Studying the Outer Solar System with Stellar Occultations

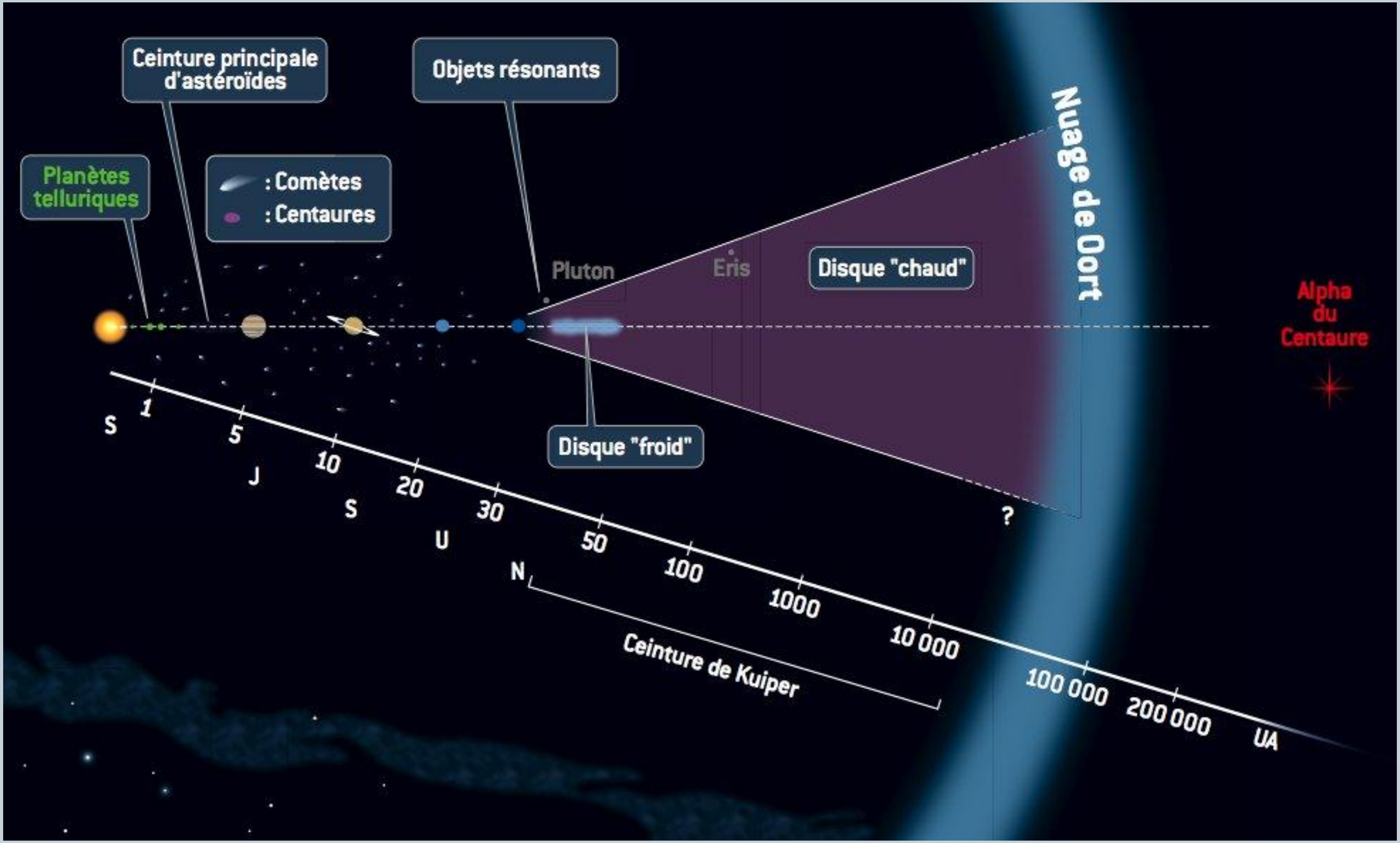
R. Vieira Martins, F. Braga-Ribas,
M. Assafin, J.I.B. Camargo, A. Dias de Oliveira, G. Rossi,
A. Gomes de Oliveira, D.N. da Silva Neto, A. Andrei

ON/MCT, OV/UFRJ, UEZO/RJ

International collaboration:
Bruno Sicardy – Observatoire Paris-Meudon
Jose Luis Ortiz – Instituto de Astrofísica de Andalucia

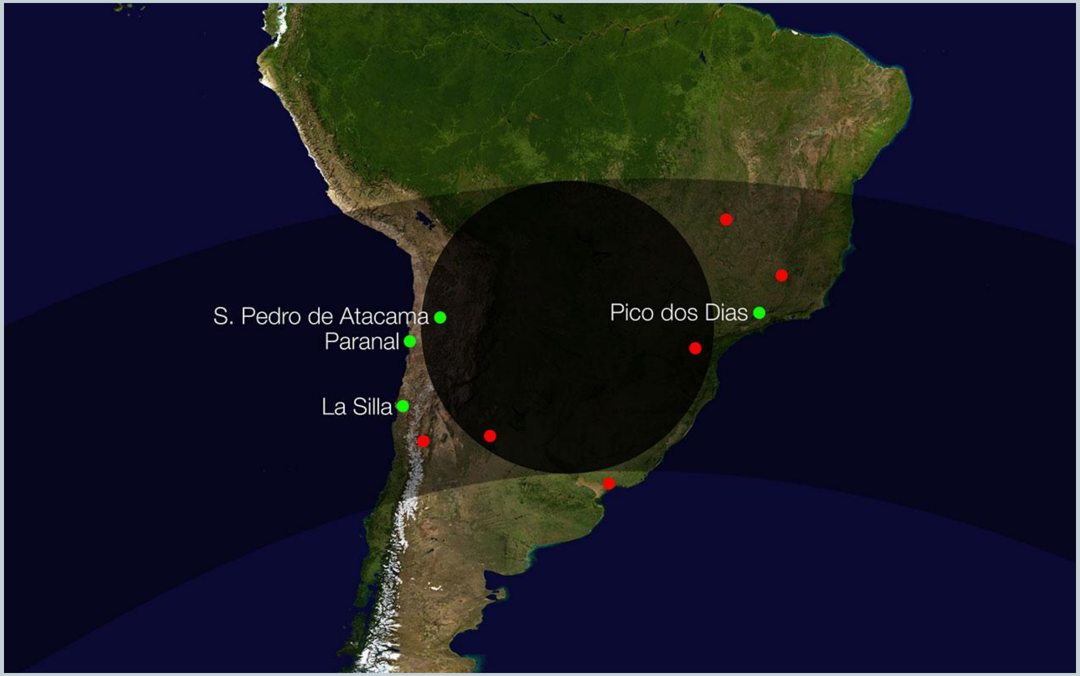
XVI CBDO -2012

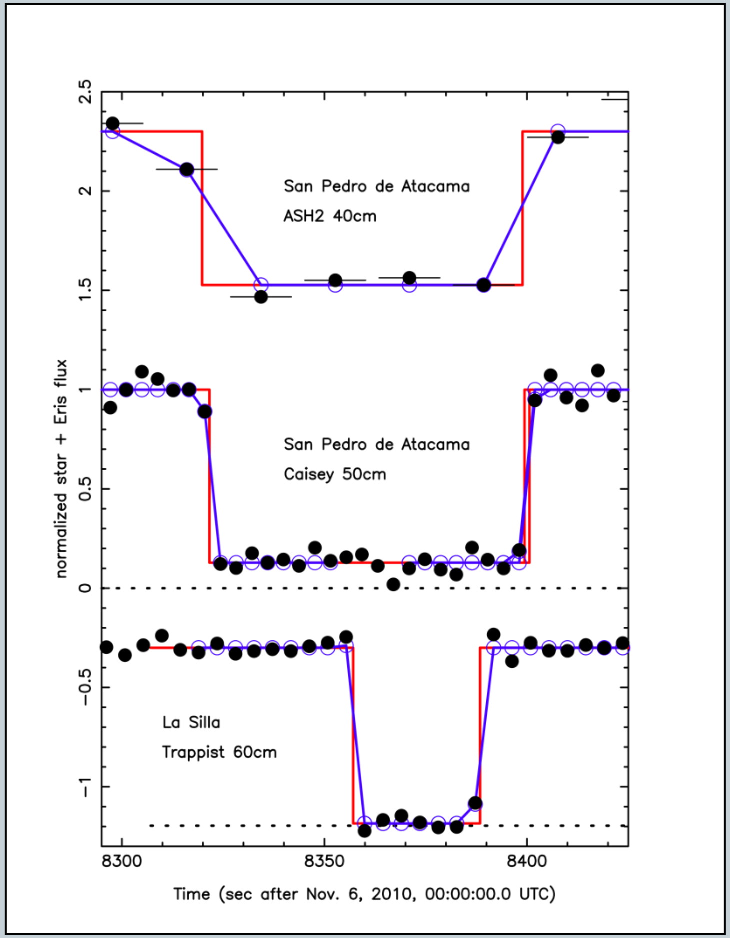
The Outer Solar System - TNOs

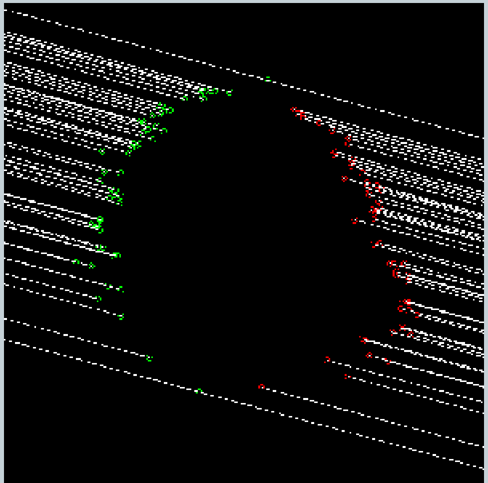


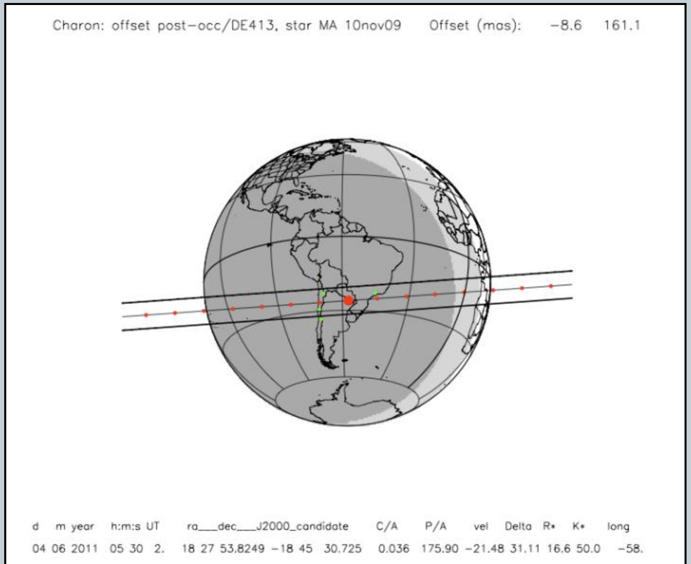
What are stellar occultations?

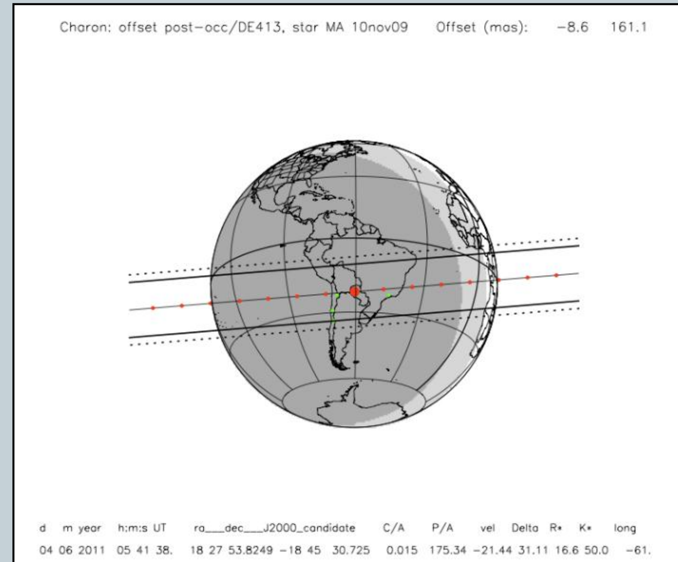
Object passing in front of a star.

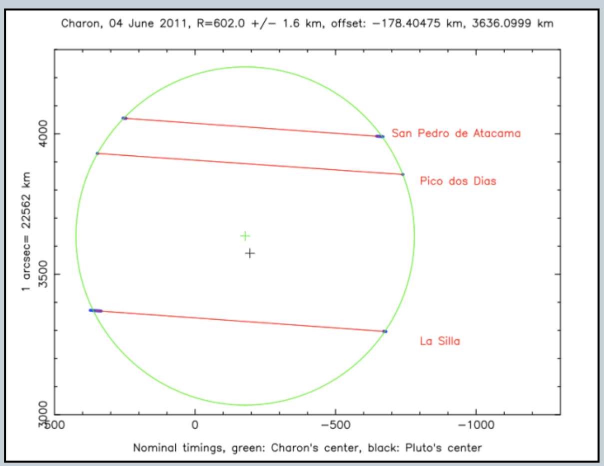


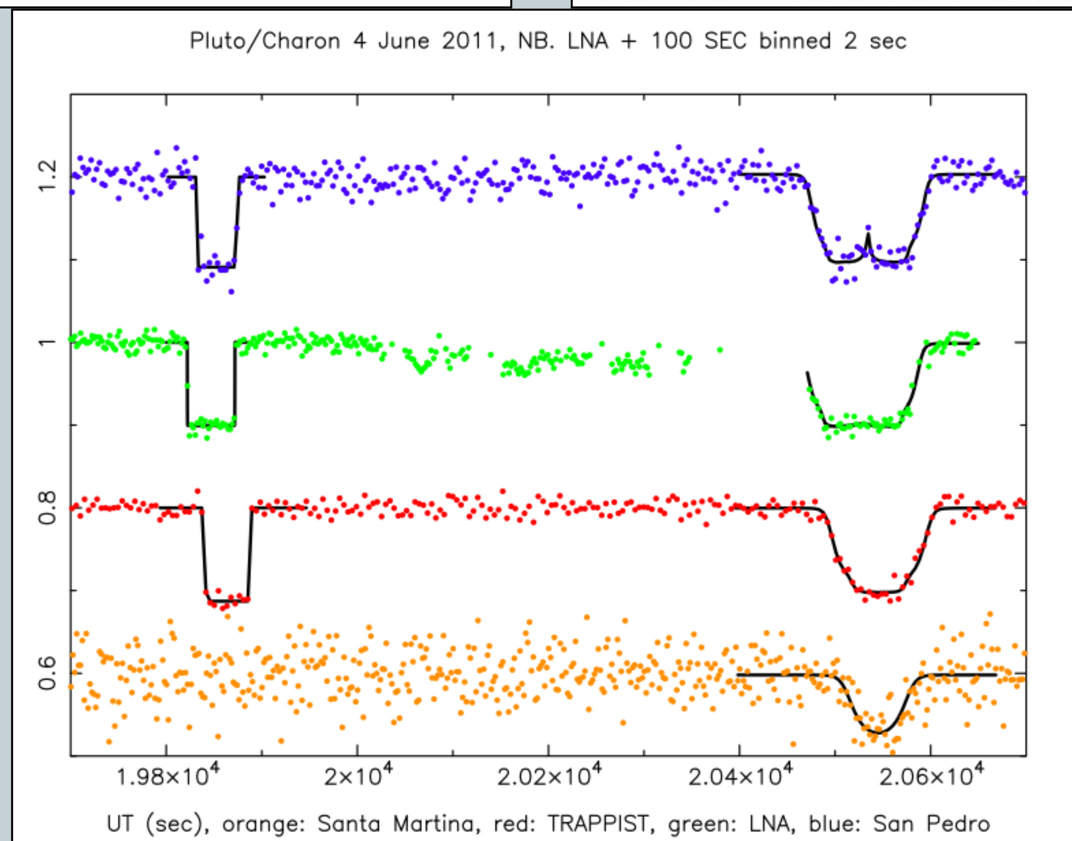





Charon: offset post-occ/DE413, star MA 10nov09 Offset (mas): -8.6 161.1
d m year h:m:s UT ra___dec___J2000_candidate C/A P/A vel Delta R* K* long
04 06 2011 05 30 2. 18 27 53.8249 -18 45 30.725 0.036 175.90 -21.48 31.11 16.6 50.0 -58.


Charon: offset post-occ/DE413, star MA 10nov09 Offset (mas): -8.6 161.1
d m year h:m:s UT ra___dec___J2000_candidate C/A P/A vel Delta R* K* long
04 06 2011 05 41 38. 18 27 53.8249 -18 45 30.725 0.015 175.34 -21.44 31.11 16.6 50.0 -61.


Charon, 04 June 2011, R=602.0 +/- 1.6 km, offset: -178.40475 km, 3636.0999 km
San Pedro de Atacama
Pico dos Dias
La Silla
1 arcsec= 22562 km
Nominal timings, green: Charon's center, black: Pluto's center

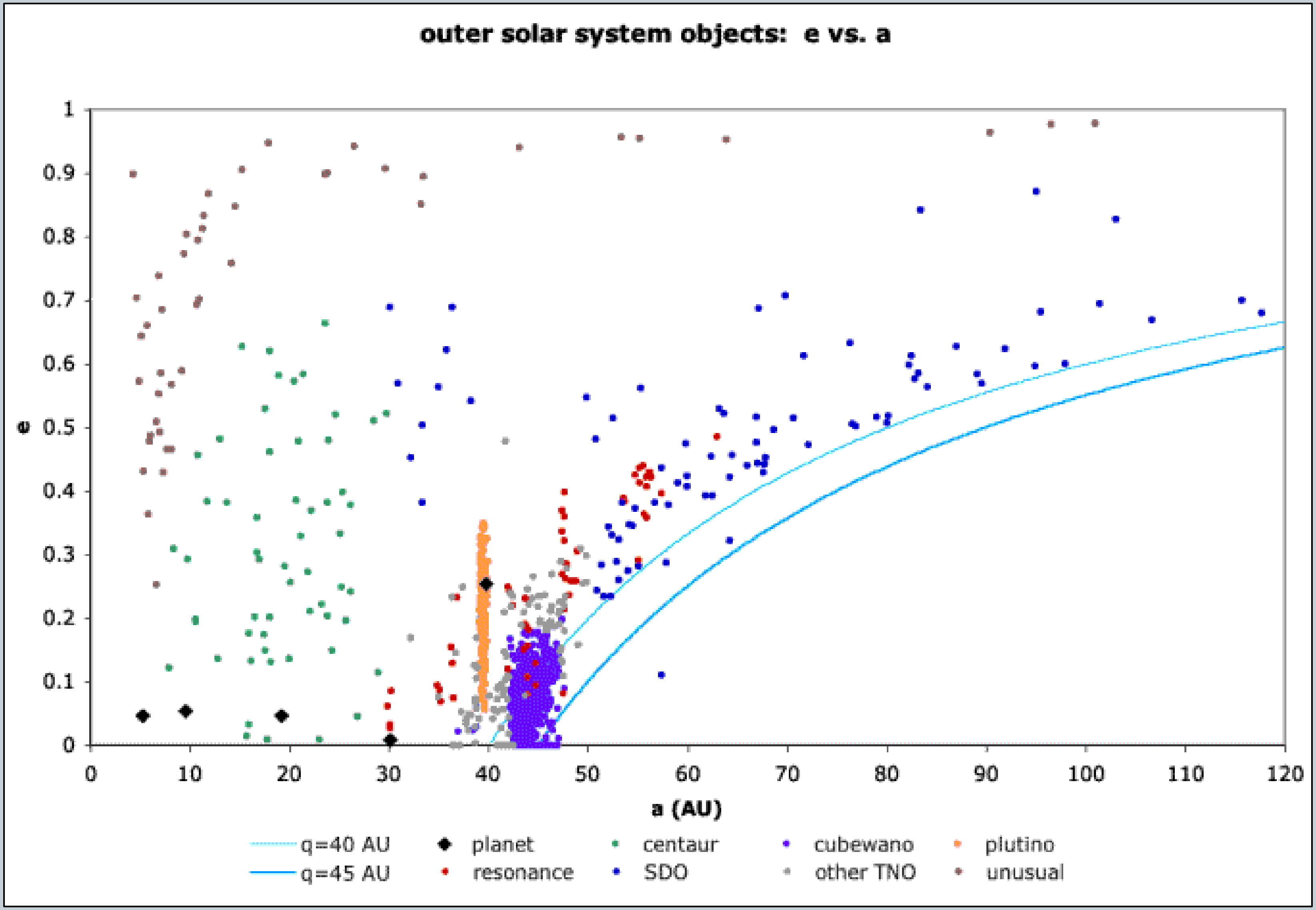

Pluto/Charon 4 June 2011, NB. LNA + 100 SEC binned 2 sec
1.2
1
0.8
0.6
1.98×10^4
2×10^4
2.02×10^4
2.04×10^4
2.06×10^4
UT (sec), orange: Santa Martina, red: TRAPPIST, green: LNA, blue: San Pedro

- **Context**

- **Stellar Occultations**

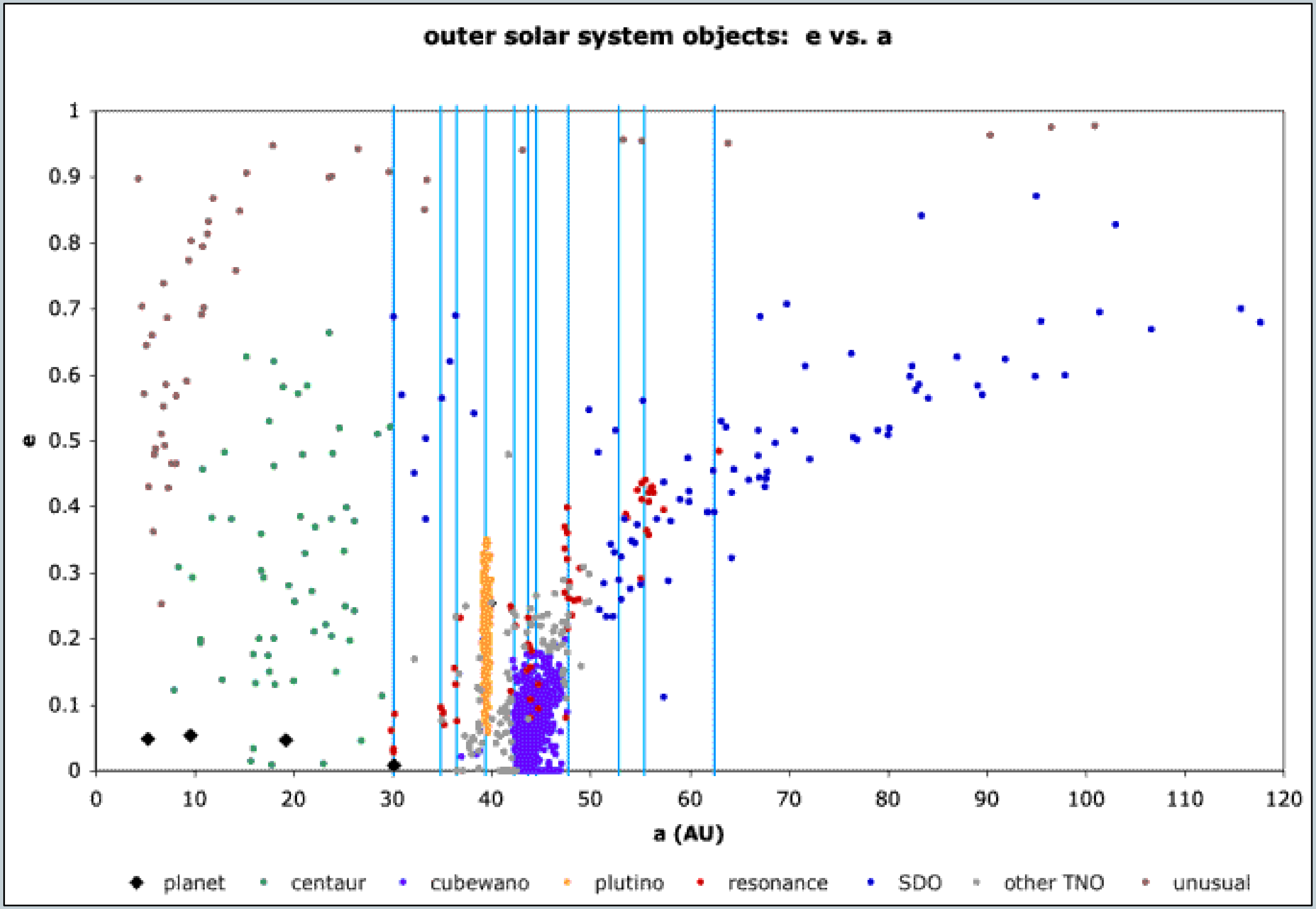
- **Results**

Context



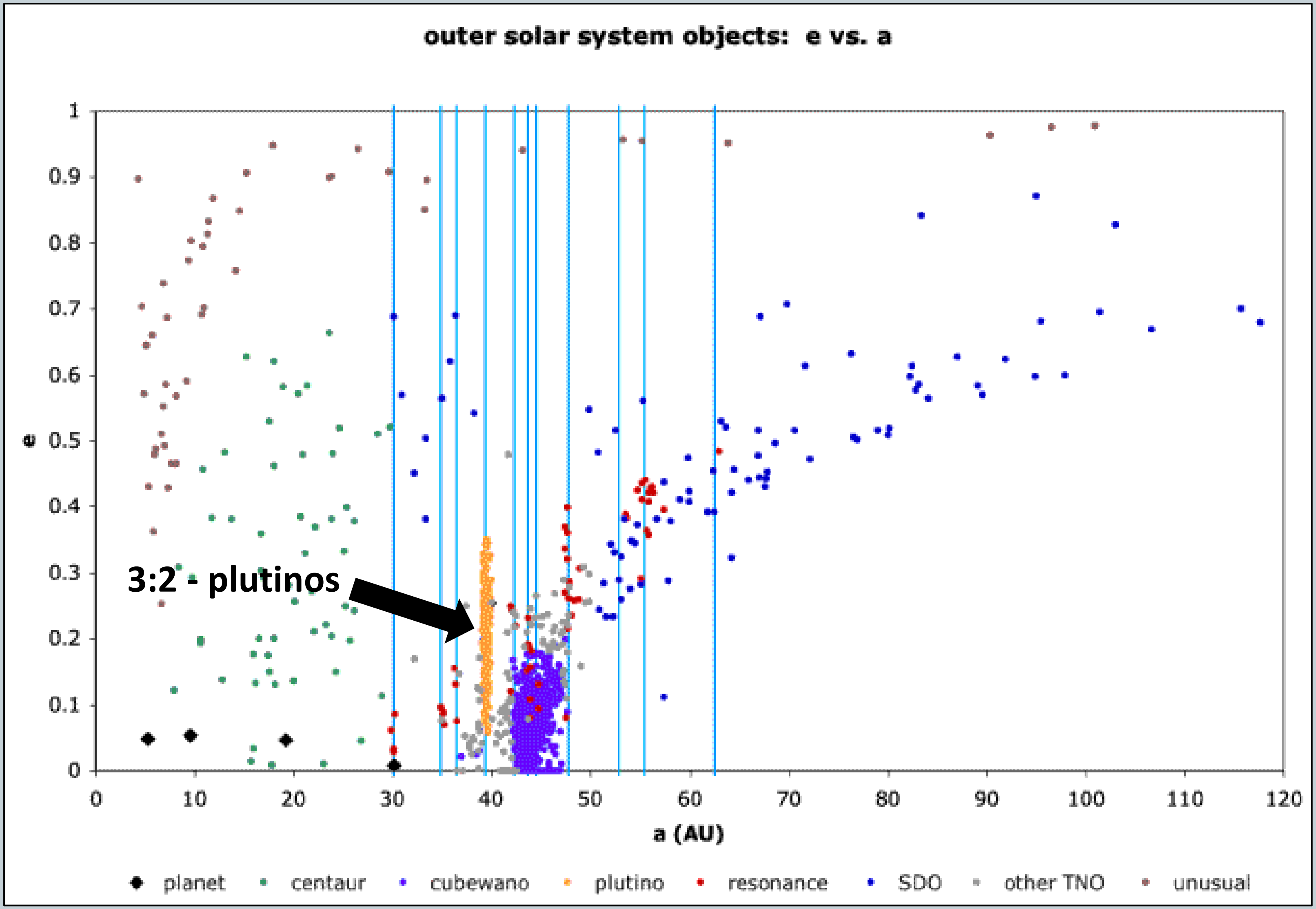
q = a (1 – e) = perihelion

Context



positions of the Neptune´s mean motion resonances

Context



outer solar system objects: e vs. a
e
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
110
120
a (AU)
3:2 - plutinos
planet
centaur
cubewano
plutino
resonance
SDO
other TNO
unusual

Context

a large number of TNOs associated to Neptune

+

Neptune growth time ≈ 10 millions years

⇓

TNOs growth time ≤ 10 millions years

-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-

small mass and large extend of the TNOs

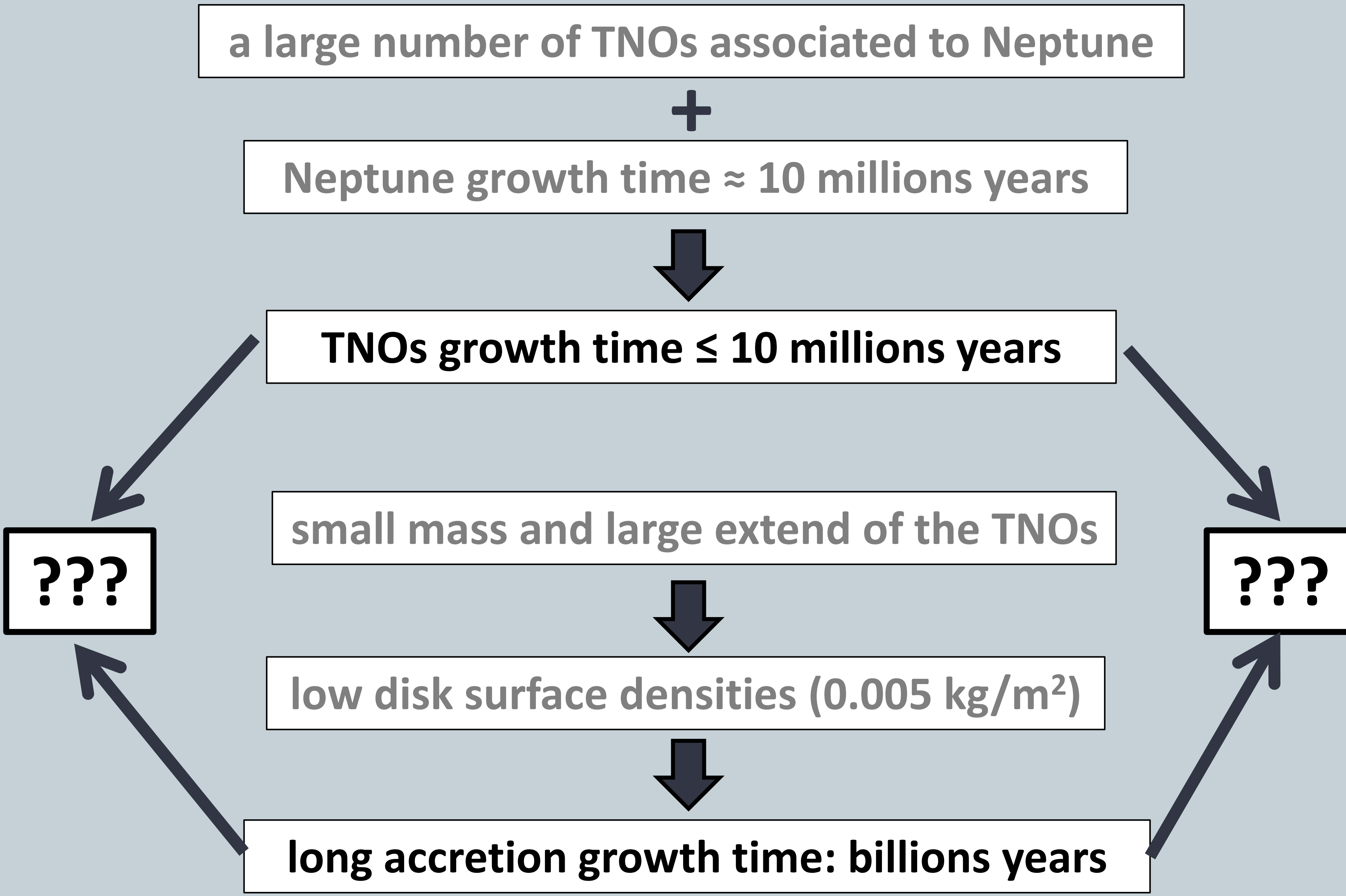
⇓

low disk surface densities (0.005 kg/m^2)

⇓

long accretion growth time: billions years

Context



a large number of TNOs associated to Neptune
+
Neptune growth time ≈ 10 millions years
TNOs growth time ≤ 10 millions years
???
small mass and large extend of the TNOs
low disk surface densities (0.005 kg/m²)
long accretion growth time: billions years
???

Context

??? –> three possibilities

1 - Growth rates was higher than believed in TNOs region.

2 - The primordial mass was 100 to 1000 times larger in the region.

3 - The TNOs was formed closer to the Sun and after they were transported to their current location.

What´s the good answer?

The TNOs store signings about their origin:

Dynamical features

orbital distribution

Physical features

- size
- form
- density
- surface
- atmosphere
- constitution

} **stellar occutations**

Stellar Occultations

What are stellar occultations?

Solar System object passing in front of a star.

Why occultations?

The other methods are indirect or expensive (mag. ≈20, size <0.1”).

Occultation disadvantages:

- rare;
- difficult prediction;
- event with fixed moment (meteorology).

120 km

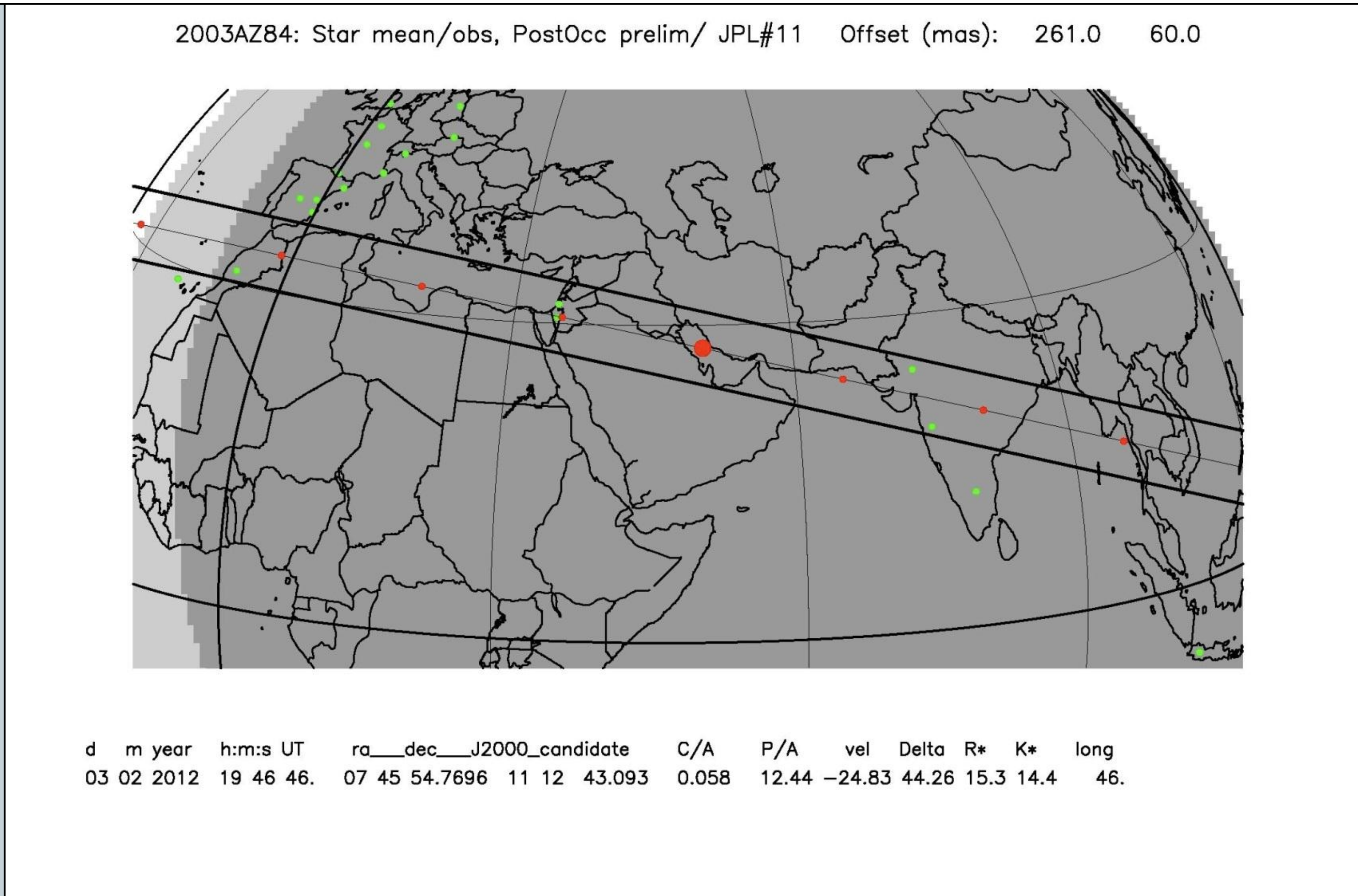
Occultation advantages:

- photometry;
- may be observed with small telescopes (depends only on the occulted star magnitude).

Stellar Occultations

Predictions

- years – star and TNO astrometry (accuracy: 50 mas);
- days – relative positions TNO-star (accuracy: 10 to 20 mas);
- observational campaign organization – global scale.



Results

<u>**Observed TNO occultations:**</u>

- Up to 2005: Pluto was the only TNO observed in an occultation;
- in 2005: the first Charon observation;
- in 2009: 2002 TX300 was observed (MIT);
- from 2009: 6 TNOs were observed (with our collaboration).

From the 12 ever observed occultations (from 8 different objects) by TNOs, we predicted 10 and observed 09.

<u>**This is due to the prediction work that we performed, we accurate astrometric prediction for the biggest TNOs**</u>**:**
- <u>ESO</u> – 2.2m telescope + Wied Field Imager (WFI);
- <u>LNA</u> – Large program.

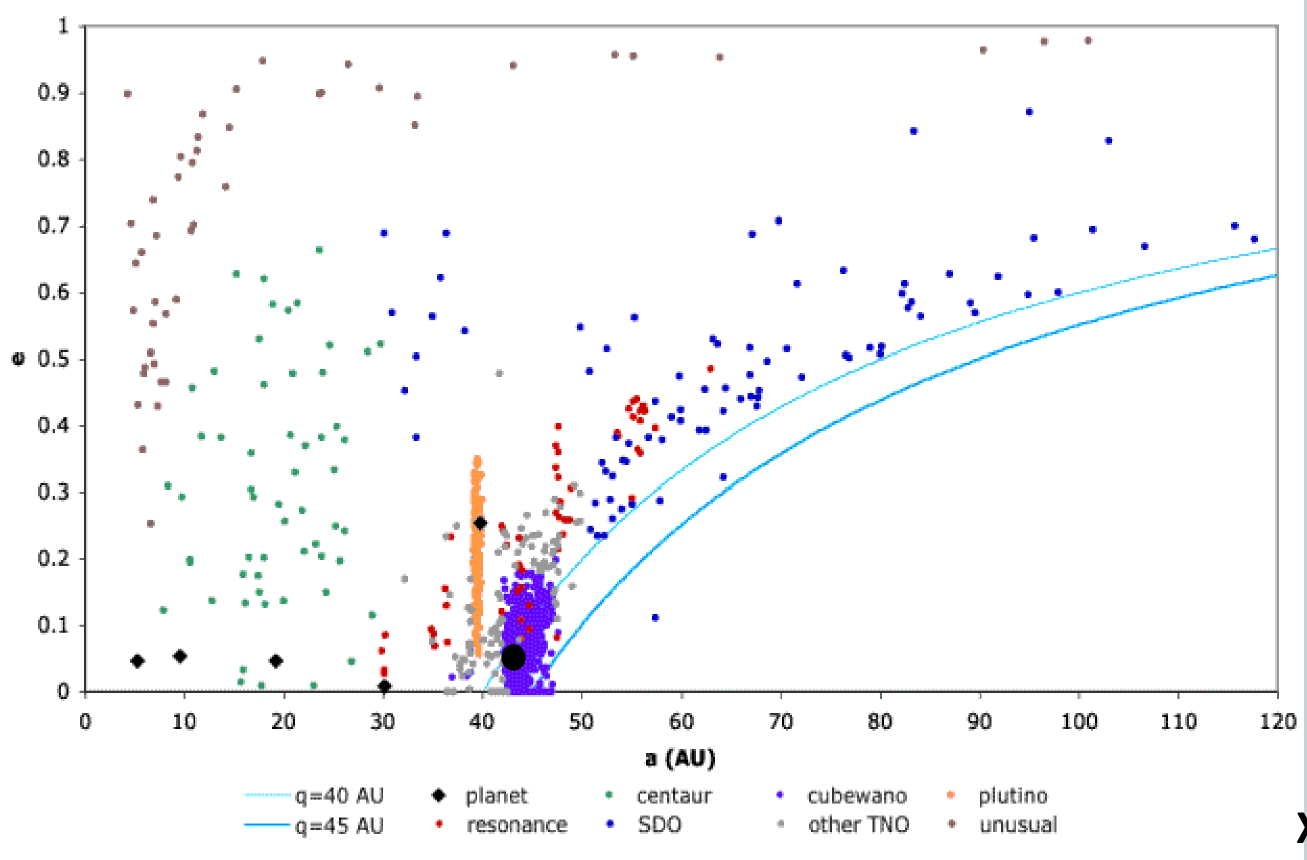
THE TNO OCCULTATION CAMPAIGNS

2003 AZ84, Ixion, 2002 TX300, Triton ...

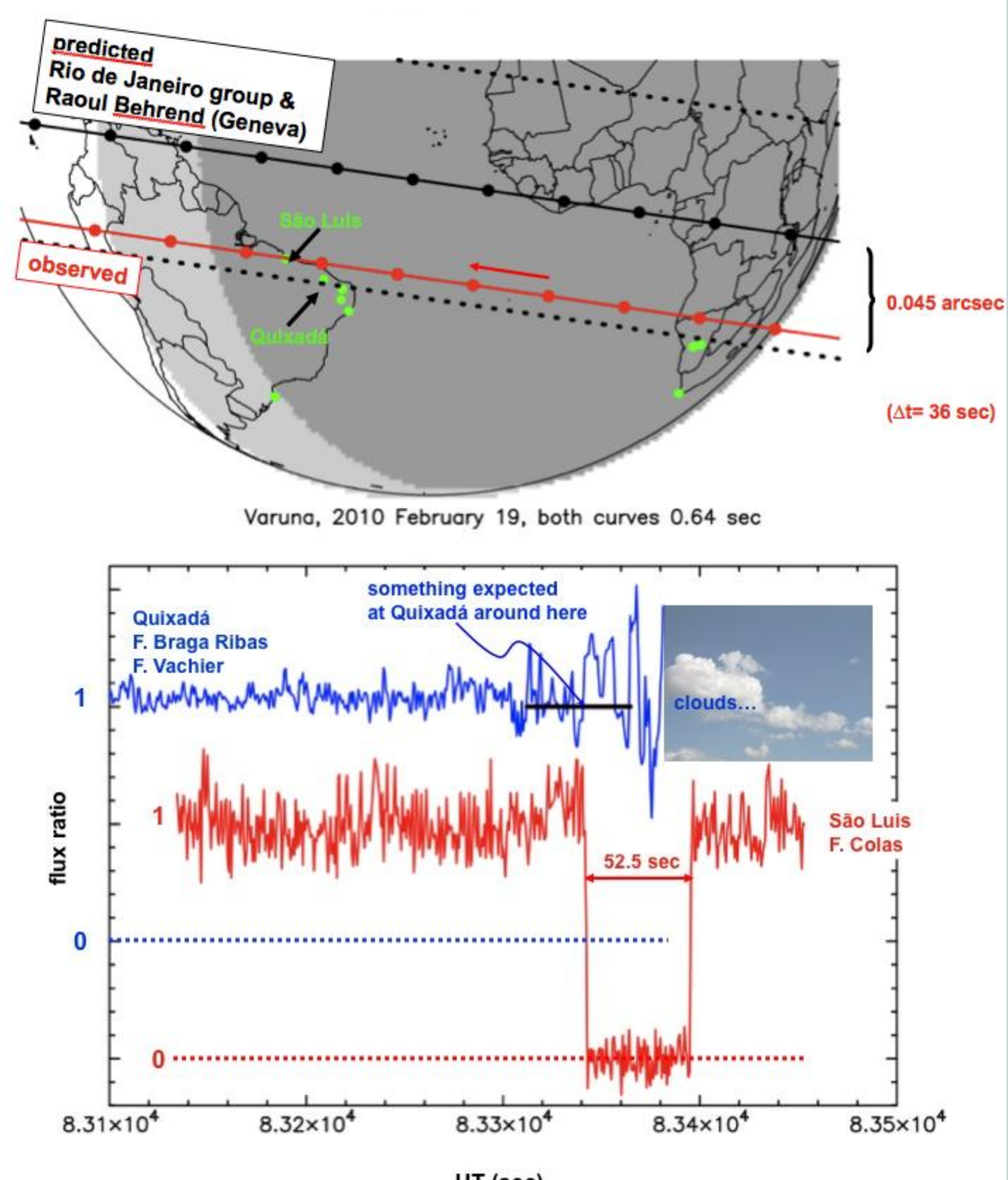
Results: Varuna

Varuna => hot classical
a = 67.7 AU, e = 0.44, i = 44°
- Now @ 42 AU;
- no satellite;
- V magnitude = 19.9

- occultation: 19/02/2009
- Northeast of Brazil
- Star mag = 11.1;
-Chords = 1+, > 4 -;
- telescopes: 0.125m, 0.3m.

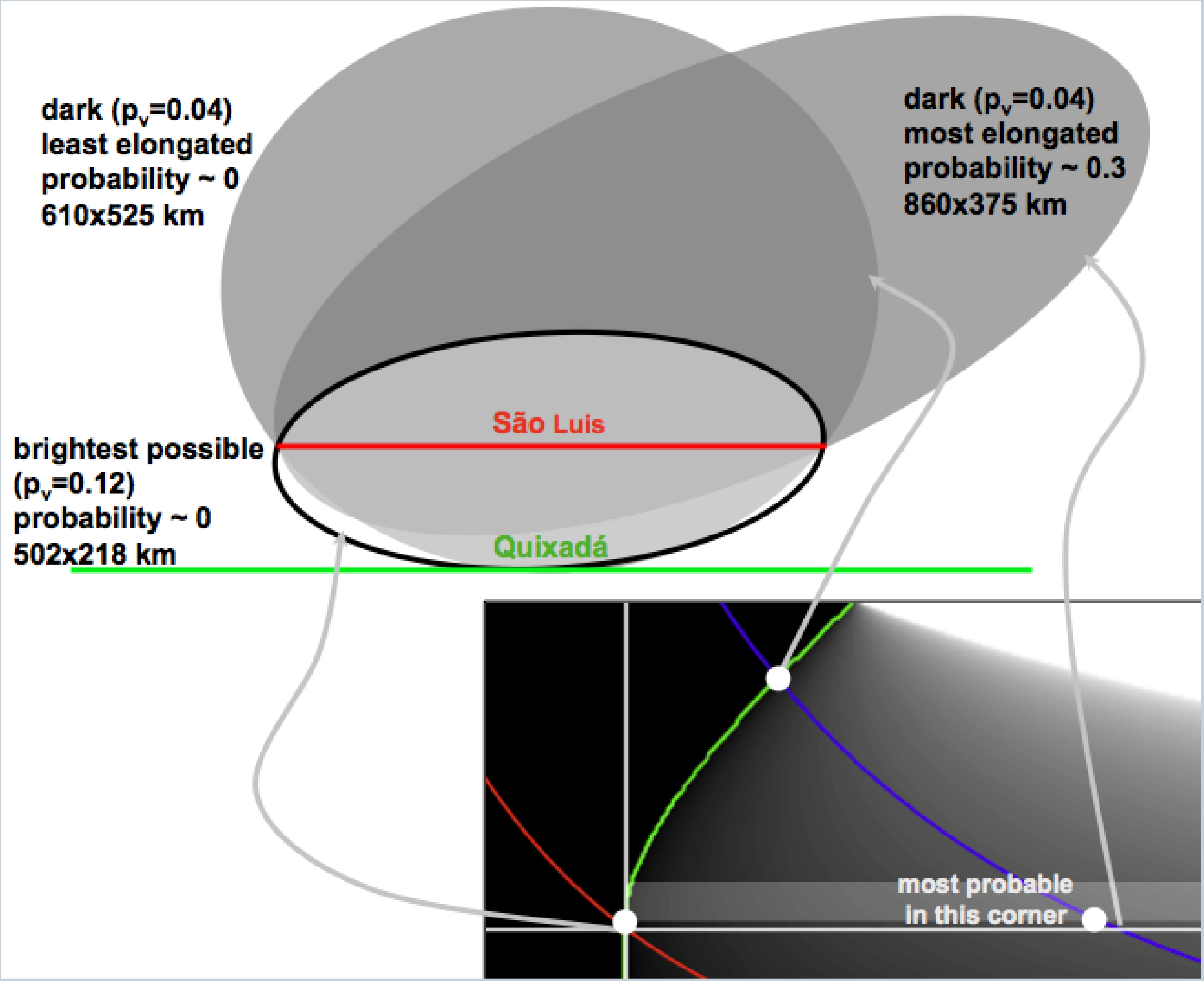


Results: Varuna



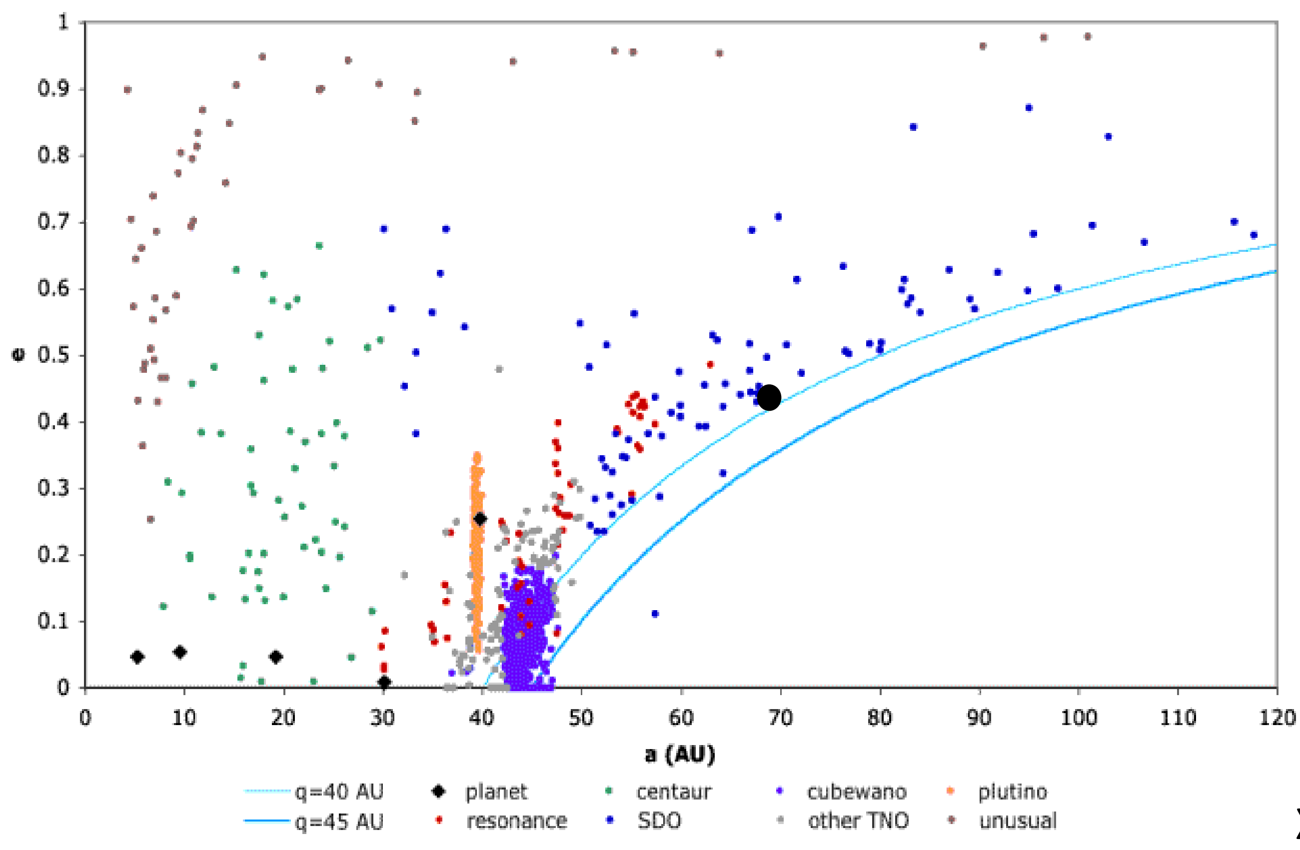
SICARDY, B., et al. The 2010, February 19 stellar occultation by Varuna In: AAS, **DPS meeting**, 2010, **Bulletin of the American Astronomical Society**, 2010. v.42. p.993

Results: Varuna



Results: Eris

<u>ERIS</u> => scattered disk **a = 67.7 AU, e = 0.44, i = 44°** **- <u>Now @ 97 AU</u>;** **- 1 satellite;** **- V magnitude = 18.7**	**- occultation: 06/11/2010** **- Chile** **- Star mag. = 17.1** **- Chords = 3 + (=2), 1 -** **- Teles.: 0.5m, 0.6m, 2.0m**



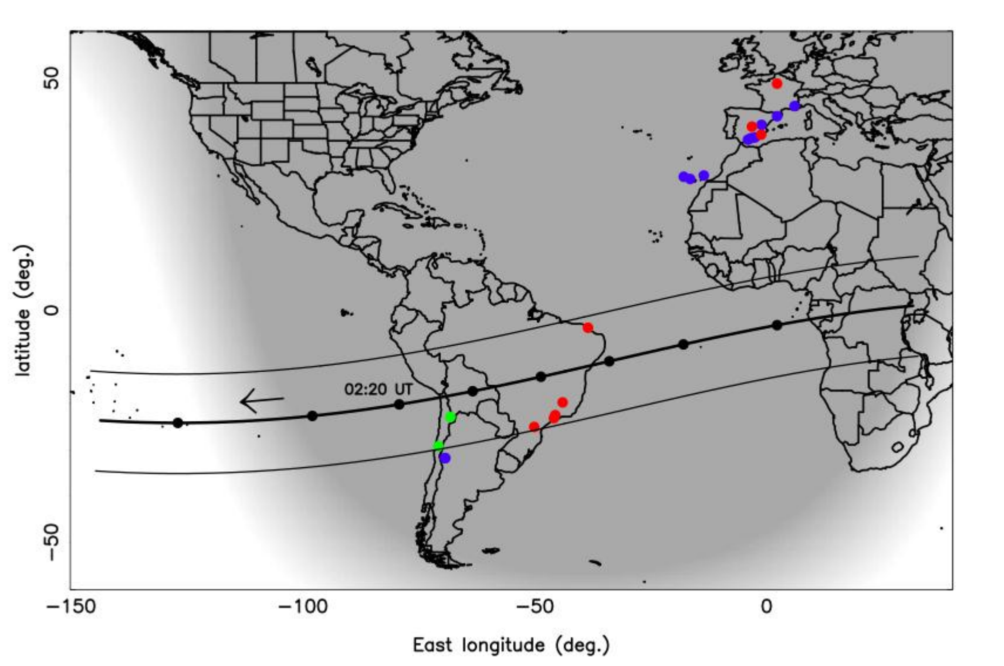
Results: Eris

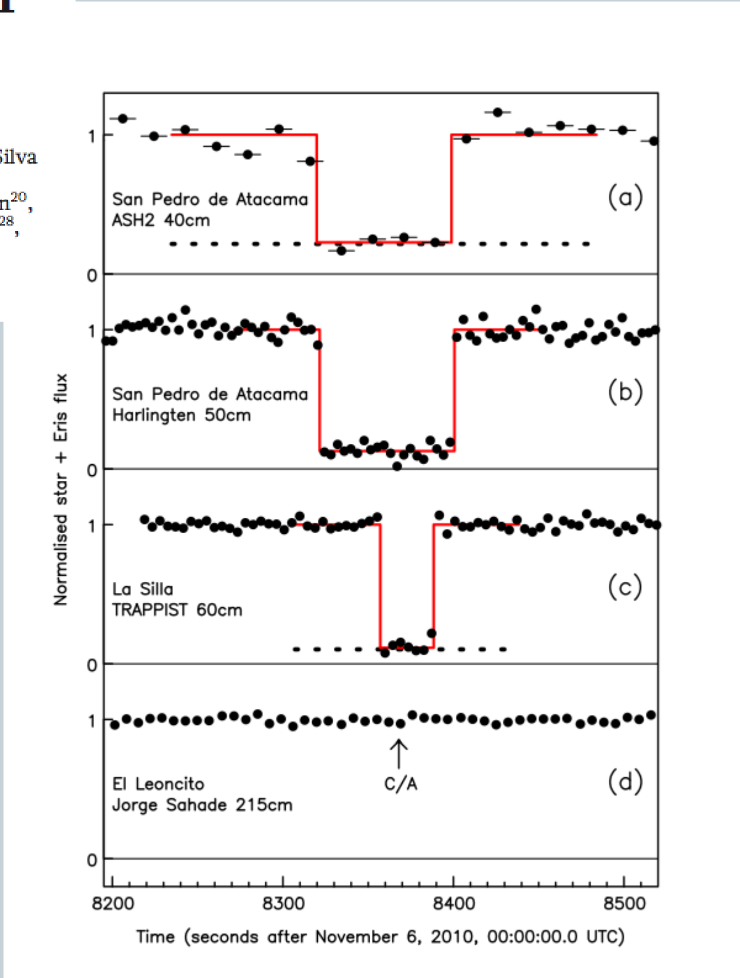
LETTER

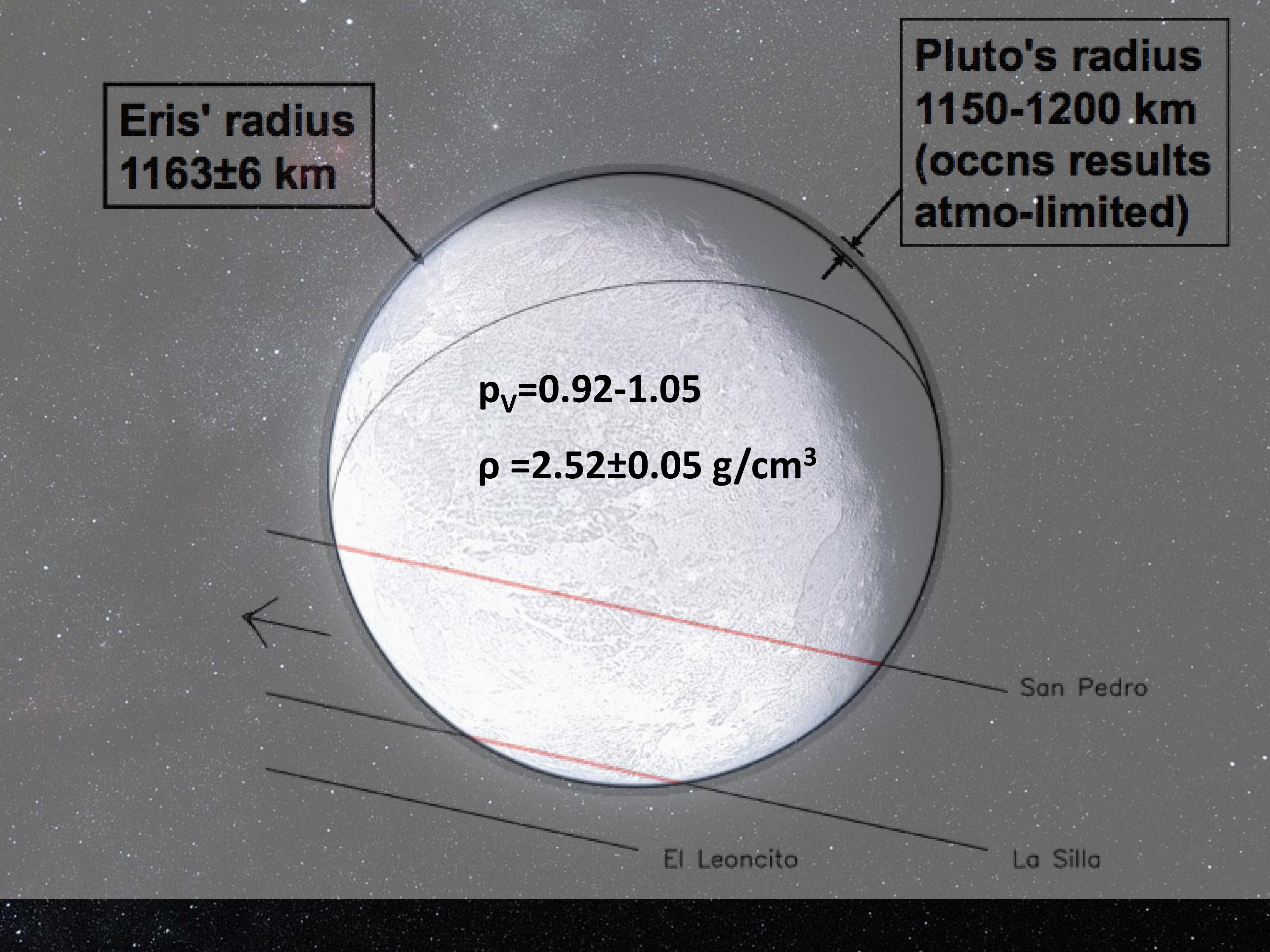
doi:10.1038/nature10550

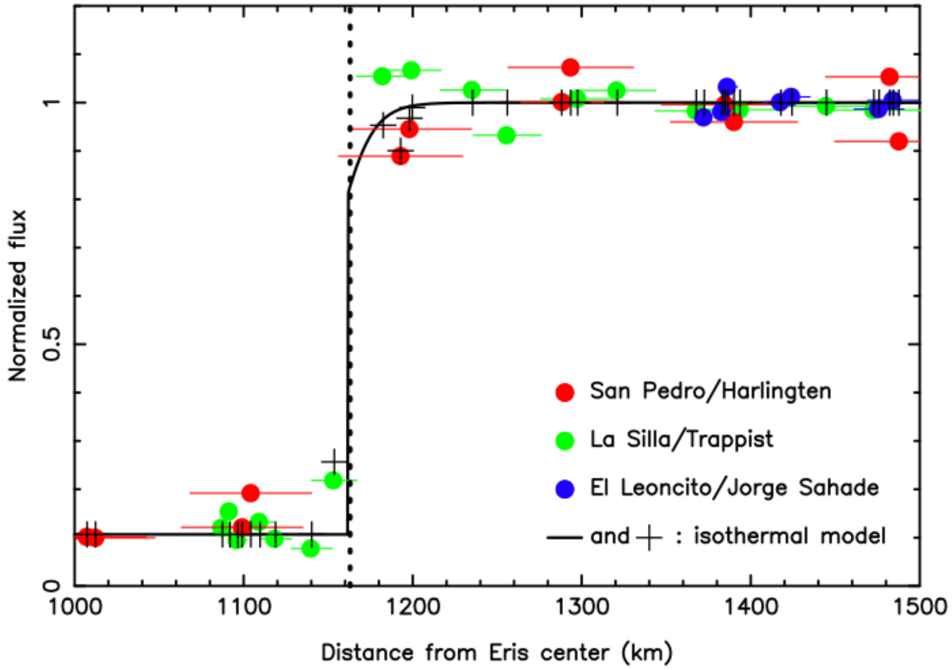
A Pluto-like radius and a high albedo for the dwarf planet Eris from an occultation

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]

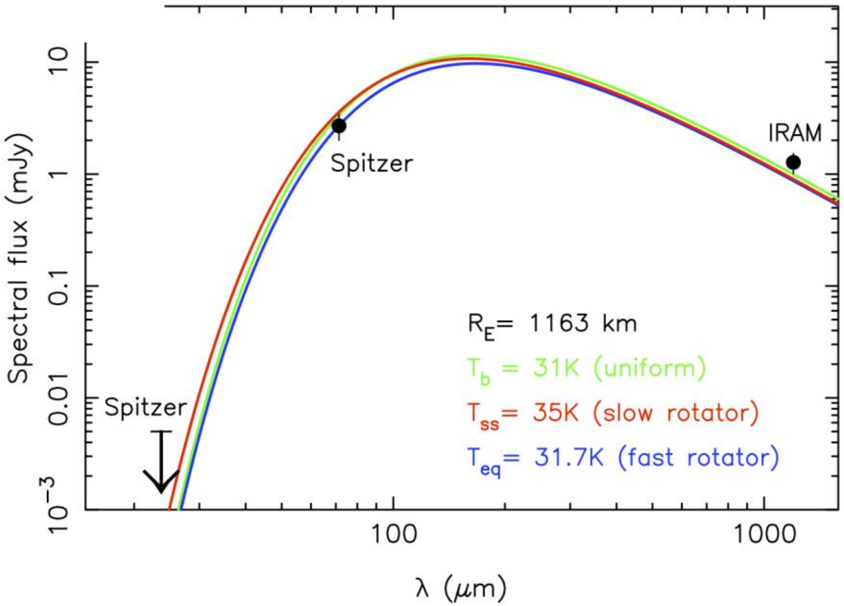





Eris' radius
1163±6 km
Pluto's radius
1150-1200 km
(occns results
atmo-limited)
pV=0.92-1.05
ρ =2.52±0.05 g/cm3
San Pedro
El Leoncito
La Silla

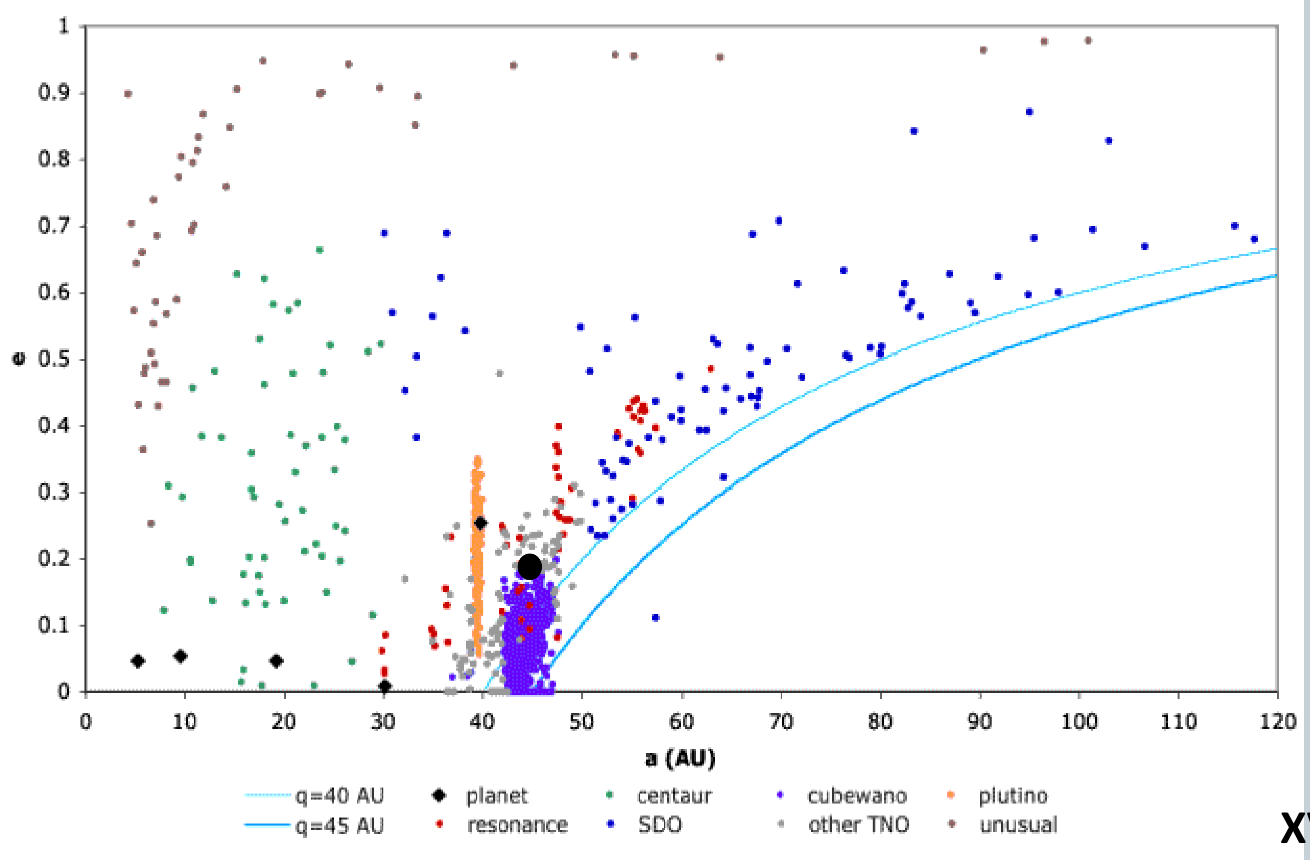


atmospheric limit of N_2, CH_4, Ar
~ 1 nanobar ($10^{-4} \times$ Pluto atmosphere)

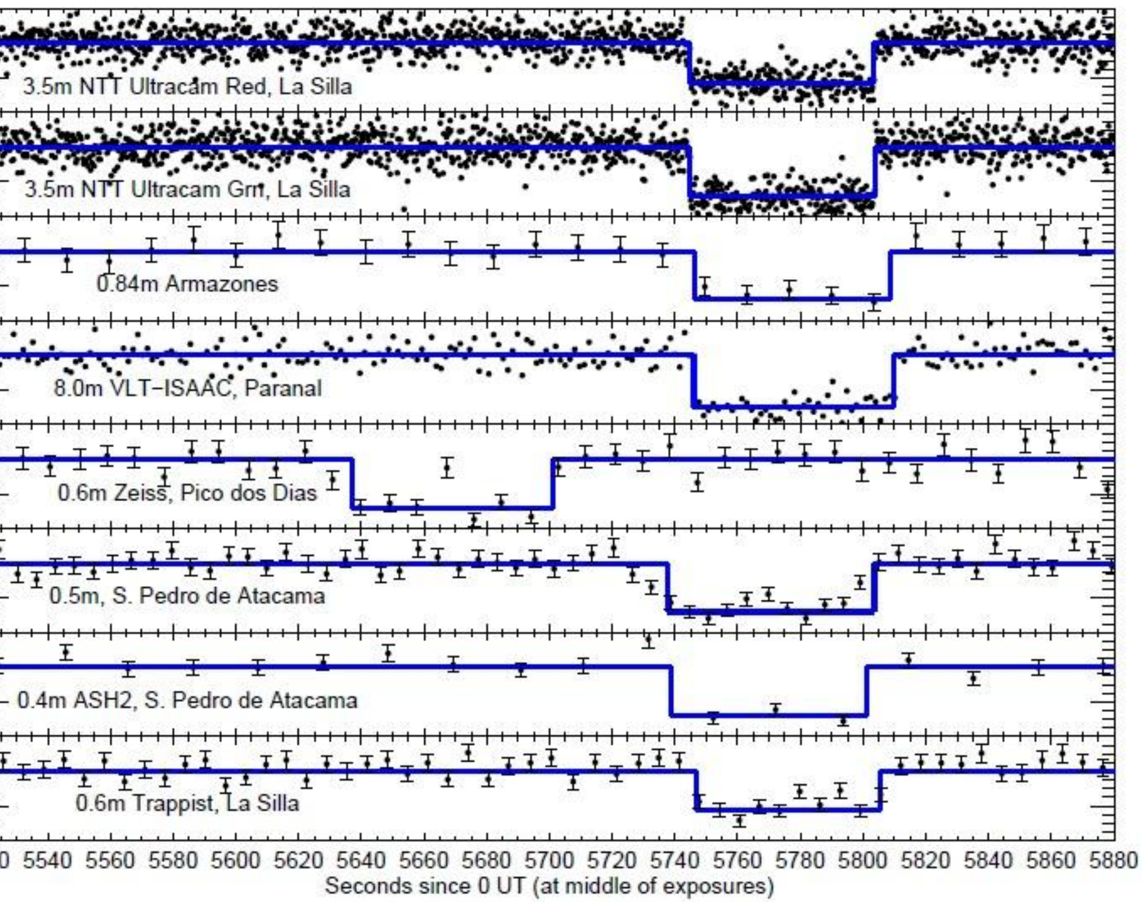


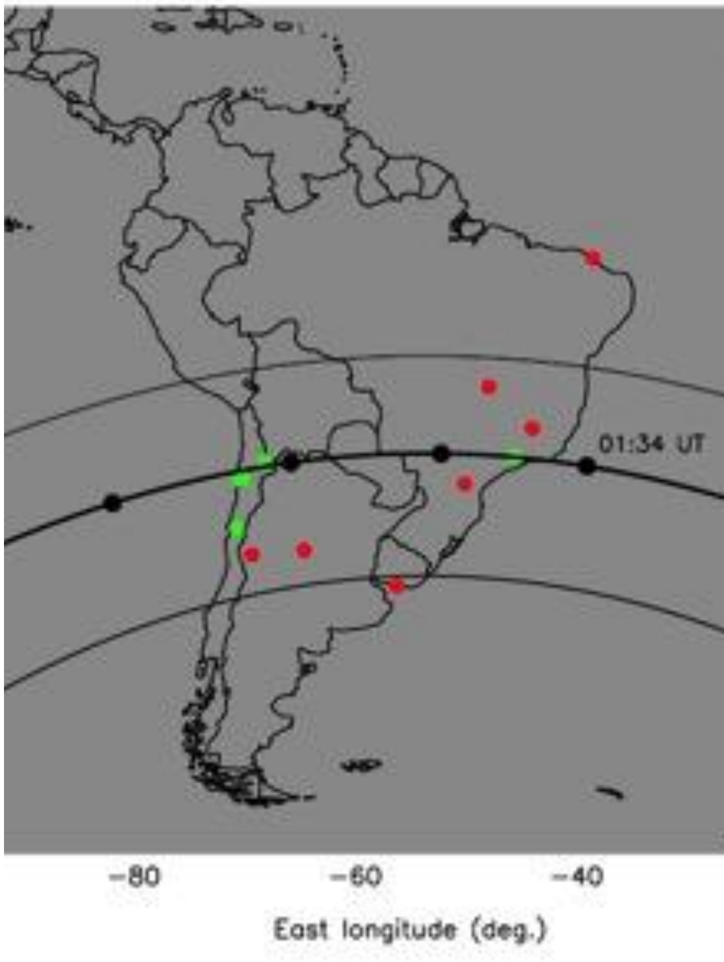
Results: Makemake

Makemake => hot classical a = 45.8 AU, e = 0.16, i = 30° - Now @ 52 AU; - no satellite; - V magnitude = 16.7	- occultation: 23/04/2011 - Chile, Brazil - Star mag. = 18.4 - Chords = 7 + (=5), 9 - ; - Teles.: 7 (from 0.4m to 8m)

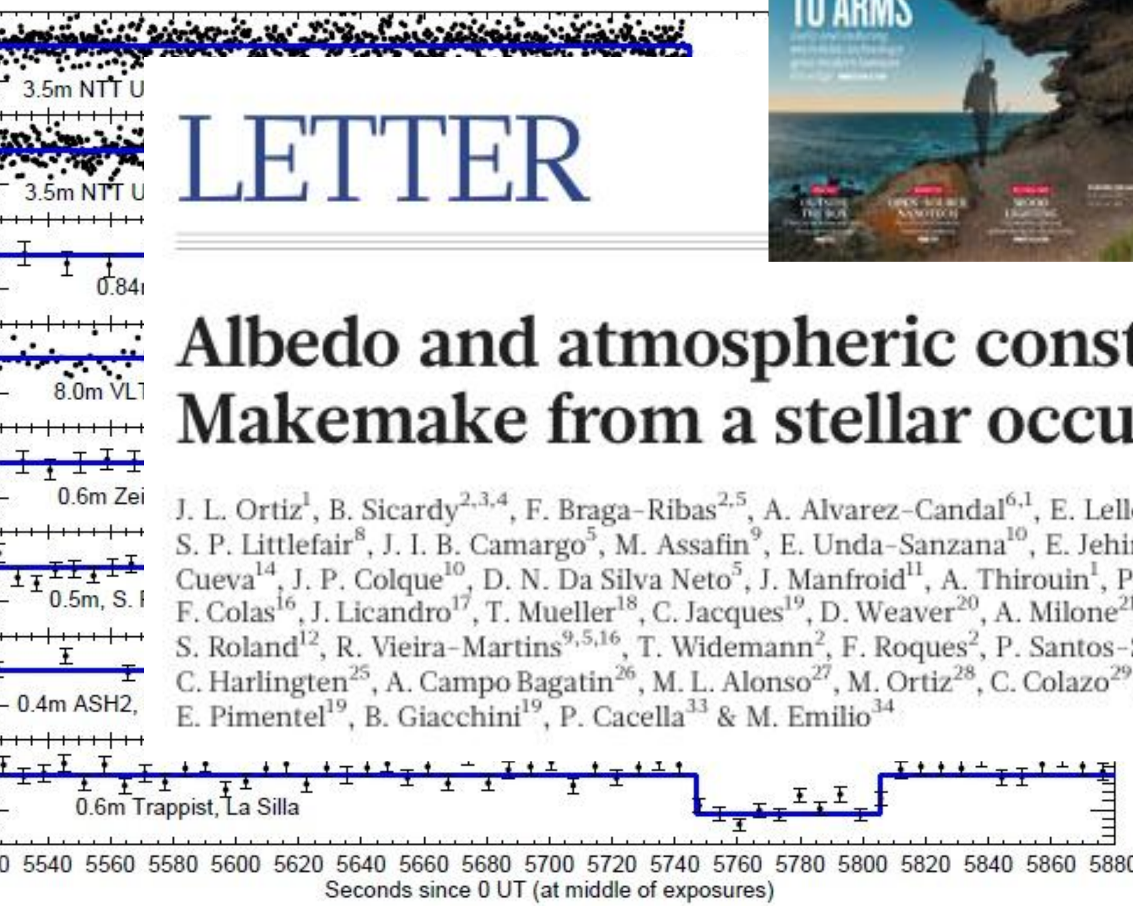


Results: Makemake





Results: Makemake

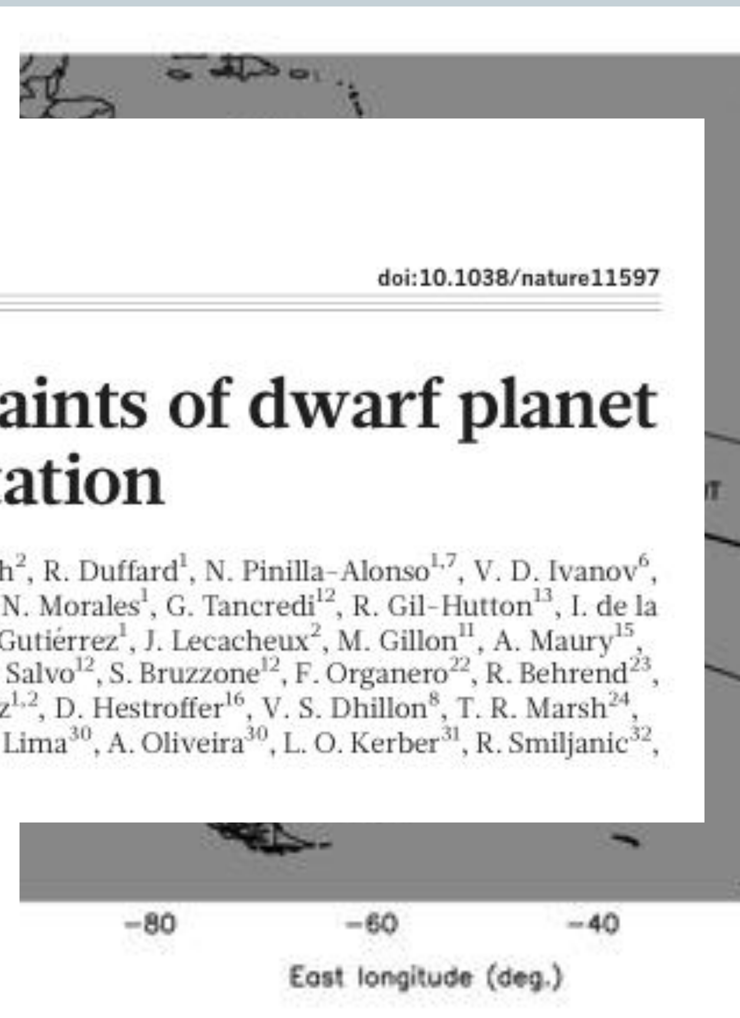


LETTER

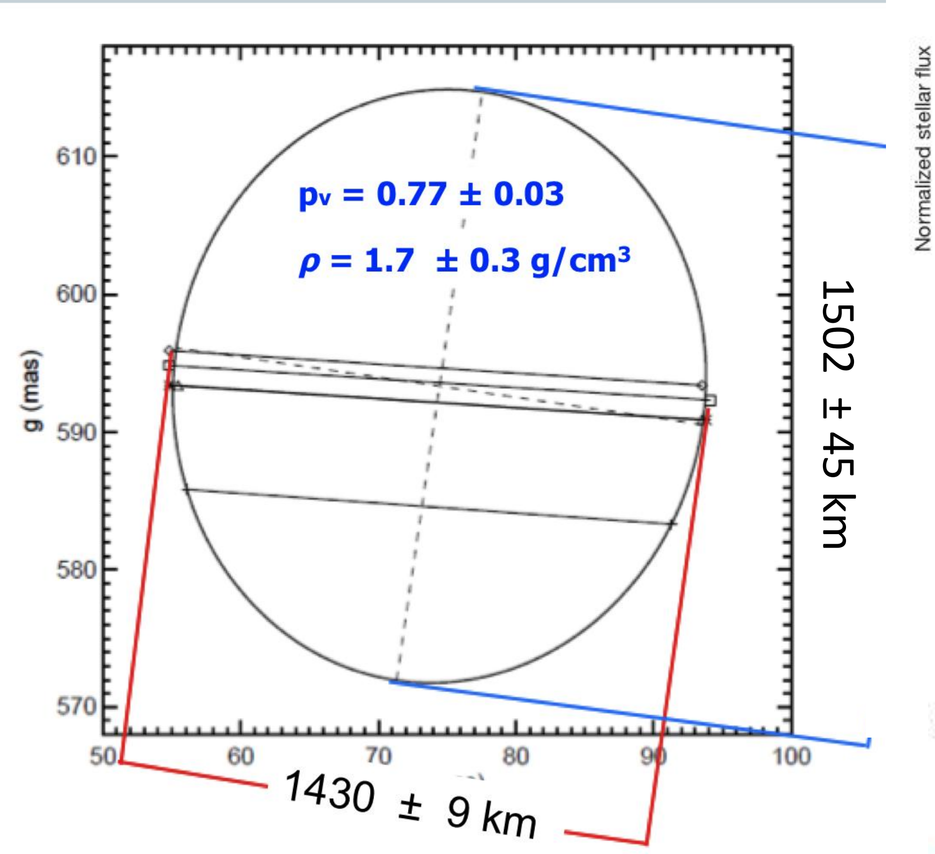
doi:10.1038/nature11597

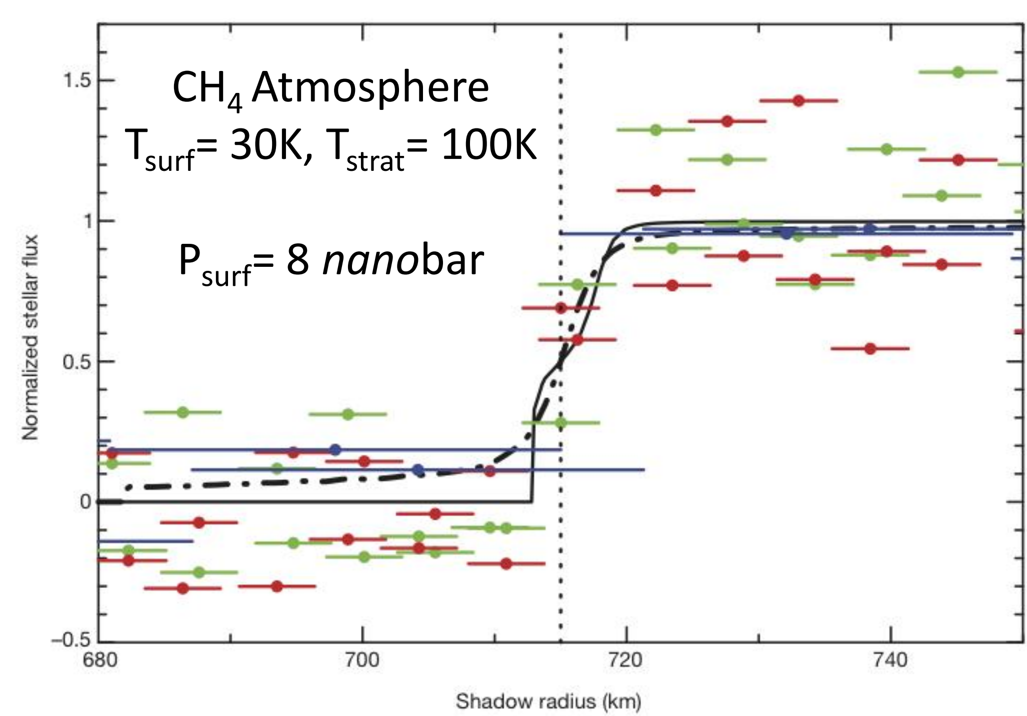
Albedo and atmospheric constraints of dwarf planet Makemake from a stellar occultation

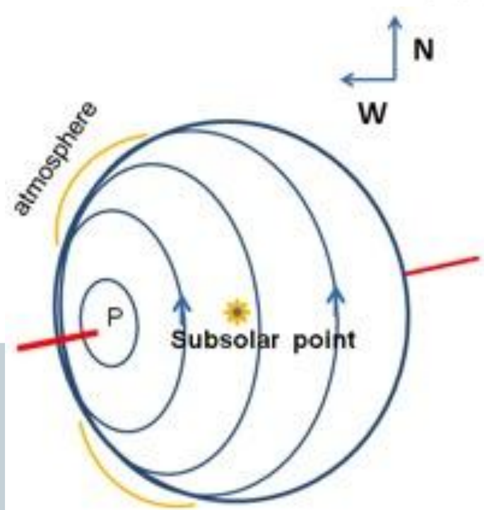
J. L. Ortiz[1], B. Sicardy[2,3,4], F. Braga-Ribas[2,5], A. Alvarez-Candal[6,1], E. Lellouch[2], R. Duffard[1], N. Pinilla-Alonso[1,7], V. D. Ivanov[6], S. P. Littlefair[8], J. I. B. Camargo[5], M. Assafin[9], E. Unda-Sanzana[10], E. Jehin[11], N. Morales[1], G. Tancredi[12], R. Gil-Hutton[13], I. de 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. Lima[30], A. Oliveira[30], L. O. Kerber[31], R. Smiljanic[32], E. Pimentel[19], B. Giacchini[19], P. Cacella[33] & M. Emilio[34]

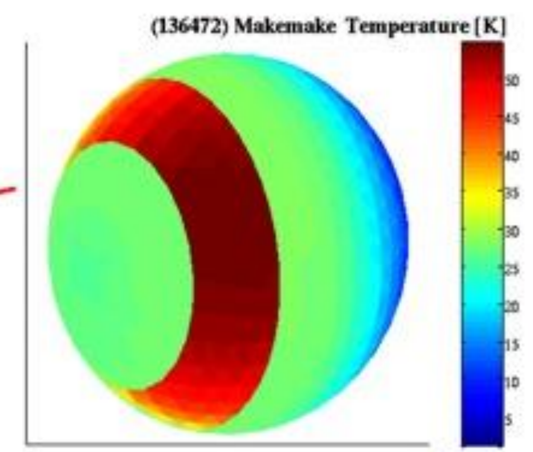


Results: Makemake



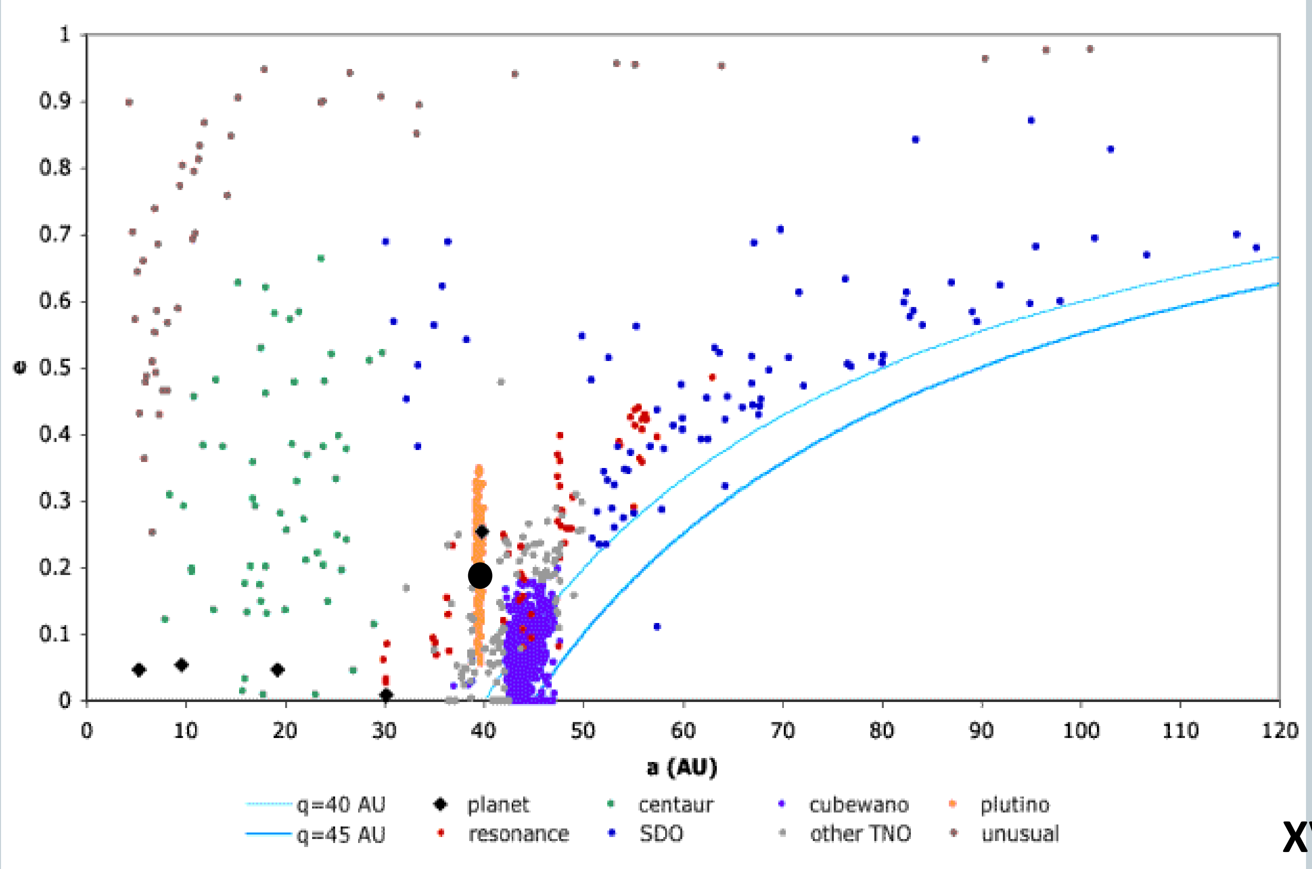




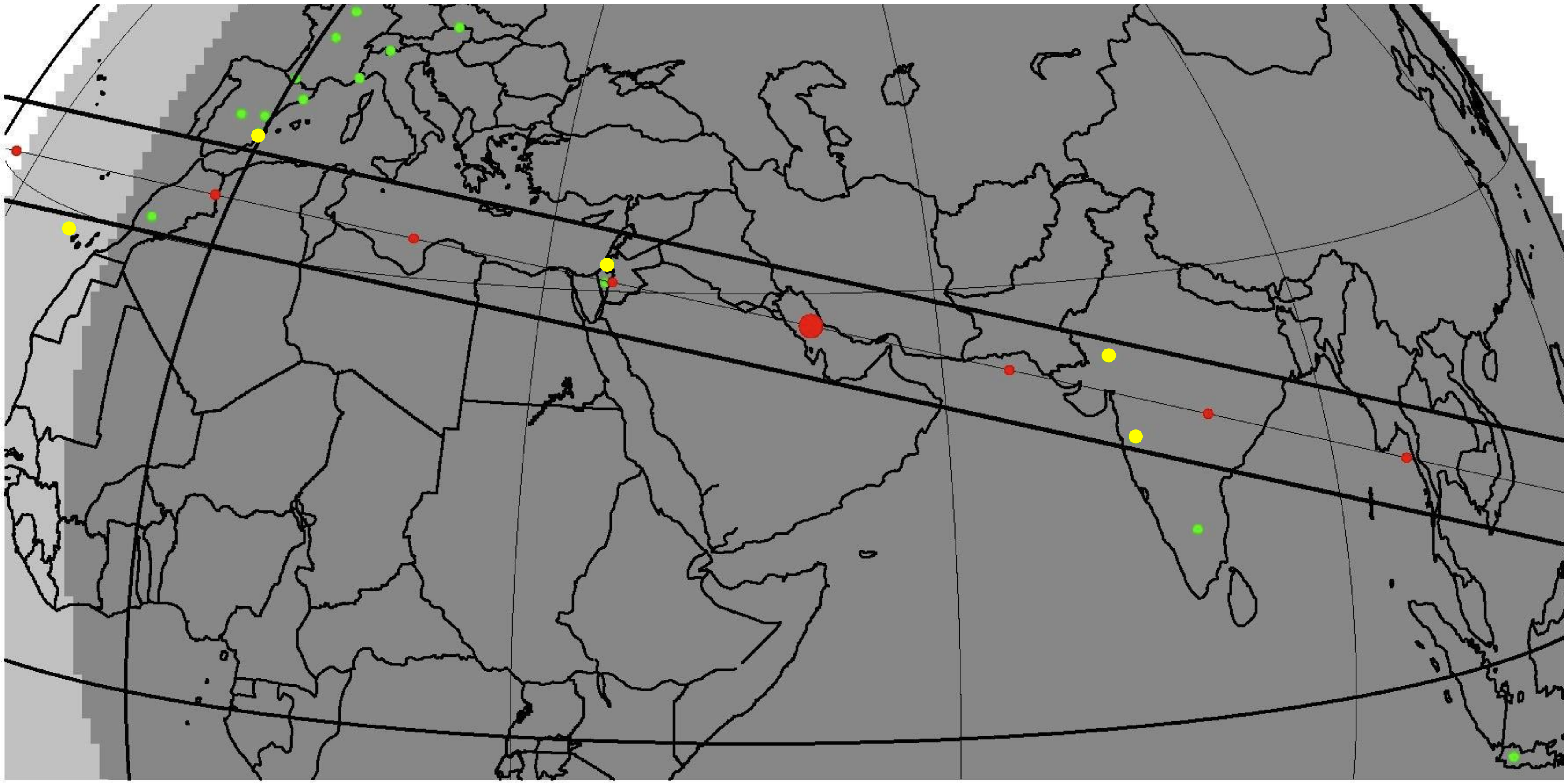


Results: 2003 AZ84

<u>2003 AZ84</u> => Plutino (2:3) a = 39.5 AU, e = 0.18, i = 17° <u>Now @ 45 AU</u>; - 1 satellite (no orbit/mass yet); - V magnitude = 20.2	- occultation: 03/02/2012 - India, Israel, Spain - Star mag. = 15.3 - Chords = 2½ +, 11 - ; - Teles.: 0.5, 0.8, 2m



THE FEBRUARY 3RD 2012 OCCULTATION BY (208996) **2003 AZ84**



Results: 2003 AZ84

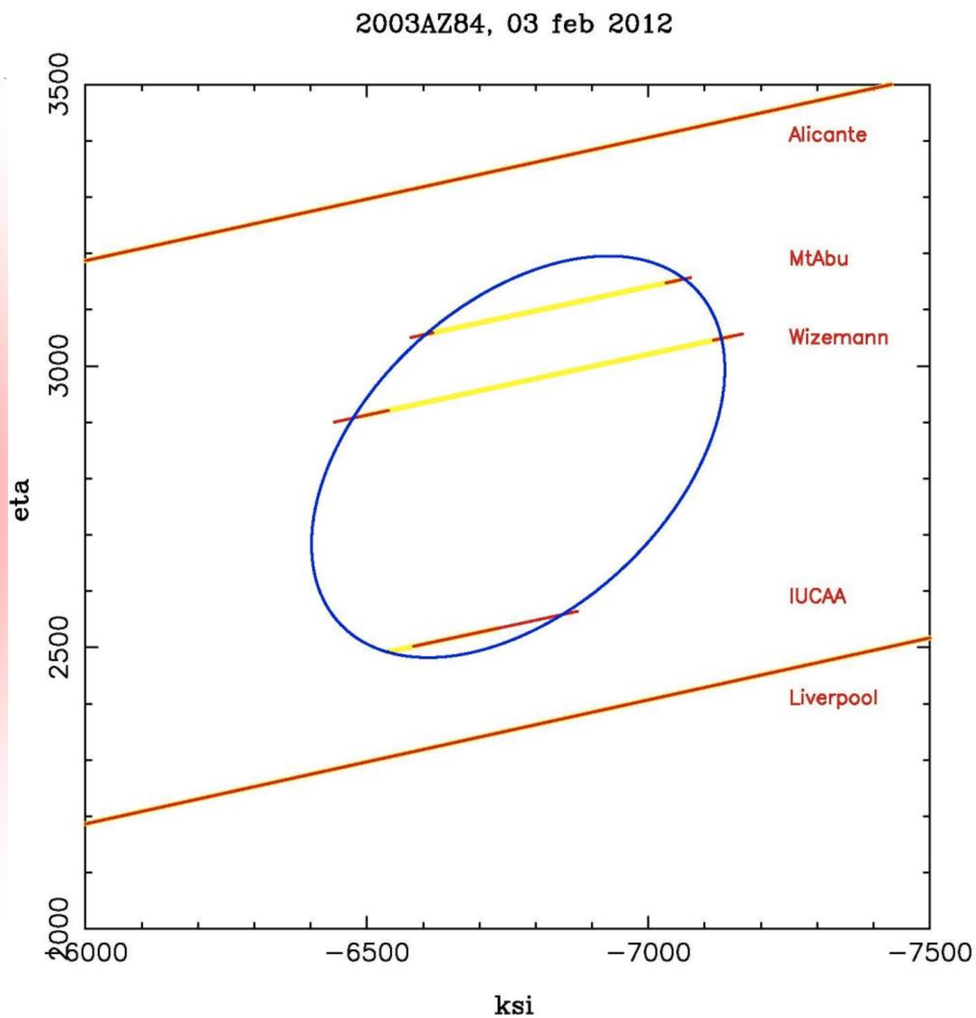
Equivalente diameter:
686 ± 14 km

Oblateness:
0.37 ± 0.1

a = 433km, b= 271km

Geometric albedo:
p_v= 0.147 ± 0.007*

**using Peixinho et al. 2012 (H_v=3.54 ± 0.05)*



Literature:

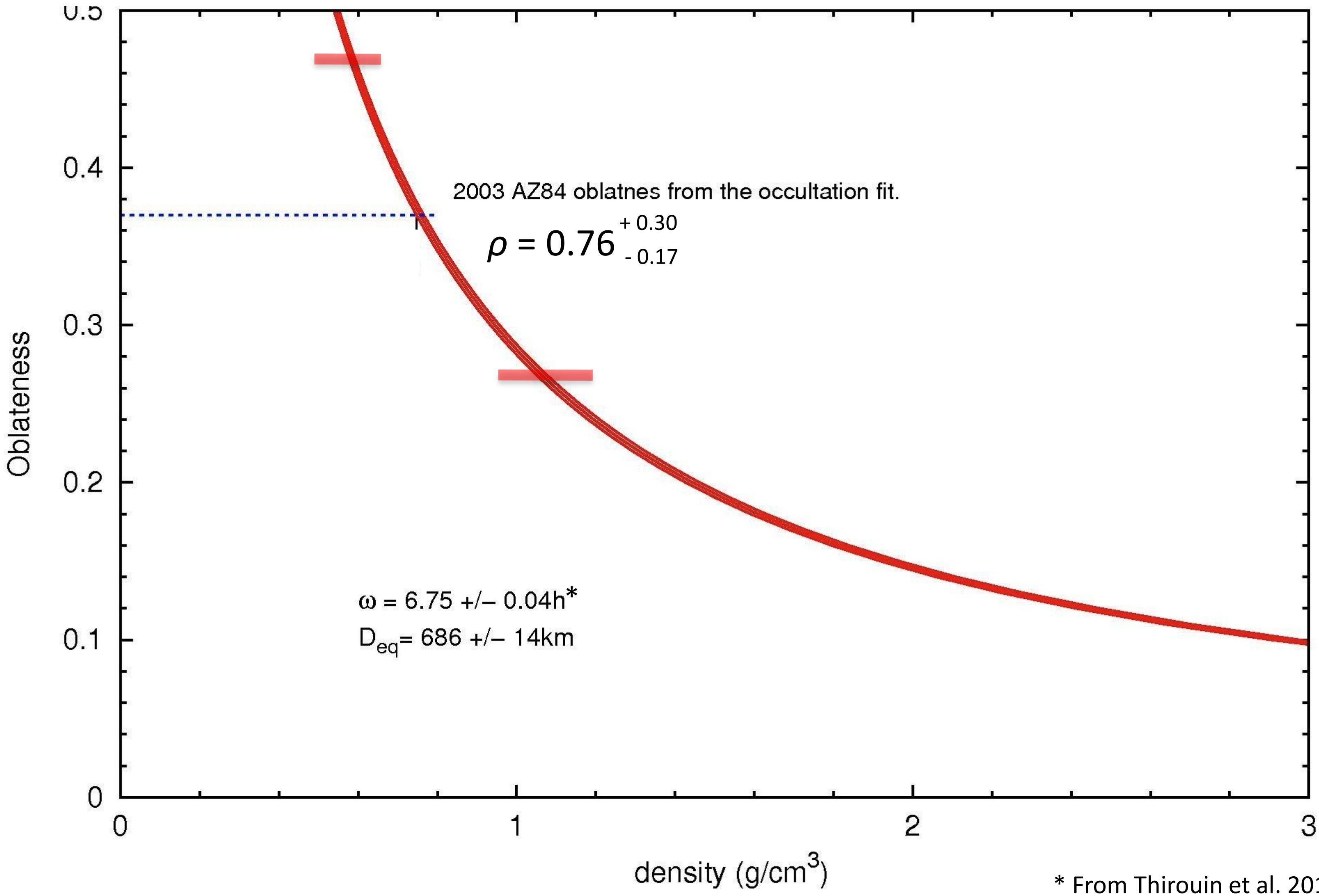
Stansberry et al. 2008
686 ± 95km

Muller et al. 2010
910 ± 60km

Mommert et al. 2012
727 ± 66km

BRAGA-RIBAS, F. et al. Stellar Occultations By Large TNOs On 2012: The February 3rd By (208996) 2003 AZ84, And The February 17th By (50000) Quaoar DPS meeting, 2012, Reno, NV – EUA. **Bulletin of the American Astronomical Society**. 2012. v.44.

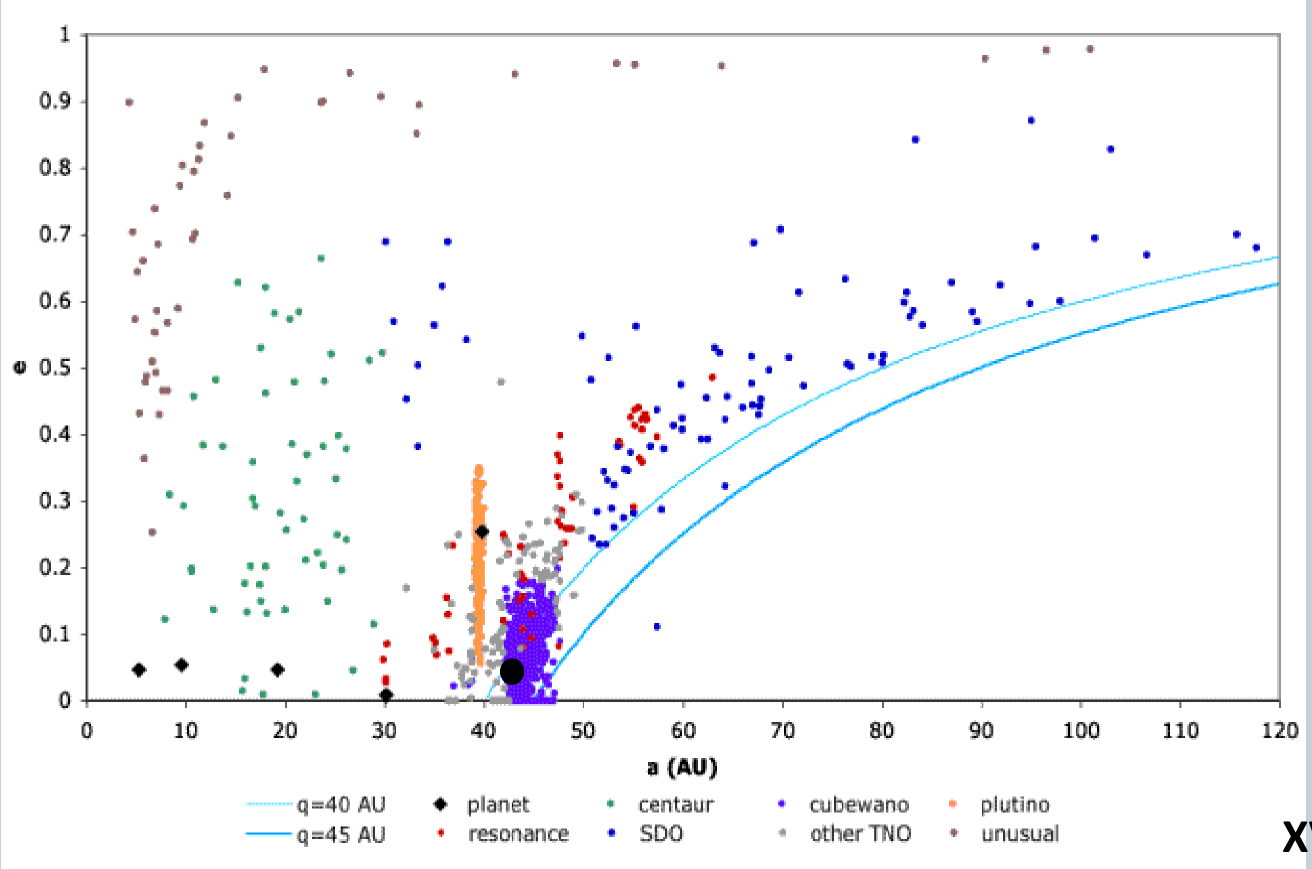
MACLAURIN HYDROSTATIC EQUILIBRIUM BODY



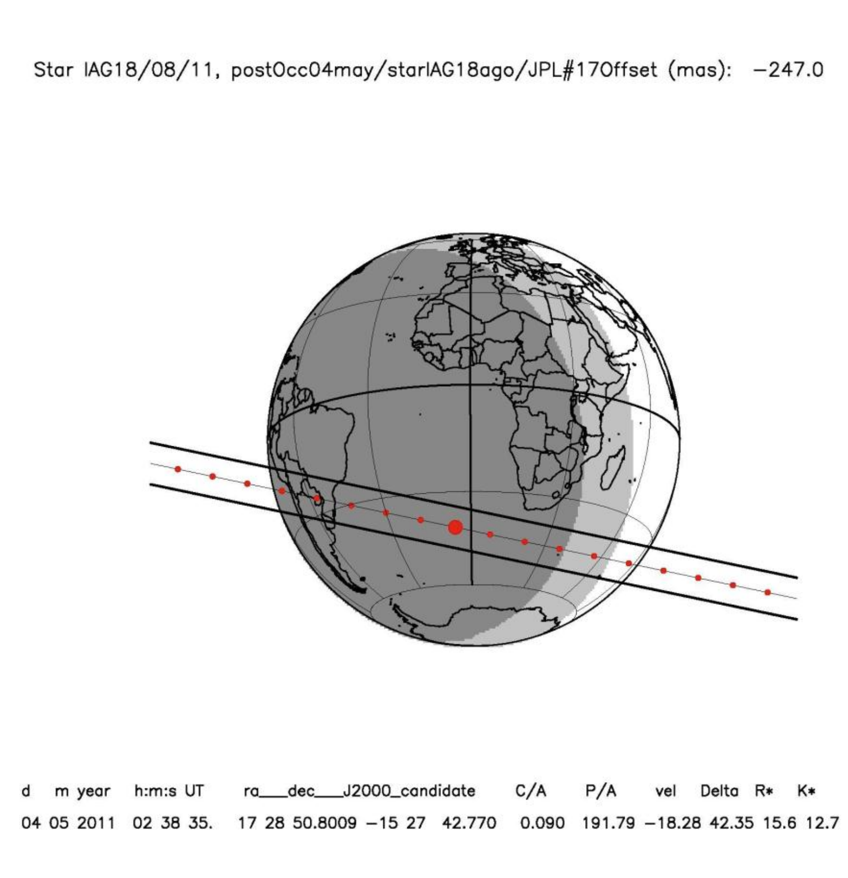
* From Thirouin et al. 2010.

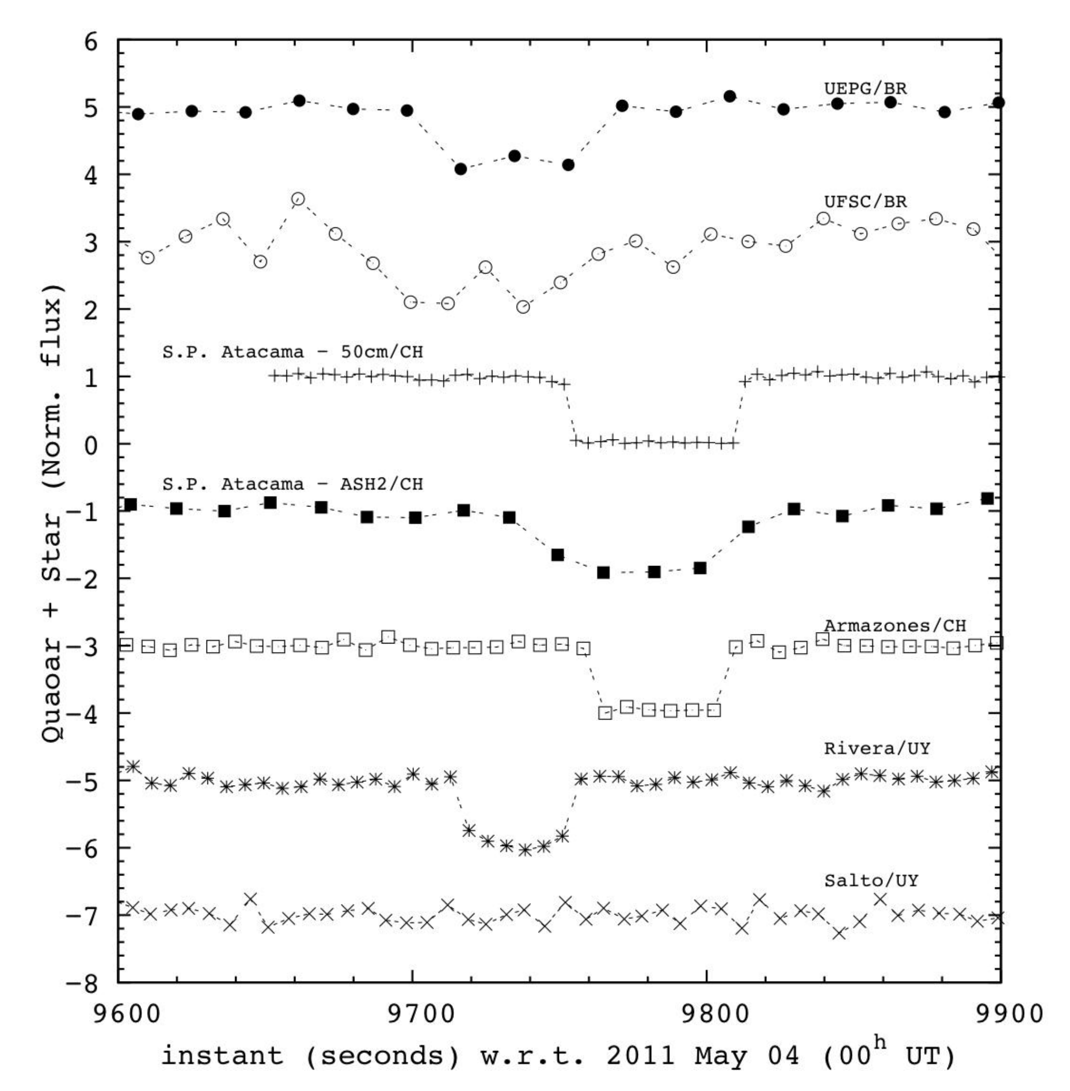
Results: Quaoar

Quaoar => hot classical	- occultation: 04/05/2011
a = 43.4 AU, e = 0.04, i = 8°	- Uruguay, Chile, Brazil.
- Now @ 43 AU;	- Star mag. = 15.6
- 1 satellite (Weywot);	- Chords = 6 + (=5), > 7 - ;
- V magnitude = 19.3	- Teles.: 0.28 to 2m



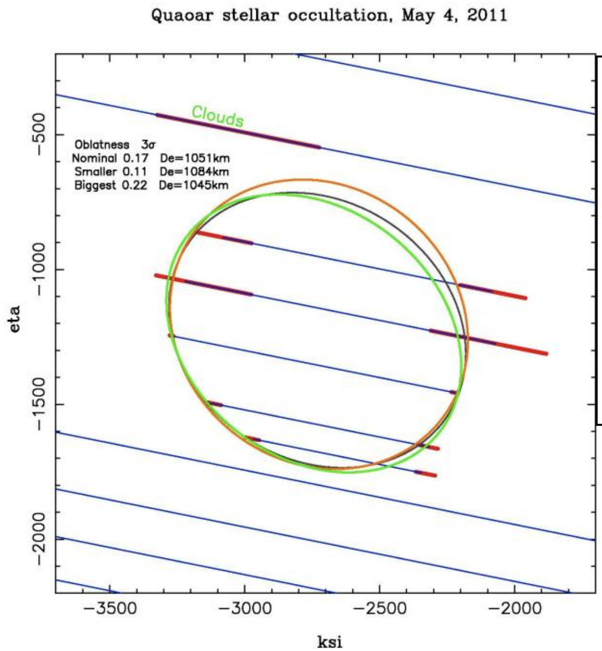
THE QUAOAR OCCULTATION: MAY 04TH **2011**





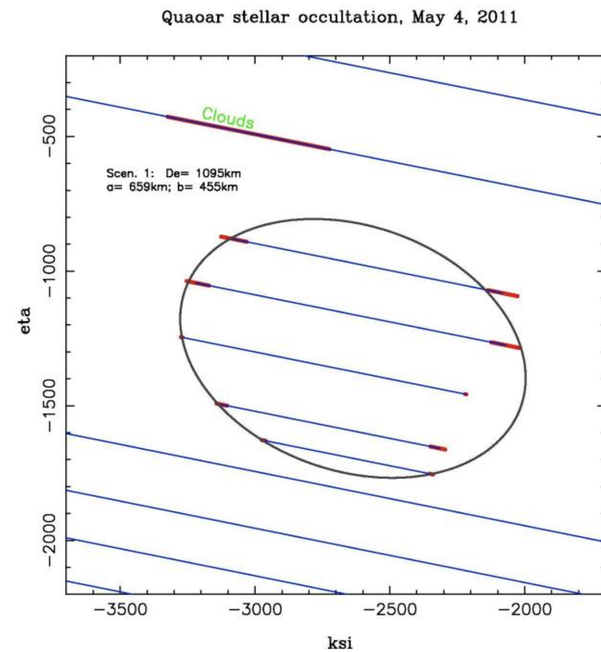
BRAGA-RIBAS, F., Sicardy, B. et al.
Stellar Occultations by TNOs: the January 08, 2011 by (208996) 2003 AZ84 and the May 04, 2011 by (50000) Quaoar, Nantes – FR. **EPSC-DPS Joint Meeting 2011**. COPERNICUS, 2011. v.1. p.1060 -

Results: Quaoar



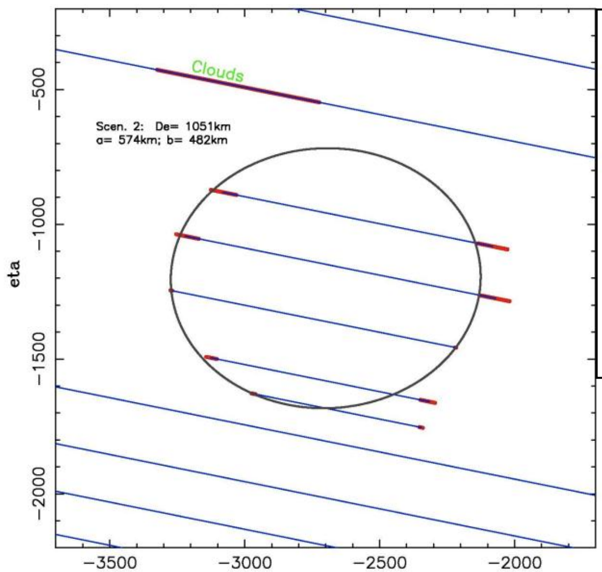
Nominal solution:

all points Included



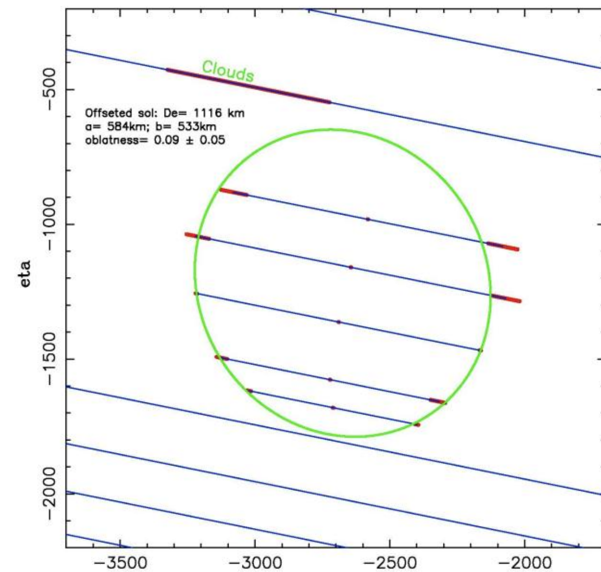
Crater solution:

very elongated



Mountain solution:

similar to nominal



Time shifted solution:

equilibrium body.

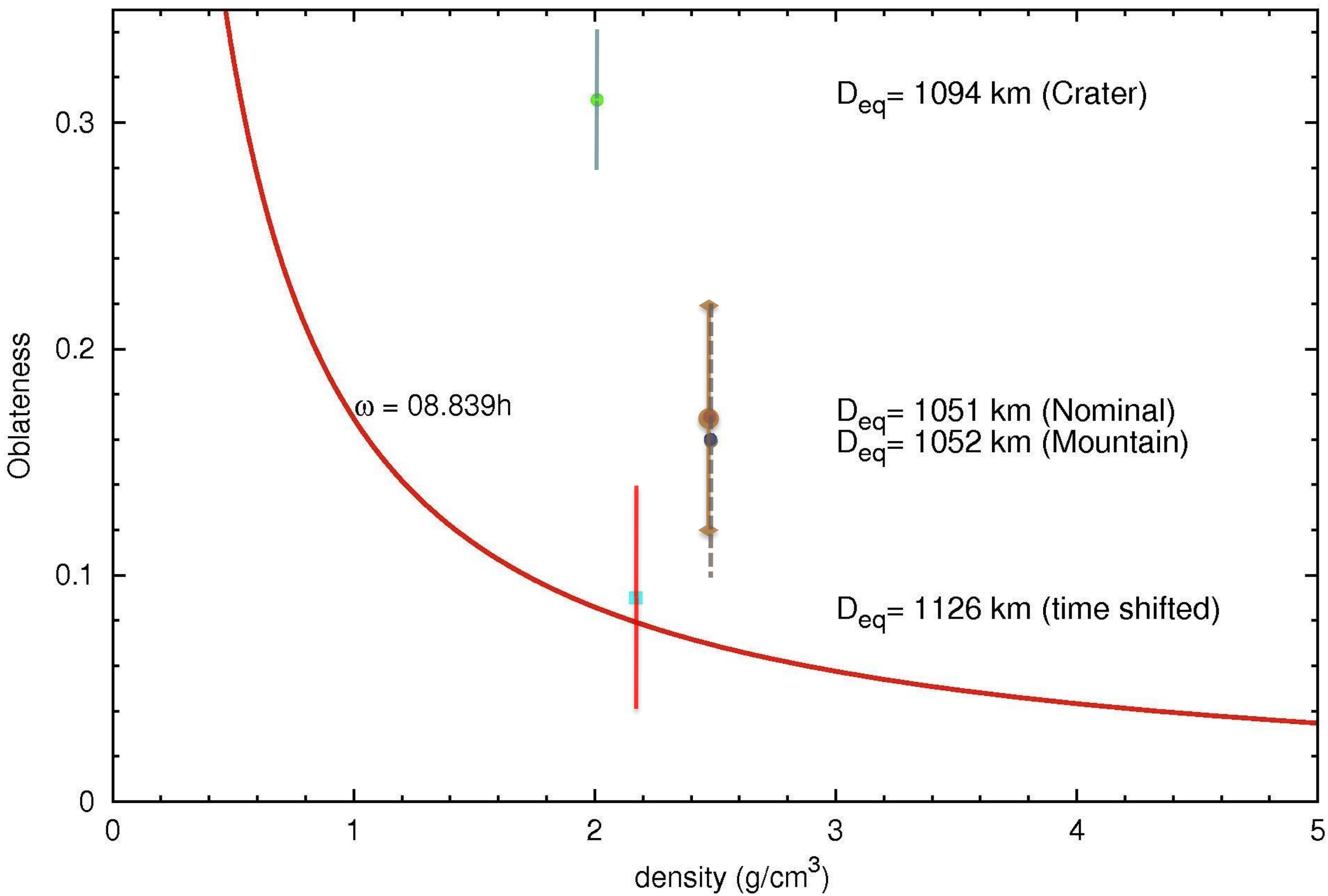
Results: Quaoar

Solutions 2011	Eq. Diameter (km)	Oblateness	Albedo	Density (g/cm^3)*
Nominal	1051	0.17 ± 0.06	0.13	2.48
Crater	1095	0.31 ± 0.03	0.11	2.01
Mountain	1052	0.16 ± 0.05	0.12	2.48
Time shift	1116	0.09 ± 0.05	0.11	2.17
ranges	**1051 – 1116**	**0.09 – 0.31**	**0.11 – 0.12**	**2.01 – 2.48**

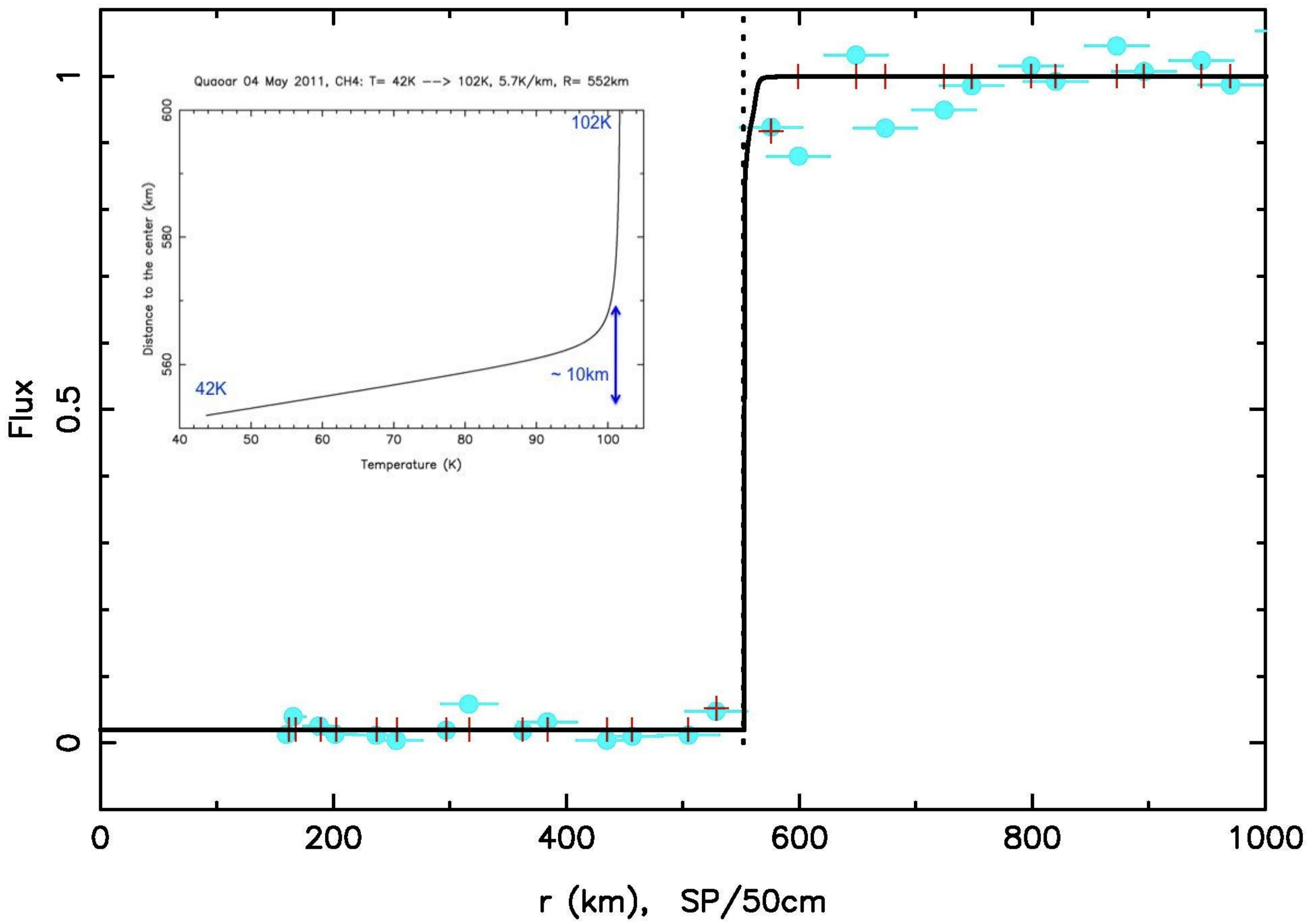
* Volume of an oblate spheroid. Mass = 1.65 ± 0.16 E21 kg from Vachier *et al.* 2012

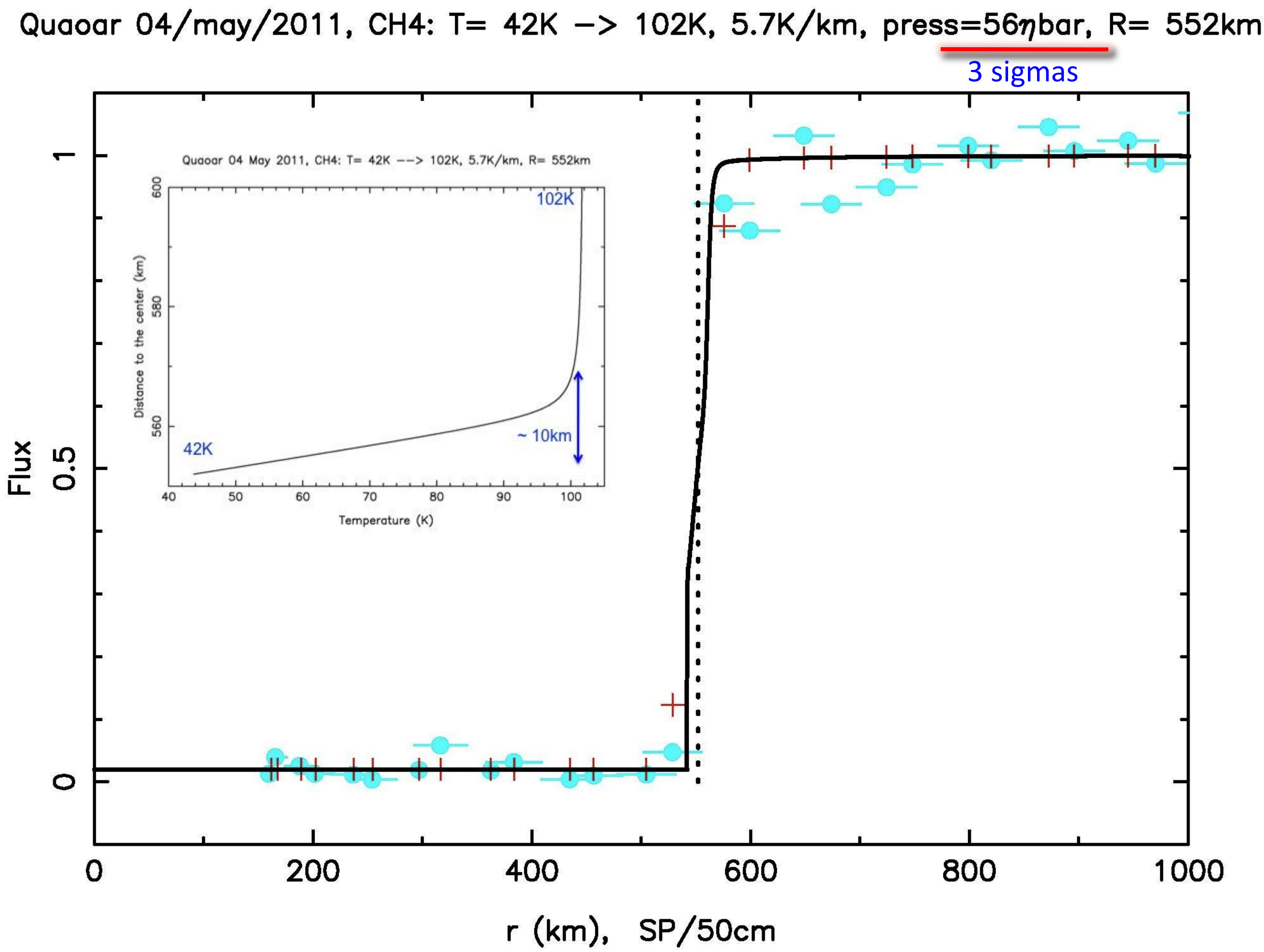
F. Vachier, *et al.* **Determination of binary asteroid orbits with a genetic-based algorithm**, A&A, v.543, p.A68, 2012.

MACLAURIN HYDROSTATIC EQUILIBRIUM BODY



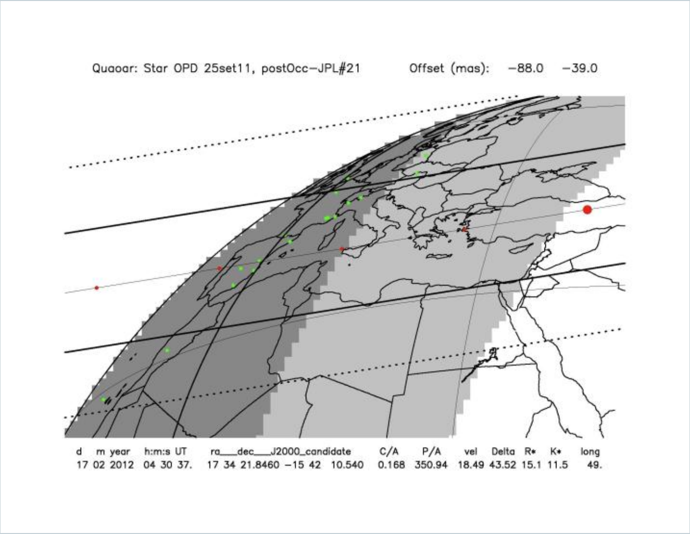
Quaoar 04/may/2011, CH4: T= 42K -> 102K, 5.7K/km, press=5ηbar, R= 552km

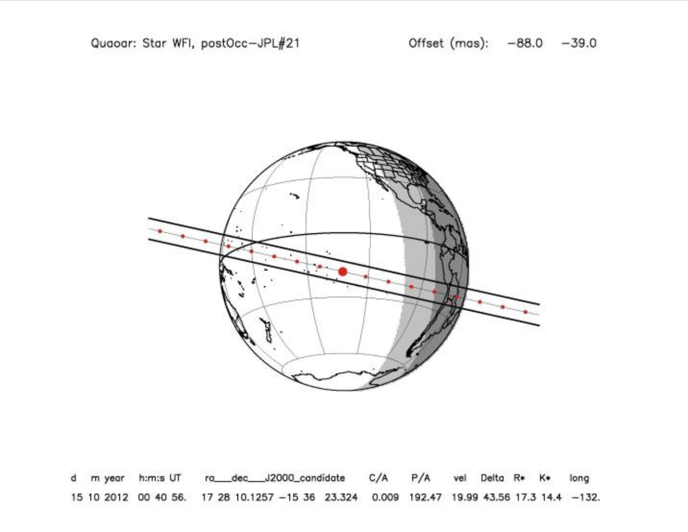


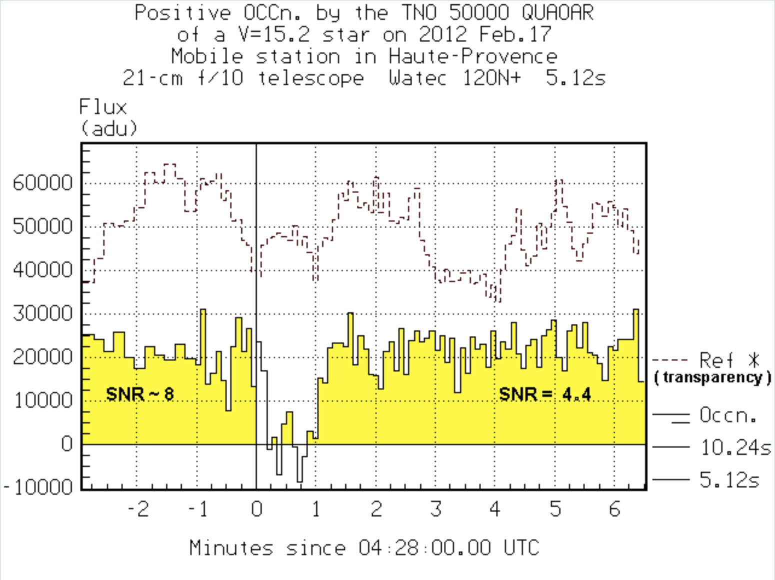


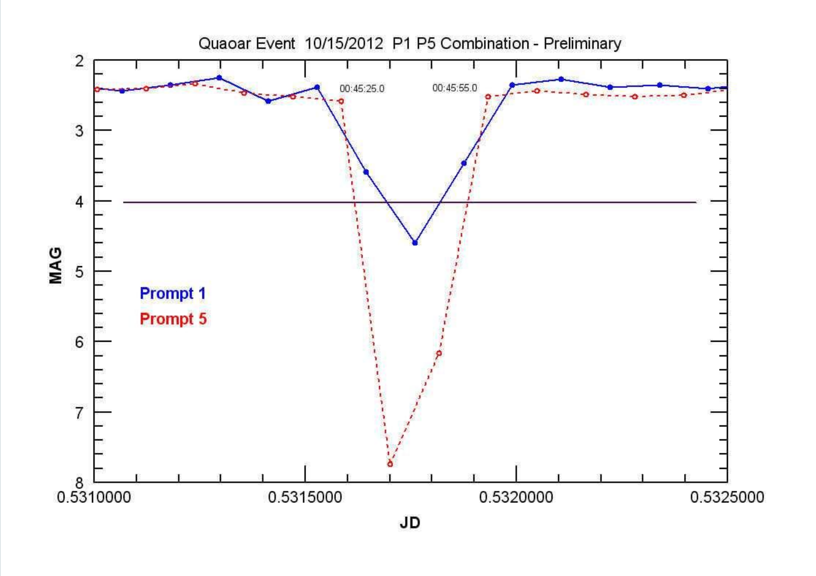
Quaoar 04/may/2011, CH4: T= 42K -> 102K, 5.7K/km, press=56ηbar, R= 552km
3 sigmas
Quaoar 04 May 2011, CH4: T= 42K --> 102K, 5.7K/km, R= 552km
102K
42K
~ 10km
Distance to the center (km)
Temperature (K)
Flux
r (km), SP/50cm

OTHER QUAOAR OCCULTATION DETECTIONS



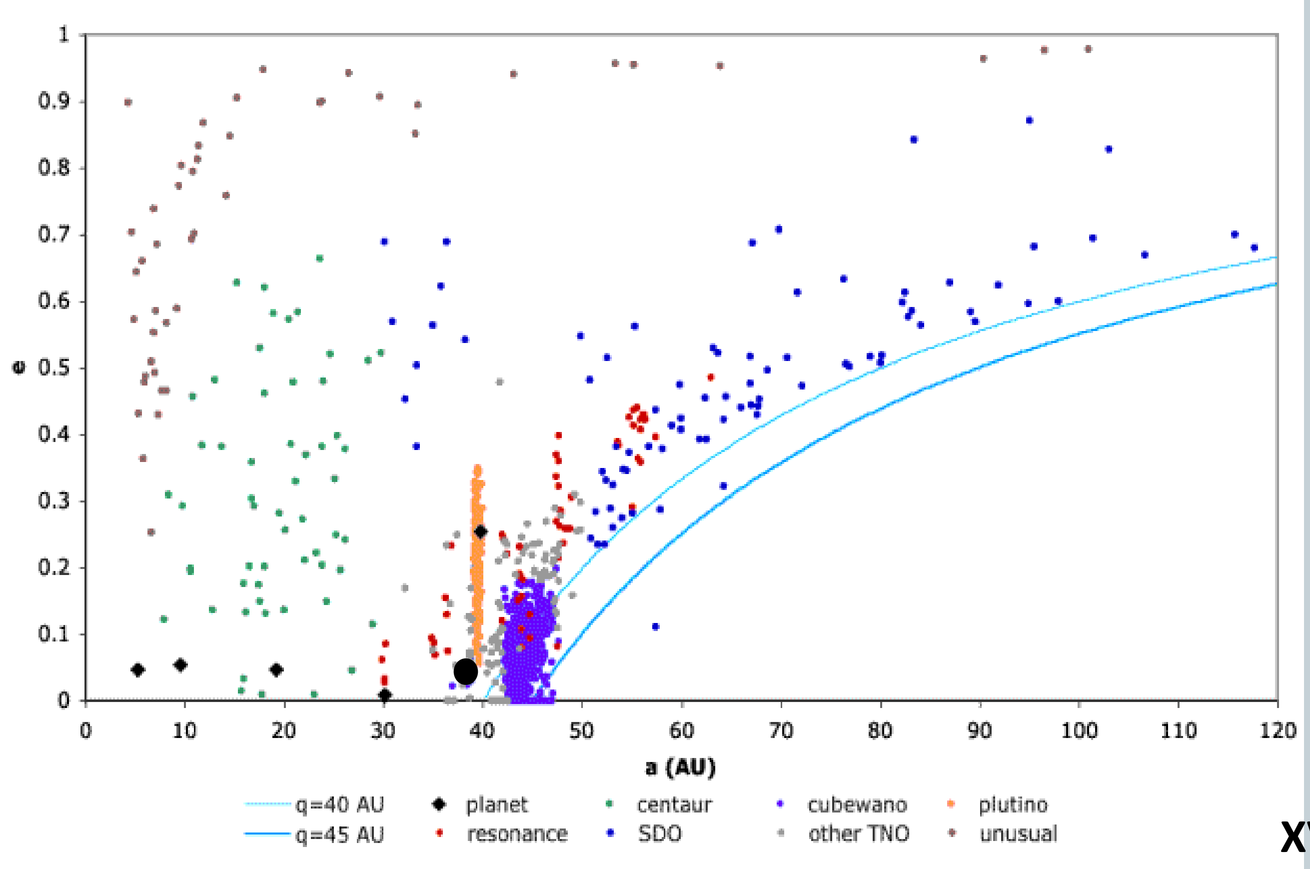






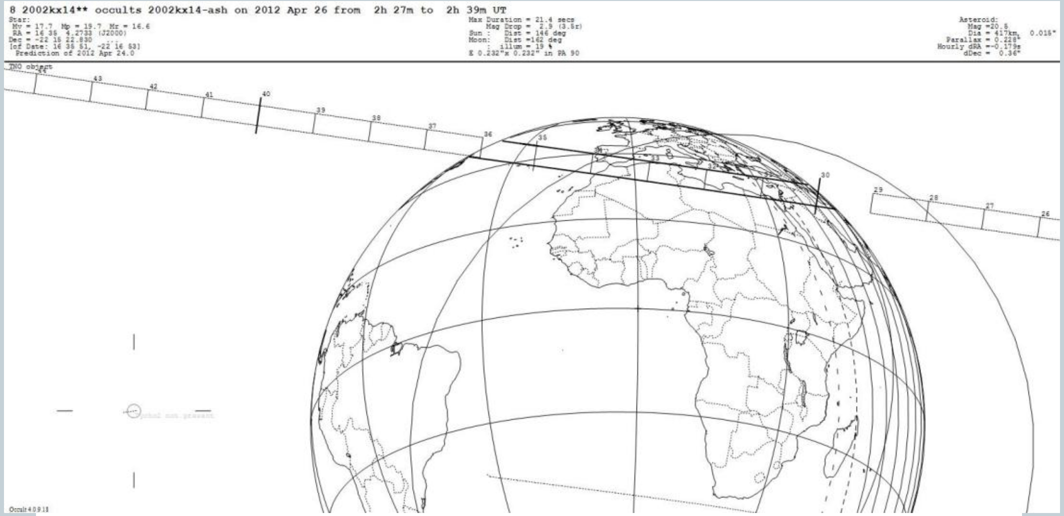
Results: 2002 KX14

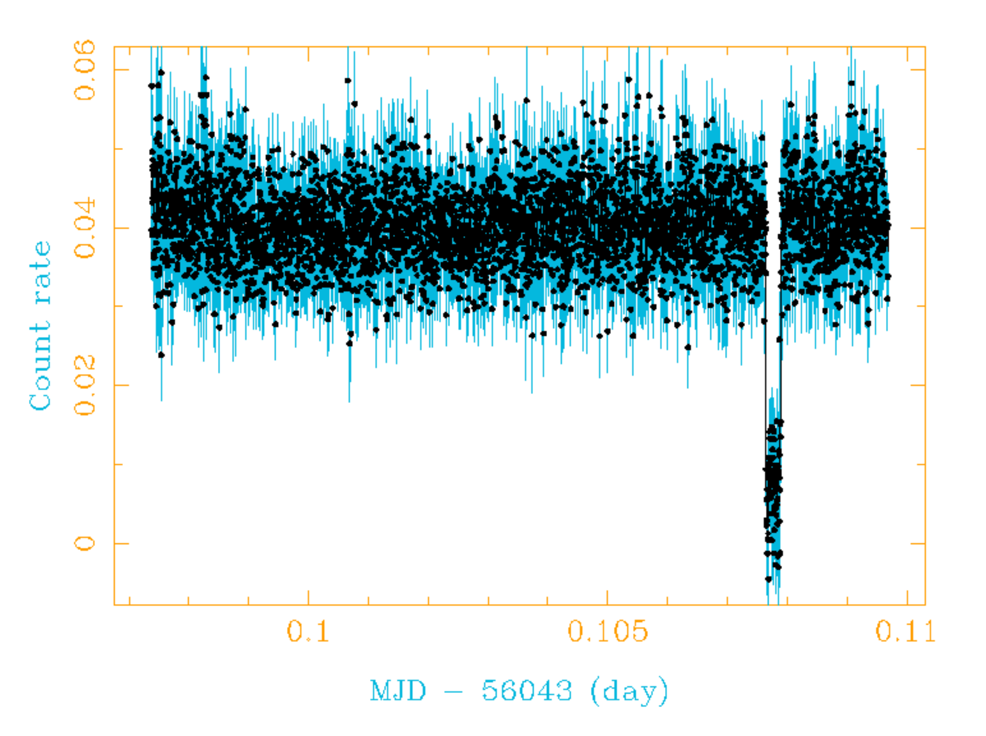
<u>2002 KX14</u> => cubewan a = 39.0 AU, e = 0.04, i = 0.4° <u>- Now @ 39 AU</u>; - no satellite; - V magnitude = 20.4	- occultation: 26/04/2012 - La Palma / Canary Island. - Star mag. = 18.1 - Chords = 1 ; - Teles.: 4.2m



XVI CBDO -2012

Results: 2002 KX14





Minimun diameter =

410 km

Stanberry et al. 2009

560 (-180/+220) km

From Vilenius et al. 2012, A&A, 541A, 94.

D = 455 ± 27 km

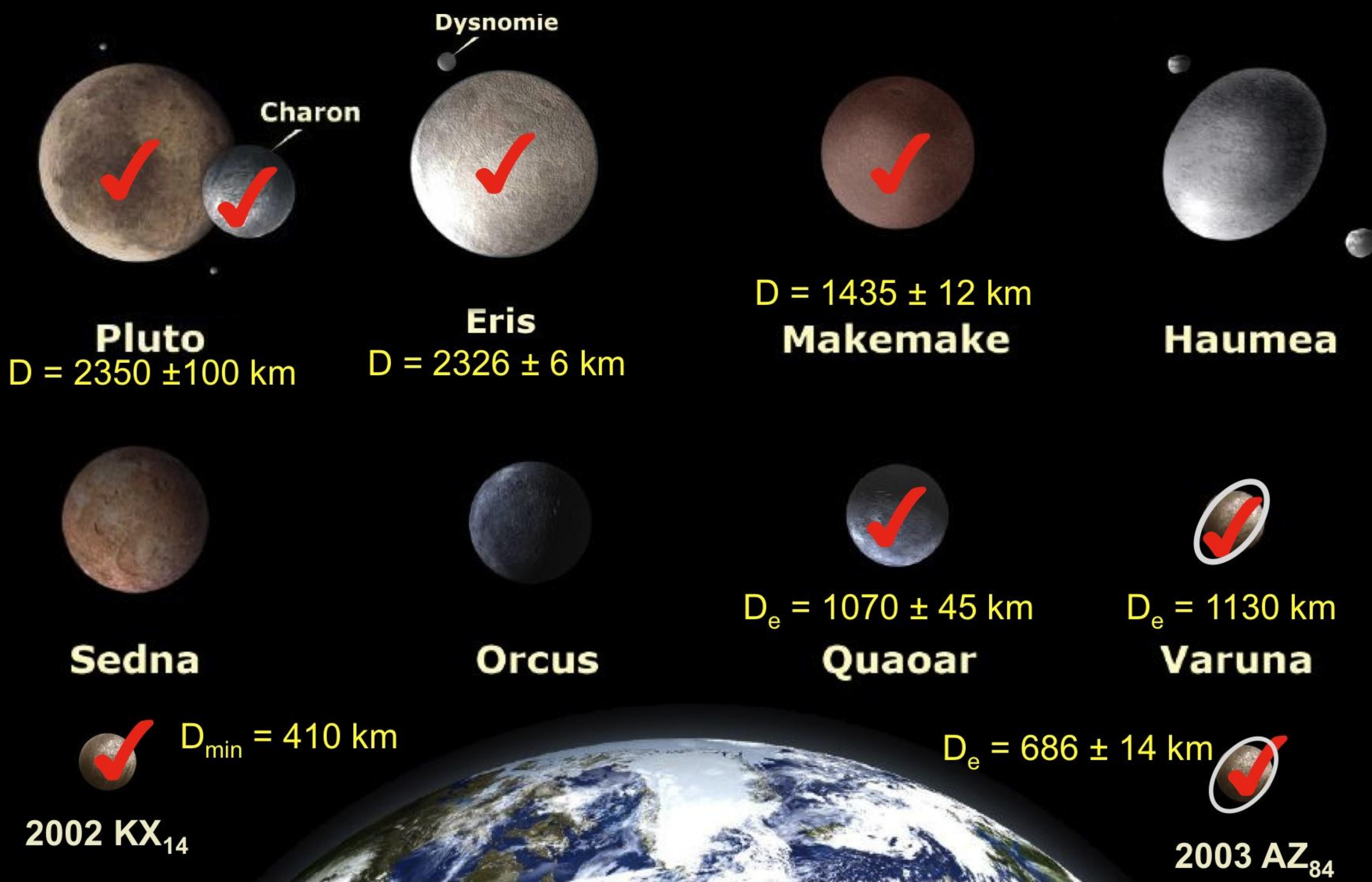
p_V= 0.097 (+0.14/-0.13)

Will put an upper limit on an possible atmosphere.

THE TNO OCCULTATION CAMPAIGNS

2003 AZ84, Ixion, 2002 TX300, Triton ...

THE TNO OCCULTATION CAMPAIGNS



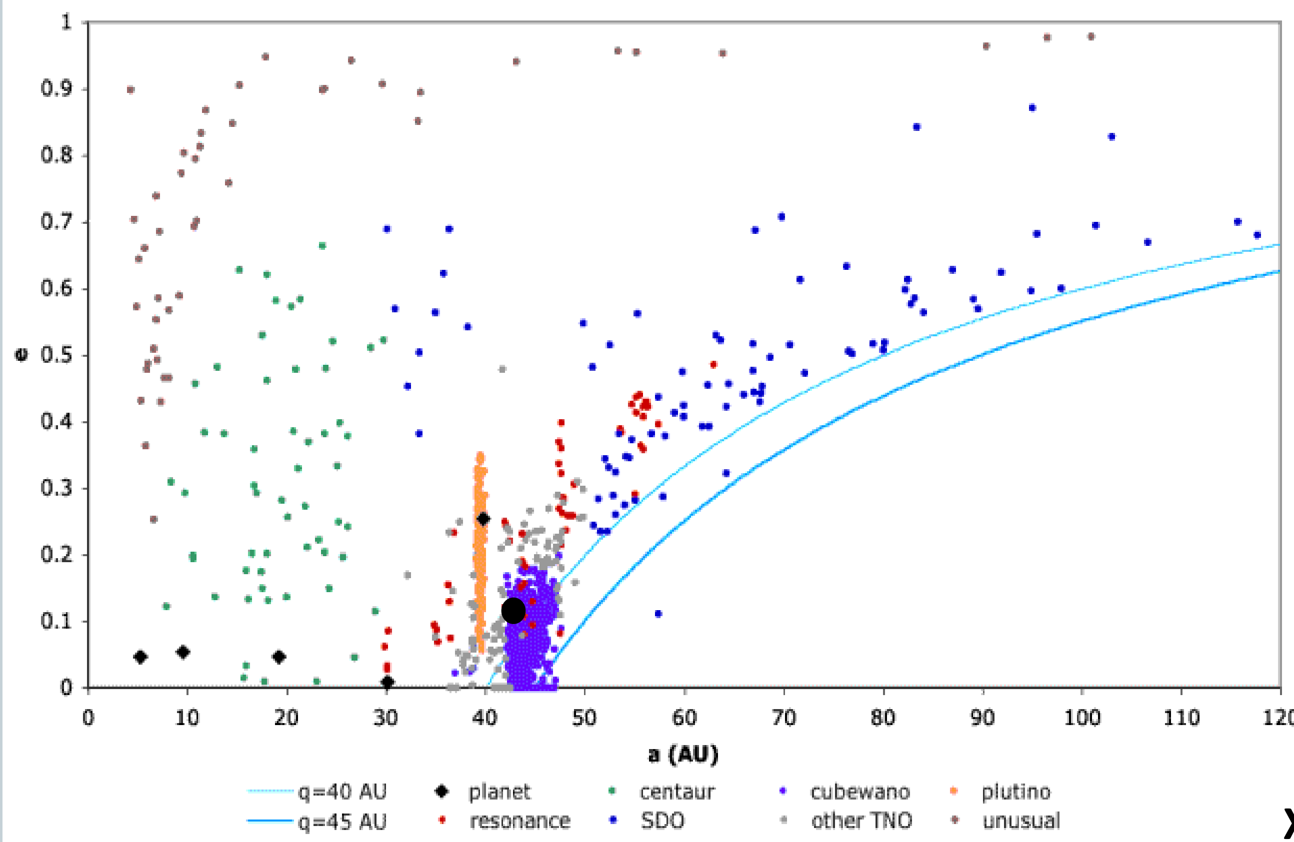
TNO	Pluto	Charon	2003 AZ84	Varuna	2002 TX300	Quaoar	Make-make	Eris
distan-ce (AU)	39.3	39.3	39.5	42.9	43.1	43.4	45.8	95.7
raio (km)	1169	603	343	309	143	535	715	1163
albedo	0.43	0.37	0.15	0.04	0.88	0.12	0.77	0.96
Oblate-ness	0	0	0.35	0.56	?	0.1 - 0.3	0.05	0
Density (g/cm^3)	2.03	1.65	0.76	-	-	2.35	1.7	2.52
Type	Plutino	Plutino	Plutino	Hot classic	Hot classic	Hot classic	Hot classic	Scatter-ed disk

Uranus, Neptune and its satellites: density ≈ 1.7 to 2, albedo ≈ 0.3 to 0.8.

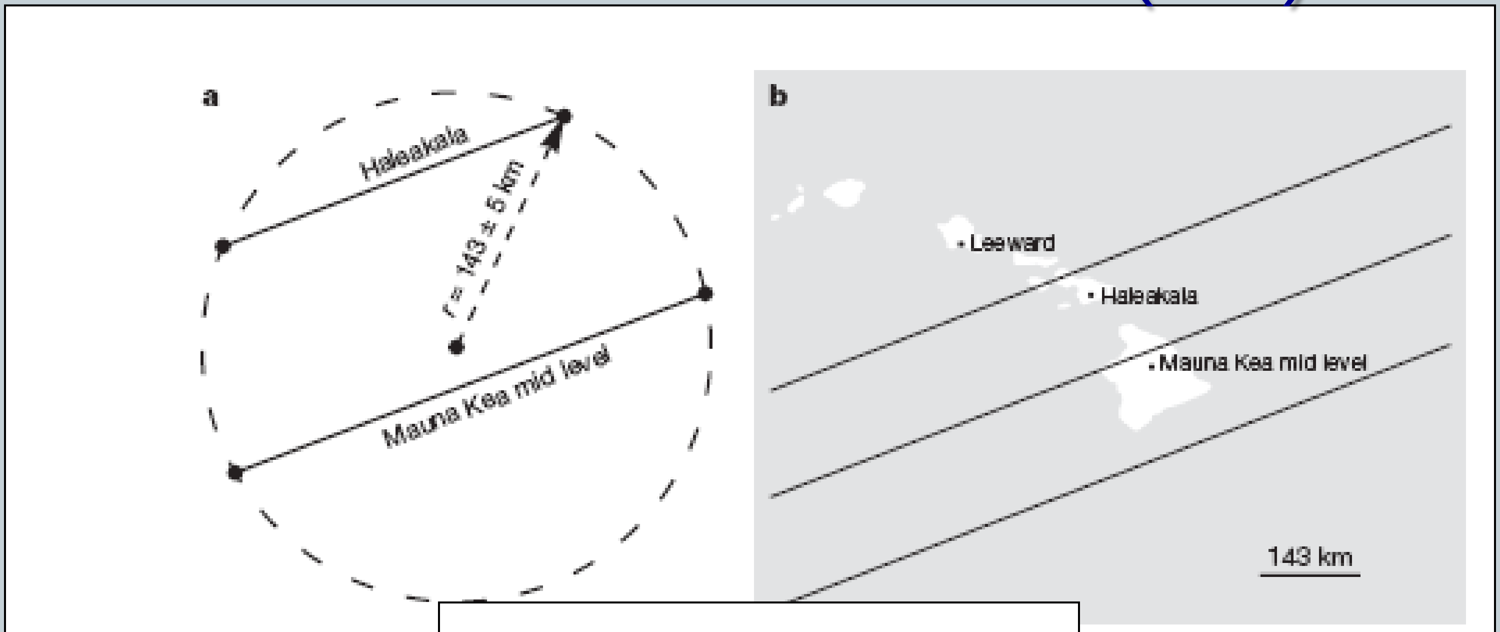
Muito obrigado!

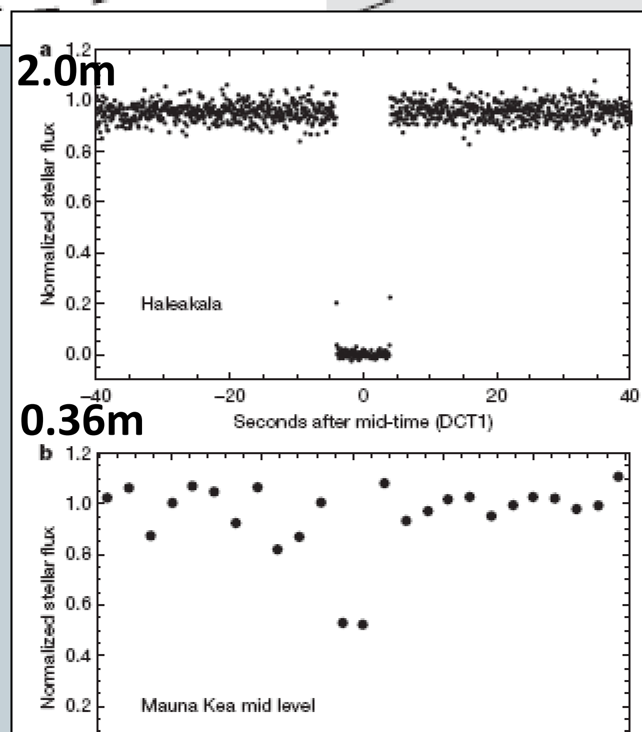
Results: 2002 TX300 (MIT)

<u>2002 TX300</u> => hot classical (Haumea family) a = 43.1 AU, e = 0.12, i = 26° - <u>Now @ 43 AU</u>; - no satellite - V magnitude = 19.4	- occultation: 09/10/2009 - Hawai, Mexico. - Star mag. = 13.2 - Chords = 2 +, 1 -; - Teles.: 0.25, 0.36, 2m



Results: 2002 TX300 (MIT)





Elliot *et al.*, Nature 465, 897, 2010

Observadores da rede de ocultações brasileira

	Identificação	Telescópio	câmara	observações
1	Santa Catarina- UFSC	28 cm	SBIG (2 s)	
2	Ponta Grossa - UEPG	40 cm	SBIG (7 s)	
3	Guaratinguetá - UNESP	40 cm	SBIG (7 s)	
4	INPE	28 cm	SBIG (2 s)	
5	LNA	1.6, 0.6, 0.6 m	várias	
6	CEAMIG (MG)	30 cm, 50 cm ?	SBIG (1 s)	
7	Brasilia (Paulo Caccela)	30 cm ?	SBIG (?)	
8	Feira de Santana - UEFS	50 cm ?	SBIG (7 s)	
9	IMPACTON - ON	1 m	(2 s)	
10	Fortaleza (Saulo Machado Filho)	30 cm	SBIG (2 s)	
11	Natal (UFRN)	35 cm	Sem câmara	

Vários telescópios sem câmara.

Organizado por Felipe e Roberto em 11/10/2012

Chronology

09/October/2009	– 2002 TX300 (MIT) – HW
19/Feburary/2010	– Varuna – BRA
06/November/2010	– Eris – CHL
08/January/2011	– 2003 AZ84 – CHL
11/February/2011	– Quaoar (MIT) – USA
23/April/2011	– Makemake – CHL, BRA
04/May/2011	– Quaoar – URY, BRA, CHL
03/February/2012	– 2003 AZ84 – IND, ISR
17/February/2012	– Quaoar – CHE, FRA
26/April/2012	– 2002 KX14 – ESP
15/October/2012	– Quaoar – CHL
13/November/2012	– 2005 TV189 (T.Janik) – CZE