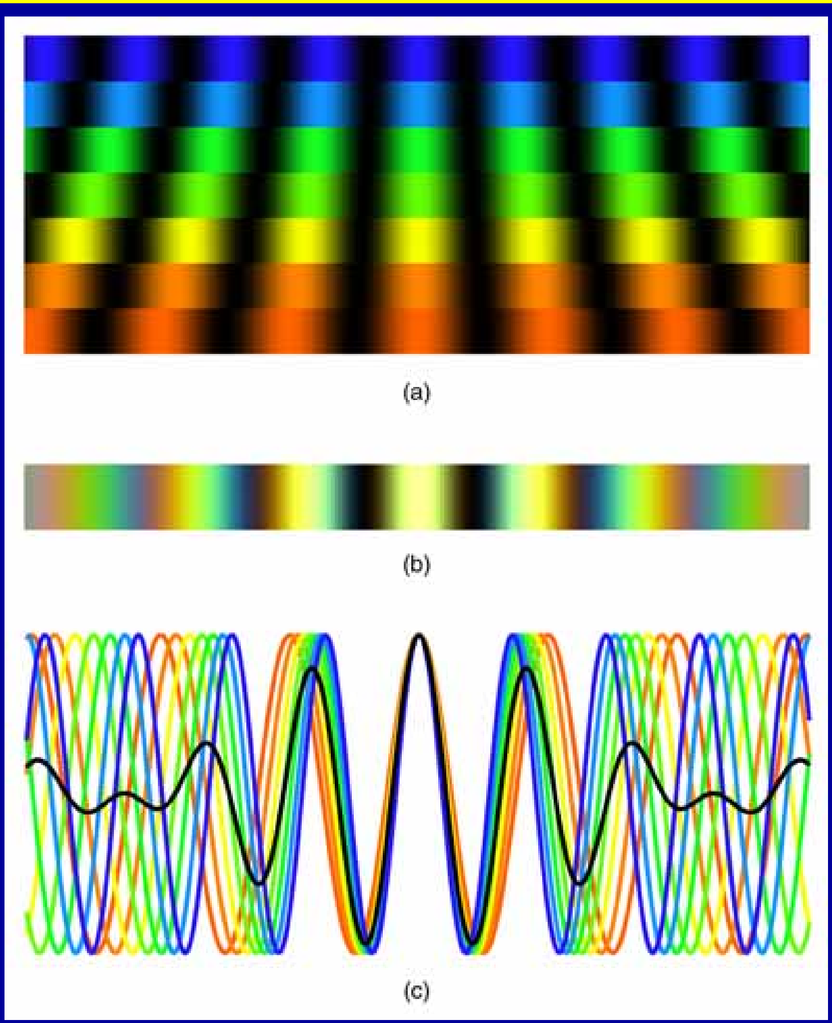
Left: Model

Right: Simulated Reconstruction without and with interferometry

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
  - Generalized Doppler imaging $\rightarrow$ asteroseismology
  - Surface structure of chemically peculiar stars
  - Tracing shocks in Mira atmospheres
- Need $R \approx 20{,}000 \ldots 100{,}000$

Channeled Spectrum and White-Light Fringes



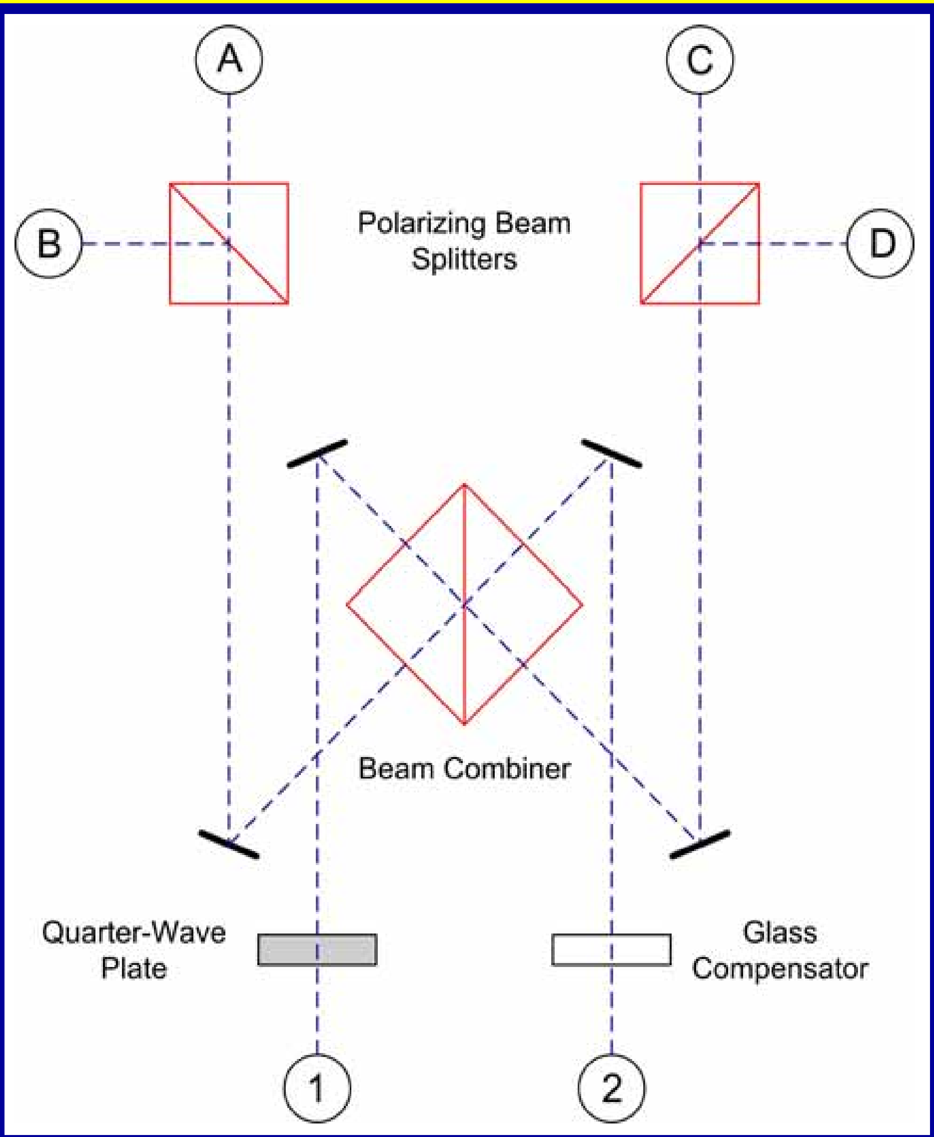
Can We Take Advantage of the VLT Instrument Suite?

- 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 ⇒ 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)

ABCD Beam Combiner without Delay Dither



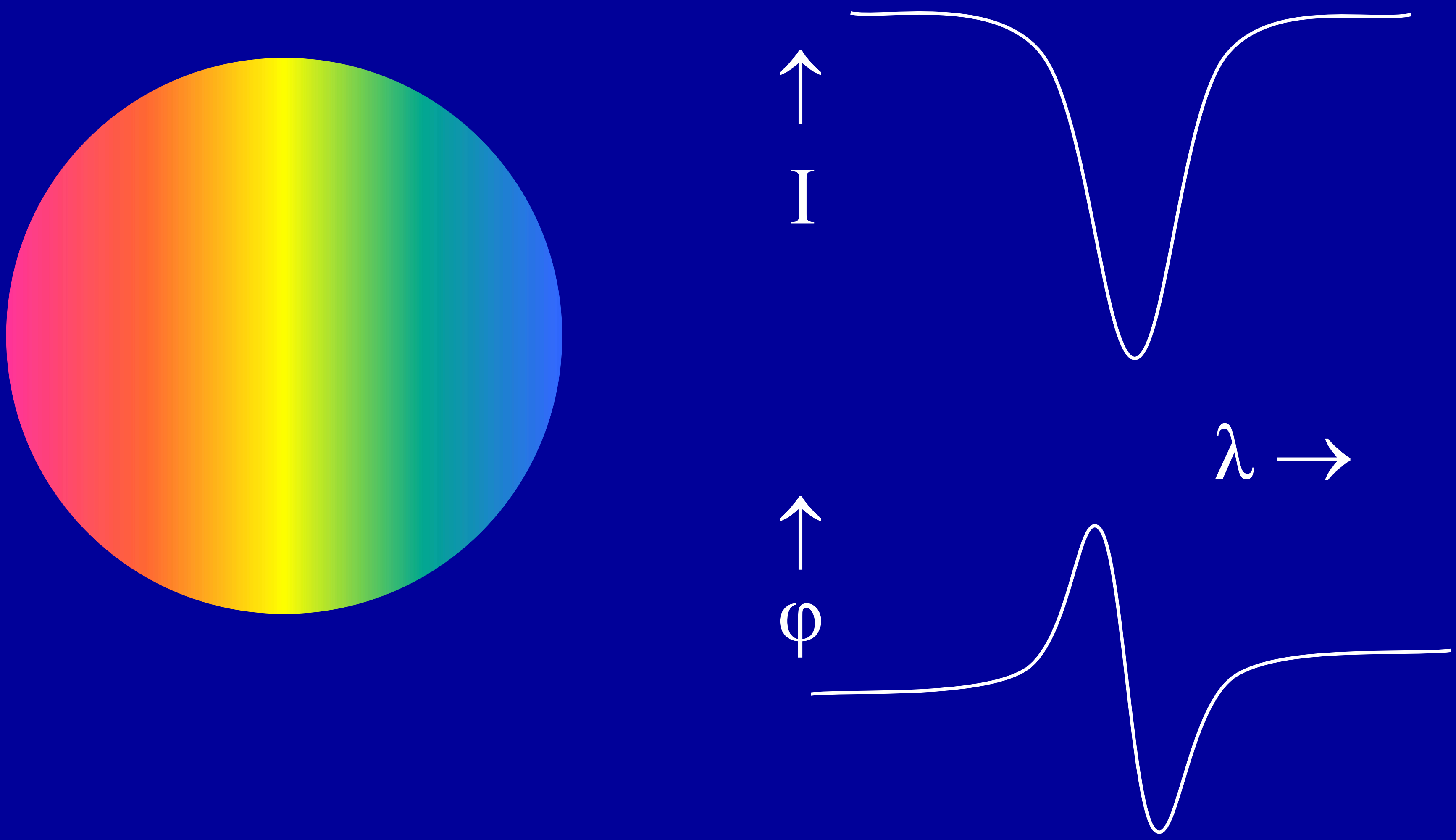
CRIRES-I and UVES-I

- 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, …

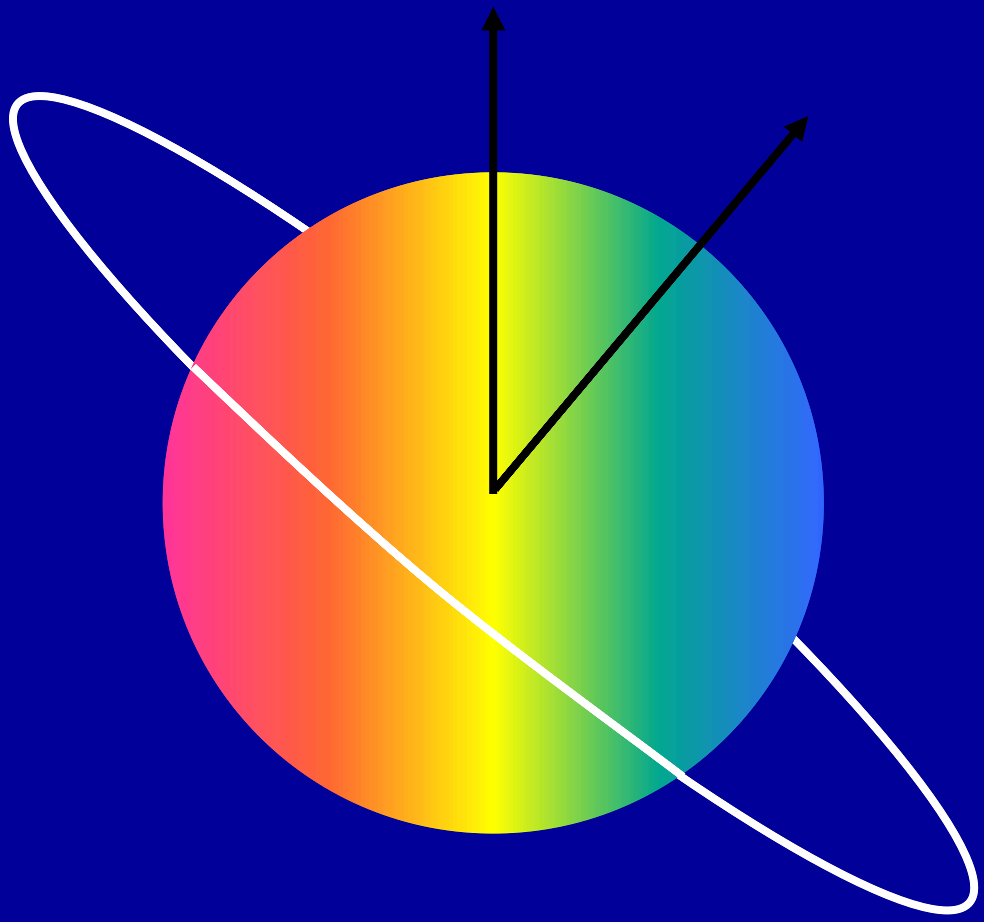
Differential Phases

Andreas Quirrenbach
Sterrewacht Leiden

Interferometer Phase across Stellar Absorption Line



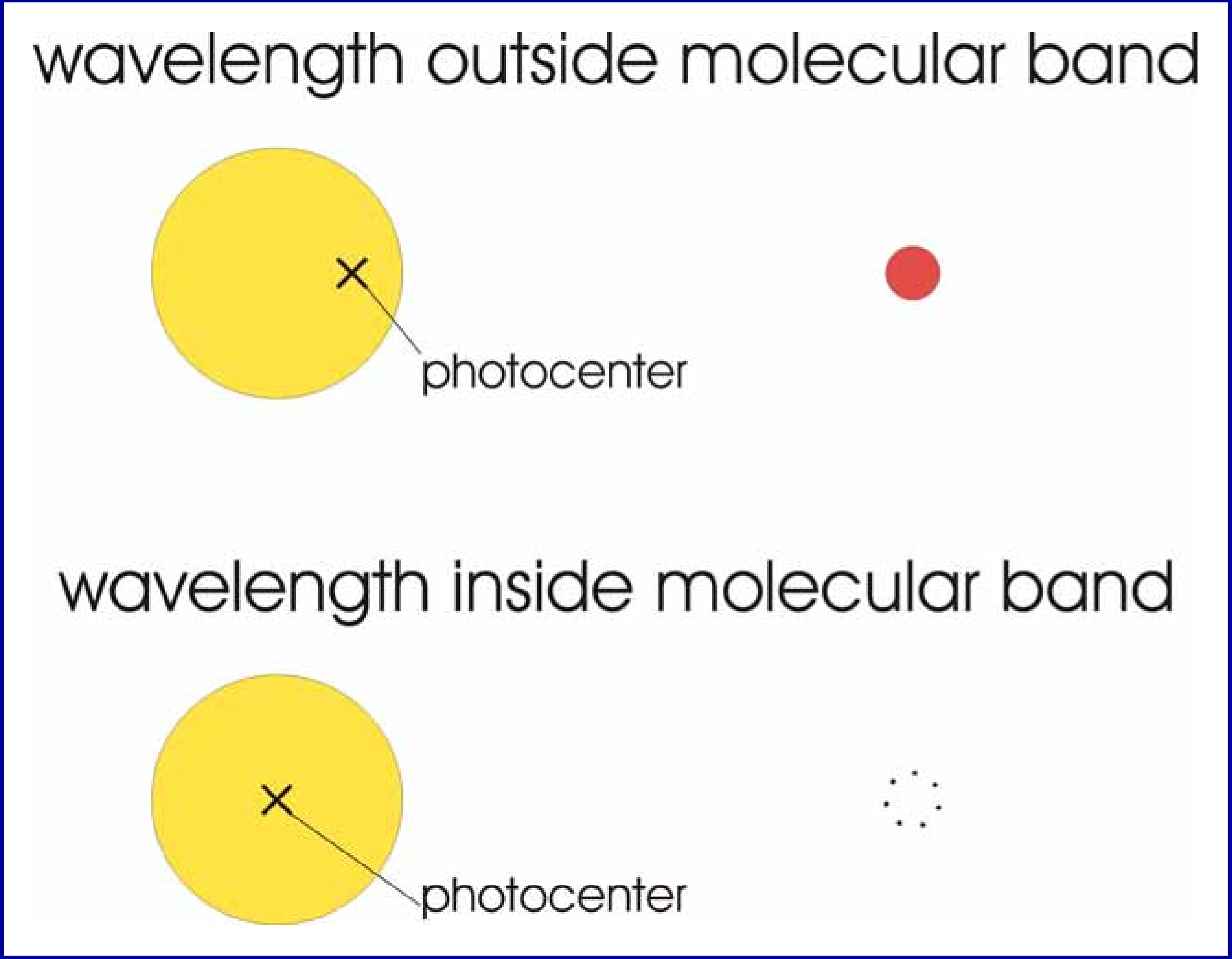
Combination of Astrometry with Spectro-Interferometry



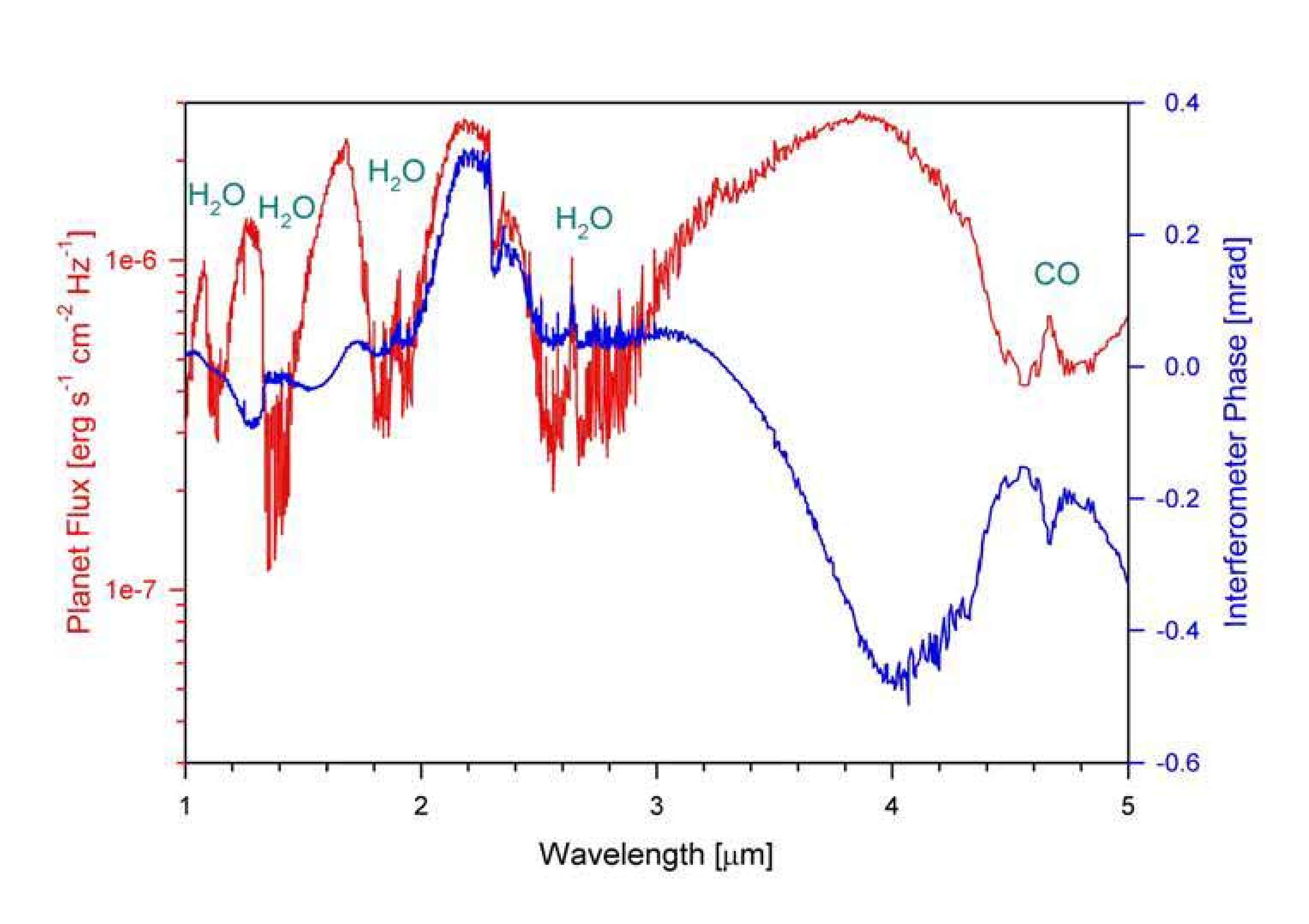
Information from Orientation of Rotation Axis

- 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

The Principle of Differential Phase Interferometry



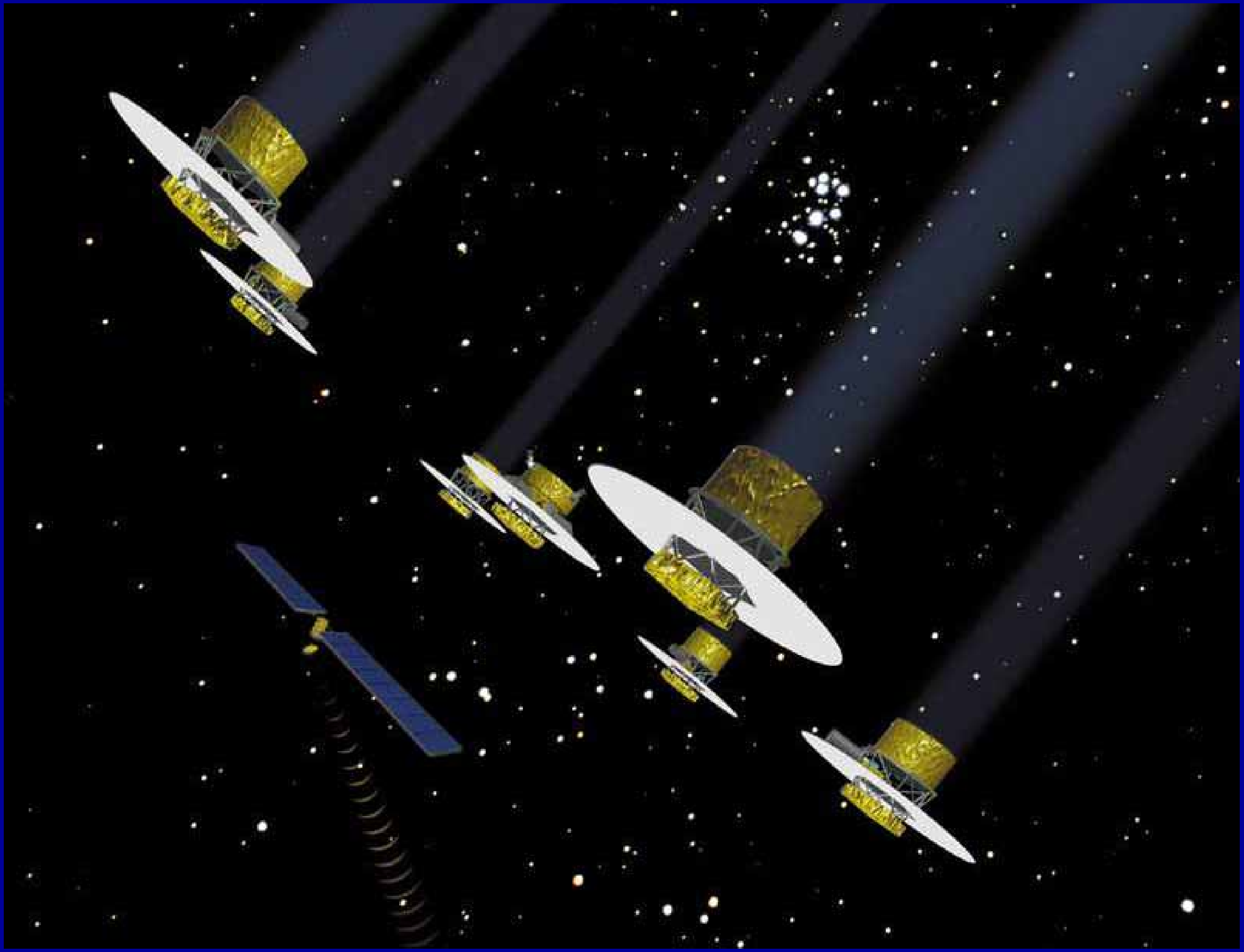
Spectrum of 51 Peg B and Phase on 100 m Baseline



Spectroscopy of Extrasolar Planets

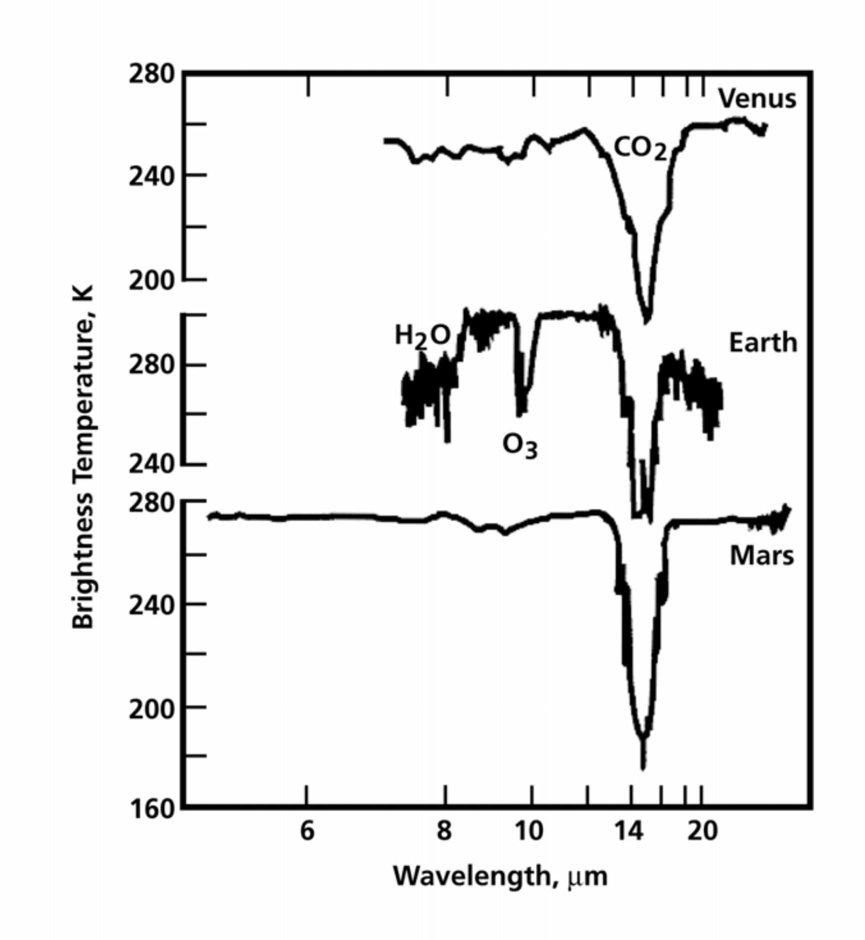
Andreas Quirrenbach
University of California, San Diego

The DARWIN Interferometer (ESA, around 2015)



Infrared Spectra of Venus, Earth, and Mars

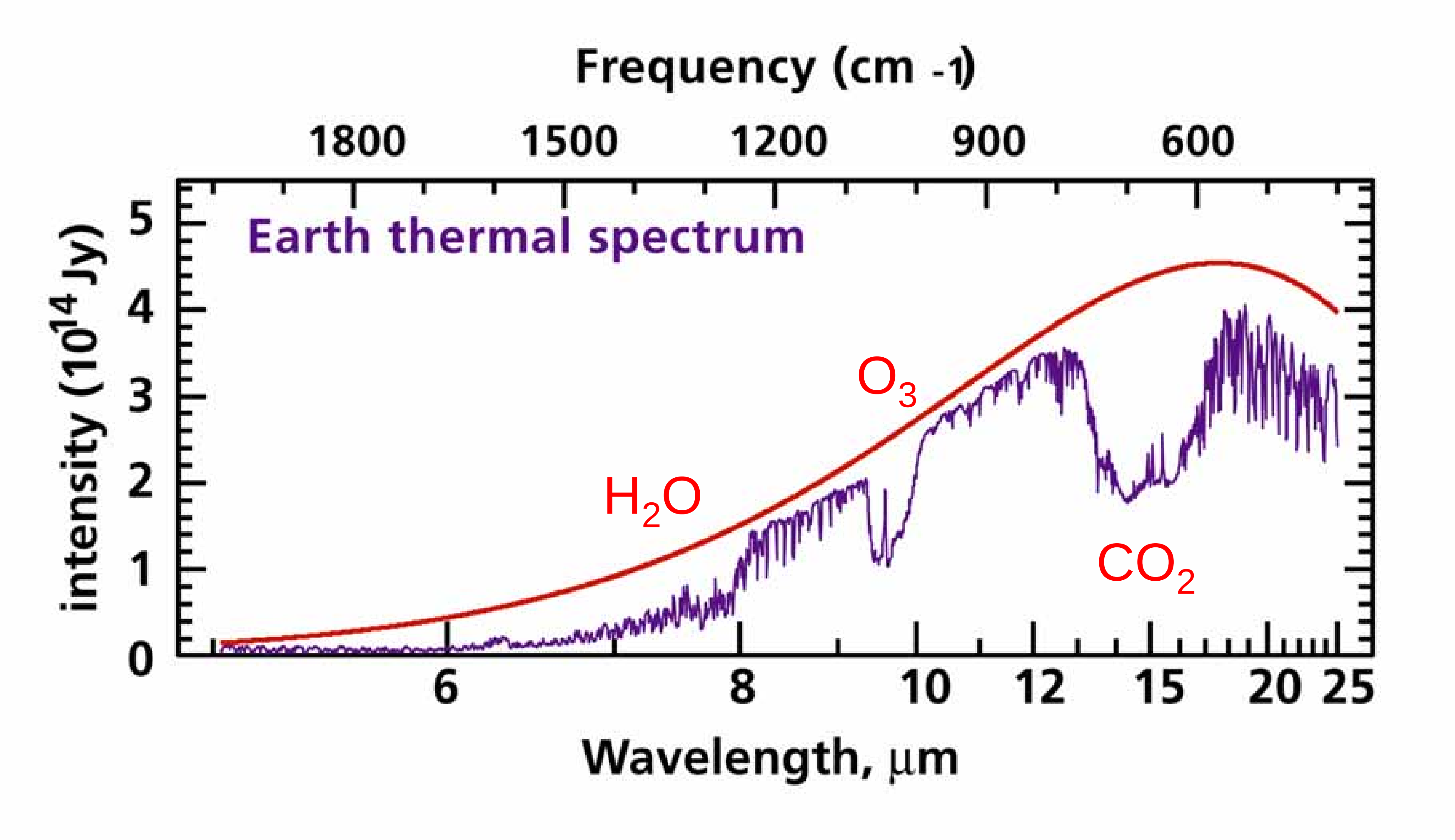
- Venus looks cold ⇒ cloud cover
- Mars is cold ⇒ no liquid water
- Earth is warm ⇒ liquid water and oxygen
- Note presence of CO_2 in all three cases



Biomarkers

- Planet temperature (from IR continuum, orbital radius, star luminosity)
- Atmospheric chemical constituents
- Secular variations indicating rotation period or actual seasonal changes

Infrared Spectrum of Earth

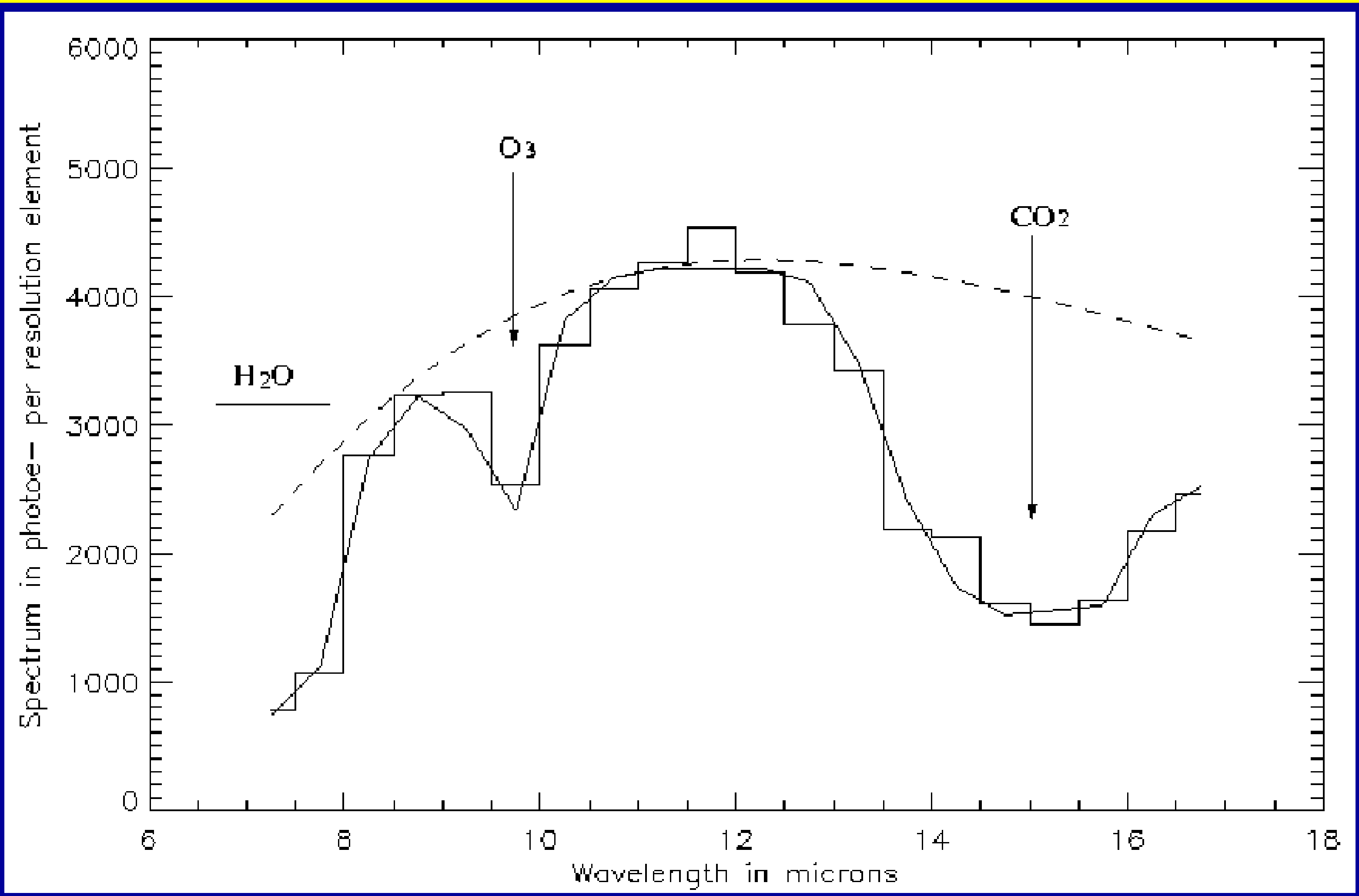


Oxygen Supplied to Earth's Atmosphere by Life

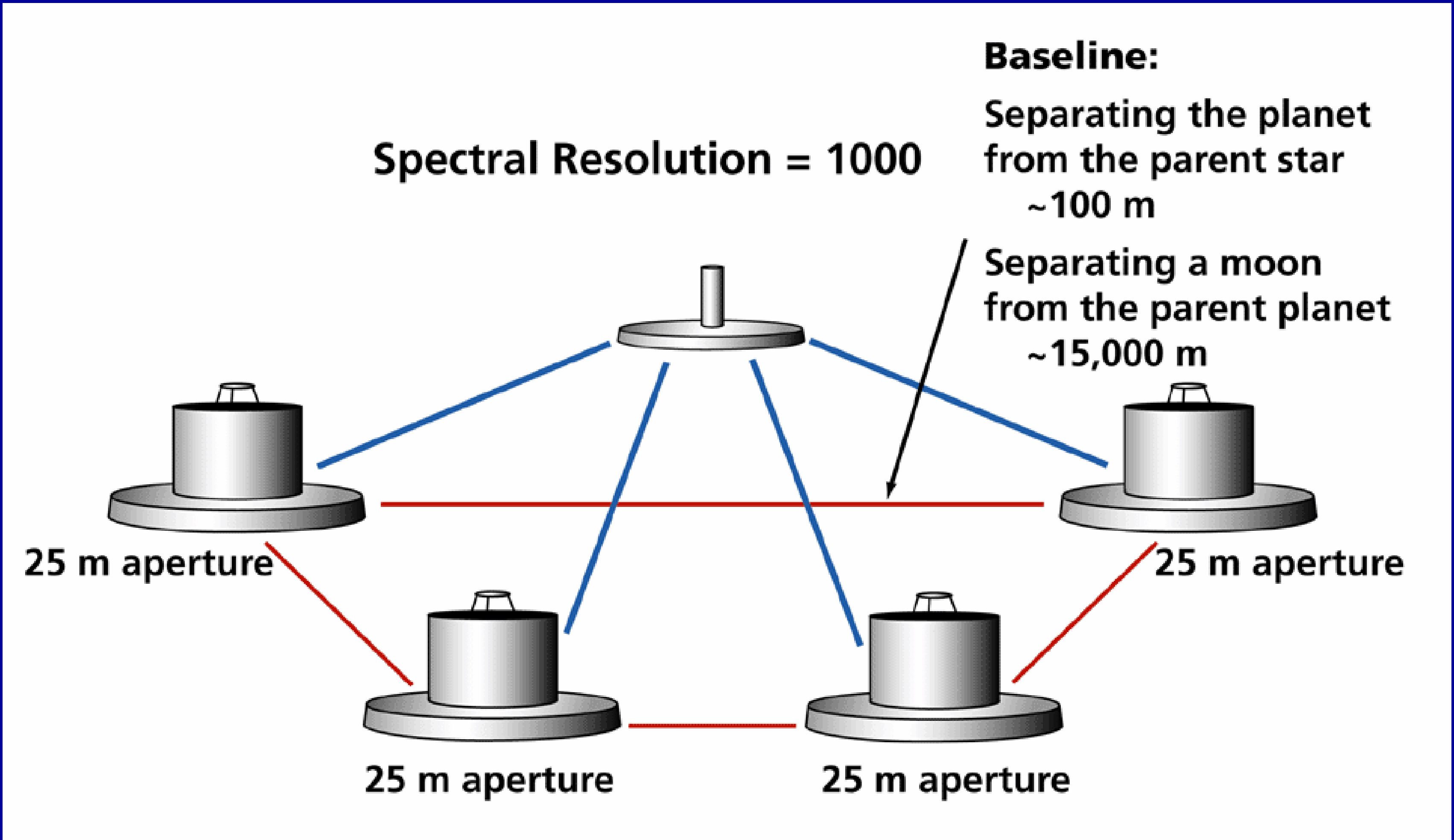
- Oxygen in an atmosphere is removed in 5 Myr by reaction with volcanic lava
- So to sustain an oxygen atmosphere ⇒ need to release oxygen from compound
- This is complex and needs a lot of energy. An example is photosynthesis:

  $CO_2 + 2\ H_2O + 8\ h\nu \rightarrow (H\text{-}CHO) + O_2 + H_2O$
- This needs complex mechanism ⇒ life

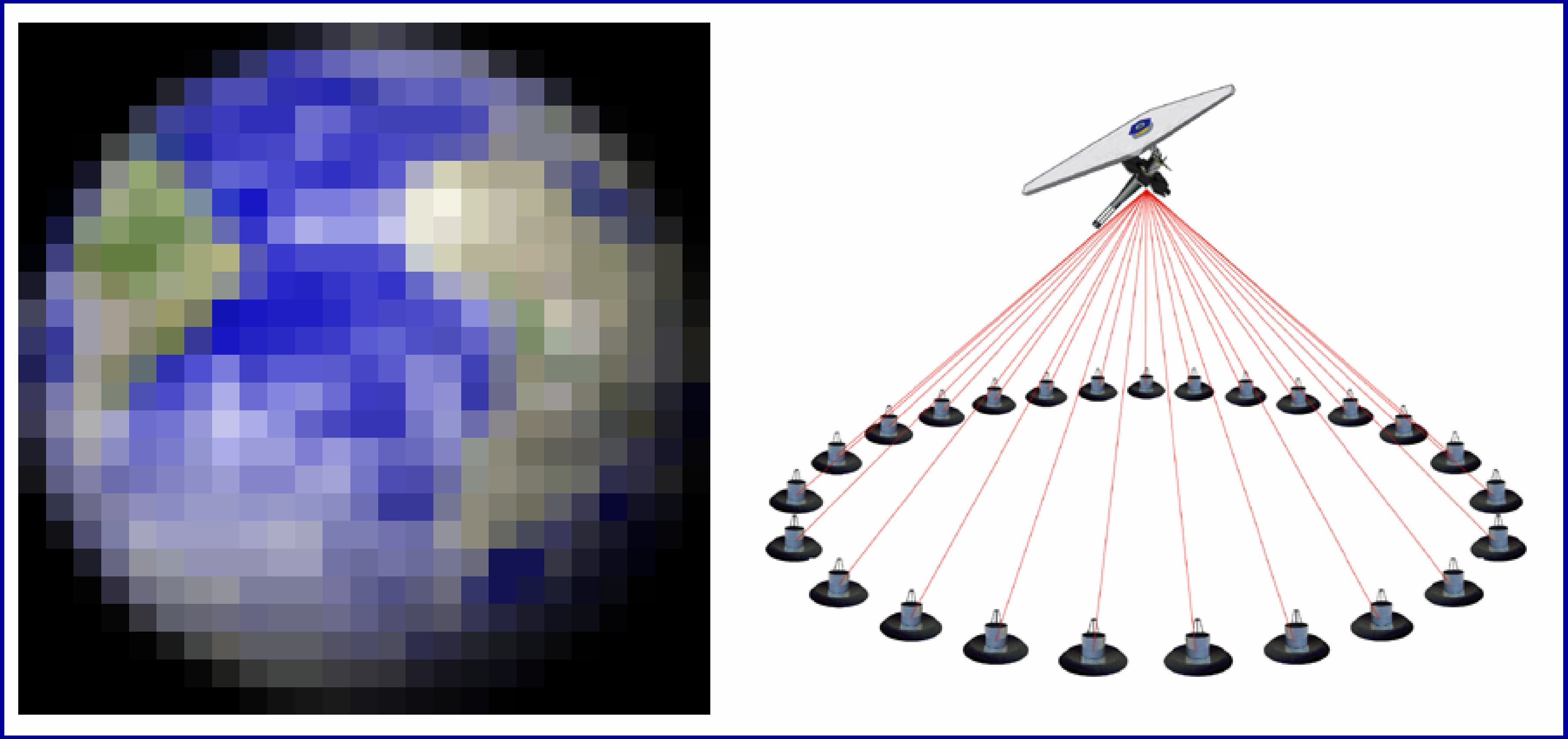
Simulated Spectrum of Exo-Earth Observed with DARWIN



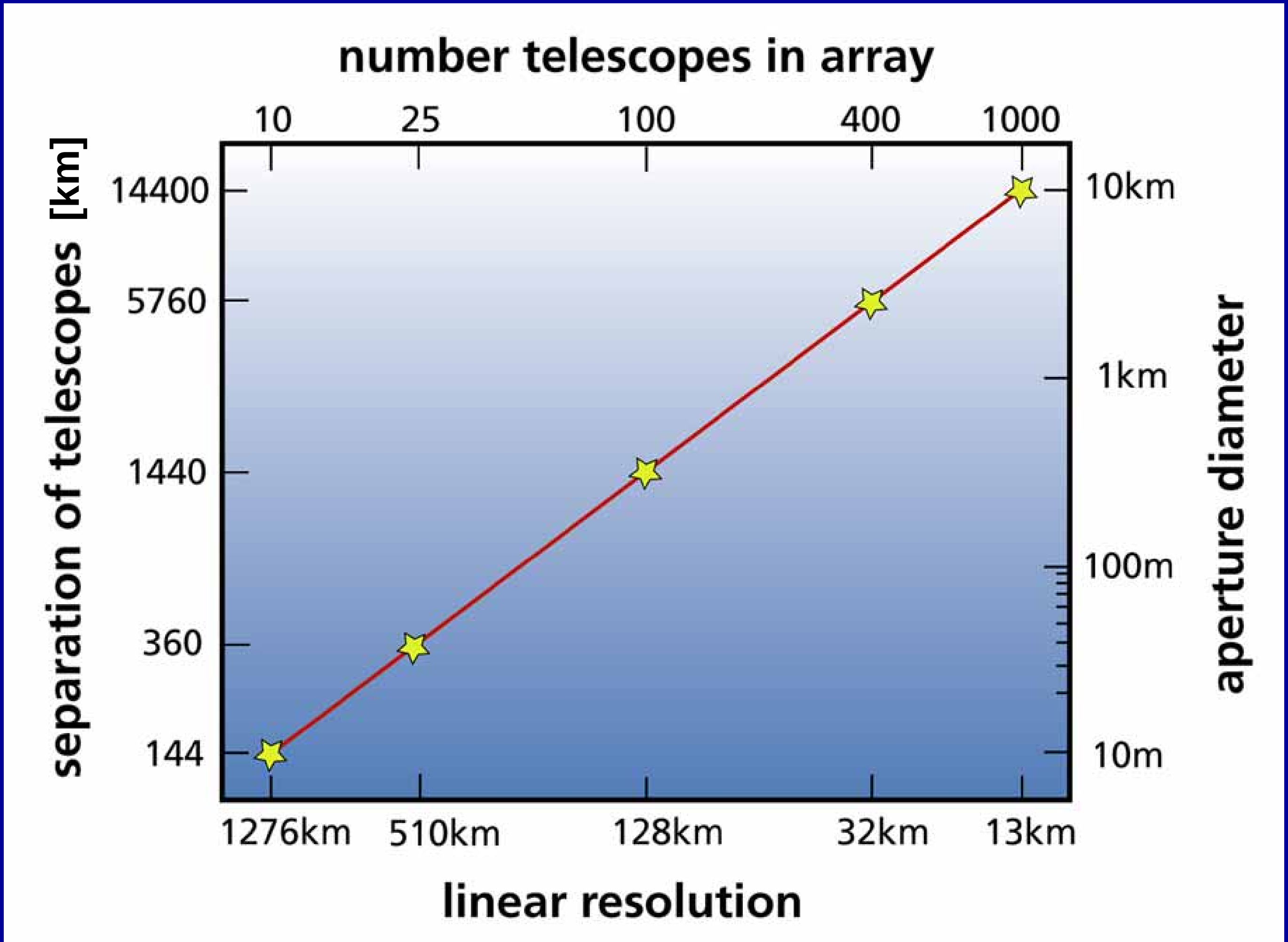
Darwin / TPF ++


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

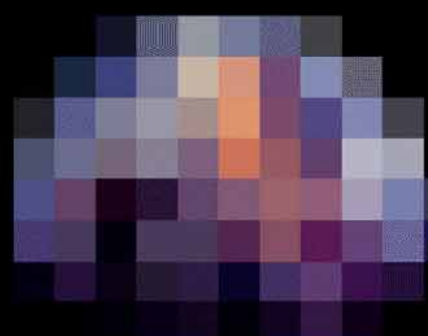
Exo-Earth Imager



Telescope and Array Scaling with Desired Resolution



Exo-Earth Imager: Interferometer Requirements

Pixel / Diameter	Pixel size @ planet (km)	Pixel angle @ 10pc (arcsec)	Image
25	510	3.4×10^{-7}	
10	1276	8.5×10^{-7}	

Interferometer Requirements

	Area	Baseline
IR	1,024 m^2	6,000 km
Vis.	9,216 m^2	303 km
IR	64 m^2	2,400 km
Vis.	576 m^2	120 km

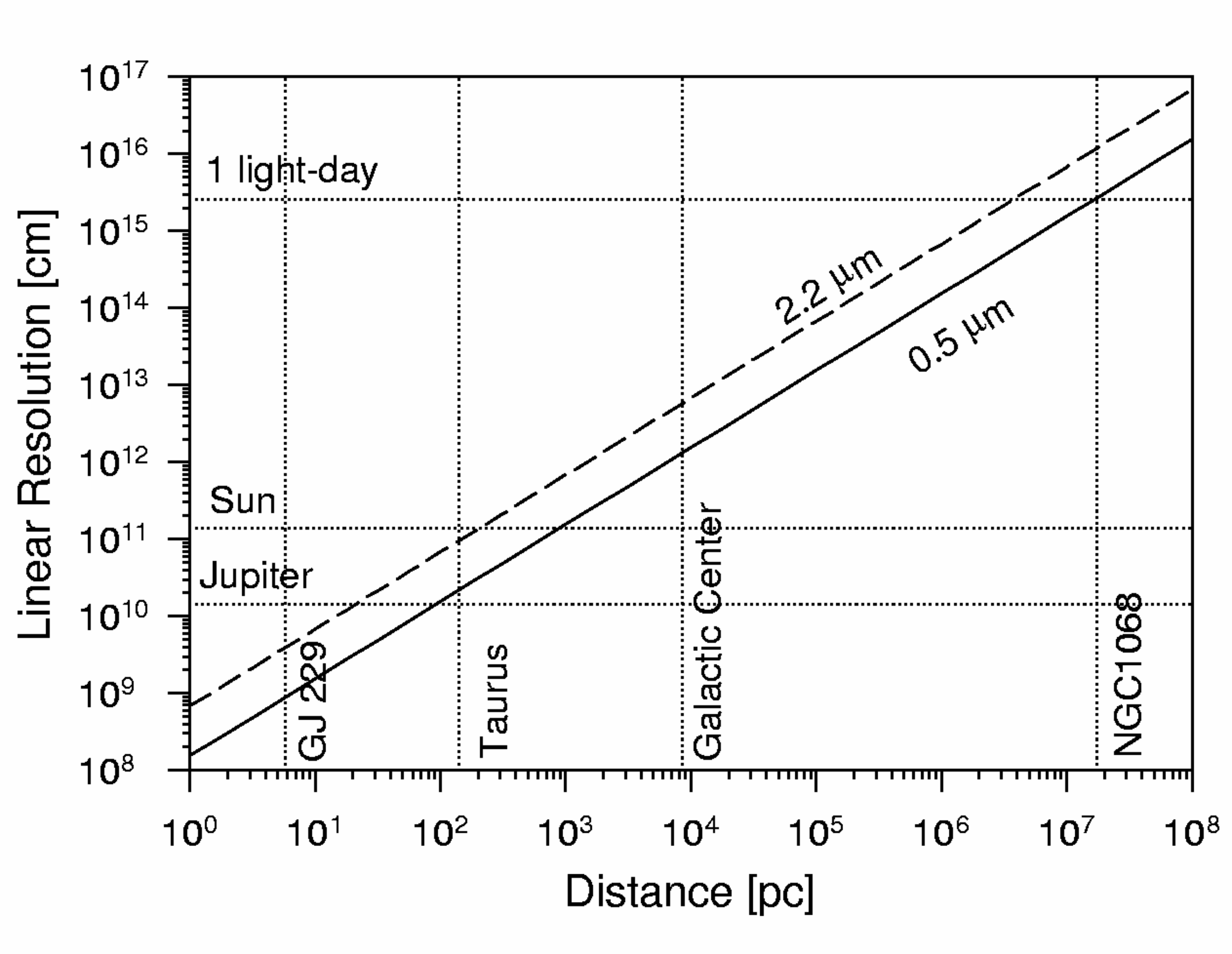
ELSA: the Future of Ground-Based Interferometry (?)

Andreas Quirrenbach
Sterrewacht Leiden

ELSA Concept

- Number of telescopes: 27
- Telescope diameter: 10 m
- Maximum baseline: 10 km
- Wavelength range: 500 nm … 20 μm (?)
- Beam transport: Single-mode fiber bundles
- Beam combination: Michelson
- Sky coverage at 600 nm: & 10%
- Cost: ≈ 400 M€

Linear Resolution of ELSA in the Local Universe



ELSA Resolution: 10 μas at 500 nm, 40 μas at 2 μm

- 15,000 km at 10 pc
  - 8 pixels across Jupiter-size object
  - 80 pixels across Solar-type star
- 0.1 AU at 10 kpc
  - GR effects on stars very close to the Galactic Center
- 200 AU (1 light-day) at 20 Mpc
  - Images of AGN Broad-line regions
  - Expansion and light echoes of supernovae

ELSA Critical Technologies

- Telescopes
- Array co-phasing
- Beam transport
- Beam combination
- Delay compensation

ELSA Telescopes

- Need to produce twenty-seven 10m telescopes for ≈ 200 M€
- Moveable for array reconfiguration if possible
- Small field-of-view
- No scientific instruments (acquisition and fiber-feeds only)
- Take advantage of OWL concept
  - Mass production of mirror segments
  - Standardized structural elements

Projected Cost of Telescopes

- Typical scaling of telescope cost with diameter is € _ $D^{2.7}$
- Scaling applies at any given time (for similar maturity of technology), not to future projection
- Example: scaling holds for Keck (10m) versus CHARA (1m) telescopes
- Apply scaling to OWL concept (around 2015): 100m for 1 G€ $\Rightarrow$ 10m for 2 M€
- Proof-of-concept for OWL?

ELSA Co-Phasing Concept

- Phase individual telescopes with multiple (?) LGS adaptive optics
- Off-axis fringe tracking on "bright" star
- Large aperture $\Rightarrow$ good fringe tracking sensitivity $\Rightarrow$ near-complete sky coverage
- Requirement: fringe tracking at $K \approx 19$
  - One of the drivers for large array elements
- Fringe-tracking chain of neighboring telescopes for bright (resolved) stars
- Fringe tracking between all telescopes for faint (unresolved) stars

ELSA Beam Transport

- Fibers are much cheaper than beam tunnels
  - Diffraction + field $\Rightarrow D_{\mathrm{opt}} = k \times \sqrt{\lambda L} + \theta L$
- Need advances in fiber technology
  - No significant light loss over 10 km
  - Low dispersion, polarization preserving
  - Fibers for infrared wavelength range
- Need metrology to monitor fiber lengths
- Fiber bundles can handle field-of-view larger than Airy disk

ELSA Site

- Need flat ≈ 10 km plateau
- Good seeing (r_0, τ_0, θ_0) important criterion
- Southern hemisphere preferred
- Requirements different from OWL criteria
- ALMA site probably (marginally) ok

VLTI, ALMA, OWL, and ELSA

- ELSA has 50 times better resolution than any other facility $\Rightarrow$ completely new science
- ELSA draws on VLTI / ALMA / OWL heritage
  - VLTI: Interferometric techniques, beam combination, …
  - ALMA: Moveable telescopes, site (?)
  - OWL: Cheap telescopes through mass production of optics and standardized structural elements
- ELSA could be feasible and affordable in 2015