Stellar occultations by TNOs

J. L. Ortiz* (Granada team), B. Sicardy (Paris team), F. Braga-Ribas (Rio team) and other usual collaborators

•Transneptunian Objects (TNOs) are very important bodies from which we can learn a lot about the solar system. Currently there are only around 1200 TNOs known, which is a tiny number compared to the nearly half a million known asteroids...

•TNOs are not like ordinary asteroids. In fact, most of us do not consider them asteroids because they have little in common with the usual asteroids between Jupiter and Mars.

*Instituto de Astrofísica de Andalucia-CSIC, Apt 3004, Granada, SPAIN

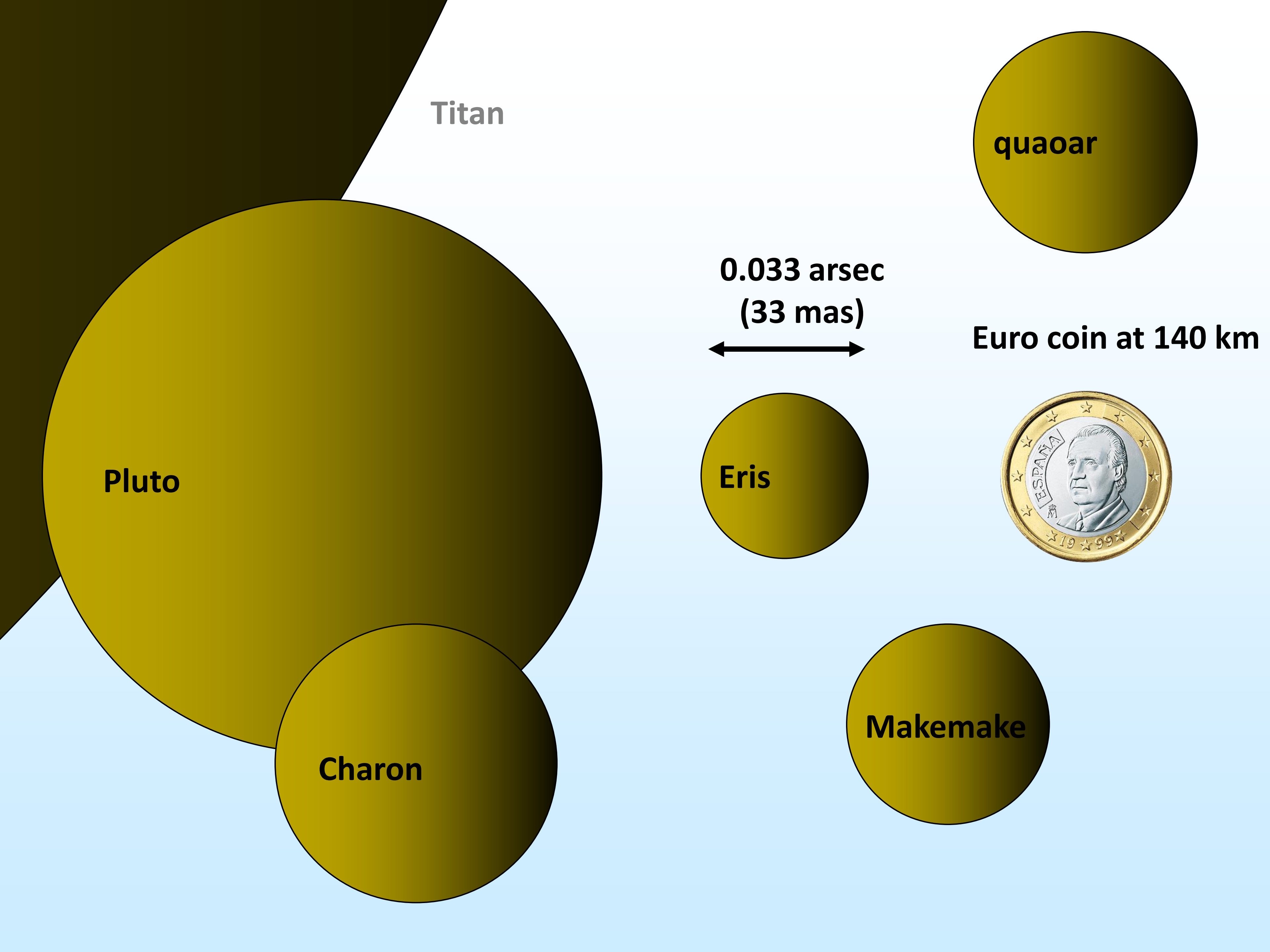
TNOs from occultations

In Granada we have been studying TNOs for more than a decade. **One of the most powerful means to study solar system objects is through stellar occultations.**

- Size, shape, albedo and the presence of atmospheres can be determined from occultations. For TNOs, stellar occultations are the best means BY FAR to obtain those basic physical properties. Thermal modeling of Herschel and Spitzer data can give constraints, but it is a very difficult technique and not very accurate.

- **Occultations by TNOs are extremely difficult to predict** because of the small angular diameters, uncertainties in stellar coordinates and uncertainties in TNO orbits (much larger than their angular diameters).

- The occultations typically last a few tens of seconds in the best cases, so fast cameras are needed, or at least cameras with small dead times.


Titan
quaoar
0.033 arsec
(33 mas)
Euro coin at 140 km
Pluto
Eris
Charon
Makemake

TNOs from occultations

In May 2007 a specific workshop in Paris Observatory was devoted to discuss details and feasibility of detecting and studying possible occultations by TNOs, based on the experience with Pluto, but addressing some specific issues.

Informal collaborations between several teams and individuals were arranged. Mainly three teams were involved. The Rio team, the Paris team and the Granada team, with different although sometimes overlapping roles.

Since late 2009 till now 14 occultations by TNOs have been recorded, that we know of (not counting the Pluto-Charon system):

TNO science through stellar occultations

2002TX300, 9 Oct 2009	american team
Varuna, 19 Feb 2010	our team
Eris, 6 Oct 2010	our team
2003AZ84, 8 Jan 2011	our team
Quaoar, 11 Feb 2011	american team
Makemake, 23 April 2011	our team
Quaoar, 4 May 2011	our team
2003AZ84, 3 Feb 2012	our team
Quaoar, 17 Feb 2012	our team
2002KX14, 26 April 2012	our team
Quaoar, 15 Oct 2012	our team
Varuna, 8 Jan 2013	Japanese amateurs alerted by our team
Sedna, 13 Jan 2013	Joseph Brimacombe (amateur)
Quaoar, 8 Jul 2013	our team

TNO science through stellar occultations

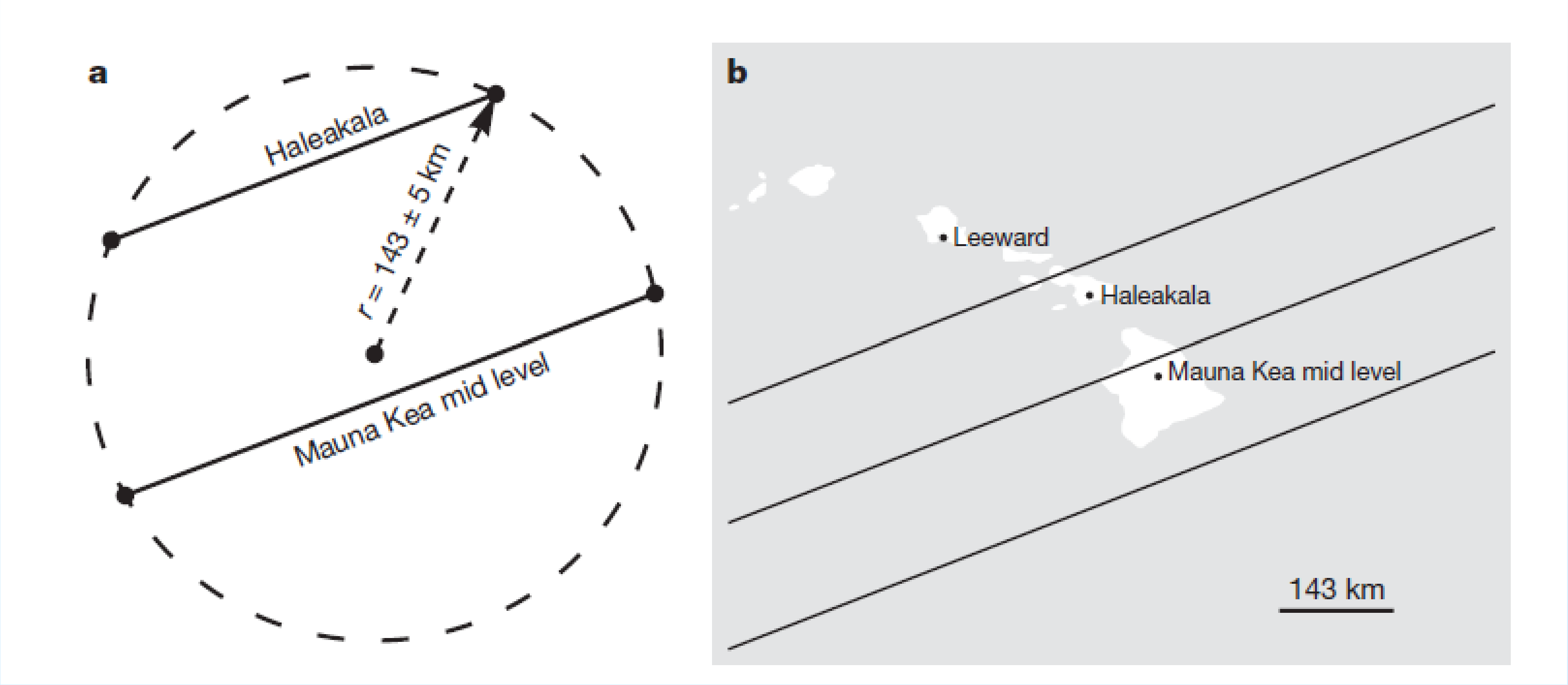
Although there have been 14 occultations recorded, in reality, several objects have caused more than one occultation and only 8 TNOs have been studied:

2002TX300	Elliot et al. 2010. Nature 458, 320
Eris	Sicardy, Ortiz, Assafin et al. (2011) Nature 478, 493
Makemake	Ortiz, Sicady, Braga-Ribas et al. (2012) Nature, 491,566
Quaoar	Braga-Ribas, Sicardy, Ortiz et al. (2013). Ap. J. 773, 26.
2003AZ84	In preparation
2002KX14	In preparation
Varuna	In preparation
Sedna	In preparation

The multichord occultations are in bold

Occultation by 2002TX300 (55636), 9 October 2009

Not done by our team. Summary:



Elliot et al (2010)

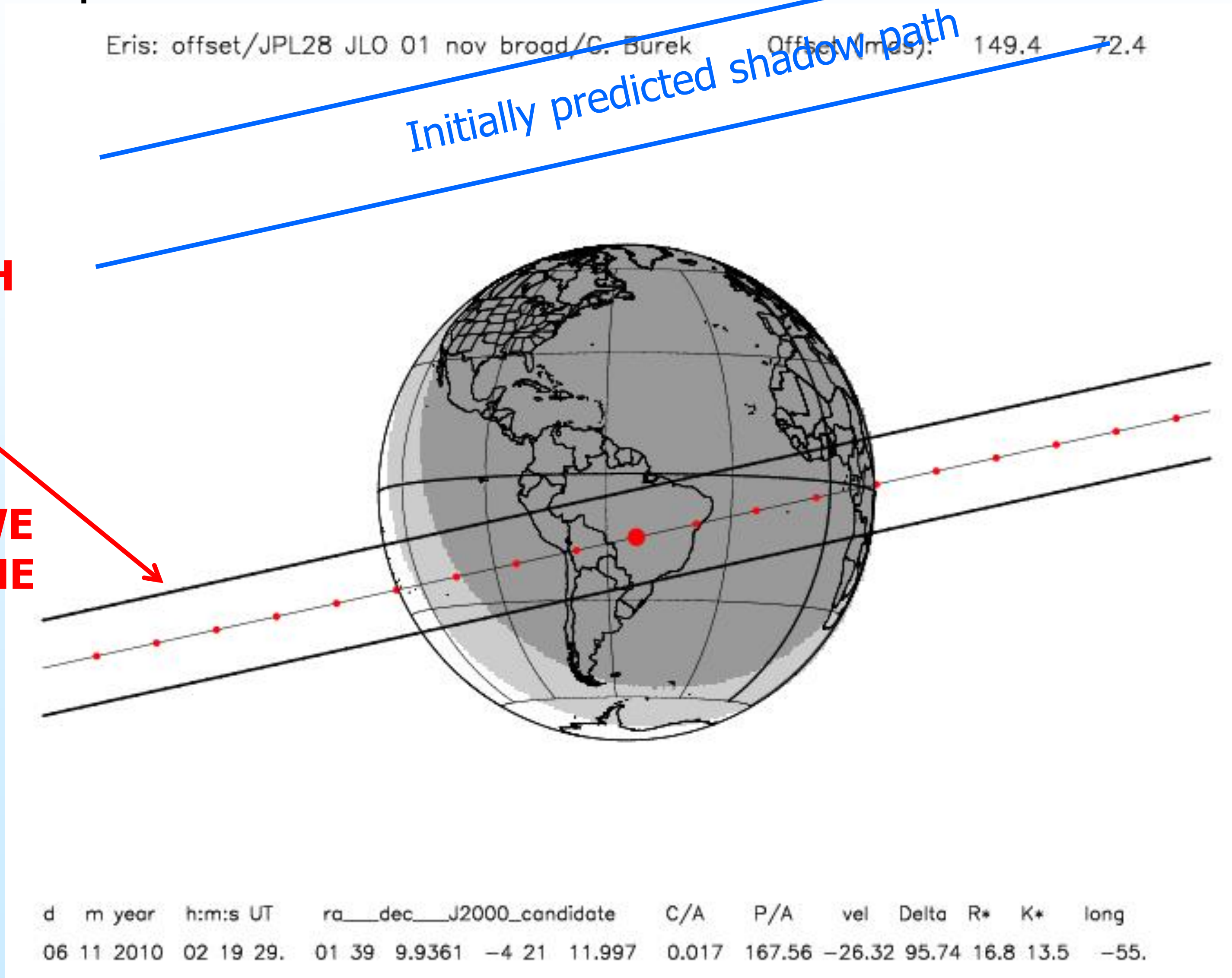
Geometric albedo 0.88 (+0.19 /-0.06)

21 Telescopes, 18 sites, only two successful chords. “Bright star”: 13.2 mag V

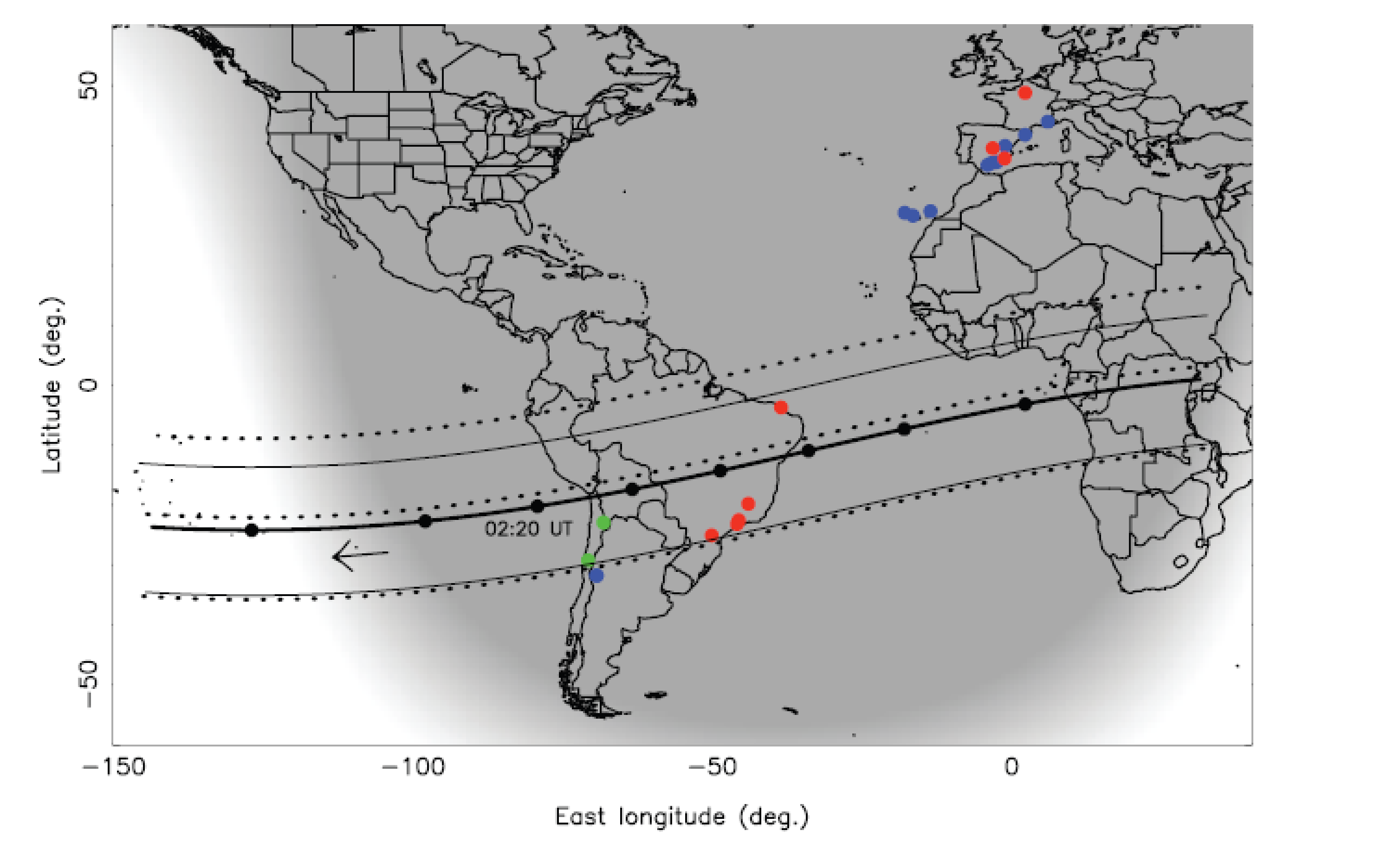
Dwarf planet Eris, 6 November, 2010

- The initial prediction by the Rio Team was not favorable. The shadow path was outside the Earth.

ONLY AFTER CAREFUL ASTROMETRIC FOLLOWUP WITH SEVERAL TELESCOPES IN CALAR ALTO, SPAIN, BUREK, ARGETINA ETC. WE ALERTED THAT THE OCCULTATION WOULD BE FAVORABLE



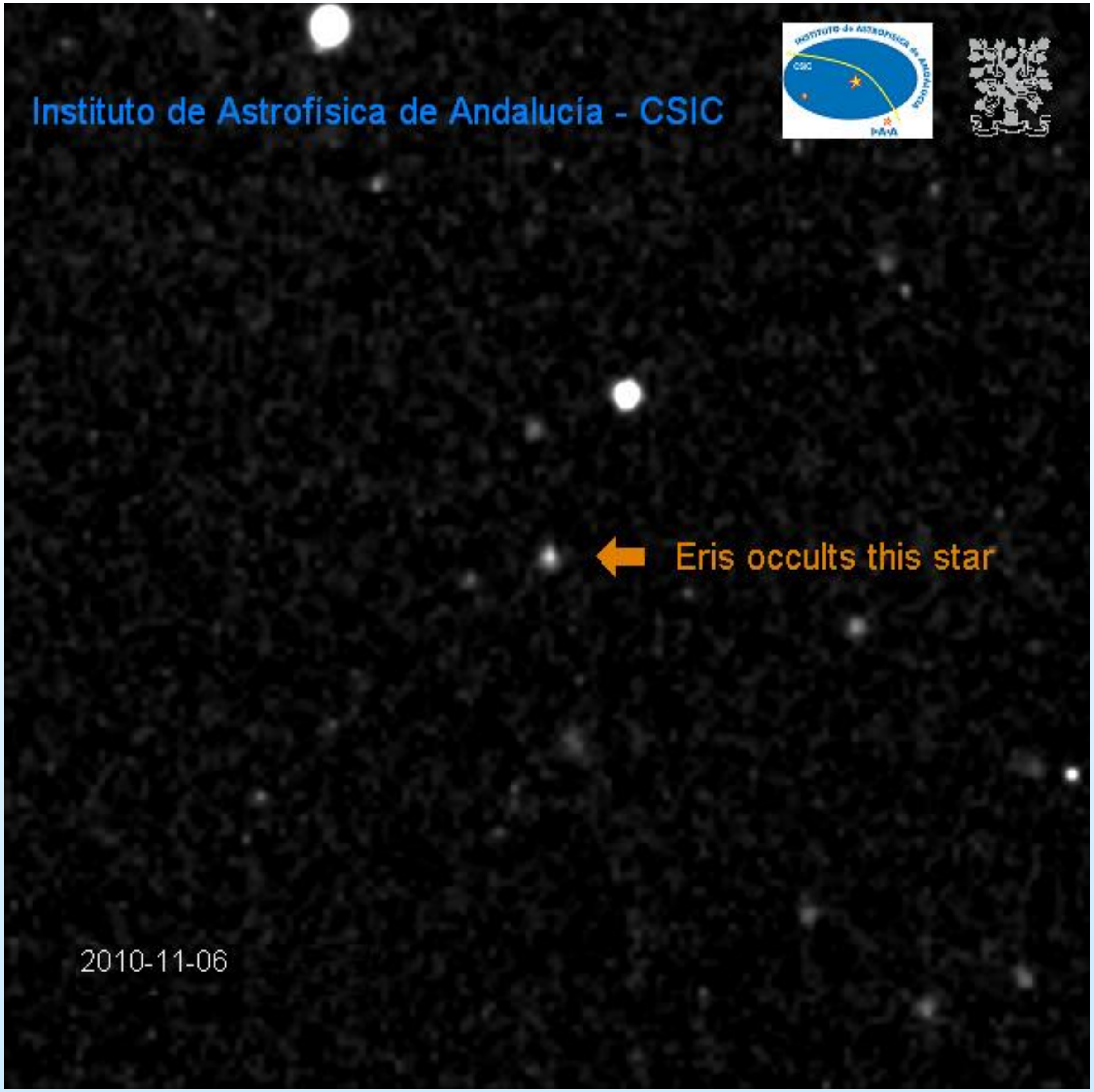
The three teams (Granada, Paris, Rio) arranged observations with many different telescopes around the globe



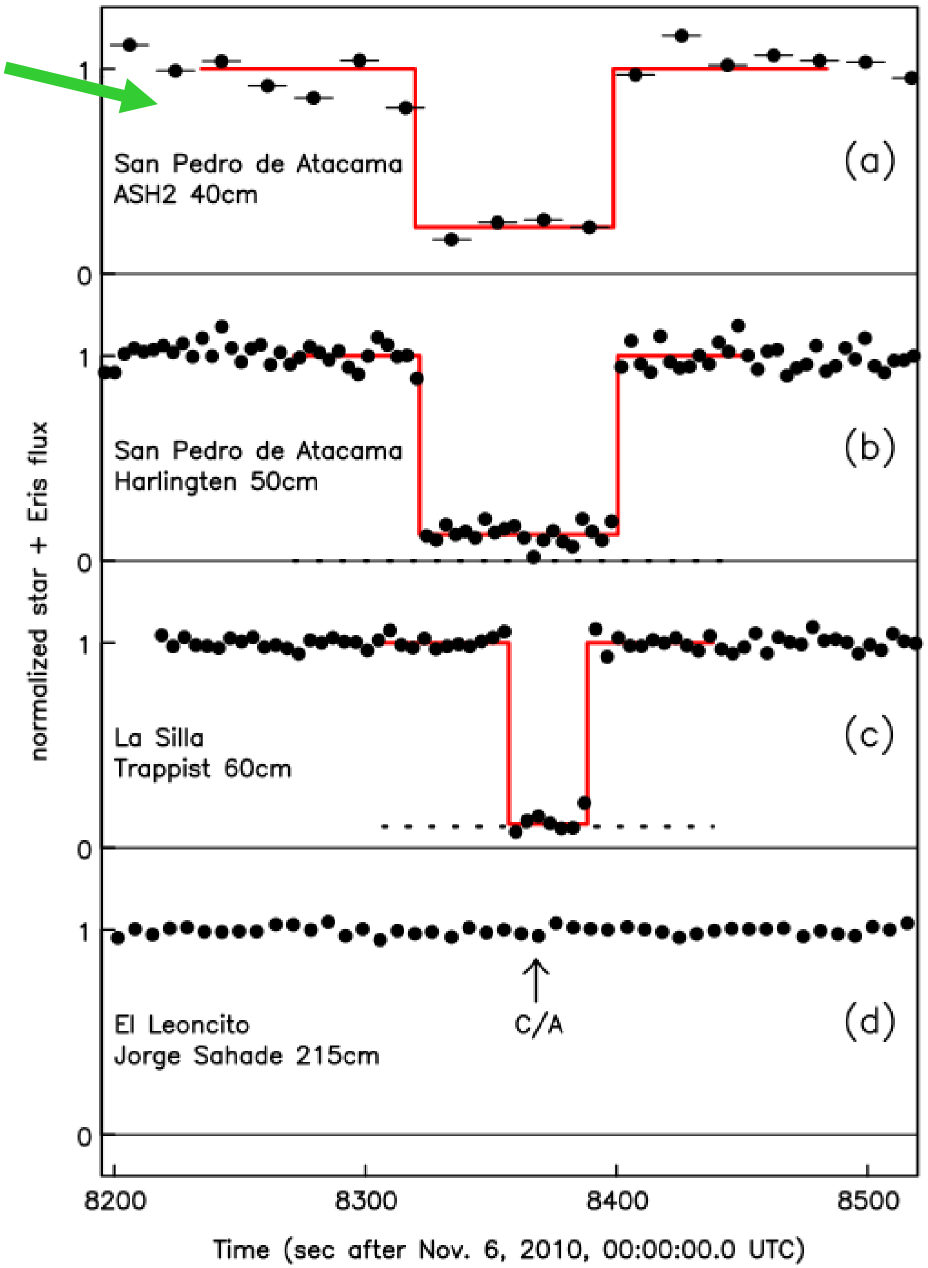
26 telescopes were involved !!!

Only 3 were successful, relatively faint star: 17.2 mag in V

Video of the occultation from our 0.4m telescope



“Our own” telescope in Chile



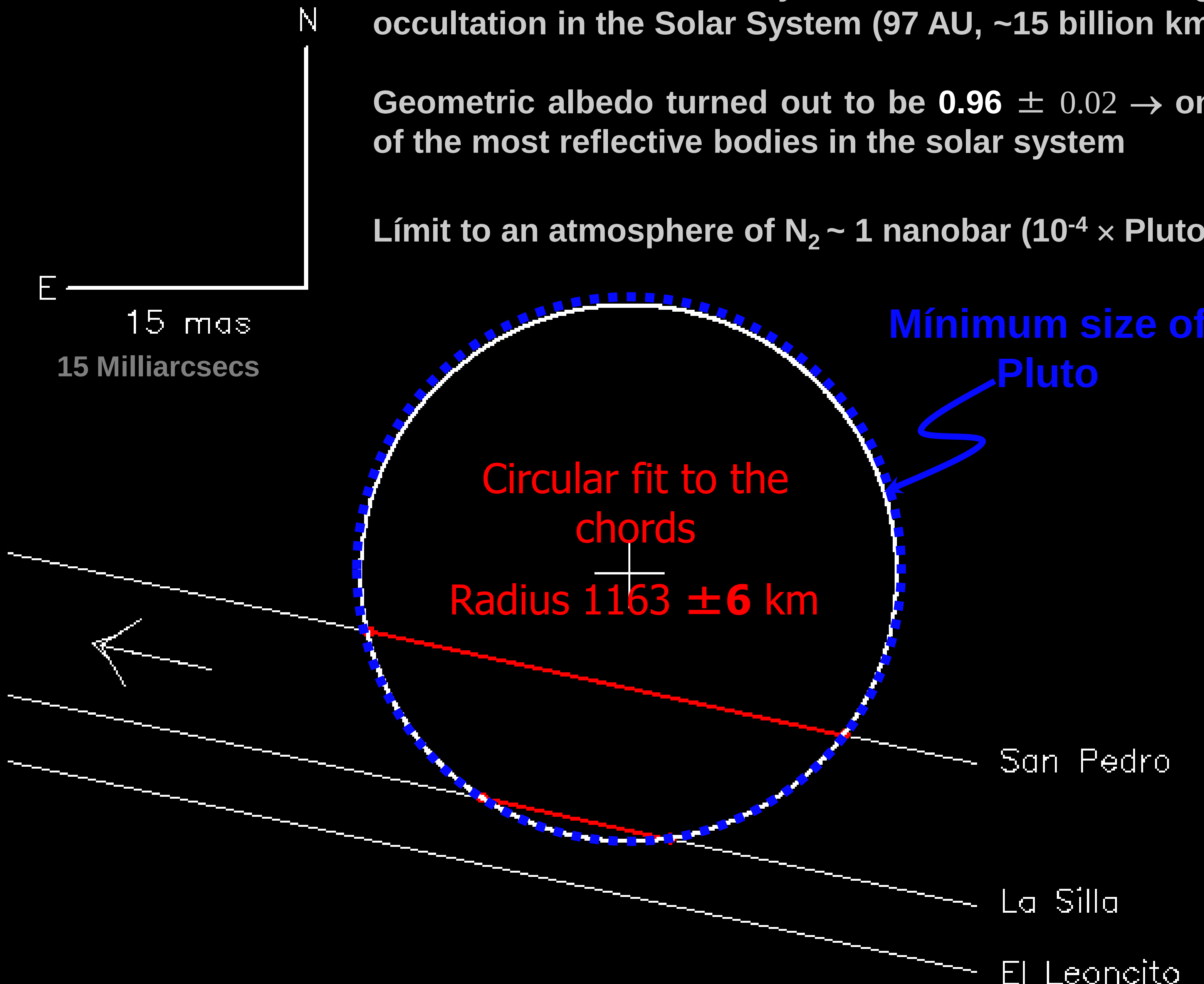
Sicardy, Ortiz et al. (2011). Nature 478, 493

The star was relatively faint: 17.2 mag in V band

The most distant body ever observed through occultation in the Solar System (97 AU, ~15 billion km)

Geometric albedo turned out to be **0.96** $\pm$ 0.02 $\rightarrow$ one of the most reflective bodies in the solar system

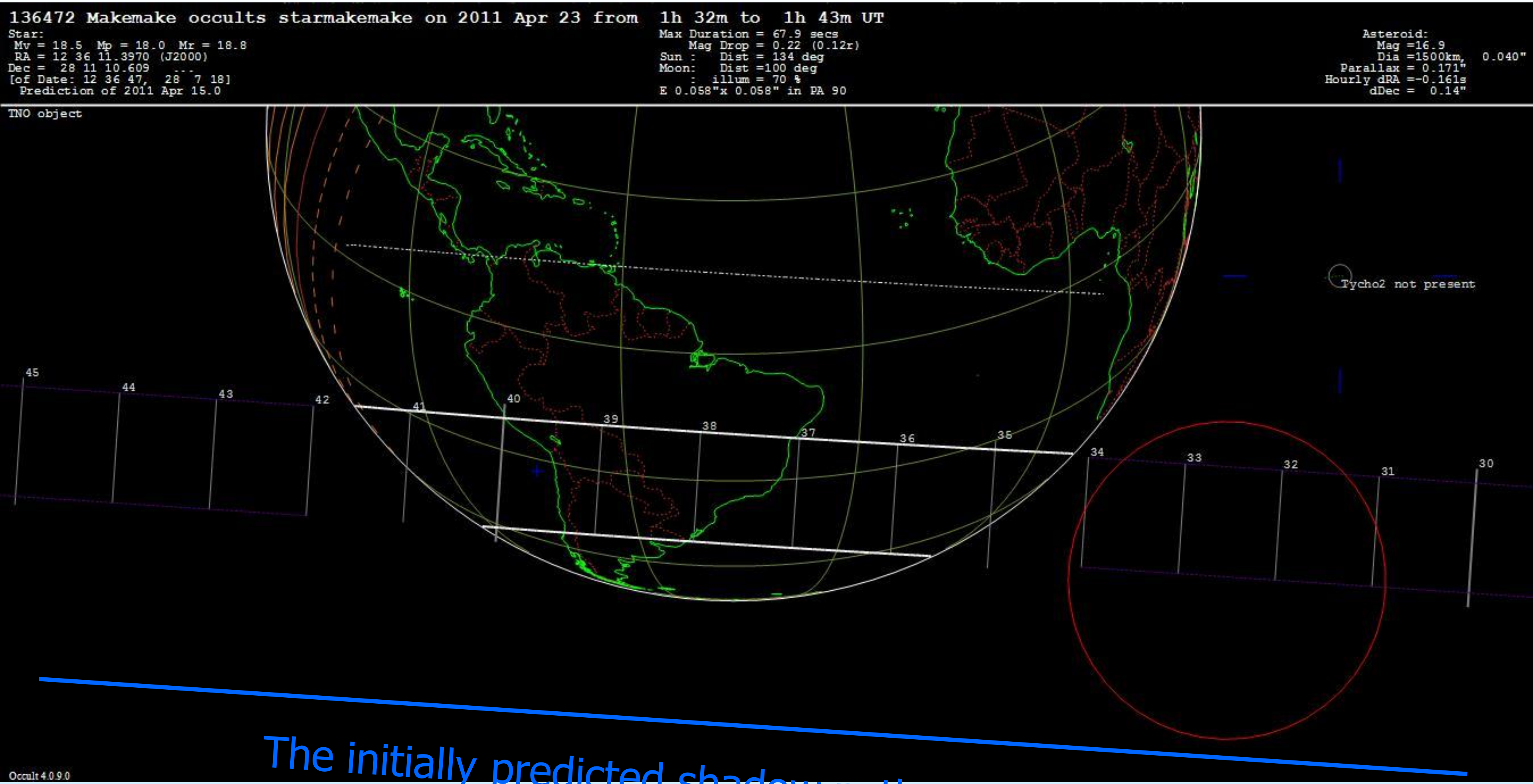
Límit to an atmosphere of N_2 ~ 1 nanobar ($10^{-4} \times$ Pluto)



Occultation by Makemake April 23rd, 2010. Predictions.

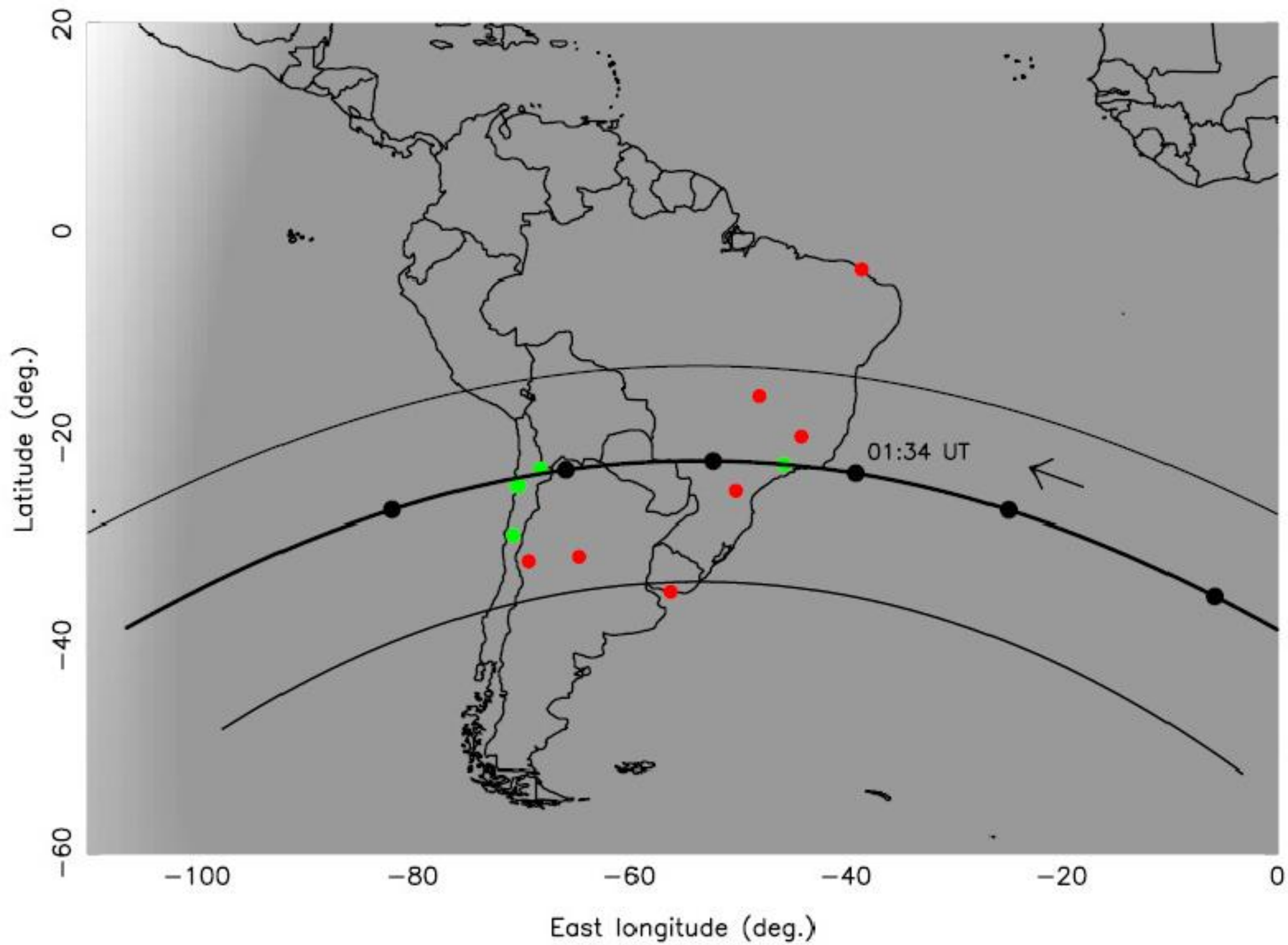
Around 10 nights prior to the occultation

Calar Alto 1.2m telescope (1 night, R filter)



The initially predicted shadow path was outside the Earth

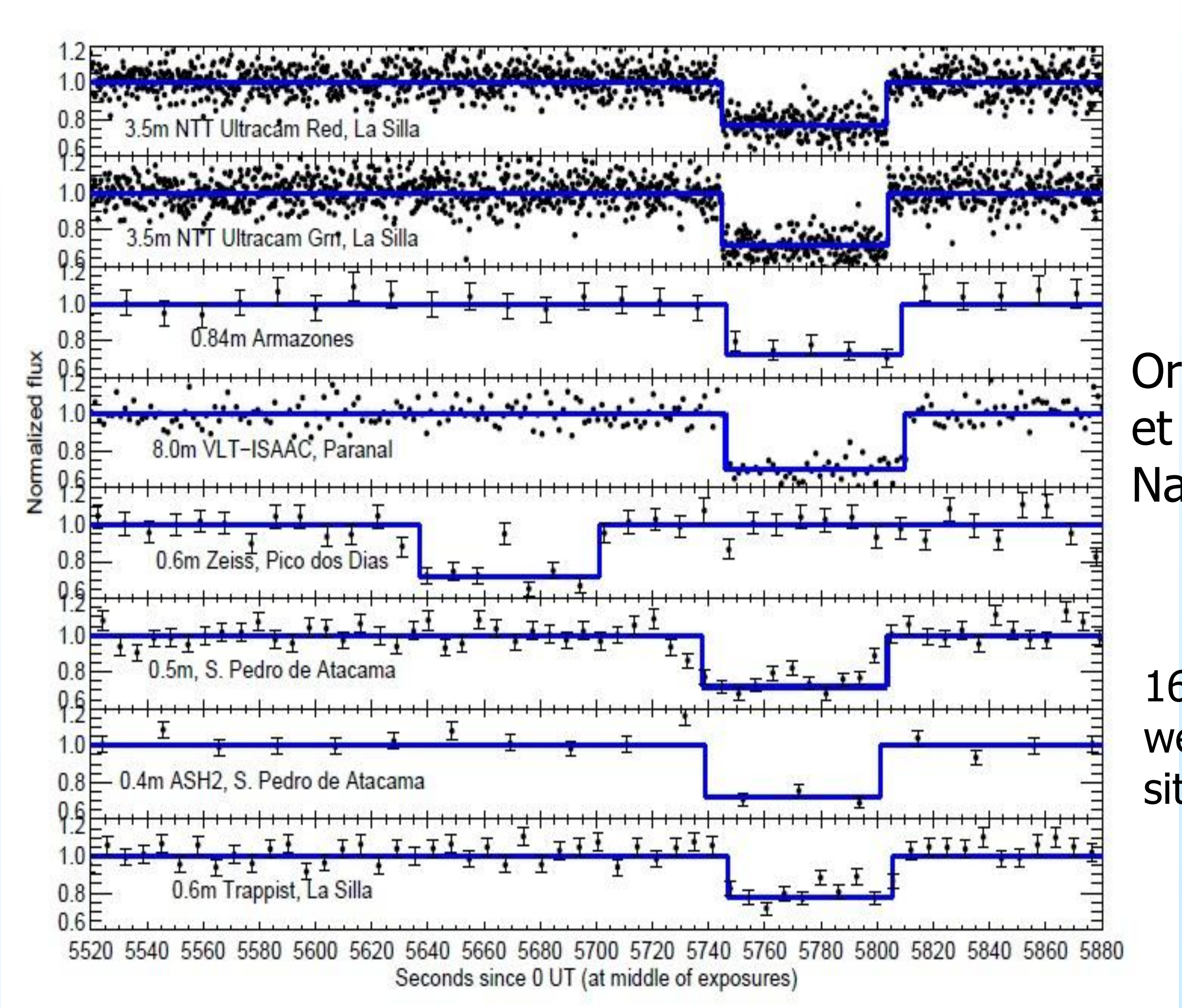
Occultation by Makemake: Observing sites



Artistic view of Makemake's shadow motion

In this projection the shadow shape should not be circular. It was an artistic licence

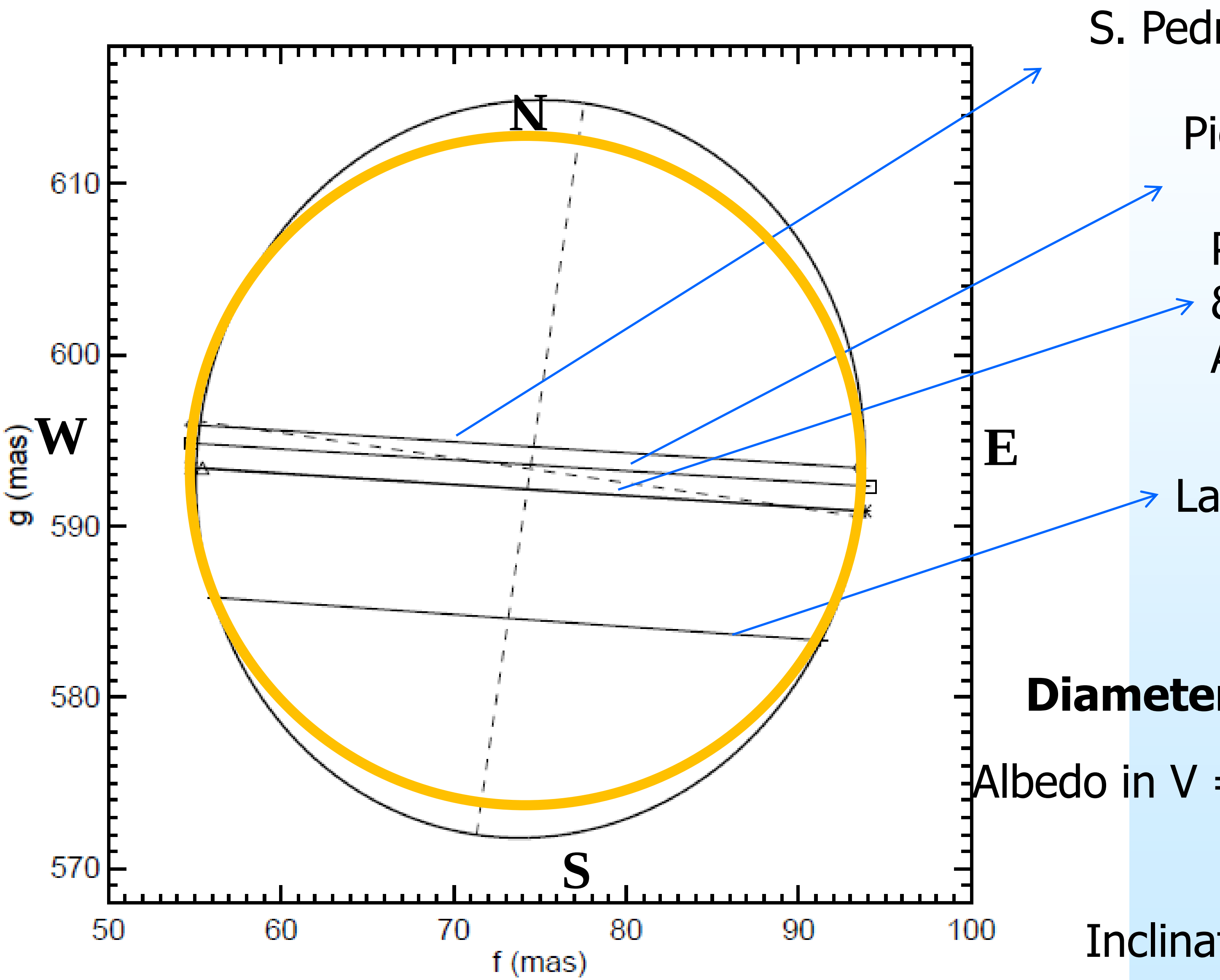
Occultation by Makemake: Data



Ortiz, Sicady, Braga-Ribas et al. (2012)
Nature, 491,566

16 telescopes involved, 7 were successful from 5 sites

Occultation by Makemake: fits to elliptical and circular shape



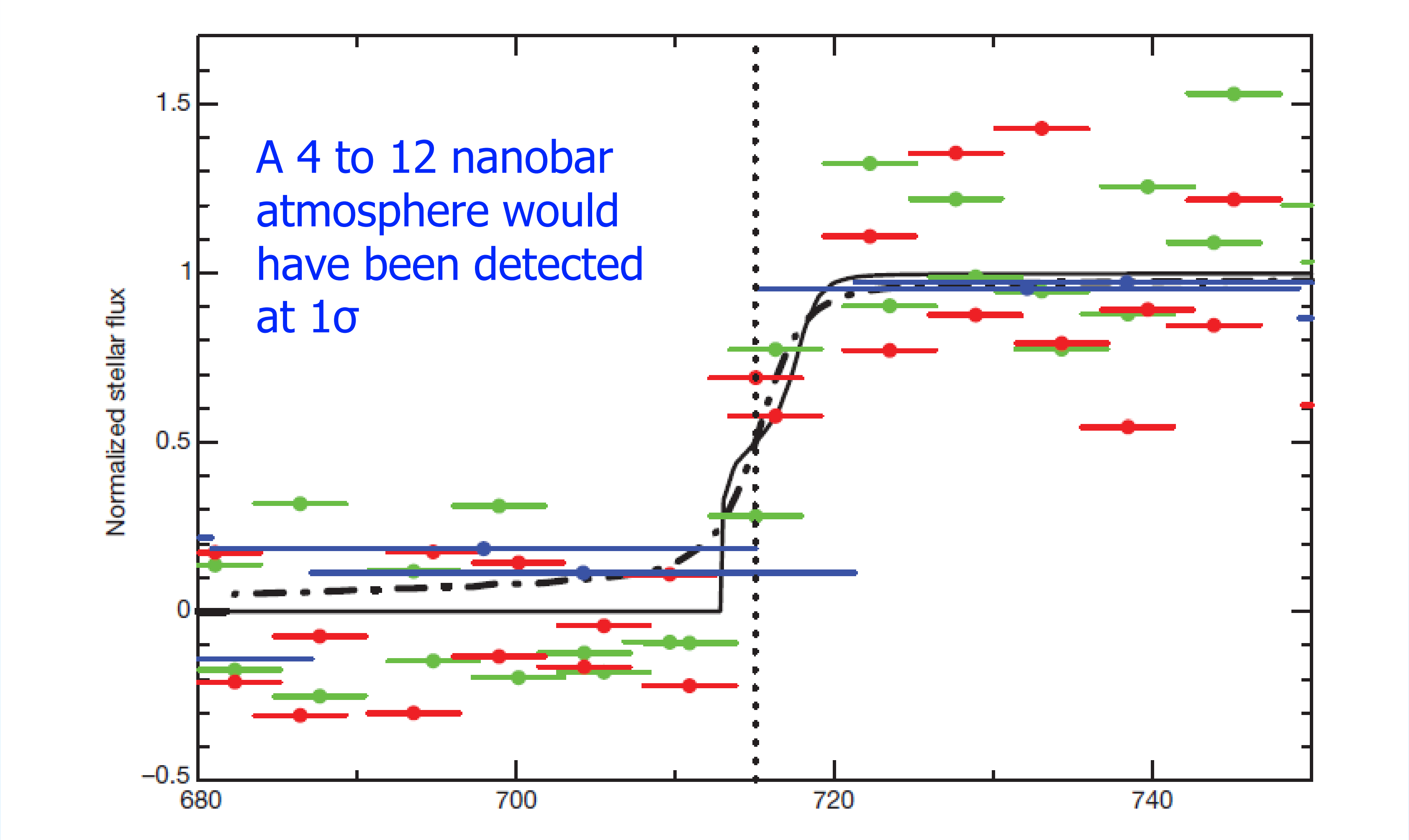
Diameter =1430 km

Albedo in V = **0.77** ±0.03

Inclination = 8 degrees

Limits on an global atmosphere

ingress/egress profiles at NTT and VLT telescopes were sharp



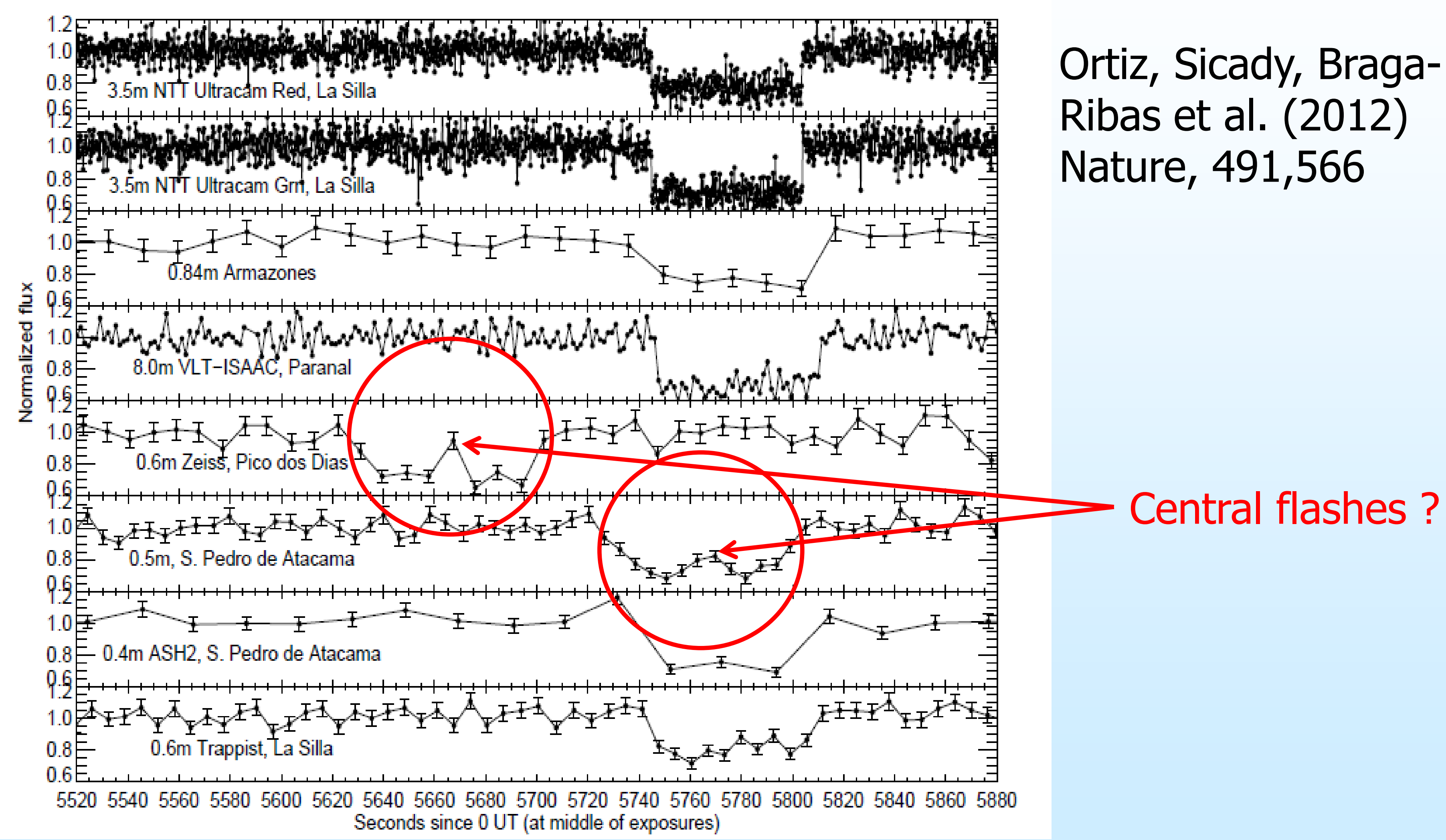
However… There might be a local atmosphere… ?

There are hints for central flashes in the chords near the center of the body

It is theoretically pausible that some areas of Makemake that have temperatures around 50 K can sublimate enough methane to cause “domes” or localized atmospheres.

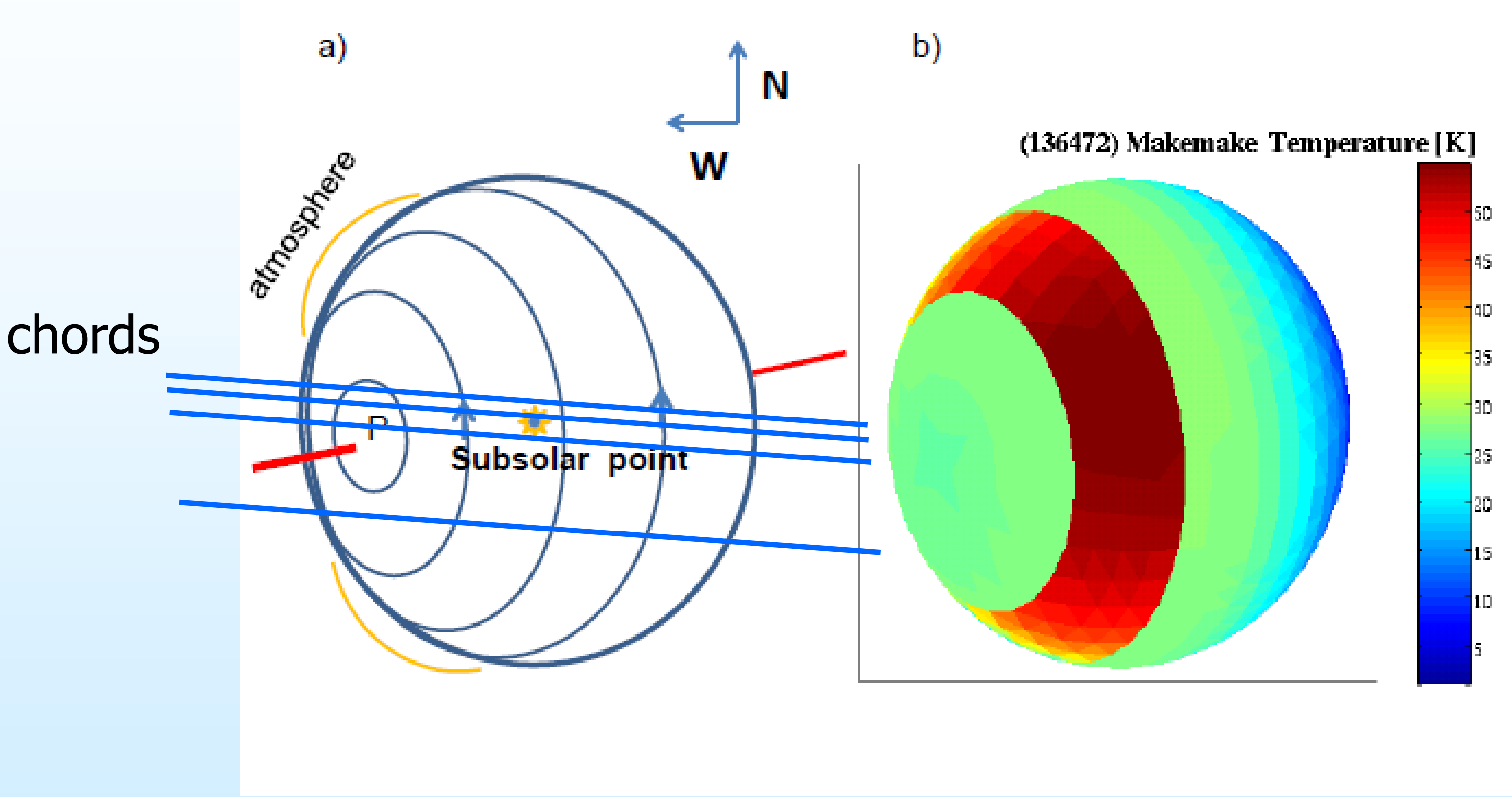
If those areas were not sampled at ingress or egress in any of the chords, we would not have seen them, but would be capable of causing central flashes

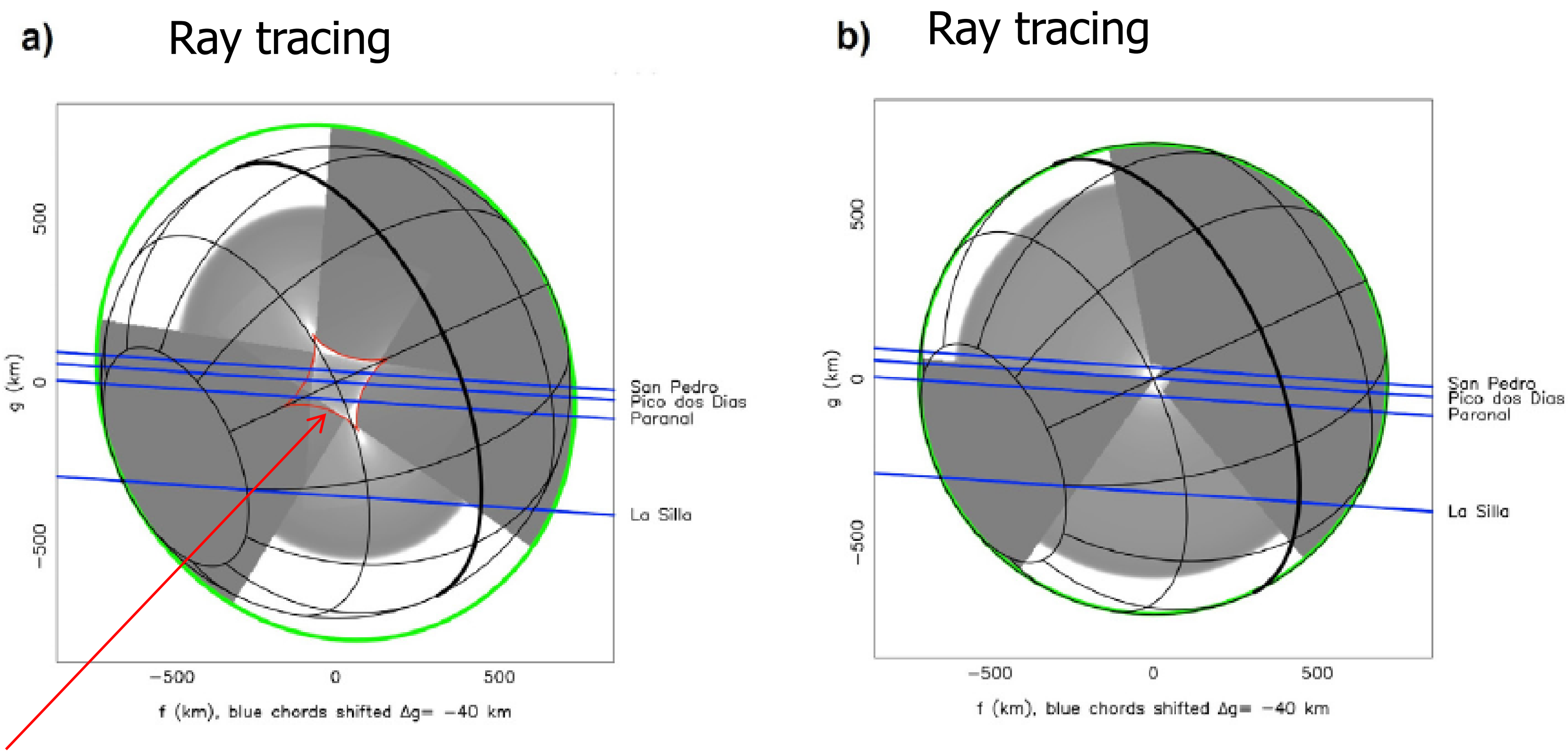
Occultation by Makemake: Data



Ortiz, Sicady, Braga-Ribas et al. (2012) Nature, 491,566

Example of a local atmosphere not sampled by the chords

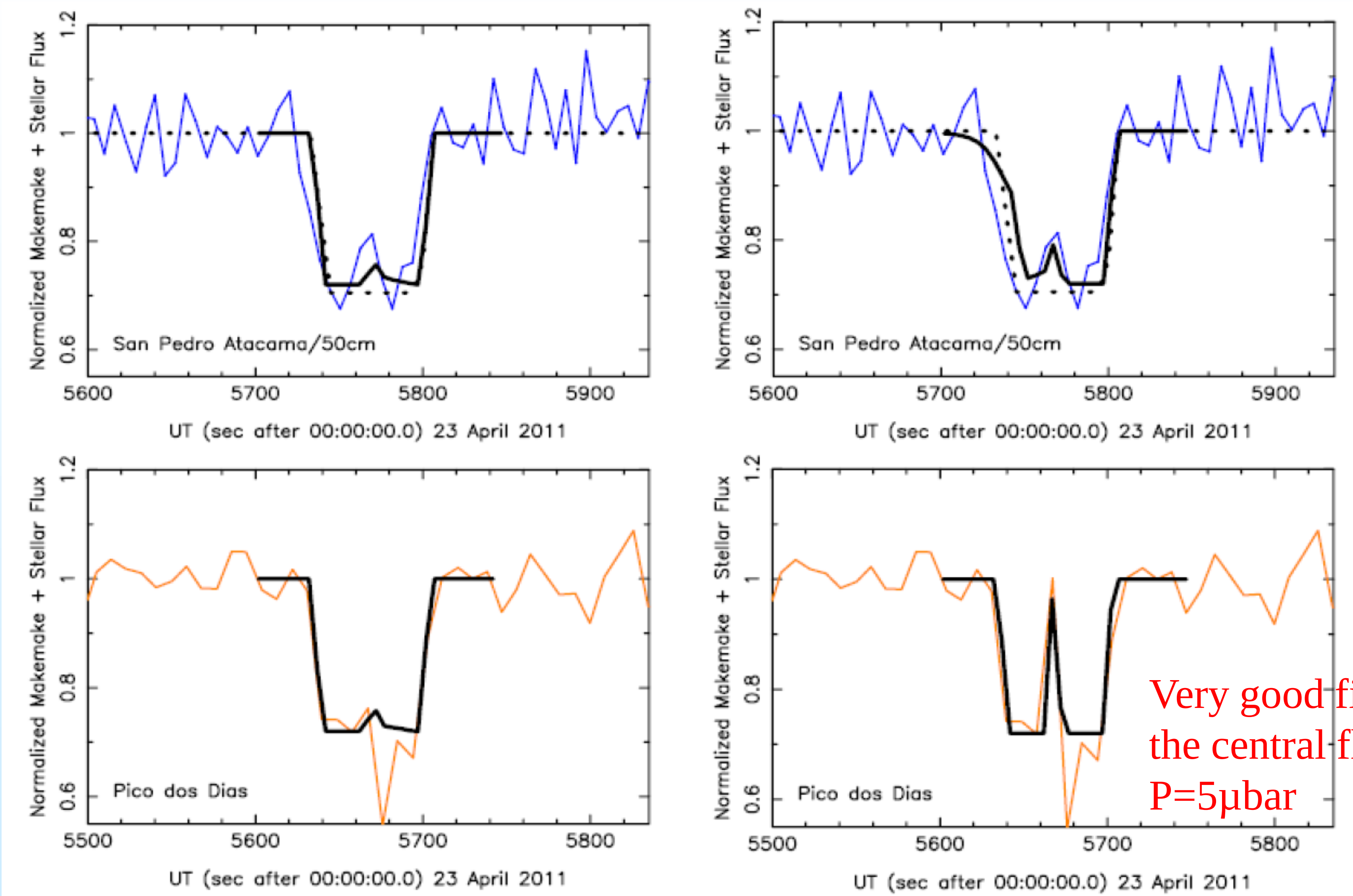




The more elongated the object, the larger the diamond shaped caustic (astroid)

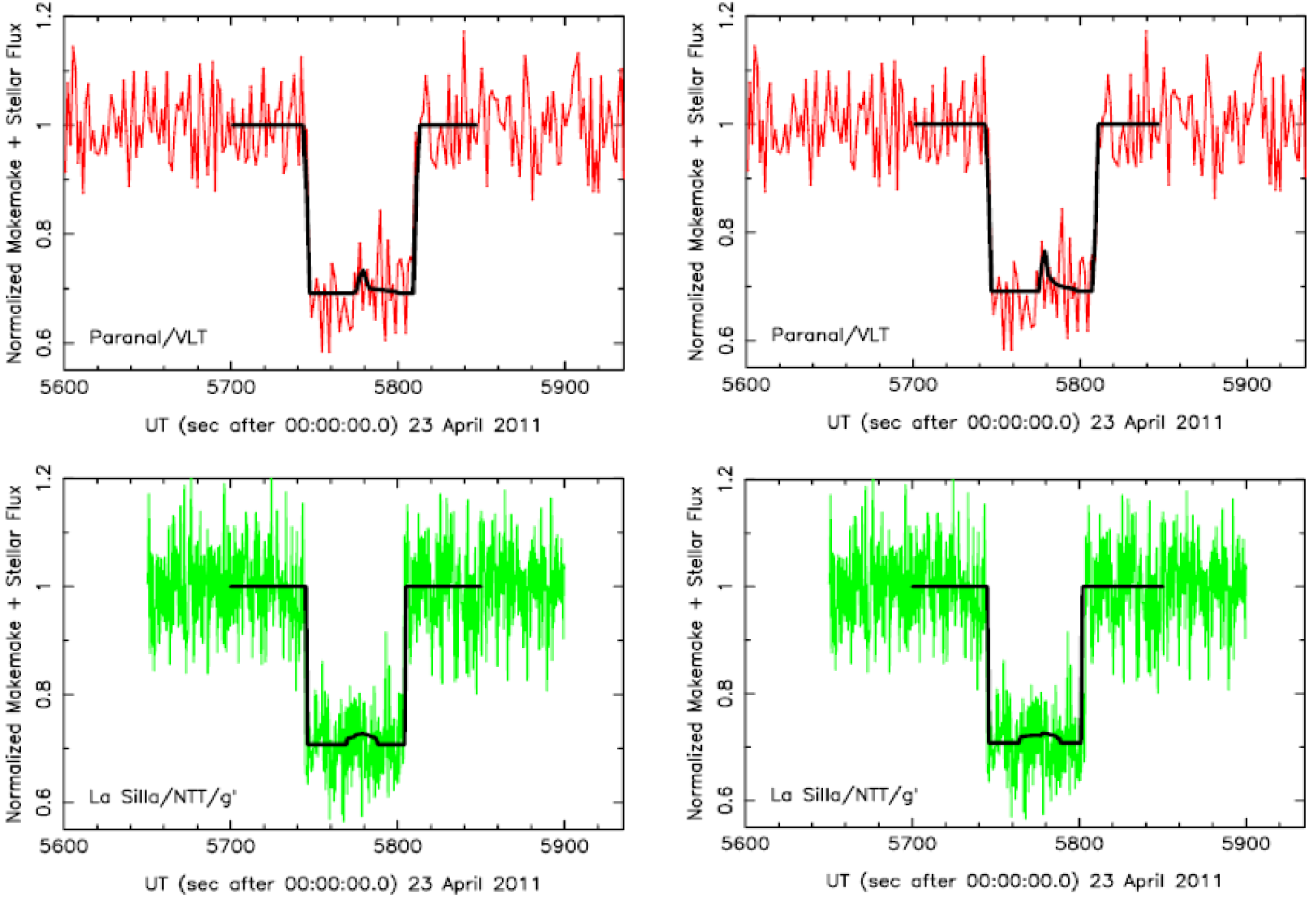
Fig. S5: a) Ray-tracing with a partial CH_4 atmosphere in the limb between 285° and 350° of Position Angle (PA), and between the symmetrical angles with respect to the minor axis (a proxy for the rotation axis). The semi-major and semi-minor axes lengths are 800 and 714 km, respectively. b) Idem, but with PAs between 275° and 350° (plus symmetrical angles), and 717 and 714 km of semi-major and semi-minor axes lengths, respectively. Both models use a temperature profile of 3 K/km until 100K is reached beyond which the atmosphere is isothermal. The surface pressure and temperature are 5 μbar and 50K. The gray scale represents the light intensity. The blue lines mark the chords at the sites indicated with labels, and the green lines indicate the local curvature of the atmosphere. The red line in the left panel marks the centers of curvature of the limb, where caustics are expected due to ray focusing. These models are used only for illustration. The modeled occultation light curves for the left and right cases are shown in Fig. S6 and compared with the observations.

Modeling of central flashes by local atmospheres

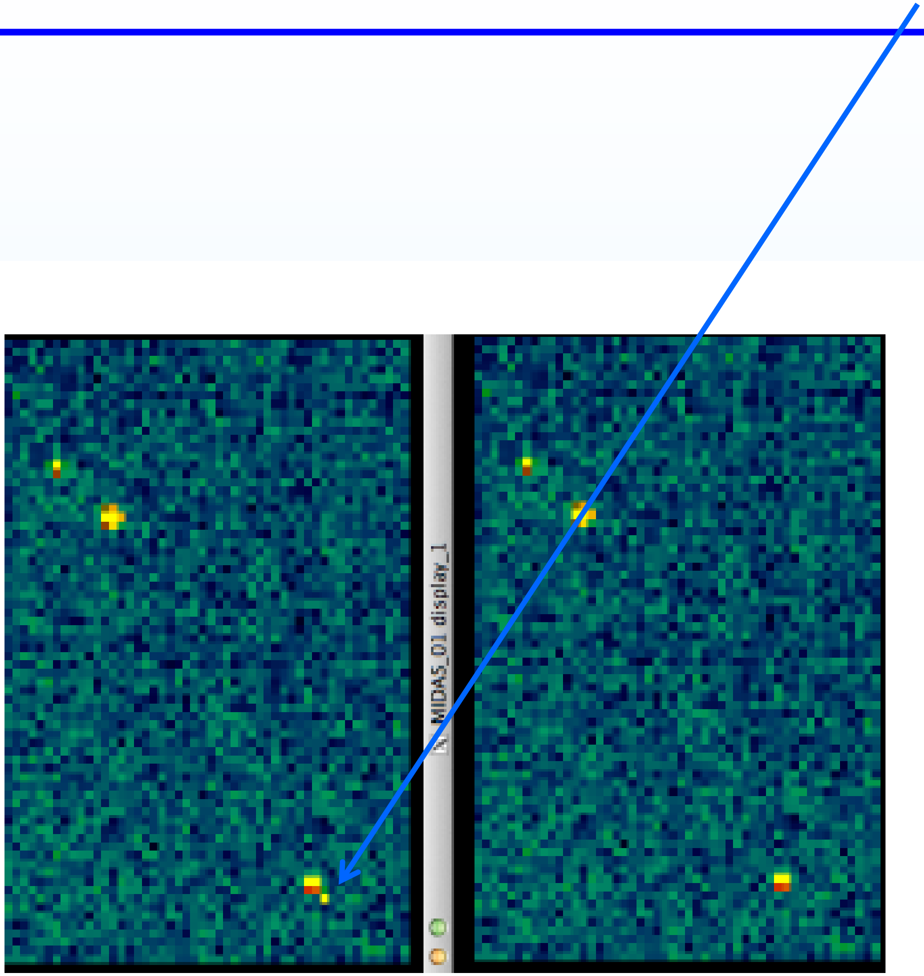


Very good fit to the central flash!
P=5μbar

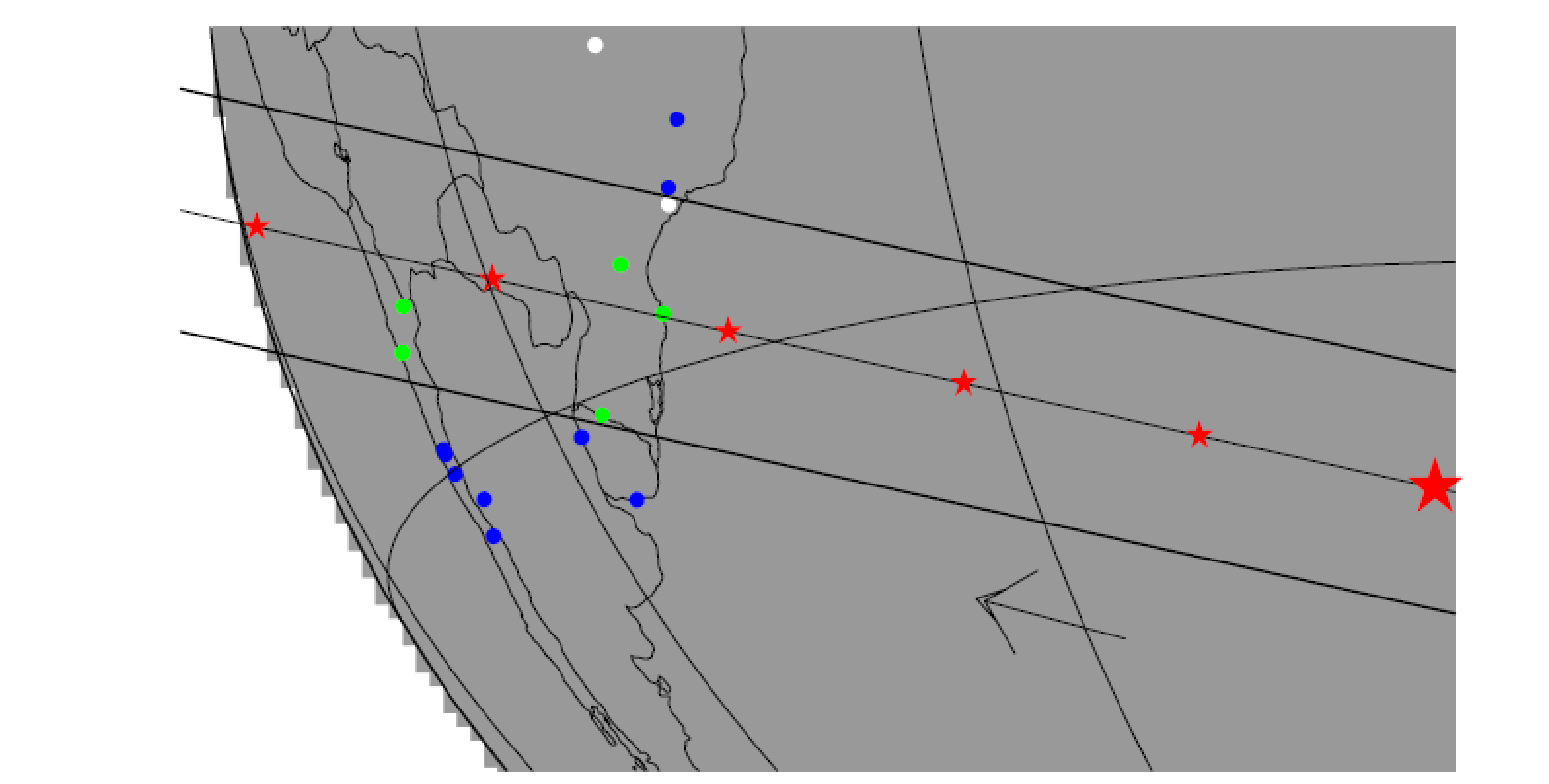
Modeling of central flashes by local atmospheres



Caveat: Cosmic ray or point source noise ?

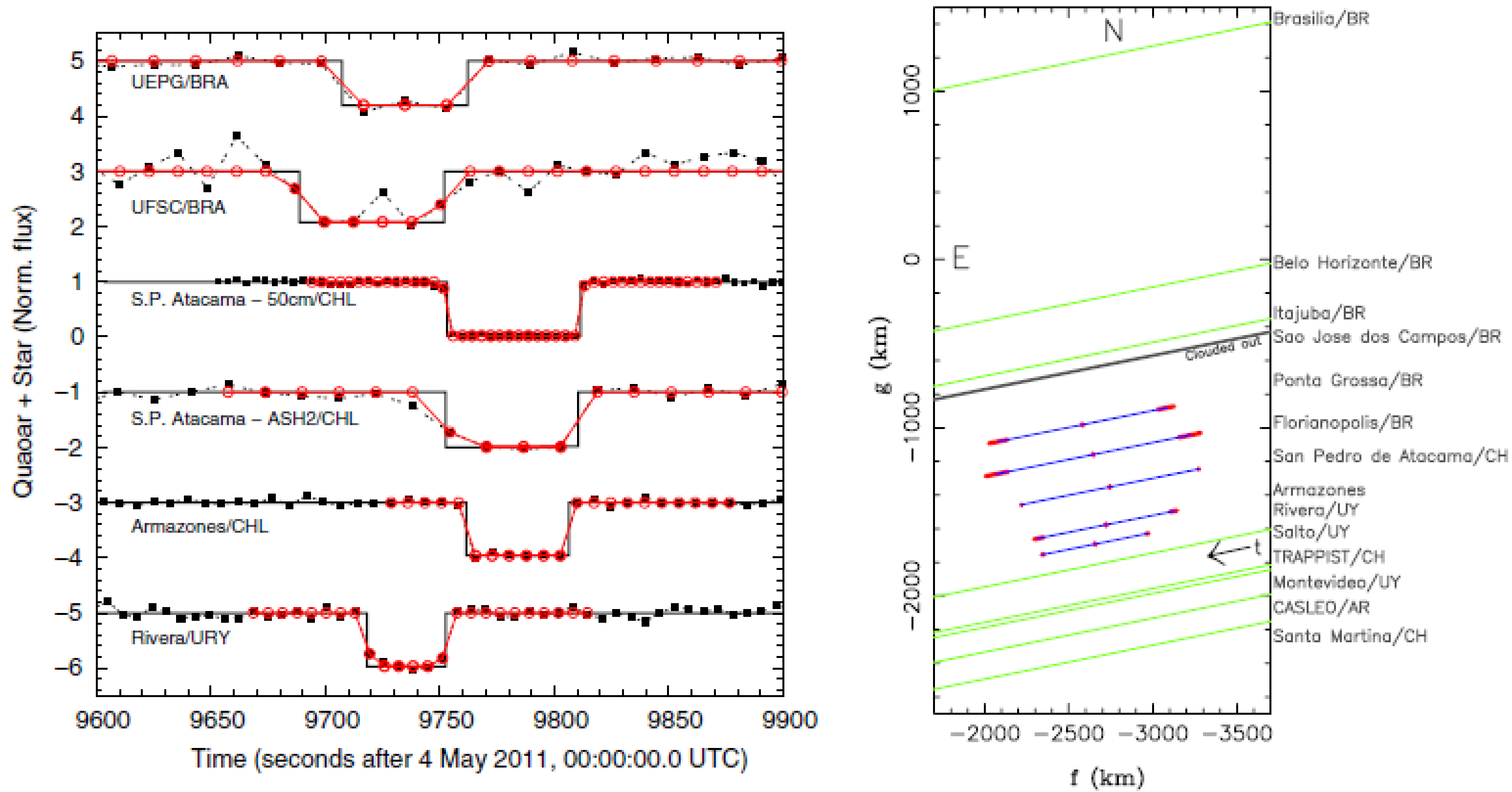


Occultation by Quaoar May 4th, 2011:



Braga-Ribas, Sicardy, Ortiz, Sicady et al. (2013).
Astrophysical Journal

Occultation by Quaoar May 4th, 2011:



Braga-Ribas, Sicardy, Ortiz et al. (2013). Astrophysical Journal 773, 26

Occultation by Quaoar, May 4th 2010:

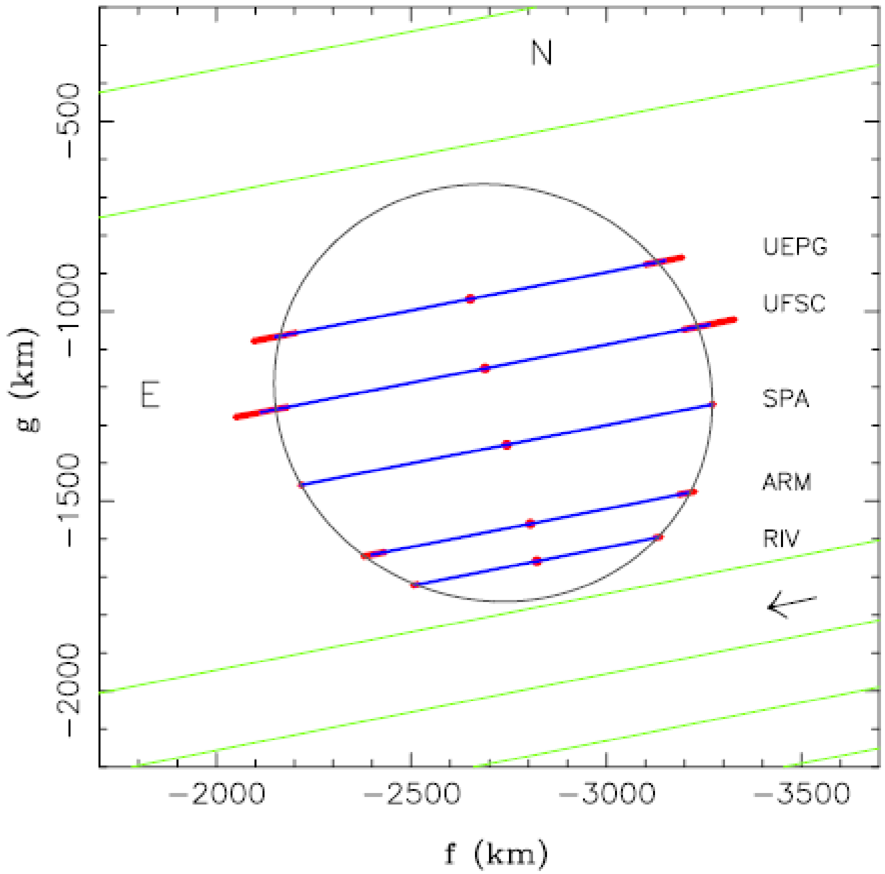
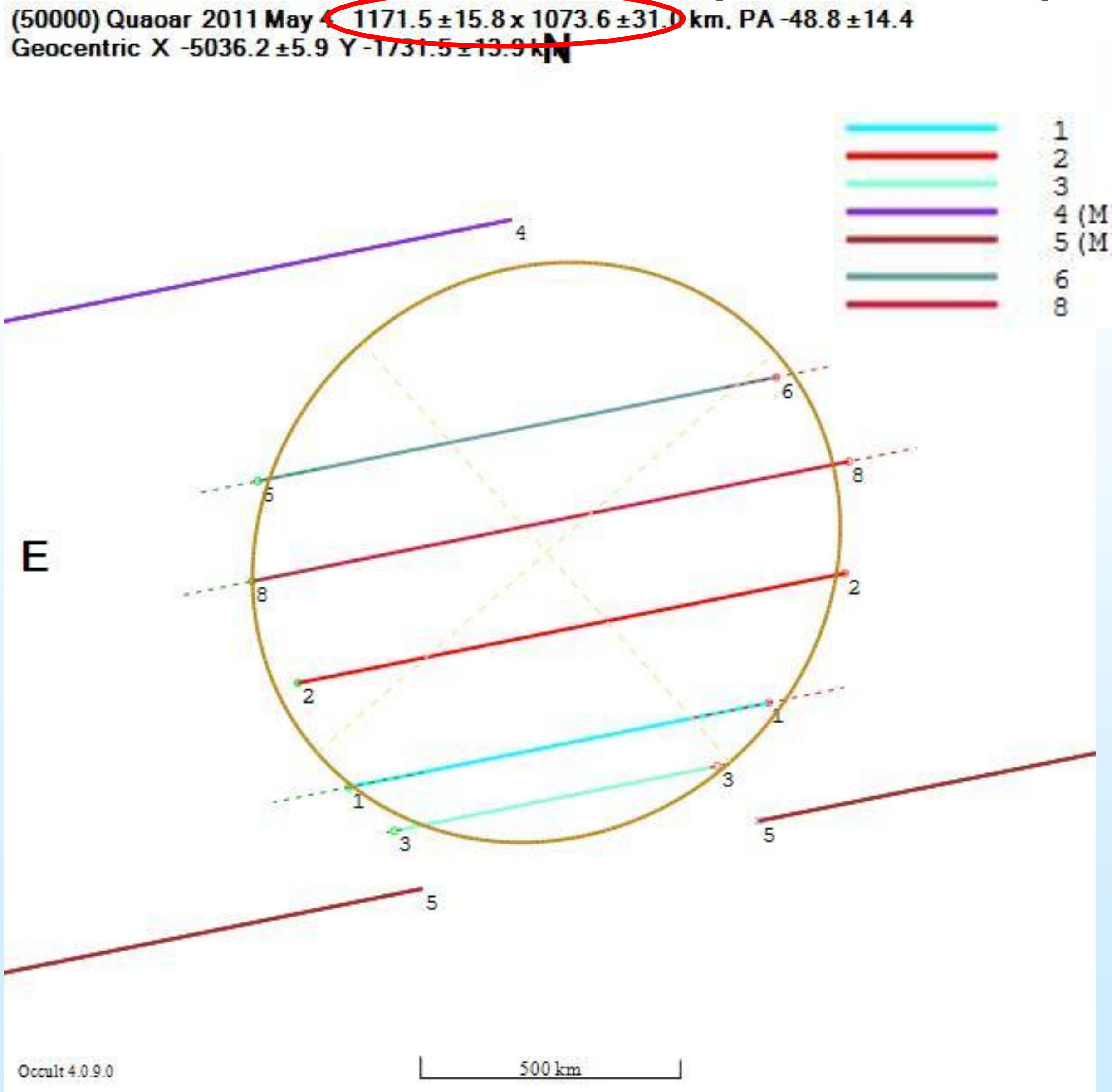


Figure 7. Best fit for the Maclaurin solution. It corresponds to the middle point of the blue dotted segment in Figure 6. It has a position angle $P = 148^\circ.4 \pm 0^\circ.9$, an equivalent radius $R_{\rm equiv} = 555 \pm 2.5$ km, an equatorial radius $R_{\rm equa} = 569^{+24}_{-17}$ km, and apparent oblateness $\epsilon' = 0.0486^{+0.0679}_{-0.0486}$. Once projection effects are accounted for, this corresponds to true oblateness $\epsilon = 0.0897 \pm 0.006$ and density $\rho = 1.99 \pm 0.14$ g cm^{-3}; see the text. To obtain this fit, the chords were shifted as follows (leaving the San Pedro de Atacama timing unchanged), Rivera: −9.1 s; Armazones: −4.6 s; Florianópolis: −2.4 s; and Ponta Grossa: −3.8 s.

Albedo 0.109 ±0.007

Braga-Ribas, Sicardy, Ortiz, Sicady et al. (2013). Astrophysical Journal 773, 26

Quaoar: my own analysis



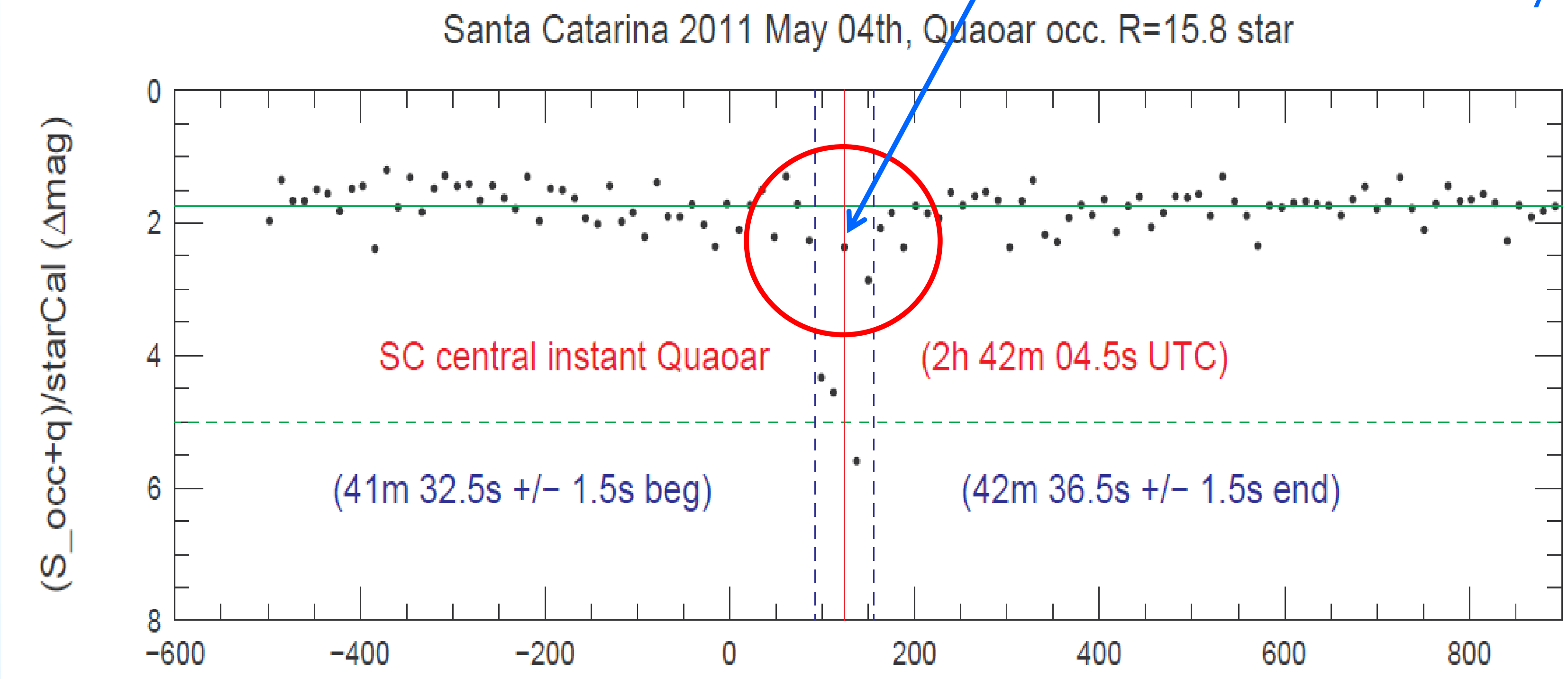
Larger size,
less elongation

Albedo in V:
0.09 ± 0.03

Using the mass detemined in Fraser and Brown (2012) and the volume determined here the **density is 1.7 ± 0.3 g/cm3**

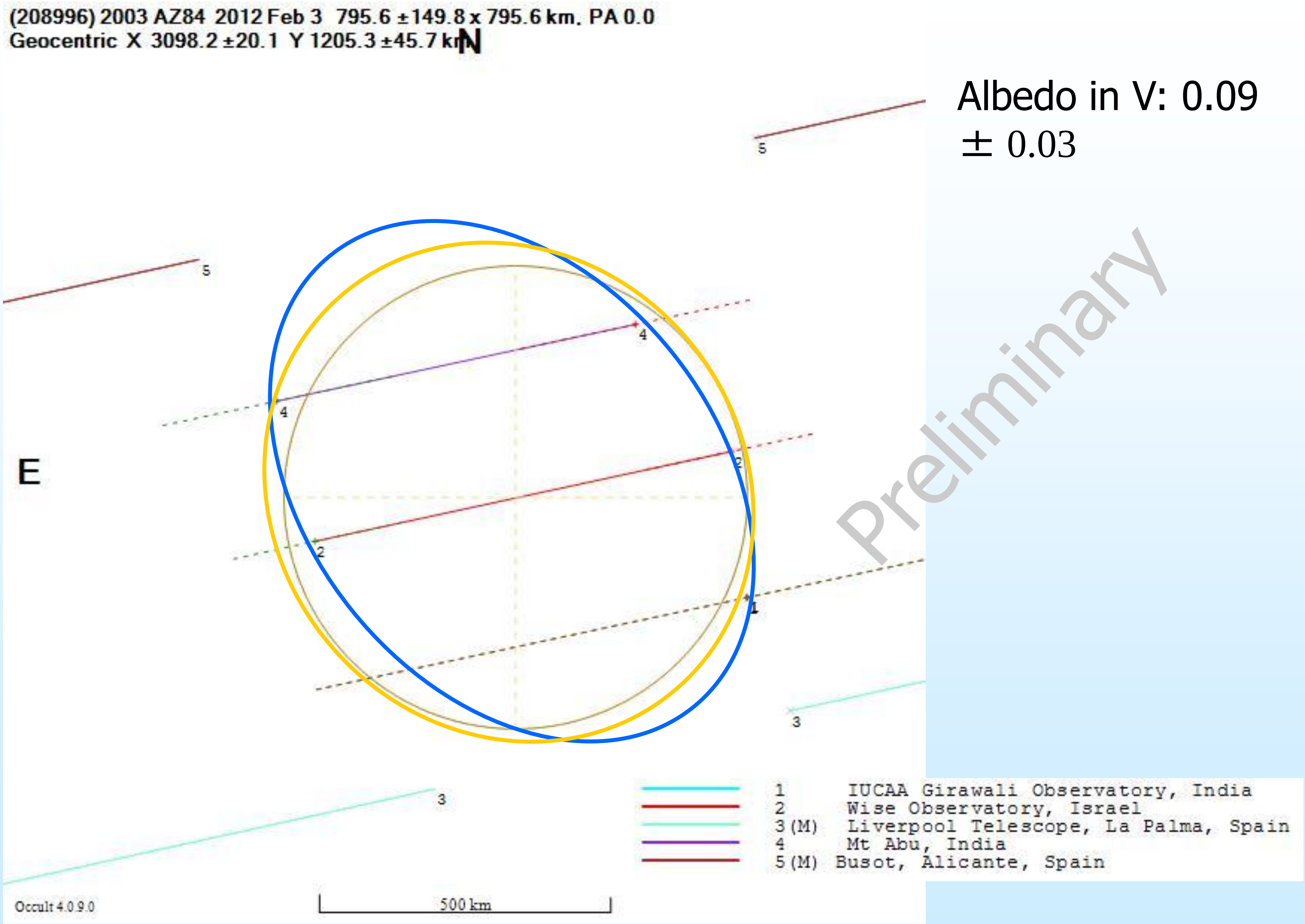
Central flash at Santa Catarina ?

It is at around 3σ above the noise and the chord is near the center of the body



Made with a C11 Schmidt-Cassegrain telescope !!

2003AZ84



Albedo in V: 0.09 ± 0.03

2002KX$_{14}$

The highest accuracy chord so far USING THE 4.2m WHT at La Palma, with the ULTRACAM camera. The uncertainty is around 1km!!.

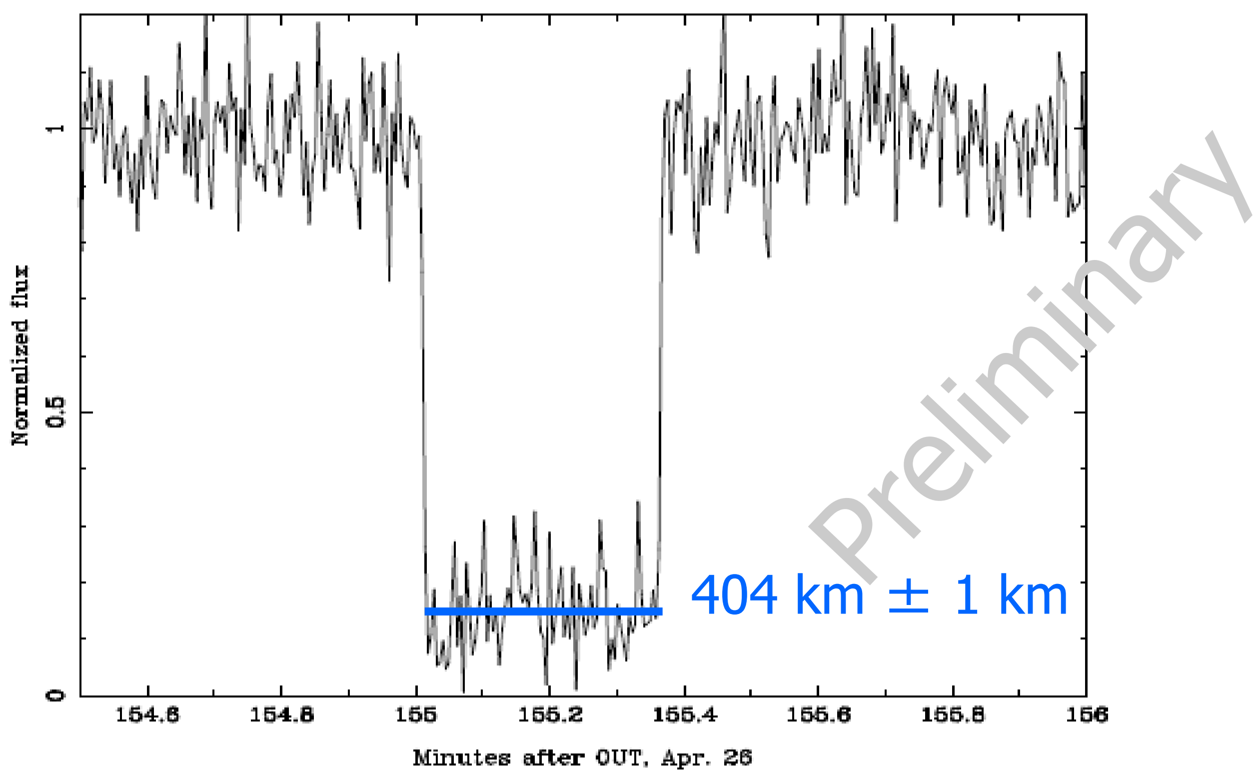
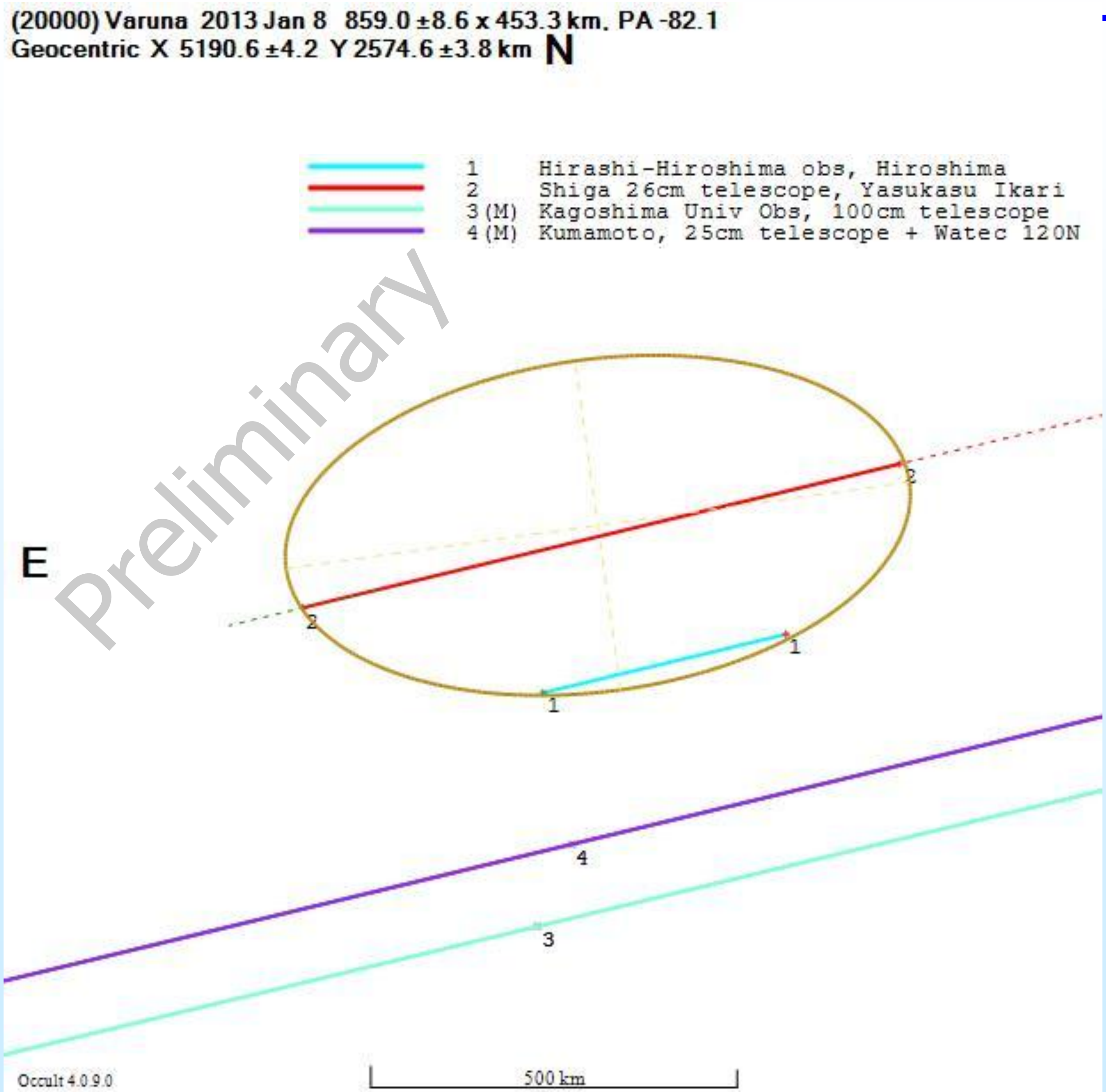


Fig. 2. Observed light-curve of the system star plus kx14. The total flux before and after the event is normalized to enhance the depth of the event.

Unfortunately, only one chord has been determined, so we get a lower limit to the diameter, under the assumption that the body is spherical, which is not true in general

Occultation by Varuna January 8, 2013:

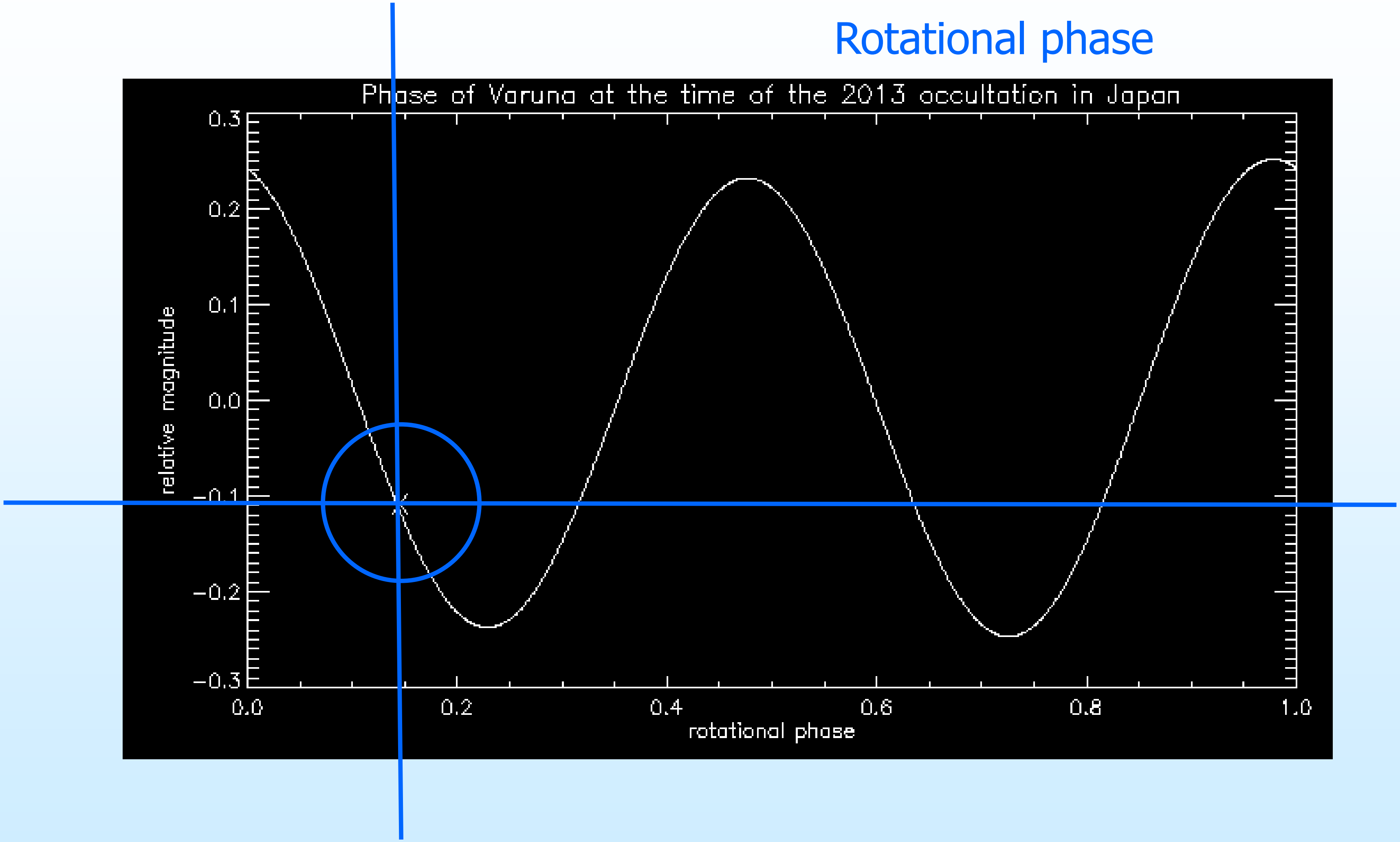


This size and shape is for a particular rotational phase. We know that Varuna is a triaxial ellipsoid.

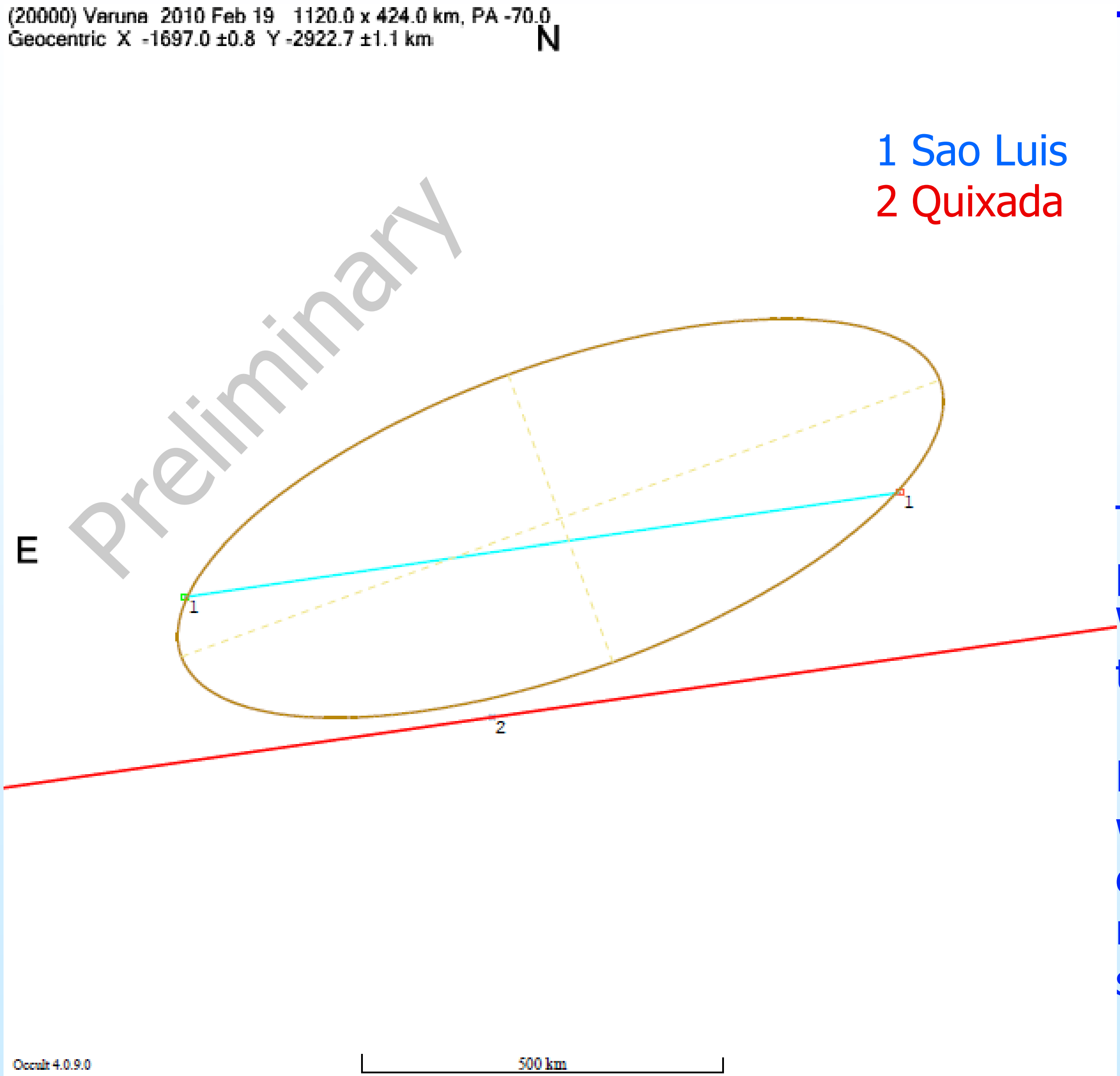
Fortunately we know at which rotation phase the event took place so we can reconstruct the full 3D structure

Occultation by Varuna January 8, 2013:

Rotational phase



Occultation by Varuna February 9, 2010:



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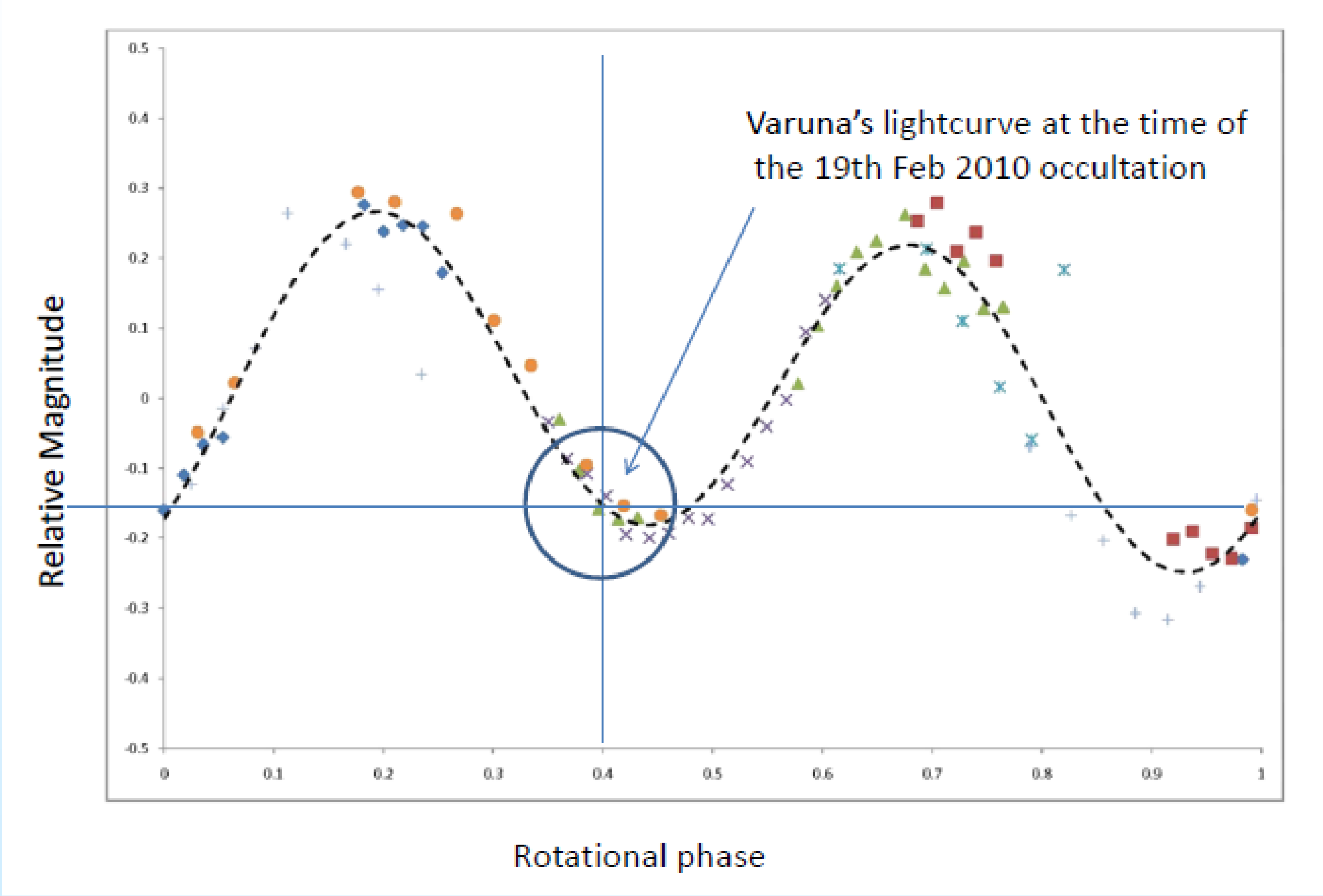
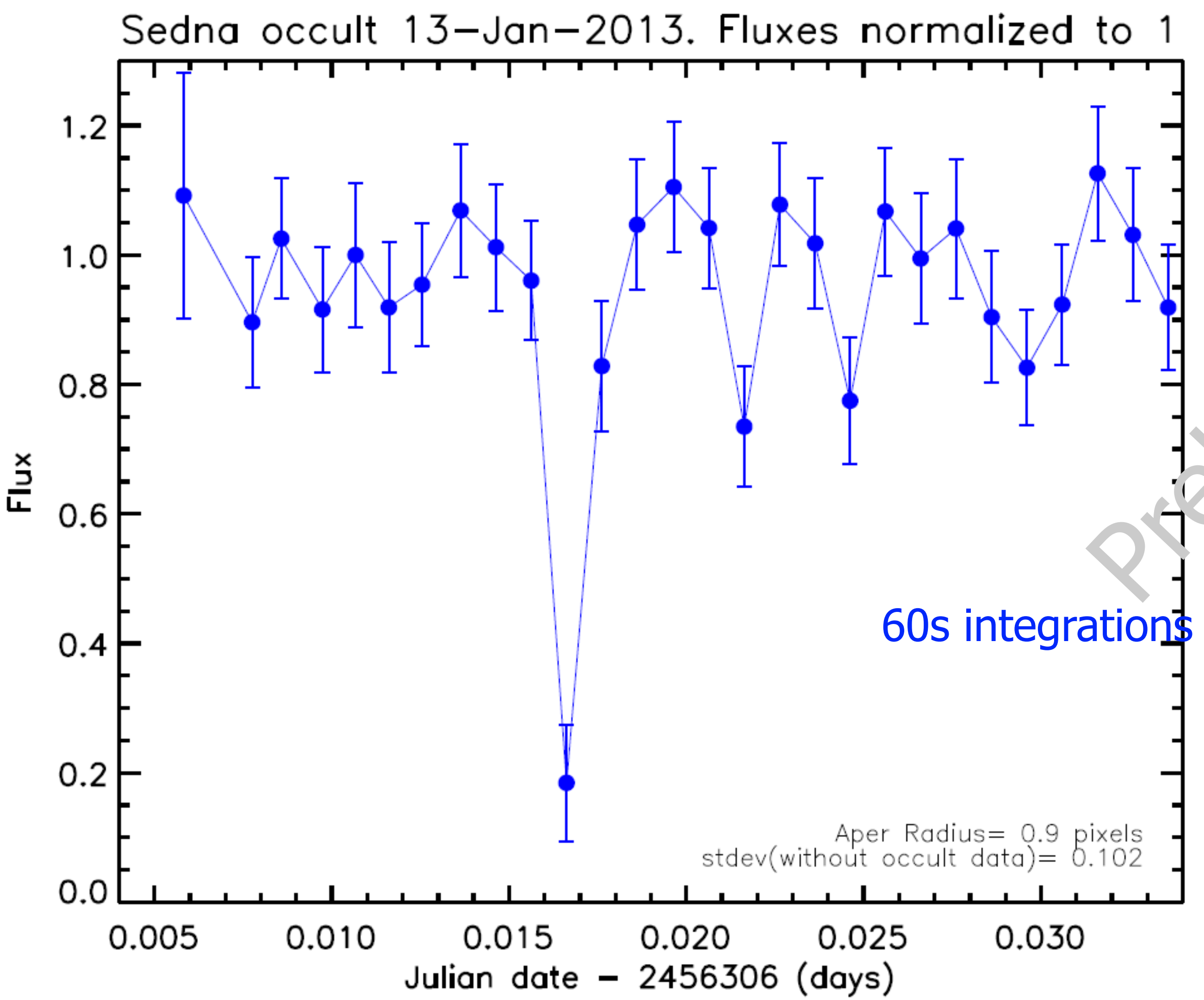
Rotational phase



Occultation by Sedna: Single point.



Our analysis of images taken by Joseph Brimacombe

Duration of the occultation : 54.05 s ± 5.7 s

Chord length: 653 km ± 69 km

Some lessons learnt on strategies

We succeed 1 every ~4 attempts. We have made in the order of 40 to 50 attempts thus far.

Most of the successful observations took place in South America. The reasons are:
-**Long North-South stretch** with good weather (mainly Chile)
-**Dense telescope coverage** (with professional and amateur-like telescopes)
-Some TNOs are in the south where the Galactic center is and there are denser star fields so occultations of these TNOs are more frequent.

Currently, a key issue is the high accuracy updates to refine predictions. We have developed the tools and the methods. But this requires a lot of observing time. We typically reach astrometry precision around 30 to 20 mas, which typically corresponds to ~3000km on Earth. So either we need very large north-south coverage or the success rate decreases to ~1/4 **The successful events involved typically 10 to 20 telescopes, which is a guarantee against bad weather, technical problems, uncertainties in the prediction etc**

Time accuracy and deadtimes are the main problems we face when analyzing the data

Some lessons learnt on strategies

Binary TNOs, difficulty in getting the astrometry right: photocenter is not in the center of the body.

Binary stars: we do not know most of the time whether the star to be occulted is binary so the photocenter does not fall in te center of the star.

Differential chromatic refraction sometimes is an issue, most of the times is not, but we must be alert and make corrections if necessary.

Proper motions of the stars: important for the initial predictions, but the problem is solved with astrometric updates.

Summary

In only ~3 years we have been successful several times: We have detected occultations by 8 Transneptunian Objects, 7 within an international collaboration and 1 by an american team. We have been beating more and more challenges. We can now predict and observe occultations of very faint stars.

Currently, a key issue is the high accuracy updates to refine predictions. We have developed the tools and the methods. But this requires a lot of observing time.

Sizes, shapes, diameters, albedos and densities have been determined for 8 TNOs and very accurate values were derived for 4 of them.

Future

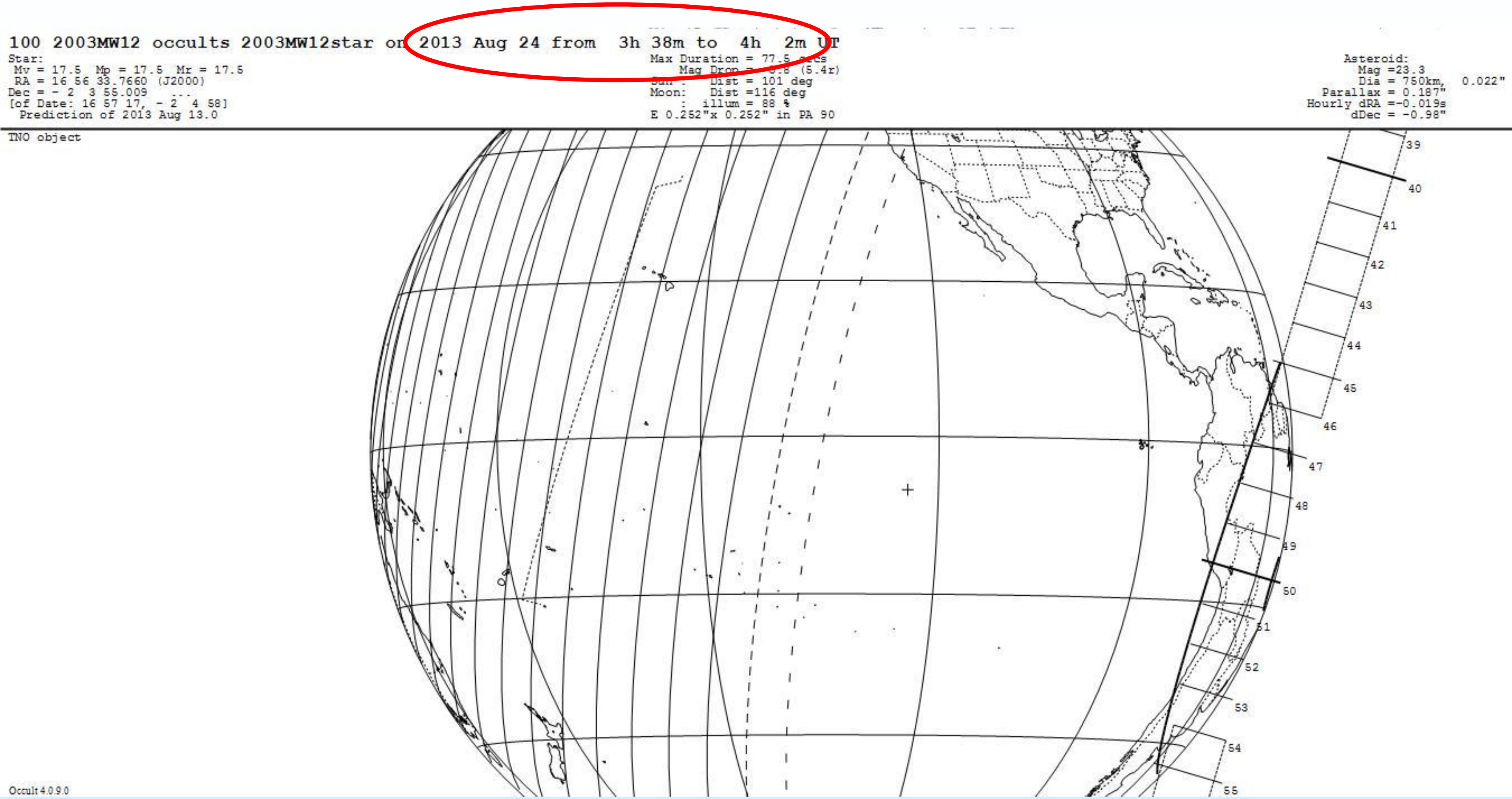
-We expect to be able to observe around 3 new occultations per year, for the 10 to 15 largest TNOs using our current techniques.

-We expect to be able to extend the success to the 100 largest TNOs, after stellar coordinates are known to a good accuracy thanks to **GAIA space mission** in a few years from now. Unfortunately, most TNOs are fainter and smaller than those already observed through occultations. This means that making accurate predictions is more difficult because larger telescopes are needed to achieve the required signal to noise ratio. On the other hand, their shadow path widths on Earth are smaller and therefore more accurate predictions are needed in comparison to what we are currently getting. Accuracies of around 0.01arcsec are needed.

-We expect to beat all these challenges using ESO and spanish facilities to make accurate predictions and observe the occultations.

-To observe future occultations, amateur and small observatories will play an important role.

Occultation last night?



Observations were arranged at several observatories in Chile and Argentina but all observatories were clouded out:

- Thanks for your attention