Lucky Star: results & beyond

Bruno Sicardy

LESIA/Observatoire de Paris
& Sorbonne Université

ESOP 38
Paris, France
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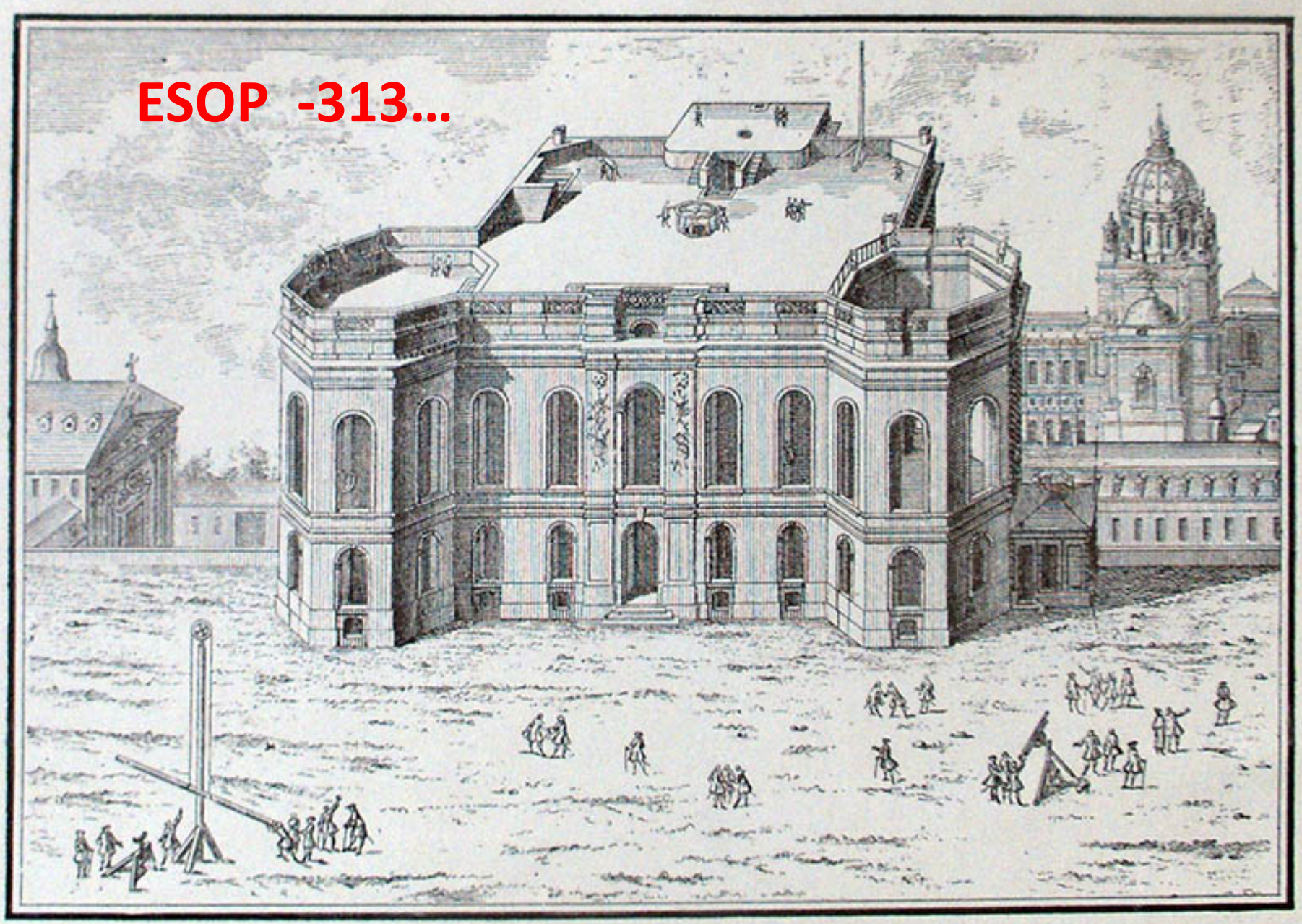
a European Research Council
Advanced Grant project:



L'OBSERVATOIRE ROYAL COMMENCÉ EN 1667 ET ACHEVÉ EN 1672.

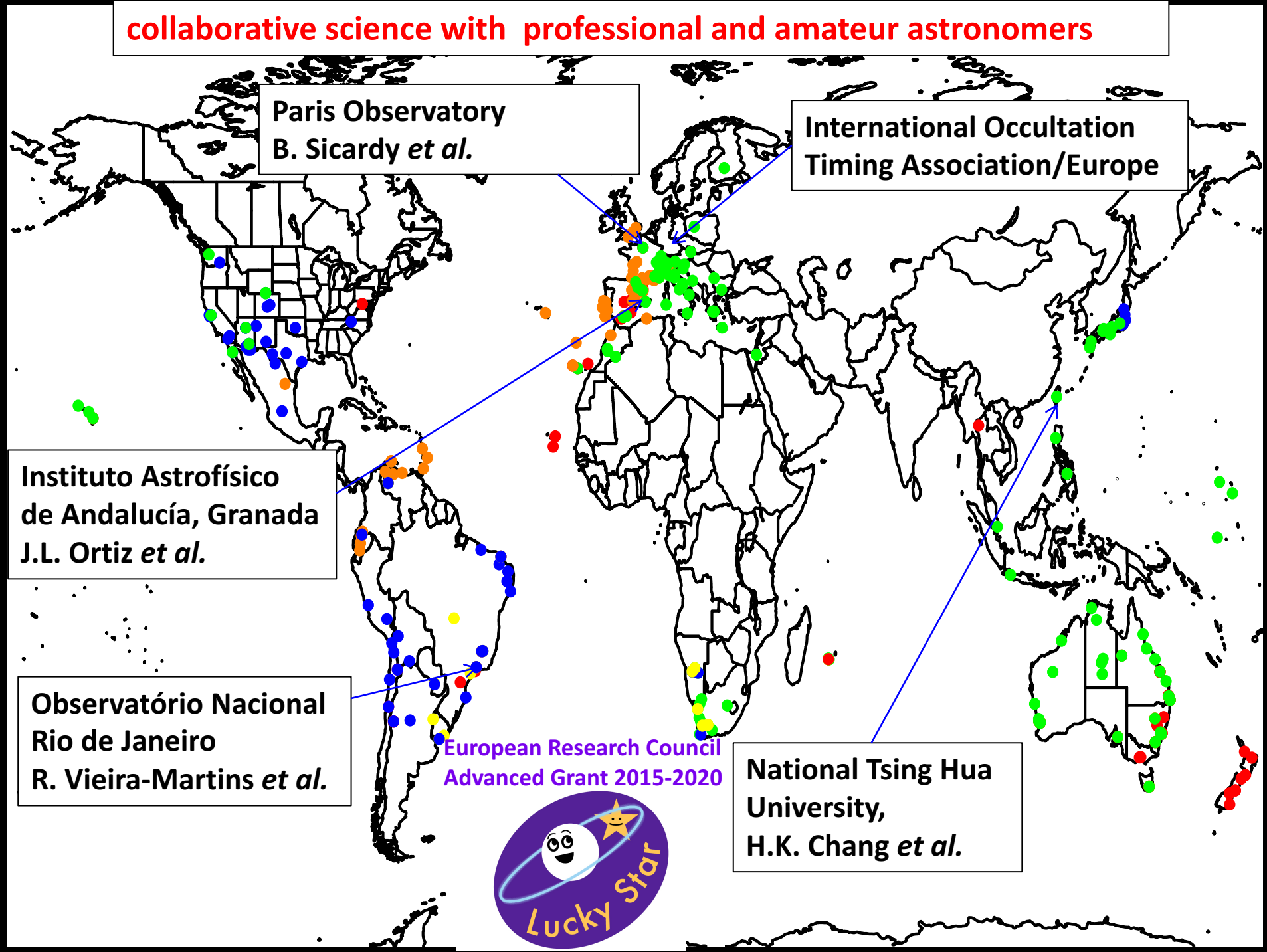
Lucky Star project

This page presents the **ERC project Lucky Star** whose aim is to study the solar system beyond Neptune with stellar occultations. The project is led by Bruno Sicardy in collaboration with groups from Paris, Meudon, Granada and Rio.

The solar system beyond Neptune contains largely unaltered material from the primordial circumsolar disk. It also kept the memory of the early planetary migrations, and thus contains essential information on the origin and evolution of our planetary system. The aim of the project is to study the Trans-Neptunian Objects (TNOs) using the stellar occultation technique. It consists in observing the passage of remote TNOs in front of those "*Lucky Stars*", that reveal shapes, atmosphere and rings of bodies from sub-km to thousand-km in size. Very few teams in the world master this method. The European-led network coordinated by B. Sicardy is now leader in predictions, instrumentation, observations and analysis related to stellar occultations, with innovative approaches and unprecedented results. In the last decade, our group led the field by discovering rings around the asteroid-like object Chariklo, detecting sub-km TNOs and drastic variations of Pluto's atmospheric pressure. Based on those noteworthy discoveries and unique skills of ours, the project will coordinate the following work packages :

1. Rings around small bodies - Understand the newly found Chariklo's rings, tackle the theory of rings' origins and evolutions around small bodies, discover new ring systems around other bodies.
2. Very small, sub-km TNOs and Oort Cloud objects - Constrain the collisional history of our early outer solar system, and possibly detect Oort Cloud objects.
3. Pluto's atmosphere - Explore Pluto's atmosphere and its atypical seasonal cycle, search for atmospheres around other TNOs.
4. Explore specific, large TNOs - Provide their sizes, shapes, albedos and densities. These programs are timely ir Horizons Pluto flyby in July 2015, and the ESA/GAIA mission expected to provide a greatly improved astrometric cat

On this website, you will find the predictions of stellar occultations by a selection of objects for the current year, the epl the predictions, the publications of the team and a selection of useful links.


collaborative science with professional and amateur astronomers
Paris Observatory
B. Sicardy *et al.*
International Occultation
Timing Association/Europe
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

Lucky Star 2015/20: main Work Packages

Main goal: do science!

WP1. Rings around small bodies: search and dynamics

WP2. Sub-km TNOs, serendipitous events

WP3. Pluto's atmosphere

WP4. Target specific large TNOs

Lucky Star 2015/20: supports

equipment: 5 EMCCD Raptorphotonics, 10 Cmos ZWO

travels: on-site campaigns, meetings, visitors

personnel: 6 post-docs
+5 PhDs (4 defended) *not* supported, but directly working in the project

Lucky Star 2015/20: main assets

Launch ESA *Gaia* mission December 2013

1st data release "DR0" July 2016 (Pluto stellar occ. July19, 2016)

DR1: September 2016 → typical accuracy 5 mas, 5-10 times better than ground-based astrometry

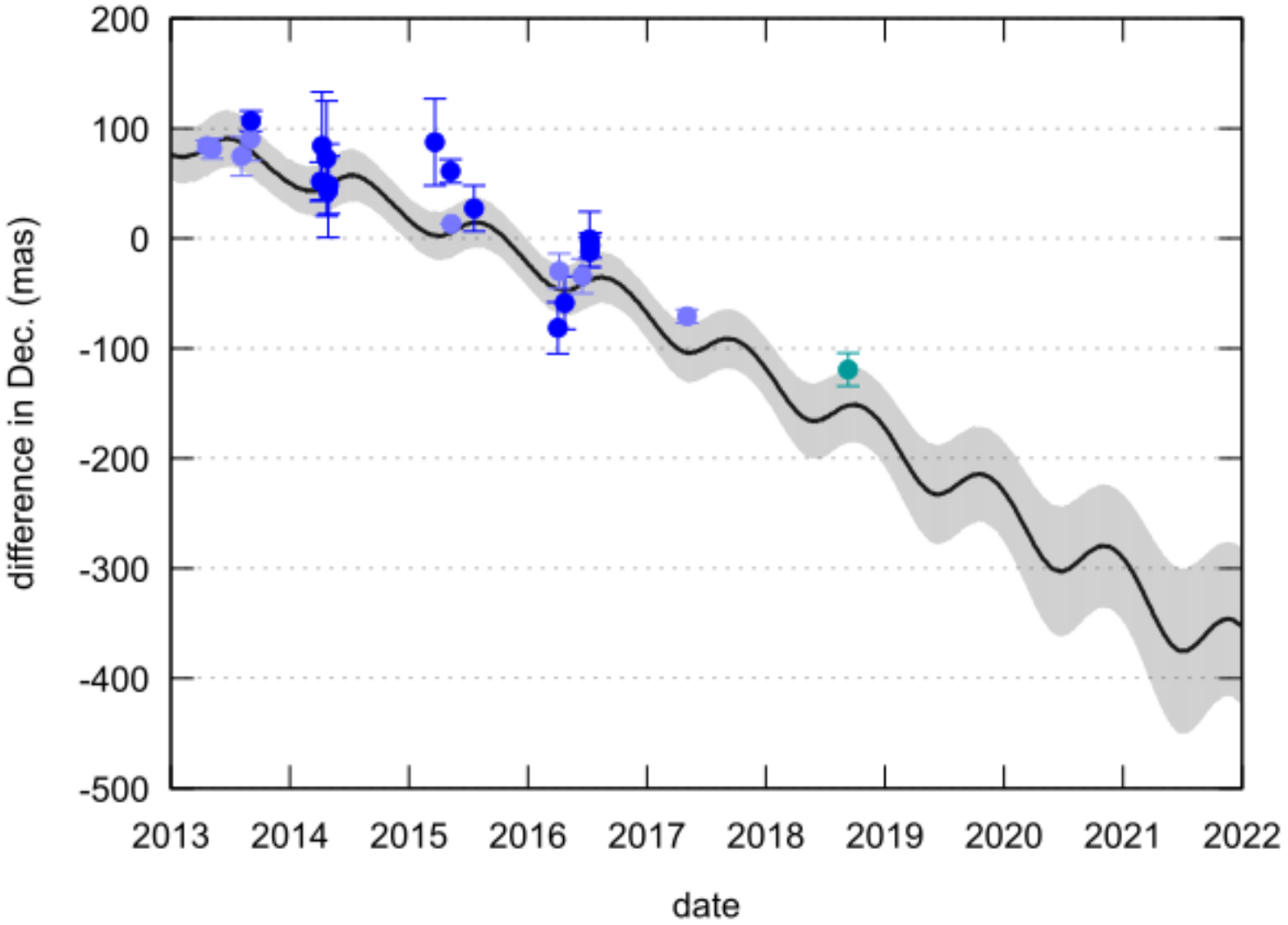
DR2: April 2018 → typical accuracy 1 mas, ~10-30 km on Earth for TNOs!

NASA *New Horizons*

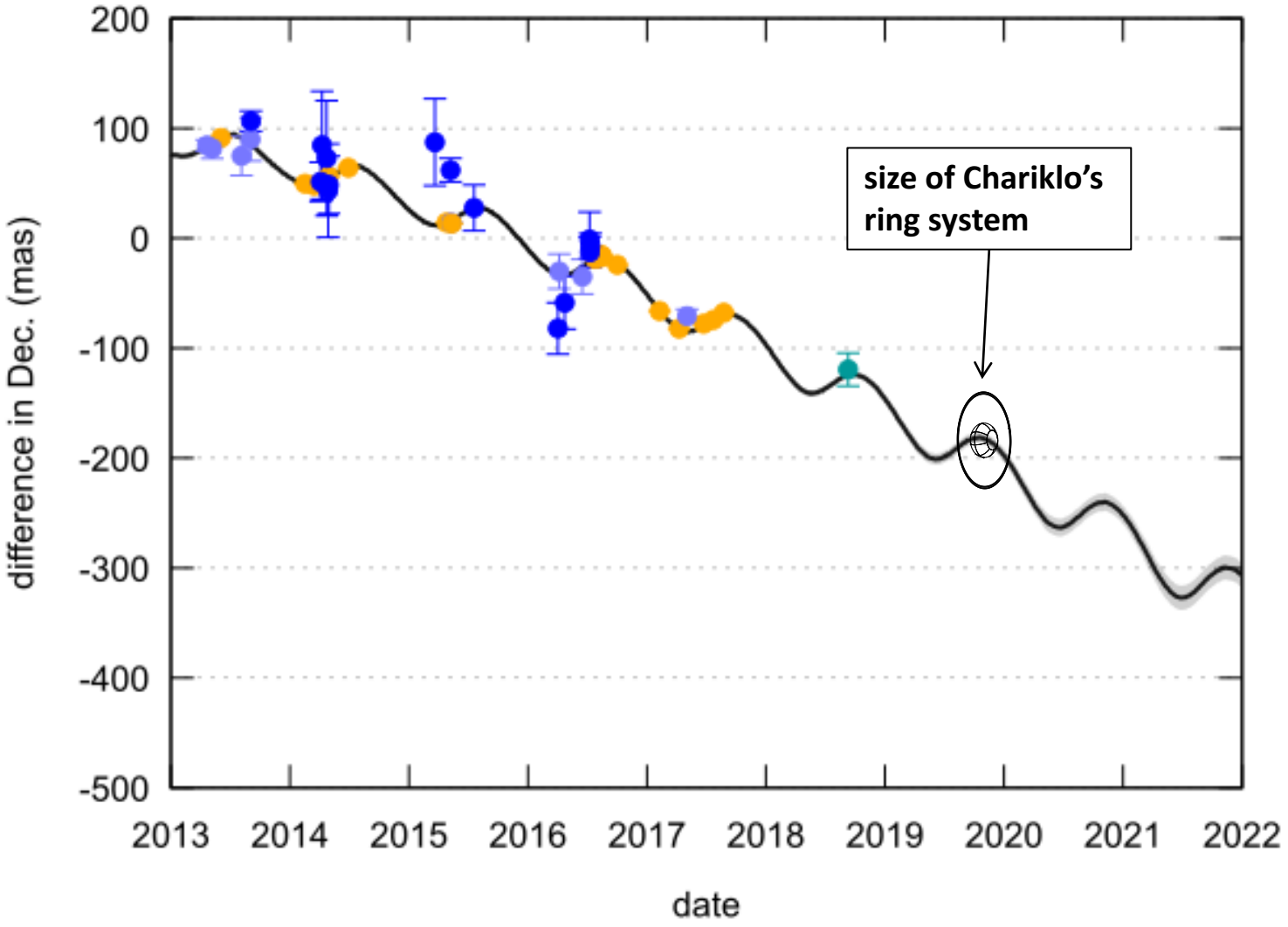
Pluto flyby July 2015, 2014 MU_{69} flyby January 2019

Highlights

Chariklo’s ephemeris, a **bootstrapping approach using GAIA**



Chariklo's ephemeris, a **bootstrapping approach using GAIA**



by Josselin Desmars

LETTER 2017

doi:10.1038/nature24051

The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation

J. L. Ortiz[1], P. Santos-Sanz[1], B. Sicardy[2], G. Benedetti-Rossi[3], D. Bérard[2], N. Morales[1], R. Duffard[1], F. Braga-Ribas[3,4], U. Hopp[5,6], C. Ries[5], V. Nascimbeni[7,8], F. Marzari[9], V. Granata[7,8], A. Pál[10], C. Kiss[10], T. Pribulla[11], R. Komžík[11], K. Hornoch[12], P. Pravec[12], P. Bacci[13], M. Maestripieri[13], L. Nerli[13], L. Mazzei[13], M. Bachini[14,15], F. Martinelli[15], G. Succi[14,15], F. Ciabattari[16], H. Mikuz[17], A. Carbognani[18], B. Gaehrken[19], S. Mottola[20], S. Hellmich[20], F. L. Rommel[4], E. Fernández-Valenzuela[1], A. Campo Bagatin[21,22], S. Cikota[23,24], A. Cikota[25], J. Lecacheux[2], R. Vieira-Martins[3,26,27,28], J. I. B. Camargo[3,27], M. Assafin[28], F. Colas[26], R. Behrend[29], J. Desmars[2], E. Meza[2], A. Alvarez-Candal[3], W. Beisker[30], A. R. Gomes-Junior[28], B. E. Morgado[3], F. Roques[2], F. Vachier[26], J. Berthier[26], T. G. Mueller[6], J. M. Madiedo[31], O. Unsalan[32], E. Sonbas[33], N. Karaman[33], O. Erece[34], D. T. Koseoglu[34], T. Ozisik[34], S. Kalkan[35], Y. Guney[36], M. S. Niaei[37], O. Satir[37], C. Yesilyaprak[37,38], C. Puskullu[39], A. Kabas[39], O. Demircan[39], J. Alikakos[40], V. Charmandaris[40,41], G. Leto[42], J. Ohlert[43,44], J. M. Christille[18], R. Szakáts[10], A. Takácsné Farkas[10], E. Varga-Verebélyi[10], G. Marton[10], A. Marciniak[45], P. Bartczak[45], T. Santana-Ros[45], M. Butkiewicz-Bąk[45], G. Dudziński[45], V. Alí-Lagoa[6], K. Gazeas[46], L. Tzouganatos[46], N. Paschalis[47], V. Tsamis[48], A. Sánchez-Lavega[49], S. Pérez-Hoyos[49], R. Hueso[49], J. C. Guirado[50,51], V. Peris[50] & R. Iglesias-Marzoa[52,53]

nature astronomy

2019

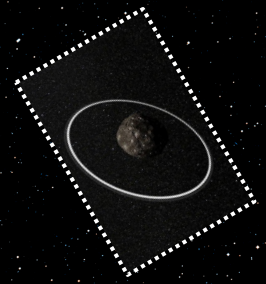
LETTERS

https://doi.org/10.1038/s41550-018-0616-8

Ring dynamics around non-axisymmetric bodies with application to Chariklo and Haumea

B. Sicardy[1*], R. Leiva[2], S. Renner[3], F. Roques[1], M. El Moutamid[4,5], P. Santos-Sanz[6] and J. Desmars[1]

all three systems shown to scale



Chariklo
(artist view)

Pluto false color
(NASA New Horizons)

Haumea
(artist view)

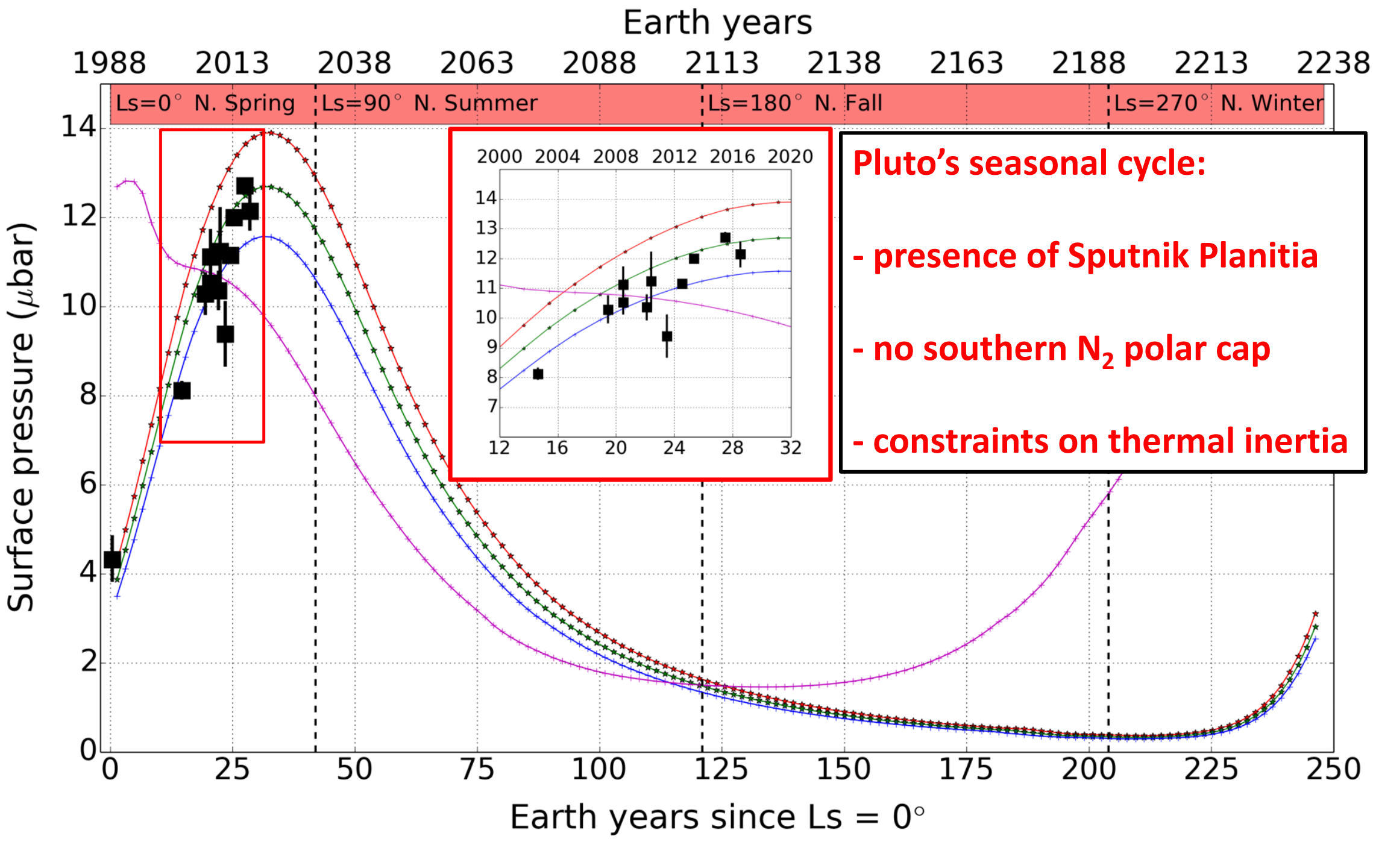
A&A 625, A42 (2019)
https://doi.org/10.1051/0004-6361/201834281

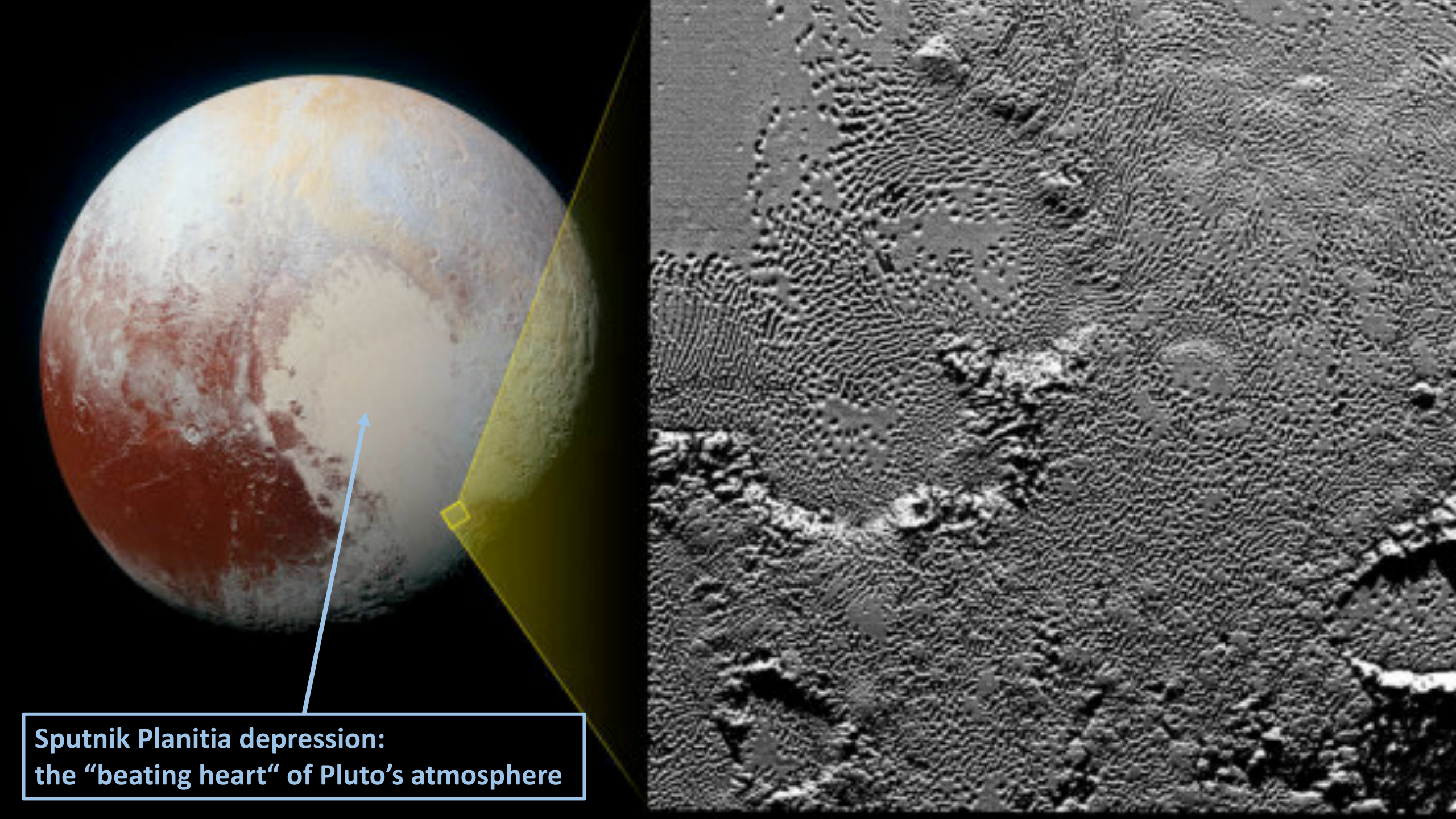
Astronomy & Astrophysics

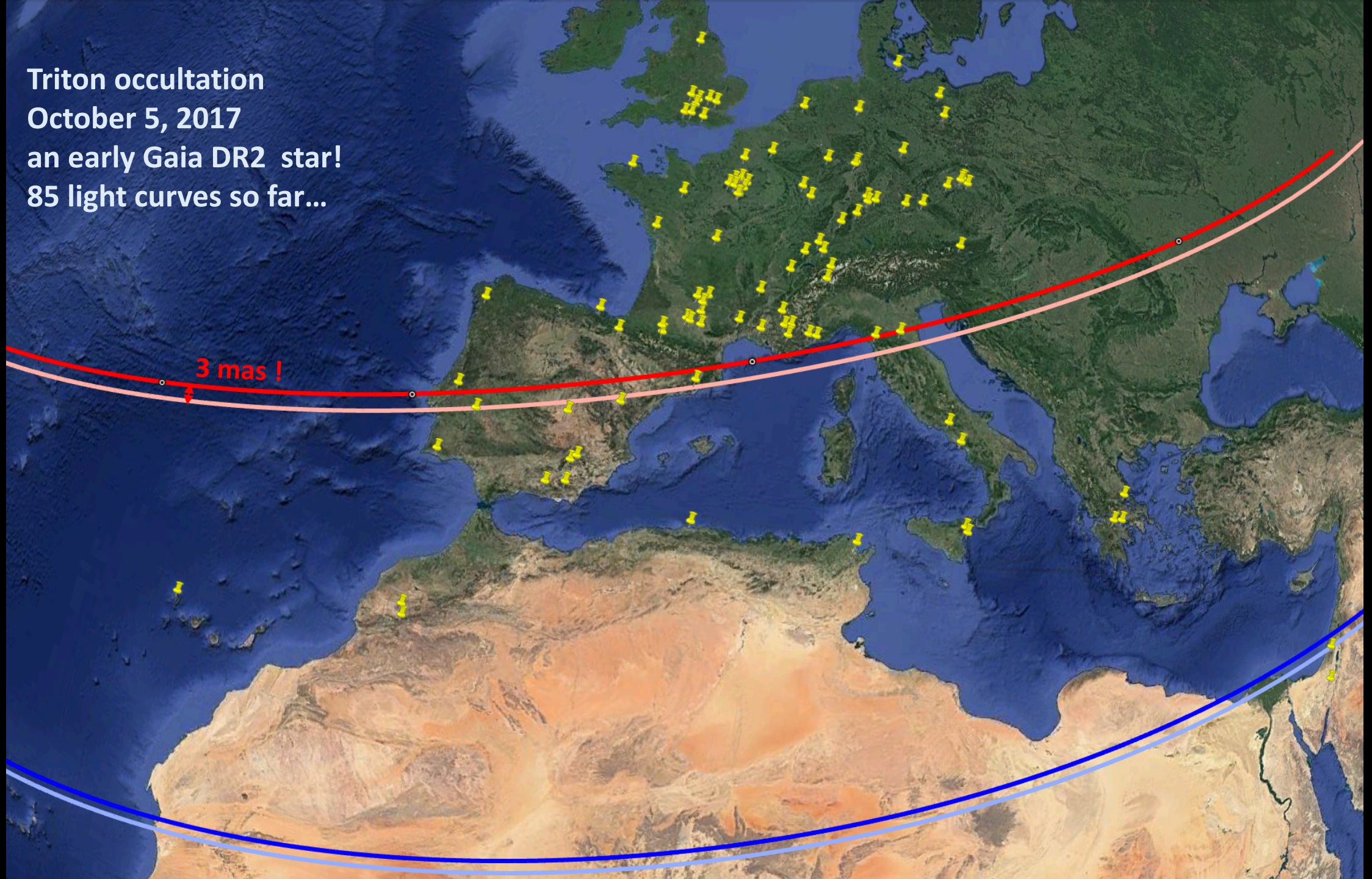
Lower atmosphere and pressure evolution on Pluto from ground-based stellar occultations, 1988–2016

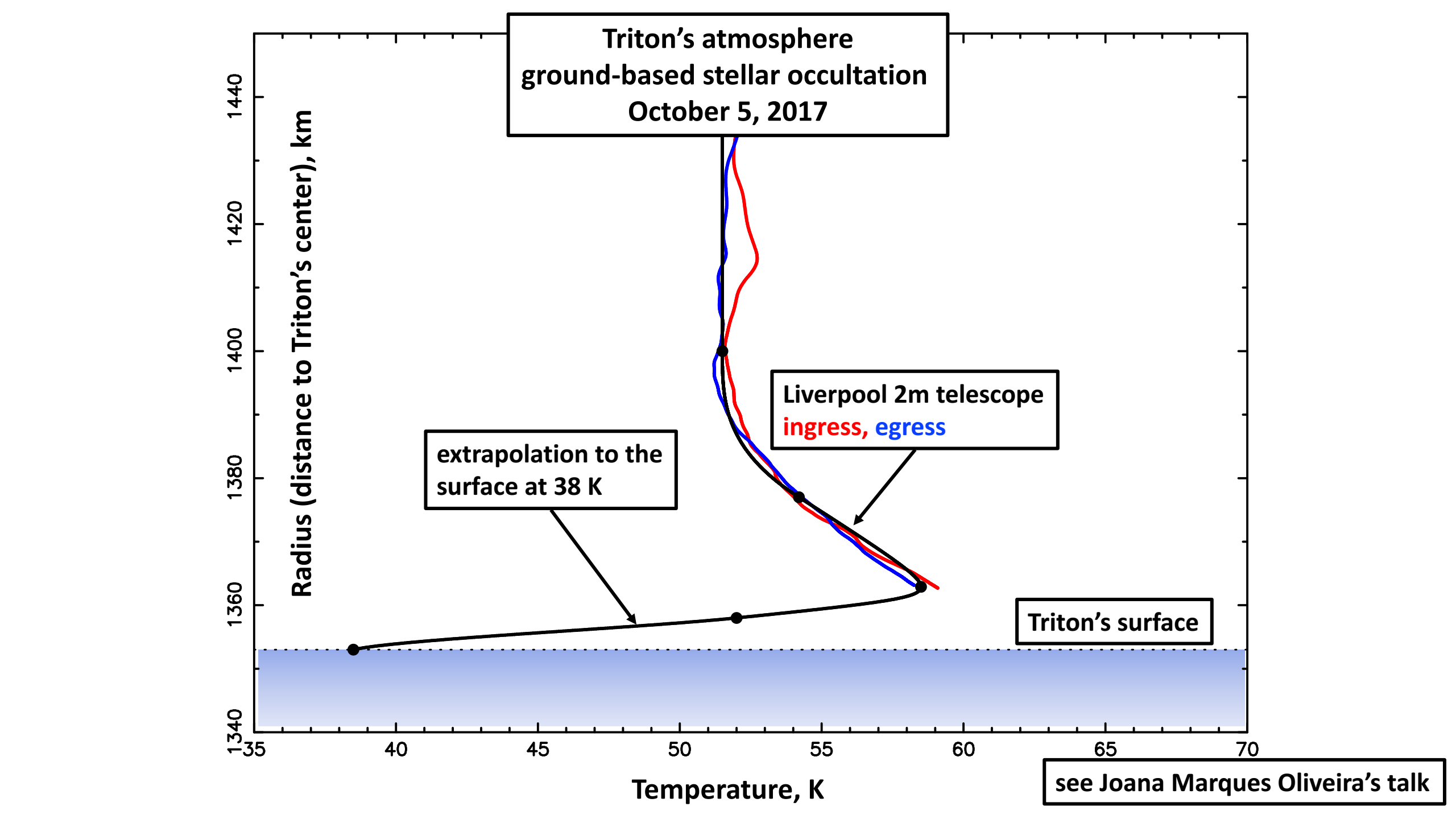
E. Meza[1,⋆], B. Sicardy[1], M. Assafin[2,3], J. L. Ortiz[4], T. Bertrand[5], E. Lellouch[1], J. Desmars[1], F. Forget[6], D. Bérard[1], A. Doressoundiram[1], J. Lecacheux[1], J. Marques Oliveira[1], F. Roques[1], T. Widemann[1], F. Colas[7], F. Vachier[7], S. Renner[7,8], R. Leiva[9], F. Braga-Ribas[1,3,10], G. Benedetti-Rossi[3], J. I. B. Camargo[3], A. Dias-Oliveira[3], B. Morgado[3], A. R. Gomes-Júnior[3], R. Vieira-Martins[3], R. Behrend[11], A. Castro Tirado[4], R. Duffard[4], N. Morales[4], P. Santos-Sanz[4], M. Jelínek[12], R. Cunniffe[13], R. Querel[14], M. Harnisch[15,16], R. Jansen[15,16], A. Pennell[15,16], S. Todd[15,16], V. D. Ivanov[17], C. Opitom[17], M. Gillon[18], E. Jehin[18], J. Manfroid[18], J. Pollock[19], D. E. Reichart[20], J. B. Haislip[20], K. M. Ivarsen[20], A. P. LaCluyze[21], A. Maury[22], R. Gil-Hutton[23], V. Dhillon[24,25], S. Littlefair[24], T. Marsh[26], C. Veillet[27], K.-L. Bath[28,29], W. Beisker[28,29], H.-J. Bode[28,29,†], M. Kretlow[28,29], D. Herald[15,30,31], D. Gault[15,32,33], S. Kerr[15,34], H. Pavlov[30], O. Faragó[29,†], O. Klös[29], E. Frappa[35], M. Lavayssière[35], A. A. Cole[36], A. B. Giles[36], J. G. Greenhill[36,†], K. M. Hill[36], M. W. Buie[9], C. B. Olkin[9], E. F. Young[9], L. A. Young[9], L. H. Wasserman[37], M. Devogèle[37], R. G. French[38], F. B. Bianco[39,40,41,42], F. Marchis[1,43], N. Brosch[44], S. Kaspi[44], D. Polishook[45], I. Manulis[45], M. Ait Moulay Larbi[46], Z. Benkhaldoun[46], A. Daassou[46], Y. El Azhari[46], Y. Moulane[18,46], J. Broughton[15], J. Milner[15], T. Dobosz[47], G. Bolt[48], B. Lade[49], A. Gilmore[50], P. Kilmartin[50], W. H. Allen[15], P. B. Graham[15,51], B. Loader[15,30], G. McKay[15], J. Talbot[15], S. Parker[52], L. Abe[53], Ph. Bendjoya[53], J.-P. Rivet[53], D. Vernet[53], L. Di Fabrizio[54], V. Lorenzi[25,54], A. Magazzú[54], E. Molinari[54,55], K. Gazeas[56], L. Tzouganatos[56], A. Carbognani[57], G. Bonnoli[58], A. Marchini[29,58], G. Leto[59], R. Zanmar Sanchez[59], L. Mancini[60,61,62,63], B. Kattentidt[29], M. Dohrmann[29,64], K. Guhl[29,64], W. Rothe[29,64], K. Walzel[64], G. Wortmann[64], A. Eberle[65], D. Hampf[65], J. Ohlert[66,67], G. Krannich[68], G. Murawsky[69], B. Gährken[70], D. Gloistein[71], S. Alonso[72], A. Román[73], J.-E. Communal[74], F. Jabet[75], S. deVisscher[76], J. Sérot[77], T. Janik[78], Z. Moravec[78], P. Machado[79], A. Selva[29,80], C. Perelló[29,80], J. Rovira[29,80], M. Conti[81], R. Papini[29,81], F. Salvaggio[29,81], A. Noschese[29,82], V. Tsamis[29,83], K. Tigani[83], P. Barroy[84], M. Irzyk[84], D. Neel[84], J. P. Godard[84], D. Lanoiselée[84], P. Sogorb[84], D. Vérilhac[85], M. Bretton[86], F. Signoret[87], F. Ciabattari[88], R. Naves[29], M. Boutet[89], J. De Queiroz[29], P. Lindner[29], K. Lindner[29], P. Enskonatus[29], G. Dangl[29], T. Tordai[29], H. Eichler[90], J. Hattenbach[90], C. Peterson[91], L. A. Molnar[92], and R. R. Howell[93]

170 co-authors!

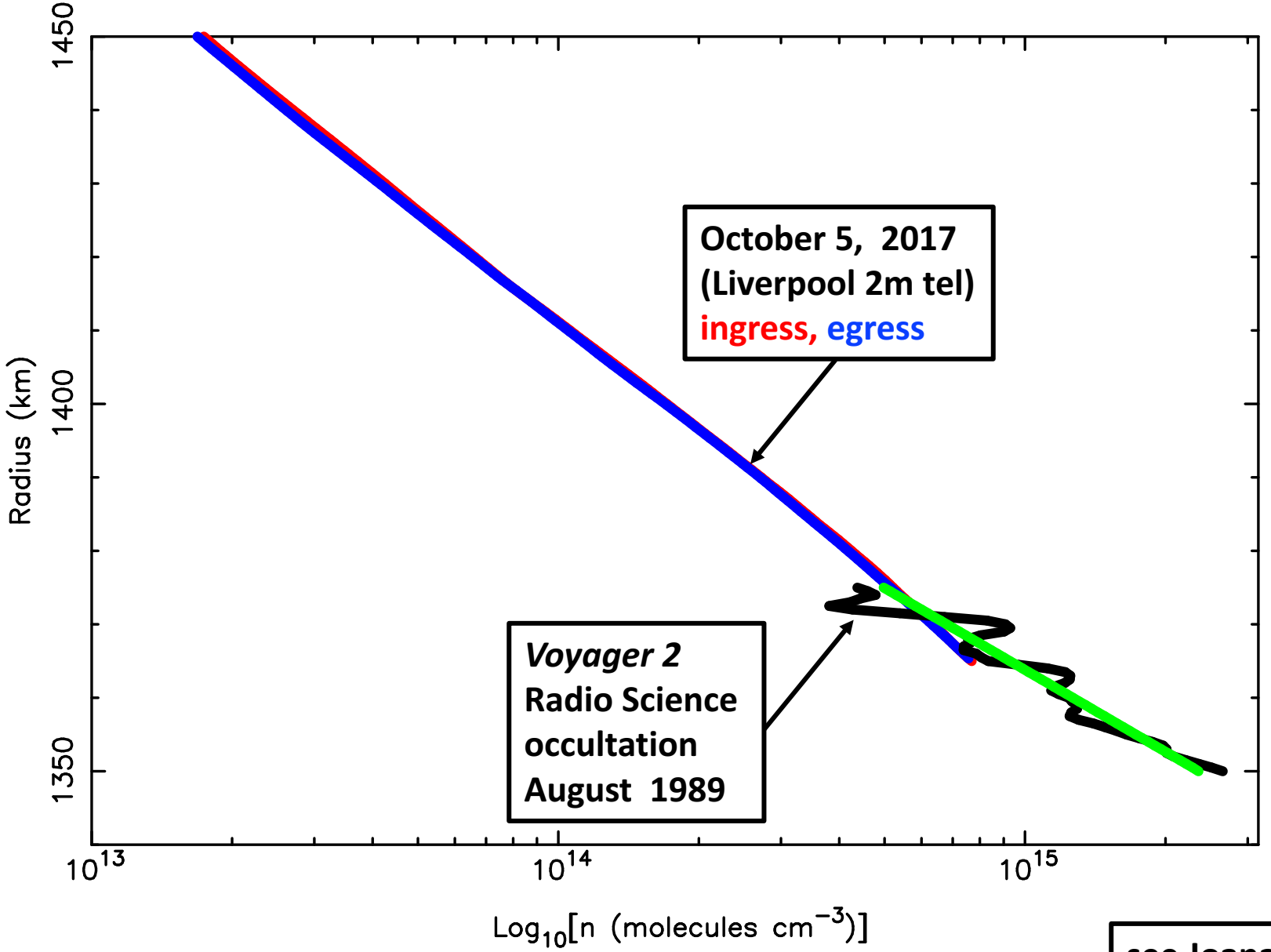

Earth years
1988 2013 2038 2063 2088 2113 2138 2163 2188 2213 2238
Ls=0° N. Spring
Ls=90° N. Summer
Ls=180° N. Fall
Ls=270° N. Winter
Surface pressure (μbar)
0 2 4 6 8 10 12 14
0 25 50 75 100 125 150 175 200 225 250
Earth years since Ls = 0°
2000 2004 2008 2012 2016 2020
7 8 9 10 11 12 13 14
12 16 20 24 28 32
Pluto's seasonal cycle:
- presence of Sputnik Planitia
- no southern N_2 polar cap
- constraints on thermal inertia


Sputnik Planitia depression:
the “beating heart“ of Pluto’s atmosphere


Triton occultation
October 5, 2017
an early Gaia DR2 star!
85 light curves so far…
3 mas !

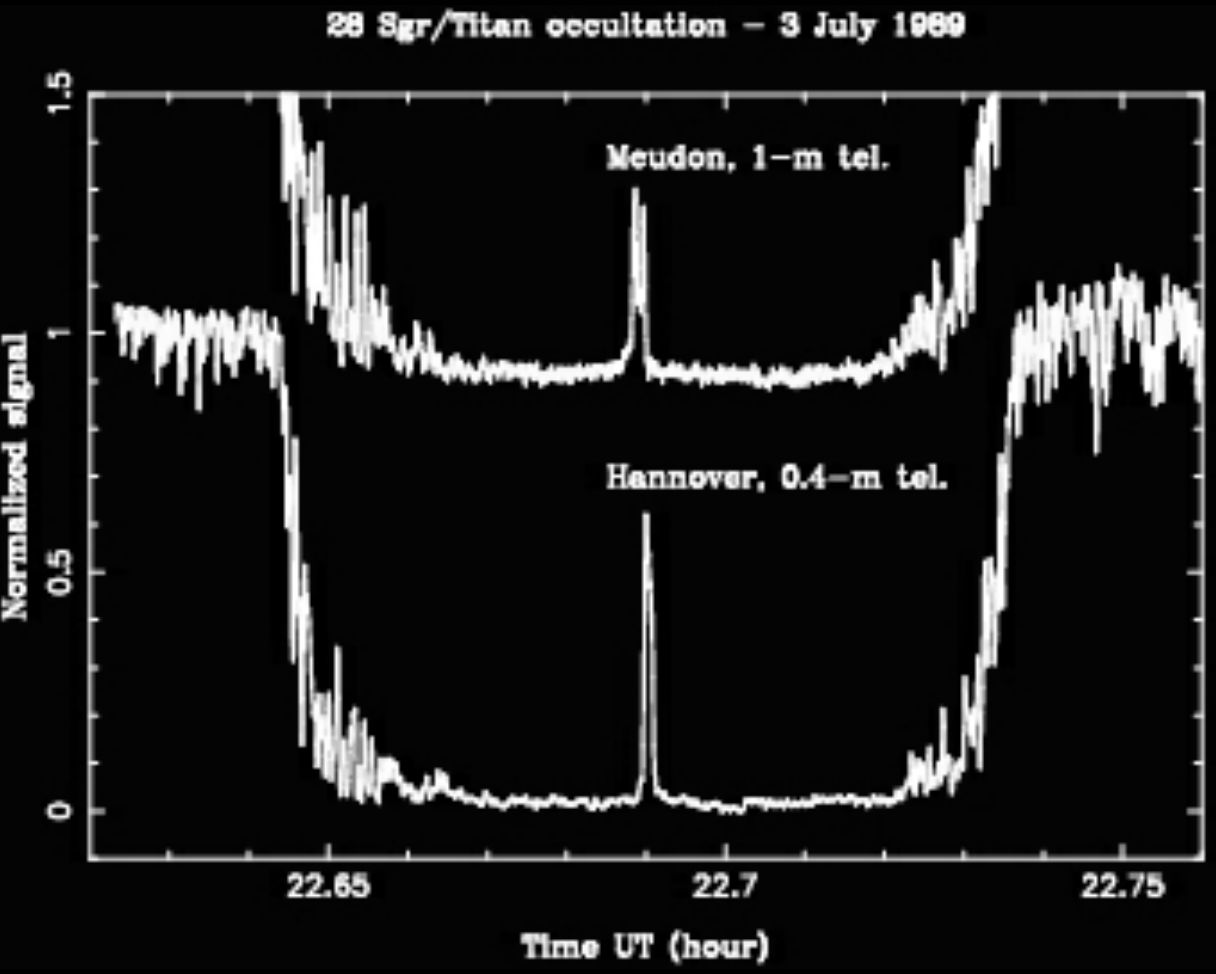

Triton's atmosphere
ground-based stellar occultation
October 5, 2017
Liverpool 2m telescope
ingress, egress
extrapolation to the
surface at 38 K
Triton's surface
Radius (distance to Triton's center), km
Temperature, K
1340
1360
1380
1400
1420
1440
35
40
45
50
55
60
65
70
see Joana Marques Oliveira's talk

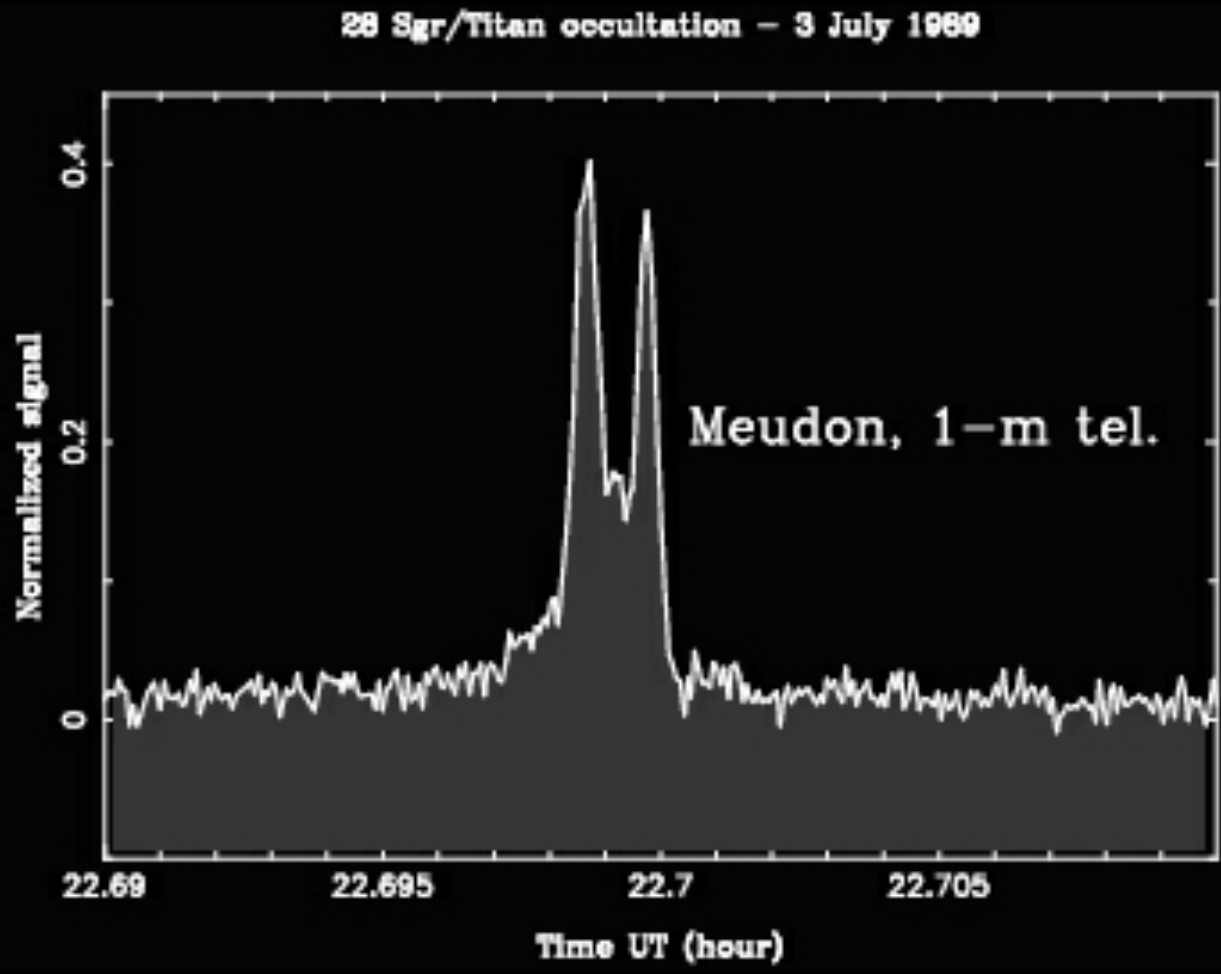
Triton's atmosphere
comparison *Voyager 2* (1989) and ground-based stellar occultation (2017)



see Joana Marques Oliveira's talk

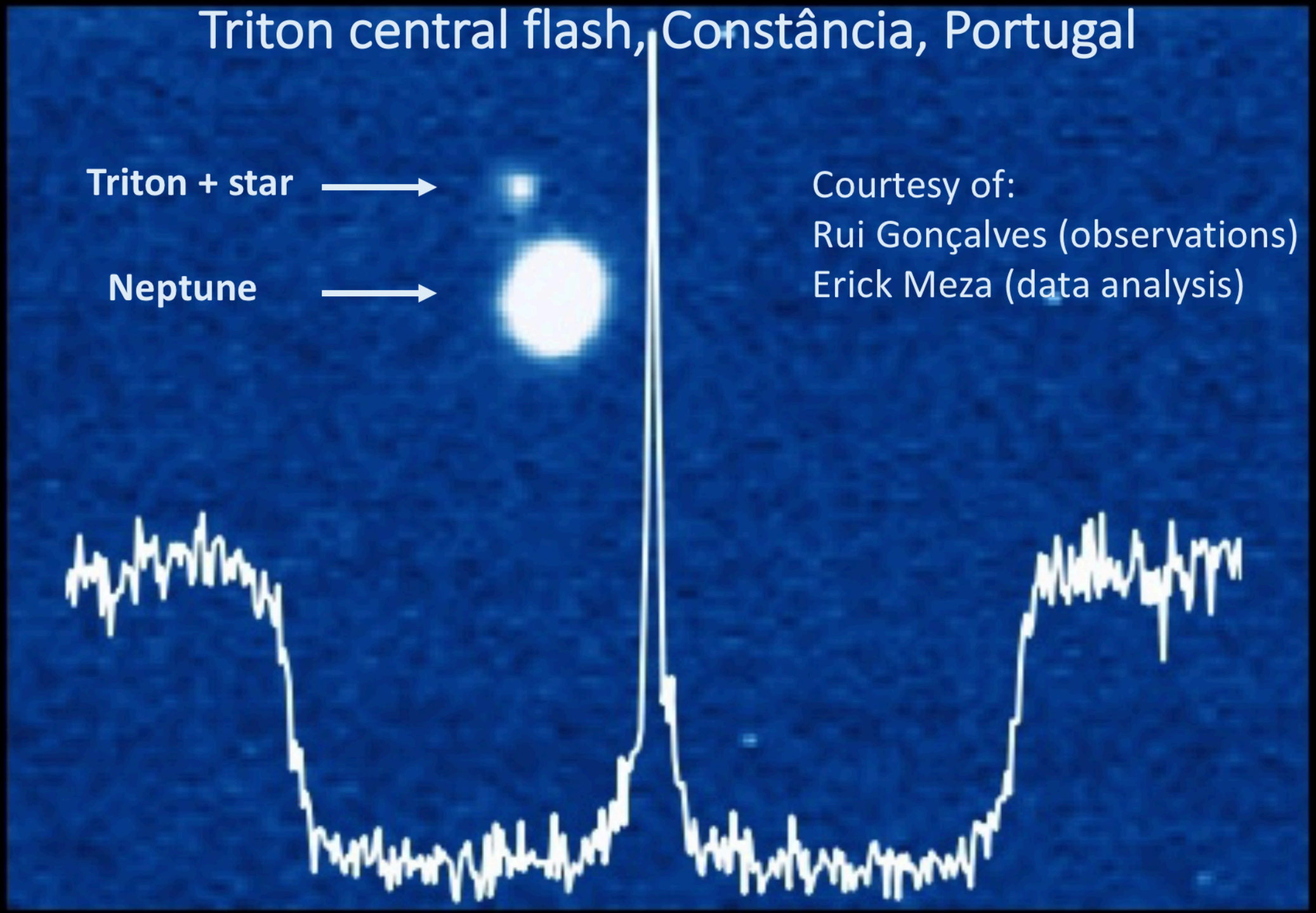
the Titan central flash of July 3, 1989

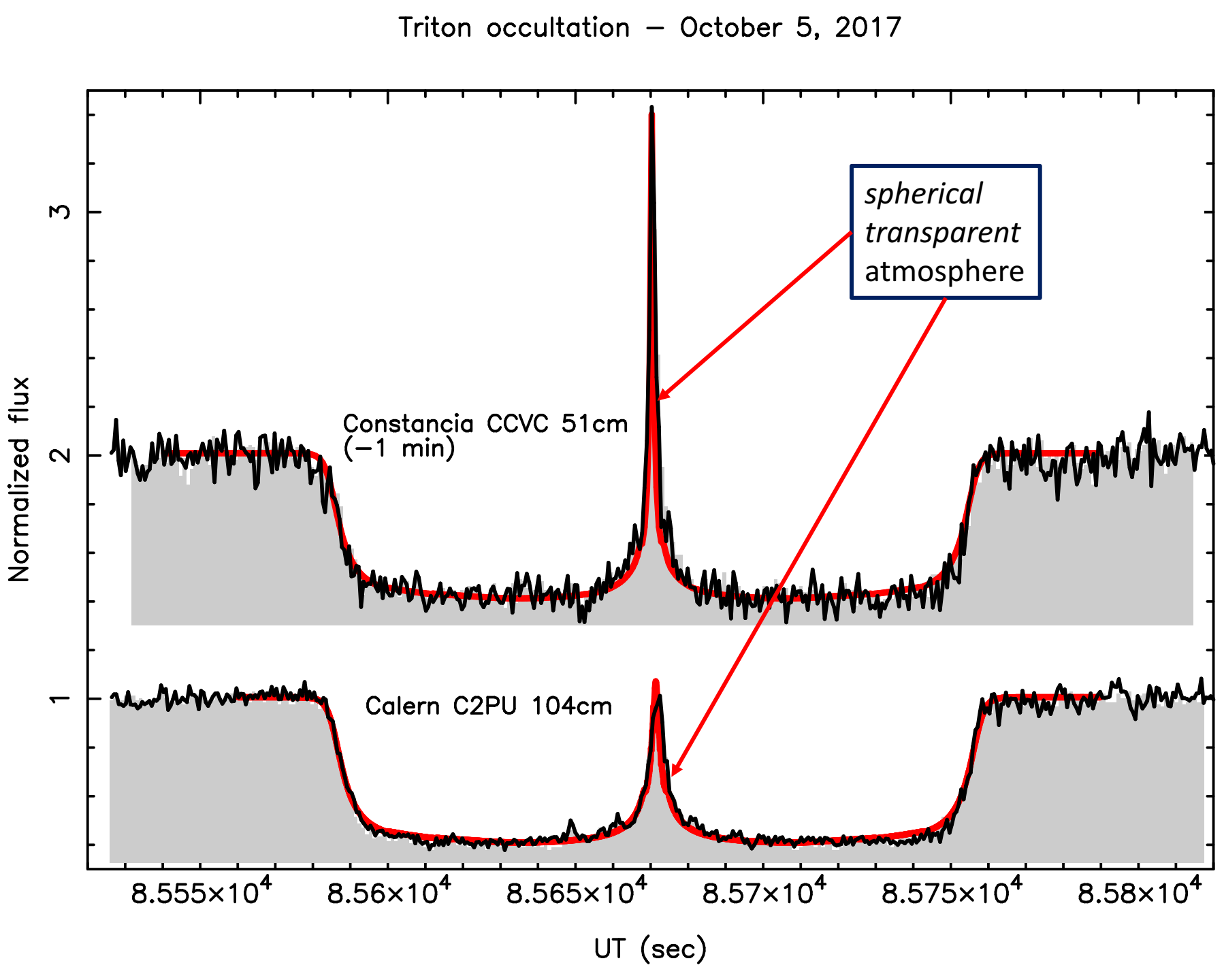




a tribute to H.-J. Bode
the start of a long collabotation

Triton central flash, Constância, Portugal




Triton occultation – October 5, 2017
spherical
transparent
atmosphere
Constancia CCVC 51cm
(–1 min)
Calern C2PU 104cm
Normalized flux
1
2
3
8.555×10^4
8.56×10^4
8.565×10^4
8.57×10^4
8.575×10^4
8.58×10^4
UT (sec)

New ERC Advanced Grant project:
Far Horizons 2021/25

Far Horizons 2021/25: main Work Packages

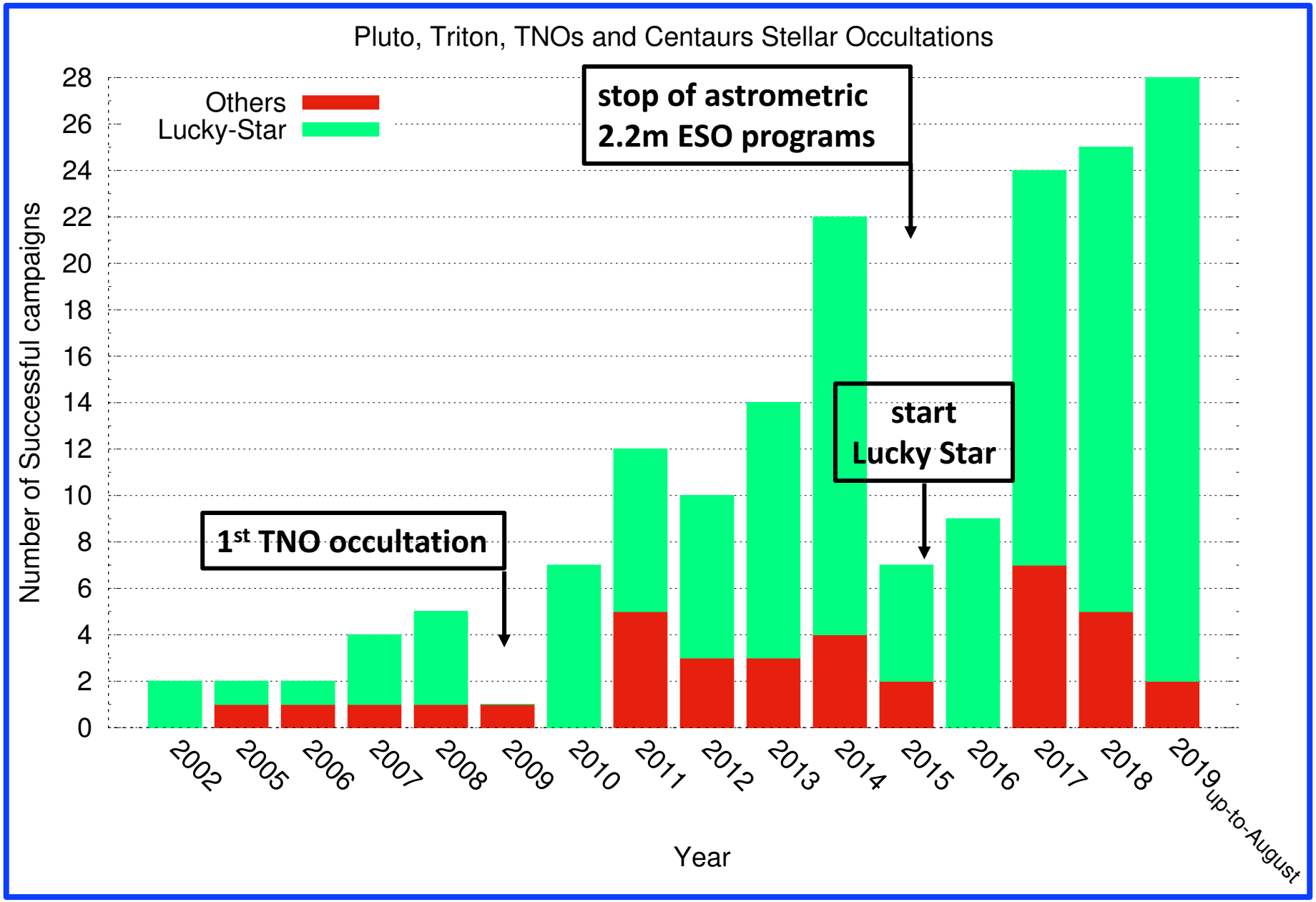
WP1. Rings around small bodies: dynamics, simulations

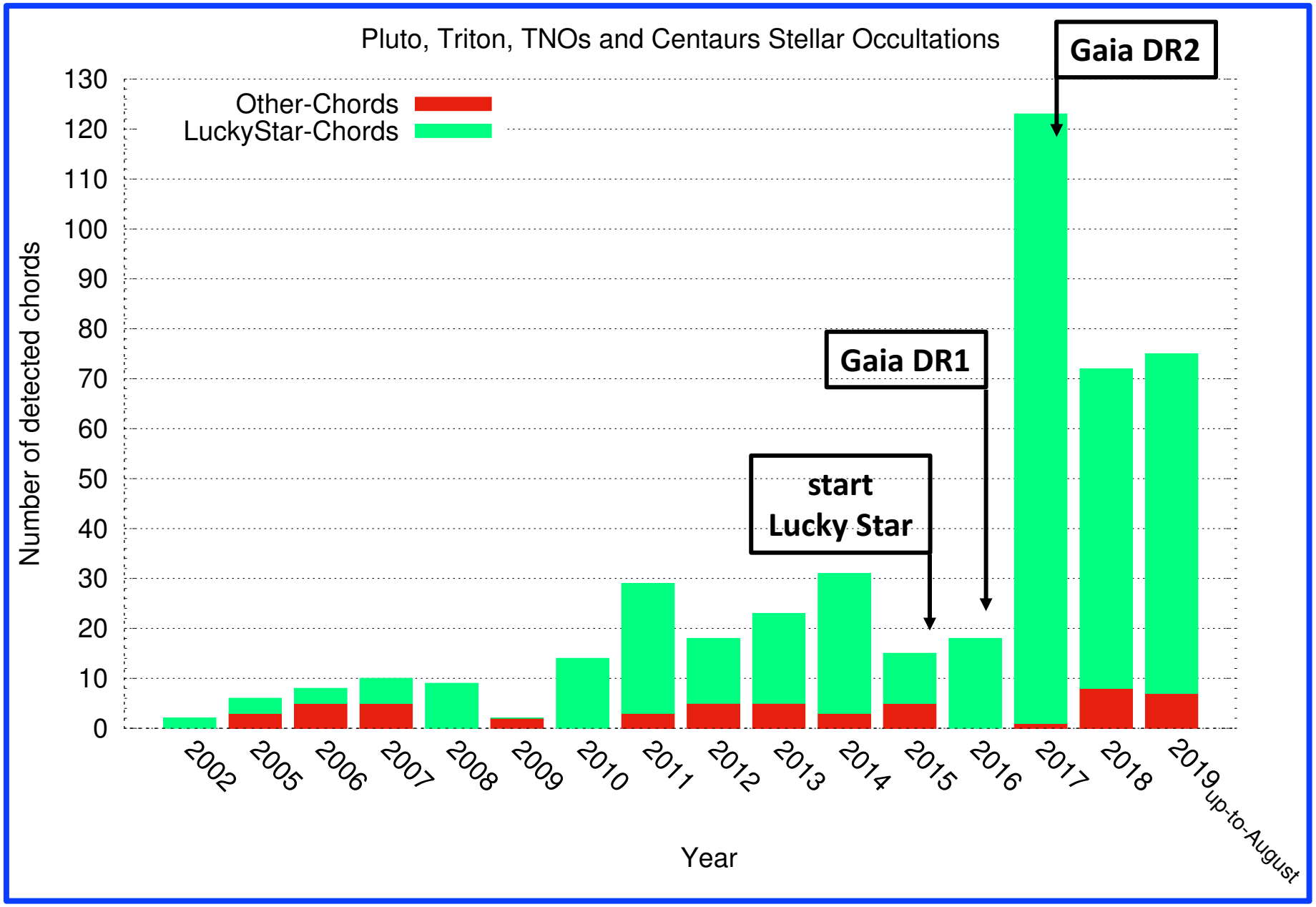
WP2. Internal structures

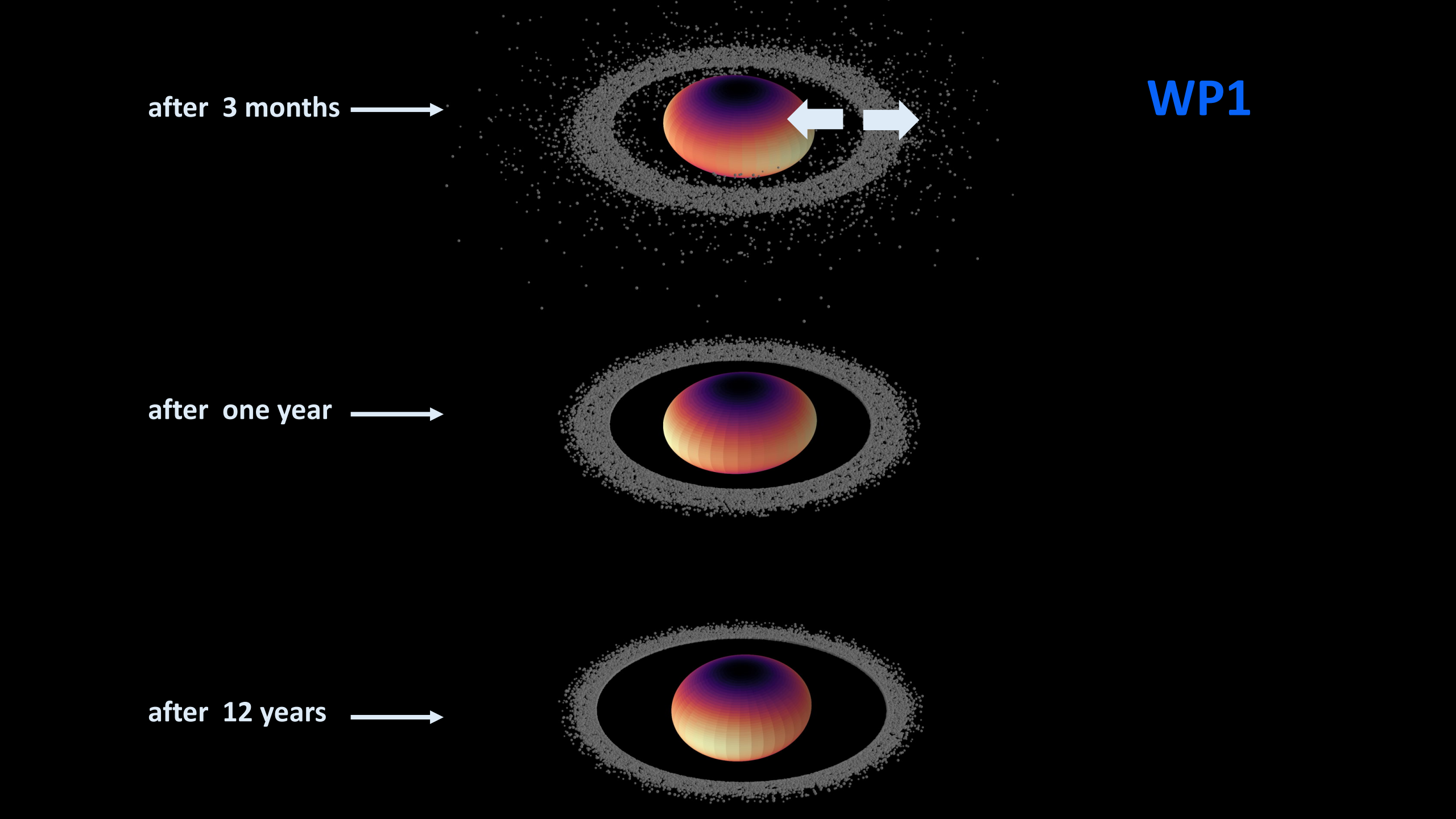
WP3. Pluto & Triton seasonal cycles, search for new atmospheres

WP4. Focus on specific targets

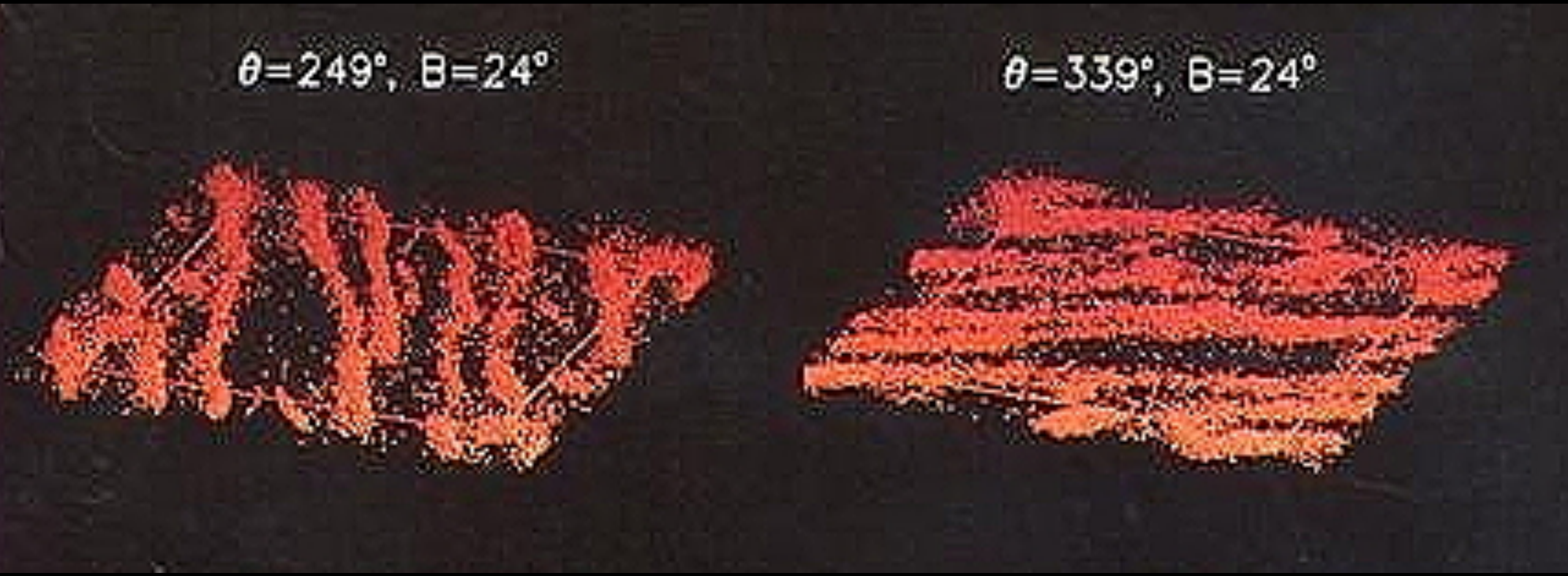
WP5. Collisional history of the early Solar system

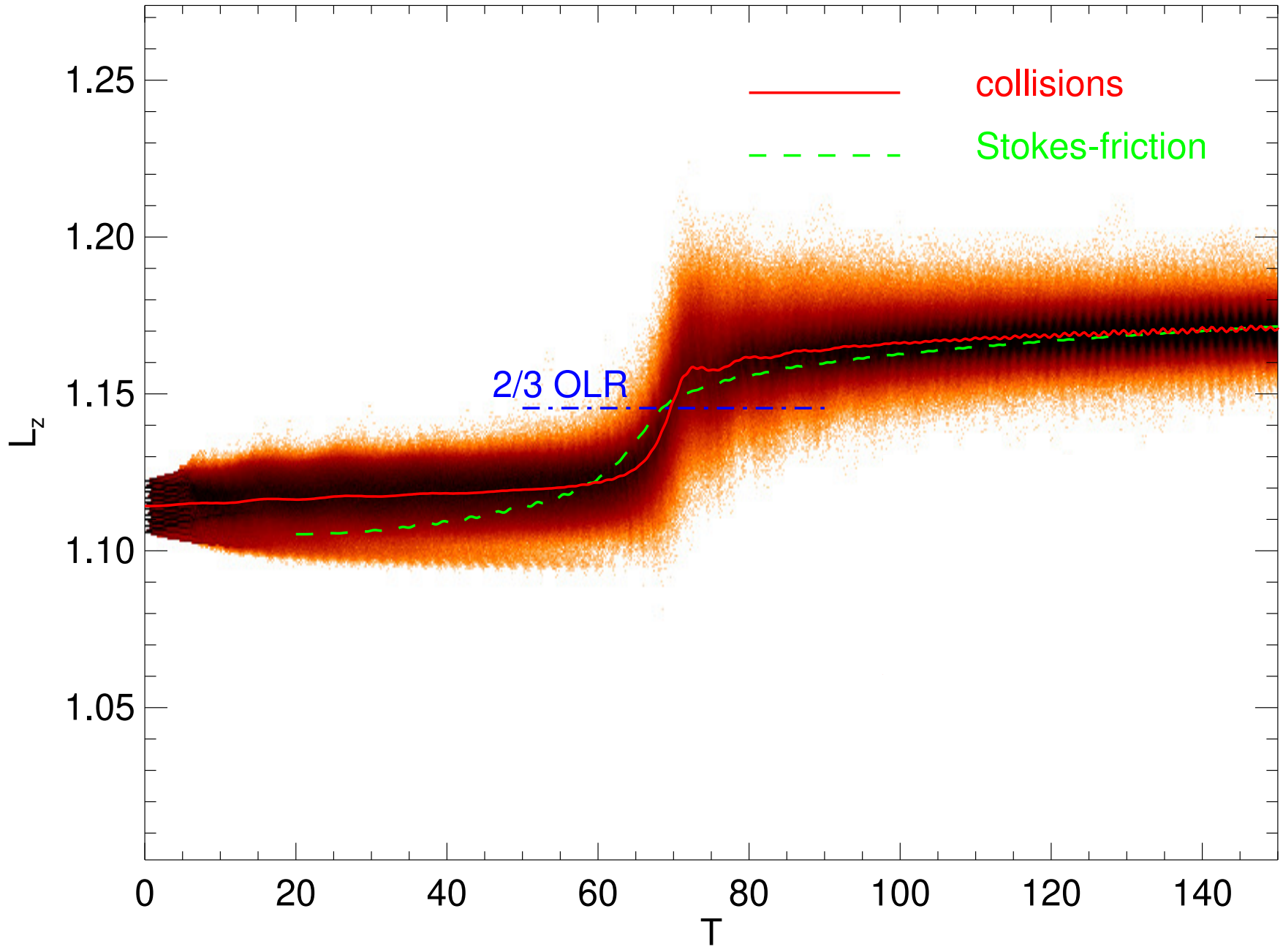

Pluto, Triton, TNOs and Centaurs Stellar Occultations
Others
Lucky-Star
stop of astrometric
2.2m ESO programs
start
Lucky Star
1st TNO occultation
Number of Successful campaigns
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
2002
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019 up-to-August
Year


Pluto, Triton, TNOs and Centaurs Stellar Occultations
Other-Chords
LuckyStar-Chords
Number of detected chords
0
10
20
30
40
50
60
70
80
90
100
110
120
130
2002
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
up-to-August
Year
Gaia DR2
Gaia DR1
start
Lucky Star


after 3 months
after one year
after 12 years
WP1

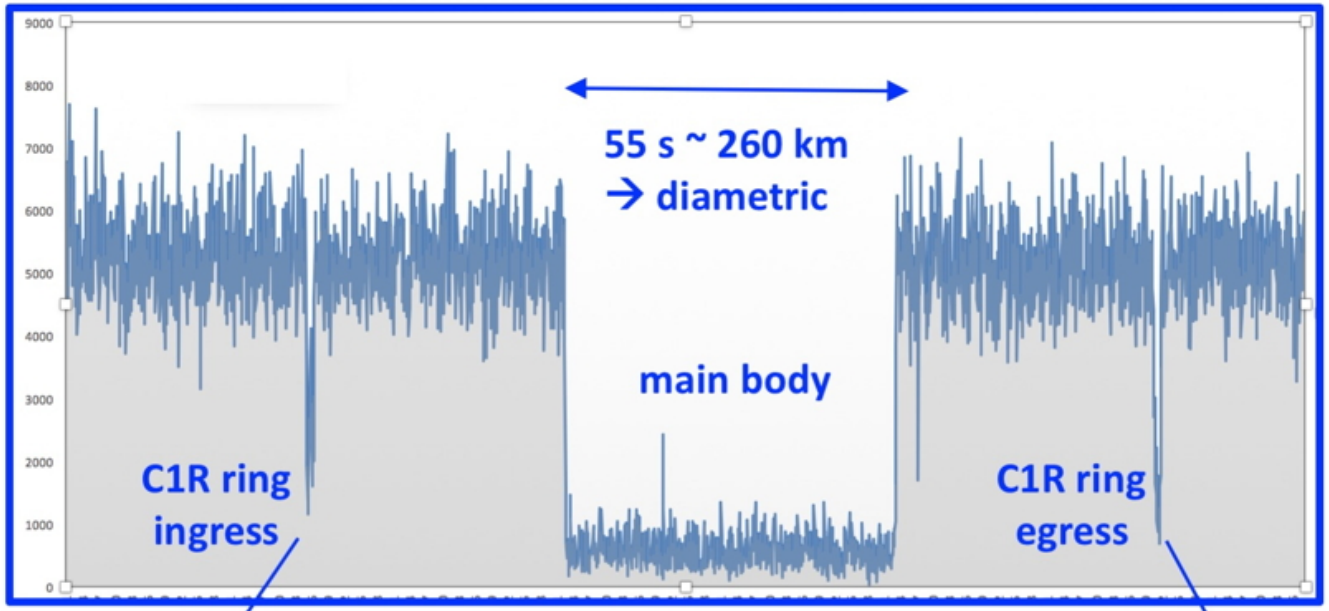
Salo *et al* 2004
collisional code of Saturn's rings



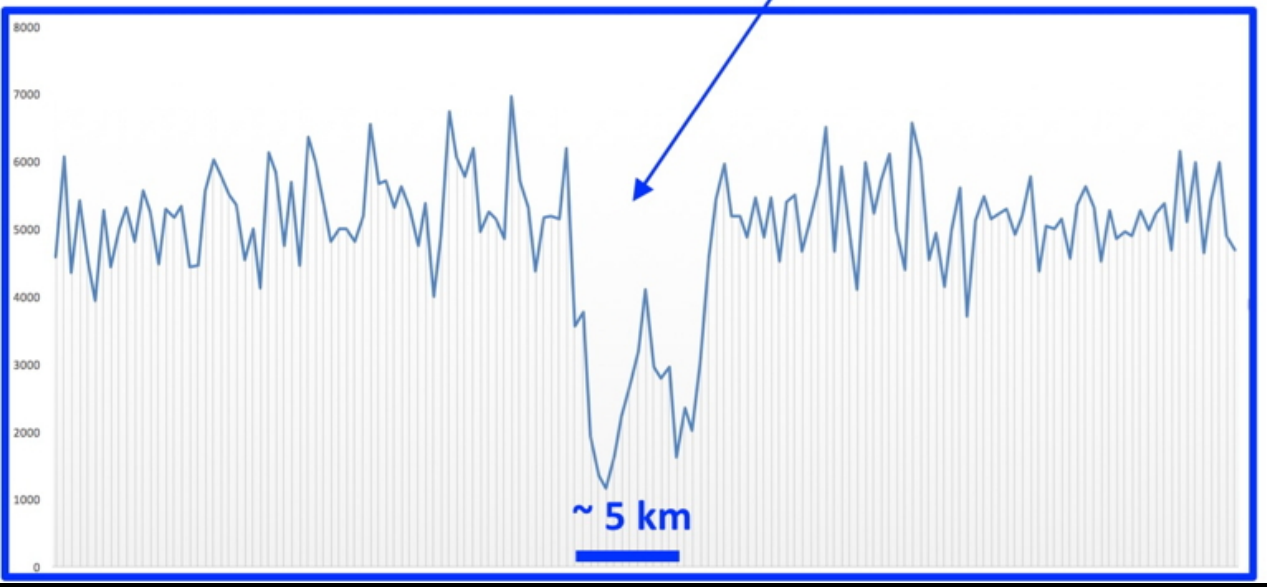

2/3 Outer Lindblad Resonance
collisions
Stokes-friction
2/3 OLR
1.25
1.20
1.15
1.10
1.05
L_z
0
20
40
60
80
100
120
140
T

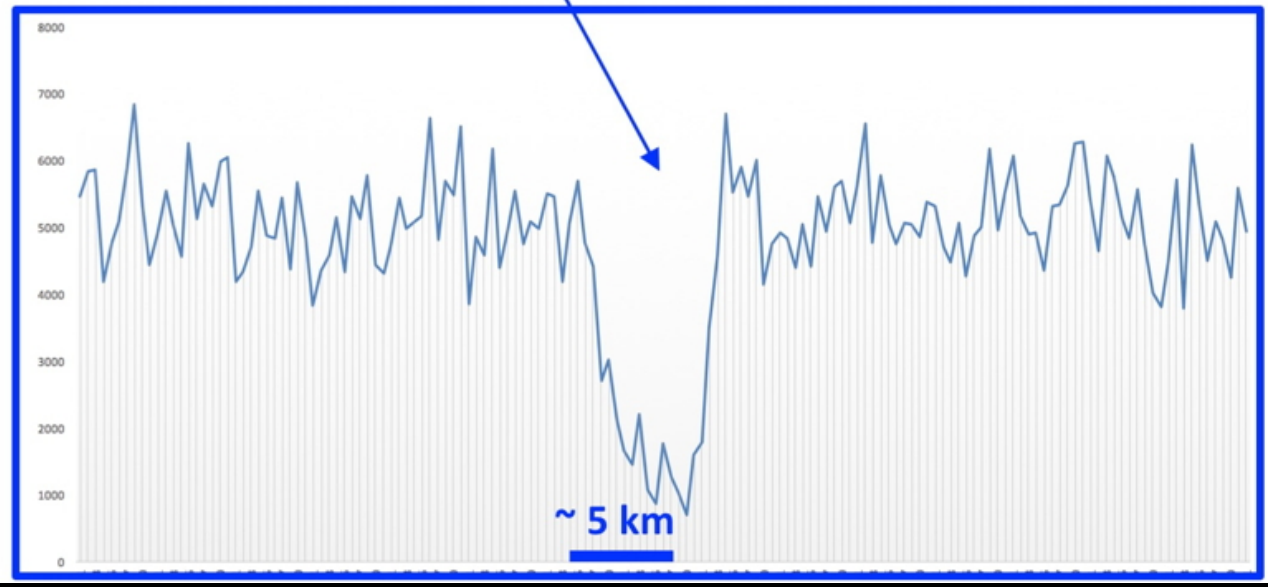
~ 2 months

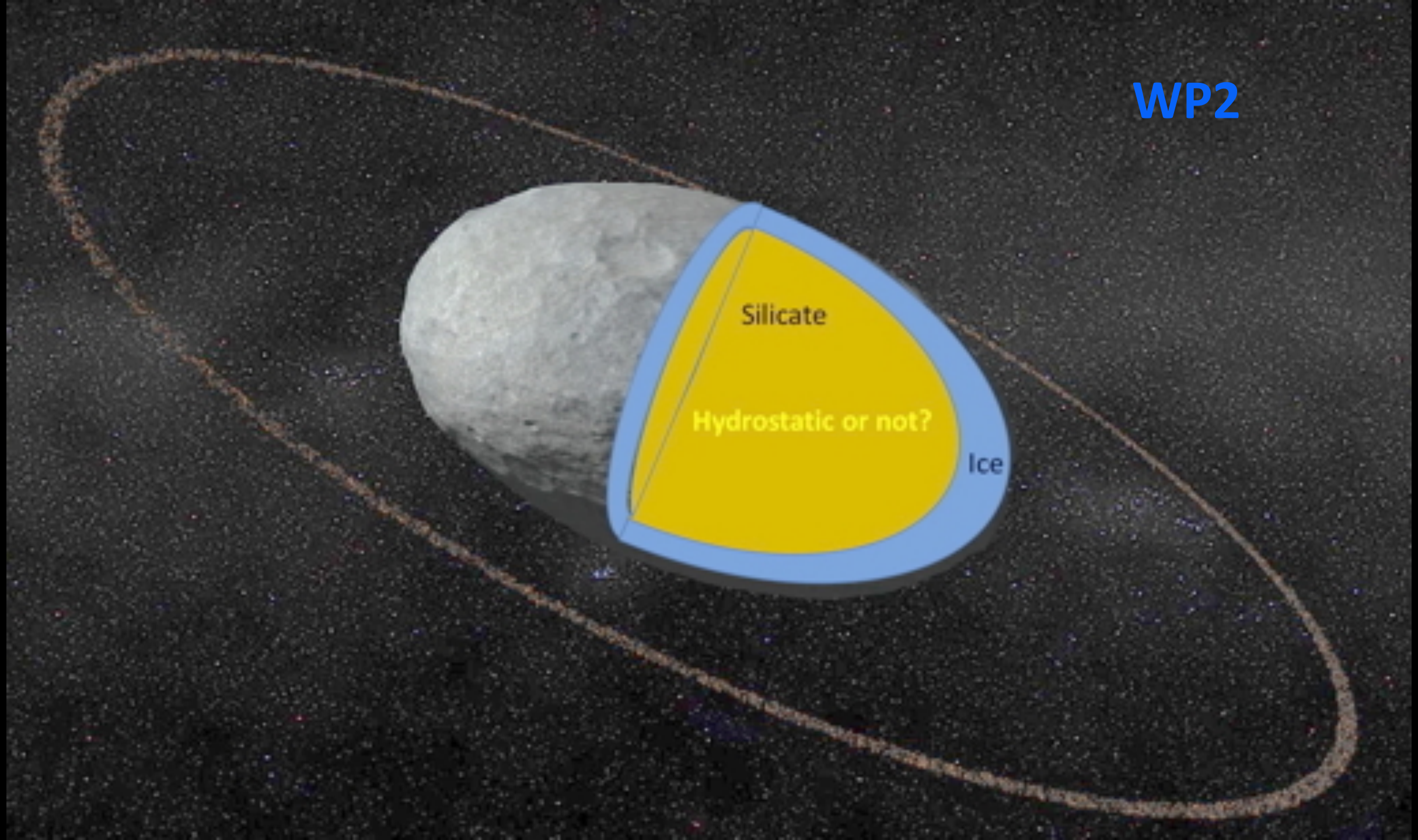

preparing the April 9, 2017
Chariklo occultation
“M2“ 50-cm telescope, Namibia
Mike Kretlow/Lucky Star

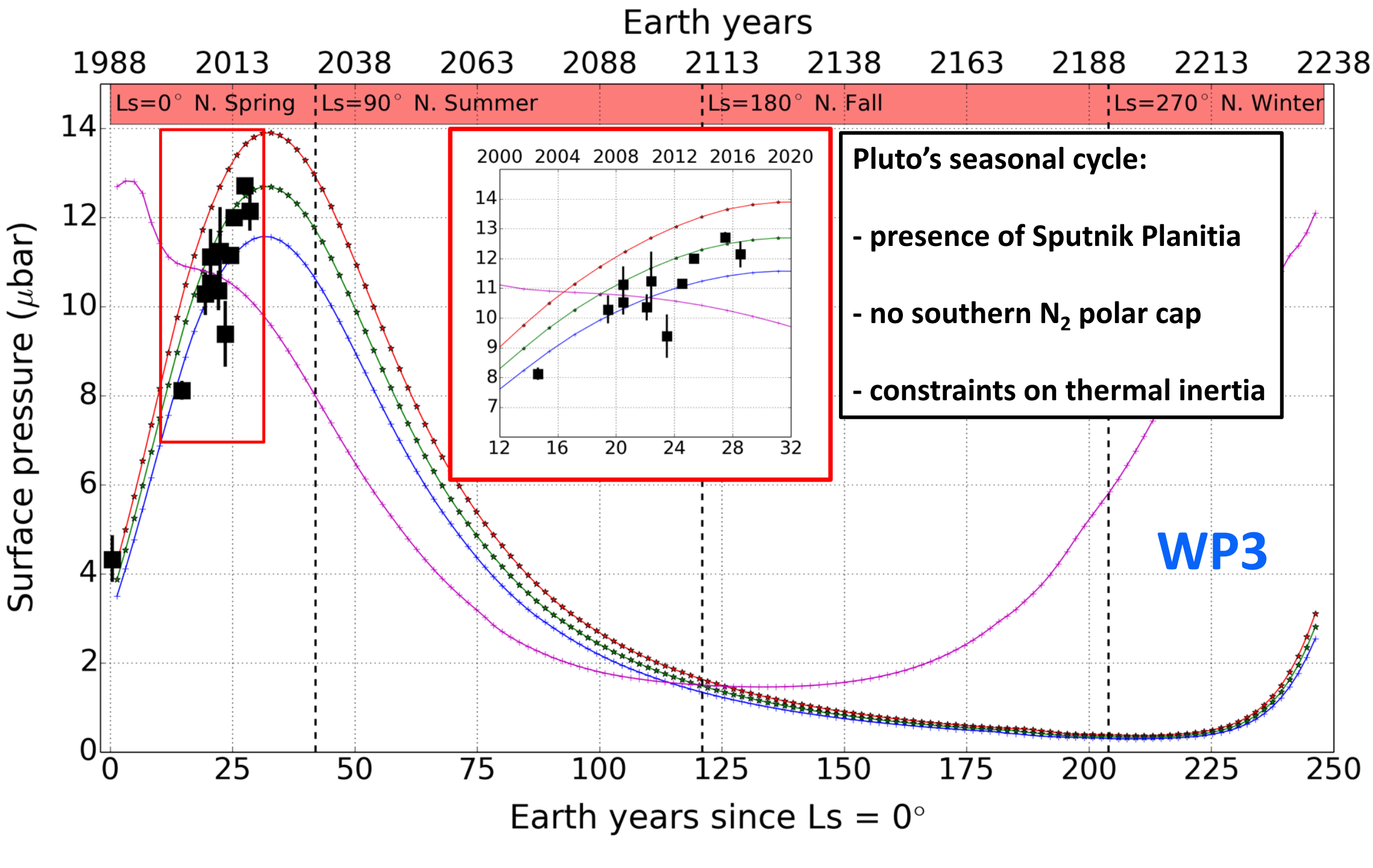


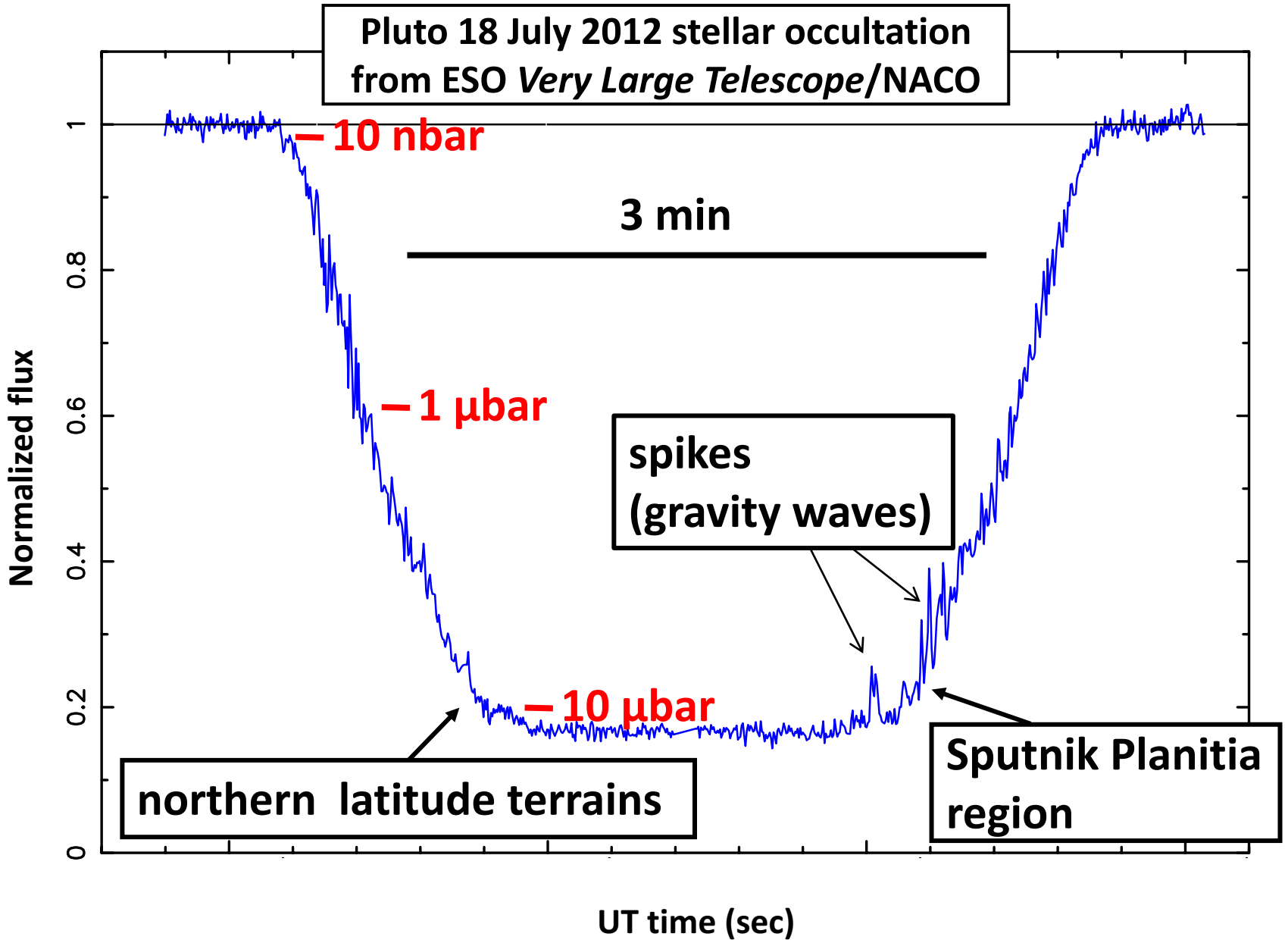
Weavers Rock
portable "M2"
50cm-telescope
Mike Kretlow
Namibia, April 9, 2017

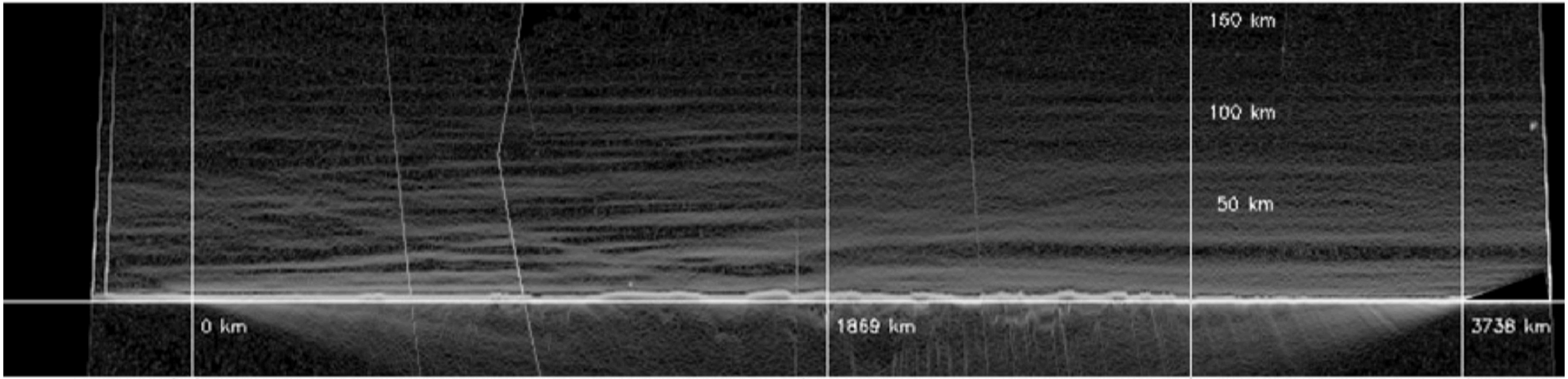





WP2
Silicate
Hydrostatic or not?
Ice


Earth years
1988
2013
2038
2063
2088
2113
2138
2163
2188
2213
2238
Ls=0° N. Spring
Ls=90° N. Summer
Ls=180° N. Fall
Ls=270° N. Winter
Surface pressure (μbar)
0
2
4
6
8
10
12
14
0
25
50
75
100
125
150
175
200
225
250
Earth years since Ls = 0°
2000
2004
2008
2012
2016
2020
7
8
9
10
11
12
13
14
12
16
20
24
28
32
Pluto's seasonal cycle:
- presence of Sputnik Planitia
- no southern N_2 polar cap
- constraints on thermal inertia
WP3


Pluto 18 July 2012 stellar occultation
from ESO *Very Large Telescope*/NACO
– 10 nbar
3 min
– 1 µbar
spikes
(gravity waves)
– 10 µbar
northern latitude terrains
Sputnik Planitia
region
Normalized flux
0
0.2
0.4
0.6
0.8
1
UT time (sec)



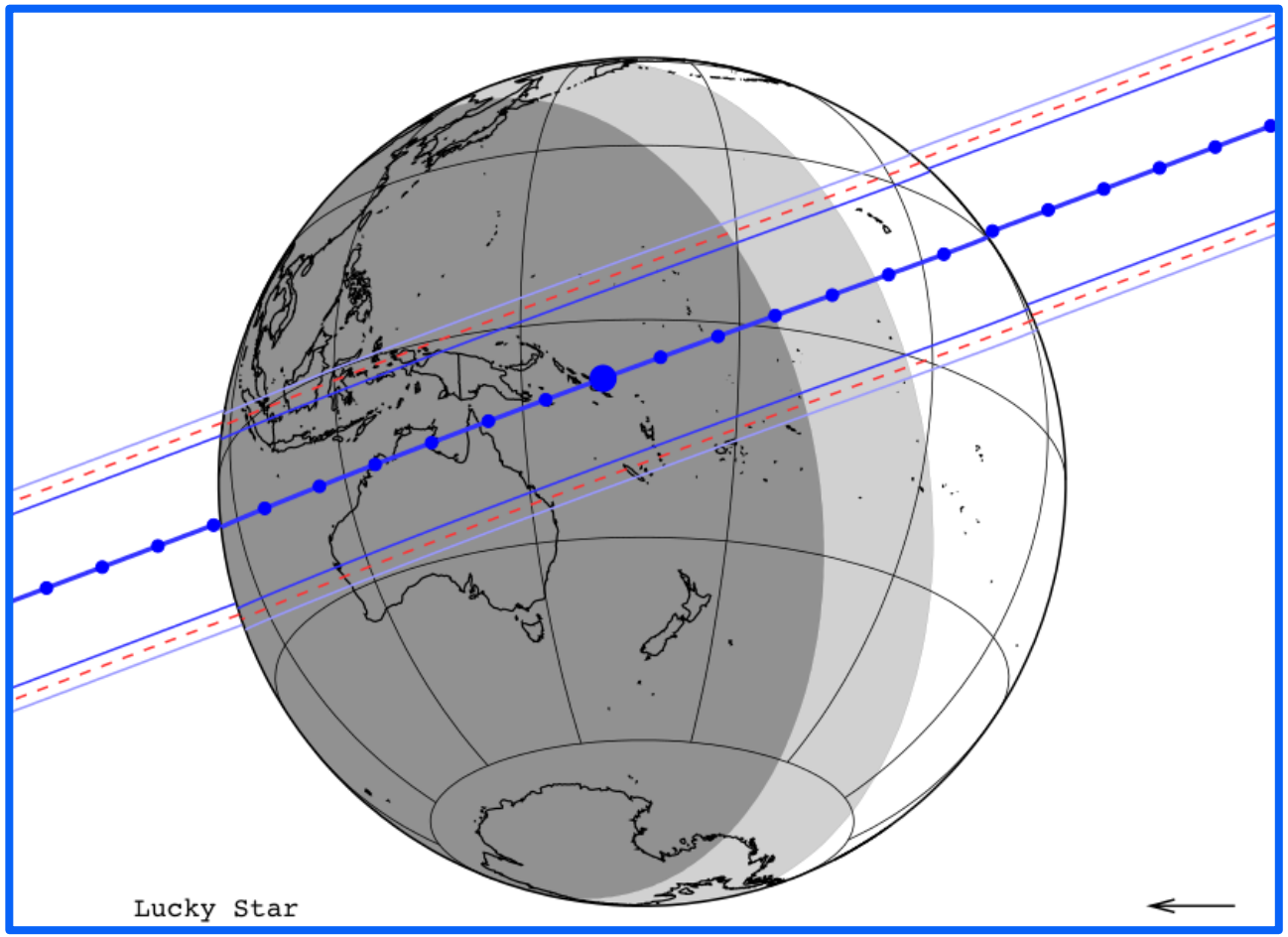
left (86°, -33.2°)

down (12°, 26.2°)

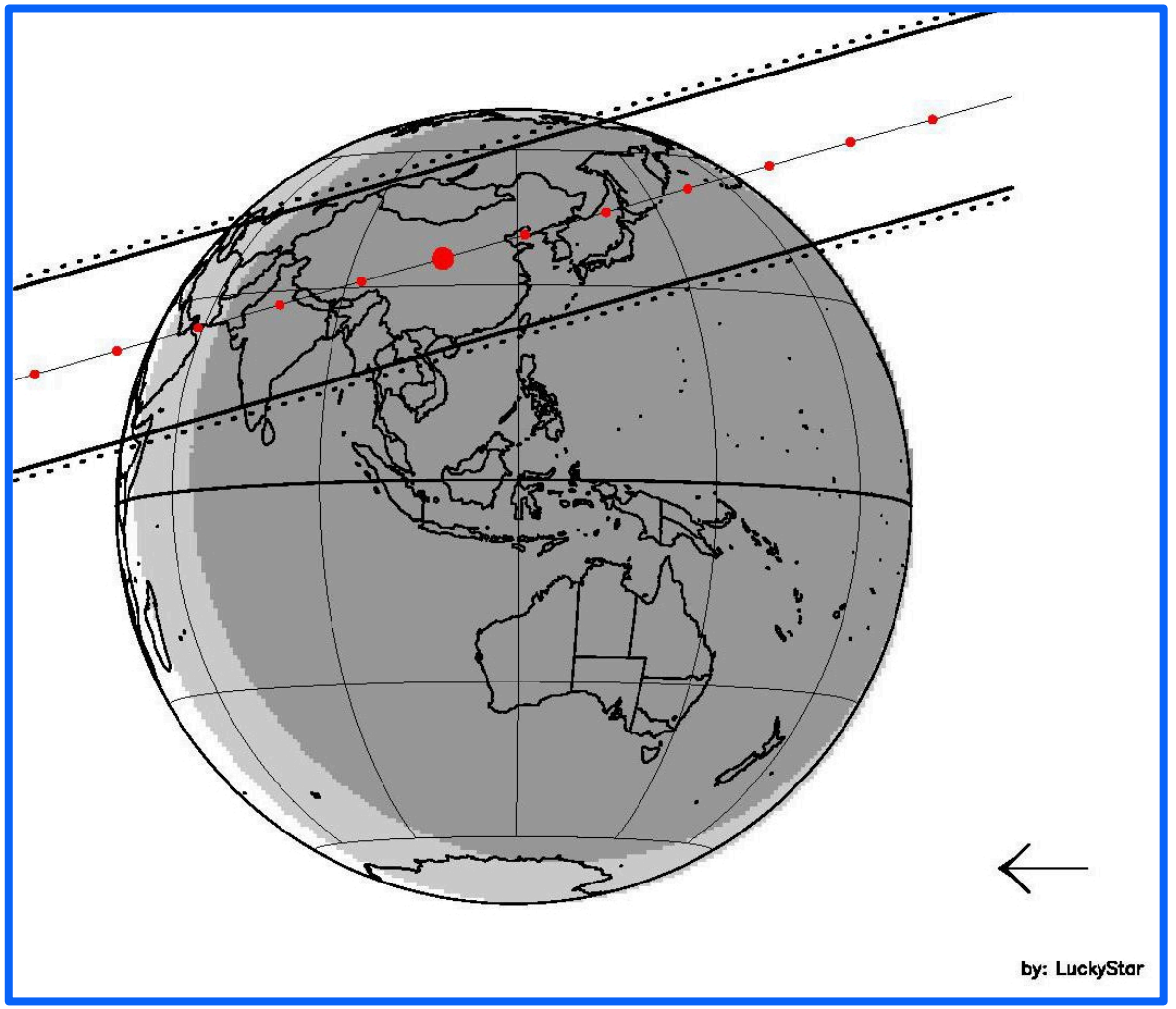
Pluto N (313°, 43.9°)

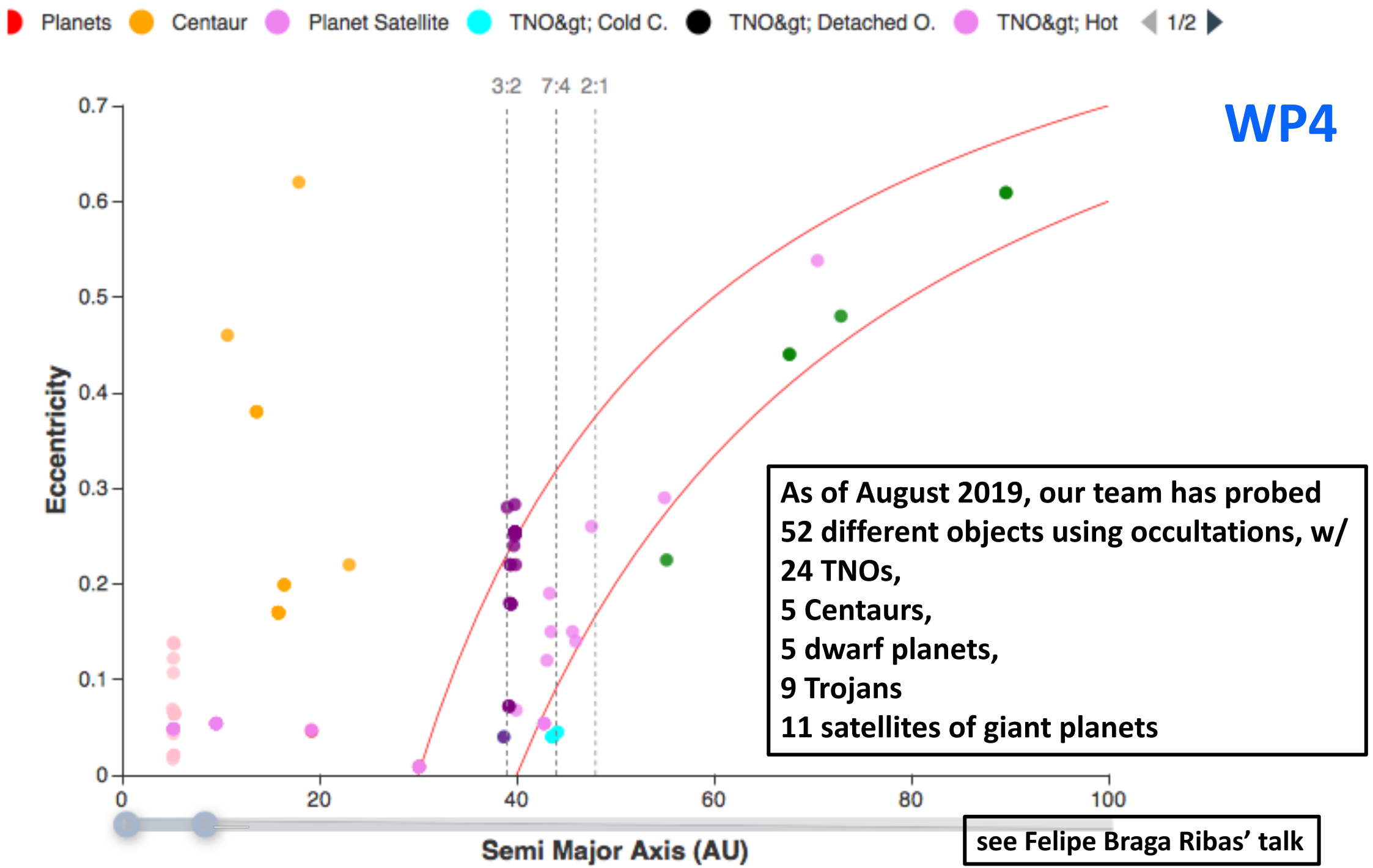
right (266°, 33.2°)

Pluto occultation June 1, 2022, G= 13.0



Triton occultation October 6, 2022, G= 11.4



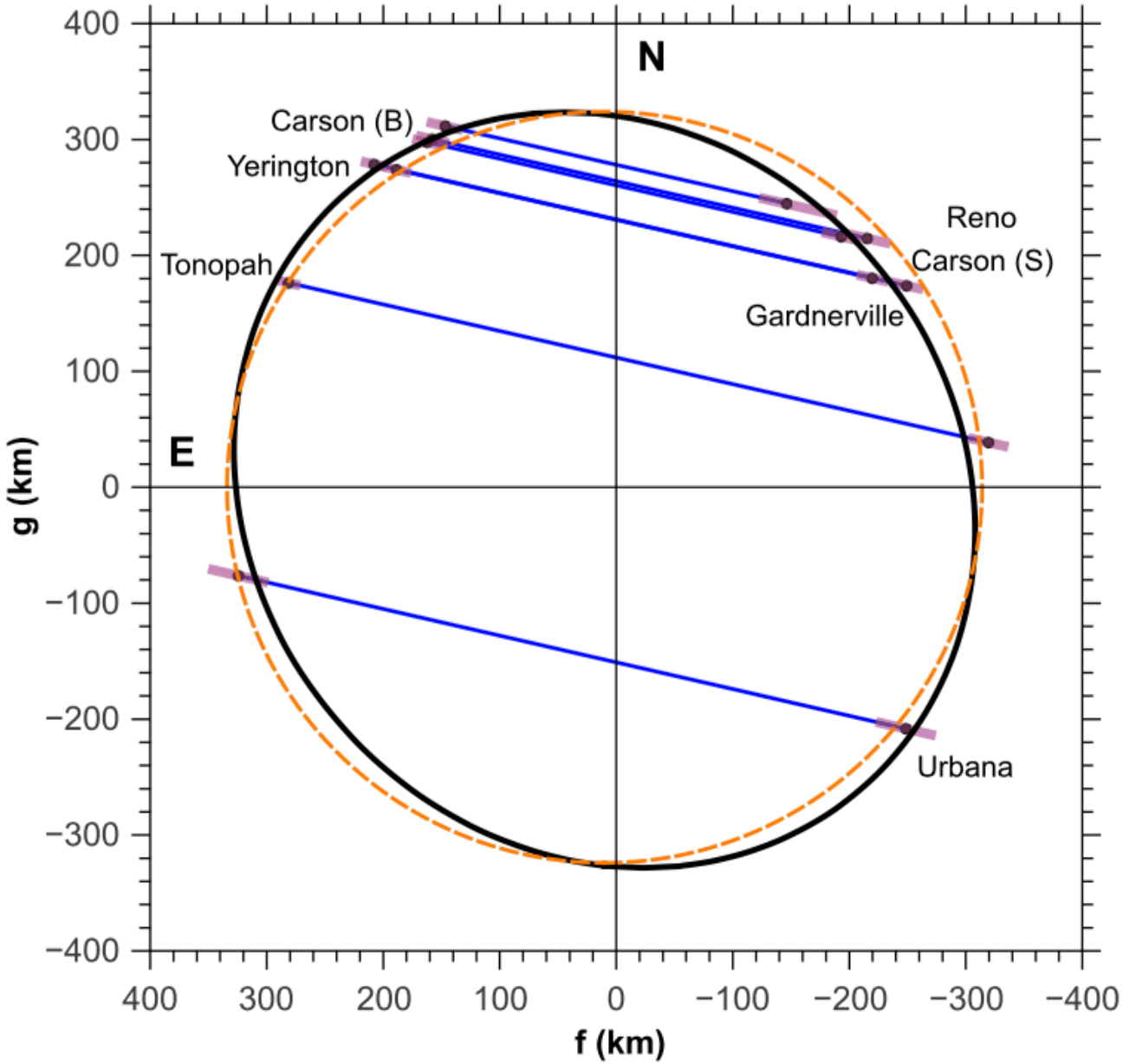


WP4

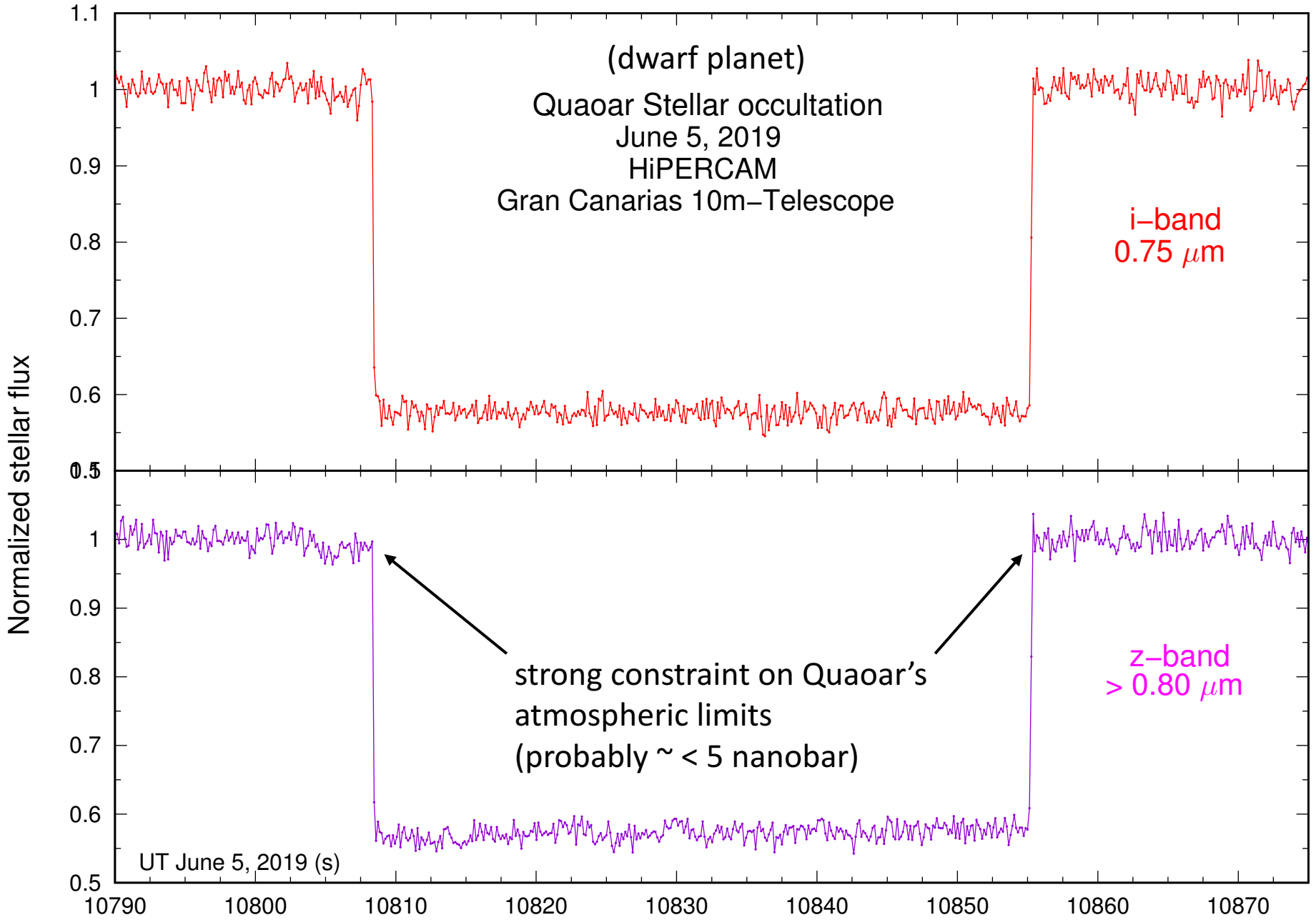
As of August 2019, our team has probed 52 different objects using occultations, w/
24 TNOs,
5 Centaurs,
5 dwarf planets,
9 Trojans
11 satellites of giant planets

see Felipe Braga Ribas' talk

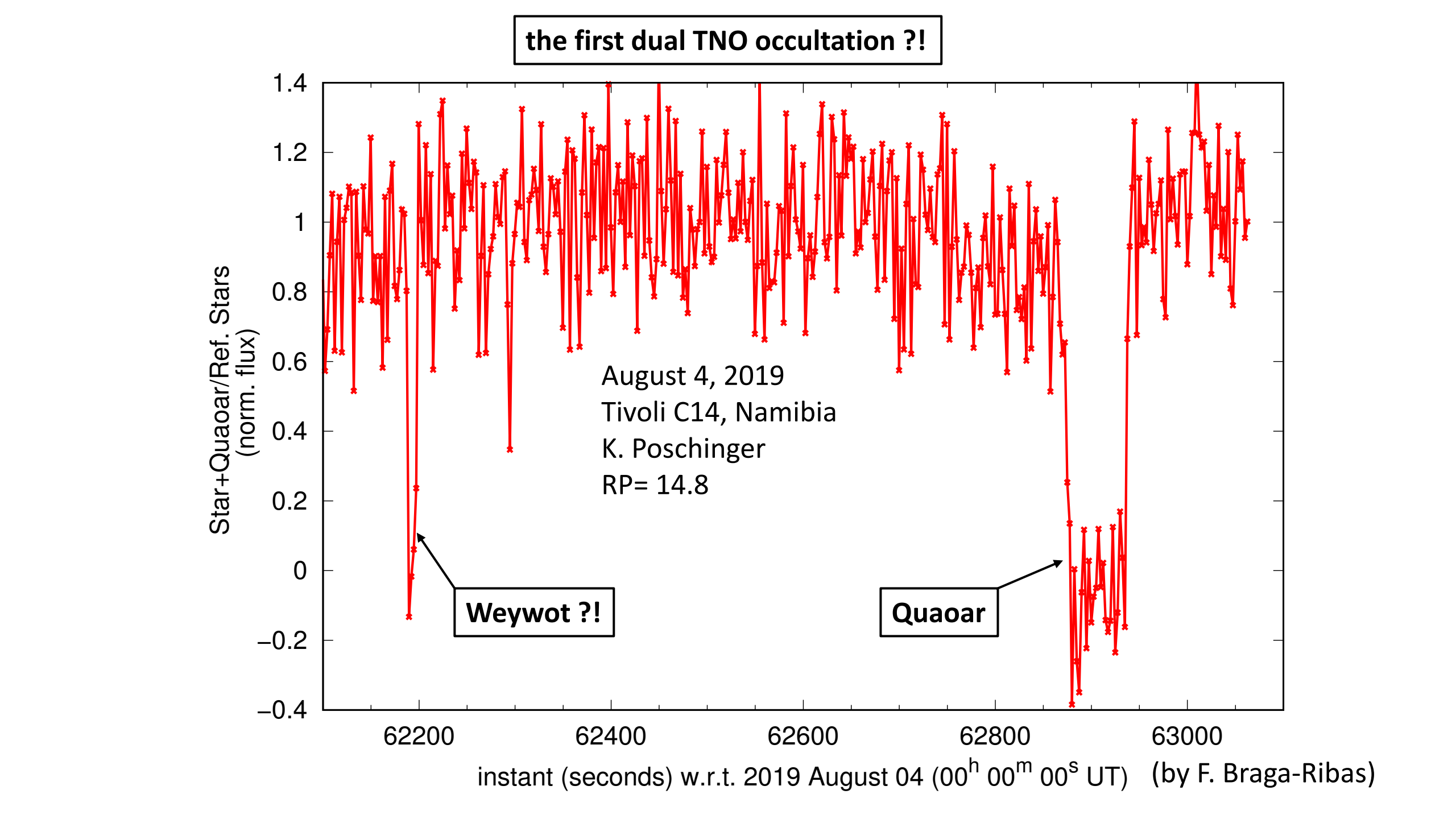
size and shape of Scattered Disk Object 2007 UK_{126}



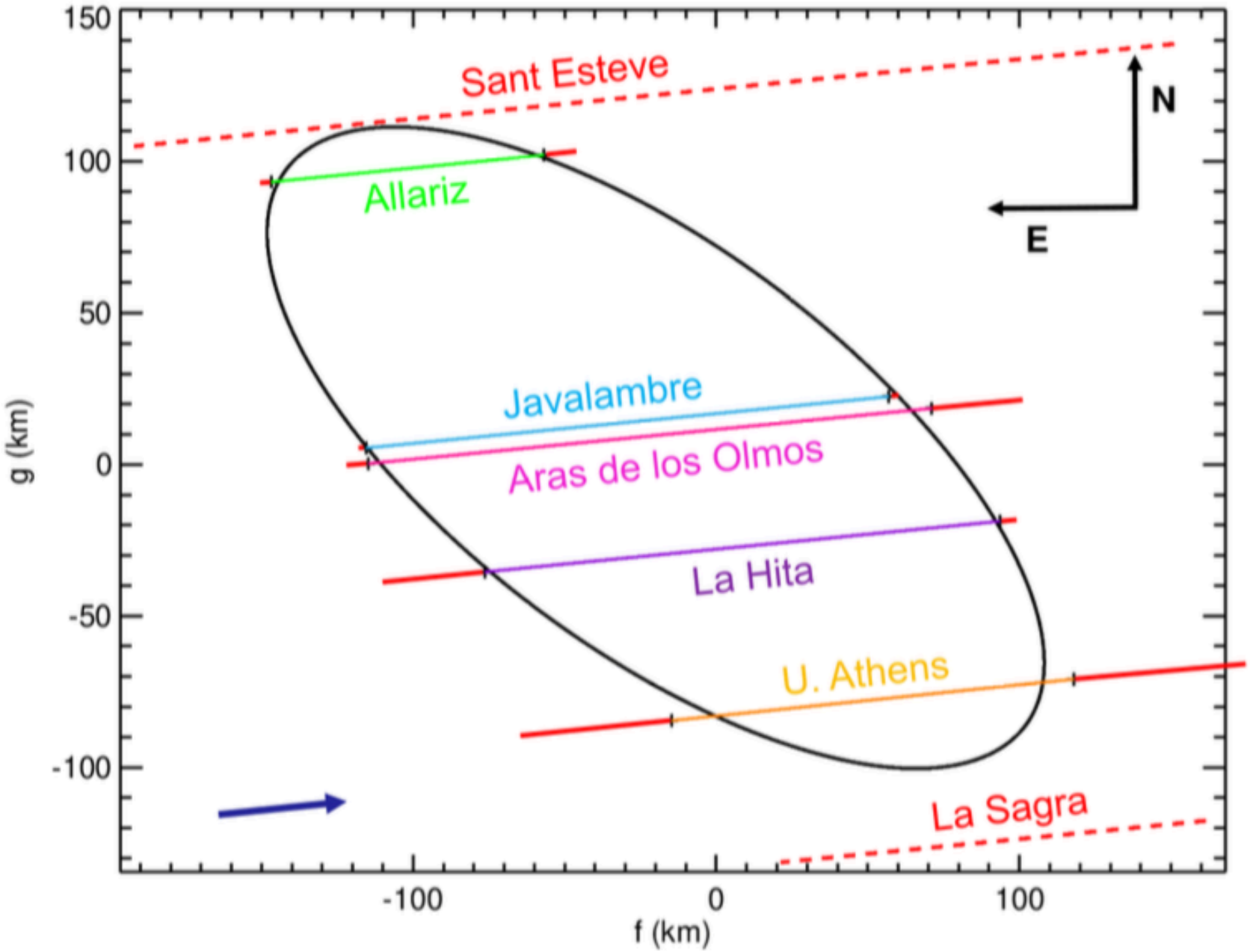
Benedetti-Rossi *et al* 2016



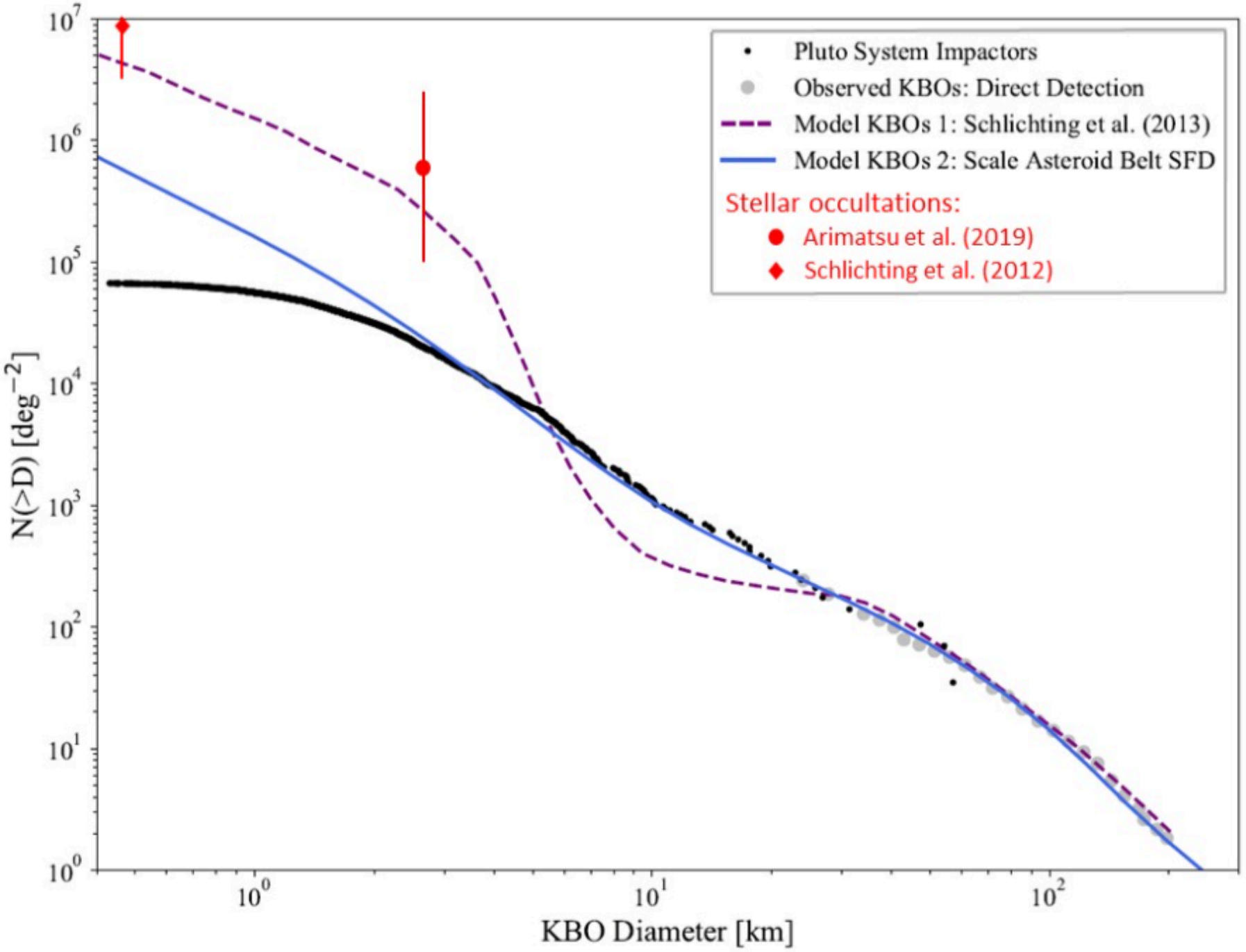
(by F. Braga-Ribas)


the first dual TNO occultation ?!
Star+Quaoar/Ref. Stars (norm. flux)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
62200
62400
62600
62800
63000
August 4, 2019
Tivoli C14, Namibia
K. Poschinger
RP= 14.8
Weywot ?!
Quaoar
instant (seconds) w.r.t. 2019 August 04 (00h 00m 00s UT)
(by F. Braga-Ribas)

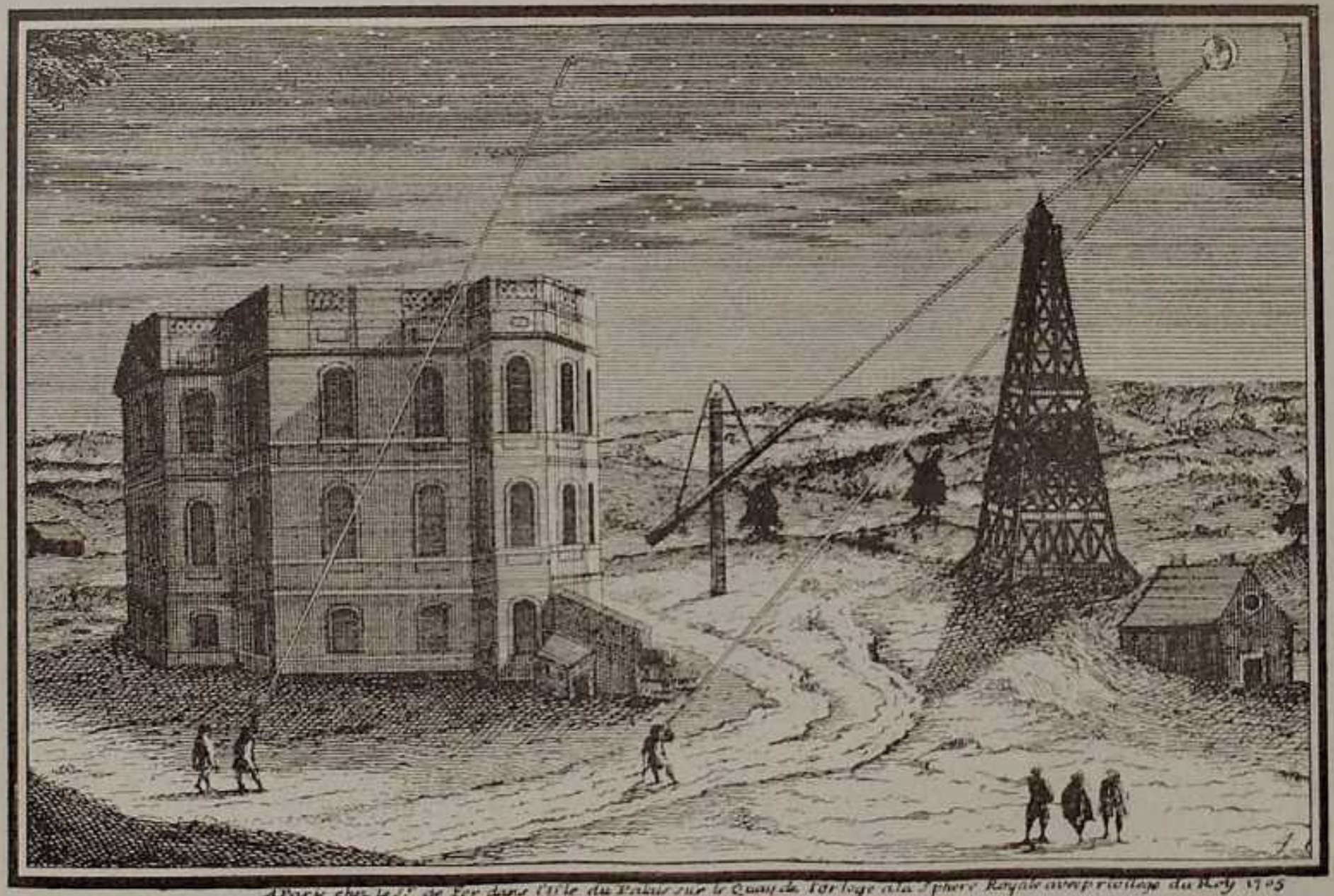
size and shape of Centaur Object 2002 GZ_{32}



Santos-Sanz *et al* 2019 submitted


Pluto System Impactors
Observed KBOs: Direct Detection
Model KBOs 1: Schlichting et al. (2013)
Model KBOs 2: Scale Asteroid Belt SFD
Stellar occultations:
Arimatsu et al. (2019)
Schlichting et al. (2012)
N(>D) [deg^{-2}]
KBO Diameter [km]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

WP5



LA TOUR DE MARLY A L'OBSERVATOIRE.

Thank you !

Lucky Star: results & beyond

Bruno Sicardy

LESIA/Observatoire de Paris
& Sorbonne Université

ESOP XXXVIII
Paris, France
29 Aug-03 Sep 2018

an ERC Advanced Grant project

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Lucky Star: results & beyond

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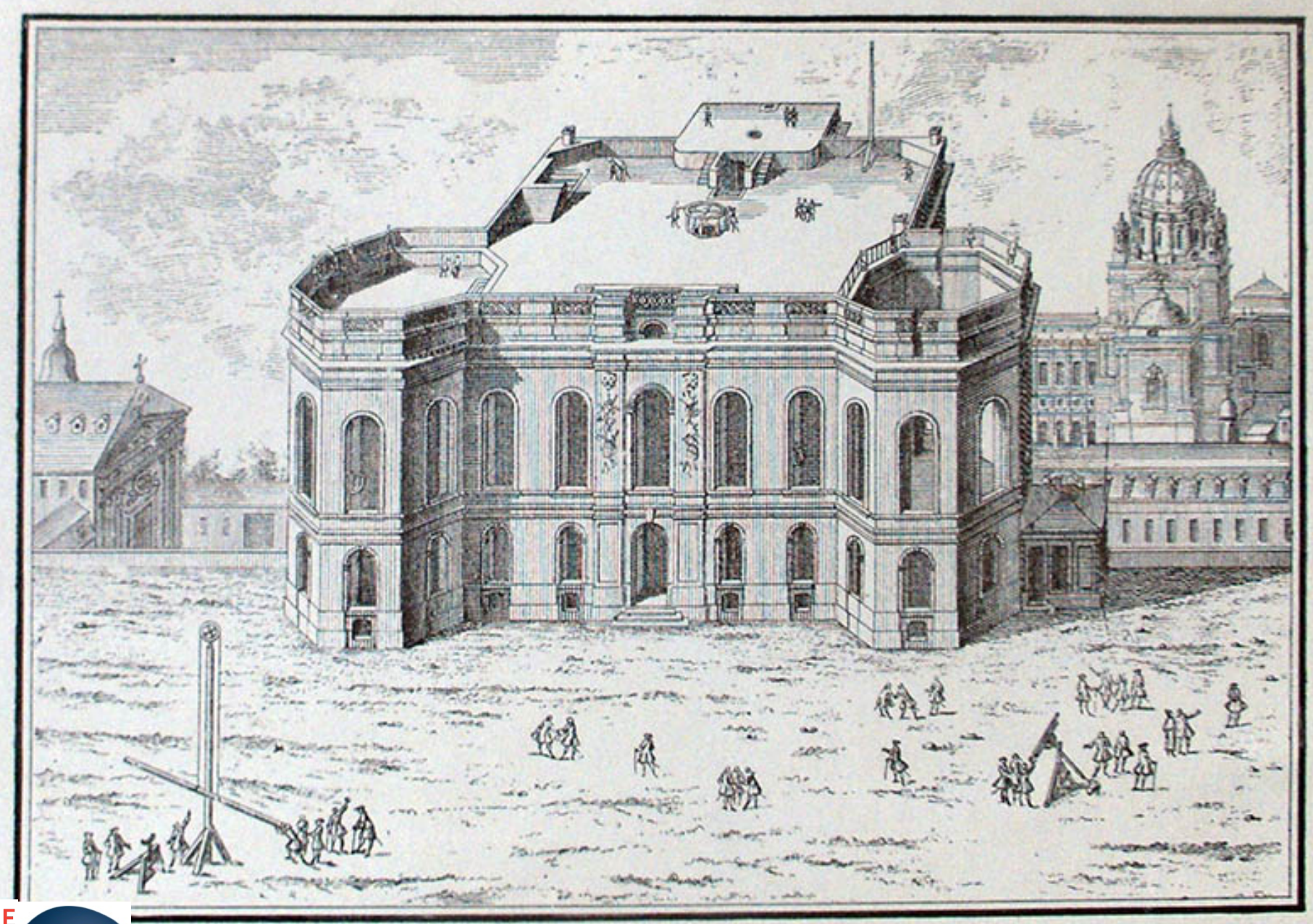

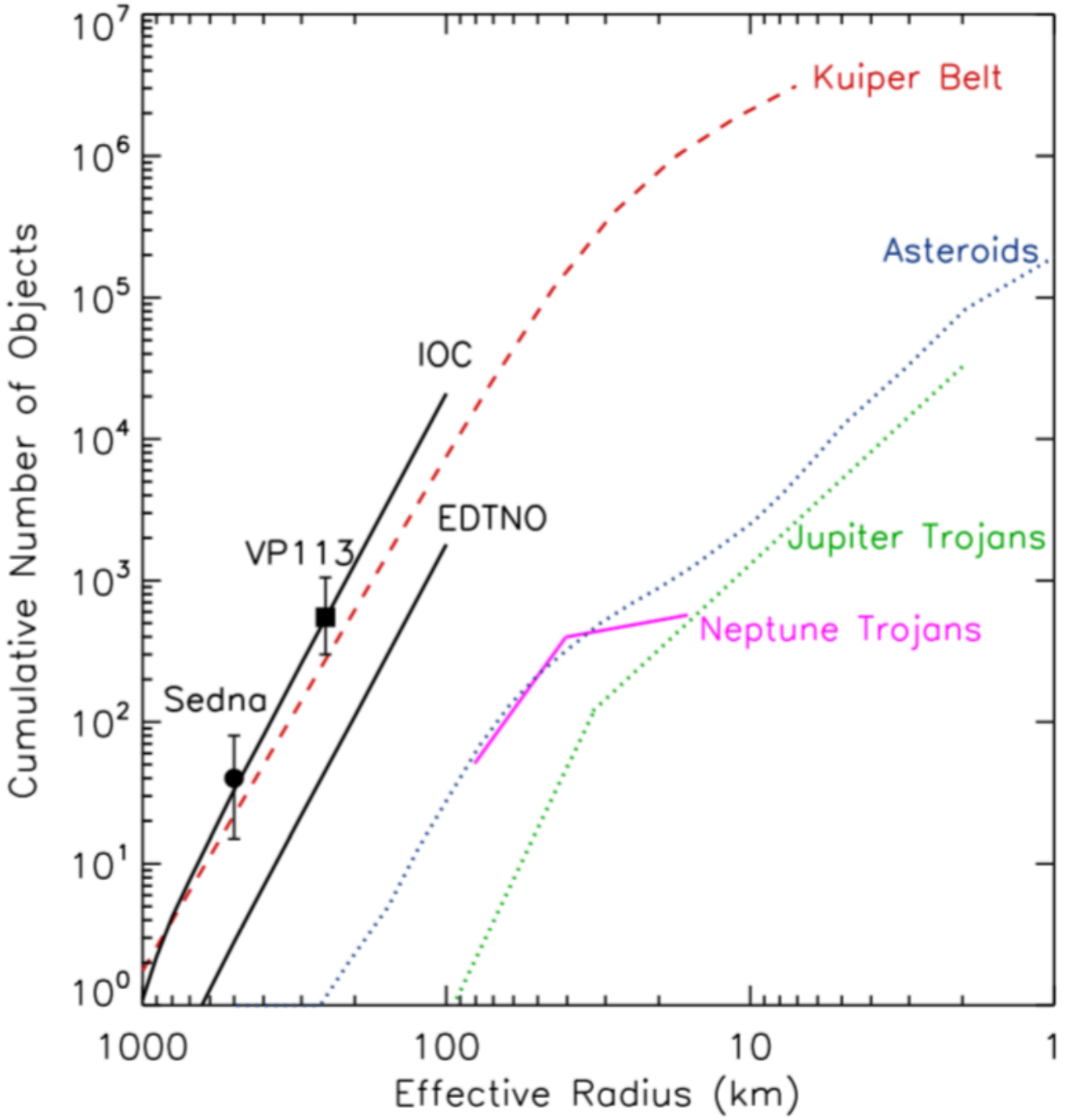

WP5

Sheppard & Trujillo 2016