Exploring the Solar System using stellar occultations

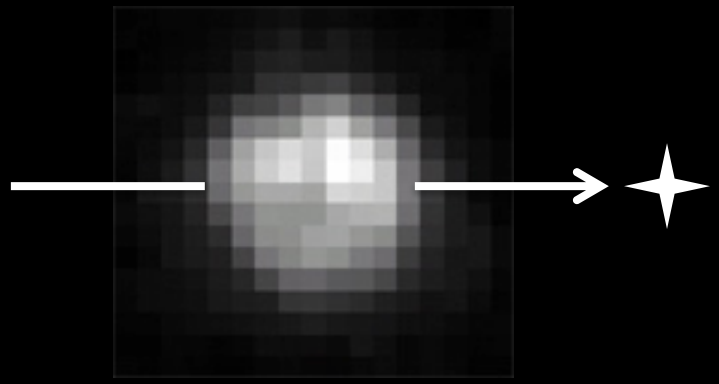
Bruno Sicardy

LESIA/Observatoire de Paris
Univ. Pierre et Marie Curie

an ERC project:

Lucky Star

l'Observatoire de Paris | LESIA | cnrs | UNIVERSITE PIERRE & MARIE CURIE LA SCIENCE A PARIS

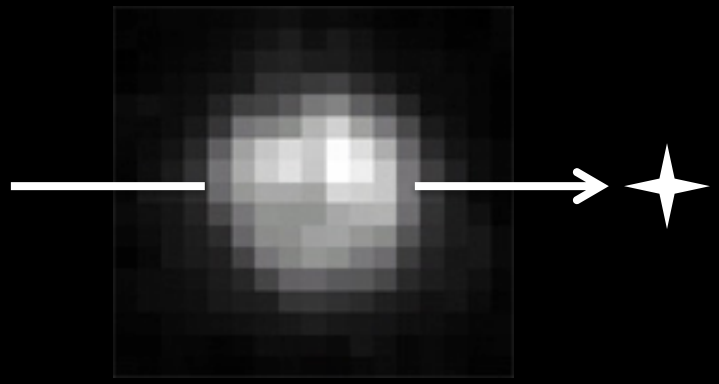


Pluto at best HST resolution
details ~ 500 km at best

Earth's Moon at the same resolution

Occultations: highly efficient method

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



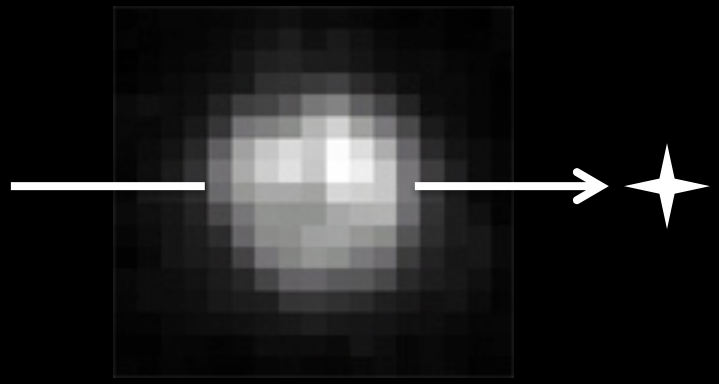
Pluto at best HST resolution
details ~ 500 km at best

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

probing the outer solar system using stellar occultations:

… an active and fruitful field since the 1980's

… with large pro-am collaborations

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.

Nature **1986**

NATURE VOL. 324 20 NOVEMBER 1986

ARTICLES

Occultation determination of Neptune's oblateness and stratospheric methane mixing ratio

E. Lellouch*, W. B. Hubbard†, B. Sicardy*‡, F. Vilas§ & P. Bouchet‖

* Observatoire de Meudon, 92190 Meudon Principal Cedex, France
† Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA
‡ Université de Paris 7, France
§ NASA Johnson Space Center, Houston, Texas 77058, USA
‖ European Southern Observatory, La Silla, Chile

Nature **1986**

NATURE VOL. 320 24 APRIL 1986 LETTERS

More dark matter around Uranus and Neptune?

B. Sicardy*†, F. Roques*, A. Brahic*†, P. Bouchet‡, J. P. Maillard§ & C. Perrier‖

* Observatoire de Paris, 92190 Meudon, France
† Université Paris 7, 2 place Jussieu, 75005 Paris, France
‡ European Southern Observatory, Casilla 19001, Santiago de Chile 19, Chile
§ Canada France Hawaii Telescope Corporation, PO Box 1597, 95743 Hawaii, USA
‖ Observatoire de Lyon, 69230 Saint Genis Laval, France

1990

letters to nature

Nature **343**, 350 - 353 (25 January 1990); doi:10.1038/343350a0

Probing Titan's atmosphere by stellar occultation

B. Sicardy*†, A. Brahic*†, C. Ferrari†, D. Gautier†, J. Lecacheux†, E. Lellouch†, F. Roques†, J. E. Arlot‡, F. Colas‡, W. Thuillot‡, F. Sèvre§, J. L. Vidal‖, C. Blanco¶, S. Cristaldi¶, C. Buil#, A. Klotz# & E. Thouvenot#

letters to nature

2003

Large changes in Pluto's atmosphere as revealed by recent stellar occultations

B. Sicardy[1,2], T. Widemann[1], E. Lellouch[1], C. Veillet[3], J.-C. Cuillandre[3], F. Colas[4], F. Roques[1], W. Beisker[5], M. Kretlow[5], A.-M. Lagrange[6], E. Gendron[1], F. Lacombe[1], J. Lecacheux[1], C. Birnbaum[7], A. Fienga[4], C. Leyrat[1], A. Maury[8], E. Raynaud[1], S. Renner[1], M. Schultheis[9], K. Brooks[10], A. Delsanti[10], O. R. Hainaut[10], R. Gilmozzi[10], C. Lidman[10], J. Spyromilio[10], M. Rapaport[11], P. Rosenzweig[12], O. Naranjo[12], L. Porras[12], F. Díaz[12], H. Calderón[12], S. Carrillo[13], A. Carvajal[13], E. Recalde[13], L. Gaviria Cavero[14], C. Montalvo[14], D. Barría[15], R. Campos[16], R. Duffard[17] & H. Levato[18]

2006

nature Vol 439|5 January 2006|doi:10.1038/nature04351

LETTERS

Charon's size and an upper limit on its atmosphere from a stellar occultation

B. Sicardy[1,2], A. Bellucci[1], E. Gendron[1], F. Lacombe[1], S. Lacour[1], J. Lecacheux[1], E. Lellouch[1], S. Renner[1], S. Pau[1], F. Roques[1], T. Widemann[1], F. Colas[3], F. Vachier[3], R. Vieira Martins[3,15], N. Ageorges[4], O. Hainaut[4], O. Marco[4], W. Beisker[5], E. Hummel[5], C. Feinstein[6], H. Levato[7], A. Maury[8], E. Frappa[9], B. Gaillard[10], M. Lavayssière[10], M. Di Sora[11], F. Mallia[11], G. Masi[11,12], R. Behrend[13], F. Carrier[13], O. Mousis[14], P. Rousselot[14], A. Alvarez-Candal[15], D. Lazzaro[15], C. Veiga[15], A. H. Andrei[15,16], M. Assafin[16], D. N. da Silva Neto[16], C. Jacques[17], E. Pimentel[17], D. Weaver[18], J.-F. Lecampion[19], F. Doncel[20], T. Momiyama[20] & G. Tancredi[21]

2011

LETTER

doi:10.1038/nature10550

A Pluto–like radius and a high albedo for the dwarf planet Eris from an occultation

B. Sicardy[1,2,3], J. L. Ortiz[4], M. Assafin[5], E. Jehin[6], A. Maury[7], E. Lellouch[1], R. Gil Hutton[8], F. Braga-Ribas[1,9], F. Colas[10], D. Hestroffer[10], J. Lecacheux[1], F. Roques[1], P. Santos-Sanz[1], T. Widemann[1], N. Morales[4], R. Duffard[4], A. Thirouin[4], A. J. Castro-Tirado[4], M. Jelínek[4], P. Kubánek[4], A. Sota[4], R. Sánchez-Ramírez[4], A. H. Andrei[5,9], J. I. B. Camargo[5,9], D. N. da Silva Neto[9,11], A. Ramos Gomes Jr[5], R. Vieira Martins[5,9,10], M. Gillon[6], J. Manfroid[6], G. P. Tozzi[12], C. Harlingten[13], S. Saravia[7], R. Behrend[14], S. Mottola[15], E. García Melendo[16,17], V. Peris[18], J. Fabregat[18], J. M. Madiedo[19], L. Cuesta[20], M. T. Eibe[20], A. Ullán[20], F. Organero[21], S. Pastor[22], J. A. de los Reyes[22], S. Pedraz[23], A. Castro[24], I. de la Cueva[25], G. Muler[26], I. A. Steele[27], M. Cebrián[28], P. Montañés-Rodríguez[28], A. Oscoz[28], D. Weaver[29], C. Jacques[30], W. J. B. Corradi[31], F. P. Santos[31], W. Reis[31], A. Milone[32], M. Emilio[33], L. Gutiérrez[34], R. Vázquez[34] & H. Hernández-Toledo[35]

2012

LETTER

doi:10.1038/nature11597

Albedo and atmospheric constraints of dwarf planet Makemake from a stellar occultation

J. L. Ortiz[1], B. Sicardy[2,3,4], F. Braga-Ribas[2,5], A. Alvarez-Candal[6,1], E. Lellouch[2], R. Duffard[1], N. Pinilla-Alonso[1,7], V. D. Ivanov[6], S. P. Littlefair[8], J. I. B. Camargo[5], M. Assafin[9], E. Unda-Sanzana[10], E. Jehin[11], N. Morales[1], G. Tancredi[12], R. Gil-Hutton[13], I. de la Cueva[14], J. P. Colque[10], D. N. Da Silva Neto[5], J. Manfroid[11], A. Thirouin[1], P. J. Gutiérrez[1], J. Lecacheux[2], M. Gillon[11], A. Maury[15], F. Colas[16], J. Licandro[17], T. Mueller[18], C. Jacques[19], D. Weaver[20], A. Milone[21], R. Salvo[12], S. Bruzzone[12], F. Organero[22], R. Behrend[23], S. Roland[12], R. Vieira-Martins[9,5,16], T. Widemann[2], F. Roques[2], P. Santos-Sanz[1,2], D. Hestroffer[16], V. S. Dhillon[8], T. R. Marsh[24], C. Harlingten[25], A. Campo Bagatin[26], M. L. Alonso[27], M. Ortiz[28], C. Colazo[29], H. J. F. Lima[30], A. S. Oliveira[30], L. O. Kerber[31], R. Smiljanic[32], E. Pimentel[19], B. Giacchini[19], P. Cacella[33] & M. Emilio[34]

2014

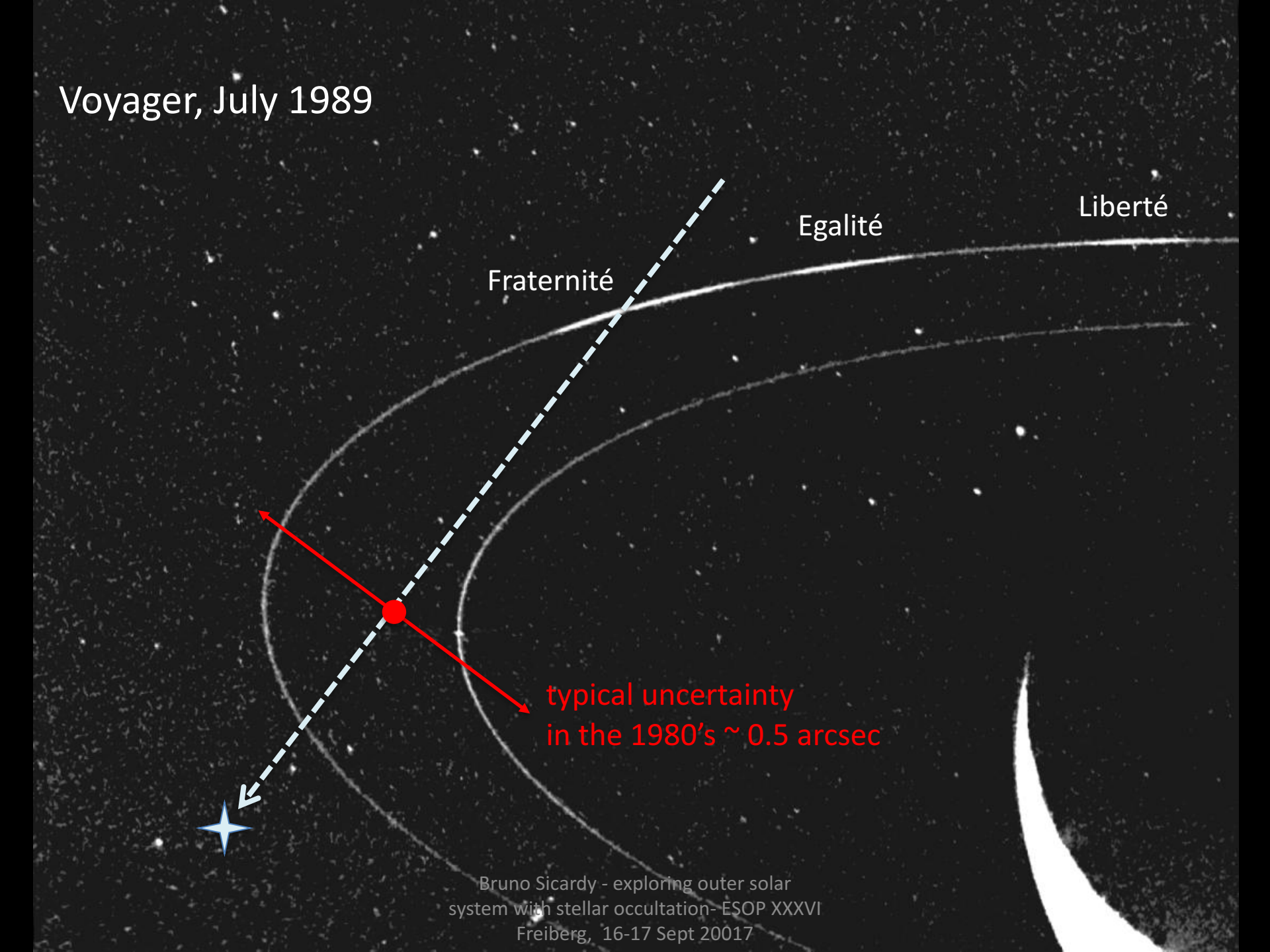
LETTER

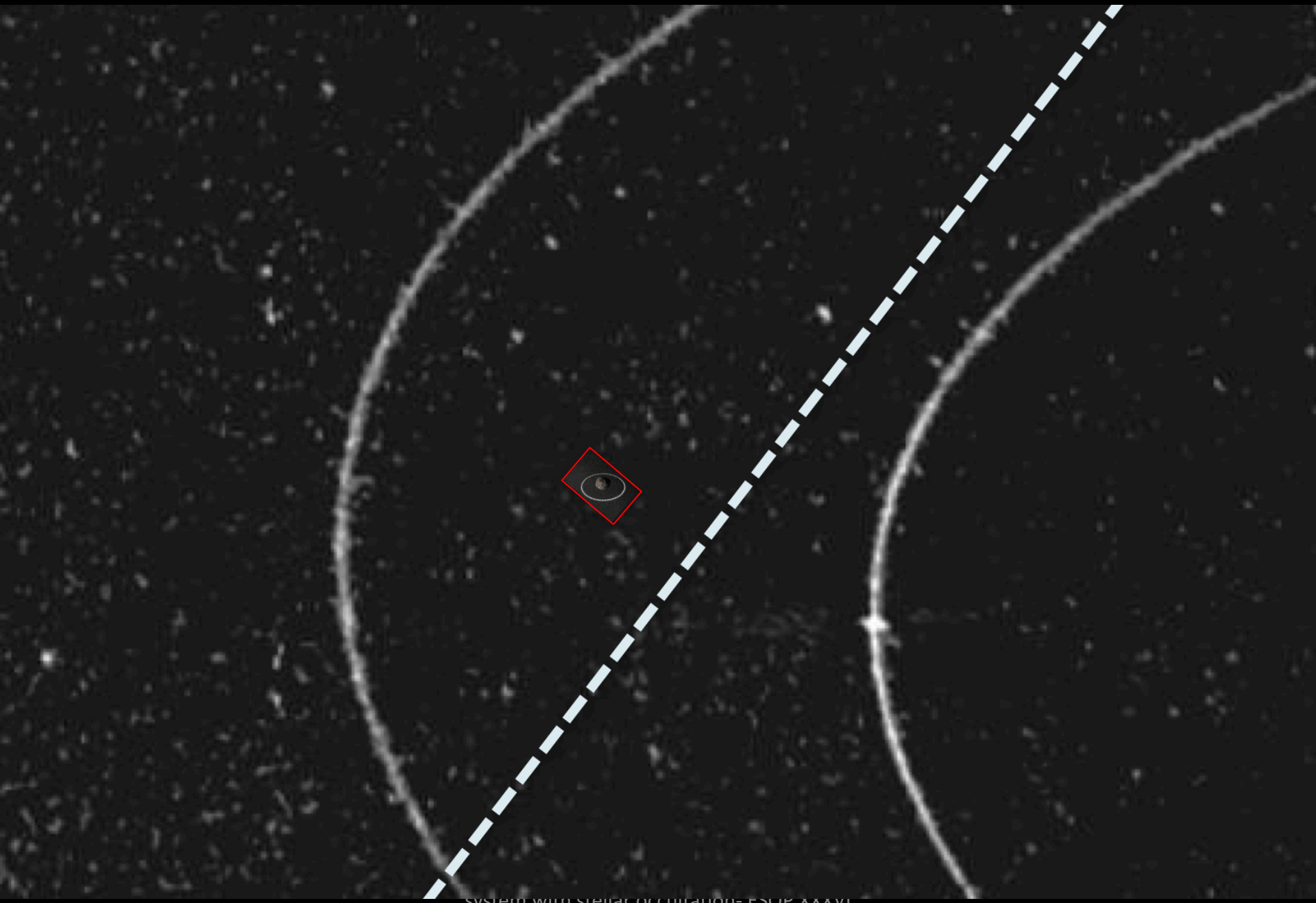
doi:10.1038/nature13155

A ring system detected around the Centaur (10199) Chariklo

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]

… and more


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



system with stellar occultation- ESOP XXXVI
Freiberg, 16-17 Sept 20017

1980's: errors of ~1 arcsec

1990's: 200 mas

2000's: Hipparcos → UCAC4 + follow up of Trans-Neptunian Objects → ~ 30 -40 mas (2016)

15 September 2016 DR1 + UCAC4-based pm → few mas

April 2018 Gaia DR2 : < 1 mas → three orders of magnitude gained!

Titan

E-ELT angular resolution at 1 µm with AO (~ 6 mas)

quaoar

Pluto

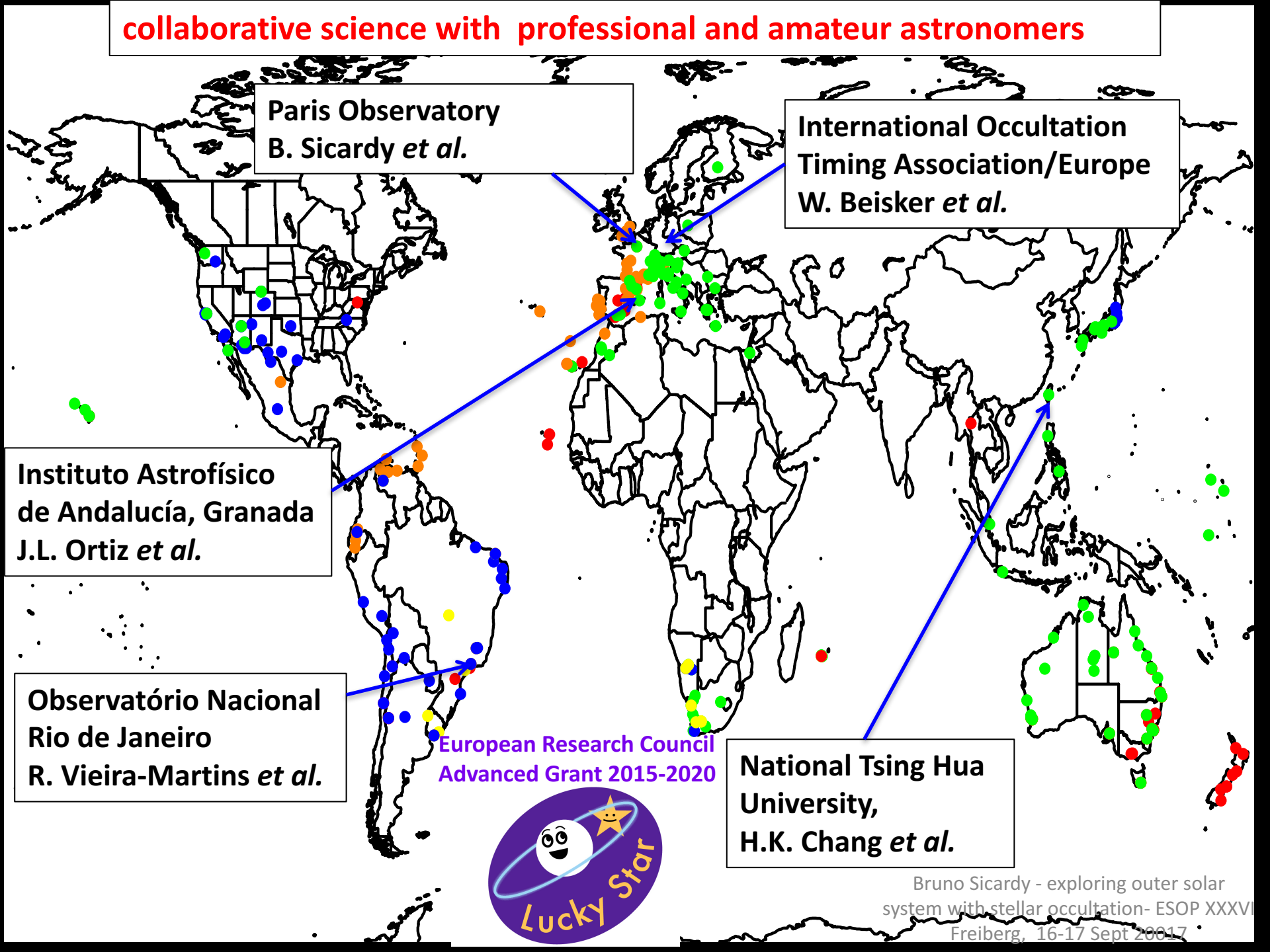
Charon

Eris

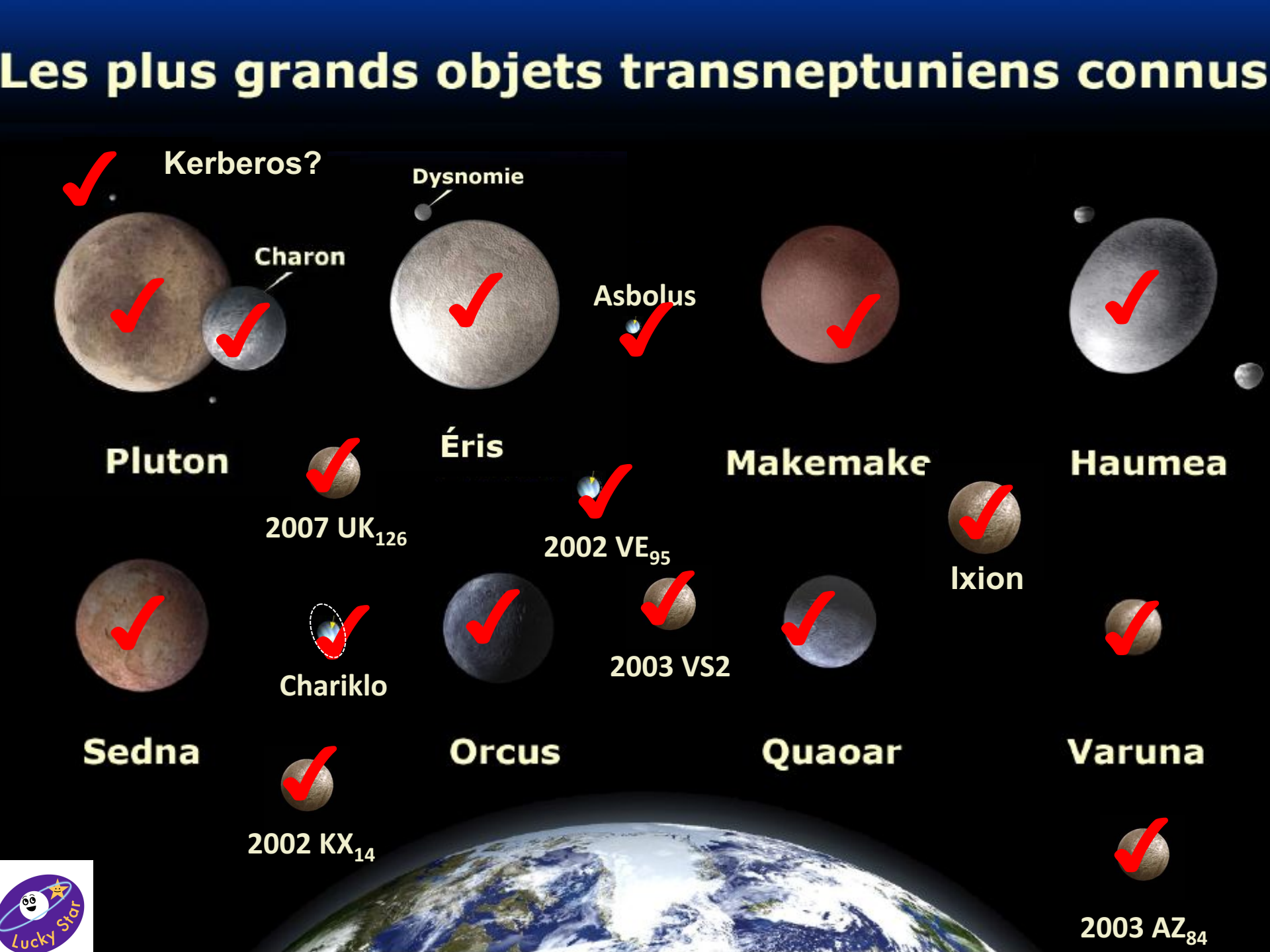
a stamp viewed at 150 km

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

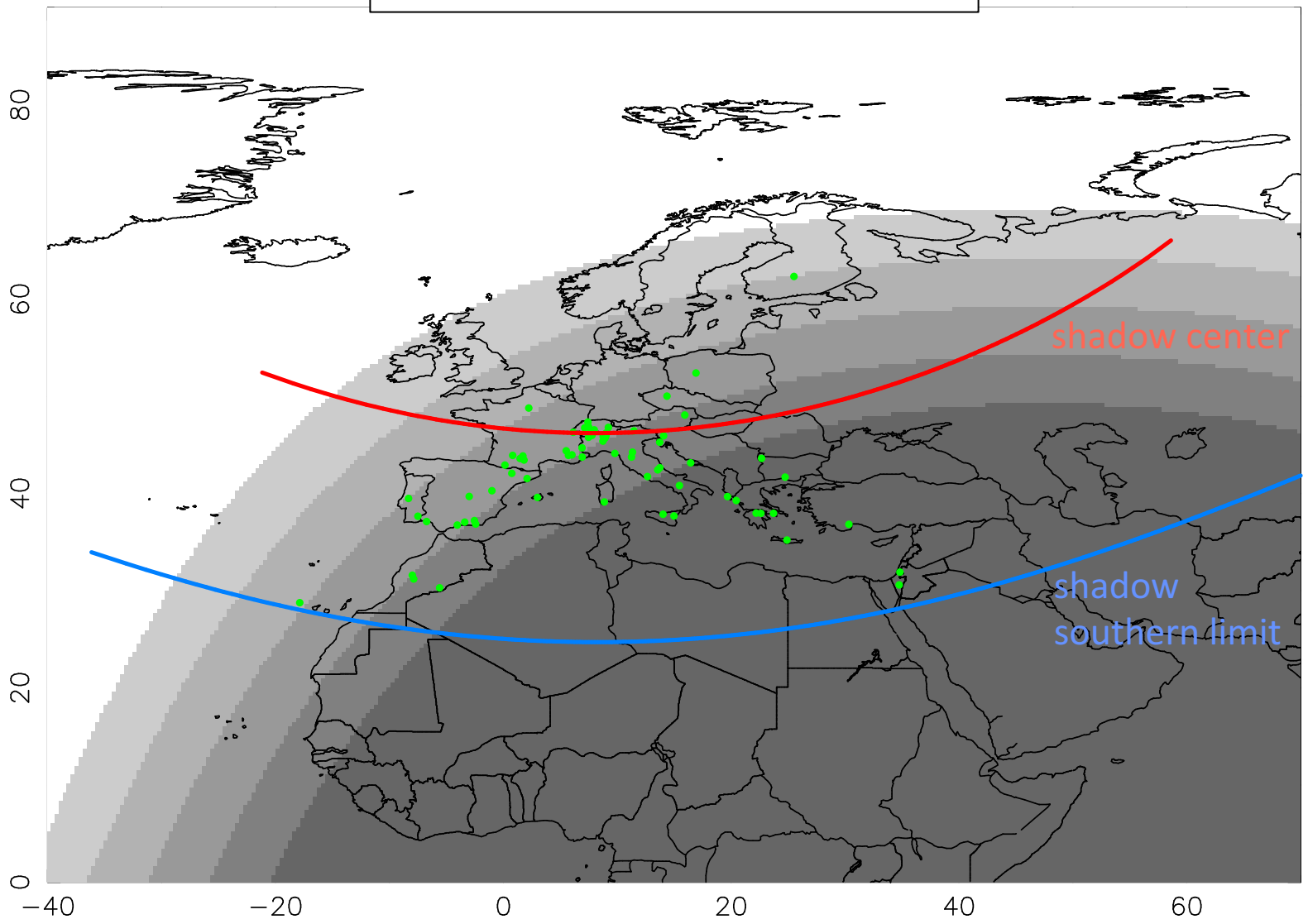
Makemake


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
National Tsing Hua University,
H.K. Chang *et al.*
Lucky Star

Les plus grands objets transneptuniens connus

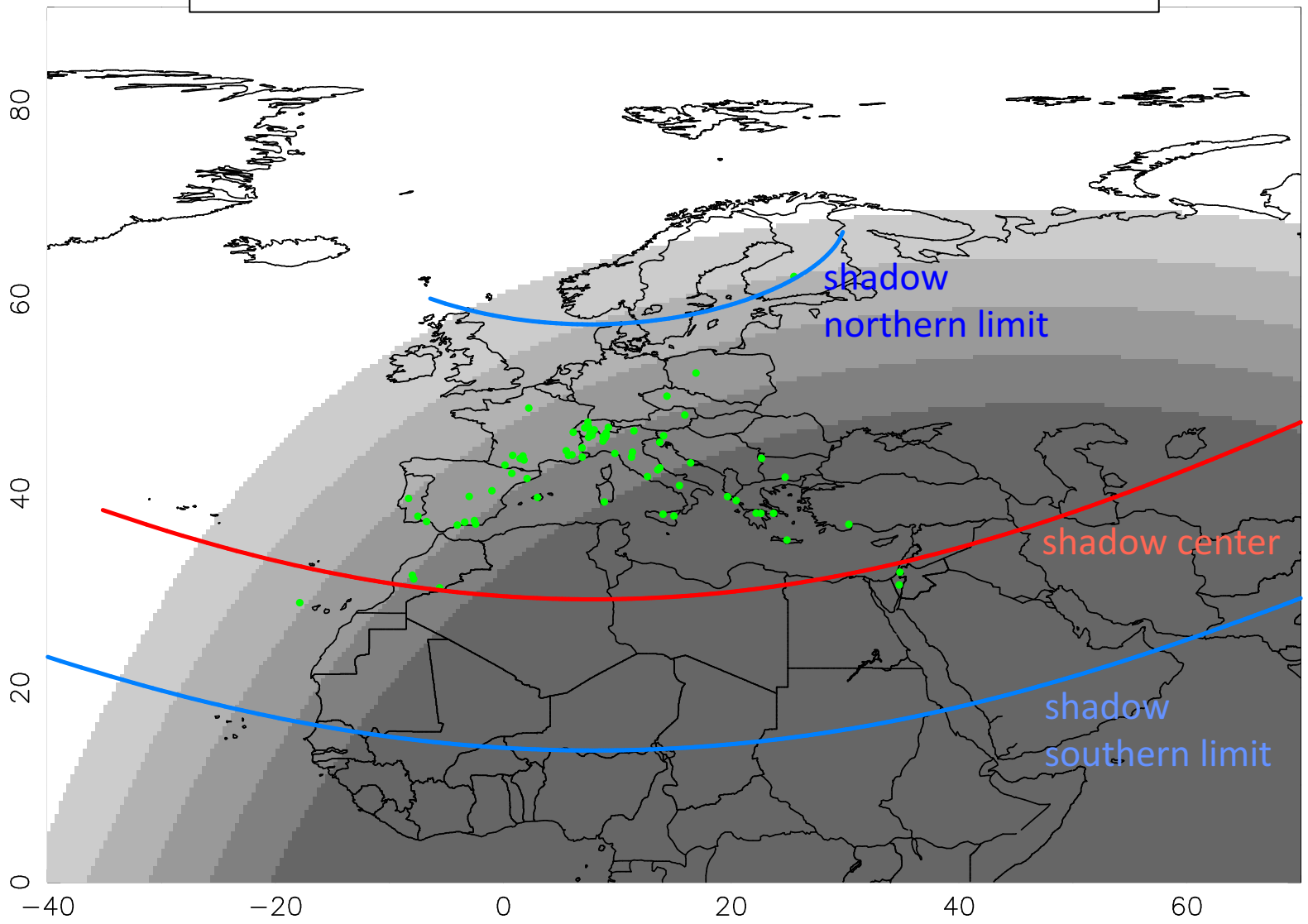


The July 19, 2016 Pluto occultation
our prediction as of early July



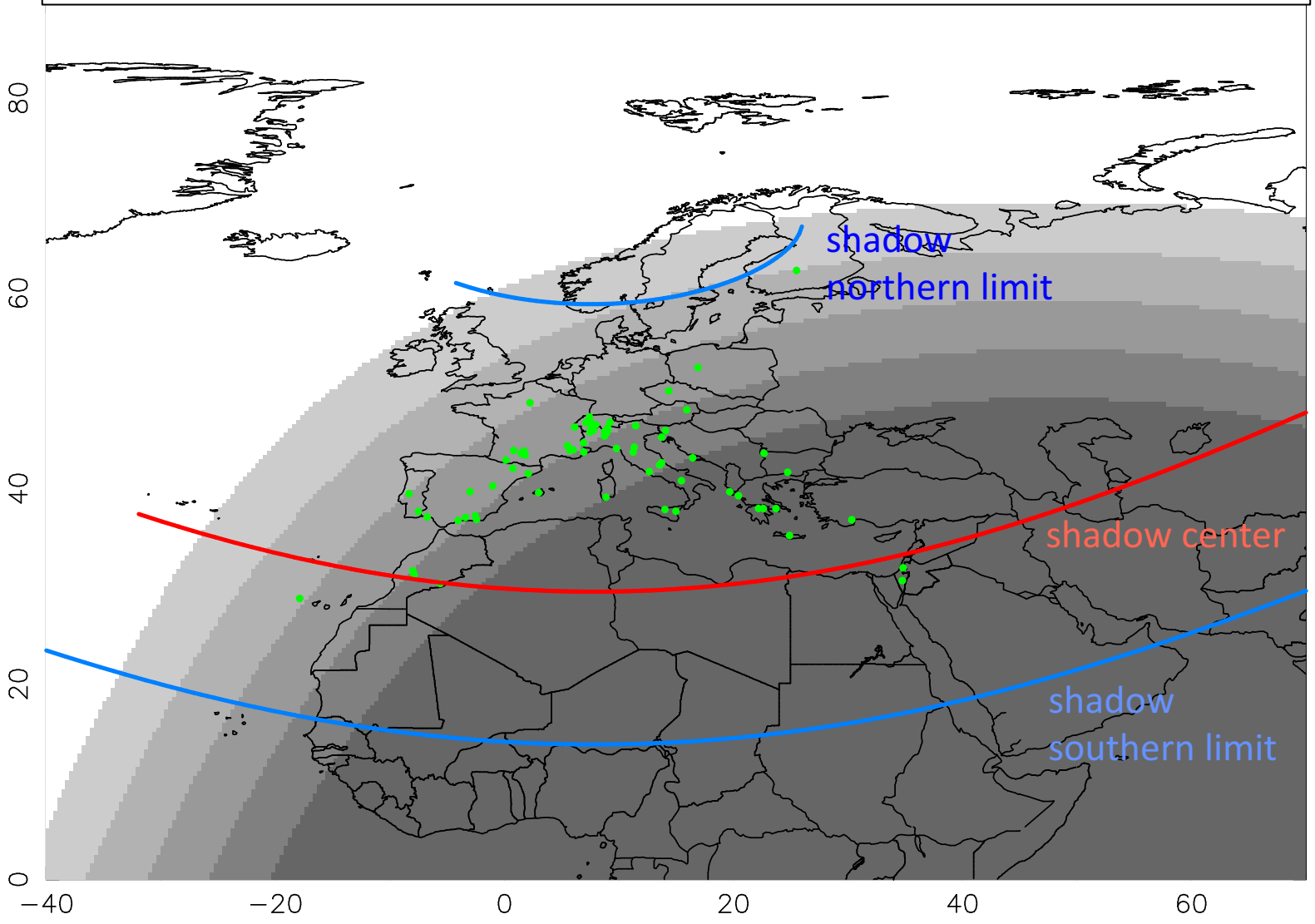
green dots: sites involved in the campaign (not all got data!)

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, ~5 mas error)



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

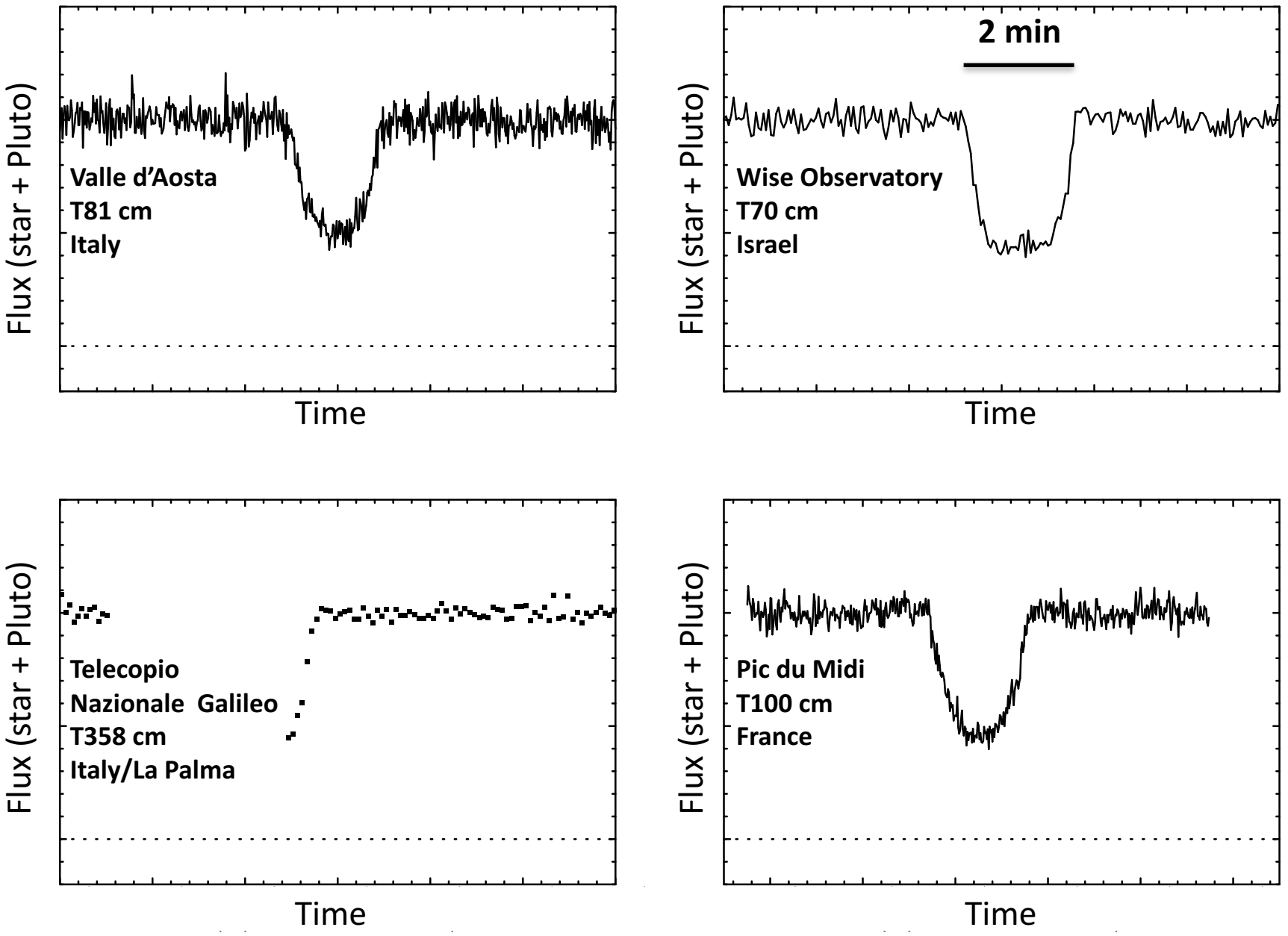
gaia

NEWS & HIGHLIGHTS

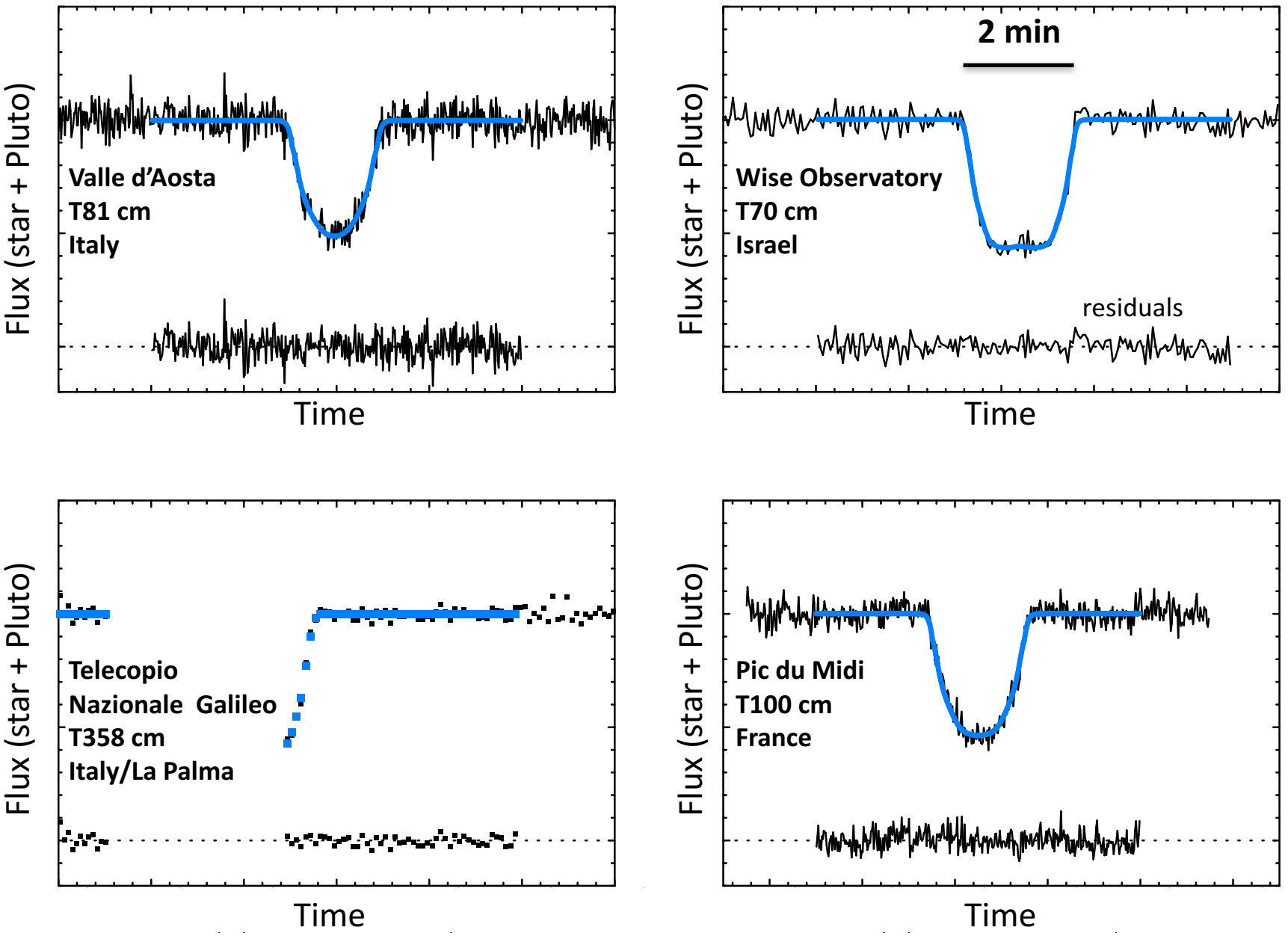
14/07/2016 **A gift from Gaia to Pluto observers on the 1st anniversary of a historic flyby**

It is just a star out of a billion, but it happens to hide behind Pluto on 19 July 2016. The improved Gaia stellar positions in Gaia-DR1 (to be released on 14 September 2016) will be useful for occultation observations. With Pluto these are of particular interest as the details of the fading, when Pluto moves in front of the star, will reveal details about the atmosphere and its possible changes since the flyby of the New Horizons mission 1 year ago (14 July 2015). Observers exactly aligned with the centre of Pluto and the star could record an ephemeral brightness increase due to light focused by the atmosphere of the dwarf planet as if it was a lens. This "central flash", showing up only for a few seconds, provides the most detailed information possible from remote observations, but also requires to accurately know the position of the star and of Pluto. The Gaia position for UCAC4 345-180315 at epoch 2015.0 in the J2000 system is Right Ascension 286.8421576 degrees and Declination -21.1745647 degrees (19h7m22.1178s -21d10’28.433”). With Gaia's position accuracy, which is 1 milliarcsec for this star at epoch 2015.0, the biggest uncertainty of the timing and location of the event as observed from the Earth will be due to uncertainty of the precise Pluto orbit. That too will be tackled by Gaia and published in future data releases.

The Pluto July 19, 2016 stellar occultation (see also talk by **Wolfgang Beisker**)



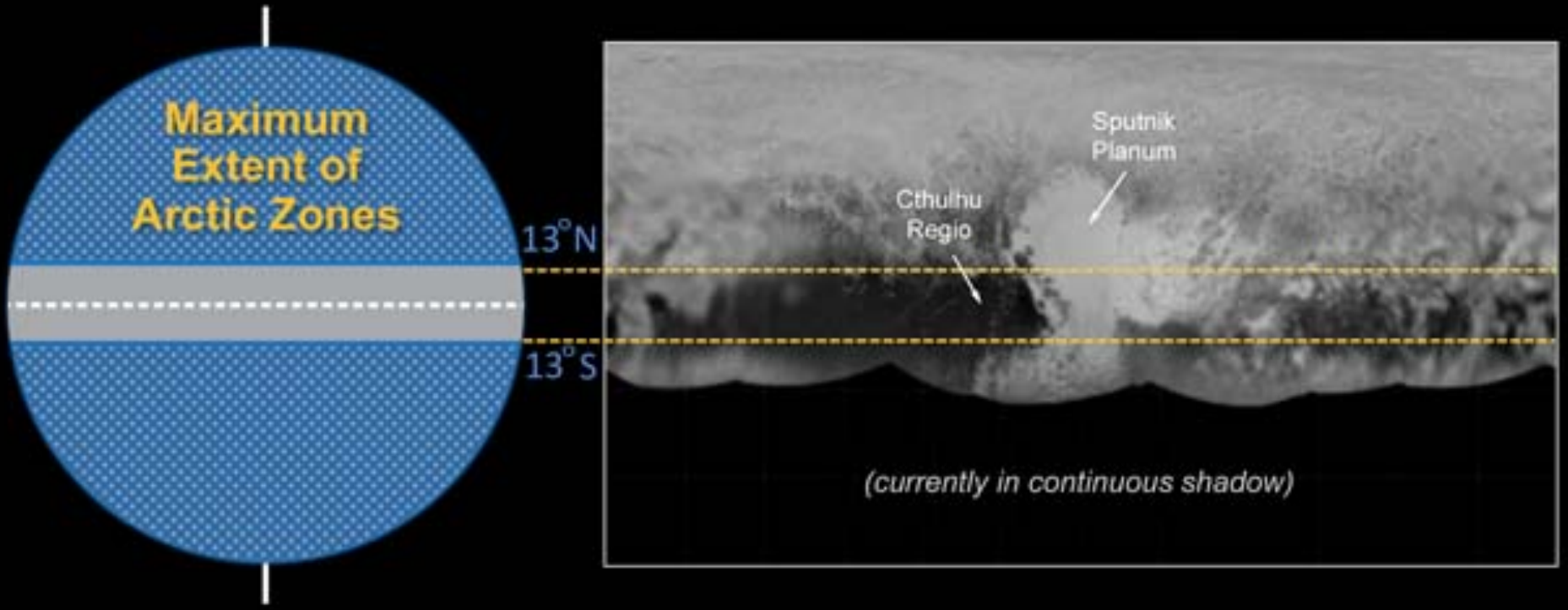
The Pluto July 19, 2016 stellar occultation (see also talk by **Wolfgang Beisker**)



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

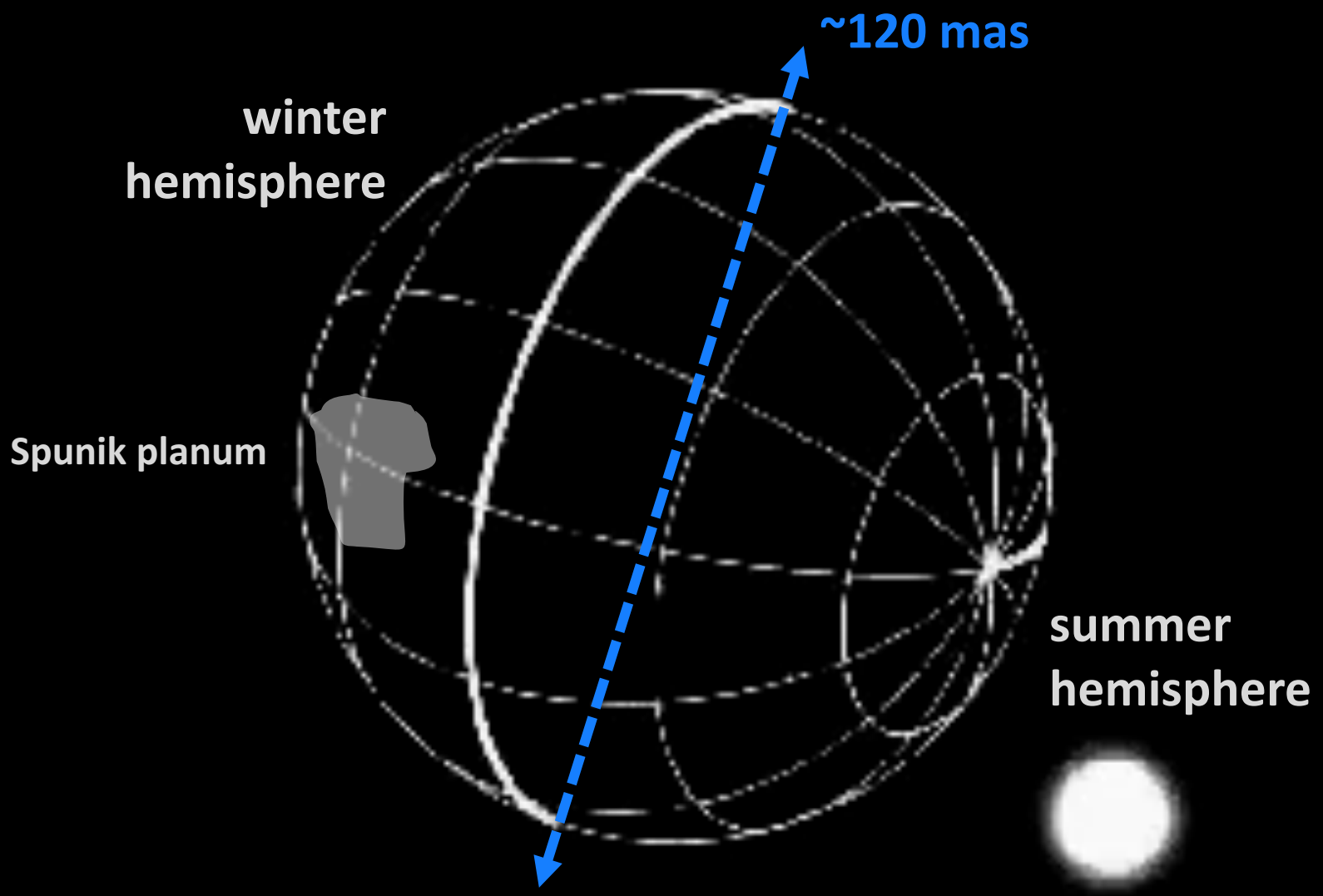
Pluto's atmosphere confounds researchers

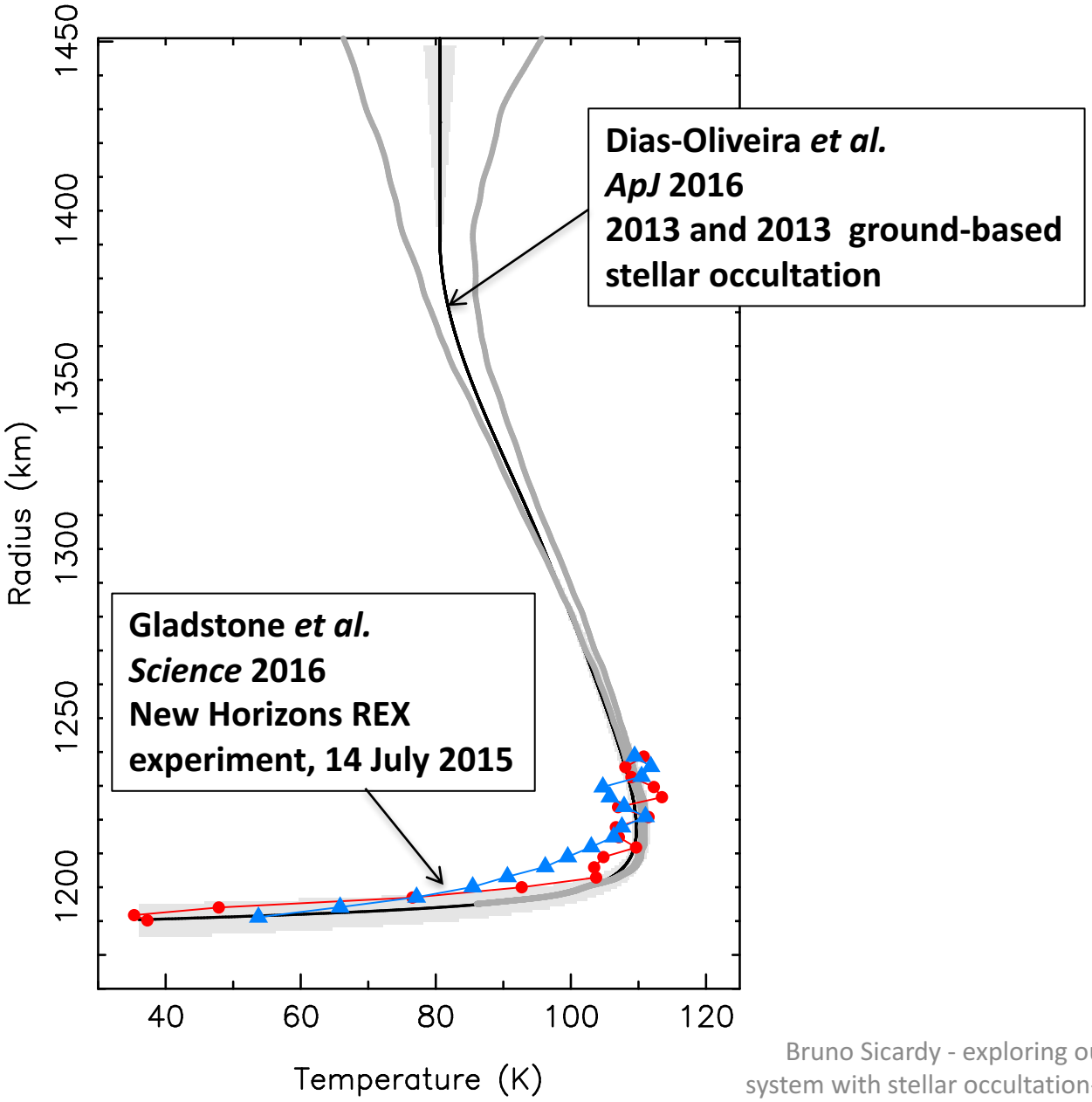
Kelly Beatty, Sky & Telescope 25 March 2016



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

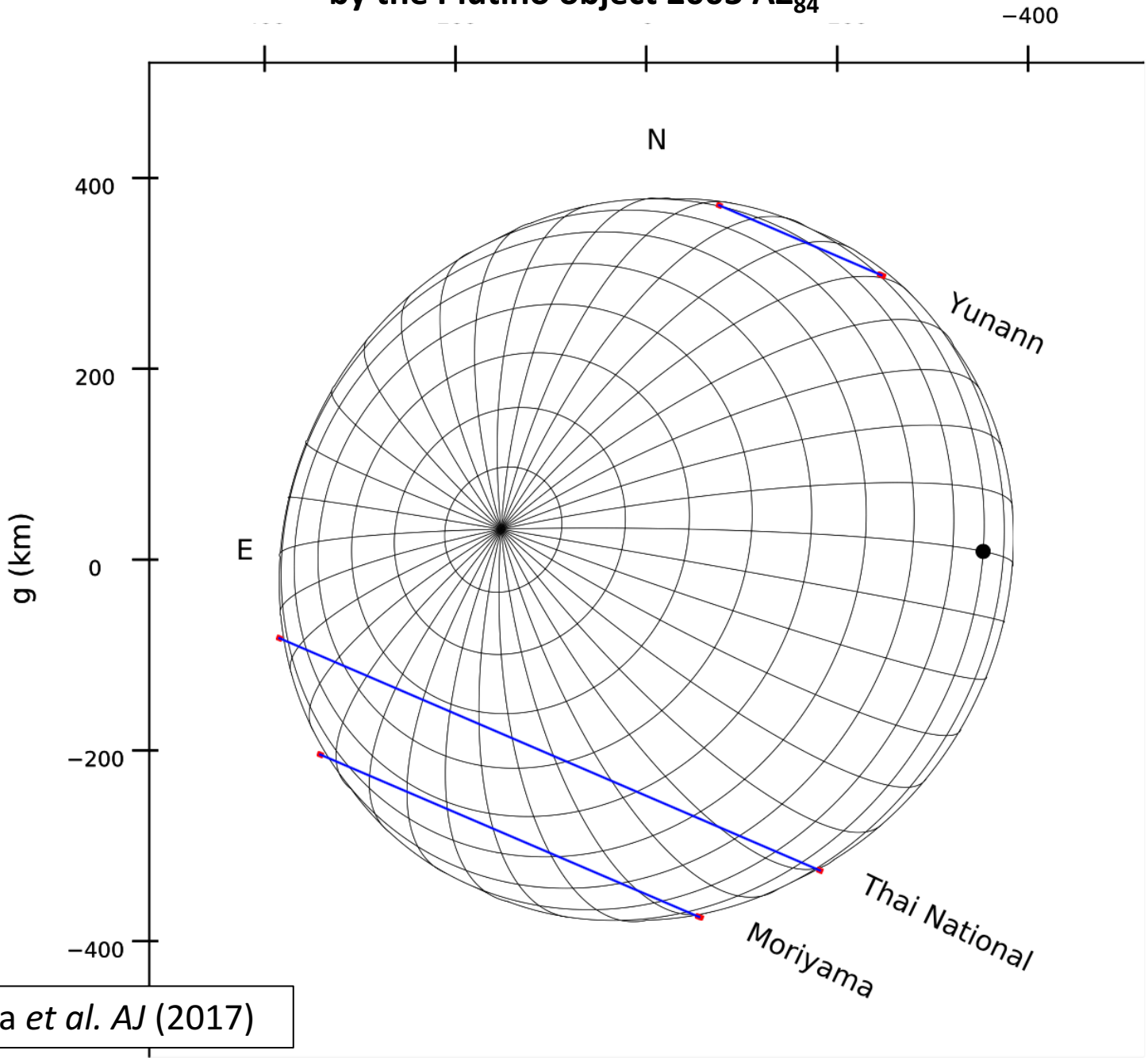
Gaia allows to make “meteorology“ of Pluto’s atmosphere




Dias-Oliveira *et al.*
ApJ 2016
2013 and 2013 ground-based
stellar occultation
Gladstone *et al.*
Science 2016
New Horizons REX
experiment, 14 July 2015
Radius (km)
1450
1400
1350
1300
1250
1200
40
60
80
100
120
Temperature (K)

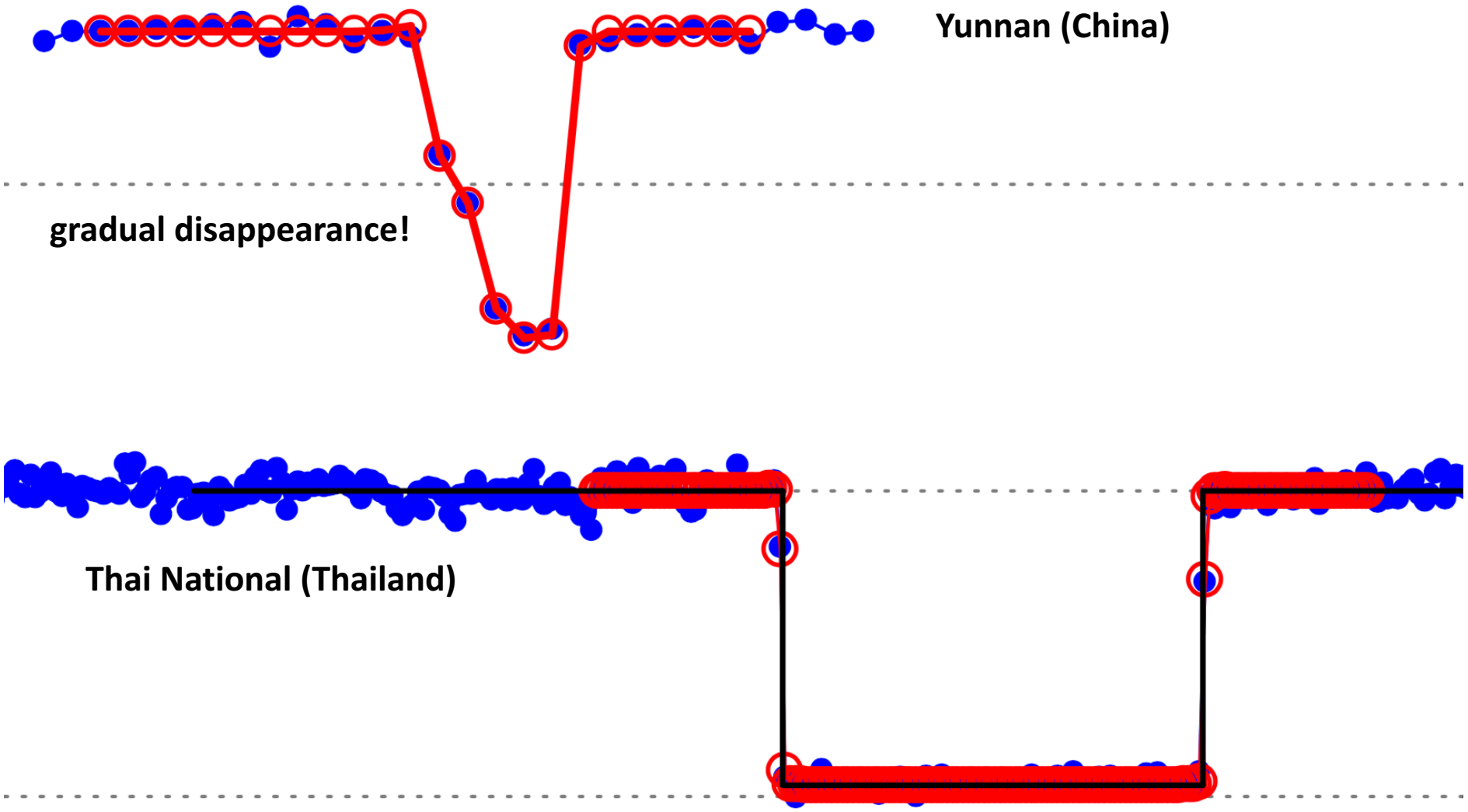
topographic features

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



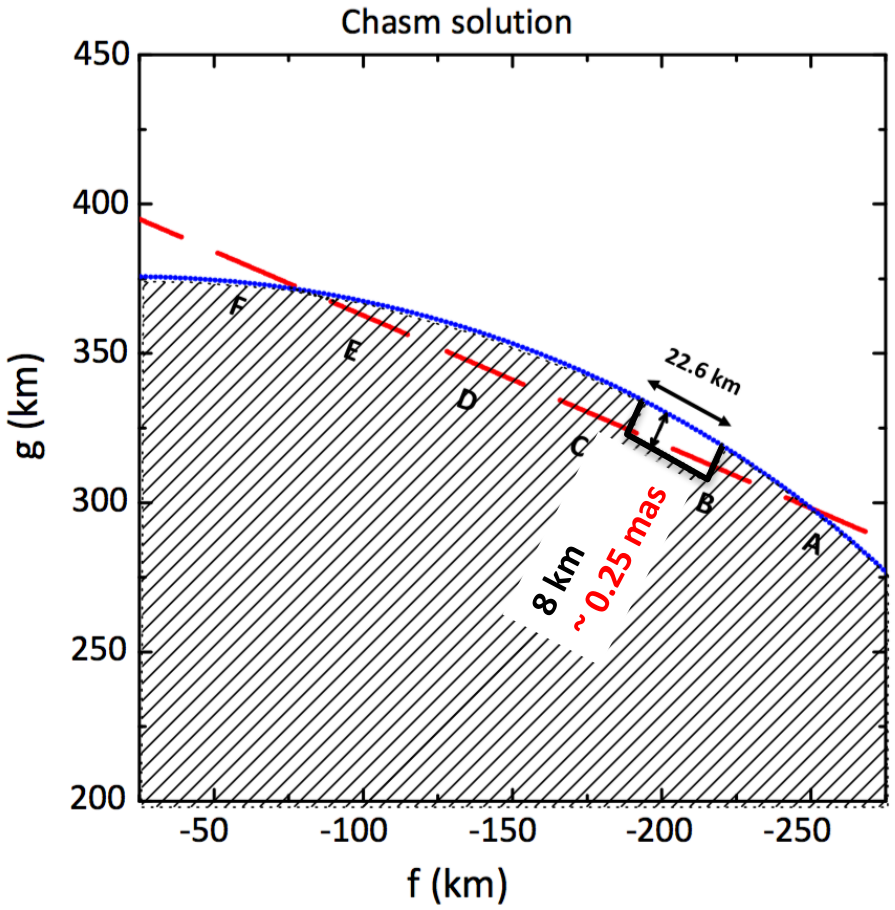
Dias-Oliveira *et al. AJ* (2017)

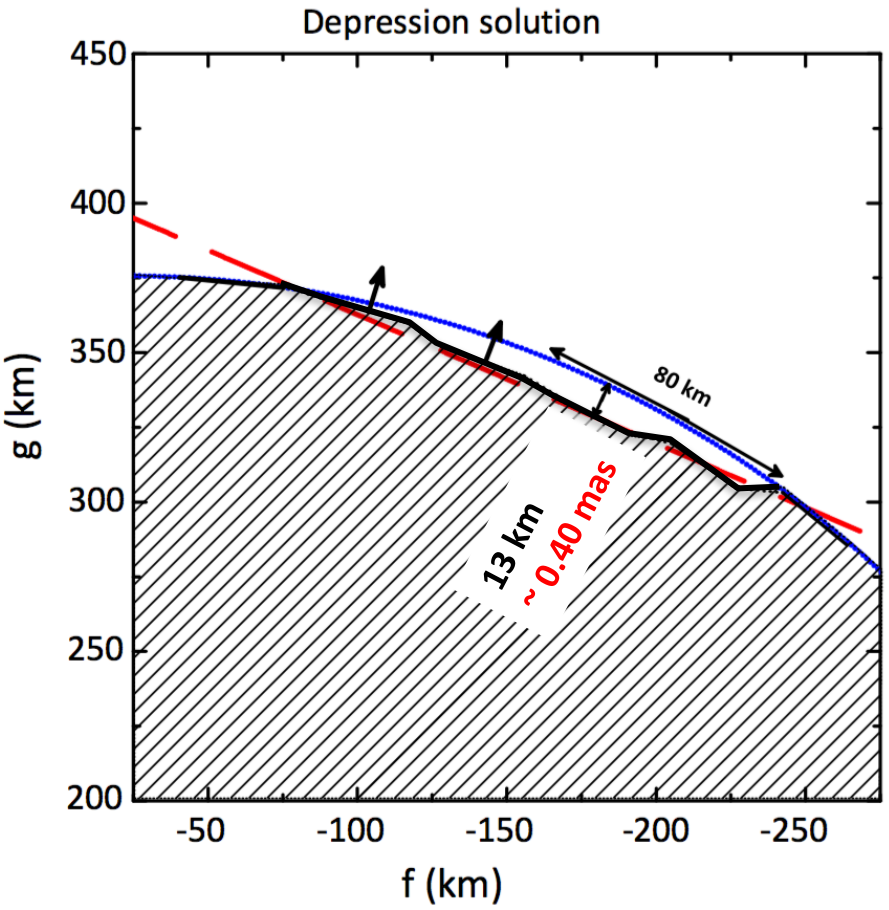
the stellar occultation of November 15, 2014 by the Plutino object 2003 AZ_{84}



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

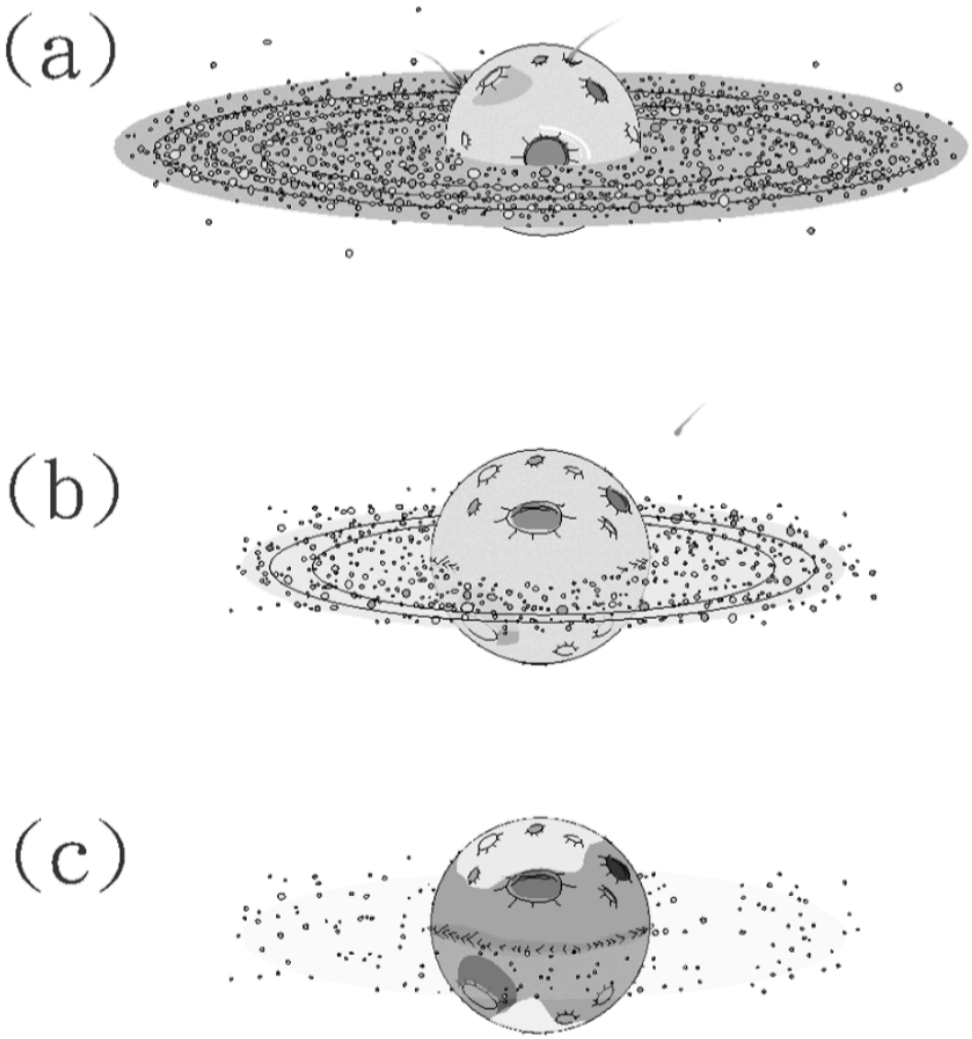
detection of topographic features on 2003 AZ_{84}'s surface



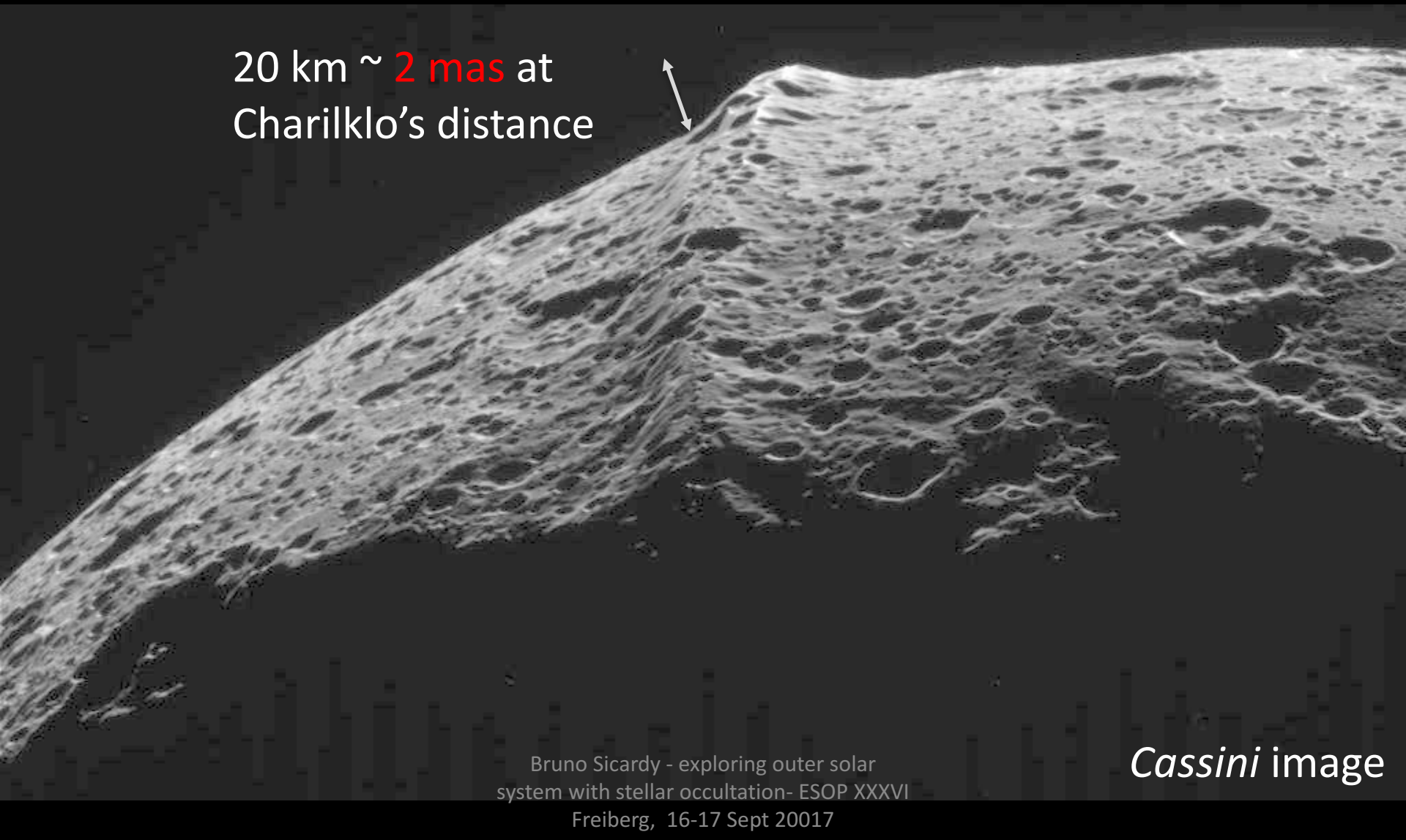


Dias-Oliveira *et al. AJ* (2017)

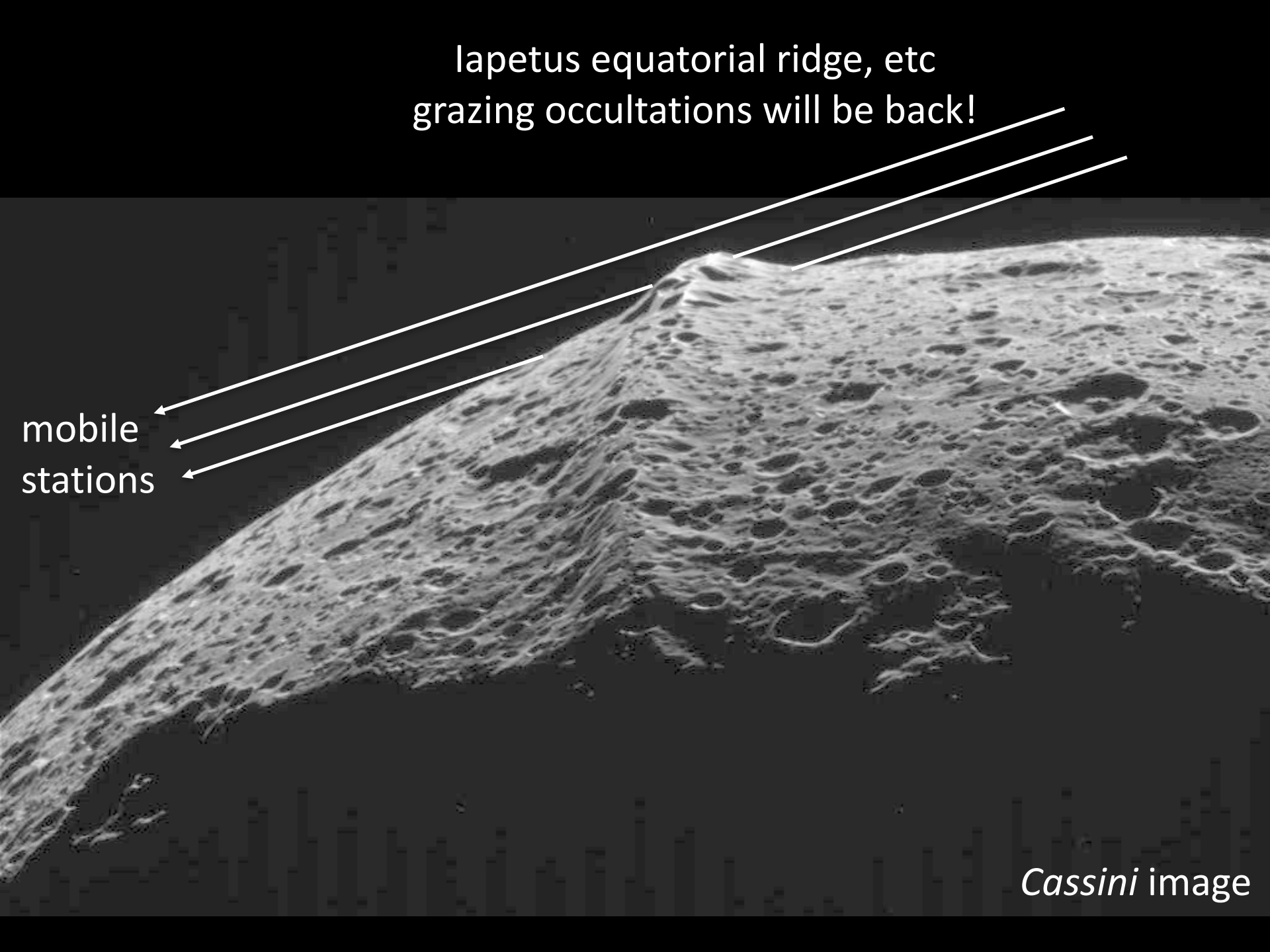
Formation of rings around Saturn's moon Iapetus
W.-H. Ip, *Geophys. Res. Letters* (2006)



Iapetus equatorial ridge

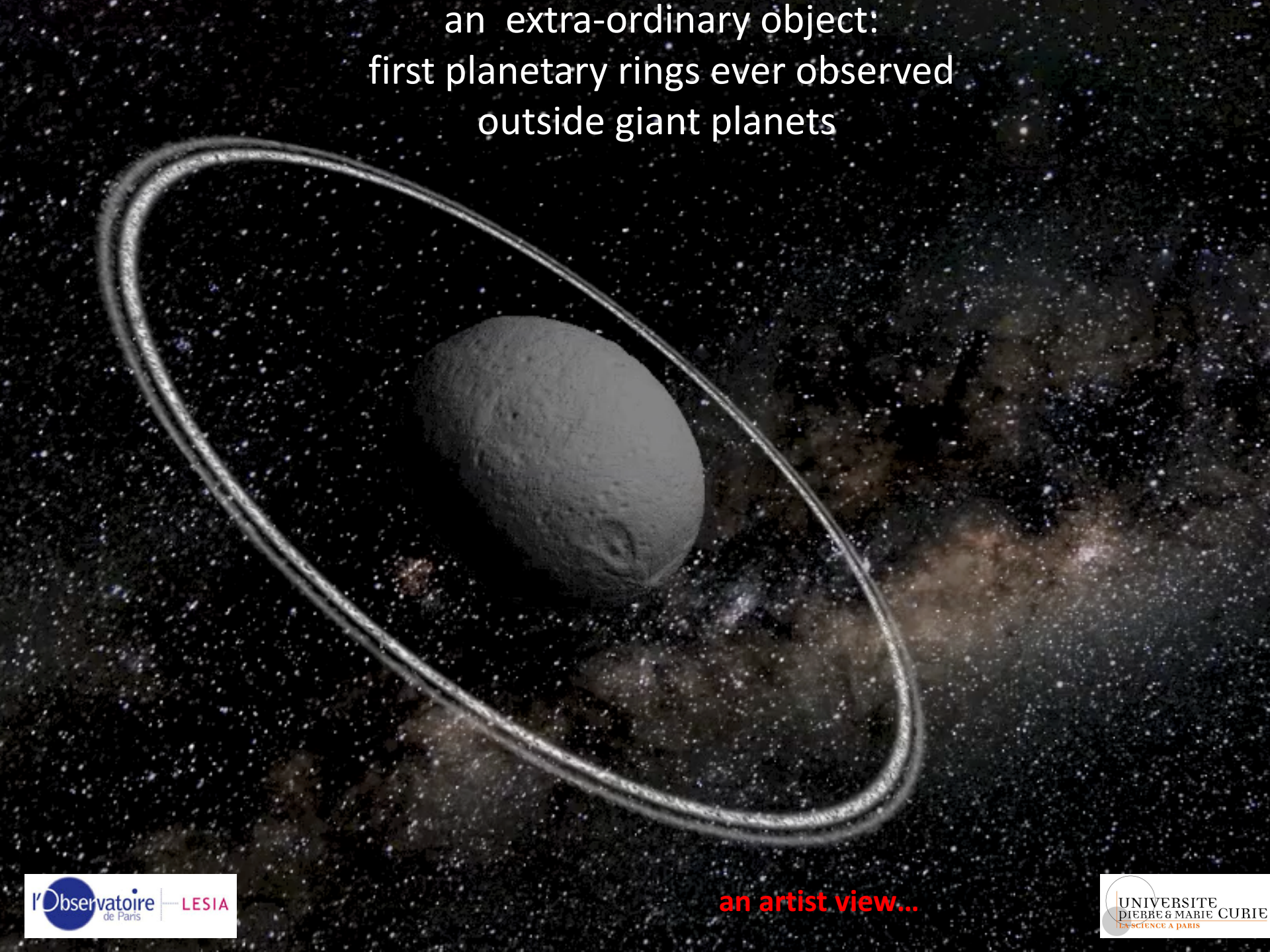


Cassini image


Iapetus equatorial ridge, etc
grazing occultations will be back!
mobile
stations
Cassini image

Chariklo example

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

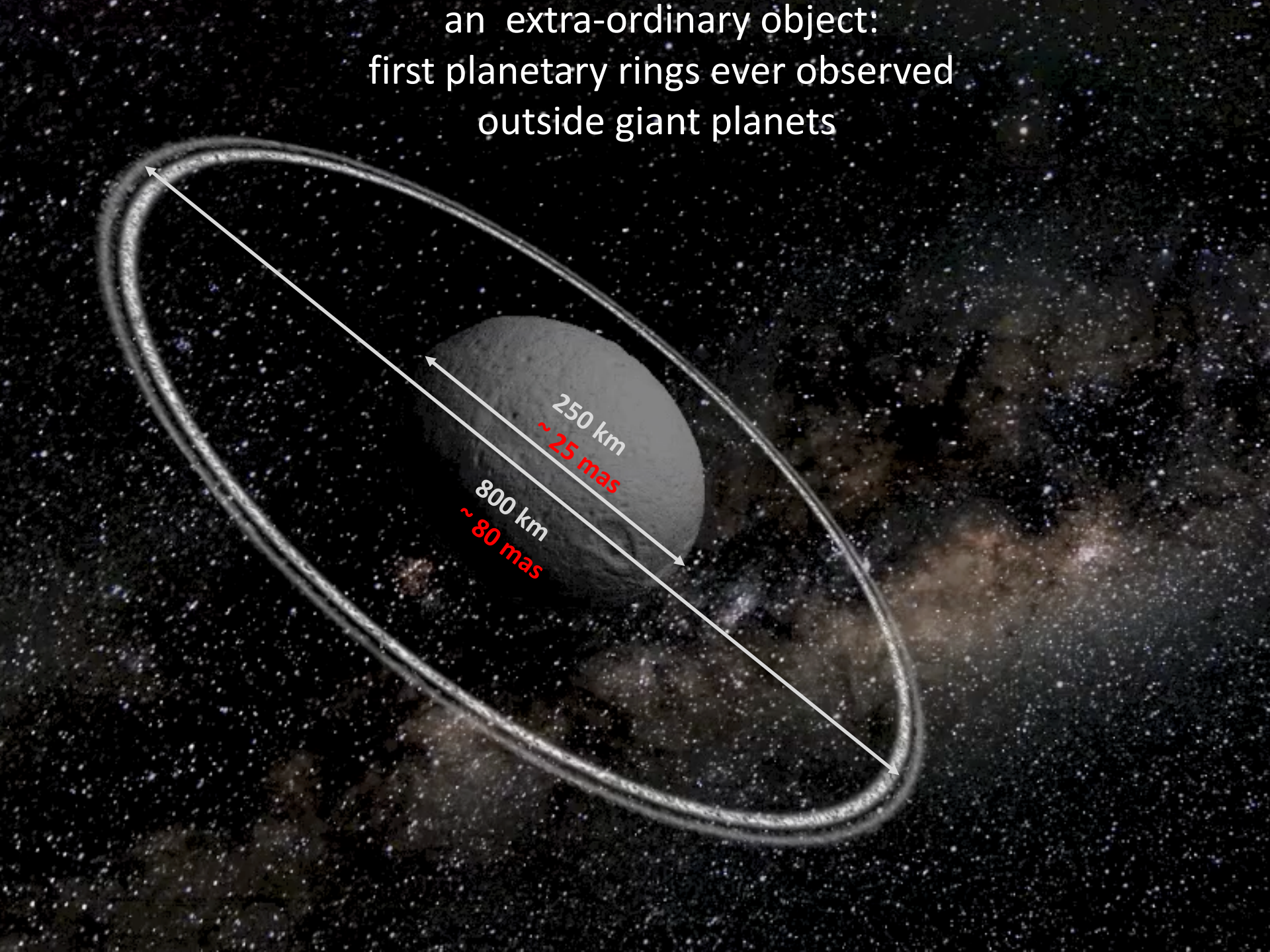


an artist view…

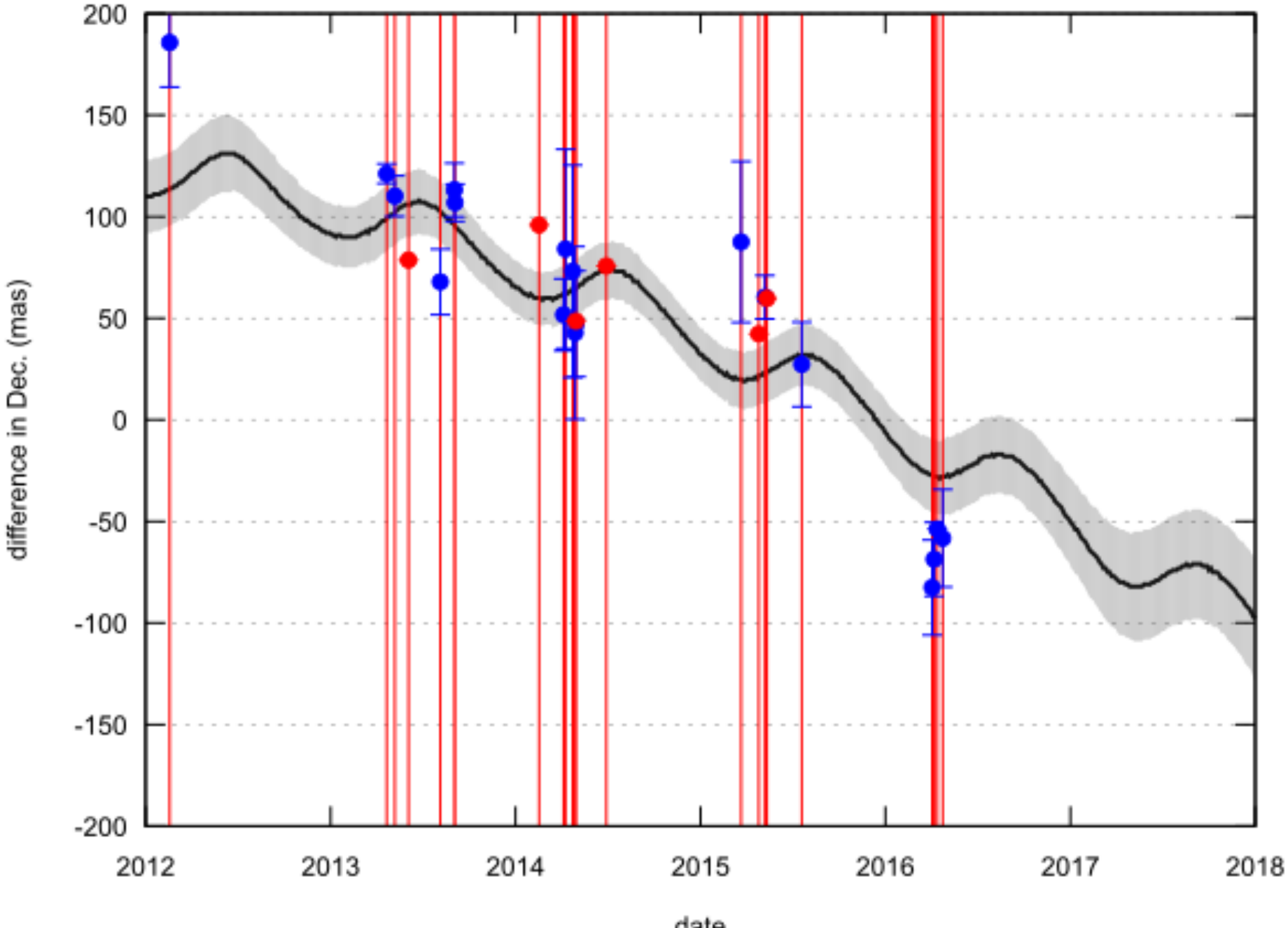
l'Observatoire de Paris — LESIA

UNIVERSITE PIERRE & MARIE CURIE
LA SCIENCE A PARIS

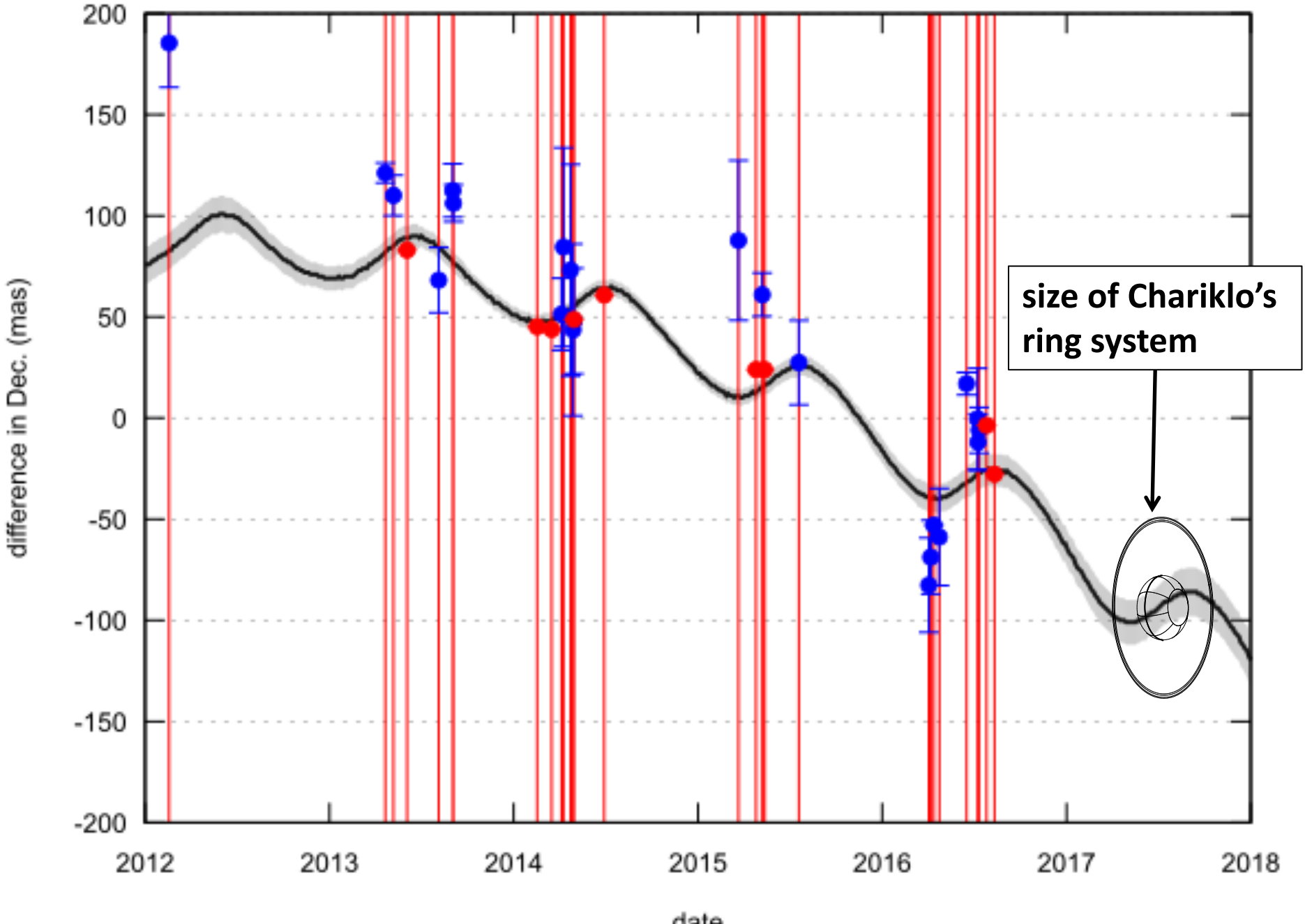
an extra-ordinary object:
first planetary rings ever observed
outside giant planets

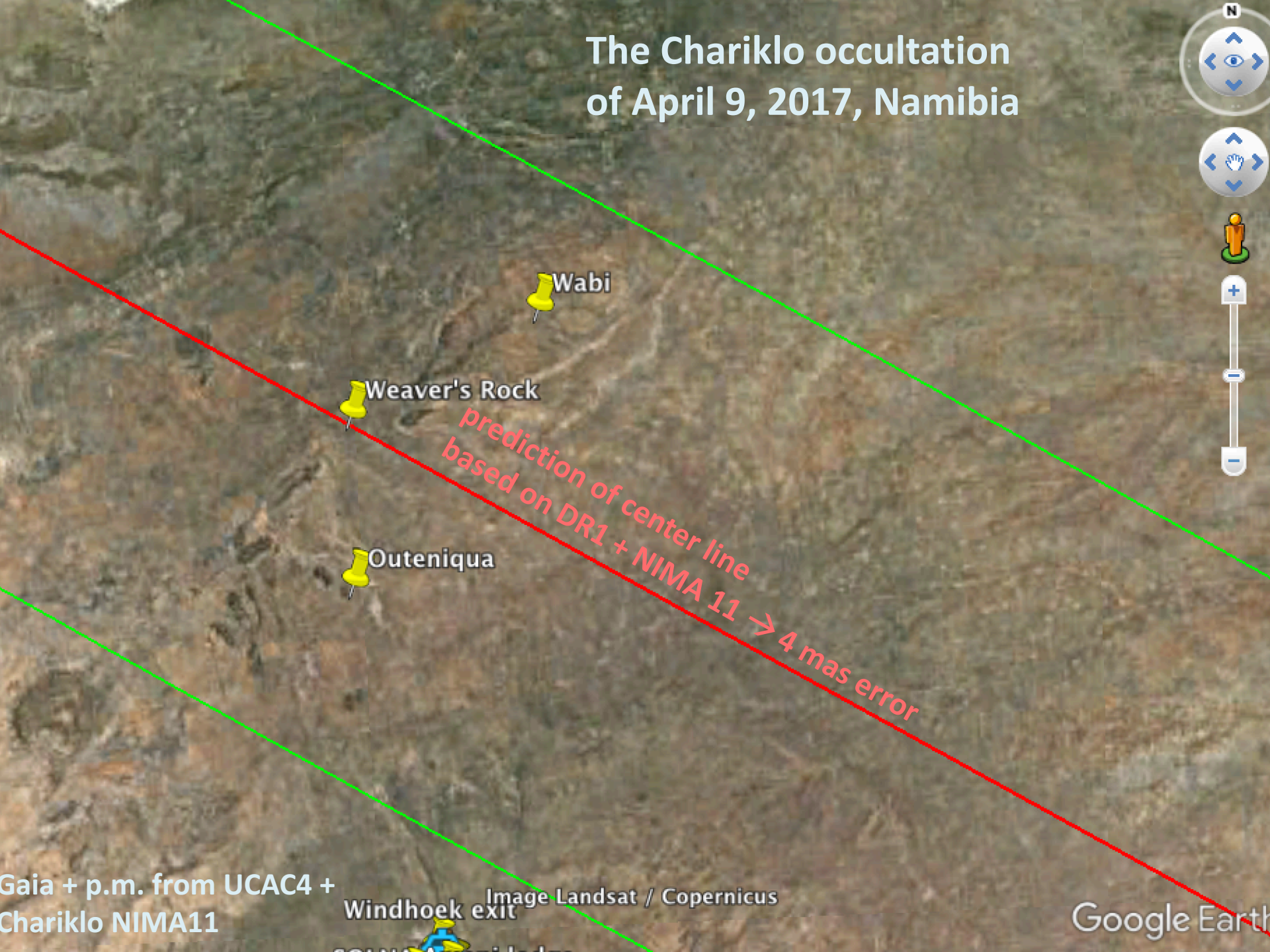


Chariklo's ephemeris, pre-GAIA



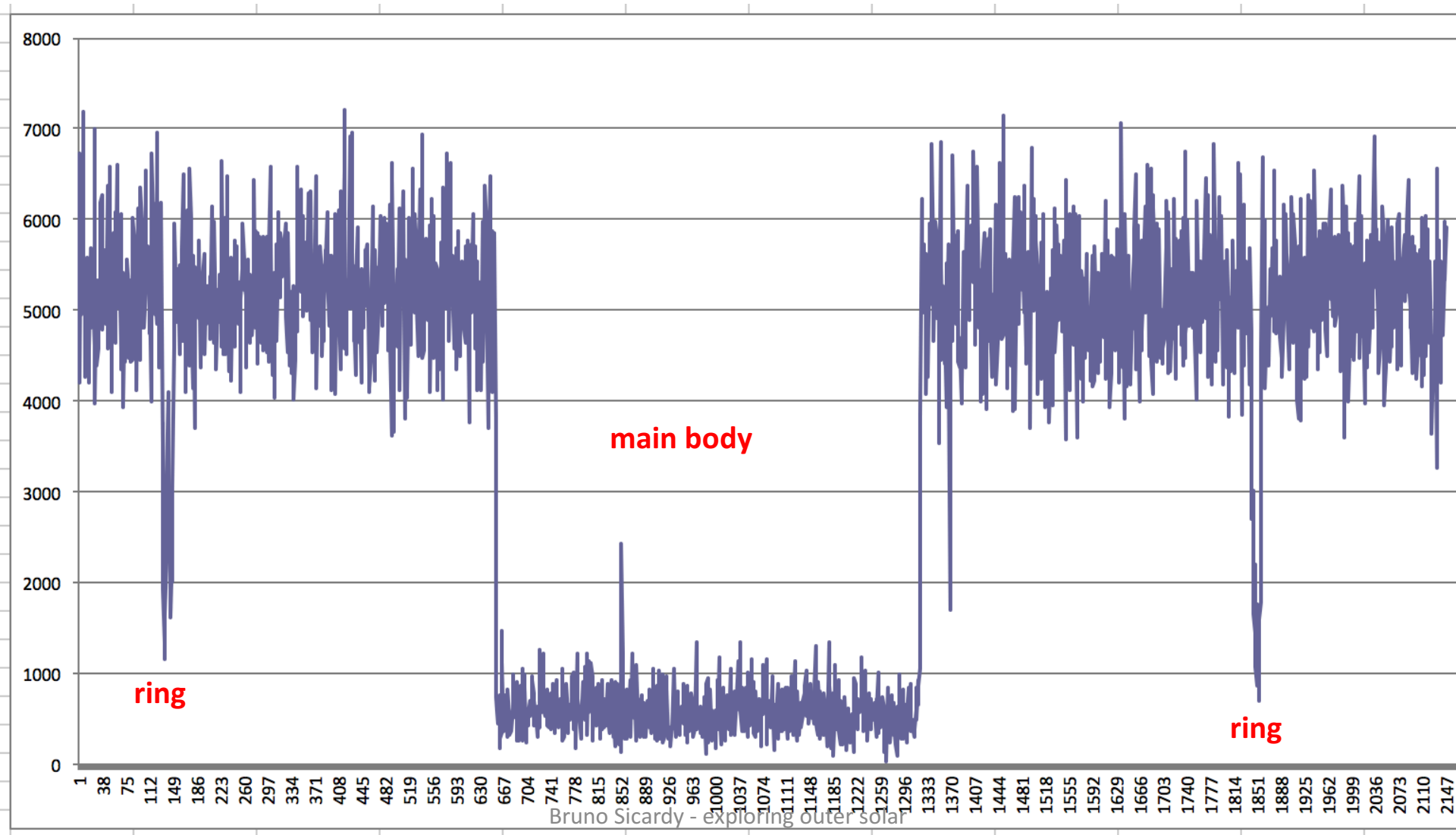
Chariklo's ephemeris, a bootstrapping approach using GAIA



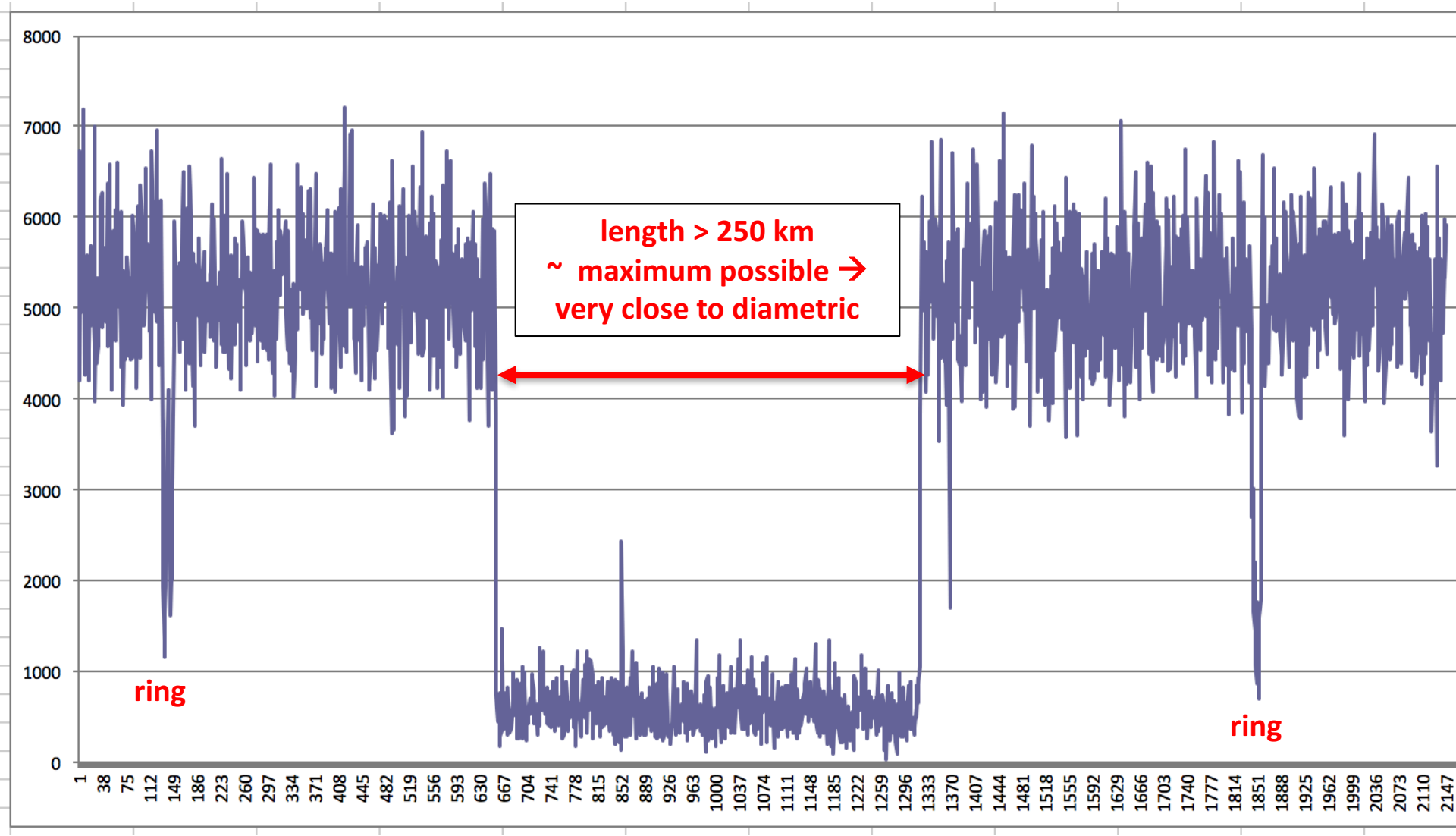

The Chariklo occultation
of April 9, 2017, Namibia
Wabi
Weaver's Rock
prediction of center line
based on DR1 + NIMA 11 ⇒ 4 mas error
Outeniqua
Gaia + p.m. from UCAC4 +
Chariklo NIMA11
Windhoek exit
Image Landsat / Copernicus
Google Earth


Chariklo occultation
Namibia April 9, 2017
see talk by Mike Kretlow

The occultation by Chariklo, Namibia April 9, 2017 (portable “M2“ 50cm telescope, Weavers Rock, Mike Kretlow)



The occultation by Chariklo, Namibia April 9, 2017
(portable “M2“ 50cm telescope, Weavers Rock, Mike Kretlow)



THREE STELLAR POSITIONS RELEASED TO SUPPORT UNIQUE OCCULTATION EVENTS

On 22 June and 23 July 2017 relatively brights stars will be occulted by the largest known centaur Chariklo. The object is unique due to the ring system around it. By observing the occultation, a better shape of Chariklo and the detailed structure of the rings can be obtained. Knowing these characteristics improves our understanding of the ring stability and formation.

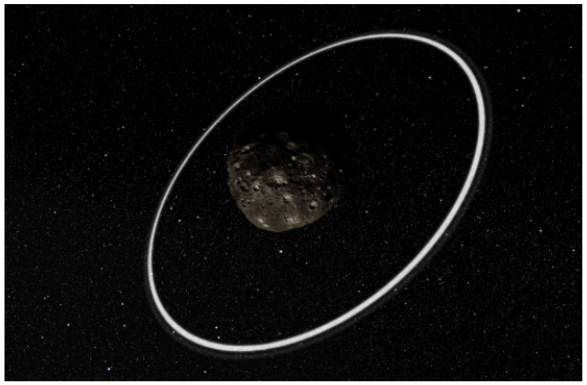
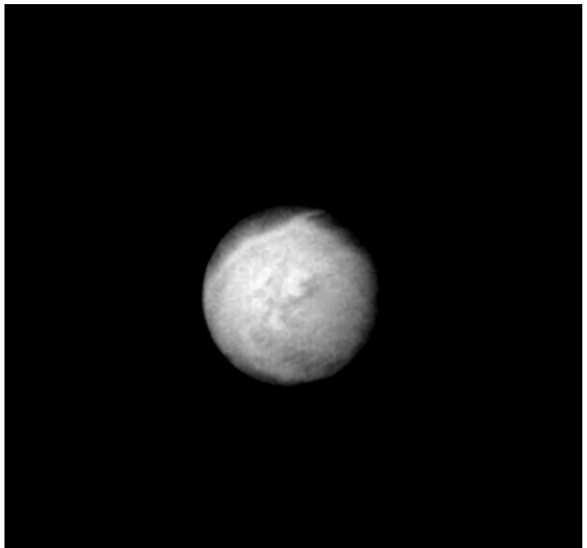
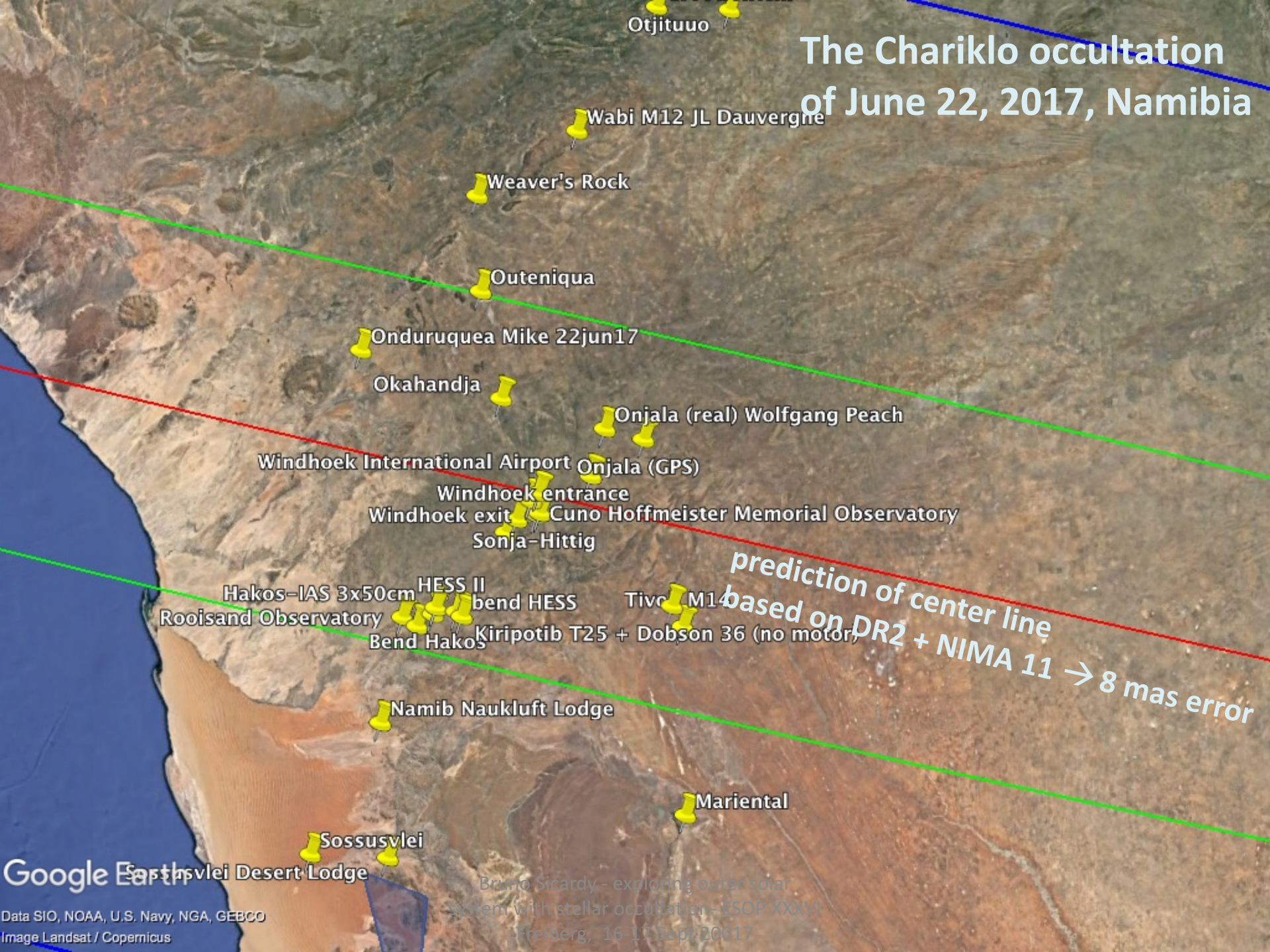


Figure 1: Artist impression of a close-up of the rings around Chariklo
(Image credit: ESO/L. Calçada/M. Kornmesser/Nick Risinger (skysurvey.org))

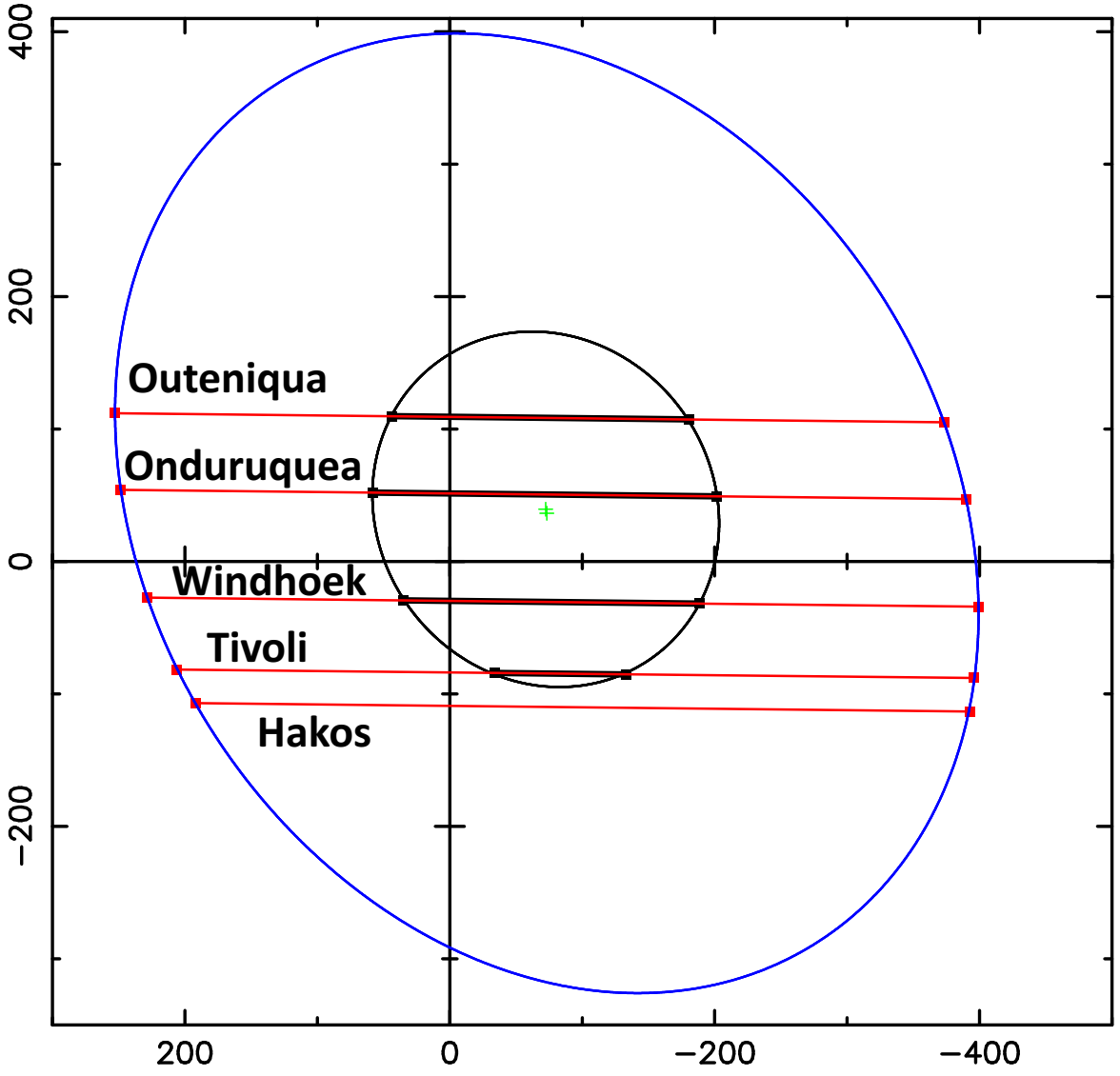
Even more unique is the occultation of a star on 5 October 2017 by Triton, the largest moon of Neptune. Triton occultations of suitable stars are extremely rare and can be used to study its atmosphere. While Gaia DR1 positions for these stars are very accurate, there are no proper motions available. This leads to large uncertainties in planning for the ground-based occultation observing campaigns. In order to help preparations for these unique events, we make the preliminary astrometric solutions for these stars, prepared for Gaia DR2, public.

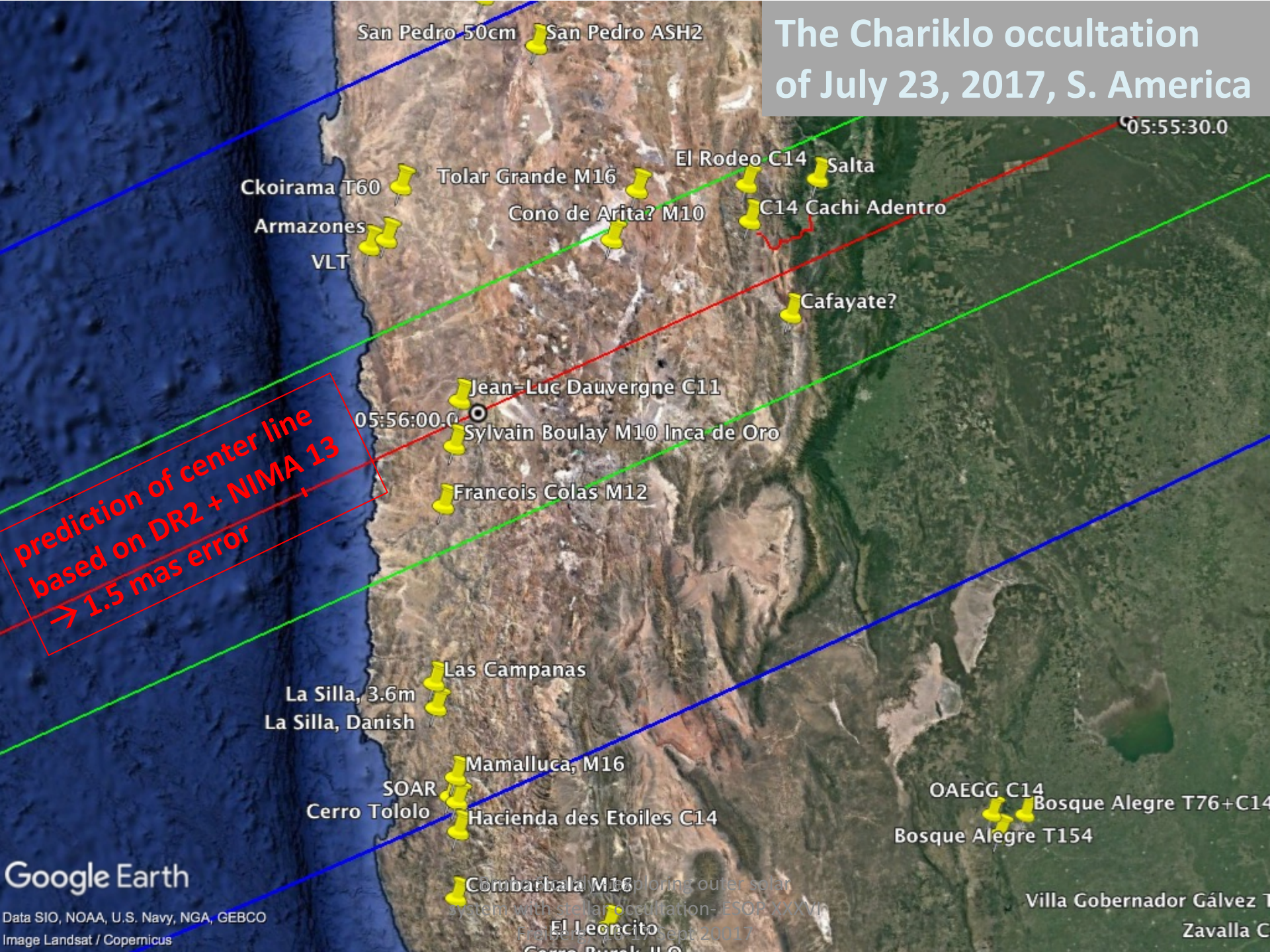


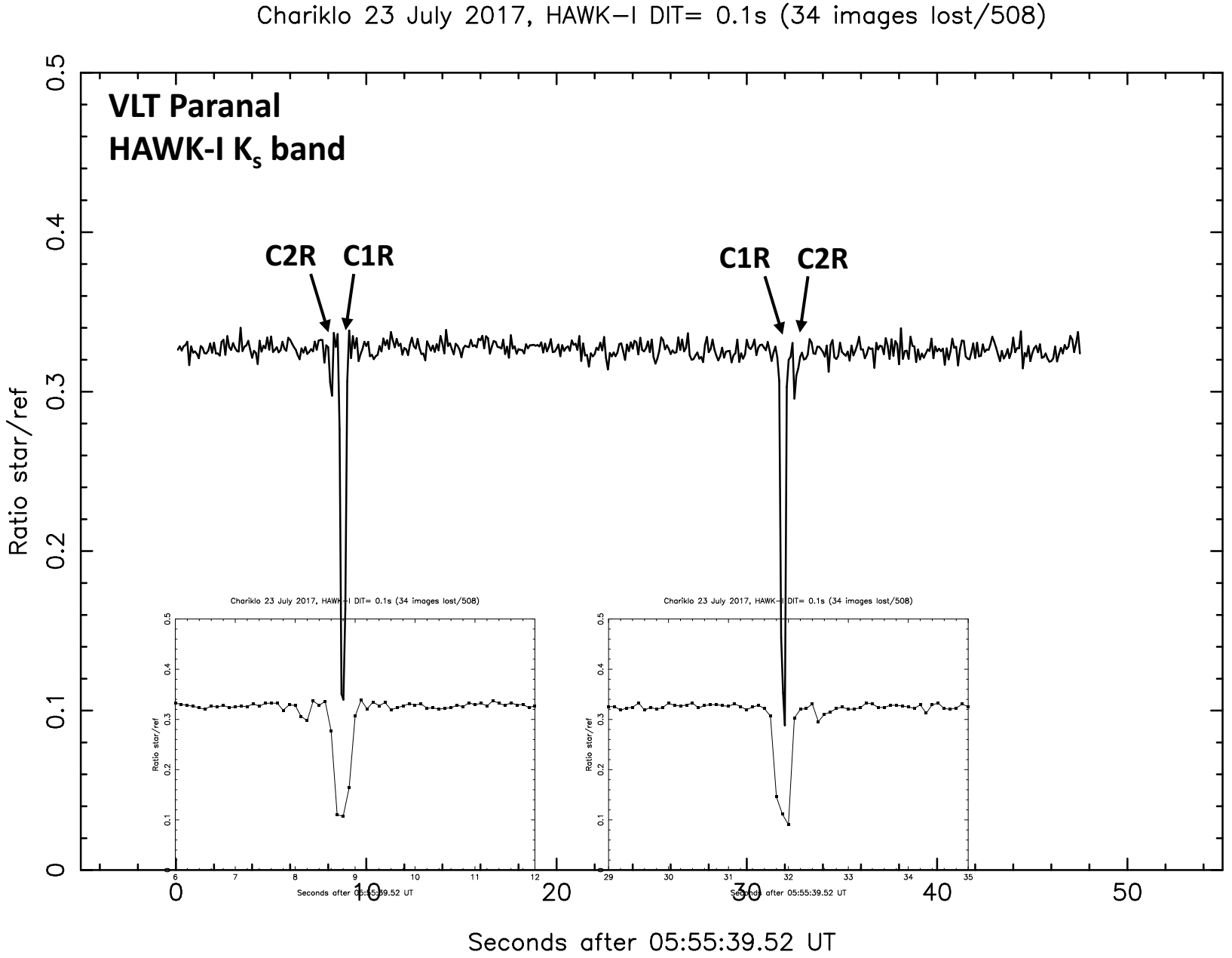

The Chariklo occultation
of June 22, 2017, Namibia
Otjituuo
Wabi M12 JL Dauvergne
Weaver's Rock
Outeniqua
Onduruquea Mike 22jun17
Okahandja
Onjala (real) Wolfgang Peach
Windhoek International Airport
Onjala (GPS)
Windhoek entrance
Windhoek exit
Cuno Hoffmeister Memorial Observatory
Sonja-Hittig
Hakos-IAS 3x50cm
HESS II
bend HESS
Rooisand Observatory
Bend Hakos
Kiripotib T25 + Dobson 36 (no motor)
prediction of center line
based on DR2 + NIMA 11 → 8 mas error
Namib Naukluft Lodge
Mariental
Sossusvlei
Sossusvlei Desert Lodge
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

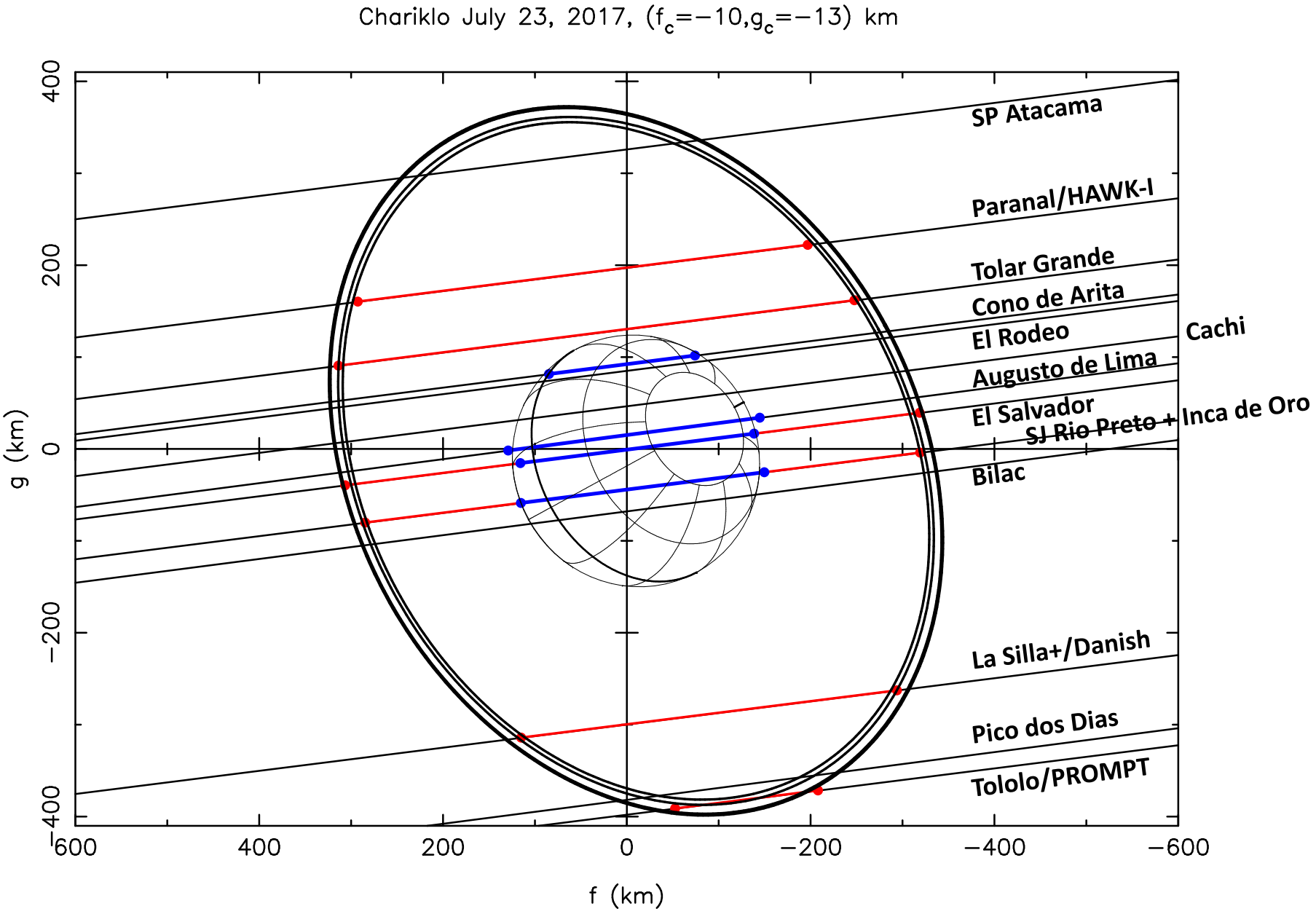
The occultation by Chariklo, Namibia June 22, 2017

high accuracy fits (~0.5 km residuals for ring and body fits)

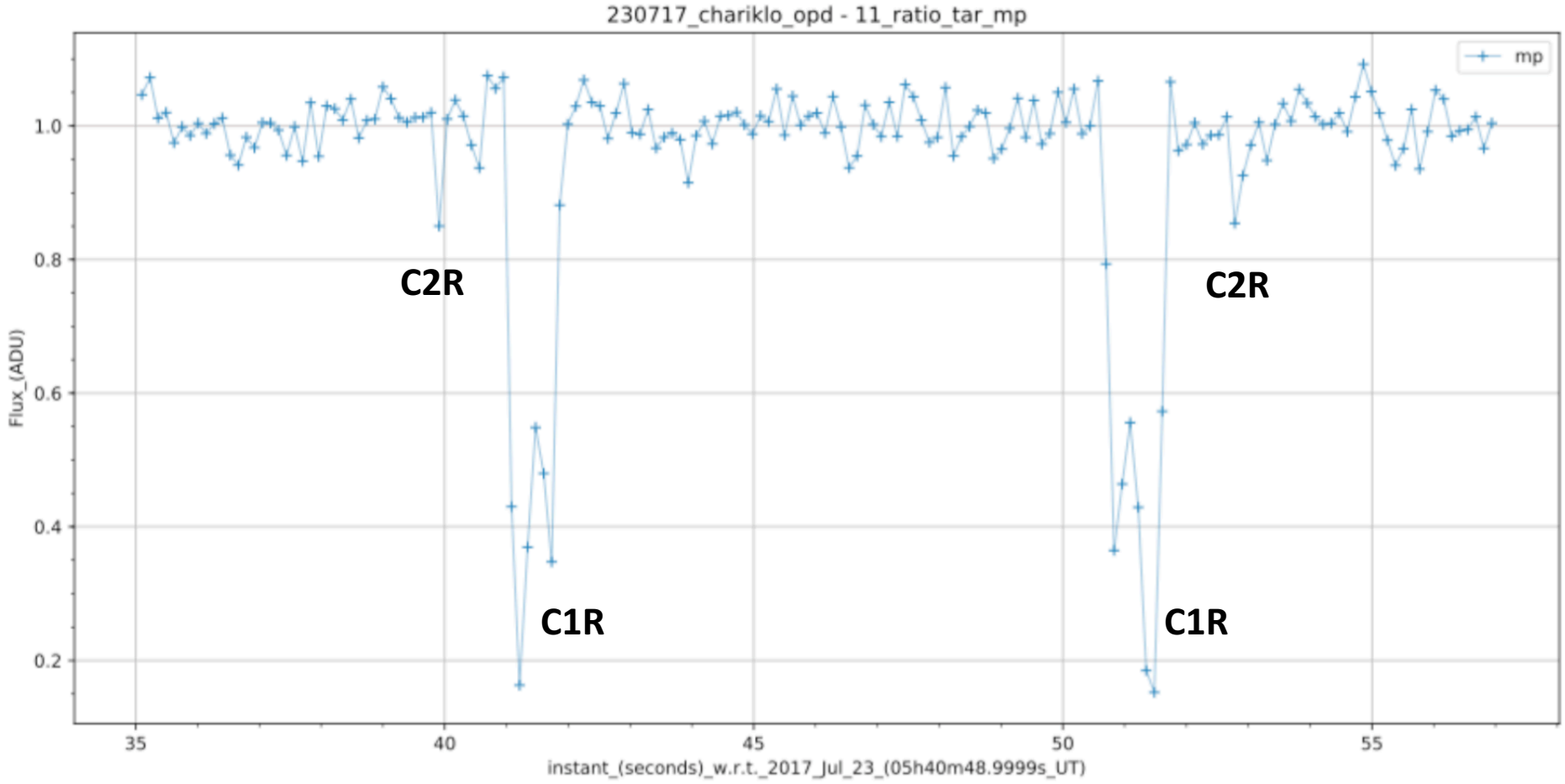


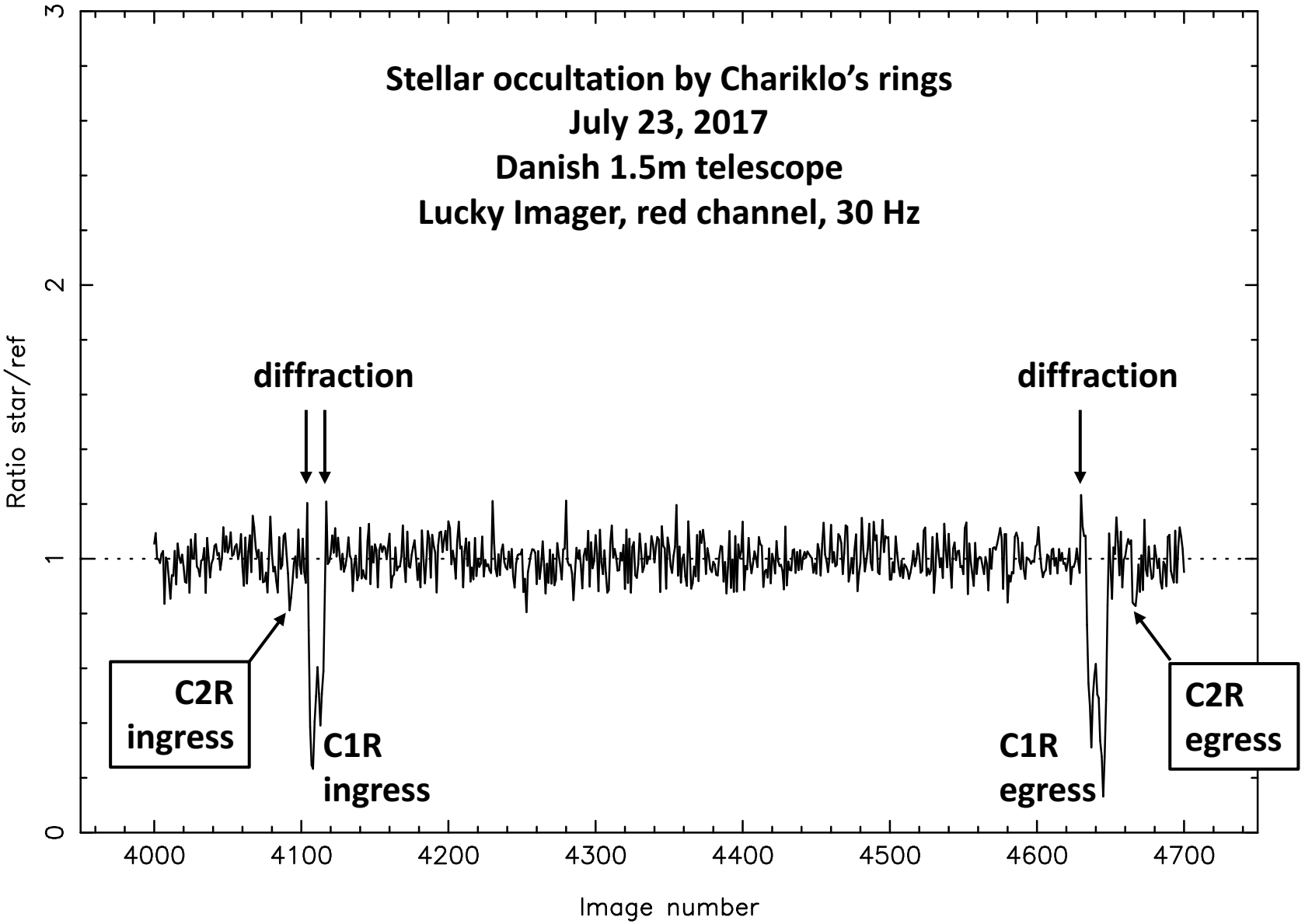

The Chariklo occultation of July 23, 2017, S. America
San Pedro 50cm
San Pedro ASH2
05:55:30.0
El Rodeo C14
Salta
Ckoirama T60
Tolar Grande M16
C14 Cachi Adentro
Cono de Arita? M10
Armazones
VLT
Cafayate?
Jean-Luc Dauvergne C11
05:56:00.0
Sylvain Boulay M10 Inca de Oro
Francois Colas M12
prediction of center line
based on DR2 + NIMA 13
≯ 1.5 mas error
Las Campanas
La Silla, 3.6m
La Silla, Danish
Mamalluca, M16
SOAR
Cerro Tololo
Hacienda des Etoiles C14
OAEGG C14
Bosque Alegre T76+C14
Bosque Alegre T154
Combarbala M16
El Leoncito
Villa Gobernador Gálvez
Zavalla
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

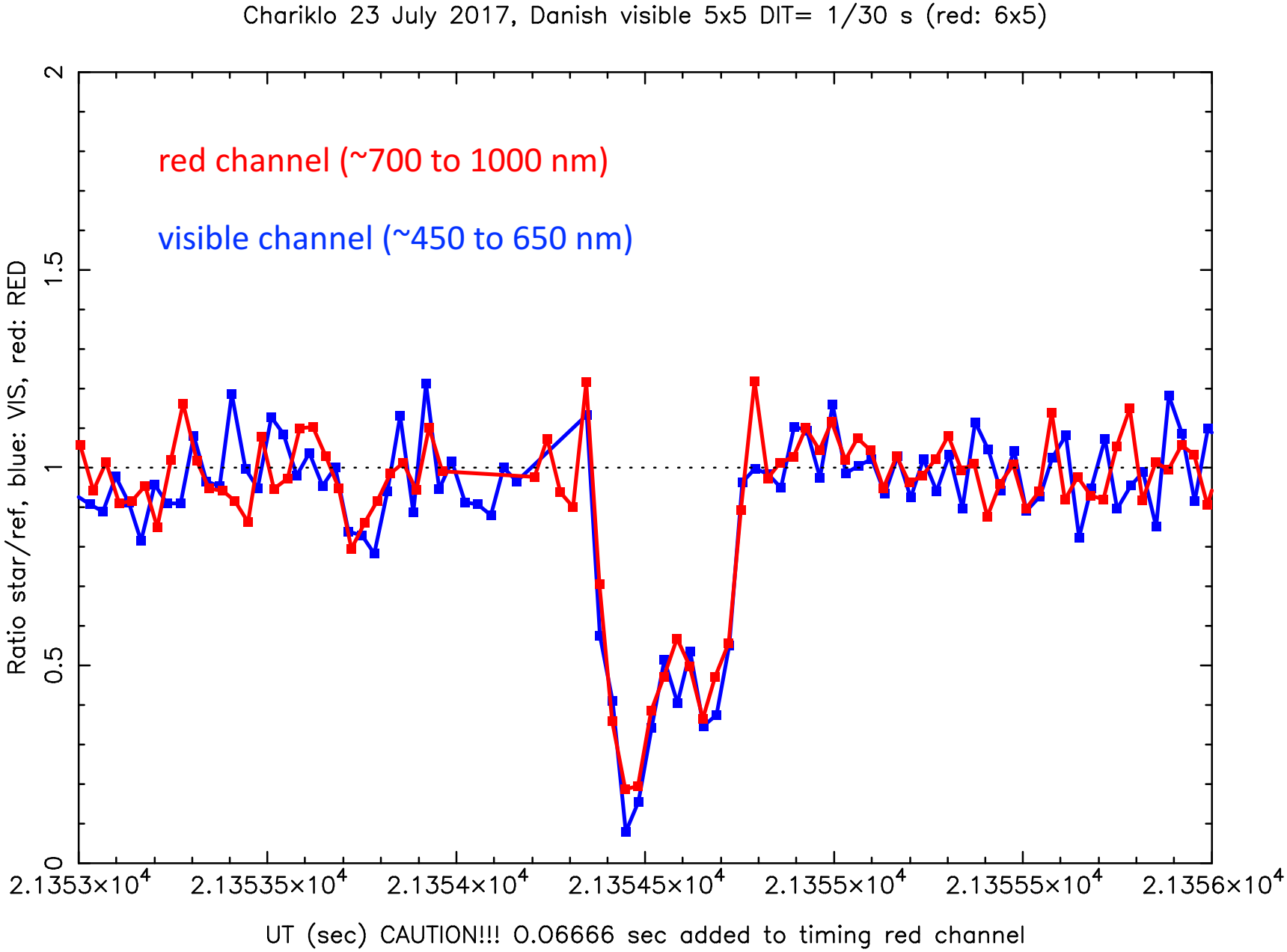

Chariklo 23 July 2017, HAWK−I DIT= 0.1s (34 images lost/508)
VLT Paranal
HAWK-I K$_s$ band
C2R
C1R
C1R
C2R
Ratio star/ref
Seconds after 05:55:39.52 UT
0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50

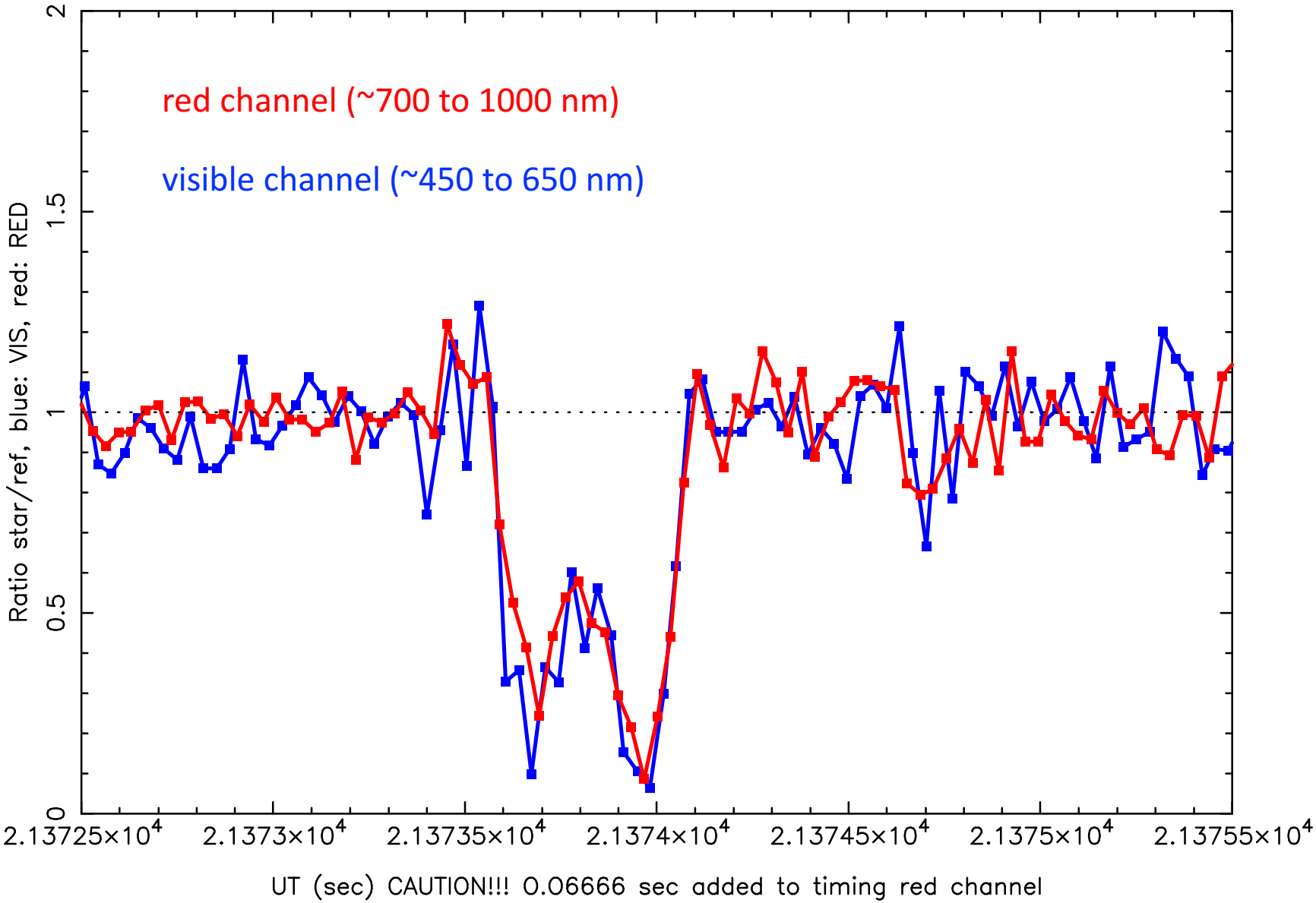

Chariklo July 23, 2017, (f_c=−10,g_c=−13) km
SP Atacama
Paranal/HAWK-I
Tolar Grande
Cono de Arita
El Rodeo
Augusto de Lima
El Salvador
SJ Rio Preto +
Bilac
Cachi
Inca de Oro
La Silla+/Danish
Pico dos Dias
Tololo/PROMPT
g (km)
f (km)
400
200
0
−200
−400
600
400
200
0
−200
−400
−600

Stellar occultation by Chariklo's rings
July 23, 2017
Pico do Dias 1.6m telescope (Brazil)
from Felipe Braga-Ribas et al.

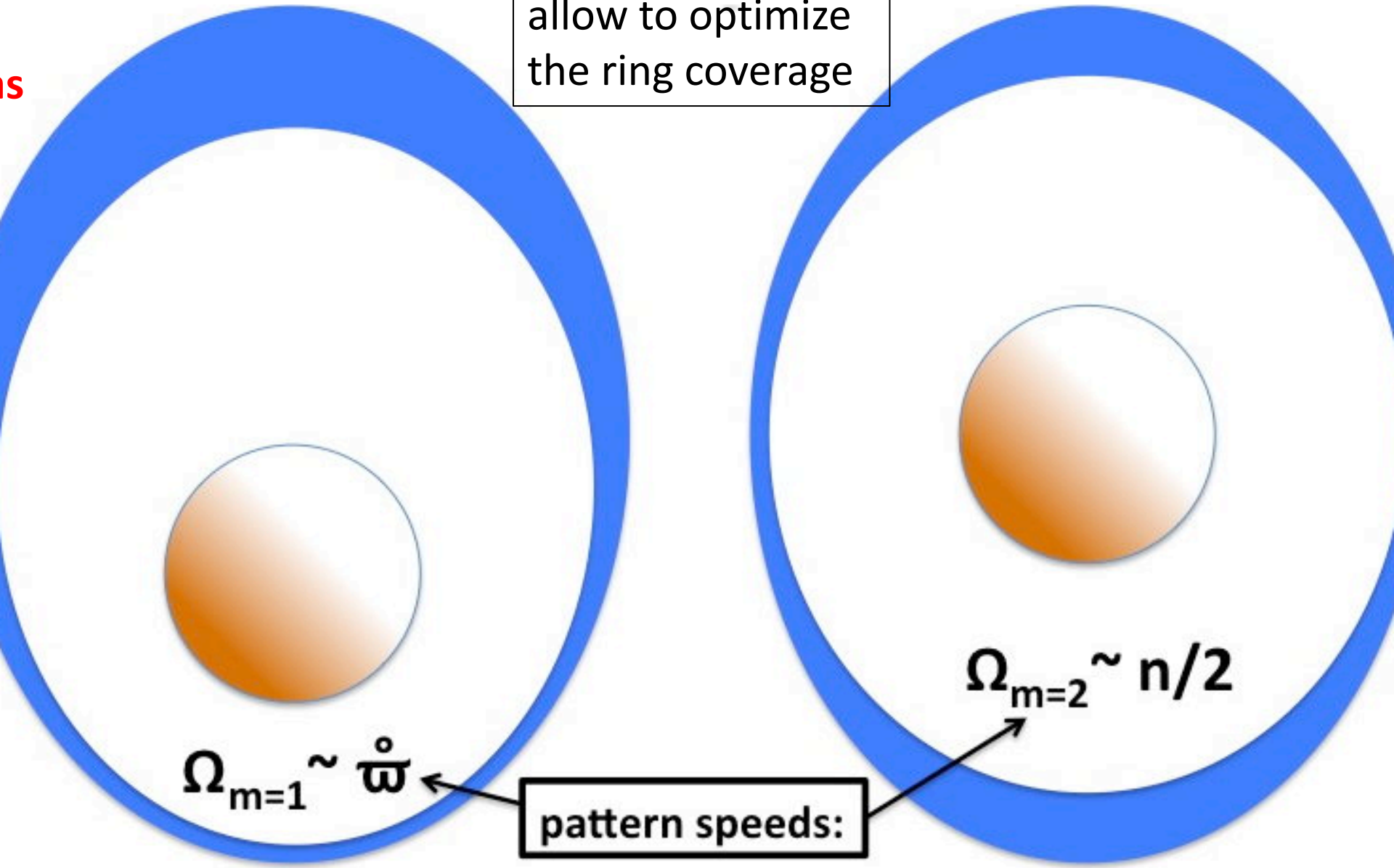



Stellar occultation by Chariklo's rings
July 23, 2017
Danish 1.5m telescope
Lucky Imager, red channel, 30 Hz
diffraction
diffraction
C2R ingress
C1R ingress
C1R egress
C2R egress
Ratio star/ref
Image number
0
1
2
3
4000
4100
4200
4300
4400
4500
4600
4700

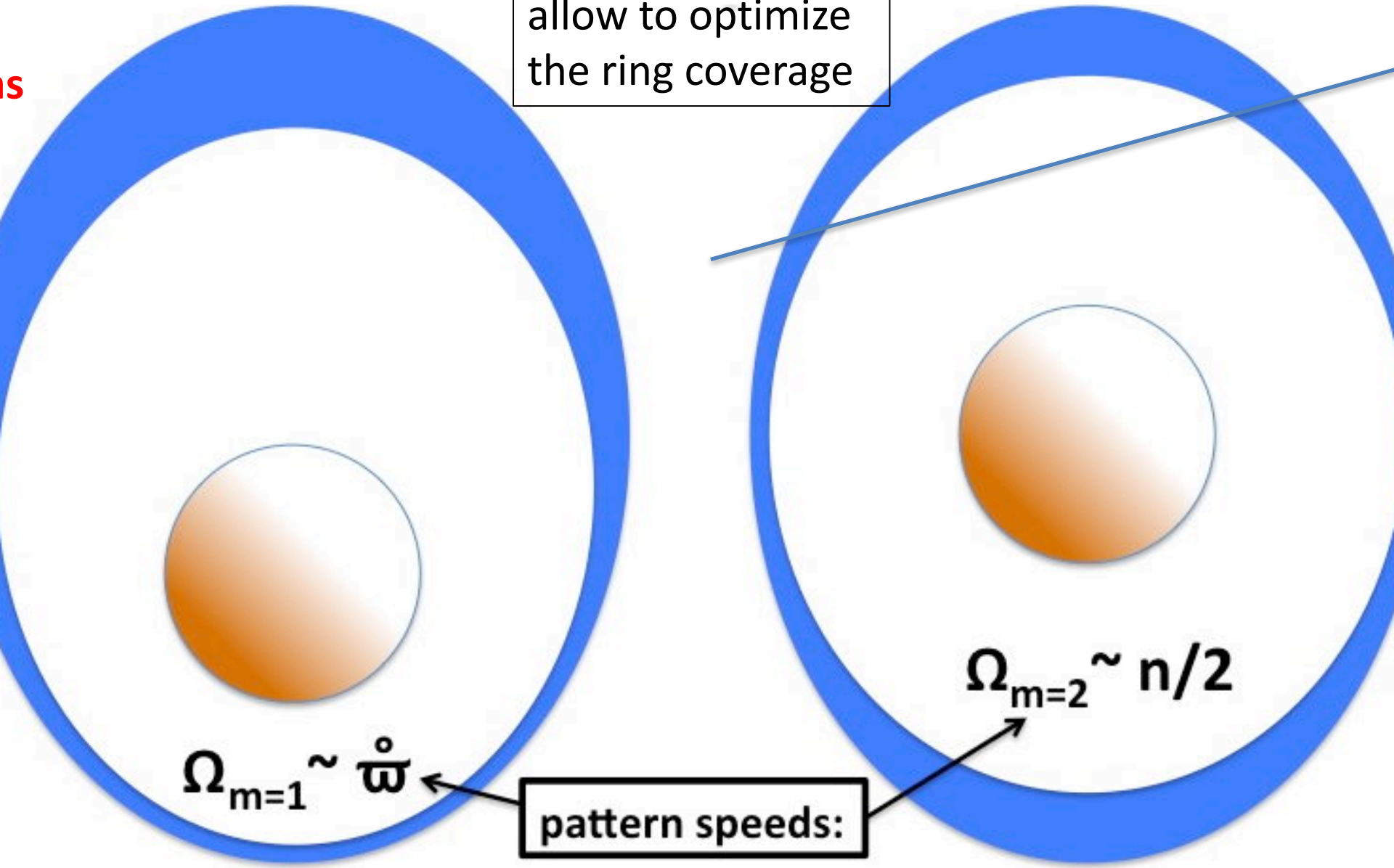

Chariklo 23 July 2017, Danish visible 5x5 DIT= 1/30 s (red: 6x5)
red channel (~700 to 1000 nm)
visible channel (~450 to 650 nm)
Ratio star/ref, blue: VIS, red: RED
0
0.5
1
1.5
2
2.1353×10^4
2.13535×10^4
2.1354×10^4
2.13545×10^4
2.1355×10^4
2.13555×10^4
2.1356×10^4
UT (sec) CAUTION!!! 0.06666 sec added to timing red channel


Chariklo 23 July 2017, Danish visible 5x5 DIT= 1/30 s (red: 6x5)
red channel (~700 to 1000 nm)
visible channel (~450 to 650 nm)
Ratio star/ref, blue: VIS, red: RED
0
0.5
1
1.5
2
2.13725×10^4
2.1373×10^4
2.13735×10^4
2.1374×10^4
2.13745×10^4
2.1375×10^4
2.13755×10^4
UT (sec) CAUTION!!! 0.06666 sec added to timing red channel

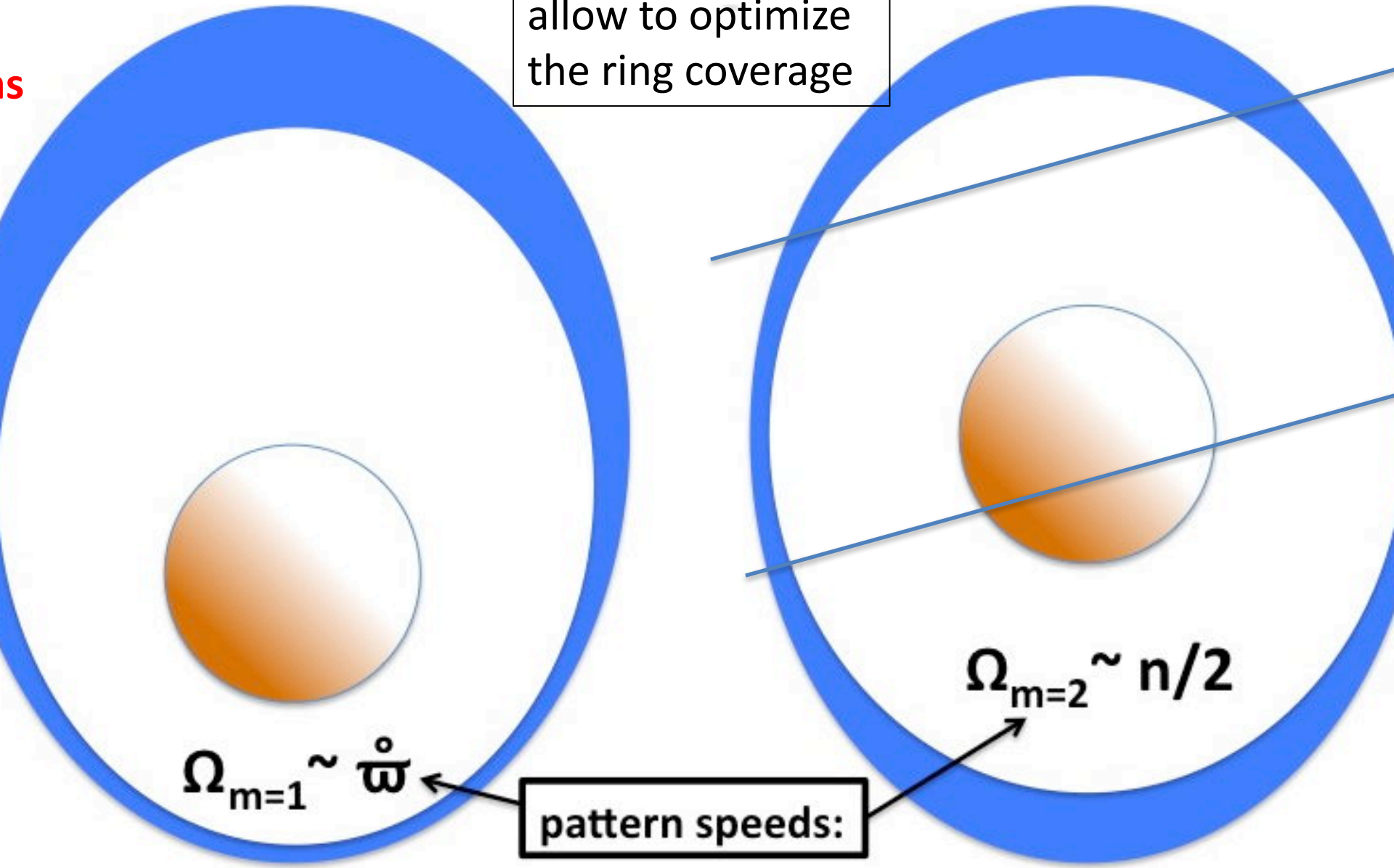
Gaia accuracy will allow to optimize the ring coverage



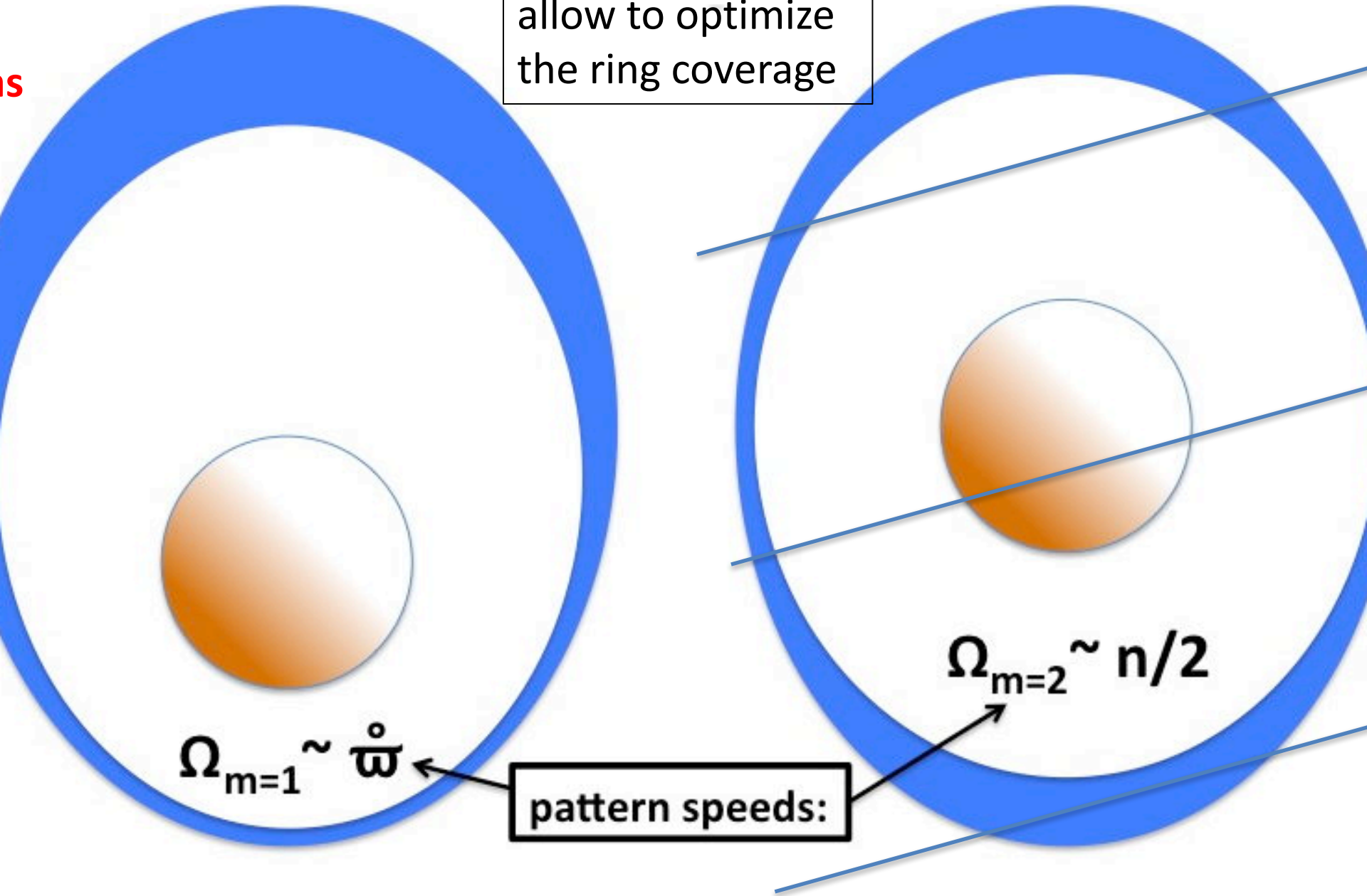
Gaia accuracy will allow to optimize the ring coverage



Gaia accuracy will allow to optimize the ring coverage



Gaia accuracy will allow to optimize the ring coverage



Conclusions

Since July 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

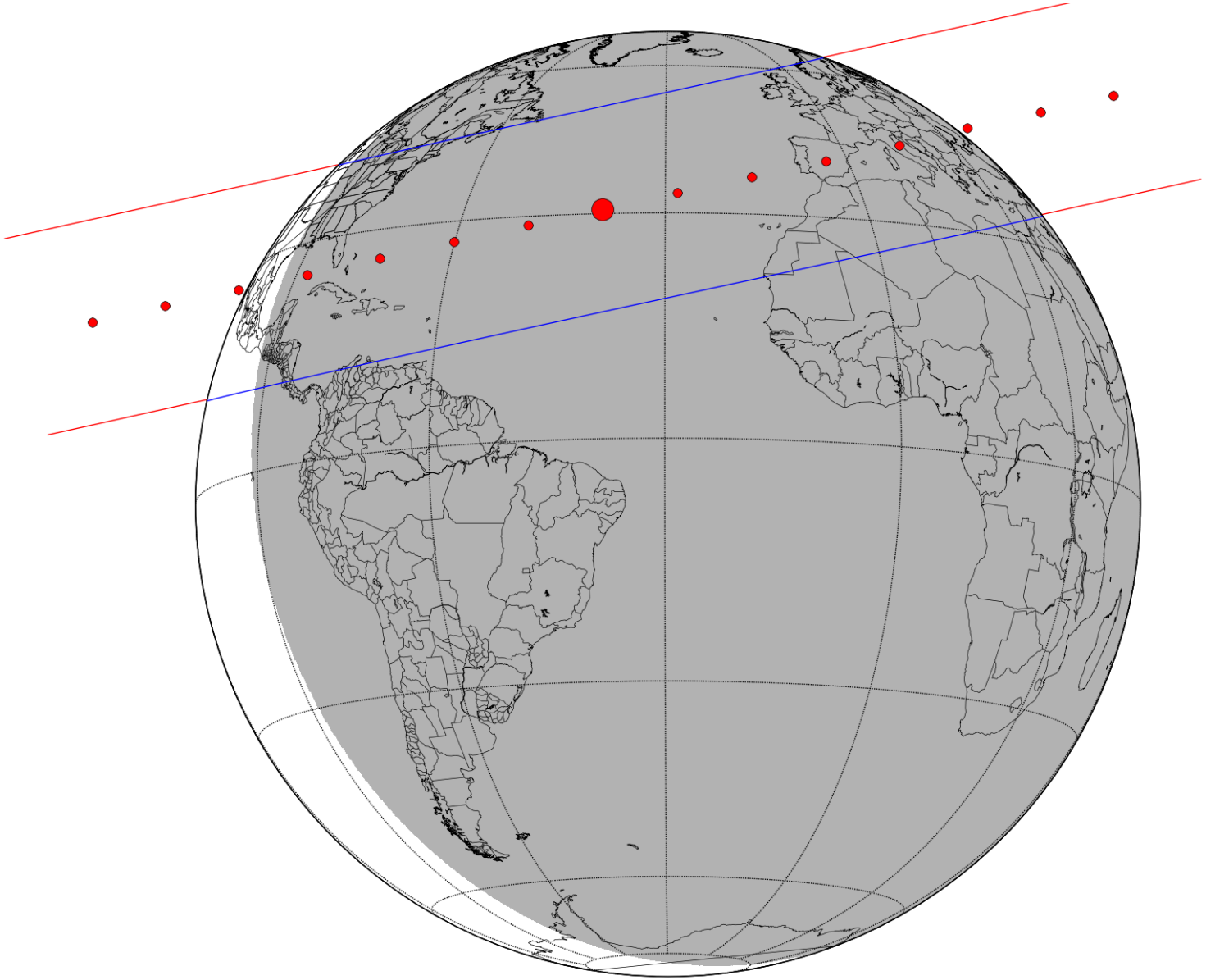
now look at the indentations!

an ERC project:

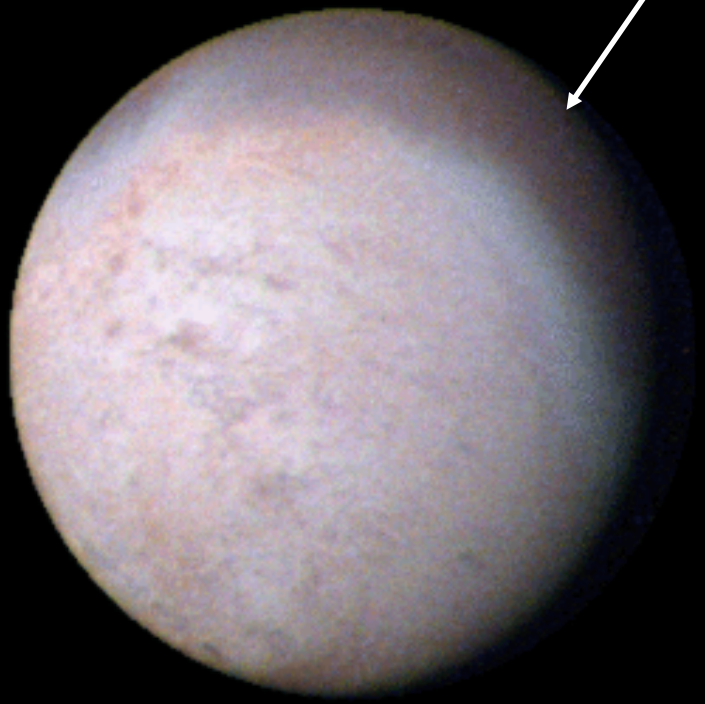
Lucky Star

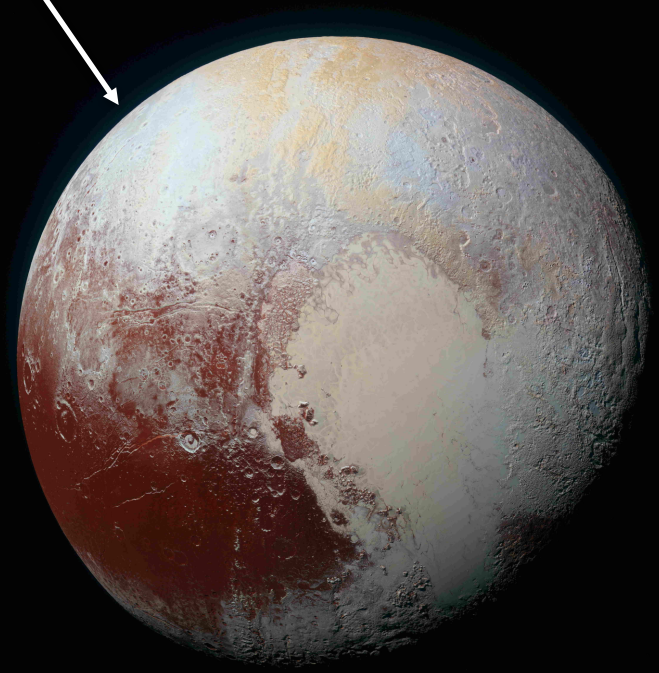
The Triton occultation of October 5.6, 2017

the Triton occultation of October 5, 2017



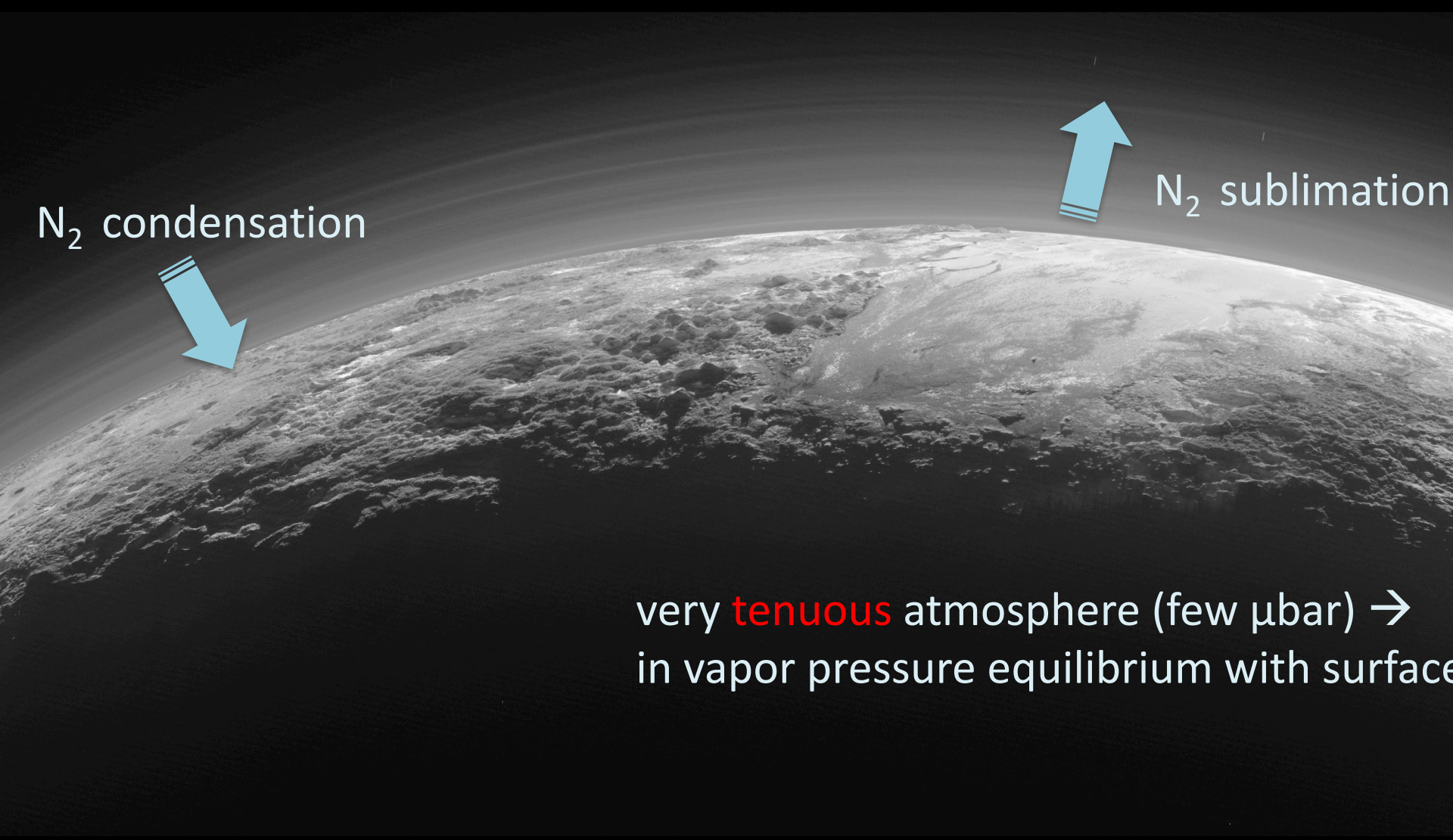
"Twin" N_2 atmospheres
(witha bit of CH_4)
~12-14 µbar at surface
sublimation of N_2 ice





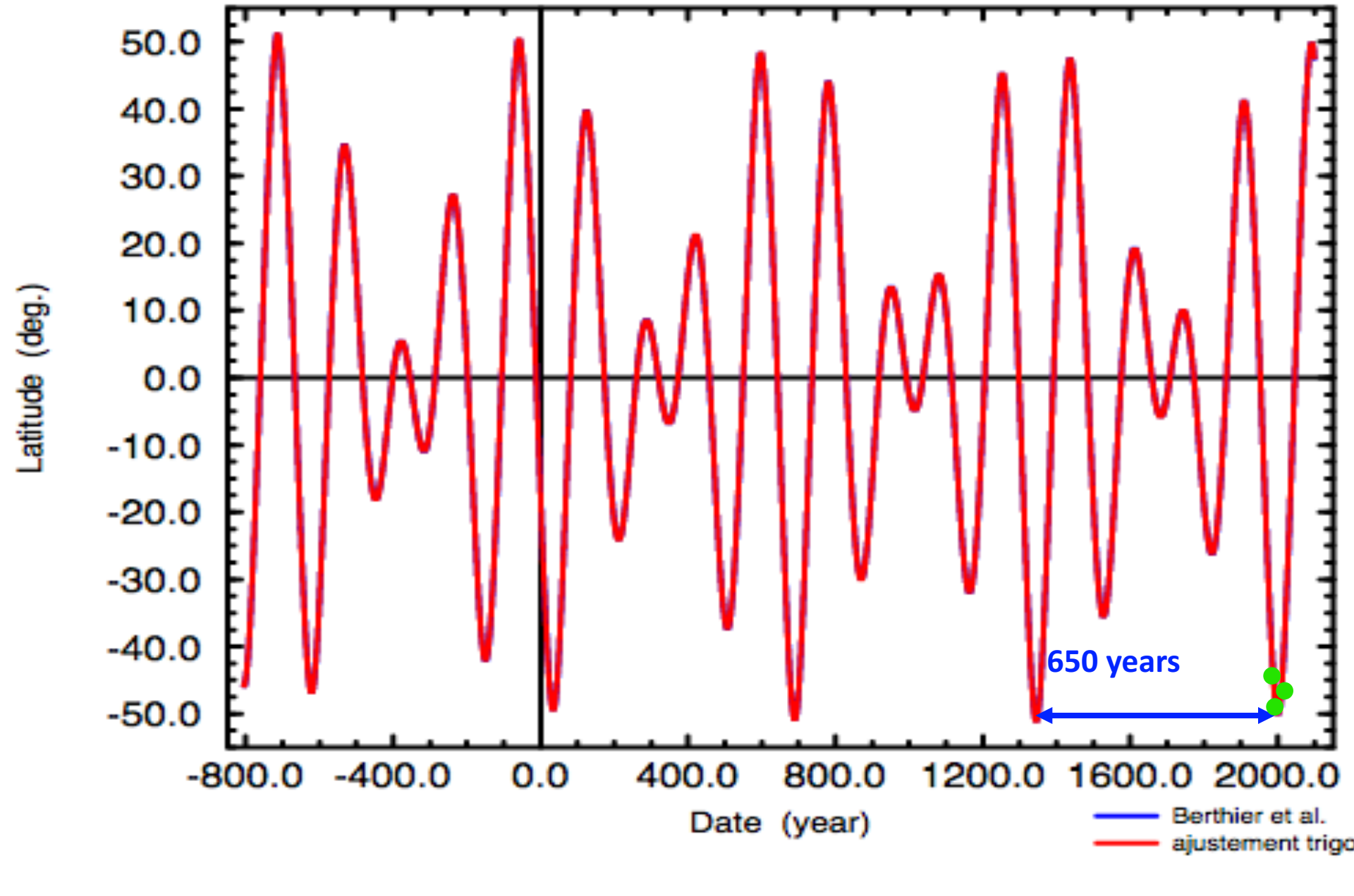
Triton *Voyager 2*
1989

Pluto *New Horizons*
2015

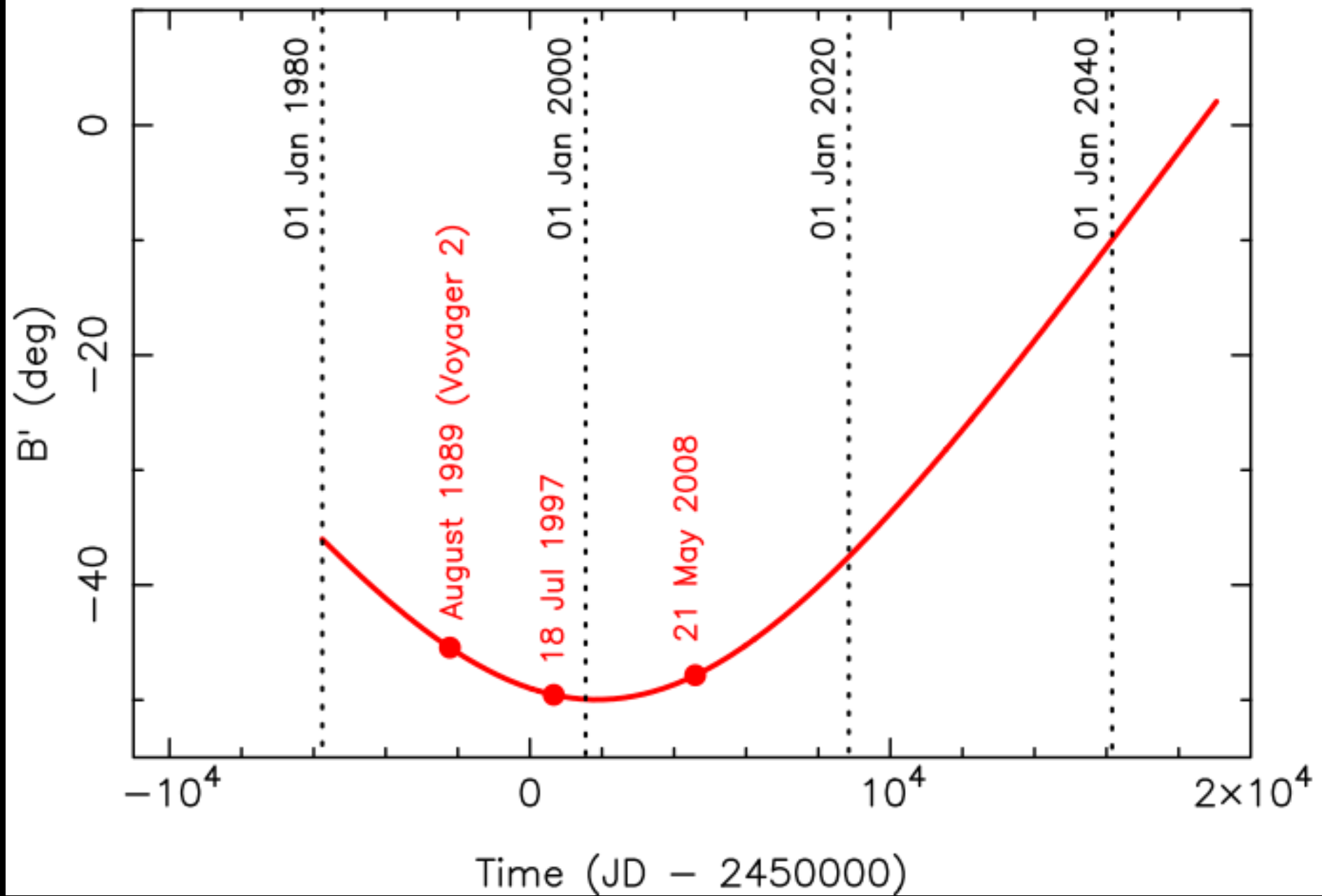


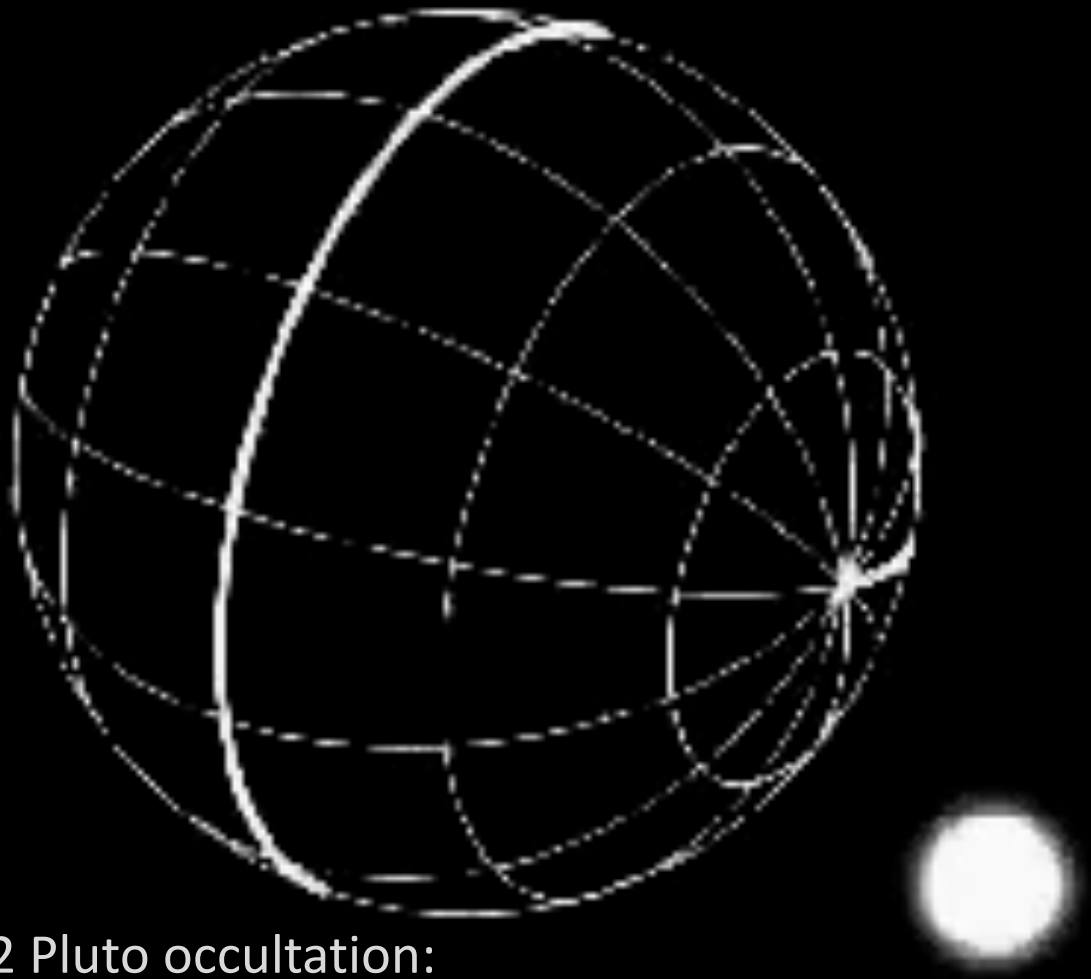
New Horizons/LORRI 14 July 2015

Triton's sub-solar latitude: the "extreme" solstice of 2000



le solstice "extrême" Triton de 2000

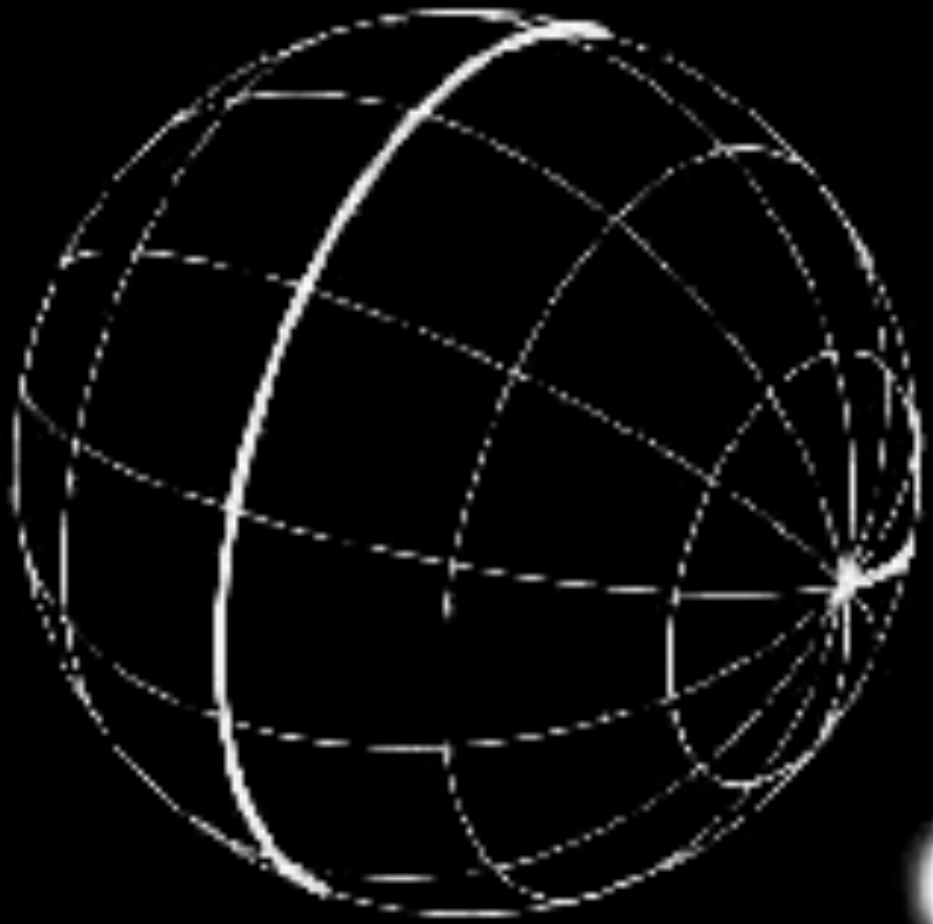




the August 21, 2002 Pluto occultation: a reconstruction of what happened

Bruno Sicardy - exploring outer solar system with stellar occultation- ESOP XXXVI
Freiberg, 16-17 Sept 20017

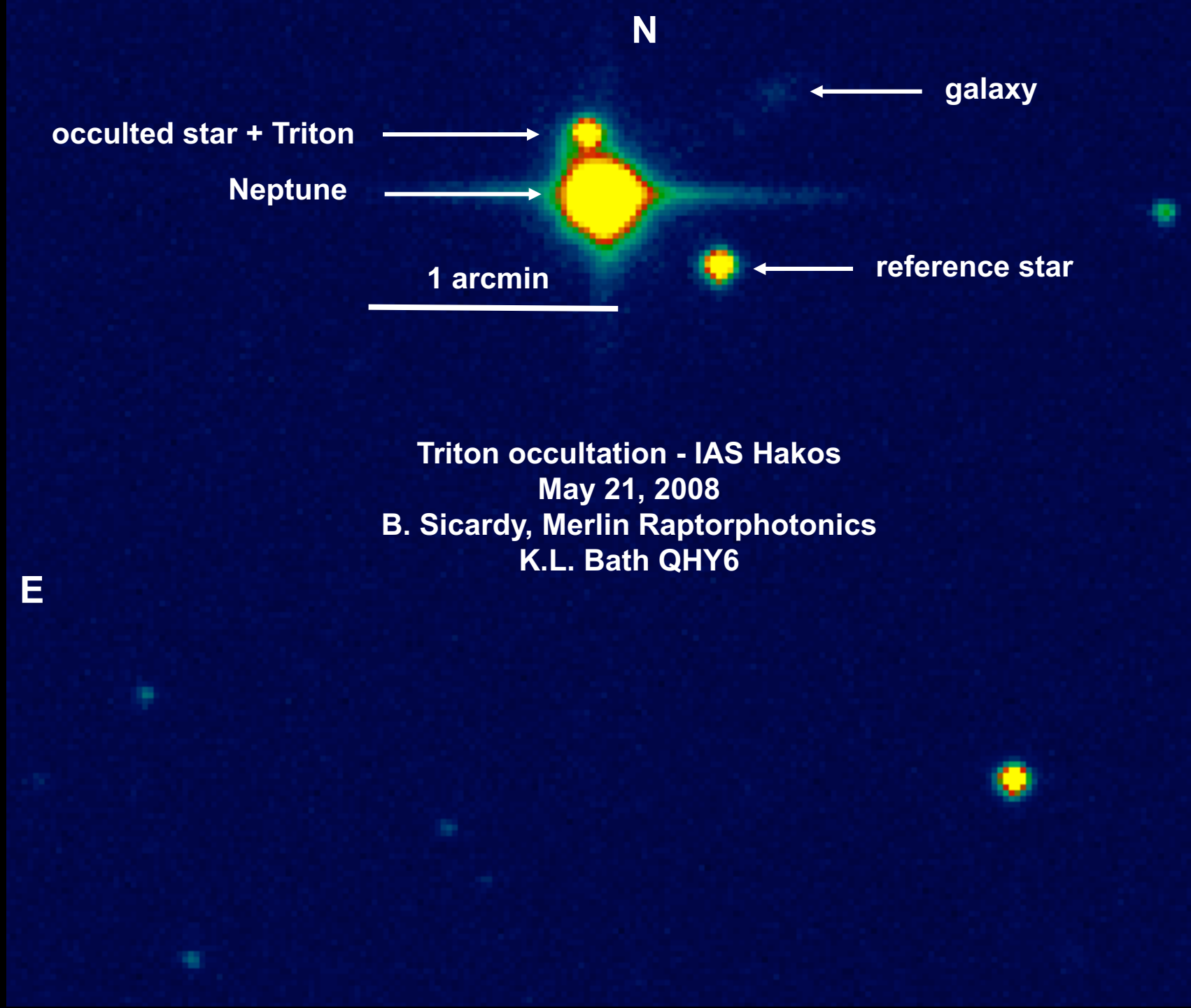
gravity waves!

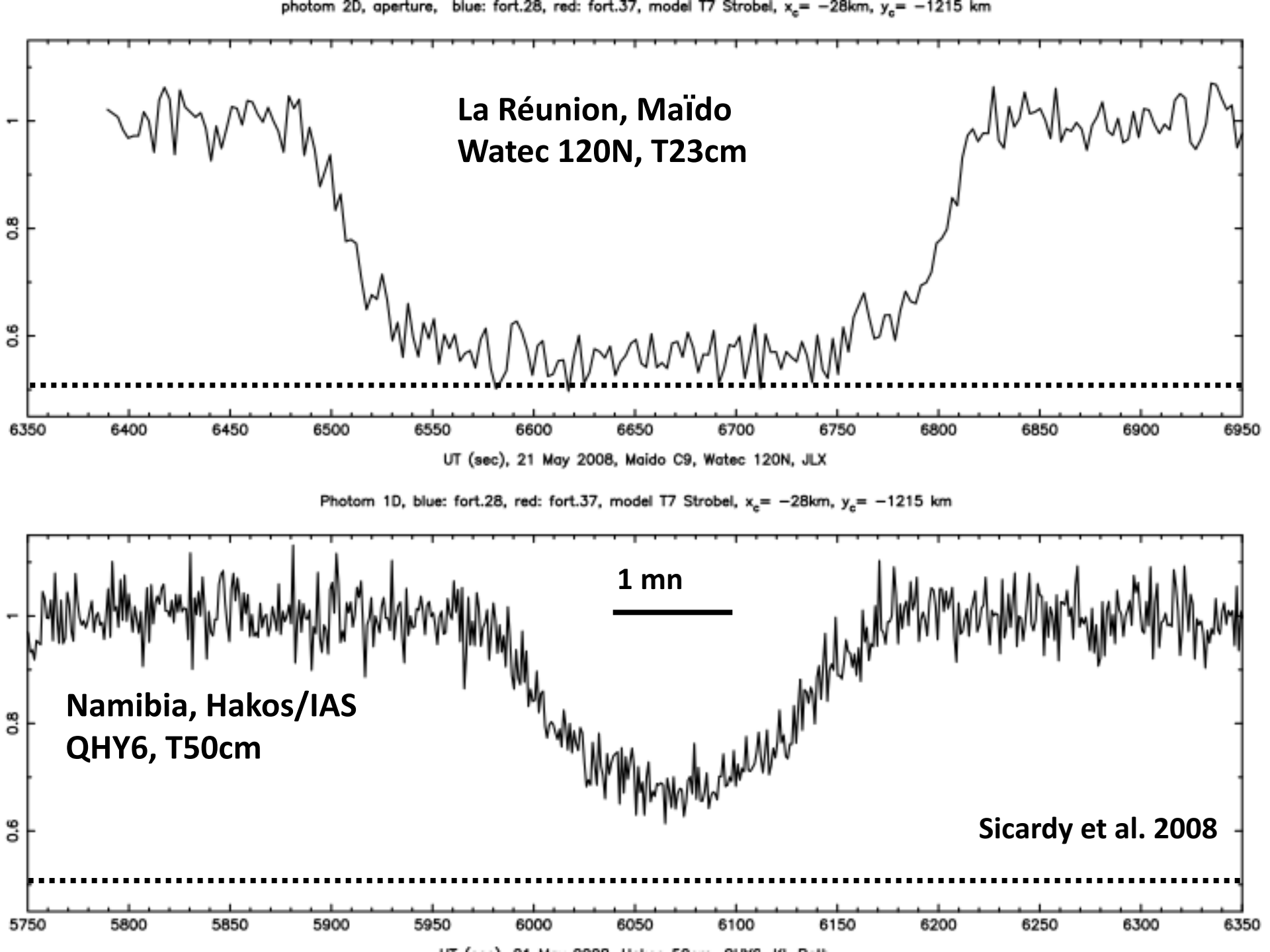


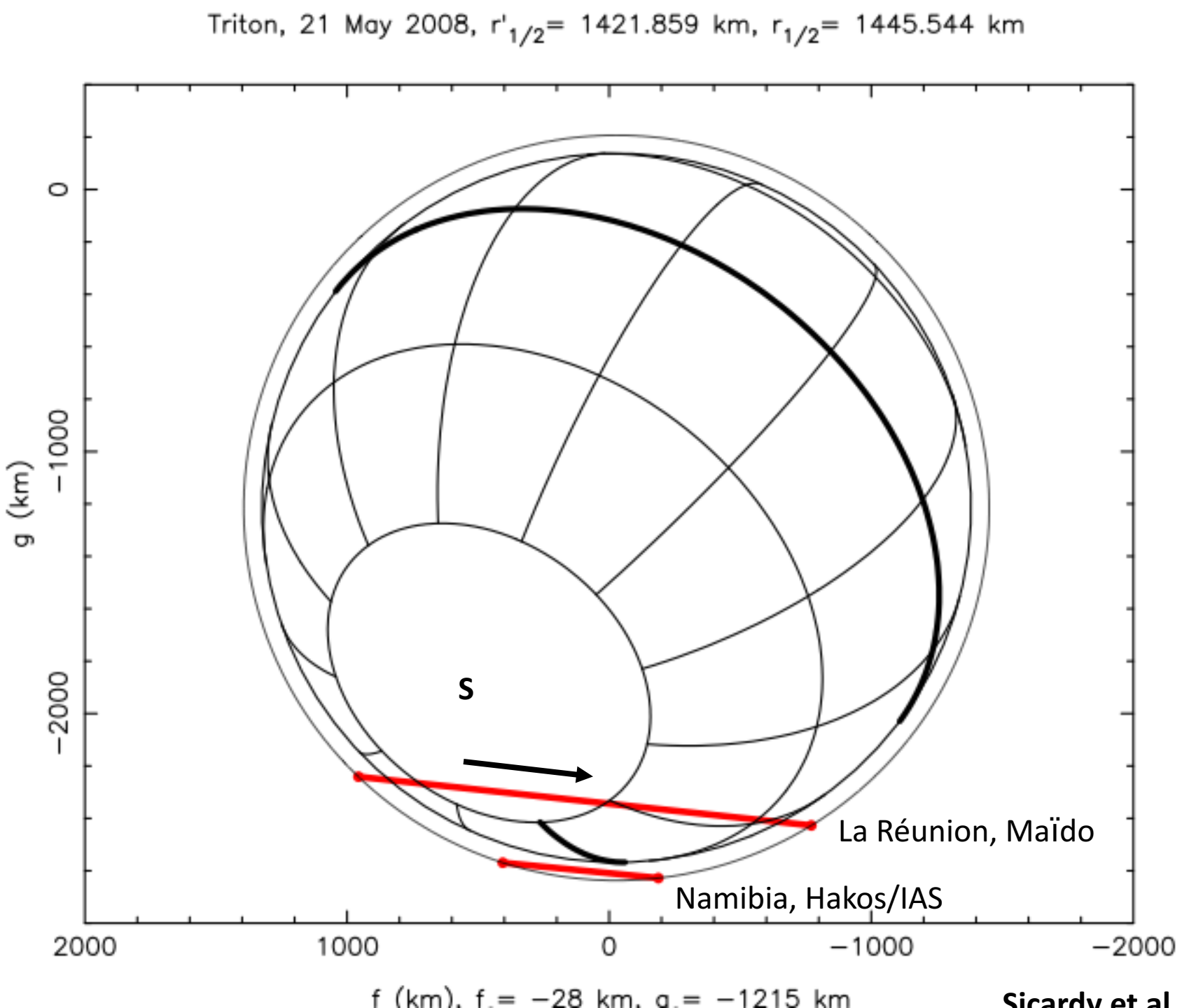
gravity waves!

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

Bruno Sicardy - exploring outer solar system with stellar occultation- ESOP XXXVI
Freiberg, 16-17 Sept 20017


N
galaxy
occulted star + Triton
Neptune
reference star
1 arcmin
Triton occultation - IAS Hakos
May 21, 2008
B. Sicardy, Merlin Raptorphotonics
K.L. Bath QHY6
E


photom 2D, aperture, blue: fort.28, red: fort.37, model T7 Strobel, x_c= −28km, y_c= −1215 km
La Réunion, Maïdo
Watec 120N, T23cm
1
0.8
0.6
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
6950
UT (sec), 21 May 2008, Maido C9, Watec 120N, JLX
Photom 1D, blue: fort.28, red: fort.37, model T7 Strobel, x_c= −28km, y_c= −1215 km
1 mn
Namibia, Hakos/IAS
QHY6, T50cm
Sicardy et al. 2008
1
0.8
0.6
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
6350



Sicardy et al. 2008

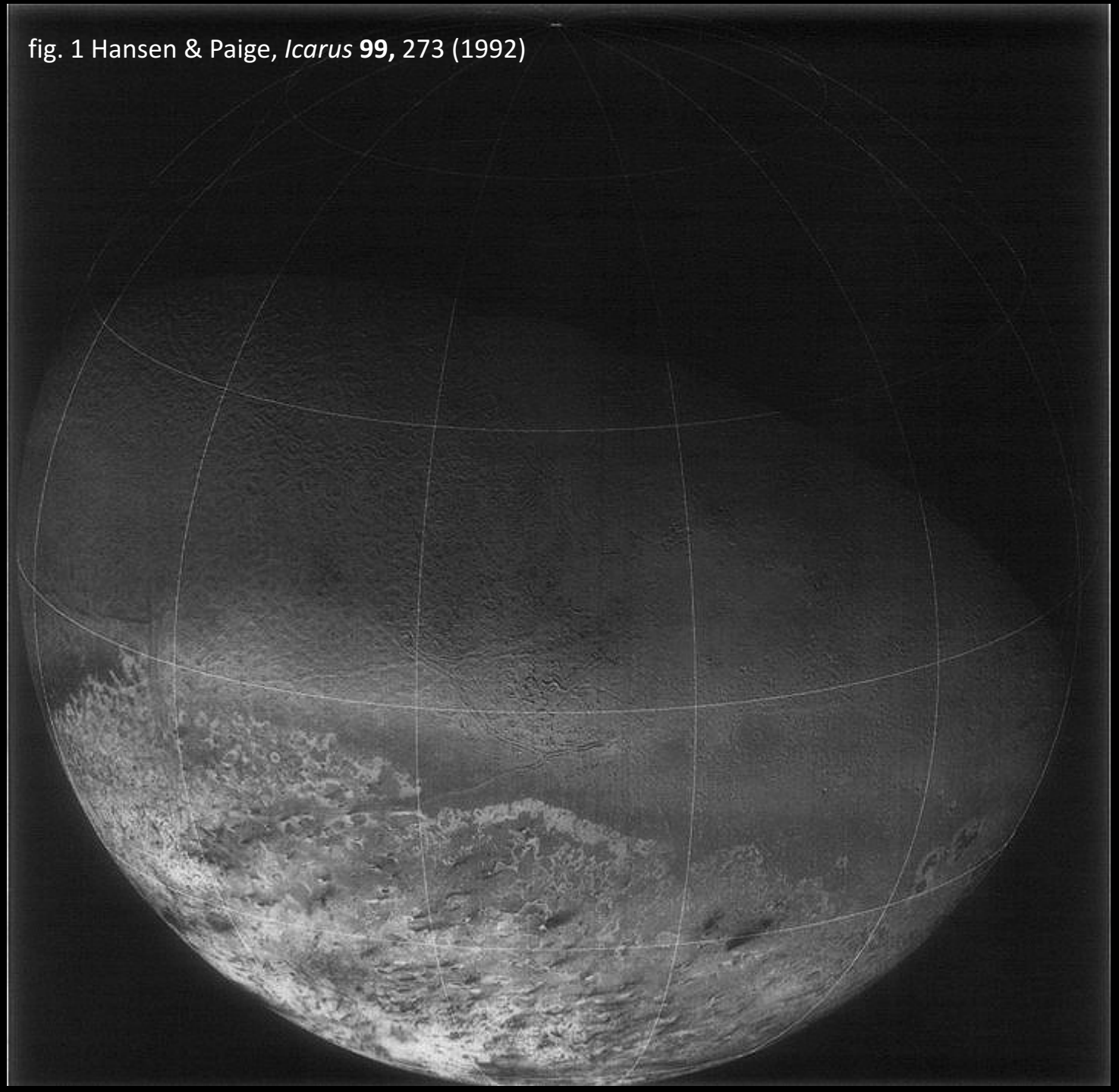


fig. 1 Hansen & Paige, *Icarus* **99,** 273 (1992)

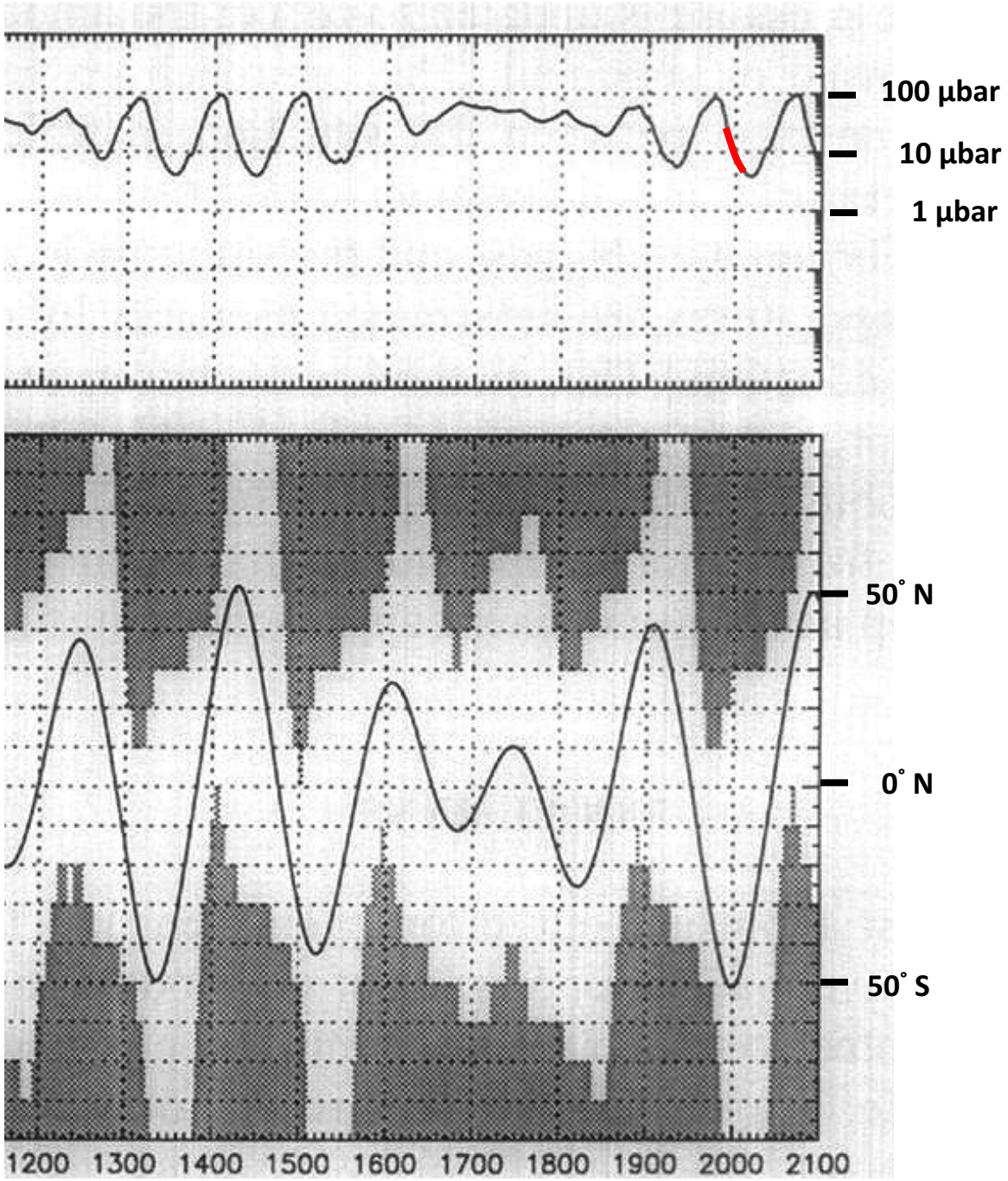
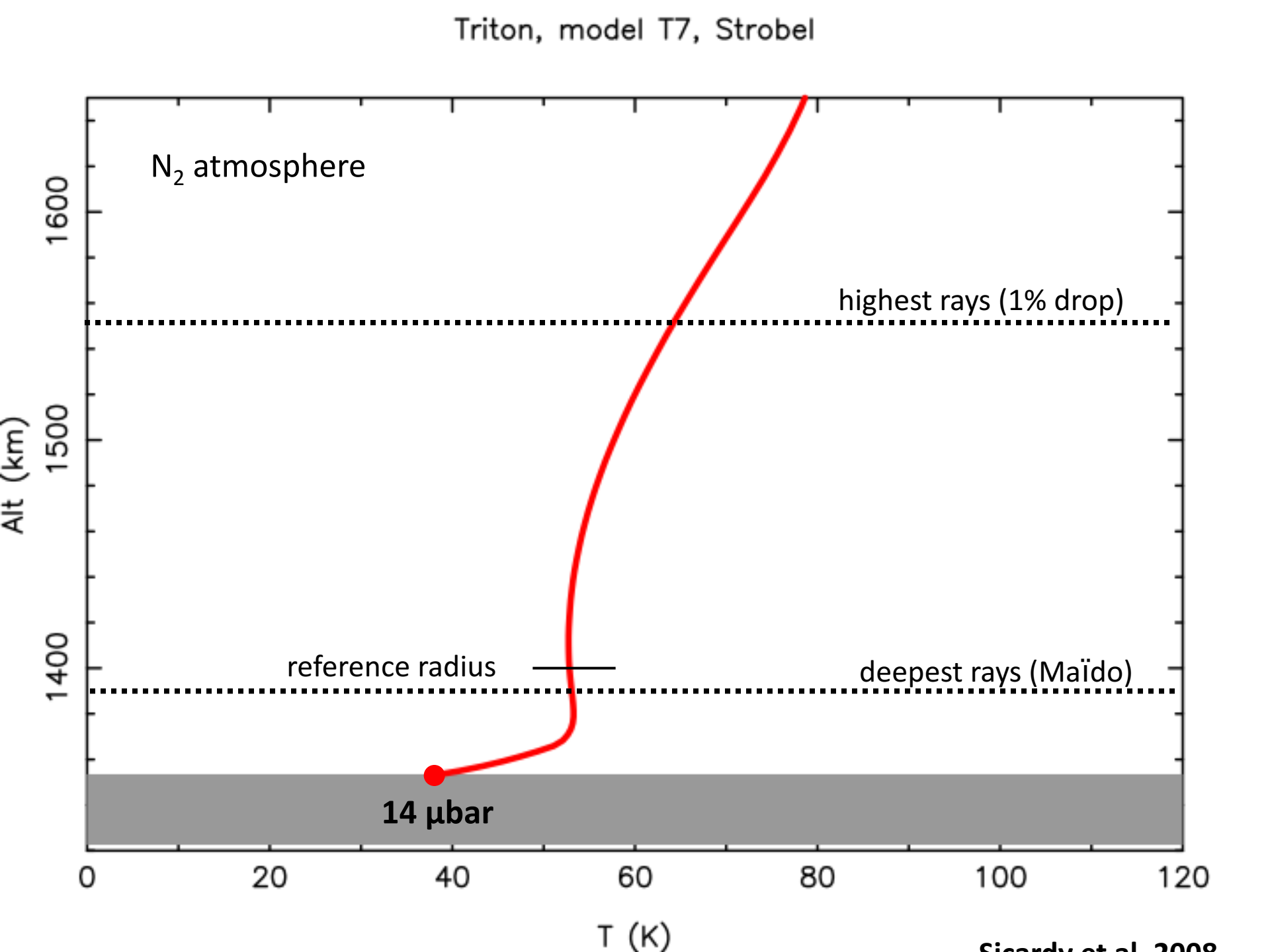
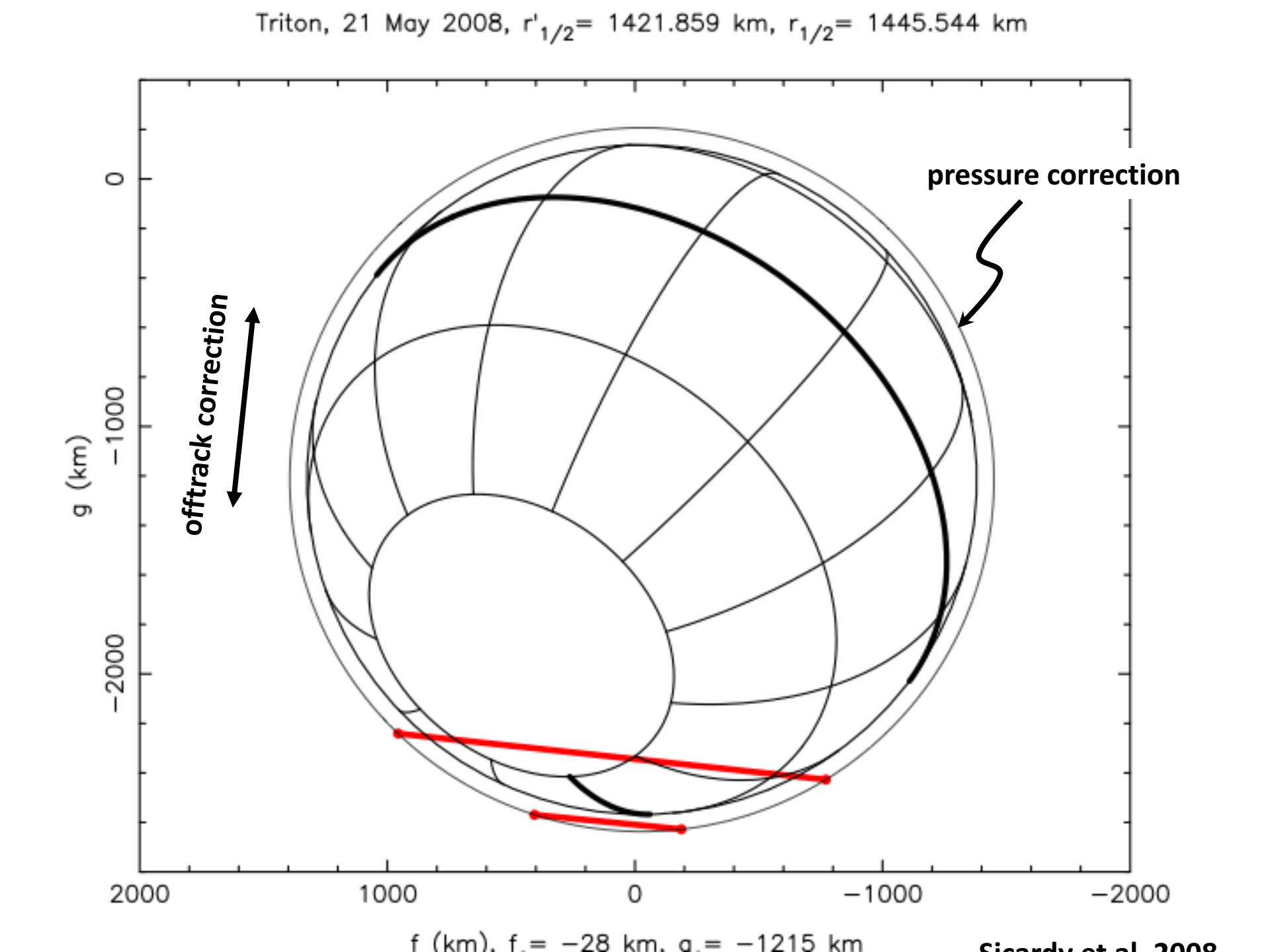


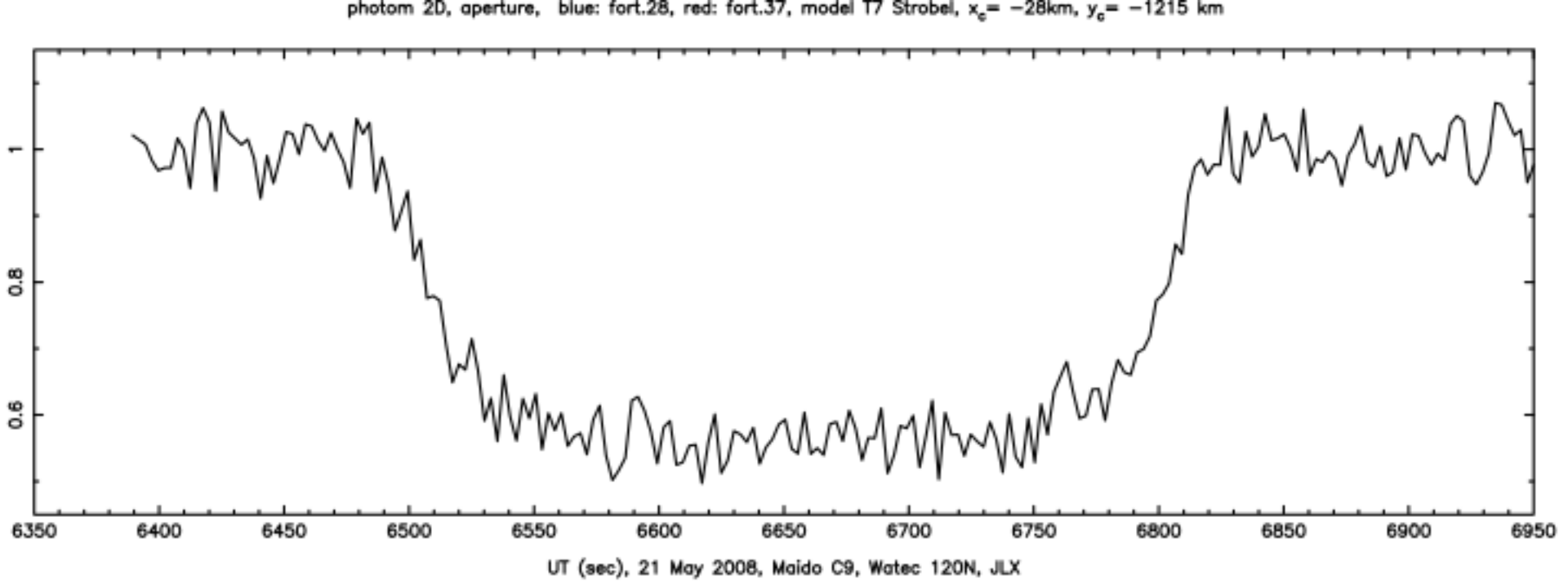
fig. 3 Hansen & Paige *Icarus* **99,** 273 (1992)

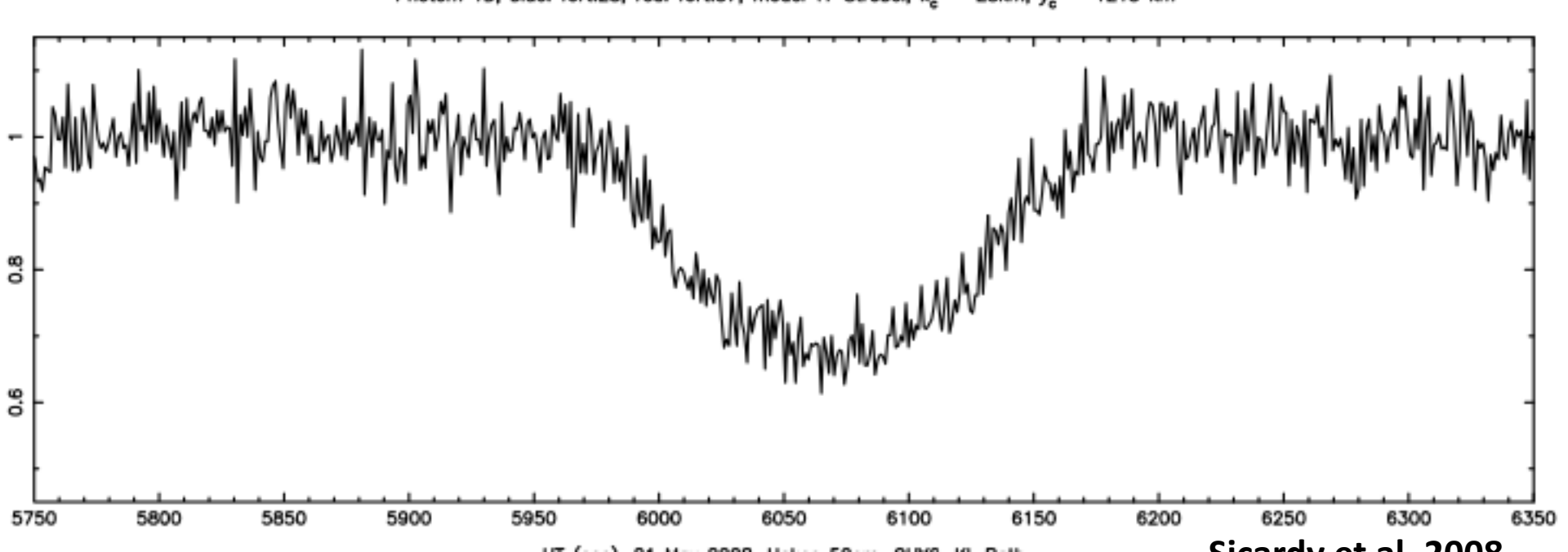


Sicardy et al. 2008

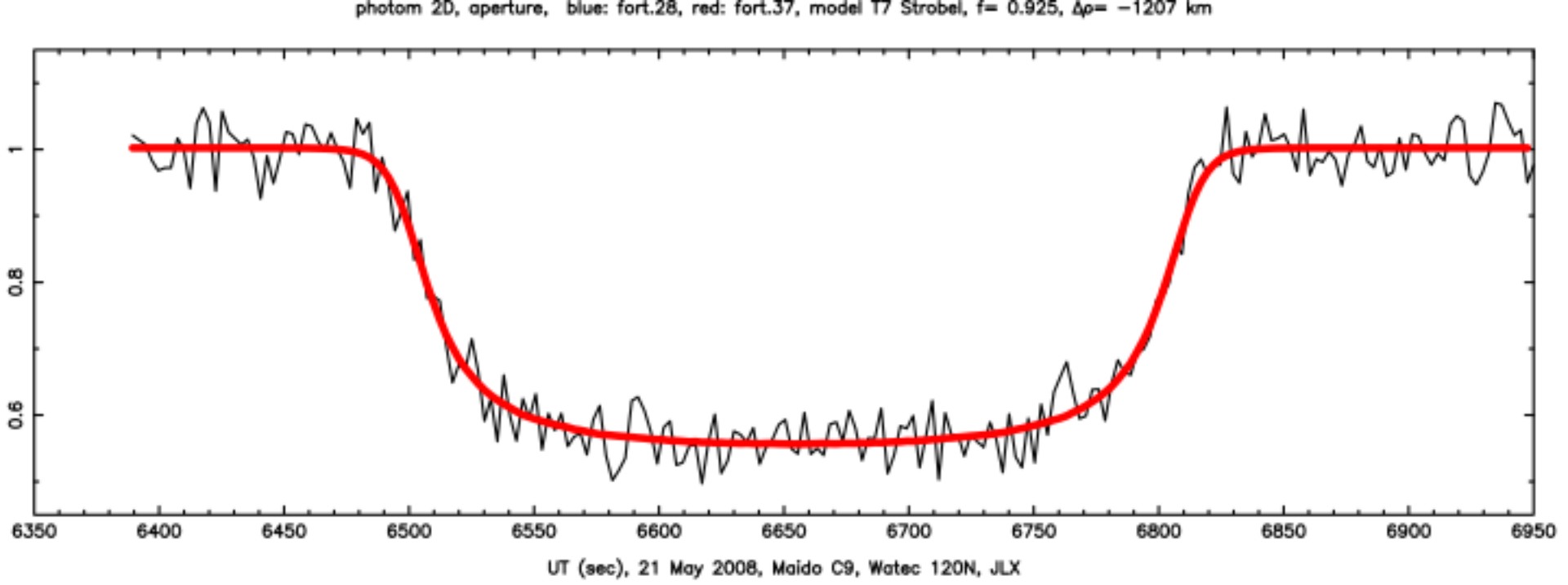


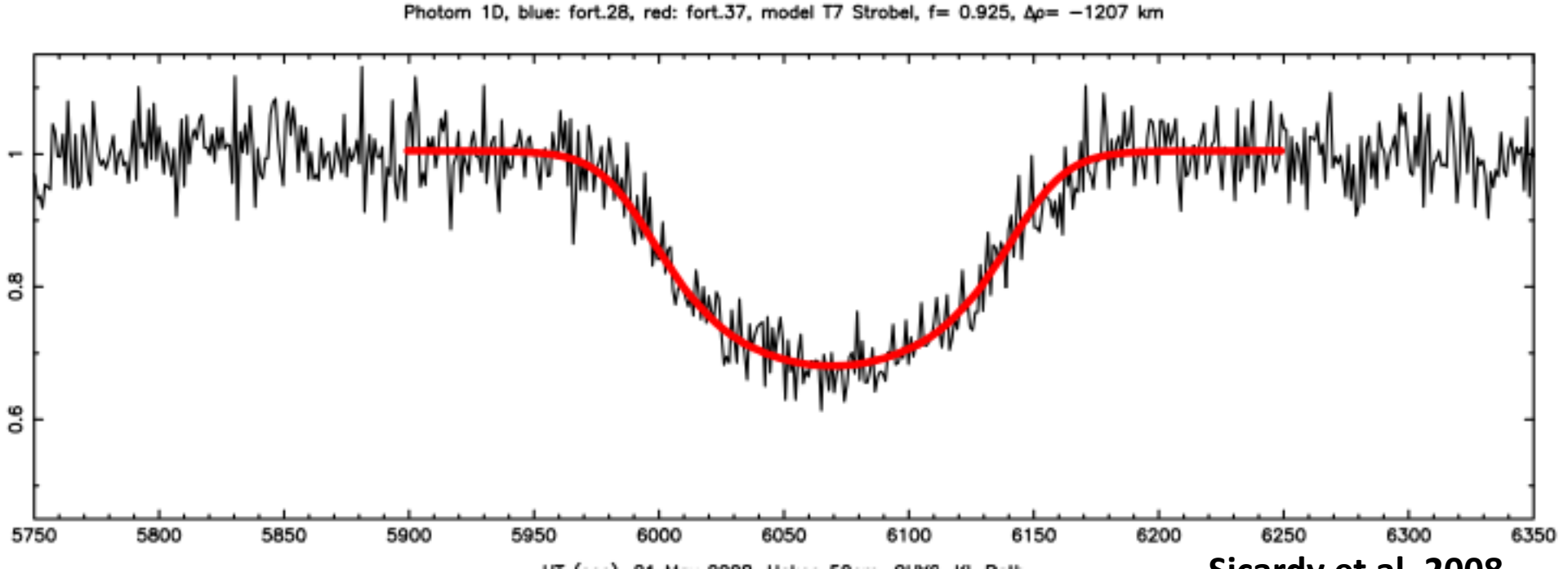
Sicardy et al. 2008



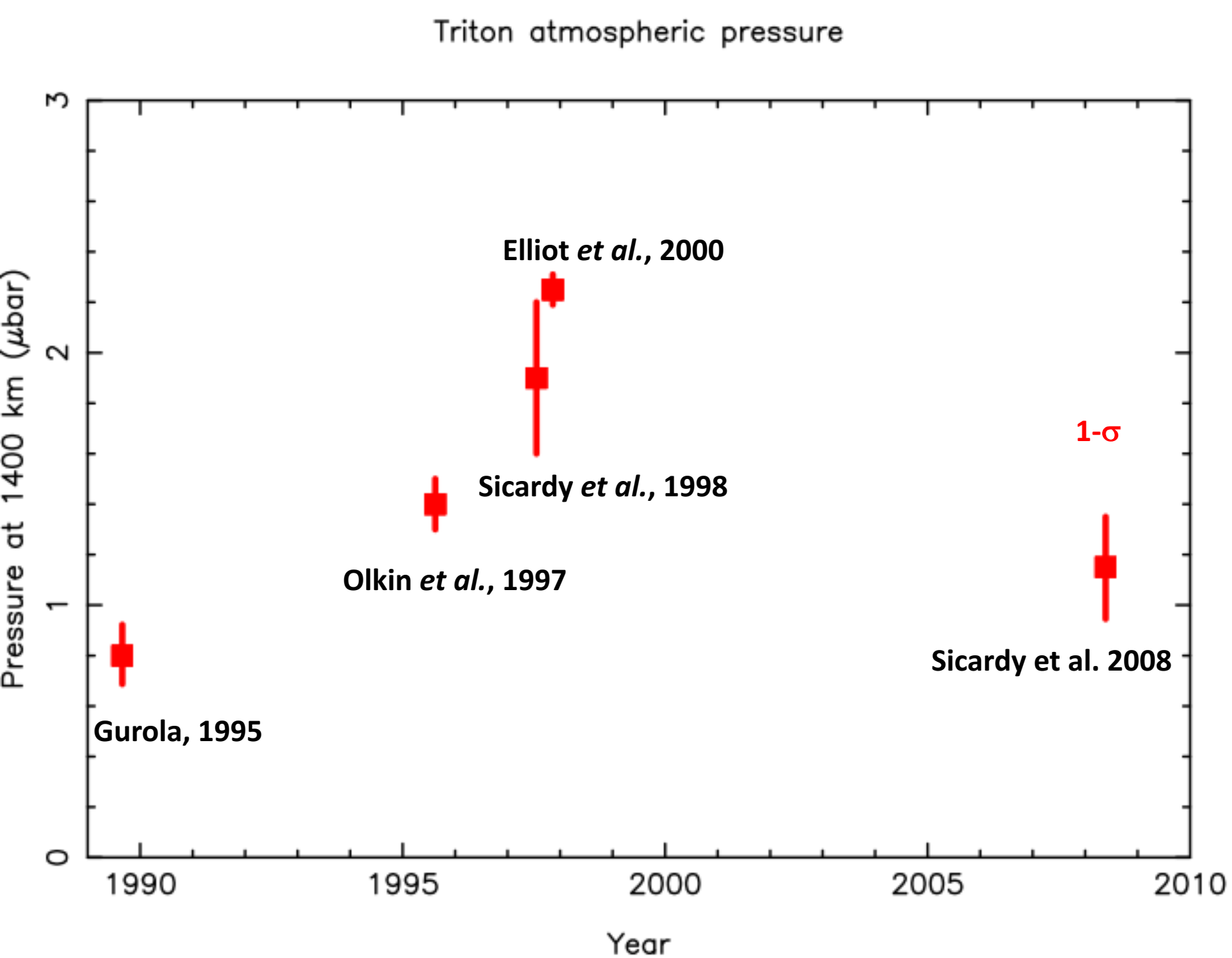


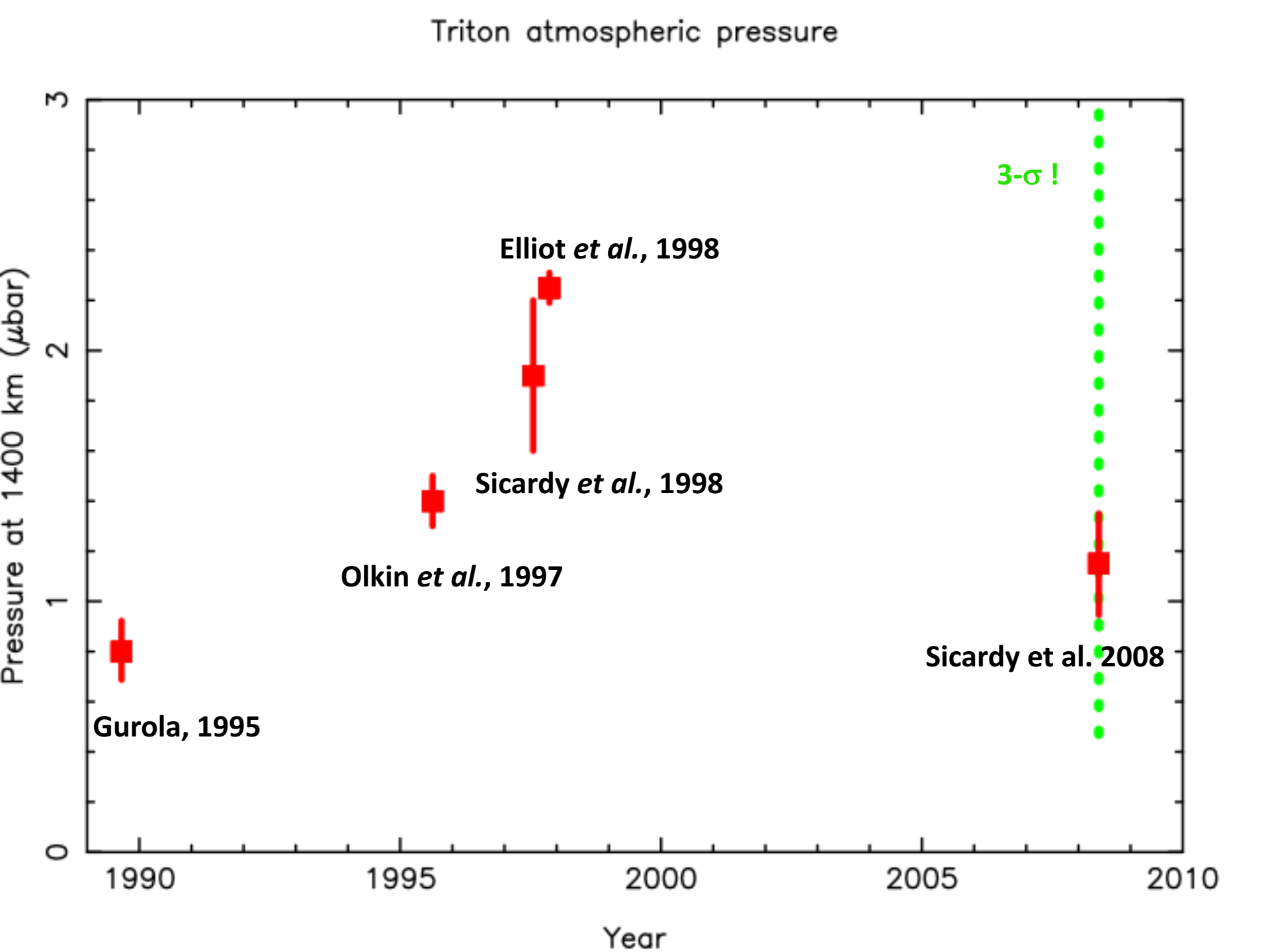
Sicardy et al. 2008



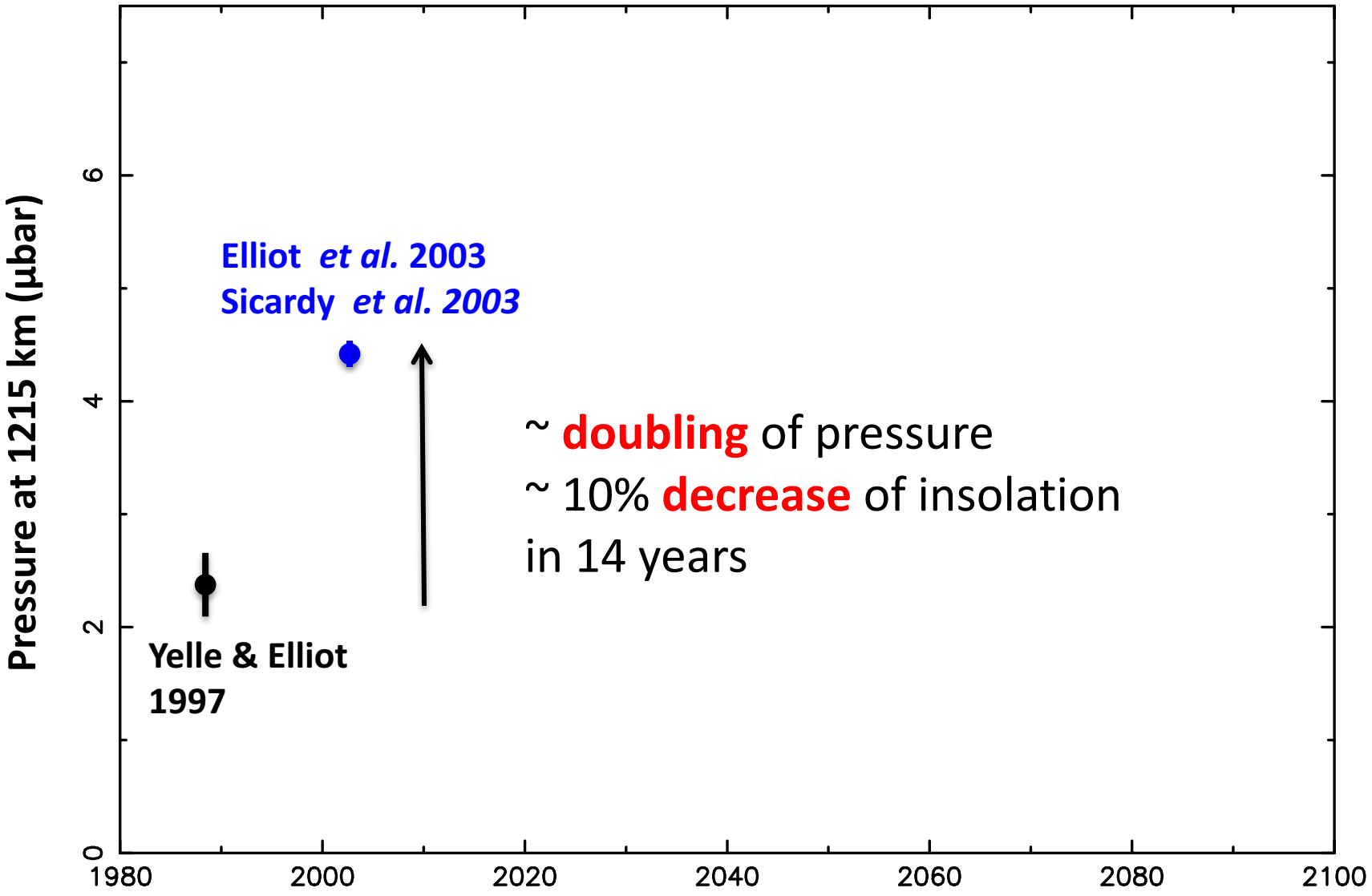


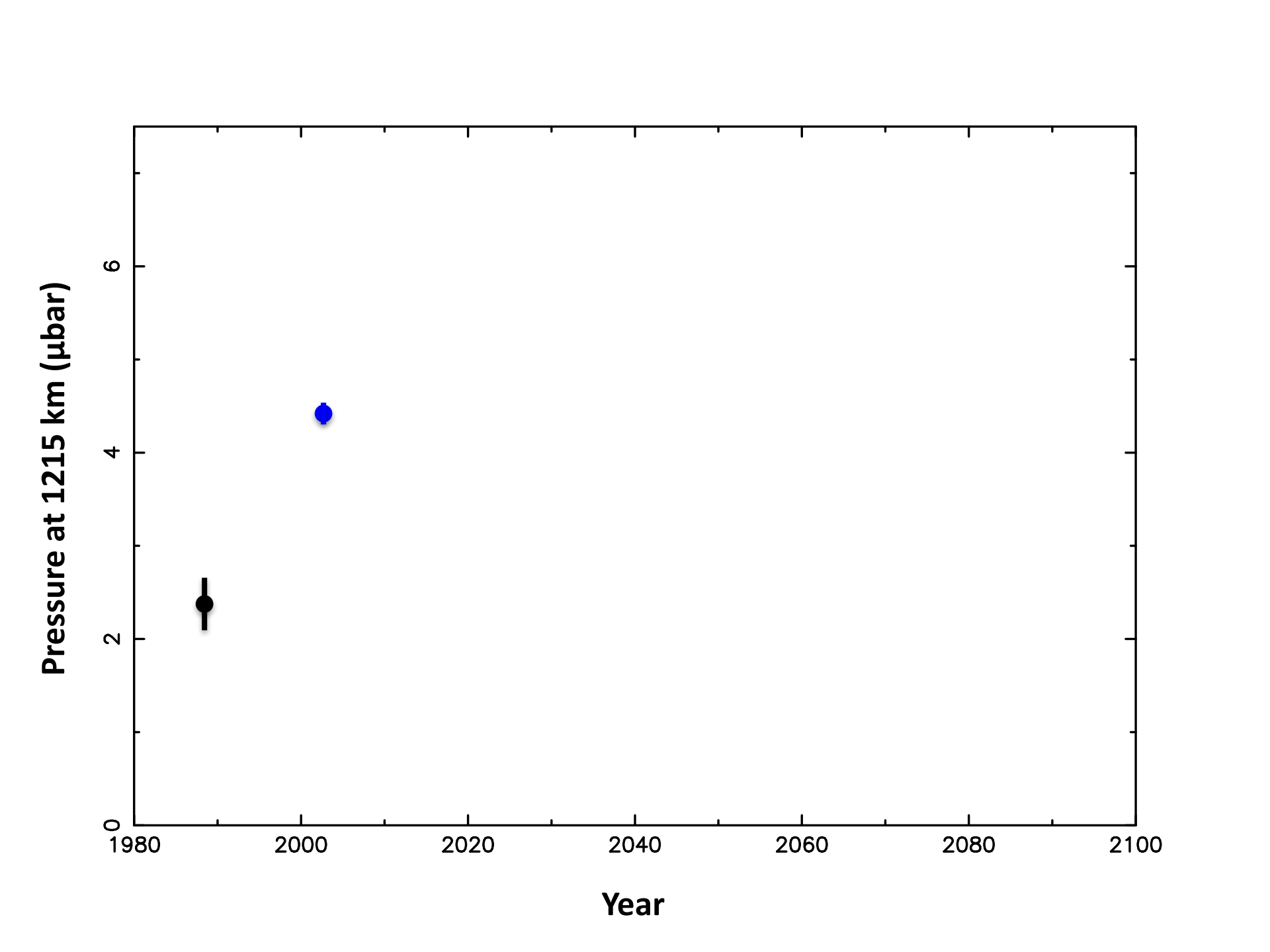
Sicardy et al. 2008

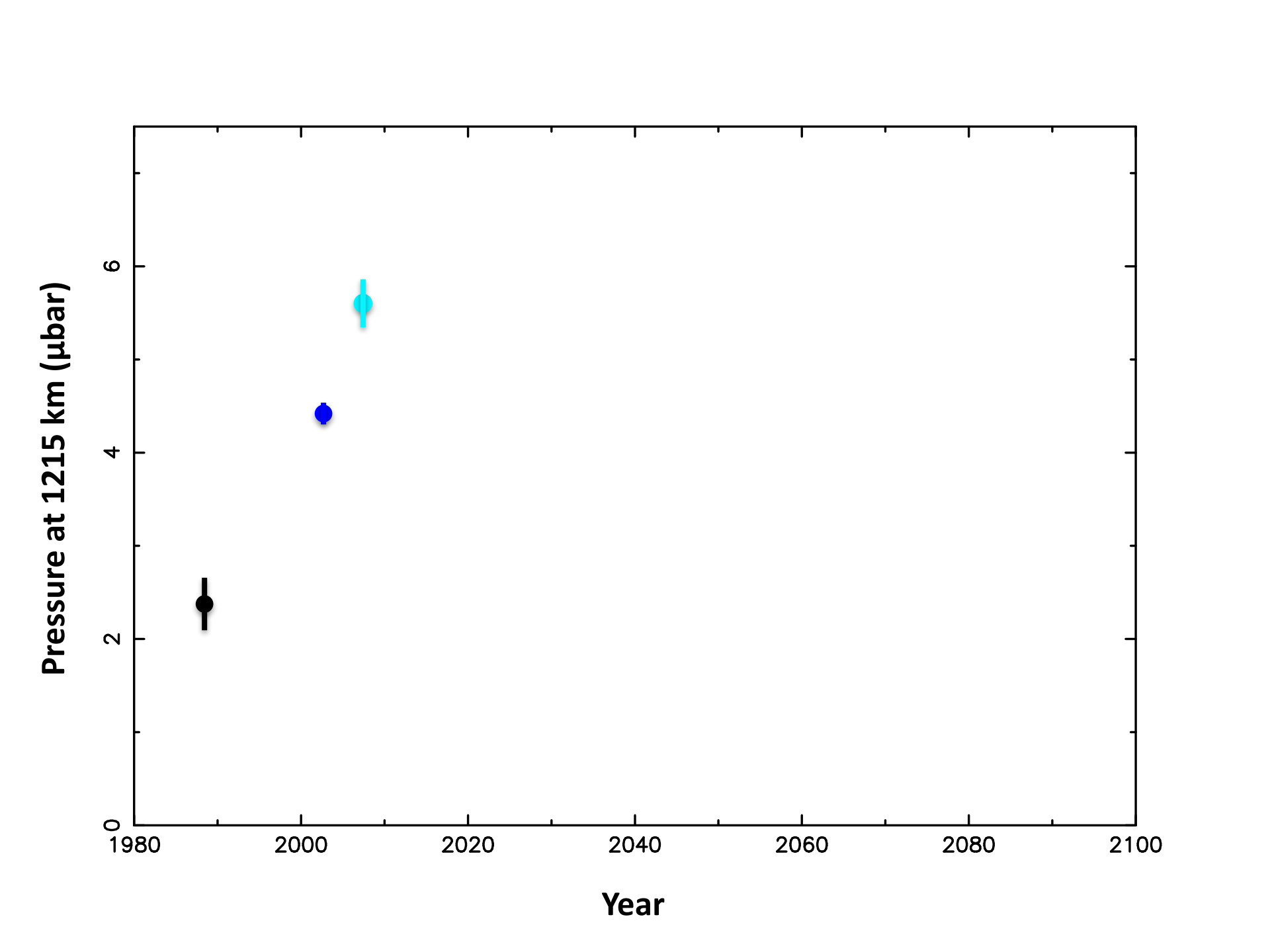

Triton atmospheric pressure
Pressure at 1400 km (μbar)
0
1
2
3
1990
1995
2000
2005
2010
Year
Elliot et al., 2000
Sicardy et al., 1998
Olkin et al., 1997
Gurola, 1995
1-σ
Sicardy et al. 2008

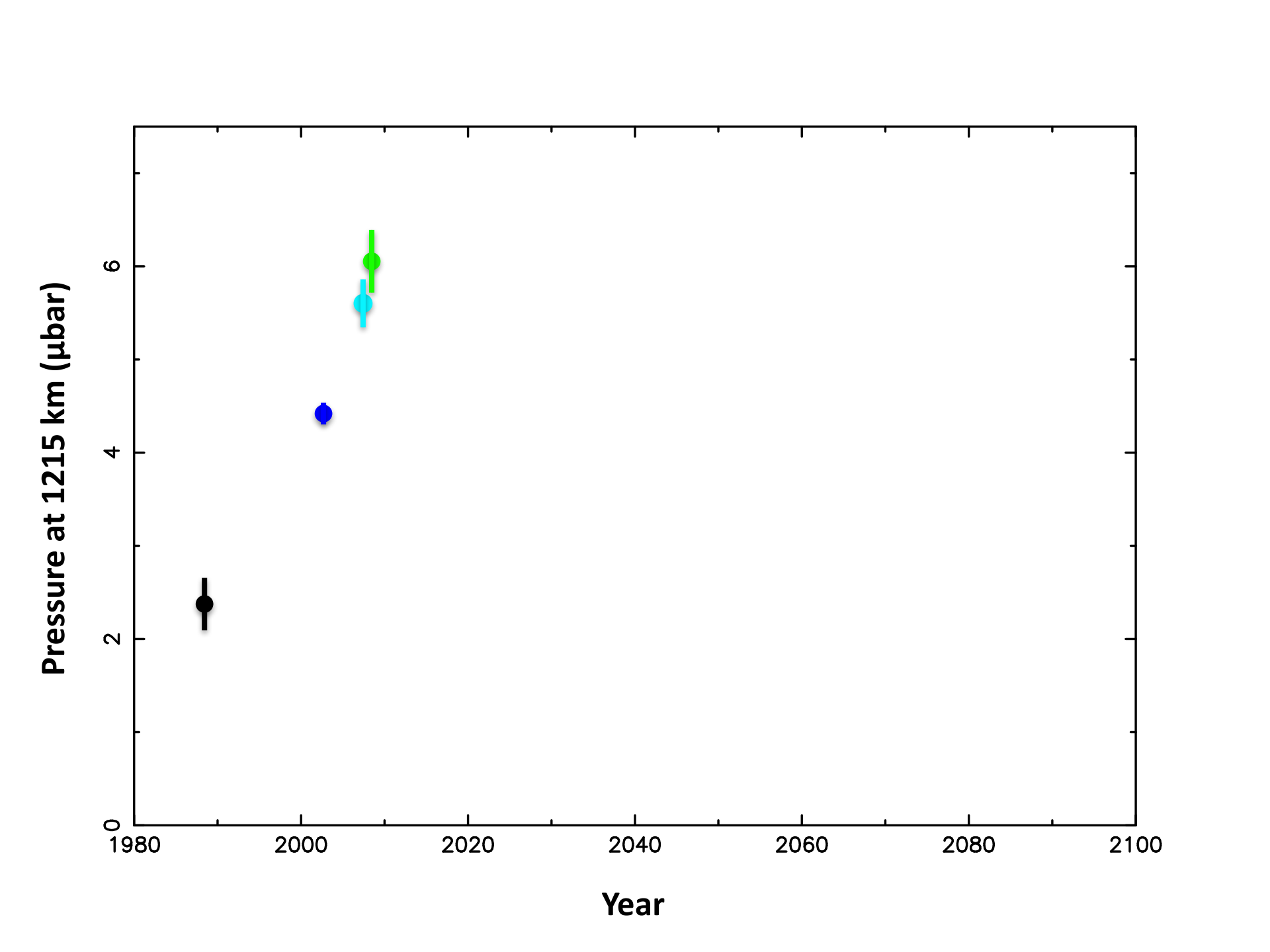

Triton atmospheric pressure
Pressure at 1400 km (μbar)
0
1
2
3
1990
1995
2000
2005
2010
Year
Gurola, 1995
Olkin et al., 1997
Sicardy et al., 1998
Elliot et al., 1998
3-σ !
Sicardy et al. 2008

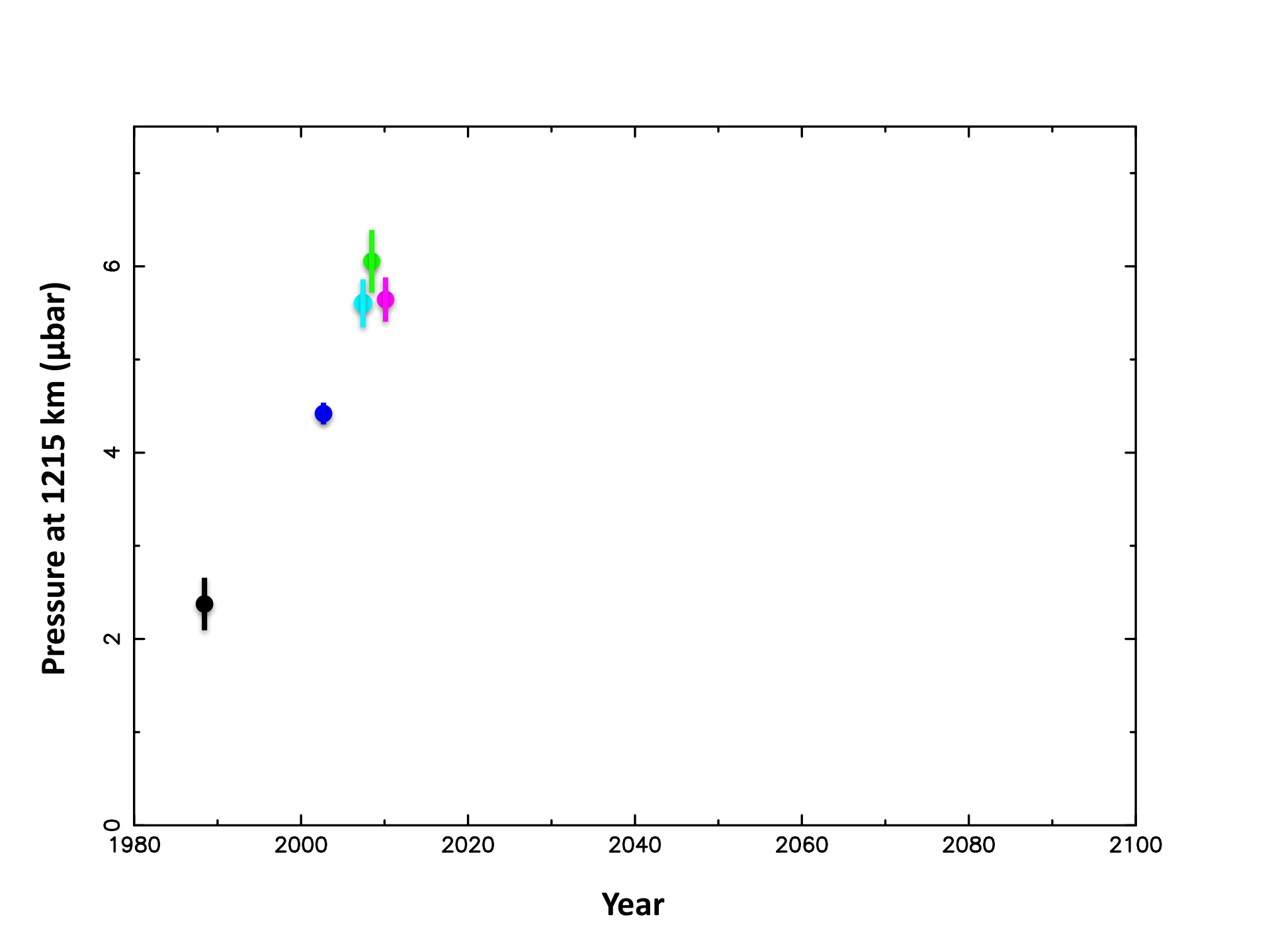
back to Pluto…

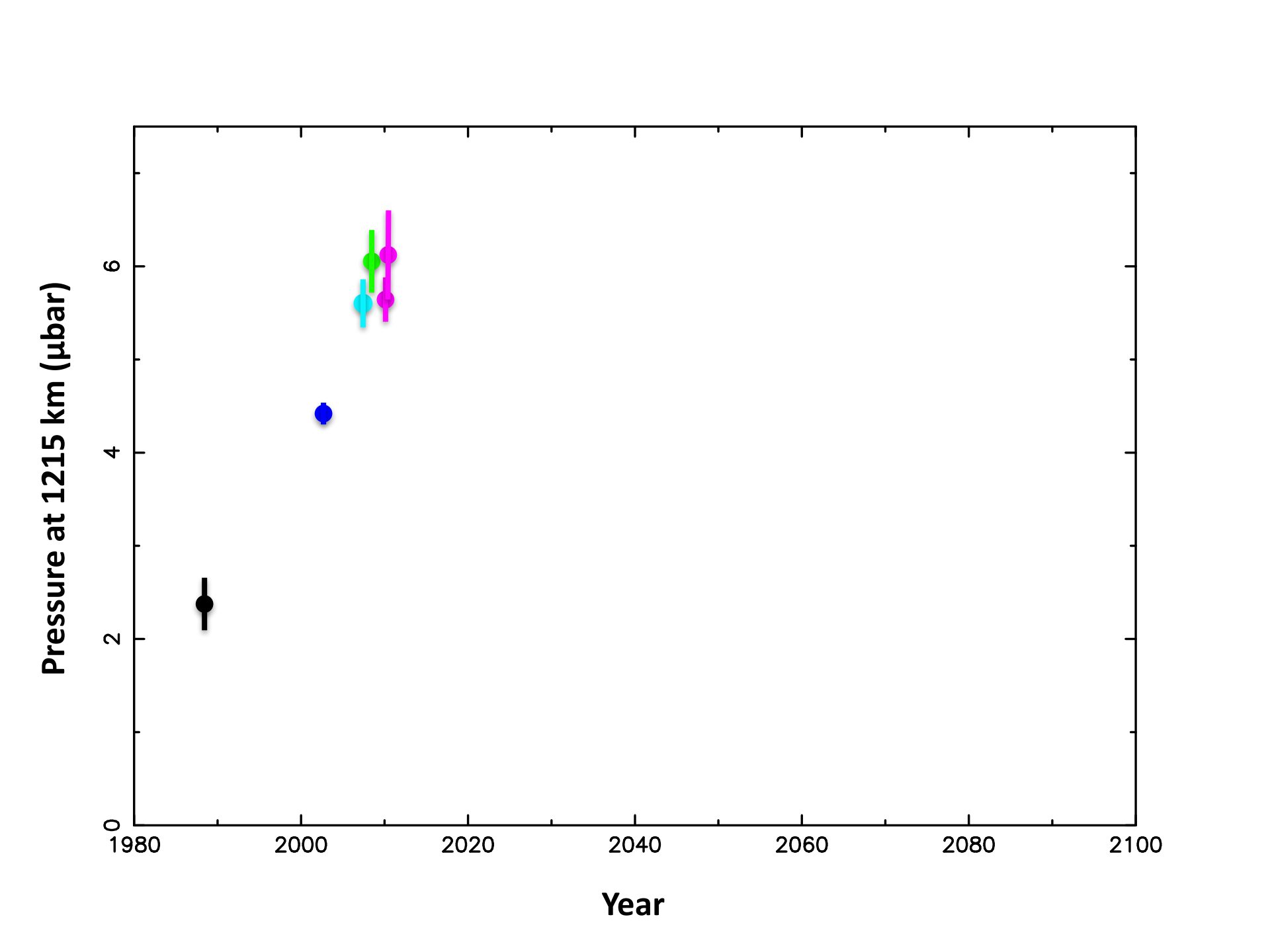

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Elliot et al. 2003
Sicardy et al. 2003
Yelle & Elliot
1997
~ doubling of pressure
~ 10% decrease of insolation
in 14 years

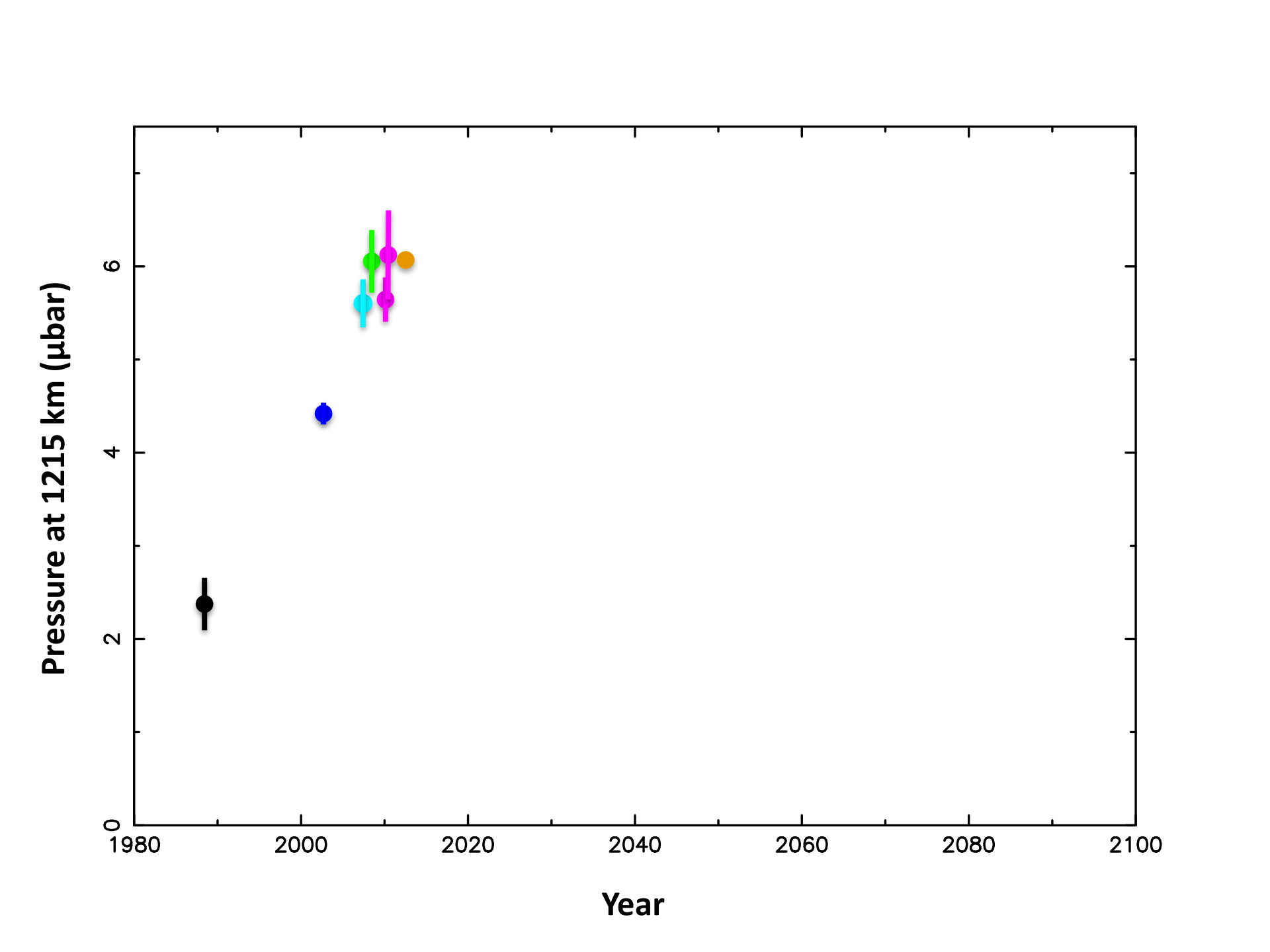

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

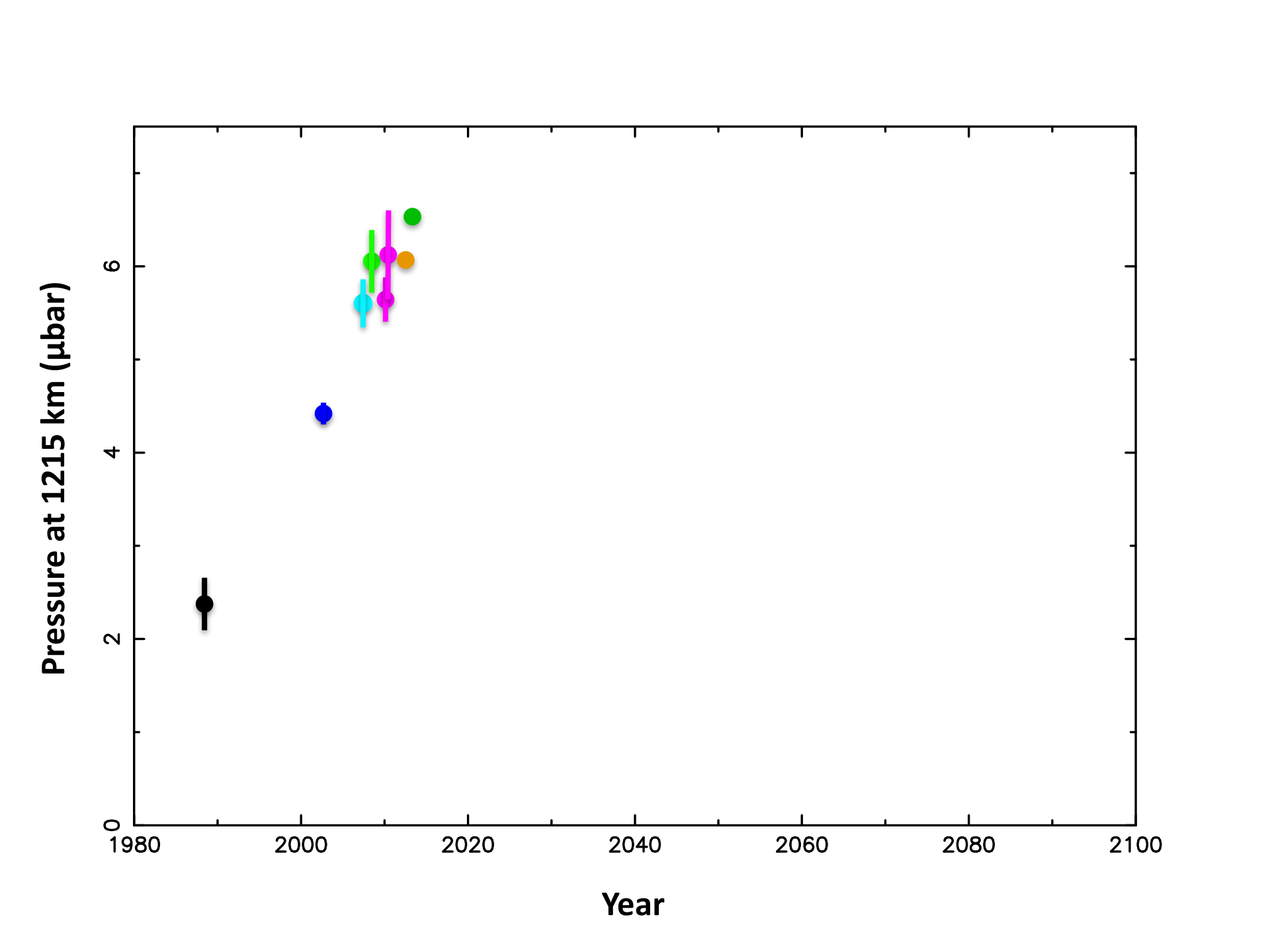

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

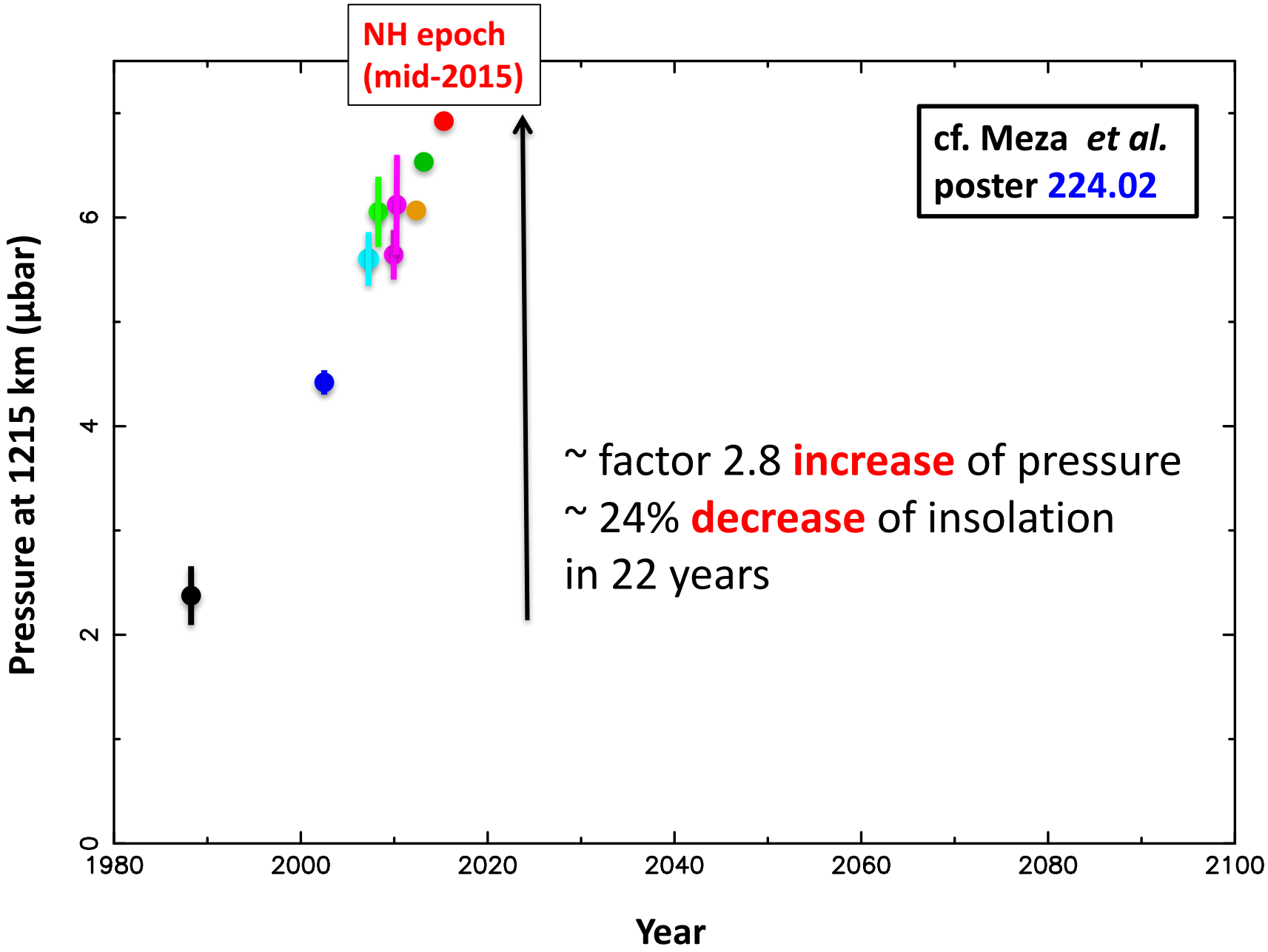

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

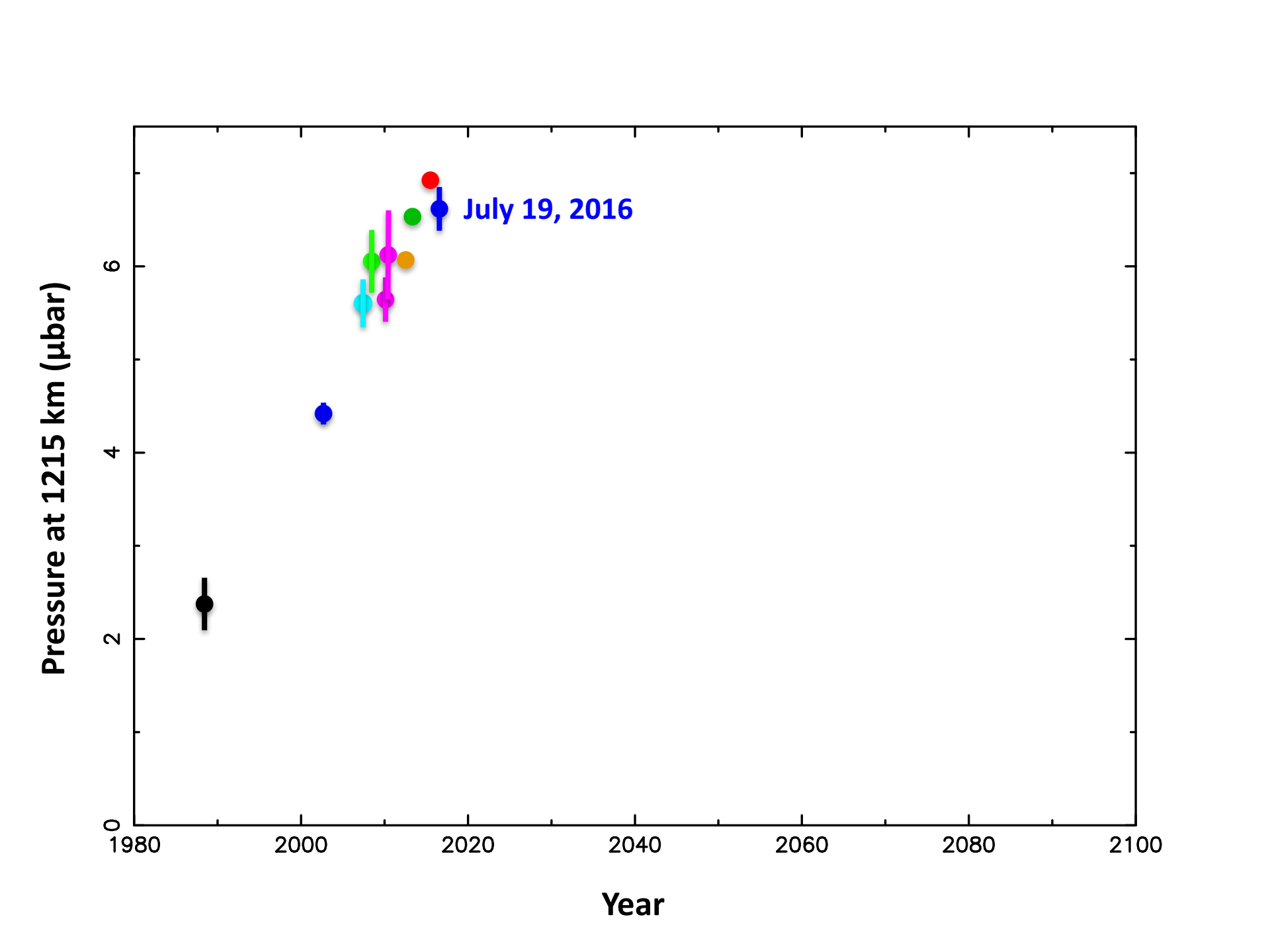

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

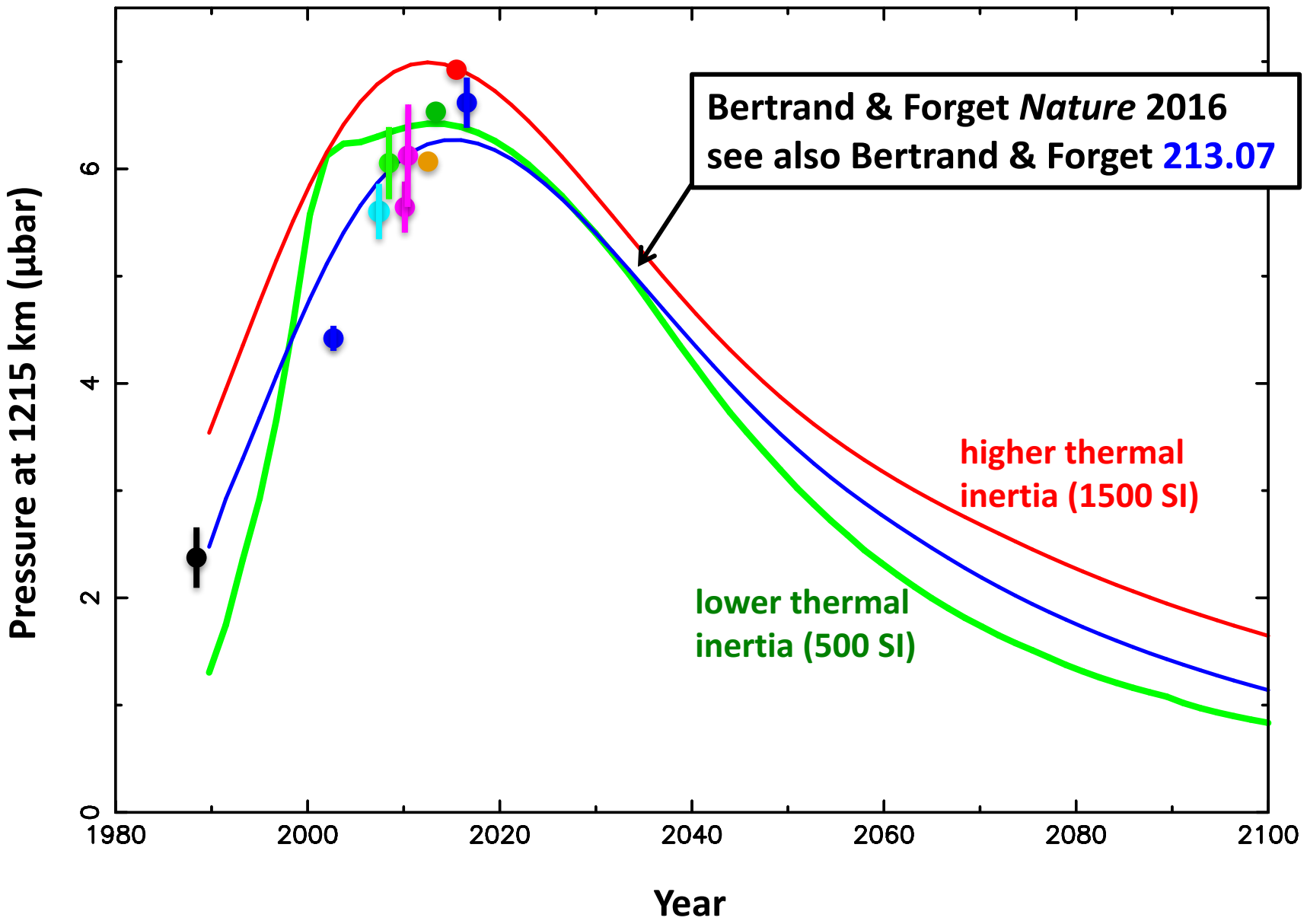

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

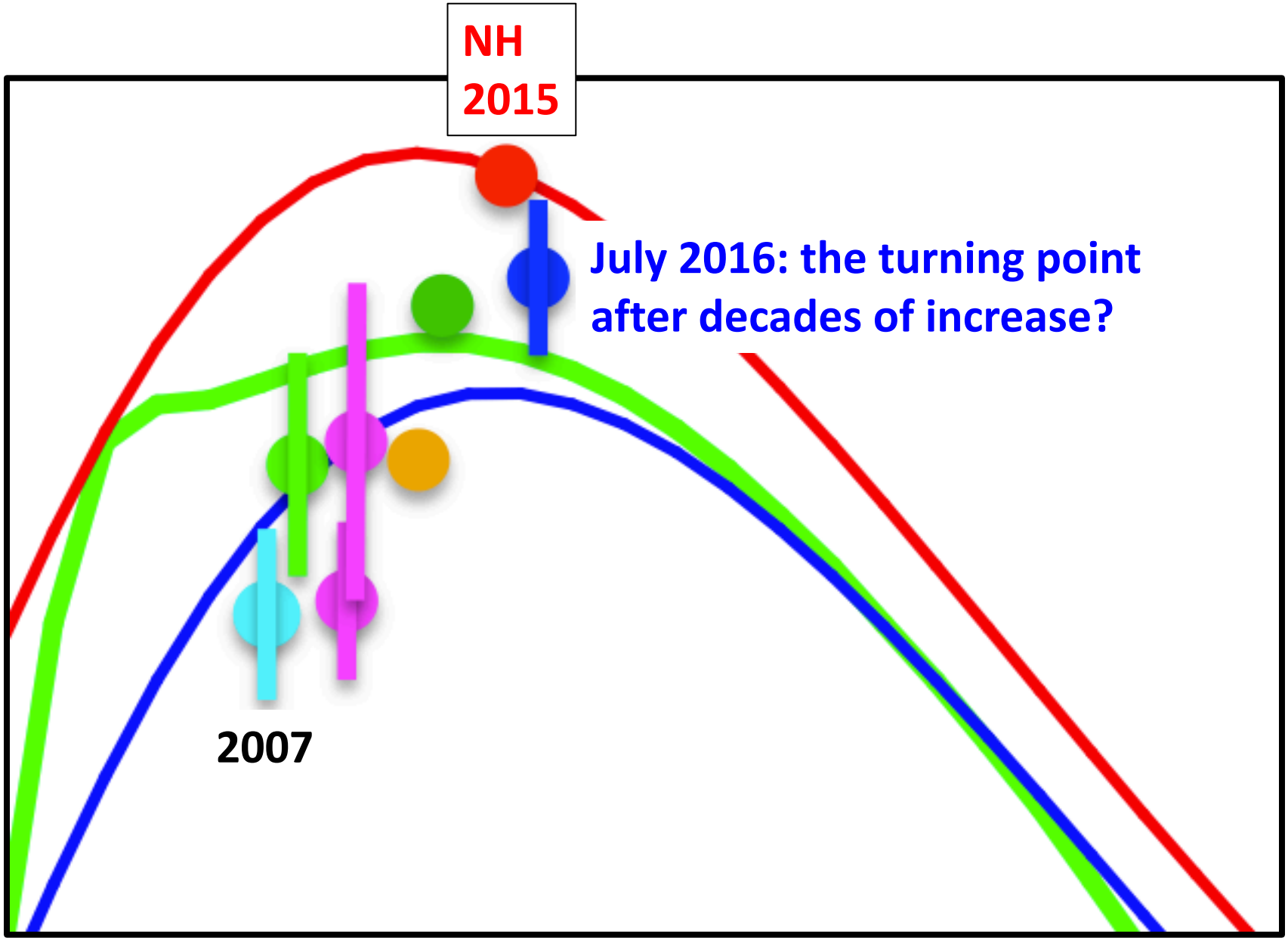

Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year


Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year

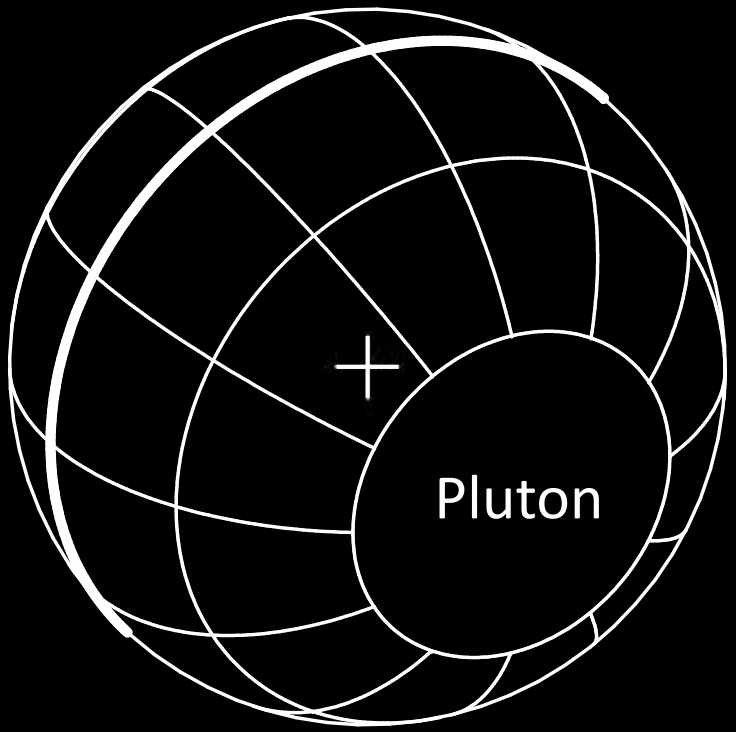

NH epoch
(mid-2015)
cf. Meza *et al.*
poster 224.02
~ factor 2.8 increase of pressure
~ 24% decrease of insolation
in 22 years
Pressure at 1215 km (μbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year


July 19, 2016
Pressure at 1215 km (µbar)
0
2
4
6
1980
2000
2020
2040
2060
2080
2100
Year


Bertrand & Forget *Nature* 2016
see also Bertrand & Forget 213.07
higher thermal inertia (1500 SI)
lower thermal inertia (500 SI)
Pressure at 1215 km (µbar)
Year
0
2
4
6
1980
2000
2020
2040
2060
2080
2100


NH
2015
July 2016: the turning point
after decades of increase?
2007

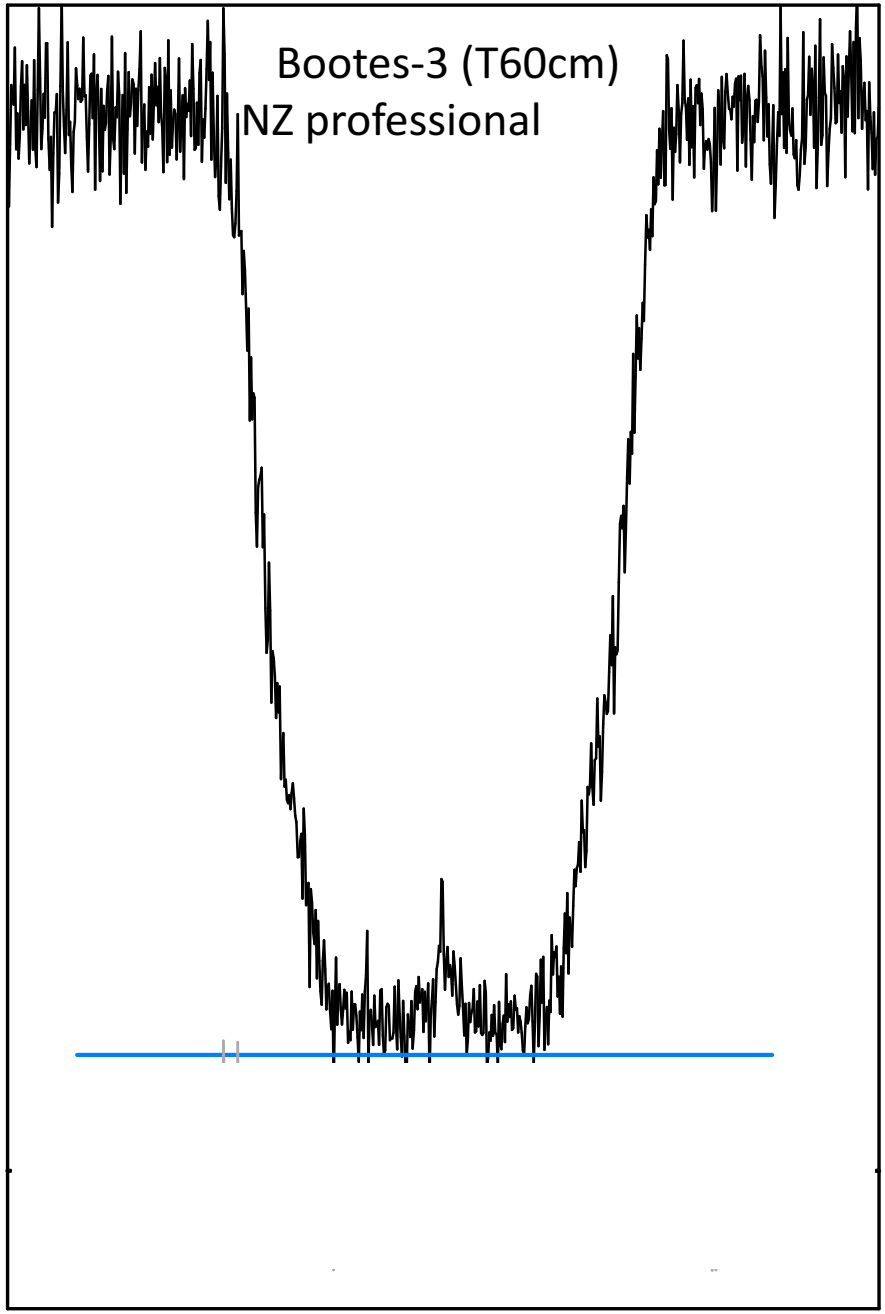
central flashes

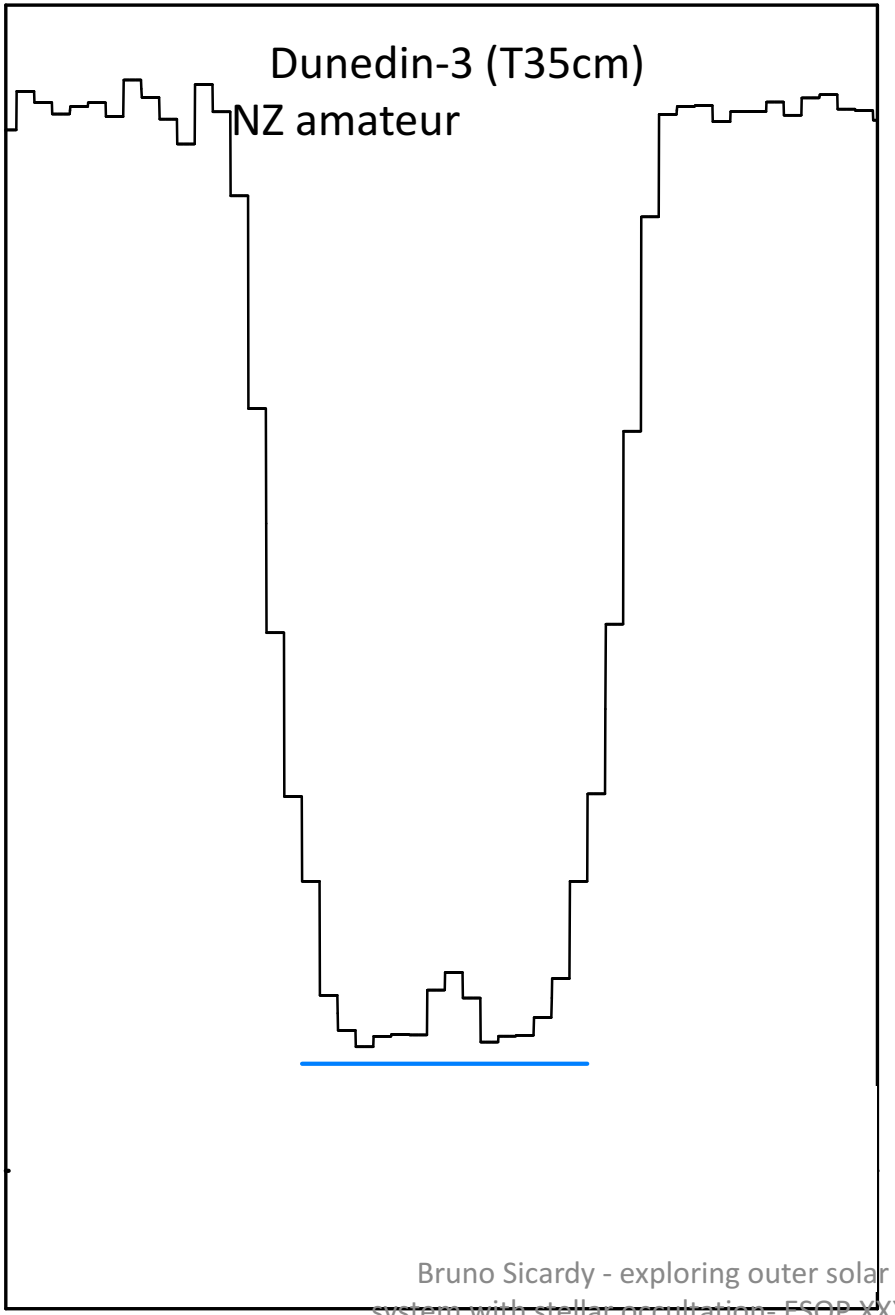


secondary image

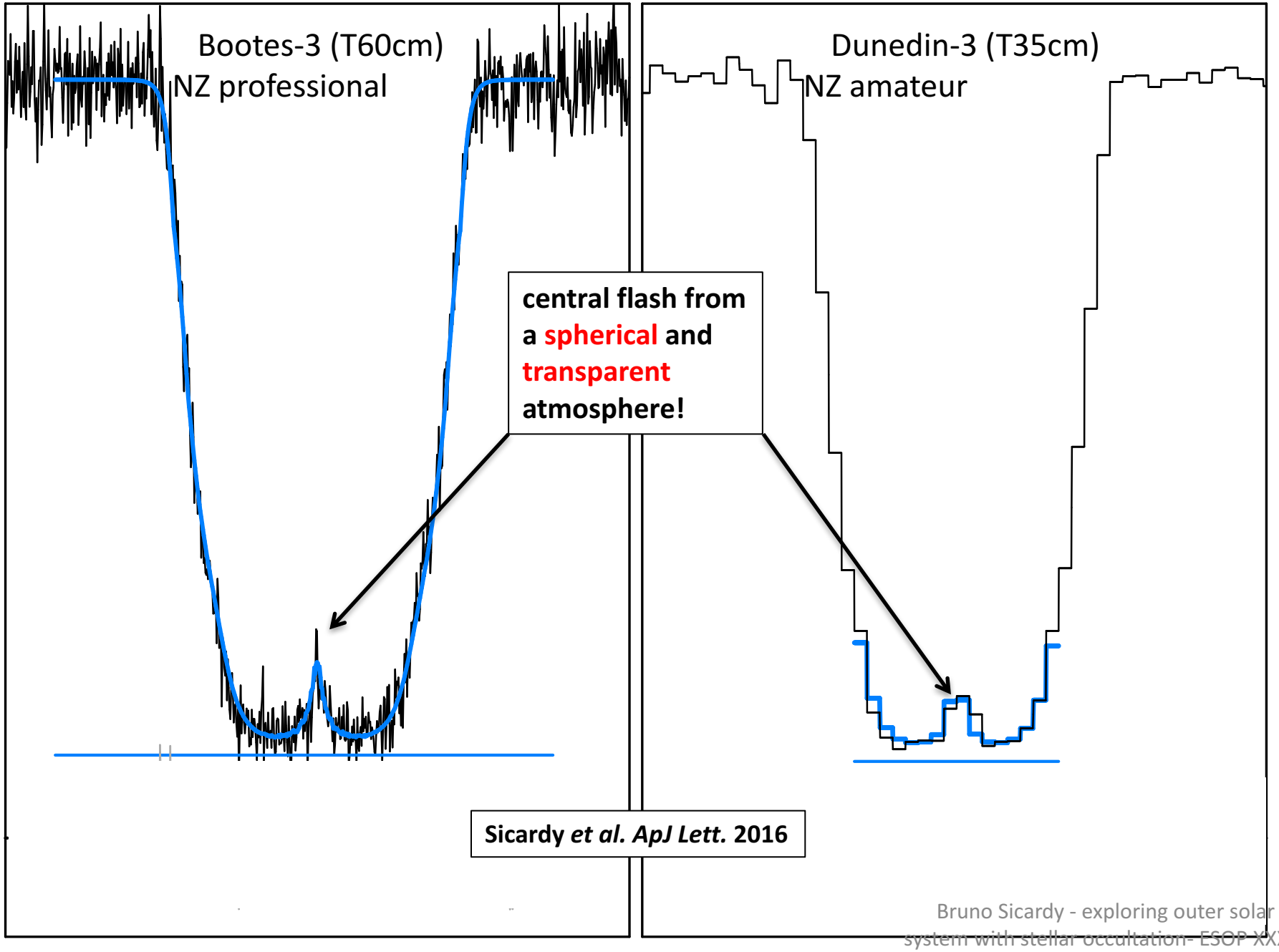
primary image
greatly enhanced

Pluto 29 June 2015 stellar occultation

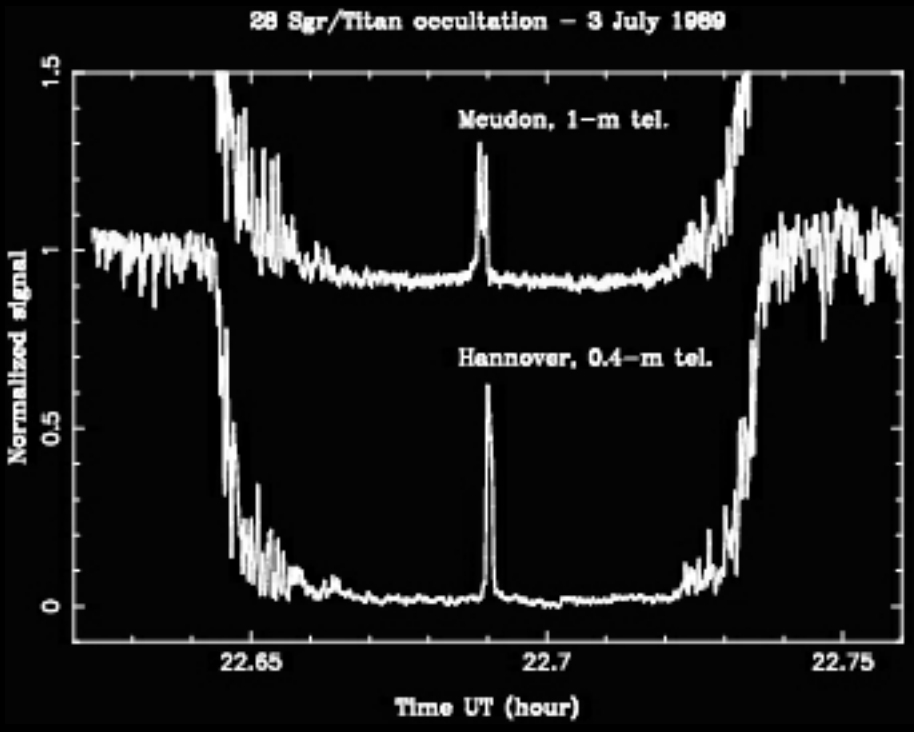


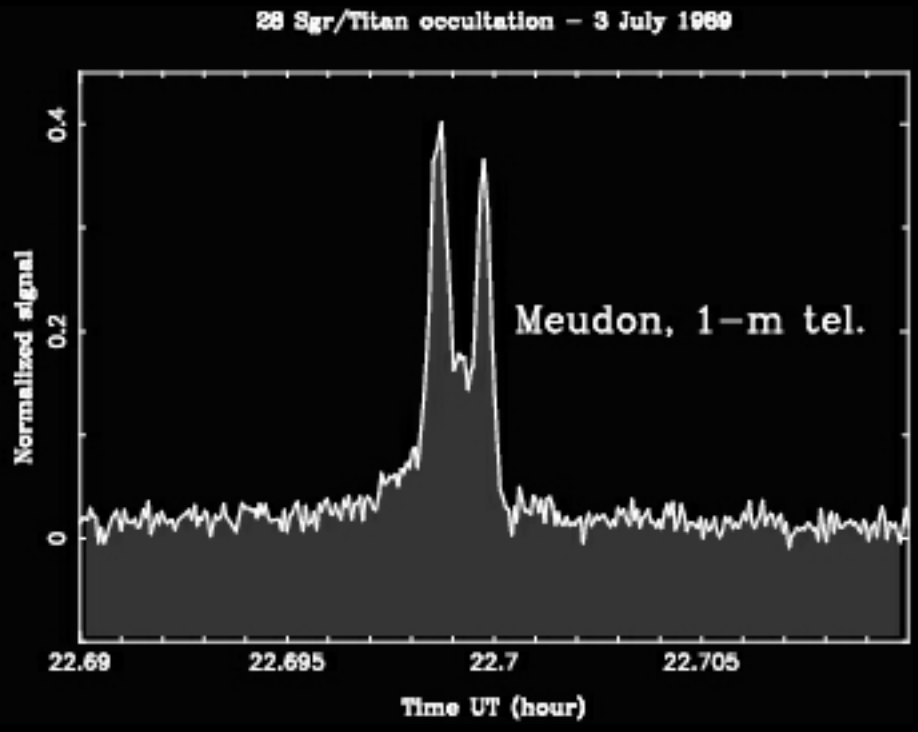


Pluto 29 June 2015 stellar occultation

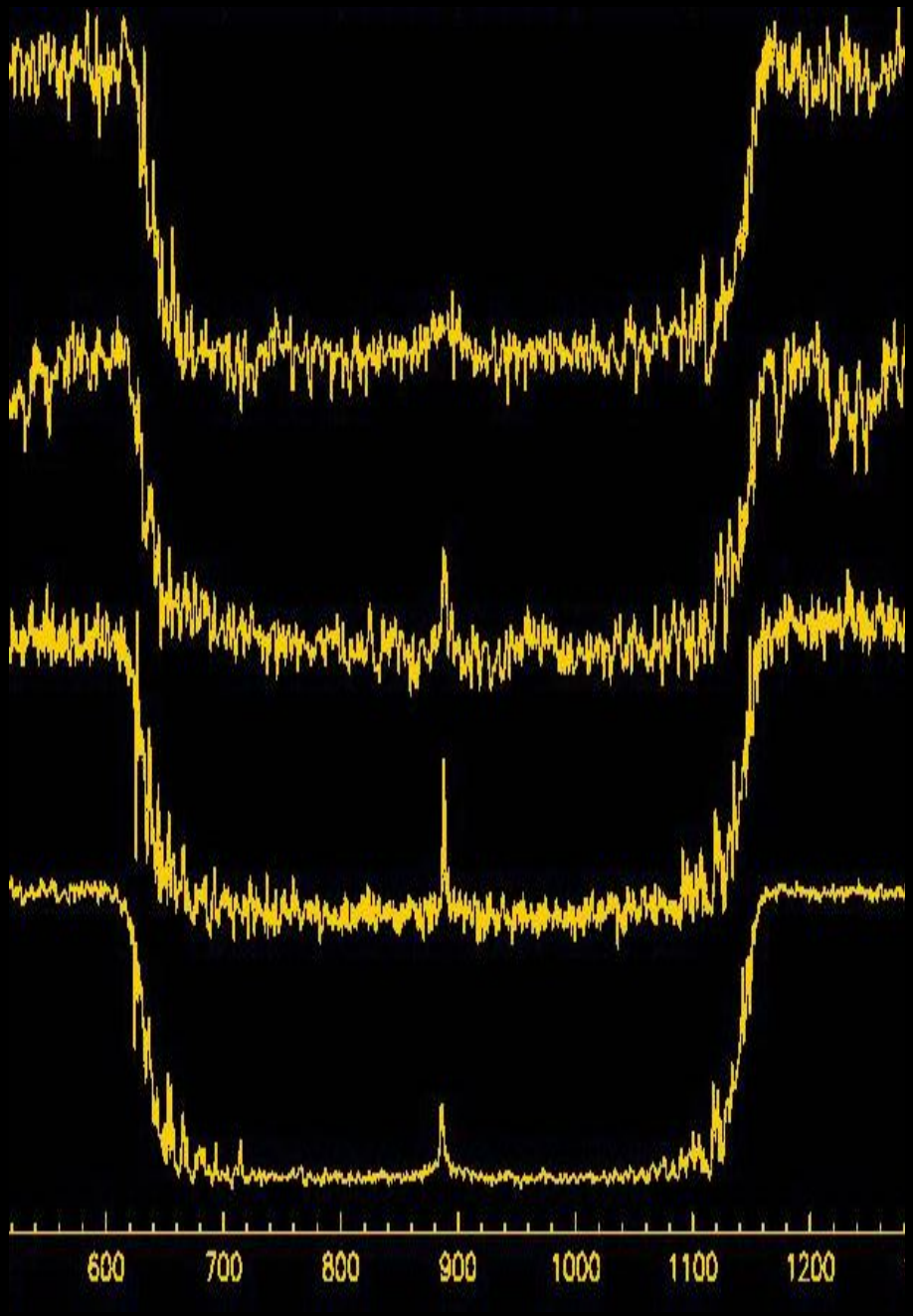


the Titan central flash of July 3, 1989





a tribute to H.-J. Bode
the start of a long collabotation



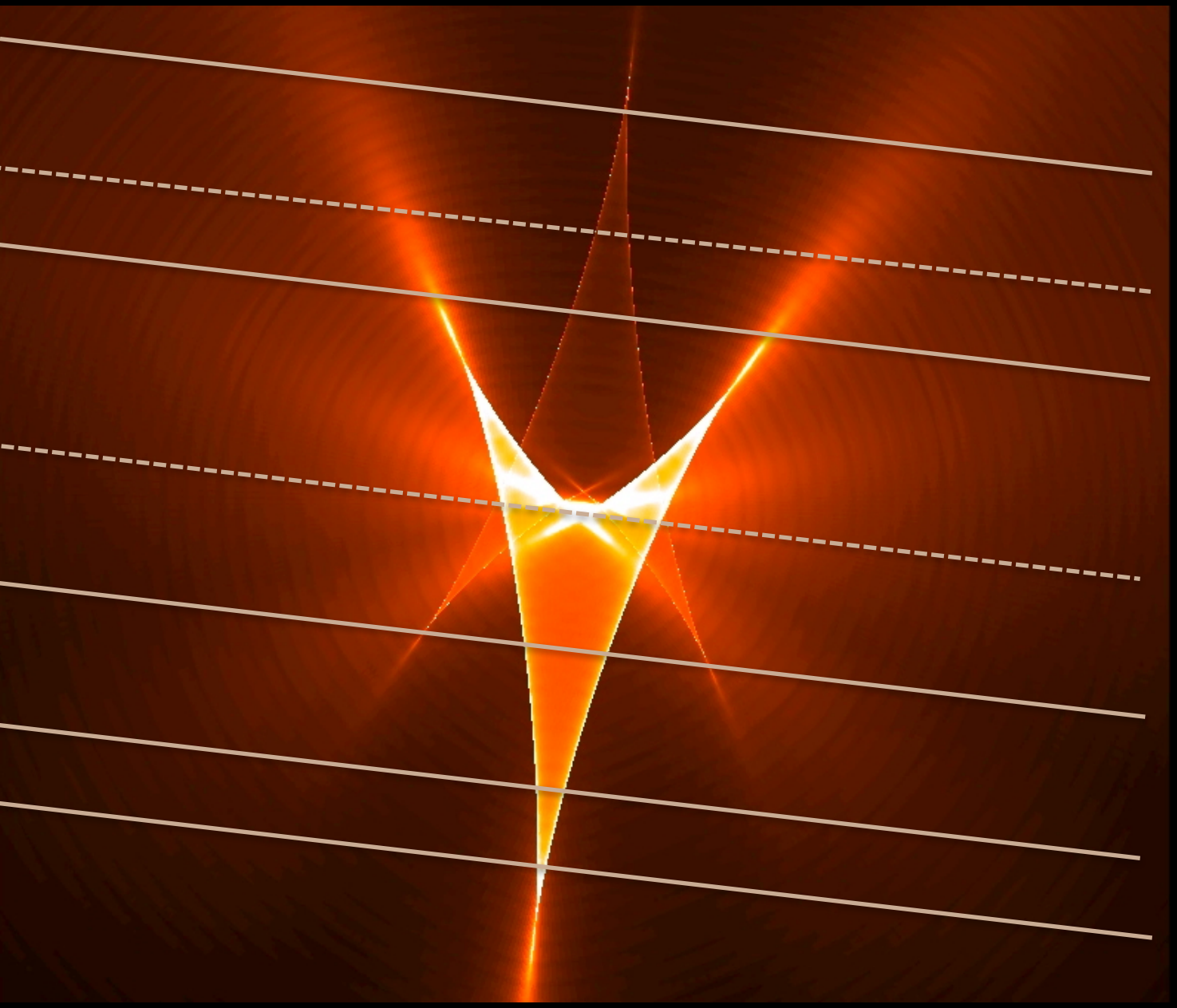
Sandfontein, M10, RG715

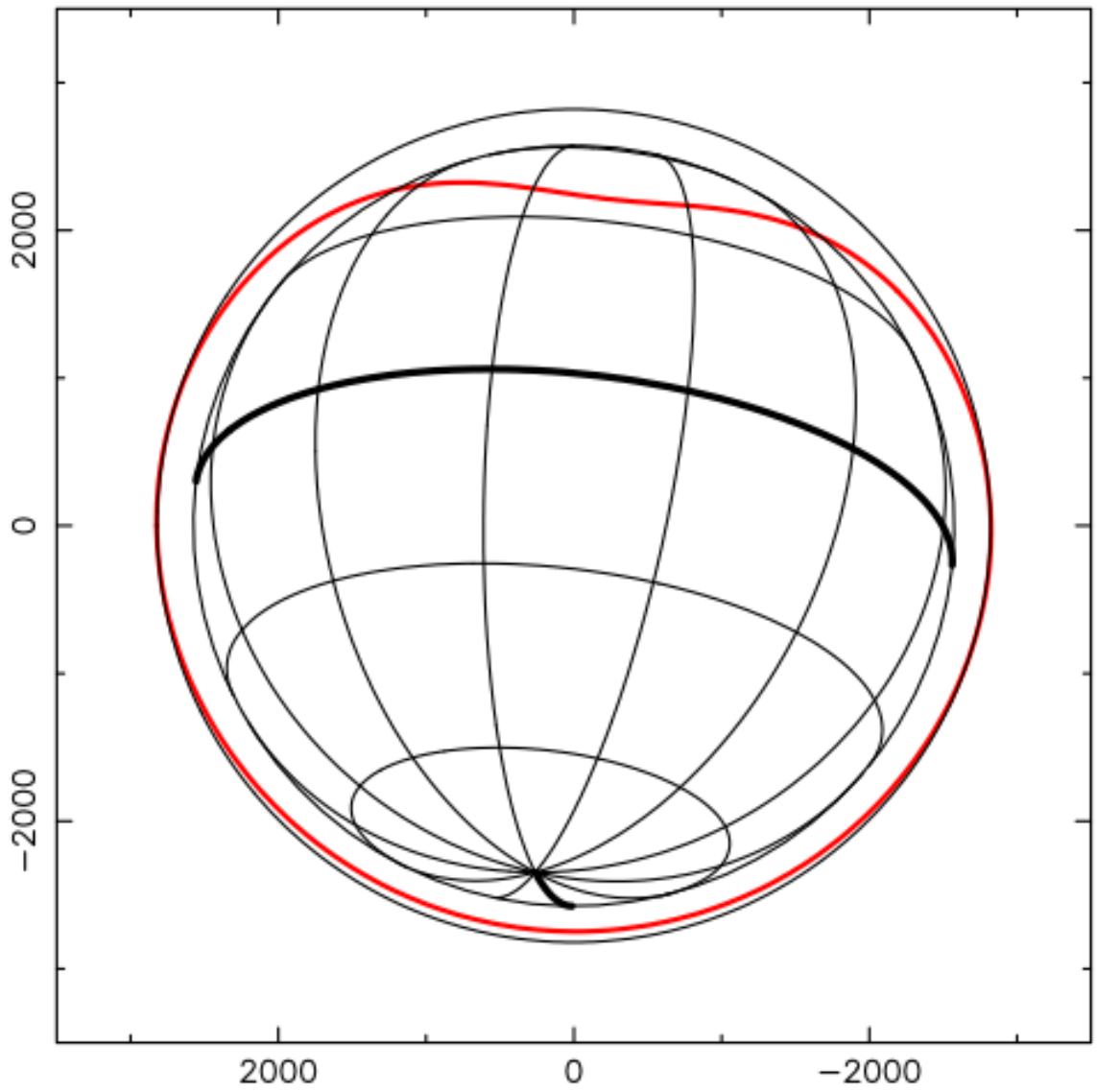
Gifberg, C14, RG715

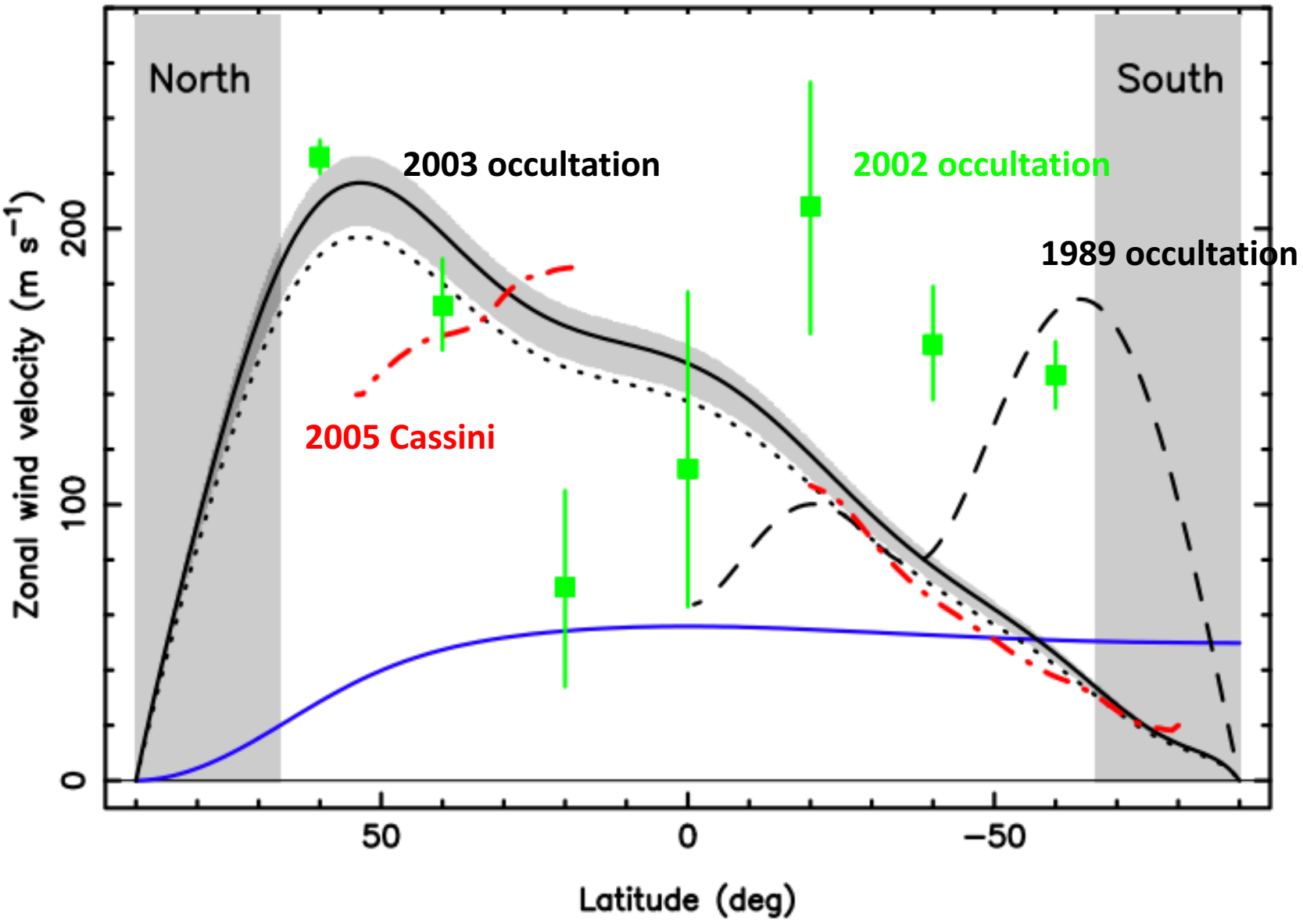
Cederberg, M12, RG715

SAAO, 1-m, I

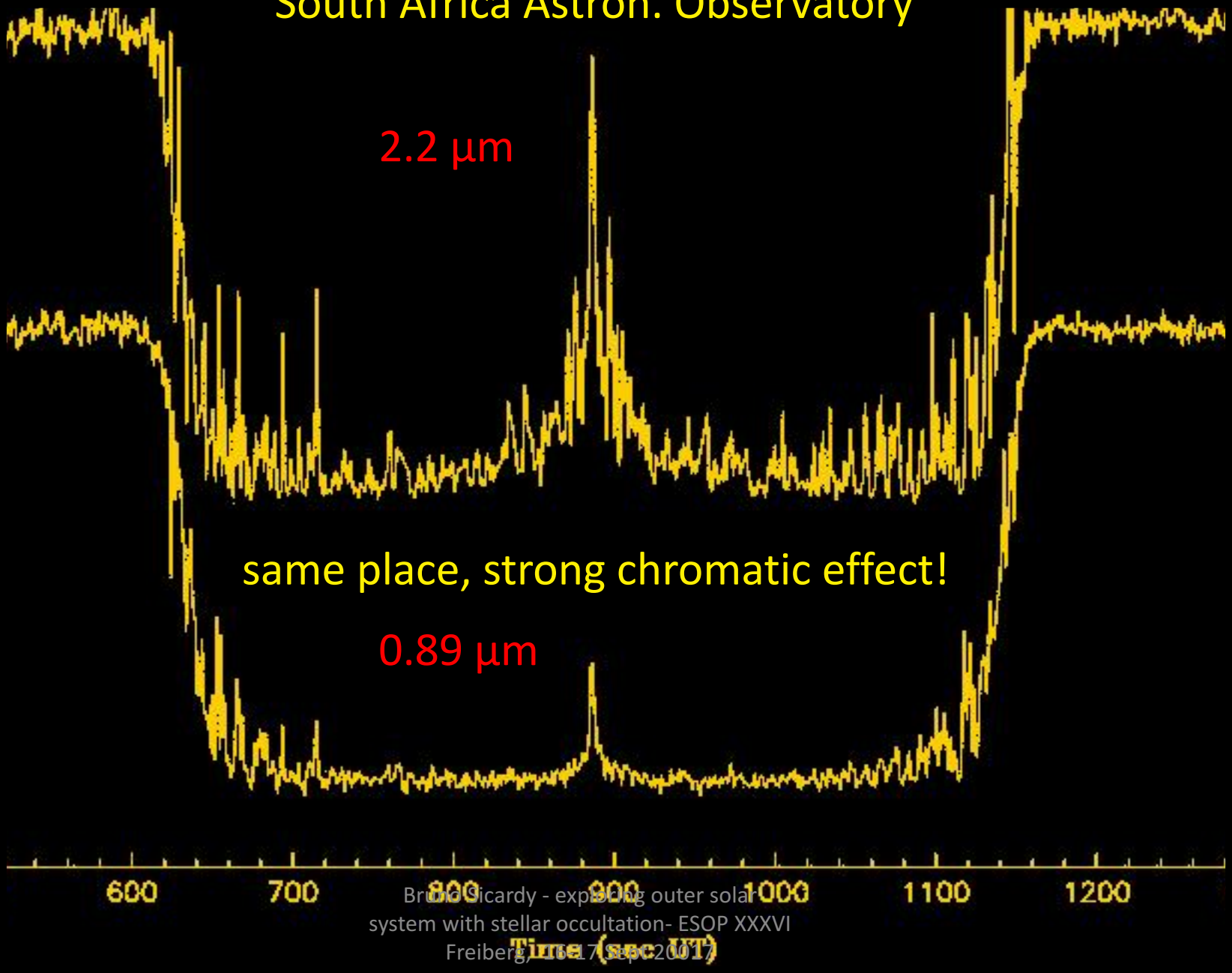
the Titan central flash of November 14, 2003
Sicardy *et al.* JGR 2006

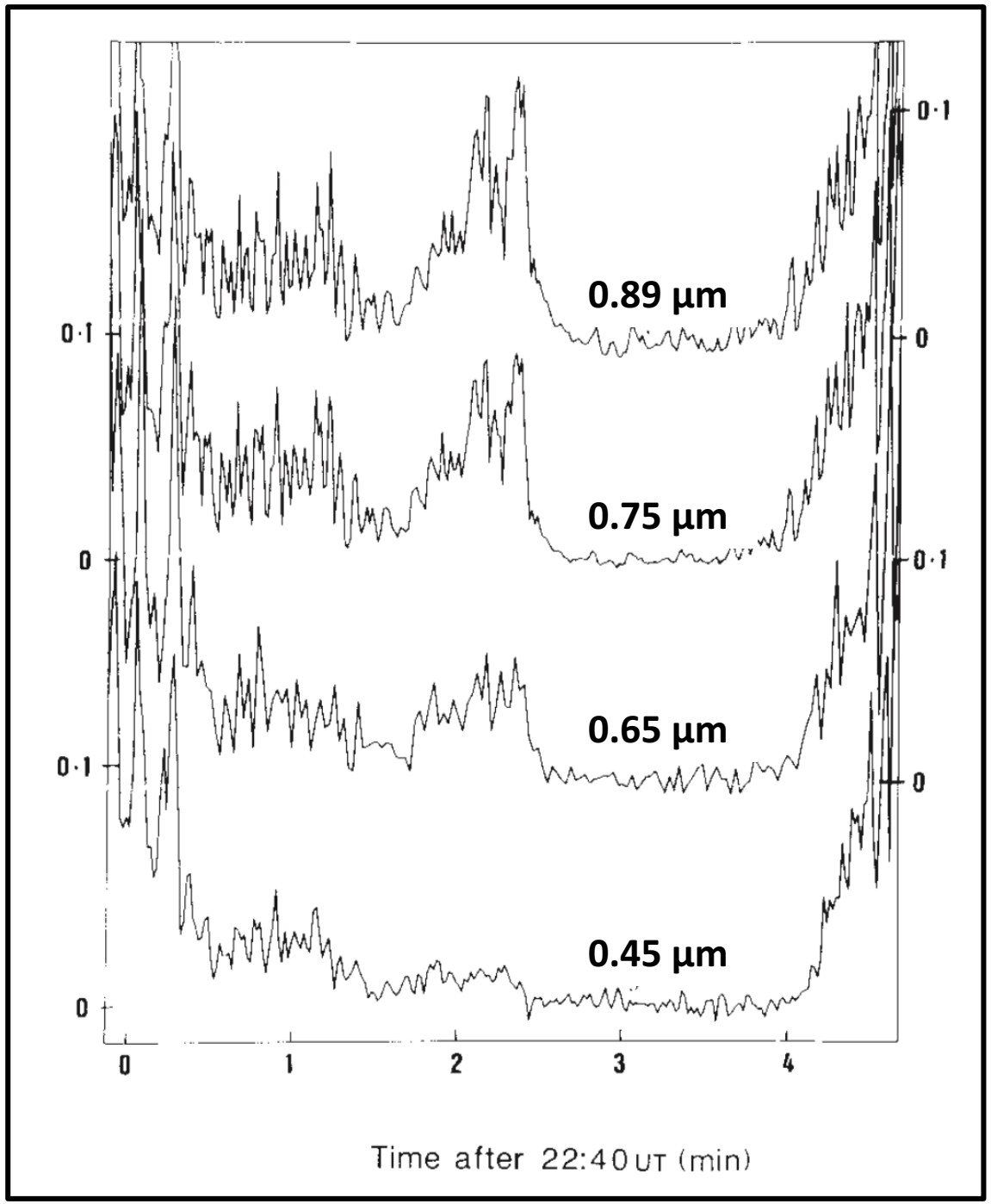

Sandfontein
Springbok
Maïdo
Nuwerus
Gifberg
Cederberg
SAAO


2000
0
−2000
2000
0
−2000


North
South
2003 occultation
2002 occultation
1989 occultation
2005 Cassini
Zonal wind velocity (m s^{-1})
0
100
200
50
0
−50
Latitude (deg)

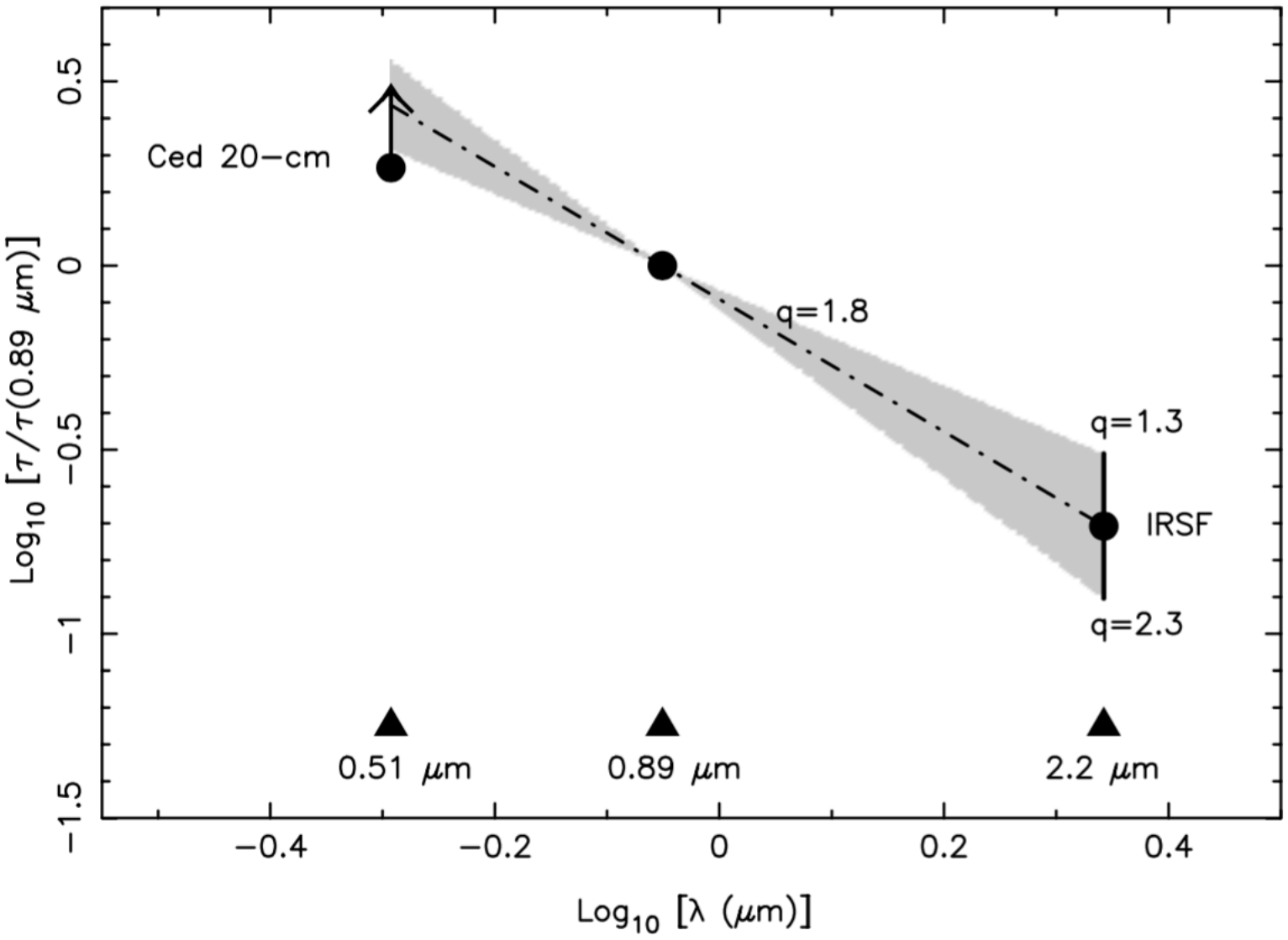
Titan stellar occultation of 14 Nov. 2003
South Africa Astron. Observatory





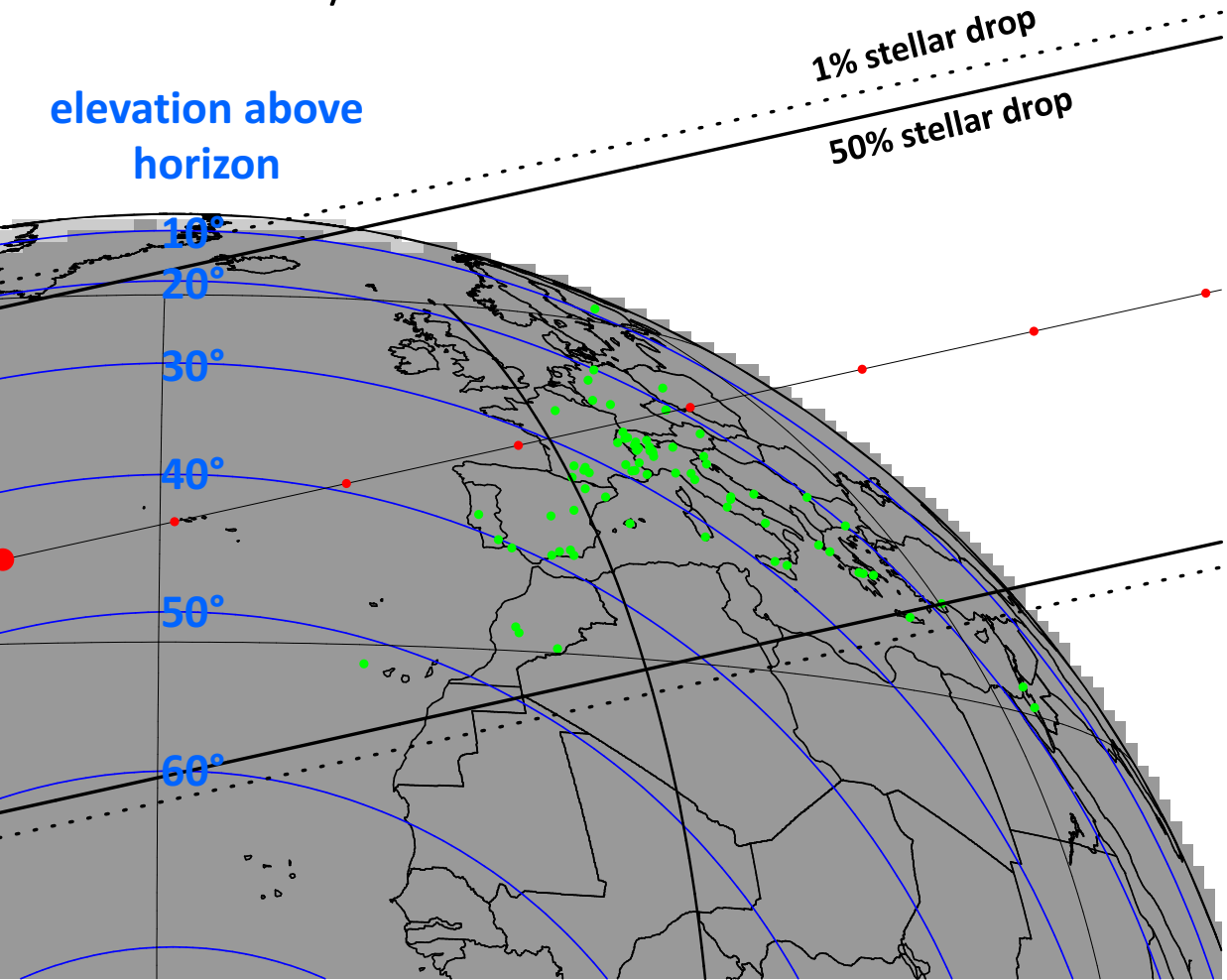
Titan central flash
Pic du Midi
July 3, 1989

Sicardy *et al.*
Nature **343**, 350 (1990)


Ced 20−cm
q=1.8
q=1.3
IRSF
q=2.3
0.51 μm
0.89 μm
2.2 μm
Log10 [τ/τ(0.89 μm)]
Log10 [λ (μm)]
0.5
0
−0.5
−1
−1.5
−0.4
−0.2
0
0.2
0.4

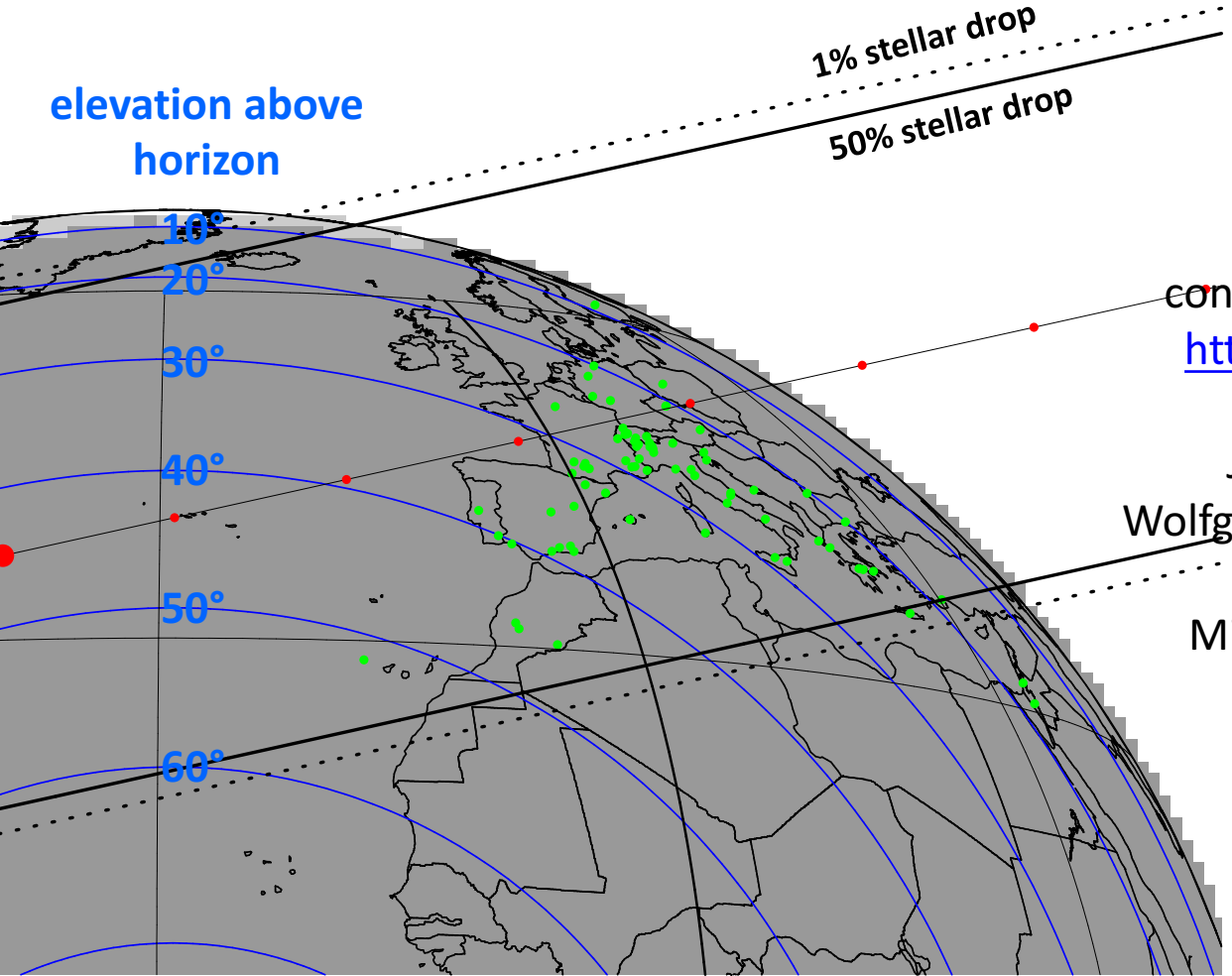
Take away list

- rare event
- latest one in 2008, last really useful 1997
- evolution of pressure ?
- shape of the atmosphere/winds?
- properties of aerosols, if any?
- similarities/differences Pluto?



Caveats

- Low elevation
- Bright Neptune at 11 arcsec (I-band may be better, SNR permitting)
- Full Moon at 33 deg.
- Accurate absolute timing sometime difficult (~ 0.1 sec or better)
- Weather may be unfavorable, backup plans should be considered



updates made in the next few days, stay tuned!

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http://astro.kretlow.de/