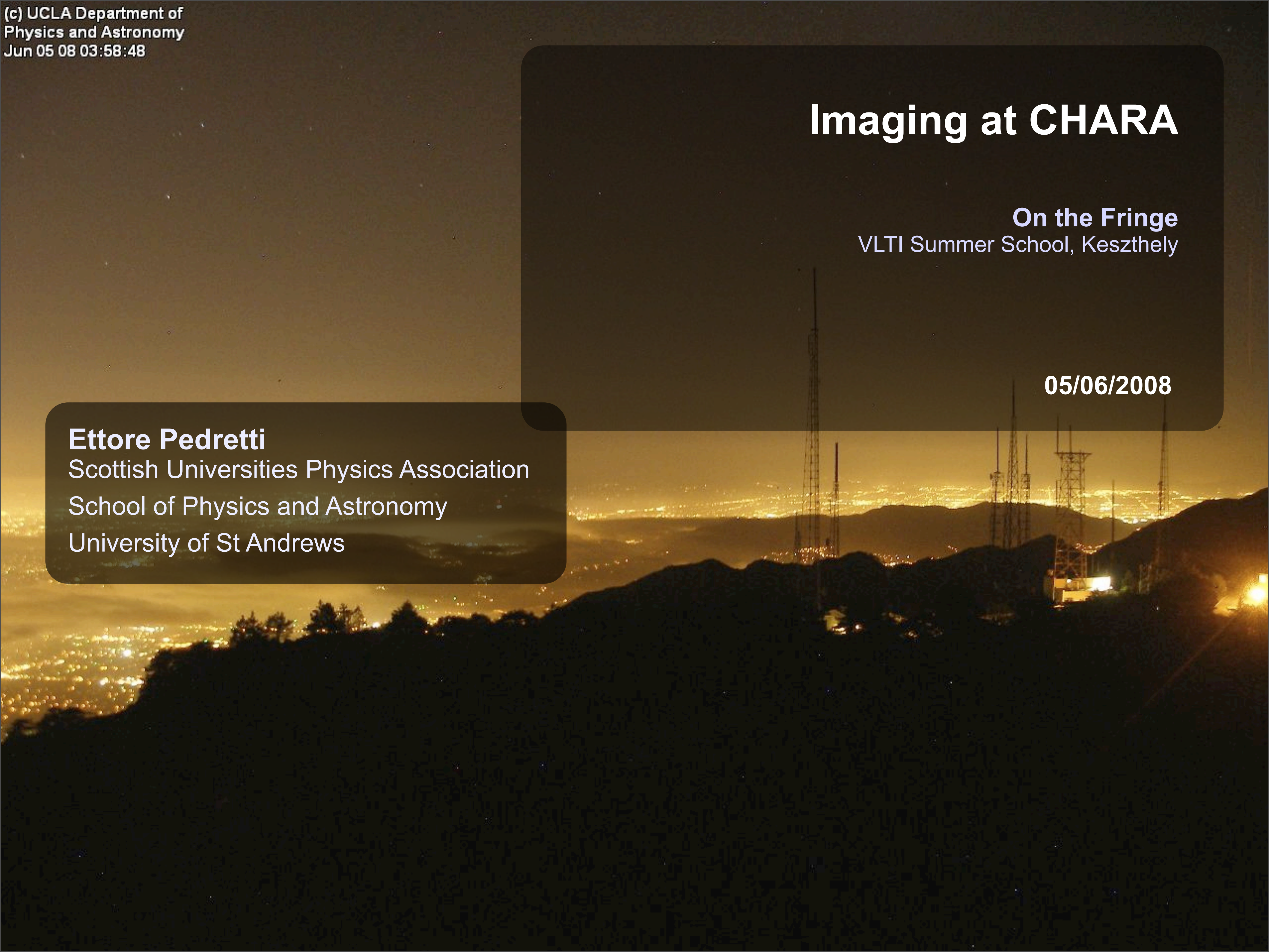


Imaging at CHARA

On the Fringe
VLTI Summer School, Keszthely

05/06/2008

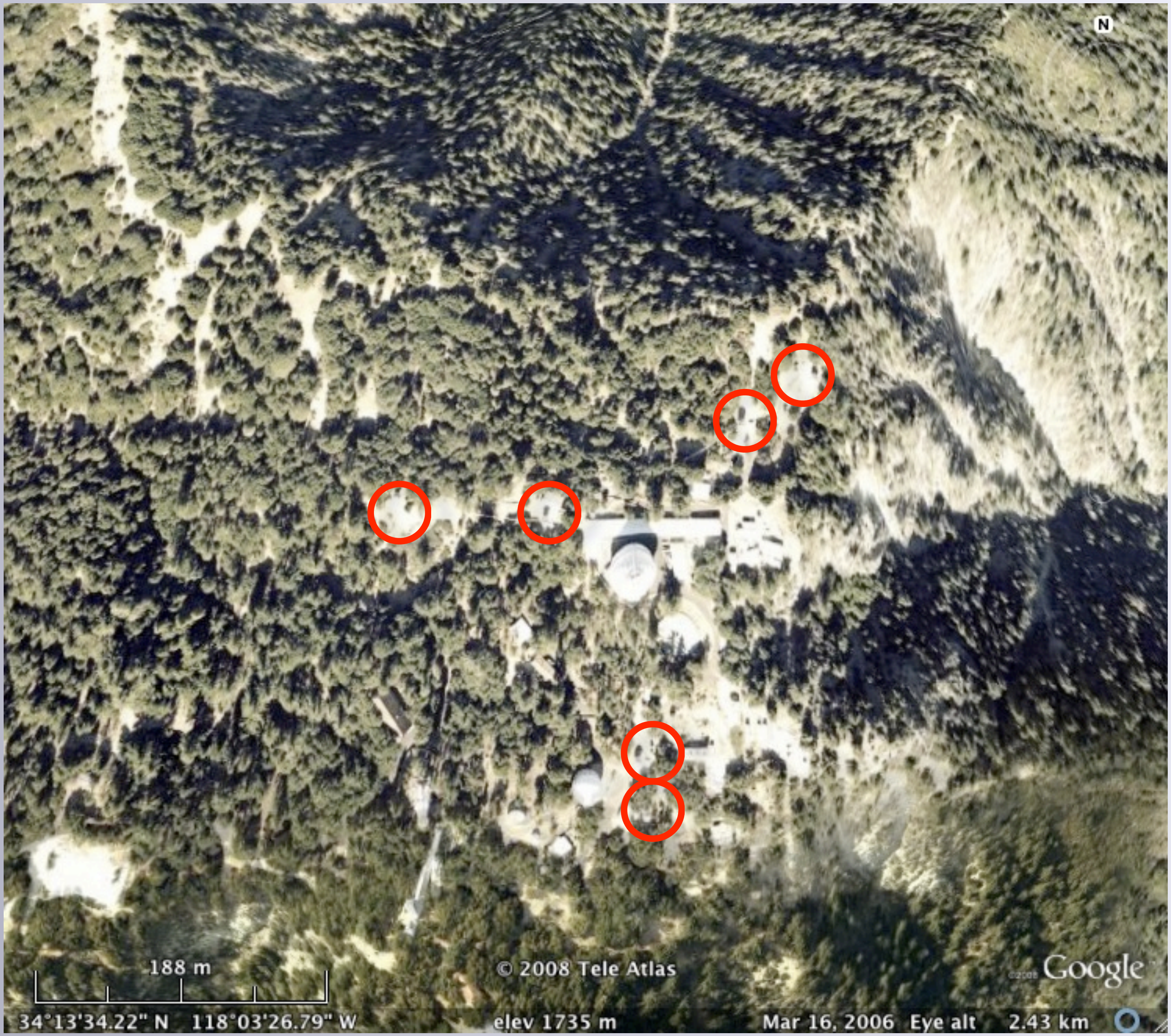
Ettore Pedretti
Scottish Universities Physics Association
School of Physics and Astronomy
University of St Andrews

Collaborators and acknowledgements

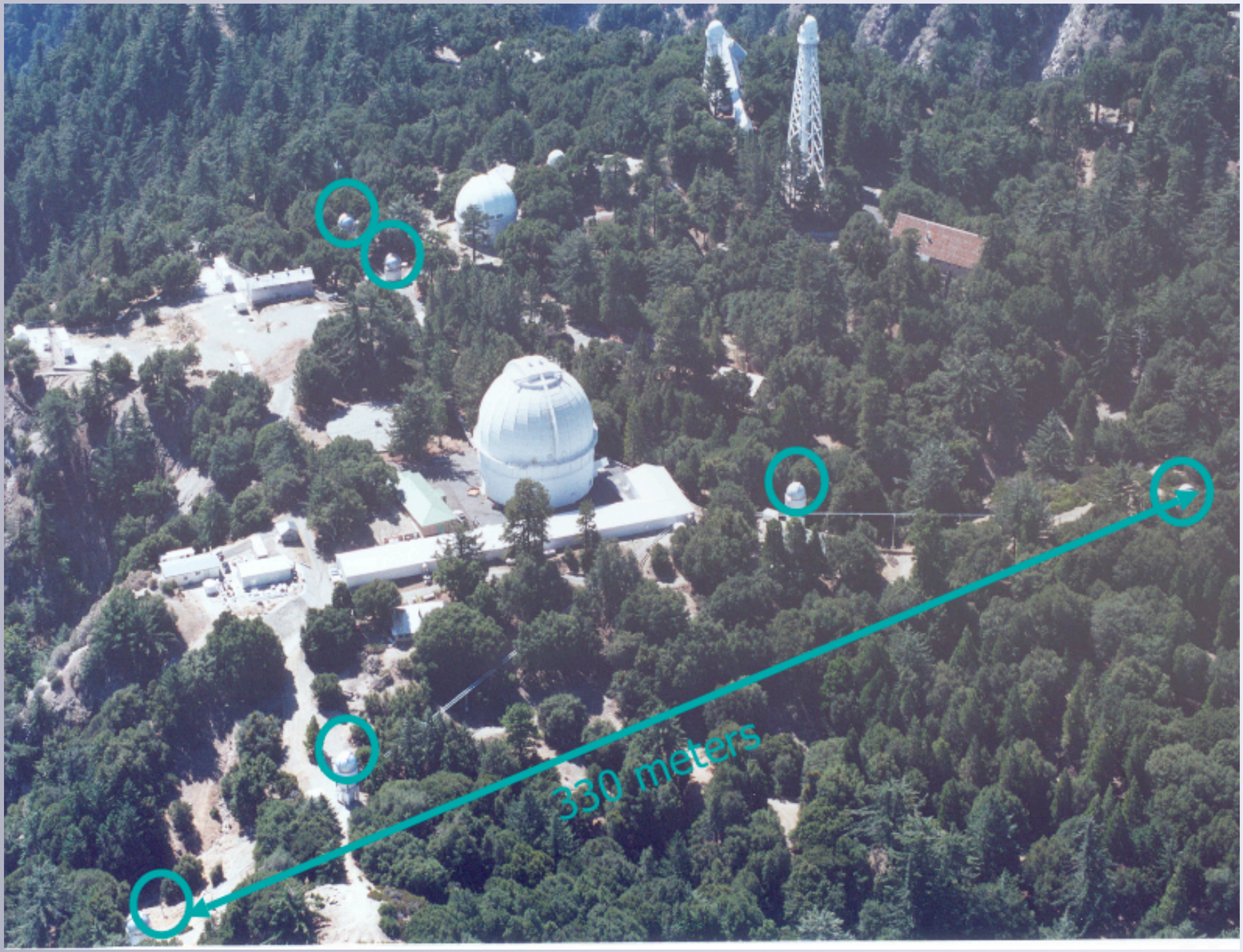
- John Monnier, University of Michigan
- Ming Zhao, University of Michigan
- Nathalie Thureau, University of St Andrews
- David Berger, University of Michigan
- Ajay Tannirkulan, University of Michigan
- Theo ten Brummelaar, Georgia State University
- Harold McAlister, Georgia State University
- Laszlo and Judith Sturmann, Georgia State University
- and many others...
- This presentation has heavily borrowed from material from John Monnier

VLBA spans 10000 Km

CHARA spans 330 m



CHARA : longest baseline in the infrared



CHARA versus VLBA

- VLBA = best angular resolution
- CHARA = best angular resolution in the infrared

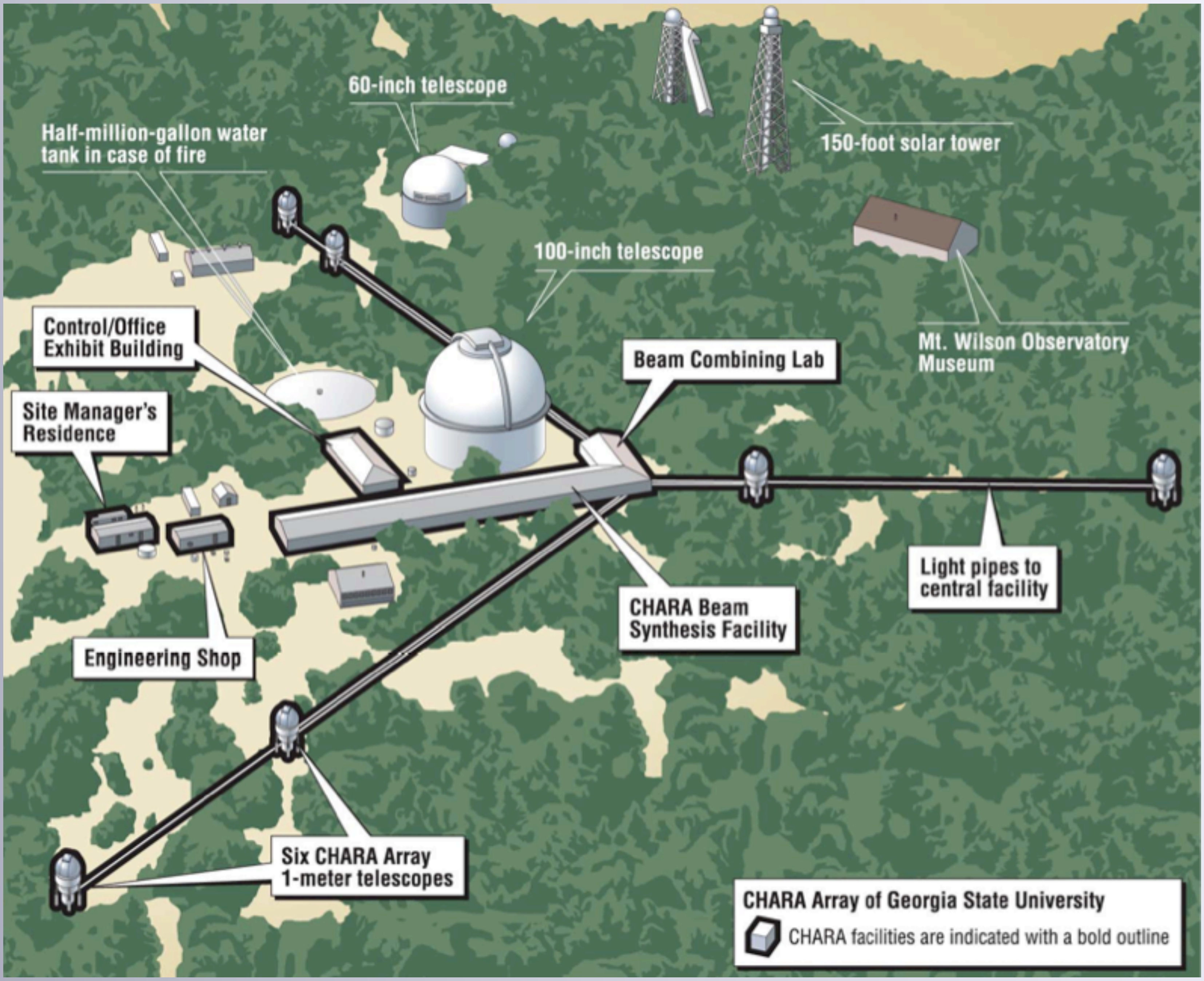
$$\theta = \frac{\lambda}{d}$$

Instrument	Wavelength	Baseline	Resolution
VLBA	1 cm	8600 Km	0.2 mas
CHARA	1.65 μm	330 m	1 mas

CHARA array

- Built and
  op
  e
  rated by Georgia State University (PI: Hal McAlister)
- Funded by State of Georgia, National Science Foundation, Keck Foundation

A cartoon of CHARA



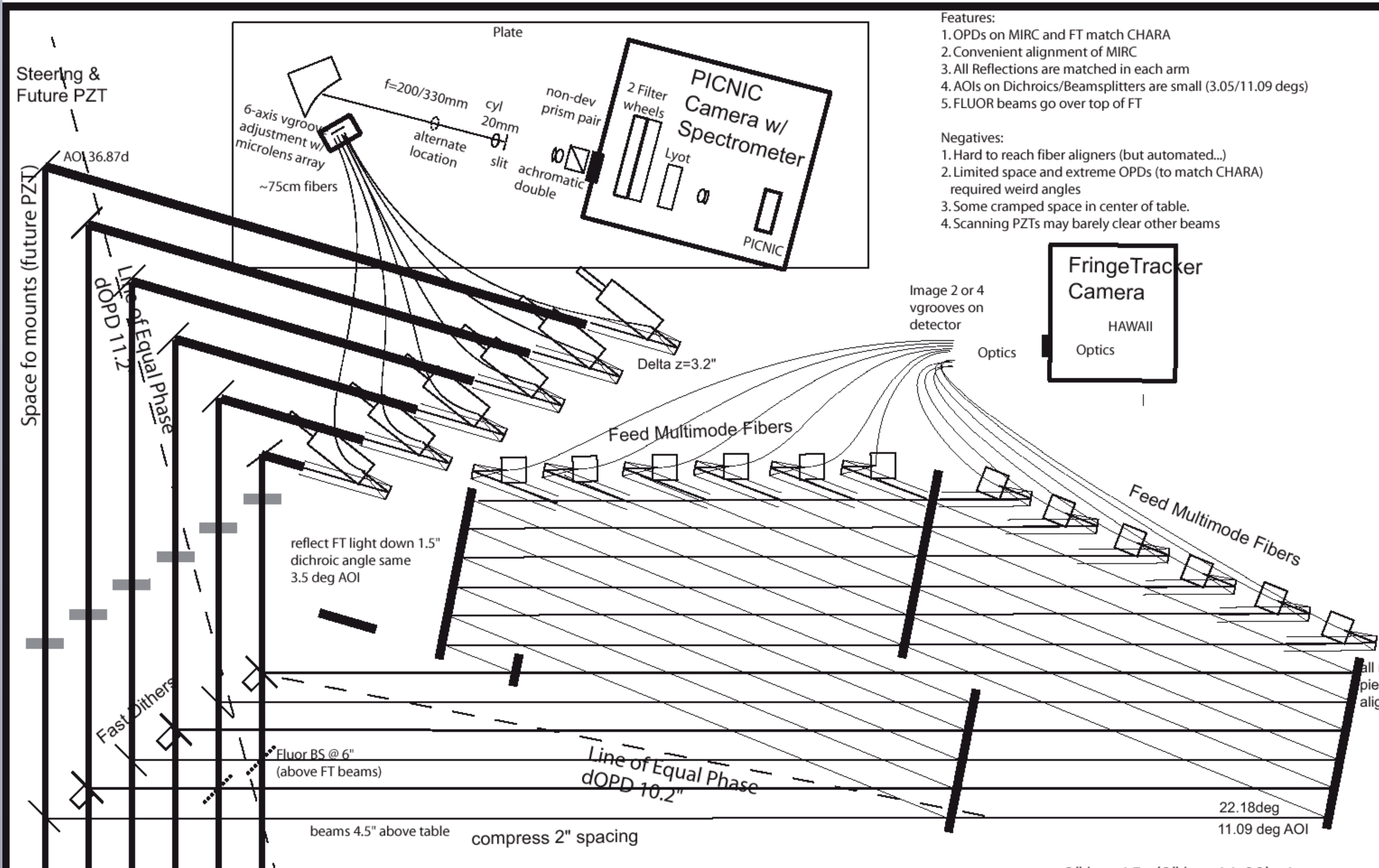
Instruments offered at CHARA

Instrument	Magnitude limit	Visibility Precision	Closure Phase Precision
Classic	K = 6.5	6-10%	NA
FLUOR	K = 4 - 5	1% typical	NA
MIRC	H = 4 - 4.5	10% or worse	0.1 - 0.5 deg (worst case)

Important Properties of Closure Phases

- Sensitive to asymmetries in brightness distribution (SKEW)
  - Centro-symmetry yields Π = 0 or 180 degs
  - Necessary for imaging (if no phase referencing)
- More robust to calibration error
  - Atmospheric turbulence generally does not bias measurement (unlike Visibility^2)
  - Reasonable hope of measurement error reducing as root(N)

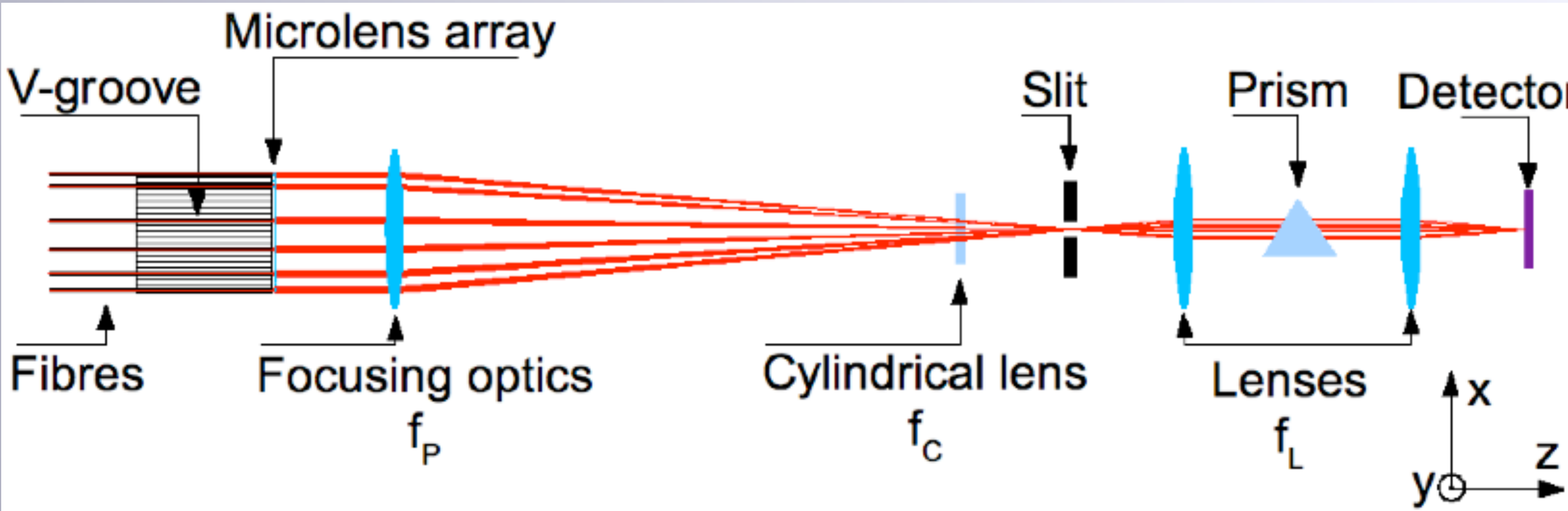
MIRC infrared table (not the final design)



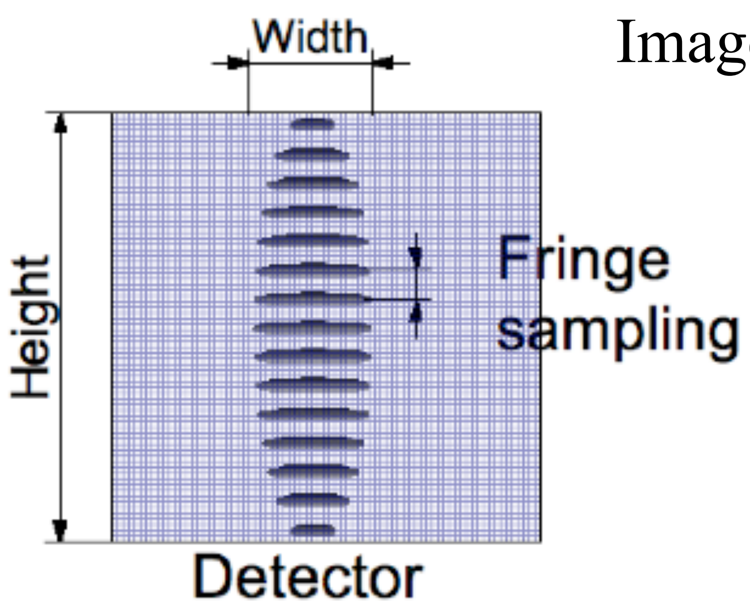
Features:
1. OPDs on MIRC and FT match CHARA
2. Convenient alignment of MIRC
3. All Reflections are matched in each arm
4. AOIs on Dichroics/Beamsplitters are small (3.05/11.09 degs)
5. FLUOR beams go over top of FT

Negatives:
1. Hard to reach fiber aligners (but automated...)
2. Limited space and extreme OPDs (to match CHARA) required weird angles
3. Some cramped space in center of table.
4. Scanning PZTs may barely clear other beams

MIRC infrared combiner



Images from Nathalie Thureau



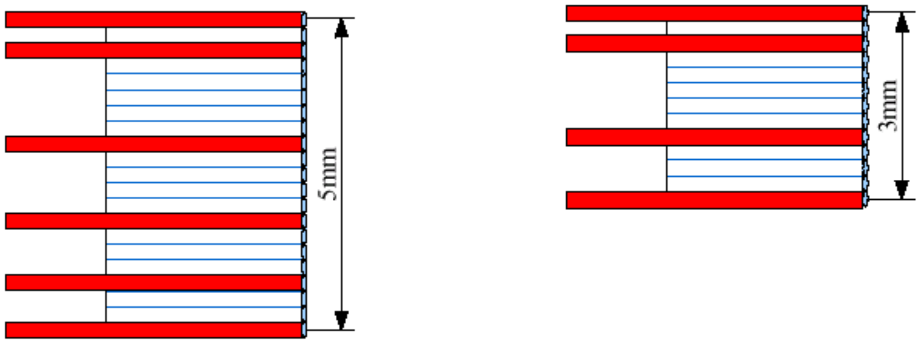
- Fringe sampling:
  - fibers spacing
  - pixel size
  - f_P
- Image Width/Height ratio:
  - f_C

Fringe sampling - 1

Minimum requirement (Nyquist): 2px/fringe
Chosen sampling: 2.5px/fringe @1.5µm

Detector = PICNIC chip
Pixel size = 40µm x 40µm

Fibers spacing: two main configurations:
- 6 telescopes: 2-6-5-4-3
- 4 telescopes: 2-6-4

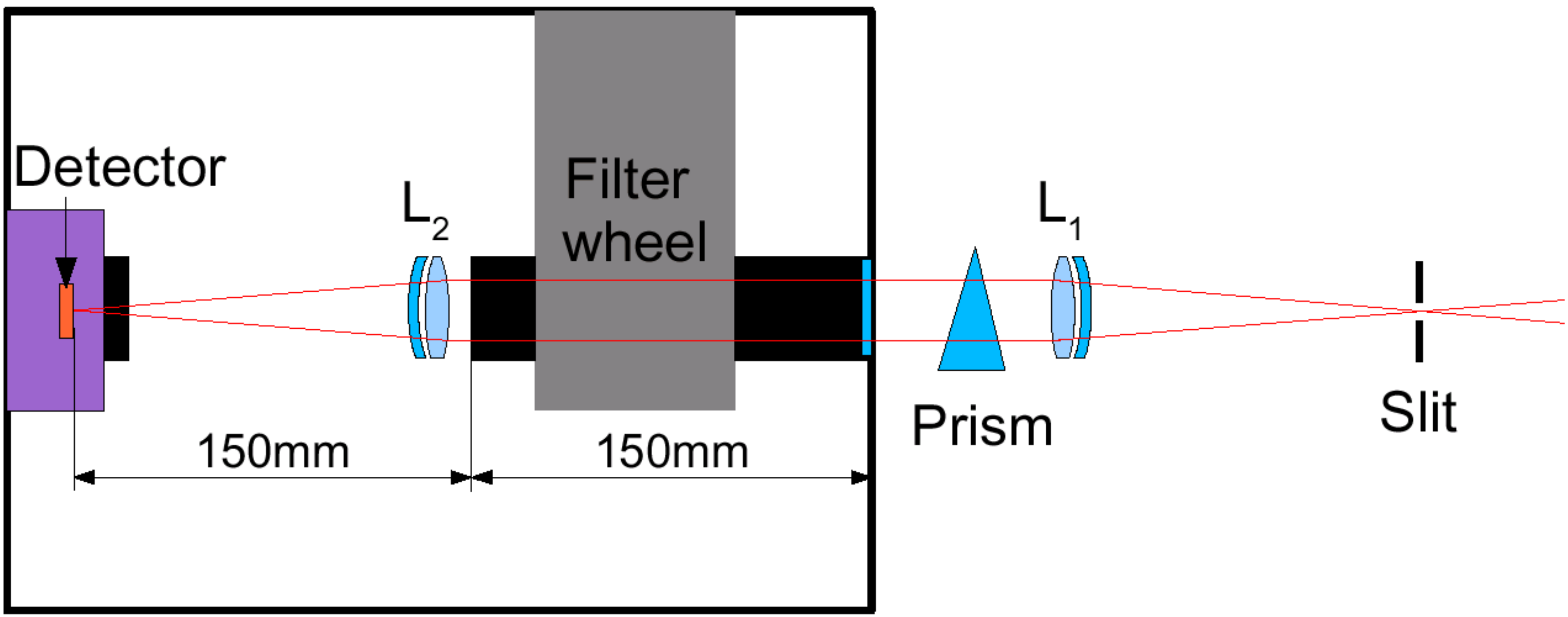


Images from Nathalie Thureau

Visibility and closure phase

N Telescopes	N Visibilities	N Independent CP
4	6	3
6	15	10

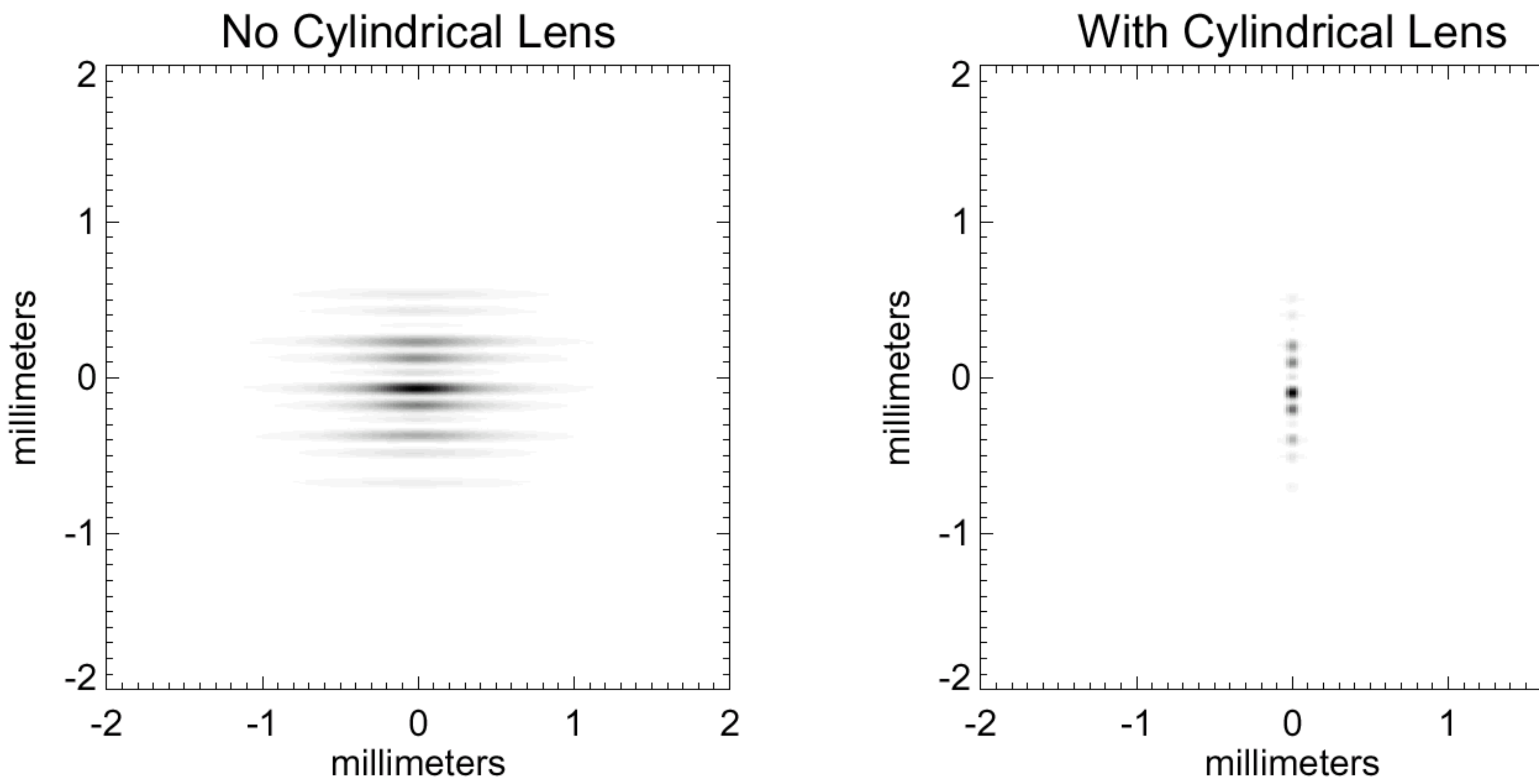
PICNIC camera and optics



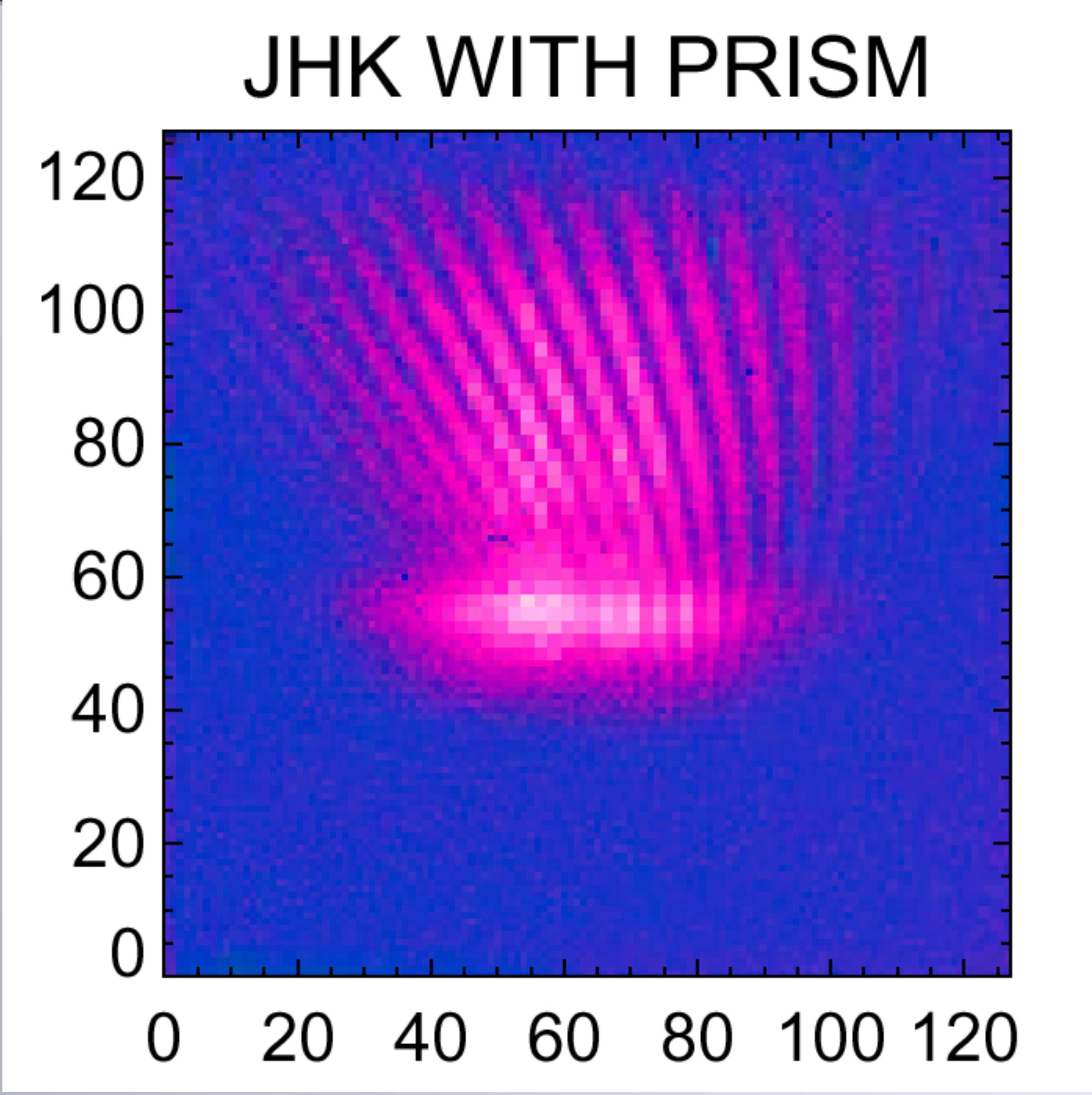
MIRC spectral resolution

- Spatial filtering with single mode fibres.
- Spectral Resolution R~35, 150, 450, using prisms, grism.
- Reduction in sensitivity due to spectral dispersion.

MIRC fringes without cylindrical lens

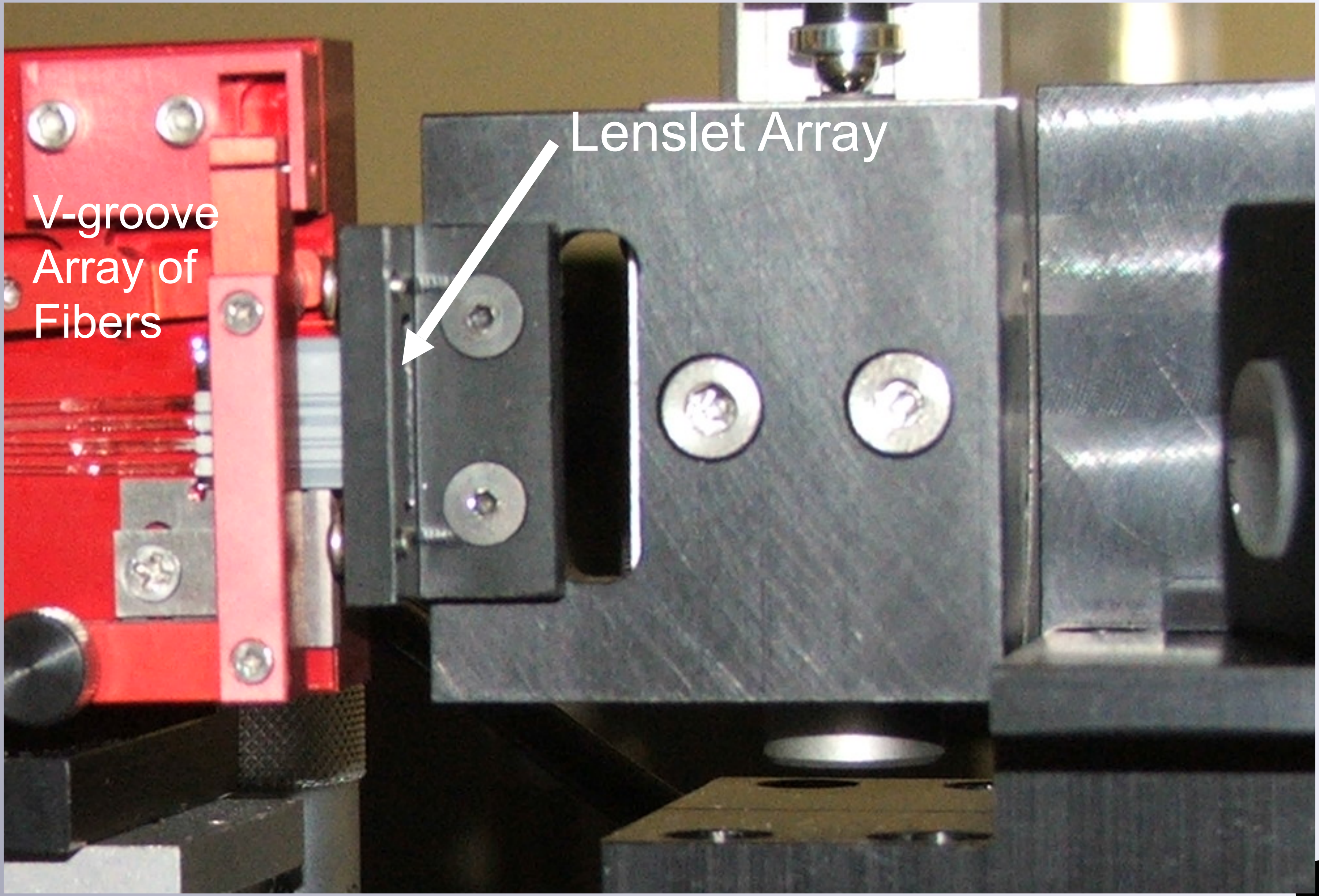


Lab dispersed fringes (two beams only)



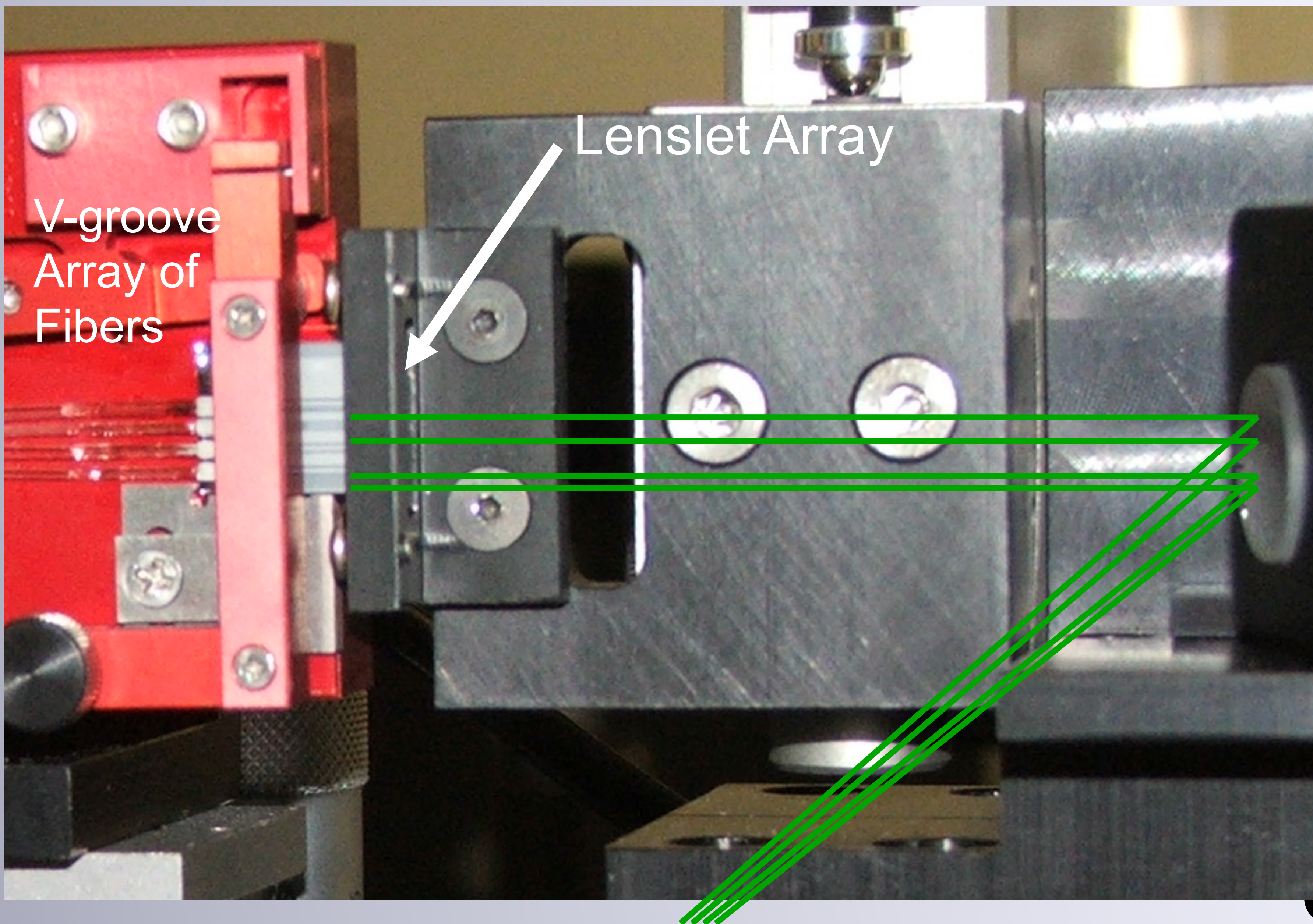
Detail of the VGROOVE

MIRC: an image plane combiner using fibers



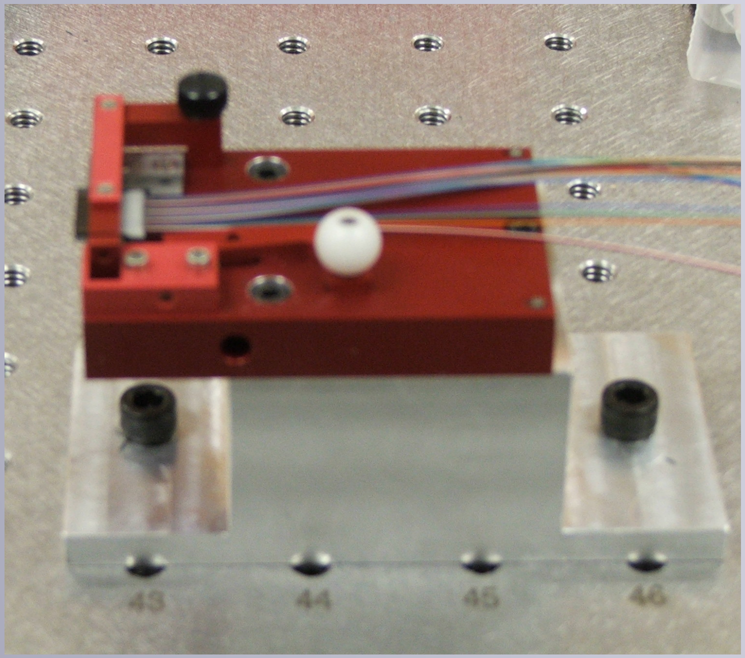
Detail of the VGROOVE

MIRC: an image plane combiner using fibers

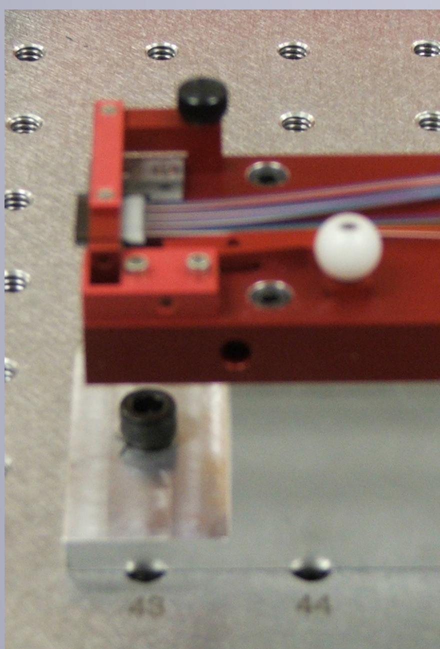


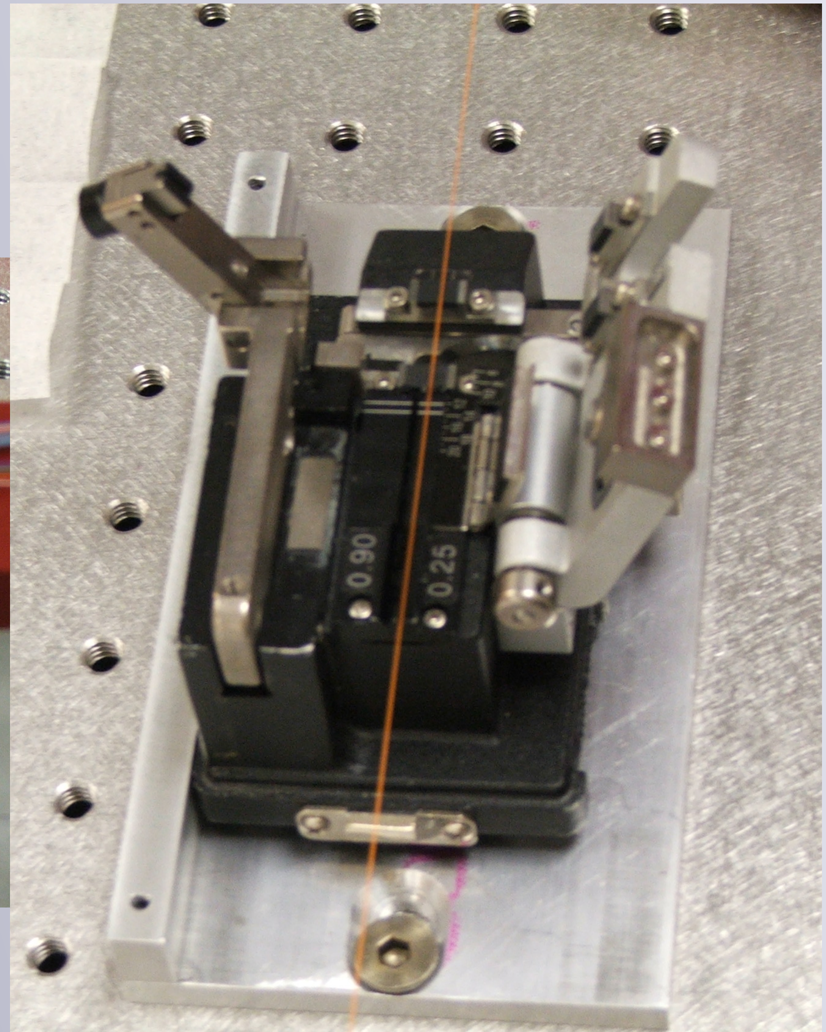
Sophisticated machinery for cutting fibres the right length

Sophisticated machinery for cutting fibres the right length

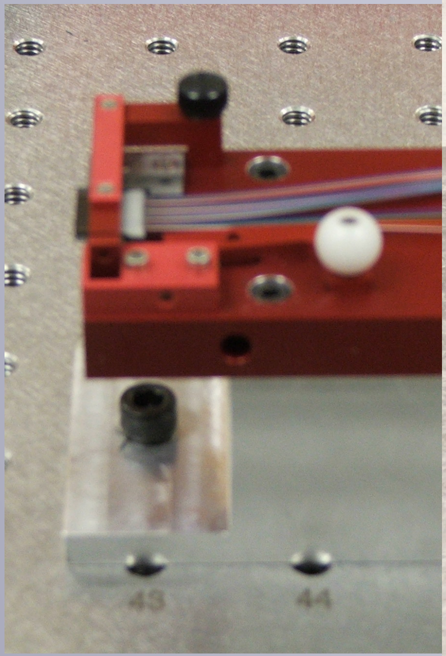


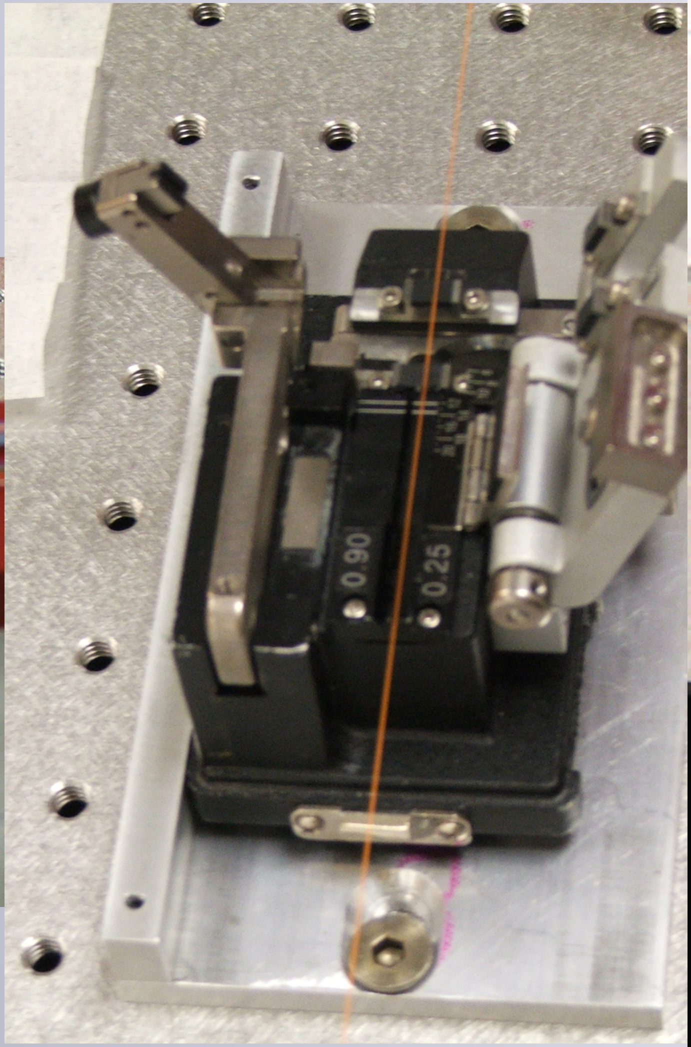
Sophisticated machinery for cutting fibres the right length

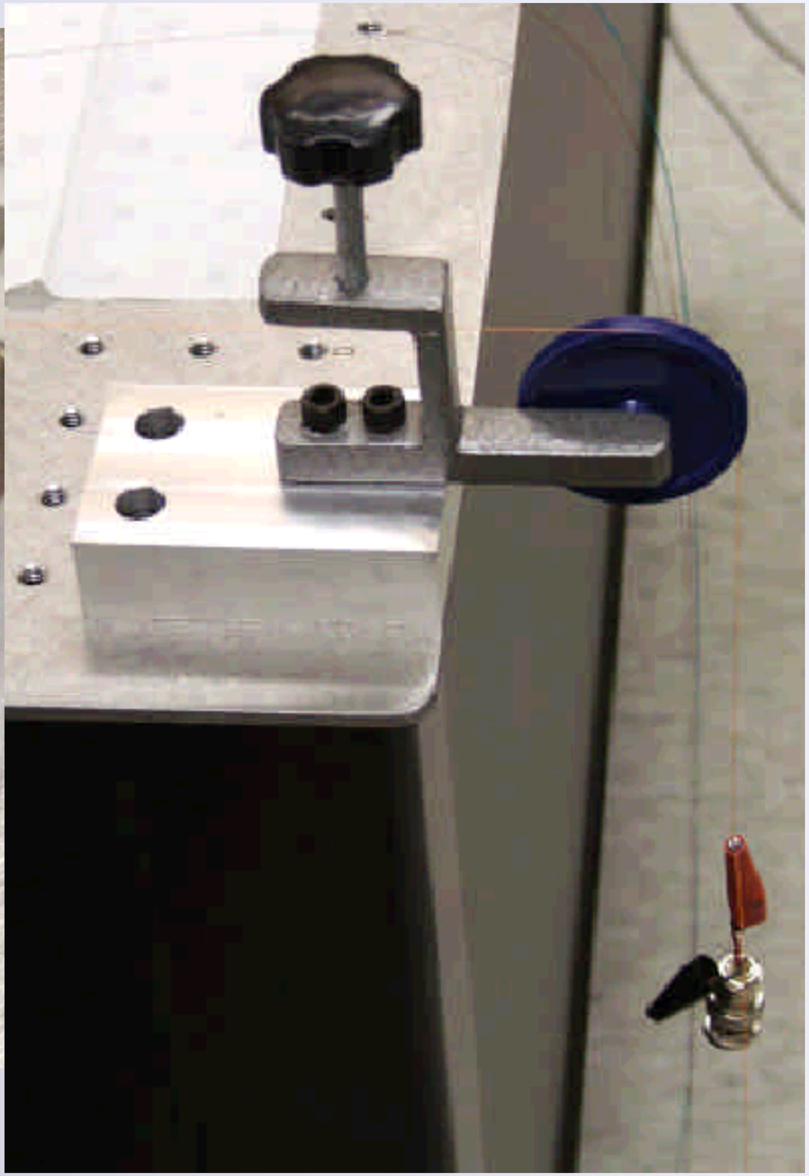




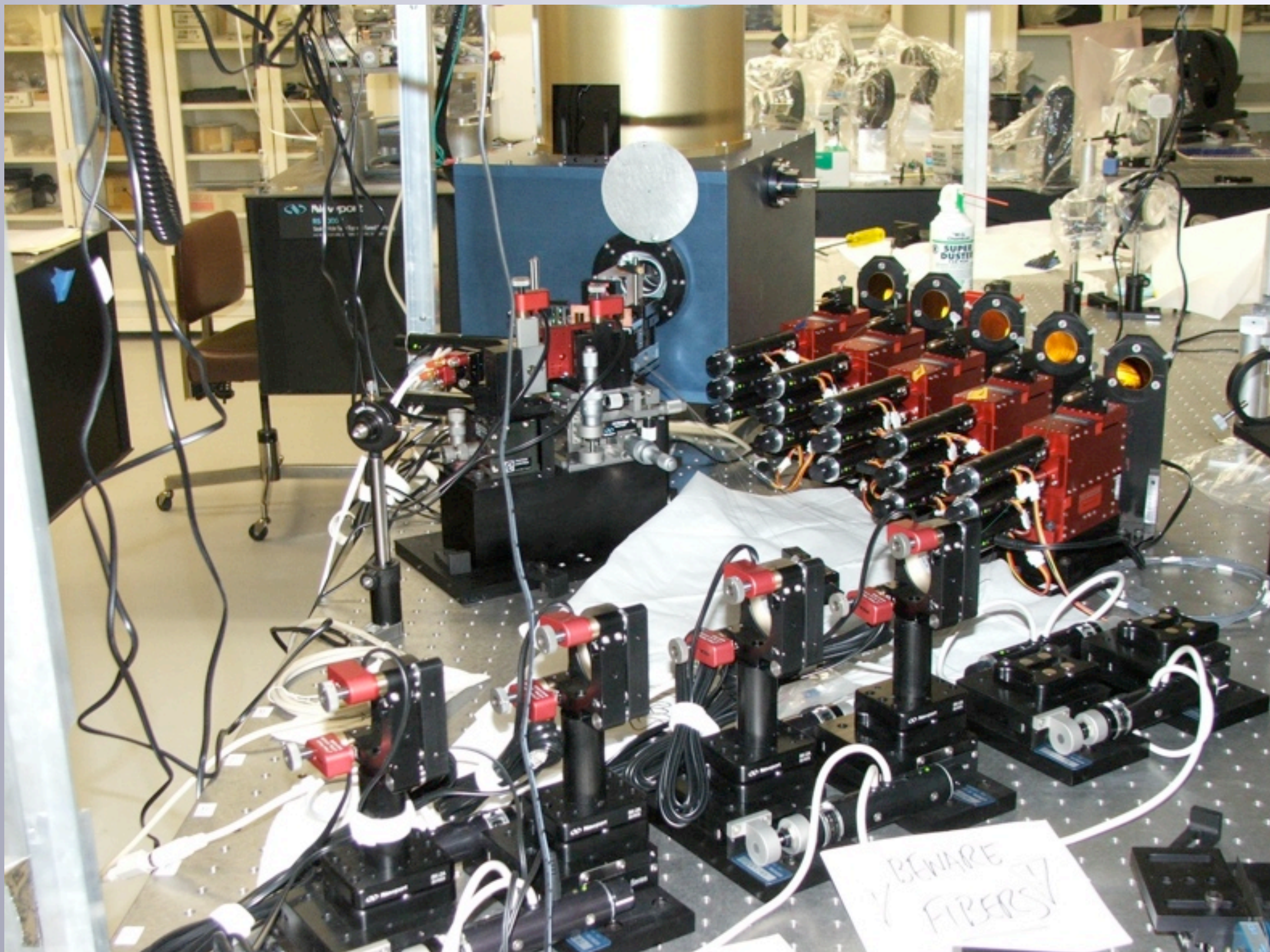
Sophisticated machinery for cutting fibres the right length

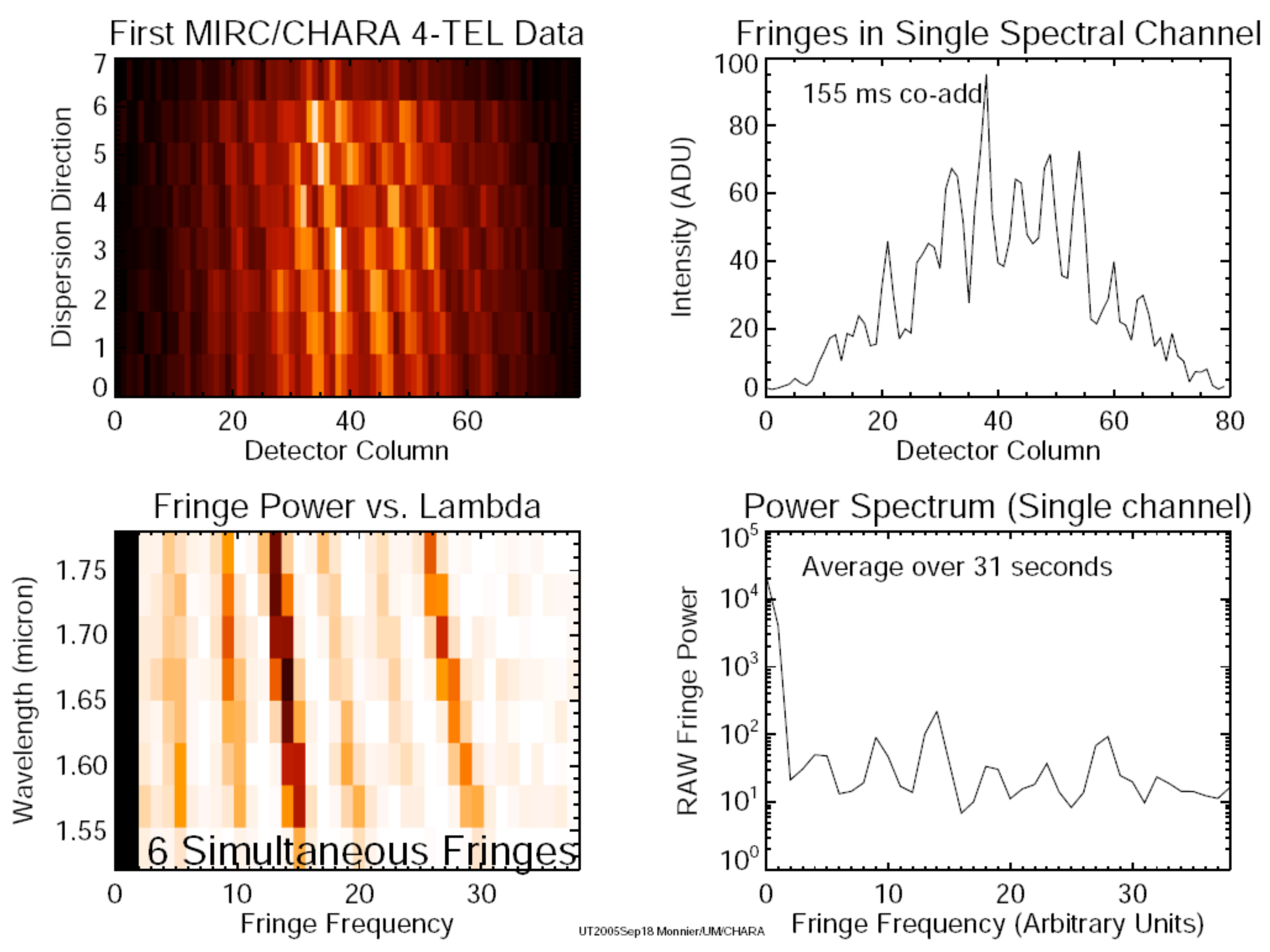






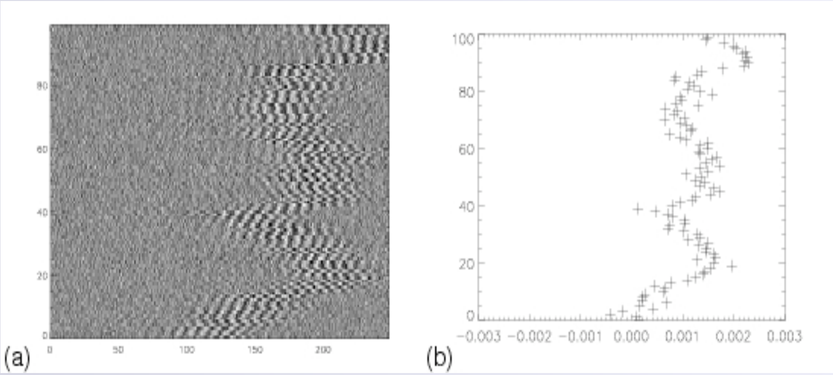
MIRC at CHARA



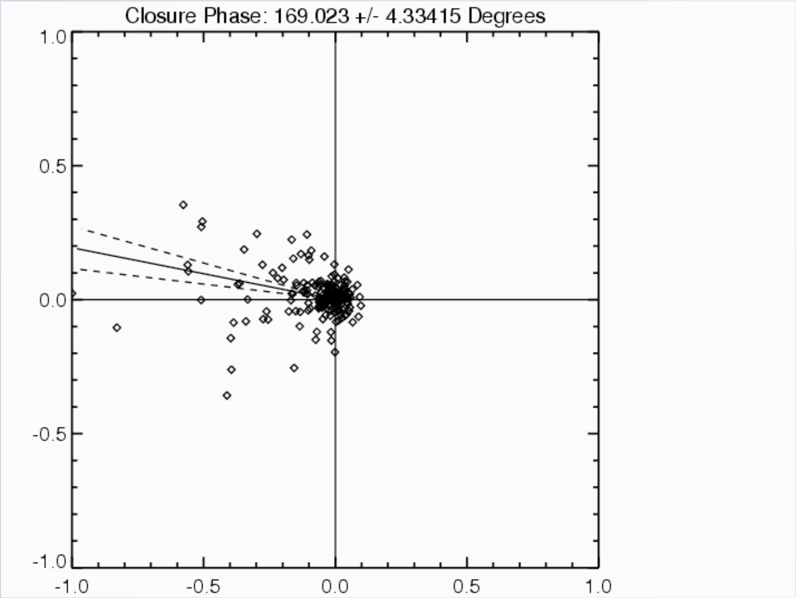

First MIRC/CHARA 4-TEL Data
Dispersion Direction
Detector Column
Fringes in Single Spectral Channel
155 ms co-add
Intensity (ADU)
Detector Column
Fringe Power vs. Lambda
Wavelength (micron)
6 Simultaneous Fringes
Fringe Frequency
Power Spectrum (Single channel)
Average over 31 seconds
RAW Fringe Power
Fringe Frequency (Arbitrary Units)
UT2005Sep18 Monnier/UM/CHARA

Importance of group delay tracking

- If fringes are not tracked they can be lost.

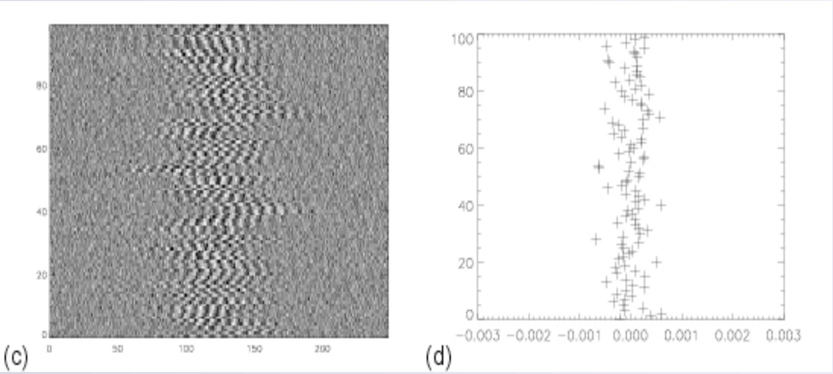


- If fringes are not acquired in the same coherence time the closure phases are affected.

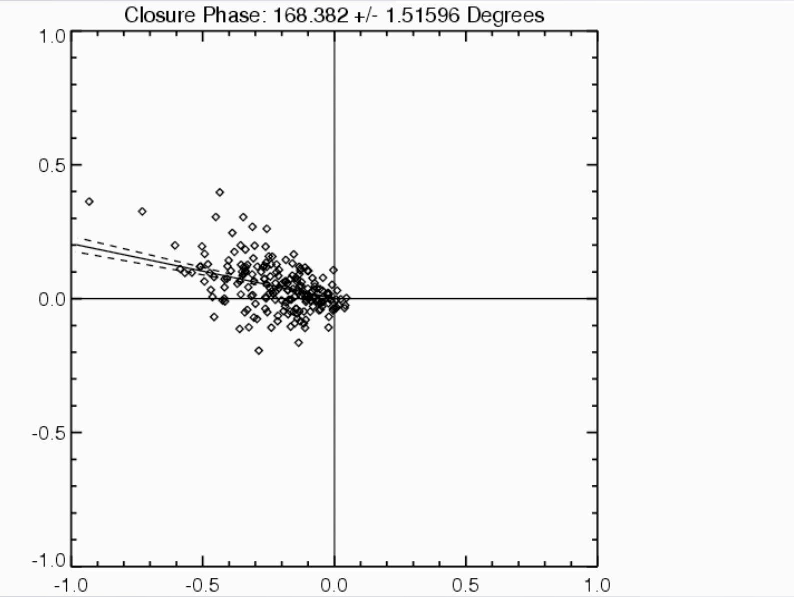


Improvement in closure-phase error

- Fringe tracker on: The fringes are kept in the coherence interval.



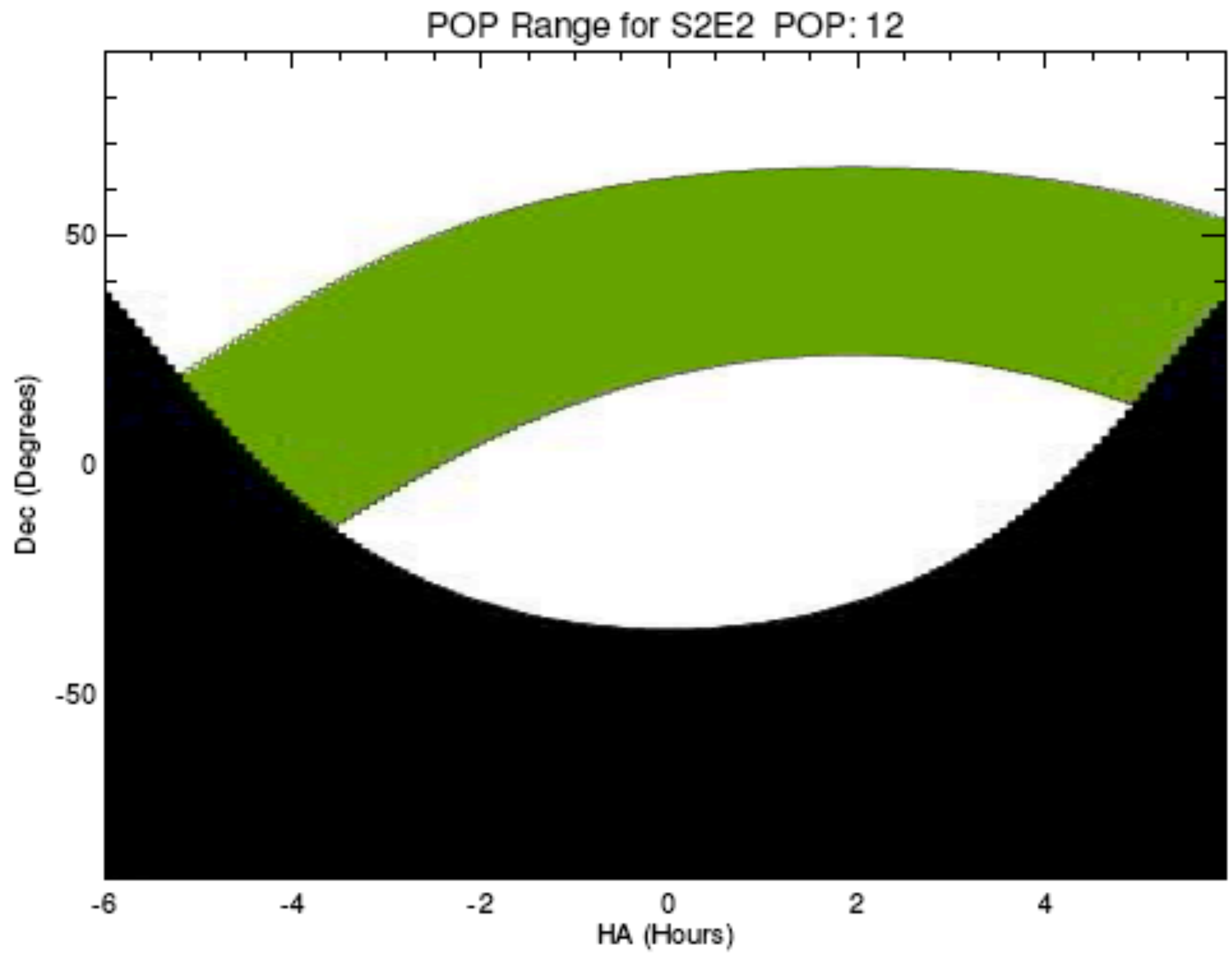
- Closure phase error is three times smaller in average. (Pedretti et al, AO, 2005)



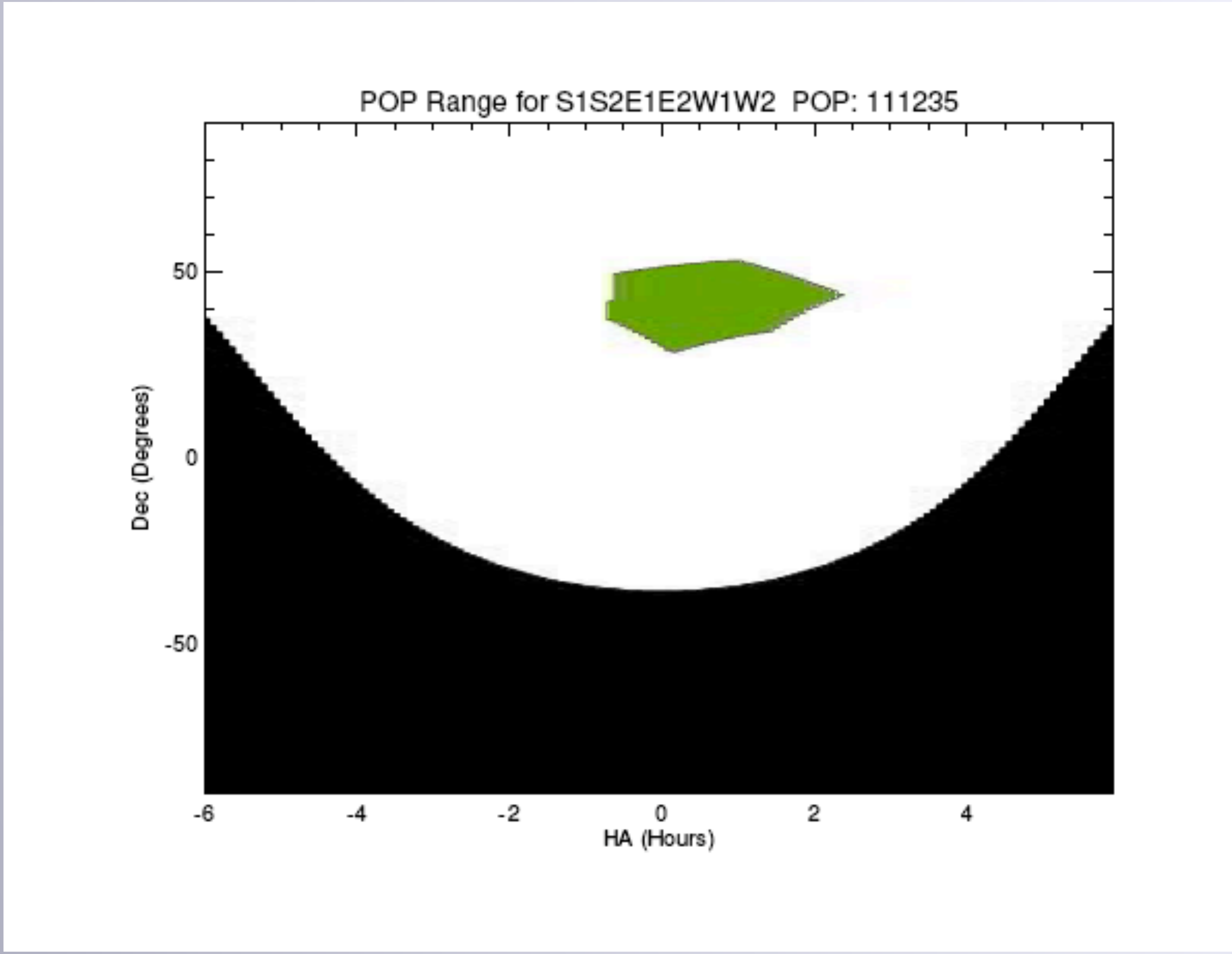
Observing with MIRC is difficult

- MIRC is highly automated (this is not the problem).
- Keeping all delay carts in delay range.
  - MUCH HARDER WITH 4 TELESCOPES!
  - Limited by longest E-W baseline.
- Because only a limited sky coverage is possible then also very hard to find bright calibrators.

Sky coverage example from Ming Zhao



Sky coverage example from Ming Zhao



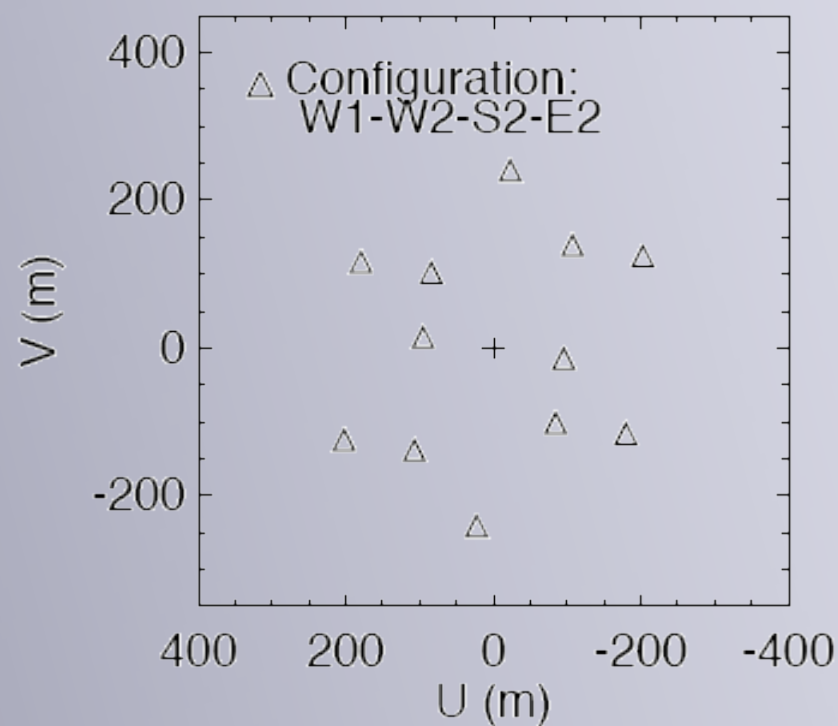
Philosophy of Data Pipeline

- Completely automated -- minimal user input
- Analyze an entire night at once
- Multiple calibration strategies in pipeline
- Input files in fits format (from PICNIC camera)
- Output files as calibrated oifits files

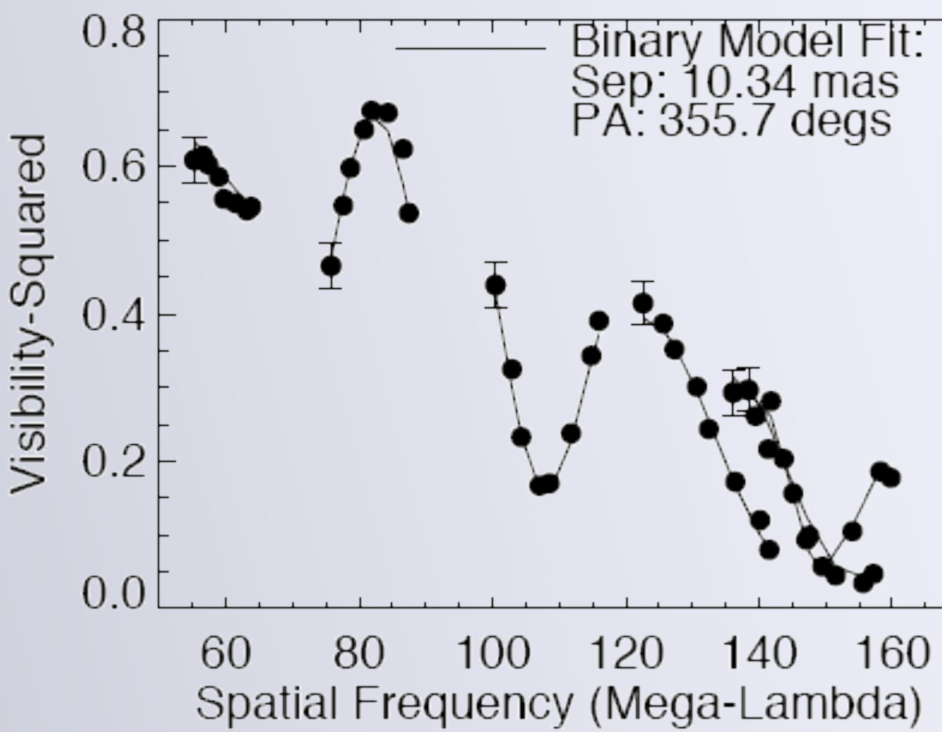
Validation

- Pipeline carefully checked against the binary IOTA Peg
  - Still some visibility calibration ‘issues’
  - Always advise getting 2 or 3 visits on each target due to visibility calibration problems

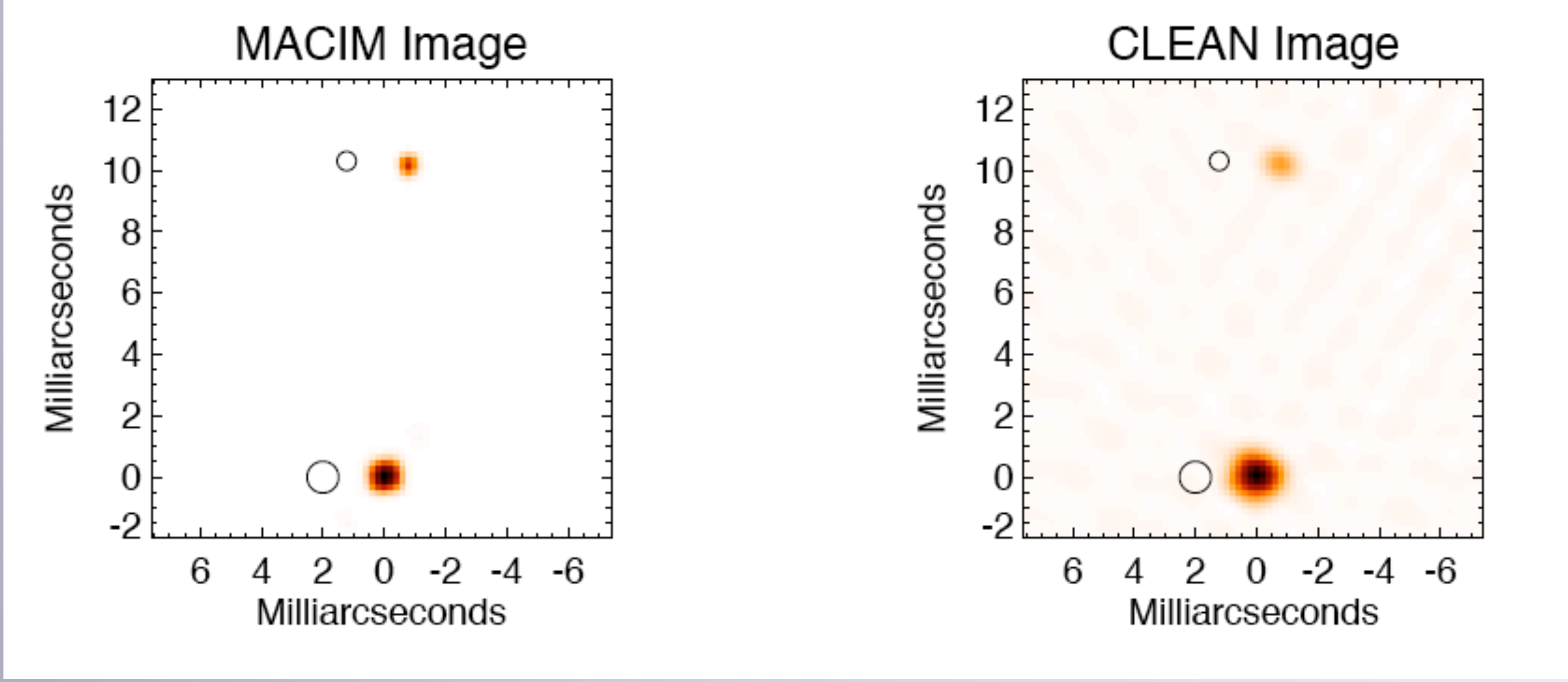
Four-Telescope CHARA-MIRC
Fourier Coverage



Single 5-minute Snapshot
for IOTA PEG



Validation


MACIM Image
CLEAN Image
Milliarcseconds
Milliarcseconds
Milliarcseconds
Milliarcseconds
12
10
8
6
4
2
0
-2
6
4
2
0
-2
-4
-6

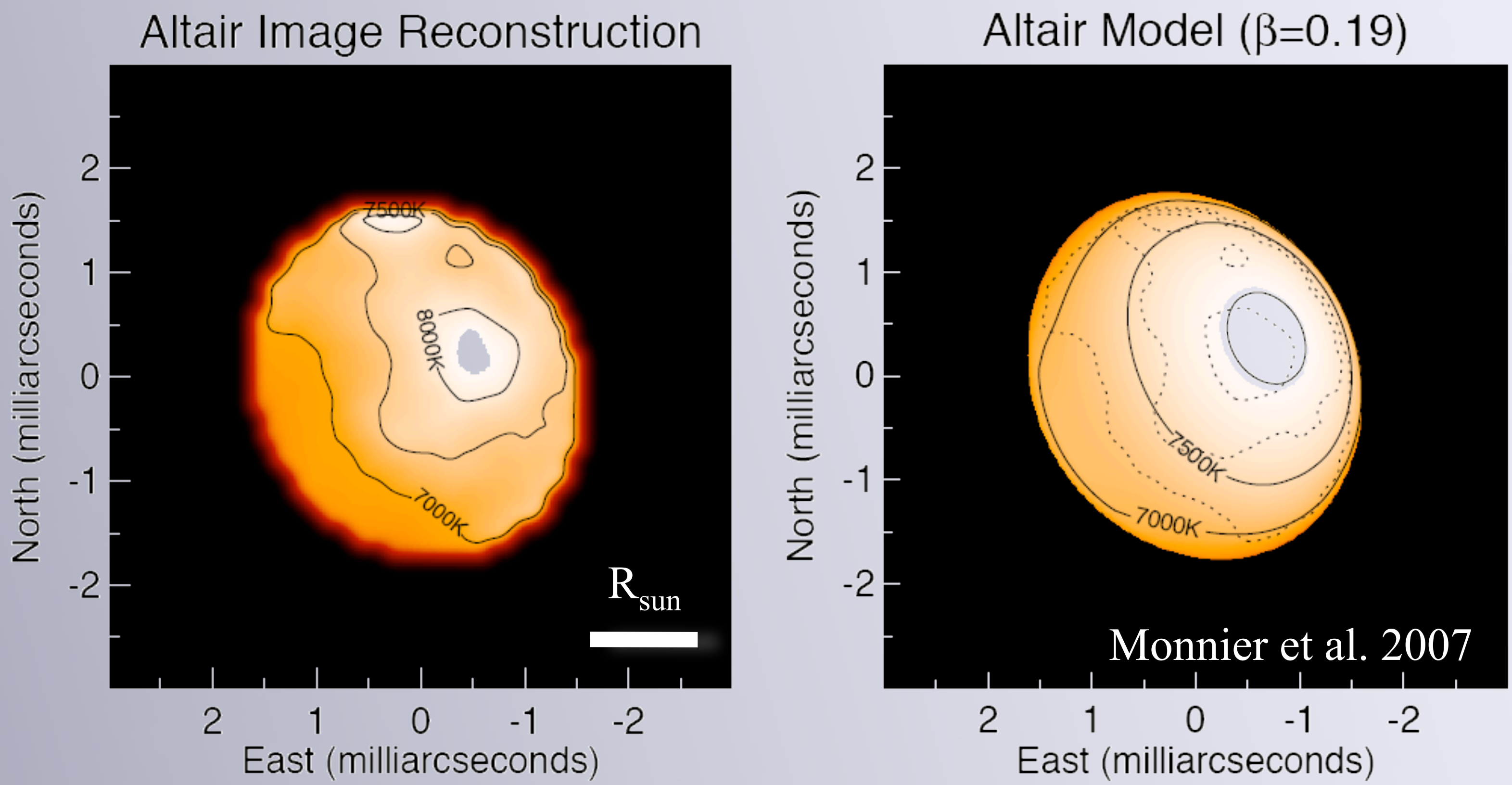
Blind imaging versus model fitting

"*Model-fitting produces the high-precision results while the role of image reconstruction is to guide the model*".

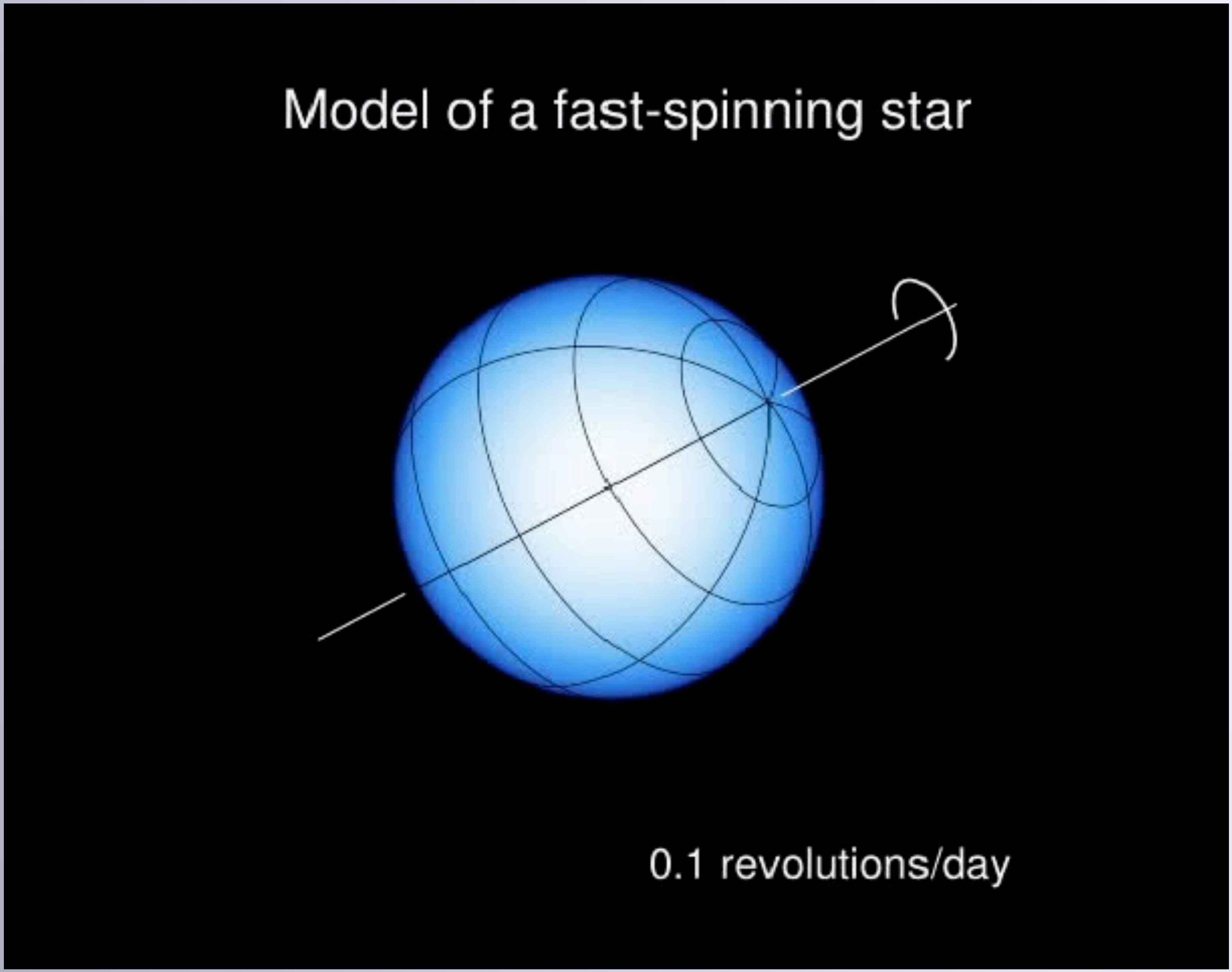
Anonymous referee

First image of a main-sequence star

- Altair (α Aql, V=0.7)
  - Nearby hot star (d=5.1pc, SType A7V, T=7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)



ALTAIR image and model from Ming Zhao



Von Zeipel theory

$$T \propto g^{\beta}$$

$$\beta = 0.25 \ radiative$$
$$\beta = 0.08 \ convective$$

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- Our model-independent image bears striking resemblance to model prediction

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- Distortion and gravity darkening robustly confirmed

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- Temperature profiles more consistent with β=0.19, compared to β=0.25 from theory

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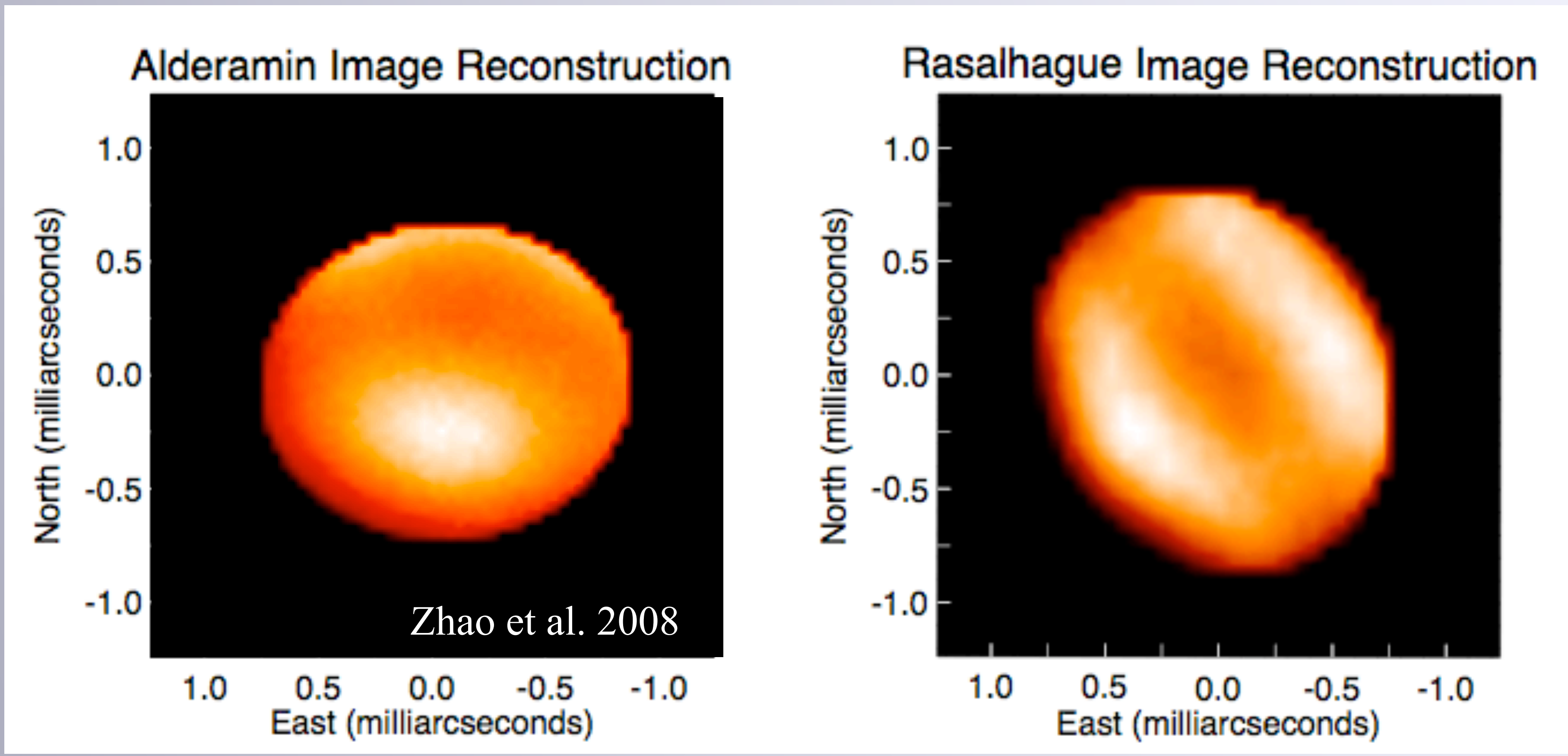
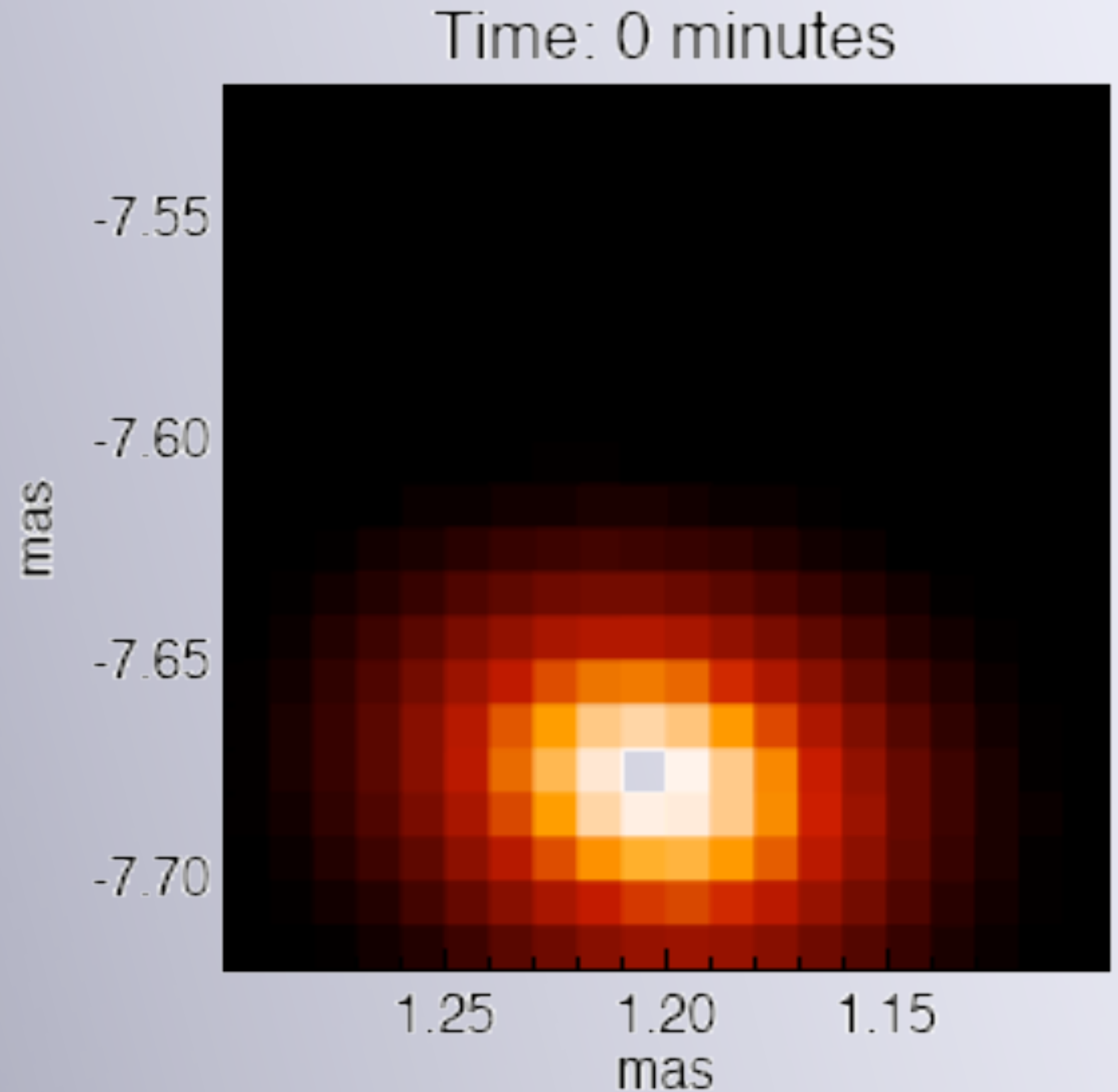
$$\beta = 0.08 \; convective$$

- Our model-independent image bears striking resemblance to model prediction
- Distortion and gravity darkening robustly confirmed
- Temperature profiles more consistent with β=0.19, compared to β=0.25 from theory
- Equator is cooler than expected from von Zeipel law
  - Differential Rotation ?

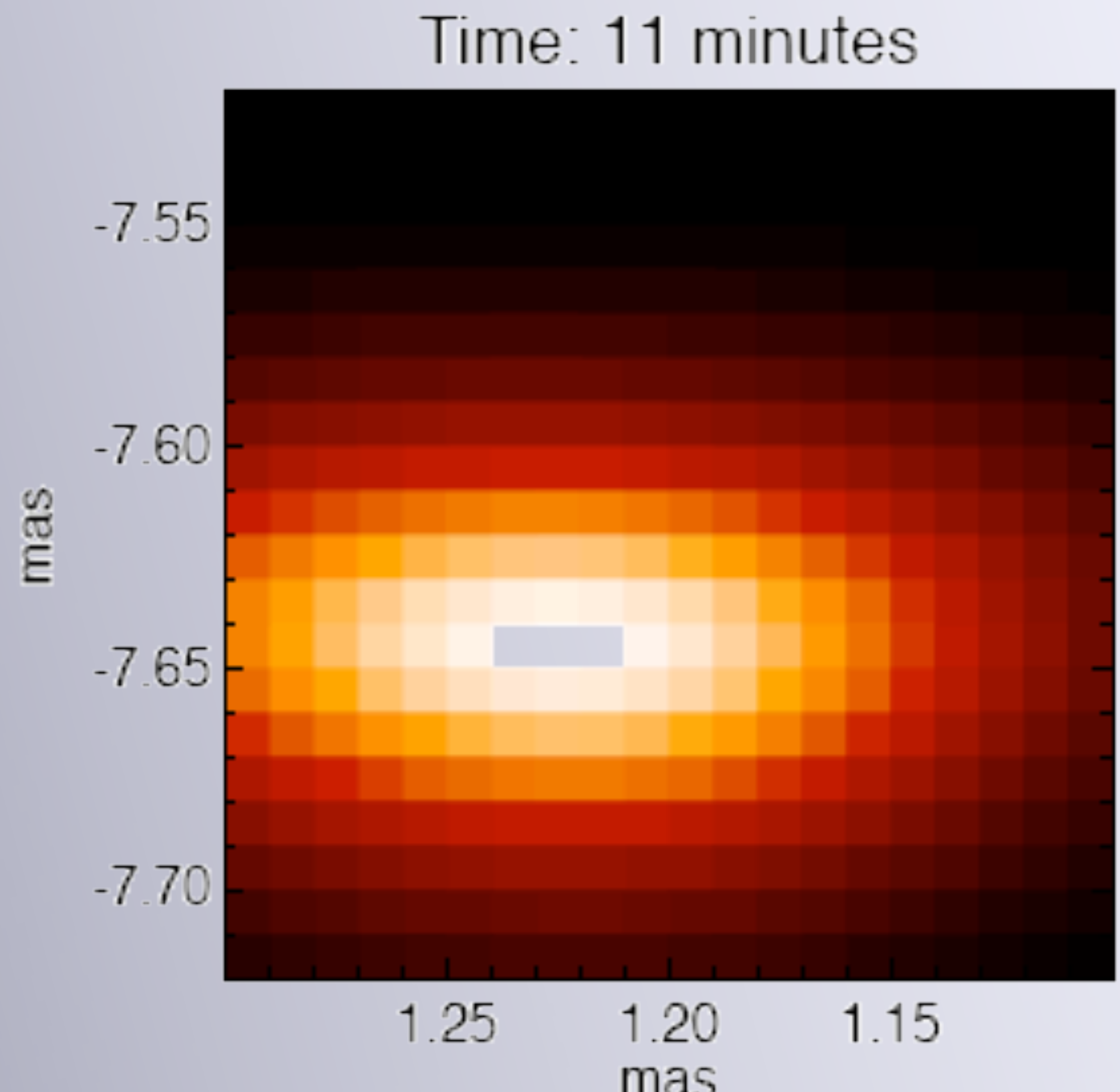
More images of rapid rotator



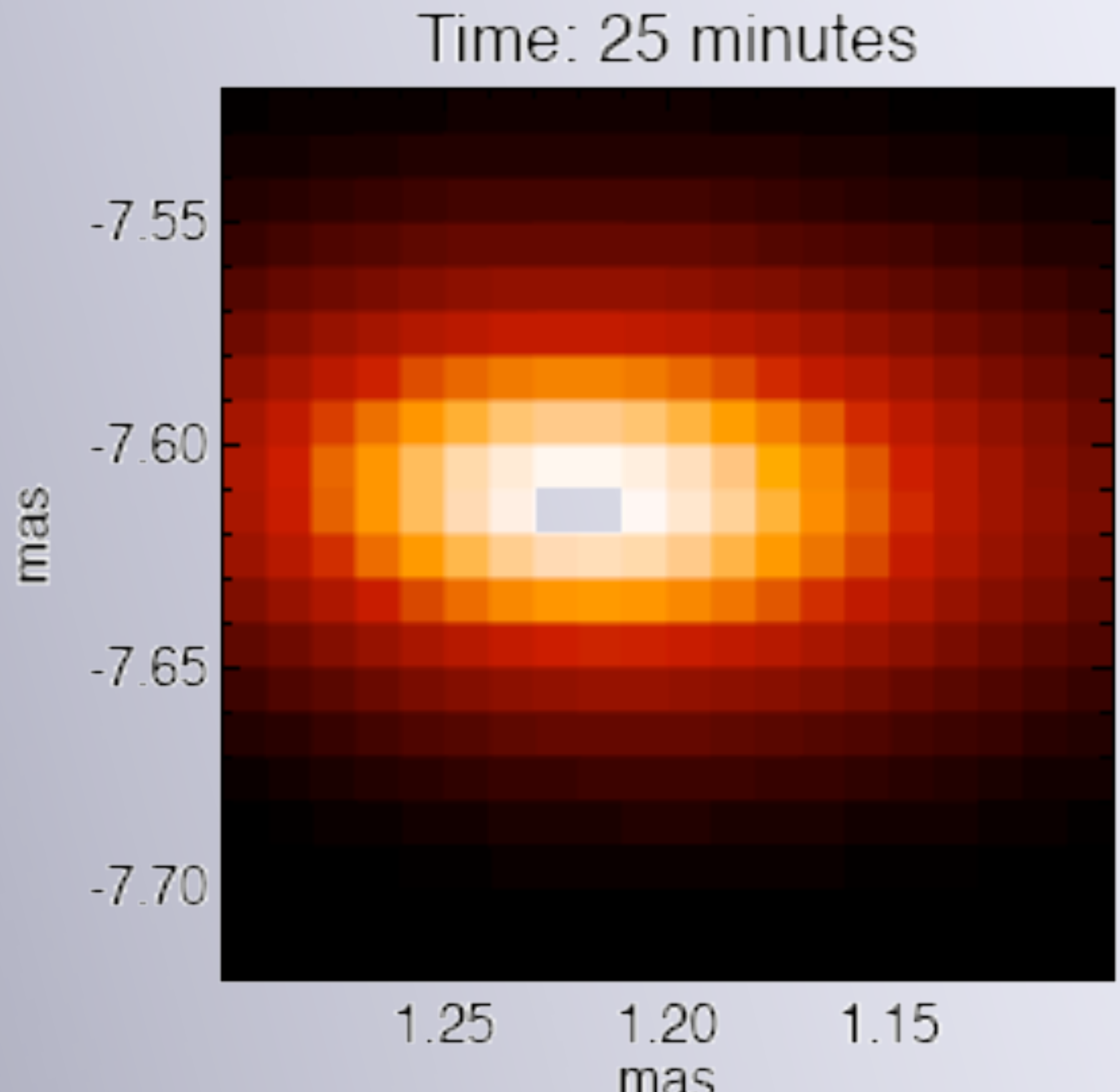
ι Peg motion through orbital phase



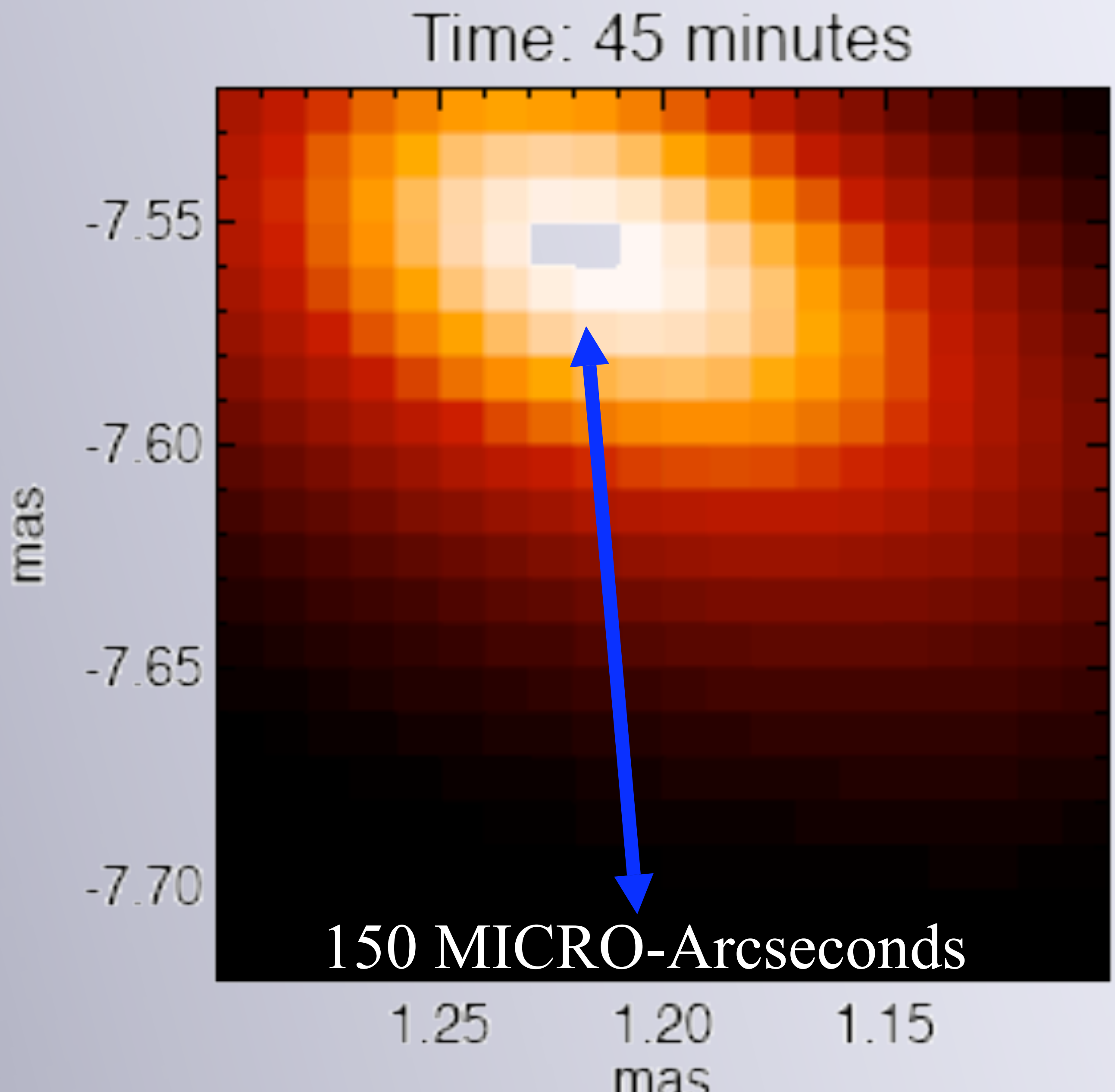
ι Peg motion through orbital phase



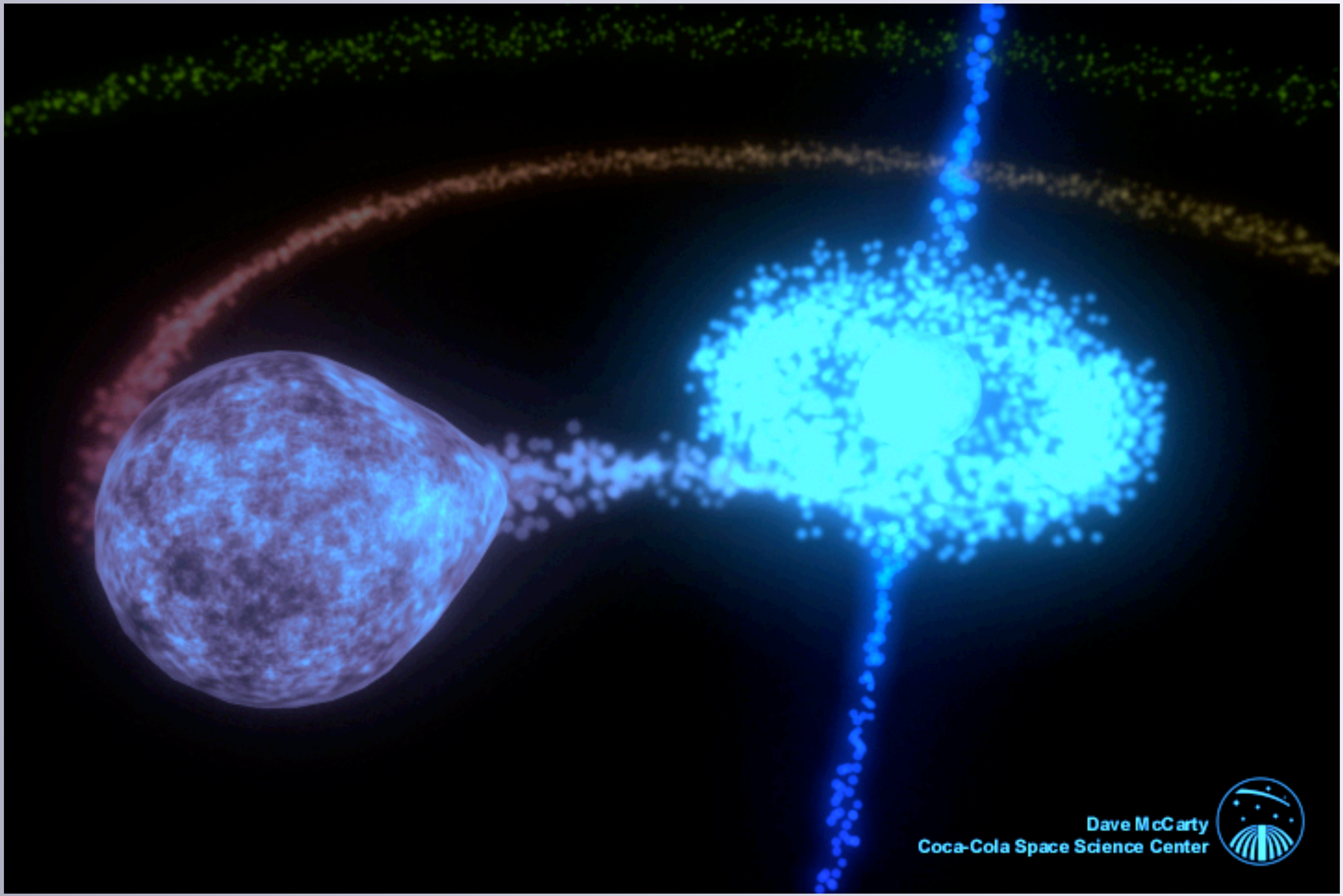
ι Peg motion through orbital phase



ι Peg motion through orbital phase



The "β Lyrae" system:

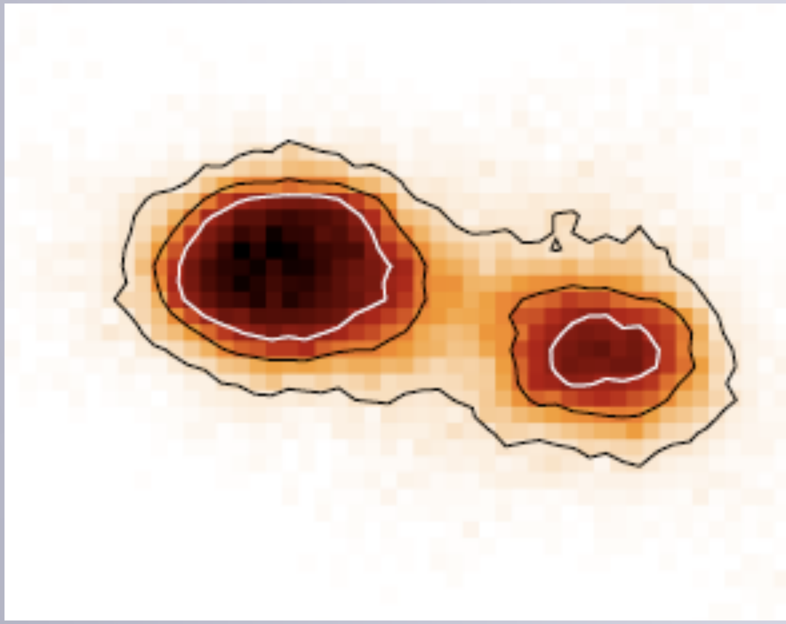


The “β Lyrae” system:

- β Lyrae: interacting and eclipsing binary (period 12.9 days)
- B6-8 II donor + B gainer in a thick disk
- V = 3.52, H = 3.35; distance ~300pc

First image of the 12.9-day eclipsing binary β Lyrae

CHARA-MIRC Image

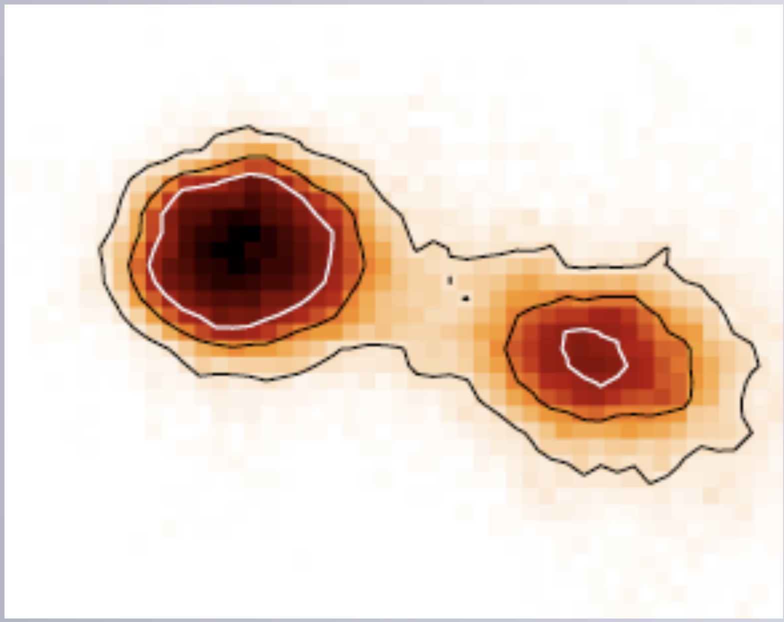


Model

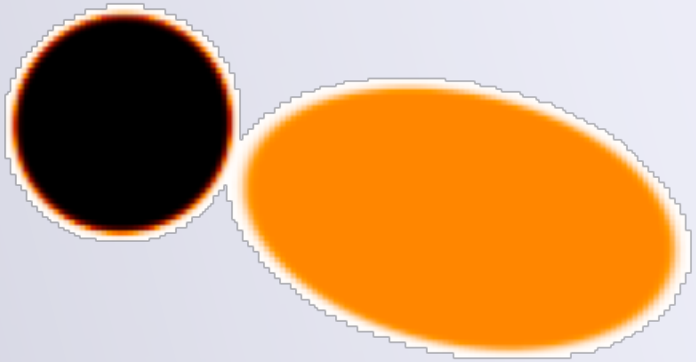
Phase = 0.132

First image of the 12.9-day eclipsing binary β Lyrae

CHARA-MIRC Image



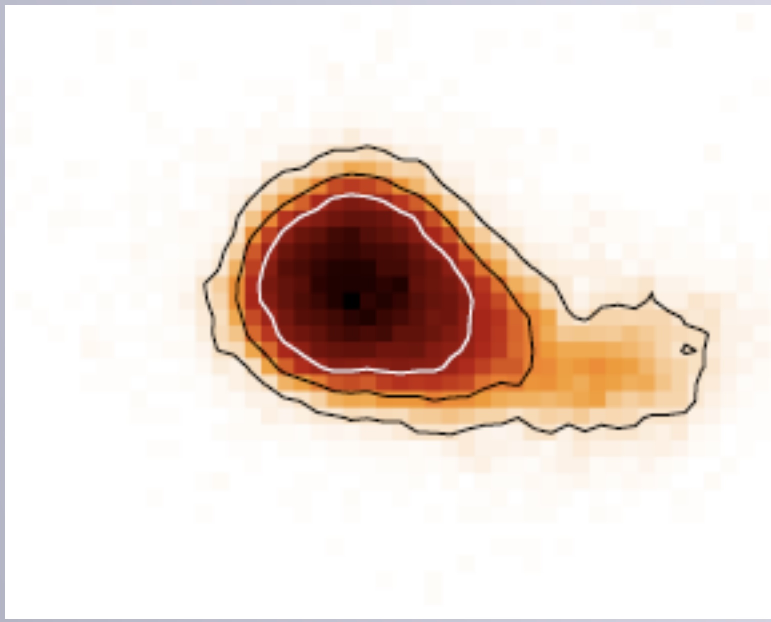
Model



Phase = 0.210

First image of the 12.9-day eclipsing binary β Lyrae

CHARA-MIRC Image

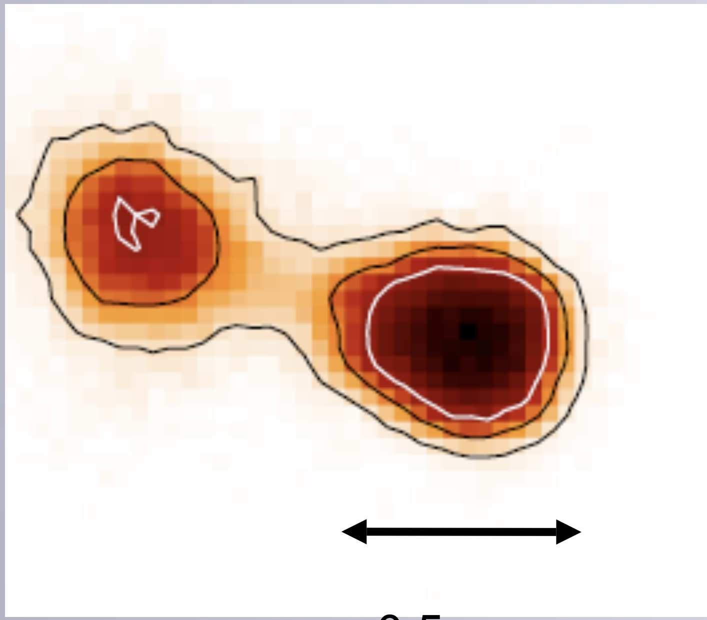


Model

Phase = 0.438

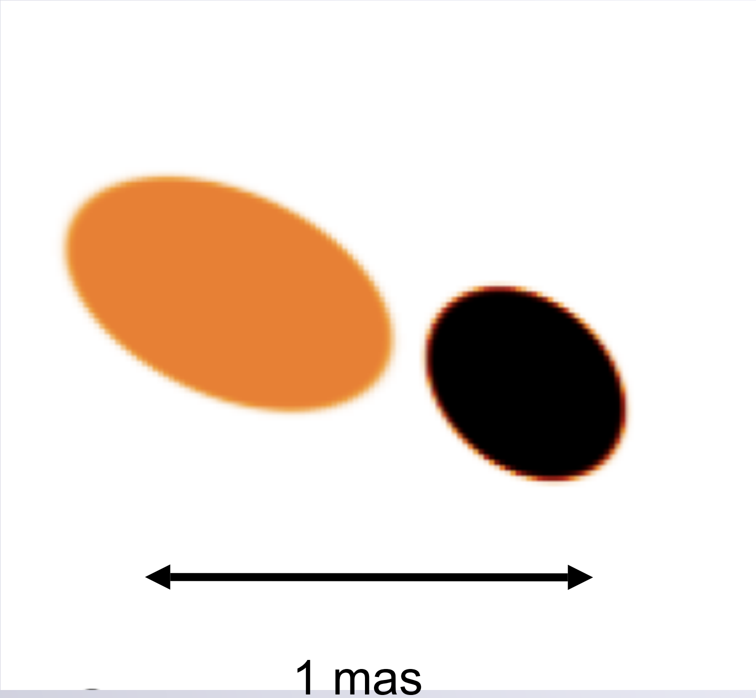
First image of the 12.9-day eclipsing binary β Lyrae

CHARA-MIRC Image



0.5 mas

Model

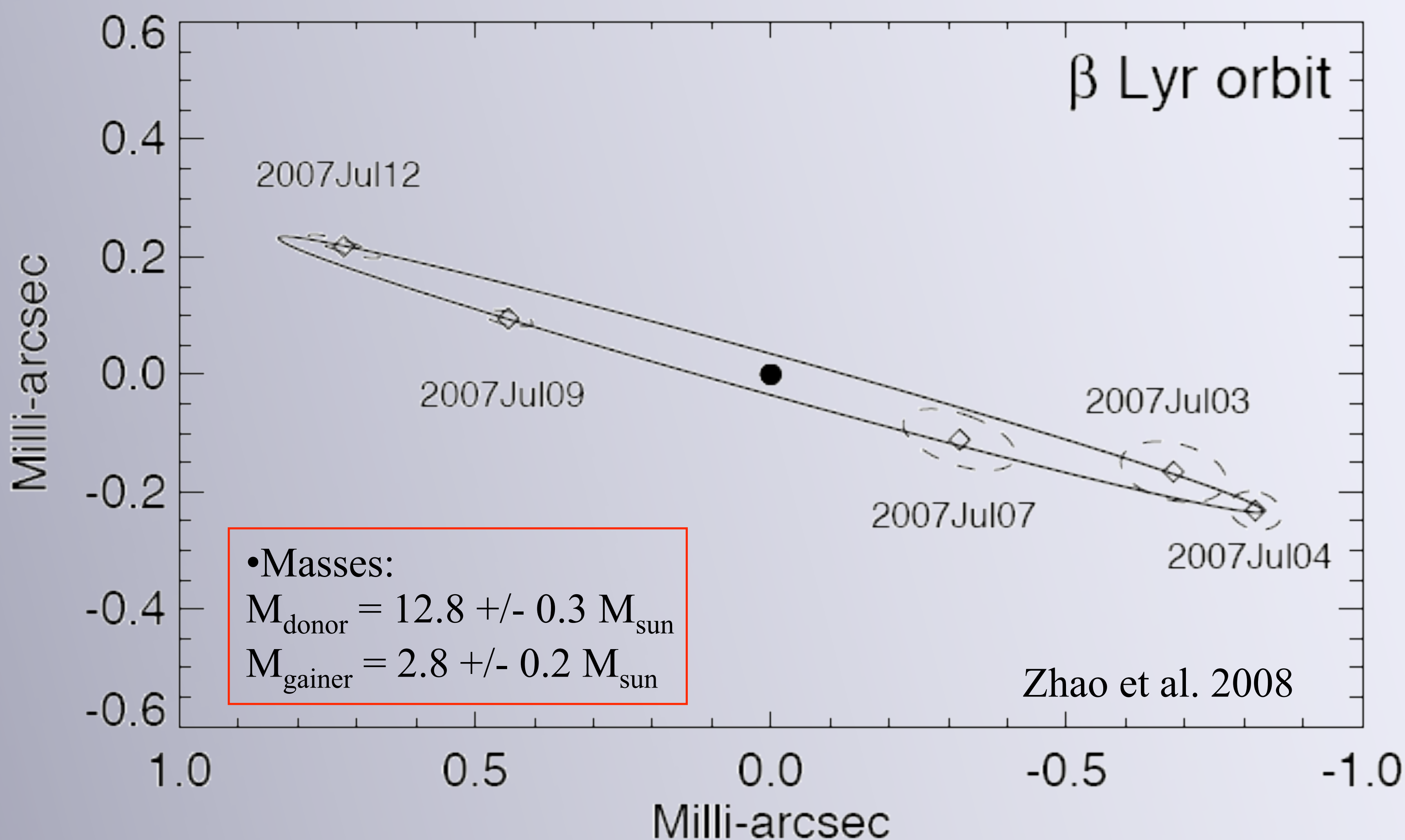


1 mas

Phase = 0.828

Zhao et al. 2008

First astrometric orbit of

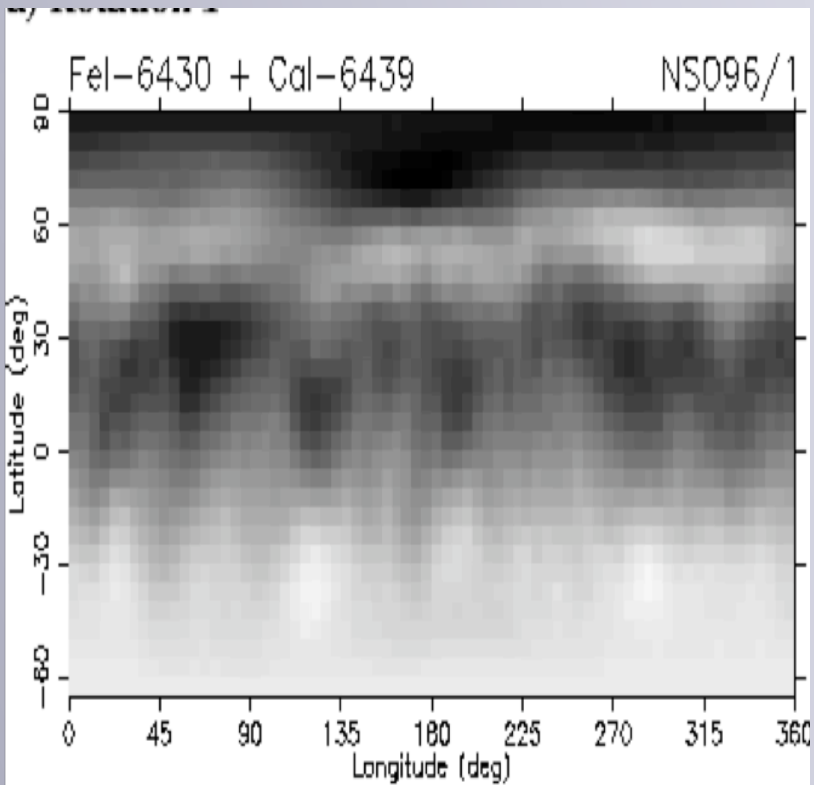


•Masses:

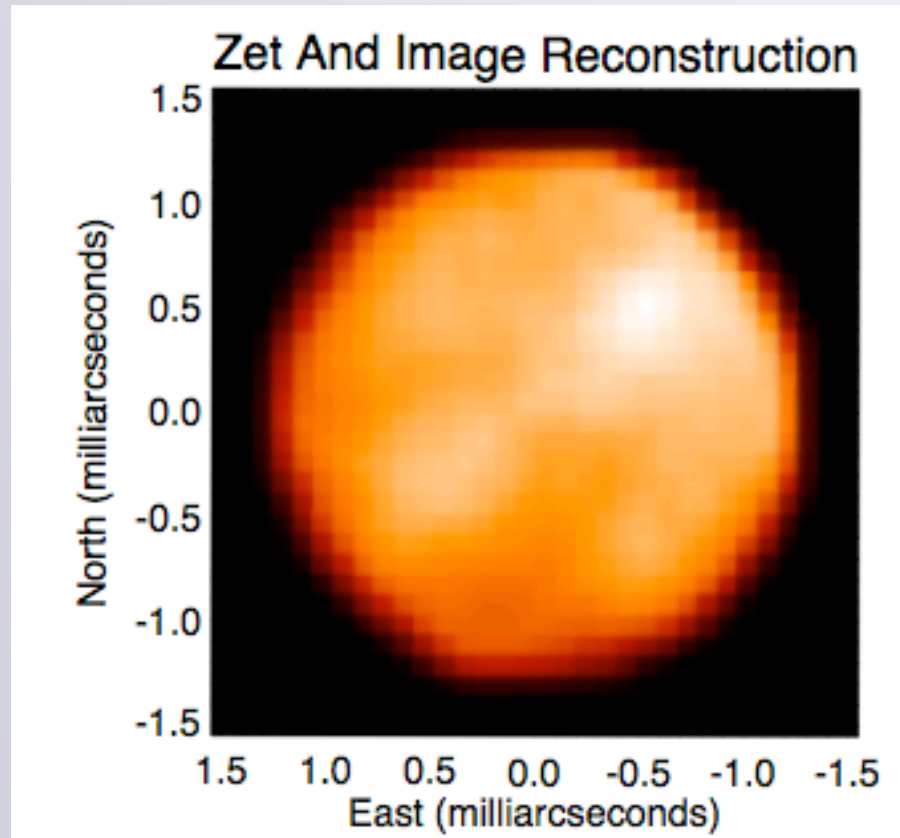
M_{donor} = 12.8 +/- 0.3 M_{sun}

M_{gainer} = 2.8 +/- 0.2 M_{sun}

Spots on Stars: Interferometry + Doppler imaging



Doppler Imaging
(Kovari et al. 2007)



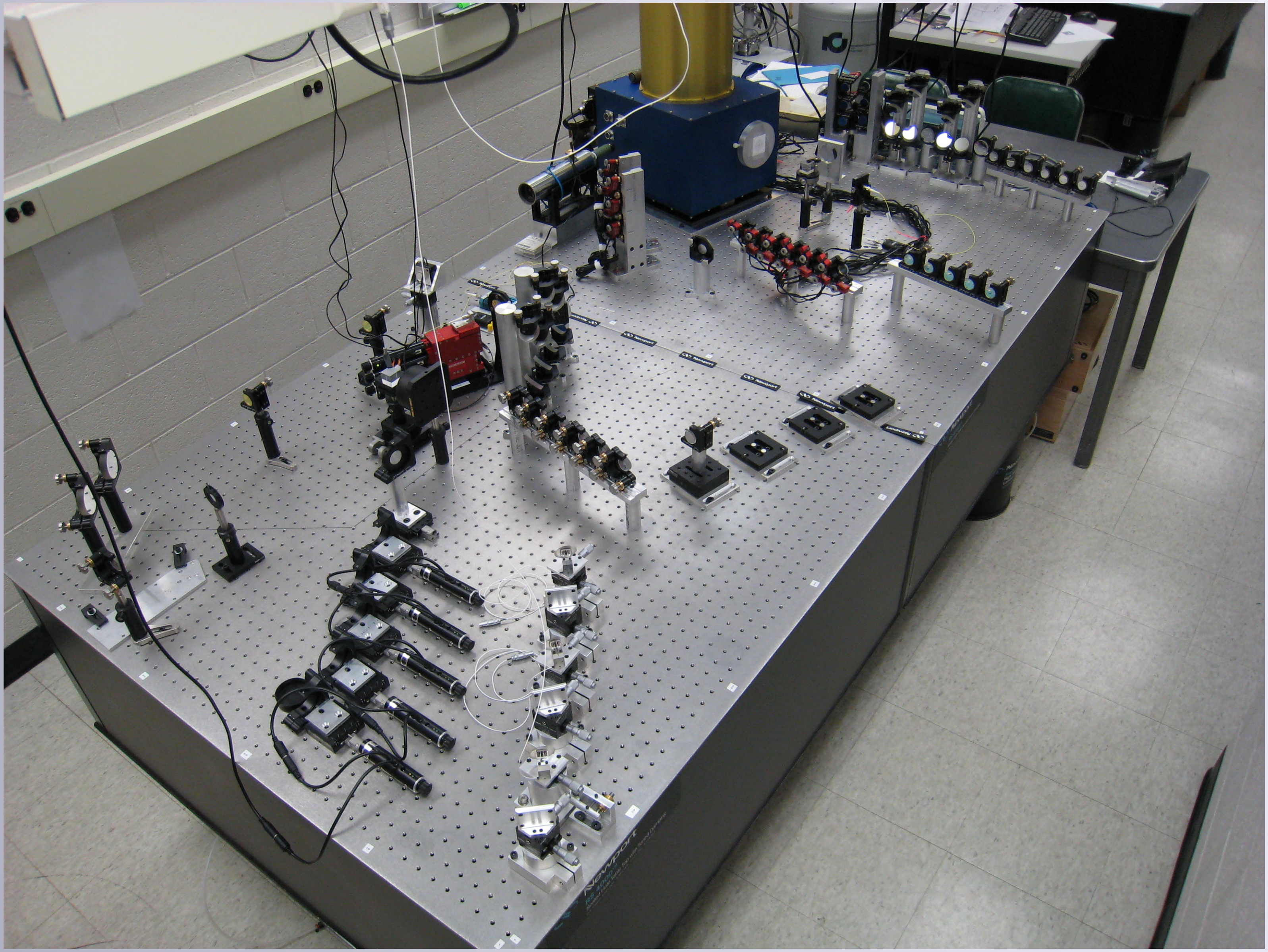
CHARA-MIRC image

Review of Major Results

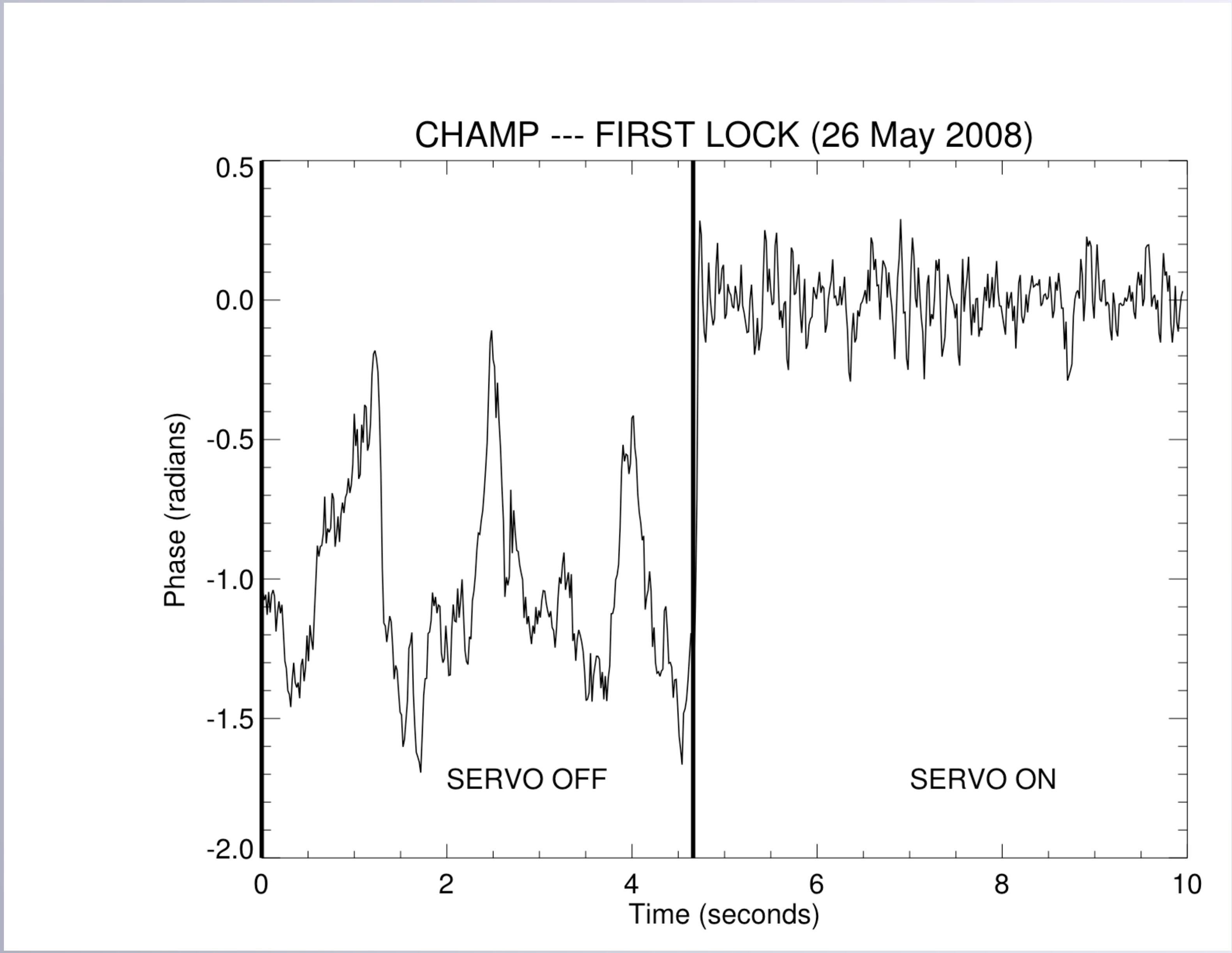
- First images of main sequence stars besides Sun
  - Temperatures not consistent with von Zeipel law, suggesting differential rotation
- Interacting binaries now accessible
  - Physics of accretion disks in close binaries
- Studies of magnetic fields and star spots underway
  - Combining interferometry + doppler imaging

Fringe tracker soon at CHARA

- Remove “atmospheric piston” and “freezes fringes”
- Longer coherence time and integration time
- Expected improvement in magnitude limit of ~3 - 4 magnitudes



CHAMP first fringe lock !!



If you do not get fringes in your run buy them in Edinburgh!!