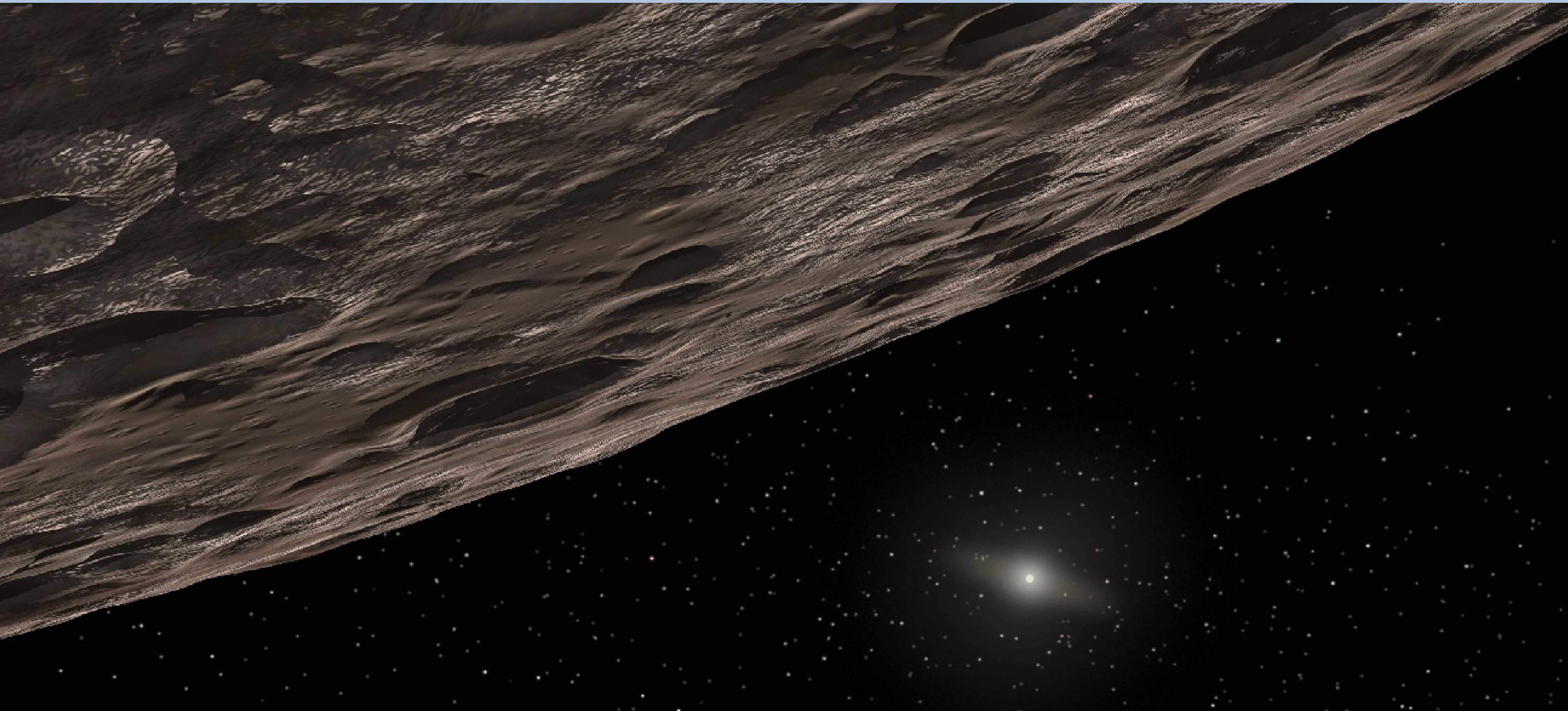
TNOs are Cool:
A Survey of the Transneptunian Region



Thomas Müller
MPE Garching

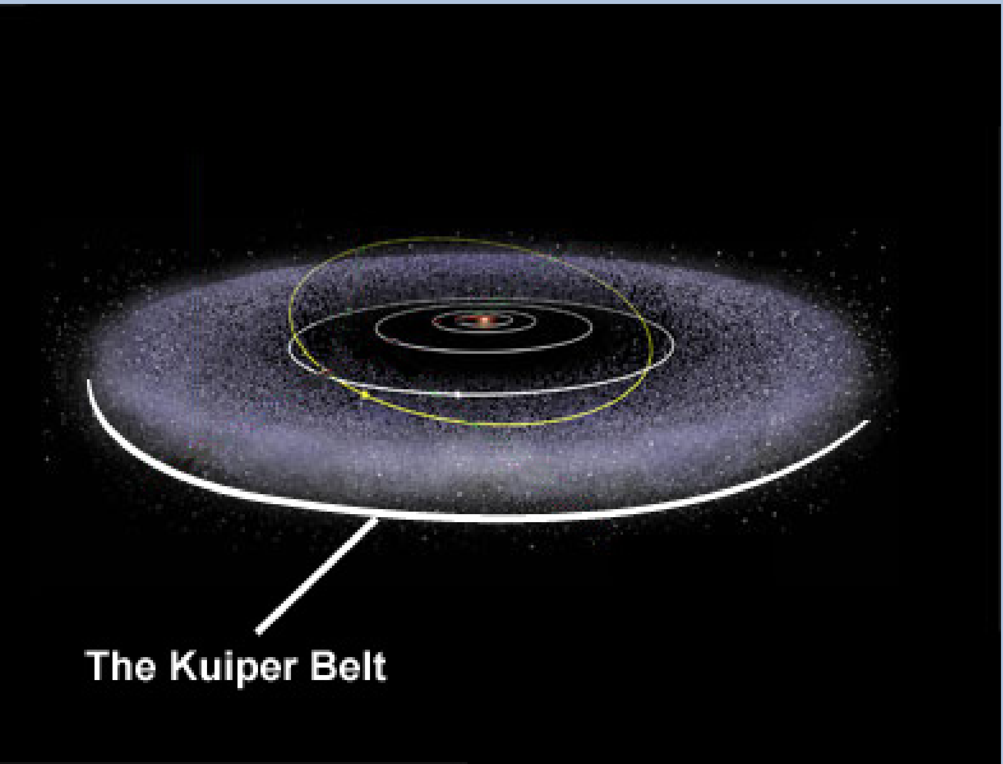
The TNOs-are-Cool Team
(39 members, 19 institutes, 9 countries)

Overview

- OT KP with 370 hours (∼15% executed)
- PACS and SPIRE photometric point-source observations
- characterisation of about 140 Trans-Neptunian Objects (with known orbits)
- target with a few mJy up to 400 mJy
- time-critical observations with follow-on constraint (confusion noise & constellations & lightcurves)
- Key element:
  highly reliable photometric accuracy in 3 (6) bands

Science Goals in a Nut Shell

- **Radiometric size and albedo solutions**
  - accurate sizes ($\rightarrow$ volumes) of TNOs
    $\rightarrow$ primordial (D$>$ 200 km) size distribution
  - accurate spectroscopic and polarimetric modeling
  - albedo vs Size vs Colour vs Composition vs Orbit vs Binarity vs ...
    $\rightarrow$ probe formation and evolution processes
- **Thermophysical properties** (from 3 to 6 Pacs/Spire bands)
  - temperatures & thermal inertia
    $\rightarrow$ ice vs rock surface, surface type
  - emissivity $\rightarrow$ grain size information
  - beaming parameter $\rightarrow$ surface roughness
- **Binary densities:** mass from Kepler's 3rd law, volume from Herschel
  $\rightarrow$ basic geophysical parameter
  $\rightarrow$ interior structure/composition
  $\rightarrow$ binary formation mechanism
- **Thermal lightcurves**
  $\rightarrow$ disentangle albedo/shape
  $\rightarrow$ spin-axis orientation
  $\rightarrow$ thermal inertia
  $\rightarrow$ large surface structures



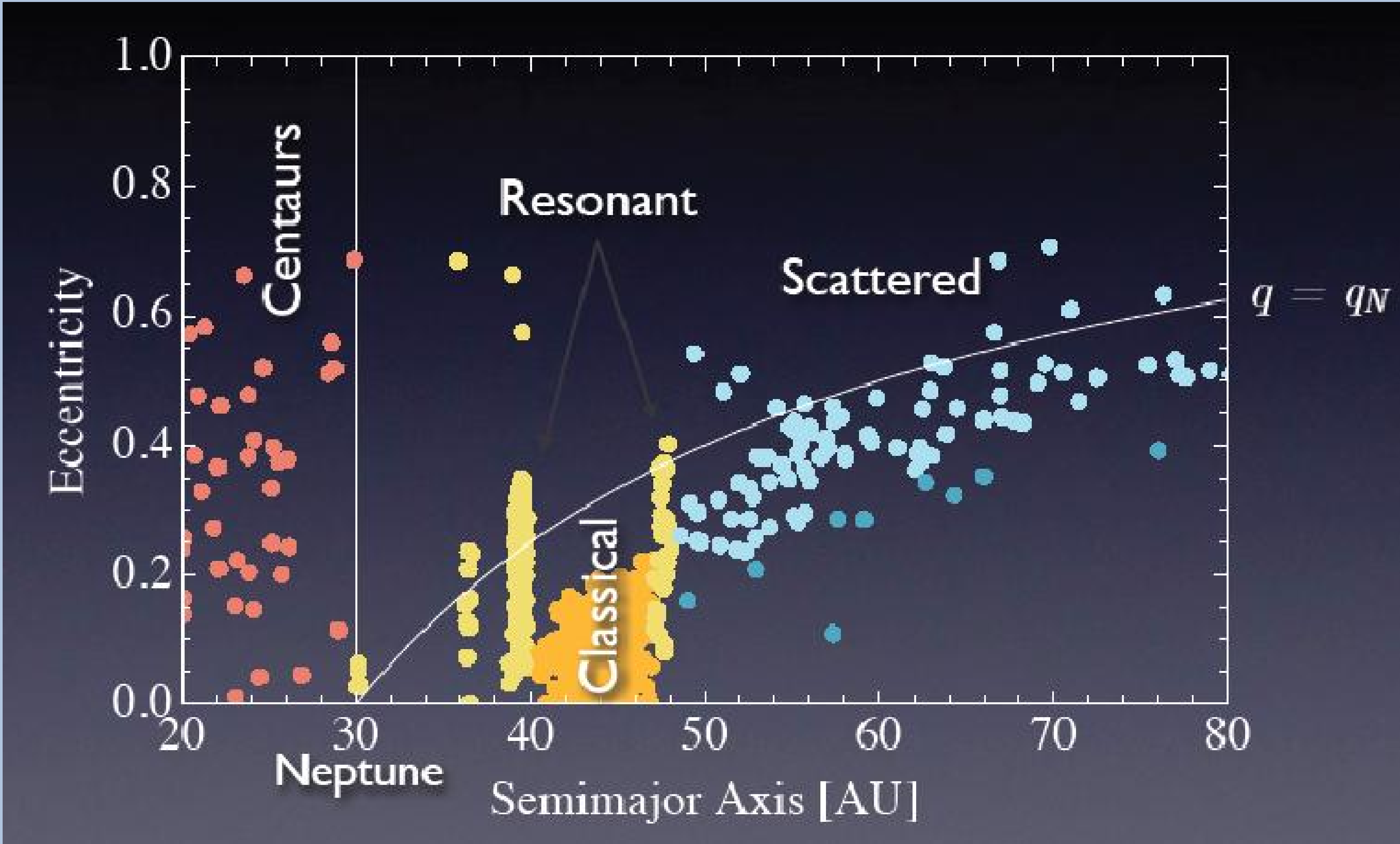
Herschel Study of the Kuiperbelt & TNOs:

$\longrightarrow$ a benchmark for understanding the solar system debris disk, and extra-solar ones as well!

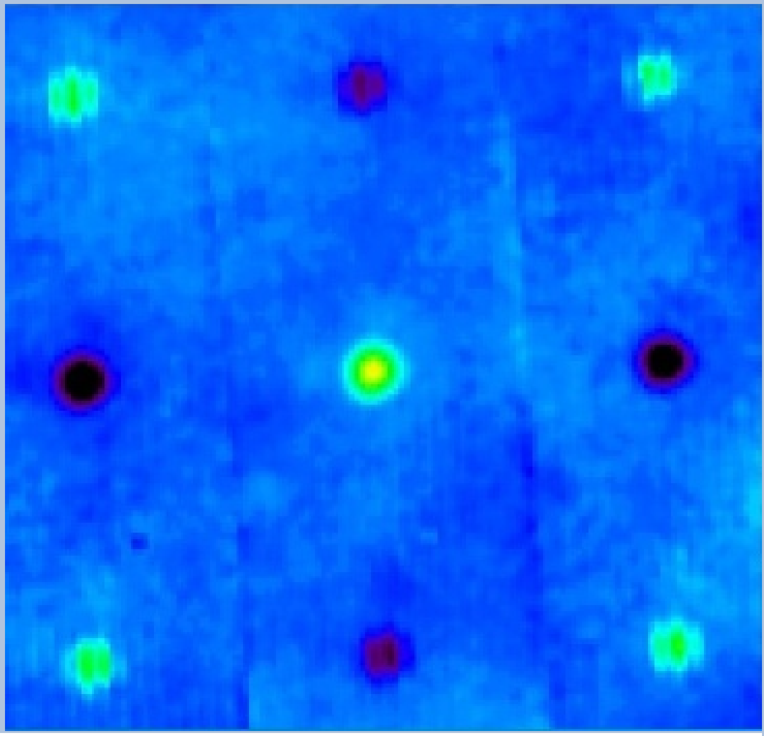
Müller et al. 2009, Earth, Moon & Planet 105, 209-219

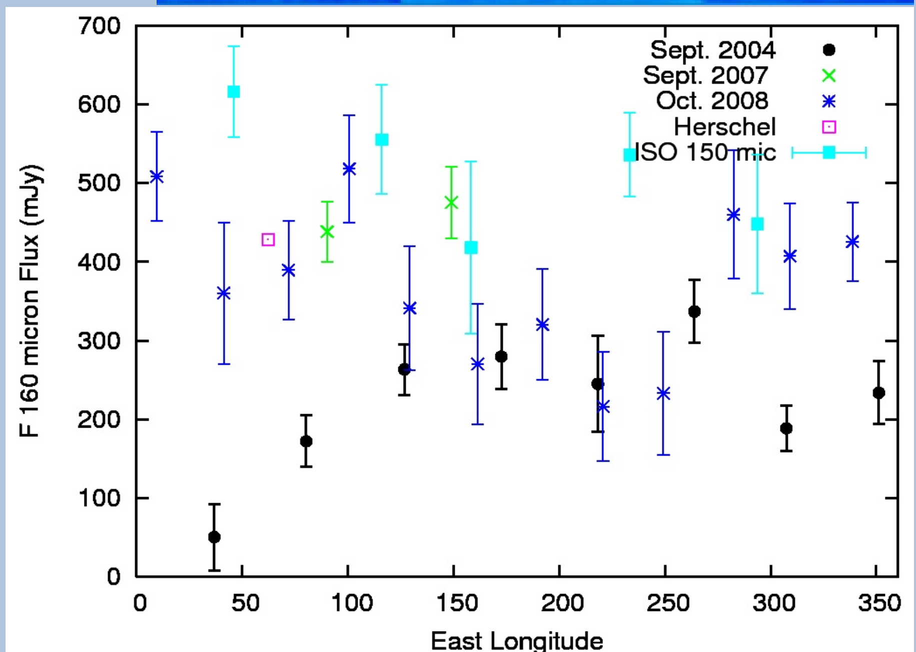
Sample Properties

- **TNOs are cool**
  - T_{ss} from 30 to 100 K (thermal peak in PACS range)
  - distances from Sun: 30 to 100 AU
  - 0.1-3 W/m^2 solar insolation
- **TNOs are dark**
  - typical albedos are just below 10%, comets typically have $< 5\%$
  - a few large TNOs have very high (>50%) albedos
  - different albedo for different dynamic types/sizes?
- **Size range**
  - from below 100 km diameter, up to sizes larger than Pluto's 2 300 km
  - single, binaries, mulitple objects
- **Grouped in different dynamic classes**
  - classical, resonant, scattered disk, detached objects
  - Centaurs


Eccentricity
Semimajor Axis [AU]
Centaurs
Resonant
Scattered
Classical
Neptune
$q = q_N$
1.0
0.8
0.6
0.4
0.2
0.0
20
30
40
50
60
70
80

PLUTO

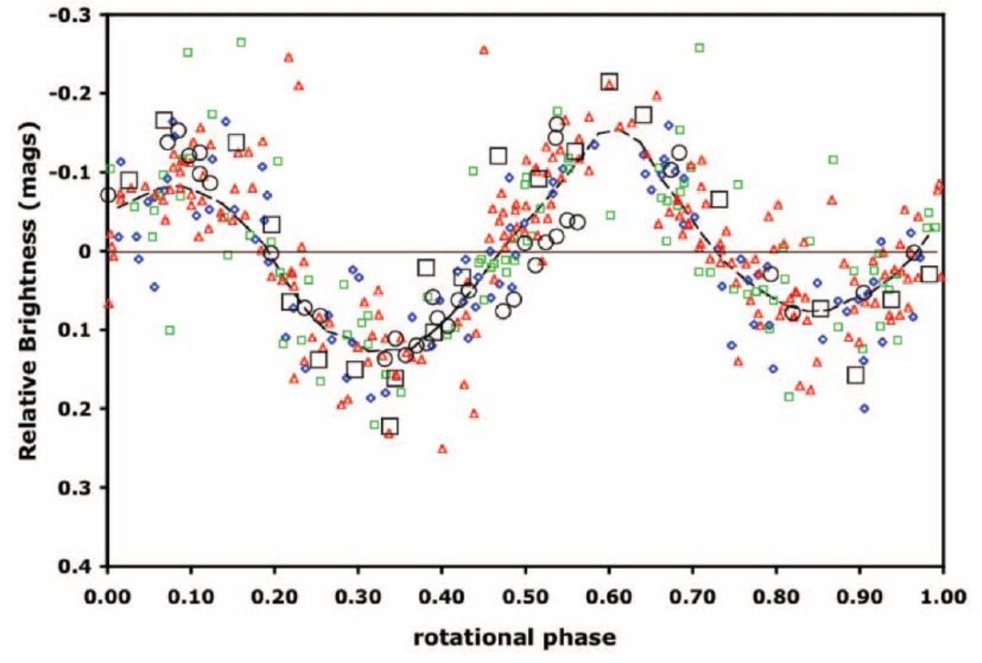


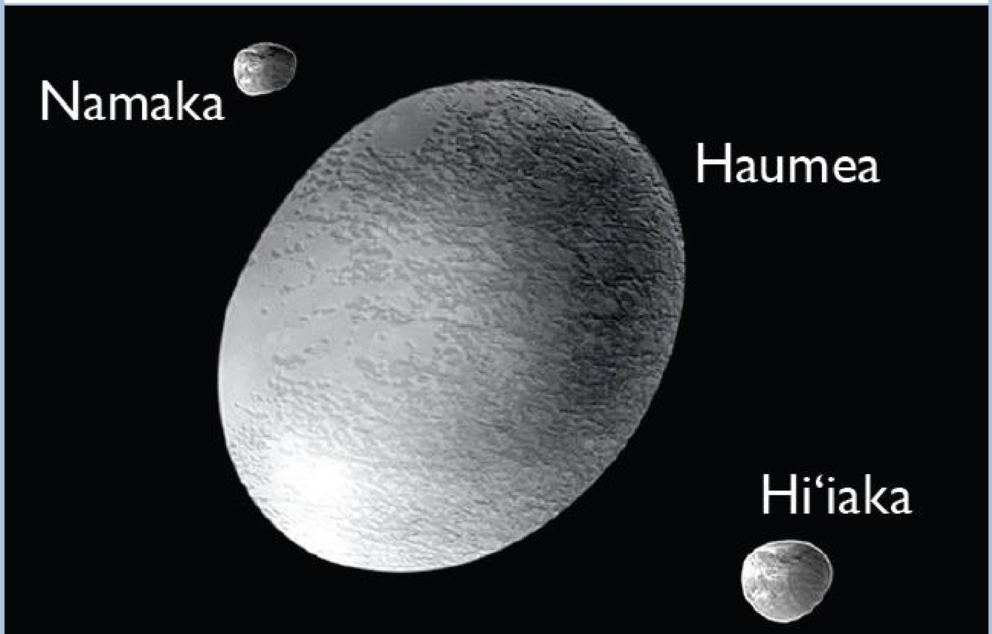


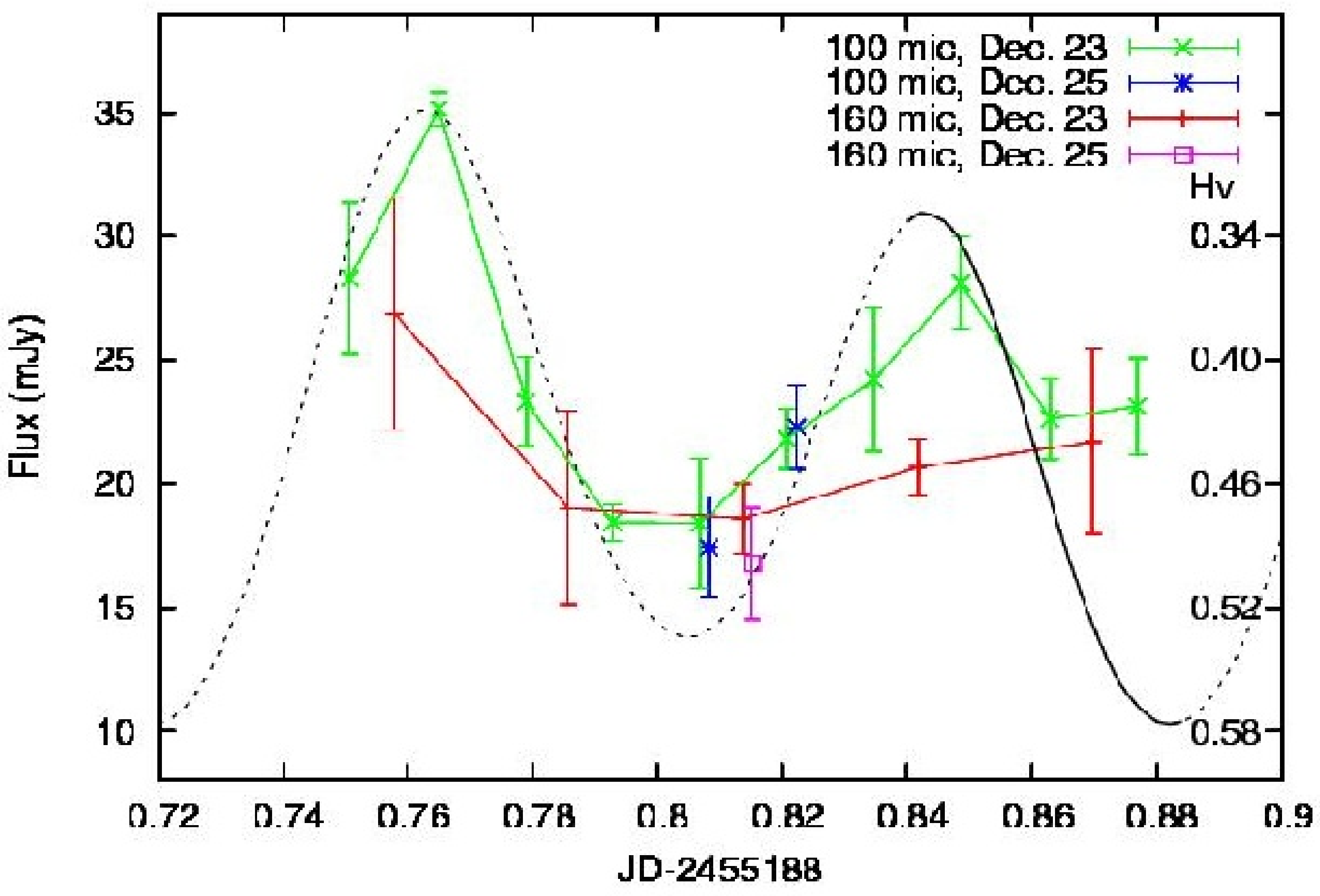
- Pluto's thermal emission, accompanied by changes in the atmosphere, evolved significantly over the last years
- Changes have been followed by Spitzer, stellar occultations, visible/NIR colours of the surface, rotational lightcurve, ...
- Driven by changes in Pluto's strongly coupled surface and atmosphere repositories of N2
- Herschel observations indicate an interesting and unexpected evolution in the far-IR emission (SDP observations)
- Important studies to enhance our eventual interpretation of results from the New Horizons encounter in 2015
- Now disappeared in GC region

Haumea: a remarkable object

- "Classical" TNO, a=43.32 AU, e=0.19, currently at r_{helio}=51 AU
- large amplitude (Δmag = 0.28 mag) lightcurve, fast rotation (3.9 h) $\rightarrow$ elongated shape, large density (ρ=2.6 g cm^{-3}) (assuming hydrostatic equilibrium), two satellites
- size about 2000×1600×1000 km, high albedo (indications from Spitzer)
- evidence for a darker and redder spot from double-peaked lightcurve, collisional origin?
- crystalline water ice features



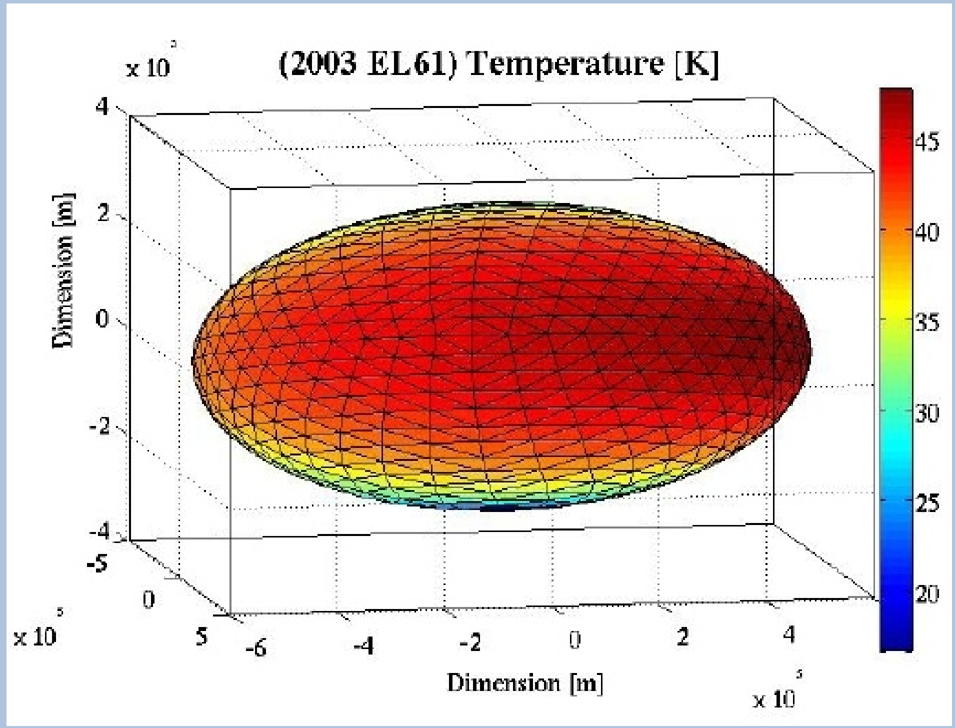




• clear 100 μm L/C, marginal 160 μm L/C • correlated with visible L/C (shape driven) • large amplitude of almost a factor of 2 in flux (only 1.3 for visible L/C) • effect of spot unclear

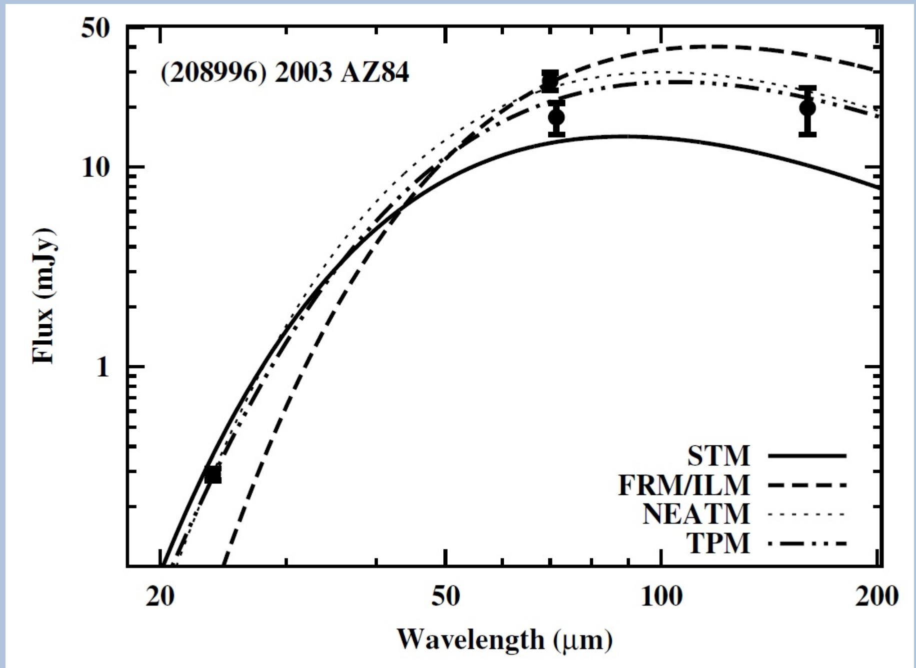
Derived radiometric properties for Haumea

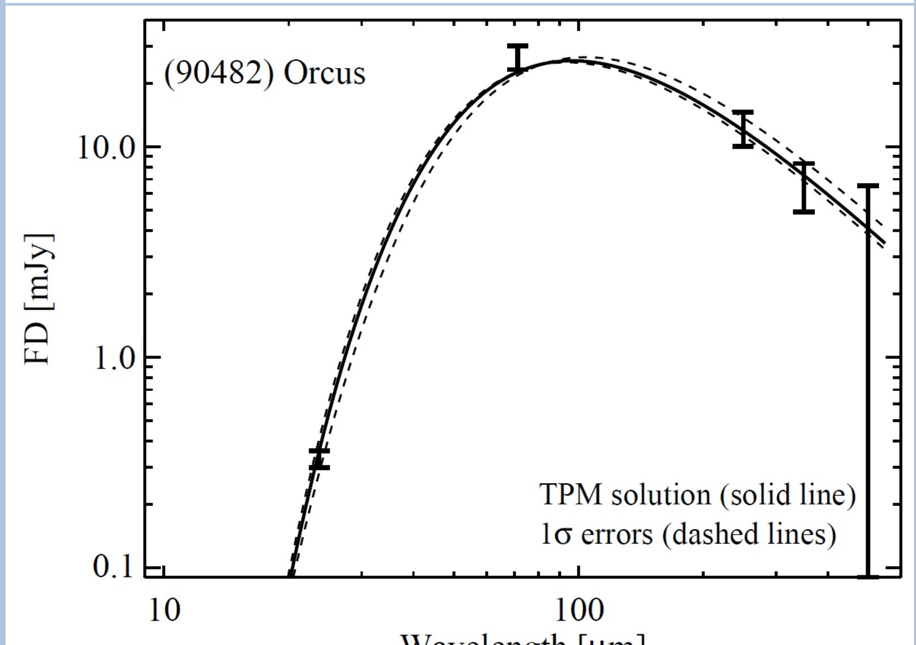
- very elongated, cigar-shaped body
- effective diameter $D_{eff} \sim 1300$ km
- geometric albedo $p_V \sim 0.75$
- beaming parameter η (combined thermal and roughness effects) ~ 1.4 (characteristic for the temperature distribution)
- dark spot cannot be confirmed



- excellent agreement with results derived from visible L/C (amplitude + rot. period) combined with hydrostatic equilibrium assumption
- fitting of the 100 μm fluxes & L/C: low thermal inertia $\rightarrow$ porous regolith?
- the highest L/C flux requires very low η: $\rightarrow$ indicating highly cratered region?
- Lellouch et al. 2010 (A&A, special issue)

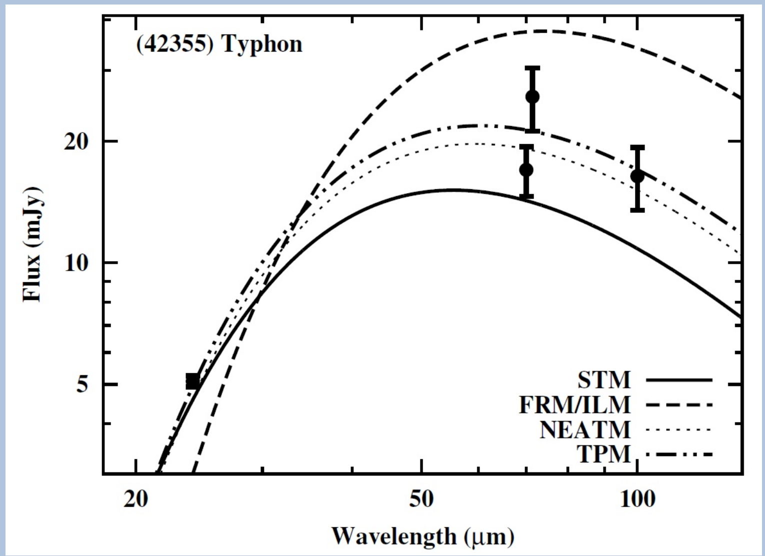
Sample target analysis/modeling



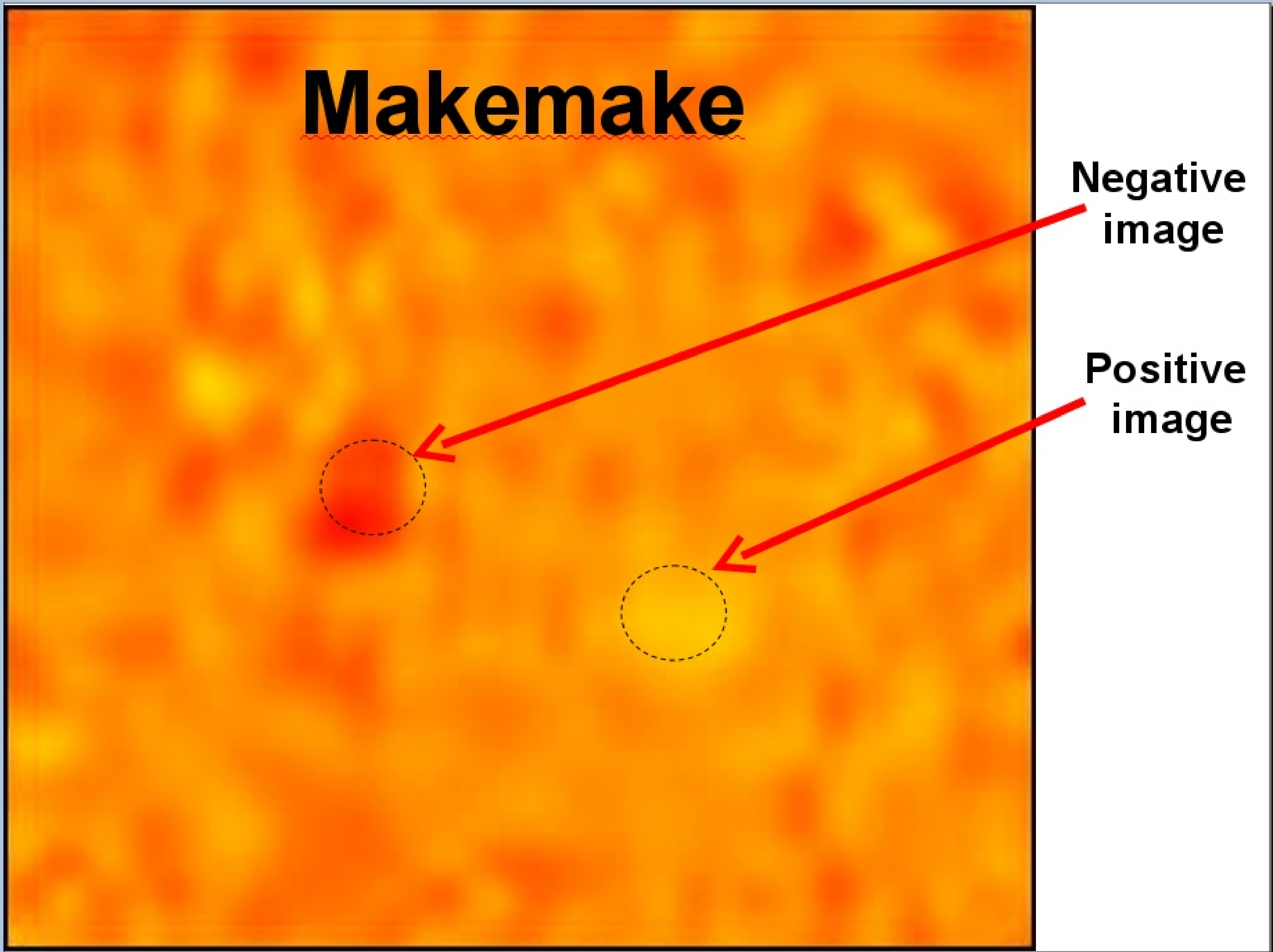


- 8 targets (6 TNOs, 2 Centaurs)
- half of the targets have Spitzer 24/70 μm data
- "canonical" models fail to match the full SED
- surface temperature distribution better explained by NEATM with a fitted (or default) beaming parameter or TPM with thermal inertia Γ as a free parameter.
- Radiometric "single albedo" model solutions work fine in these cases
- resonable agreement with Spitzer results on overlap targets
- Müller et al. 2010 & Lim et al. 2010

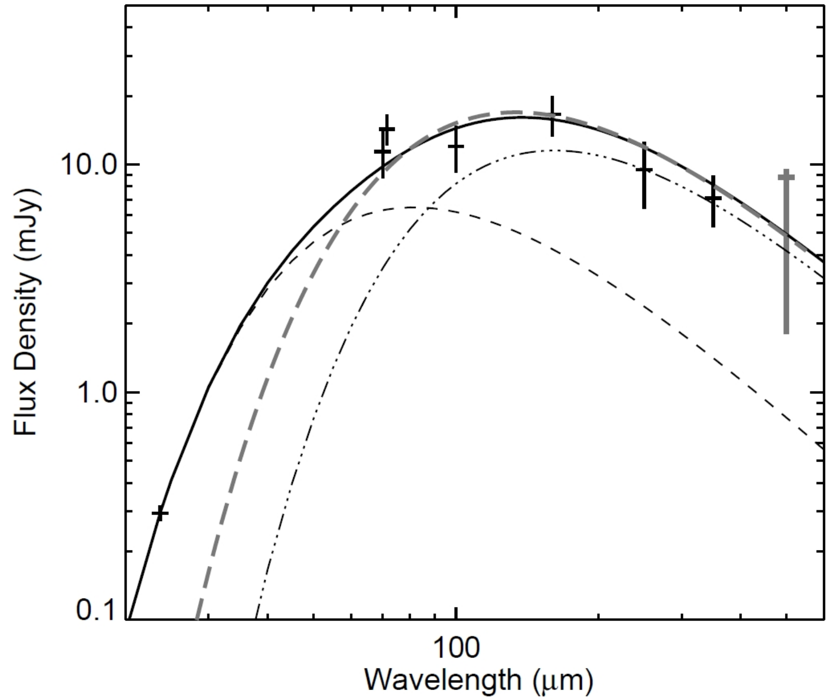
Derived radiometric properties for sample targets



- 6 targets have albedos below 10%, 2 targets are at 20% or above
- Sizes range from 70 to almost 1000 km
- thermal inertias are in the range 0-25 $\mathrm{J m^{-2} s^{-0.5} K^{-1}}$ with a tendency to very small values → low heat conductivities → surface might be covered by loose regolith having low heat capacity in poor thermal contact
- some targets have indications of ices on the surface, but a solid compact layer of ice can be excluded since this would have a much higher thermal inertia
- the two targets with higher albedo:
  2005 TB190 (19%, D_{eff}=375 km) and Orcus (27%, D_{eff}=850 km)
- Typhon is a binary with known mass (Kepler's 3^{rd} law), combined with the Herschel-derived size: $\Rightarrow \rho$=0.58...0.75 g cm^{-3}, similar to comets


Makemake
Negative image
Positive image

What makes Makemake?



- "Giant dwarf planet" (16^{th} mag)
- strongest absorption bands from methane ice in the entire solar system (volatile even at temperatures found at 52 AU)
- visual L/C variation <3% (spherical object? pole-on?), no known satellite
- rotation period about 7.7 h
- Lim et al. 2010 (A&A, special issue)

$\Rightarrow$ No robust radiometric size/albedo solution found

$\Rightarrow$ Belonging to the highest albedo targets in the solar system

$\Rightarrow$ Two-terrain model needed with 4 surface parts at very high albedo ($0.78 < p_V < 0.90$) and 1 surface part at very low albedo ($0.02 < p_V < 0.12$)

$\Rightarrow$ Effective diameter: $1360 < D < 1480$ km

$\Rightarrow$ But why is Makemake not showing a strong visual L/C?

2-terrain models, no lightcurve variation

Conclusions & Outlook

We see a large and very interesting diversity in object properties, but the main goal of this project is to provide diagnostics of physical evolution and to put constraints on formation models, based on a large object sample, covering the different dynamic types.

- programme perfectly matched to PACS & SPIRE photometers
- fine-tuning on data-reduction side still needed (small-map processing, tracking, follow-on)
- optimized observing technique with a 1-3 day follow-on measurement to beat the conf. noise
- about 15% observed (out of > 1000 AORs!)

TNOs are Cool!

maybe not for the mission planners ...