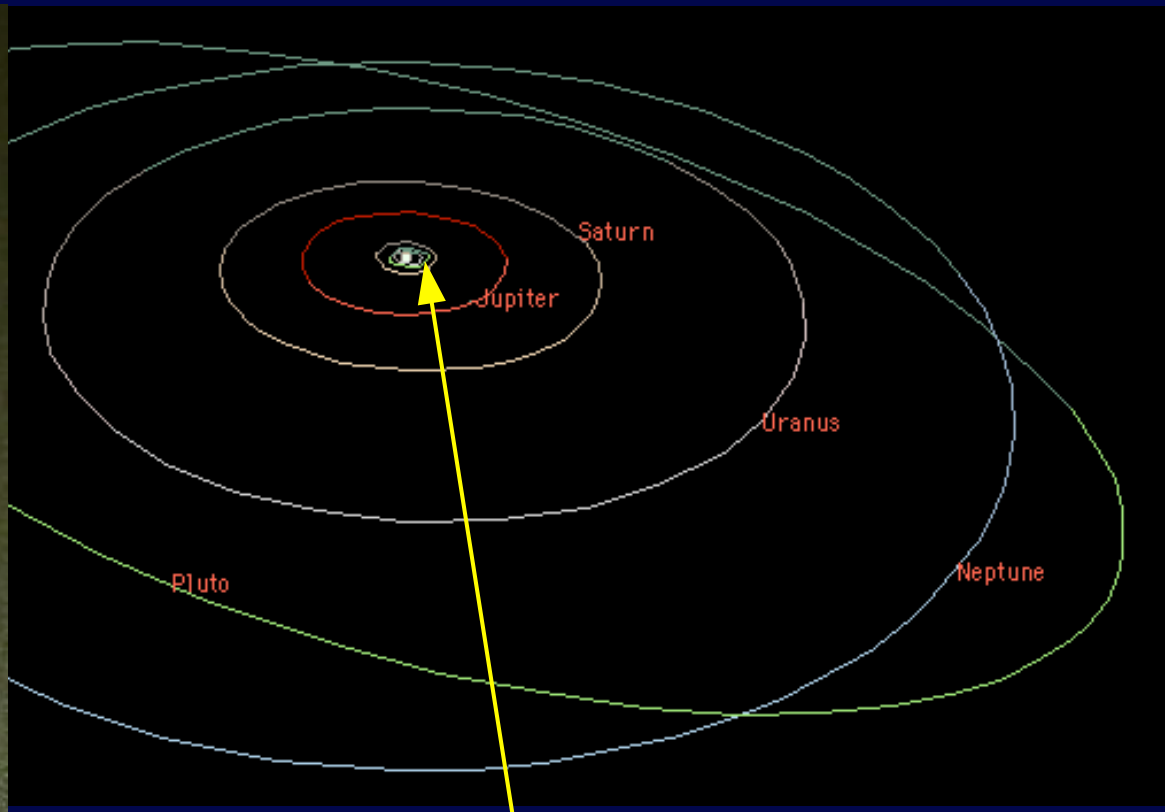
Planetary Ices

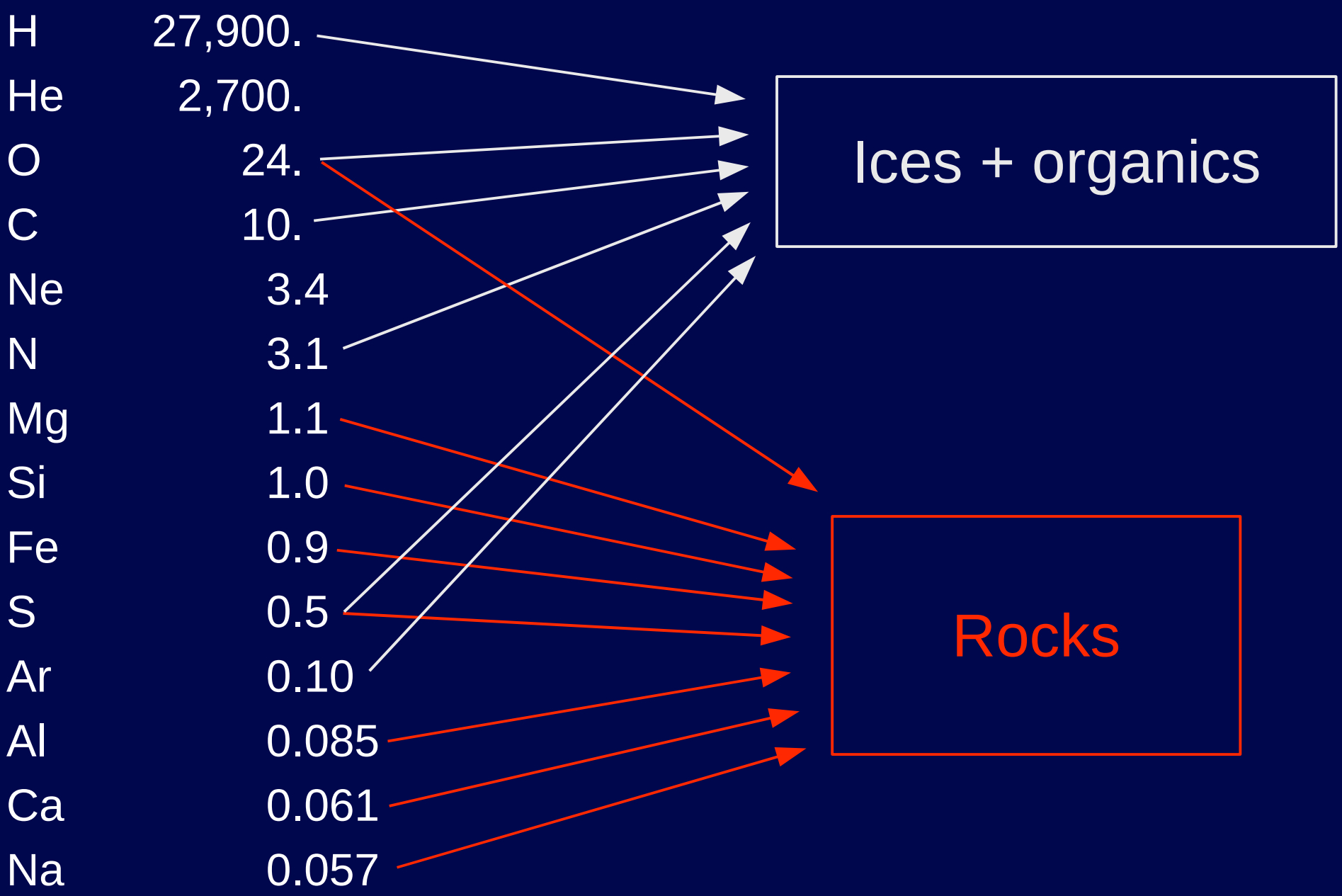
Will Grundy

Ices: minerals which are thermally unstable at “room” temperature



“Room” temperature at 1 AU is a lot hotter than equilibrium temperatures in most of the Solar System

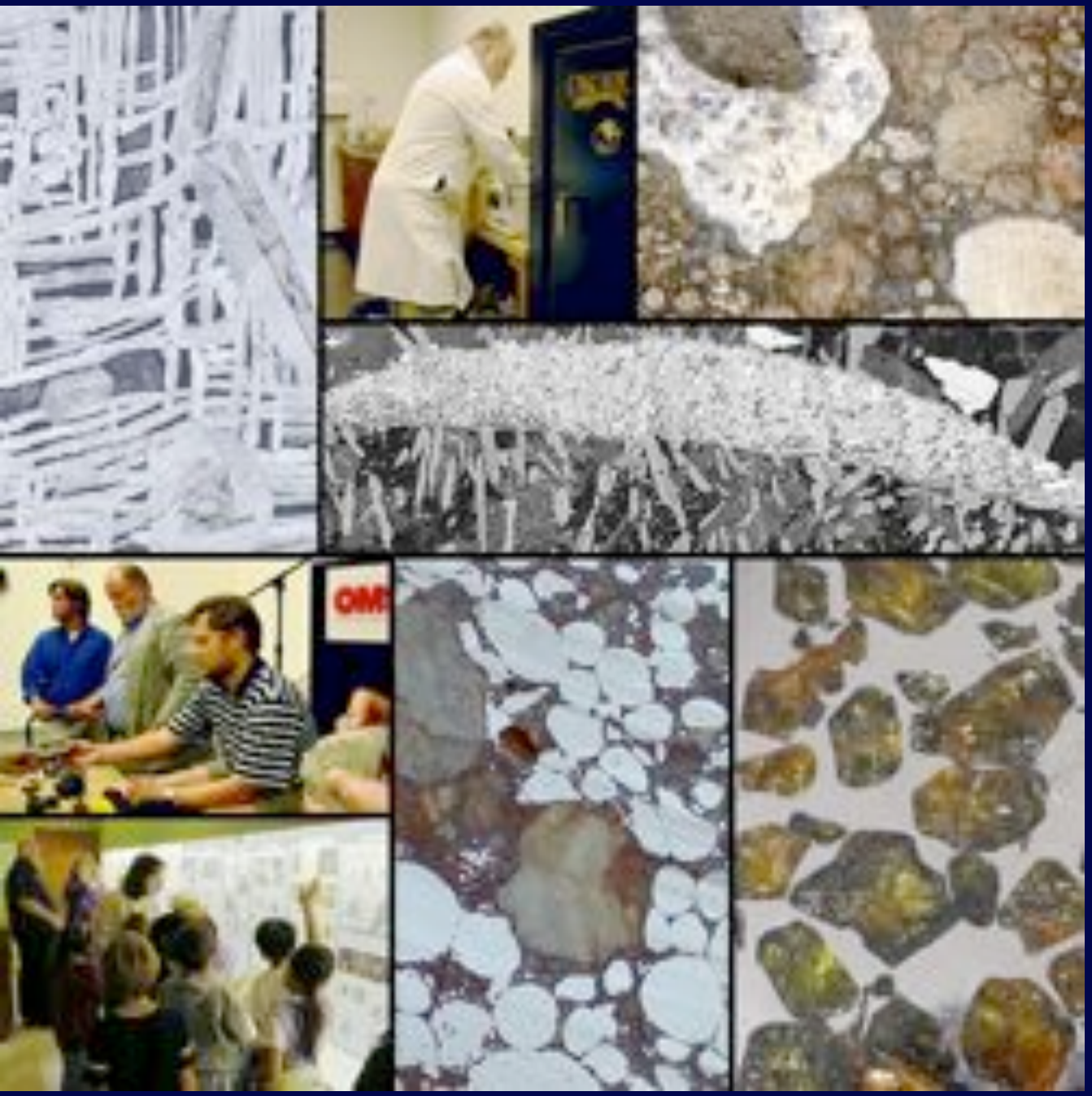
Ice-forming elements are abundant

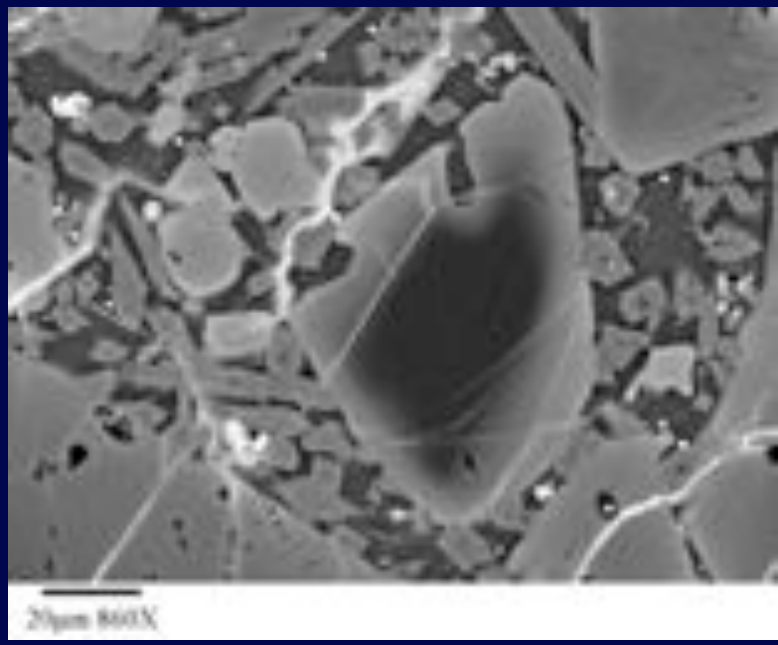


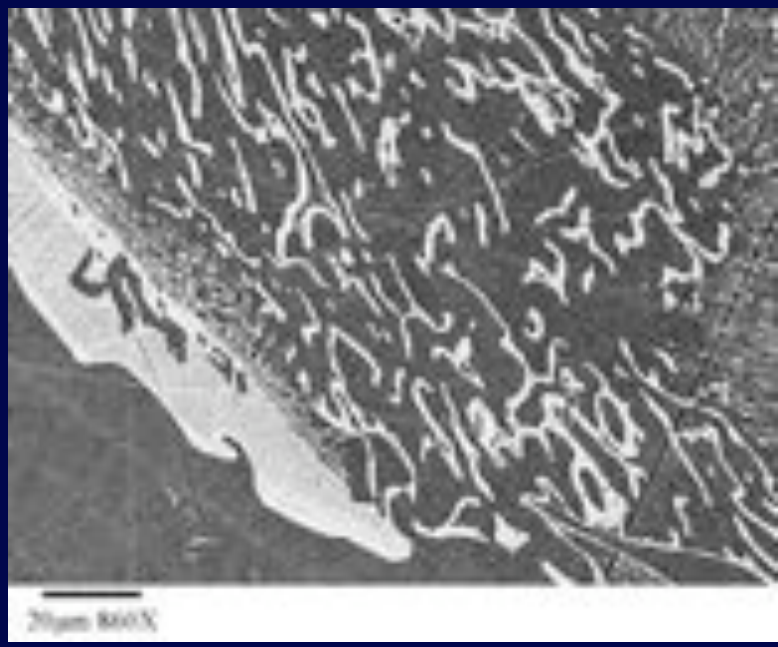
A Few Selected Topics

- Prospects for ice petrology
- Implications of the volatility of ices
- Prospects for ice remote sensing
- Organic materials
- How “pristine” are TNOs and comets?
- Amorphous -vs- crystalline ice kerfuffle

Lab Petrology: Meteorites

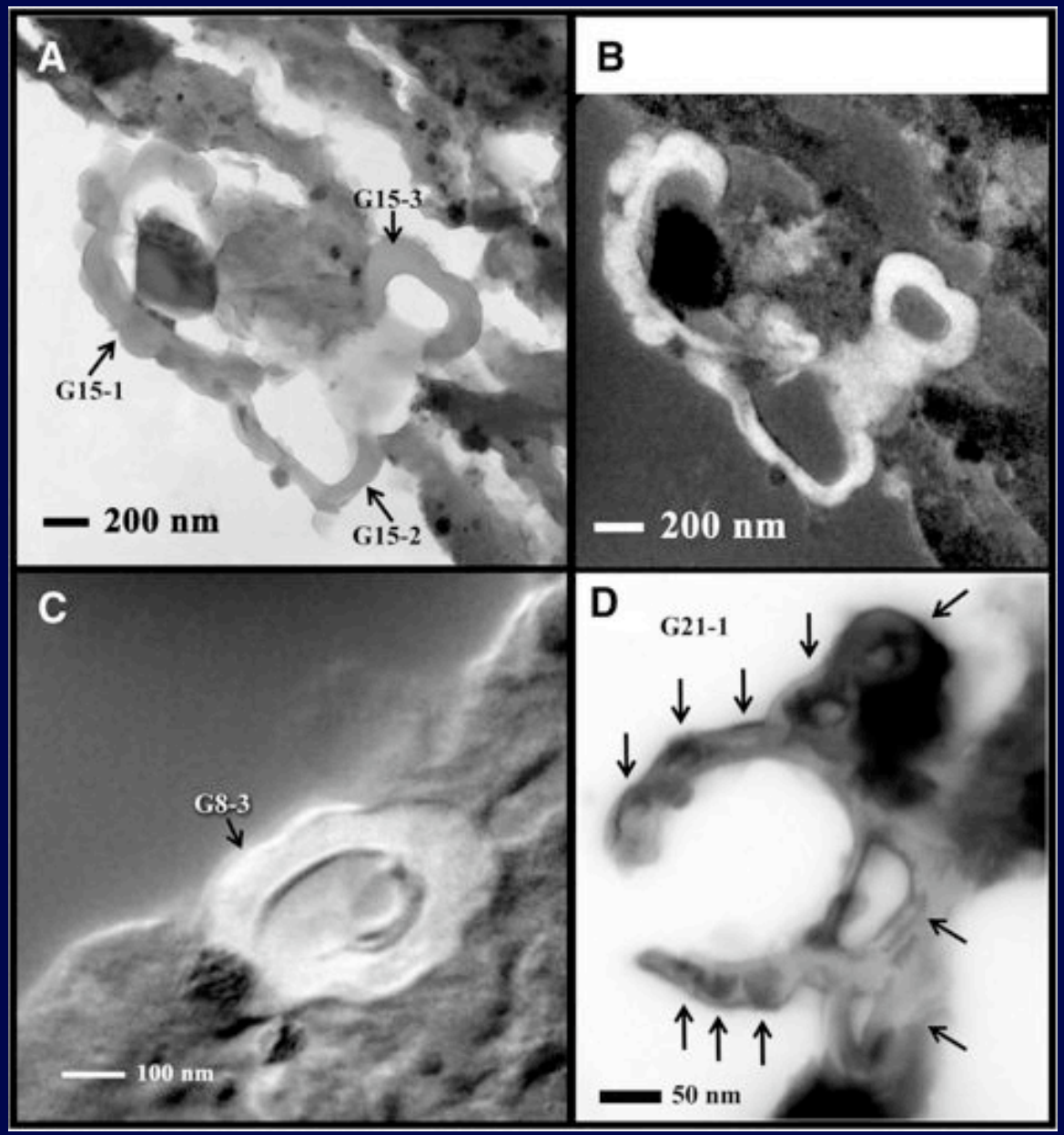






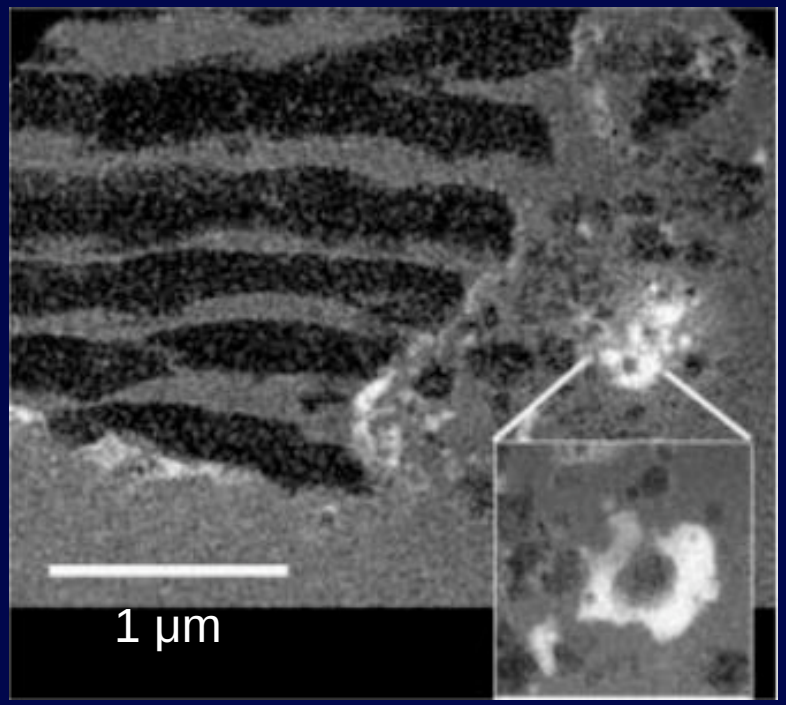
Lab Petrology: Organic Globules

Tagish Lake meteorite



Nakamura-Messenger et al. 2006

Comet 81P/Wild 2

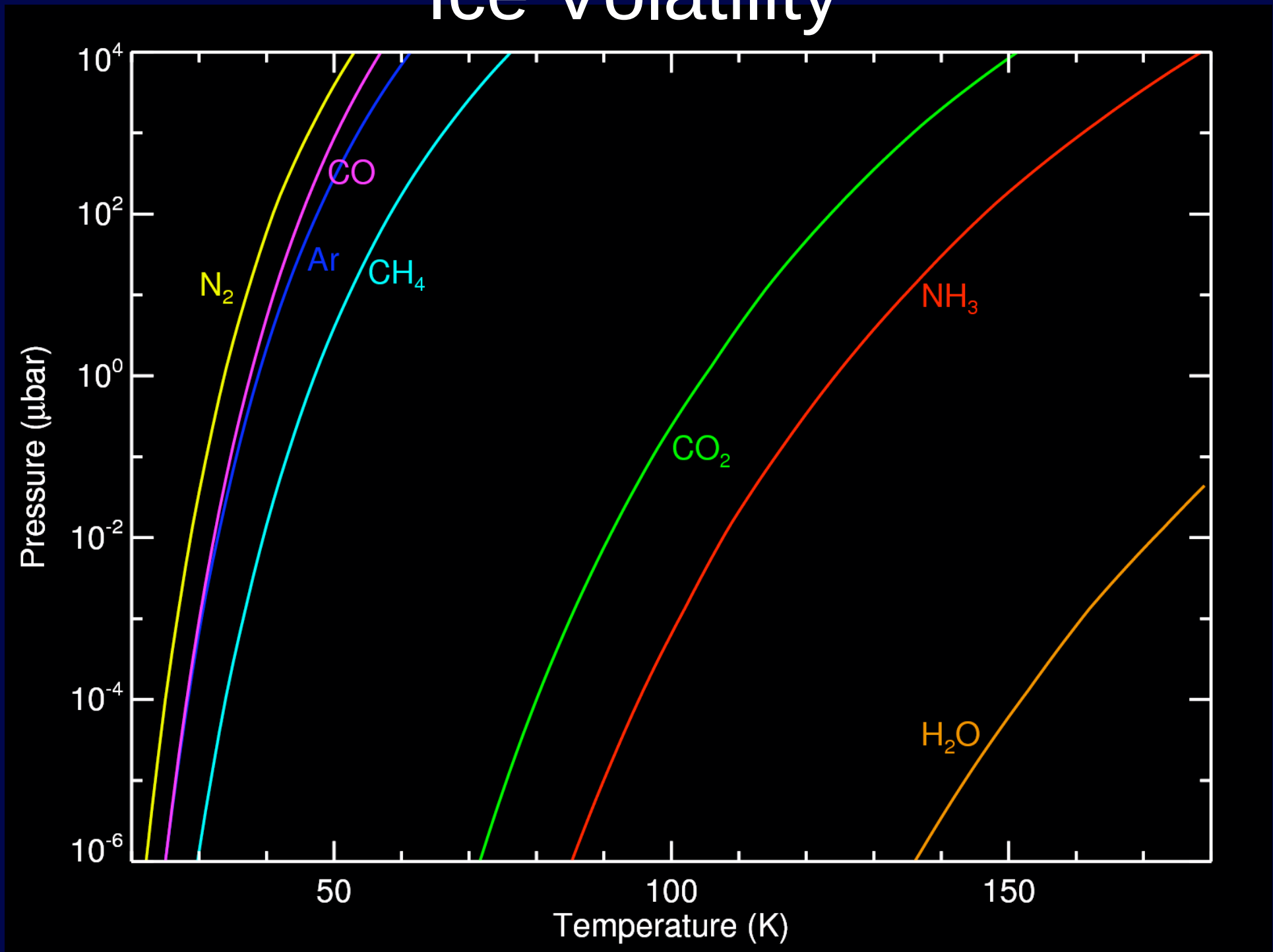


Brownlee et al. 2006

Cryo-petrology?

- Expect spectacular information content on lower temperature events recorded by intact icy and organic samples
- Lab techniques are familiar, but not as applied to cryogenic samples, maintained and handled cold and under vacuum
- Are any labs capable of even doing this work?

Ice Volatility



Volatility of Icy Samples

$$\text{Sublimation rate} = P_{\text{vap}} \sqrt{\frac{\mu}{2\pi R T}}$$

For H_2O, ~1 mm/year at ~145 K
For CO_2, this happens ~80 K
For NH_3, this happens ~70 K
For CH_4, this happens ~35 K

Volatility of Icy Samples

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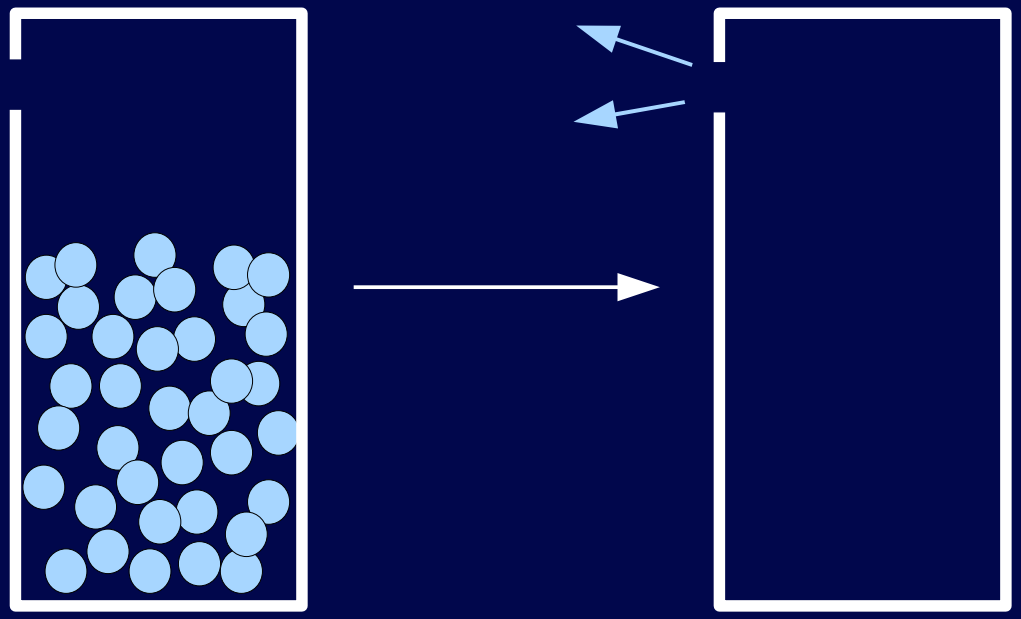

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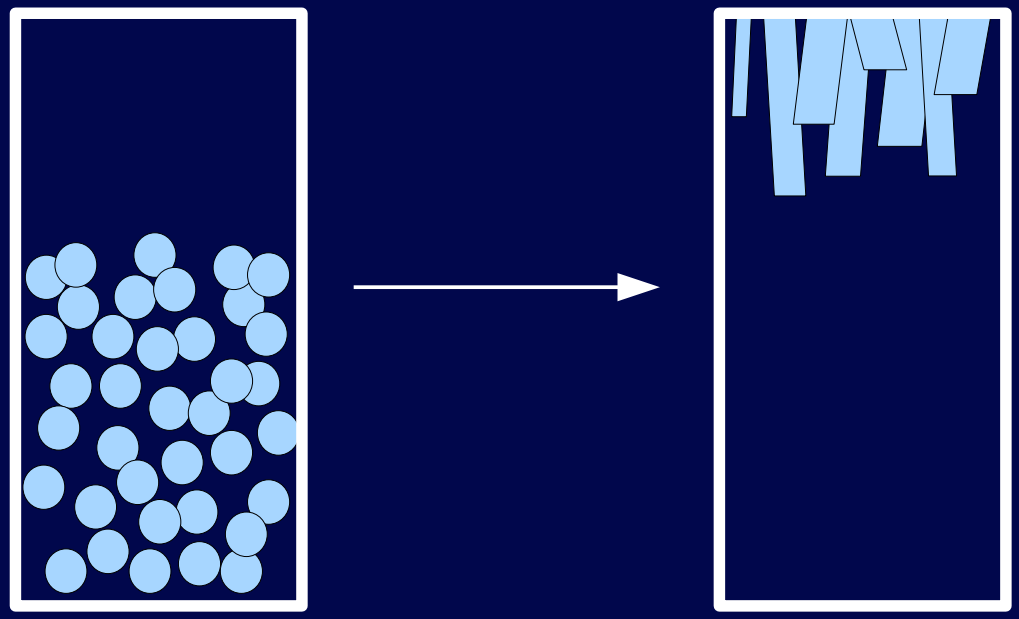
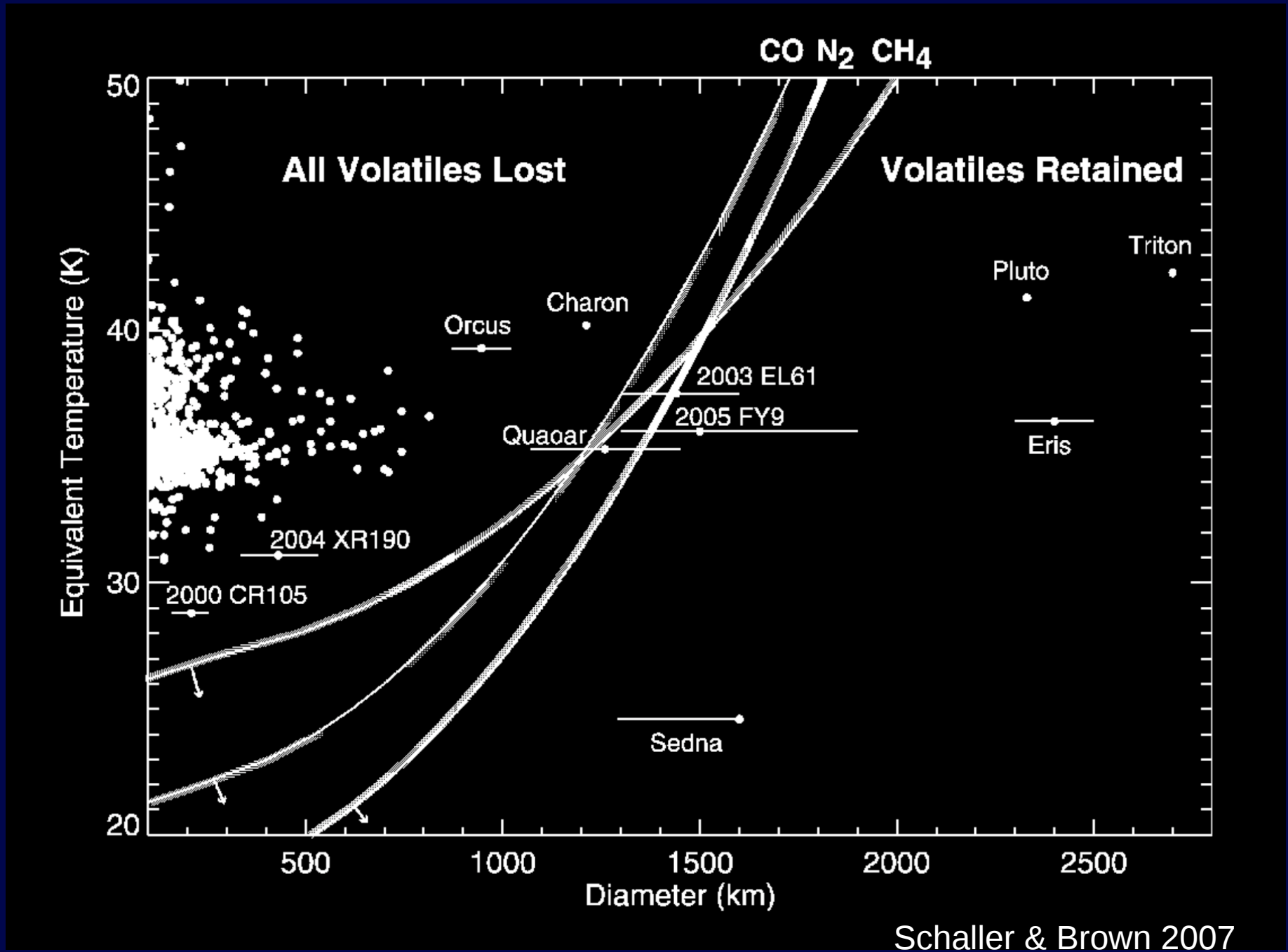
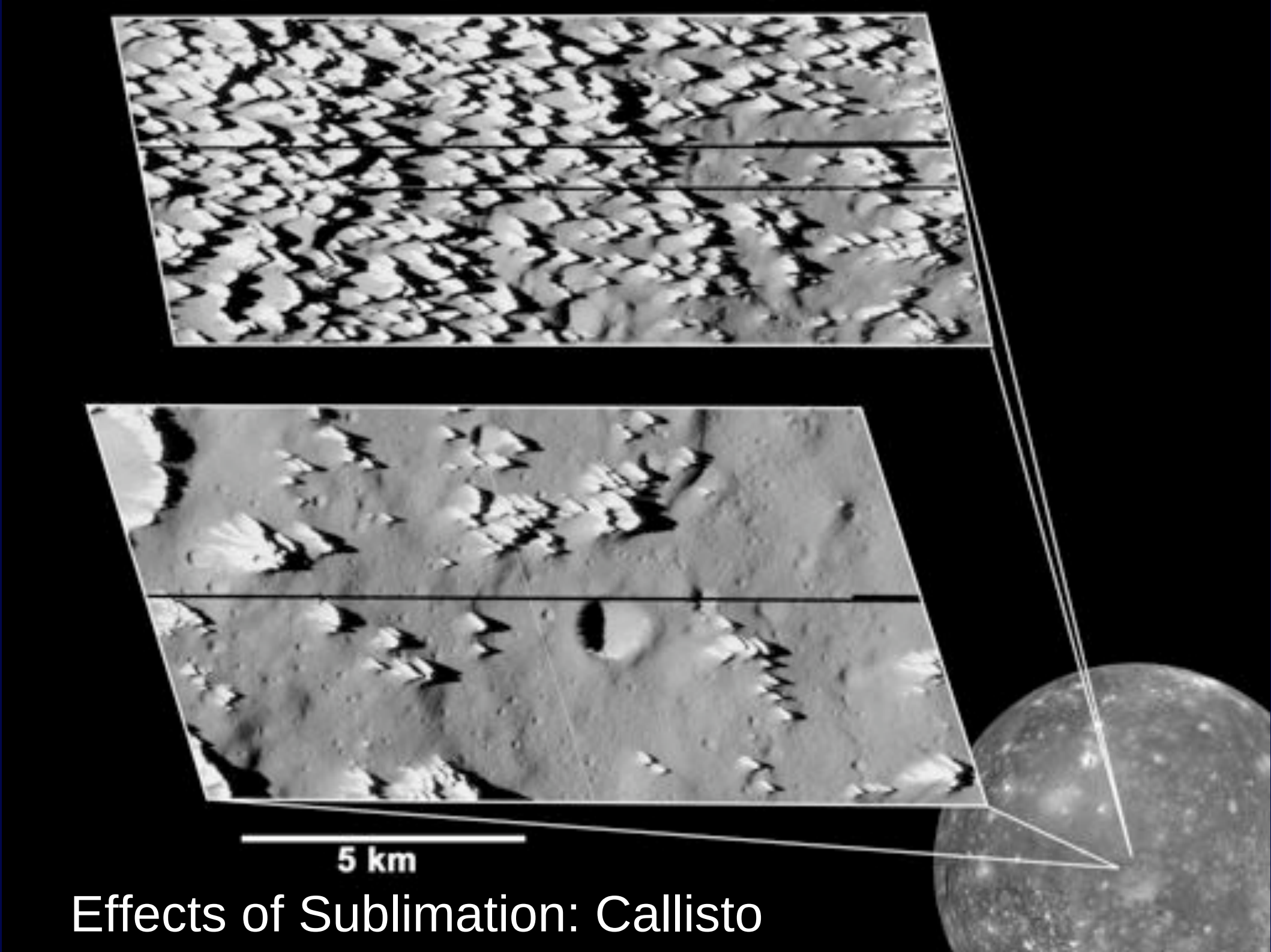


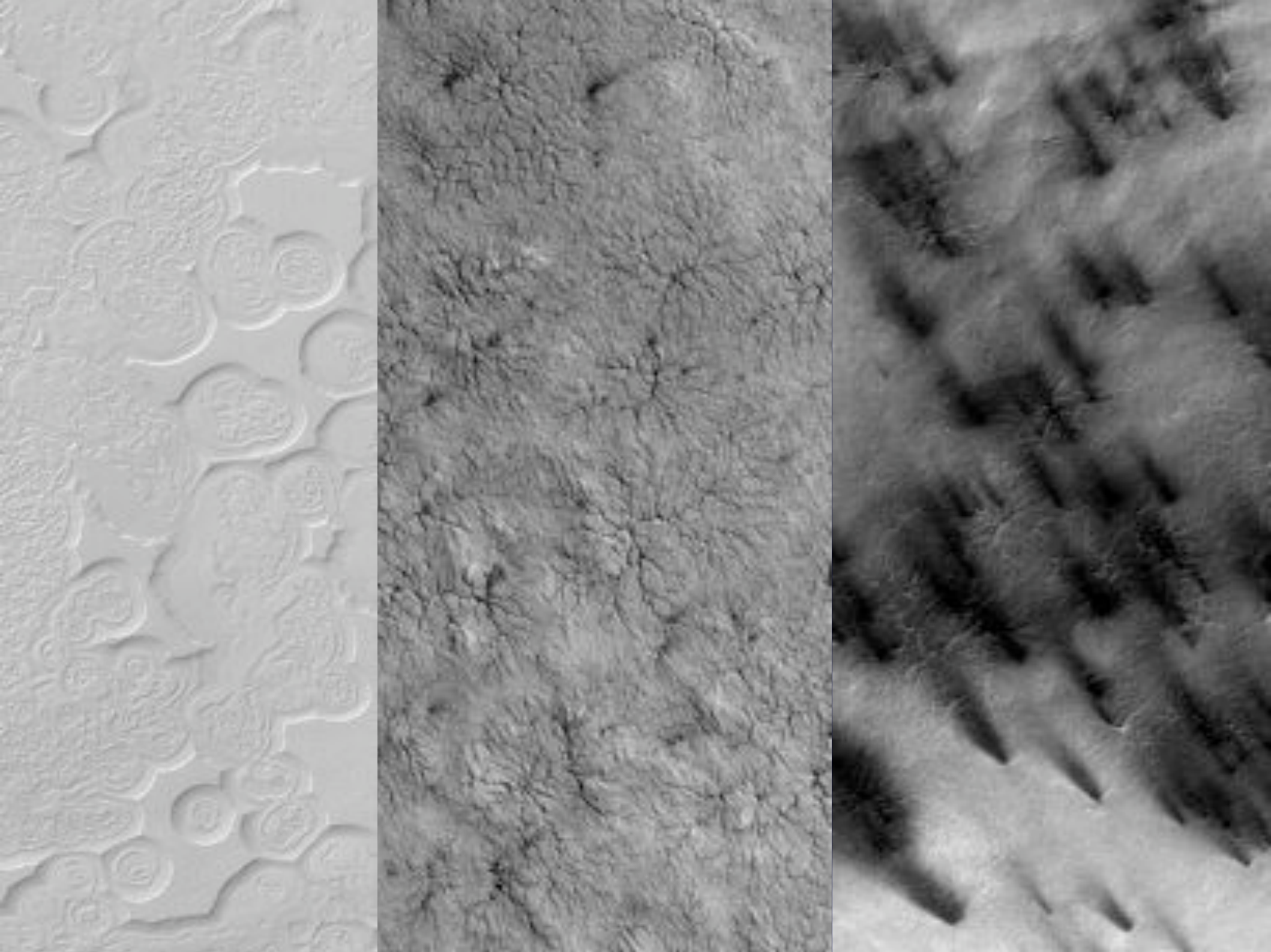
Surface Volatile Loss



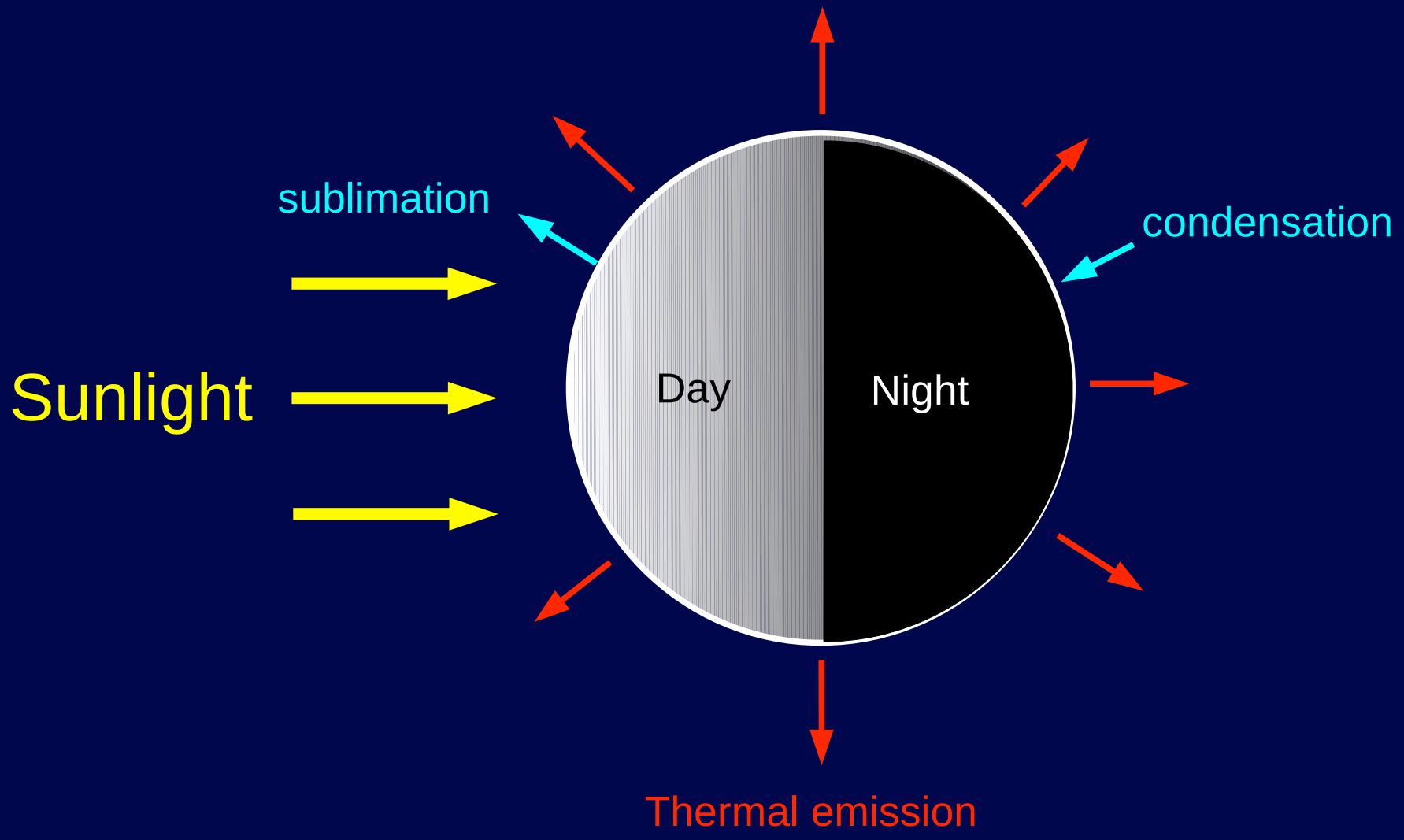
Schaller & Brown 2007

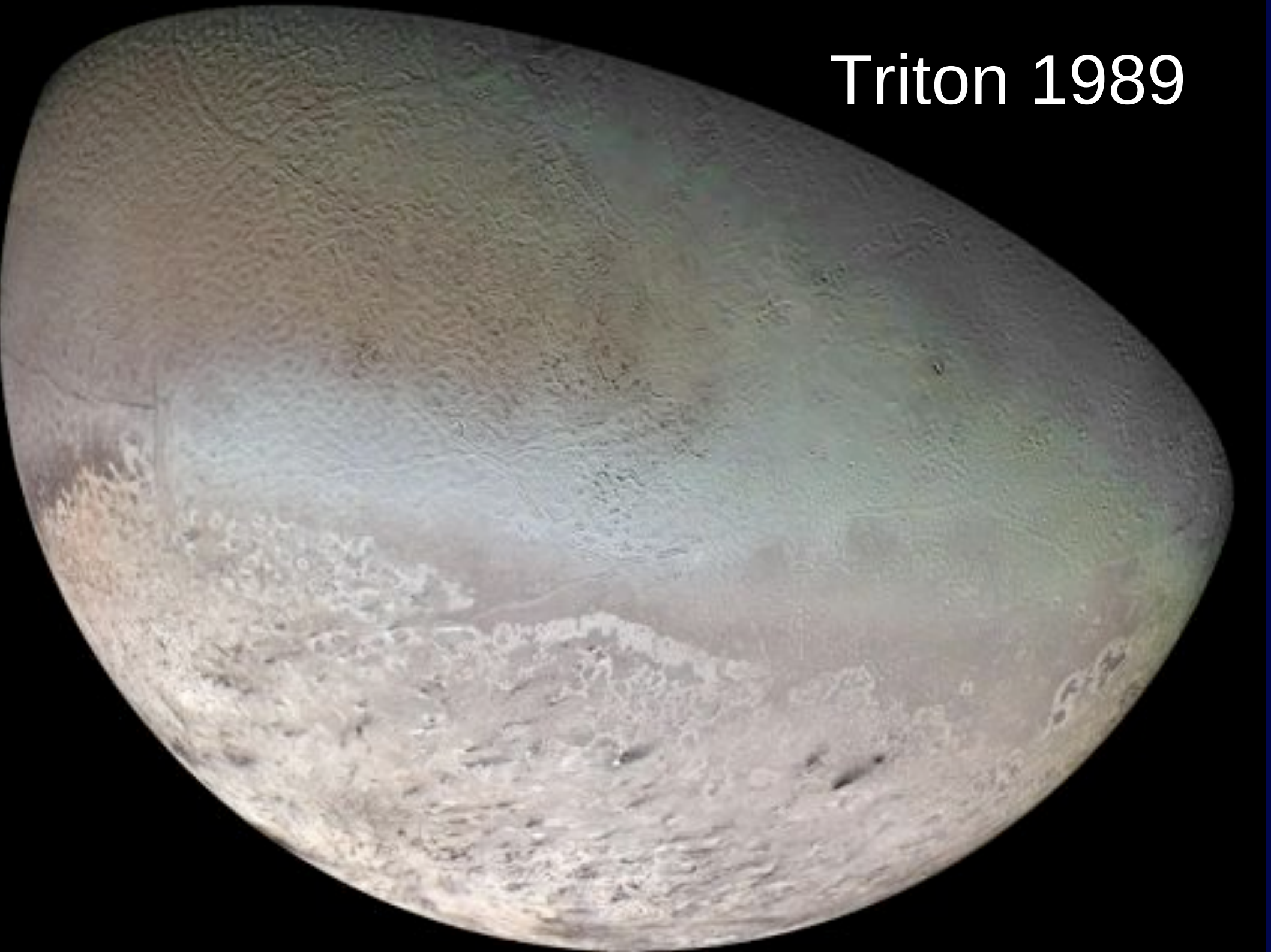


Effects of Sublimation: Callisto

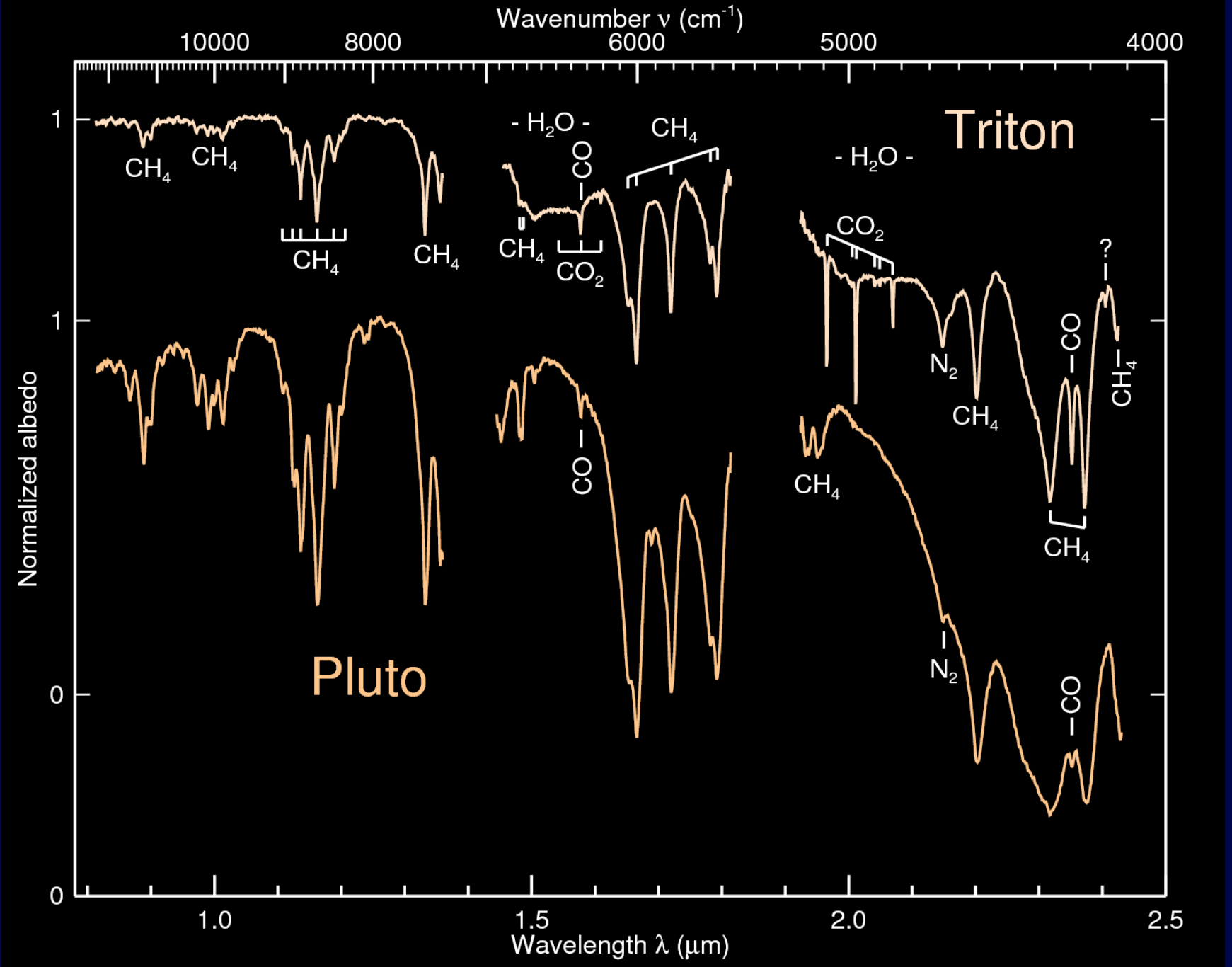


Seasonal Volatile Transport

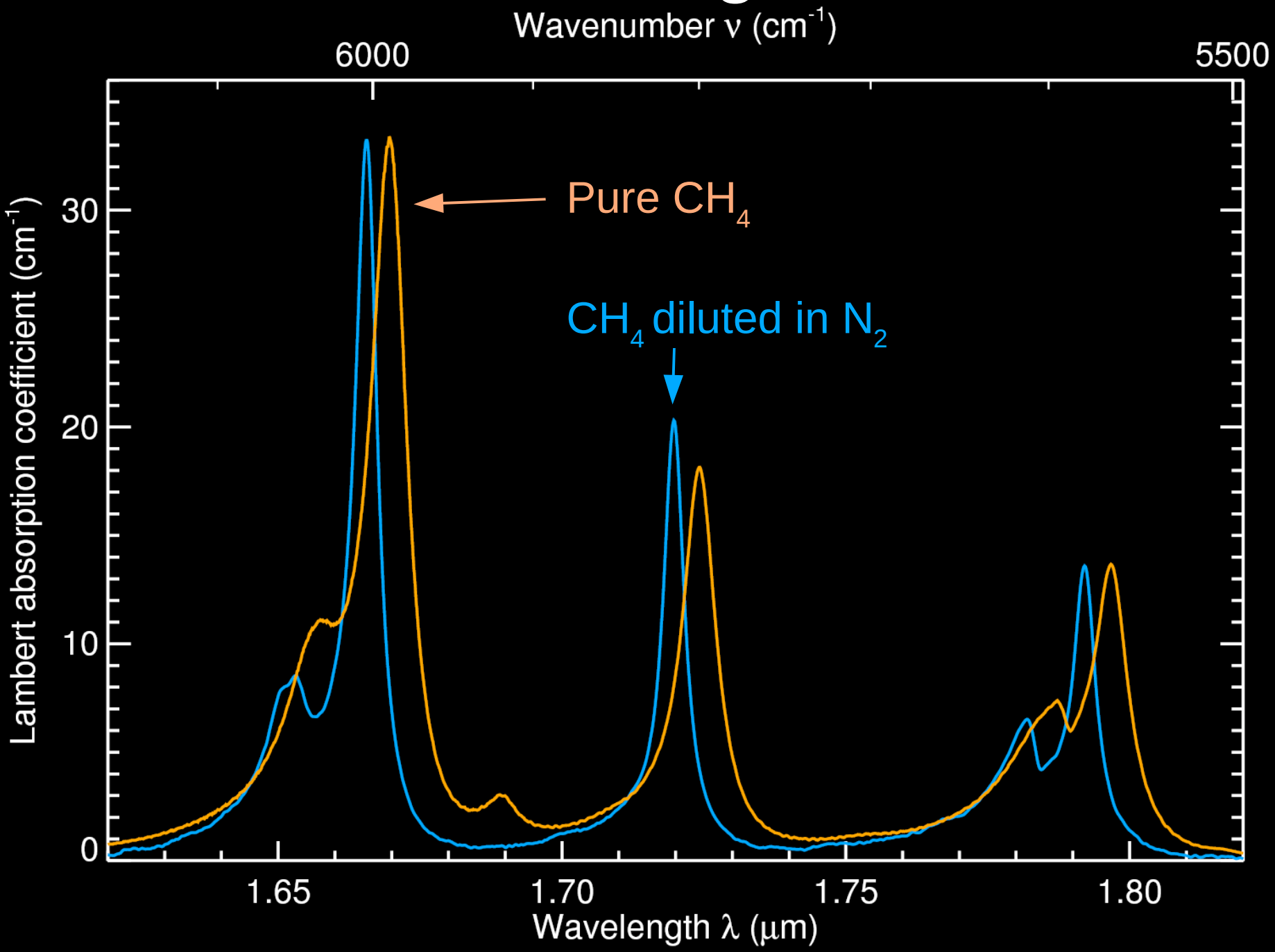



Triton 1989

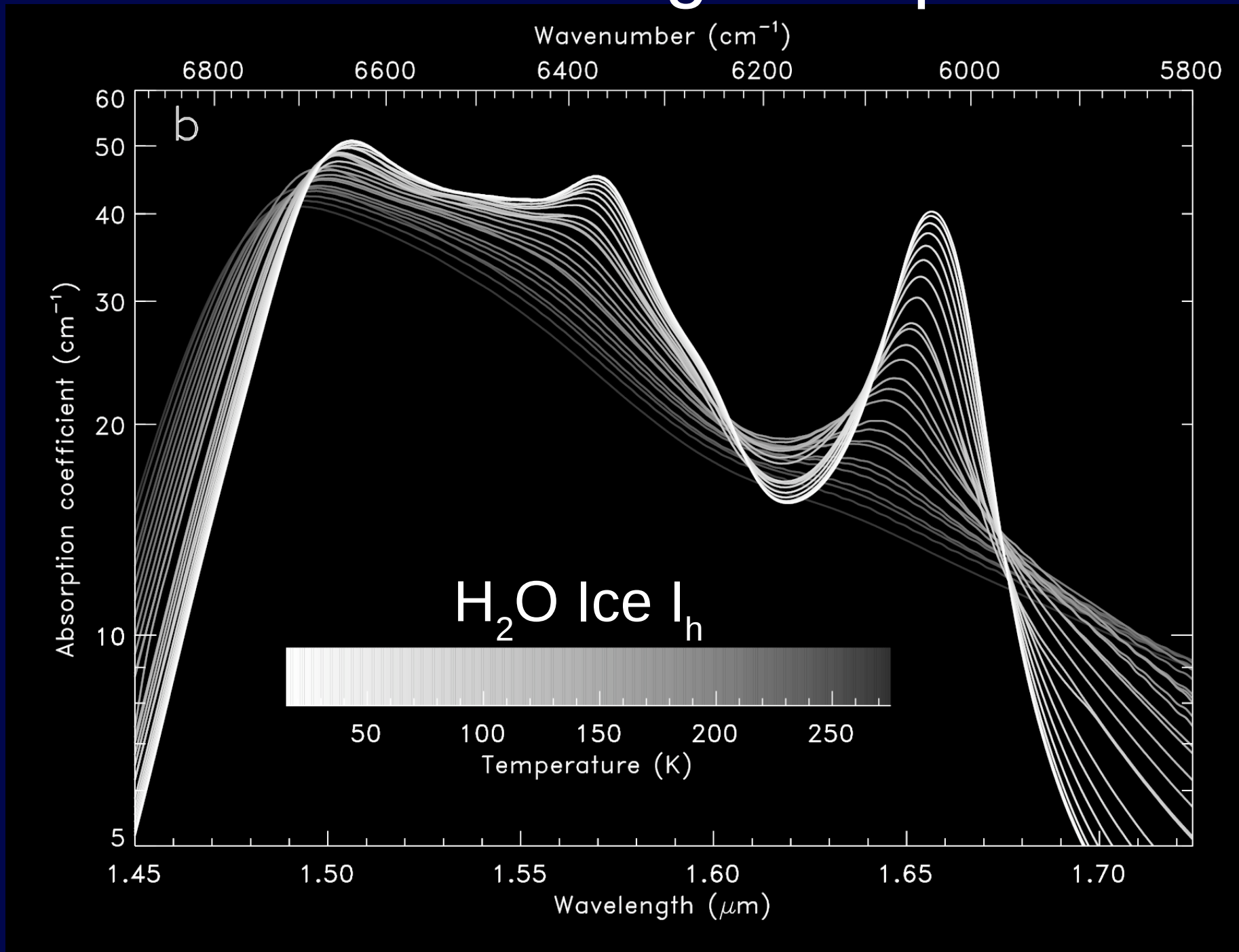
Ice Remote Sensing: Composition



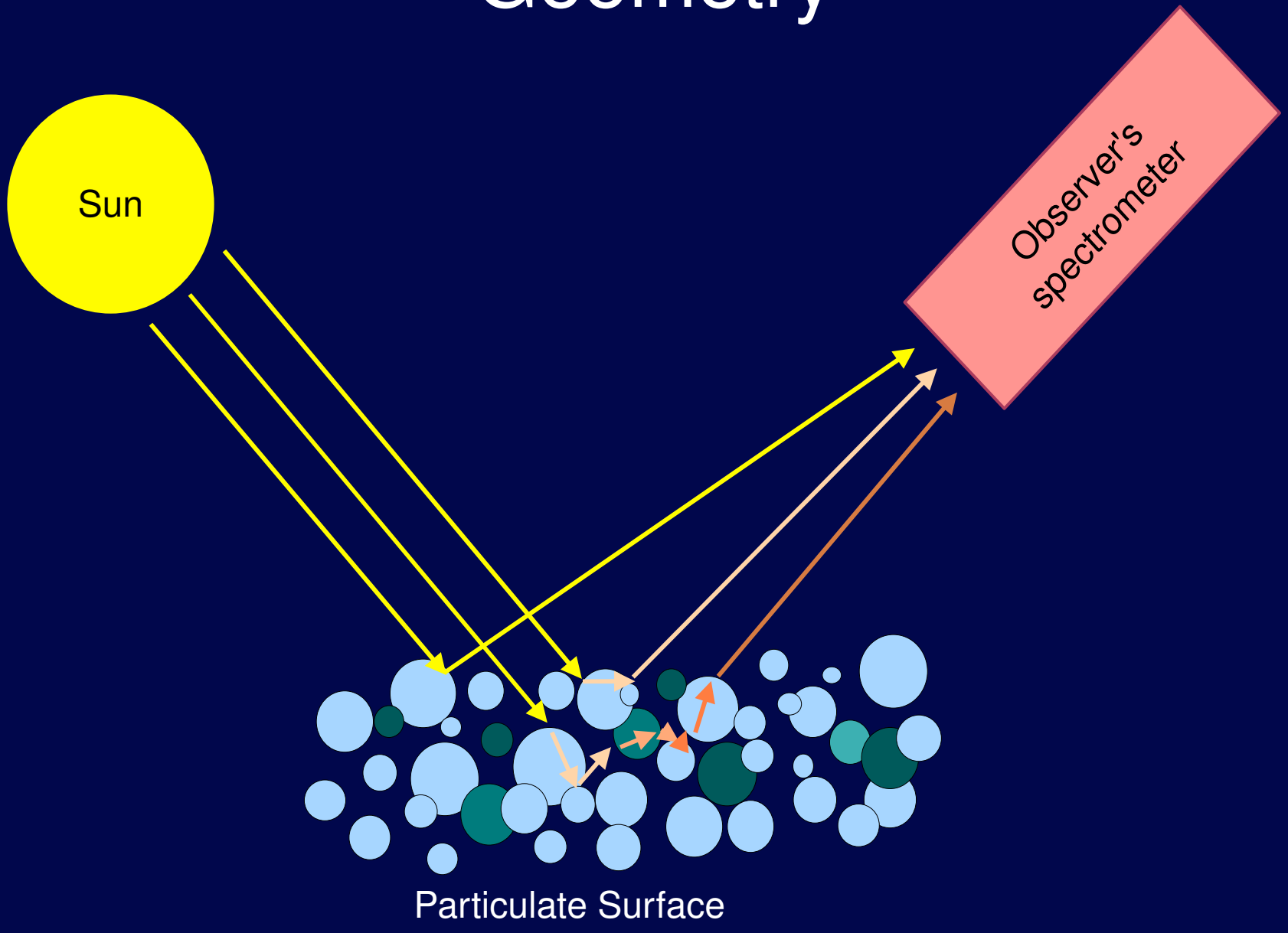
Ice Remote Sensing: Phase State



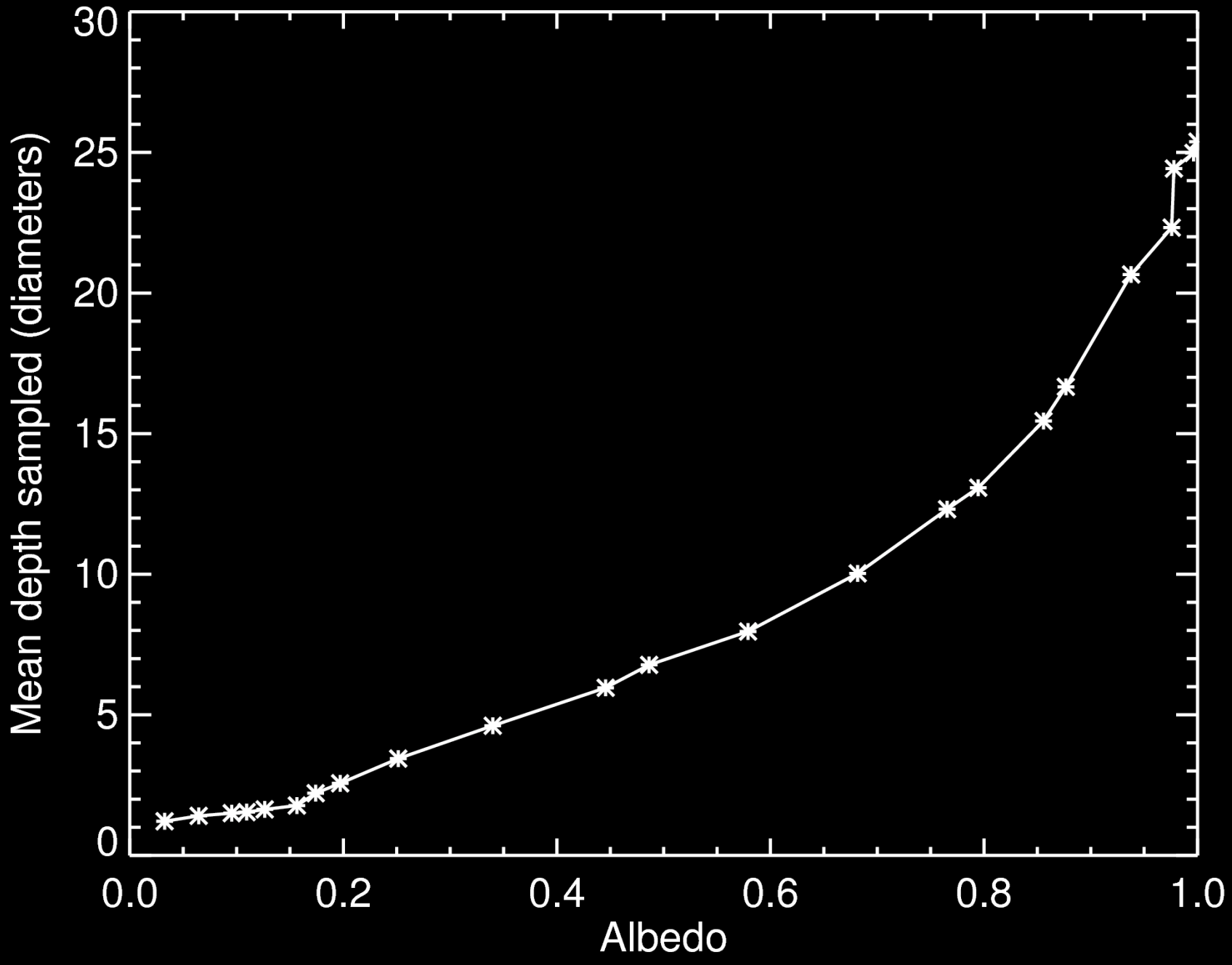
Ice Remote Sensing: Temperatures



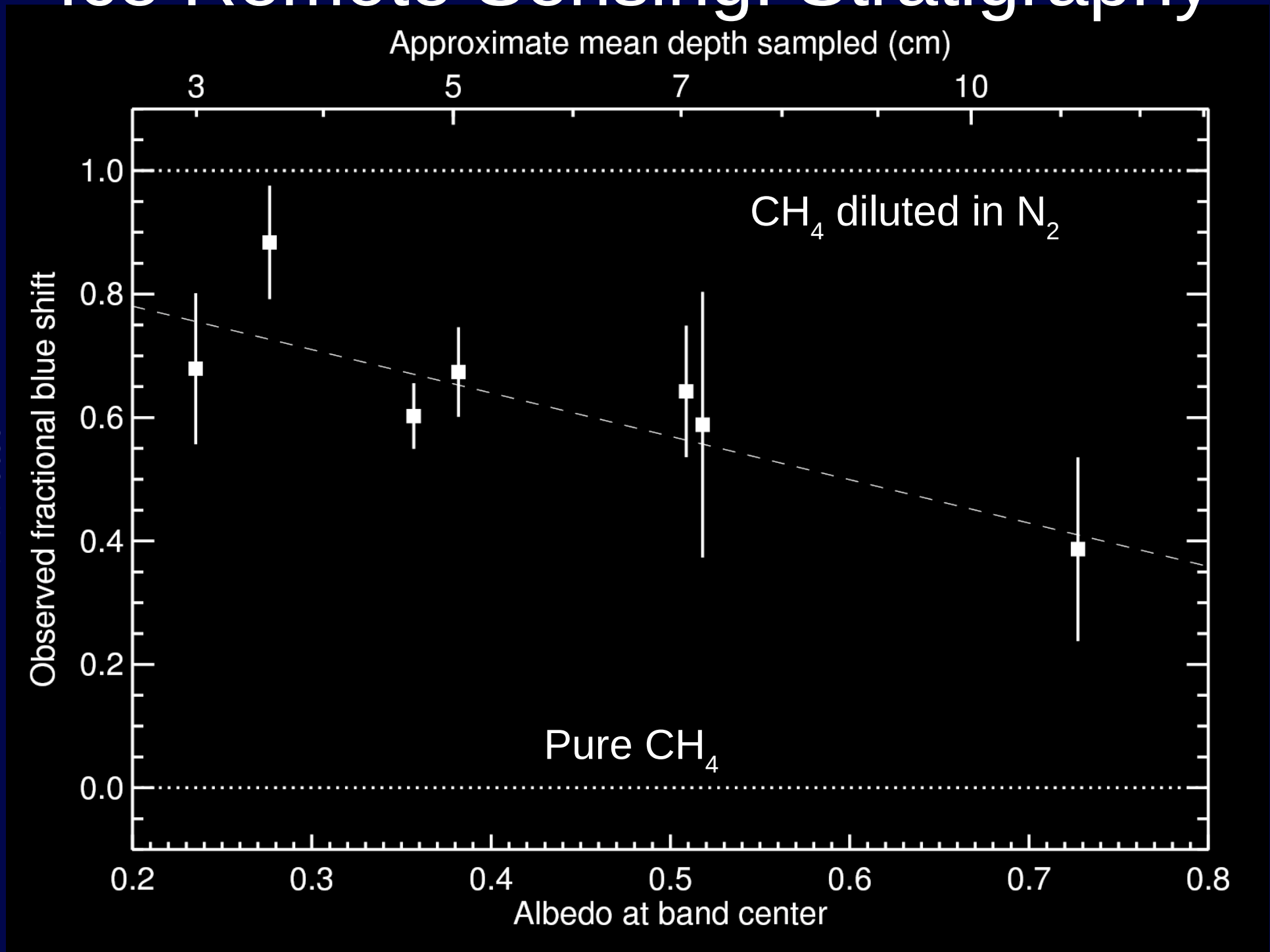
Multiple-Scattering Reflectance Geometry



Wavelength-Depth Relation



Ice Remote Sensing: Stratigraphy

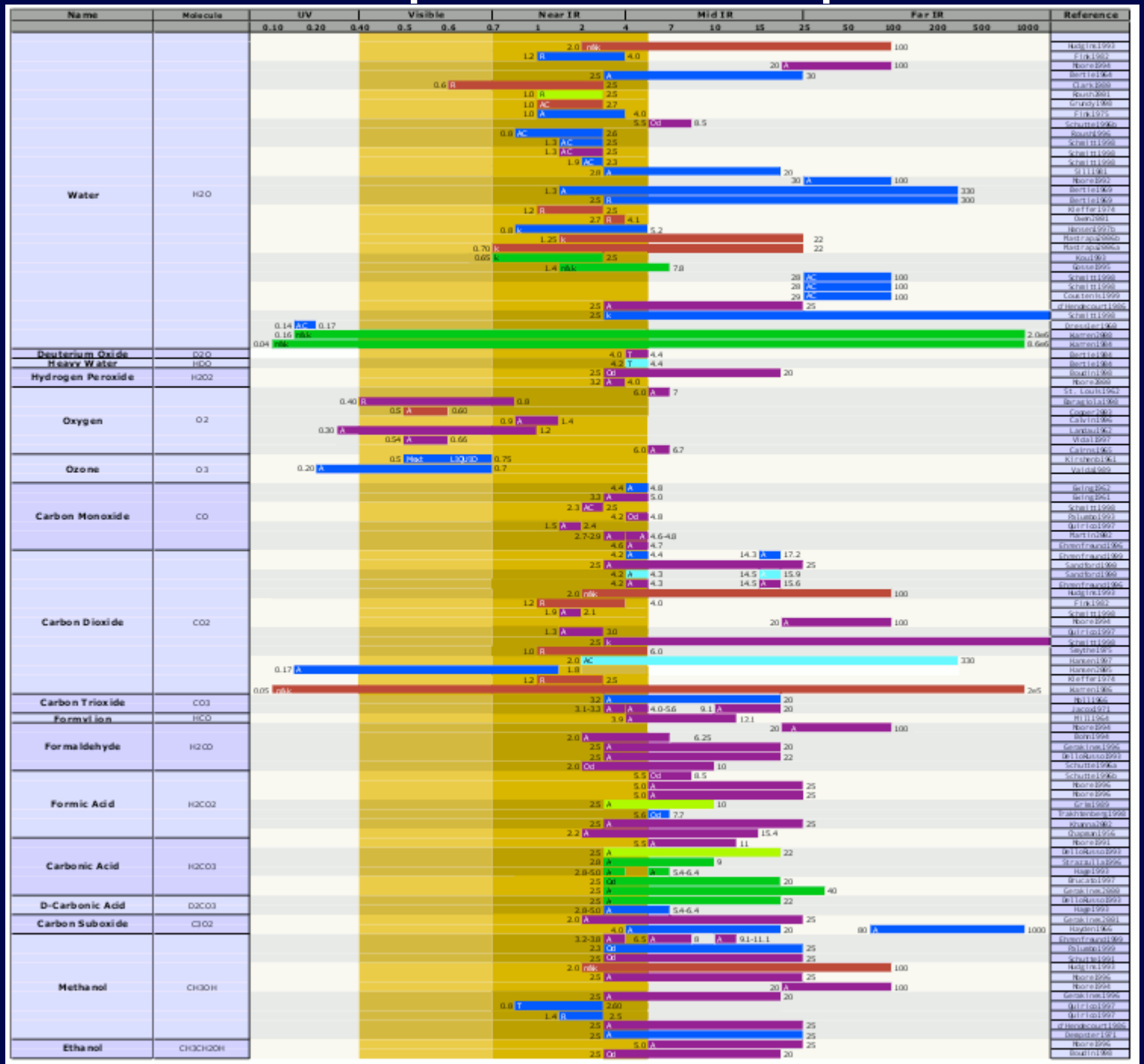


Ice Remote Sensing

- Narrow, near-IR bands enable extraction of lots information from a spectrum
- Deriving composition and texture is reasonably well advanced already, but fundamental data are still missing for far too many species
- More lab work is also needed to be able to extract detailed phase/thermodynamic state, isotopic abundances, etc.

Prospects for ice remote sensing are tremendous but lab work is needed!

Brad Dalton's compilation at http://mos.seti.org



Organic and Carbonaceous Materials

- Huge range of volatilities from CH_4 to graphite
- More complex and refractory organics tend to have poorer remote sensing prospects, but they are a lot easier to bring home undamaged
- Could witness a wide range of history and thermal conditions:
  - Pre-solar
  - Protoplanetary nebula
  - Modern photolysis and radiolysis

How “Pristine” are TNOs & Comets?

Nature -vs- nurture: what characteristics record formation conditions as opposed to subsequent processing?

- Proposal writers like pristine bodies
- Modelers like processes which alter bodies

Some Evidence From Comets

- Compositional homogeneity of fragments (Dello Russo et al. 2007)
- Low bulk densities (Sosa & Fernandez 2009)
- Activity at large distances, interpreted as amorphous ice (Meech et al. 2009)
- Fragile texture (Deep Impact, Breakups, etc.)
- Organic globules (Tagish Lake, Wild 2)

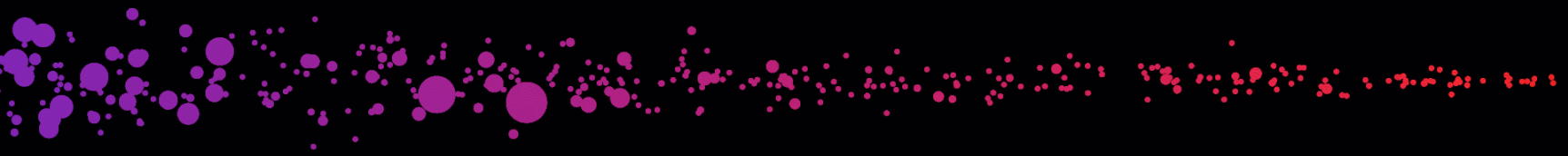
Some Evidence From TNOs

- Clustering of colors (Barucci et al. 2005)
- Absence of size dependence of colors (Doressoundiram et al. 2008)
- Rarity of color lightcurve variation (Doressoundiram et al. 2005)
- Colors of captured binaries (Benecchi et al. 2009)
- Low densities of some small TNOs
- Differences of “Cold Classical” TNOs

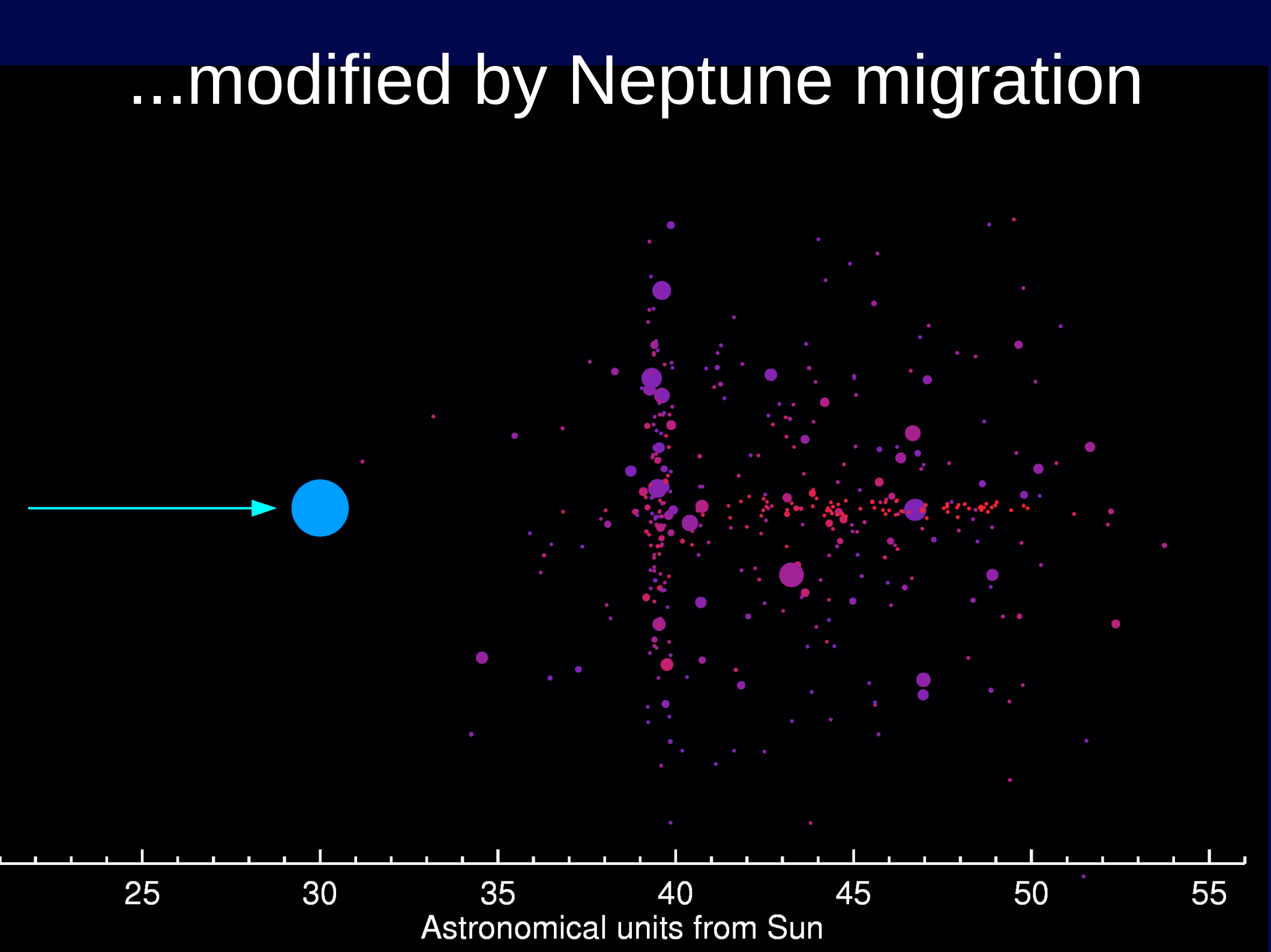
Early, dense, quiescent disk...

Possible compositional zoning or gradients from:

- Solar heating & energetic radiation
- Radial mixing, sublimation & recondensation
- Dynamical time scales & radiogenic heating



...modified by Neptune migration



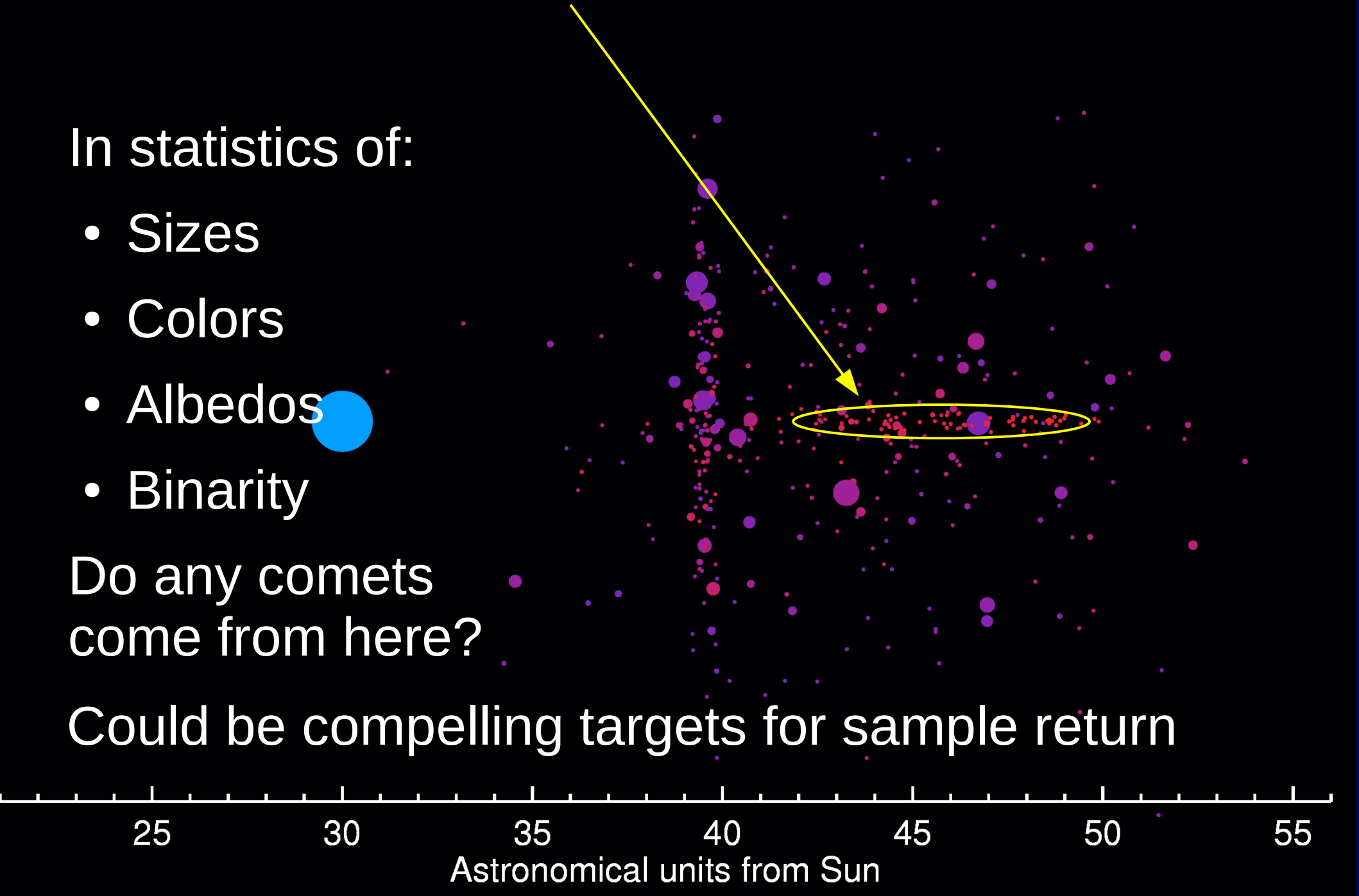
Cold Classicals Are Different

In statistics of:

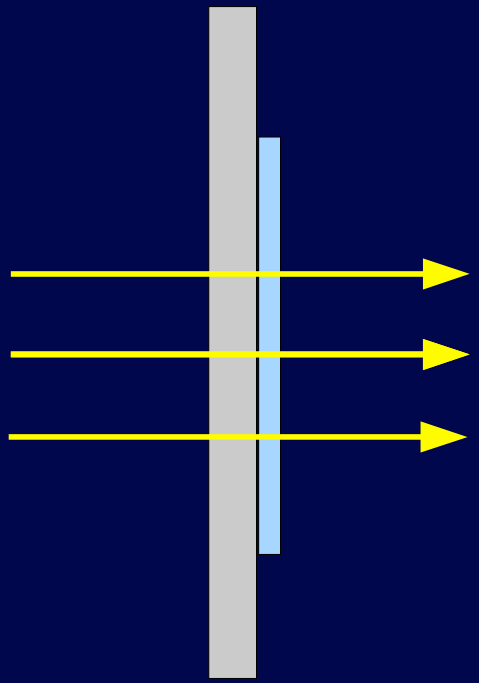
- Sizes
- Colors
- Albedos
- Binarity

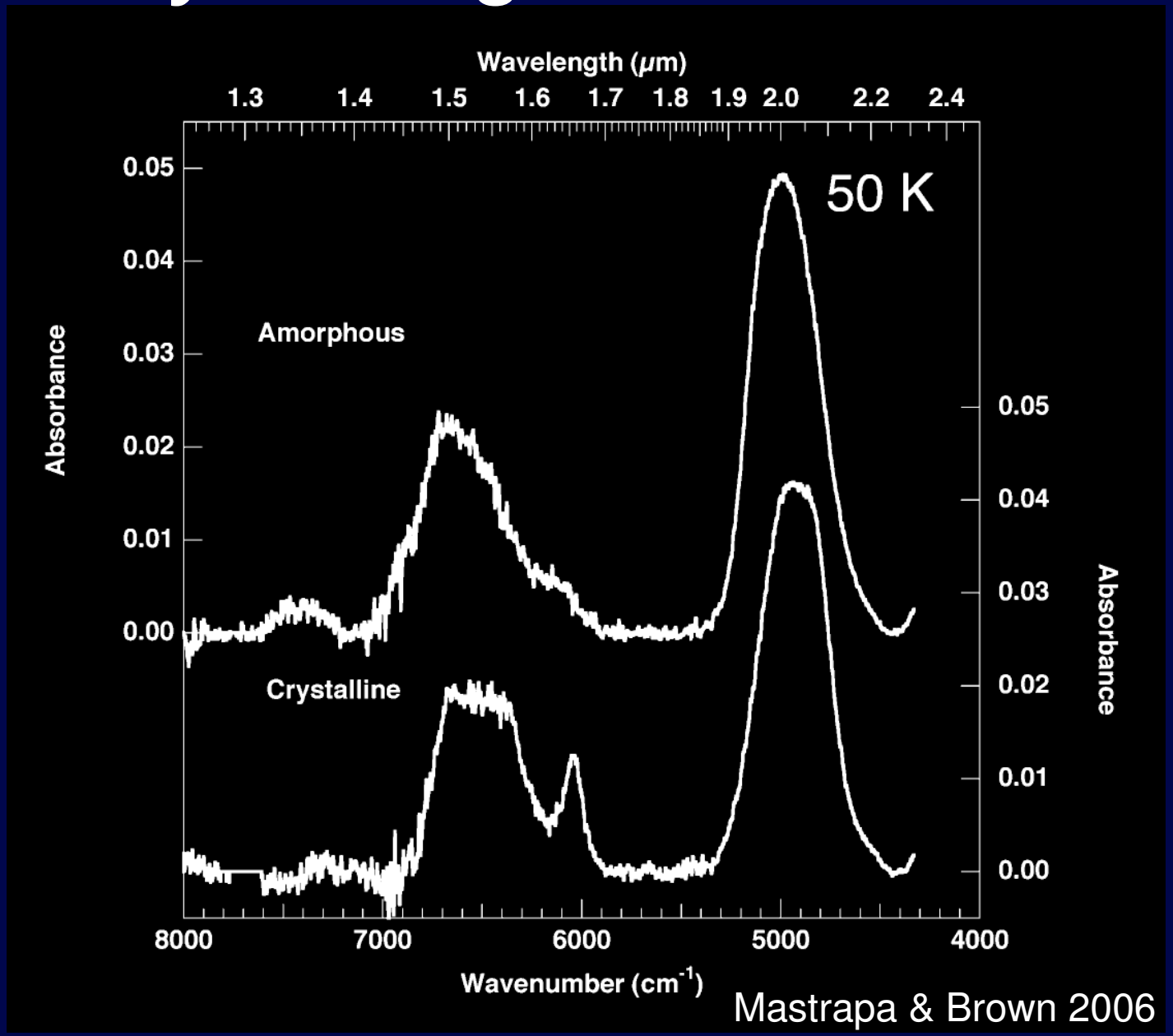
Do any comets come from here?

Could be compelling targets for sample return

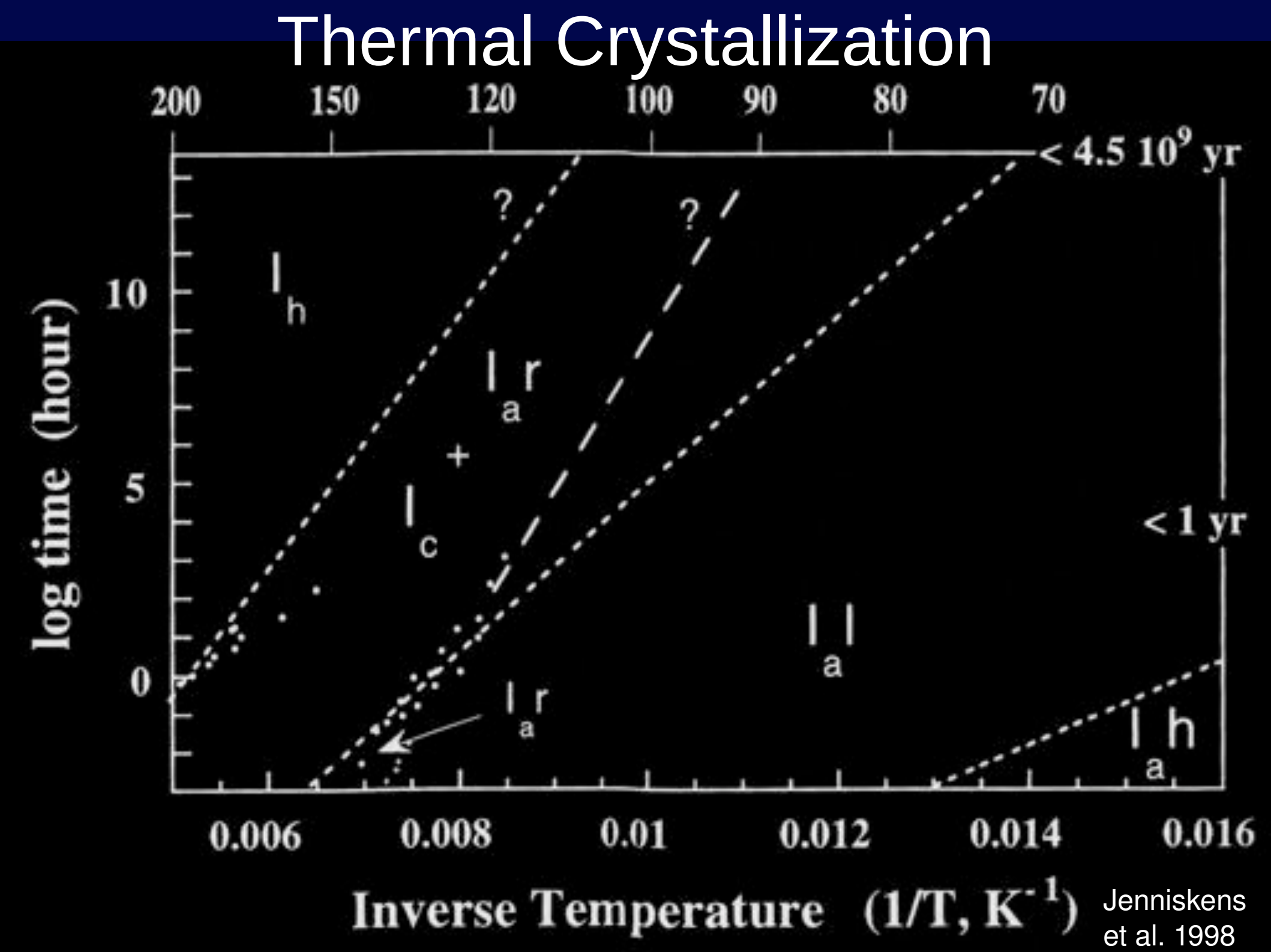


Crystalline -vs- Amorphous H_2O spectrally distinguishable





Thermal Crystallization



Jenniskens et al. 1998

But surfaces all look crystalline:

- Uranian satellites
- Triton
- Charon
- TNOs (Orcus, Quaoar, Haumea,

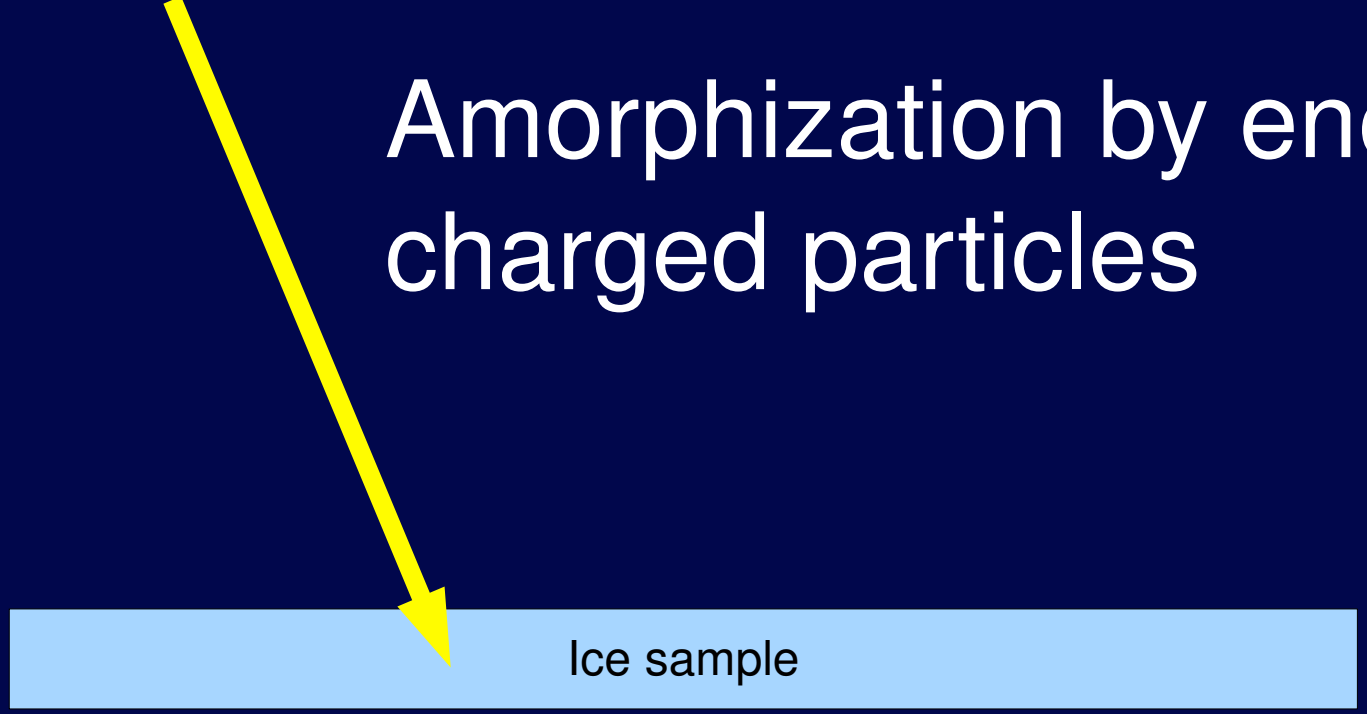
These objects are all cold enough that their surfaces ought to be amorphous.

But they aren't.

How does it crystallize?

- Eruptive resurfacing?
- Micrometeorite annealing?
- Sputtering erosion exceeds amorphization?
- Non-thermal crystallization?

Amorphization by energetic charged particles



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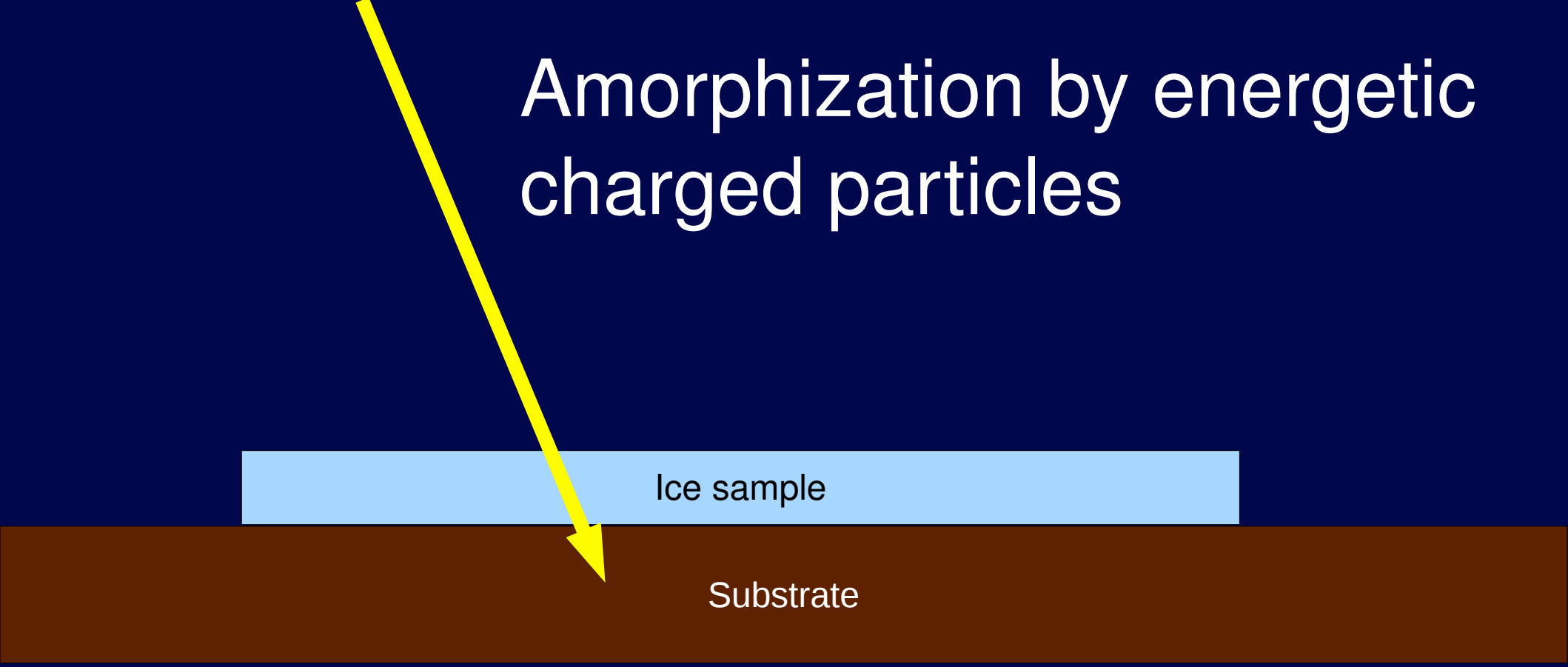

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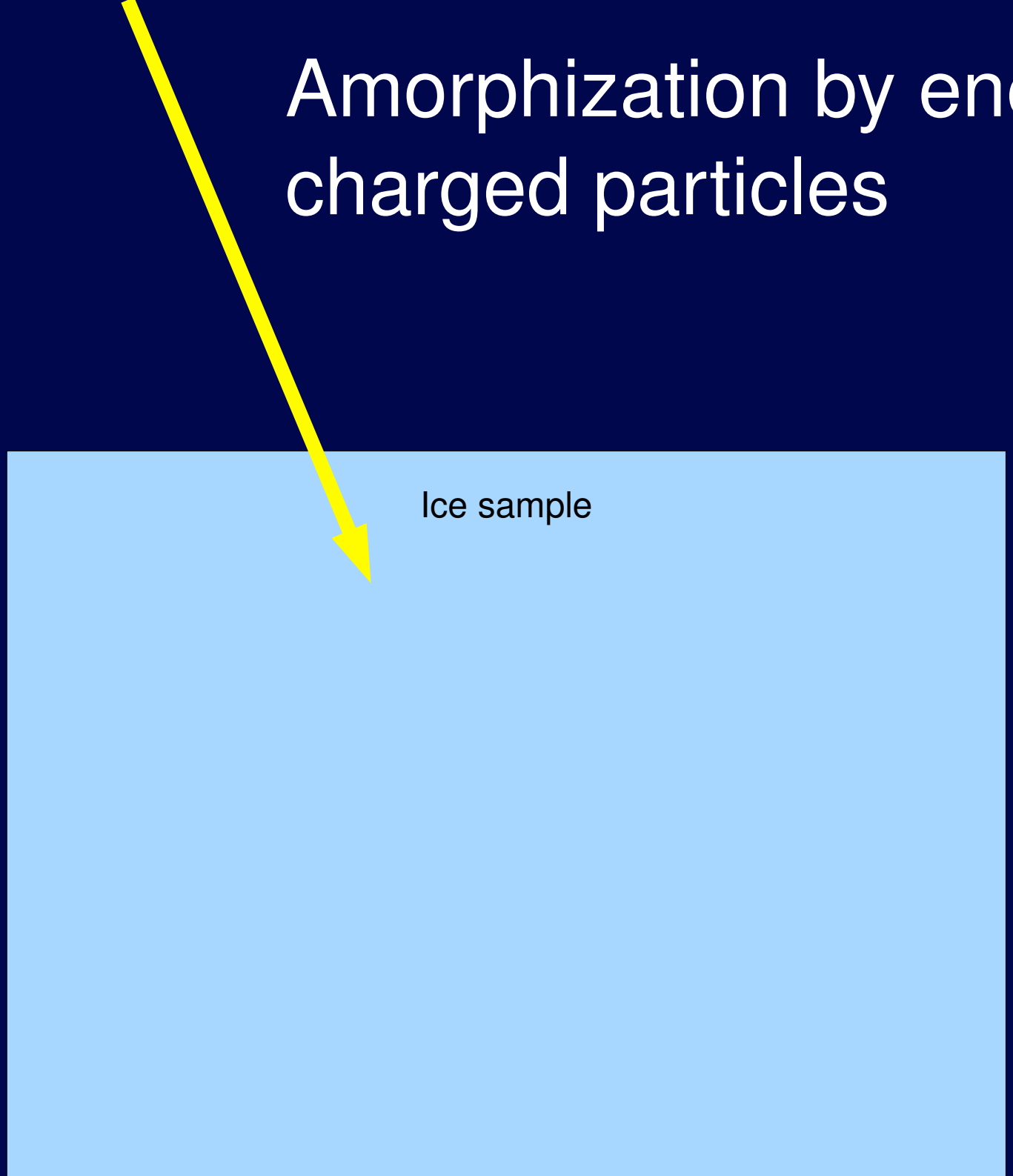

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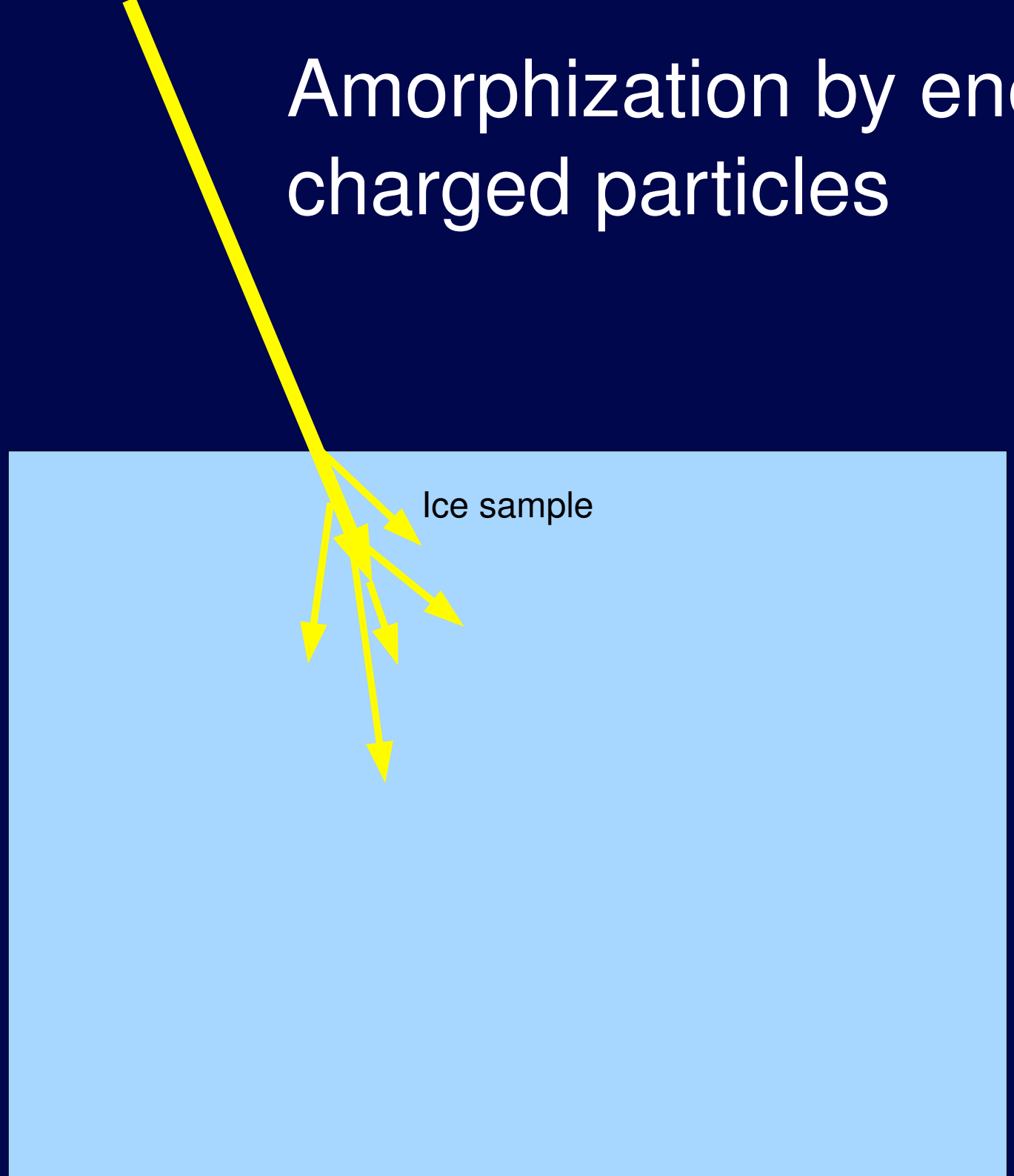

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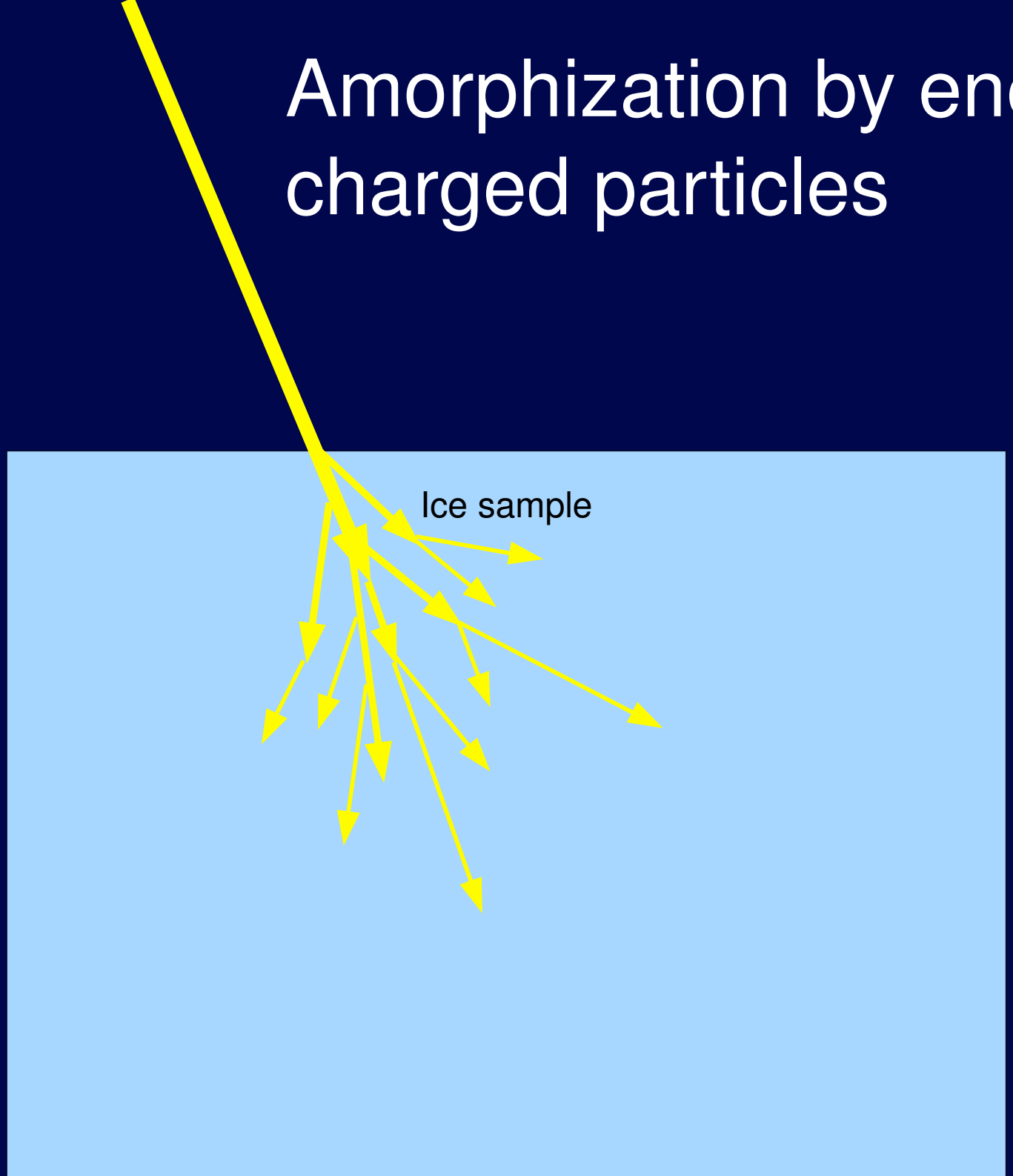
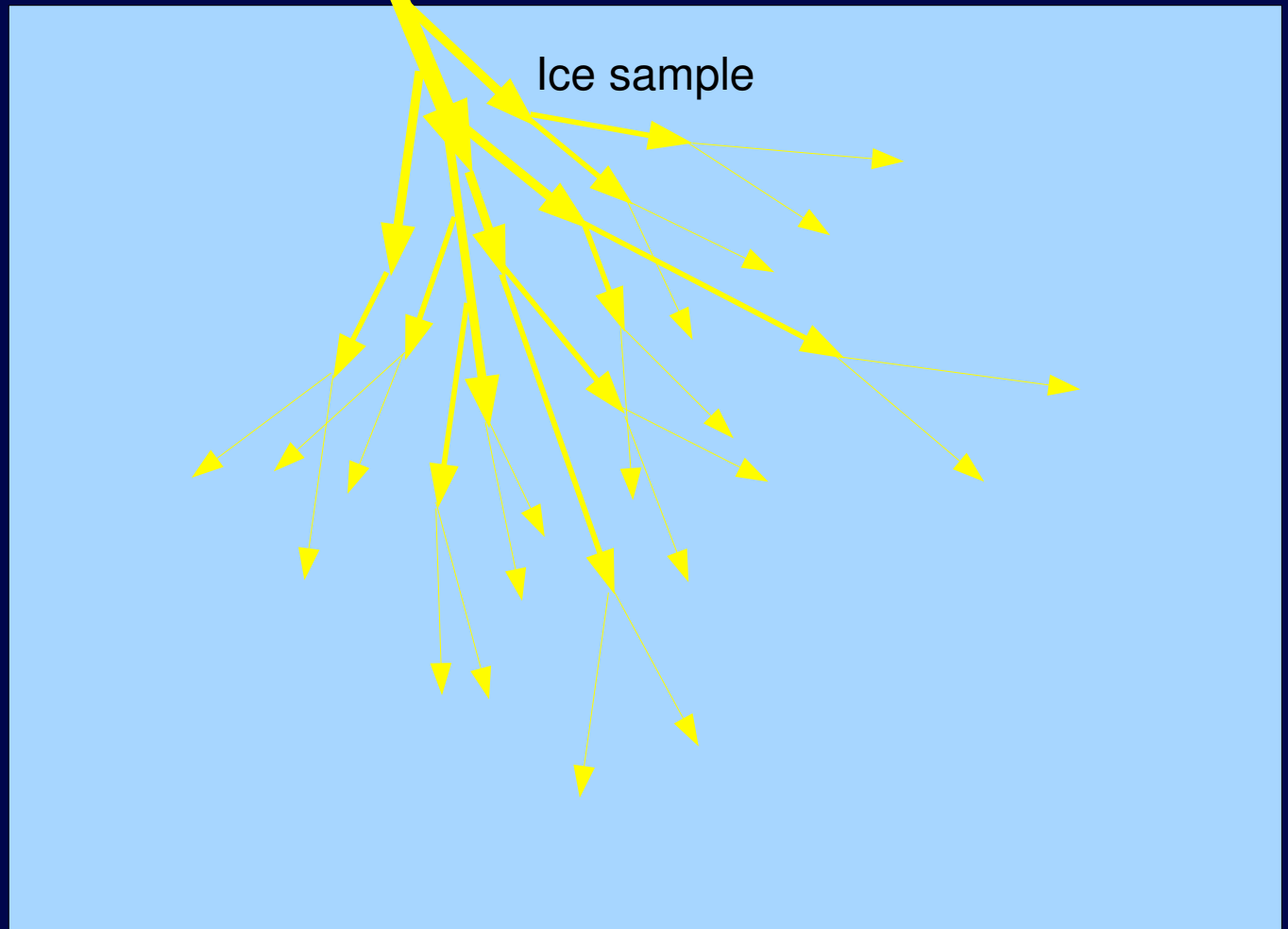
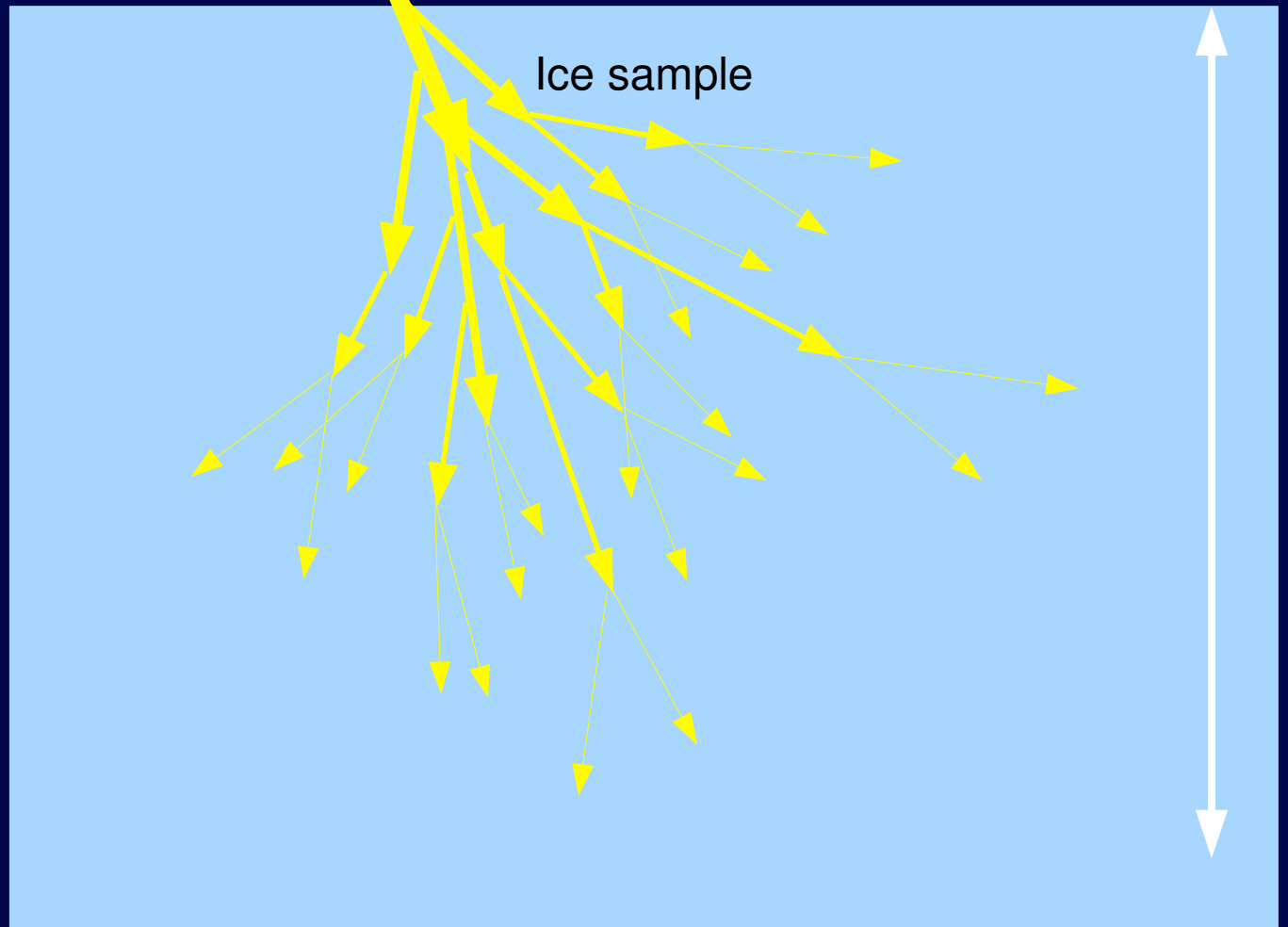


Amorphization by energetic charged particles

→ cascade of energy



Amorphization by energetic charged particles
→ cascade of energy



Reflectance spectroscopy probes deep into ice, mm to cm depths.

Future Work

- New Horizons observations of Nix and Hydra: are their surfaces crystalline, but ancient?
- New Horizons dust observations: is abundance beyond Neptune high enough to anneal ice?
- Laboratory experiments to explore non-thermal crystallization mechanisms?