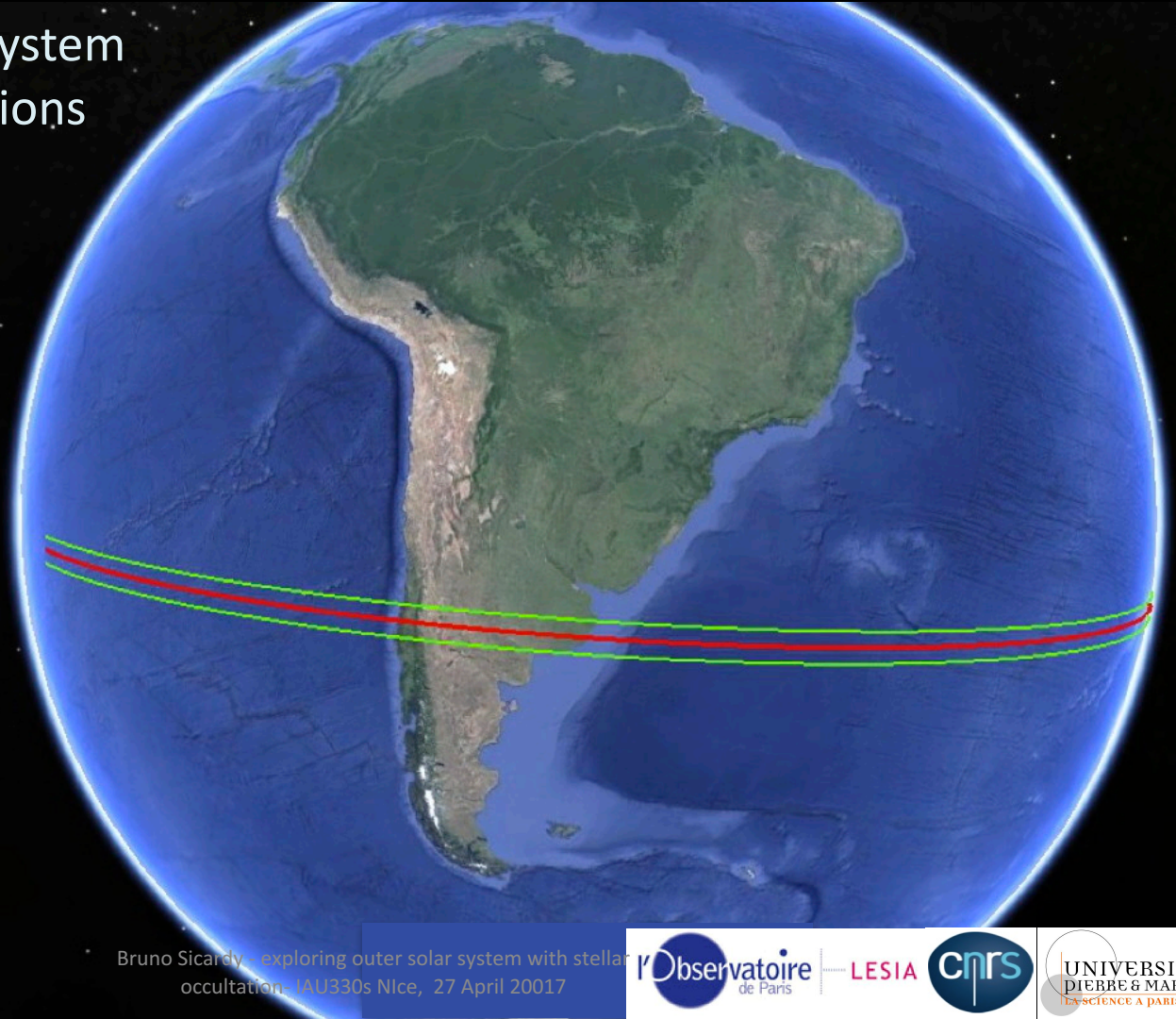
# Exploring the Solar System using stellar occultations

Bruno Sicardy

**LESIA/Observatoire de Paris**
**Univ. Pierre et Marie Curie**

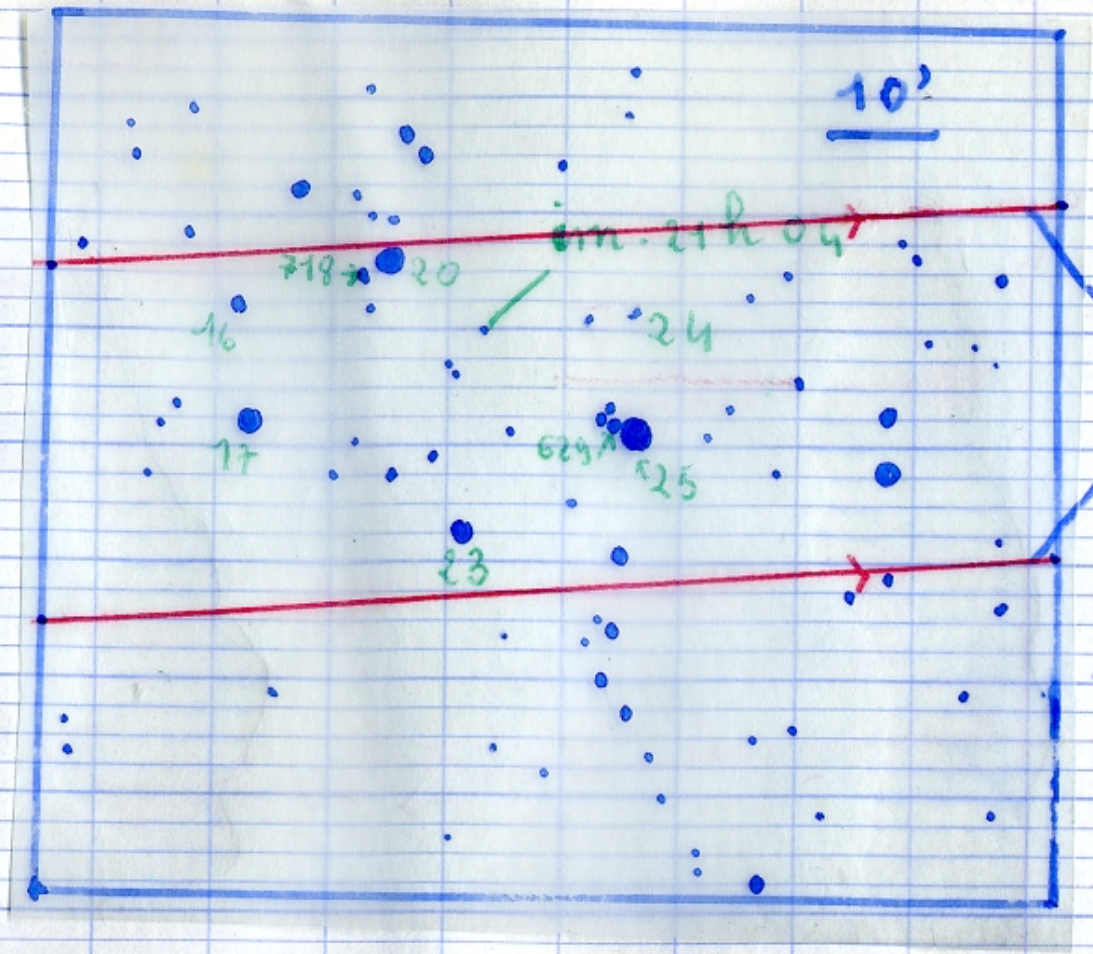


an ERC project:

Monaco, ca. 1973

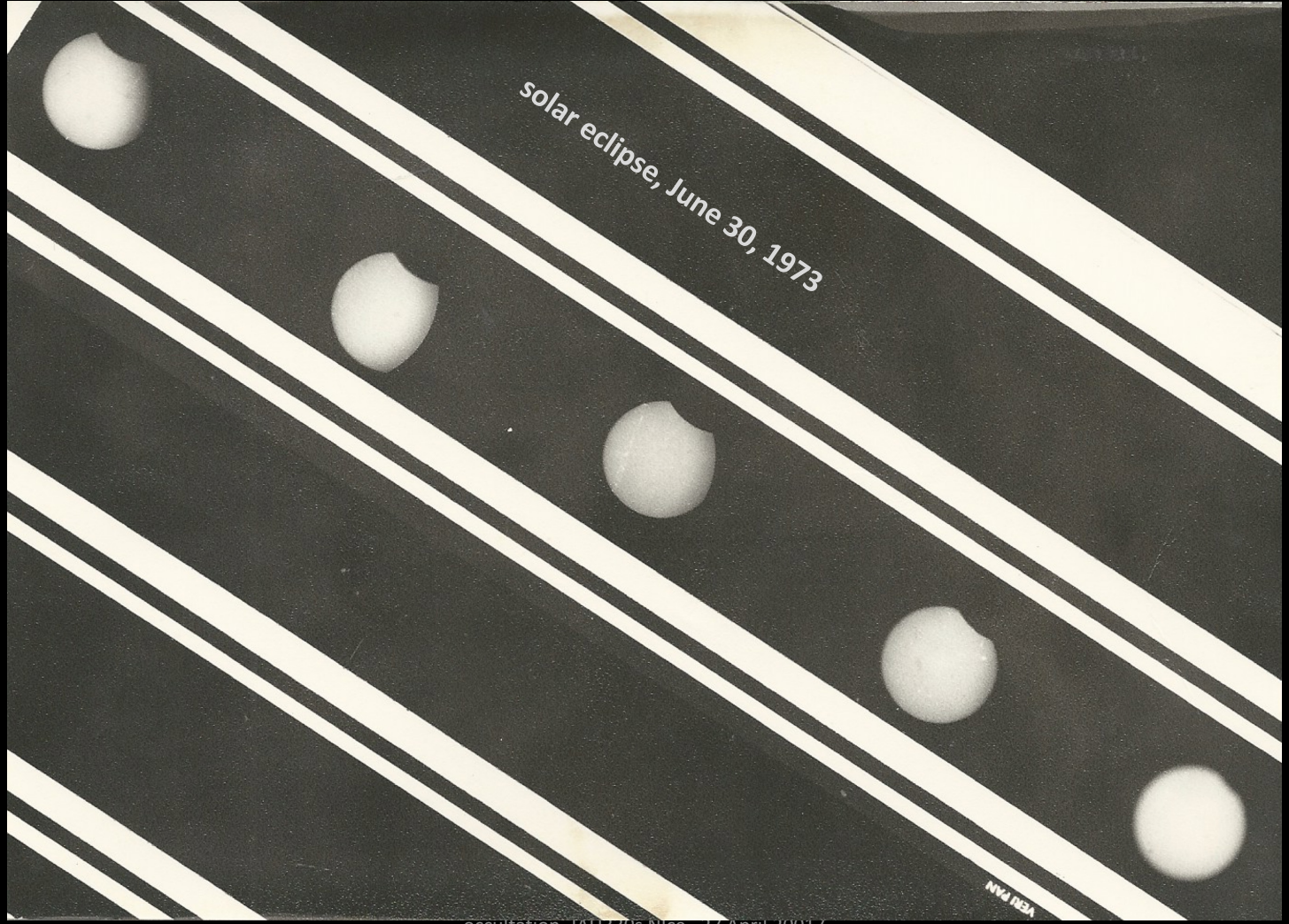
Beausoleil, ca. 1973

suite de
p. 6





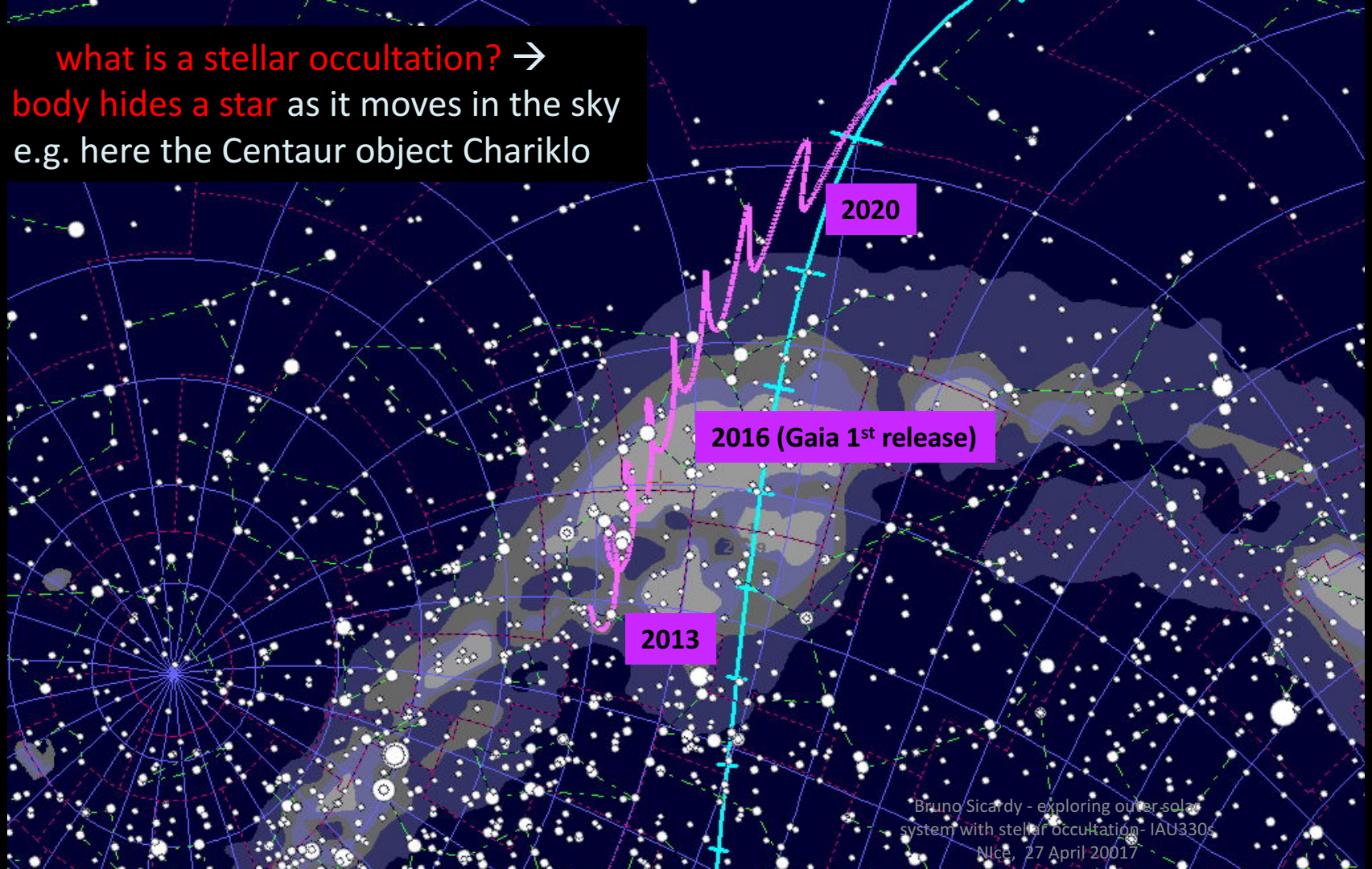

**Pleiades occultation by the Moon, 19 mars 1972**


solar eclipse, June 30, 1973

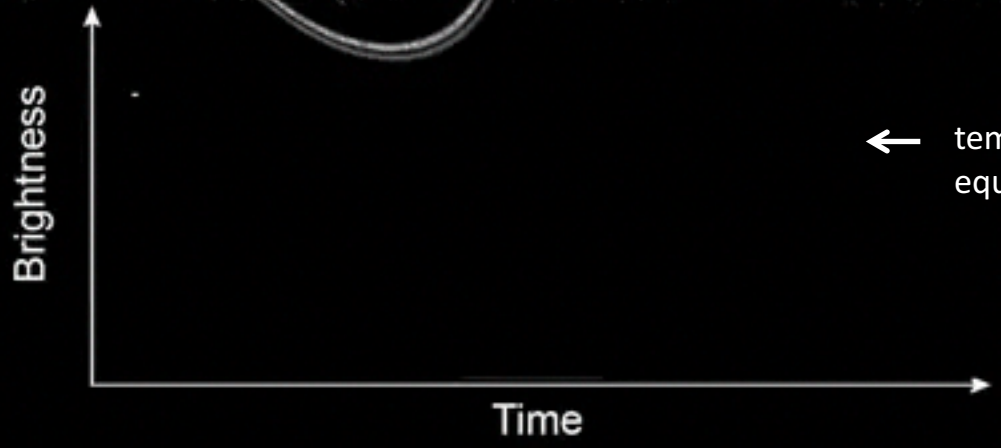
what is a stellar occultation? →

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**

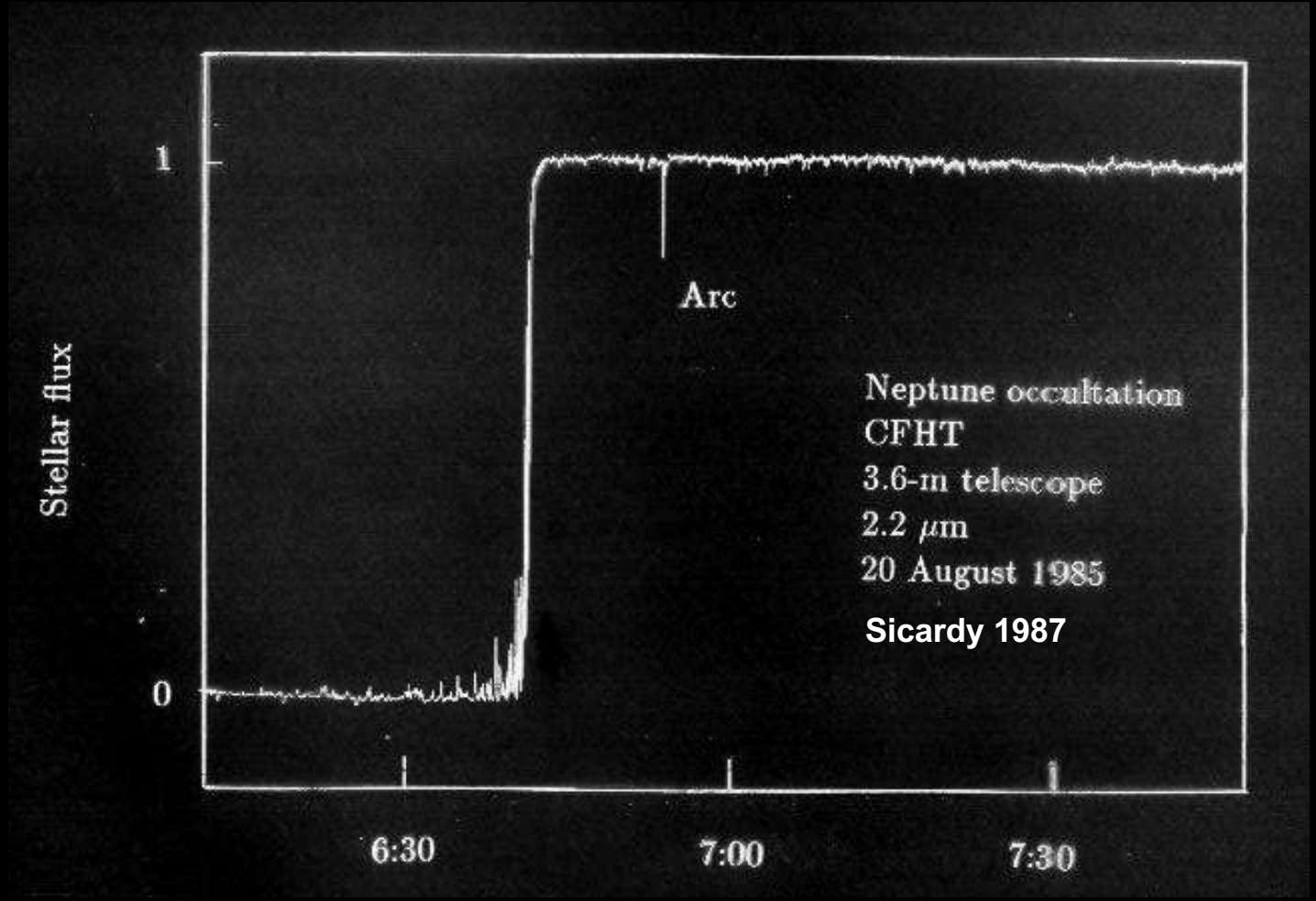
ARTICLES

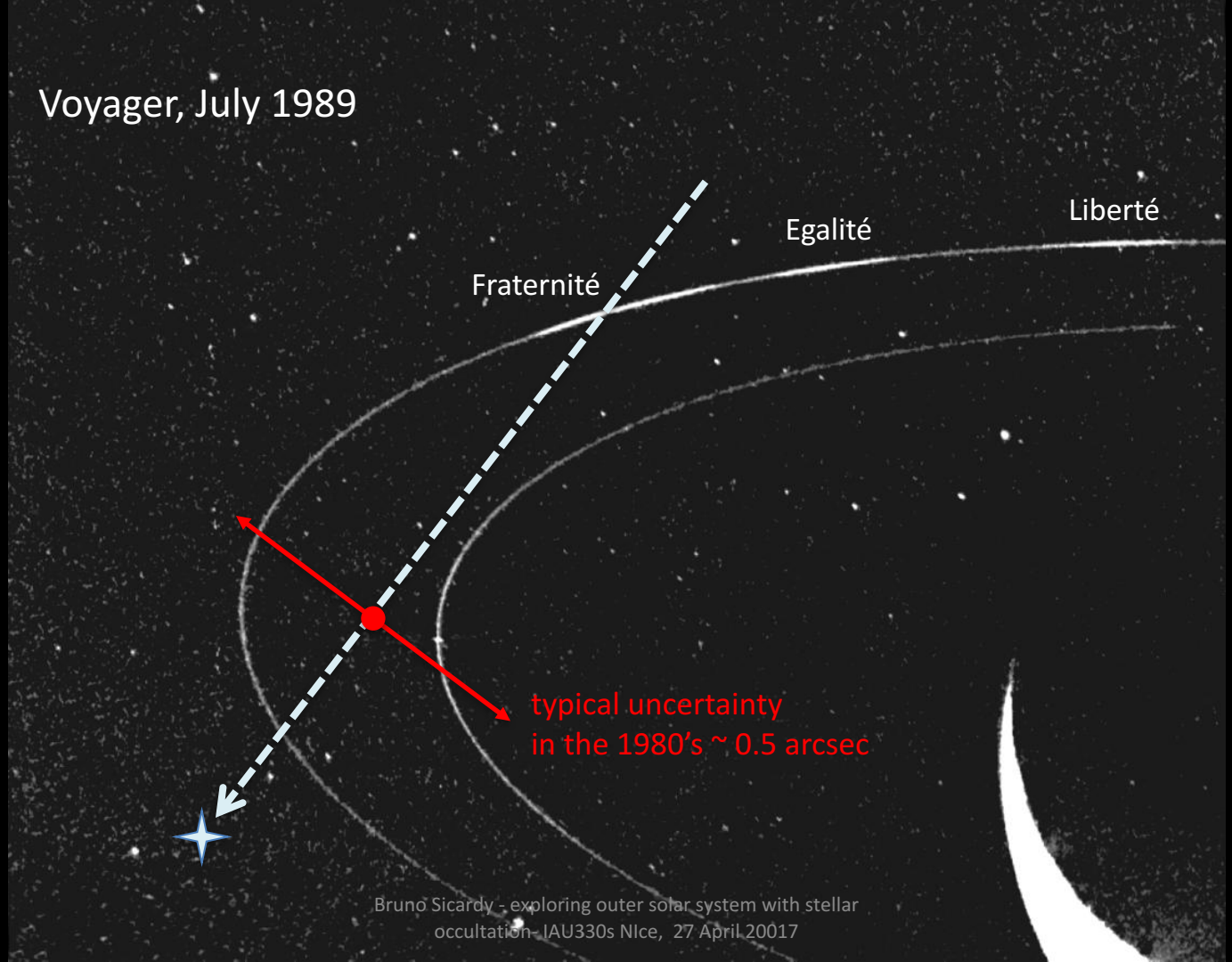
# Occultation detection of a neptunian ring-like arc

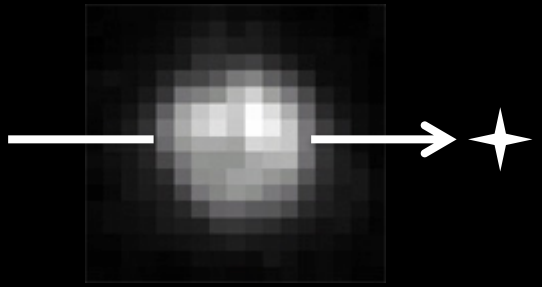
**W. B. Hubbard*, A. Brahic†, B. Sicardy†, L.-R. Elicer‡, F. Roques† & F. Vilas*§**

* 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

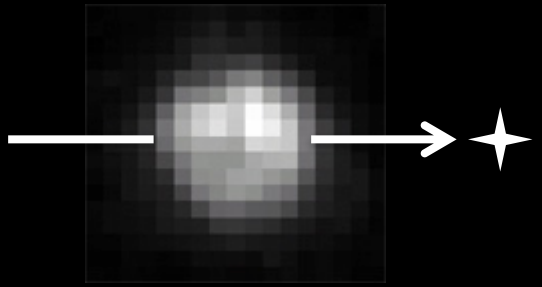


Pluto at best HST resolution
details ~ 500 km at best

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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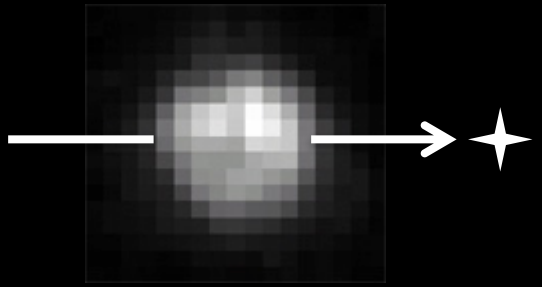
Earth's Moon at the same resolution

Occultations: highly efficient method

spatial resolution ~ fraction of km

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



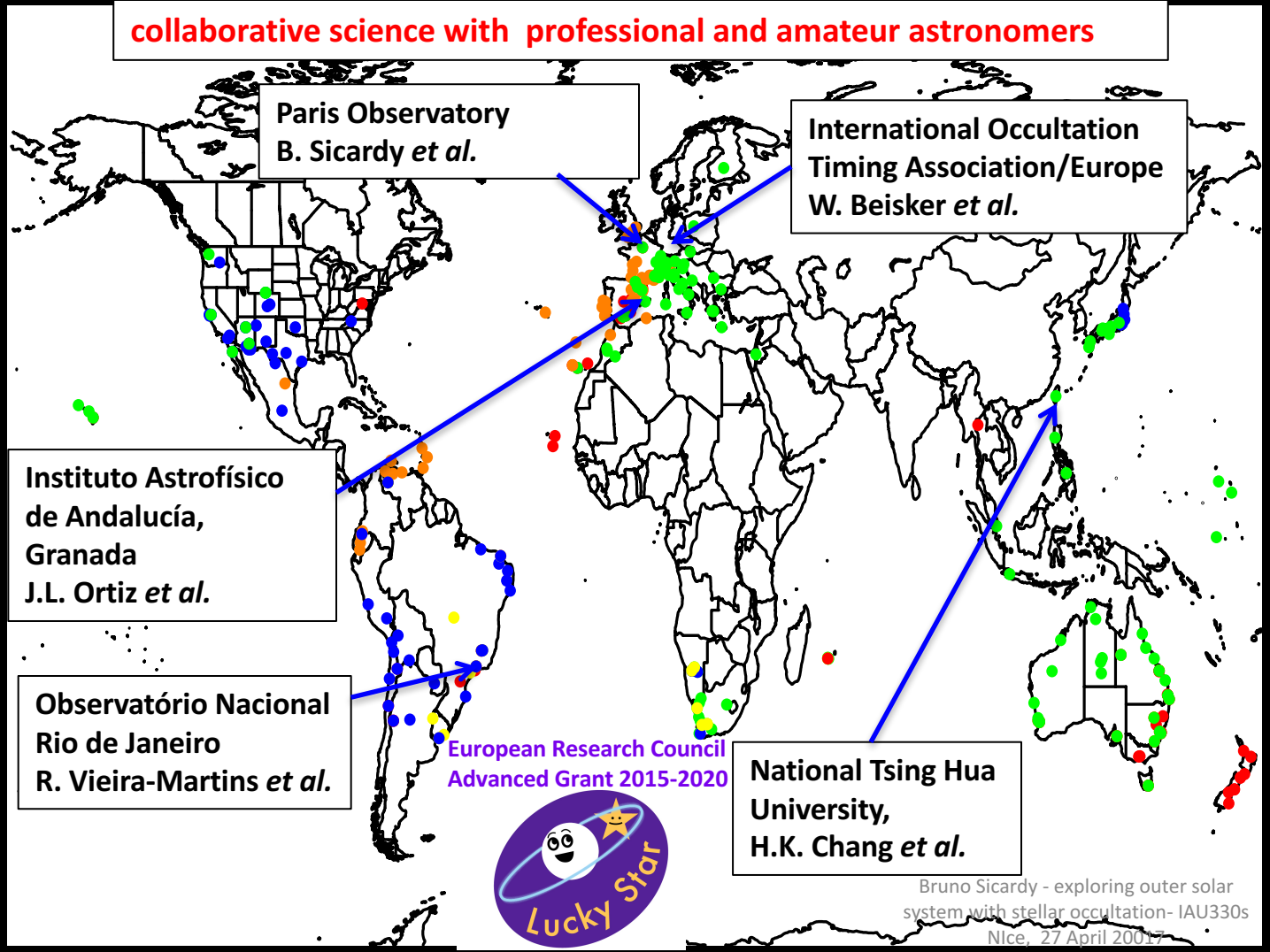
Pluto at best HST resolution
details ~ 500 km at best

Earth's Moon at the same resolution

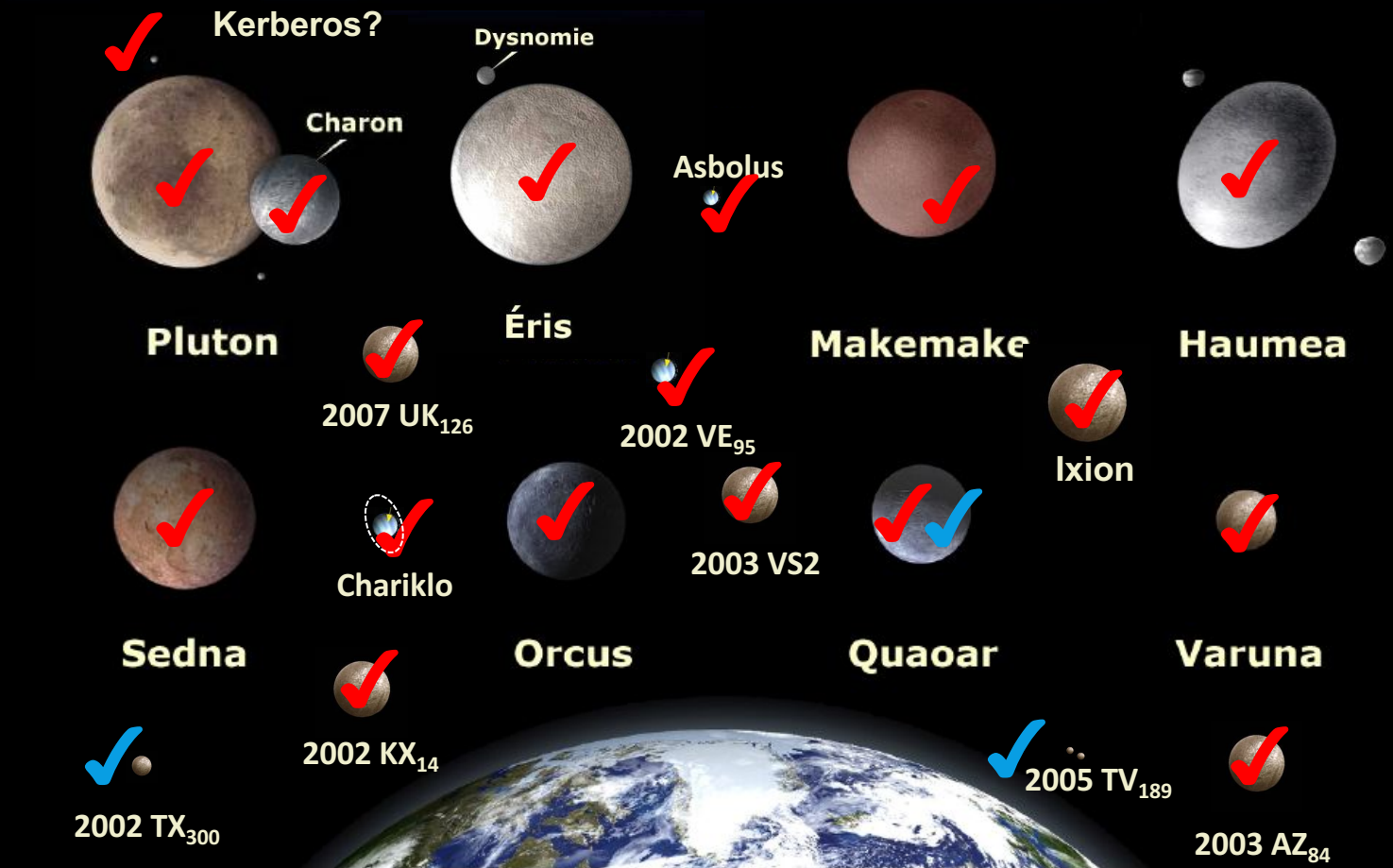
Occultations: highly efficient method

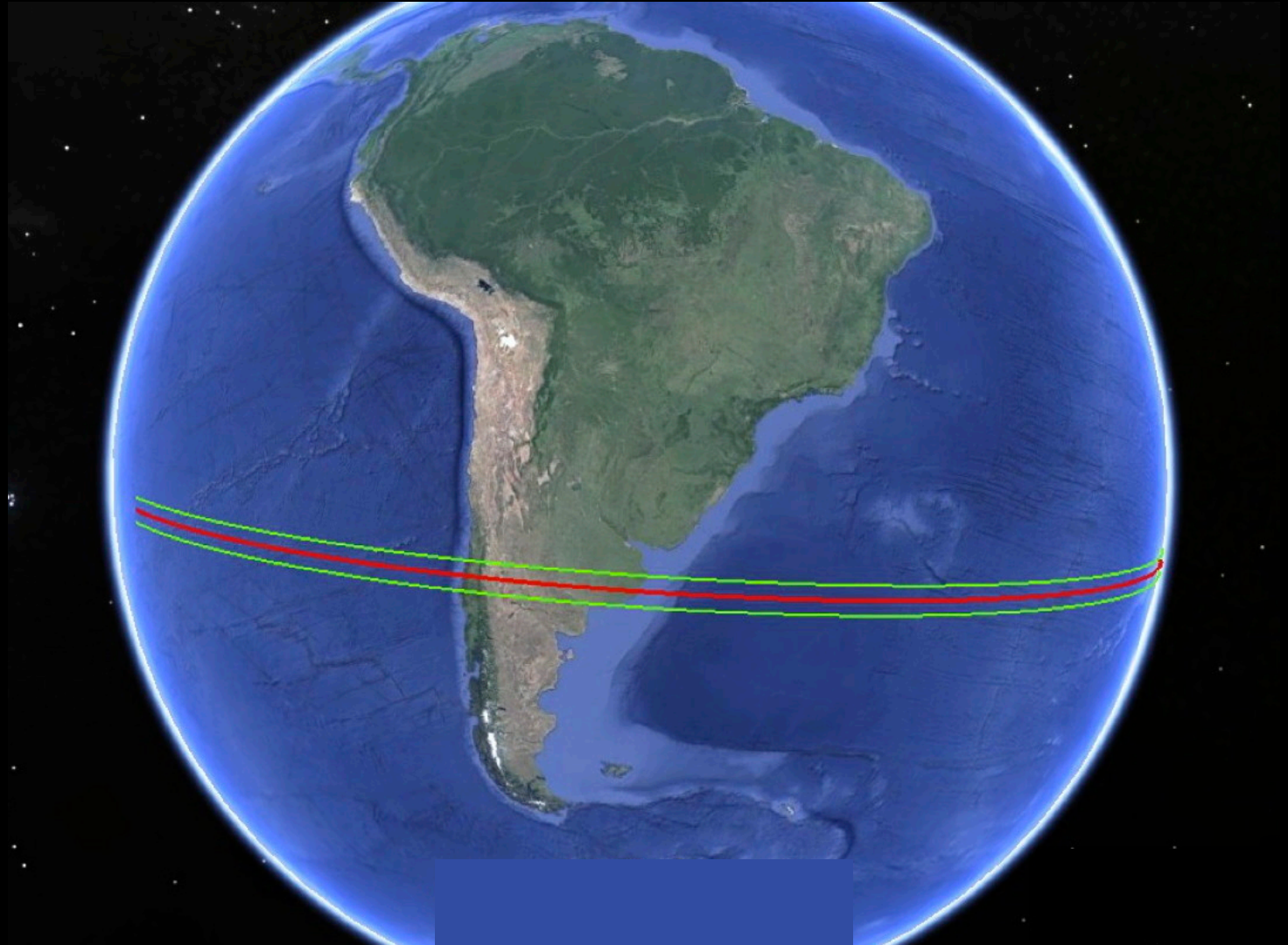
spatial resolution ~ fraction of km
sensitivity to atmosphere ~ a few nanobars

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


collaborative science with professional and amateur astronomers
Paris Observatory
B. Sicardy *et al.*
International Occultation
Timing Association/Europe
W. Beisker *et al.*
Instituto Astrofísico
de Andalucía,
Granada
J.L. Ortiz *et al.*
Observatório Nacional
Rio de Janeiro
R. Vieira-Martins *et al.*
European Research Council
Advanced Grant 2015-2020
Lucky Star
National Tsing Hua
University,
H.K. Chang *et al.*

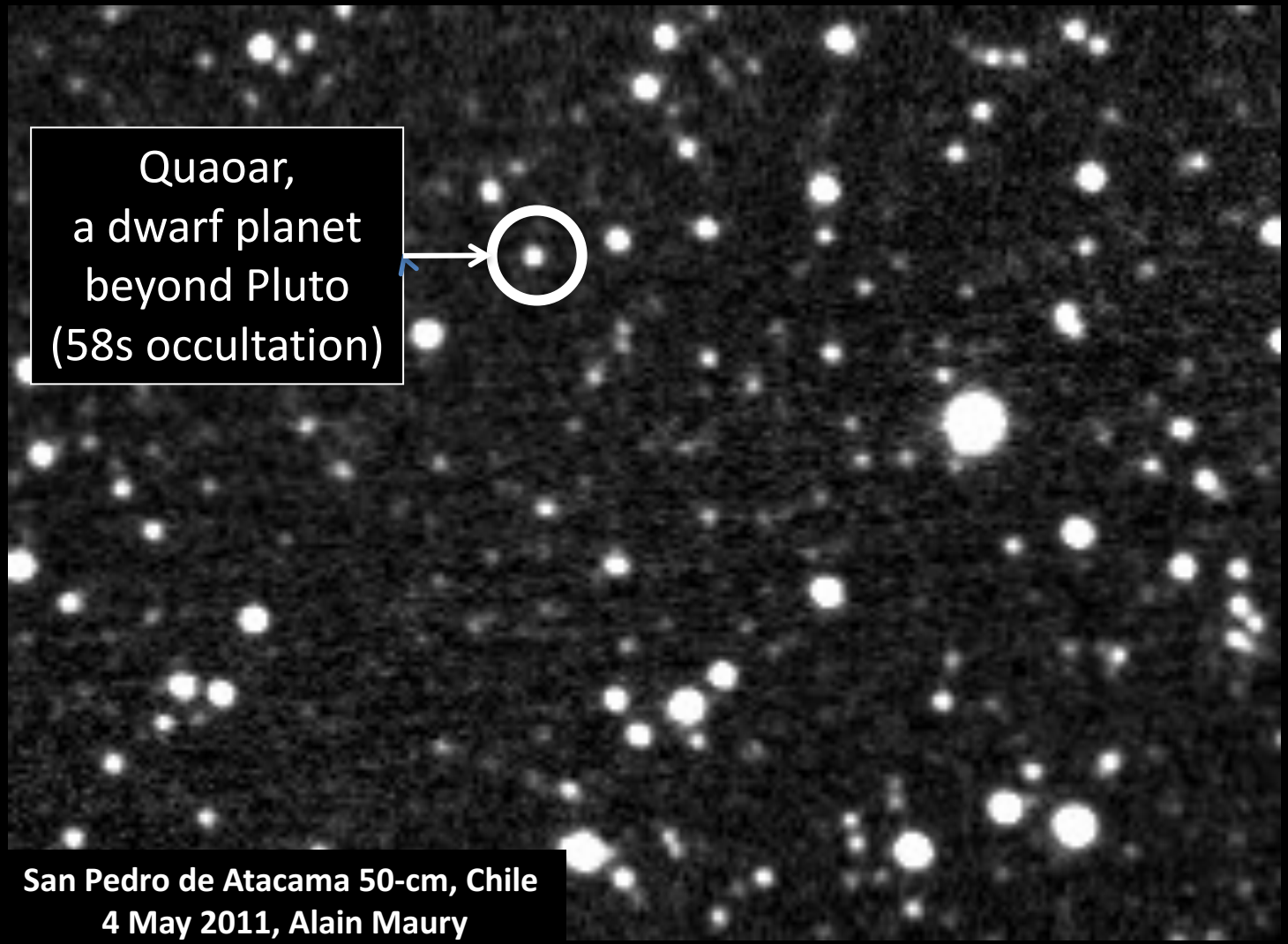
# Les plus grands objets transneptuniens connus



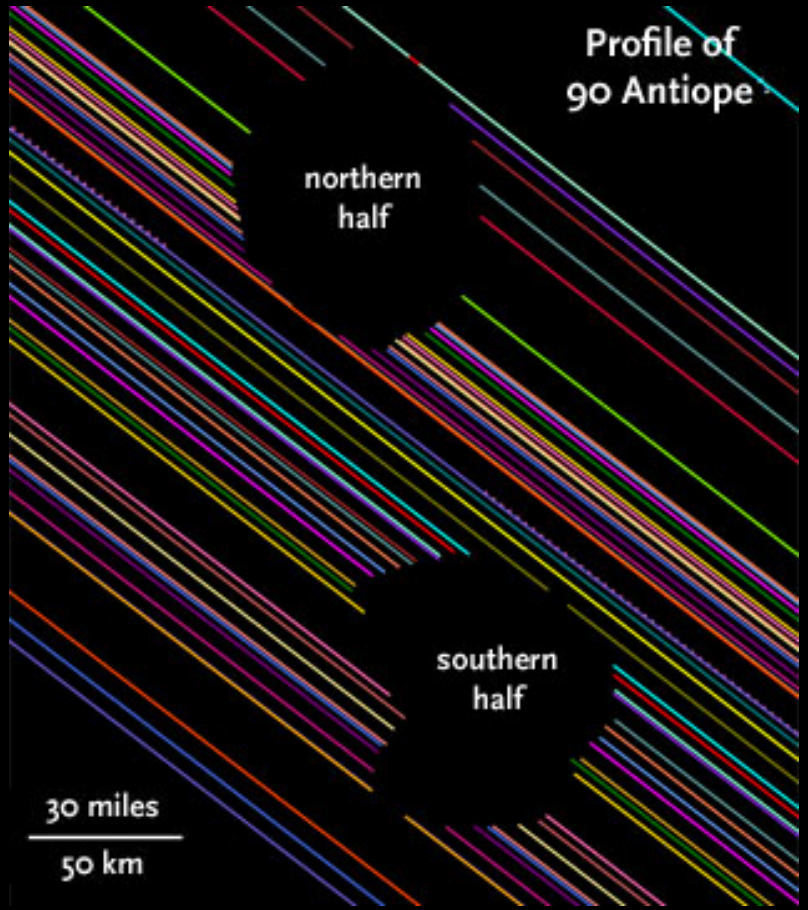



Chariklo occultation
Namibia April 9, 2017
© Mike Kretlow

Pluto occultation
Mt John, New Zealand
June 2006



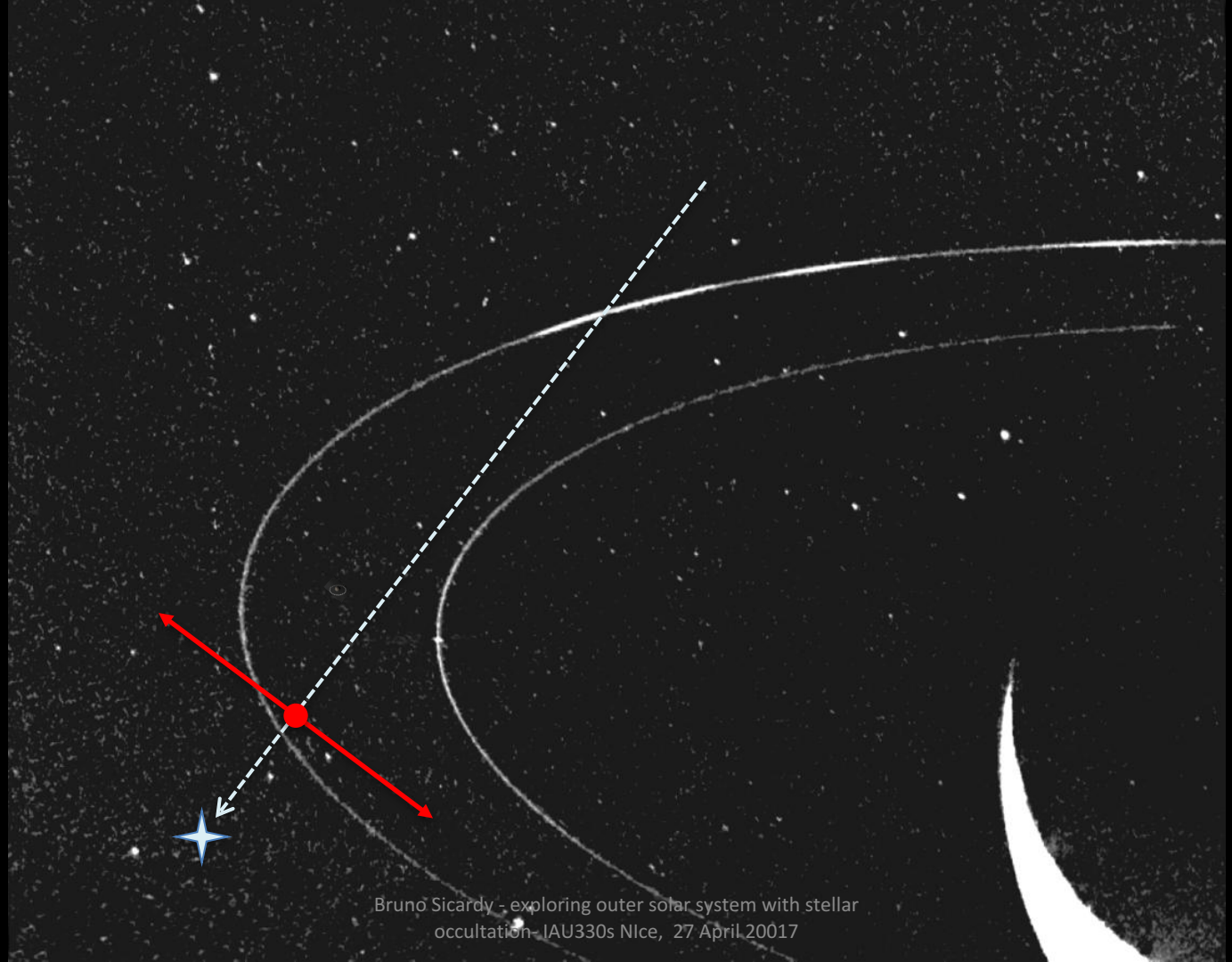

**San Pedro de Atacama 50-cm, Chile**
**4 May 2011, Alain Maury**

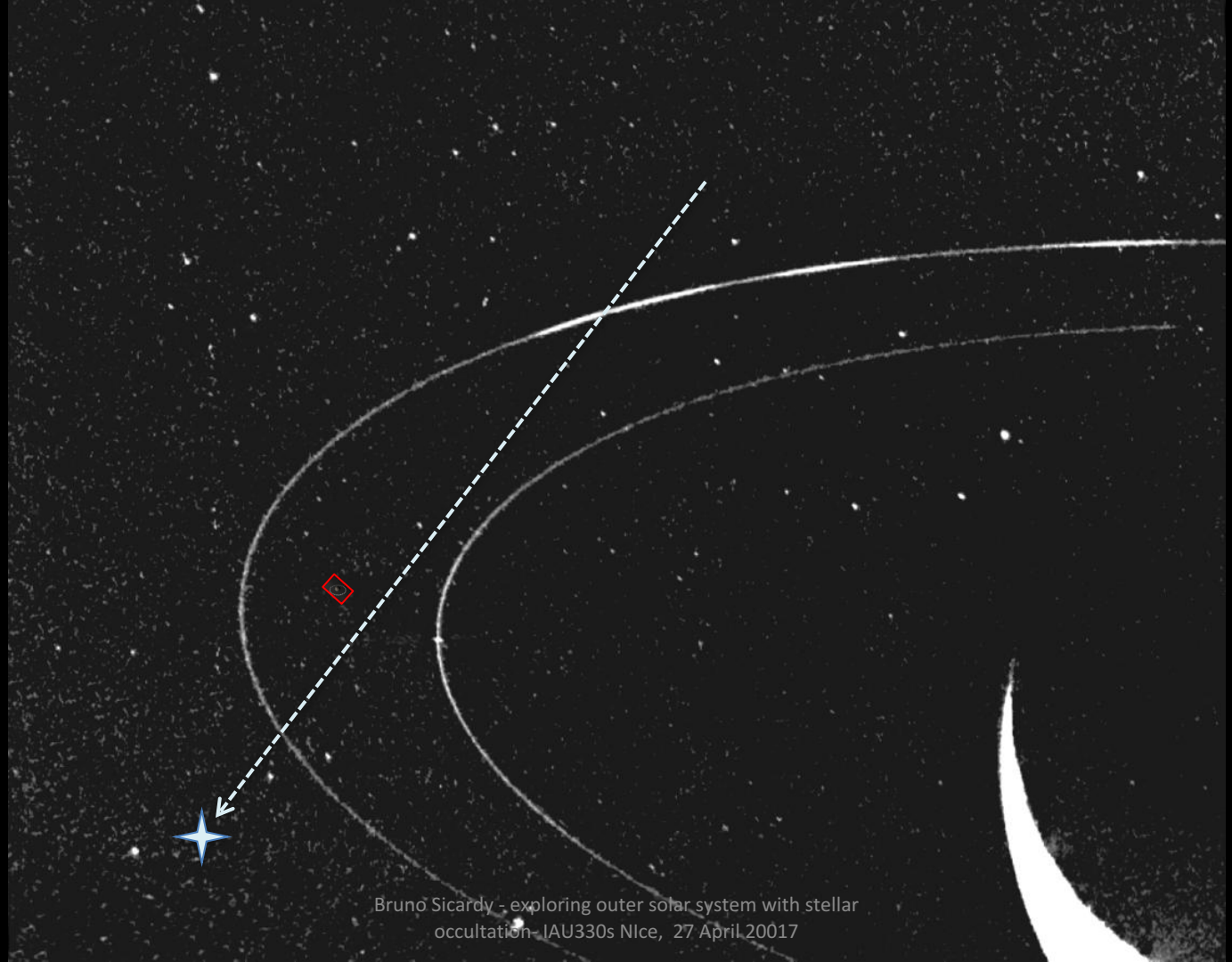


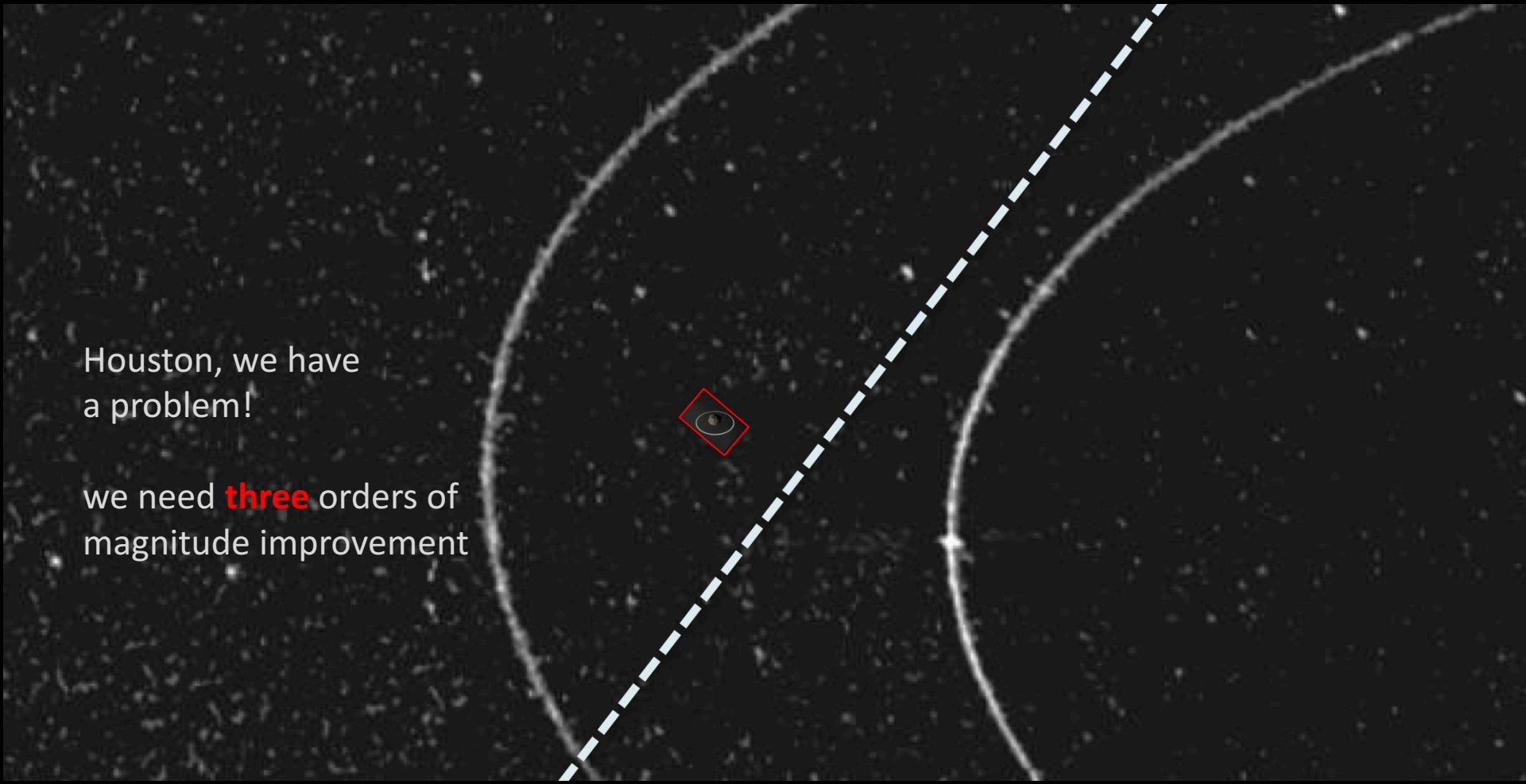

Antiope occultation
Kelly Beatty Sky & Telescope
9 Sept. 2011

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

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






Houston, we have
a problem!
we need three orders of
magnitude improvement

Titan

quaoar

Pluto

Eris

a stamp viewed at 150 km


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

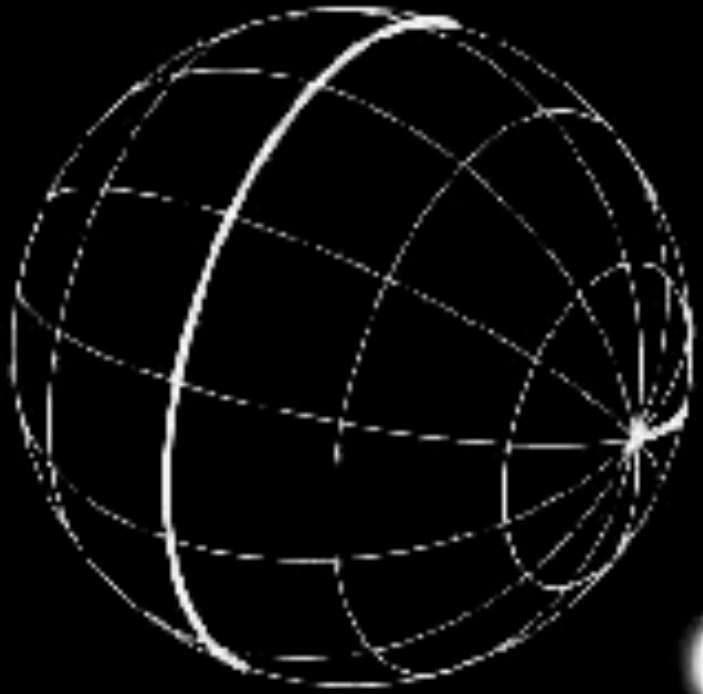
Charon

Makemake

Charon occultation,
Paranal, Chile
July 2005

# an example: Pluto’s atmosphere

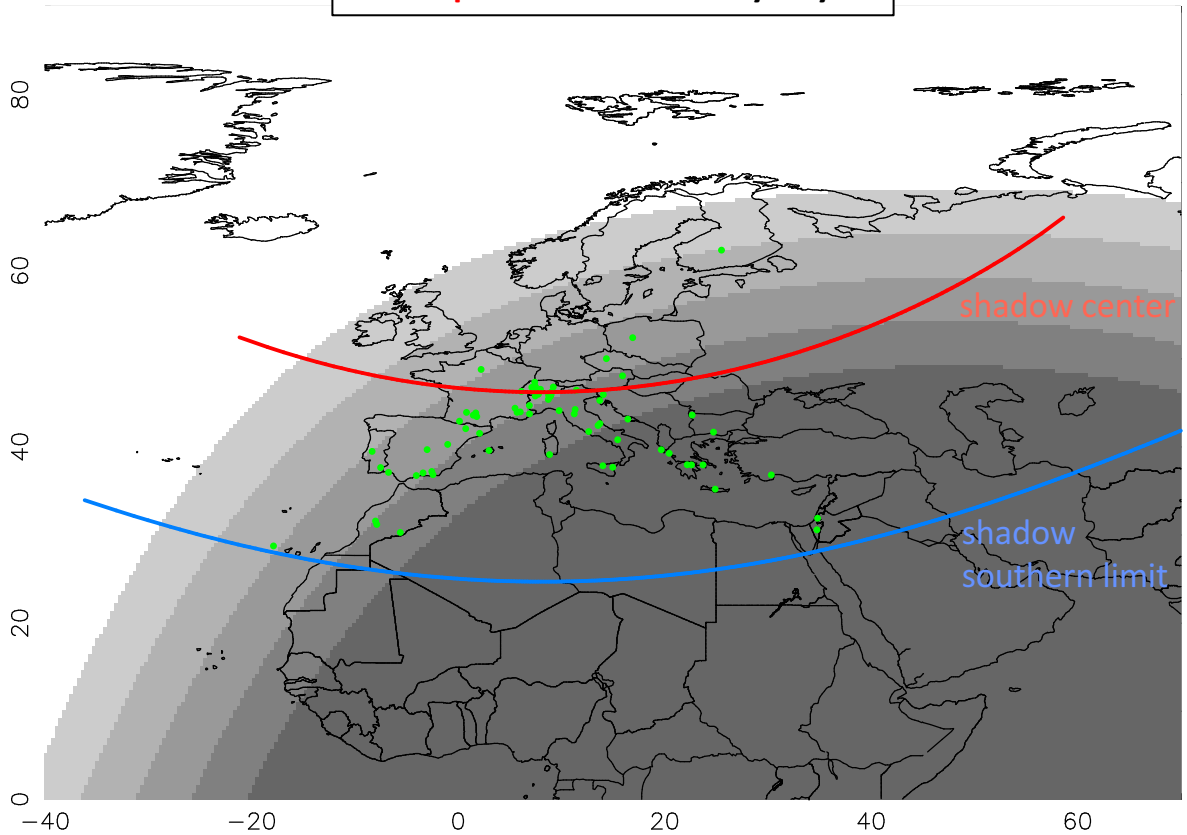
gravity waves!



gravity waves!

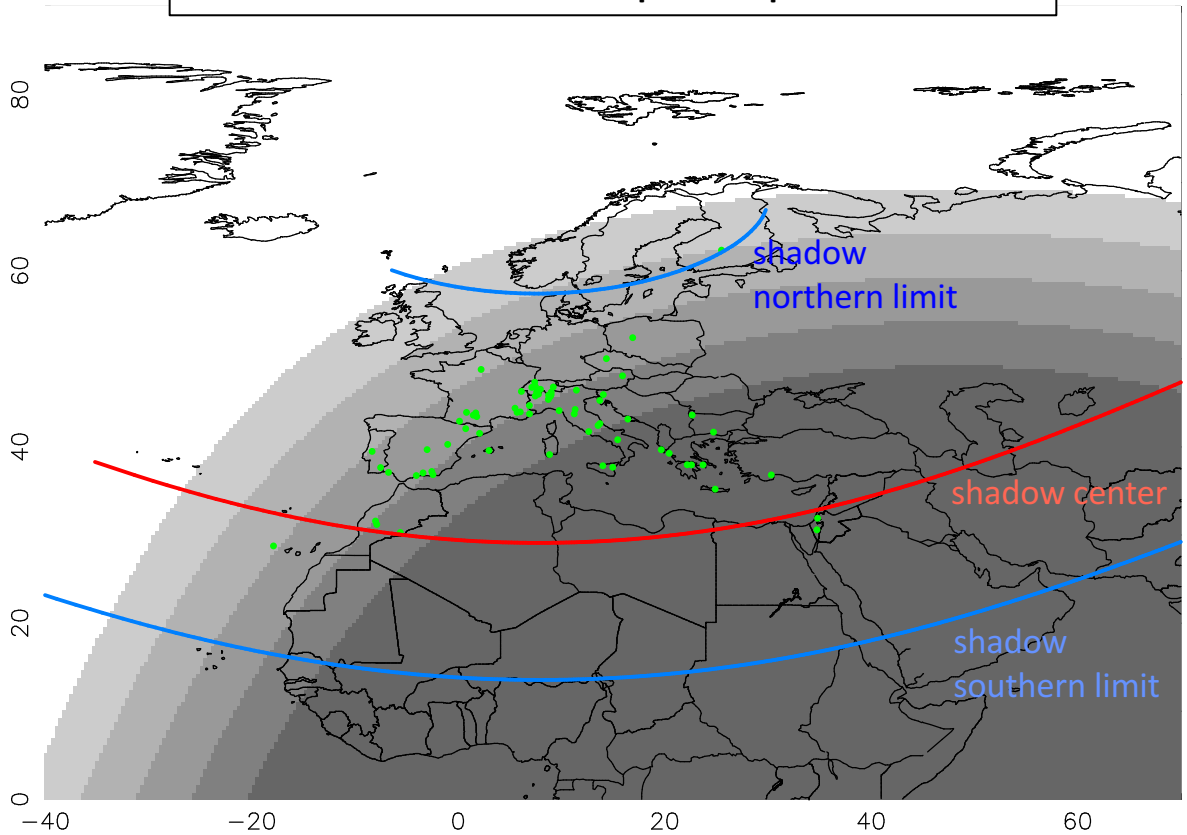
the August 21, 2002 Pluto occultation:
a reconstruction of what happened

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



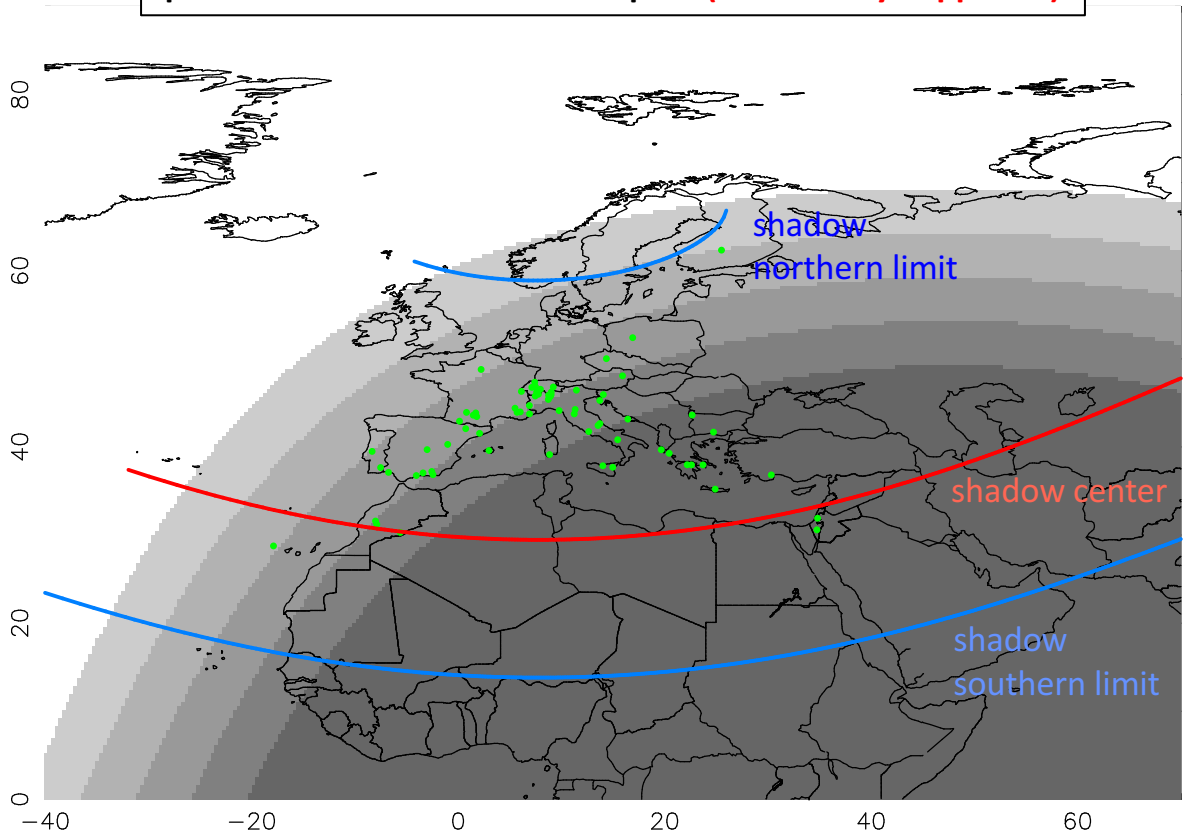

green dots: sites involved in the campaign (not all got data!)

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



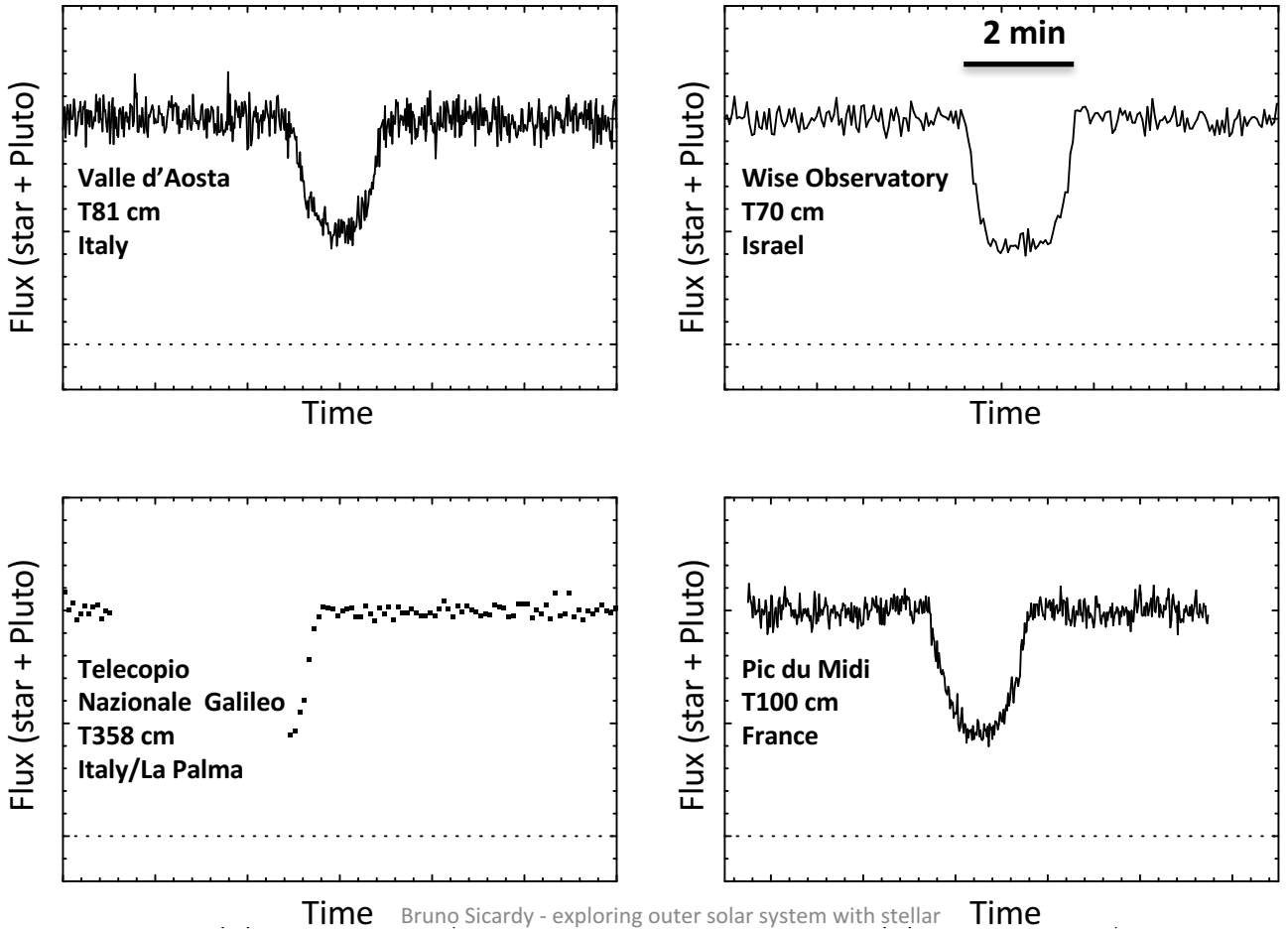

green dots: sites involved in the campaign (not all got data!)

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

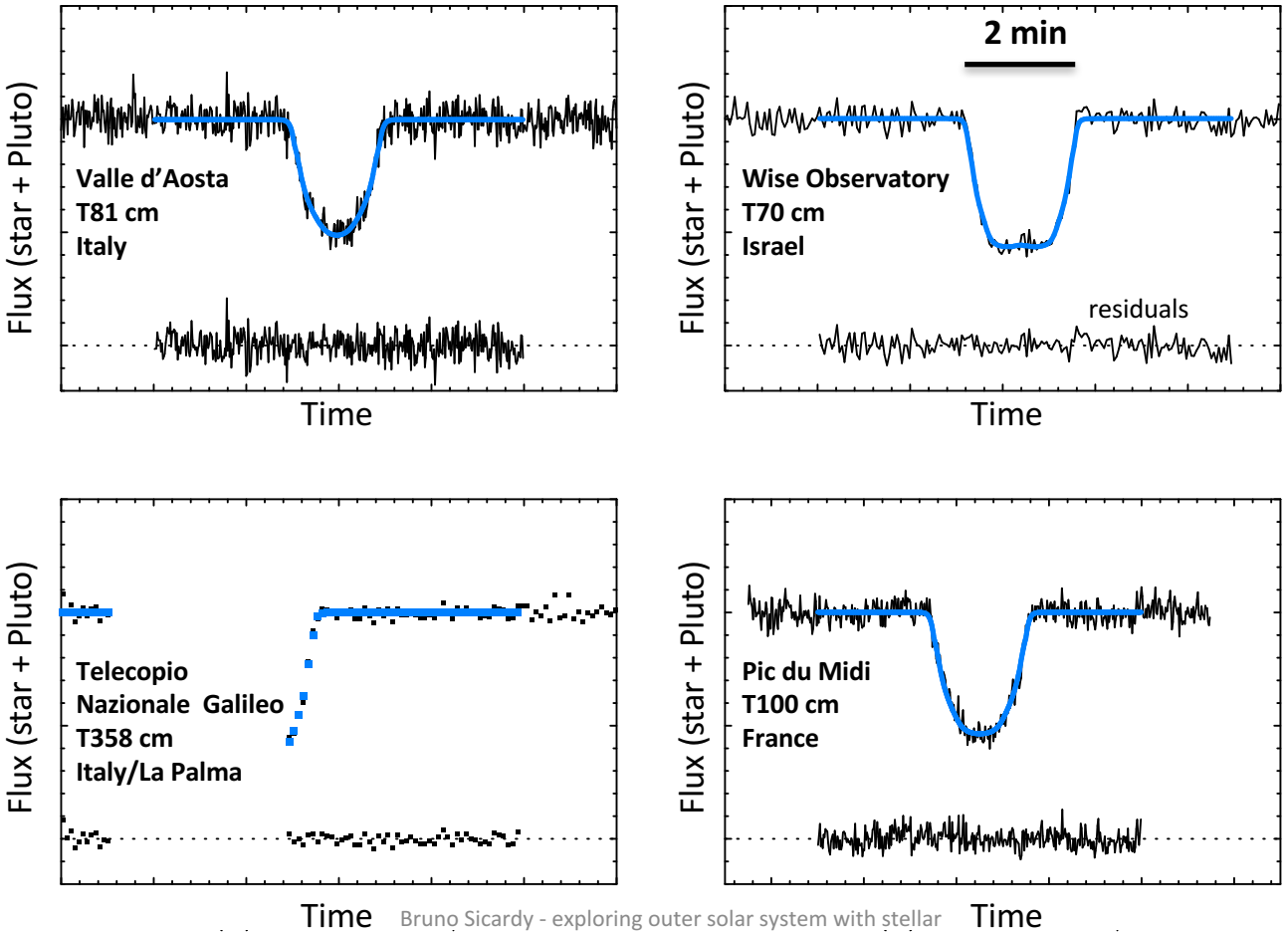



green dots: sites involved in the campaign (not all got data!)

# The Pluto July 19, 2016 stellar occultation

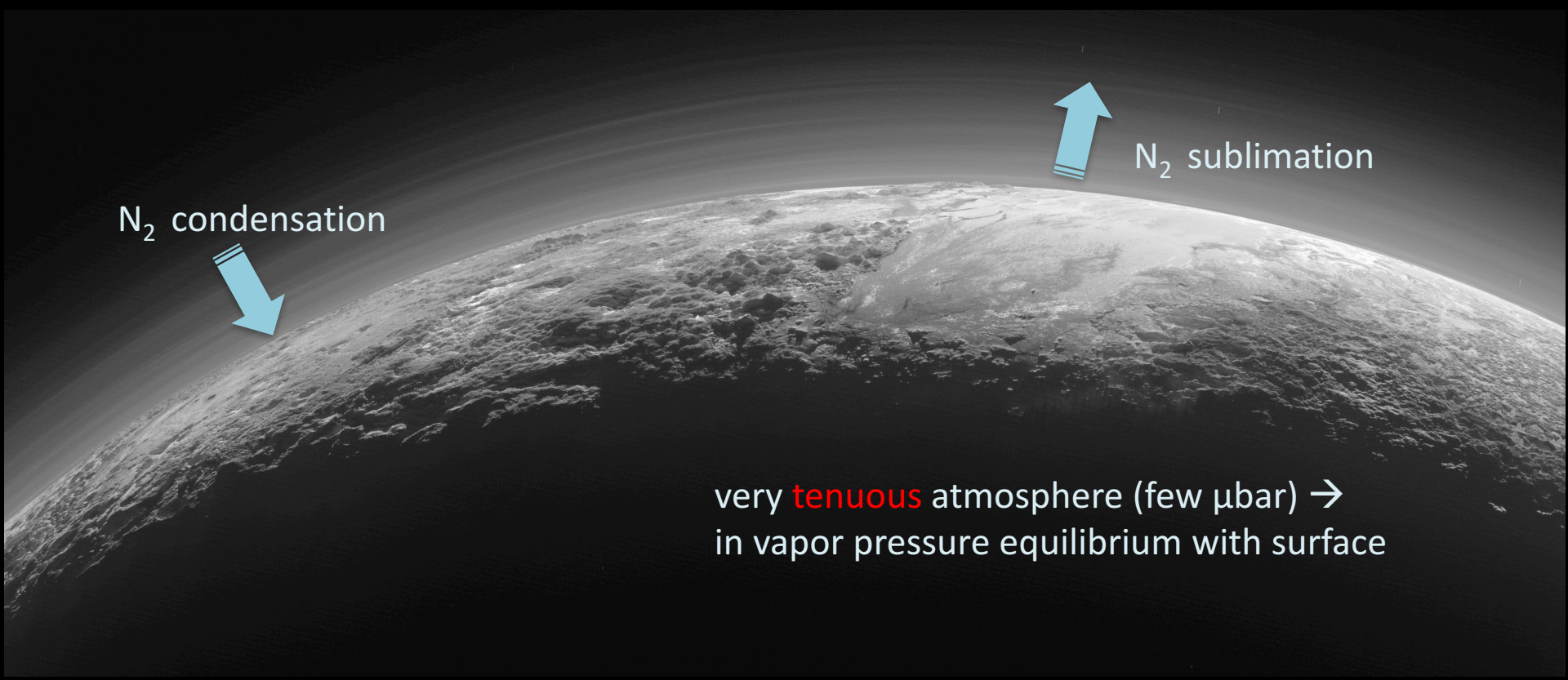


# The Pluto July 19, 2016 stellar occultation



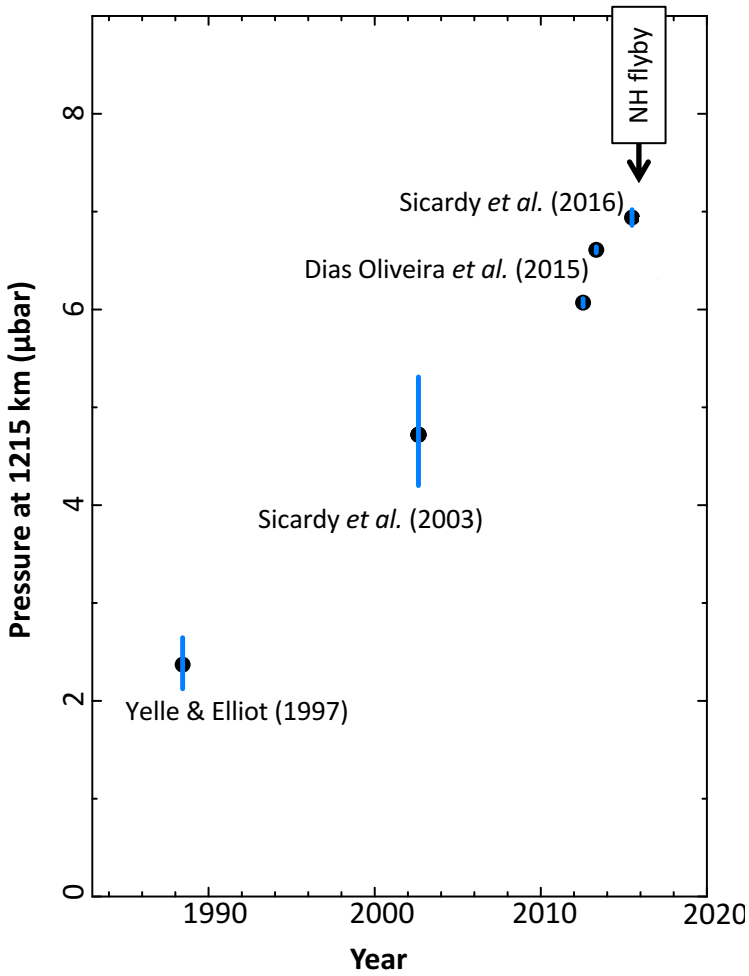


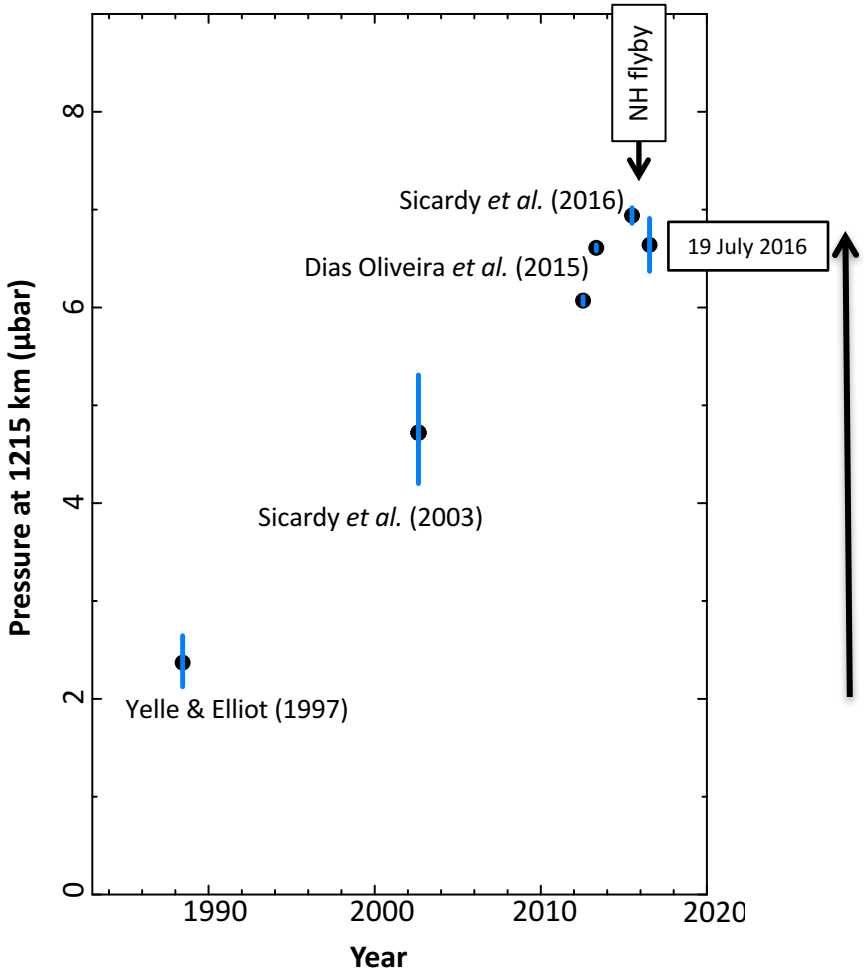

blue= simultaneous fit to the data using a Pluton atmospheric model






*New Horizons/LORRI* 14 July 2015

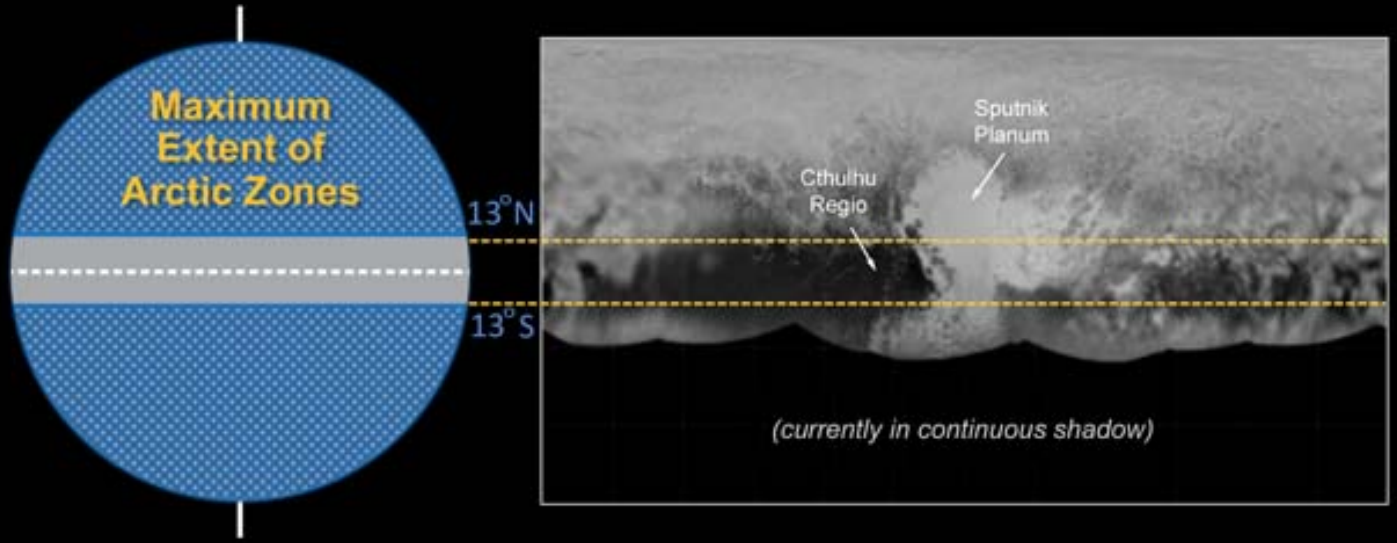

NH flyby
Sicardy et al. (2016)
Dias Oliveira et al. (2015)
Sicardy et al. (2003)
Yelle & Elliot (1997)
Pressure at 1215 km (µbar)
Year
0
2
4
6
8
1990
2000
2010
2020




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

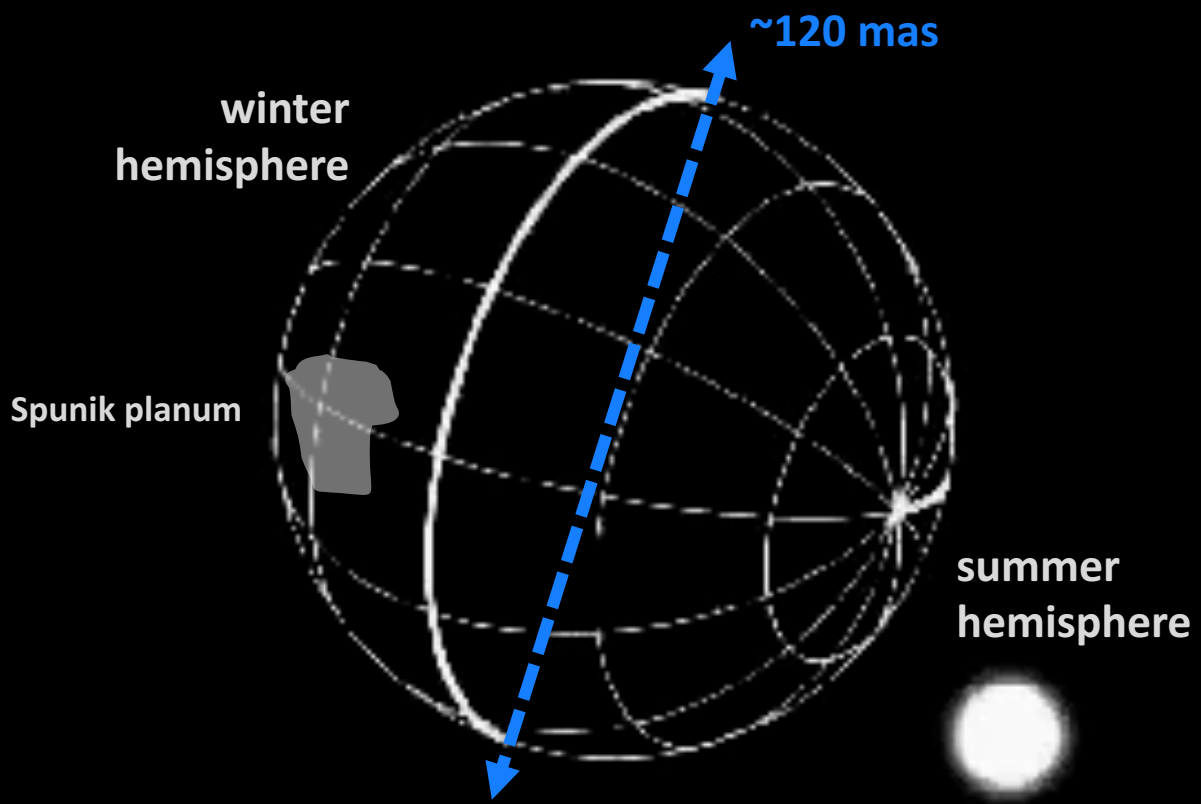
# Pluto's atmosphere confounds researchers

Kelly Beatty, Sky & Telescope 25 March 2016

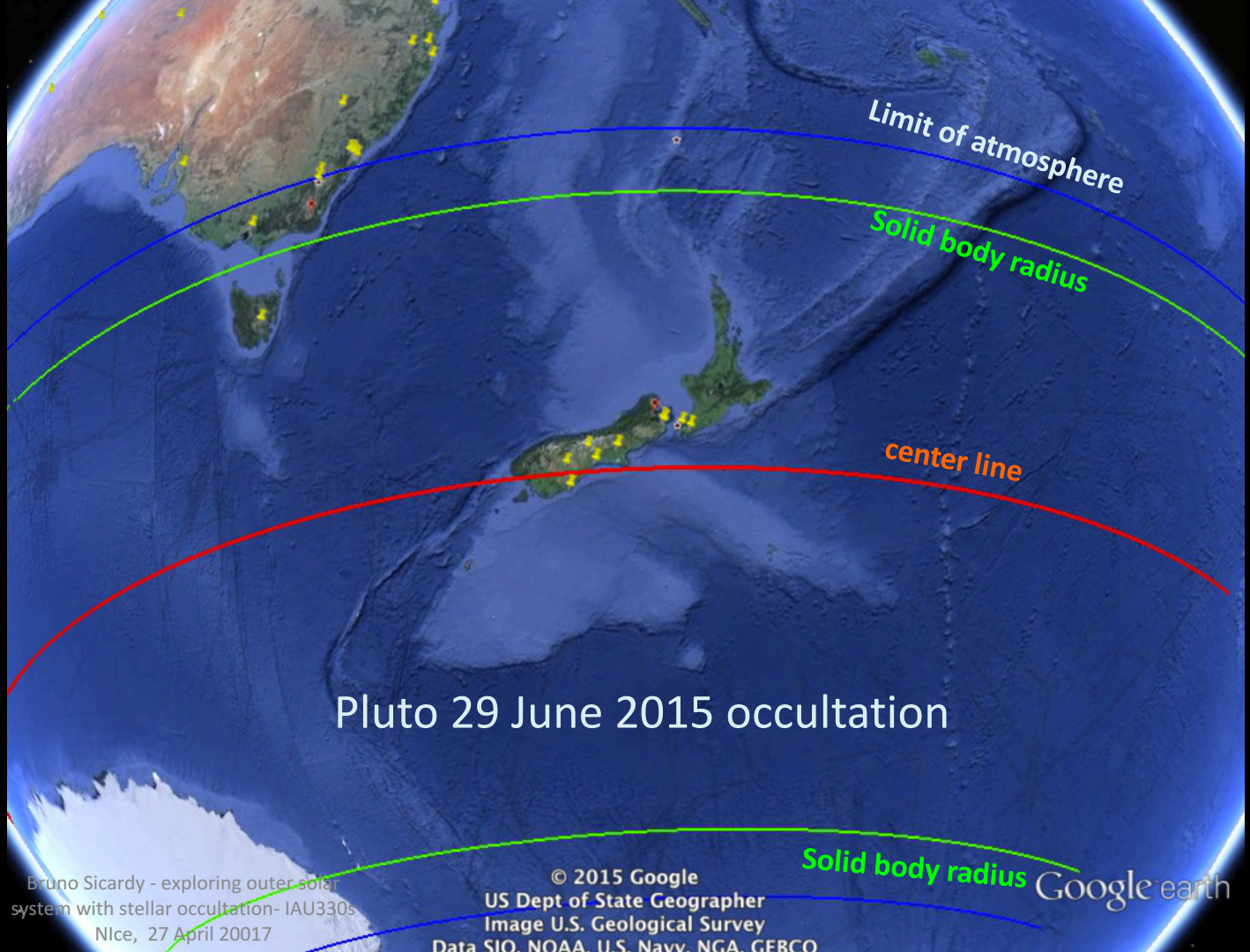


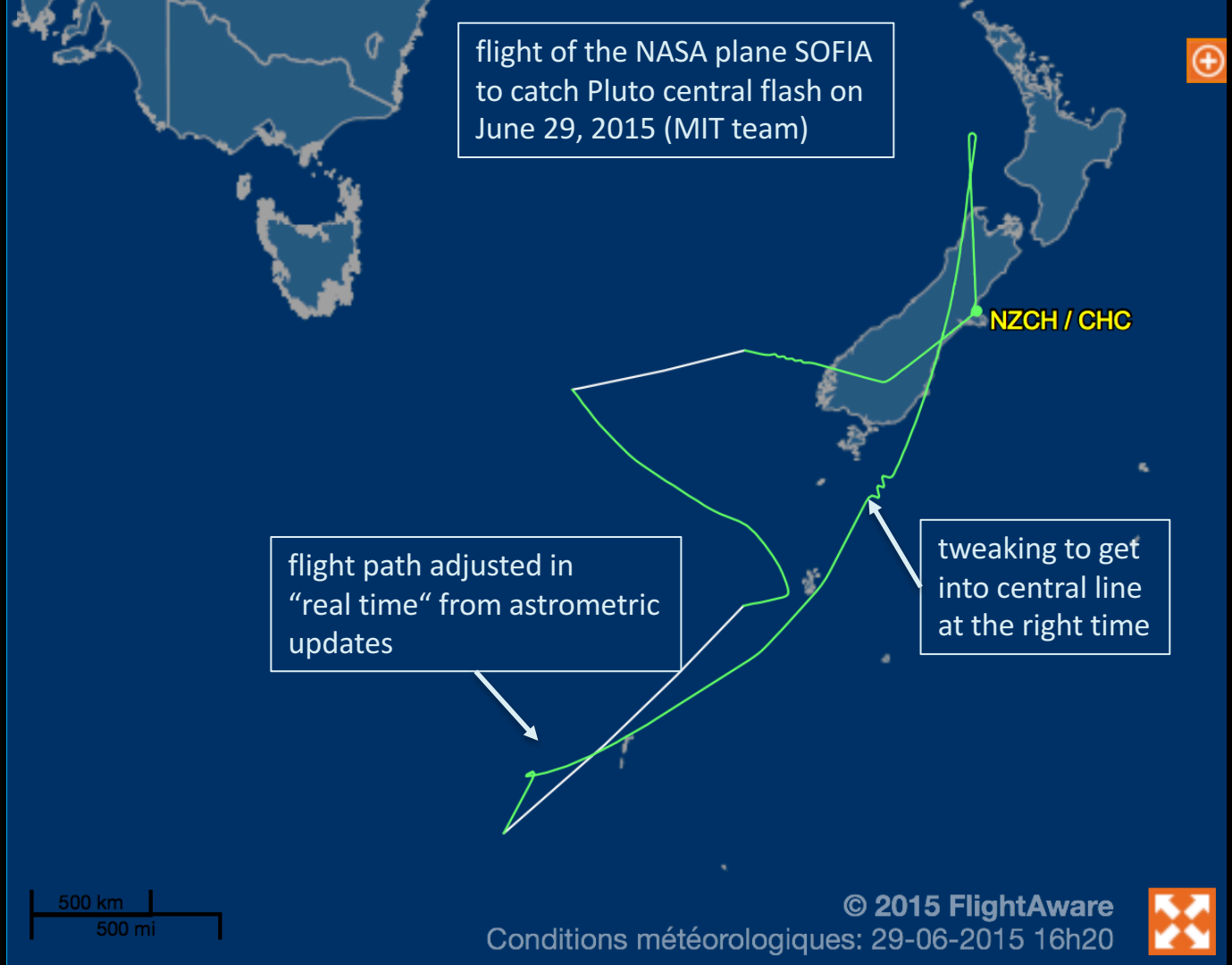

www.skyandtelescope.com/astronomy-news/plutos-atmosphere-confounds-researchers-032520166

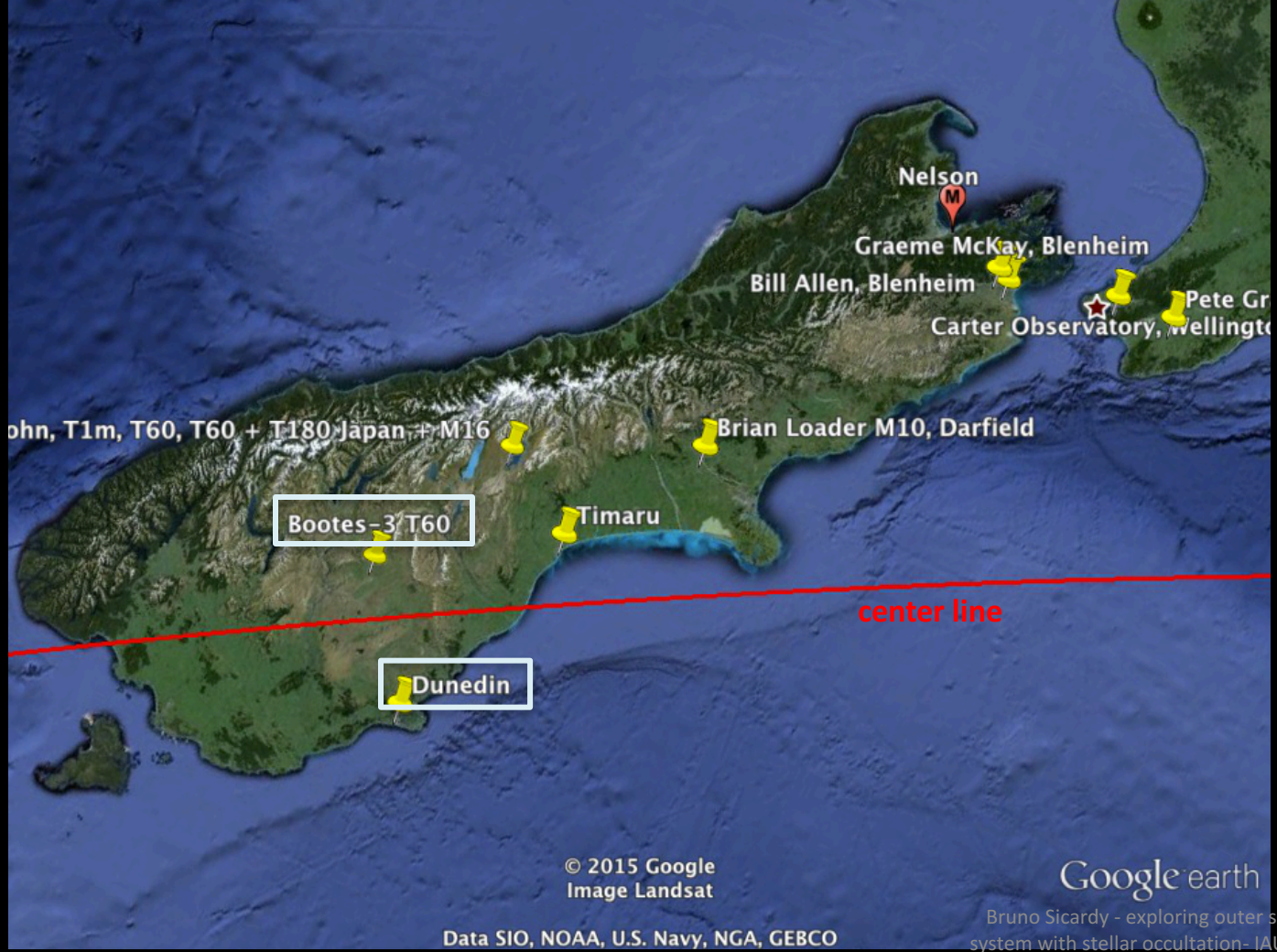
# Gaia allows to make “meteorology“ of Pluto’s atmosphere

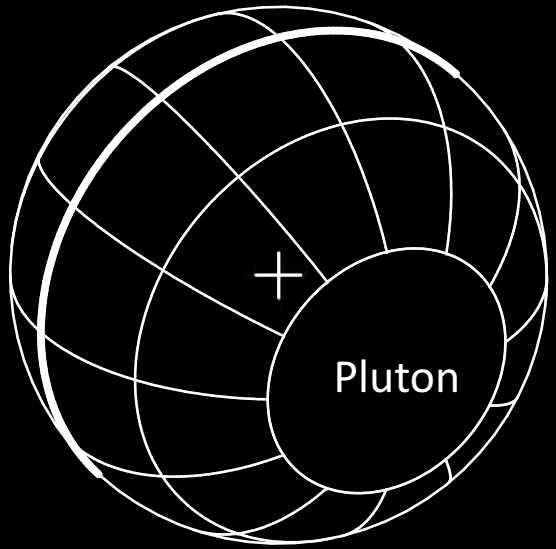


central flashes


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

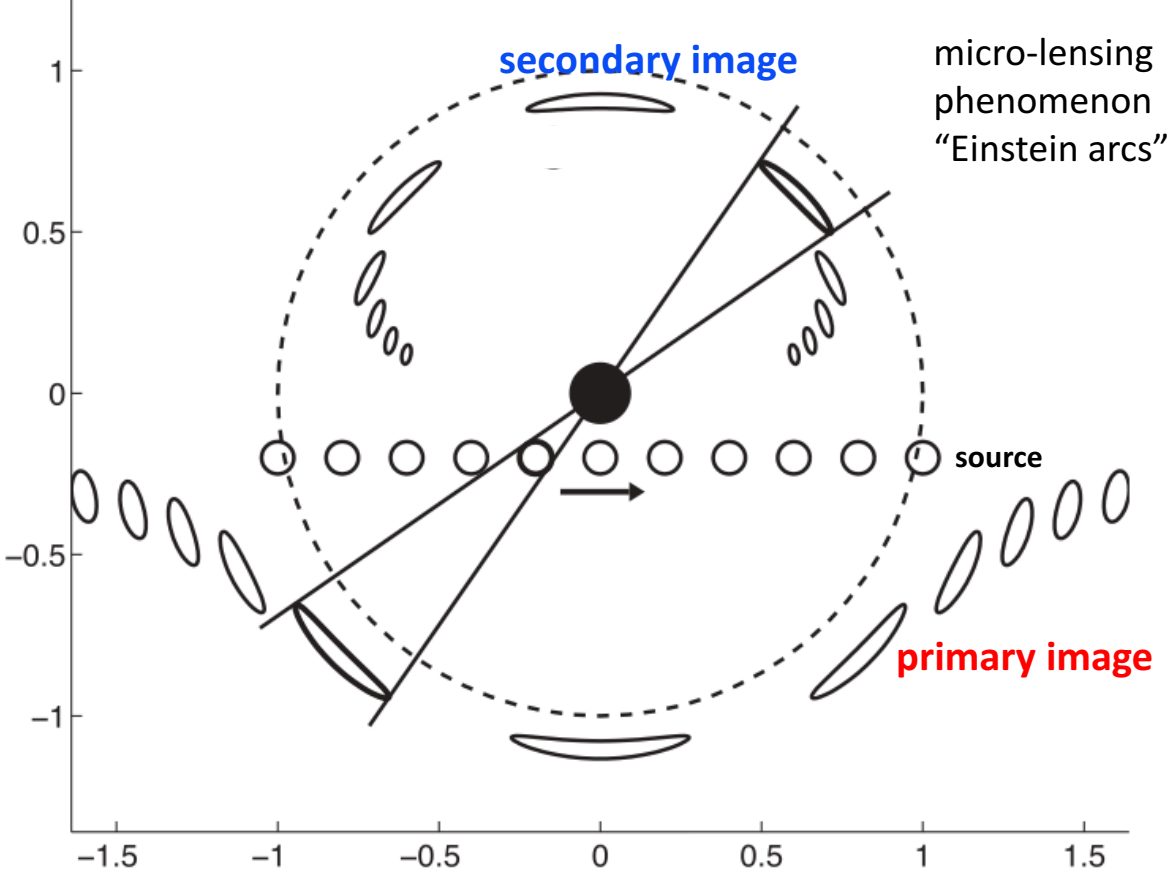

flight of the NASA plane SOFIA to catch Pluto central flash on June 29, 2015 (MIT team)
NZCH / CHC
flight path adjusted in “real time“ from astrometric updates
tweaking to get into central line at the right time
500 km
500 mi
© 2015 FlightAware
Conditions météorologiques: 29-06-2015 16h20


Nelson
Graeme McKay, Blenheim
Bill Allen, Blenheim
Carter Observatory, Wellingto
ohn, 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

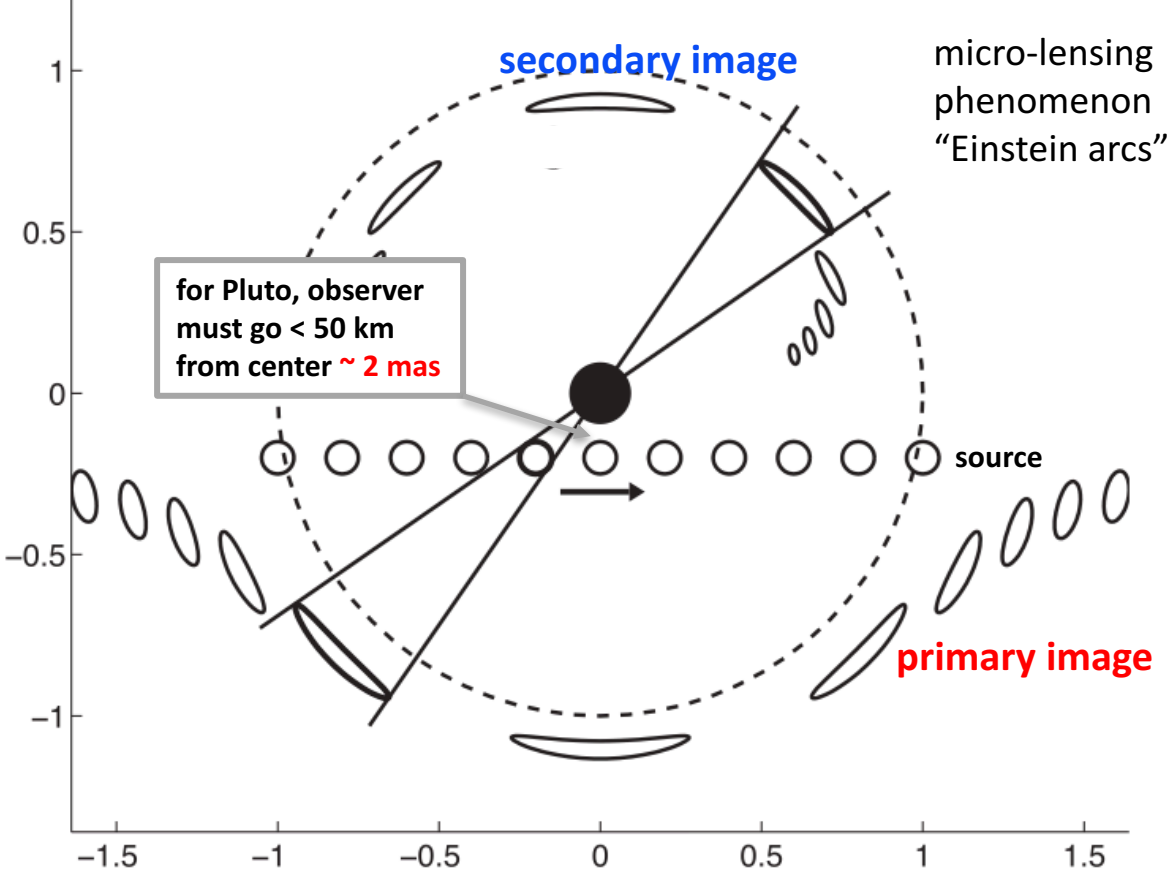



secondary image

primary image
*greatly enhanced*



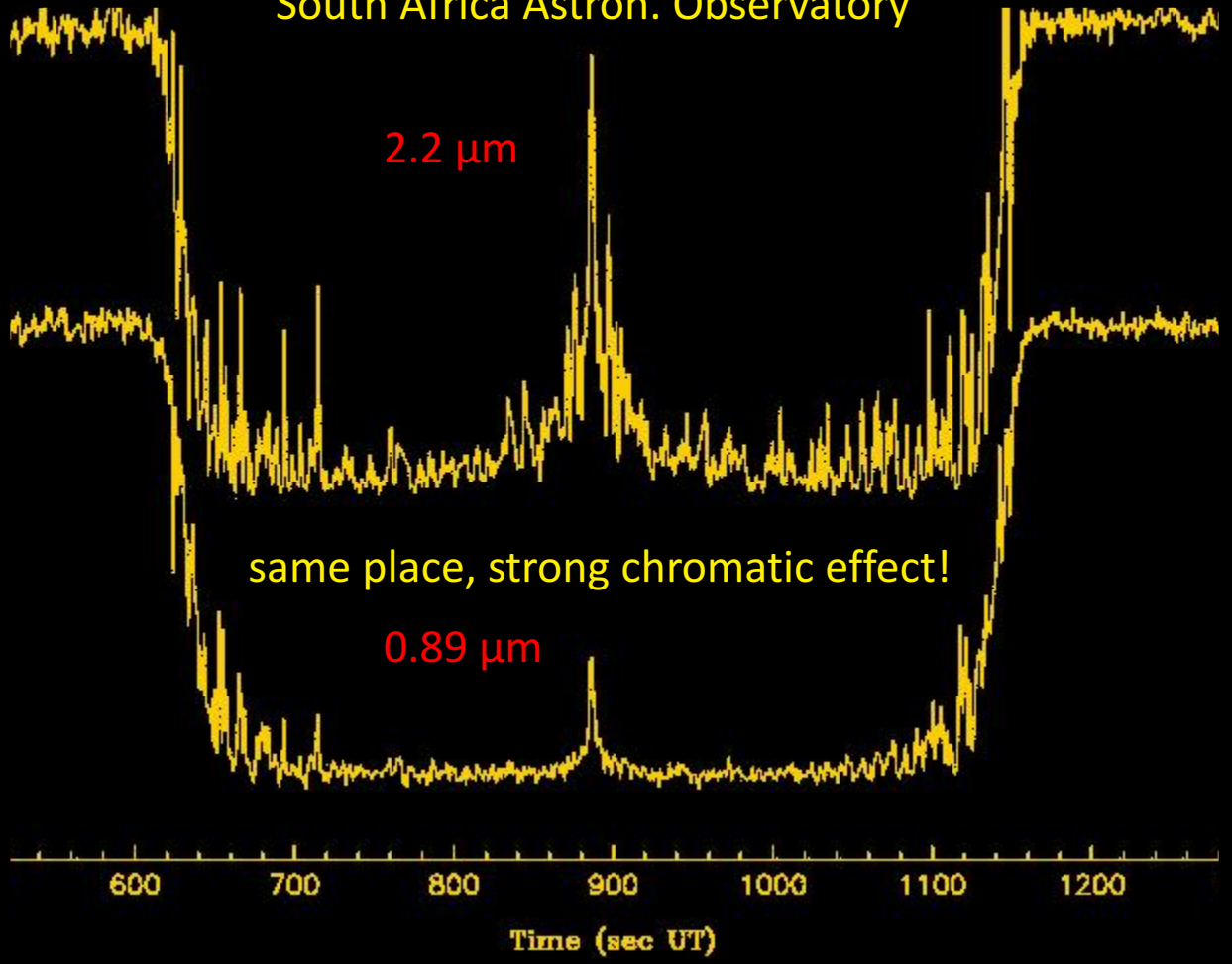

Abe *et al.*
*MNRAS* (2013)



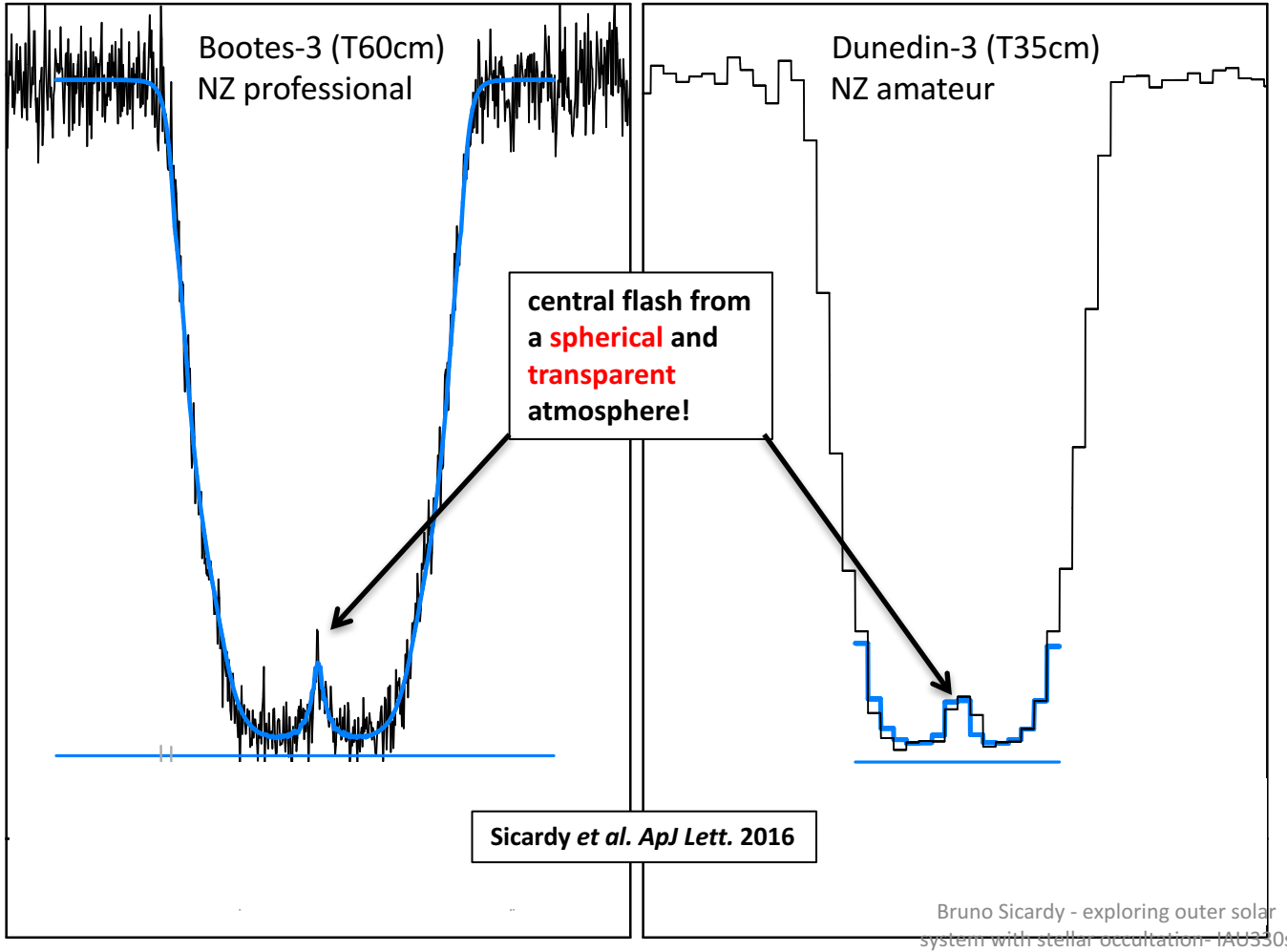

Abe *et al.*
*MNRAS* (2013)

Titan occultation
Namibia
November 2003

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

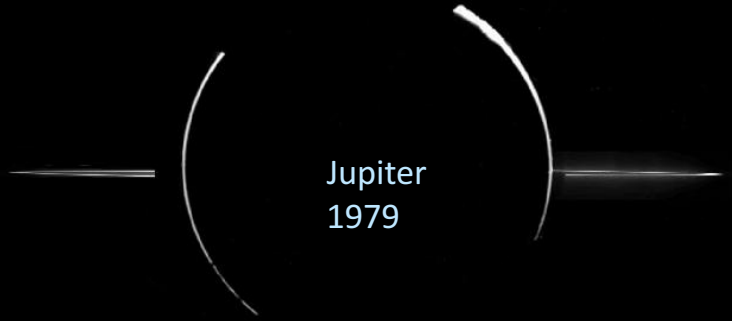


Pluto 29 June 2015 stellar occultation

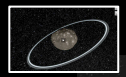


# discovery of rings

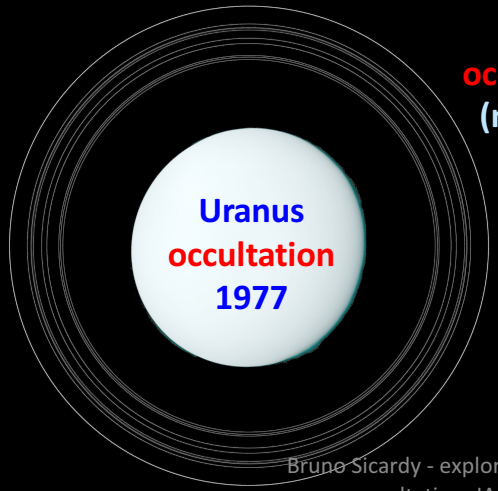
# … first rings ever discovered around a body other than a giant planet

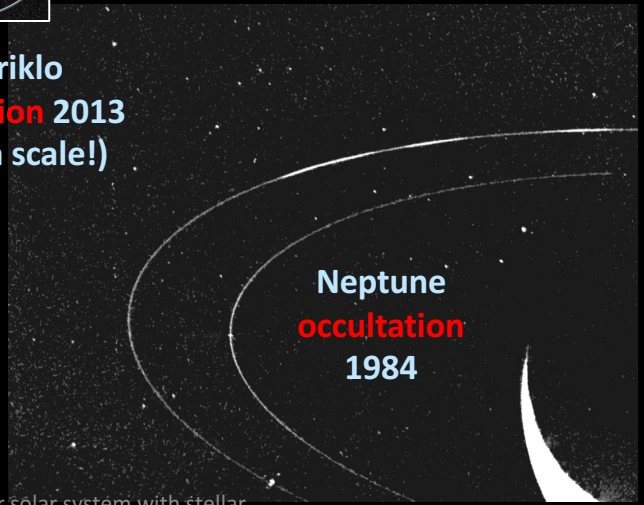






Chariklo
occultation 2013
(not on scale!)



**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]

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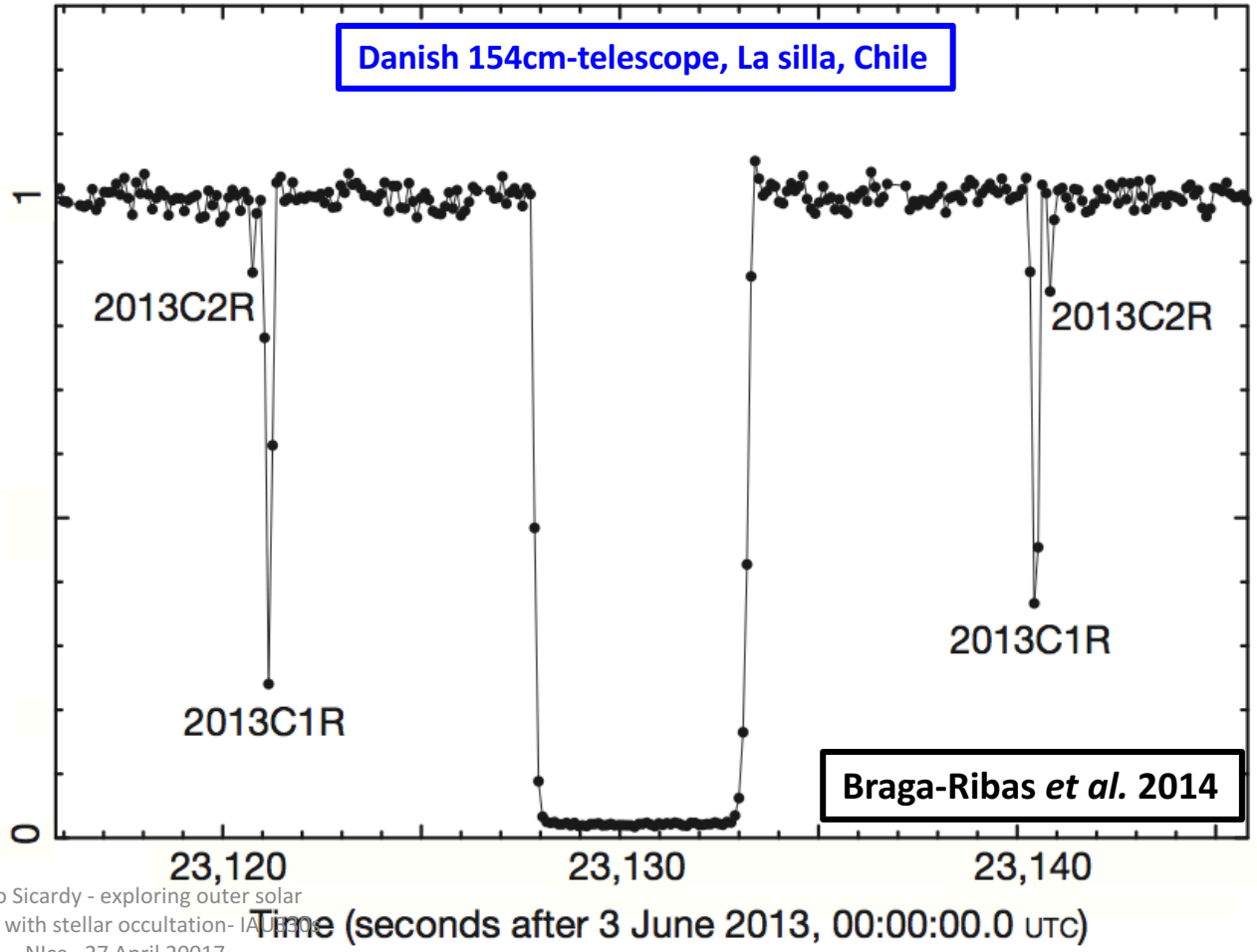
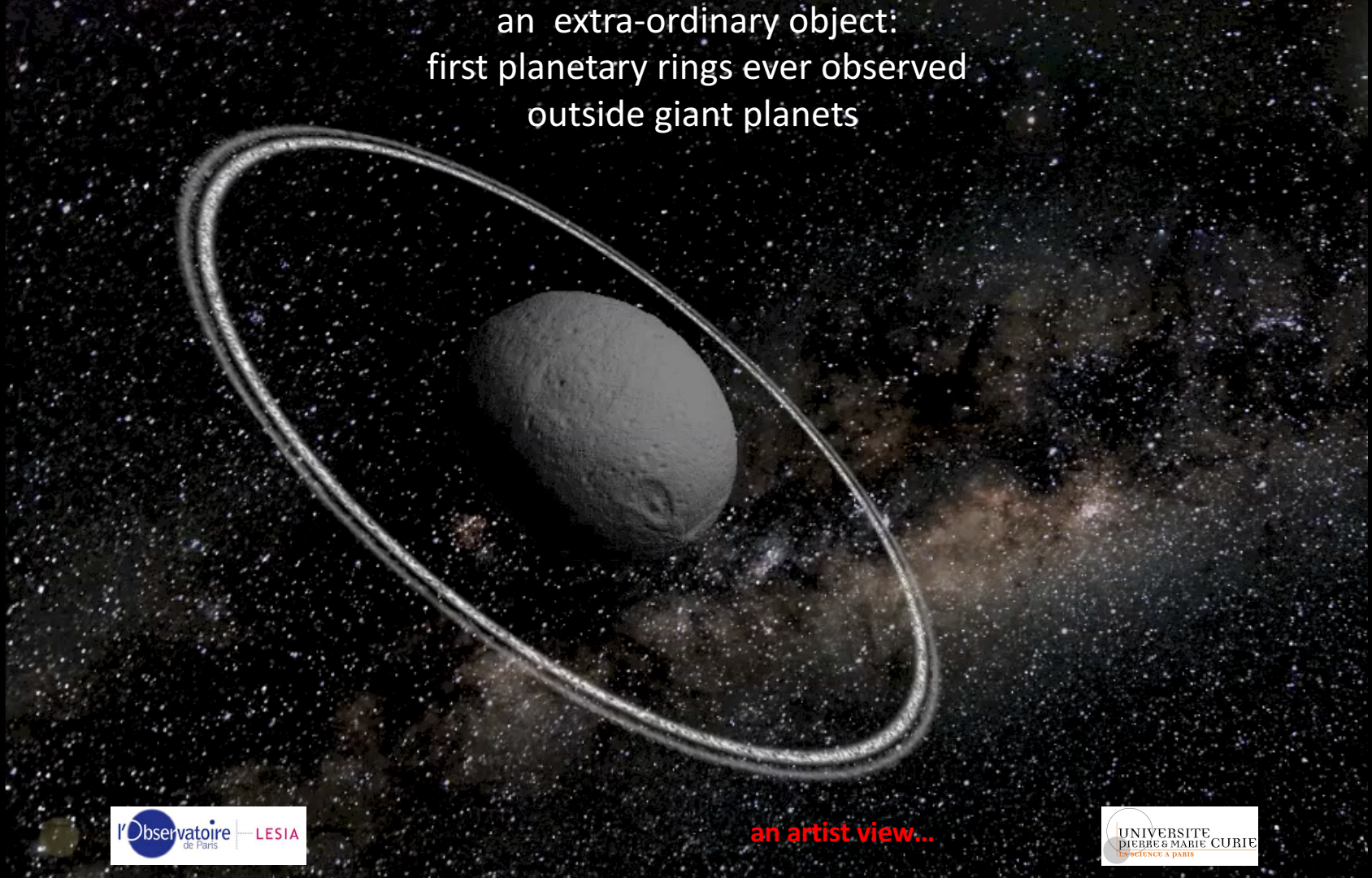
# 20 seconds that changed our conception of rings…

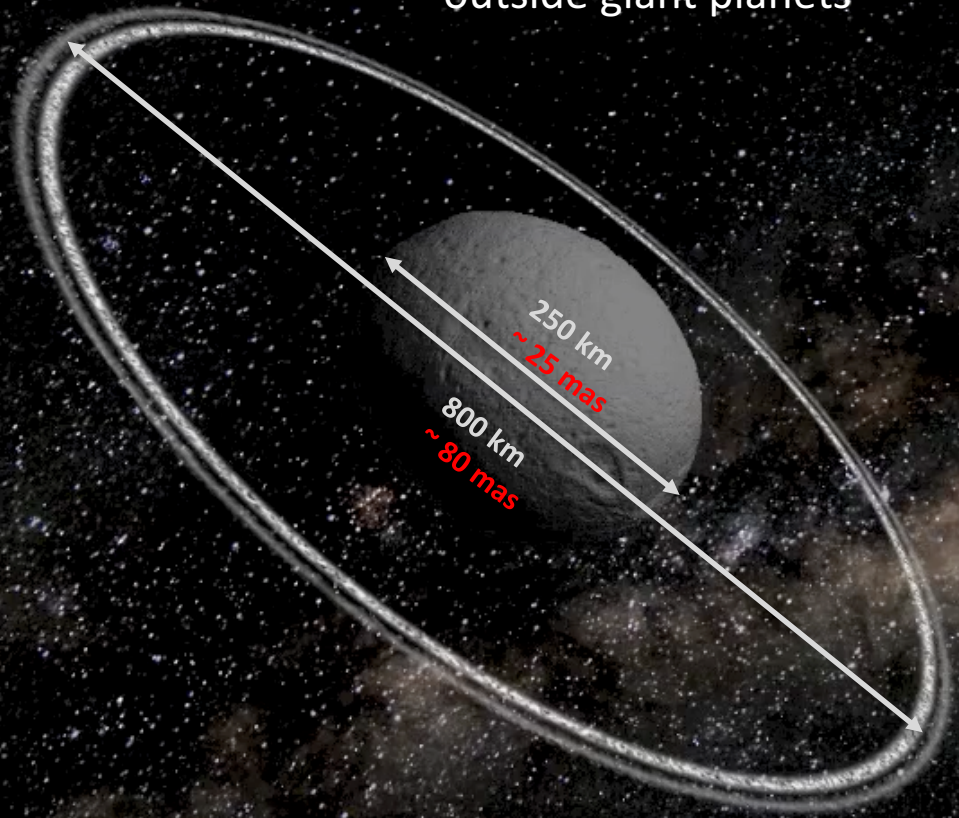


an extra-ordinary object:
first planetary rings ever observed
outside giant planets

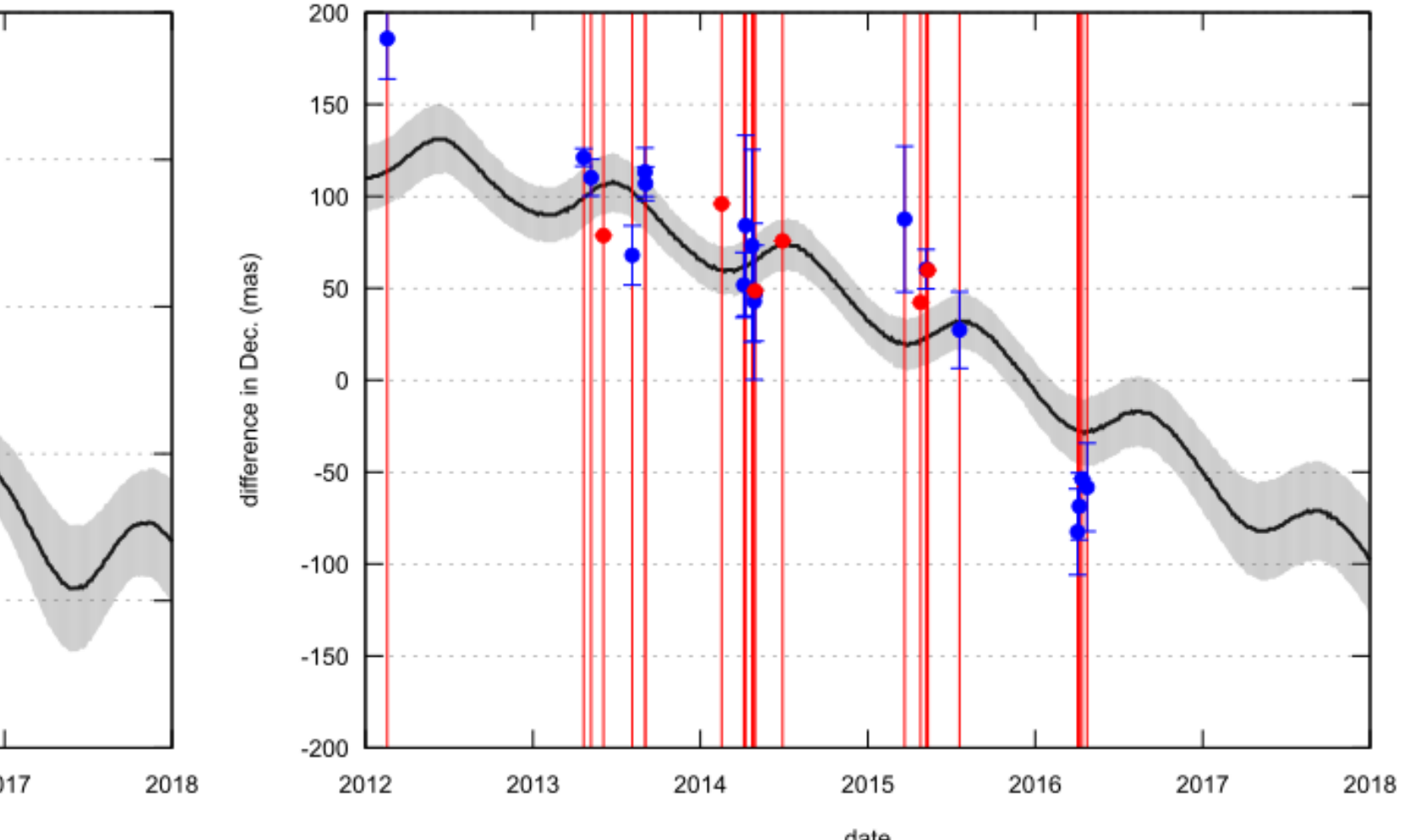


an artist view…

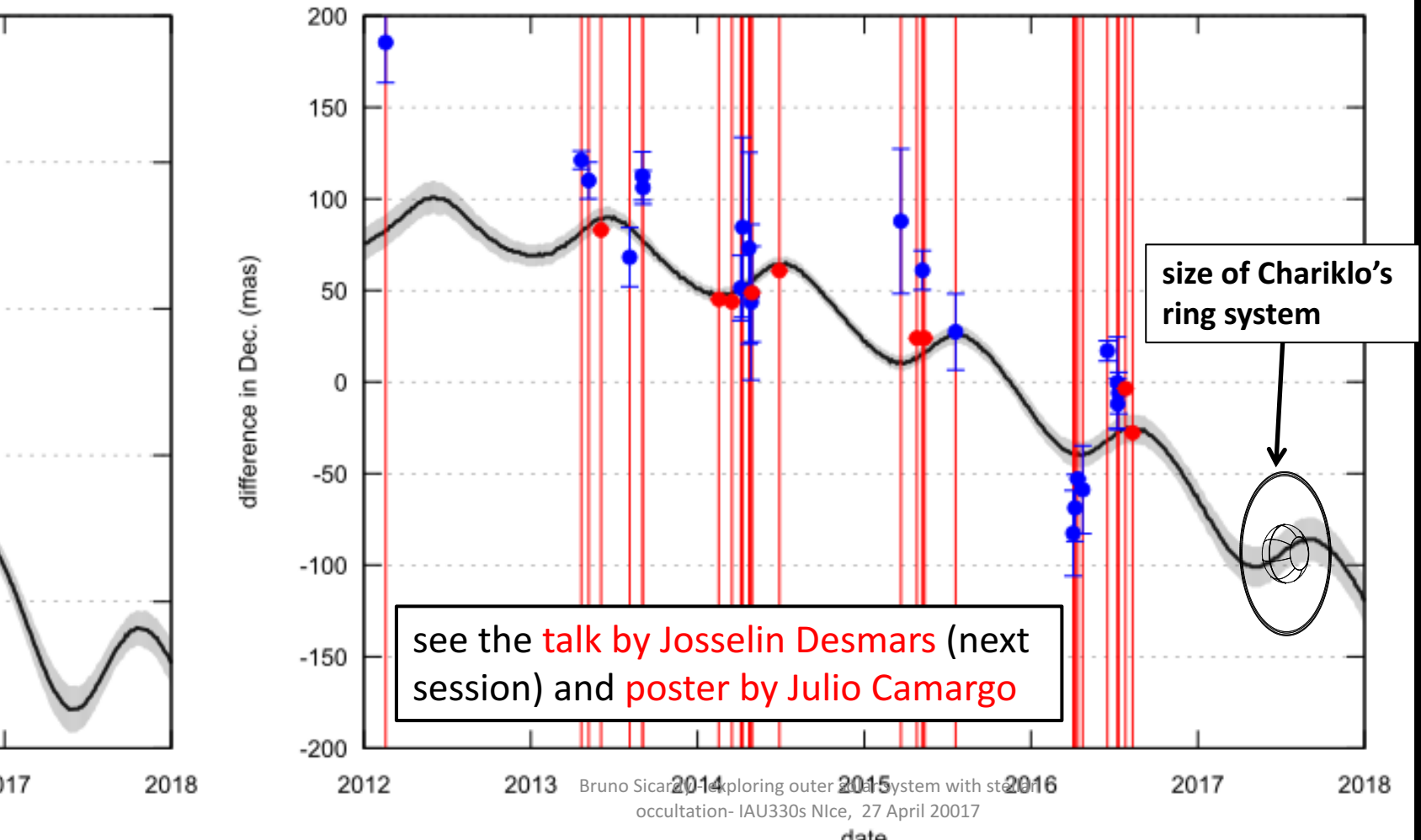
an extra-ordinary object:
first planetary rings ever observed
outside giant planets

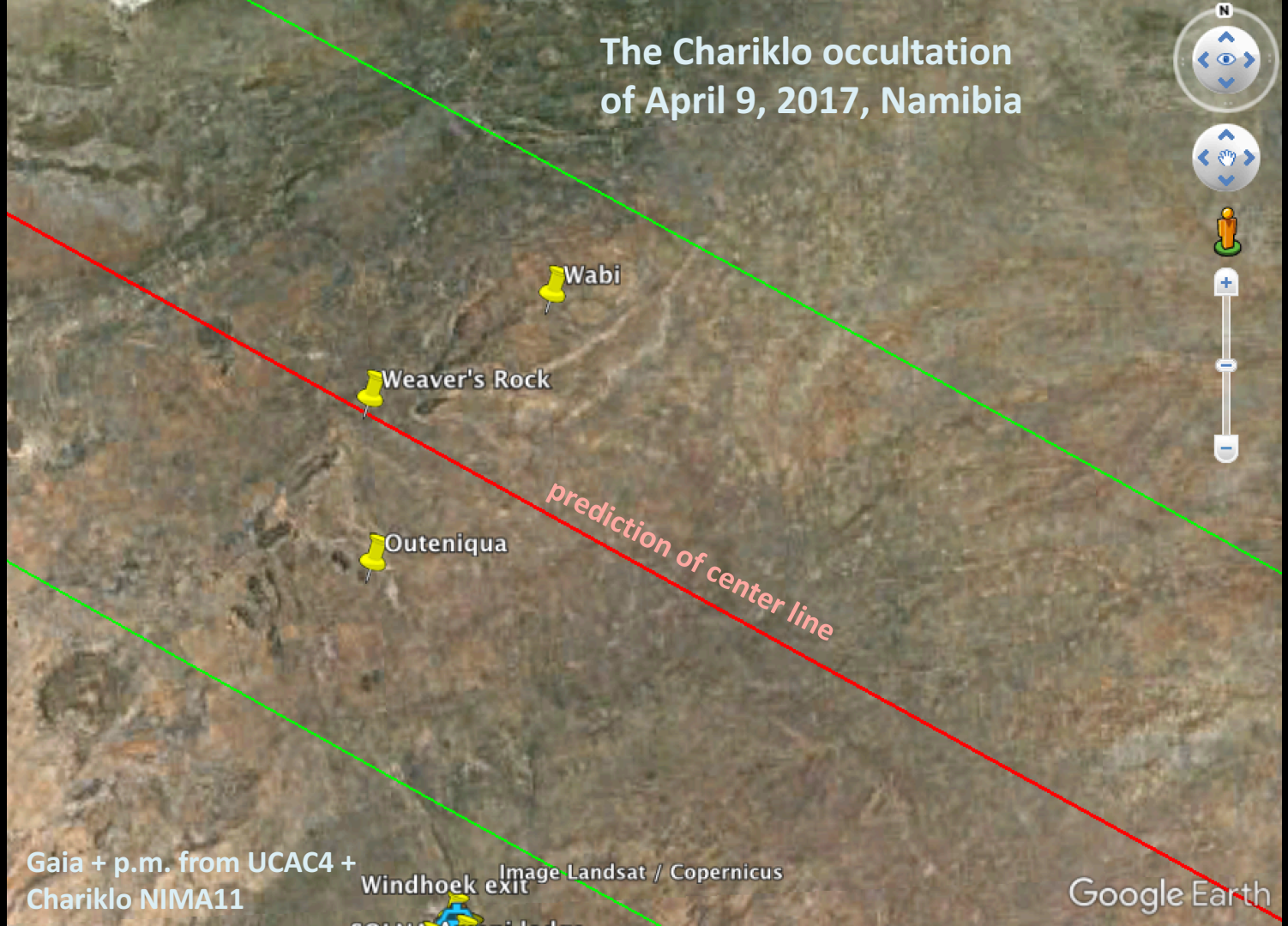


# Chariklo's ephemeris, pre-GAIA



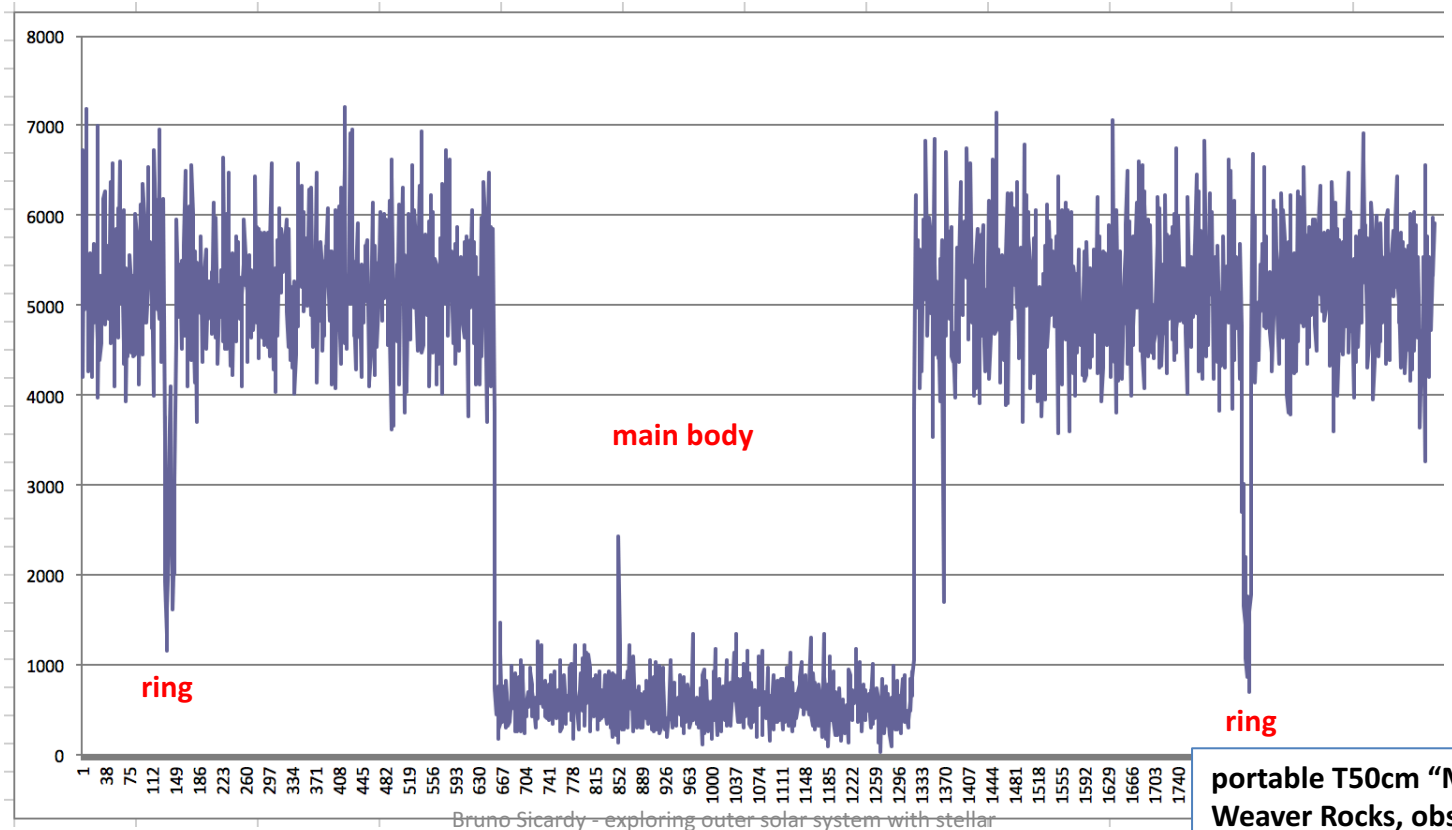
# Chariklo's ephemeris, a bootstrapping approach using GAIA




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

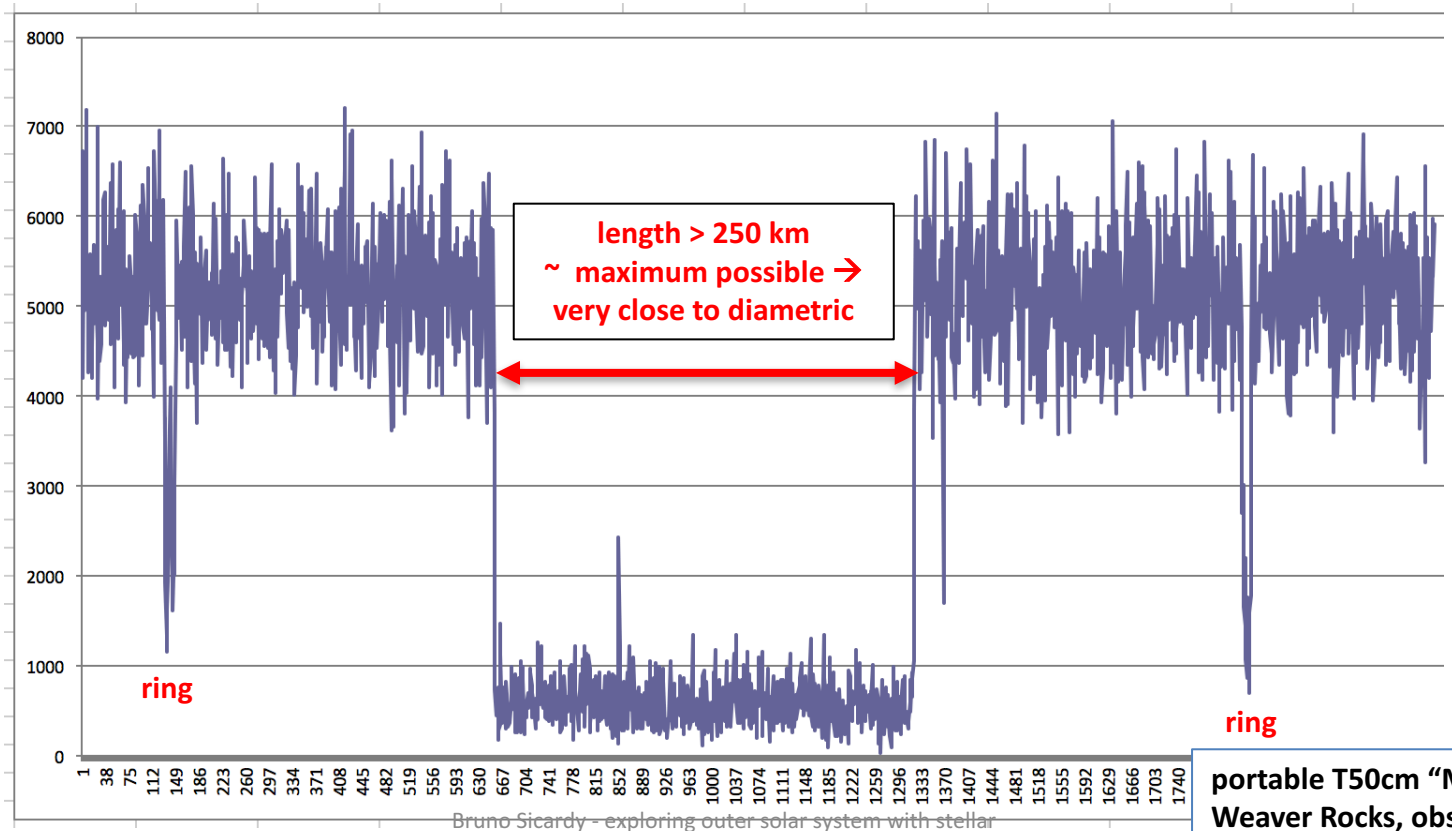
Mike Kretlow preparing the Chariklo occultation of April 9 ,2017 at Weavers Rocks (Namibia, « m2 » 50-cm telescope)
© jean-Luc Dauvergne

# The occultation by Chariklon, Namibia April 9, 2017
(see the talk by Diane Bérard next session)



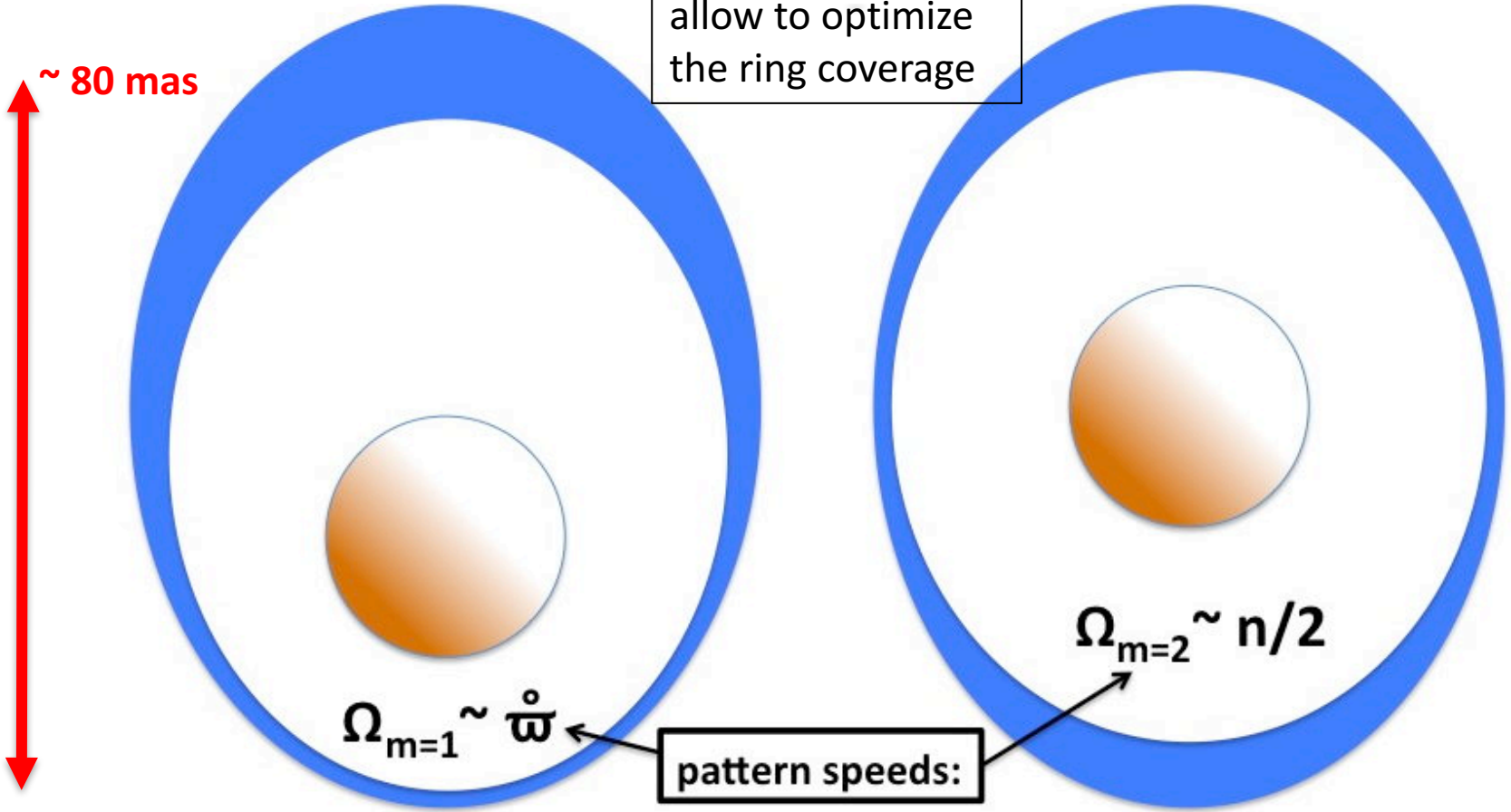

portable T50cm "M2" telescope, Weaver Rocks, obs. Mike Kretlow
analysis Jean-Luc Dauvergne

# The occultation by Chariklon, Namibia April 9, 2017
# (see the talk by Diane Bérard next session)

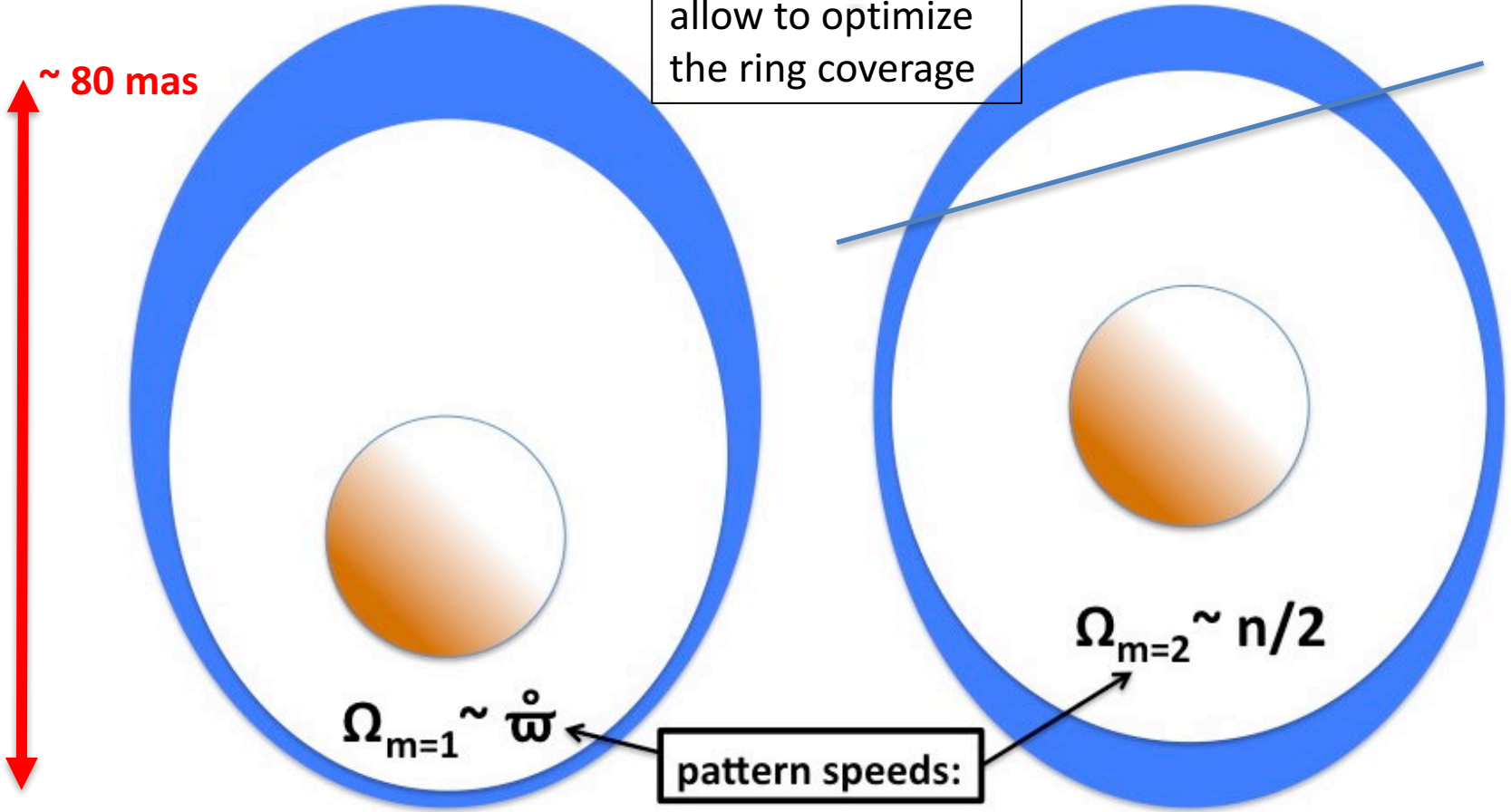



portable T50cm "M2" telescope, Weaver Rocks, obs. Mike Kretlow
analysis Jean-Luc Dauvergne

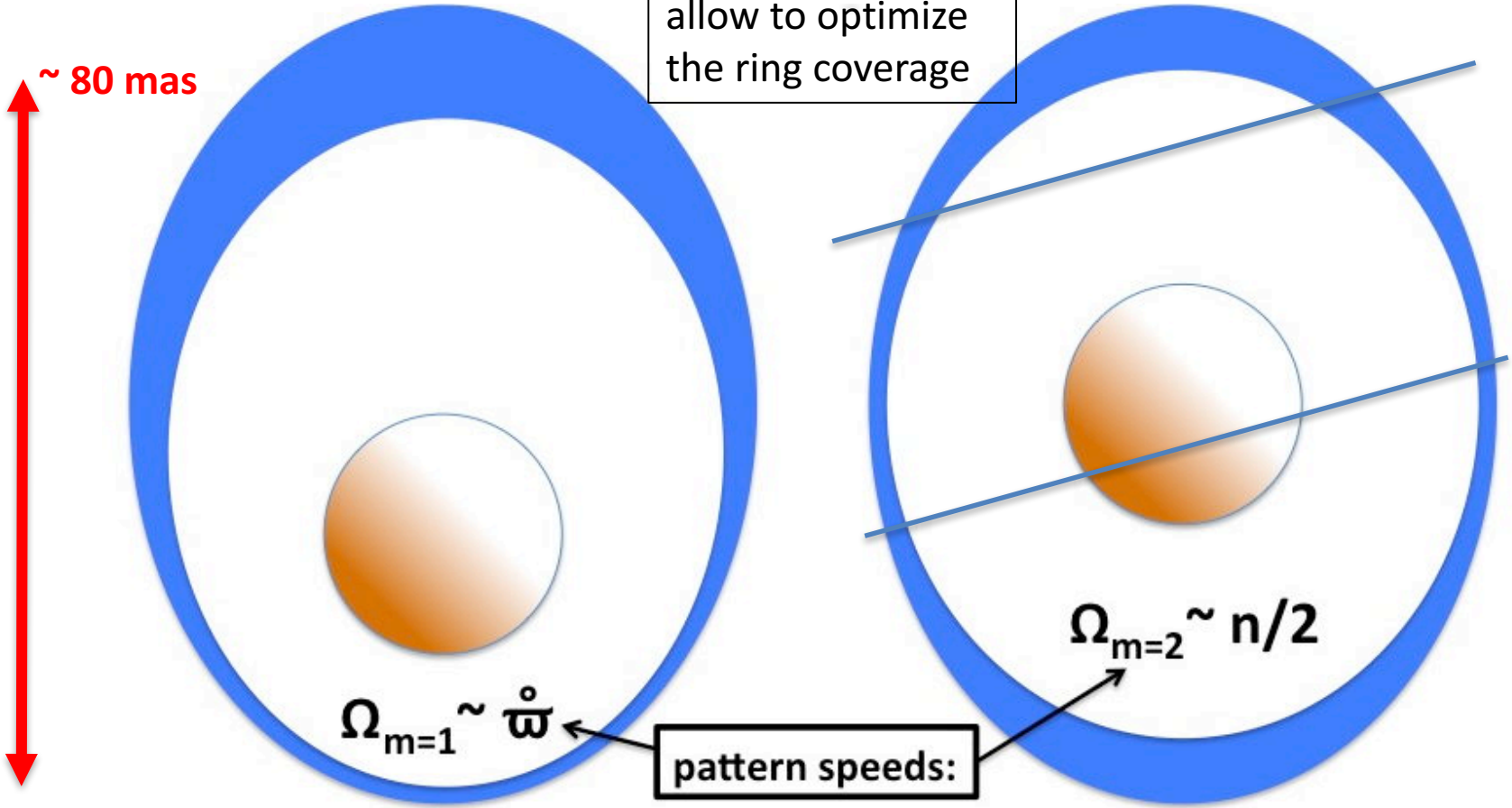
Gaia accuracy will allow to optimize the ring coverage

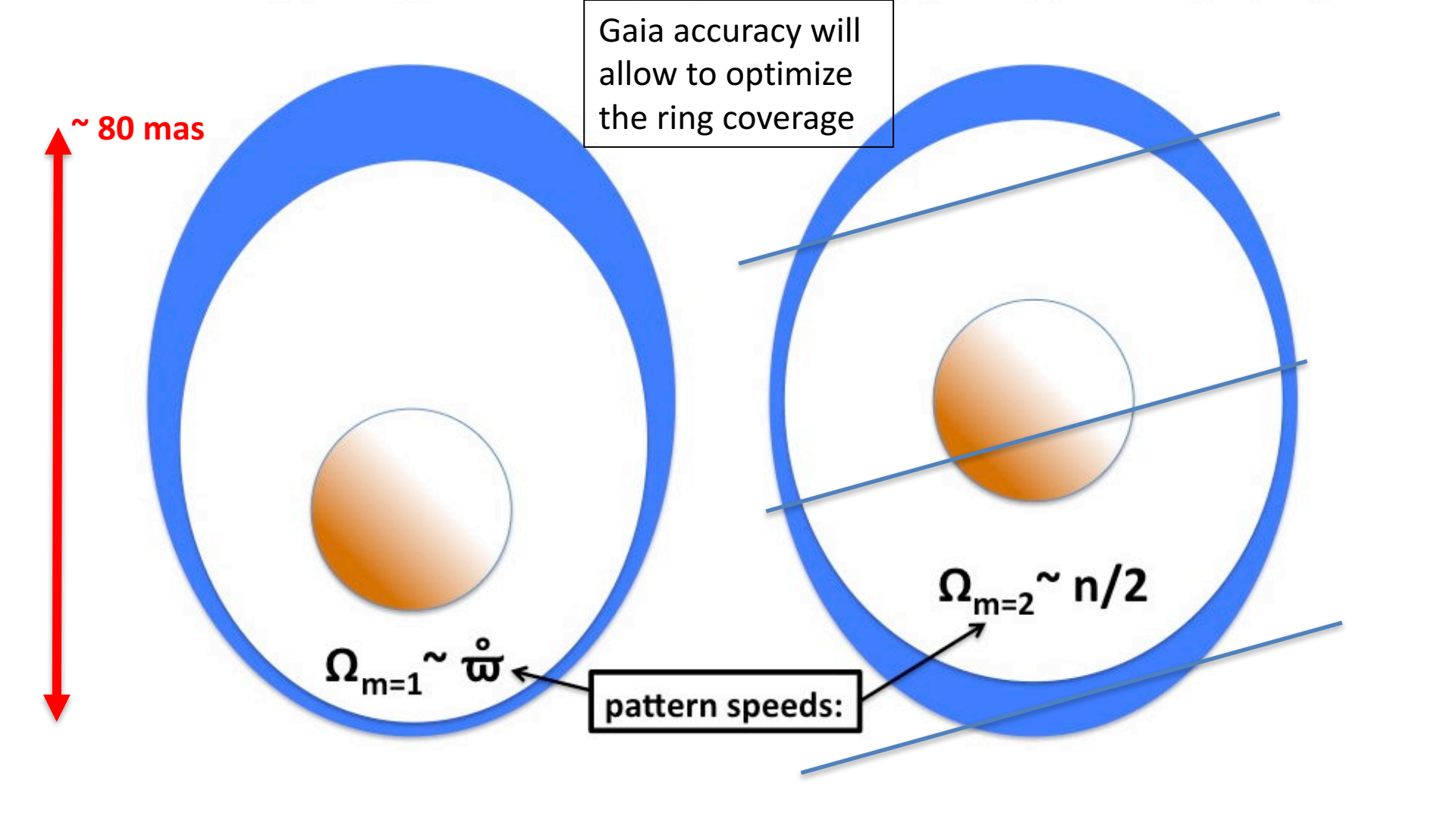


Gaia accuracy will allow to optimize the ring coverage



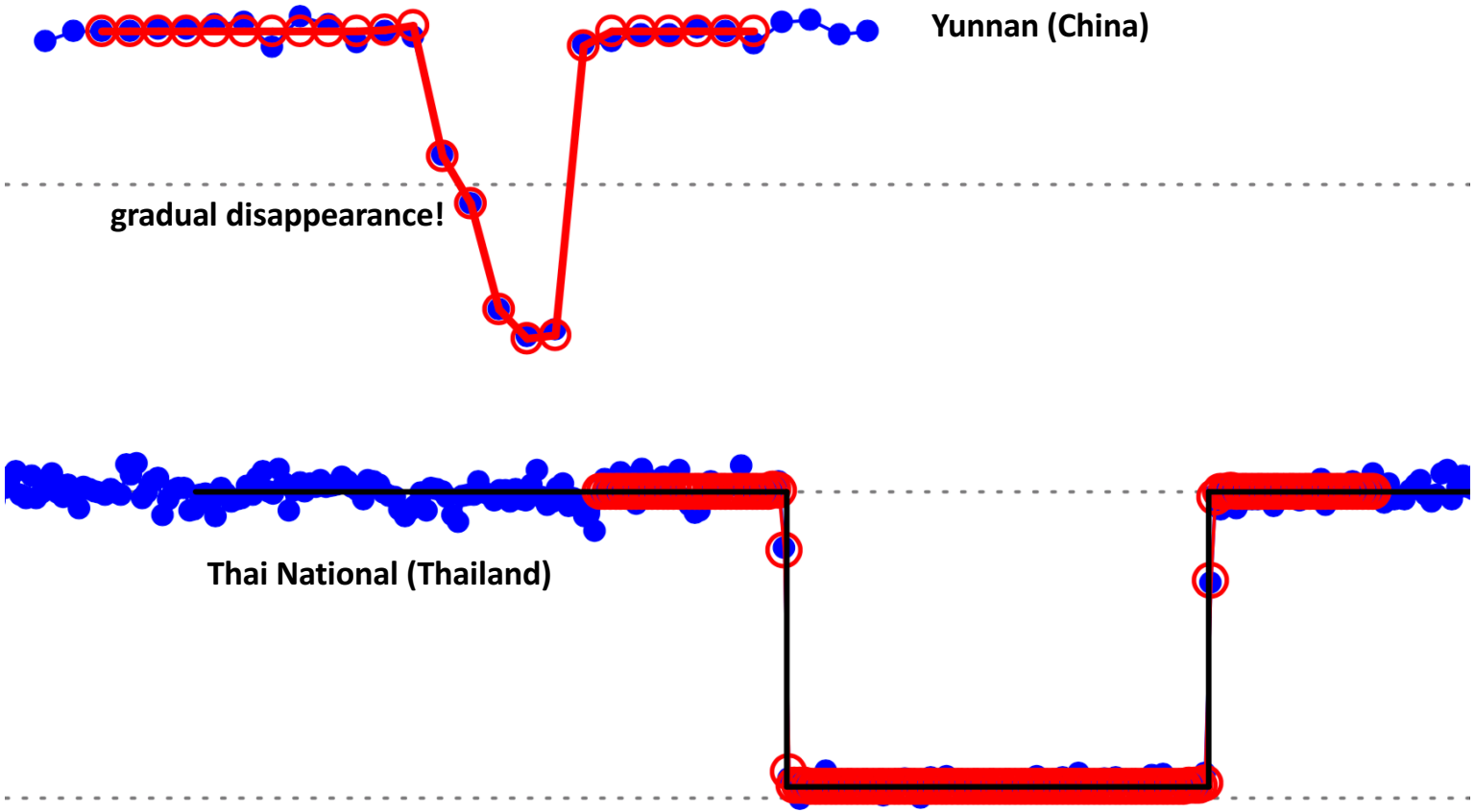
Gaia accuracy will allow to optimize the ring coverage



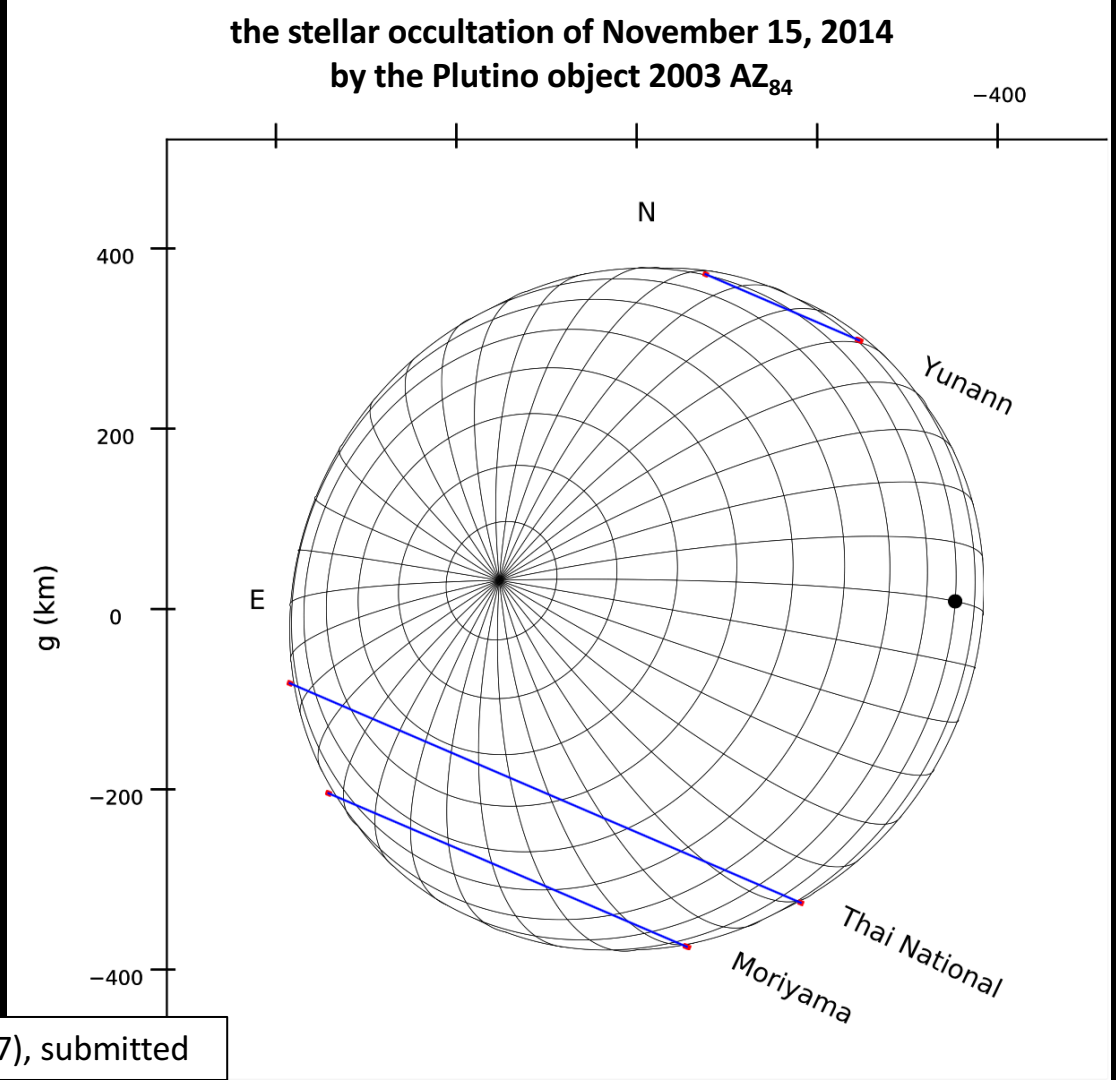

Gaia accuracy will allow to optimize the ring coverage
~ 80 mas
$\Omega_{m=1} \sim \dot{\varpi}$
pattern speeds:
$\Omega_{m=2} \sim n/2$

# topographic features

the stellar occultation of November 15, 2014
by the Plutino object 2003 $AZ_{84}$

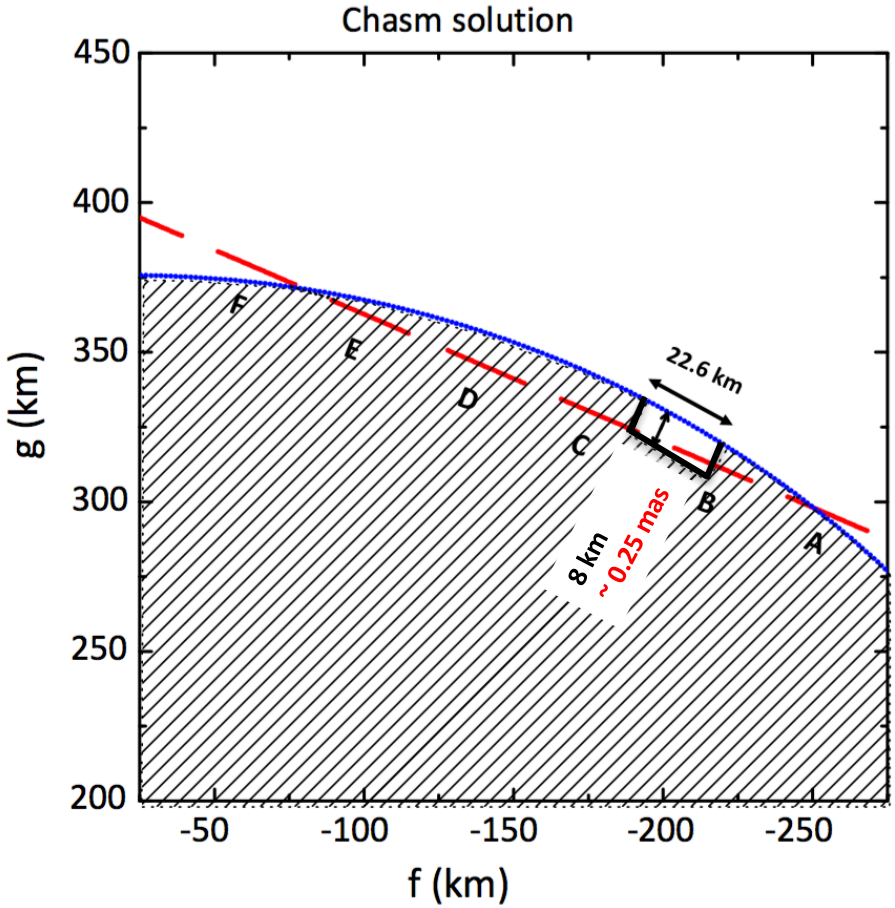


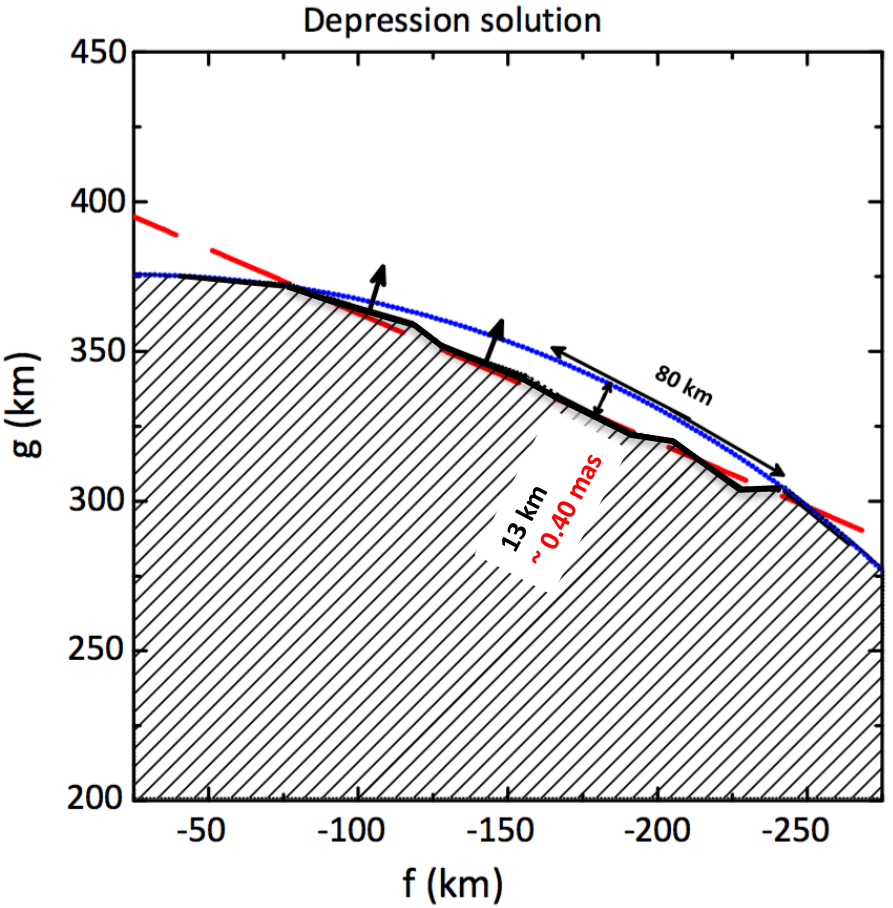

Dias-Oliveira *et al. AJ* (2017), submitted




Dias-Oliveira *et al. AJ* (2017), submitted

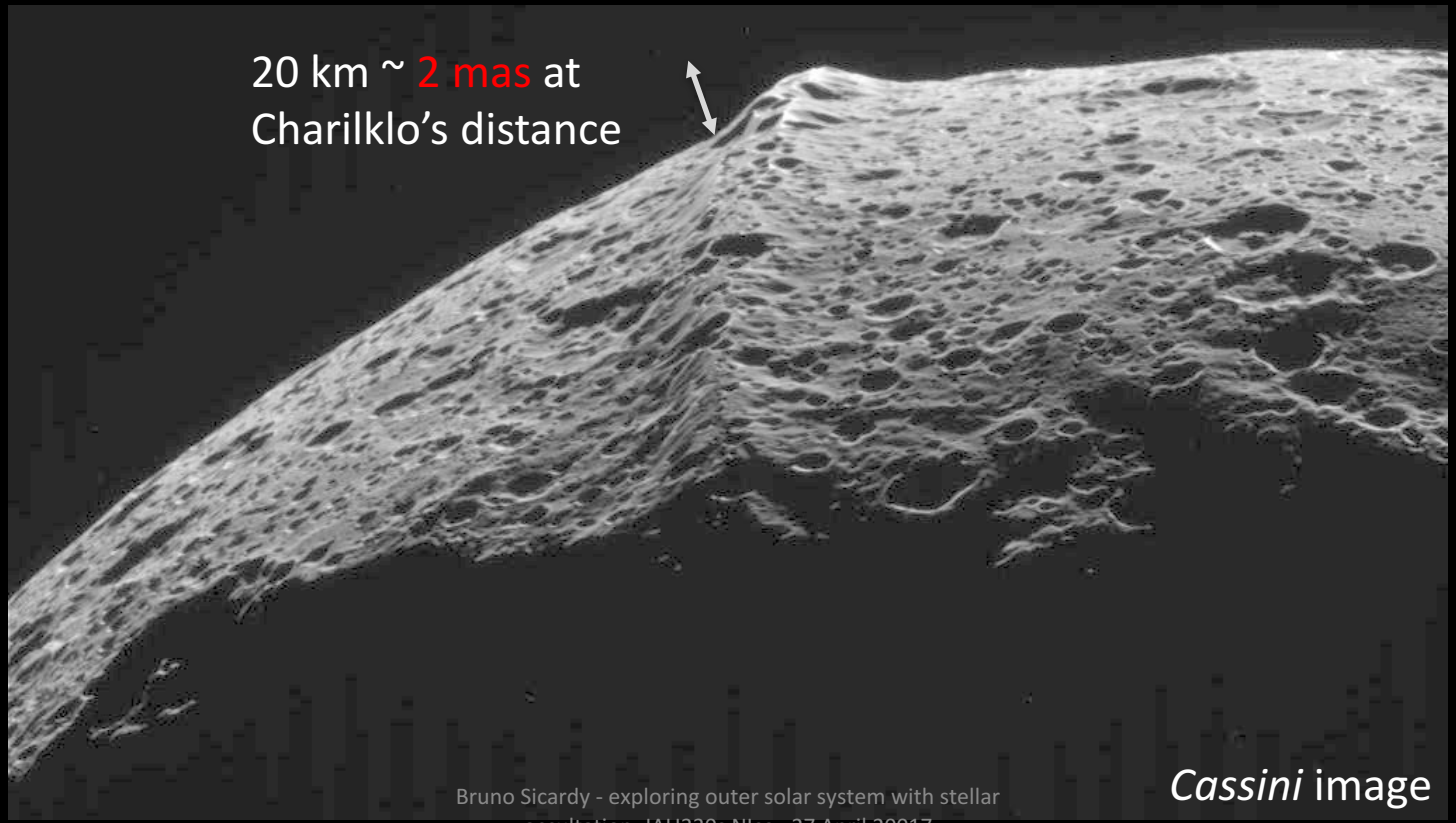
**detection of topographic features**
**on 2003 $AZ_{84}$'s surface**



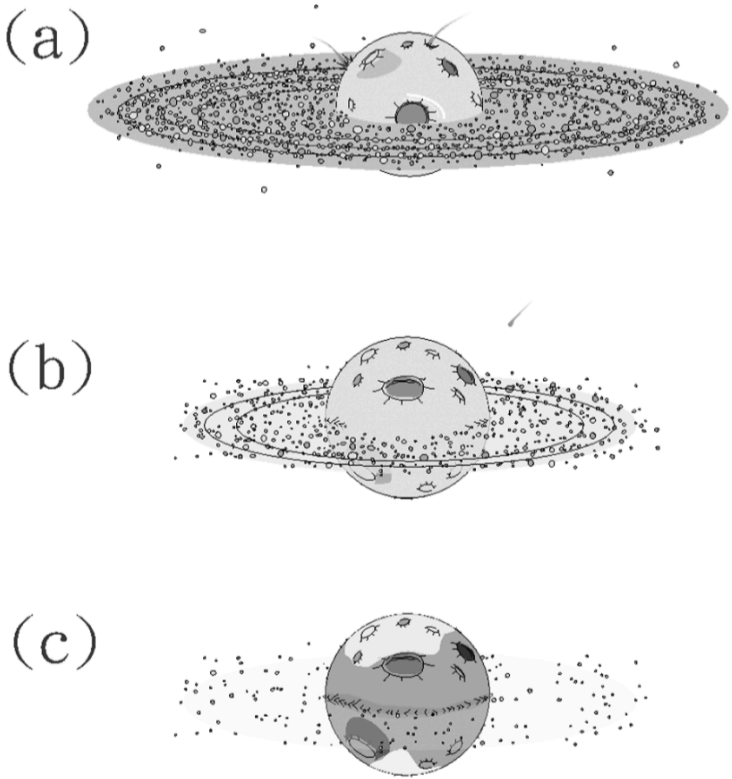




Dias-Oliveira *et al. AJ* (2017), submitted

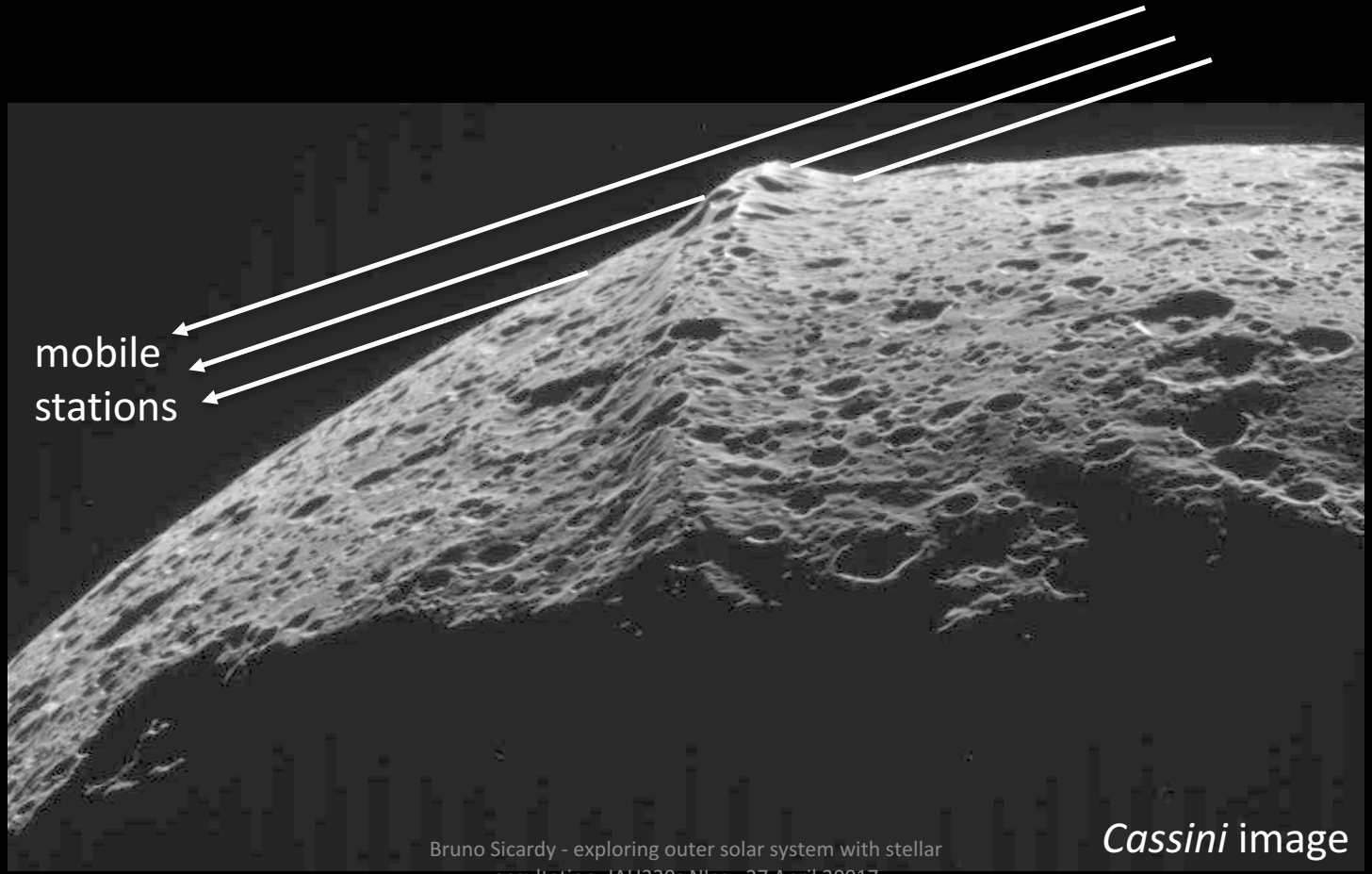
# Iapetus equatorial ridge



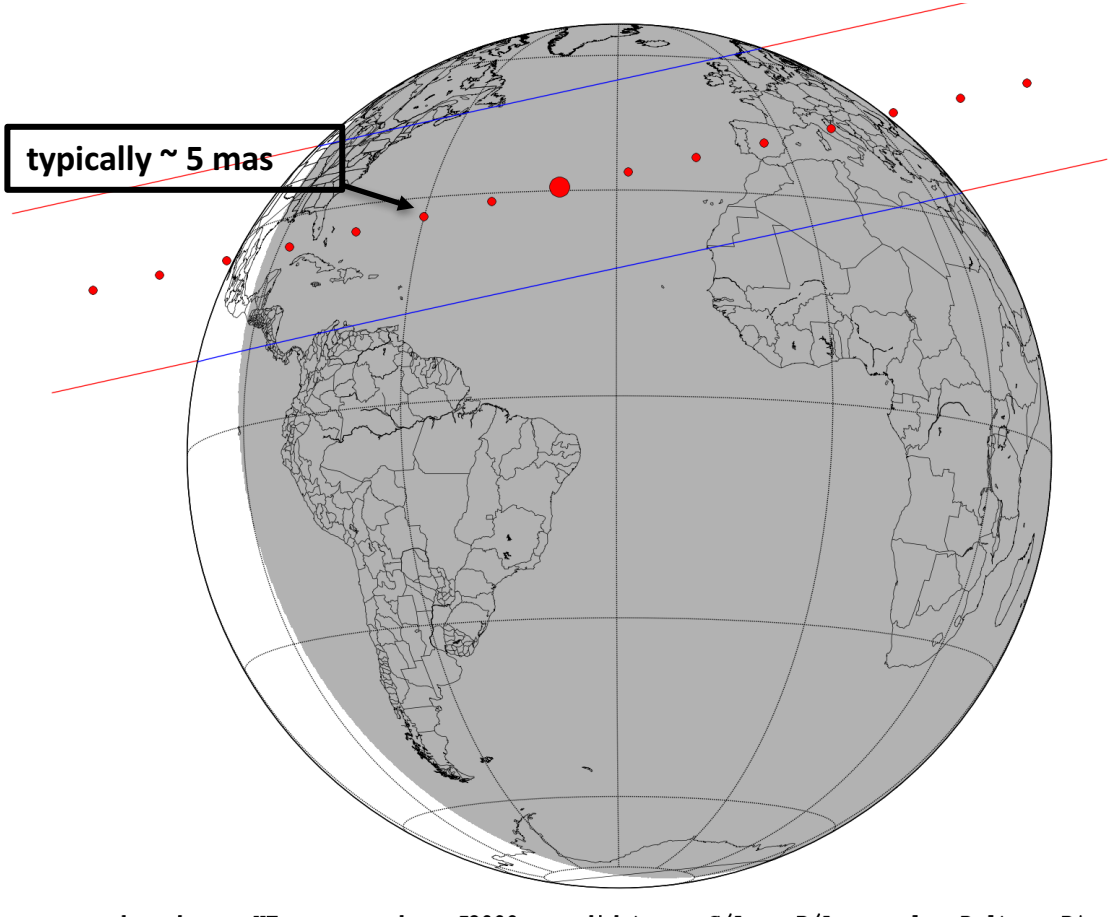
**Formation of rings around Saturn's moon Iapetus**
**W.-H. Ip, *Geophys. Res. Letters* (2006)**



# Iapetus equatorial ridge



the Triton occultation of October 5, 2017



# Conclusions

**Since July 19, 2016, we have observed 4 occultations with prediction accuracies at a few mas level → thank you Gaia!**

**In the near future, we foresee to:**

**discover new ring systems**

**discover atmospheres around the biggest TNO's**

**study shape and geology of those bodies**


look at the indentations!


an ERC project: