Revealing the disk in Epsilon Auriage using multi-epoch interferometry

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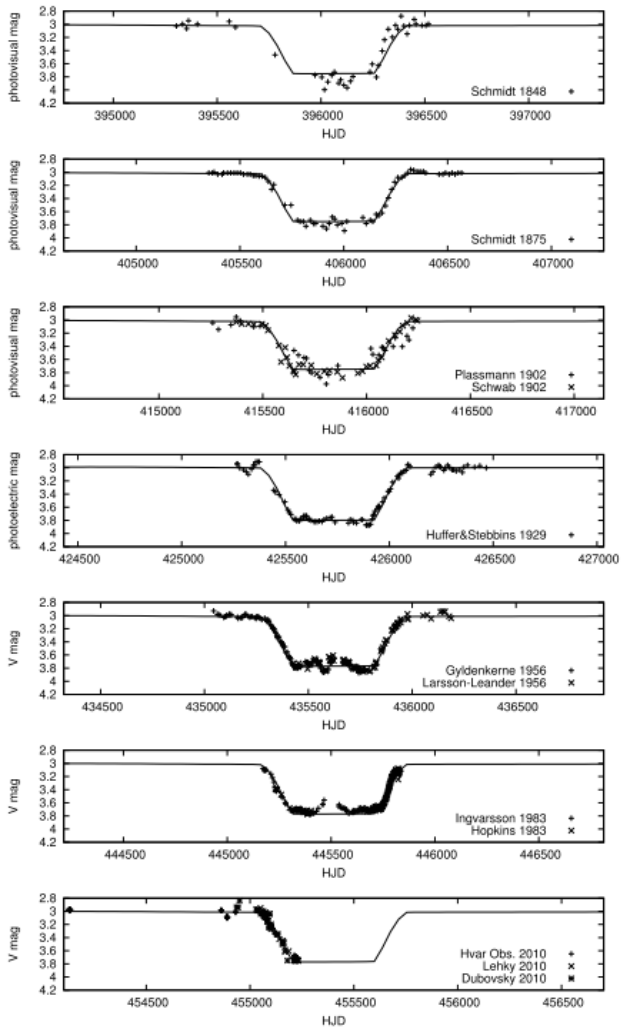
Outline

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

Pre-Eclipse Understanding



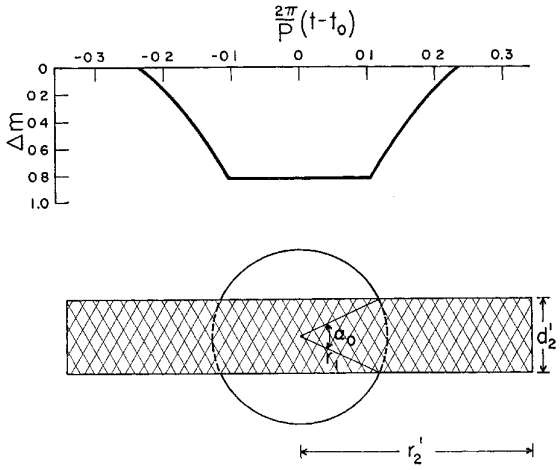
Chadima et al (2010)

- Discovered in 1821
- 27.1 Year Period Confirmed 1903

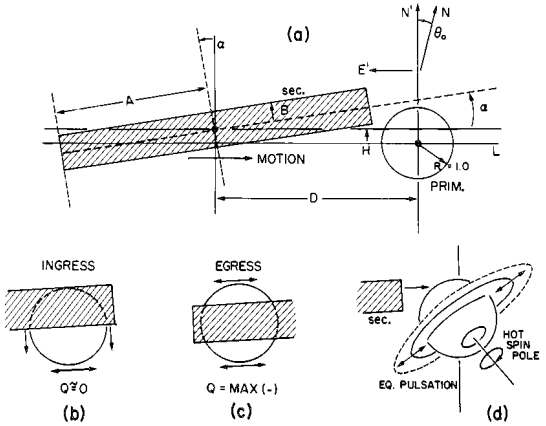
Explaining The Eclipses

- Hyperionized IR Star
- Black Hole

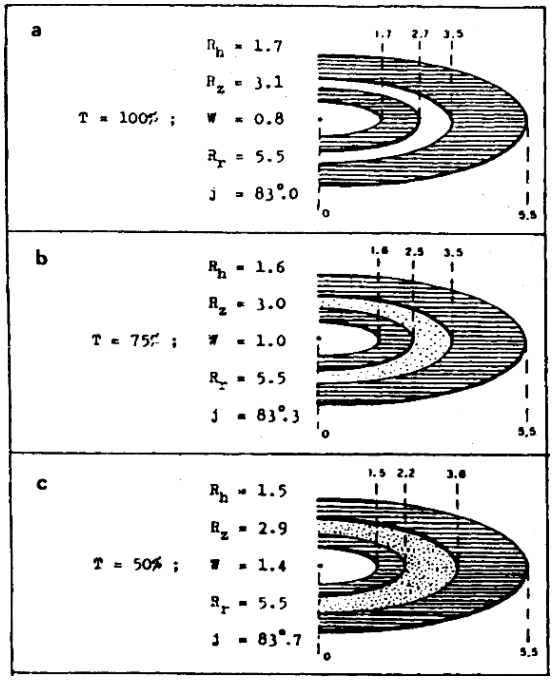
Pre-Eclipse Understanding



Huang (1965)



Kemp (1986)



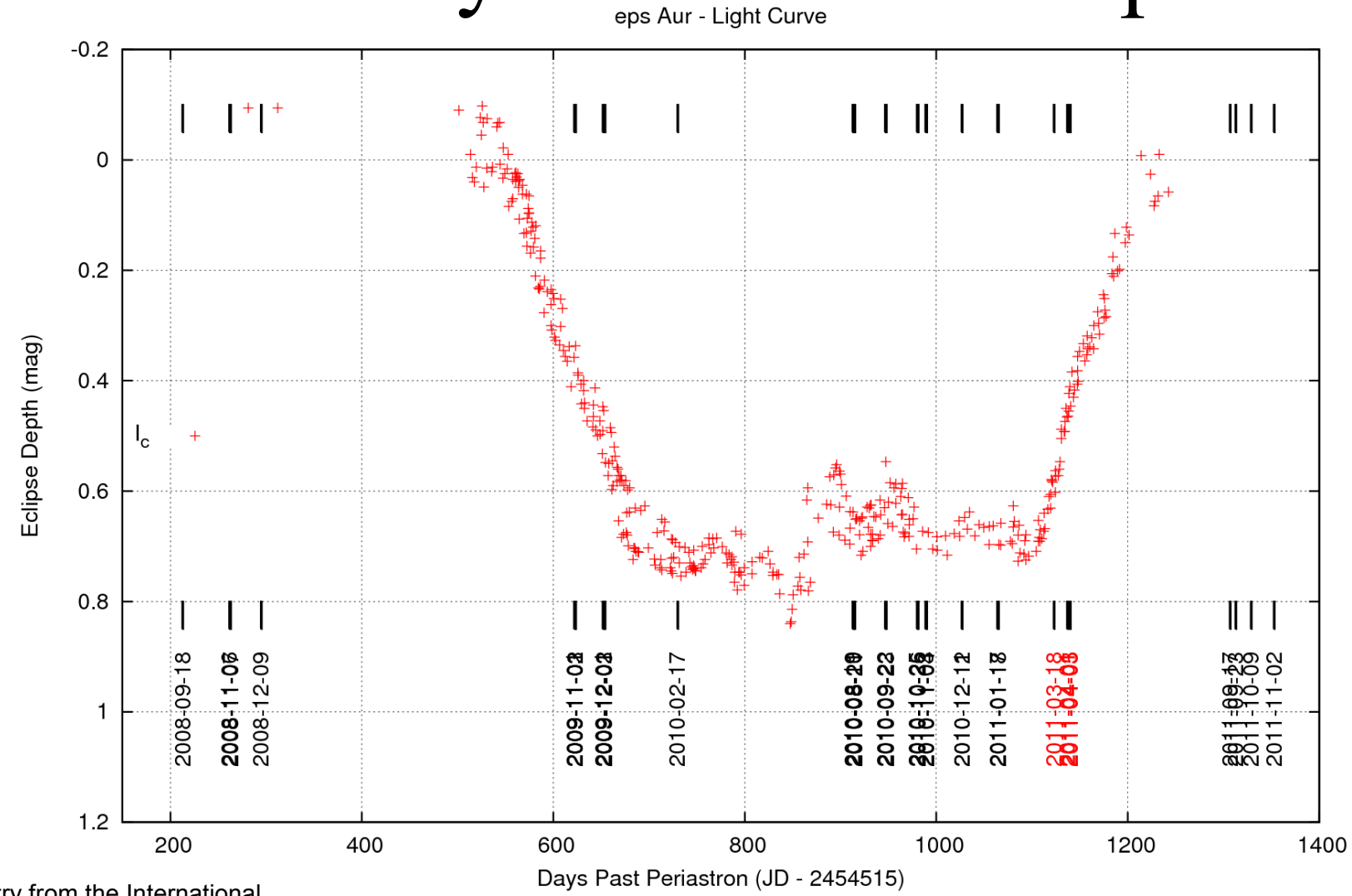
Ferluga (1990)

1965: Block of Opaque Material
1986: Block is tilted
1990: Disk consists of rings of material, is also highly inclined.

Questions to be answered

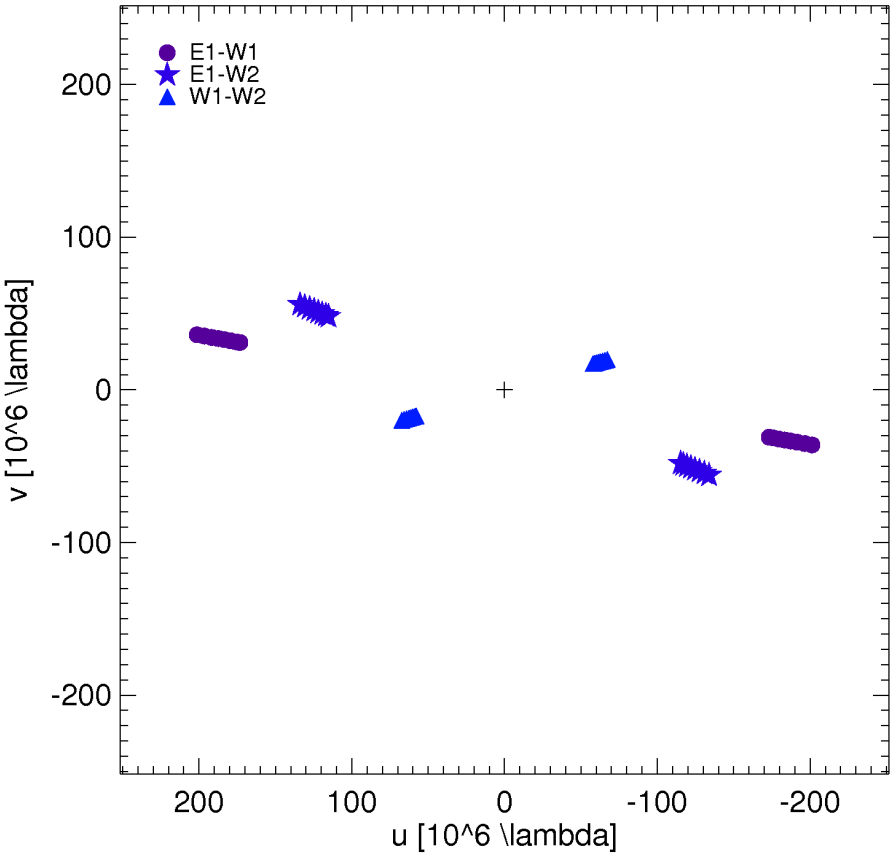
- Is there really a disk?
- If so, what are its geometric properties?
  - Radius, height, opacity, inclination, flaring
- More fundamentally:
  - What is the distance to the system?
  - What is the mass ratio => evolutionary state?
- What causes the photometric variations?
  - In eclipse AND out of eclipse

Photometry and CHARA Epochs

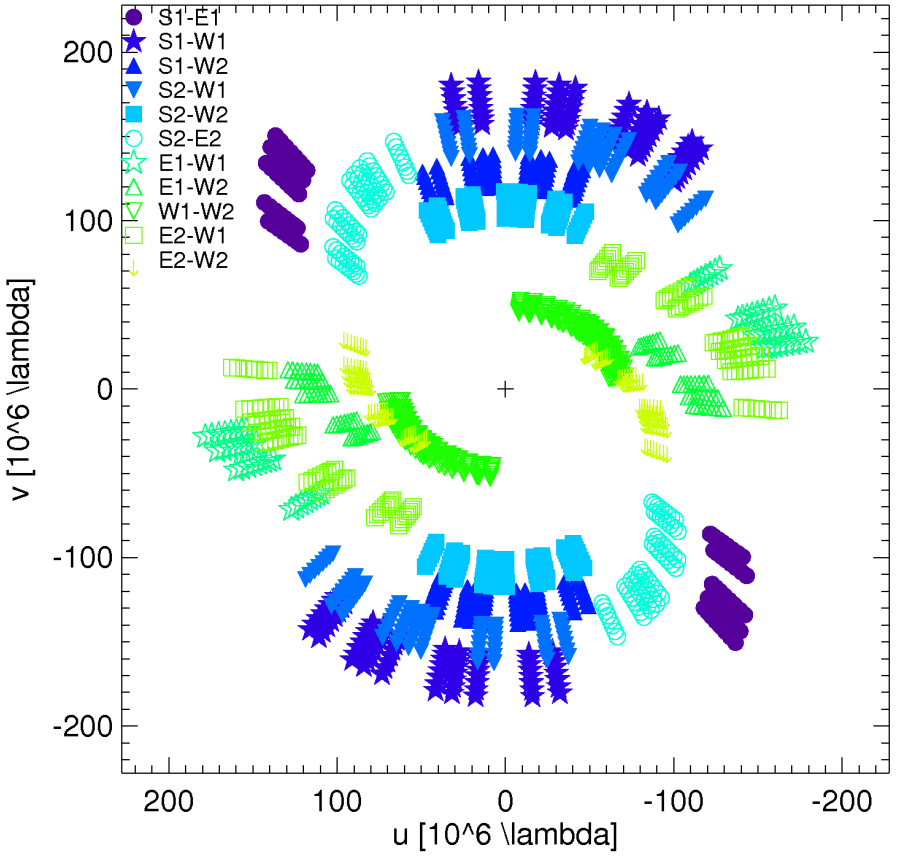


Photometry from the International Epsilon Auriage Campaign
Hopkins et al 2012

UV Coverage

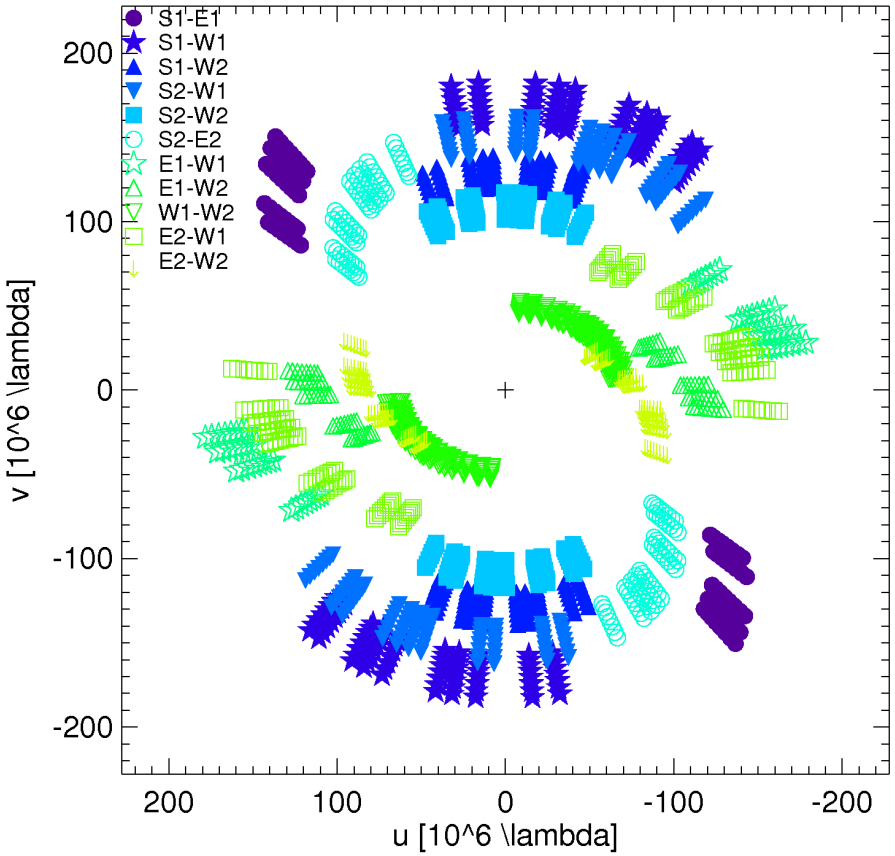


2008-09

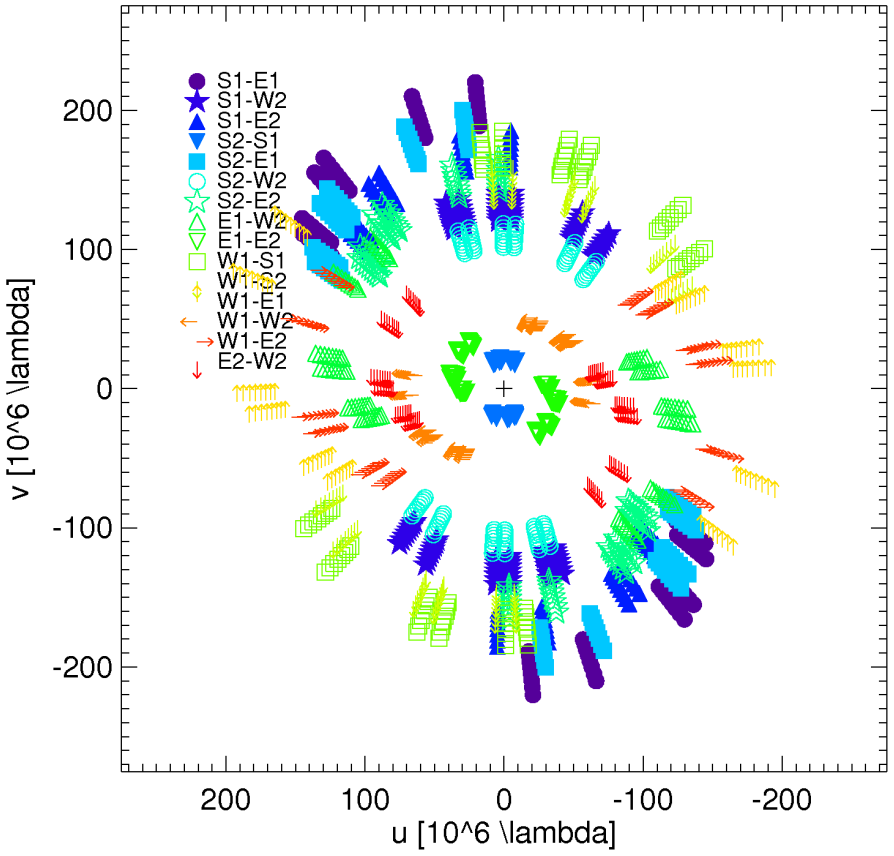


2009-11 (4T, 3 Nights)

UV Coverage

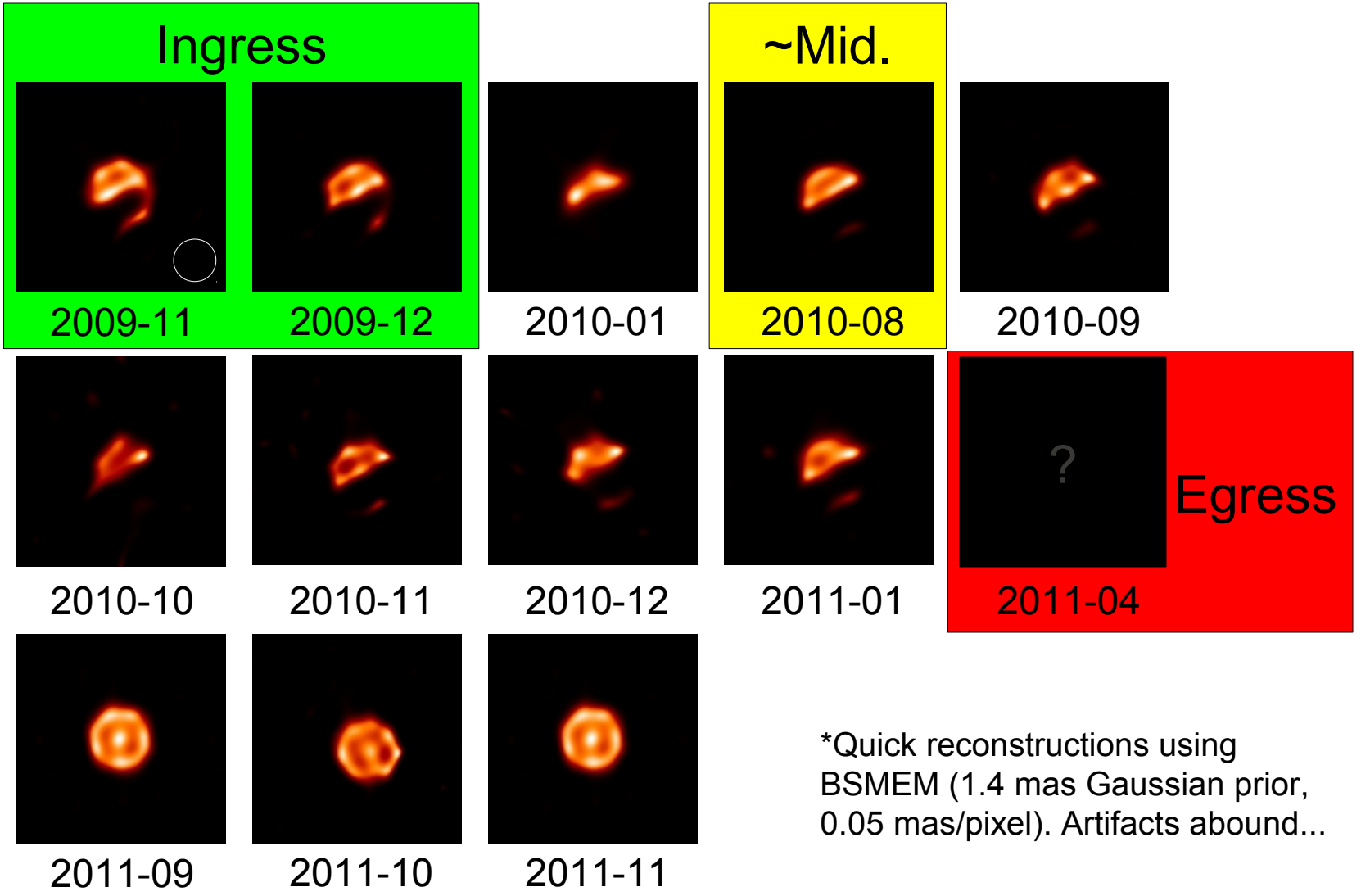


2009-11 (4T, 3 Nights)



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

$\Omega \sim 92$ +/- 3 (VdK)

$\omega = 39.2$ (Stefanik)

$i = 89\text{-}90$

$T \sim 27.1$ yr (Stefanik)

$e = 0.227$ +/- 0.011 (Stefanik)

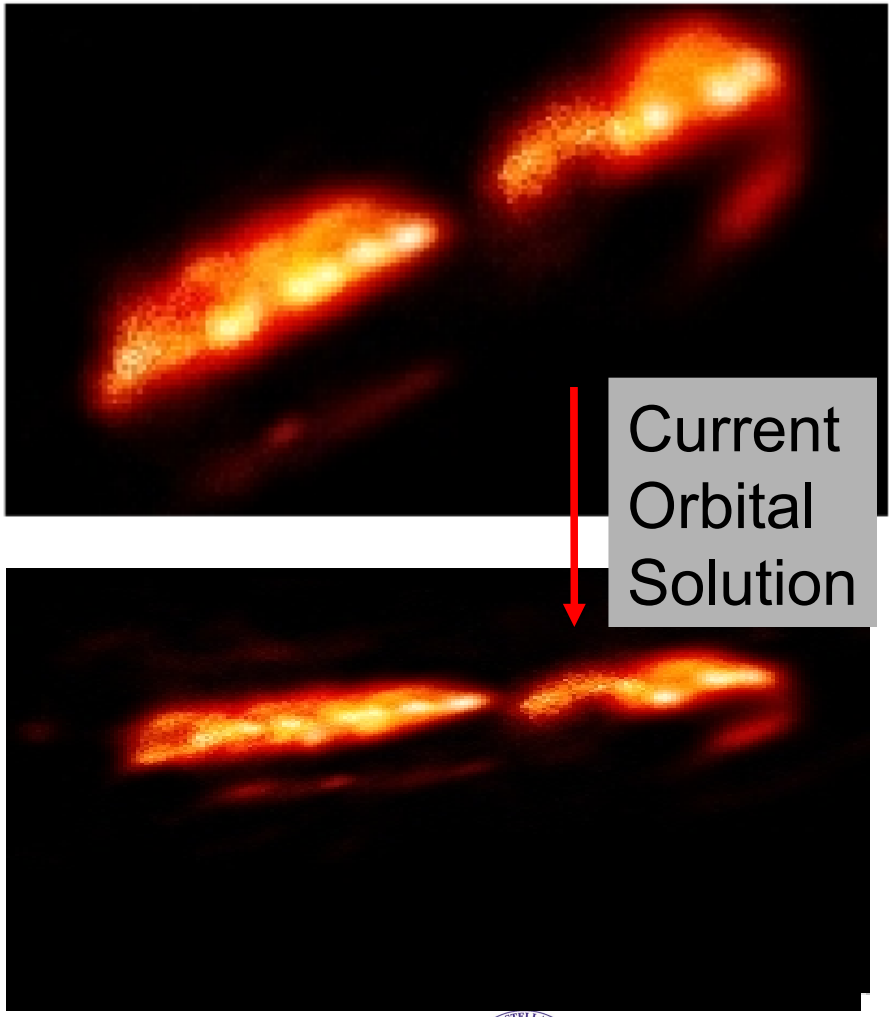
$\tau \sim 2{,}454{,}515$ (Stefanik)

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

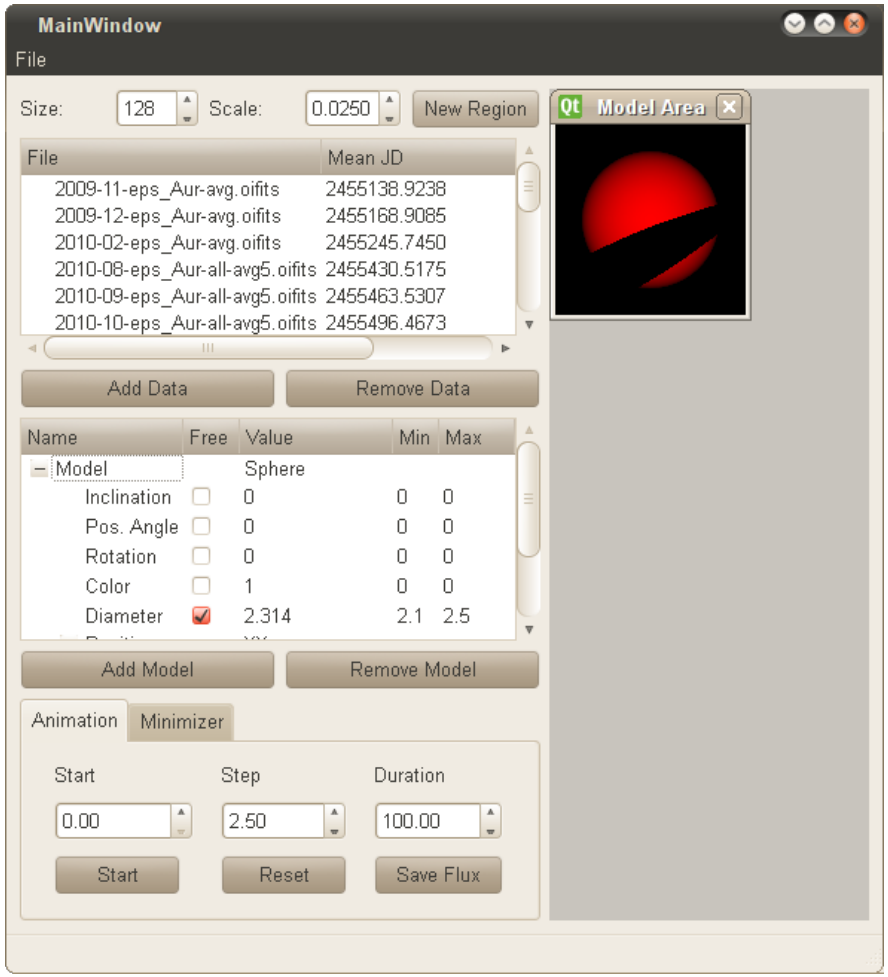
$\alpha_1 = 22.7$ +/- 1 (VdK)

$d = 625$ +/- 585 pc (HIPPARCOS)

Clearly we need something better...



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.

Bayesian Nested Sampling

Bayes' Theorem

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

Pr(Θ|D,H) = P(Θ), posterior probability

Pr(D|Θ,H) = L(Θ), likelihood

Pr(Θ|H) = π(Θ), prior

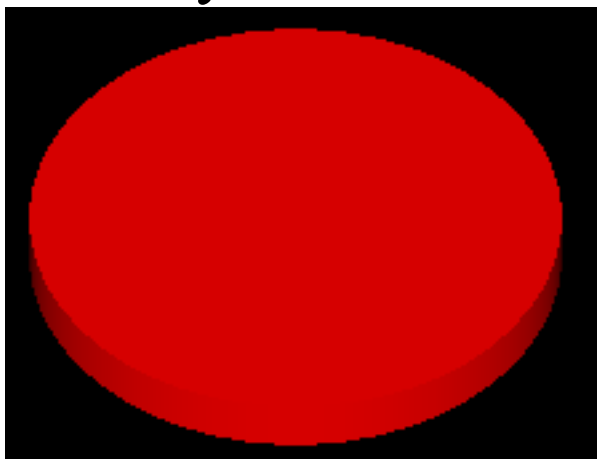
Pr(D|H) = Z, Bayesian evidence

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

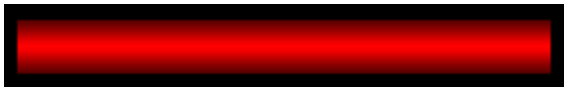
$$L(\Theta)=\sum_{i}\frac{1}{\sqrt{2\pi}\,\sigma_{i}}e^{\frac{-(M(\Theta)-D_{i})^{2}}{2\sigma_{i}^{2}}}$$

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

SIMTOI: Multi-Epoch Fitting

Disk A: 

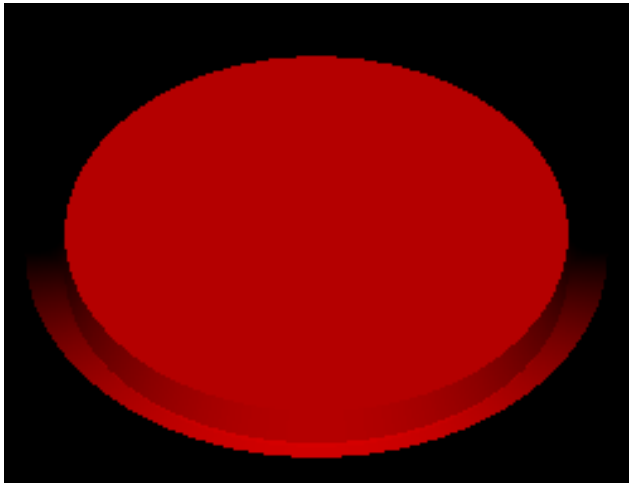
- Scale Height Exterior

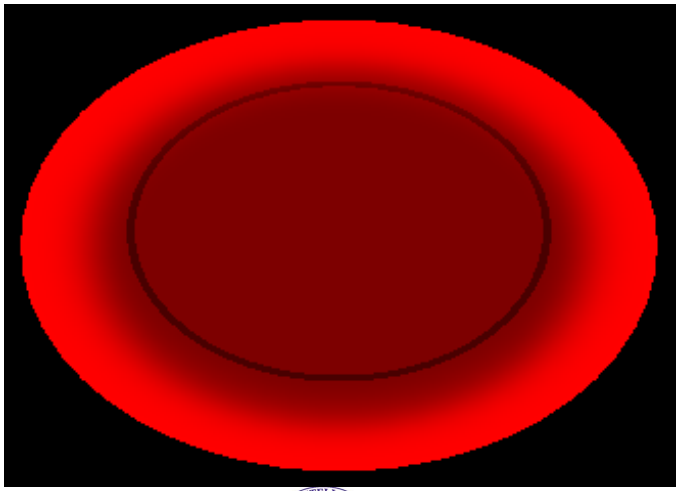
Disk B: 

- Gaussian Exterior

Disk C: 

- Power Law Exterior



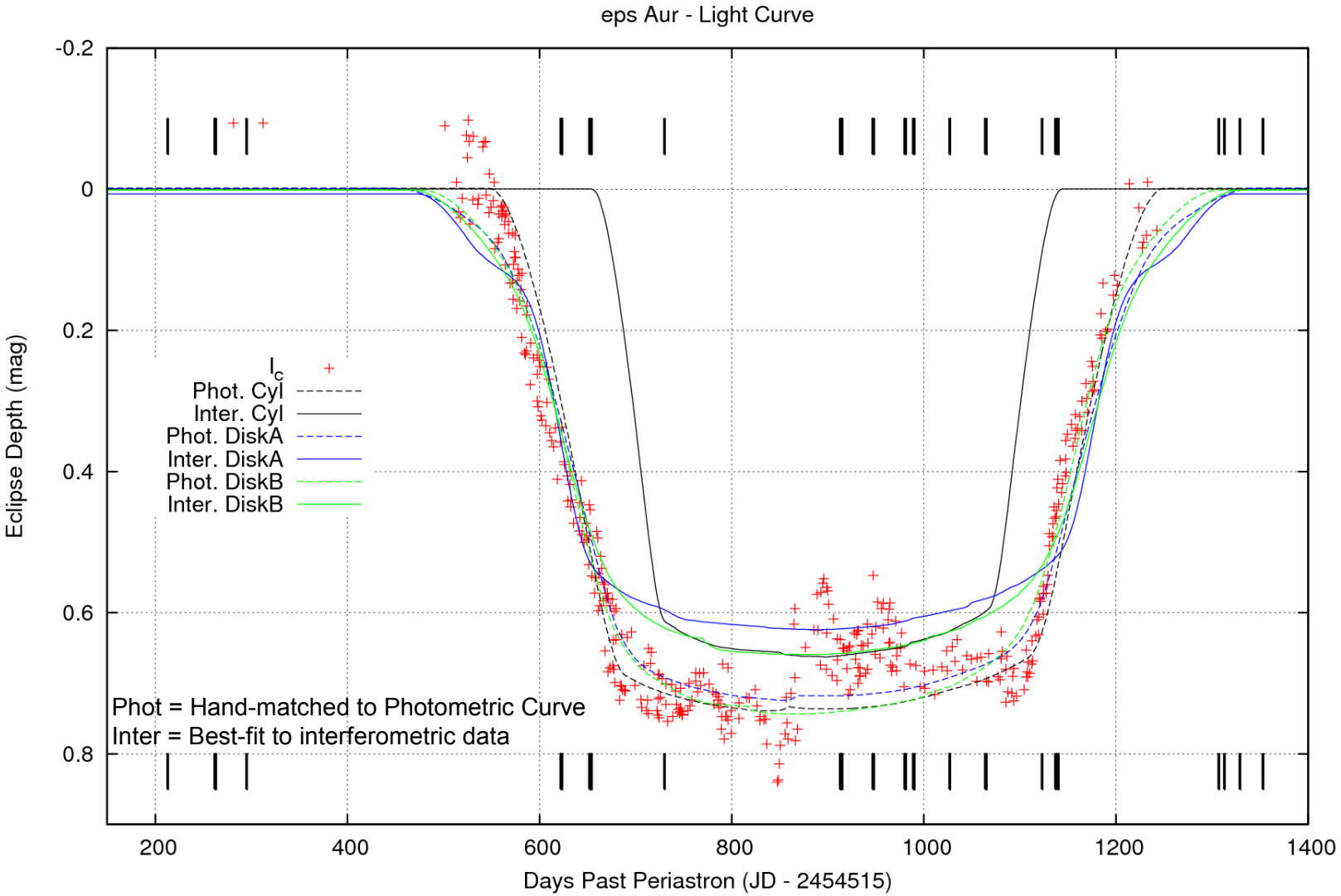


Can add transparency too: 

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



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

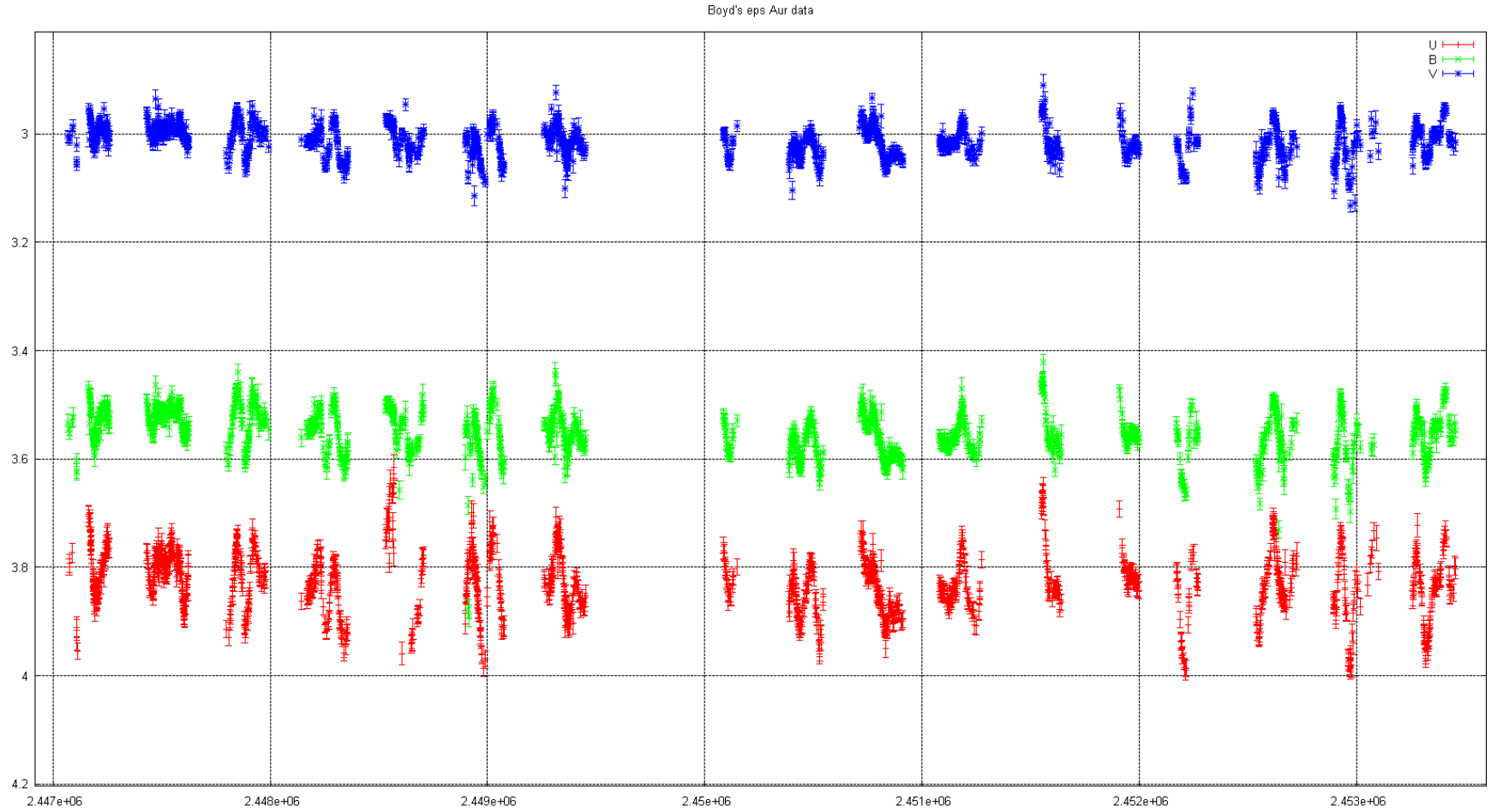
Constrain Orbit, Refit

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

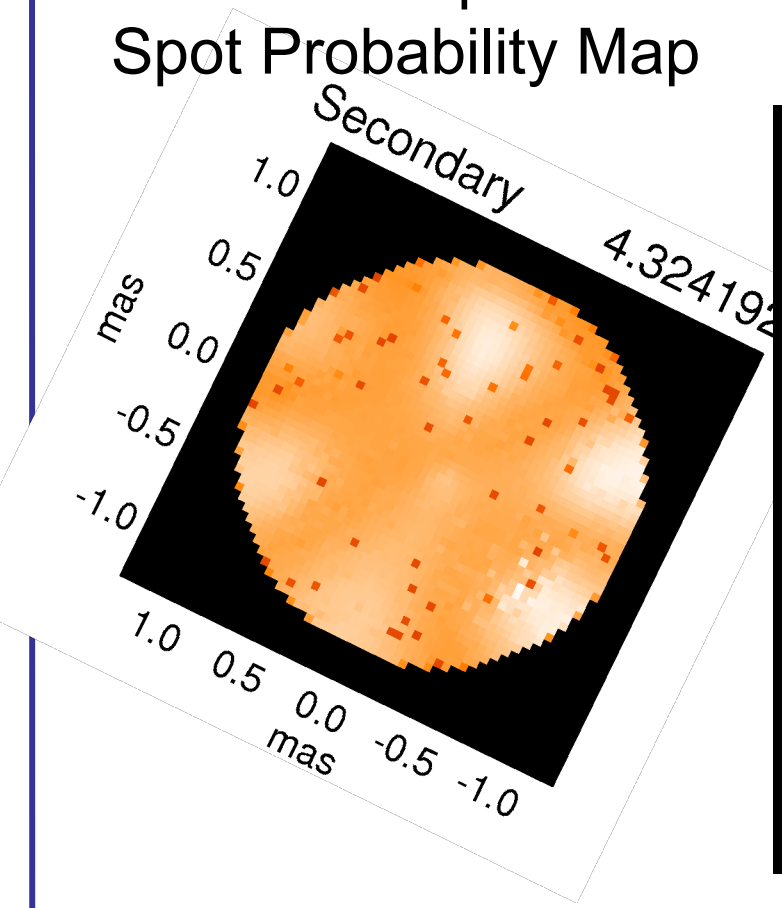
- ~~Is there really a disk?~~ Yes!
- ~~If so, what are its geometric properties?~~ ~Done
  - ~~Radius, height, opacity, inclination, flaring~~
- ~~More fundamentally:~~ Chapter 2 of Dissertation
  - ~~What is the distance to the system?~~
  - ~~What is the mass ratio => evolutionary state?~~
- What causes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

Out of Eclipse Variations!



Convection, Non-Radial Pulsation?

2011-09 eps Aur
Spot Probability Map



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