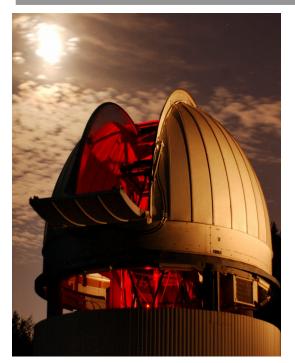


## Data Format, Modeling, and Imaging



### Gail Schaefer

The CHARA Array of Georgia State University

Mount Wilson, CA

With contributions from: Fabien Baron and Laurent Bourgès



















- 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: Data exchange standard for Optical Interferometry
- Target and instrument information tables:
  - OI\_TARGET
  - OI\_ARRAY
  - OI\_WAVELENGTH
- Data tables:
  - OI\_VIS2
  - OI\_T3













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## 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           |  |  |  |
|   | ТЗРНІ   | 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  |  |  |  |
|   | Georgia <u>State</u> University 🐲 💭 l'Observatoire – LESIA 😥 net of a la contra d'Azur Exervatoire de Paris |   |  |  |  |

## 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)



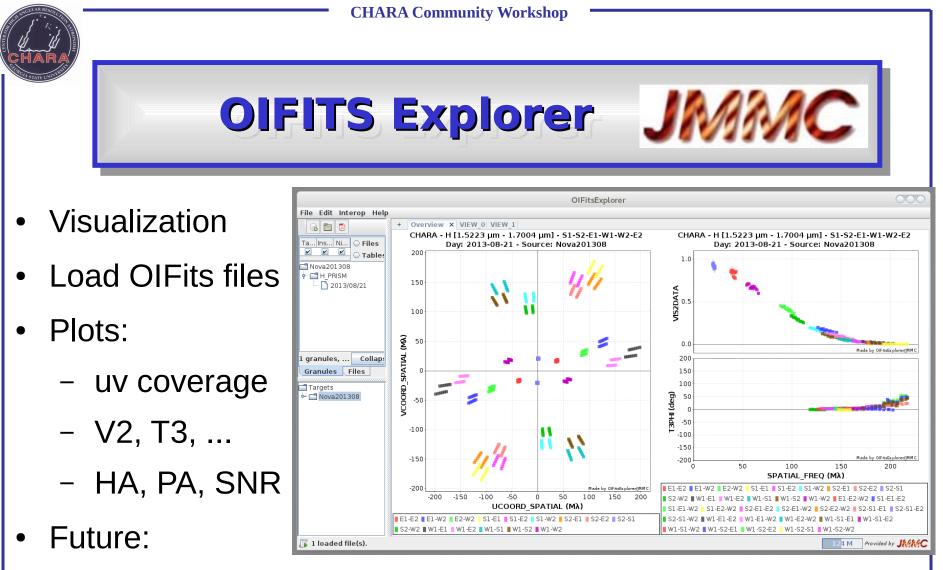












- Editor: flag and export merged OIFITS files

l'Observatoire

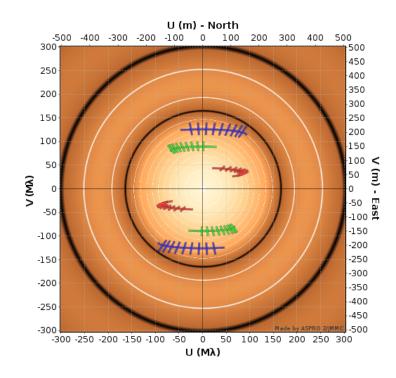
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Better data selection graphically

GeorgiaStateUniversity

## **Data Analysis**



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







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

| • • •  | UTpro   |   |                                   |   |
|--|---|---|-----------------------------------|---|
|  | User Manual   |   |                                   |   |
| Load offics Delete selectio                      | n Attach/Detach frame   |   |                                   |   |
|  | H075732_Final litprox   |   |                                   |   |
| Settings tree                                    | Target panel  |   |                                   |   |
| Settings   | Ident: HD75732  |   |                                   |   |
| E Fies   | Model list  | Selected file list  |                                   |   |
| 🔻 🚞 Targets                                      | limb_inear backg  |   | agma05.2012.04,18.05.08.fts.g2    |   |
| Target(HD75732)                                  | backgr  |   | SigmaD5.2012.04.18.05.08.ftts.gz] |   |
| Shared parameters(0)                             | circle  | FIN(55CNCE2E151 BINB3   | Sigma05.2012.04.18.05.08.fits.gz] |   |
| ▼ ■ Results<br>► ■ Rt Lesult 2014-08-12 04:45:51 | dhk<br>dmk_B  | ReissCNCE2E152 Bin82  | Sigma05.2012.04.17.05.19.fits.gz] |   |
| Mit Kesuk 2014-08-12 14-45 51                    | dik p   | ar Sink(SSCNCE2E152_BinB3_  | Sigma05.2012.04.17.05.19.fts.gz]  |   |
| Fit Result 2017-03-03 05:05:33                   | elong   |   | Sigma05.2011.11.23.09.30.fts.gz]  |   |
| T Plots  |   |   | [5igma05.2011.11.23.10.48.fts.gz] |   |
| Easelines of targets [1]                         |   |   | 54gma01.2011.11.23.12.42.fts.gz]  |   |
| UV coverage of targets [1]                       | Parameters  |   |                                   |   |
| Model VIS2 of targets [1] 0.00*                  | Name Type Units Value   | Ministalian MaxValue Scale  | HasFixedhialse                    |   |
|  | imb_Inear1.flux_weight flux_weight  | 1 0   | 9                                 |   |
|  | imb_inear1.x1 x mas<br>imb_inear1.v1 y mas  |   |                                   | LITpro  |
|  | imb inear1.diameter1 diameter mas 0.72  |   | Liar Mercal                       |   |
|  | limb_linear1.a1_coeff1 a1_coeff 0.59  |   | Attach/Detach frame               |   |
|  |   |   |                                   | HD95712_final/itprox  |
|  |   |   |                                   |   |
|  |   | Settings tree   | Frame panel                       |   |
|  |   | Settings  | Attach/Detach frame               | ing png 1 Save as   |
|  |   | ► Files   | Model VIS2 off targets [1] 0.00*  |   |
|  | Fitter setup  | Targets   | description                       |   |
|  | 🗹 Normalize total flux Select data to fit: 🗌 VISamp 🔄 VISphi 🗹 VIS2 🔲 T3amp   | <ul> <li>Target(H075732)</li> <li>Shared parameters[0]</li> </ul> |                                   |   |
|  | Plot model panel  | w Results   |                                   |   |
|  | The most pane   | FR Result 2014-08-12 04:45:51                                     |                                   |   |
|  |   | FR Result 2014-08-12 05:00:12                                     |                                   |   |
|  | Plot image 😡 xmin -30 ymin -30 xr   | FR Result 2017-03-03 05:05:33                                     |                                   |   |
|  | Plot UV Map   | v Plots   |                                   |   |
|  | Mot Radial 😯 MS2 0 🗌 Residuals 🥑 Overplot model with cut angle  | Baselines of targets [1]  |                                   | Jan tan haataa haataa haataa haa t  |
|  |   | Votel VIS2 of targets [1]   |                                   |   |
|  | Plot sniffer map 😧 xmin -10 ymin -10 x  | and a second or confiner (11) or on                               |                                   | 1.0 -( )  |
|  |   |   |                                   |   |
|  | Cuts in the chi2 space panel  |   |                                   |   |
|  |   |   |                                   |   |
|  | Plot Chi2 1D Parameter[flux_weight] 1 min -30   |   |                                   |   |
|  |   |   |                                   |   |
|  | Solution of the second |   |                                   | Žoe –   |
| Run fit 🕢 😡                                      | Name Type Units Value Min<br>limb_linear1.flux.weight1 flux.weight 1  | Na  |                                   |   |
| Use max iterations                               | imb_inear1.flux_weight flux_weight 1 imb_inear1.x1 x mas 0  |   |                                   |   |
| ose max nerations L                              |   |   | ·                                 | 8   |
|  |   | -   |                                   |   |
|  |   |   |                                   |   |
| C petModelRadialPlot process finished            |   |   |                                   |   |
| 0,   |   |   |                                   | g 0.2-  |
|  |   |   |                                   |   |
|  |   |   |                                   |   |
|  |   |   |                                   |   |
|  |   |   |                                   | 0.0-  |
|  |   |   |                                   |   |
|  |   |   |                                   | Jan program pro |
|  |   |   |                                   |   |
|  |   |   |                                   | 0. 1. 2. 3. 10 <sup>+8</sup> 4.   |
|  | anne Ligi (2016)  |   |                                   | spatial frequency in 1/rad  |
| Roxanne  |   |   |                                   | opened respectively in these  |
| i concernitio                                    |   |   |                                   |   |
|  |   |   |                                   |   |
|  |   | kus fit   |                                   |   |
|  |   | Use max iterations  |                                   |   |
|  |   |   |                                   |   |
|  |   |   |                                   |   |
|  |   |   |                                   |   |









LITpr⇔



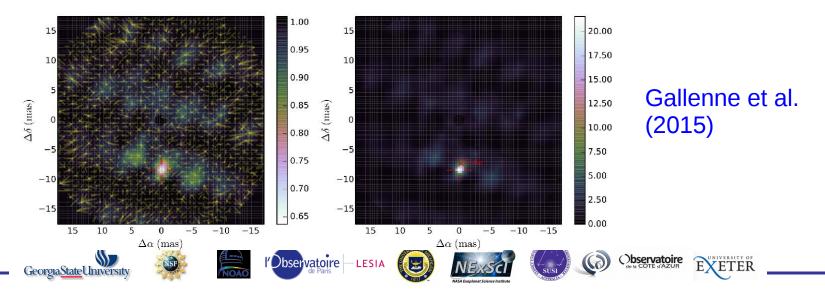








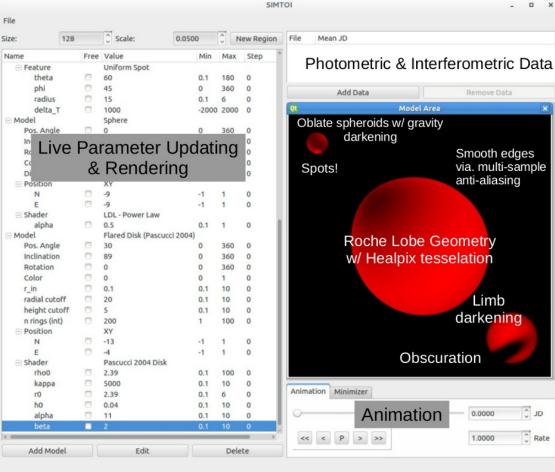
- Companion Analysis and Non-Detection in Interferometric Data
- Grid search for binary companions
- Estimate detection limits
- https://github.com/amerand/CANDID



## **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













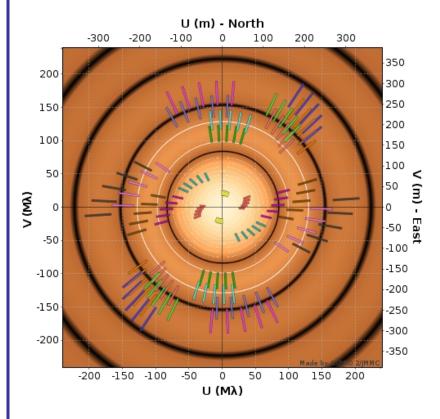


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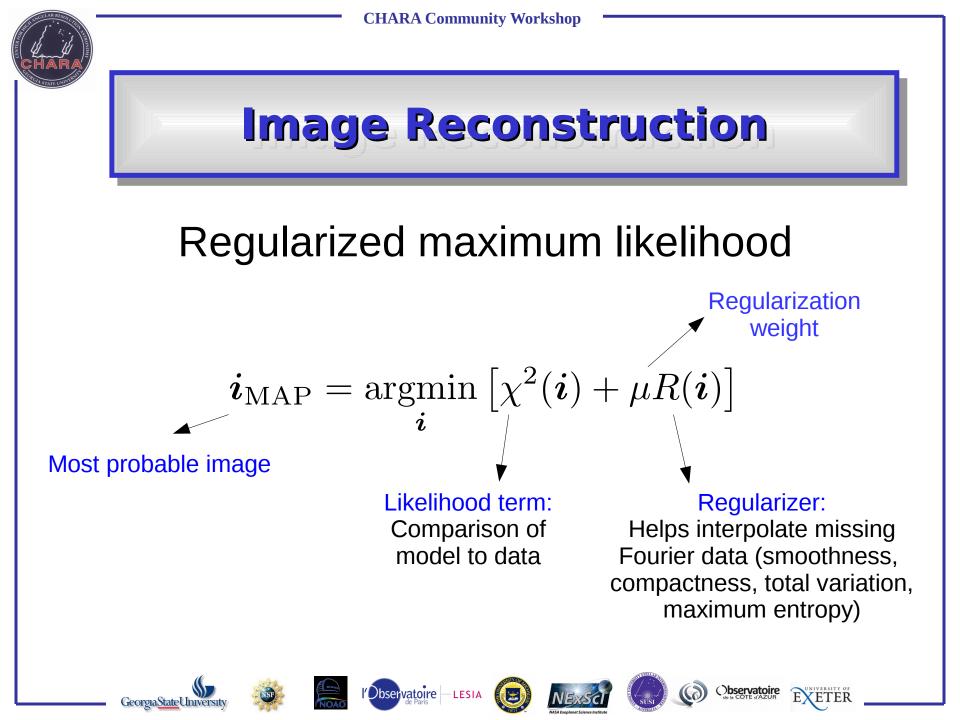
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### **Image Reconstruction**



- 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 Software**

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











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## **Imaging Tutorial**



## Principles of image reconstruction in optical interferometry: tutorial

#### ÉRIC THIÉBAUT<sup>1,\*</sup> AND JOHN YOUNG<sup>2</sup>

<sup>1</sup>University of Lyon, University Lyon 1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France <sup>2</sup>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





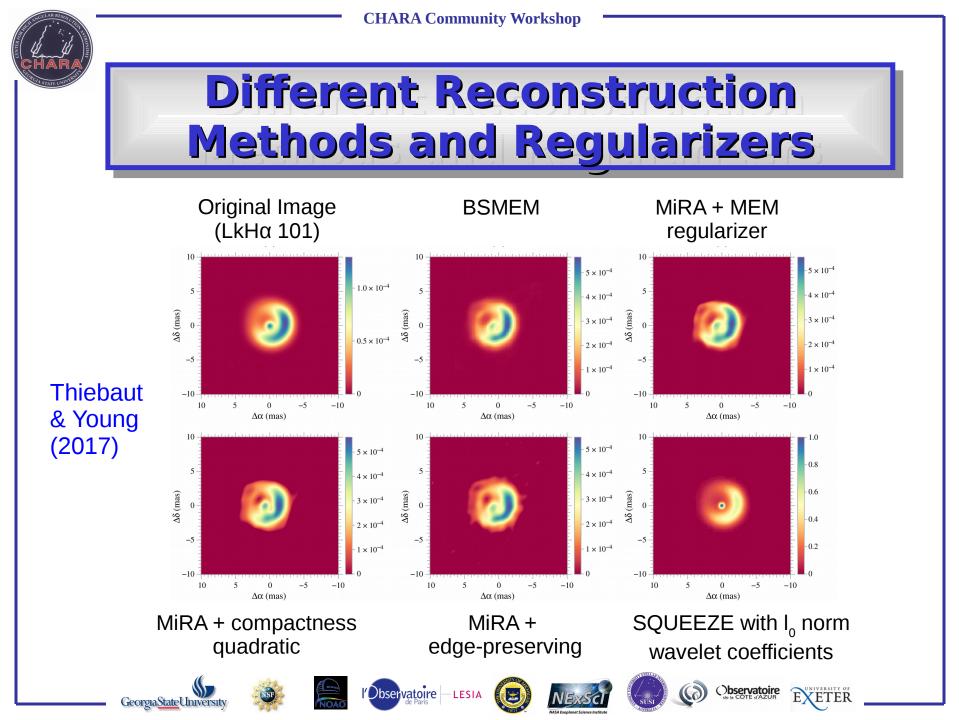










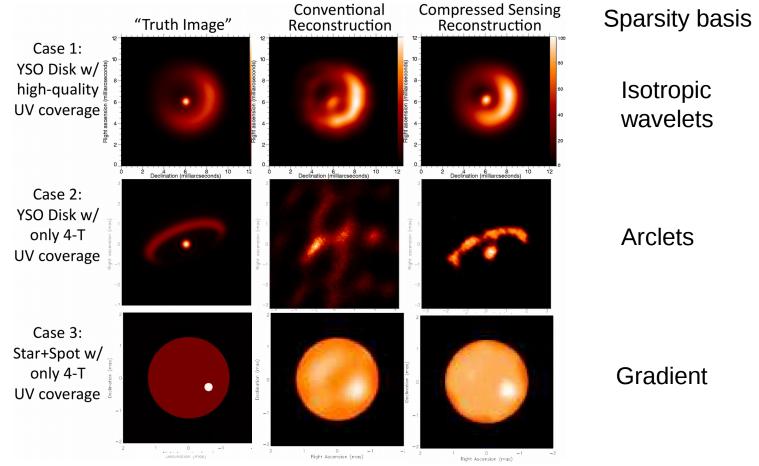


## High Fidelity Imaging of Complex Targets is Difficult

Millour & Vannier (BSMEM) Rengaswamy (unamed method) Elias (CASA) AZ Cyg 2012 IAU Interferometry **Beauty Contest** Baron et al. 2012 -2 (1.5 million (mos)) (1.5 million (mos)) A 2 ( 2) Appl Appendix (max) Dicht Astension (mar) Young (BSMEM) Thiébaut & Soulez (MiRA) Monnier (MACIM) Bet Fak Model 64 Center = 12 00 0.0000, 00 00 0.000 J2000.0 4 Truth/Model  $\sim$ Y (mas) 4 2 3 2 Disto Assession (max) a 2 ( 2) and a state of (max). Mary & Vannier (MIROIRS) Millour & Vannier (MiRA) Hofmann, Schertl & Weigelt (IRS)  $\sim$ 4 γŤ 4 0 -2 $^{-4}$ Right Ascension (mas) l'Observatoire - LESIA Observatoire EXETER GeorgiaStateUniversity



## **Ongoing Research on Better Regularization**



#### Baron et al., in prep







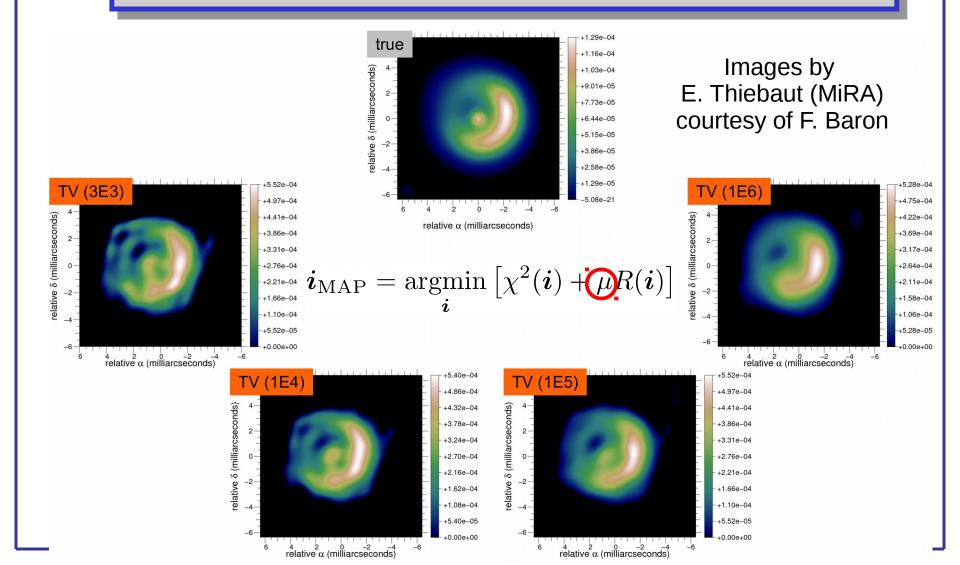


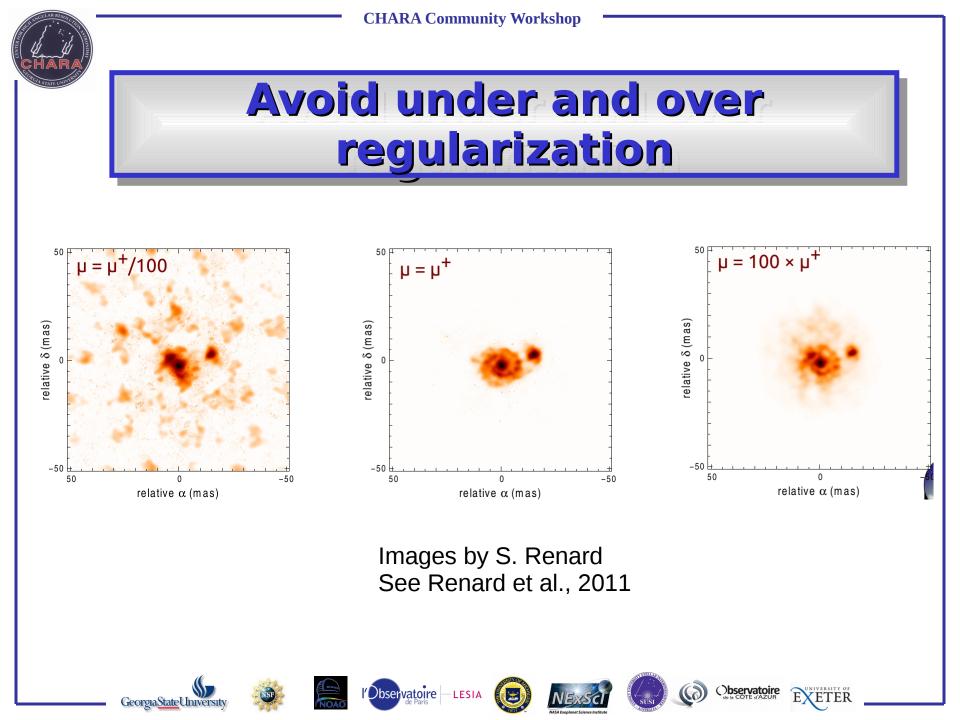






## **Regularization Weight**







## Artifact Detection

#### 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 reconstuctions
- Were spurious features introduced in • simple model?
- Were feature correctly recovered in • the complex model?









-1.0

-0.5



0.5

0.0

Right Ascension (mas)



1.0





Right Ascension (mas)

0.5

1.0

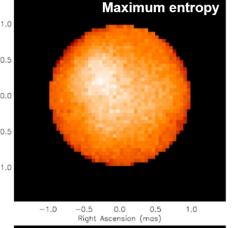
This method will help identify the best regularization

-1.0

# 0.0

-0.5 -0.5 -1.0 1.0 1.0 -0.5 0.5 Right Ascension (mas) Right Ascension (mas) Uniform disc regularizer **Total variation** 1.0 1.0 0.5

Model



**Fabien Baron** 



