# Solving a 190-year astronomical mystery: the story of epsilon Aurigae

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2014-01-21

# Outline

- Epsilon Aurigae
  - Background
  - Photometry
  - Spectroscopy
  - Astrometry
  - Interferometry
- GSU research topics
  - Young stellar objects
  - Novae

# Background

Epsilon Aurigae research in collaboration with:

Robert Stencel, John Monnier, Gail Schaefer, Ming Zhao, Fabien Baron, Xiao Che, Rob Parks,

Chris Tycner, Bob Zavalia, Don Hutter, Hal McAlister, Michelle Creech-Eakman, various folks from PTI,

Theo ten Brummelaar, Chris Farrington, PJ Sallave-Goldfinger, Judit Sturmann, Laszlo Sturmann, Ettore Pedretti, Nathalie Thureau, Nils Turner, Sean M. Carroll

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

# Epsilon Aurigae

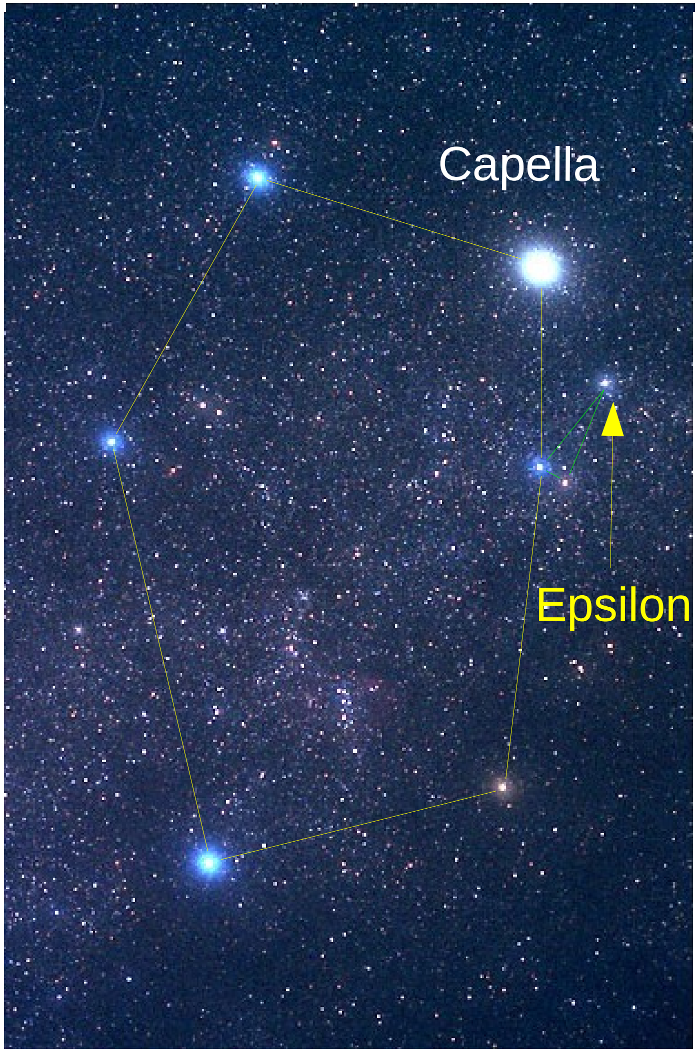
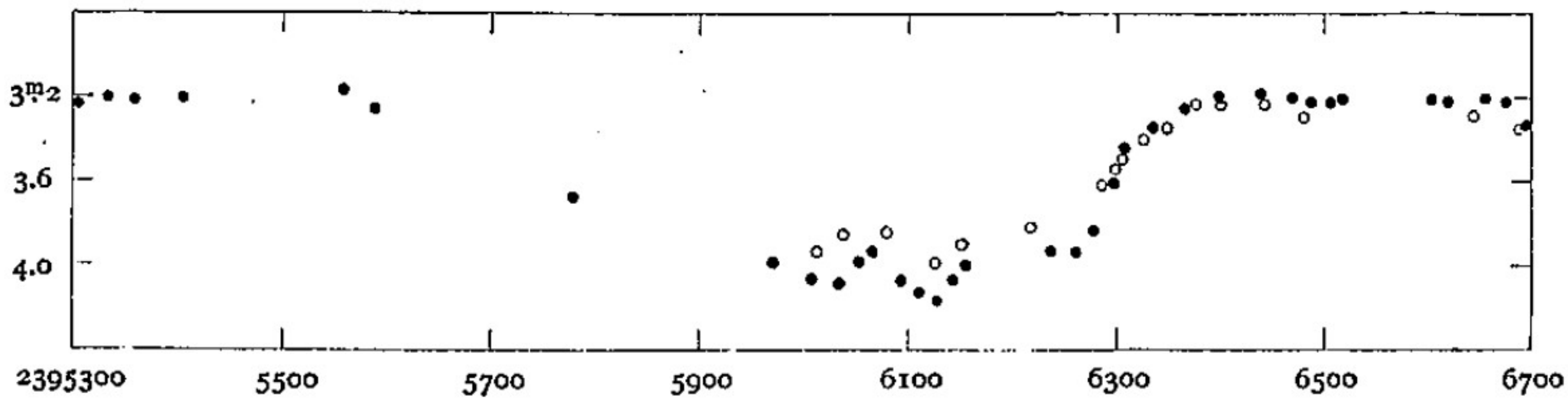



Image credit: Jerry Lodriguss

# The (first?) discovery?



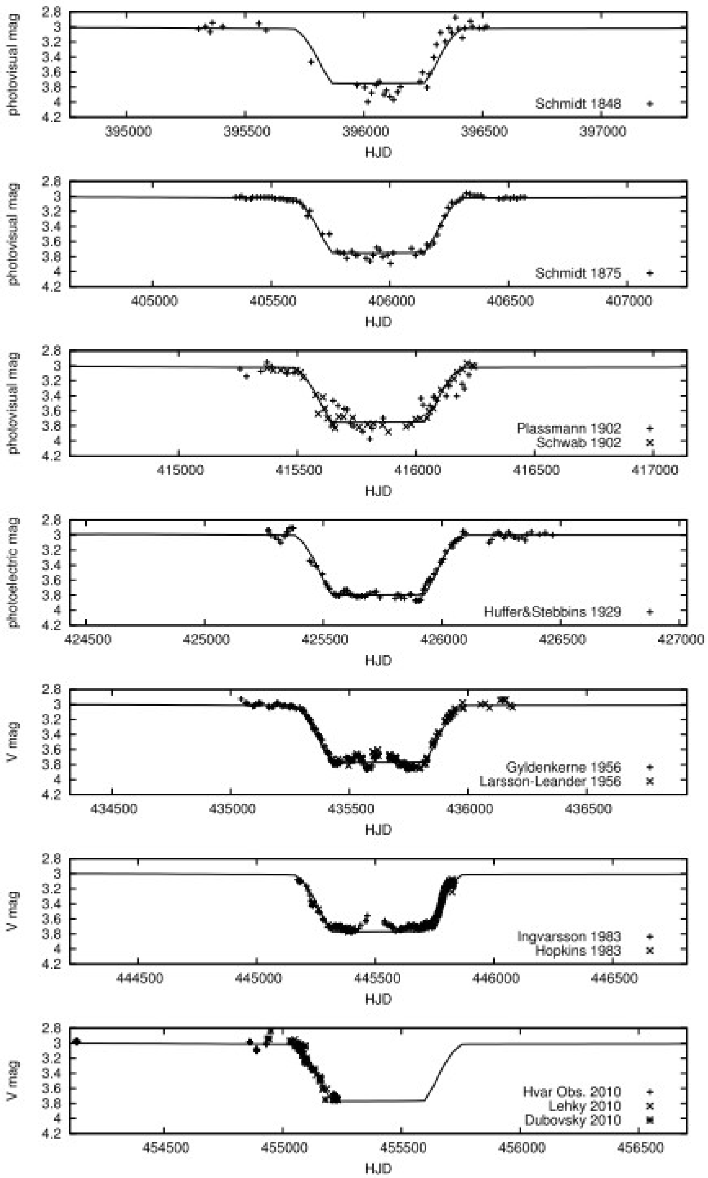

1846-1847 Eclipse of epsilon Auriage, filled points by Argelander; Image Credit: Güssow (1936)

"... 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, from Quedlinburg)

For a historical overview of astronomical photometry, see Weaver (1946) etc.

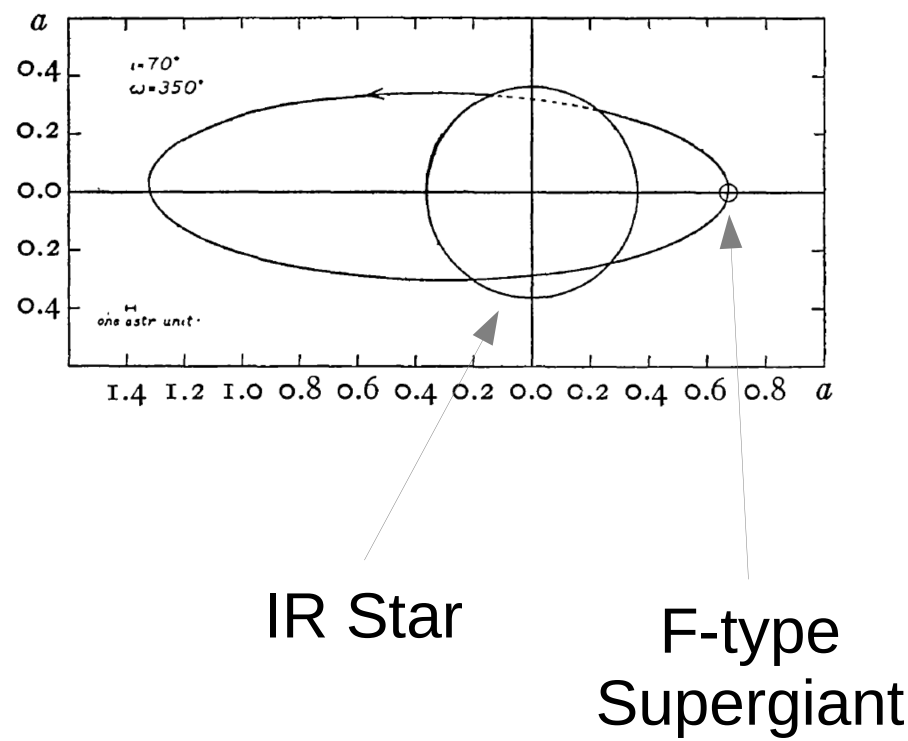
# As of 1903, we knew...



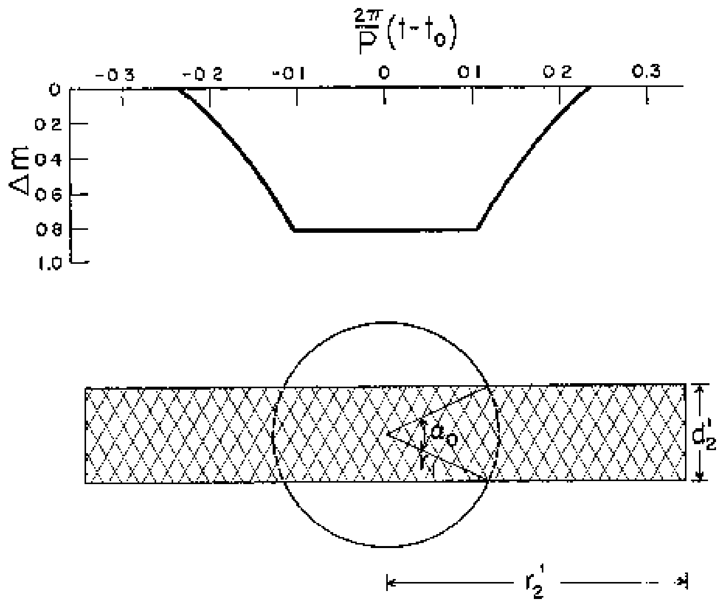

- Photometric Monitoring:
  - System dims by ~50% every 9890 days (27.1 years) (Ludendorff, 1903), stays faint for ~2-years
- Spectroscopic Monitoring:
  - Epsilon Aurigae is a single line spectroscopic binary
- Dimming thought to be due to an eclipse.
- System composition
  - Visible component is F0Ia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

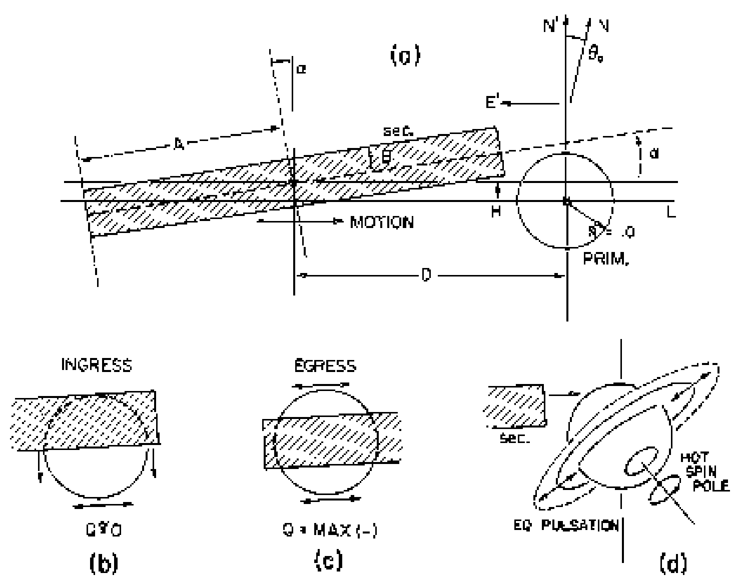
# Early explanations for the eclipse

- 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



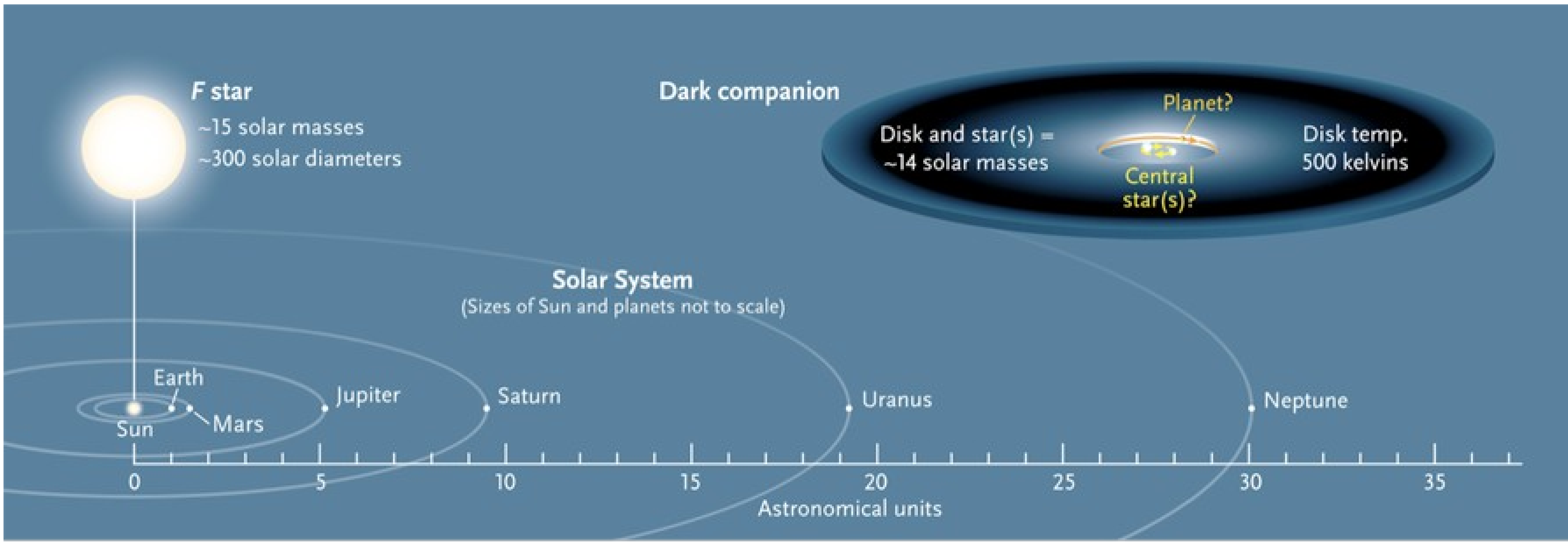
# 1985 model



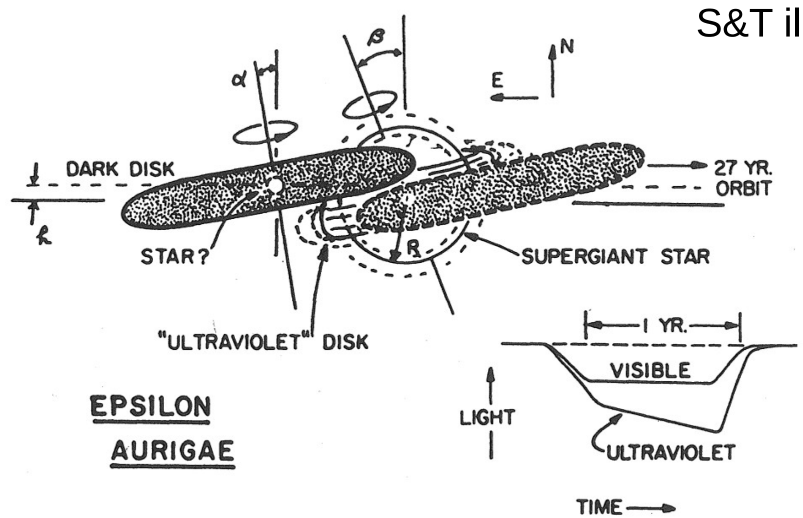




- 1965: Huang
  - The first analytical model supporting a disk-like object as the cause of the eclipse.
- 1986: Kemp
  - Obtained polarimetry during the 1983 eclipse, argued that the disk is inclined.

# 2009 Model of eps Aur




S&T illustration by Casey Reed



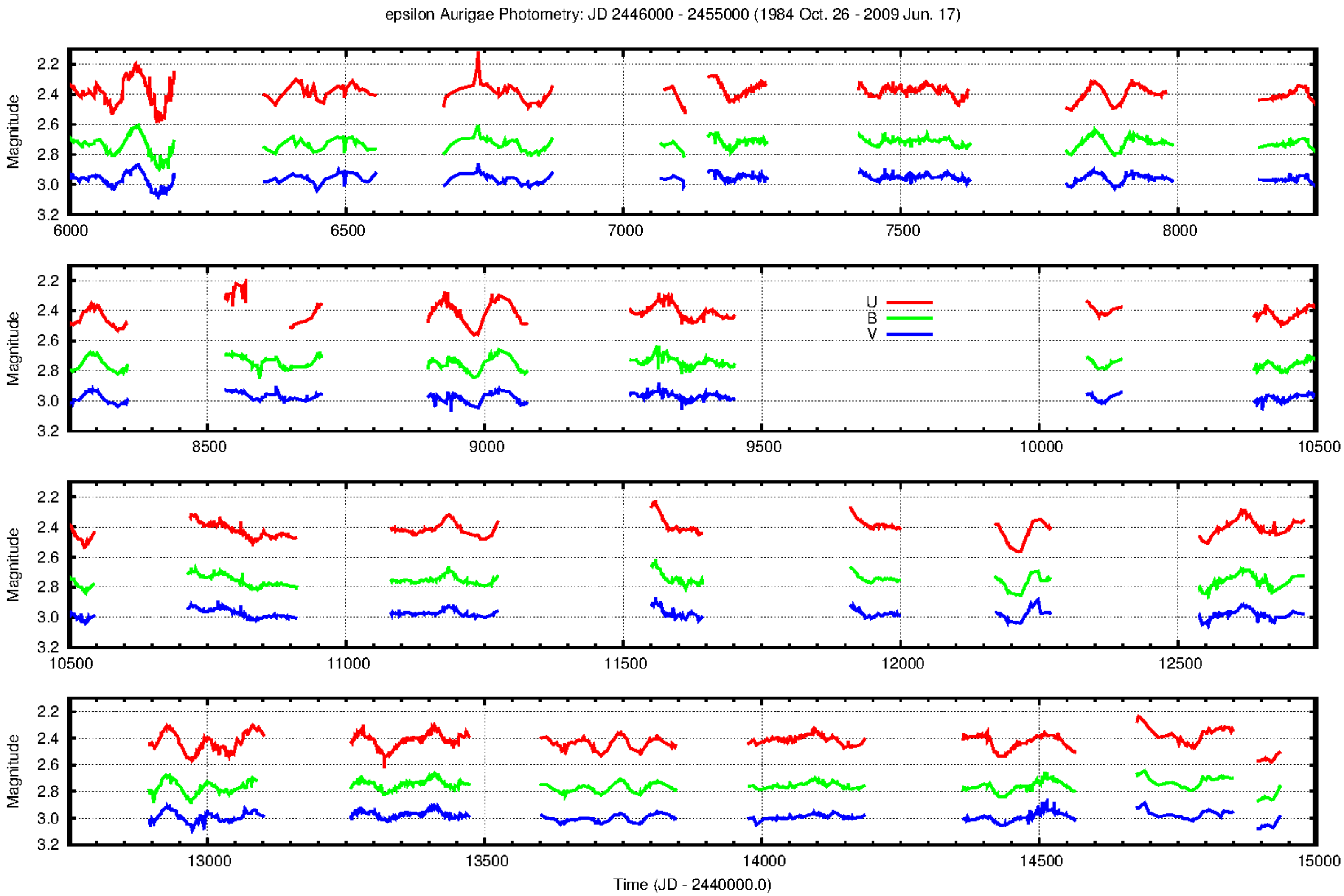

Kemp (1983)

# 2009: fundamental questions remain

- What causes the eclipse?
- What is the distance to the system?
- In what evolutionary state do we observe the binary?
  - What are the spectral types of the components?
  - What are the masses of the components?
- What causes the photometric variability?

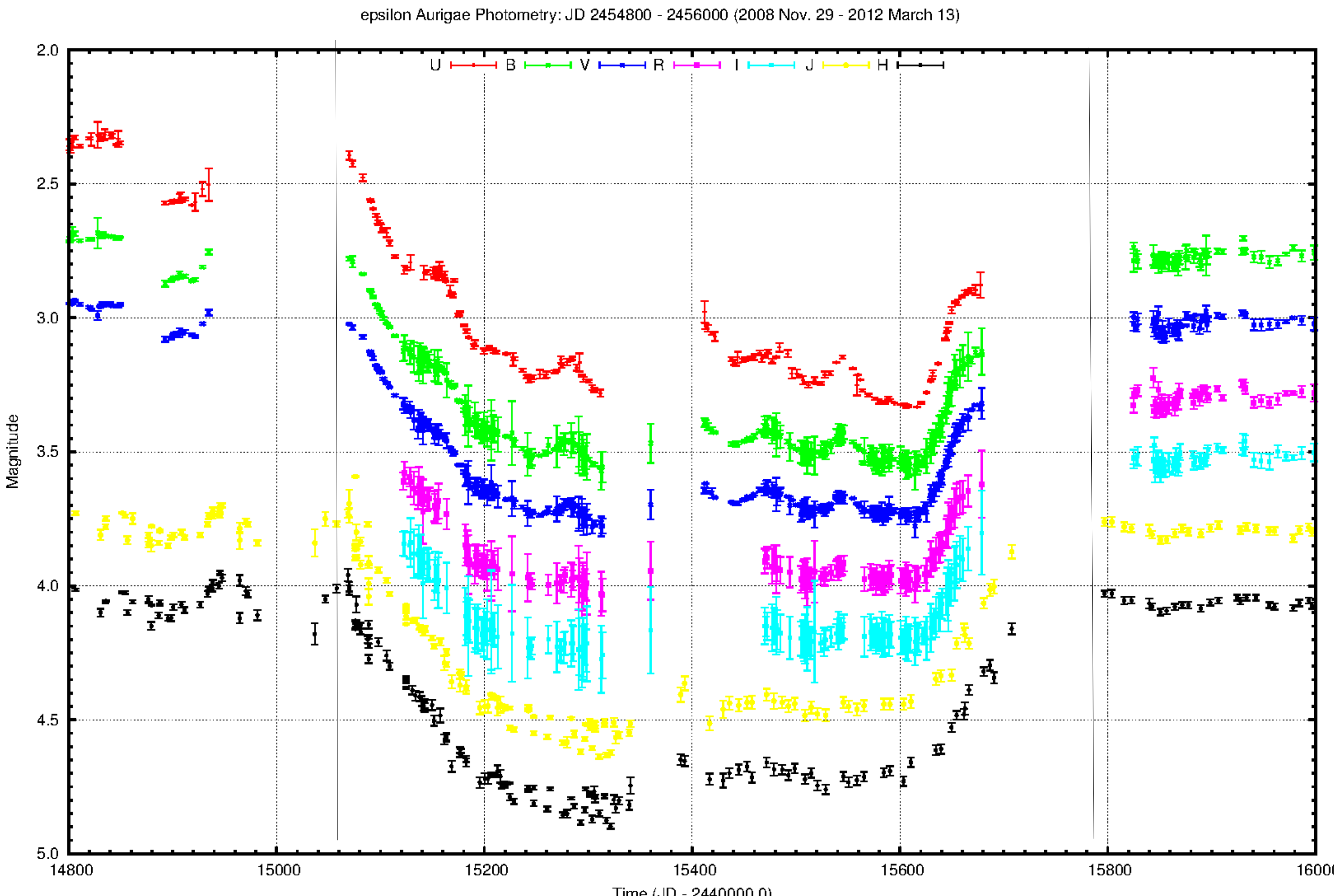
# Photometry

# 27 years of photometry




Photometry from L. Boyd and J. Hopkins (amateur collaborators)

# 2009-2011 eclipse

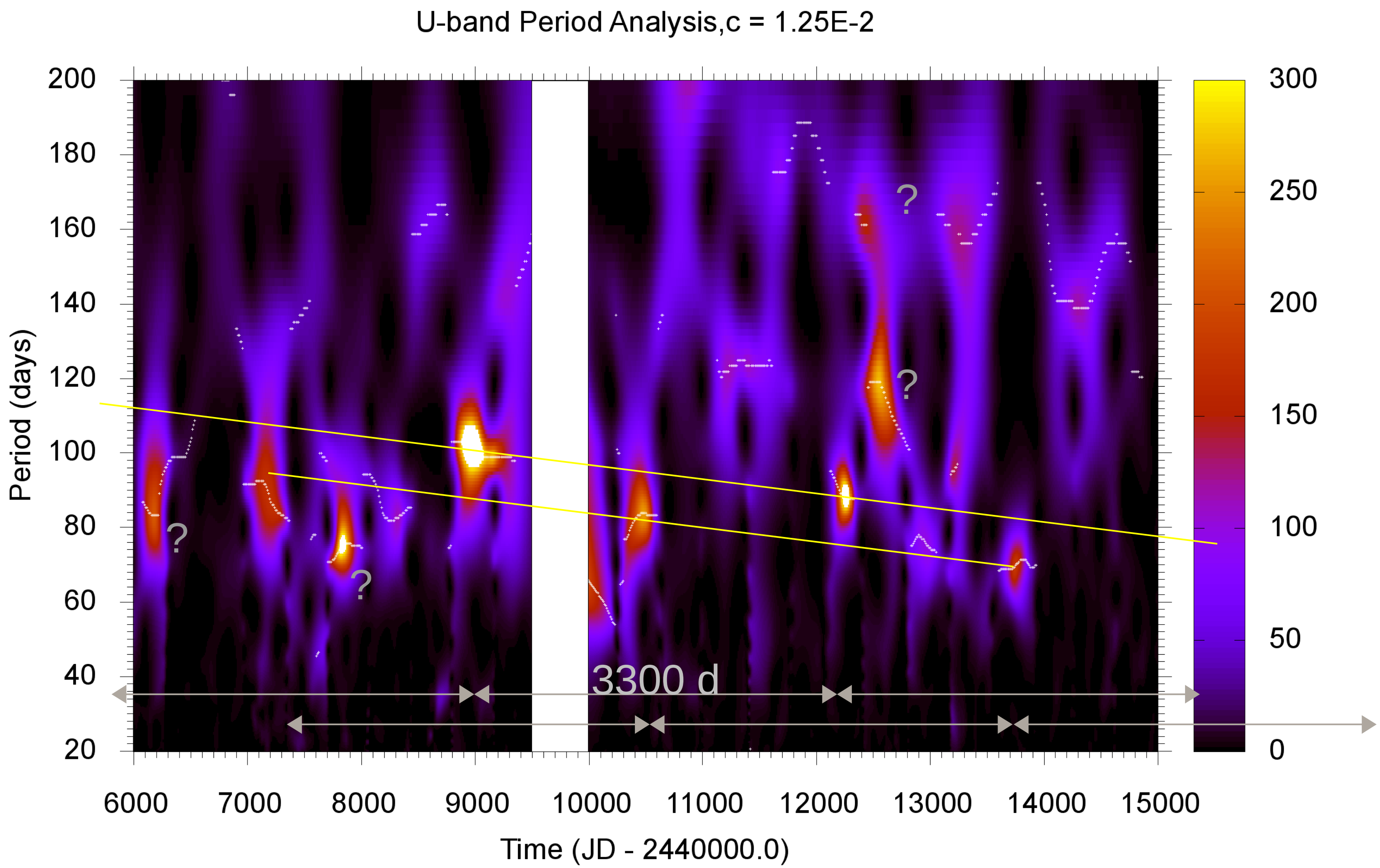



1st contact

4th contact

Photometry from AAVSO & amateur collaborators

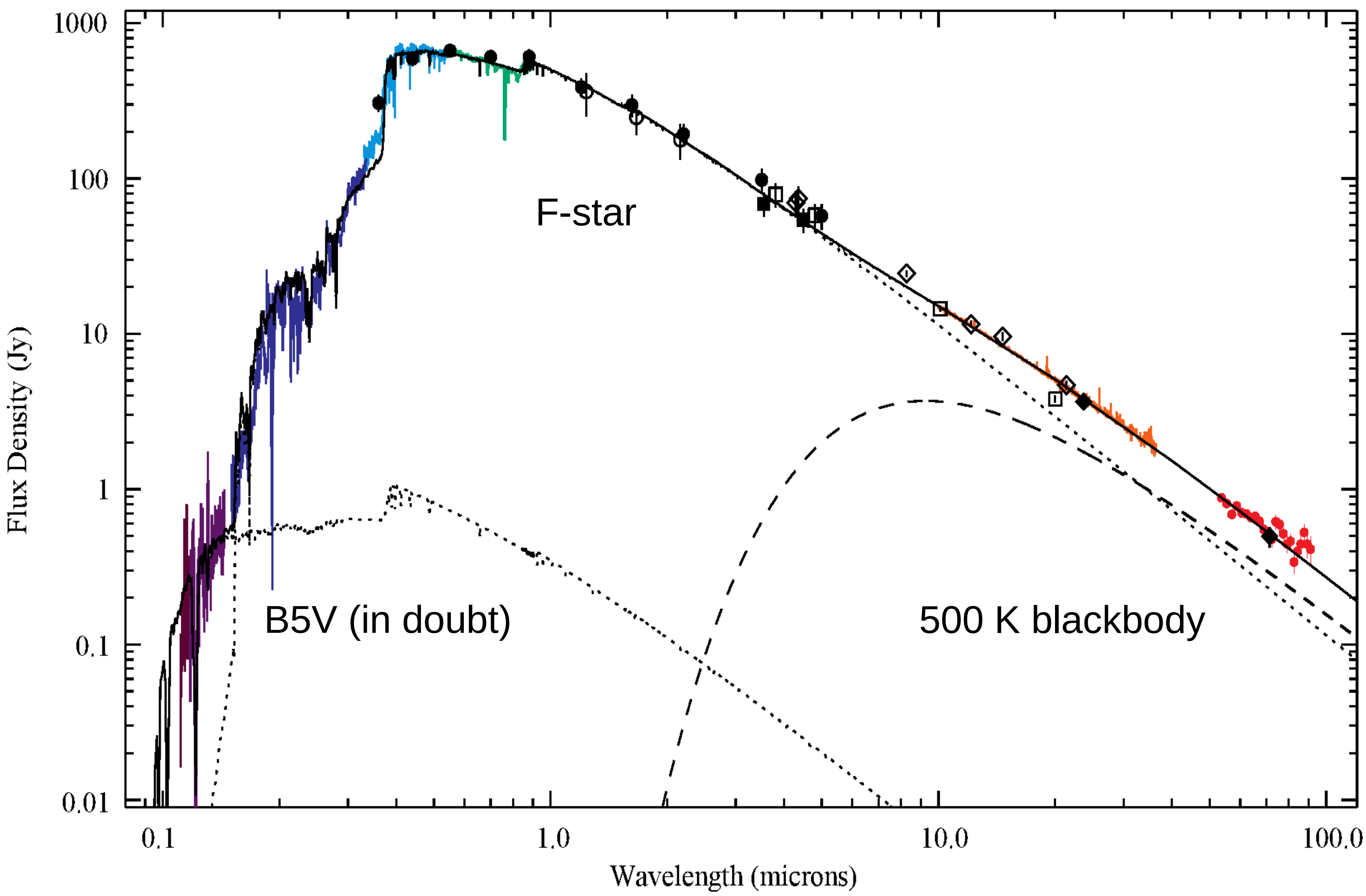
# WWZ analysis




See Kloppenborg et al. 2011 for further details

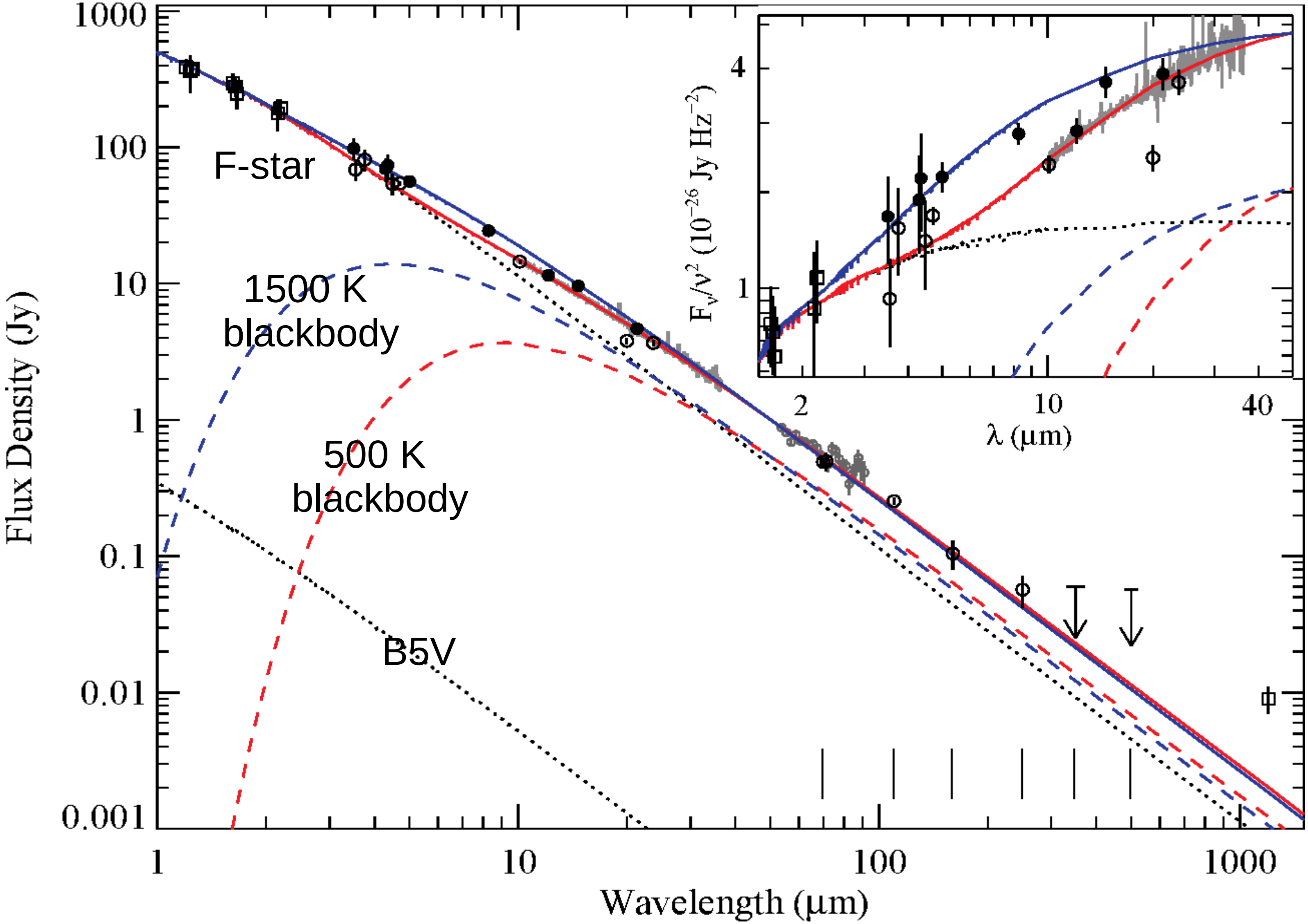
# Spectroscopy

# Eps Aur SED: Three components



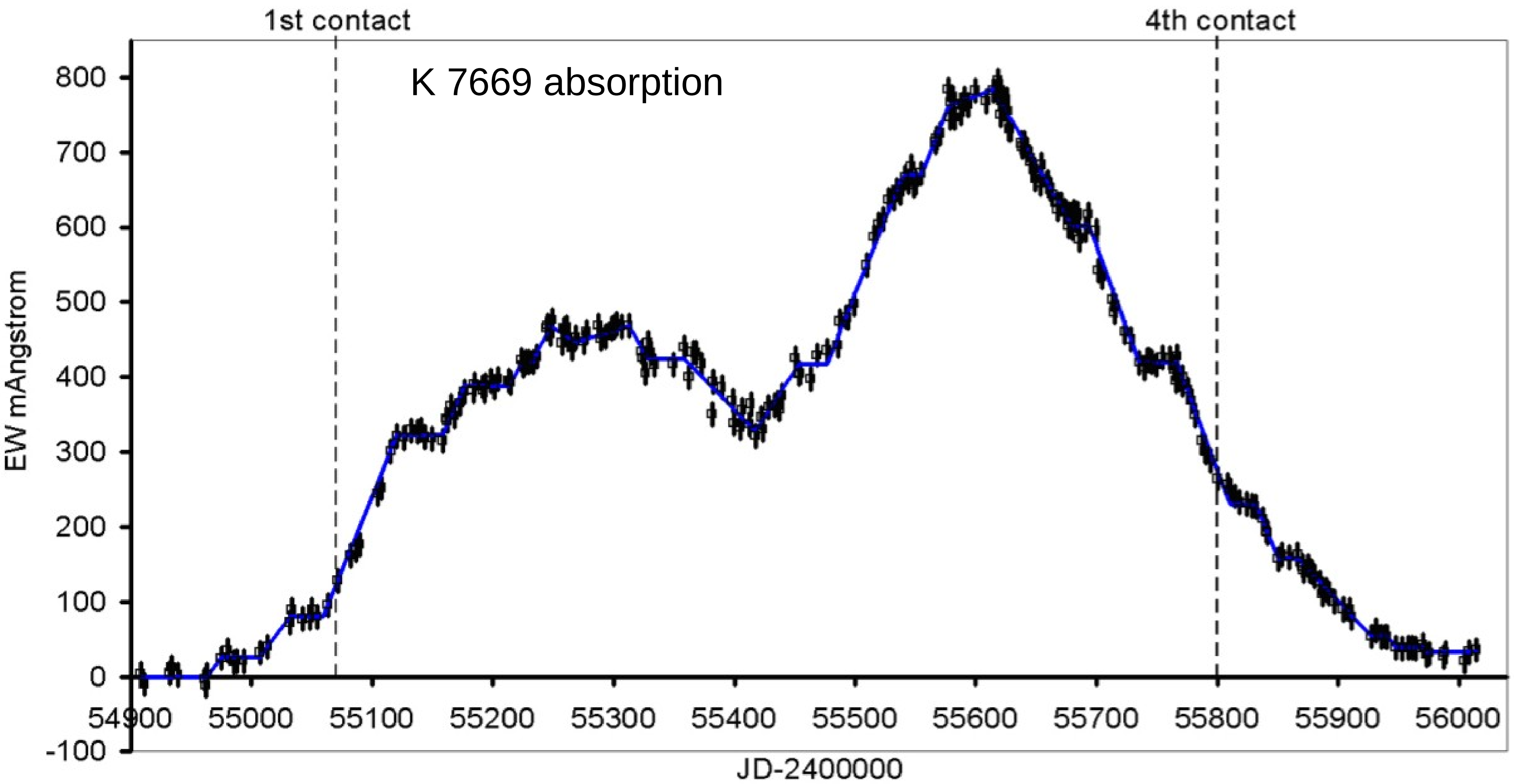

From Hoard et al. 2010

# Hot and hotter




From Hoard et al. 2012

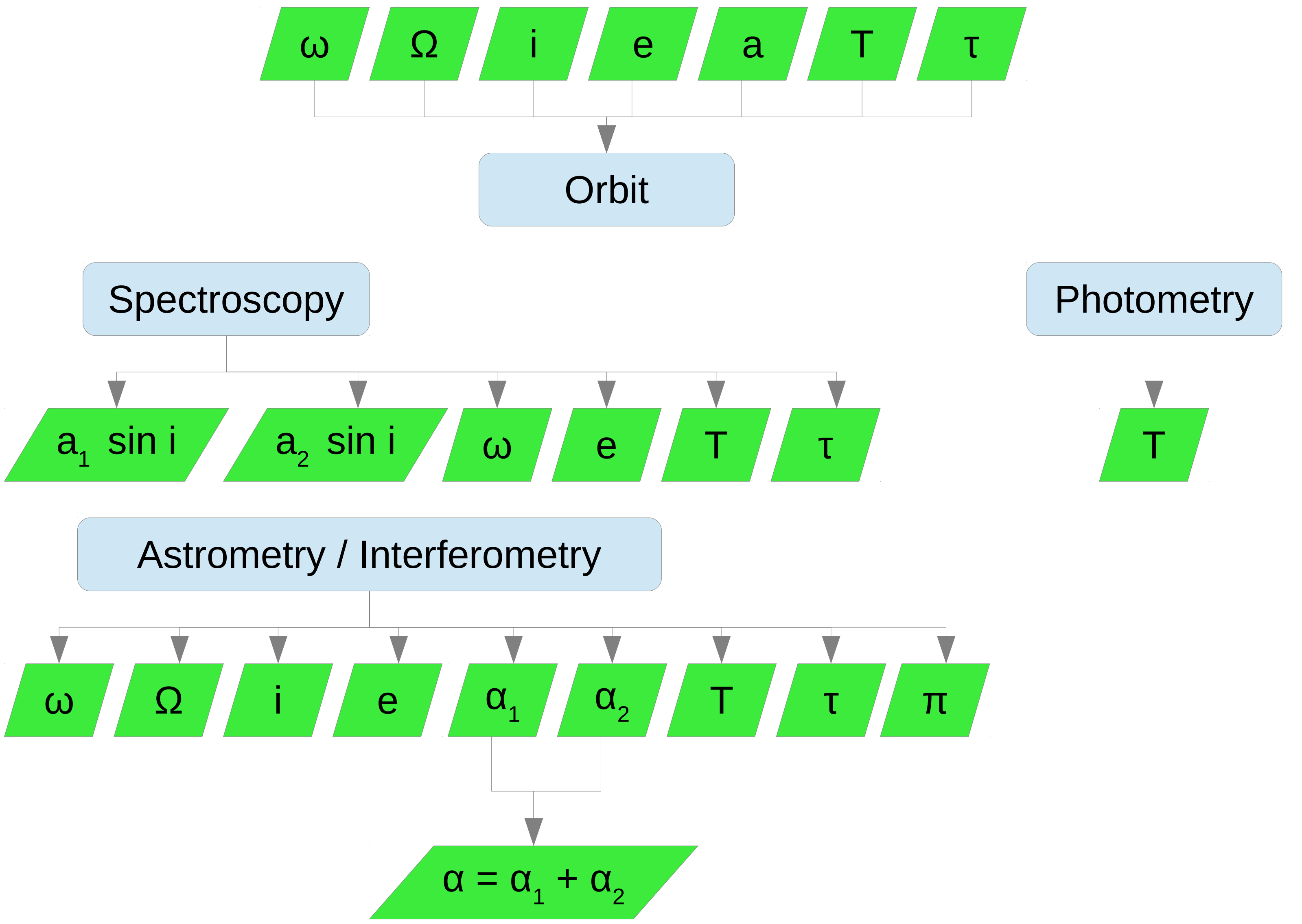
# Work from amateur astronomers



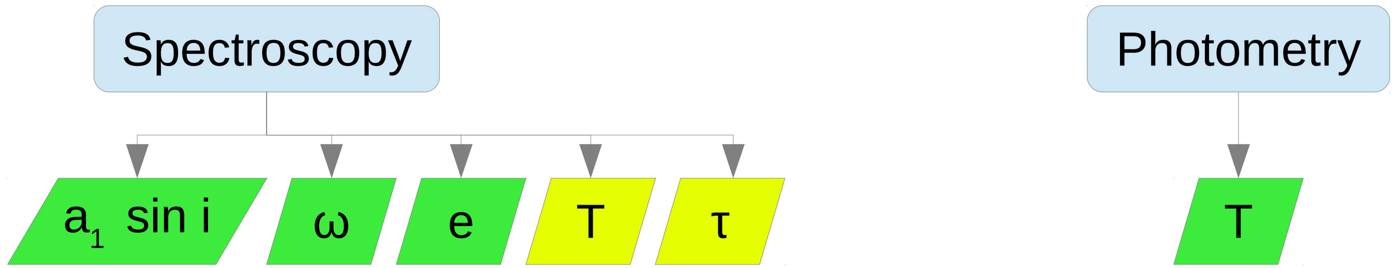

See Leadbeater et al. 2012

# Astrometry

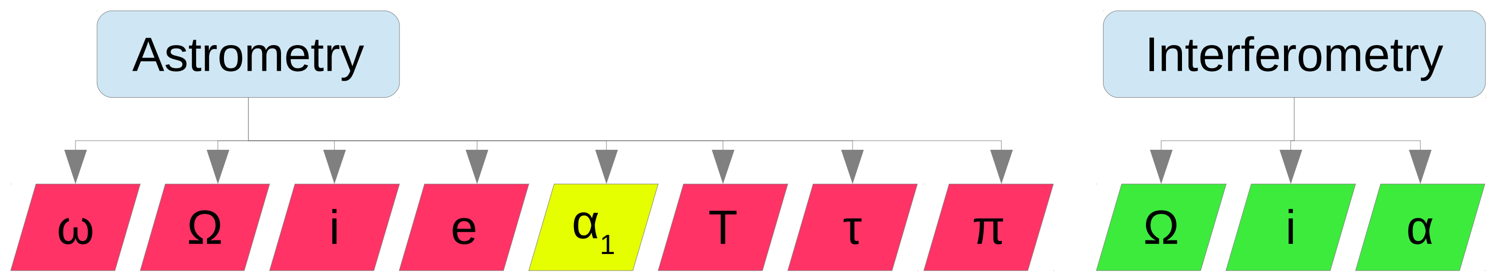
# Dynamical parallaxes



# But with eps Aur...




$$f(M) = (a_1 \sin i)^3/T^2 = (M_2 \sin i)^3/(M_1 + M_2)^2$$



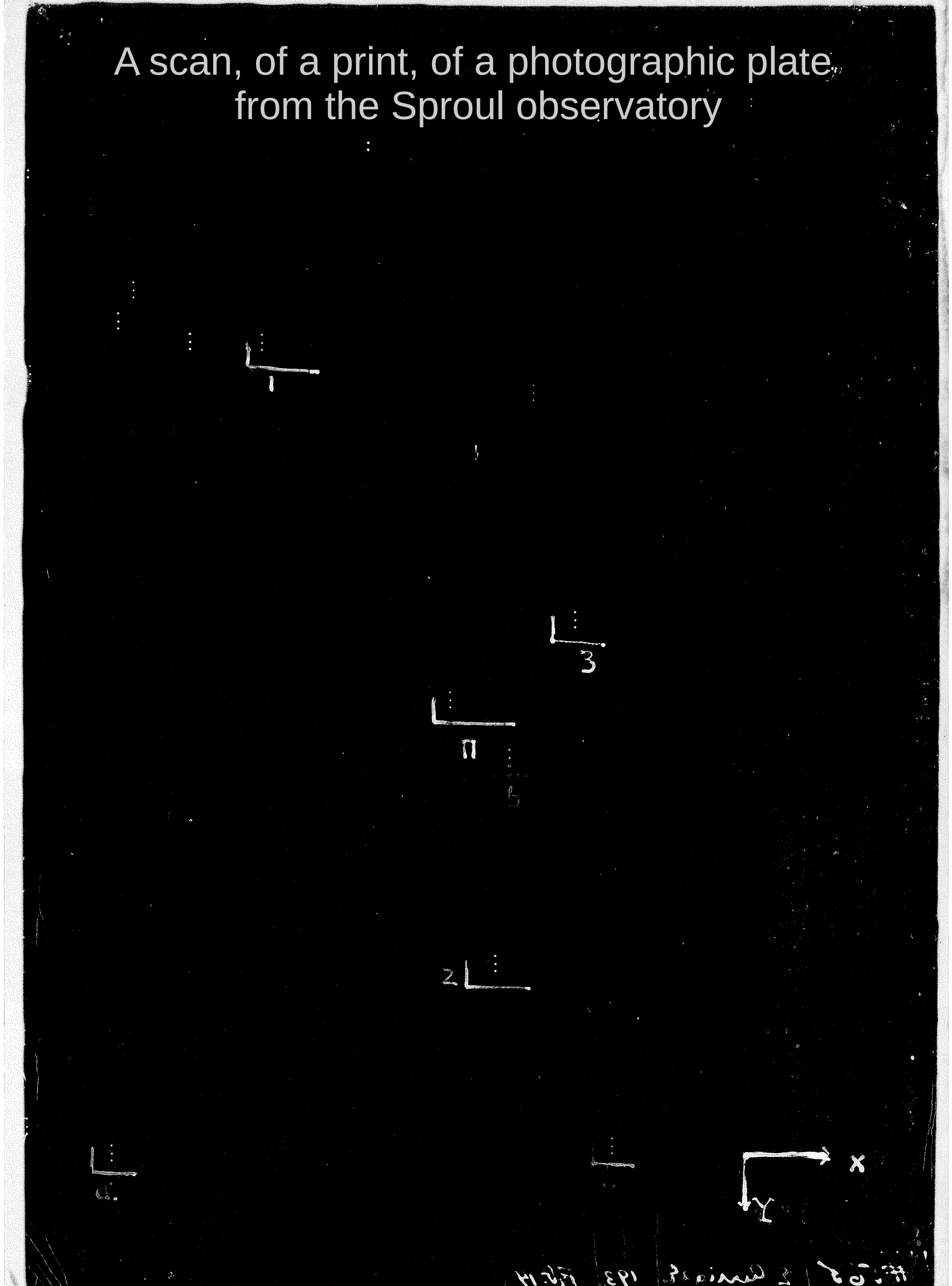

$$q = \frac{M_1}{M_2} = \frac{\alpha_2}{\alpha_1} = \frac{\alpha}{\alpha_1} - 1$$

$$M_2 = \frac{f(M)(1+q)^2}{\sin^3 i}$$

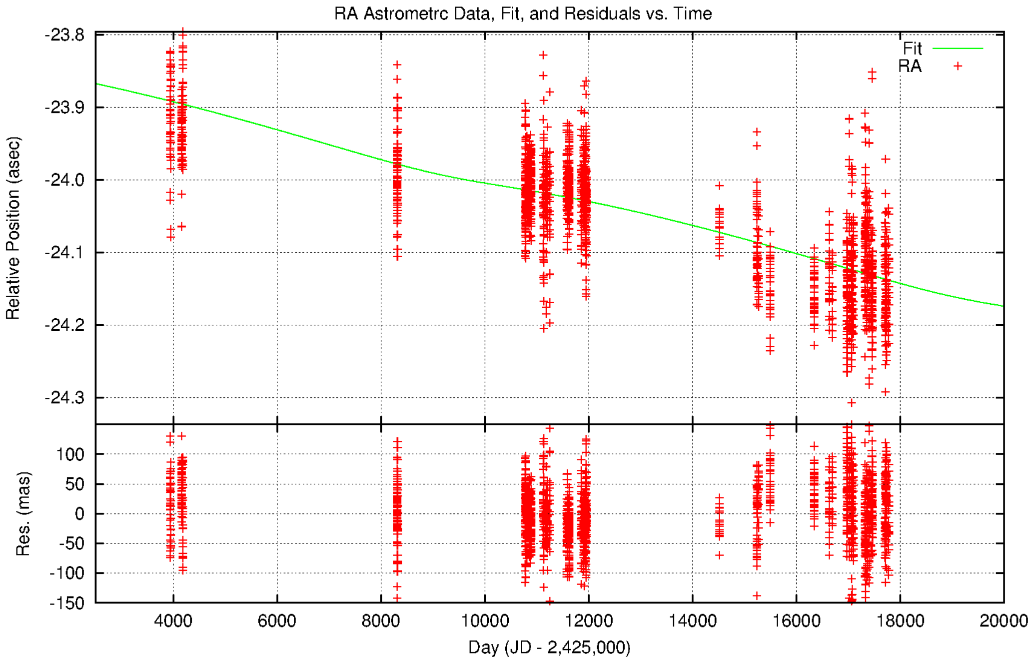
$$M_1 = M_2 q.$$

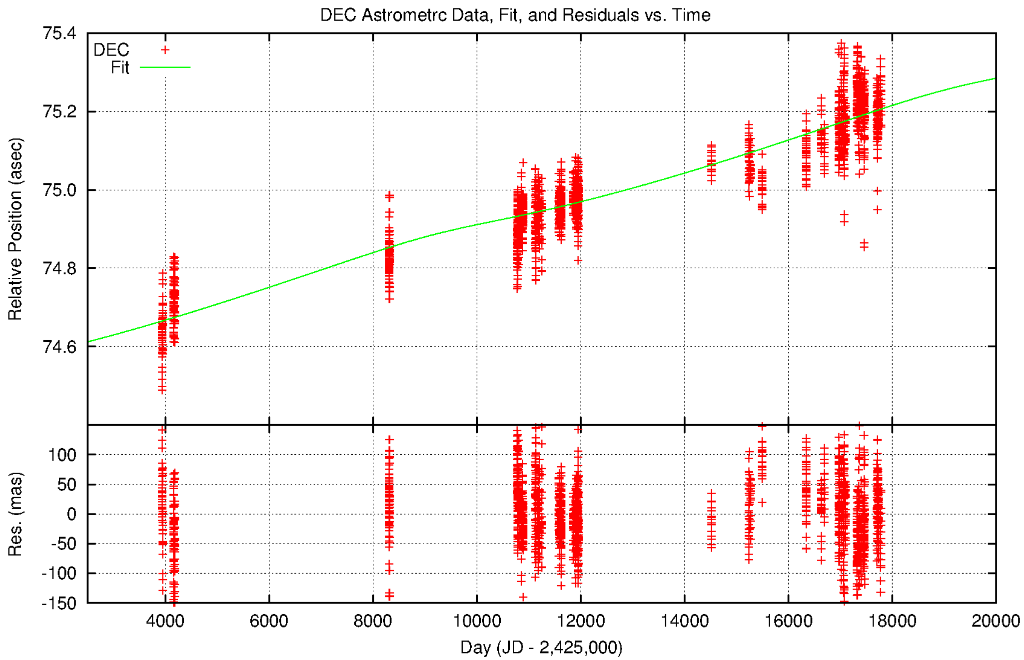
Getting the masses in epsilon Auriage will require much effort!

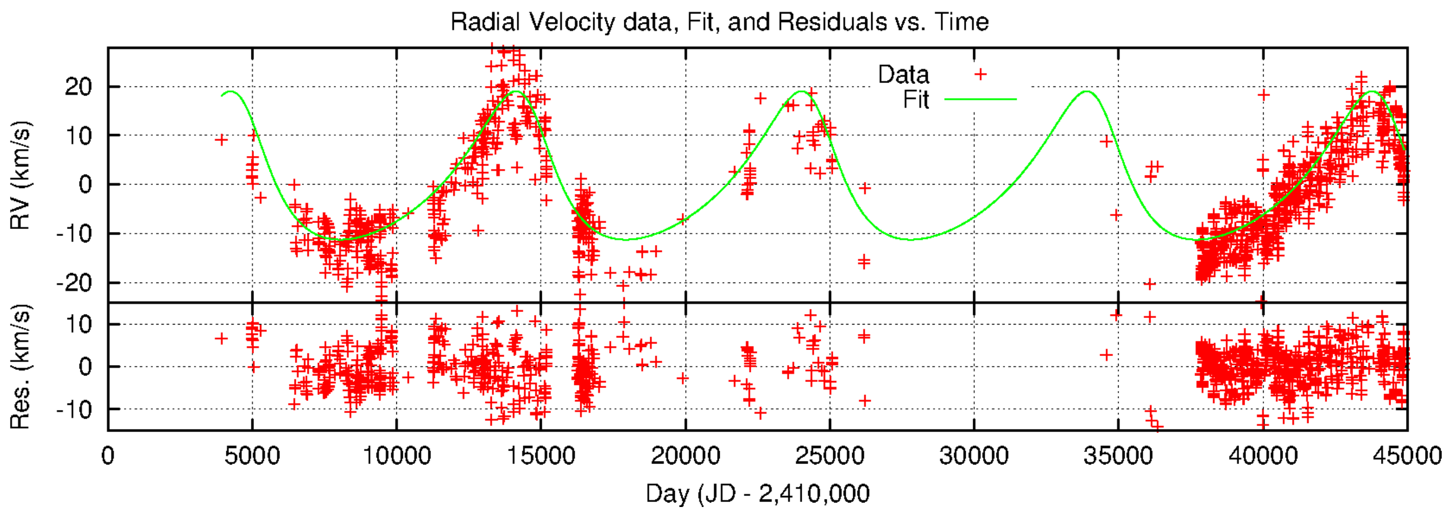
A scan, of a print, of a photographic plate
from the Sproul observatory



# Bayesian fit to RV + Astrometric data

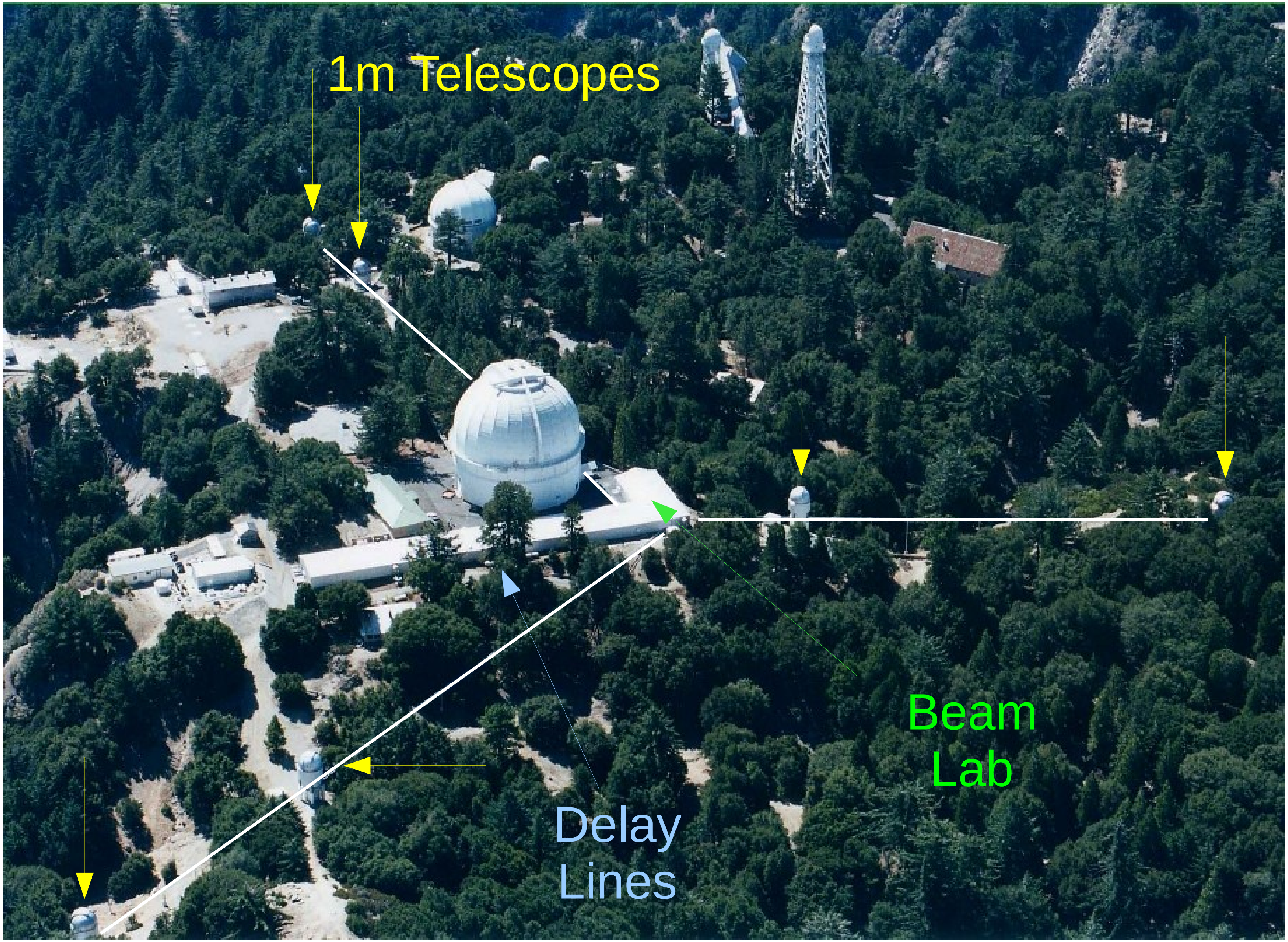


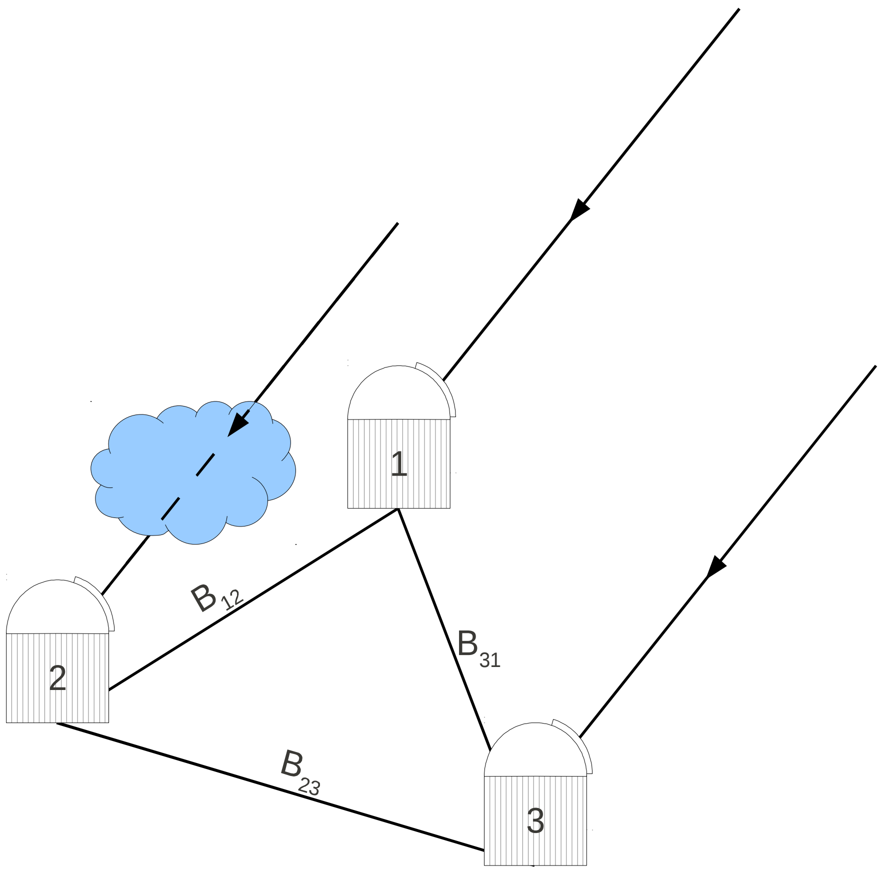



# Interferometry

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



# Optical interferometry data products




- UV points
- Visibility squared

$$|V|^2$$

- Triple product

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

Triple Amplitude

Closure Phase

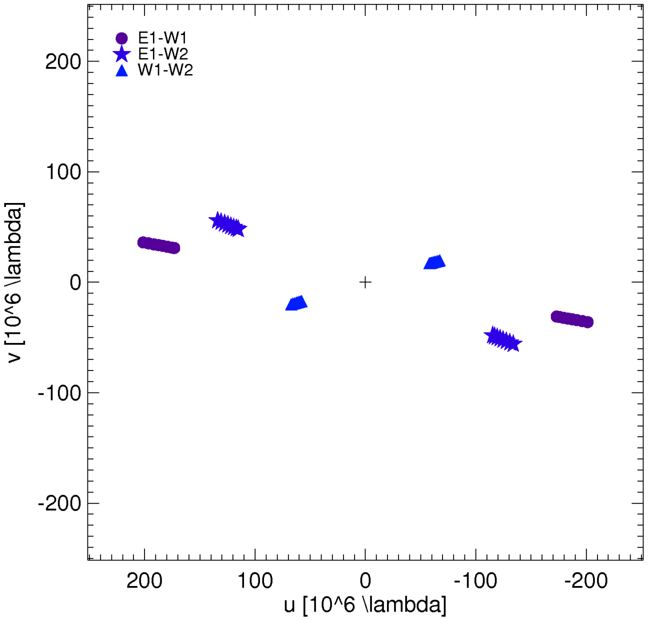
$$\phi_{123} = \phi_{12} + \phi_{\mathrm{atm}} + \phi_{23} + (-\phi_{\mathrm{atm}}) + \phi_{31}$$

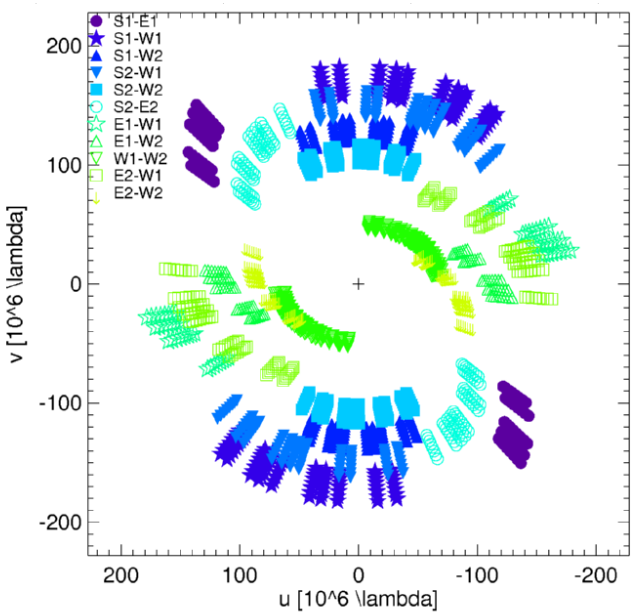
Differential quantities (spectrally dispersed data)

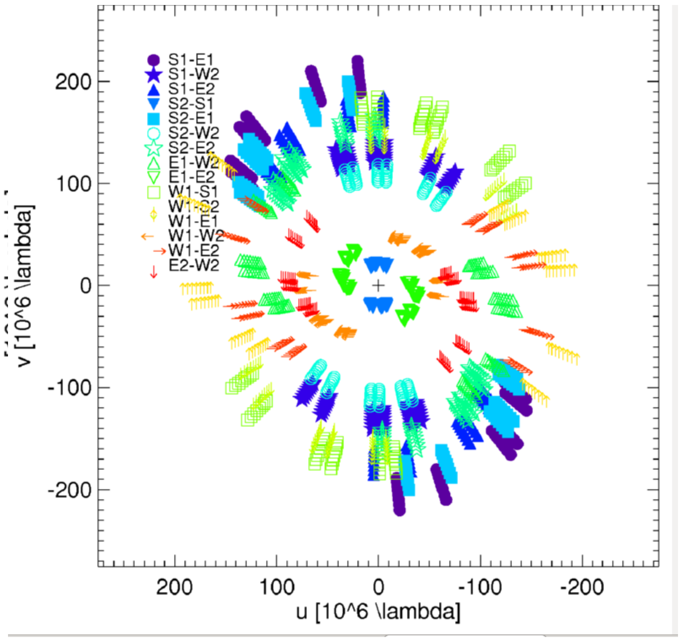
  - Visibilities
  - Phase

- Closure Amplitudes

# UV Coverage



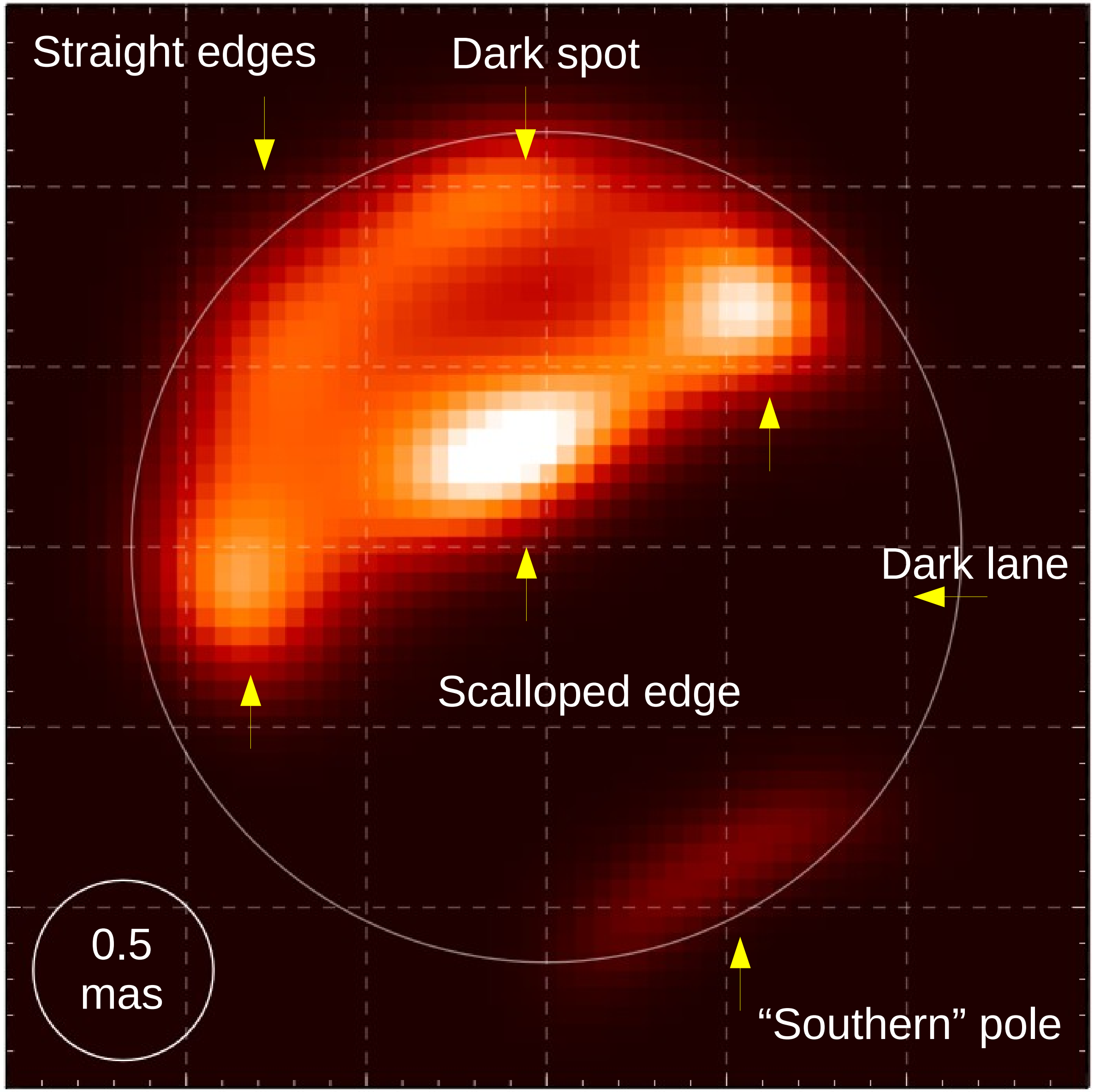




2008-09
(3T, 1 bracket)

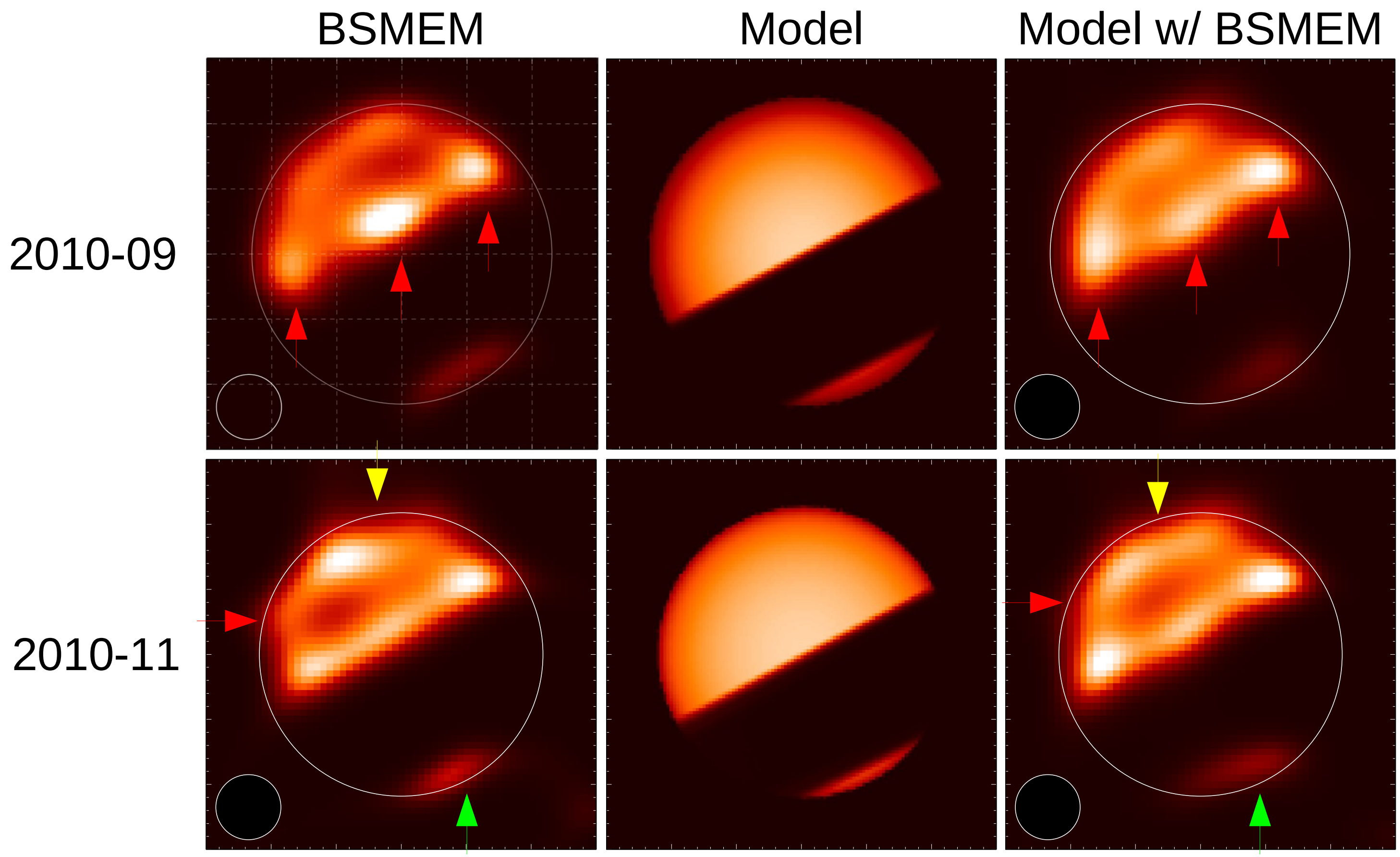
2009-11
(4T, 3 Nights)

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

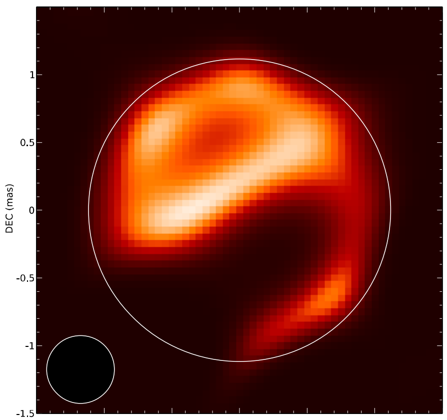
Undecided:

- Straight Edges on F-star

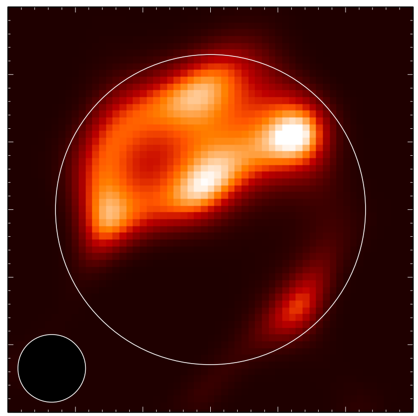
# Five of 14 model-independent images

Ingress (CHARA-MIRC)

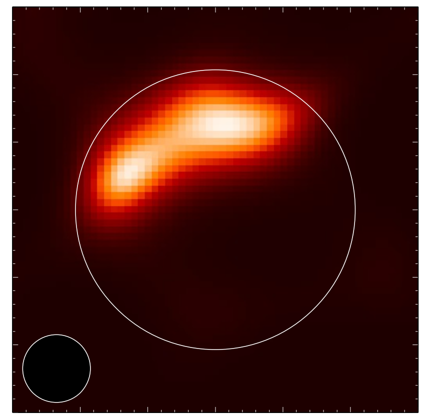
2009-11




2009-12

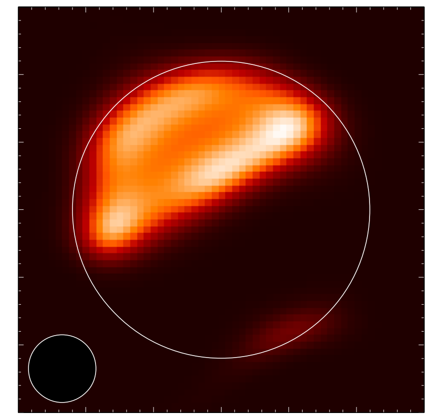


2010-02



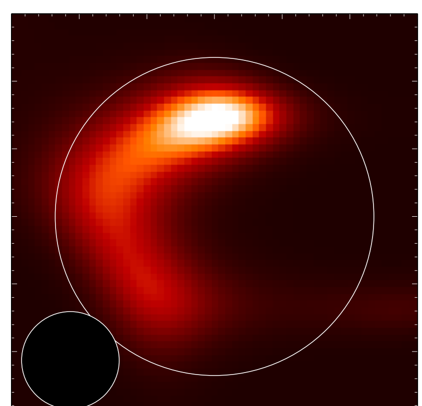
Mid-eclipse
(CHARA-MIRC)

2010-08

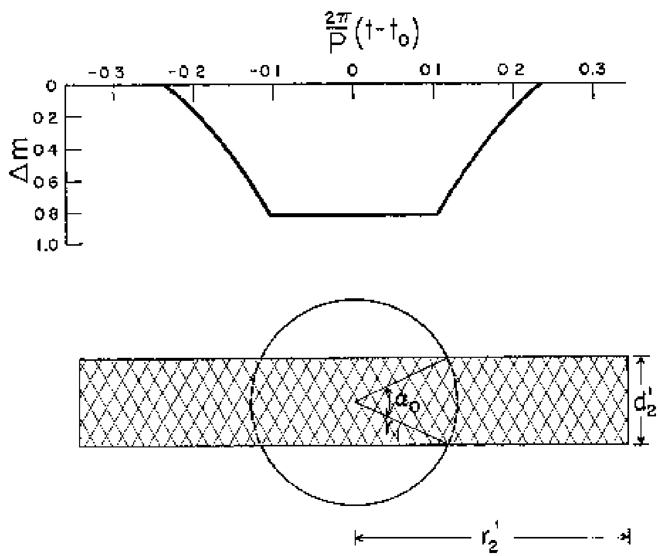


Egress
(CHARA-CLIMB)

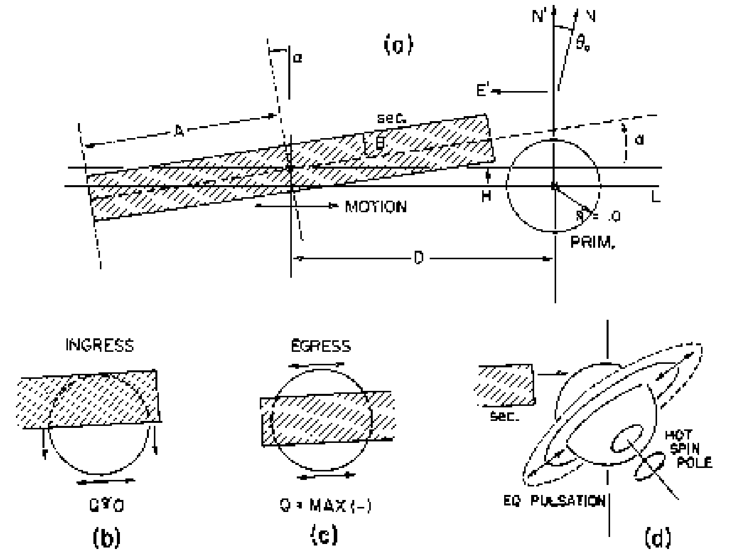
2010-04



# How do we model the disk?




Huang 1965 “brick”




Kemp 1986 “inclined brick”

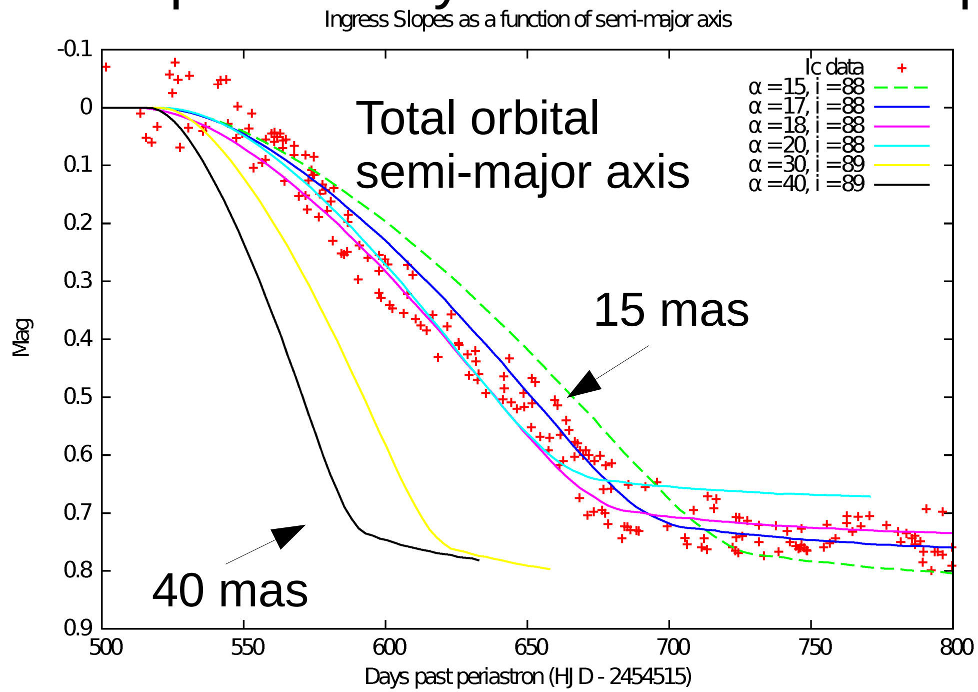
# New software: liboi and SIMTOI

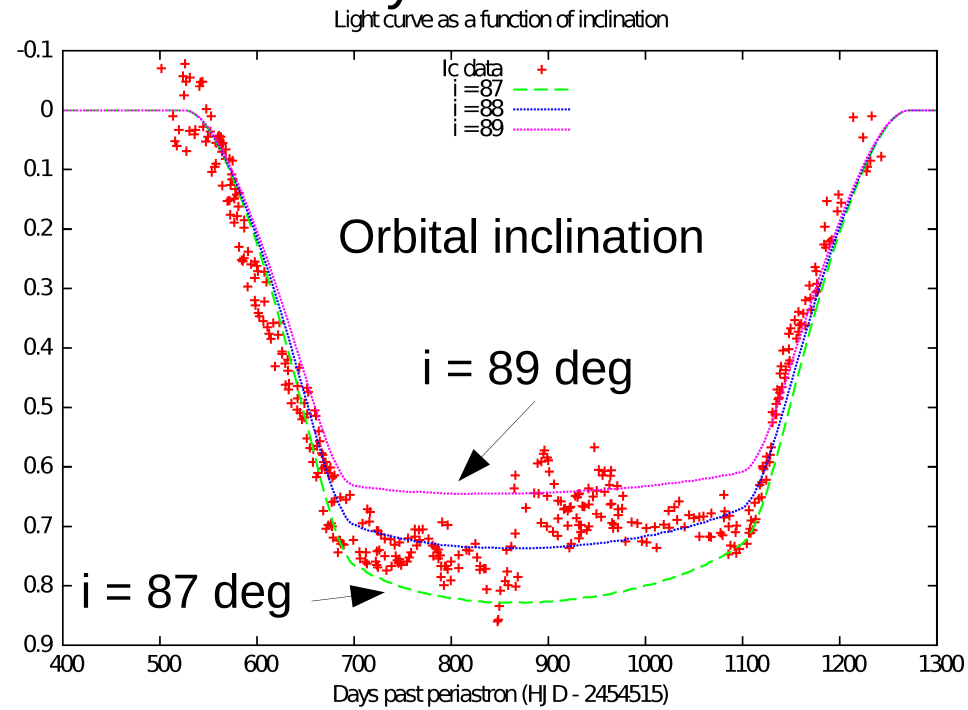
- OpenCL Interferometry Library (liboi)
  - GPU computing library for OI
  - Image + OIFITS → Simulated observations
  - Can perform ~280 (image → data → chi2r) / second
  - About 150x faster than the same algorithms on a CPU

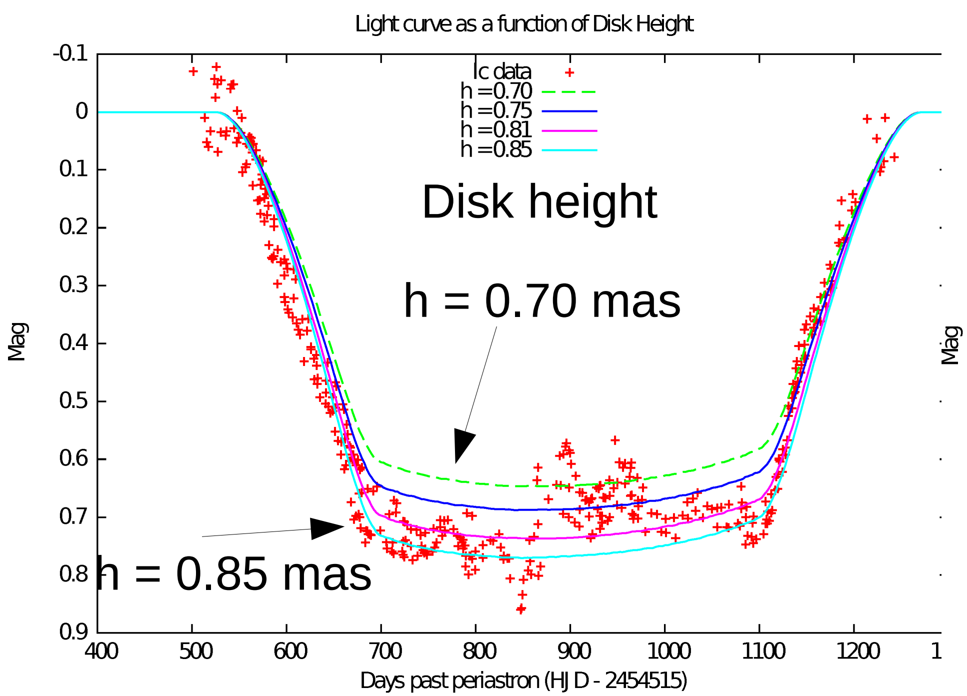
- SImulation and Modeling Tool for Optical Interferometry (SIMTOI)
  - Models rendered using OpenGL (computer graphics)
  - Environment is fully 3D, time-dependent, and includes orbits!
  - Has several minimization engines
  - Callable via. scripting languages
  - Uses liboi as a backend for fast computations

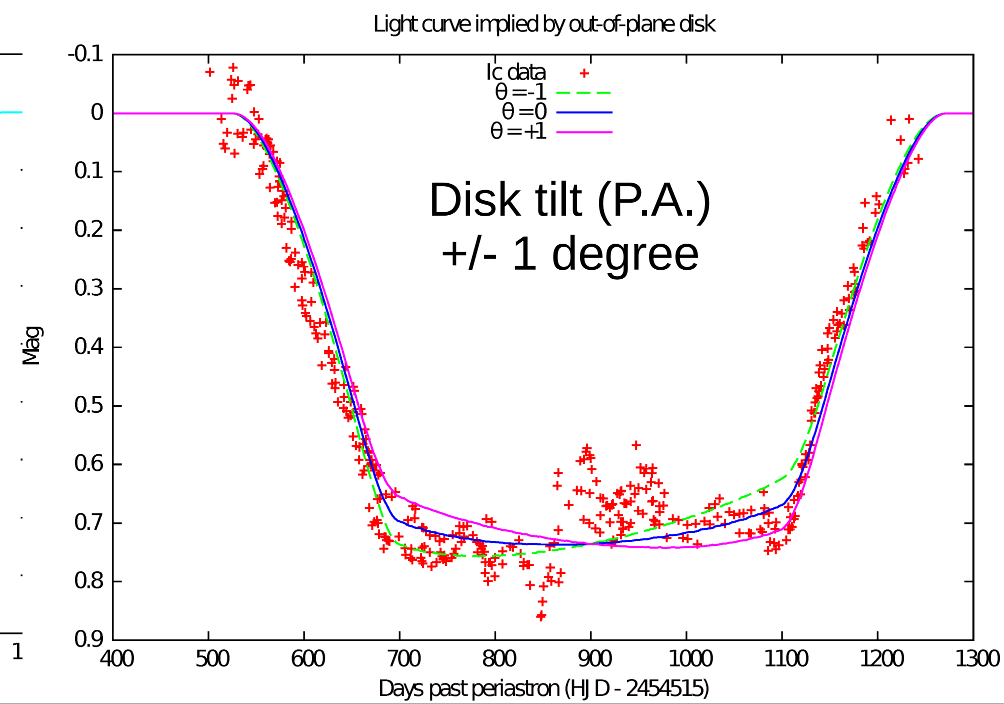
Both are open source. Find them at http://github.com/bkloppenborg

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



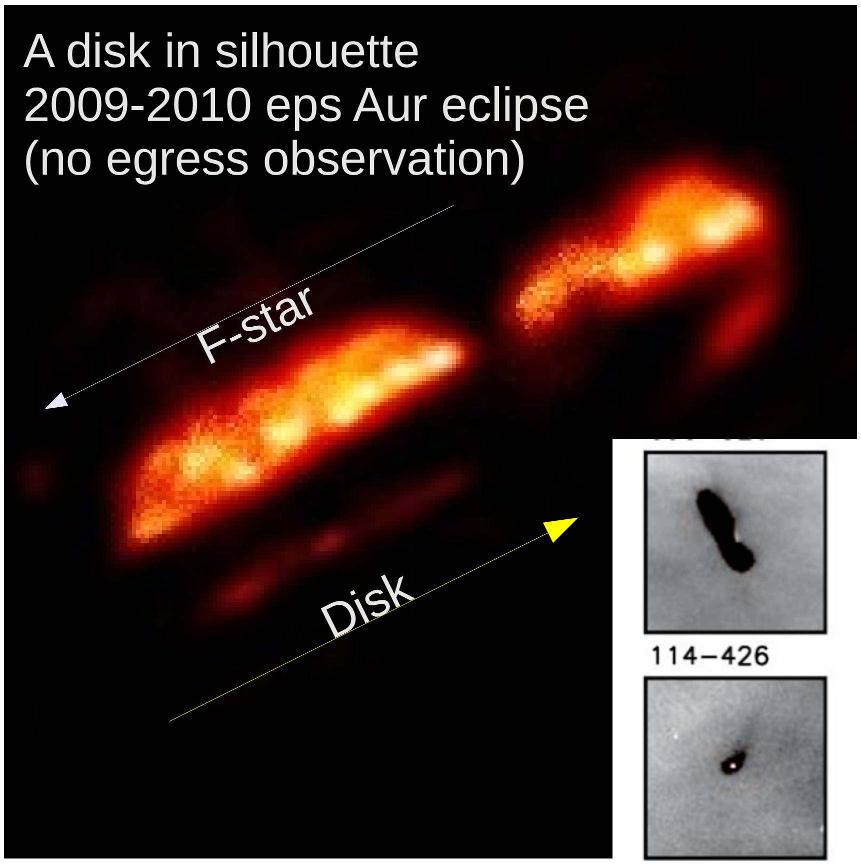



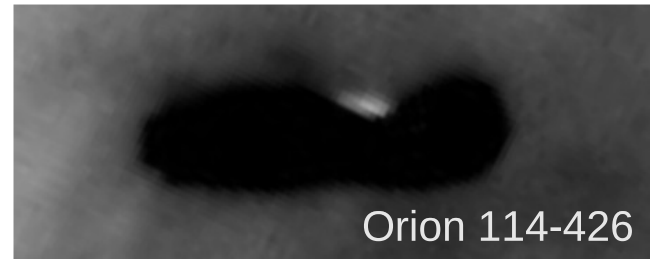




Photometry is Ic band, from AAVSO contributors

# Our models were inspired by resolved images of proplyds




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

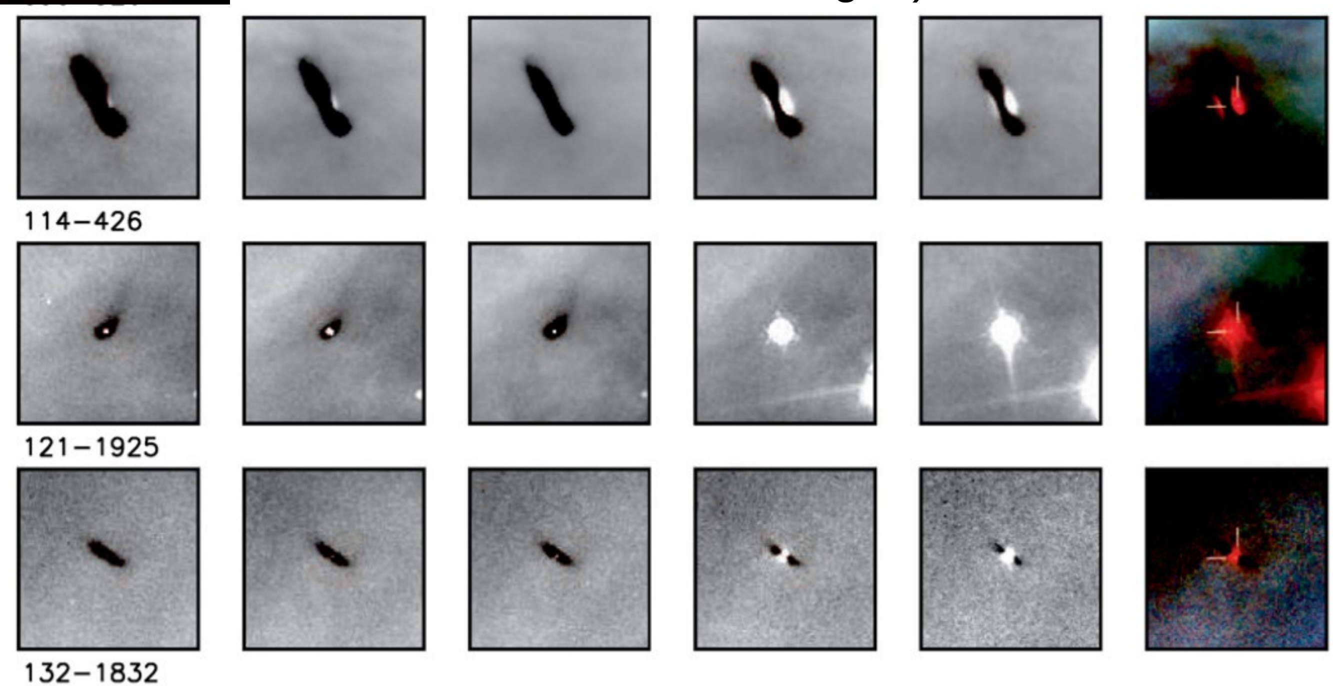
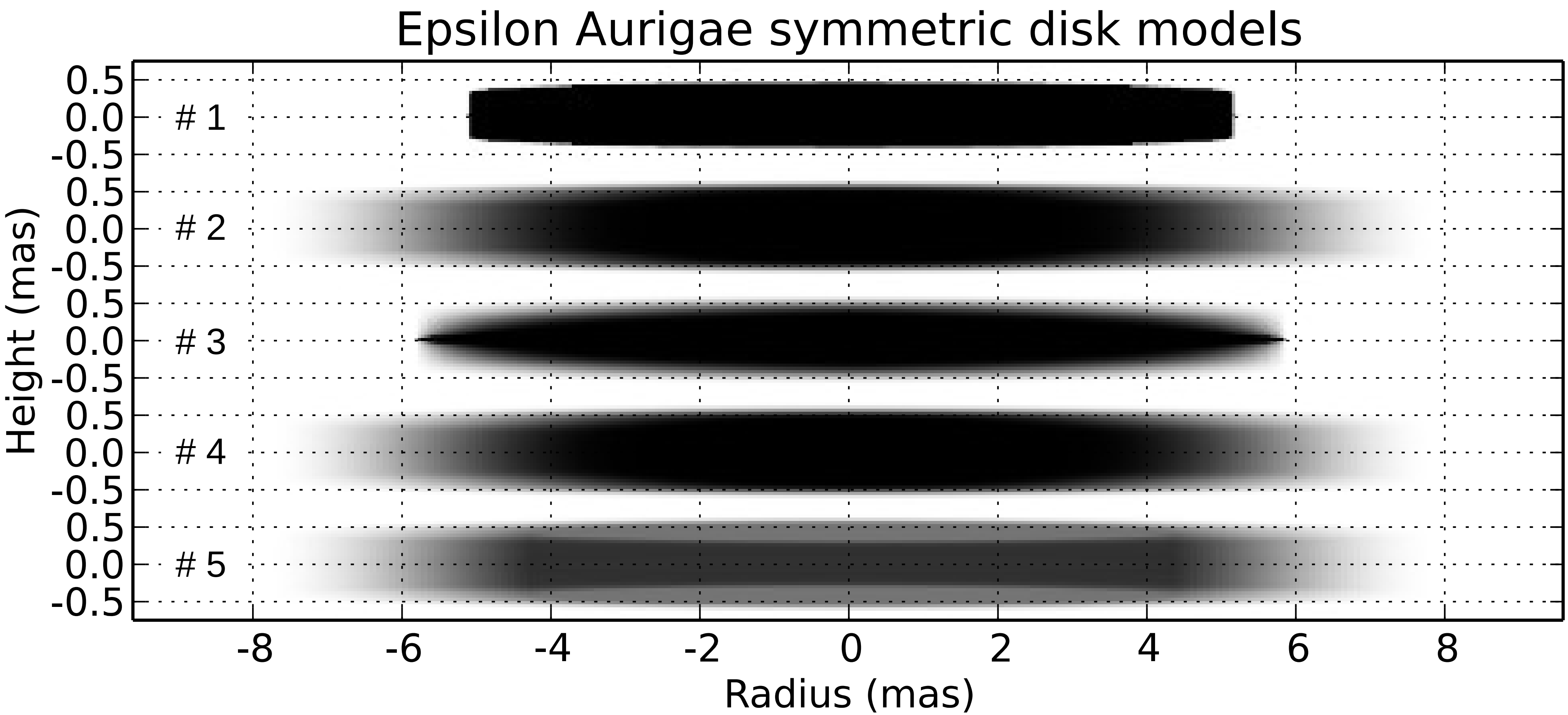
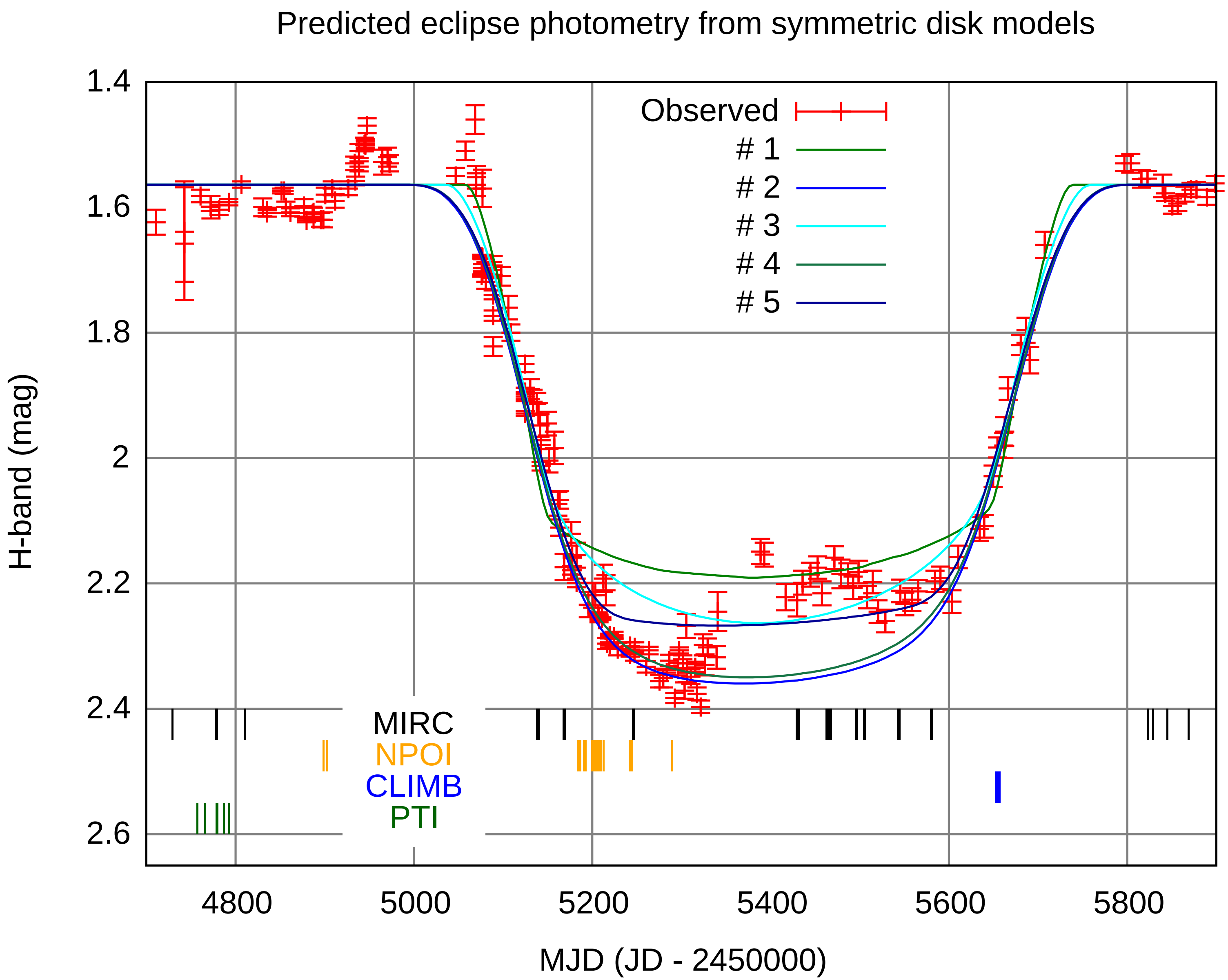


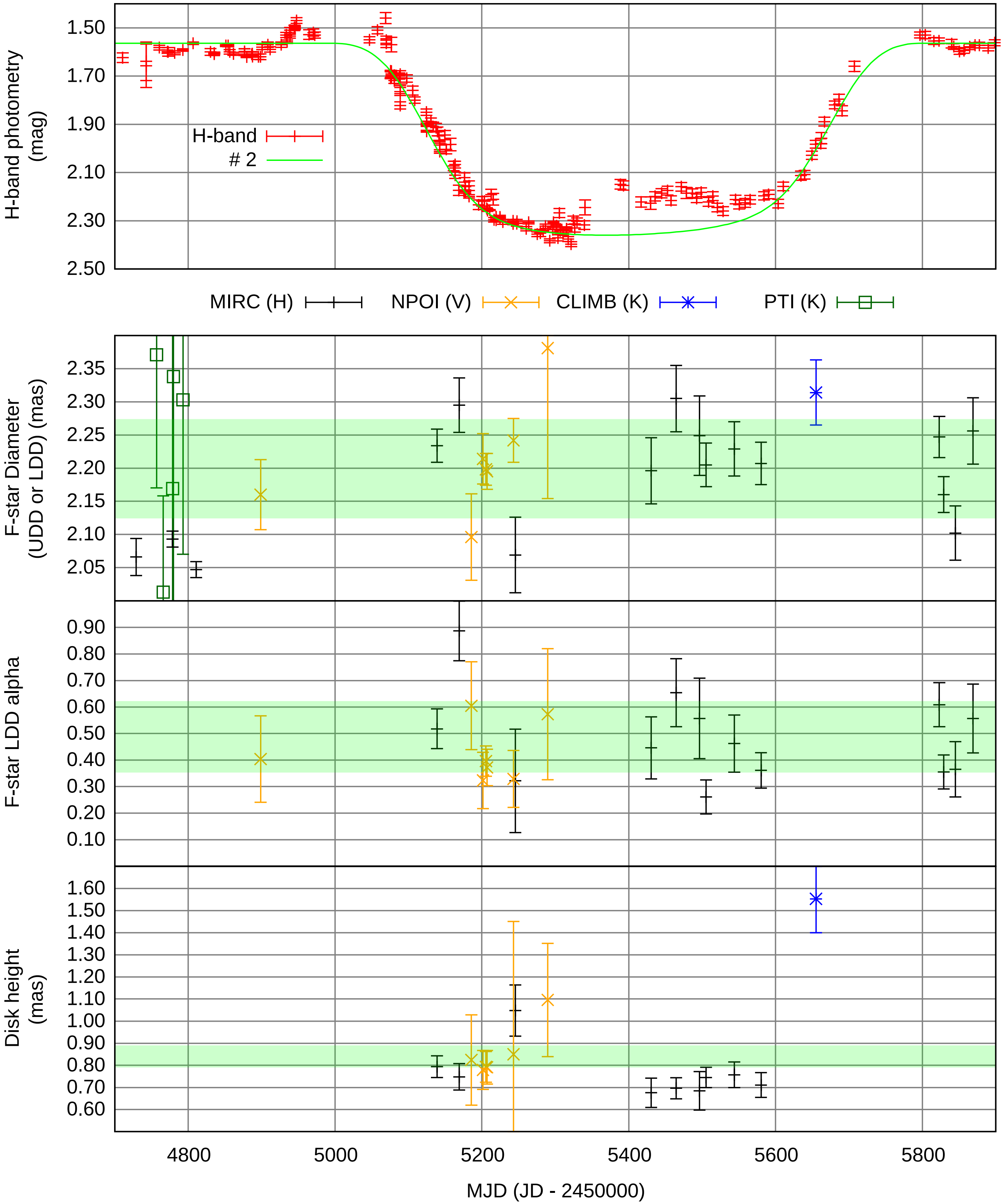

Image of Orion protoplanetary disks from Ricci et al. 2008 and Miotello et al. 2012

# Best-fit symmetric disk models



# The disk is not symmetric





H-band photometry
(mag)
H-band
# 2
MIRC (H)
NPOI (V)
CLIMB (K)
PTI (K)
F-star Diameter
(UDD or LDD) (mas)
F-star LDD alpha
Disk height
(mas)
MJD (JD - 2450000)

# Young Stellar Objects

# An overview of YSOs

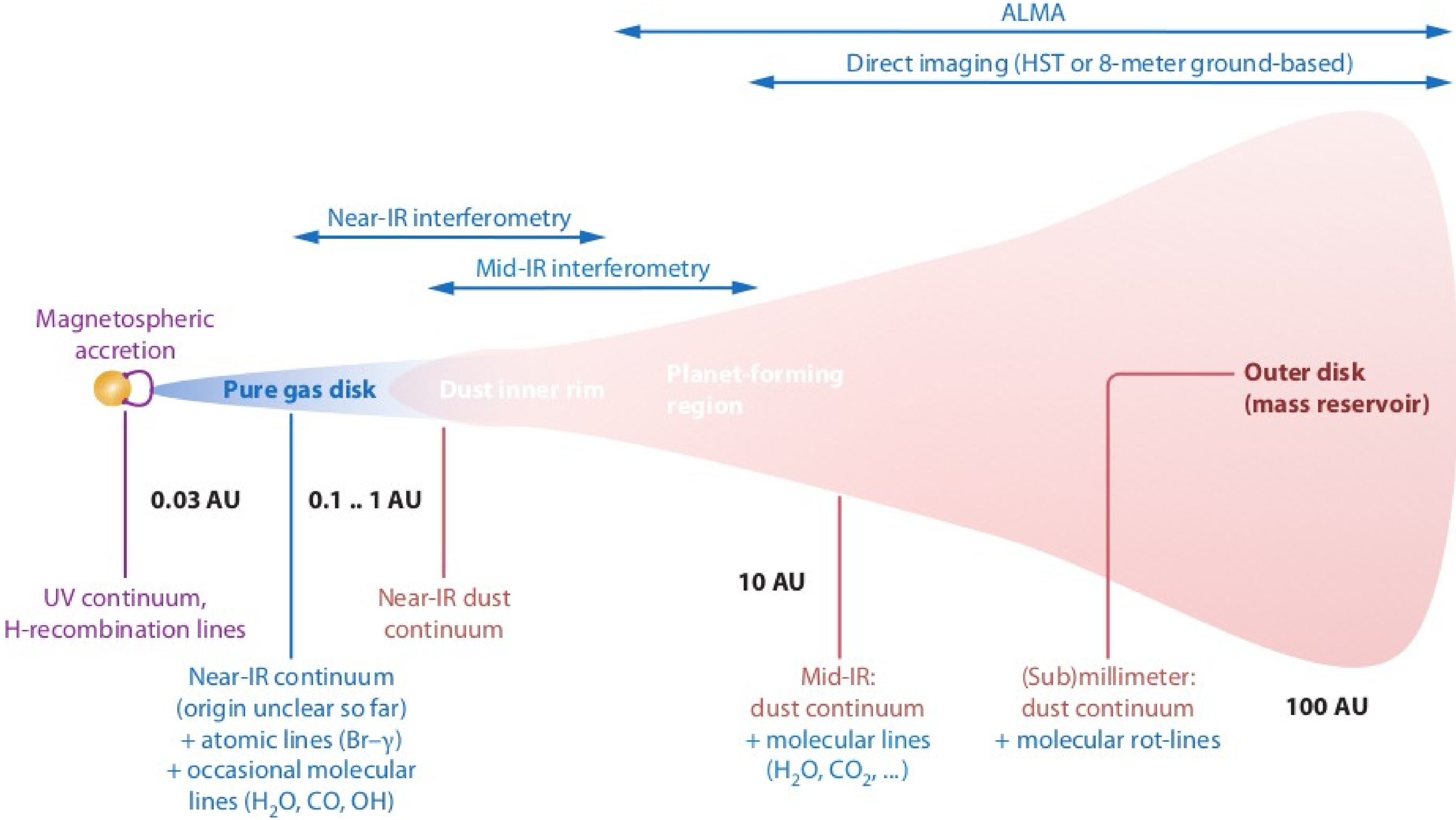
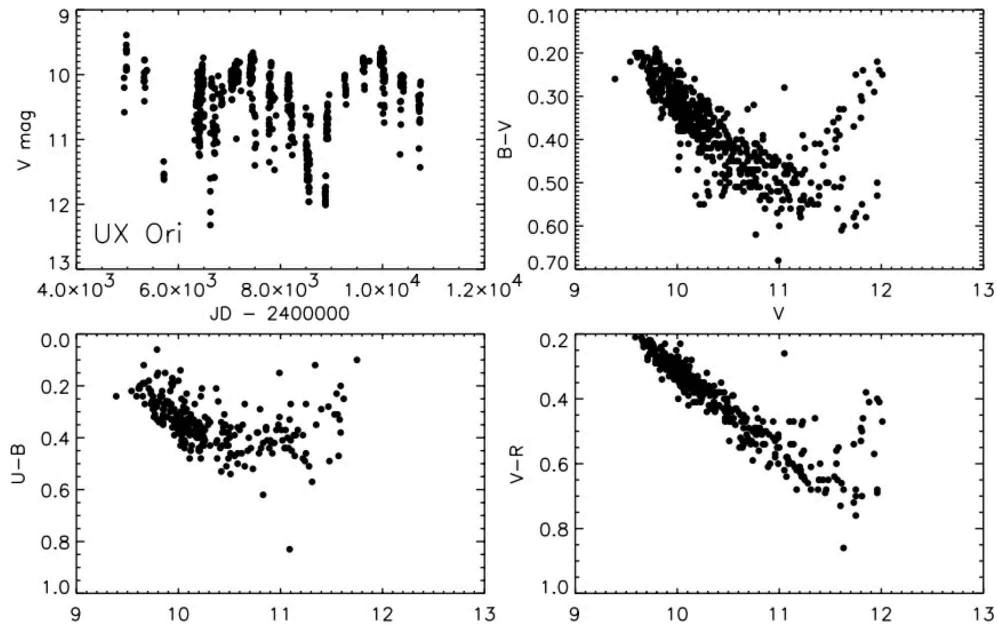



Image from Dullemond and Monnier 2010

# Variable YSOs

UXors (Zaitseva 1983; Grinn 1998) Prototype: UX Ori

- Feature rapid (few hour/day), irregular fading with superimposed repeating patterns
- Color reversal called “bluing” at minimum light
- Probably Herbig Ae/Be stars seen at high inclination





a. Inner few AU of a Herbig Disk (modified from Dullemond et al. 2010)

b. Accretion luminosity changes

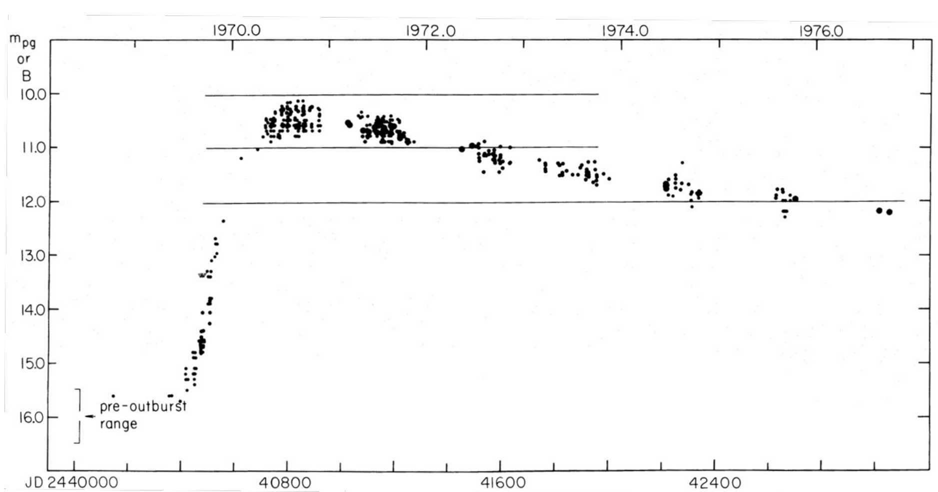
c. PUIR Instabilities

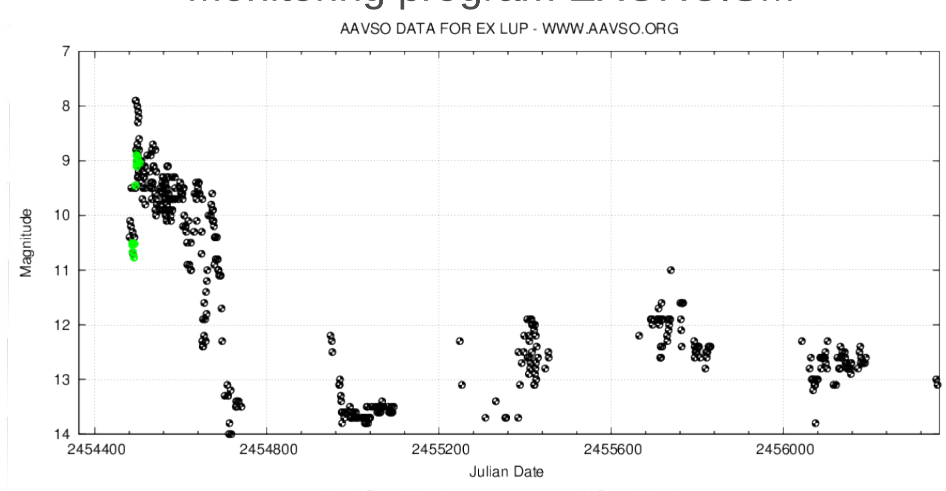
d. Wind-driven dust clouds

# Eruptive YSOs

- FUor (Hartman & Kenyon 1985)
  Prototype: FU Ori
  - Long outbursts of 10s of years
  - Accretion rates $10^{-4} – 10^{-5}$ MSolar/yr
  - When in eruption, spectra dominated by absorption lines
  - Progenitors thought to be Classical TTauri Stars (CTTS)

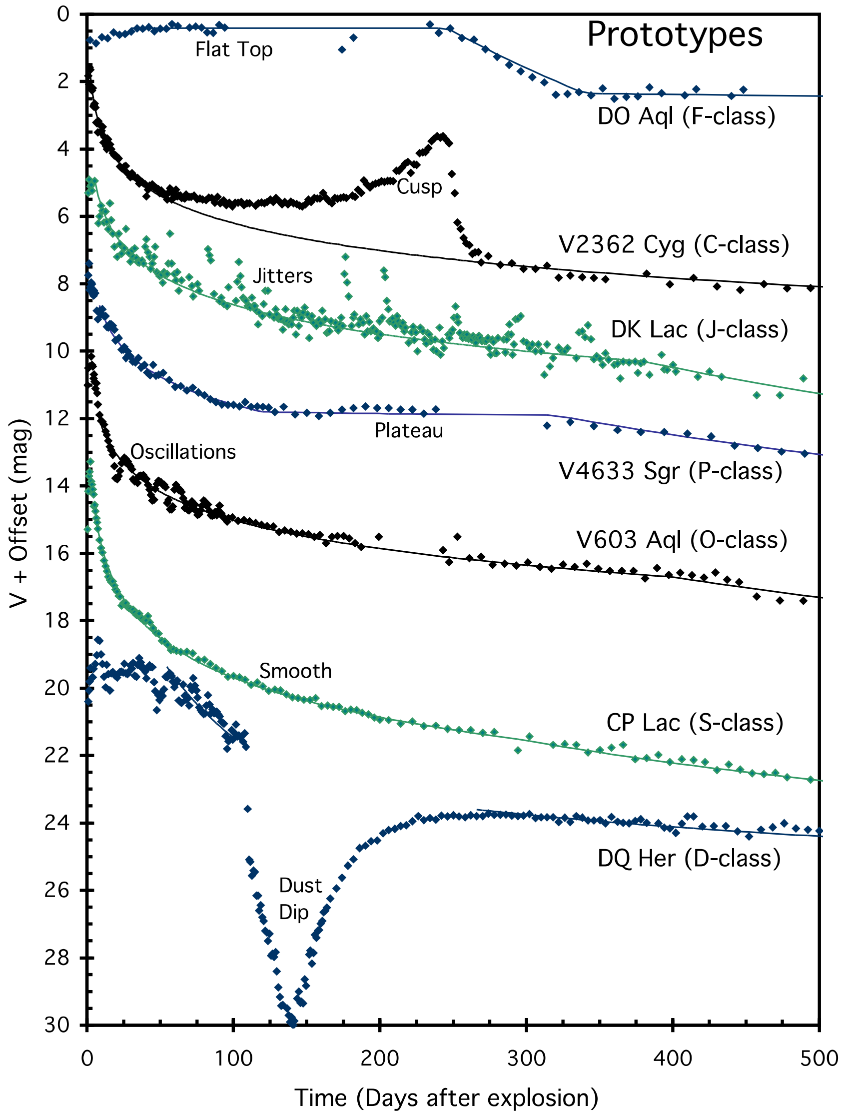
- EXor (Herbig 1989)
  Prototype: EX Lup
  - Short outbursts (weeks-months) with similar recurrence times
  - Accretion rates of $10^{-6} – 10^{-7}$ MSolar/yr
  - Resemble CTTS when in quiescence; characterized by numerous emission lines when erupting.
  - 23 Known objects with 8.5 < V < 20+; 6.2 < K < 13.2; 0.2 < N < 10
  - Monitoring program EXORCISM

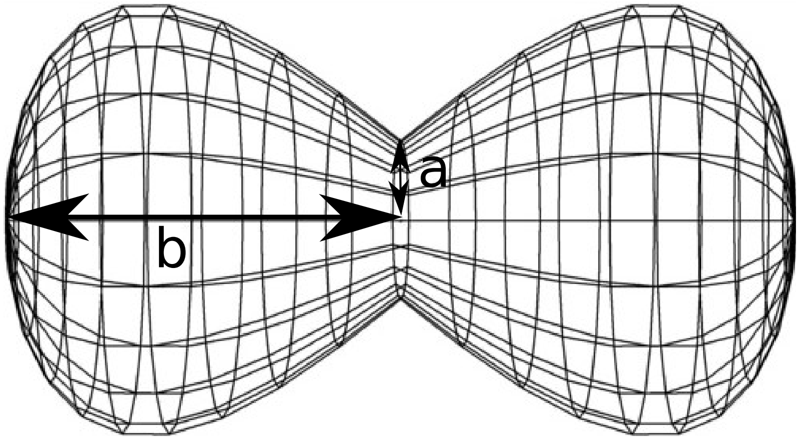


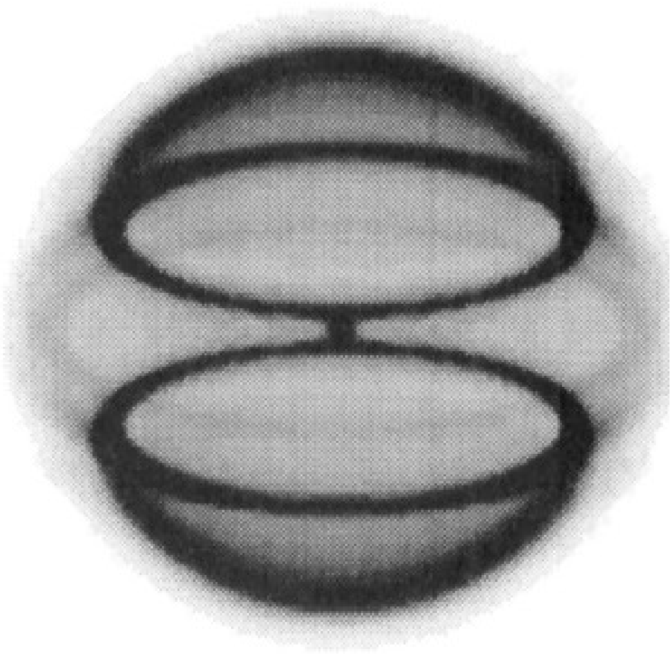



# Novae

# Novae observables

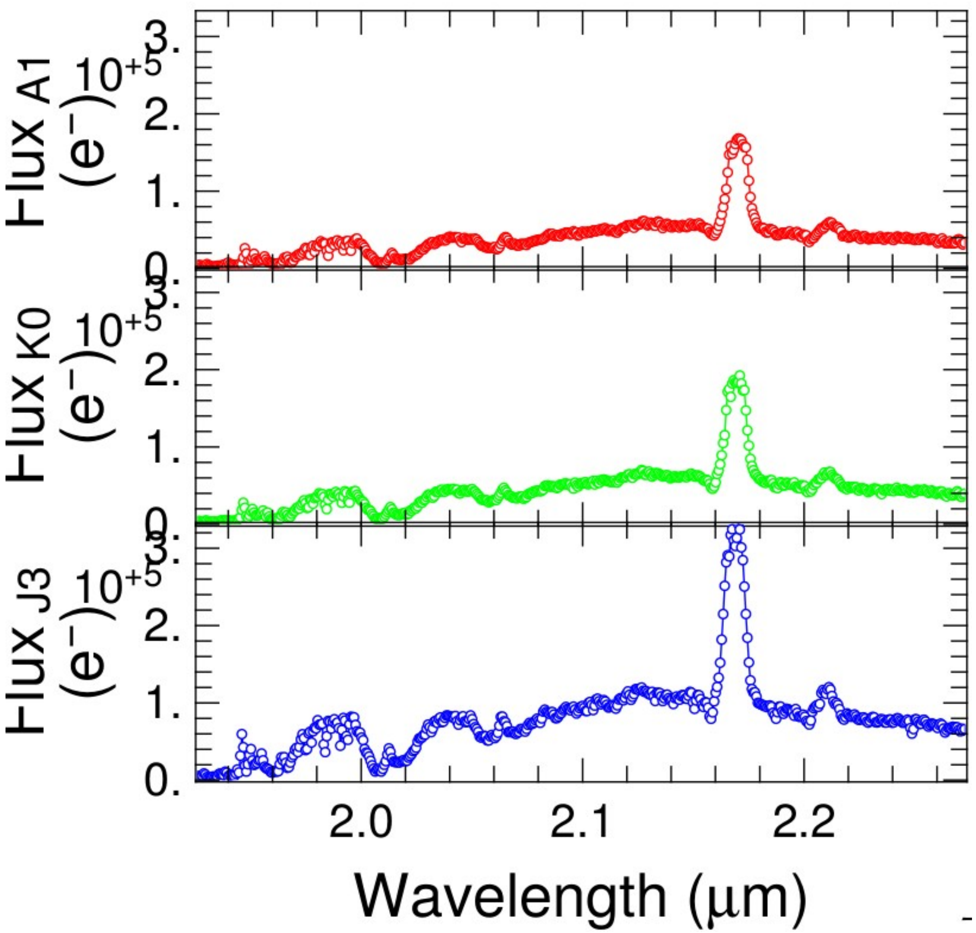


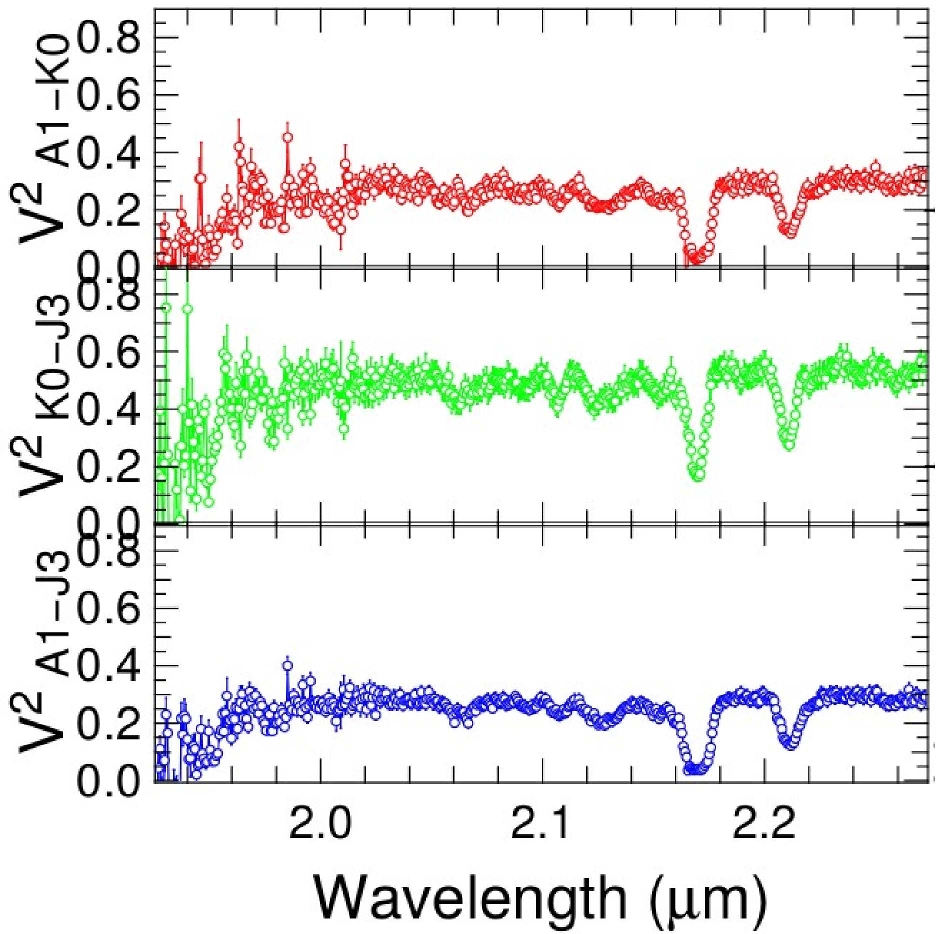



Figures: (left) Strope et al. 2010, (right top) Riberio 2013; (right bottom) Loyd 1997

# Nova Cen 2013




Figures: (left) Strope et al. 2010, (right top) Riberio 2013; (right bottom) Loyd 1997

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