Infrared Characterization of TNOs

Spitzer, Herschel and *JWST*

John Stansberry

Space Telescope Science Institute

IAC Winter School

2016

TNO/Small-body Physical Properties

- After "there it is" – *"what it is?"*
  1. Size, shape, reflectivity, mass, density, temperature, color, …
  2. Atmosphere, thermal character, composition (surface, interior), …
  3. Geology, history, compositional heterogeneity, activity, …
- Global properties (1, 2) determined telescopically
- Surface variations (3) determined via spacecraft encounter

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Telescopic Characterization

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- A few basic concepts and principles
- *Spitzer & Herschel* – Thermal method
- *JWST* - Compositions

Herschel

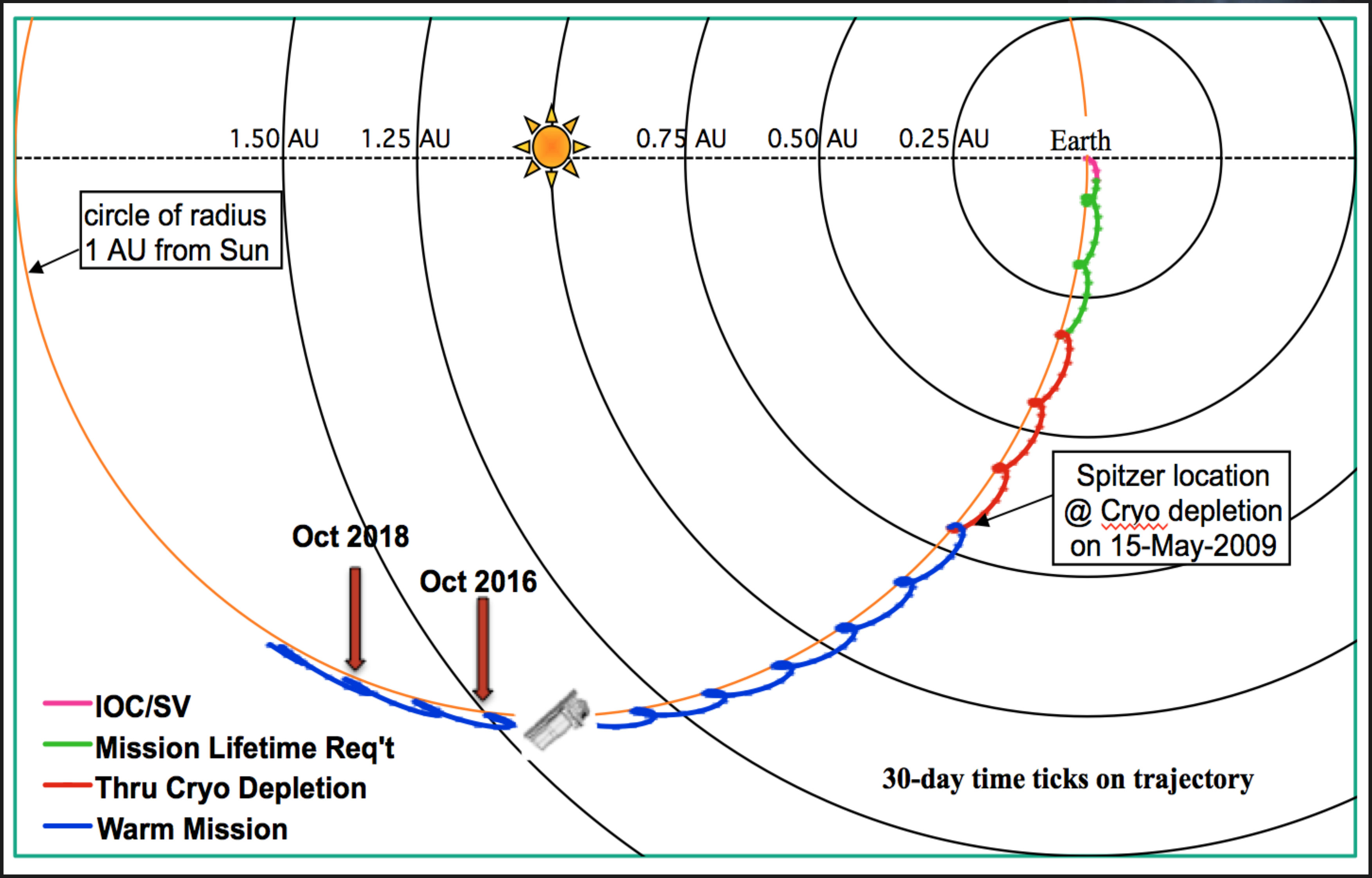
- Infrared Space Observatory (ESA): 2009 – 2013 (4 years cryogenic)
- 3.5 m telescope, L2 Orbit
- Photometry and spectroscopy (55 to 672 μm), liquid helium cooled instruments PACS, SPIRE, HIFI
- Telescope passively cooled to ~70K

"TNOs are Cool" Key Programme: photometric (PACS & SPIRE) observations of about 130 TNOs/Centaurs; PI: T. Müller

Spitzer Space Telescope

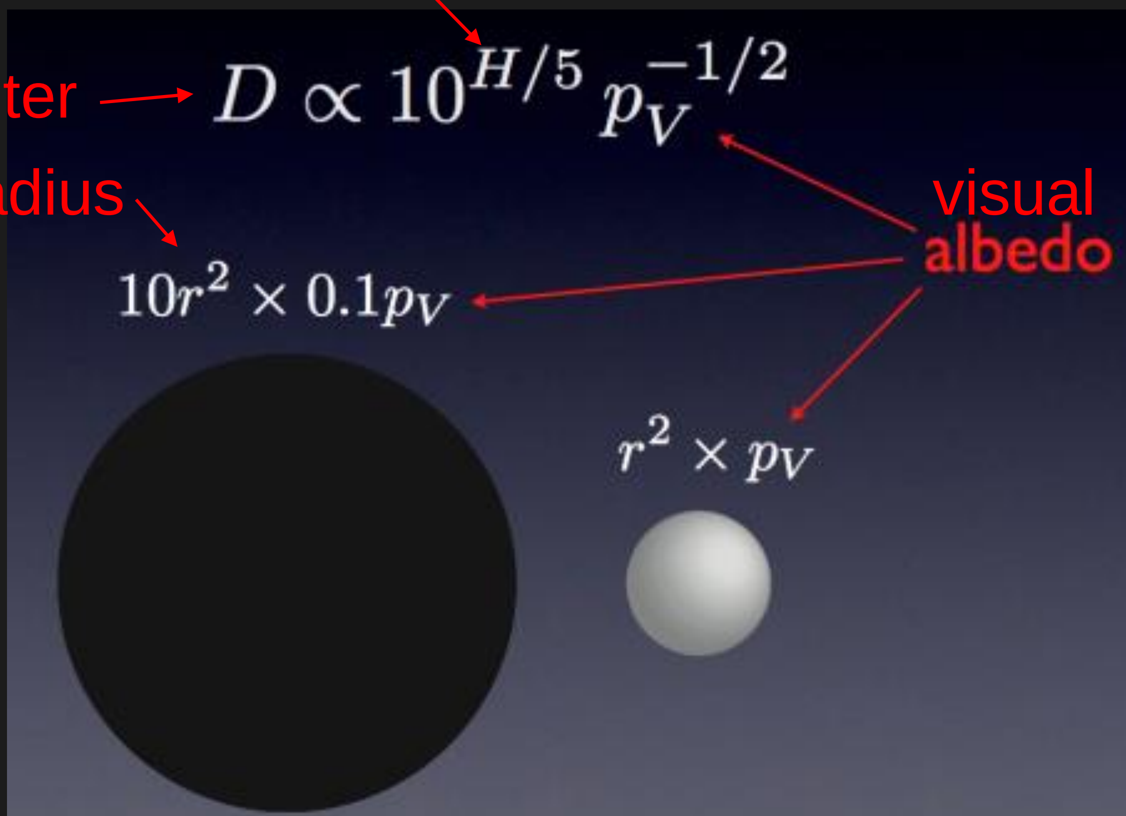
- 85-cm Beryllium mirror, T < 15 K
  - Diffraction Limit: 5.5 μm
  - Background Limited 3 – 160 μm
- Three Focal Plane Instruments
  - ~5K operating temperatures
  - Imaging: 3.6 -160 μm
  - Spectroscopy: 5.3 – 40 μm
  - SED: 51 – 106 μm
- Heliocentric Earth Trailing Orbit
- Launched warm, cooled down on orbit
  - Cryogenic mission lasted 5.5 years
  - Warm mission (3.6 & 4.5 μm imaging) continues until ~2017.

Spitzer: Earth-Trailing Solar Orbit



Size vs. Visual Albedo

A large low-albedo object can reflect the same amount of sunlight as a small high-albedo object…



However, large low-albedo objects emit much more in the thermal (larger *and* warmer)…

Thermal Method Basic Equations

$$T_{SS} = (S_0(1\text{-}A)/\eta\varepsilon\sigma)^{1/4}$$

S_0 = Insolation (W/m2)
A = Bolometric Albedo
η = “Beaming Parameter”
ε = emissivity
σ = Stefan-Boltzmann constant

$$A = q\, p_V$$

q = phase integral

$$H_V = V - 5log(r\Delta) + 2.5log[(1-G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

H_V = absolute magnitude of the target
V = apparent magnitude
“RΔ” = distance correction
“GΦ” = phase function

$$R = 665\text{ km }\ 10^{-Hv/5}\ p_V^{1/2}$$

R = target radius

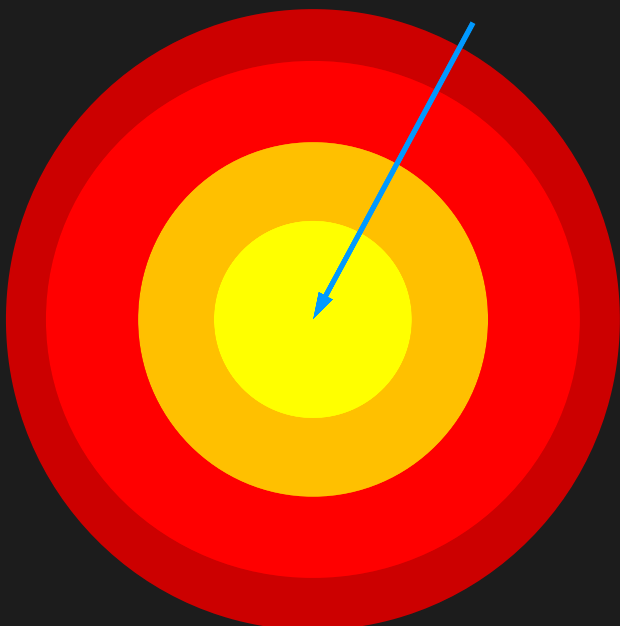
$$\pi R^2(1-A)S = \eta\varepsilon\sigma R^2 \int_{-\pi}^{\pi}\int_{-\pi/2}^{\pi/2} T^4(\theta,\phi)\cos\phi\, d\phi\, d\theta$$

Energy balance equation

Types of Simple Thermal Models

Standard Thermal Model (STM)

$T_{Max} = (S_0(1\text{-}A)/\eta\varepsilon\sigma)^{1/4}$

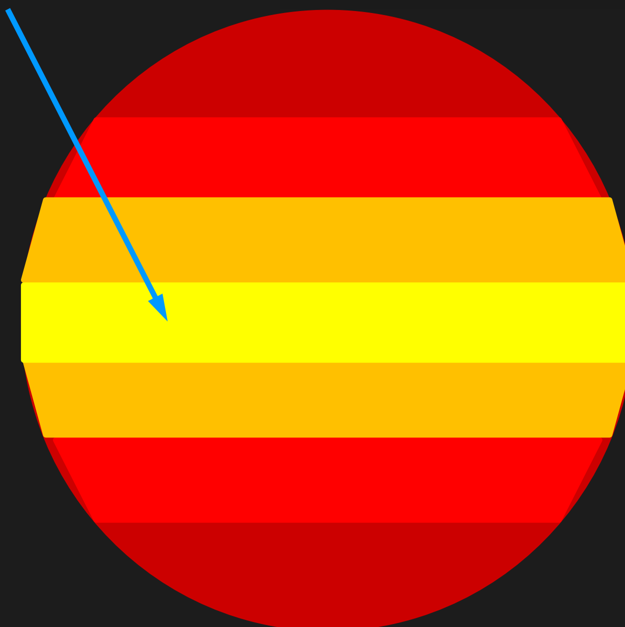


- Equivalent to assuming thermal inertia $\Gamma = 0$ (instantaneous thermal equilibrium with insolation).
- Temperature distribution depends on the angle from the subsolar point, θ, as $\cos^{1/4}(\theta)$.
- The "beaming parameter", η, allows the model to be tuned to account for the effects of roughness, non-0 thermal inertia, rotation. Values $\sim 0.5 < \eta < 2$ are observed.

See e.g.
Harris, Icarus 1998

Fast Rotator or Isothermal Latitude Model (ILM)

$T_{Max} = (S_0(1\text{-}A)/2\eta\varepsilon\sigma)^{1/4}$



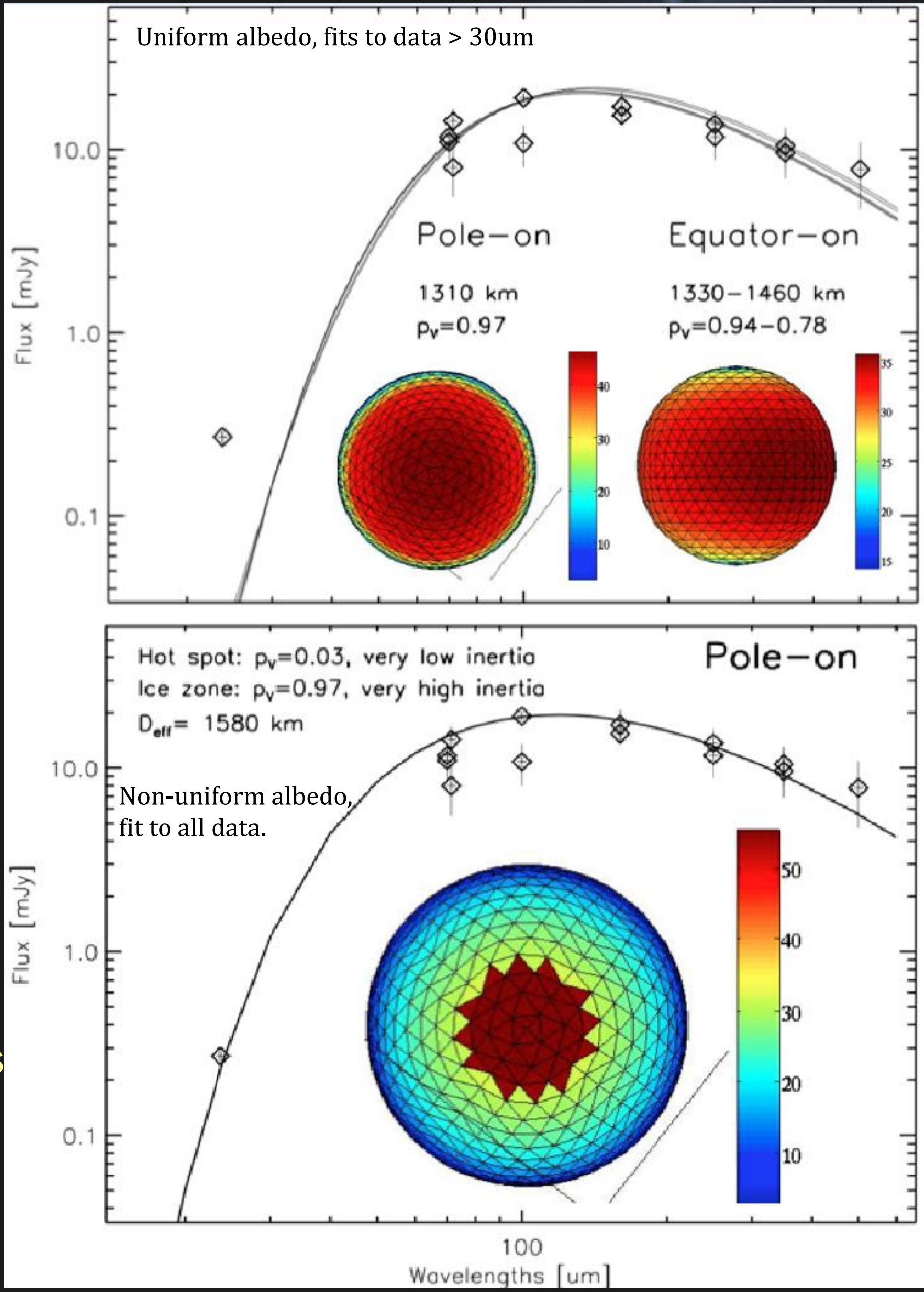
- Equivalent to assuming thermal inertia $\Gamma = \infty$ (nightside and dayside temperatures are equal).
- Temperature distribution depends on the latitude, λ, as $\cos^{1/4}(\lambda)$, and is lower than for the STM.
- The beaming parameter rolls up effects such as thermal inertia, roughness, and finite rotation, similarly to the STM.

Thermophysical Models (TPM)

- TPM accounts for
  - Diurnal insolation variations
    - Spin ***vector***
  - Subsurface conduction (Γ = thermal inertia)
  - Surface roughness
    - Parameterized as RMS slope
    - Roughness causes localized temperature enhancements, enhanced emission at small phase angles
  - Actual viewing geometry
- Finite element approach
  - Model predicts T(x,y,z)
  - Can incorporate inhomogeneous properties
    - Albedo, thermal inertia, …
  - Can account for non-spherical objects
- Results give direct physical insights
  - Application requires knowledge of, or asumptions about, multiple target properties

See, e.g., Spencer, Icarus 1990

TPM Models for Makemake (Mueller 2011)



Types of Simple Thermal Models

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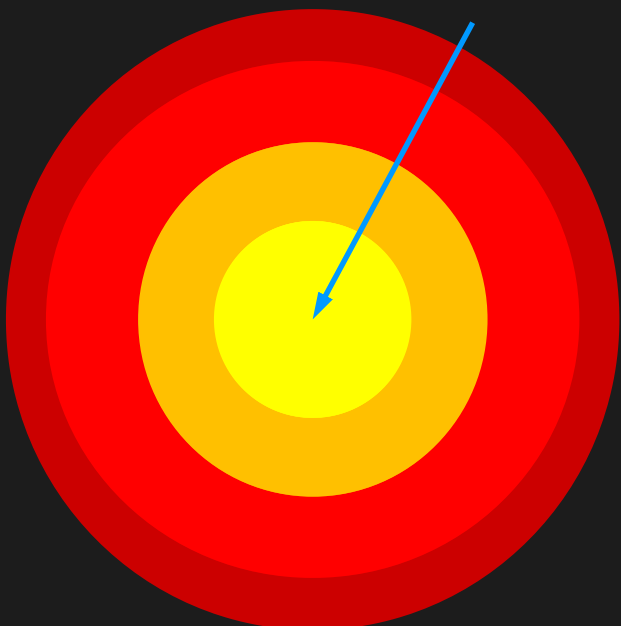

Fast Rotator or Isothermal Latitude Model (ILM)

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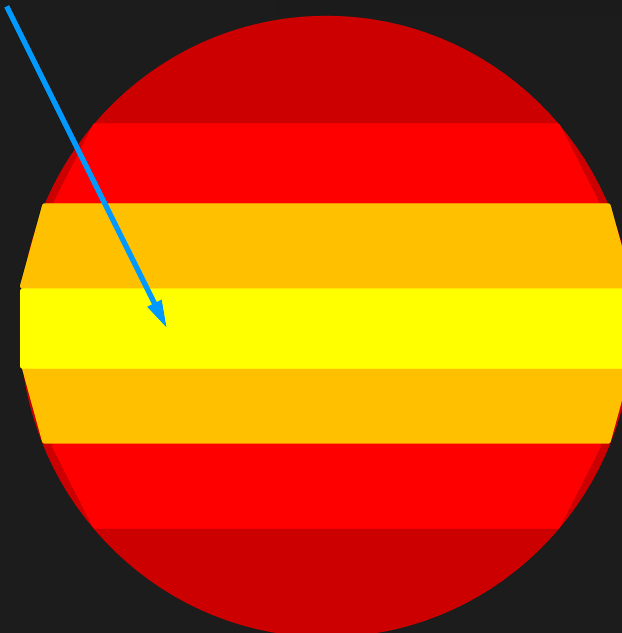


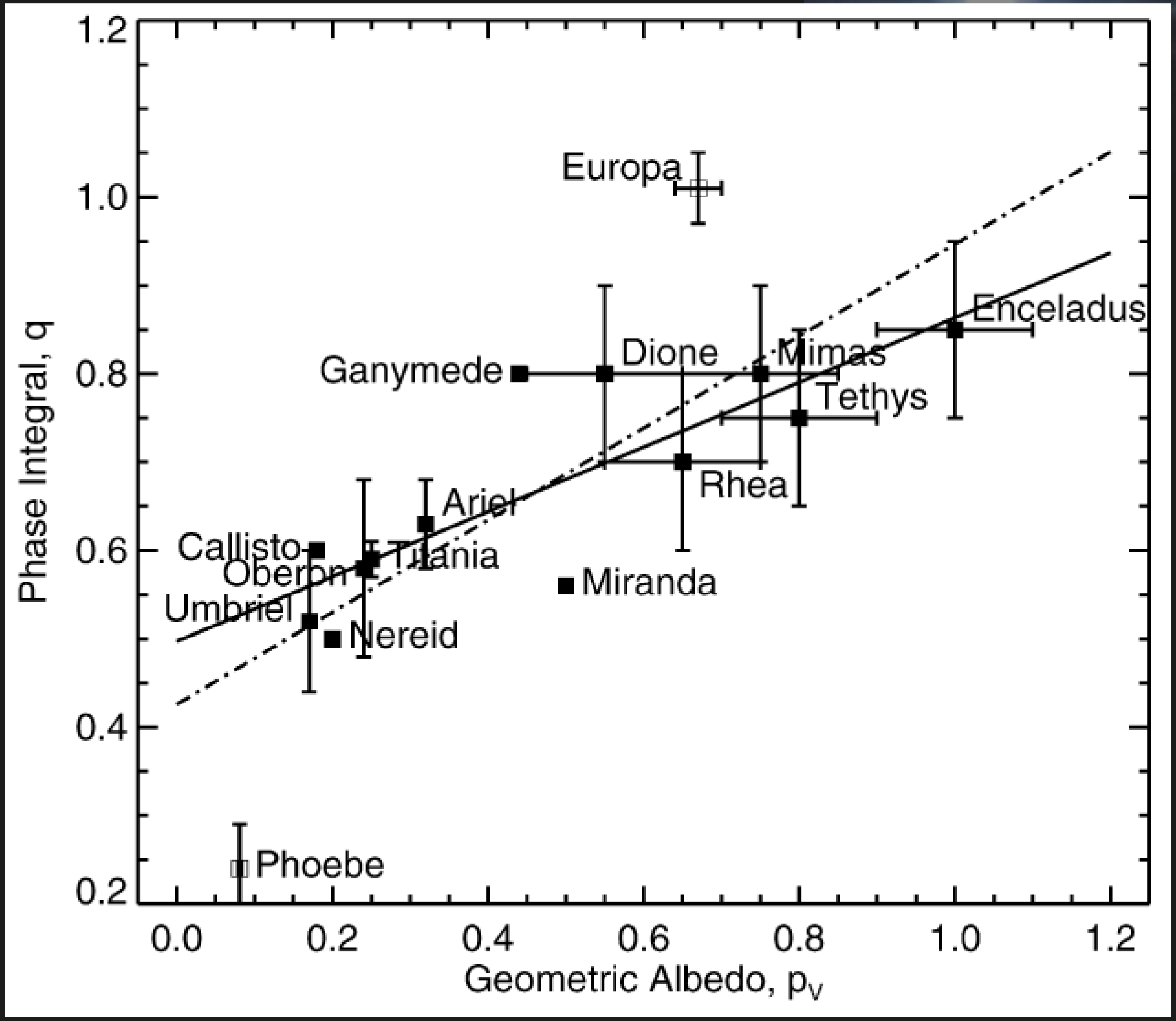
- The STM and ILM give results for p_V and D as accurate as results from thermophysical models (TPM).
- Extensions to these account for viewing at non-zero phase angles (e.g. NEATM) and sub-observer latitude.
- The ‘beaming parameter’ has no direct physical interpretation (but see previous chart).
- There are fewer STM / ILM free parameters than for the TPM. Given that there are usually only a few thermal data points (1 – 3 in most cases) in the simpler models are in some ways preferred.

Phase Integral, q

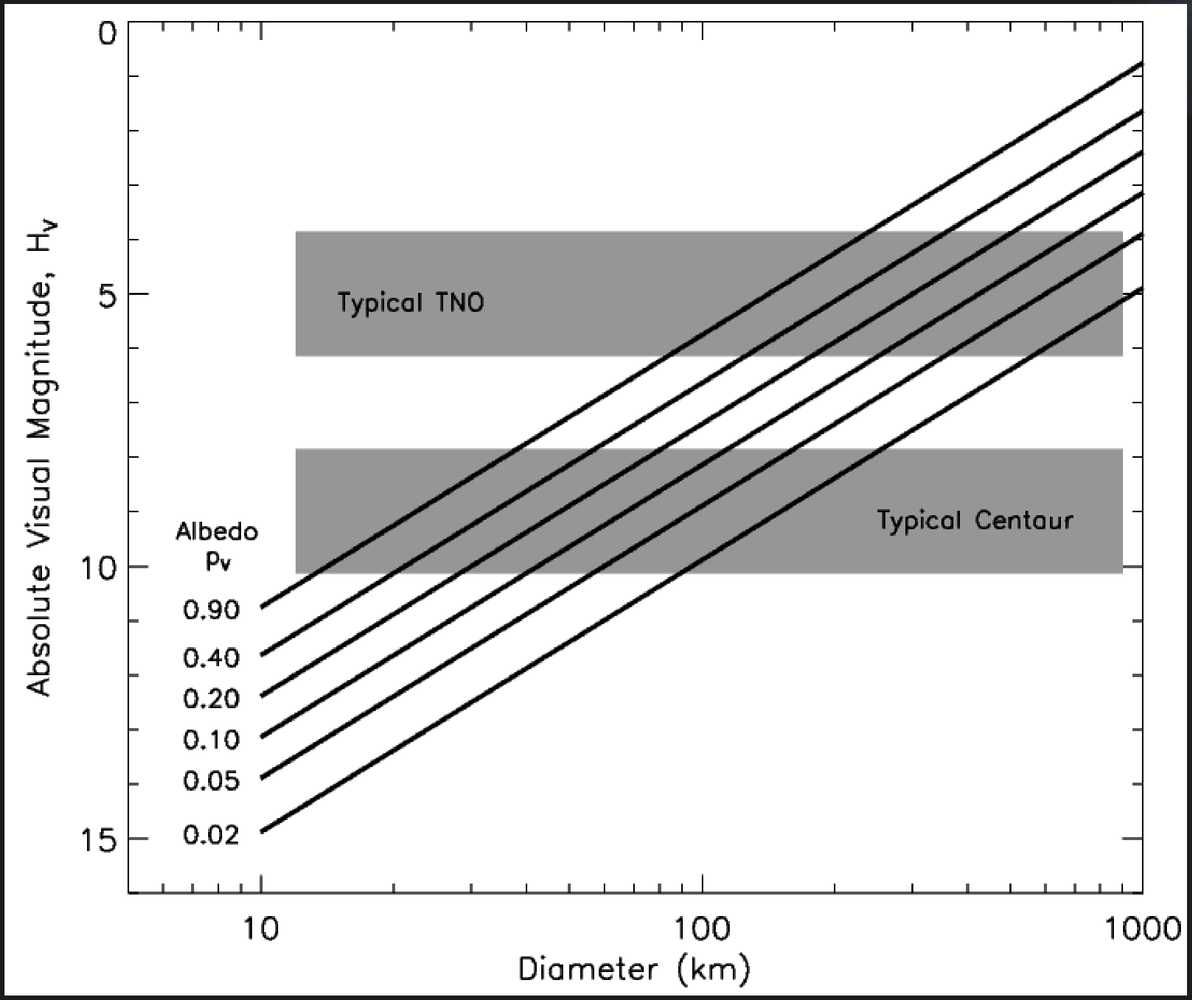
Converts geometric albedo to bolometric albedo, which is used for calculating energy balance.

$q = 0.336\, p_V + 0.479$

Brucker et al. 2009



Absolute Magnitude: Size and Albedo



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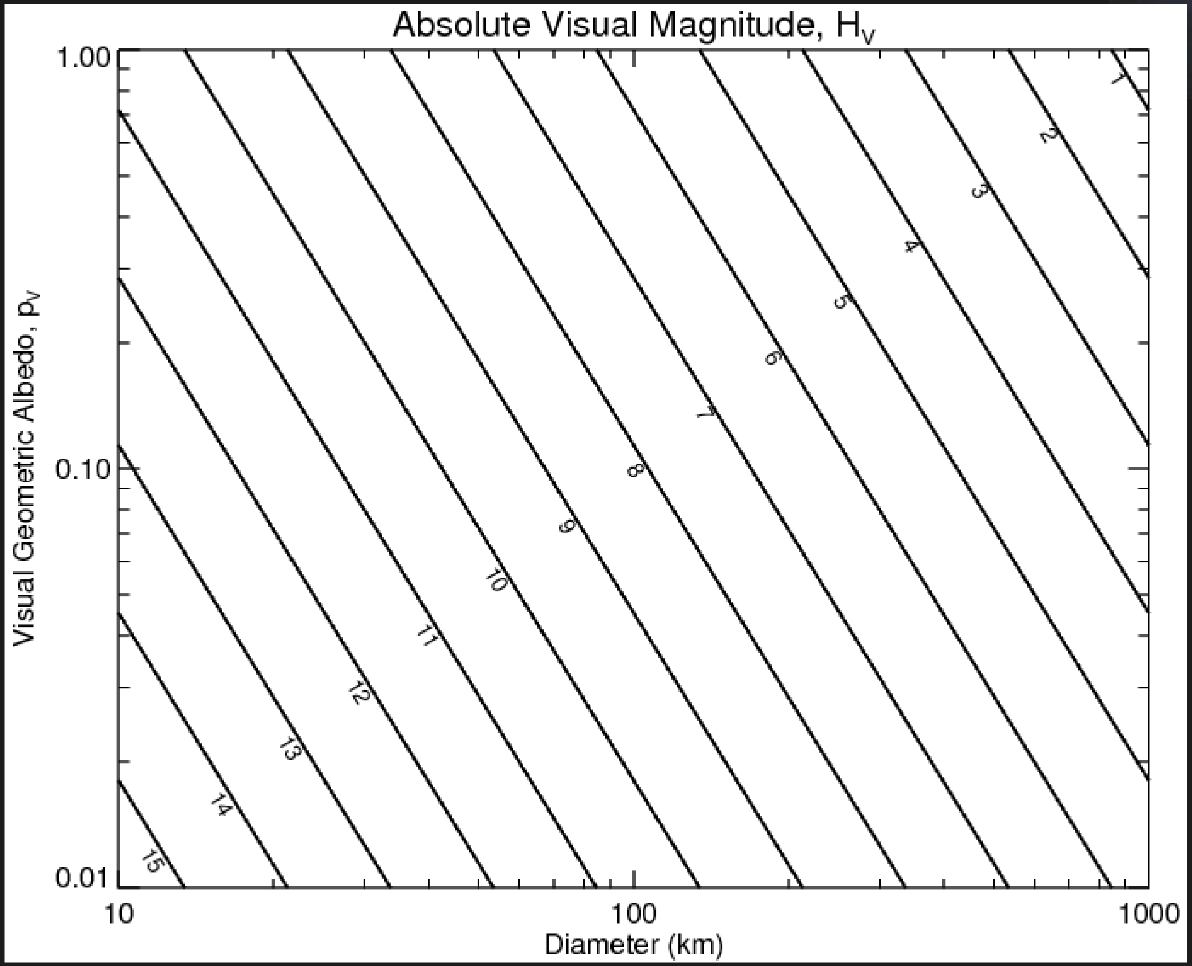
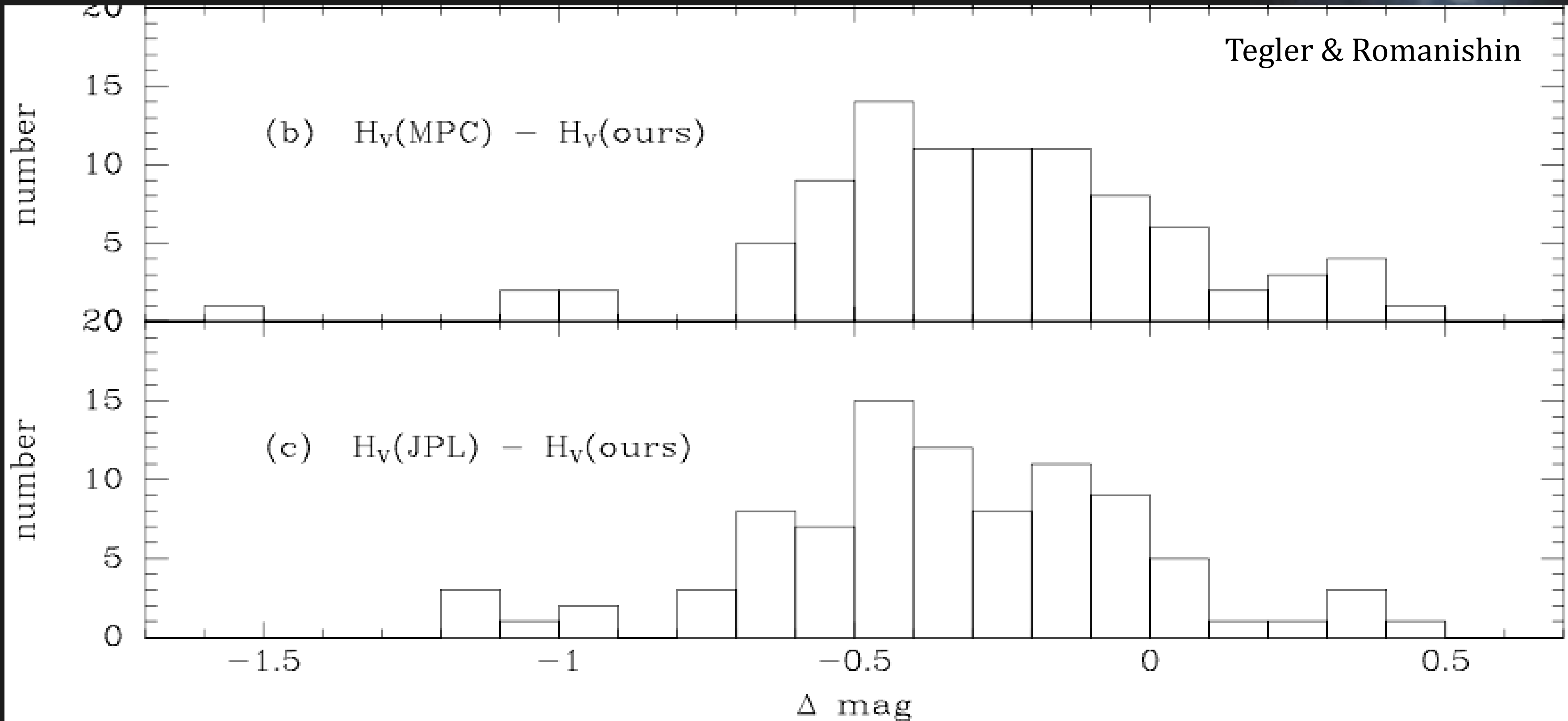
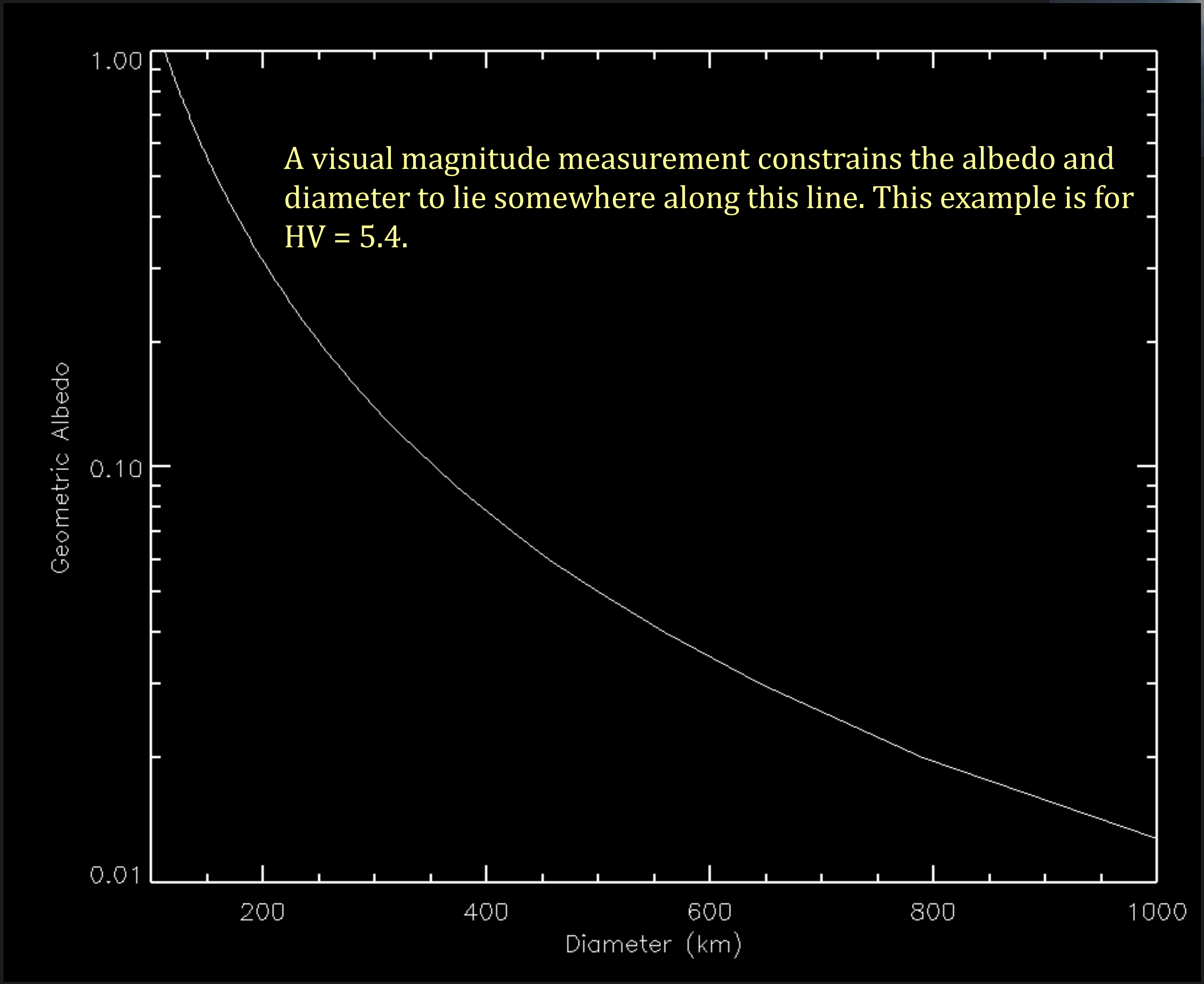


Beware of HV from MPC, Horizons



H magnitudes from these services are biased ~0.25 mag too bright, on average…

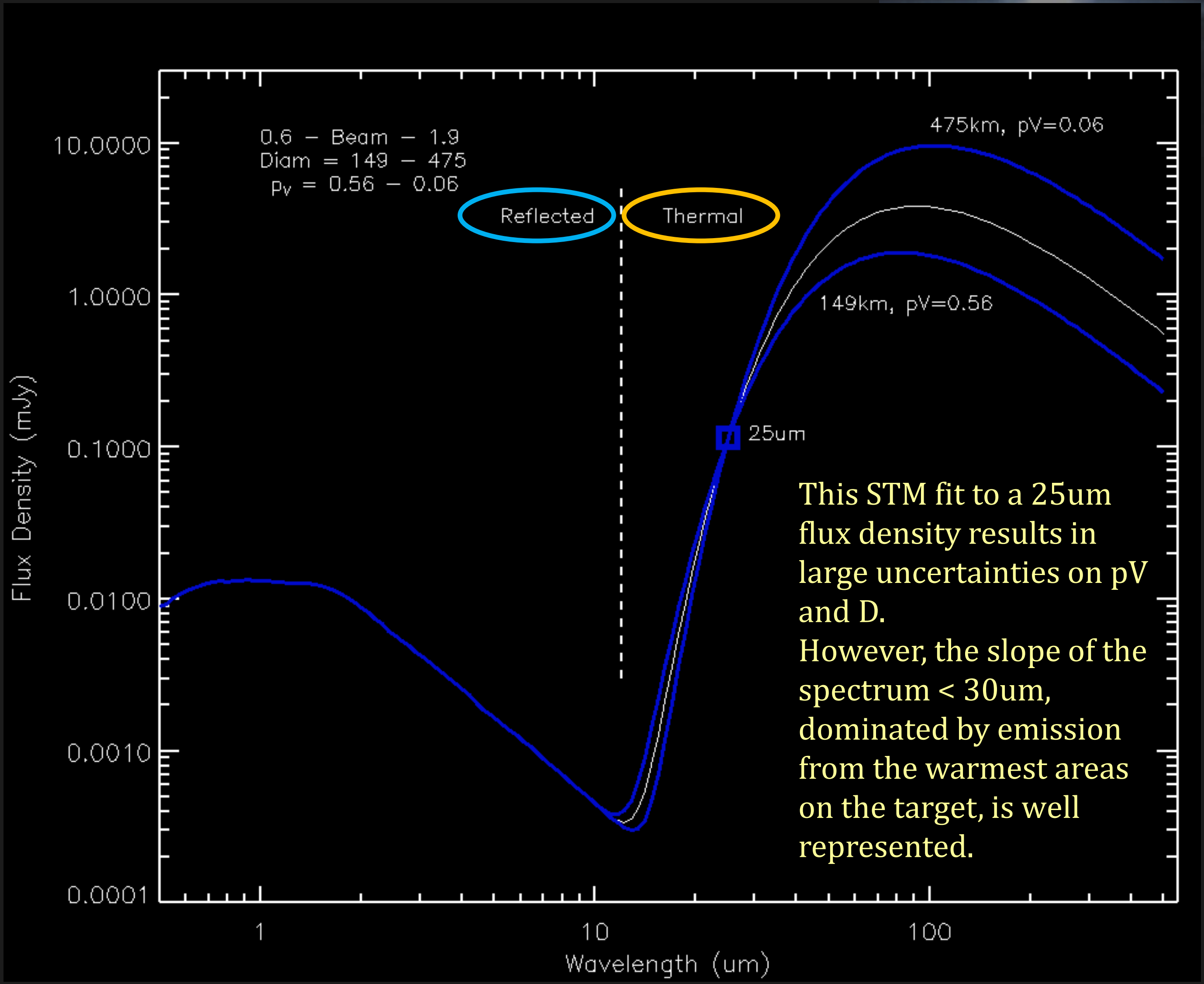
Size and Albedo: Visual Constraint Only



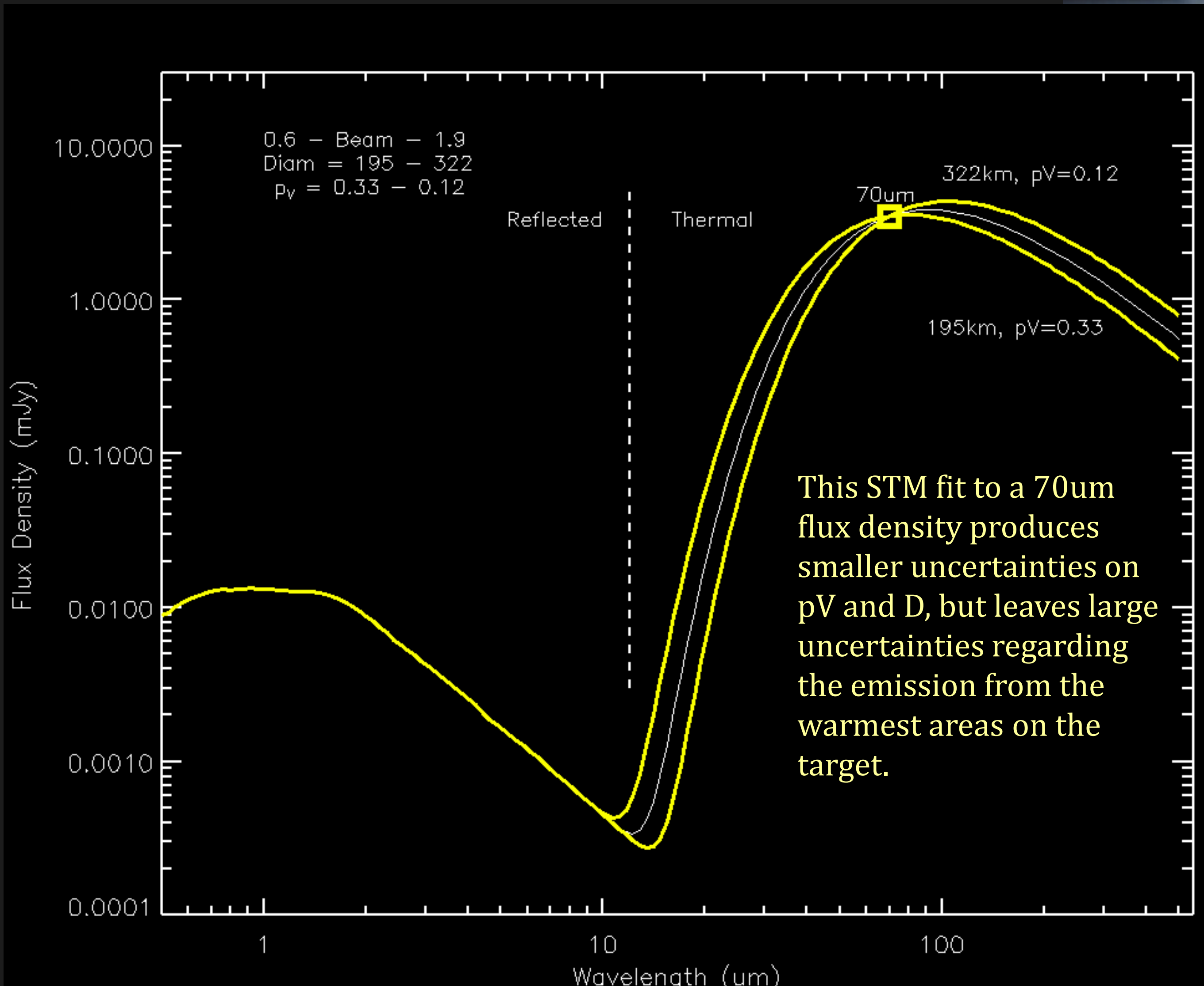
Standard Thermal Model Fits

The spectrum of an object consists of a reflected and emitted (thermal) component.

In these examples the STM beaming parameter is set to limiting values of 0.6 and 1.9.

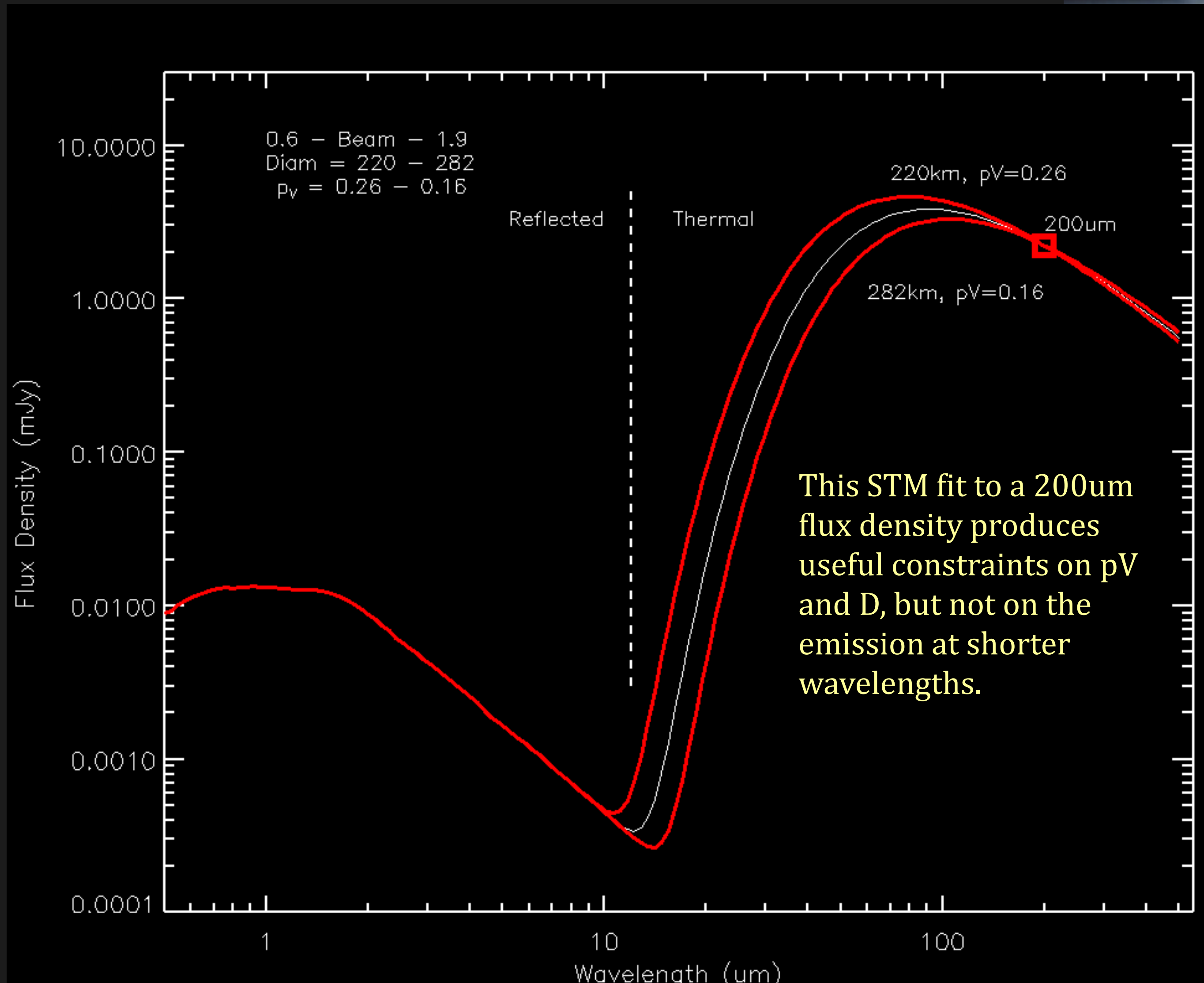


Standard Thermal Model Fits

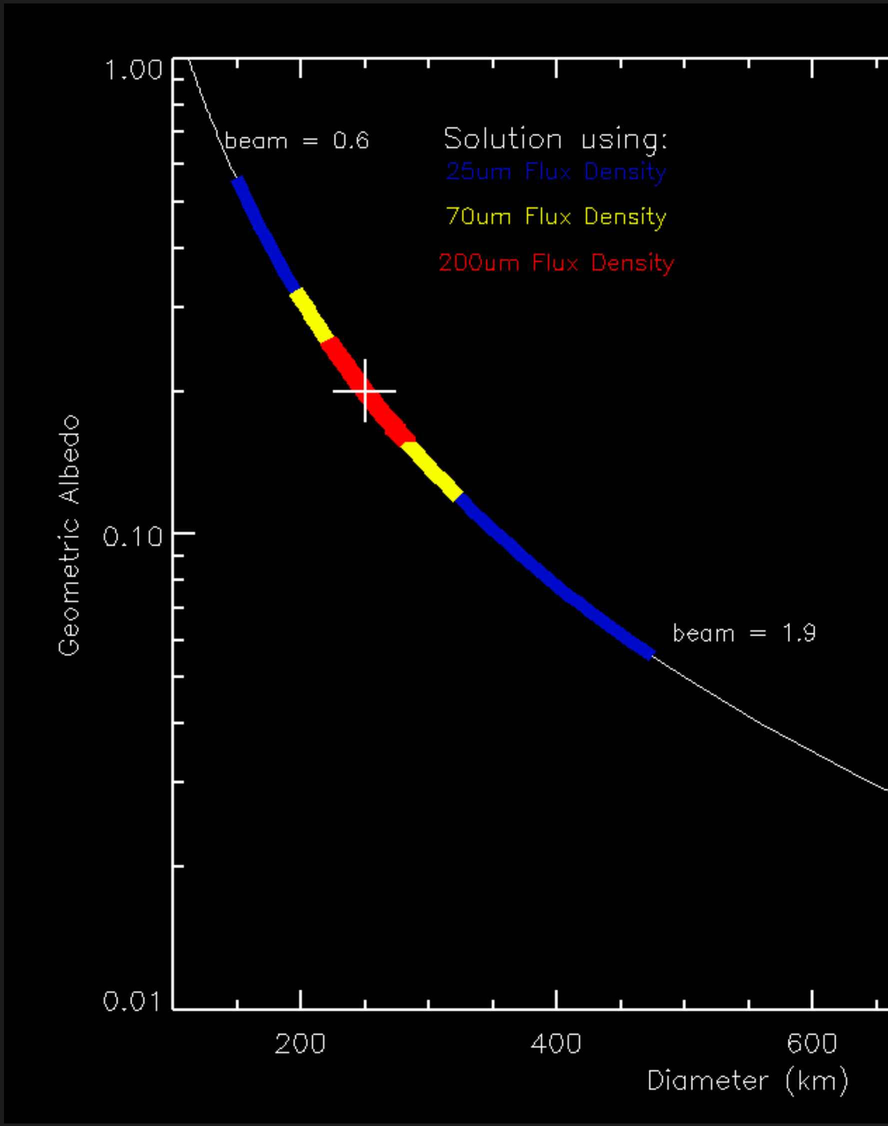


This STM fit to a 70um flux density produces smaller uncertainties on pV and D, but leaves large uncertainties regarding the emission from the warmest areas on the target.

Standard Thermal Model Fits

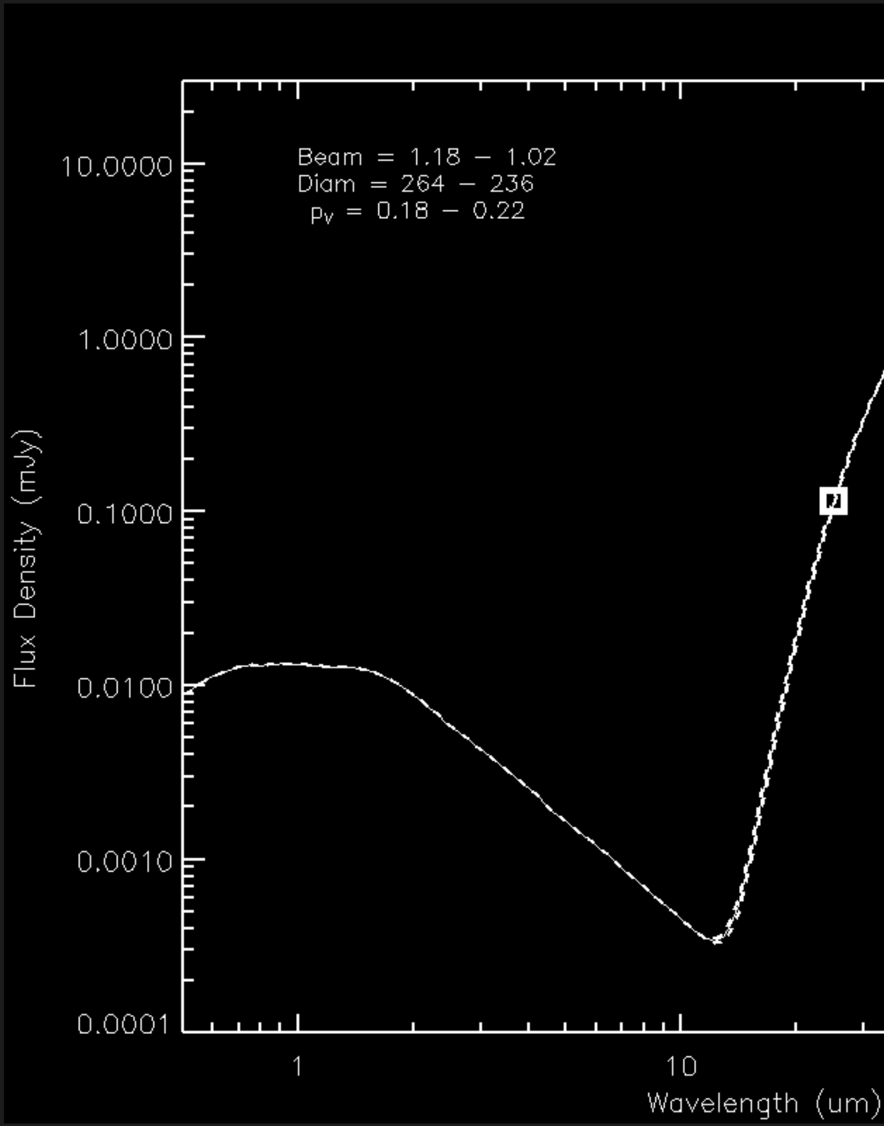


STM Uncertainties on D, p_V

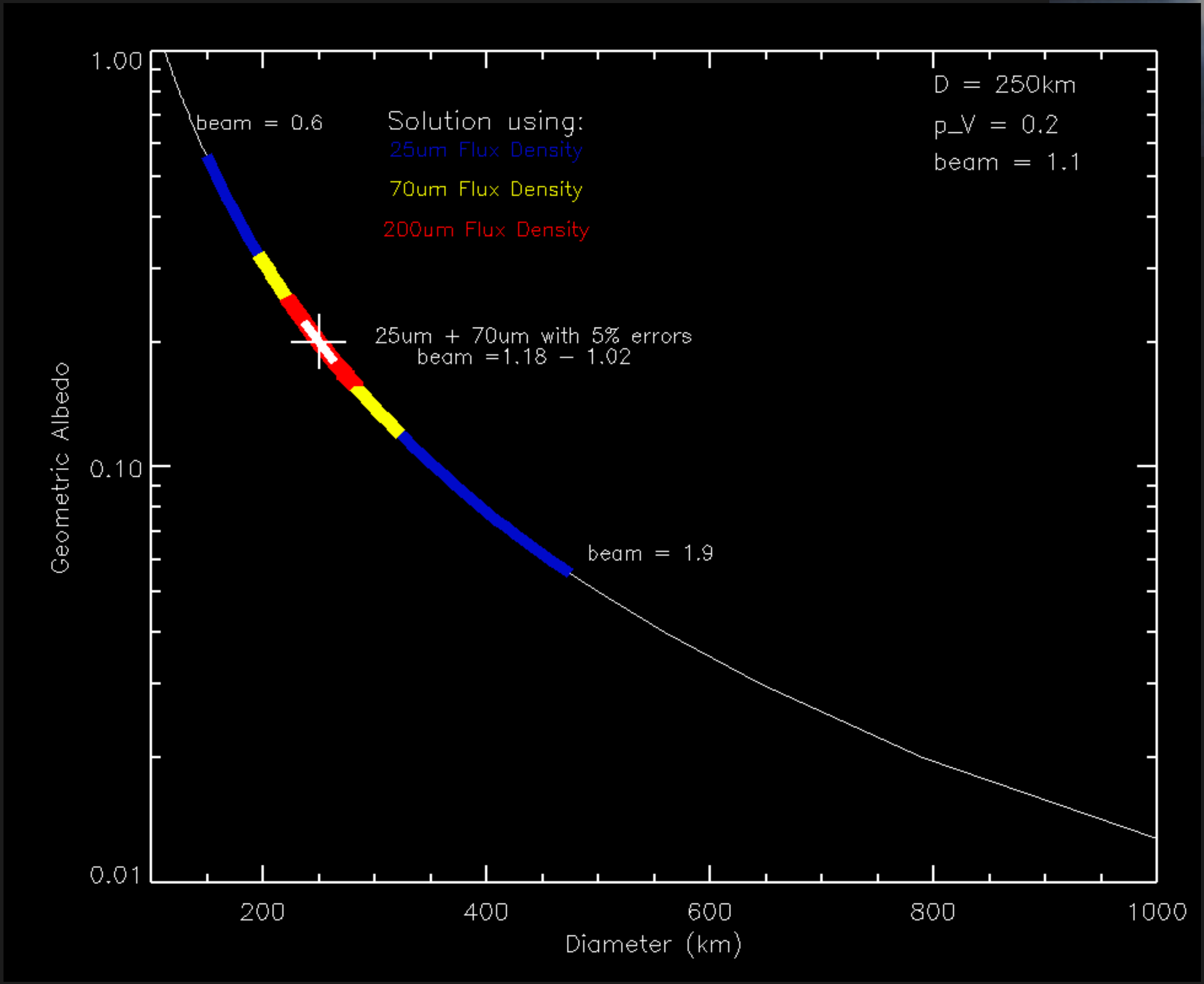


Uncertainties on the fitting parameters depend on the wavelength of the thermal measurement relative to the wavelength of the peak of the thermal emission.

STM Fits using two Thermal Fluxes

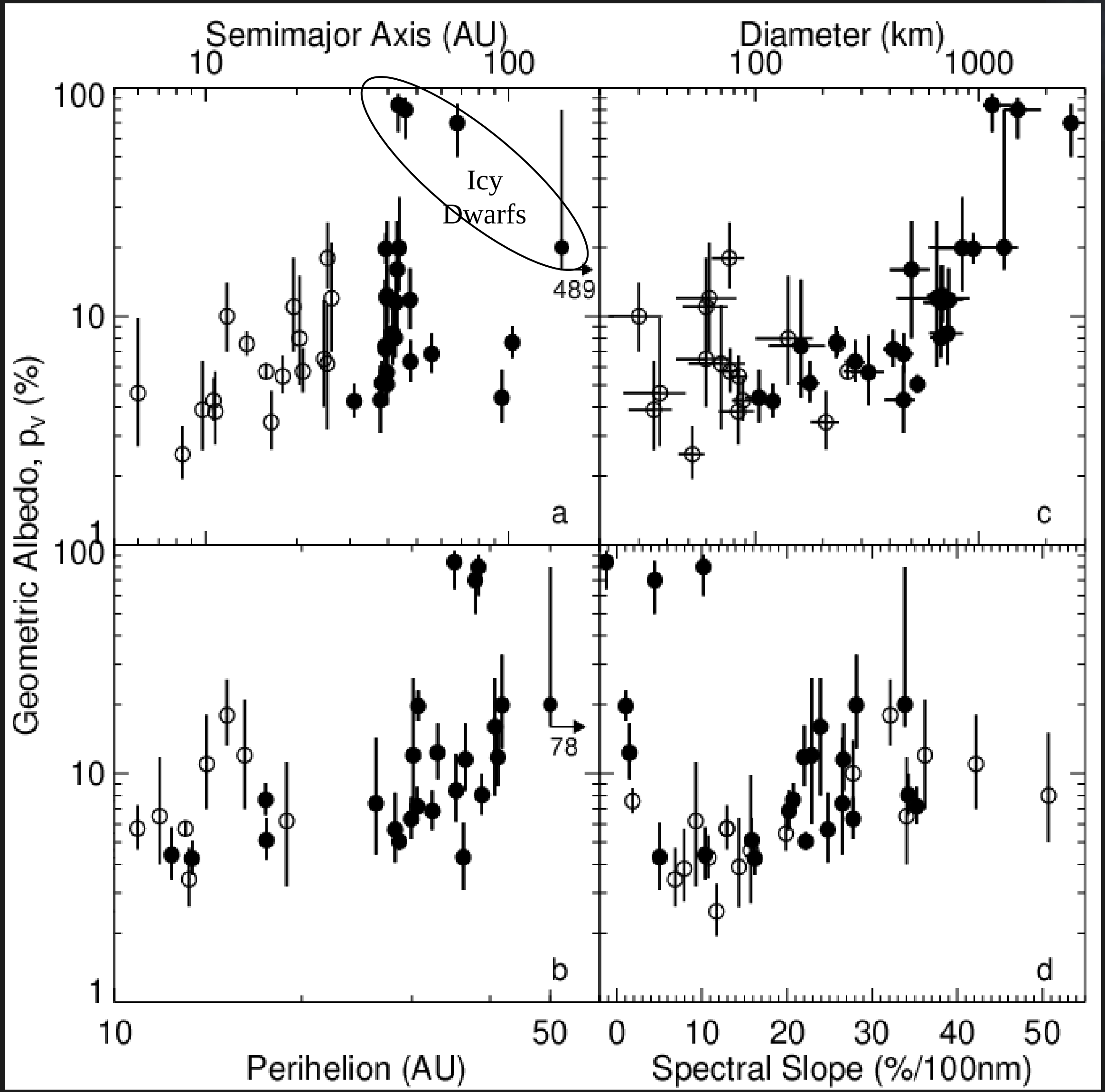


Fits to more than one thermal wavelength provide a direct measurement of the 'color temperature' of the emission, producing much smaller uncertainties on D and p_V.



1.00
0.10
0.01
Geometric Albedo
200
400
600
800
1000
Diameter (km)
beam = 0.6
Solution using:
25um Flux Density
70um Flux Density
200um Flux Density
D = 250km
p_V = 0.2
beam = 1.1
25um + 70um with 5% errors
beam =1.18 – 1.02
beam = 1.9

TNO Albedos and Sizes: *Spitzer* Results

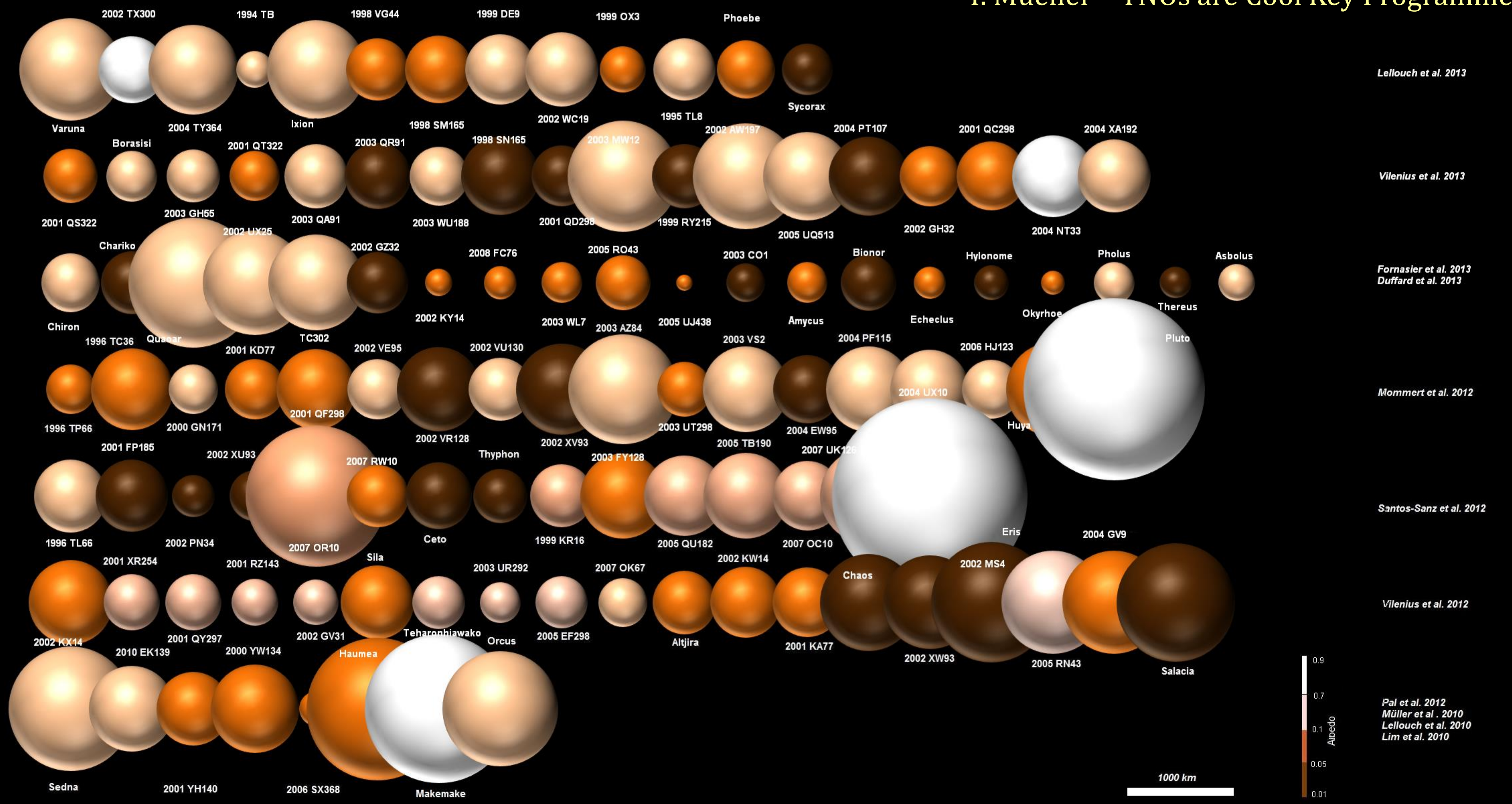


Stansberry et al. 2008
32 objects
Spitzer 24um & 70um

Open points: Centaurs
Filled points: TNOs

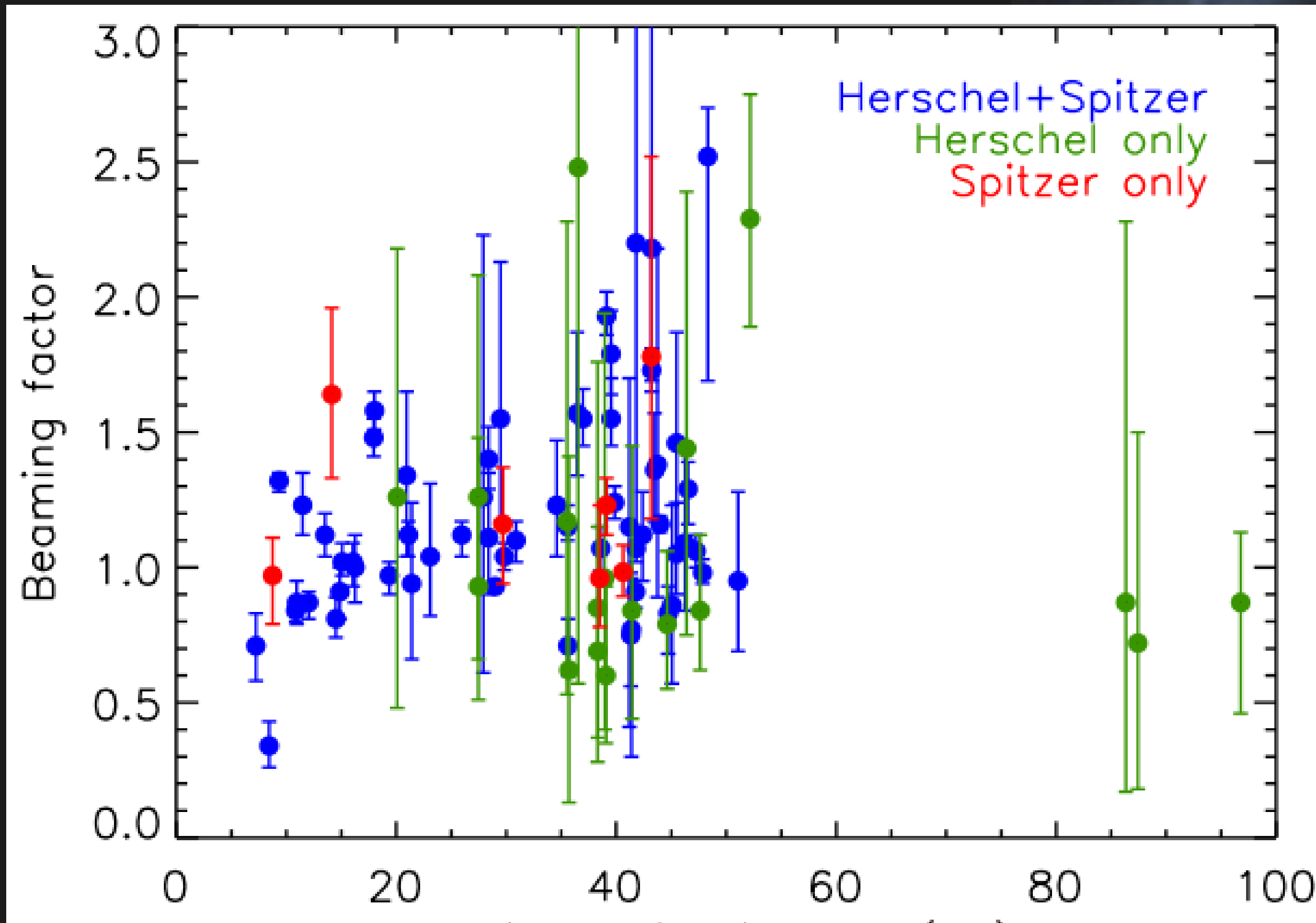
TNO Size & Albedo: *Herschel* Results

T. Mueller – TNOs are Cool Key Programme



Note that red ≠ dark, at least for cold-classical TNOs…

Beaming Parameter for TNOs



Lellouch 2013

Beaming Parameter for TNOs

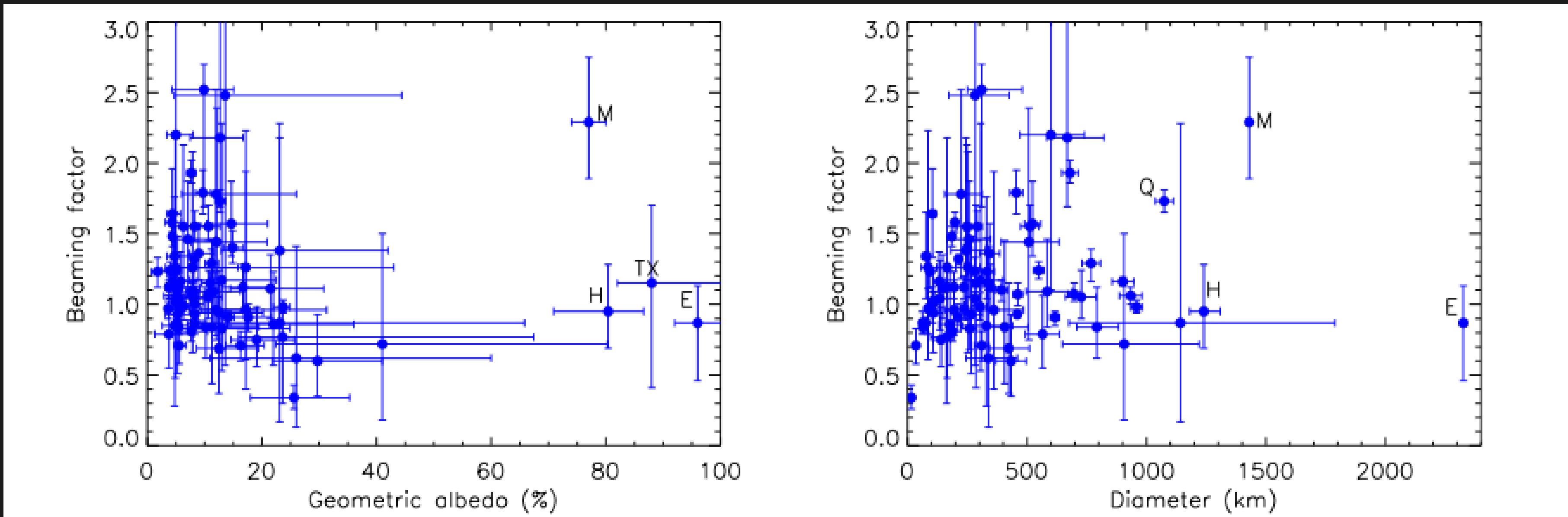
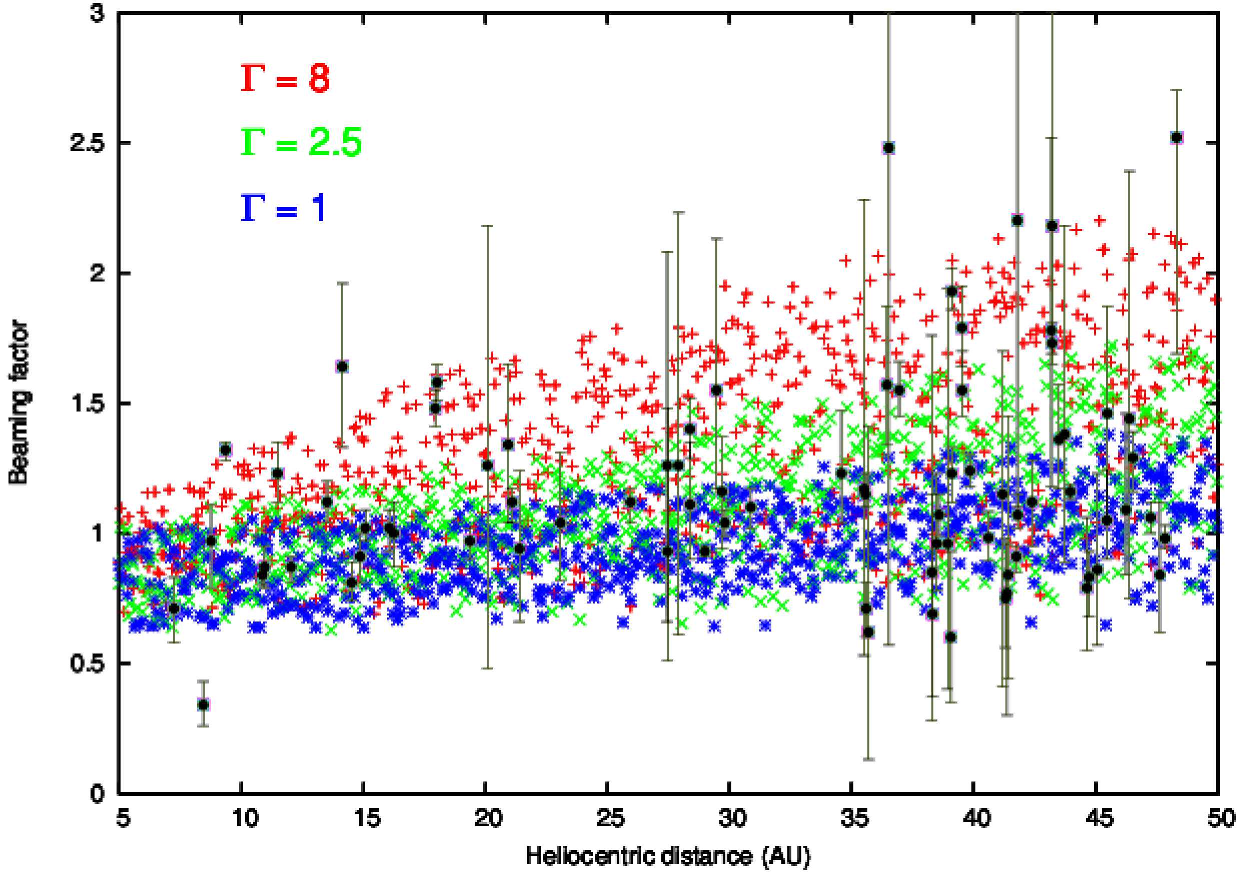


Fig. 2. Beaming factor η as a function of **Left:** geometric albedo and **Right:** diameter. Labels M, H, TX, E, Q refer to Makemake, Haumea, 2002 TX_{300}, Eris and Quaoar, respectively.

Lellouch 2013

Thermal Inertia from Beaming for TNOs



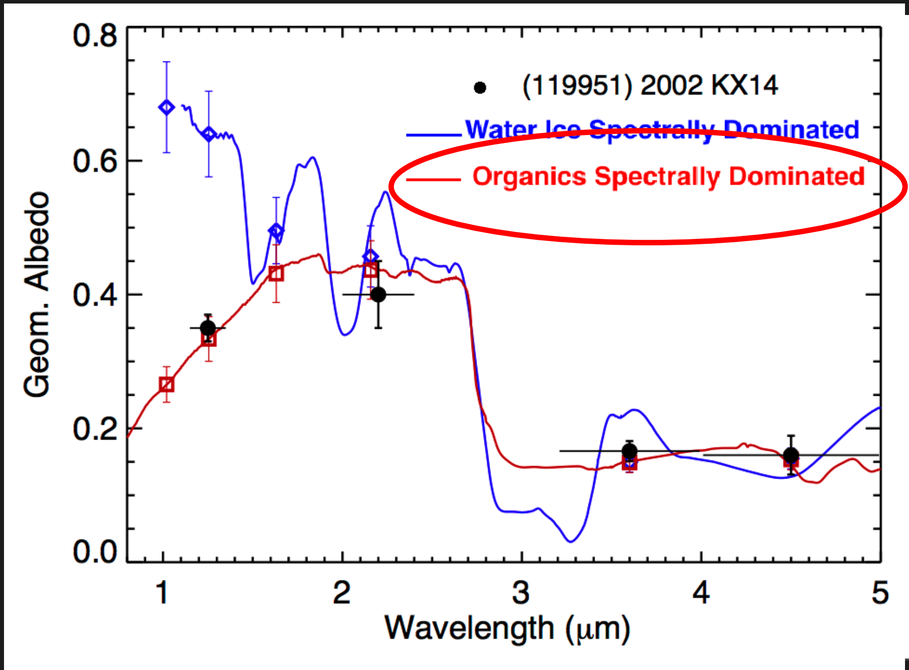
Lellouch 2013

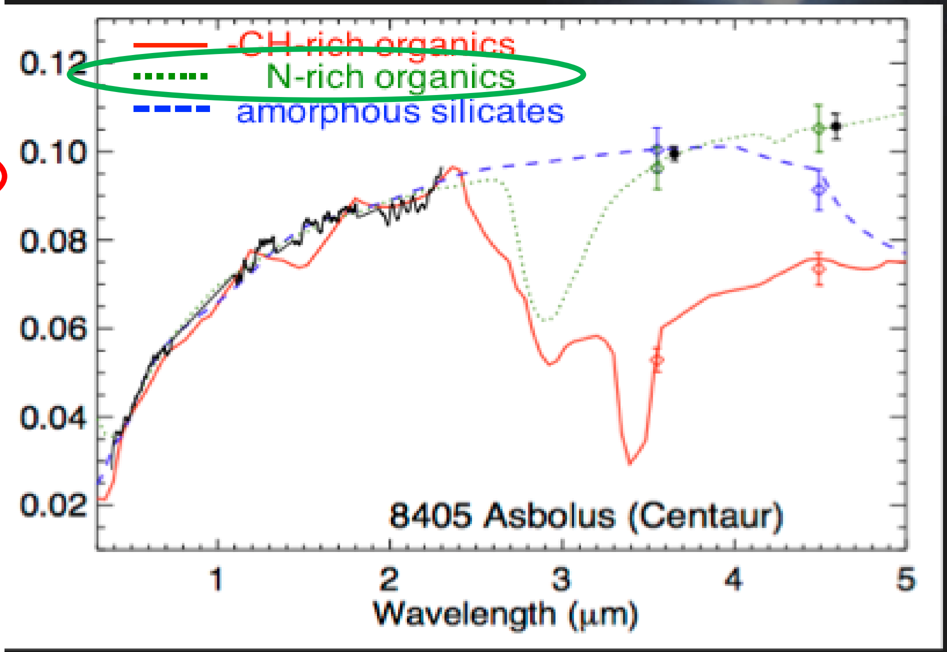
Fig. 11. Beaming factor η as a function of heliocentric distance r_h for the entire sample, compared with Monte-Carlo simulations assuming a rotation period of 8 h, a geometric albedo of 0.1, a uniform distribution of the polar axes on the sphere, and a random distribution of surface roughnesses. Thermal inertia $\Gamma = 1$, 2.5 and 8 MKS cases are shown here. Although $\Gamma = 8$ MKS may seem needed to account for the three points with $\eta = 1.5$-1.8 at 13-18 AU, this case underpredicts the number of small η values at $r_h > 25$ AU, and $\Gamma = 2.5$ MKS provides the overall best fit.

TNO Composition

Spitzer/IRAC Composition Constraints

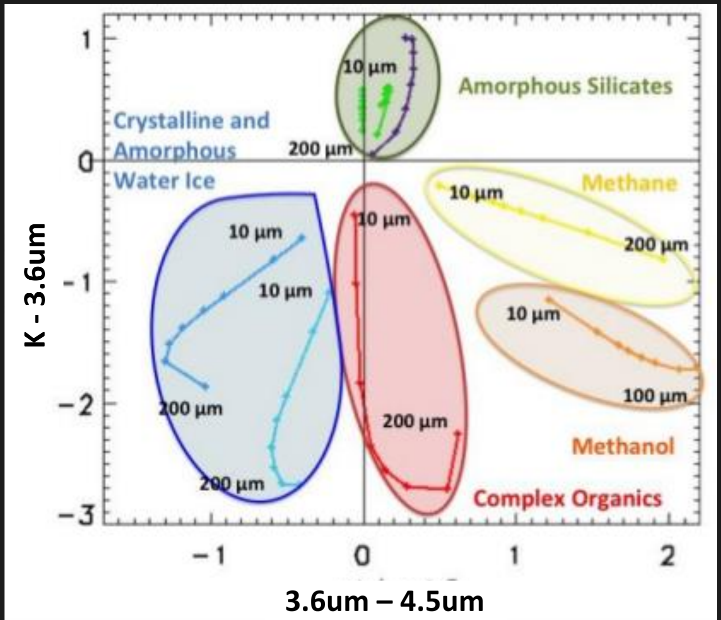
Figures courtesy of N. Pinilla-Alonso, *in prep.*

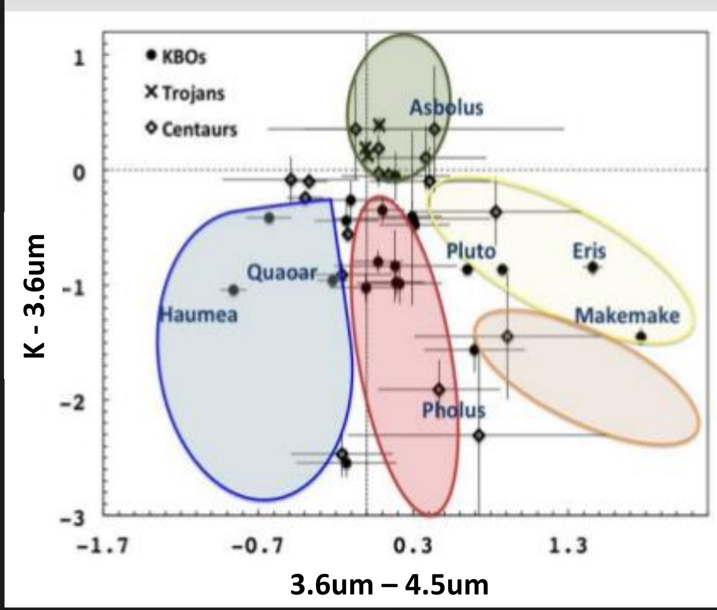




- IRAC 3.6 & 4.5 micron photometry + vis & nIR
  - Silicates, H2O, different kinds of organics can be differentiated
  - Molecular ices can as well (N2, CO, CO2, CH4)

Spitzer/IRAC: K/3.6/4.5 Composition Map

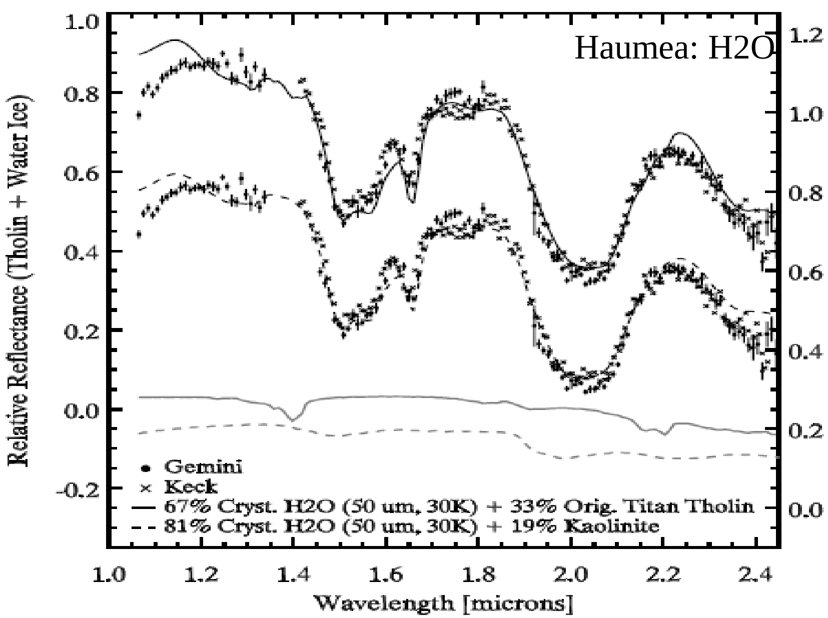


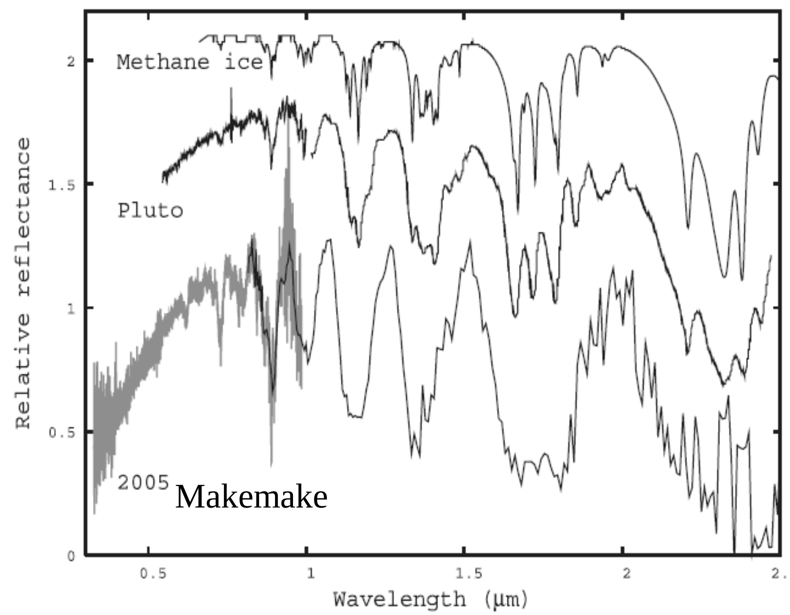


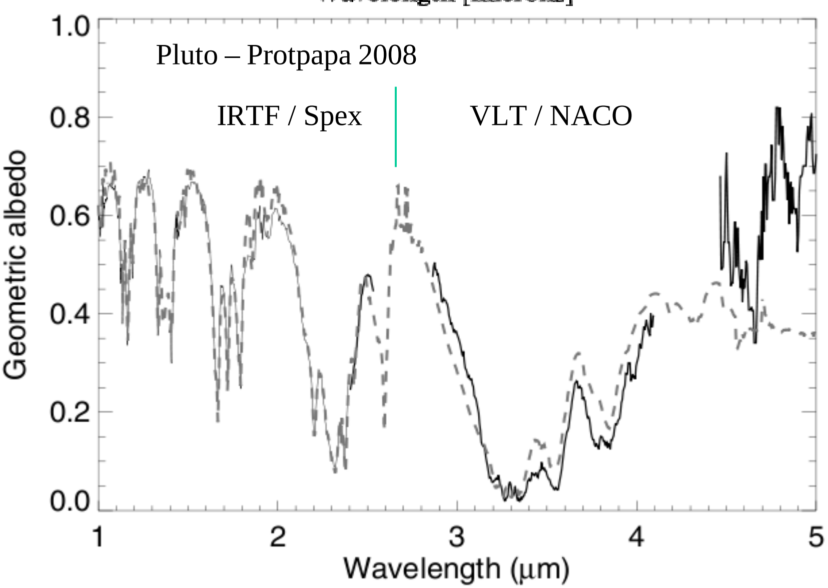
Figures courtesy of N. Pinilla-Alonso, *in prep.*
See also dalleOre 2015.

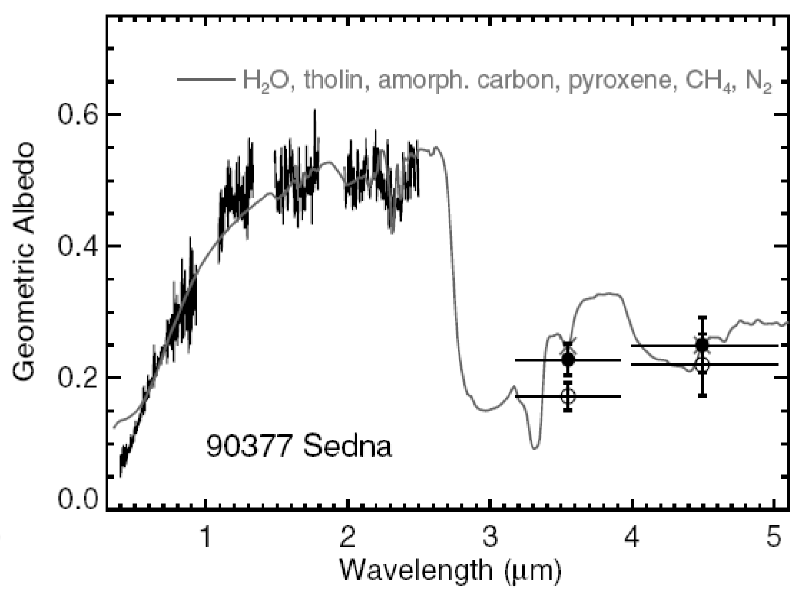
- Ice components map into unique regions in K + IRAC color/color space
- Much more Spitzer data available
  - ~50 KBOs + Centaurs w/ decent IRAC colors

TNO Dwarf Planets – Spectra







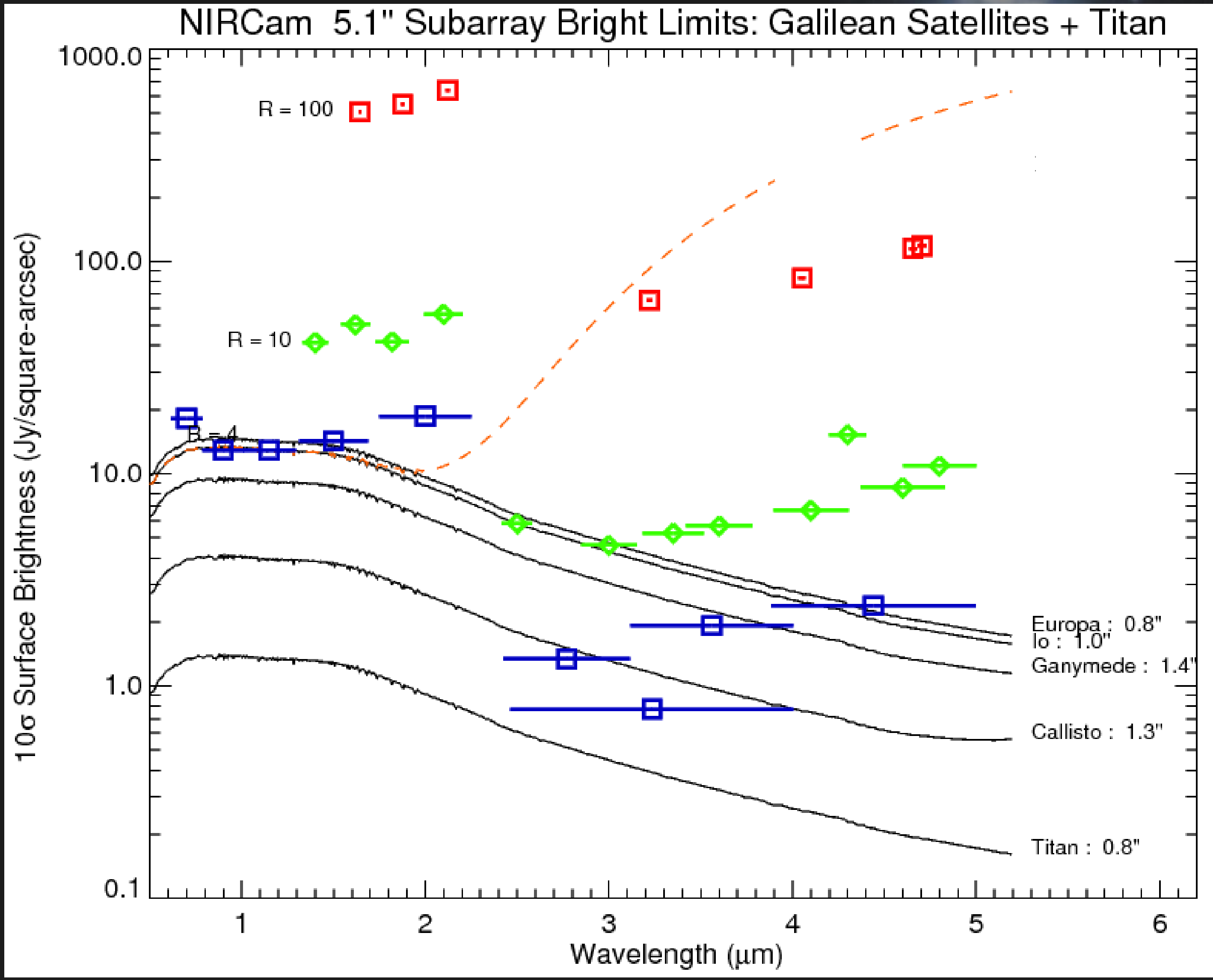


TNO Dwarf Planet spectra are dominated by molecular ices.

They, too, are red in the optical, probably due to organics (except Haumea?)

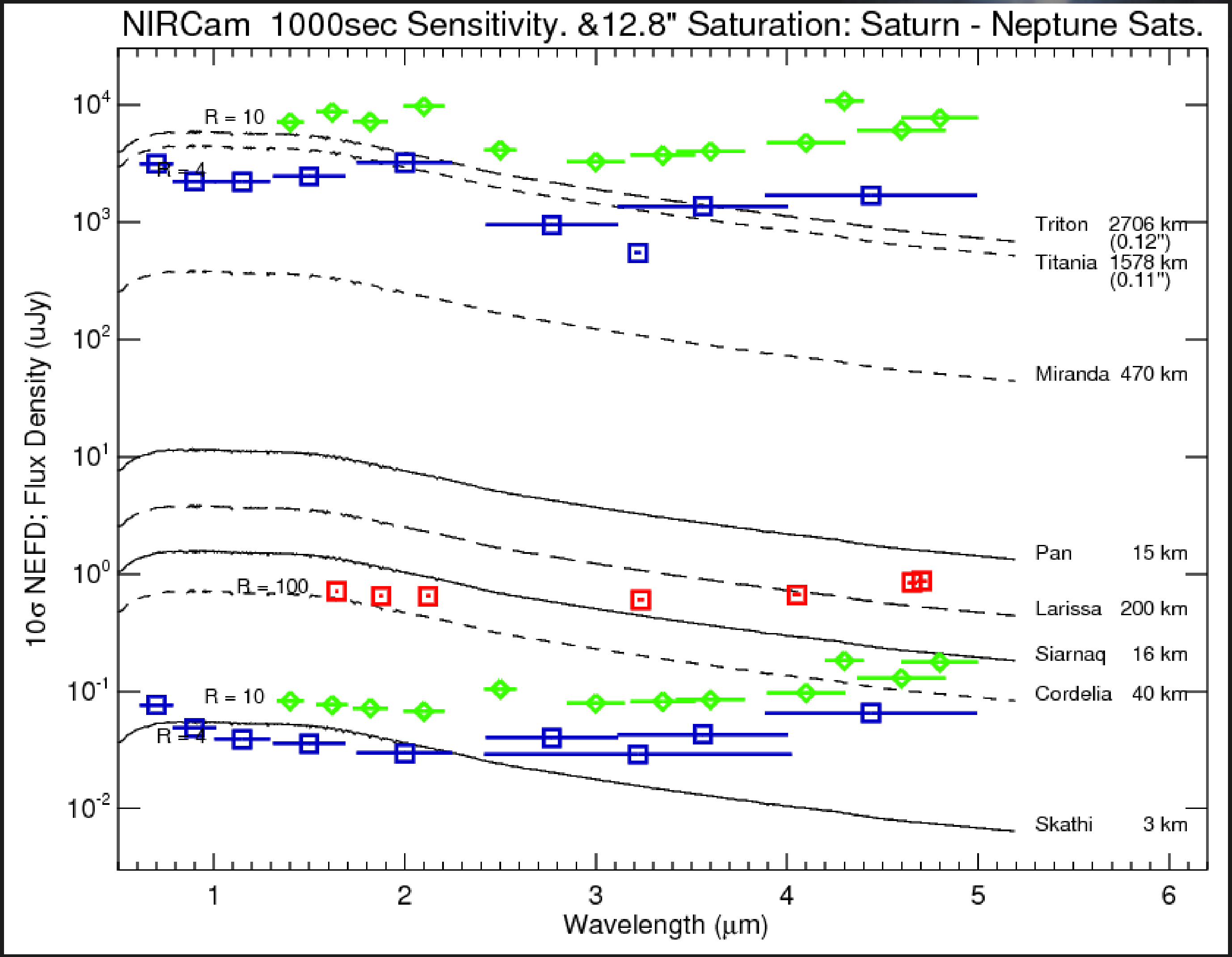
Resolved Satellite Imaging: NIRCam

- Well-resolved satellites
- 160^2 subarray bright limits

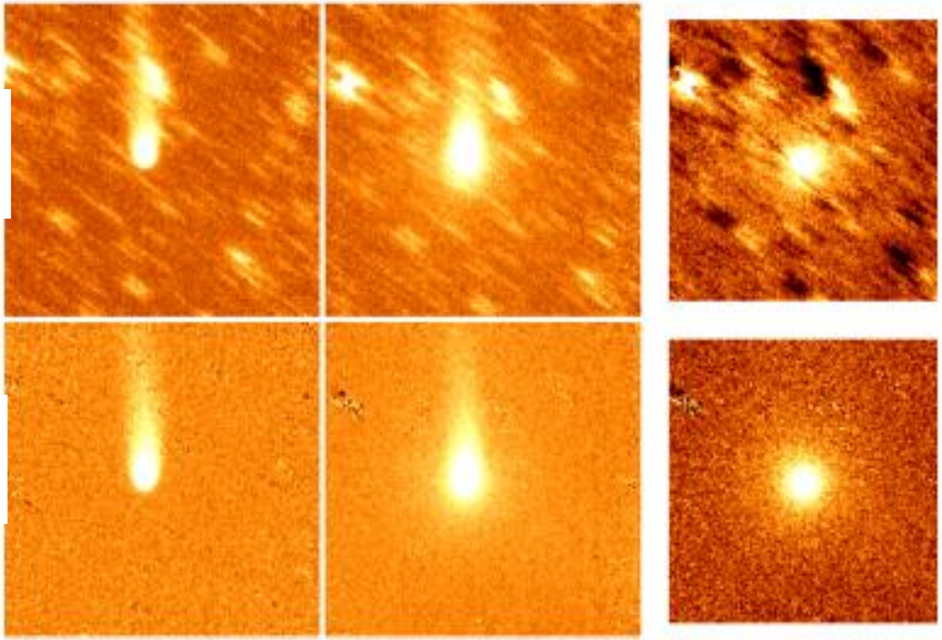


Satellite Photometry with NIRCam

- 400^2 subarray bright limits
- 1000 second exposure sensitivity



Activity in Distant Comets and Centaurs

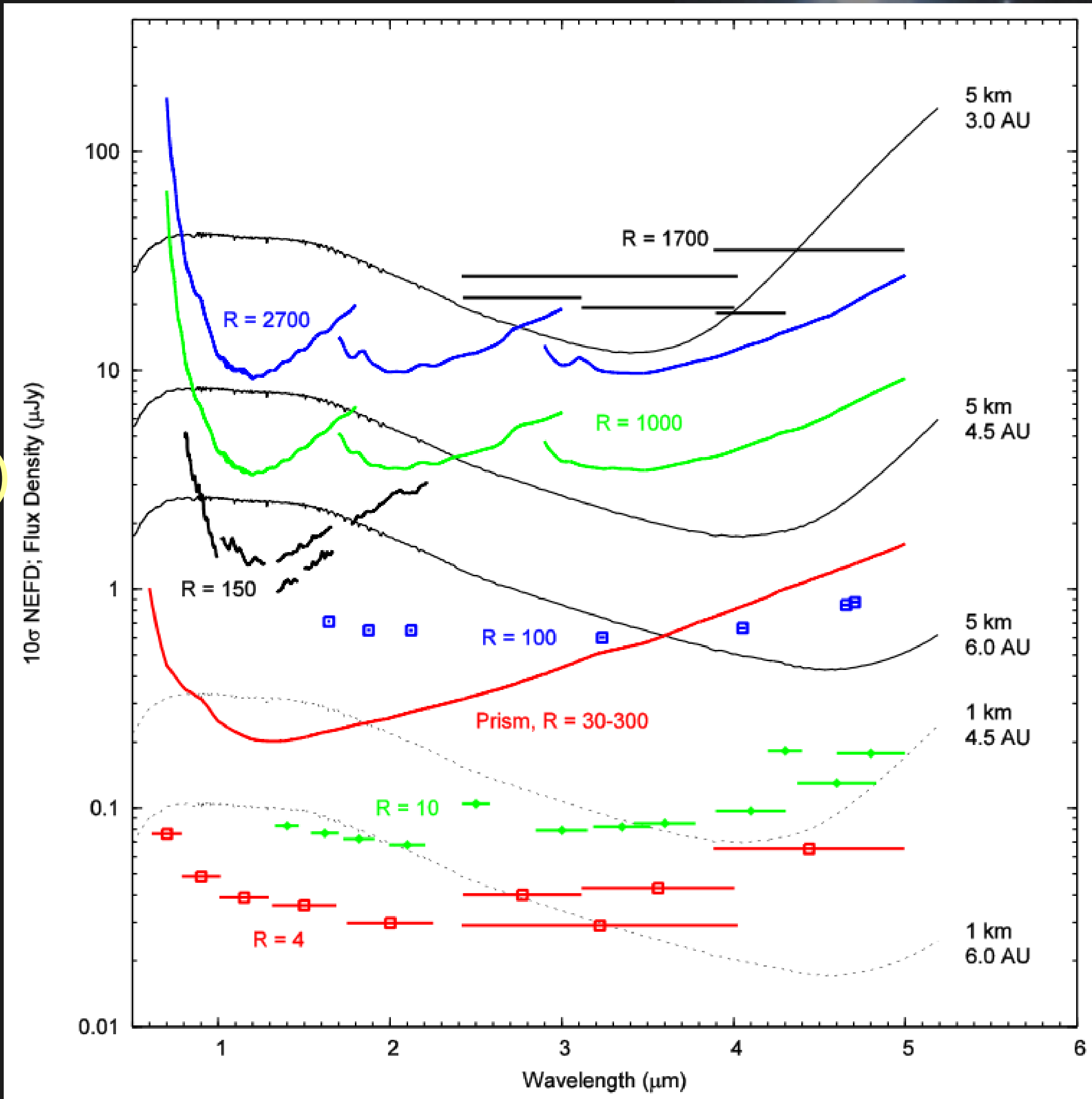


Courtesy of Mike Kelley, UMD

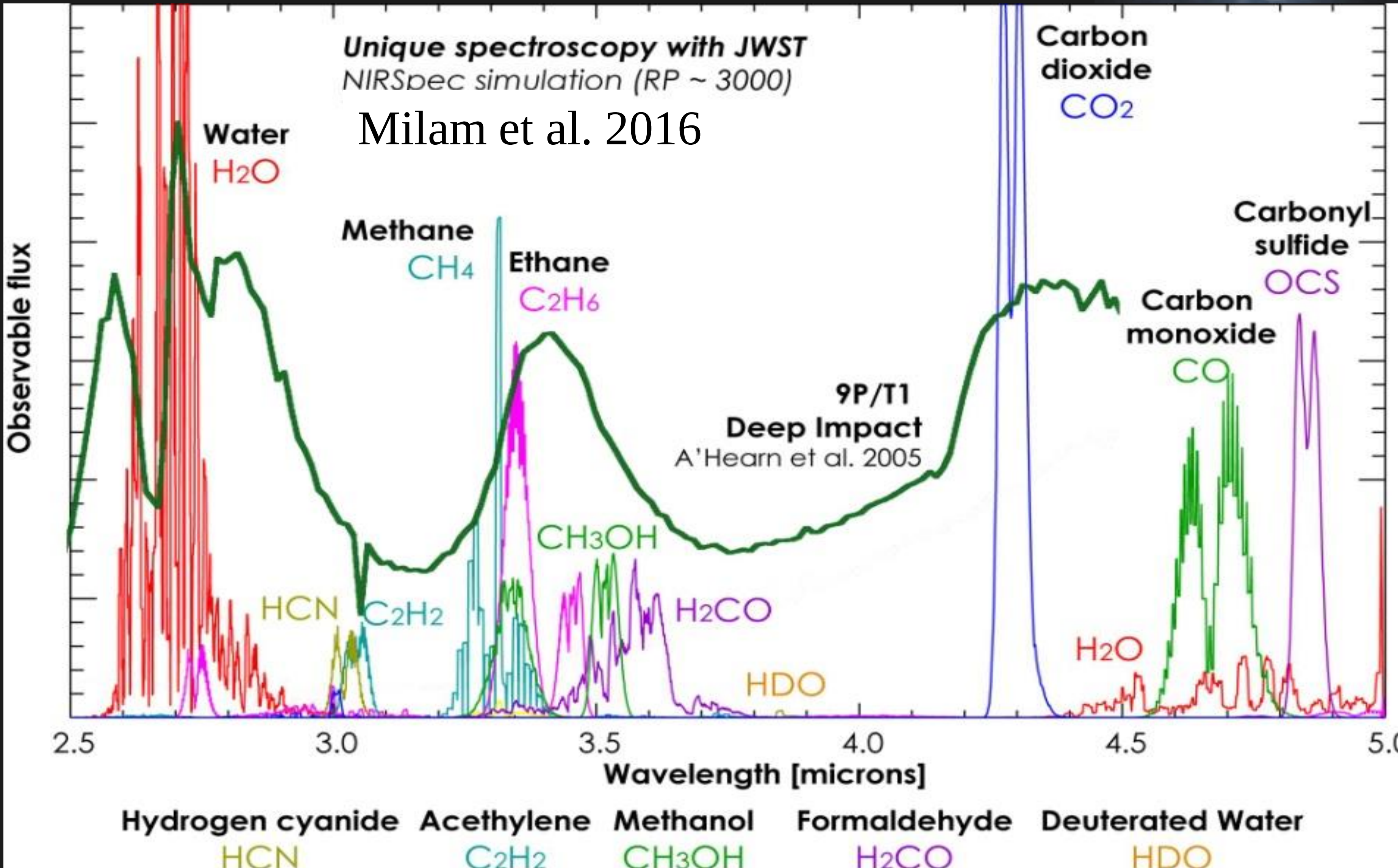
Figure 1: *Spitzer*/IRAC images of comet C/2013 A1 (Siding Spring) taken 2014 March 26 (r_h=3.1 AU, 30-s exposures, 47 repeats, Galatic latitude = -65 deg). Top left: 3.6-µm median-combined mosaic (dust). Top center: 4.5-µm median-combined mosaic (dust+gas). Top right: 4.5-µm gas coma after dust subtraction. Bottom row: the same images, but after subtracting the shadow observation (i.e., stellar background). The shadow observation greatly improves the data quality. The derived gas fluxes are similar for the two techniques, but our ability to examine the morphology of the coma in the original data is nearly lost due to background contamination.

Cometary Nuclei with NIRSpec & NIRCam

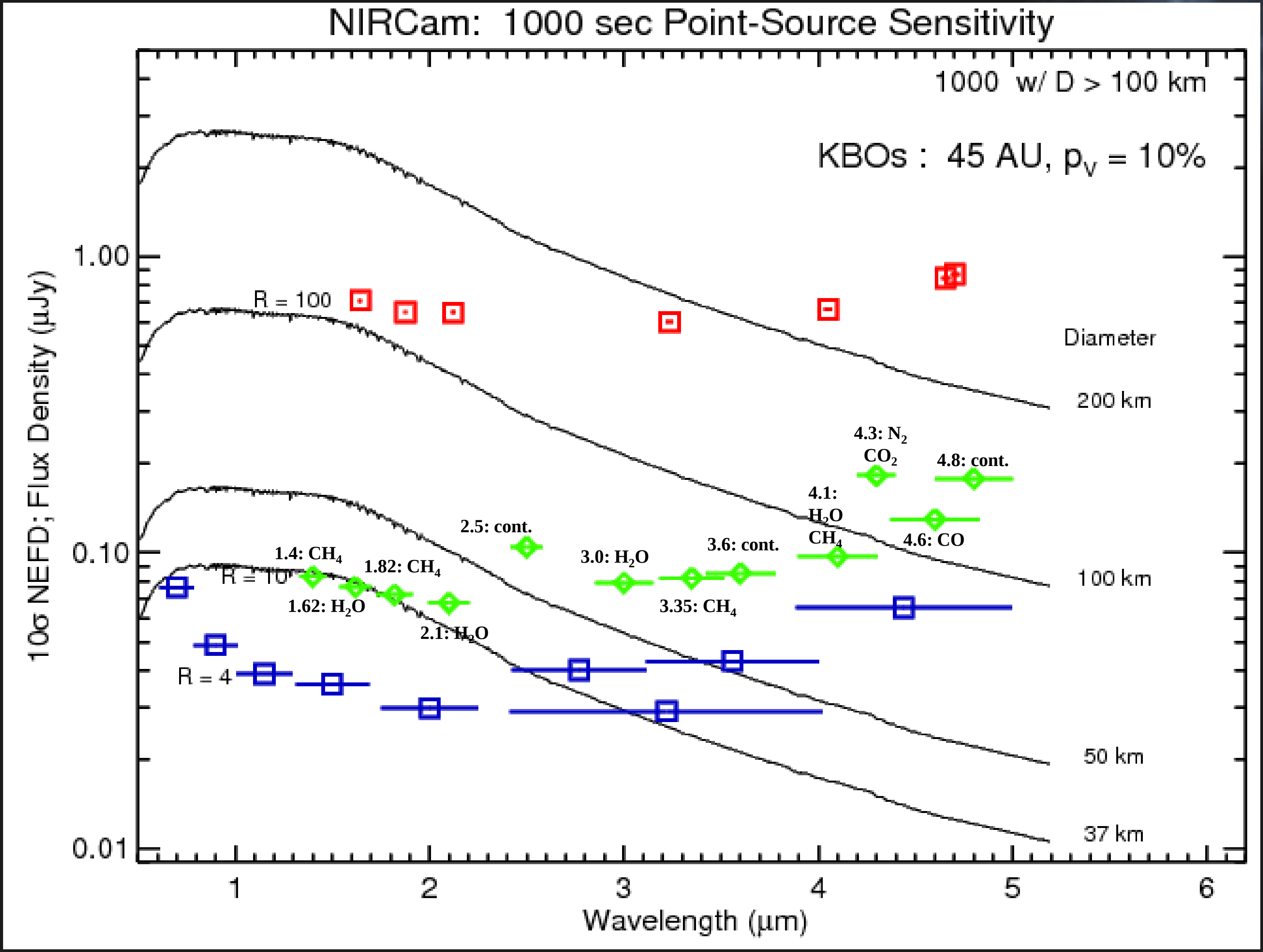
- Comets can be studied throught the 1-5 um region
- High sensitivity (1000 sec sensitivities shown)
- At distances where H2O is unlikely to drive activity



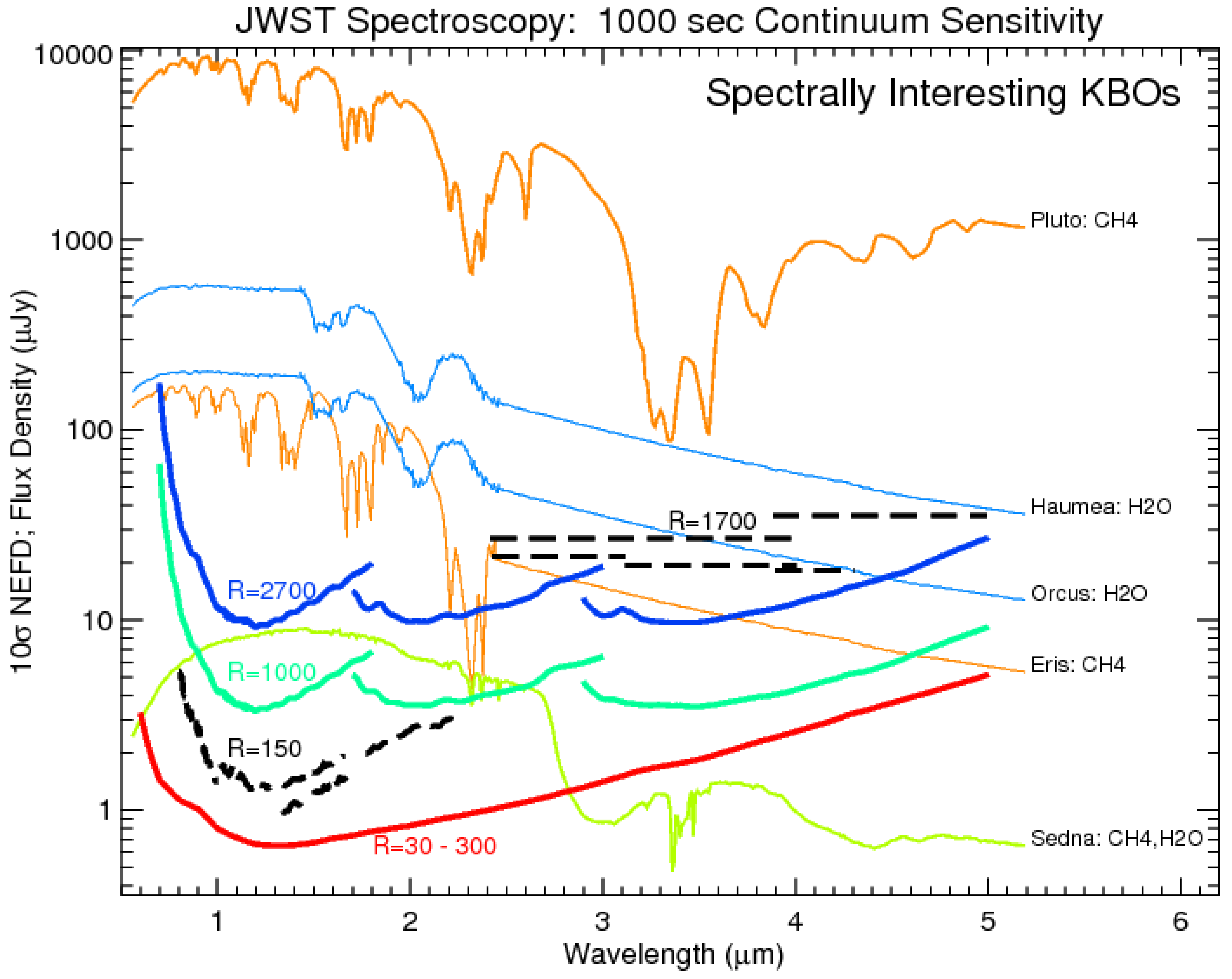
Simulated Comet Spectra



KBO Photometry with NIRCam

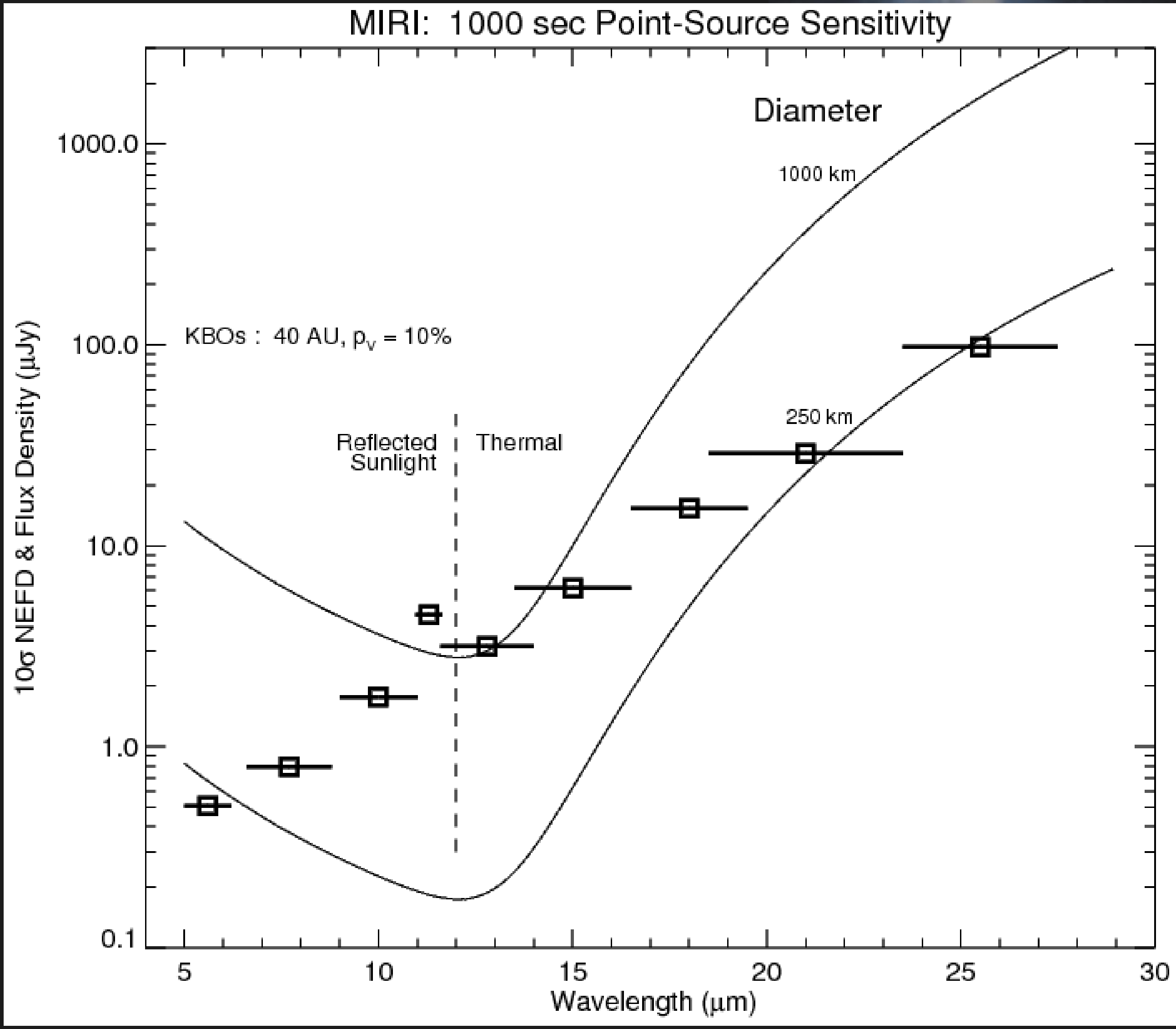


KBO Spectroscopy with NIRSpec



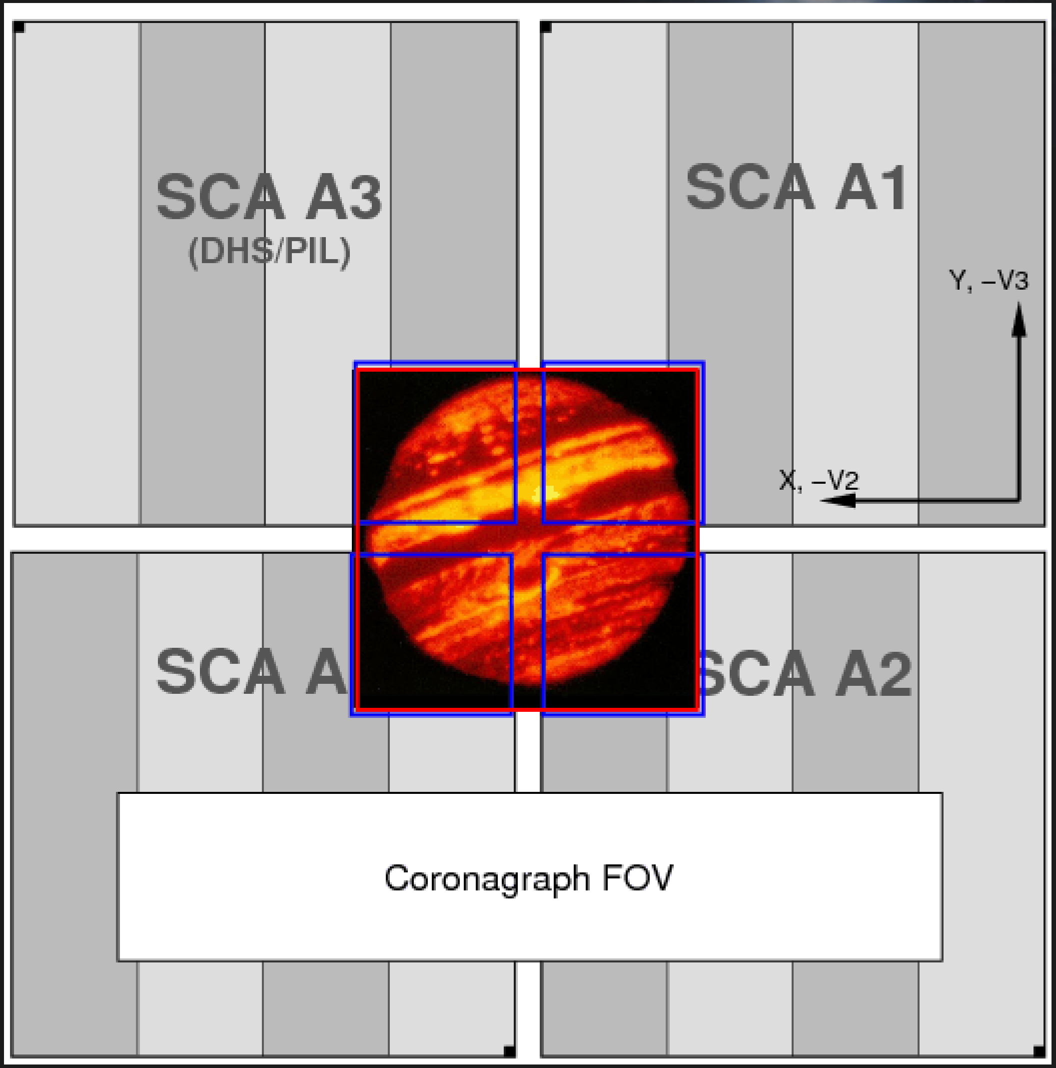
KBO Thermal Radiometry with MIRI

- MIRI can measure temperature distributions for quite small KBOs
- Sensitivity well matched to that of ALMA
- Valuable for
  - Thermal inertia
    - Composition
    - Regolith structure
  - Emissivity
  - Albedo
  - Diameter



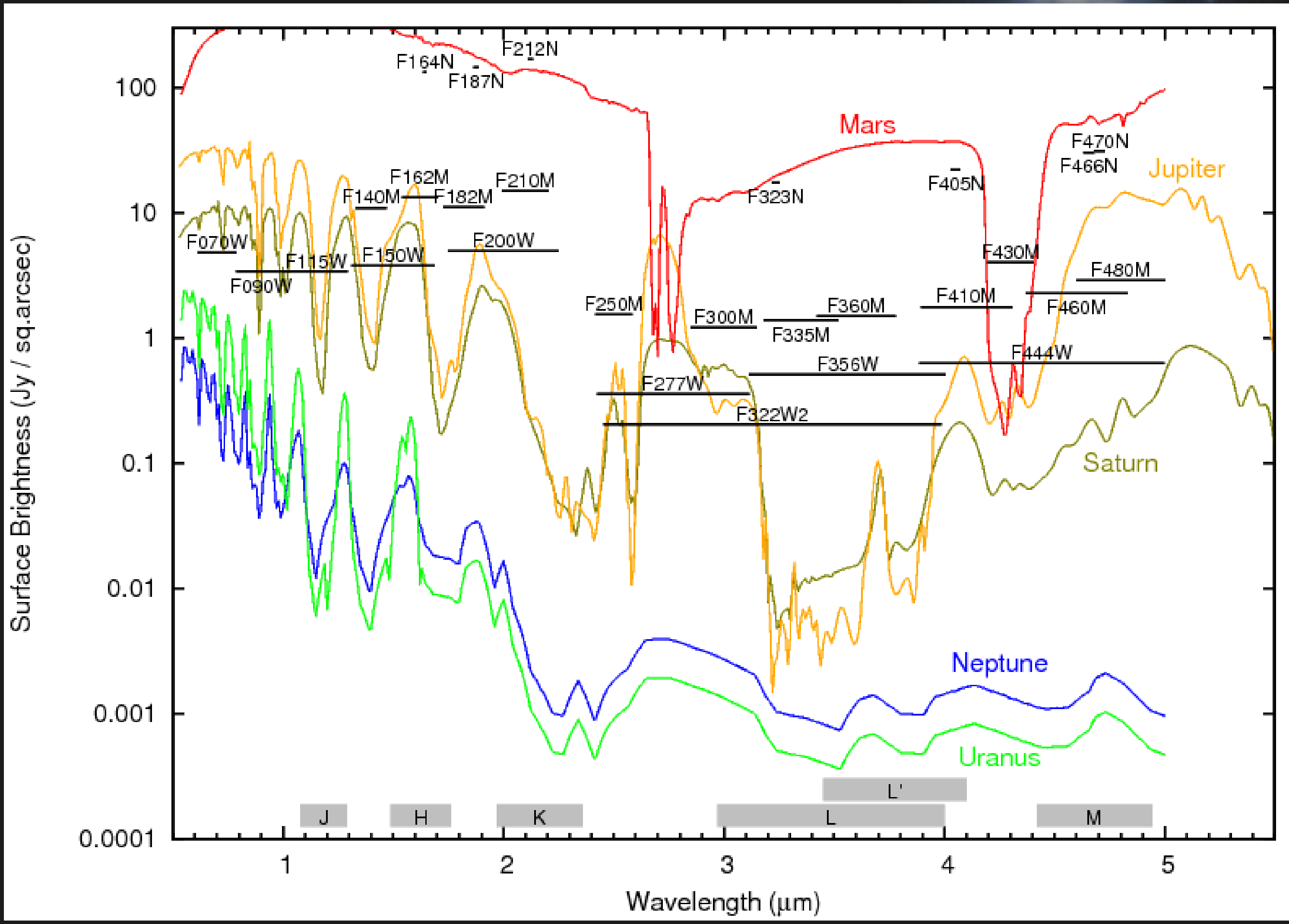
JWST Capabilities: Giant Planets Imaging

- NIRCam Subarrays
  - short integration times
  - Significant FOV
  - Simultaneous 0.6-2.3 (shortwave) and 2.4-5 (longwave) coverage
    - Matched FOVs
  - Smaller subarrays available: 640^2 (shown), 320^2, 160^2
  - Dithers fill detector gaps in the short-wave channel

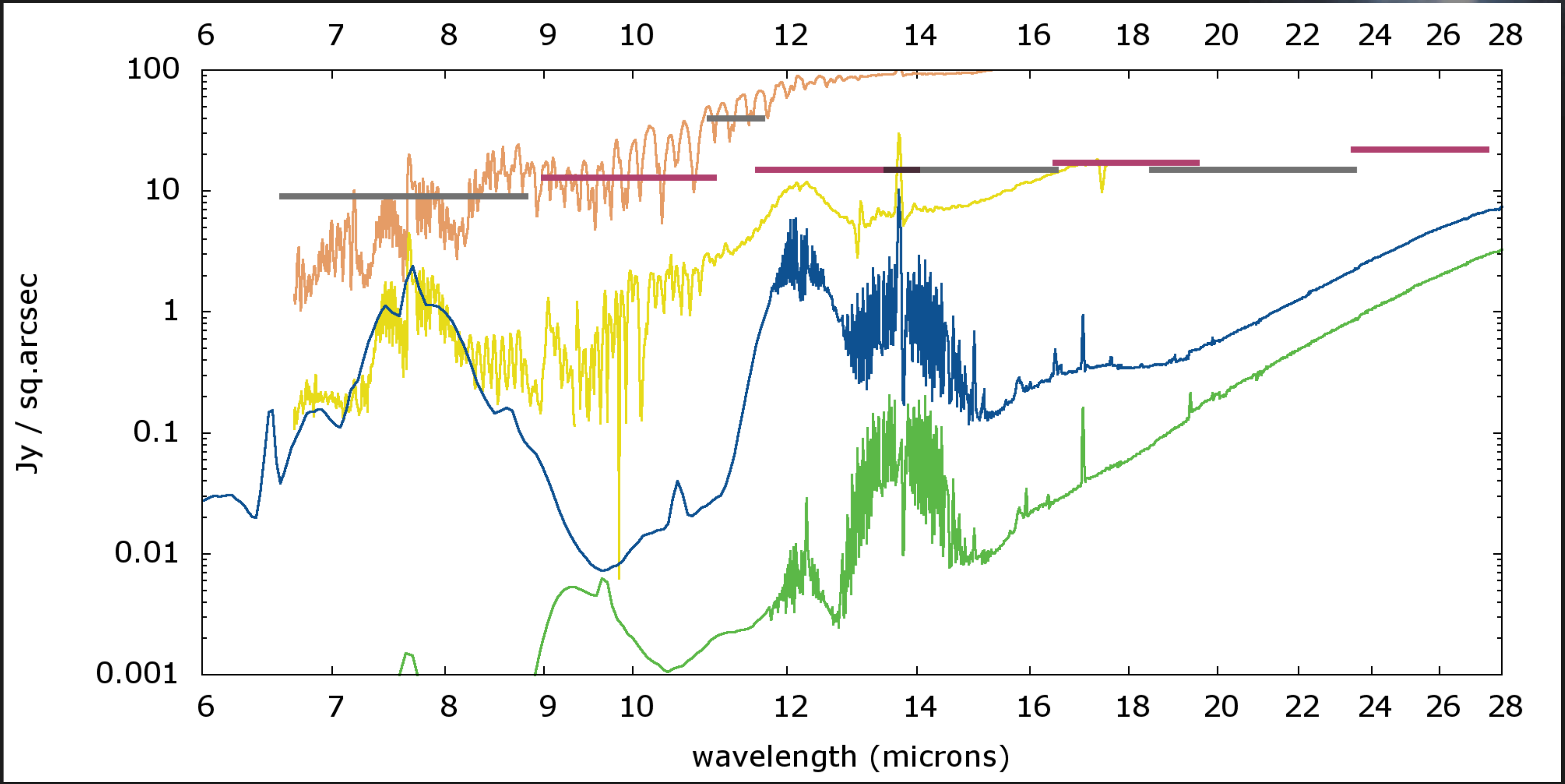


Giant Planet Imaging with NIRCam

- Bright limits for 640x640 subarrays
- 160x160 limits are 15x higher

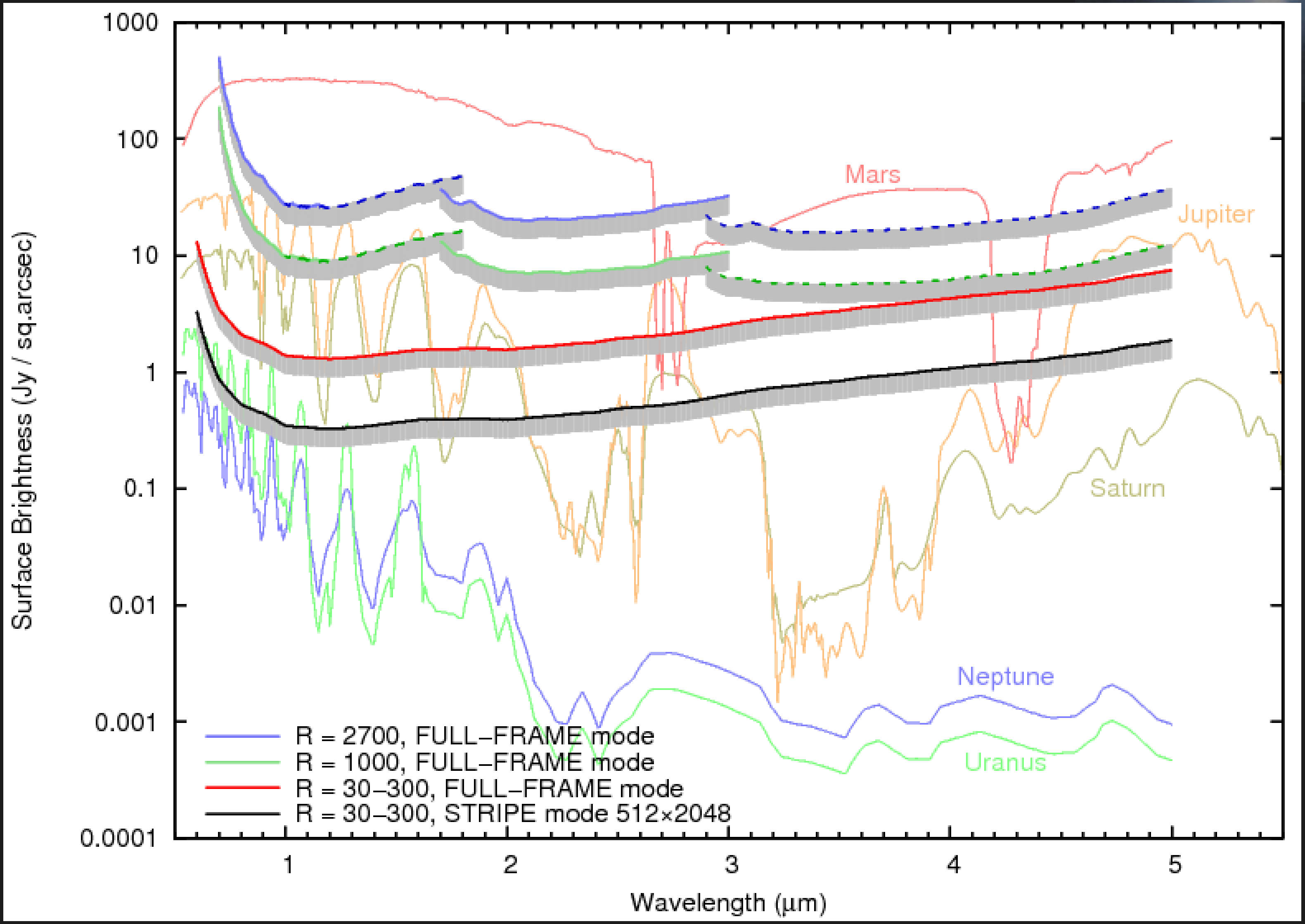


Giant Planet Imaging with MIRI



- Bright limits for 64x64 subarrays (6.4” FOV)
- MIRI IFU spectroscopy limits are ~100x higher

Giant Planet Spectroscopy: NIRSpec IFU



PASP Special Issue

(Jan 4, 2016)

Innovative Solar System Science with the James Webb Space Telescope

Stefanie Milam, Special Editor

http://iopscience.iop.org/1538-3873/128/959

11 topical papers

http://iopscience.iop.org/1538-3873/128/960

1 high-level paper (Norwood et al.)

10 JWST Solar System Focus Groups

(and 11 papers! http://iopscience.iop.org/1538-3873/128/959

- **Asteroids** (Andy Rivkin, JHU/APL)
- **Comets** (Chick Woodward, U. Minnesota)
- **Giant Planets** (Jim Norwood, NMSU)
- **Mars** (Geronimo Villanueva, GSFC)
- **NEOs** (Cristina Thomas, GSFC)
- **Occultations** (Pablo Santos-Sanz, IAA-CSIC, Spain)
- **Rings** (Matt Tiscareno, Cornell)
- **Satellites** (Laszlo Kestay, USGS)
- **Titan** (Conor Nixon, GSFC)
- **TNOs** (Alex Parker, SwRI)
- JWST Solar System Capabilities (Milam, GSFC)

How will we Continue to Explore TNOs?

JWST and future space-based
(SPICA? FIRST? UVOIR?)
and large ground-based
observatories will be the way.