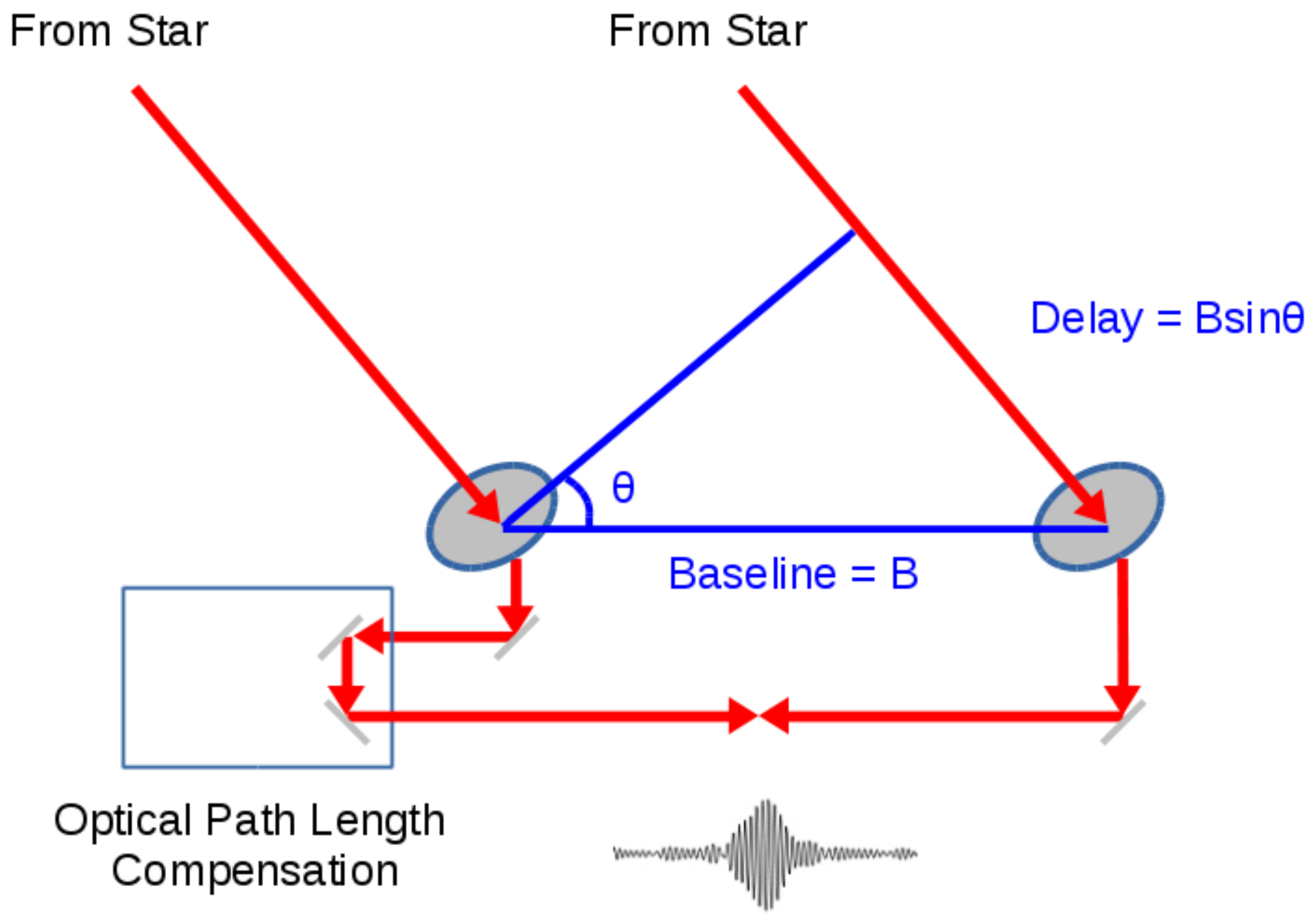
Precision Astrometry Using Long Baseline Interferometry

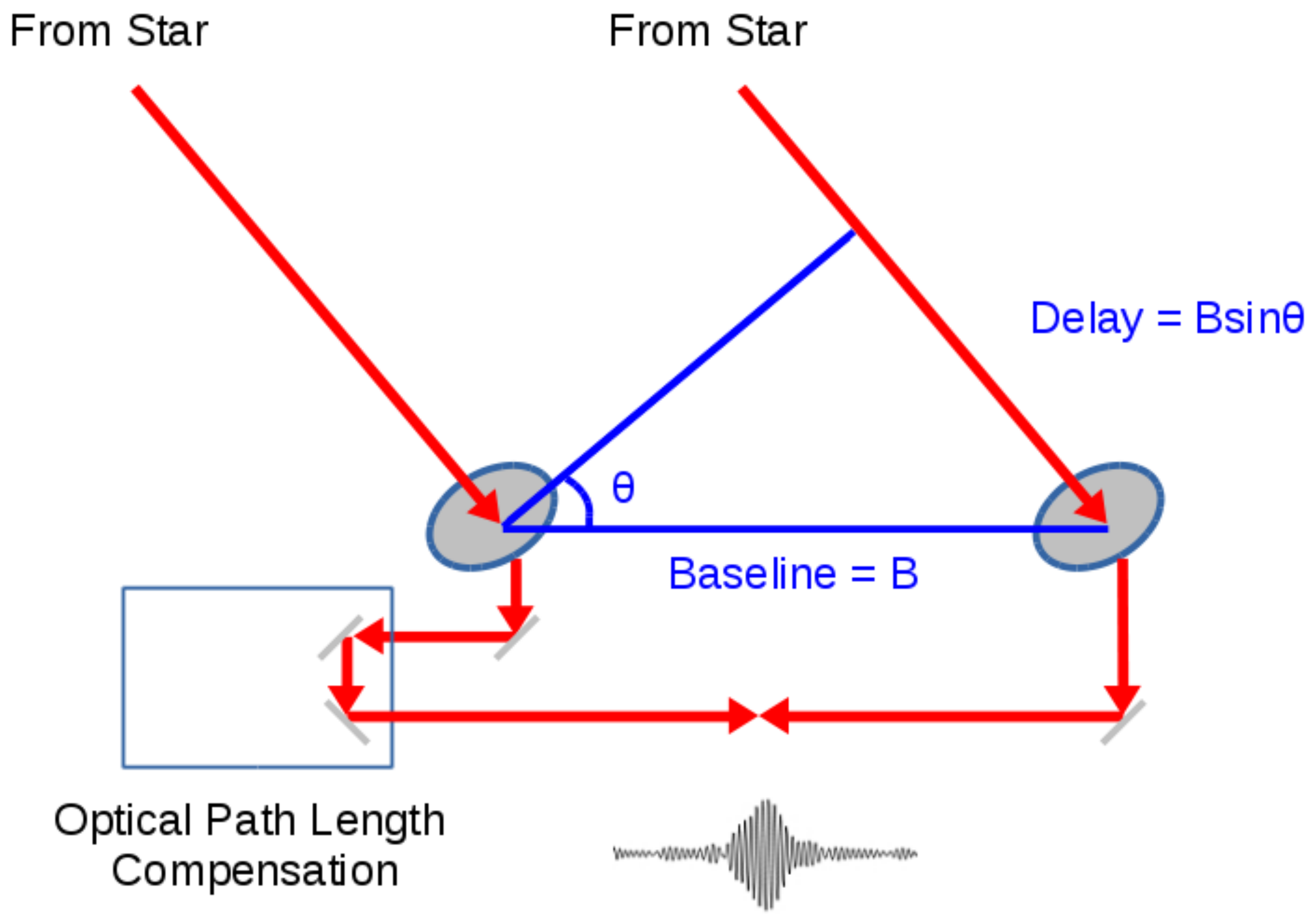
Gail Schaefer

CHARA Array of
Georgia State University

Long Baseline Optical/Infrared Interferometry

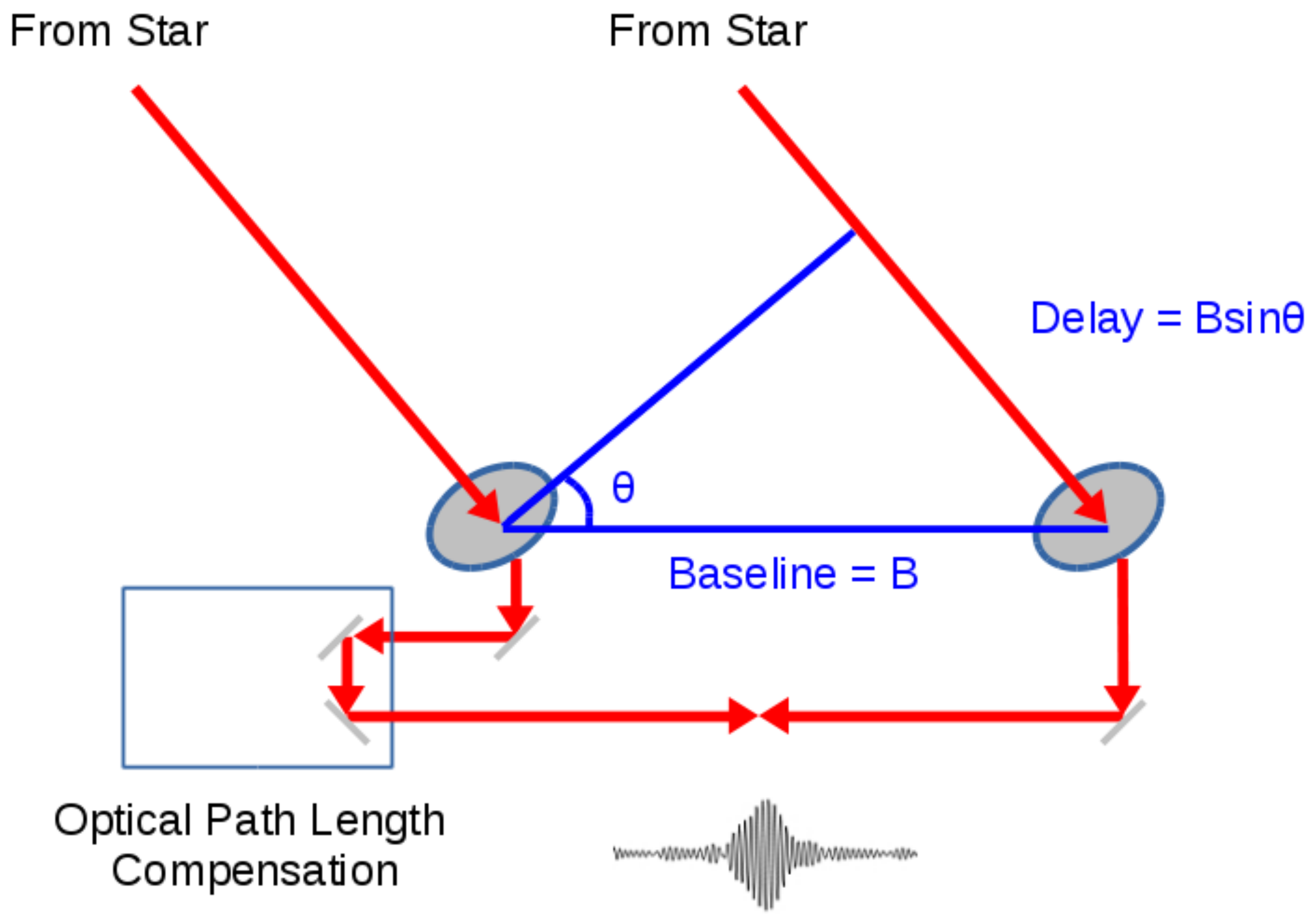


Long Baseline Optical/Infrared Interferometry

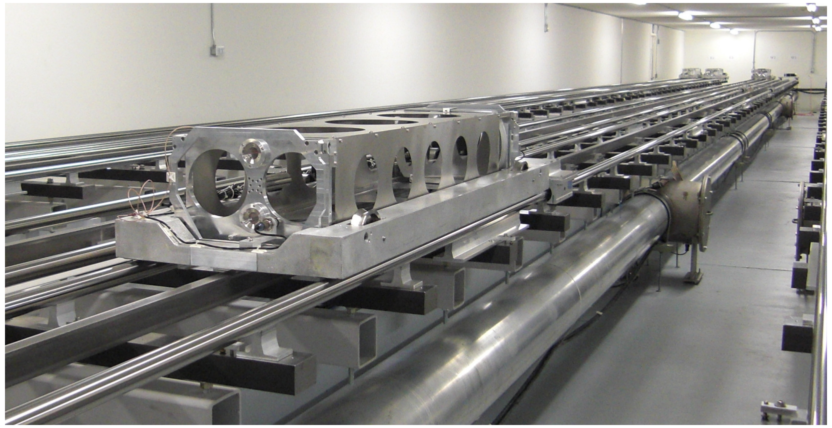


Transport light from telescope into lab

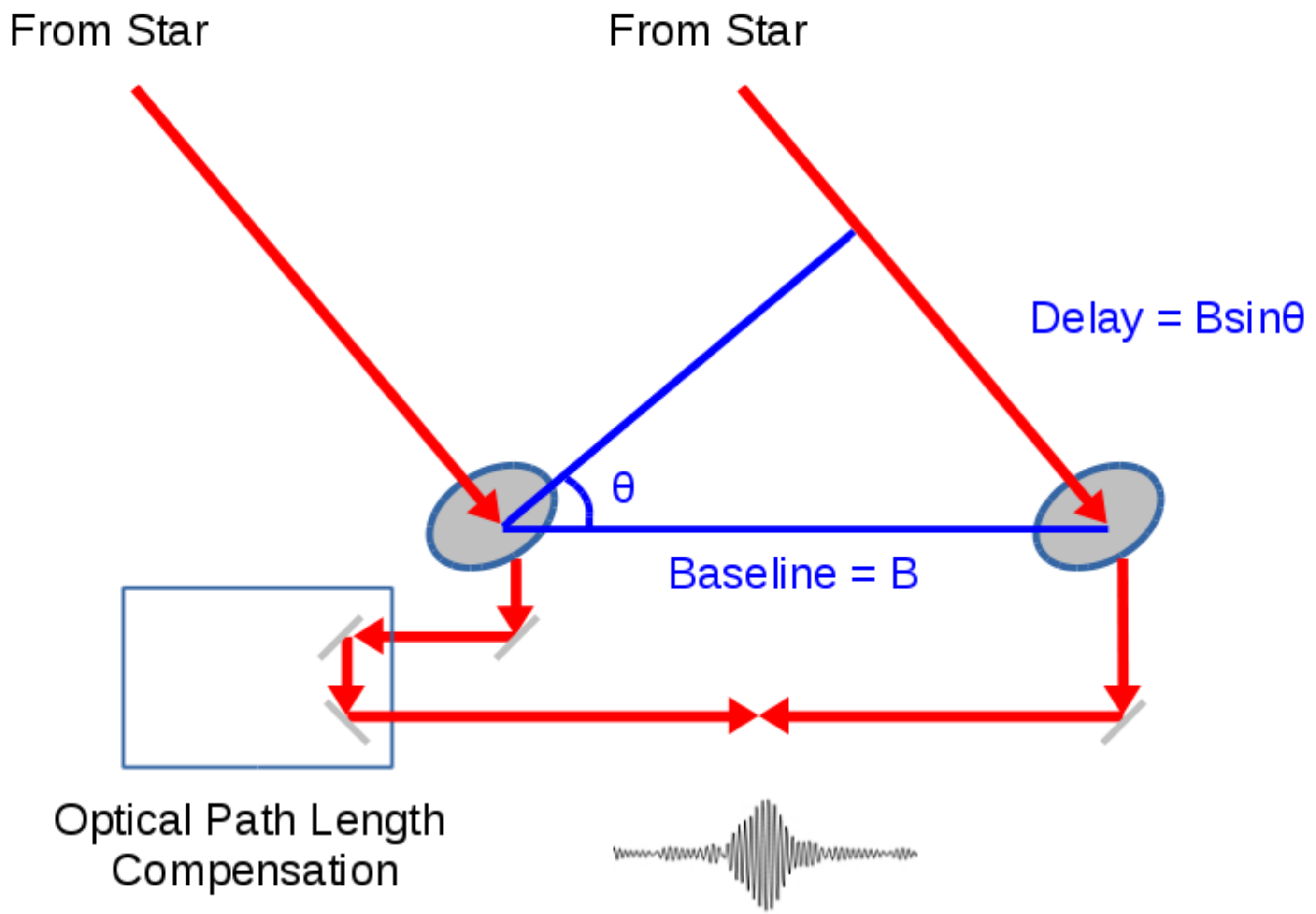
Long Baseline Optical/Infrared Interferometry



Delay line cart:
Pathlength equalization

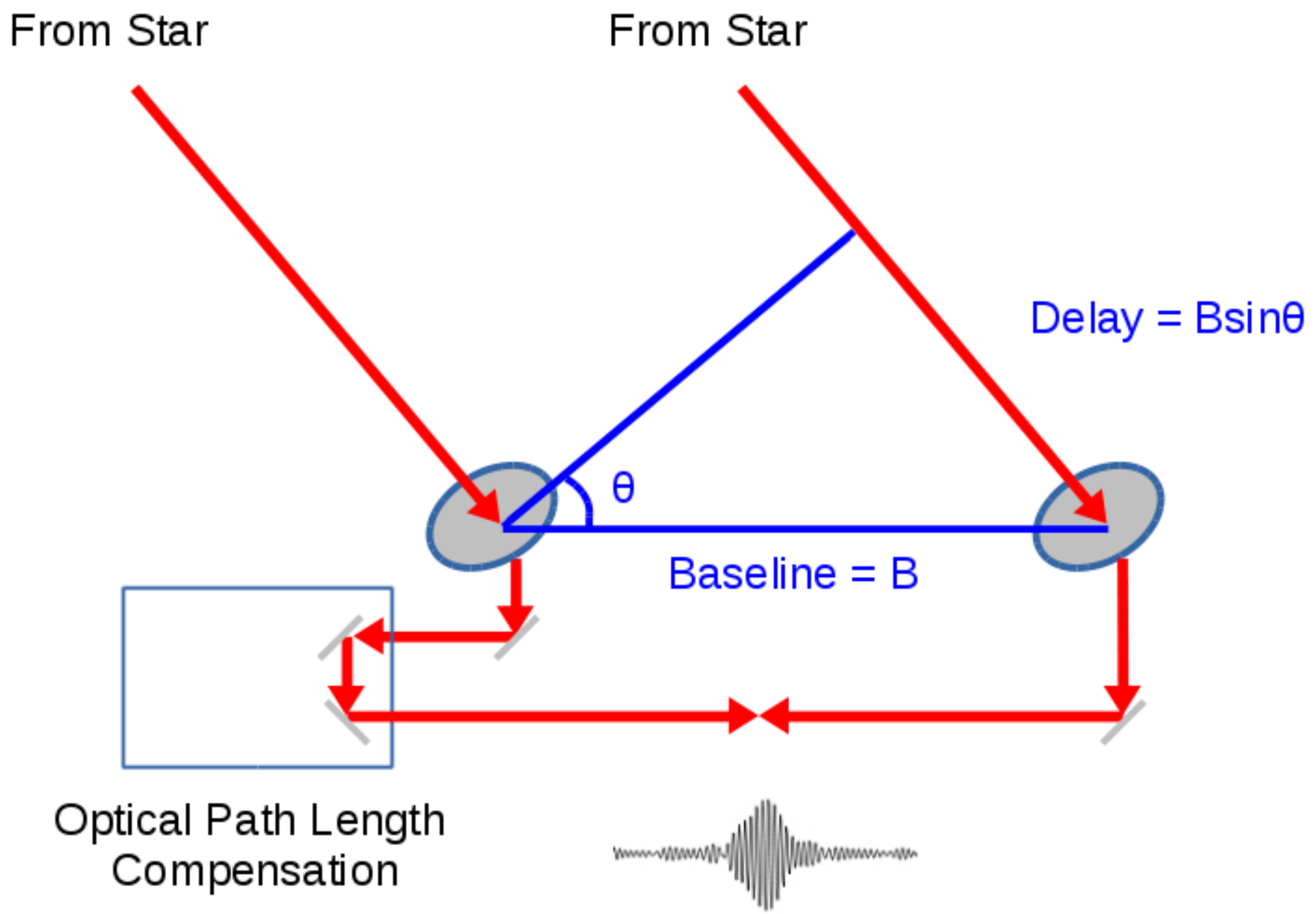


Long Baseline Optical/Infrared Interferometry



Beam Combination

Long Baseline Optical/Infrared Interferometry

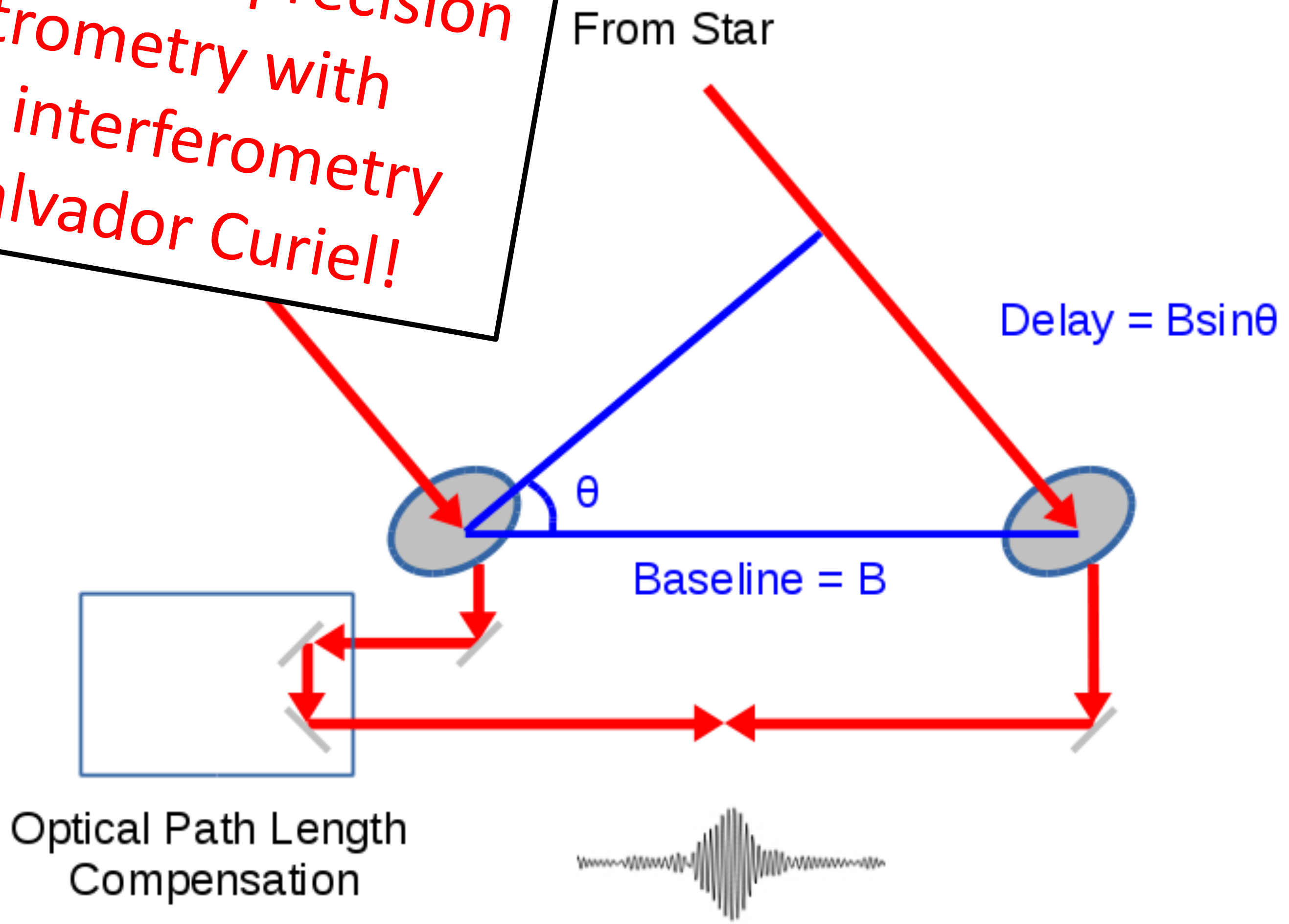


Spatial Resolution:
0.5 λ/B

Resolution ≈ 0.5 mas for 300 meter baseline in H-band (1.6 μm)

Long Baseline Optical/Infrared Interferometry

See poster on precision astrometry with radio interferometry by Salvador Curiel!



Spatial Resolution:
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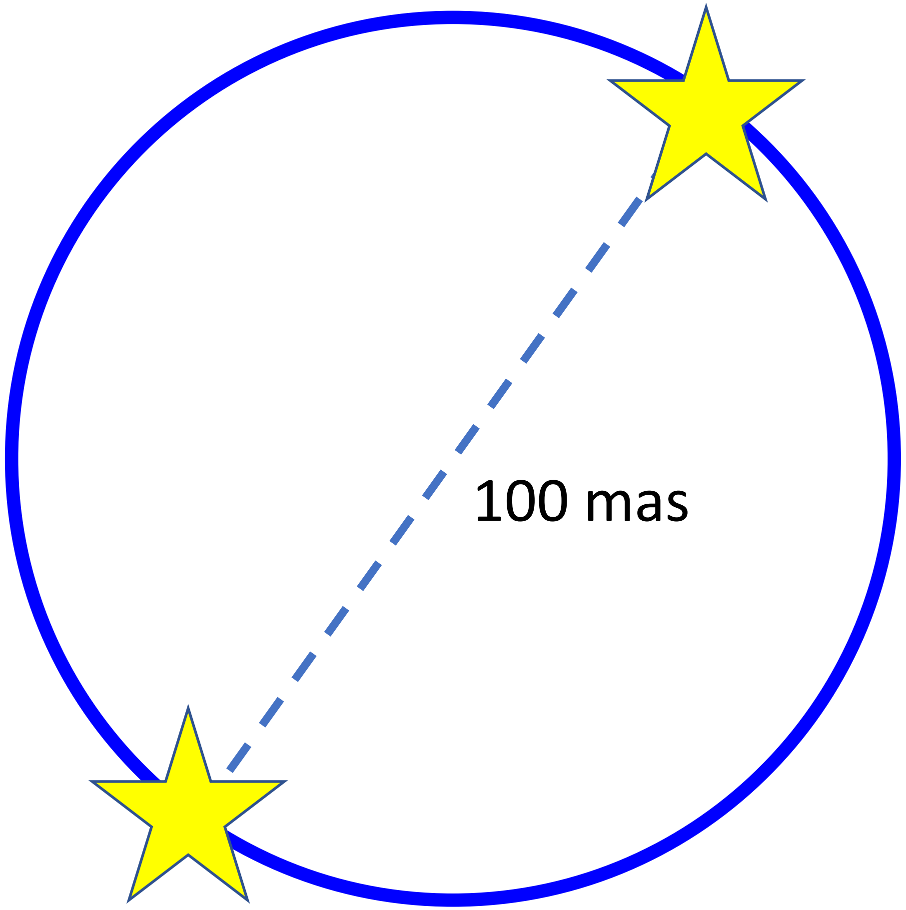
Resolution ≈ 0.5 mas for 300 meter baseline in H-band (1.6 μm)

Comparisons with Gaia

Gaia

- Spatial Resolution: 100 mas
- Astrometric precision: 10 μas
- Absolute, wide-angle



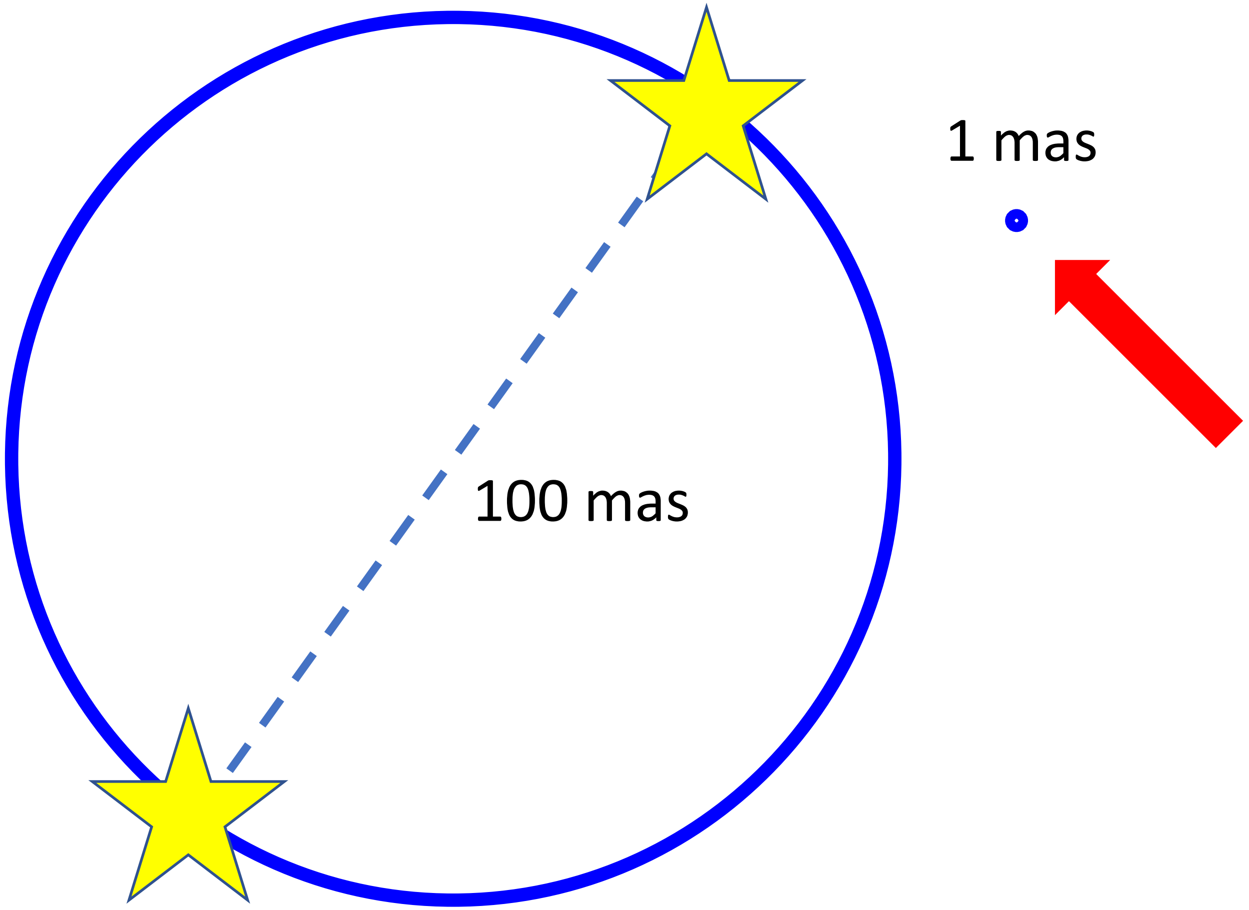
Comparisons with Gaia

Gaia

- Spatial Resolution: 100 mas
- Astrometric precision: 10 μas
- Absolute, wide-angle

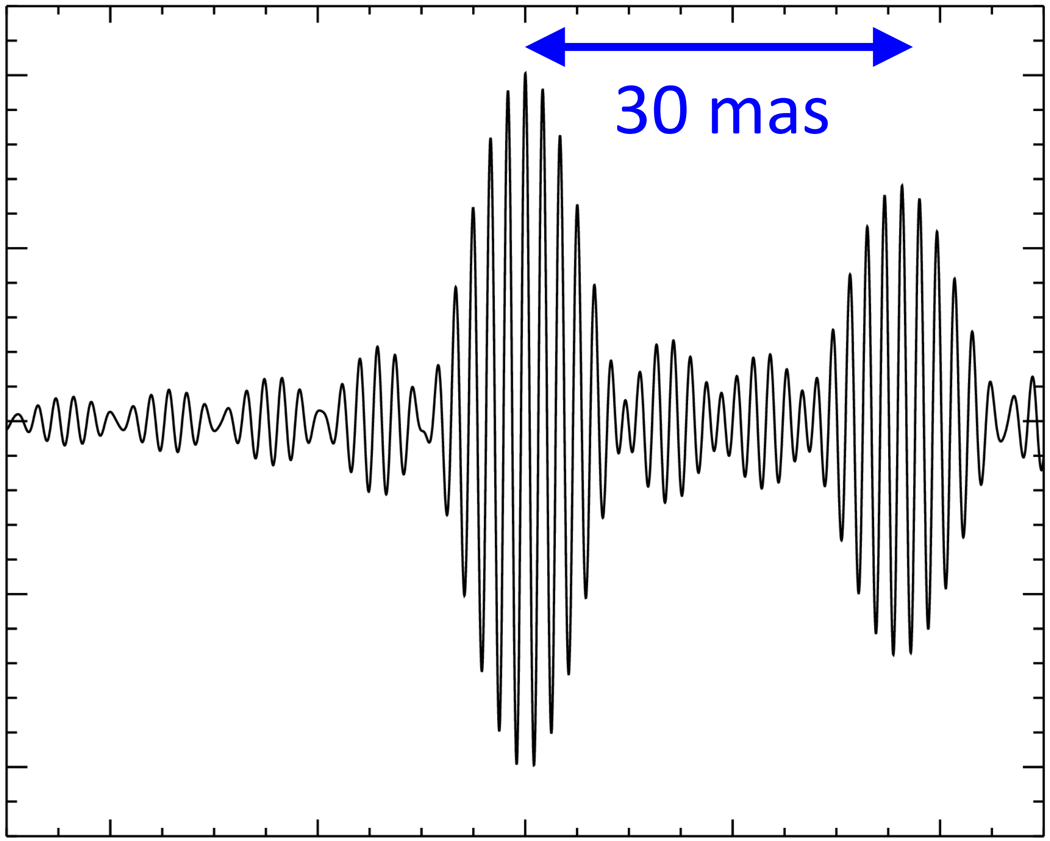
Long Baseline O/IR Interferometry

- Spatial Resolution: 0.5 mas
- Astrometric precision: 20-50 μas
- Relative, narrow-angle



Interferometric Binary

Separated Fringe Packet



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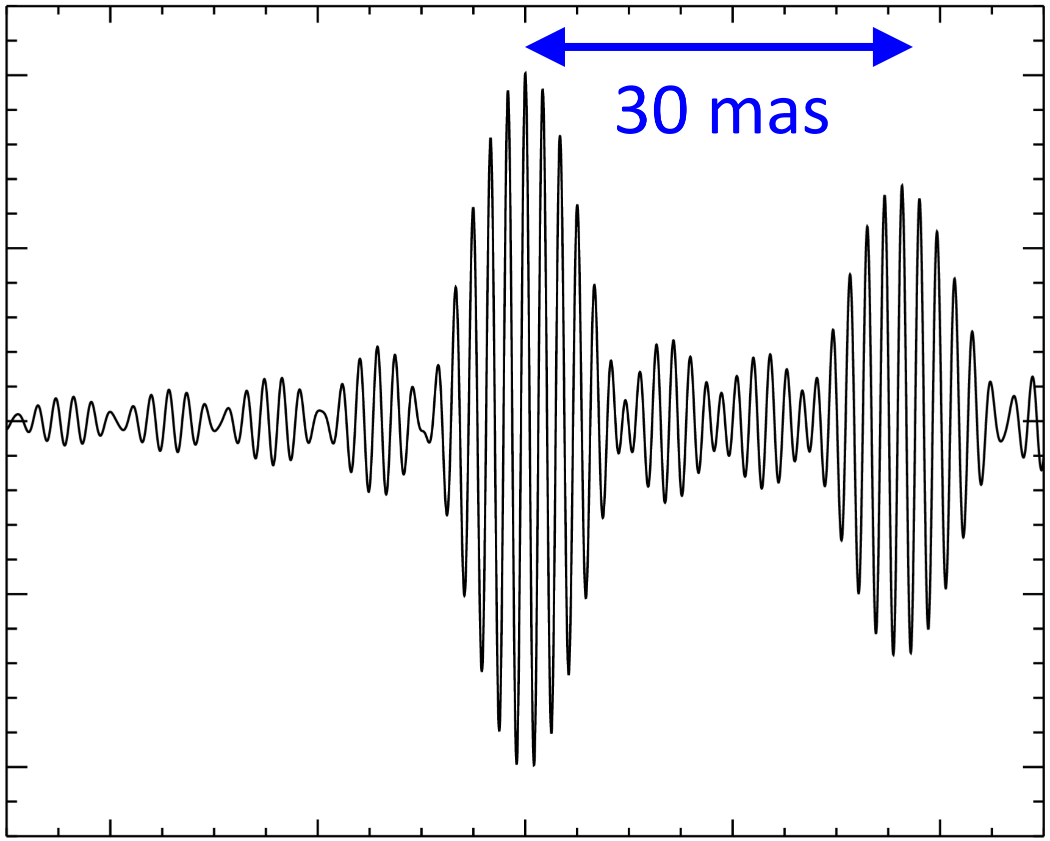
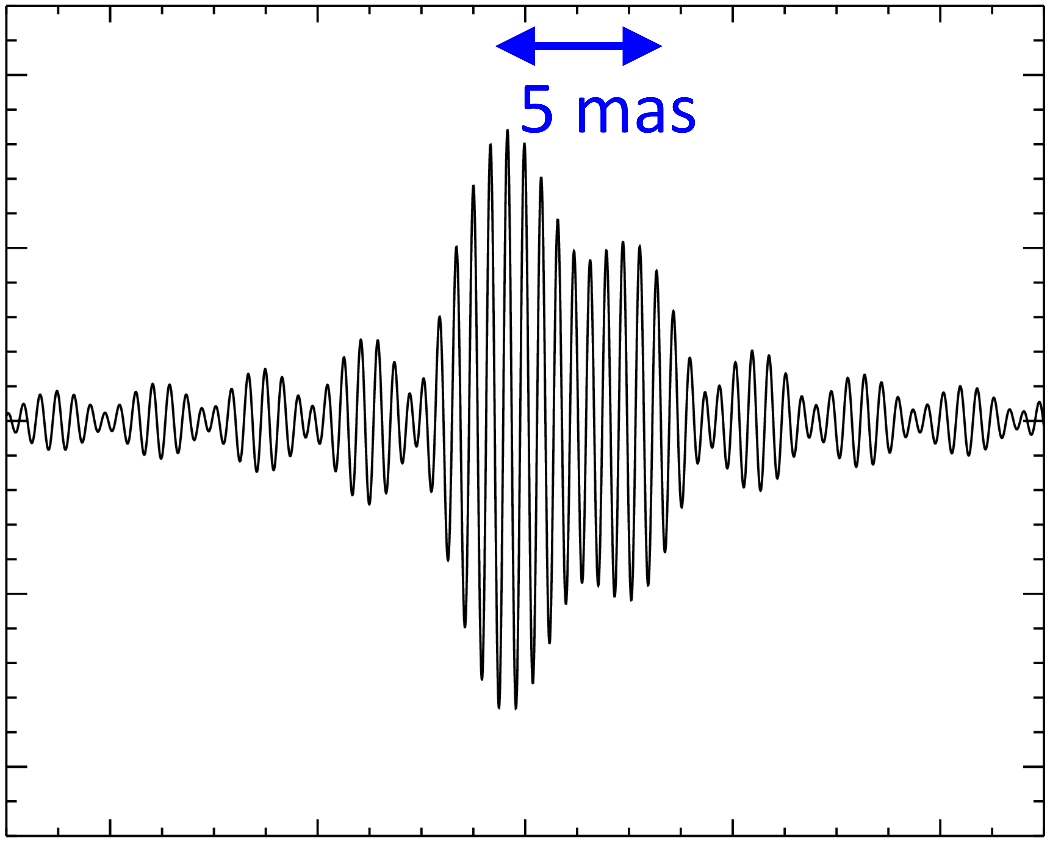
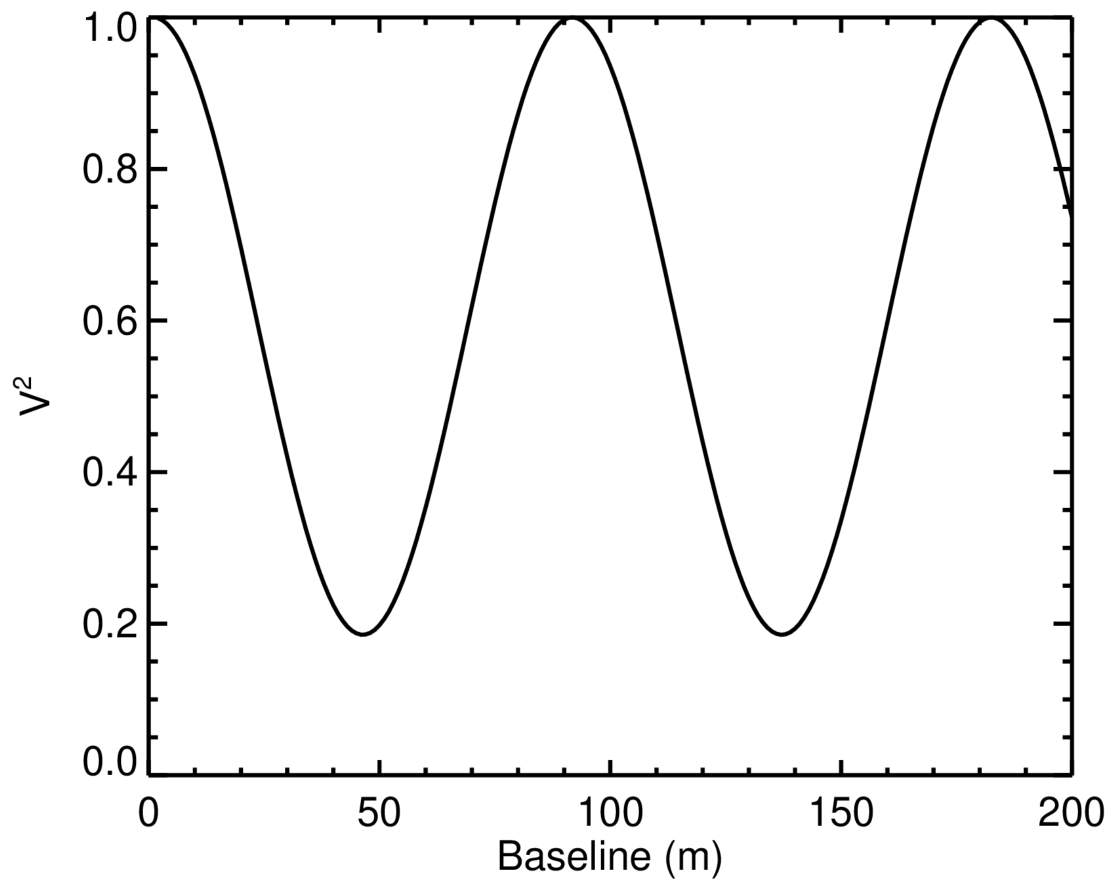


Modulated Fringe Packet



Interferometric Binary

Visibility Modulation

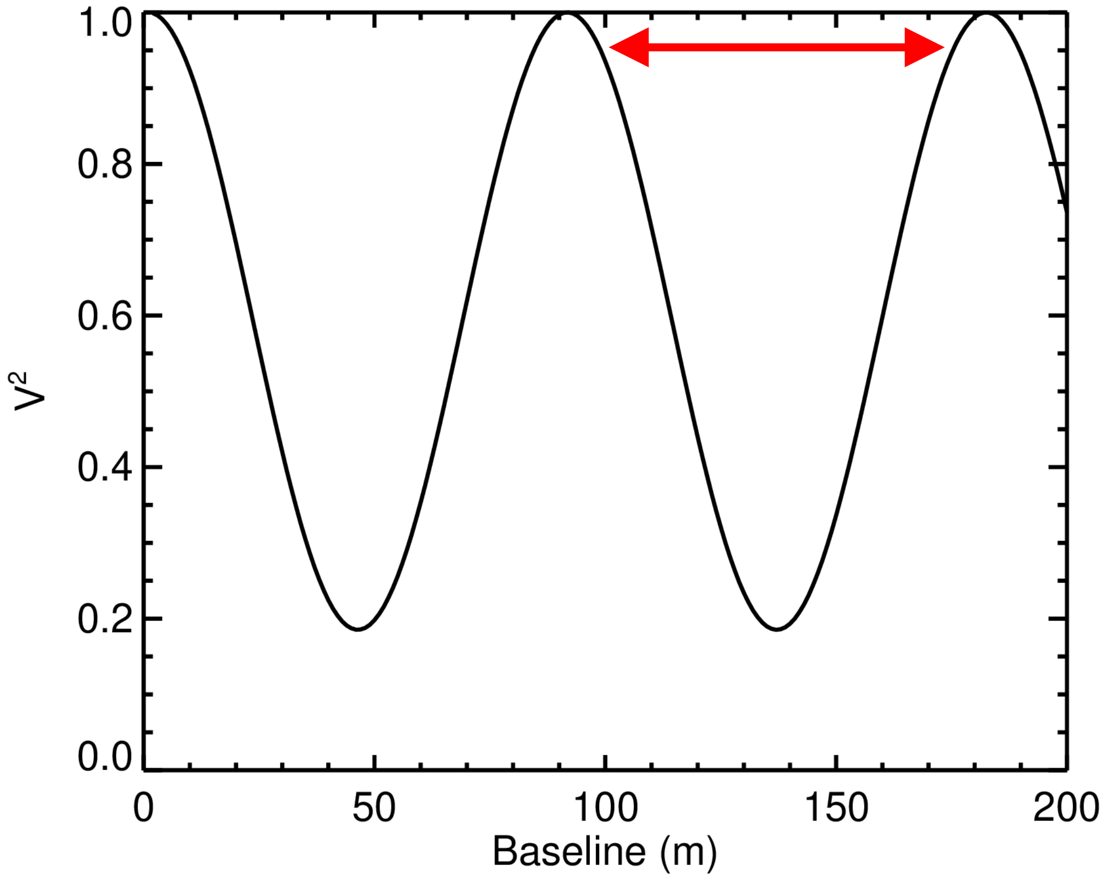


- Fringe packet for the two components overlap
- Amplitude of fringes varies periodically

$$V = \frac{f_1 V_1 + f_2 V_2 \exp[-2\pi i(u\Delta\alpha + v\Delta\delta)]}{f_1 + f_2}$$

Interferometric Binary

Visibility Modulation

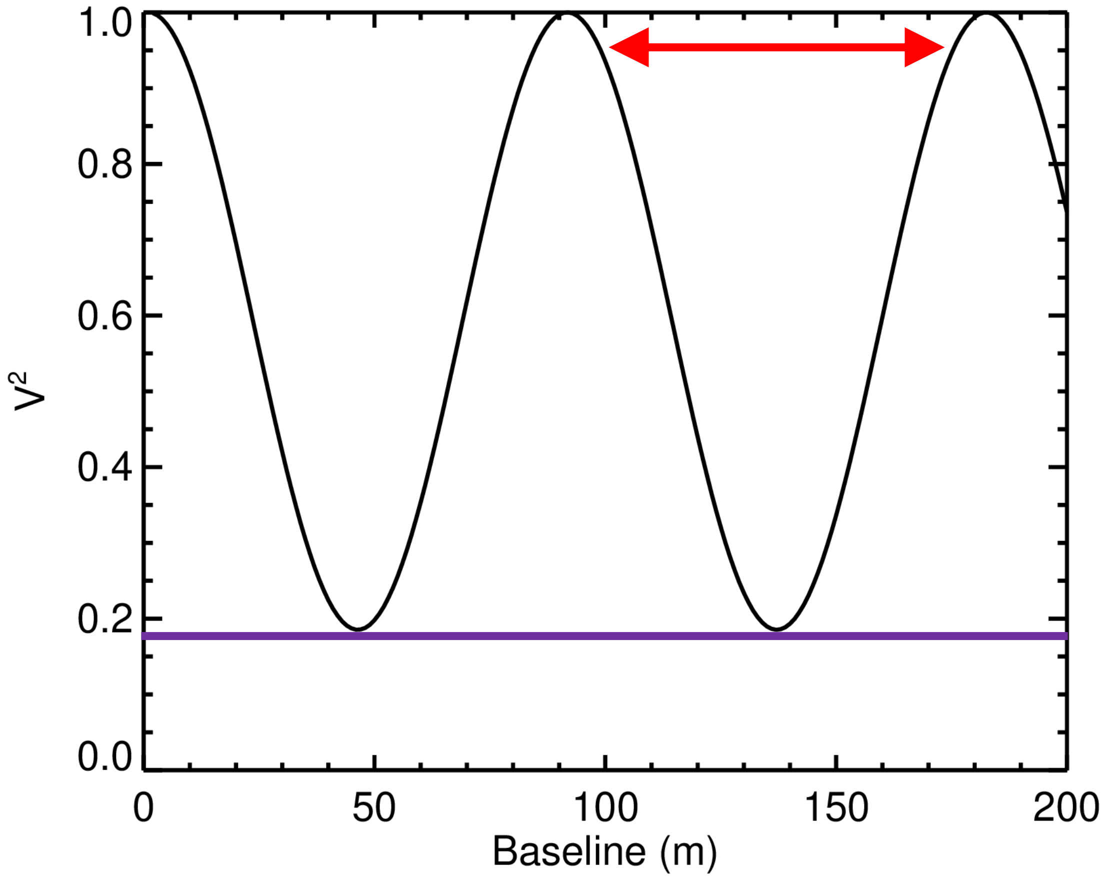


- Fringe packet for the two components overlap
- Amplitude of fringes varies periodically
  - Binary Separation (Δα, Δδ)

$$V = \frac{f_1 V_1 + f_2 V_2 \exp[-2\pi i(u\Delta\alpha + v\Delta\delta)]}{f_1 + f_2}$$

Interferometric Binary

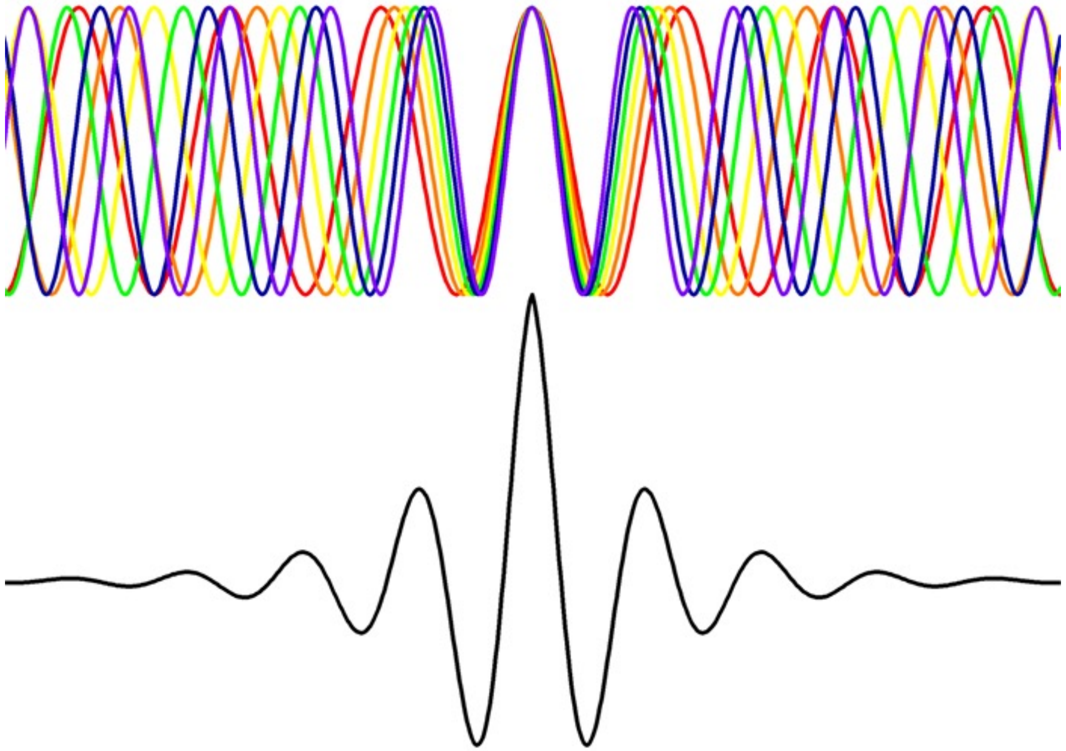
Visibility Modulation



- Fringe packet for the two components overlap
- Amplitude of fringes varies periodically
  - Binary Separation ($\Delta\alpha$, $\Delta\delta$)
  - Flux Ratio (f_2/f_1)

$$V = \frac{f_1 V_1 + f_2 V_2 \exp[-2\pi i(u\Delta\alpha + v\Delta\delta)]}{f_1 + f_2}$$

Interferometric Field of View



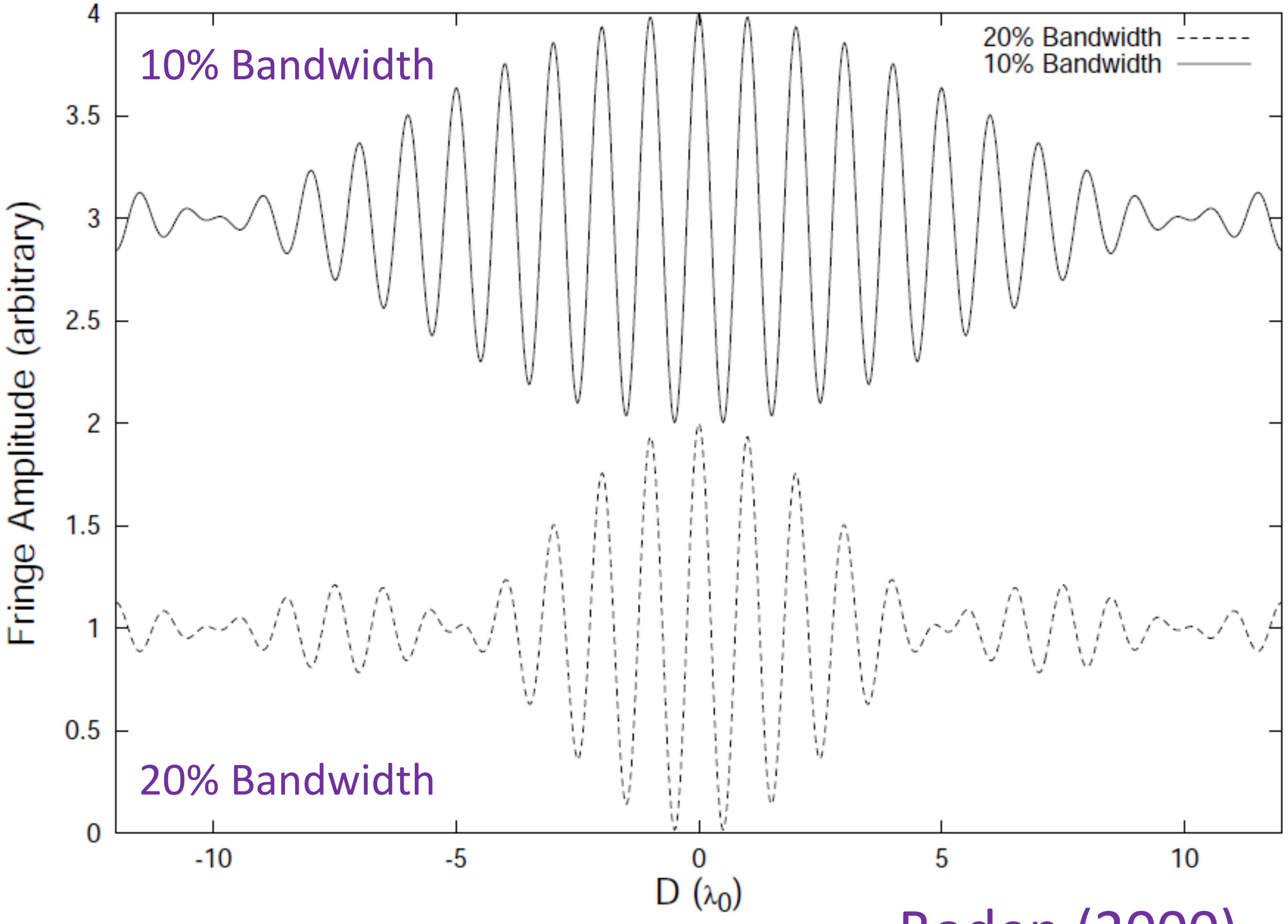
- Interferometric field of view set by the coherence length:

$$\frac{\lambda^2}{\Delta\lambda}$$

- Spectral Resolution: $R = \frac{\lambda}{\Delta\lambda}$

https://www.e-education.psu.edu/mcl-optpro/theory/node795

Interferometric Field of View



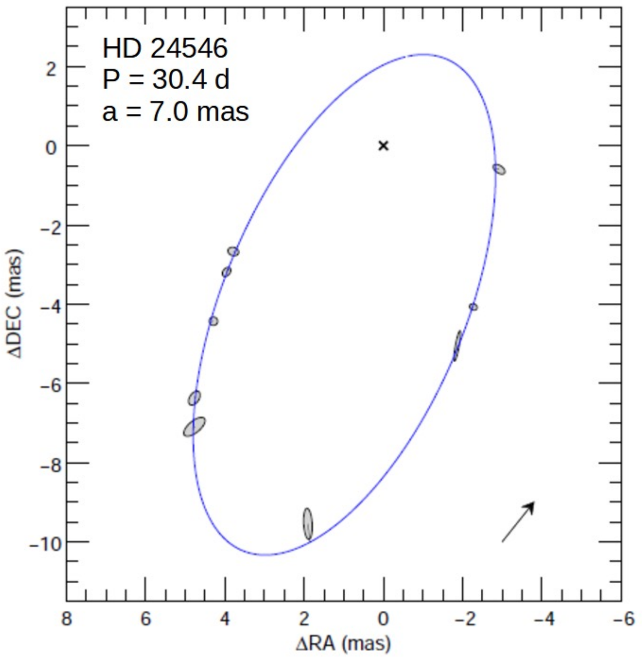
Boden (2000)

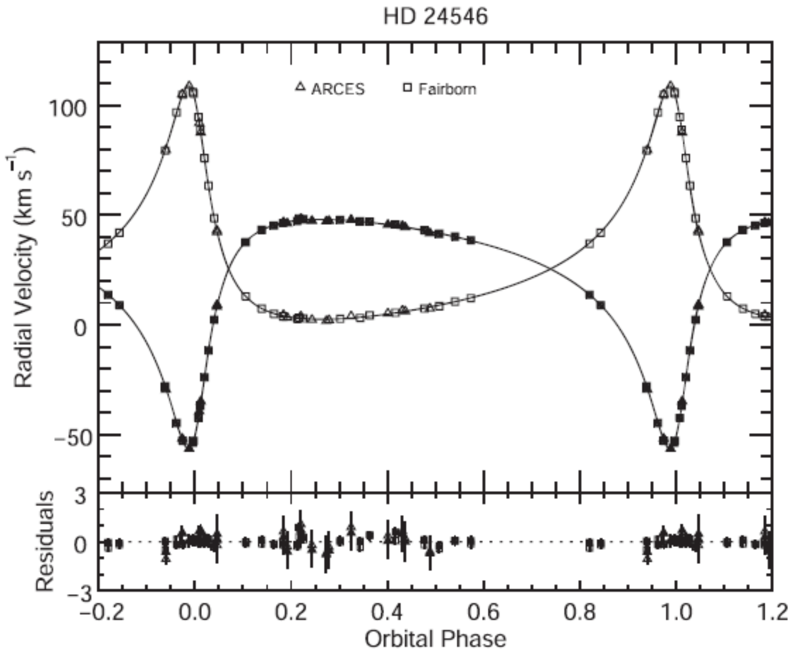
- Interferometric field of view set by the coherence length:

$$\frac{\lambda^2}{\Delta\lambda}$$

- Spectral Resolution: $R = \frac{\lambda}{\Delta\lambda}$
- FOV ≈ 200 mas for B = 300 m, λ = 1.6 μm, R = 190
- FOV ≈ 50 mas for B = 300 m, λ = 1.6 μm, R = 50

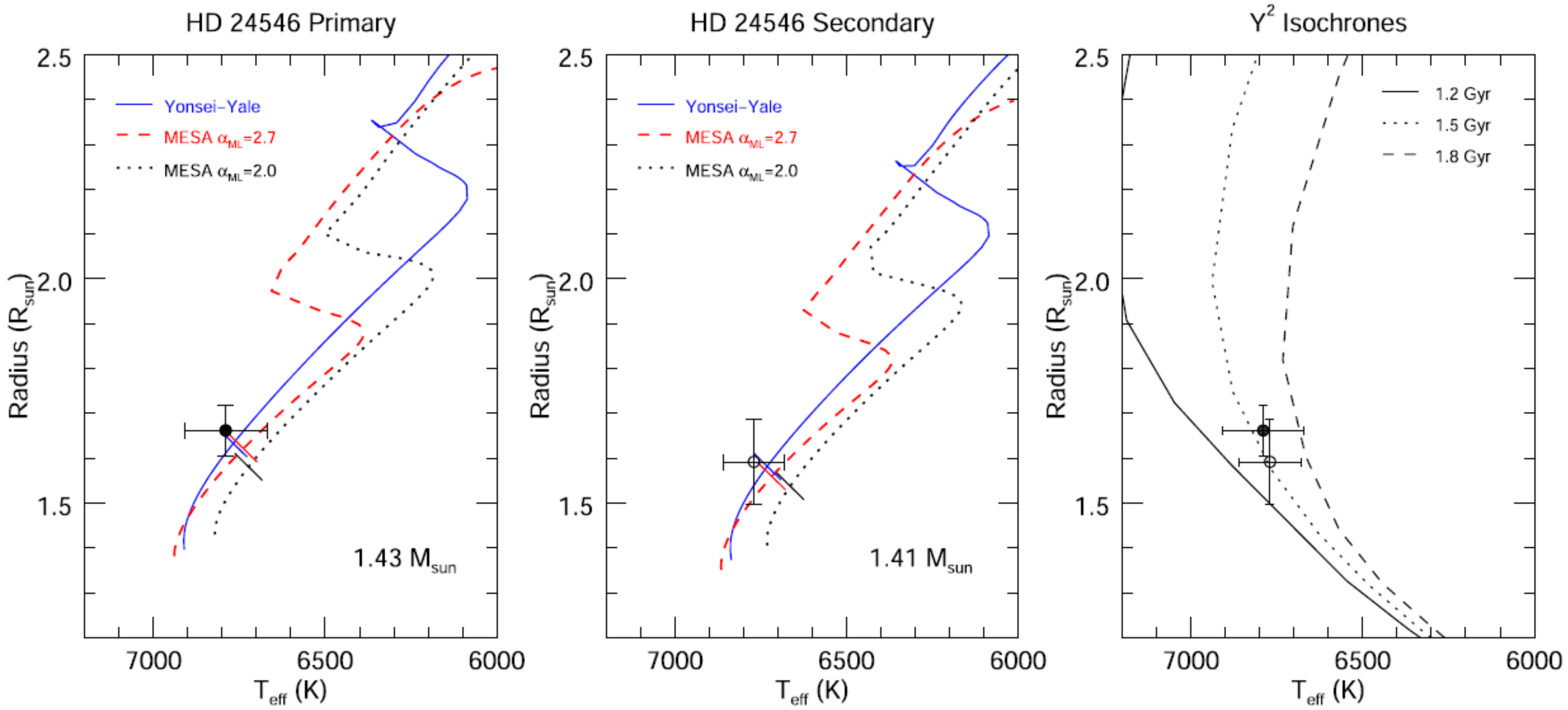
Binary Orbits





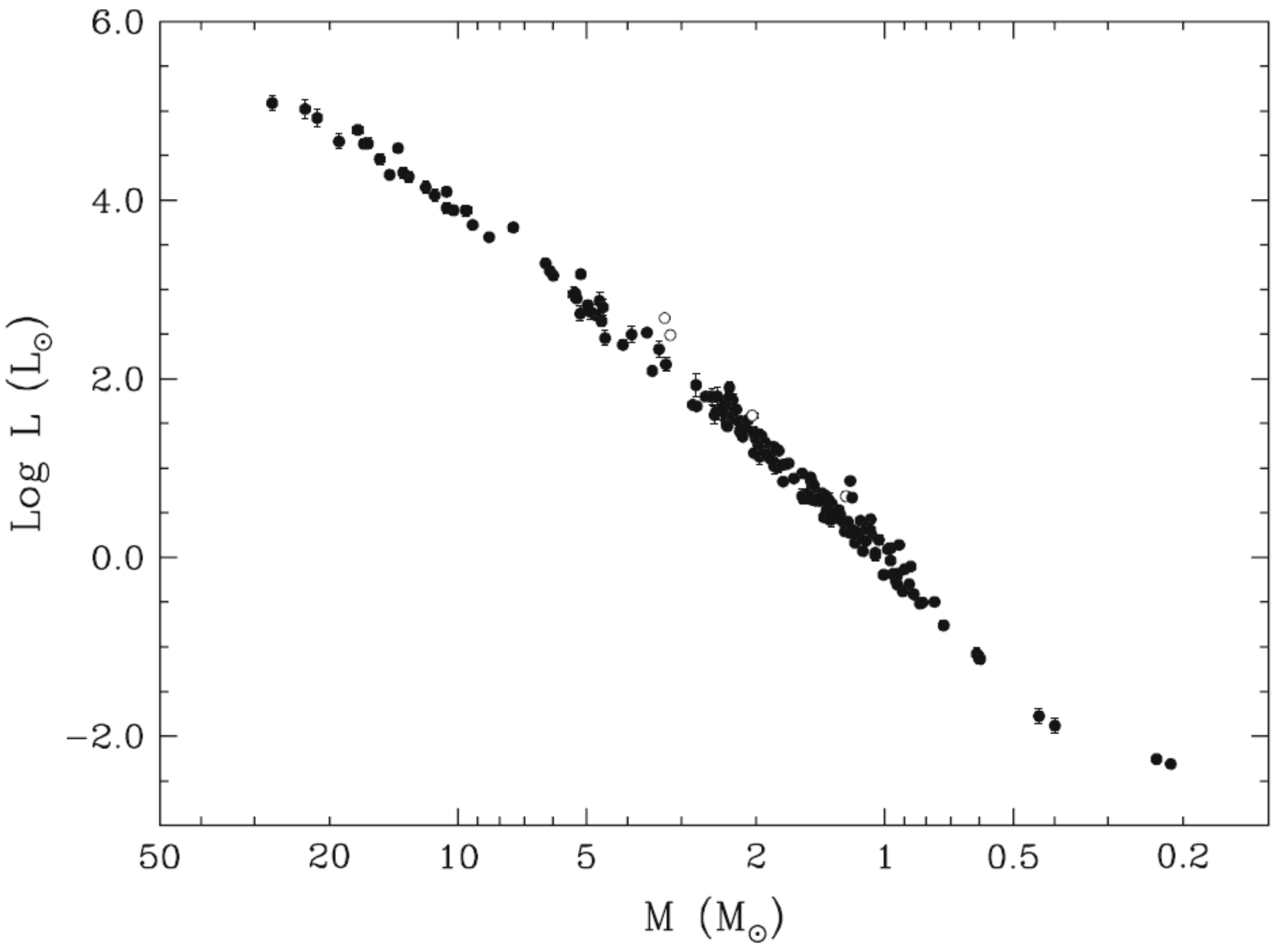
- Spatially resolved orbits of spectroscopic binaries
- Masses and distances with 1-3% precision
- Lester et al. (2020)

Fundamental Properties: Masses of Binary Stars



Lester et al. (2020)

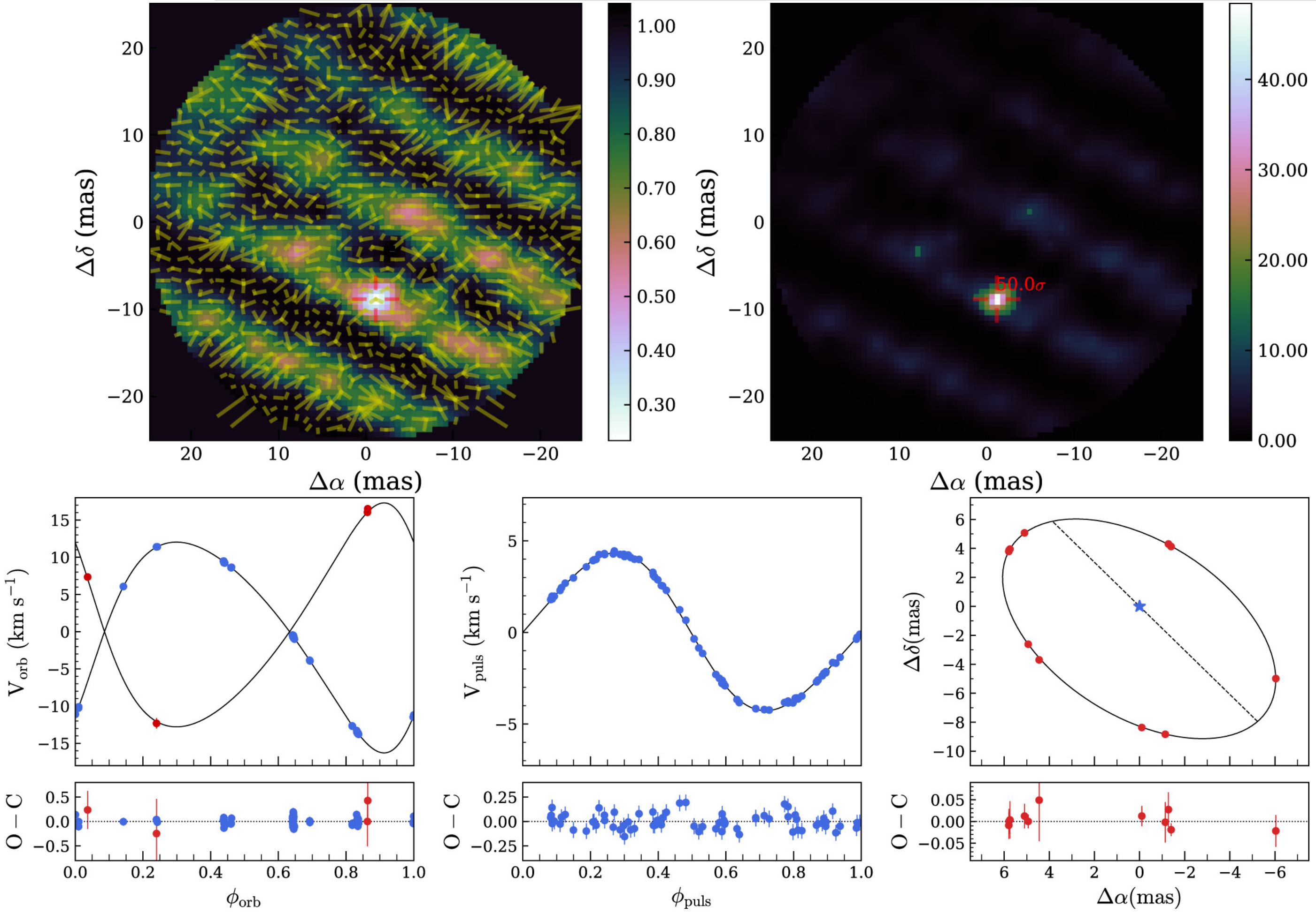
Fundamental Properties: Masses of Binary Stars



Mass-Luminosity Relation

Torres et al. (2010)

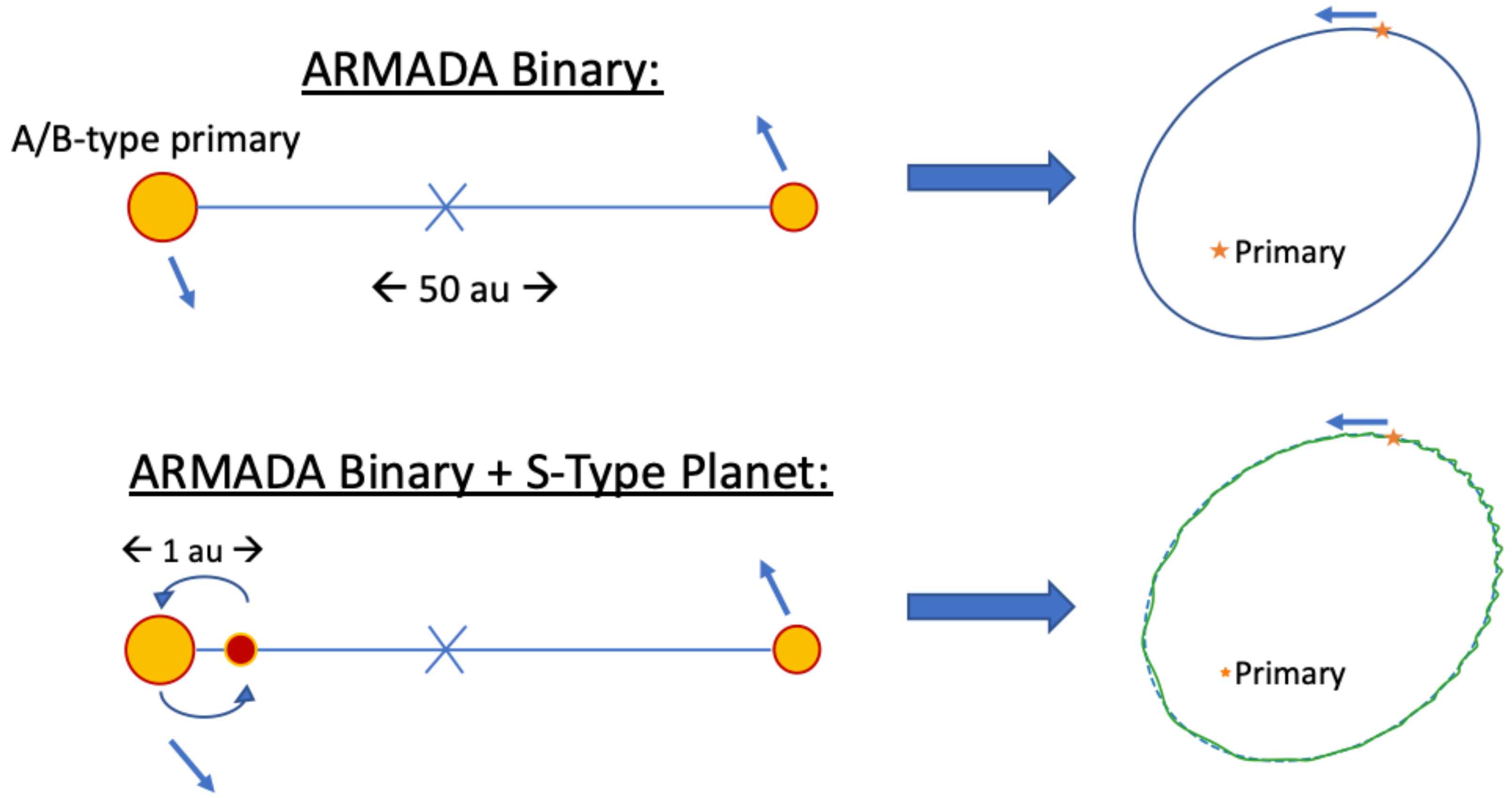
1% Distance to Cepheid V1334 Cygni



- Orbital parameters
  - P = 5.3 yr, a = 8.5 mas
- 1% geometric distance
  - d = 720.35 ± 7.84 pc
- Precise masses of Cepheid and companion
- Companion: 3.3% flux
- Impacts integrated magnitude and calibration of P-L relation
- Gallenne et al. (2018)

Micro-arcsecond Precision Astrometry

Detecting Wobble in Binary Orbits

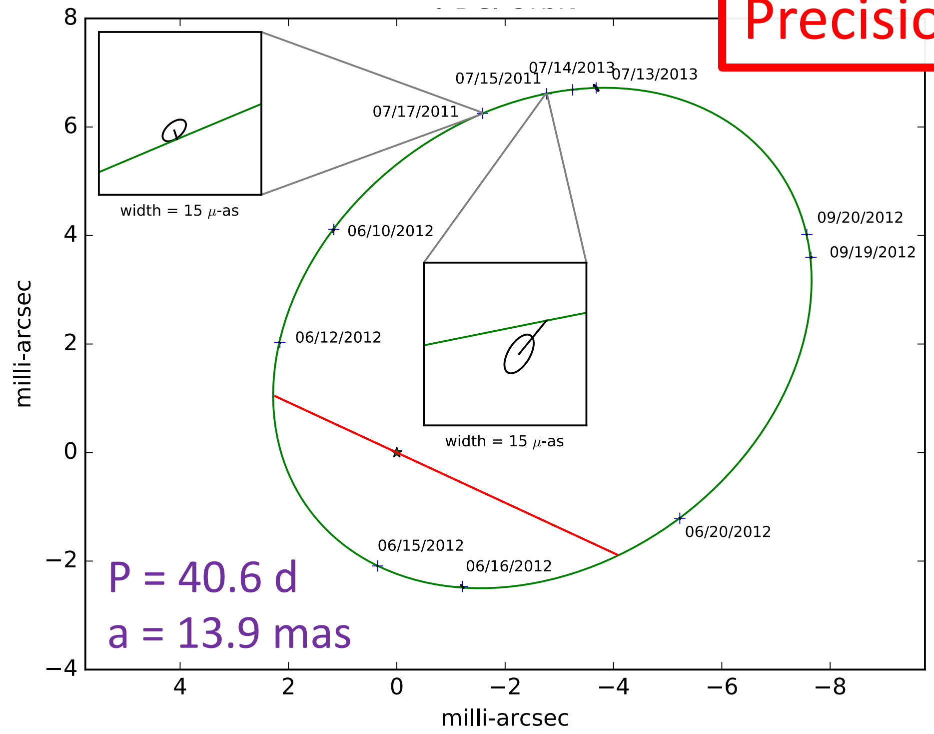


T. Gardner

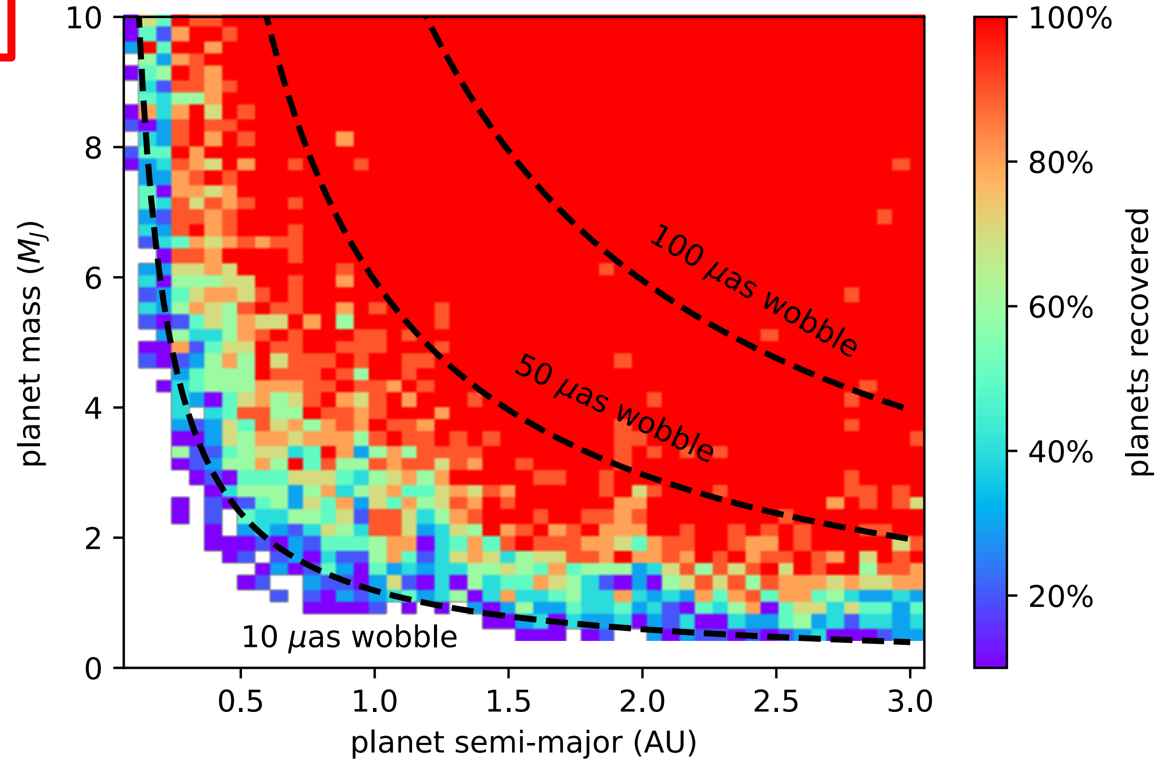
Micro-arcsecond Precision Astrometry
Detecting Wobble in Binary Orbits

δ Del Orbit

10 μas Precision!



Simulated Detection Limits



Gardner et al. (2018)

Micro-arcsecond Precision Astrometry
Detecting Wobble in Binary Orbits

PHASES

Muterspaugh et al. (2010)

Palomar Testbed Interferometer, CA

Three 40 cm apertures

110 m max baseline

Micro-arcsecond Precision Astrometry
Detecting Wobble in Binary Orbits

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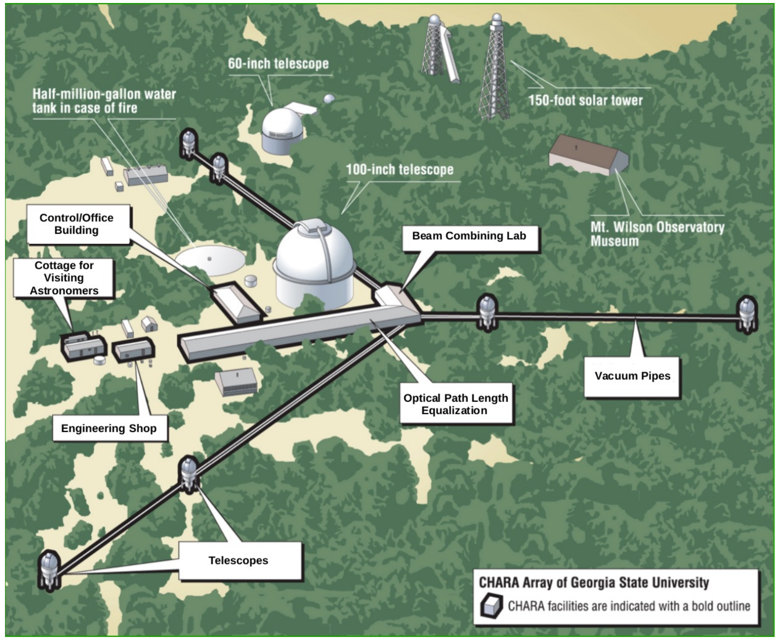
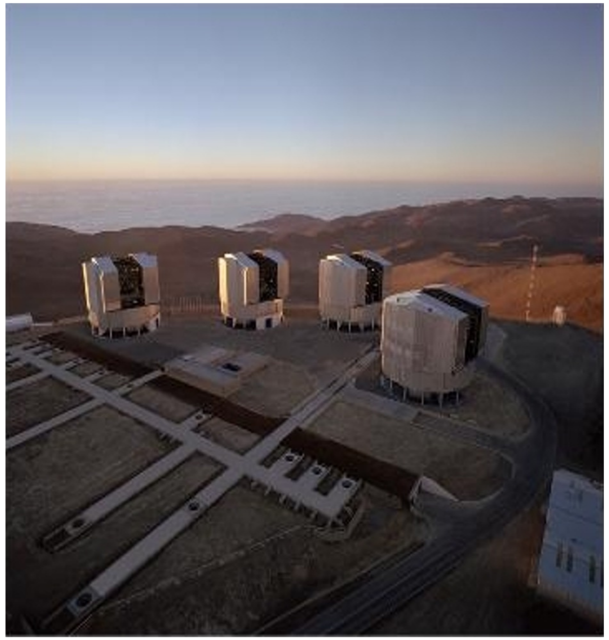
ARMADA
Gardner et al. (2021, 2022 submitted)



CHARA Array – Mount Wilson, CA

Six 1 m telescopes

330 m max baseline



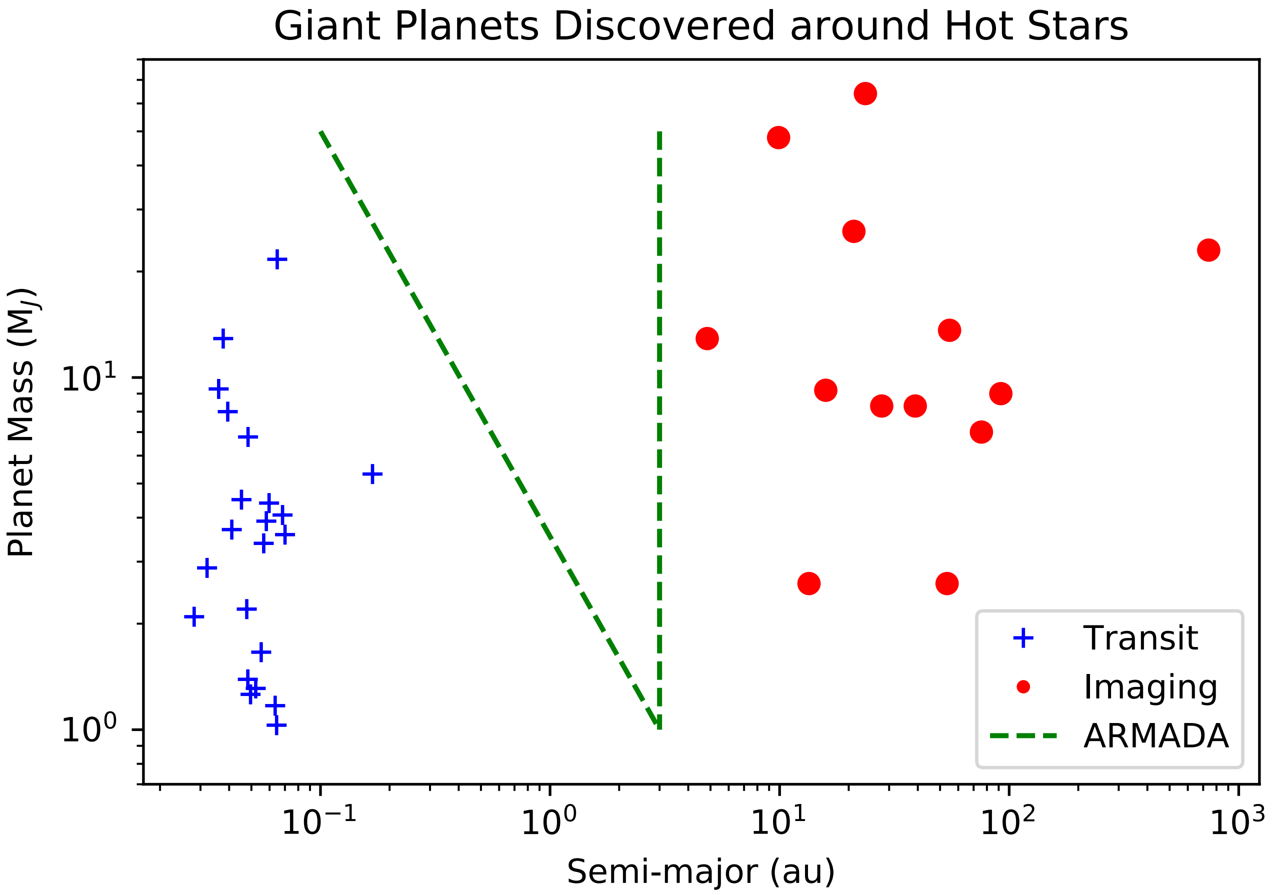
VLTI – Paranal, Chile

Four 8-m UTs, four 1.8 m ATs

130 m / 200 m max baseline

ARMADA Survey

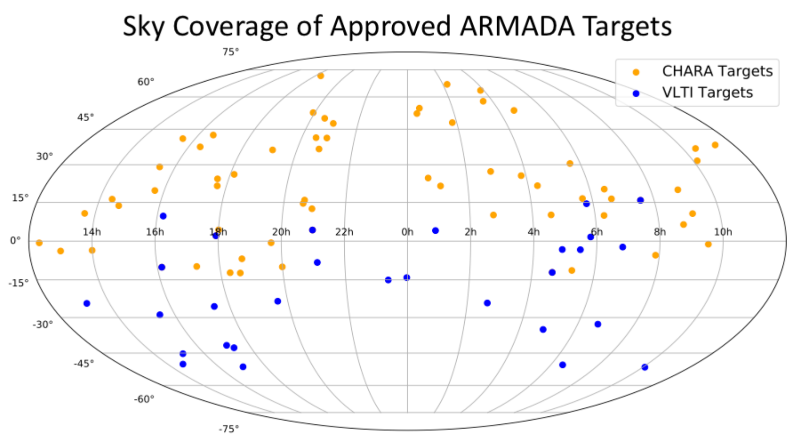
Searching for Planets in Intermediate Mass Binaries

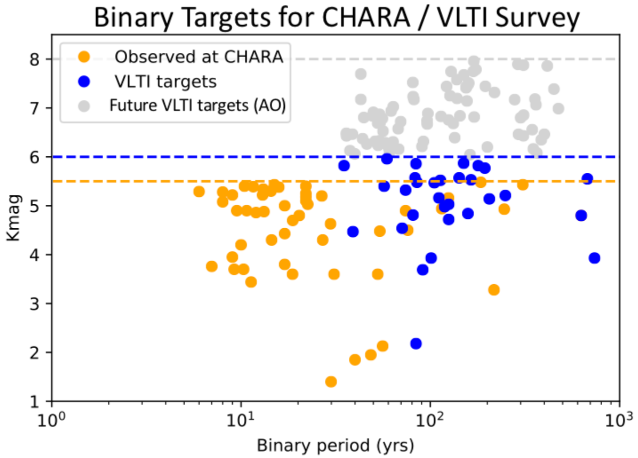


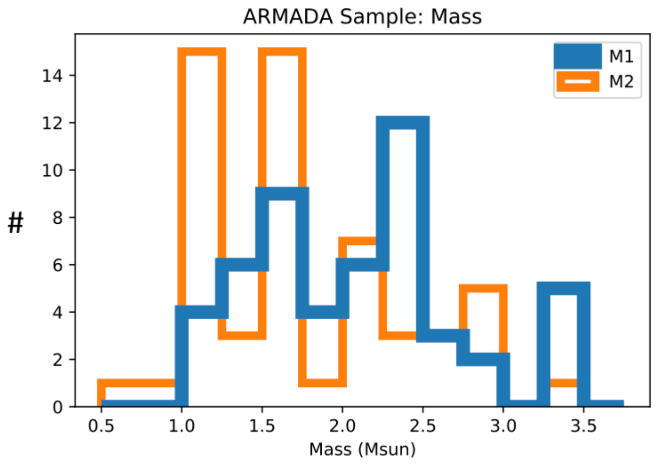
- Monitoring 70 binaries
- Binary separations of 50-200 mas
- CHARA/MIRCX in the North
- VLTI/GRAVITY in the South
- Gardner et al. (2021, 2022)

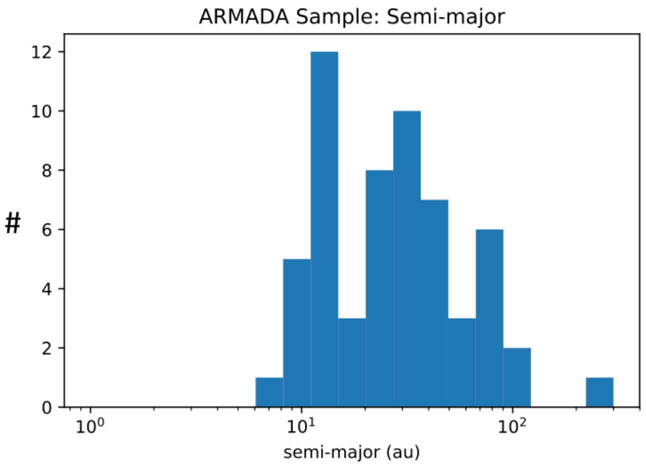
ARMADA Survey

Detecting Wobble in Binary Orbits





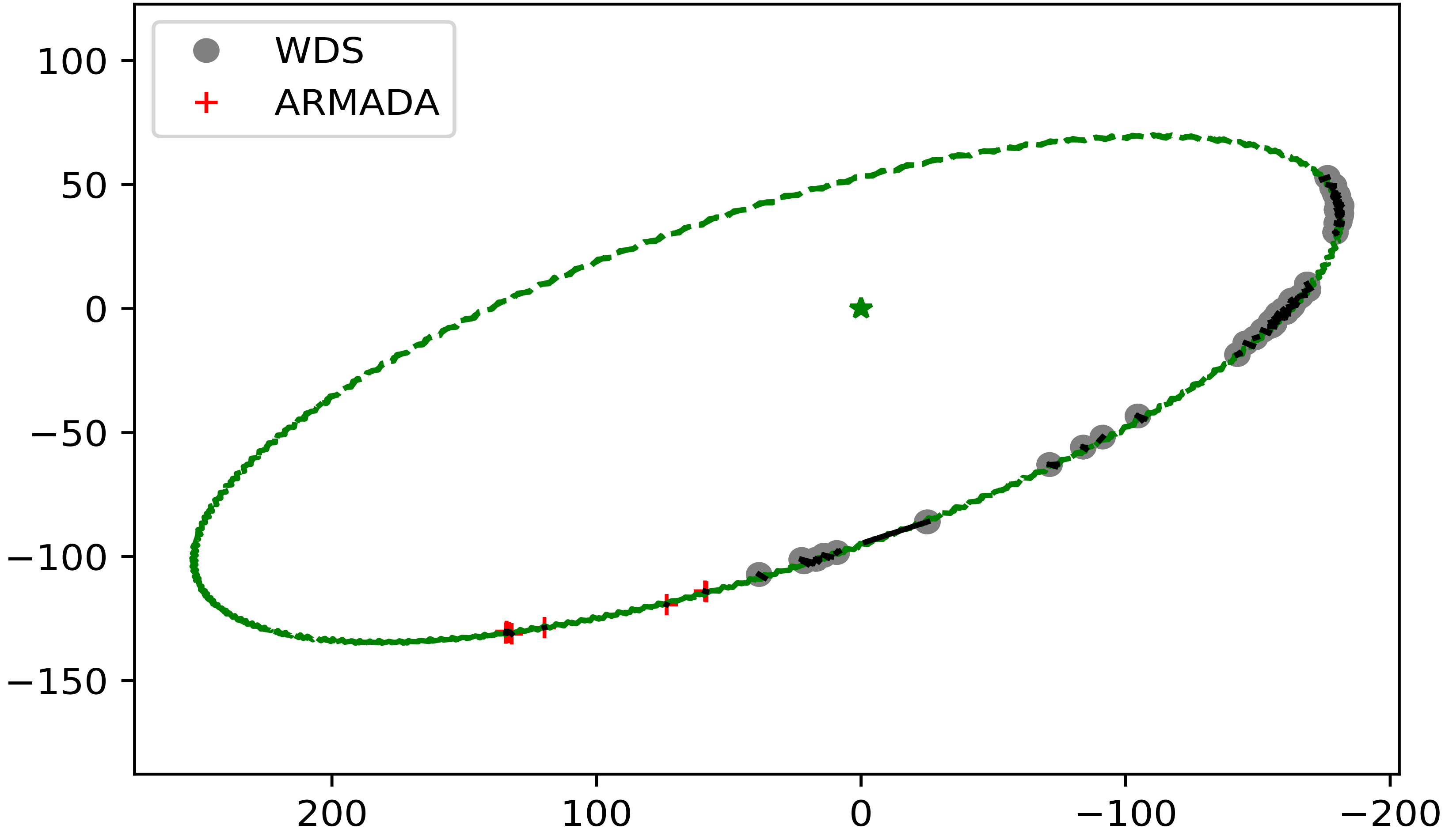




Tyler Gardner

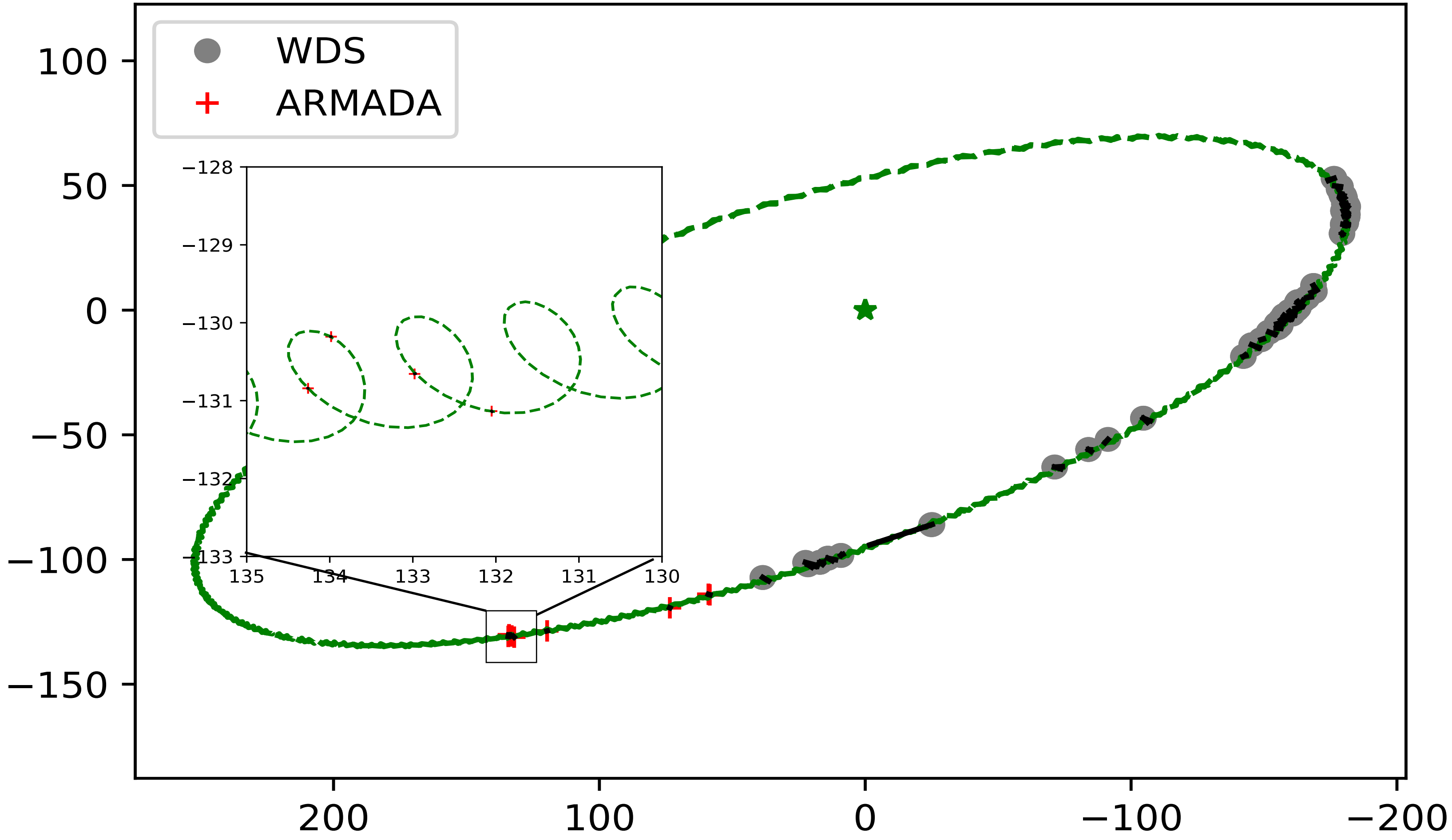
(U. Michigan → Exeter)

Kappa Peg: Triple System



- PHASES: Search for substellar companions at Palomar Testbed Interferometer
  Muterspaugh et al. (2010)

Kappa Peg: Triple System



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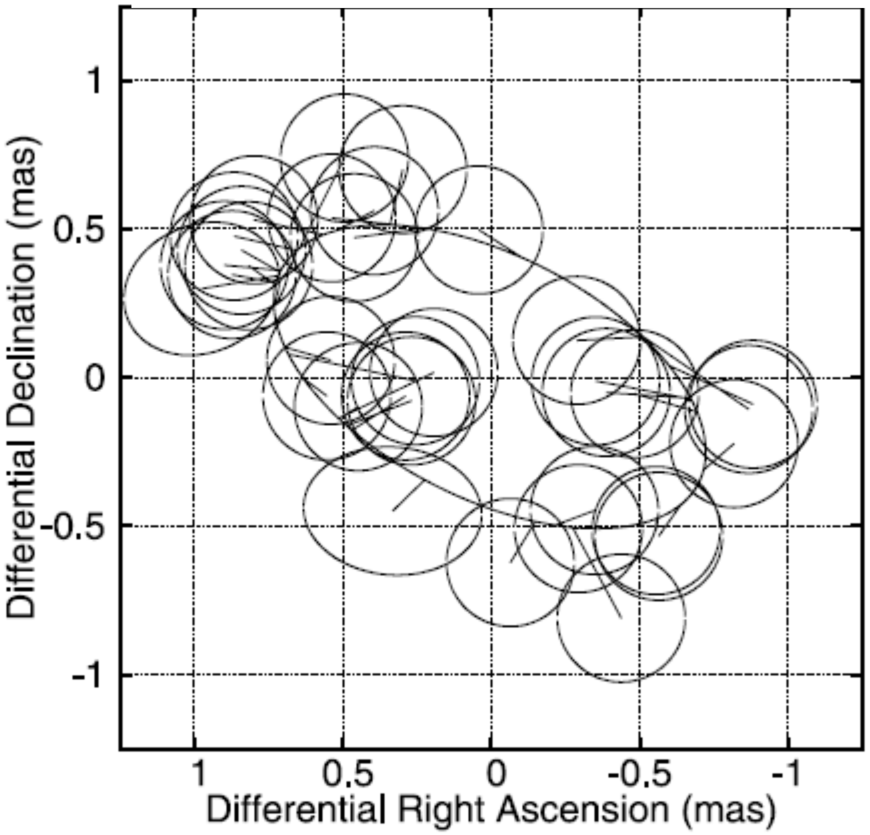
  Muterspaugh et al. (2010)

- ARMADA Survey: CHARA/MIRC-X
  Gardner et al. (2021)

Kappa Peg – Inner Orbit

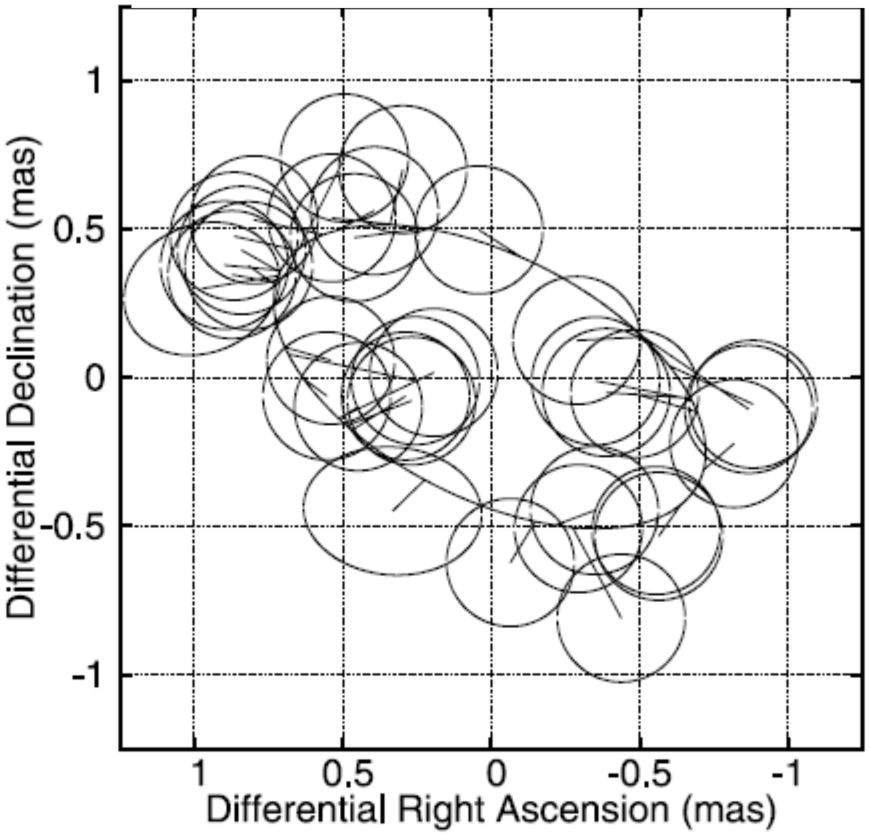
Kappa Peg Inner Orbit – PHASES



Muterspaugh et al. (2006)

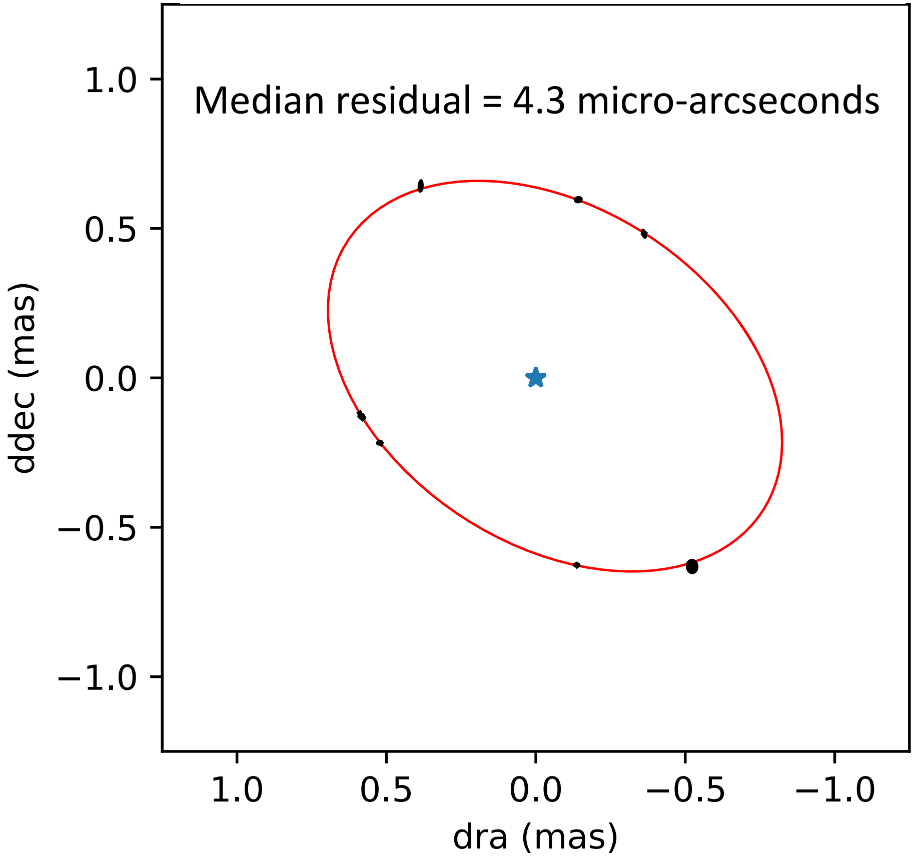
Kappa Peg – Inner Orbit

Kappa Peg Inner Orbit – PHASES



Muterspaugh et al. (2006)

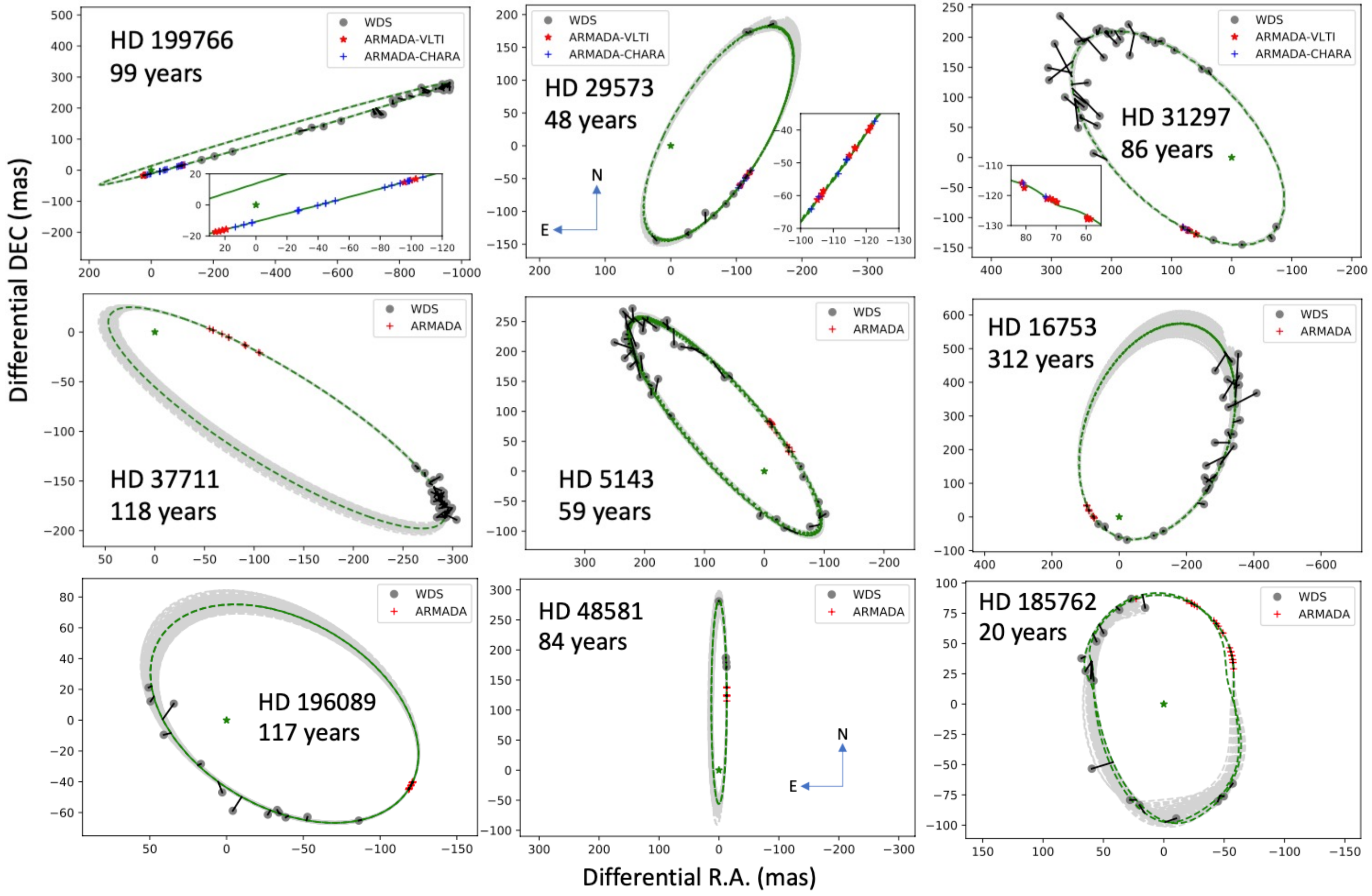
Kappa Peg Inner Orbit – MIRC-X



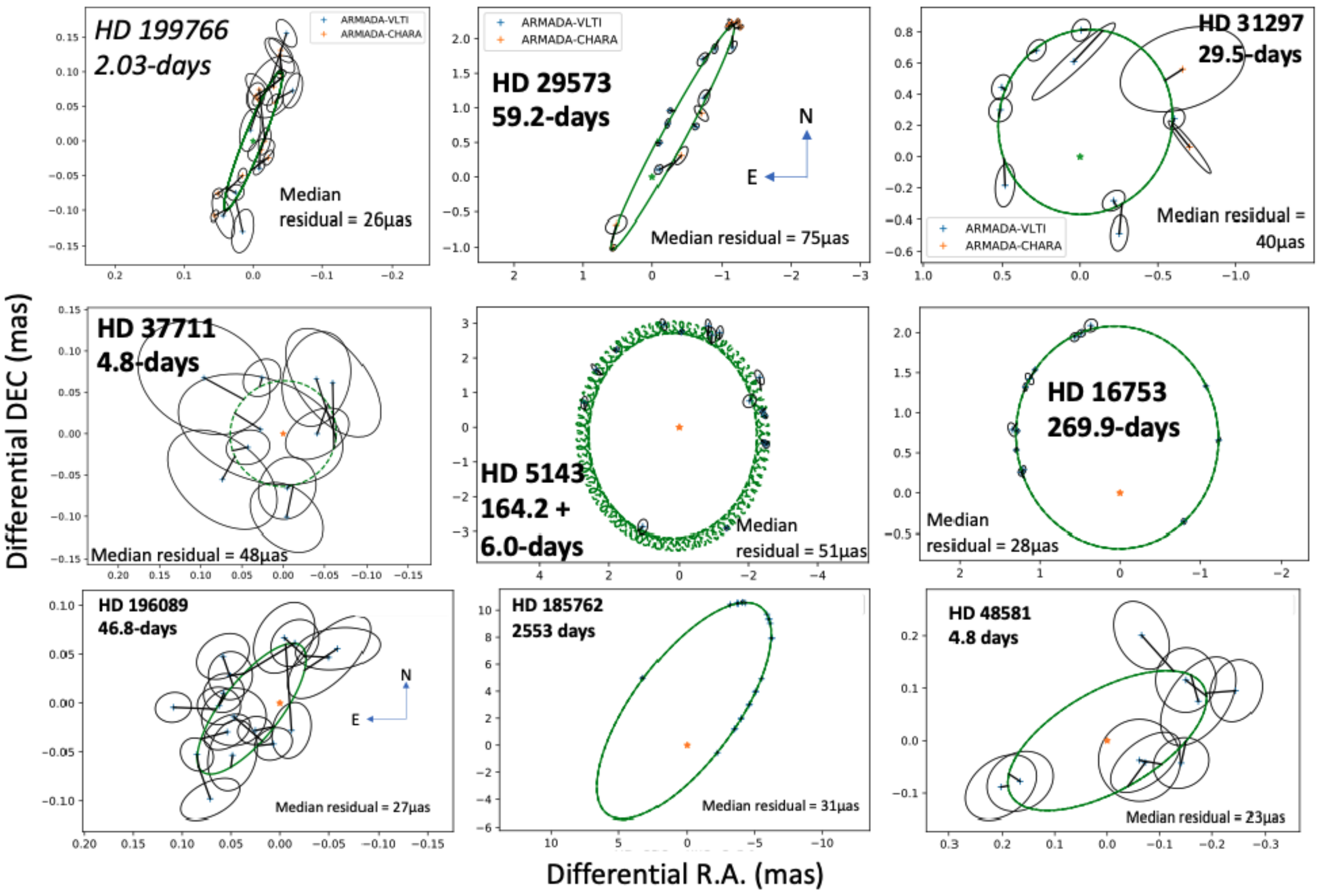
Gardner et al. (2021)

- ARMADA is 100% complete for compact triple systems
  - Orbital elements
  - Masses
  - Mutual Inclinations

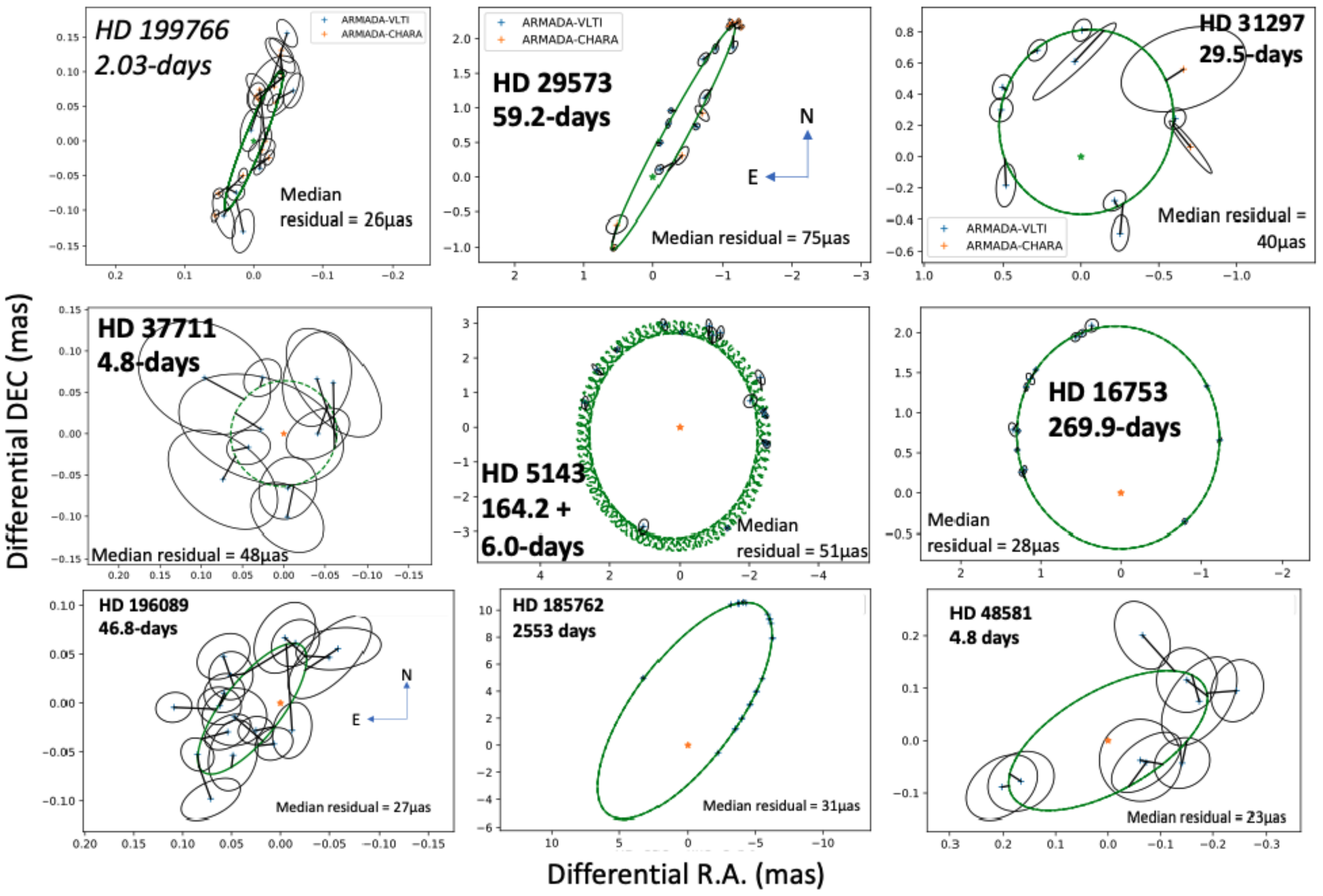
Newly Detected Triple Systems at CHARA and VLTI: Outer Binary Orbits



Newly Detected Triple Systems at CHARA and VLTI: Inner Wobbles

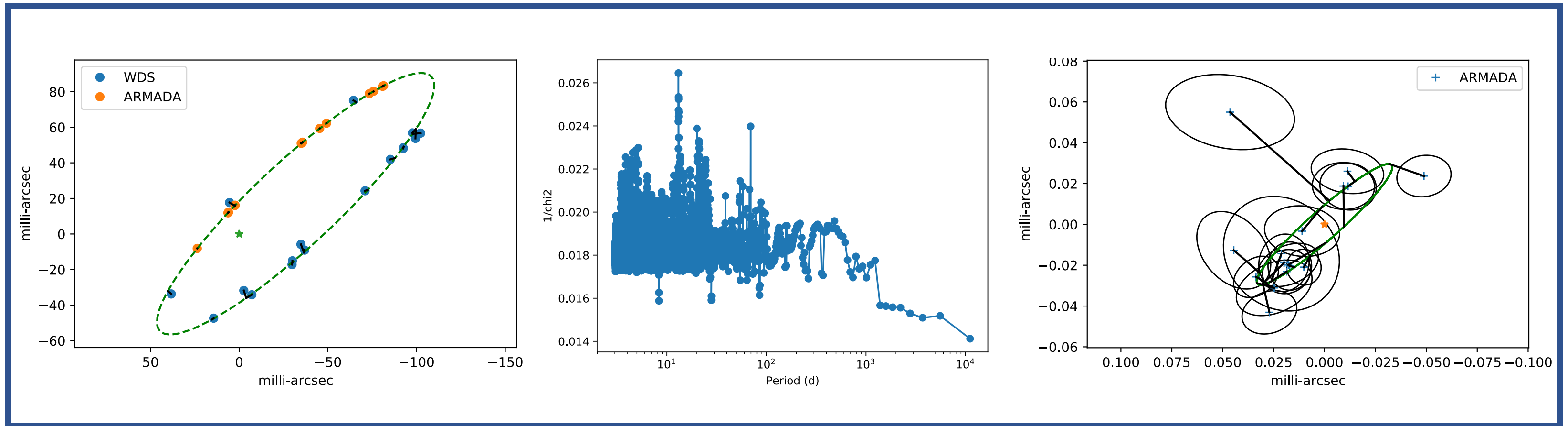


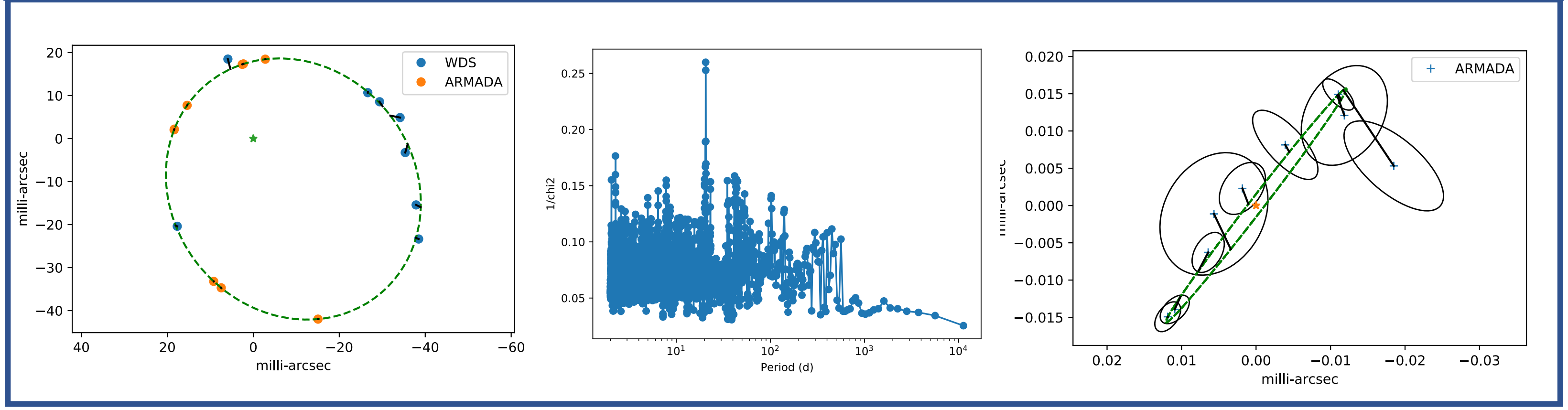
Newly Detected Triple Systems at CHARA and VLTI: Inner Wobbles



- 15 new triple detections published in Gardner et al. (2021, 2022 submitted)
- 20-50 μas median precision in astrometry (joint fit with RV)
- Most inner systems misaligned relative to outer orbits

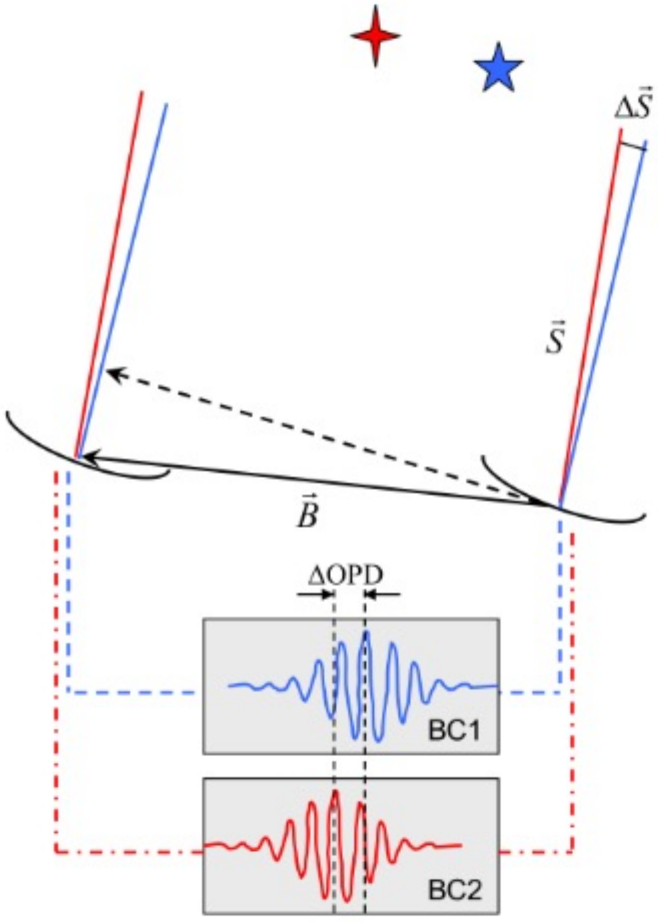
Substellar Candidates for CHARA/MIRCX





- Both candidates are around A-type binaries with masses ~ 50 Mjup
- Need follow-up confirmation: astrometry or high precision RV

Dual Field Mode

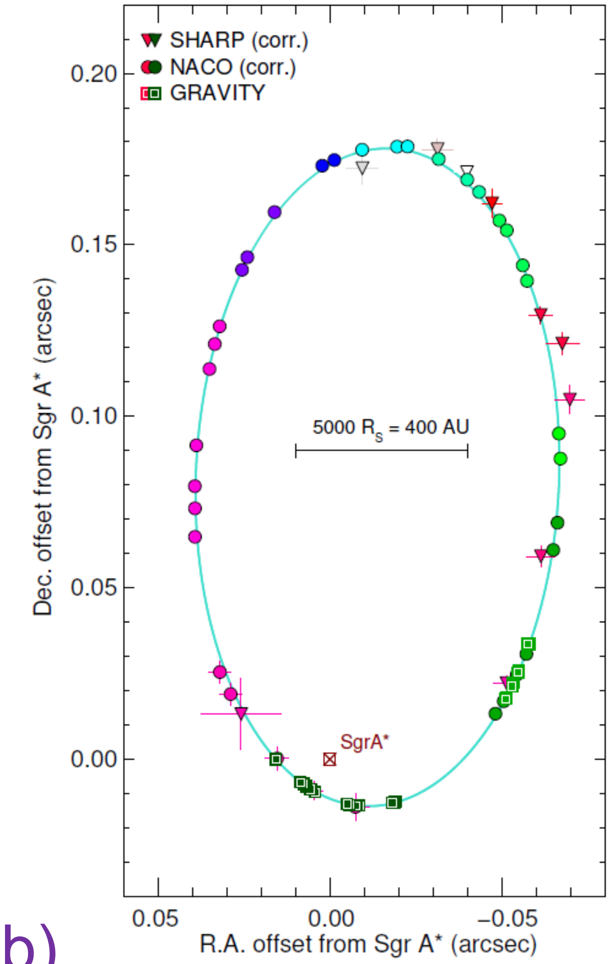


$$\Delta OPD(t) = \Delta\vec{S}\cdot\vec{B} + \Delta OPD_{atm} + \Delta OPD_{met}$$

- Difference in the fringe envelope position of the two objects as seen by the beam combiners is a measure of the object separation on sky
- VLTI/GRAVITY – extends field of view out to 2'' (UT) and 4'' (AT)
- GRAVITY wide – out to 30''

Pfuhl et al. (2021), Glindemann et al. (2003)

VLTI Gravity: Galactic Center



GRAVITY Collaboration et al. (2018a, 2022a, 2022b)

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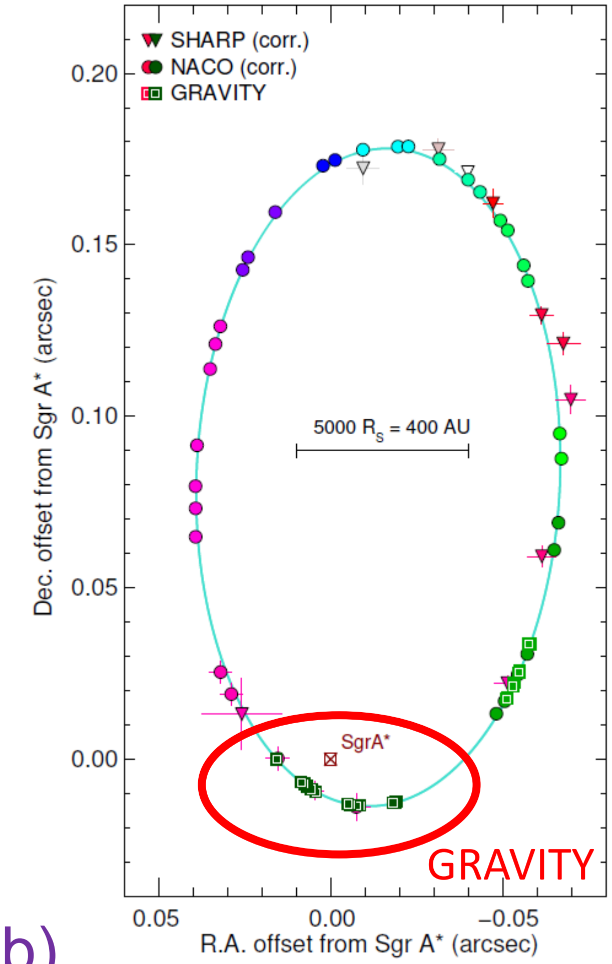
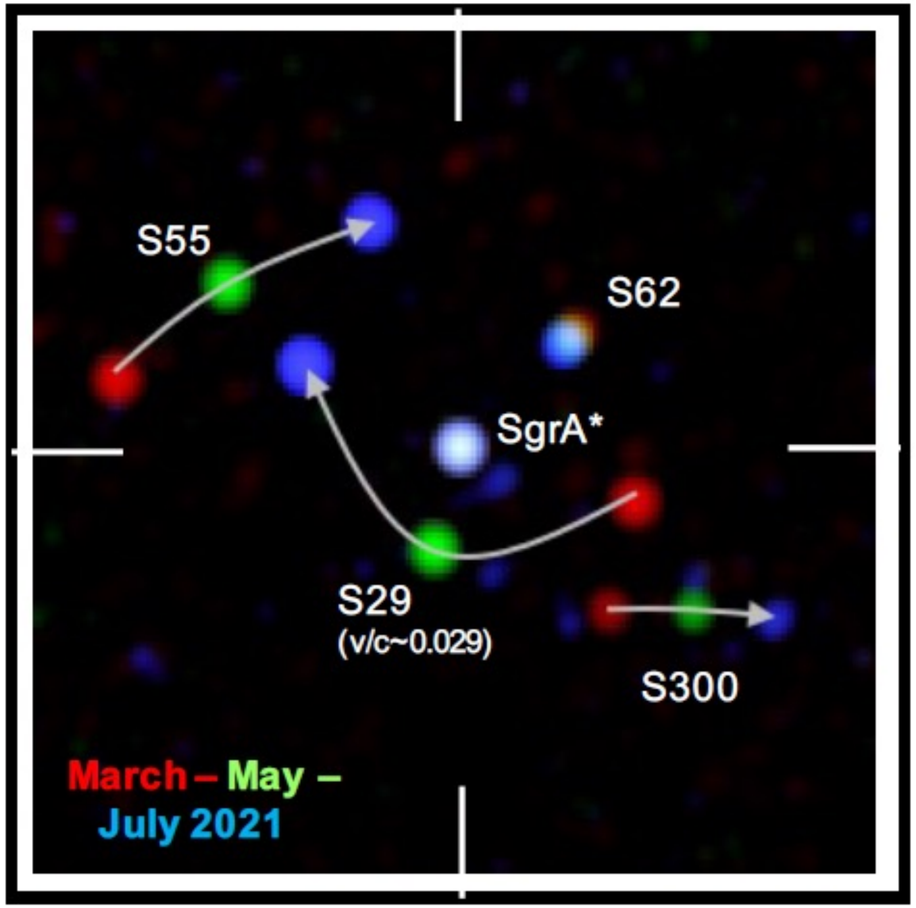
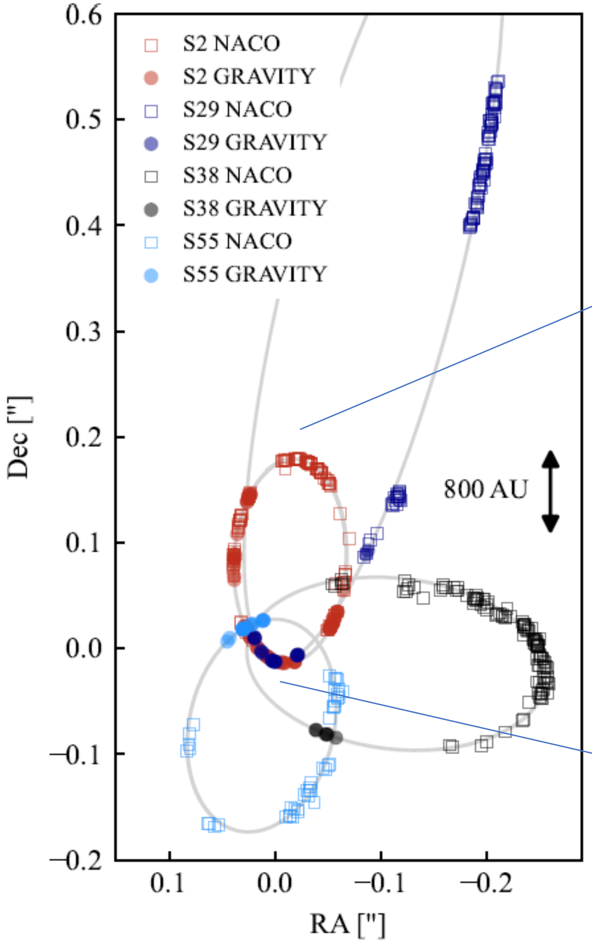


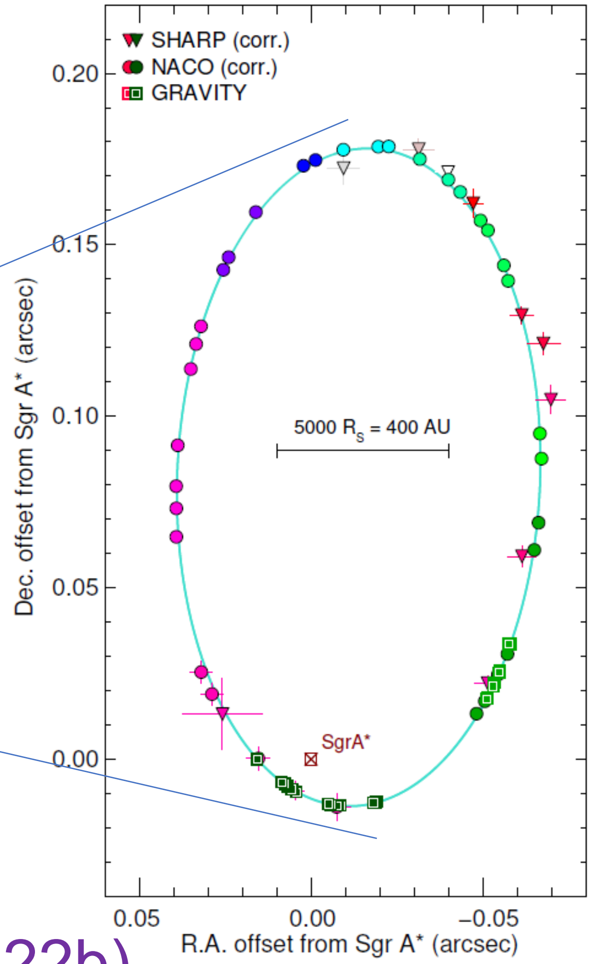
GRAVITY Collaboration et al. (2018a, 2022a, 2022b)

VLTI Gravity: Galactic Center

0.05" (415 AU, 0.5×10^4 Rs)

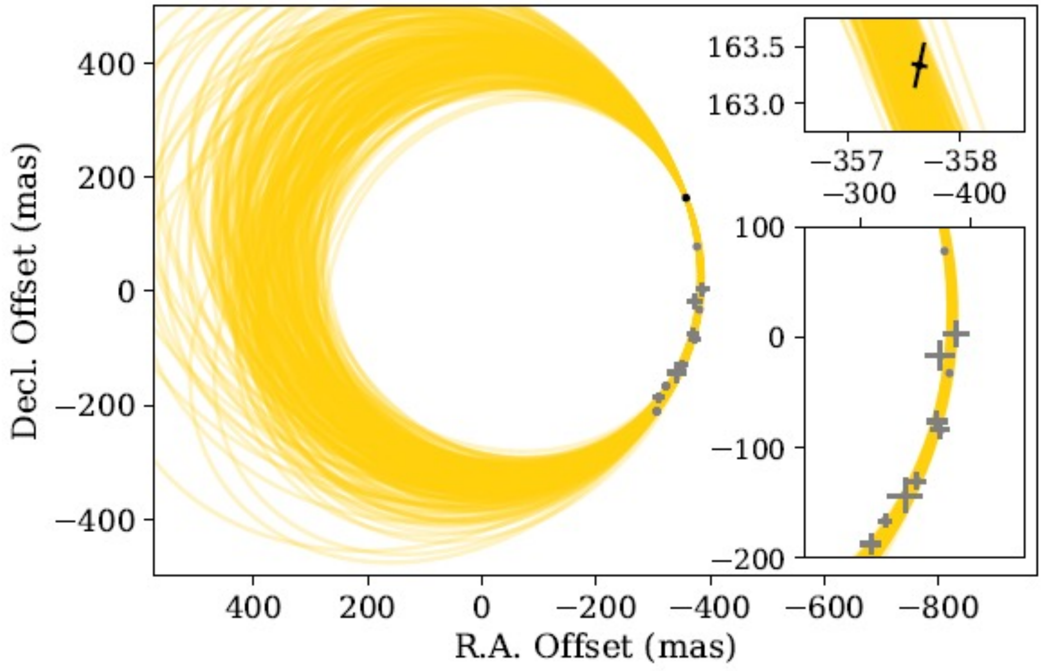




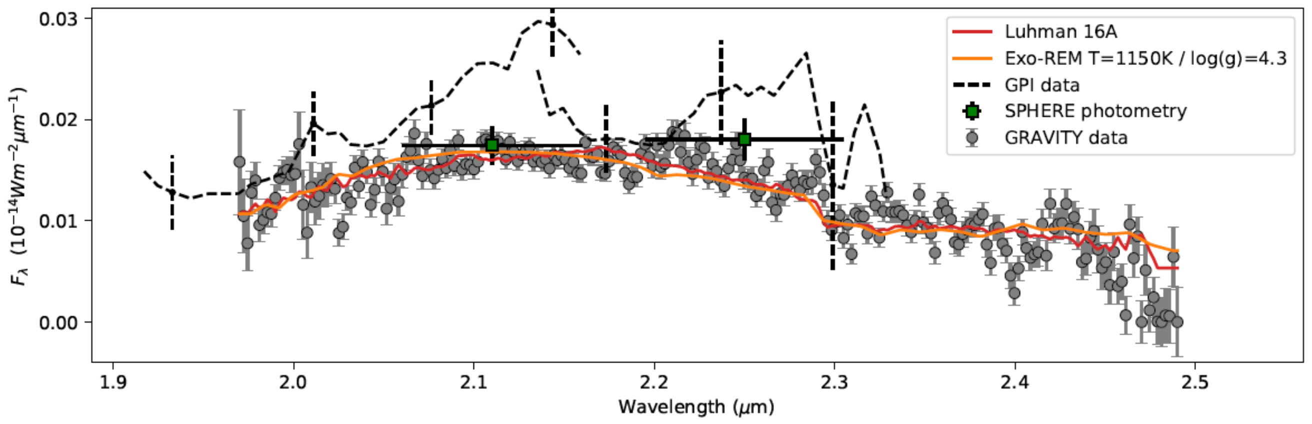


GRAVITY Collaboration et al. (2018a, 2022a, 2022b)

Exoplanet Astrometry with VLTI/GRAVITY



- Keplerian orbit of HR 8799 e.
- GRAVITY K band spectrum of HR8799 e (R ~ 500)



GRAVITY Collaboration et al. (2018b)

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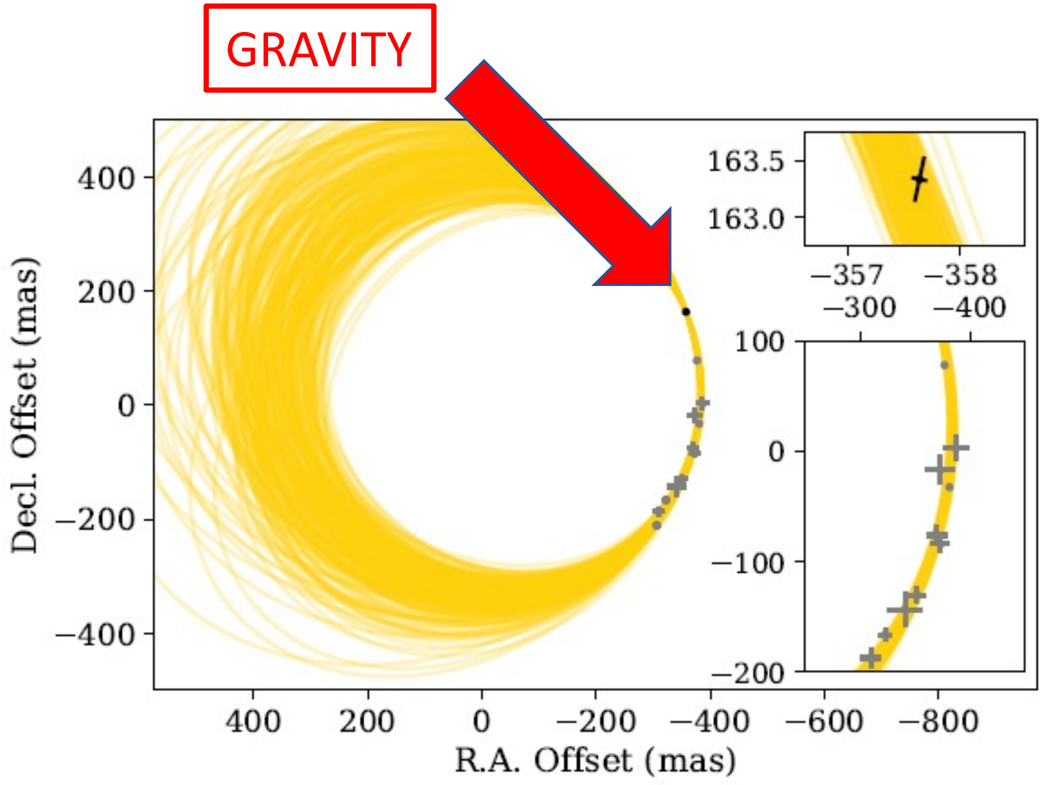

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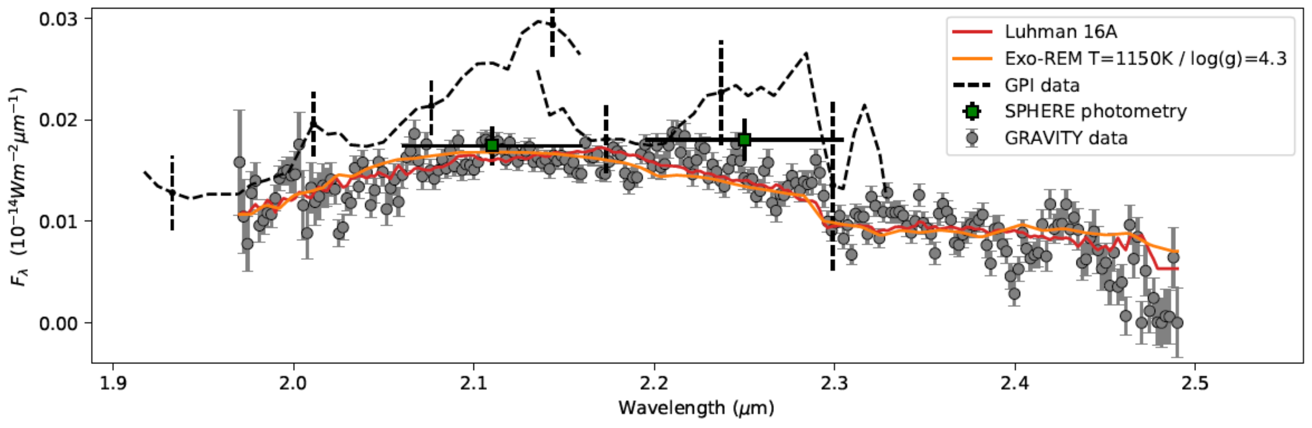
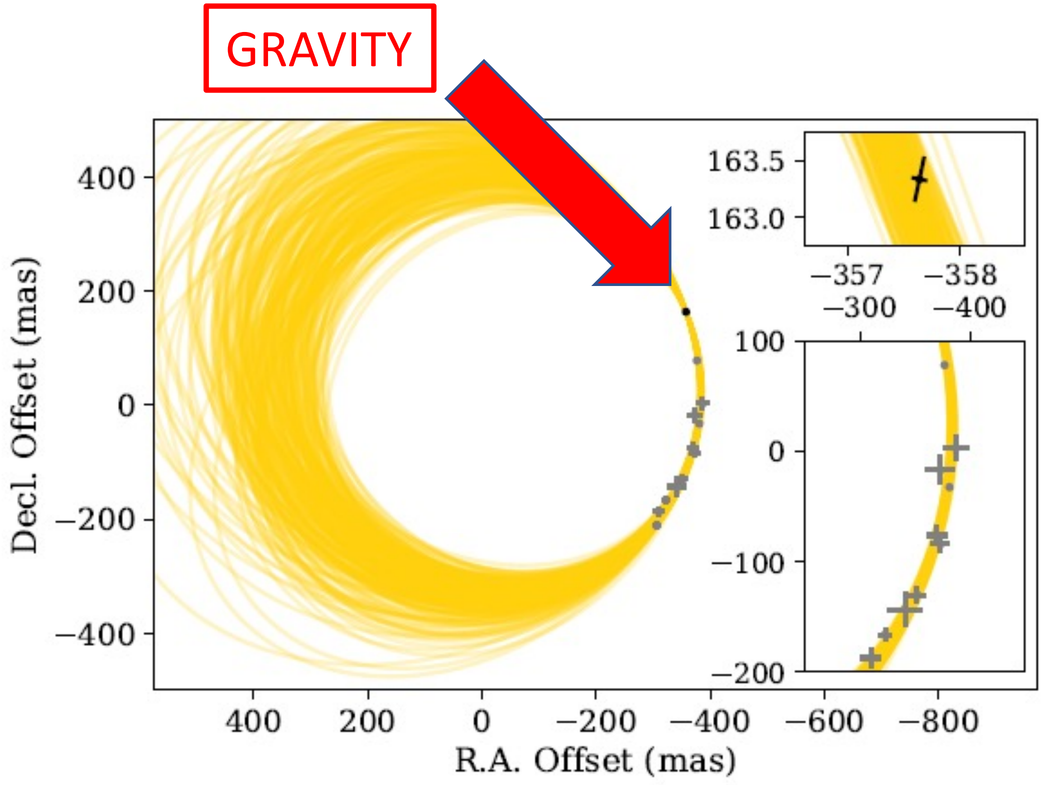


GRAVITY Collaboration et al. (2018b)

Exoplanet Astrometry with VLTI/GRAVITY

See talk by Pierre Kervella!



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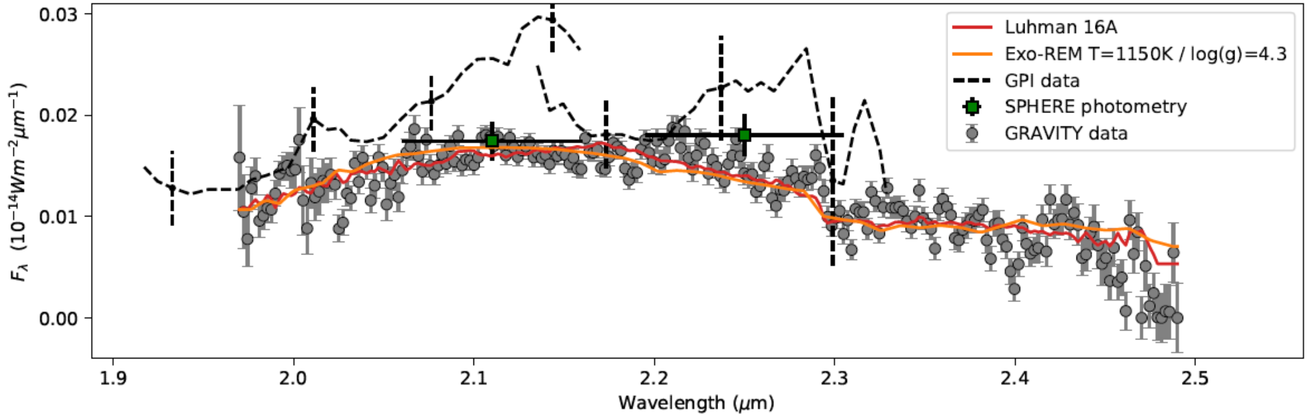
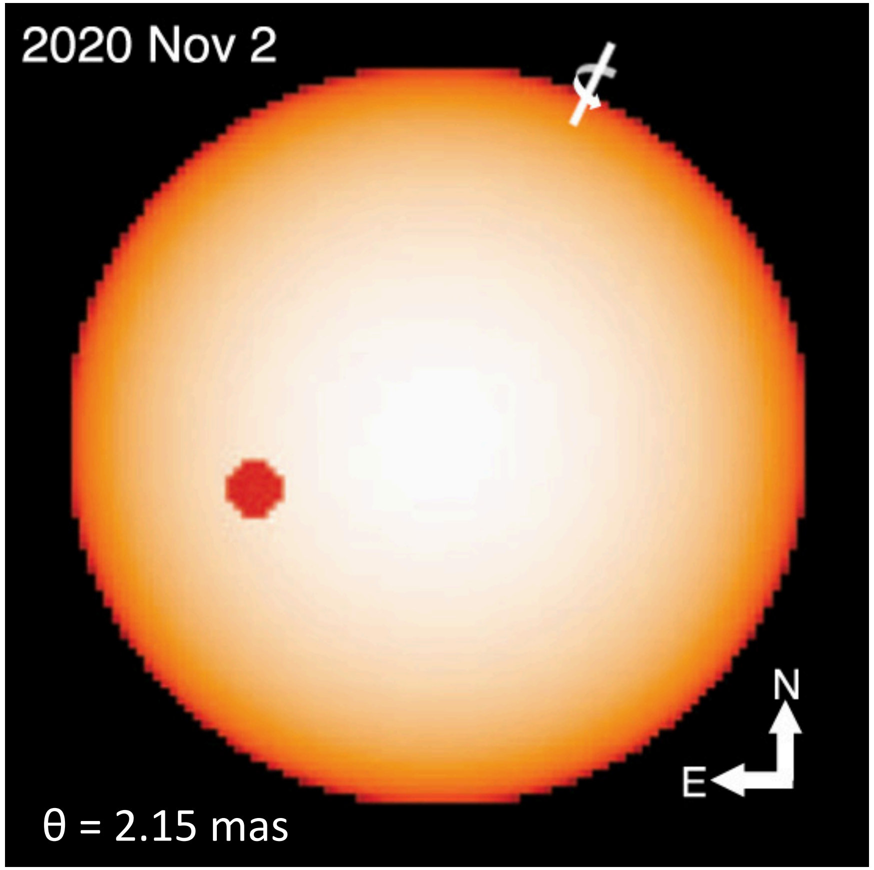


GRAVITY Collaboration et al. (2018b)

Imaging Stellar Surface Features

Star Spot Jitter

CHARA MIRC-X Starspot Model

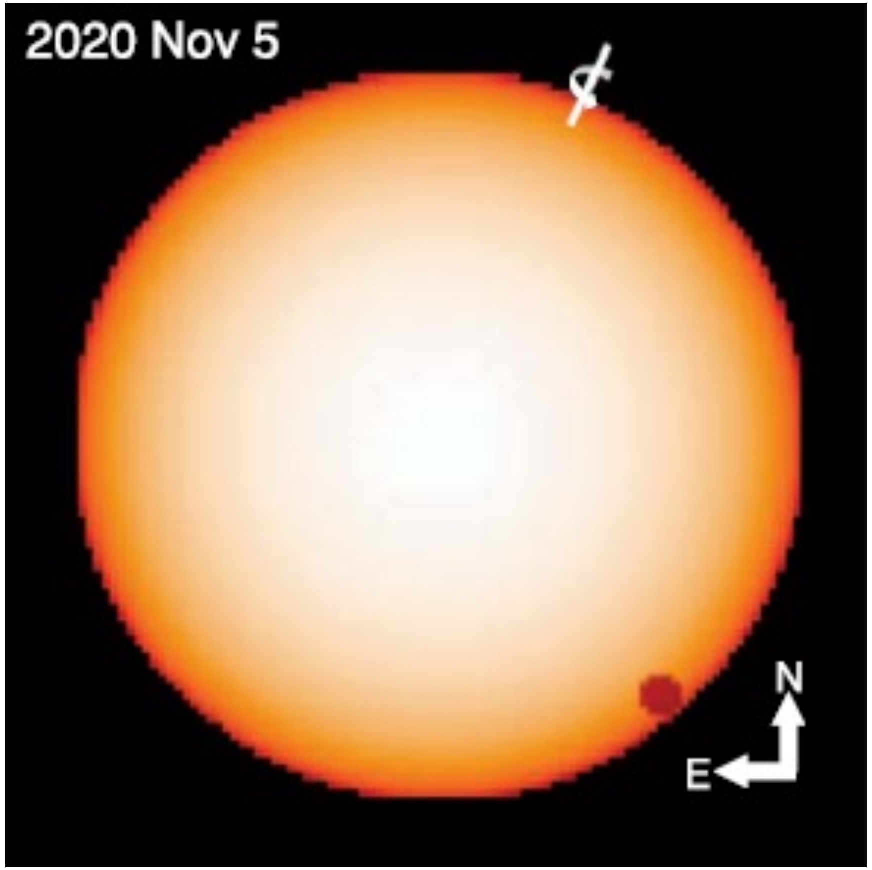


- ε Eridani – closest K2V star and exoplanet host
- TESS photometry light-curve inversion
- Produce activity model to reduce rms scatter in radial velocities
- Disentangle stellar activity from planet
- Interferometric imaging: stellar inclination and orientation with respect to the debris disk

Roettenbacher et al. (2022)

Star Spot Jitter

CHARA MIRC-X Starspot Model

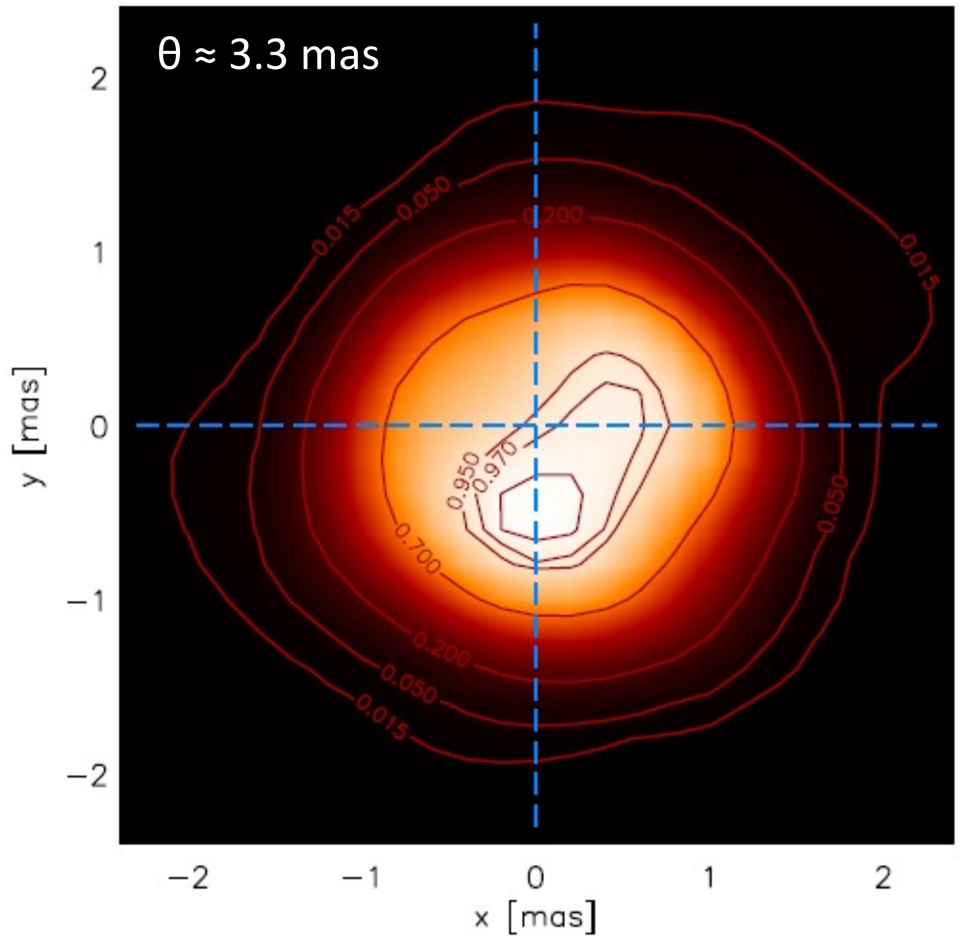


- ε Eridani – closest K2V star and exoplanet host
- TESS photometry light-curve inversion
- Produce activity model to reduce rms scatter in radial velocities
- Disentangle stellar activity from planet
- Interferometric imaging: stellar inclination and orientation with respect to the debris disk

Roettenbacher et al. (2022)

Convective Spots

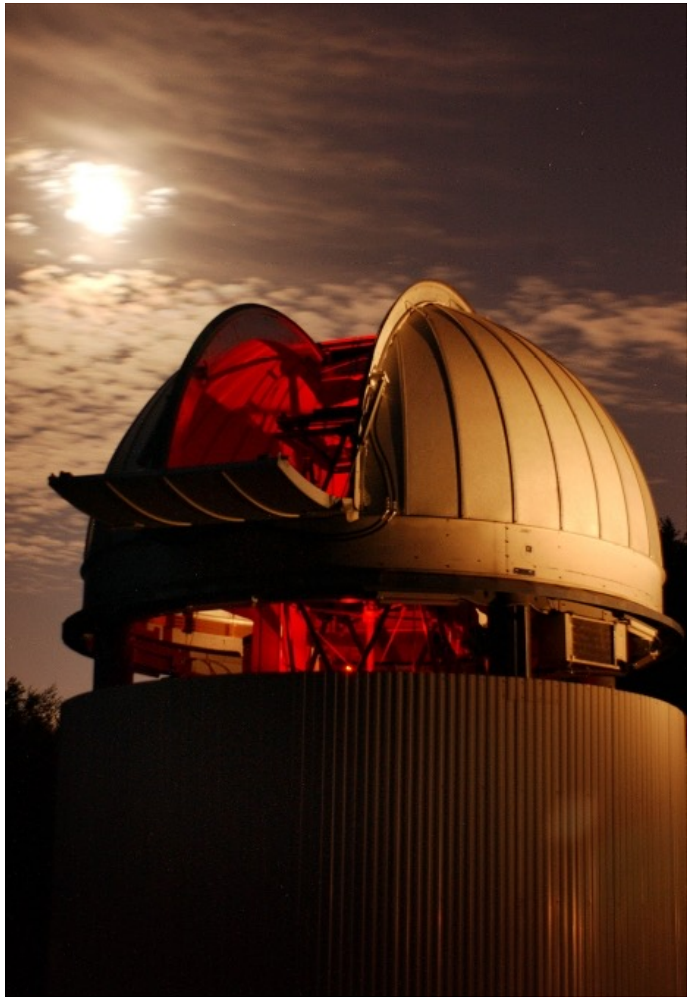
CHARA MIRC-X Image



- CL Lac: Asymptotic Giant Branch Star
- Brightness asymmetry
- Photocenter variability caused by convection-related structures that accounts for large parallax error
- Use Gaia measurement uncertainties to extract the fundamental properties of AGB stars using RHD simulations

Chiavassa et al. (2020)

Apply for Time!



- Community access time is available at both the CHARA Array and VLTI
- Key science drivers
  - Stellar diameters – exoplanet hosts
  - Binary Orbits
  - Stellar Surface Imaging
  - Circumstellar Disks
- Questions?

CHARA Array: Beam Combiners

Current Instruments

MIRC-X
6T, H-band (J)
Prism R=50, H < 6.5 – 7.5
Grism R=190, H < 5.5 – 6.5

MYSTIC
6T, K-band
Prism R=49, H < 6.5 – 7.5
Grism R= 278, 981, 1724

CLASSIC/CLIMB
JHK, Broadband
2T: K < 7.0 – 8.0
3T: K < 6.0 – 7.0

Upcoming Instruments

PAVO
2T
630-900 nm, R=30
Rmag < 7.0 – 8.0

SPICA
6T, 600 – 860 nm
R = 140, 4400, 13000
Commissioning: 2022A

SIMARIL
3T, HK
Improved sensitivity
Commissioning: 2023

Past Instruments

VEGA
2T – 4T, 450 – 850 nm
R = 1700, 6000, 30000
Operational: 2007 – 2020

FLUOR/JouFLU
2T, K-band
Operational: 2002 – 2018

AO/Tiptilt Tracking: V < 12 mag

Magnitude limits are given as a range from typical to best case sensitivities.