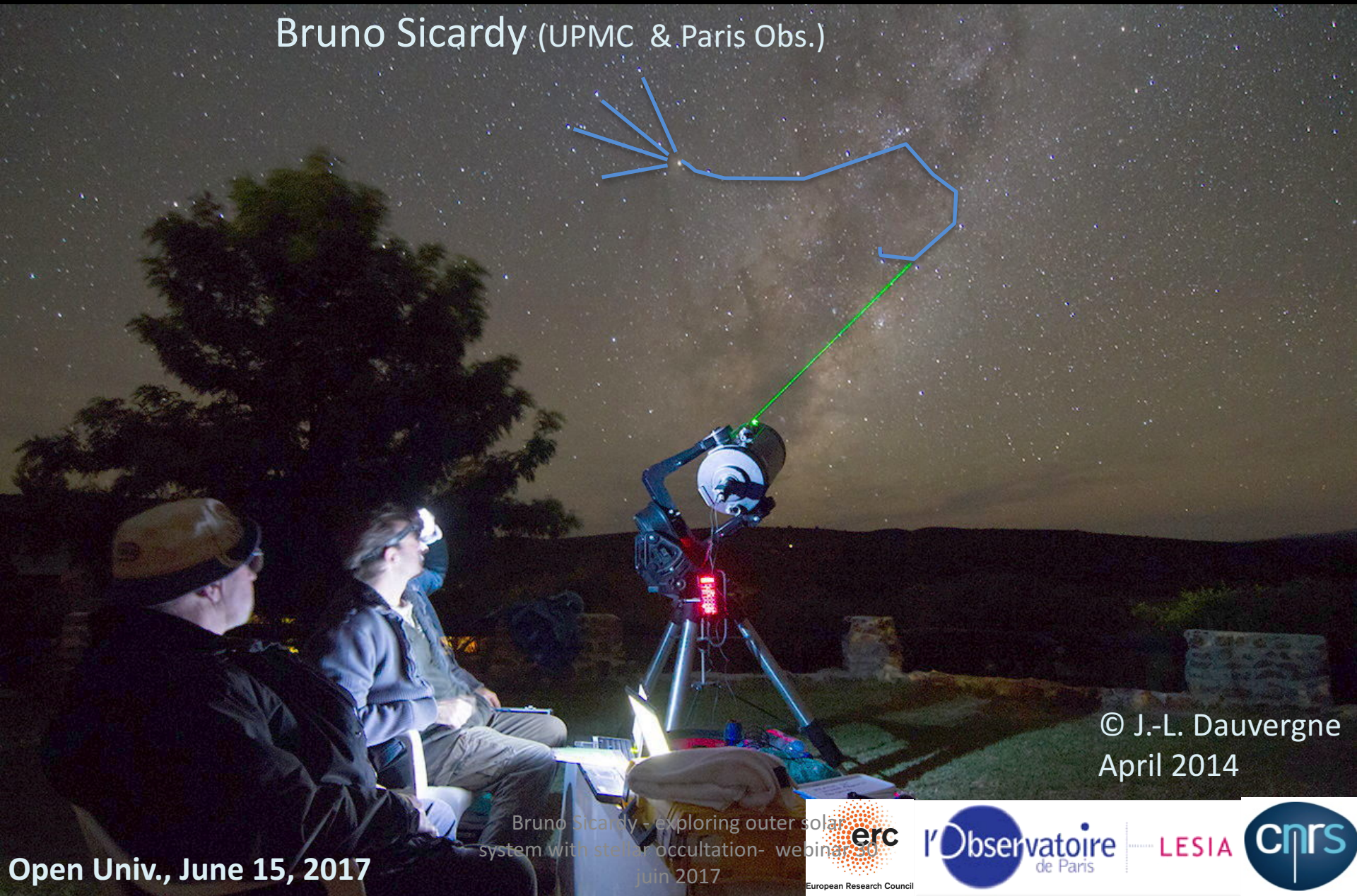
Exploring the Solar Sytem using stellar occultations

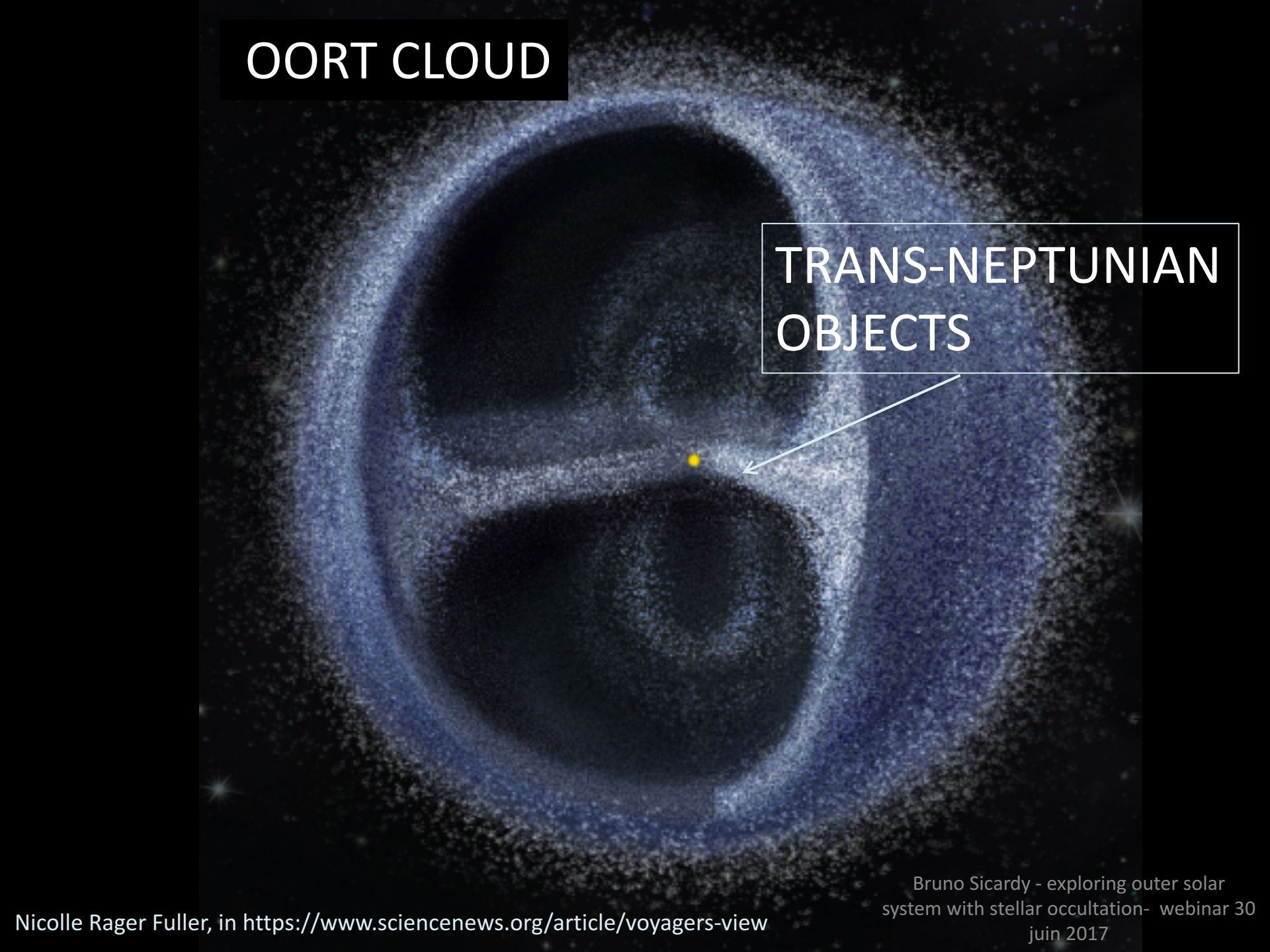
Bruno Sicardy (UPMC & Paris Obs.)



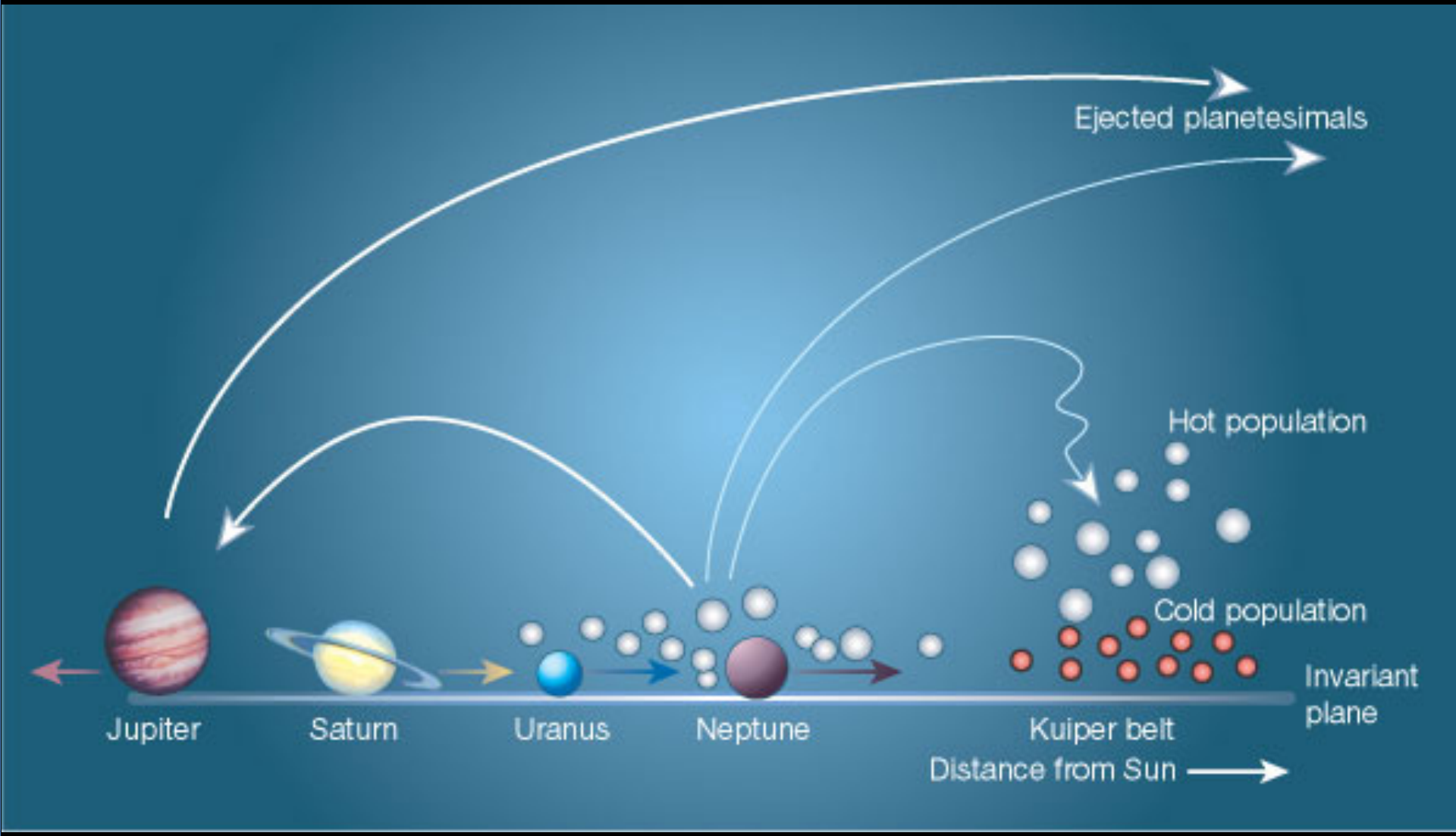
© J.-L. Dauvergne
April 2014

Open Univ., June 15, 2017

erc European Research Council
l'Observatoire de Paris
LESIA
cnrs



Nicolle Rager Fuller, in https://www.sciencenews.org/article/voyagers-view

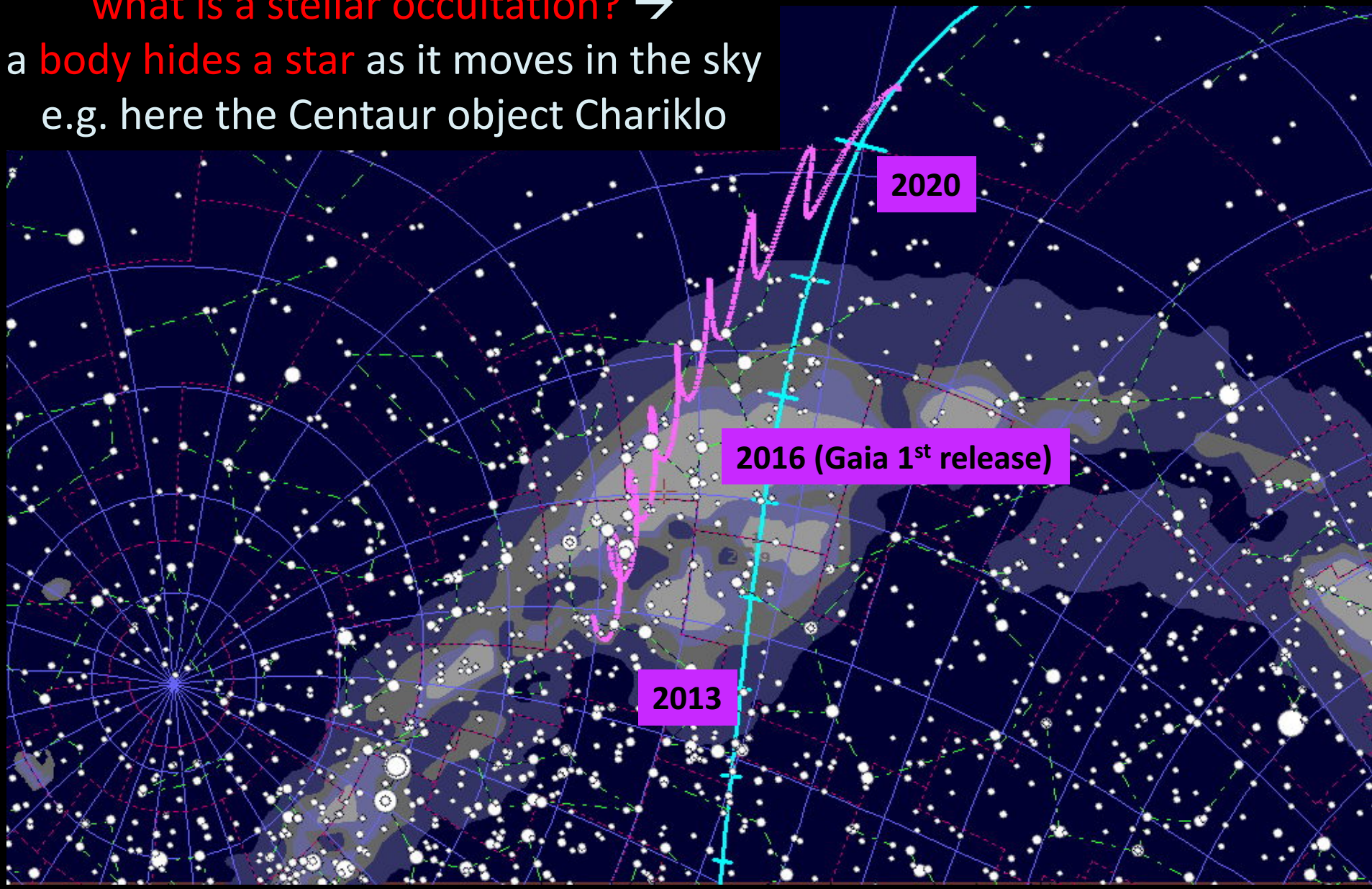


Morbidelli & Levison, *Nature* 2003

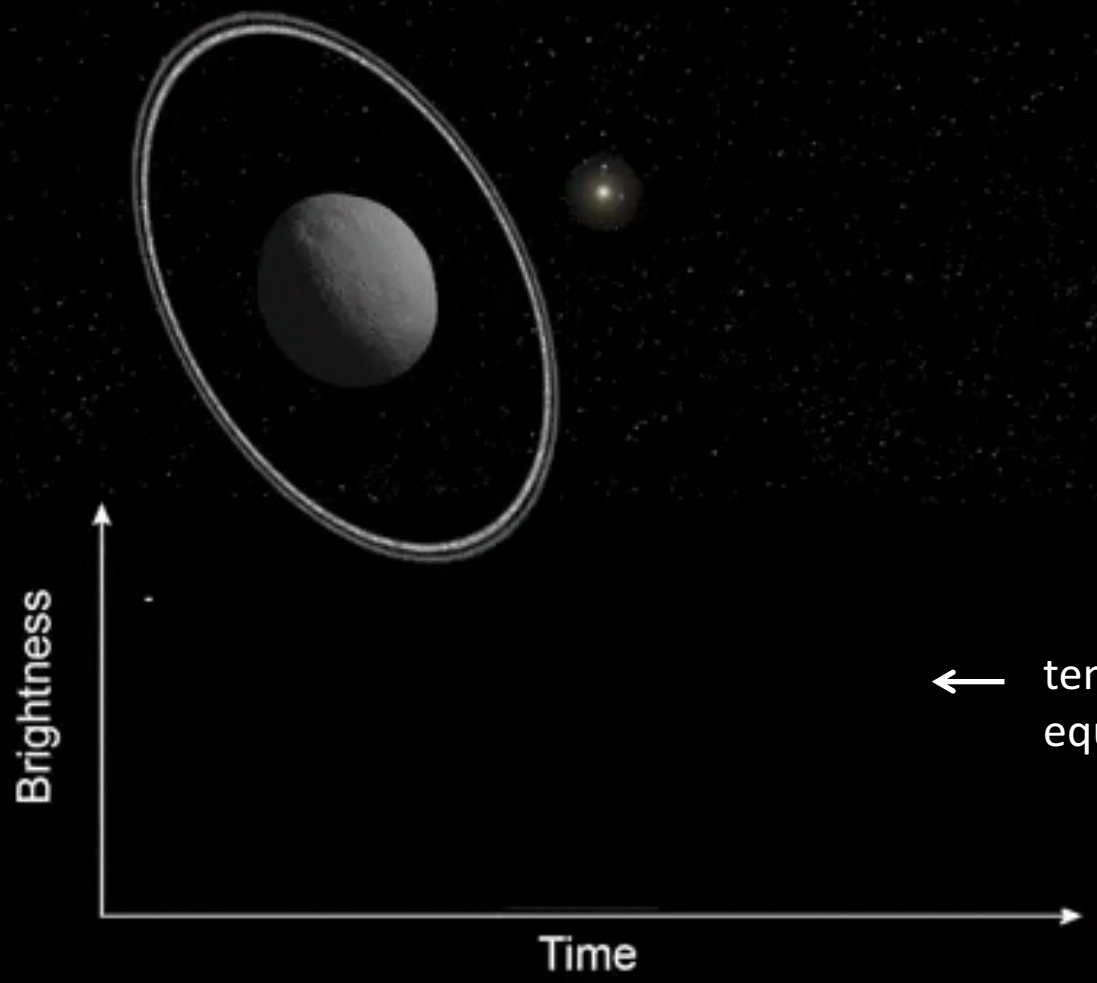
what is a stellar occultation? →

a body hides a star as it moves in the sky

e.g. here the Centaur object Chariklo



the object is *not* resolved →



← temporal resolution equivalent to < 1km

Nature 1986

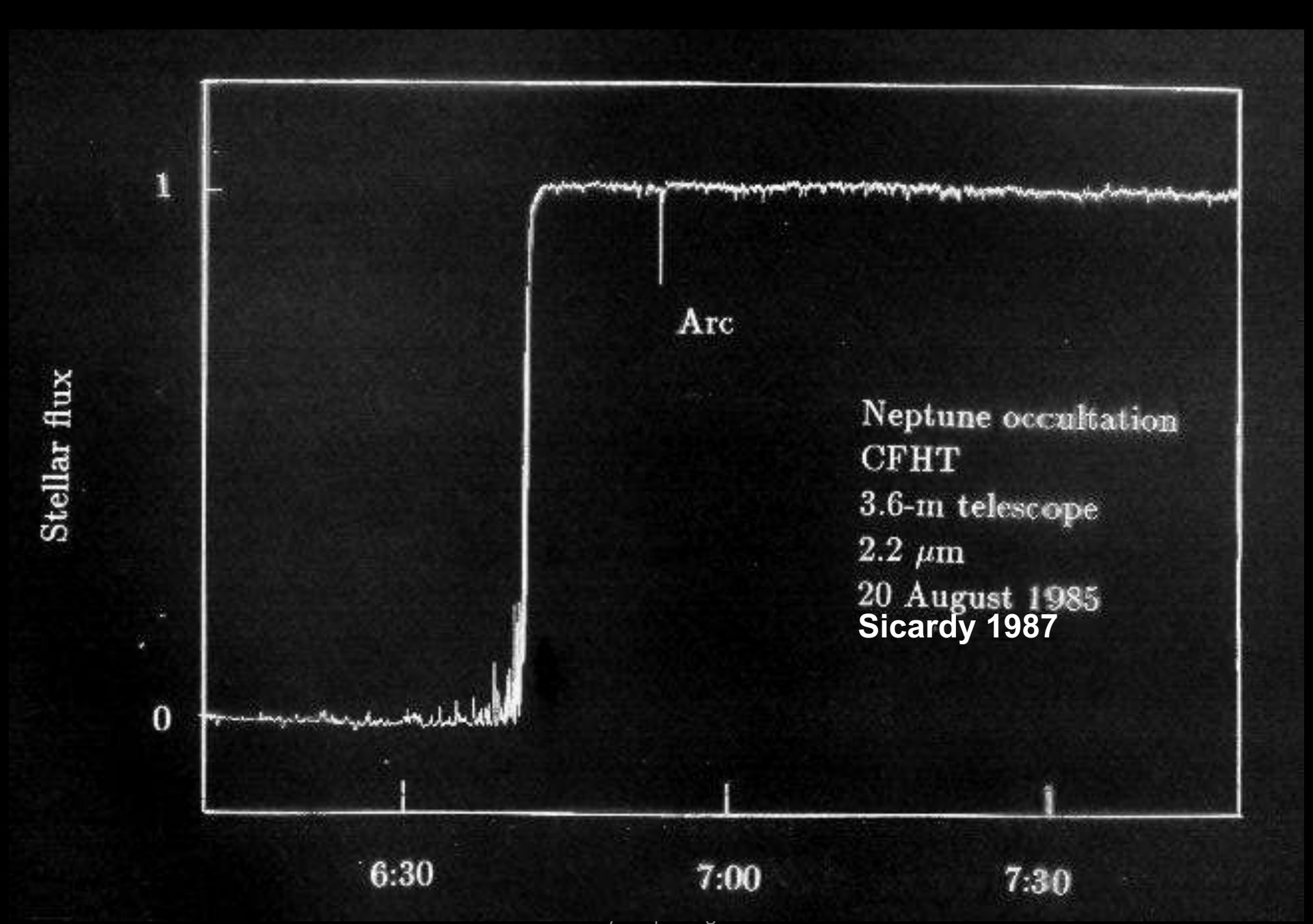
ARTICLES

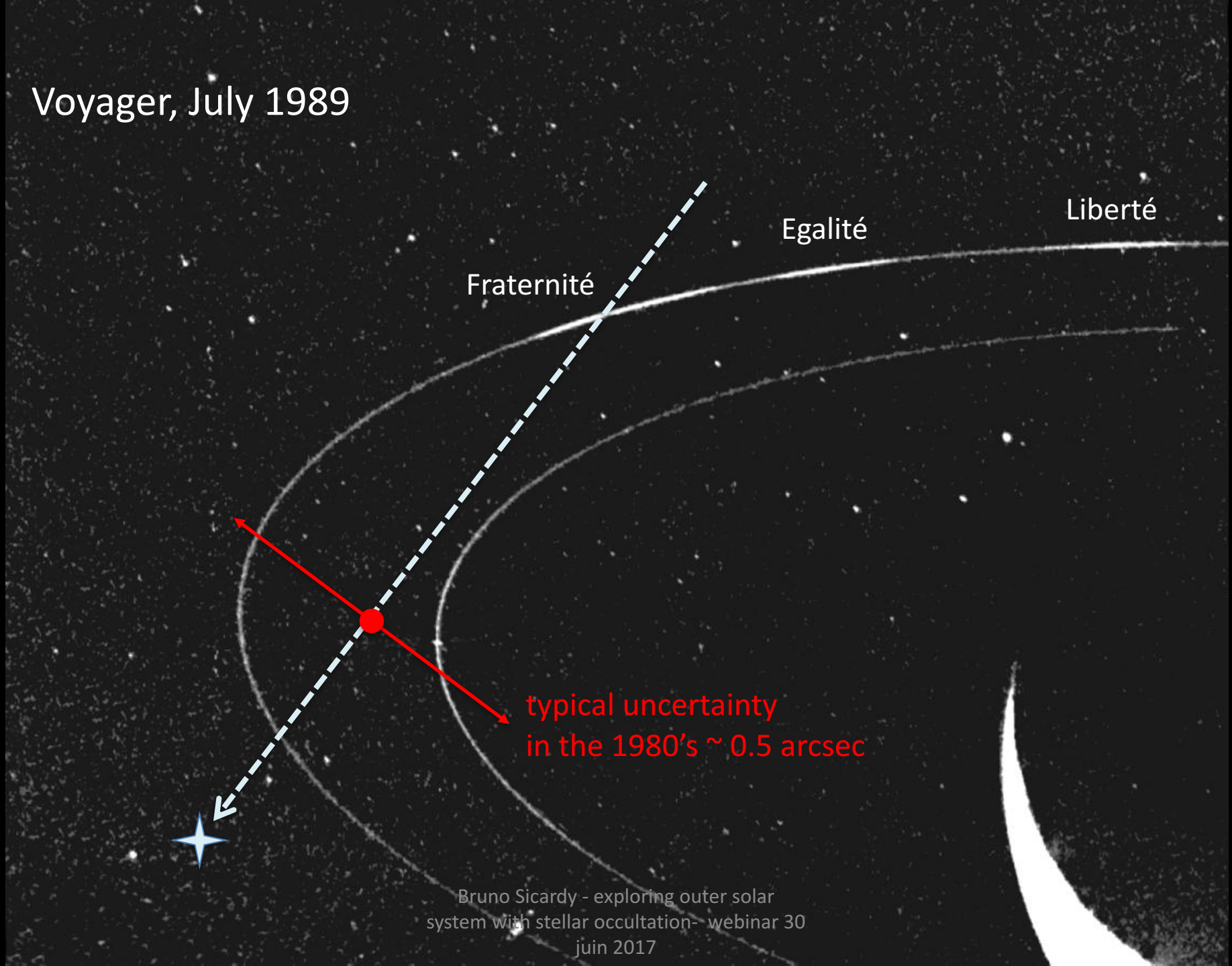
Occultation detection of a neptunian ring-like arc

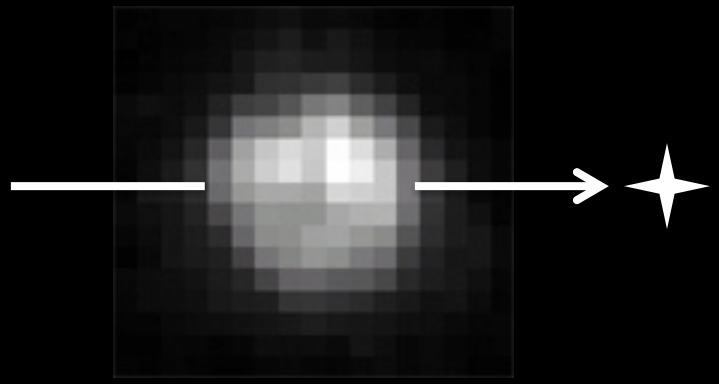
W. B. Hubbard*, A. Brahic†, B. Sicardy†, L.-R. Elicer‡, F. Roques† & F. Vilas*§

* Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA
† Université Paris VII, Observatoire de Paris, 92190 Meudon, France
‡ Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

The apparent closest approach of the star SAO186001 to Neptune was observed photoelectrically on 22 July 1984 at Cerro Tololo Inter-American Observatory. A 32% signal drop lasting about 1.2 s was probably caused by a partially transparent arc of material at a distance of 67,000 km from Neptune. Neptune's arc(s) do not vary smoothly with azimuth, unlike the rings of other jovian planets.


Stellar flux
1
0
Arc
Neptune occultation
CFHT
3.6-m telescope
2.2 μm
20 August 1985
Sicardy 1987
6:30
7:00
7:30


Voyager, July 1989
Liberté
Egalité
Fraternité
typical uncertainty
in the 1980's ~ 0.5 arcsec

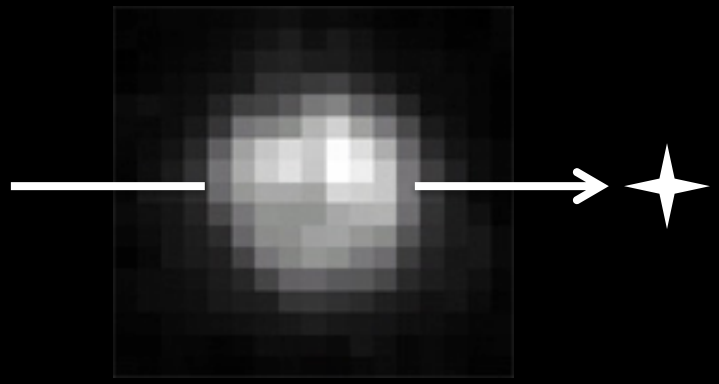


Pluto at best HST resolution
details ~ 500 km at best

Earth's Moon at the same resolution

Occultations: highly efficient method

http://pluto.jhuapl.edu/Participate/community/What-We-Know.php?link=Making-Maps



Pluto at best HST resolution
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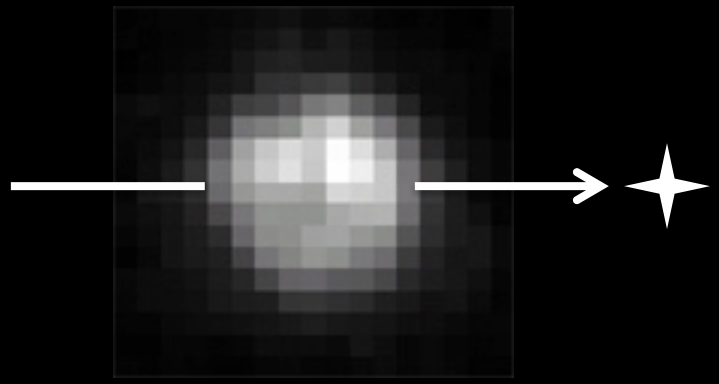
Earth's Moon at the same resolution

Occultations: highly efficient method

spatial resolution ~ fraction of km

http://pluto.jhuapl.edu/Participate/community/What-We-Know.php?link=Making-Maps



Pluto at best HST resolution
details ~ 500 km at best

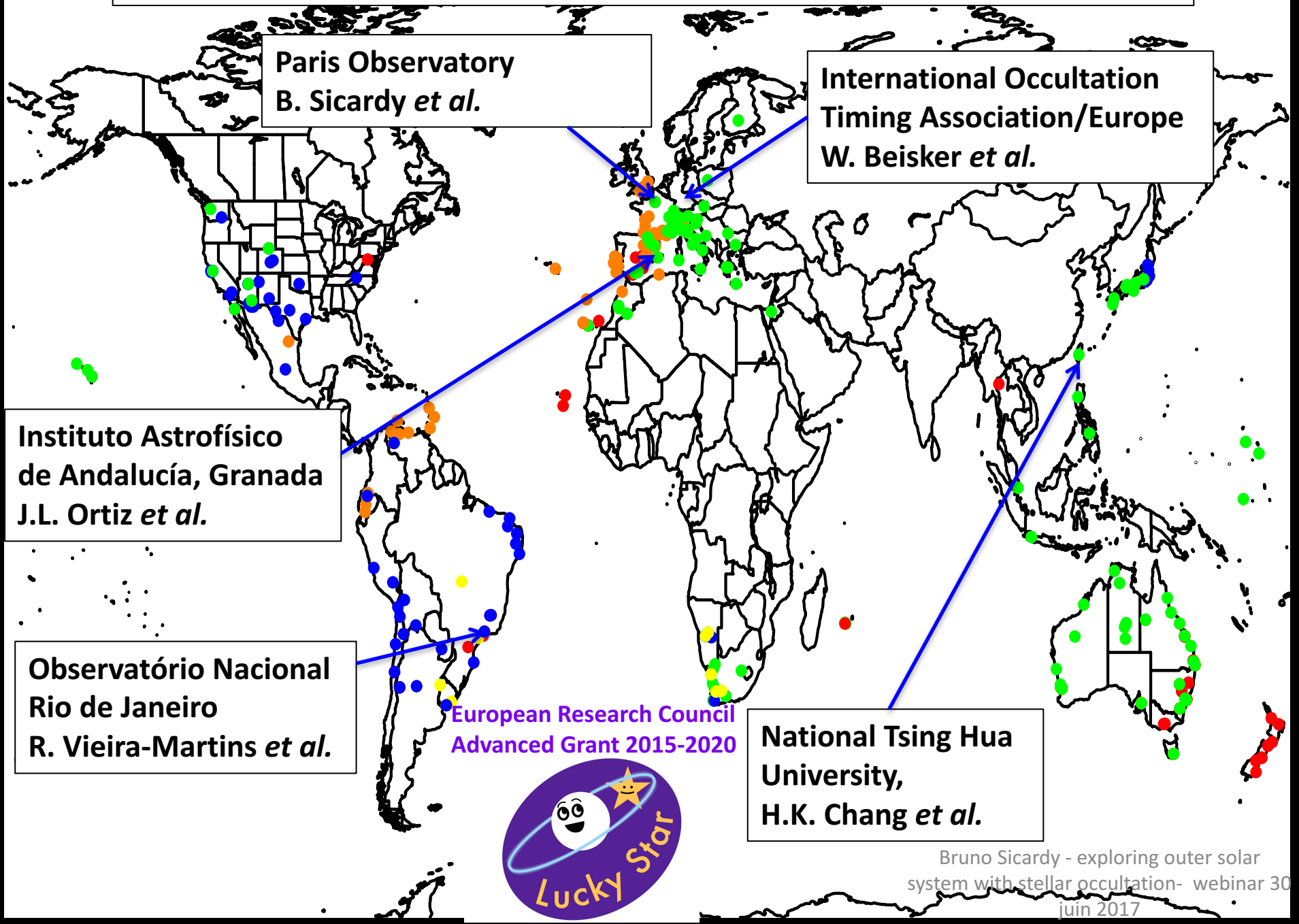
Earth's Moon at the same resolution

Occultations: highly efficient method

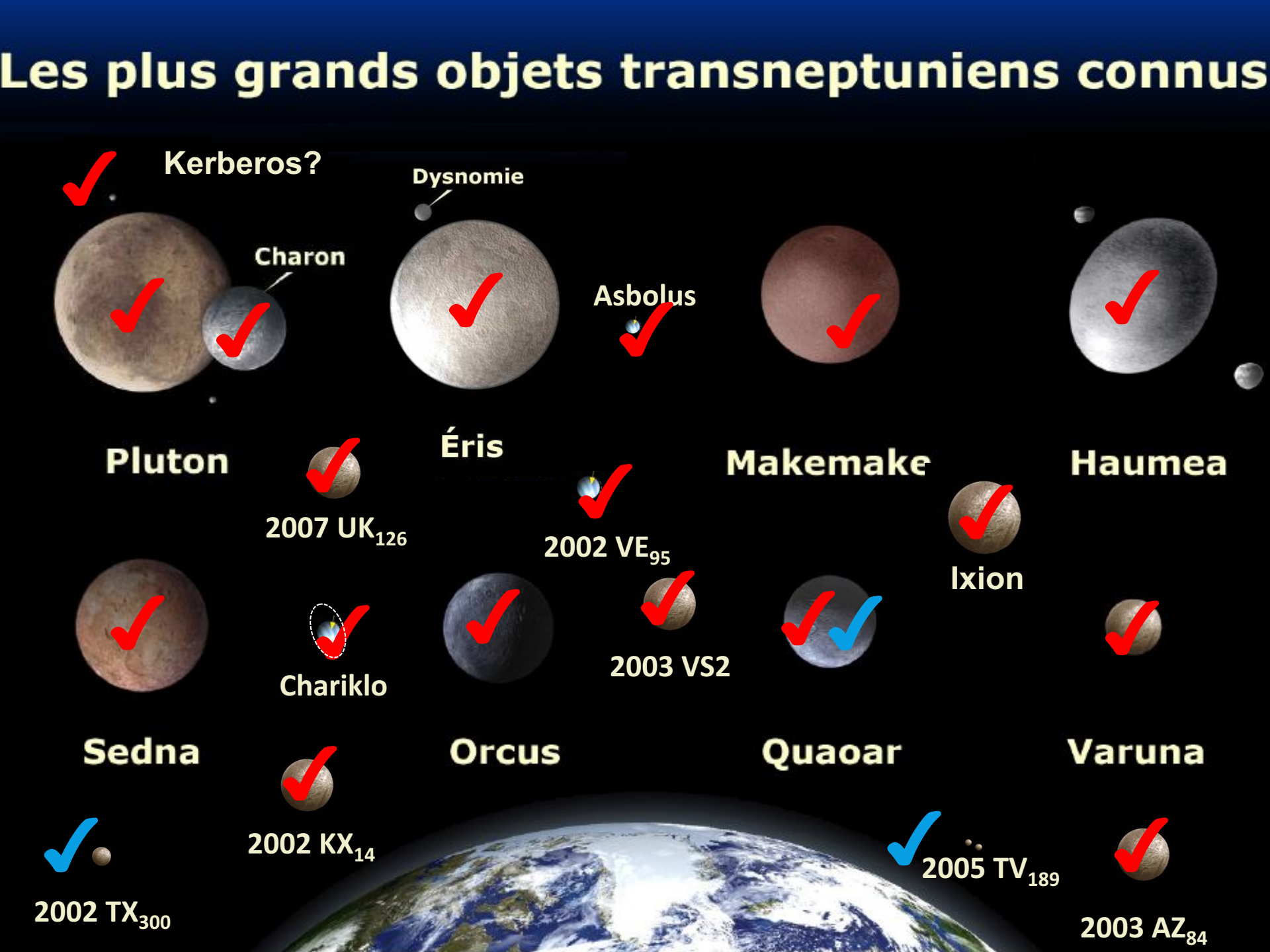
spatial resolution ~ fraction of km
sensitivity to atmosphere ~ a few nanobars

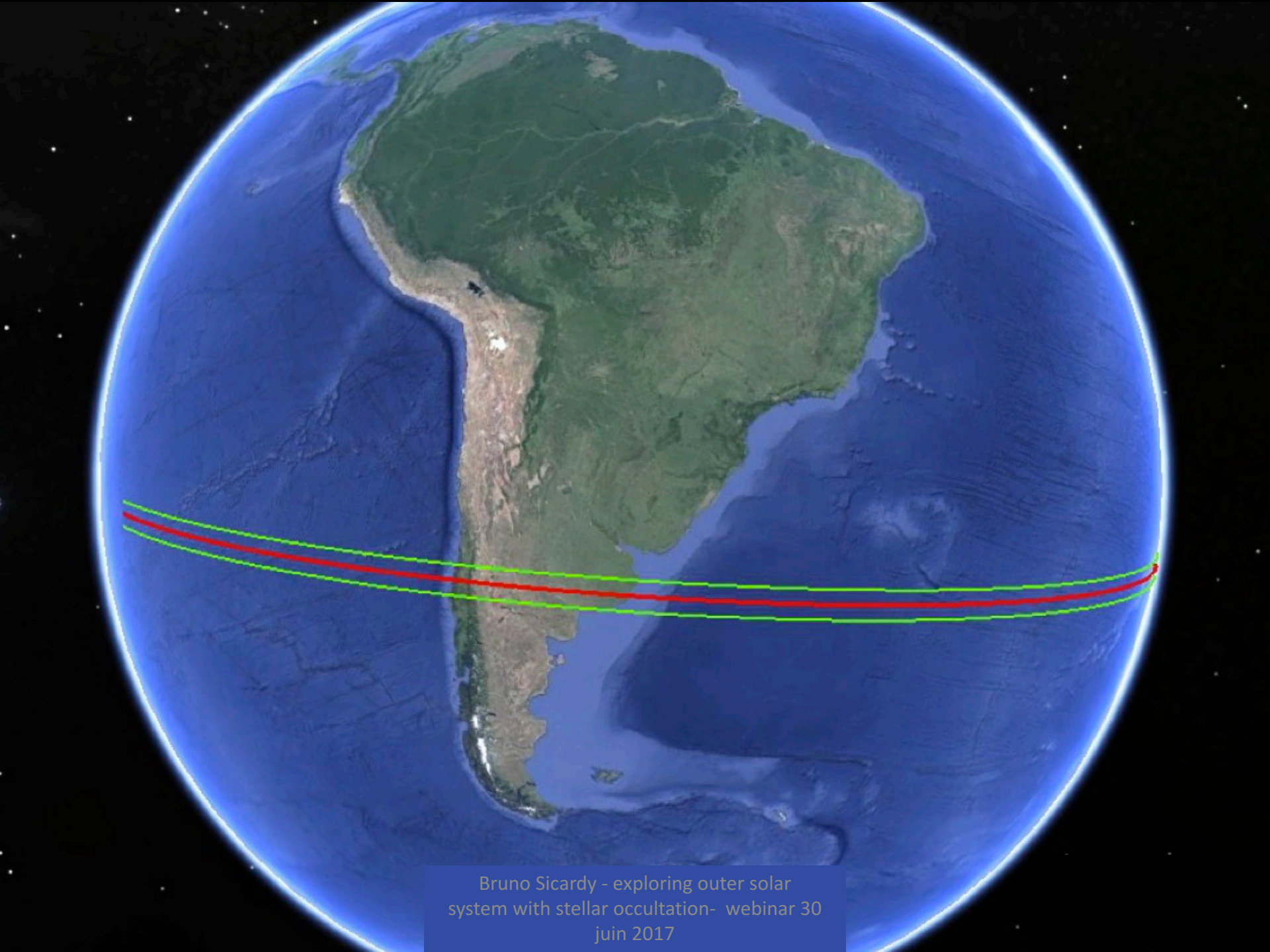
http://pluto.jhuapl.edu/Participate/community/What-We-Know.php?link=Making-Maps

collaborative science with professional and amateur astronomers



Les plus grands objets transneptuniens connus





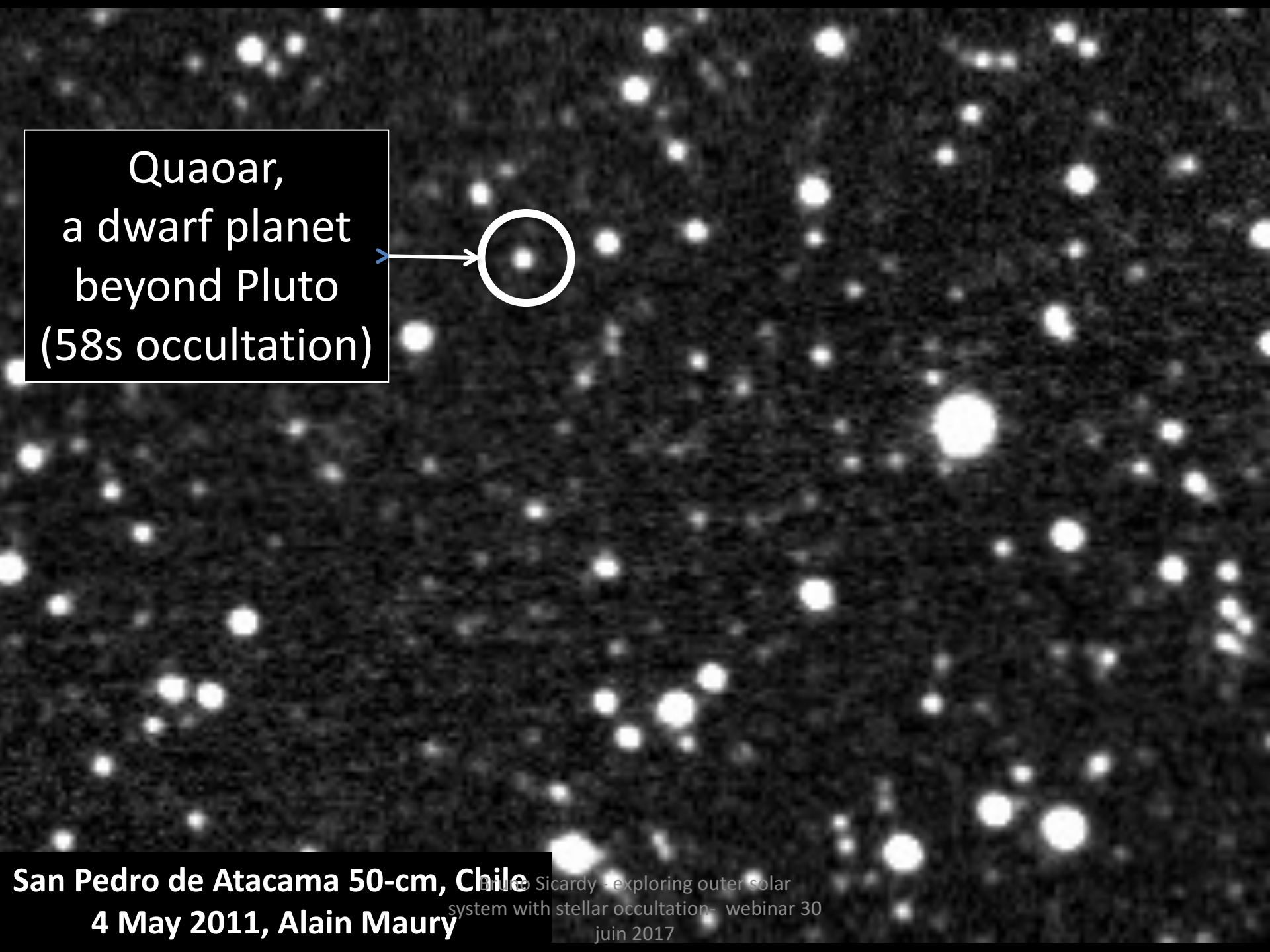
Bruno Sicardy - exploring outer solar system with stellar occultation- webinar 30 juin 2017


DELL

Chariklo occultation
Namibia April 9, 2017

VLT, July 2005

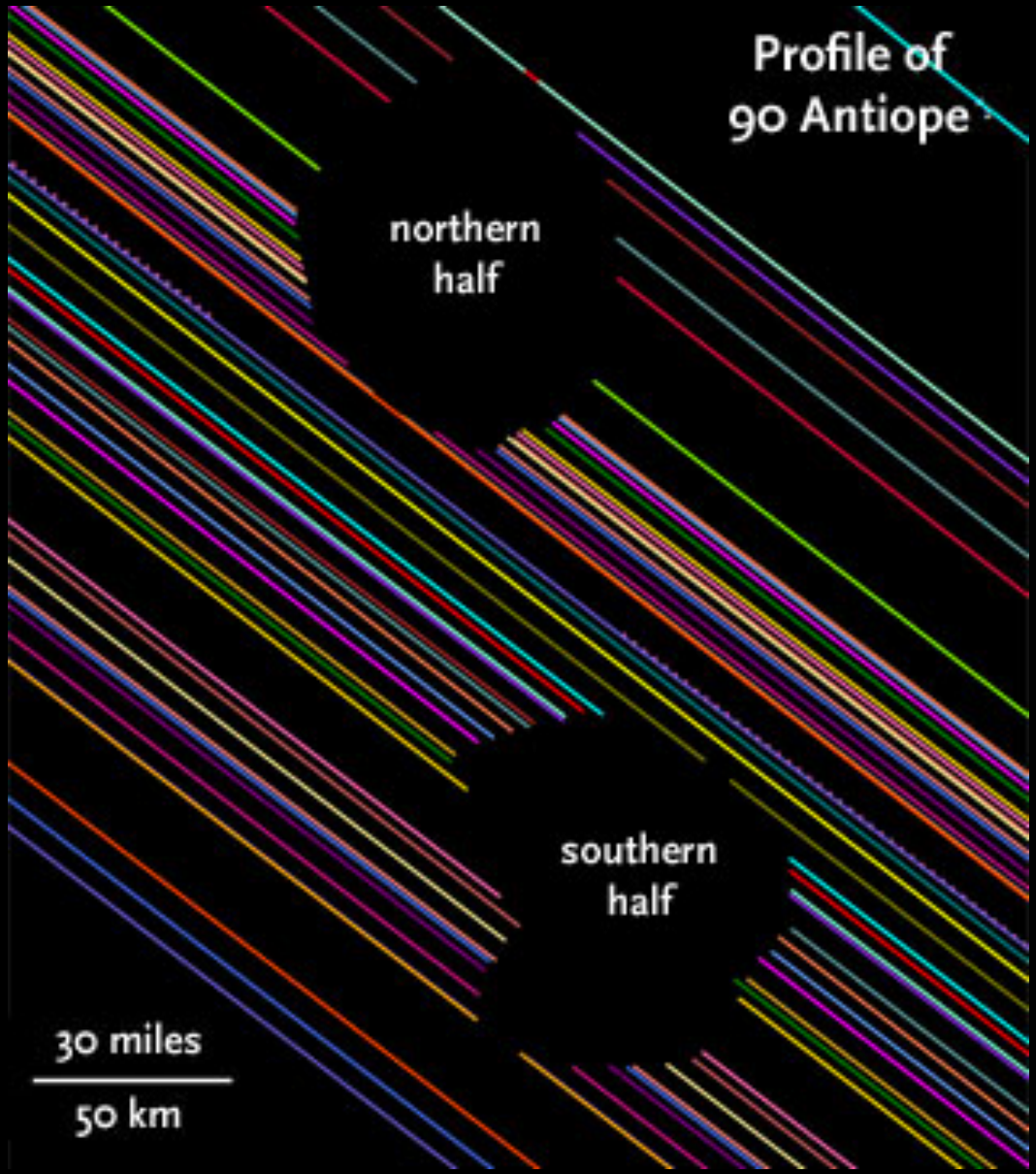
Pluto occultation
Mt John, New Zealand
June 2006



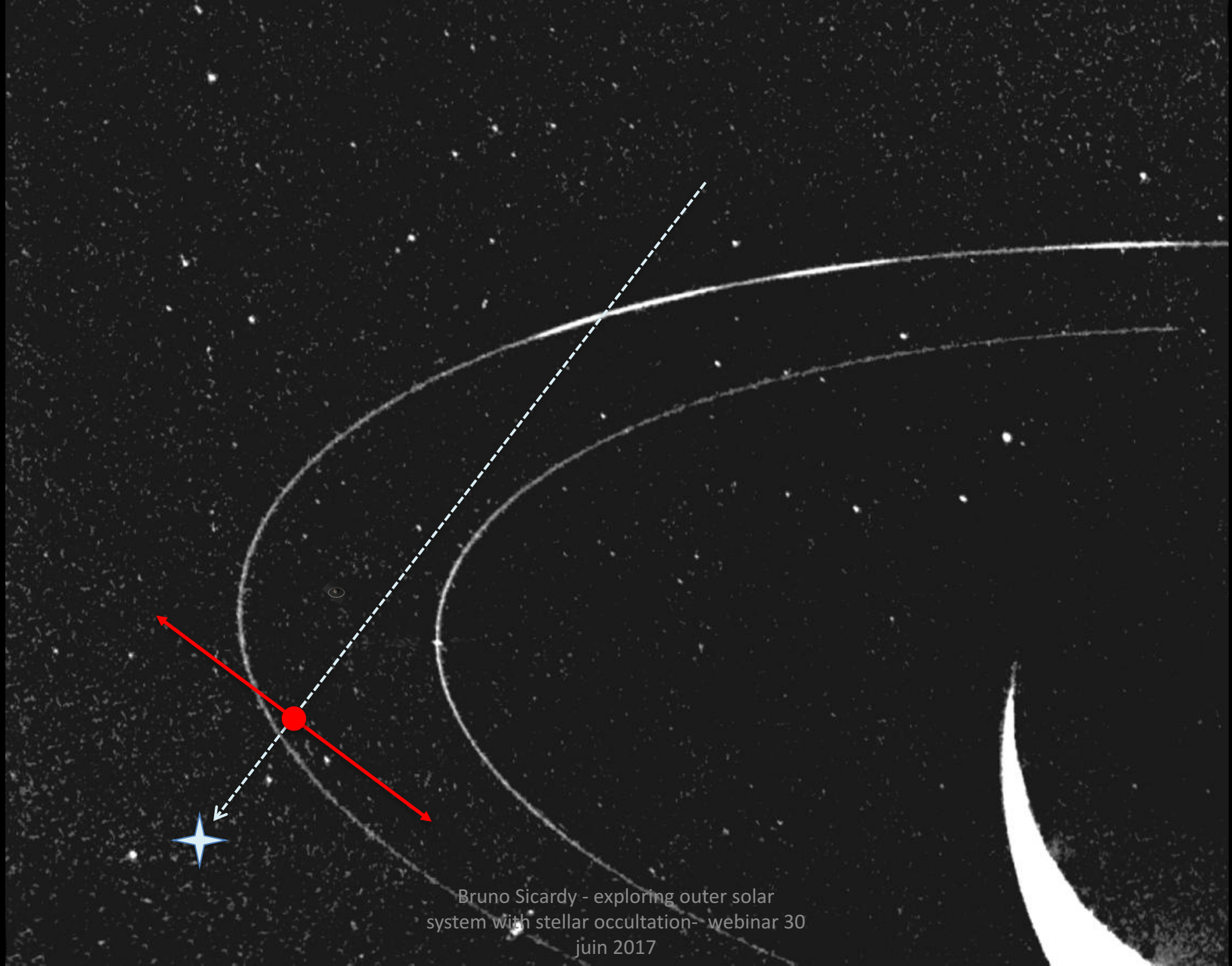
San Pedro de Atacama 50-cm, Chile
4 May 2011, Alain Maury

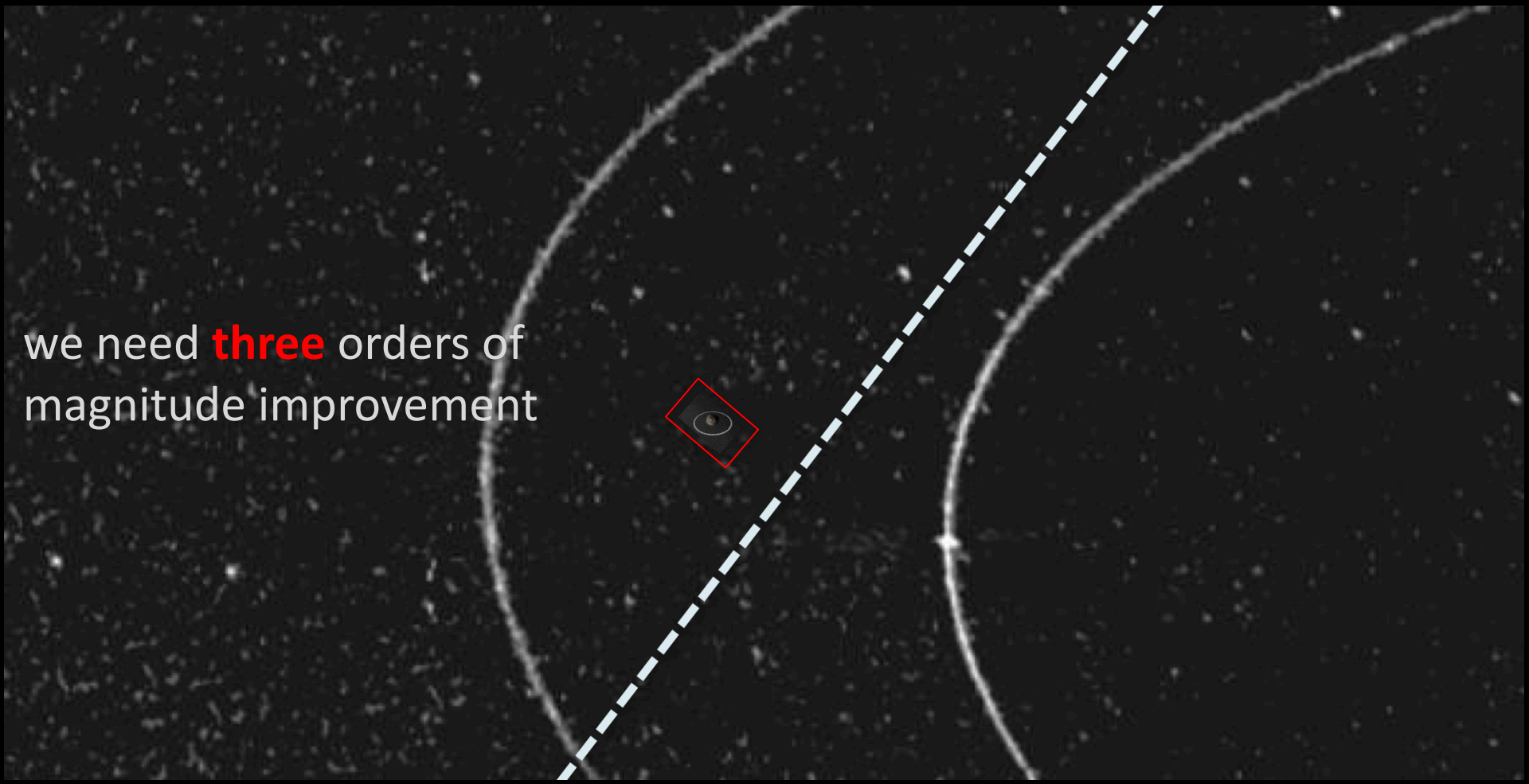
Antiope occultation
Kelly Beatty Sky & Telescope
9 Sept. 2011

from F. Colas, F. Marchis with US and European amateurs



www.skyandtelescope.com/astronomy-news/observing-news/antiope-occultation-yields-double-bonanza/




we need three orders of
magnitude improvement

Titan

quaoar

Pluto

Eris

a stamp viewed at 150 k

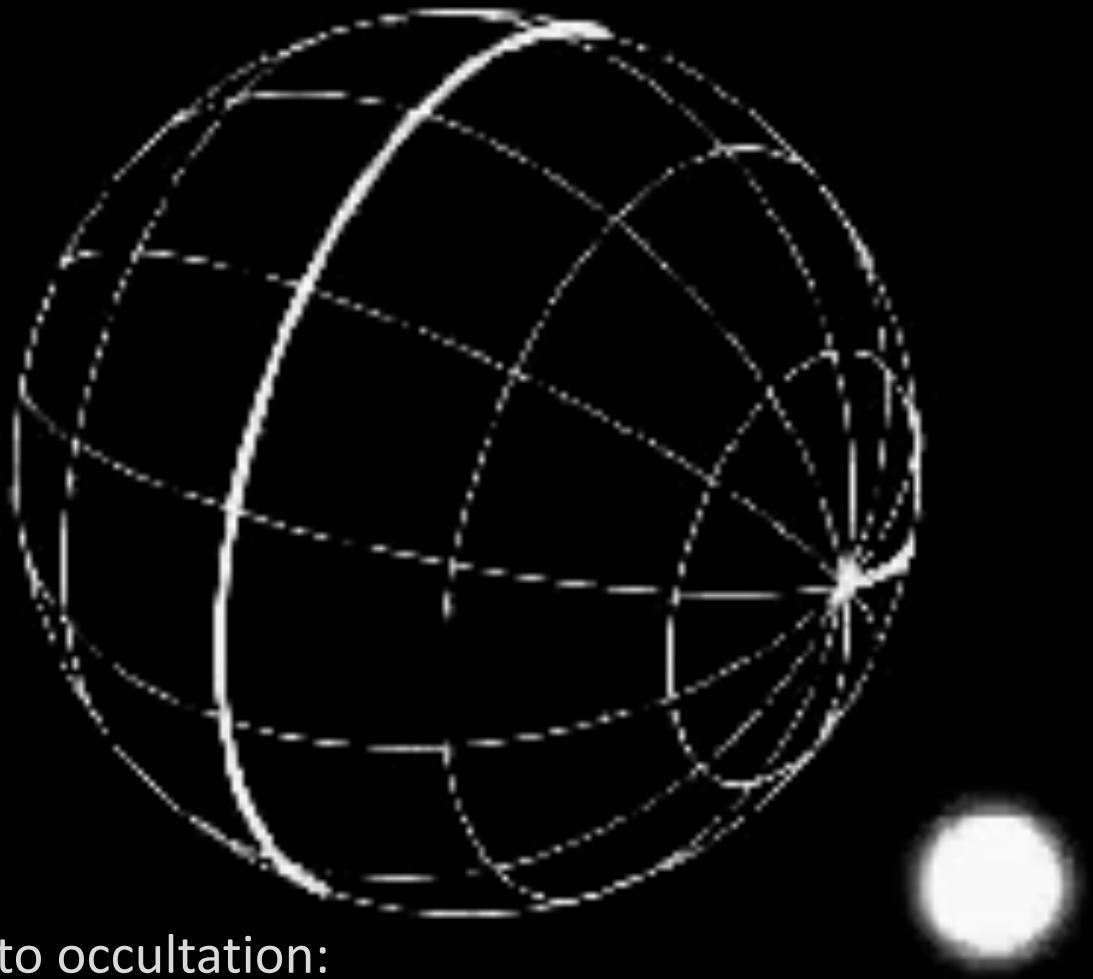
10^{-7} radian
~20 mas →
very small !!

Charon

Makemake

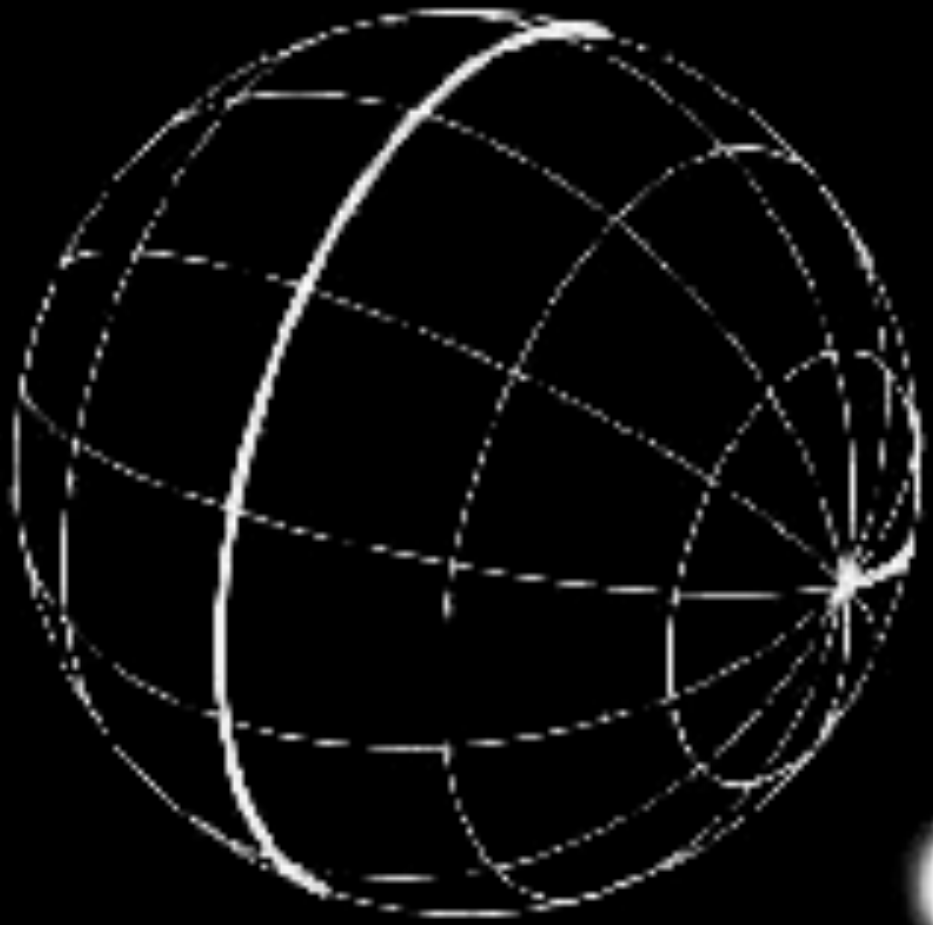
Charon occultation,
Paranal, Chile
July 2005

an example: Pluto’s atmosphere



August 21, 2002 Pluto occultation:
econstruction of what happened

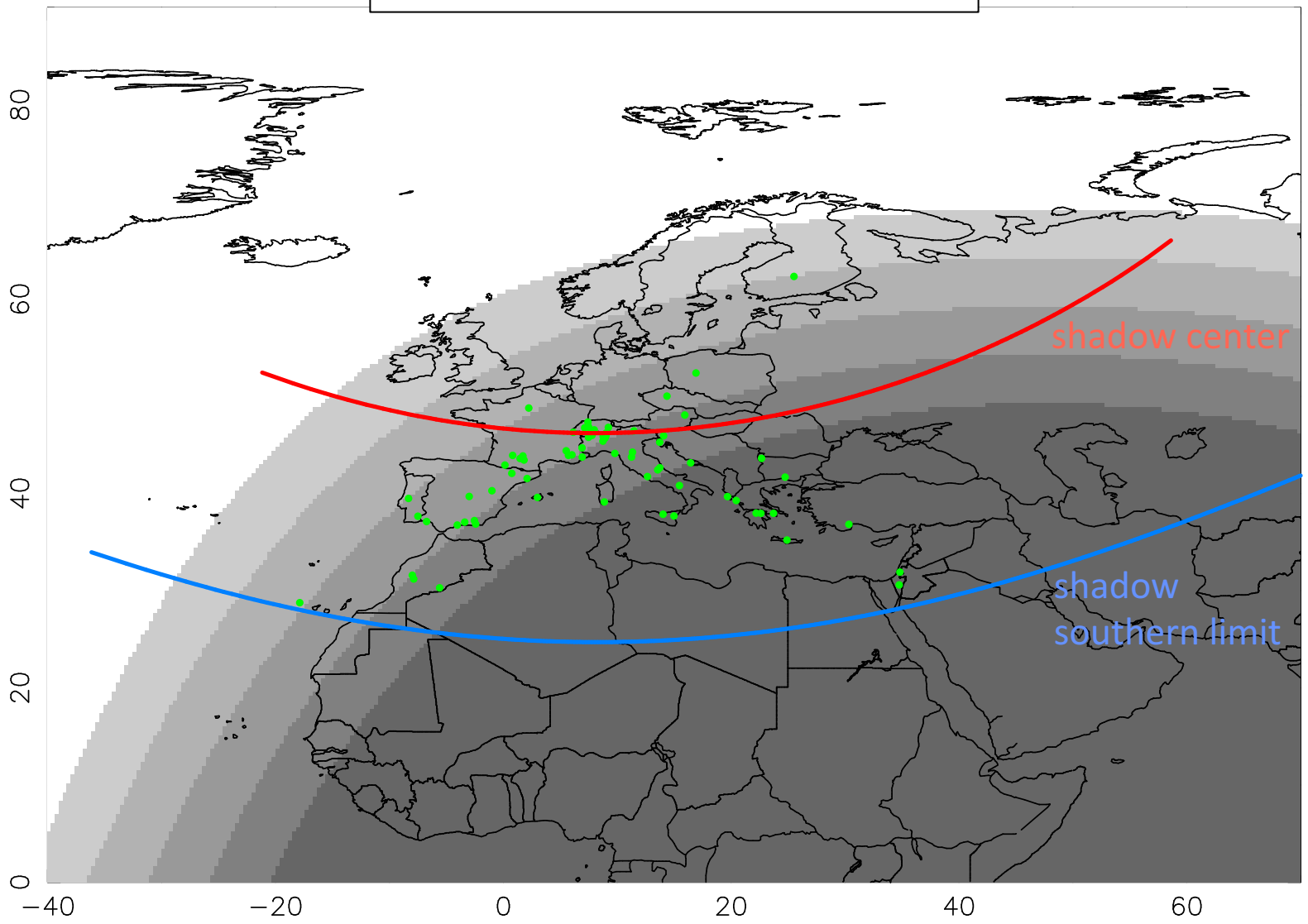
gravity waves!



gravity waves!

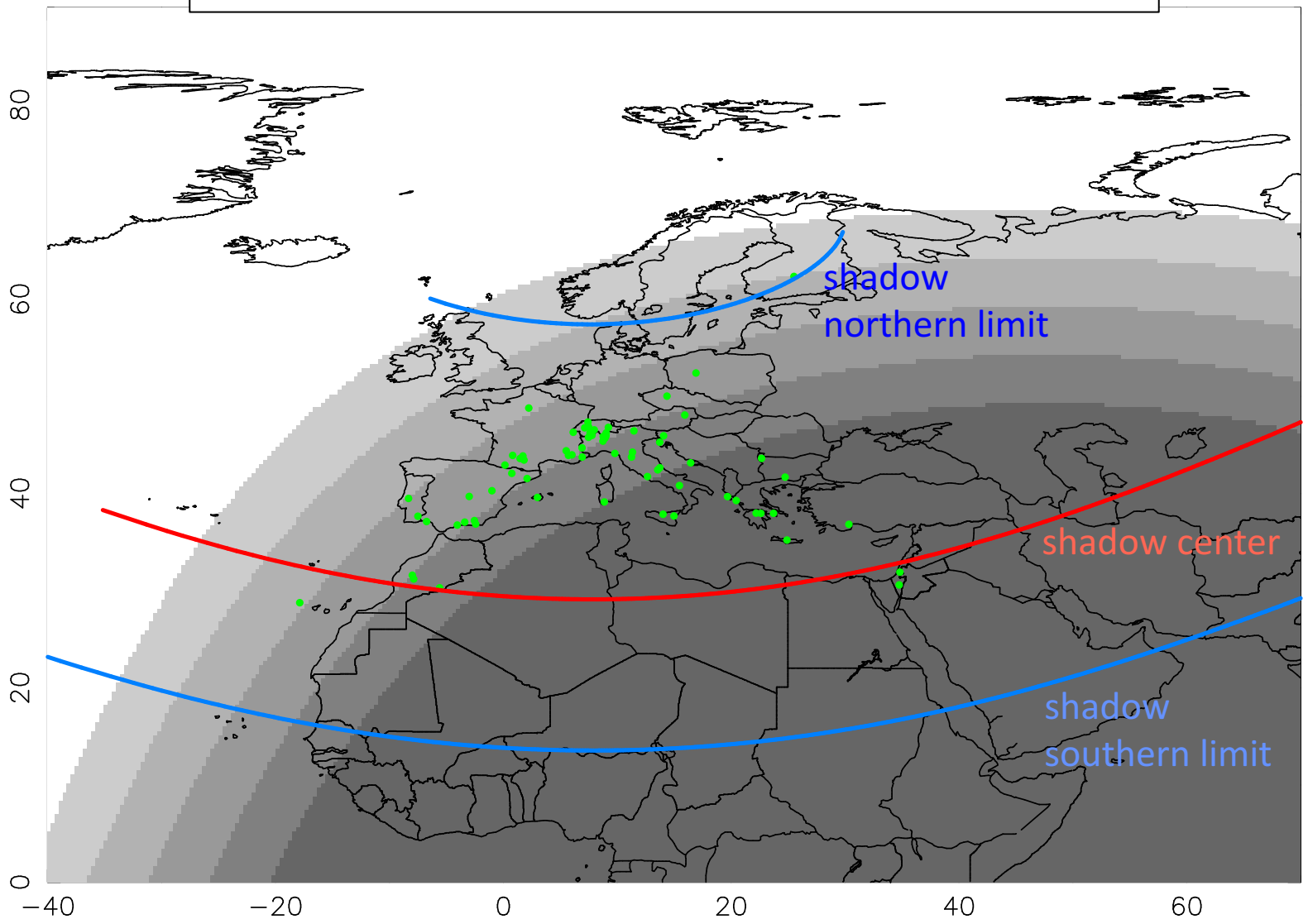
August 21, 2002 Pluto occultation:
econstruction of what happened

The July 19, 2016 Pluto occultation
our prediction as of early July



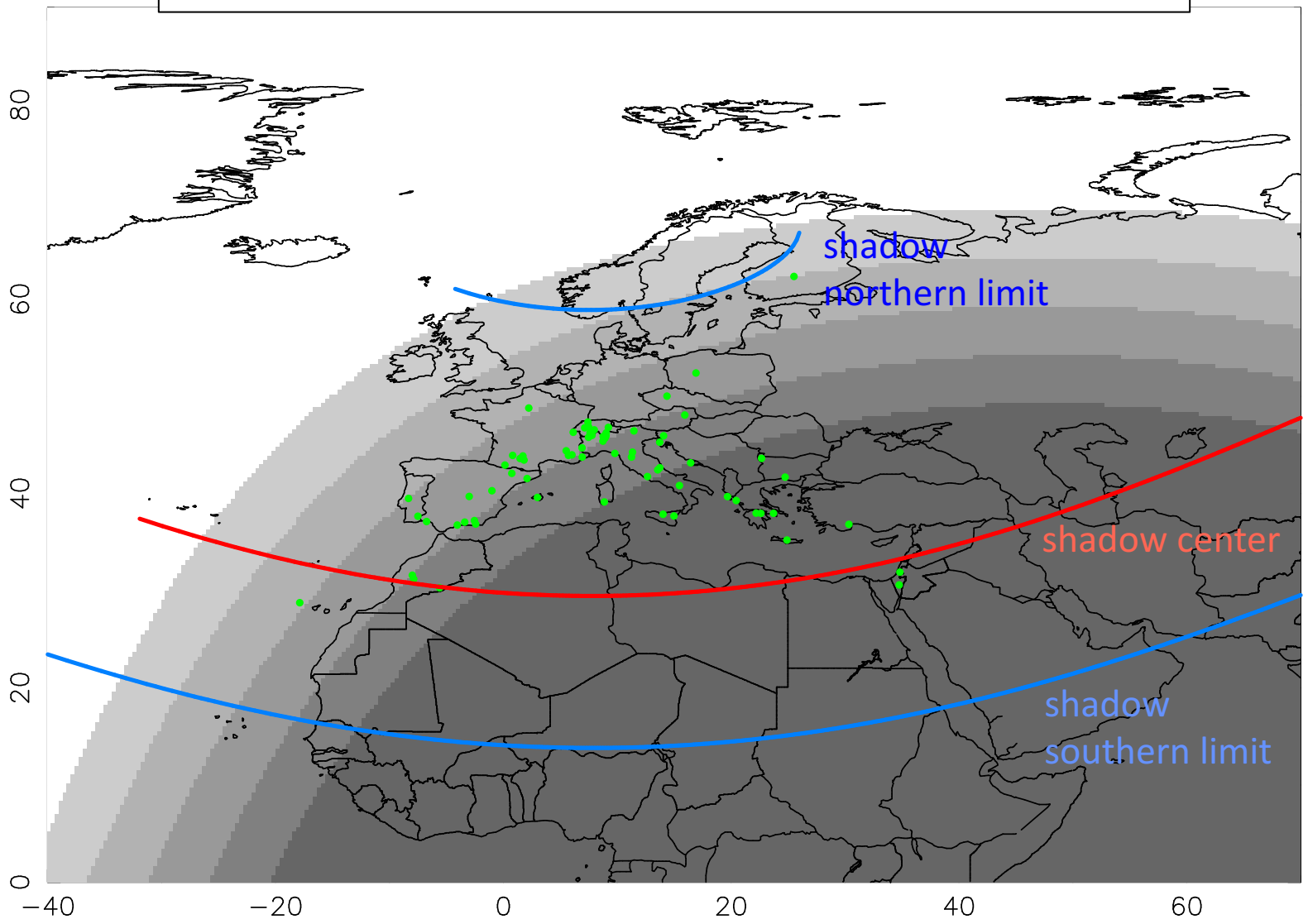
green dots: sites involved in the campaign (not all got data!)

The prediction using the GAIA "DR0" catalog (one star!)
+ the New Horizons-updated ephemeris



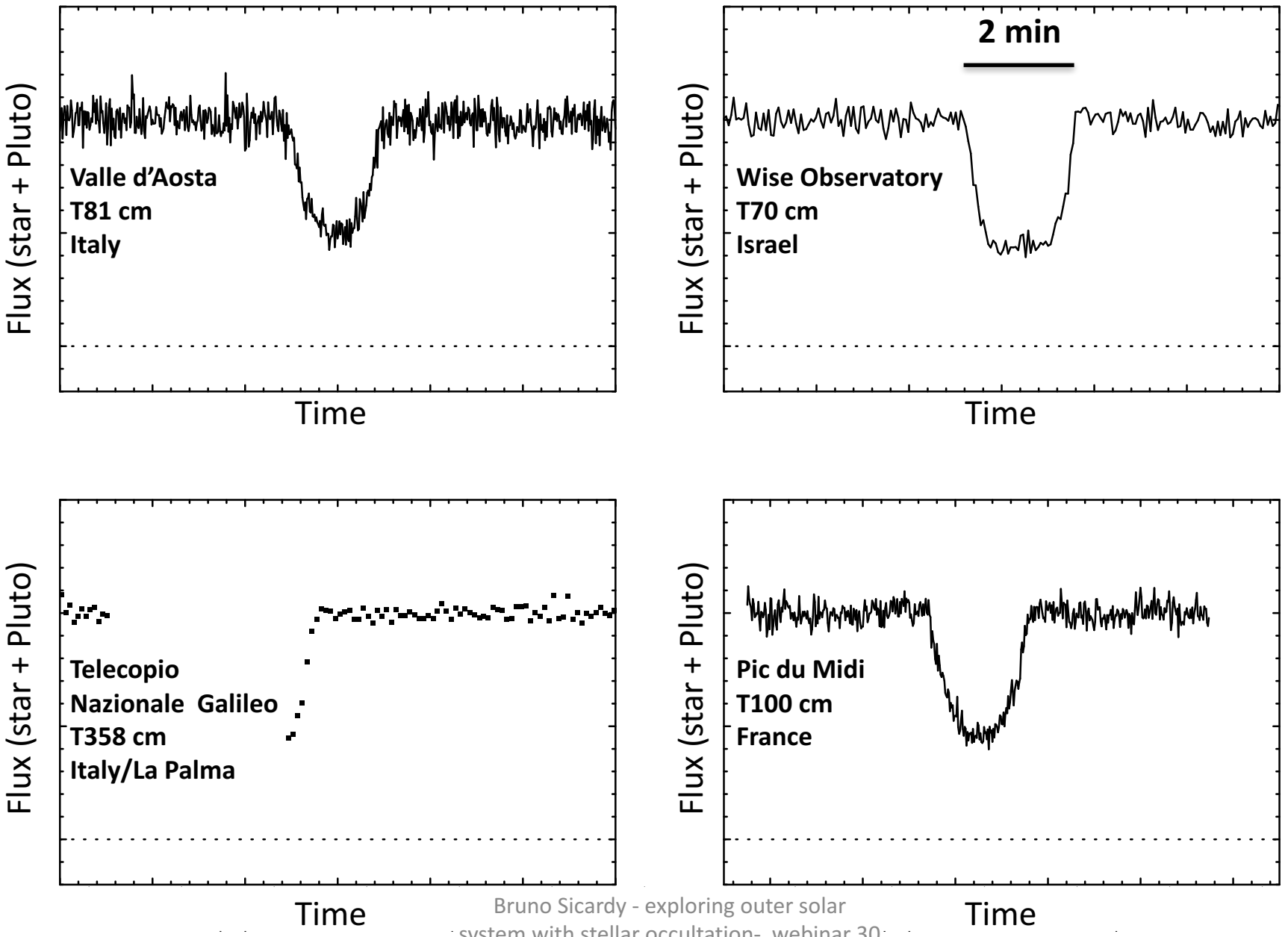
green dots: sites involved in the campaign (not all got data!)

The July 19, 2016 Pluto occultation
post-occultation reconstructed path (what really happened)

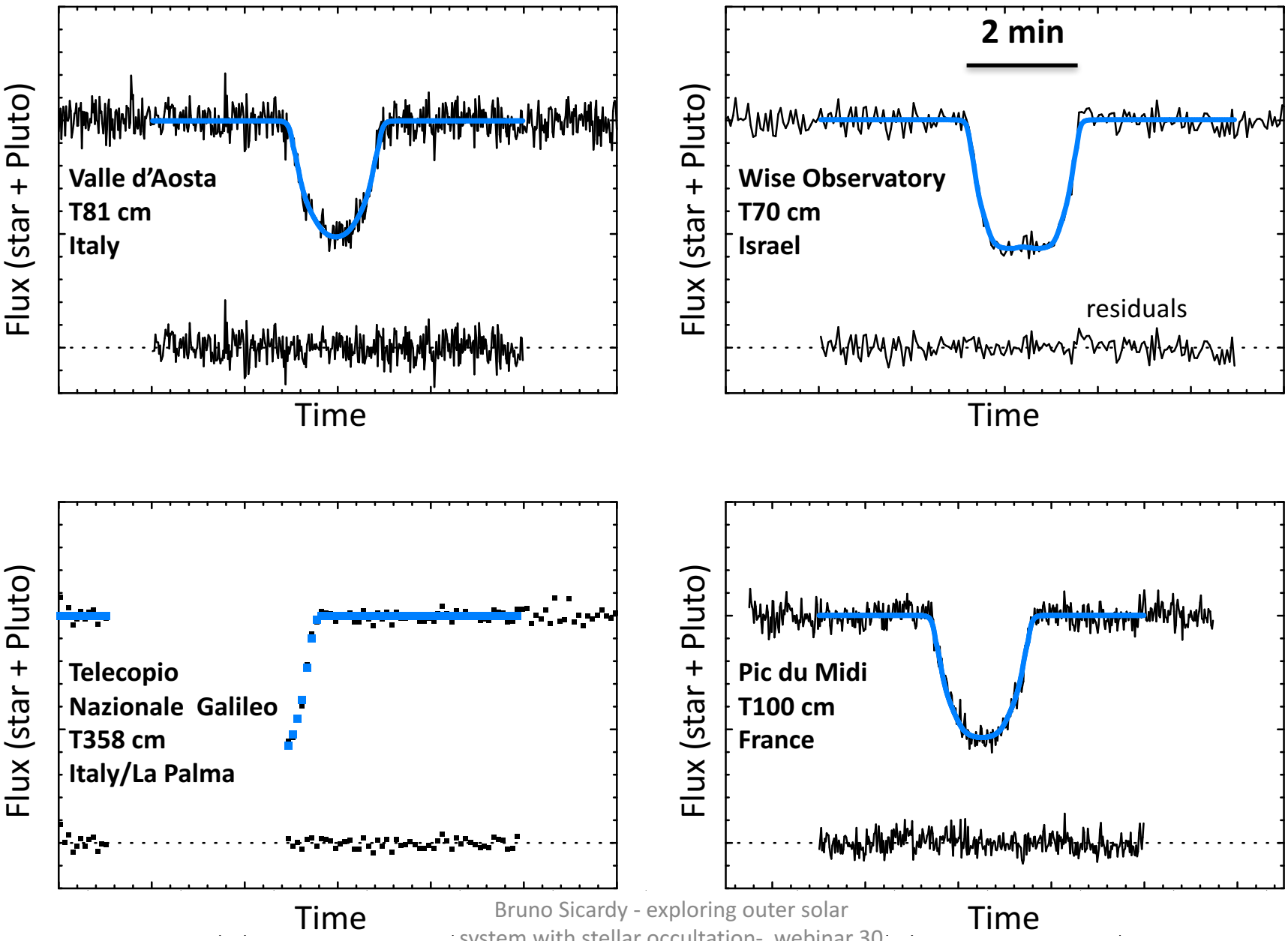


green dots: sites involved in the campaign (not all got data!)

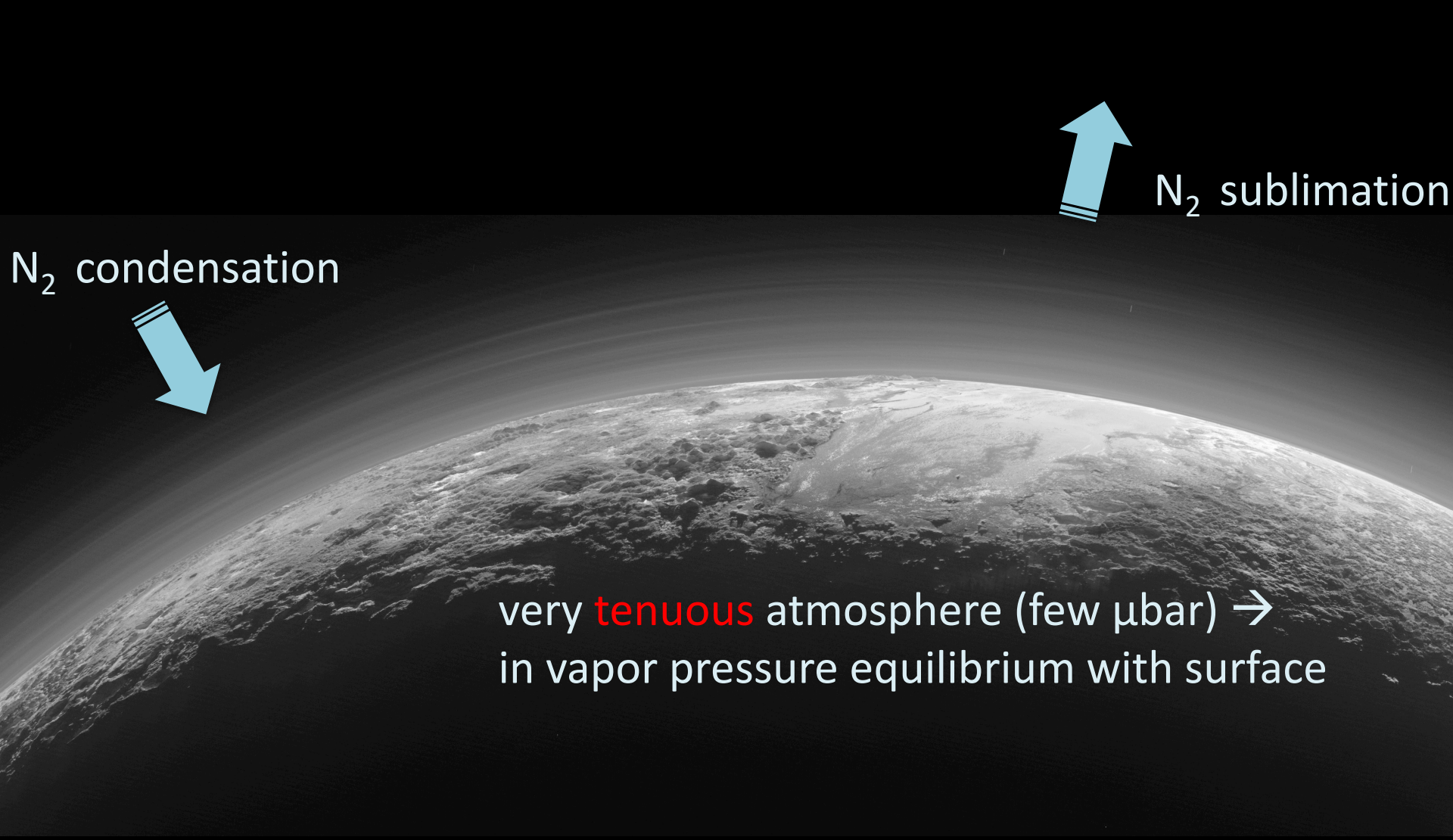
The Pluto July 19, 2016 stellar occultation



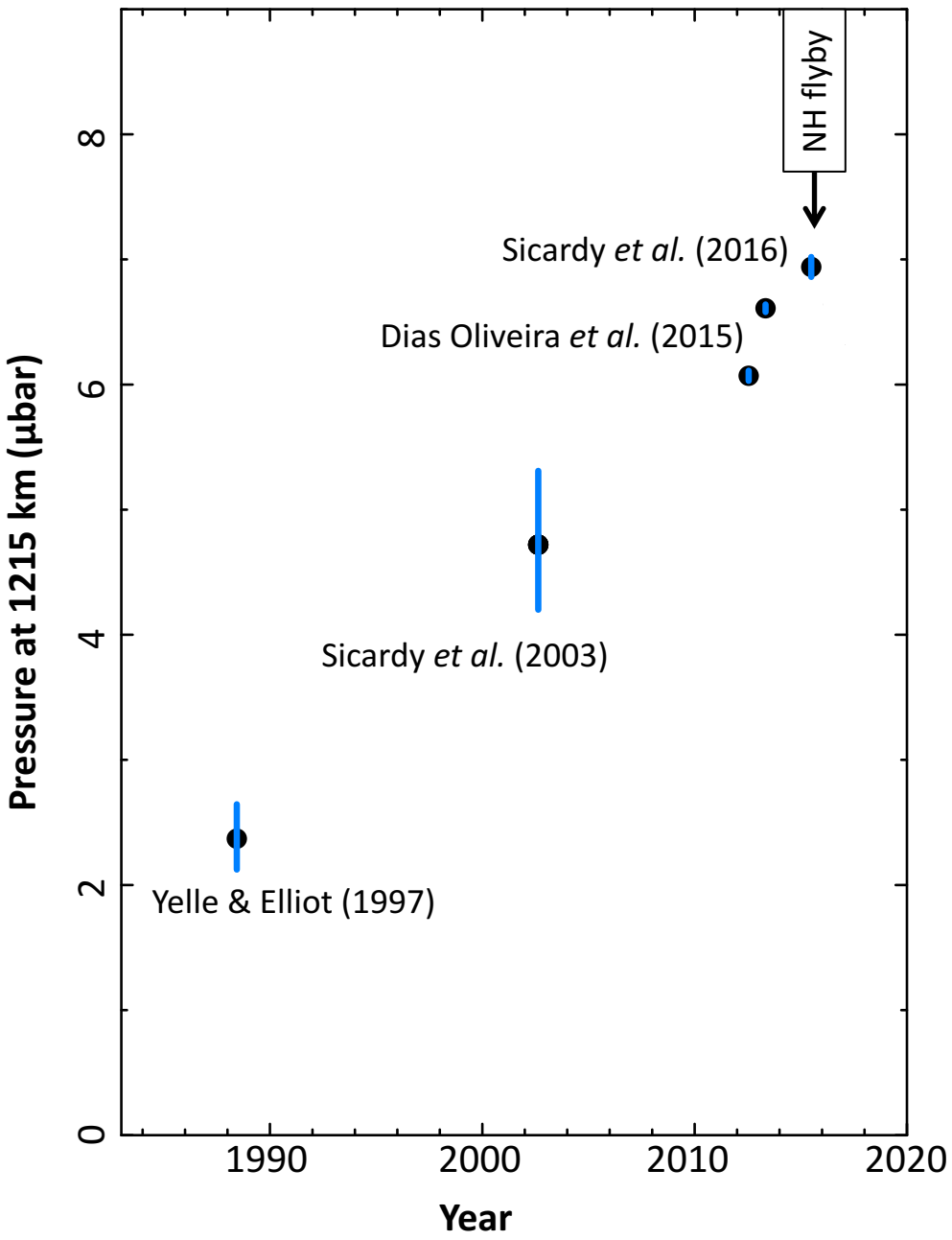
The Pluto July 19, 2016 stellar occultation

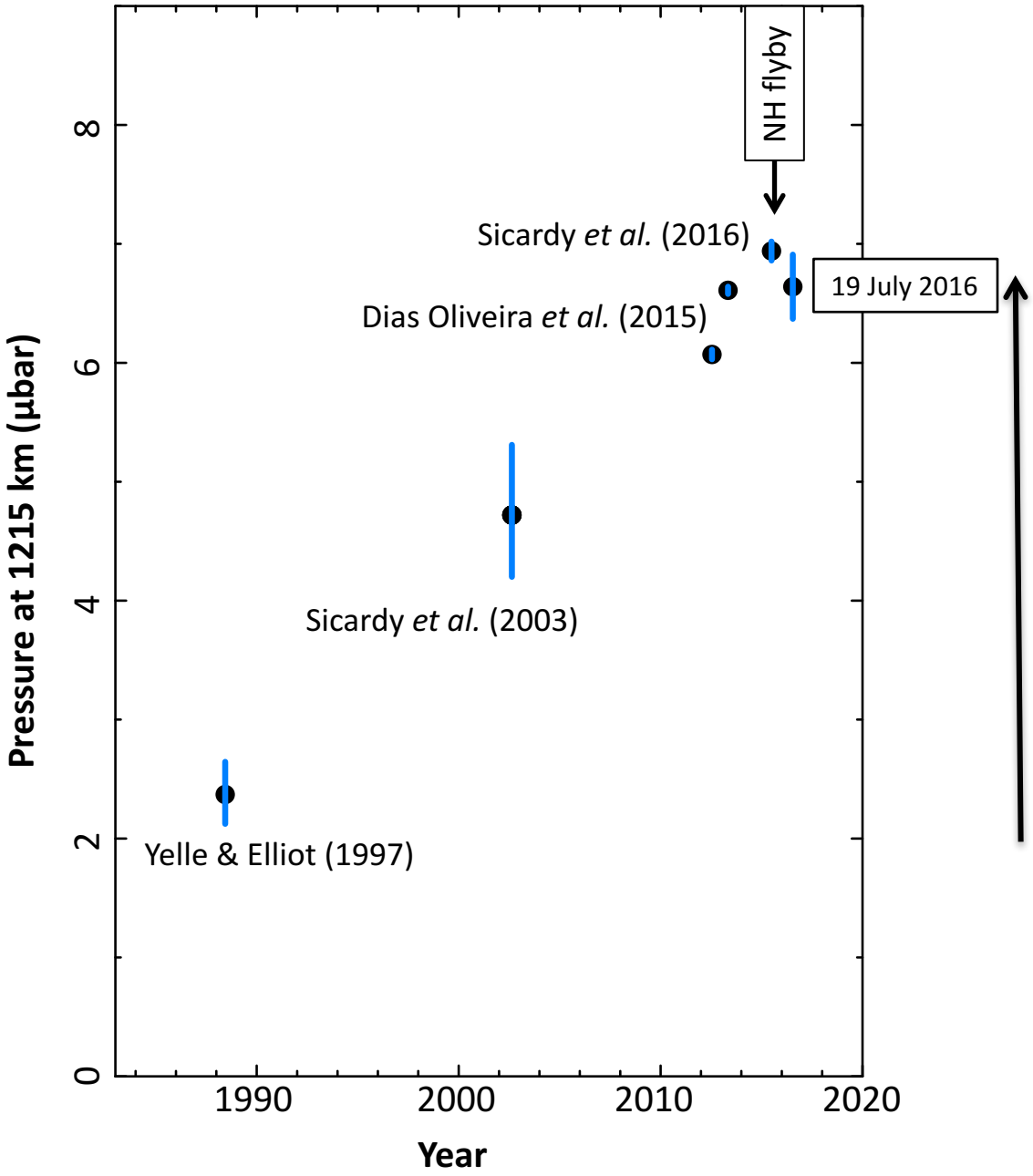


blue= simultaneous fit to the data using a Pluton atmospheric model



New Horizons/LORI

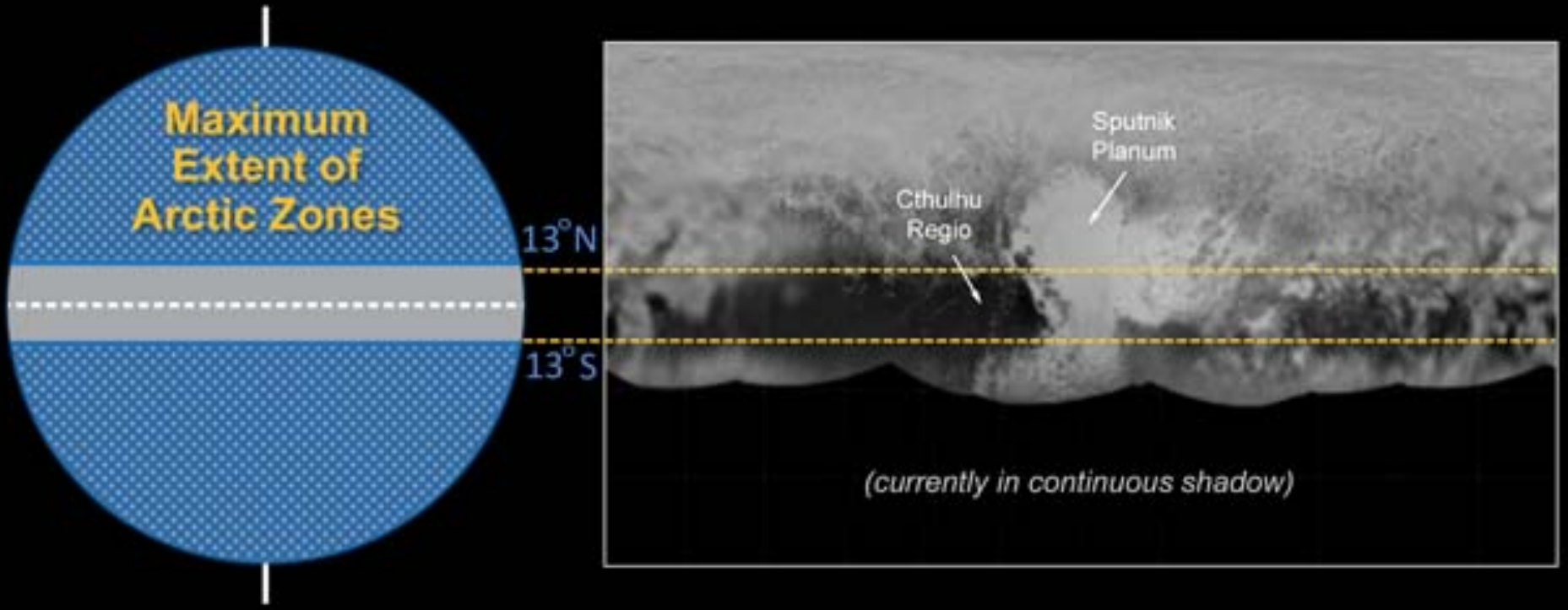

NH flyby
Sicardy et al. (2016)
Dias Oliveira et al. (2015)
Sicardy et al. (2003)
Yelle & Elliot (1997)
Pressure at 1215 km (µbar)
Year
0
2
4
6
8
1990
2000
2010
2020



paradoxical **increase** of pressure (factor ~ 2.8) but ~ 24% **decrease** of insolation in 22 years

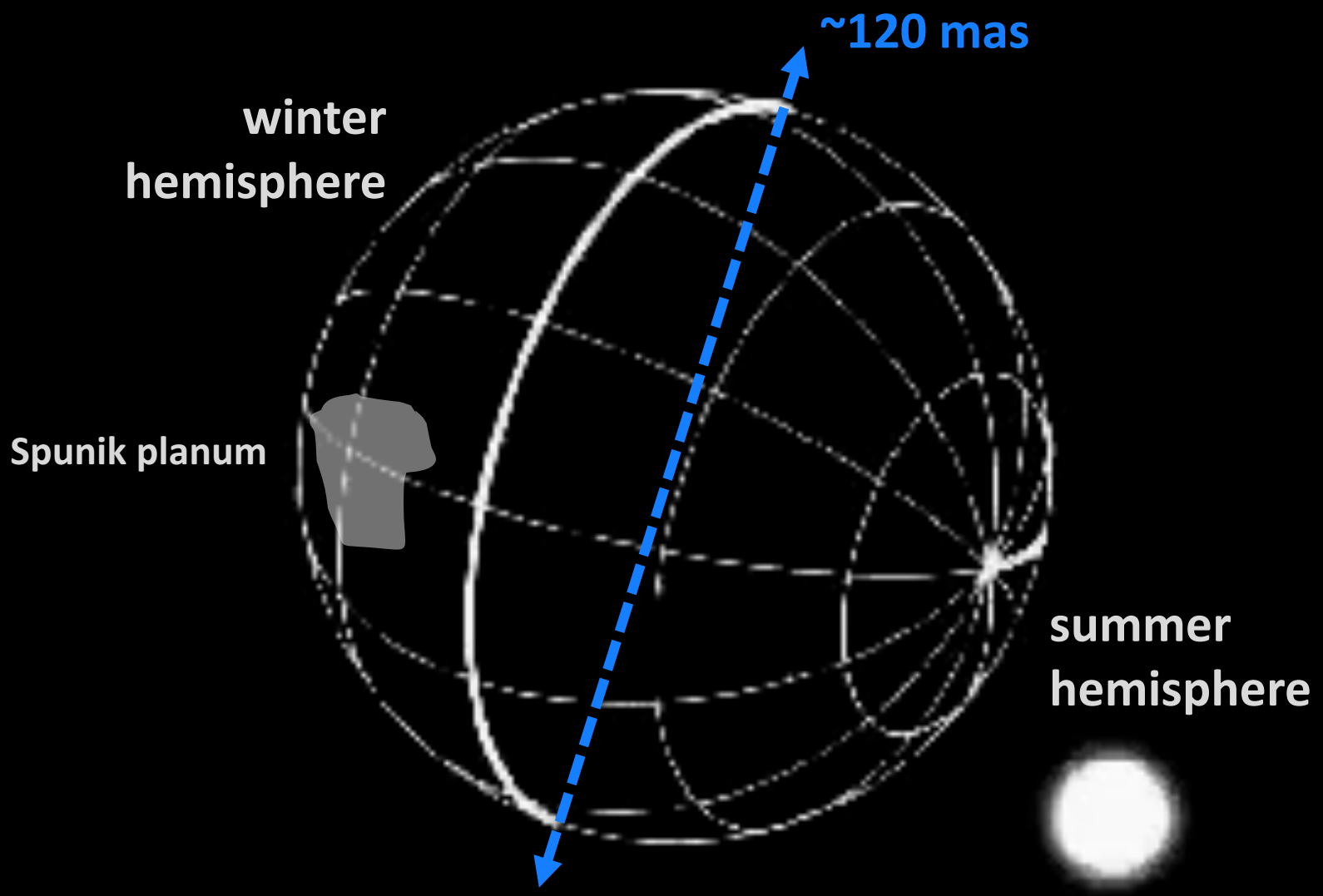
Pluto's atmosphere confounds researchers

Kelly Beatty, Sky & Telescope 25 March 2016

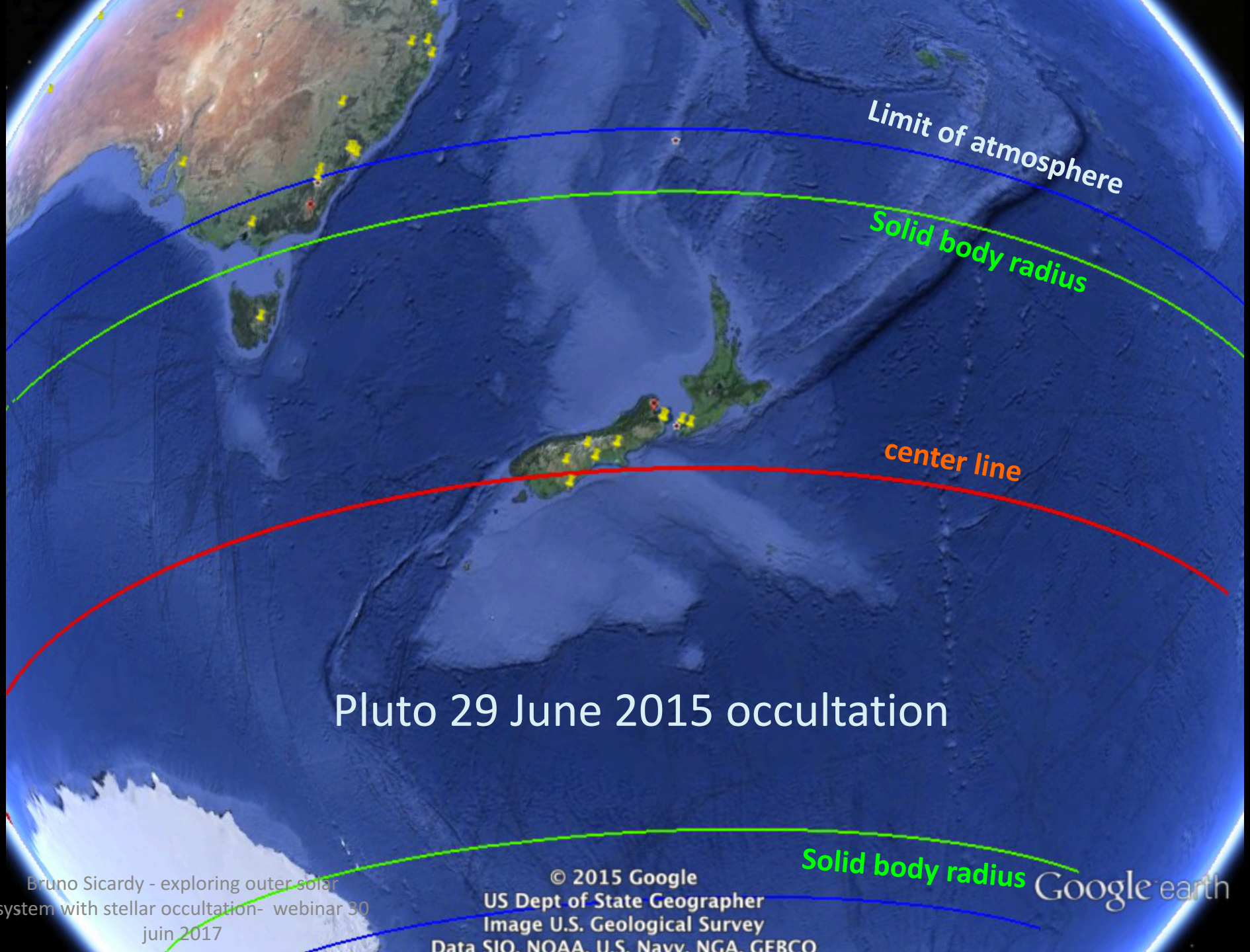


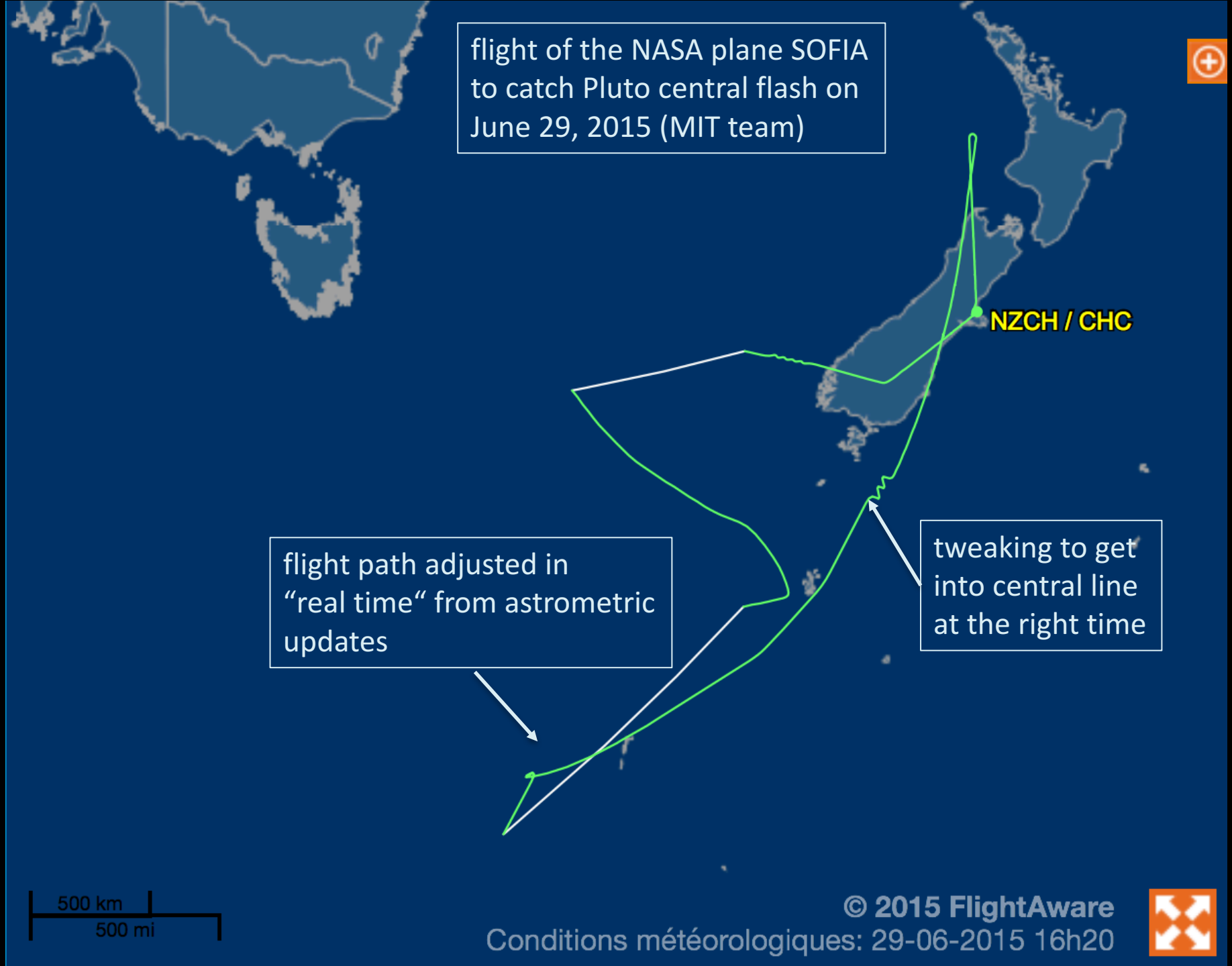
www.skyandtelescope.com/astronomy-news/plutos-atmosphere-confounds-researchers-032520166

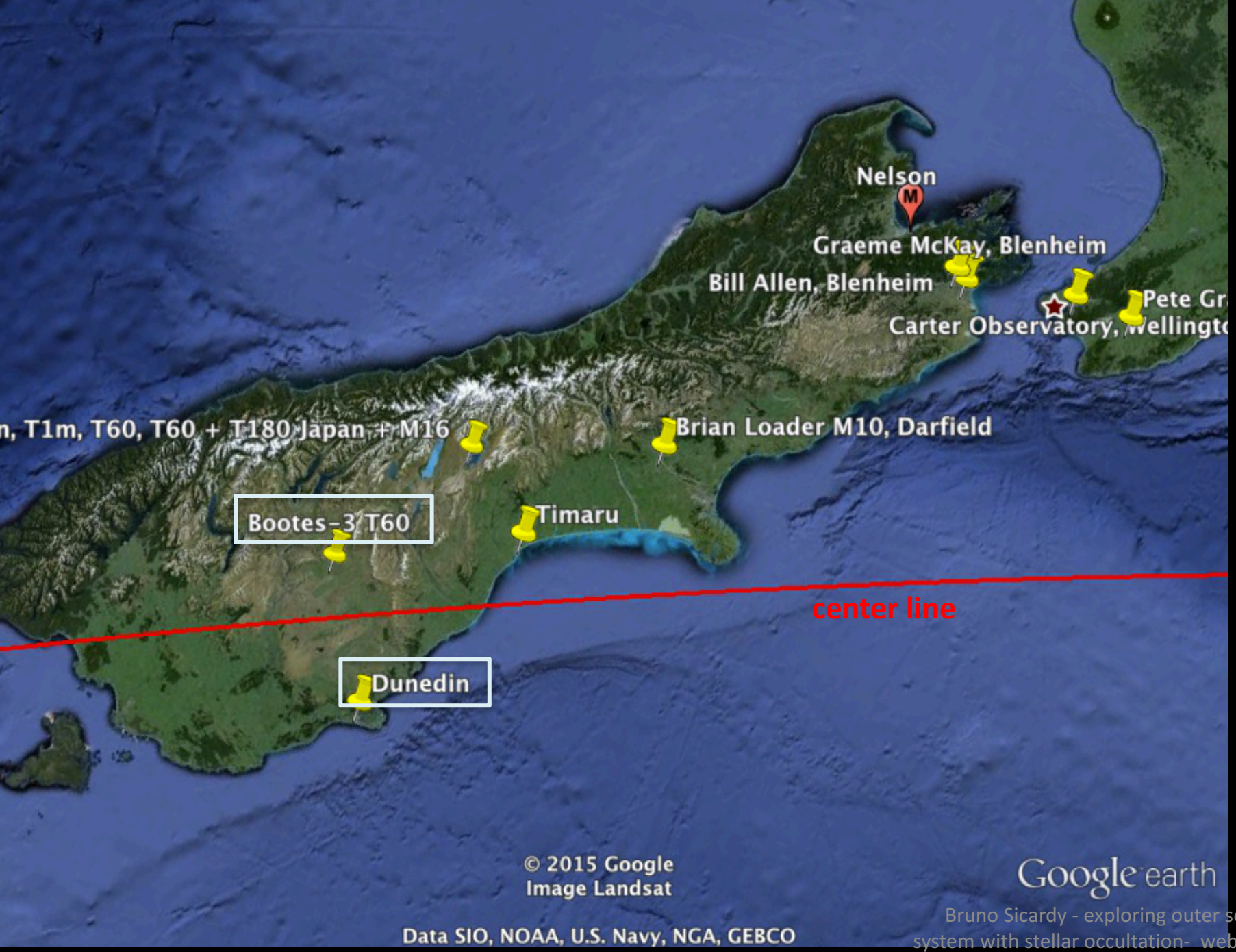
Gaia allows to make “meteorology“ of Pluto’s atmosphere

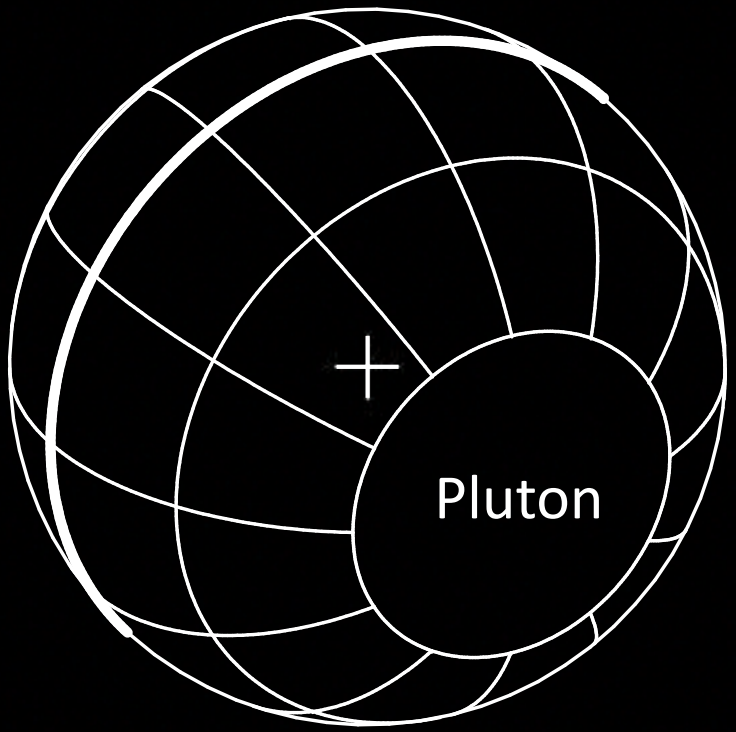


central flashes


Limit of atmosphere
Solid body radius
center line
Pluto 29 June 2015 occultation
Solid body radius
© 2015 Google
US Dept of State Geographer
Image U.S. Geological Survey
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

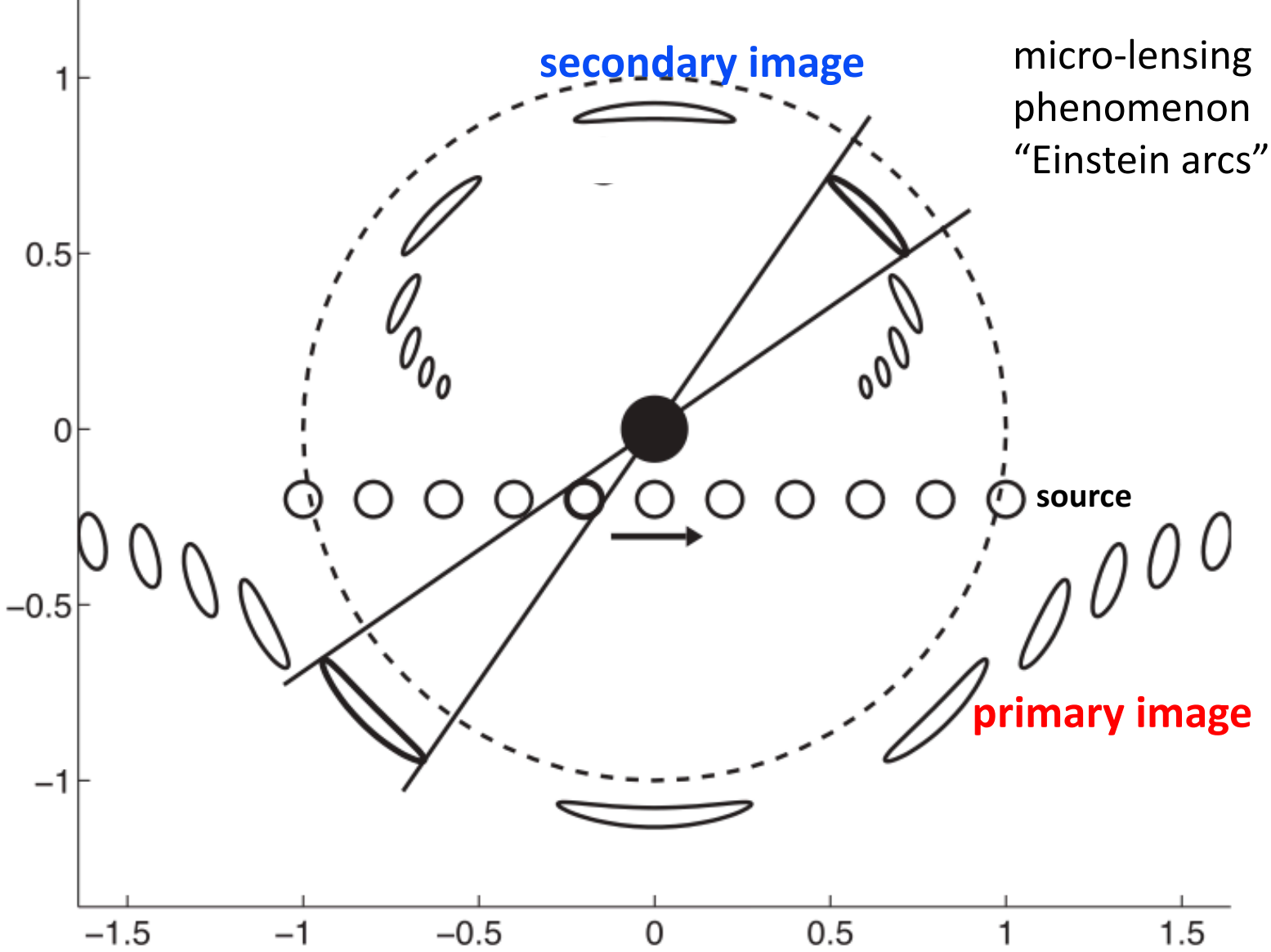

flight of the NASA plane SOFIA to catch Pluto central flash on June 29, 2015 (MIT team)
NZCH / CHC
flight path adjusted in “real time“ from astrometric updates
tweaking to get into central line at the right time
500 km
500 mi
© 2015 FlightAware
Conditions météorologiques: 29-06-2015 16h20

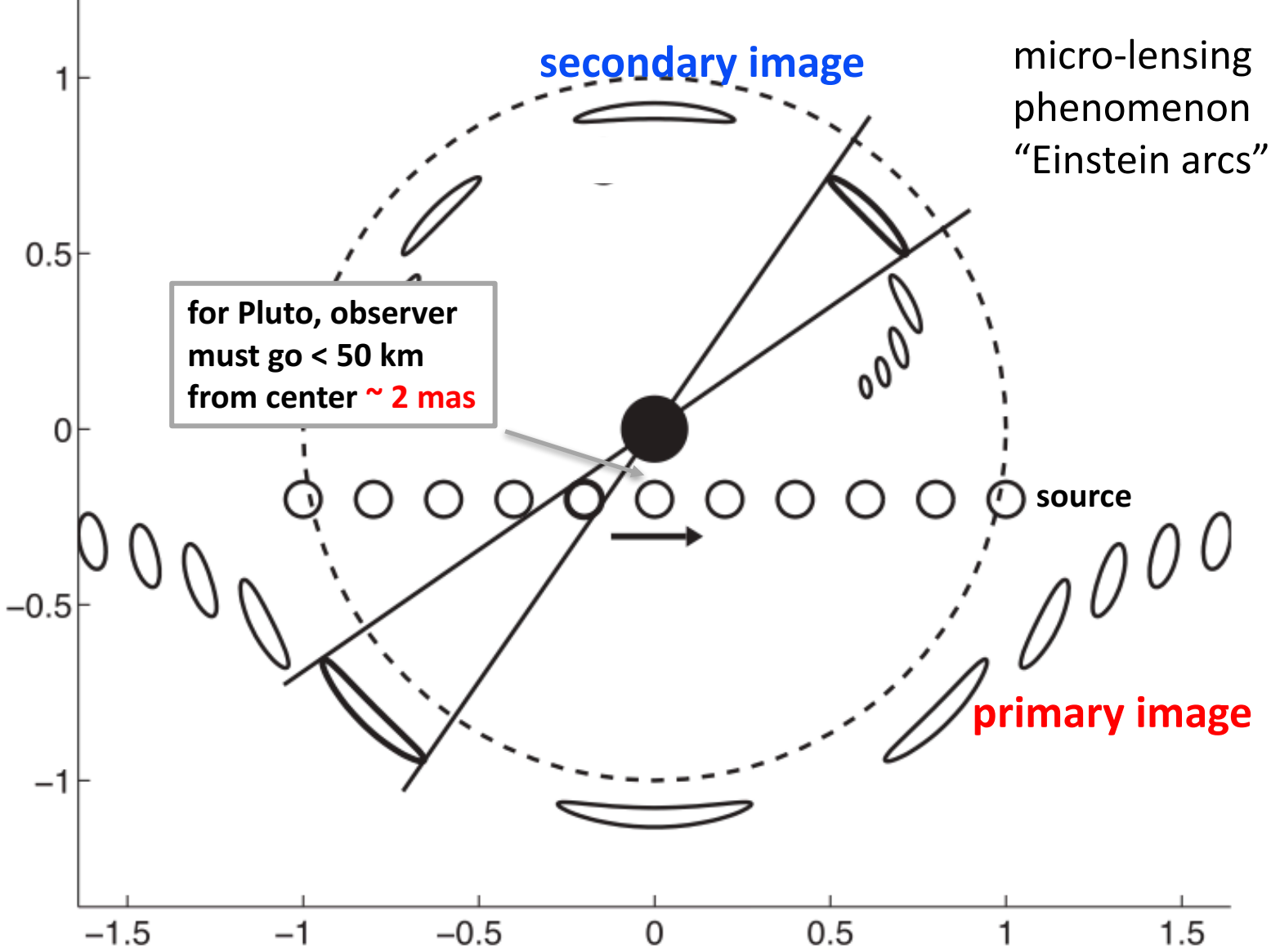

Nelson
Graeme McKay, Blenheim
Bill Allen, Blenheim
Carter Observatory,
n, T1m, T60, T60 + T180 Japan + M16
Brian Loader M10, Darfield
Bootes-3 T60
Timaru
center line
Dunedin
© 2015 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth



secondary image

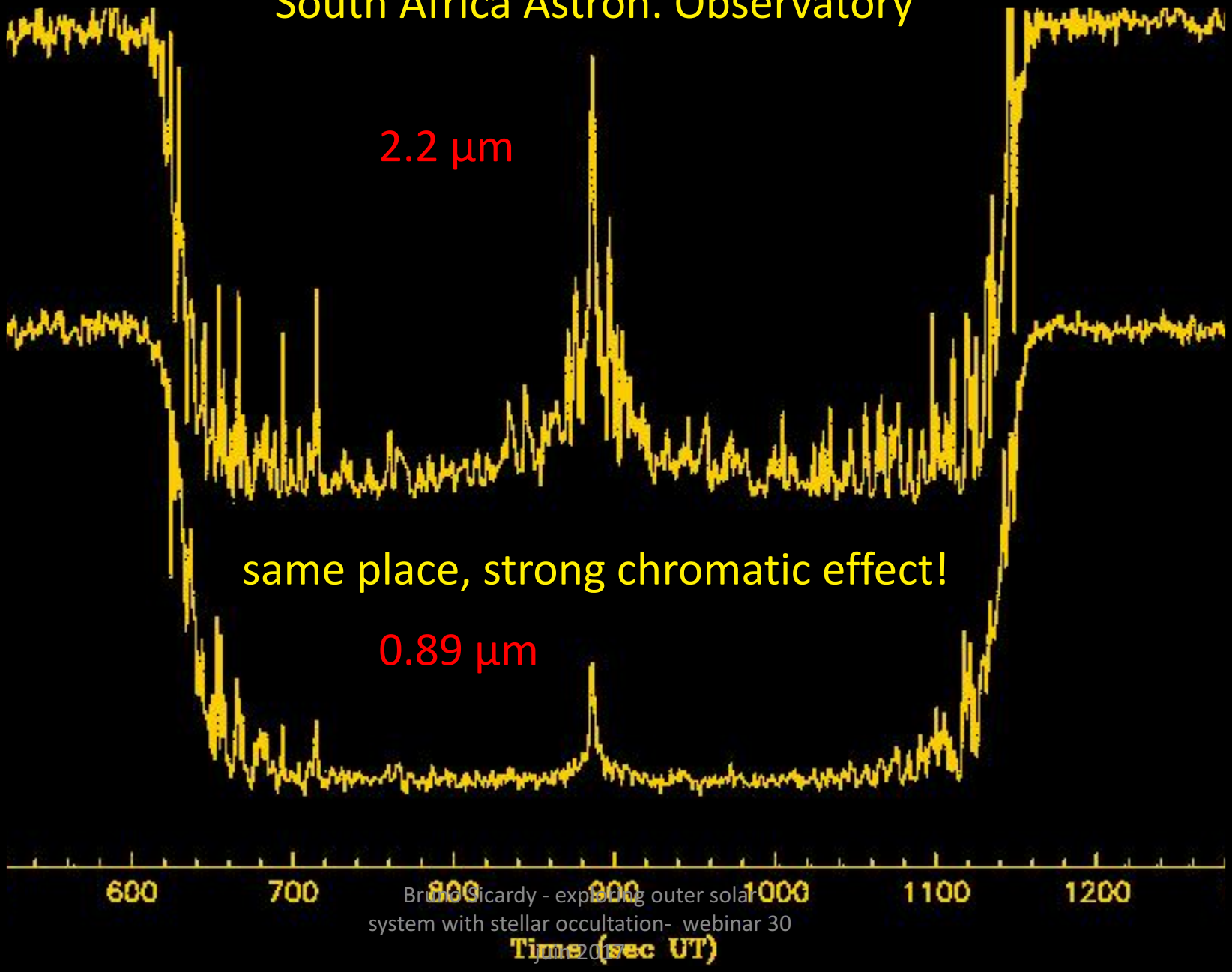
primary image
greatly enhanced


secondary image
micro-lensing
phenomenon
“Einstein arcs”
source
primary image
1
0.5
0
−0.5
−1
−1.5
−1
−0.5
0
0.5
1
1.5

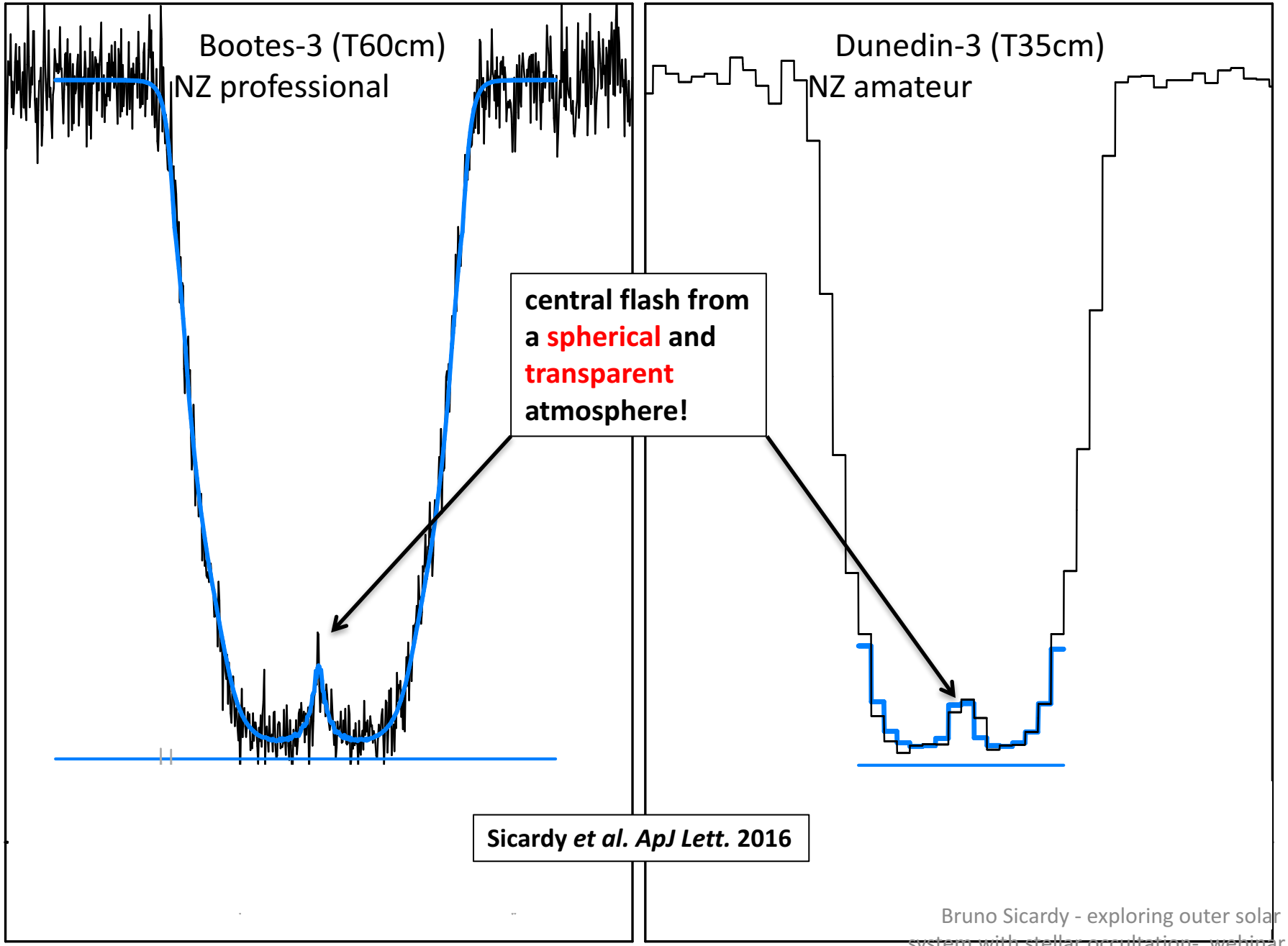

secondary image
micro-lensing phenomenon "Einstein arcs"
for Pluto, observer must go < 50 km from center ~ 2 mas
source
primary image
1
0.5
0
−0.5
−1
−1.5
−1
−0.5
0
0.5
1
1.5

Titan occultation
Namibia
November 2003

Titan stellar occultation of 14 Nov. 2003
South Africa Astron. Observatory



Pluto 29 June 2015 stellar occultation

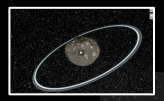


discovery of rings

… first rings ever discovered around a body other than a giant planet

Jupiter
1979

Saturn
1610



Chariklo
occultation 2013
(not on scale!)

Uranus
occultation
1977

Neptune
occultation
1984

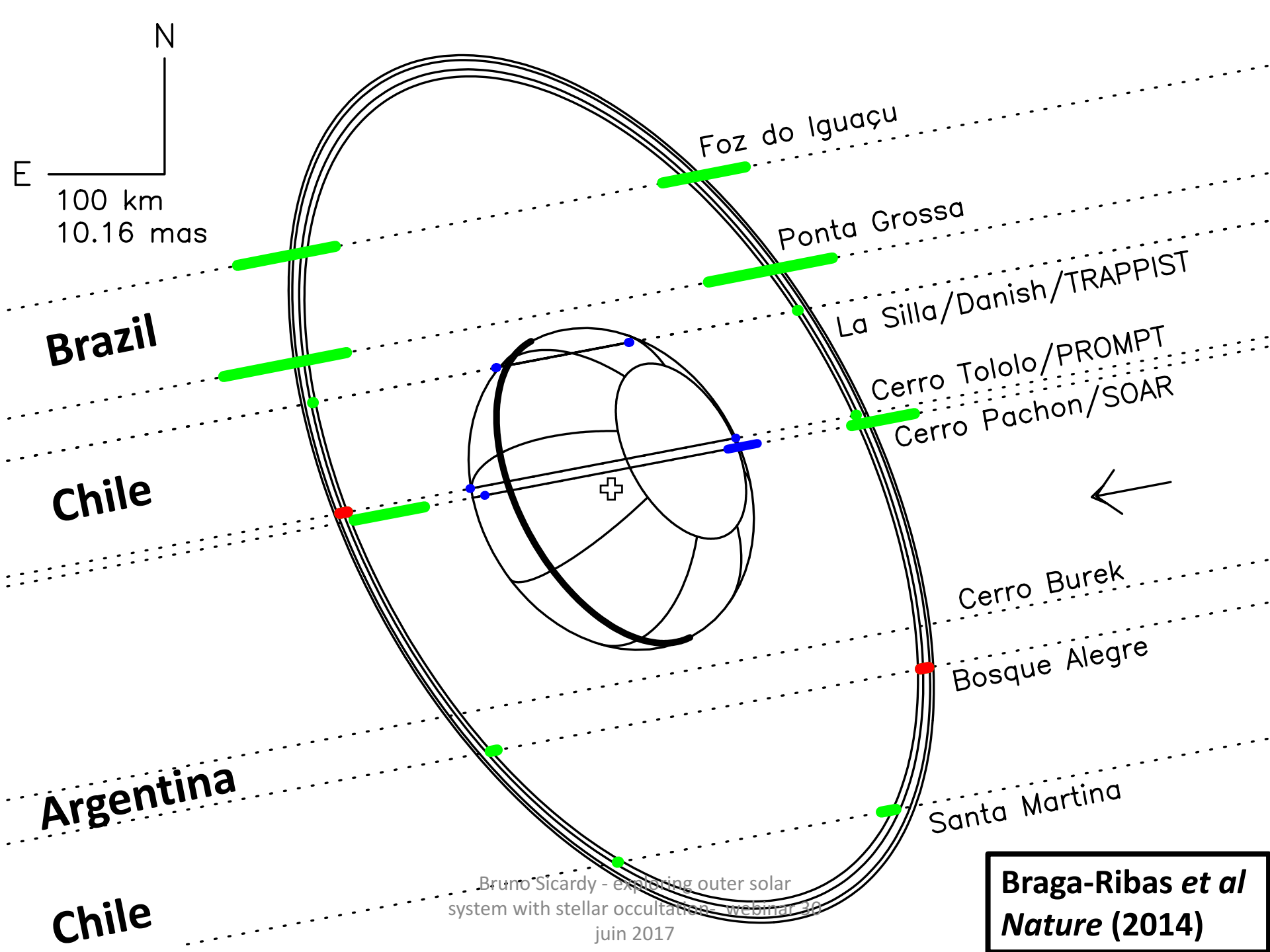
Nature, 3 April 2014 issue

LETTER

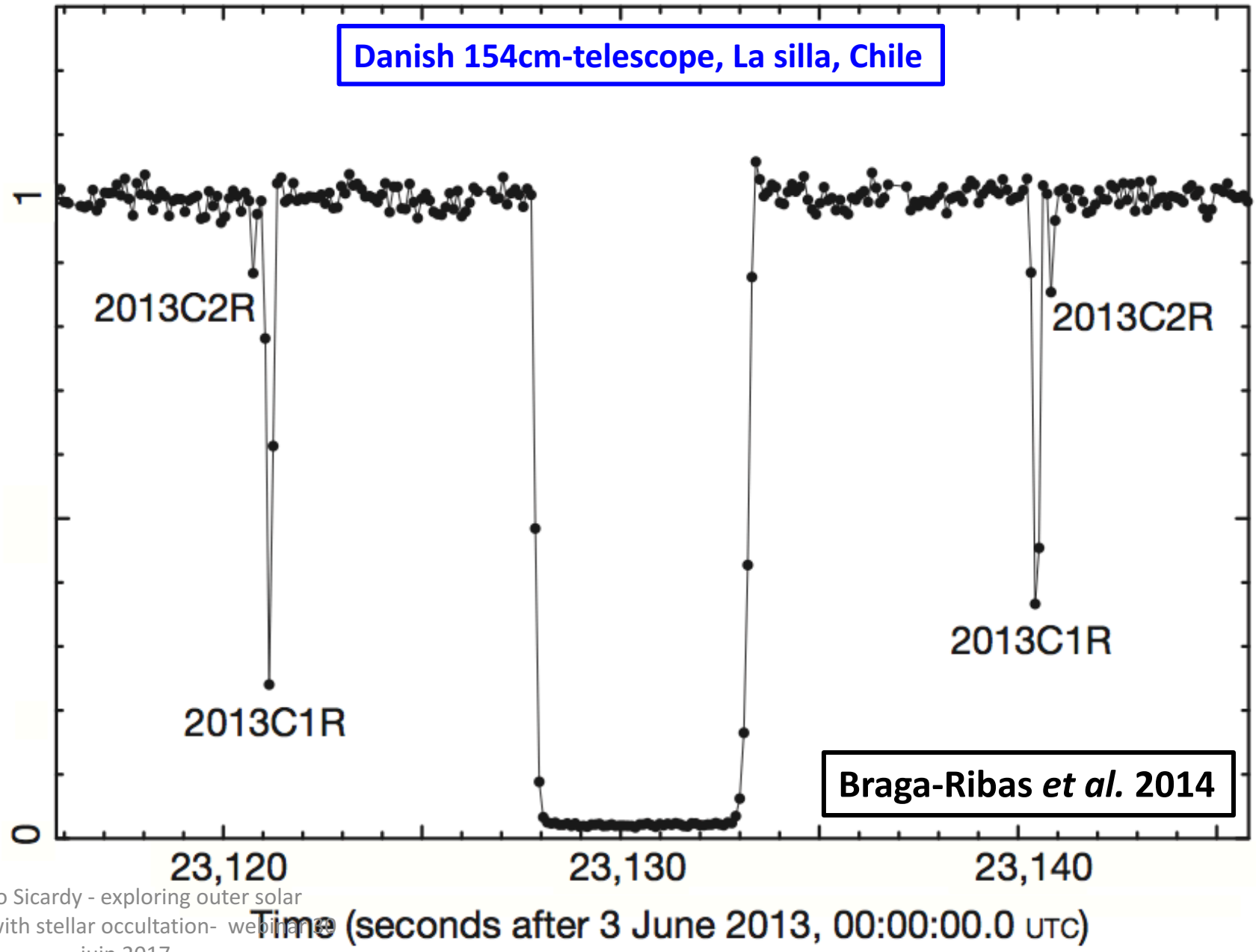
doi:10.1038/nature13155

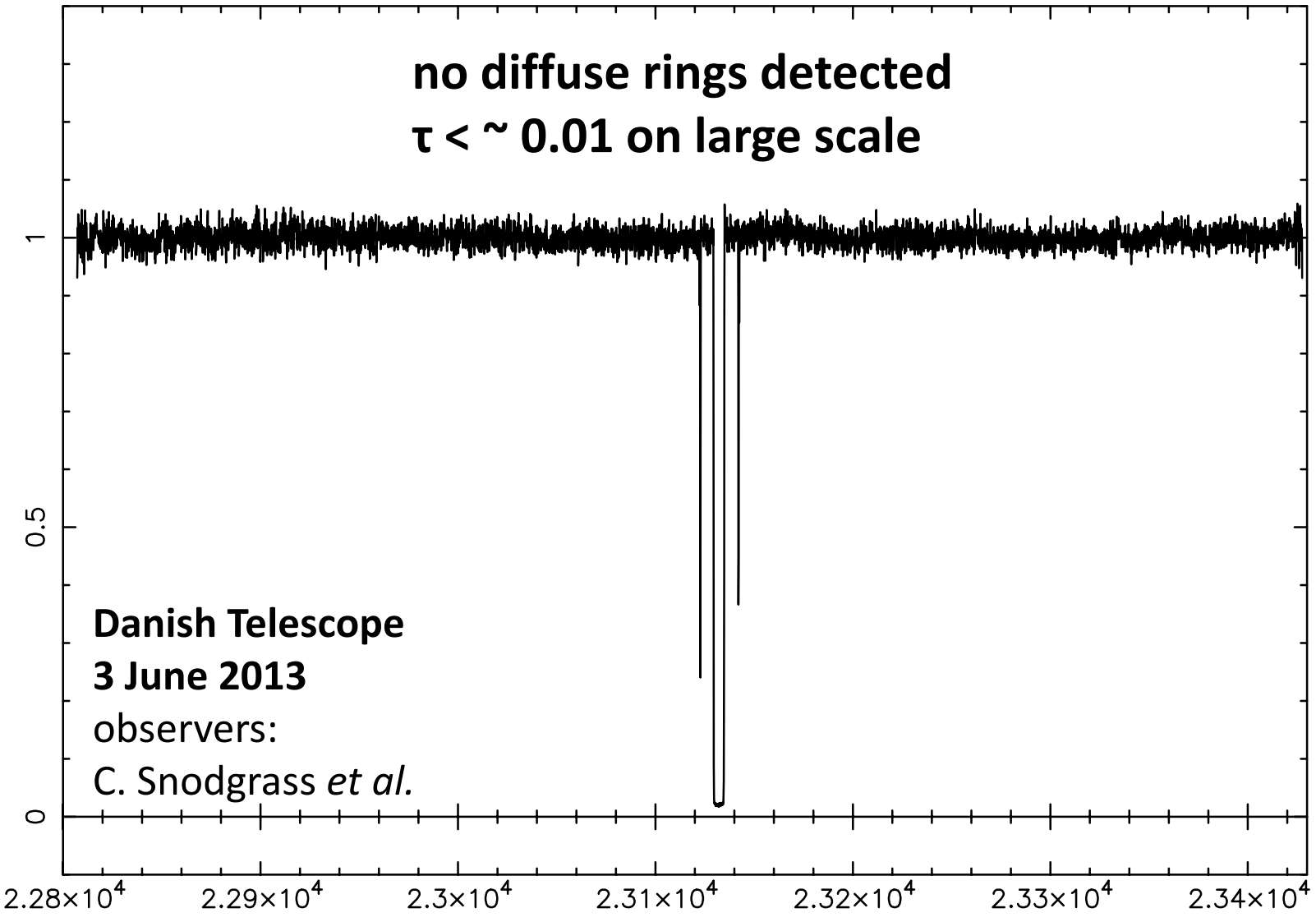
A ring system detected around the Centaur (10199) Chariklo on June 3, 2013

F. Braga-Ribas[1], B. Sicardy[2], J. L. Ortiz[3], C. Snodgrass[4], F. Roques[2], R. Vieira-Martins[1,5,6], J. I. B. Camargo[1], M. Assafin[5], R. Duffard[3], E. Jehin[7], J. Pollock[8], R. Leiva[9], M. Emilio[10], D. I. Machado[11,12], C. Colazo[13,14], E. Lellouch[2], J. Skottfelt[15,16], M. Gillon[7], N. Ligier[2], L. Maquet[2], G. Benedetti-Rossi[1], A. Ramos Gomes Jr[5], P. Kervella[2], H. Monteiro[17], R. Sfair[18], M. El Moutamid[2,6], G. Tancredi[19,20], J. Spagnotto[21], A. Maury[22], N. Morales[3], R. Gil-Hutton[23], S. Roland[19], A. Ceretta[20,24], S.-h. Gu[25,26], X.-b. Wang[25,26], K. Harpsøe[15,16], M. Rabus[9,27], J. Manfroid[7], C. Opitom[7], L. Vanzi[28], L. Mehret[10], L. Lorenzini[11], E. M. Schneiter[14,29,30,31], R. Melia[14], J. Lecacheux[2], F. Colas[6], F. Vachier[6], T. Widemann[2], L. Almenares[19,20], R. G. Sandness[22], F. Char[32], V. Perez[19,20], P. Lemos[20], N. Martinez[19,20], U. G. Jørgensen[15,16], M. Dominik[33], F. Roig[1], D. E. Reichart[34], A. P. LaCluyze[34], J. B. Haislip[34], K. M. Ivarsen[34], J. P. Moore[34], N. R. Frank[34] & D. G. Lambas[14,30]


N
E
100 km
10.16 mas
Foz do Iguaçu
Ponta Grossa
La Silla/Danish/TRAPPIST
Cerro Tololo/PROMPT
Cerro Pachon/SOAR
Cerro Burek
Bosque Alegre
Santa Martina
Brazil
Chile
Argentina
Chile
Braga-Ribas *et al* *Nature* (2014)

20 seconds that changed our conception of rings…

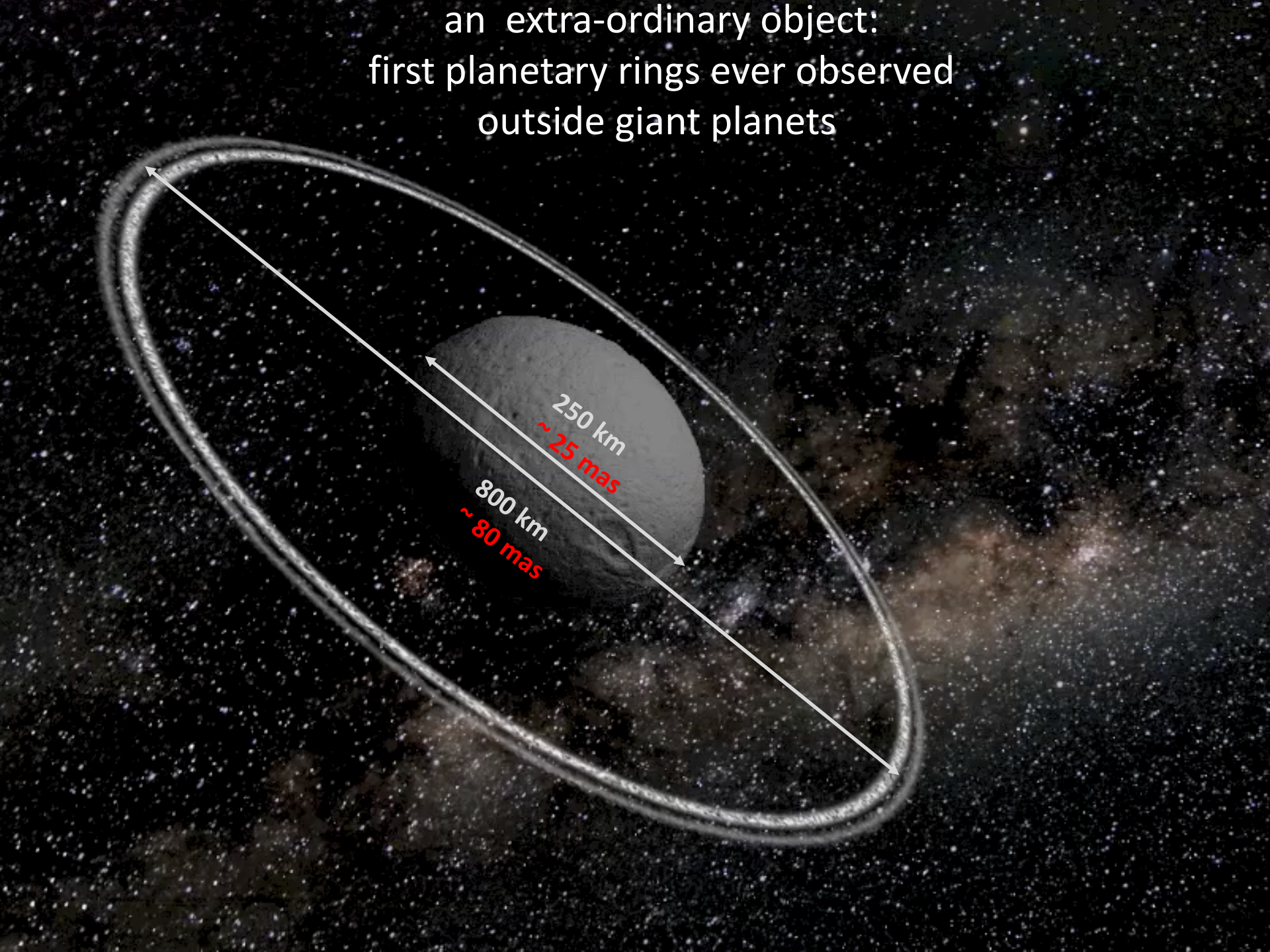



no diffuse rings detected
τ < ~ 0.01 on large scale
Danish Telescope
3 June 2013
observers:
C. Snodgrass *et al.*
1
0.5
0
2.28×10^4
2.29×10^4
2.3×10^4
2.31×10^4
2.32×10^4
2.33×10^4
2.34×10^4
UT (sec)

an extra-ordinary object:
first planetary rings ever observed
outside giant planets

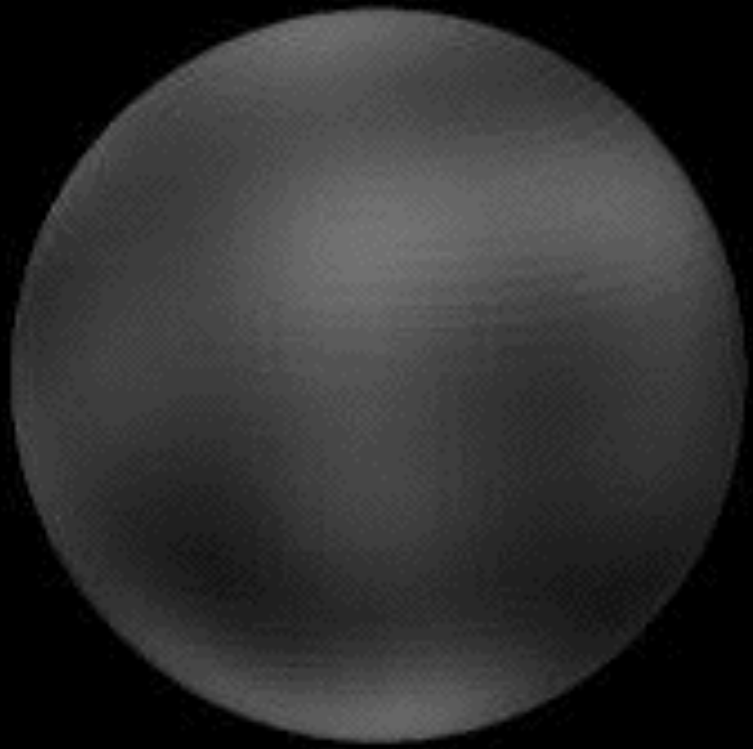
an artist view… credit ESO

an extra-ordinary object:
first planetary rings ever observed
outside giant planets



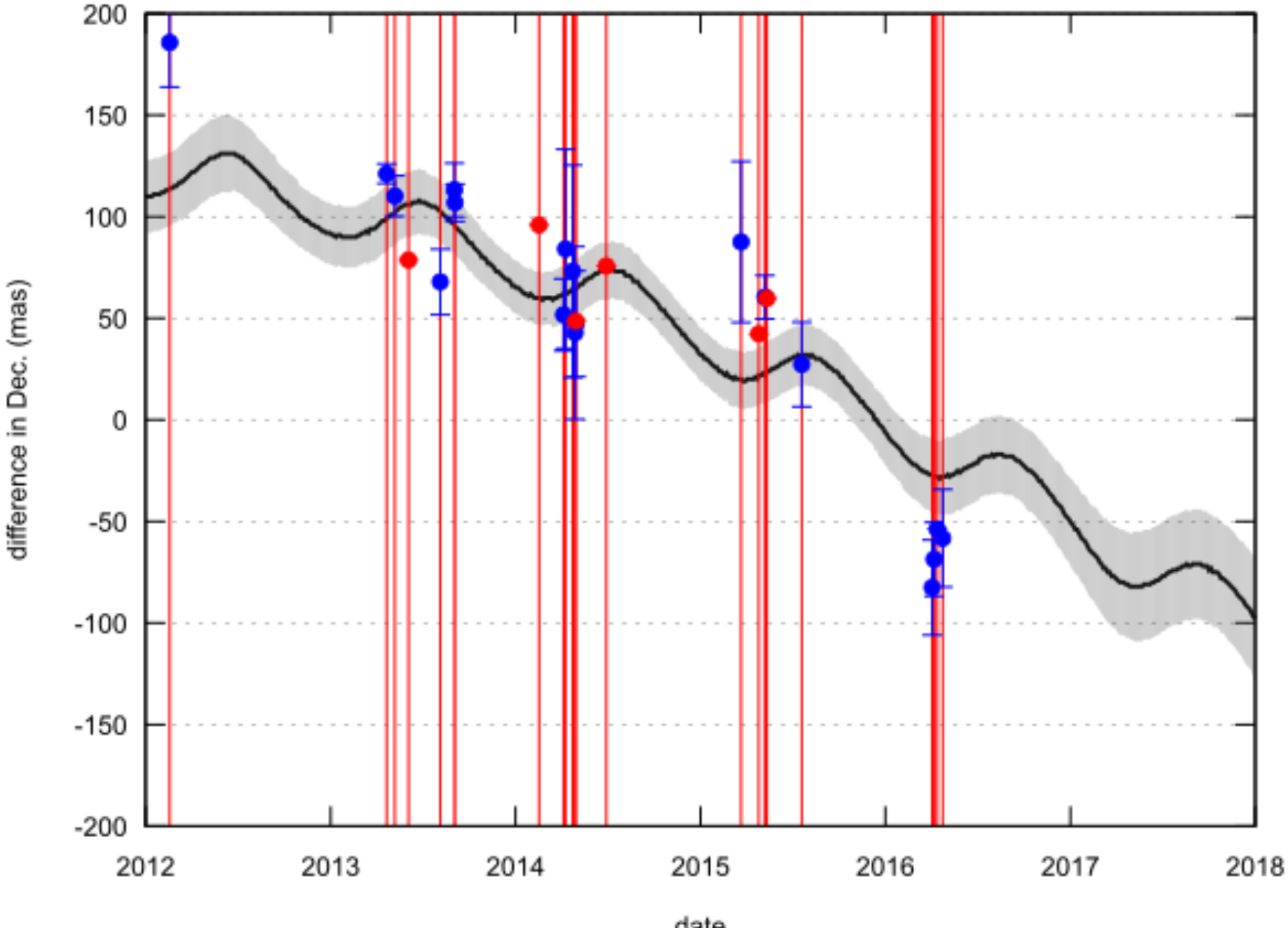
a montage comparing Chariklo and Pluto

Chariklo

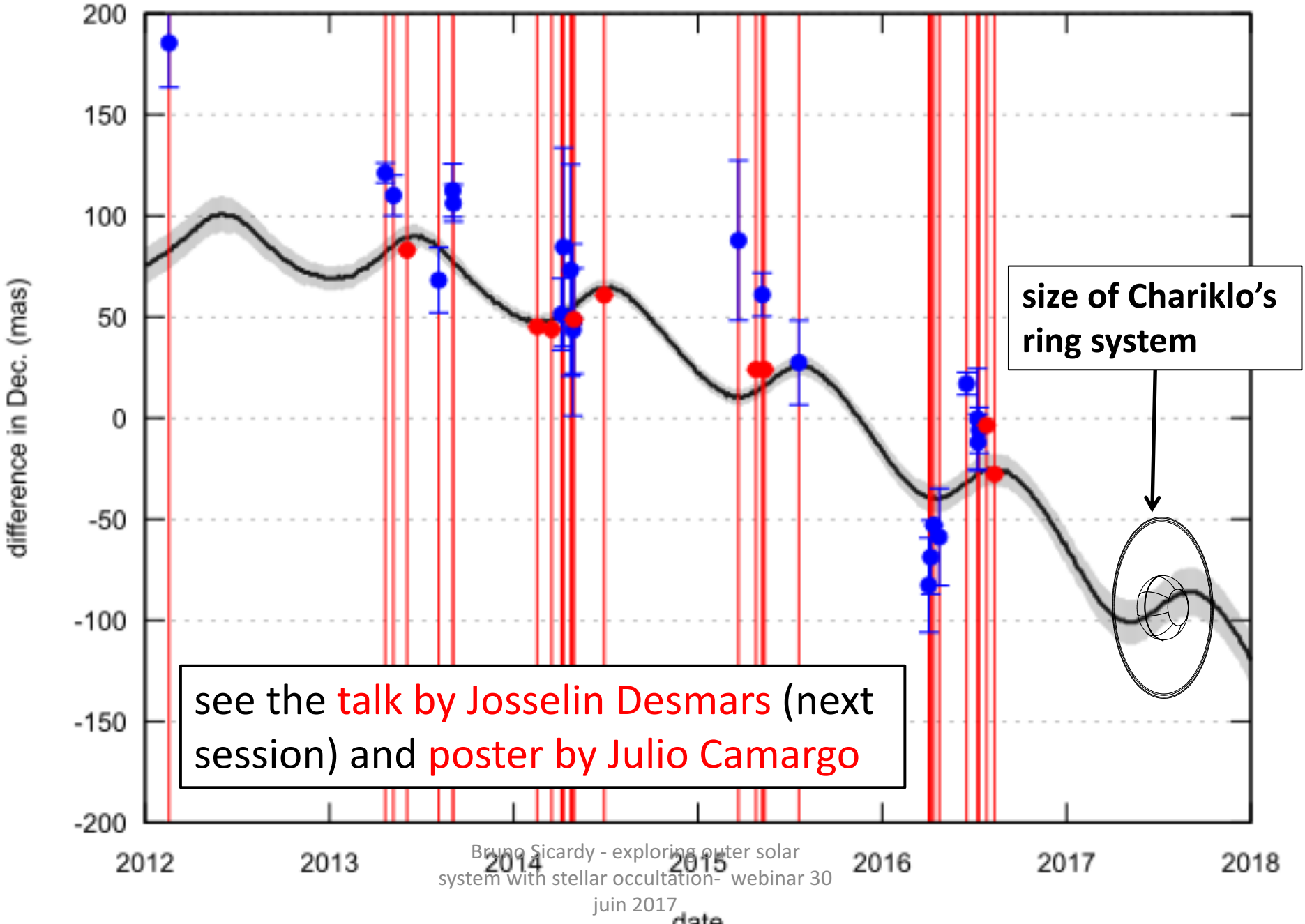


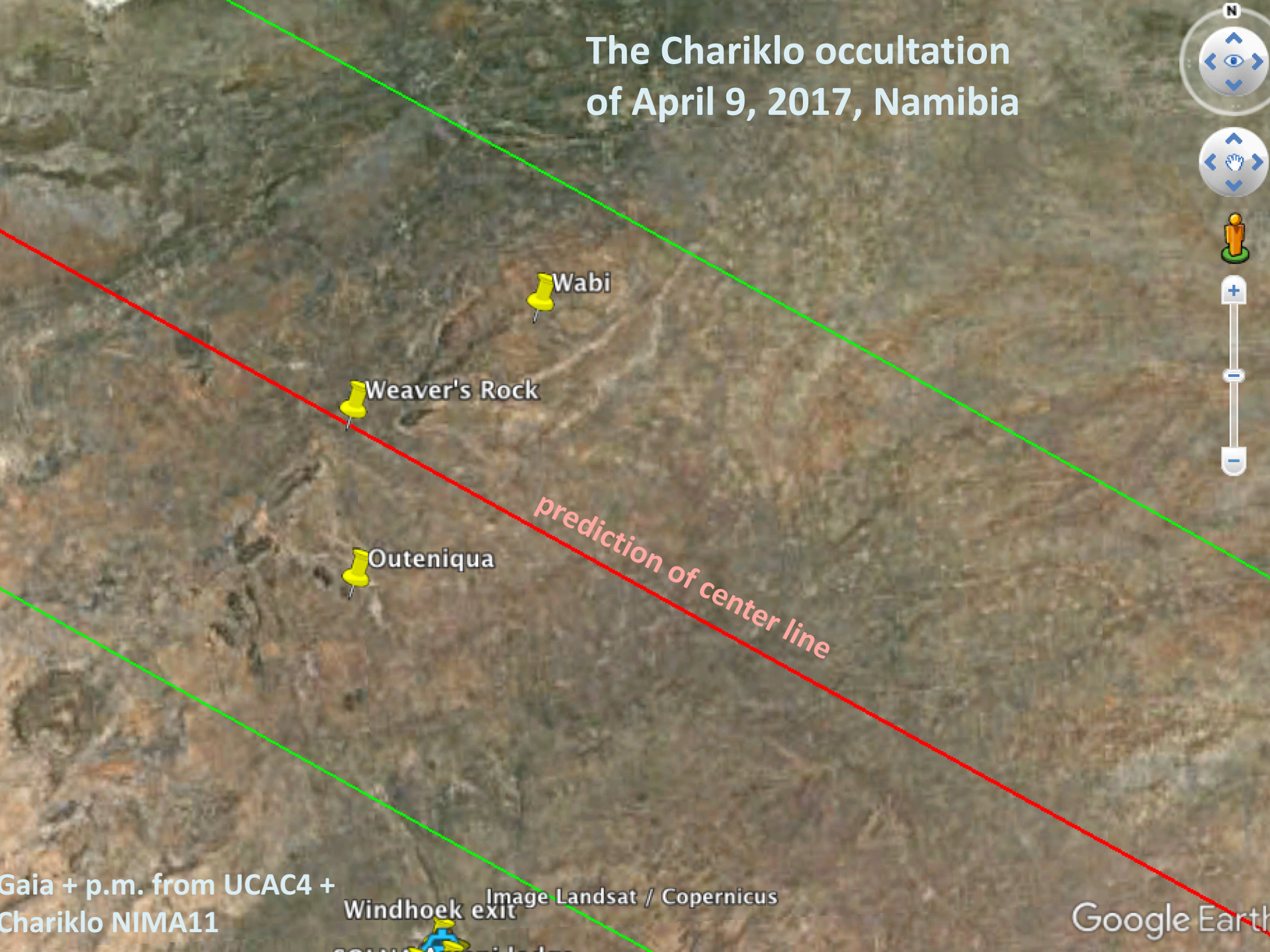
Pluto

Chariklo's ephemeris, pre-GAIA



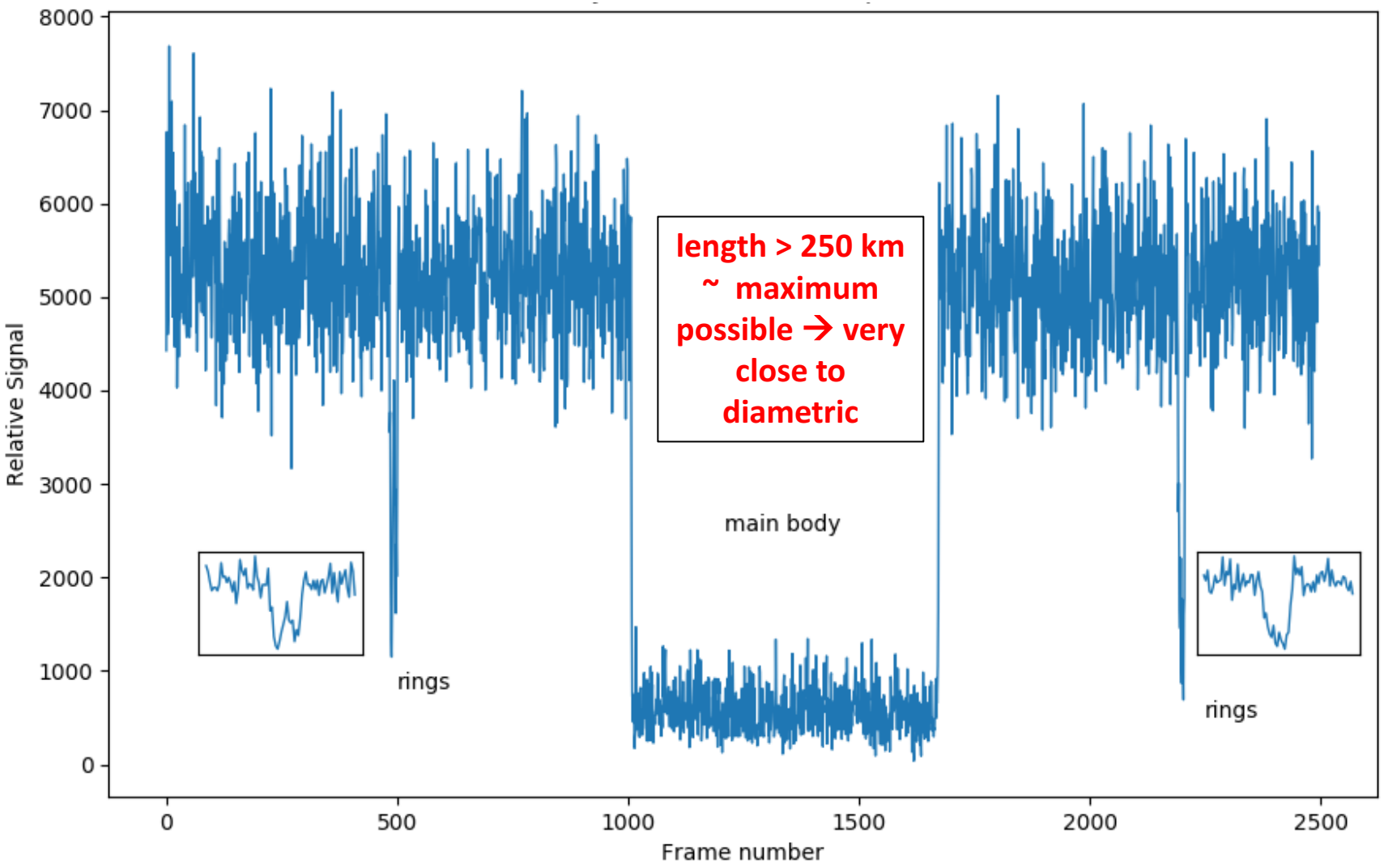
Chariklo's ephemeris, a bootstrapping approach using GAIA

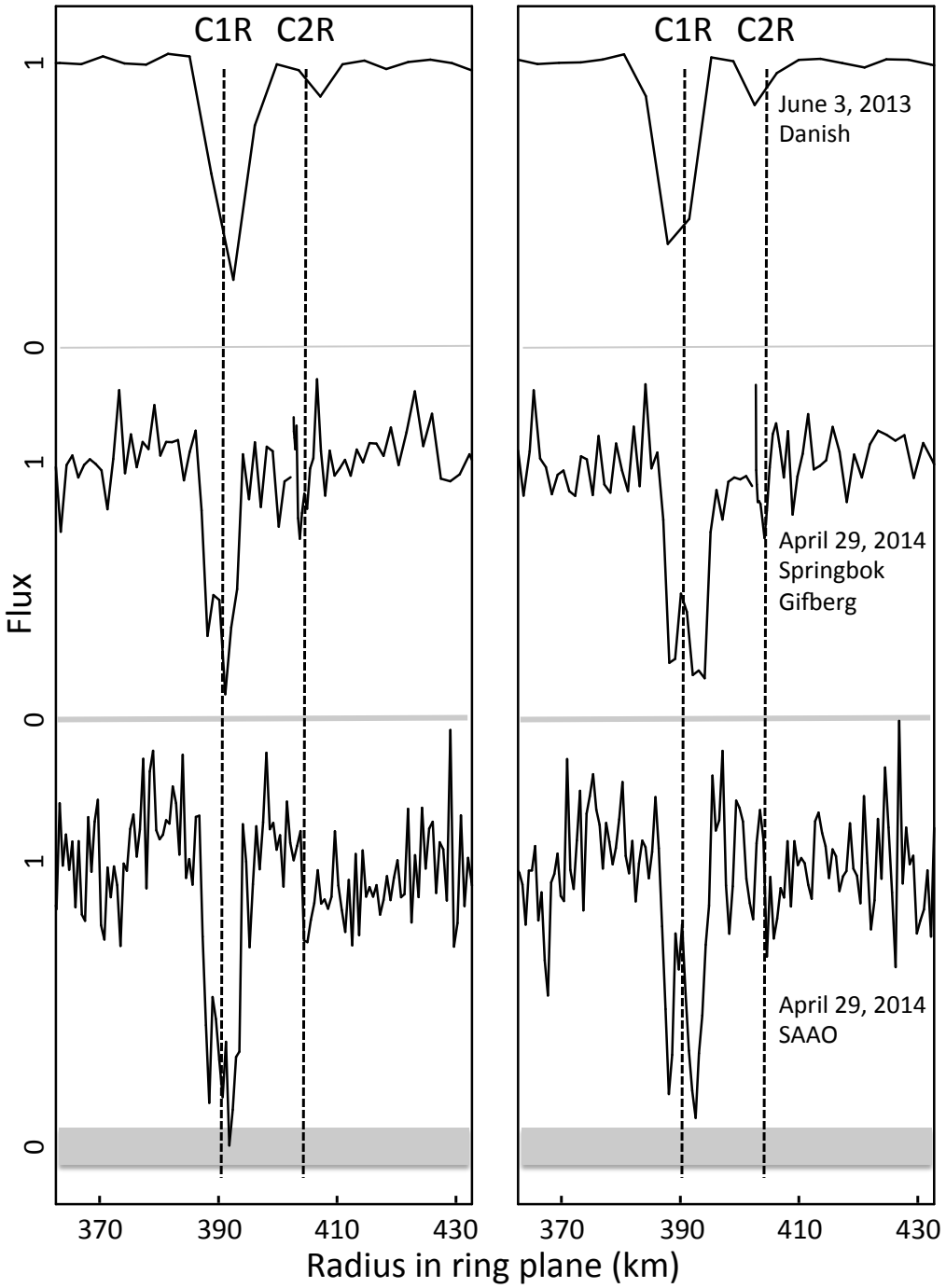



The Chariklo occultation
of April 9, 2017, Namibia
Wabi
Weaver's Rock
Outeniqua
prediction of center line
Gaia + p.m. from UCAC4 +
Chariklo NIMA11
Windhoek exit
Image Landsat / Copernicus
Google Earth

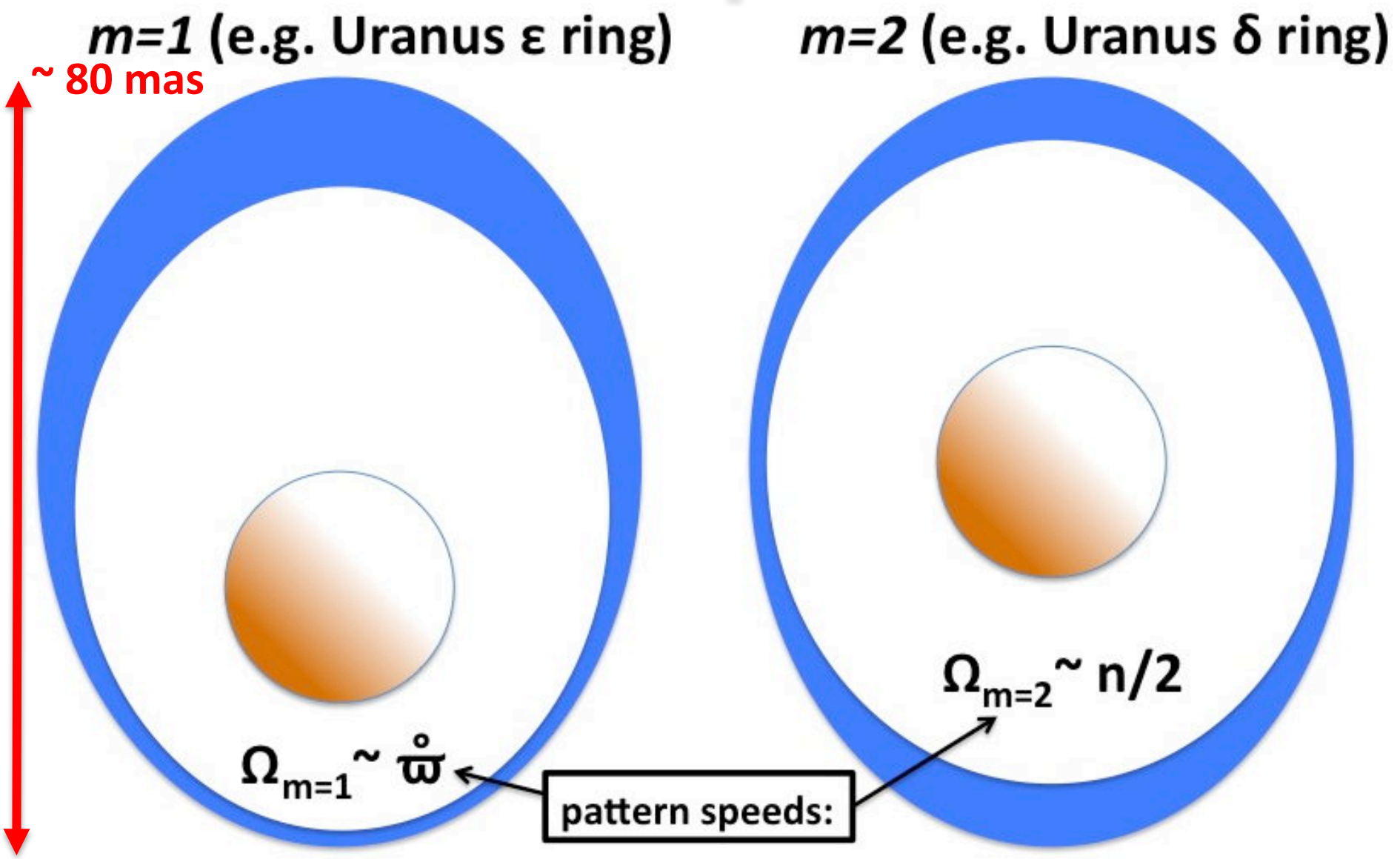

Mike Kretlo
the Chariklo
of April 9 ,20
Weavers Ro
« m2 » 50-c
© jean-Luc

The occultation by Chariklon, Namibia April 9, 2017

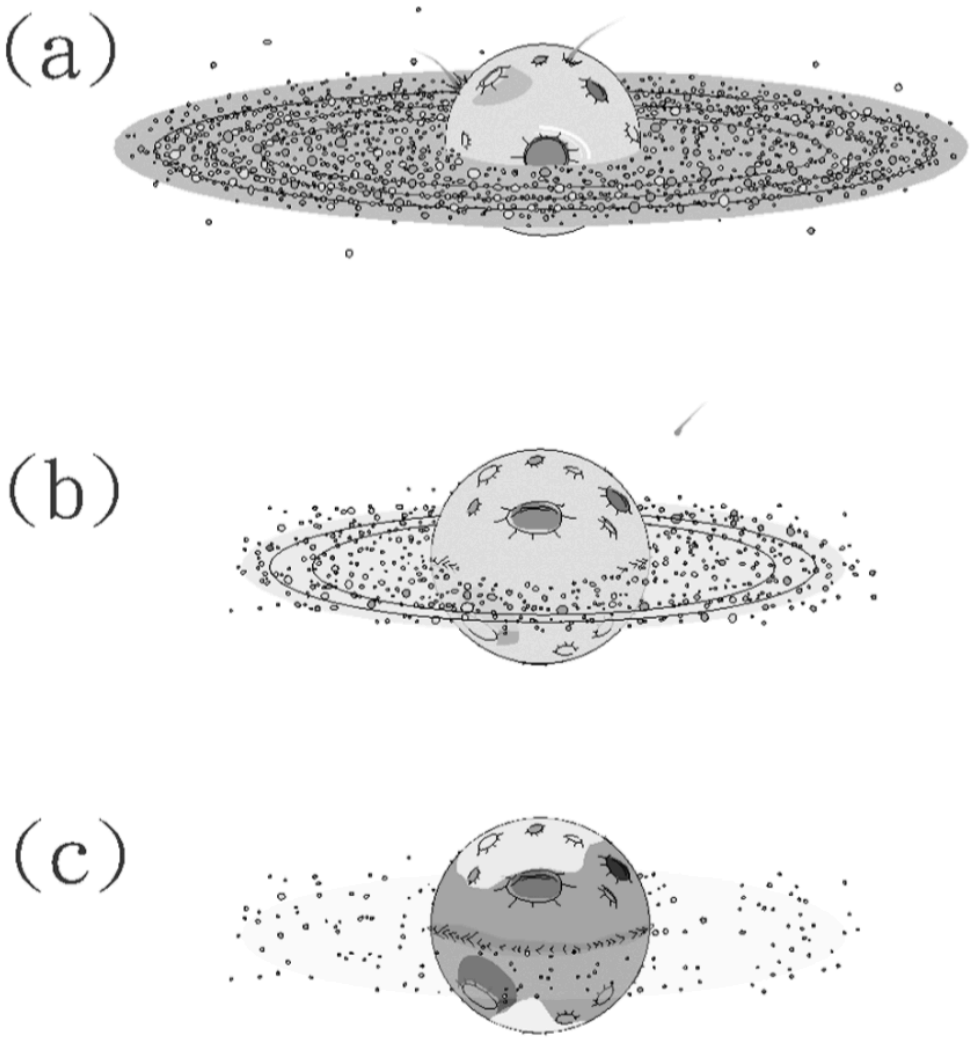




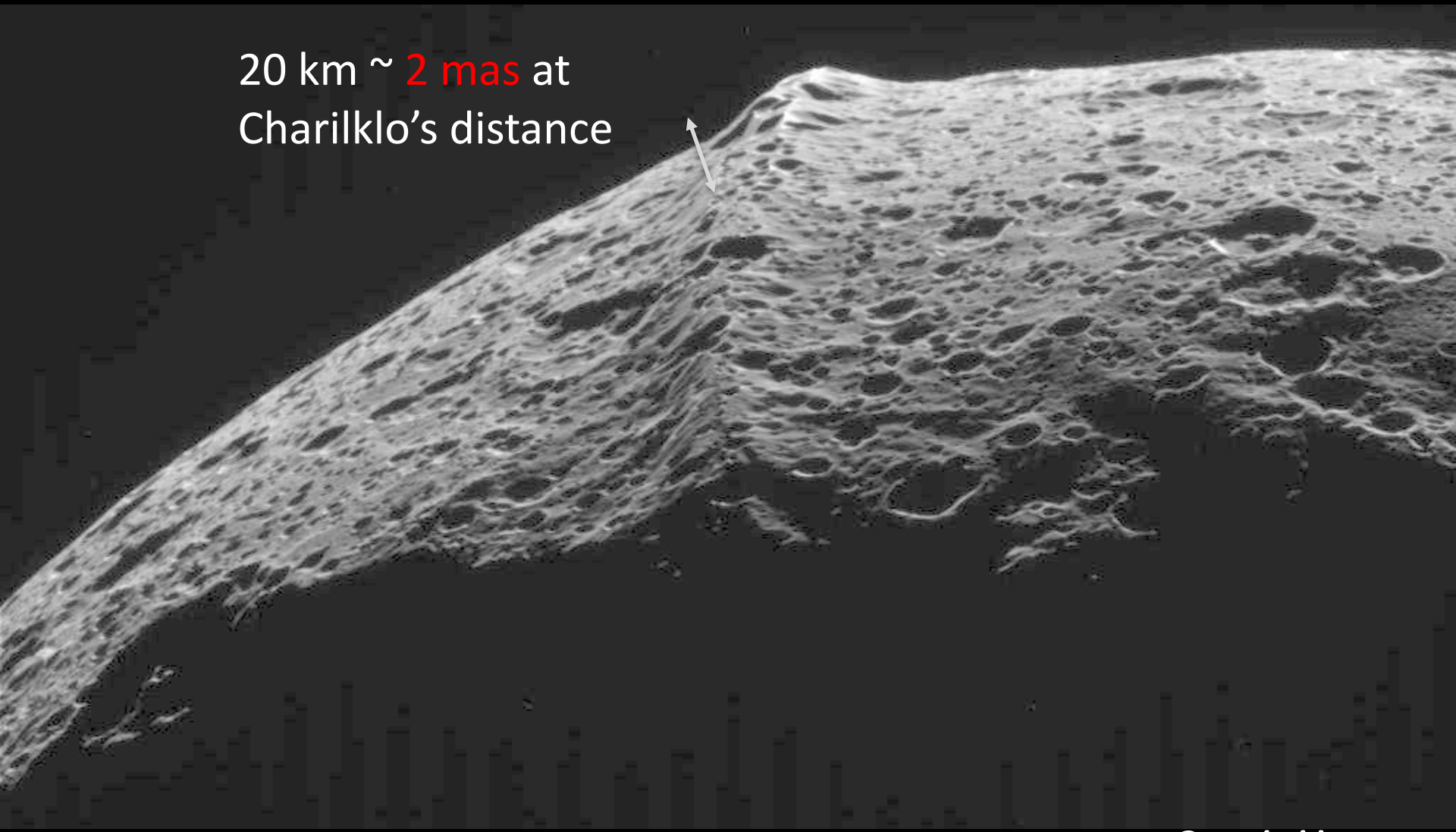
Sicardy et al. 2017


m=1 (e.g. Uranus ε ring)
m=2 (e.g. Uranus δ ring)
~ 80 mas
Ωm=1 ~ ϖ̊
Ωm=2 ~ n/2
pattern speeds:

Formation of rings around Saturn's moon Iapetus
W.-H. Ip, *Geophys. Res. Letters* (2006)

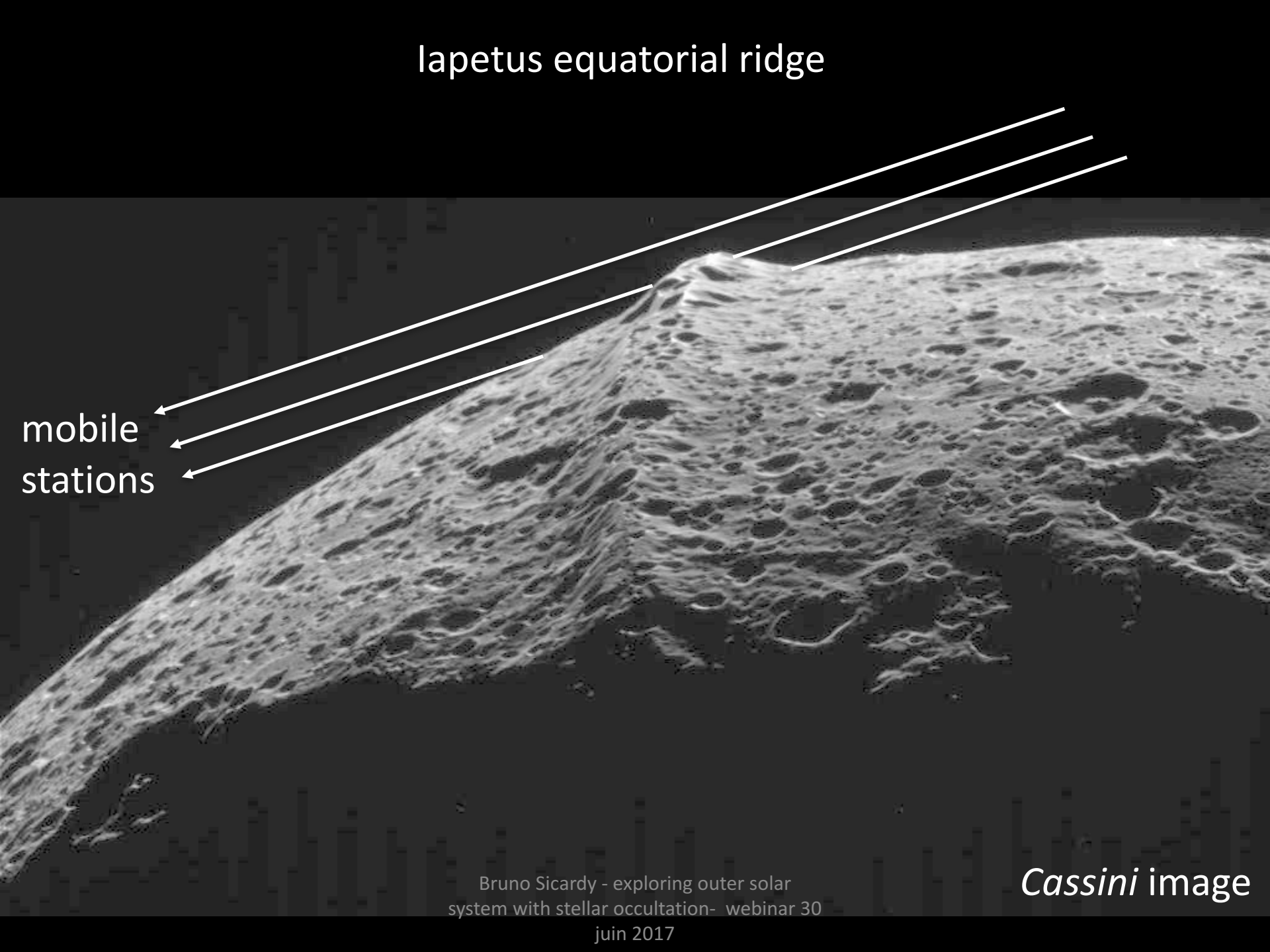


Iapetus equatorial ridge



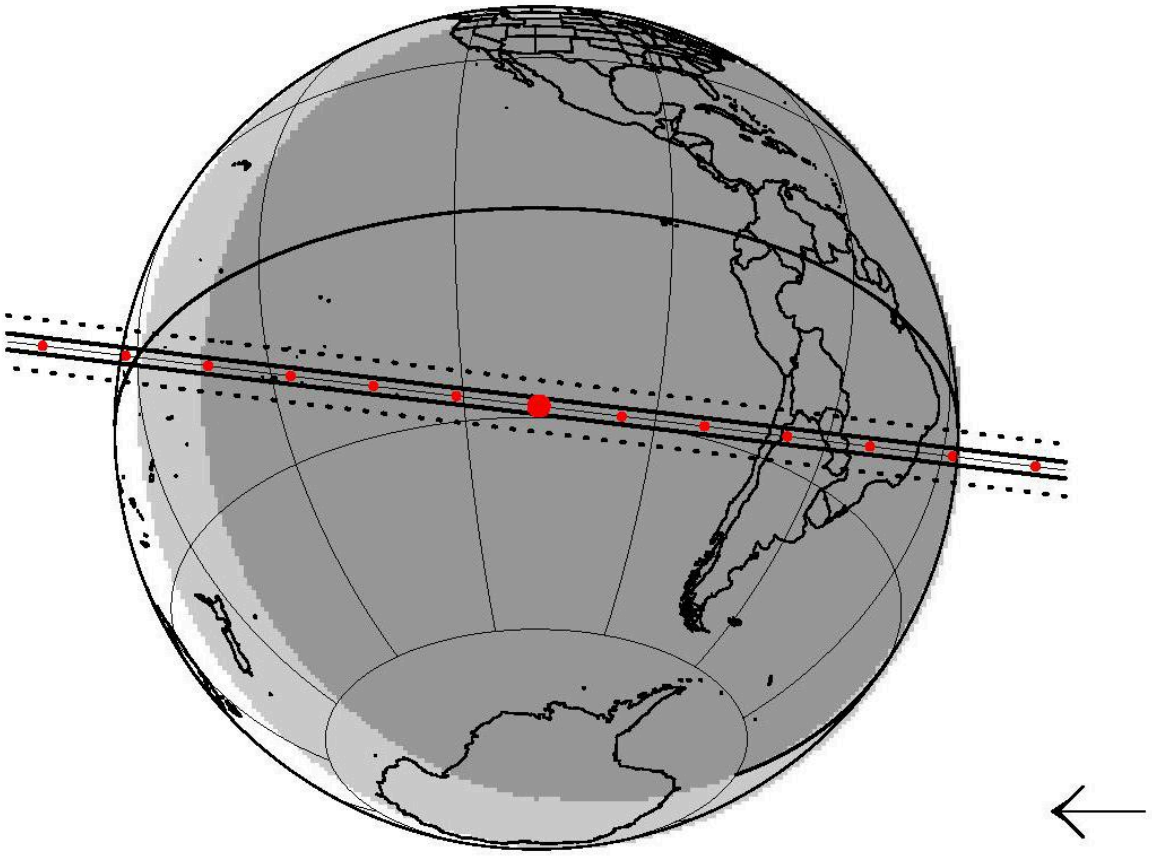
Cassini image

Iapetus equatorial ridge



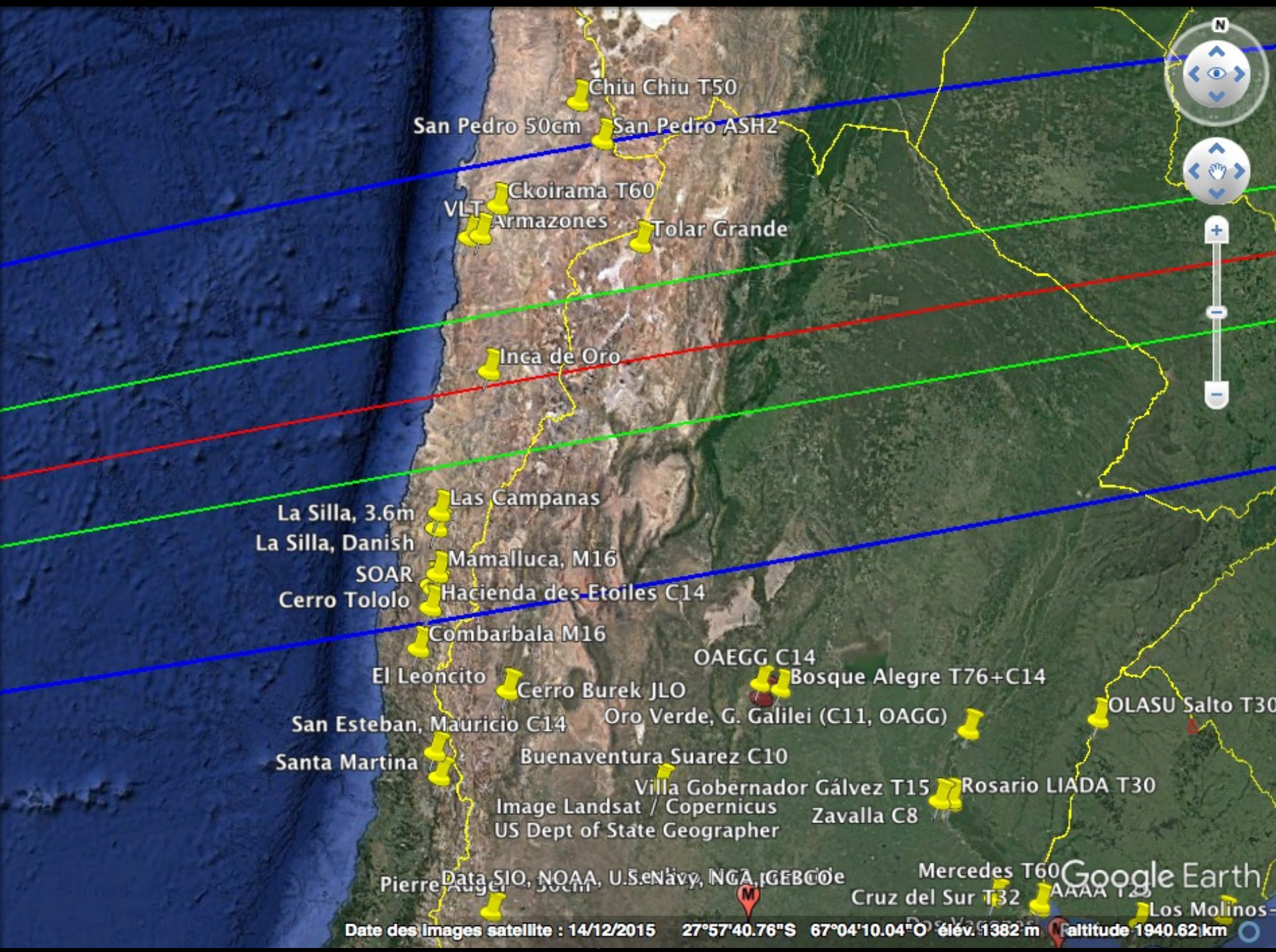
Cassini image

Chariklo+rings occultation, July 23 2017
improved NIMA 11 ephem. + pre-release
of DR2 Gaia star position

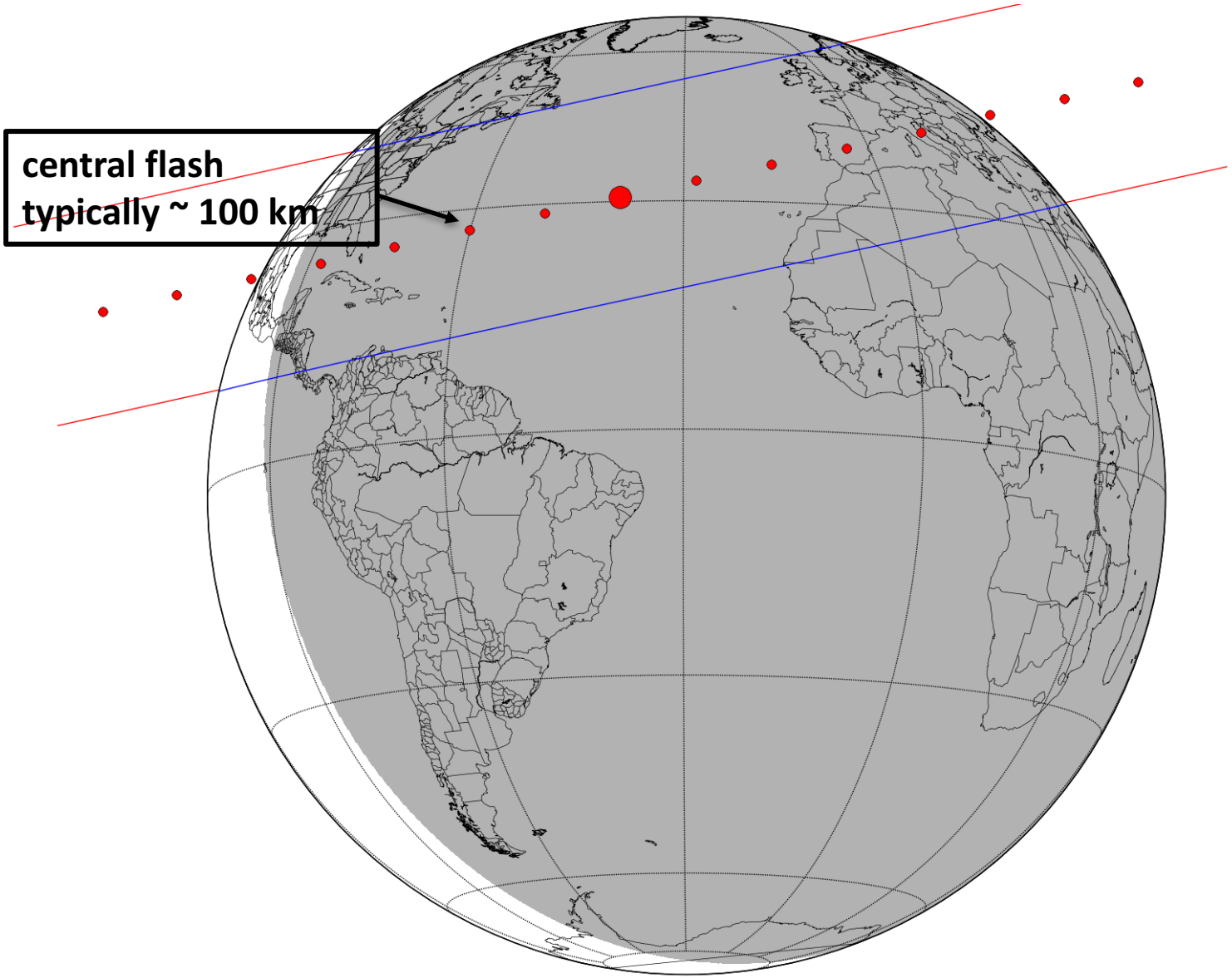


by: LuckyStar

d	m	year	h:m:s UT	ra___dec___J2000_candidate	C/A	P/A	vel	Delta	G*	J*	long
23	07	2017	05 58 52.	18 48 09.2214 −31 26 32.460	0.031	6.94	−21.01	14.72	14.0	12.4	−109.


Chiu Chiu T50
San Pedro 50cm
San Pedro ASH2
Ckoirama T60
VLT
Armazones
Tolar Grande
Inca de Oro
Las Campanas
La Silla, 3.6m
La Silla, Danish
Mamalluca, M16
SOAR
Hacienda des Etoiles C14
Cerro Tololo
Combarbala M16
OAEGG C14
El Leoncito
Cerro Burek JLO
Bosque Alegre T76+C14
OLASU Salto T30
Oro Verde, G. Galilei (C11, OAGG)
San Esteban, Mauricio C14
Santa Martina
Buenaventura Suarez C10
Villa Gobernador Gálvez T15
Rosario LIADA T30
Zavalla C8
Image Landsat / Copernicus
US Dept of State Geographer
Data SIO, NOAA, U.S.Navy, NGA, GEBCO
Mercedes T60
Cruz del Sur T32
Los Molinos
Google Earth
Date des images satellite : 14/12/2015
27°57'40.76"S 67°04'10.04"O élev. 1382 m altitude 1940.62 km

the Triton occultation of October 5, 2017



http://lesia.obspm.fr/lucky-star/predictions/

thank you!

http://lesia.obspm.fr/lucky-star/predictions/

Predictions of stellar occultations by TNOs and Centaurs in 2017

ERC Project Lucky Star

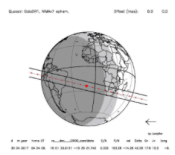
Predictions for 2018 →

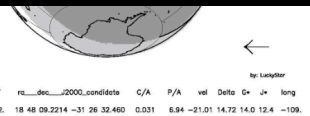
This page presents the prediction of occultations by selected TNOs and Centaurs for 2017. These predictions are made in the framework of Lucky Star project (led by B. Sicardy) and in collaboration with groups from Paris, Meudon, Granada and Rio. Information about the predictions can be found in Assafin et al. (2010) for Pluto system predictions, Assafin et al. (2012) for the TNO predictions, Camargo et al. (2014) for TNO and Centaur predictions. Ephemerides of the selected objects come from Desmars et al. (2015) and they are regularly updated thanks to observations from Minor Planet Center and our own observations made at ESO, Pic du Midi, Calar Alto, Sierra Nevada and Observatorio do Pico dos Dias. Predictions make use of Gaia DR1 (Gaia Collaboration, 2016) for the positions of stars.

For three very specific occultations occurring this year, the Gaia team has provided position, proper motion and parallax for the three occulted stars with the preliminary Gaia Data Release 2. The events are for Chariklo on 22 June 2017 and 23 July 2017, and for Triton on 5 October 2017.

IMPORTANT: If you plan to observe one of these predicted events, please contact J. Desmars .

Date Filter: 2017-04-30 — 2017-09-01 | Object Selection: Choose an object | Magnitude Filter: 5.0 — 18.0

Date	Object	G Magnitude	Map
2017-Apr-30 04:04	Quaoar	17.9	



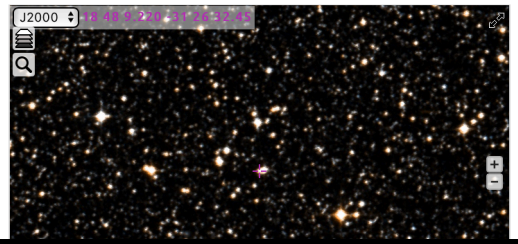
Information about the map:

- The straight and continue lines are the shadow limits considering the estimated radius;
- Each red dot is spaced by one minute, the nominal occultation time is to the big red dot (that is the geocentric closest approach);
- The arrow shows the direction of the shadow motion;
- The precision that mainly depends on the object is about 20 mas and can be down to the mas level for specific object such as Pluto or Chariklo (1 mas corresponds to 0.7 x Δ in km where Δ is the geocentric distance of the body in au);
- The star G* and J* are the G (from Gaia) and J (from 2MASS) magnitudes, *normalized to a body moving at 20km/s* in order to enhance very slow events;
- The body offset is at the upper right corner, if JPL ephemeris is used;
- Areas in dark grey correspond to full night (Sun elevation below -18 degrees) and areas in light grey correspond to twilight (Sun elevation between -18 and 0 degrees) while daytime is in white;
- Be careful, the dates are from the moment of the event in Universal Time, the night of the event may begin at the date before.

Occultation circumstances

Object	(10199) Chariklo
Size (km)	248
Date	2017-07-23 05:58:52
Star position	18 48 09.2214 -31 26 32.460
Stellar catalogue	preliminary Gaia DR2
Proper motion	μRA*=4.03mas/yr, μDE=-6.22mas/yr
Object position	18 48 09.2113 -31 26 32.413
Ephemeris	NIMAv11
C/A	0.031
P/A	6.94
velocity (km/s)	-21.014
Geocentric distance Δ (au)	14.723
G mag*	14.0
J mag*	12.4

Sky map (Aladin)



We thank funding from the European Research Council under the European Community's H2020 2014-2020 ERC Advanced Grant Agreement n°669416 *"Lucky Star"*