# CHARA + MIRC imaging, & recent progress in understanding "epsilon Aurigae"

## *Rosetta stone or Pandora's box?*

2010, the **year** of total eclipse

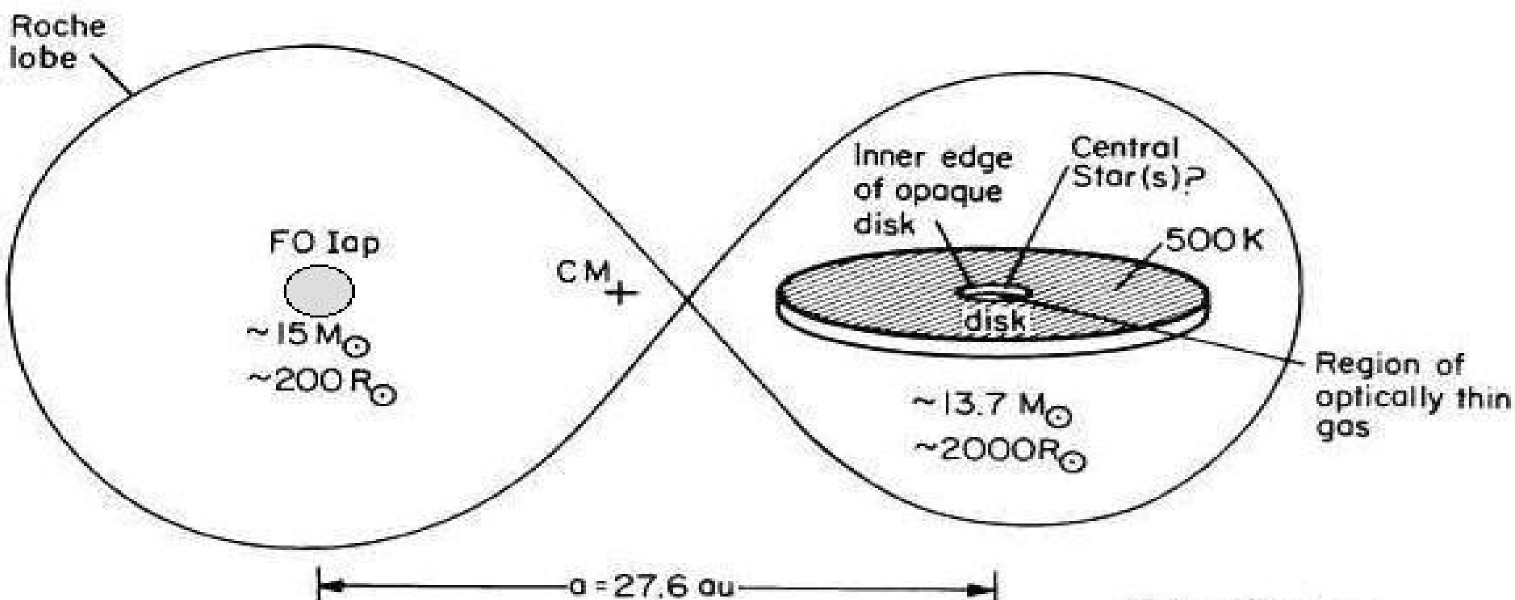

& APOD: http://antwrp.gsfc.nasa.gov/apod/ap100108.html

# First of all, Thank You!

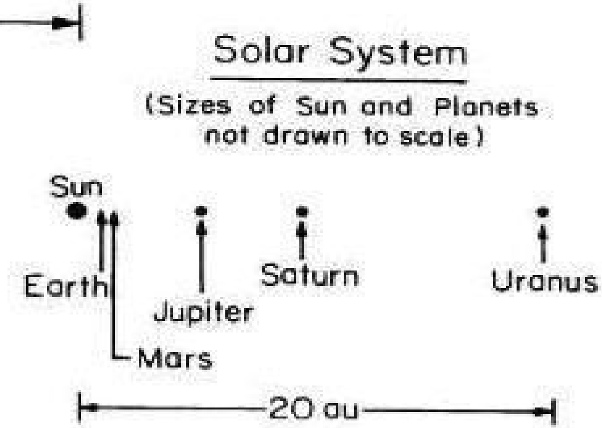
It's an honor and privilege to have access to this amazing array of telescopes...

... and equally amazing array of people!

# .ε Aur – a long history: 1920's Struve et al.; 1965, first black hole binary candidate; 1991, favored system model, high masses:




Assigning the F supergiant type implies a high mass but invisible companion object...
system distance ~ 625 pc




Model for the epsilon Aurigae system
Carroll et al. 1991 Ap.J. 367: 278.

# Today:
# a changing scene

- Is the F supergiant  actually a massive star, or a “phony”
- Is the disk actually observable?  Is it like other disks?
- Could there be a black hole inside the disk?
- Given answers to those questions, what's the evolutionary status of the star(s) in this binary system?

# The F "supergiant"

Why it *could be* a massive star, F0Ia:

- Very bright for its distance → 30,000 time solar luminosity
- Spectrum details resemble supergiant class star
  (low surface gravity, extended)
- Early F supergiant would be ~ 10 to 15 solar masses

Problems with this classification:

- Star is huge, 150X solar size, 2X similar supergiants
- Variability ~100 days → over-luminous if Cepheid-like
- Abundances: solar, but with excess Na, Ba, $^{13}CO$...

# The dark companion

M/L >> 1

*The cause of the primary eclipses*

“Unseen” except for weak spectral lines during eclipses, and these resemble the F star spectrum

Theorized to be:

- a swarm of meteors (1924)
- a huge “infrared star” (1932)
- a cloaked Be star (1961) or BH
- a large, cold disk (1956, 1965...)

# So what's new?

FOUR DEVELOPMENTS SINCE THE STATION FIRE:

1. SPECTRAL ENERGY DISTRIBUTION RESOLVED

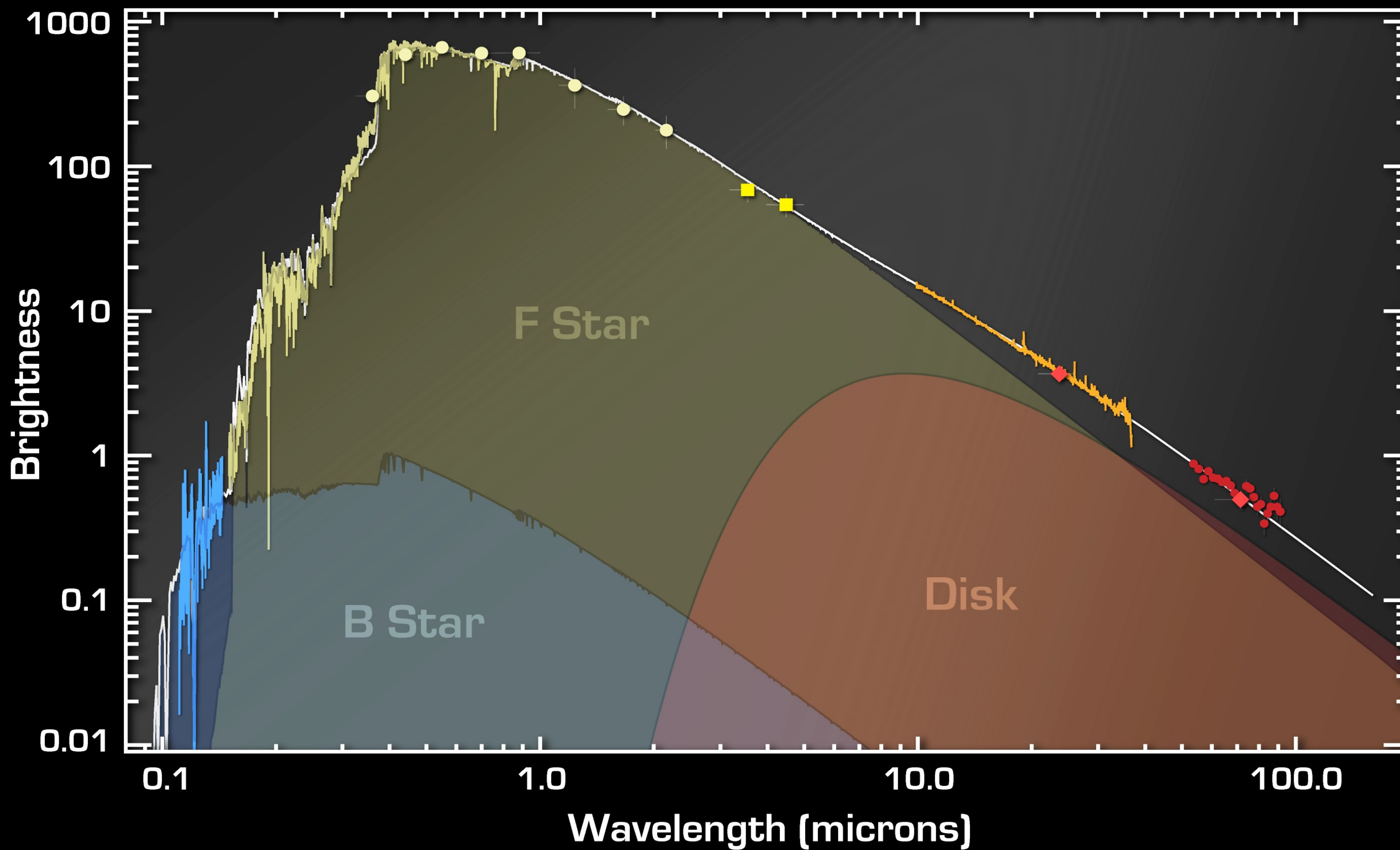
2. CHARA+MIRC IMAGING OF THE DISK ITSELF

3. EVIDENCE FOR DISK SUBSTRUCTURE

4. XRAYS, or not.

→ A modern, comprehensive model for the binary!

# Development #1: A complete Spectral Energy Distribution




Spectrum of Binary Star Epsilon Aurigae Spitzer Space Telescope • IRAC • IRS • MIPS

NASA / JPL-Caltech / D. Hoard (Spitzer Science Center/Caltech) ssc2010-02a

# System properties: B5V star (5.9Mo) → F star ~ 2 – 3 Mo, disk << 1Mo

$\epsilon$ Aurigae from the Far-UV to the Mid-IR

**2010 Hoard, Howell & Stencel, Astrophysical Journal, submitted.**

TABLE 2
THE MODEL

| Component | Parameter | Value | Reference |
|---|---|---|---|
| System | Adopted Distance, $d$ (pc) | 625 | HIPPARCOS (Perryman et al. 1997) |
| | Inclination, $i$ (°) | 89 ($\gtrsim 87$) | this work, Lissauer et al. (1996) |
| | Orbital Separation, $a$ (AU) | 18.1–19.6 | this work |
| F Star | Spectral Type | F0 II–III? (post-AGB) | this work |
| | Temperature, $T_F$ (K) | 7750 | this work, Castelli (1978) |
| | $\log g$ | $\lesssim 1.0$ | this work, Castelli (1978) |
| | Radius, $R_F$ ($R_\odot$) | $135 \pm 5$ | this work |
| | Angular Diameter, $D_\alpha$ (mas) | $2.01 \pm 0.07$ | this work |
| | Mass, $M_F$ ($M_\odot$) | 2.2–3.3 | this work |
| B Star | Spectral Type | B5V | this work |
| | Temperature, $T_B$ (K) | 15,000 | Cox (2000) |
| | $\log g$ | 4.0 | Cox (2000) |
| | Radius, $R_B$ ($R_\odot$) | 3.9 | Cox (2000) |
| | Mass, $M_B$ ($M_\odot$) | 5.9 | Cox (2000) |
| Disk | Temperature, $T_{disk}$ (K) | $550 \pm 50$ | this work |
| | Radius, $R_{disk}$ (AU) | 3.8 | this work, Lissauer et al. (1996) |
| | Height, $H_{disk}$ (AU) | 0.475 | this work |
| | Assumed Mass, $M_{disk}$ ($M_\odot$) | $\ll 1$ | this work |
| | Inferred Dust Grain Radius, $r_{grain}$ ($\mu$m) | $\gtrsim 10$ | this work, Lissauer et al. (1996) |
| | Transmissivity Factor | 0.3 | this work |
| | Emissivity Factor | 2.43 | this work |

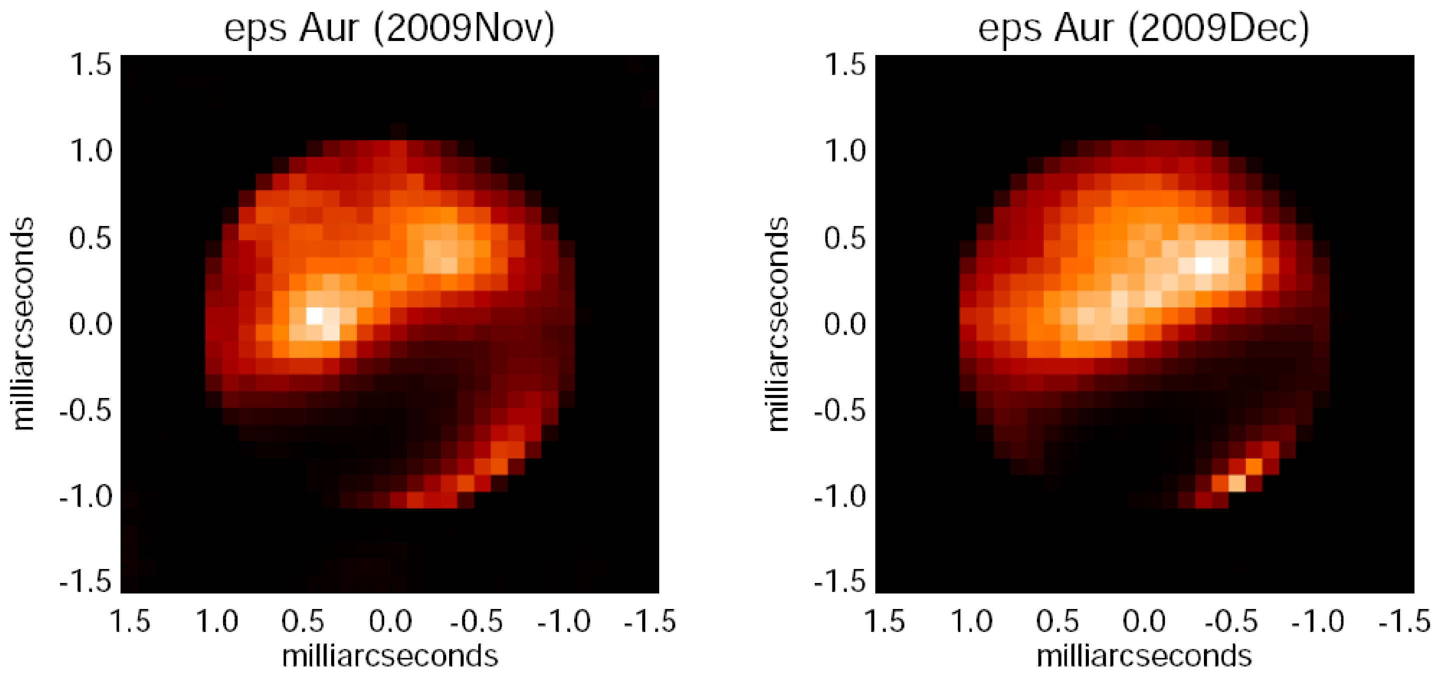
# Development #2:
# Interferometric Imaging

Evidence argues the binary star sep ~10 - 20 milli-arcsec
epsilon Aurigae is 625 parsec away.  At that distance:
1 arcsec (5 micro-radians) spans 625AU
1 milli-arcsec (5 nano-radians) spans 0.625 AU

→ Required telescope size (at near infrared, 2 microns):
5E-9 radians / 2E-6 meters = 250 meters...
Where can I find a telescope that large?
The CHARA Array at Mount Wilson Observatory

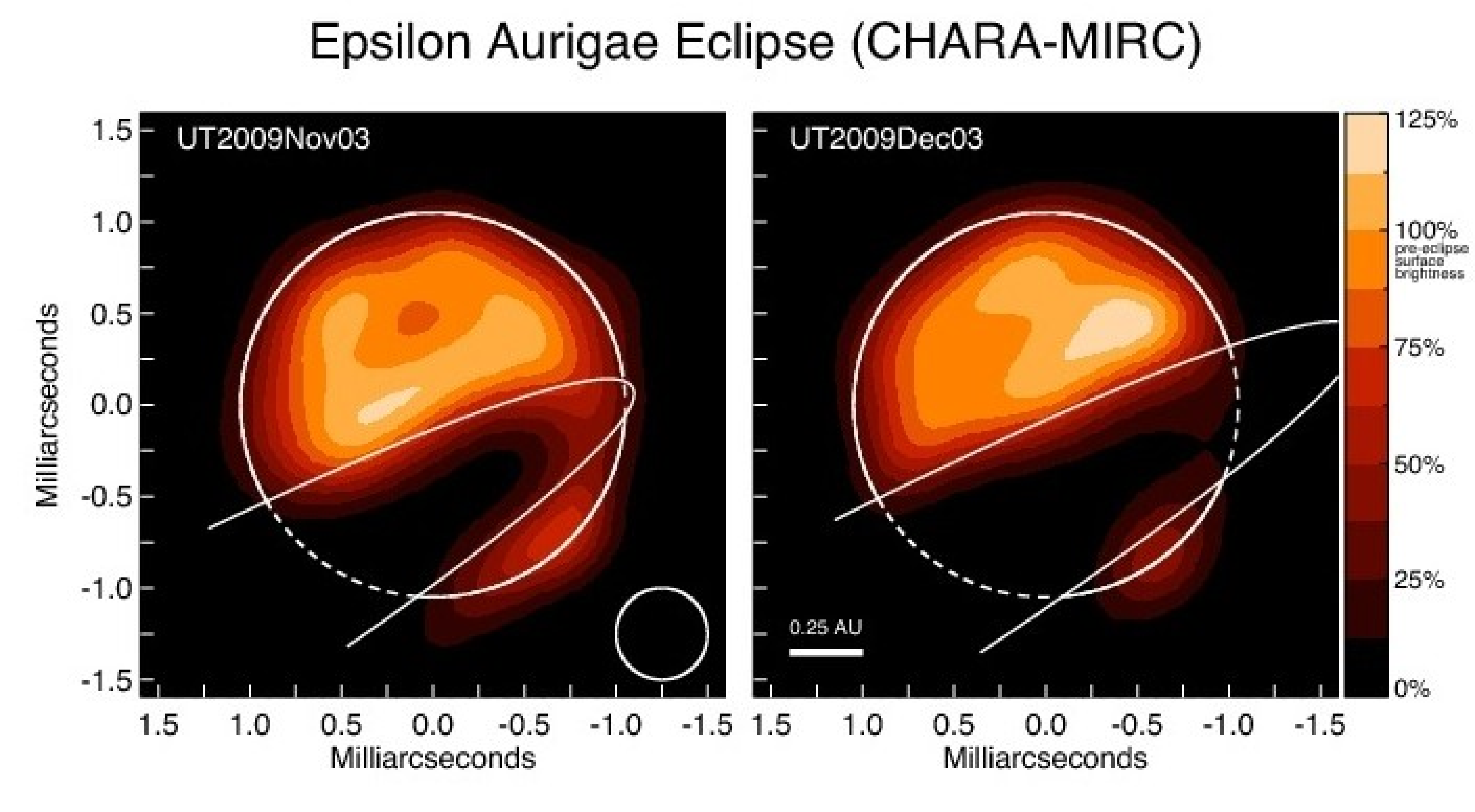
*Please note: much of the following should be considered EMBARGOED INFO...*

# What we saw last autumn...




Early gen image by John Monnier. Note movement of dark disk toward right. Also note: leading edge in Nov not sharp; training edge in Dec 'truncated' ...and what are those “hot spots”?

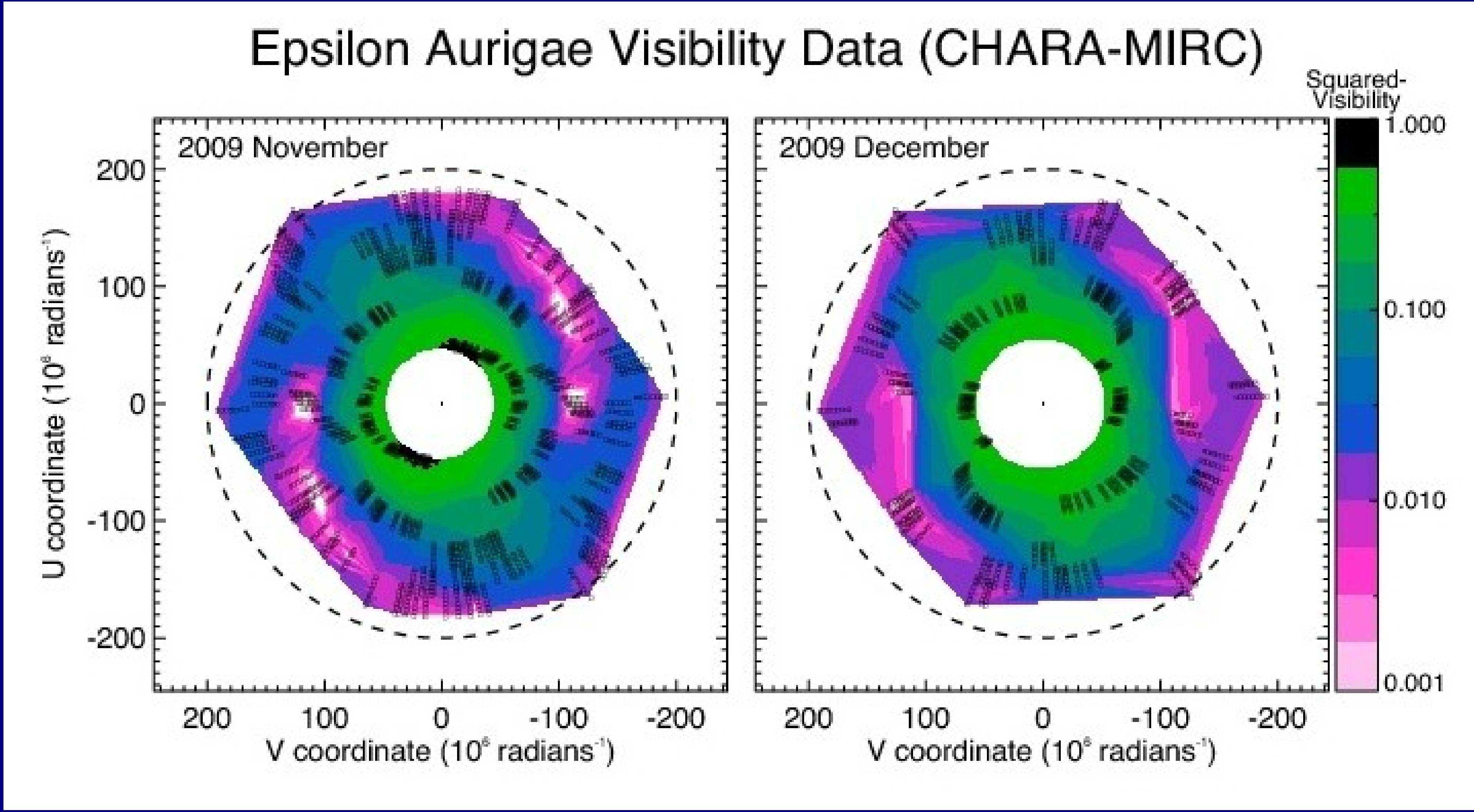
# Evidence for the dark disk



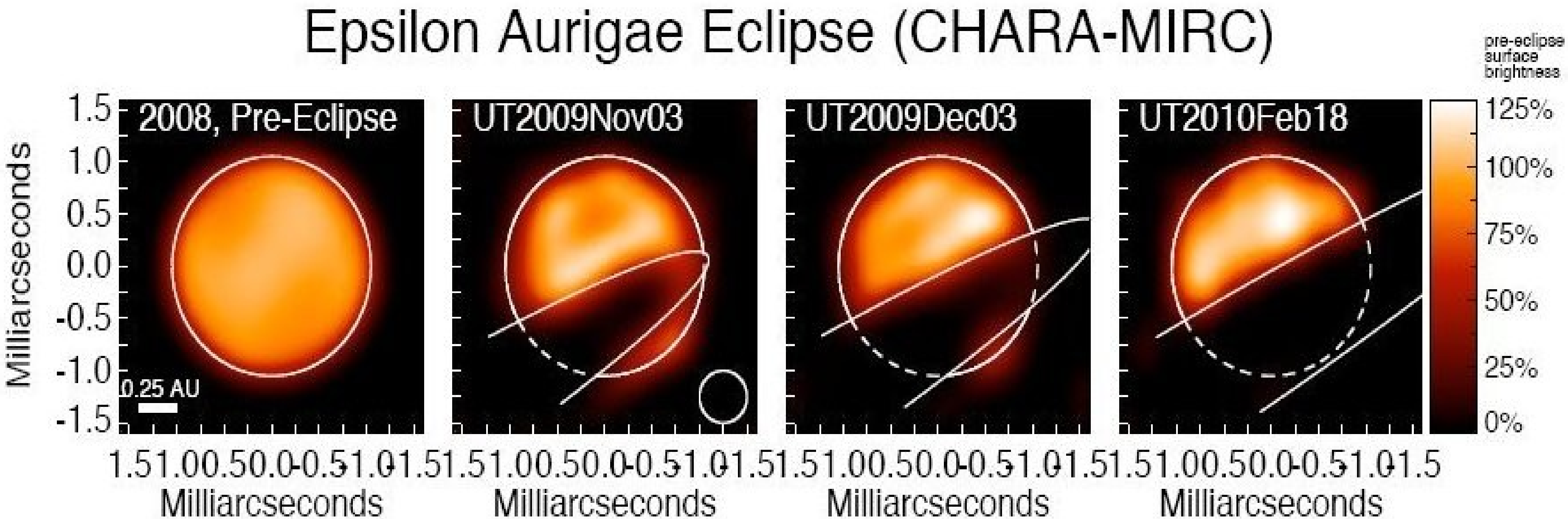

Nature Letter, 2010 April, in press → ellipsoidal model fit.

The movie! http://www.ns.umich.edu/podcast/video2.php?id=1211

UV coverage was excellent for the first pair of images, but much less for the Feb 2010 data (understandably). However, the model can help reconstruct images from far fewer samples – with a risk of lost detail...



Third eclipse epoch confirms the trend, within model limitations.




*Follow-up obs needed, 2010-11*

Mid-eclipse is 4 Aug 2010 // Totality ends Mar 2011 // Eclipse ends May'11

# What this initial interferometric imaging has told us, so far...

Fitted ellipse indicates <u>relative motion</u> of objects: <u>25 km/sec</u>

<u>F star motion</u>, previously measured from radial velocities, was <u>15 km/sec</u> during observing timeframe

→ <u>disk component</u> = 25 – 15 = <u>10 km/sec</u>

IMPLIED MASS RATIO: 2 / 3 → F star is lighter than companion!

SED model says disk contains B5V star, nominal 6 Msolar
→ F star, despite high luminosity, is < or = 4 M solar

*this is not a normal high mass supergiant...*
*...more likely some terminal stage of evolution...*

# Also from the interferometry results

SED disk dimensions and interferometric image opacity

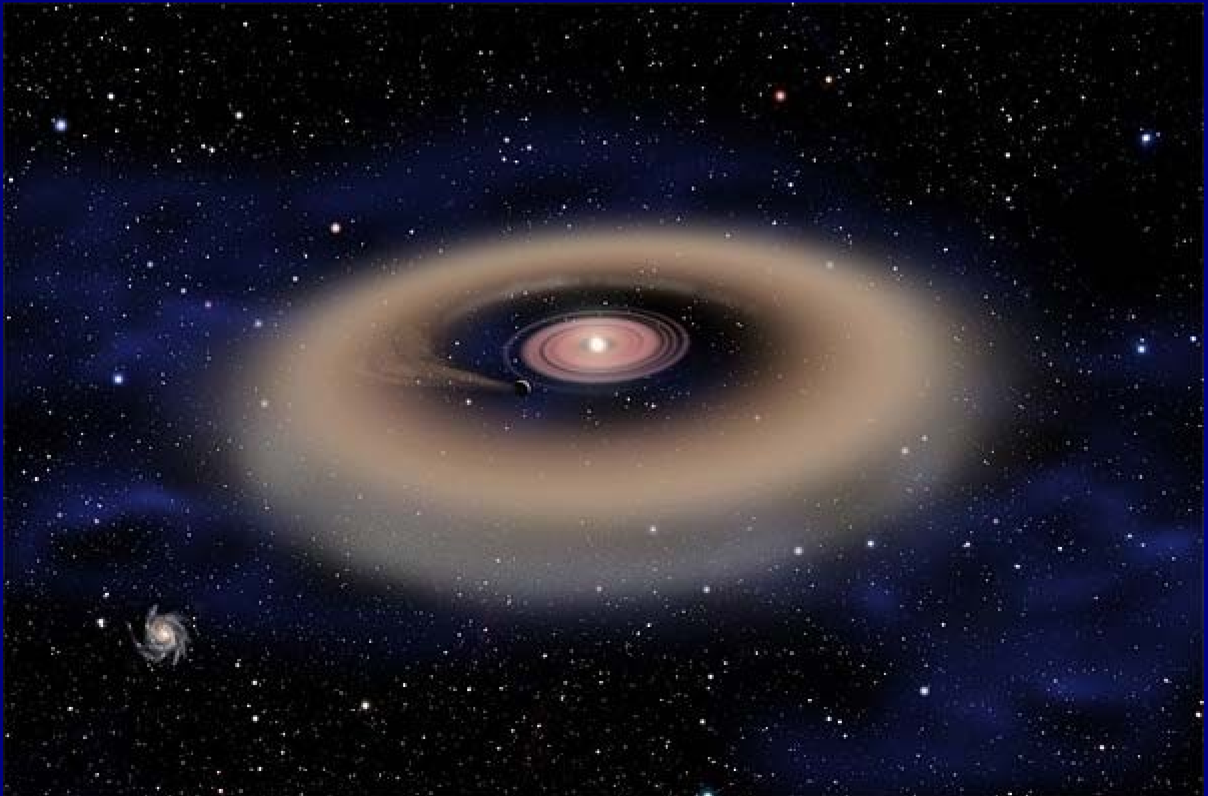
→ disk mass from volume and dust opacity:

With asssumed dust opacity ~ 10 $cm^2/gm$:

density = 1 / [opacity * length] ~ $10^{-10}$ $kg/m^3$

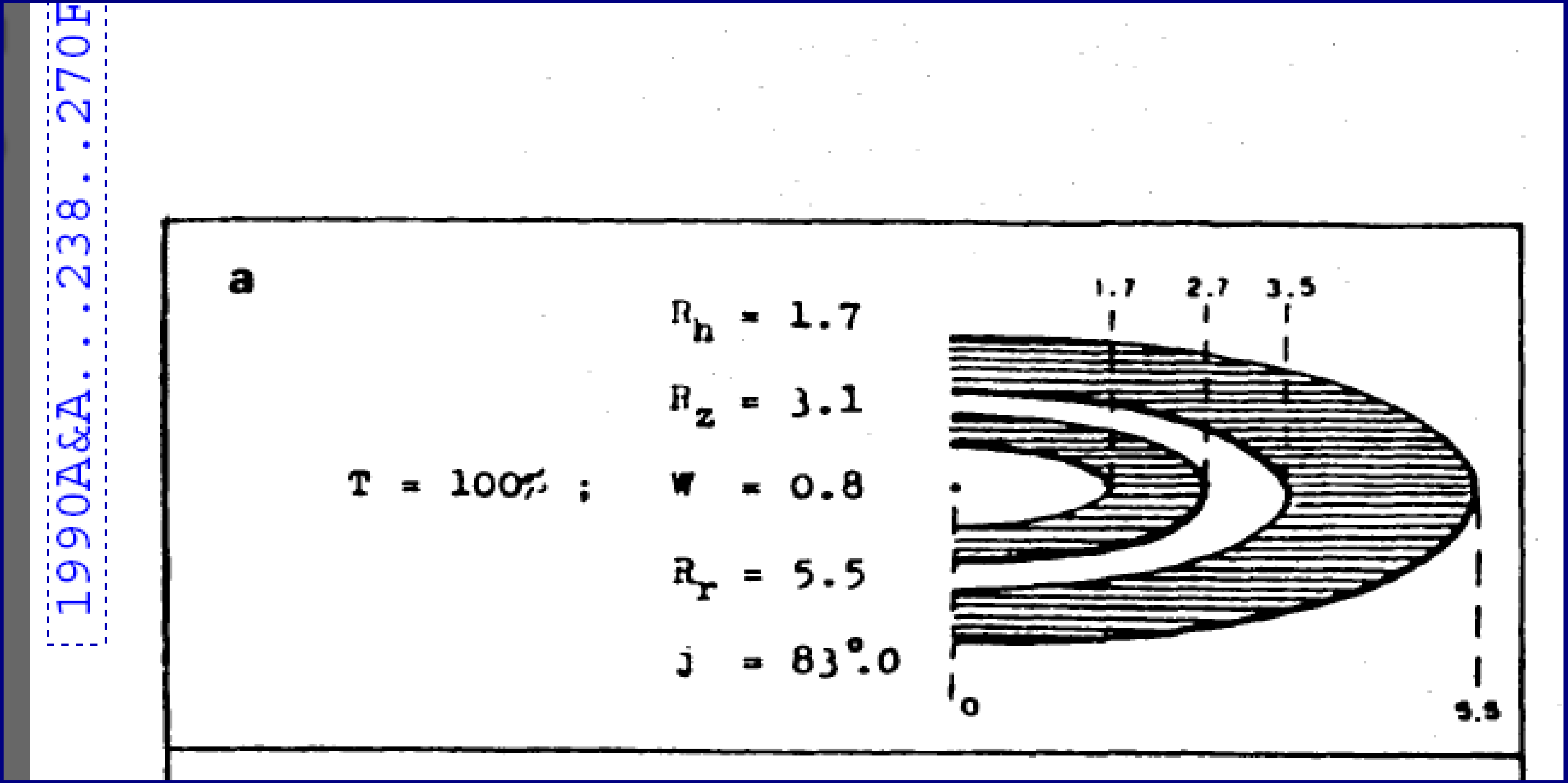
disk volume: 7 x $10^{34}$ $m^3$ → disk mass = $10^{25}$ kg < $M_{earth}$

disk scale height consistent with SED values and these: ~½ AU



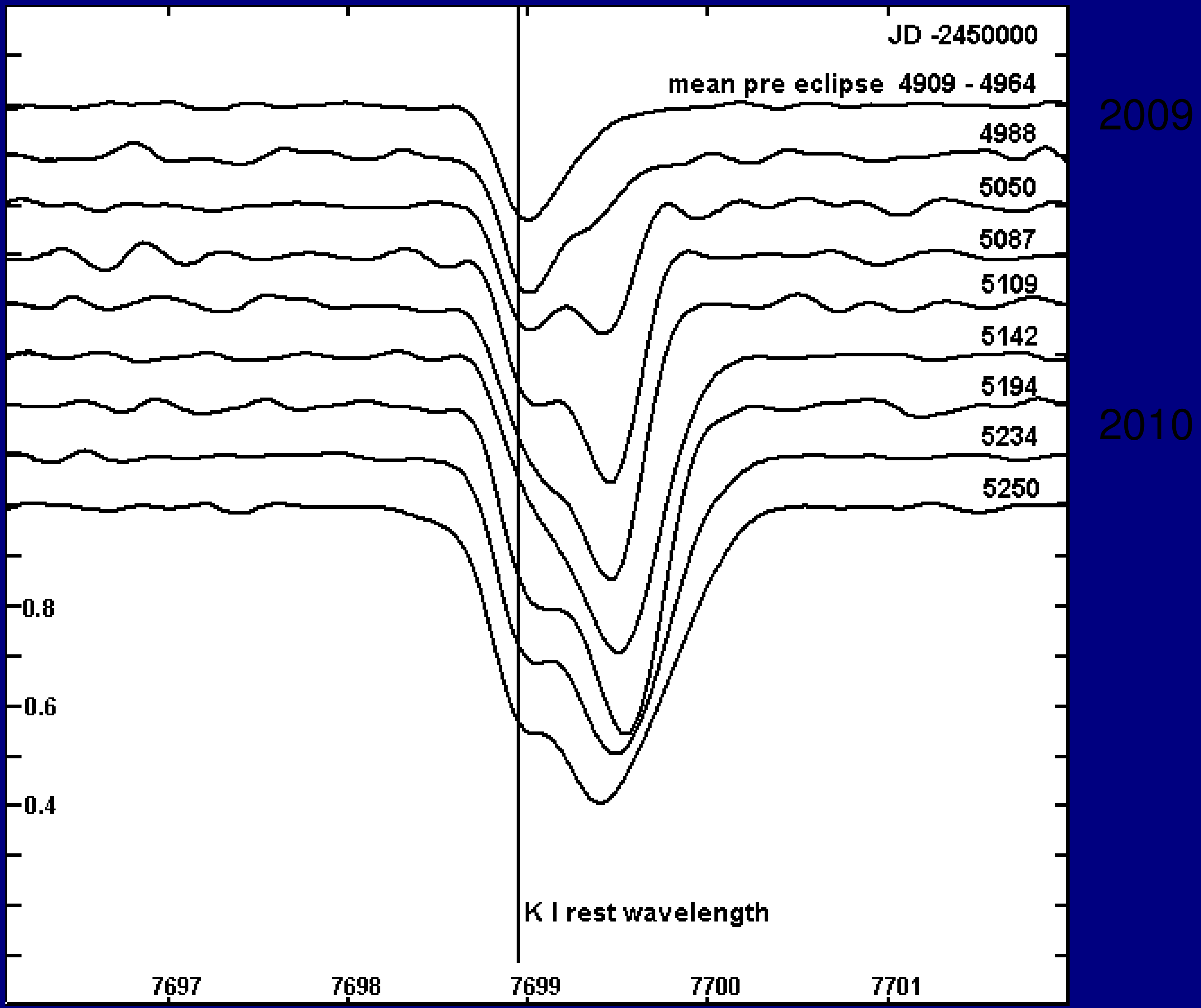
# **Development #3**: a rotation curve for the disk

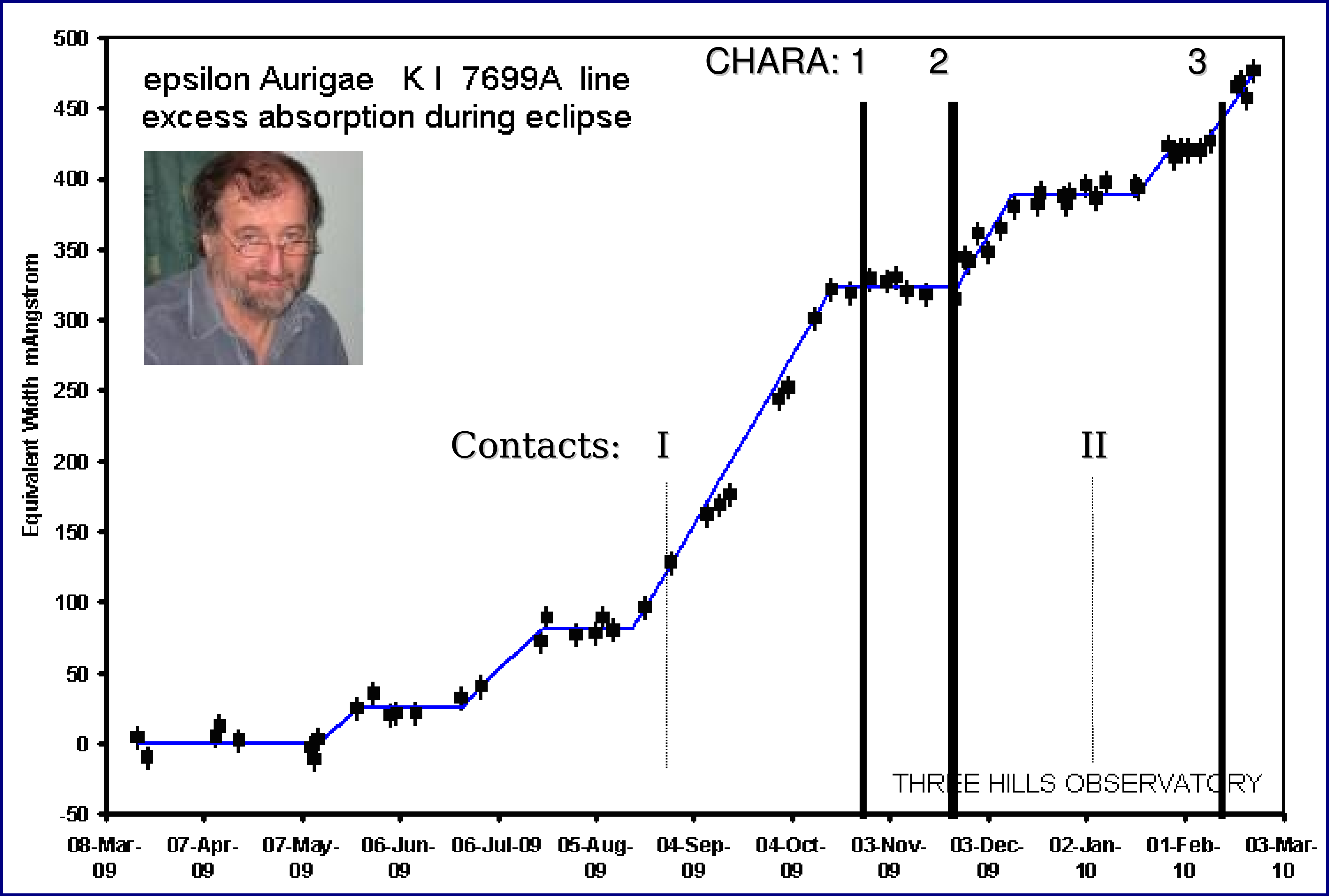
Ferluga (1990) shell line monitoring & light curve model, 1983 eclipse, led to his multi-ring disk model (units are AU)




Disk sub-structure? You betcha!

# Tomography of the disk:
# new data, neutral potassium line monitoring






NOTE THE STEP FUNCTIONS! (Leadbeater & Stencel, 2010 arXiv 1003.)

How to interpret the stepwise changes in equivalent width in the K I 7699A line?

Simplest explanation involves similar excitation conditions across this portion of the disk, but changing DENSITY → concentric shells or rings.

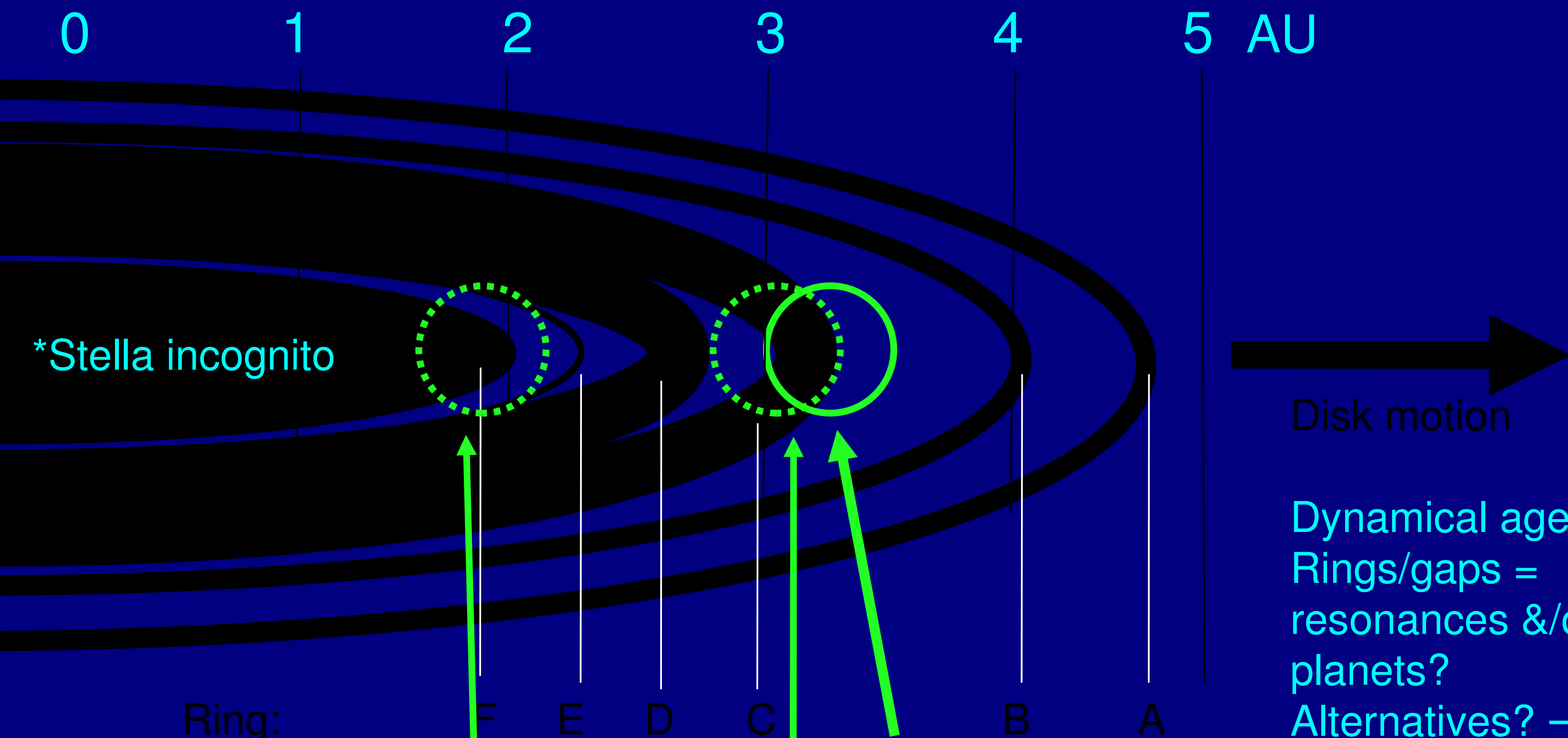
Given the MIRC image opacity, disk is likely opaque at 7699A too, which implies we could be seeing optically thin 'atmospheric' shells extending above the disk.

Low excitation excesses in K, Na in eps Aur are reminiscent of radiation-induced excesses in exospheres of Mercury and Io.

# The Nature Letter result is now only part of the story.

## ...CHARA+MIRC *merely* saw Rings “C” & “F”

The neutral potassium E.W. results, nearly to scale:



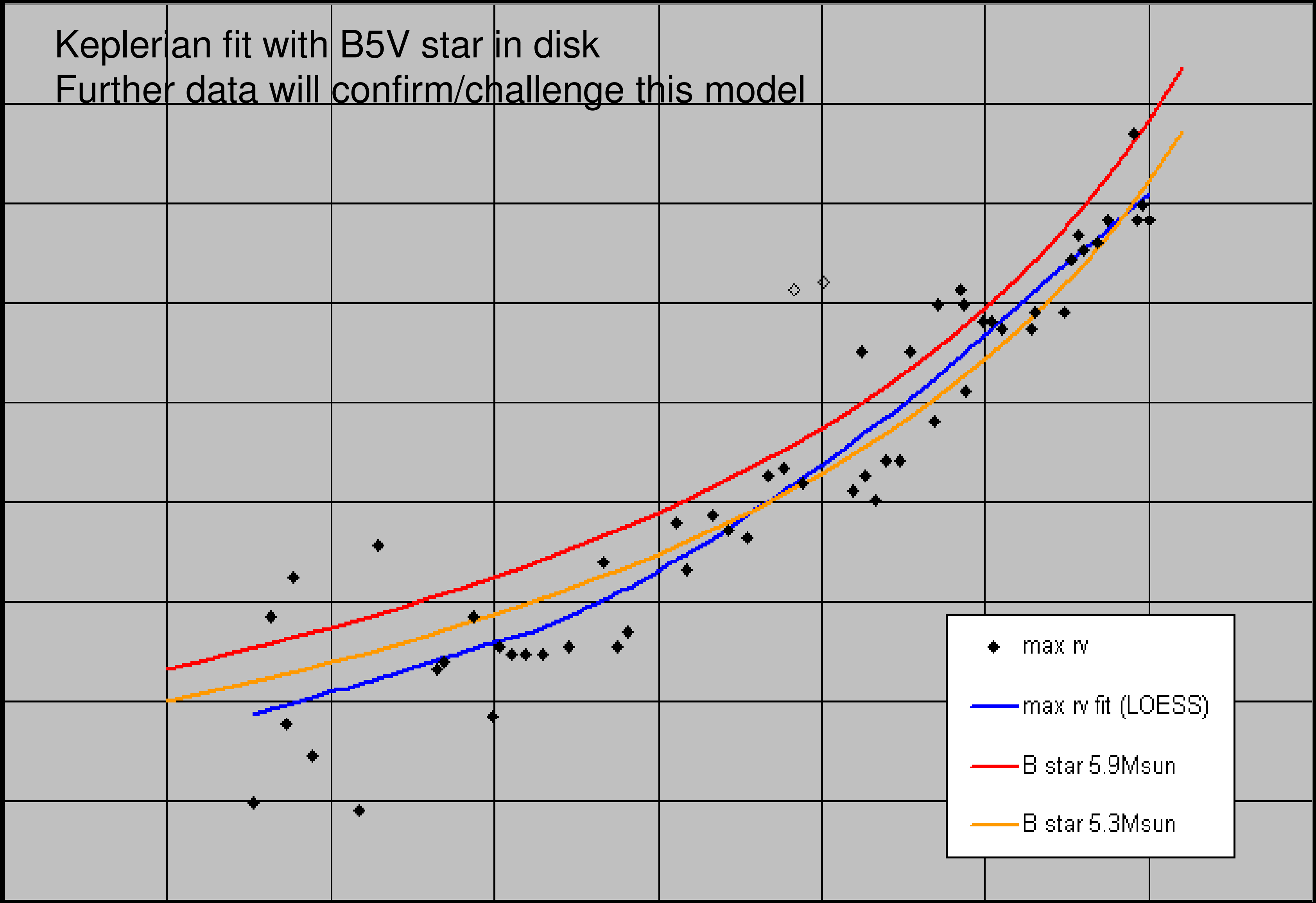

CHARA: F star in Feb Dec Nov

Ring thicknesses ~ 50% of measured, to avoid overlap

Disk tilt exaggerated for clarity ( sin i ~ 1)

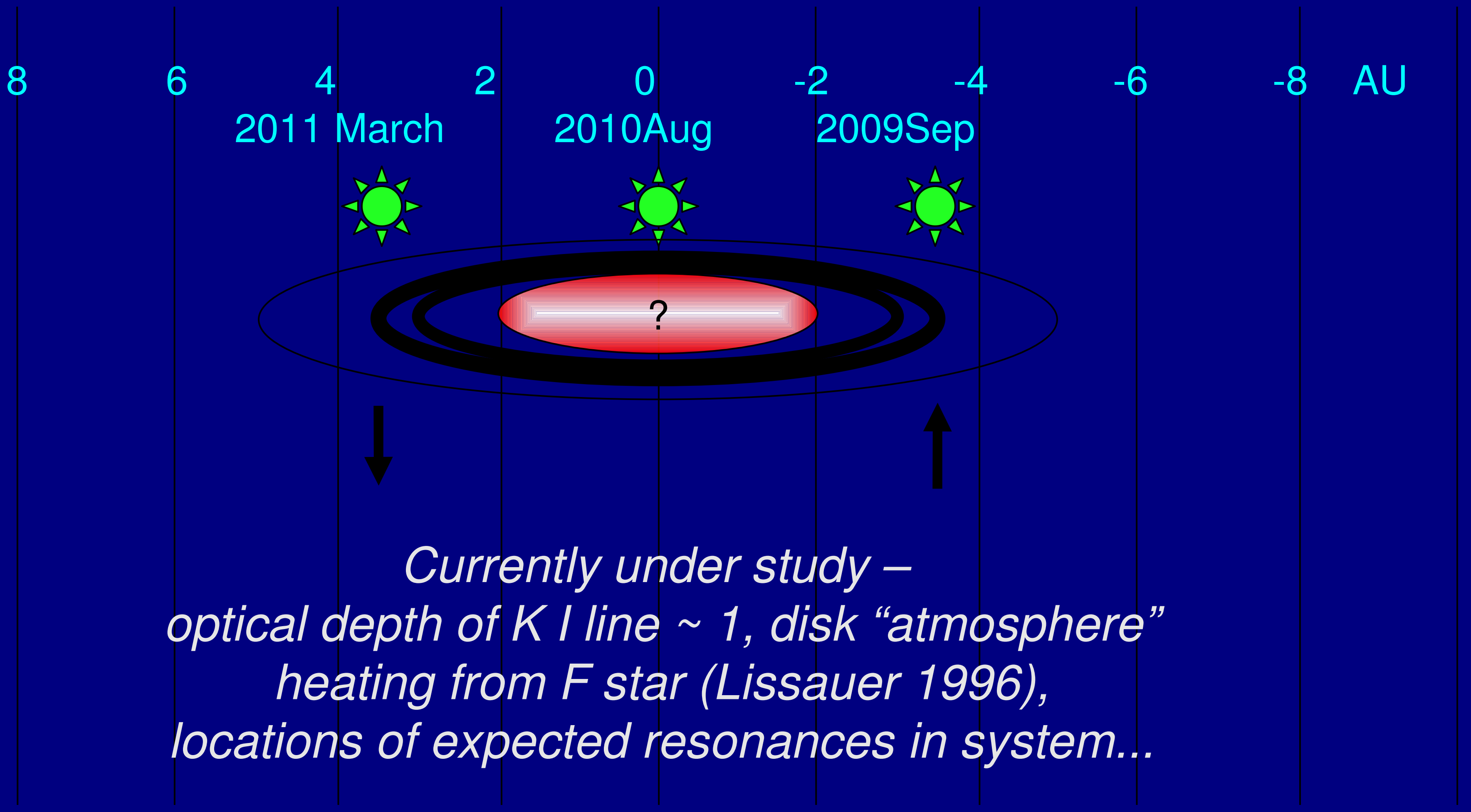
Dynamical age?
Rings/gaps = resonances &/or planets?
Alternatives? →

*R.Stencel, 24Feb2010*



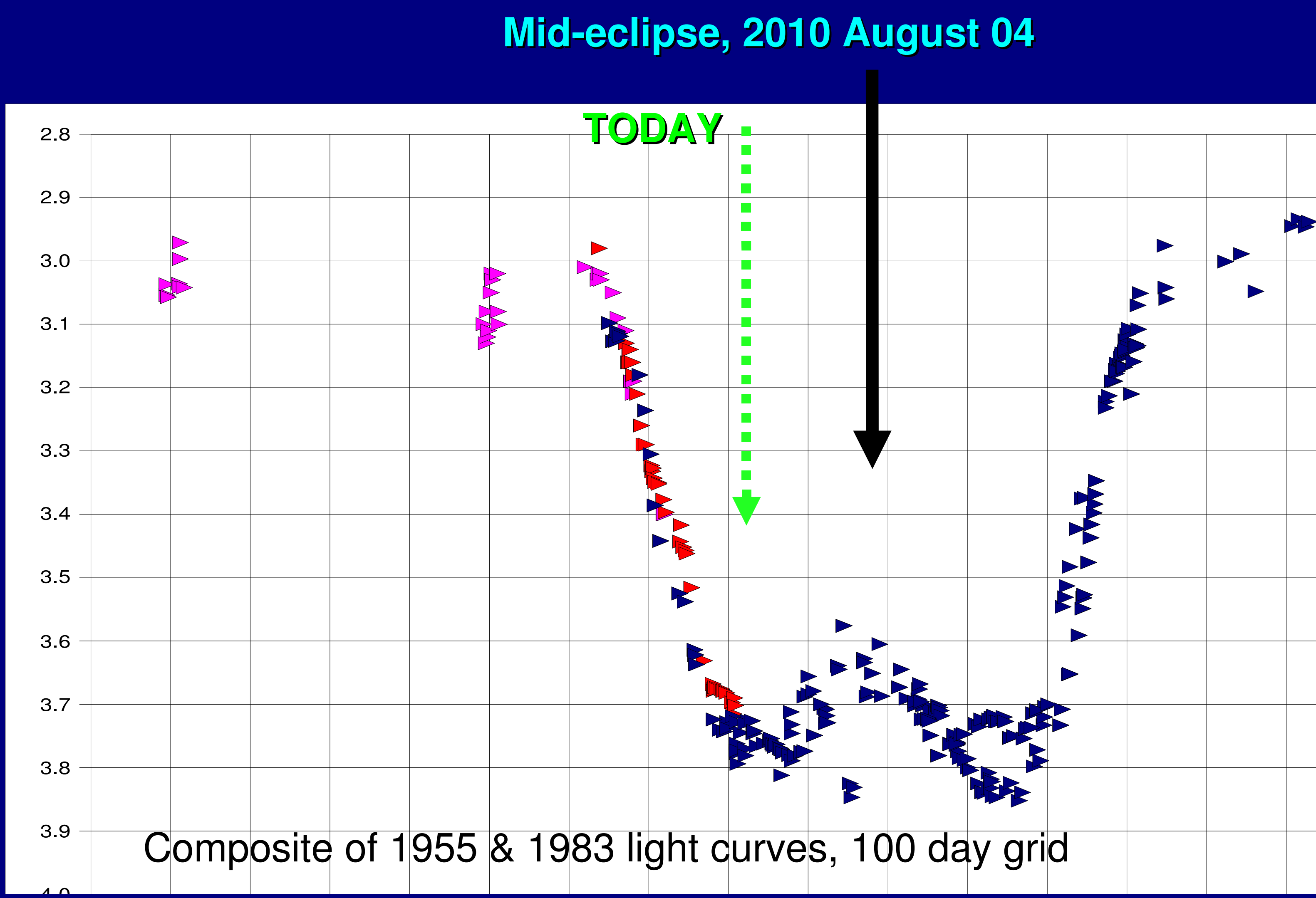

# Disk rotation curve, v(r)

# Tying it all together...




*Currently under study –*
*optical depth of K I line ~ 1, disk "atmosphere"*
*heating from F star (Lissauer 1996),*
*locations of expected resonances in system...*

# Mid-eclipse brightening:
# central clearing, and/or gravitational lens?



# Wish list:

Now that we can 'predict' the rest of eclipse events –

- Mar'10-Mar'11, CHARA+MIRC time, monthly monitoring

- NIR acquisition and tracking cameras for CHARA

  → extend into daytime; take advantage of the early morning seeing that solar astronomy at Mt. Wilson uses.

- Keck NIRSPEC time – high res 2+4 um CO profiles

- *Plus ANY/ALL earth & sky telescopic resources for*

  *the mid-eclipse lensing event: 4 Aug. 2010*

  *3Mo F star and 6Mo B star aligned to 1 milli-arcsec*

  *(however, star to star sep vs dist → tiny lensing)*

# Development # 4: a lack of Xrays

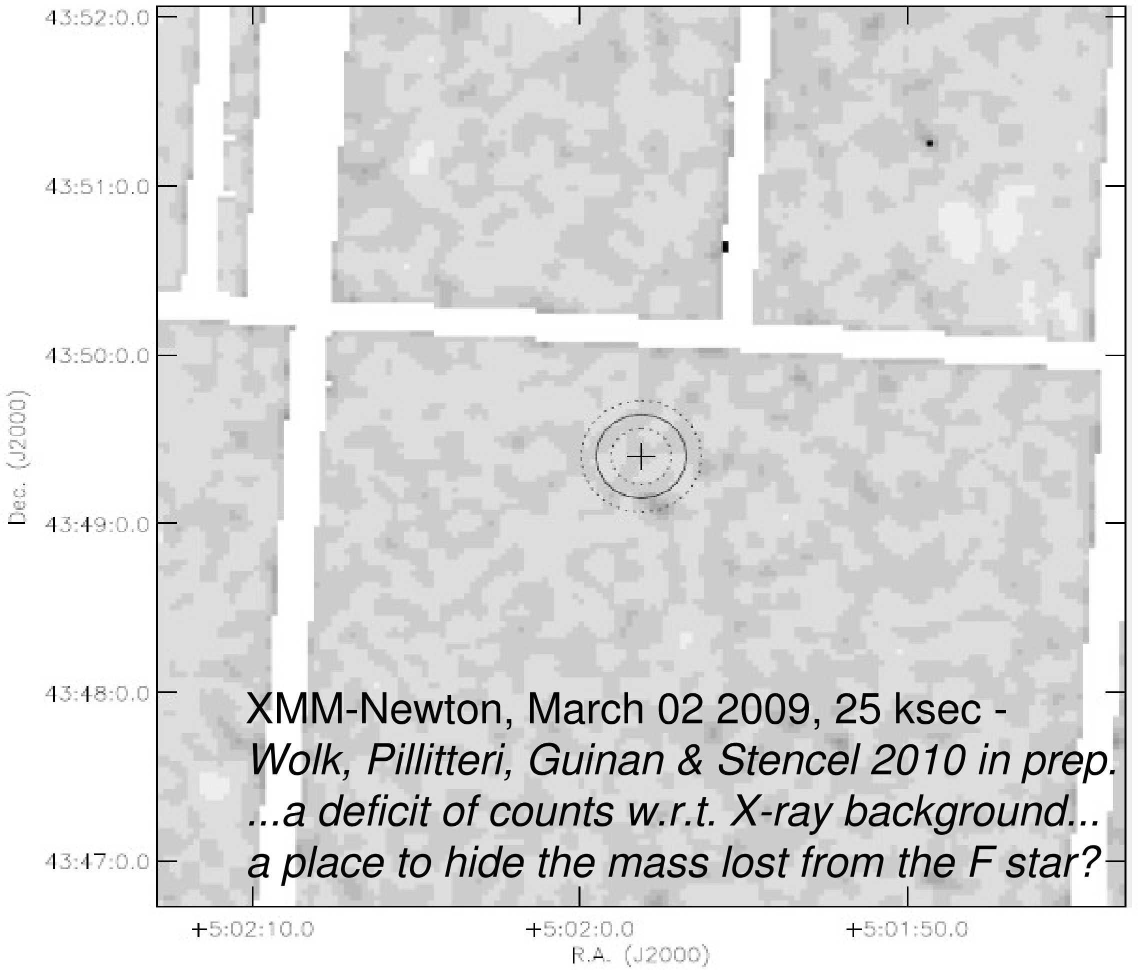



Fig. 1.— PN smoothed image (0.25-8.0 keV) on power law scale, centered on $\epsilon$ Aurigæ (indicated by the 'plus' sign). The three circles indicate 10″, 15″and 20″extraction radii.

# So, where does this leave us?
# .ε Aur, a changing scene

- Is the F supergiant actually a massive star, or a “phony”?
  - *SEEMS TO BE IN A POST-AGB LIKE STATE*

- Is the disk actually observable? Is it like other disks?
  - *DISK DETAILS ARE EMERGING! Models needed.*

- Could there be a black hole inside the disk?
  - *PROBABLY NOT, BUT STAY TUNED*

- Given answers to those questions, what's the evolutionary status of the star(s) in this binary system?
  - *Algol paradox again...*
  - *MASS TRANSFER vs MISSING MASS...*

# What's next?


epsilon Aurigae
The puzzling case of the
dusty disc and the phony star
The variable star epsilon Aurigae has perplexed astronomers for decades, but
Keith cooper finds that its latest eclipse is beginning to yield some long awaited answers.

# “It's not over 'til it's over...”

- Ingress began August 2009
- Totality started Jan 2010
- Mid-eclipse predicted for August 2010
- Totality ends March 2011
- Eclipse ends May 2011
- Next eclipse starts 2036

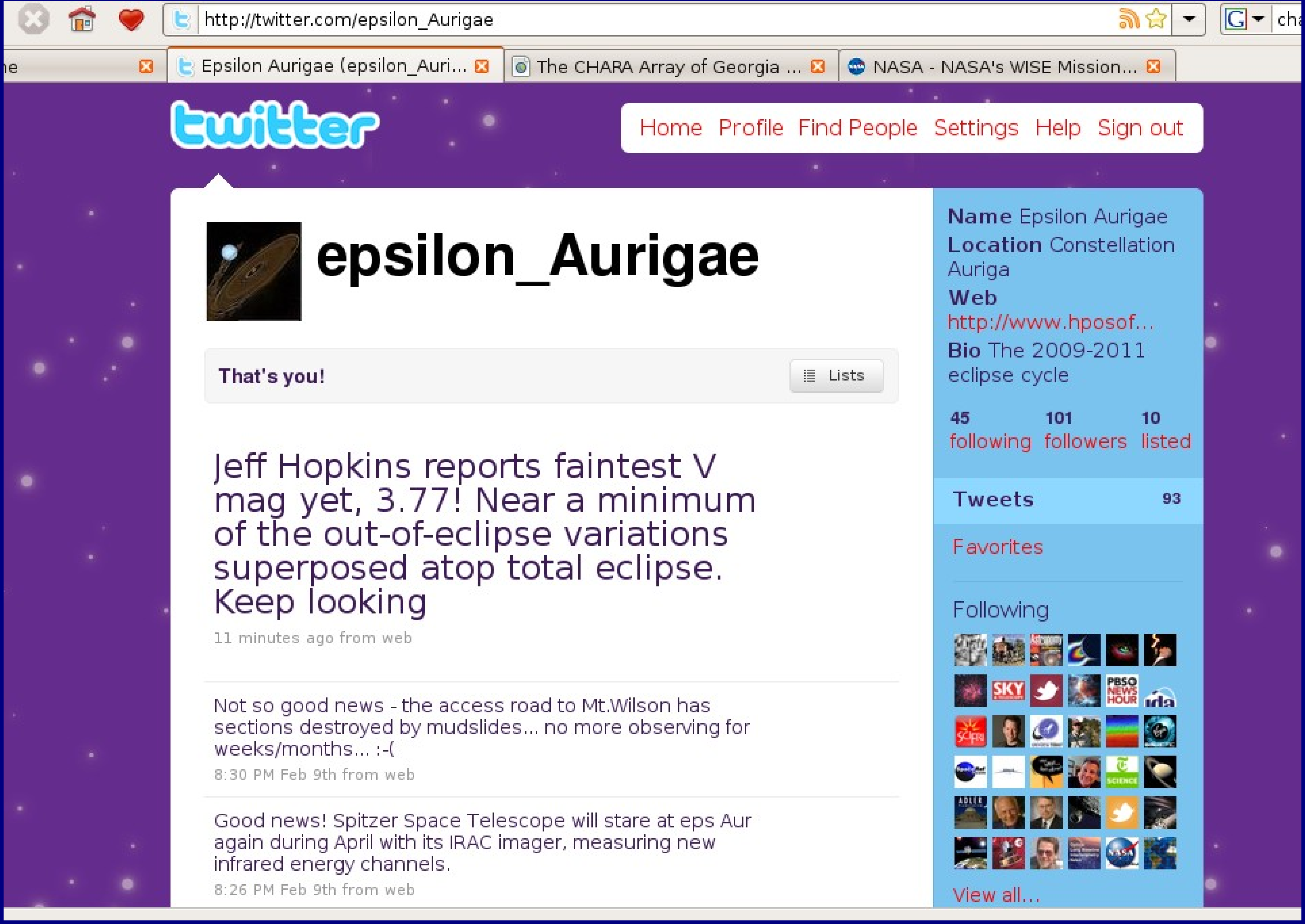
# In play:

| Observational thrust: | Relevance: |
|---|---|
| Mid-eclipse observations | Central opening in disk? |
| Interferometric imaging (MIRC plus VEGA & PAVO) | Disk shape, scale height, opacity structure |
| Infrared spectra | Re-appearance of CO – “perhaps from sublimating comets”<br>Limits on dust properties |
| Other data | UBVRIJH, SMEI, HST... |

# Inspiration... & outreach opportunity: www.citizensky.org ...

# & How Tweet it is...

## www.twitter.com/epsilon_Aurigae



Thanks for listening.

*Any questions?*

# End of slides,
# backup slides follow...

# Backup slides

# A 20th century mystery

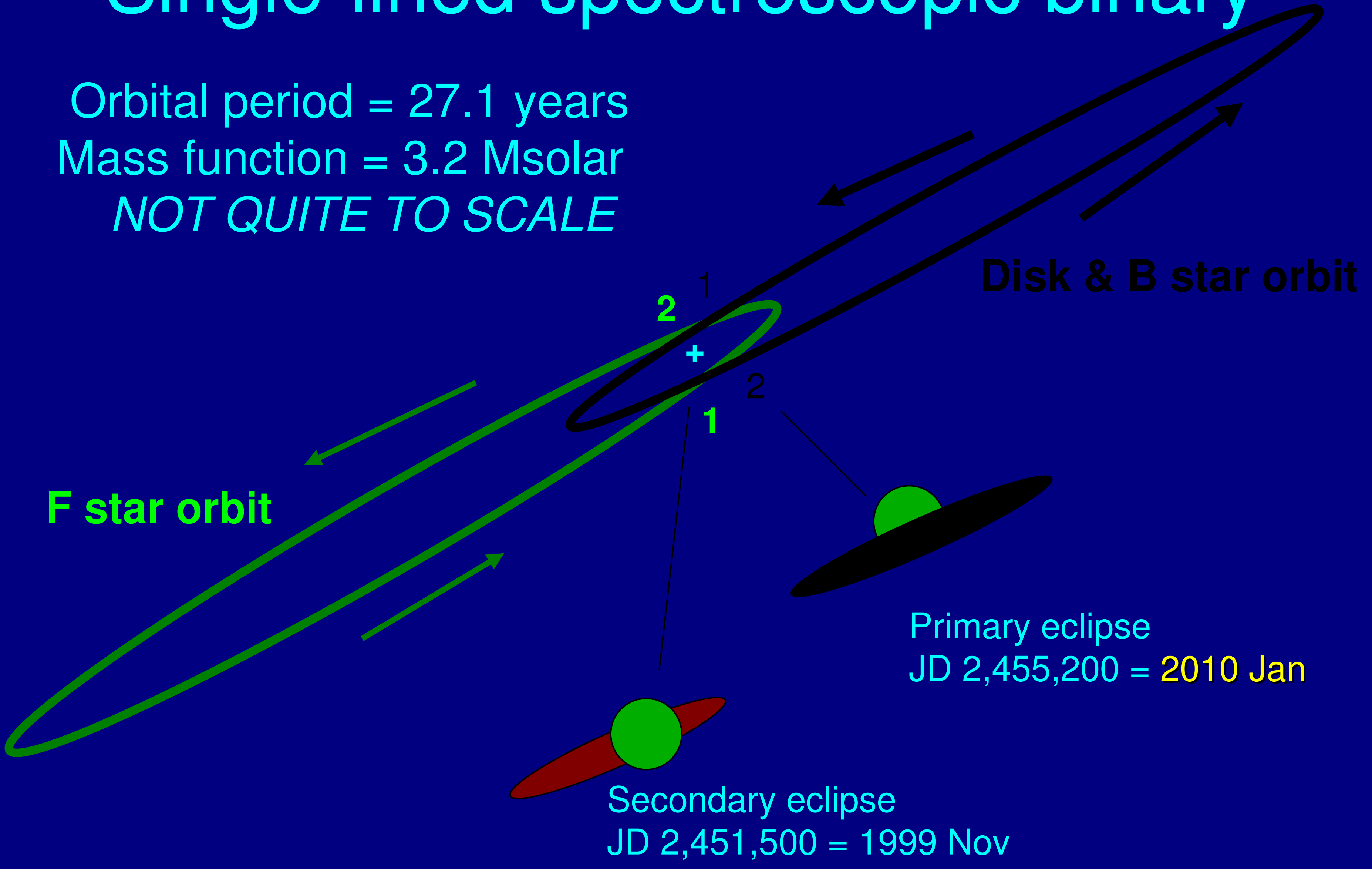
- Binary star theory (1912), Algol paradox
- The rise of astronomical spectroscopy
- Quantum theory & spectrum interpretation

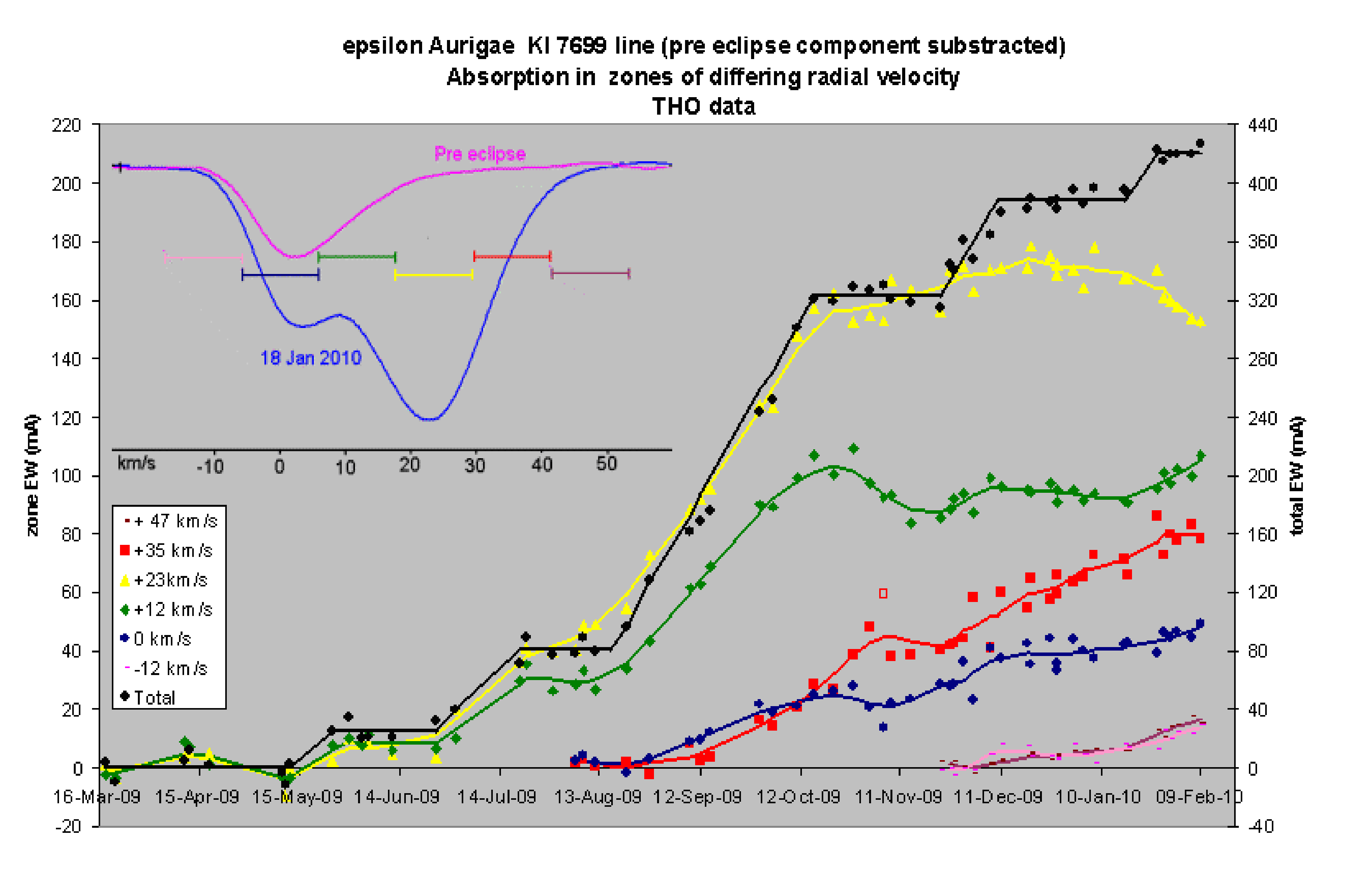
# Single-lined spectroscopic binary

Orbital period = 27.1 years

Mass function = 3.2 Msolar

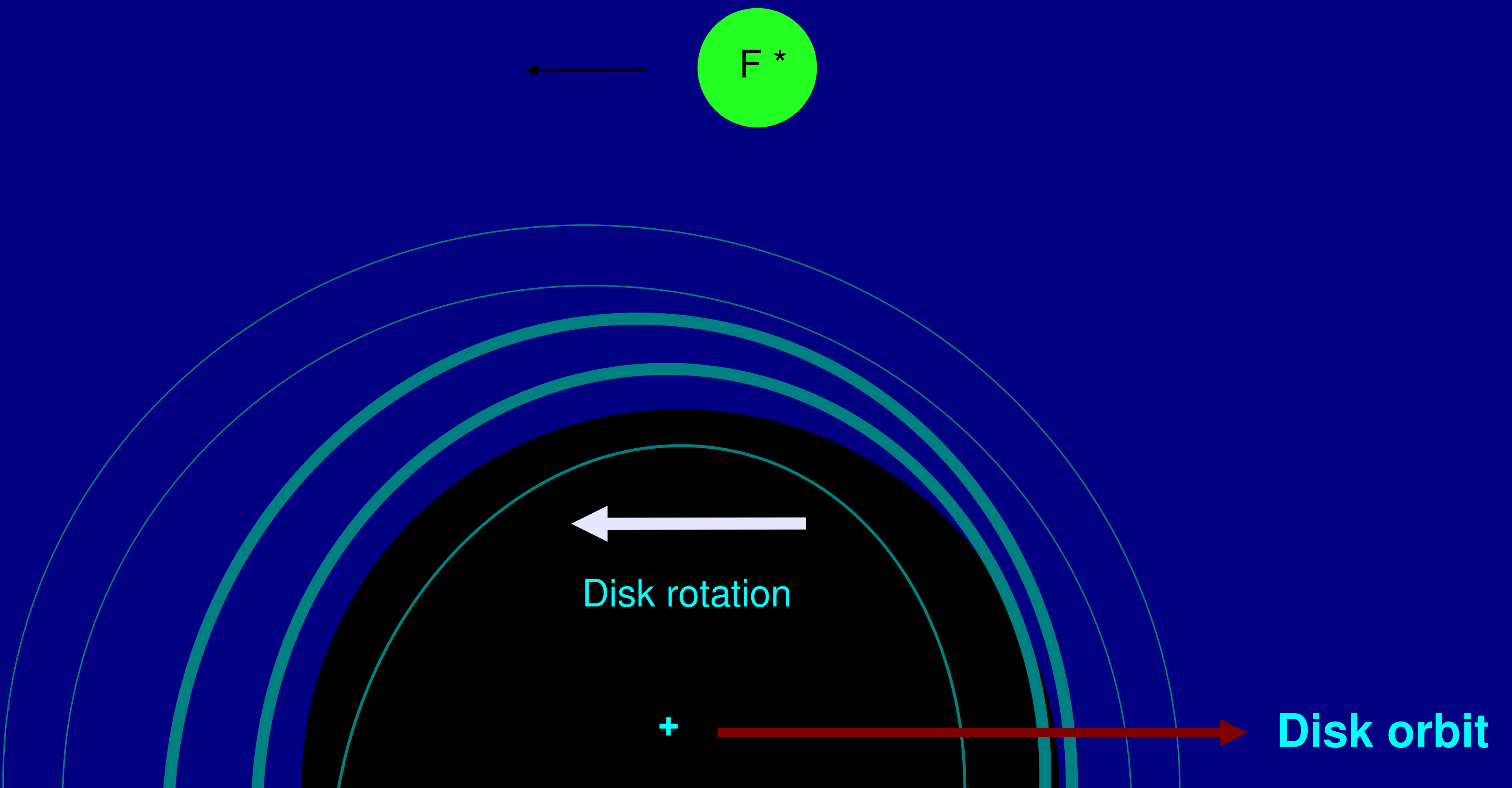
*NOT QUITE TO SCALE*



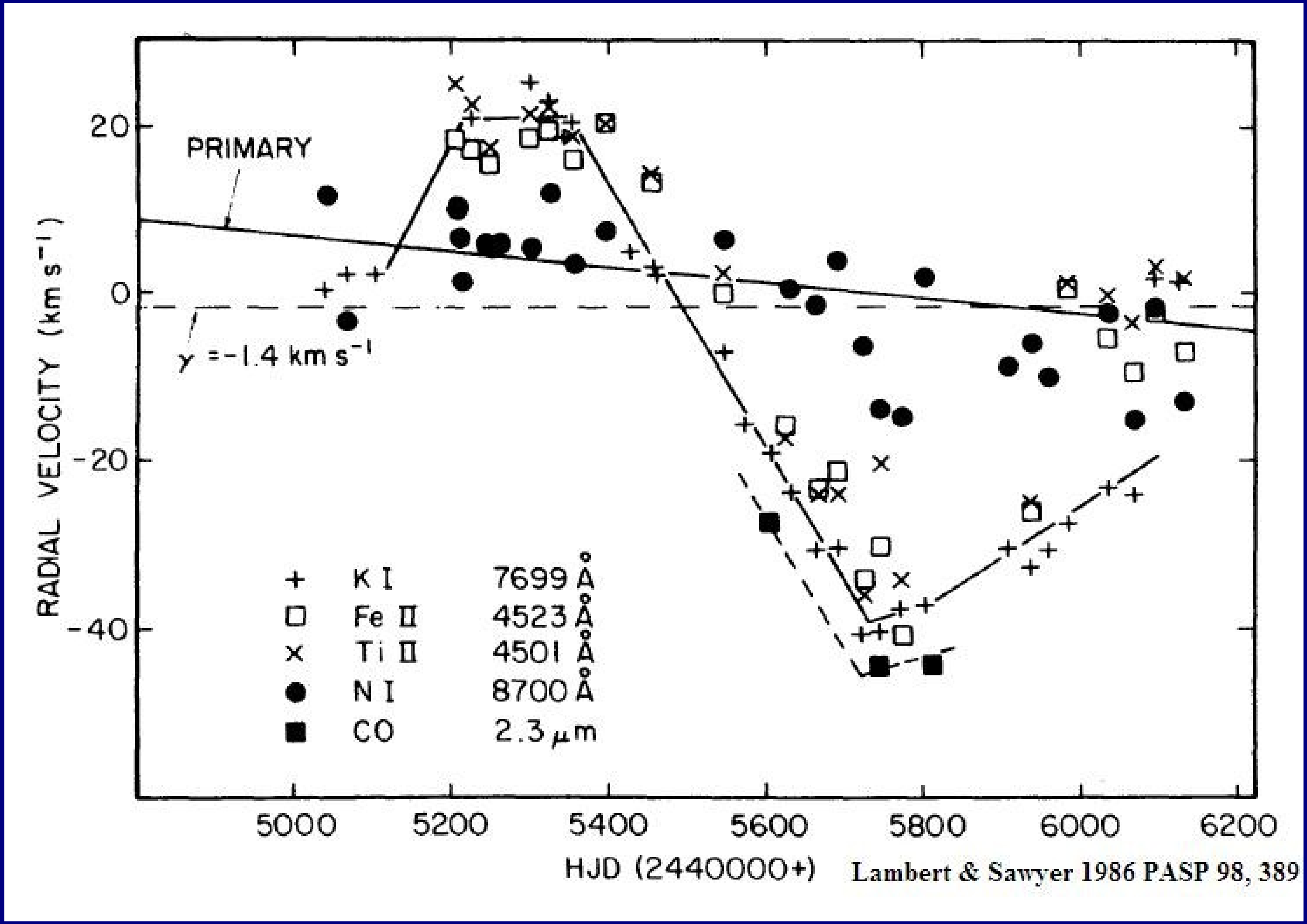


epsilon Aurigae KI 7699 line (pre eclipse component substracted)
Absorption in zones of differing radial velocity
THO data
zone EW (mA)
total EW (mA)
Pre eclipse
18 Jan 2010
km/s
-10
0
10
20
30
40
50
+ 47 km/s
+35 km/s
+23km/s
+12 km/s
0 km/s
-12 km/s
Total
16-Mar-09
15-Apr-09
15-May-09
14-Jun-09
14-Jul-09
13-Aug-09
12-Sep-09
12-Oct-09
11-Nov-09
11-Dec-09
10-Jan-10
09-Feb-10
220
200
180
160
140
120
100
80
60
40
20
0
-20
440
400
360
320
280
240
200
160
120
80
40
0
-40

# Alternative view of K I structure, accounting for pre/post mid-eclipse asymmetries *(need a good disk model)*



# Observed disk motions:
## is it +/- 30, or +20, -40?

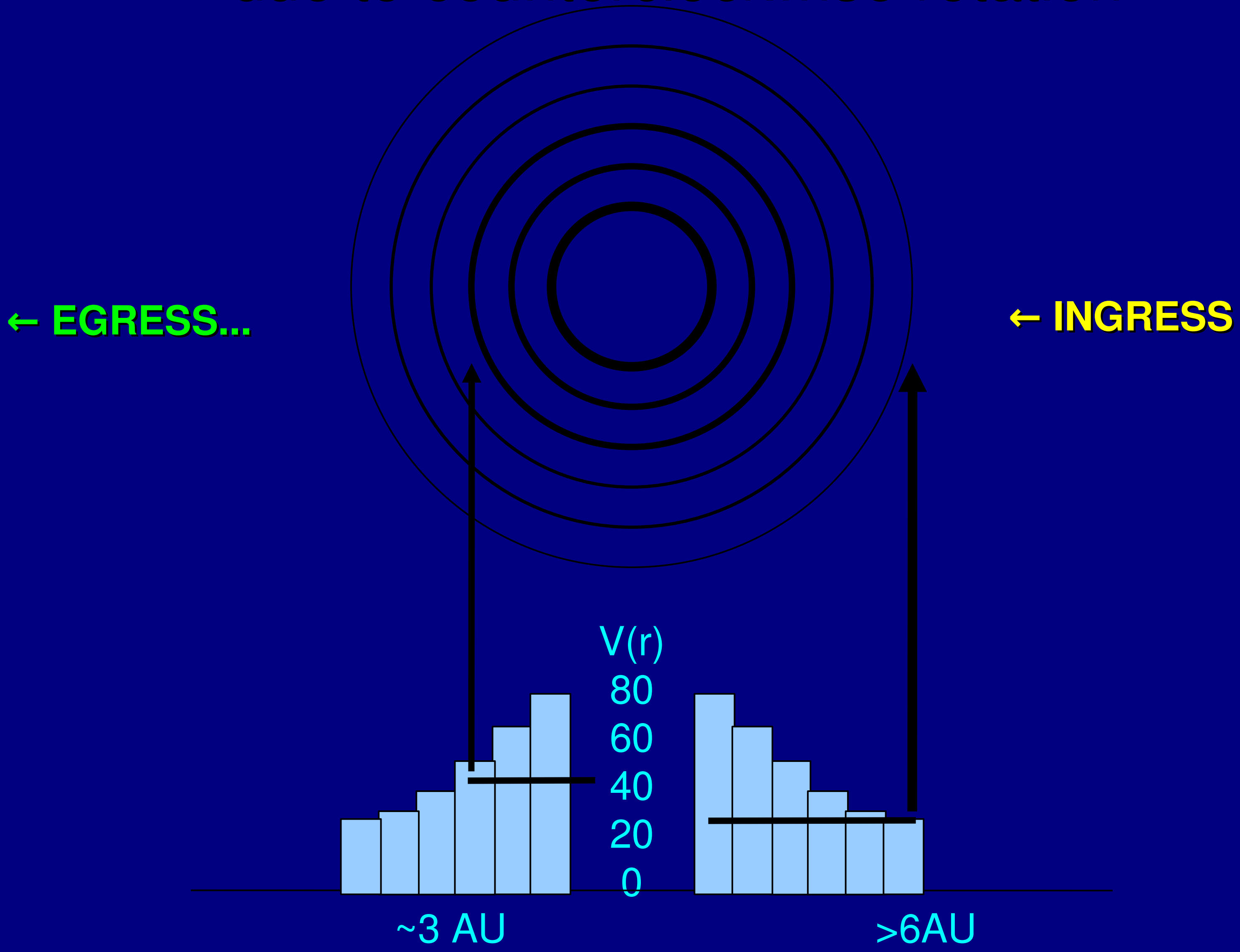


# Keplerian disk velocities

secondary mass
5.9 Mo

| disk, a (AU) | a^3/M | P(yr) | v(circ, km/sec) | |
|---|---|---|---|---|
| 1 | 0 | 0 | 72 | |
| 2 | 1 | 1 | 51 | |
| 3 | 5 | 2 | 42 | |
| 4 | 11 | 3 | 36 | **...EGRESS** |
| 5 | 21 | 5 | 32 | |
| 6 | 37 | 6 | 30 | |
| 7 | 58 | 8 | 27 | |
| 8 | 87 | 9 | 26 | |
| 9 | 124 | 11 | 24 | |
| 10 | 169 | 13 | 23 | **...INGRESS** |

# Disk optical depth 'asymmetry' due to counterclockwise rotation



Among the possible causes of the observed discontinuities are:

(1) nested ring structure related to disk Keplerian sub-structure and tidal resonances with the F star,

(2) nested parabolic arcs representing a cometary evaporation of the disk in the presence of the F star UV radiation,

(3) optical depth variations enabling study of different portions of the disk, particularly in terms of ingress (morning) and egress (evening) sides of the disk, relative to exposure to F star UV radiation.

Combinations of these effects are possible, plus unanticipated complications are inevitable, given the long history of studies of this star.

Alternately, it is useful to recognize the presence of the F star has at least three effects on the disk:

(1) heating the top and bottom of the disk given that the F star diameter (1.5 AU) subtends nearly twice the thickness of the disk (0.9 AU);

(2) heating of the facing portion of the disk, and

(3) tidal effects (resonances).

Thus far, we are ignoring additional effects of the point-like (10 solar radii) B5V star presumed to be present in the center of the disk itself.

# → Tomography of the star

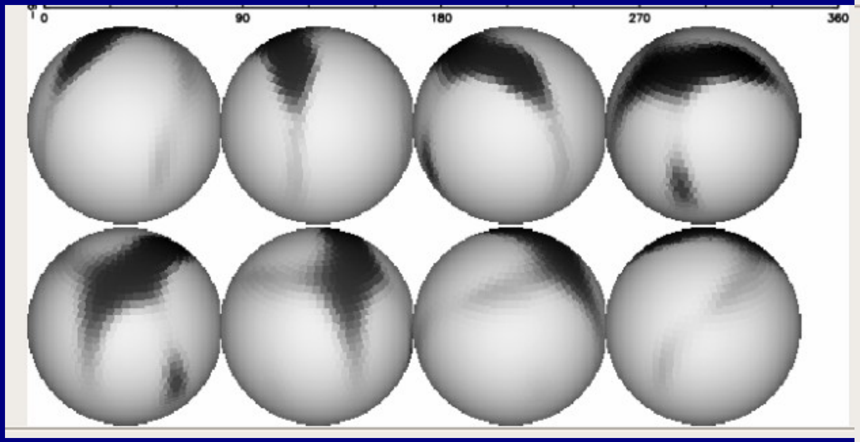
Hint of photospheric bright spots in the MIRC images...

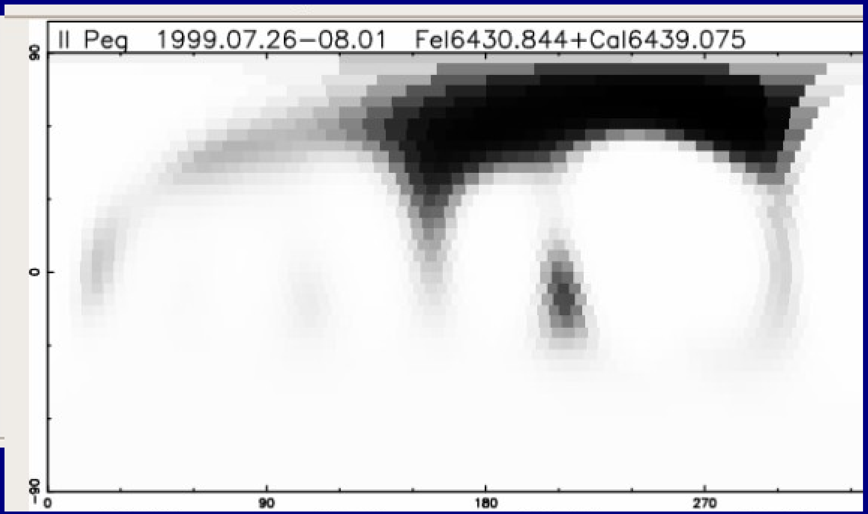
Out of eclipse light variations, ~0.1 mag, ~100 days, v.v.blue

Could these be 'asteroseismic' – e.g. tops of giant convective cells, tidally enhanced at sub-disk longitudes?

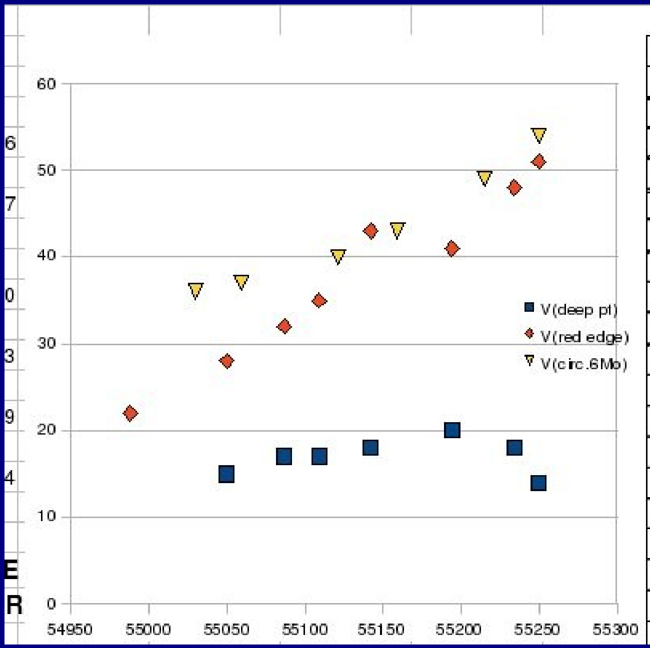
"Easy answer" - seek Doppler imaging followup...

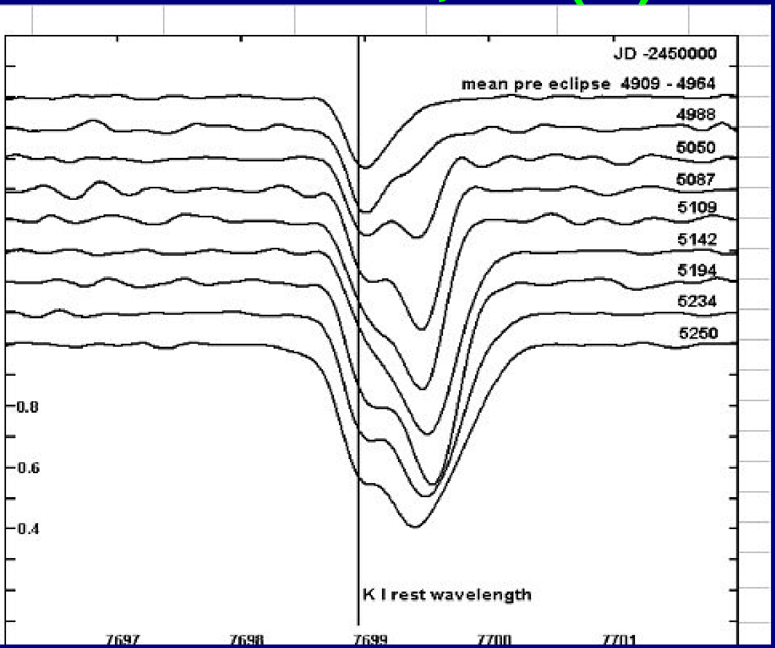
*(thanks, Paul Hemenway for the suggestion)*



# Disk rotation curve, v(r)




Leadbeater & Stencel 2010 arXiv; the 1986 coverage by Lambert & Sawyer was too sparse.

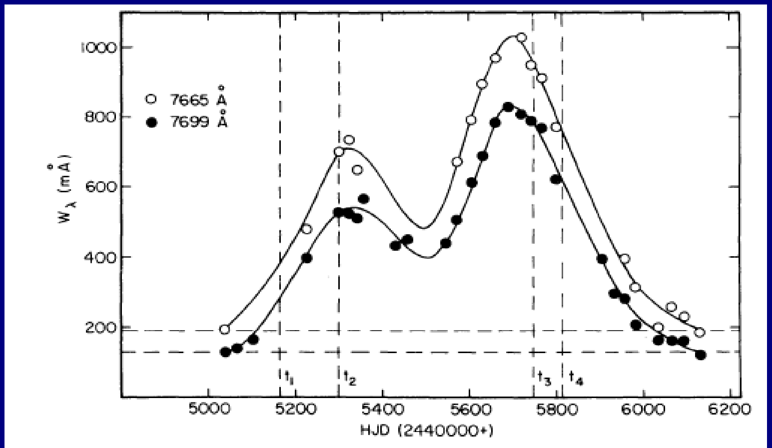
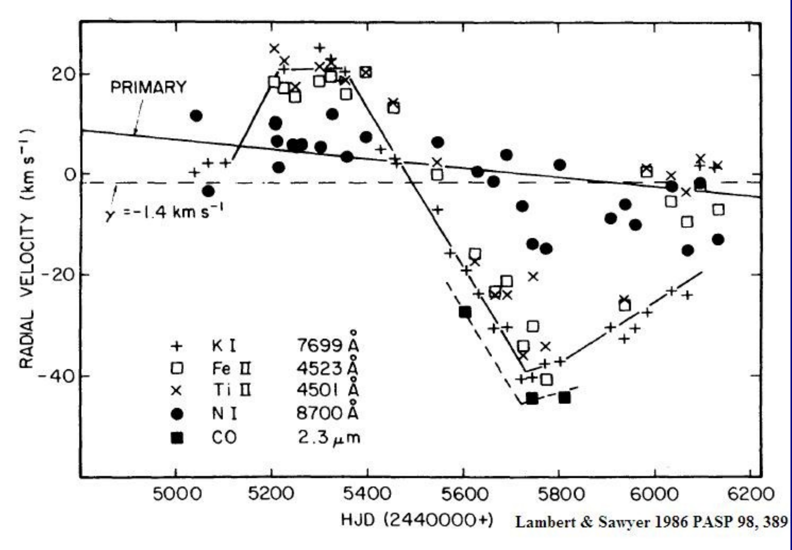



FIG. 5–Variation of the equivalent width of the K I 7664 and 7699 Å lines. Schmidtke's (1985) estimated times of first through fourth contact are indicated by the broken lines.



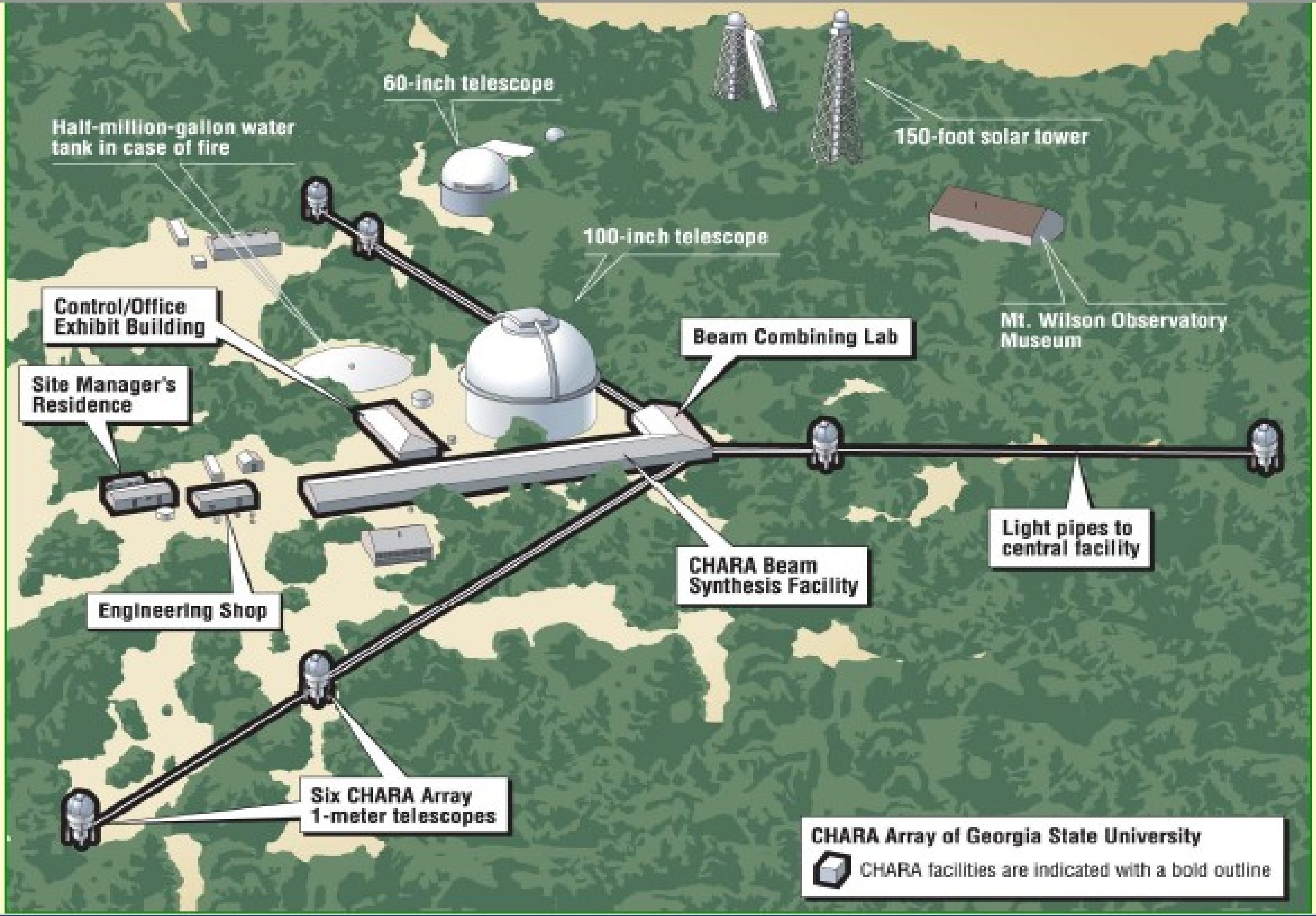
# Today's topic: “Hobby-horse”...

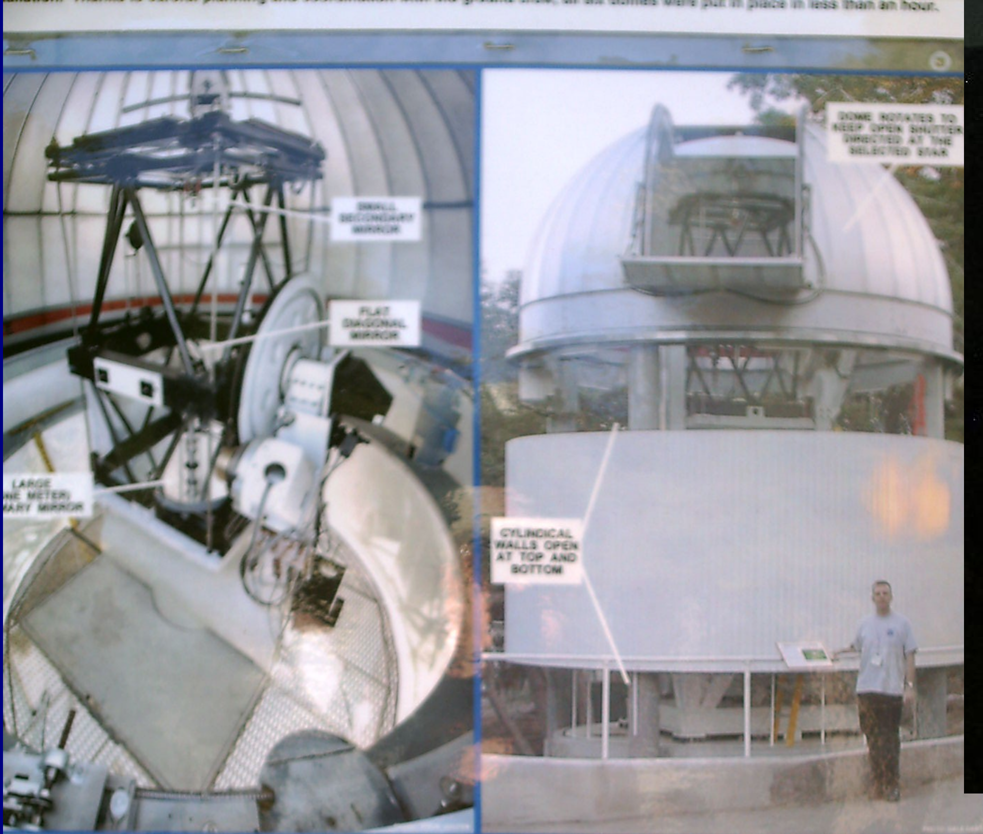
A hobby horse (or hobbyhorse) can be several things [wikipedia]:

* "Irish Hobby" or "hobby" ; an extinct type of horse.
* A toy horse, consisting of a model of a horse's head, usually wooden, attached to a stick. This is often used by children to simulate riding a horse, see hobby horse.
* A toy horse suspended by springs from a frame
* The figure of a horse fastened around the waist in the Morris dance.
* Euphemistically, in Shakespearean times, a prostitute or promiscuous woman...

* Someone's favorite topic, to which he constantly reverts.

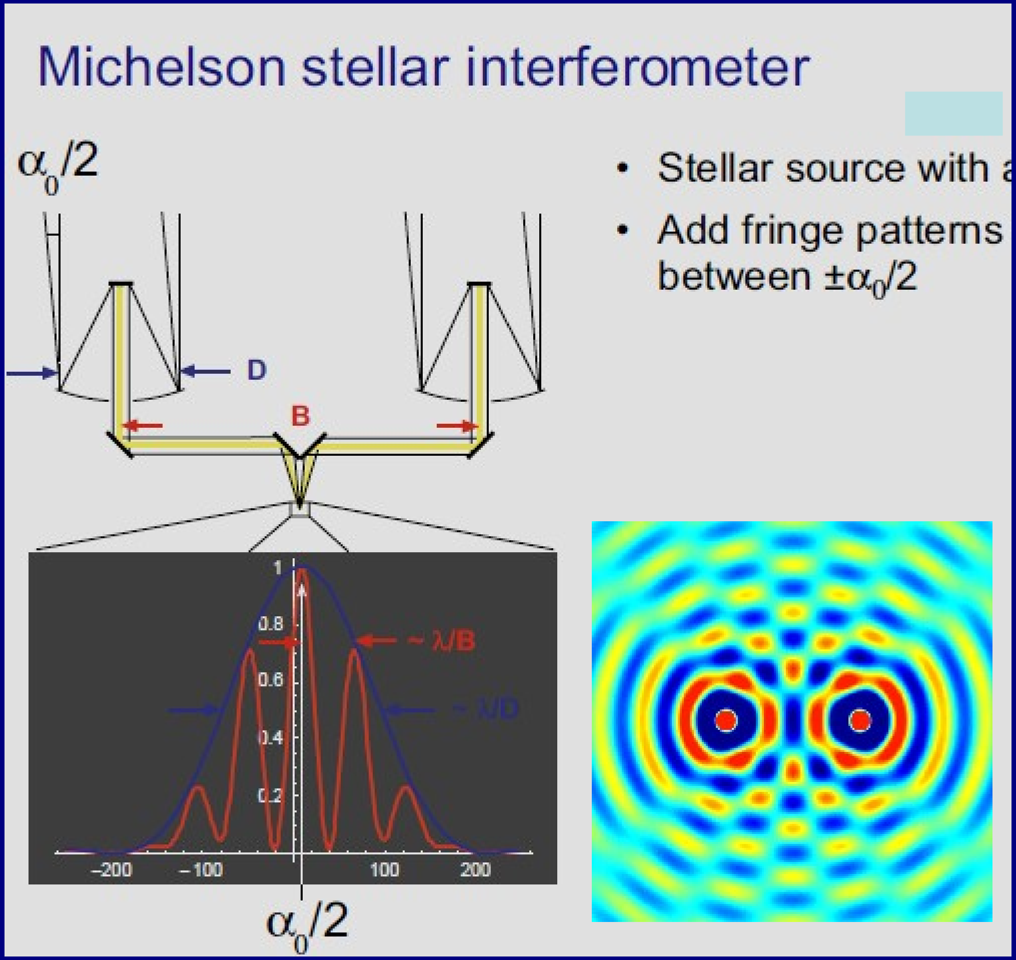
# Layout of the CHARA Array




SMALL SECONDARY MIRROR
FLAT DIAGONAL MIRROR
LARGE
DOME ROTATES TO KEEP OPEN SHUTTER DIRECTED AT THE SELECTED STAR
CYLINDICAL WALLS OPEN AT TOP AND BOTTOM


OPTICAL CARTS
OPTICAL PATH LENGTH EQUALIZATION
(DELAY LINE OPTICS)

# How does it work? By combining telescopes:




Each pair of telescopes produces an antenna pattern on the sky, perpendicular to the baseline, and resolves lambda / baseline.

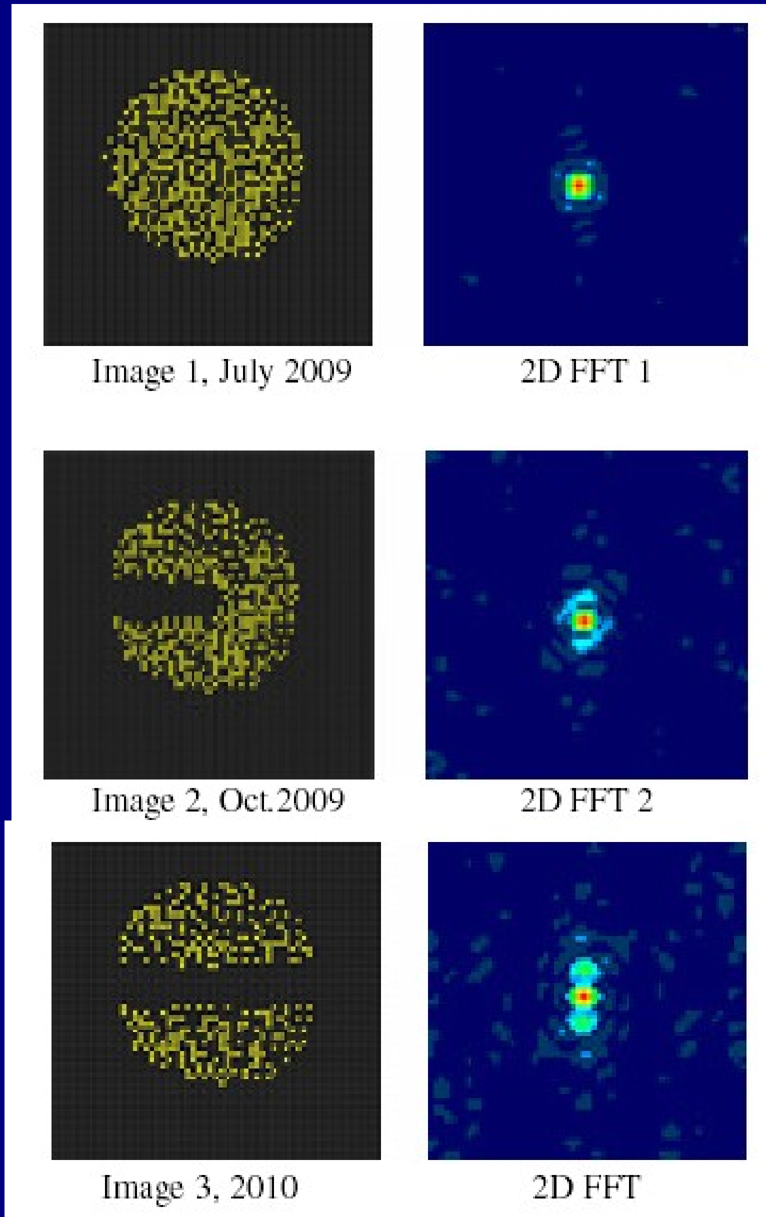
| Baseline | Resolution* |
| --- | --- |
| 1 meter | 0.1 arcsec |
| 10 m | 0.01” |
| 100 m | 0.001” |
| | *=1 milli-arcsec* |

**at 550 nm (V band)*

*Compare with VLA, New Mexico*
*3 cm, radio telescope*
*27 km max spacing*
*→ micro-radian resolution →*

# What to expect during eclipse?

Image space →
Scale is
Milli-arcsec
(nano-radians)




← Interferometric
view with fringes

Direct test of the
Huang disk model

A worthy task
for modern
interferometers
like CHARA,
NPOI, (MROI)

# Polarimetry

- Some key papers (very few to choose from)

Jack Kemp 1986 Astrophys. Journal

*Epsilon Aurigae - Polarization, light curves, and geometry of the 1982-1984 eclipse*

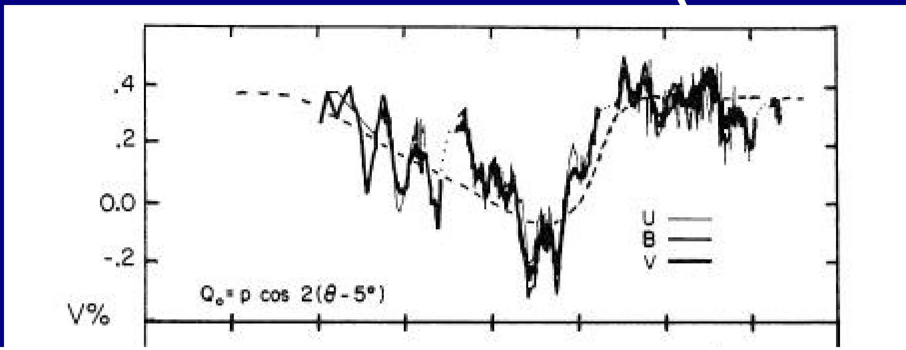
David Harrington & Jeff Kuhn

*2009 Astrophys Journ.*

*(survey) Ubiquitous Hα-Polarized Line Profiles*

Gary Cole, 2010?

# "Recent" (i.e. the only) results




Kemp, 1986

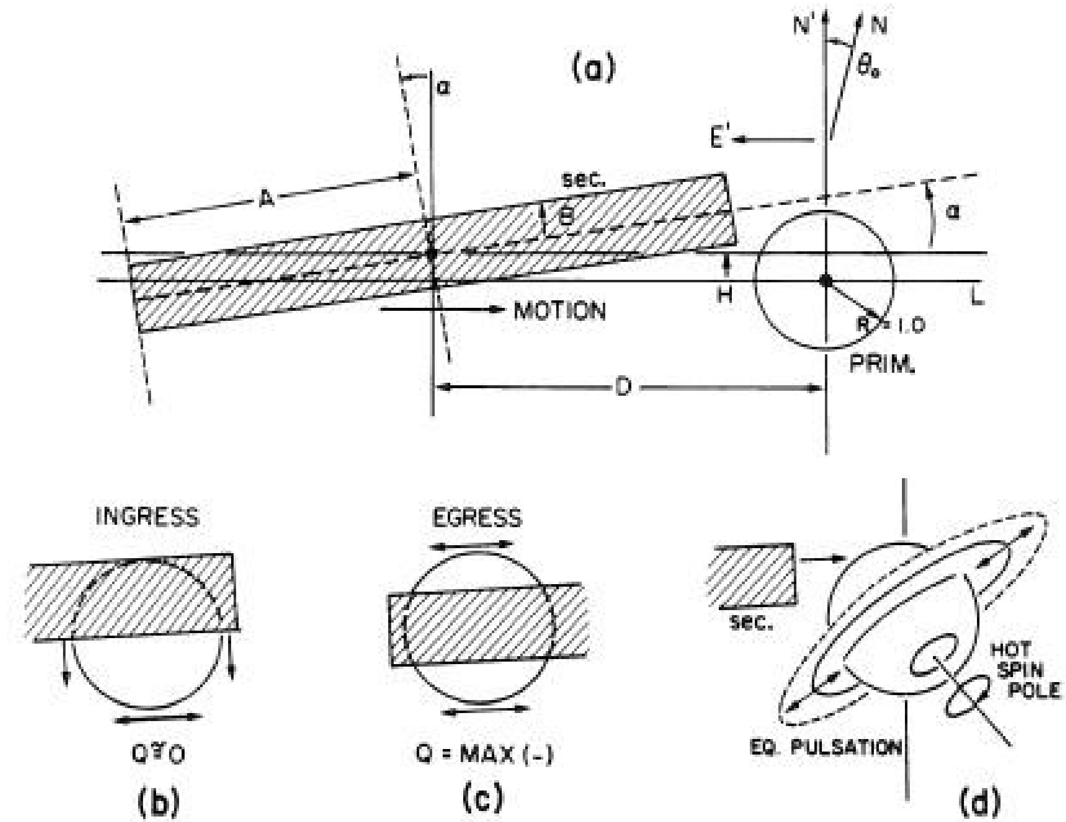



FIG. 2.—Model geometry of the eclipse, showing in Fig. 2*a* the model parameters. In Fig. 2*d* is a hypothetical geometry for future modeling involving a tilted, rotating primary star with nonspherical pulsations possibly correlated with the spin axis.

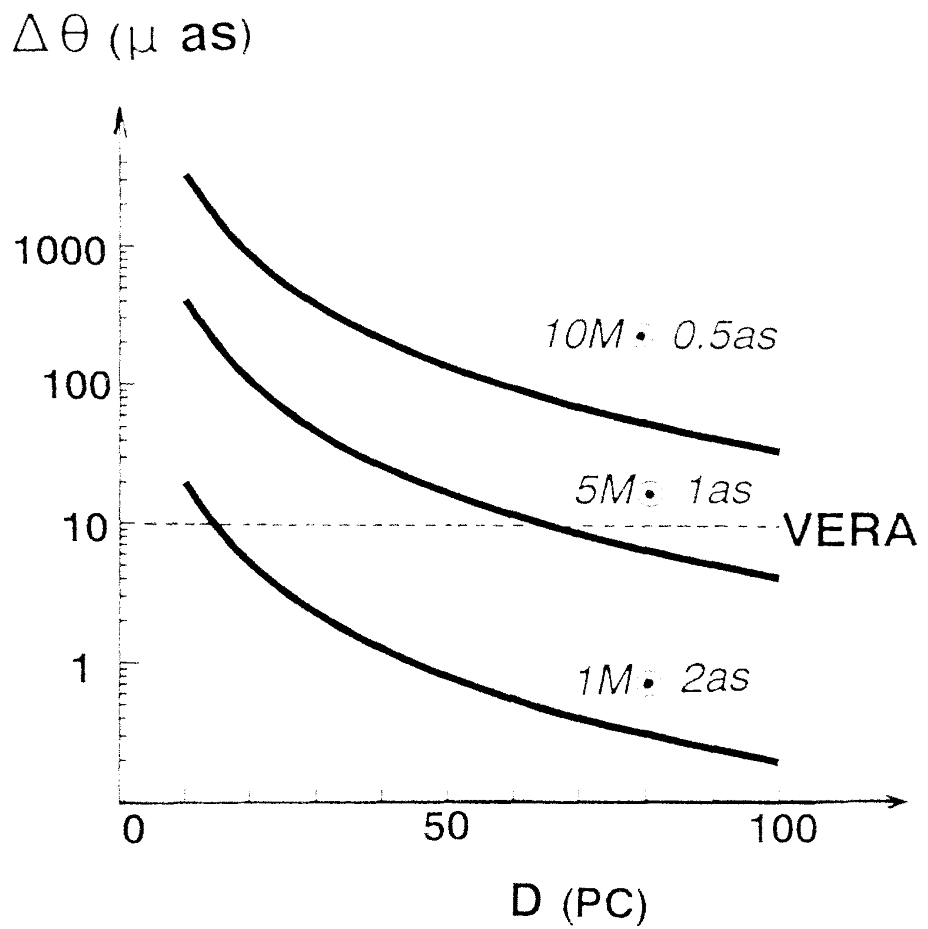
J.Kemp et al. 1986 Astrophys.J. 300,L11.

## How big a lensing effect? Huge? ... *at micro-arcsec level*

Hosokawa et al. (1993)

http://www.terrapub.co.jp/e-library/vlbi/pdf/chapter3/VLBI282.PDF

$$\Delta\theta_x = \frac{x}{D}\left(1 - \frac{4GM}{c^2 D\theta^2}\right), \quad \Delta\theta_y = \frac{y}{D}\left(1 + \frac{4GM}{c^2 D\theta^2}\right).$$



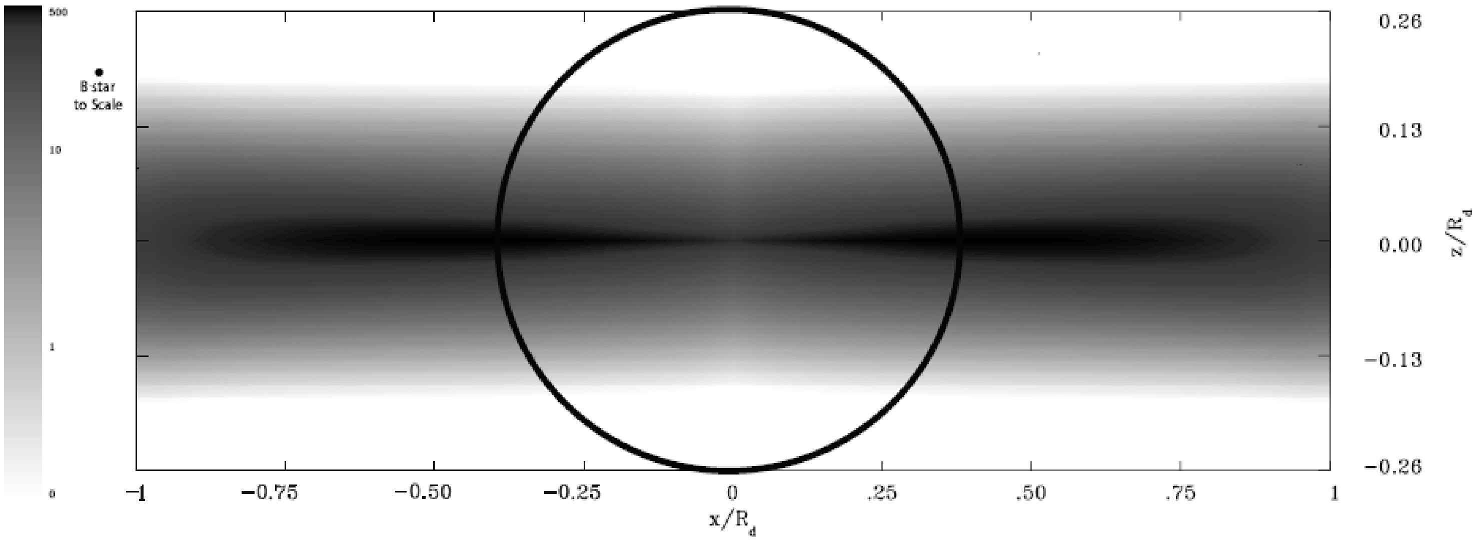



Fig. 3.— An optical depth profile for a hydrostatic disk with a hole. As in the previous figure except that this is a medium opacity case (maximum optical depth=500) with a central hole of radius 0.9 $R_D$. The diameter of possible central stars is indicated on the left - X-rays from such a star could be visible through the central hole if there were near the light of sight.

We haven't yet seen directly into the center of the disk – but we can try for it this summer 2010

OBSERVING: Yes – see Mars!
@ DU's Chamberlin Observatory
This Saturday 2/20: 7-10pm…if clear
Be prepared for cooler temperatures