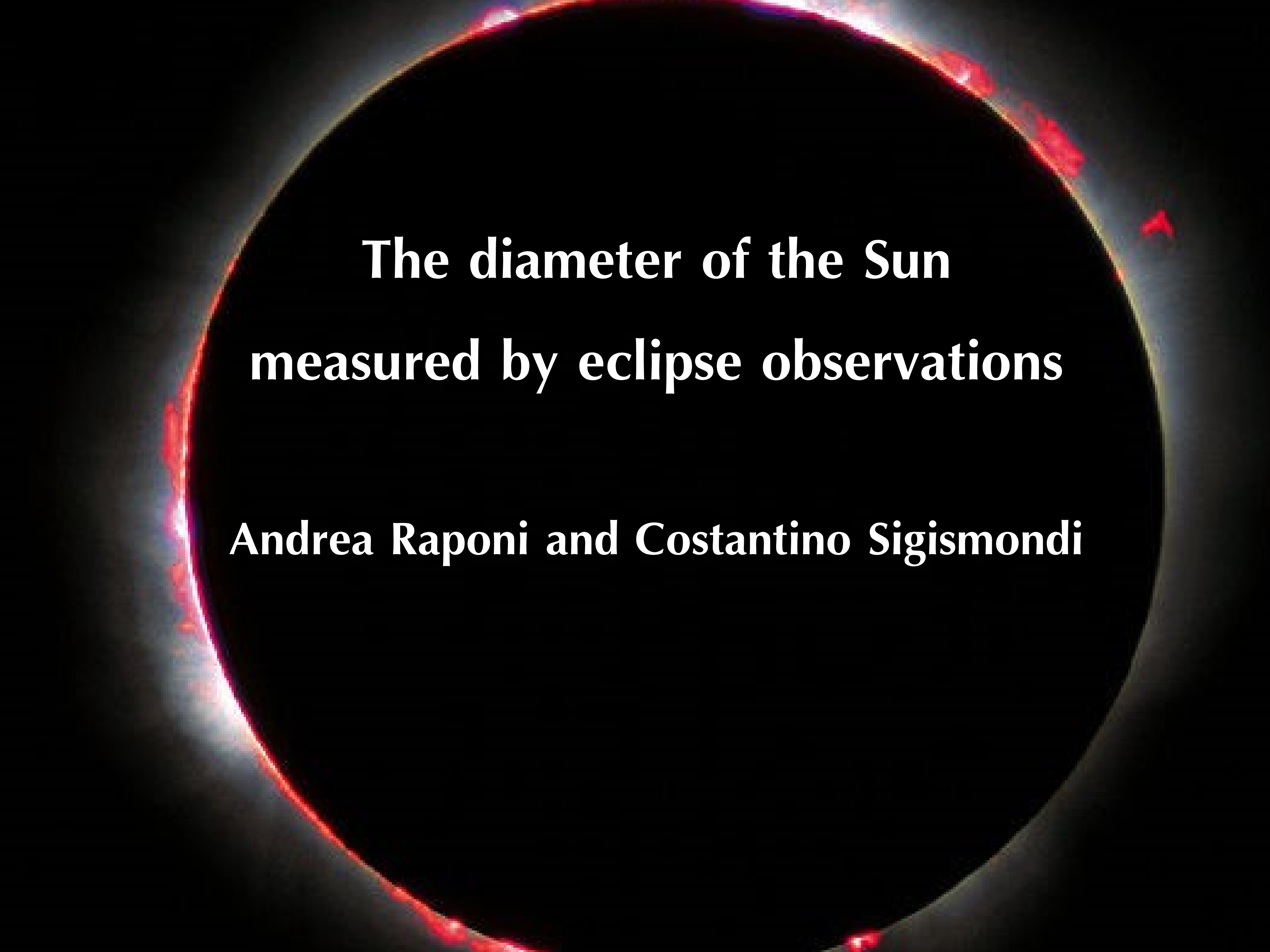
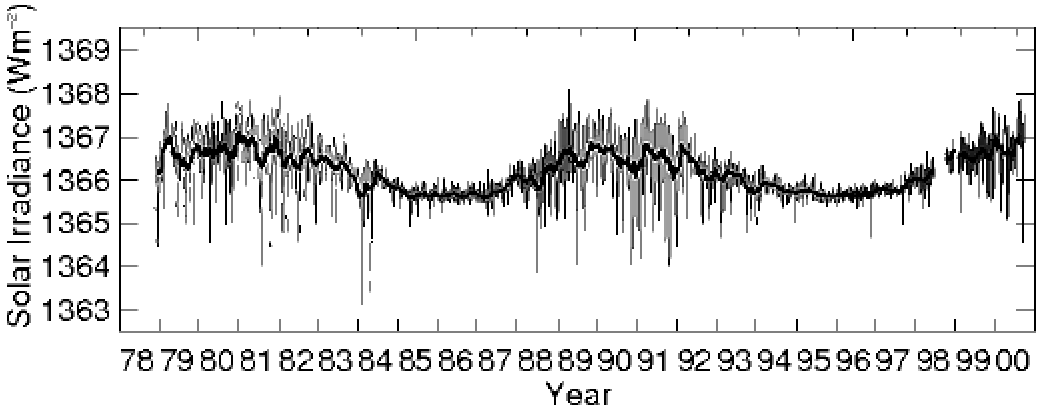


The diameter of the Sun measured by eclipse observations

Andrea Raponi and Costantino Sigismondi

Solar parameters variability



The variation of the Total Solar Irradiance could be explained by:

- **Surface magnetism:**
  can explain up to **96%** (SOHO data, Krivova et al. 2003)

Luminosity, Temperature, Radius : link and relative variation

$$L_{\odot} = 4\pi R_{\odot}^2 \sigma T_{eff}^4 \qquad \Delta L/L = 2\Delta R/R + 4\Delta T_{eff}/T_{eff}$$

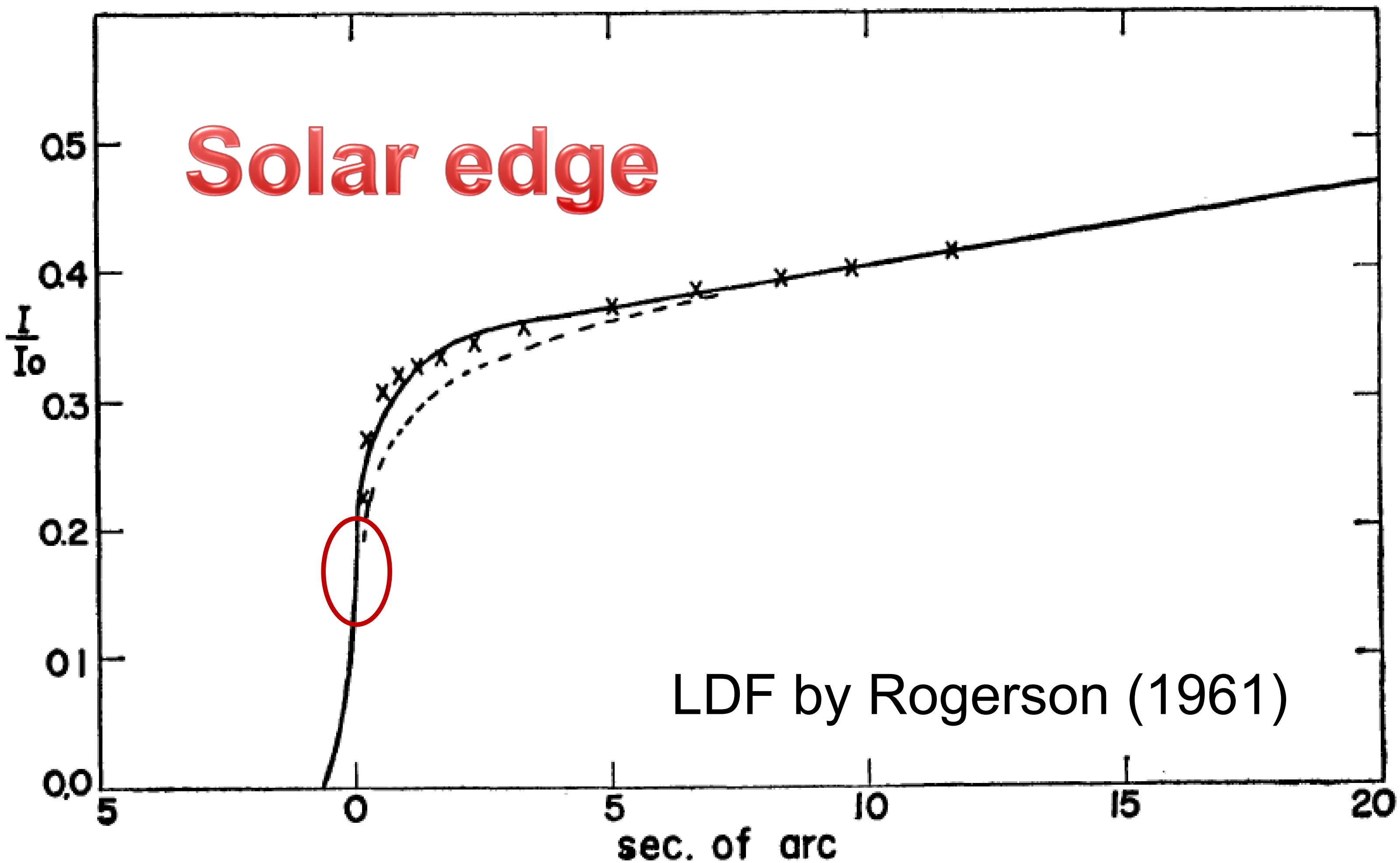
- **Photosferic temperature variation:**
  $\Delta T = 0 \pm 0.3$ K at the center of the solar disk (Livingston et al. 2005)

- **Radius (diameter) variation:**
  the most uncertain parameter of the solar cycle-related changes:
  SDS ➔ $\Delta R \approx$ -200 mas = -145 km; SOHO ➔ ΔR = +23 mas = + 17 km

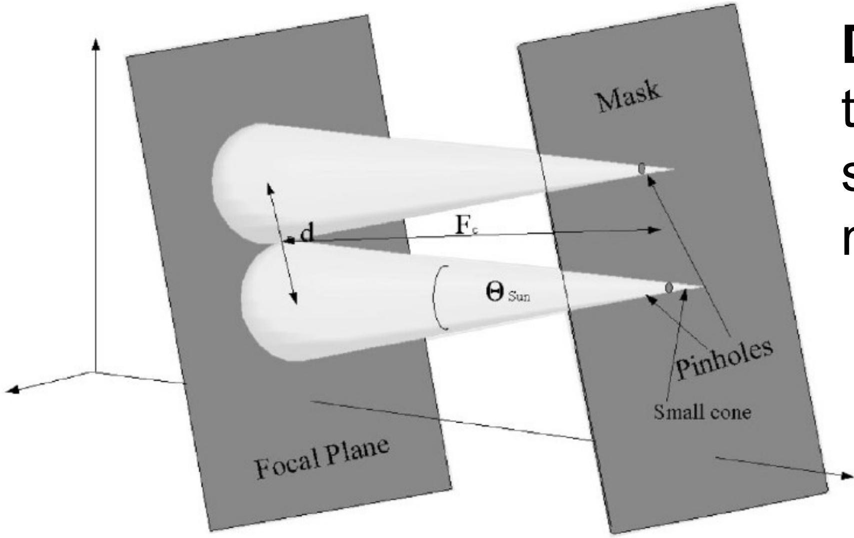
what about SDO?

Measuring the Solar Diameter: definition of the edge

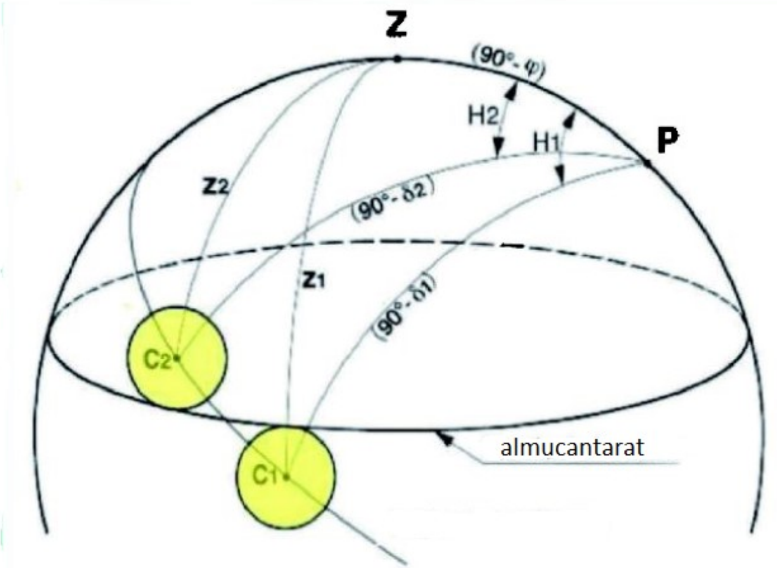
The Inflection Point Position of the Limb Darkening Function is the definition of the solar edge

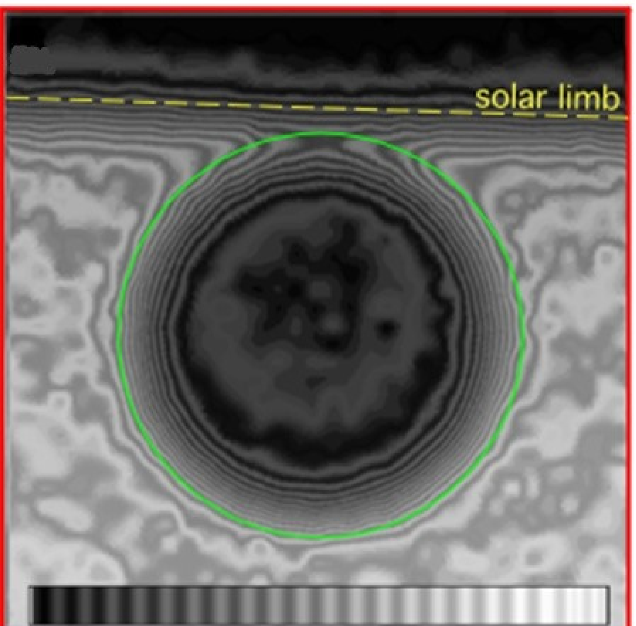


Measuring the Solar Diameter: Methods



Direct measure, heliometers:
two pinhole concept $\theta_{\odot} = (d - d_p)/f_c$
simple method but excellent thermal and mechanical stability is required.



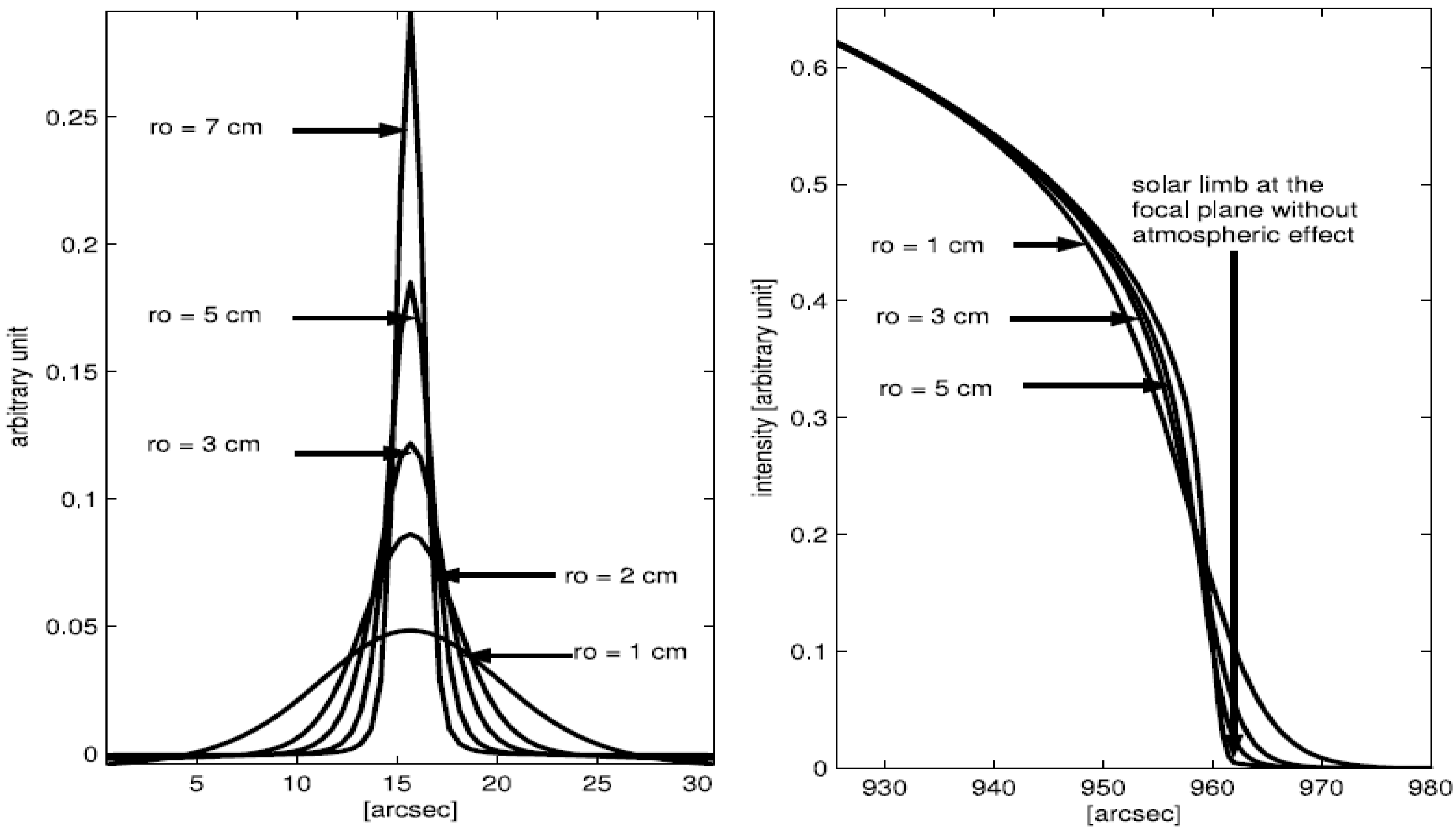


Planetary transits:
The ephemeris and the time duration of the transit give the measure of the diameter, but it is affected by black drop phenomenon.

Drift scan method: $\theta_{\odot} = \omega/t$
transit of the Sun to a given meridian or almucantarat.
It bypasses the optical aberration but it is still affected by atmospheric seeing.

Measuring the Solar Diameter: problems

PROBLEM 1: The Point Spread Function of the telescope and atmosphere displace the Inflection Point Position inwards

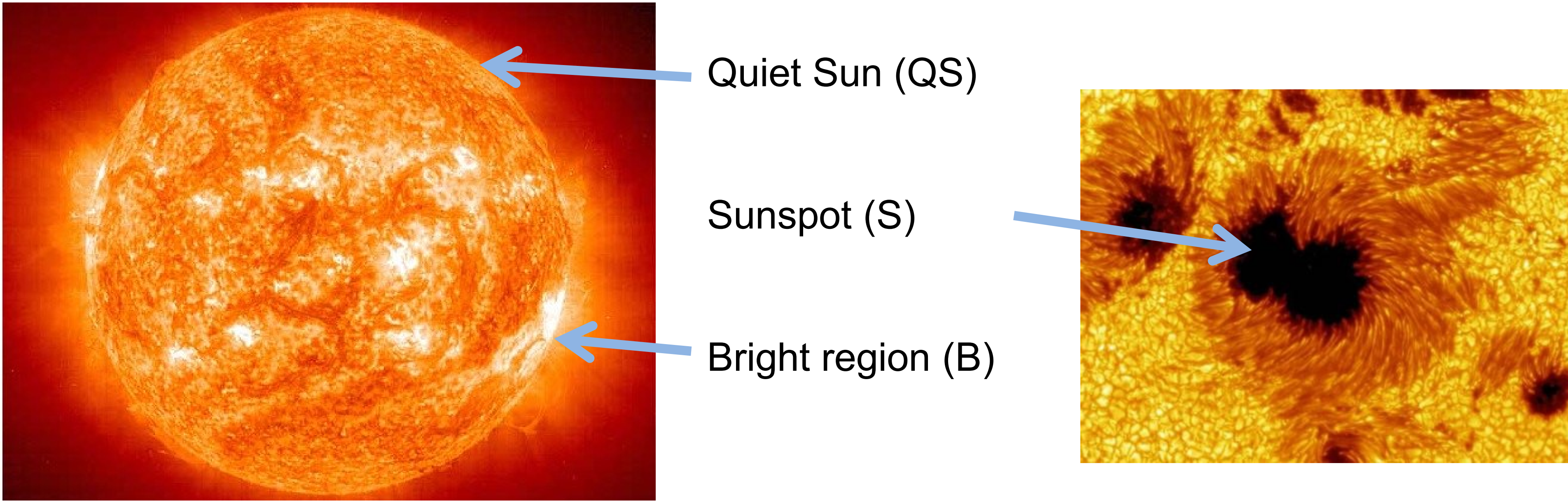


FWHM ~ λ/D or FWHM ~ λ/r_0

r_0 = 5 cm ➔ displacement =123 mas

Measuring the Solar Diameter: problems

PROBLEM 2: The Inflection Point is displaced by Solar Active Regions



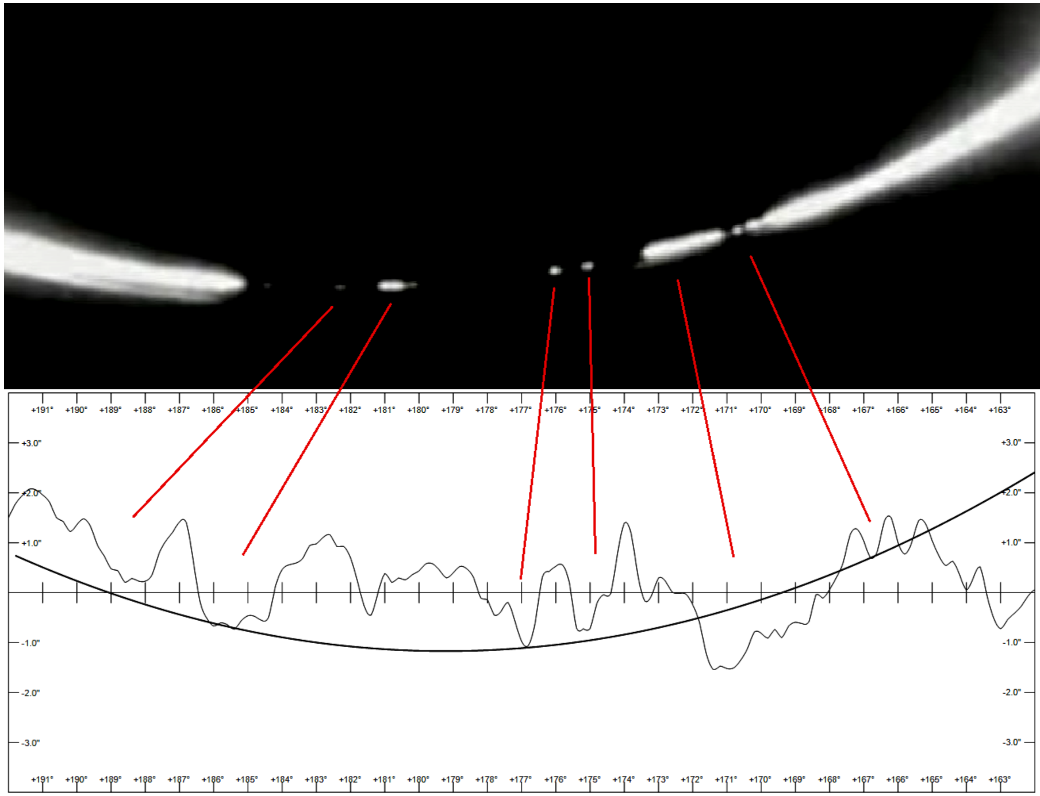
Model types	ΔIPP (400 nm)	ΔIPP (600 nm)	ΔIPP (800 nm)
B-QS for FCH09	35.86 mas	55.82 mas	46.95 mas
S-QS for FCH09	– 50.40	– 183.32	– 197.60
B-QS for VAL81	6.70	13.49	15.39
S-QS for VAL81	– 11.74	– 6.96	– 1.63
B-QS for COSI	– 4.10	4.10	1.40
S-QS for COSI	– 285.10	– 290.80	– 285.30

We need to observe in the Quiet Sun

Measuring the Solar Diameter: Eclipse observations

With the eclipse observation we are able to reduce the problems

Exploiting the **Baily's Beads** observations. When the beads appear (or disappear) the solar limb is tangent to the bottom of a lunar valley we can compare observations with the position of the standard size: 1919.26 arcsec at 1AU, (Auwers 1891)



We rule out problem of the PSF
and active solar regions observing at poles

Measuring the Solar Diameter: Eclipse observations

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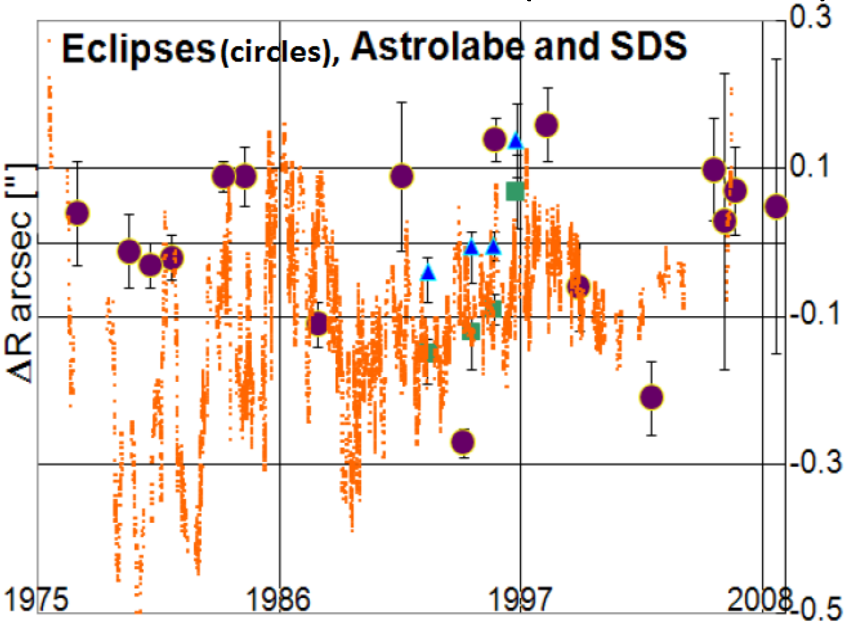
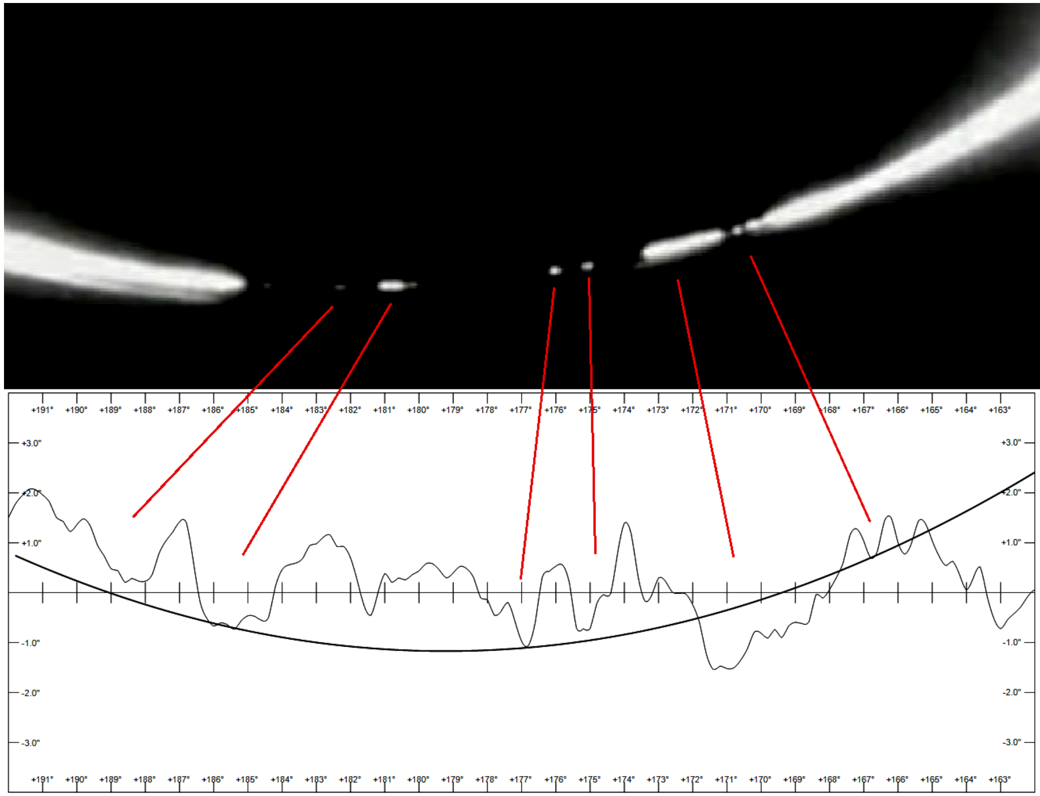


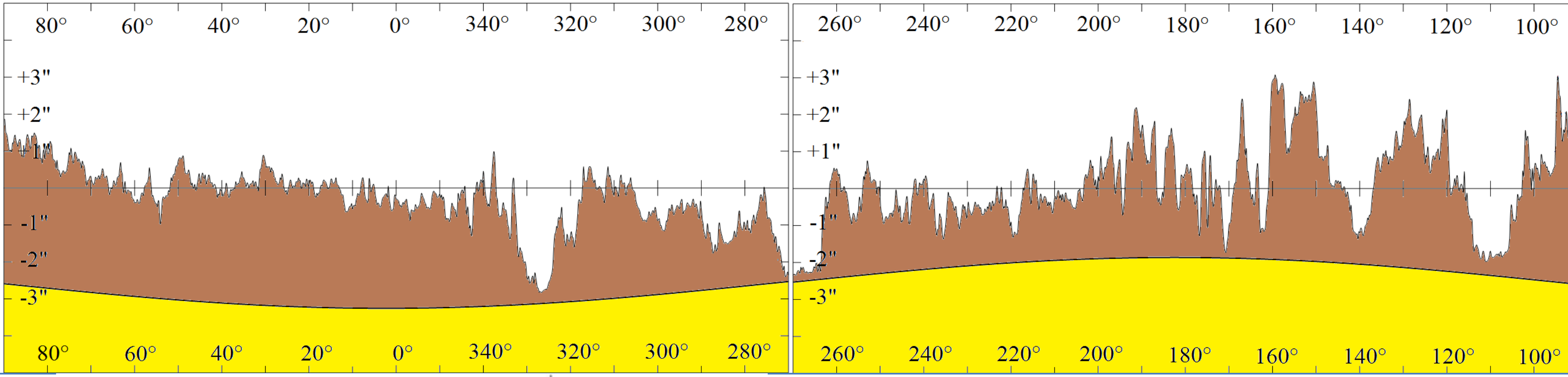


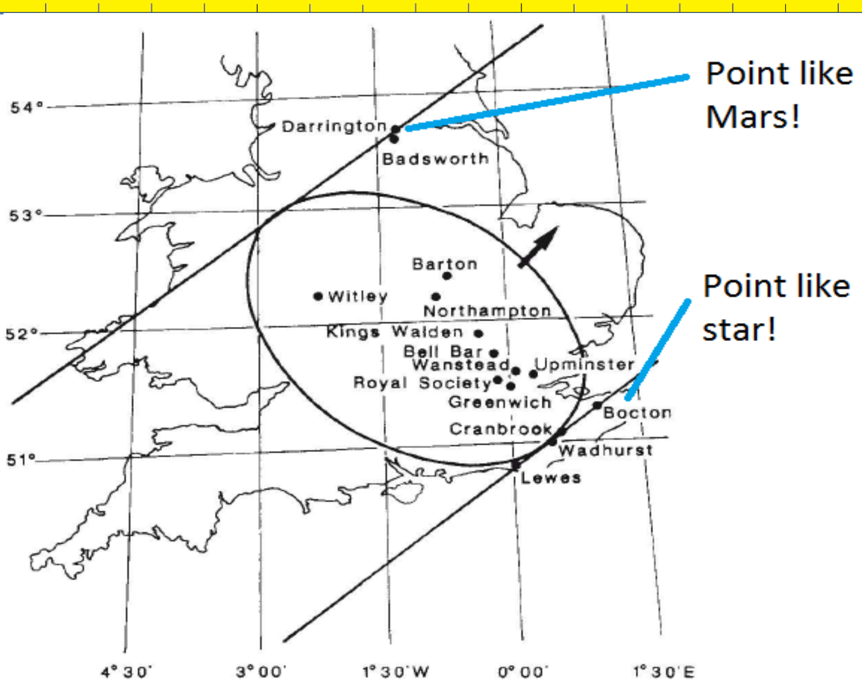
We rule out problem of the PSF and active solar regions observing at poles

However, results are not compatible

Historical Eclipses

Clavius, 1567, Rome, observed an annular eclipse.
With Occult 4 software we are able to analyze the ephemeris at the time:
It would require a larger radius ➔ ΔR ($R_{real} - R_{standard}$) > +2.5 arcsec !!

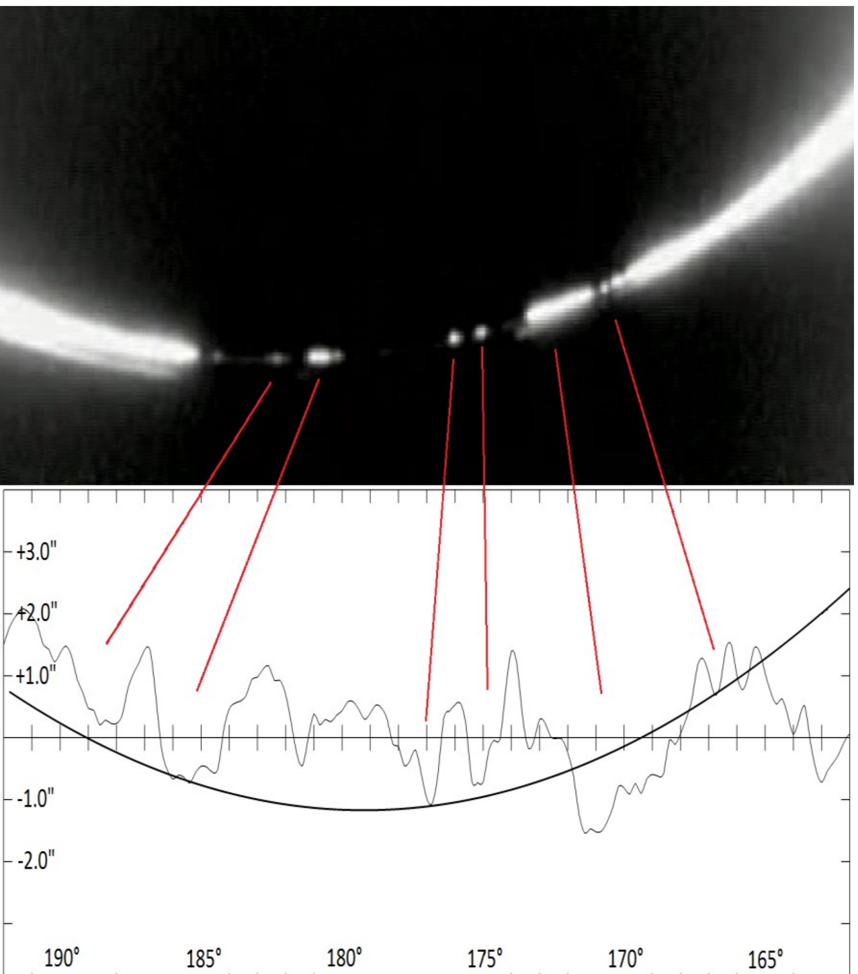


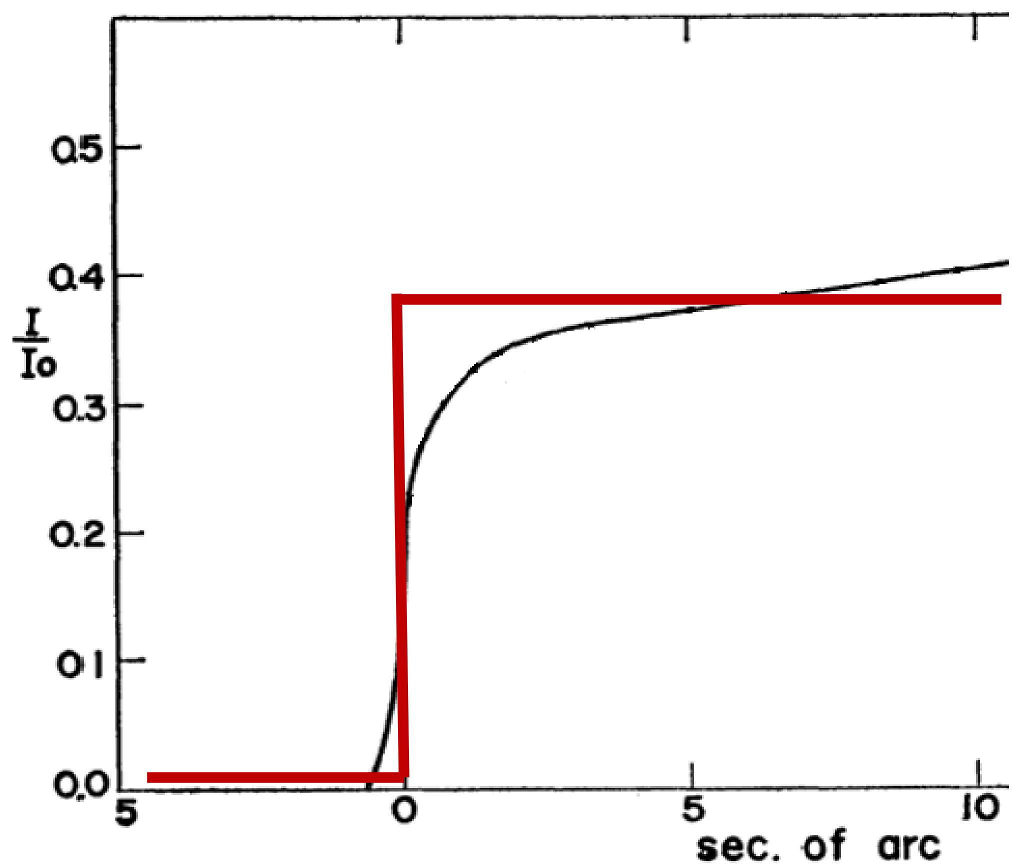


Halley, 1715, England, collected observations of the total eclipse. Thanks to the observations on the limit of the shadow we are able to infer a lower limit of the Sun's diameter:
ΔR > +0.38 ± 0.2 arcsec with respect to the standard radius (959.63 arcsec)

Classical method of Eclipse: problems

The **Classical Method** measures the solar radius considering Baily's beads like **on-off events** ➔ the luminosity profile of the solar limb is a **step function**: when the beads appear (or disappear) the step has overcome the lunar edge in a lunar valley.

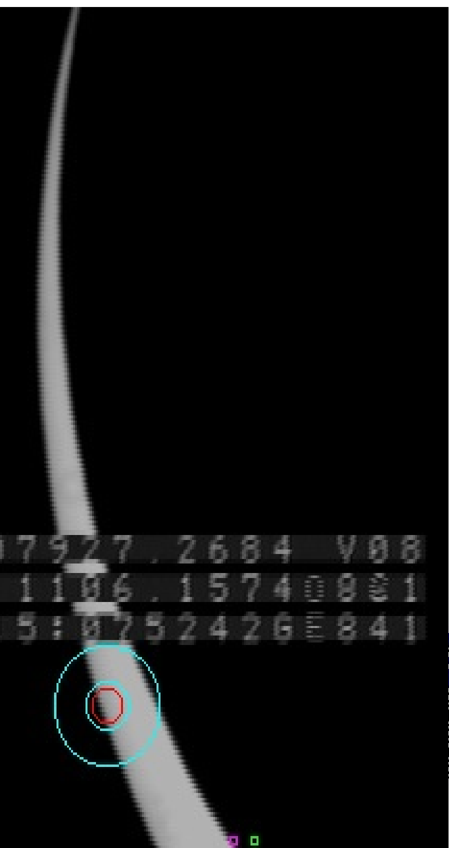


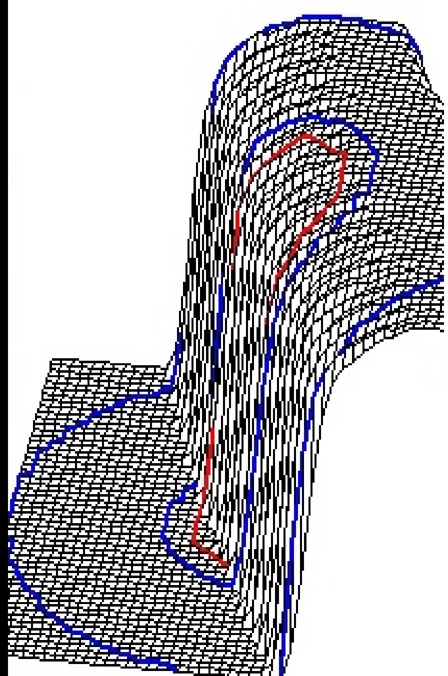


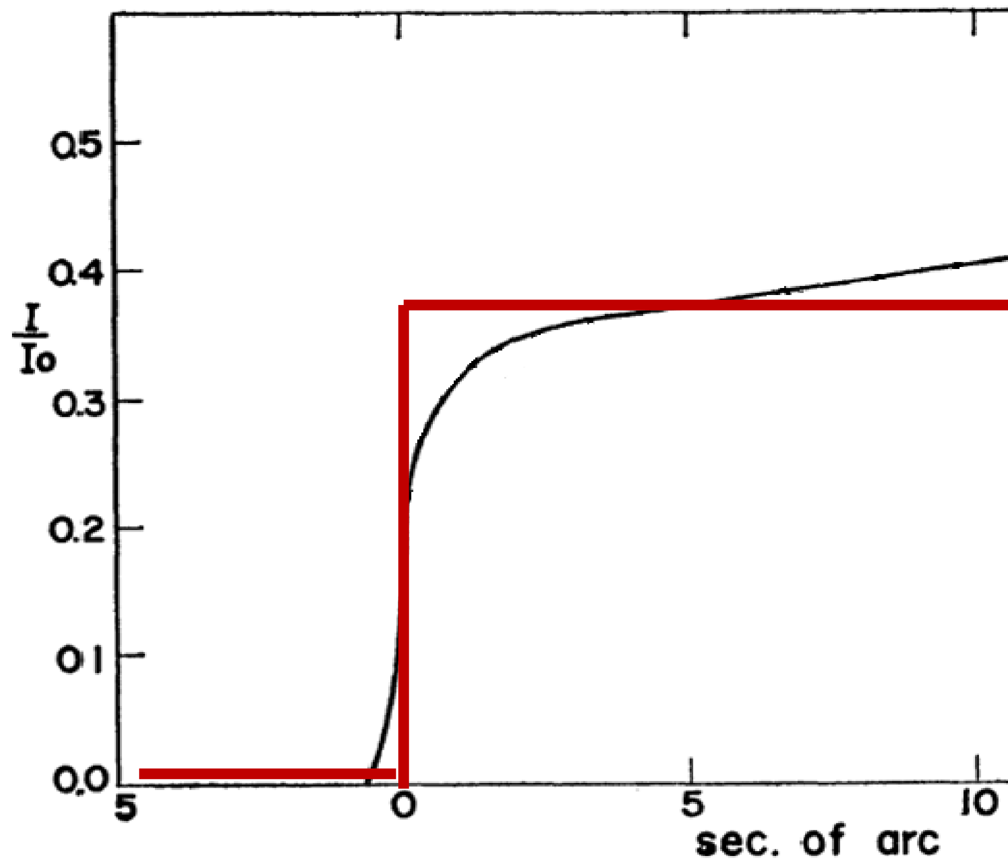
Classical method of Eclipse: problems

Different optical instruments have different sensitivity and different Signal / Noise ratio

➢ The Limb Darkening Function is **not** a **step profile**:
we can not consider the bead as an ON-OFF signal





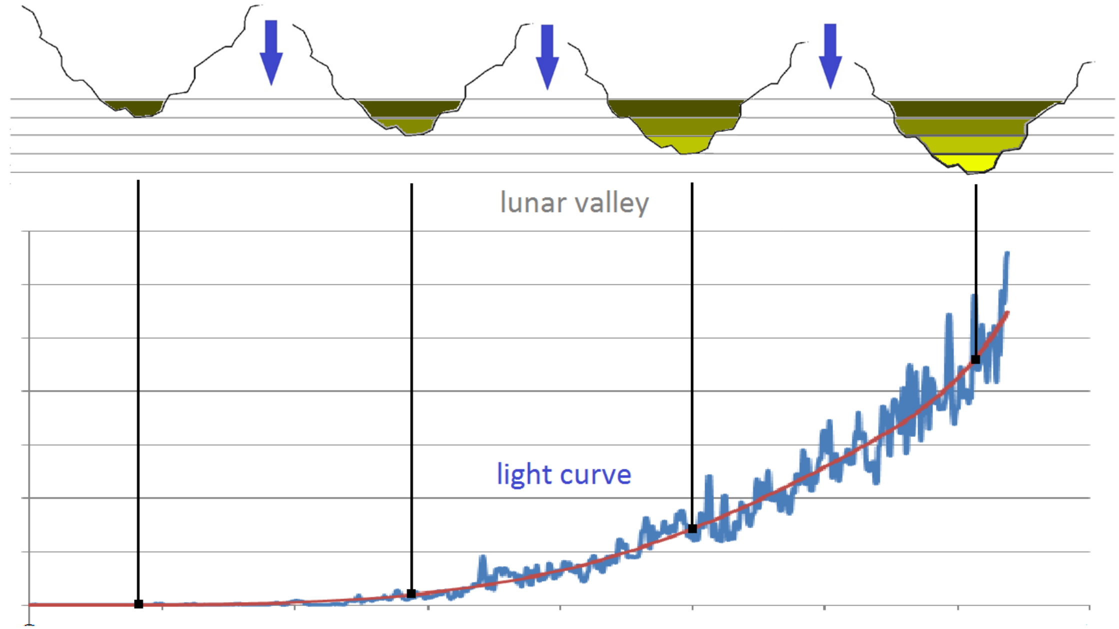


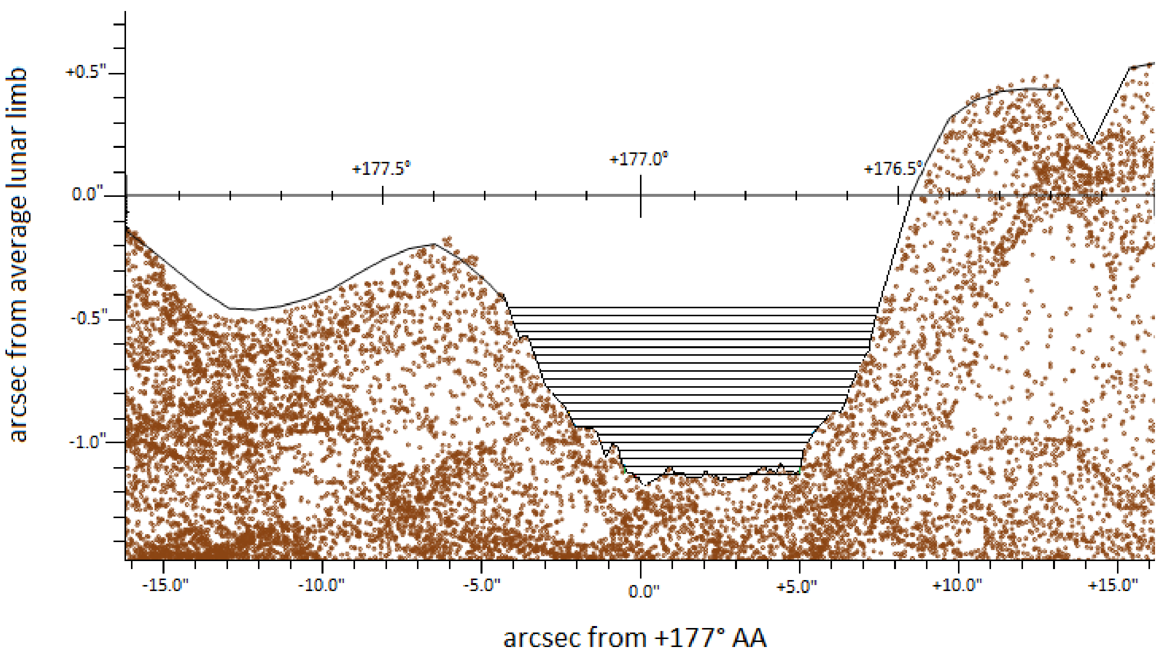
A new approach to eclipses

We can consider the light curve of the bead as a convolution between the LDF(x) and the width of the lunar valley ω(x):

$$L(y) = \int LDF(x)\, w(y-x)\, dx$$

y = the distance between the bottom of the lunar valley and the standard solar limb.

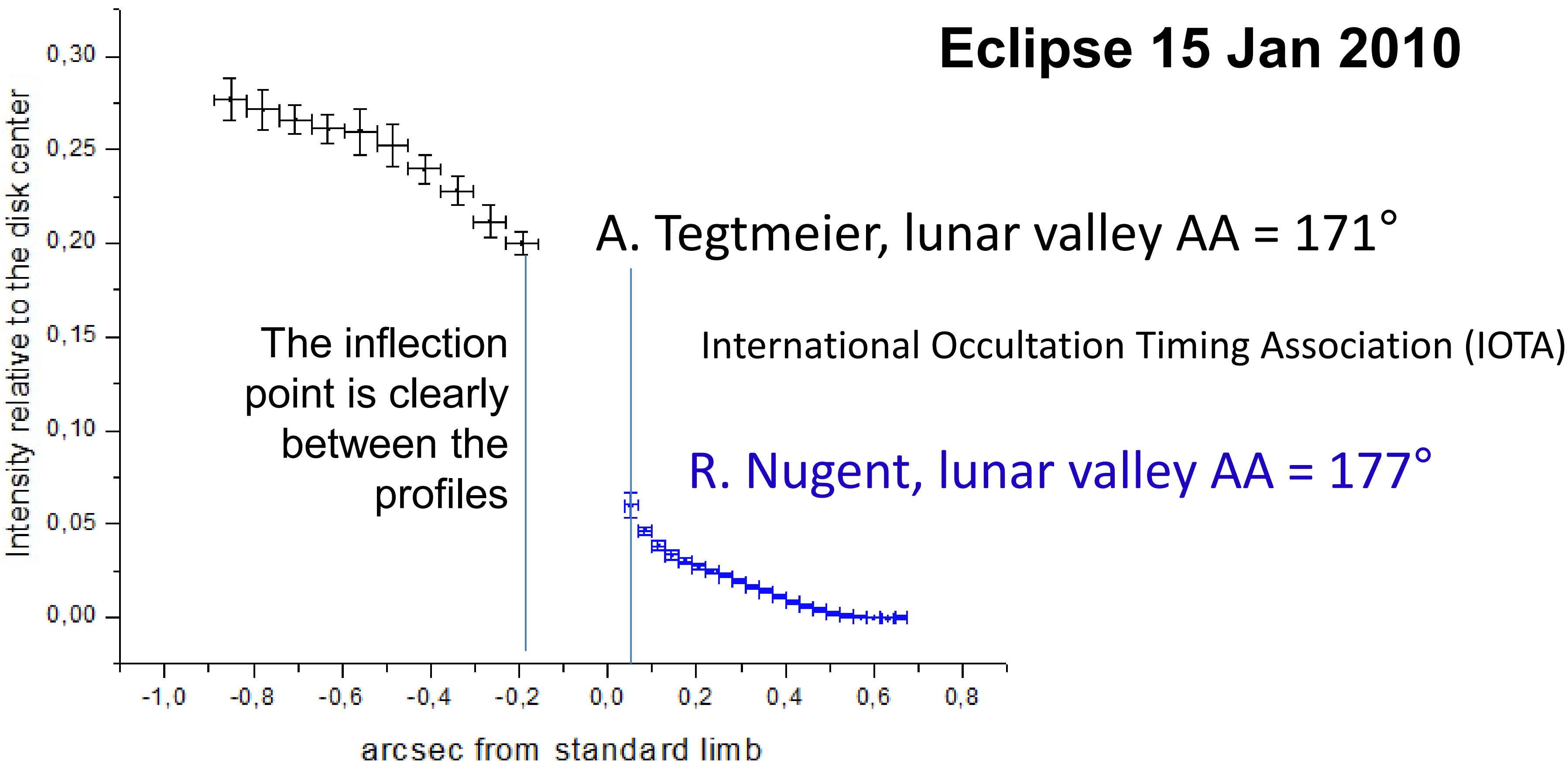




To deconvolve the relation we need the analysis of the lunar valley profile in order to discretize the solar edge and the lunar valley into layers.

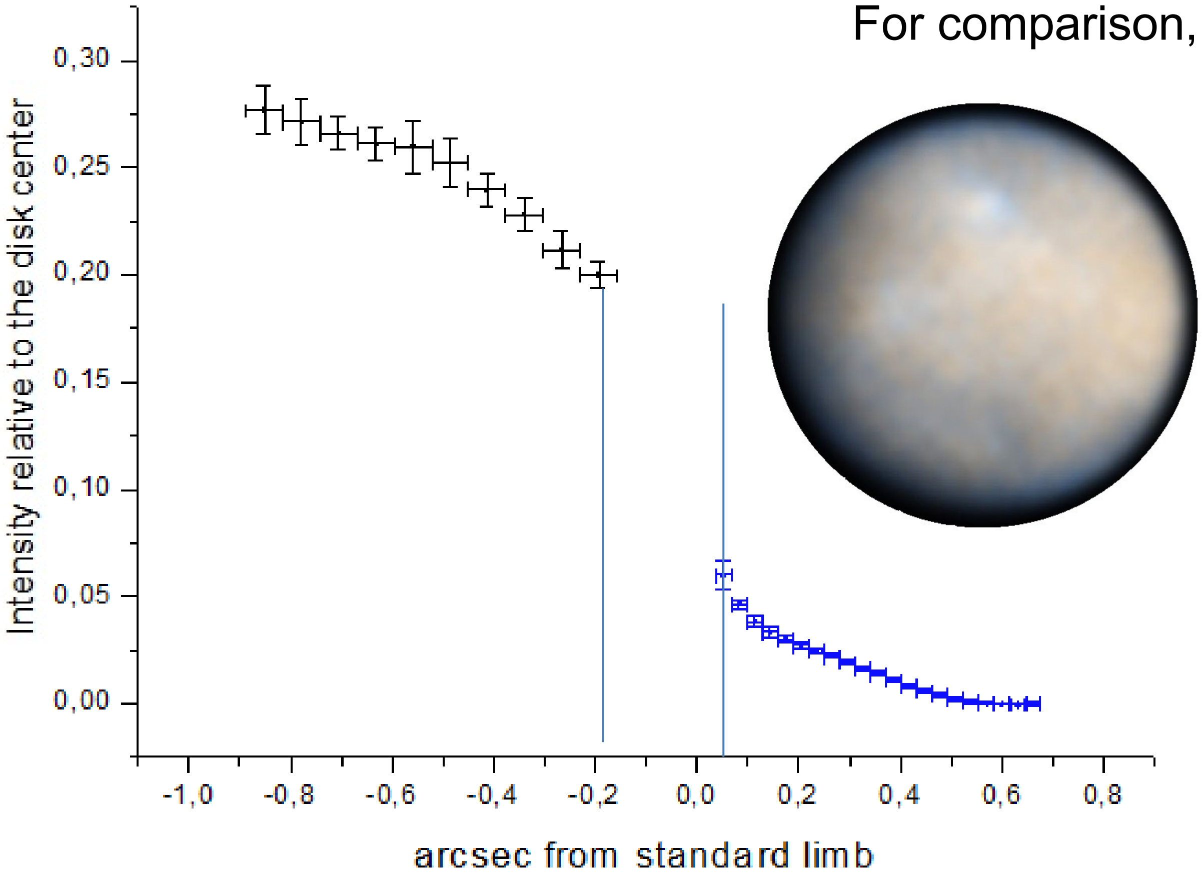
Solar Physics, **278**, pp.269-283, 06/2012

Infer the Inflection Point Position: 8 bits dynamic range, diverse observations



-0.19 arcsec $< \Delta R\ (R_{real} - R_{standard}) < +0.05$ arcsec

An application of the method



For comparison, Ceres observed by HST

-0.19 arcsec < ΔR ($R_{real} - R_{standard}$) < $+0.05$ arcsec

Simplifying the approach

Bead Light Curve

Width of the Lunar Valley

$$L(y) = \int LDF(x)\, w(y - x)\, dx$$

Distance between lunar edge and standard solar edge

Obtaining the Limb Darkening Function from the Bead Light Curve is not straightforward because one has to analyze the shape of the Lunar Valley (the function ω) and perform the deconvolution.

But we can assume ω like a step function, namely the valley like a rectangle:

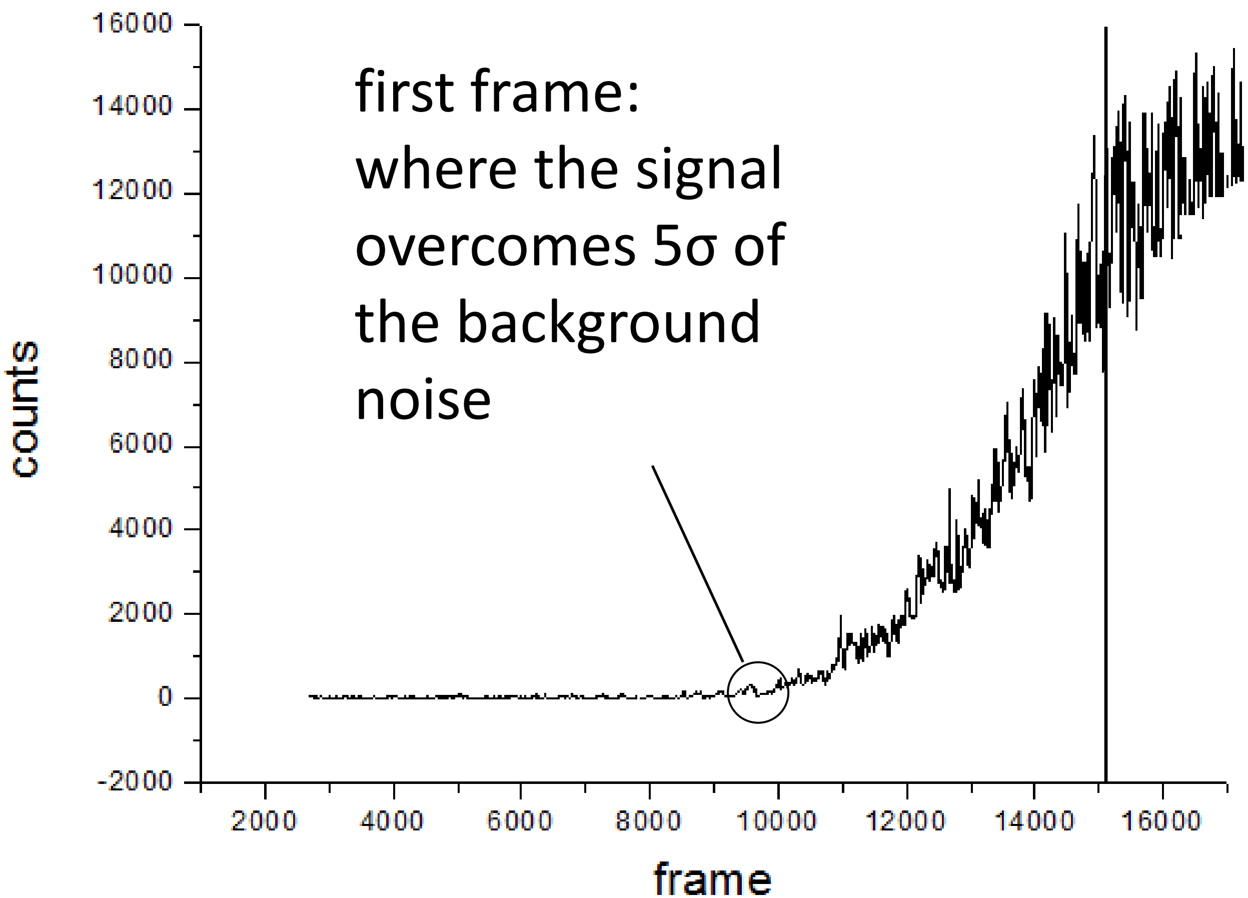
$$\omega = \begin{cases} 0 & \text{for } x < y \\ k & \text{for } x > y \end{cases}$$

➔ *First Derivative*

$$L(y)' = k \cdot LDF$$

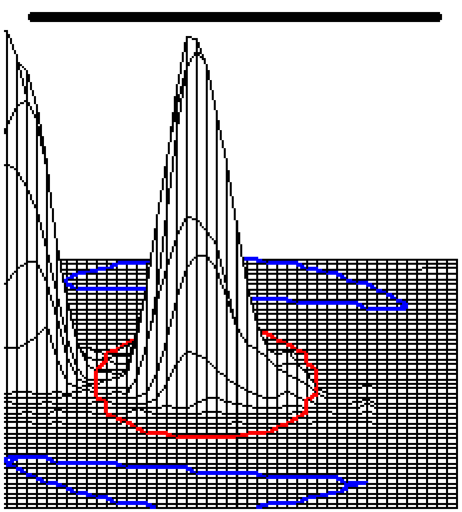
Linear transformation of the LDF, keeping its shape and thus its Inflection Point Position.

STEP 1/5 *Select the useful part of the light curve*



first frame:
where the signal overcomes 5σ of the background noise

last frame:
when the bell shape of the bead (3D window) reach its top

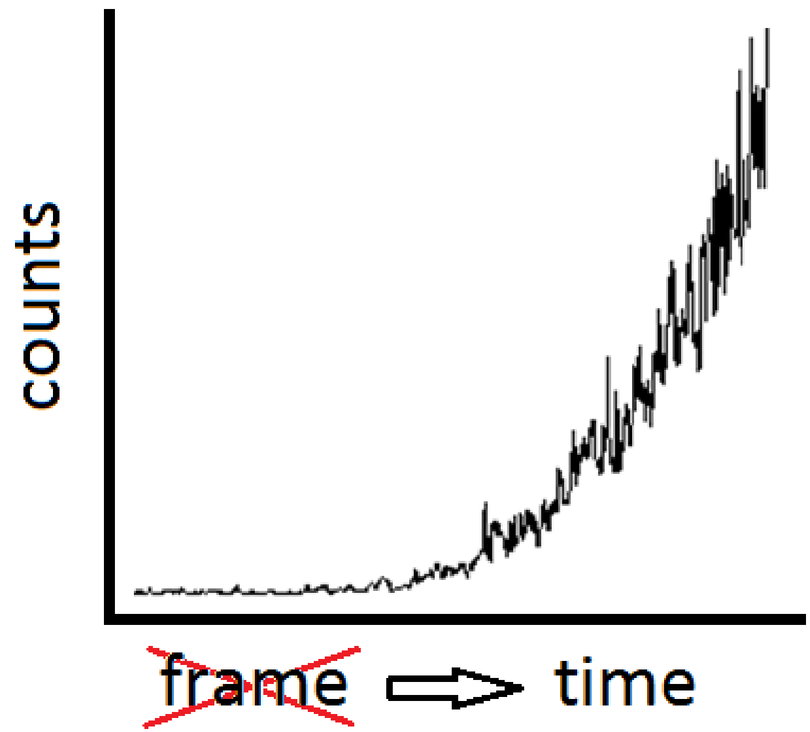


STEP 2/5 *Find the relation: Frame - UTC Time*

time = frame · m + q

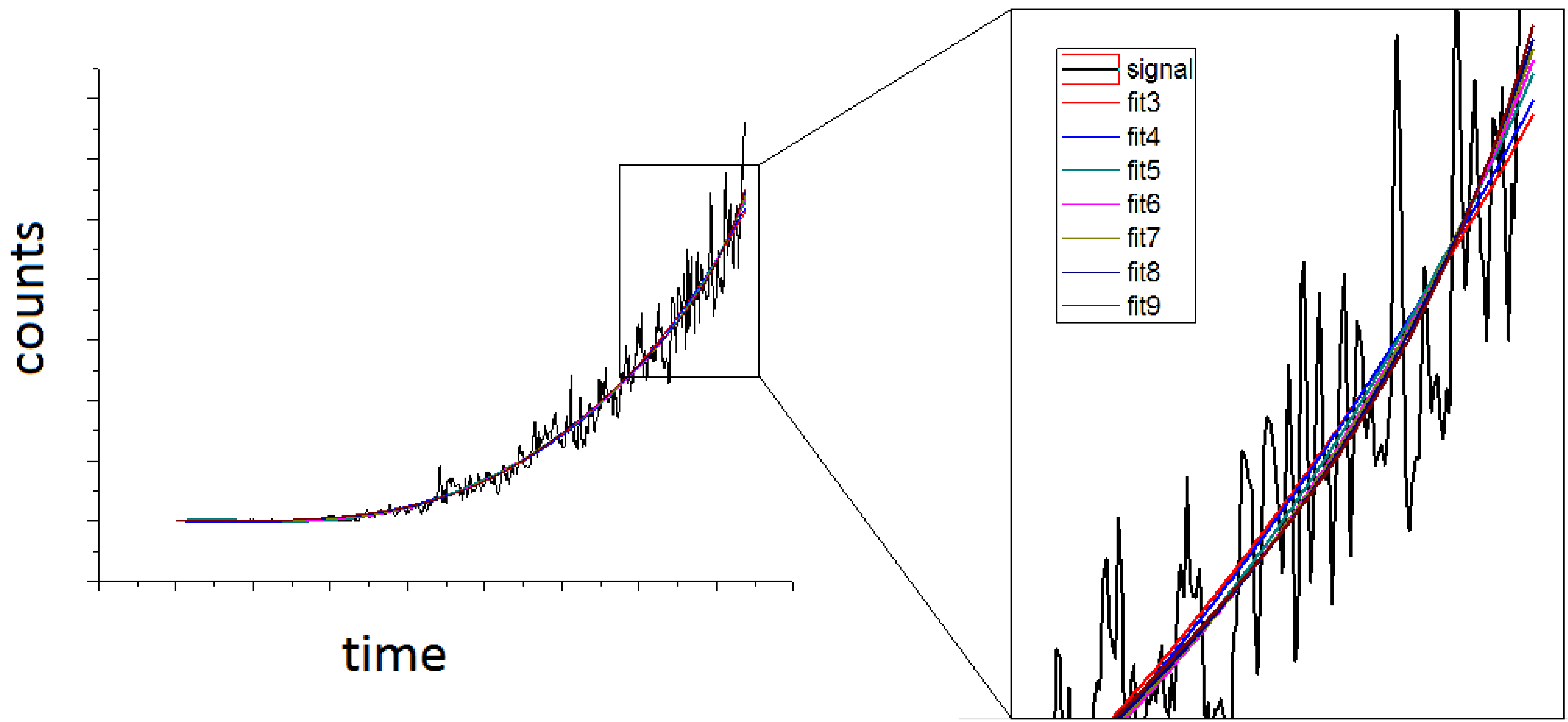
m = (time2-time1) / (frame2-frame1)
q = time1 - frame1 · m

To plot the light curve of the bead in function of the time

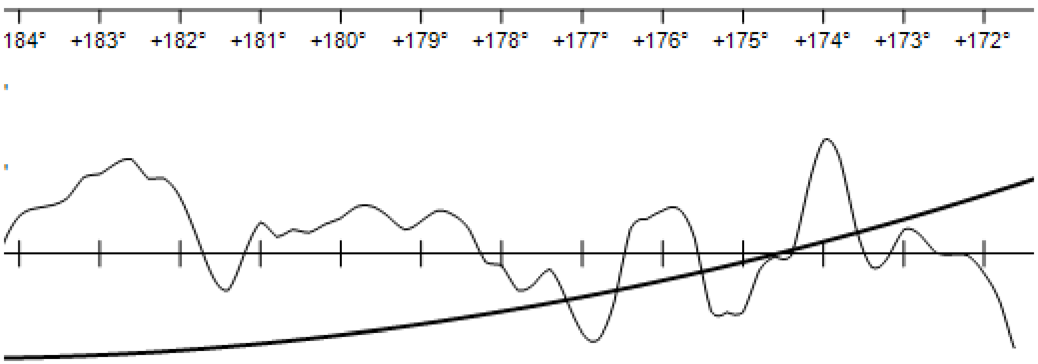


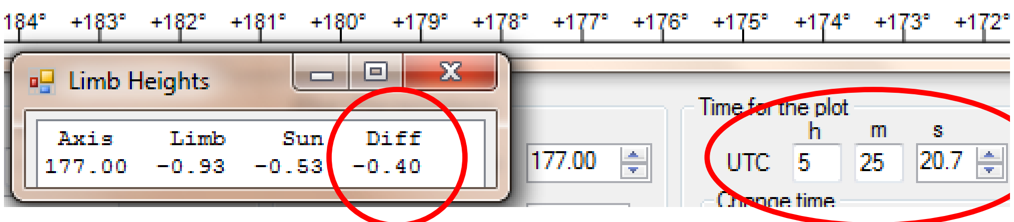
STEP 3/5 *Perform polynomial fits to flatten the noise*

There are different functions that fit the light curve.
We can take polynomial functions from 3° to 9° grade.
Their differences are due to the electronic noise.



STEP 4/5 *Find the relation: UTC Time – y (ΔR)*



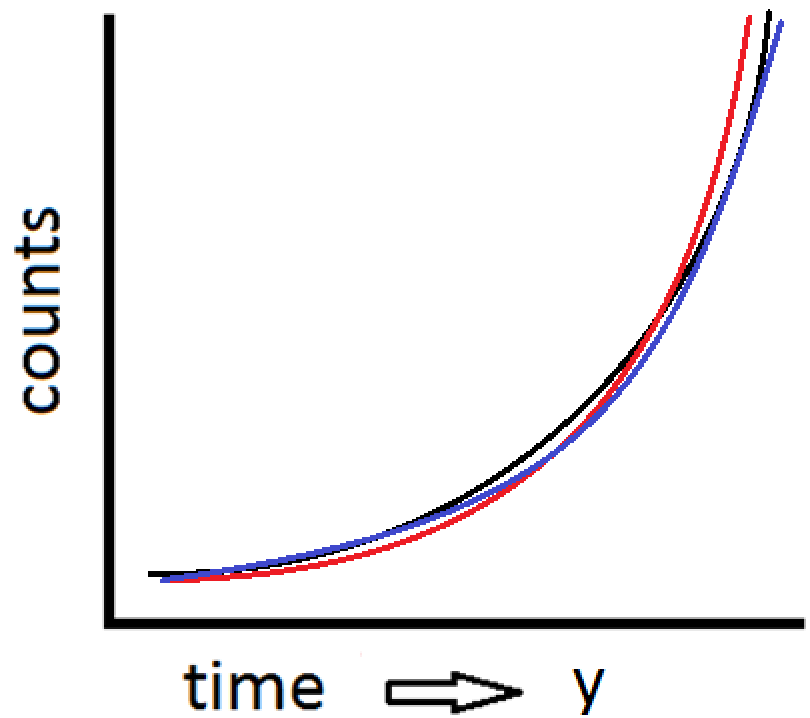


$$y = time \cdot m + q$$

$$m = (y2 - y1) / (time2 - time1)$$

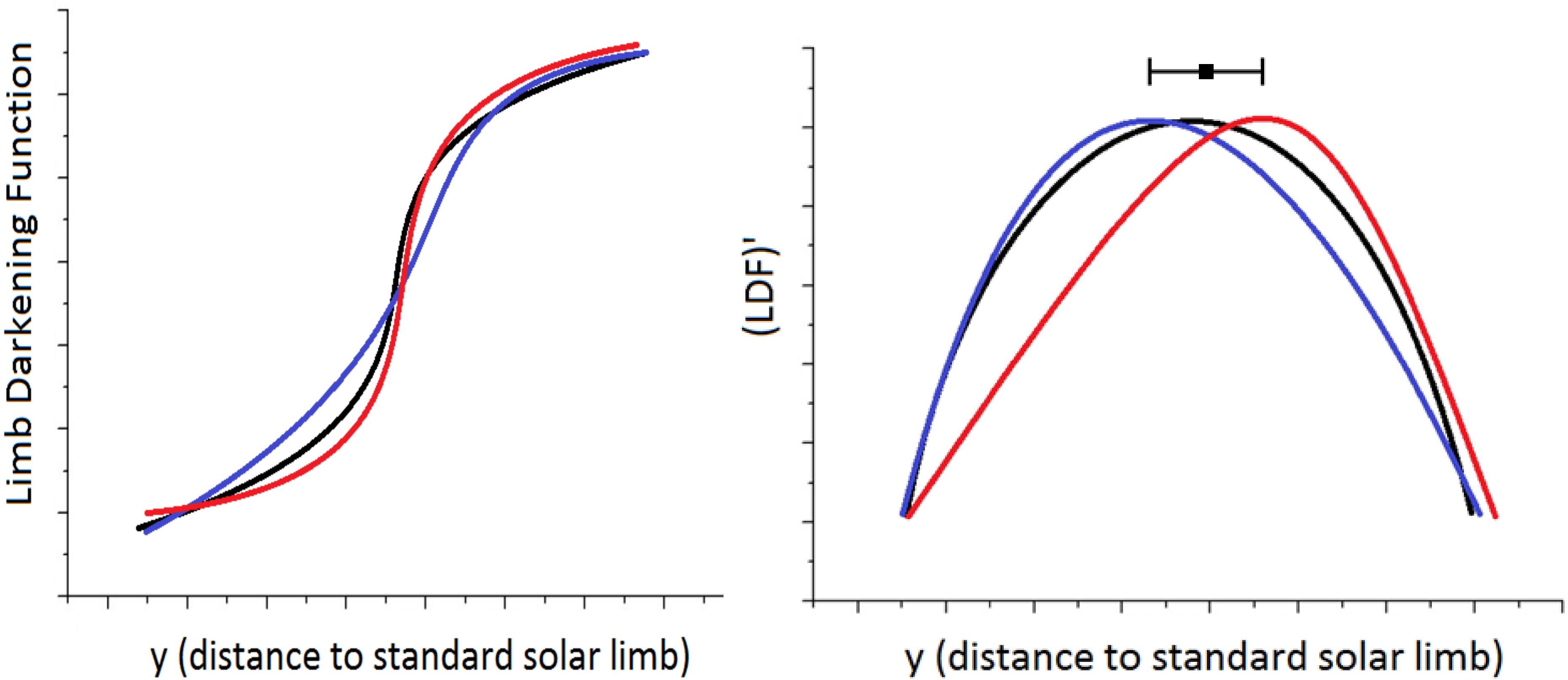
$$q = y1 - time1 \cdot m$$

To plot the light curve of the bead in function of ΔR. At this point we have some polynomial fits instead of the signal detected.

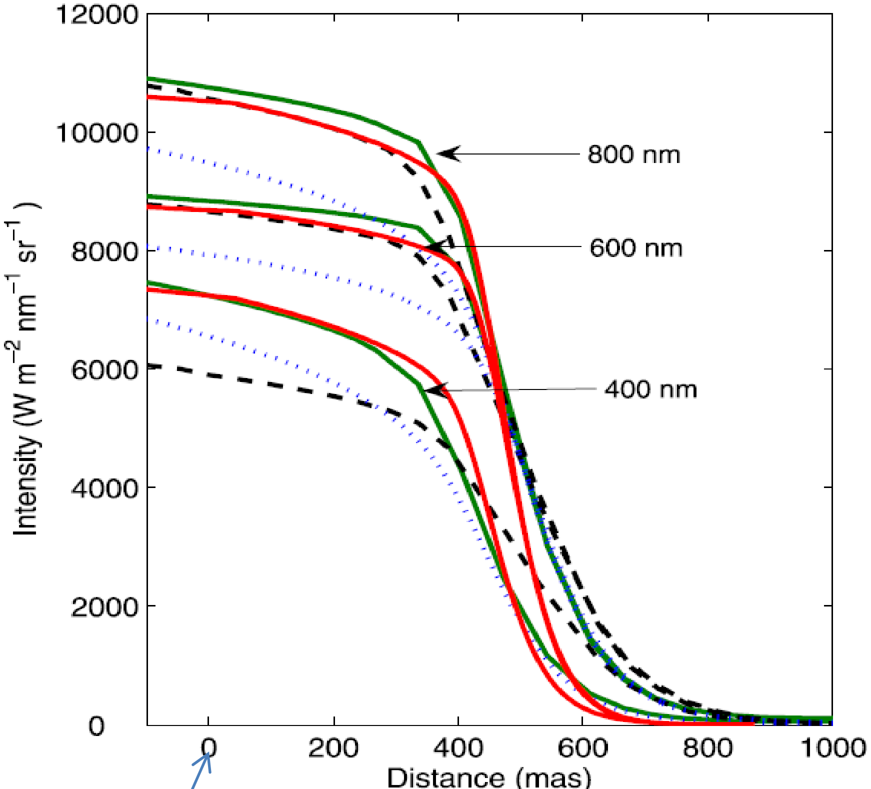


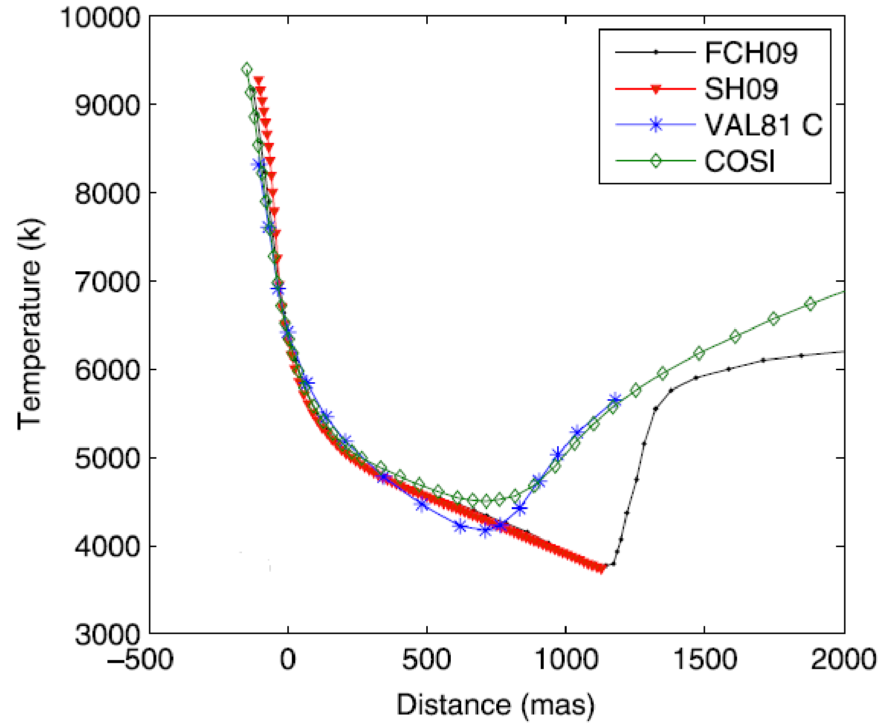
STEP 5/5 *Infer the Inflection Point Position: 12 bits dynamic range, single observation*

First derivative of the LDF
(second derivative of the light curve)



Obtaining the best solar atmospheric model





$\tau_{500} = 1$

➔discriminating the models according to the variability of the IPP with wavelength (Thuillier et al. 2011).

Models	ΔIPP1 (600 - 400)	ΔIPP2 (800-400)
VAL-C81	50.6	69.2
COSI	32.5	53.8
FCH09	– 19.8	1.7
SH09	26.0	37.0

Conclusion

Summary

The new method of eclipses permits to:

- ❑ monitore the solar diameter to constrain the solar models
- ❑ obtain information on solar atmosphere thanks to LDF measurement

Suggestions

❑Increase the dynamic range of the CCD detectors to extend the sampling of the luminosity function to regions internal and luminous than IPP.

❑ To obtain comparable measures we need to observe in specific band pass or wavelength.

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Thank you