Imaging Stars with the CHARA Interferometer

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with major contributions from Ming Zhao, Ettore Pedretti, Nathalie Thureau, Fabien Baron, Xiao Che, Brian Kloppenborg, and the MIRC and CHARA group

Stars are far away

- Galaxies crowd the universe

  $D_{galaxies} = \sim 40\ R_{galaxy}$

- Stars take up hardly any space

  $D_{stars} = \sim 40\ \text{million}\ R_{star}$

Comparison: Atomic Nucleii

$D_{atom} = \sim 100000\ R_{nucleus}$

Angle on the sky

→ 1 degree

→ 0.000001 deg

5 milliarcseconds

→ *Few arcseconds*

Diffraction-*limited*

REMEMBER:
NEAREST STARS
~5 MILLICARSECONDS

$$\Delta\theta \approx \frac{\lambda}{D}$$

Wavelength of light

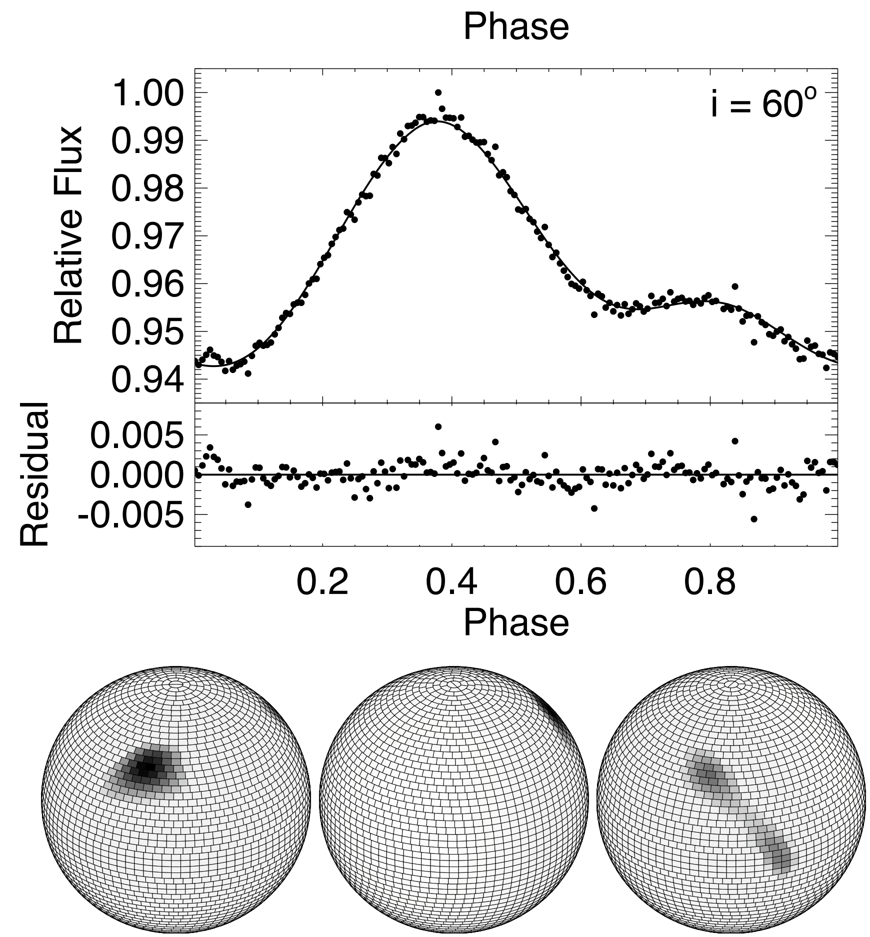
Diameter of telescope

Observatory	Wavelength	Diameter	Angular Resolution
Hubble Space Telescope	500 nm	2.4m	43 milliarcsecond (mas)
Keck Observatory	1.65 μm	10m	34 mas
E-ELT	1.65 μm	39m	9 mas

Conclusion: No single optical/IR telescope can image the surfaces of main sequence stars (<5 mas)

Light curve inversion

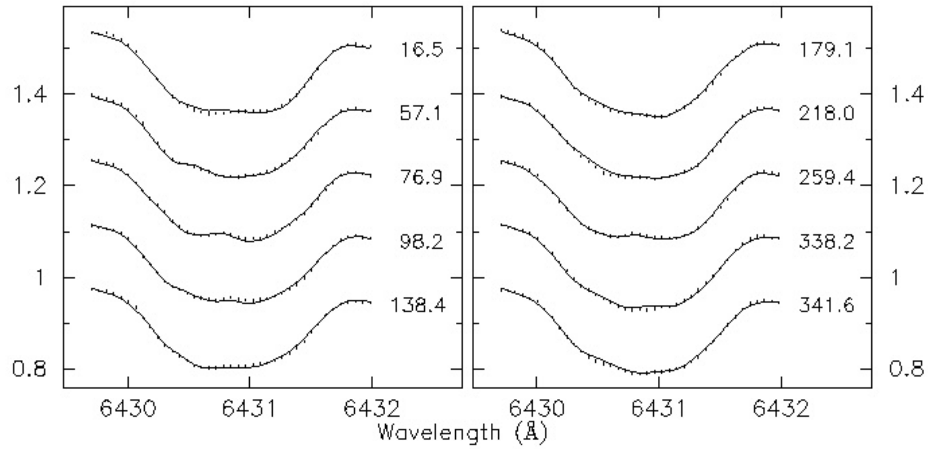
- Hot and cool spots rotate on surface of star, causing photometric variability
- Strengths:
  - Widely Applicable
  - Spot Longitudes constrained
  - KEPLER
- Weaknesses:
  - Generally requires very high precision photometry
  - Spot latitude constraints weak
  - Stellar inclination weakly constrained
  - Only sees longitude variation, ie. Cannot “see” polar spots, gravity darkening



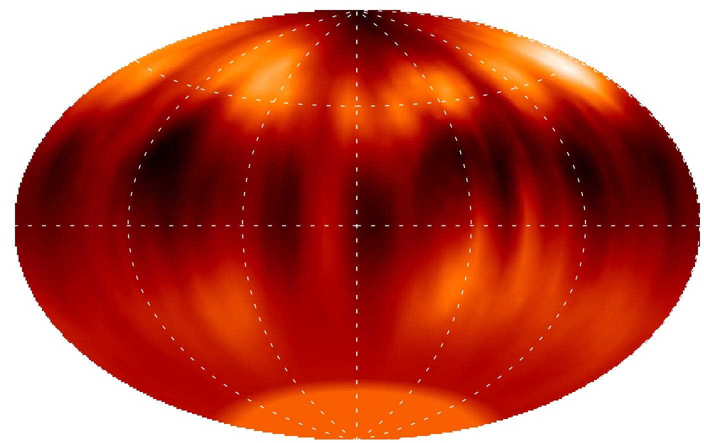
Reottenbacher et al. 2013

Doppler imaging

- Hot and cool spots rotate on surface of star, causing distortion in the line profiles
- Strengths:
  - Widely Applicable
  - Spot Longitudes and latitudes constrained
- Weaknesses:
  - Requires high cadence, high SNR, high spectra R
  - Requires “rapid” rotation, vsini>15km/s
  - Serious modelling uncertainties for the non-time-changing component, e.g., polar spots, gravity darkening



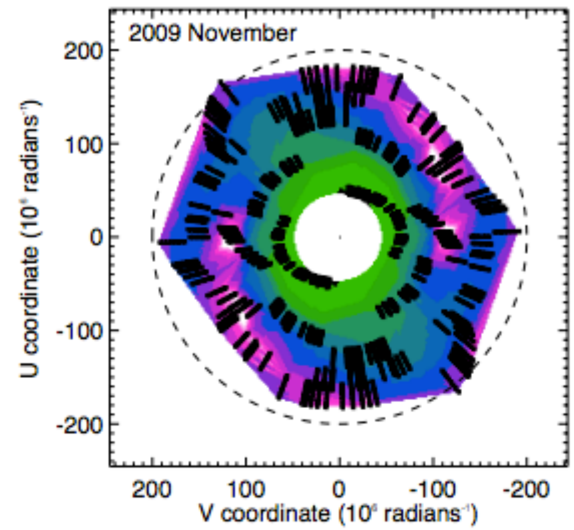
zeta And / UVES 2008

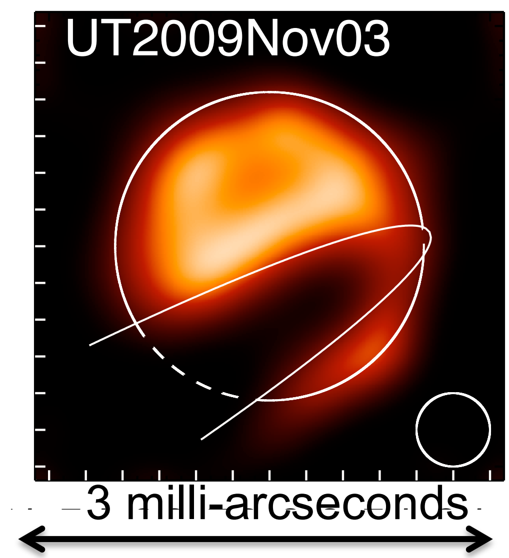


Korhonen et al. 2010

Interferometric imaging

- Hot and cool spots can be imaged directly and seen to rotate
- Strengths:
  – Can determine inclination and orientation of sky
  – No bias against measuring polar spots or gravity darkening
  – No fundamental limit to technique, with future facilities
- Weaknesses:
  – Requires “large” enough stars
  – Lower # of pixels across star
  – Difficult to get uv coverage





Kloppenborg et al. 2010

Angular Resolution of Interferometer

REMEMBER:
NEAREST STARS
~5 MILLICARSECONDS

$$\Delta\theta \approx \frac{\lambda}{B}$$

Wavelength of light

Baseline of Interferometer

Observatory	Wavelength	Baseline	Angular Resolution
ALMA	0.3 mm	12km	5 mas
NPOI	700 nm	>60 m	<2.4 mas
VLTI	1.65 mm	140m	2.4 mas
CHARA	700nm 1.65 mm	330m	0.4 mas 1.0 mas

Conclusion: We have the resolution to image nearby stars!

How does an interferometer work again?

$$< \vec{E}_1 \cdot \vec{E}_2 > \propto \cos 2\pi \frac{B_{\rm proj}}{\lambda} \delta$$

Response for source at position δ

Response for arbitrary brightness distribution I_λ

$$\tilde{\mathcal{V}} = \int I_\lambda(\delta) \cos(2\pi \frac{B_{\rm proj}}{\lambda} \delta) d\delta$$

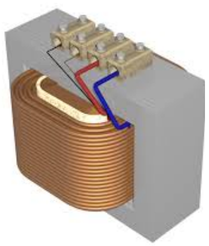
$$\mathrm{FT}(I(\delta)) = \tilde{\mathcal{V}}(\frac{B_{\rm proj}}{\lambda}) = \int I_\lambda(\delta) \cos(2\pi \frac{B_{\rm proj}}{\lambda} \delta) d\delta$$

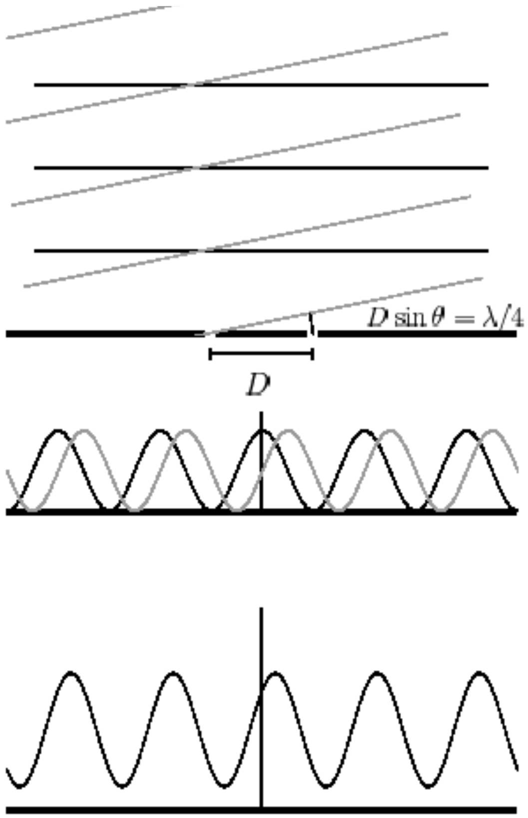
Complex Visibility

One Fourier Component of the Image

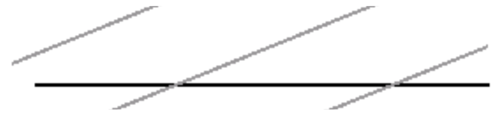
Van Cittert – Zernike Theorem

An Optical Fourier Transformer





$V = 0.7$



Basics

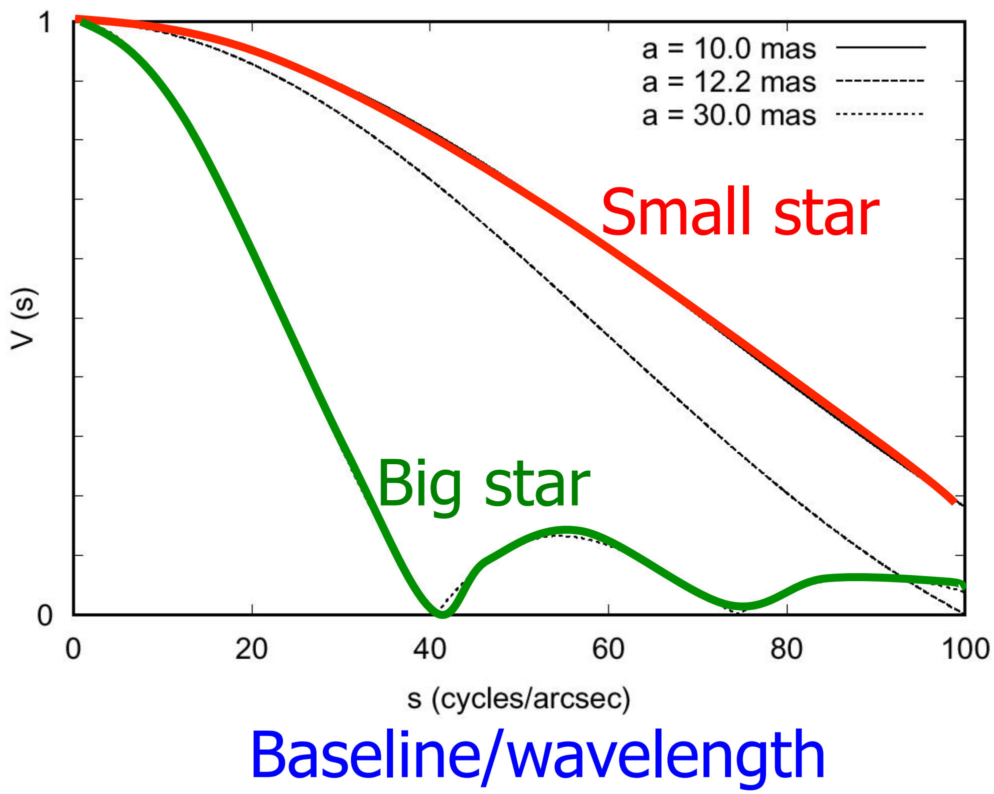
- The amplitude of fringe corresponds to Fourier amplitude of a single Fourier component of brightness distribution
- The phase corresponds to the Fourier phase
- You need amplitudes & phases for imaging

Collect them all to win!

Normalized Visibility V

Lipman Thesis 1998

Which visibilities do you need?

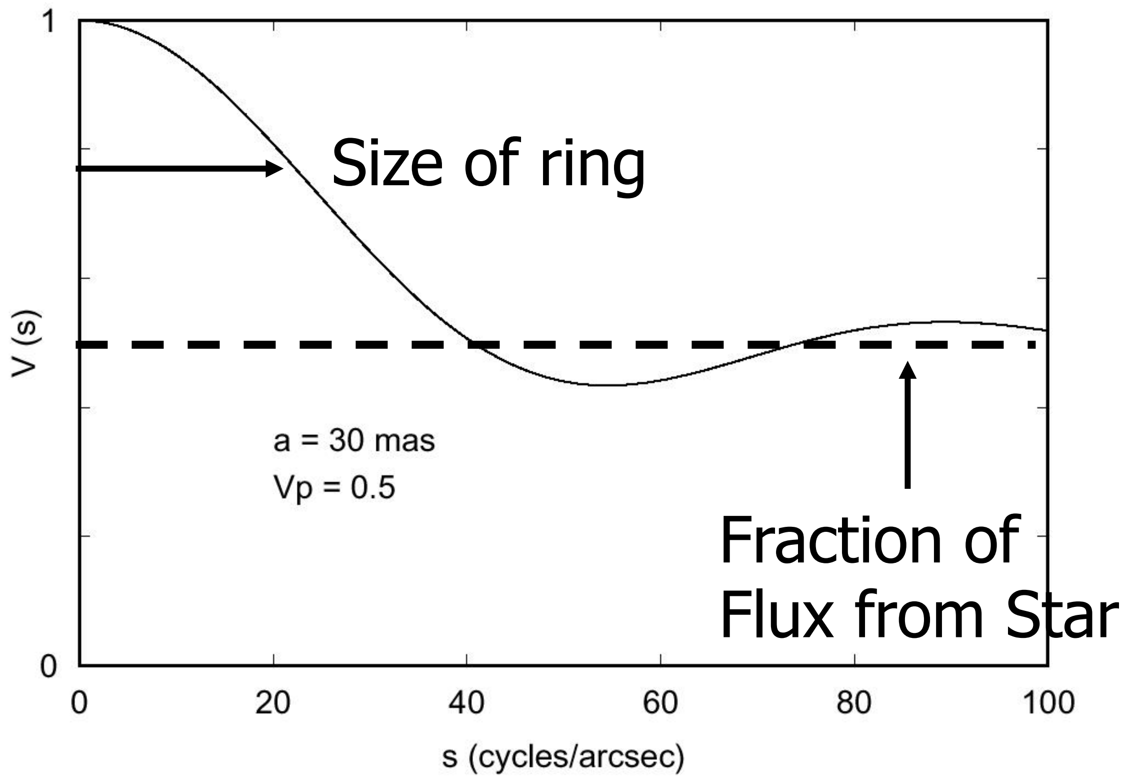


Uniform Disk:

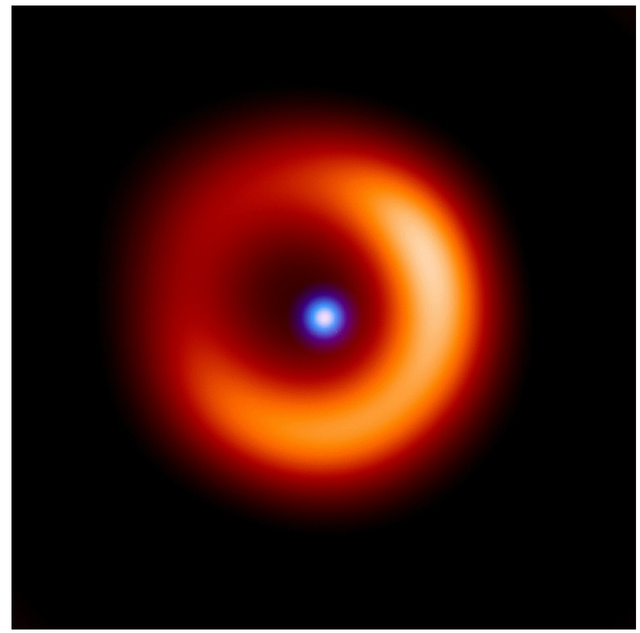
$$V(s) = \left| \frac{2J_1(\pi a s)}{\pi a s} \right|$$

From the Michelson Summer School Notes 2000

Star + Dust Shell

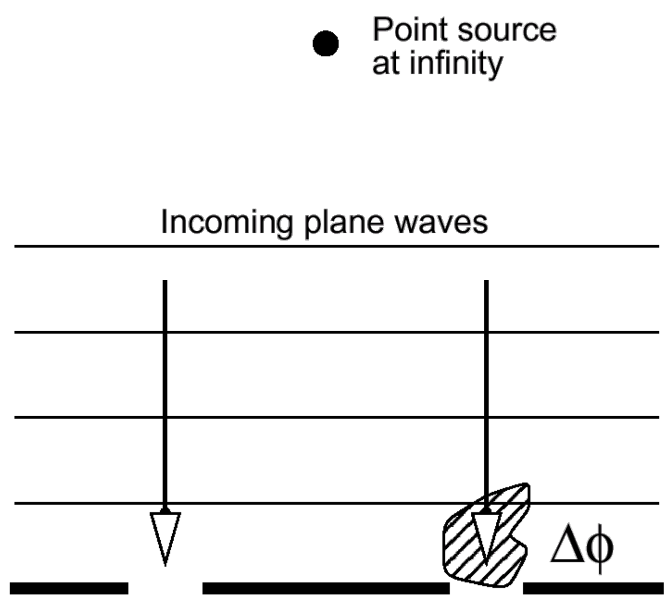


Baseline/wavelength



LESSON: you must sample the appropriate baselines, large and small, Depending on your science goals.

Problem:
Atmosphere Corrupts the Phase



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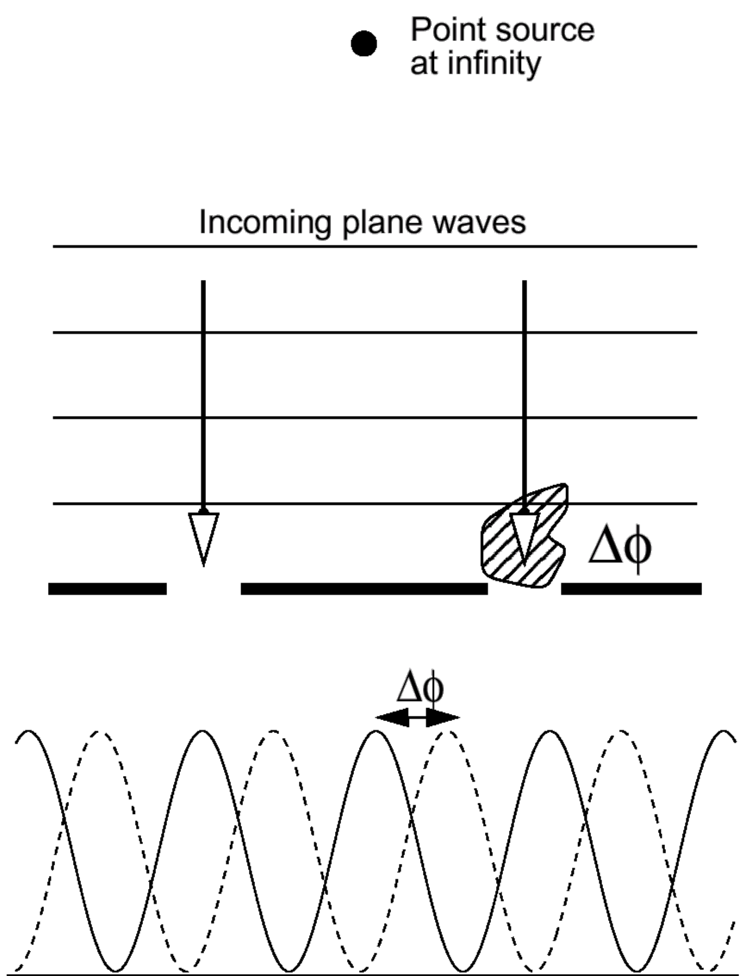
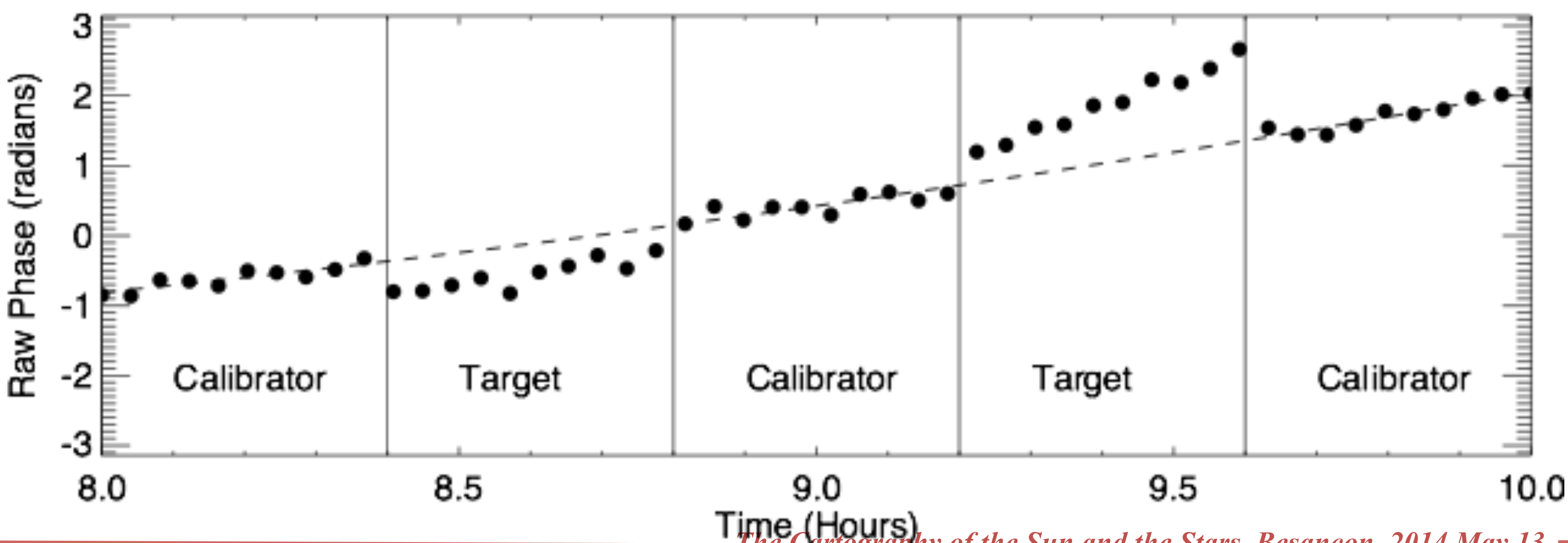
Atmosphere Corrupts the Phase



Phase Referencing

(Radio "Fast Switching" or IR dual-star module)

- Alternate between a calibrator and target WITHIN isoplanatic patch and WITHIN t0
  - Easy for VLA, ALMA; Possible for VLBA; Difficult < 1 mm-wave
  - Not normally possible for optical/infrared, except with Keck-ASTRA (RIP) or VLTI-PRIMA (RIP)



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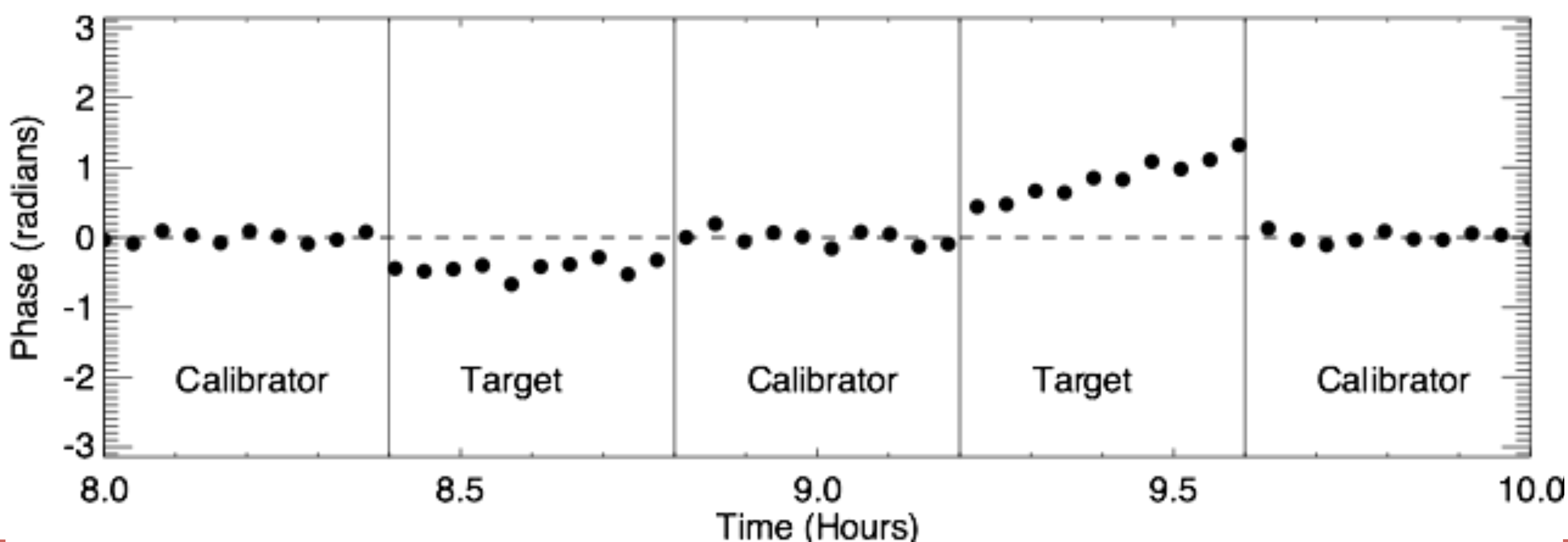
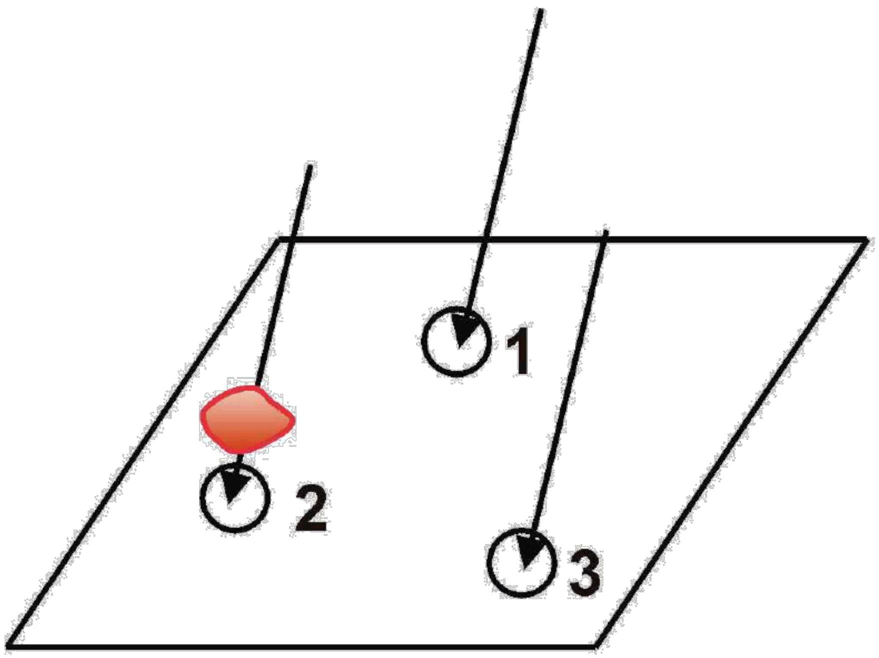


The "Closure Phase" is Not Corrupted

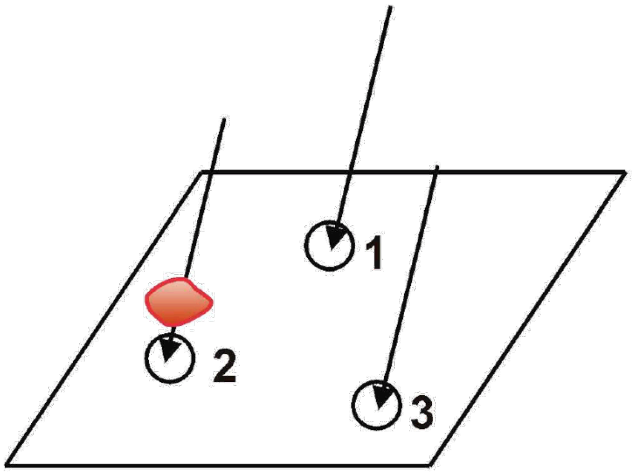


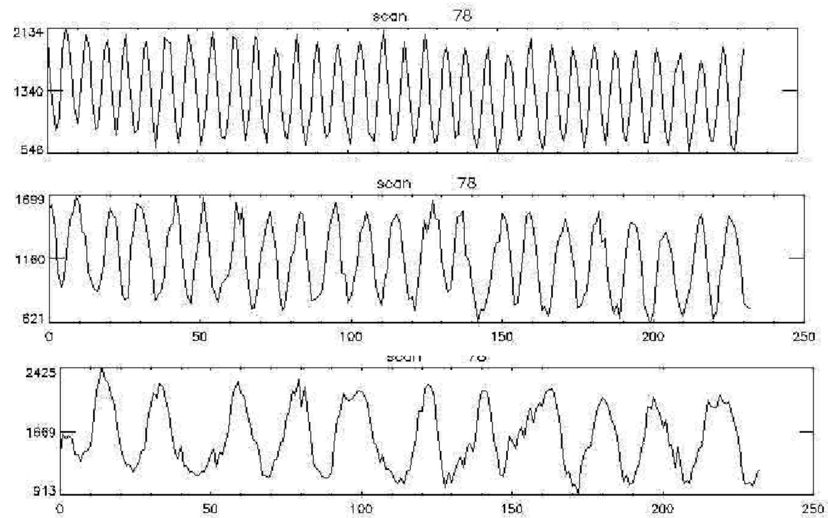
Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	=	$\Phi_o(1\text{-}2)$	+	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	=	$\Phi_o(2\text{-}3)$	+	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	=	$\Phi_o(3\text{-}1)$	+	$[\phi(1)-\phi(3)]$

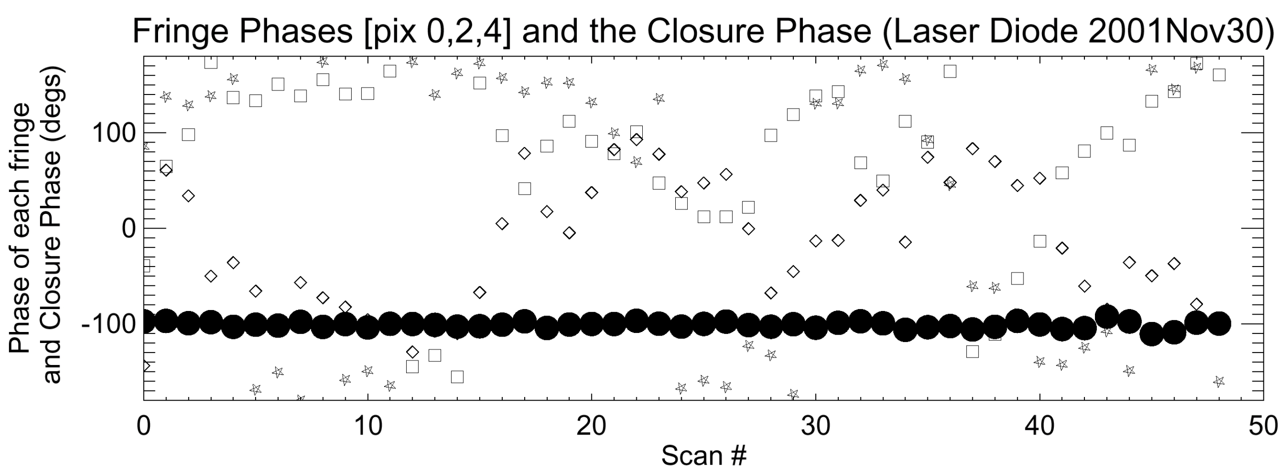
Closure Phase (1-2-3) $= \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$

Pair-wise Combination at IOTA

Closure Phase is a Good Observable

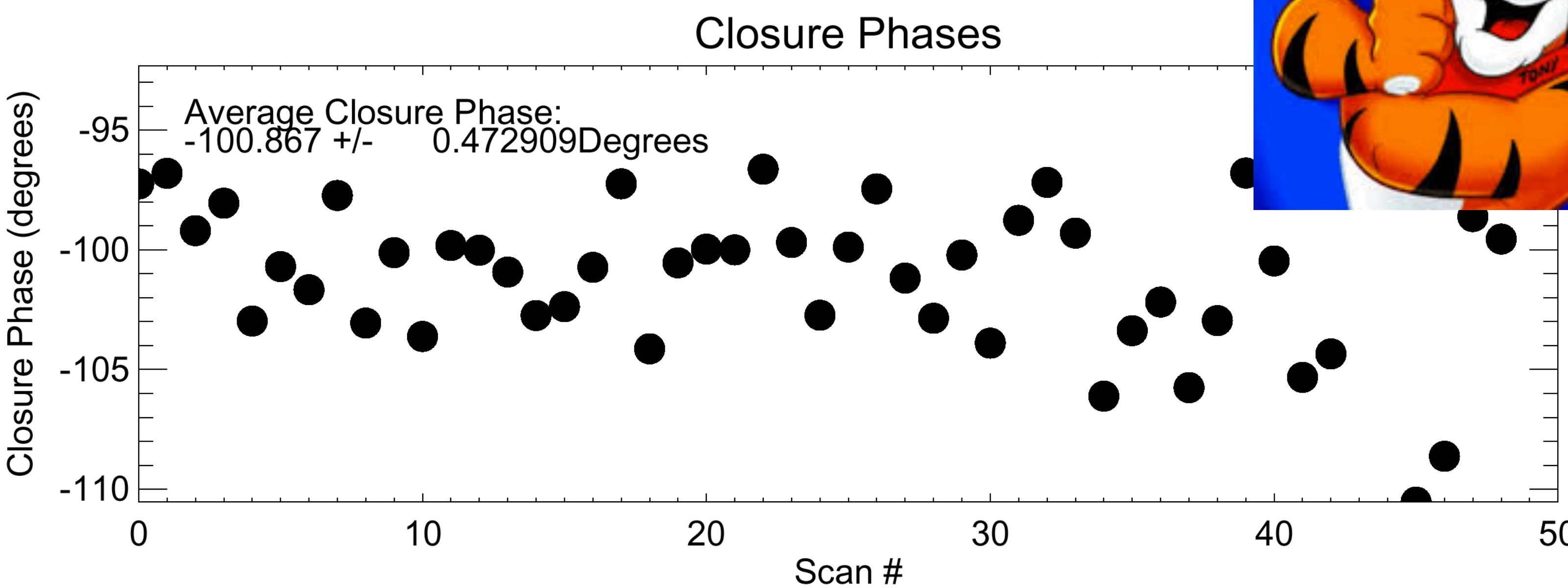






Pair-wise Combination at IOTA

Closure Phase is a ~~Good~~ GREAT! Observable

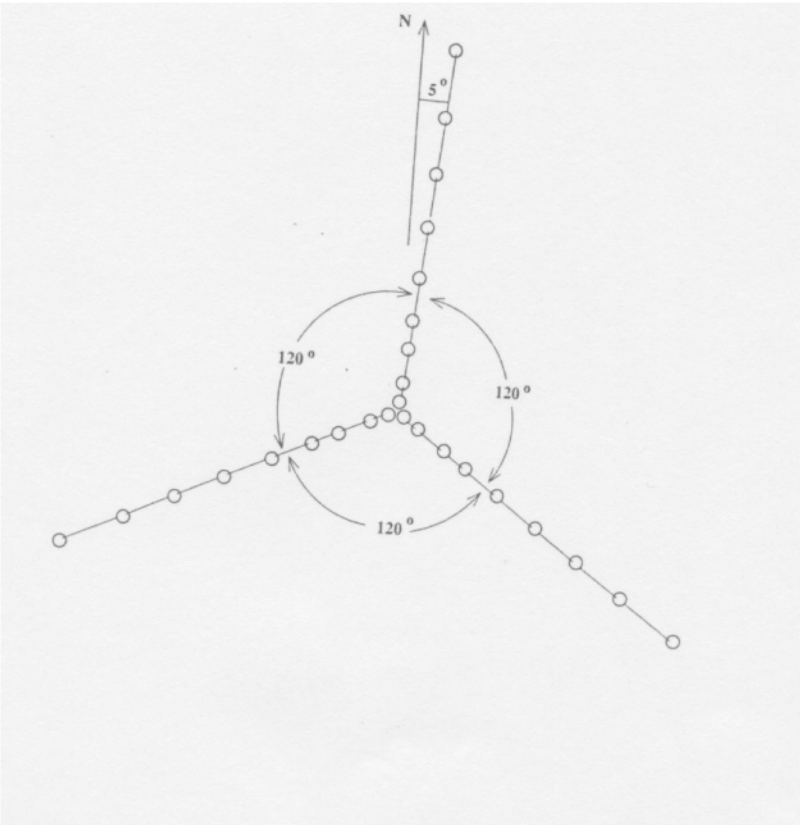


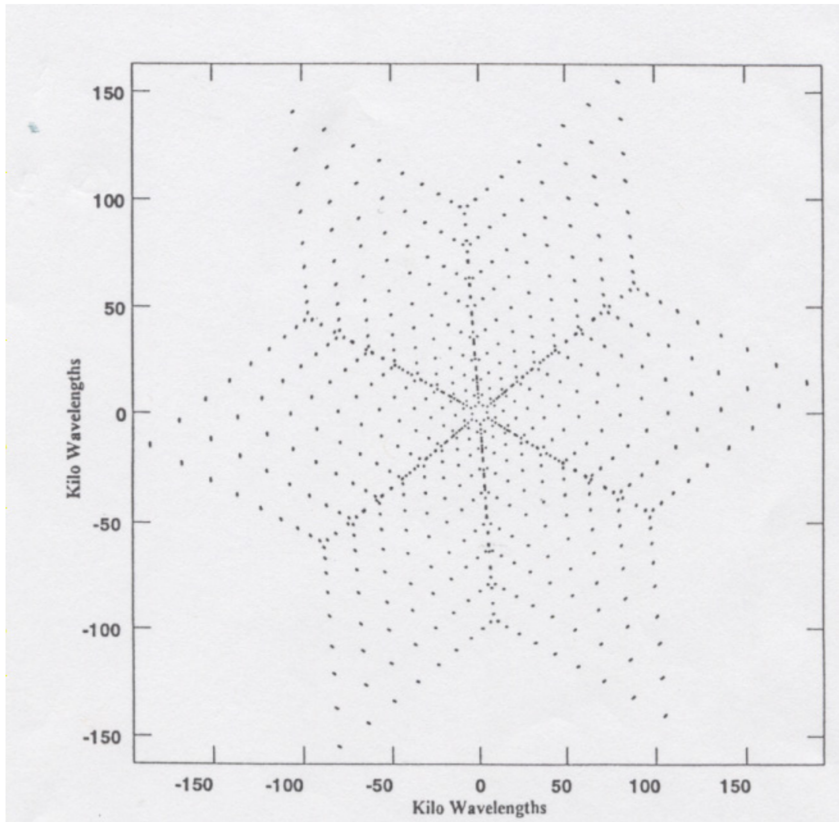
Basics of Interferometric Imaging

Number of Telescopes	Number of Fourier Phases
3	3
7	21
21	210
27	351
50	1225

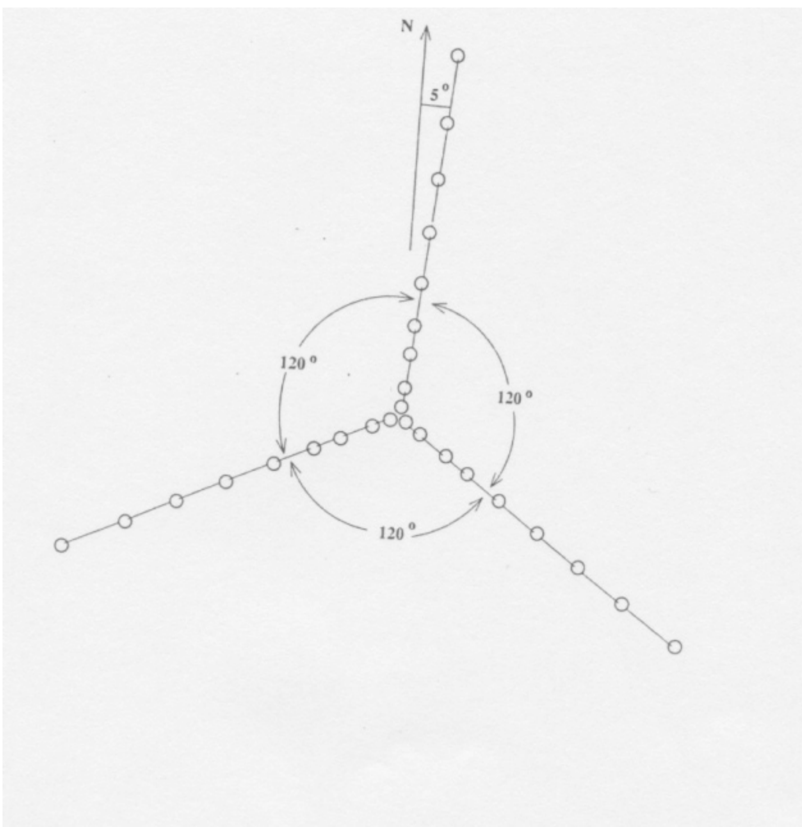
- How much data do you need?
  - The number of filled pixels ~> number of independent visibility measurements (degrees of freedom argument)
- Dynamic Range expected to be 1000:1 to 100:1
  - From calibration errors mainly
- What range of baselines?
  - Longest baselines set your highest resolution
  - Diffraction-limit of individual telescope usually sets the maximum field-of-view of the interferometer
  - Sometimes the shortest baseline 'over-resolves' your target, meaning you are out of luck!
- How can you get enough data with only a few telescopes?

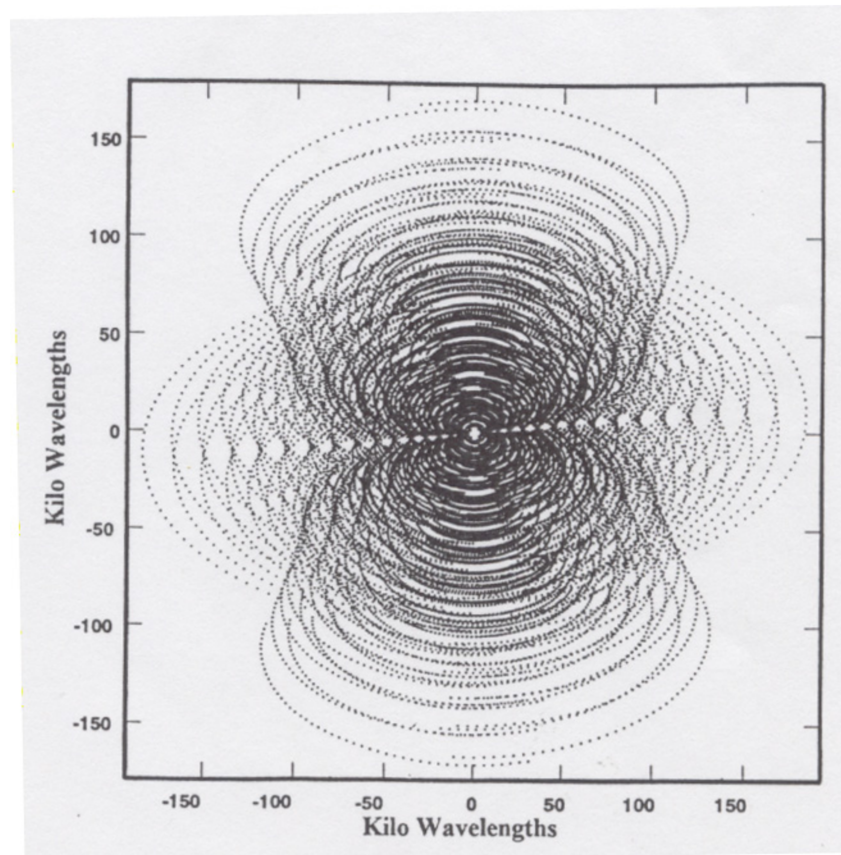
Very Large Array (VLA)



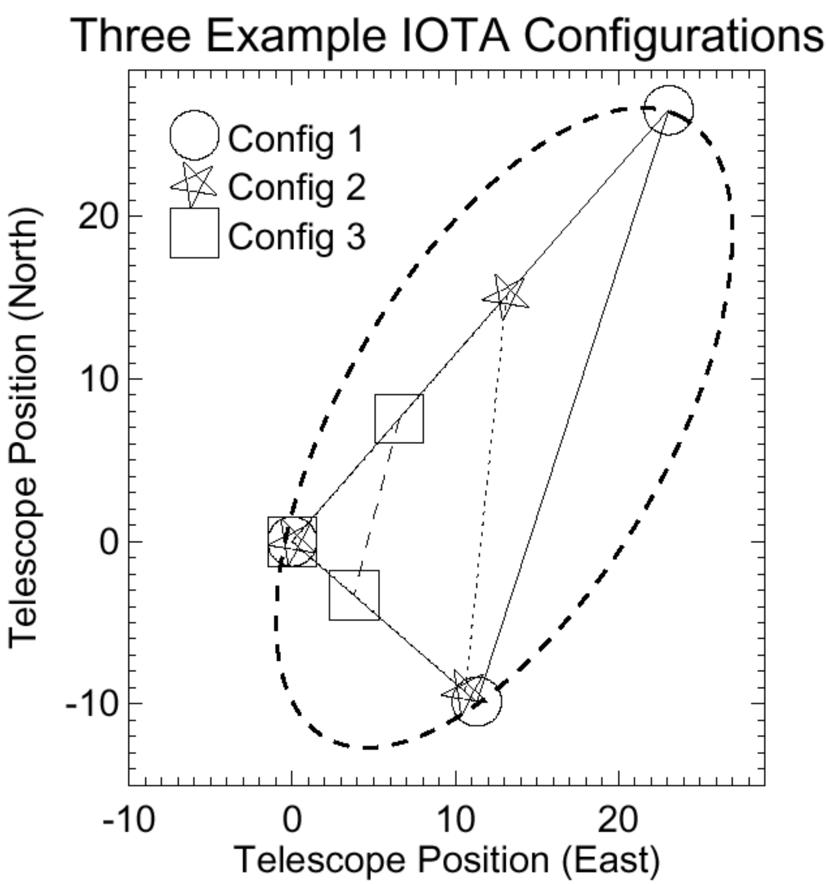


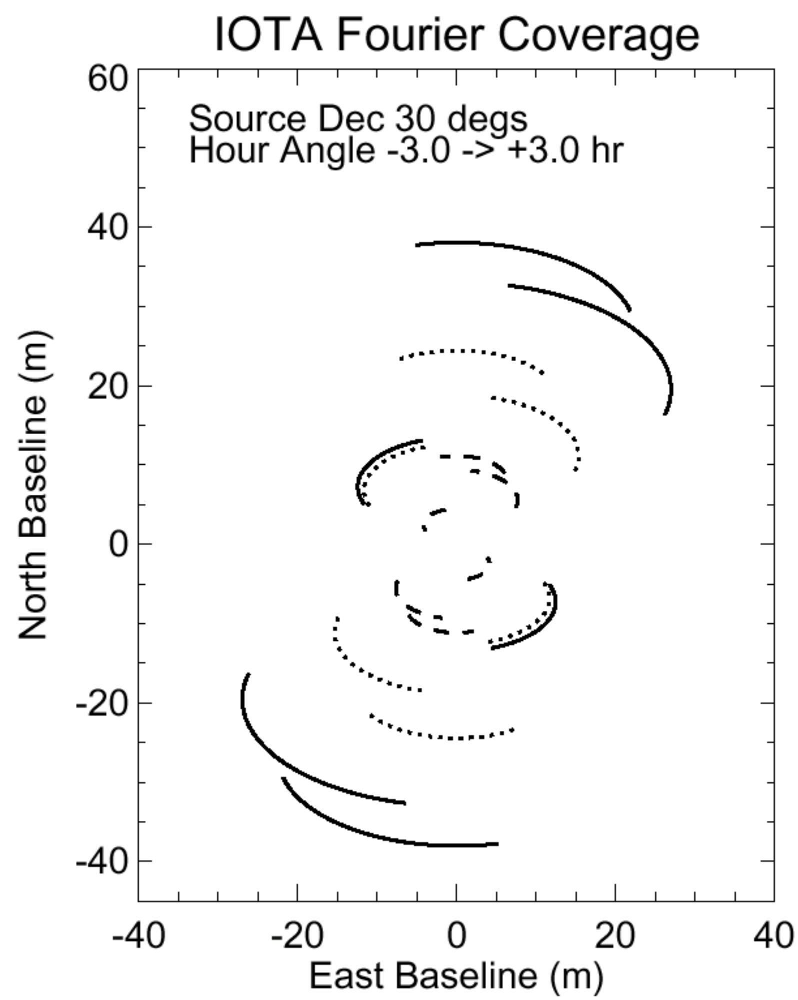
Very Large Array (VLA)





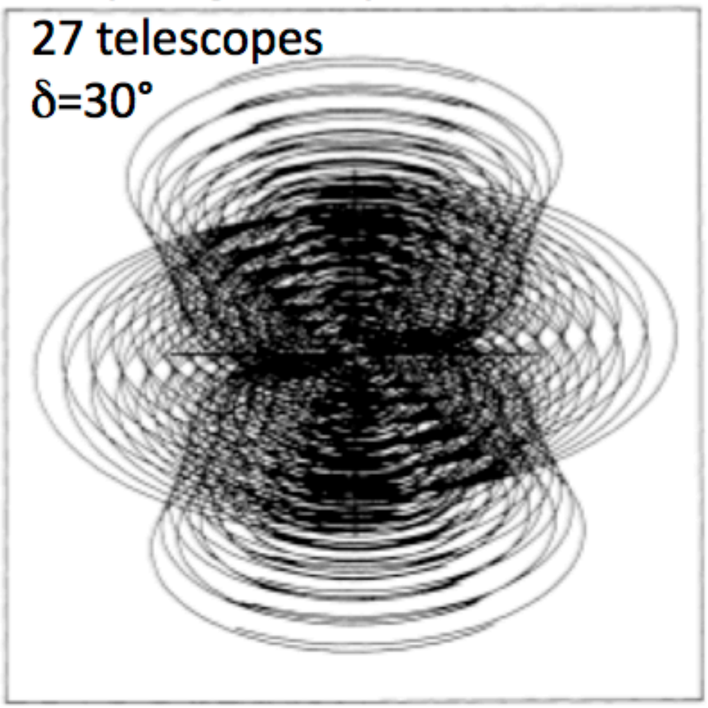
IOTA-3T: Moving Telescopes + Waiting for Earth to turn



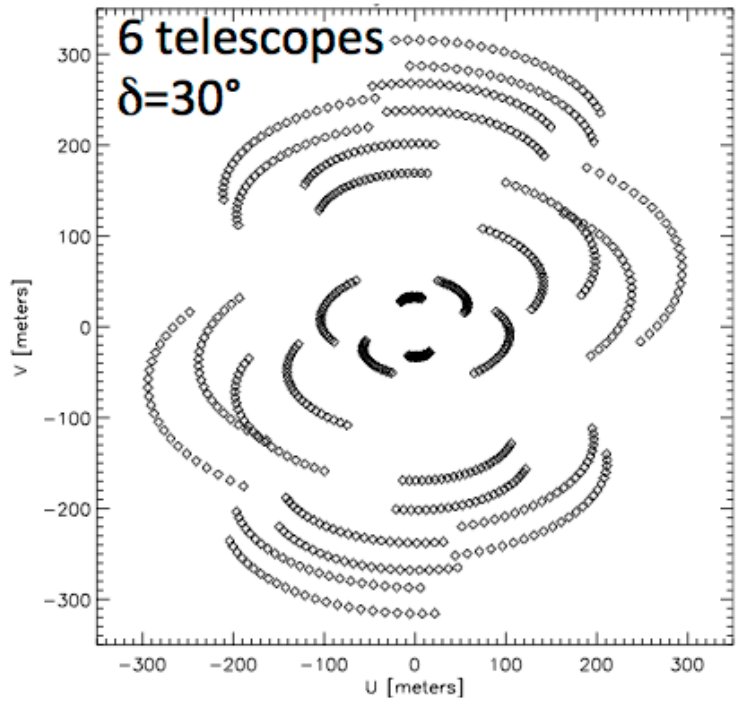


UV coverage:
VLA vs CHARA

Very Large Array



CHARA Array

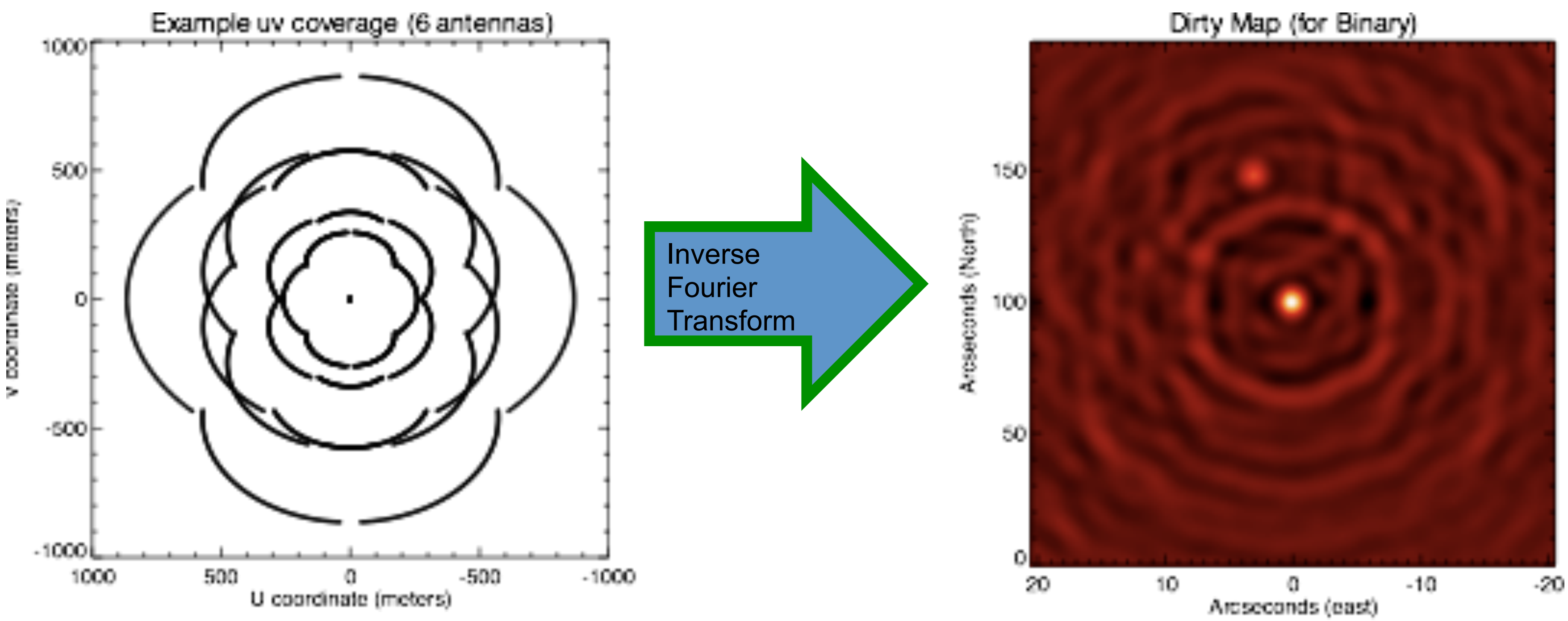


Deconvolution & Aperture Synthesis

- To reconstruct an image from sparsely sampled (u,v) data, one must interpolate into regions where data does not exist.
- This is Identical to multiplying the true Complex Visibility by an Aperture Function.
- Since Multiplication in the (u,v) space is the same as Convolution in image space (see Convolution Theorem), the problem can be re-cast as a Deconvolution problem.
- Popular methods of Deconvolution include CLEAN and the Maximum Entropy Method.

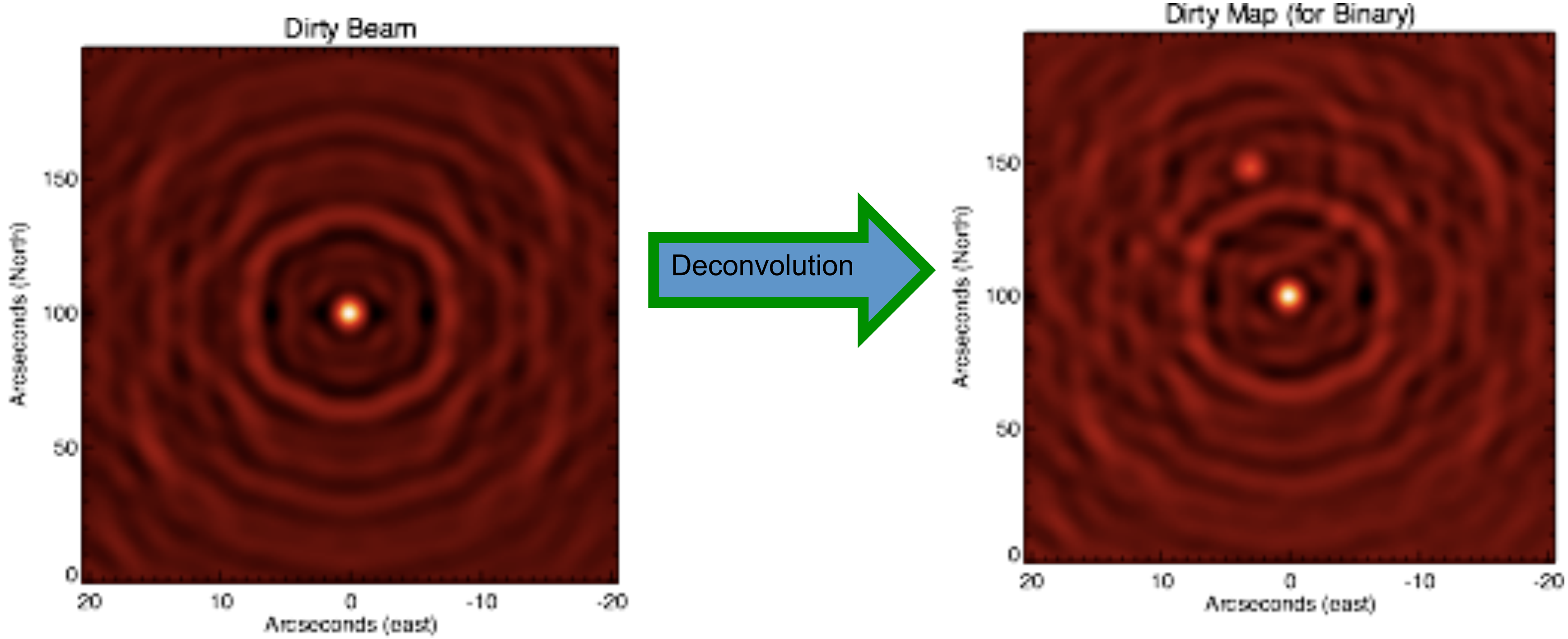
Imaging Methods

- Poor UV coverage leads to artifacts in your image



Deconvolution with CLEAN

"Point Spread Function"
From known UV coverage



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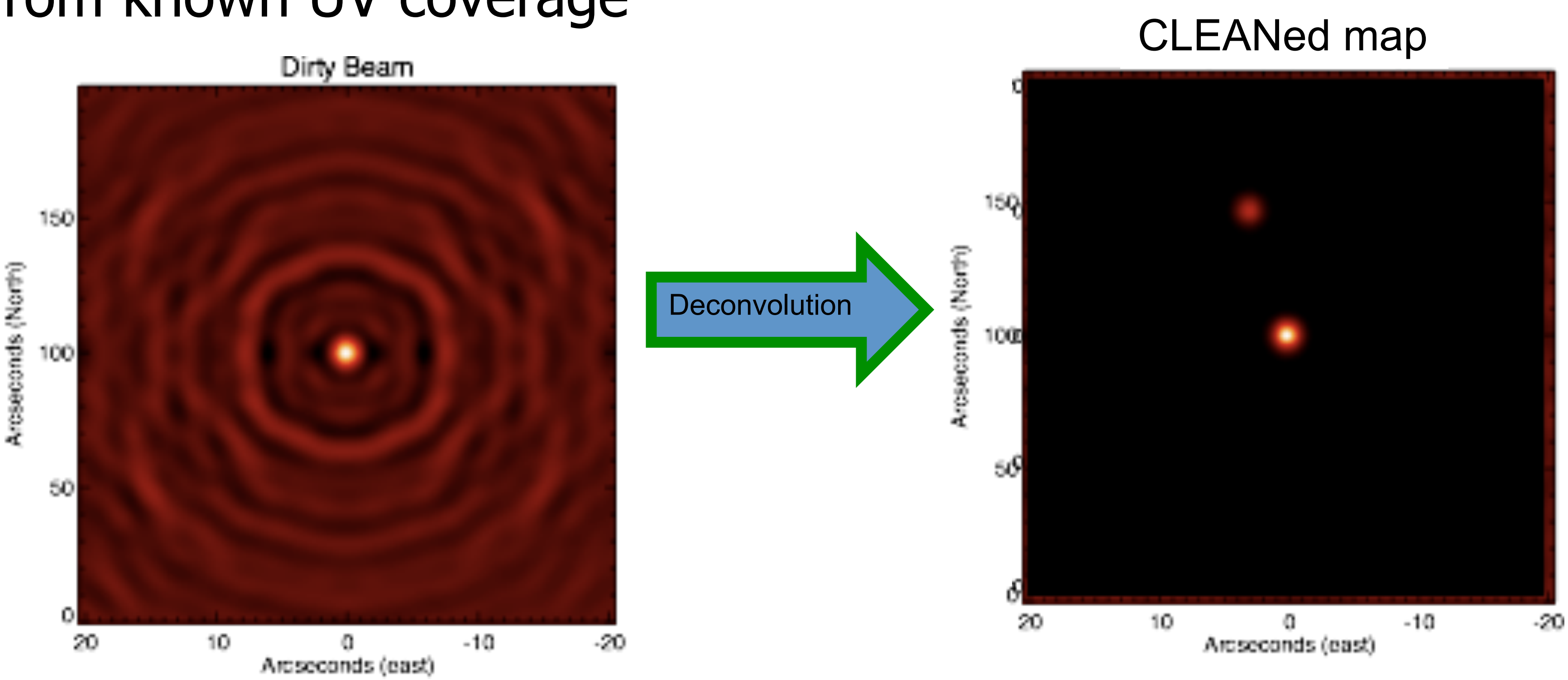
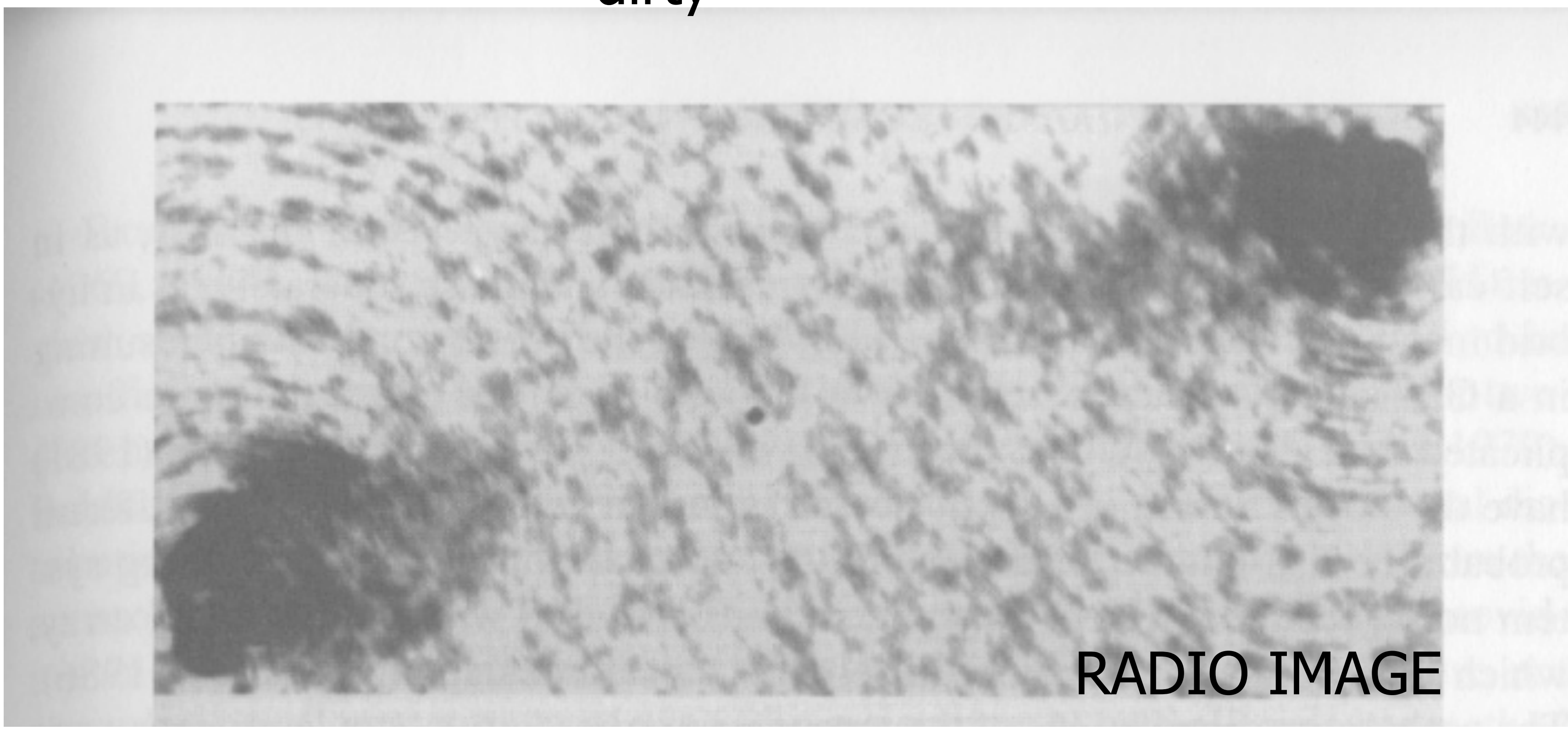


CLEAN example: Cygnus A

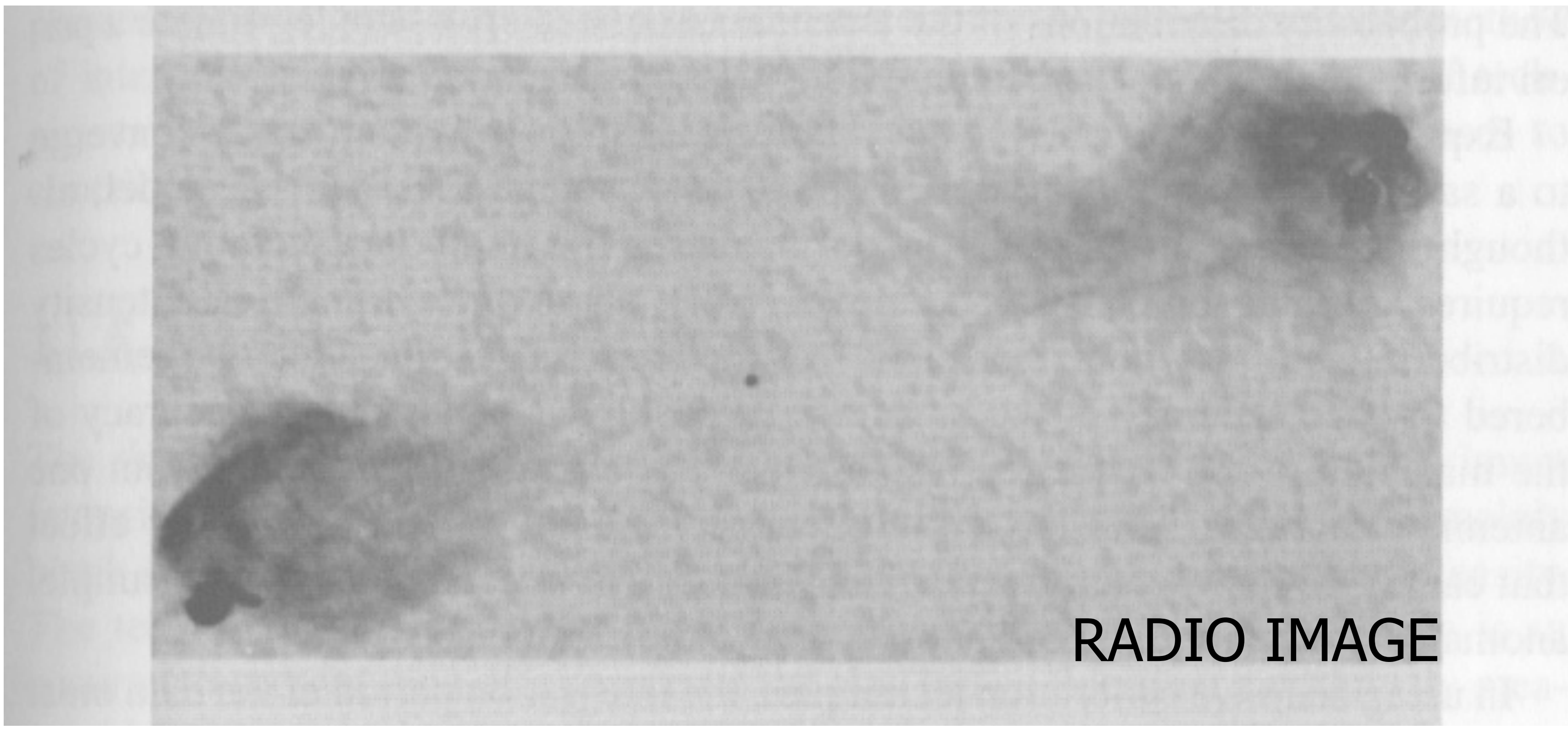
dirty



From Thompson, Moran, Swenson

CLEAN example: Cygnus A

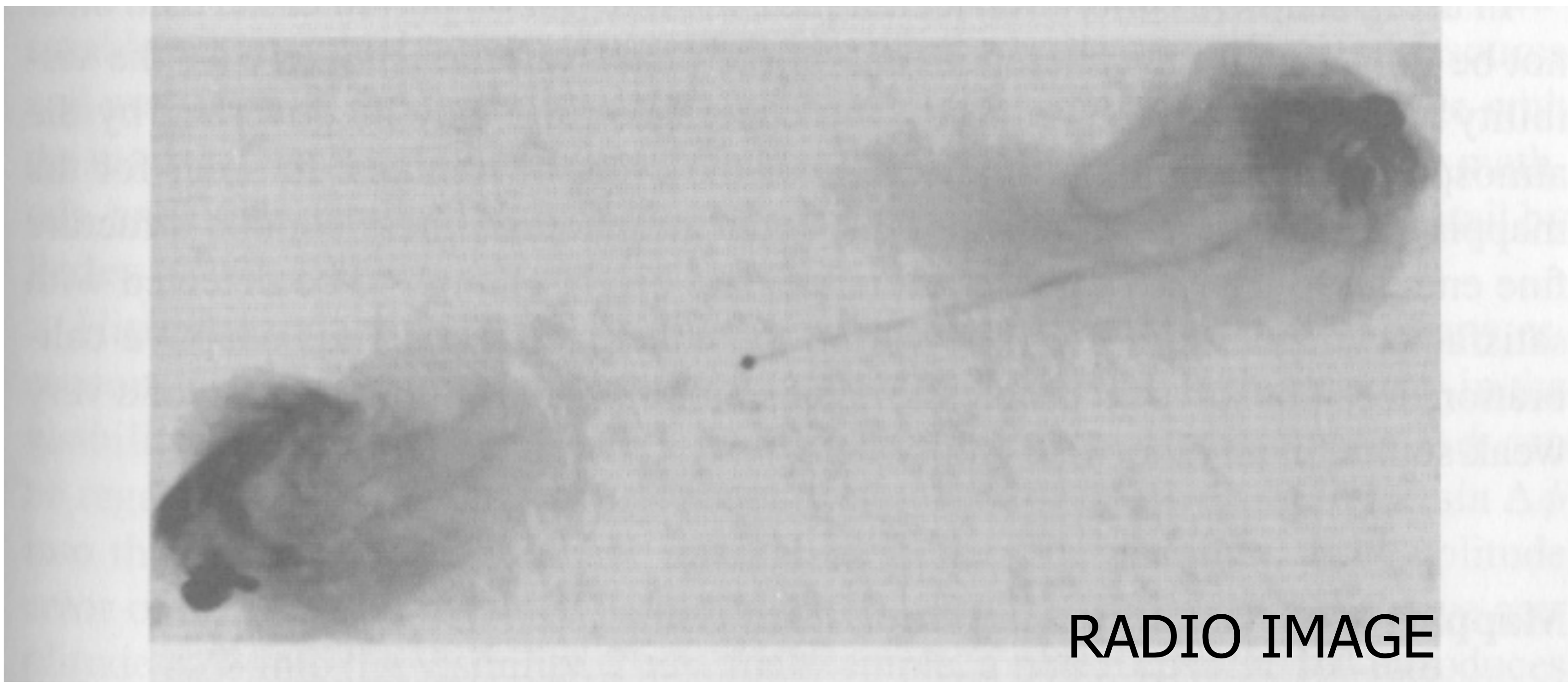
CLEANed



From Thompson, Moran, Swenson

CLEAN example: Cygnus A

CLEANed
+ *Self-calibration* (using closure phases in an iterative way)



From Thompson, Moran, Swenson

Regularization: Maximum Entropy Method (MEM)

With finite (u,v) coverage and with noisy data, there are an <u>infinite</u> number of images which will fit the data.

So how do we choose? *(use a forward transform method)*

Find "smoothest" image consistent with data (χ^2~1)

MEM uses the "entropy" S to parameterize the "smoothness."

Fraction of flux in pixel i

Skilling & Bryan (1984)

Entropy $$S = -\sum_i f_i \ln \frac{f_i}{I_i}$$ Image prior

Sum over all pixels

Regularization: Maximum Entropy Method (MEM)

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…y in pixel i

Skilling & Bryan (1984)

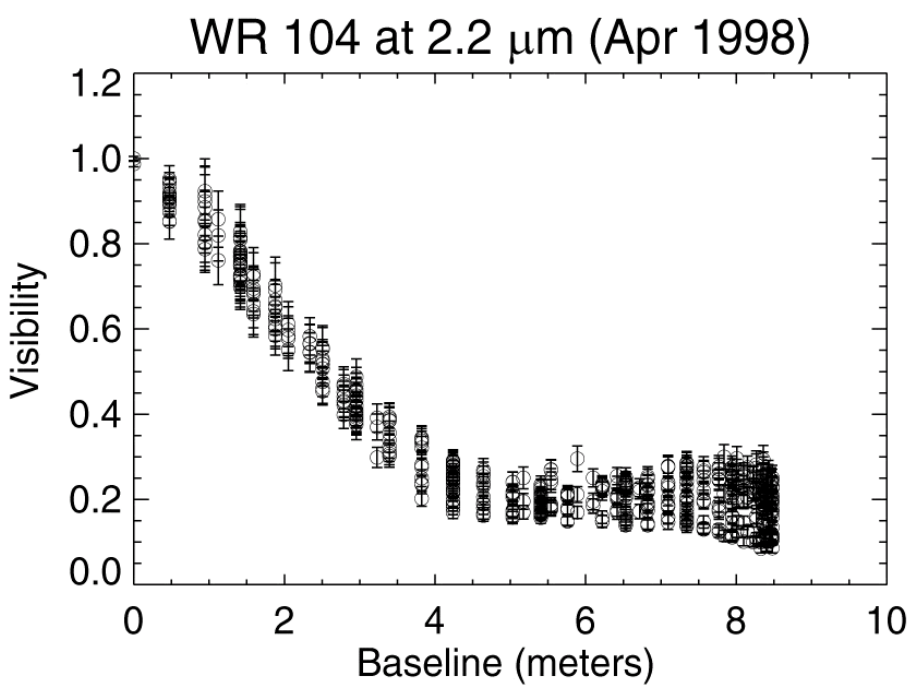
Entropy $S = - \sum_i$ …

Image prior

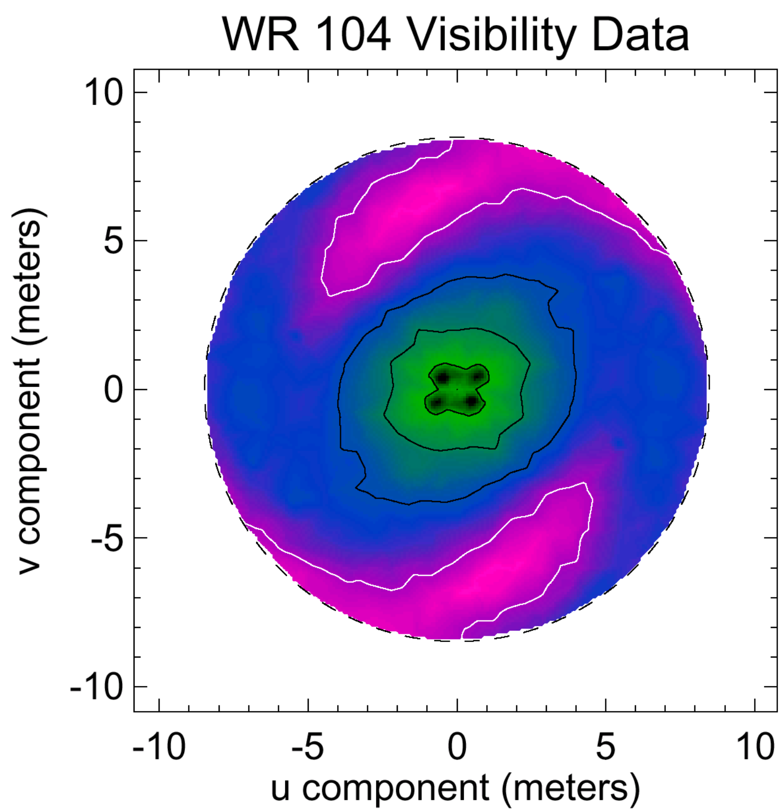
Sum over al…

CHOOSE ANY WELL-MOTIVATED REGULARIZER YOU LIKE!
MEM IS NOT A UNIQUE CHOICE

WR 104 Data

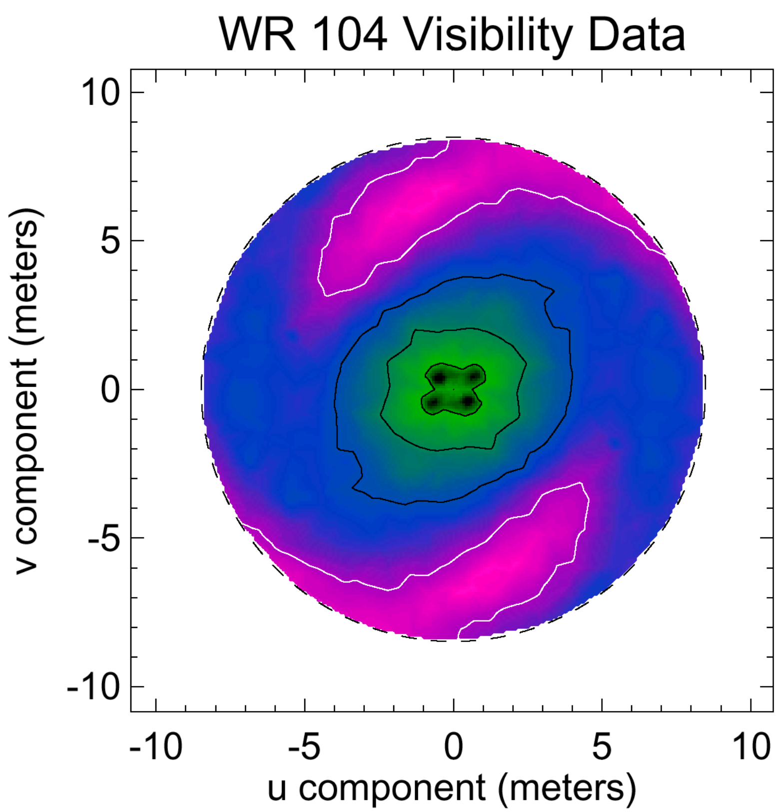


WR 104 at 2.2 μm (Apr 1998)
Visibility
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Baseline (meters)

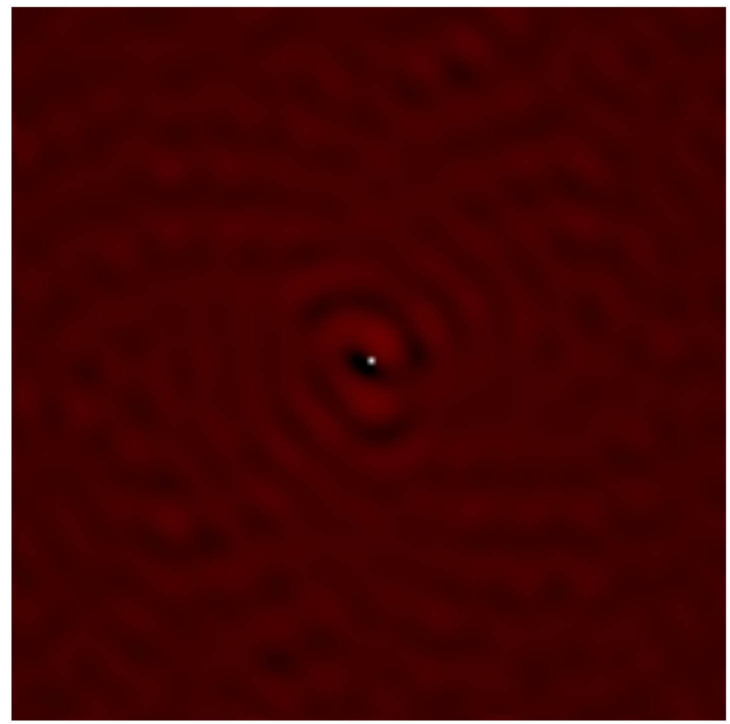


WR 104 Visibility Data
v component (meters)
10
5
0
-5
-10
u component (meters)

WR 104 MEM Reconstruction



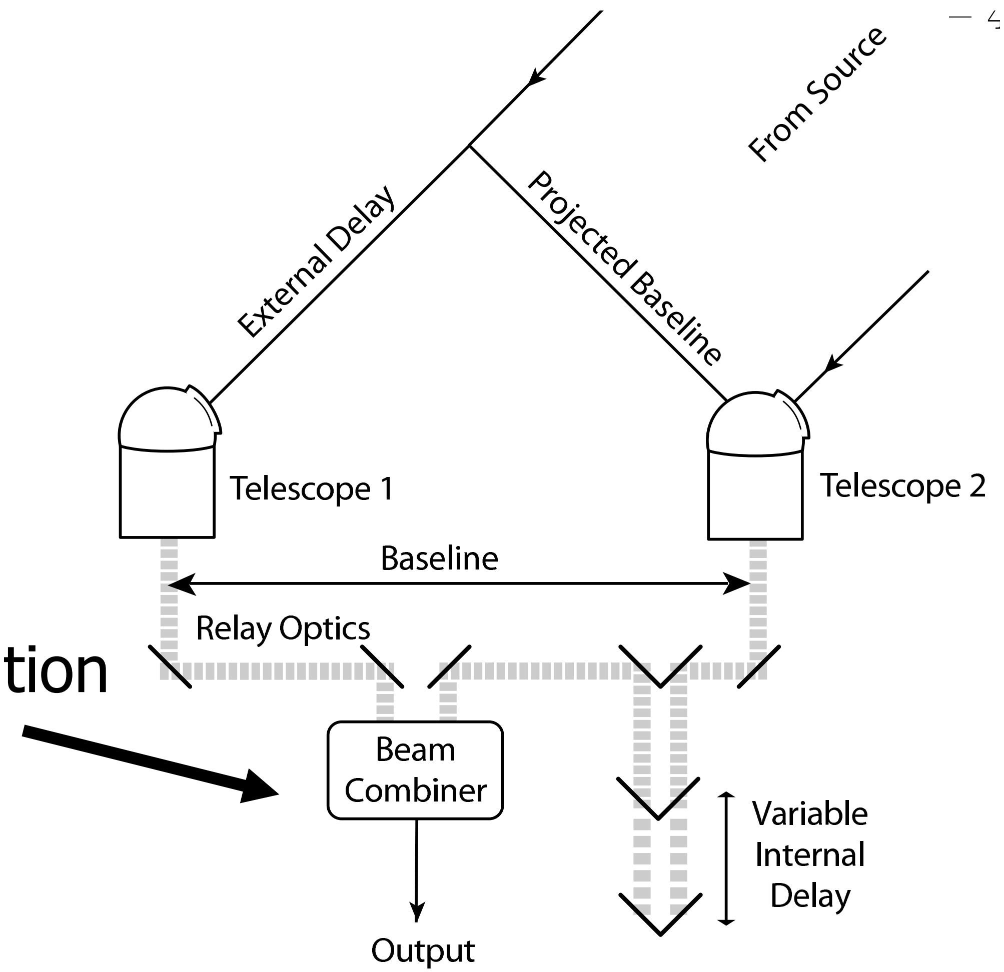
Iterations 1 to 30



WR 104 (2.2 microns)

What kind of beam combination do you want for Imaging?

Beam Combination



Monnier & Allen 2012

Beam Combination

in pairs…

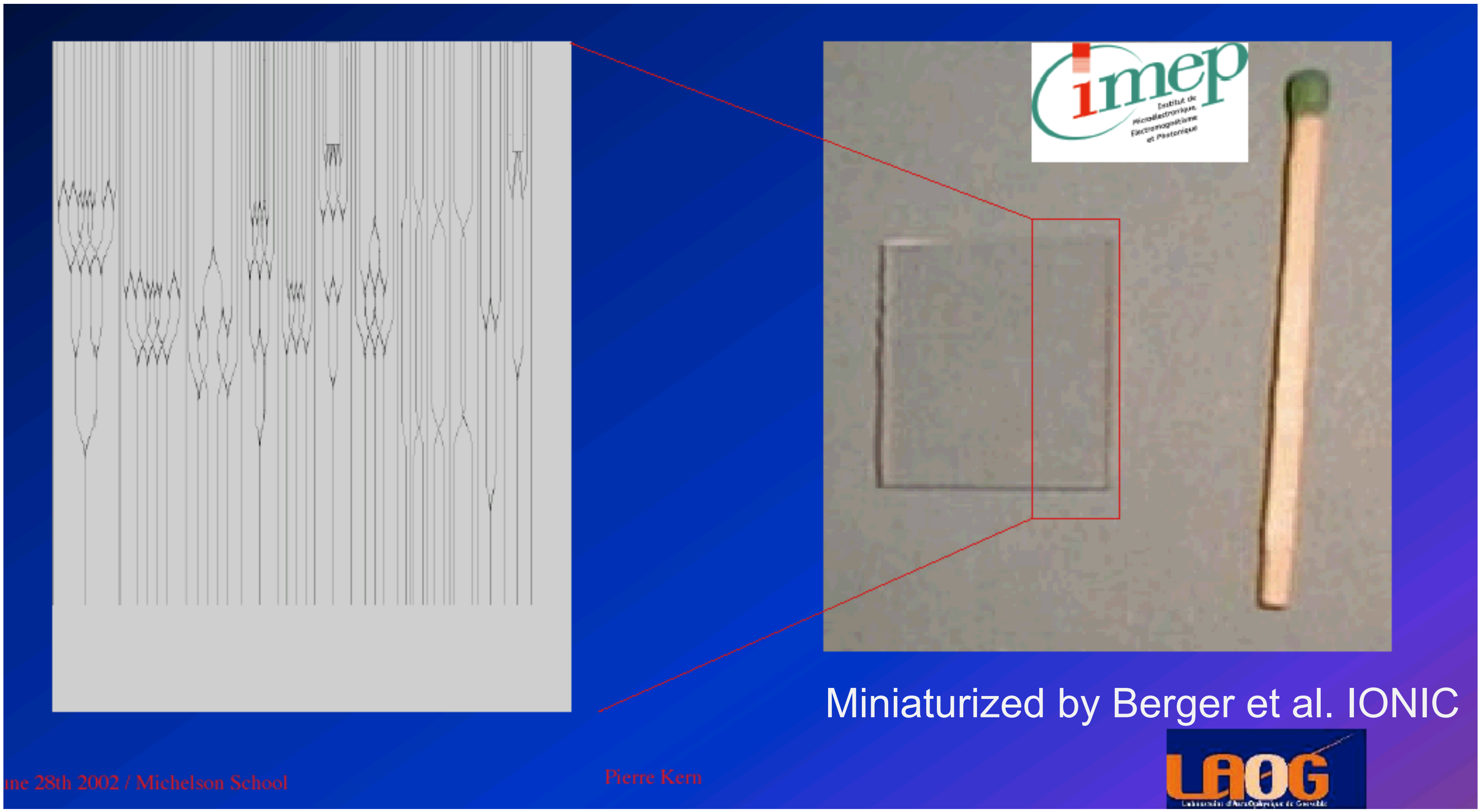
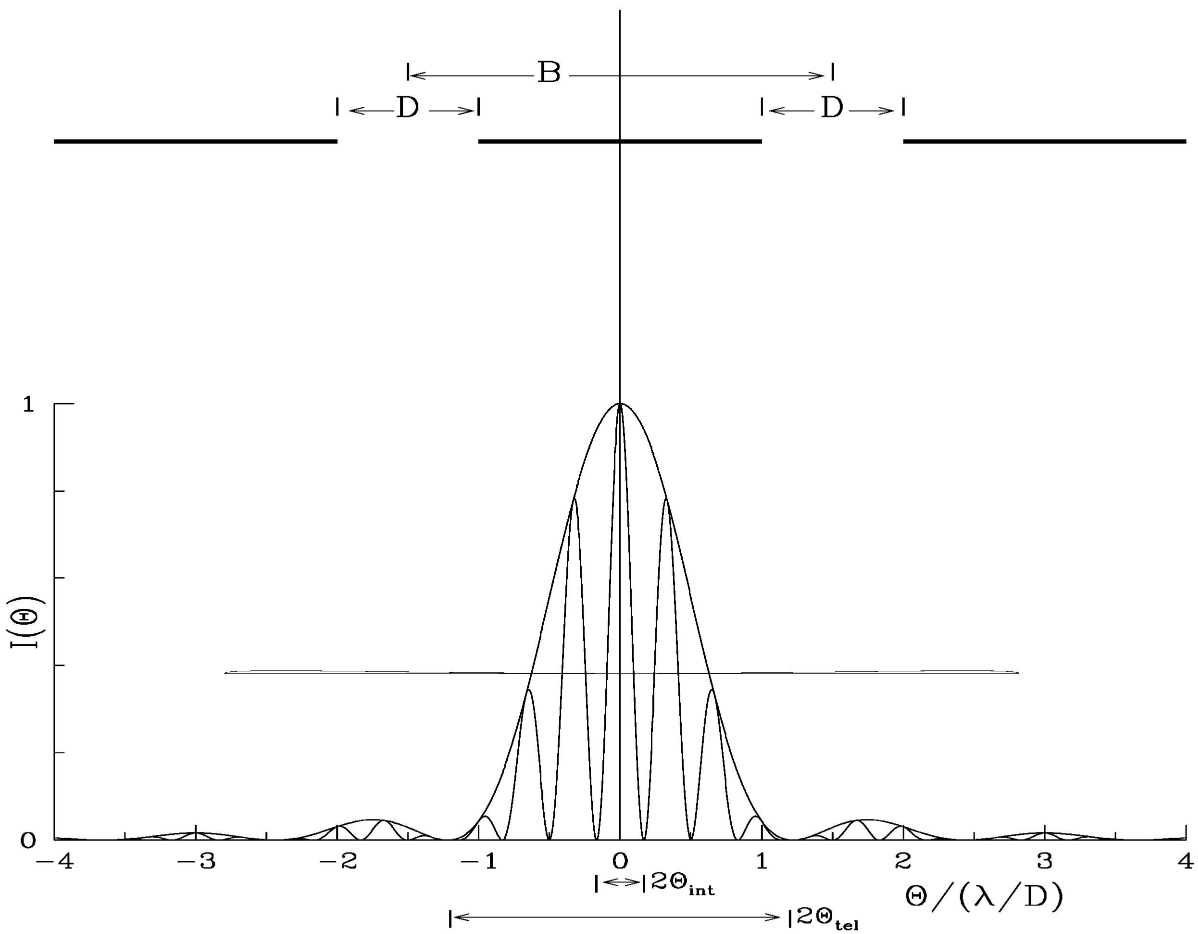
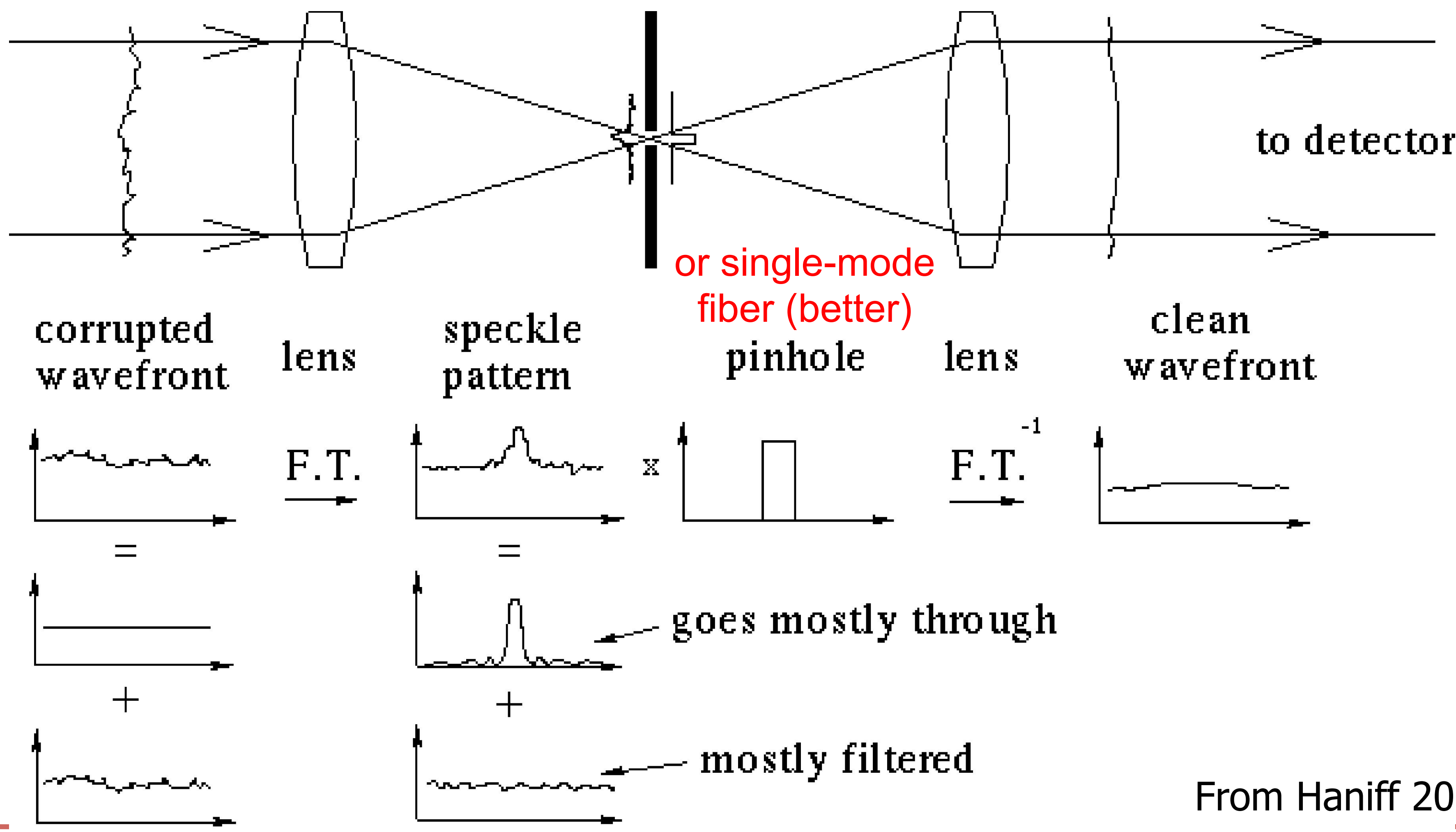


Image-Plane Combination

like aperture masking

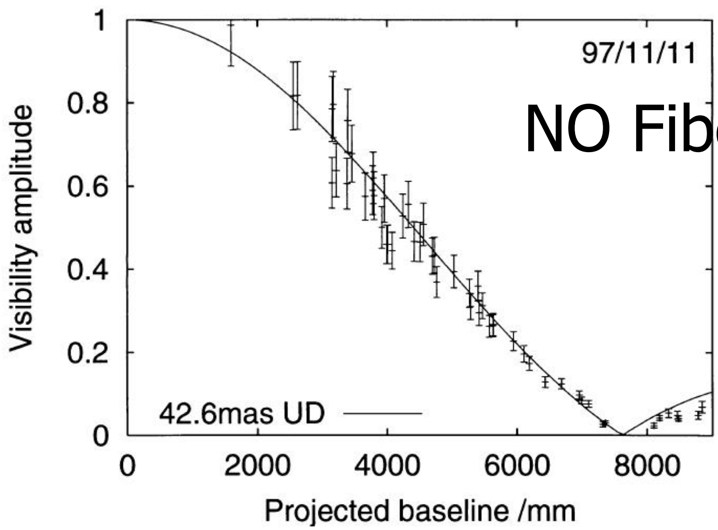


Spatial Filtering

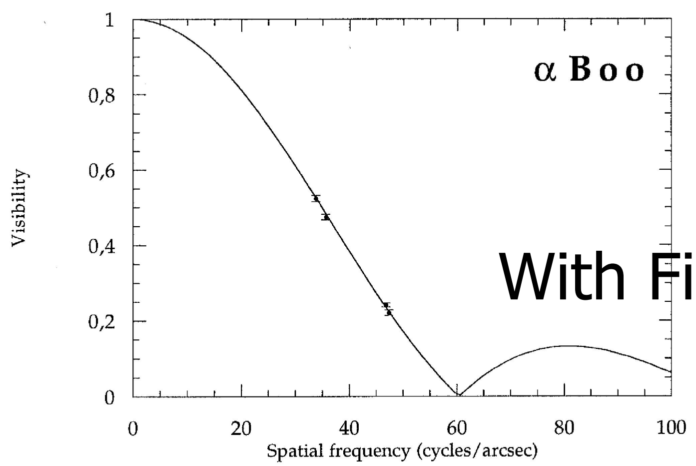


From Haniff 2002

Calibration Improvement



NO Fibers



With Fibers

Zoom

Foresto, Perrin, et al. (olden days)

CHARA Interferometer

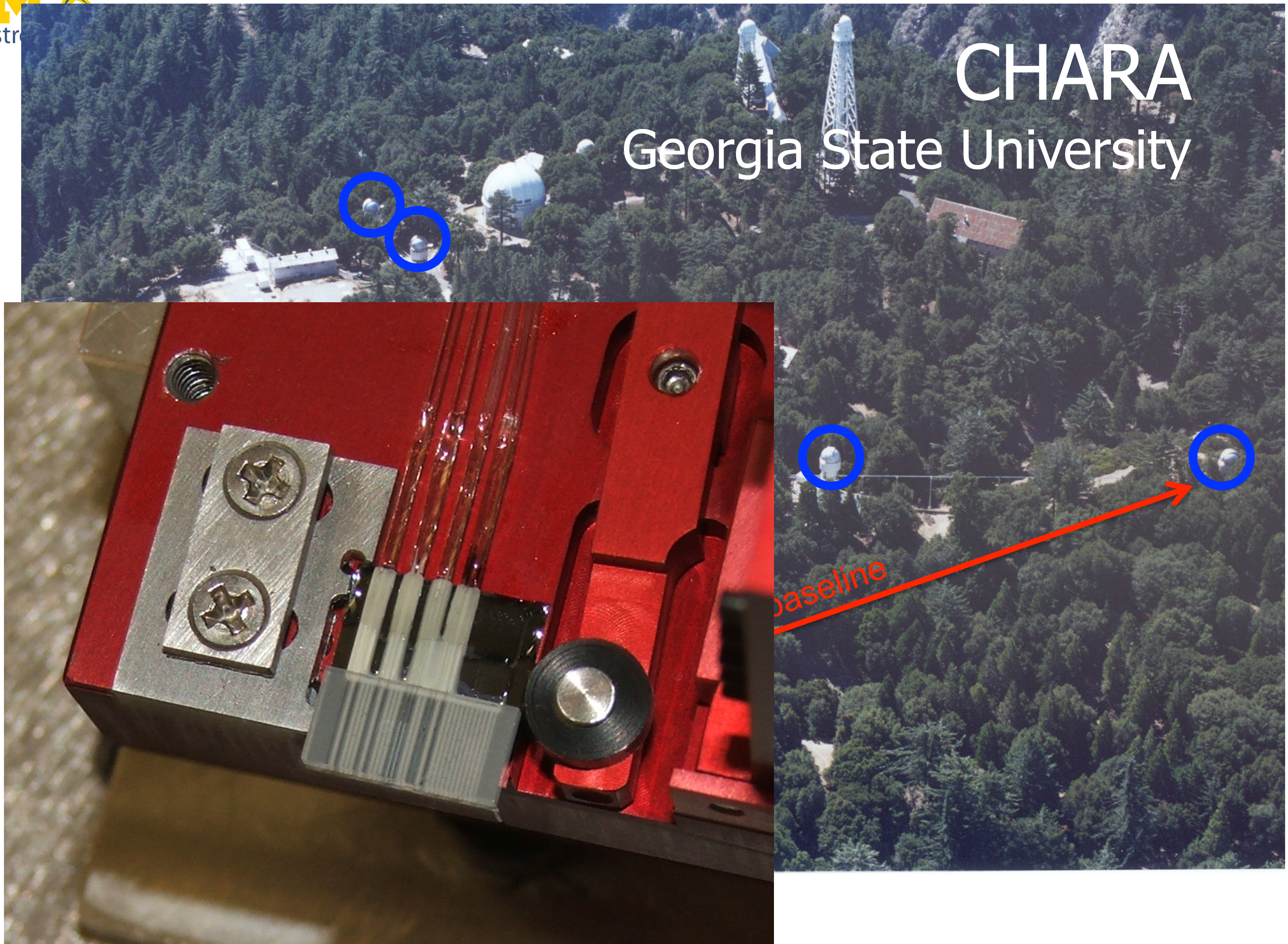
- Built and operated by Georgia State University (PI: Hal McAlister)
  - Funded by State of Georgia, National Science Foundation, Keck Foundation
  - Other collaborators: Observatoire de Paris-Meudon, U. Michigan, U. Sydney, Observatoire de Nice
- At visible/IR wavelengths, highest resolution in the world (0.3 to 1 milliarcseconds)
- MIRC instrument only infrared instrument combining 6 telescopes simultaneously

Michigan Infrared Combiner (MIRC)

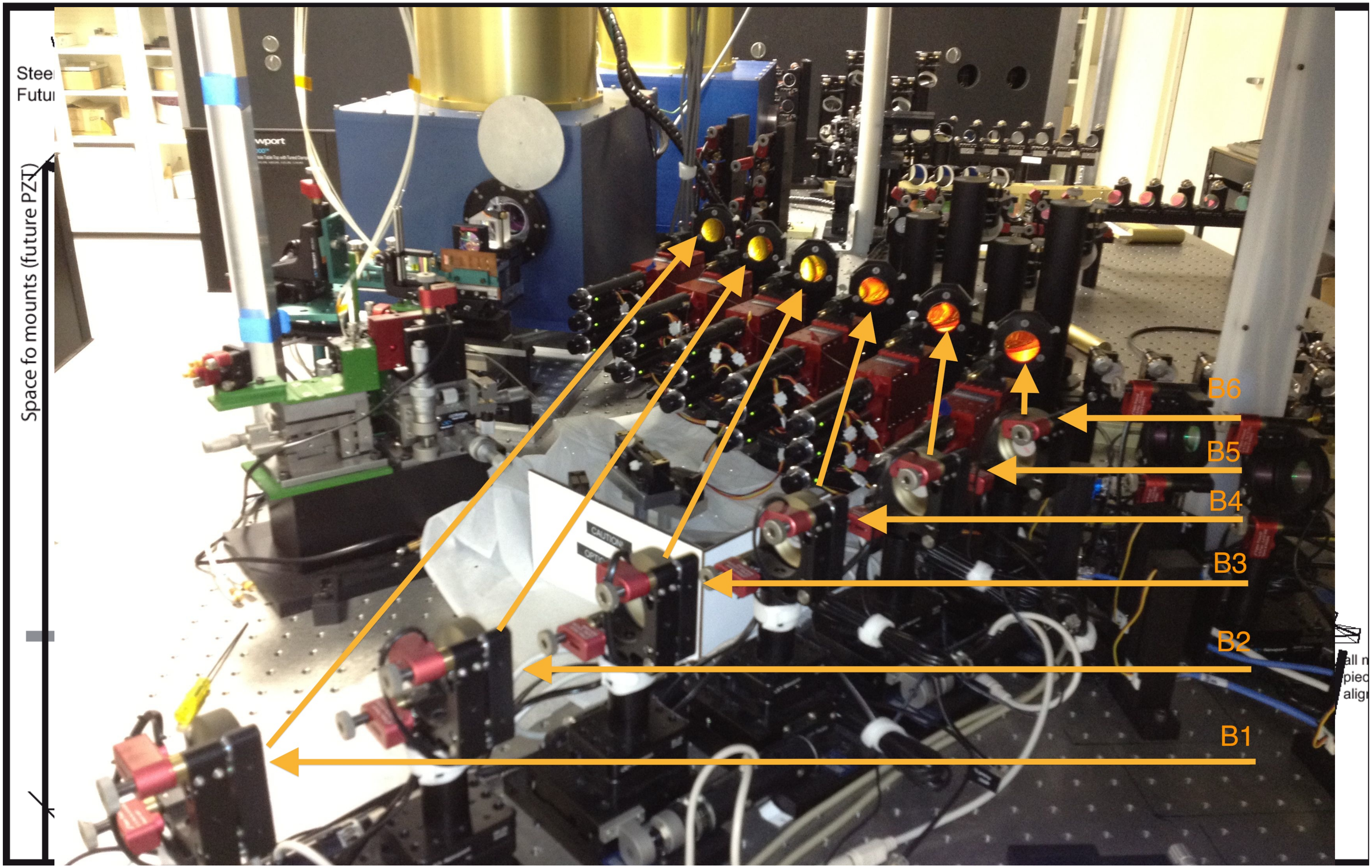
Guiding Principles:

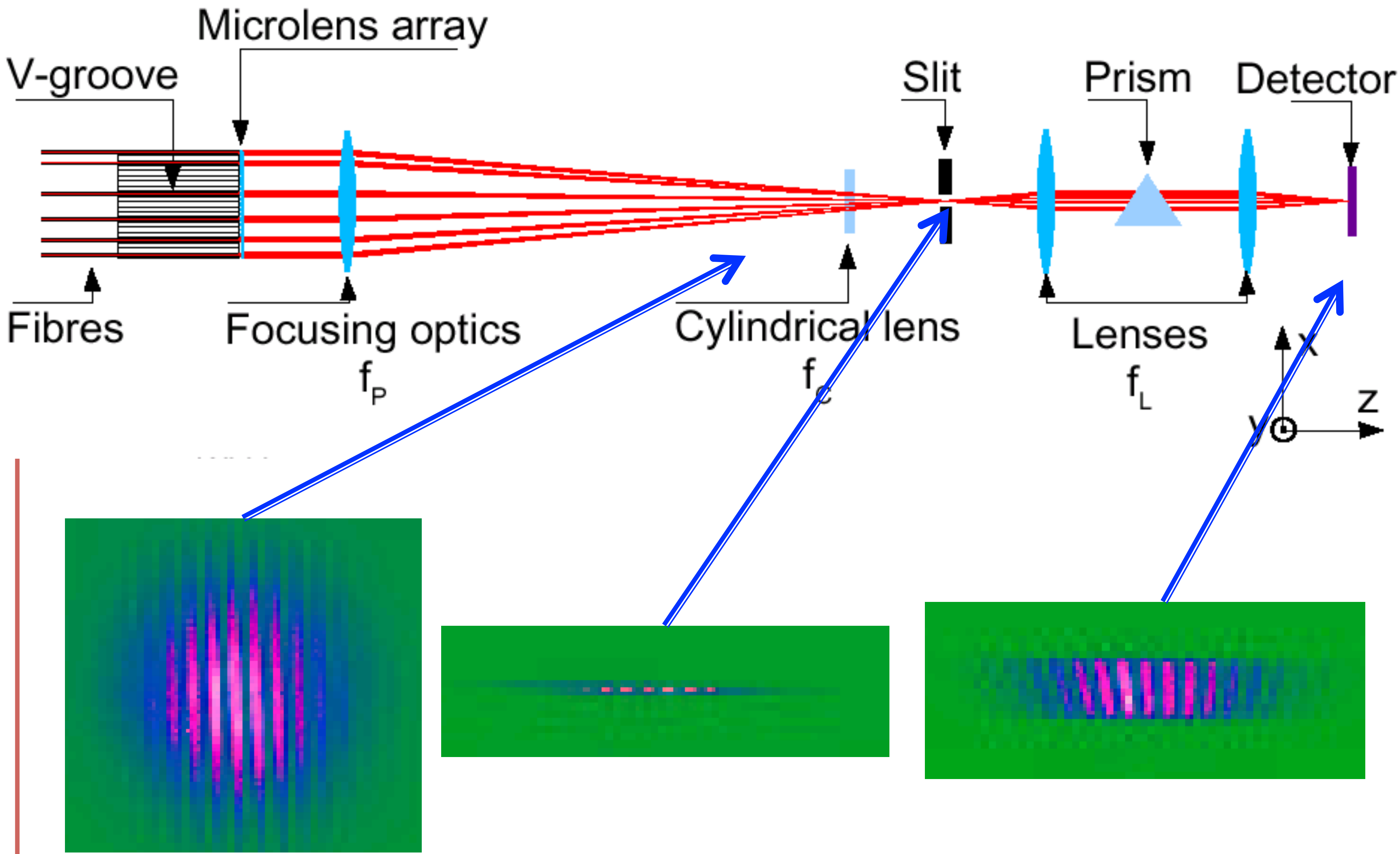
1) Maximum Calibration Precision for Closure Phases
2) Imaging

- Infrared Sensitivity (H/K, 1.45-2.4 microns)
- Image Plane All-in-One Combination for 4 → 6 telescopes
- Spectral Dispersion: R~42, 150, 450
- Spatial Filtering with SM Fibers (w/ photometric taps)

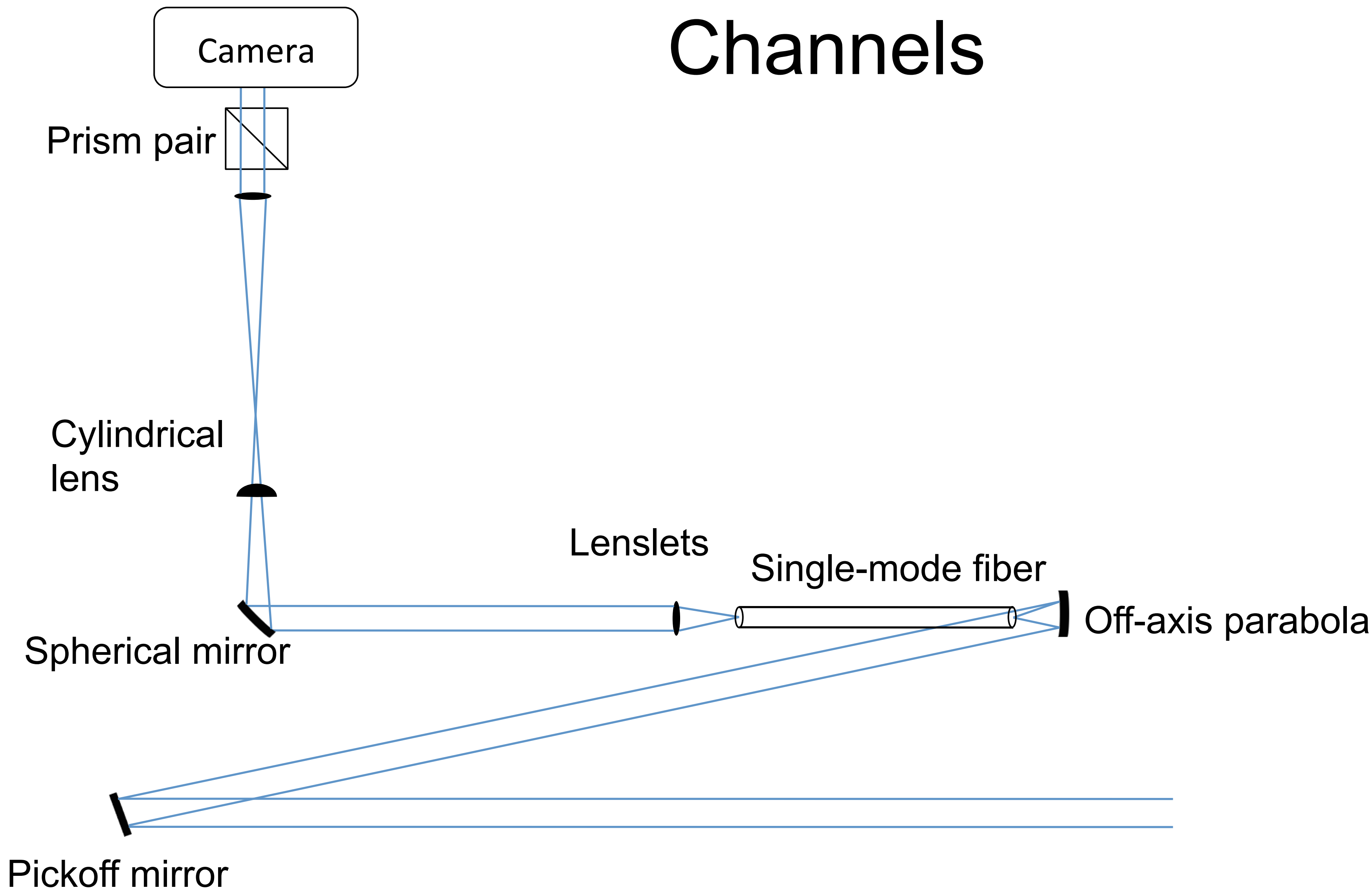

CHARA
Georgia State University
baseline

Optical Layout

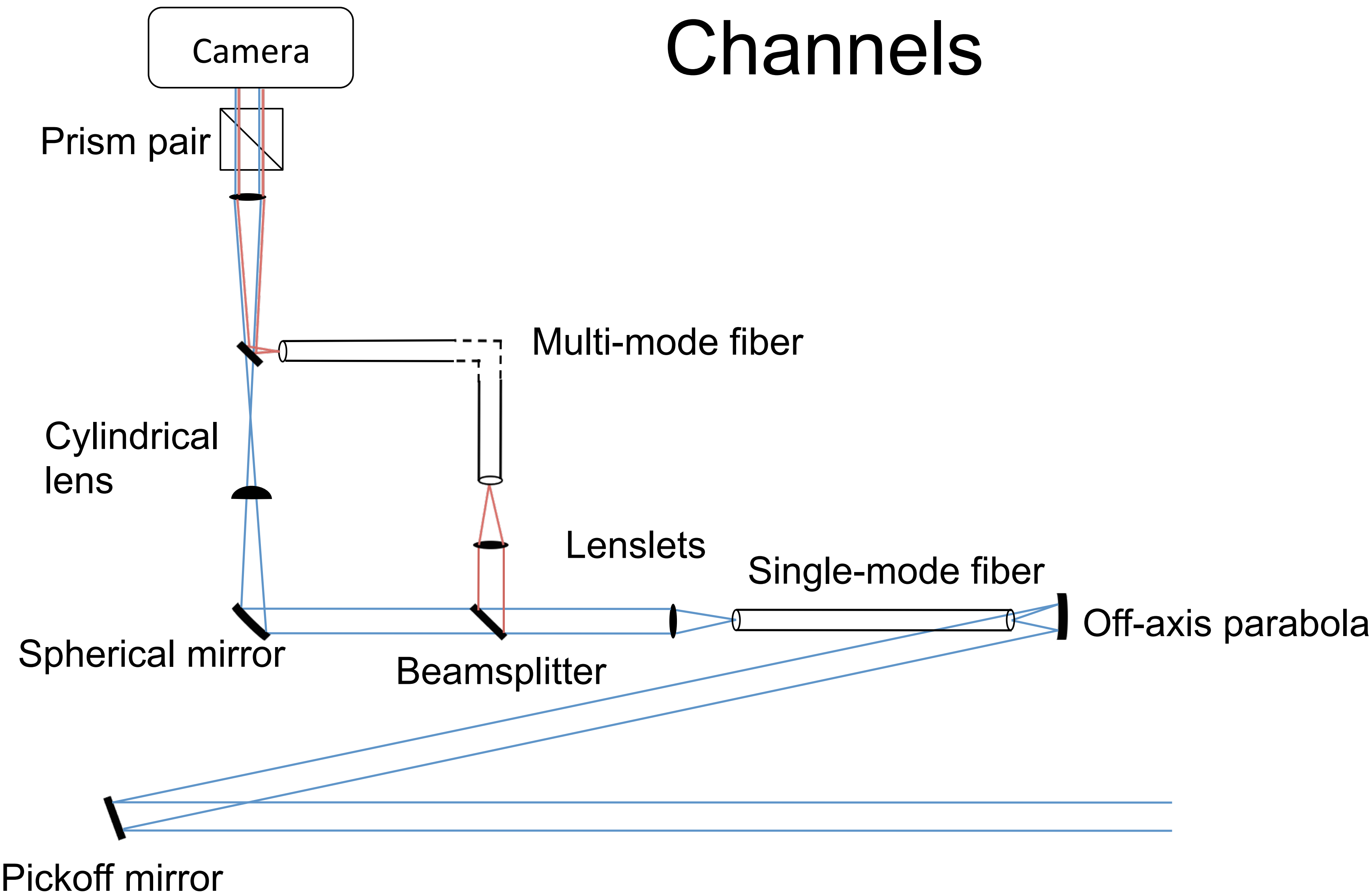



Microlens array
V-groove
Slit
Prism
Detector
Fibres
Focusing optics
fP
Cylindrical lens
fC
Lenses
fL
x
z
y

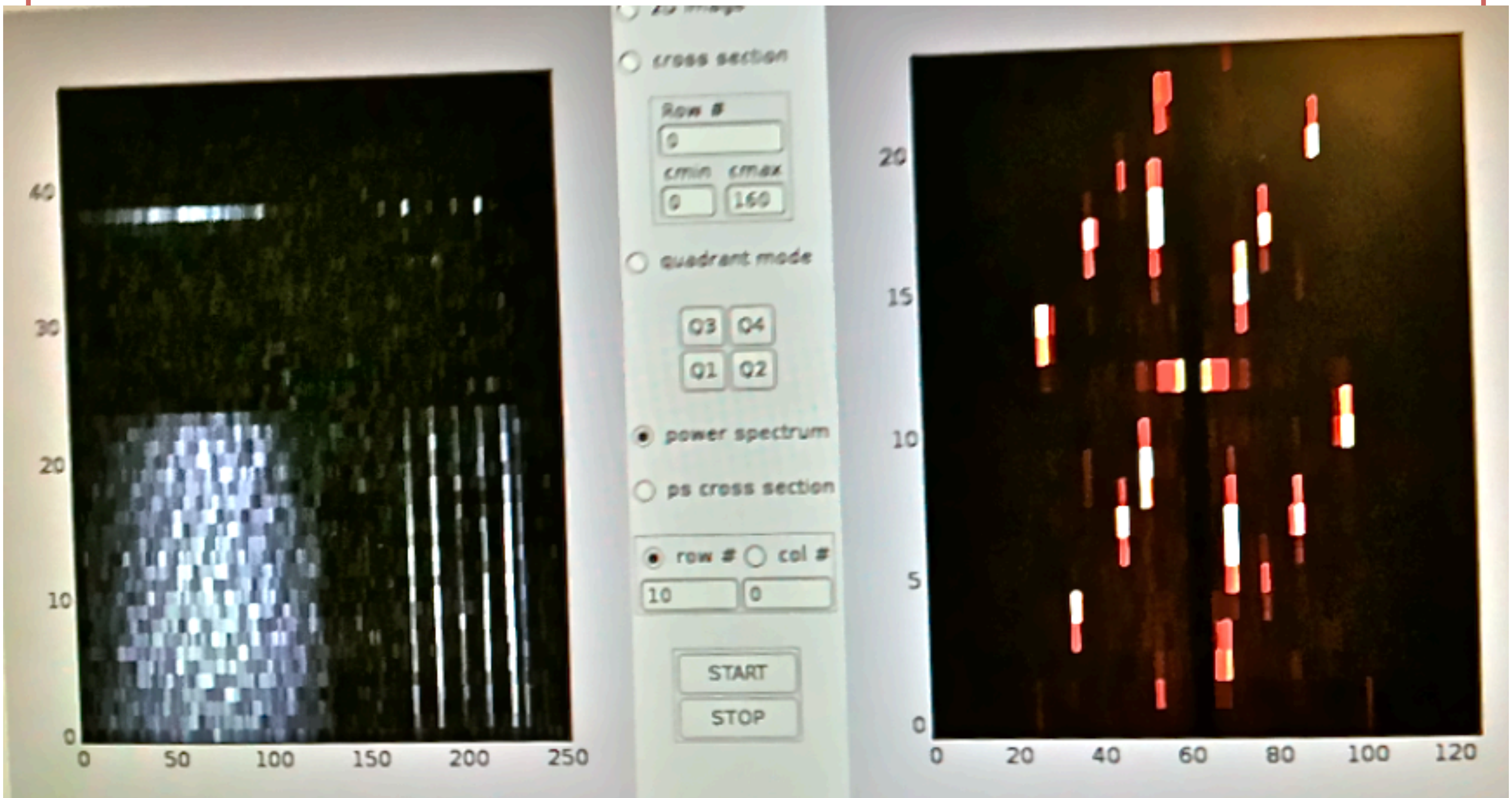
Photometric Channels



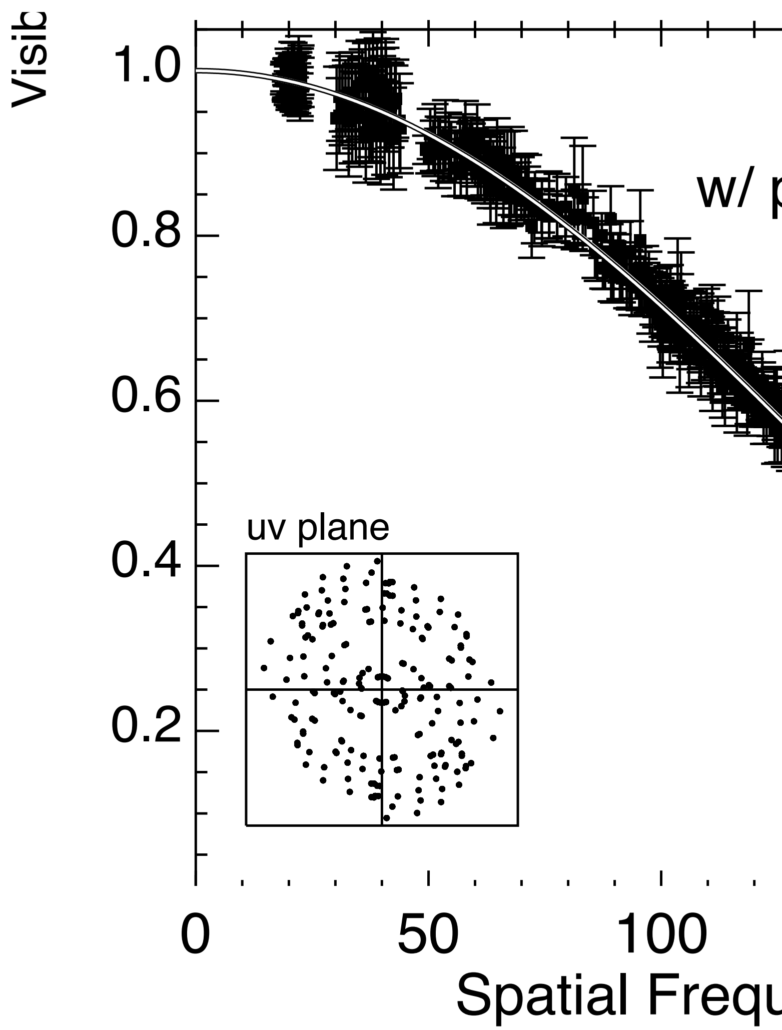
Photometric Channels



Fringes and Photometric Channels on detector



Xiao Che's PhD project radically improved data quality and quantity! (MIRC4 -> MIRC6+photometric channels)



Precision Stellar Parameters

Interferometry, Stellar Evolution, asteroseismology

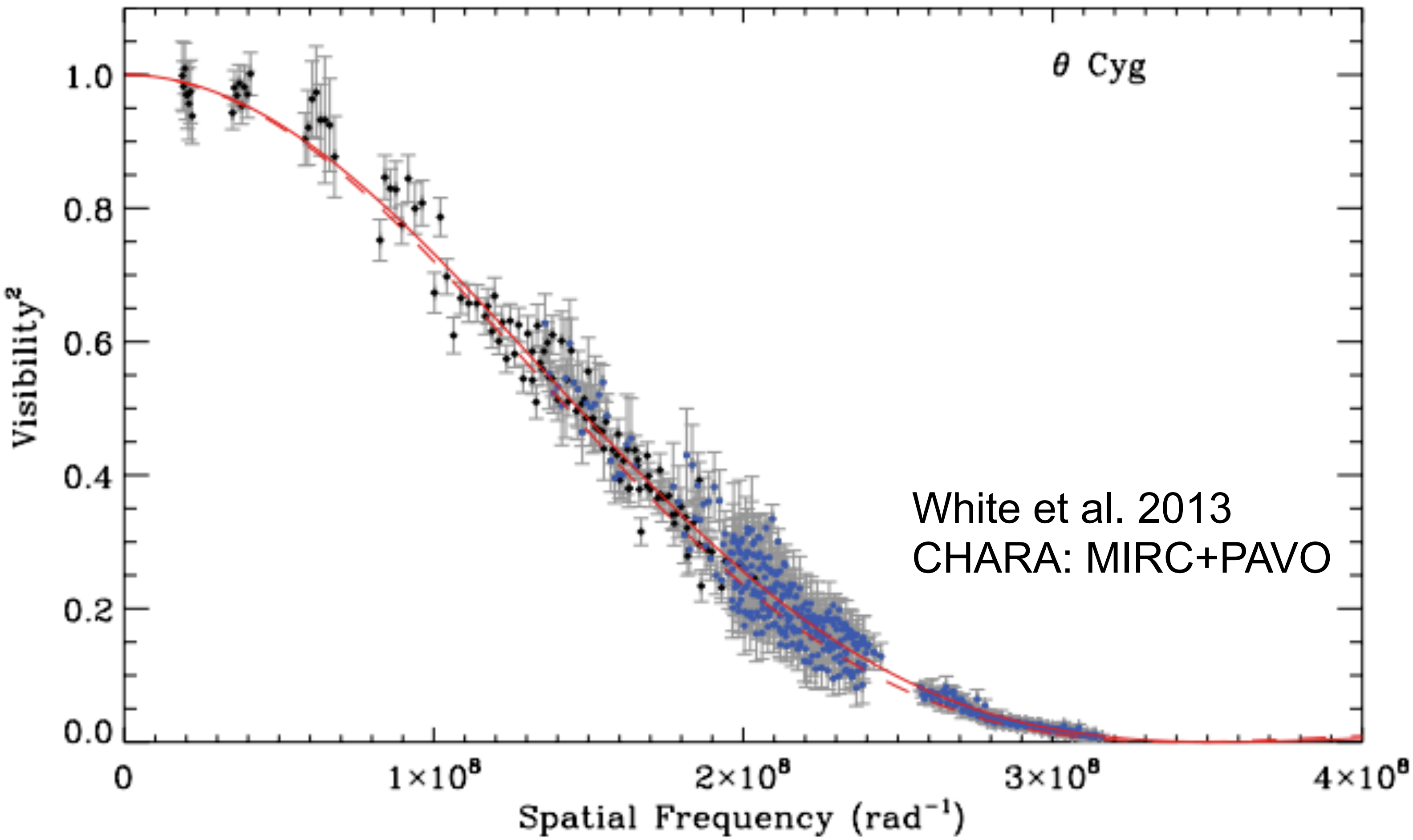
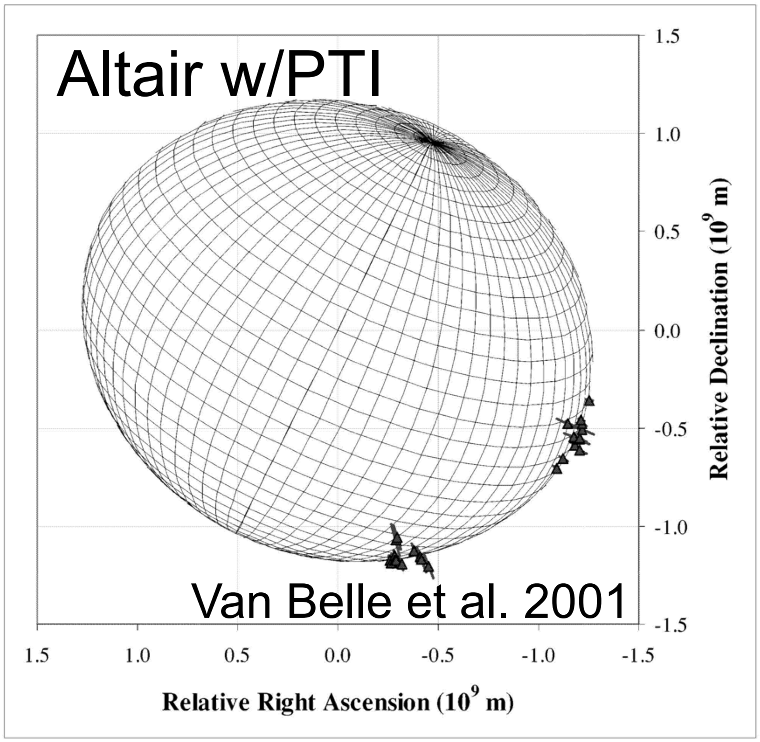


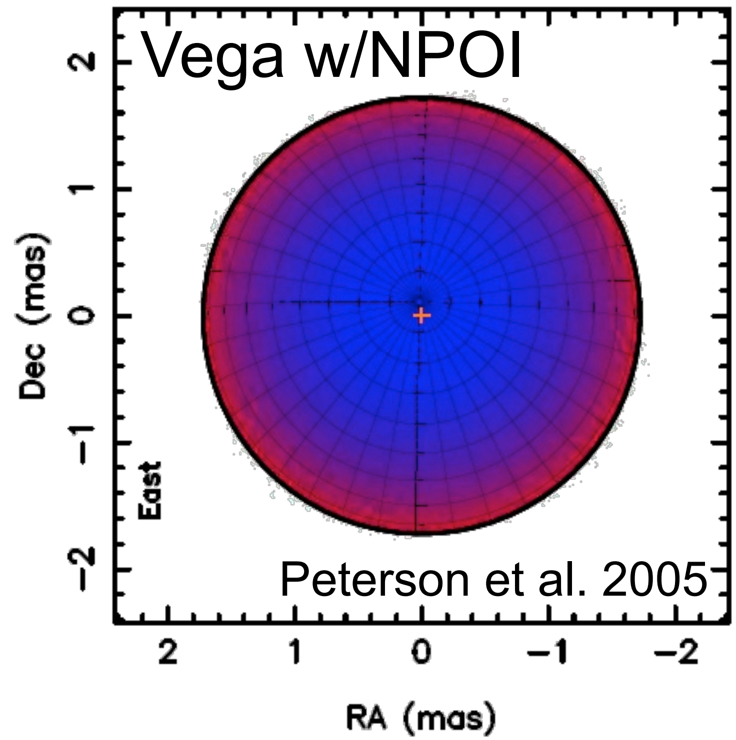
Figure 1. Squared visibility versus spatial frequency for θ Cyg for PAVO (blue circles) and MIRC (black diamonds) data. The red lines show the fitted limb-darkened model to the combined data. The solid line is for $\mu = 0.47 \pm 0.04$ (PAVO) while the dashed line is for $\mu = 0.21 \pm 0.03$ (MIRC).

Imaging Stellar Surfaces: Resolving Rapid Rotation

- Rapid rotation of hot stars is expected to
  - Distort stellar photosphere
  - Cause "gravity darkening" along the stellar equator (von Zeipel 1924)
  - Modify interior angular momentum and differential rotation
- Importance in many areas
  - Rotation-induced mixing (Pinsonneault 1997)
  - Interpretation of H-R diagram (Maeder & Maynet 2000)
  - Affects circum-stellar environments
  - Truth test for interior models of massive stars

Models of rotating stars: first look with interferometers



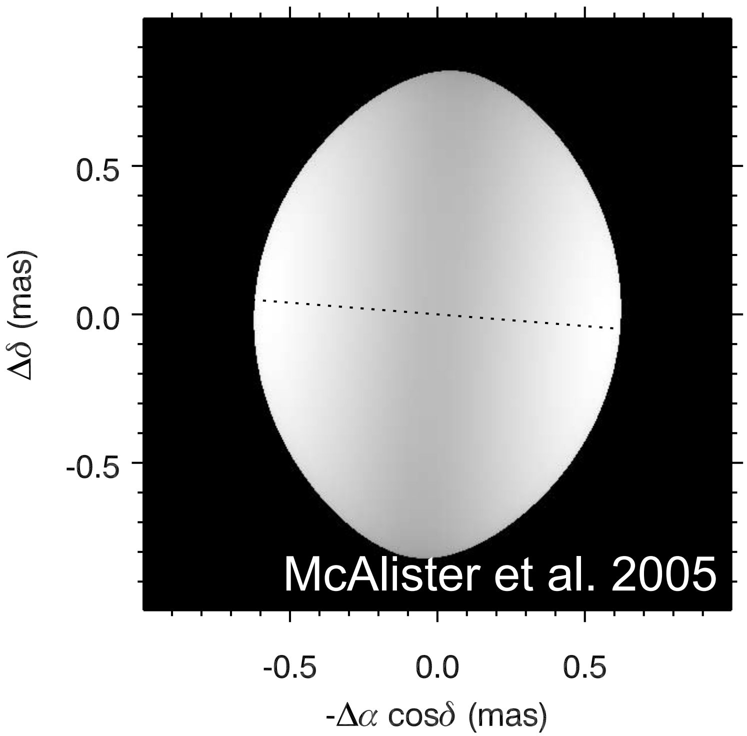


rotating at ~92% of breakup
- observed to 14% elongated
- van Belle et al (2001) using PTI

rotating at ~91% of breakup
- Peterson et al (2005) using NPOI
- Aufdenberg et al (2006) using CHARA
- Modified by Monnier et al. (2012)

More models of rapid rotation

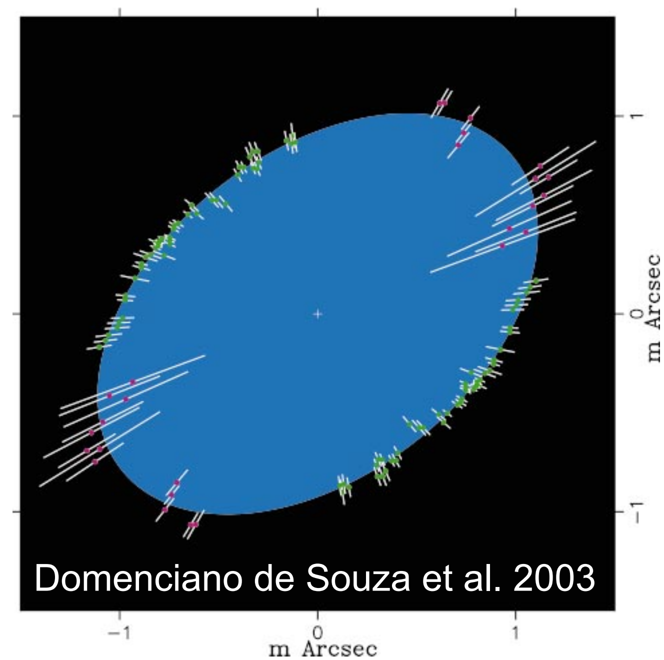
Regulus w/CHARA



rotating at ~98% of breakup

– Gravity darkening β~0.25±0.11

Achernar w/VLTI

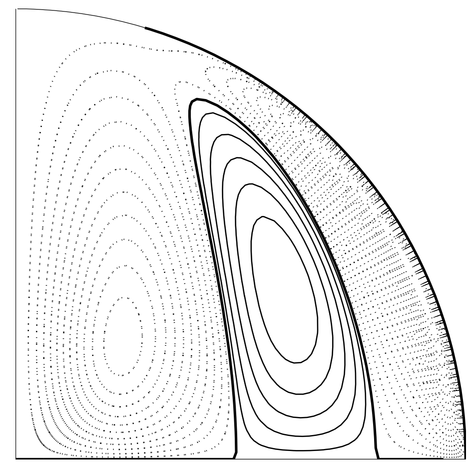


Major / Minor = 1.56

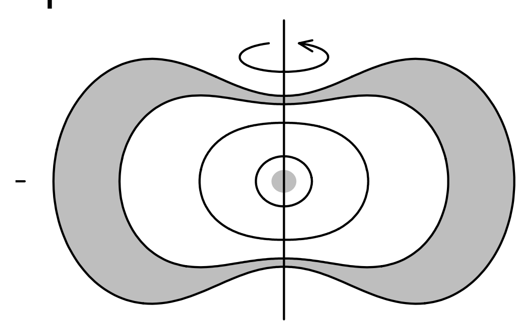
– Impossibly elongated based on classic Roche potential
– Be Disk emission?

Motivation for imaging

- Modeling results are "model dependent"
  - Von Zeipel (1924): solid body rotation, point gravity, simplistic radiative transfer model for outer layers
- Hydrodynamic modeling suggests complications..
  - Meridional circulation
  - Radial & latitudinal differential rotation
  - E.g., Jackson et al. 2004; MacGregor 2007; Espinosa Lara & Rieutord 2007; and many since
- "Model-Independent" imaging can test wider class of models



Espinosa Lara & Rieutord 2007

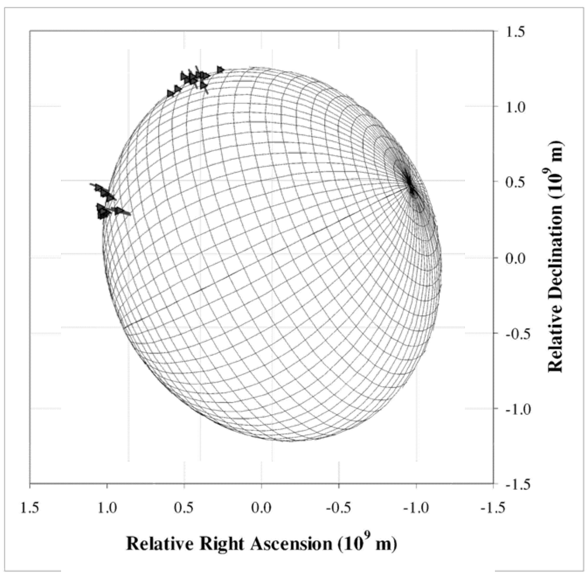


MacGregor 2007

First image of a main-sequence star
(besides the Sun…)

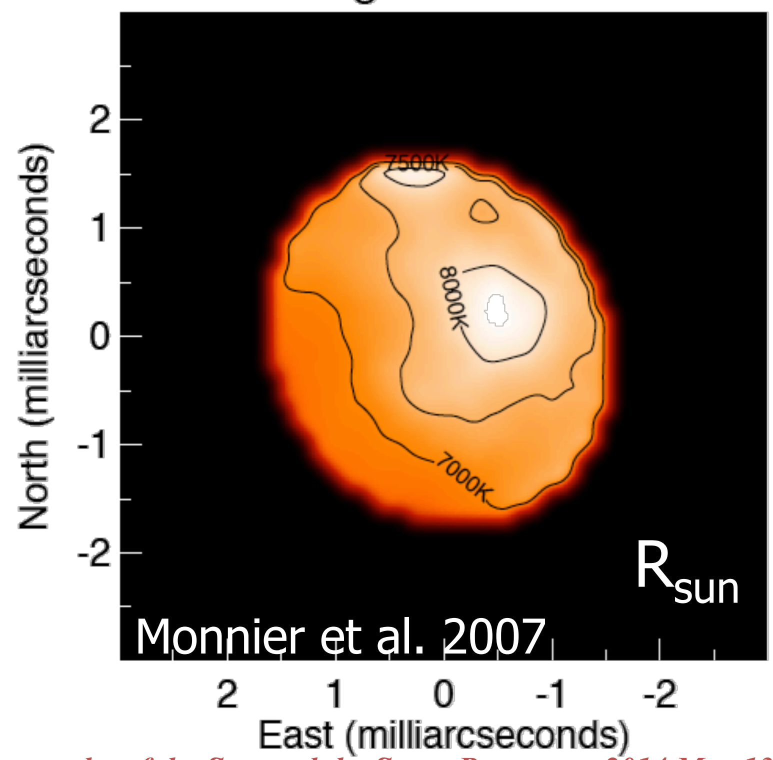
- Altair (α Aql, V=0.7)
  - Nearby hot star (d=5.1pc, SType A7V, T=7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)

14% elongated

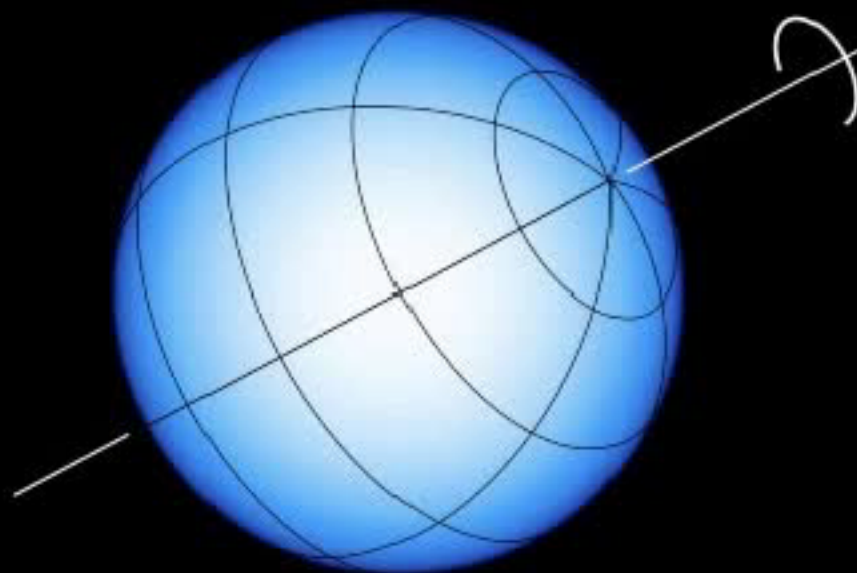


Van Belle et al. 2001
(corrected)

Altair Image Reconstruction



Model of a fast-spinning star



0.1 revolutions/day

Modeling and Animation by Ming Zhao

Scrutinizing von Zeipel Theory

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

Surface temperature

Effective gravity

HOT stars
(von Zeipel 1924)

$$\beta = 0.25 \ radiative$$

$$\beta = 0.08 \ convective$$

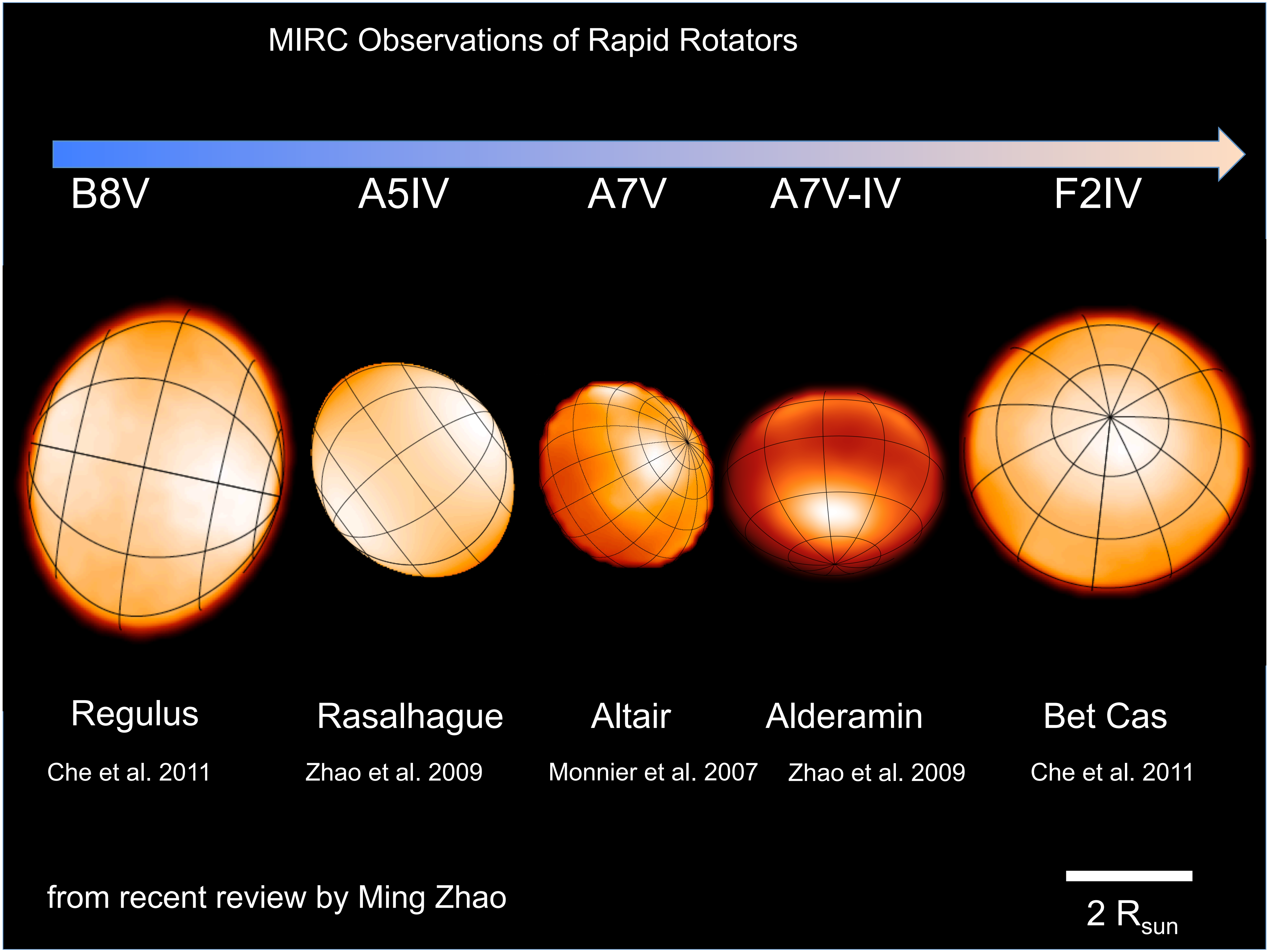
Cool stars
(Lucy 1967)

- Our model-independent image bears striking resemblance to model prediction
  - Distortion and gravity darkening robustly confirmed

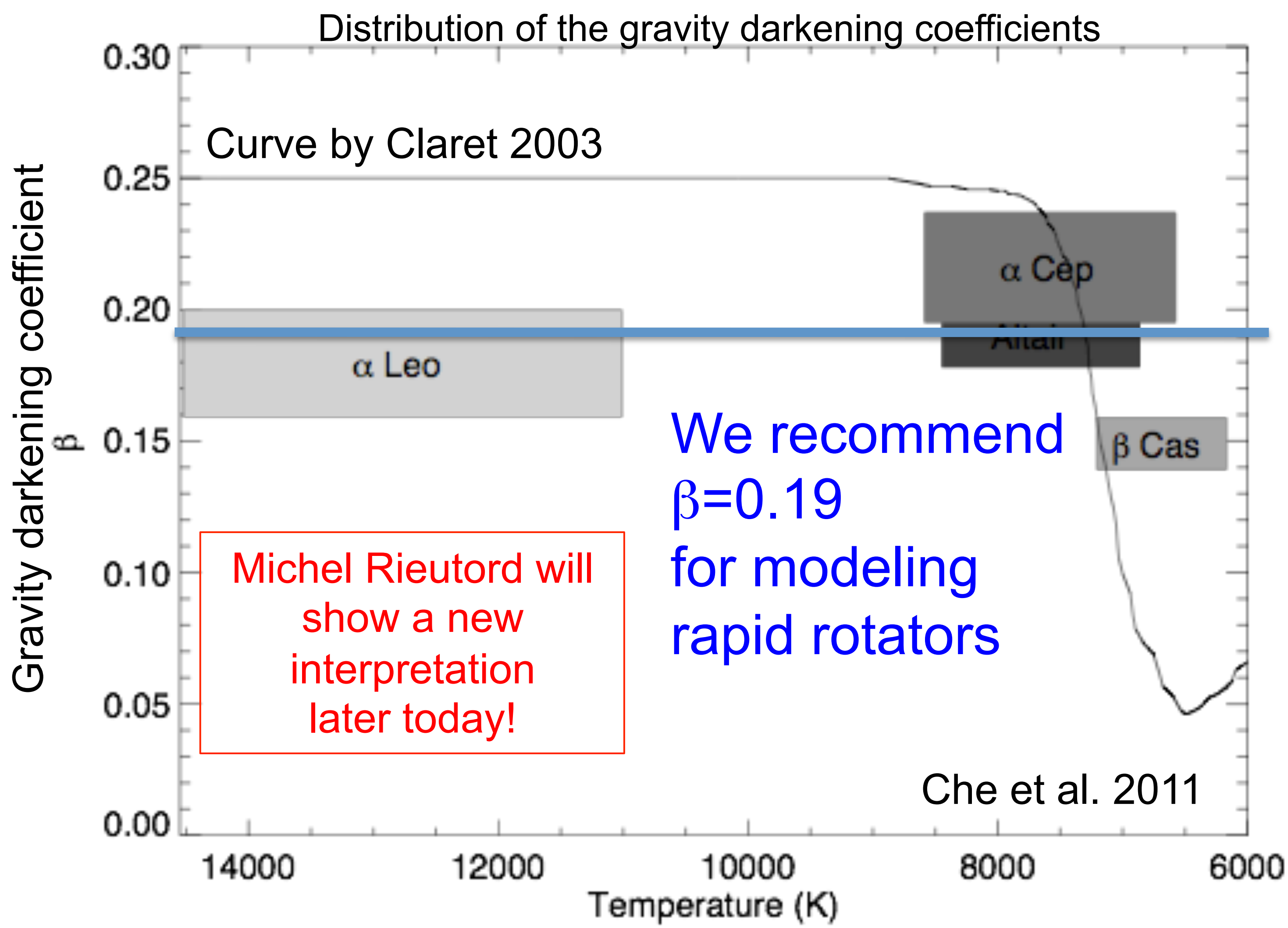
- Temperature profiles more consistent with β=0.19, compared to β=0.25 from theory
  - Equator is convective? Equator is <7000K
  - Differential Rotation?
  - Meridional flows?

Extending the Sample

Star	Spectral Type	Appox. Teff
Regulus (α Leo)	B8IV	11900K
Vega (α Lyr)	A0V	9520K
Denebola (β Leo)	A3V	8720K
Rasalhague (α Oph)	A5IV	8200K
Altair (α Aql)	A7V	7850K
Alderamin (α Cep)	A7IV-V	7850K
Caph (β Cas)	F2 IV	6890K

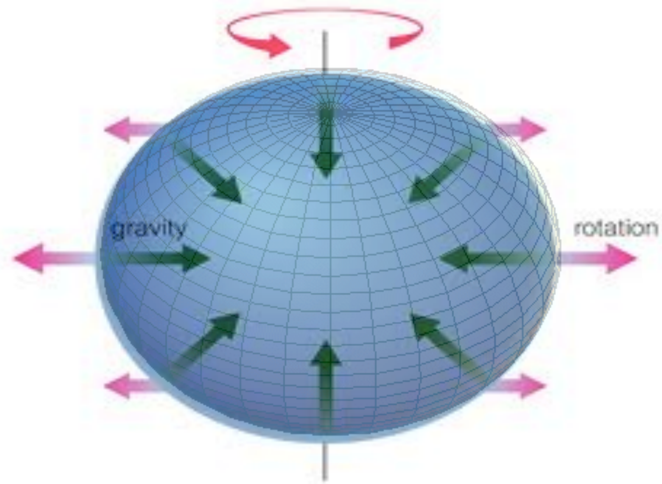

MIRC Observations of Rapid Rotators
B8V
A5IV
A7V
A7V-IV
F2IV
Regulus
Rasalhague
Altair
Alderamin
Bet Cas
Che et al. 2011
Zhao et al. 2009
Monnier et al. 2007
Zhao et al. 2009
Che et al. 2011
from recent review by Ming Zhao
2 R_{sun}

Scrutinizing von Zeipel Theory



New Method to Measure Mass of Single Star

- Oblateness depends only on dimensionless ratio between surface gravity and centrifugal force
- Spectroscopy (v sin i) + interferometry (inclination, oblateness) => Mass



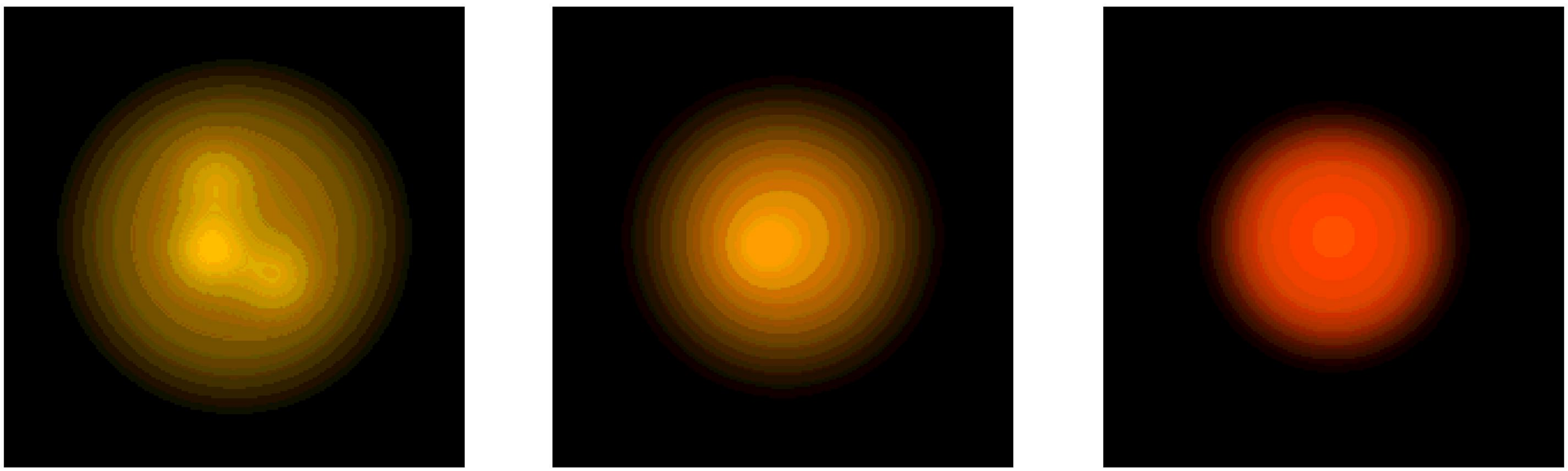
Example β Cas

H-R diagram: 1.89+/-0.03 Msun (+/- systematics)	Oblateness Method: 1.82 +0.10 Msun (limited by model)

What about other stars?

Betelgeuse (COAST Interferometer)

700 nm | 905 nm | 1290 nm



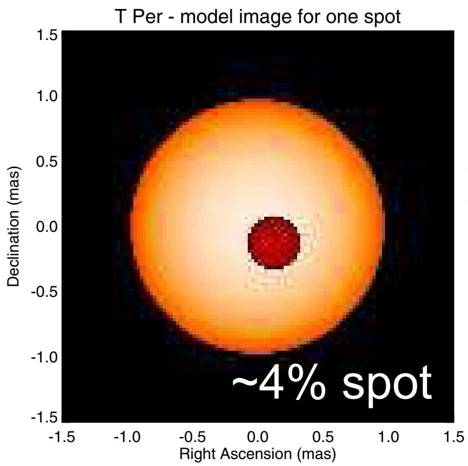
15 Nov 97 | 21 Nov 97 | 11 Nov 97

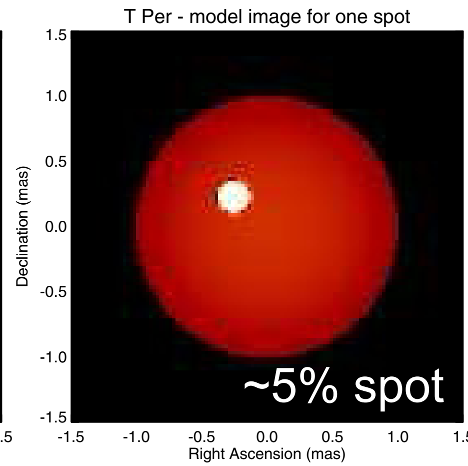
Young et al. 2000

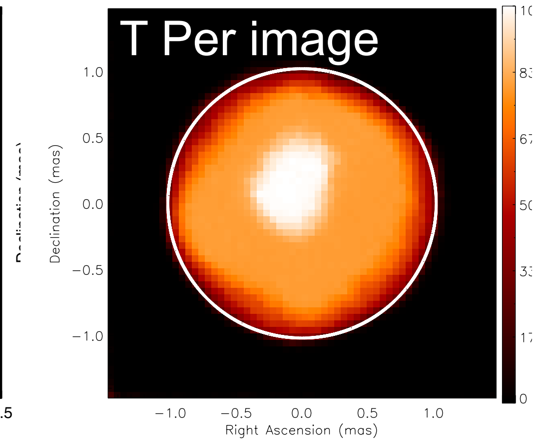
MIRC Red Supergiants

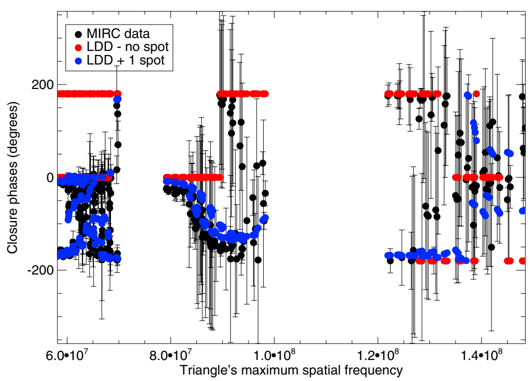
Single-spot models

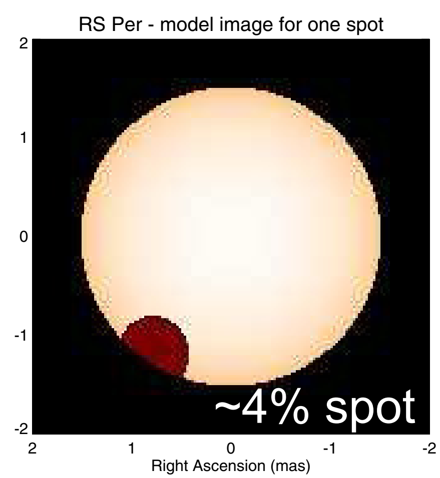
Imaging

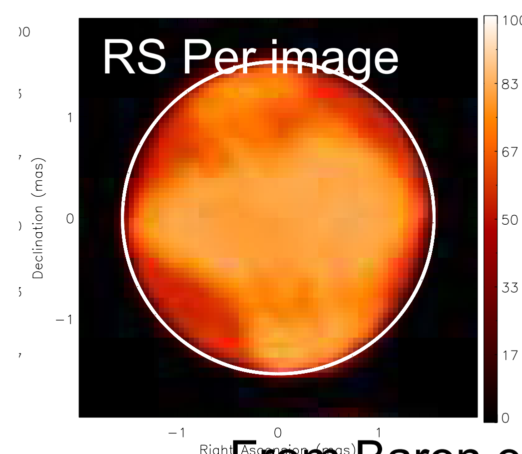








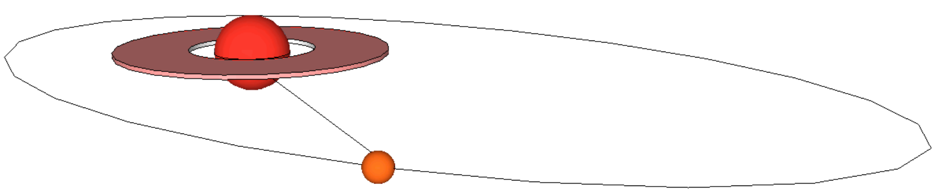


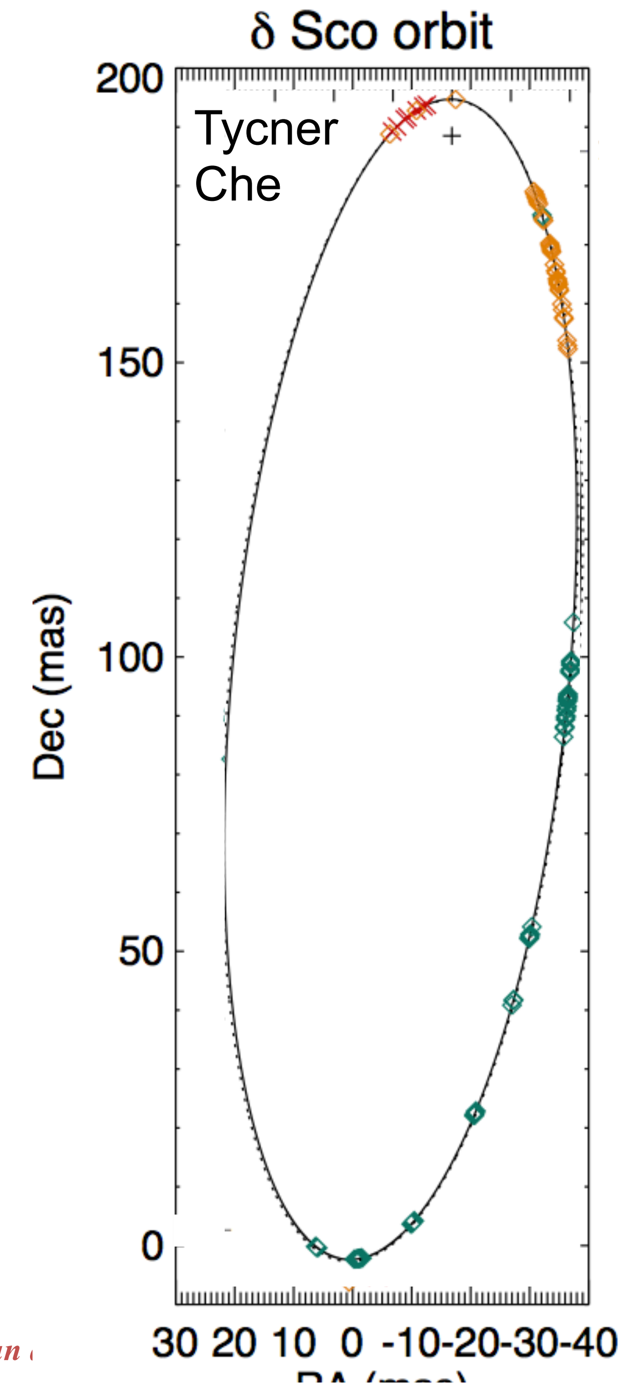


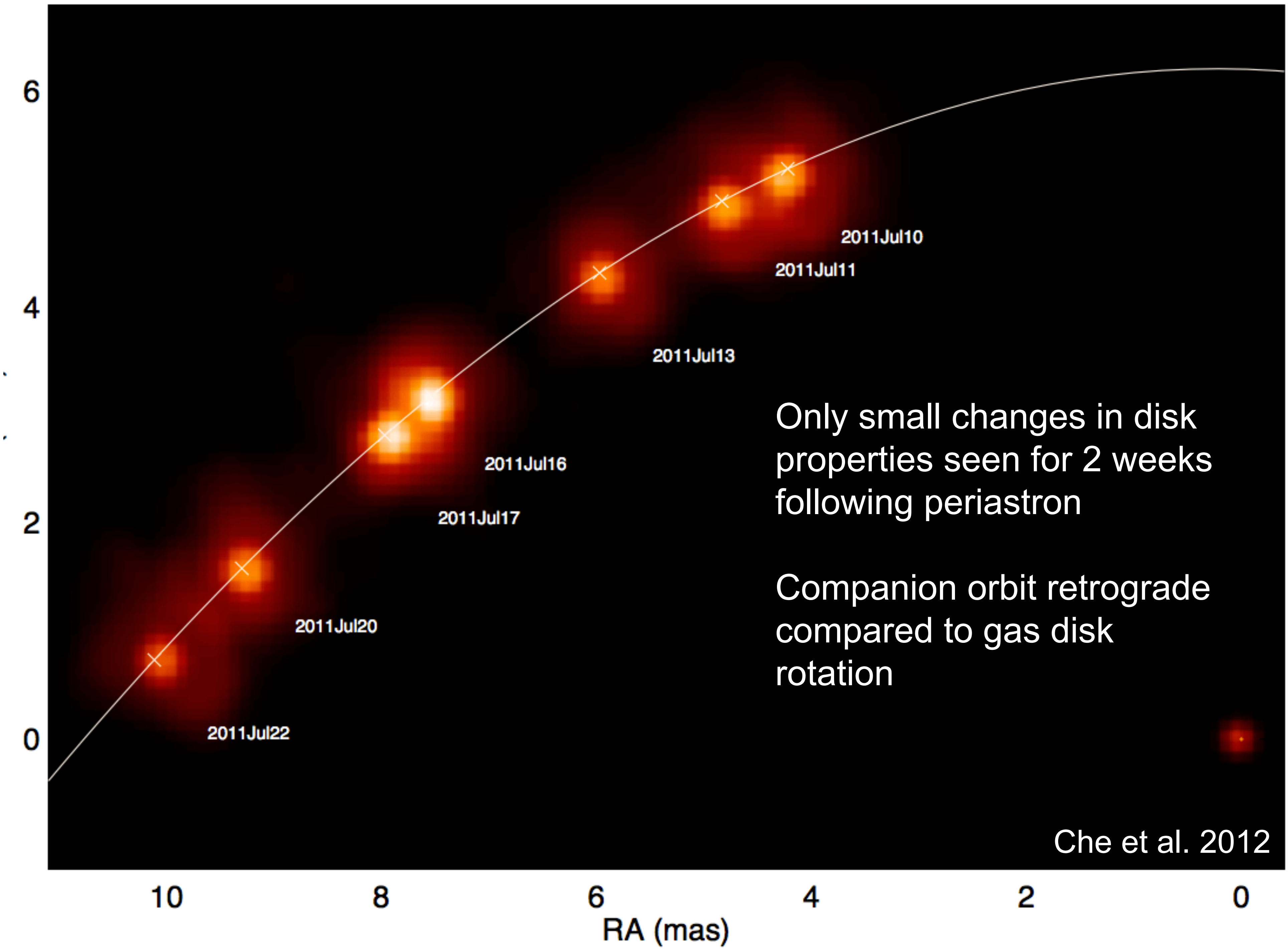
From Baron et al. 2014

Delta Sco

- Be binary: B0.5Ve + B2V
- High eccentricity: ~ 0.94
- Period: ~ 10 years
- Gas disk grew strong just after periastron passage in 2001
- What about this time ?

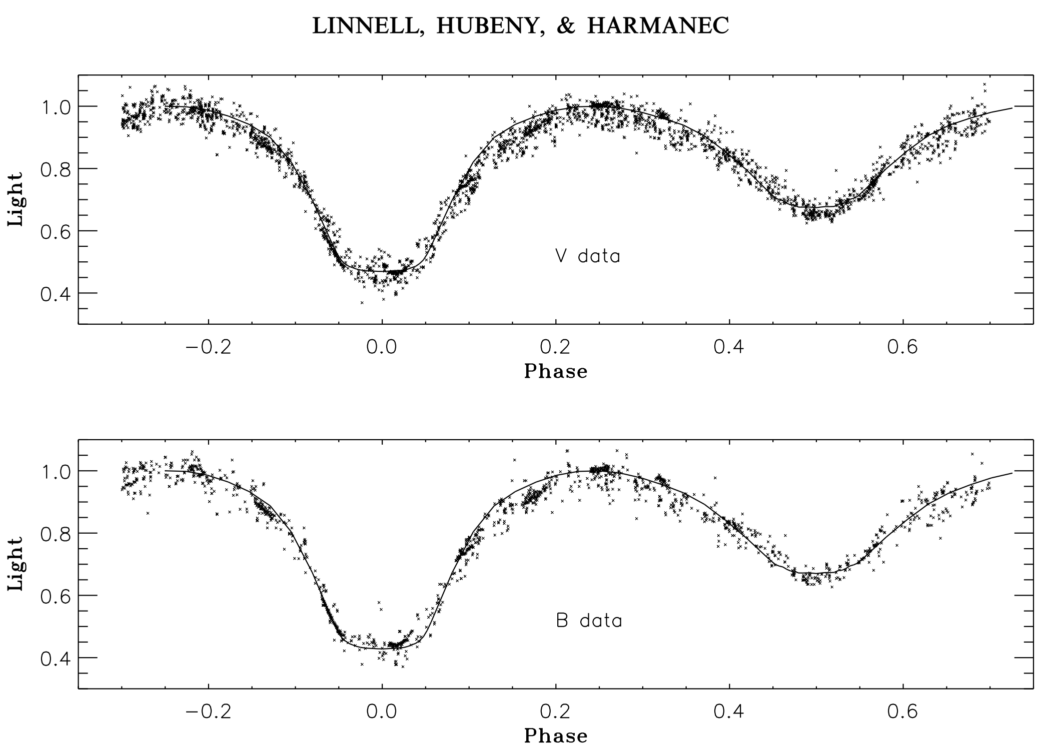


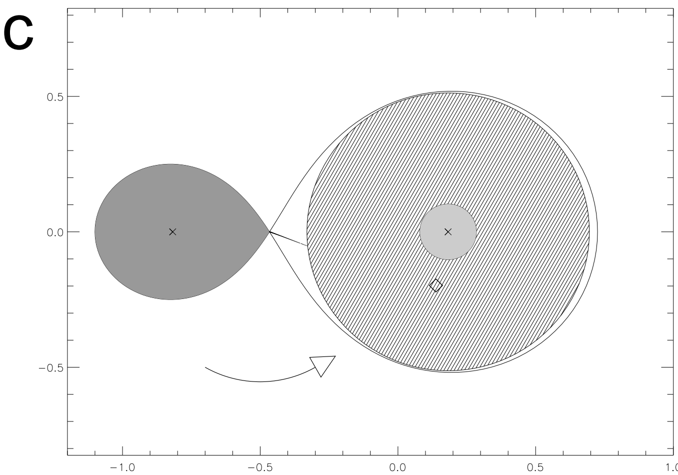


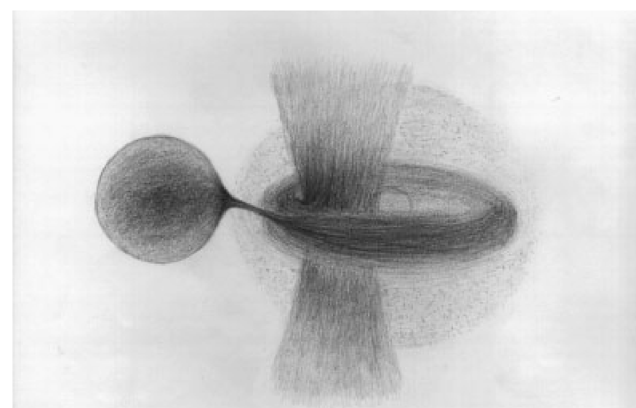

6
4
2
0
2011Jul10
2011Jul11
2011Jul13
2011Jul16
2011Jul17
2011Jul20
2011Jul22
Only small changes in disk properties seen for 2 weeks following periastron
Companion orbit retrograde compared to gas disk rotation
Che et al. 2012
10
8
6
4
2
0
RA (mas)

A well-known “β Lyrae” system:

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

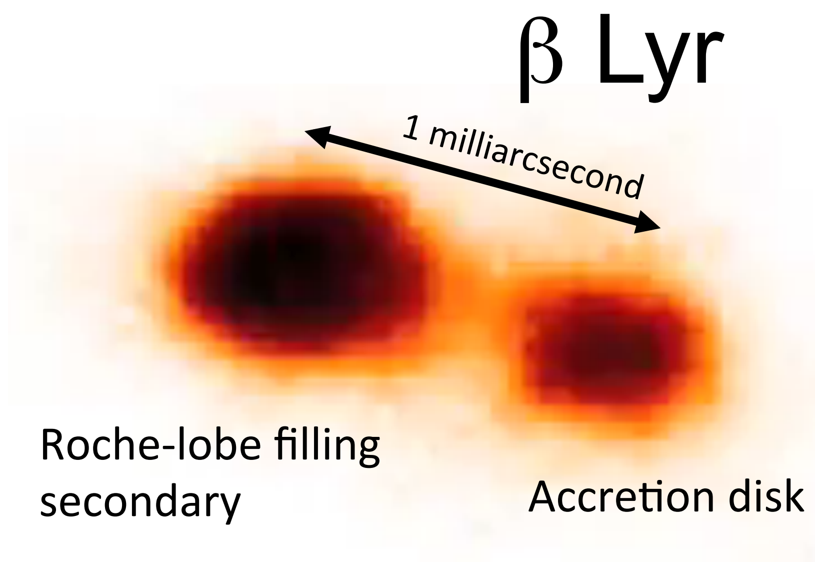






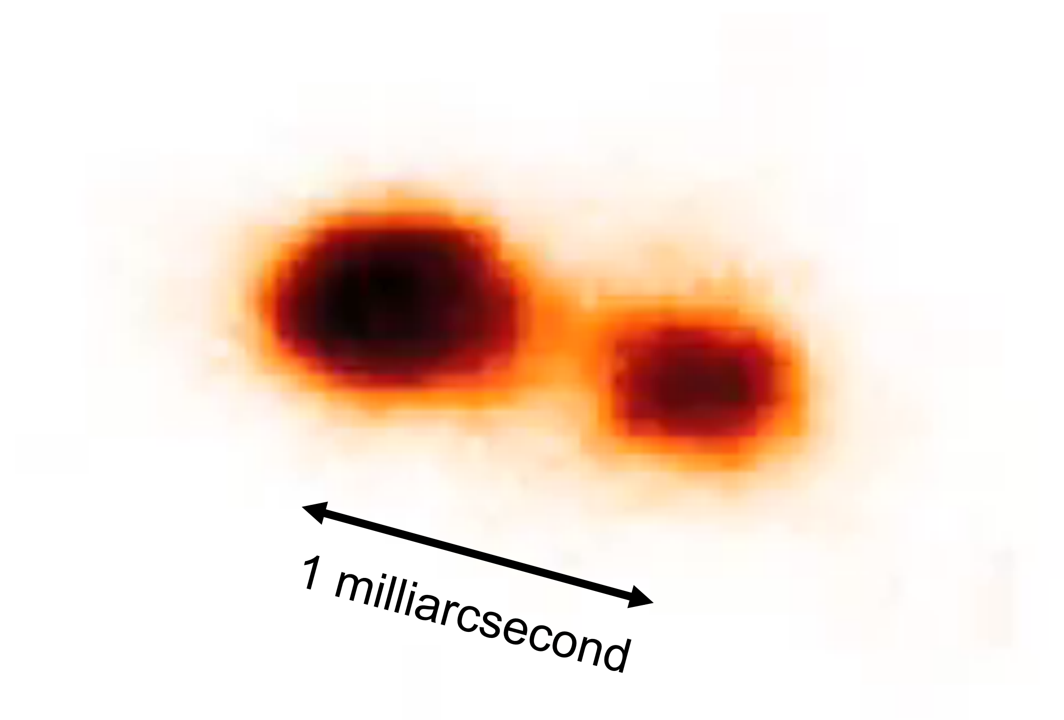
Linnell et al. 1998; Harmanec 2002

First Image of Interacting Binary



Zhao et al. 2008

First Movie of Interacting Binary

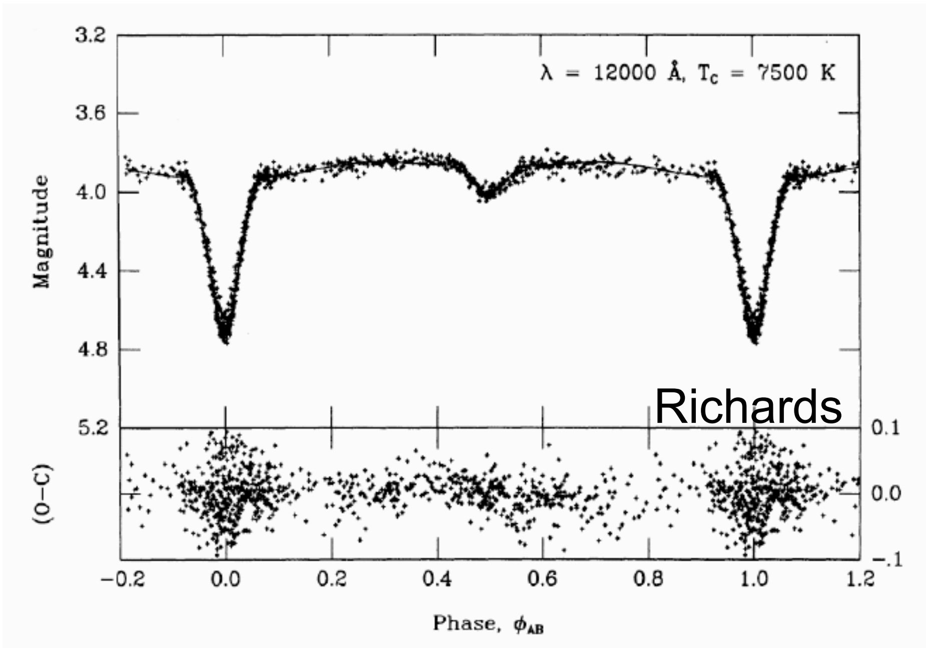


Zhao et al. 2008

Another Classic: Algol

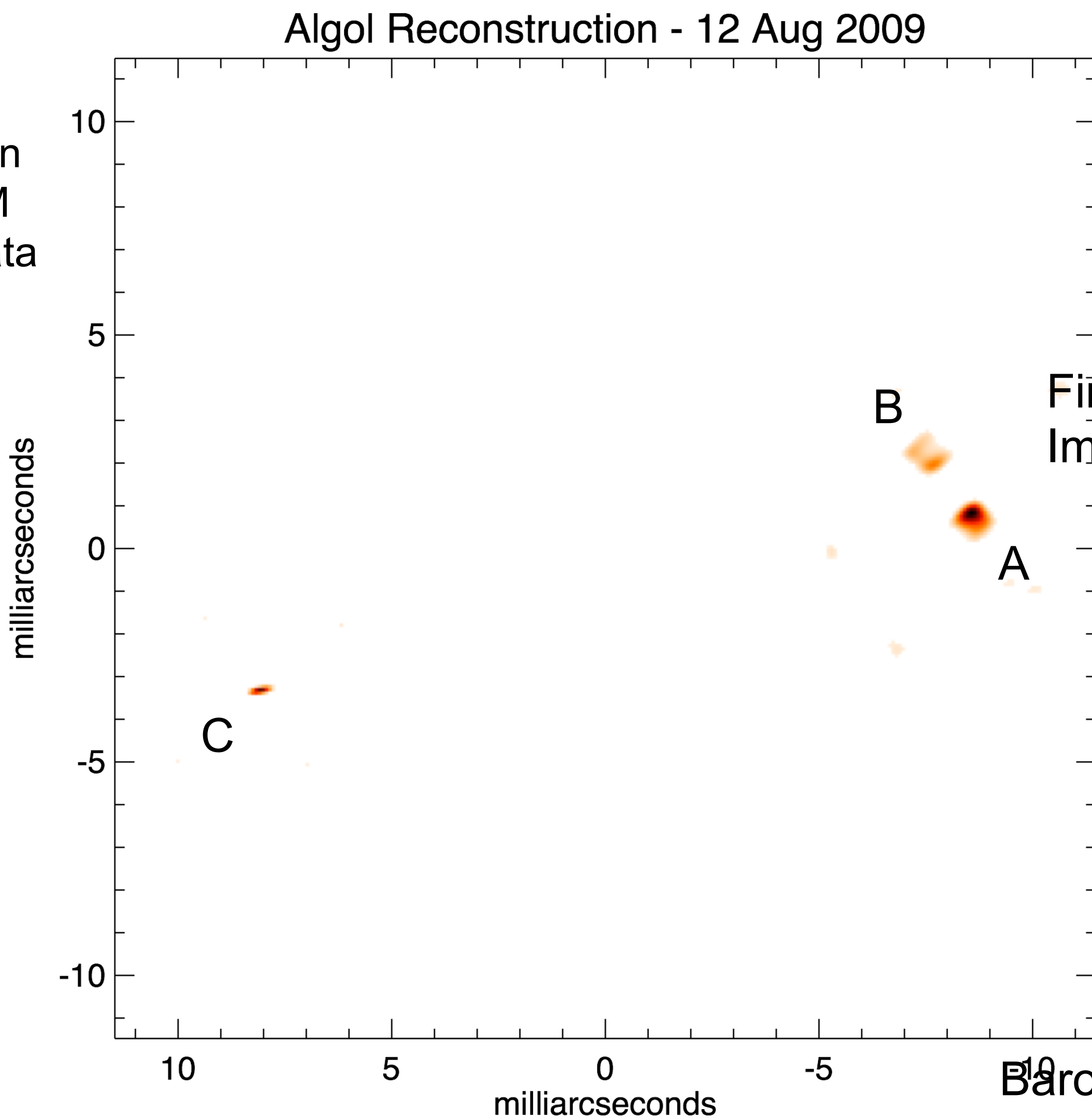
A-B in semi-detached "Algol type" system: Algol B fills its Roche Lobe, Algol A roughly spherical
P~2.87 days

Also has a wide companion Algol C: period 680 days



Algol Triple system

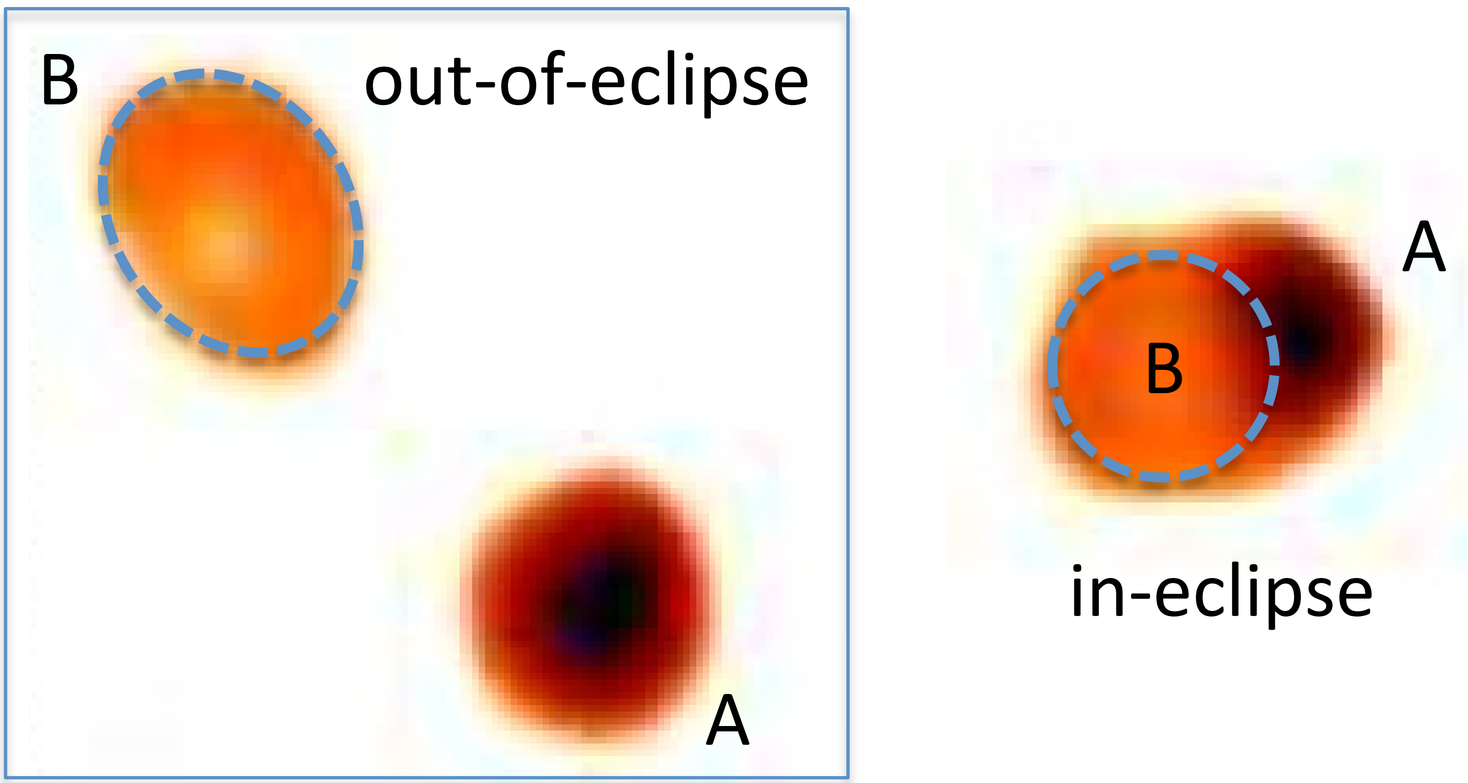
Image reconstruction with BSMEM from MIRC data



First fully-resolved Image of Algol AB

Baron et al. 2012

Algol Snapshots

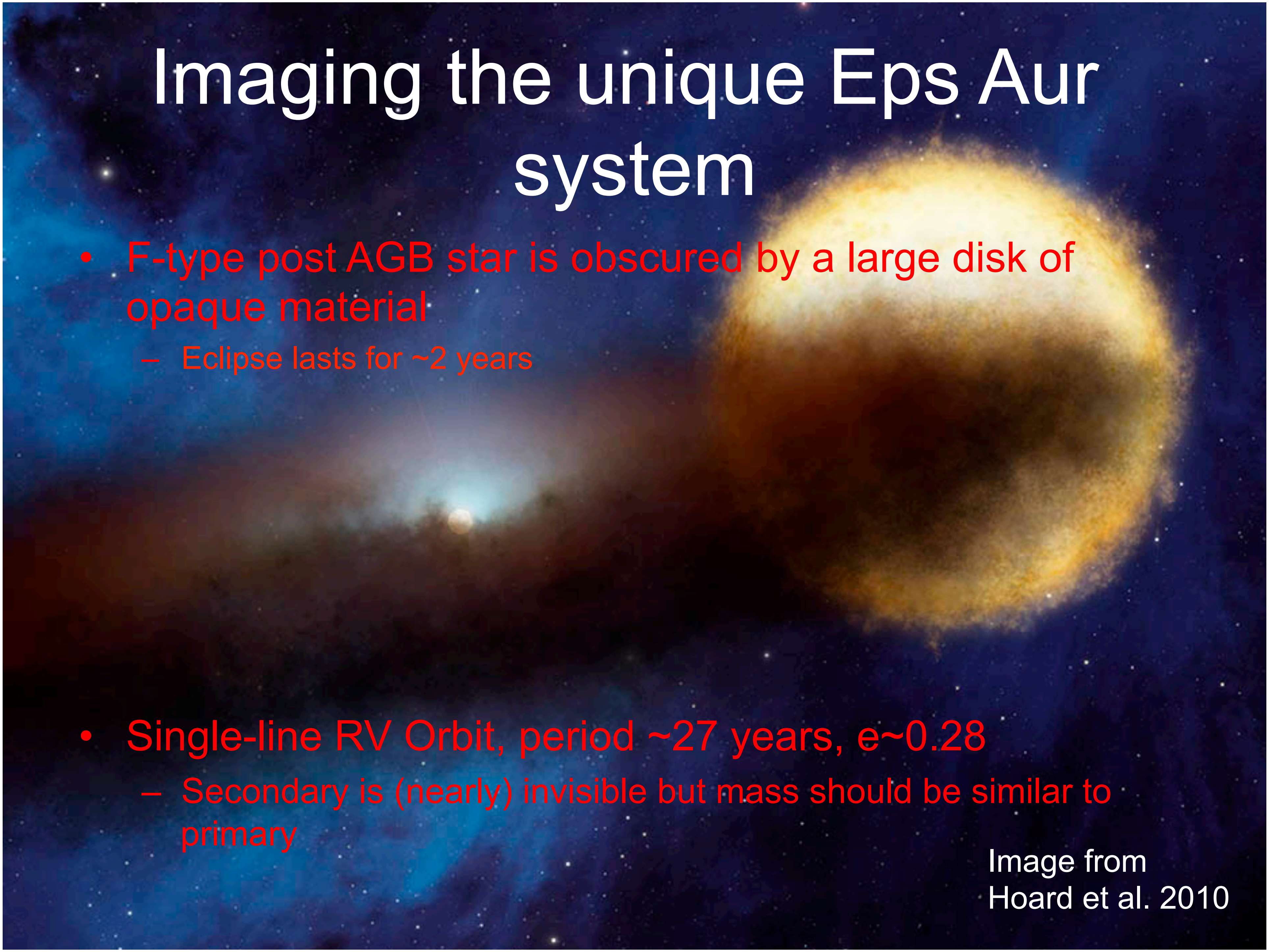


Baron et al. 2012

See movie of 55 epochs on wikipedia

Imaging the unique Eps Aur system

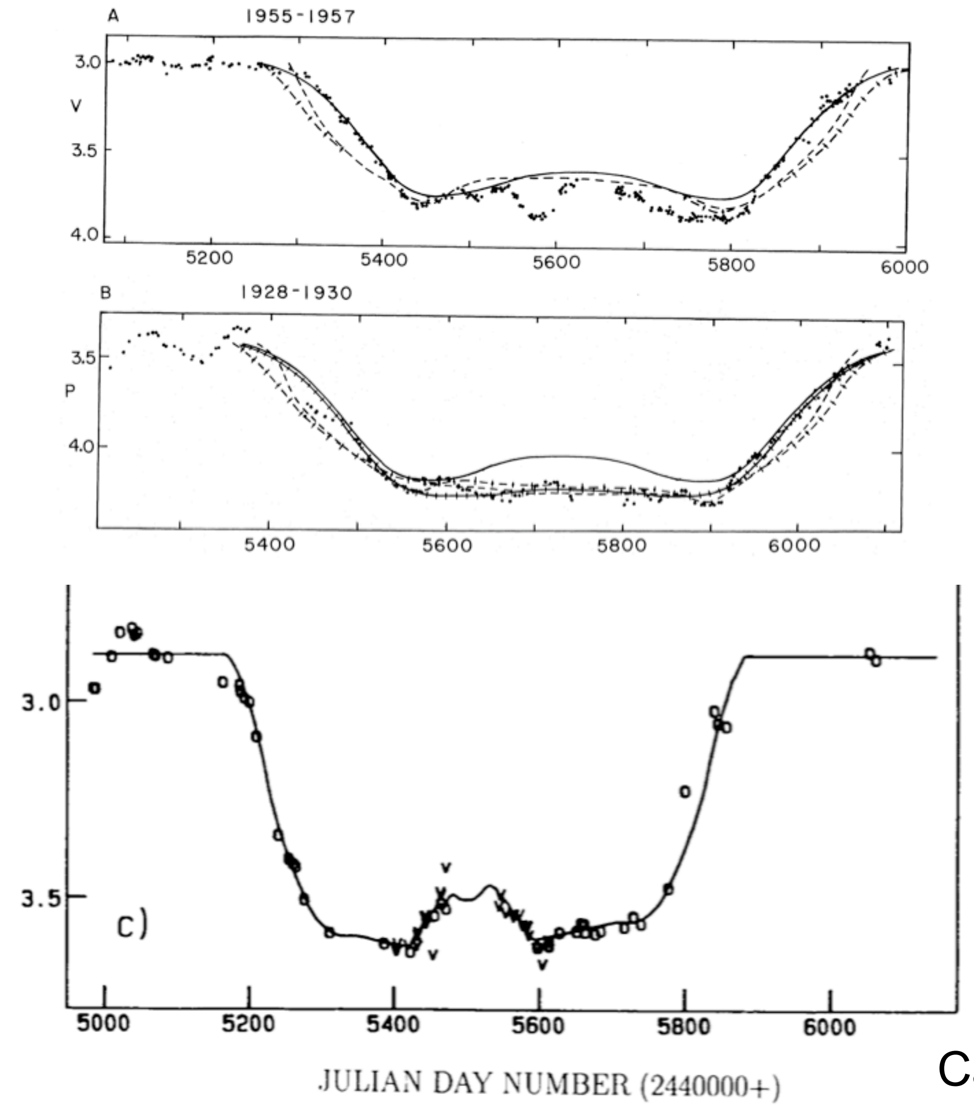
- F-type post AGB star is obscured by a large disk of opaque material
  - Eclipse lasts for ~2 years



- Single-line RV Orbit, period ~27 years, e~0.28
  - Secondary is (nearly) invisible but mass should be similar to primary

Image from
Hoard et al. 2010

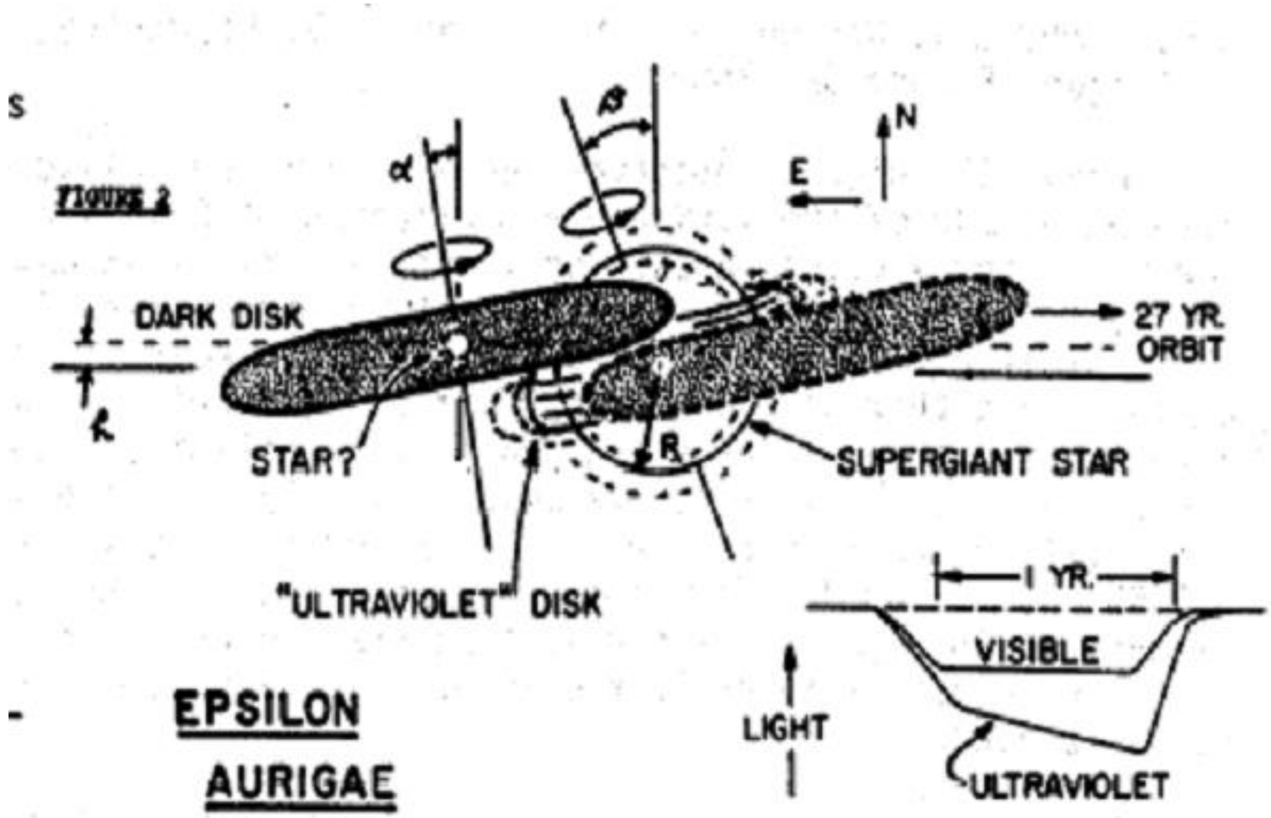
Recent eclipses of eps Aur



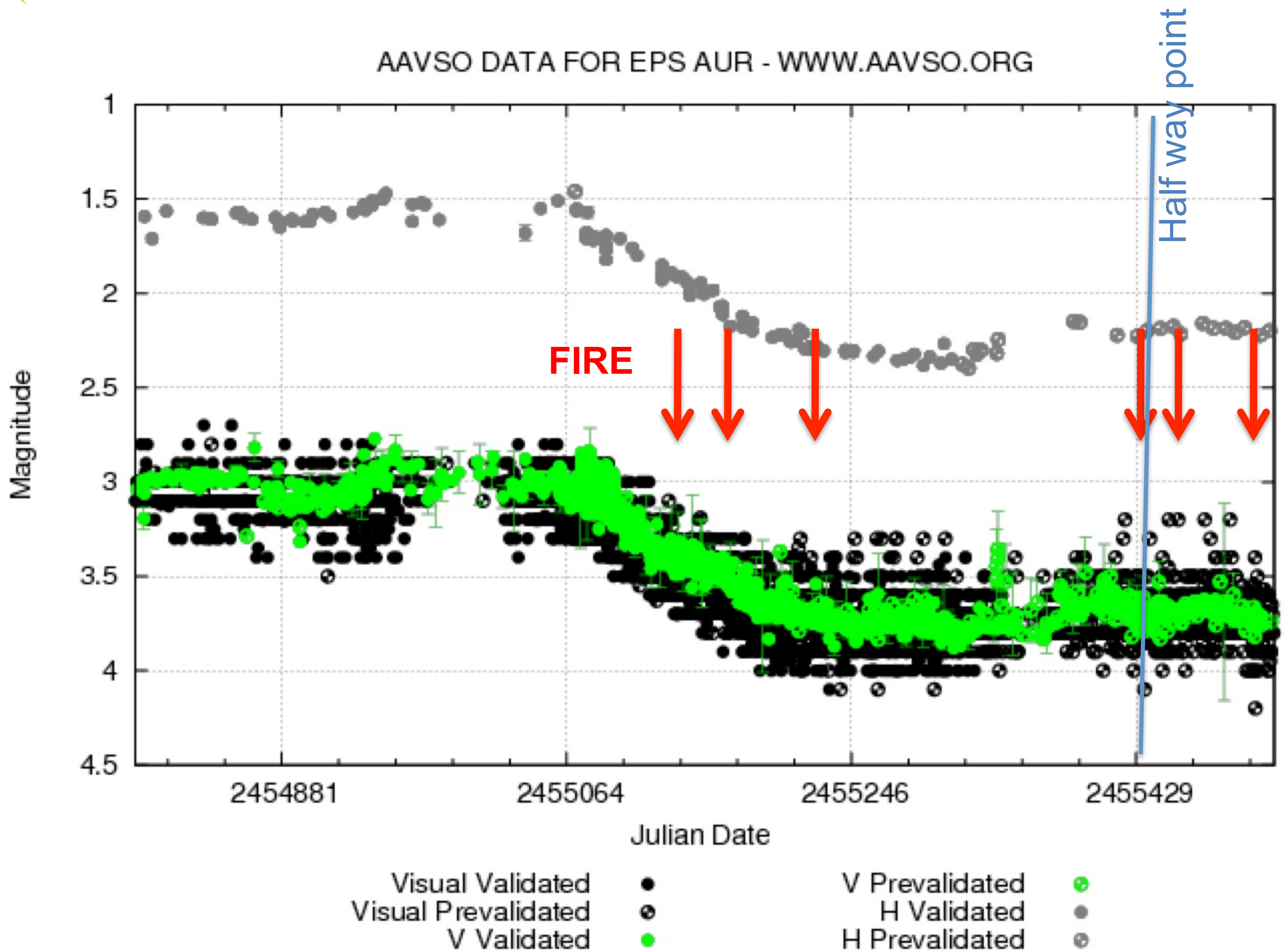
Huang 1974

Carroll et al, 1991 ApJ

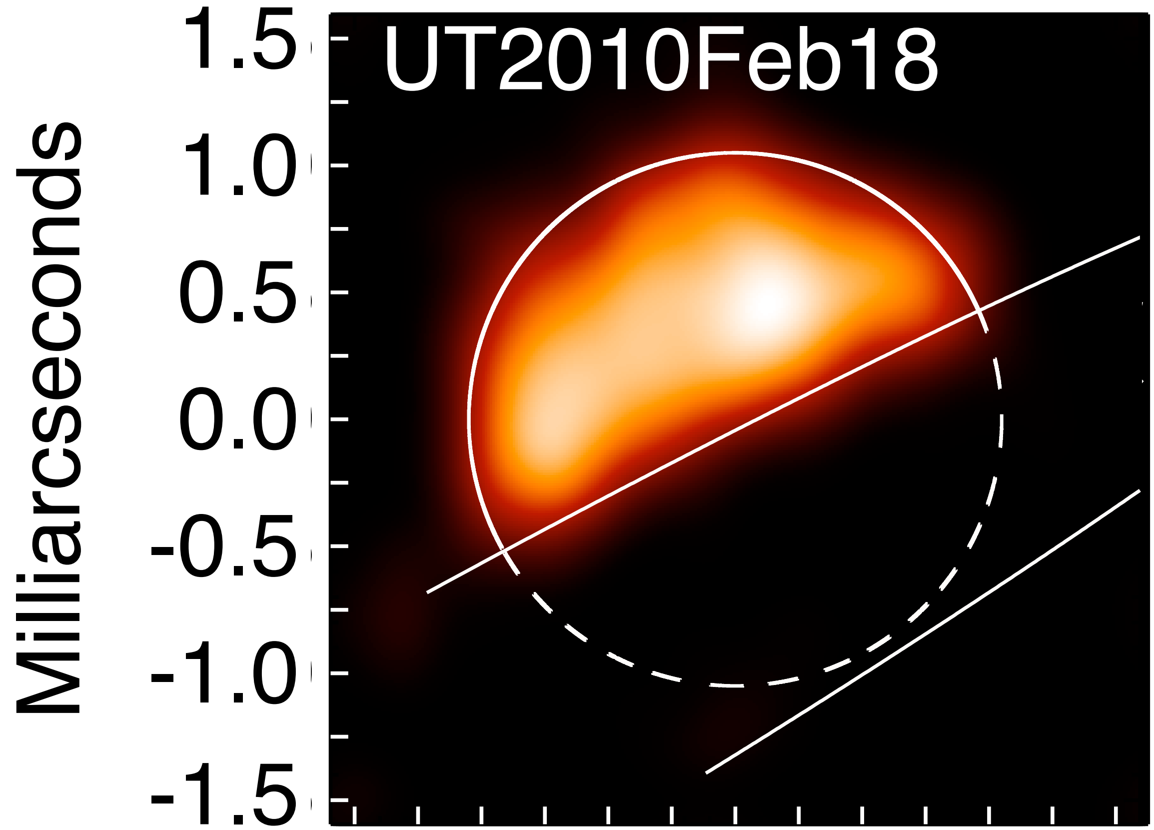
Model of the Eclipse



Kemp 1980


AAVSO DATA FOR EPS AUR - WWW.AAVSO.ORG
Magnitude
1
1.5
2
2.5
3
3.5
4
4.5
2454881
2455064
2455246
2455429
Julian Date
FIRE
Half way point
Visual Validated
Visual Prevalidated
V Validated
V Prevalidated
H Validated
H Prevalidated

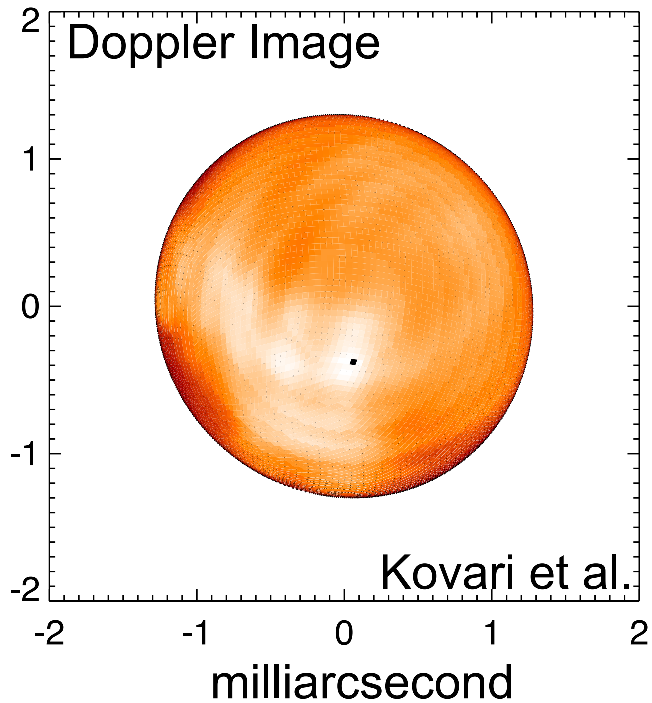
The eps Aur Eclipse of 2009-2011 view from MIRC/CHARA

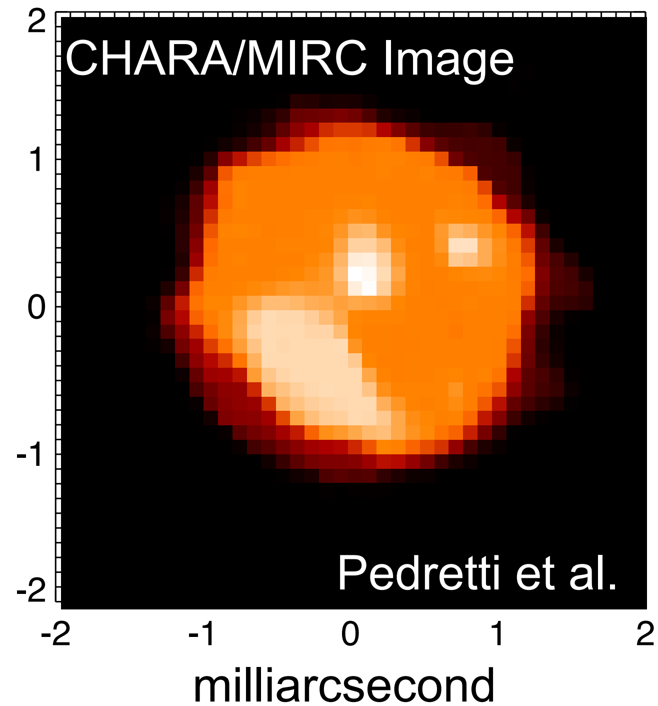


Kloppenborg et al. 2010, Nature

What's next?

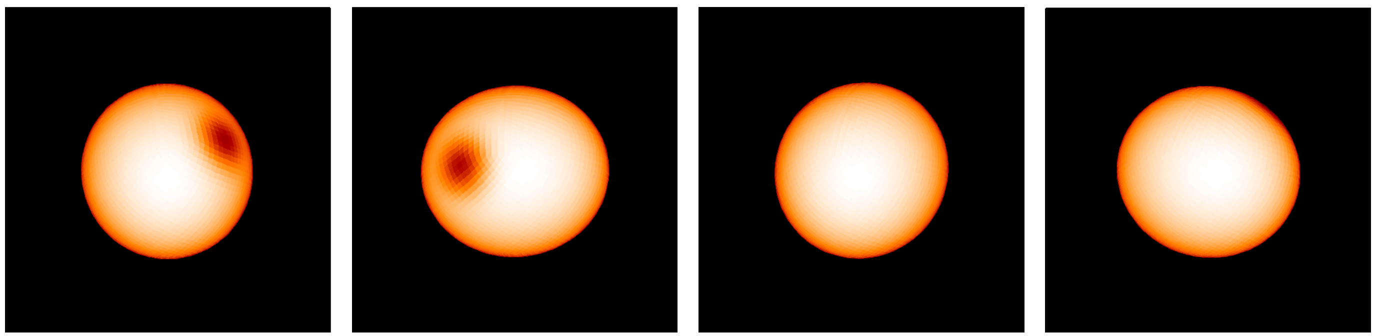
- Active stars with magnetic spots
  - Test doppler and light curve inversion methods
  - Probe "static" effects, active latitudes, polar spots (i.e., Strassmeier et al.

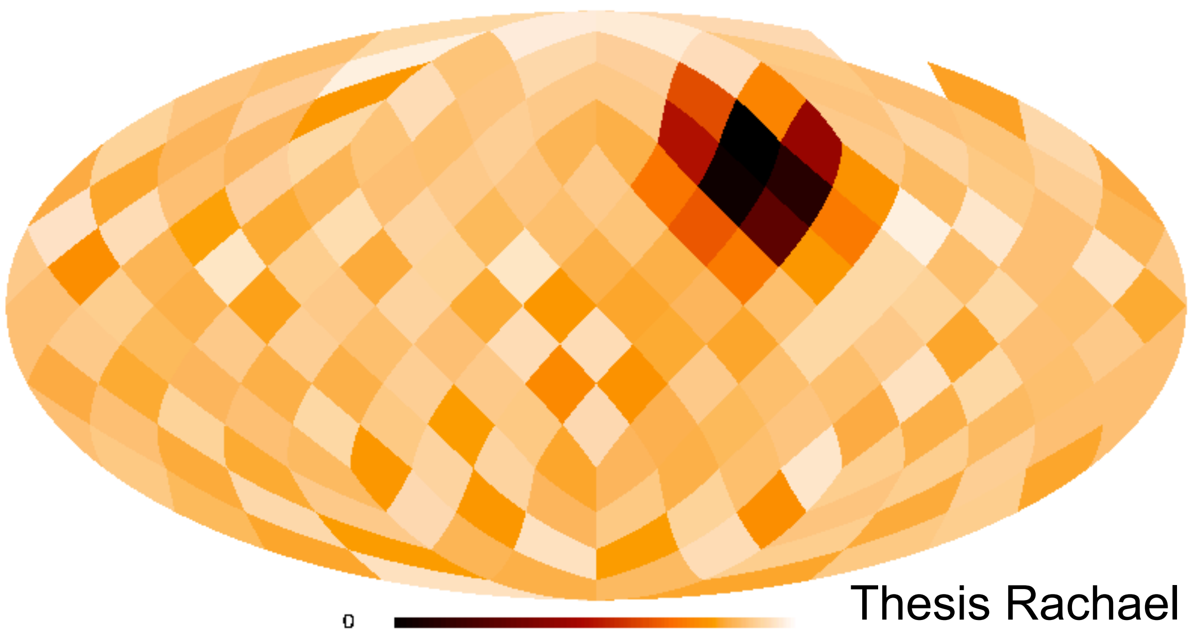




Imaging on Sphere

(same method as Doppler Imaging)

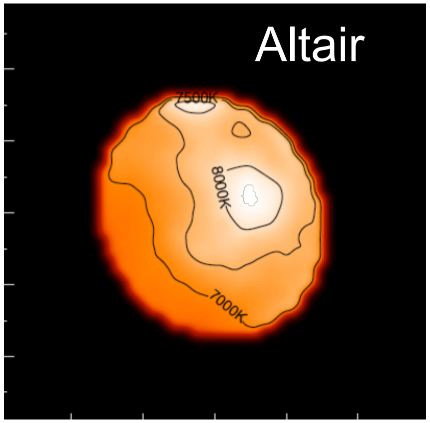


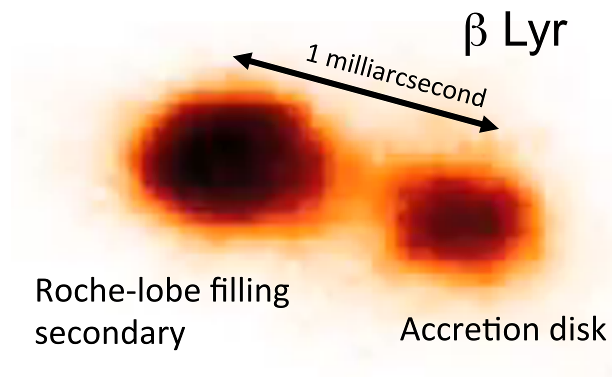


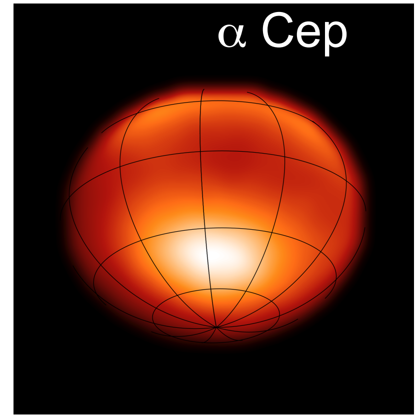
Thesis Rachael Roettenbacher

Future imaging work

- Imaging in the visible
  - Higher resolution, more targets, more temperature/line sensitive
  - CHARA/PAVO, CHARA/VEGA, NPOI/VISION, VLTI/new BC(?)
- Spectro interferometry on resolved spectral lines
  - VLTI/AMBER and CHARA/Vega have potential to do very interesting work here to constrain differential rotation, image mass loss, etc.
- Imaging red giants & magnetically-active stars require better uv coverage than typically obtained
  - Special targets can be done at CHARA/MIRC, NPOI/VISION, VLTI/PIONIER, VLTI/GRAVITY
- With greater sensitivity using new detectors, great potential for imaging dust shells in young stars and mass-losing stars
  - Near-IR: CHARA/MIRC, VLTI/GRAVITY+PIONIER
  - Mid-IR: VLTI/MATISSE







First five years of infrared imaging with the Michigan Infrared Combiner (MIRC)

Thanks to everyone at CHARA and UM
that has made this possible