Imaging the transiting disk in the epsilon Aurigae system

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Funding:
NSF DRL-0840188, AST 10-16678, William Hershel Womble Estate

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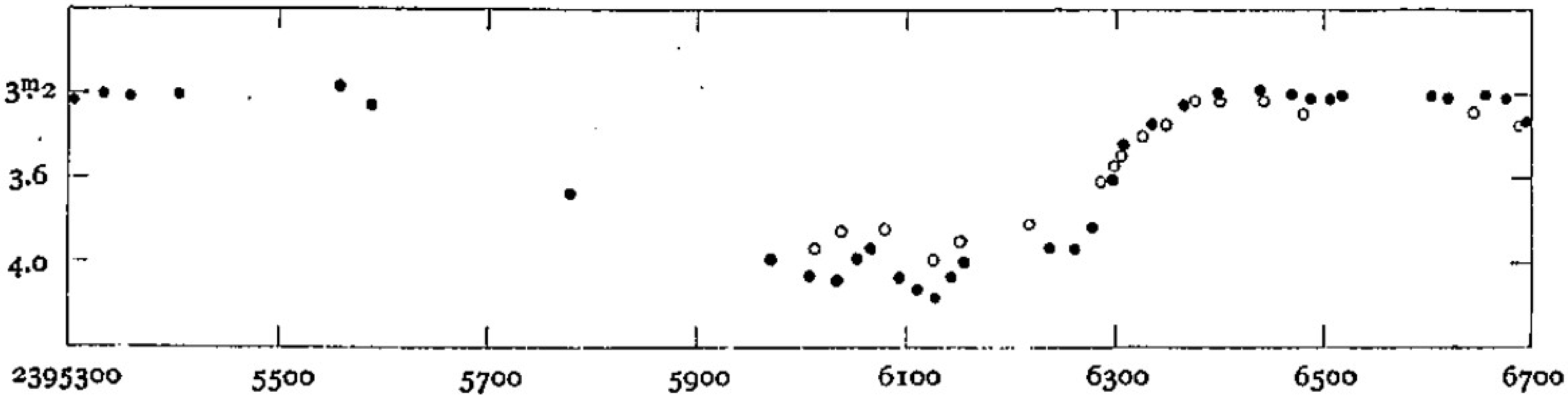
OI Imaging Workshop
University of Michigan
2012-08-08

Outline

- What is epsilon Aurigae?
- Open research questions
- Enter interferometry
  - Examples of data
  - Images
  - Modeling (Bayesian)
- Results
- Conclusion

The First (?) Discovery



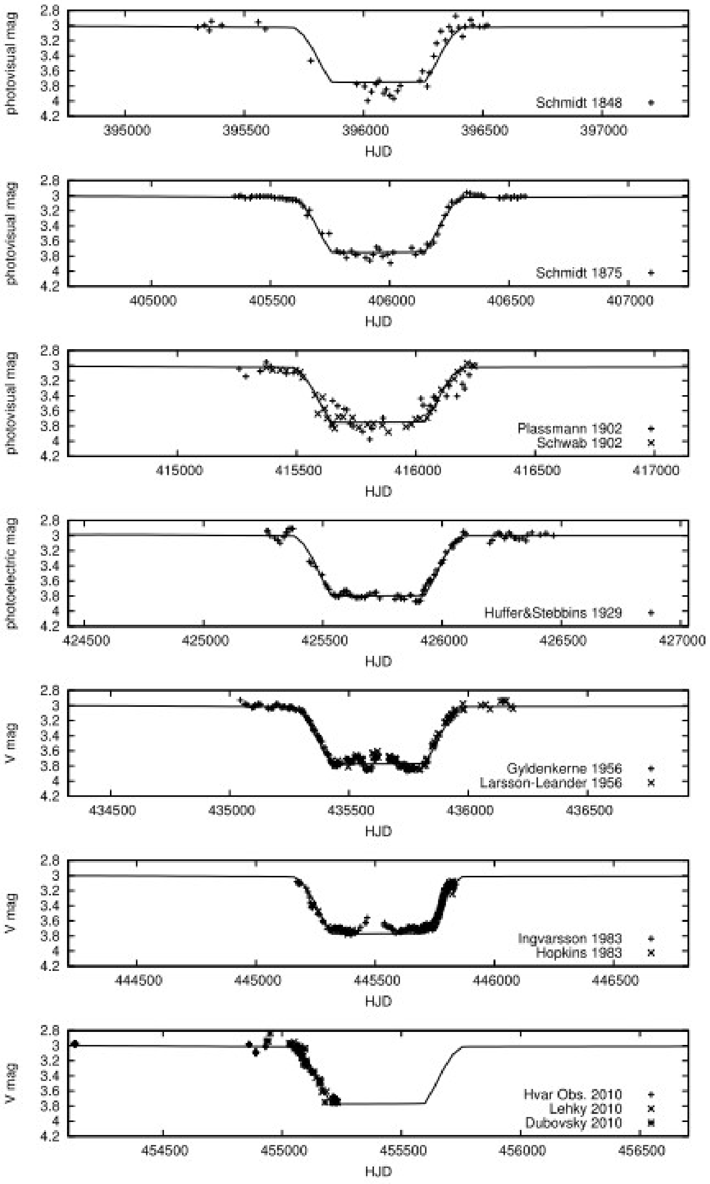
1846-1847 Eclipse of epsilon Auriage; Image Credit: Gussow (1936)

Den Stern in der Ziege des Fuhrmanns sehe ich oft gegen ζ und η so schwach, dafs er kaum zu erkennen war. Hat man dies schon beobachtet?

-Fritsch (1824)

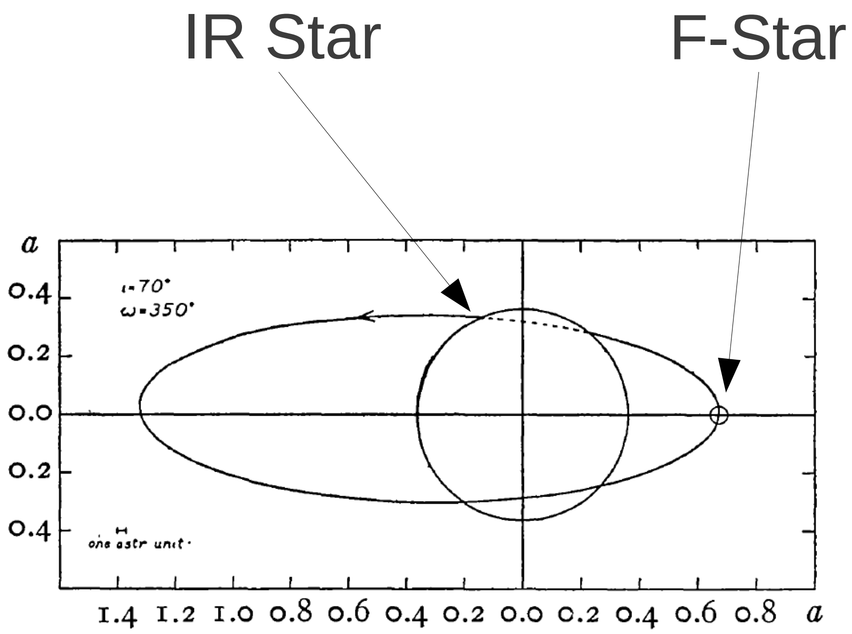
Knowledge as of 1903

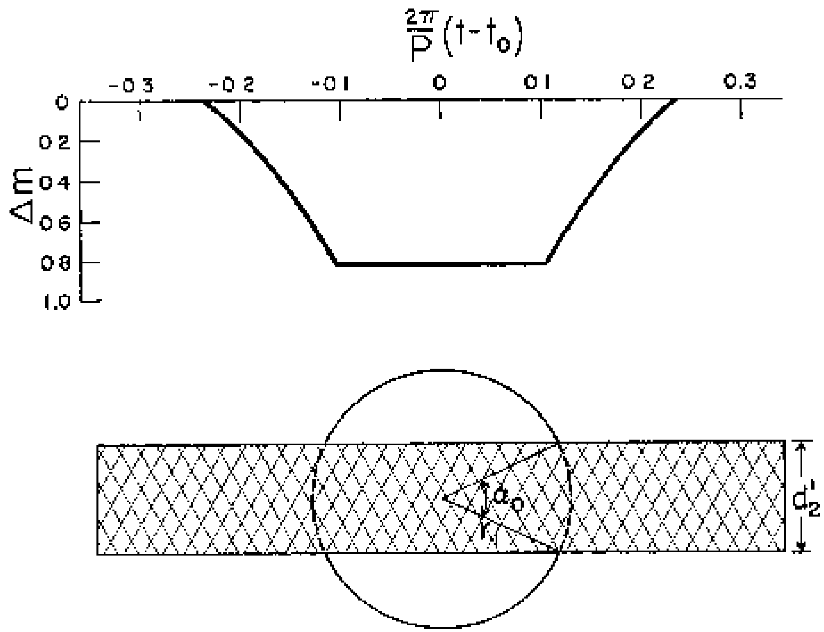
- Photometric Monitoring:
  - System dims by ~50% every 9890 days (27.1 years) (Ludendorff, 1903), stays faint for ~2-years
- Spectroscopic Monitoring:
  - Epsilon Aurigae is a single line spectroscopic binary
- Dimming thought to be due to an eclipse.
- System composition
  - Visible component is F0Ia
  - Other component: unknown

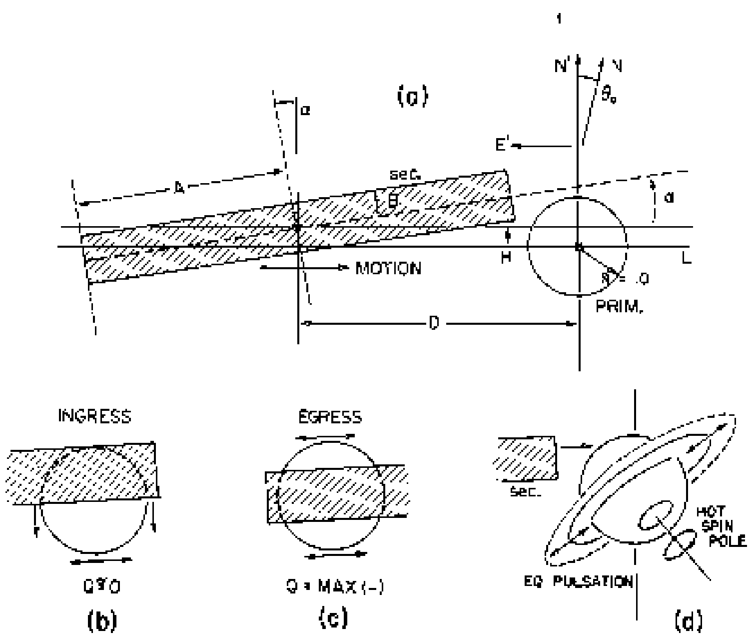


Background on eps Aur

- 1912: Ludendorff
  - A swarm of meteorites, 10-100 um in diameter.
- 1937: Struve et al.
  - A large semitransparent infrared orbited by an F-type supergiant.
- 1938: Schoenberg et al.
  - A super-cool star that forms solid particles during convection





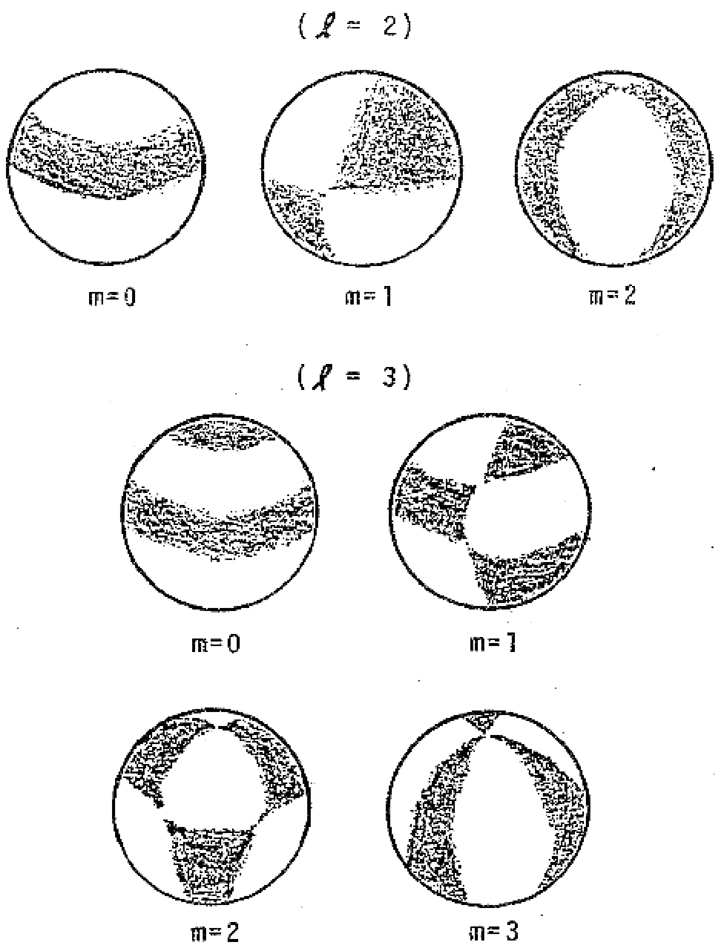


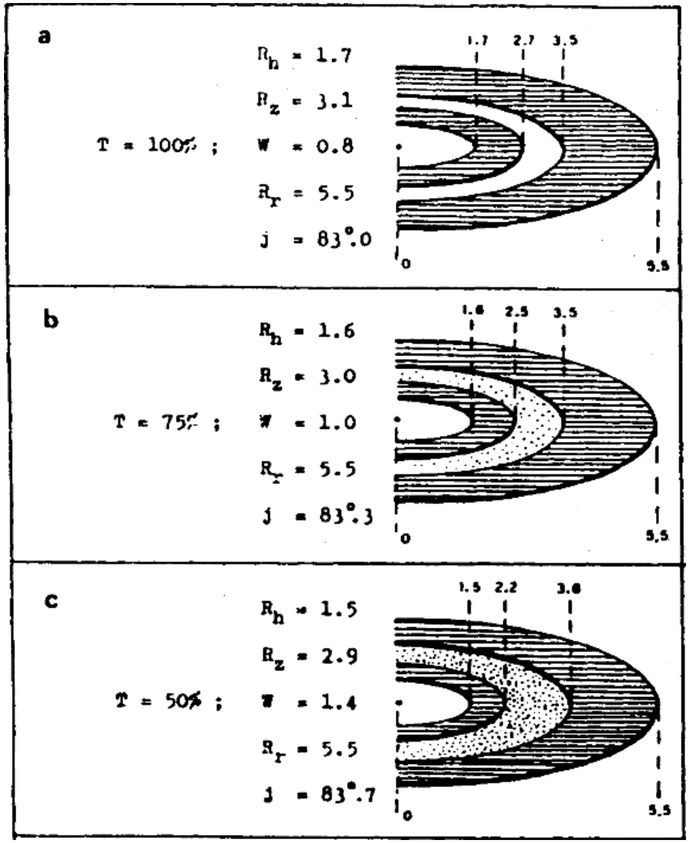
- 1965: Huang
  - The first analytical model supporting a disk-like object as the cause of the eclipse.

- 1986: Kemp
  - Obtained polarimetry during the 1983 eclipse, argued that the disk is inclined.

From the 1983 eclipse

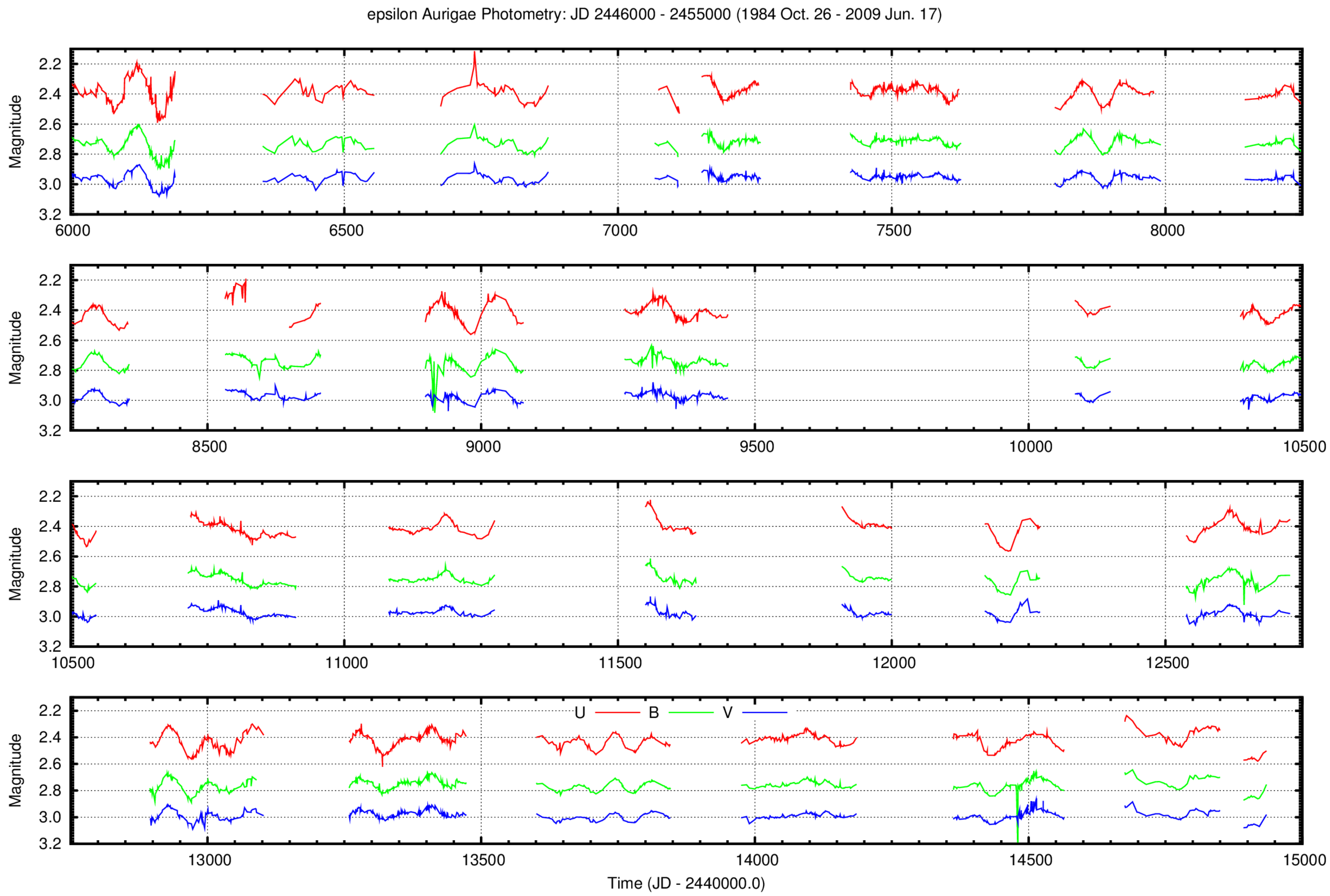
- 1989: Henson
  - F-star might be undergoing non-radial pulsation.





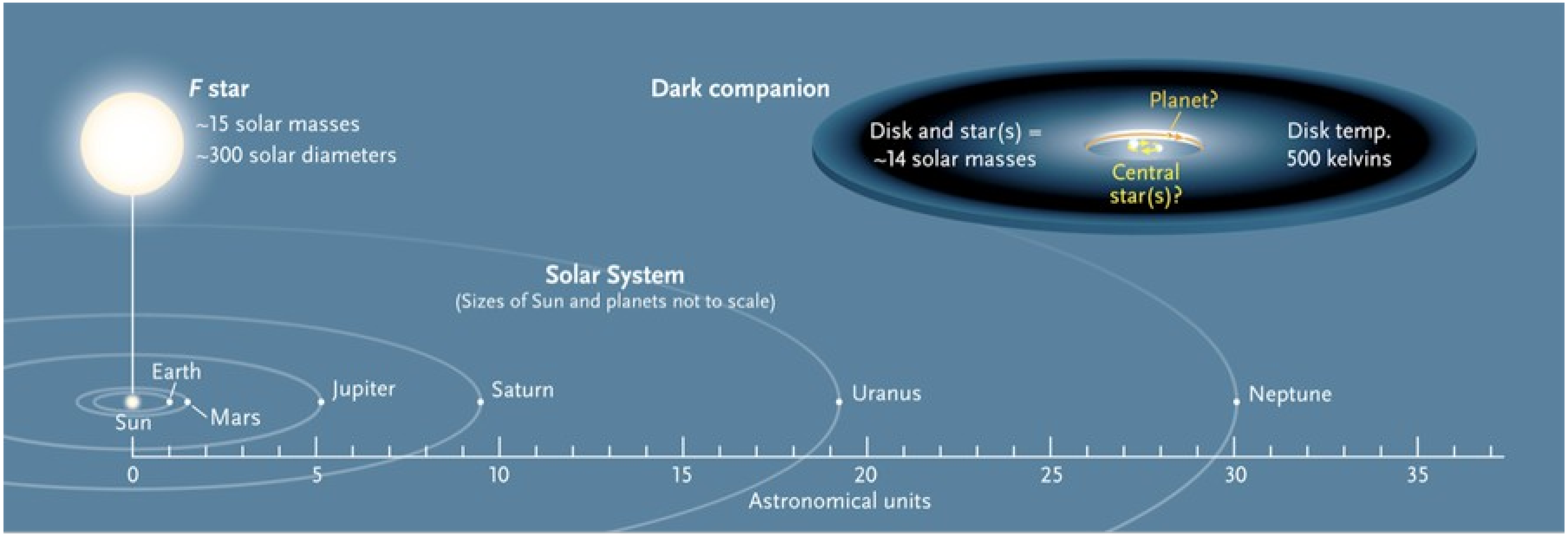
- 1990: Ferluga
  - Tweaked the Huang model, proposed the disk consisted of a series of rings.

1983-2012: Long-term photometry

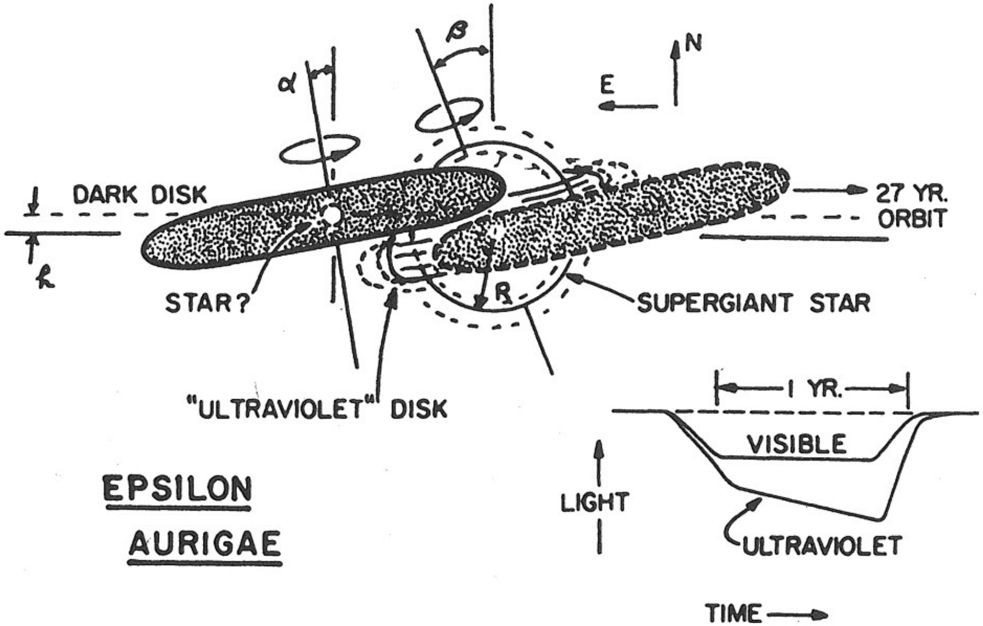


Kloppenborg et al (2012, submitted)

2009 Model of Eps Aur



S&T Illustration by Casey Reed

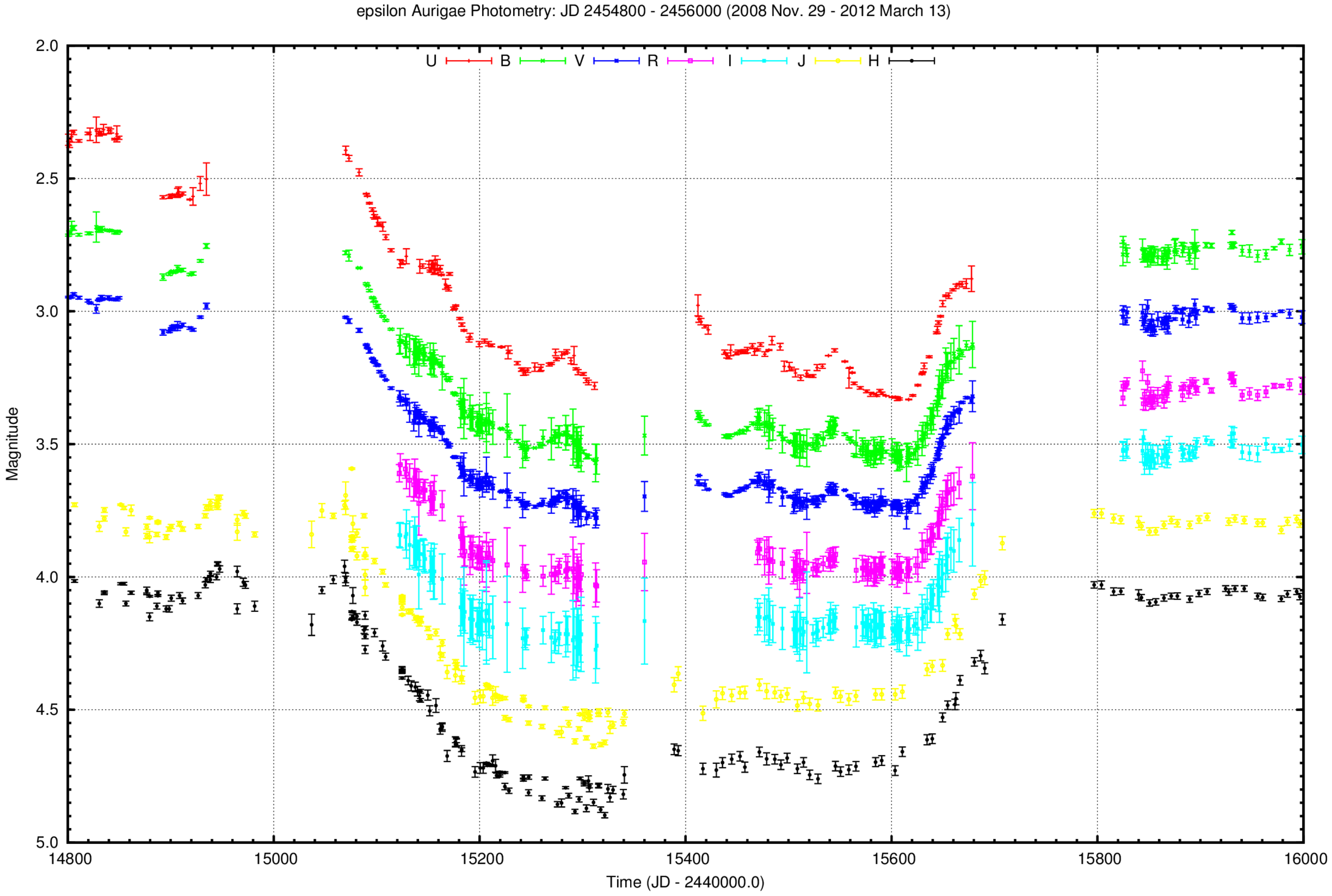


Kemp (1983)

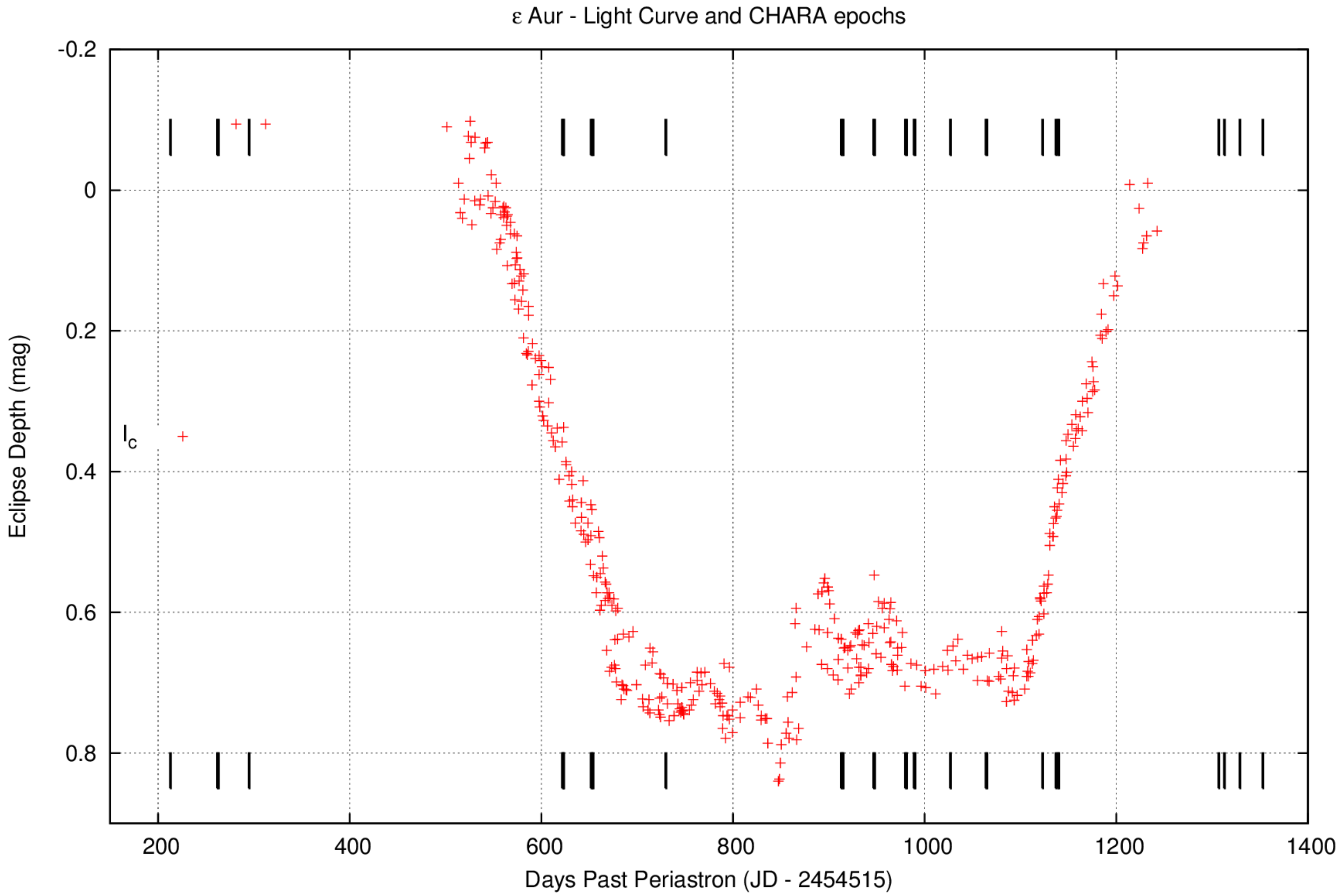
Some of the Research Questions

- The system:
  - What are the fundamental parameters (mass, radius, luminosity) of the components in the system?
  - What is it's evolutionary state?
- The eclipse:
  - What causes it?
  - Orbital parameters?
  - Fractional coverage?
- The eclipsing body:
  - Composition (gas, dust, debris?)
  - Dynamic stability (inside: one or two stars?)
- The F-star:
  - What causes the out-of-eclipse variations?

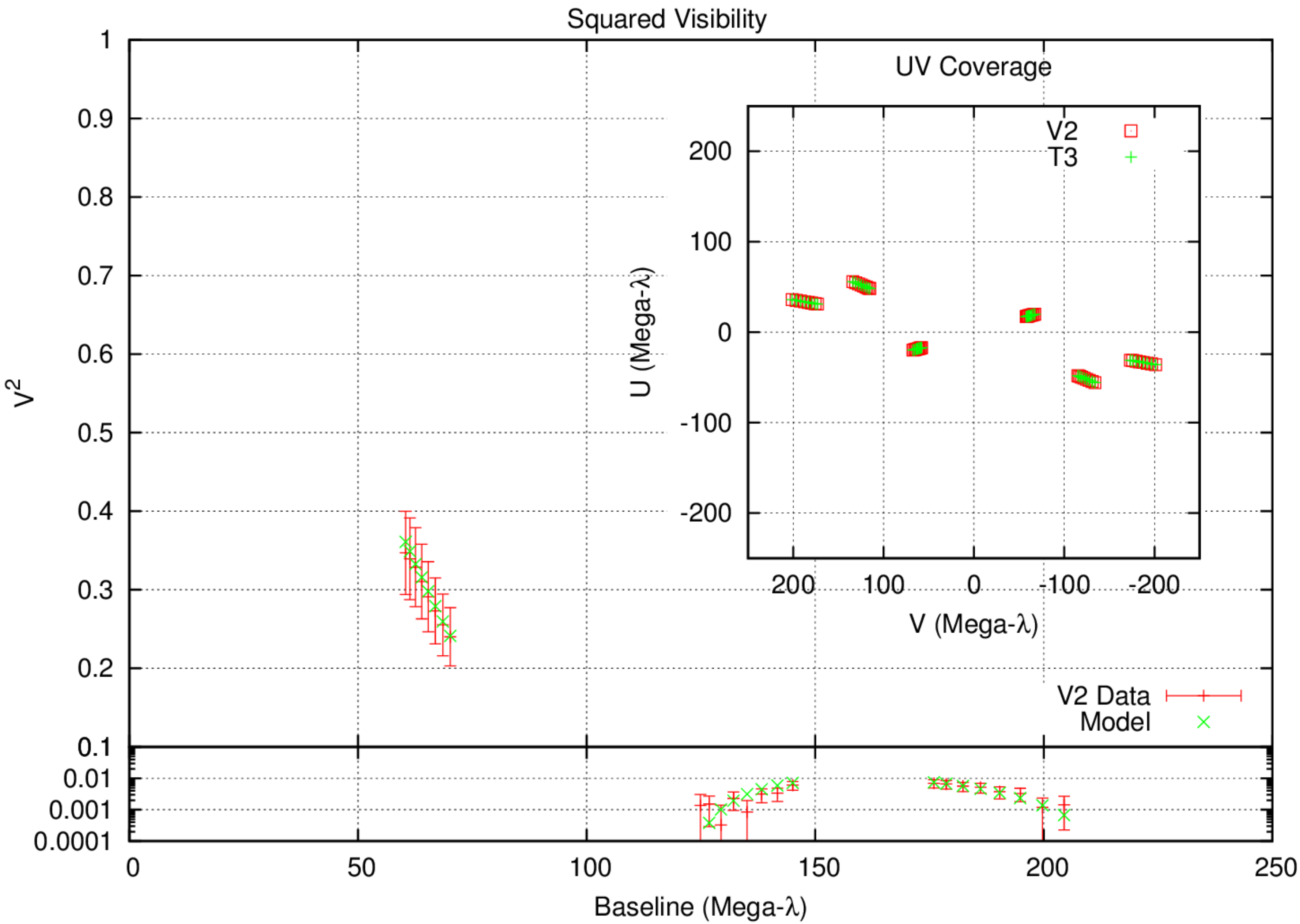
2009-2012 Eclipse Photometry



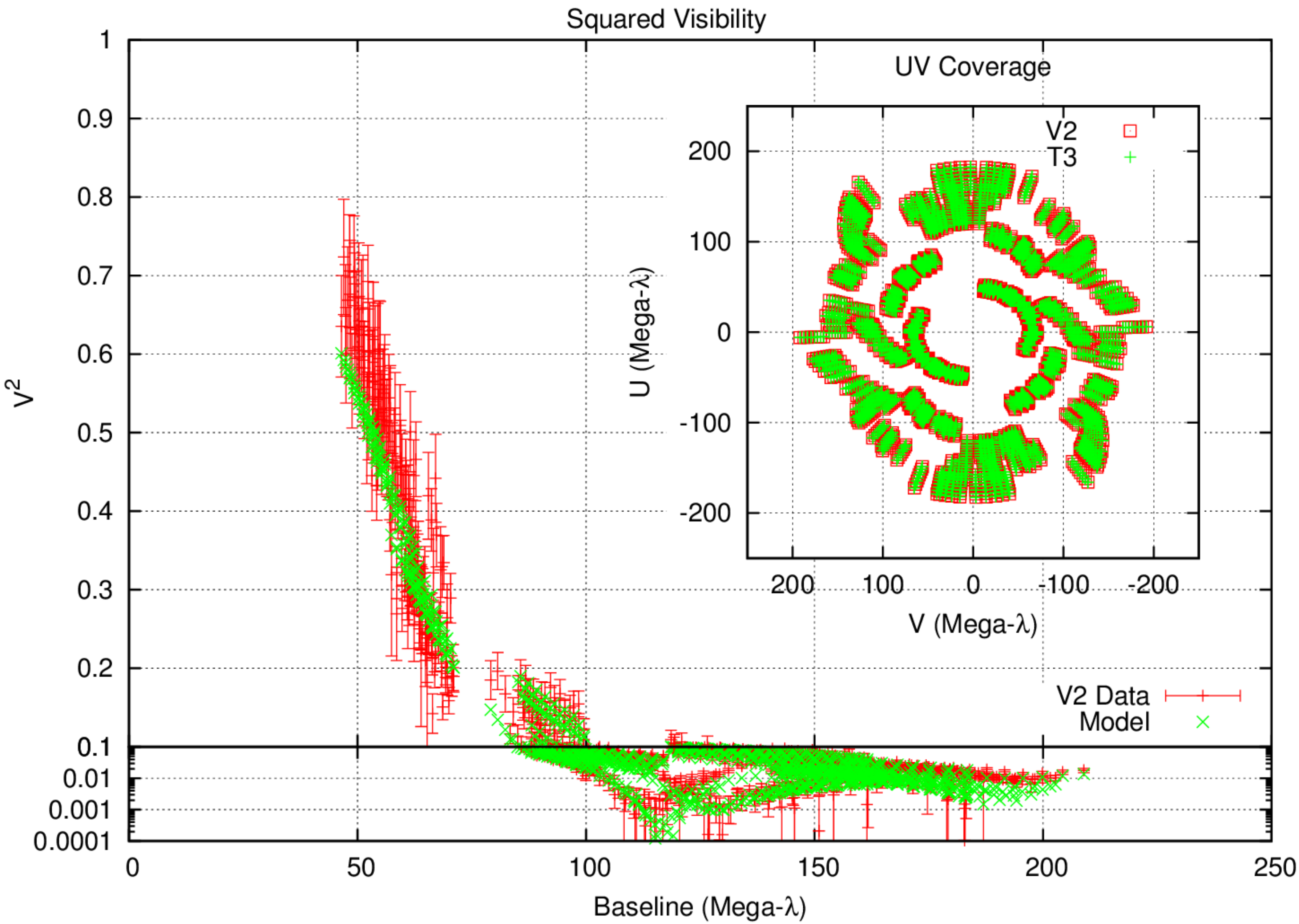
CHARA Observations



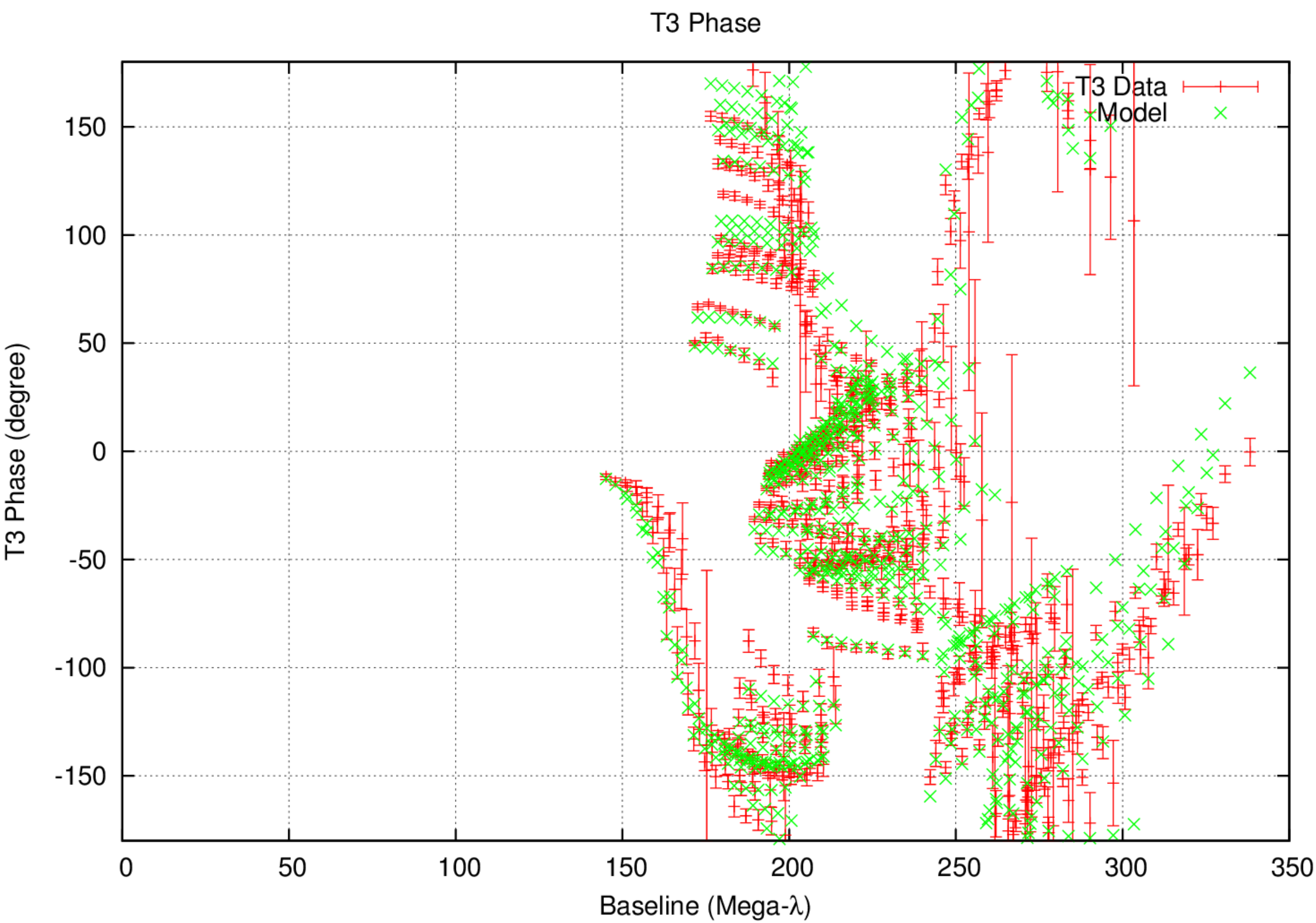
CHARA, 2008 Sept. (pre-eclipse)



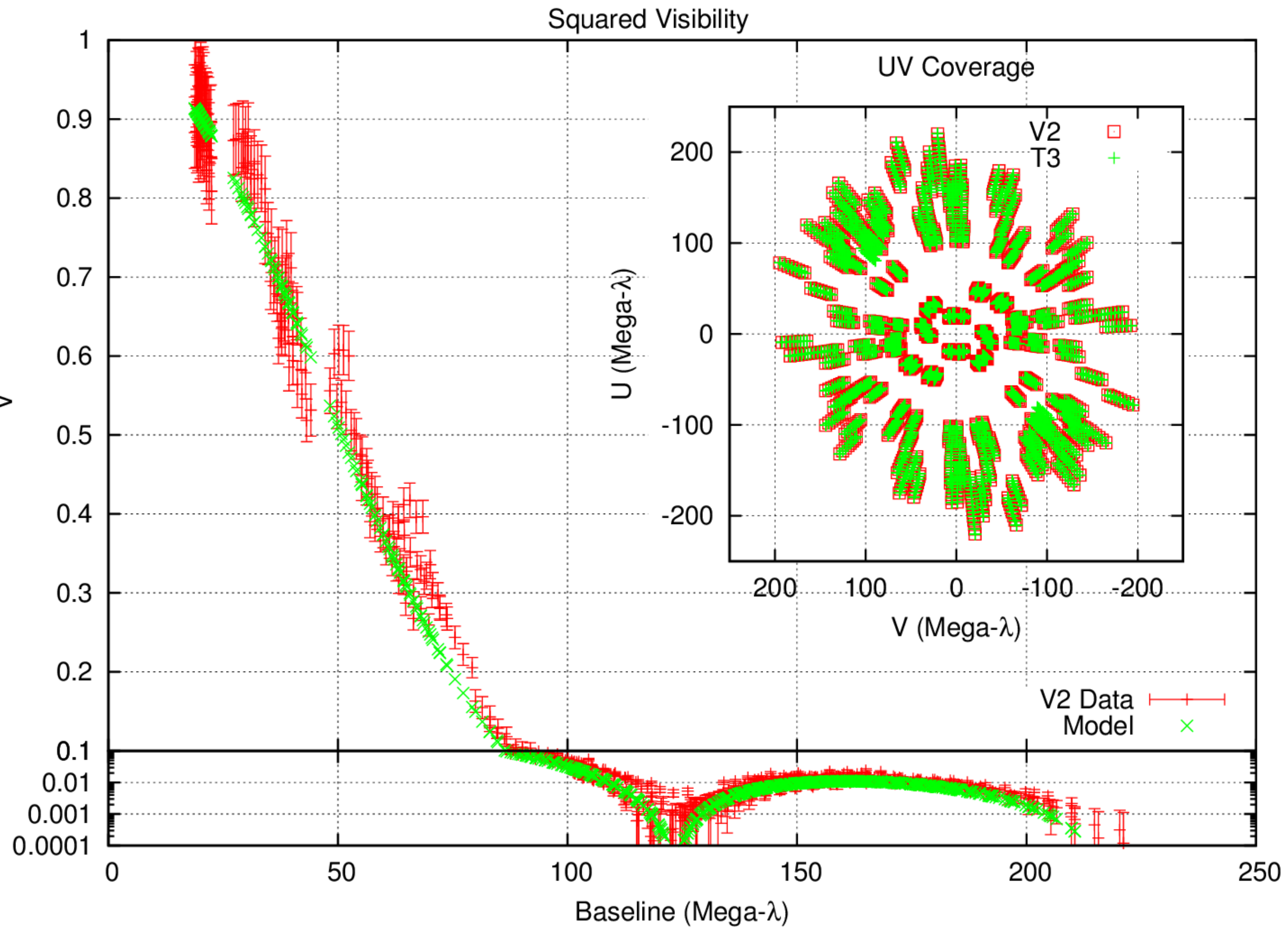
CHARA, 2009 Nov. (eclipse ingress)



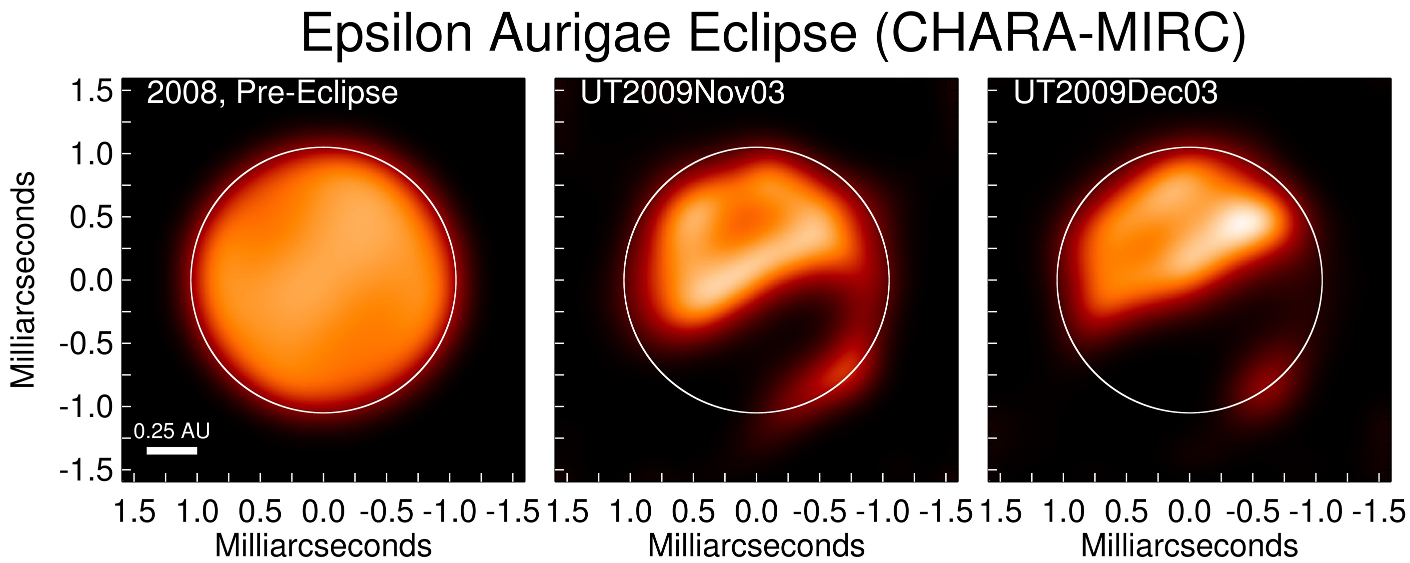
CHARA, 2009 Nov. (eclipse ingress)



CHARA, 2011 Nov. (post-eclipse)

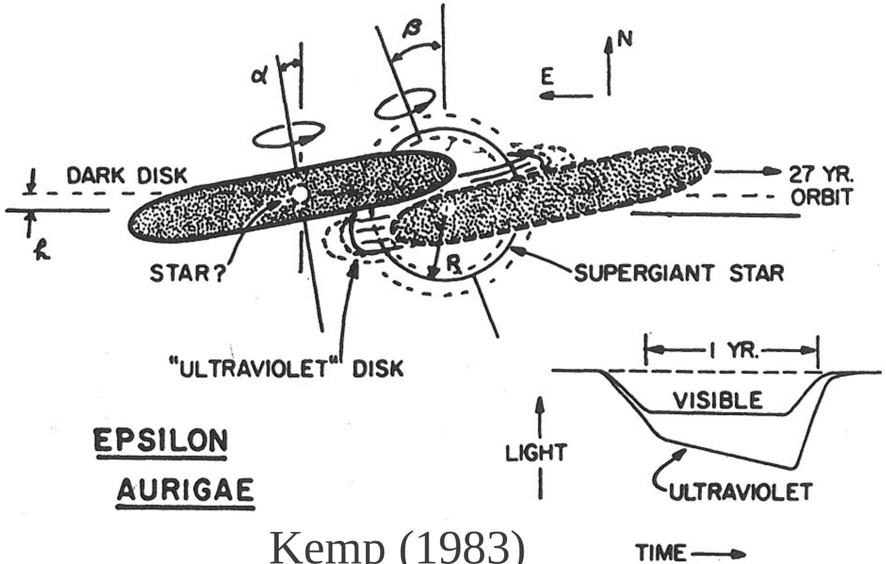


Enter OI Imaging



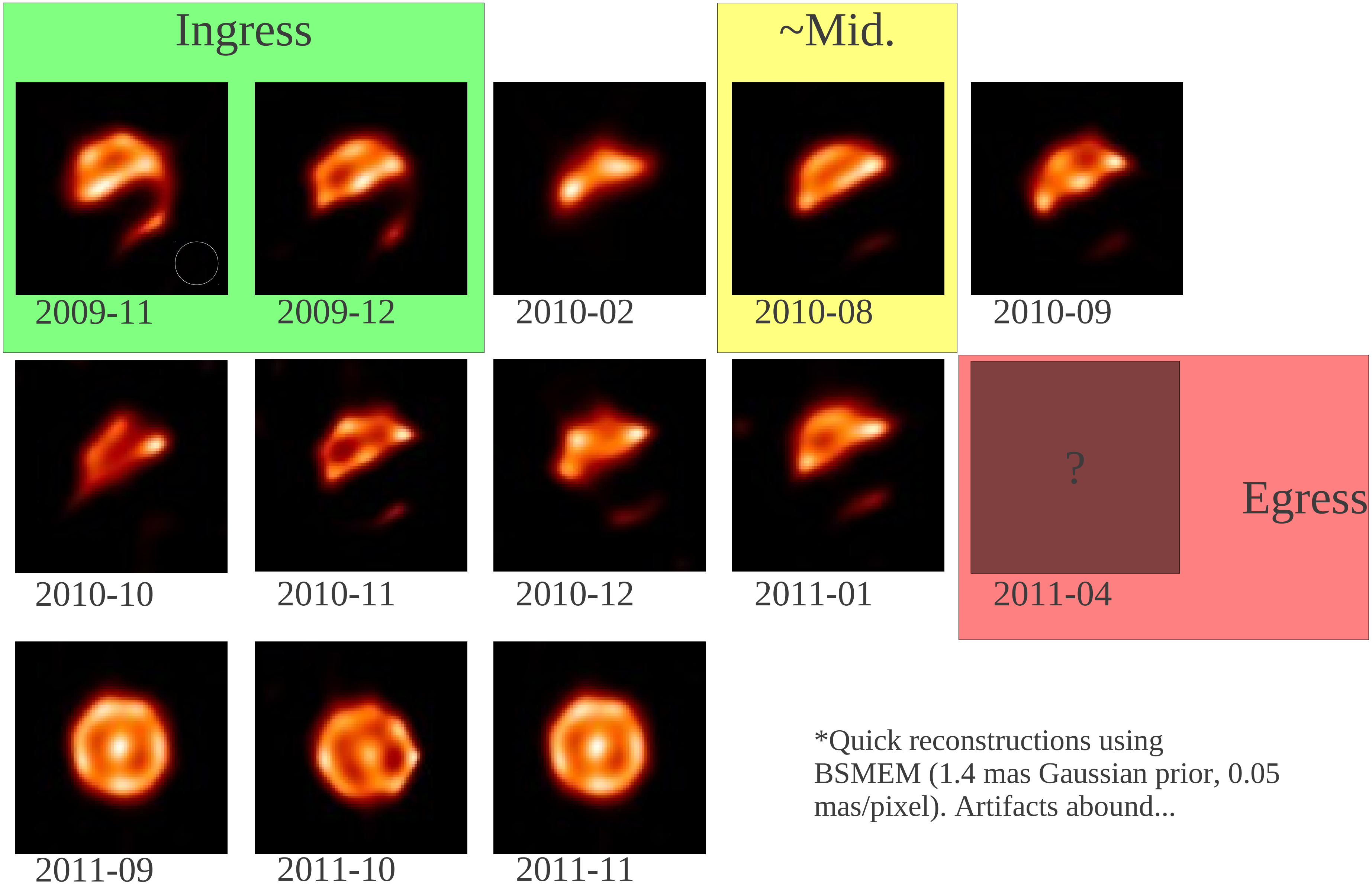
Kloppenborg et al. (2010)

- OI Imaging Shows
  - The eclipsing object is disk-like
  - Polarization-predicted impact parameter **might** be wrong
  - Potential surface features



Kemp (1983)

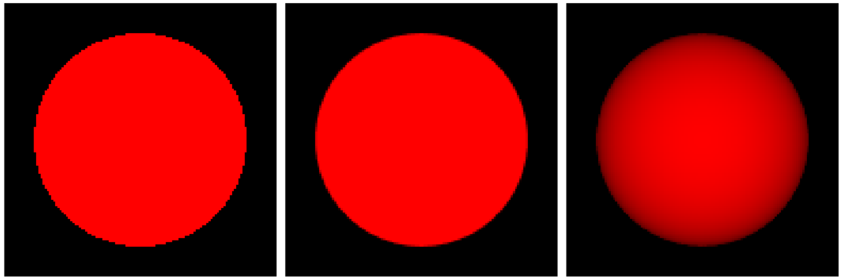
Model independent images



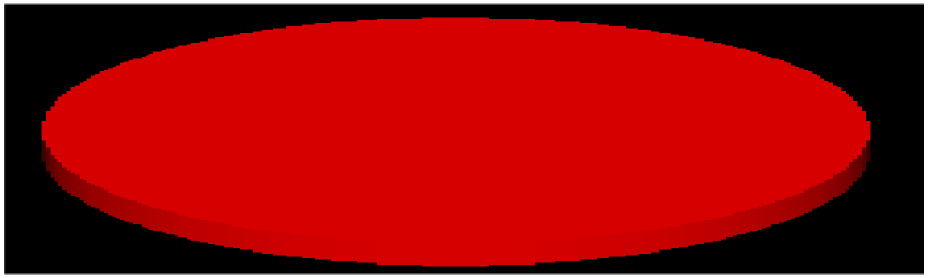
*Quick reconstructions using BSMEM (1.4 mas Gaussian prior, 0.05 mas/pixel). Artifacts abound...

Modeling: SIMTOI

- SImulation and Modeling Tool for Optical Interferometry
  - Generates interferometric observables from geometrical models
  - Models are fully 3D and time-dependent
  - First interferometric modeling tool to use GPU acceleration (via. my OpenCL Interferometry Library)
  - Multiple minimization engines
  - Bayesian model selection
  - Find it on GitHub

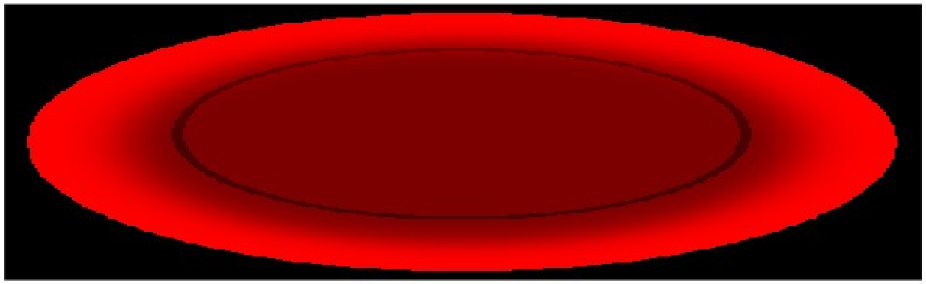


(a) Aliased (b) Anti-aliased (c) Limb Darkened

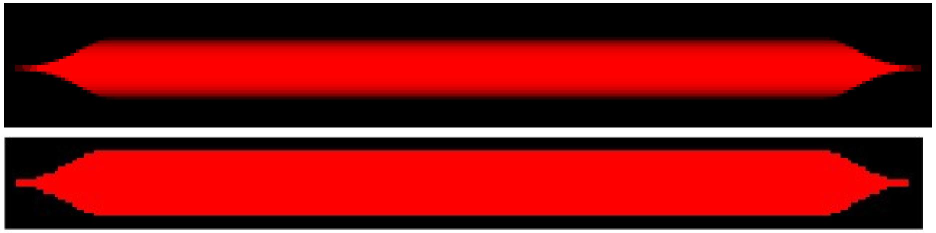


(a) Cylinder

(b) Cylinder

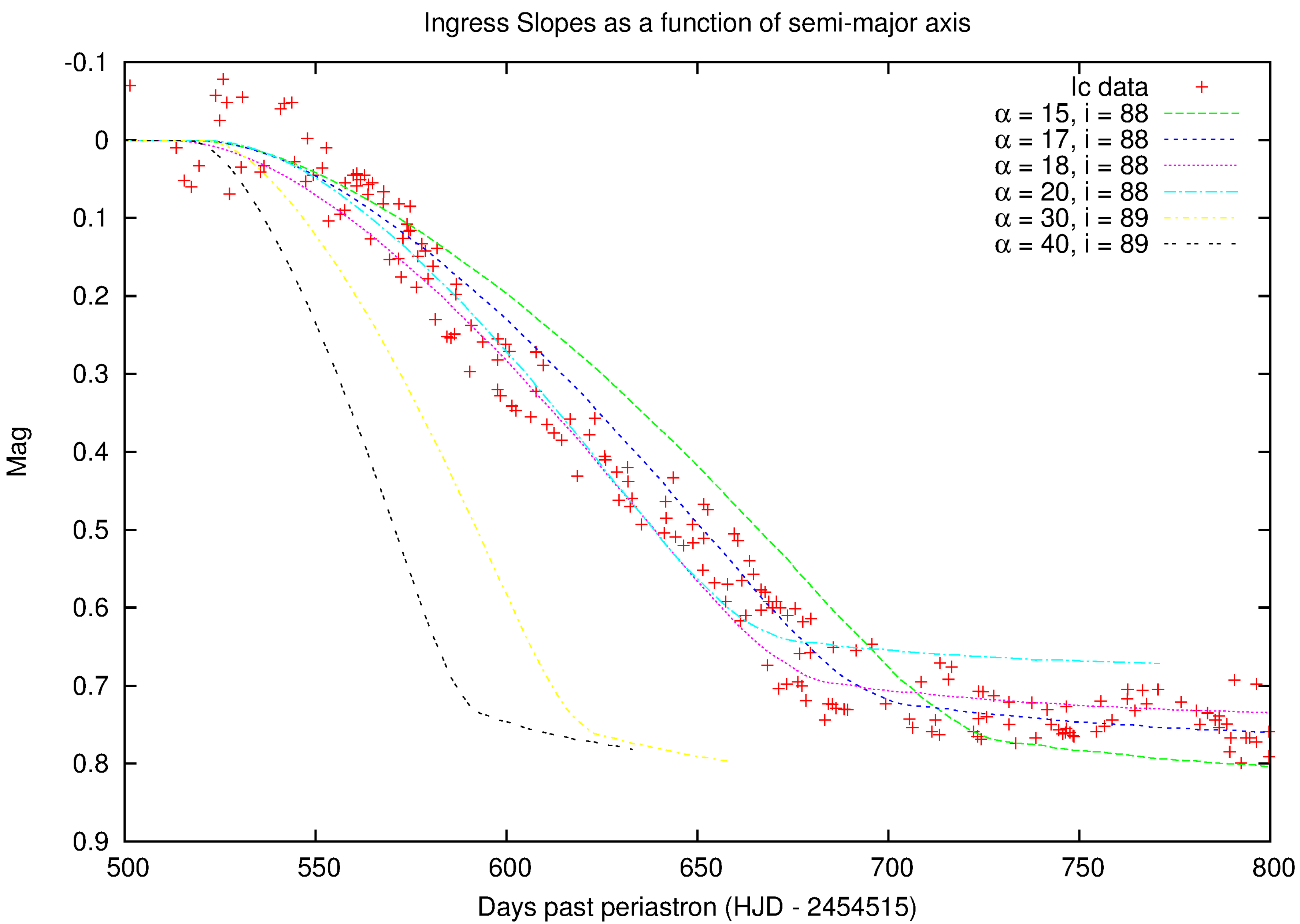


(e) Disk B

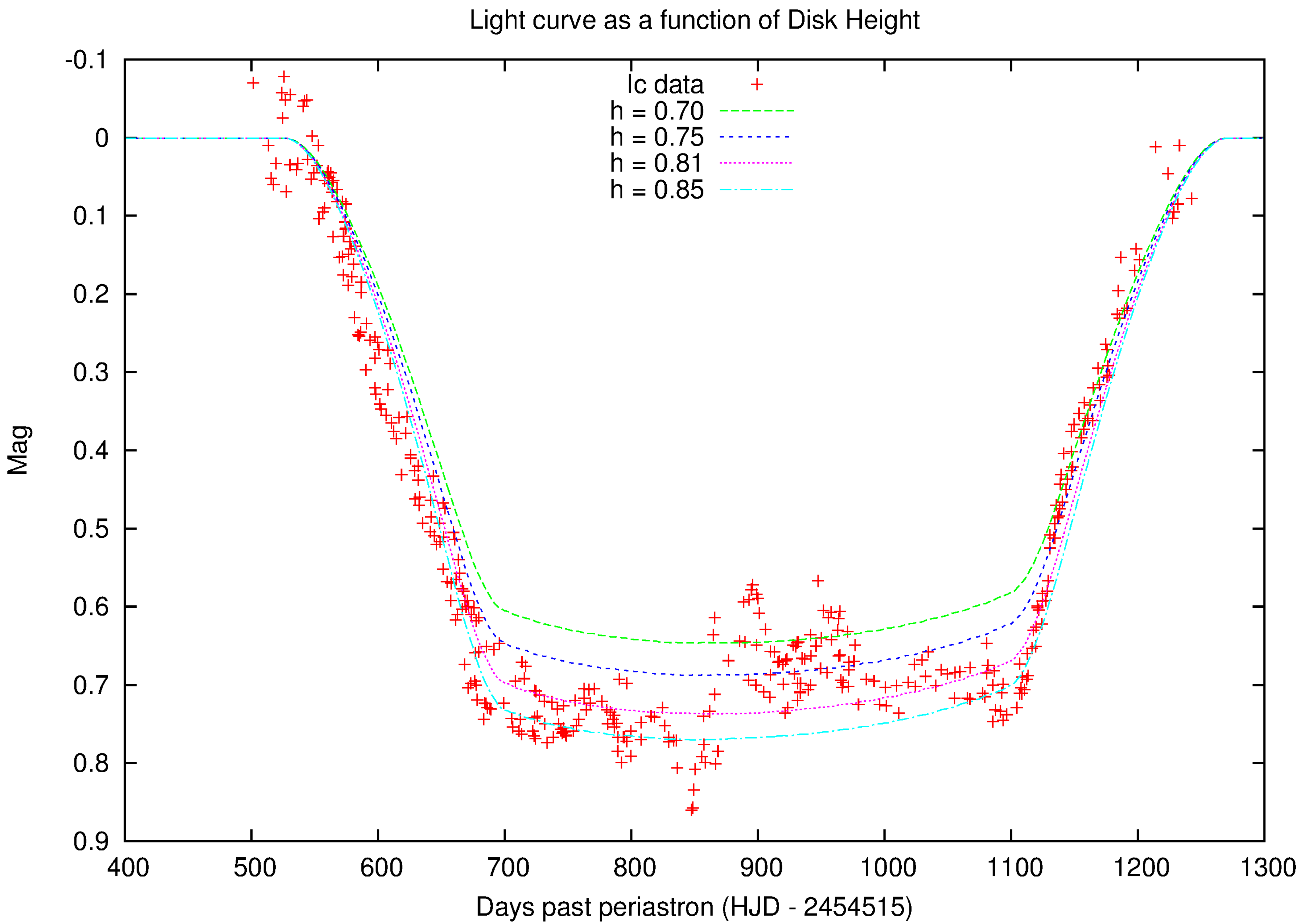


(f) Disk B

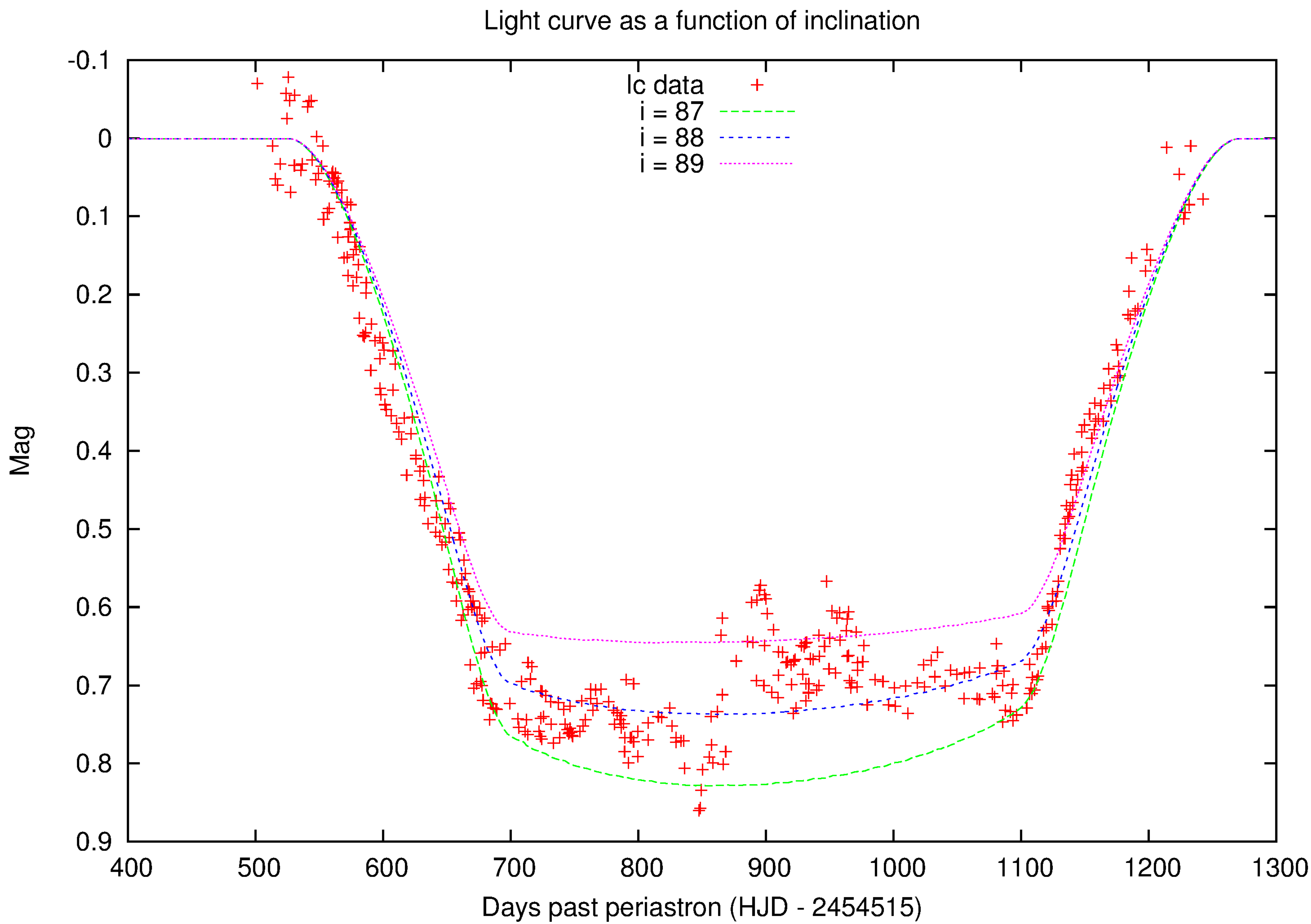
Implied light curves



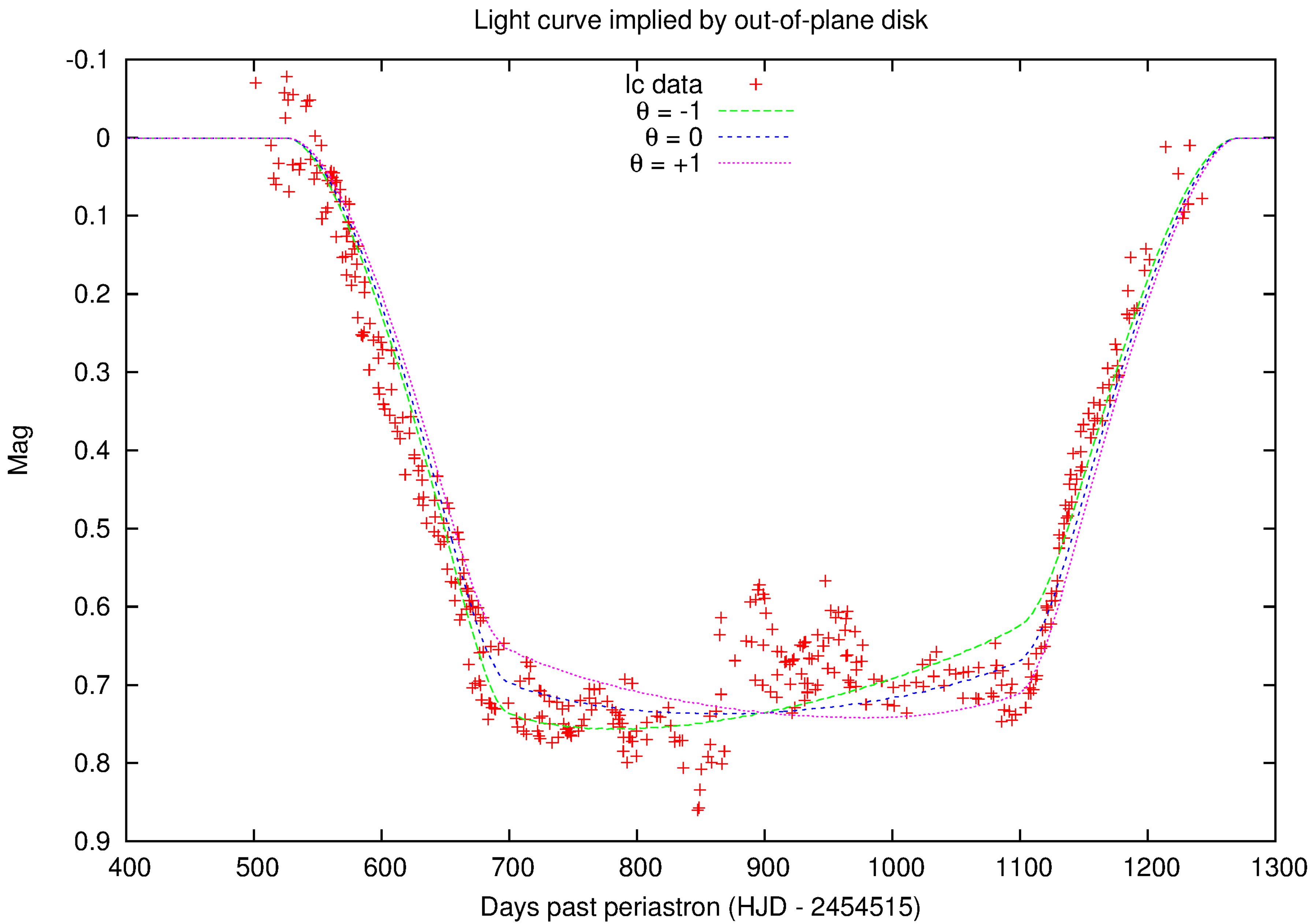
Implied light curves



Implied light curves



Implied light curves



Caveats of rendered modeling

- Detriments of rendered modeling
  - Artificial minimia:
    - Mixing discrete (i.e. pixels) with continuous probability can lead to jump discontinuities in the posterior probability distribution
    - Easily fixed by using minimization engine that is aware of discrete probability on some variables.
  - Longer execution times:
    - A DFT or NUFFT is $O(n^2)$ or $O(m + n \log(n))$
    - Partially alleviated by GPU computing.
- Benefits:
  - Geometry really considered, obscuration super easy.
  - Modeling complex objects (i.e. eps Aur, non-radial pulsation, eclipsing binaries, spots) is easier.
  - Implementing a new model is as simple as rendering it.

Interferometric Data: Summary

- PTI
  - 24 obs. → 21 epochs
  - 1997-10 to 2008-11
- CHARA (MIRC, CLIMB)
  - 39 nights → 16 epochs
  - 2008-09 to 2011-11
- NOI:
  - 35 Nights → 14 Epochs
  - 2006-02 to 2010-04
- Images:
  - Star is round (spots?)
  - Southern half eclipsed
  - Disk theory likely correct
- Bayesian Modeling:
  - F-star:
    - LDD ~ 2.27 mas
    - LCD ~ 0.66
  - Disk:
    - Height ~ 0.75 mas
    - Diam. ~ 9.9 mas
    - Edge decay ~ 1.9
  - System:
    - Total semi-major axis α ~ 36.2 mas
    - Ω ~ 298 deg.
- Noteworthy:
  - F-star shrinking by ~ 1% / year?

Conclusion

- Interferometric images:
  - Show that a disk is responsible for the eclipse
  - Give us an idea of what we need to model
- Interferometric model fitting:
  - Provide estimates of
    - Stellar parameters (diameter, darkening coefficient)
    - Disk parameters (diameter, height, edge opacity, flaring)
    - Orbital parameters (alpha_T, Omega, inc)