# Water, Hydroxyl, and Ice in the Asteroid Belt

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JHU/APL

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SOFIA Community Task Force Tele-talk

# Outline

- A bit of setup
- The L-band Main-belt/NEO Observing Program (LMNOP)
  - Some initial results
  - Toward a taxonomy of hydrated minerals on asteroids
- Where SOFIA comes in

# Collaborators and Fellow Travelers

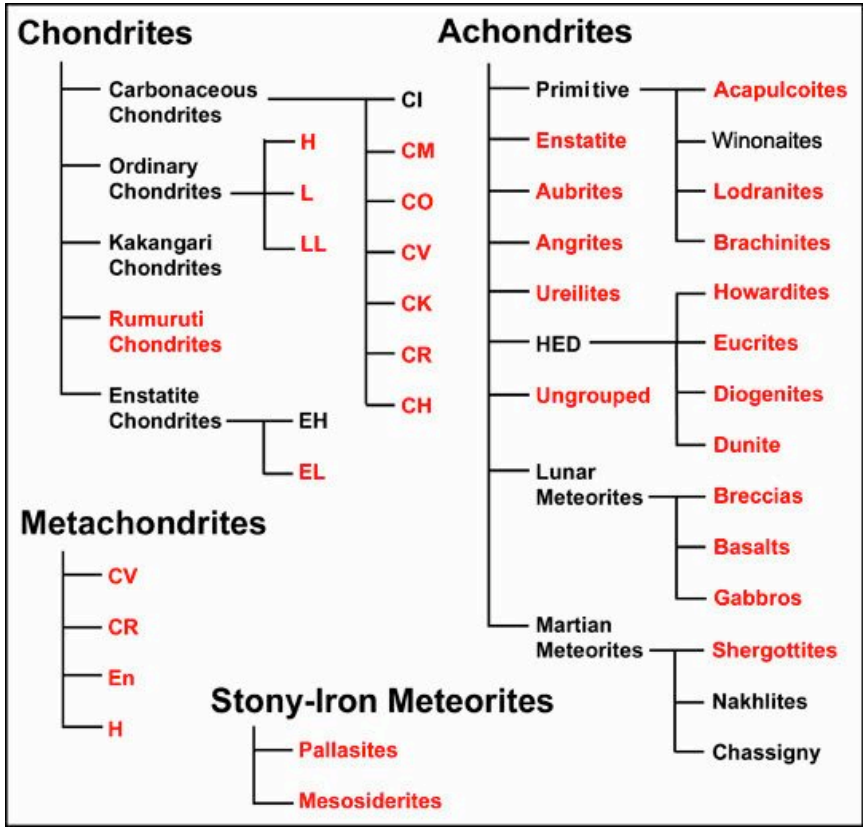
- Josh Emery
- Humberto Campins
- Julie Castillo-Rogez
- Eric Volquardsen
- Ralph Milliken
- Lucy Lim
- Ellen Howell

# Meteorites: the original sample return

- $10^8$ kg of mass accreted/year
- 50,000-100,000 falls of 10 g or more
- Impact of ~m-sized object ~every year

# Meteorite Classification

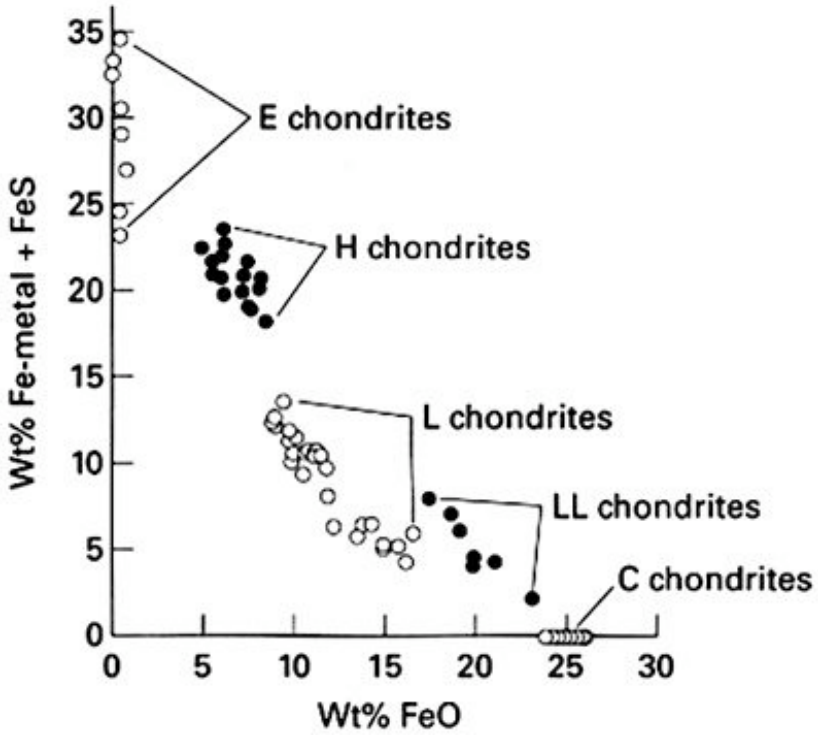
- Two main groupings:
  - Chondrites: (relatively) pristine, unprocessed, undifferentiated
  - Achondrites: products of melting, igneous rocks, differentiated
- Chondrites > 85% of falls




From NAU Meteorite Laboratory (http://www4.nau.edu/meteorite/)

# Chondrites

- Four types of chondrites, differing in O isotopes, exact elemental ratios
- 90% of chondrites classified as ordinary chondrites
- Carbonaceous chondrites 5% of chondrite total
- CC generally considered closest matches to solar

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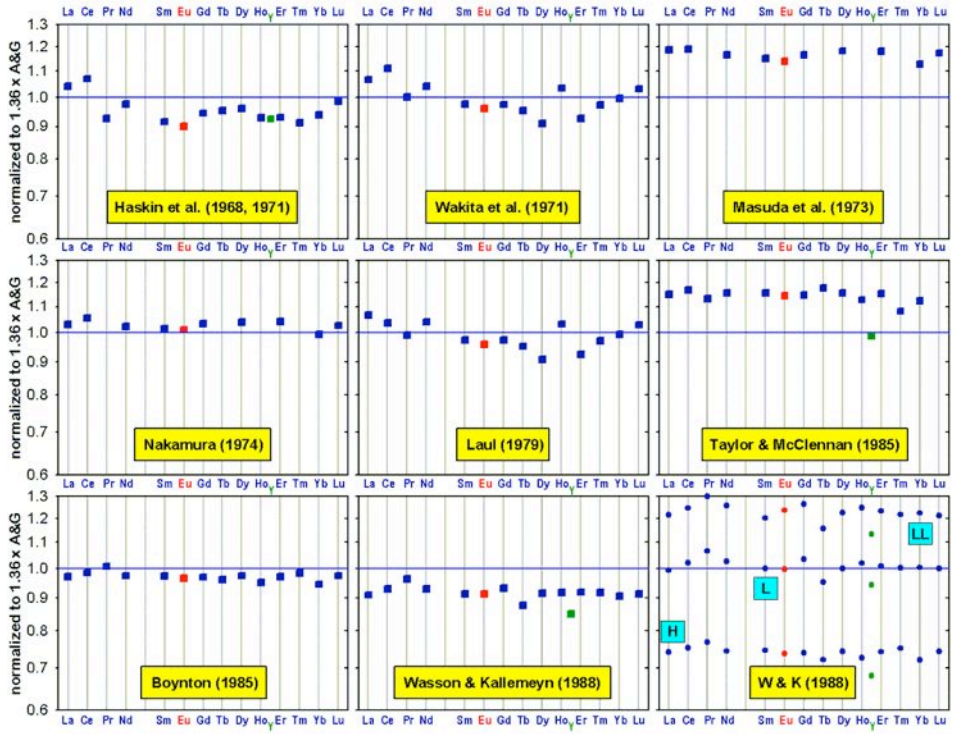
# Chondrites as planetary ingredients

- Elemental abundances good match to solar for rock-forming elements
- Mineral composition match to nebular condensation expectation
- Textures (etc.) consistent with low-T history
- Contain CAIs, oldest solar system solids
- *Chondrites representative original starting material of inner solar system*
- (Chondrites representative of rocky portions of outer solar system objects, too!)




REE patterns compiled by Korotev (meteorites.wustl.edu/goodstuff/ree-chon.htm)

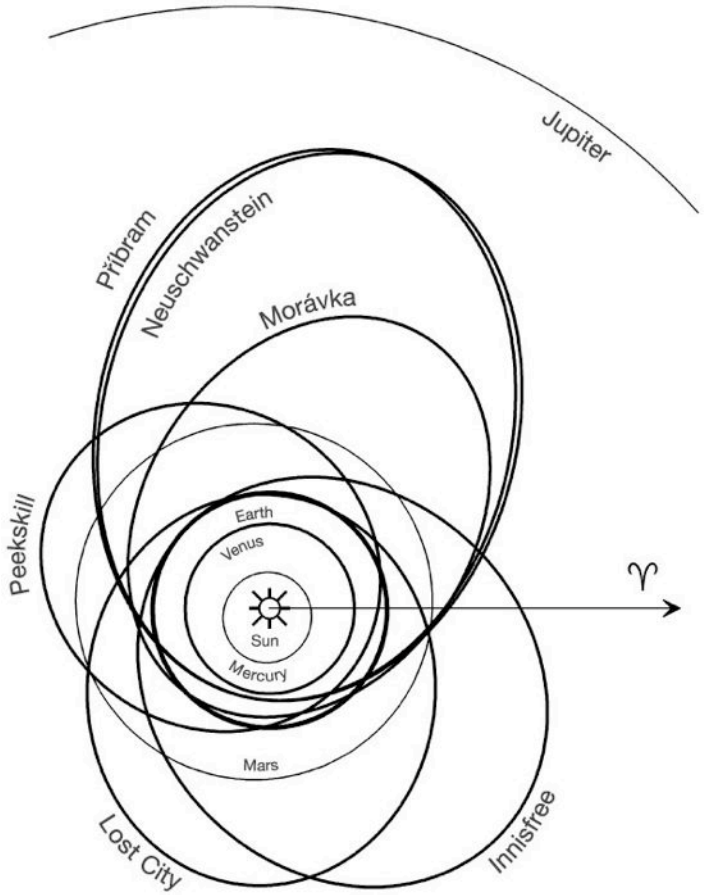
# Carbonaceous chondrites

- The most primitive materials in the meteorite collection*
- Many (most?) aqueously altered, formed beyond ice line
- CM abundant hydrated minerals, ~10% $H_2O$ (or equivalent in OH) by weight
- CI practically all hydrated minerals, up to 20% $H_2O$ by weight
- Also, organic material including amino acids


*by some measure of “primitiveness”

# Identifying meteorite parent bodies

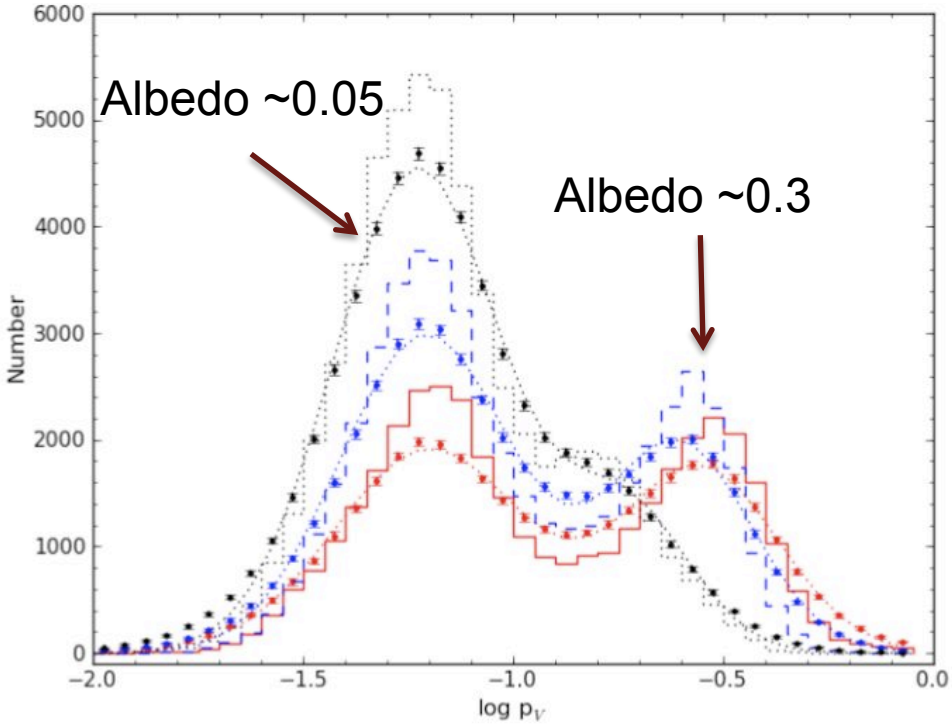
- Immediate parents = NEOs
- NEO orbits evolve from main asteroid belt
- Fireball tracks match asteroid belt orbits
- *Remote sensing/lab spectroscopy to make further links*
- (Moon, Mars special cases)
- Some material may be too weak to survive passage from main belt to NEO, or from NEO to Earth.
- **Organic, water-rich objects high priority for NASA (ESA, JAXA, RSA…) sample return**




Spurny et al. (Nature, 2003)

# The prevalence of carbonaceous material

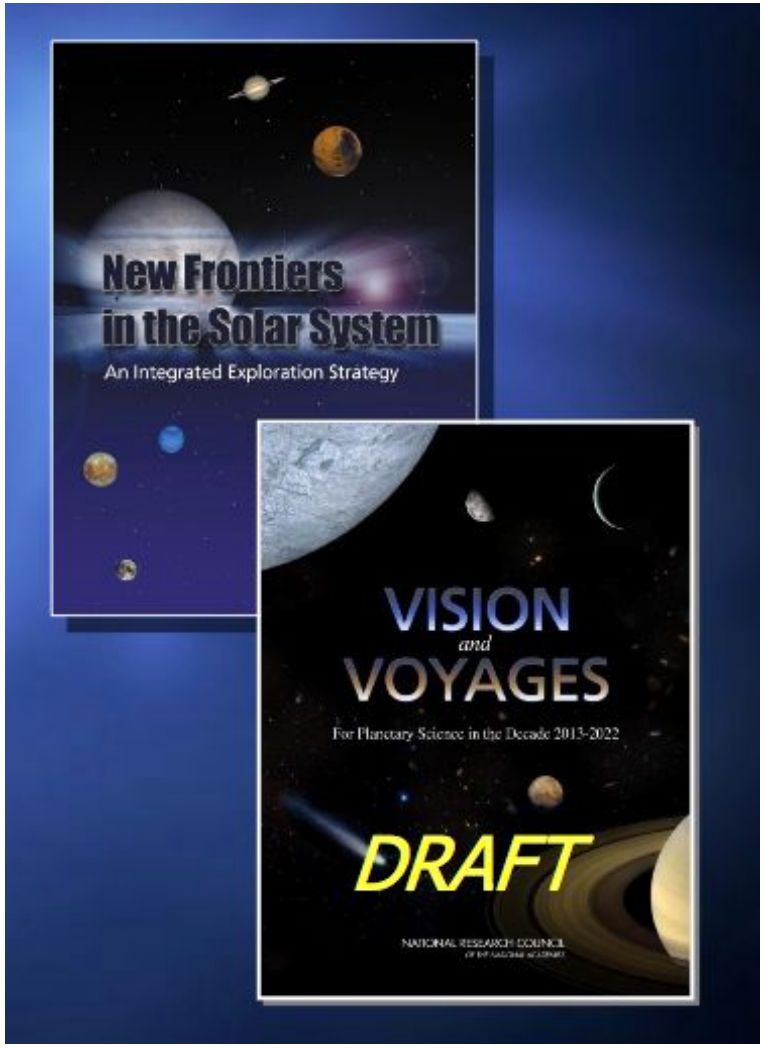
- Evidence suggests low-albedo asteroids dominate asteroid belt
- Carbonaceous material dominates IDP population
- However, carbonaceous chondrites are rare falls (~5%)
  - There's reason to believe some are too fragile to survive passage to Earth




Masiero et al. 2011: WISE data

# Carbonaceous Chondrites, Hydrated Minerals, and the People Who Love Them

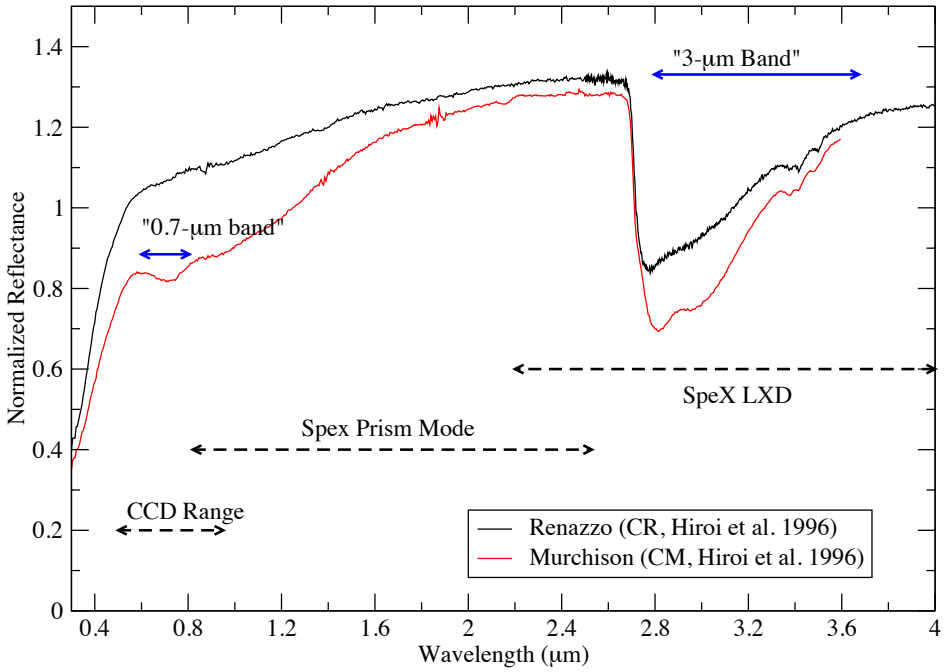
- Sample return from a water/ organics-rich C chondrite high scientific priority, in the works for ISAS, NASA. Finalist for ESA.
- Recent dynamical models suggest carbonaceous material may have been delivered from outer solar system
- Missions are expensive, rare, fail (sorry, Russia)
- Remote sensing required for reconnaissance, plus data for vast majority of objects



# Spectroscopic Detection of Hydrated Minerals in Asteroids

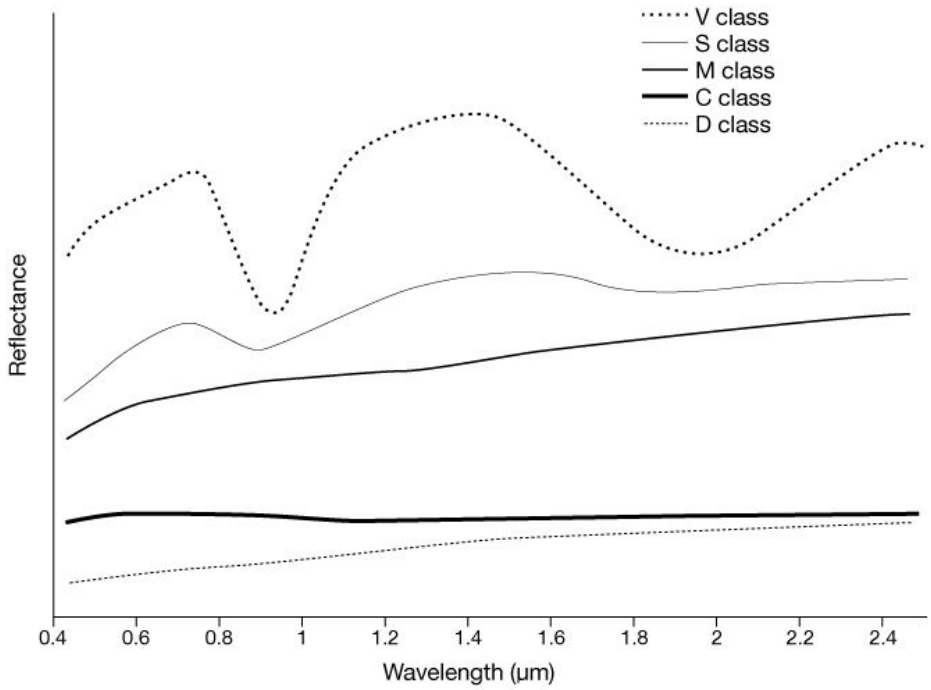
- Two important spectral regions

1. 3-µm Region
   - 2.7 µm OH fundamental
   - ~3.0 $H_2O$ overtone
   - Few suitable observing sites
2. 0.7-µm band
   - $Fe^{2+}$-$Fe^{3+}$ charge transfer band
   - Seen in some phyllosilicates
   - Good correlation with some groups



# Asteroid Taxonomy (in a small number of bullets)

- Three main "complexes" and handful of outlying classes
- Defined using 0.4-1.0 µm data, starting to incorporate to 2.5 µm
- Longer wavelengths: OH/ $H_2O$, other volatiles
- Carbonaceous chondrites associated with C complex
- Comet nuclei usually D class



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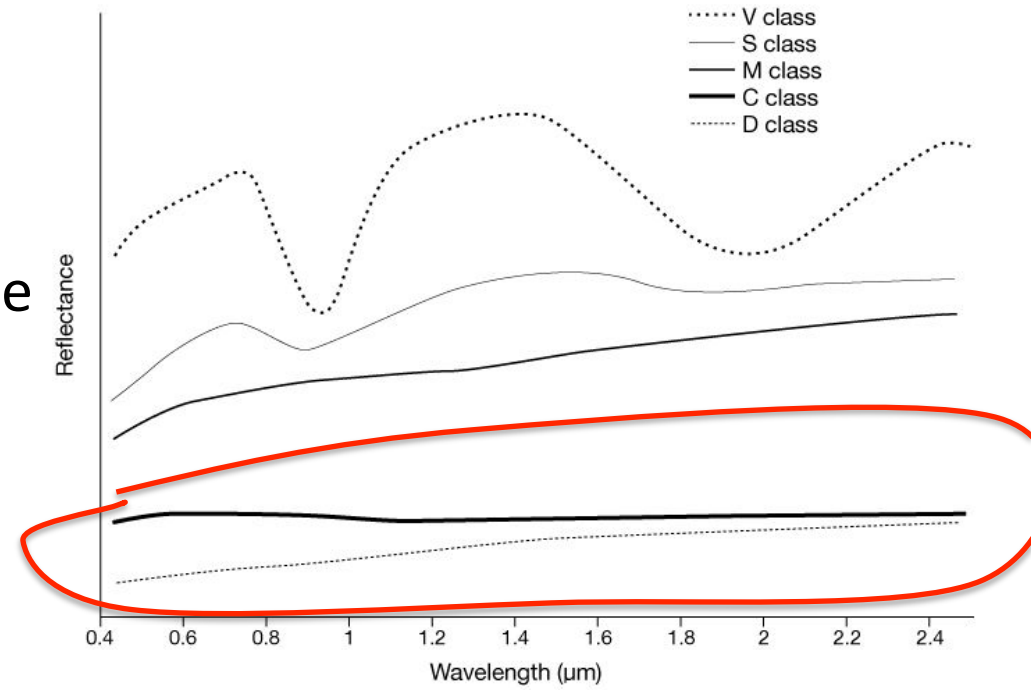
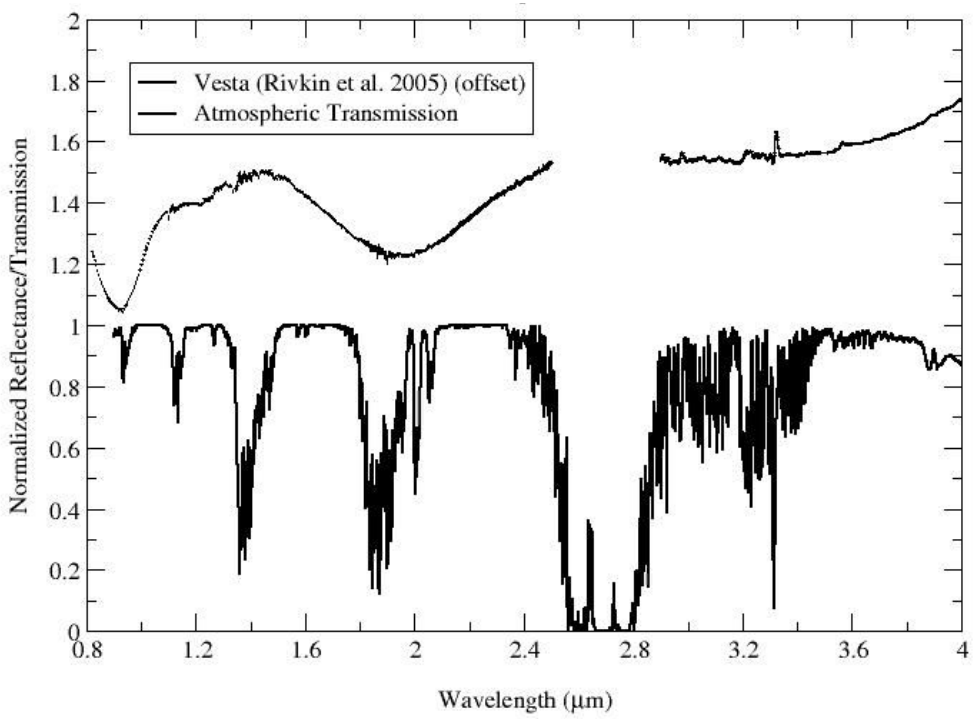


# Observing in the 3-µm Region

- While 0.7-µm band is useful *not diagnostic*
- Strong absorptions in 3-µm region from interesting species
  - OH ~2.7 µm
  - $H_2O$ ~2.9-3.0 µm
  - CH ~3.3-3.4 µm
  - $CO_2$, $CH_4$, $NH_3$, carbonates…
- Earth's atmosphere limits observing sites
- New instruments, new reduction pipelines ⟶new opportunities!



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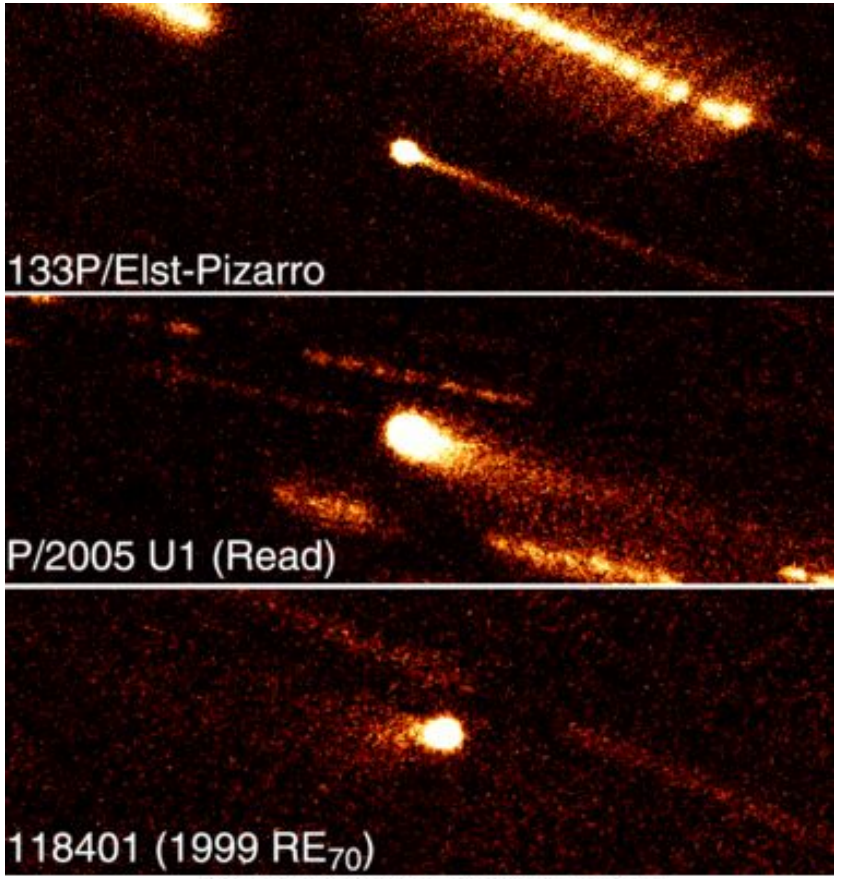
# “Main Belt Comets”

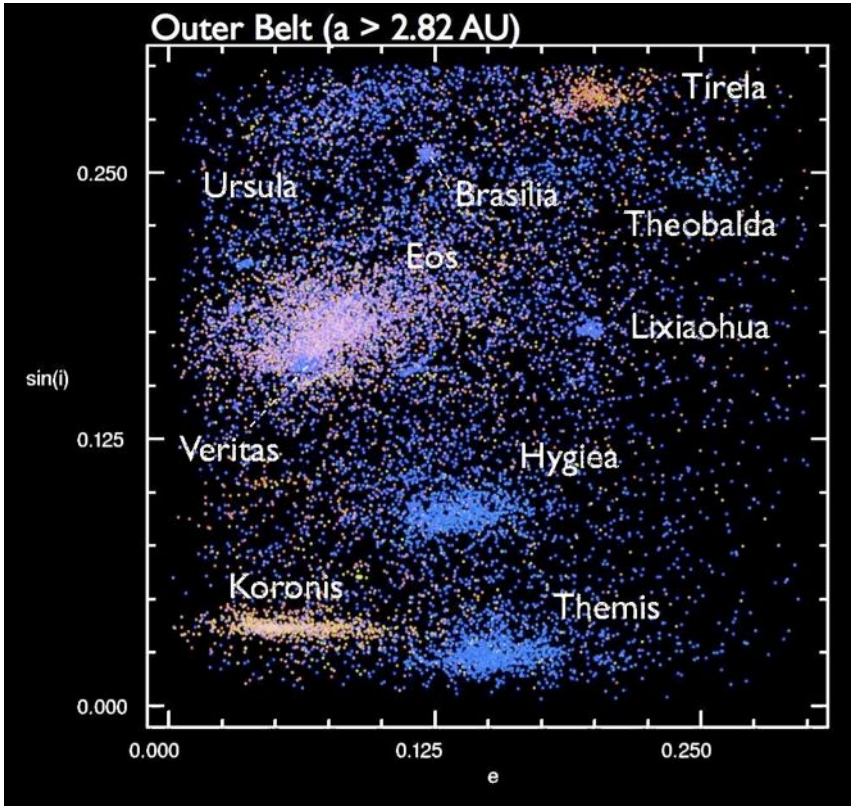
- Objects on asteroidal orbits exhibiting cometary activity
  - 3 of 5 in Themis Family
  - Can’t evolve from cometary orbits
- Thermodynamical arguments: activity must be driven by ice sublimation
  - Recent impact exposure of ice?
- Too small/faint for spectroscopic ice detection



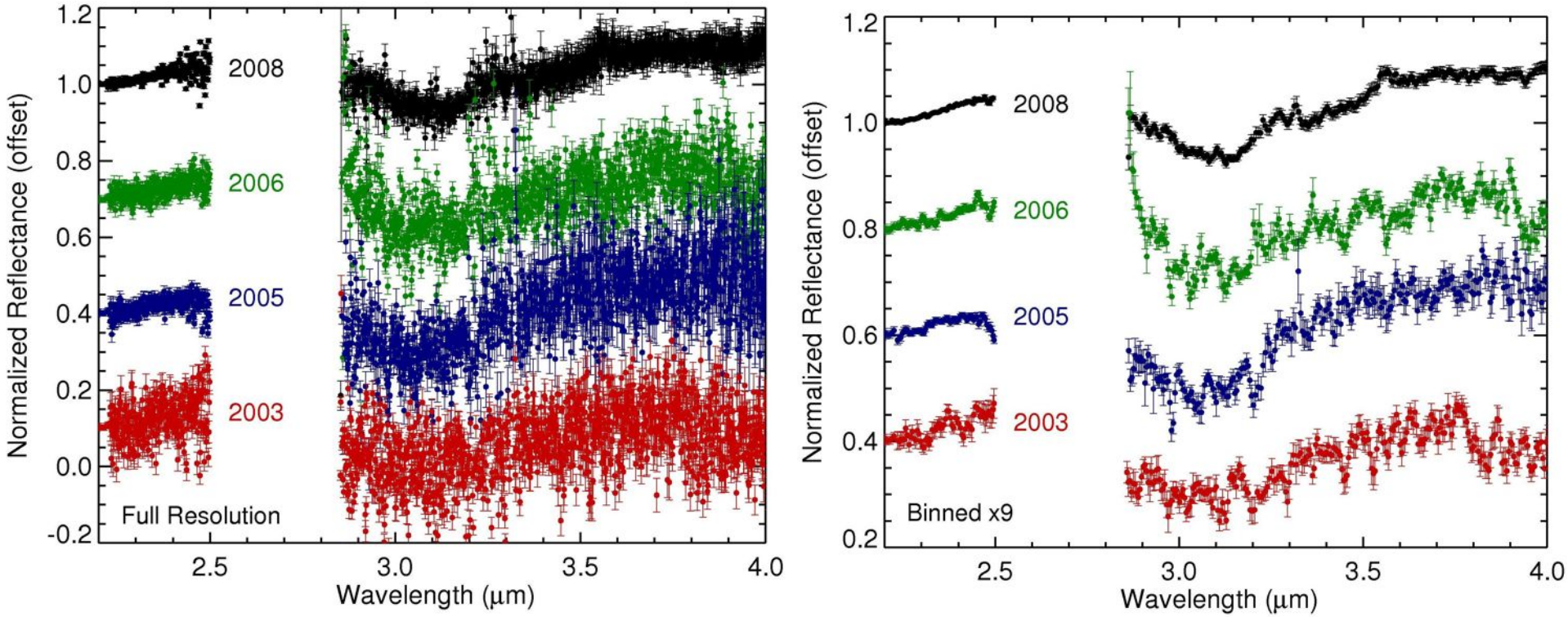

(Images taken with the UH 2.2-meter telescope by H. Hsieh and D. Jewitt, University of Hawaii.)

# Themis Dynamical Family

- Formed by breakup of ~300-400 km object, ~2 Gya
- 3.08-3.24 AU, *e* 0.09-0.22
- One of largest families
- Perhaps 3% of all asteroids are members of family
- C complex



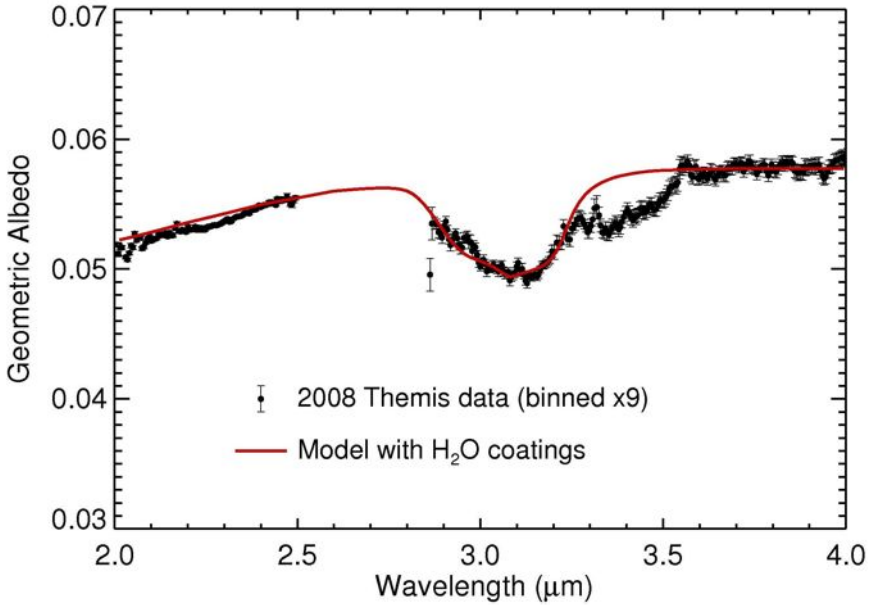
# Results

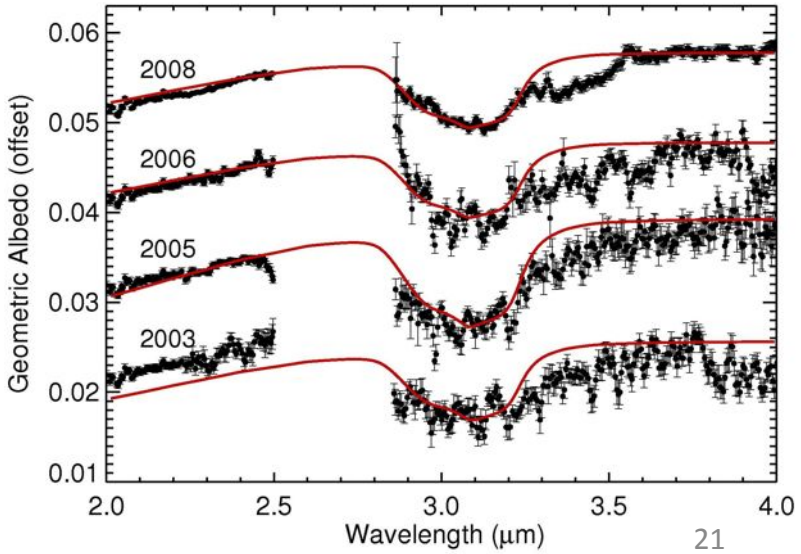



- Absorption feature in all spectra
  - Fairly broad, rounded
  - Centered at ~ 3.1 μm

# Themis fits to ice frost

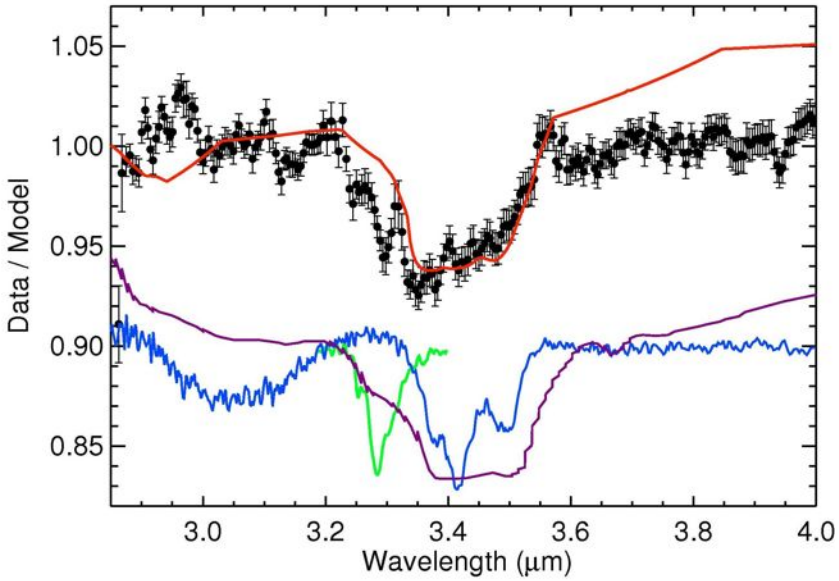
- Max absorption coeff for $H_2O$ ice at 3.1 μm
  - very strong ⟶ saturates easily
- Very short path lengths to keep from saturating
  - grain coatings ~ 0.045 μm thick on 30 μm grains
  - ~30% coated grains (intimate mixture)
  - ~10% of surface as areal mixture (not thoroughly modeled)

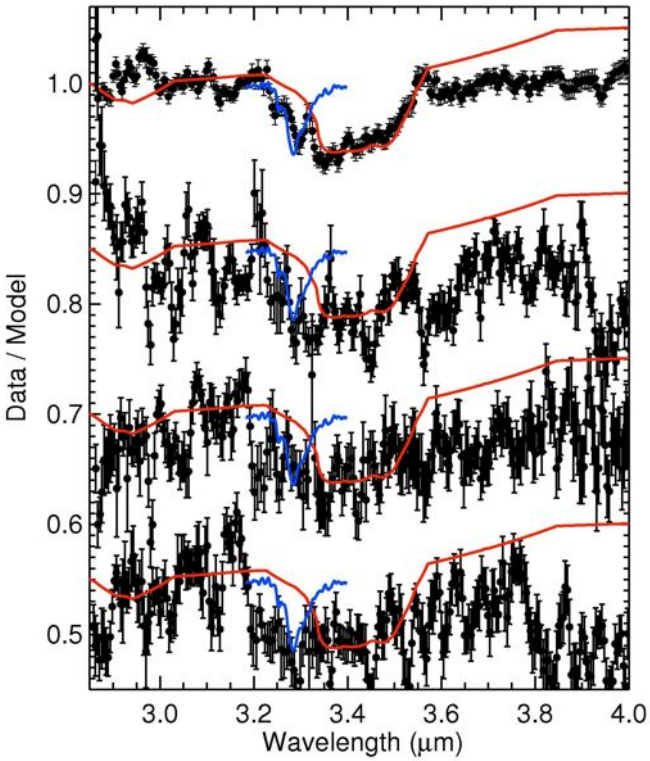


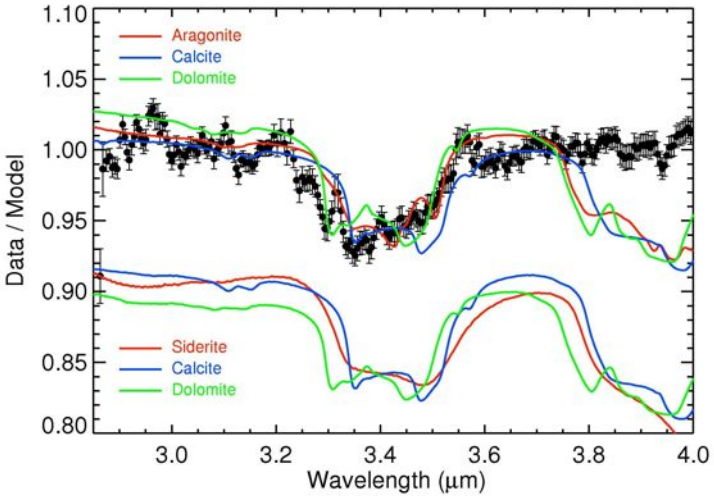



# Analysis - Organics

- Feature at ~3.4 μm that is not fit by $H_2O$ model



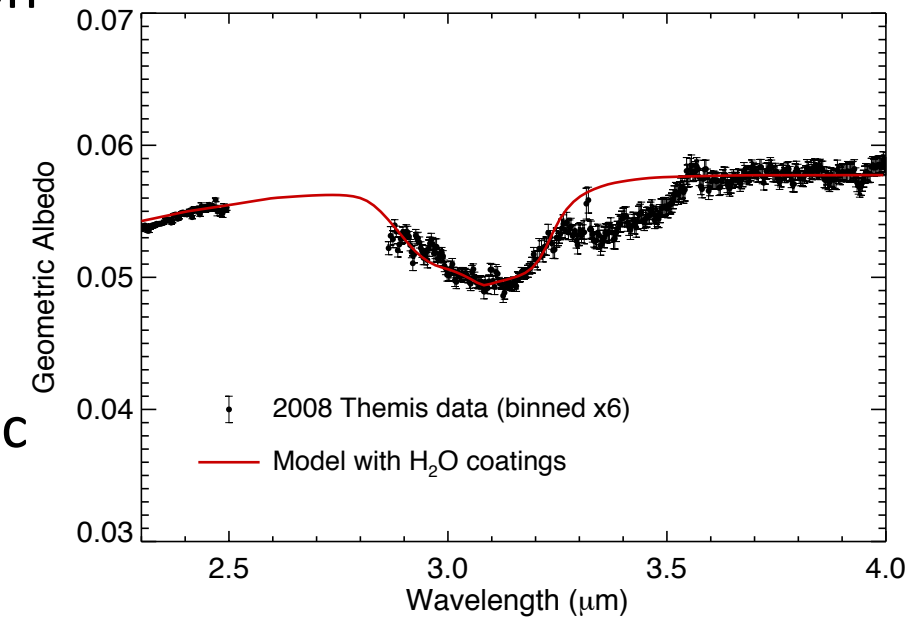




- Organics → $–CH_2$ and $–CH_3$ aliphatic stretch
  - small 3.3 μm → aromatics?

# 24 Themis, ice, and Occam's Razor

- Discovery of ice frost + organics on 24 Themis (Rivkin & Emery, Campins et al. 2010)
  - Quickly followed by discovery on 65 Cybele (Licandro et al. 2011)
  - Consistent with relationship to MBCs
- Aqueous alteration is* exothermic
  - Melt ice, react with rock to make hydrated minerals, heat system, melt more ice…
  - So might expect ice or hydrated minerals, not both?
- No evidence of hydrated minerals on Themis
- So no melting? And undifferentiated Themis et al.?

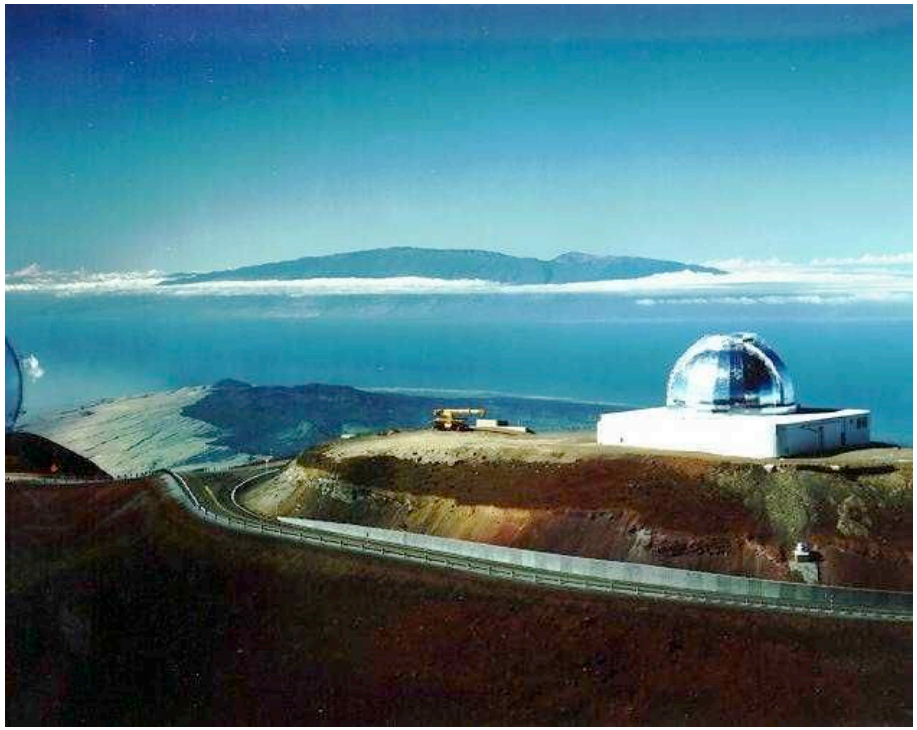



Rivkin and Emery (2010)

*for some value of "is" (Clinton, 1998)

# L-band Main-belt/NEO Observing Project (LMNOP)

- IRTF (3-m telescope on Mauna Kea), using Spex instrument (2-4 μm)
- 317 observations of 179 objects, 100 C-complex (as of 3/1/13)
- Survey paper in preparation, have been focusing on interesting objects (Ceres, Vesta, Themis, Lutetia…)
- Anticipate stopping point fall 2013 (SpeX upgrade)



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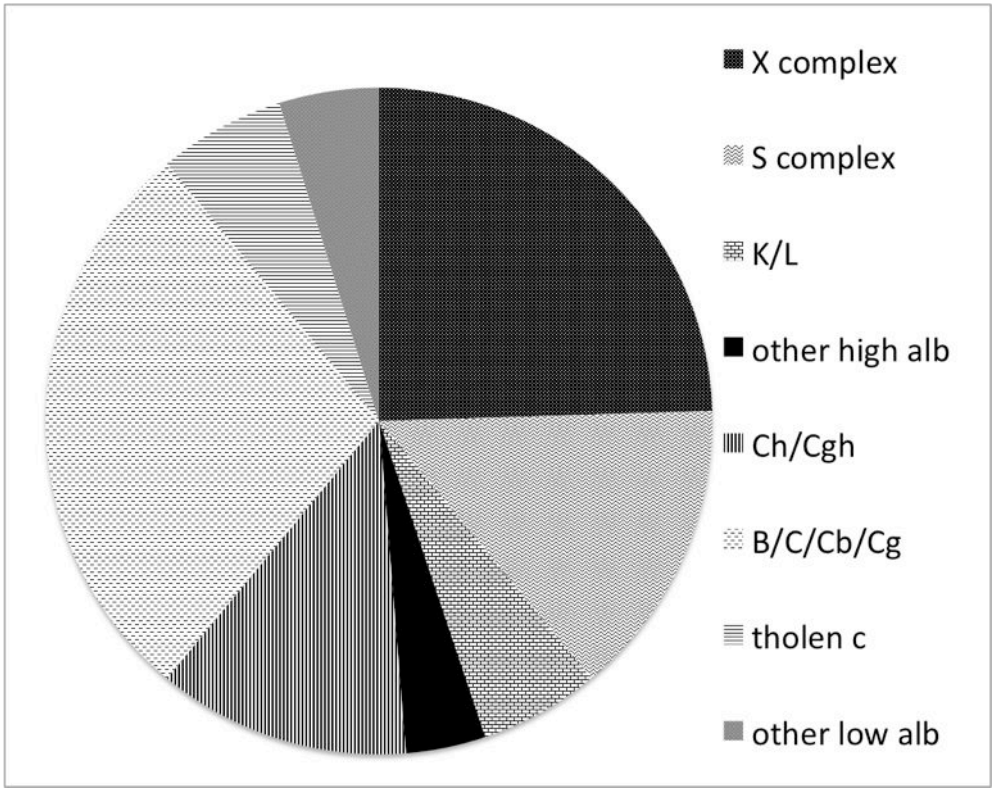


Breakdown of observations

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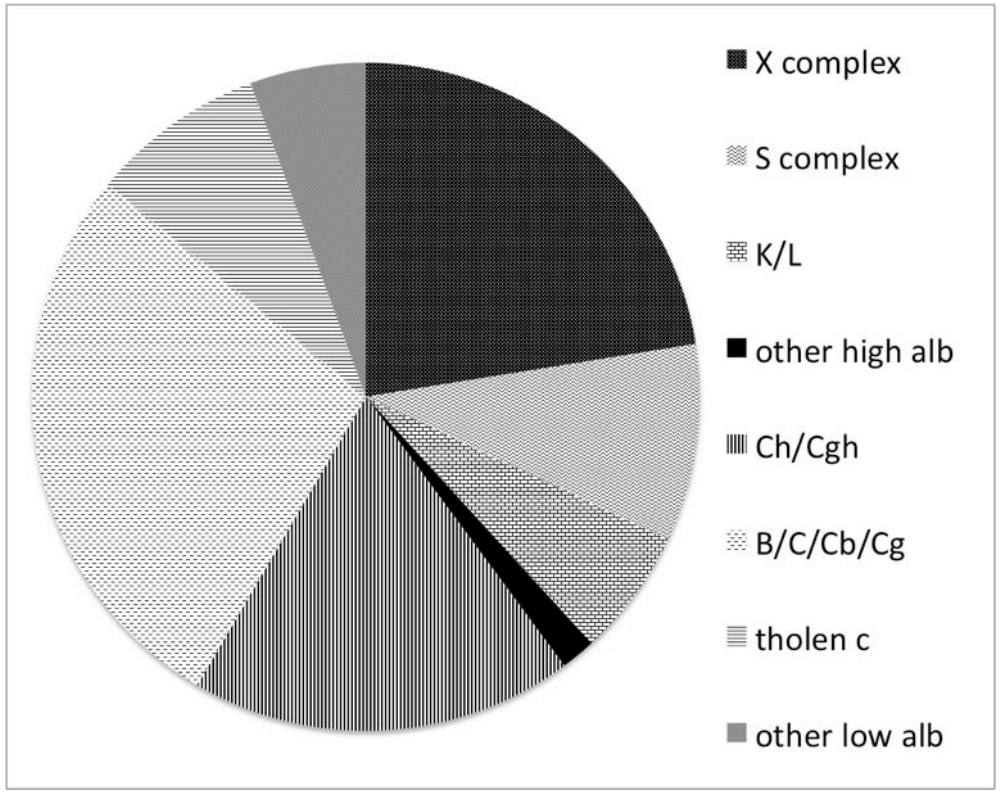
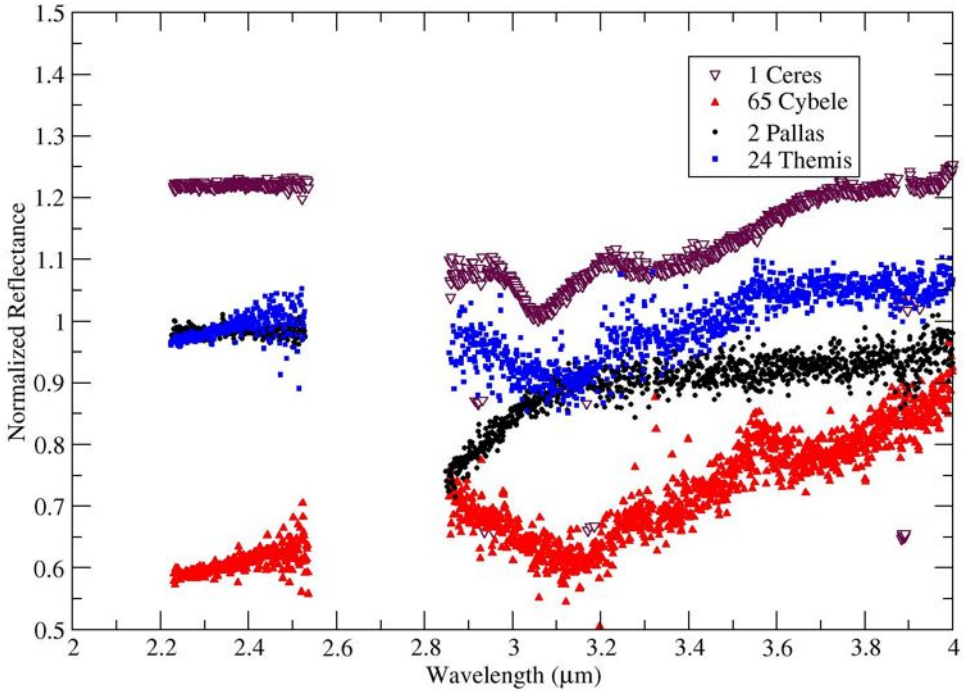



Breakdown of objects

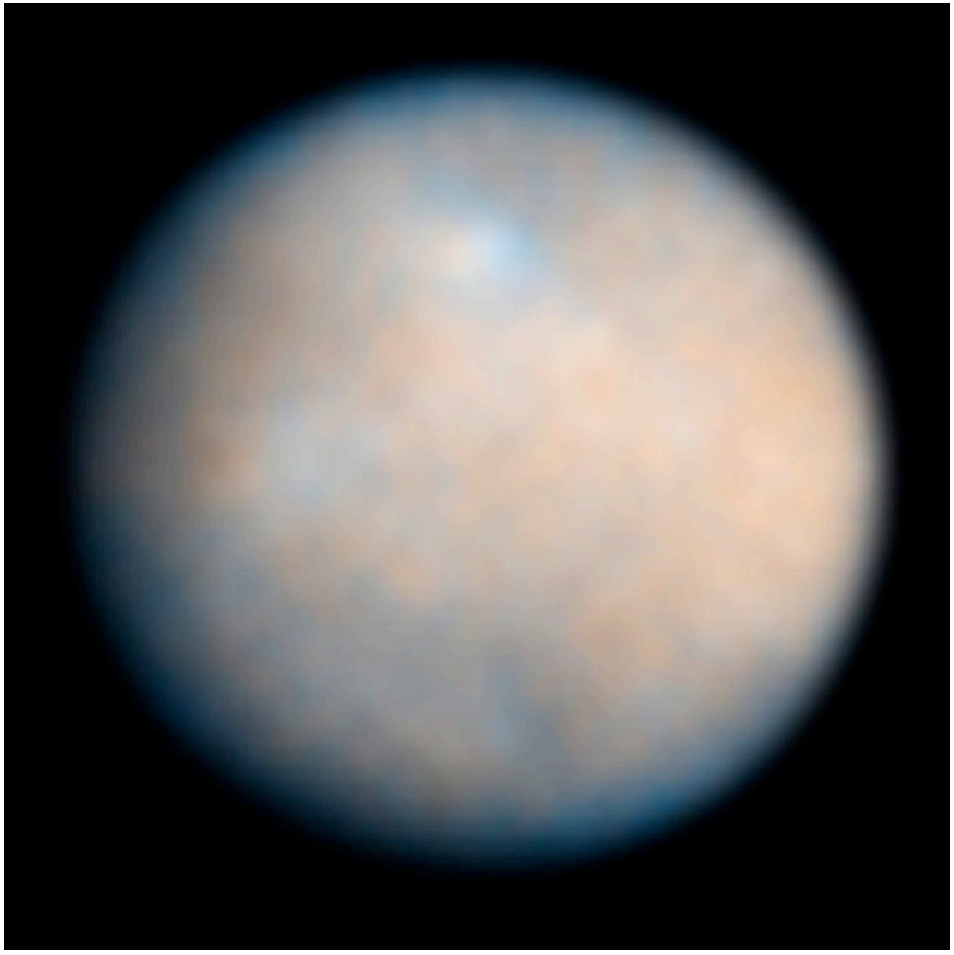
# Band shapes in 3-µm region

- "Pallas type", linear shape beyond 2.8 µm
  - → CM-like, phyllosilicates?
- "Ceres type", minimum ~3.05 µm, additional minima
  - → Brucite, carbonates?
- "Themis type", minimum ~3.1 µm
  - → Frost, organics?
  - → Separate "Cybele type"?
- No band



# A detour to Ceres

- Largest object in main belt, (in)famously classified as a "dwarf planet"
- ~2x larger than Pallas, Vesta, Hygiea, Themis parent body
- Surface minerals (brucite, carbonates) formed via aqueous alteration in presence of $CO_2$
- Shape model suggests ice mantle over rocky core
- Thermal models suggest liquid water may persist today just above rocky core
- Hygiea has similar spectrum: similar history?



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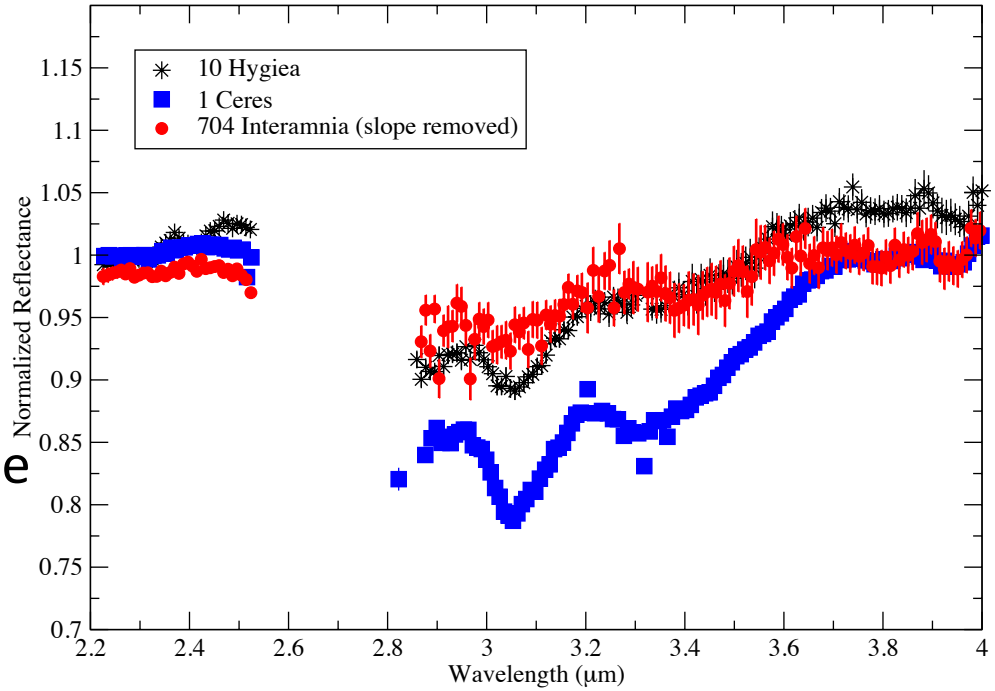

# Some initial findings

- Ch asteroids are highly likely to be Pallas types (>29/31)
- B asteroids are less likely to be Pallas types than other types
- 20 low-albedo asteroids are larger than 200 km:5 are Ceres-like, 6 Pallas-like, 5 are Themis/Cybele-like, 4 are too noisy to tell.
- Three of the 4 largest C-complex asteroids are Ceres-types

| Object | SMASS class | 3-µm type |
|---|---|---|
| 1 Ceres | C | Ceres |
| 2 Pallas | B | Pallas |
| 10 Hygiea | C | Ceres |
| 704 Interamnia | B | Ceres |
| 52 Europa | C | Ceres? |
| 511 Davida | C | Pallas |
| 87 Sylvia | X | ?? |
| 65 Cybele | Xc | Themis/Cybele |
| 31 Euphrosyne | Cb | Themis/Cybele |
| 624 Hektor | D (Tholen) | ?? |

Ten largest low-albedo asteroids
Hektor data from Emery et al.

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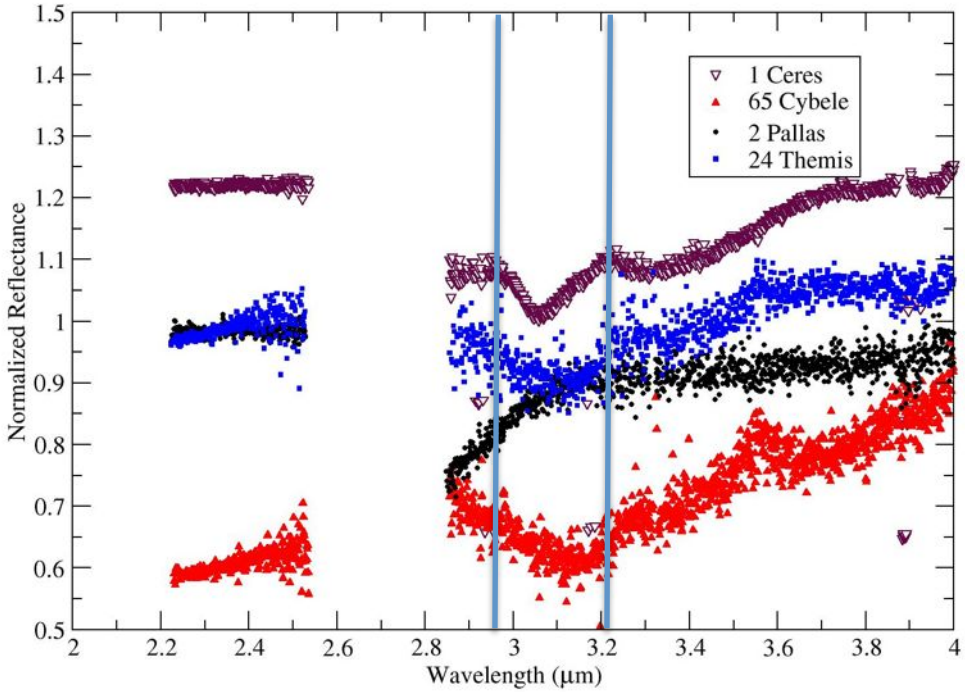
| 31 Euphrosyne | Cb | Themis/Cybele |
| 88 Thisbe | B | Themis/Cybele? |
| 324 Bamberga | CP (Tholen) | Themis/Cybele |
| 451 Patientia | C (Tholen) | Ceres |

Ten largest C-complex asteroids

# Quantifying band shapes: first crack!

- Use band depths at 2.95 and 3.2 as proxy for band shape
- Removed linear continuum 2.3-3.5 μm
- Pallas-types form linear trend, others split off
- Consistent with CC meteorites, minerals
- Non-Pallas types in direction of ice



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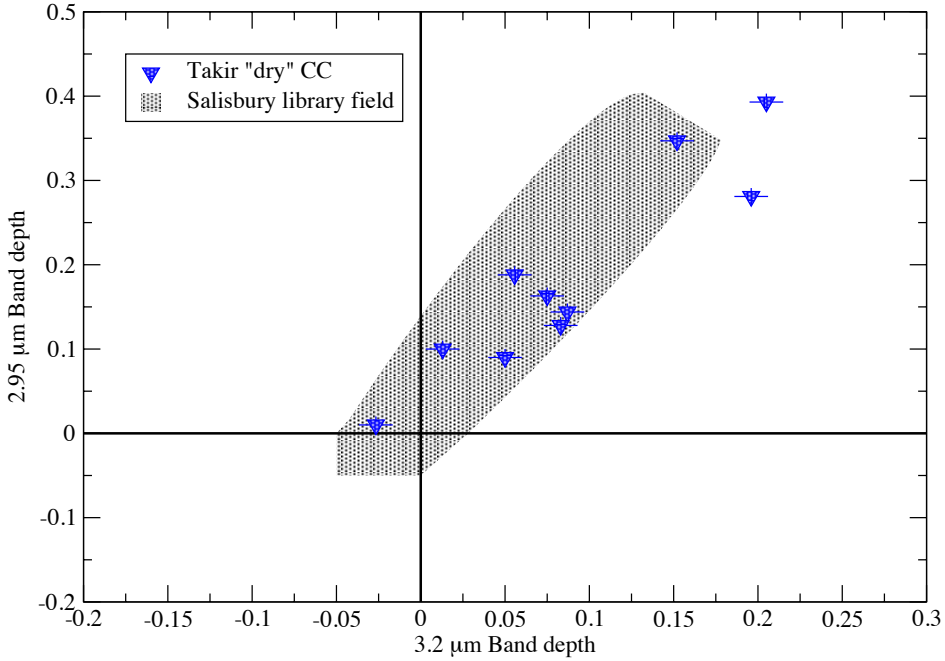

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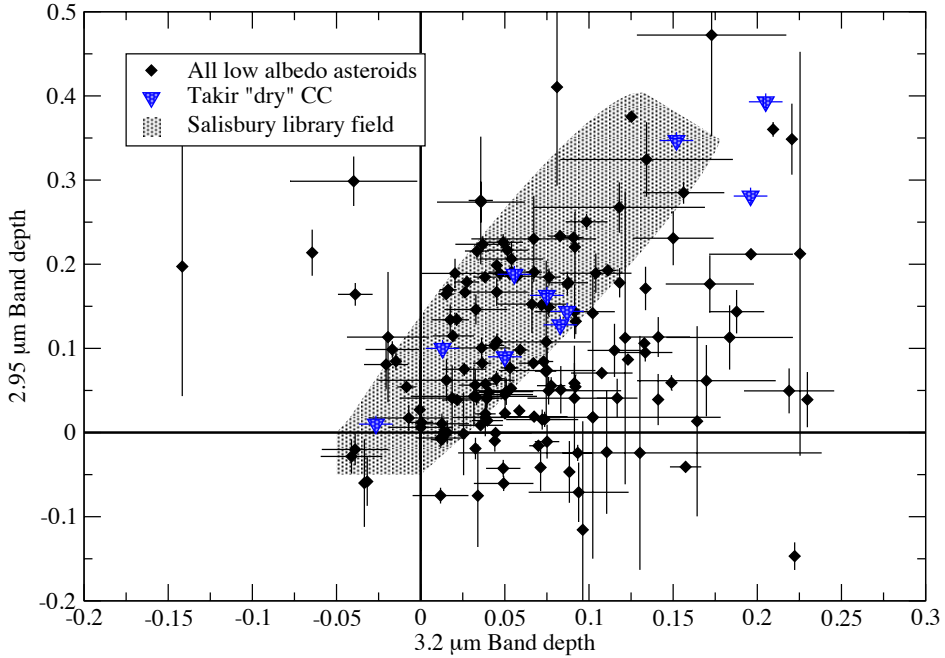

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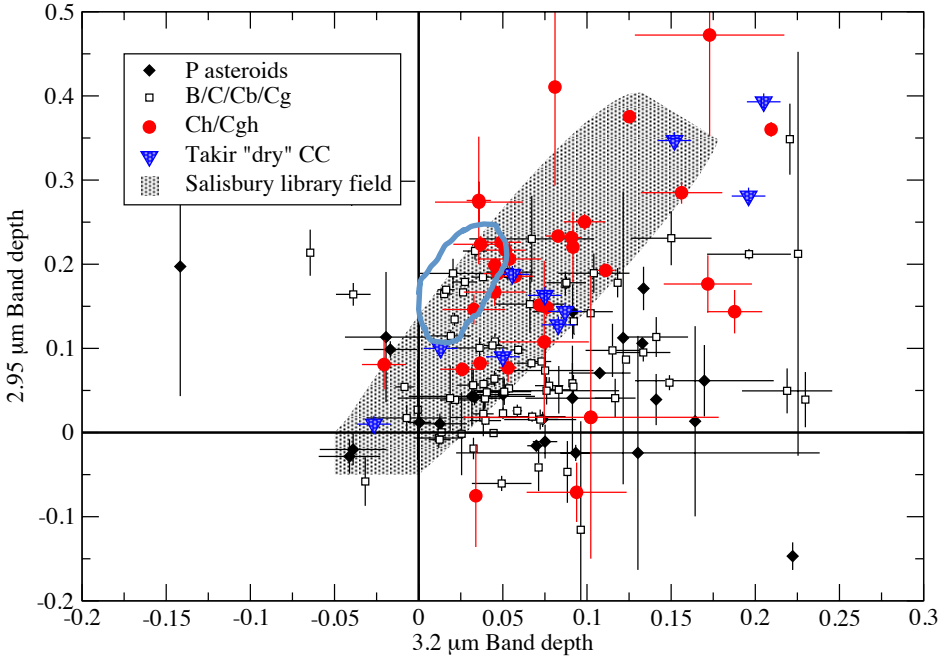


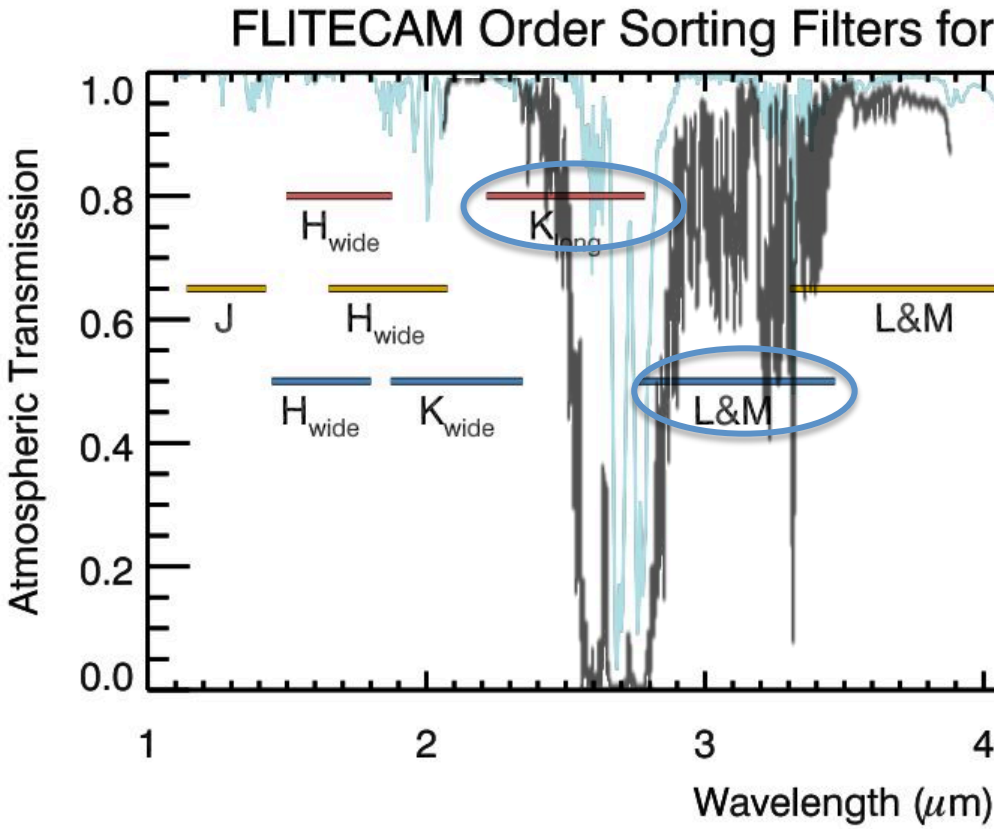
# Caveats

- Error analysis not yet done
- Repeat observations (7x Cybele, 6x Themis, Hygiea, Pallas)
- Sample likely biased in unknown ways
- Imperfect continuum removal
- *Implicit assumption that similar spectra means similar composition, though more modeling still necessary*


On the plus side, Karl Rove isn't doing the statistical analysis for me

# Our SOFIA observations and how they'll help us

- SOFIA transmission MUCH better at λ of interest
- Obtain useable data for first time from majority of "water gap"
- Allow direct comparisons to lab spectra tying meteorite reflectance to composition
  - Best meteorite analog
  - Better spectral modeling
  - Coexistence of ice and phyllosilicates?




Gray overlay: Mauna Kea model transmission
1.2 mm PW, airmass 1.0

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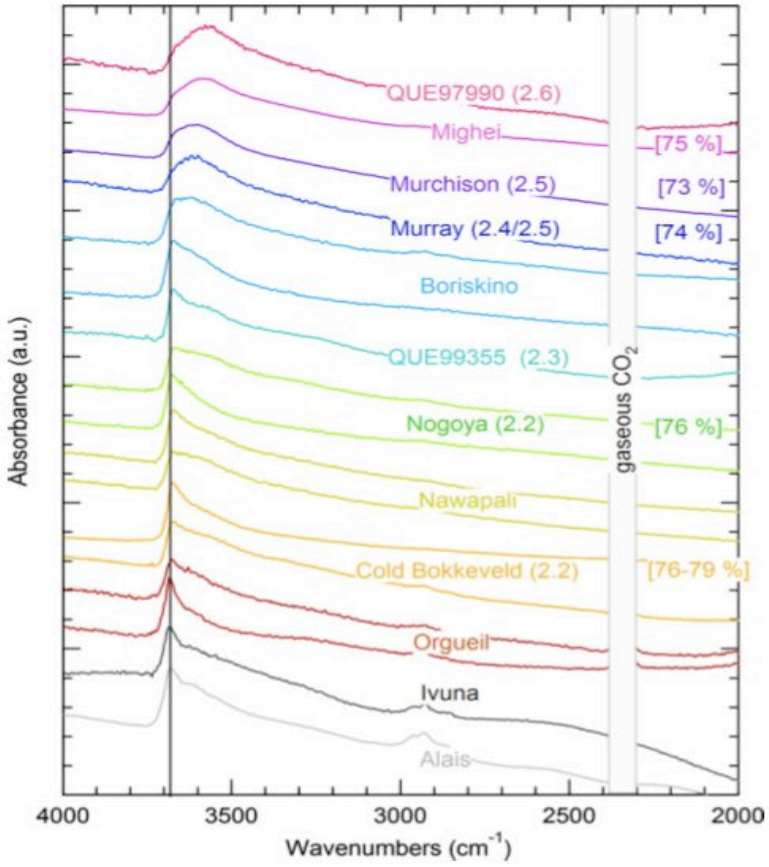


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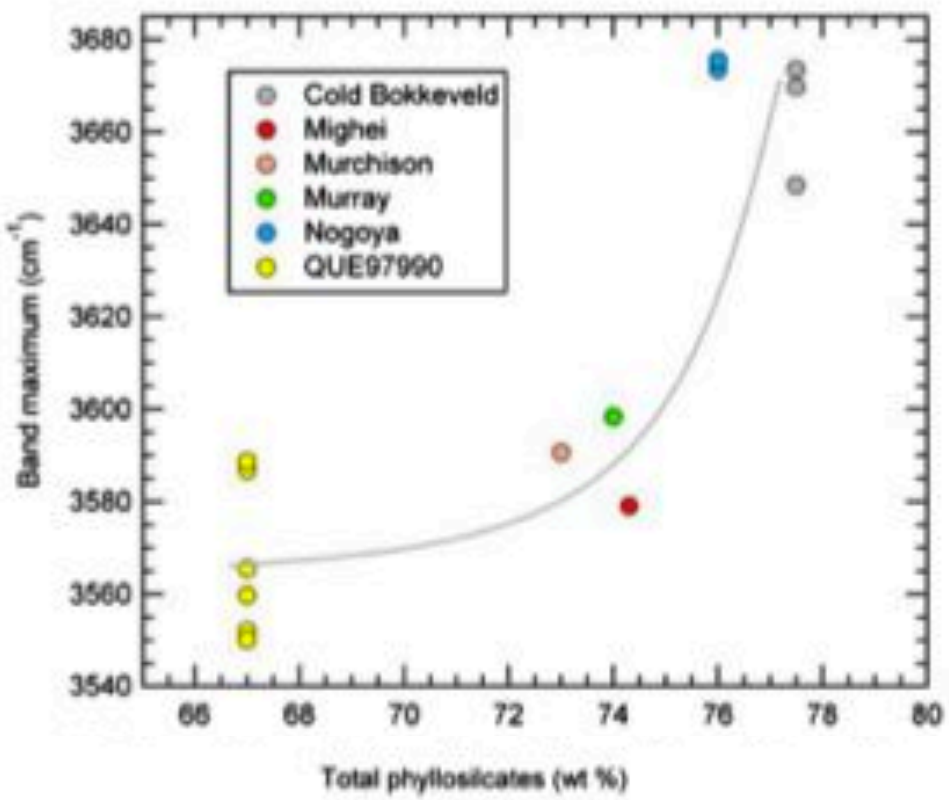



Beck et al. (2010)

# Our SOFIA observations and how they'll help us

- SOFIA transmission MUCH better at λ of interest
- Obtain useable data for first time from majority of "water gap"
- Allow direct comparisons to lab spectra tying meteorite reflectance to composition
  - Best meteorite analog
  - Better spectral modeling
  - Coexistence of ice and phyllosilicates?

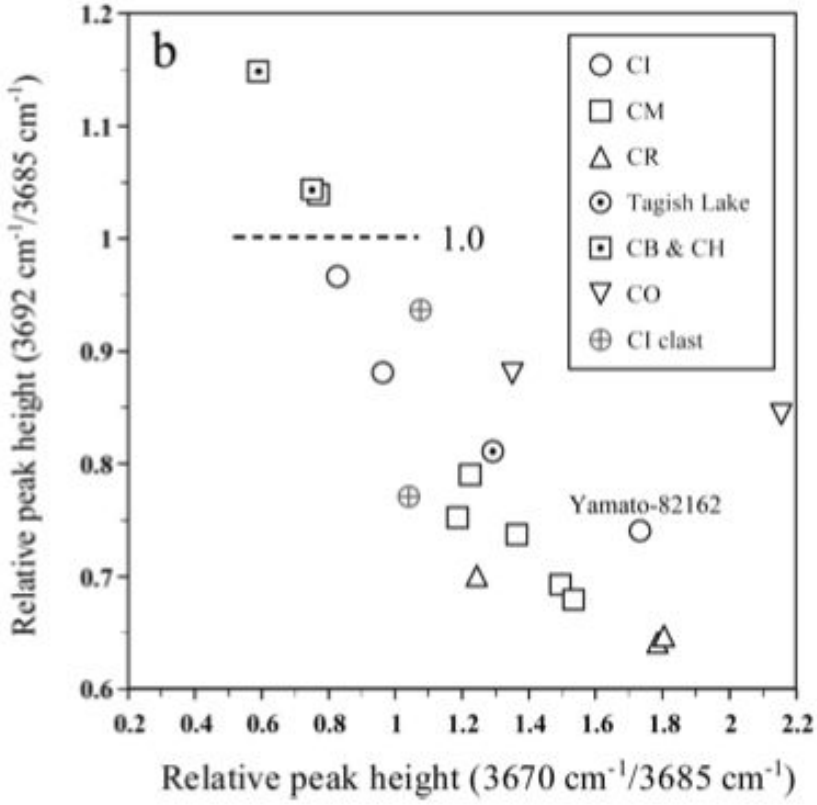



Fig. 7. Relative peak heights of 3520 and 3600 $cm^{-1}$ normalized to those of 3400 $cm^{-1}$ (a) and those of 3670 and 3692 $cm^{-1}$ to 3685 $cm^{-1}$ (b). Peak heights are estimated after baseline correction. CR and CM chondrites are distinguishable from the other chondrite classes.

Osawa et al. (2005)

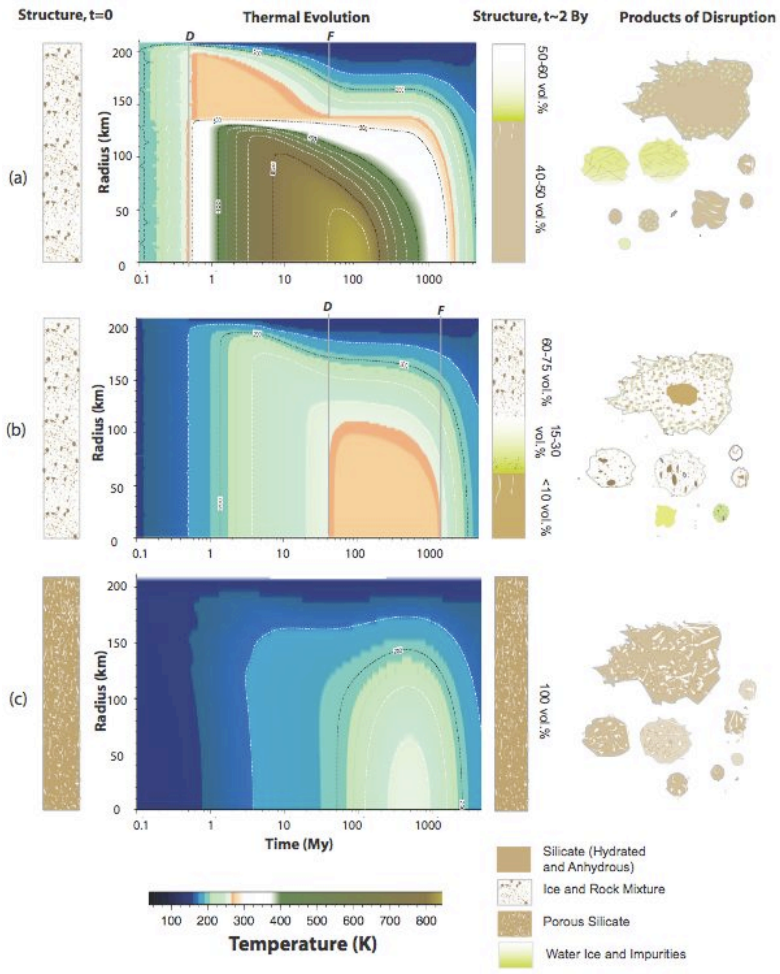
# SOFIA time granted

- 2 hours total on FLITECAM
- 4 targets
  - Ceres 2x678 sec
  - Pallas 2x1182 sec
  - Vesta 2x552 sec
  - Bamberga 2x1182 sec
- 30 sec exposures x N cycles
- A2, C2 grisms

- Ceres
  - Better spectral modeling
  - Dawn support
- Pallas
  - Direct comp to CCs
  - Most common asteroid type
- Vesta
  - Dawn support
  - Whole-disk data
- Bamberga
  - Water ice?
  - Look for OH

# Future Work and Further Speculation

- Geophysical modeling
  - What do surface compositions tell us about interiors?
- Continued observations
  - Family observations
  - Relationship to lunar OH?
- Future mission targets?
  - Ceres in 2015
  - 1999 RQ36




Castillo-Rogez and Schmidt (2010)

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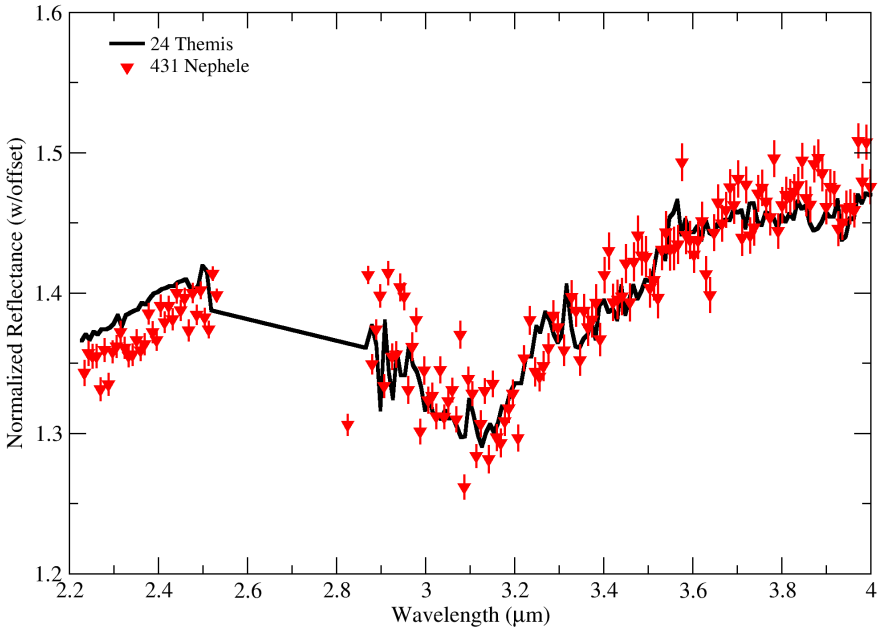


Yet-unpublished data

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Mars Phoenix image

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# Summary

- OH- and water-bearing objects dominate asteroid belt
- A variety of hydrated mineralogies are present on asteroids
- Ceres-like spectra (brucite+carbonate+clays?) are found on most of the largest asteroids
- Some evidence of shallow absorptions on NEOs: solar wind or impactor contamination?
- SOFIA will provide unique, critical data in “water gap”