Imaging in Optical Interferometry

Gail Schaefer

Director of the CHARA Array

Georgia State University

Useful Reviews for Imaging in Optical Interferometry

904 Vol. 34, No. 6 / June 2017 / Journal of the Optical Society of America A Tutorial

Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

Principles of image reconstruction in optical interferometry: tutorial

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Astron Astrophys Rev (2012) 20:53
DOI 10.1007/s00159-012-0053-0

REVIEW ARTICLE

Imaging the heart of astrophysical objects with optical long-baseline interferometry

J.-P. Berger · F. Malbet · F. Baron · A. Chiavassa · G. Duvert · M. Elitzur · B. Freytag · F. Gueth · S. Hönig · J. Hron · H. Jang-Condell · J.-B. Le Bouquin · J.-L. Monin · J.D. Monnier · G. Perrin · B. Plez · T. Ratzka · S. Renard · S. Stefl · E. Thiébaut · K.R.W. Tristram · T. Verhoelst · S. Wolf · J. Young

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Proceedings / Volume 9907 / Article

4 Aug 2016 | Conference Proceedings

Interferometric image reconstruction: techniques, results, and future direction

Fabien Baron | Author Affiliations

Proceedings Volume 9907, https://doi.org/10.1117/12.2233392 | Event Info

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Proceedings / Volume 11446 / Article

13 Dec 2020 | Conference Proceedings

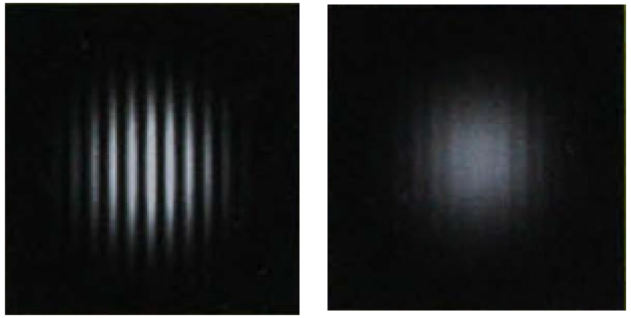
Inference in optical interferometry: a quick review of modeling and imaging techniques

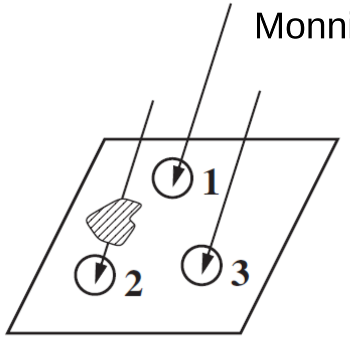
Fabien R. Baron | Author Affiliations

Proceedings Volume 11446, https://doi.org/10.1117/12.2561582 | Event Info

Observables in Optical Interferometry

- Squared visibility amplitudes
  - Contrast of fringes
- Closure phases
  - Sensitive to asymmetries
  - 0° or 180° for point symmetric sources
- Differential visibilities and phases
  - Obtained for spectrally dispersed data – line vs. continuum
  - Kinematics
- uv coordinates
  - Position of telescopes projected on to the sky





Monnier et al. 2003

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

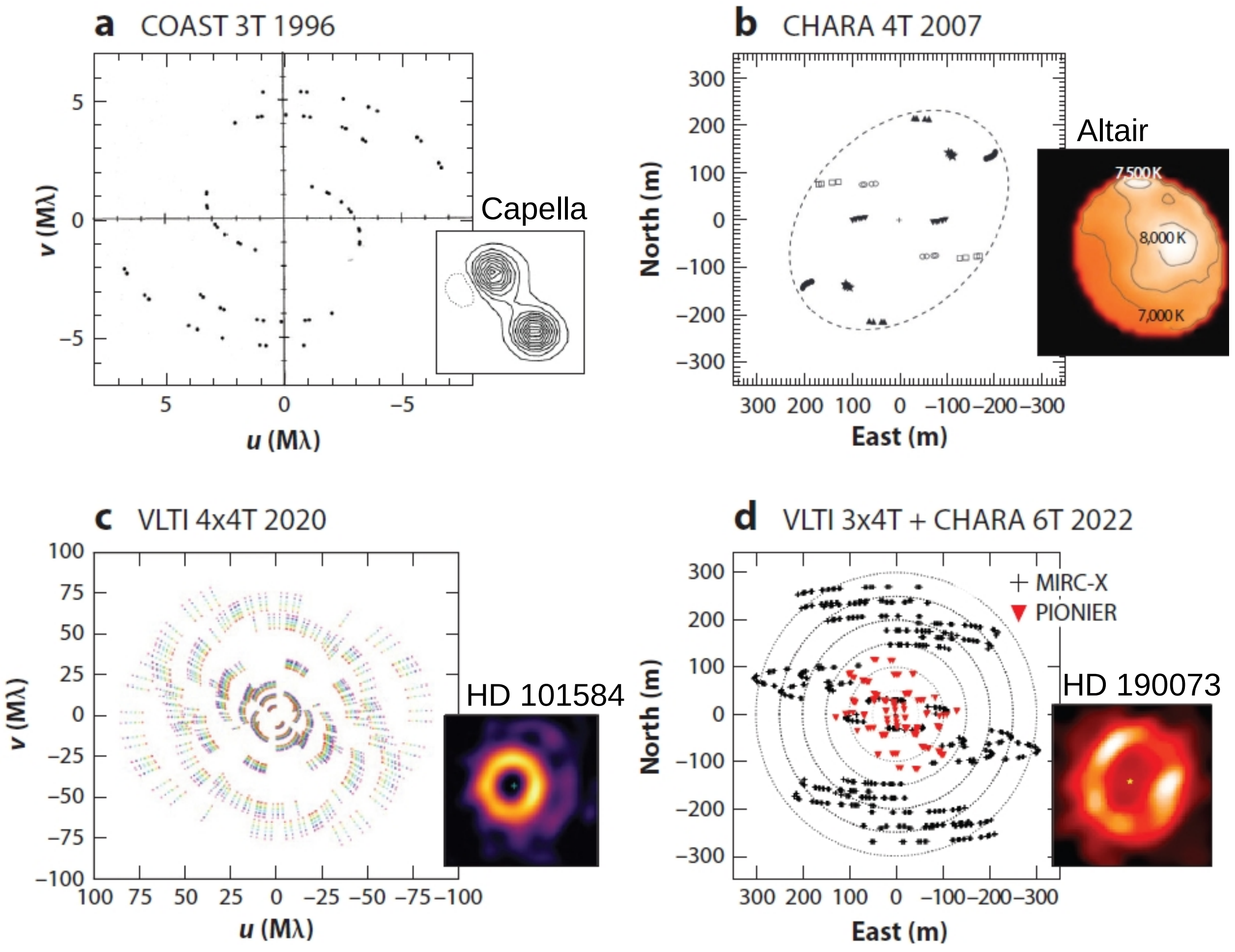
Sparse uv coverage

Baldwin et al. (1996)

Monnier et al. (2007)

Kluska et al. (2020)

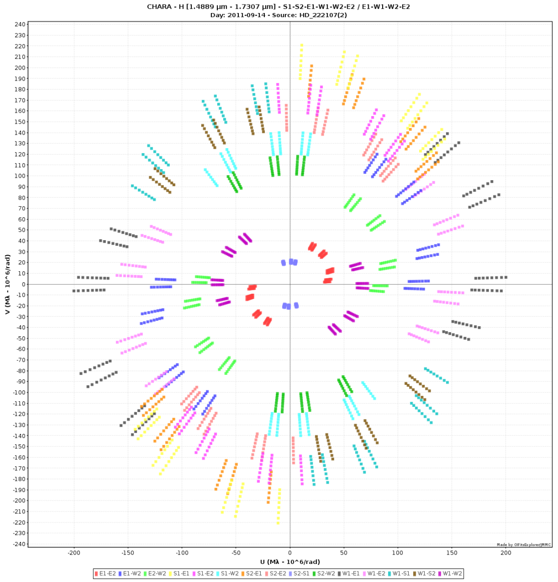
Ibrahim et al. (2023)

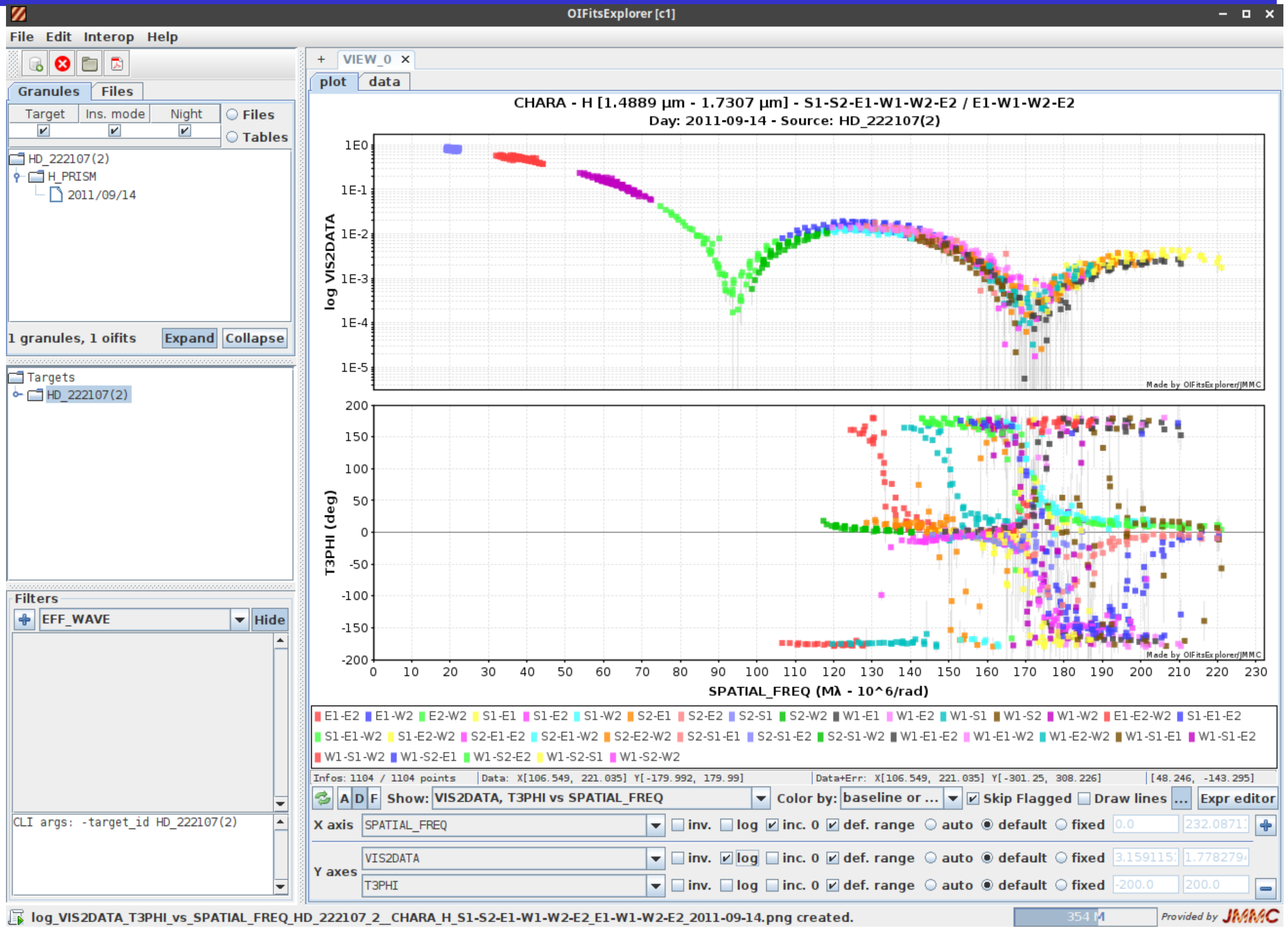


Eisenhauer et al. 2024

Step 1: Inspect Data

OIFits Explorer





https://www.jmmc.fr/english/tools/data-analysis/oifits-explorer

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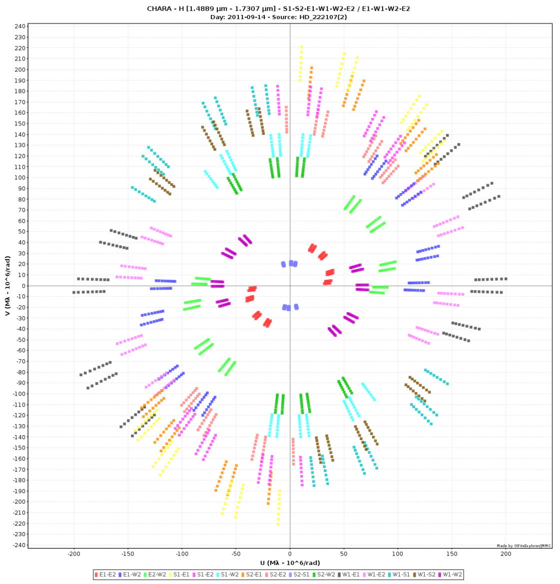
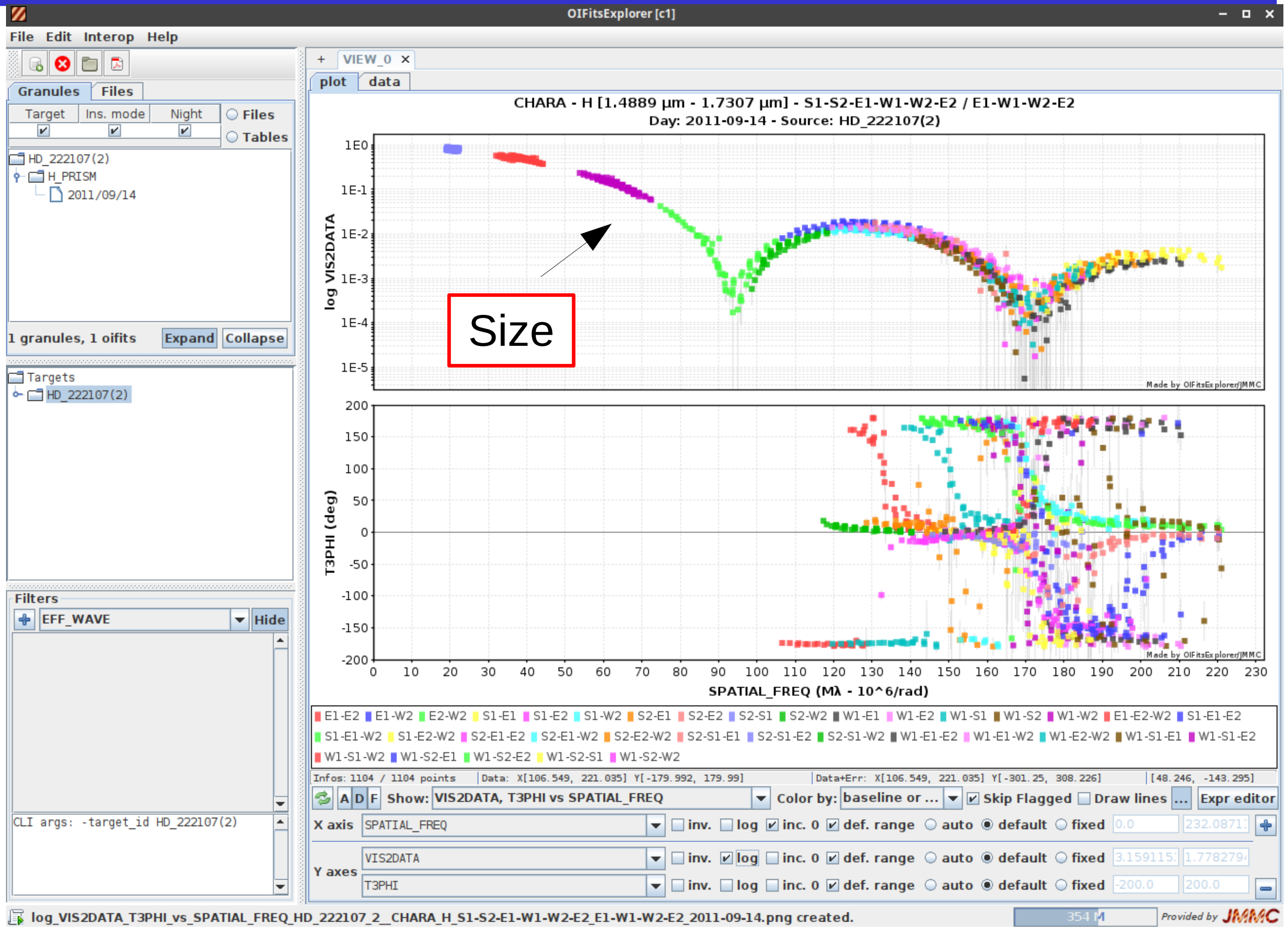
OIFits Explorer





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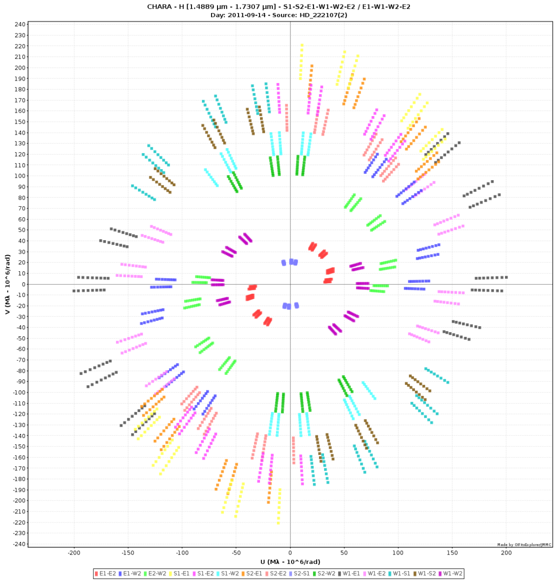

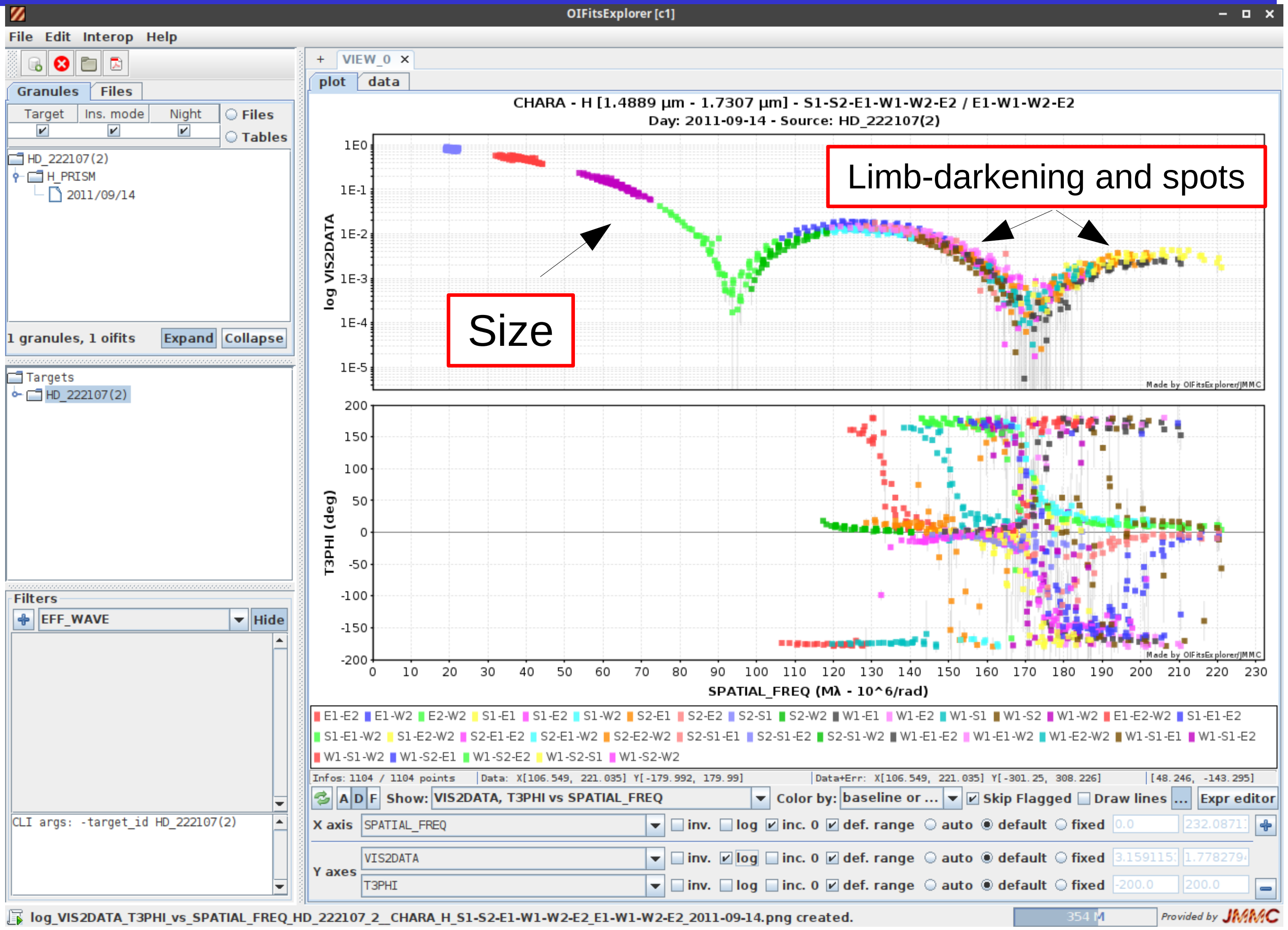

https://www.jmmc.fr/english/tools/data-analysis/oifits-explorer

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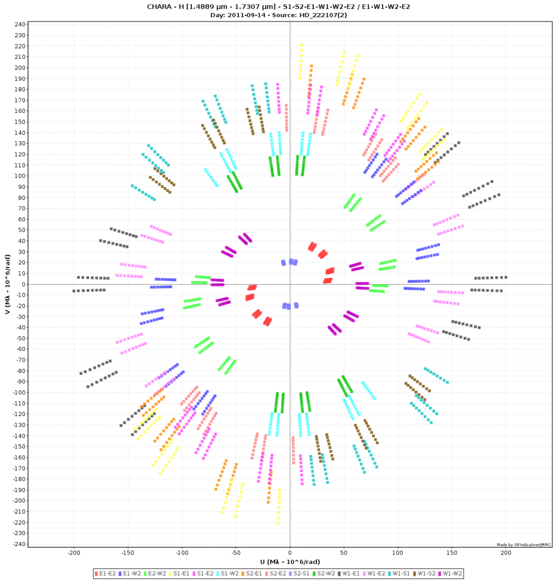
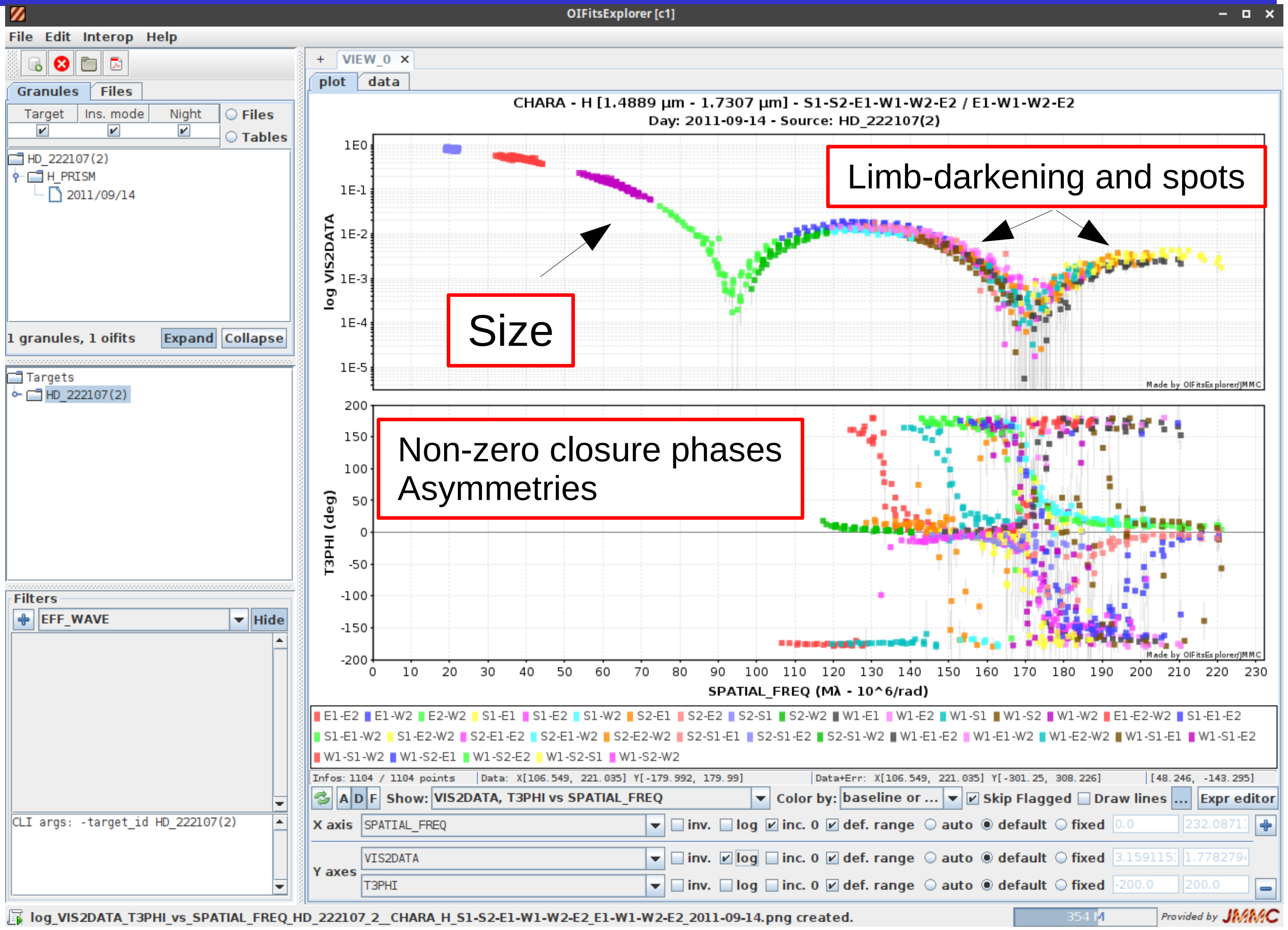
OIFits Explorer





https://www.jmmc.fr/english/tools/data-analysis/oifits-explorer

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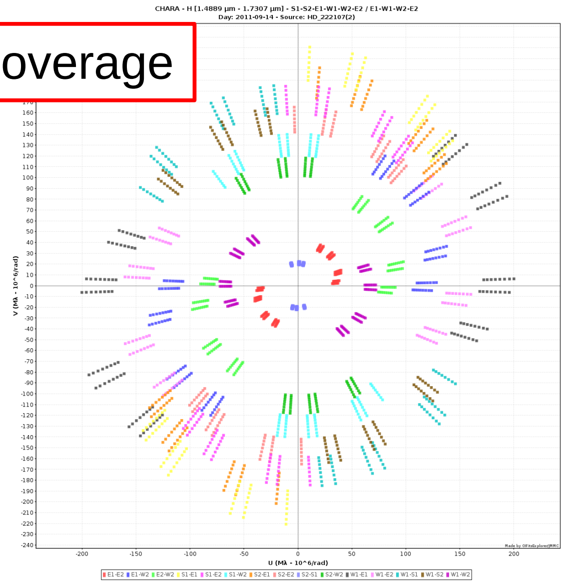
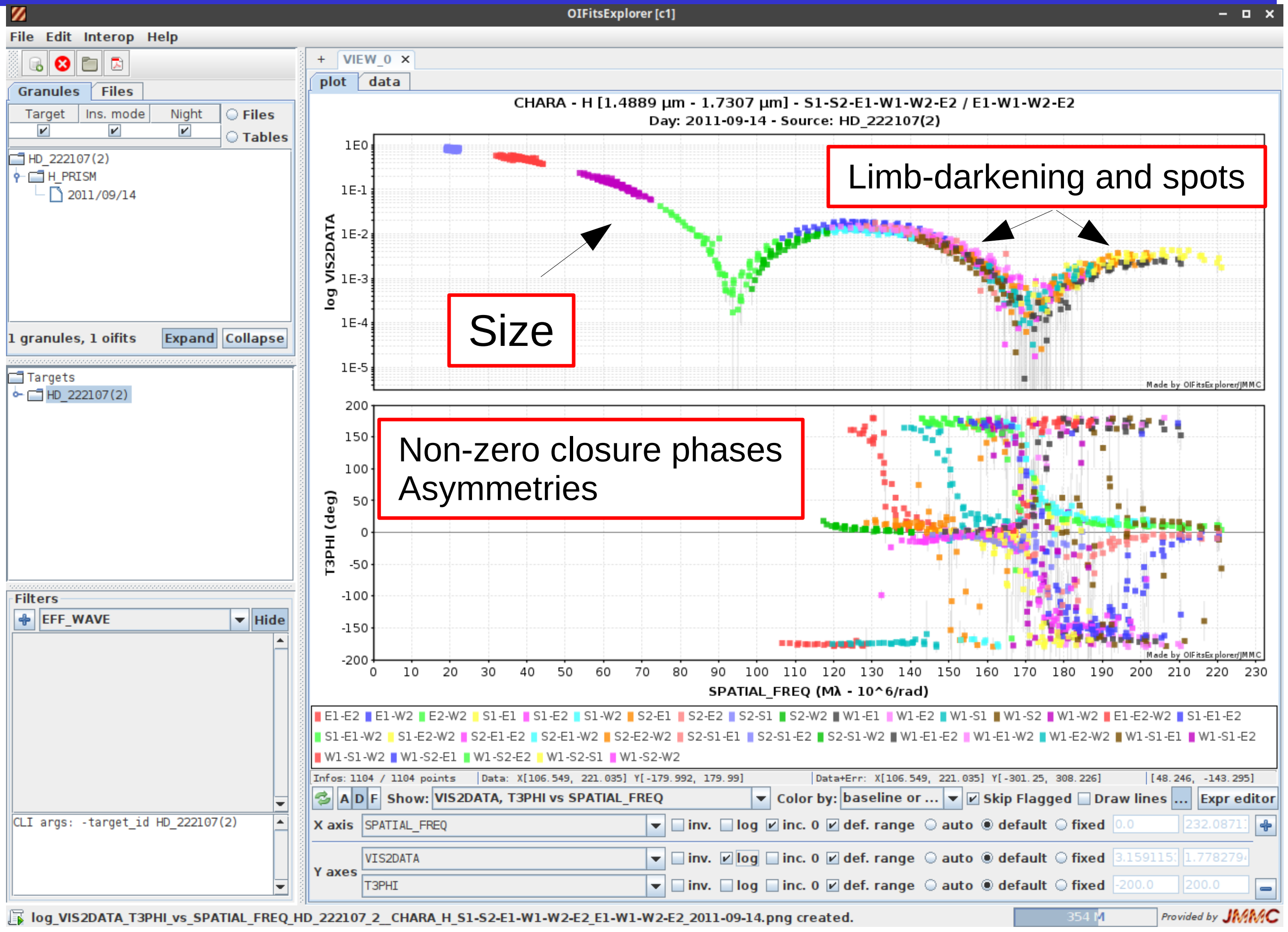
OIFits Explorer





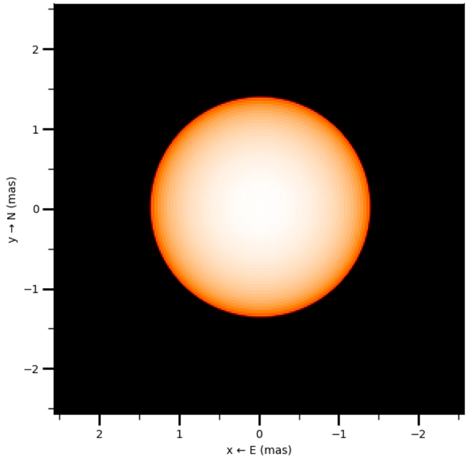
https://www.jmmc.fr/english/tools/data-analysis/oifits-explorer

Step 2: Model Fitting

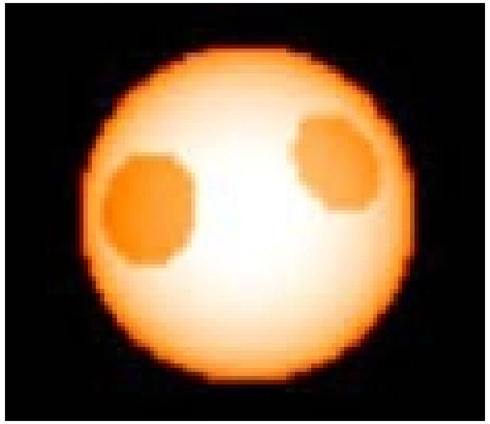
- PMOIRED
  - Parametrc Modeling of Optical InteRferomEtric Data
  - https://github.com/amerand/PMOIRED
- OITOOLS
  - All-in-One Tool Package for Optical Interferometry
  - https://github.com/fabienbaron/OITOOLS.jl
- RadPy
  - Robust Angular Diameters in Python
  - https://pypi.org/project/rsadpy/
- JMMC Litpro
  - https://www.jmmc.fr/english/tools/data-analysis/litpro/

Common Types of Models

Limb-darkened disk

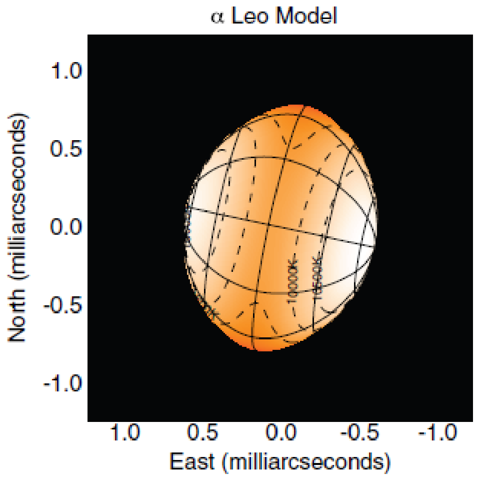


Spots



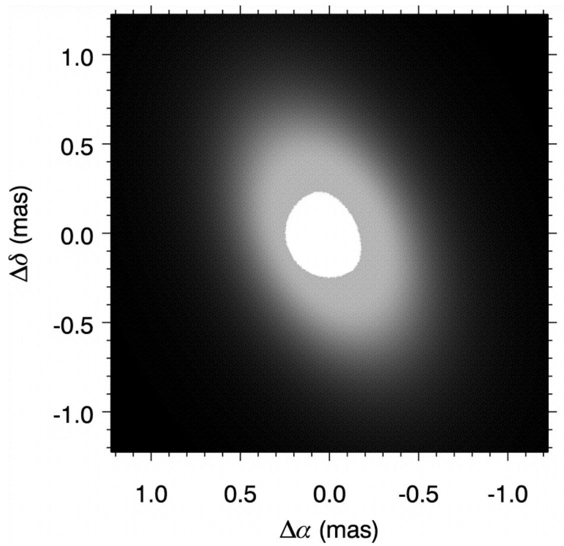
Parks et al. (2021)

Oblate Speriod



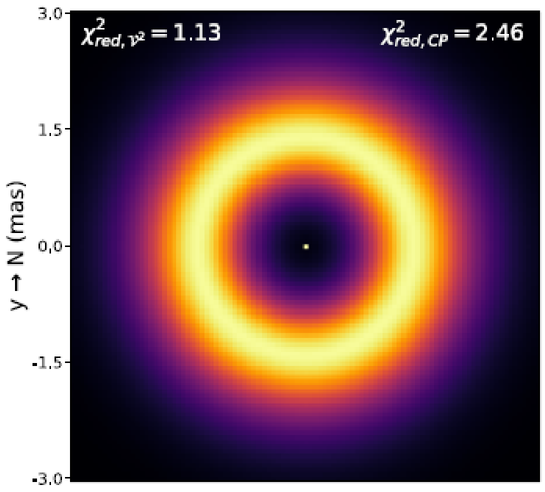
Che et al. (2011)

Analytic Disk Model



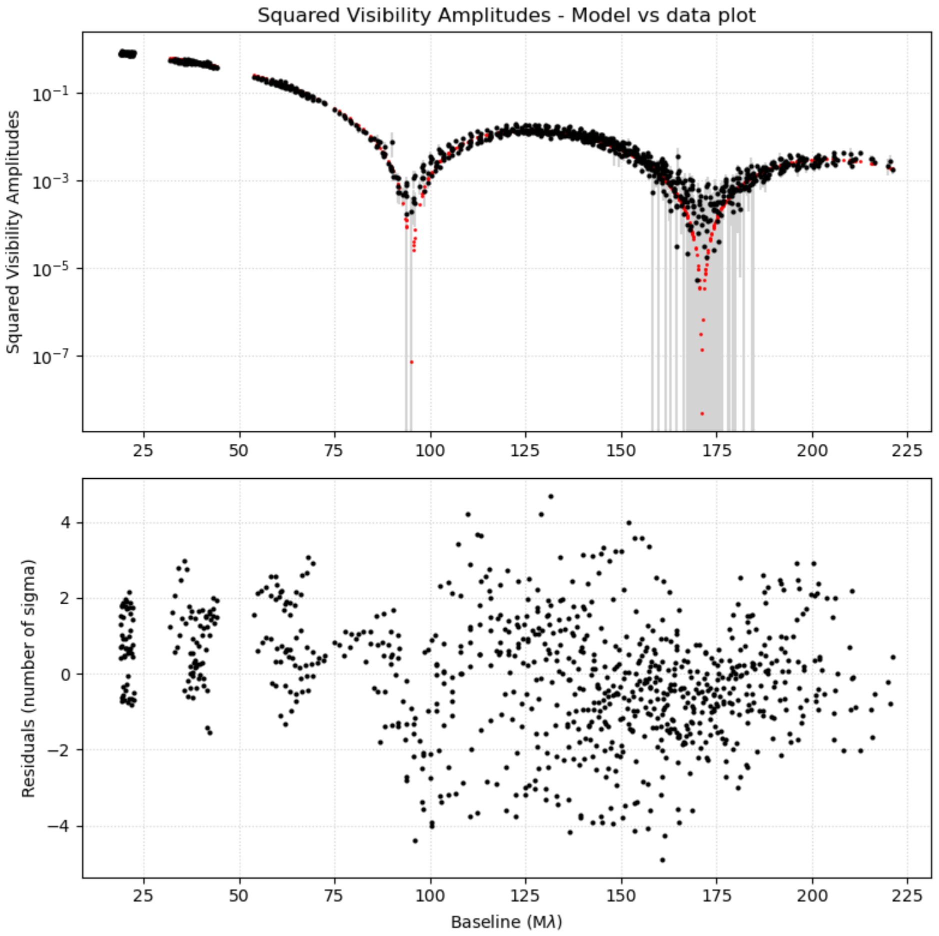
Gies et al. (2007)

Ring Model

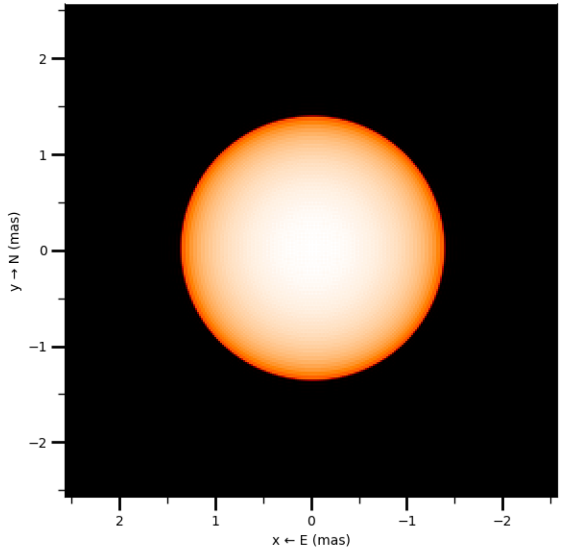


Ibrahim et al. (2023)

Step 2: Model Fitting



Limb-darkened Disk



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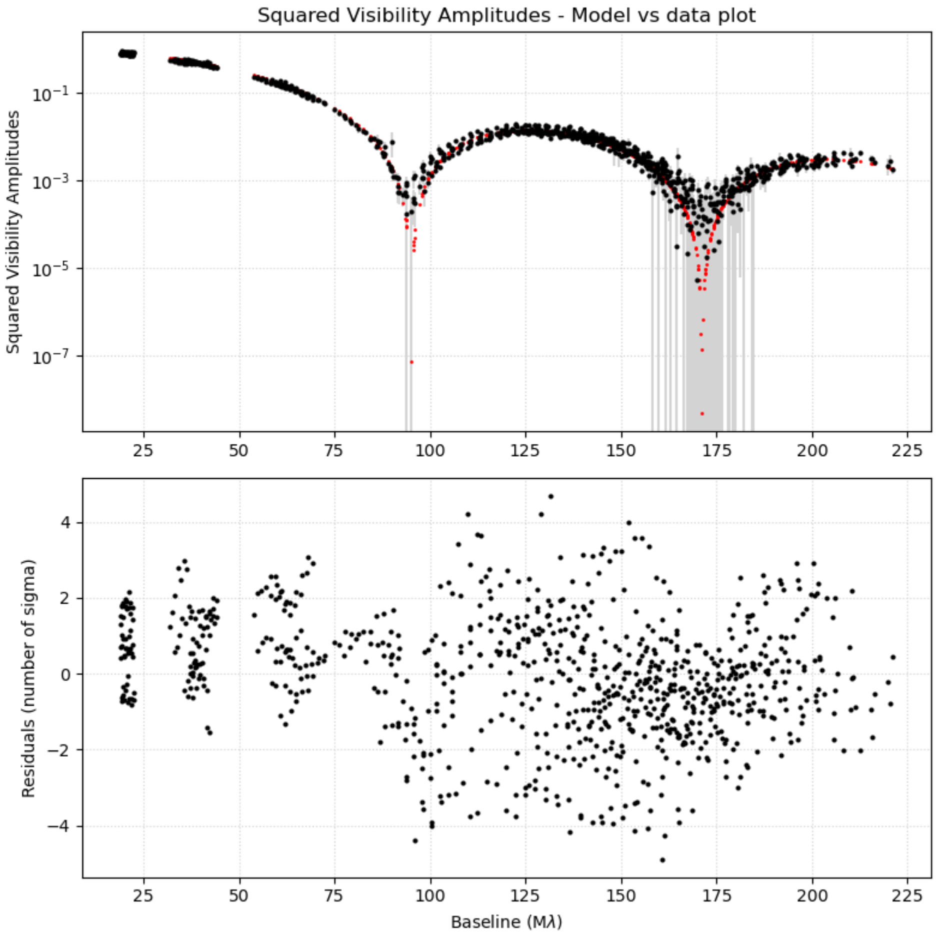
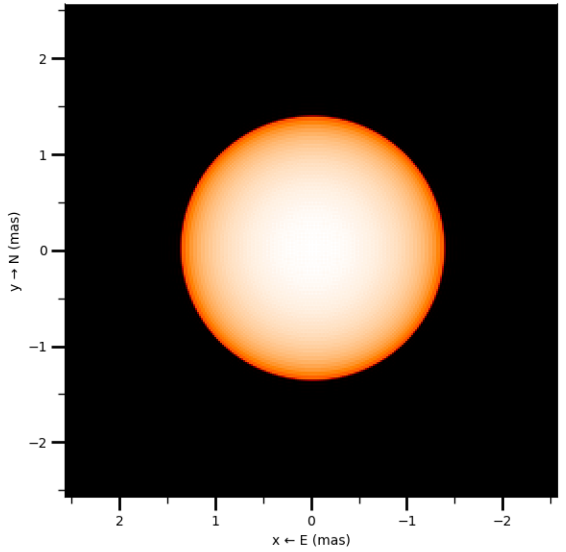
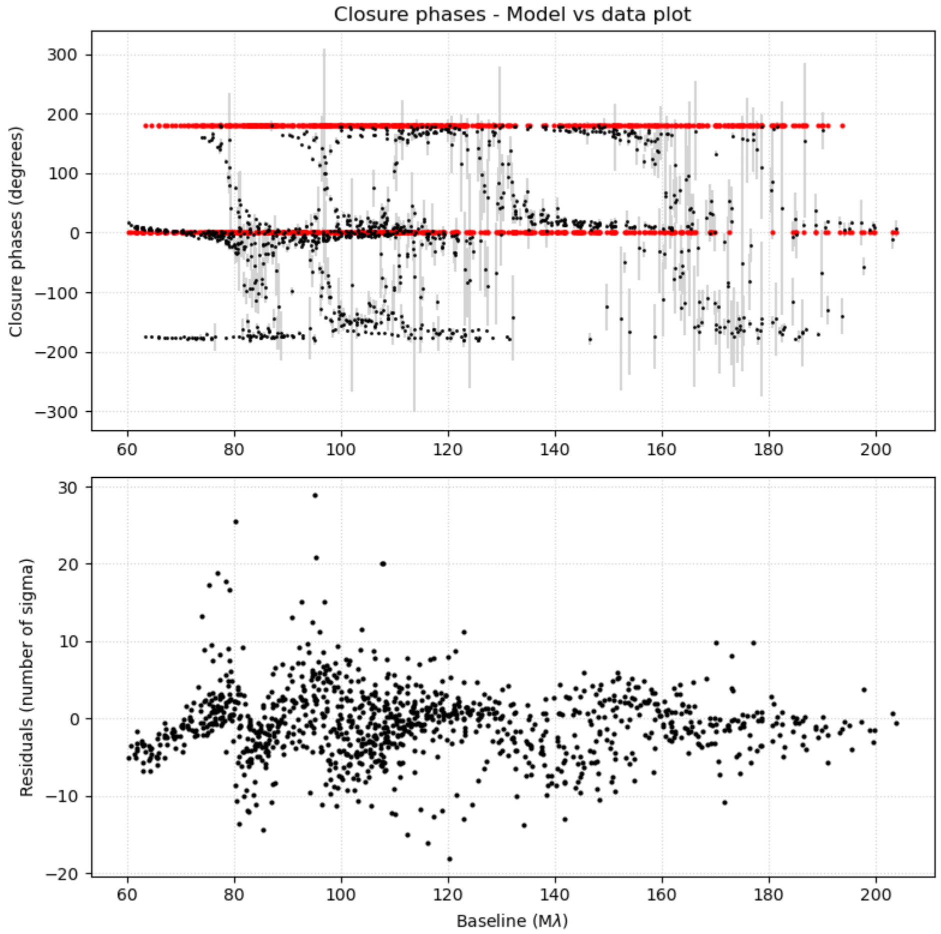


Limb-darkened Disk





Imaging Reconstruction Routines

Name	Authors
BSMEM	Baron, Buscher, Young
Building Block Method	Hofmann, Weigelt
IRBIS	Hofmann, Weigelt
MACIM	Ireland, Monnier
MiRA	Thiebaut
WISARD	Meimon, Mugnier, Le Besnerais
SQUEEZE	Baron, Monnier, Kloppenborg
SPARCO	Kluska et al.
PAINTER	Schutz et al.
MiRA-3D	Soulez et al.
OIMAGING	JMMC
OITOOLS	Baron
ROTIR	Baron
SURFING	Monnier

Imaging Reconstruction

- Interferometry measures Fourier transform of the sky brightness at a discrete, incomplete set of spatial frequencies.
- Image reconstruction is ill-posed inverse problem of recovering the image from this incomplete sampling.
- Minimize cost function:

$$J(x) = \chi^2(x) + \mu R(x)$$

Likelihood $\chi^2(x)$:
Measures how well
of image matches data
(V2, T3phi, T3amp)

Hyper-parameter μ:
Controls trade-off between
fitting data and enforcing
prior

Regularization $R(x)$:
Encode prior knowledge about
what good images look like

Regularizers

Regularizations One of the following:

- Quadratic smoothness

$$f_{\text{prior}}(\boldsymbol{x}) = \|\mathbf{D} \cdot \boldsymbol{x}\|^2$$

- Soft support

$$f_{\text{prior}}(\boldsymbol{x}) = \sum_j x_j^2 / x_j^{\text{prior}}$$

- Edge preserving smoothness
  (total variation)

$$f_{\text{prior}}(\boldsymbol{x}) = \mu \sum_{j,k} \left(\sqrt{(\mathbf{D}_j \cdot \boldsymbol{x})_k^2 + \epsilon^2} - \epsilon \right)$$

- Entropy

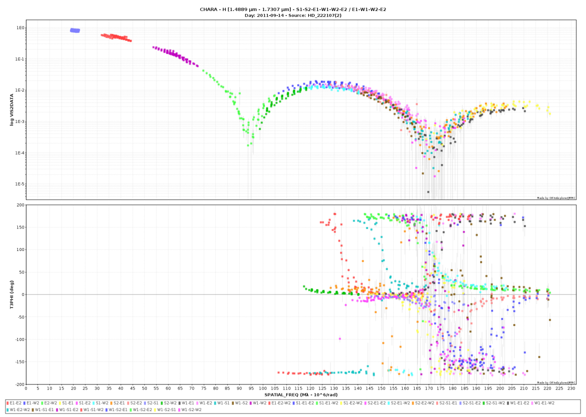
$$f_{\text{ent5}}(\boldsymbol{x}; \boldsymbol{x}_{\text{prior}}) = \sum_j \left[x_j^{\text{prior}} - x_j + x_j \log\left(x_j / x_j^{\text{prior}} \right) \right]$$

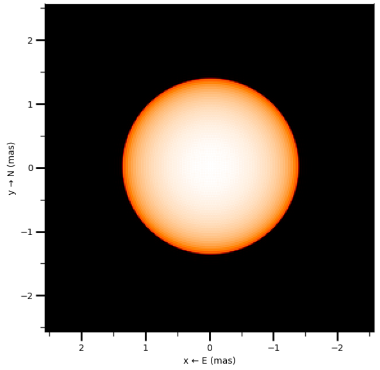
Regularizers

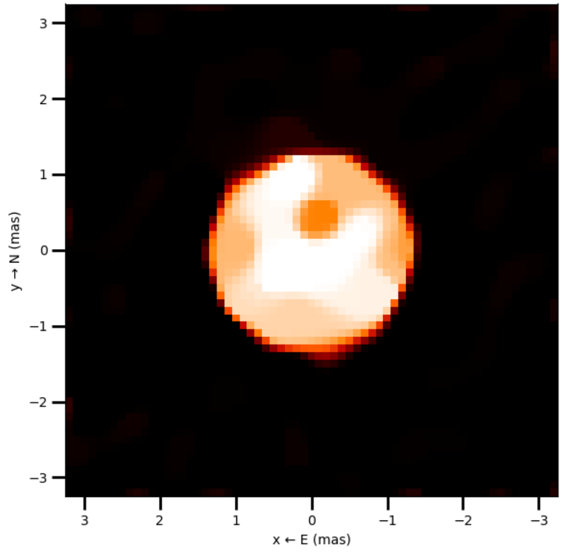
Regularizer	Effect
`centering`	Penalizes centroid offset from image center
`tv`	Edge-preserving smoothness ($\sum \|\|\nabla x\|\|_1$)
`tvsq`	Smooth edges ($\sum \|\|\nabla x\|\|_2^2$)
`entropy`	Concentrates flux, suppresses empty regions
`compactness`	Penalizes flux × distance² from center
`l1l2`	Intermediate between sparse and smooth
`support`	Hard/soft pixel mask

Reconstructed Image of Spotted Star Lambda Andromeda

- Starting Image
  - Limb-darkened disk model
- Select reconstruction software
  - OITOOLS
- Select pixel size + FOV
- Choice of regularizers
  - Centering penalize centroid offset
  - Total Variation – minimize gradients

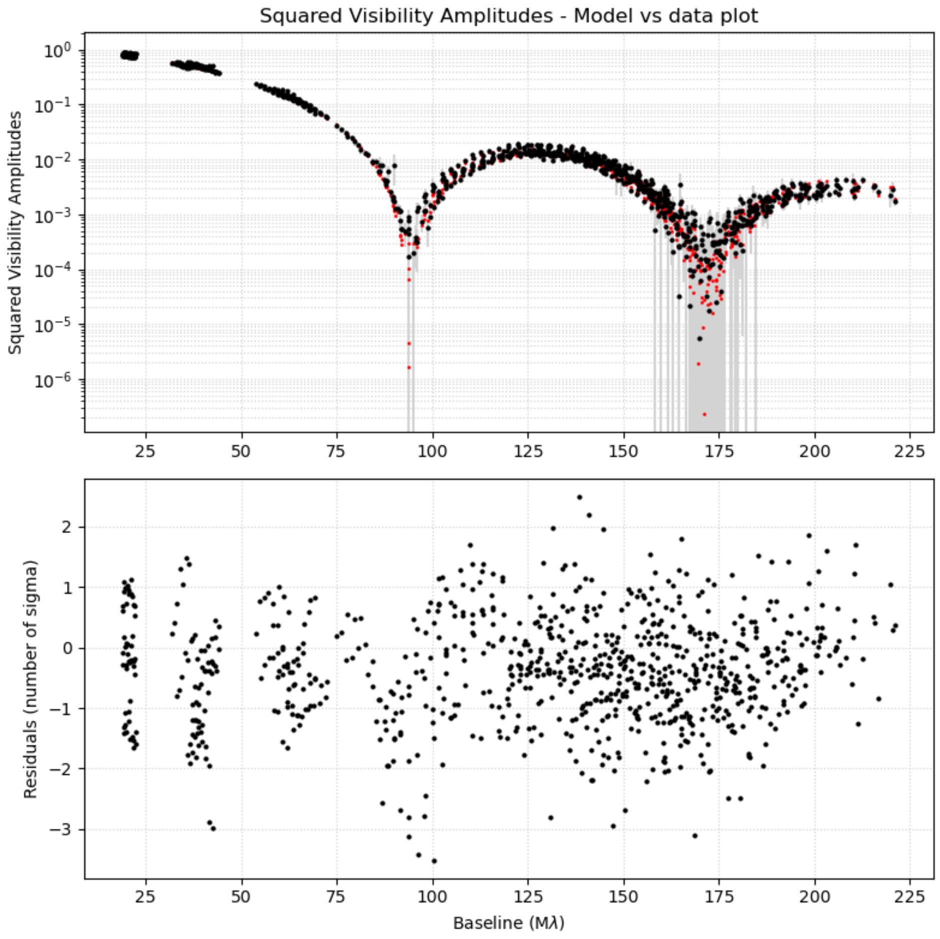


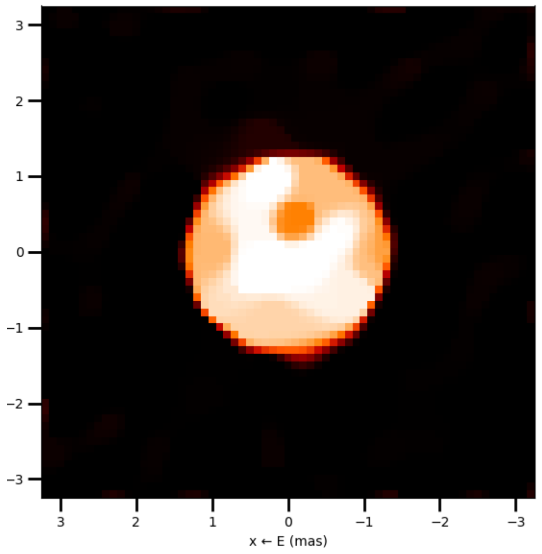


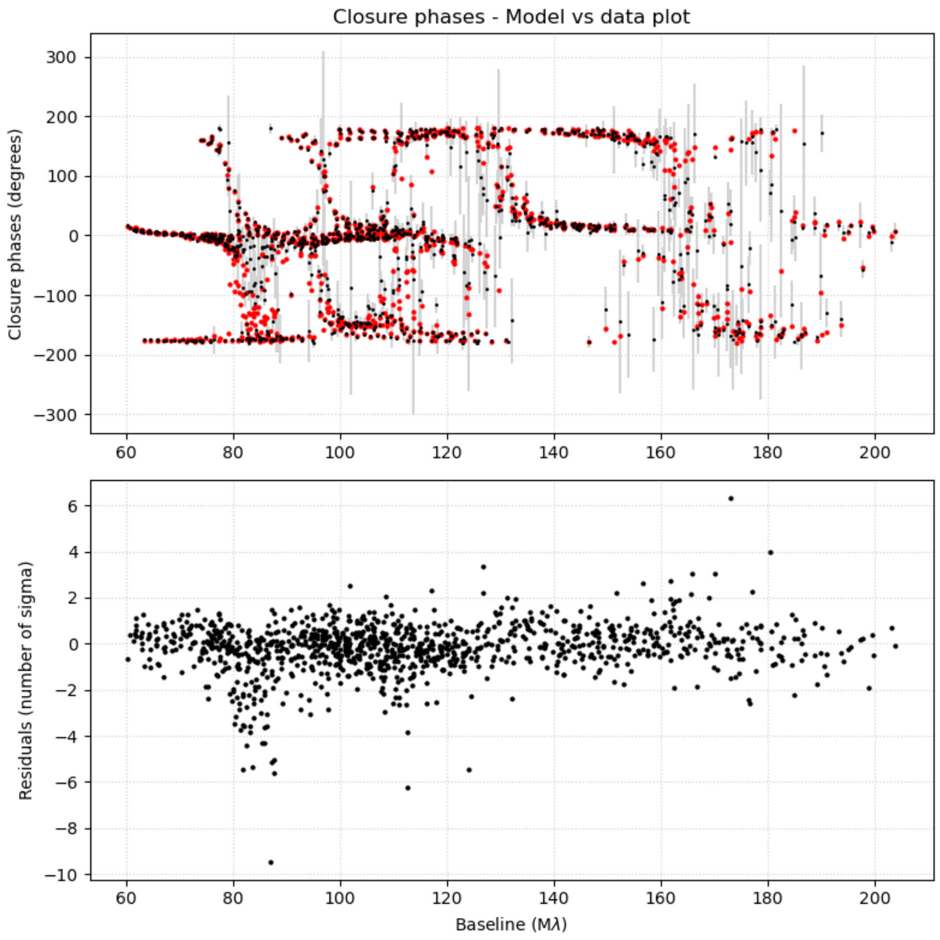


Data from:
Parks et al. (2021)
Martinez et al. (2021)

Reconstructed Image of Spotted Star
Examine Residuals





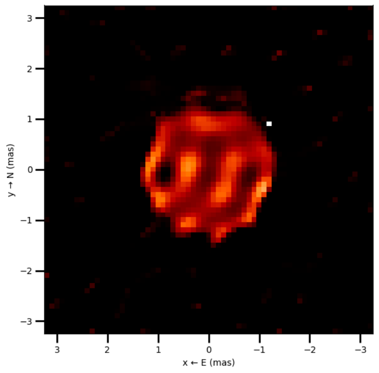


L-Curve

Selection of Regularizer weight

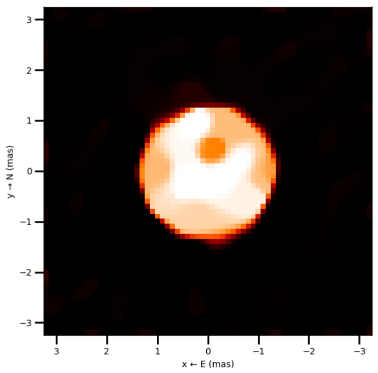
Minimize $\chi^2(x) + \mu R(x)$

μ = 10

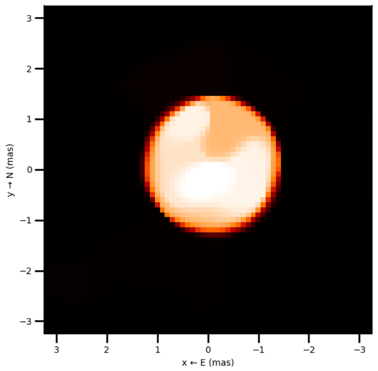


Overfitting noise

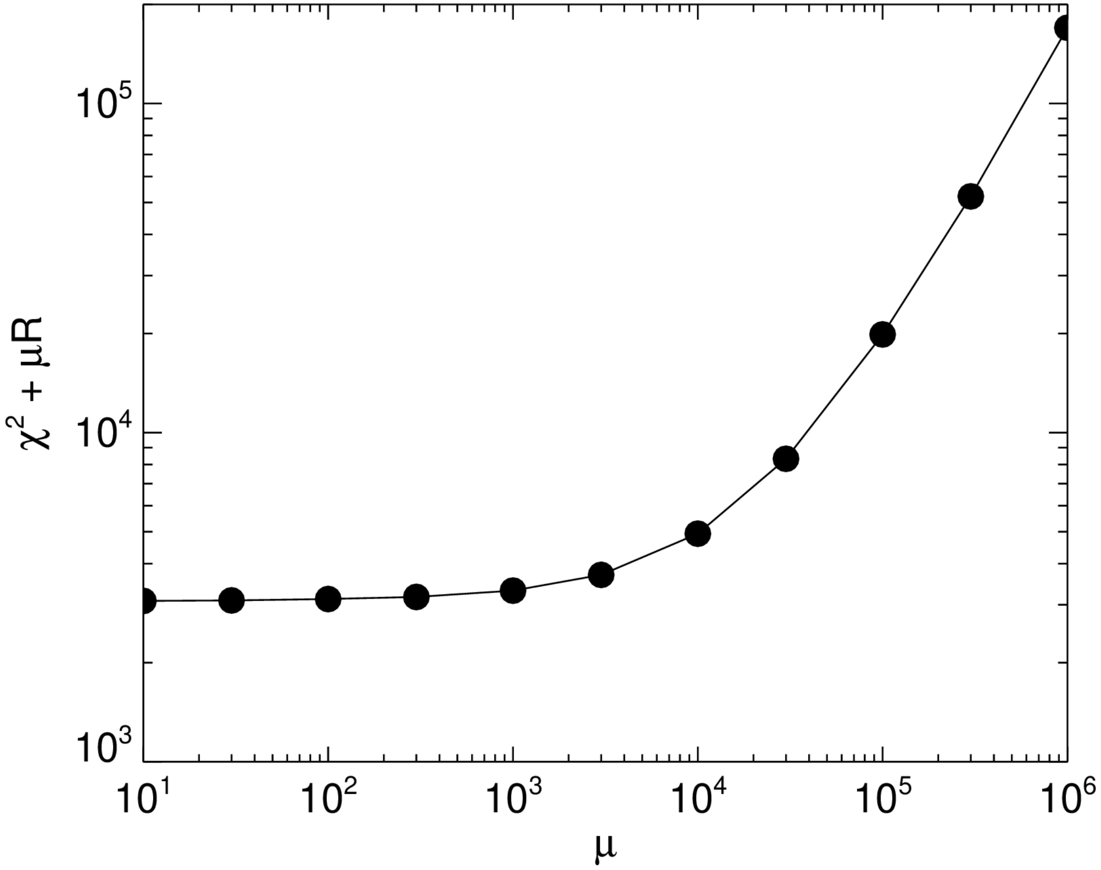
μ = 10^3



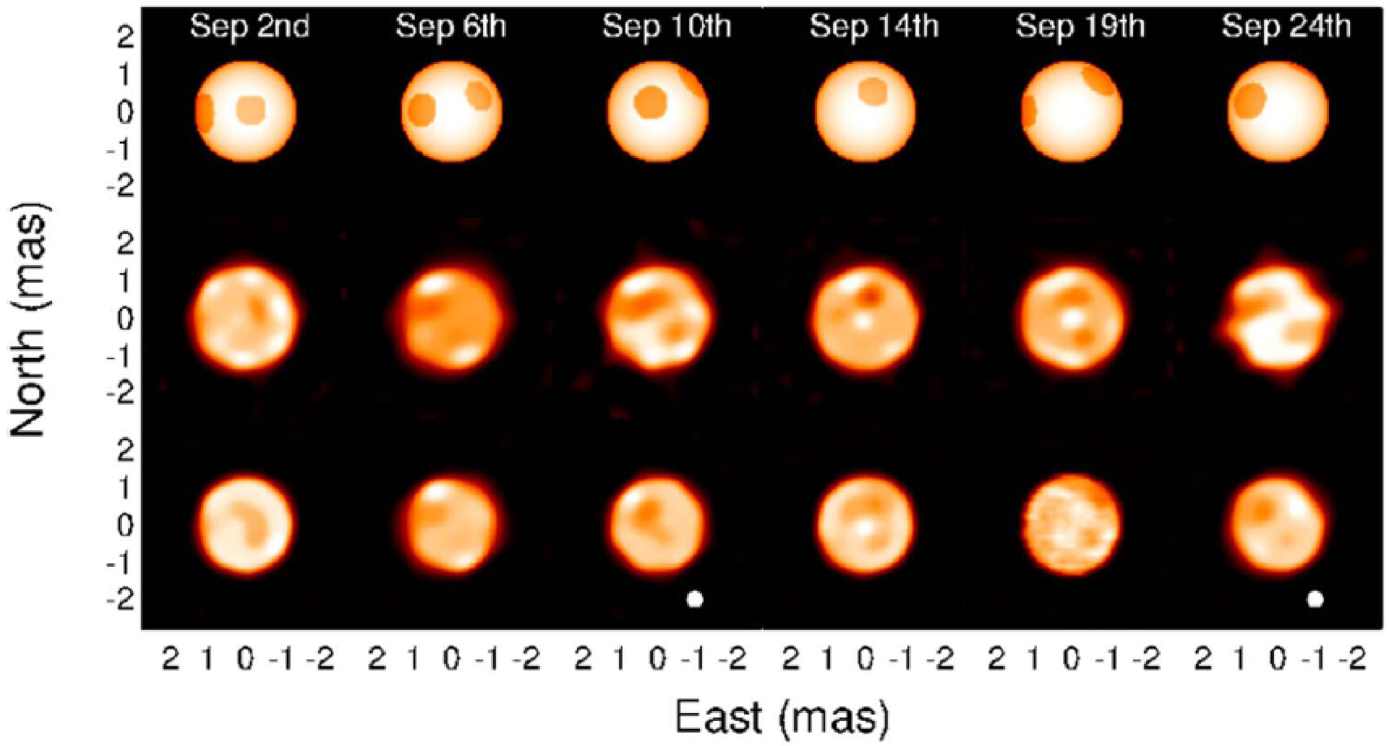
μ = 10^5



Over smoothed - lose structure



Look for Artifacts



Spot Model

Squeeze image reconstruction

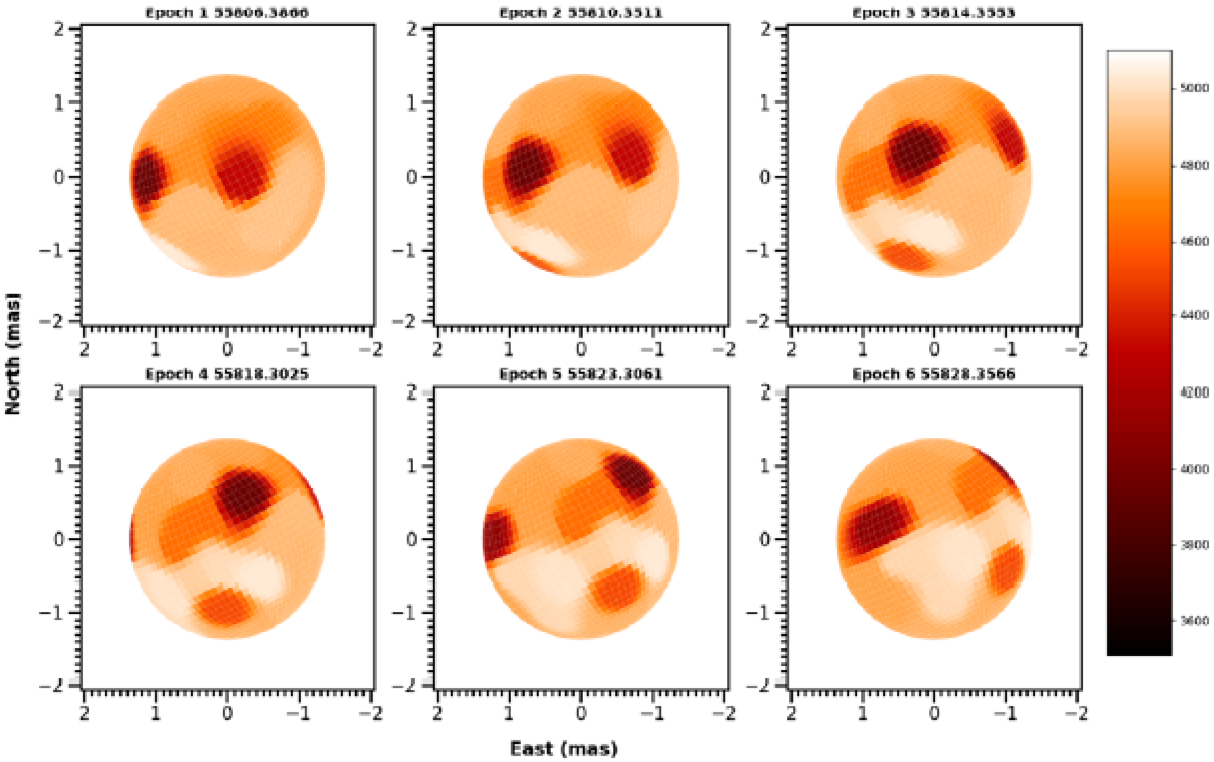
Simulated artifact check

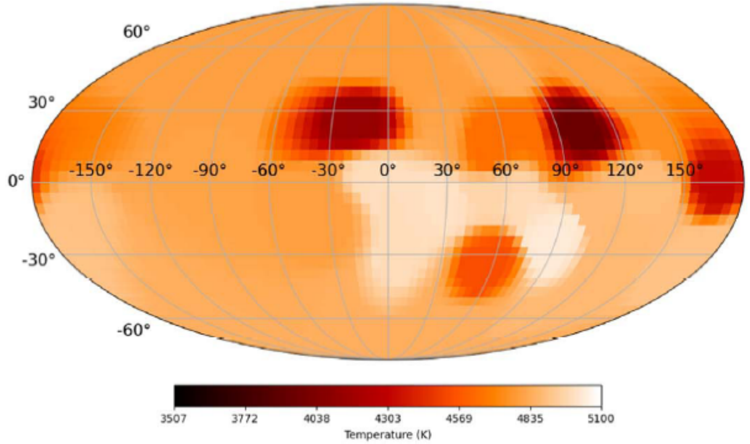
Reconstruct image of model data without spots

Use same uv sampling as data

Parks et al. (2021)

Imaging on a Sphere





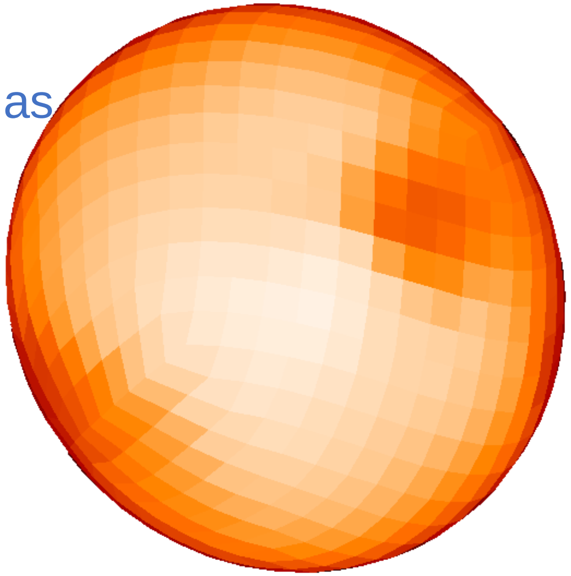
Mollweide Projection

Reconstruct image on surface of spheroid using ROTIR

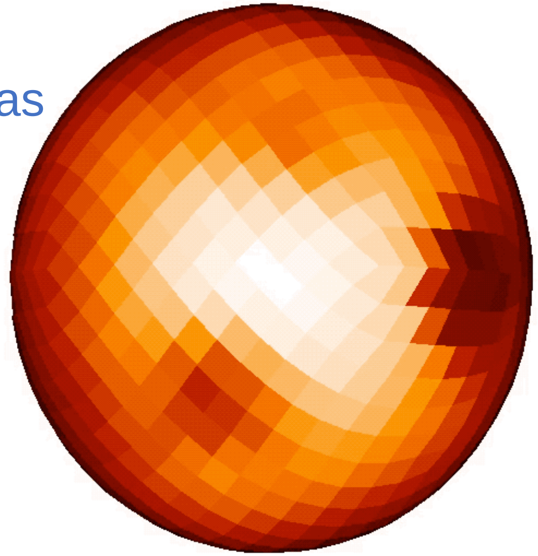
Martinez et al. (2021)

Imaging on a Sphere using SURFING

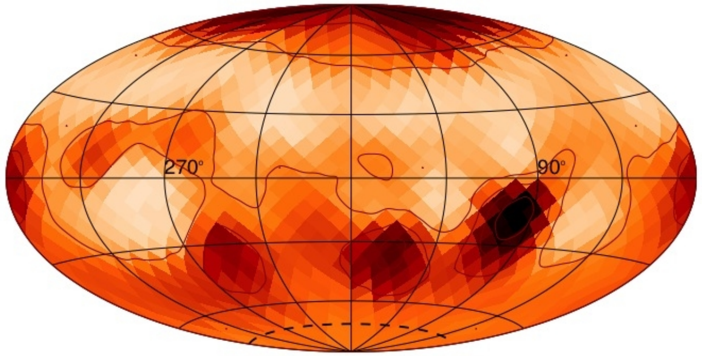
Zet And
θ = 2.5 mas



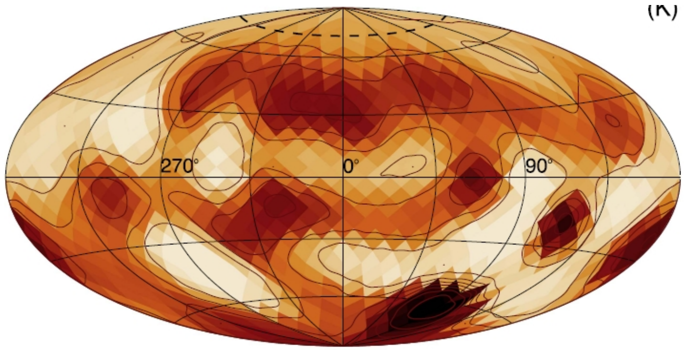
Sig Gem
θ = 2.4 mas



Roettenbacher et al. (2016)



Roettenbacher et al. (2017)



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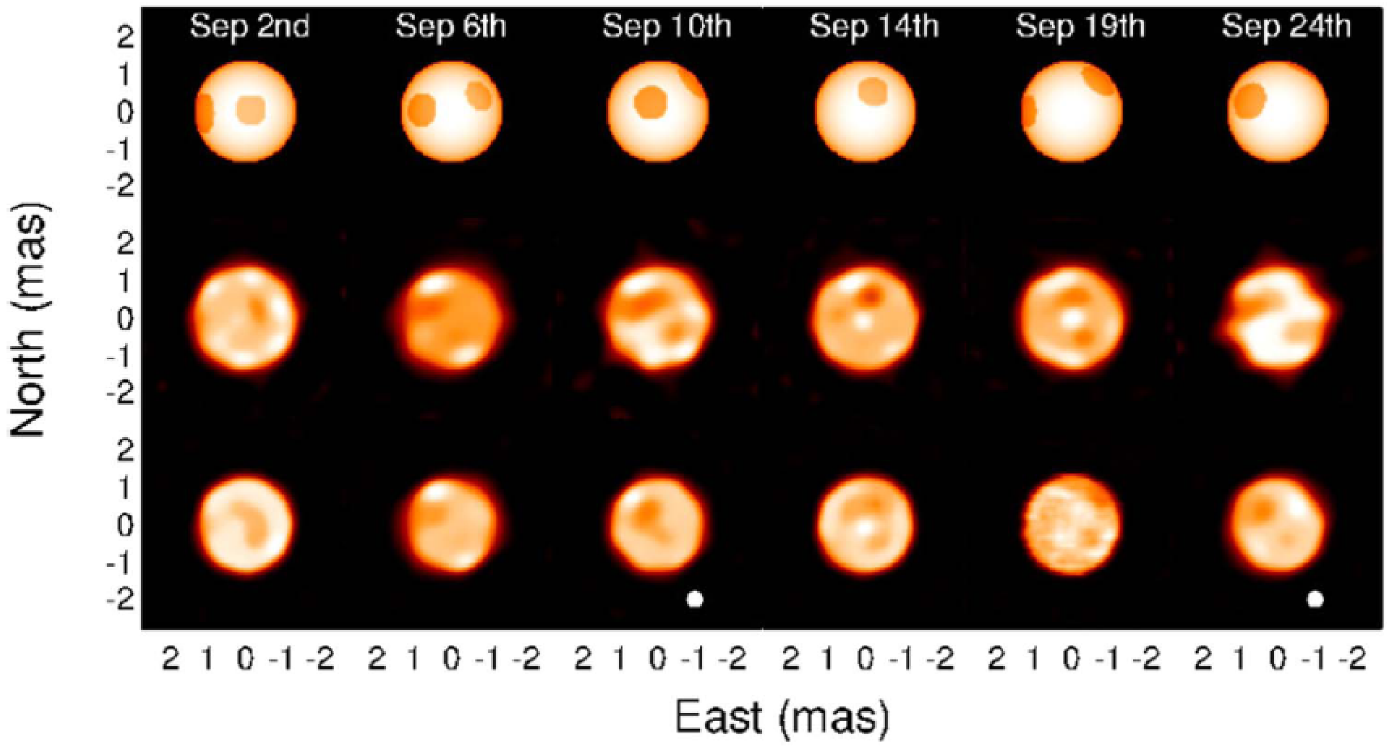

Spot Model

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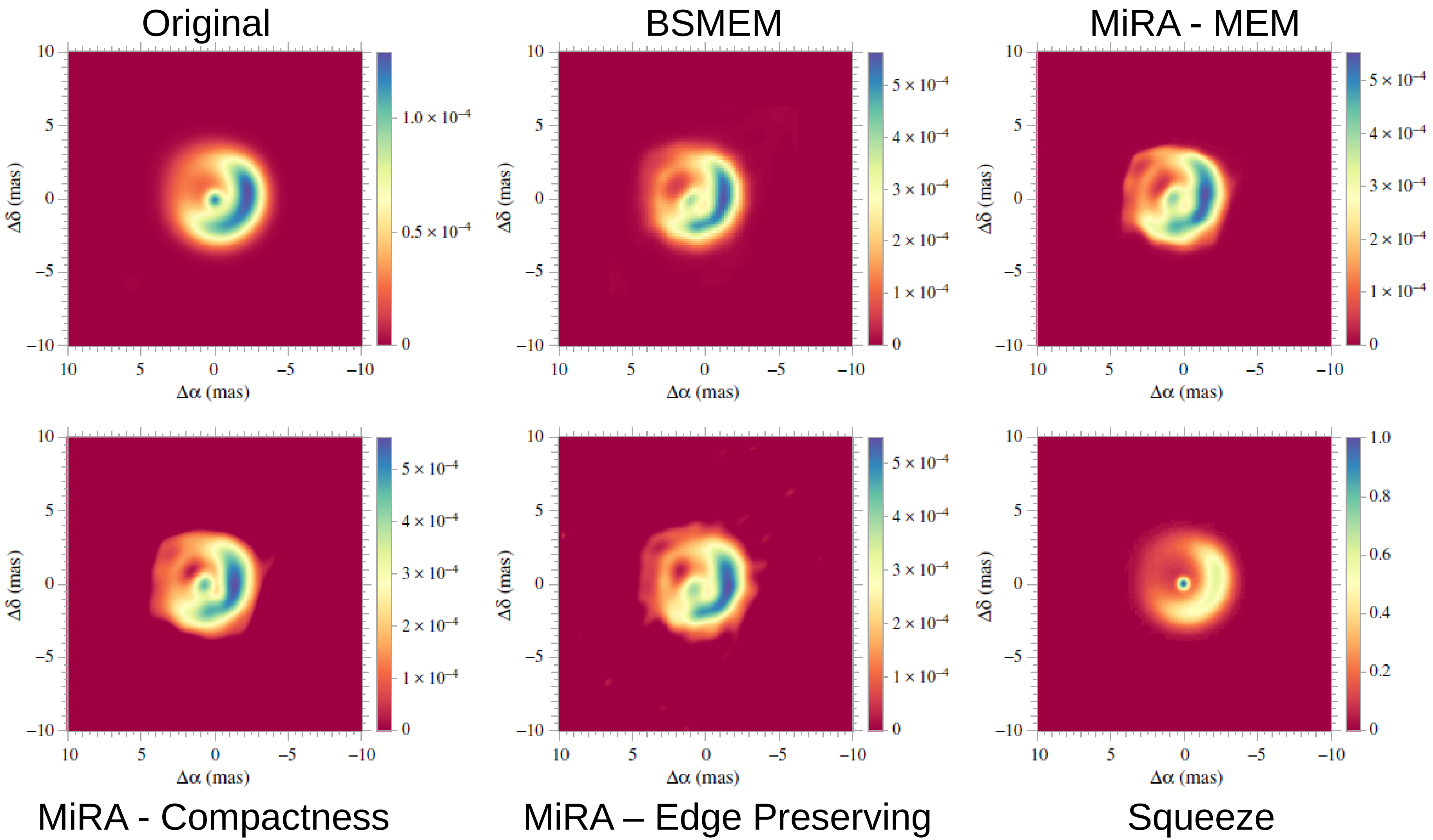
Use same uv sampling as data

Parks et al. (2021)

Different Reconstruction Routines
LkHα 101: Thiebaut et al. 2017



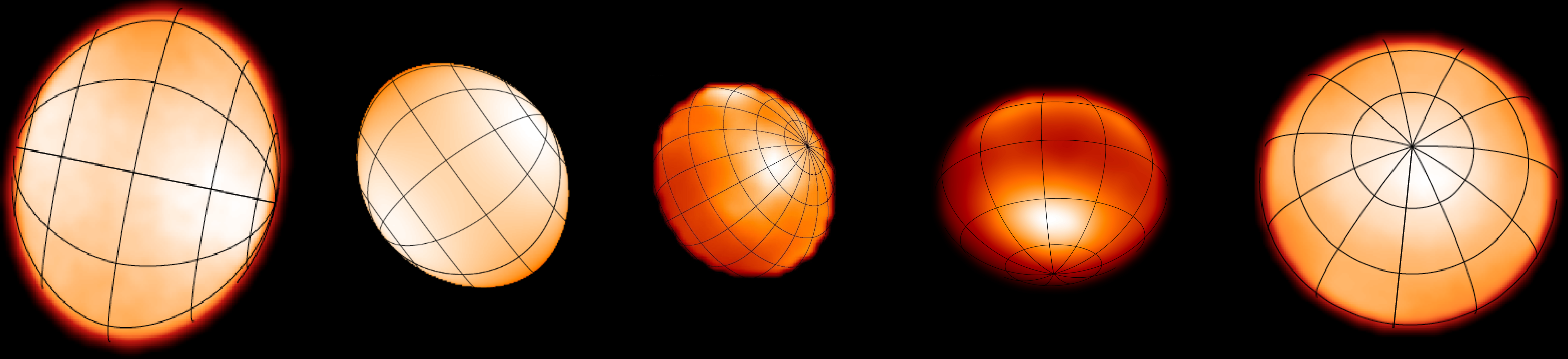
Science Highlights

on Imaging in

Optical Interferometry

Rapidly Rotating Stars

B8V	A5IV	A7V	A7V-IV	F2IV



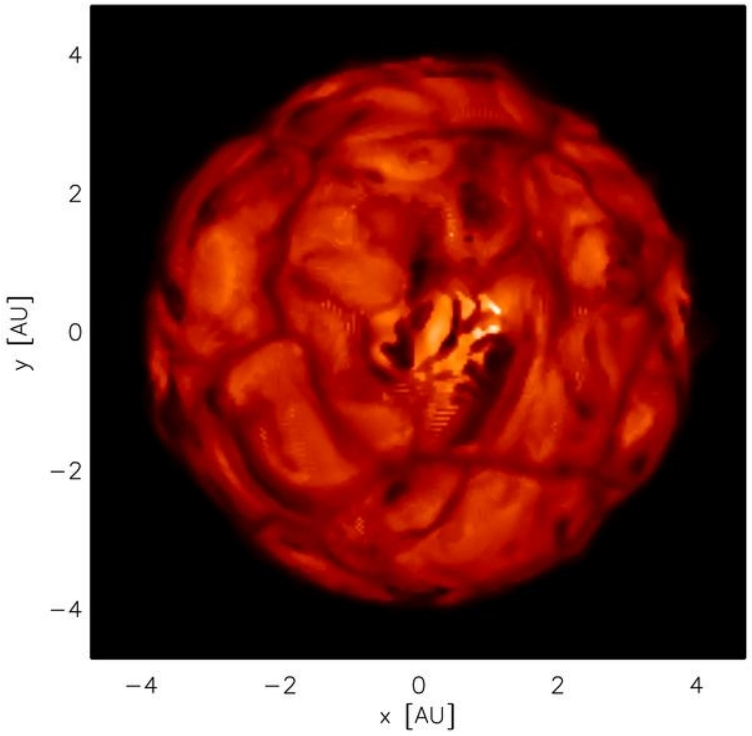
Regulus	Rasalhague	Altair	Alderamin	β Cas
Che *et al*. 2011	Zhao *et al*. 2009	Monnier *et al.* 2007	Zhao *et al*. 2009	Che *et al*. 2011

Courtesy of Ming Zhao

- Oblateness
- Limb-darkening
- Gravity Darkening

2 R_{sun}

Convection in Giant and Supergiant Stars



Model Simulation
Chiavassa et al. (2021)

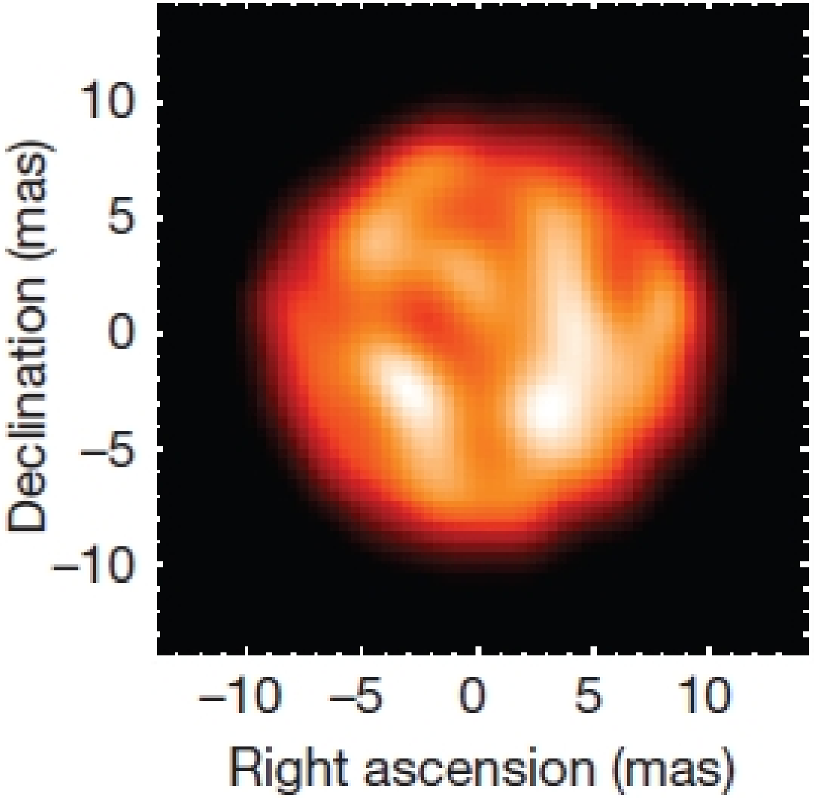


Image Reconstruction of π^1 Gru
Paladini et al. (2018)

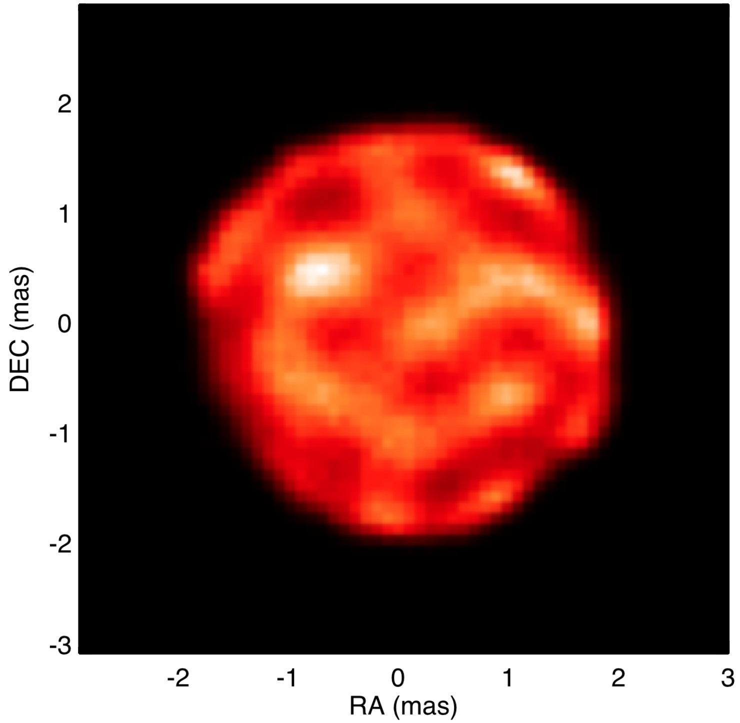
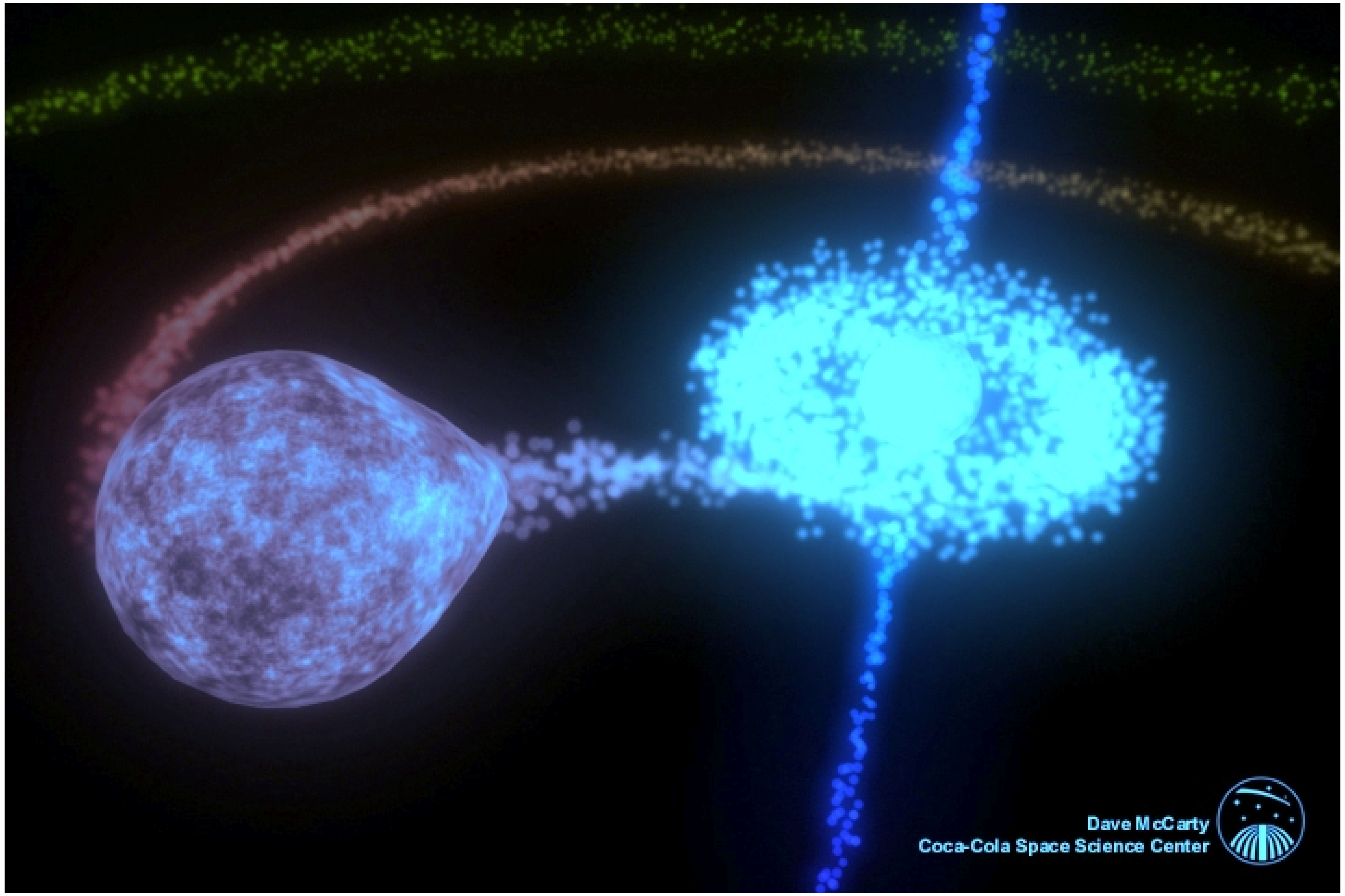


Image Reconstruction of AZ Cyg
Norris et al. (2021)

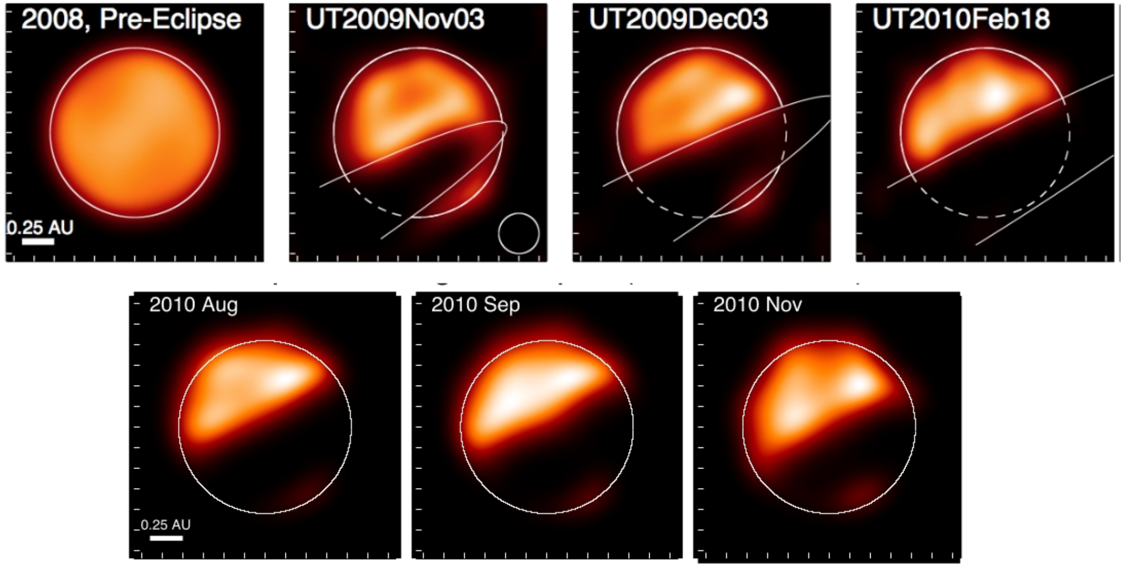
Mass Transfer in Interacting Binaries

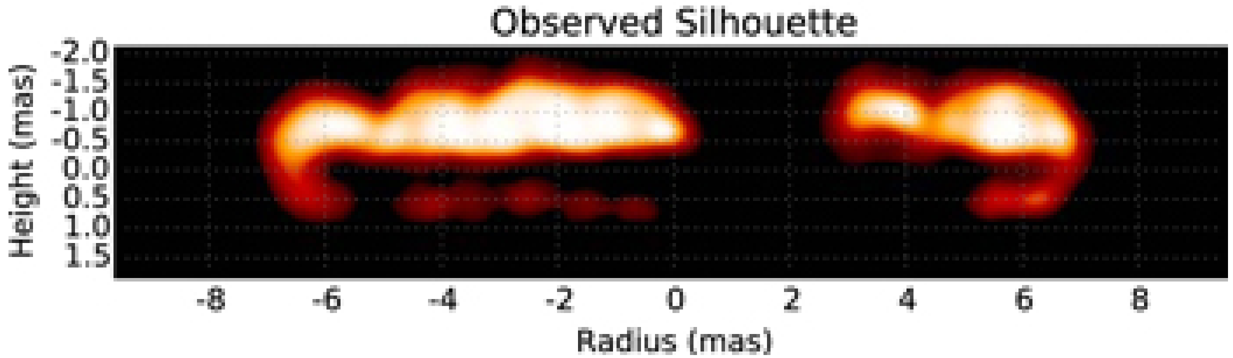


Beta Lyrae
P = 12.9 days
a = 0.87 mas

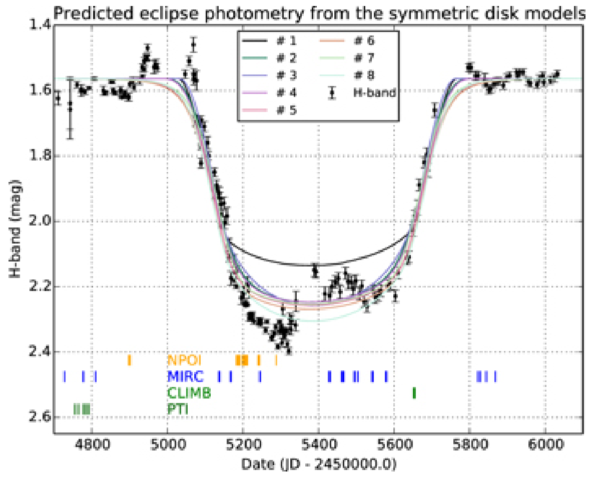
Zhao et al. (2008)

Eclipsing Binary: Epsilon Aurigae

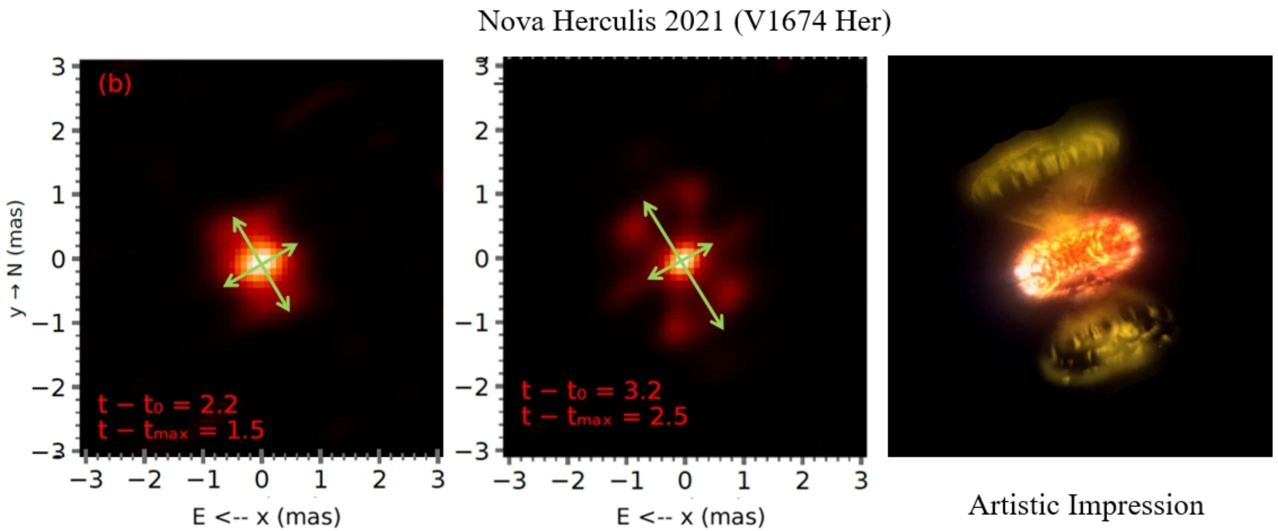


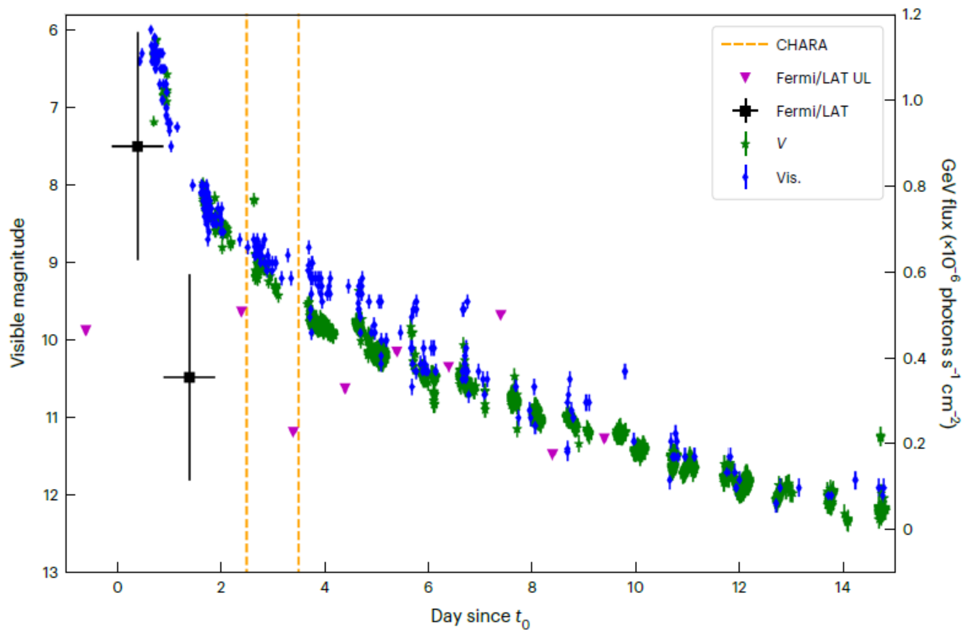


Kloppenborg et al. (2010, 2015)



Perpendicular Ooutflows in Nova V1674 Her

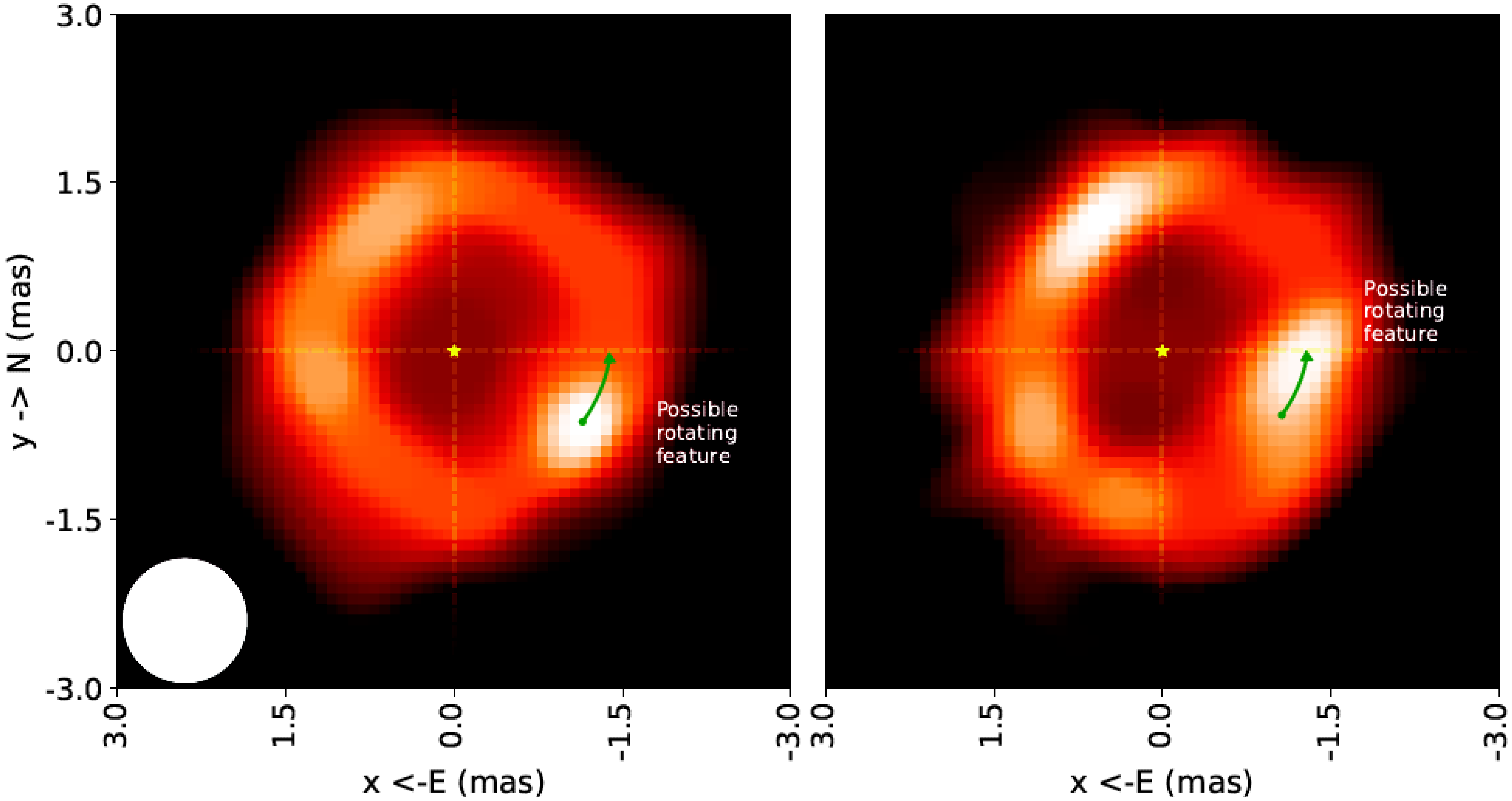




Aydi et al. (2025)

Protoplanetary Disks and Planet Formation

V1925 Aql



Ibrahim et al. (2023)

Optical Interferometry Tutorial
Wednesday June 3

- 2:00-2:30 R. Norris (NMT) -- Quick overview of Imaging and Imaging Tools in Optical Interferometry
- 2:30-3:00 C. Kane (GSU) -- Imaging the Coolest Rapid Rotators with the CHARA Array
- 3:00-3:30 N. Ibrahim (Univ. Michigan) -- The CHARA Array YSO Imaging Survey
- 3:30-4:00 D. Frothingham (NMT) -- Designing an OIR Observation: Investigations of Mass Loss and Atmospheres in RSGs
- 4:00- 4:30 N. Anugu (CHARA/GSU) -- Imaging the Dynamic Surfaces of Evolved Massive Stars with Optical Interferometry
- 4:30 on -- Discussions/questions