Ice onTNOs: Focus on 136108 Haumea

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Collaborators:

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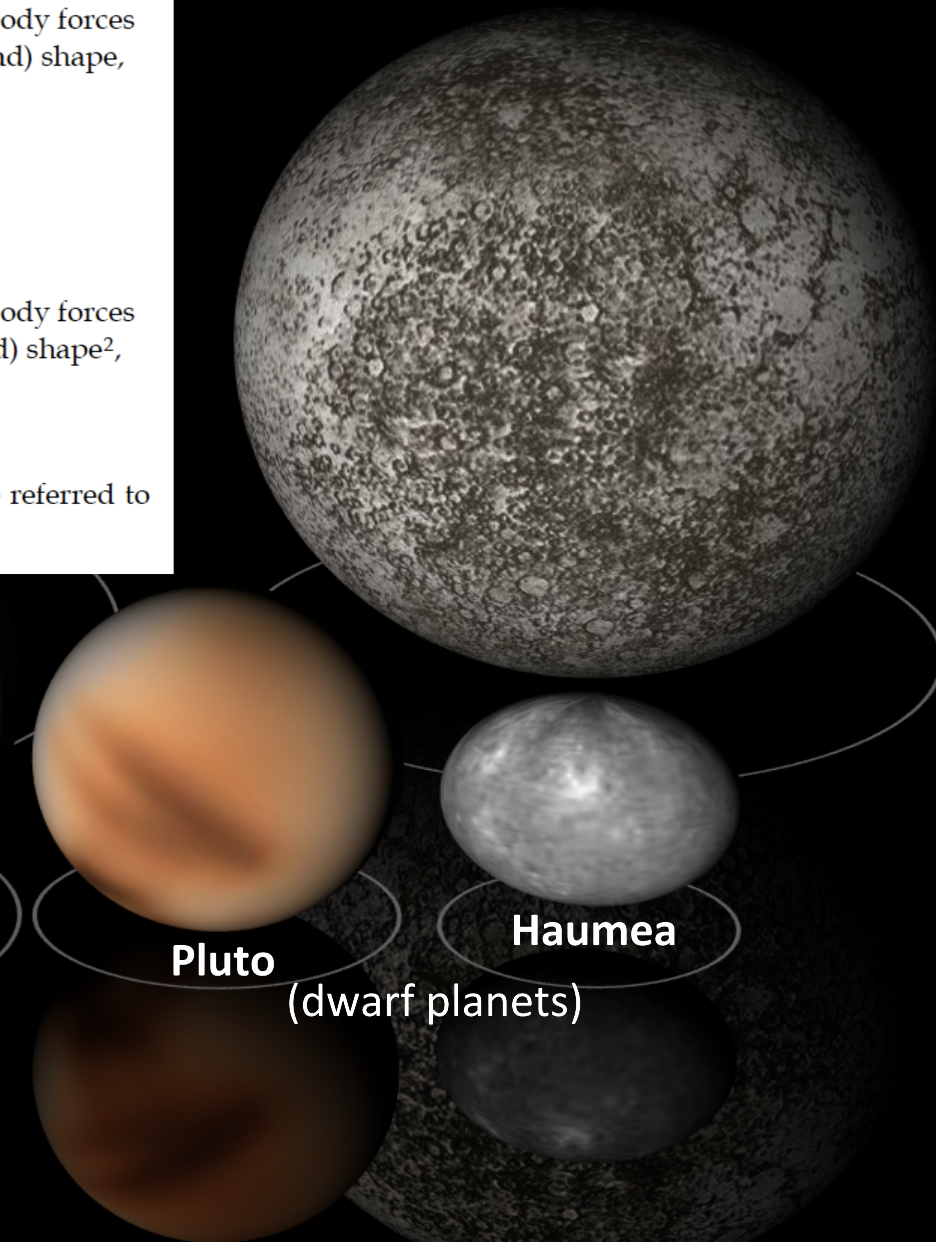
(1) A planet[1] is a celestial body that
(a) is in orbit around the Sun,
(b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
(c) has cleared the neighbourhood around its orbit.

(2) A "dwarf planet" is a celestial body that

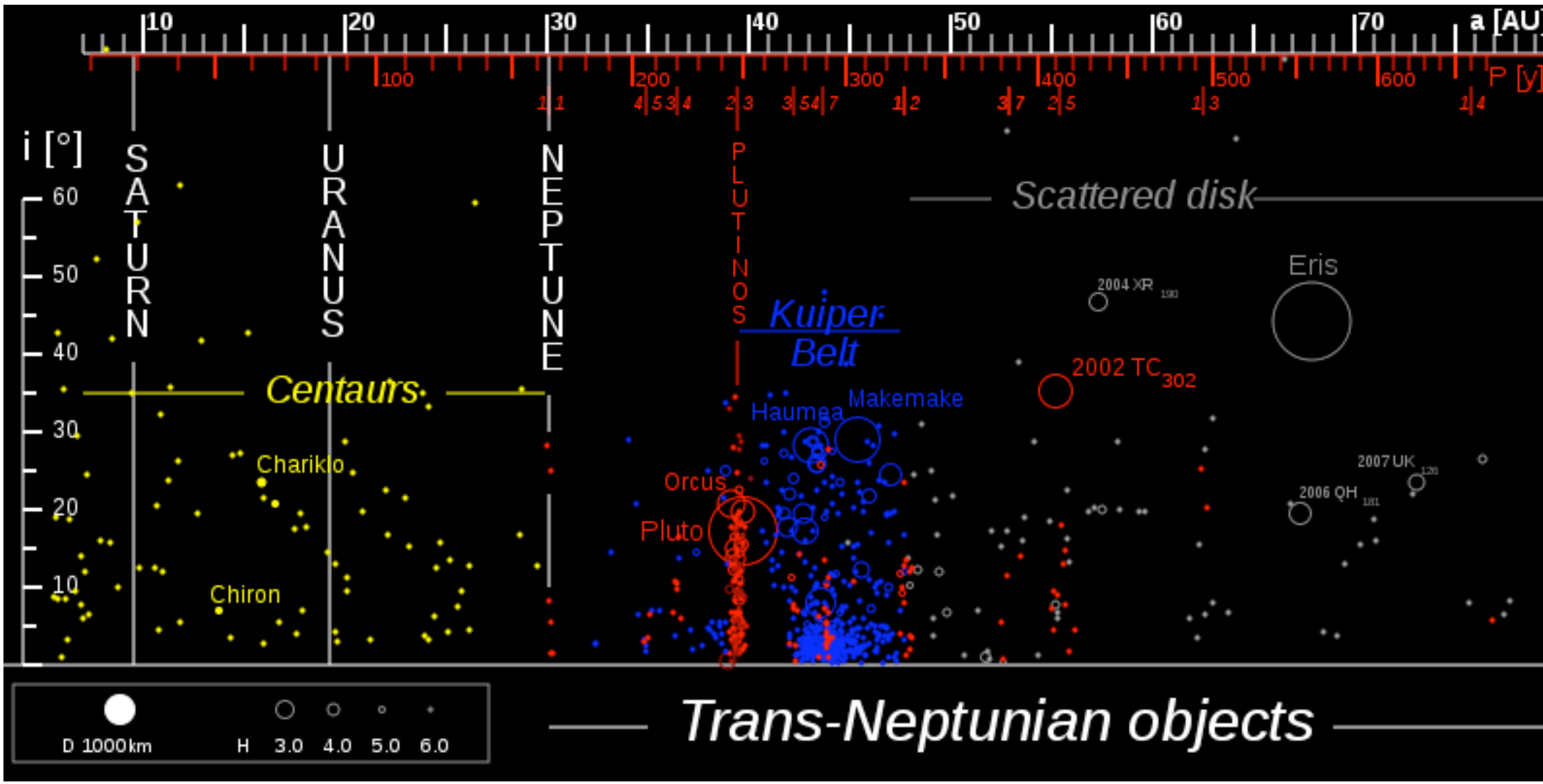
(a) is in orbit around the Sun,
(b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape[2],
(c) has not cleared the neighbourhood around its orbit, and
(d) is not a satellite.

(3) All other objects[3], except satellites, orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".

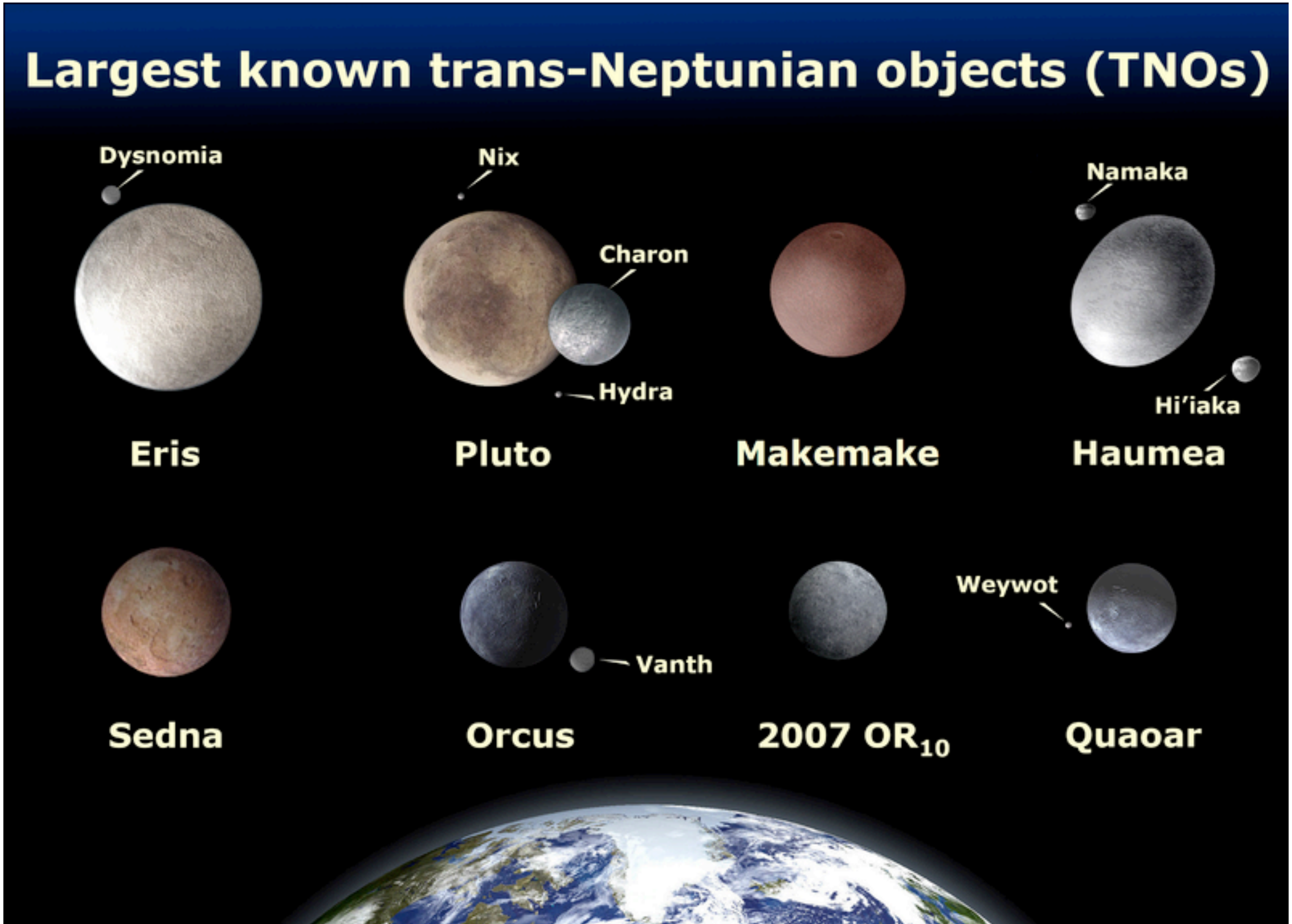
Name	Region of Solar System	Orbital radius (AU)
Ceres	Asteroid belt	2.77
Orcus	Kuiper belt (plutino)	39.17
Pluto	Kuiper belt (plutino)	39.48
Haumea	Kuiper belt	43.13
Quaoar	Kuiper belt (plutino)	43.405
Makemake	Kuiper belt	45.79
2007 OR_{10}	Scattered disc (10:3?)	67.21
Eris	Scattered disc	67.67
Sedna	(unique)	518.57



Distribution of TNOs



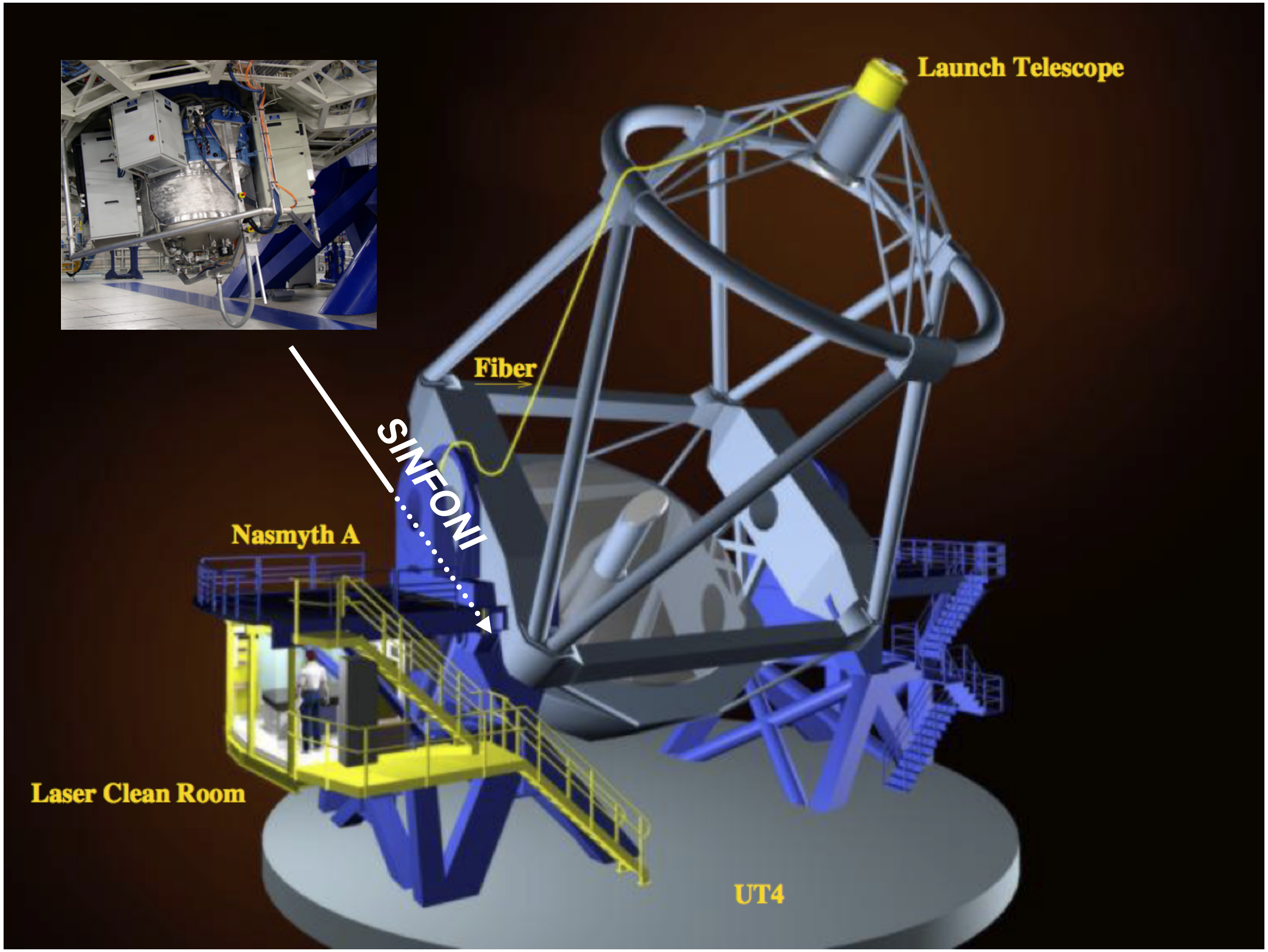
Largest TNOs



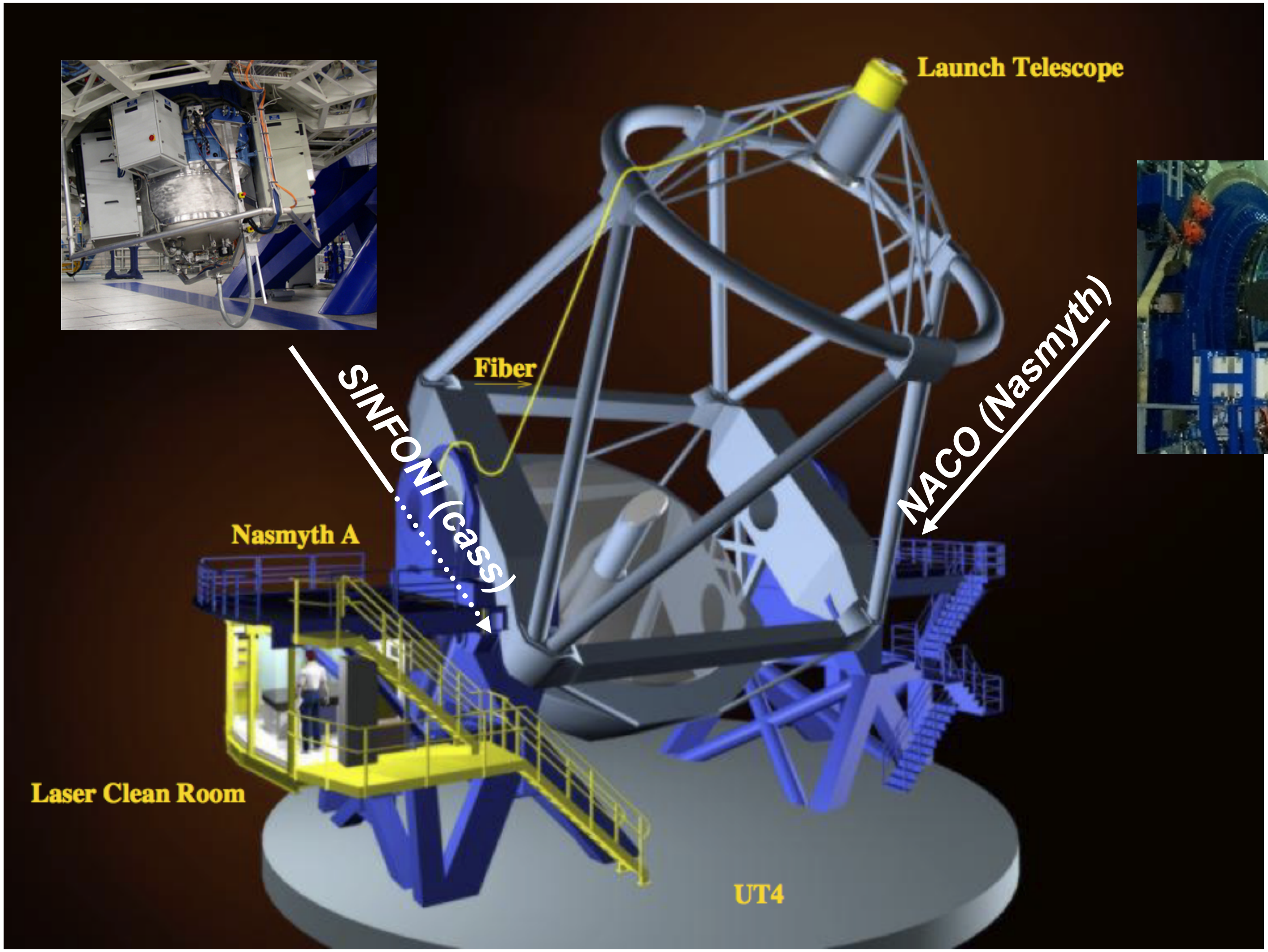
Icy bodies in the OPSII context

- Reservoir of volatiles in the solar system (H_2O, N_2, CH_4, CO, CO_2, C_2H_6, NH_3OH, etc)
- Small bodies population more hydrated than originally pictured
  - Main-belt comets (Hsieh and Jewitt 2006)
  - Themis asteroids family (Campins et al. 2010, Rivkin and Emery 2010)
- Transport of water to the inner terrestrial planets (e.g. talk by Paul Hartogh)

SINFONI at UT4



SINFONI + NACO at UT4



SINFONI = MACAO + SPIFFI

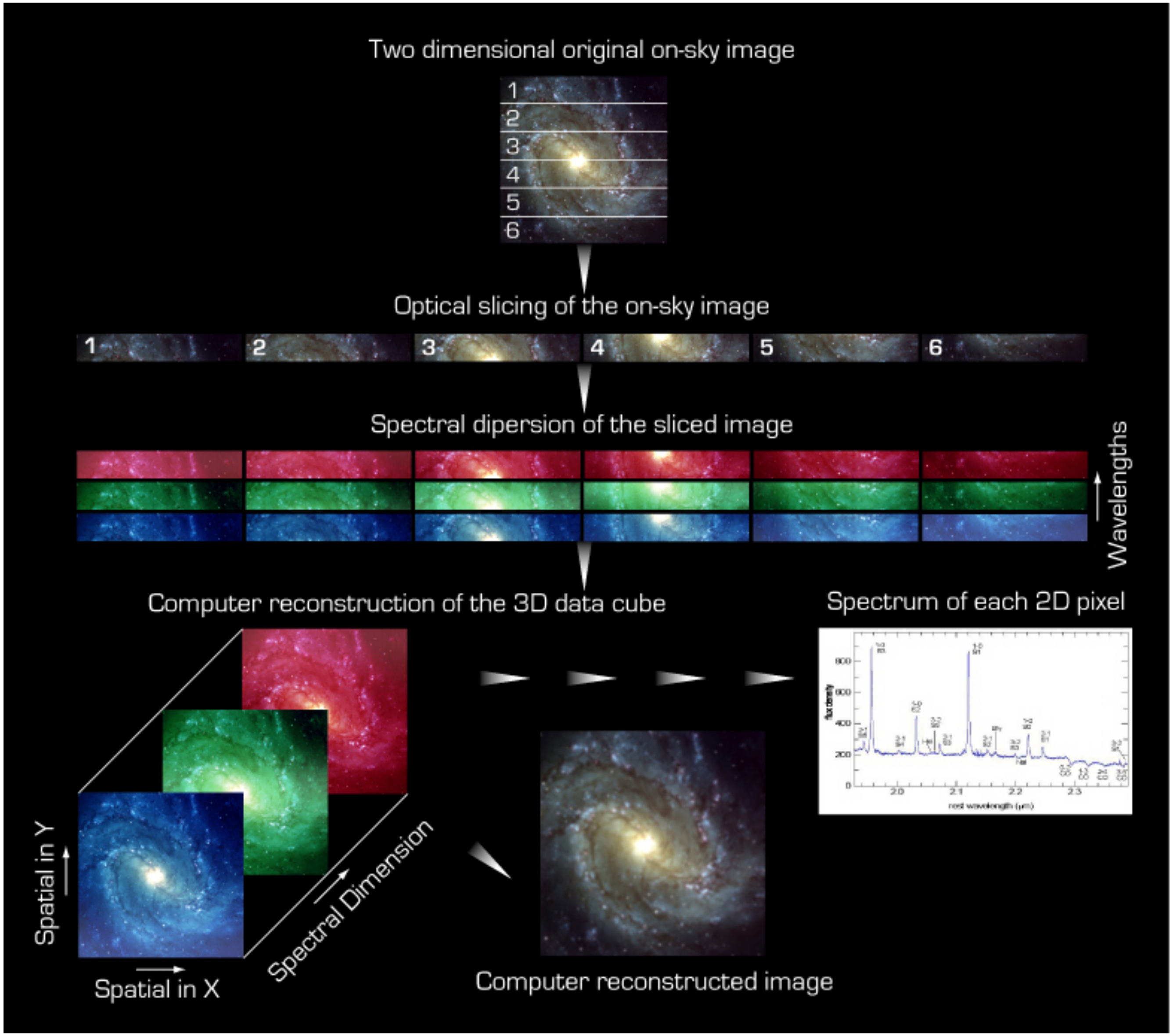
(SINFONI=Spectrograph for INtegral Field Observations in the Near Infrared)

- AO SYSTEM: MACAO (Multi-Application Curvature Adaptive Optics):
  - Similar to UTs AO system for VLTI
  - 60 elements curvature sensing bimorph mirror
  - NGS or LGS
  - Developed by ESO
- NEAR-IR SPECTRO: SPIFFI (SPectrometer for Infrared Faint Field Imaging):
  - 3-D spectrograph, 32 image slices, 1-2.5μm
  - Developed by MPE:Max Planck Institute for Extraterrestrial Physics + NOVA: Netherlands Research School for Astronomy

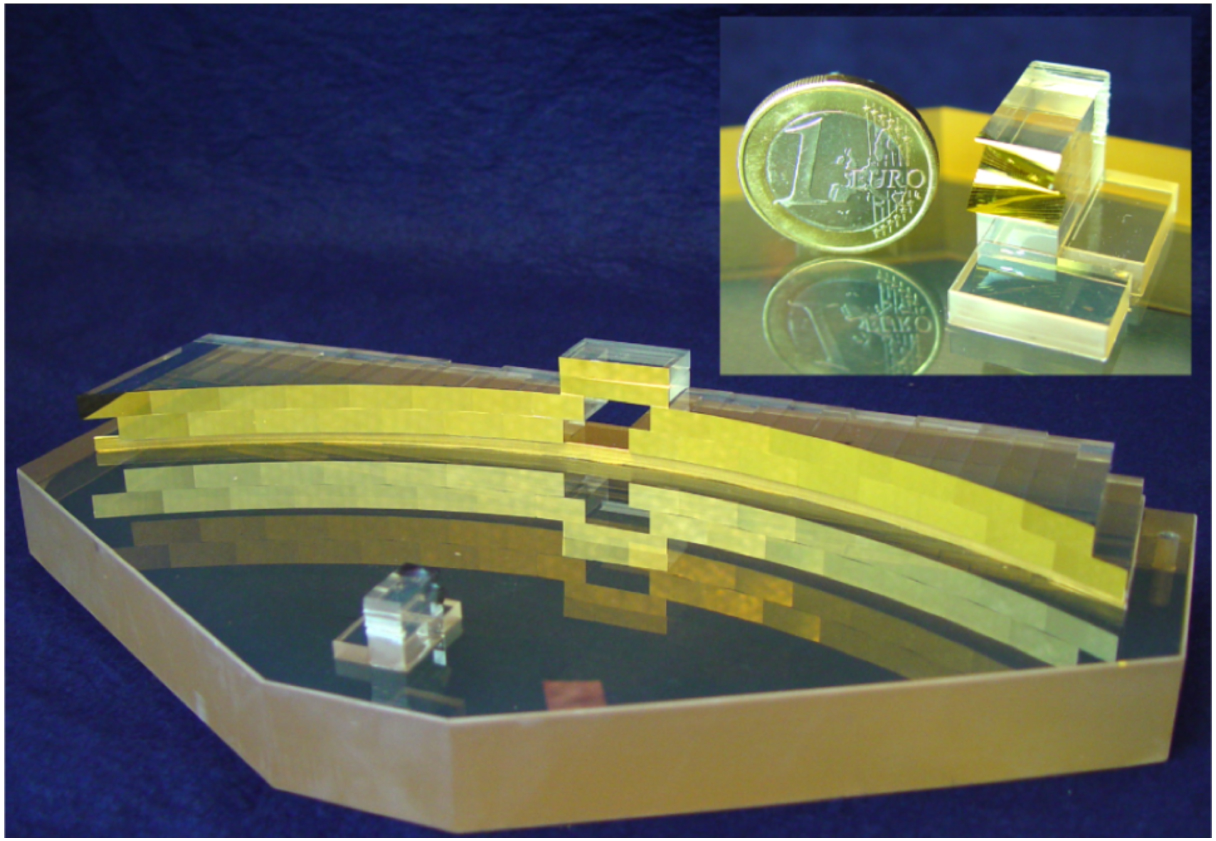
SINFONI - Main characteristics

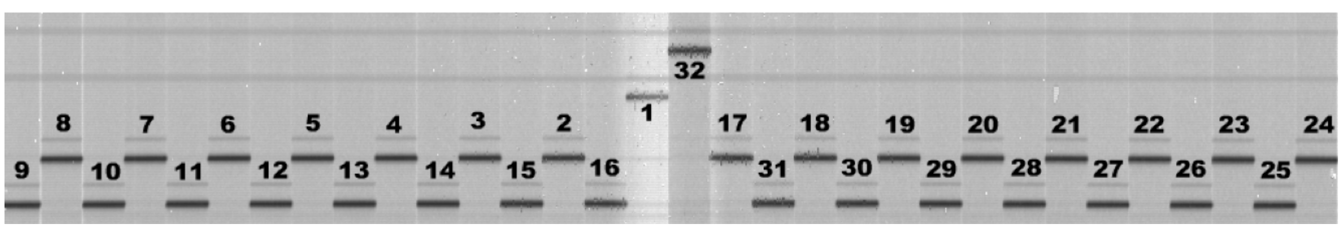
• Location	UT4 Cassegrain
• Wavelength range	1-2.5μm
• Detector	2048 x 2048 HAWAII array
• Gratings	J,H,K,H+K
• Spectral resolution	1500 (H+K-filter) to 4000 (K-band) (outside OH lines)
• Limiting magnitude	(0.1"/spaxel) K~18.2, H+K~19.2 in hr, SNR~10
• FoV sampling	32 slices
• Spatial resolution	0.25"/slice (no-AO), 0.1"(AO), 0.025" (AO)
• Resulting FoV	8"x8", 3"x3", 0.8"x0.8"
• Modes	noAO, NGS-AO, LGS-AO

SINFONI - IFS Principles

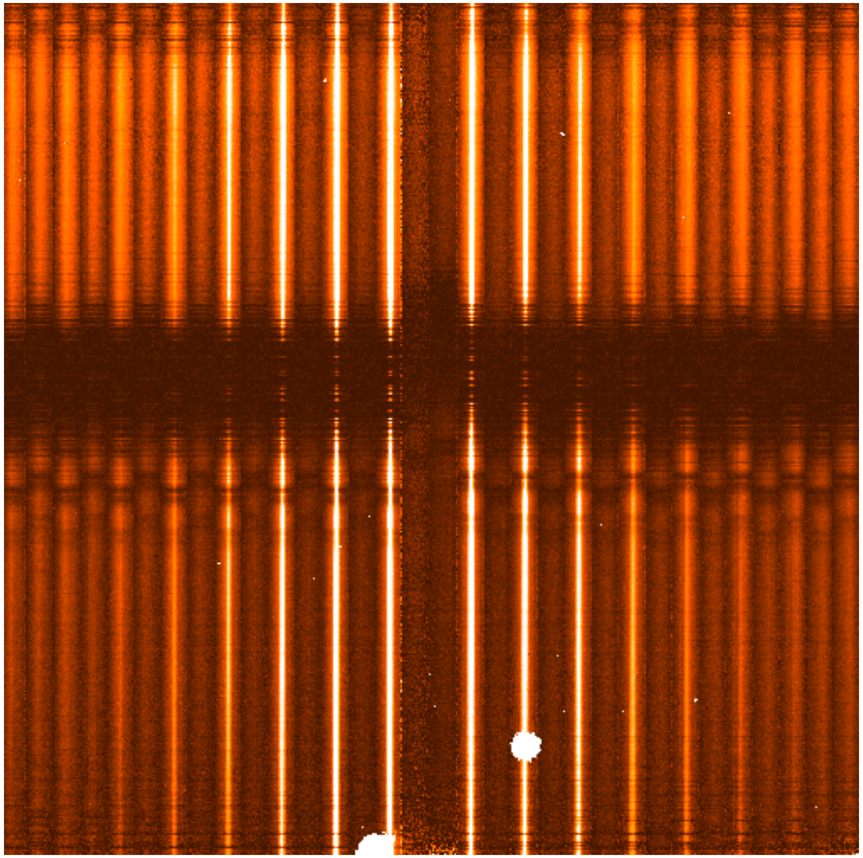


SINFONI - IFS Principles (Cont'd)

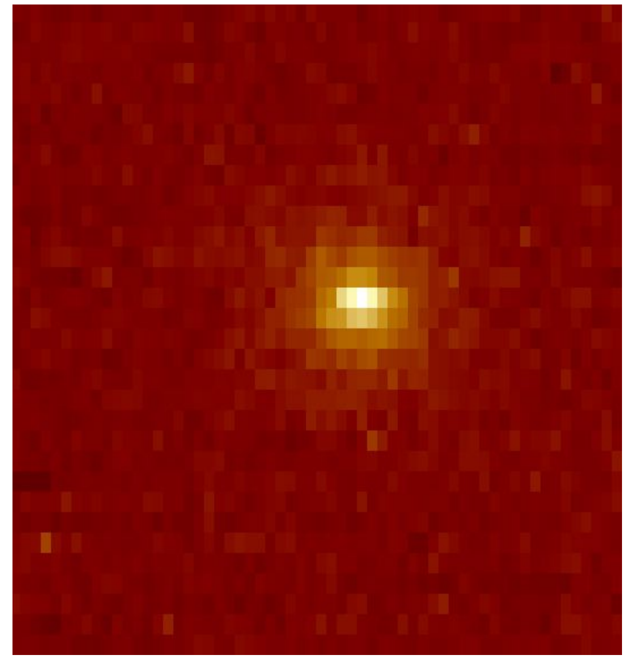




SINFONI - products



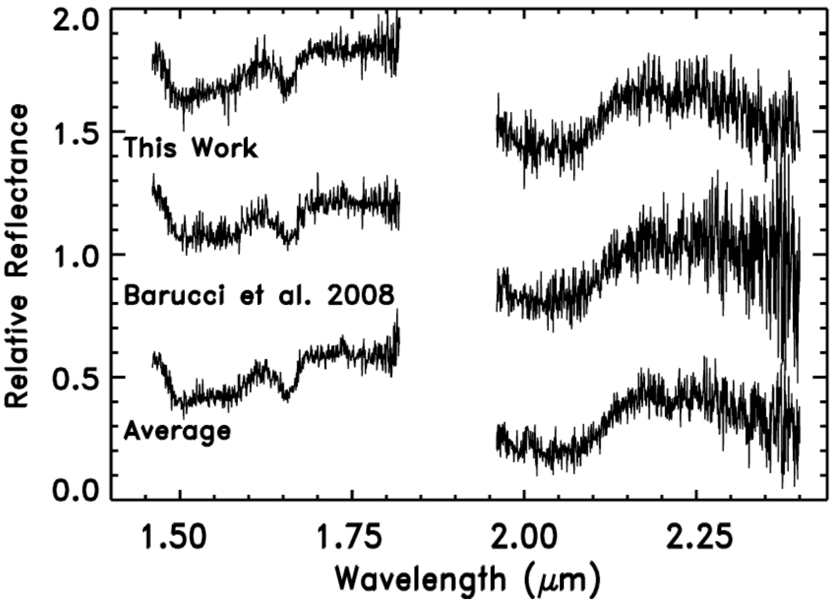
PSF spectrum H+K



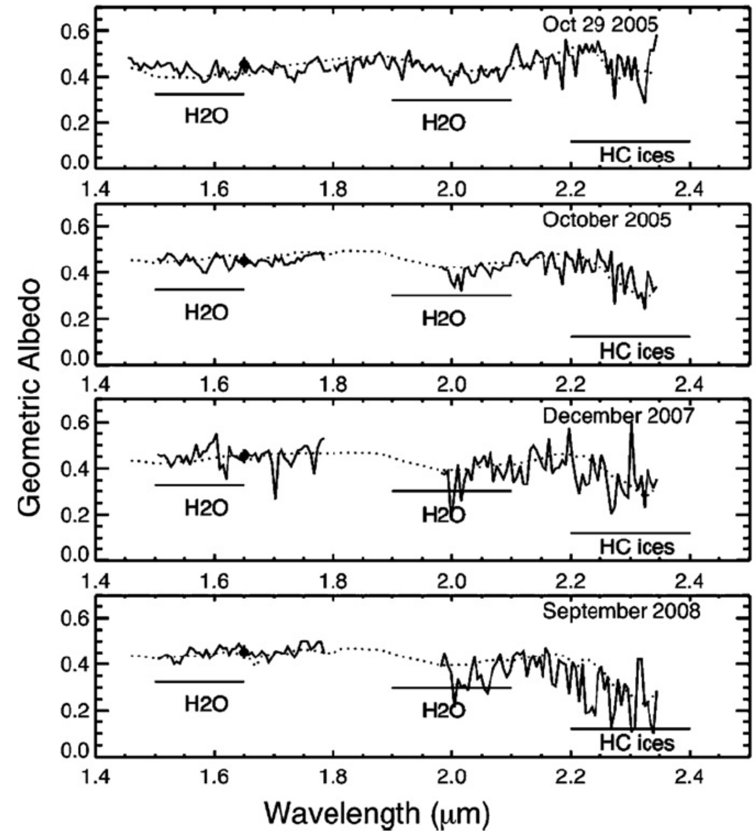
Reconstructed image

TNOs spectroscopy

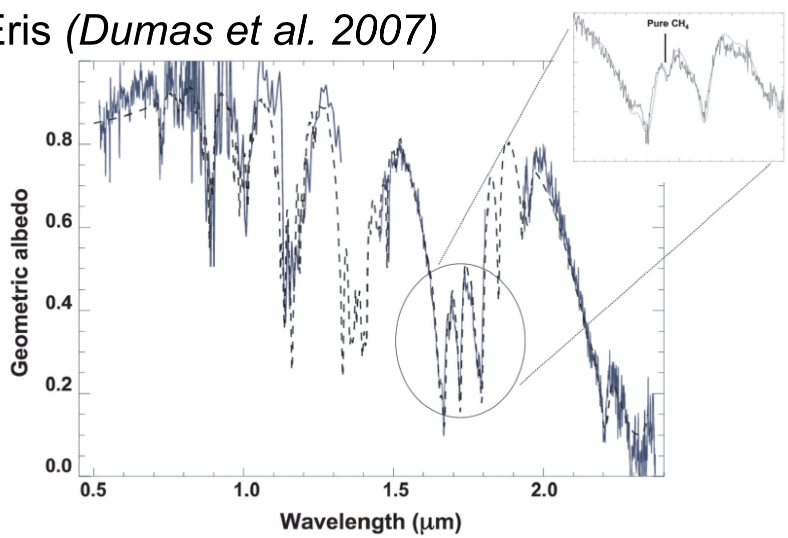
Orcus *(Carry et al. 2012)*



Sedna *(Barucci et al. 2010)*



Eris *(Dumas et al. 2007)*



Summary of SINFONI results (ESO Large Program) in Guilbert et al. 2009

Haumea / ID card

Characteristics	Value	Comments
Aphelion	51.5 AU	
Perihelion	34.7 AU	
Semi-major axis	43.1 AU	
Eccentricity / inclination	0.195 / 28.2deg.	
Rotation period	3.9h	Lacerda et al. (2008)
Number of satellites	2	Hi`iaka + Namaka (Brown et al. (2005)
Radius	575x762km	Spitzer + Herschel
Density	2.3-3.3g.cm^3	Rabinowitz et al. (2006)
Albedo	0.6-0.8	Spitzer/Herschel
Temperature	<50K	

Main particularities

- Fast rotation
- Oblong shape
- Water ice surface
  - BUT high density
  - No Methane???
- Close-in satellites
- TNO Family (see talk by Colin)
- *Almost* uniform surface (lightcurve studies point to redder albedo feature)

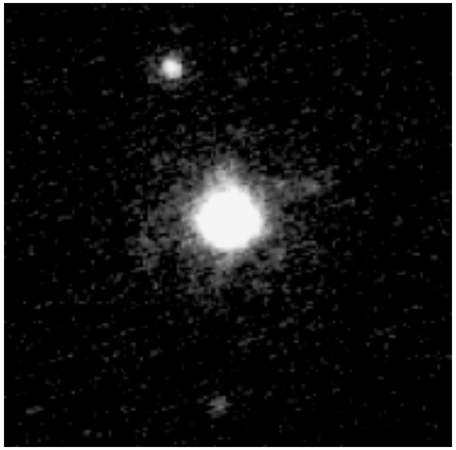
Density satellites/SSSB

Object	Density (g.cm^3)	Albedo
Haumea (TNO)	2.3-3.3 g.cm^3	0.6-0.8
Vesta (minor planet)	3.4 g.cm^3	0.4
Ceres (minor planet)	2.0-2.2 g.cm^3	0.1
Pluto (dwarf planet/TNO)	2.03	0.5-0.7
Charon (dwarf planet/TNO)	1.7	0.38
Eris (dwarf planet/TNO)	2.2-2.5	0.9
Orcus (dwarf planet/TNO)	1.5	0.3
Ganymede (satellite)	1.9	0.4
Callisto (satellite)	1.8	0.2
Europa (satellite)	2.9	0.7

Discoveries timeline

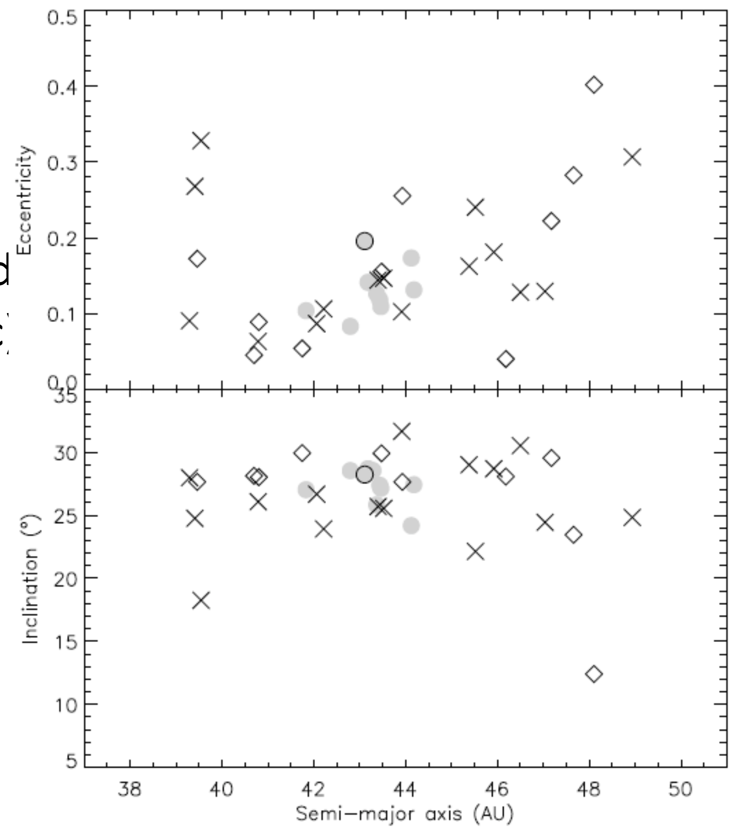
- ~ co-discovery by Brown et al. (Palomar Mountain) and Ortiz (Sierra-Nevada, Granada) [discovery credited to Granada's team but name came from Caltech's team]

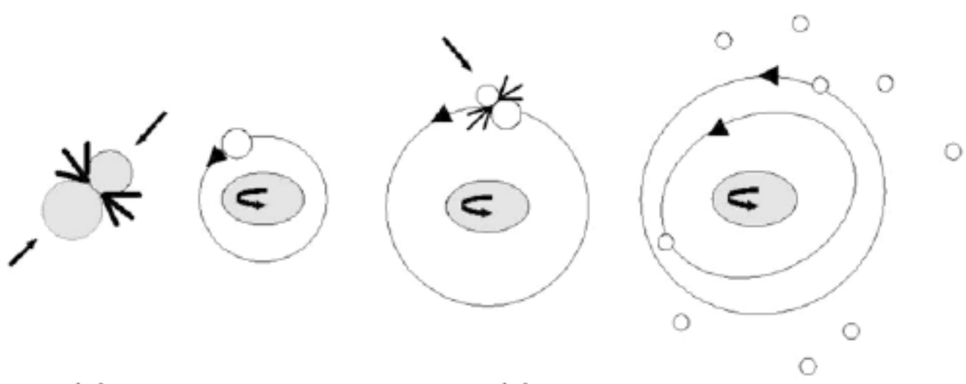
- Water ice surface (Barkume et al. 2006)
- Family of TNOs linked to Haumea (Ragozzine and Brown 2007)
- Lightcurve & red spot (Lacerda et al. 2008)


LGS-AO Keck image of the Haumea system

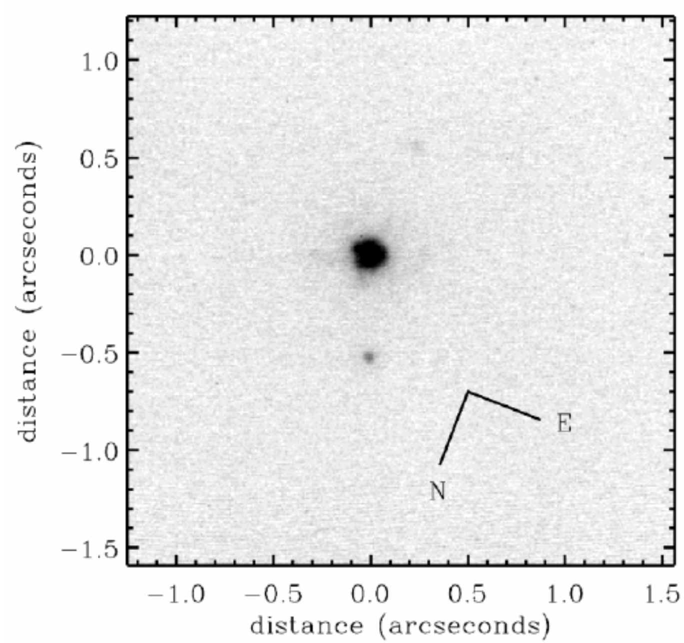
Haumea Family

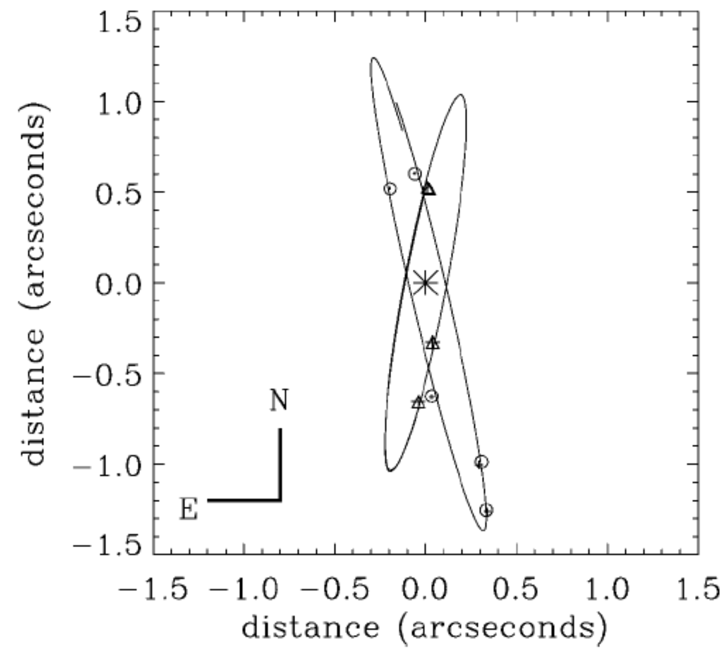
- Impactor w/ density ~2 g.cm^3, <2000km in diameter
- Difficulty to conciliate low velocity dispersion of family members (~140m.s^{-1}) and fast spin (e.g. Schlichting and Sari, 2009. Leinhardt et al. 2010. Ortiz et al. 2011, etc)
- Family members need confirmation w/ water ice signature (Snodgrass et al. ApJ 2010, Carry et al. 2012 – submitted).





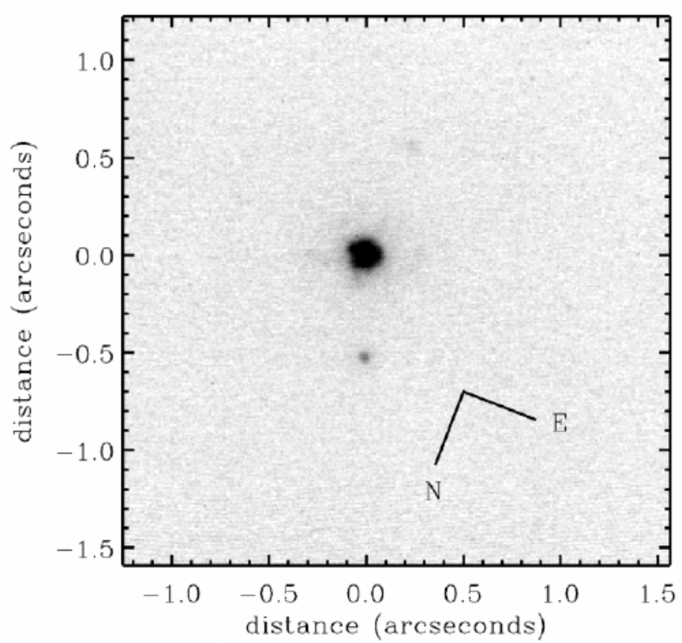
Haumea's Keck observations

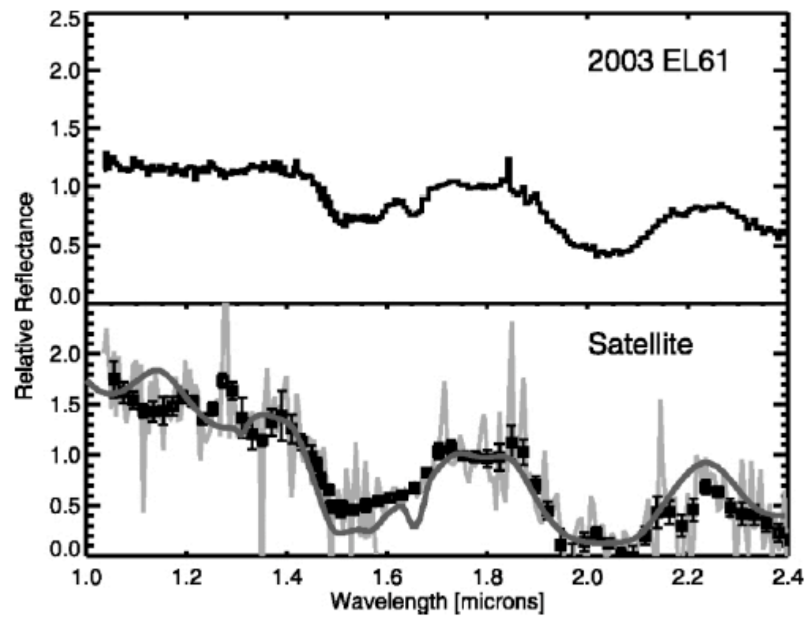




- Keck discovery of the triple system reported by Brown et al, 2005 ; Brown et al, 2006
- Spatially resolved study of the system requires combination of Adaptive Optics (AO) and Laser Guide Star (LFS).

Haumea’s Keck observations

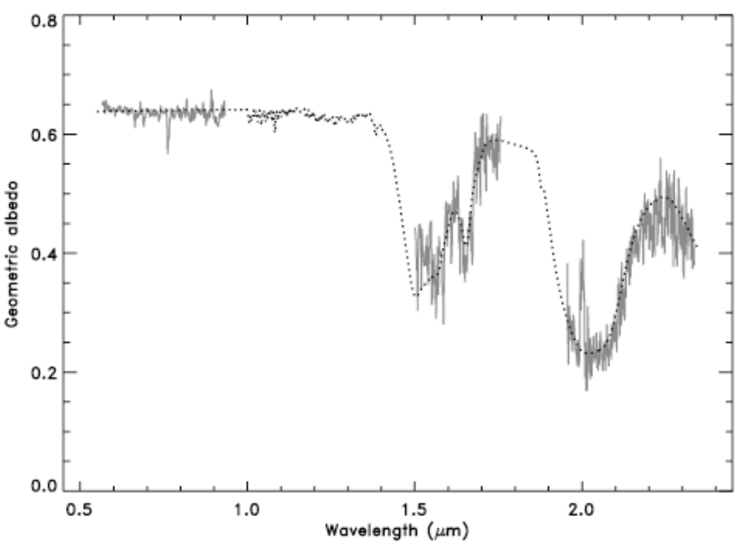


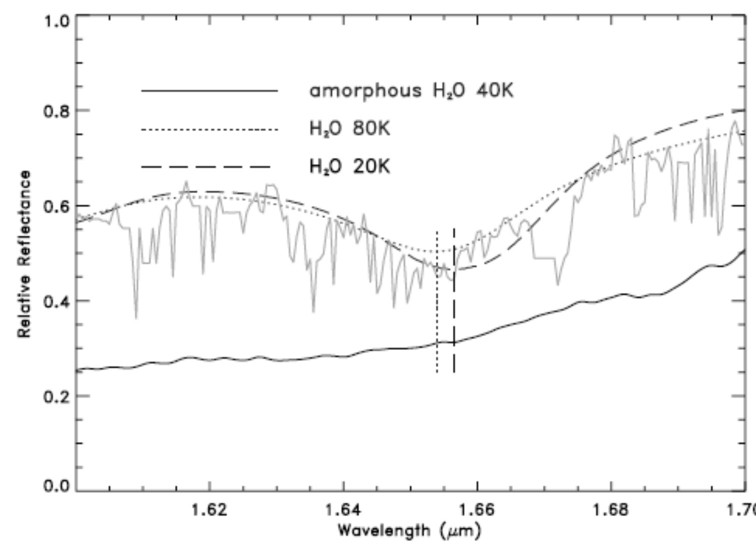


- Keck discovery of the triple system reported by Brown et al, 2005 ; Brown et al, 2006
- Spatially resolved study of the system requires combination of Adaptive Optics (AO) and Laser Guide Star (LFS).
- Near-IR spectrophotometry reveals the presence of 1.65μm crystalline water ice feature for Haumea

VLT SINFONI observations

- Seeing limited (DDT observations VIS/near-IR)





Merlin et al. (2007).

Hapke modeling returns composition of 88% crystalline water ice (particle size of 10 µm),9% amorphous water ice (130 µm), and 3% amorphous carbon

AO-LGS SINFONI results

- PARSEC Laser (MPE):
  - Continuum laser with 4-5W power on sky
  - 50cm wide laser beam excites Na (0.589μm) layer at ~90km altitude

- Aircraft detection camera

- Artificial star Rmag~ 12

- Increase sky coverage from 1% to nearly 80%

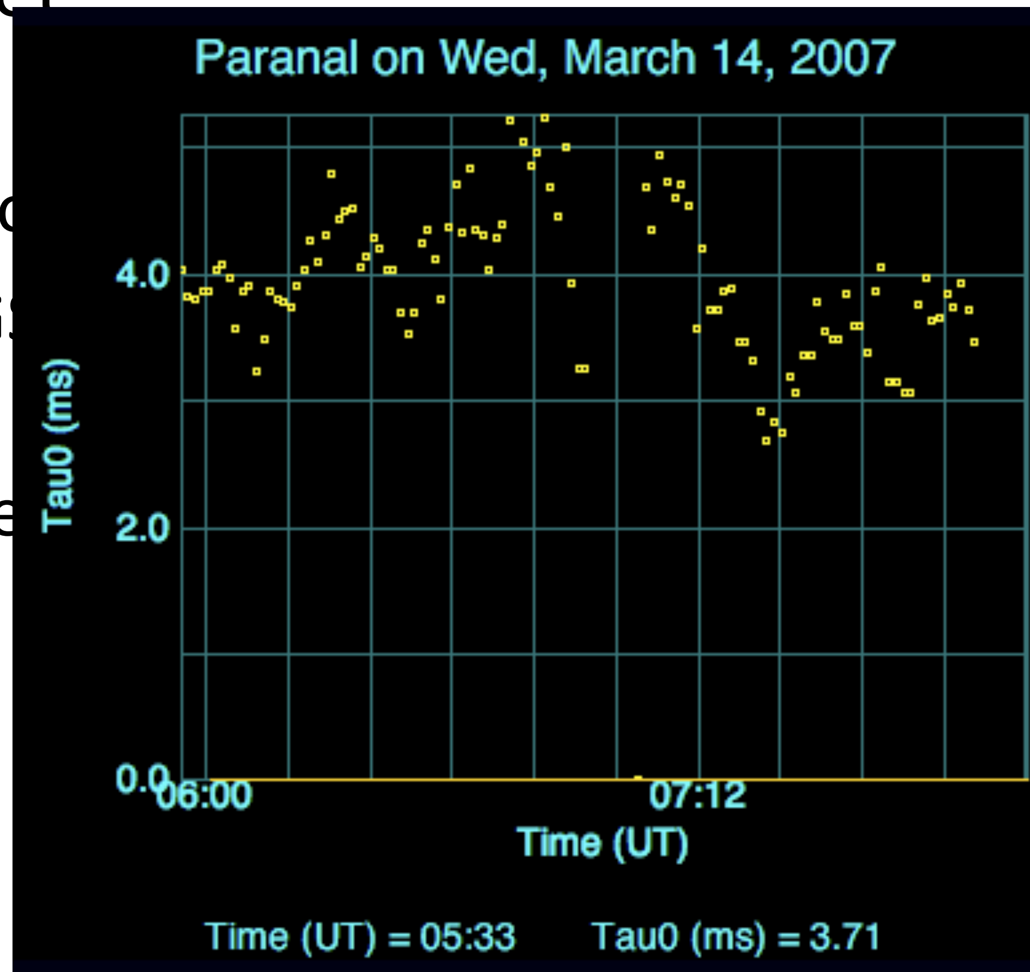
- Strehl achieved ~ 20-25% under best conditions

AO-LGS SINFONI results

- Optimal LGS target
  - V_{mag} (Haumea) ~ 17.2
  - Tip-tilt provided on target
  - Enable to test LGS system performance with SINFONI strap
  - Still requires excellent conditions

AO-LGS SINFONI results

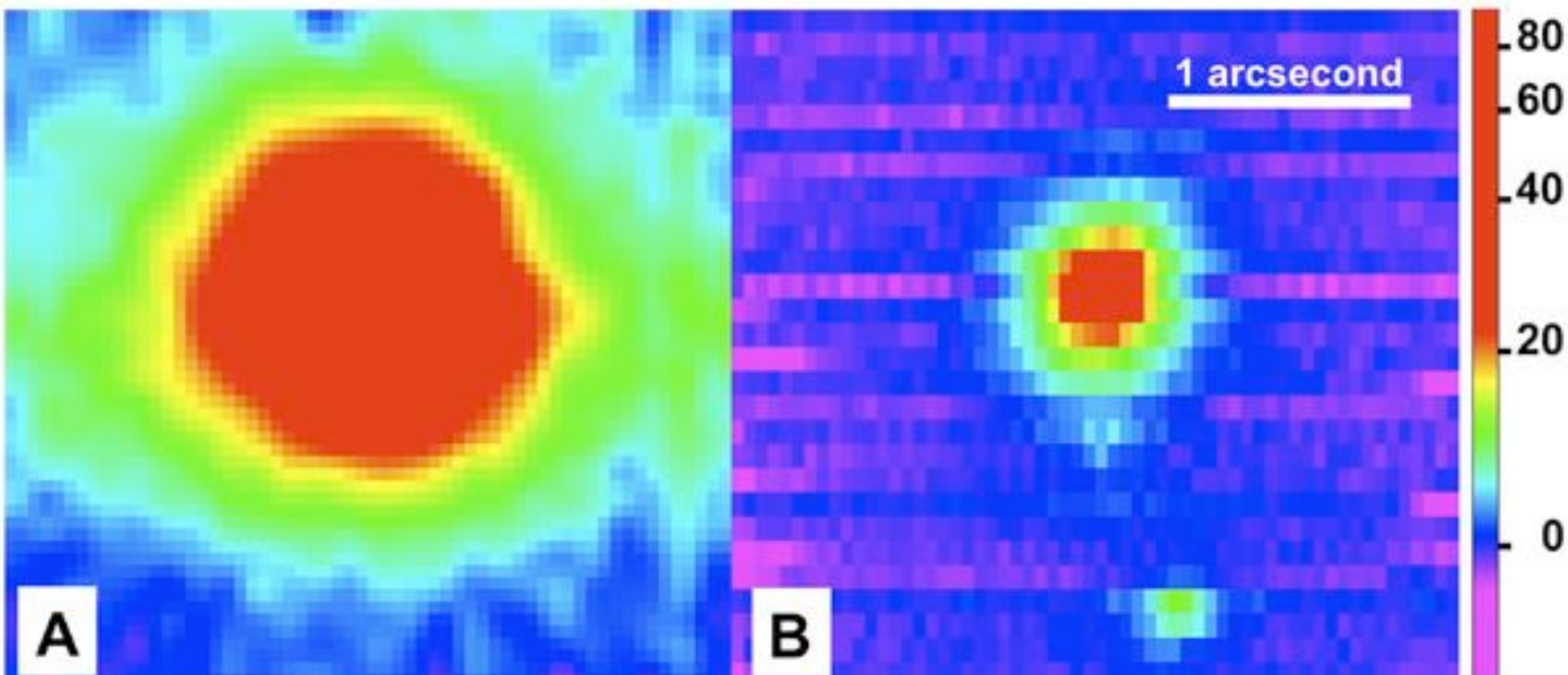
- Optimal LGS target
  - V_{mag} (Haumea) ~
  - Tip-tilt provided c
  - Enable to test LGS
    SINFONI strap
  - Still requires exce



AO-LGS SINFONI results

- Contrast improvement is dramatic

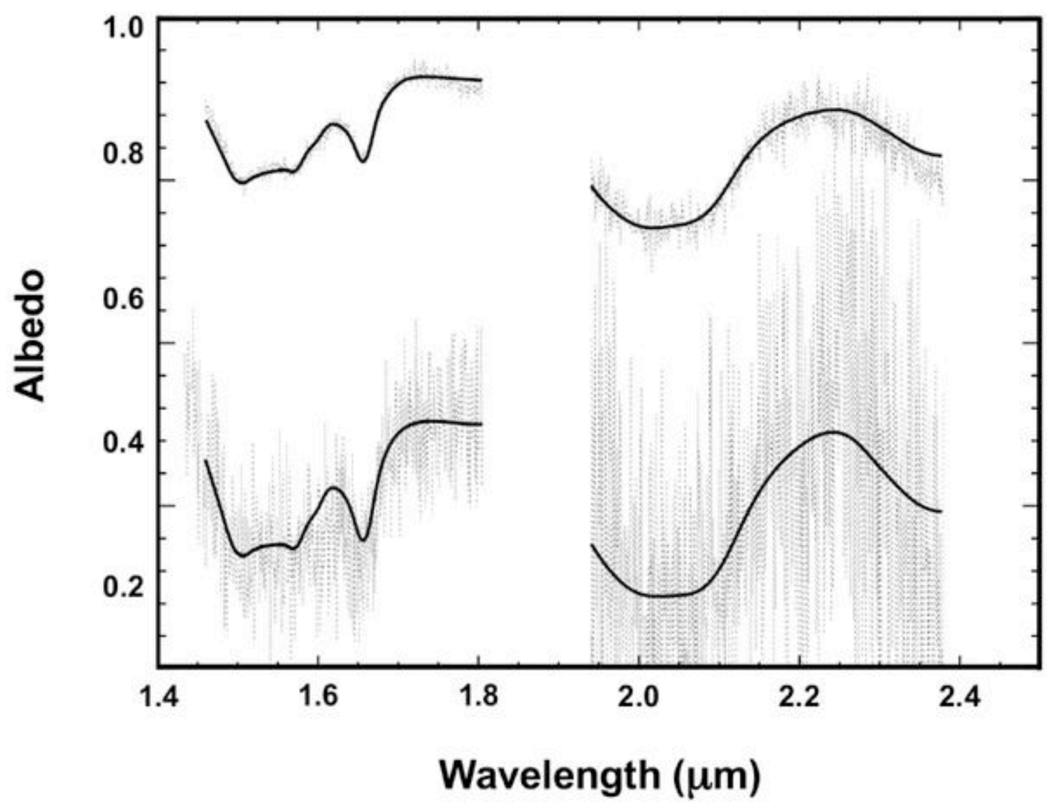
SINFONI's H+K band reconstructed image



Dumas et al. 2011

AO-LGS SINFONI results

- Best SNR near-IR spectrum of Haumea
- Isolated spectrum of largest satellite (Hi`iaka)



(Dumas et al. 2011)

AO-LGS SINFONI results

- Haumea's surface:
  - Very deep crystalline water ice bands
  - 73% (particle size of 9 μm) of crystalline water ice, 25% (particle size of 10 μm) of amorphous water ice, and 2% (particle size of 10 μm) of Titan Tholin.
  - $H_2O \cdot NH_3$ feature needs confirmation at 2.21μm
- Hiiaka's surface:
  - 100% of crystalline water ice (particle size of 20 μm)
  - Model point to fresher ice than present on Haumea

AO-LGS SINFONI results

- Source of heat needed for keeping ice crystalline, including on small satellites (200-400km diam.). Temp. > 90K at some point in history.
  - Low efficiency of amorphization processes (Zheng et al. 2009)
  - Radiogenic heating
  - Tidal torque heating
    - Orbit of interior satellite (Namaka) torqued by Hiiaka
    - Satellites orbits are such that they currently undergo mutual events between Haumea-Namaka

AO-LGS SINFONI results

- Radiogenic heating (^{40}K, ^{232}Th, ^{238}U):
  - 2 layer (rock + ice) model. Rock ~ 88-97% of mass
  - Radiogenic energy ~ 10^{10} W (10 times Ceres') for Haumea (10^{6} W for Namaka and 10^{7} W for Hiiaka)

- Tidal heating
  - Energy transferred to ice layer comes from orbital + tidal energy
  - Oblong body with satellites on inclined eccentric orbits can be neglected in 1st approximation due to fast-rotation (Ferraz-Mello 2008).

AO-LGS SINFONI results

- Tidal heating (Cont'd)
  - Energy released by tidal effect:

$$\dot{E}_{\mathrm{th}} = \frac{3}{2} \mathcal{G} m^2 \frac{r^5}{a^6} \Omega \, k_{\mathrm{d}} . \epsilon, \qquad (1)$$

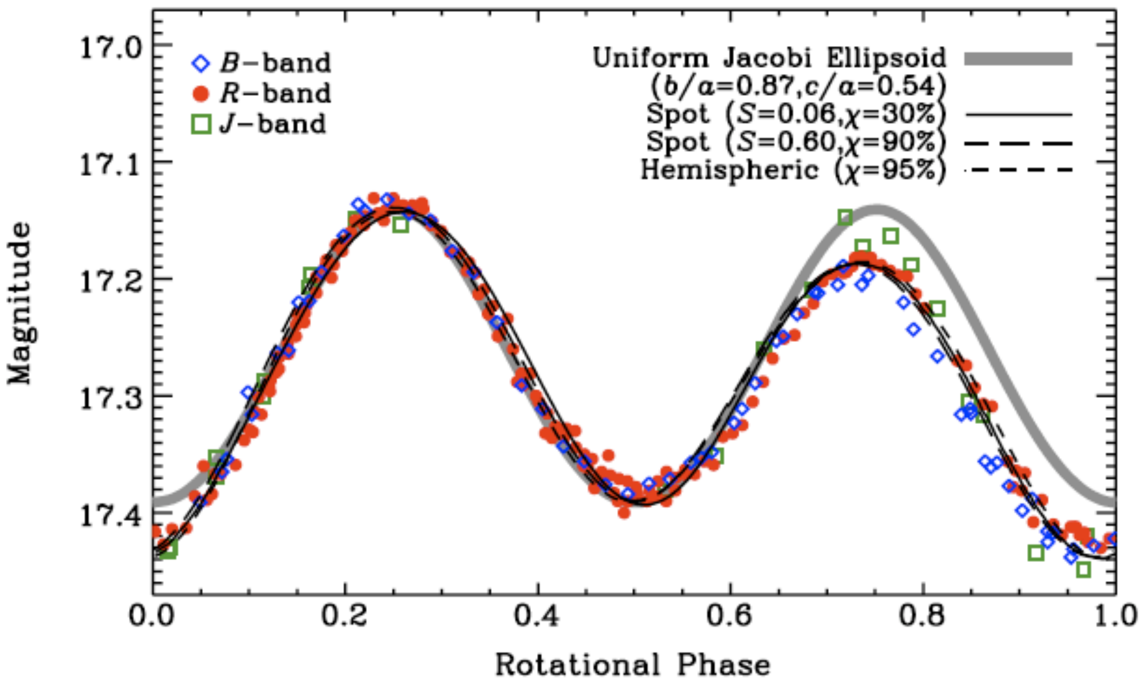
where a is the semi-major axis of the orbit; Ω, m, and r Haumea's spin rate, mass, and equivalent radius; k_{d} the Love dynamical number, ϵ the phase lag of the tide and $\mathcal{G}$ the constant of gravitation.

  - Energy on Hiiaka ~ 10^7W, on Haumea ~ 5.10^9W
  - Could produce ΔT of ~50K over a few 2-5 Gy

- **Under certain conditions tidal heating could contribute to maintain crystalline ice over the surfaces of the Haumea's system.**

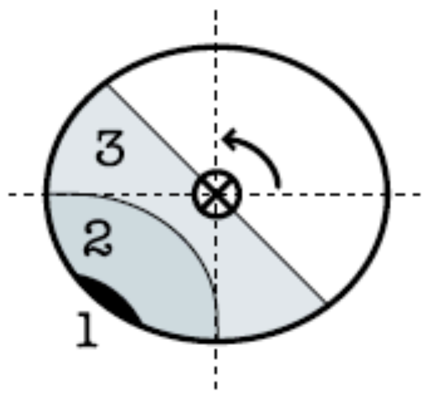
Haumea’s spot

- Investigating the nature of the spot detected on Haumea’s surface with SINFONI-LGS high-SNR spectral data



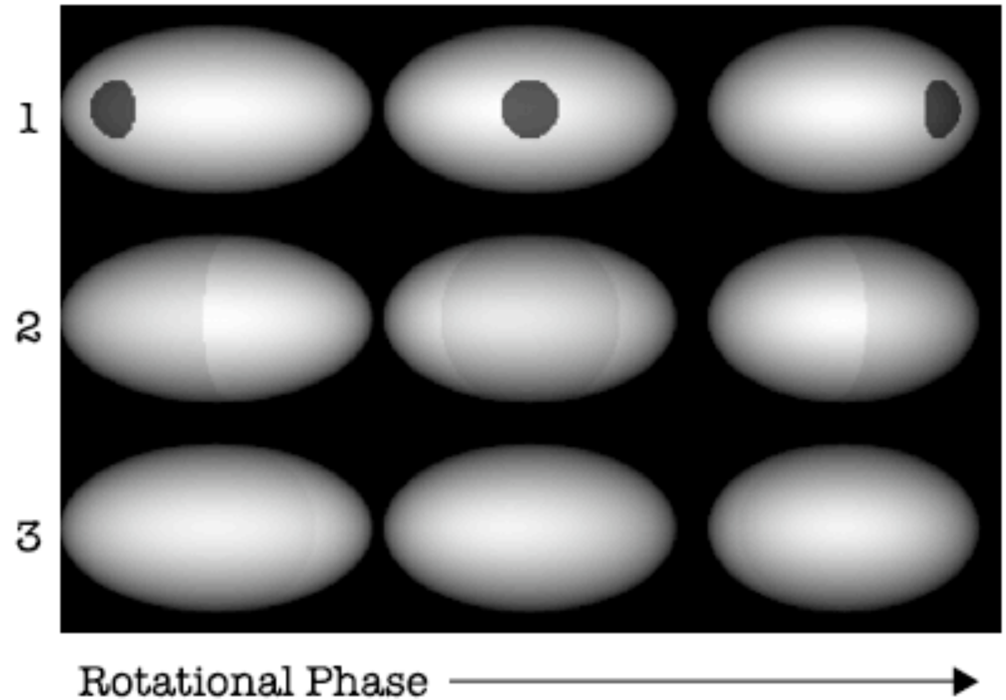
Lacerda, Jewitt, Peixinho. 2008. AJ, 135, 1749

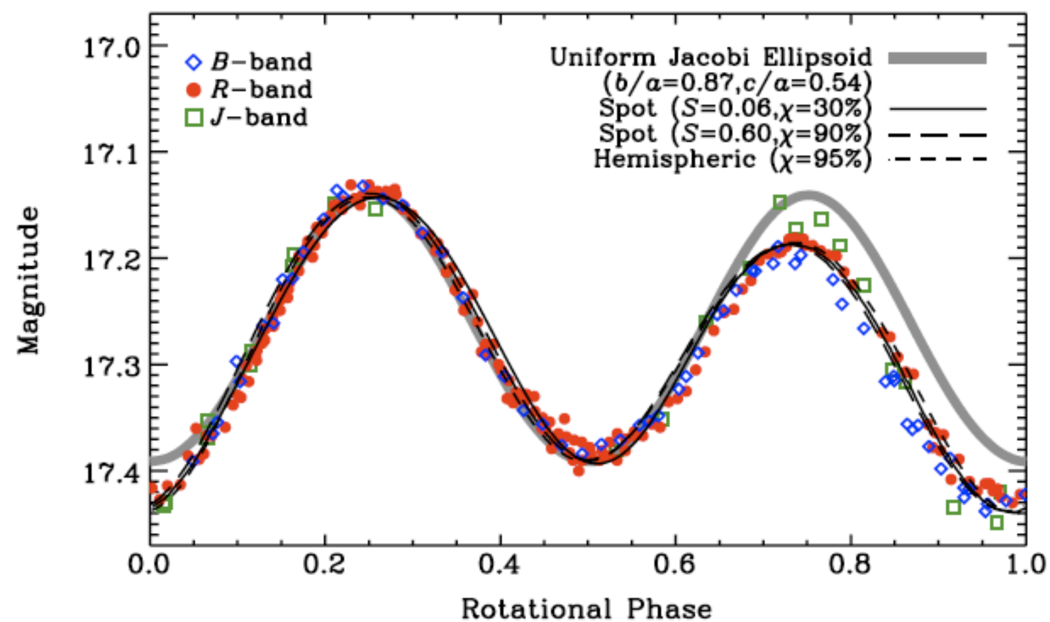
North Pole View



DRS MODELS:
1. Spot (S=0.06, χ=30%)
2. Spot (S=0.60, χ=90%)
3. Hemispheric (χ=95%)

Equatorial View

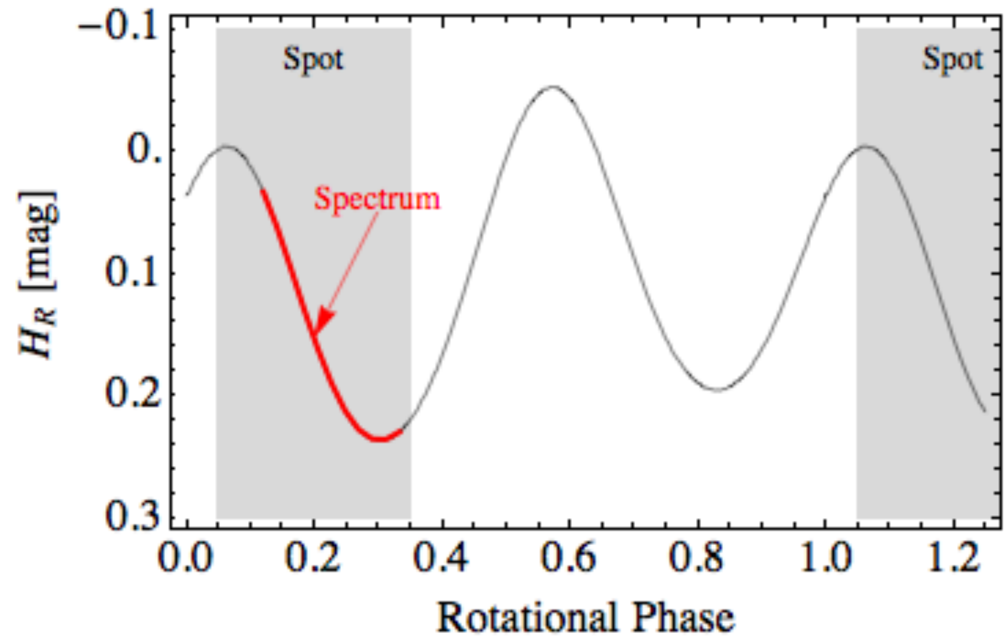




Lacerda, Jewitt, Peixinho. 2008. AJ, 135, 1749

New 2011 observations

- Poor meteo conditions prevented use of LGS when spot was visible …
- …But luckily enough, our 2007 observations were obtained at that phase and combination with 2011 data will help study nature of Haumea’s red spot
- Rotational surface compositional mapping partly possible



Comparison on/off spot

WORK IN PROGRESS

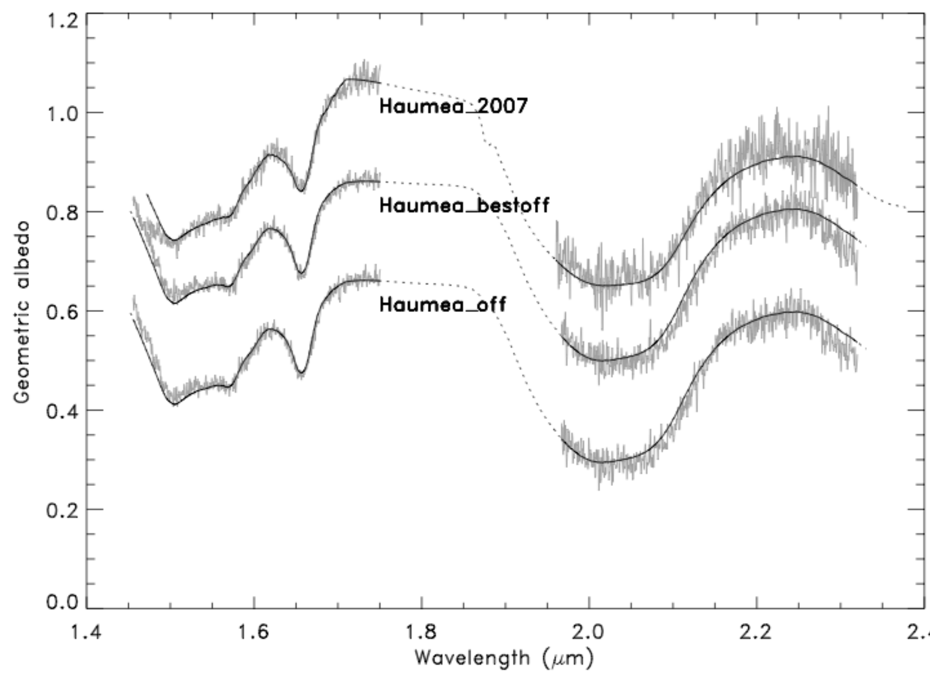
- Abundance of crystalline *vs* amorphous water ice (more crystalline off spot?)
- Additional compound in models?
- Is a rotational trend seen when spot is rotating into view?
- Re-reduction/analysis of

2007 data with same pipeline

version

- Effect of solar analog in 2007

Data to be adressed

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Hilke Schlichting, UCLA
Bill Dent, ESO-ALMA
Sebastian Wolf, Kiel University
Nature and orbits of planetary bodies
Dave Jewitt, UCLA
Willy Benz, Bern University
Caroline Terquem, Institut d'Astrophysique de Paris
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