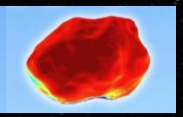
What can we learn of TNOs / Centaurs from the combination of thermal data and stellar occultations?

Pablo Santos-Sanz, José Luis Ortiz , Thomas G. Müller, Csaba Kiss, Nicolás Morales, René Duffard and the SBNAF team

Artistic view.
Credit: IAA-CSIC/UHU

THERMOPS - III

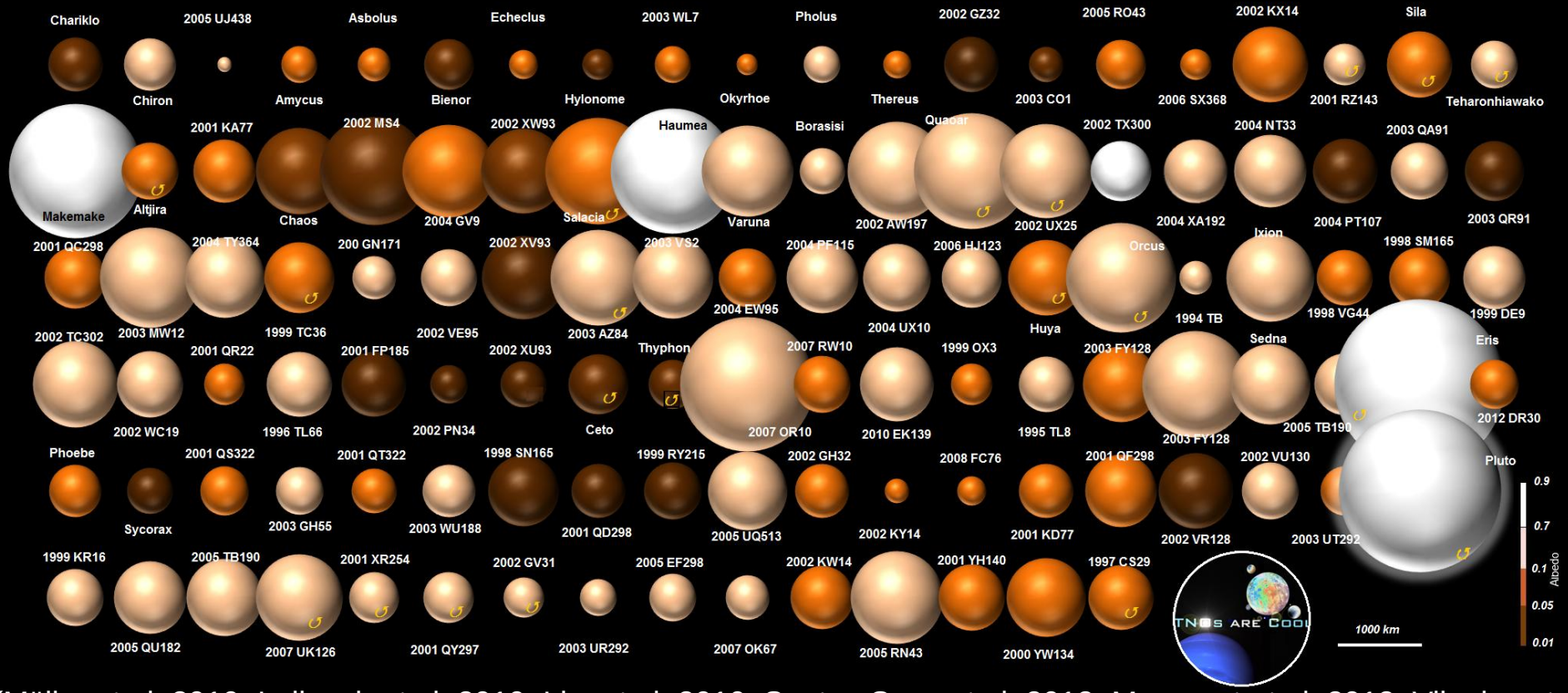


Thermal observations

TNOs are Cool

sizes, albedos, thermal properties (and mass densities)

Typical uncertainties ~10% in diameters and ~ 20% in albedos



(Müller et al. 2010, Lellouch et al. 2010, Lim et al. 2010, Santos-Sanz et al. 2012, Mommert et al. 2012, Vilenius et al. 2012, Pal et al. 2012, Fornasier et al. 2013, Lellouch et al. 2013, Vilenius et al. 2014, Duffard et al. 2014, Santos-Sanz et al. 2017, Kovalenko et al. 2017, Vilenius et al. 2018…)

http://public-tnosarecool.lesia.obspm.fr/

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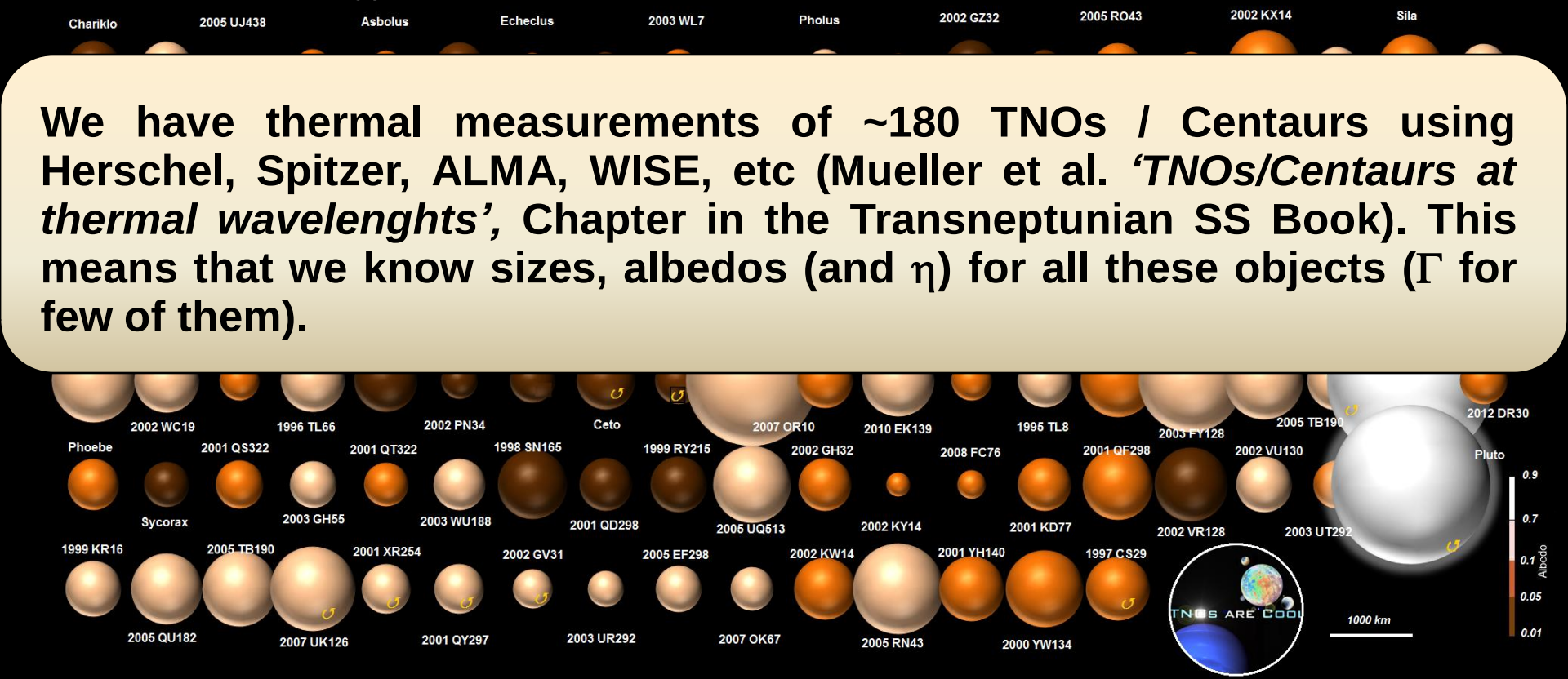


We have thermal measurements of ~180 TNOs / Centaurs using Herschel, Spitzer, ALMA, WISE, etc (Mueller et al. *'TNOs/Centaurs at thermal wavelenghts',* Chapter in the Transneptunian SS Book). This means that we know sizes, albedos (and η) for all these objects (Γ for few of them).

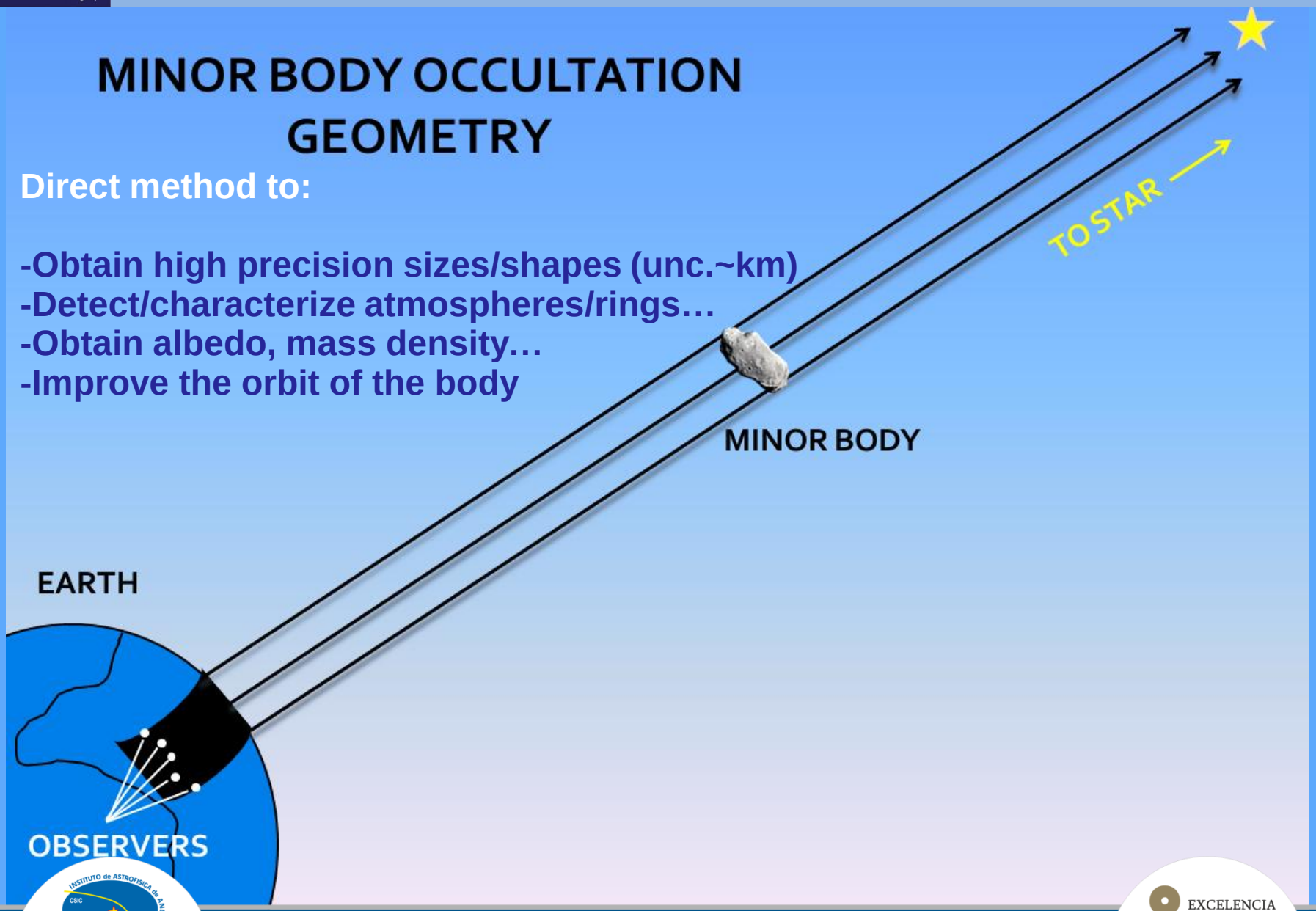
(Müller et al. 2010, Lellouch et al. 2010, Lim et al. 2010, Santos-Sanz et al. 2012, Mommert et al. 2012, Vilenius et al. 2012, Pal et al. 2012, Fornasier et al. 2013, Lellouch et al. 2013, Vilenius et al. 2014, Duffard et al. 2014, Santos-Sanz et al. 2017, Kovalenko et al. 2017, Vilenius et al. 2018…)

http://public-tnosarecool.lesia.obspm.fr/

Thermal observations: bulk densities

Object	ρ (g·cm^{-3})	Reference
(136199) Eris	**2.40+0.46-0.37**	Santos-Sanz et al. 2012
(50000) Quaoar	**2.18+0.43-0.36**	Fornasier at al. 2013
(90482) Orcus	**1.53+0.15-0.13**	Fornasier et al. 2013
(120347) Salacia	**1.29+0.29-0.23**	Fornasier et al. 2013
(174567) Varda	**1.27+0.41-0.44**	Vilenius et al. 2014
(55637) 2002 UX25	**0.79 ± 0.10**	Kovalenko et al. 2017
(47171) 1999 TC36	**0.64+0.15-0.11**	Mommert et al. 2012
(119979) 2002 WC19	**3.47 ± 1.7**	Kovalenko et al. 2017
(79360) Sila	**0.73 ± 0.28**	Vilenius et al. 2012
(148780) Altjira	**0.30+0.50-0.14**	Vilenius et al. 2014
2001 QC298	**1.14+0.34-0.30**	Vilenius et al. 2014
(26308) 1998 SM165	**0.51+0.29-0.14**	Stansberry+ 2008, Spencer+ 2006
(65489) Ceto	**0.64+0.16-0.13**	Santos-Sanz et al. 2012
(275809) 2001 QY297	**0.92+1.30-0.27**	Vilenius et al. 2014
2001 XR254	**1.00+0.96-0.56**	Vilenius et al. 2014
(88611) Teharonhiawako	**0.60+0.36-0.33**	Vilenius et al. 2014
(469705) 2005 EF298	**1.10+0.66-0.56**	Kovalenko et al. 2017
(66652) Borasisi	**2.1+2.6-1.2**	Vilenius et al. 2014
(42355) Typhon	**0.60+0.72-0.29 / 0.36+0.08-0.07**	Stansberry+ 2008, Santos-Sanz+ 2012

Stellar occultations



Direct method to:

-Obtain high precision sizes/shapes (unc.~km)
-Detect/characterize atmospheres/rings…
-Obtain albedo, mass density…
-Improve the orbit of the body

Stellar occultations by TNOs/Centaurs

Titan

10 mas

Quaoar

Pluto

0.033 arsec
(33 mas)

Diameter of 1 Euro
coin at 140 km

Eris

Charon

Makemake

Stellar occultations by TNOs/Centaurs

DATE	OBJECT	Our team	REFERENCE
09 Oct 2009	2002 TX300	no	Elliot et al. (2010)
19 Feb 2010	Varuna	yes	Sicardy et al. DPS (2010)
06 Nov 2010	Eris	yes	Sicardy et al. (2011)
08 Jan 2011	2003 AZ84	yes	Dias-Oliveira et al. (2017)
11 Feb 2011	Quaoar	yes	Person et al. BAAS (2011)
23 Apr 2011	Makemake	yes	Ortiz et al. (2012)
04 May 2011	Quaoar	yes	Braga-Ribas et al. (2013)
29 Nov 2011	Chiron	no	Ruprecht et al., DPS (2015)
03 Feb 2012	2003 AZ84	yes	Dias-Oliveira et al. (2017)
17 Feb 2012	Quaoar	yes	Braga-Ribas et al. (2013)
26 Apr 2012	2002 KX14	yes	Alvarez-Candal et al. (2014)
25 Jun 2012	Echeclus	no	
15 Oct 2012	Quaoar	yes	Braga-Ribas et al. (2013)
13 Nov 2012	2005 TV189	no	
08 Jan 2013	Varuna	yes	
13 Jan 2013	Sedna	yes	
03 Jun 2013	Chariklo	yes	Braga-Ribas et al. (2014)
09 Jul 2013	Quaoar	yes	

Table adapted from Ortiz et al., Chapter in the Transneptunian SS

Stellar occultations by TNOs/Centaurs

DATE	OBJECT	Our team	REFERENCE
29 Aug 2013	Eris	yes	
24 Nov 2013	Asbolus	yes	
02 Dec 2013	2003 AZ84	yes	Dias-Oliveira et al. (2017)
12 Dec 2013	2003 VS2	yes	
11 Feb 2014	Varuna	yes	
16 Feb 2014	Chariklo	yes	Bérard et al. (2017)
01 Mar 2014	Orcus/Vanth	yes	Braga-Ribas et al. (2017)
04 Mar 2014	2003 VS2	yes	
16 Mar 2014	Chariklo	yes	Bérard et al. (2017)
29 Apr 2014	Chariklo	yes	Leiva et al. (2017)
24 Jun 2014	Ixion	yes	
28 Jun 2014	Chariklo	yes	Leiva et al. (2017)
07 Nov 2014	2003 VS2	yes	
15 Nov 2014	2007 UK126	yes	Benedetti-Rossi at al. (2016)
15 Nov 2014	2003 AZ84	yes	Dias-Oliveira et al. (2017)
26 Apr 2015	Chariklo	yes	Bérard et al. (2017)
12 May 2015	Chariklo	yes	Bérard et al. (2017)
03 Dec 2015	2002 VE95	yes	

Table adapted from Ortiz et al., Chapter in the Transneptunian SS

Stellar occultations by TNOs/Centaurs

DATE	OBJECT	Our team	REFERENCE
12 Jun 2016	Chariklo	yes	
25 Jul 2016	Chariklo	yes	Bérard et al. (2017)
08 Aug 2016	Chariklo	yes	Leiva et al. (2017)
10 Aug 2016	Chariklo	yes	Bérard et al. (2017)
10 Aug 2016	Chariklo	yes	Bérard et al. (2017)
15 Aug 2016	Chariklo	yes	Bérard et al. (2017)
20 Aug 2016	Chariklo	yes	
01 Oct 2016	Chariklo	yes	Leiva et al. (2017)
21 Jan 2017	Haumea	yes	Ortiz et al. (2017)
08 Feb 2017	Chariklo	yes	
07 Mar 2017	Orcus/Vanth	no	Sickafoose et al. 2017
09 Apr 2017	Chariklo	yes	
20 May 2017	2002 GZ32	yes	Santos-Sanz et al. In prep
24 May 2017	2003 FF128	no	
22 Jun 2017	Chariklo	yes	
10 Jul 2017	2014 MU69	no	
17 Jul 2017	2014 MU69	no	
23 Jul 2017	Chariklo	yes	

Table adapted from Ortiz et al., Chapter in the Transneptunian SS

Stellar occultations by TNOs/Centaurs

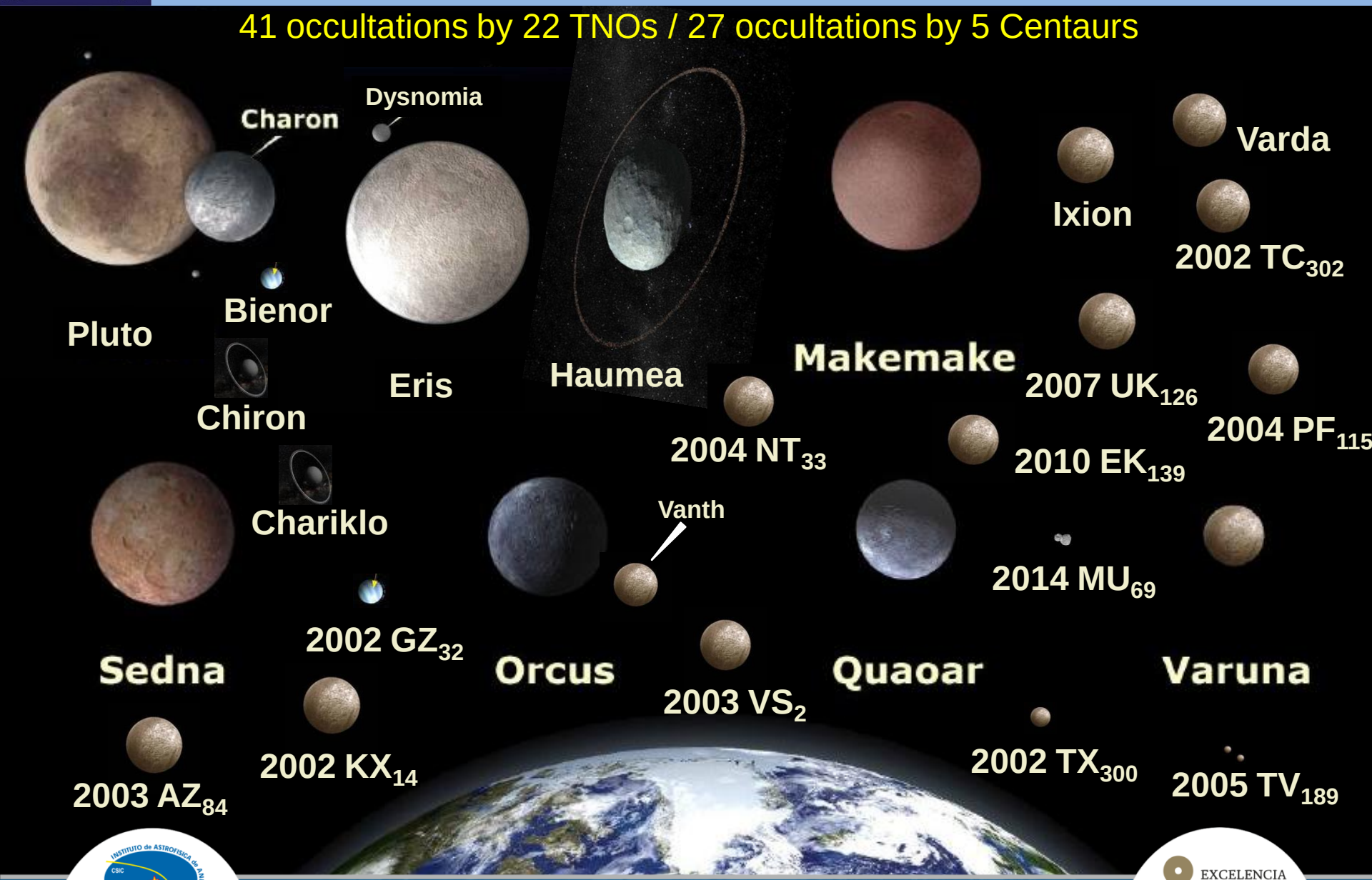
DATE	OBJECT	Our team	REFERENCE
24 Aug 2017	Chariklo	yes	
17 Nov 2017	2004 NT33	yes	
29 Dec 2017	Bienor	yes	
28 Jan 2018	2002 TC302	yes	
02 Apr 2018	Bienor	yes	
15 Jul 2018	2010 EK139	yes	
26 Jul 2018	Quaoar	yes	
02 Sep 2018	Quaoar	yes	
10 Sep 2018	Varda	yes	
19 Sep 2018	2002 KX14	yes	
28 Sep 2018	2004 PF115	yes	
28 Nov 2018	Chiron	yes	
24 Dec 2018	2005 RM43	yes	
30 Dec 2018	2002 WC19	yes	
11 Jan 2019	Bienor	yes	Morales et al. In prep.
4 Feb 2019	2005 RM43	yes	

Table adapted from Ortiz et al., Chapter in the Transneptunian SS

Small Bodies Near And Far

Stellar occultations by TNOs/Centaurs

41 occultations by 22 TNOs / 27 occultations by 5 Centaurs



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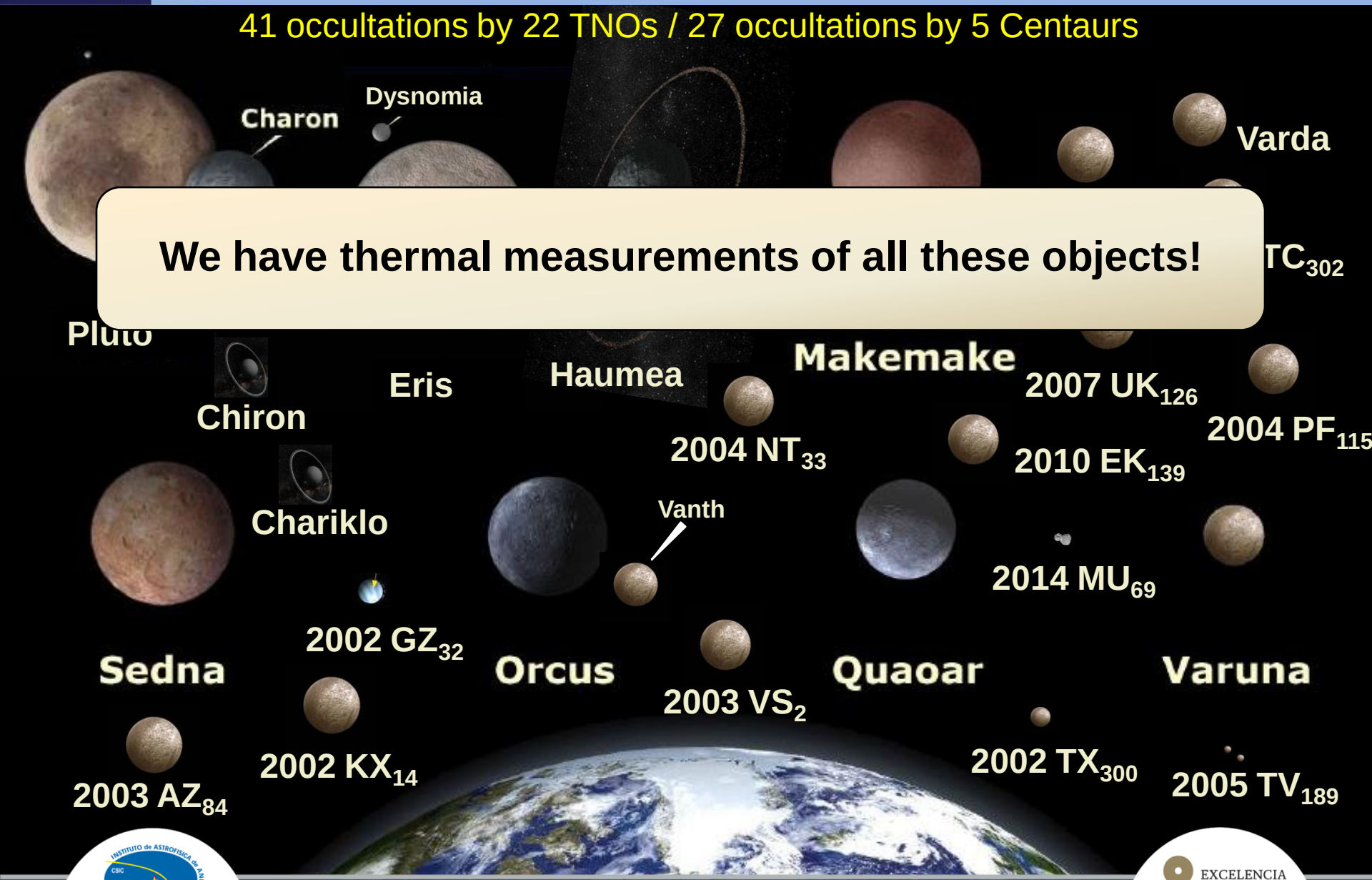
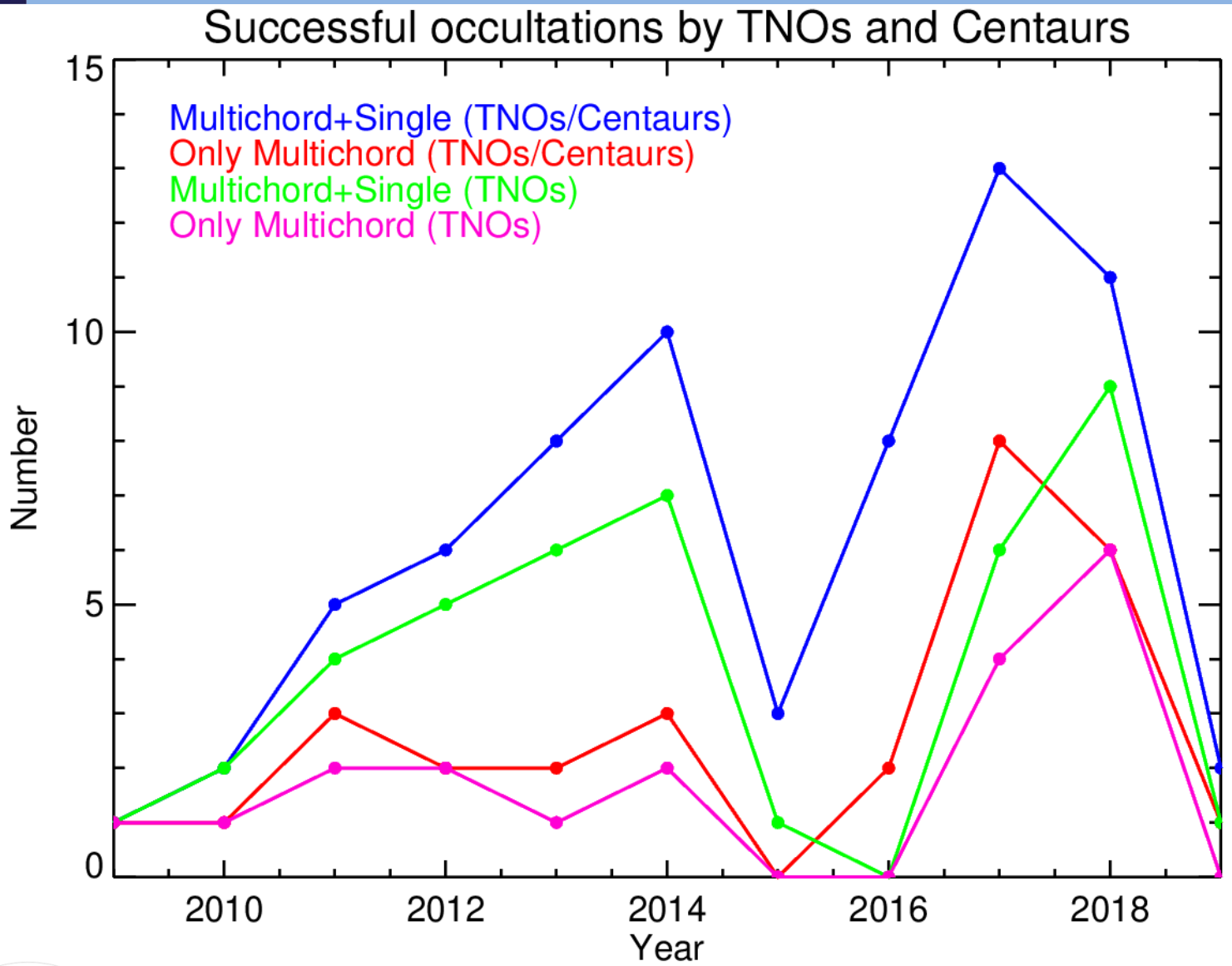


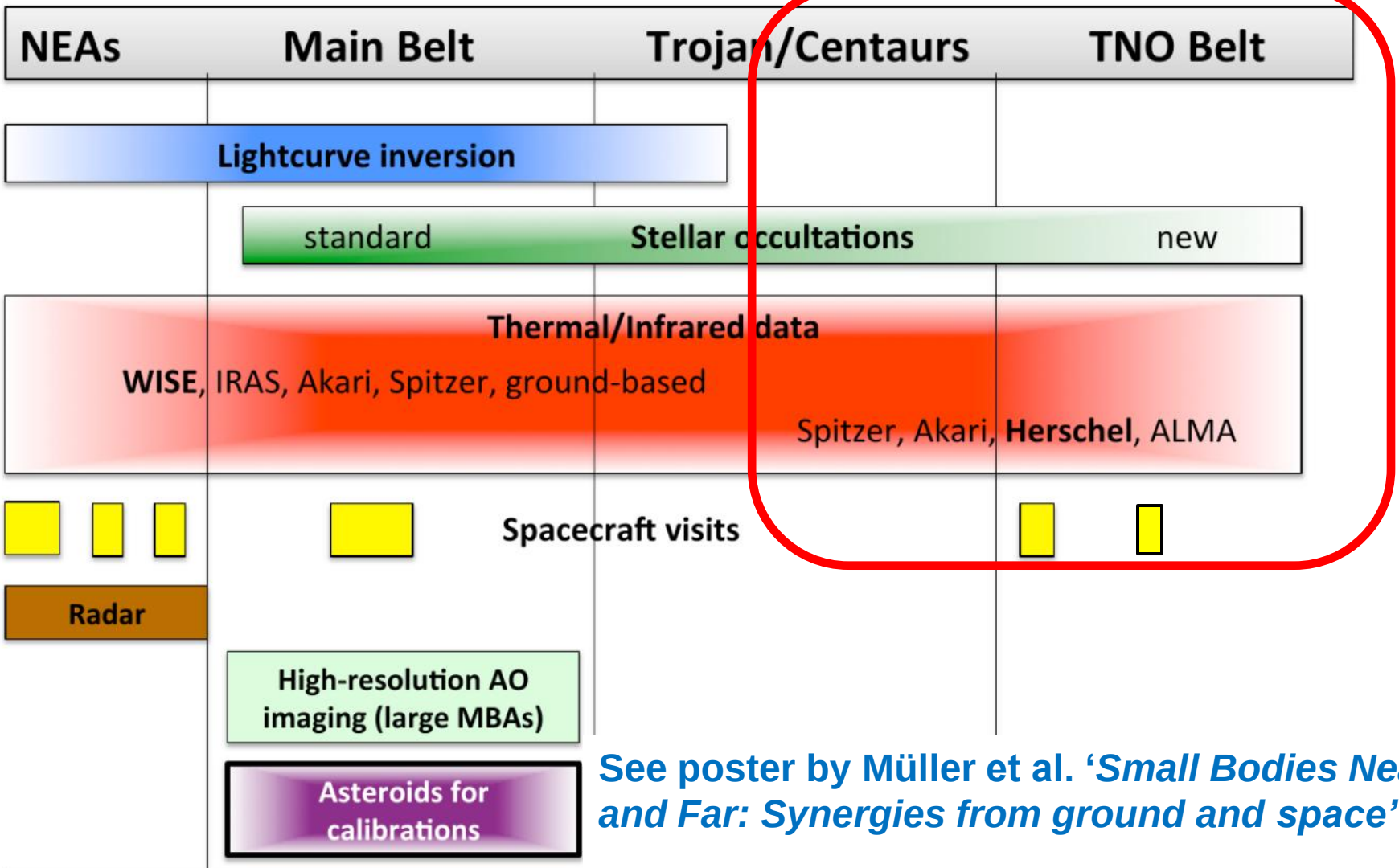
EXCELENCIA SEVERO OCHOA

Stellar occultations by TNOs/Centaurs



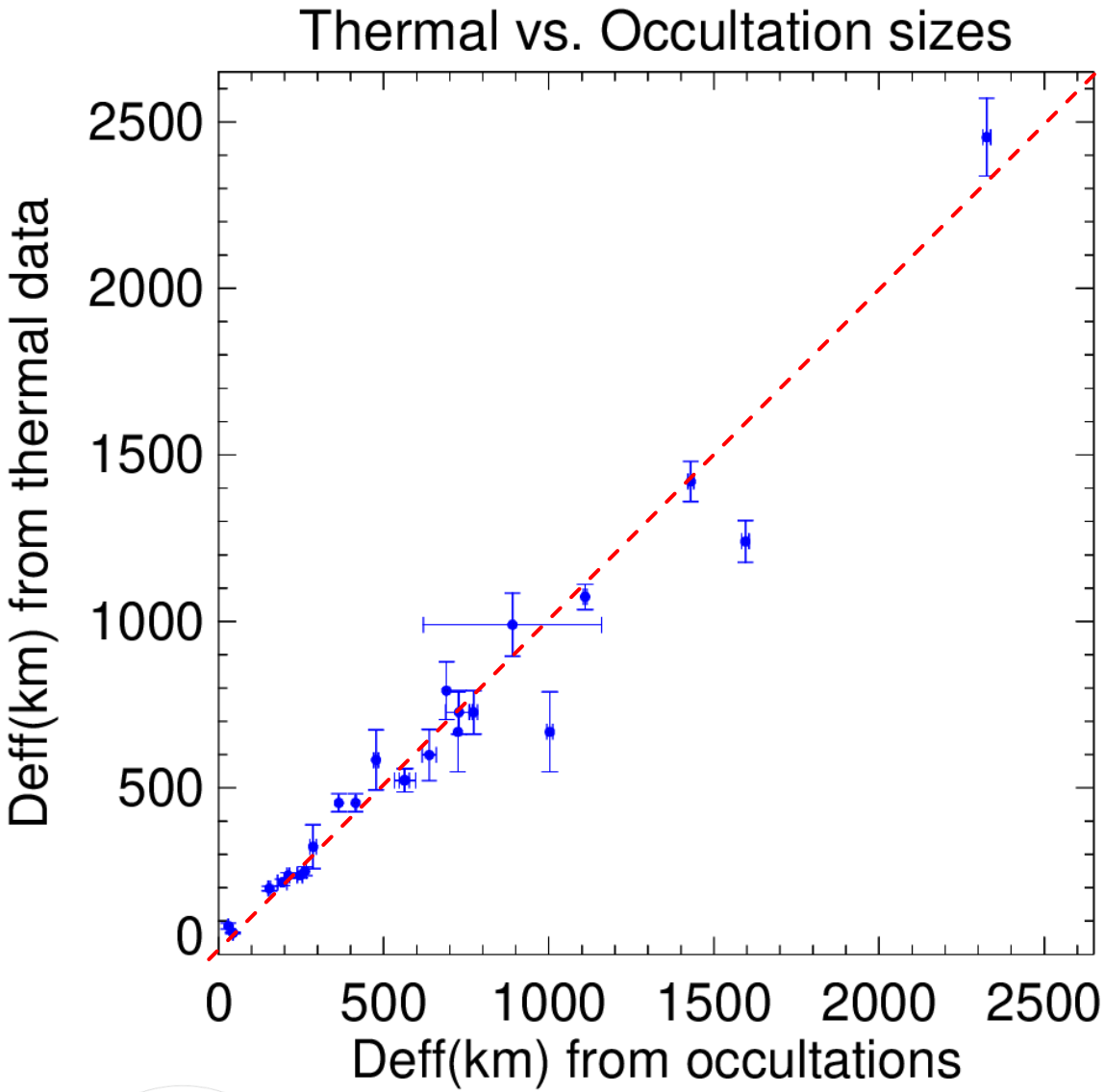
(Adapted from Ortiz et al., Chapter in the Transneptunian SS)

Combining both techniques



See poster by Müller et al. '*Small Bodies Near and Far: Synergies from ground and space*'

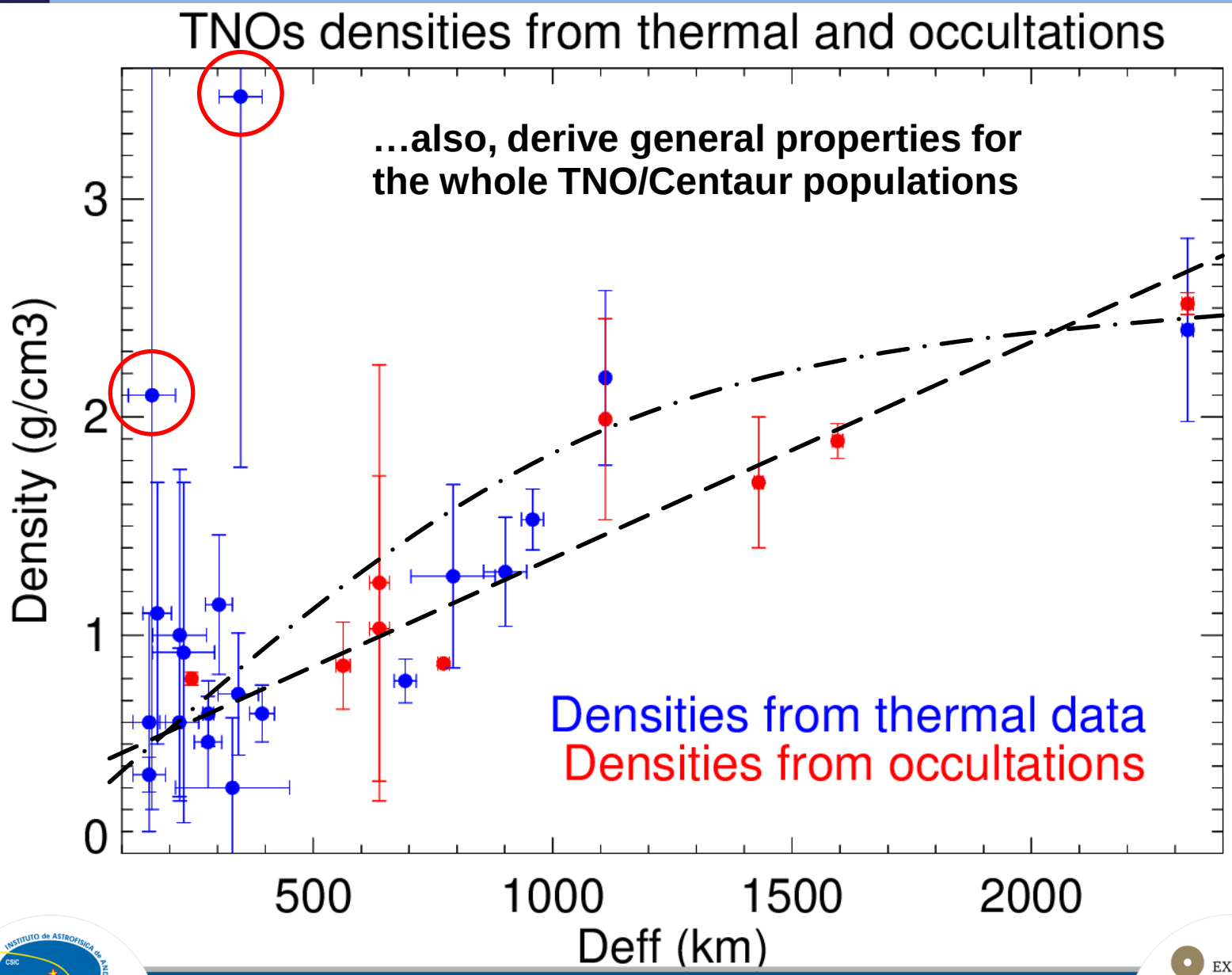
Combining both techniques



Stellar occultations and thermal measurements are complementary techniques with clear and important synergies:

- Refining of TPMs using results from occultations
- Obtaining a detailed physical and thermal characterization of **selected TNOs/Centaurs**: diameter, albedo, shape (3D), mass density, surface properties (Γ, roughness, emissivity), etc.

Combining both techniques

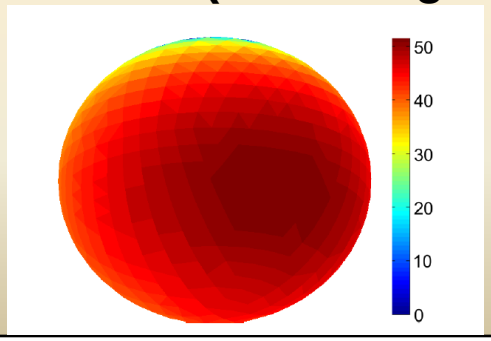


Combining both techniques

2007 UK_{126} (Schindler et al. 2017) → 3-chords stellar occultation + thermal data

Results from the occultation used to constrain the TPM (assuming P = 8 h):

- D_{eff} = 599-629 km, a/c = 1.08-1.22
- T_{ss} ~ 50-55 K
- **Orientation near equator-on (θ=45-90º)**



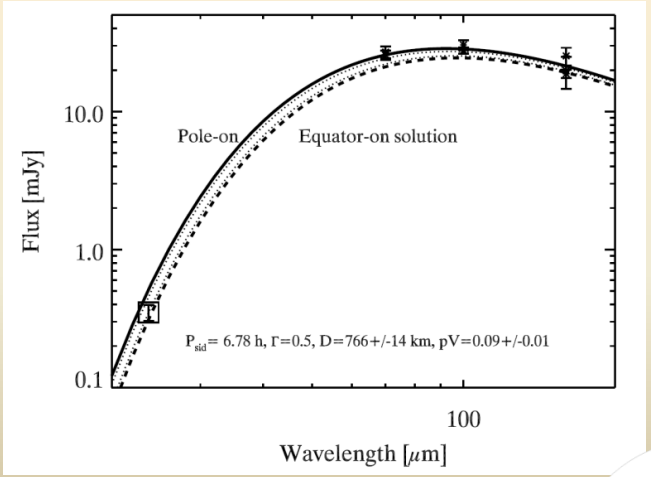
Surface T distribution on 2007 UK_{126}, as predicted by the best TPM

2003 AZ_{84} (Santos-Sanz et al. 2017) → thermal data + multi-chord stellar occultation

Results from the occultation used to constrain the TPMs (P = 6.78 h):

- **Orientation near pole-on ±30º**

Absolute PACS and MIPS fluxes for 2003 AZ84 with various TPMs: pole-on, pole-on +30, pole-on +60, equator-on



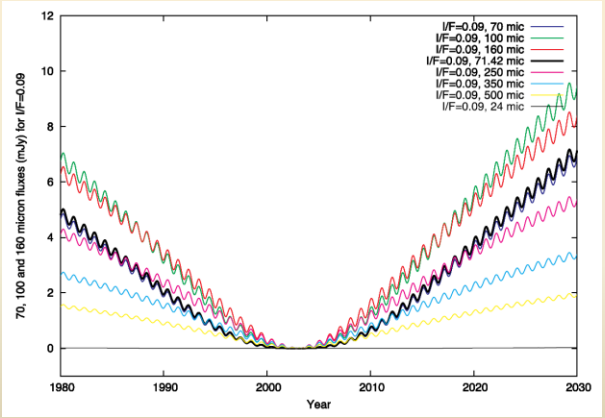
Combining both techniques

Makemake, Chiron, Chariklo (Lellouch et al. 2017)→ thermal data + stellar occultations

Thermophysical analysis of ALMA data (+ Spitzer / Herschel) using results from different stellar occultations (thermal emission of rings included in the analysis)

Haumea (Müller et al. 2018) → thermal data + multi-chord stellar occultation

Reinterpretation of the thermal emission of the <u>Haumea-ring-satellite system</u> (Spitzer/Herschel) using results derived from the occultation:



- Haumea's crystalline water ice surface with Γ **~ 5 MKS**
- **Satellites:** $p_v \gtrsim 0.5$ → $D_{Hi'iaka}$**~300km,** D_{Namaka}**~150km** → $\rho > 1.0$ **g/cm^3 !**
- **Thermal emission of the ring** during Spitzer/Herschel observations was **small but not negligible** (e.g. the ring contributed ~1-1.5 mJy to the Herschel data): this **ring contribution to the total flux will increase over the next decades → JWST-MIRI would allow to confirm Haumea's thermal properties.**

Other examples -in preparation- of the exploitation of the synergy between stellar occultations and thermal data: 2002 TC_{302} , 2002 GZ_{32} , Bienor...

Conclusions

Around 180 TNOs/Centaurs have been observed at thermal wavelengths with Spitzer, Herschel, ALMA and WISE

We have observed around 70 stellar occultations by 27 TNOs / Centaurs (22 TNOs and 5 Centaurs)…and counting. Thermal observations are available for all these objects

The synergy between thermal observations and stellar occultations has been exploited for few TNOs / Centaurs (e.g. Haumea, Makemake, 2003 AZ_{84}, 2007 UK_{126}, Chariklo, Chiron) and is being explored for few more (e.g. 2002 TC_{302}, Bienor, 2002 GZ_{32} …and counting!)

The information and results obtained from occultations are a key element for the validation of thermal modelling techniques applied to TNOs / Centaurs

TNOs / Centaurs from thermal and occultations

Artistic view.
Credit: IAA-CSIC/UHU

Thank you!

Small Bodies Near And Far

http://www.mpe.mpg.de/~tmueller/sbnaf/

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

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