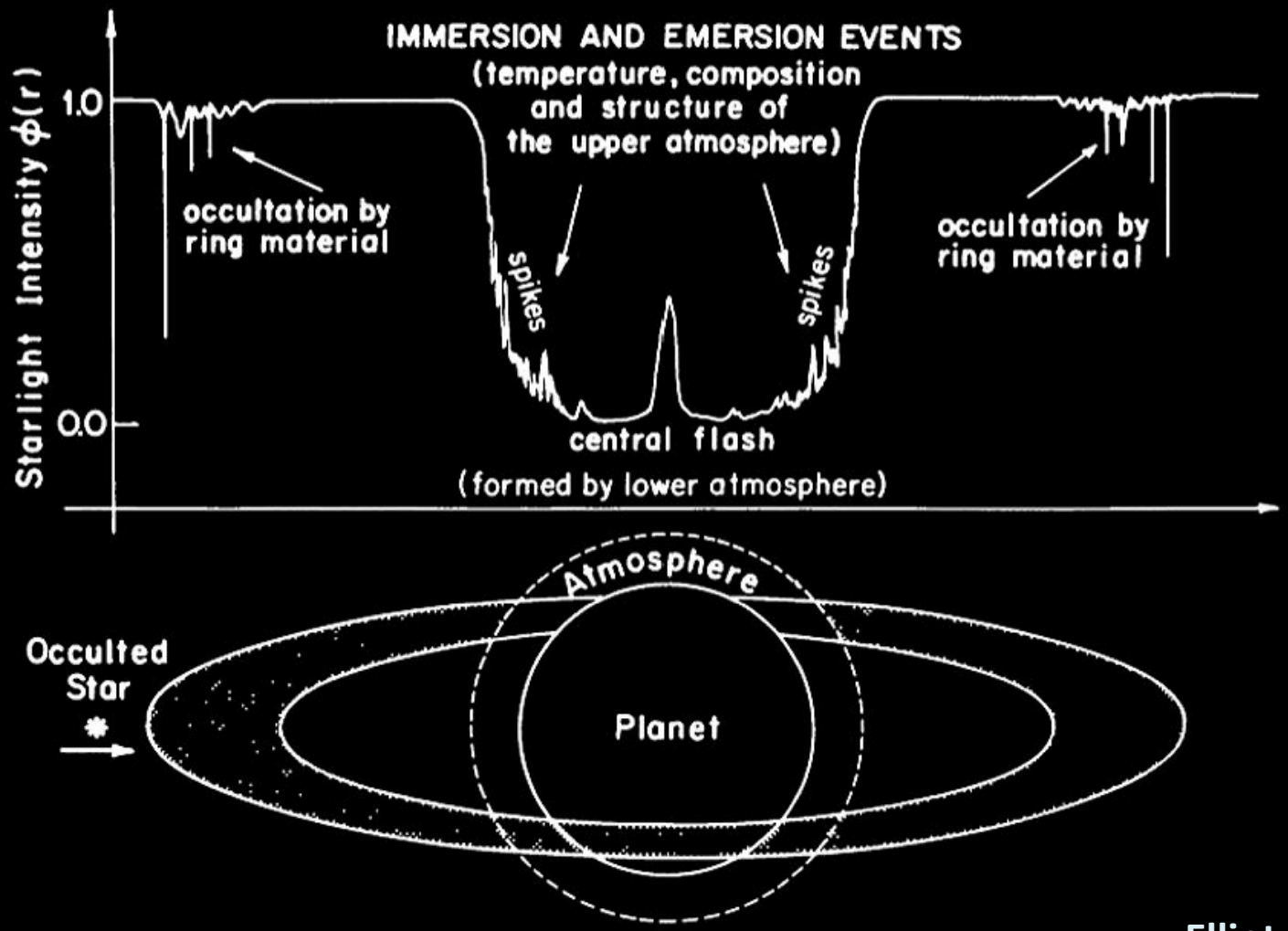
Studying the Solar System with Stellar Occultations

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

High Time Resolution Optical Astrophysics
Royal Astronomical Society, London
2013 April 12


IMMERSION AND EMERSION EVENTS
(temperature, composition
and structure of
the upper atmosphere)
Starlight Intensity φ(r)
1.0
0.0
occultation by
ring material
spikes
spikes
occultation by
ring material
central flash
(formed by lower atmosphere)
Atmosphere
Occulted
Star
Planet

Elliot, 1979

airless objects

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

atmospheres

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

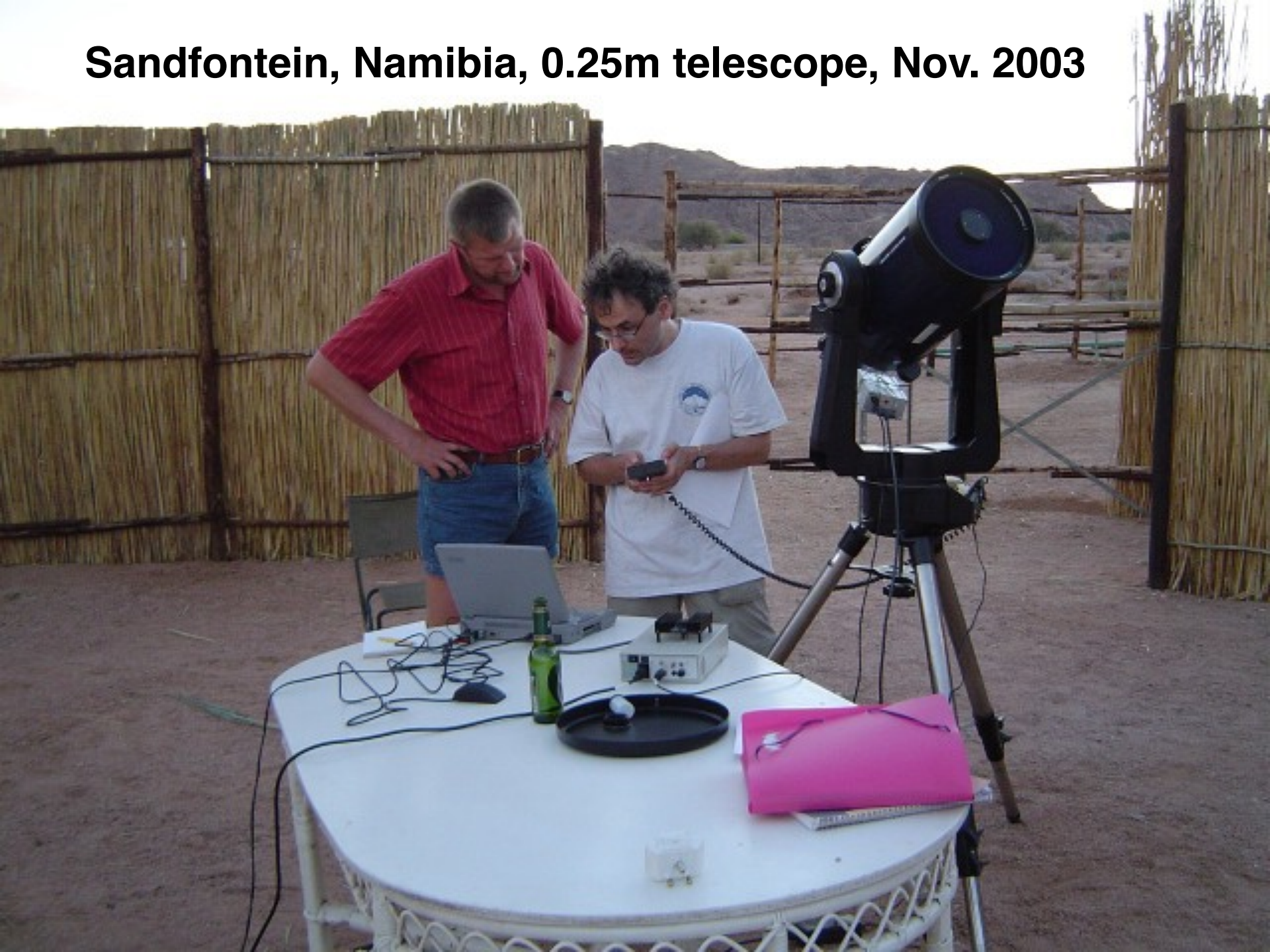
- strength: can achieve what nobody else can do

- weakness: difficult to predict, and thus to plan, especially on large telescopes. Dates and places imposed

$\Rightarrow$ need in general high accuracy astrometry :
50 milli-arcsec (mas) several years in advance,
~20 mas a few weeks in advance

Eris' shadow, 6 November 2010
San Pedro
La Silla
El Leoncito

Sandfontein, Namibia, 0.25m telescope, Nov. 2003



Ultracam VLT/8.2m 2005

ARTICLES

Occultation detection of a neptunian ring-like arc

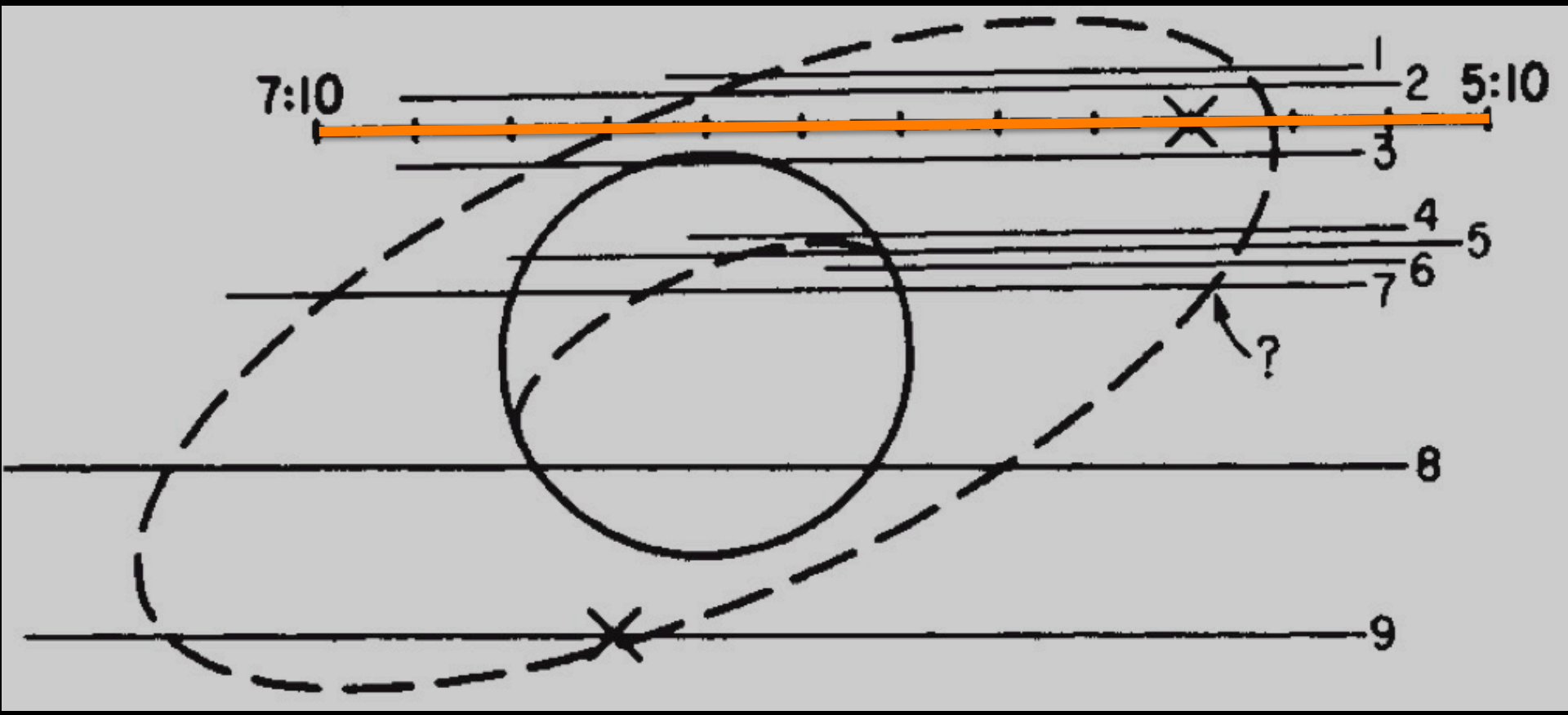
W. B. Hubbard*, A. Brahic†, B. Sicardy†, L.-R. Elicer‡, F. Roques† & F. Vilas*§

* 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

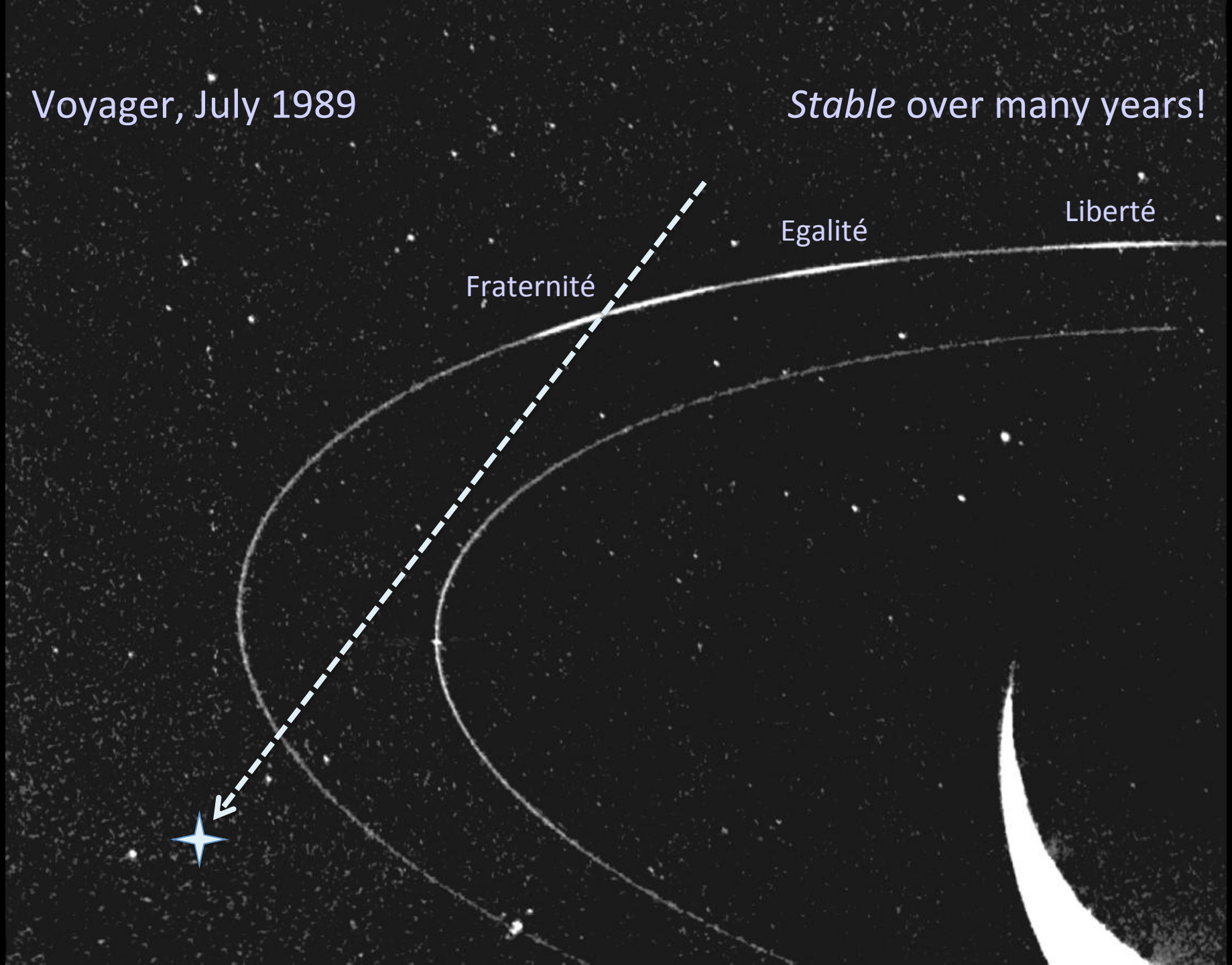
The apparent closest approach of the star SAO186001 to Neptune was observed photoelectrically on 22 July 1984 at Cerro Tololo Inter-American Observatory. A 32% signal drop lasting about 1.2 s was probably caused by a partially transparent arc of material at a distance of 67,000 km from Neptune. Neptune's arc(s) do not vary smoothly with azimuth, unlike the rings of other jovian planets.

20 February 1986

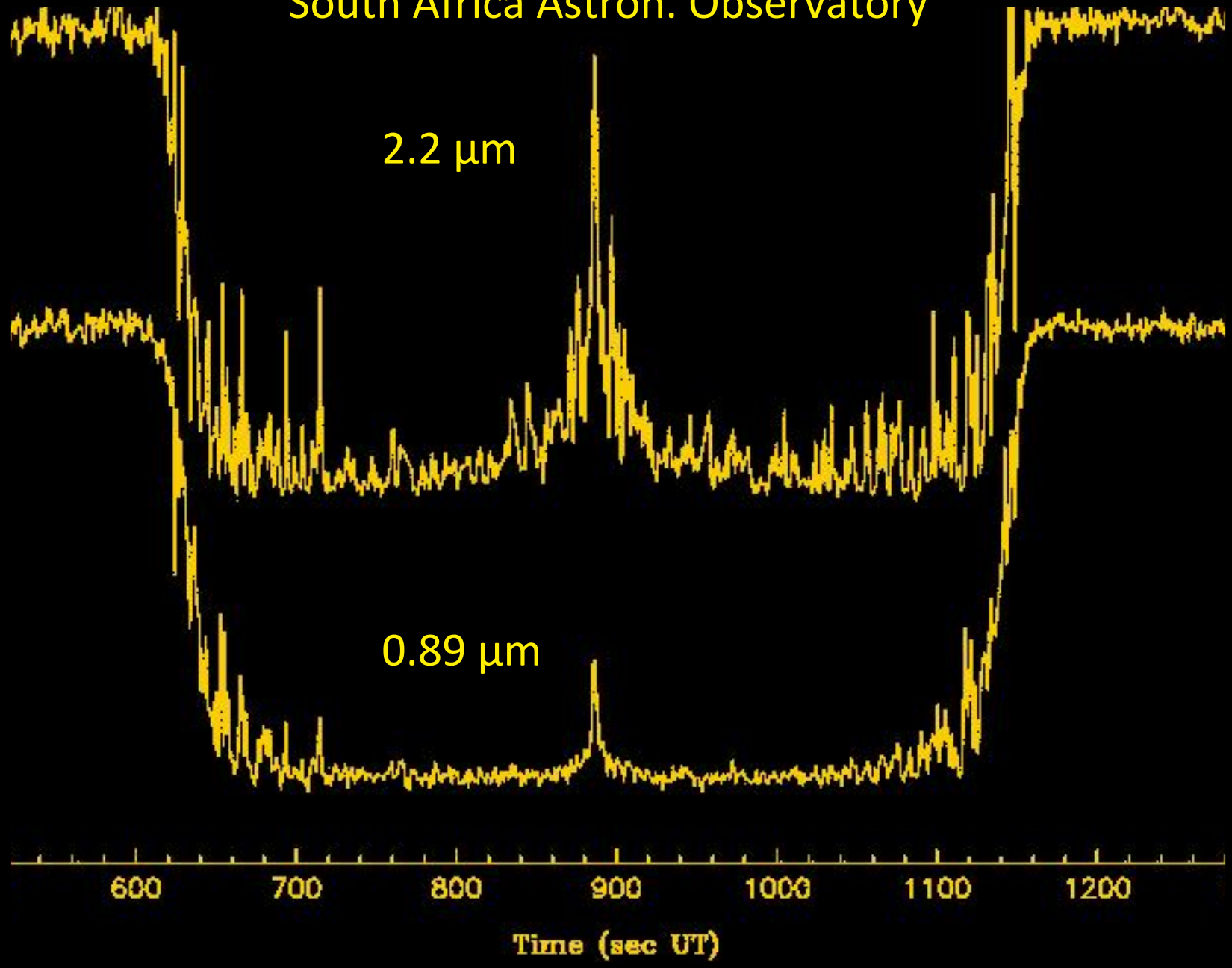
22 July 1984: discovery of ring-arcs of Neptune with a stellar occultation at ESO and CTIO

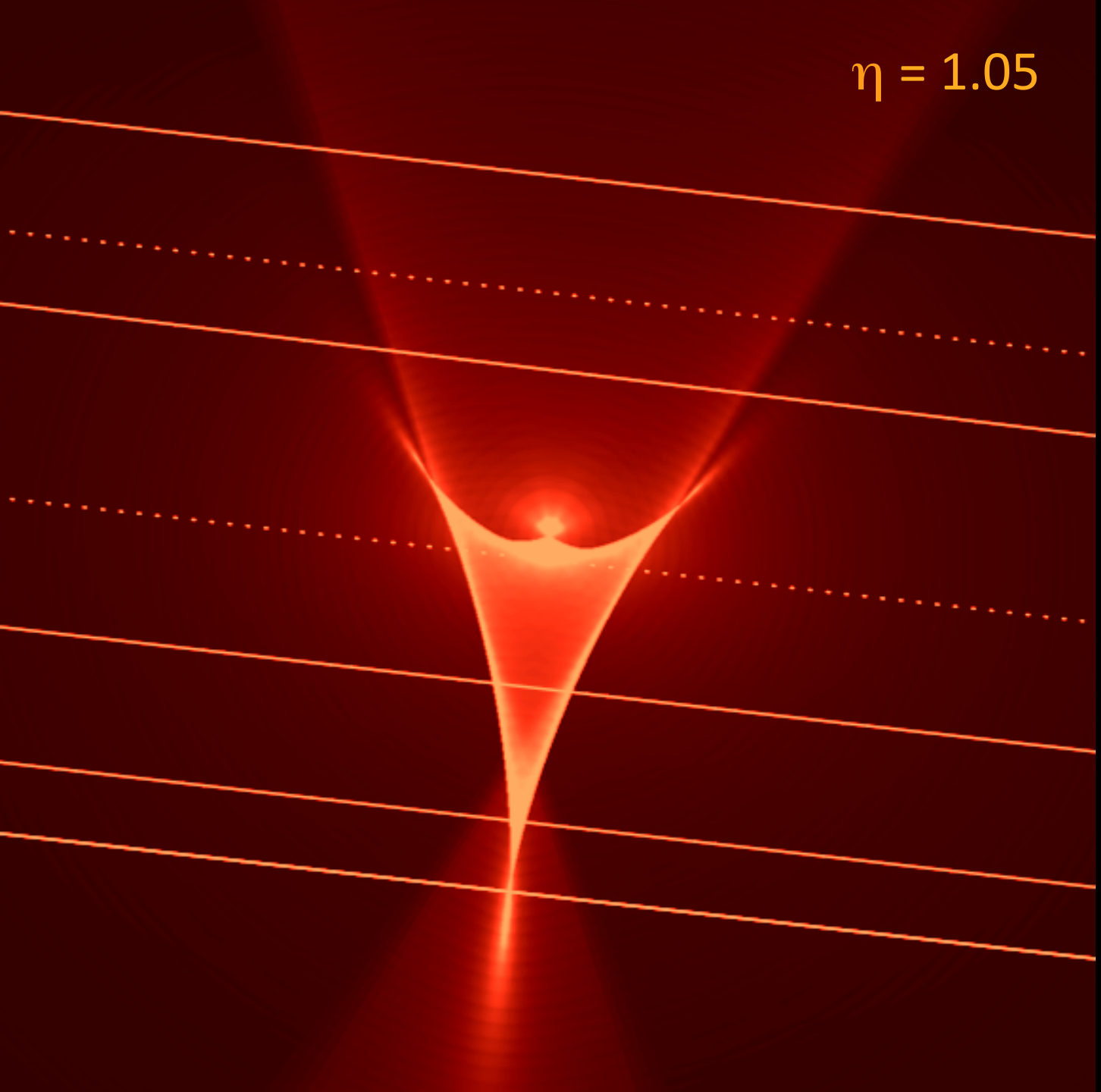


from Hubbard *et al., Nature, 1986*
& Sicardy *et al. Icarus, 1991*


Voyager, July 1989
Stable over many years!
Liberté
Egalité
Fraternité

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

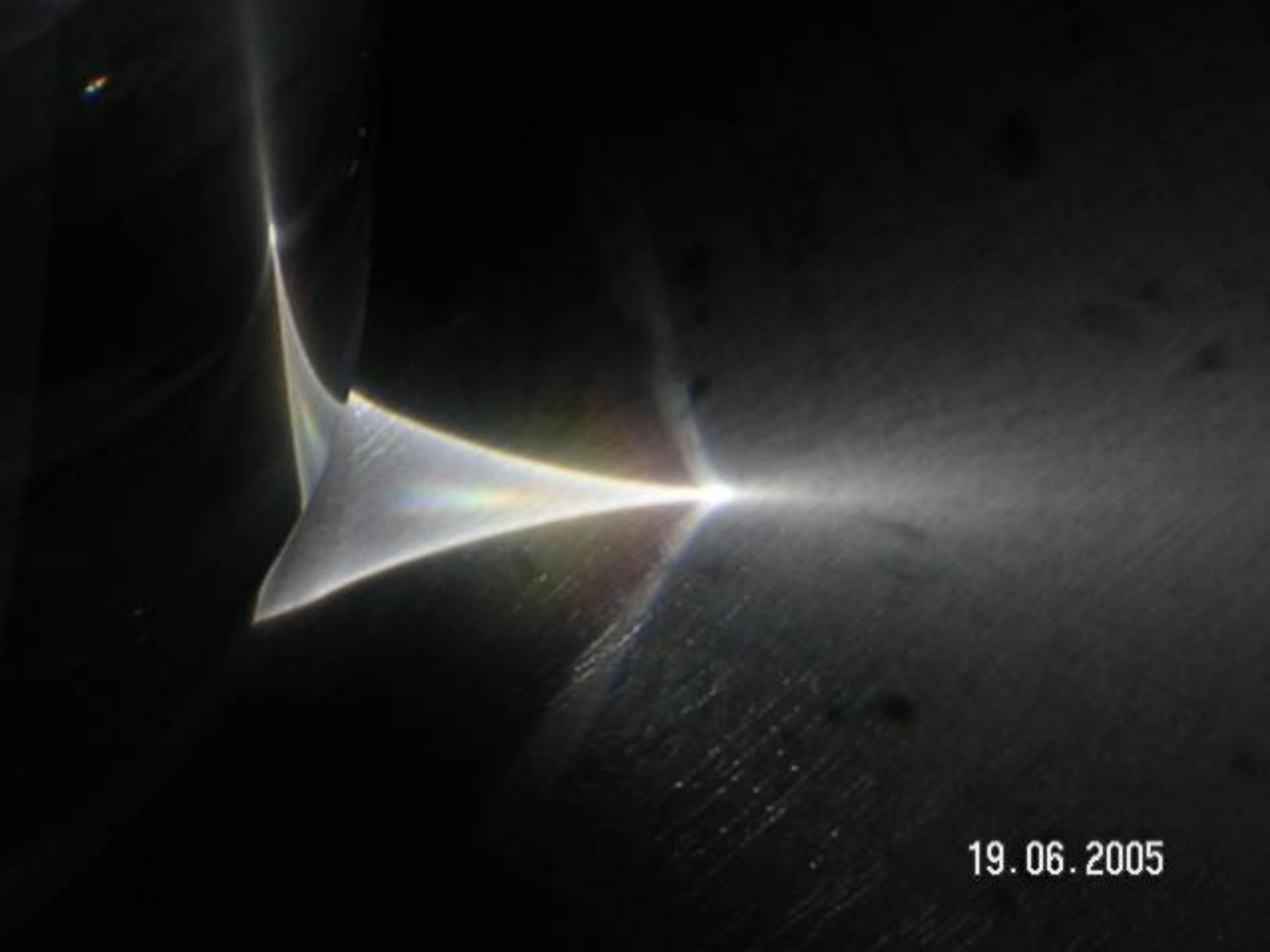




Namibia

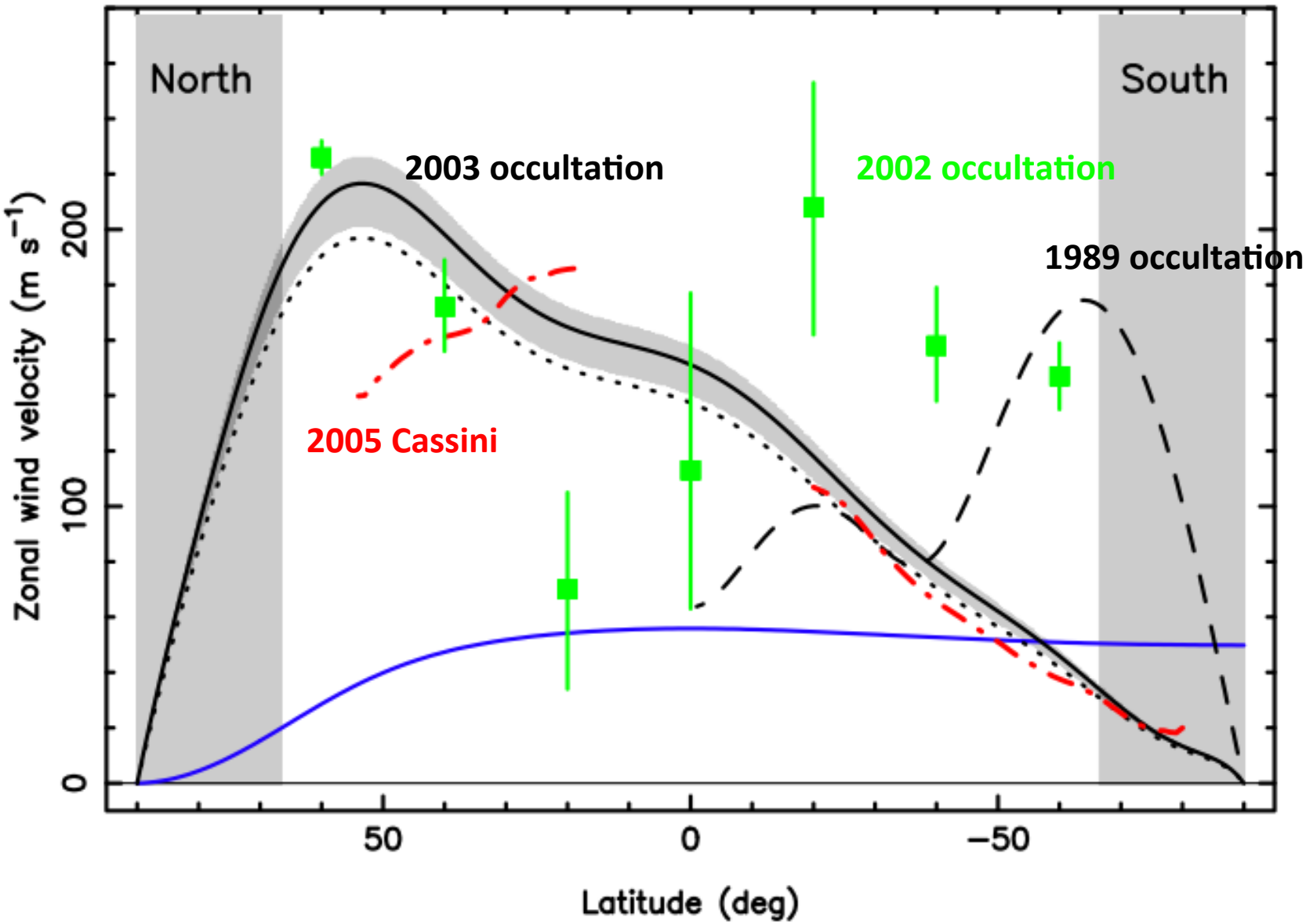
La Réunion

South Africa


19.06.2005

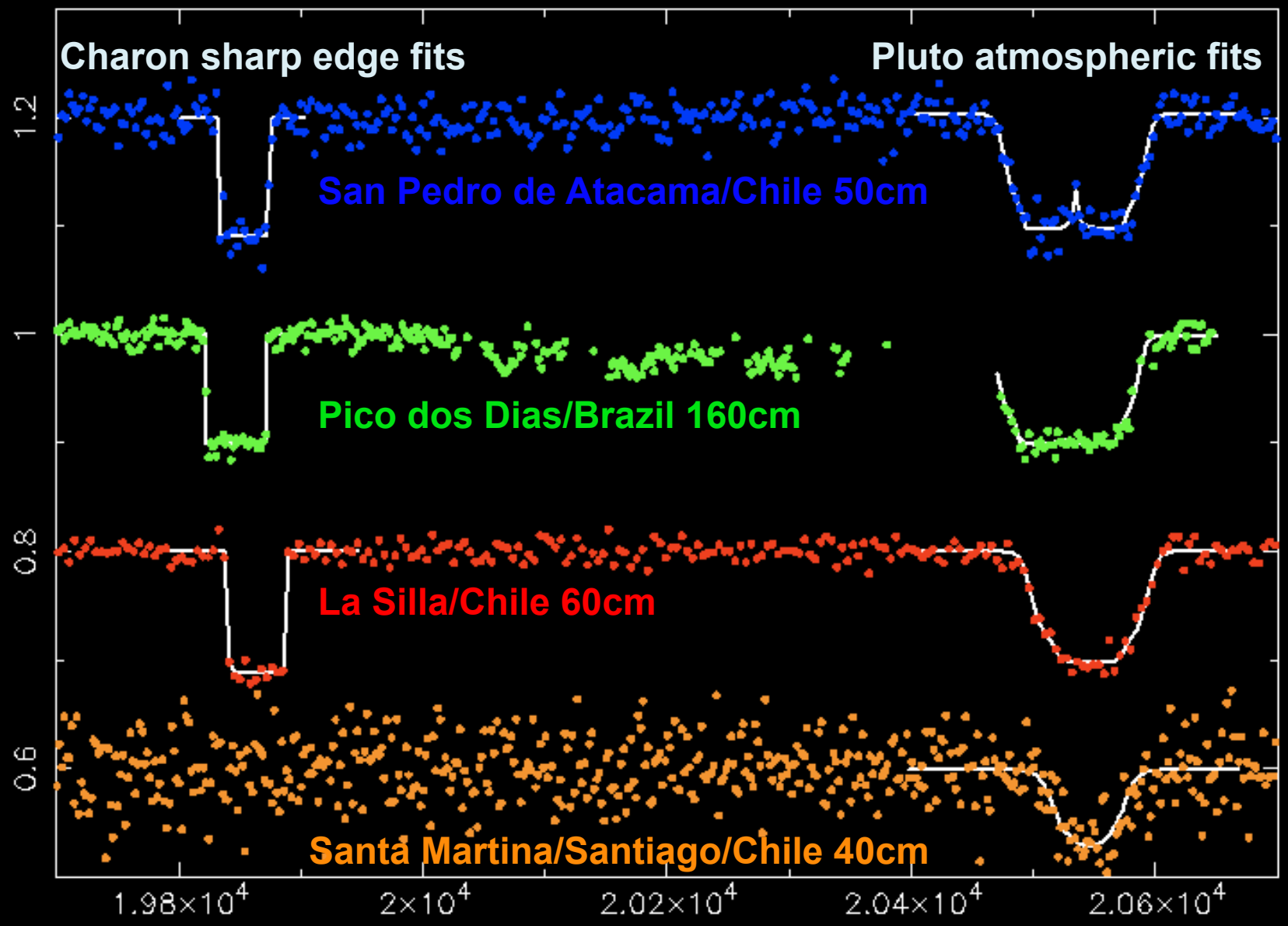
multiple images during the 14 november 2003 Titan occultation (central flash)

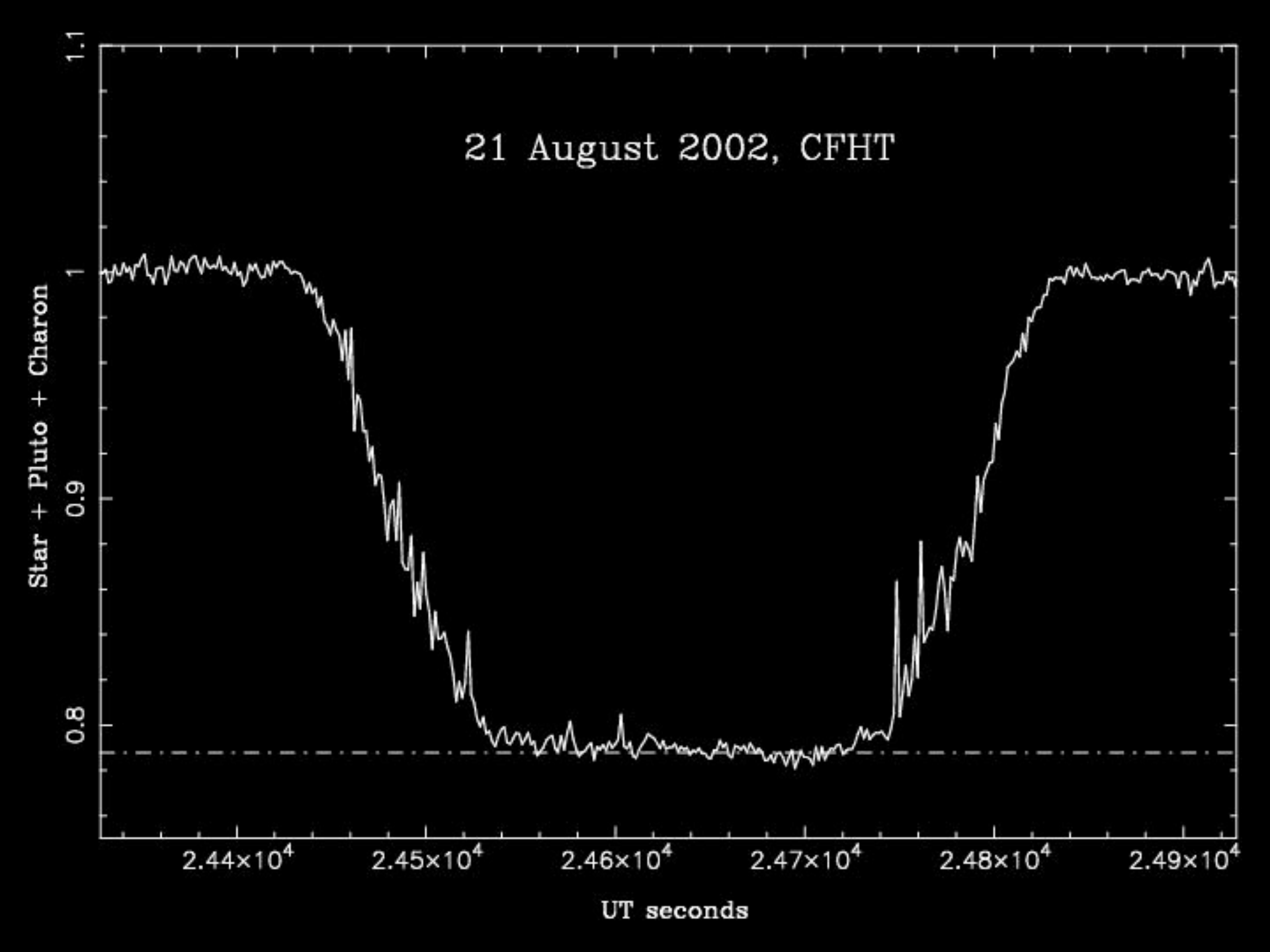
zonal wind regime of Titan's atmosphere at 250 km alt.

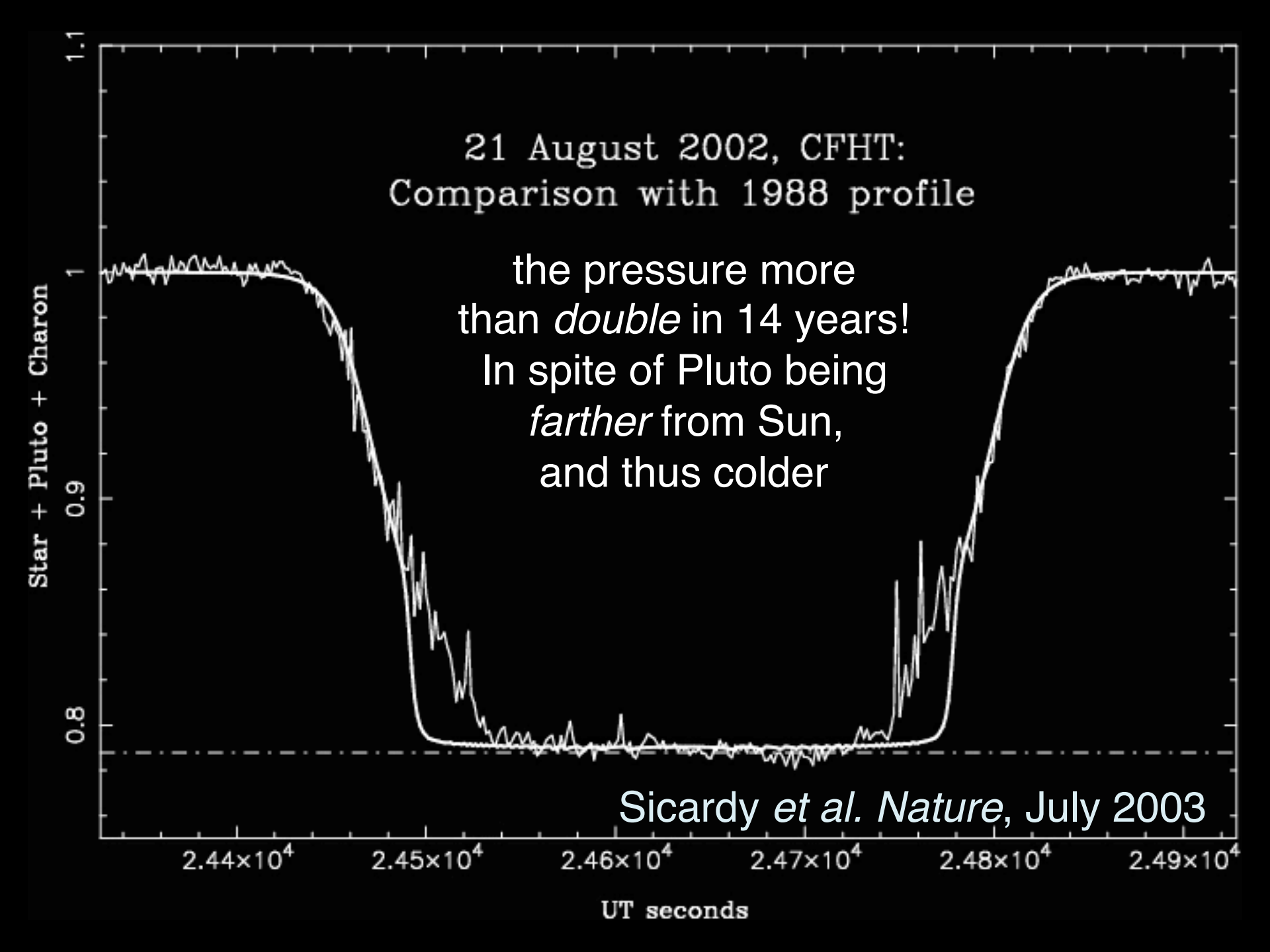


Pluto/Charon

the dual Pluto/Charon event of 4 June 2011




21 August 2002, CFHT
Star + Pluto + Charon
1.1
1
0.9
0.8
2.44×10^4
2.45×10^4
2.46×10^4
2.47×10^4
2.48×10^4
2.49×10^4
UT seconds


21 August 2002, CFHT:
Comparison with 1988 profile
the pressure more
than *double* in 14 years!
In spite of Pluto being
farther from Sun,
and thus colder
Sicardy *et al. Nature*, July 2003
Star + Pluto + Charon
1.1
1
0.9
0.8
2.44×10^4
2.45×10^4
2.46×10^4
2.47×10^4
2.48×10^4
2.49×10^4
UT seconds

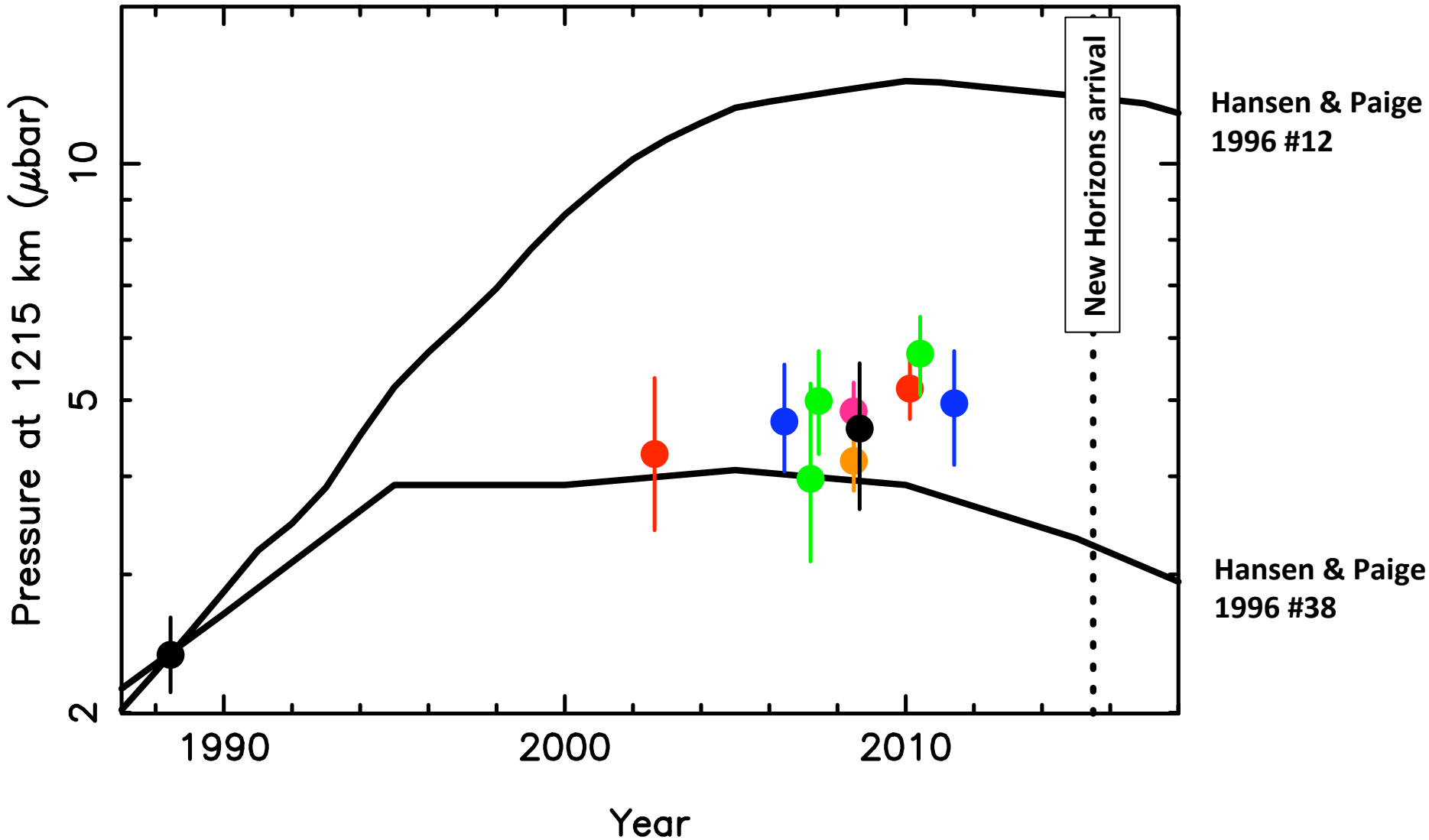
2003

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

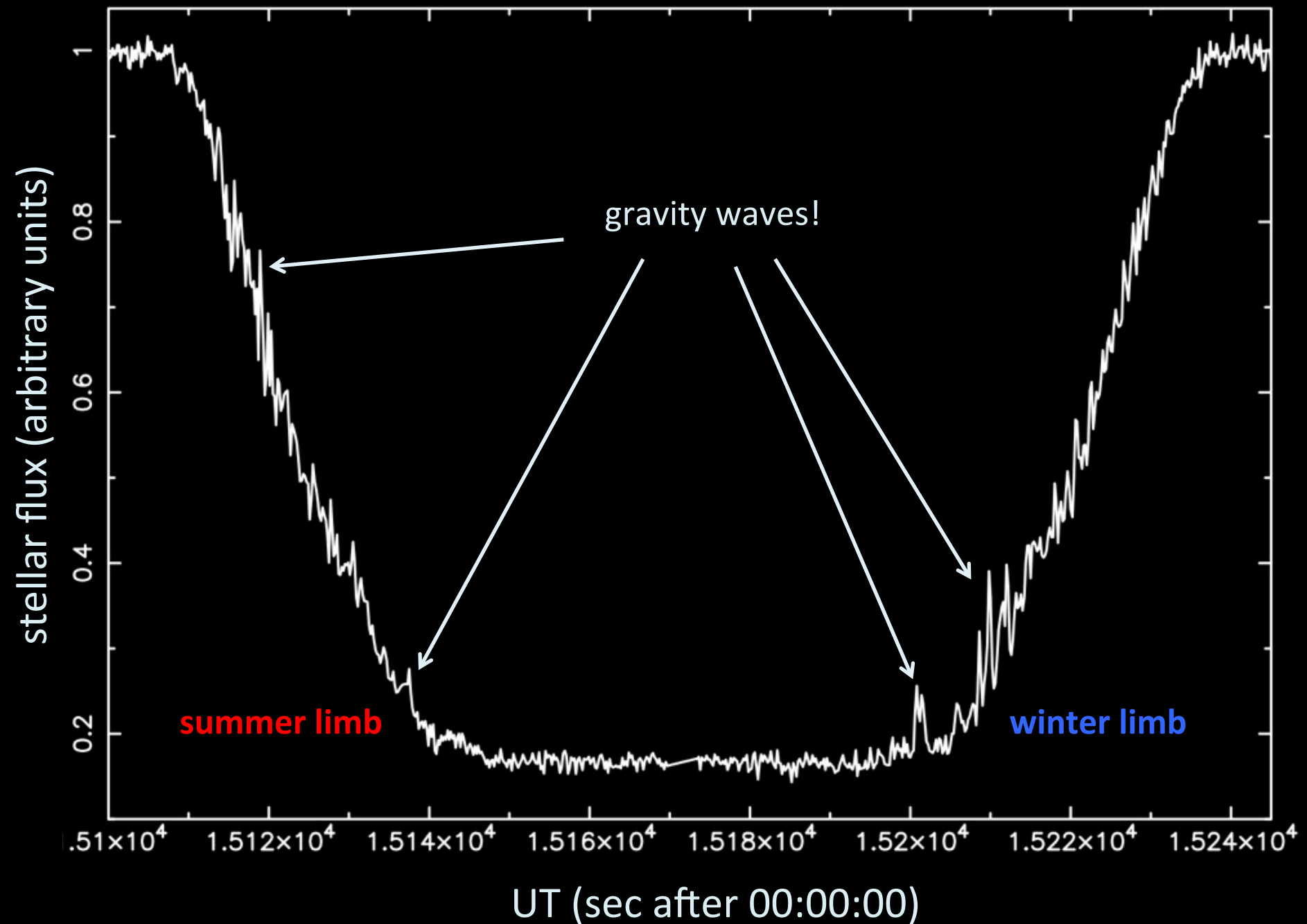
B. Sicardy[1,2], T. Widemann[1], E. Lellouch[1], C. Veillet[3], J.-C. Cuillandre[3], F. Colas[4], F. Roques[1], W. Beisker[5], M. Kretlow[5], A.-M. Lagrange[6], E. Gendron[1], F. Lacombe[1], J. Lecacheux[1], C. Birnbaum[7], A. Fienga[4], C. Leyrat[1], A. Maury[8], E. Raynaud[1], S. Renner[1], M. Schultheis[9], 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]

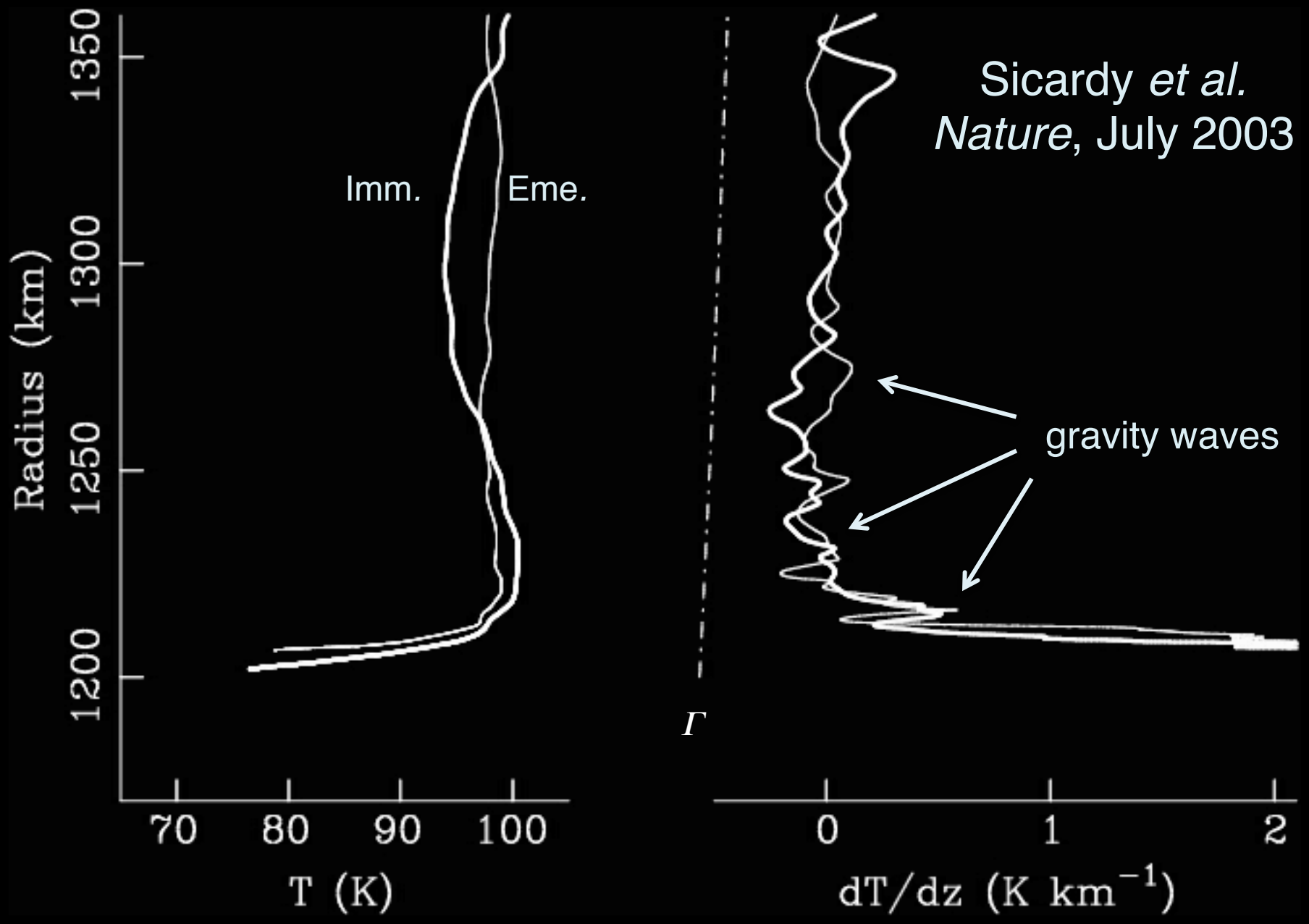
NATURE | VOL 424 | 10 JULY 2003 | www.nature.com/nature

Comparison of Pluto occultation results with theoretical volatiles transport models

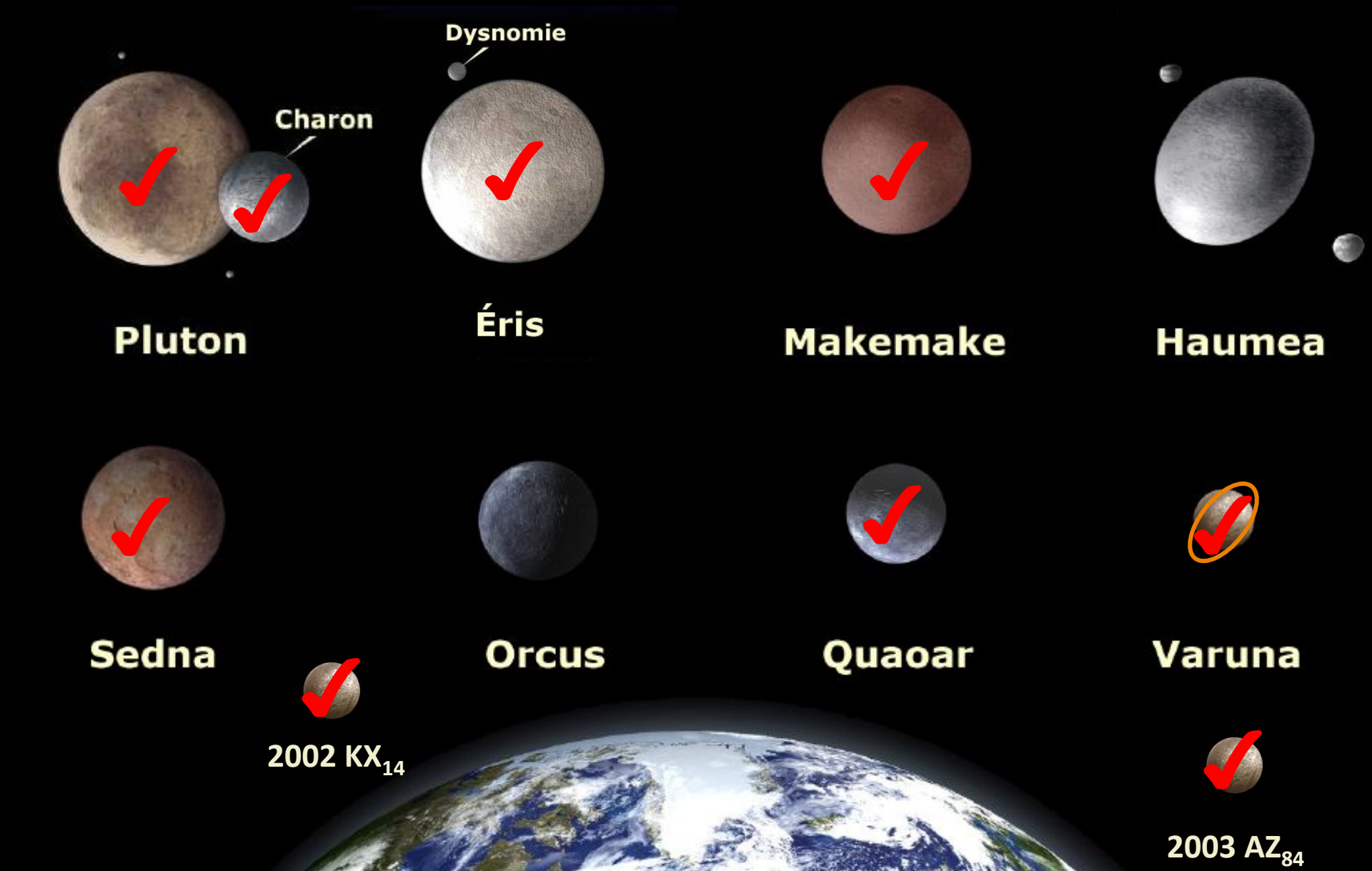


Stellar occultation 18 July 2012, NACO/VLT H band

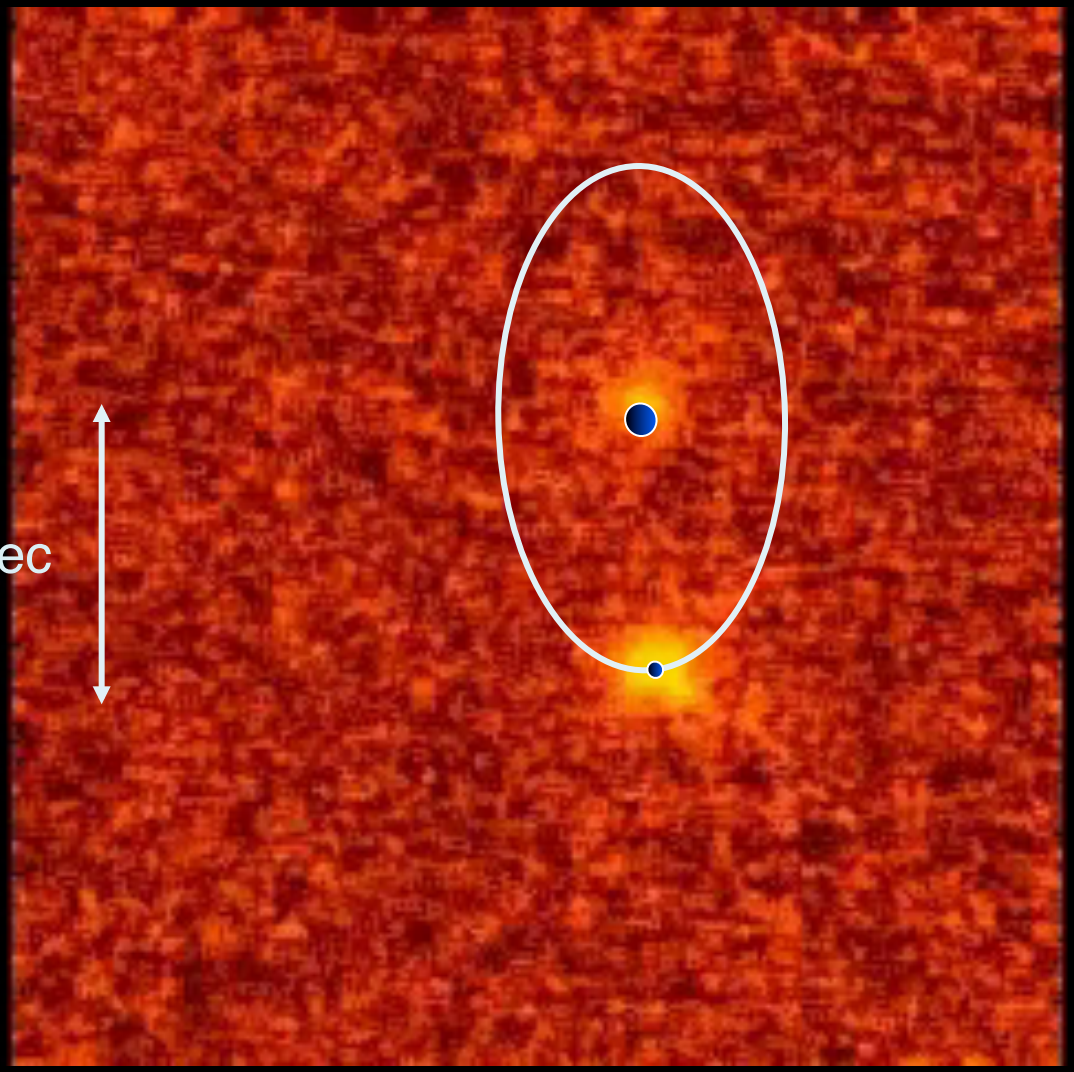



Sicardy *et al.*
Nature, July 2003
Imm.
Eme.
Radius (km)
1200
1250
1300
1350
70
80
90
100
T (K)
Γ
gravity waves
0
1
2
dT/dz (K km^{-1})

Les plus grands objets transneptuniens connus



VLT/NACO K band, Charon occultation 11 July 2005



2006

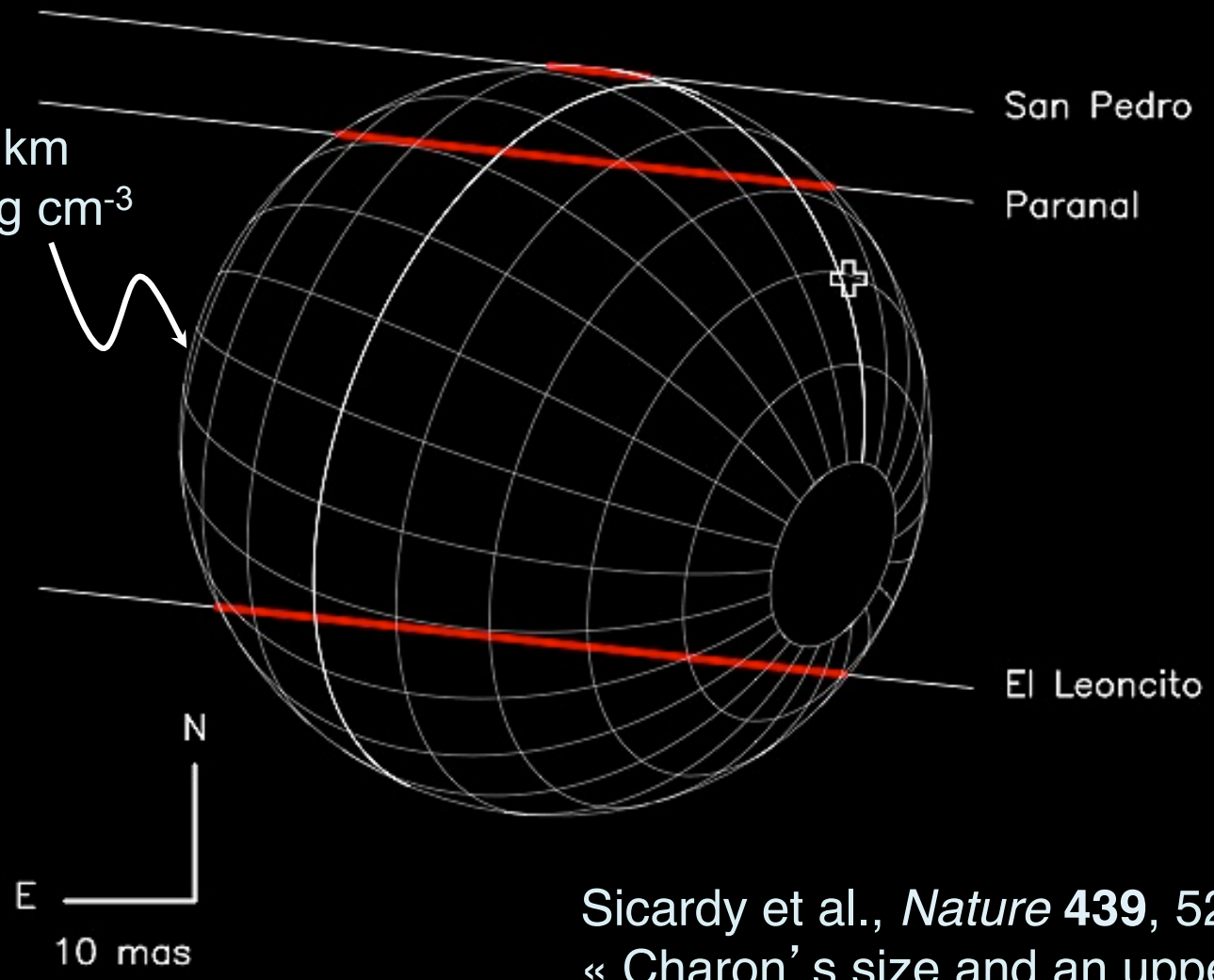
nature Vol 439|5 January 2006|doi:10.1038/nature04351

LETTERS

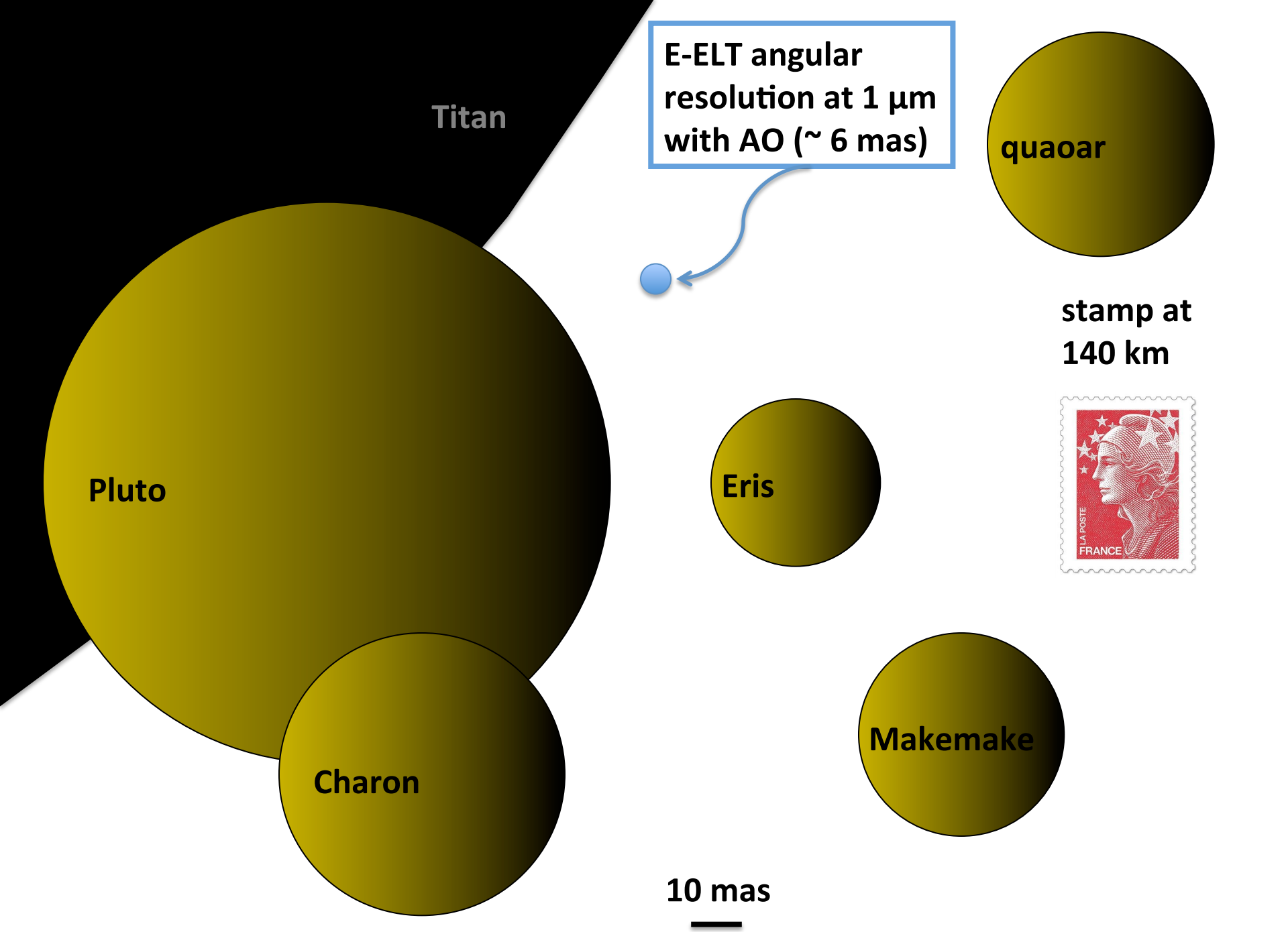
Charon's size and an upper limit on its atmosphere from a stellar occultation

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]

R= 603.6±1.4 km
ρ= 1.71±0.08 g cm^{-3}



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


Titan
E-ELT angular resolution at 1 µm with AO (~ 6 mas)
quaoar
stamp at 140 km
LA POSTE
FRANCE
Pluto
Eris
Makemake
Charon
10 mas

Eris

2011

LETTER

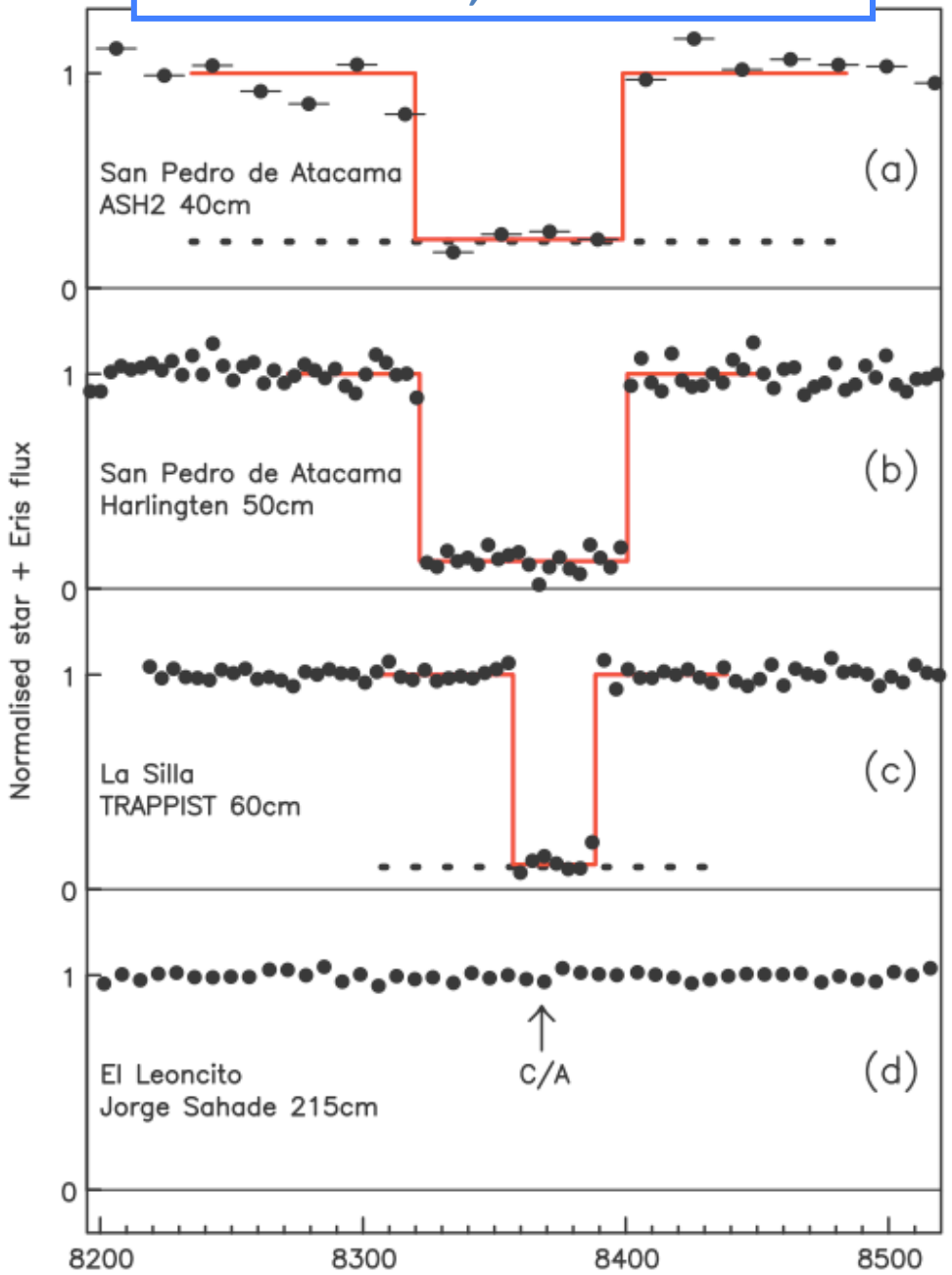
doi:10.1038/nature10550

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]

27 OCTOBER 2011 | VOL 478 | NATURE | 493

Eris occultation, 6 November 2010



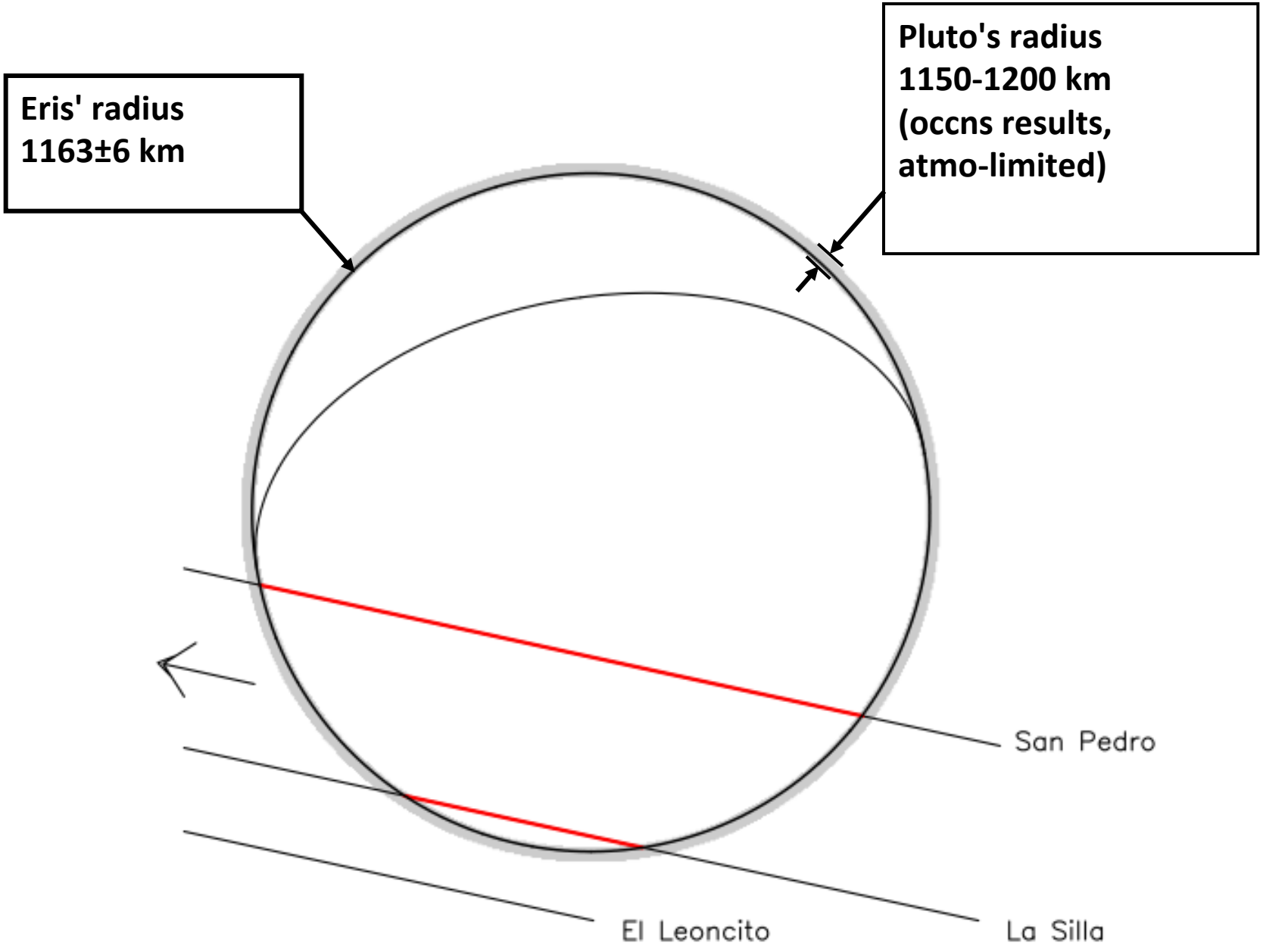
San Pedro

San Pedro

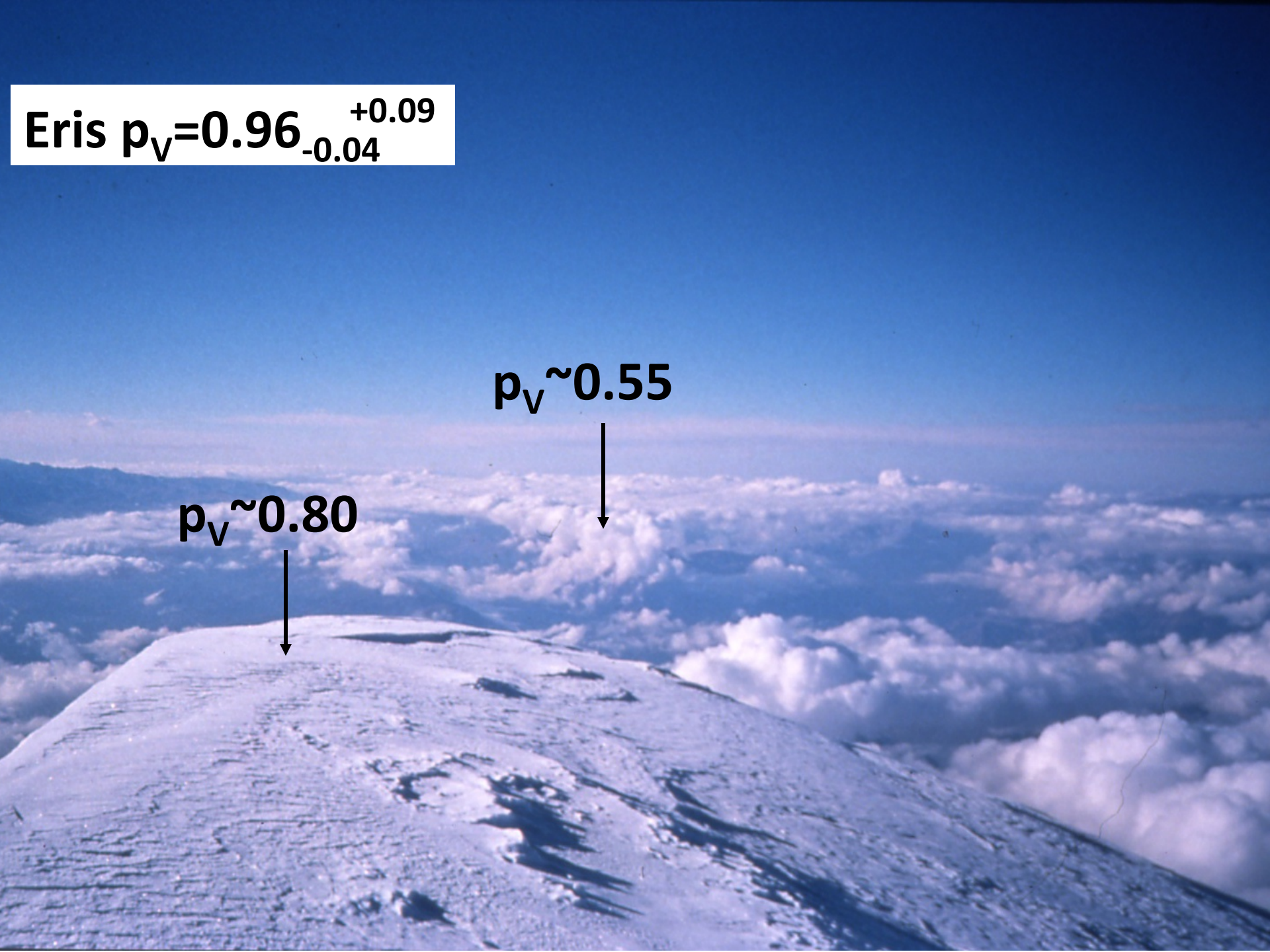
La Silla

El Leoncito

Sicardy et al. Nature 2011


Eris' radius
1163±6 km
Pluto's radius
1150-1200 km
(occns results,
atmo-limited)
San Pedro
El Leoncito
La Silla

Eris
p_V=0.96


Eris $p_V=0.96^{+0.09}_{-0.04}$
p_V~0.55
p_V~0.80

high albedo
low albedo

Makemake

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]

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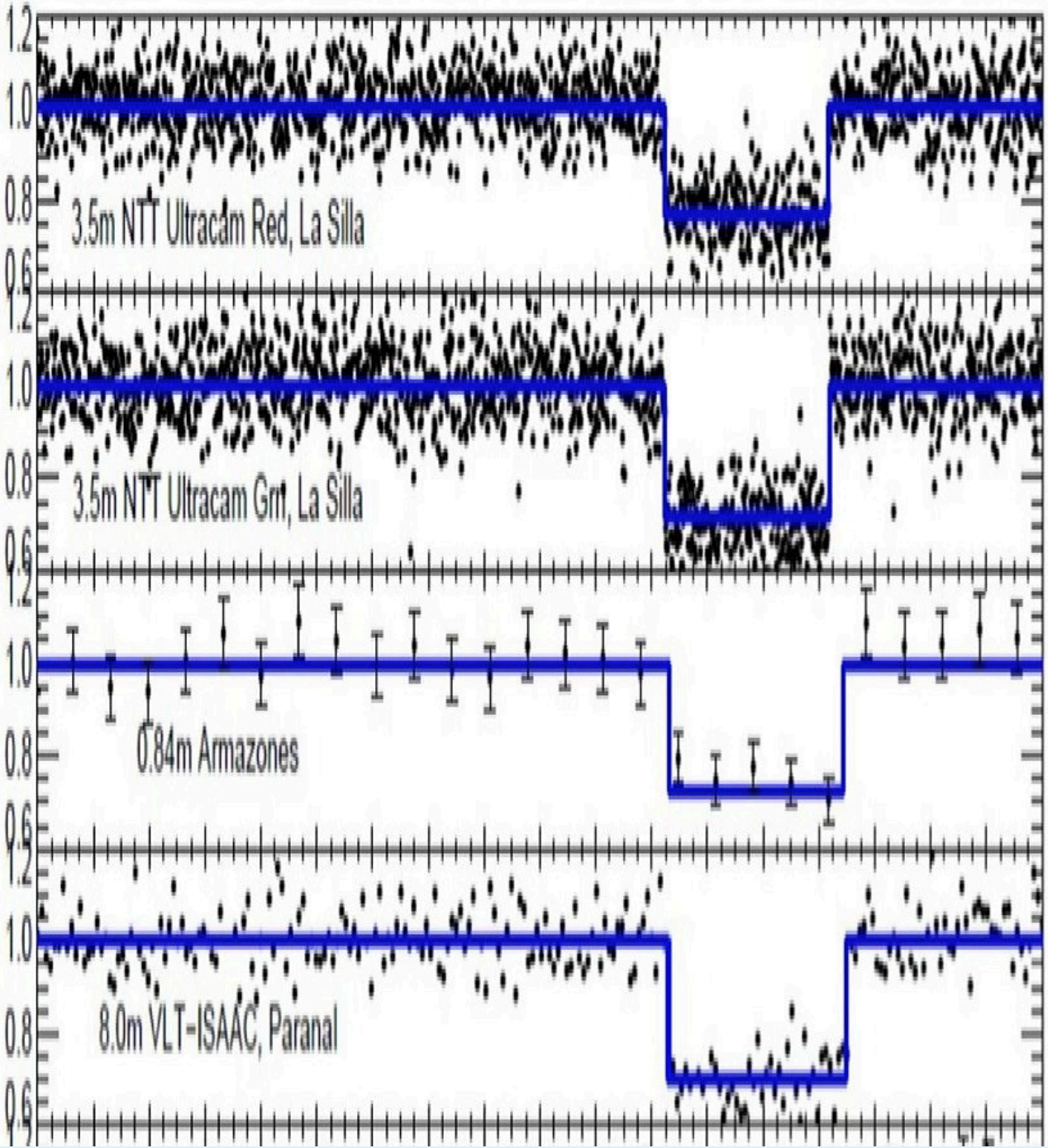


NTT/Ultracam red

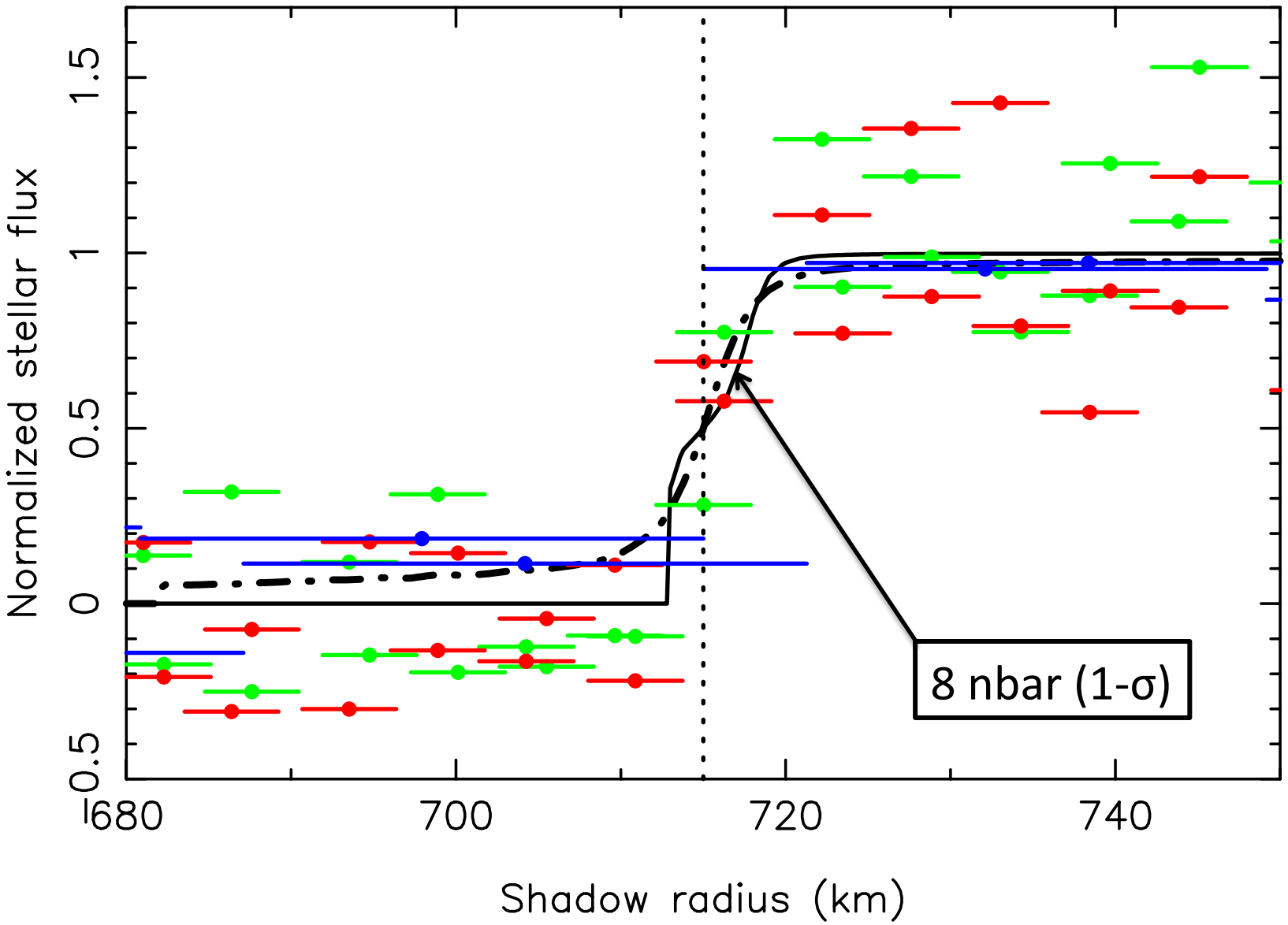
NTT/Ultracam green

Armazones clear

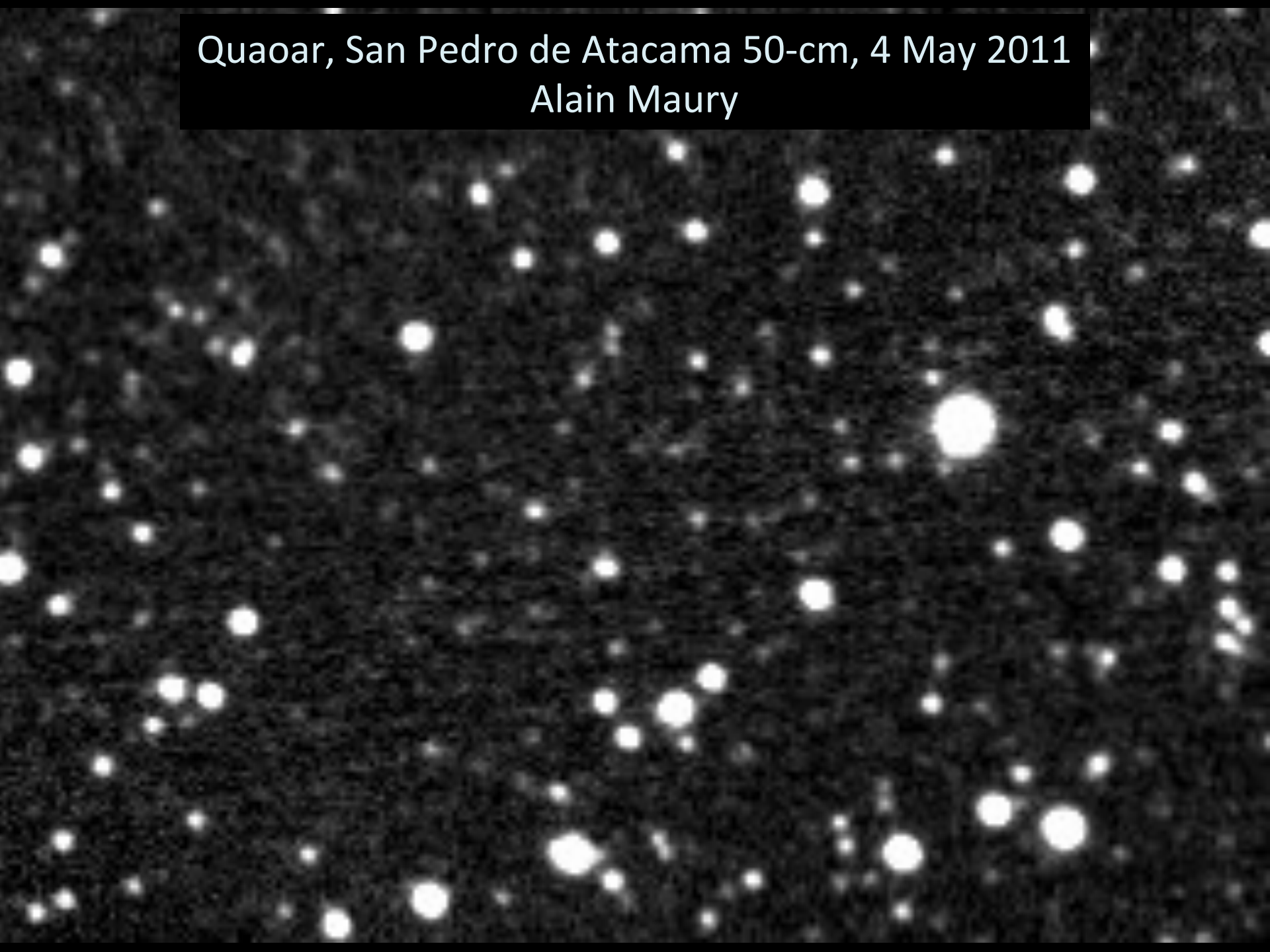
VLT/ISAAC J-band

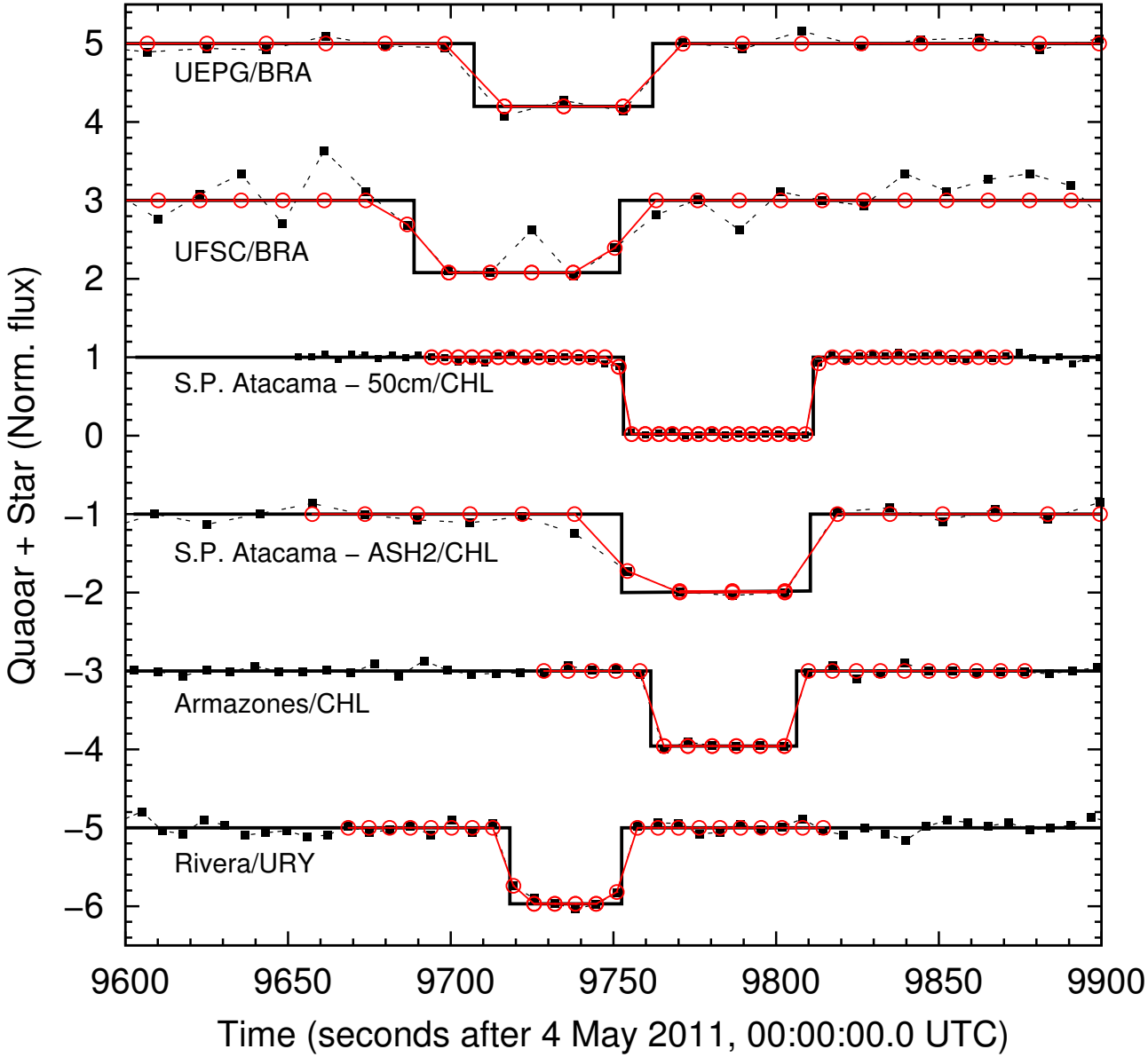
Ortiz *et al.* 2012
Nature, 22 Nov. 2012

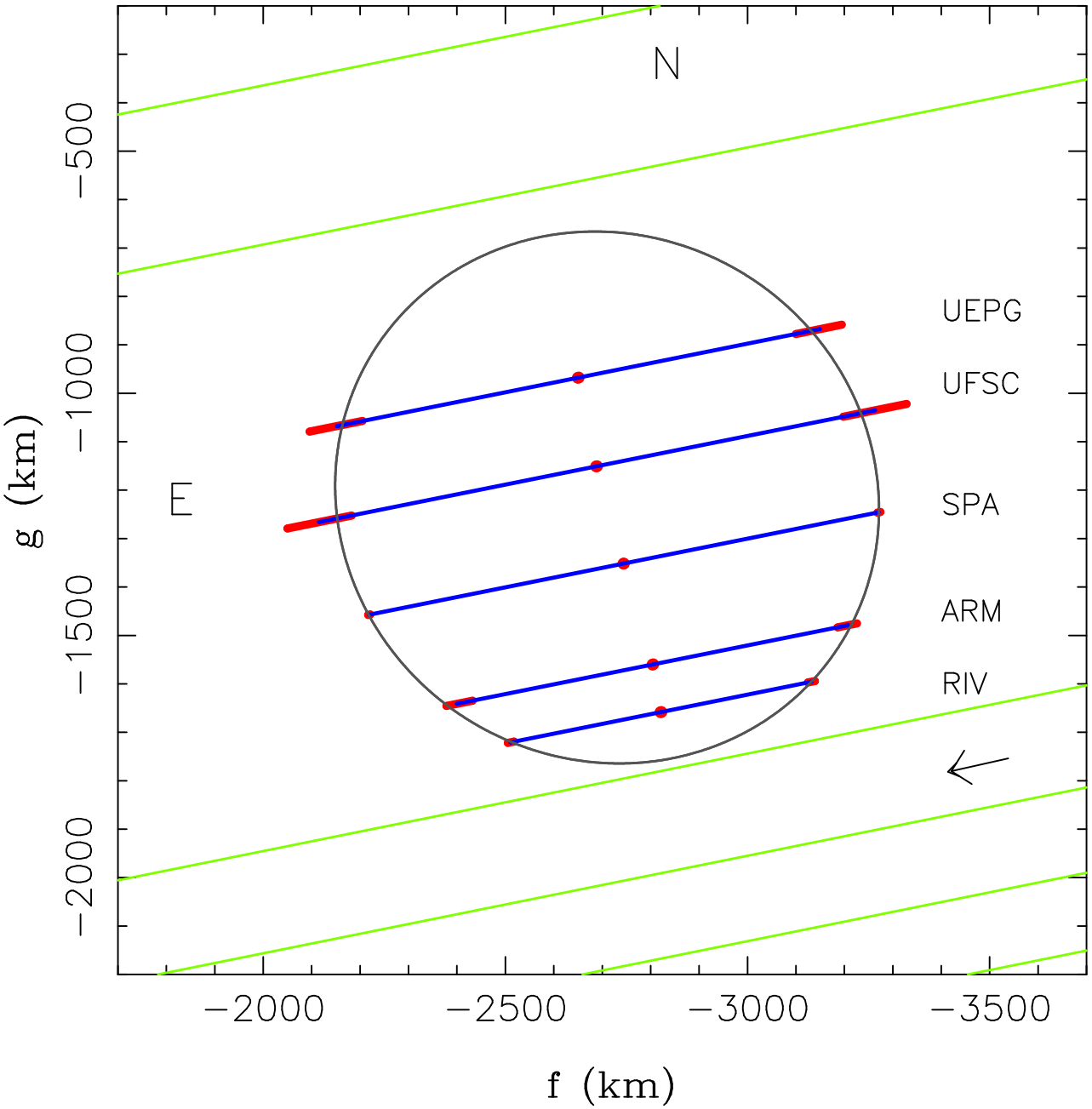
limits on CH_4 Makemake atmosphere



Quaoar


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


UEPG/BRA
UFSC/BRA
S.P. Atacama – 50cm/CHL
S.P. Atacama – ASH2/CHL
Armazones/CHL
Rivera/URY
Quaoar + Star (Norm. flux)
Time (seconds after 4 May 2011, 00:00:00.0 UTC)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
9600
9650
9700
9750
9800
9850
9900



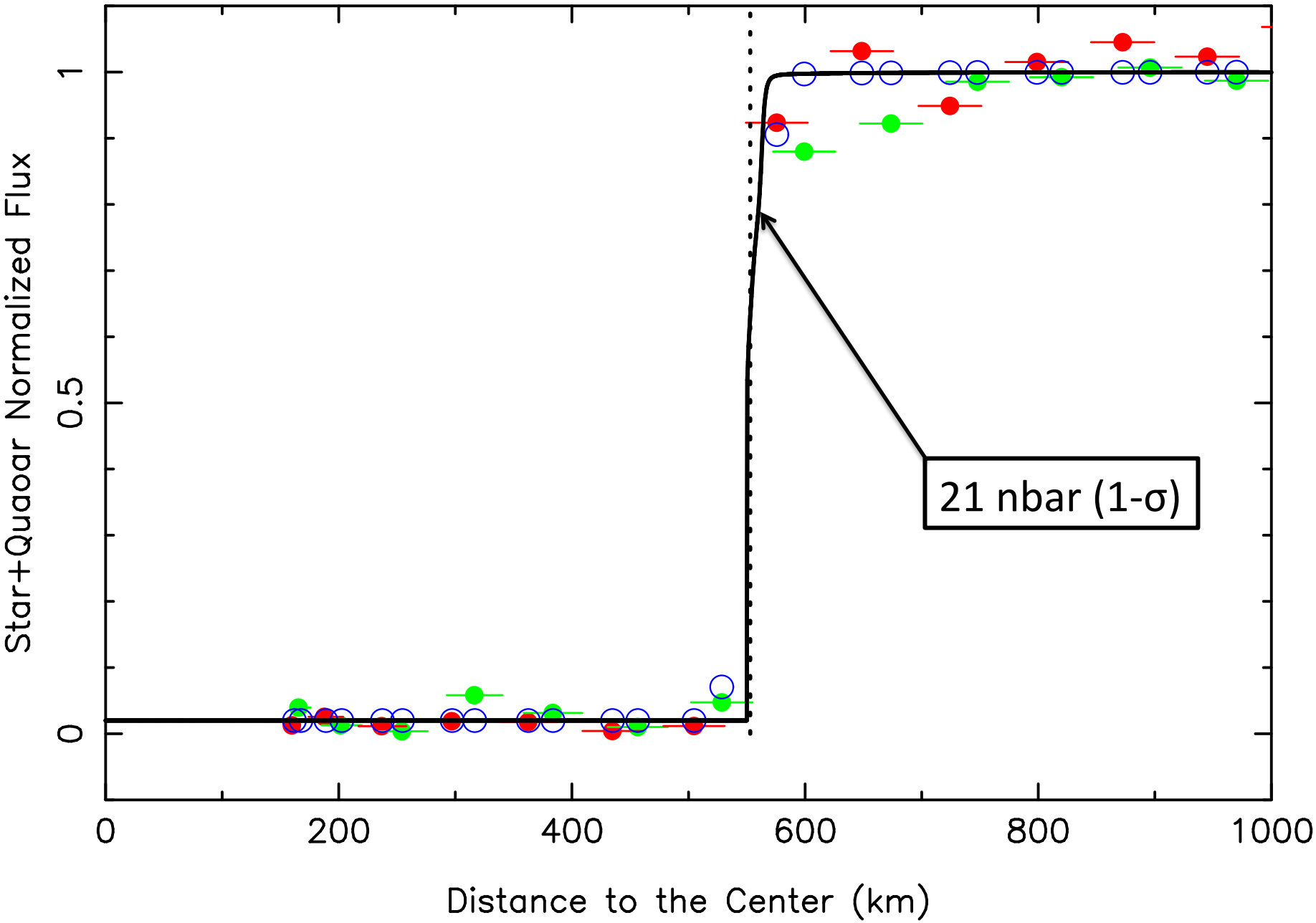
Quaoar 4 May 2011

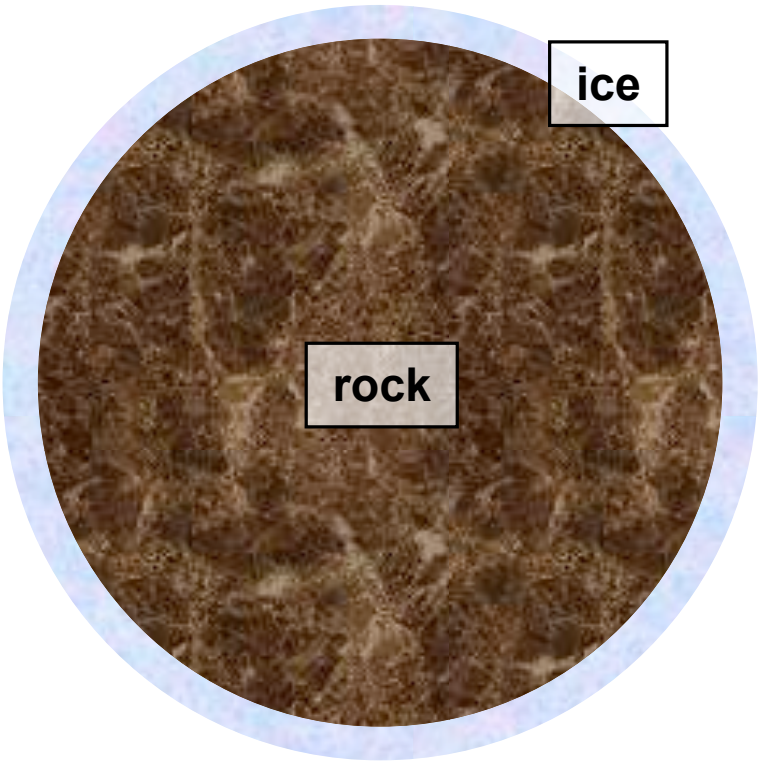
R_{equiv}= 555 ± 2.5 km

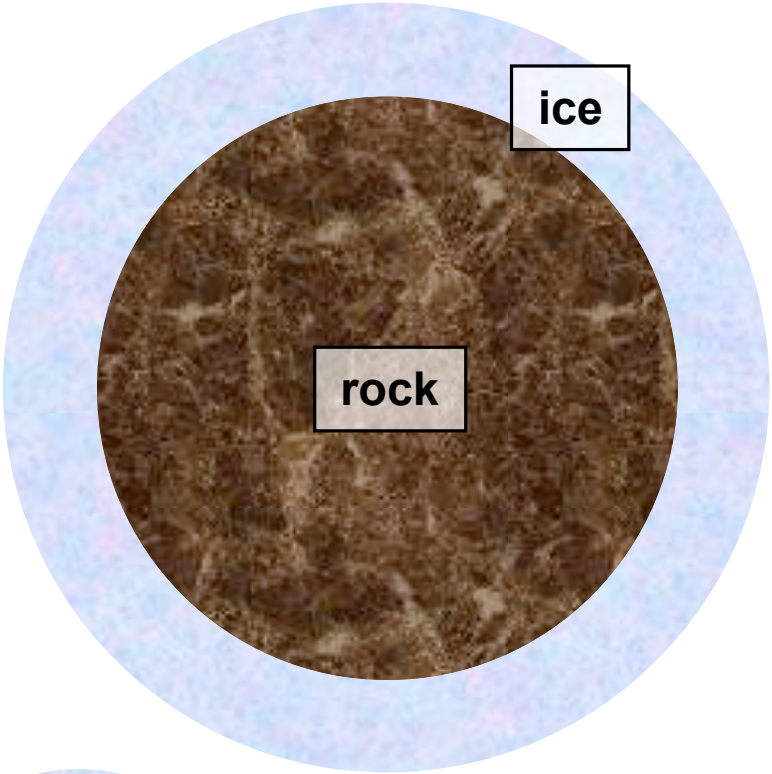
p_V= 0.109 ± 0.007

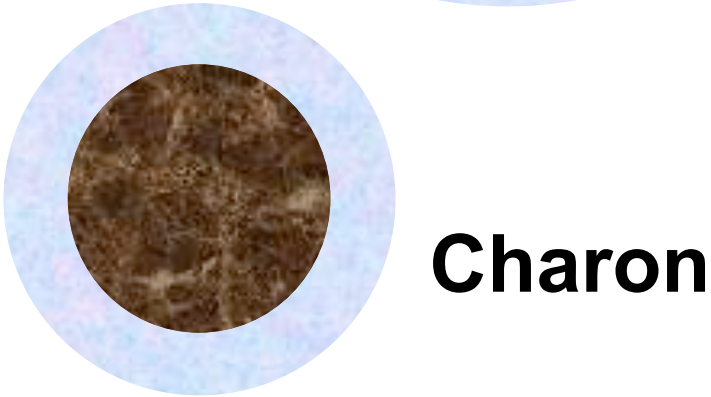
ρ= 2.0 ± 0.46 g cm^{-3}

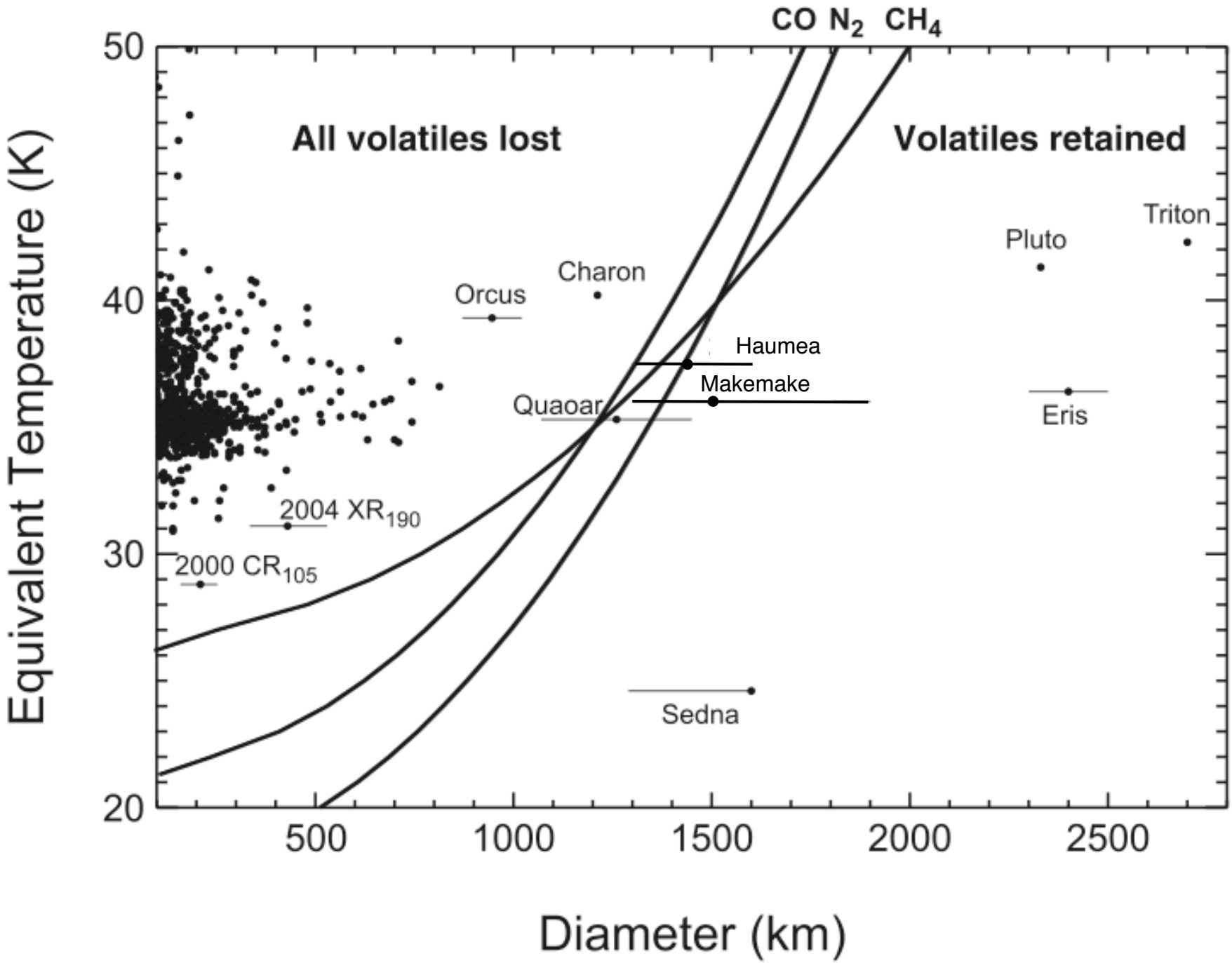
Braga-Ribas et al. (2013, submitted)

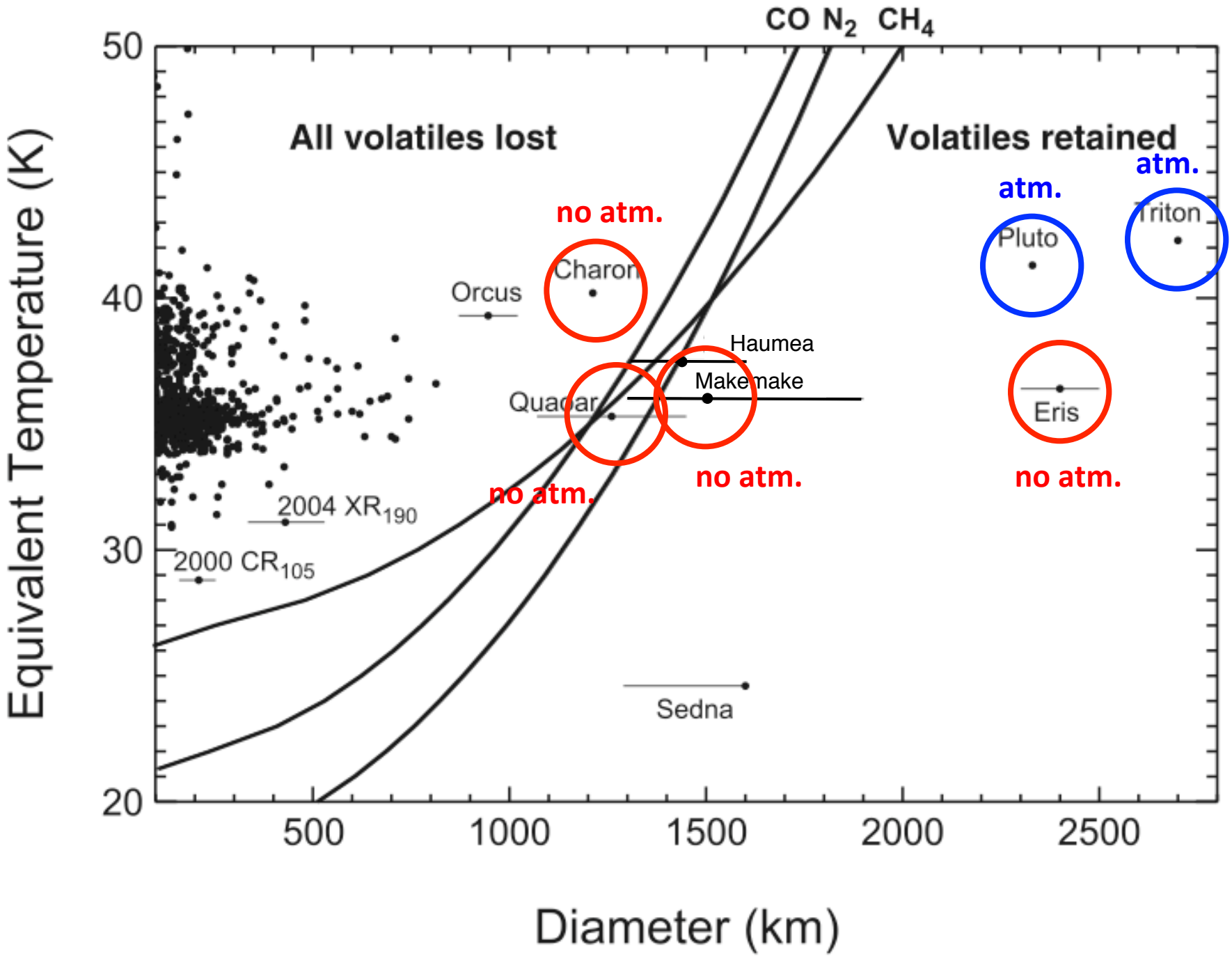

Star+Quaoar Normalized Flux
0
0.5
1
0
200
400
600
800
1000
Distance to the Center (km)
21 nbar (1-σ)


Eris
ice
rock


Pluto
ice
rock


Charon


CO
N_2
CH_4
All volatiles lost
Volatiles retained
Triton
Pluto
Charon
Orcus
Haumea
Makemake
Quaoar
Eris
2004 XR_{190}
2000 CR_{105}
Sedna
50
40
30
20
500
1000
1500
2000
2500
Equivalent Temperature (K)
Diameter (km)


CO
N_2
CH_4
All volatiles lost
Volatiles retained
no atm.
atm.
atm.
Charon
Orcus
Pluto
Triton
Haumea
Makemake
Quaoar
Eris
no atm.
no atm.
no atm.
no atm.
2004 XR_{190}
2000 CR_{105}
Sedna
Equivalent Temperature (K)
Diameter (km)
50
40
30
20
500
1000
1500
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2500

thank you…

High Time Resolution Optical Astrophysics
Royal Astronomical Society, London
2013 April 12