Interferometric results from the epsilon Aurigae eclipse

(Its more than just images!)

Max-Planck-Institut
für Radioastronomie

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2013-07-30 – AAS Giants of Eclipse Meeting

Collaborators

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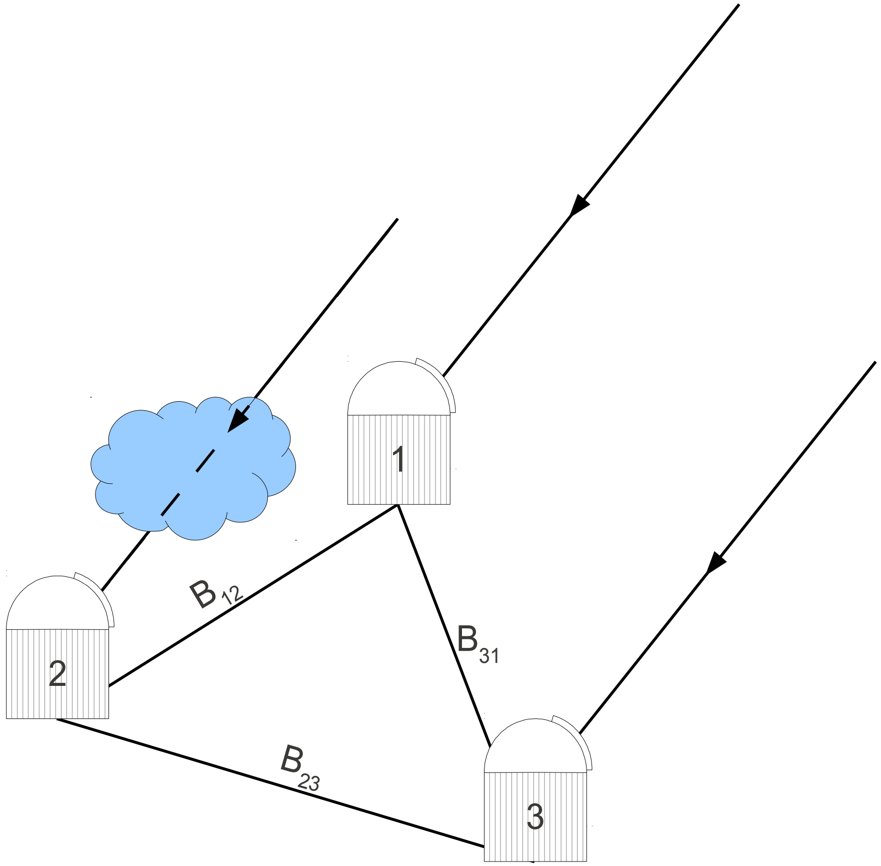
- **UM**: J. D. Monnier, X. Che
- **CHARA/GSU**: G. Schaefer, F. Baron, T. ten Brummelaar, C. Farrington, R. Parks, PJ Goldfinger, J. Sturman, L. Sturman, N. Turner, H. McAlister
- **NPOI**: C. Tycner, B. Zavala, D. Hutter
- **Penn. State**: M. Zhao
- **U. St. Andrews**: E. Pedretti, N. Thureau

Overview

- Optical Interferometry (OI) Data Products
- OI image reconstruction
- Data sources for eps Aur project
- Artifact assessment and eps Aur images
- System models and results
- Applied statistical methods

Optical interferometry data products



- UV points
- Visibility squared

$$|V|^2$$

- Triple product (the bispectra)

$$T_{ijk} = V_{ij}V_{jk}V_{ki}$$
$$= |V_{ij}V_{jk}V_{ki}|e^{i(\phi_{ij}+\phi_{jk}+\phi_{ki})}$$

Triple Amplitude　　　Closure Phase

$$\phi_{123} = \phi_{12} + \phi_{\mathrm{atm}} + \phi_{23} + (-\phi_{\mathrm{atm}}) + \phi_{31}$$

- Differential quantities (spectrally dispersed data)
  - Visibilities
  - Phase
- Closure Amplitudes
- Data are saved as OIFITS files

OI imaging is an ill-posed model fitting problem

- Model fitting
  - Well-posed problem N(data) > N(parameters)
  - Small number of parameters (often of different nature)
  - Constraints on parameters to keep them physical

- Image reconstruction
  - This is still model-fitting...
  - High number of identical parameters
    - e.g. pixels, wavelets, etc.
  - Ill-posed problem N(data) << N(pixels)
  - Need some prior information needed to regularize the solution

Slide content from *Aperture Synthesis Imaging*. Baron (2012)

Bayes theorem applied to imaging

$$\Pr(i|D, M) = \frac{\Pr(i|M)\Pr(D|i, M)}{\Pr(D|M)}$$

data

prior

likelihood

image

imaging model (image description, prior choices, ...)

marginal likelihood (constant for a given reconstruction)

N(data) << N(pixels)... need more constraints:

Regularized Maximum Likelihood:

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

regularization weight

regularization function

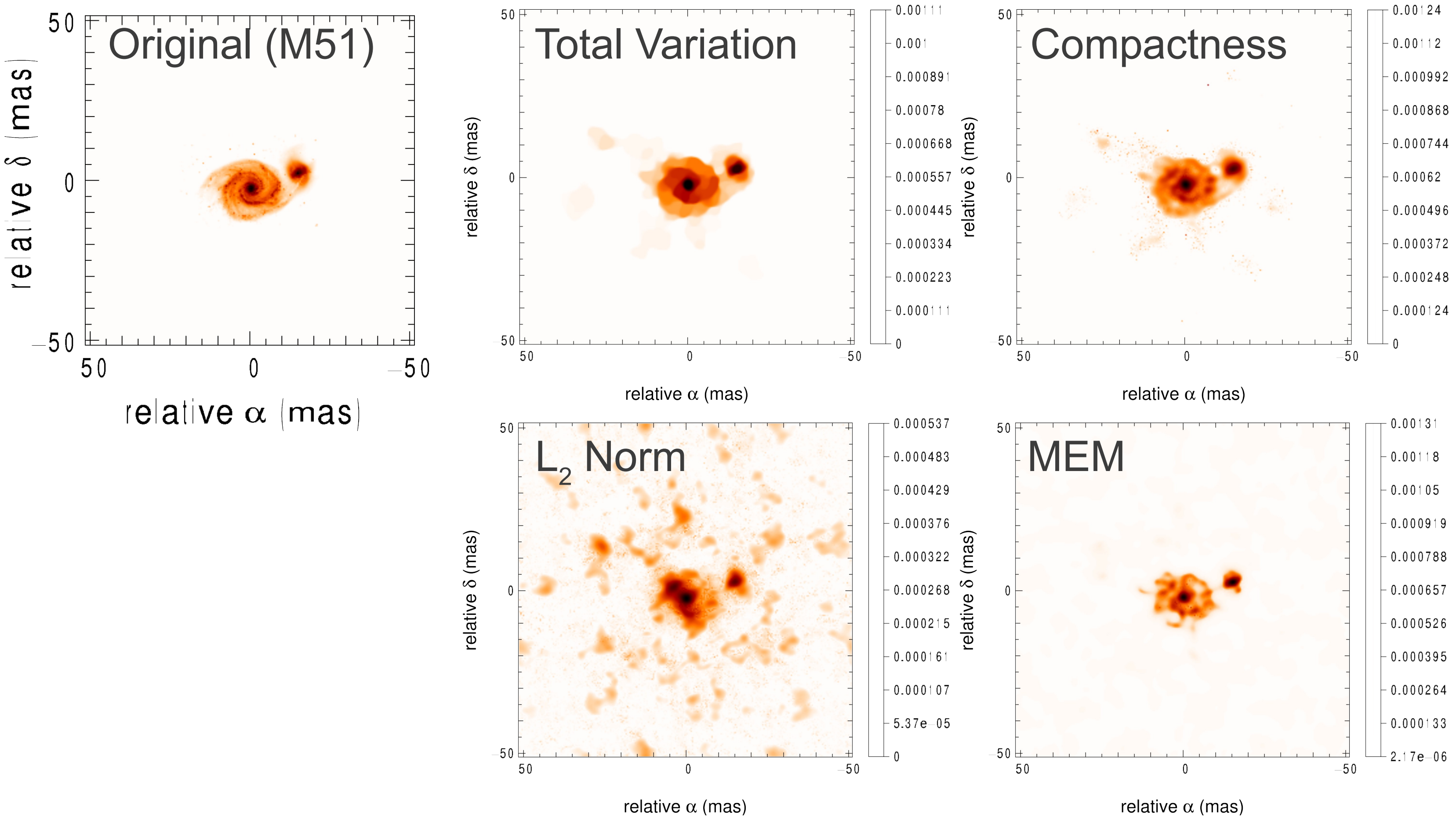
Positivity: $\forall n, i_n \geq 0$

Normalization to unity: $\sum_n i_n = 1$

Slide content from *Aperture Synthesis Imaging*. Baron (2012)

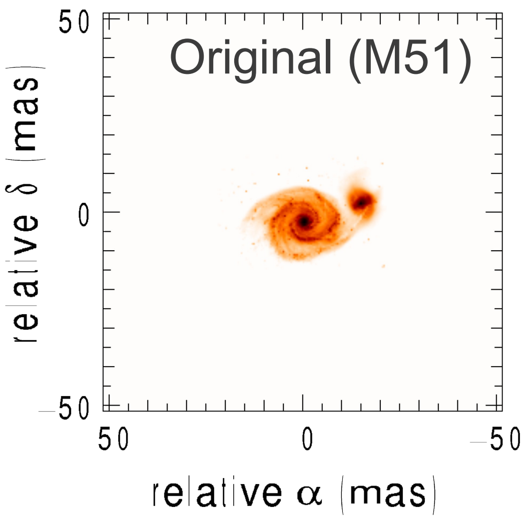
Which regularization function?

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



Images from Renard (2012)

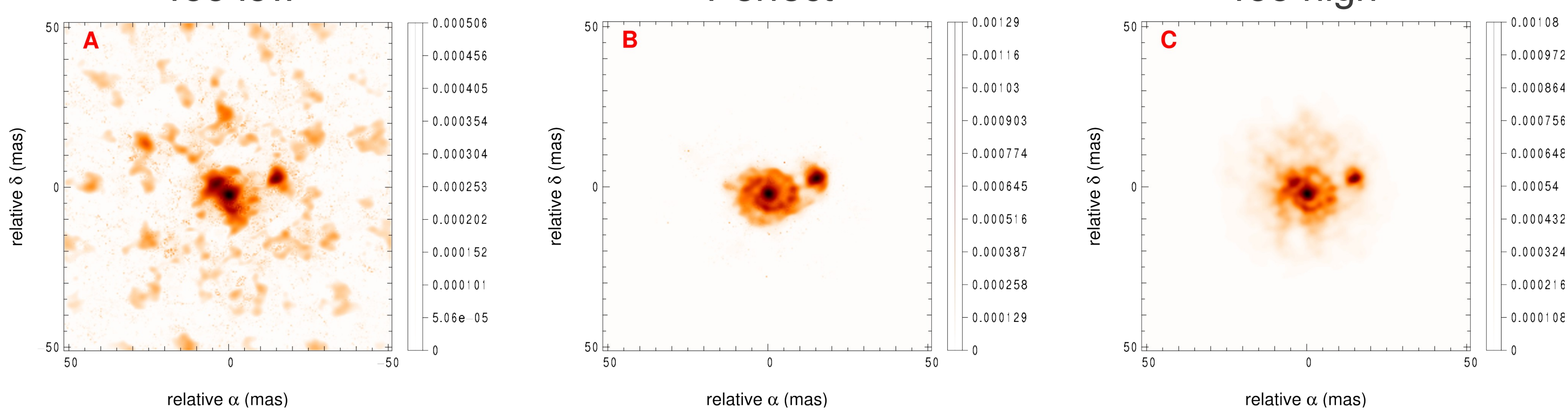
What value for the multiplier?



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

What regularization weight value?

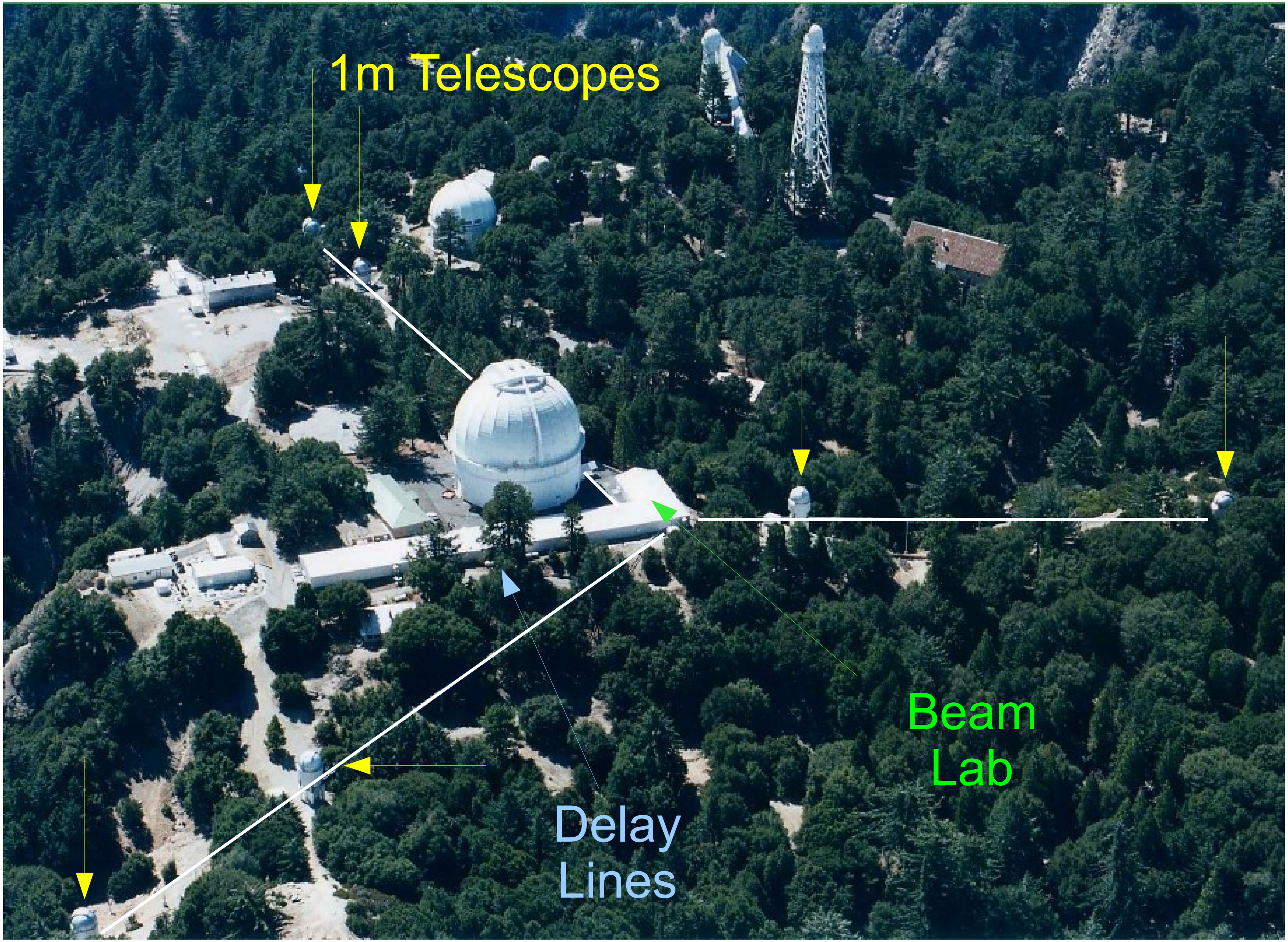
Too low | Perfect | Too high



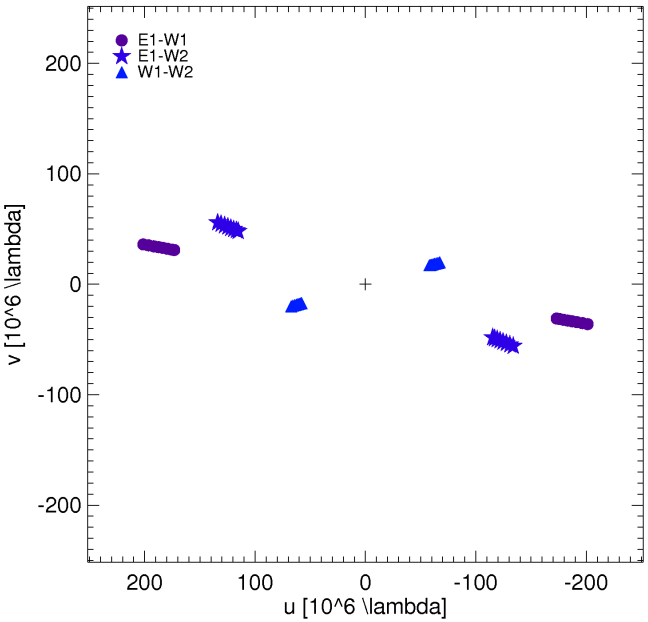
Images from Renard (2012)

Eps Aur Interferometry

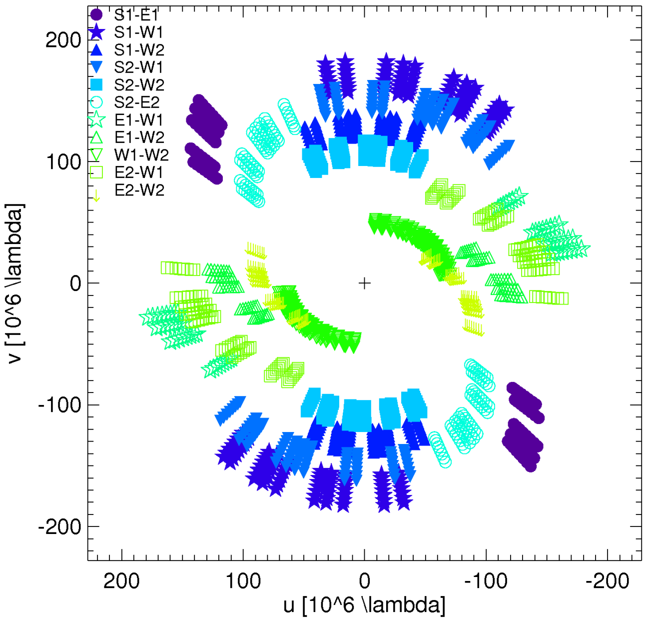
Data from multiple interferometers
CHARA-MIRC, CHARA-CLIMB, NPOI, PTI



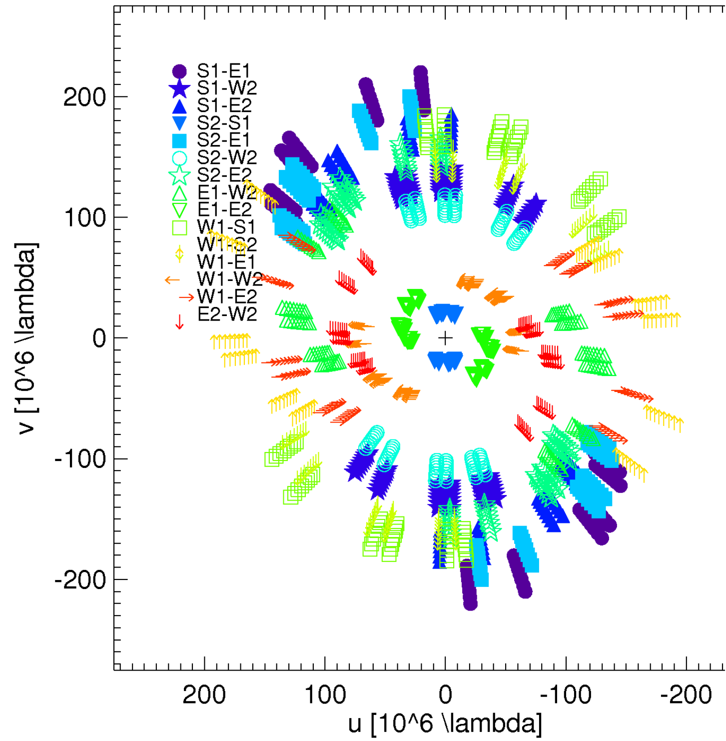
UV Coverage



2008-09
(3T, 1 bracket)

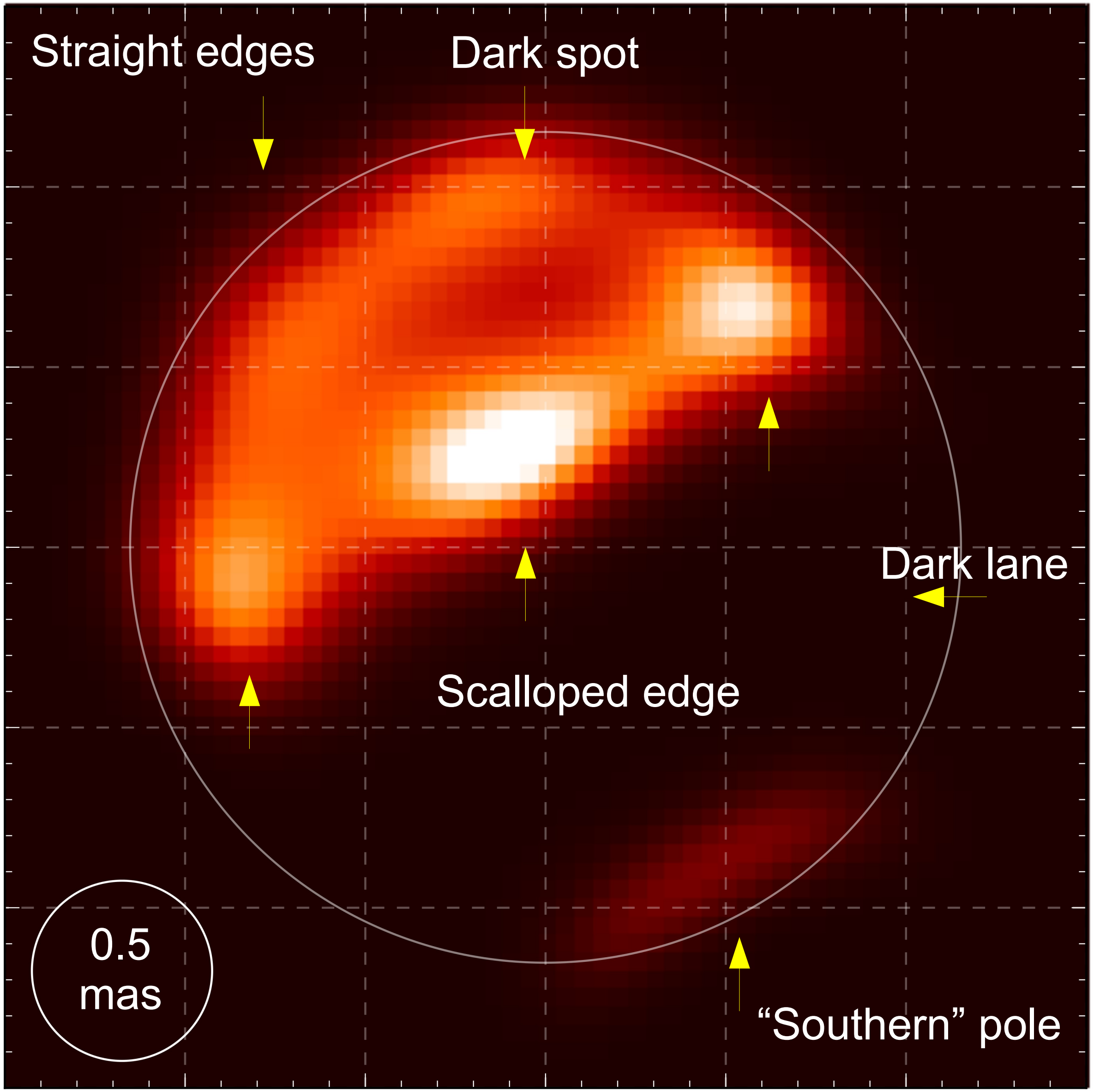


2009-11
(4T, 3 Nights)

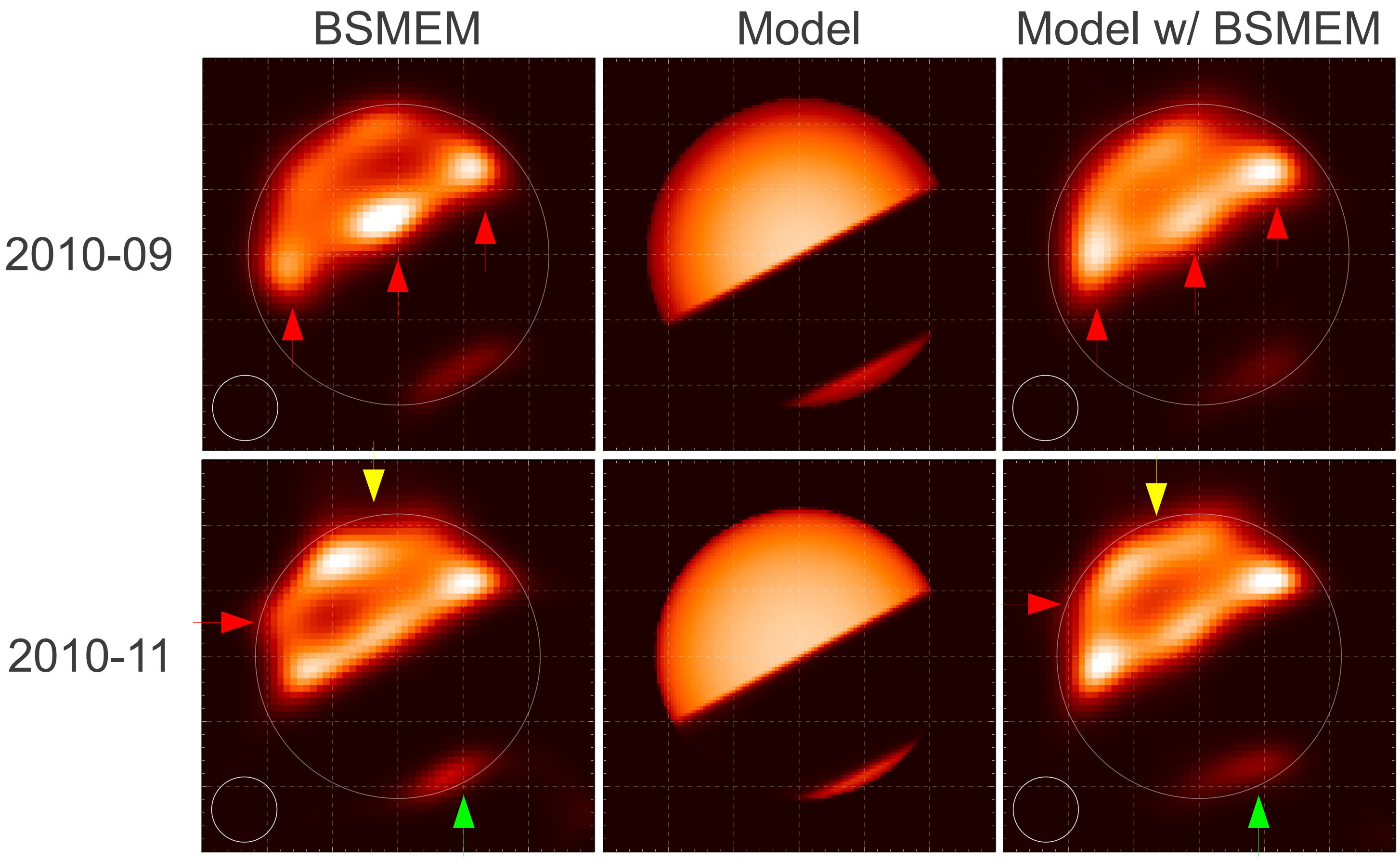


2011-09
(6T, 1 Night)

What can we trust in the images?



Artifacts abound



Likely Artifacts:

- Bright Spots along equator
- Bright spot at North Pole
- Dark alias in northern hemisphere
- Scalloped Edge of disk

Not Artifacts:

- Southern Pole

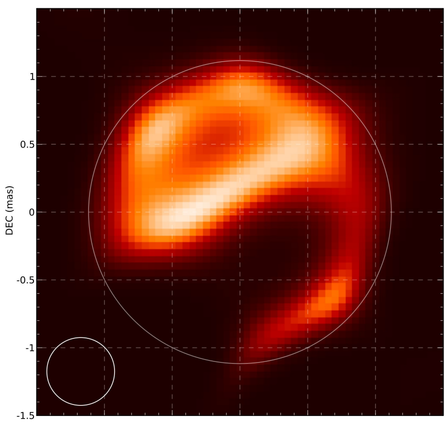
Undecided:

- Straight Edges on F-star

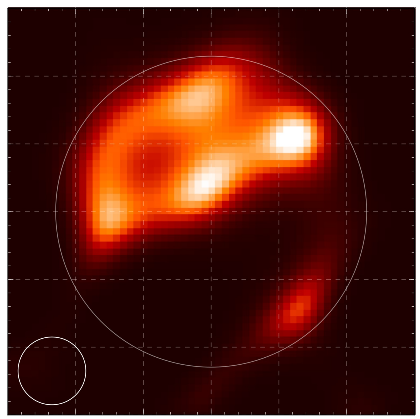
Five of 14 model-independent images

Ingress (CHARA-MIRC)

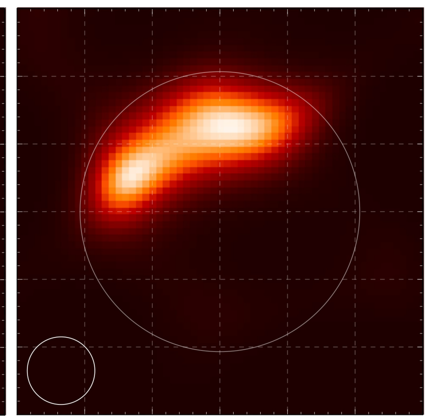
2009-11



2009-12

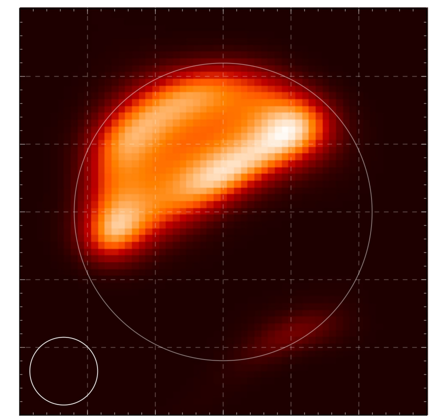


2010-02



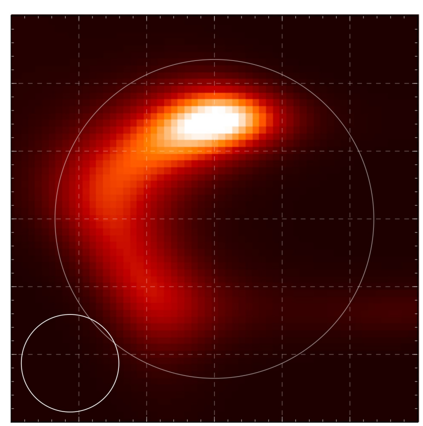
Mid-eclipse
(CHARA-MIRC)

2010-08

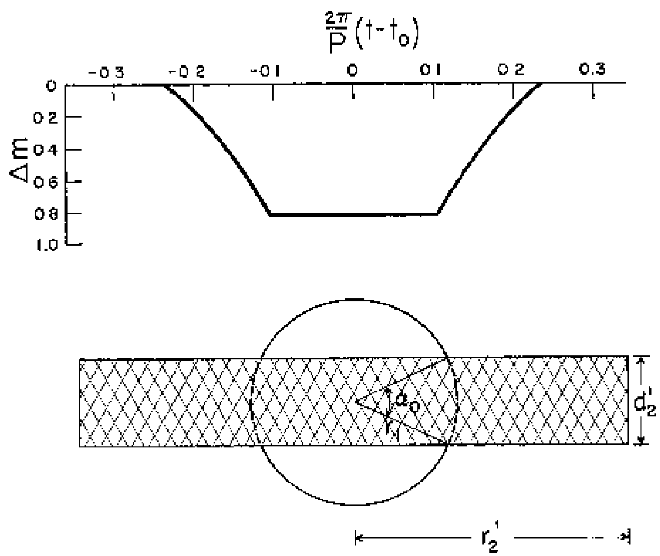


Egress
(CHARA-CLIMB)

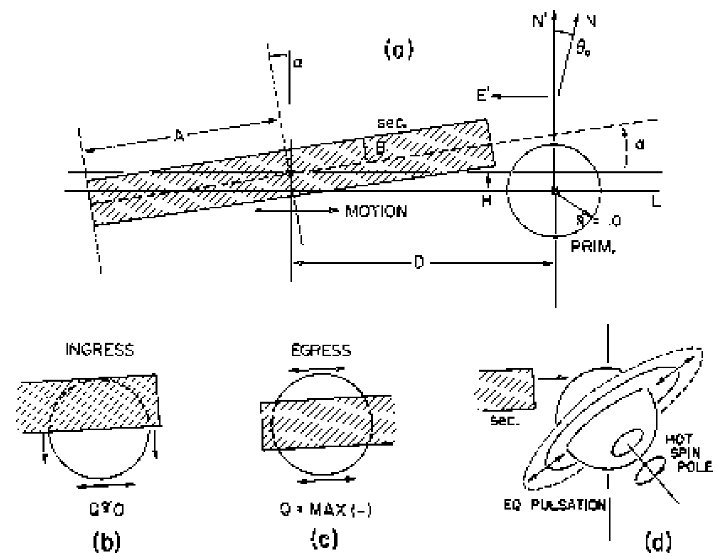
2010-04



How do we model the disk?



Huang 1965 “brick”



Kemp 1986 “inclined brick”

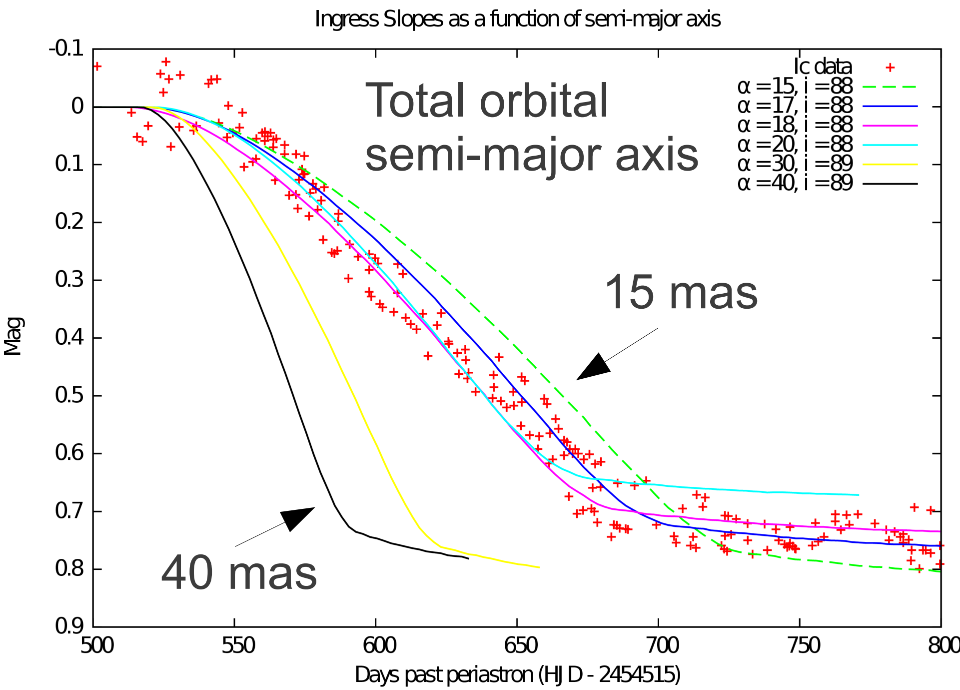
New software: liboi and SIMTOI

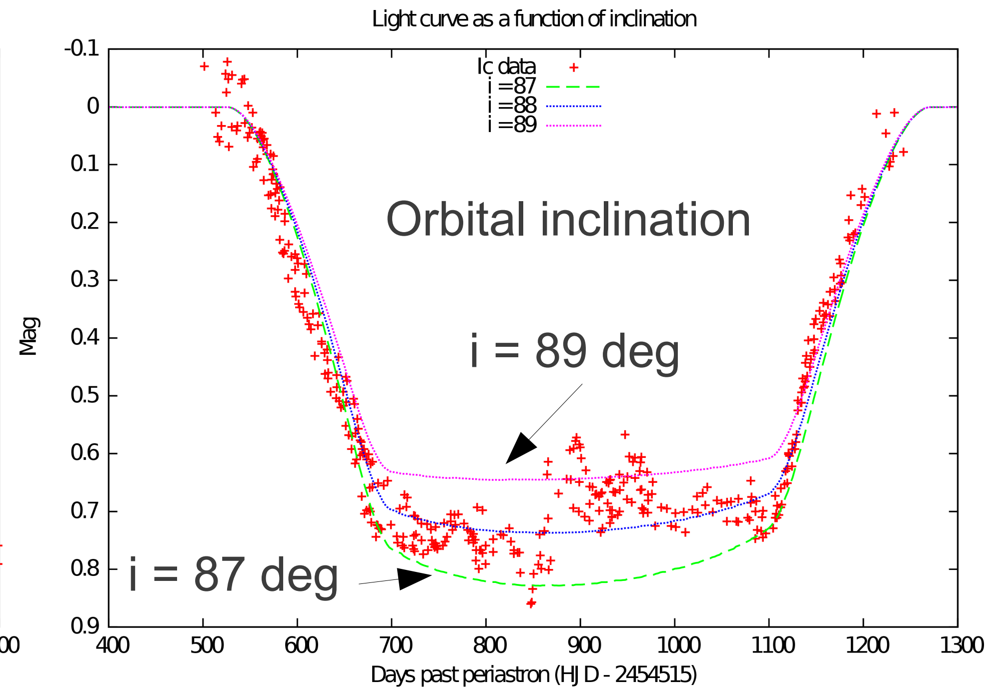
- OpenCL Interferometry Library (liboi)
  - GPU computing library for OI
  - Image + OIFITS → Simulated observations
  - Can perform ~280 (image → data → chi2r) / second
  - About 150x faster than the same algorithms on a CPU

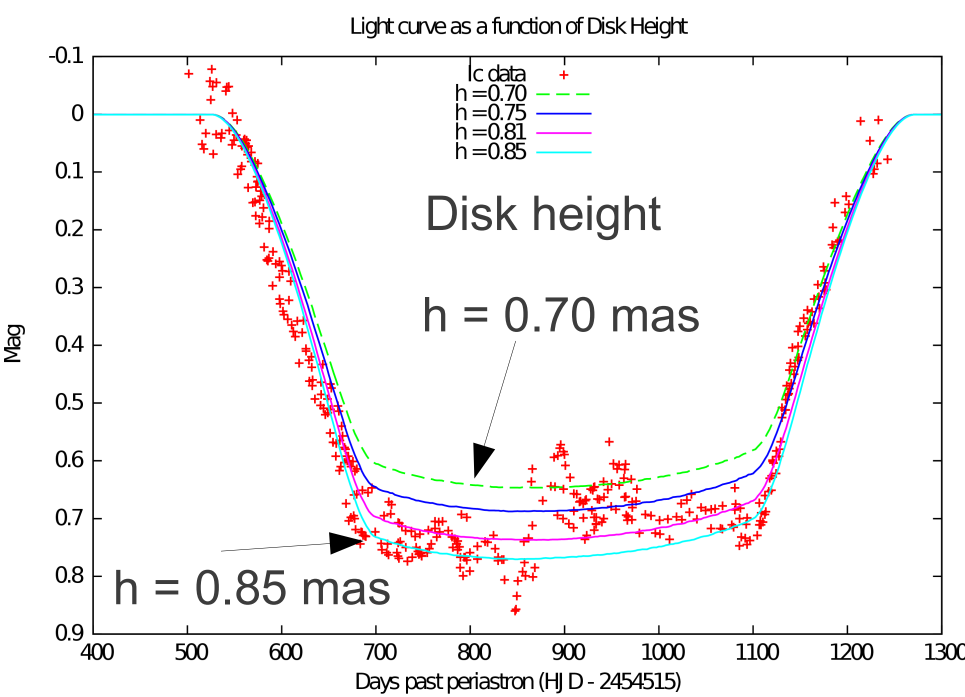
- SImulation and Modeling Tool for Optical Interferometry (SIMTOI)
  - Models rendered using OpenGL (computer graphics)
  - Environment is fully 3D, time-dependent, and includes orbits!
  - Has several minimization engines
  - Callable via. scripting languages
  - Uses liboi as a backend for fast computations

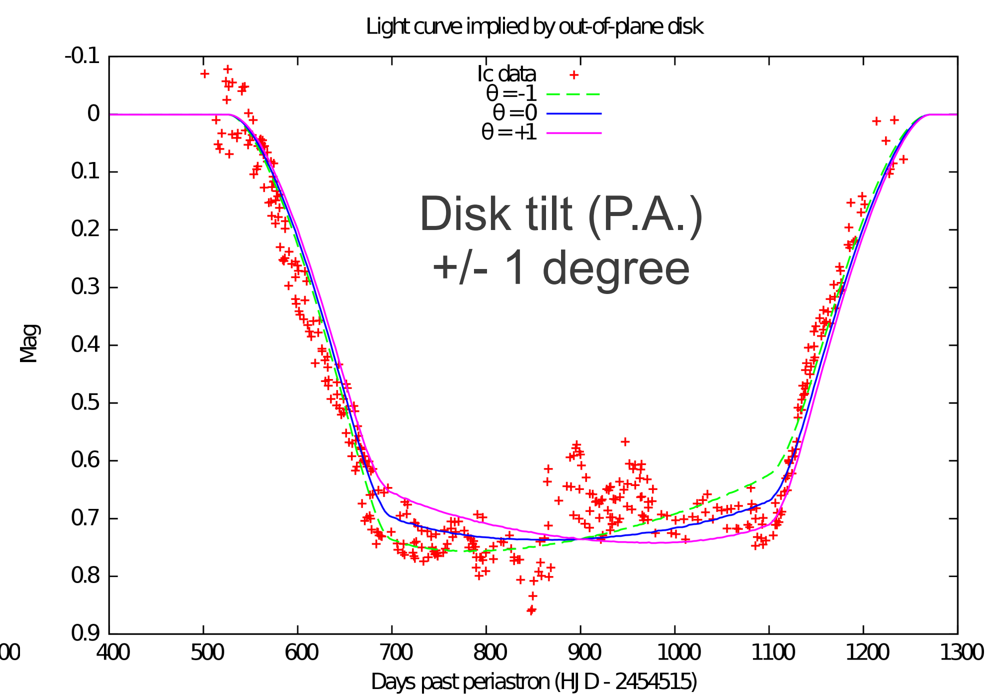
Both are open source. Find them at http://github.com/bkloppenborg

The photometry hints at the orbital parameters... if you have a disk model



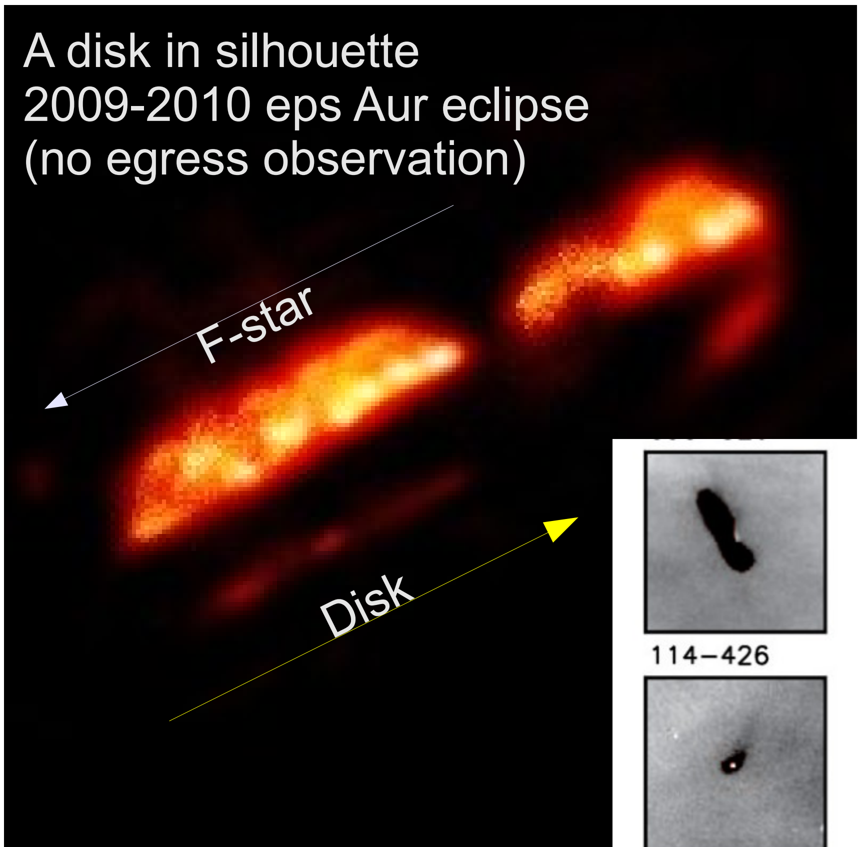


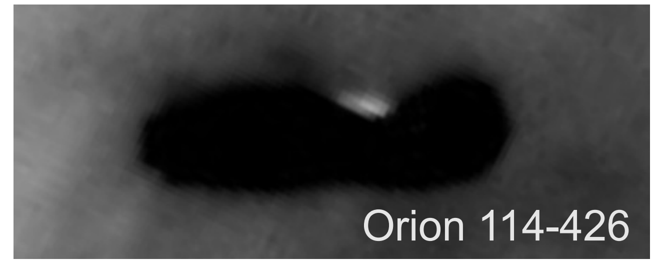




Photometry is Ic band, from AAVSO contributors

Our models were inspired by resolved images of proplyds





Protoplanetary disks seen in silhouette (Hubble images, filters F435W, F555W, F658N, F775W, F850LP, and merged)

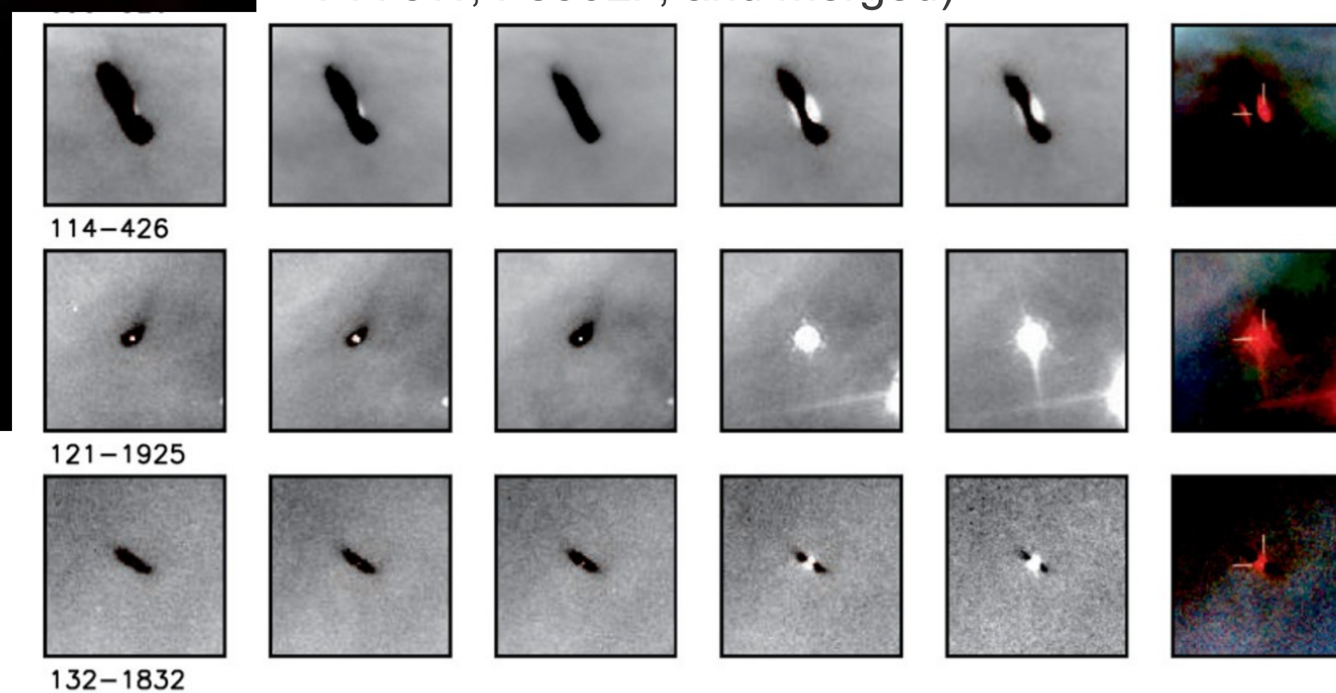
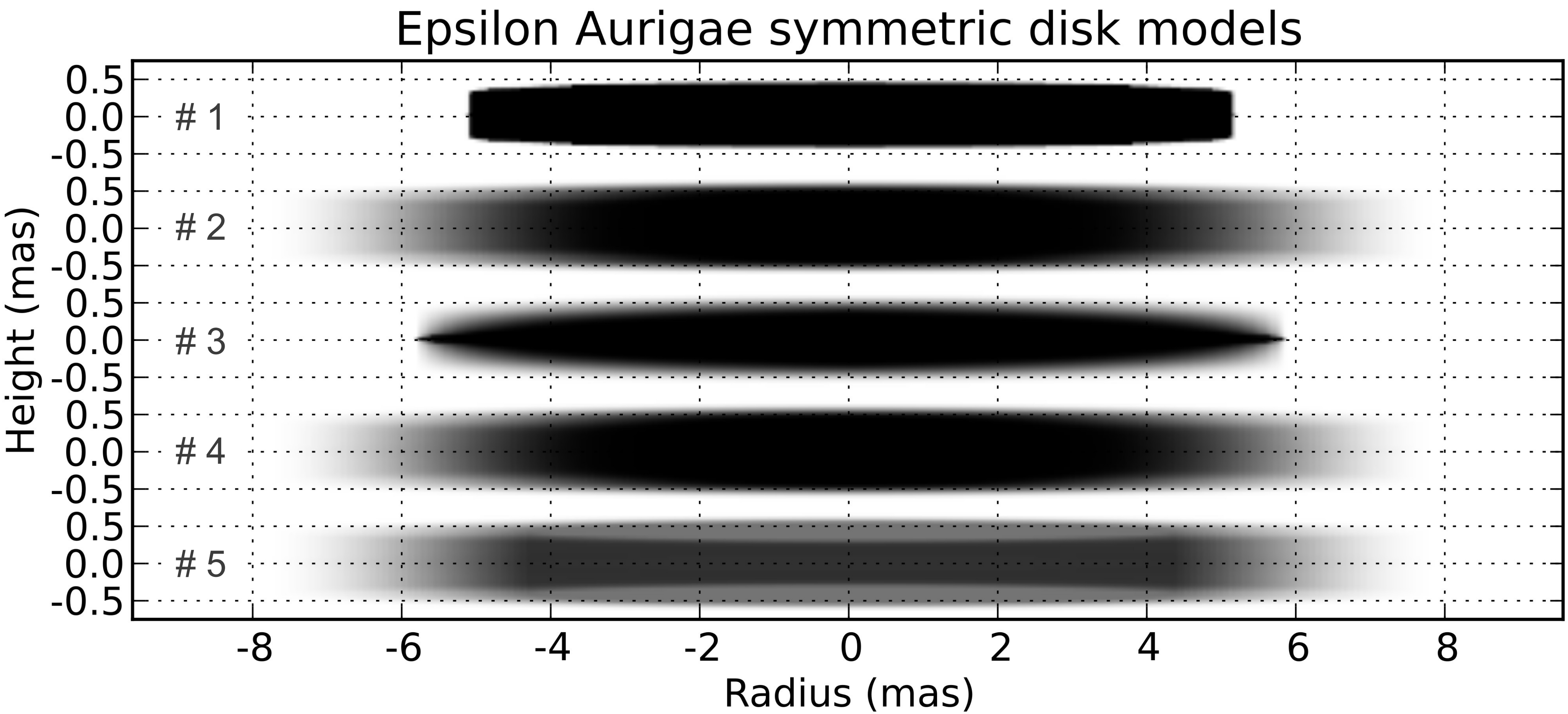
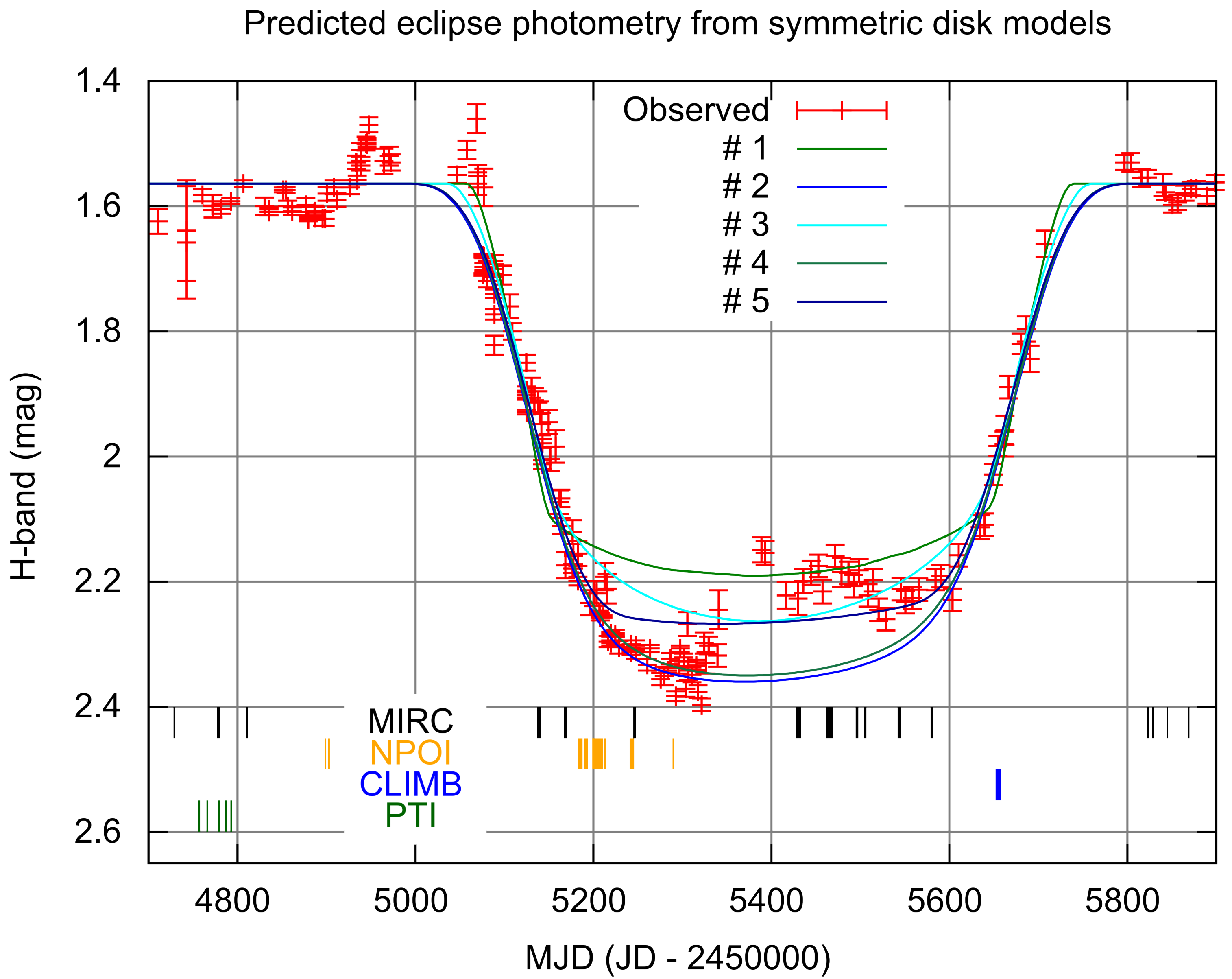


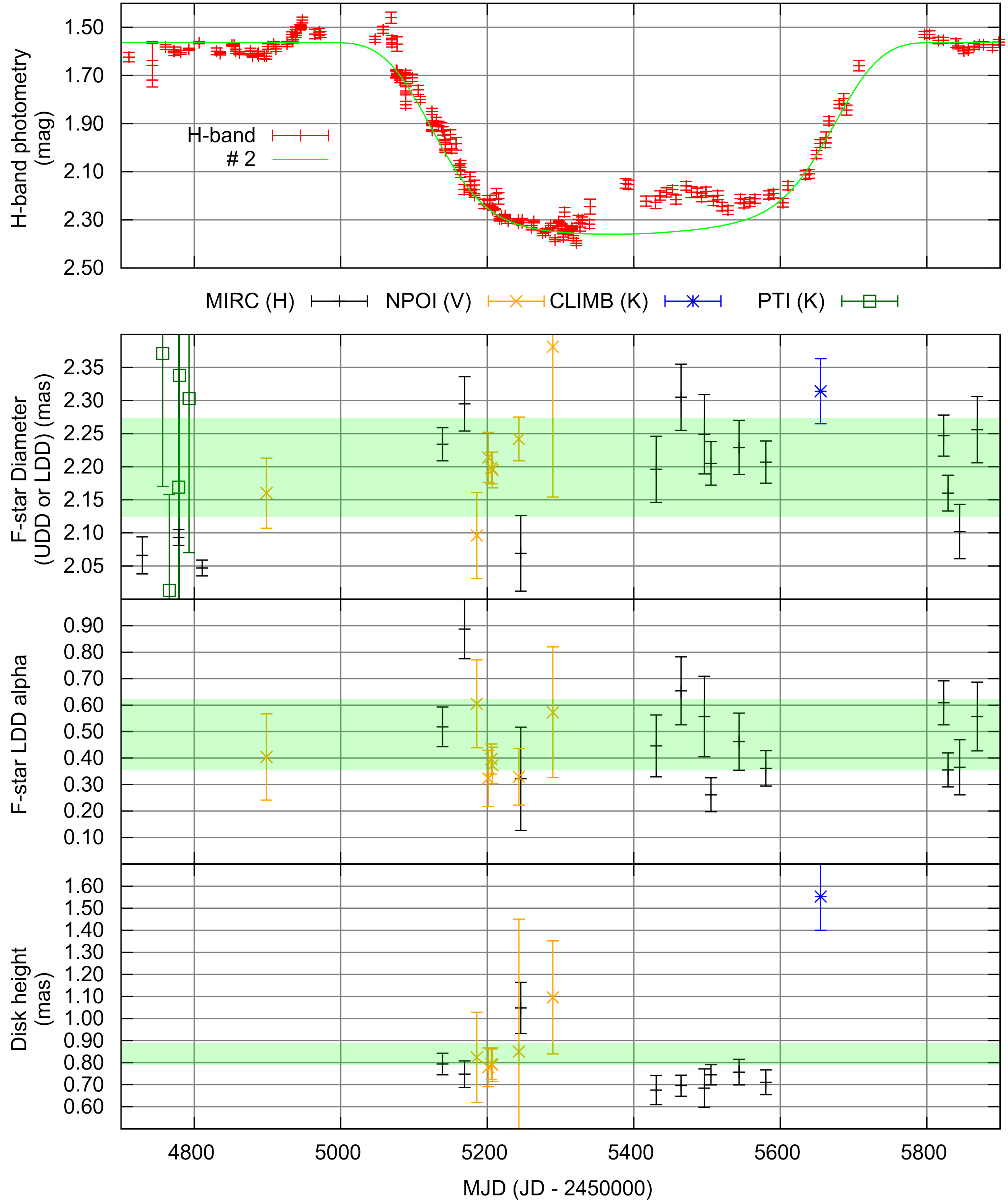
Image of Orion protoplanetary disks from Ricci et al. 2008 and Miotello et al. 2012

Best-fit symmetric disk models



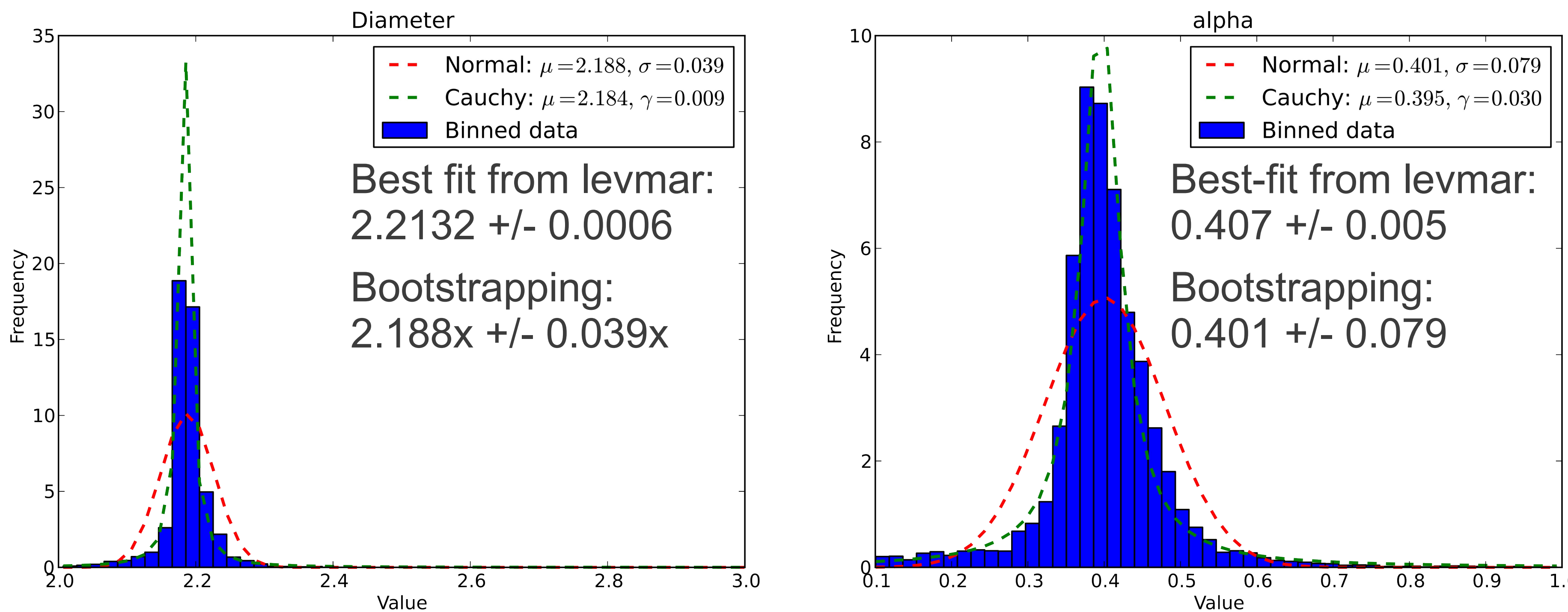
The disk is not symmetric





H-band photometry (mag)
1.50
1.70
1.90
2.10
2.30
2.50
H-band
2
MIRC (H)
NPOI (V)
CLIMB (K)
PTI (K)
F-star Diameter (UDD or LDD) (mas)
2.35
2.30
2.25
2.20
2.15
2.10
2.05
F-star LDD alpha
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
Disk height (mas)
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
4800
5000
5200
5400
5600
5800
MJD (JD - 2450000)

Bootstrapping provides more realistic uncertainties



- Model: Hestroffer LDD applied to sphere
  - Statistics appear to follow Cauchy distributions
  - Both parameters show (slight) skewness

Conclusions

- OI image reconstruction is tricky
  - A careful analysis of image artifacts is needed

- Eps Aur:
  - OI has significantly constrained the orbit
  - The disk is **asymmetric** and is now quantified
  - Mid-eclipse brightening is **not** due to a central clearing in the disk
  - Bootstrapped uncertainties are reasonable

  - Publication coming very soon!

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(Its more than just images!)

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