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**One sentence before starting**

**I have rarely met a friendlier people  
than in Taiwan**

**So my warm thanks for hosting me go out  
again, especially to Profs. Wen-Ping Chen &  
Chow-Choong Ngeow, Chien-Cheng Lin, and all  
the staff of NCU and Lulin Observatory!**



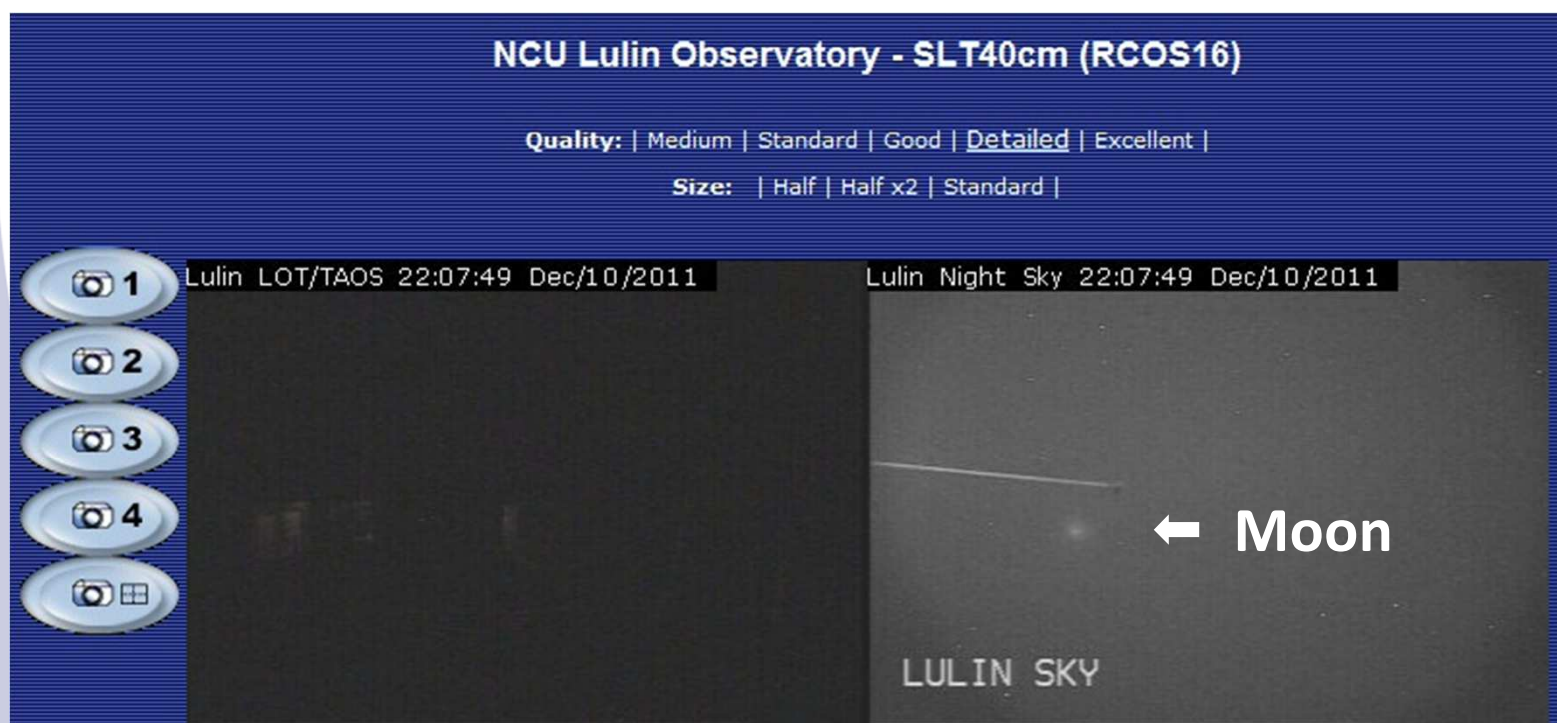
# My trip to and stay at Lulin Observatory

- added to my fondness of the Taiwanese landscape
- although we did not get data as planned for the Dec. 10, 2011, total lunar eclipse...



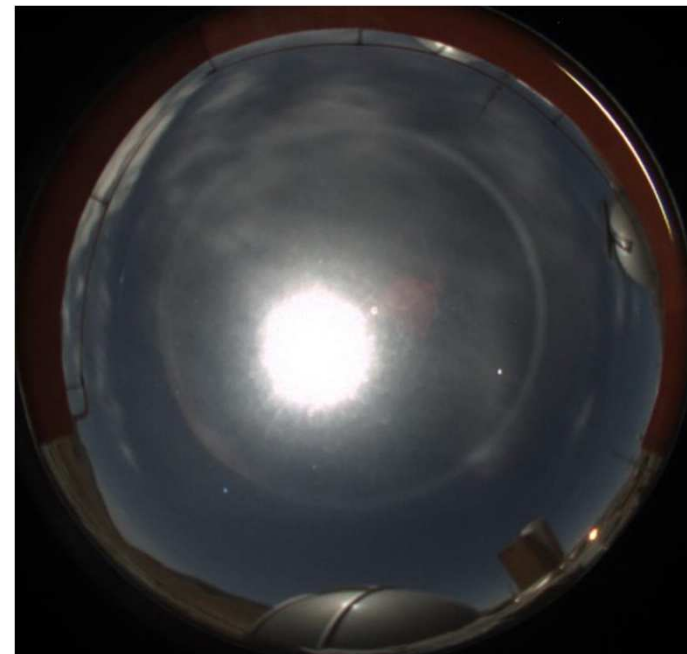
# The weather situation on Dec. 10th, 2011

- seemed to be unusual, even abnormal for the season



## We took the night away

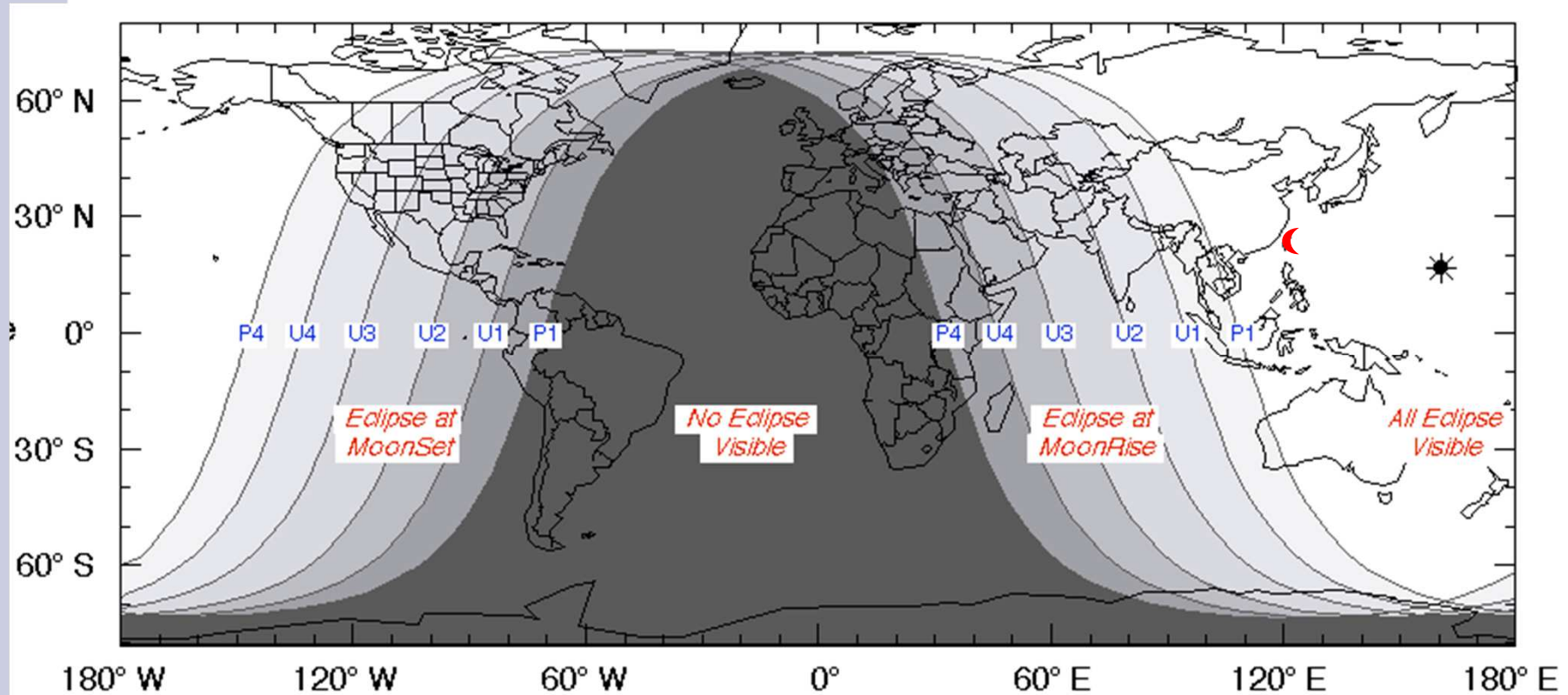
- by watching webcasts from Hawaii, HongKong, and
- live images from Savio Fong's remotely controlled telescope in 4350 m altitude near Lhasa, Tibet





But...

I could be back (if you want me so)  
on January 31st, 2018 - for another try...





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# Around the world with absolute lunar eclipse photometry

**Elmar Schmidt**

**SRH University of Applied Sciences  
Heidelberg, Germany**

**Invited talk at the  
Graduate School of Astronomy  
National Central University  
Zhongli, Taiwan**

Elmar Schmidt, Professor of Physics  
School of Engineering & Architecture  
Inquiries: [elmar5@web.de](mailto:elmar5@web.de)

**Dec. 13th, 2011**



## Introductory remarks

- **My current main professional task is to teach Mathematics (with a bit of Operations Research), Physics, and Technical Mechanics to first and second year undergraduate engineering students, and some selected courses to our master students**
- **My scientific interests are in the photometry of eclipses and skylight, and also in various phenomena of atmospheric optics**
- **Both come from a mixed private-professional experience in optics and astronomy**



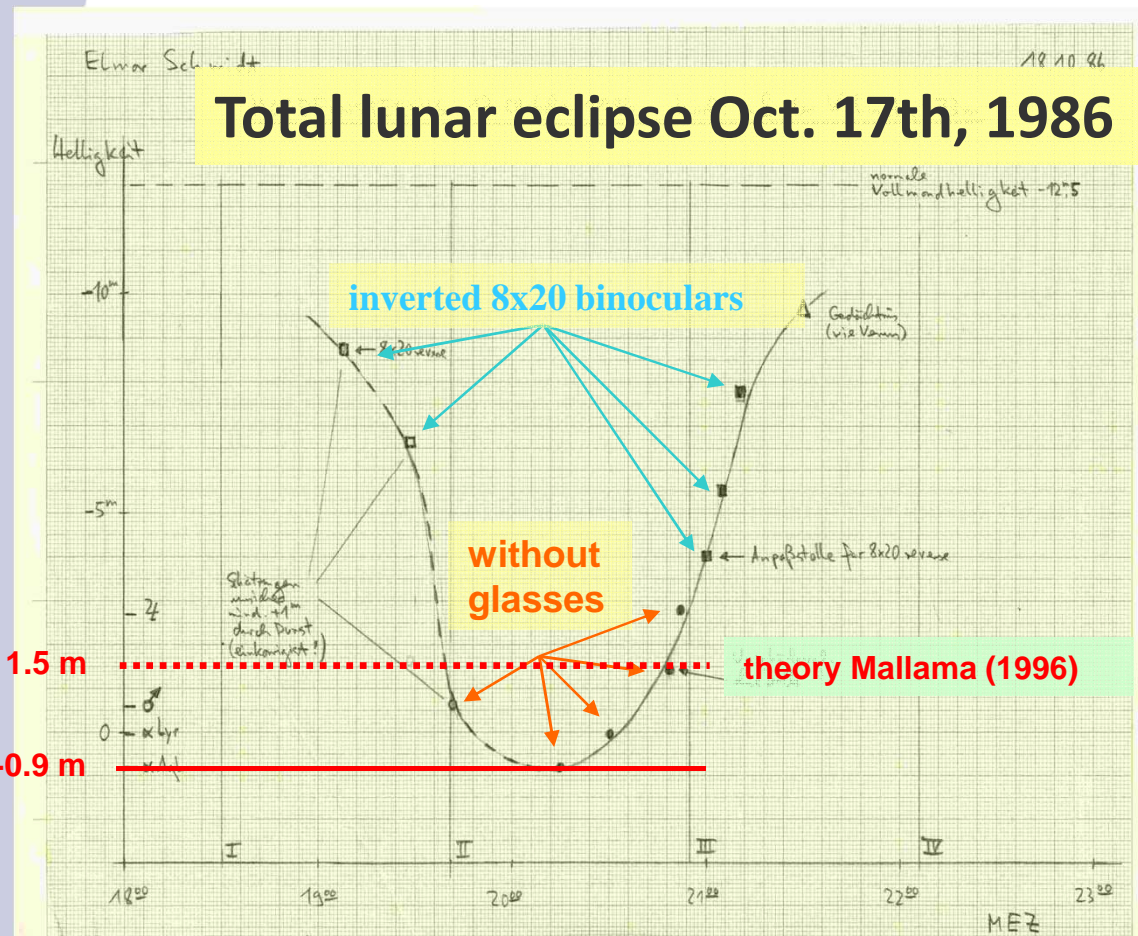
# Classical findings from lunar eclipses

(listed by the late Frantisek Link)

- spherical shape of the earth (4th century B.C.)
- relative dimensions of system Earth-Moon-Sun (3rd to 2nd century B.C.)
- theory of lunar motion (2nd century A.D. to ca. 1970es)
- determining of geographical longitude (16th to 18th century)
- chronology (Columbus' eclipse etc.)



# The „old days“ of visual estimates



- Most visual estimates are based on comparing the eclipsed Moon to planets and bright stars by
  - reducing its brightness with inverted binoculars or silvered spheres
  - or defocusing it via short-sightedness
- the results tend to be uneven and imprecise: here a factor of 9 is unexplained, but in addition to Nevado del Ruiz (Nov. 1985) at least five volcanic eruptions were observed in 1986*



## Another approach: the Danjon Scale

- L=0**    **Very dark** eclipse  
*Moon almost invisible, especially at mid-totality*
- L=1**    **Dark** eclipse, grey or brownish in coloration  
*details distinguishable only with difficulty*
- L=2**    **Deep red** or rust-colored eclipse.  
*very dark central shadow; outer umbra is relatively bright*
- L=3**    **Brick-red** eclipse  
*umbral shadow usually has a bright or yellow rim*
- L=4**    **Very bright** copper-red or **orange** eclipse.  
*umbral shadow has a bluish, very bright rim*

### Problems

- *highly subjective, as one has to compare events separated by many years (e.g., I never saw a L=0 or 1)*
- *not a true measure of the earth's umbra's darkness, because an L-value is dominated by the eclipse's magnitude (i.e. centrality)*

# Absolute photometry to the rescue



## (Konica-)Minolta

Si-photodiode based, industry standard luminance meters\*

### CS -100 (for 1990 eclipse)

- $1^\circ$  measuring spot
- range (299 000 – 0.01)  $\text{cd/m}^2$
- colorimetric data

### LS -110 (for 2007, 2010, 2011 eclipses)

- $(1/3)^\circ$  measuring spot
- range (999 900 – 0.01)  $\text{cd/m}^2$

*\*kindly provided by Roche Diagnostics, Mannheim, on behalf of Mr. C. Wersig*

# Calibration check\* for the LS-110



- critical to get around the opposition effect's slope
- an incandescent lamp in an integrating sphere produces standard luminances of  
**1048 cd/m<sup>2</sup> and 107.7 cd/m<sup>2</sup>**
- the deviations to our photometers were not greater than 0.8% *and then corrected*

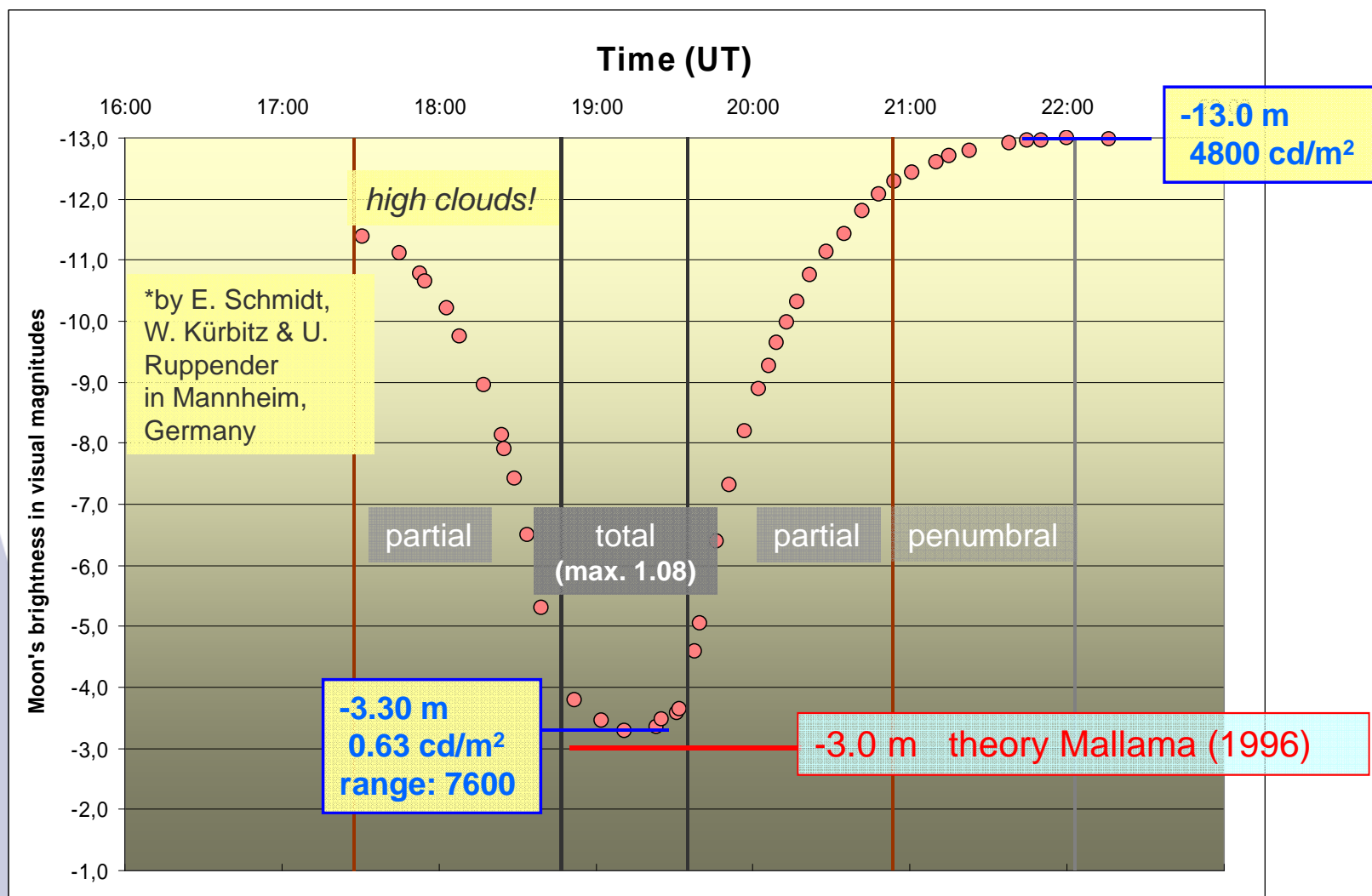
*\*Dr.-Ing. D. Kooss,  
Lichttechnisches Institut,  
Technical University of Karlsruhe*

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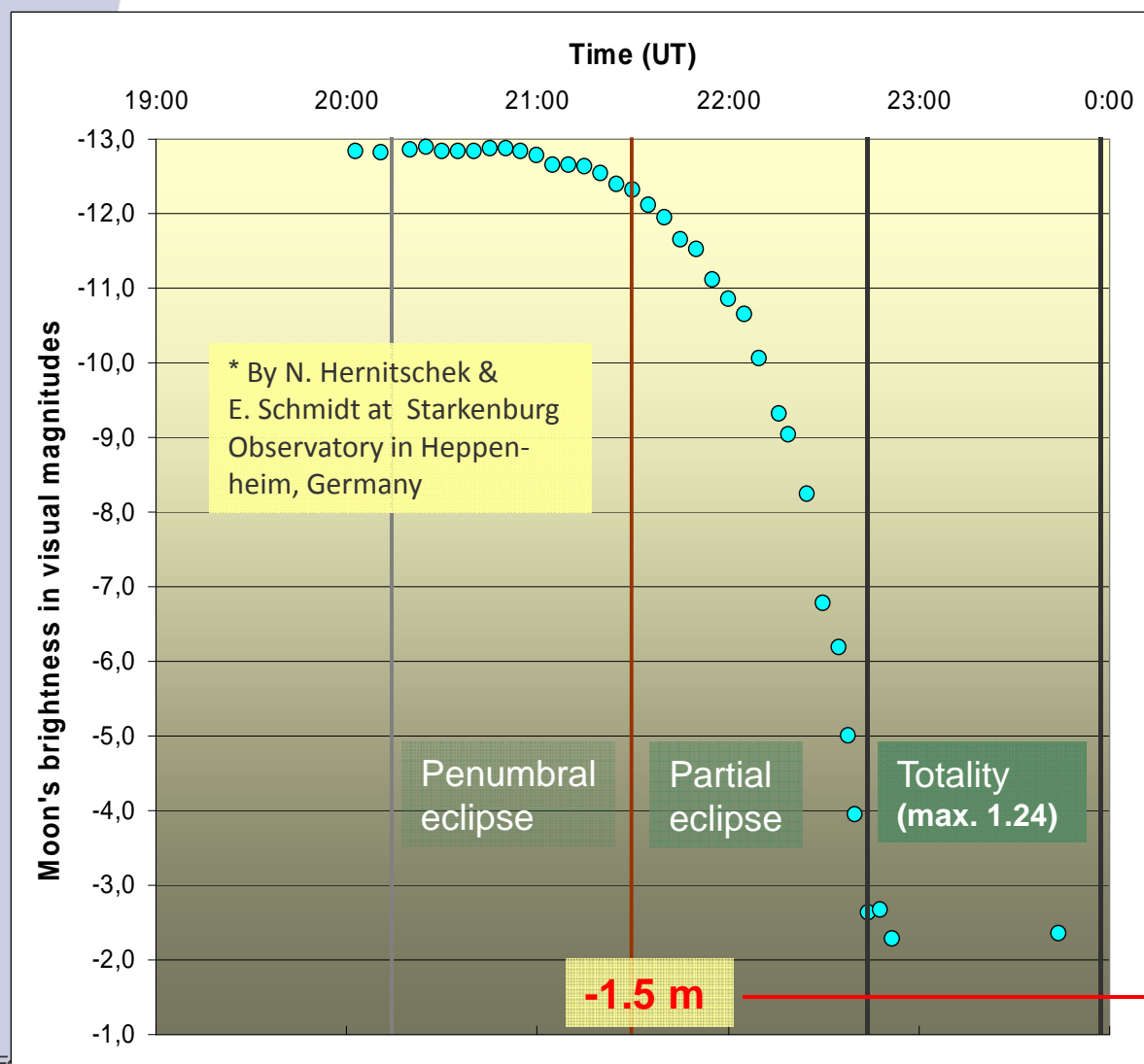
# Light curve\* for Feb., 9th, 1990 eclipse







# Light curve\* for March 3rd, 2007 eclipse



## brightness range:

-12.89 m = 4345 cd/m<sup>2</sup>  
- 2.29 m = 0.25 cd/m<sup>2</sup>  
(a factor of 17 400)

the extrapolated minimum  
level fits the prediction by  
A. Mallama (1996)



**March 3, 2007**  
*mosaic of 15  
photos with  
20" Cassegrain  
telescope*

© 2007 Jens Hackmann,  
Weikersheim, Germany  
<http://www.kopfgeist.com/>

# An eclipsed Moon's red color is from twilight



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Photo from a 37 km high weather balloon



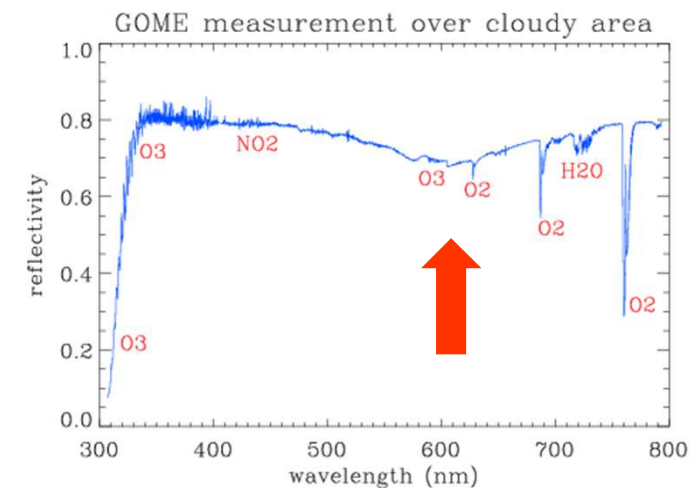
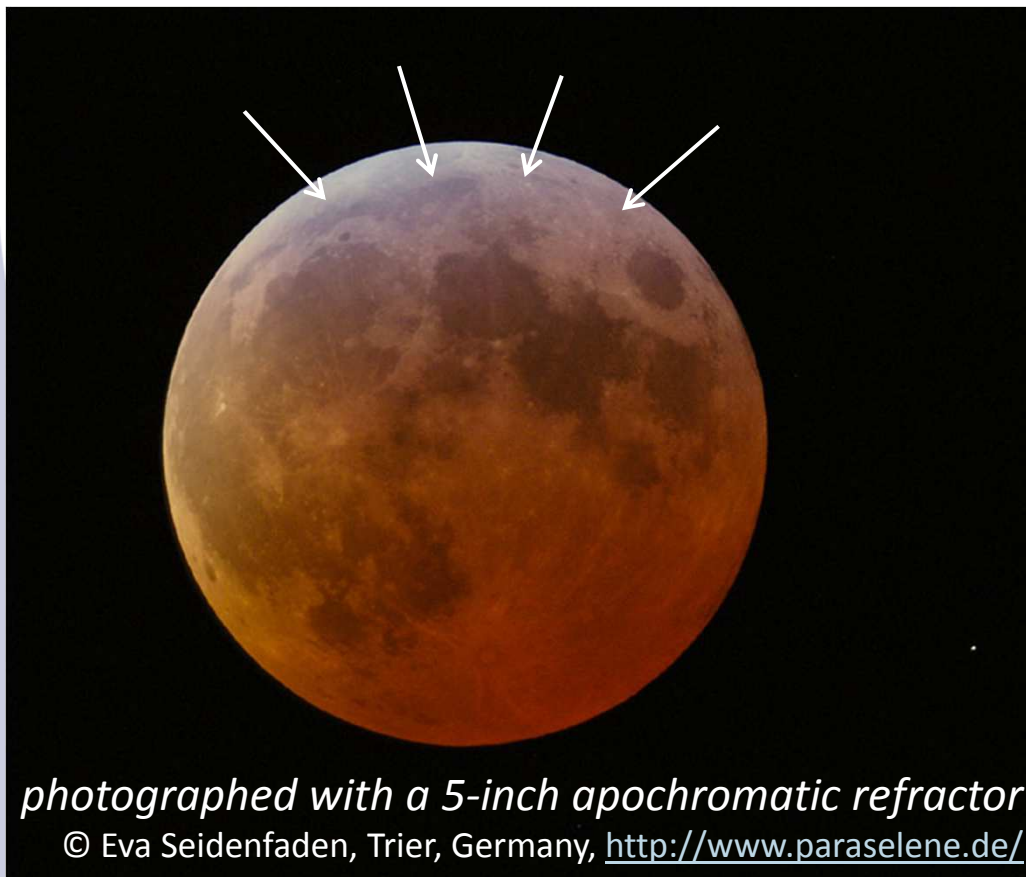
„Lunisolar“ eclipse as seen by Surveyor III

© . E. Schmidt; Heidelberg 2011

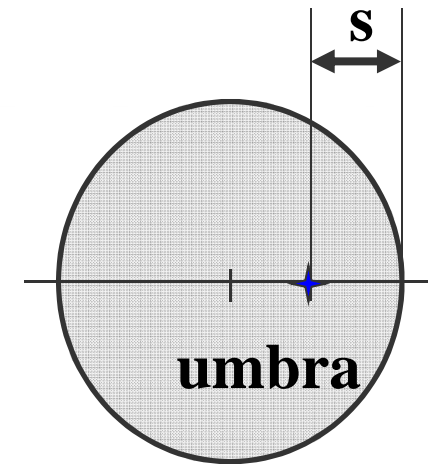
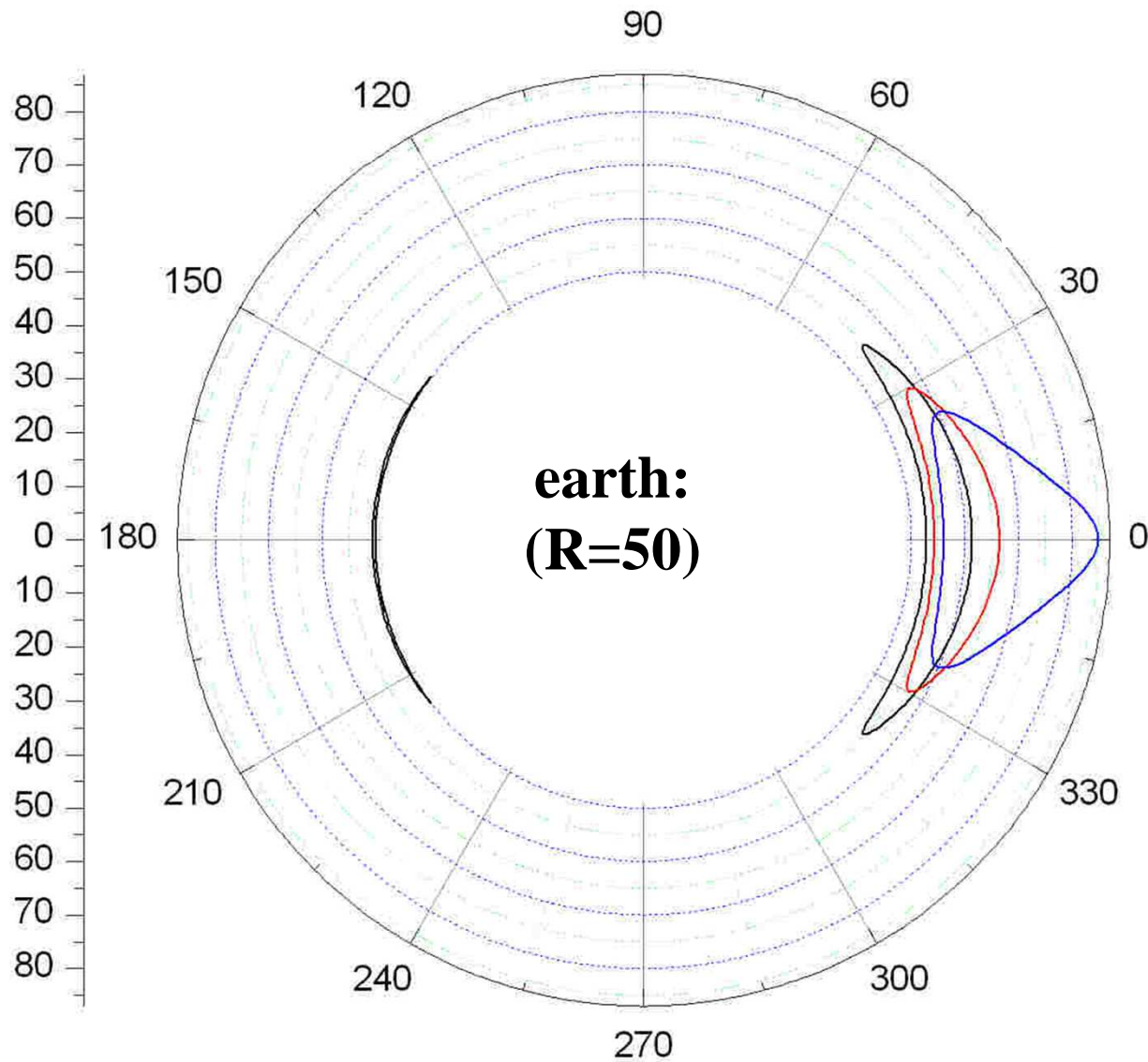


# The blueish-turquoise outermost umbra

- is a sensitive probe for the stratospheric ozone layer and its 602 nm absorption (Chappuis band)



# Contributing parts in atmosphere of earth (height (x-50) in km) to certain parts of umbra



**s=100km**

**s=1000km**

**s=1900km**

**Raytracing the atmosphere as a gradient index lens (M. Vollmer)**



# Phenomena associated with lunar eclipses

(listed by the late Frantisek Link)



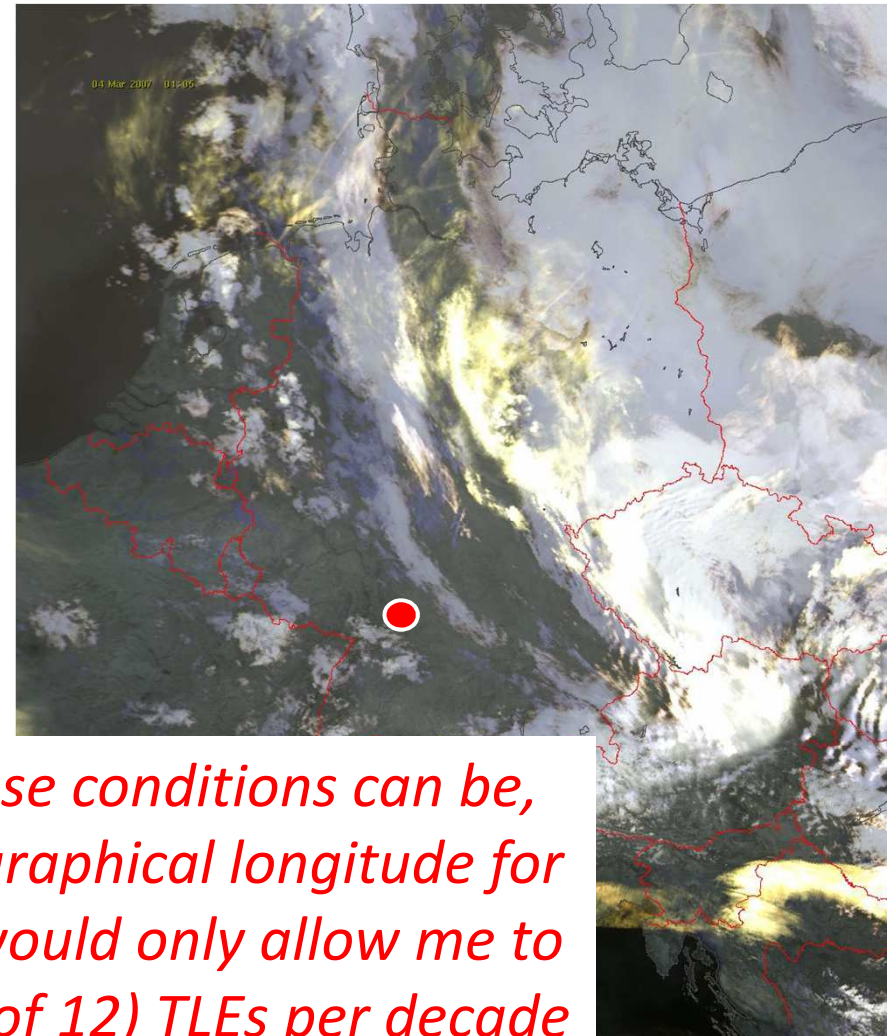
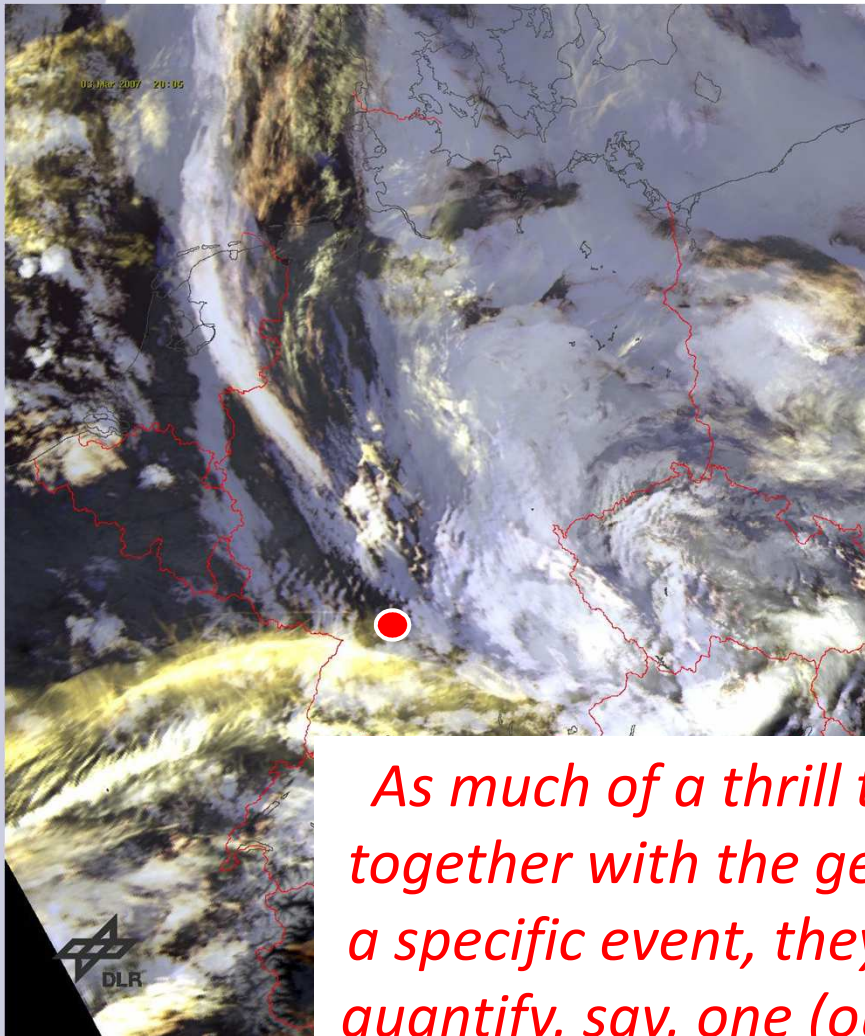
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- ca. 1.7% enlargement of the Earth's shadow (17th century to present), caused by the intransparency of lower atmosphere
- inverse relationship of brightness and stratospheric dust from volcano eruptions
- distribution of ozone in the atmosphere; F. Link (1933), who first confirmed the Umkehr effect (line reversal in solar spectra) from Götz (1931)
- *existence of a high absorbing layer and its relation to interplanetary matter (meteoritic dust)*
- *variation of brightness with solar cycle (still unclear)*
- *light excess in the shadow suggesting existence of lunar luminescence (doubtful)*
- applications to other occulting astronomical objects



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# Weather at the March 3, 2007 eclipse



*As much of a thrill these conditions can be, together with the geographical longitude for a specific event, they would only allow me to quantify, say, one (out of 12) TLEs per decade*



*So let's go to places...*

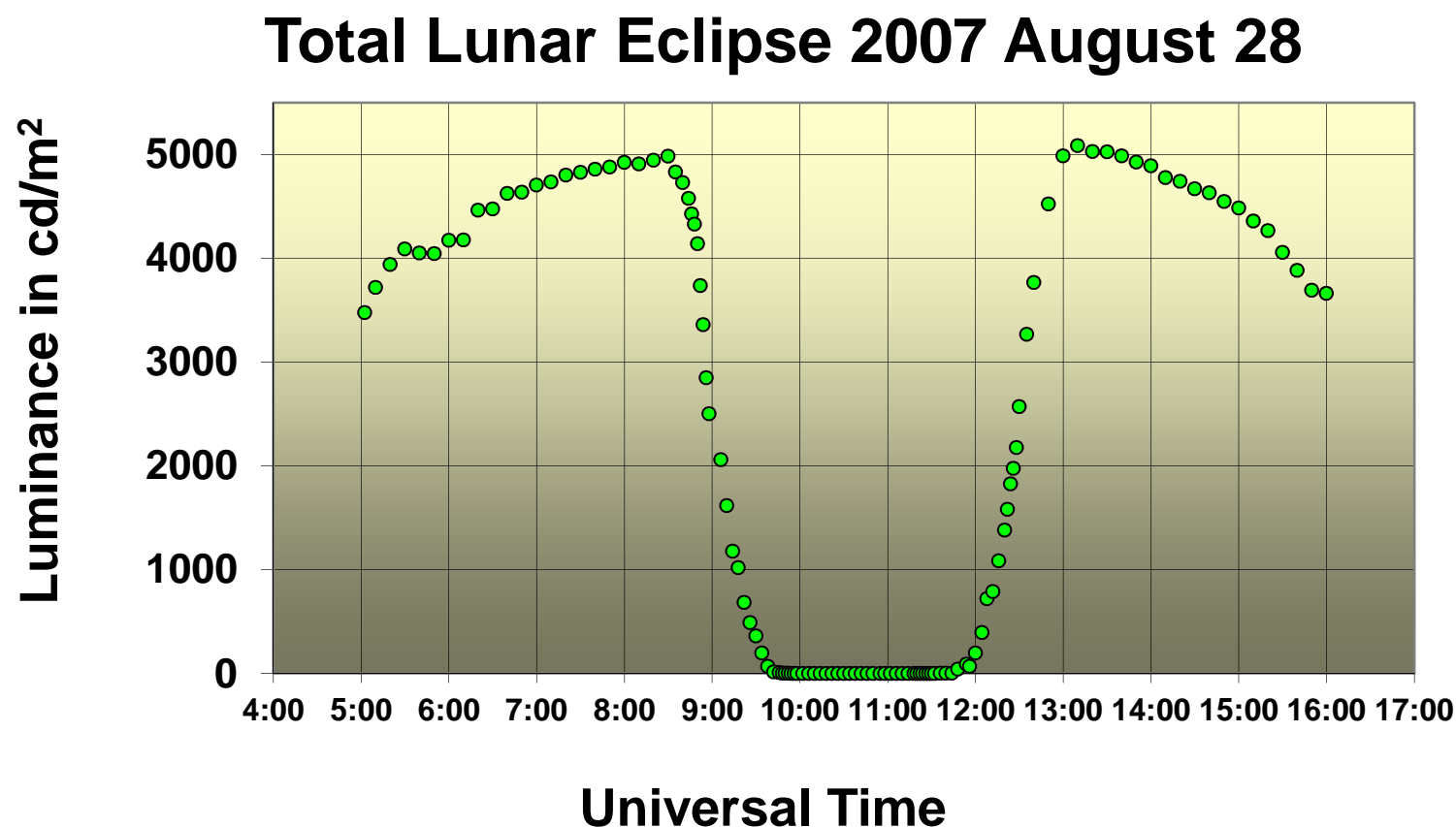


Mauna Loa Observatory, Hawaii, Aug. 27th/28th 2007





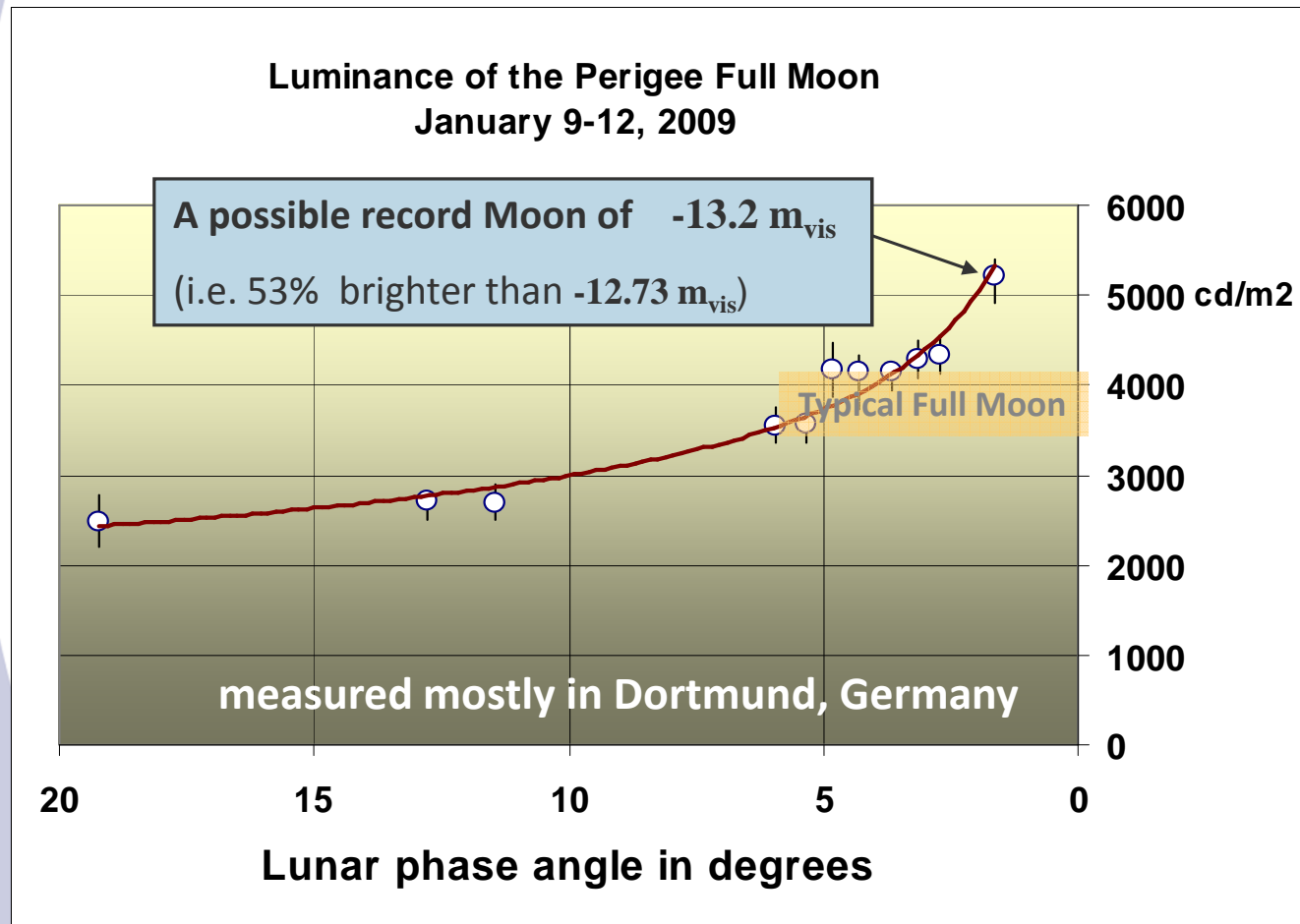
# The linearly scaled light curve (thus details in the minimum are suppressed)



# The lunar opposition effect



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*The effect is also well known for Mars, the asteroids, Saturn's rings and the moons of the outer planets*

**Near Full Moon its luminance almost doubles(!),  
although the illuminated area increases by less than 5%**





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# The lunar opposition surge at close-up





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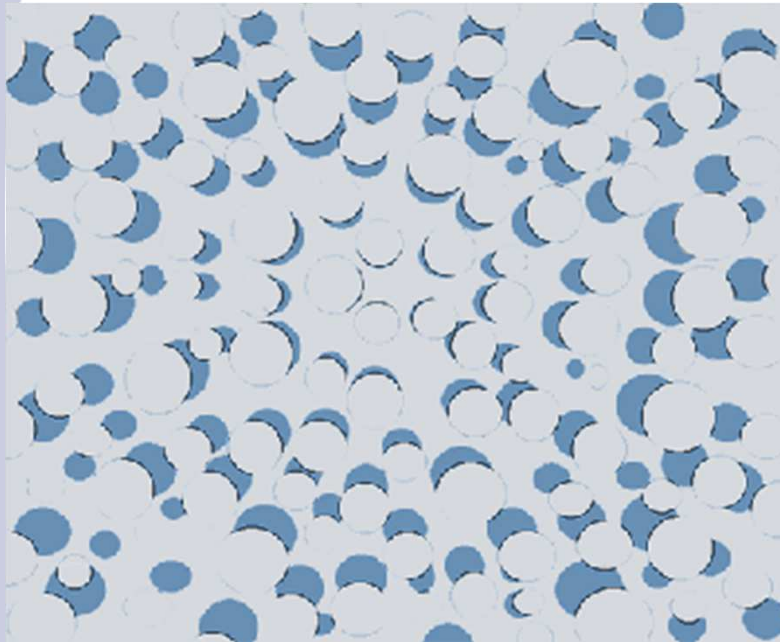
# The opposition effect is for Earthlings too



Photos by Eva Seidenfaden, Trier  
<http://www.paraselenene.de>

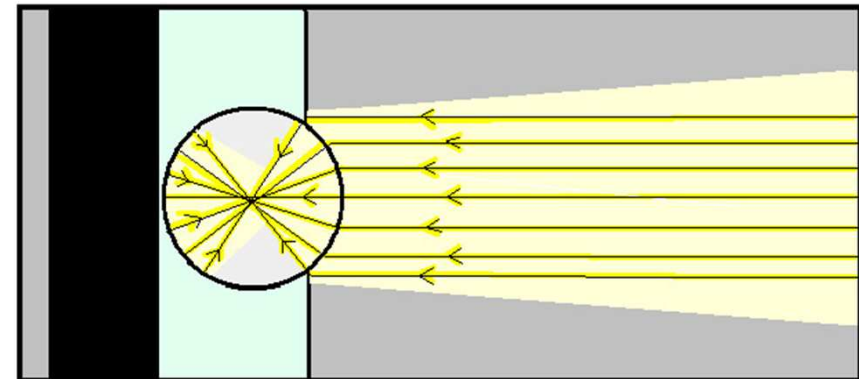
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## Now, how comes the opposition effect?



Most of it is shadow-hiding on granular or rough surfaces at bidirectionally near-normal incidence

It can be enhanced by retroreflexion (coherent backscattering), e.g. from glassy spherules in the lunar regolith soil





## If the Moon were a giant painted disk

then its projected area specific brightness (luminance) would be the same from any angle, and a Full Moon of course two times brighter overall than a Half Moon

*much in the same way, that a sheet of paper or a projection screen shows us the same whiteness from any angle*

## If the Moon were a giant painted ball

then it can be shown by integrating Lambert's cosine law, that the Full Moon would be  $\pi$  times brighter than the Half Moon

→ *actually it is more than ten times brighter*

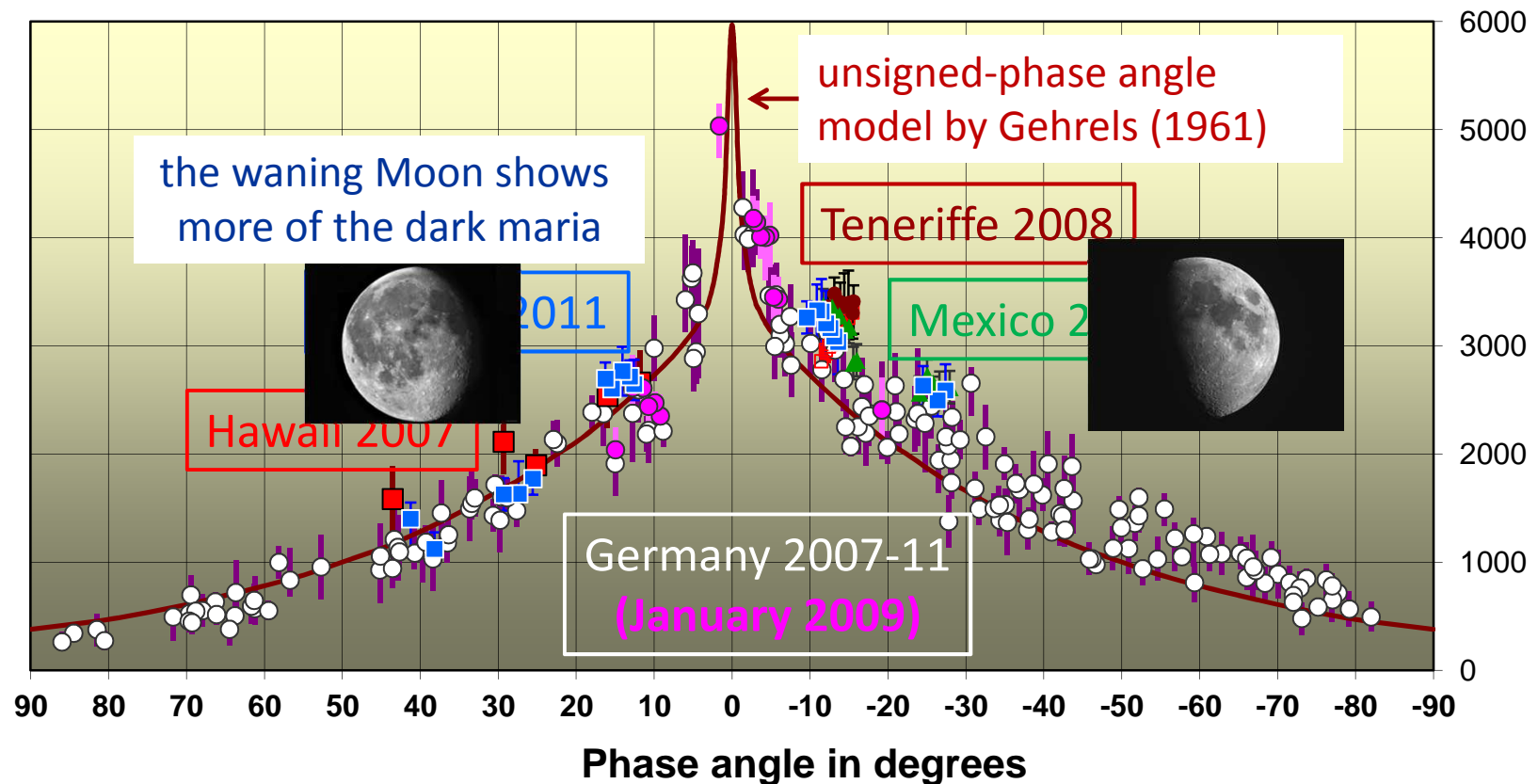


# Five years of lunar phase brightness data



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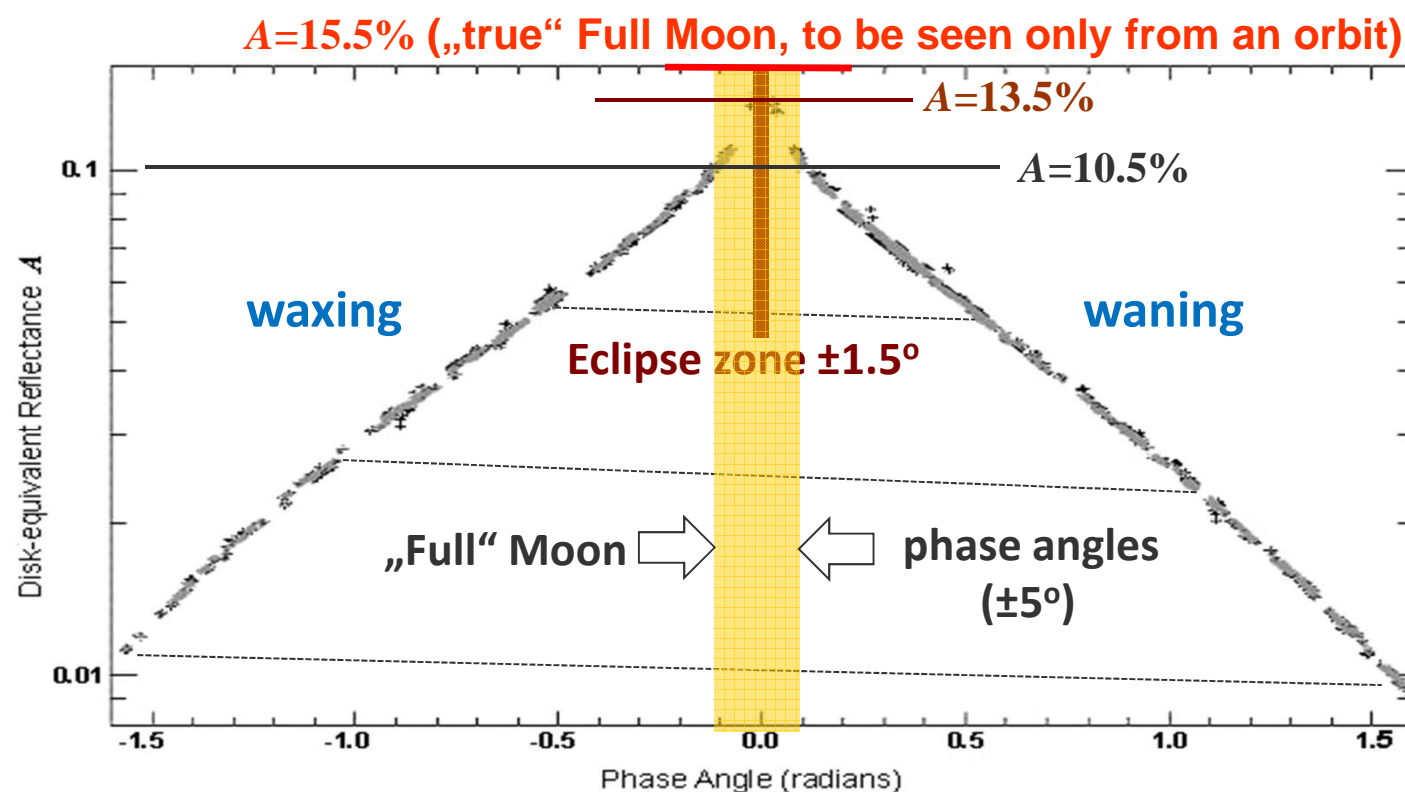
Air mass-corrected lunar phase luminance function



- the errors are due to unaccounted for atmospheric aerosol
- the asymmetry is for real, however, and due to lunar topography



# A better picture from perfect skies



**Near the Full Moon the lunar optical albedo  $A$  (reflectivity) increases from 10.5% to 13.5%**

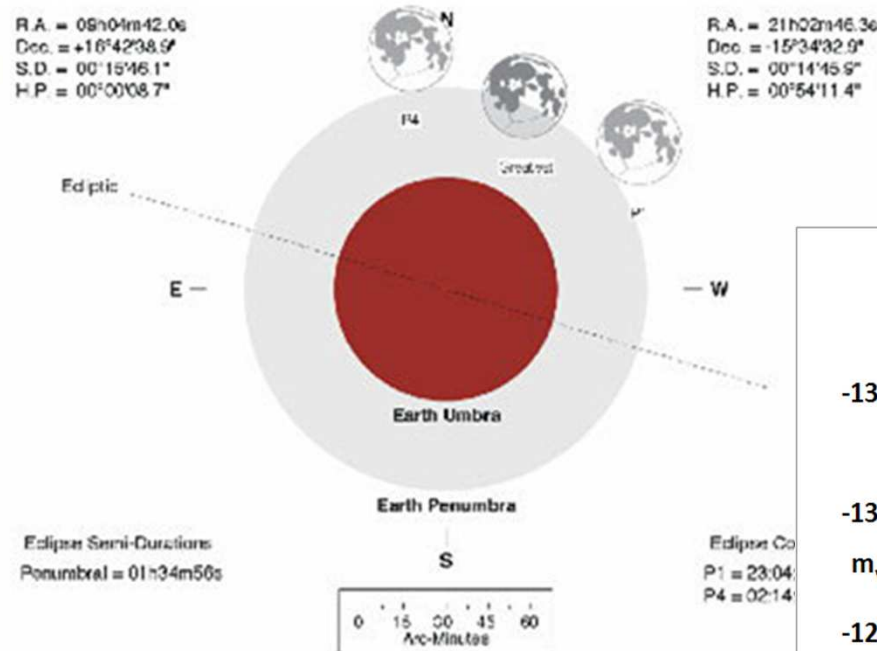
**Data from ROLO (RObotic Lunar Observatory), Flagstaff, Arizona**

[http://www.moon-cal.org/database/image\\_archive.php](http://www.moon-cal.org/database/image_archive.php)

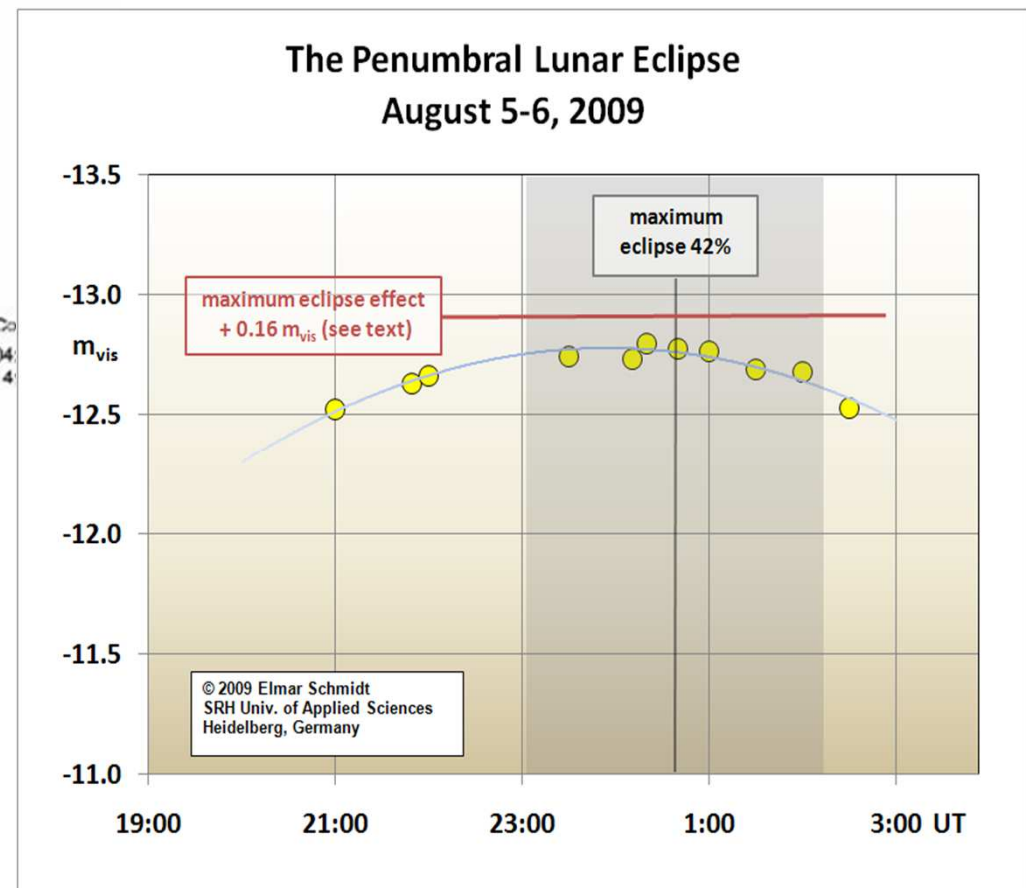
# Still brighter: an eclipse that wasn't...



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... the lunar opposition surge is stronger than even a 42% penumbral eclipse, giving us the ***Fullest Moon possible***





## My approach to absolute lunar photometry

- there is no true terrestrial Full Moon, because it inevitably gets eclipsed then
- then there are very large variations in both its claimed and measured brightness
- the only safe way is to use solar quantities which are well established, namely the solar luminance

$$L_{Sun} = 150 \cdot 10^9 \text{ cd/m}^2$$

corresponding to -26.73 m<sub>vis</sub>

# My photometric model for the Moon

- starts with a so-called emittance  $M$  obtained from the lunisolar illuminance  $E^*$  times the phase-angle dependent albedo  $C(\alpha)$

$$M_{Moon} = C(\alpha) \cdot \tilde{E}_{Sun} = C(\alpha) \cdot L_{Sun} \cdot \left( \frac{R_{Sun}}{d_{Sun-Moon}} \right)^2$$

*\*the terrestrial (not the free space!) value is handy here, because it includes the air mass already*

- the Moon's luminance, by hemispherical diffusion of the impinging sunlight and the cosine law diminishes (approximately\*) by Lambert's divisor  $L_{Moon} = \frac{M_{moon}}{\pi}$

*\*corrections to Lambertian reflection by the Lommel-Seliger law*

- Illuminance from the Moon is then Sun-analogous

$$E_{Moon} = L_{Moon} \cdot \Omega_{Moon} + L_{Moonlit Sky} \cdot \pi \quad \text{where} \quad \frac{L_{Moonlit Sky}}{L_{Moon}} = \frac{L_{Sunlit Sky}}{L_{Sun}}$$



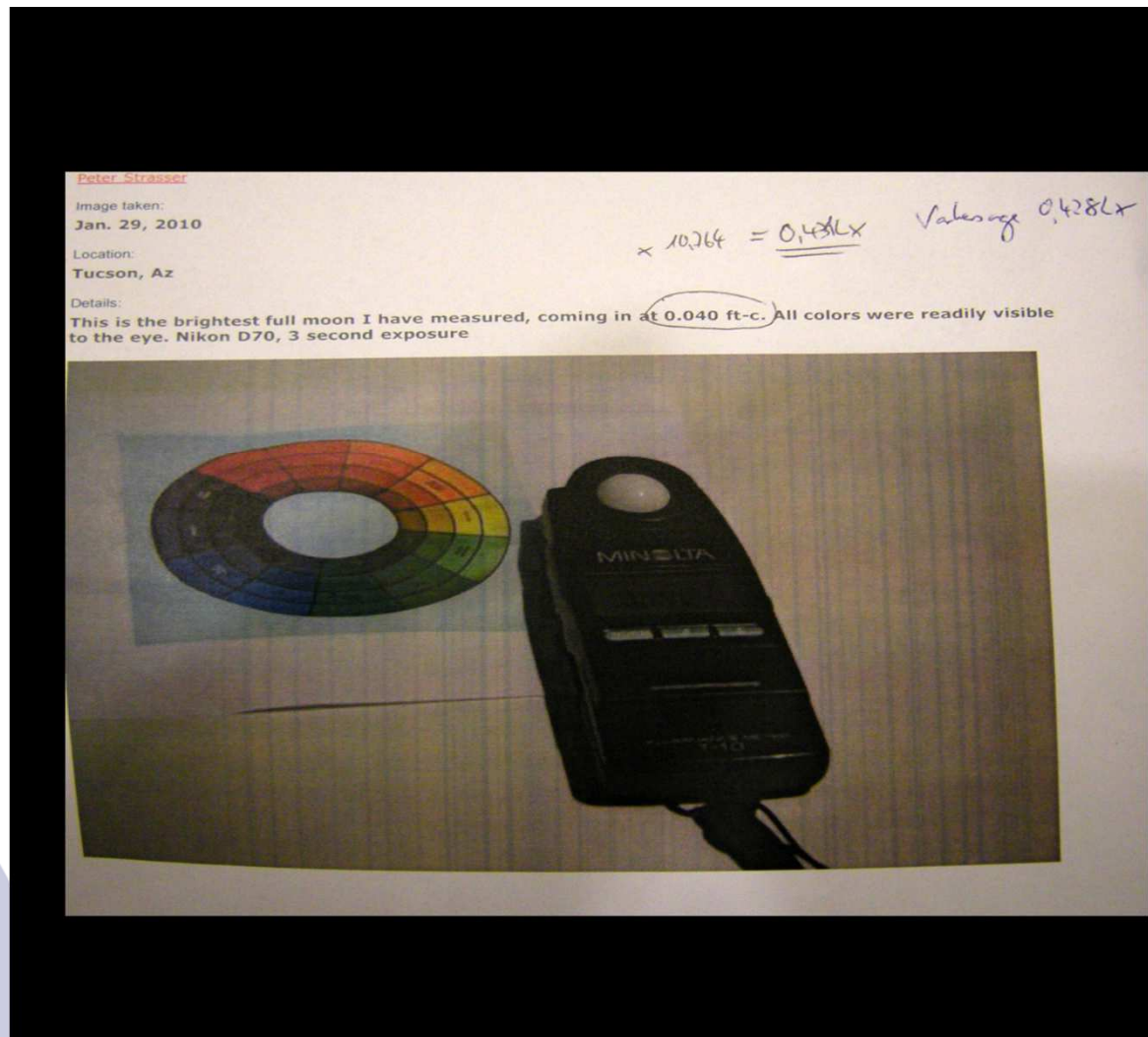


# Lunisolar photometric spreadsheet

| FULL MOON                             | (Brightness) |              |           | Units                 |
|---------------------------------------|--------------|--------------|-----------|-----------------------|
|                                       | Min          | Mean         | Max       |                       |
| Moon-Earth distance                   | 406700       | 384400       | 356400    | km                    |
| Moon's angular diameter               | 29,38        | 31,08        | 33,52     | arc minutes           |
| Moon's solid angle                    | 5,735E-05    | 6,420E-05    | 7,468E-05 | sr                    |
| solar radius                          |              | 696000       |           | km                    |
| lunar radius                          |              | 1740         |           | km                    |
|                                       |              | 14997960     |           |                       |
| Sun-Full_Moon distance                | 152501900    | 0            | 147451600 | km                    |
| lunar albedo (opposition effect!)     | 0,110        | <b>0,125</b> | 0,145     |                       |
| terrestrial direct lunar luminance    | 3437         | 4172         | 5169      | cd/m <sup>2</sup>     |
| variation (best guess)                |              | 619          |           | +/- cd/m <sup>2</sup> |
| direct illuminance from Full Moon     | 0,197        | 0,268        | 0,386     | lx                    |
| diffuse illumiminance (blue sky)      | 0,019        | 0,040        | 0,086     | lx                    |
| corresponding Full Moon sky luminance | 0,006        | 0,013        | 0,027     | cd/m <sup>2</sup>     |
| total illuminance                     | 0,216        | 0,308        | 0,472     | lx                    |
| variation (best guess)                |              | 0,094        |           | +/- lx                |
| alternative calculation               | 0,217        | 0,309        | 0,474     | lx                    |

# Critical test: the Perigee Full Moon: Jan 29th, 2010

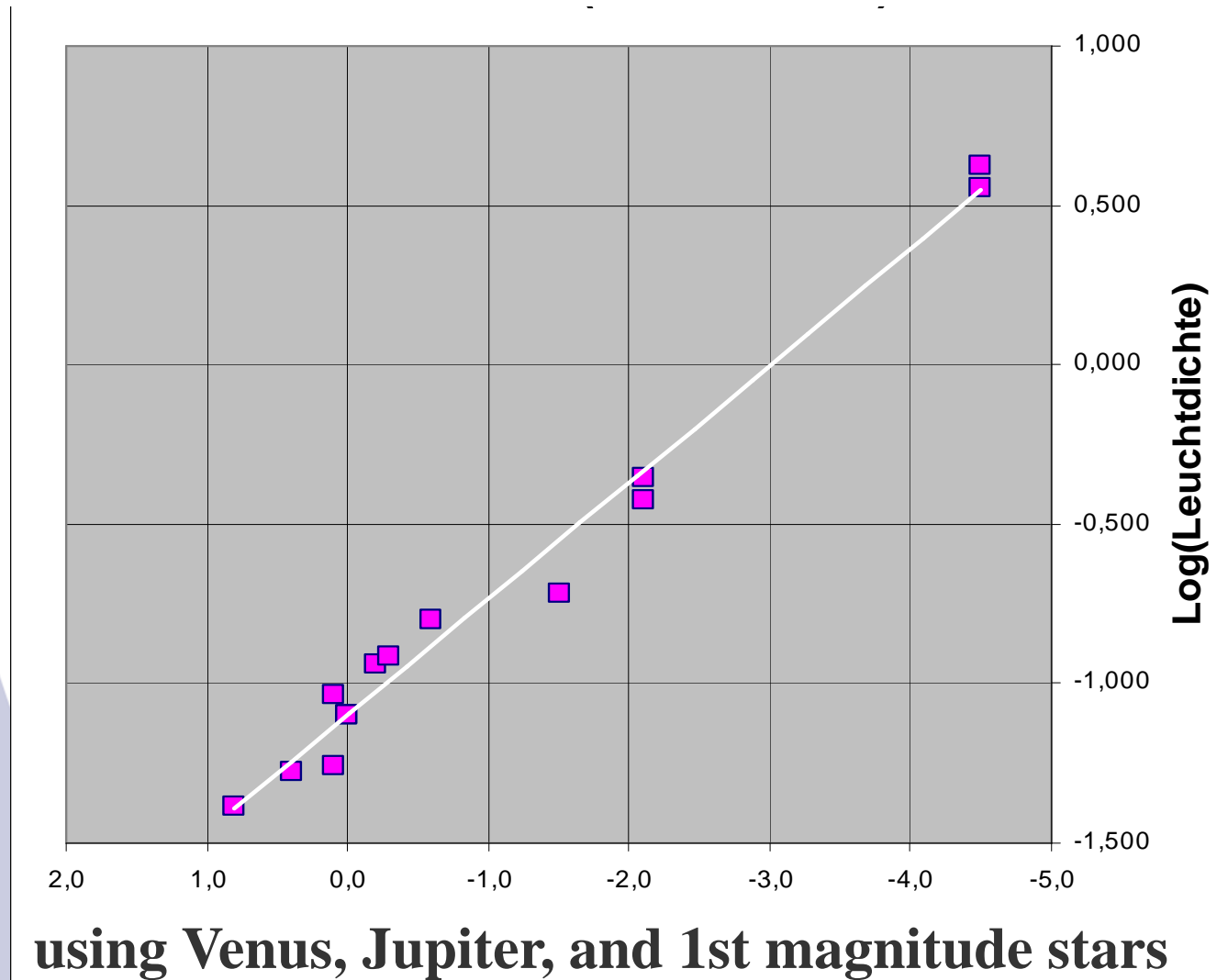
Measurement 0.431 lx by Peter Strasser, Tucson, AZ  
My model 0.428 lx



## Further calibration, correction & errors

- the absolute luminance measuring error of the LS-110 photometer is better than  $\pm 0.5\%$
- atmospheric extinction in our data is calibrated to zero zenith distance at sea level by using the air mass function of Kasten and Young and an optical density of 0.098 (obtained by convoluting  $\lambda^{-4}$  Rayleigh (monomolecular clear air) scattering characteristics with  $V_\lambda$ )
- the eclipse light curves are at first only air-mass corrected
- for comparing eclipses and for studying the opposition effect the respective measurements must be standardized to a solar distance of 1.a.u. (for luminances) and to the lunar mean distance 384 500 km (for visual magnitudes)
- the lunar magnitudes were adjusted at  $3670 \text{ cd/m}^2 = -12.73 m_{\text{vis}}$
- a linear correlation of magnitude vs. log(luminance) was corroborated for eclipse-like conditions by measuring bright planets and stars

## Linearity of $\log(\text{Luminance})$ vs. visual magnitudes for luminances 0.041-4.22 $\text{cd/m}^2$







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**Now, for some more lunar  
eclipse travels of mine  
around the world...**



Dec. 2010: Guadalajara, Mexico



At our partner university's  
Tapalpa guesthouse (2443 m)

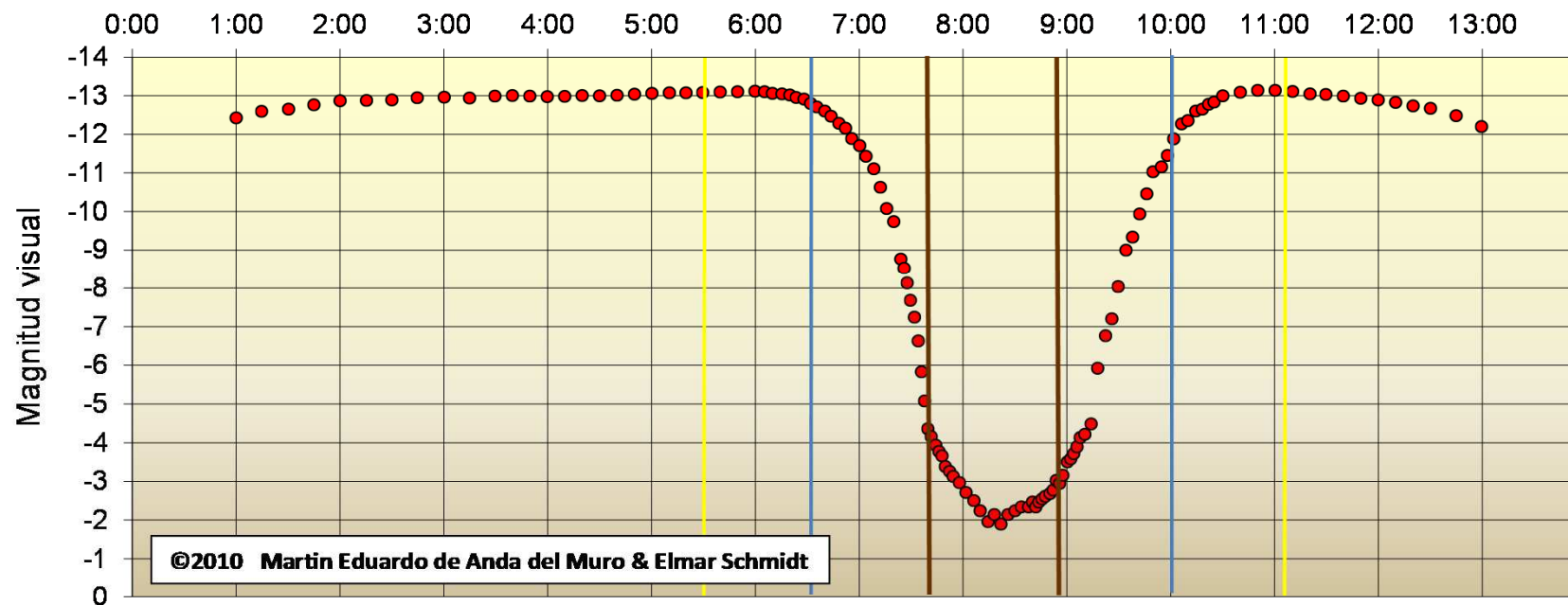
# Dec. 21st, 2010 LPOD (Lunar Picture of the Day) Dec. 23rd, 2010



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## Eclipse lunar total 21 de diciembre 2010 médido en la Cabaña UNIVA en Tapalpa, Jalisco, México

Tiempo Universal (Hora Central + 6 horas)



This 12 hour coverage of Dec. 21st lunar eclipse is believed to be one of the most complete and precise light curves for any such events. All reported magnitudes are standardized to an air mass of 1.0 of a Rayleigh atmosphere. Only the first and last hour of measurements were compromised somewhat by aerosol at lower lunar elevations. Otherwise, the sky conditions at a remote mountain site in central Mexico (103°42'42" W, 19°59'43" N, altitude 2443 m) were nearly perfect. The colored vertical lines designate the six eclipse contact times. More details will be published.

The investigation was a collaboration between Universidad del Valle de Atemajac (UNIVA) in Guadalajara, México, and SRH University of Applied Sciences in Heidelberg, Germany. The assistance of Guillermo de Tamirano Navarro, Jorge Armando Flores Montoya and Oscar Alejandro Ledón Mú is gratefully acknowledged.





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June 2011

Astrofarm Hakos\* (1834 m)

Namibia (South West Africa)

(\*40 sq.km owned by a single family)



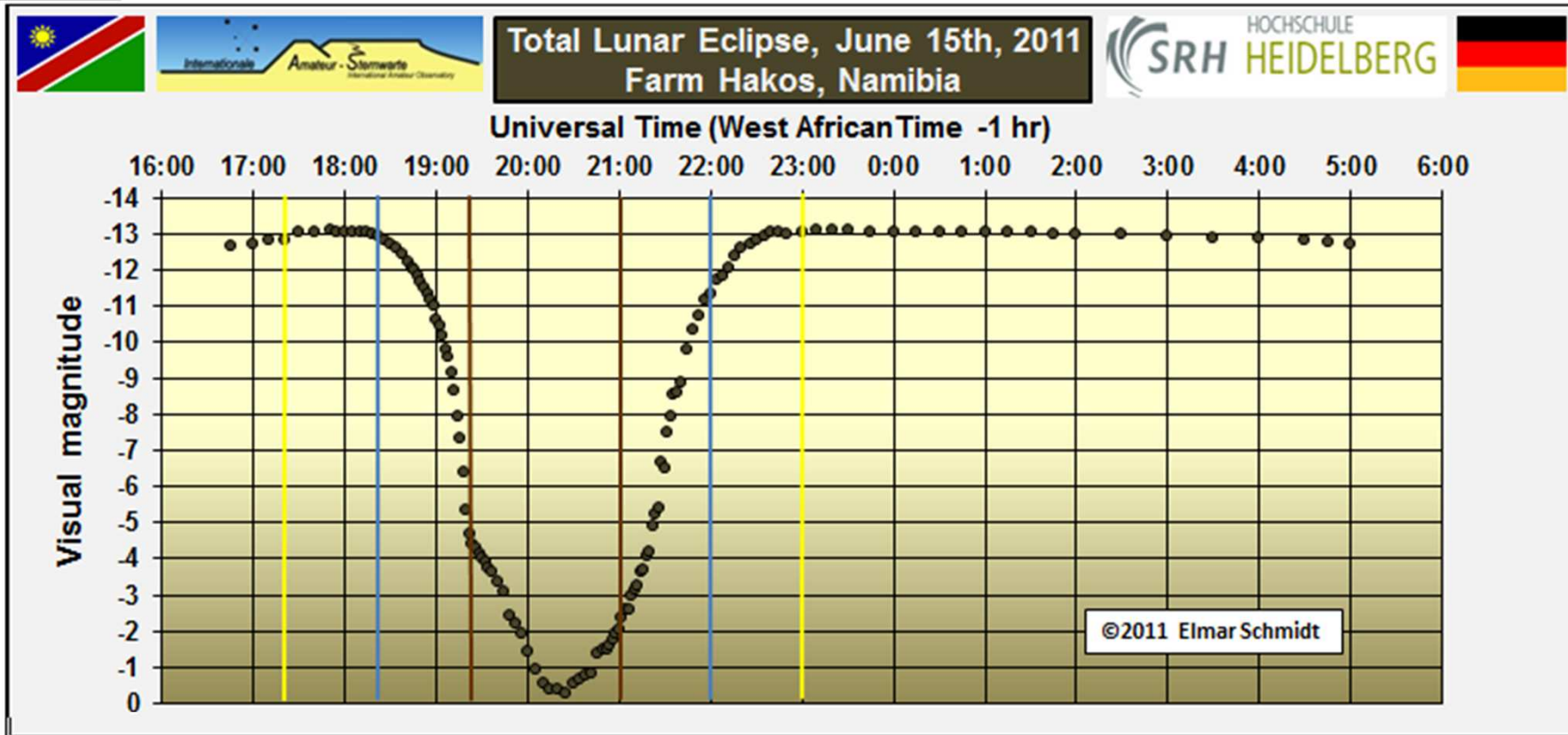
Folie 41



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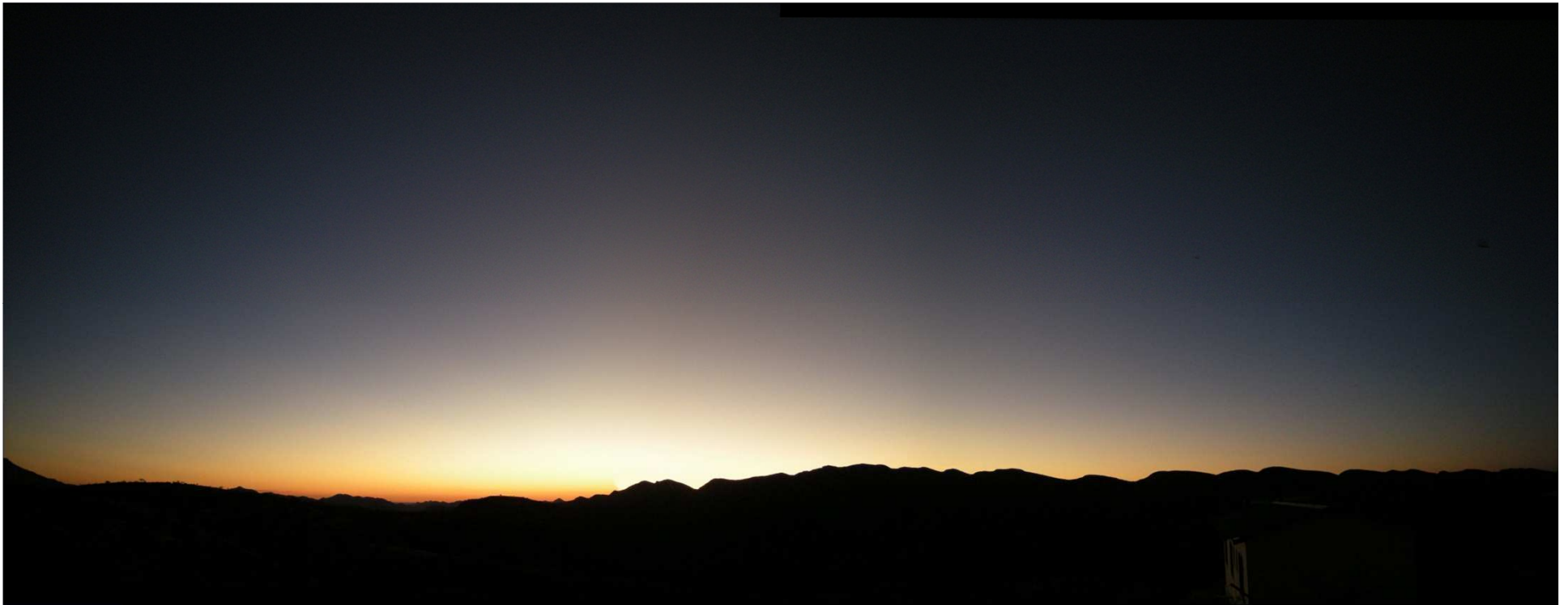
# June, 15th, 2011 LPOD (Lunar Picture of the Day) June, 17th, 2011



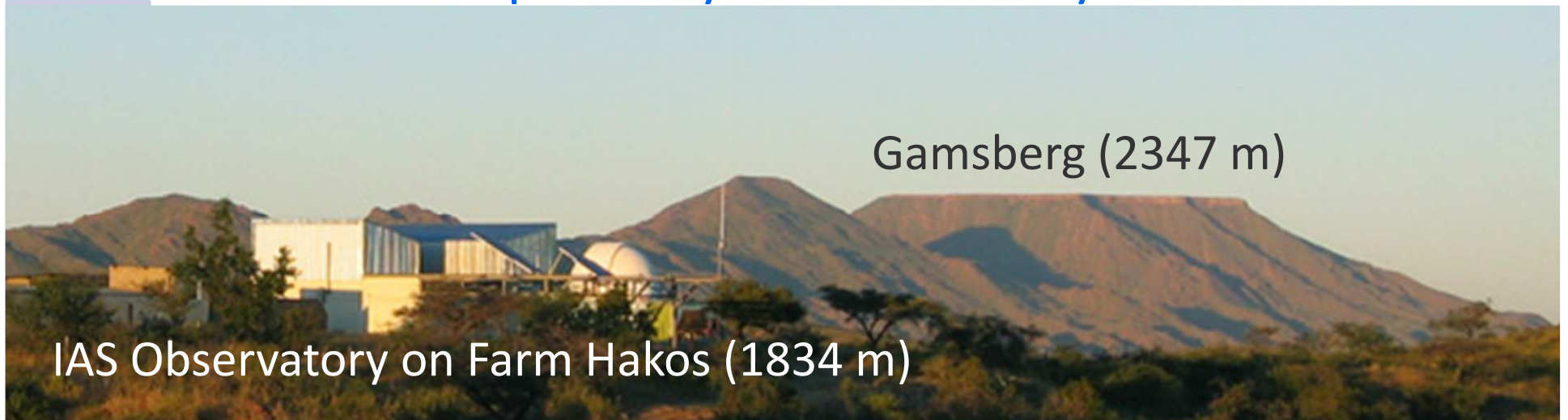
The June 15<sup>th</sup>, 2011 total lunar eclipse was followed photometrically from a mountain site in Namibia (16°21'47" E, 23°14'06" S, altitude 1834 m). All plotted magnitudes are standardized to an air mass of 1.0 of a Rayleigh atmosphere, which cannot correct for aerosol at low lunar altitudes during the first hour. This eclipse was "central", because the Moon travelled through the center of the umbra. This led to its comparative darkness, with the light curve bottoming out at a magnitude of  $-0.35 m_{viz}$ , implying a linear brightness reduction in excess of 120 000. The colored vertical lines designate the six eclipse contact times. The light curve's asymmetry compared to the geometrical phases is probably due to a combination of lunar topography and potential anomalies in the Earth's shadow, which will be further analyzed and published.

Diagrammbereich

This work is part of ongoing research at SRH University of Applied Sciences in Heidelberg, Germany. It was supported by useful information on the Farm Hakos from Internationale Amateursternwarte ( [www.ias-observatory.org](http://www.ias-observatory.org) ), for which the author wishes to thank Karl-Ludwig Bath and Dr. Carsten Jacobs. The assistance and hospitality of Waltraud Eppelmann, Friedhelm Hund, and their team at Farm Hakos ( [www.natron.net/tour/hakos](http://www.natron.net/tour/hakos) ) is gratefully acknowledged.



As a Southern sky astronomical resource,  
Namibia is probably second to only Chile



Gamsberg (2347 m)

IAS Observatory on Farm Hakos (1834 m)





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Semi-quantitative  
derivation of the Earth  
shadow's optical density  
and color during the  
March 3rd 2007 TLE

© Ivan Goncalves,  
Nimes, France

The luminance range of  
more than

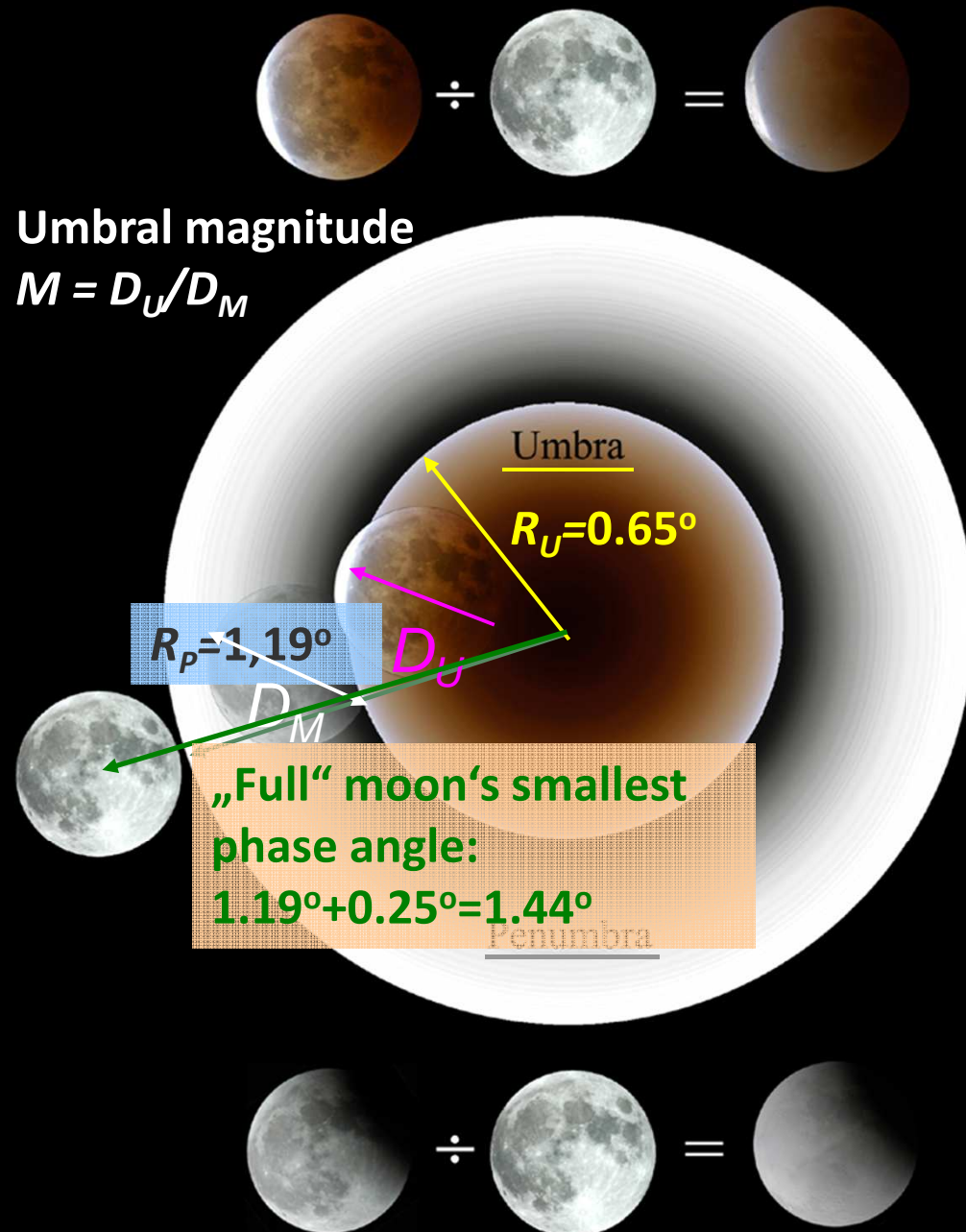
**4 orders of magnitude**

can only be shown in a  
slide by re-scaling it at  
the border between  
umbra and penumbra

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Umbral magnitude

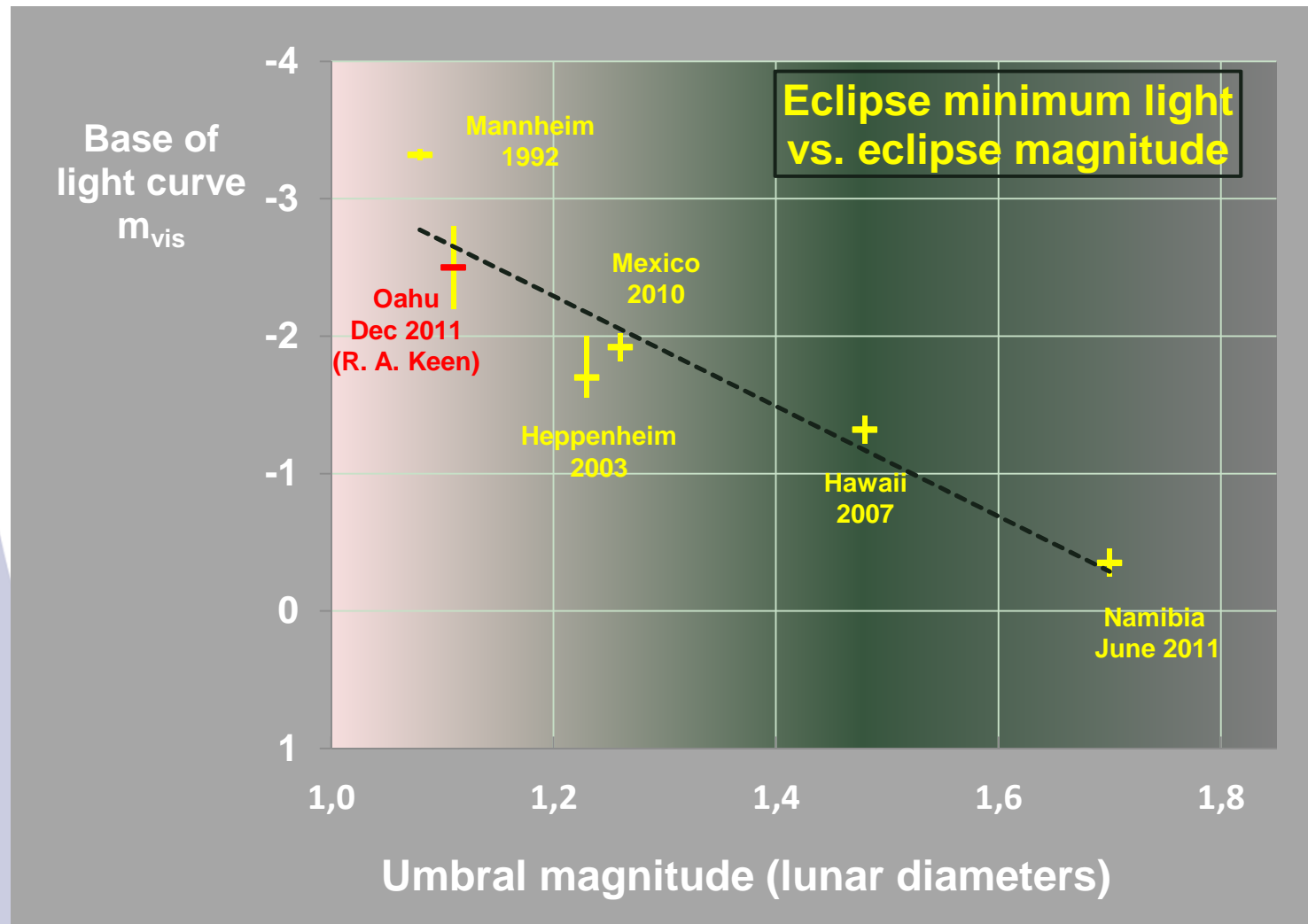
$$M = D_U / D_M$$



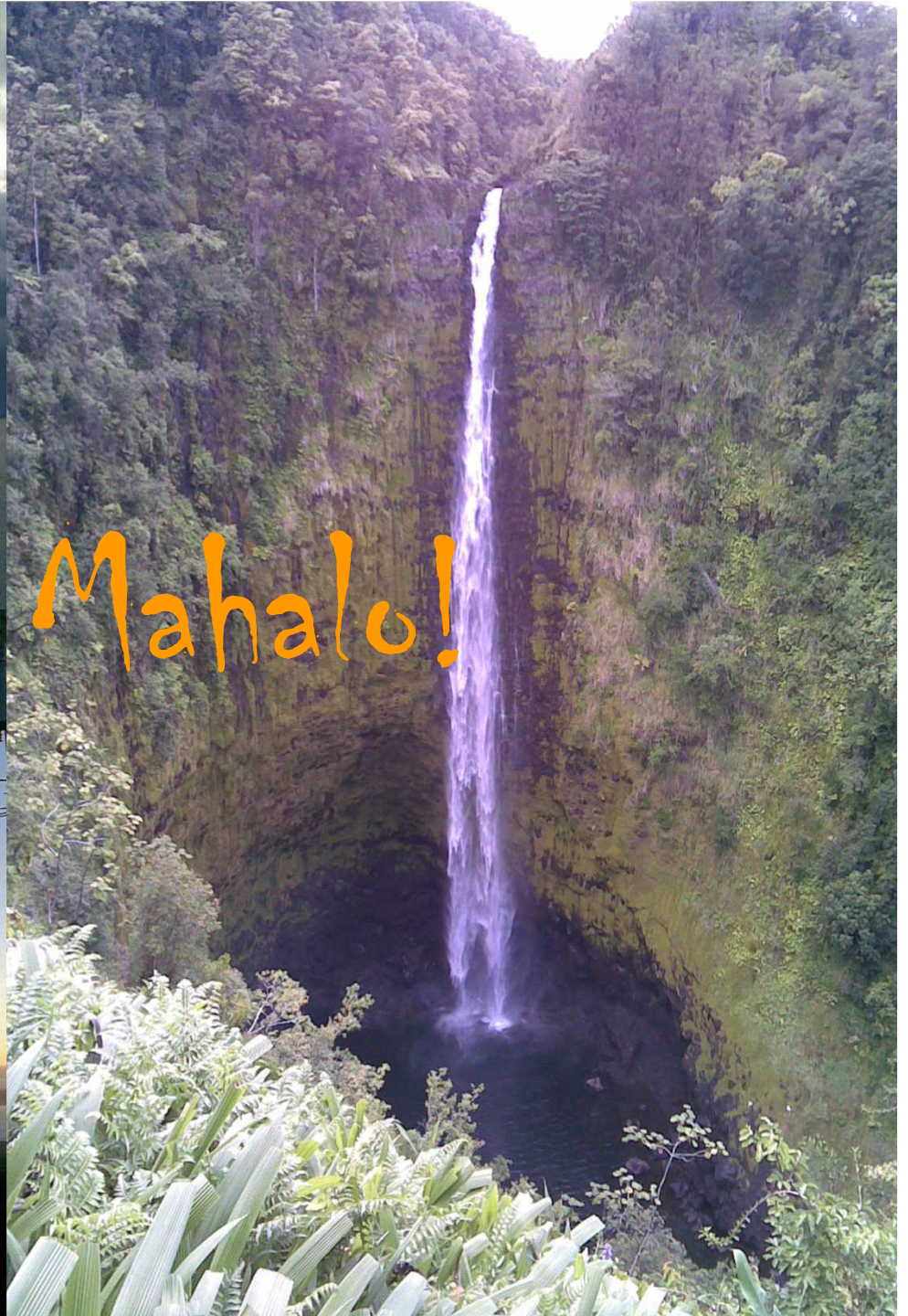
# A first correlation diagram



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Xièxie - Mahalo!