Prediction and High-Speed Photometry of Stellar Occultations supporting SOFIA Missions

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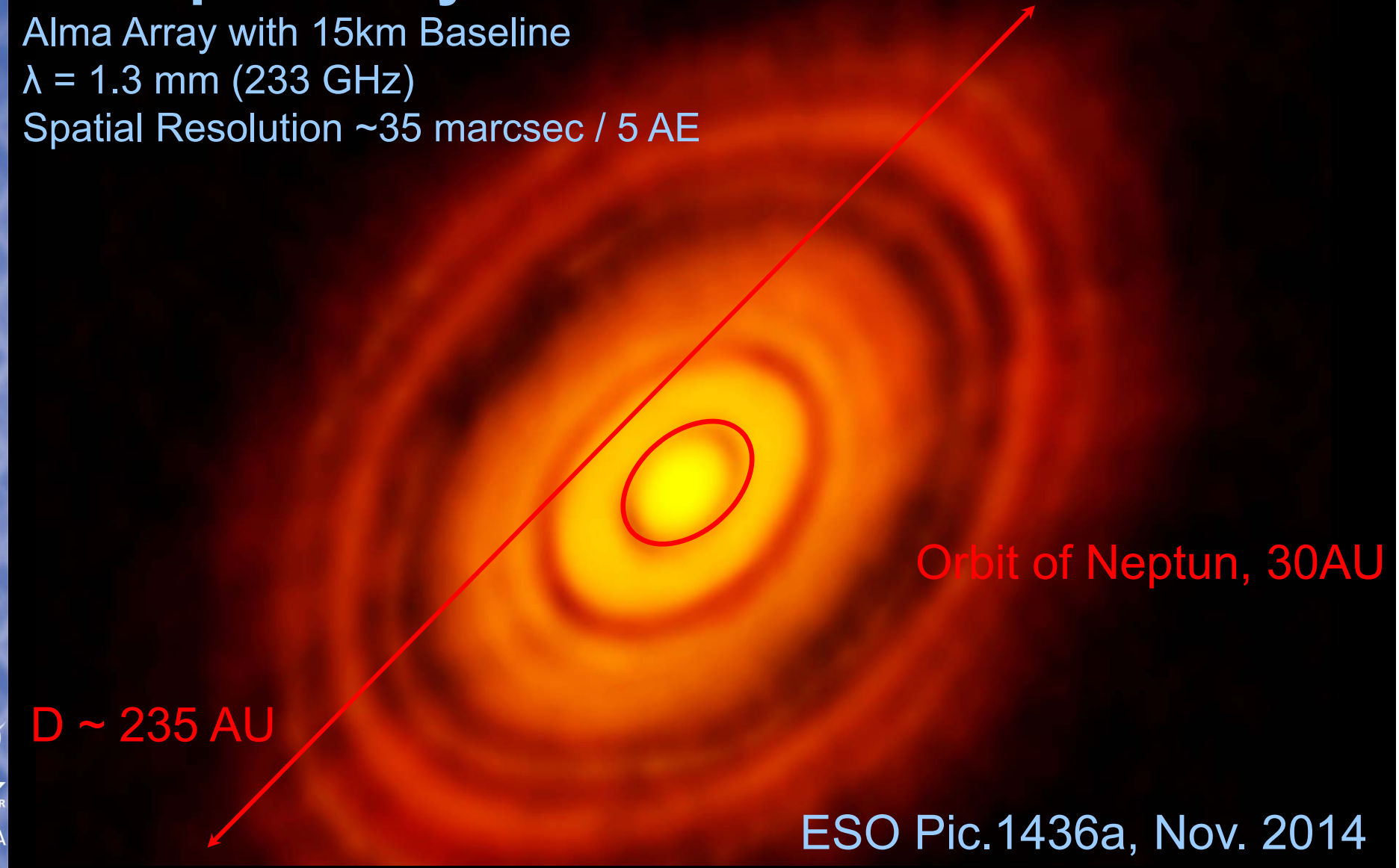
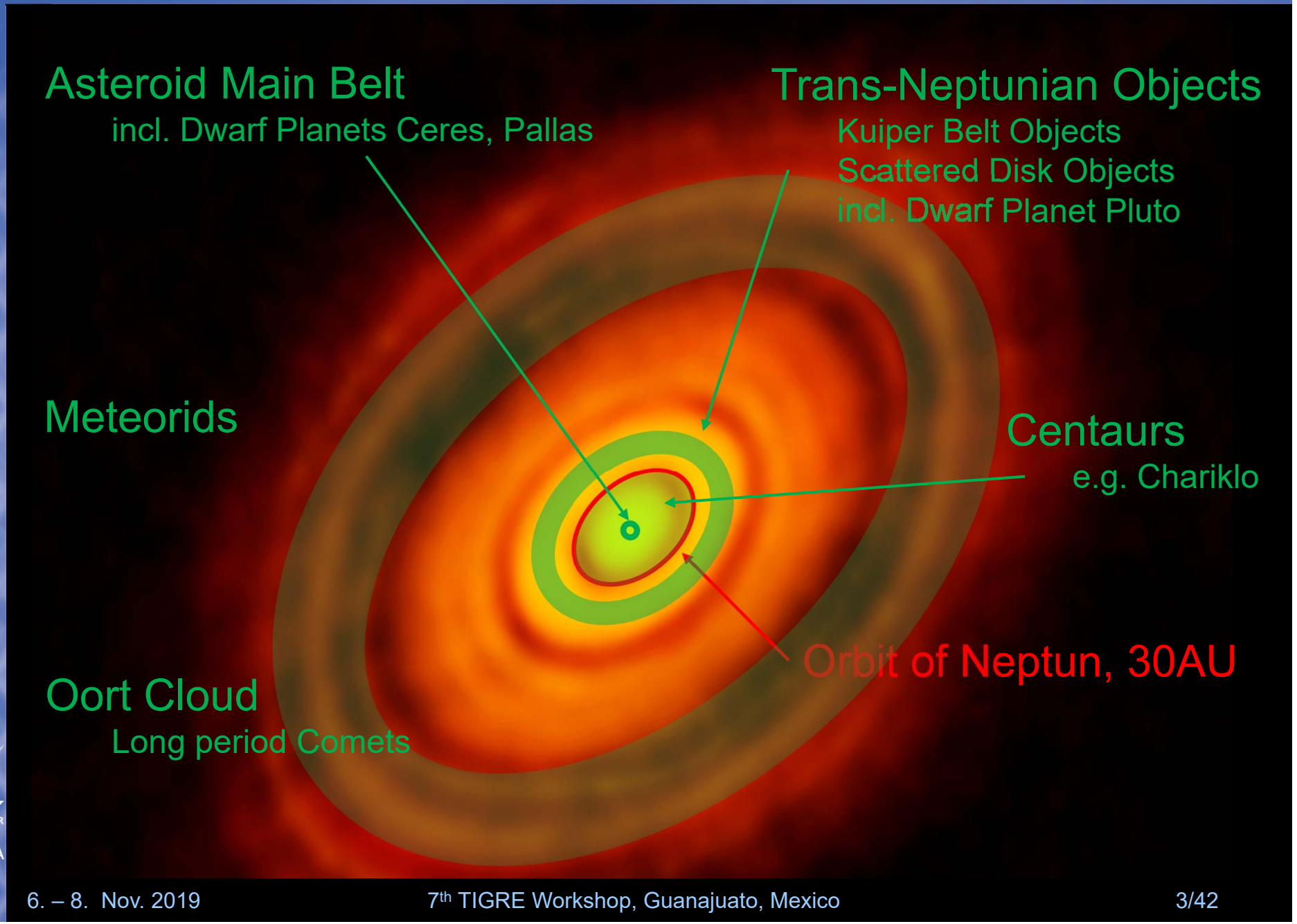
Protoplanetary Disk around HL Tauri

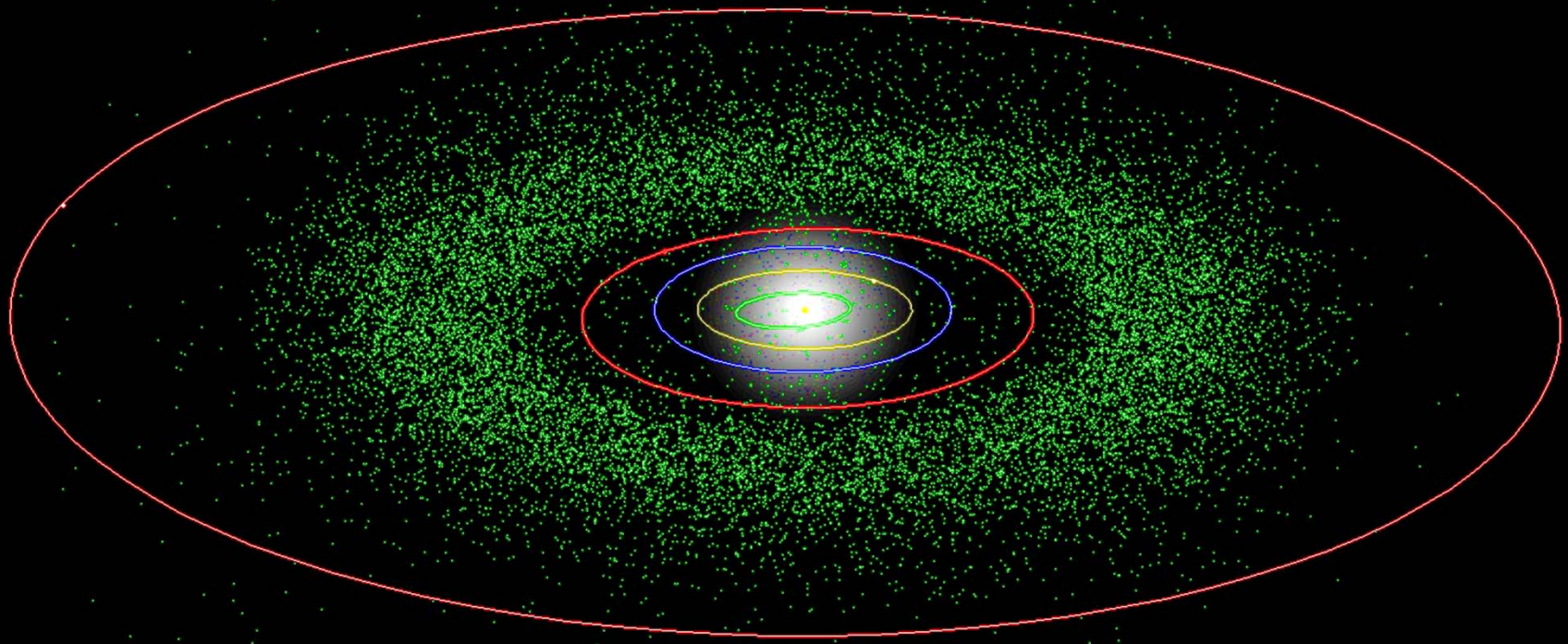
Alma Array with 15km Baseline
λ = 1.3 mm (233 GHz)
Spatial Resolution ~35 marcsec / 5 AE




Asteroid Main Belt
incl. Dwarf Planets Ceres, Pallas
Trans-Neptunian Objects
Kuiper Belt Objects
Scattered Disk Objects
incl. Dwarf Planet Pluto
Meteorids
Centaurs
e.g. Chariklo
Orbit of Neptun, 30AU
Oort Cloud
Long period Comets

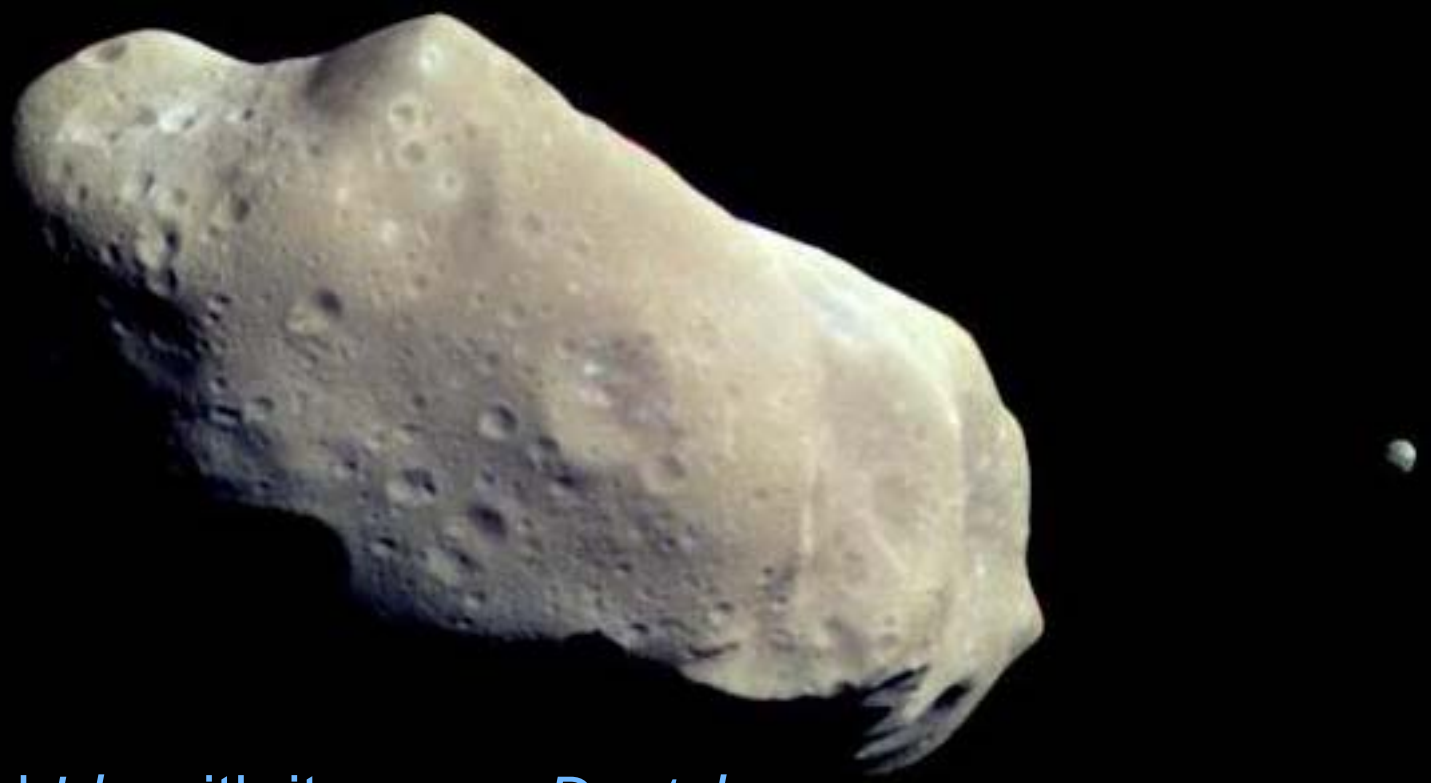
Asteorids

- Estimate: ~ 5 Mio bodies of D > 1km
- ~ 725 000 known Objects in Main Belt, 1.8 – 4 AU
- Total mass estimate 10^{-4} … 10^{-3} m_{Earth}
- Residual population of planetesimals and proto-planets



Ceres	**1801**	**Piazzi**	**D = 975 km**	**Dwarf Planet**
Pallas	**1802**	**Olbers**	**D = 560 km**	**Des. Dwarf Planet**
Juno	**1804**	**Harding**	**D = 267 km**	**Des. Dwarf Planet**
Vesta	**1807**	**Olbers**	**D = 516 km**	**Des. Dwarf Planet**

Examples of Asteroids and Dwarf Planets in the Main Belt



Asteroid *Ida* with its moon *Dactyl*

Galileo spacecraft 1993, d ~ 10,000km

59.8 x 25.4 x 18.6 km

$\rho = 2.6 \pm 0.5$ g /cm^3

$m = 4.2 \pm 0.6 \times 10^{16}$ kg (~ 7×10^{-9} m_{Earth})

Dactyl 1.6 x 1.4 x 1.2 km

Examples of Asteroids and Dwarf Planets in the Main Belt

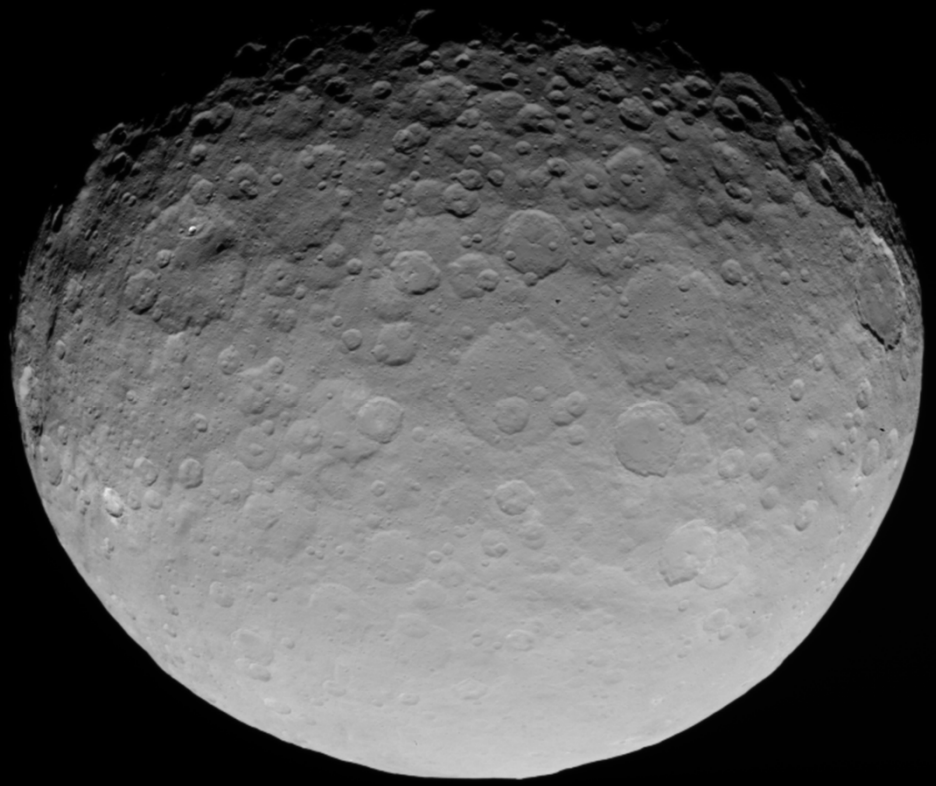
Eros – first discovered “near Earth” asteroid

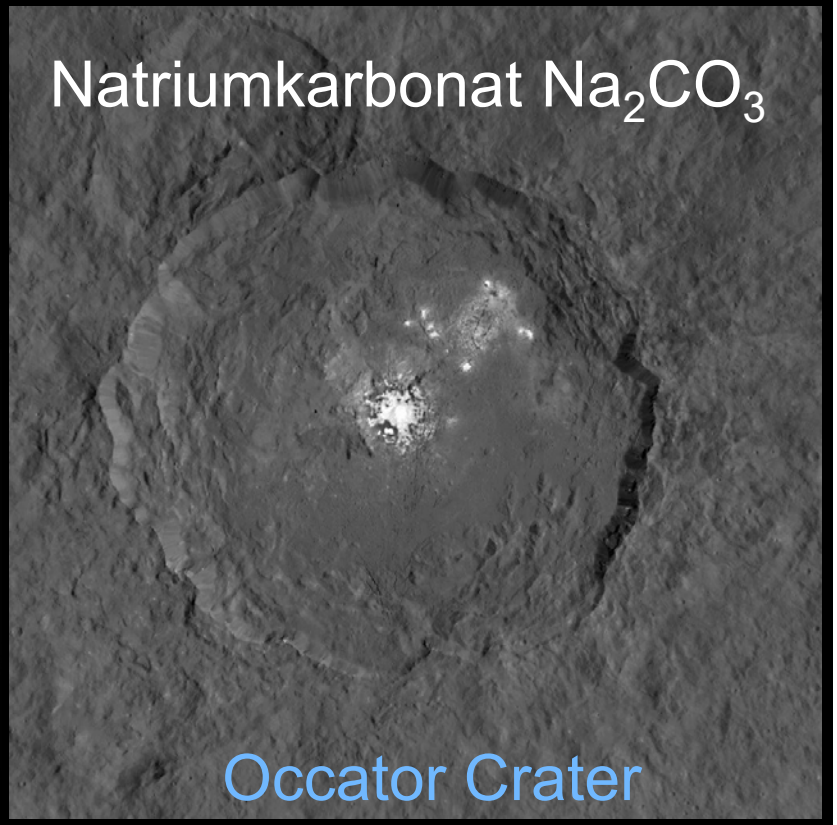
NEAR Shoemaker spacecraft in 2000, 200km orbit around Eros

34.4 x 11.2 x 11.2 km m = 6.687 ± 0.003 x 10^{15} kg (~ 1 x 10^{-9} m_{Earth})

ρ = 2.67 ± 0.03 g /cm^3

Examples of Asteroids and Dwarf Planets in the Main Belt





Dwarf Planet Ceres, largest object in Main Belt

DAWN spacecraft 4. May 2015, d ~ 13,600 km

Framing Camera (MPS, DLR, TU Braunschweig)

D_{mean} = 946 km m = 9.393 ± 0.003 x 10^{20} kg (~ 1.5 x 10^{-4} m_{Earth})

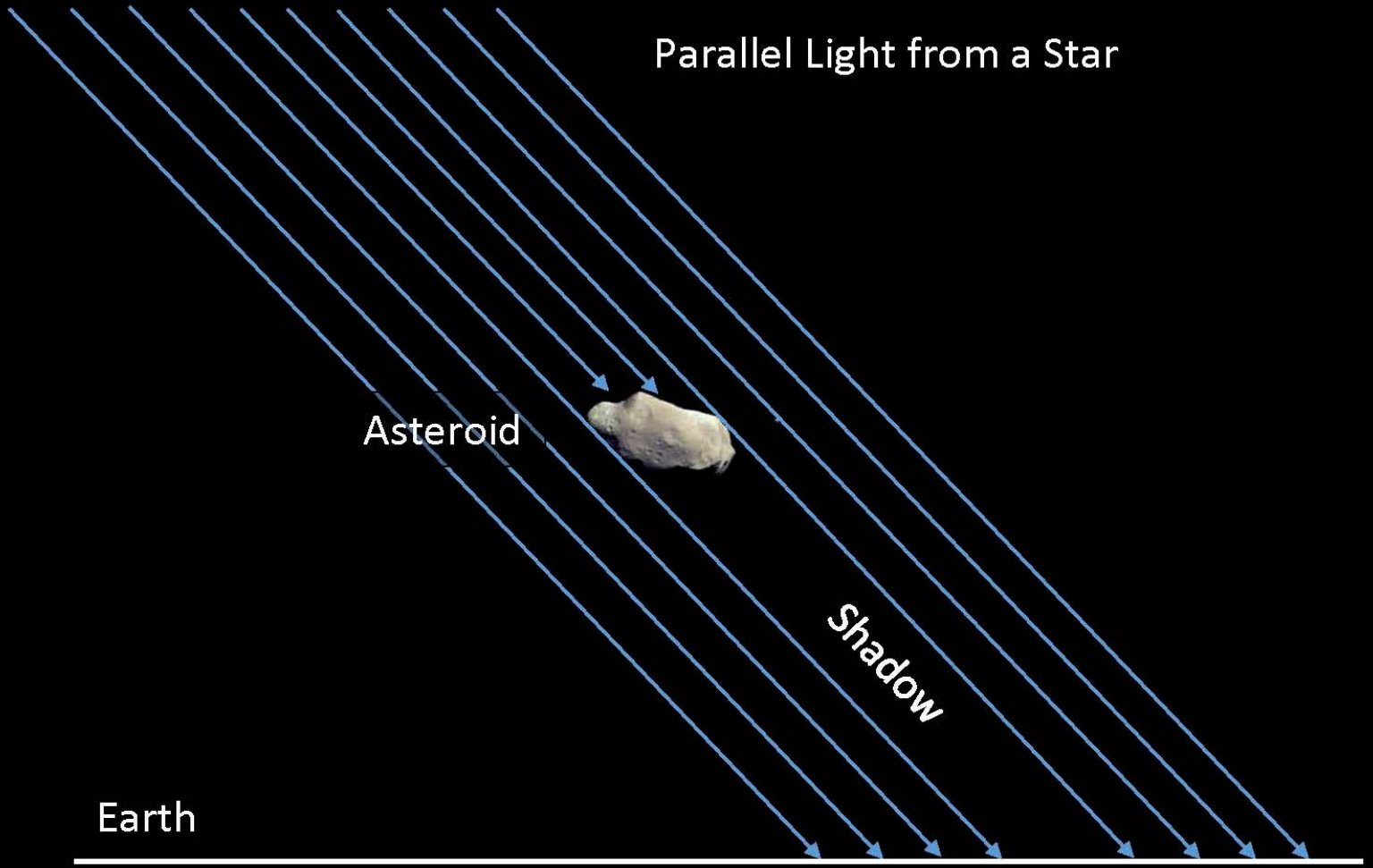
ρ = 2.16 g /cm^3

Examples of Asteroids and Dwarf Planets in the Main Belt

Asteroid Vesta

DAWN spacecraft 2011, d_{mean} ~ 680 km, resolution ~ 65 m/pixel
Framing Camera (MPS, DLR, TU Braunschweig)
572.6 x 557.2 x 445.4 km m = 2.59 x 10^{20} kg (~ 4.3 x 10^{-5} m_{Earth})
$\rho = 3.456 \pm 0.035$ g /cm^3

Stellar Occultation by a Minor Planet



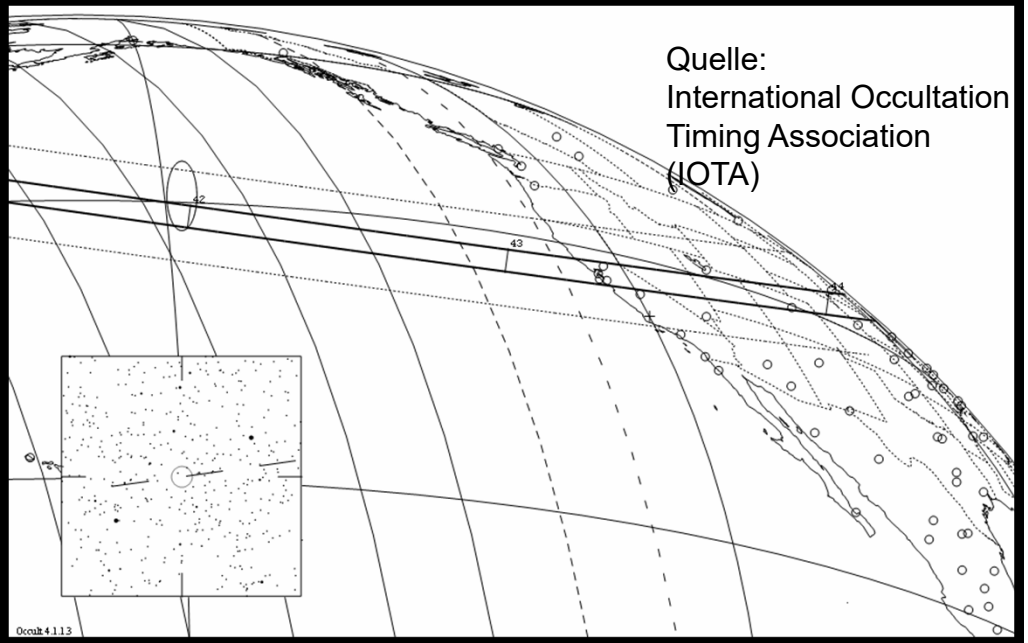
Schematic Light Curves of a stellar Occultation by Minor Planets

Bare Minor Planet
no Atmosphere

Minor Planet
with Atmosphere

Occultation by (34) Circe on 06. Okt. 2014

Astronomical Telescope of the University of Stuttgart, ATUS

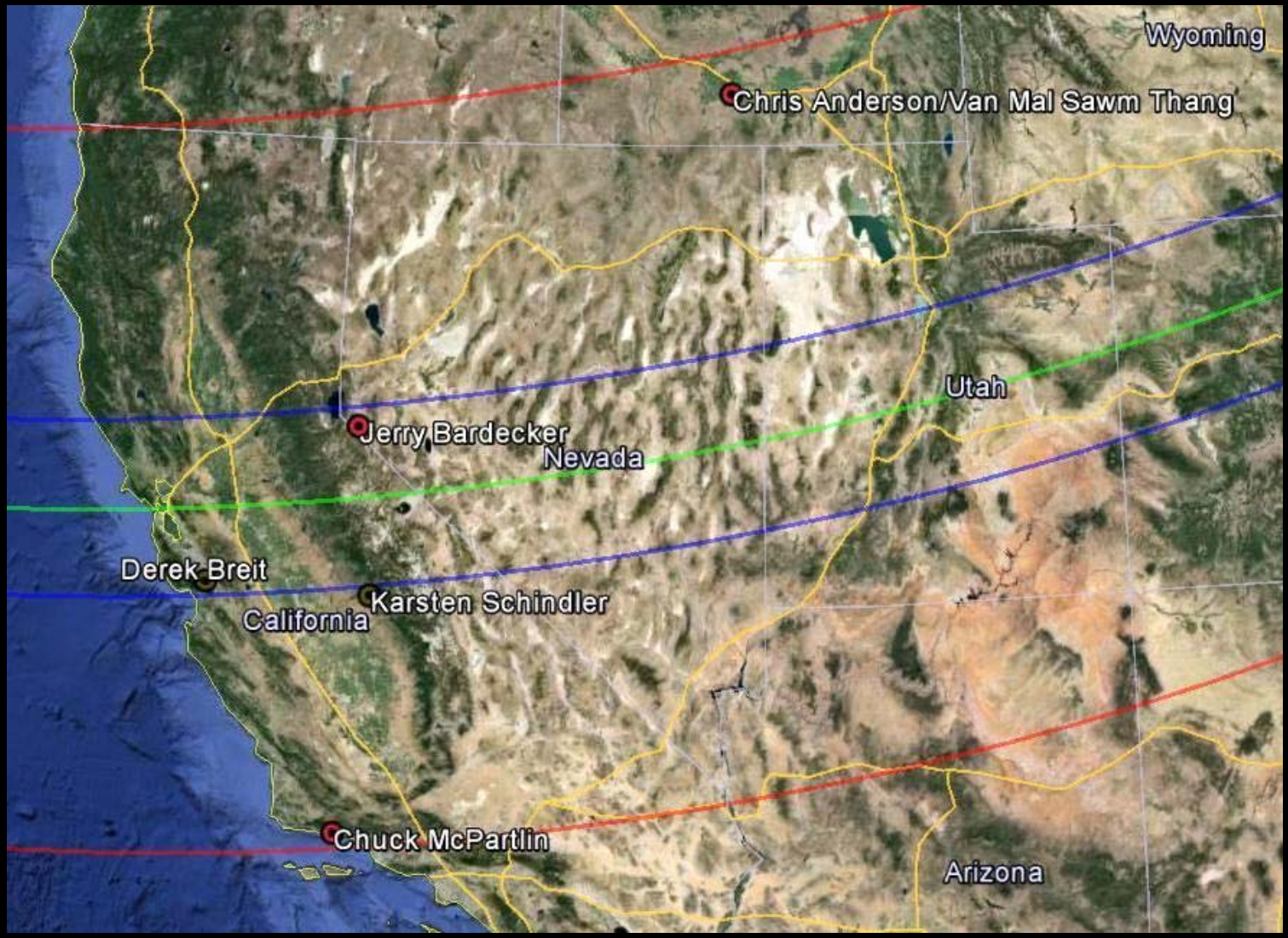


Uncertainties:

GAIA DR2

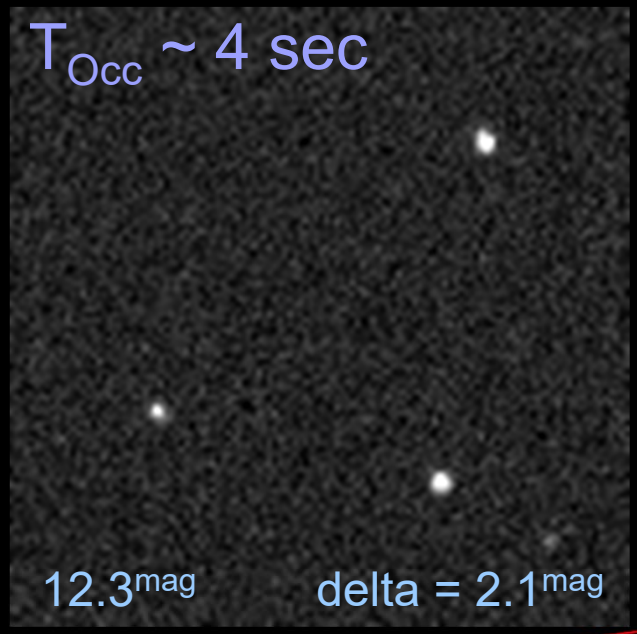
- Exact Position of the star (Astrometry!)
- Orbit/Position of the Minor Planet
- Size, Form & Orientation of the Minor Planet
- Possible Duplicity of target star

(34) Circe shadow prediction on 06. Okt. 2014

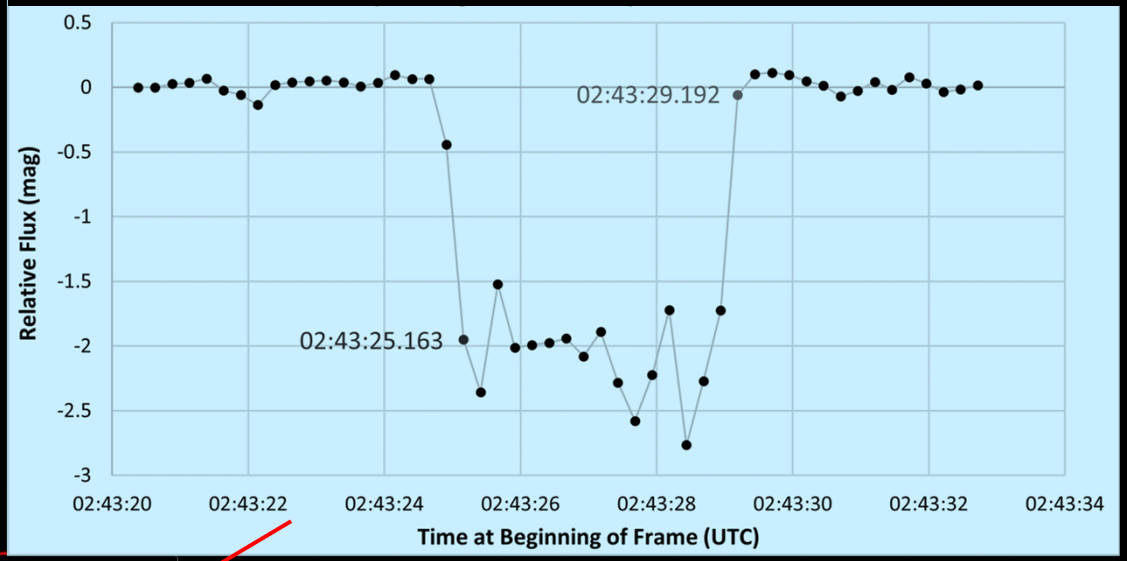


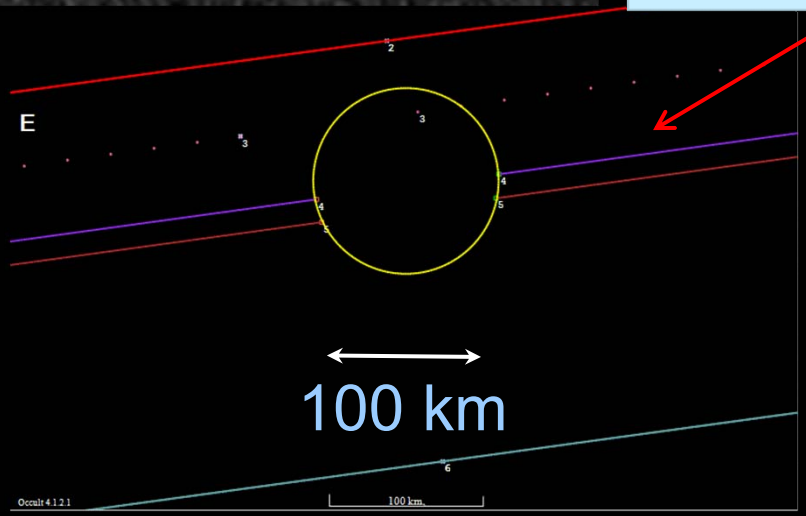
Occultation by (34) Circe on 06. Okt. 2014

Stratospheric Observatory For Infrared Astronomy



Astronomical Telescope of the University of Stuttgart
ATUS, 0.6 meter RC System



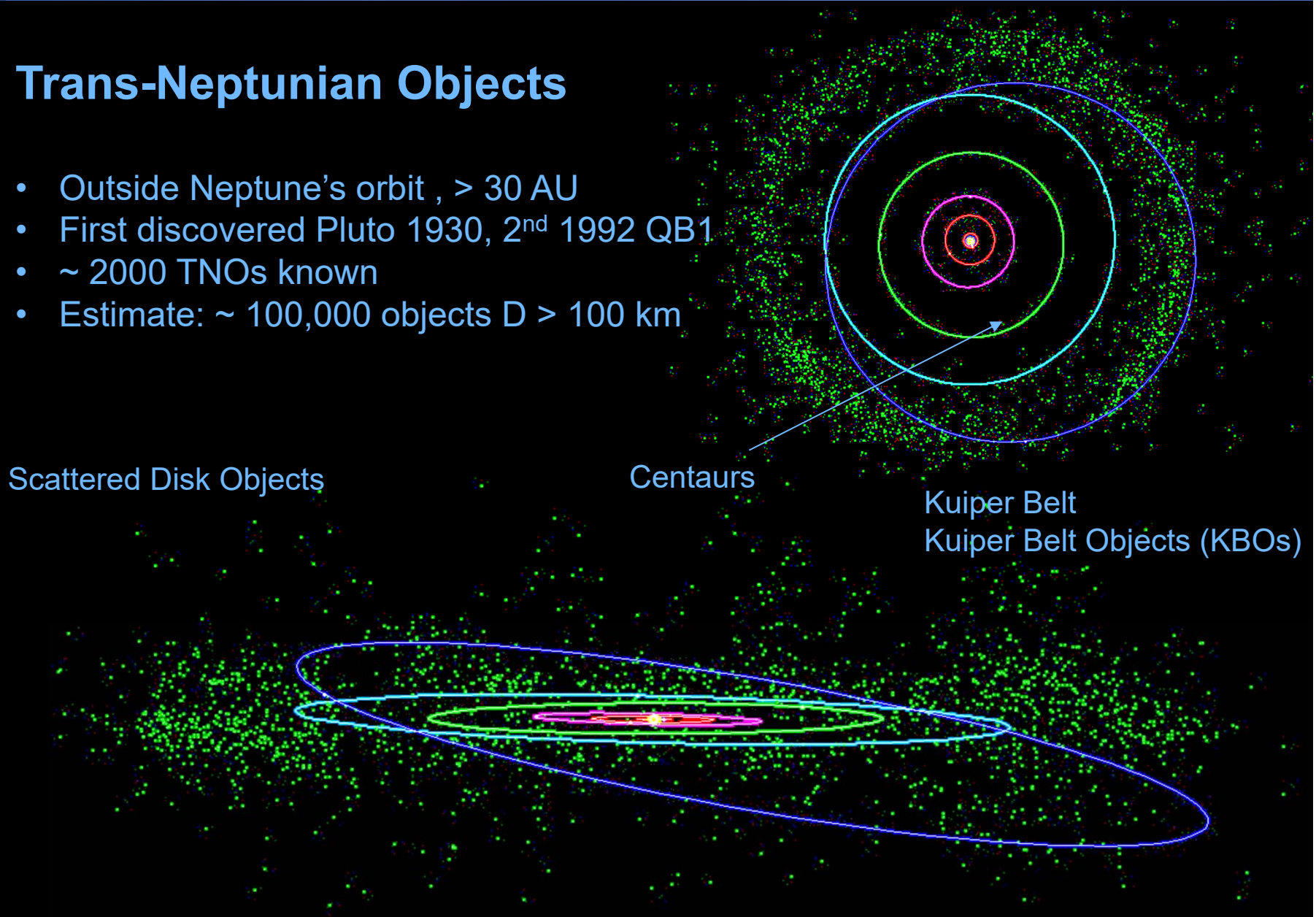


Metis 07. März 2014

Quelle: IOTA

Trans-Neptunian Objects

- Outside Neptune's orbit , > 30 AU
- First discovered Pluto 1930, 2nd 1992 QB1
- ~ 2000 TNOs known
- Estimate: ~ 100,000 objects D > 100 km



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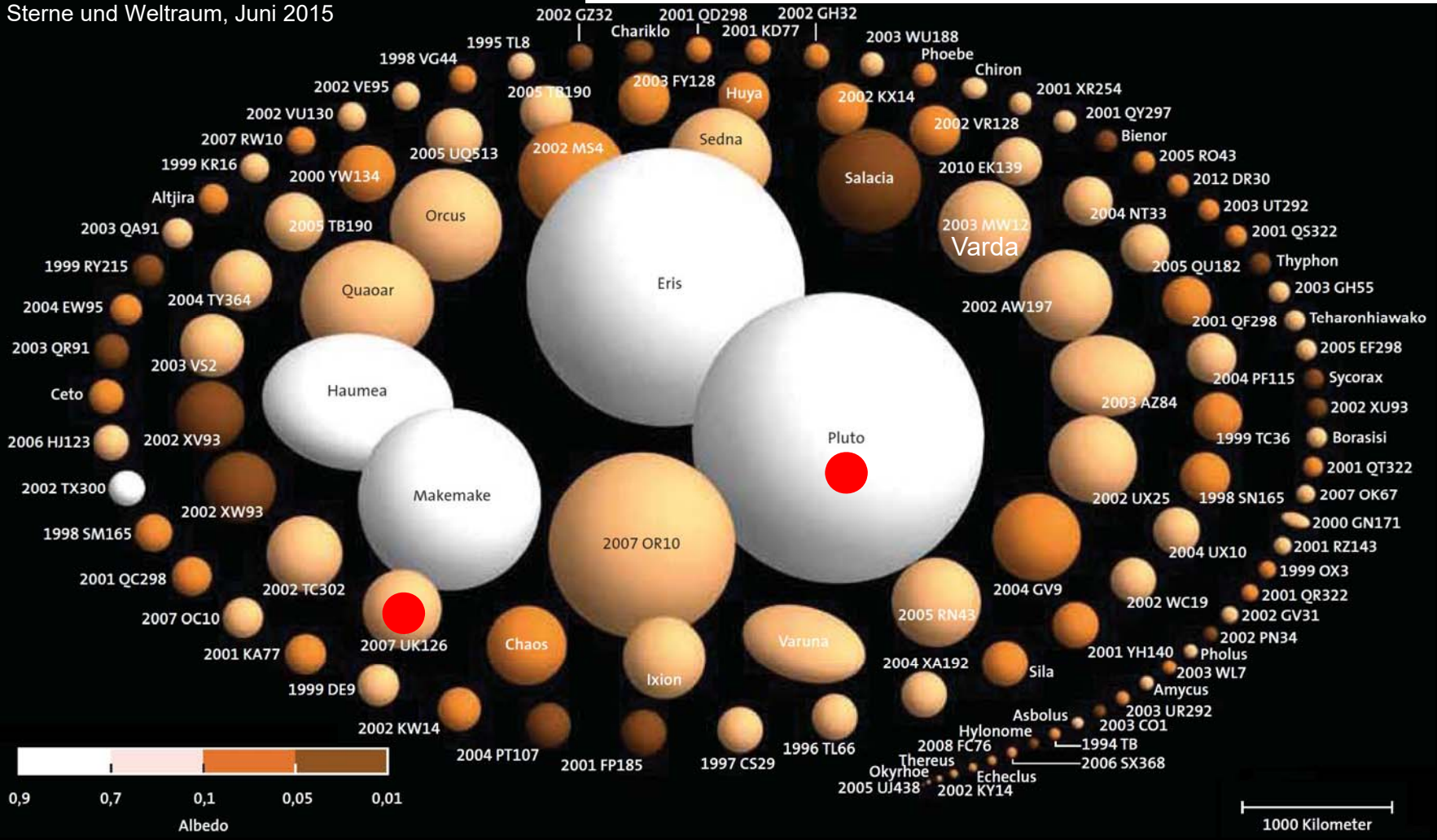
Trans Neptunische Objekte (TNOs)

October 2019: 1899 TNOs + 755 Centaurs, SDO

Sterne und Weltraum, Juni 2015



2007 UK_{126}

- Entdeckung 19. Okt. 2007, Palomar Observatory
  Zurück verfolgt bis Aug. 1982 auf Platten von Siding Spring & Palomar Obs.
  Verbesserte Bahnberechung: i = 23,34º, e = 0.49, a = 74,01 AE, U = 636,73[a]
- Perihel Durchgang 18. März 2046, r_H = 37,522 AE, m_v ~ 19,13[mag]
- Keine Messung des Durchmessers
- Geschätzter Durchmesser aufgrund FIR Emission: 599 ± 77 km
- Flache Lichtkurve Δm = 0,03 ± 0,01 mag; uneindeutige Rotationsperiode (11 / 14,3 / 20.3 h), Trennung zwischen Form- und Albedo-Effekten unmöglich
- Hubble entdeckte am 13. Nov. 2008 einen Satelliten; Umlaufbahn bislang unbekannt, Δm = 3,97 ± 0,24 mag

- Bedeckung am 15. November 2014 UTC

  Stern UCAC4 448-006503 in Eridanus
  RA_{J2000} = 04h 29m 30.6s, Dec_{J2000} = -00° 28‘ 20.9“,
  m_V = 15.86 [mag], m_B = 17.00 [mag], m_J = 14.34 [mag] on.

  2007 UK_{126} $r_{geoz.}$ = 42,572 AE, $r_{helioz.}$ = 43,47 AE
  nahe Opposition am 1. Dez. 2014, Phasenwinkel 0º,56 , m_v ~ 19,84 [mag]

Occultation by TNO (229762) 2007 UK_{126} in November 2014

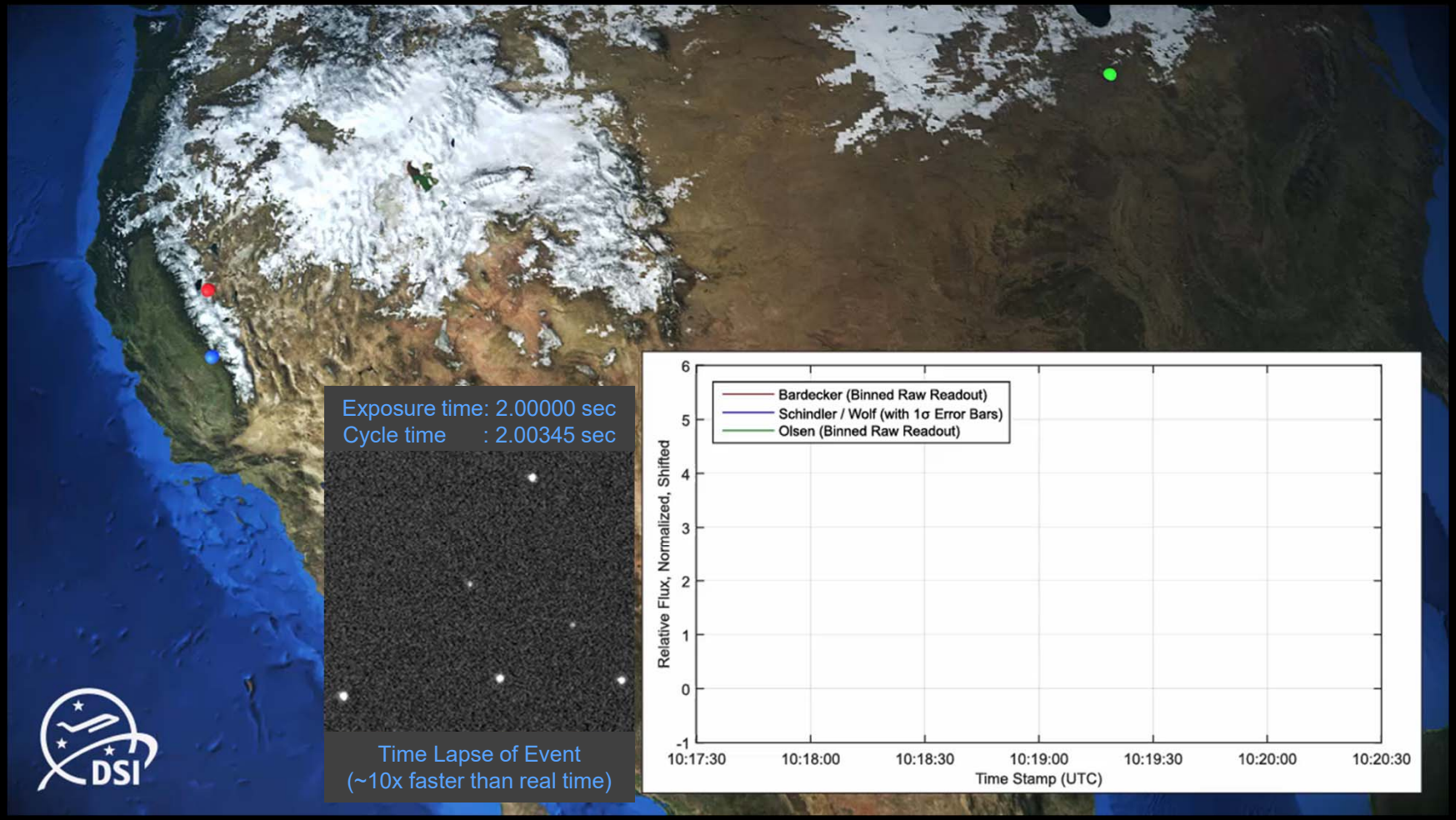
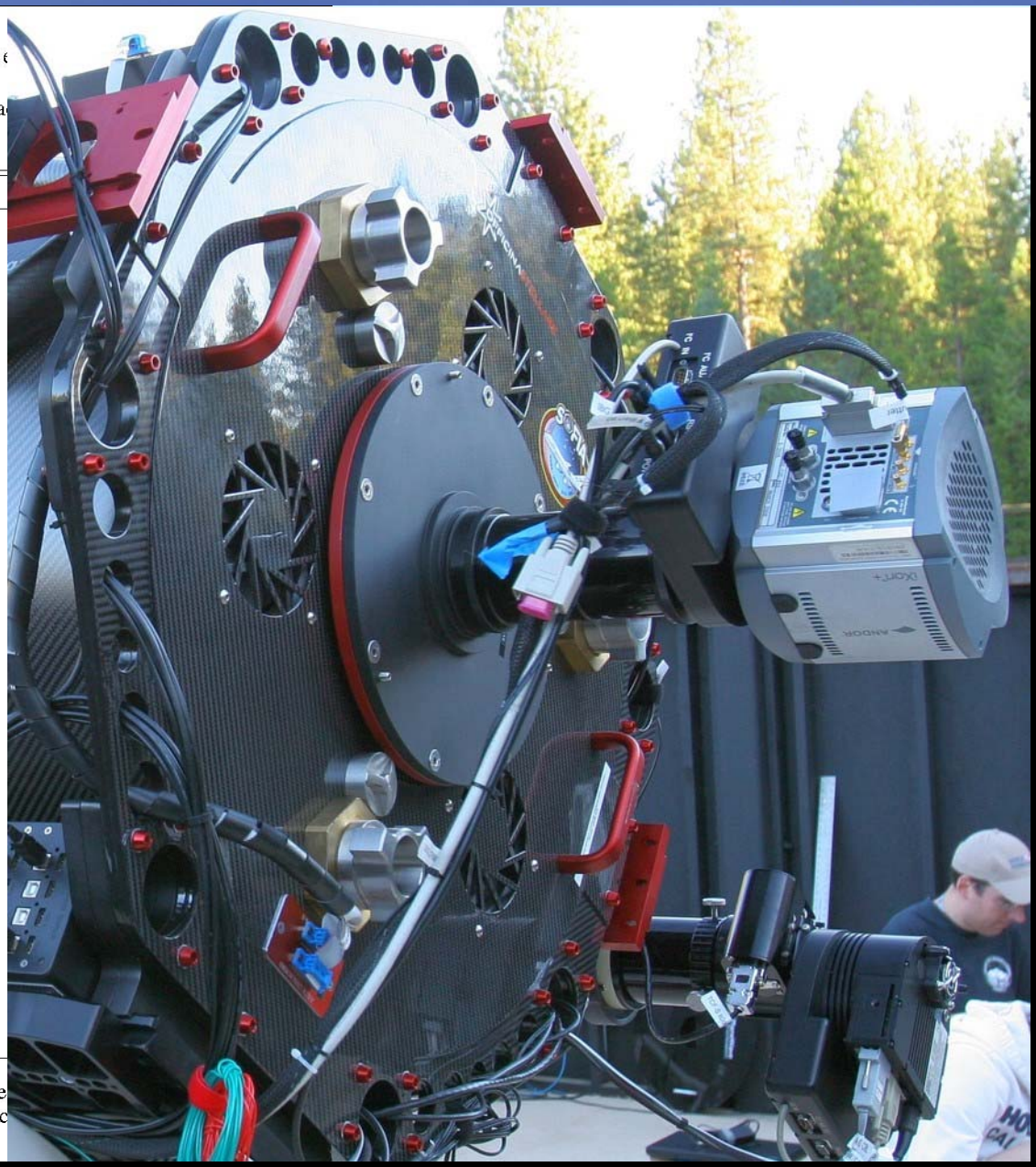
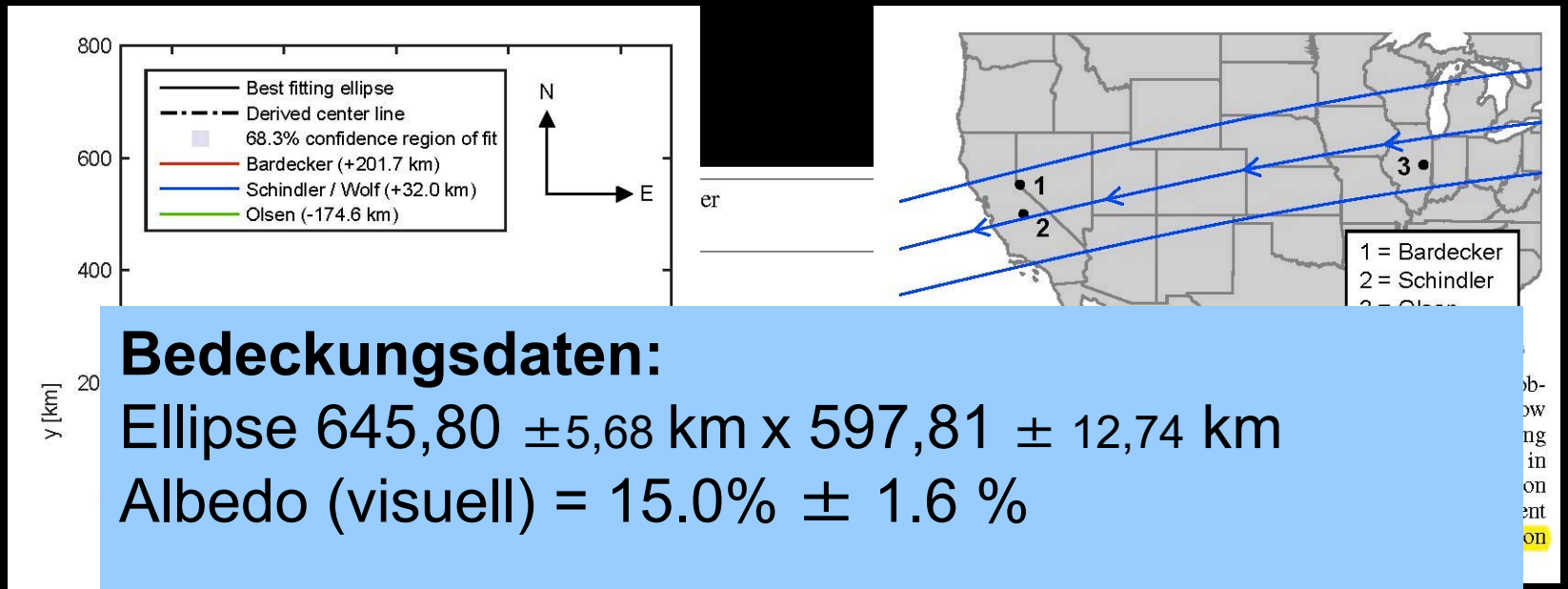


Table 2. Locations, setups and image a
light curves.

Observer
Closest city
Latitude N (deg mm ss.ss)
Longitude W (deg mm ss.ss)
Altitude (m)
Telescope type
Aperture, focal ratio
Camera
Sensor type
Sensor cooling (temperature[a])
Frame grabber card
File format
GPS time logger
Integration time (s)
Camera-internal frame accumulation
Cycle time per frame (s)
Disappearance (D) time from square-well fit (UTC)
Reappearance (R) time from square-well fit (UTC)
Duration of event (s)
Chord length (km)
SNR[c] , star & target combined

Notes. None of the observers have use
to the telescope setup at the time of rec
point.





Bedeckungsdaten:

Ellipse 645,80 ±5,68 km x 597,81 ± 12,74 km

Albedo (visuell) = 15.0% ± 1.6 %

Kombiniert mit FIR Helligkeiten:

Effektiver Durchmesser = 599 - 629 km

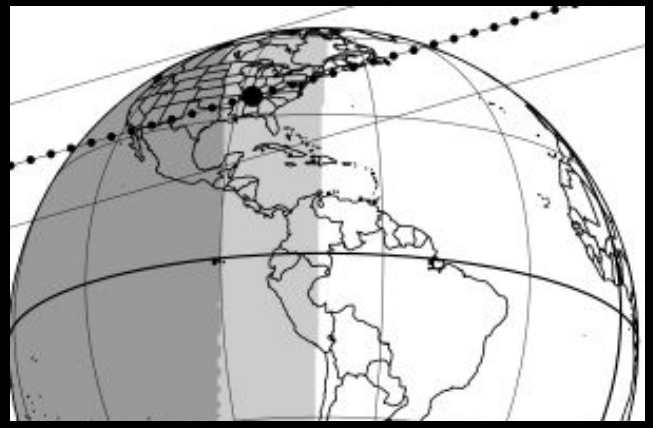
Oberflächentemperatur (subsolar) = 50 – 55 Kelvin

Fig. 4. The derived ellipse fit and its 68.3% confidence region (gray). Uncertainties of each individual ellipse parameter are summarized in Table 5. The angle θ gives the rotation of the major axes, measured from east to north. The plotted error bars of the D and R locations have been derived from the timing deviations given in Table 2. The major and minor axes are indicated by the dotted lines. The distances provided in the legend are topocentric with respect to the center line derived for the best fit (dash-dotted line). The chord by Schindler & Wolf sampled 2007 UK_{126} almost at the center line, while the chords by Bardecker and Olsen sampled the upper and lower part quasi symmetrically. The geocentric distance of 2007 UK_{126} was r_G = 42.572 AU at the time of the observation.

Table 5. Geometric parameters of the best fitting ellipse and associated uncertainties.

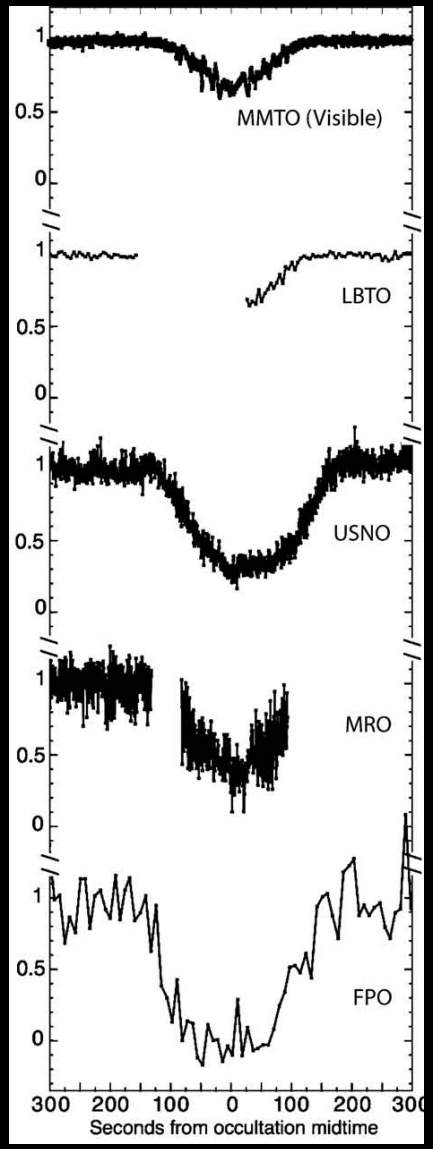
Parameter	Value
a_{EI} (km)	645.80 ± 5.68
b_{EI} (km)	597.81 ± 12.74
x_{EI} (km)	6.57 ± 2.06
y_{EI} (km)	−10.82 ± 3.13
θ_{EI} (deg)	21.25 ± 5.65

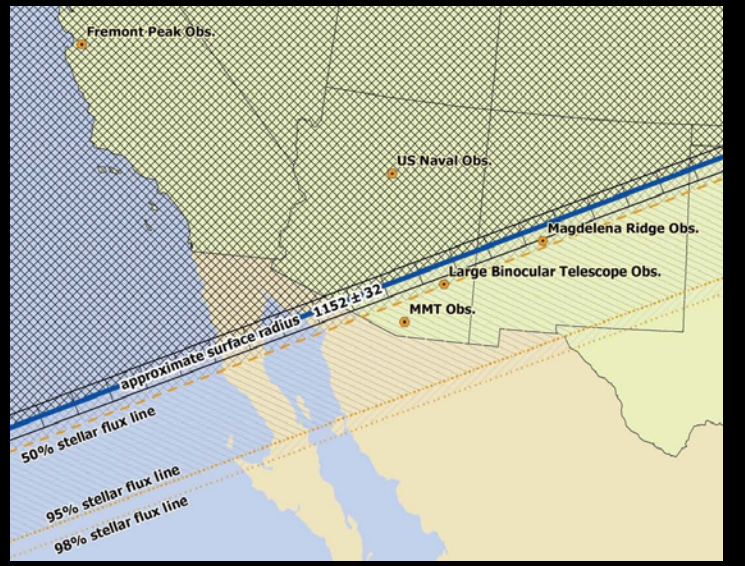
Stellar Occultation by Pluto, 18. March 2007, 10:56 UT



IOTA Prediction

0.32 m Mobile Telescope
ST-10 CCD Camera

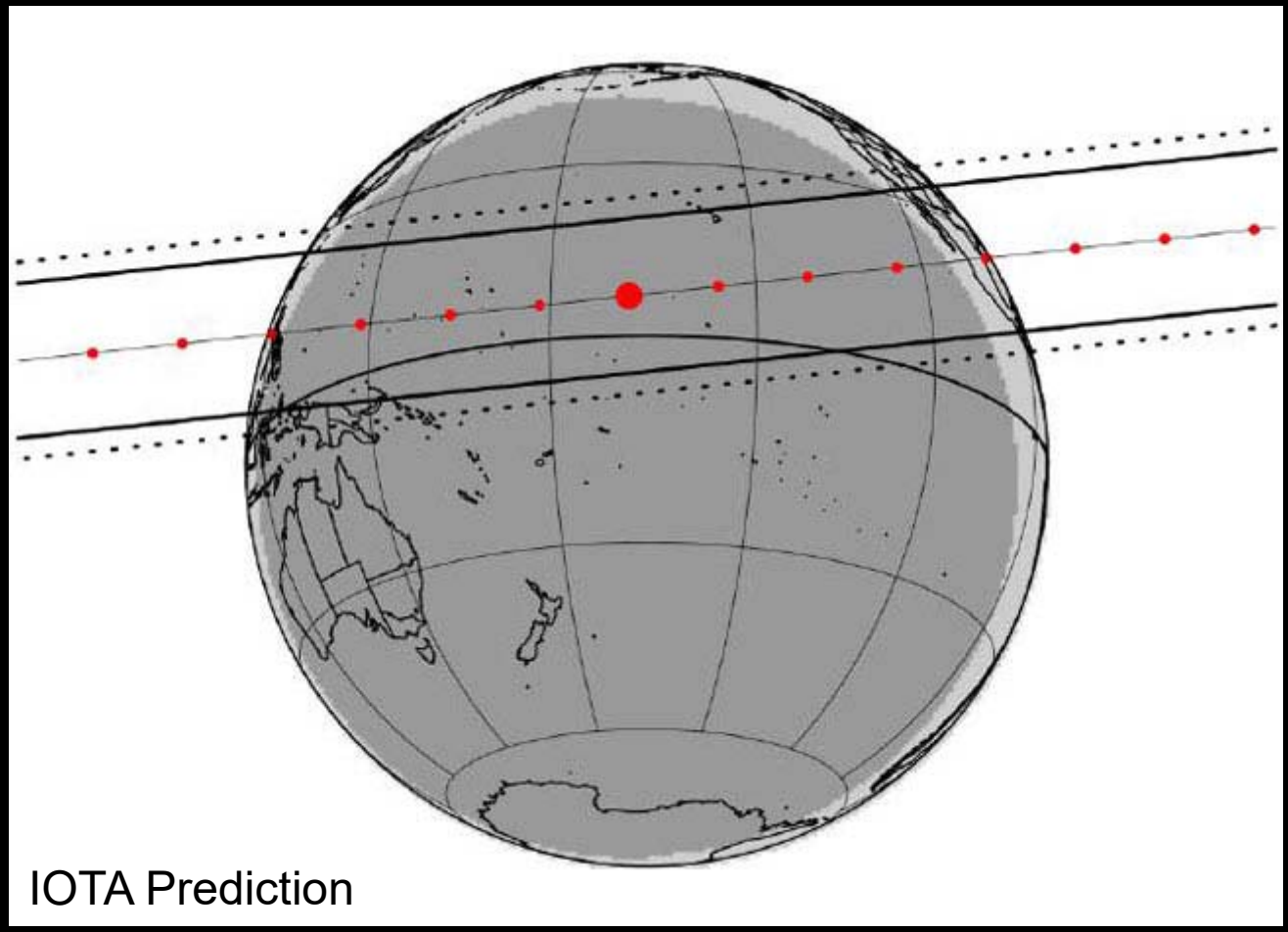




- **FP (DSI) next to central shadow line**
- **“Grazing” for the other observers**
- **Atmosphere measured $r_{50\%}$ = 1291 ±5 km**
- **Wind speed on Pluto ≤ 3 $^{m}/_{s}$ at R = 1400 km**

Person M., et al., AJ, 136:1510-1518, 2008 Oct.

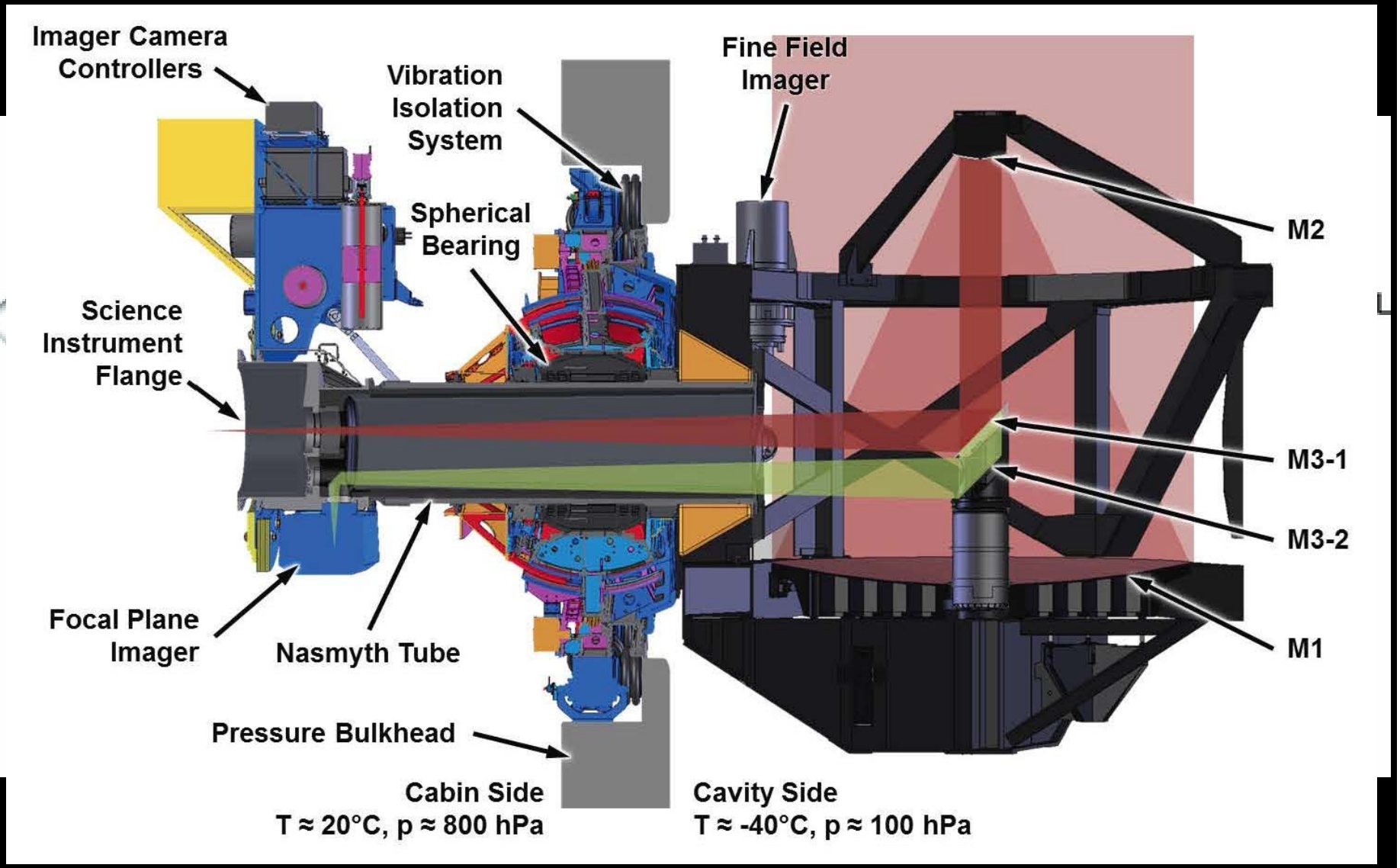
What if no ground based telescopes are available ?



IOTA Prediction

Stellar Occultation by Pluto, 23. Juni 2011, 11:24 UT

Fly into the Shadow Path – to the right place at the right time


Imager Camera Controllers
Vibration Isolation System
Fine Field Imager
Spherical Bearing
M2
Science Instrument Flange
M3-1
M3-2
Focal Plane Imager
Nasmyth Tube
M1
Pressure Bulkhead
Cabin Side
T ≈ 20°C, p ≈ 800 hPa
Cavity Side
T ≈ -40°C, p ≈ 100 hPa

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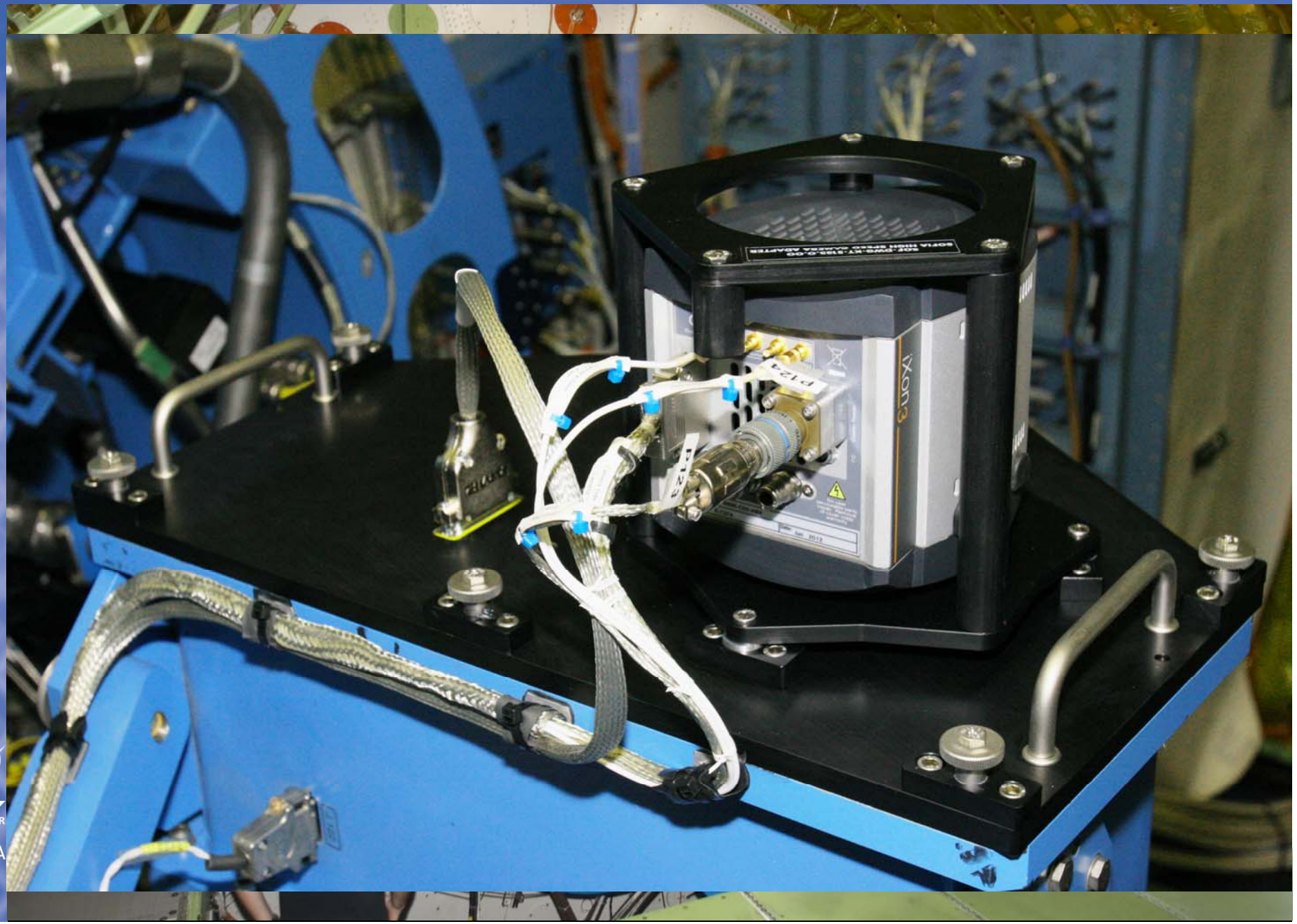
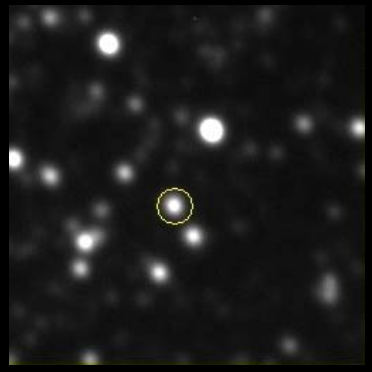


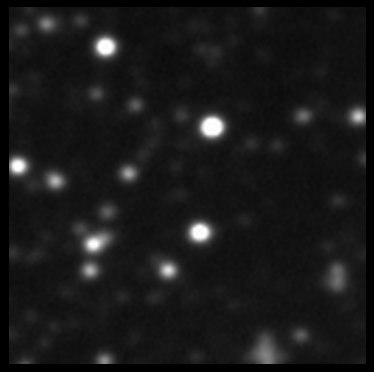

SOFIA
PLUTO
OCCULTATION
HIPO
FDC
June 22/23, 2011

SOFIA observed a stellar occultation by Pluto on 23. Juni 2011, 11:24 UT

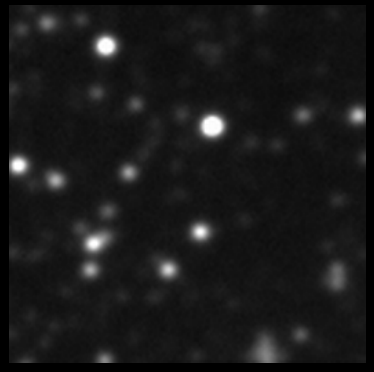
- Dwarf Planet Pluto (V~14mag) occulted a star (V~14.4mag)
- SOFIA flys into the shadow of Pluto over the Pazific
- SOFIA Instrumentation: *High Speed Imaging Photometer for Occultations* (HIPO, Lowell Obs.), und *Fast Diagnostic Camera* (FDC, DSI)
- Both instruments measured successfully the light curve



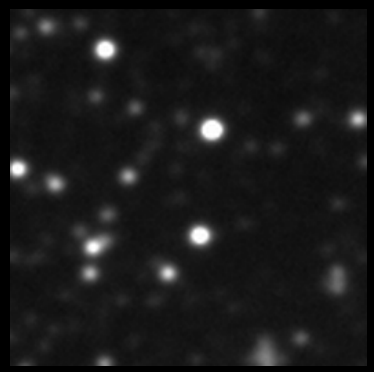
Pluto (circled) 13 arcsec from star, 200 min before the occultation



Just before the occultation, Light = Pluto + Star



During the occultation, Light = Pluto



After the occultation, Light = Pluto + Star

Measured light curves

D_{Tel} [m]

US Naval Obs. Flagstaff — 1.3

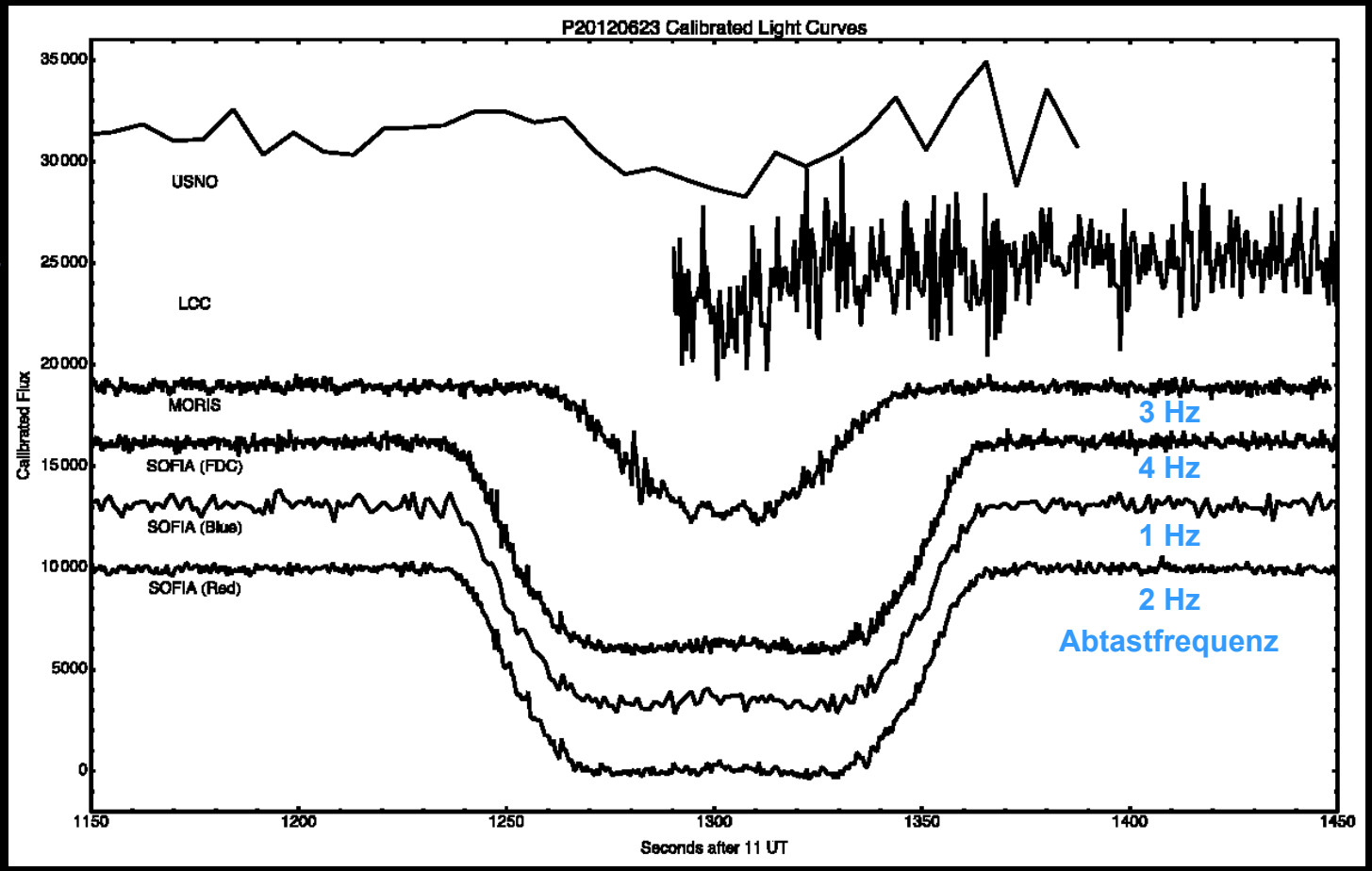
Leeward Comm. College, HI — 0.5

IRTF, HI — 3.0

SOFIA, FDC — 4 Hz

SOFIA, HIPO blue — 1 Hz

SOFIA, HIPO red — 2 Hz



Person M. et al., AJ, 146:83 (15pp), 2013 Oct.

Measured light curves

D_{Tel} [m]

US Naval Obs. Flagstaff — 1.3

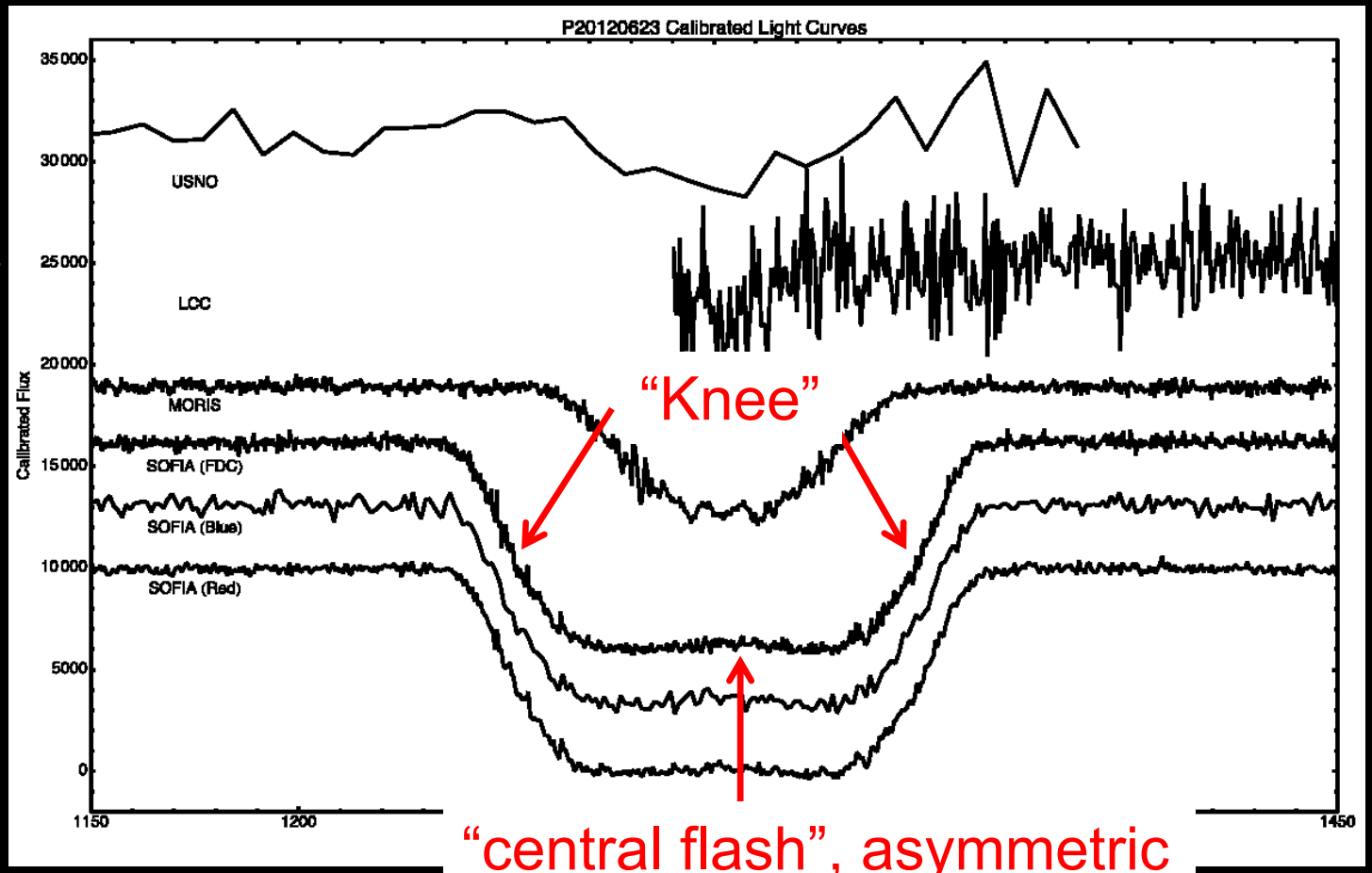
Leeward Comm. College, HI — 0.5

IRTF, HI — 3.0

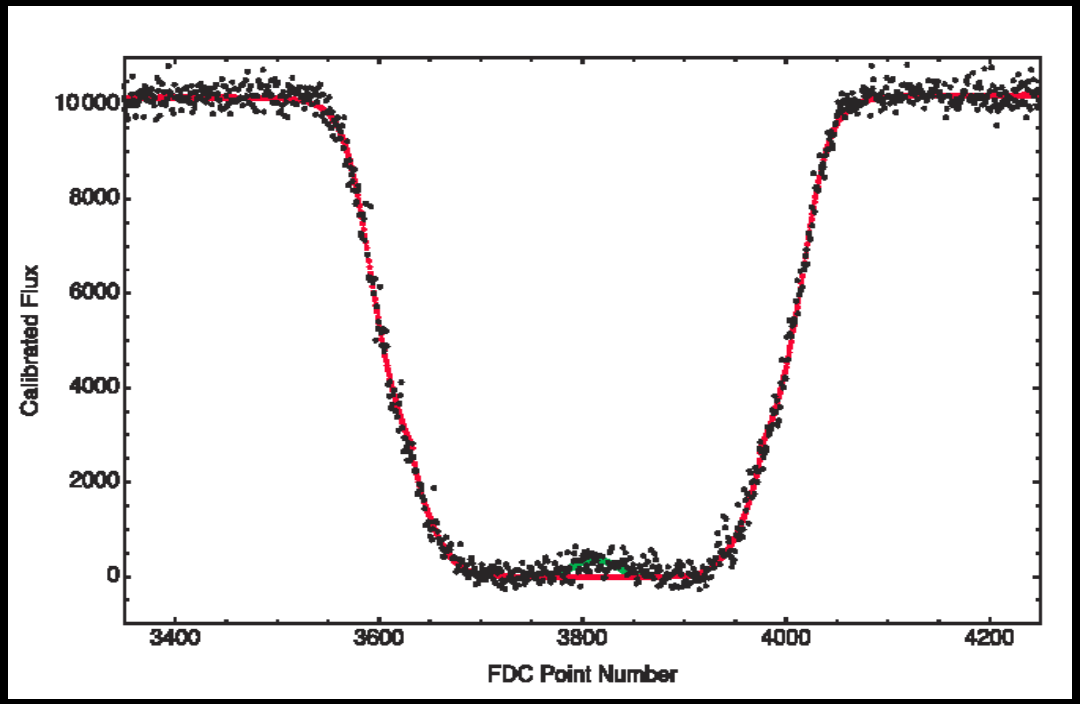
SOFIA, FDC — 3.0

SOFIA, HIPO blue — 2.5

SOFIA, HIPO red — 2.5



Person M. et al., AJ, 146:83 (15pp), 2013 Oct.



FDC lightcurve with fitted
Modell of the lower atmosphere
With a haze layer („Knee“)
and
Strong thermal gradient in the lower layers(„Flash“)

Asymmetry of the Flash is caused by ellipticity of Pluto‘s atmosphere, ε ~ 0.06; caused by winds close to surface, ~ 200 $^{m}/_{s}$

Results

- Pluto still has a stable atmosphere (not frozen out; T, p stable since 2006)
- $r_{50\%}$ = 1288 ± 1 km (1291 ± 5 km in 2007)
- “Knee” changed 1988 – 2011 (inversion layer up to r ~ 1220 km)
- Asymmetric flash, ellipticity of the atmosphere caused by winds

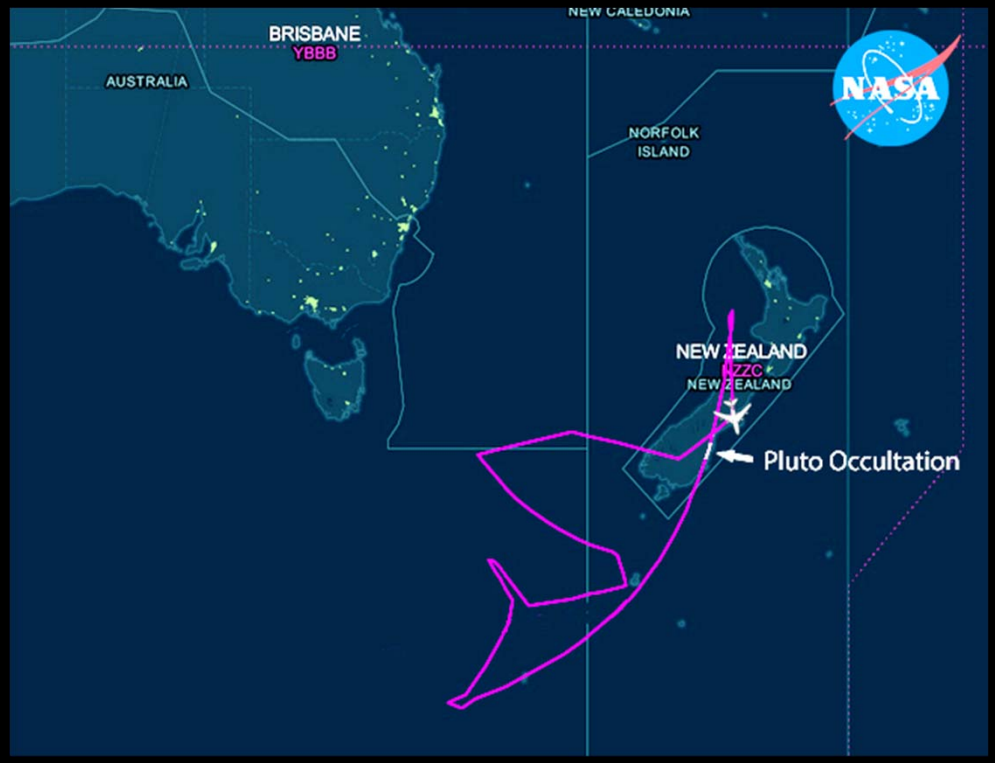
Person M. et al., AJ, 146:83 (15pp), 2013 Oct.


STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
SOFIA
FORCAST · GREAT
HIPO · FLITECAM
NASA · DLR · USRA · DSI
2ND SOUTHERN DEPLOYMENT · NEW ZEALAND 2015

Stellar Occultation by Pluto 29 June 2015

UCAC2 139-209445 11.9^{mag} in r‘

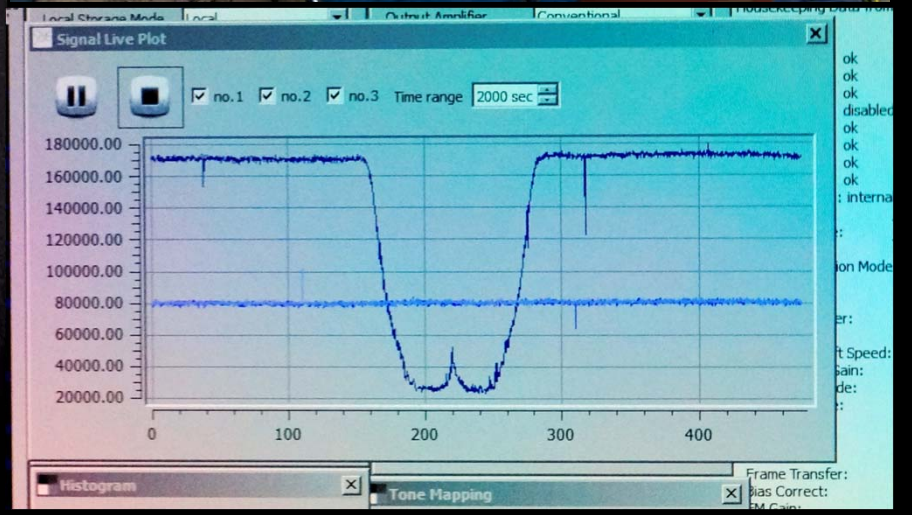
Within 2 weeks of New Horizons’ closest approach to Pluto 14 July 2015



Inflight course correction
220 km North

Simultaneous measurement in 4 spectral bands
HIPO: Blau & Rot, FLITECAM: NIR, FPI^{+}: VIS

Pluto Bedeckung am 29.06.2015



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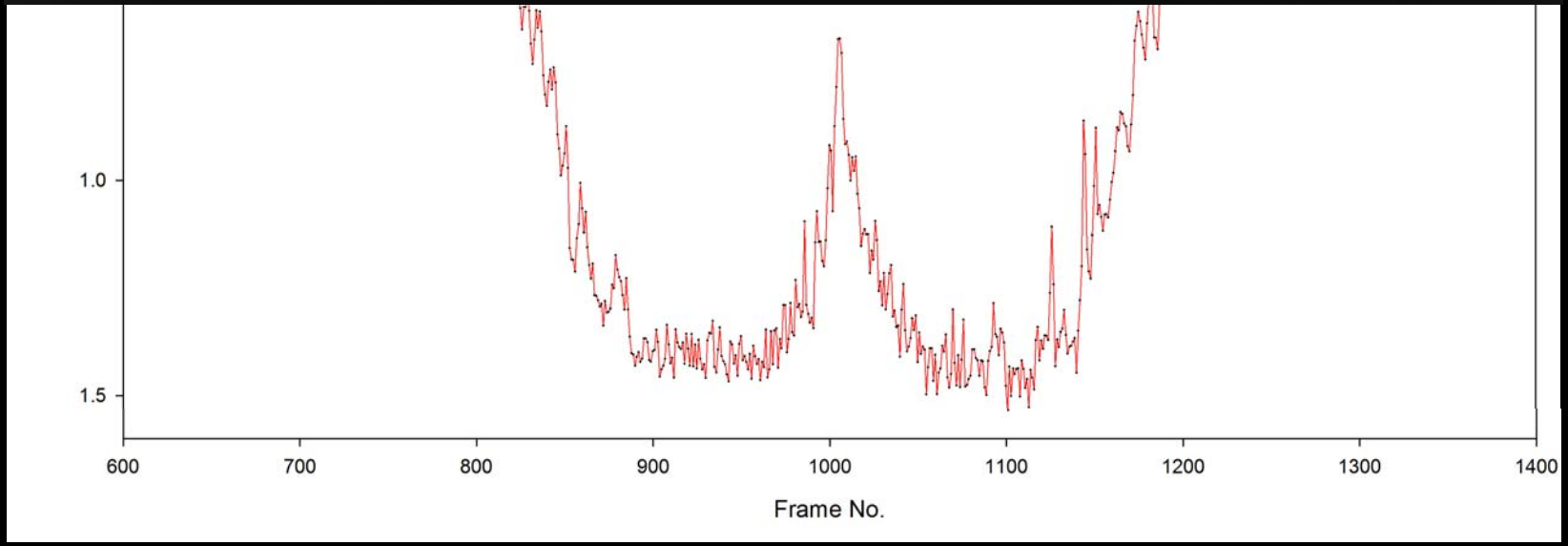
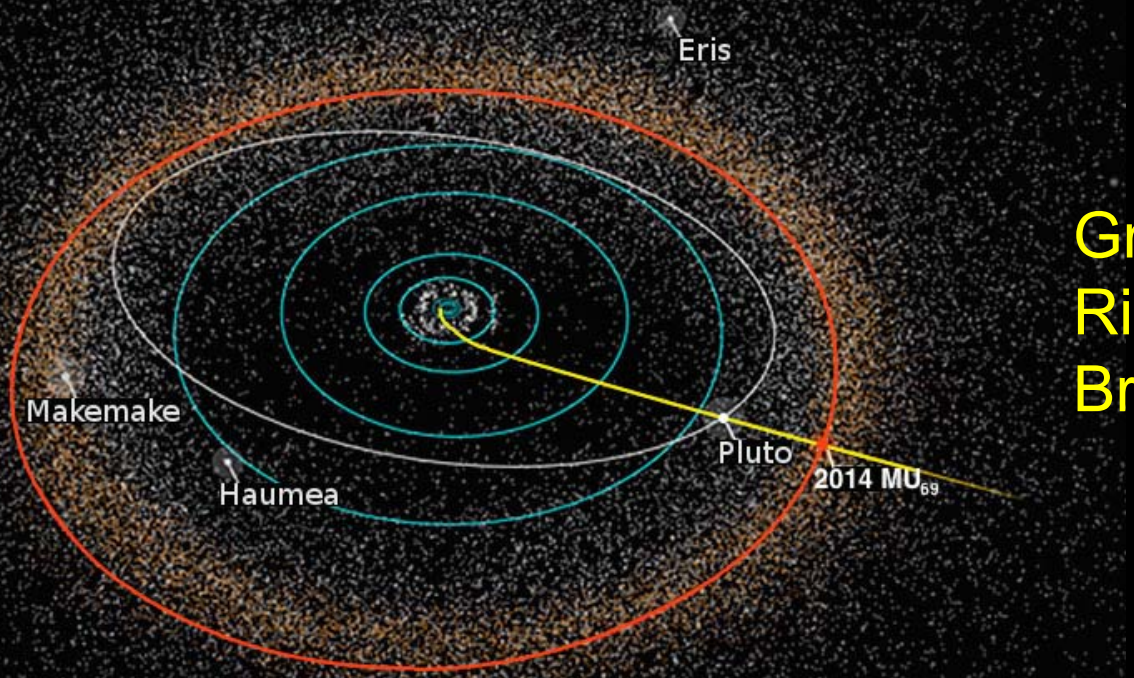
NASA/New Horizons


1.0
1.5
600
700
800
900
1000
1100
1200
1300
1400
Frame No.

New Horizons next Stop: 2014 MU 69

Entdeckung: Hubble @ 26.8 mag, Umlaufzeit 298 a

Geschätzte Größe 30 … 45 km entspricht ~ 1 mas



Größe ?
Ringe ? (Chariklo)
Bruchstücke ?

Vorbeiflug am 1.1.2019
Entfernung zur Sonne ca. 43 AU

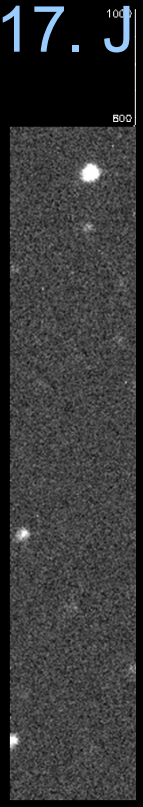
Stratospheric Observatory For Infrared Astronomy

Beob

03. J

10. J

17. J



Stratospheric Observatory For Infrared Astronomy

Possible Collaboration TIGRE - SOFIA

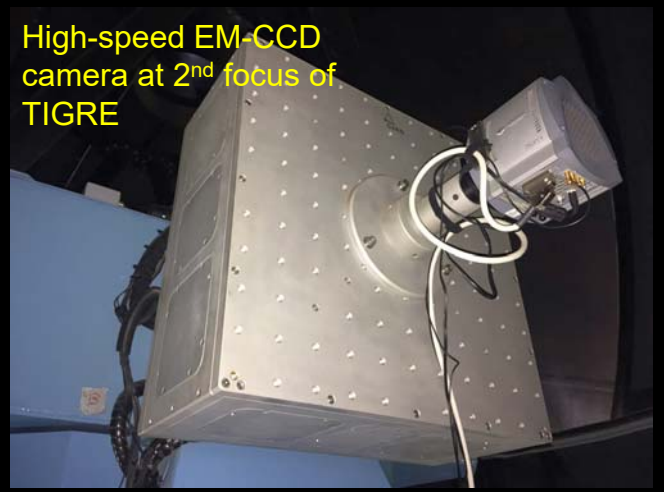
1

High Speed Photometry of Occulatations with Shadow over TIGRE

Titan 17. June 2018 in preparation of SOFIA mission 18. July 2019 over Australia

or

Parallel to SOFI mission for additional occultation cord



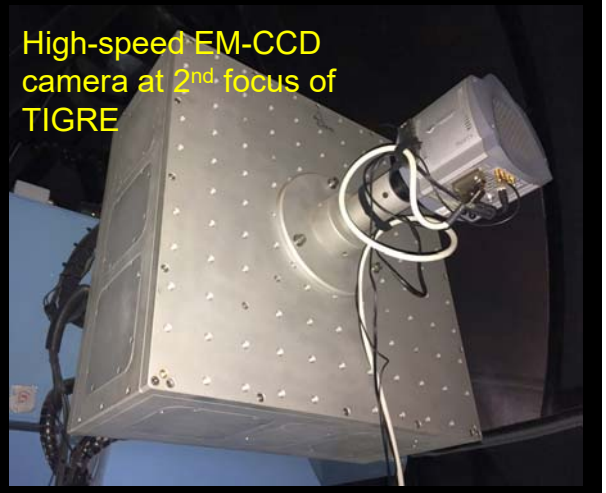
Possible Collaboration TIGRE - SOFIA

2

Astrometry of TNOs & Centaurs with TIGRE

Refinement of occultations predictions for accurate positioning of SOFIA

- Test images to find astrometric stablity
- Define a small number of objects of interest
- „Long term“ monitoring of position for ephemeries correction
- „Last minute“ astrometry (SOFIA already airborne)
- Permanent mounting of camera required
- Operations modus to be defined
- Collaboration TIGRE – DSI (– MIT ?)



Stratospheric Observatory For Infrared Astronomy


Vielen Dank!