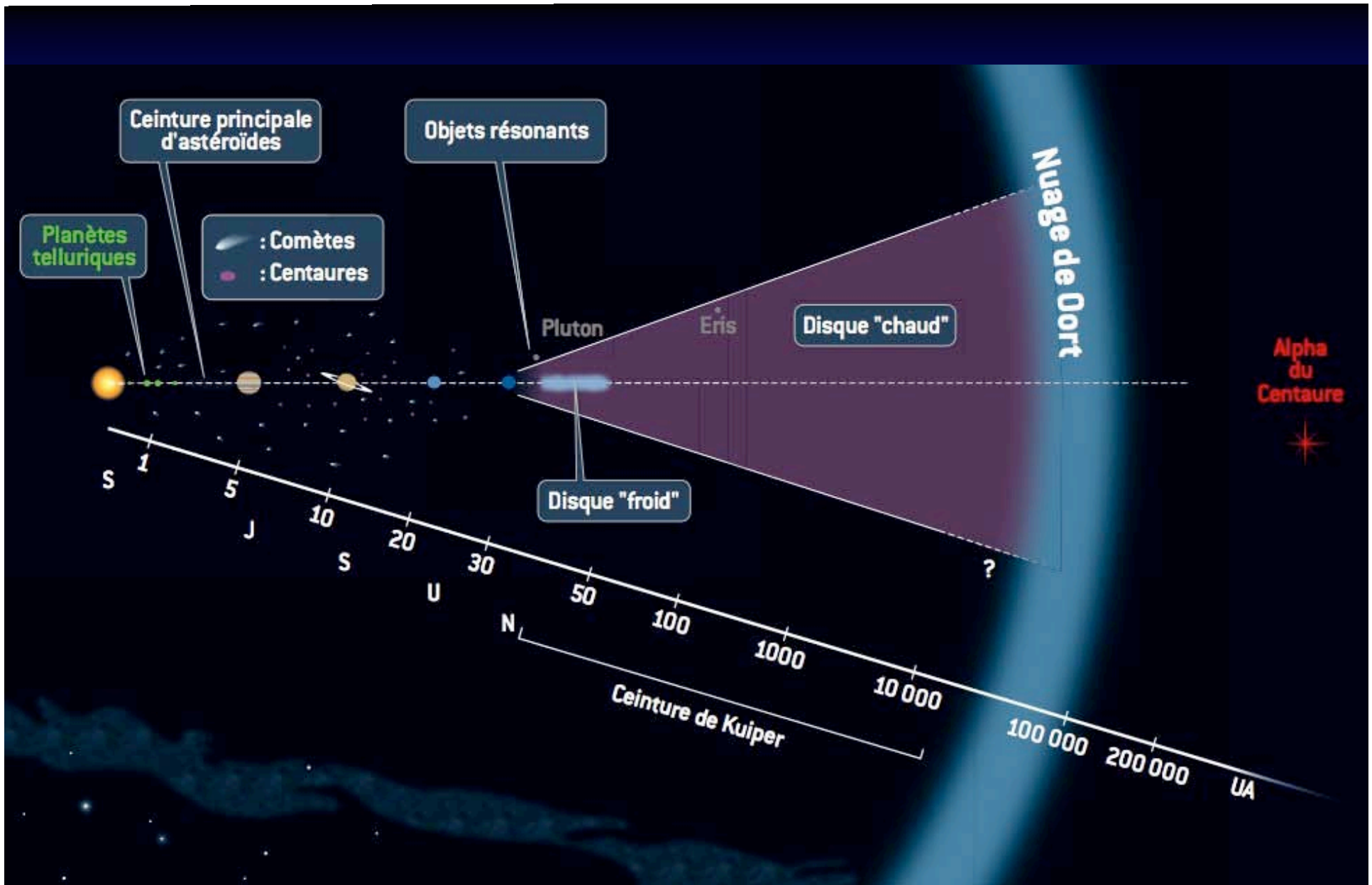


Probing trans-Neptunian Objects
with stellar occultations in Gaia era

Bruno Sicardy
Observatoire de Paris - LESIA
& université Pierre et Marie Curie

Solar system science
before and after Gaia
Pisa 4-6 May 2011



Doressoundiram & Lellouch, "Aux confins du système solaire"

airless Trans-Neptunian Objects (TNO's)

- radius, shape & limb features at kilometric accuracy
- density, if mass known from satellite motion ---> internal structure
- albedo ---> composition, state of surface
- if double occultation primary/secondary: accuracy ~ 10 km, e.g. *Pluton/Charon* ---> better orbital elements

TNO's with atmosphere

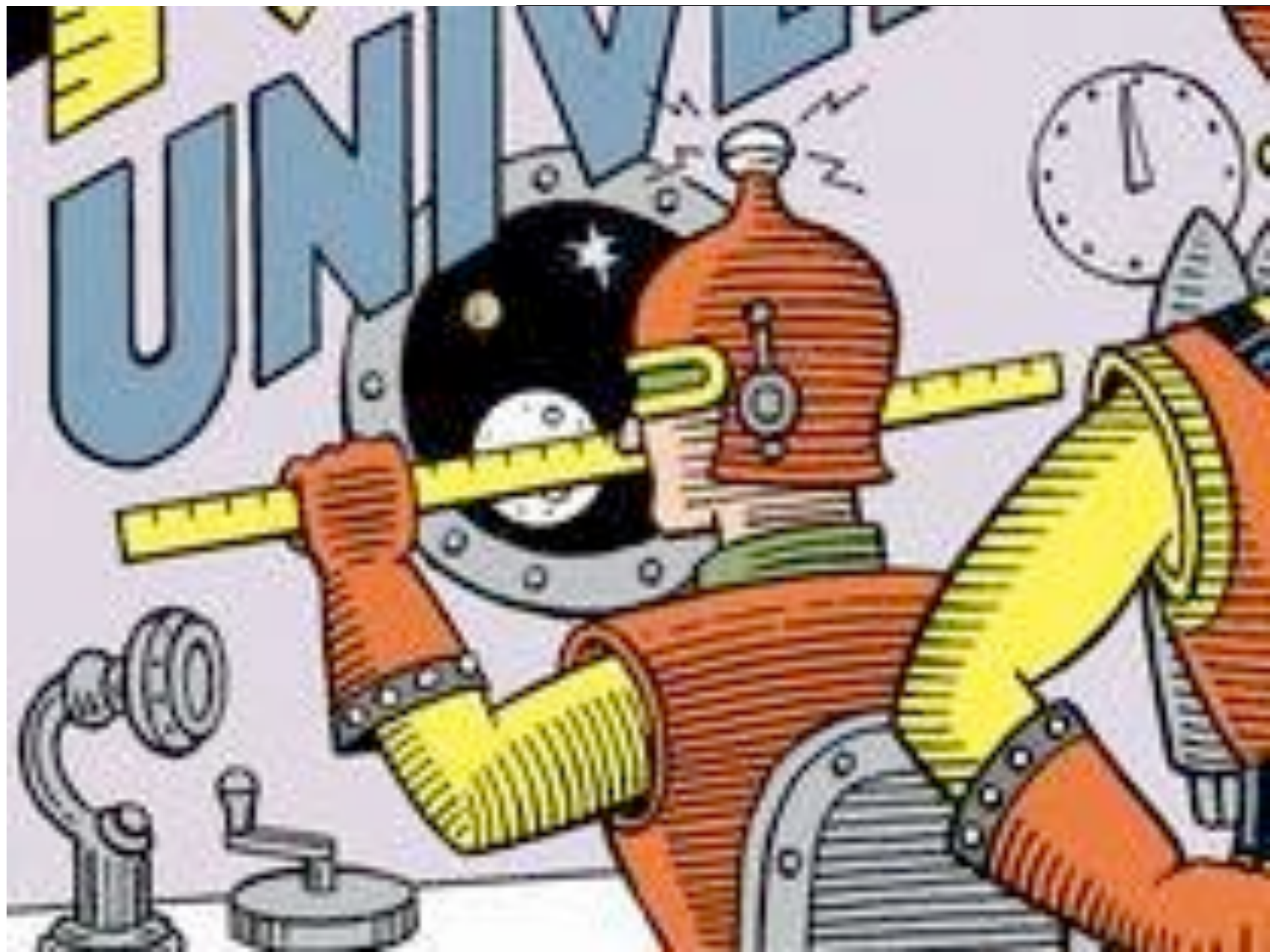
- density & temperature profiles down to nbar levels
- variations with time
- detection of activity (e.g. gravity waves)
- zonal winds measurements through central flash
- haze properties through chromatic dependence

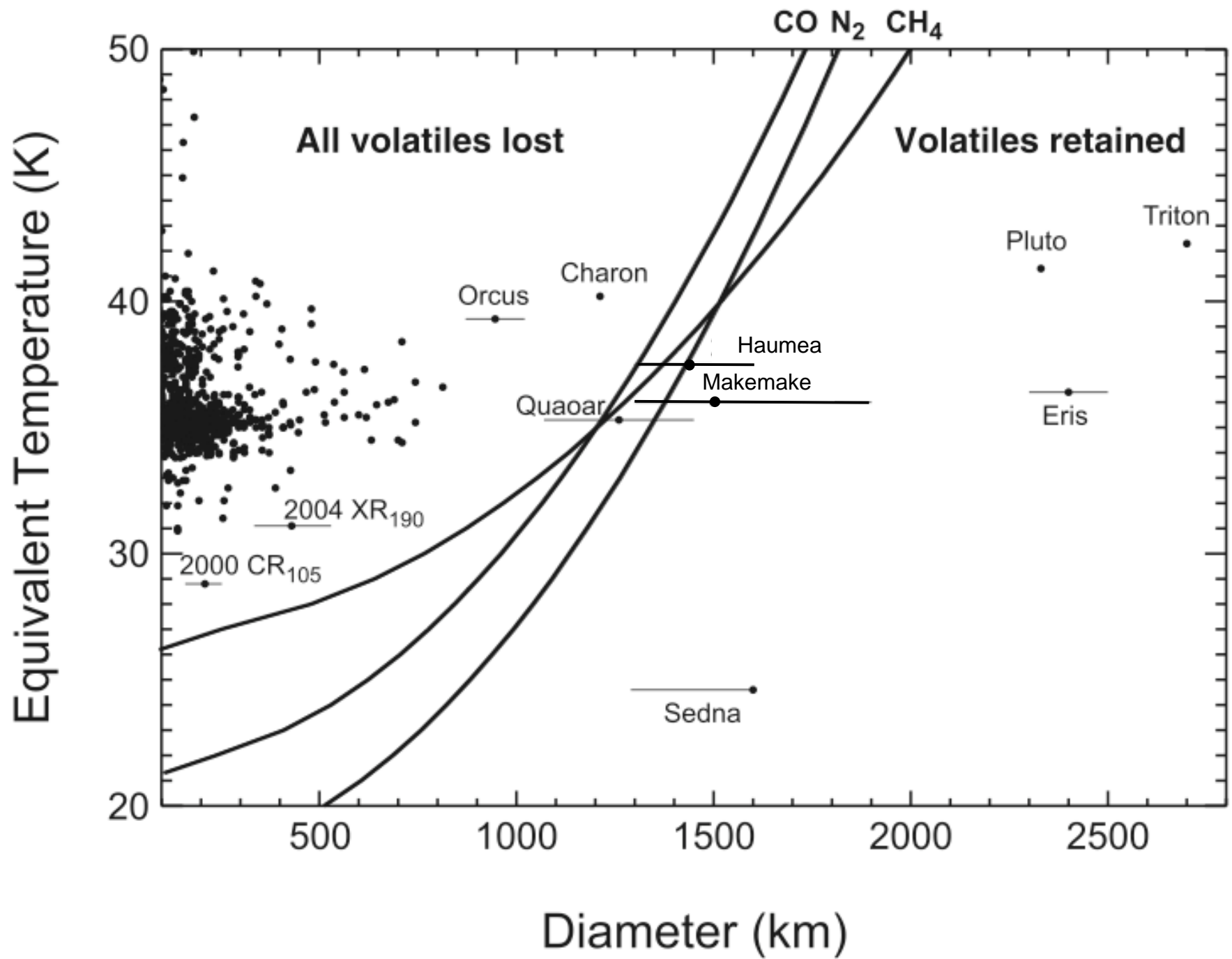
- strength: can achieve what nobody else can do
- weakness: difficult to predict, and thus to plan, especially on large telescopes

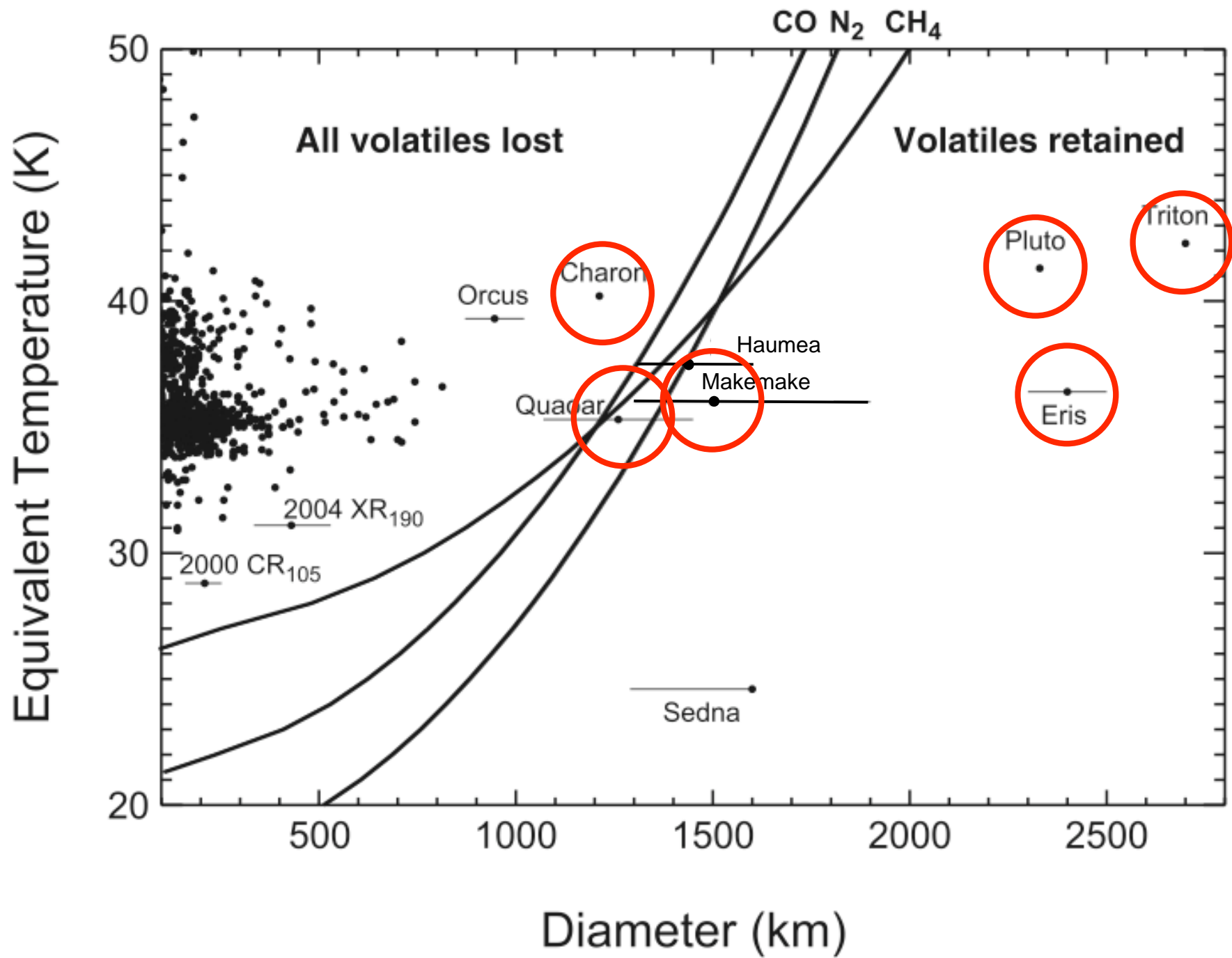
⇒ depending on body and background stellar field:
one occultation of interest every month, year,
decade



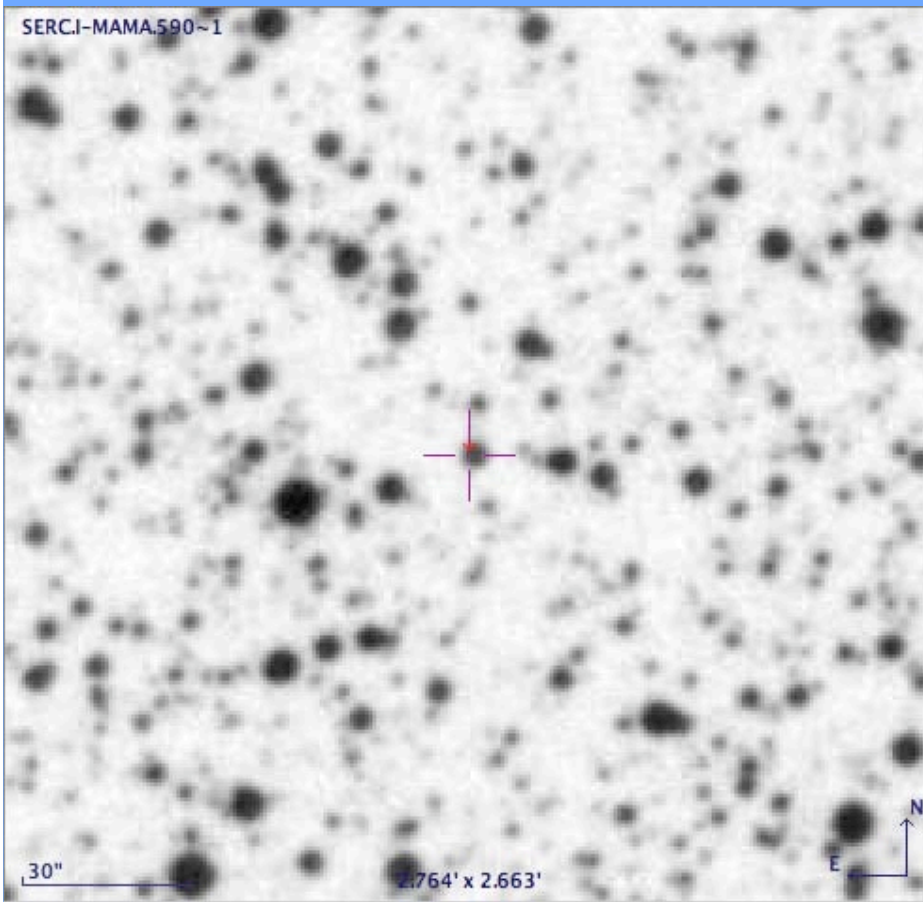
New York Times 11 January 2011: "The War of the Worlds, Round 2"







~ 3x3 arcmin fields of view



Pluton ~ 240 candidates
in 2011

Eris ~ 1 candidate 06 Nov. 2010
next: 29 August 2013

thousands of stars measured against UCAC2 stars positions →
r.m.s. deviations ~ 50 mas

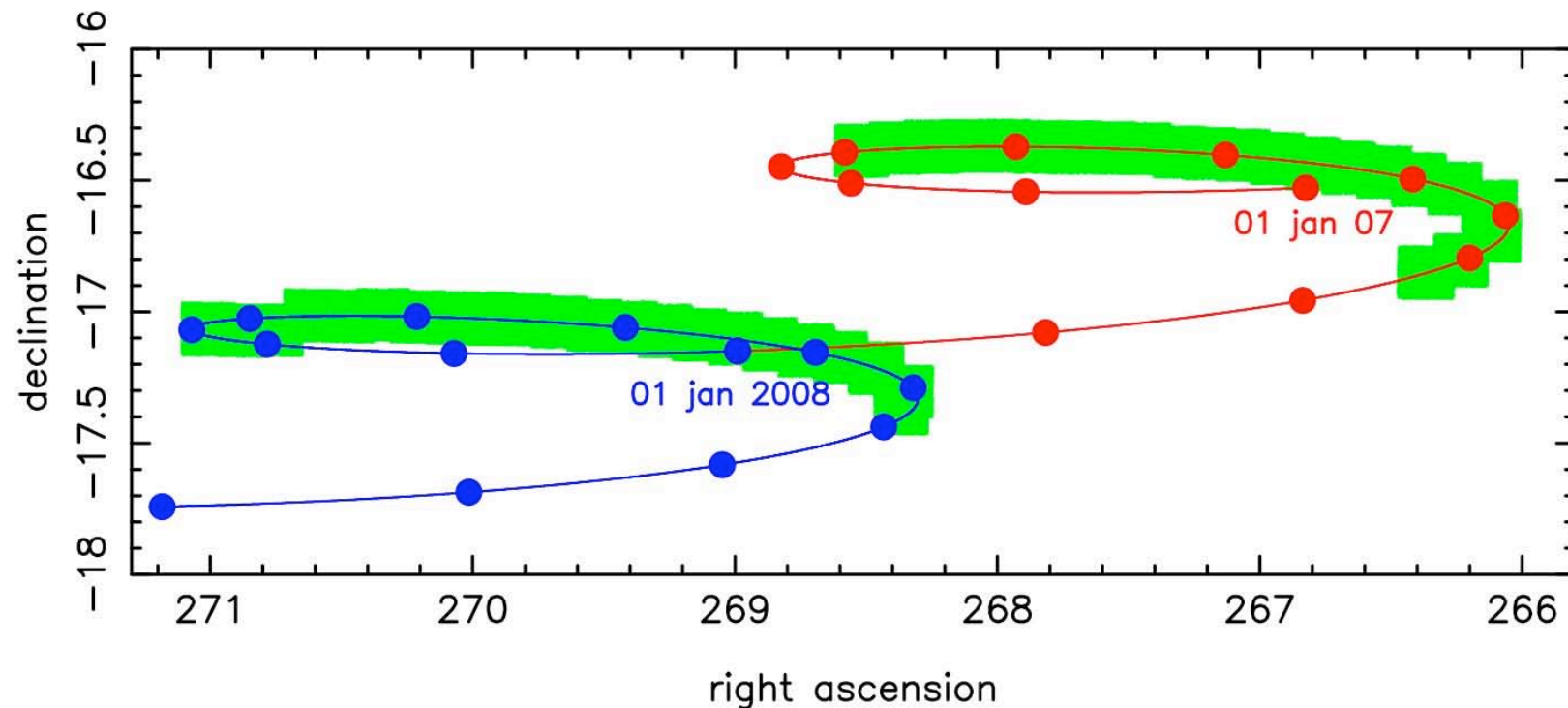
THEN updates 1-3 weeks before → accuracy 20-30 mas

M. Assafin et al. (ON, Rio de Janeiro)

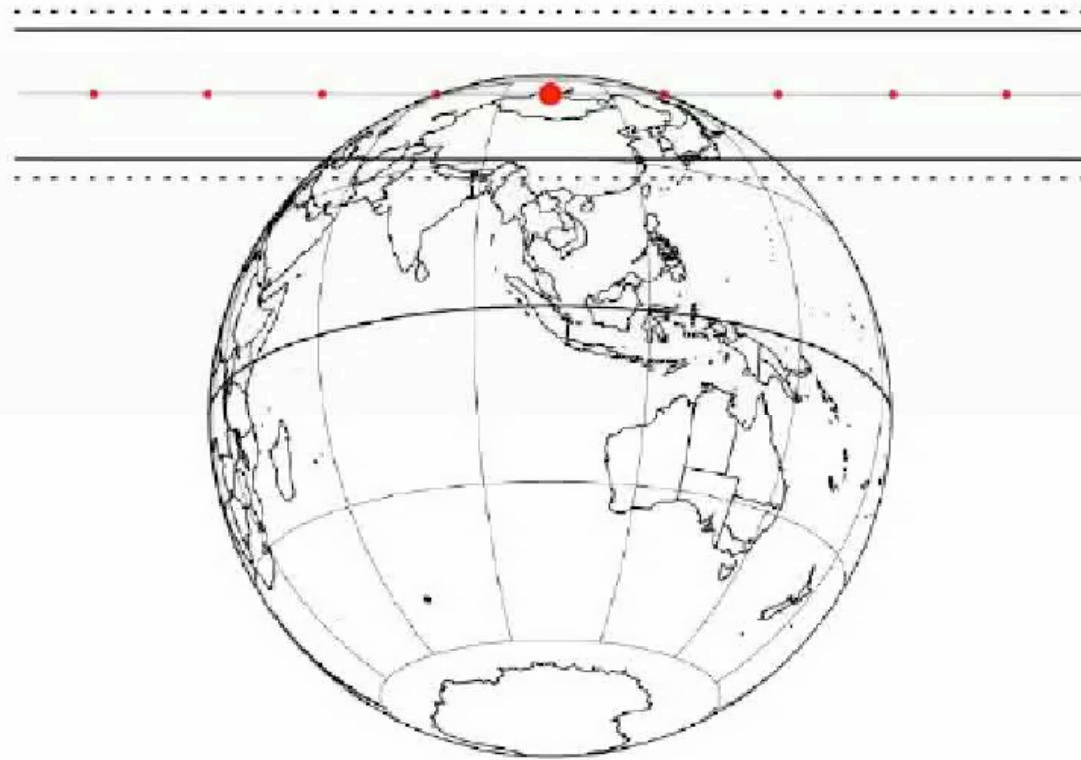
R. Behrend (Geneva Obs)

J.L. Ortiz et al. (IAA Granada)

J2000 – Pluton DE413 – catalogue_Raoul_02jun07.txt

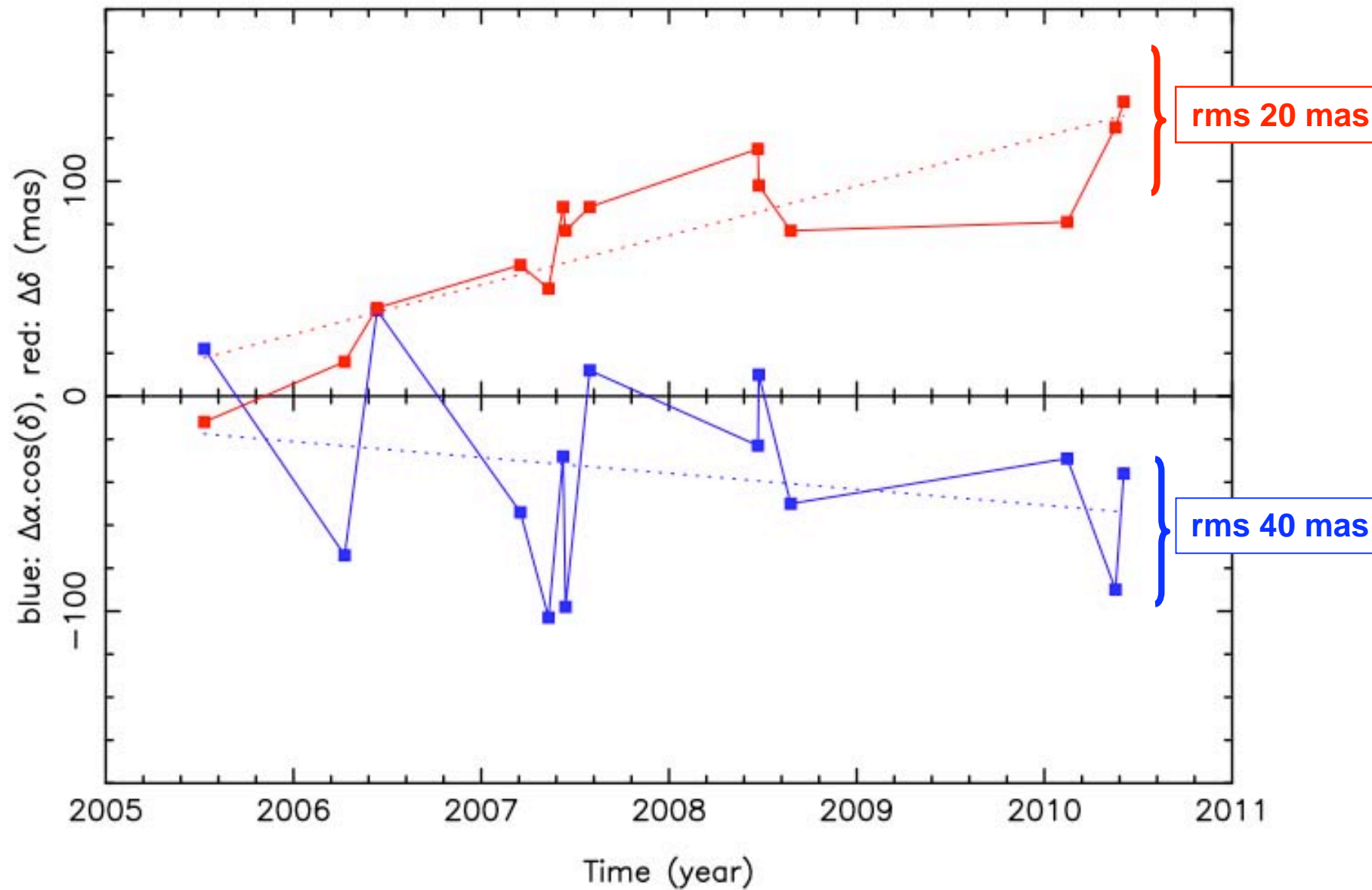


www.lesia.obspm.fr/perso/bruno-sicardy/



d	m	year	h:m:s UT	ra	dec	J2000	candidate	C/A	P/A	vel	Delta	R*	K*	long
02	01	2011	04 44 10.	18 22	0.1425	-18 49	58.097	0.252	0.02	35.59	32.93	16.6	14.0	103.

Pluto offset with respect to DE413



Titan

quaoar

0.033 arsec
(33 mas)

stamp at
140 km



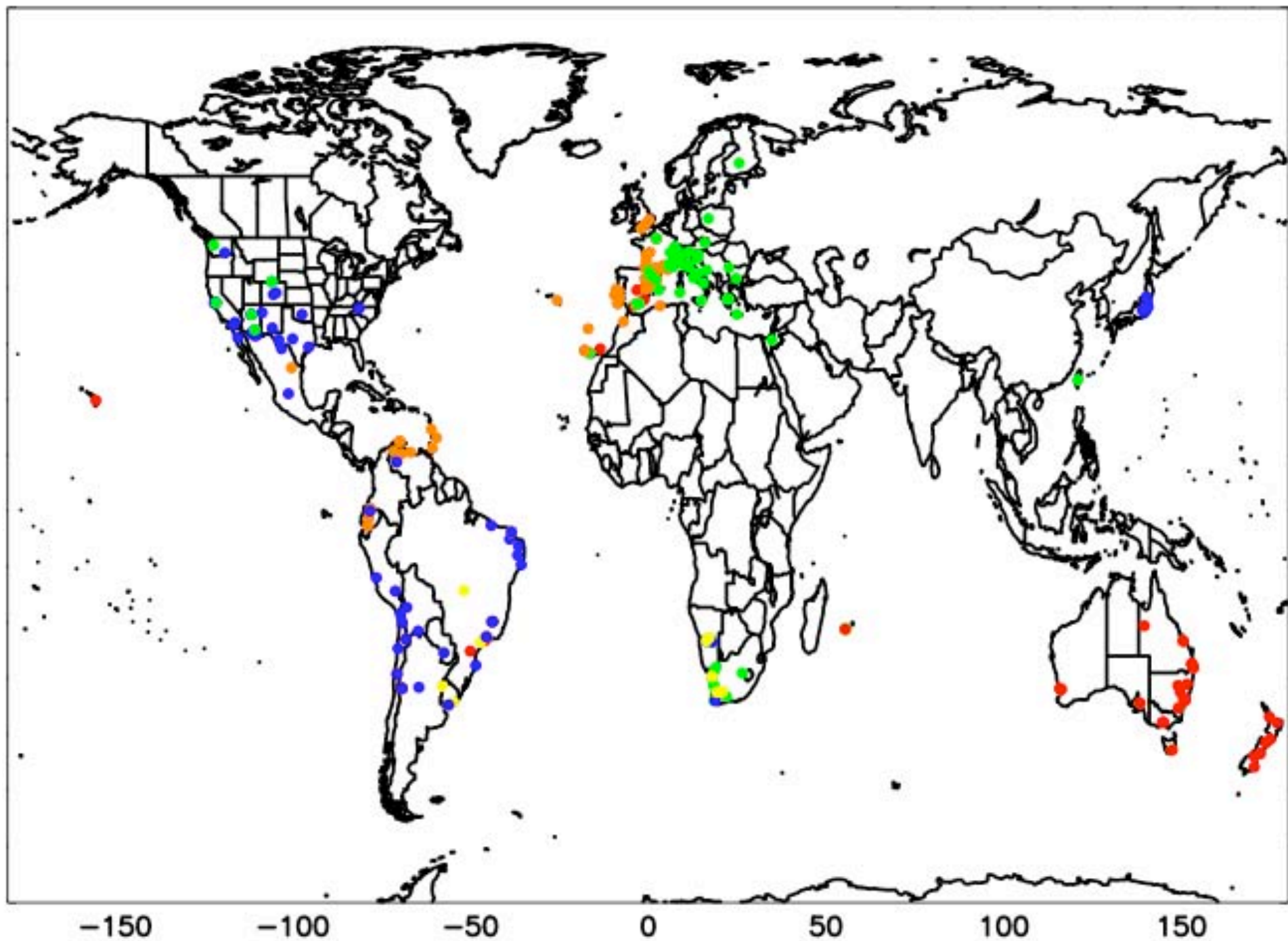
Pluton

Eris



Charon

Makemake



Les plus grands objets transneptuniens connus



Pluton



Éris



Makemake



Haumea



Sedna



Orcus



Quaoar

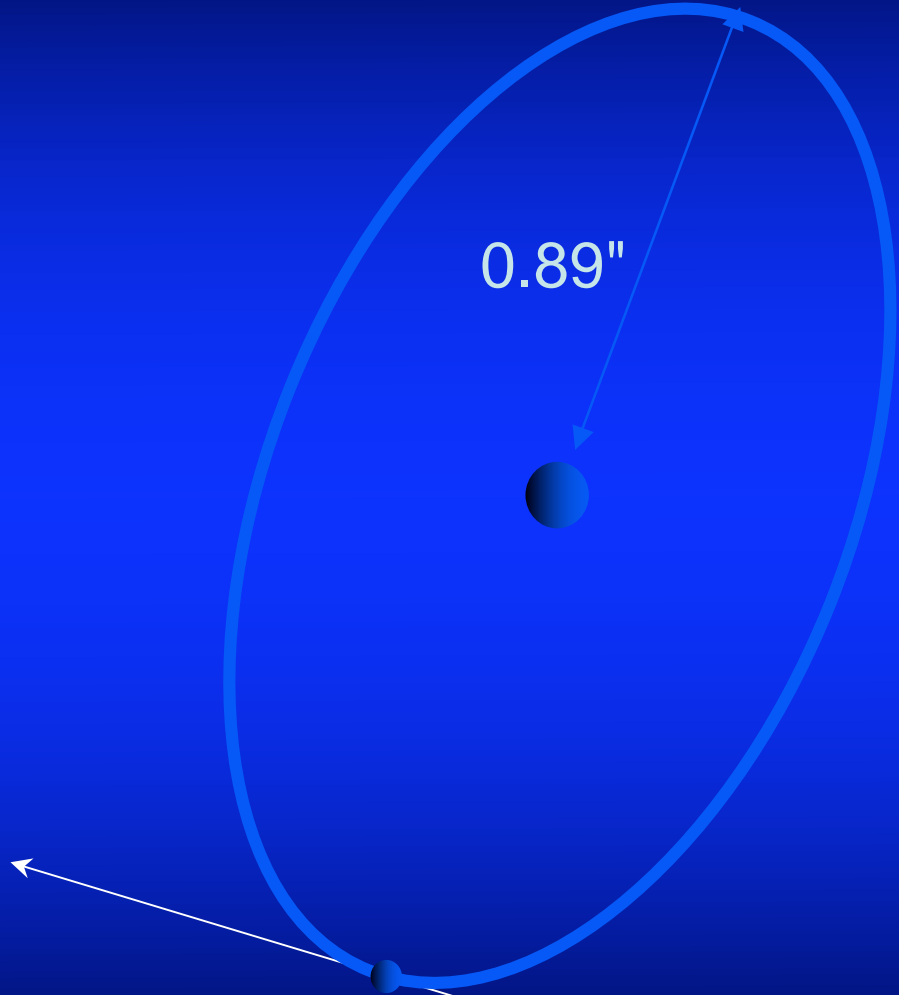


Varuna



2003 AZ₈₄



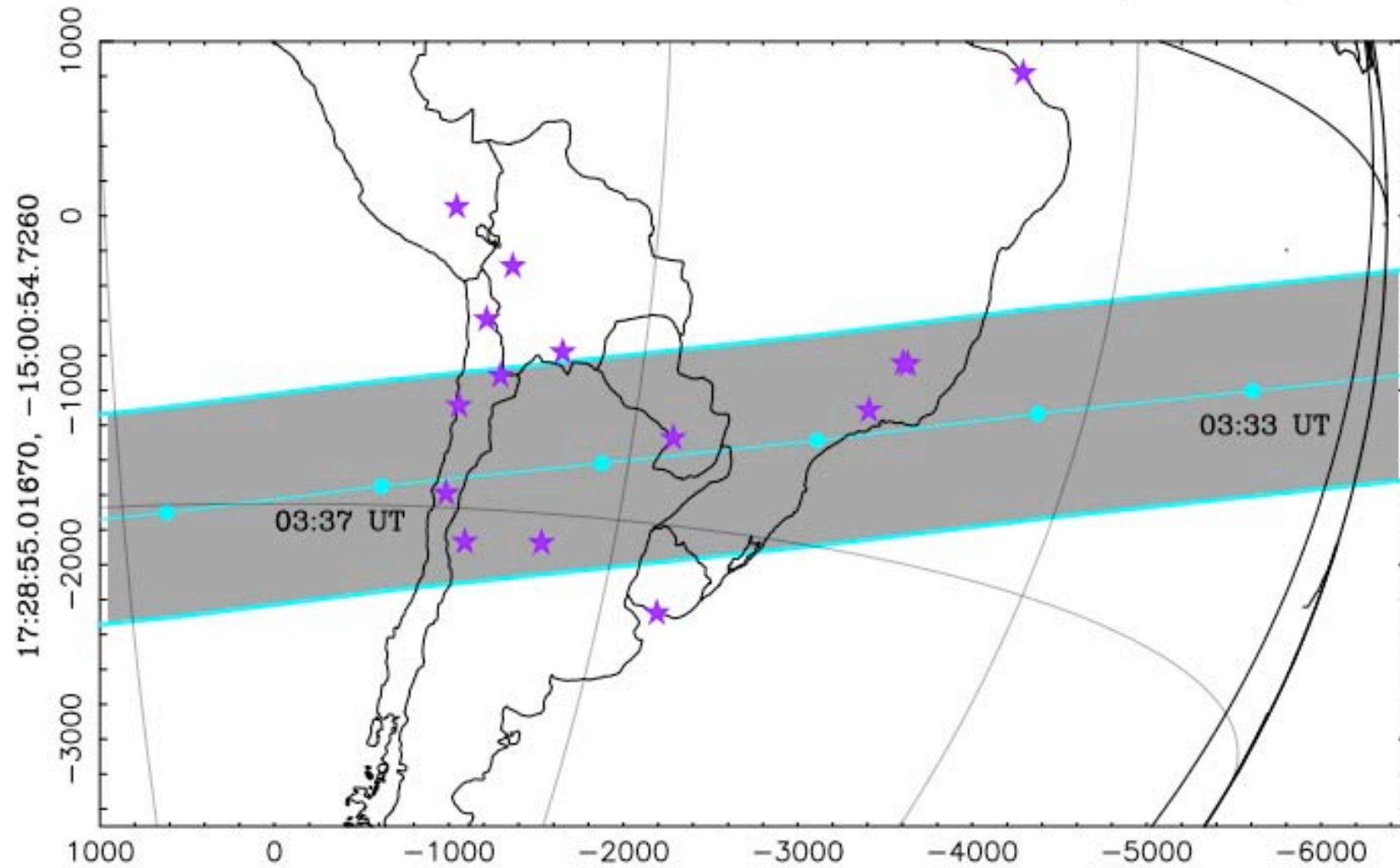


2UCAC 26257135
(D. Herald, Aug. 2004)

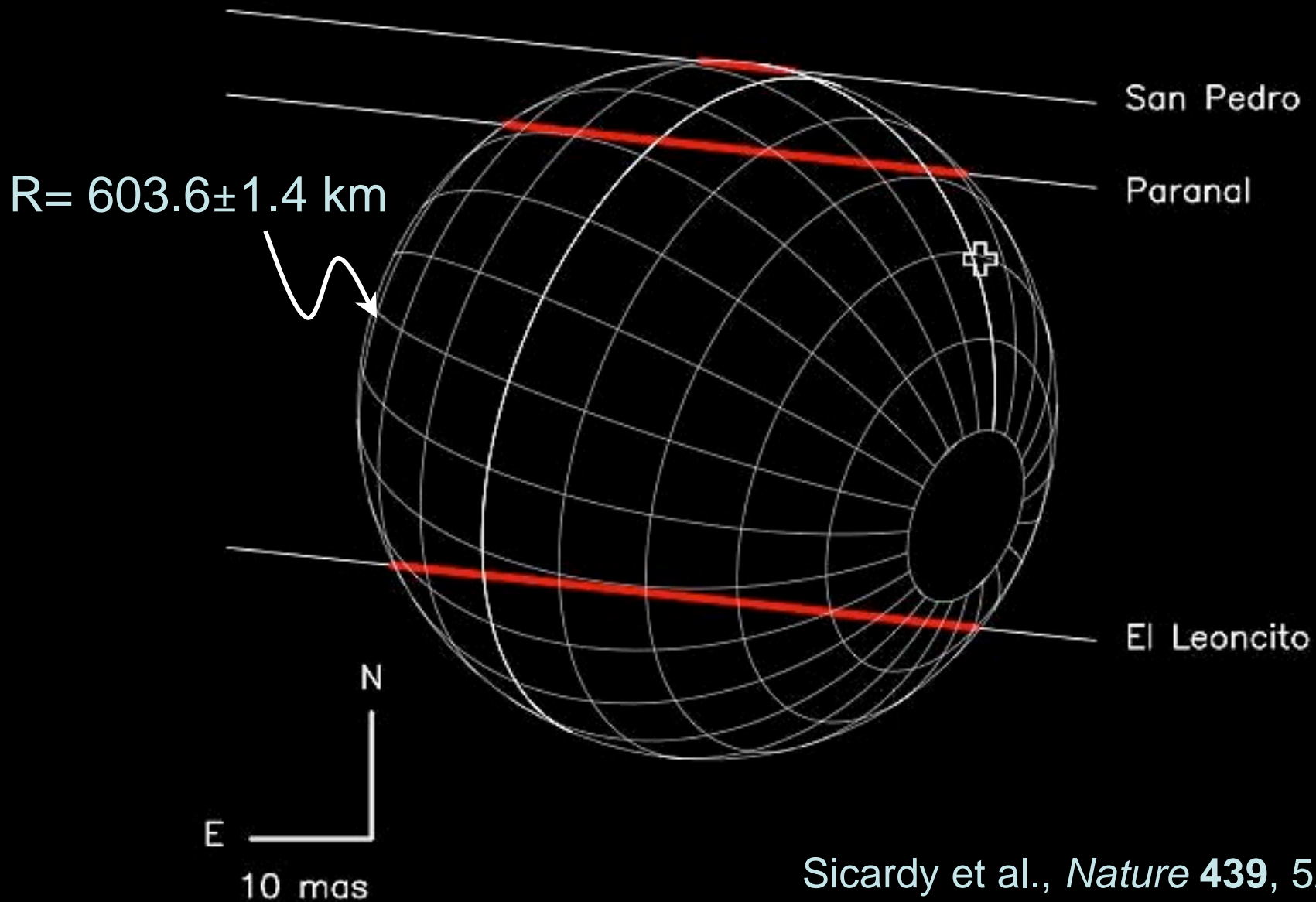


Charon

Charon UCAC2 2625 7135, correction DE413: 0.021 -0.011 (post-event)

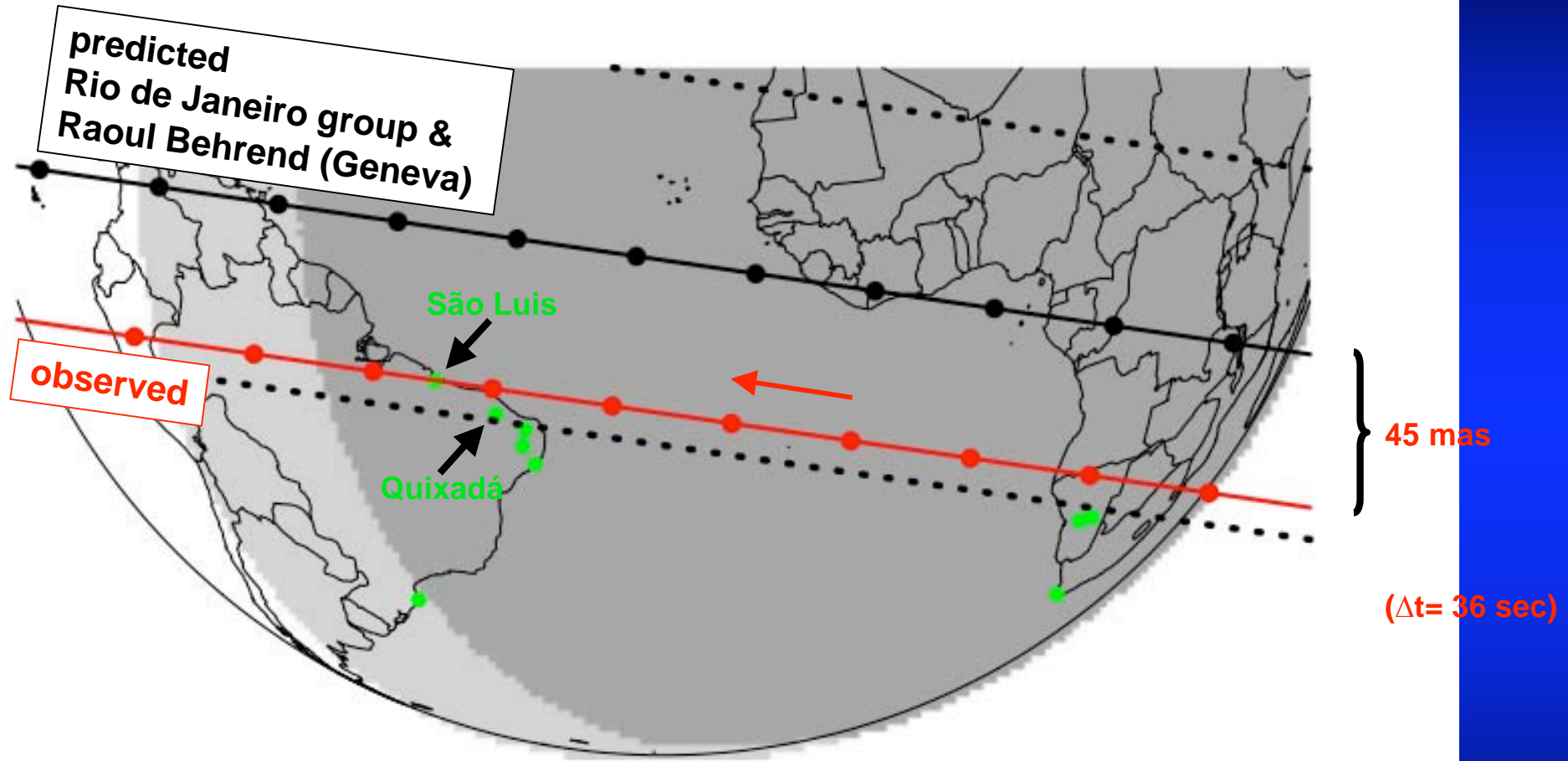


11 July 2005, 03:36 UT, 1" = 21809 km, JPL, DE-0413 Plu013

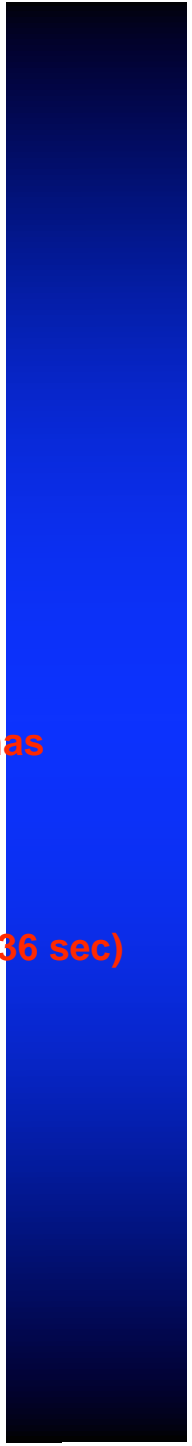


Sicardy et al., *Nature* **439**, 52, 2006
« Charon's size and an upper limit on its atmosphere from a stellar occultation »

Varuna



distance: 42.75 UA



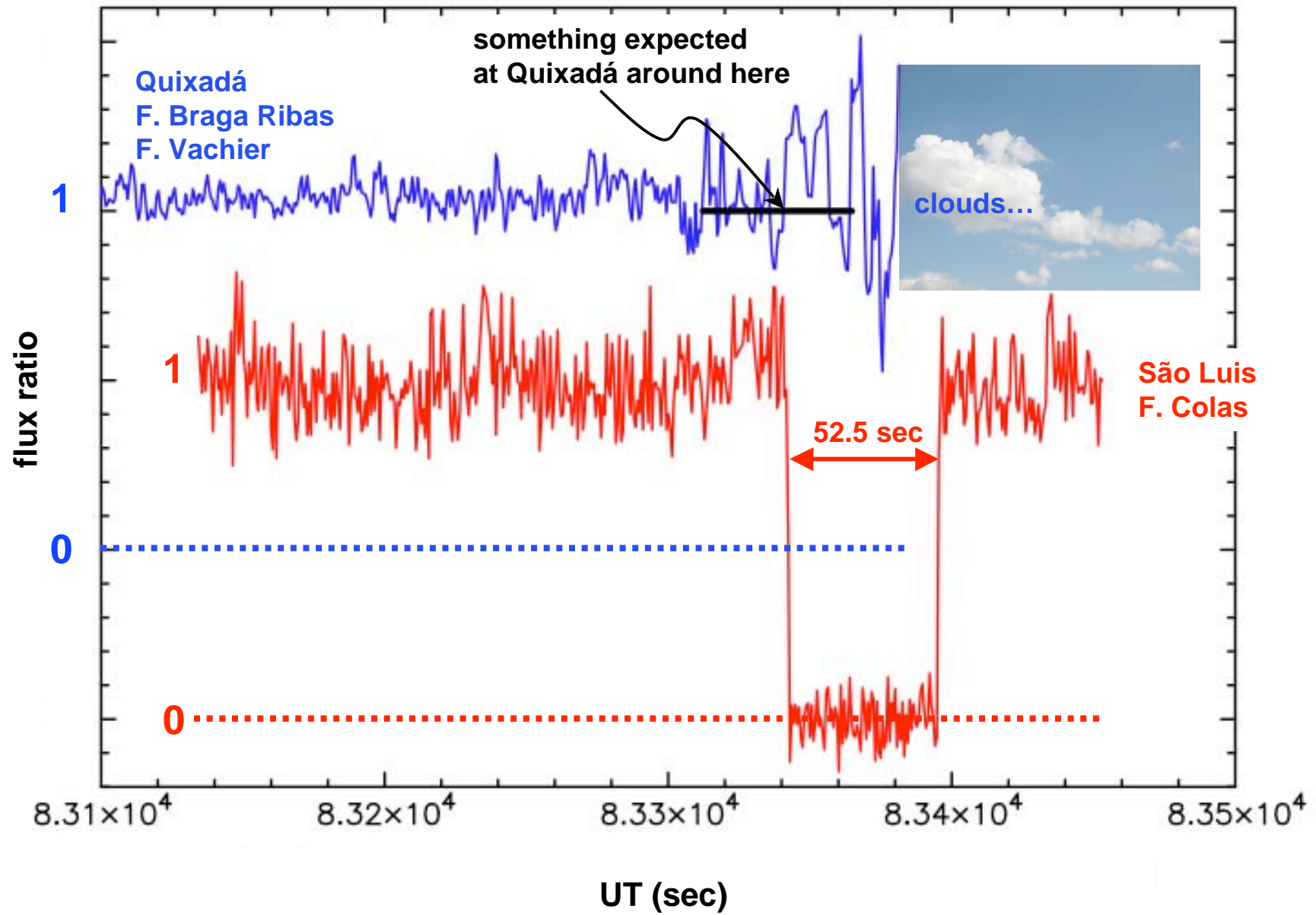


São Luis, Maranhão, Brazil, February 2010, F. Colas

São Luis, Brazil
telescope 12.5 cm, alt.: 2 m
F. Colas

Mangrove, São Luis, from <http://www.blogg.org/blog-16247-offset-415.html>

Varuna, 2010 February 19, both curves 0.64 sec



dark ($p_v=0.04$)
least elongated
probability ~ 0
610x525 km

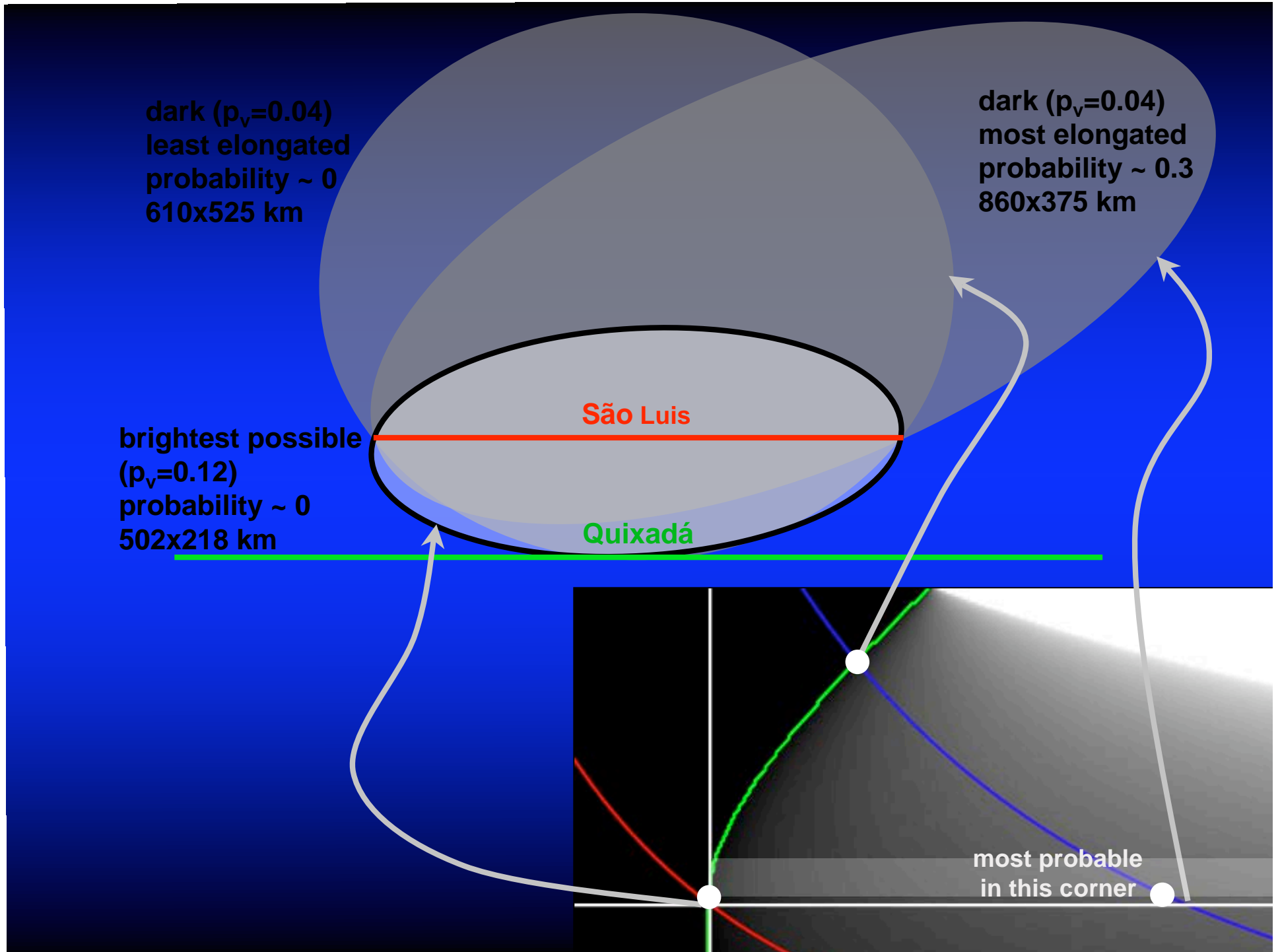
dark ($p_v=0.04$)
most elongated
probability ~ 0.3
860x375 km

brightest possible
($p_v=0.12$)
probability ~ 0
502x218 km

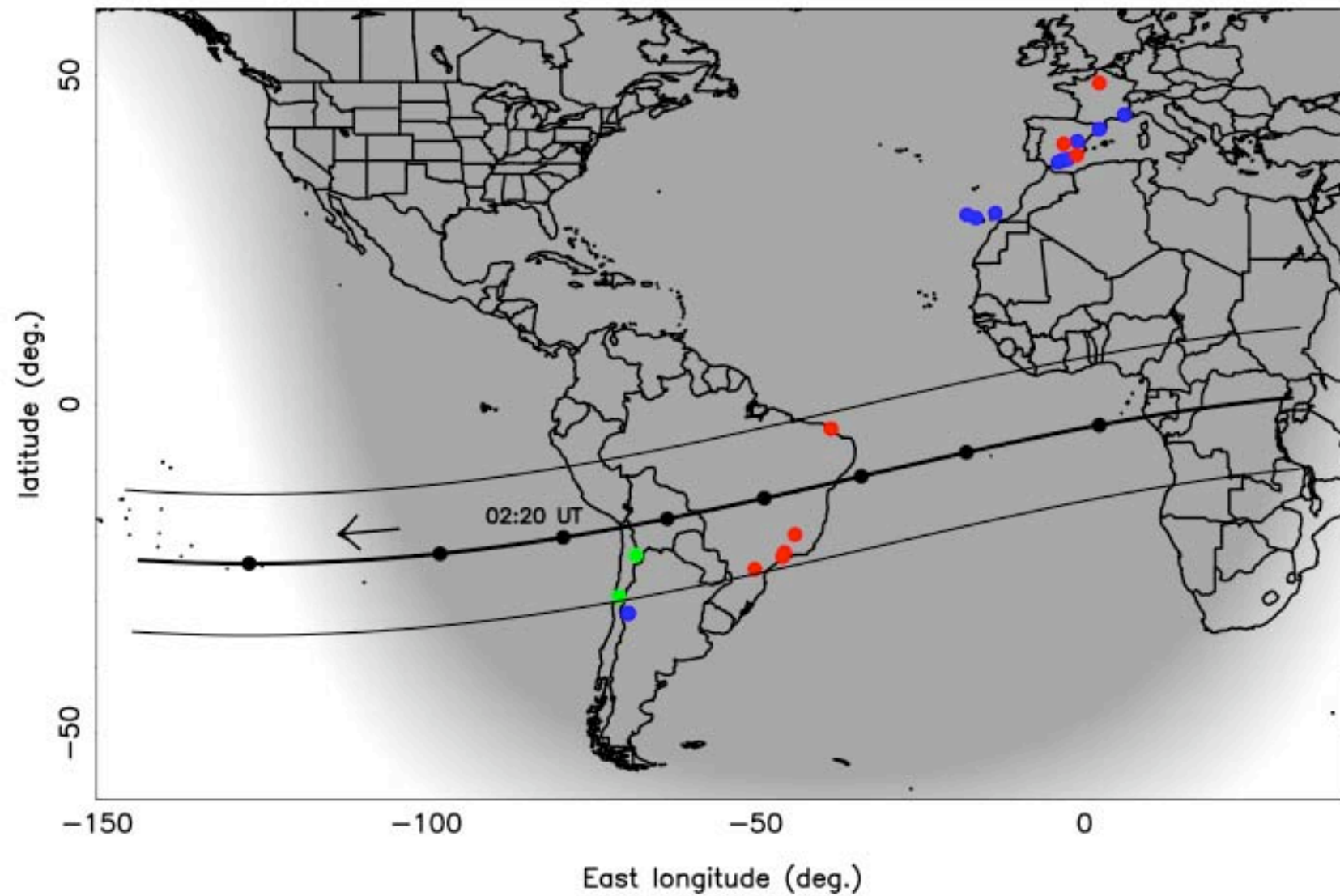
São Luis

Quixadá

most probable
in this corner



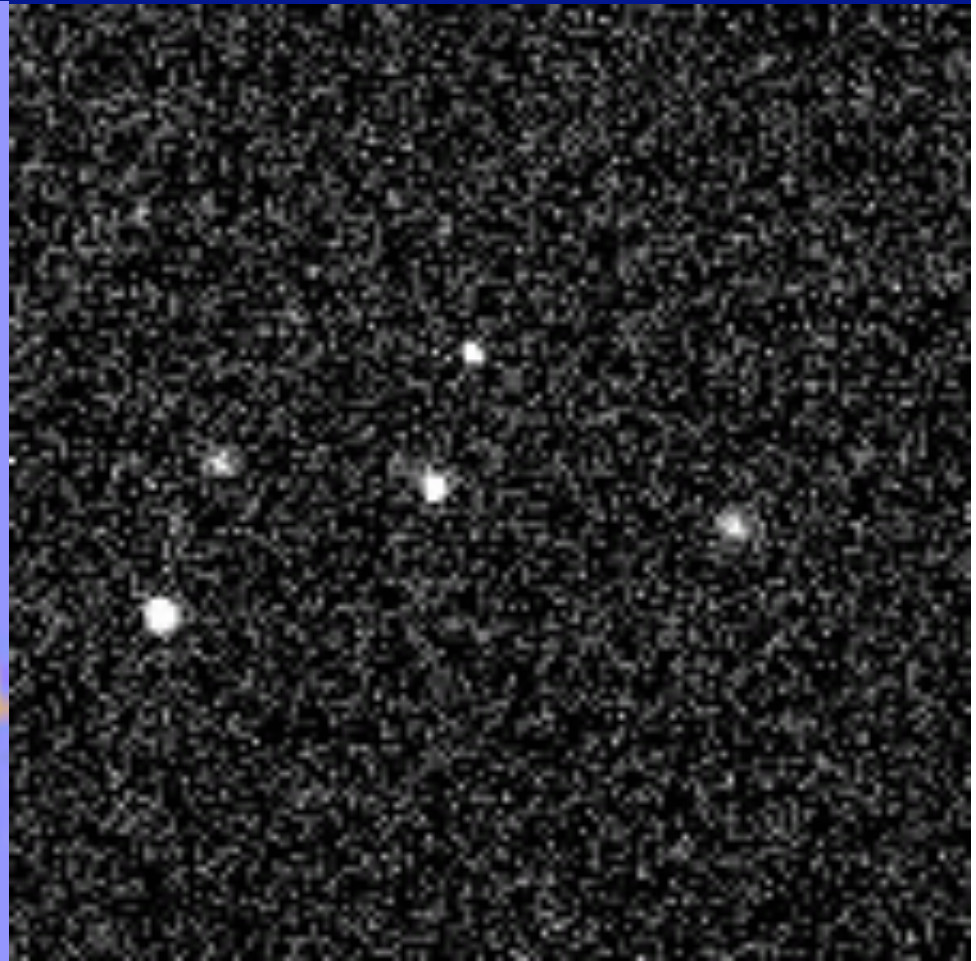
Eris



6 novembre 2010, Sicardy *et al.* *Nature* 2011, to be submitted

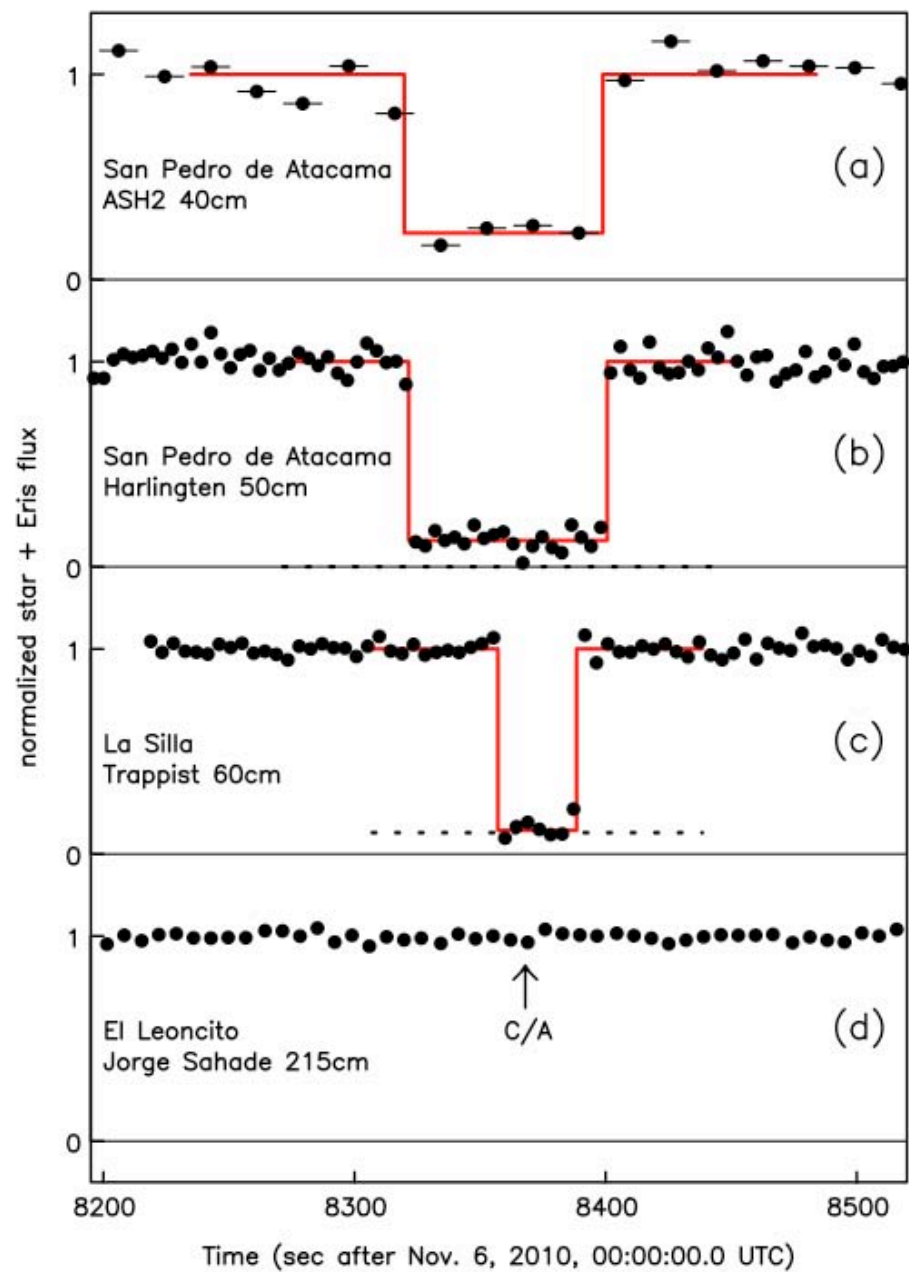
Occultation by
136199 Eris
San Pedro de
Atacama

Celestial Exploration
November 5th 2010



Alain Maury, 50 cm
Sand Pedro de Atacama

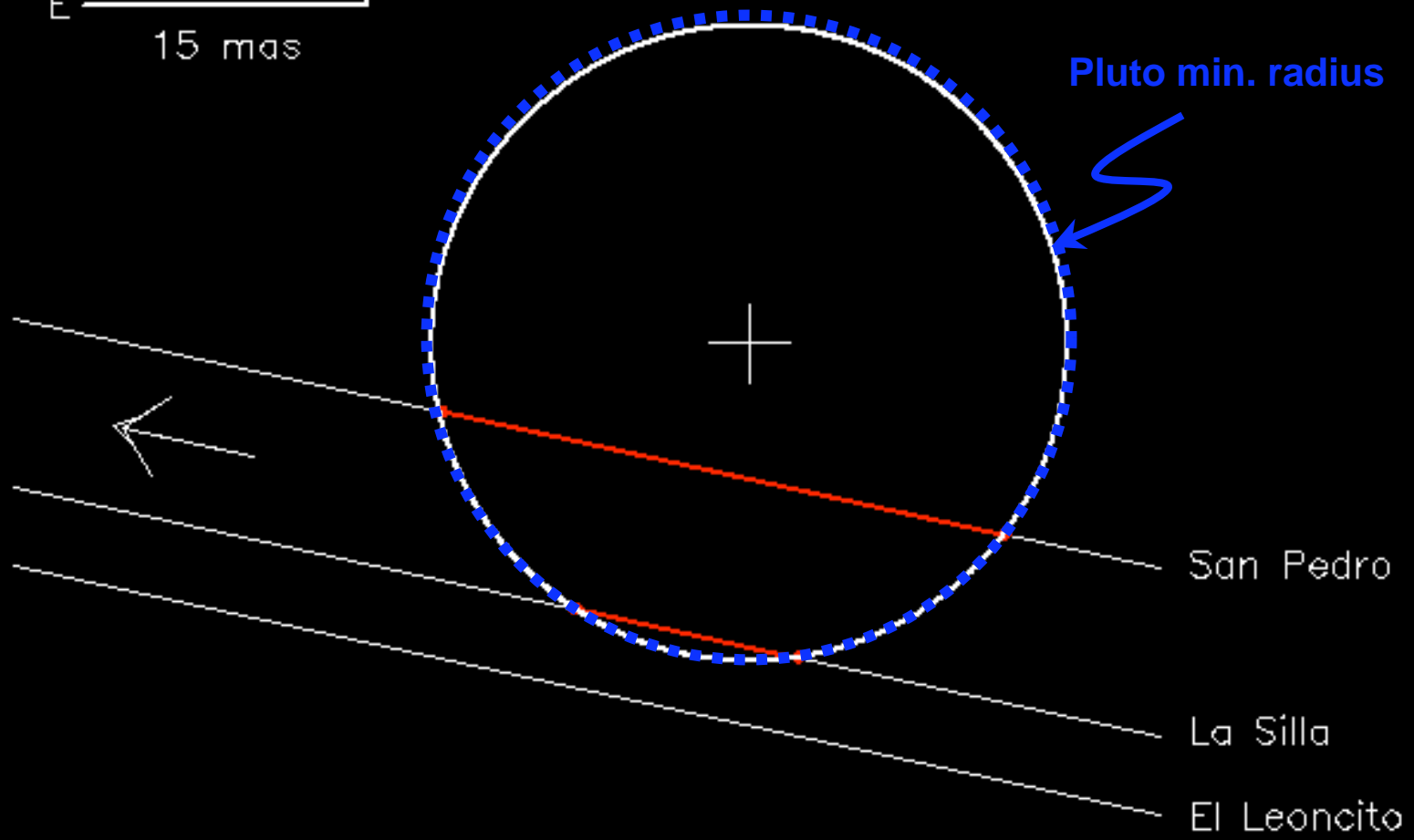
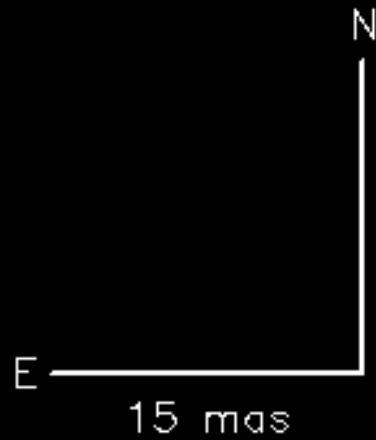
Emmanuel Jehin, 60 cm
La Silla



most remote object observed in solar system (97 UA, 15 billions km)

p_v close to one \rightarrow one of brightest objects of solar system

atmospheric limit of $N_2 \sim 1$ nanobar ($10^{-4} \times$ Pluton atmosphere)



2006

LETTERS

The trans-neptunian object ~~UB₃₁₃~~ ^{Eris} is larger than Pluto 

F. Bertoldi^{1,2}, W. Altenhoff², A. Weiss², K.M. Menten² & C. Thum³

2010

SOLAR SYSTEM

**Pluto is again
a harbinger**

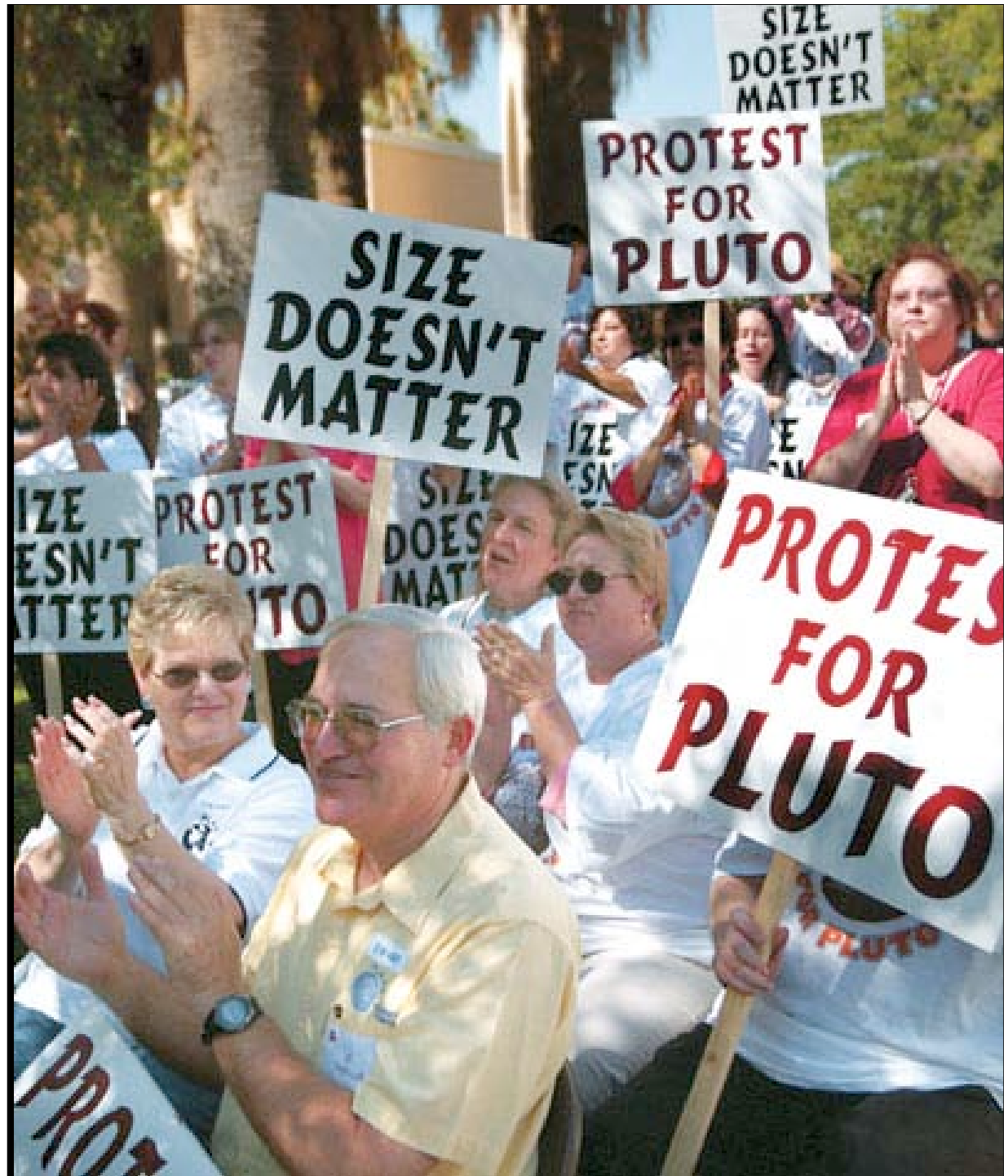
New astronomical and laboratory data show that the abundances of the two dominant ices, nitrogen and methane, on the surfaces of the Solar System's two largest dwarf planets are surprisingly similar — raising fresh questions.

S. ALAN STERN

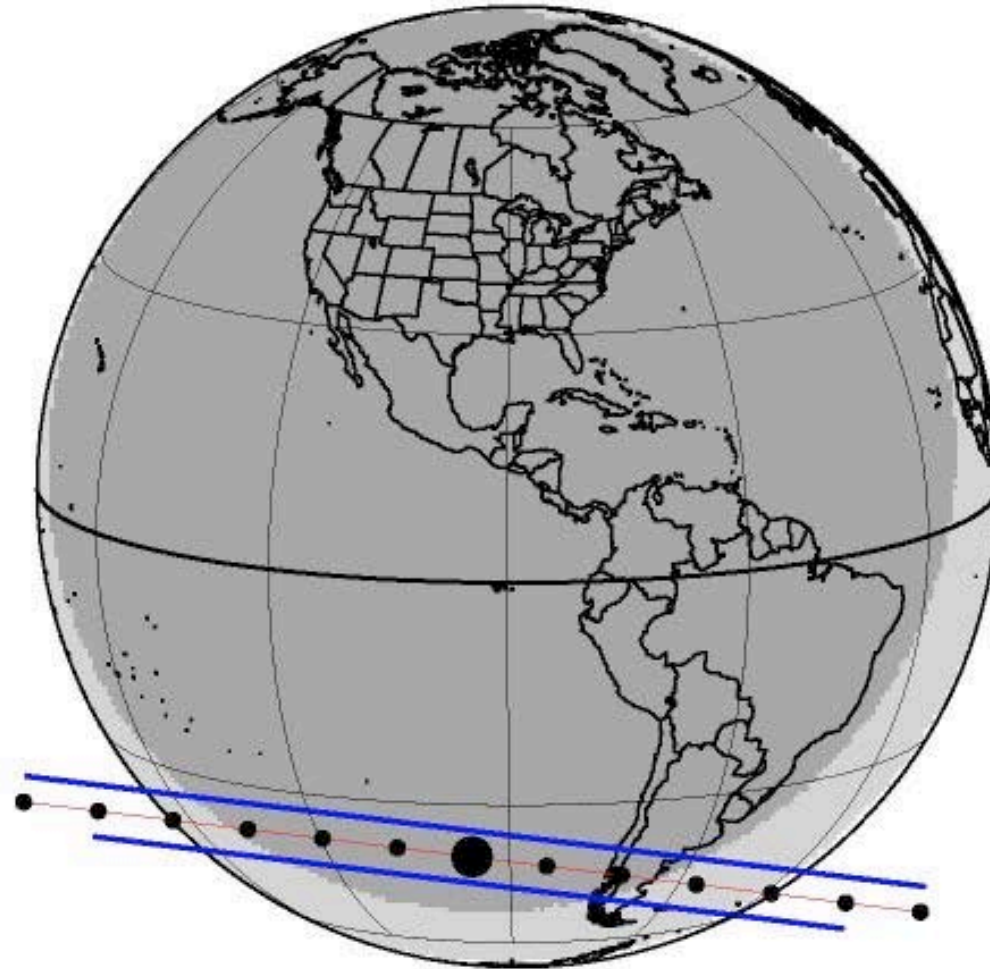
Mike W... 4 decembre 2010,
14:03

Dear Mr. Sikardy,[...] I am an artist/writer/attorney and have loved Pluto since I first learned about as a little boy. I asked President George W. Bush in July 2002 when I met him in Portland, Oregon [...]

Anyway, I am very glad that Eris will lose more diameter based on the final calculations of the stellar occultation. Given the bad behavior of Mike "Pluto-Killer" Brown, it would make it even more joyous, I must admit, if Eris were to lose enough diameter to make it virtually certain that Pluto is larger. Alan Stern told me that New Horizons, barring a mishap, will measure Pluto's diameter, too.



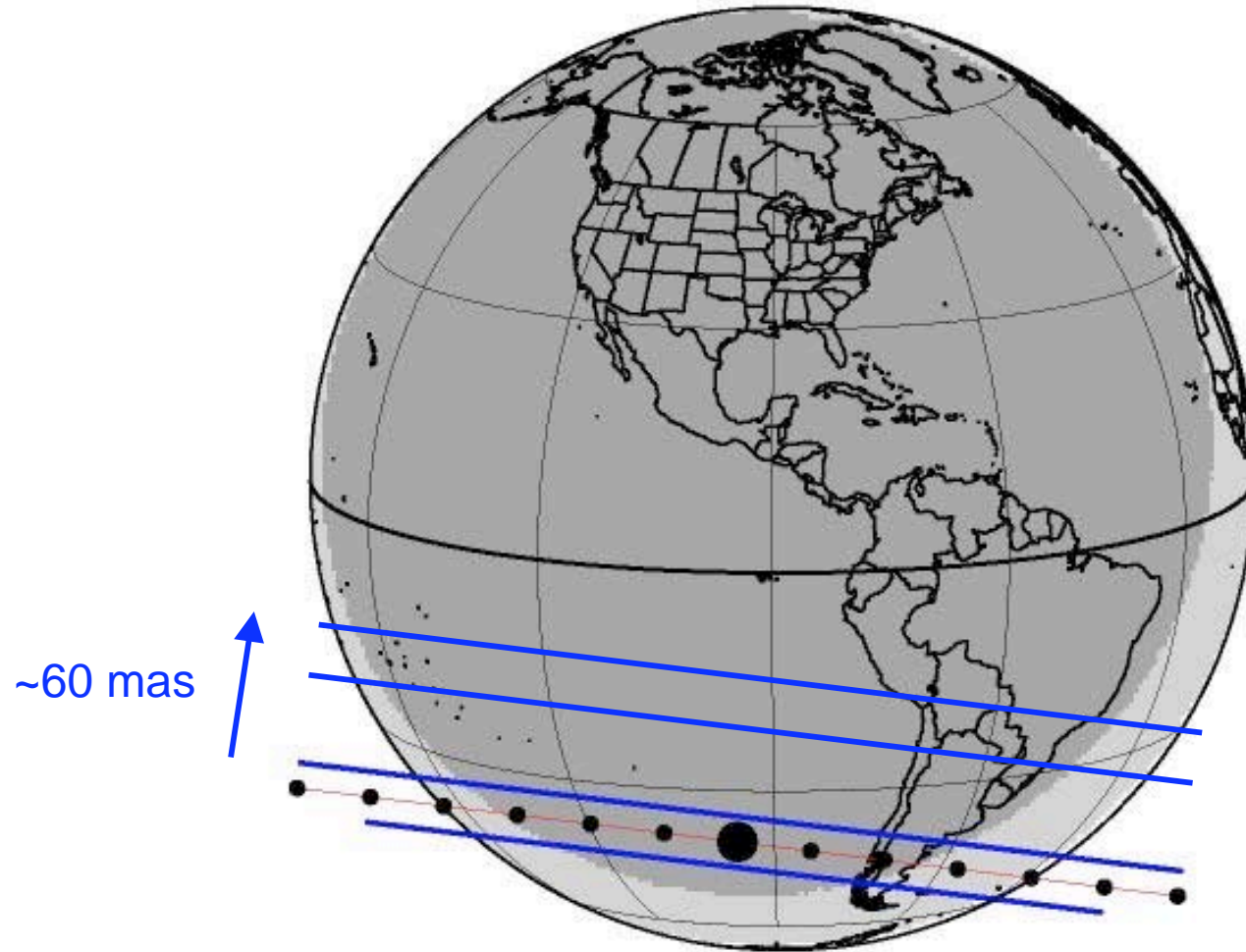
2003 AZ84



d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	R*	K*	long
08	01	2011	06 28 57.0	07 43	41.8228	+11 30 23.580	0.154	187.00	-26.01	44.32	18.5	50.0	-89

Credits: Rio Team & B. Sicardy

2003 AZ84



d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	R*	K*	long
08	01	2011	06 28 57.0	07 43	41.8228	+11 30 23.580	0.154	187.00	-26.01	44.32	18.5	50.0	-89

Credits: Rio Team & B. Sicardy

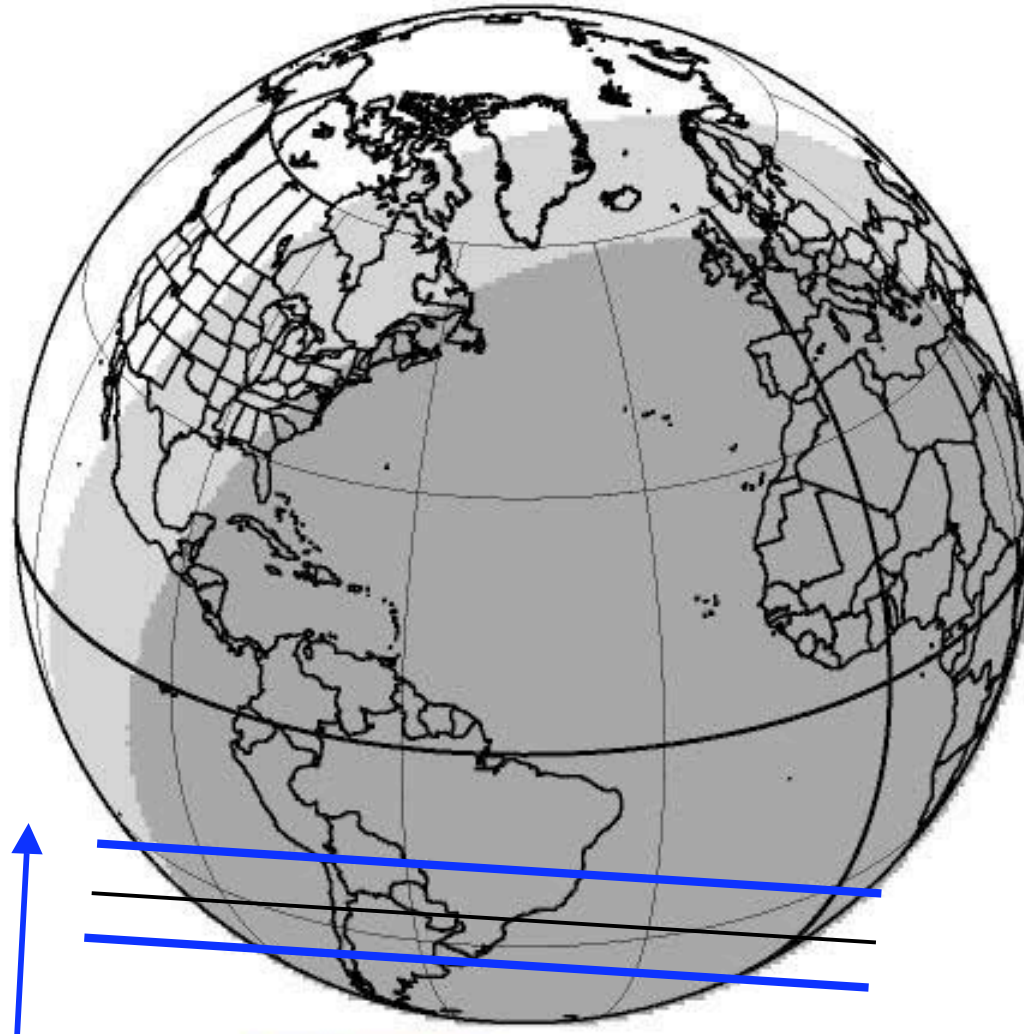
Makemake



d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	R*	K*	long
23	04	2011	01 37 08.0	12 36 11.3962	+28°11'	●.526	0.208	183.80	-22.09	51.50	18.4	50.0	-46

Credits: Rio Team & B. Sicardy

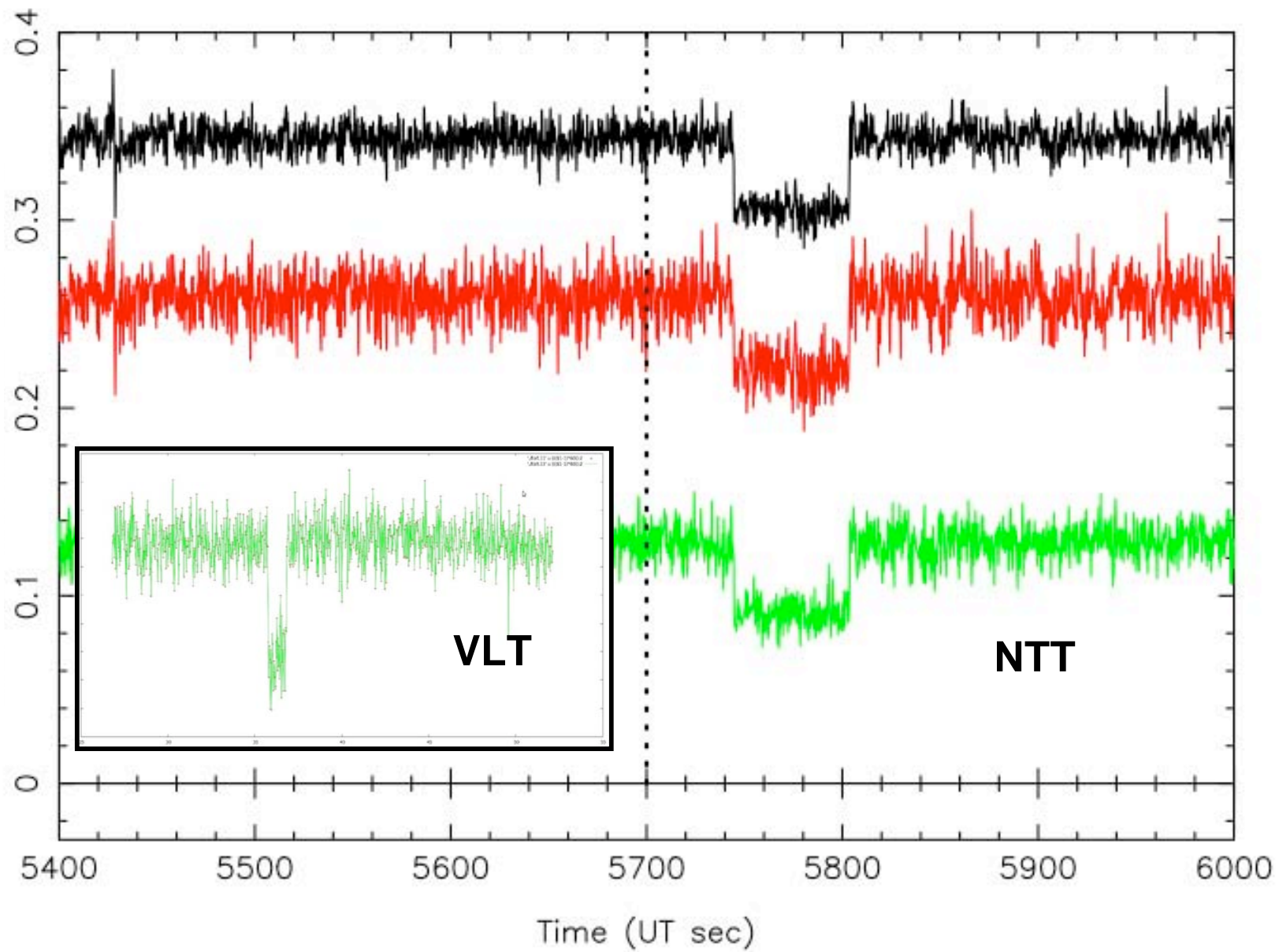
Makemake



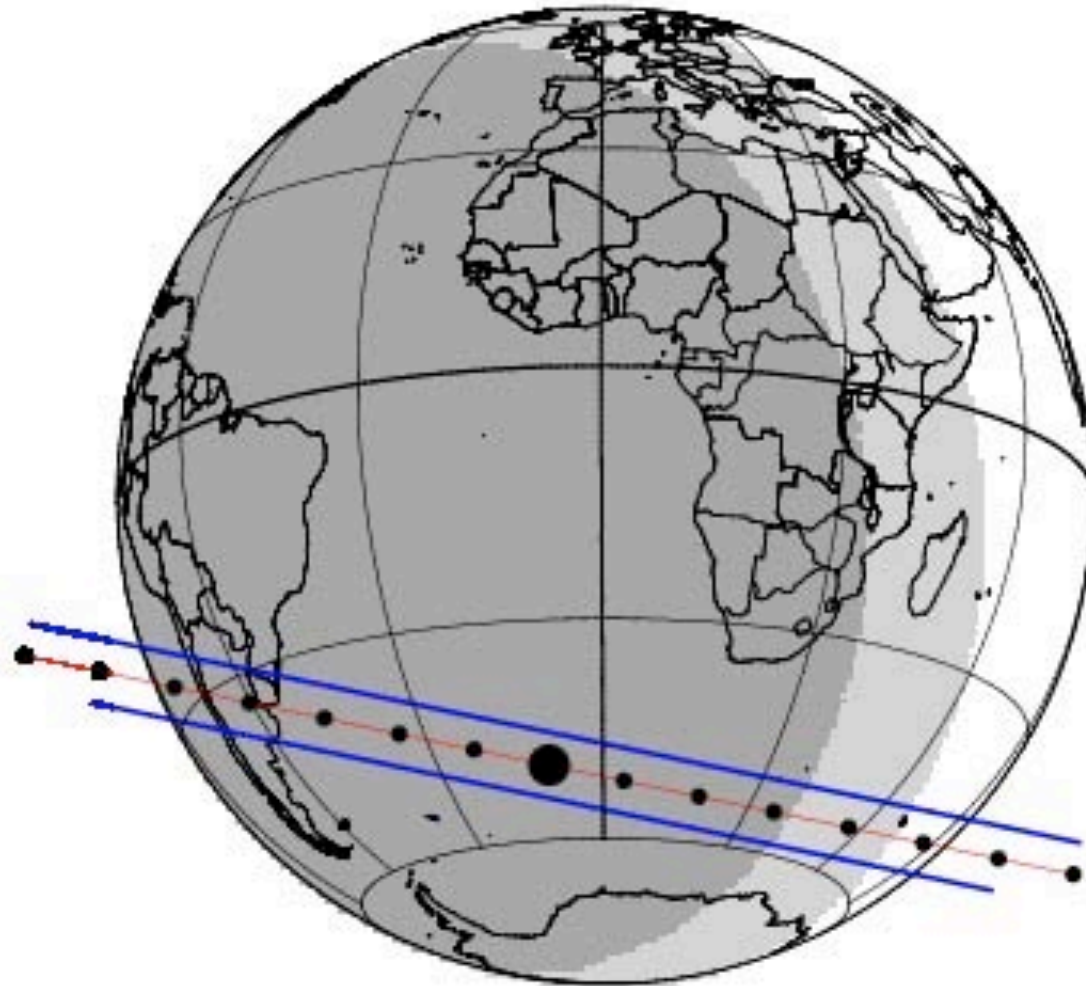
~60 mas

d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	R*	K*	long
23	04	2011	01 37 08.0	12 36 11.3962	+28°11	●.526	0.208	183.80	-22.09	51.50	18.4	50.0	-46

Credits: Rio Team & B. Sicardy



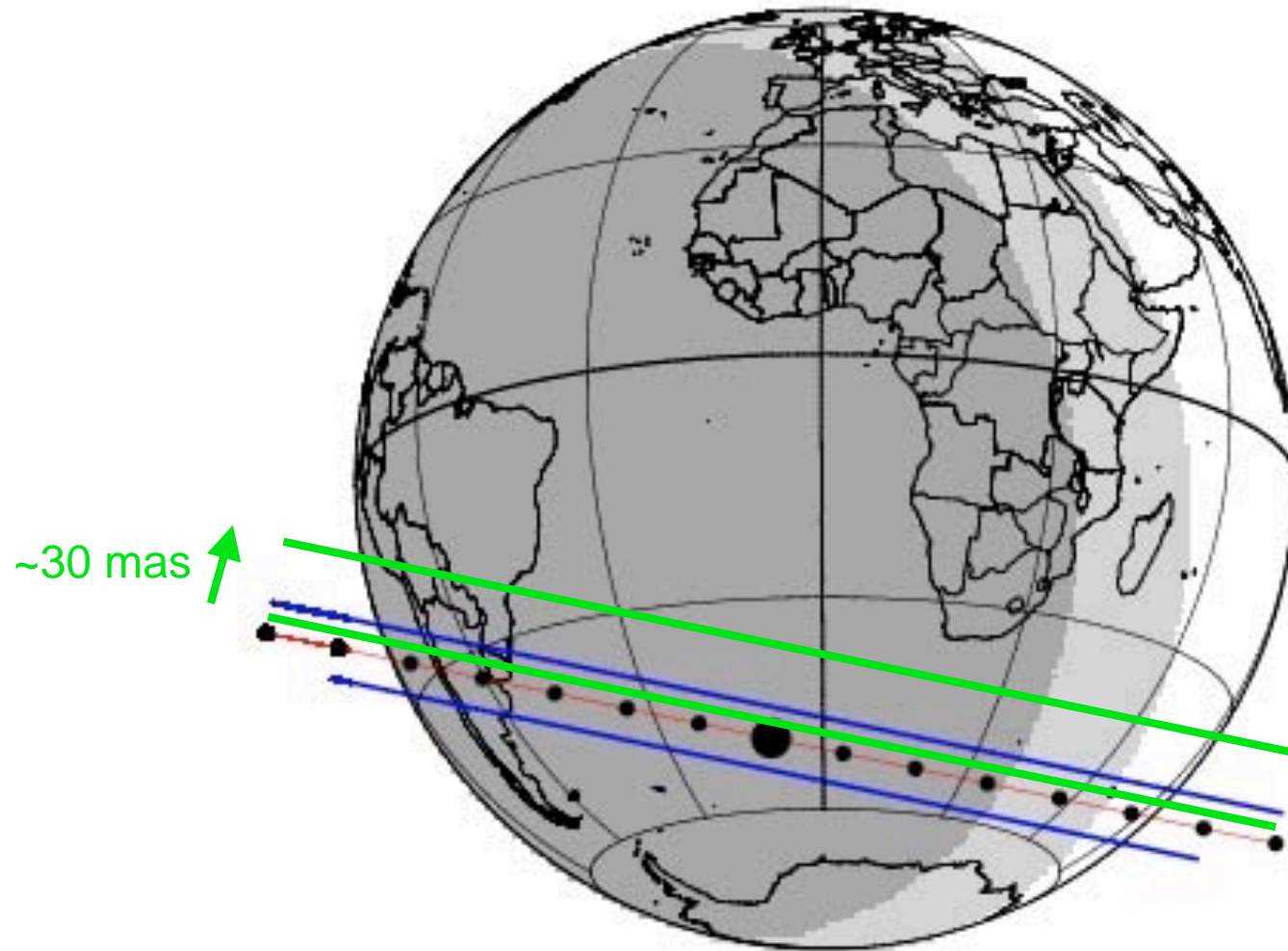
Quaoar



d	m	year	h:m:s UT	ra	dec	J2000	candidate	C/A	P/A	vel	Delta	R*	K*	long
04	05	2011	02 40 35.0	17 28 50.8058	-15 27 42.735			0.117	191.77	-18.28	42.35	15.7	12.7	0

Credits: RSo Team & B. Sicardy

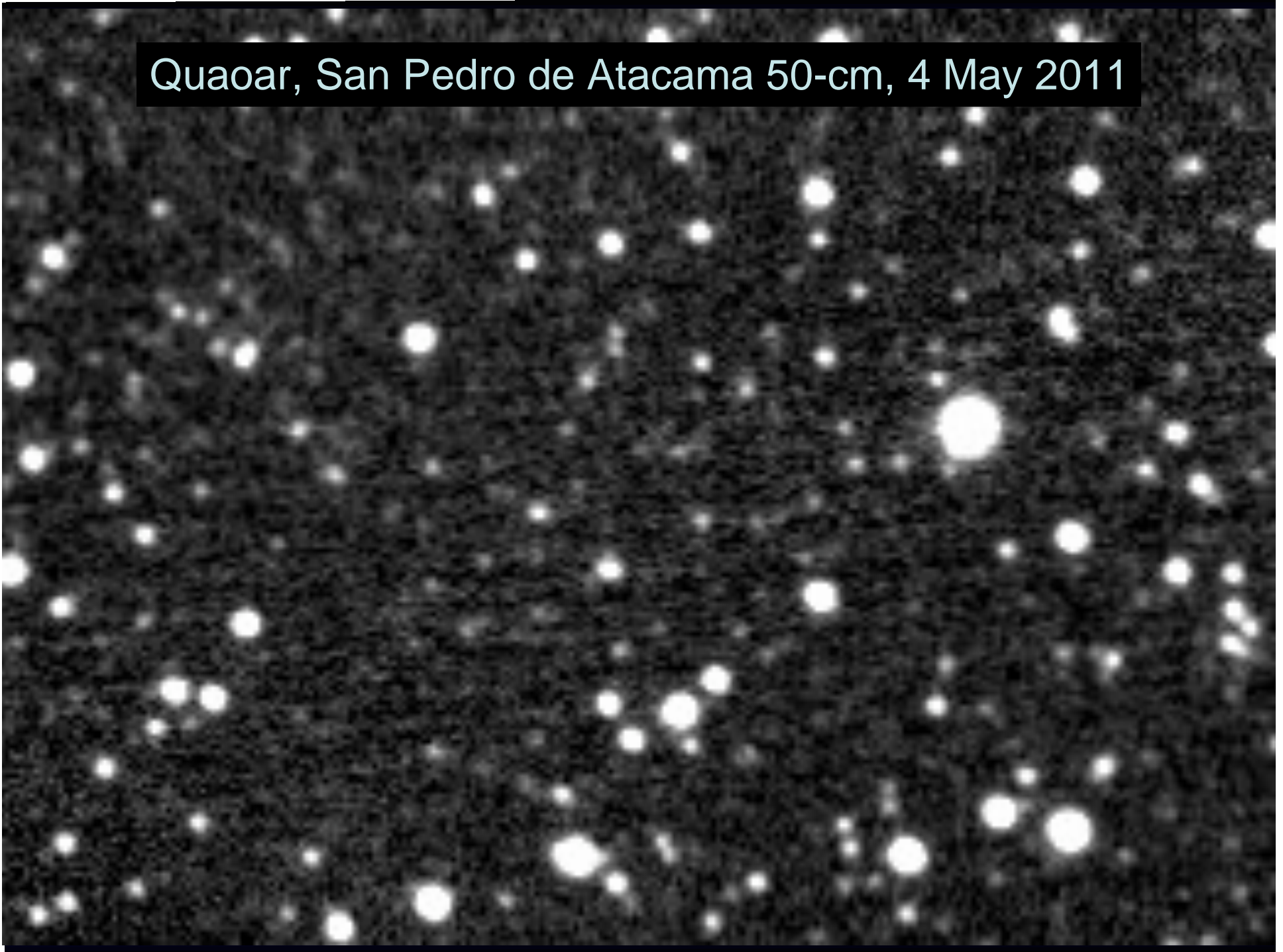
Quaoar



d	m	year	h:m:s	UT	ra	dec	J2000	candidate	C/A	P/A	vel	Delta	R*	K*	long			
04	05	2011	02	40	35.0	17	28	50.8058	-15	27	42.735	0.117	191.77	-18.28	42.35	15.7	12.7	0

Credits: RSo Team & B. Sicardy

Quaoar, San Pedro de Atacama 50-cm, 4 May 2011

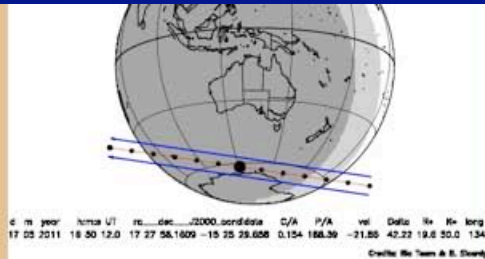


Date	Object	Site
22 June 2008	Pluto & Charon	Australia, Indian Ocean ● ●
24 June 2008	Pluto	Pacific ●
15 August 2008	Pluto	W. USA ●
29 December 2008	2003 AZ84	Run 082.C-0500 (ESO - VTL & NTT)
04 March 2009	Nix	Hawaii
21 April 2009	Pluto	La Réunion Island ●
23 August 2009	Pluto	Australia & New Zealand ●
05 June 2009	Nix	Australia & New Zealand
30 June 2009	2002 MS4	Run 083.C-0451 (ESO – VTL & NTT)
14 February 2010	Pluto	Europe ●
19 February 2010	Varuna	South Africa, Namibia, Brazil ●
19 May 2010	Pluto	Run 085.C-0225 (ESO – VTL & NTT) ●
04 June 2010	Pluto	Australia & New Zealand ●
07 June 2010	Quaoar	Run 085.C-0225 (ESO – VTL & NTT)
22 June 2010	Nix	Australia & New Zealand
04 July 2010	Pluto	Southern Africa, Brazil, Argentina, Chile ●
28 August 2010	Hydra	Run 085.C-0225 (ESO – VTL & NTT)
06 November 2010	Eris	Europe, Brazil, Argentina, Chile ●
08 January 2011	2003 AZ84	Chile ●
02 February 2011	Quaoar	Europe
06 February 2011	Orcus	Canaries, Venezuela
03 March 2011	2003 VS2	Europe
07 March 2011	Ixion	Chile
02 April 2011	Orcus	Chile
13 April 2011	Quaoar	Chile
23 April 2011	Makemake	Brasil, Argentina, Chile ●
01 May 2011	Huya	off Earth
04 May 2011	Quaoar	South Africa, South America ●
14 May 2011	Quaoar	Europe
16 May 2011	Quaoar	Europe (off Earth ?)
17 May 2011	Hydra	North America
21 May 2011	Chariklo	Africa (bright)
23 June 2011	Pluto & Charon	Pacific
27 June 2011	Pluton & Hydra	Pacific

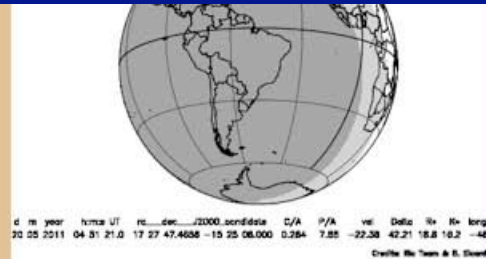
UCAC2 catalog +
update +
Pluto ephemeris correction

UCAC2 catalog +
update +
Pluto ephemeris correction

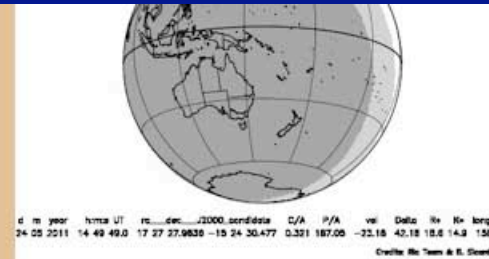
ABOUT 1400 EVENTS posted
on B. Sicardy's home page



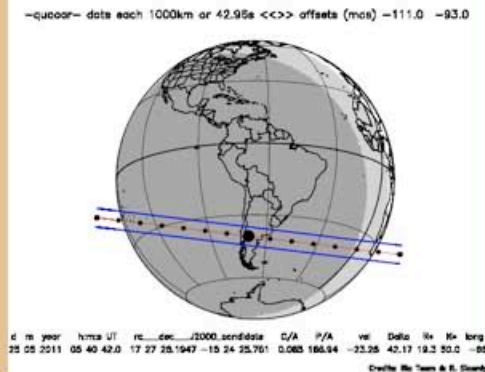
2011-05-17



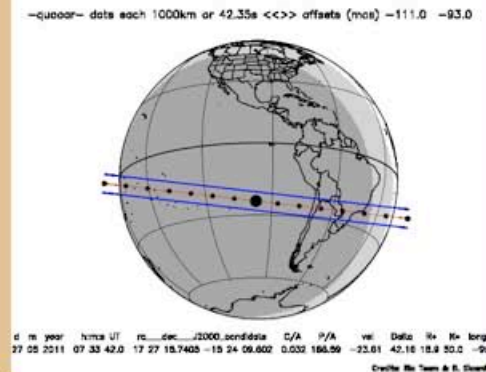
2011-05-20



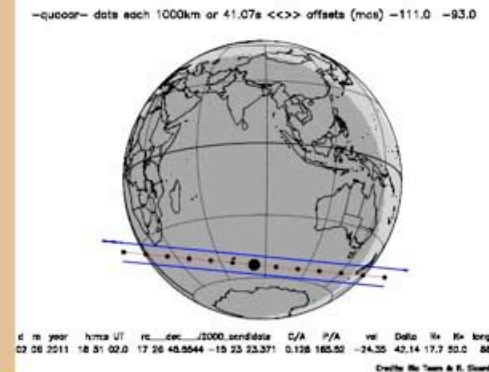
2011-05-24



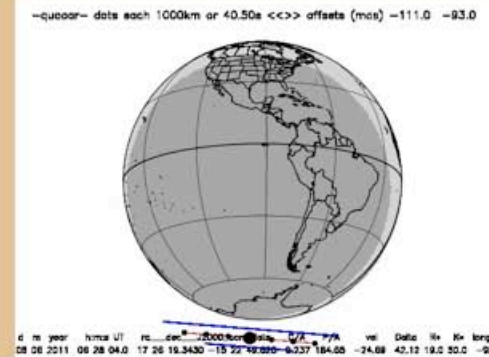
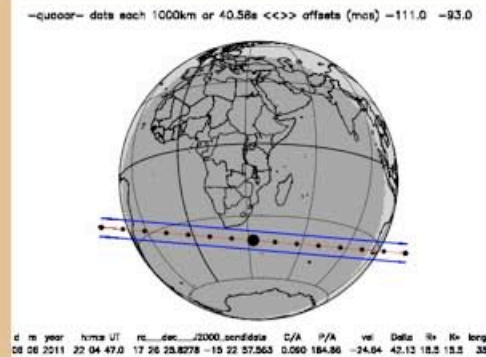
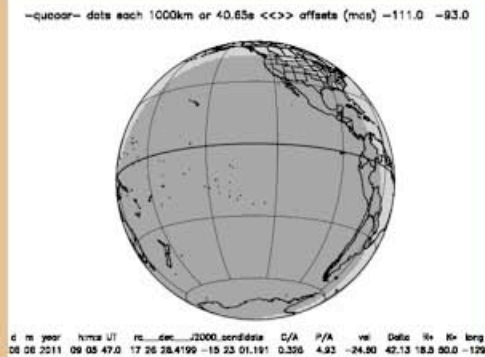
2011-05-25



2011-05-27




2011-06-02




Conclusions

TNOs occultations in Gaia's era

at < 1 mas accuracy:

 huge relieve in occultation planning (now 99% time spent in astrometric predictions & updates)

 chose TNO, chose telescope, get many chords on body (size, shape & limb features at km-accuracy)

 TNOs with atmosphere (Pluto,...): central flash \rightarrow zonal winds, haze properties


 get satellites: shape & orbital elements

photo Alain Maury