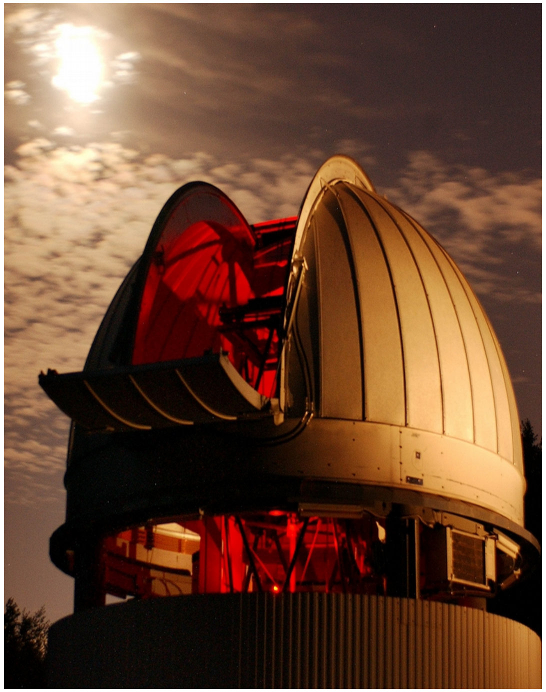
Data Format, Modeling, and Imaging



Gail Schaefer

The CHARA Array of
Georgia State University

Mount Wilson, CA

With contributions from:
Fabien Baron and Laurent Bourgès

Data Reduction

- CHARA staff and consortium members will support data reduction to OIFITS format
- Many users may find it informative to run reduction software and calibration themselves
- Data analysis, model fitting, image reconstruction performed by users

OIFITS Format

- OIFITS: Data exchange standard for Optical Interferometry
- Target and instrument information tables:
  - OI_TARGET
  - OI_ARRAY
  - OI_WAVELENGTH
- Data tables:
  - OI_VIS2
  - OI_T3

OI_VIS2 Table (OIFITS)

TARGET_ID	Target number
TIME	UTC time of observation (s)
MJD	Modified Julian Date
INT_TIME	Integration time (s)
VIS2DATA	Squared Visibility
VIS2ERR	Error in Squared Visibility
UCOORD	U coordinate of data (m)
VCOORD	V coordinate of data (m)
STA_INDEX	Station numbers
FLAG	Flag

OI_T3 Table (OIFITS)

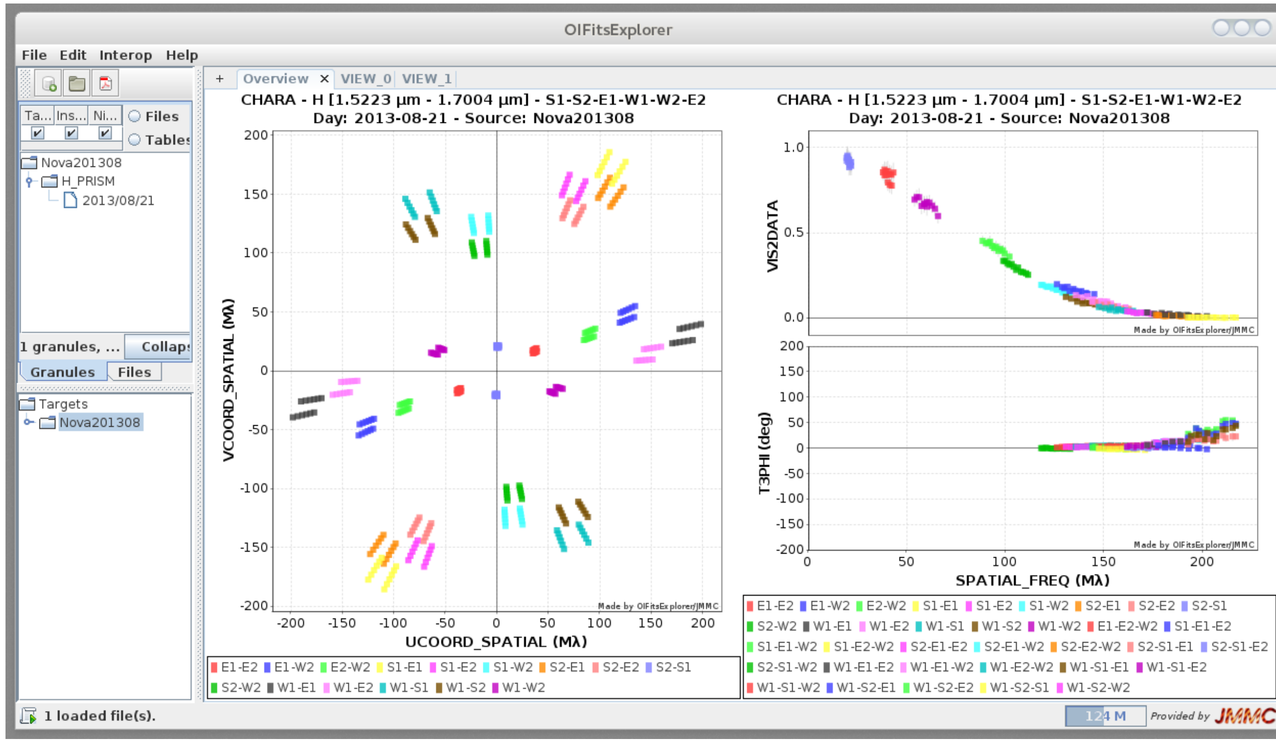
TARGET_ID	Target number
TIME	UTC time of observation (s)
MJD	Modified Julian Date
INT_TIME	Integration time (s)
T3AMP	Triple Product Amplitude
T3AMPERR	Error in Triple Product Amplitude
T3PHI	Triple Product Phase in degrees
T3PHIERR	Error in Triple Product Phase in degrees
U1COORD	U coordinate of baseline AB in triangle (m)
V1COORD	V coordinate of baseline AB in triangle (m)
U2COORD	U coordinate of baseline BC in triangle (m)
V2COORD	V coordinate of baseline BC in triangle (m)
STA_INDEX	Station numbers
FLAG	Flag

Software for Reading/Writing OIFITS Files

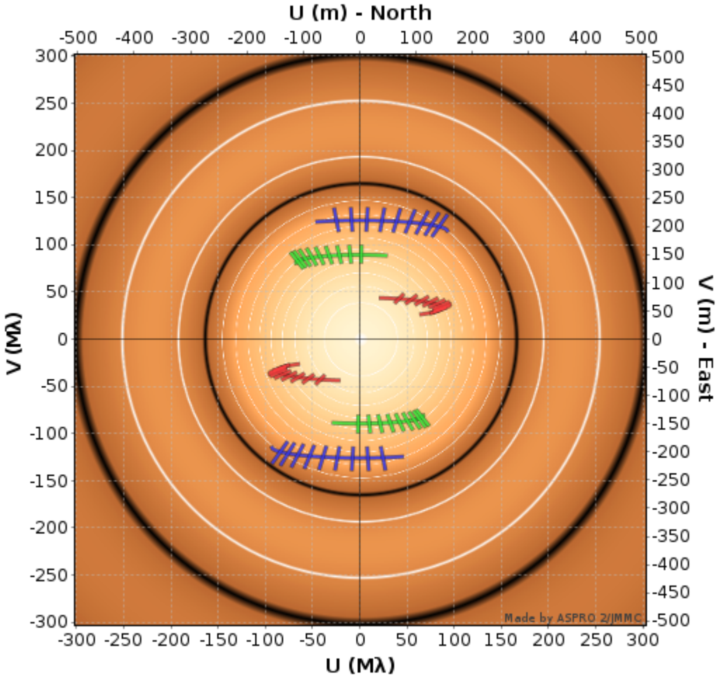
- OIFITSlib – C Library
  - https://github.com/jsy1001/oifitslib
- IDL OIFITS Library – by John Monnier
  - http://dept.astro.lsa.umich.edu/~monnier/oi_data/
- OIFITS Explorer – by JMMC
  - http://www.jmmc.fr/oifitsexplorer_page.htm
- OITOOLS.jl – in development by Fabien Baron
  - Data visualization and modeling (Julia)

OIFITS Explorer

- Visualization
- Load OIFits files
- Plots:
  - uv coverage
  - V2, T3, ...
  - HA, PA, SNR
- Future:
  - Editor: flag and export merged OIFITS files
  - Better data selection graphically



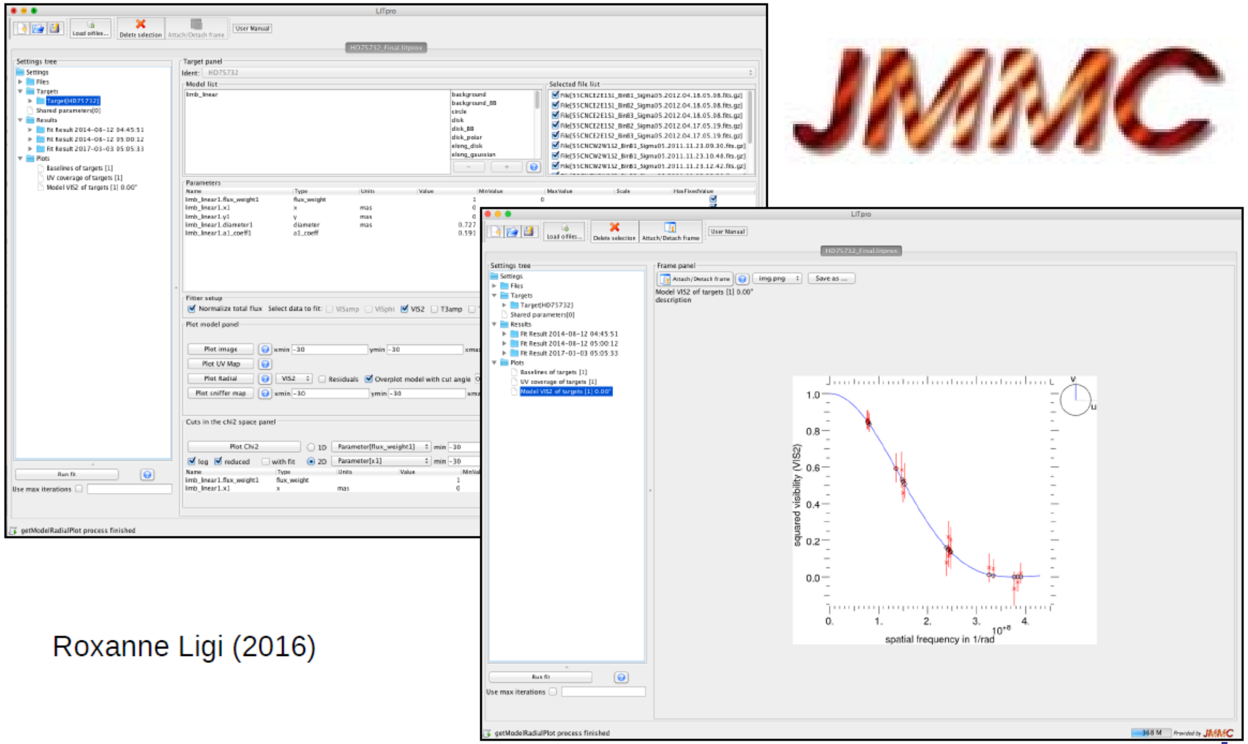
Data Analysis



- Interferometers measure the Fourier Transform of the brightness distribution
- Sparse sampling
- Geometric model fitting
- Physical models
- Image reconstruction

Model Fitting: LITpro

- Fit geometric and limb-darkened models
- Plots to visualize data, models, and results of fits
- Tools to find global minimum



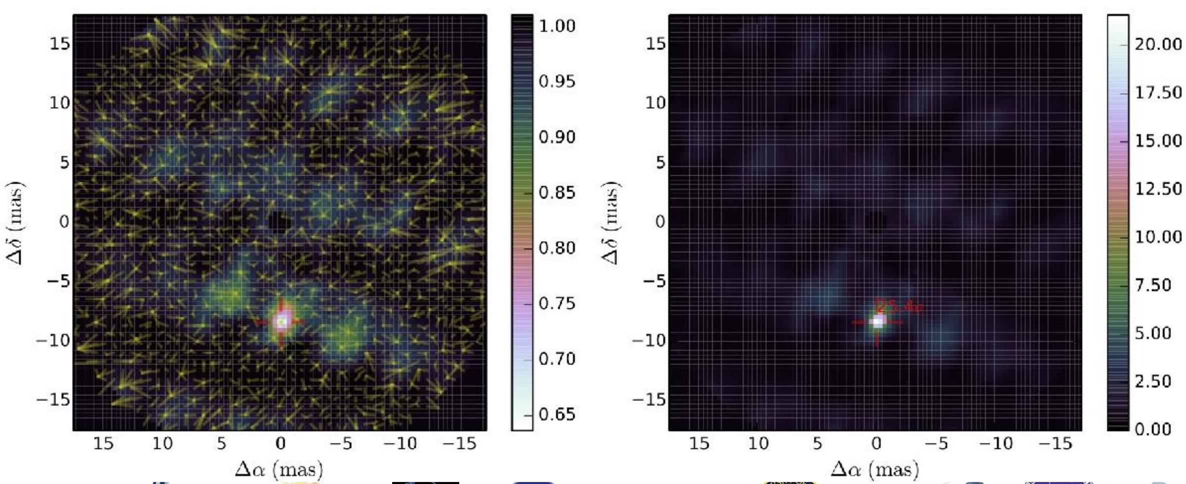
Roxanne Ligi (2016)

LITpro

http://www.jmmc.fr/litpro_page.htm

Model Fitting: Companion Search - CANDID

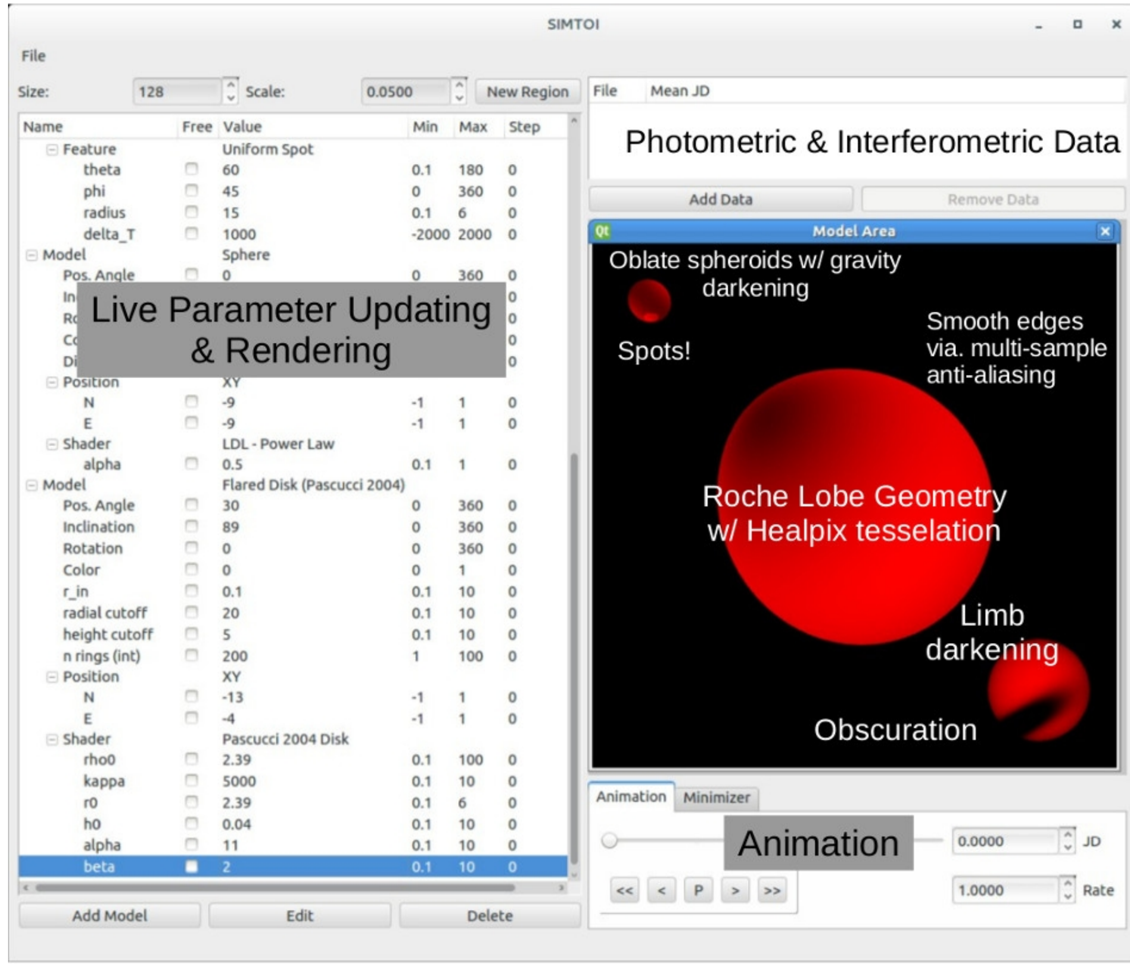
- Companion Analysis and Non-Detection in Interferometric Data
- Grid search for binary companions
- Estimate detection limits
- https://github.com/amerand/CANDID



Gallenne et al. (2015)

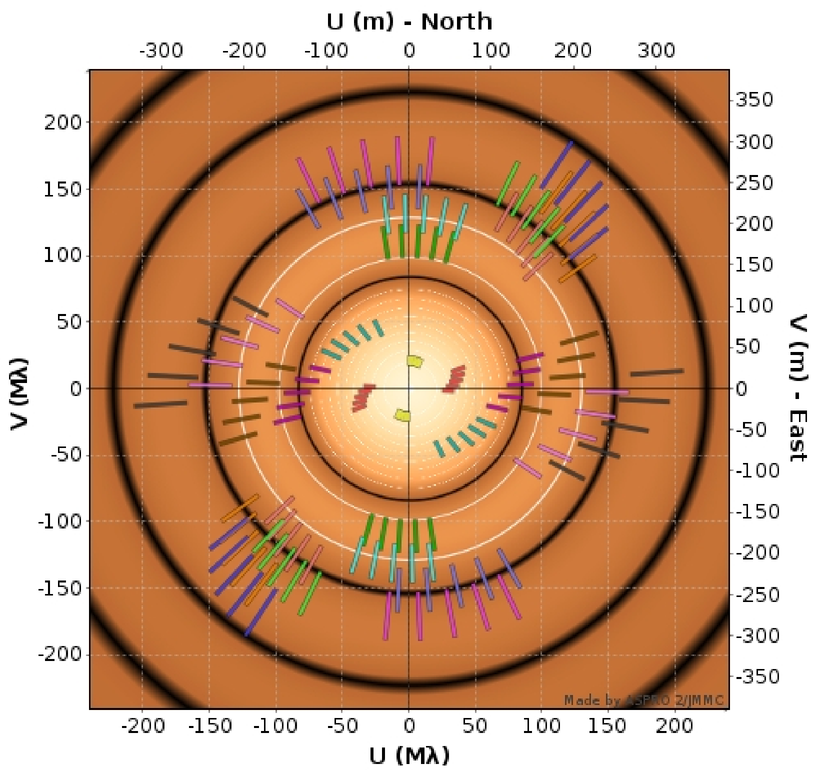
Model Fitting: SIMTOI

- SIMTOI: SImulation and Modeling Tool for Optical Interferometry
- Written by Brian Kloppenborg
- GPU accelerated
- Photometry + interferometry
- Physical models
- Global optimization
- Keplerian orbits



https://github.com/bkloppenborg/simtoi

Image Reconstruction



- Sparse sampling of Fourier frequencies in plane of sky
- Inverse Fourier transform to obtain image
- Compromise between:
  - Fitting available data
  - Keeping the image as regular (simple) as possible

Image Reconstruction

Regularized maximum likelihood

Regularization weight

$$\boldsymbol{i}_{\mathrm{MAP}} = \underset{\boldsymbol{i}}{\operatorname{argmin}} \left[\chi^2(\boldsymbol{i}) + \mu R(\boldsymbol{i}) \right]$$

Most probable image

Likelihood term:
Comparison of model to data

Regularizer:
Helps interpolate missing Fourier data (smoothness, compactness, total variation, maximum entropy)

Image Reconstruction Software

Software	Optimization	Regularizer	Multi-Spectral	Simultaneous Model Fitting
BSMEM	Trust region gradient	Maximum Entropy Method	No	No
MACIM	Simulated annealing	Maximum Entropy Method, Darkness	No	Yes
MiRA	Variable Metric Limited Memory with bound constraints	Many	No	Yes
SQUEEZE	Parallel Tempering	Many	Yes	Yes
PAINTER	Alternating Direction Method of Minimizers	Many	Yes	No

Imaging Tutorial

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

Éric Thiébaut[1,*] and John Young[2]

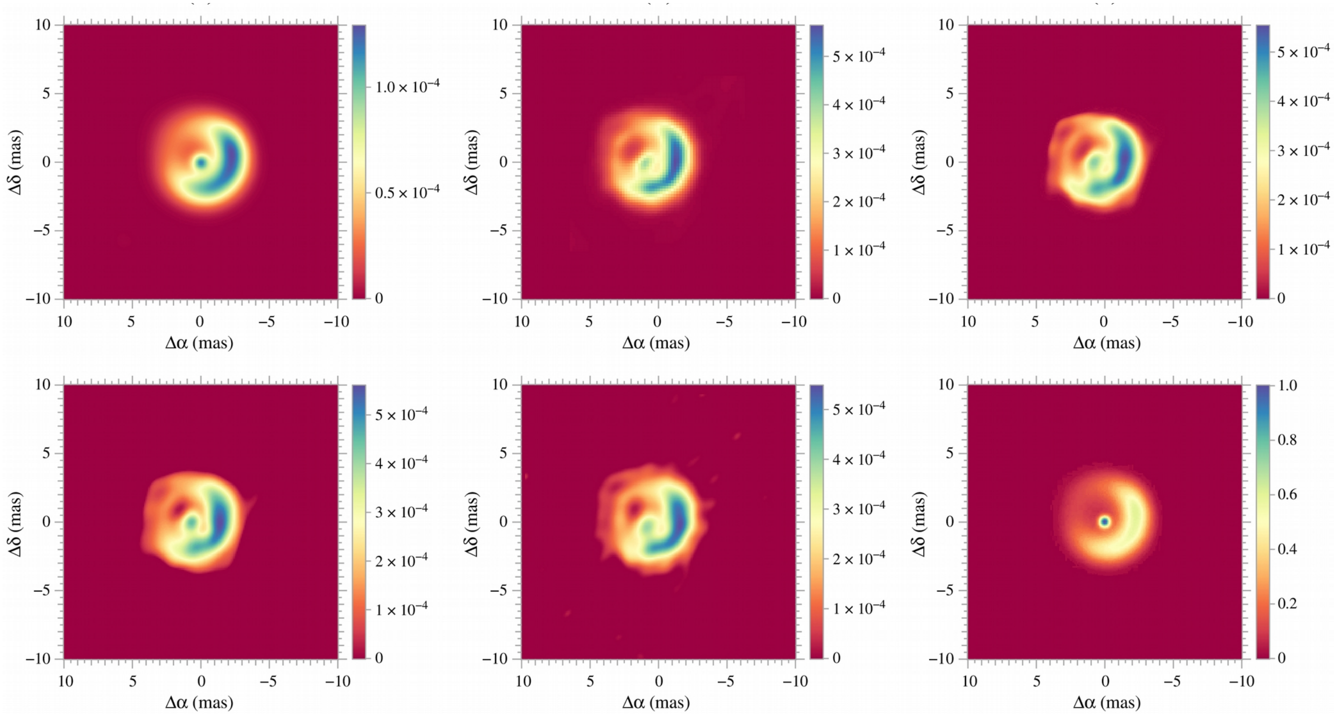
[1]*University of Lyon, University Lyon 1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France*
[2]*University of Cambridge, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK*
**Corresponding author: eric.thiebaut@univ-lyon1.fr*

JMMC is developing a common interface for "classic" image reconstruction software

http://www.jmmc.fr/oimaging.htm

Different Reconstruction Methods and Regularizers

Original Image (LkHα 101) | BSMEM | MiRA + MEM regularizer



MiRA + compactness quadratic | MiRA + edge-preserving | SQUEEZE with l_0 norm wavelet coefficients

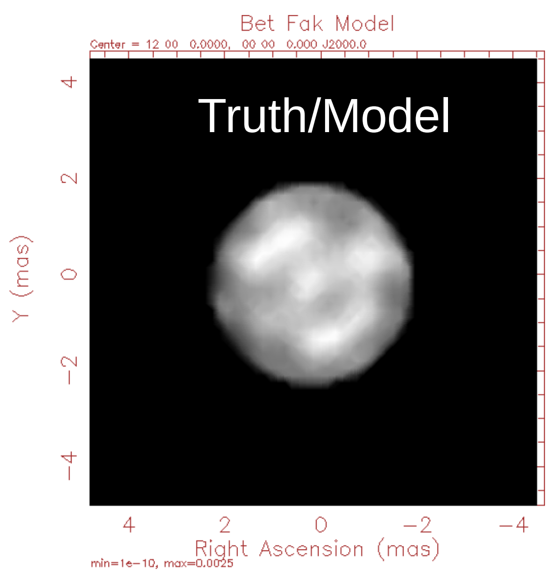
Thiebaut & Young (2017)

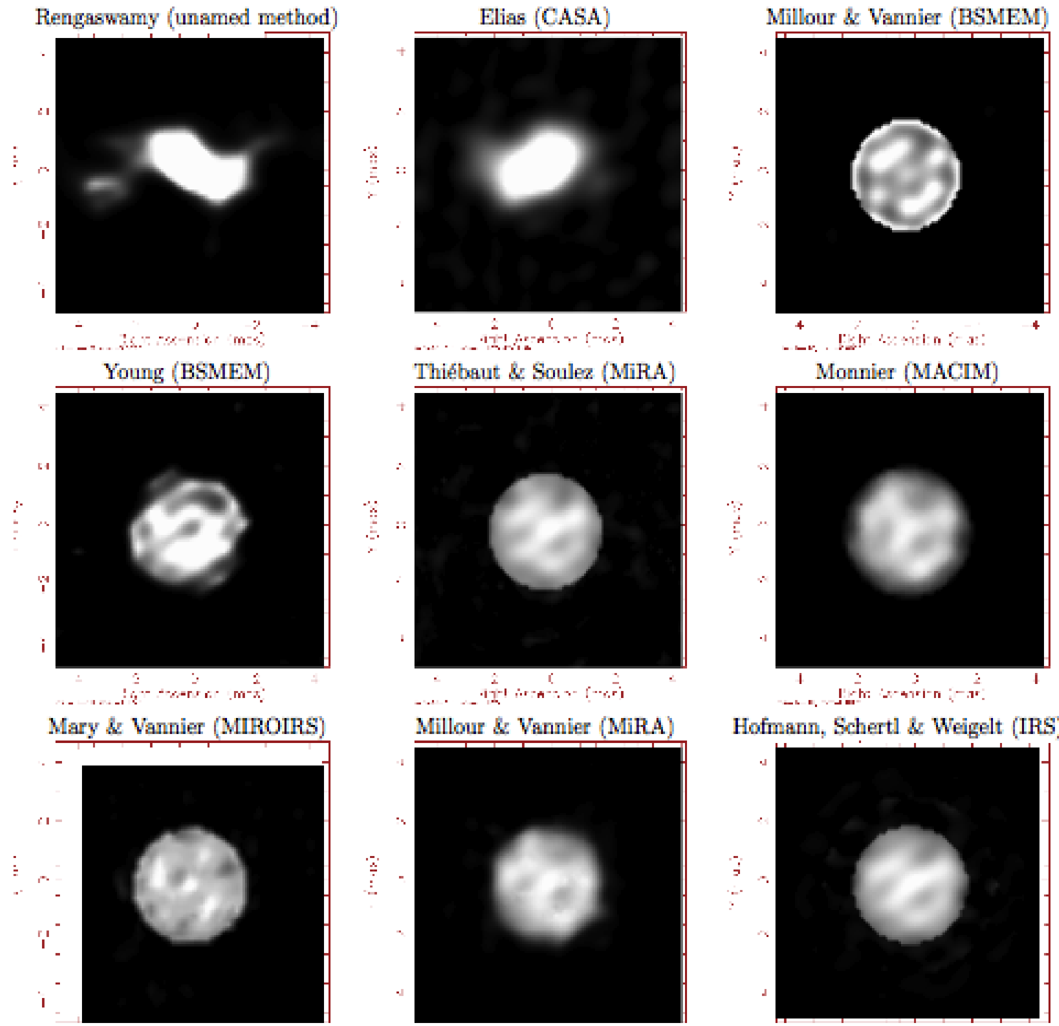
High Fidelity Imaging of Complex Targets is Difficult

AZ Cyg

2012 IAU Interferometry Beauty Contest

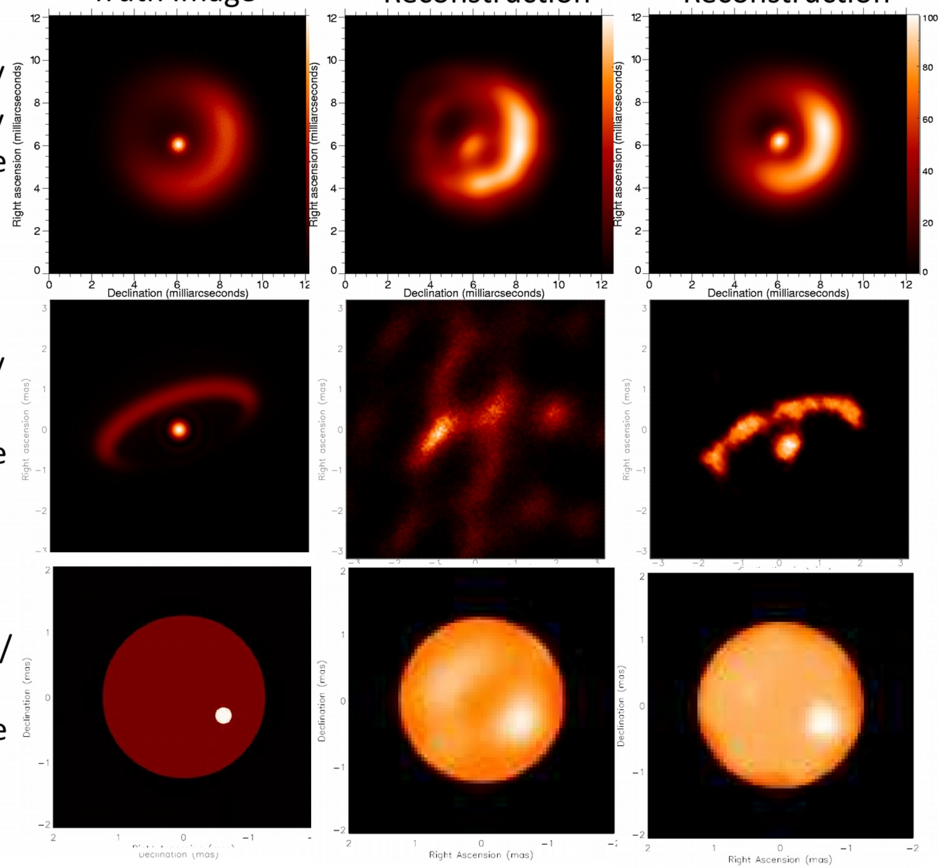
Baron et al. 2012





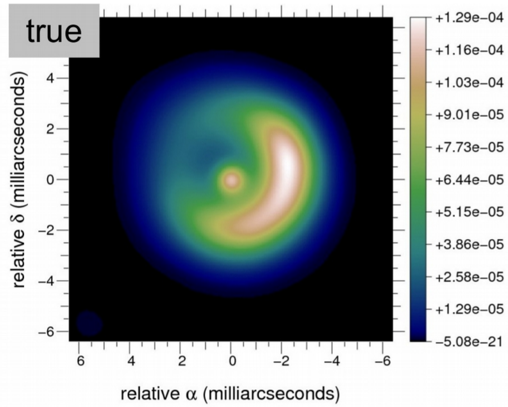
Ongoing Research on Better Regularization

	"Truth Image"	Conventional Reconstruction	Compressed Sensing Reconstruction	Sparsity basis
Case 1: YSO Disk w/ high-quality UV coverage				Isotropic wavelets
Case 2: YSO Disk w/ only 4-T UV coverage				Arclets
Case 3: Star+Spot w/ only 4-T UV coverage				Gradient

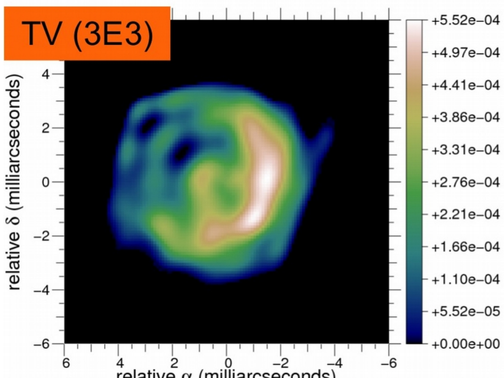


Baron et al., in prep

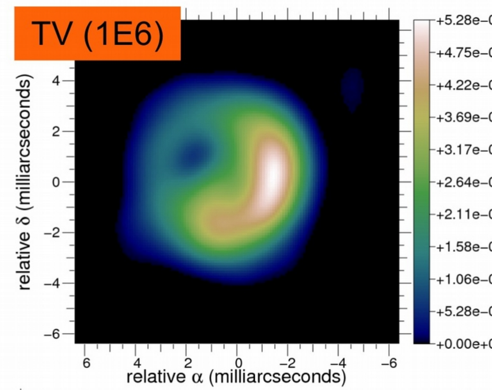
Regularization Weight

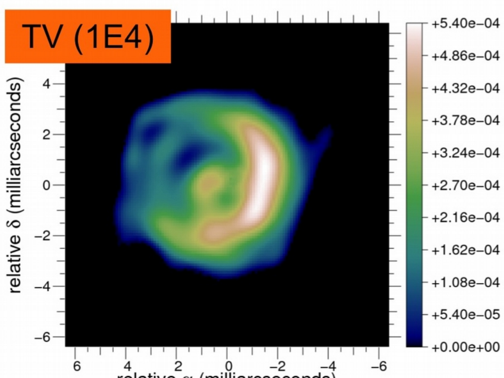


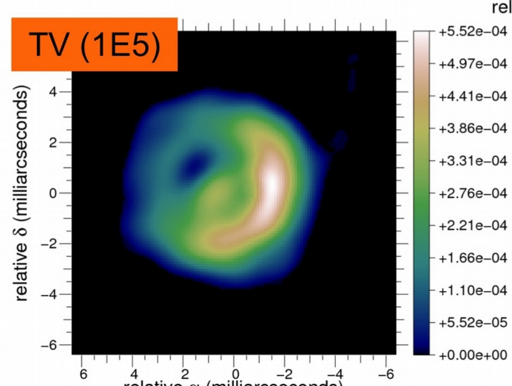
Images by
E. Thiebaut (MiRA)
courtesy of F. Baron



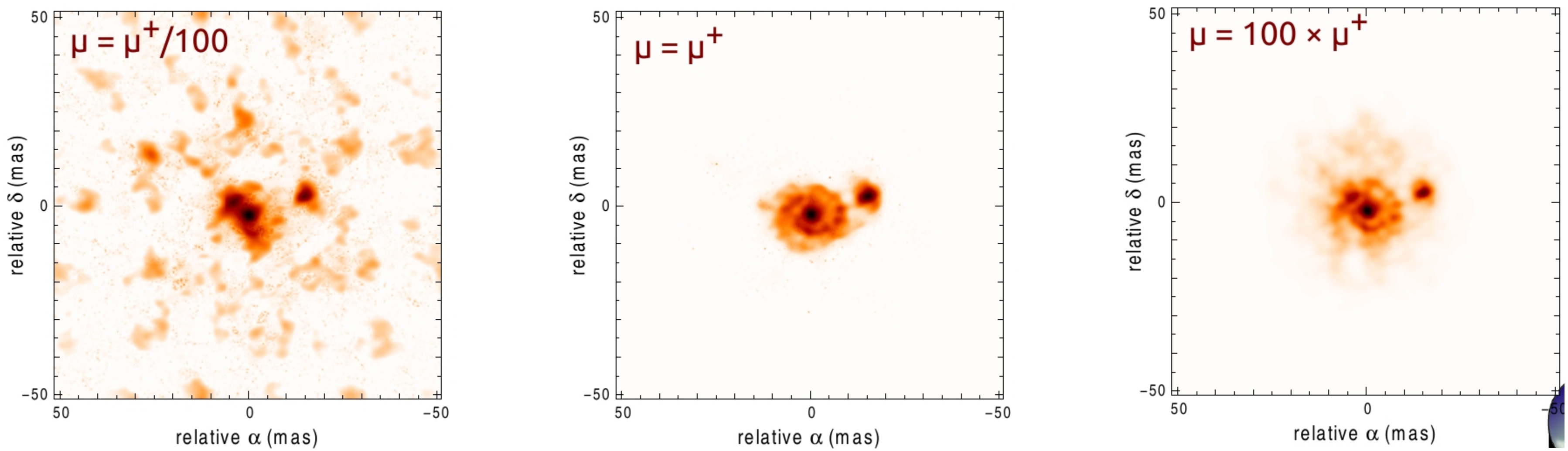
$$\boldsymbol{i}_{\mathrm{MAP}} = \underset{\boldsymbol{i}}{\operatorname{argmin}} \left[\chi^2(\boldsymbol{i}) + \mu R(\boldsymbol{i}) \right]$$







Avoid under and over regularization

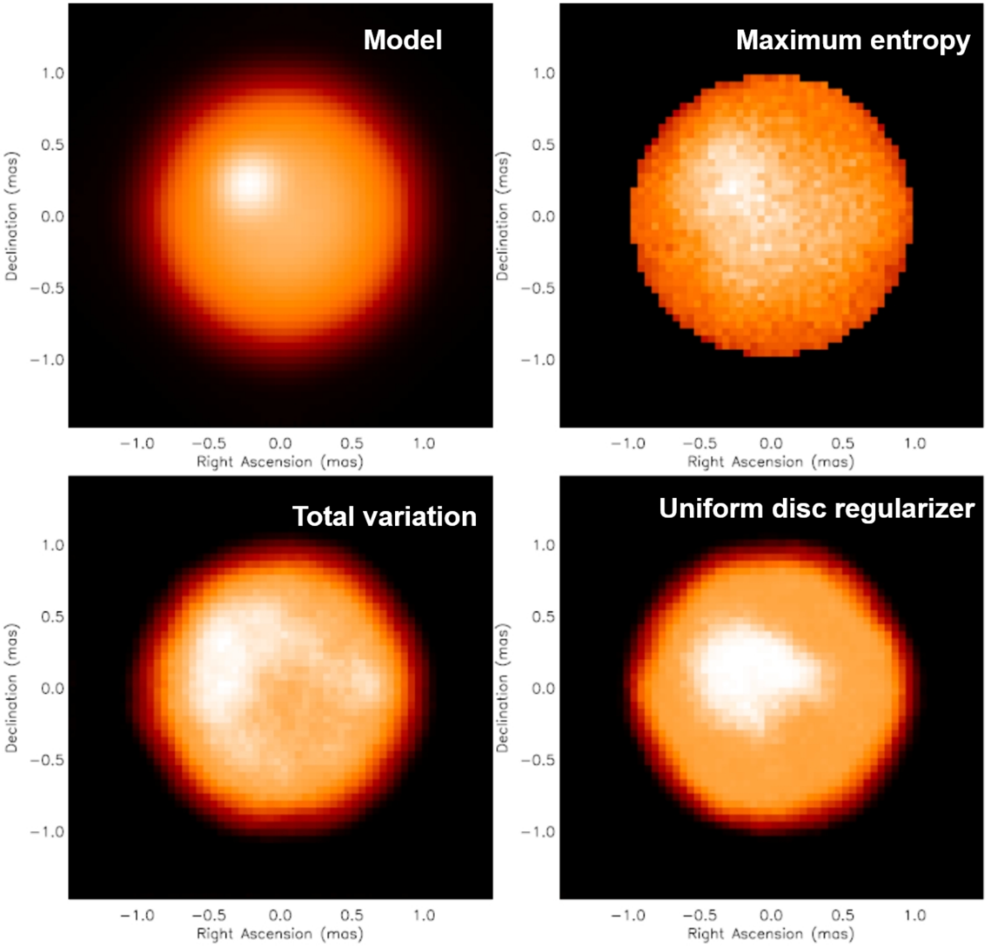


Images by S. Renard
See Renard et al., 2011

Artifact Detection

Fabien Baron

- Use two control sets:
  - model image of object with complexity (e.g., spotted star)
  - much simpler model image with no features (e.g. limb-darkened disk)
- Simulate observations – copy Fourier coverage and signal to noise from original data
- Reconstruct images for two control data sets and check fidelity of reconstructions
- Were spurious features introduced in simple model?
- Were feature correctly recovered in the complex model?



This method will help identify the best regularization

Links for modeling and imaging software available on the CHARA website:

http://www.chara.gsu.edu/analysis-software/