Ice in the Solar System

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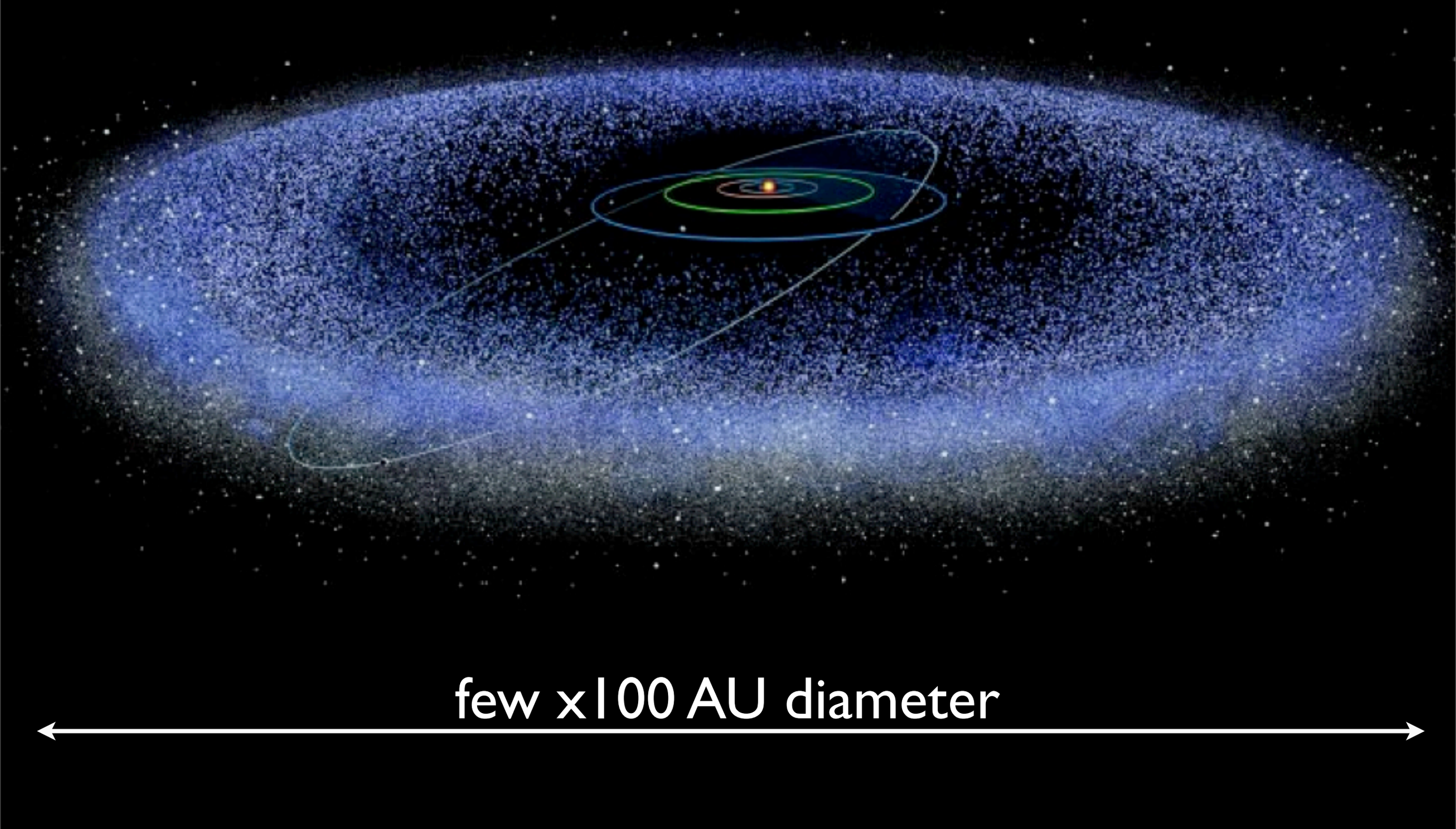
Objective: To give a broad overview of ice and its importance.

Outline of the Talk:

1. Introduction & Motivation
2. Surface Ice (ice beyond snow-line)
3. Interior Ice

Kuiper Belt - our local icebox



few x100 AU diameter

Isothermal Blackbody Temperature

$$T_{BB} = \frac{278}{R^{1/2}}$$

Ice too cold to sublimate R > 6 AU

Outside the Snow Line

Ice sublimates negligibly R > 6 AU

Surface ice, detected through vibrational transitions (fundamental @ 3 μm, overtones & combinations at 2 μm and 1.5 μm) is widespread at larger distances

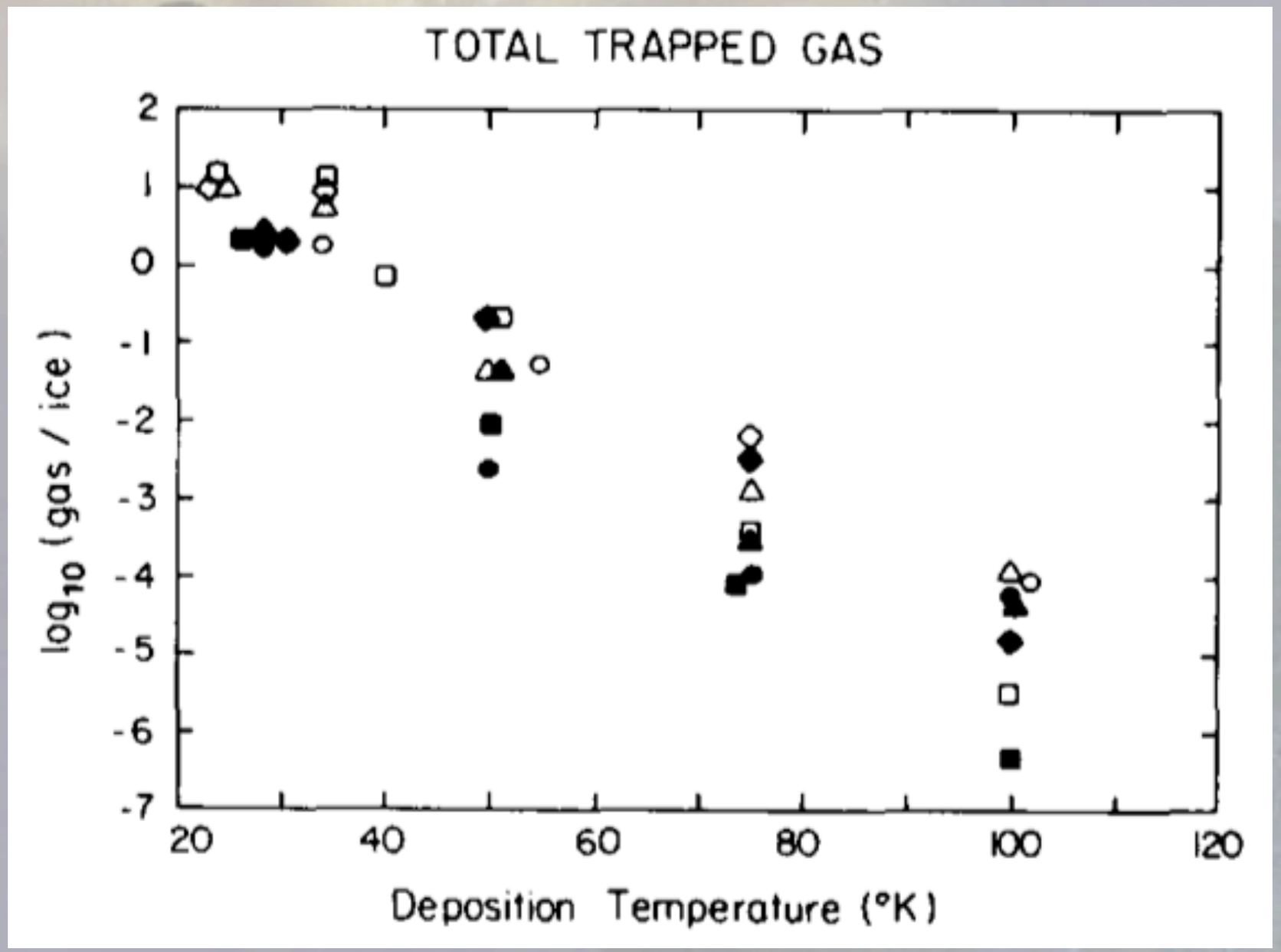
Crystallization Time

$$\tau_{cr} = 3.0 \times 10^{-21} \exp\left[\frac{E_A}{kT}\right]$$

$$\Delta E = 9 \times 10^4 \quad Jkg^{-1}$$

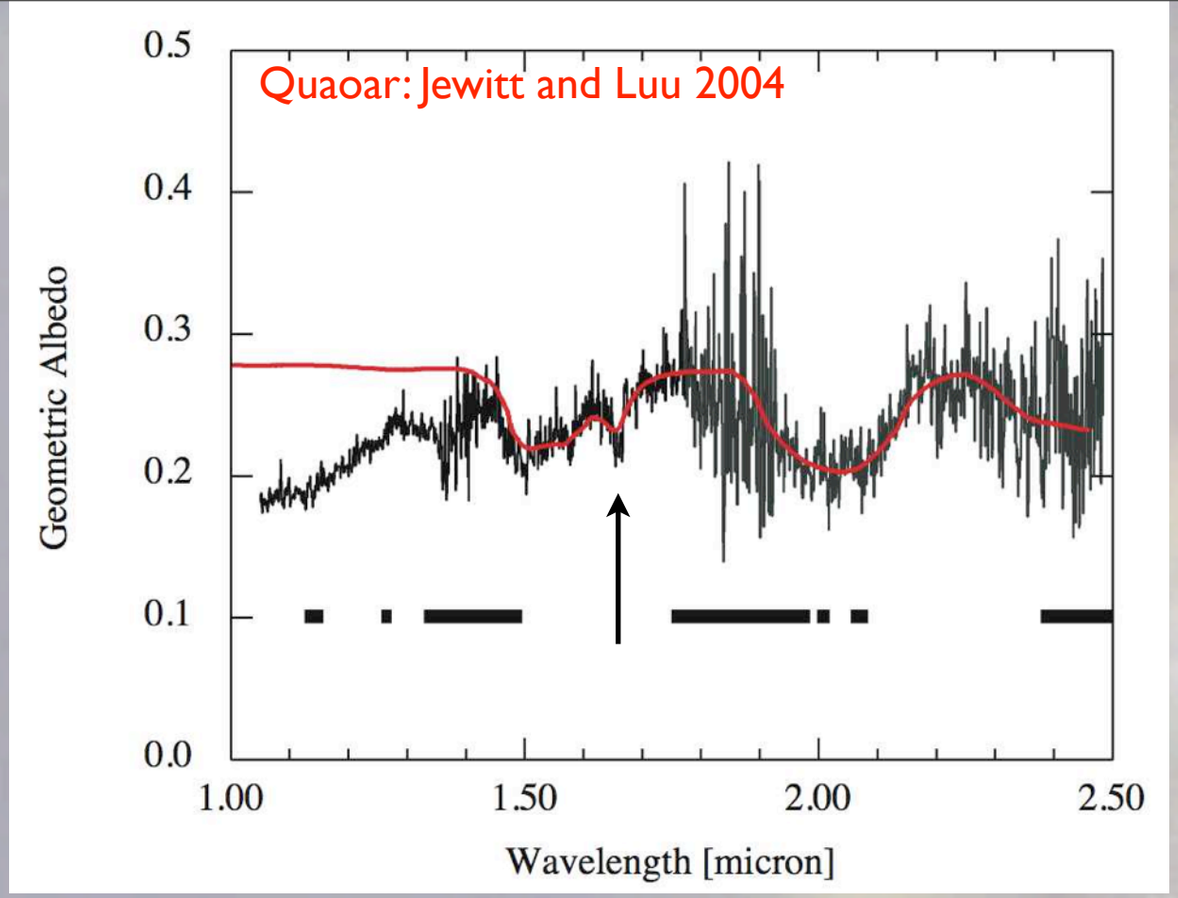
What is the state of the ice?

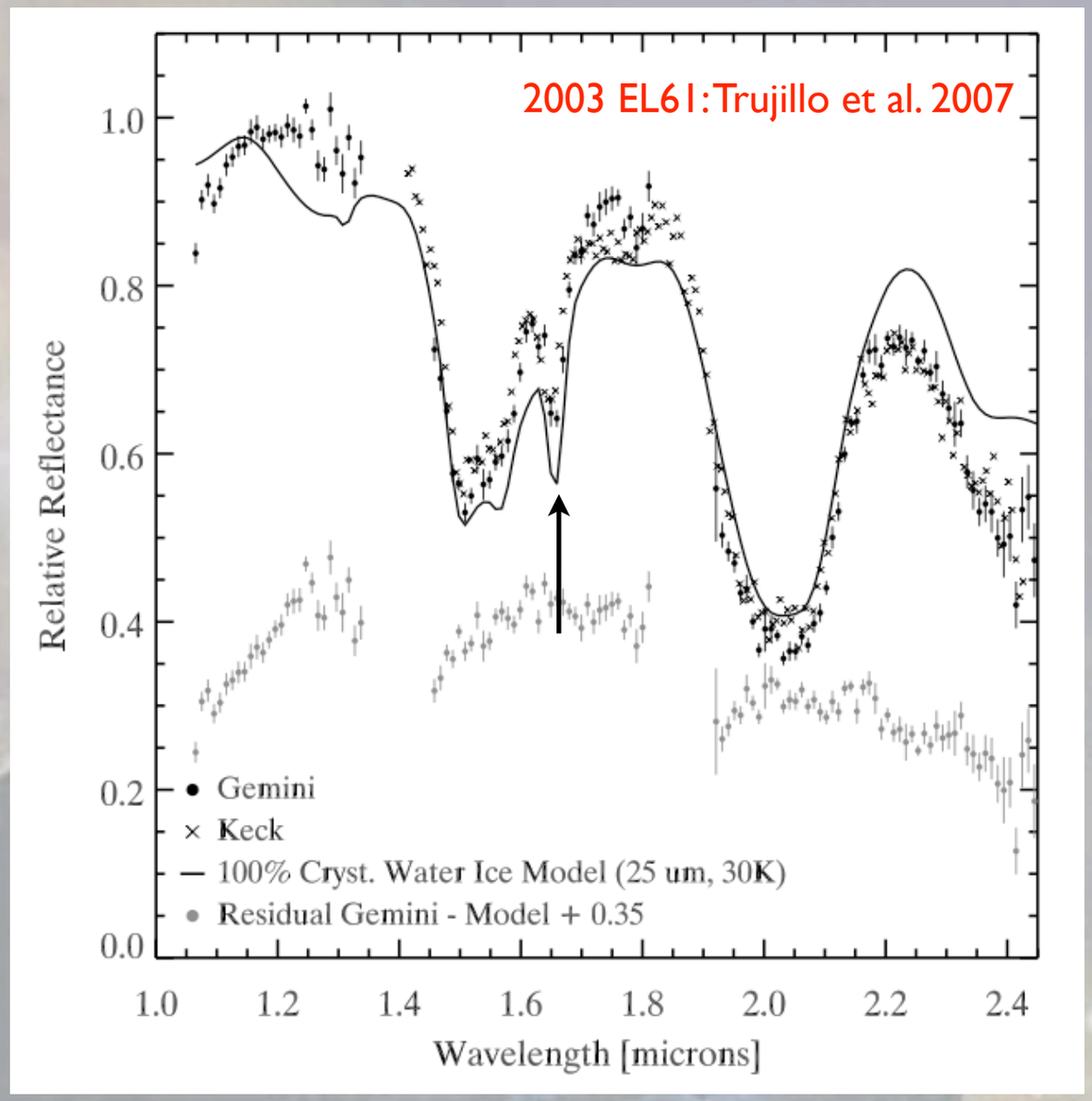
Gas Trapping

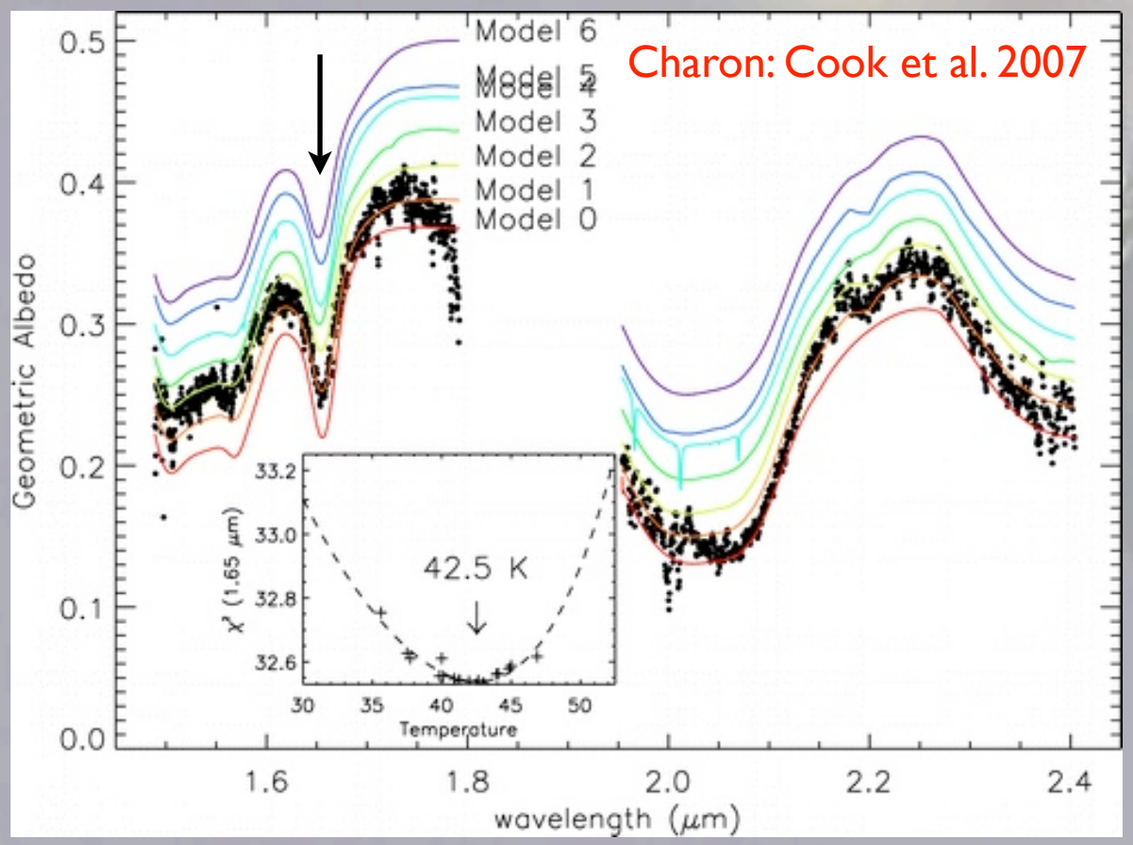


Bar-Nun & Kleinfeld 1989

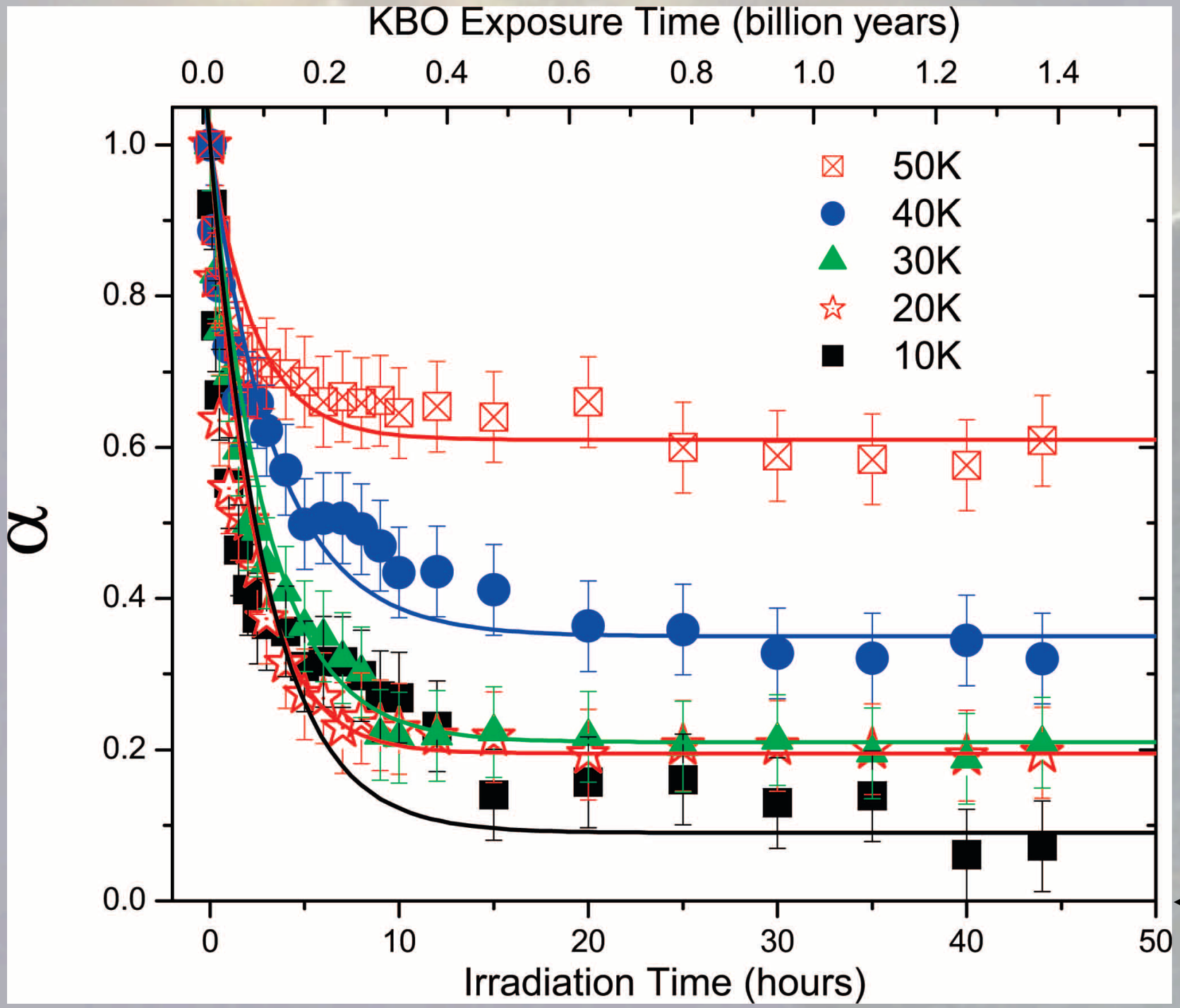
Crystallization releases trapped gas and energy:
result = explosive


Quaoar: Jewitt and Luu 2004
Geometric Albedo
0.0
0.1
0.2
0.3
0.4
0.5
1.00
1.50
2.00
2.50
Wavelength [micron]


2003 EL61: Trujillo et al. 2007
Relative Reflectance
0.0
0.2
0.4
0.6
0.8
1.0
Gemini
Keck
100% Cryst. Water Ice Model (25 um, 30K)
Residual Gemini - Model + 0.35
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Wavelength [microns]


Charon: Cook et al. 2007
Model 6
Model 5
Model 4
Model 3
Model 2
Model 1
Model 0
Geometric Albedo
0.0
0.1
0.2
0.3
0.4
0.5
42.5 K
χ² (1.65 μm)
33.2
33.0
32.8
32.6
30
35
40
45
50
Temperature
1.6
1.8
2.0
2.2
2.4
wavelength (μm)

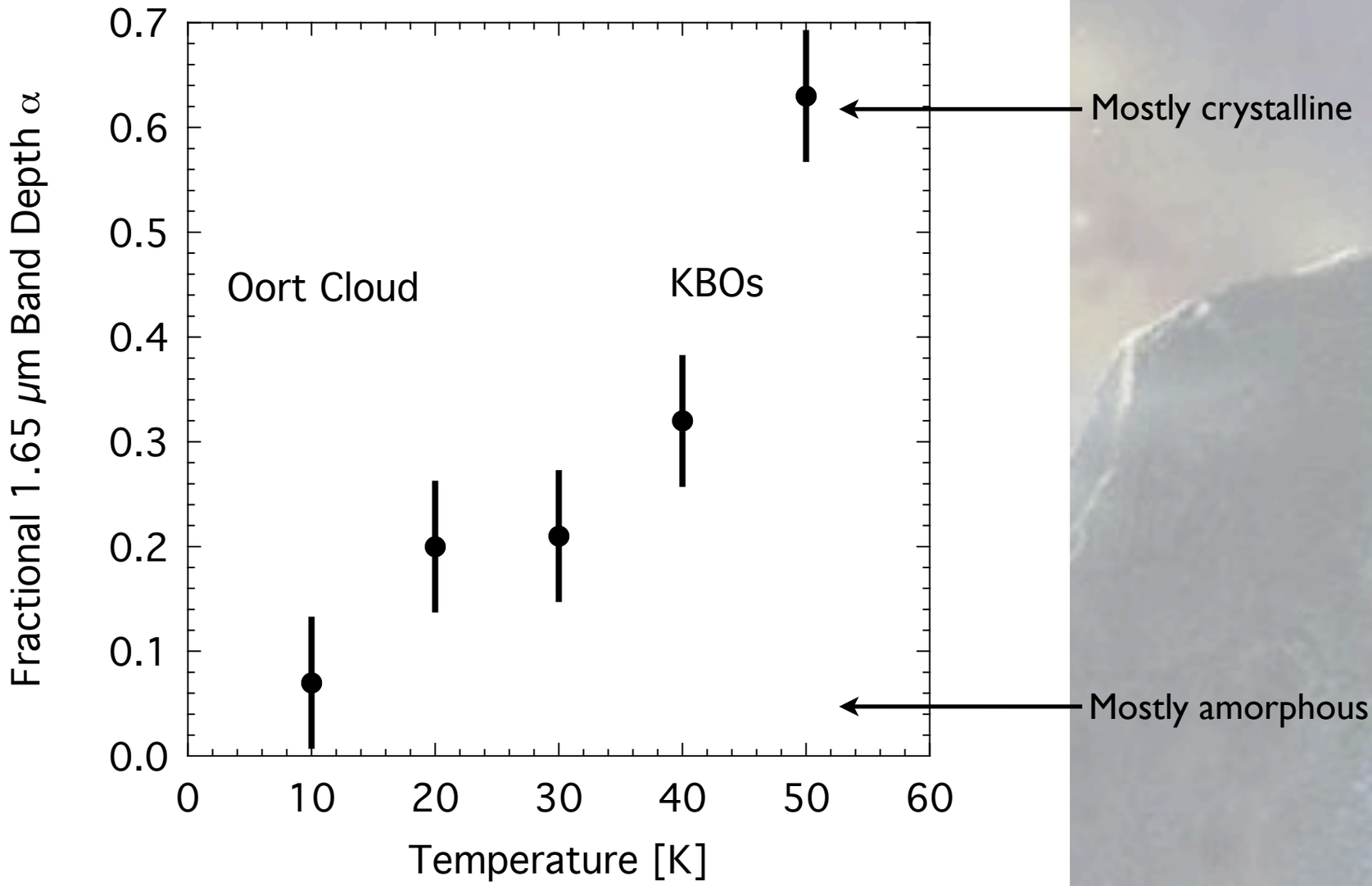
Hawaii Ultra-High Vacuum Machine



← Pure crystalline

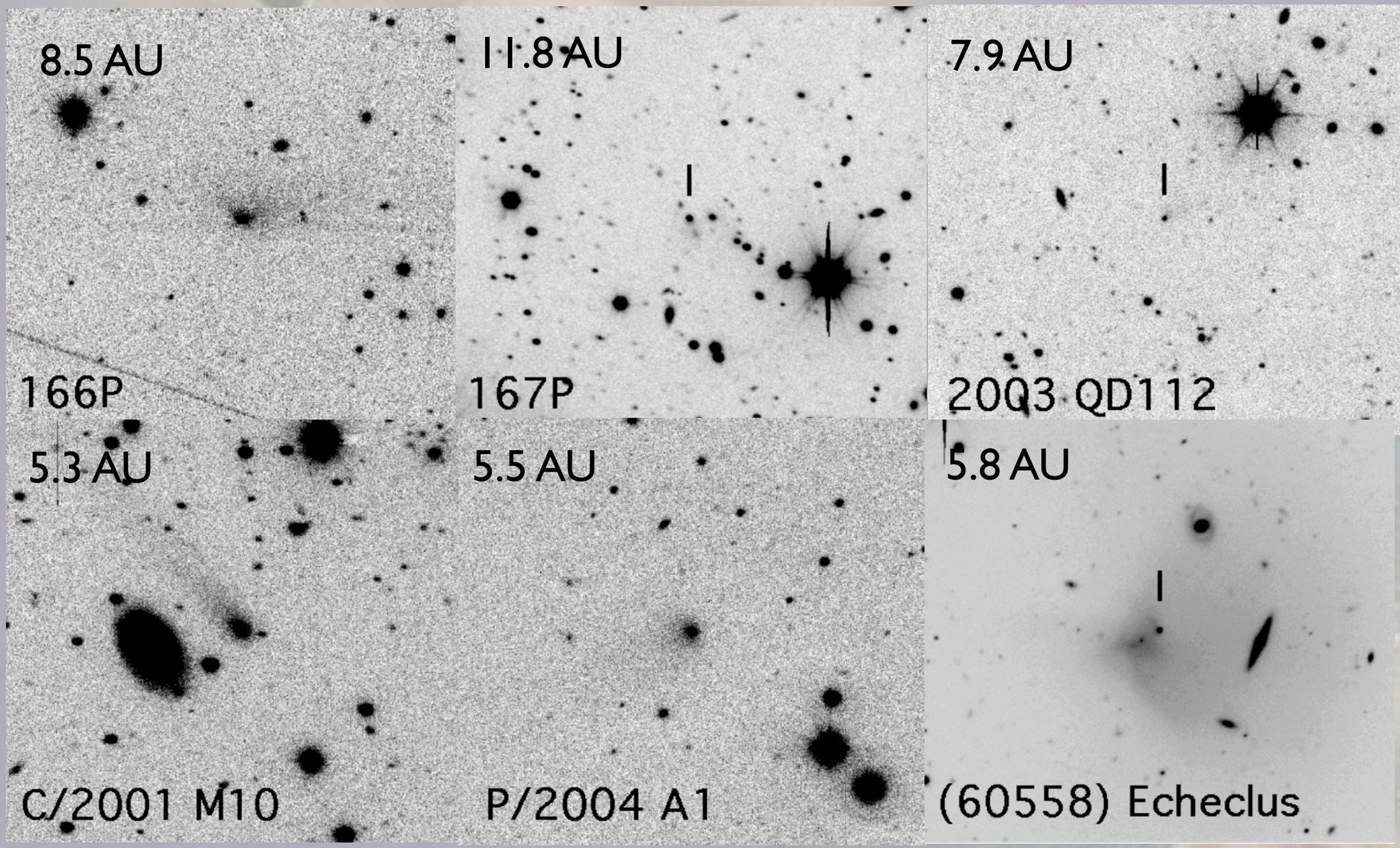
← Pure amorphous

Zheng, Jewitt and Kaiser (2008)

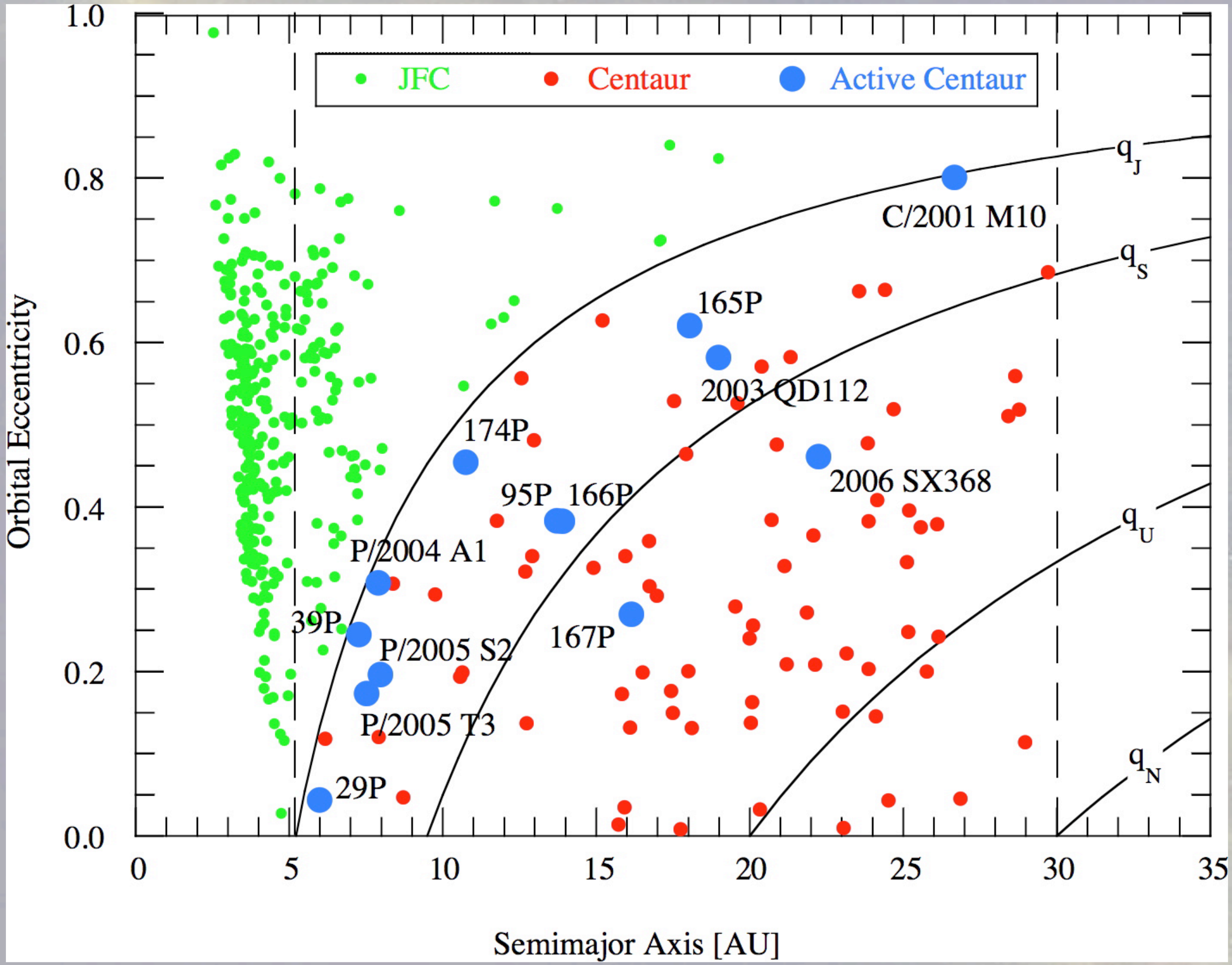


Zheng et al. 2008 (5keV electrons)
c.f. Strazzulla et al 1992 (3kev He+ ions)

Evidence from the Active Centaurs



Sample Active Centaurs - Keck and UH 88


JFC
Centaur
Active Centaur
1.0
0.8
0.6
0.4
0.2
0.0
Orbital Eccentricity
0
5
10
15
20
25
30
35
Semimajor Axis [AU]
q_J
q_S
q_U
q_N
C/2001 M10
165P
2003 QD112
174P
95P
166P
2006 SX368
P/2004 A1
39P
P/2005 S2
167P
P/2005 T3
29P

$$\tau_{cr} = 3.0 \times 10^{-21} \exp\left[\frac{E_A}{kT}\right]$$

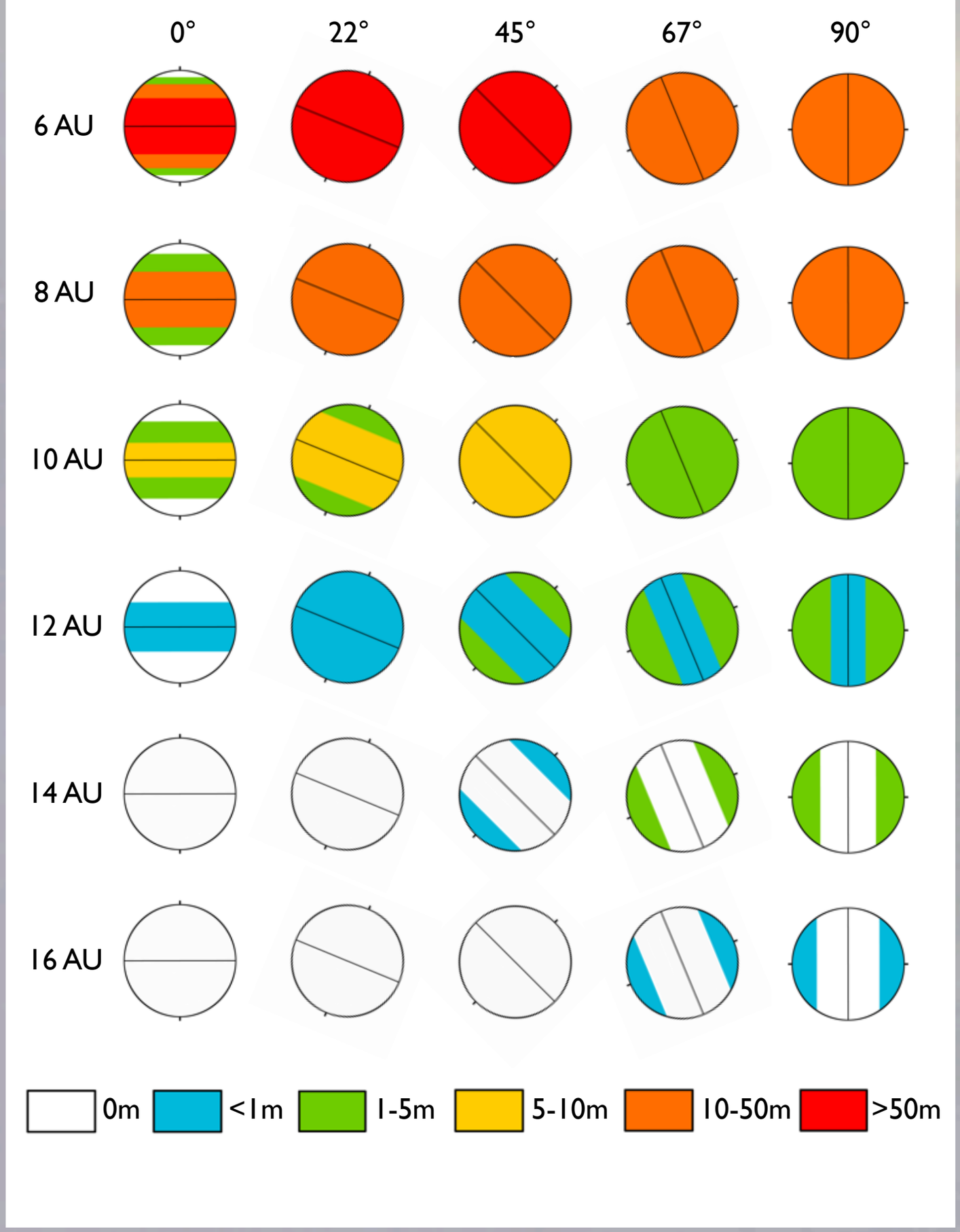
Setting condition for crystallization $\tau_{cr} \leq \tau_k$

gives.... $$\frac{3}{2} \ln R_{au} = -47.26 + \frac{E_A \sqrt{R_{au}}}{kT_1}$$

Solutions for coldest (hottest) isothermal (subsolar) equilibria are

$$7 \leq R_{au} \leq 14 \text{ AU}$$

- this is about what we observe



Centaur activity is observed only on objects where crystallization time ≤ orbit period

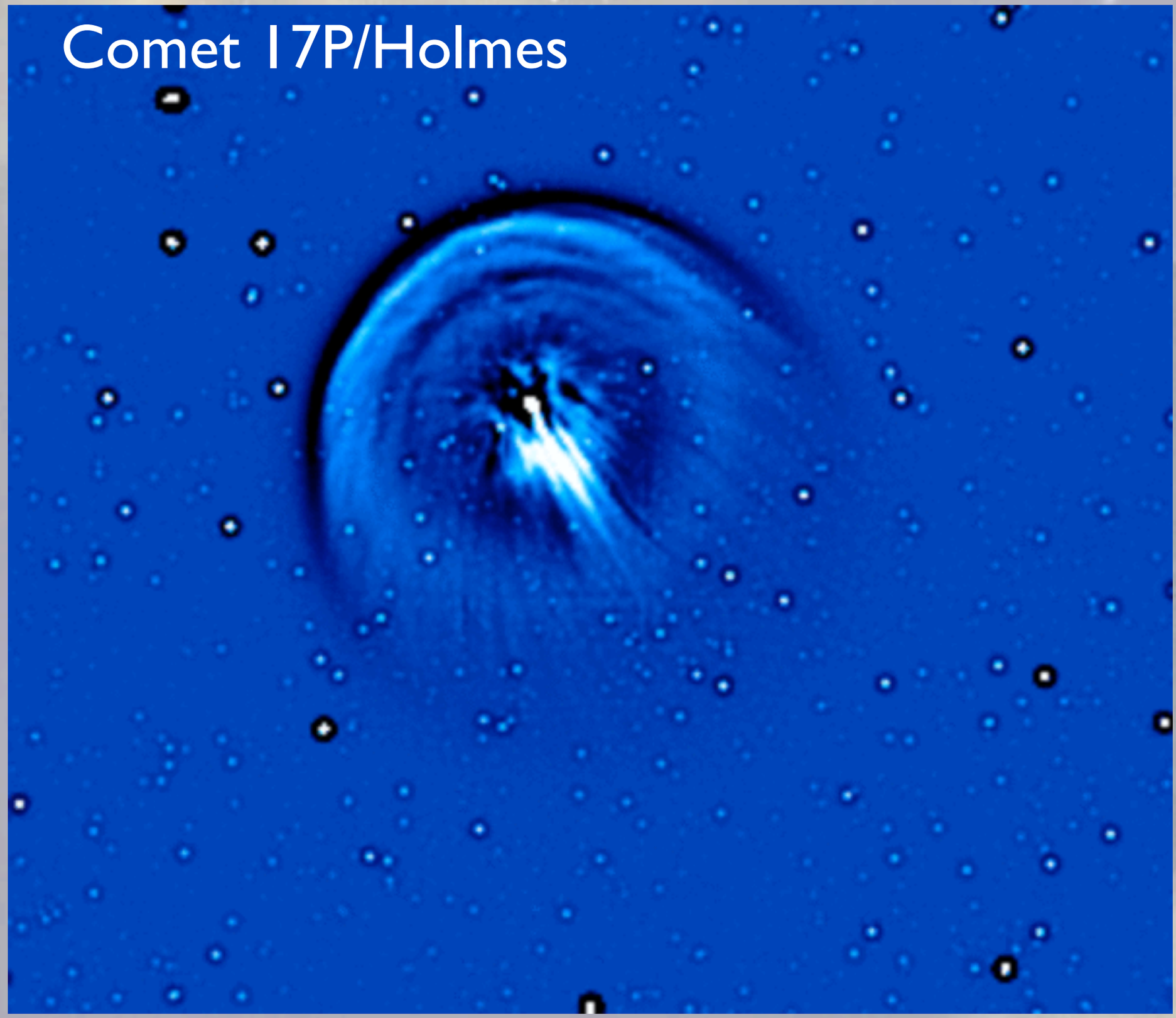
consistent with amorphous -> crystalline transition as activity driver.

Detailed thermal model by Aurelie Guilbert (UCLA)

Exothermic phase transition: $\Delta E = 9 \times 10^4$ J/kg

Crystallization might trigger a runaway

Comet 17P/Holmes

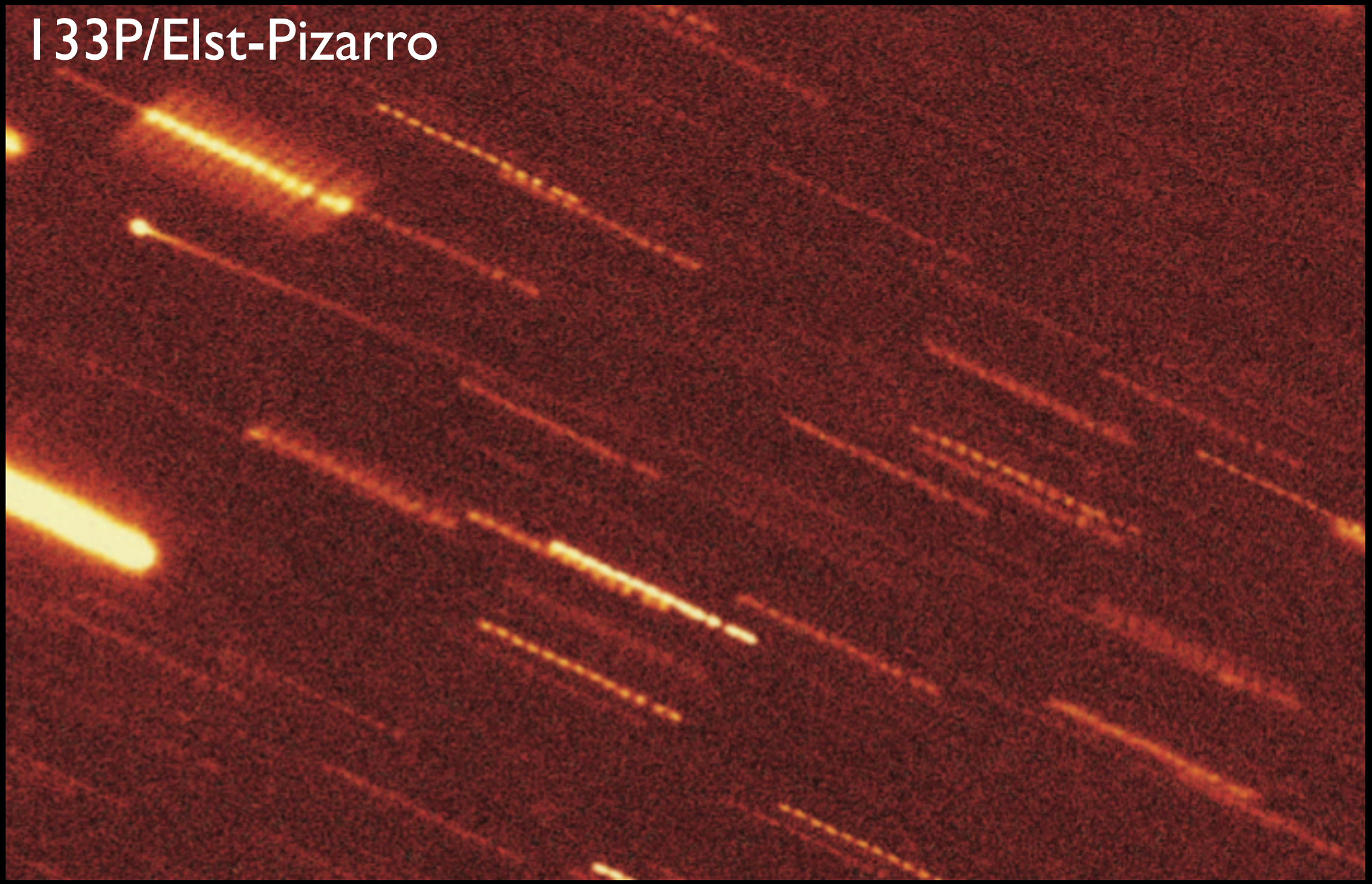


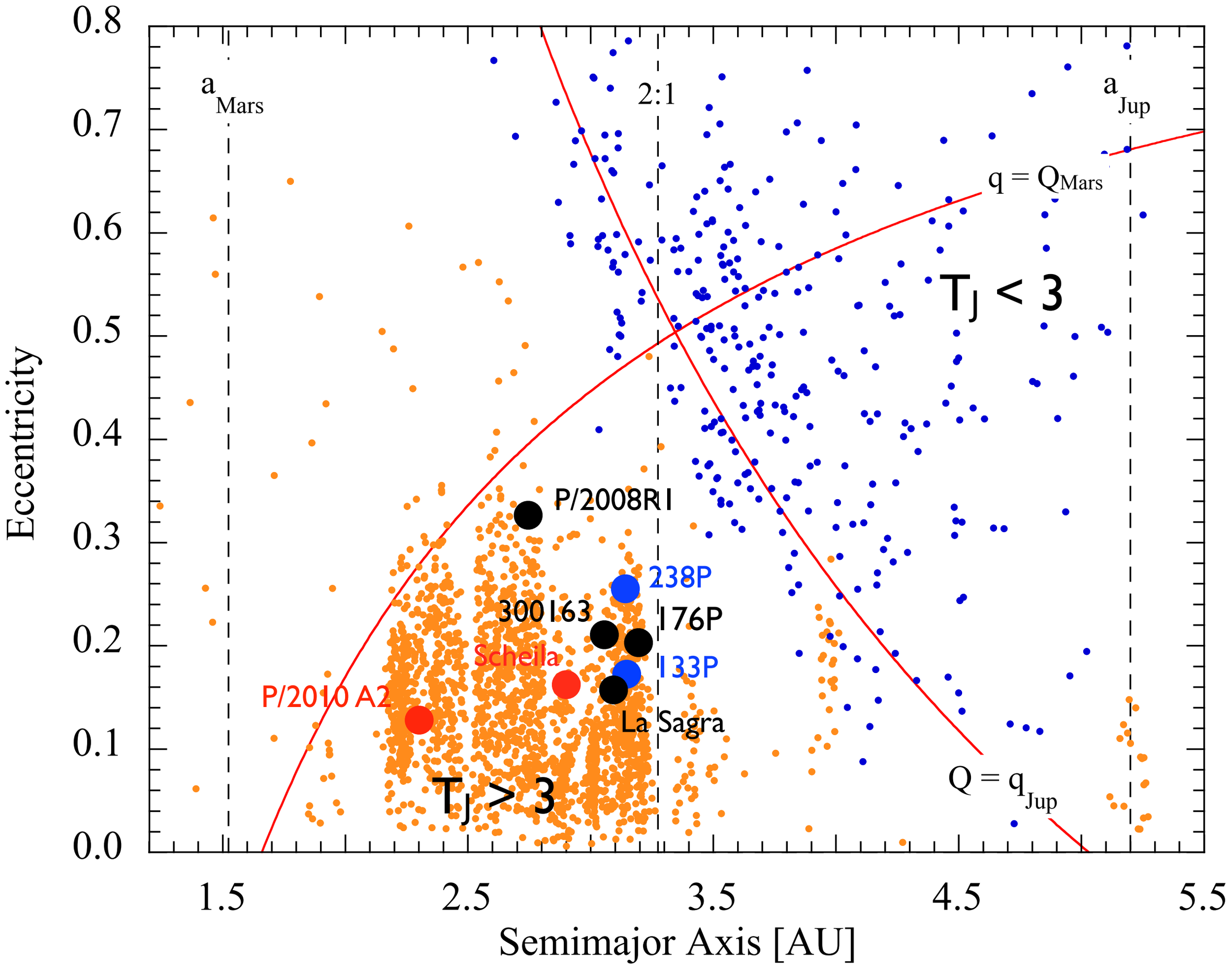
Mini-Summary

- Ice in the Kuiper Belt (& Oort Cloud) is cold enough to be amorphous. Surface ice, though, is crystalline. Indirect evidence suggests that Kuiper belt objects are *internally* amorphous.

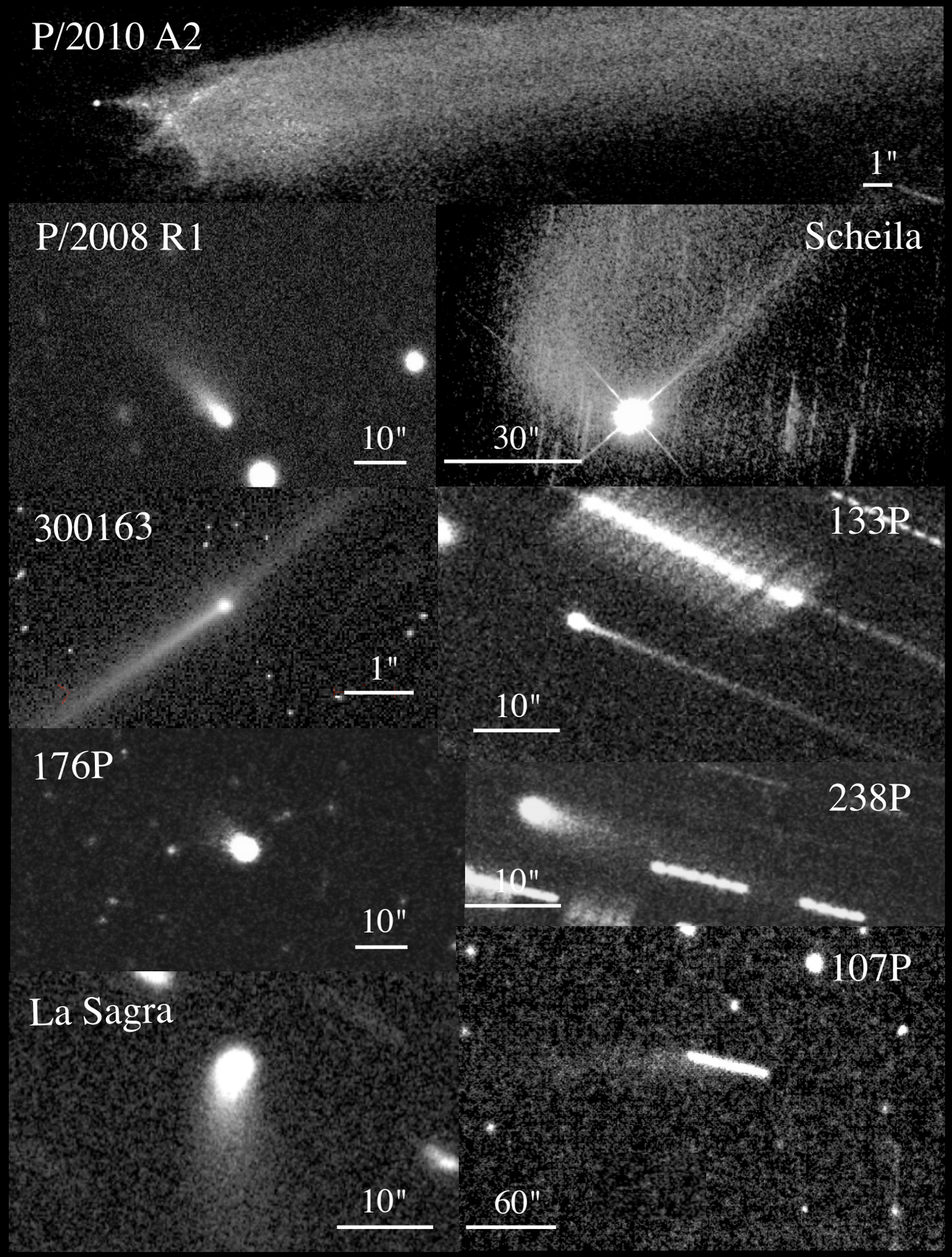
- Crystallinity affects volatile gas carrying ability of the ice.

Inside the Snow Line


133P/Elst-Pizarro


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Eccentricity
a Mars
2:1
a Jup
q = Q Mars
T J < 3
P/2008R1
238P
300163
176P
Scheila
133P
P/2010 A2
La Sagra
T J > 3
Q = q Jup
1.5
2.5
3.5
4.5
5.5
Semimajor Axis [AU]

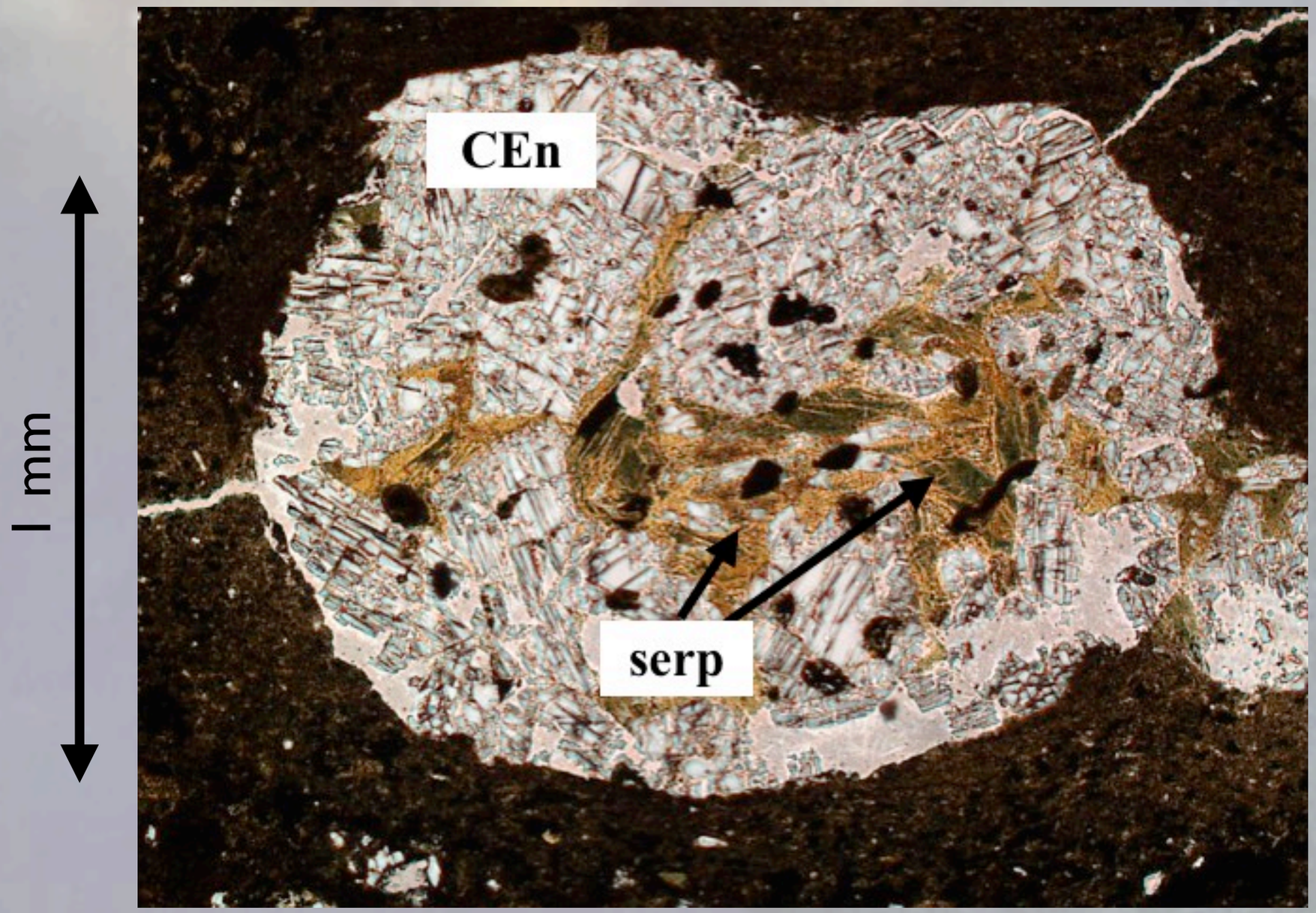
Main-belt Comets



Conduction cooling Time

$$\tau_c \sim \frac{a^2}{\kappa}$$

Hydrated Minerals in Murchison Chondrule



Brearley, via Chizmadia

Murchison CM2 Chondrite

Phyllosilicates, clays, carbonates, serpentine, salt...all found

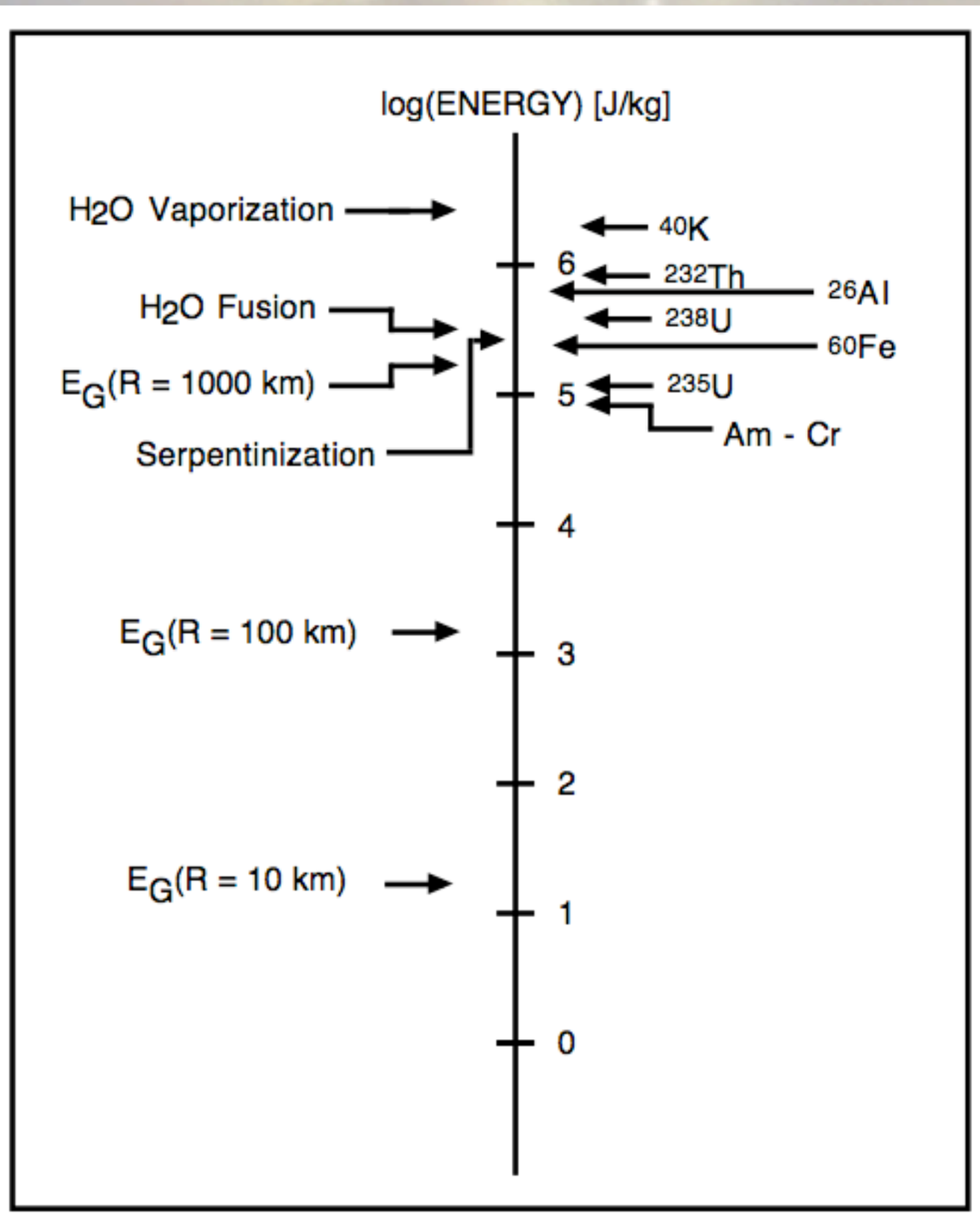
Serpentinization (hydration)

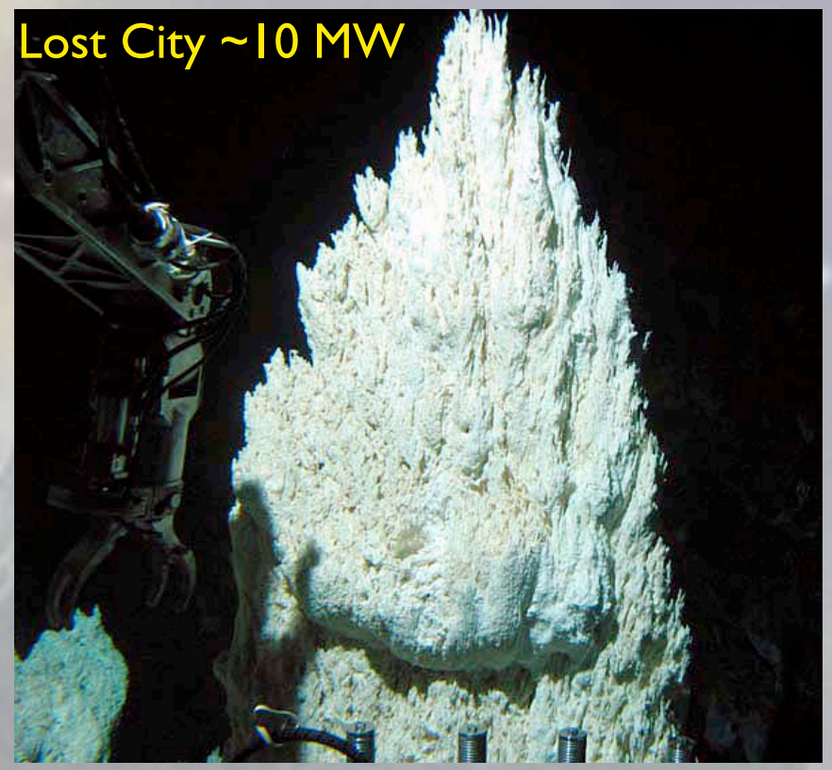
$$Mg_2SiO_4 + MgSiO_3 + 2H_2O \leftrightarrows Mg_3Si_2O_5(OH)_4$$

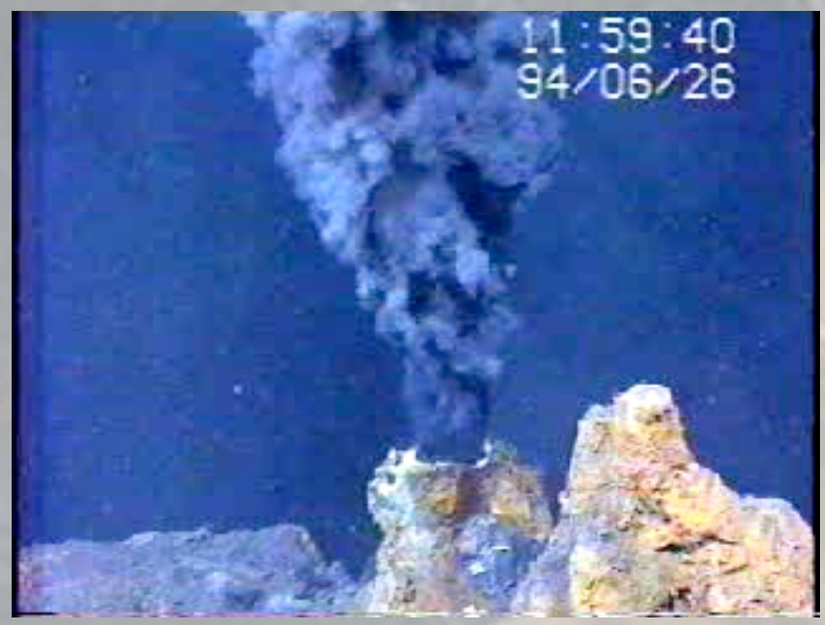
Exothermic $\Delta E = 3x10^5$ J/kg

Also releases H_2, reduces C-compounds, making CH_4: the start of organic chemistry

Energy Production

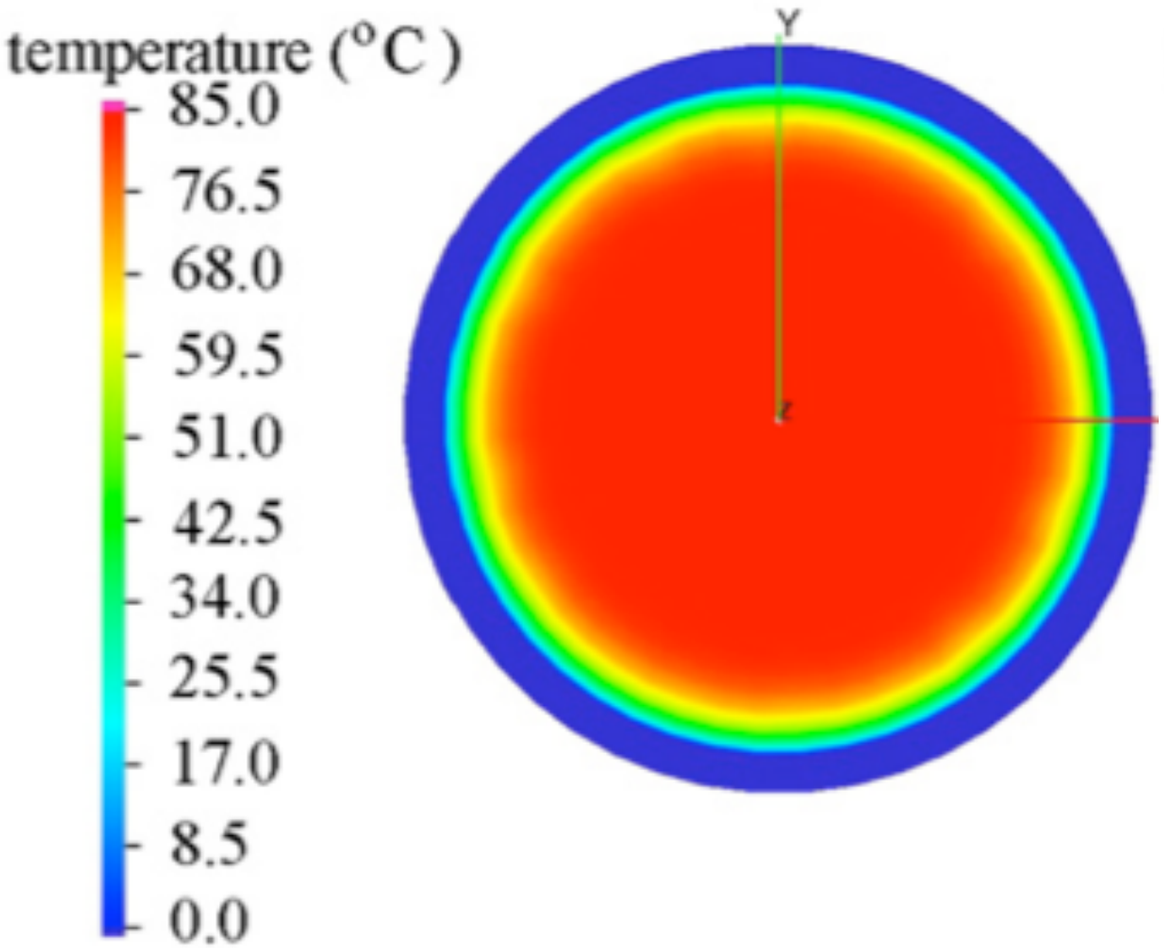




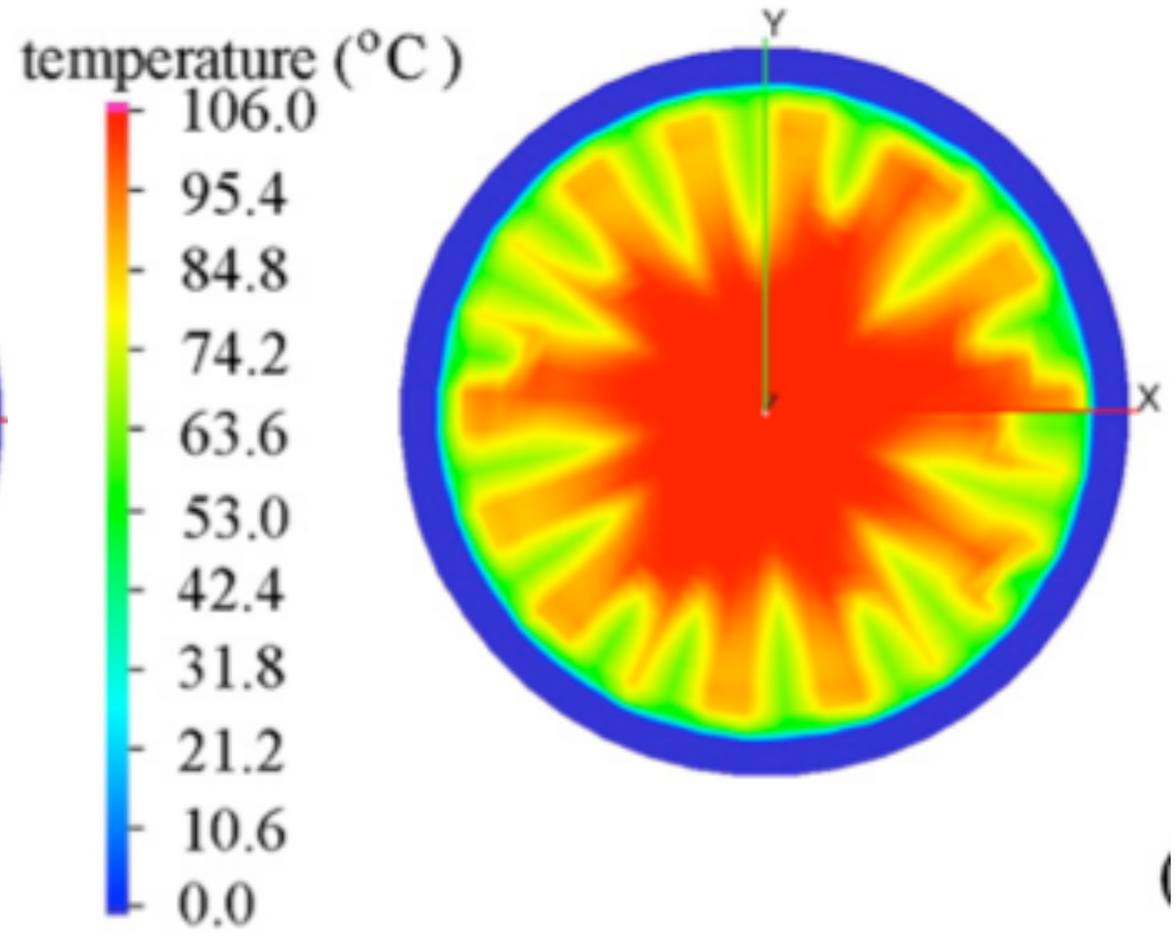


a = 50 km, ^{26}Al(t=0) = 5e-8

1.4 Myr



2.2 Myr



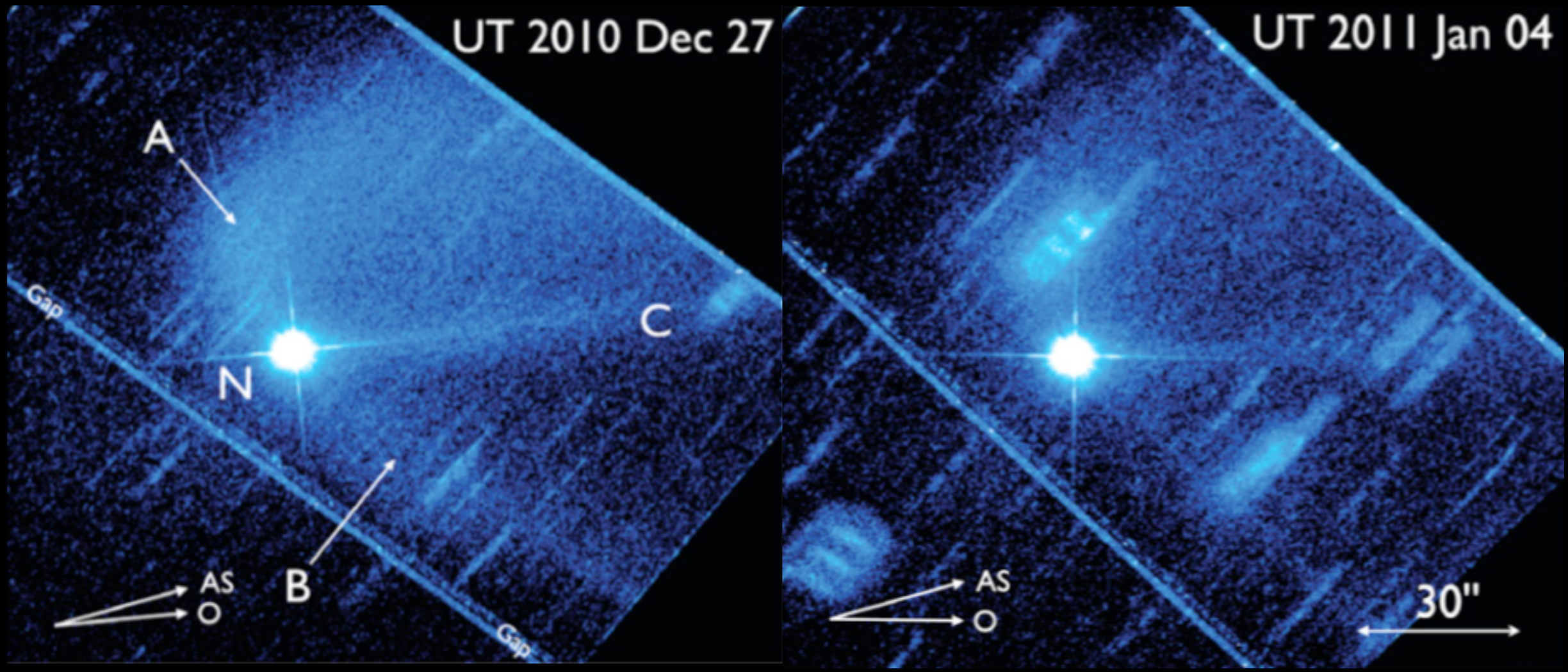
Palguta et al. (2010)

- Convection plumes create non-uniform thermal and mineralogical structure

- Complex hydrothermal systems drive chemistry
- Carbonaceous chondrites contain organics up to amino acids.....

Bonus Discovery

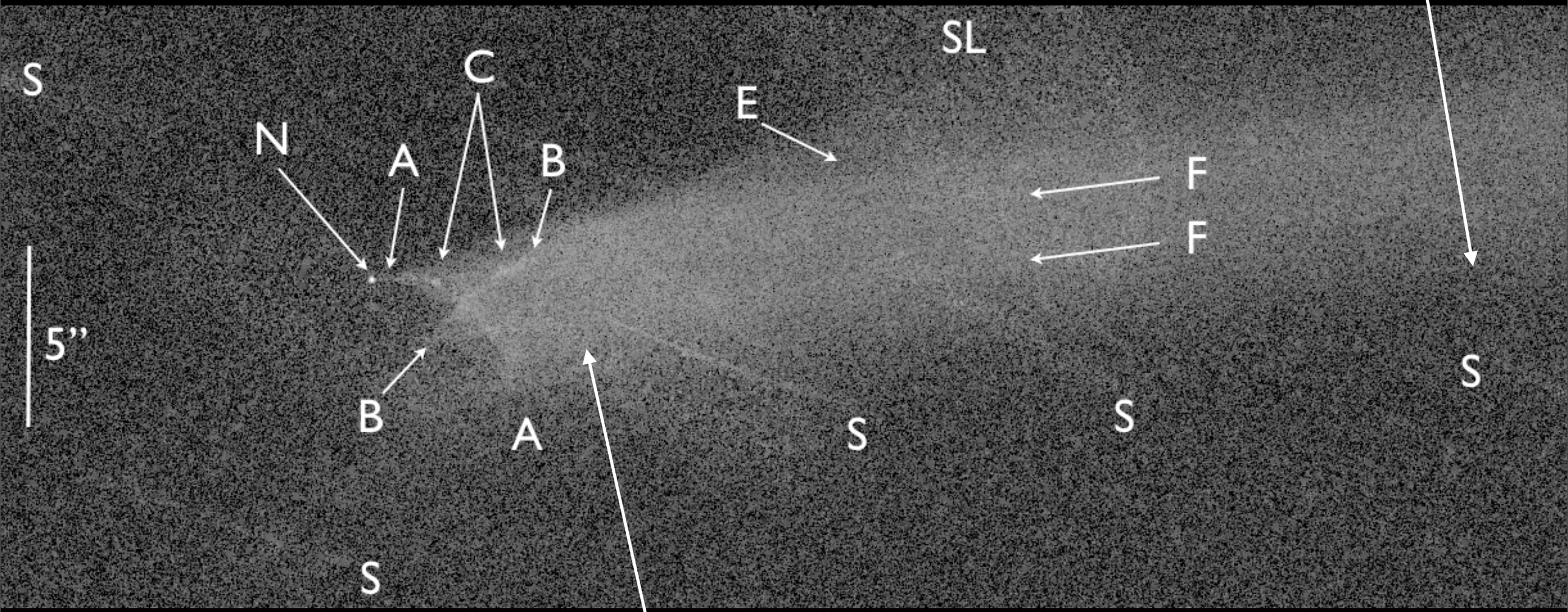
(596) Scheila



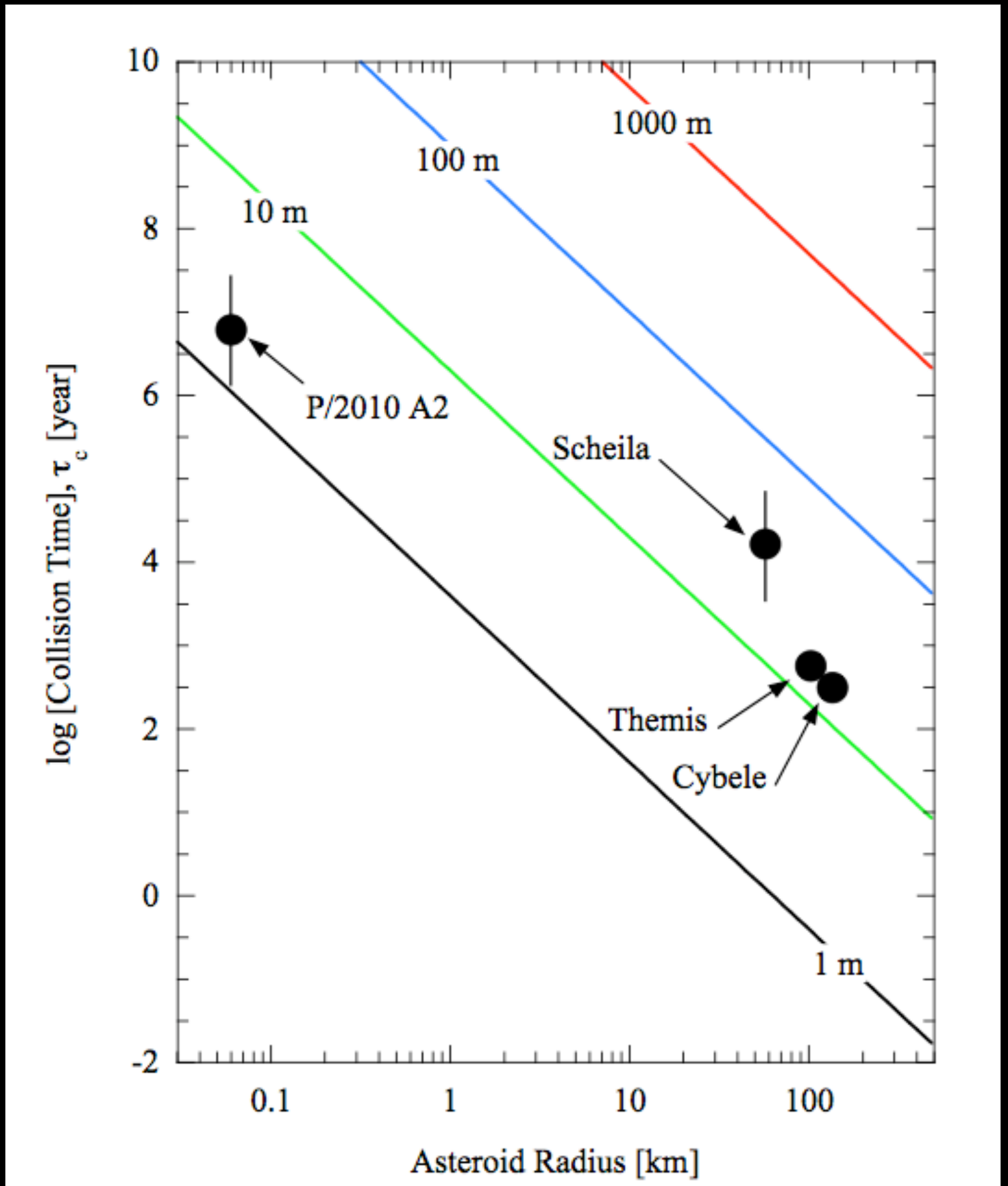
D = 113 km

P/2010 A2

~1 mm



D ~ 100 m


10
8
6
4
2
0
-2
log [Collision Time], τ_c [year]
1000 m
100 m
10 m
1 m
P/2010 A2
Scheila
Themis
Cybele
0.1
1
10
100
Asteroid Radius [km]

Summary

1). Planets and ice are both needed for life as we know it

2). Ice in outer solar system should be amorphous. Spectral evidence is lacking. Physical (outgassing) evidence is suggestive. Kuiper belt is probably amorphous.

3) Ice in asteroids is unstable unless protected from sublimation. Evidence for ice in asteroids is strong.

4) Water on Earth probably derived at least in part from wet asteroids. Biogenic precursors likewise.

5) Recently discovered impacts in belt - analogs of debris disk production