



Revealing the disk in Epsilon Auriage using multi-epoch interferometry

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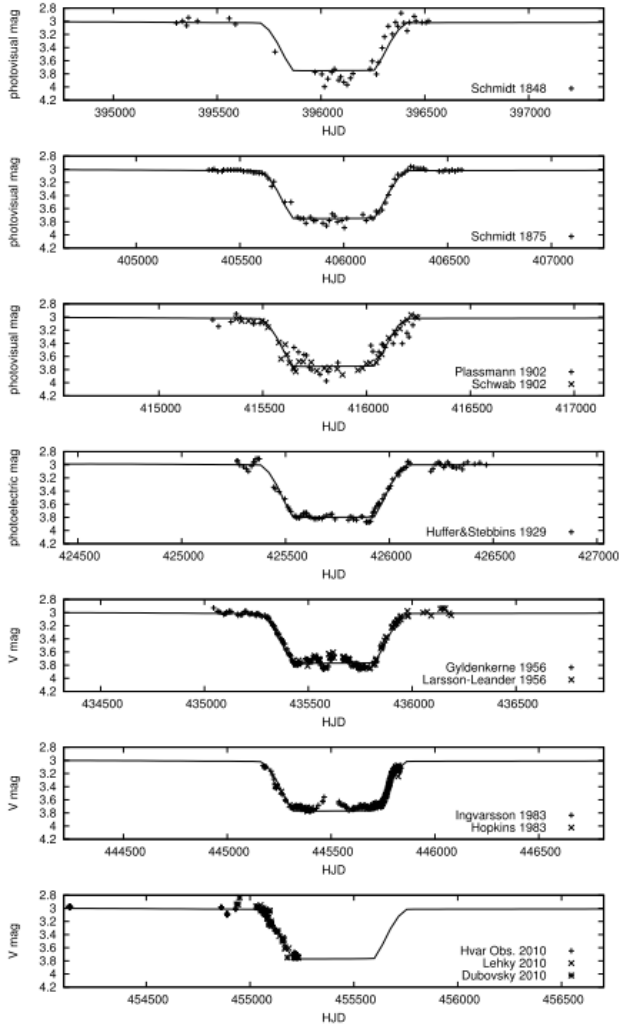




Outline

- 2008 Status Quo
- Enter Interferometry
- New Modeling Techniques
 - Bayesian Statistics
 - SIMTOI and liboi
- Modeling Results, Simulated Light Curves
- Post-eclipse calibration

Pre-Eclipse Understanding



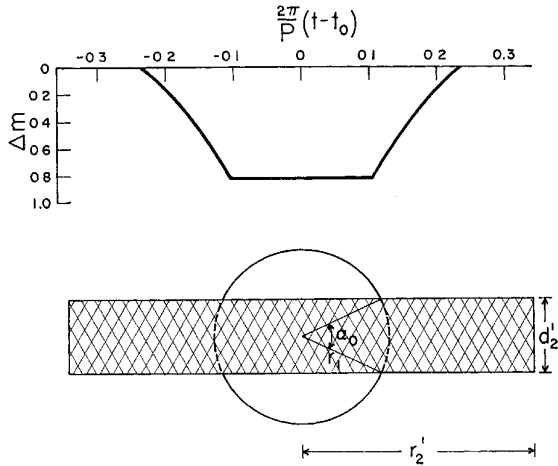
- Discovered in 1821
- 27.1 Year Period
- Confirmed 1903

Explaining The Eclipses

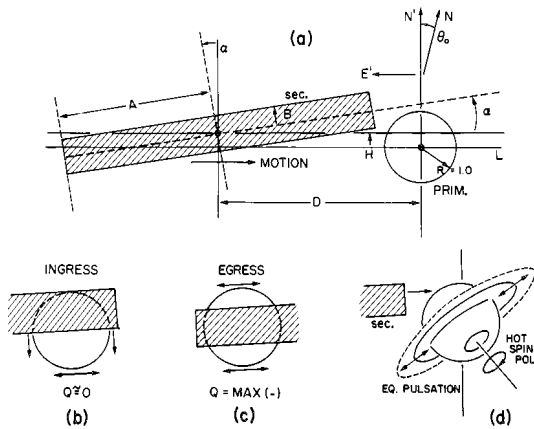
- Hyperionized IR Star
- Black Hole

Chadima et al (2010)

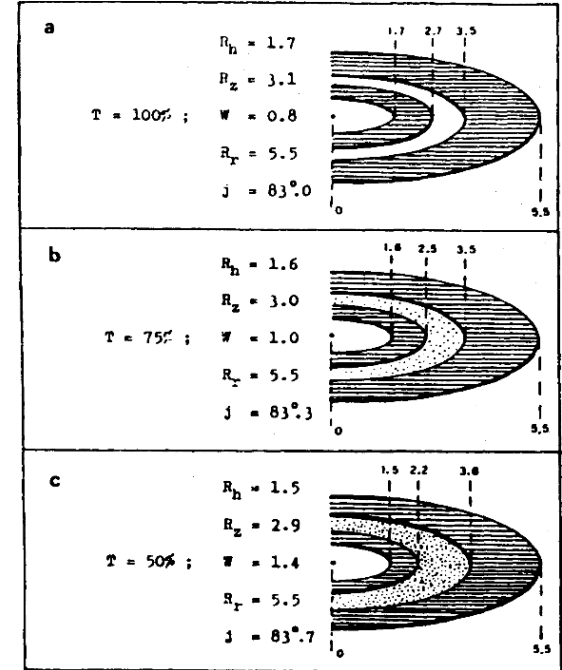
Pre-Eclipse Understanding



Huang (1965)



Kemp (1986)



Ferluga (1990)

1965: Block of Opaque Material

1986: Block is tilted

1990: Disk consists of rings of material, is also highly inclined.



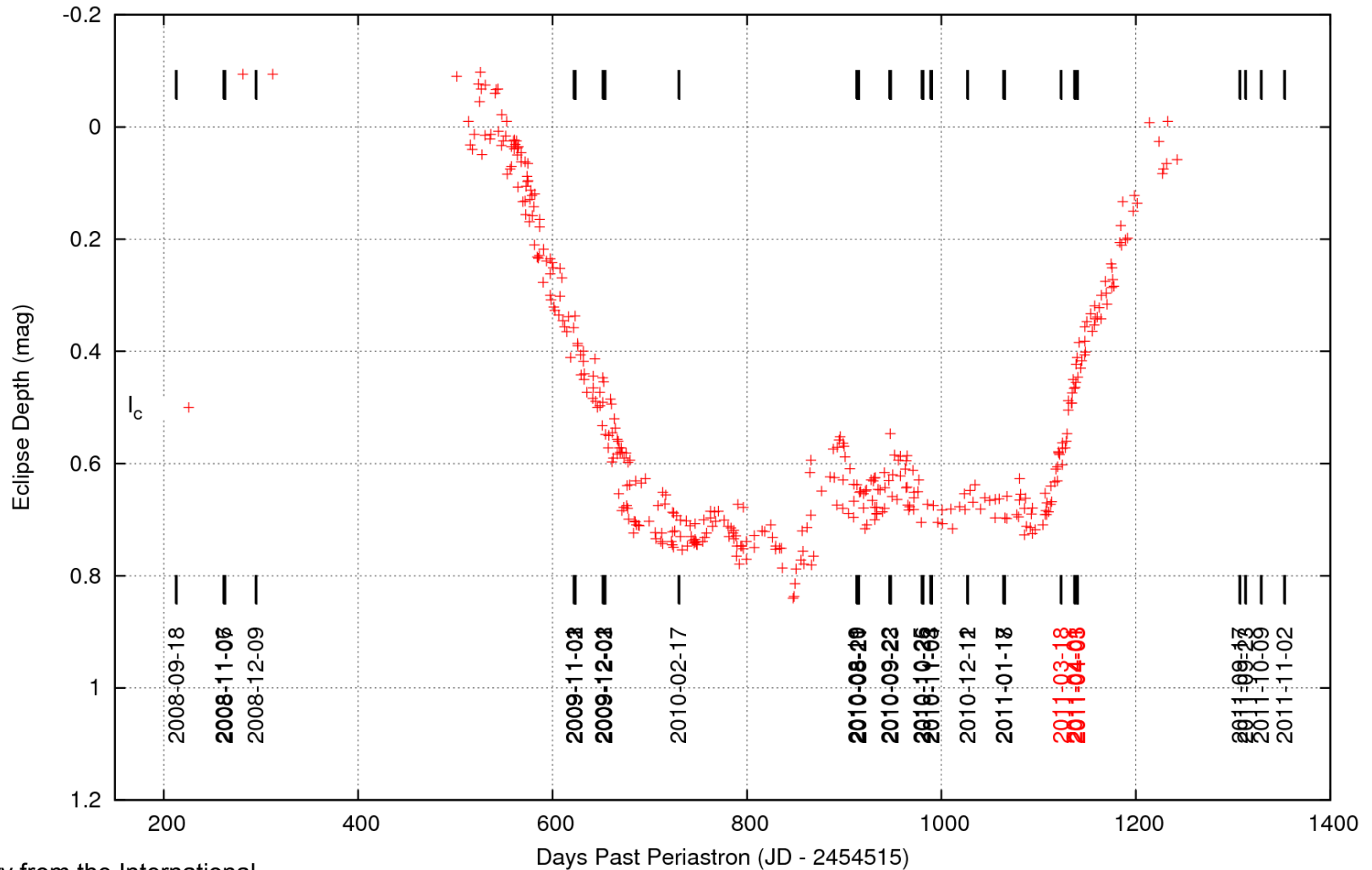
Questions to be answered

- Is there really a disk?
- If so, what are its geometric properties?
 - Radius, height, opacity, inclination, flaring
- More fundamentally:
 - What is the distance to the system?
 - What is the mass ratio => evolutionary state?
- What causes the photometric variations?
 - In eclipse AND out of eclipse



Photometry and CHARA Epochs

eps Aur - Light Curve



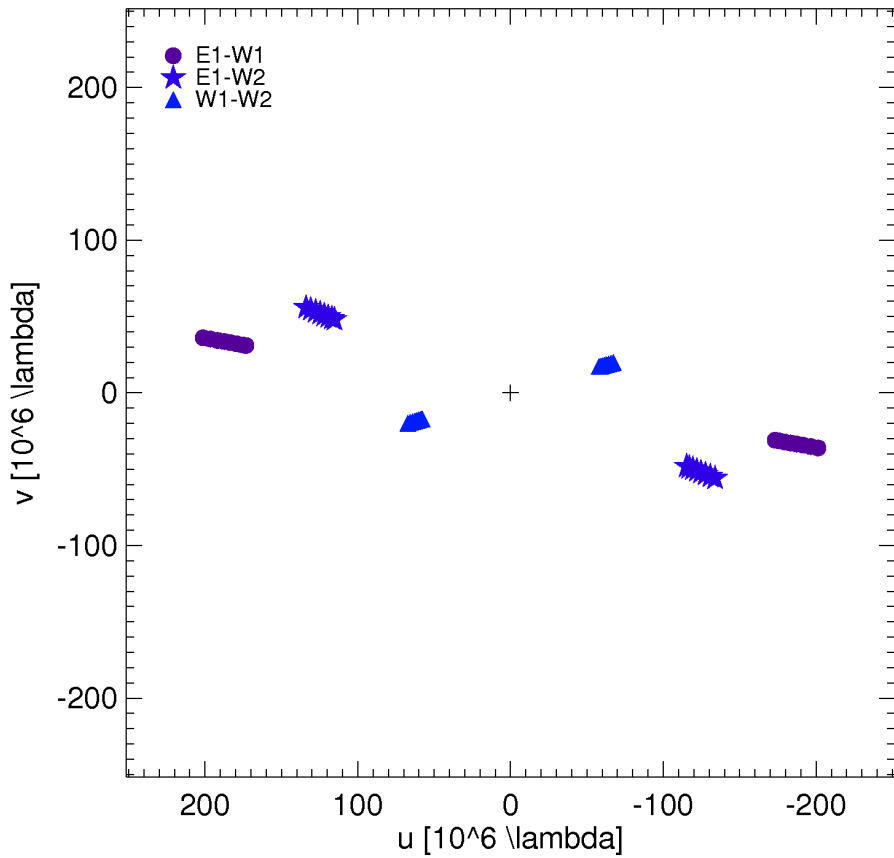
Photometry from the International Epsilon Aurigae Campaign
Hopkins et al 2012



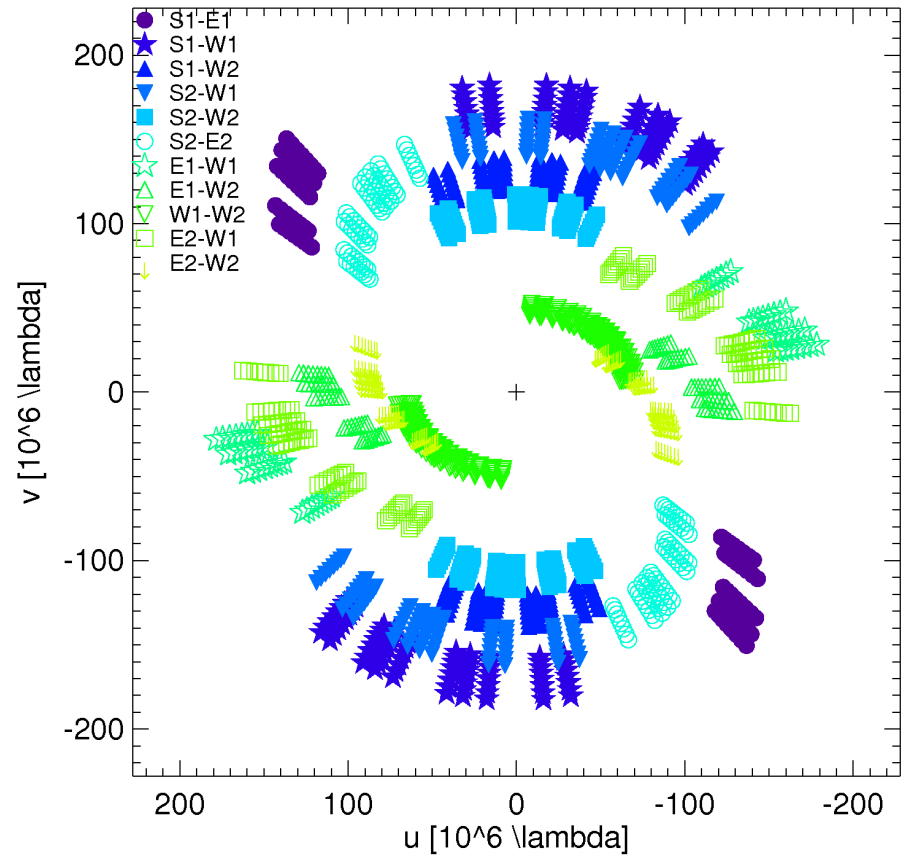
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UV Coverage



2008-09



2009-11 (4T, 3 Nights)



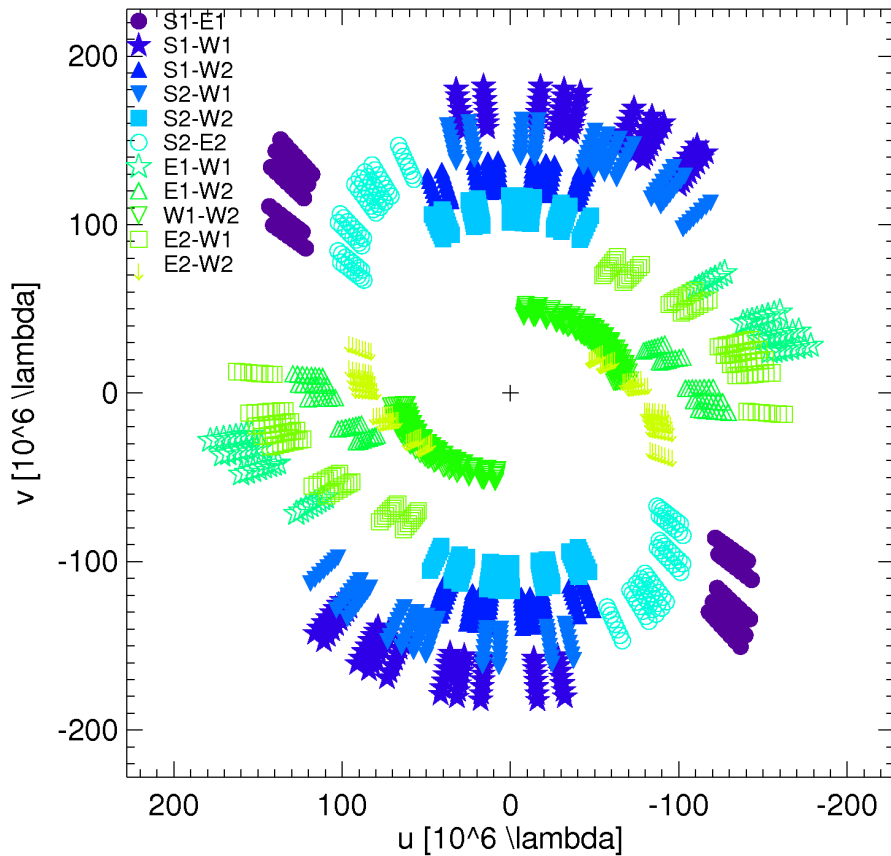
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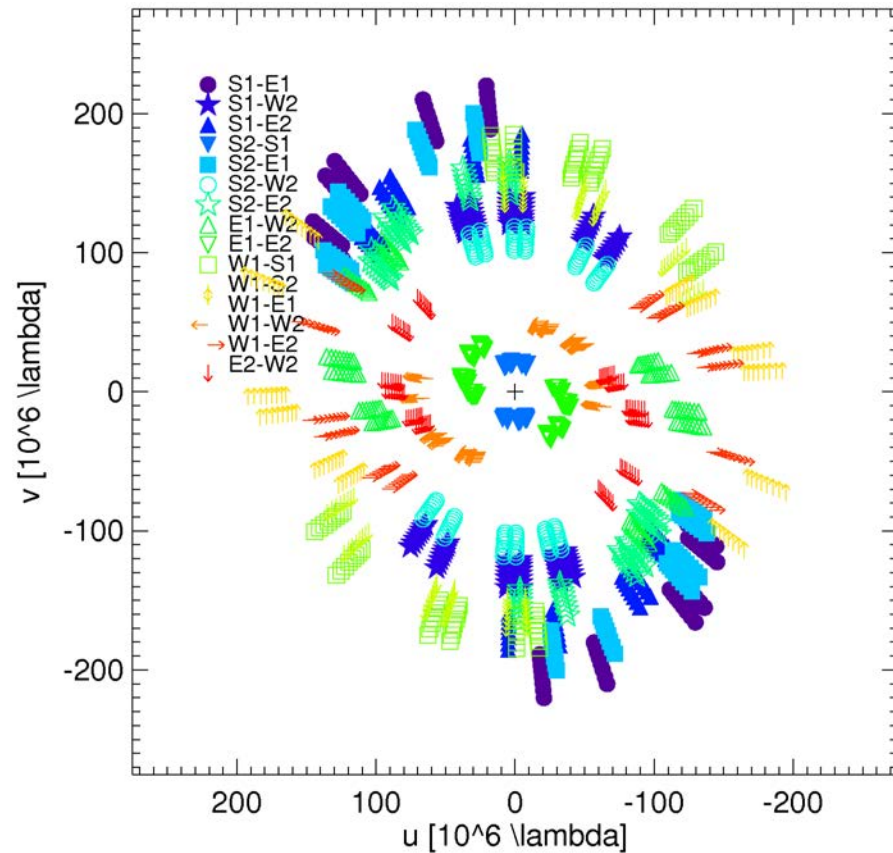
Observatoire de la CÔTE d'AZUR



UV Coverage



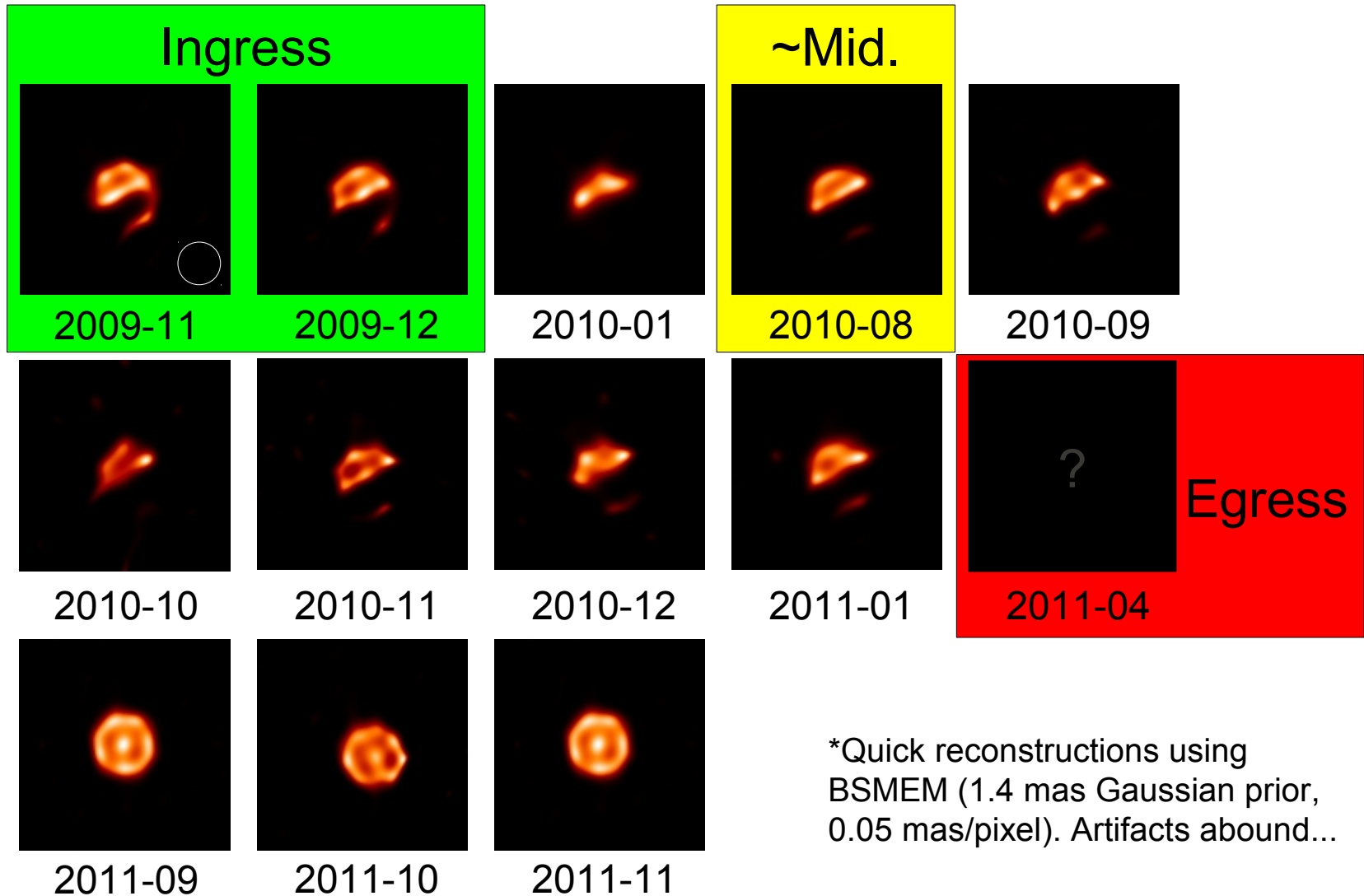
2009-11 (4T, 3 Nights)



2011-09 (6T, 1 Night)



Model Independent Images



*Quick reconstructions using BSMEM (1.4 mas Gaussian prior, 0.05 mas/pixel). Artifacts abound...



Modeling requires an astrometric orbit

$$\Omega \sim 92 \pm 3 \text{ (VdK)}$$

$$\omega = 39.2 \text{ (Stefanik)}$$

$$i = 89-90$$

$$T \sim 27.1 \text{ yr (Stefanik)}$$

$$e = 0.227 \pm 0.011 \text{ (Stefanik)}$$

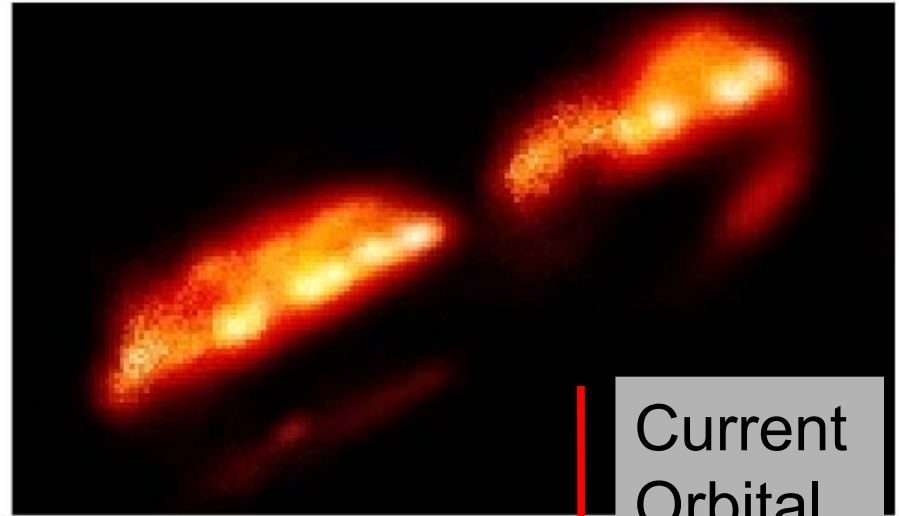
$$\tau \sim 2,454,515 \text{ (Stefanik)}$$

$$a_1 \sin(i) \sim 1800 \text{ E6 km (Stefanik)}$$

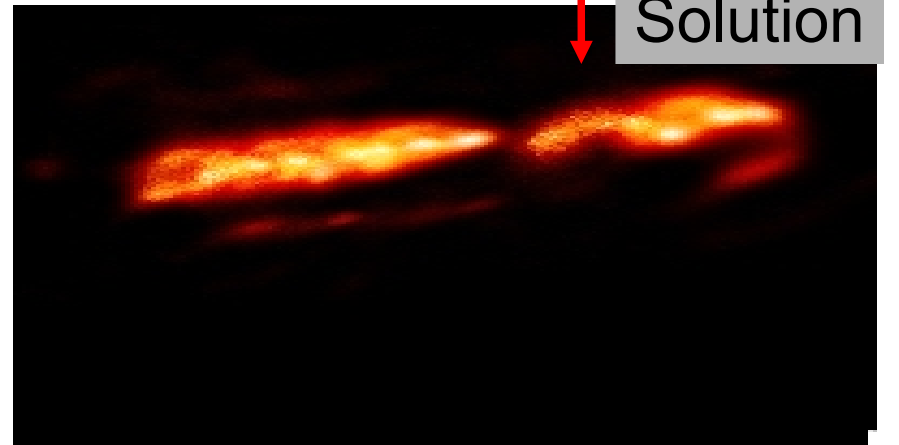
$$\alpha_1 = 22.7 \pm 1 \text{ (VdK)}$$

$$d = 625 \pm 585 \text{ pc (HIPPARCOS)}$$

Clearly we need something better...

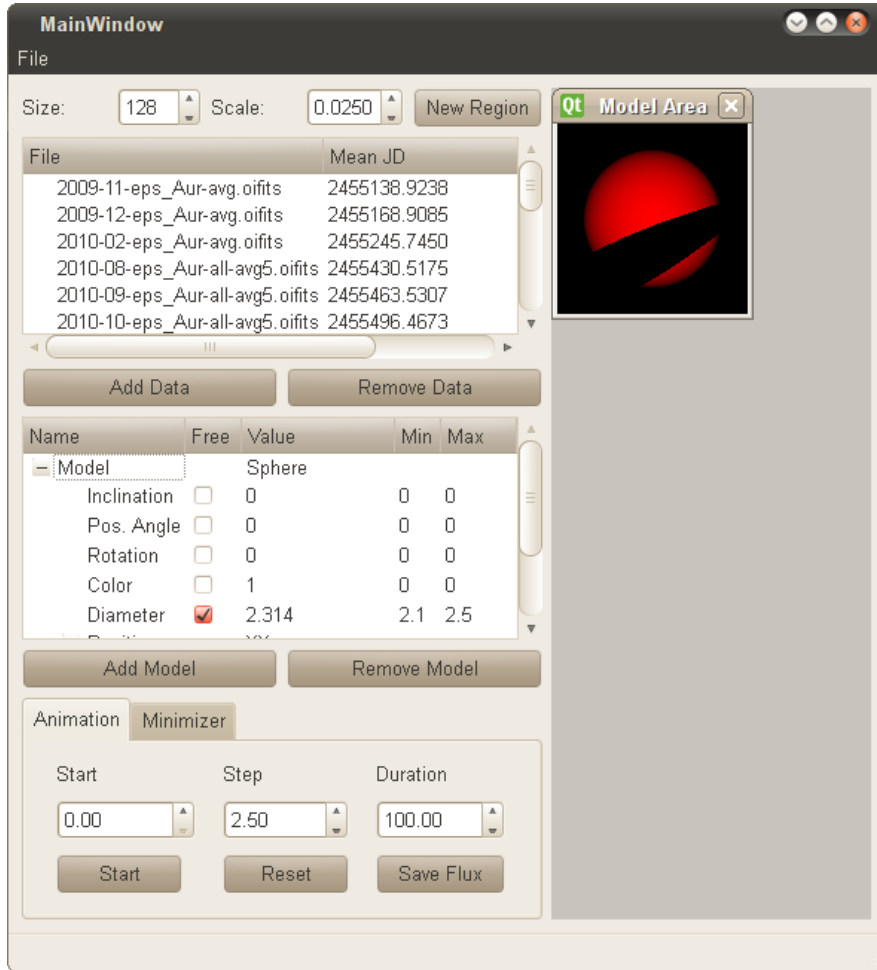


Current
Orbital
Solution





Simulation and Modeling Tool for Optical Interferometry



Cross Platform (OpenCL, OpenGL, and QT)

Made for LARGE data sets and leverages GPU computing using the OpenCL Interferometry Library (liboi, backend for GPAIR 2)

2D or 3D positioning of objects (XY, XYZ, or an Orbit)

Modeled objects can be time dependent!

Models stars, disks, teapots... anything you can render in OpenGL

Code is capable of modeling surface features (spots, non-radial pulsation) and geometric affects (limb/gravity darkening)

Two minimizers already implemented (levmar and MultiNest), others easily added.

Made to have spectral dependencies.

Currently does V2, T3, Diff V coming soon

Public (open source) release of SIMTOI and liboi after eps Aur paper is published.



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Bayesian Nested Sampling

Bayes' Theorem

$$Pr(\Theta|D, H) = \frac{Pr(D|\Theta, H) * P(\Theta|H)}{Pr(D|H)}$$

$Pr(\Theta|D, H) = P(\Theta)$, posterior probability

$Pr(D|\Theta, H) = L(\Theta)$, likelihood

$Pr(\Theta|H) = \pi(\Theta)$, prior

$Pr(D|H) = Z$, Bayesian evidence

$$Z = \int L(\Theta) \pi(\Theta) d^D \Theta$$

$$L(\Theta) = \sum_i \frac{1}{\sqrt{2\pi\sigma_i}} e^{-\frac{(M(\Theta) - D_i)^2}{2\sigma_i^2}}$$



Single Epoch Modeling

- Trial 1:
 - Star: LDD (Hesteroffer)
 - Disk: Cylinder
- Trial 2:
 - Star LDD
 - Disk: Gaussian





Trial 1: Cylinder

| Epoch | Mean JD | LDD (mas) | beta | disk_inc (deg) | disk_t (deg) | disk_h (mas) | orbit_inc (deg) | orbit_O (deg) | log_Z |
|--------------|---------|--------------|-------|-------------------|-----------------|-----------------|--------------------|------------------|-----------|
| 2008-09 | 2454729 | 2.263 | 0.624 | | | | | | 415.689 |
| 2008-11 | 2454779 | 2.318 | 0.638 | | | | | | 3187.141 |
| 2008-12 | 2454811 | 2.542 | 0.999 | | | | | | 890.674 |
| 2009-11 | 2455139 | 2.328 | 0.931 | 89.898 | 32.534 | 0.514 | 86.978 | 119.367 | 1911.029 |
| 2009-12 | 2455169 | 2.136 | 0.939 | 89.768 | 39.209 | 0.509 | 88.051 | 132.931 | -5208.256 |
| 2010-02 | 2455246 | 2.406 | 0.470 | 85.240 | 25.648 | 0.744 | 88.709 | 120.724 | 1524.632 |
| 2010-08 | 2455431 | 2.279 | 0.703 | 93.789 | 27.298 | 0.535 | 87.656 | 134.945 | -1978.407 |
| 2010-09 | 2455464 | 2.283 | 0.662 | 88.612 | 26.407 | 0.791 | 87.222 | 131.844 | 11998.910 |
| 2010-10 | 2455496 | 2.328 | 0.811 | 85.966 | 25.046 | 0.510 | 87.325 | 124.594 | 2995.415 |
| 2010-11 | 2455505 | 2.236 | 0.278 | 94.347 | 26.358 | 0.502 | 86.088 | 138.872 | 4272.137 |
| 2010-12 | 2455543 | 2.326 | 0.892 | 85.564 | 25.242 | 0.503 | 85.023 | 139.447 | 666.028 |
| 2011-01 (18) | 2455580 | 2.233 | 0.227 | 85.952 | 23.855 | 0.533 | 85.286 | 133.161 | 2254.839 |
| 2011-03 | | | | | | | | | |
| 2011-04 | | | | | | | | | |
| 2011-09 | 2455826 | 2.257 | 0.638 | | | | | | |
| 2011-10 | 2455845 | 2.267 | 0.820 | | | | | | -4013.208 |
| 2011-11 | 2455869 | 2.240 | 0.550 | | | | | | 19558.861 |

| Epoch | LDD | beta | disk_inc | disk_t | disk_h | orbit_inc | orbit_O | log_Z |
|-------|-------|-------|----------|--------|--------|-----------|---------|----------|
| Ave | 2.296 | 0.679 | 88.793 | 27.955 | 0.571 | 86.927 | 130.654 | 2748.249 |
| Stdev | 0.091 | 0.231 | 3.484 | 4.885 | 0.113 | 1.237 | 7.407 | 6311.044 |

Sum 38475





Trial 2: Gauss Disk

| Epoch | Mean JD | LDD (mas) | beta | disk_inc (deg) | disk_t (deg) | disk_h (mas) | orbit_inc (deg) | orbit_O (deg) | disk_hz (mas) | log_Z |
|--------------|---------|-----------|-------|----------------|--------------|--------------|-----------------|---------------|---------------|------------|
| 2008-09 | 2454729 | 2.263 | 0.624 | | | | | | | 415.689 |
| 2008-11 | 2454779 | 2.318 | 0.638 | | | | | | | 3187.141 |
| 2008-12 | 2454811 | 2.542 | 0.999 | | | | | | | 890.674 |
| 2009-11 | 2455139 | 2.473 | 0.924 | 87.761 | 25.558 | 0.435 | 89.742 | 125.334 | 1.001 | 9647.359 |
| 2009-12 | 2455169 | 2.493 | 1.000 | 89.405 | 24.115 | 0.592 | 89.309 | 121.110 | 0.348 | 4495.831 |
| 2010-02 | 2455246 | | | | | | | | | |
| 2010-08 | 2455431 | 2.500 | 0.872 | 89.965 | 28.625 | 0.627 | 87.938 | 143.016 | 0.304 | -12400.317 |
| 2010-09 | 2455464 | 2.500 | 0.995 | 87.012 | 26.591 | 0.523 | 86.284 | 121.268 | 0.103 | -7972.043 |
| 2010-10 | 2455496 | 2.445 | 0.803 | 87.358 | 25.766 | 0.583 | 86.604 | 117.267 | 0.109 | 2050.017 |
| 2010-11 | 2455505 | | | | | | | | | bad |
| 2010-12 | 2455543 | | | | | | | | | really bad |
| 2011-01 (18) | 2455580 | | | | | | | | | even worse |
| 2011-03 | | | | | | | | | | |
| 2011-04 | | | | | | | | | | |
| 2011-09 | 2455826 | 2.257 | 0.637 | | | | | | | 8012.850 |
| 2011-10 | 2455845 | 2.263 | 0.810 | | | | | | | -4011.618 |
| 2011-11 | 2455869 | 2.253 | 0.582 | | | | | | | 19546.729 |

| Epoch | LDD | beta | disk_inc | disk_t | disk_h | orbit_inc | orbit_O | log_Z |
|-------|-------|-------|----------|--------|--------|-----------|---------|----------|
| Ave | 2.392 | 0.808 | 88.300 | 26.131 | 0.552 | 87.975 | 125.599 | 2169.301 |
| Stdev | 0.119 | 0.164 | 1.307 | 1.655 | 0.075 | 1.553 | 10.146 | 8697.936 |

beta = limb darkening coefficient



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SIMTOI: Multi-Epoch Fitting

Disk A: 

- Scale Height Exterior

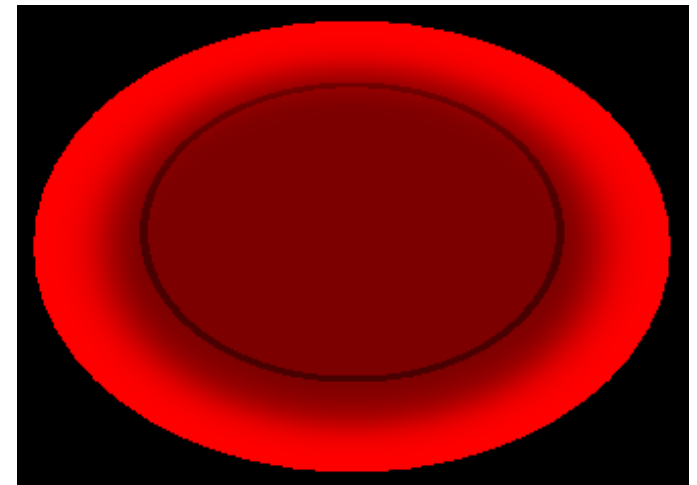
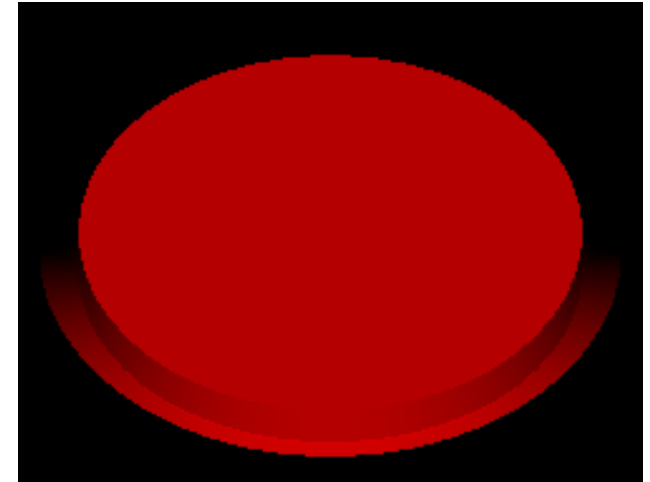
Disk B: 

- Gaussian Exterior

Disk C: 

- Power Law Exterior

Can add transparency too:





Multi-Epoch Results

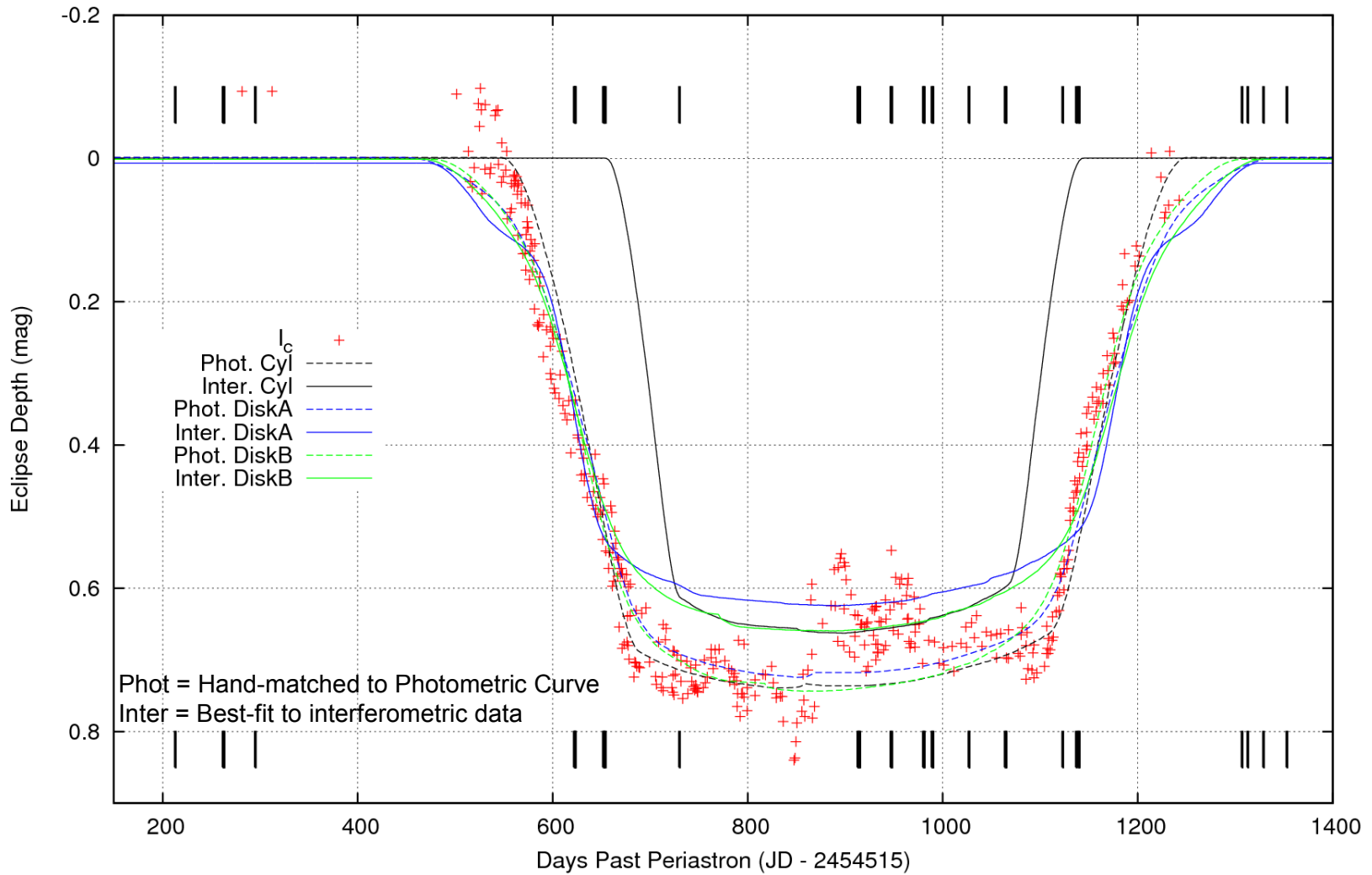
| Label | LDD (mas) | Beta | Type | Disk_d (mas) | Disk_h (mas) | Beta | Orbit_i (deg) | Orbit_O (deg) | Orbit_alpha (mas) | log_Z |
|------------|--------------|-------|----------|-----------------|-----------------|-------|------------------|------------------|----------------------|-------|
| Phot. Cyl | 2.329 | 0.416 | Cylinder | 12.594 | 0.788 | | 89.133 | 116.914 | 41.075 | |
| Inter. Cyl | | | Cylinder | | | | | | | |
| Phot. A | 2.280 | 0.370 | Disk A | 8.500 | 0.810 | 0.500 | 88.390 | 116.620 | 22.200 | |
| Inter. A | 2.285 | 0.380 | Disk A | 19.832 | 0.680 | 1.147 | 89.275 | 116.911 | 49.686 | 19493 |
| Phot. B | 2.314 | 0.415 | Disk B | 11.995 | 0.850 | 1.469 | 88.990 | 117.080 | 35.590 | |
| Inter. B | 2.314 | 0.415 | Disk B | 11.995 | 0.757 | 1.469 | 88.992 | 117.084 | 35.596 | 47002 |





Implied Light Curves

eps Aur - Light Curve



I_c Photometric Data from 2009-2011
 International eps Aur Campaign
 (Hopkins et al. 2012)



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Constrain Orbit, Refit

| Label | JD | LDD (mas) | Beta | Disk_h (mas) | Decay Fact. (mas) | log_Z |
|--------------|---------|--------------|-------|-----------------|----------------------|------------|
| 2008-09 | 2454729 | 2.263 | 0.313 | | | 414.81 |
| 2008-11 | 2454779 | 2.319 | 0.319 | | | 3185.79 |
| 2008-12 | 2454811 | 2.852 | 0.996 | | | 1229.64 |
| 2009-11 | 2455139 | 2.383 | 0.543 | 0.707 | 1.555 | 8964.67 |
| 2009-12 | 2455169 | 2.472 | 0.844 | 0.747 | 1.264 | 6781.61 |
| 2010-02 | 2455246 | 2.499 | 0.404 | 1.135 | | 1001.96 |
| 2010-08 | 2455431 | 2.279 | 0.341 | 0.799 | | -4071.08 ? |
| 2010-09 | 2455464 | 2.285 | 0.329 | 0.783 | | 10621.73 |
| 2010-10 | 2455496 | 2.353 | 0.455 | 0.798 | | 2697.34 |
| 2010-11 | 2455505 | 2.321 | 0.300 | 0.801 | | 1062.91 |
| 2010-12 | 2455543 | 2.329 | 0.449 | 0.794 | | 69.09 |
| 2011-01 (18) | 2455580 | 2.328 | 0.300 | 0.771 | | 1042.66 |
| 2011-03 | | | | | | |
| 2011-04 | | | | | | |
| 2011-09 | 2455826 | 2.257 | 0.319 | | | 8010.69 |
| 2011-10 | 2455845 | 2.261 | 0.401 | | | -4010.15 * |
| 2011-11 | 2455869 | 2.245 | 0.282 | | | 19553.68 |

Total: 56555.36





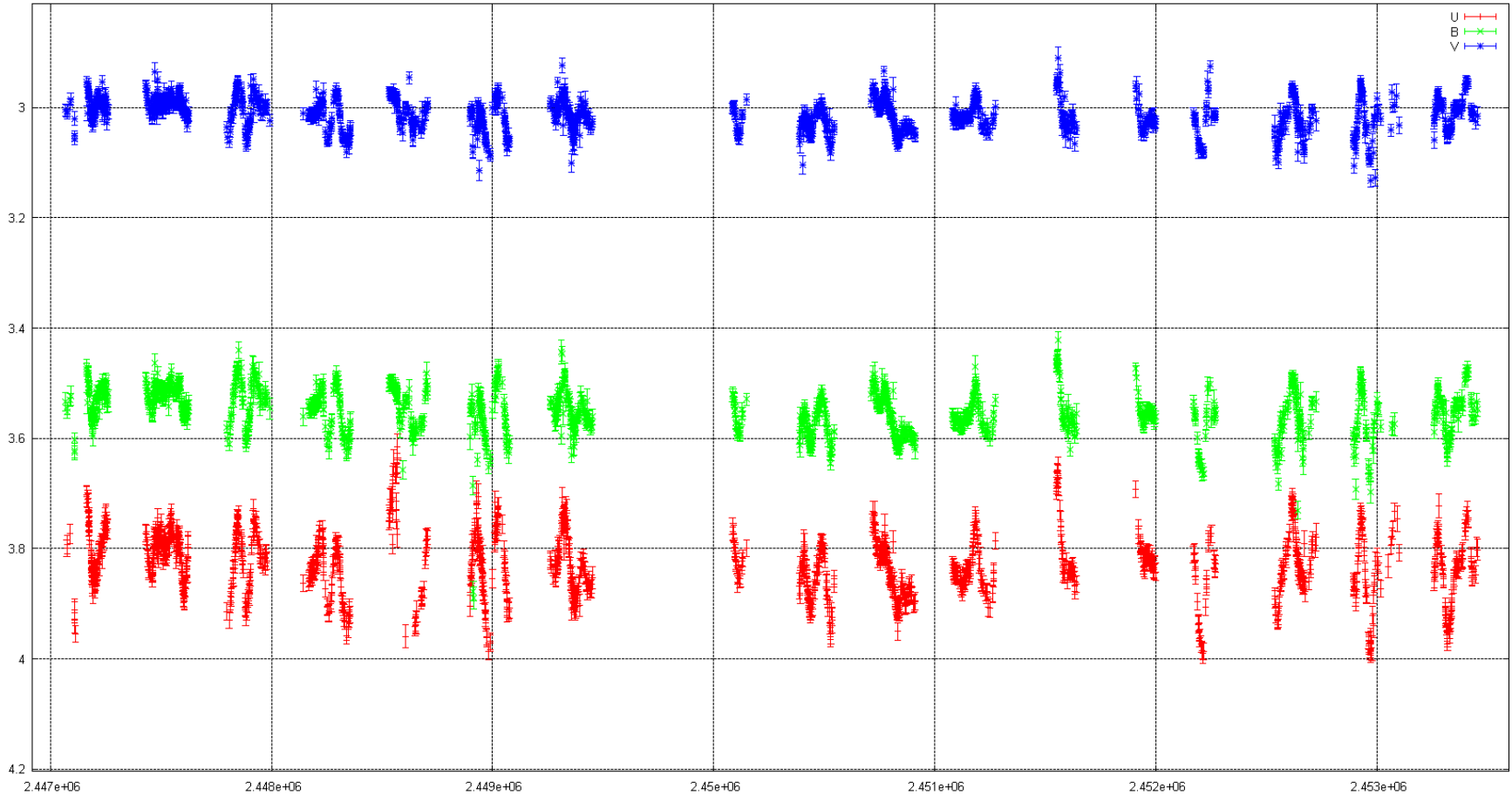
Questions to be answered

- ~~Is there really a disk? Yes!~~
- ~~If so, what are its geometric properties? ~Done~~
 - ~~Radius, height, opacity, inclination, flaring~~
- ~~More fundamentally: Chapter 2 of Dissertation~~
 - ~~What is the distance to the system?~~
 - ~~What is the mass ratio \Rightarrow evolutionary state?~~
- What causes the photometric variations?
 - In eclipse AND out of eclipse



Out of Eclipse Variations!

Boyd's eps Aur data



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Convection, Non-Radial Pulsation?

2011-09 eps Aur
Spot Probability Map

$l = 6, m=4$ non-radial pulsation
(Kochukhov 2004)

