The Physical Properties of Near Earth Asteroids

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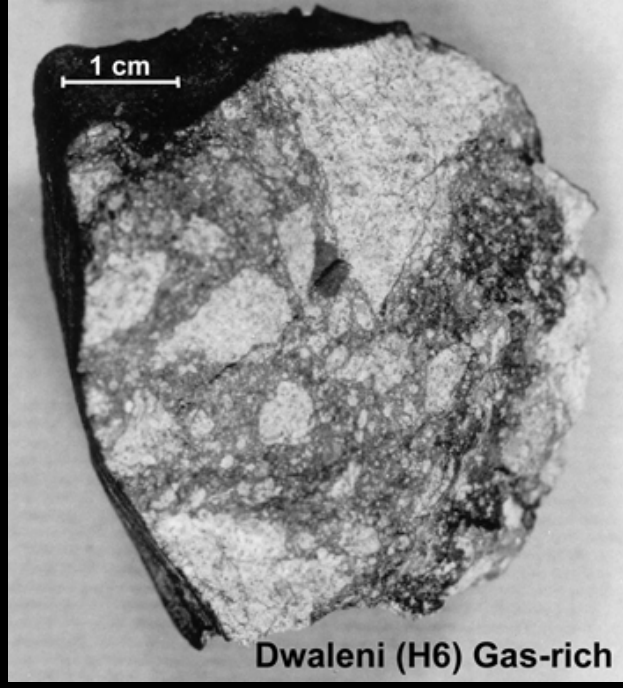
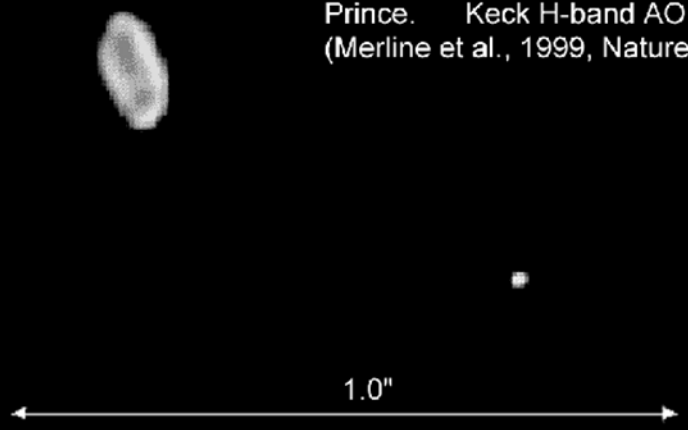
What Do We Need to Know About NEA Physical Properties?

- Asteroid Structure
  - Rubble pile?
  - Coherent object?
- Material Strength
  - Tough? Weak?
- Mineralogy
- Thermal Properties
- Surface texture
  - Dusty regolith?
  - Boulder field?

Sources of Data

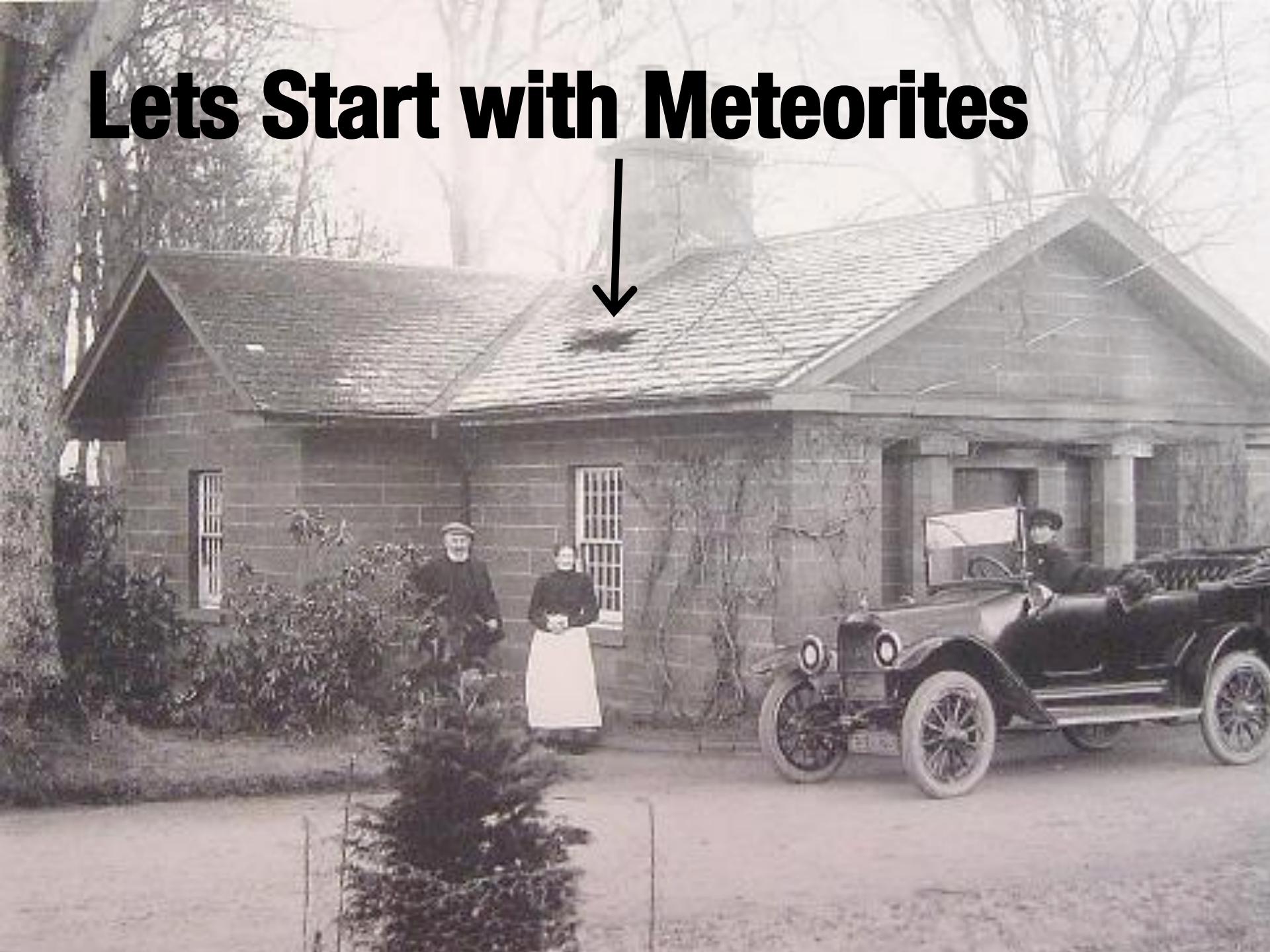
- Meteorites
  - Strong? Weak?
- Observations of Bolides
- Meteorite Strewnfields
- Observations of NEAs
  - Rotation rates
  - Binaries
- Physics
  - Microgravity
  - Cohesion
  - Thermal cycles





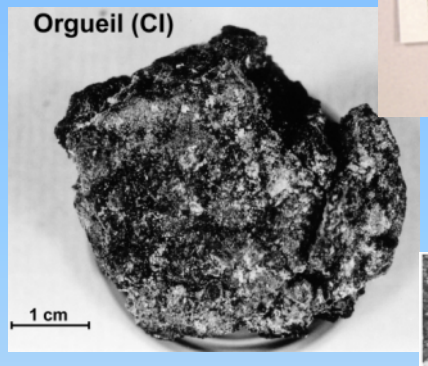
45 Eugenia and moon, Petit Prince. Keck H-band AO. (Merline et al., 1999, Nature)

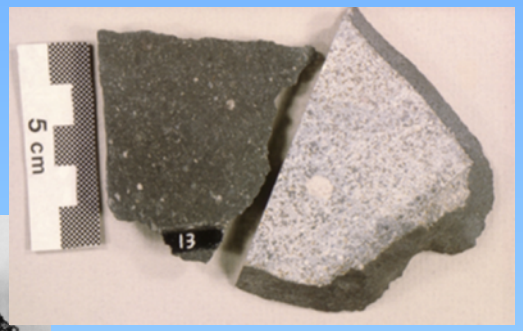
Lets Start with Meteorites



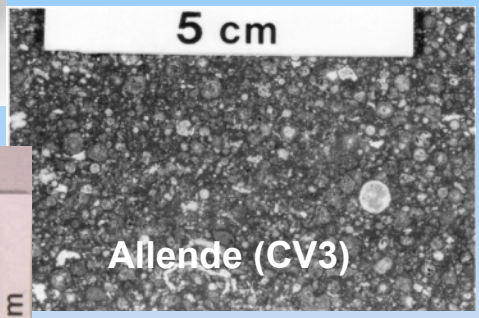
Meteorite Types

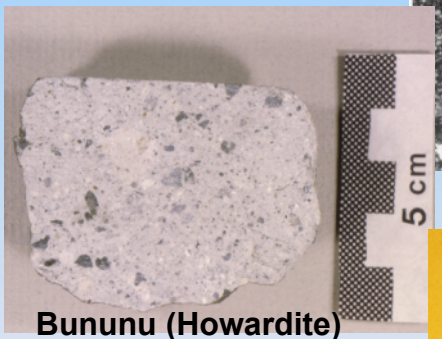
- Chondrites (ordinary, enstatite)
  - Stones, chondrules, olivine, pyroxene, metal, sulfides, usually strong
- Volatile-rich Carbonaceous Chondrites (CI, CM)
  - Hydrated silicates, carbon compounds, refractory grains, very weak.
- Other Carbonaceous (CO, CV, CK, CR, CH)
  - Highly variable, chondules, refractory grains, often as strong as ordinary chondrites
- Achondrites
  - Igneous rocks from partial melts or melt residues
- Irons
  - Almost all FeNi metal
- Stony-irons
  - Mix of silicates and metal



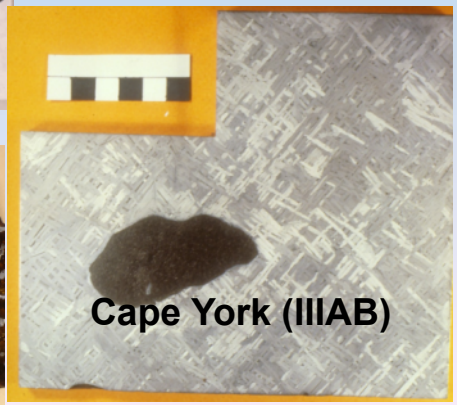


Farmington (L5)
Farmville (H4)

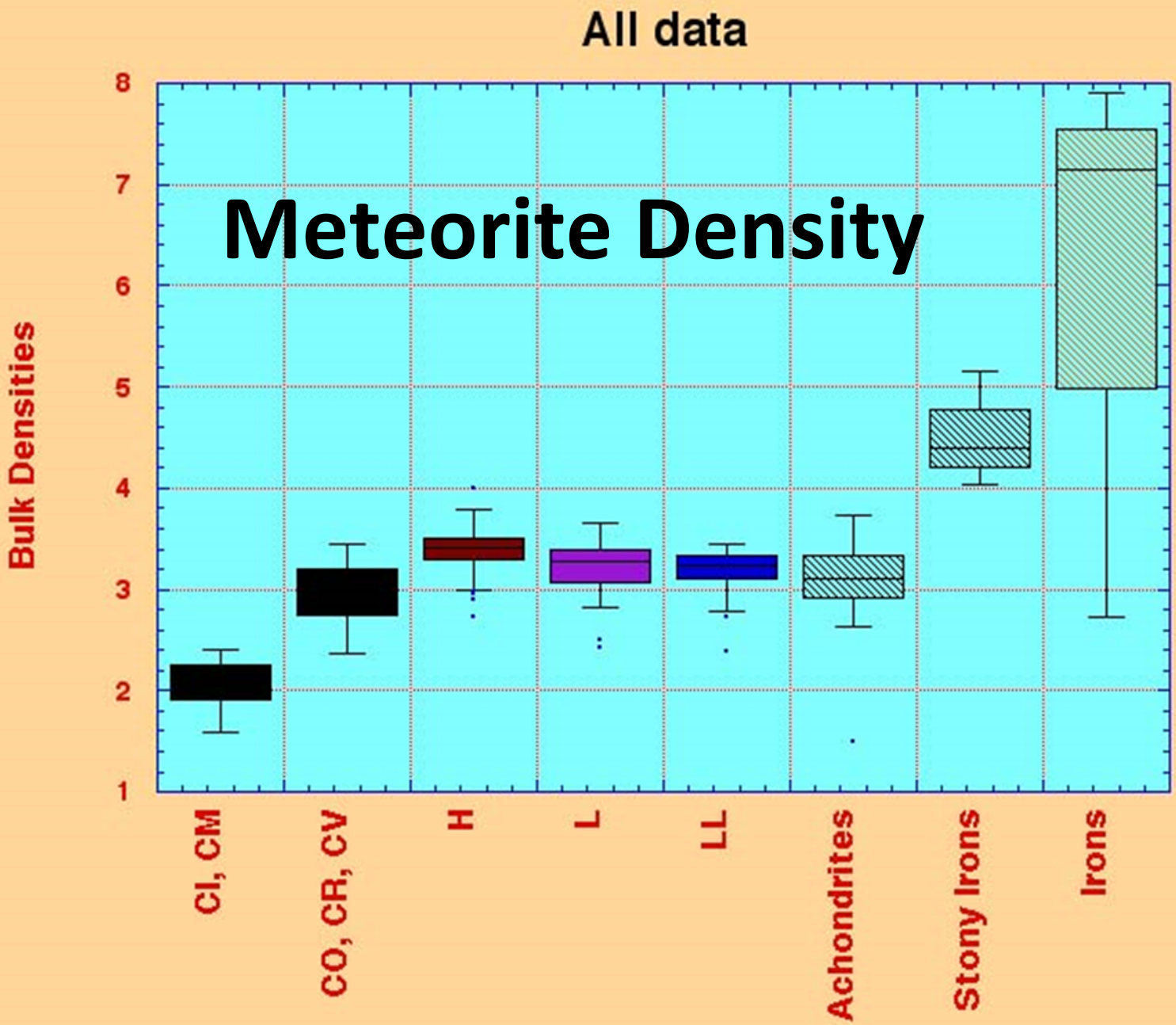




Bununu (Howardite)



Meteorite Density



Meteorite Compressive Strength

Material	Meteorite Type	Compressive Strength (MPa)
Concrete (Unreinforced)	Typical Sidewalk	20 (3000 psi)
Charcoal Briquette		~2
Granite		100–140
Medium dirt clod		0.2-0.4
La Lande, NM	L5	373.4
Tsarev	L5	160-420
Covert (porosity 13%)	H5	75.3
Krymka	LL3	160
Seminole	H4	173
Holbrook, AZ (porosity 11%)	L6	6.2
Tagish Lake	C2	0.25-1.2
Murchison	CM	~50
Bolides	?	0.1-1

December 10, 1984: Claxton, Georgia

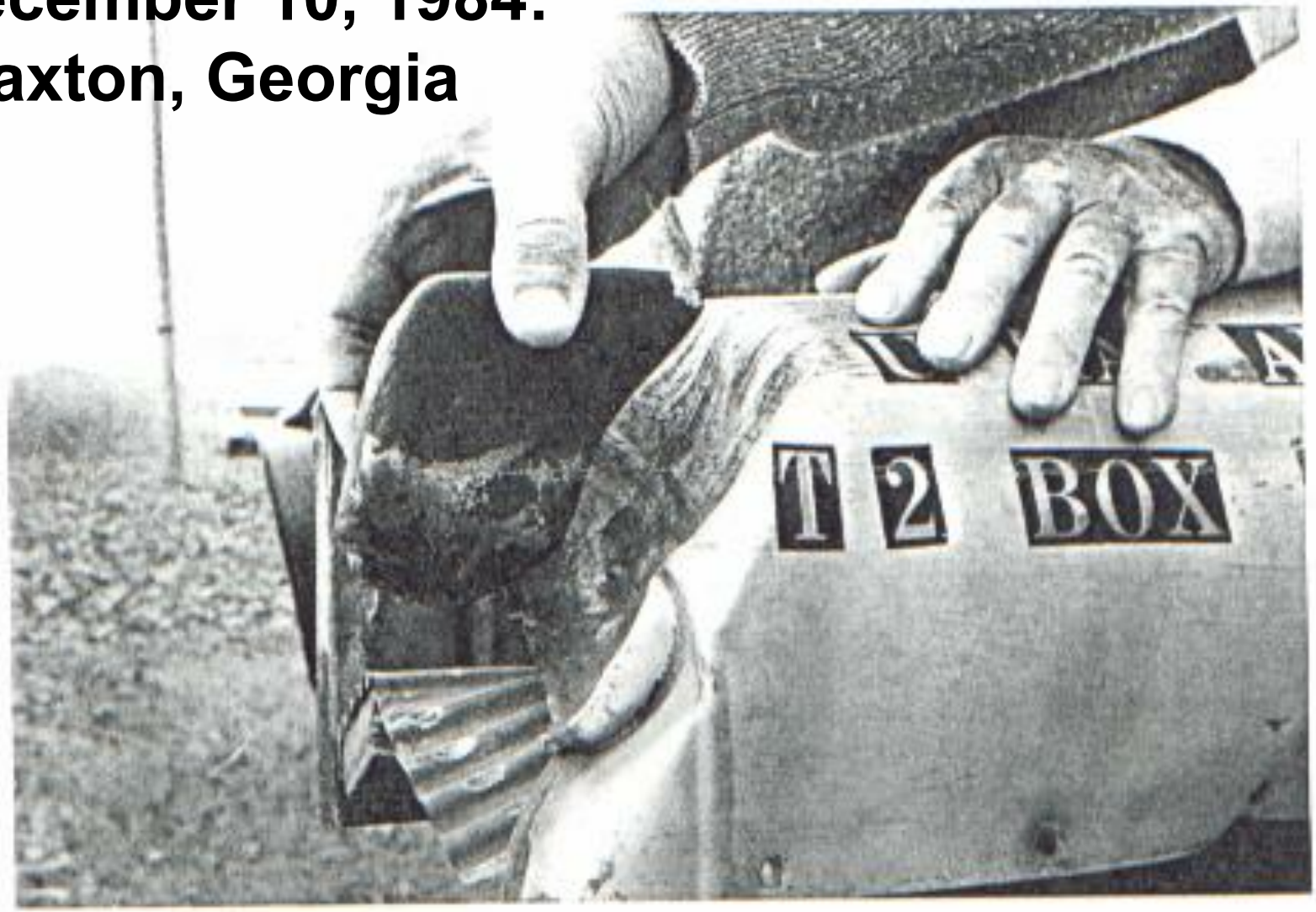
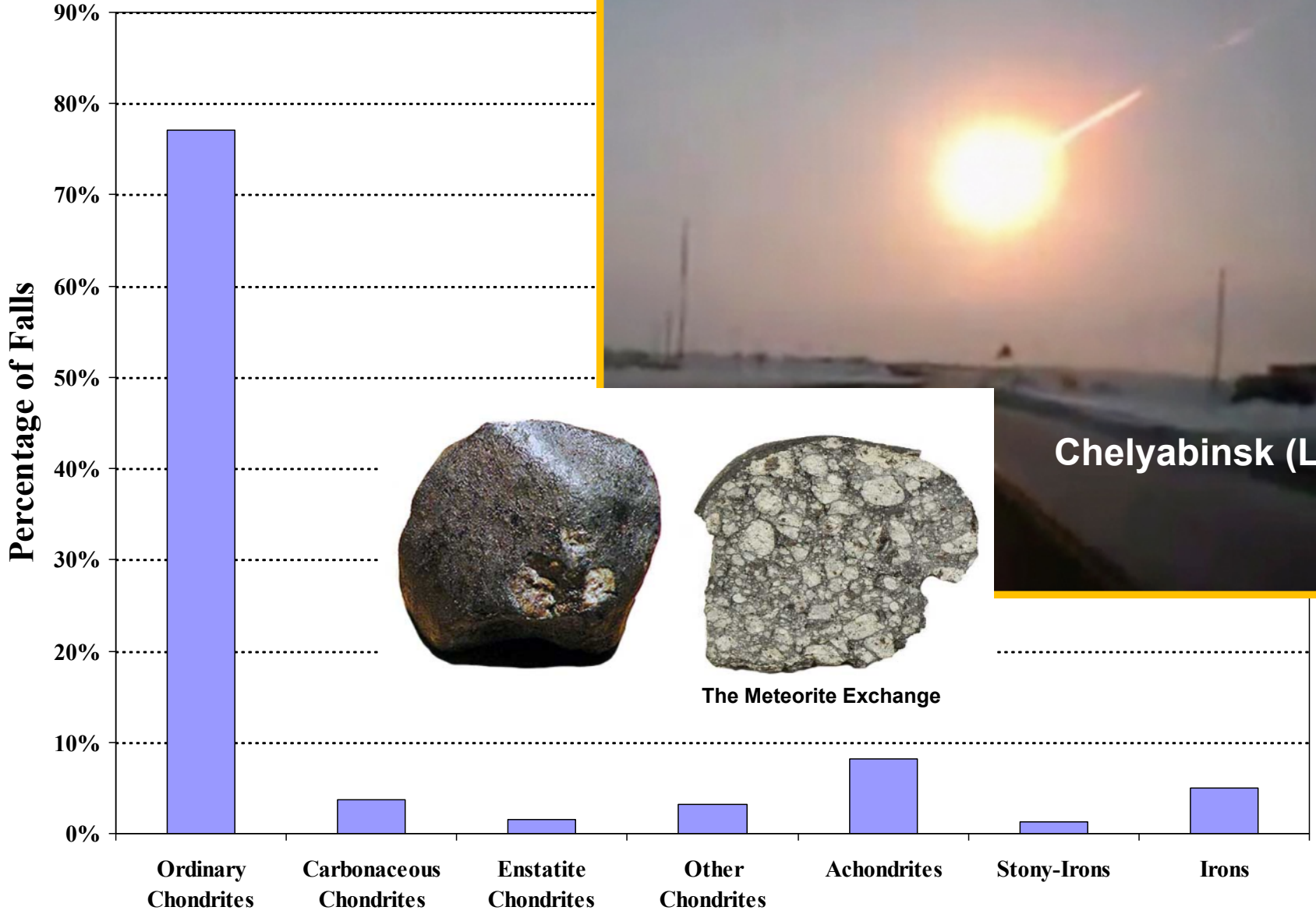
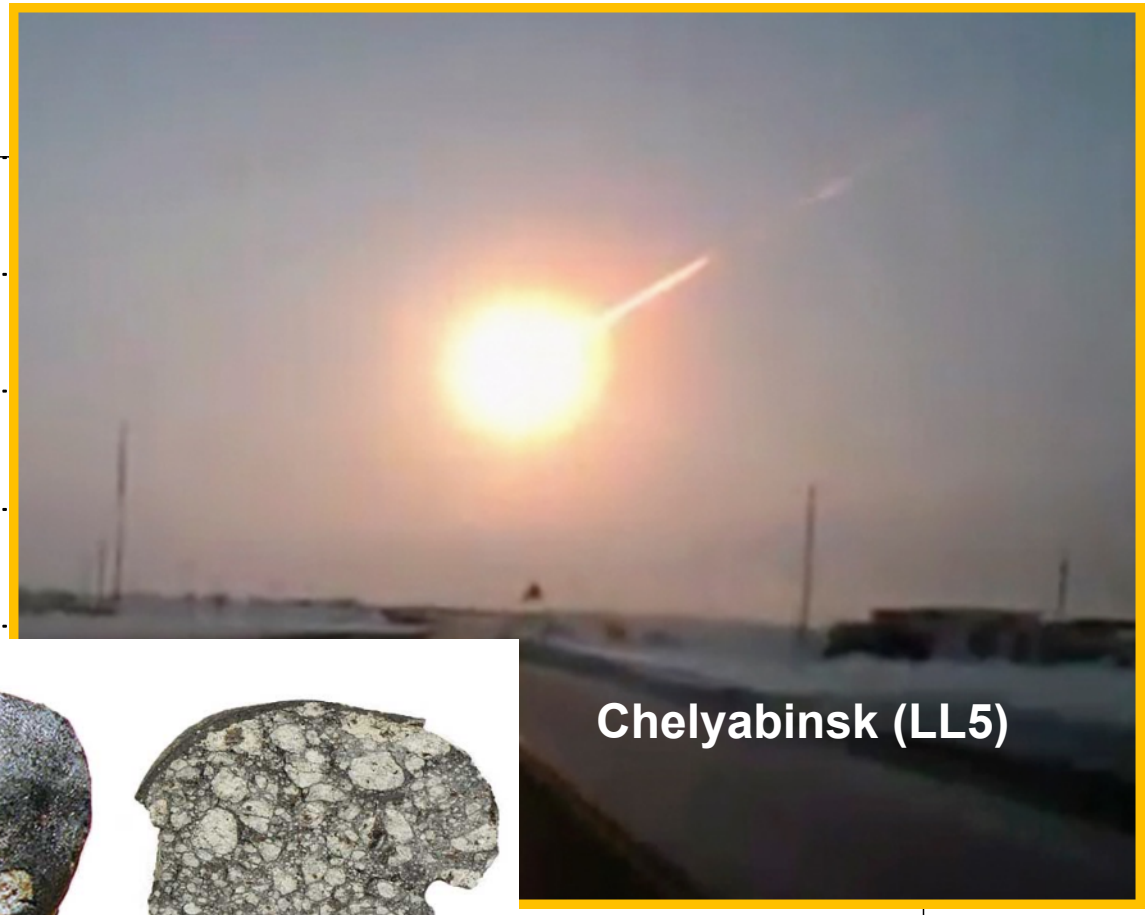


Fig. 3 Damage done to mailbox by Claxton, GA chondrite. Matching marks shows exact orientation of impact. Mailbox has been put back into original position. Photo credit to Visual Concepts, Claxton, GA.

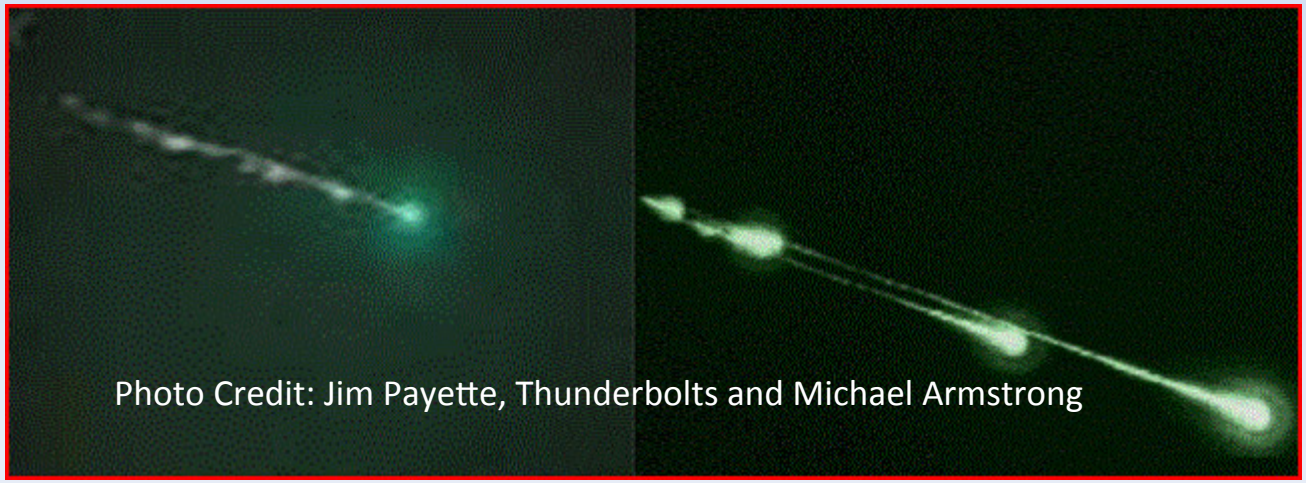




The Meteorite Exchange

Bolides

- The light and sound from objects moving through the Earth's atmosphere
- The stress and friction of atmospheric interaction provide data on the strength of NEAs

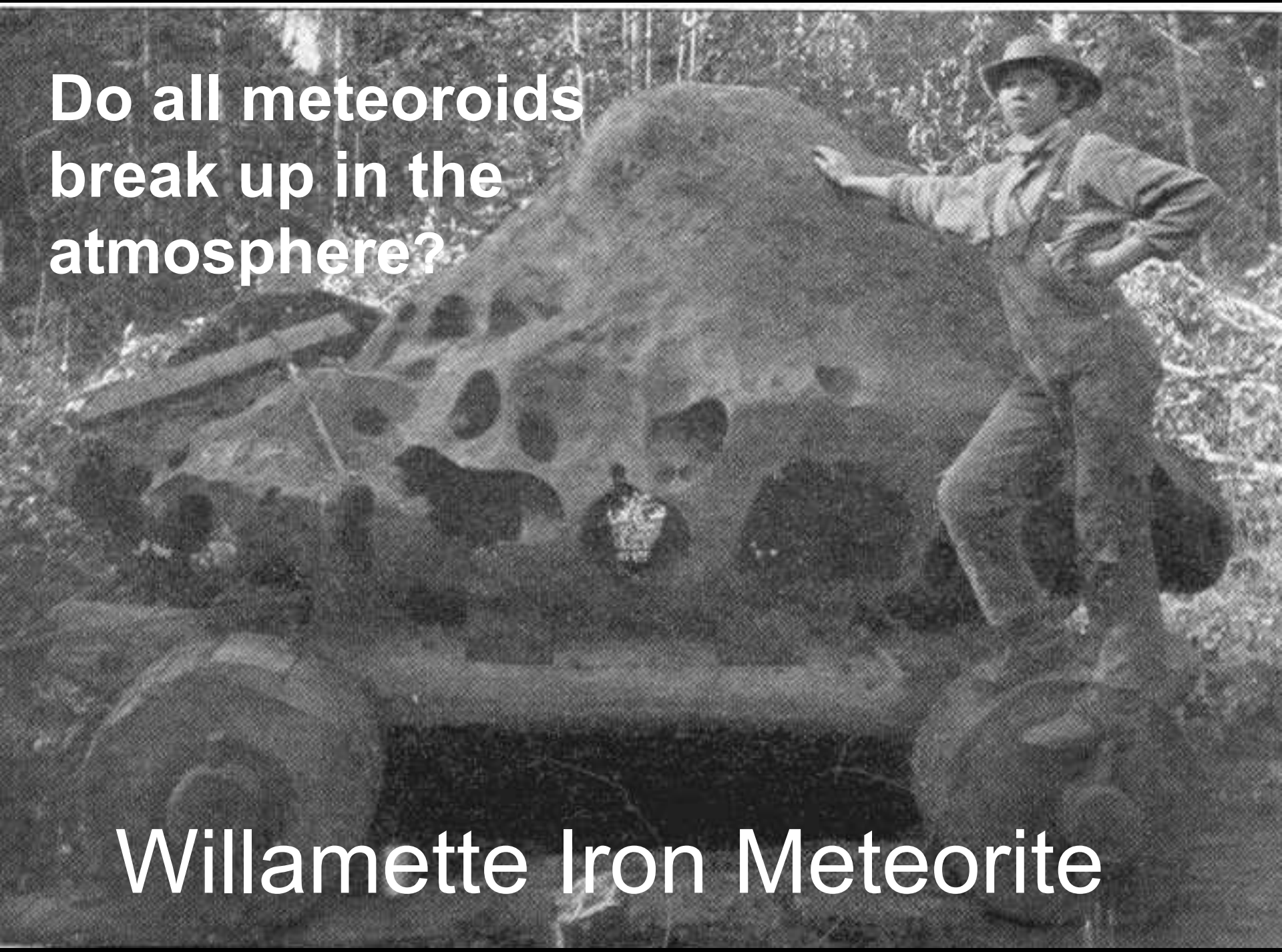


Bolides with Recovered Meteorites

Meteorite	Comp. Strength range of Met. Type (MPa)	Initial Mass (Metric Tons) / Diameter (Meters)	Compressive Strength at First Breakup (MPa)	Max. Compressive Strength (Mpa)
Prıbram (H5)	77-247	1.3 / 0.9	0.9	
Lost City (H5)	77-247	0.16 / 0.45	0.7	2.8
Innisfree (L5)	20-450	0.04 / 0.28	0.1	3
Tagish Lake (C2)	0.25-1.2	65 / 4.2	0.3	2.2
Moravka (H5-6)	77-327	1.5 / 0.93	<0.9	5
Neuschwanstein (EL6)		0.3 / 0.55	3.6	9.6
Park Forest (L5)	20-450	10 / 1.8	0.03	7
Villalbeto de la Pena (L6)	63-98	0.6 / 0.7		5.1
Bunburra Rockhole (Ach)		0.022 / 0.24	0.1	0.9
Almahata Sitta (Ure, OC)		70 / 4	0.2-0.3	1
Jesenice (L6)	63-98	0.17 / 0.45	0.3	3.9
Grimsby (H4-6)	77-327	0.03 / 0.13	0.03	3.6

Note that all data are estimates that are <u>Inferred</u> from observations of the bolide, breakup altitude, and the pattern of the breakup.

From: Popova et al., 2011


Do all meteoroids break up in the atmosphere?
Willamette Iron Meteorite

Selected Large Meteorites

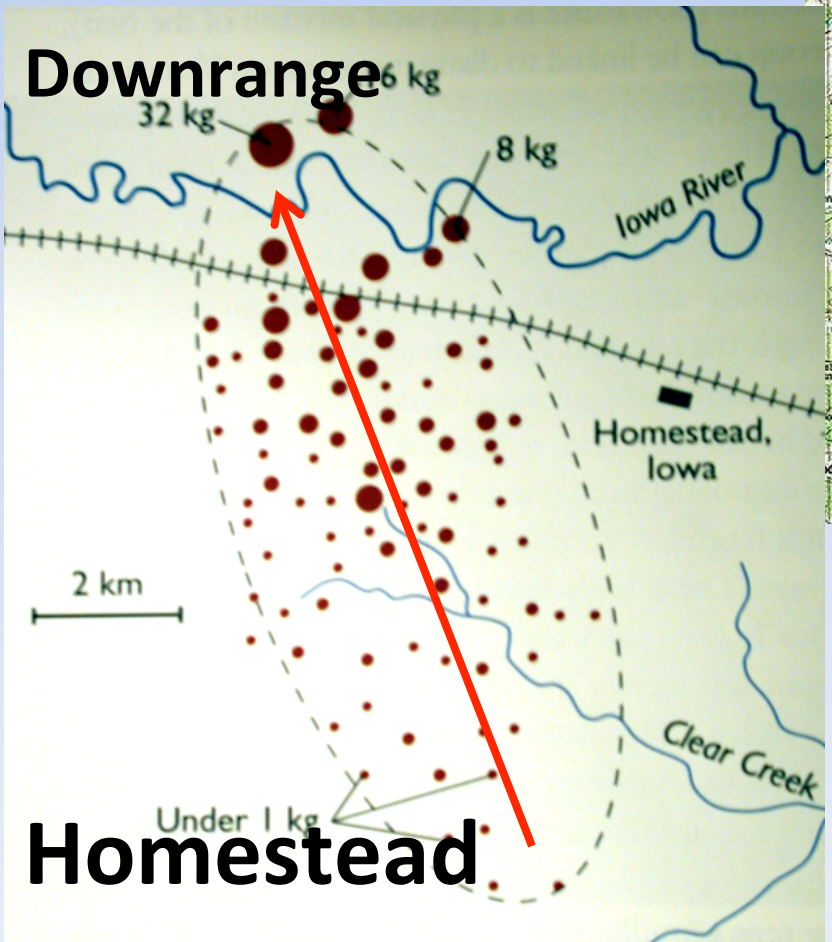
Meteorite	Date	Mass (Kg)	Fragments
Campo del Cielo (IAB Iron)	Find	100,000	30
Sikhote-Alin (IIAB Iron)	Feb. 12, 1947	70,000	9,000
Hoba (IVB Iron)	Find	60,000	1
Cape York (IIIAB Iron)	Find	58,000	8
Willamette (IIIAn Iron)	Find	14,500	1
Pultusk (H5)	Jan. 30, 1868	8,863	70,000
Allende (CV3)	Feb. 8, 1969	5,000	1,000
Jilin City (H5)	Mar. 8, 1976	4,000	100
Tsarev (L5)	Dec. 6, 1922	1,132	40
Knyahinya (L5)	June 9, 1866	500	1000
Mocs (L6)	Feb. 3, 1882	300	3000
Homestead (L5)	Feb. 12, 1875	230	500
Holbrook (L/LL6)	July 19, 1912	218	14,000
Forest City (H5)	May 2, 1890	122	2,000

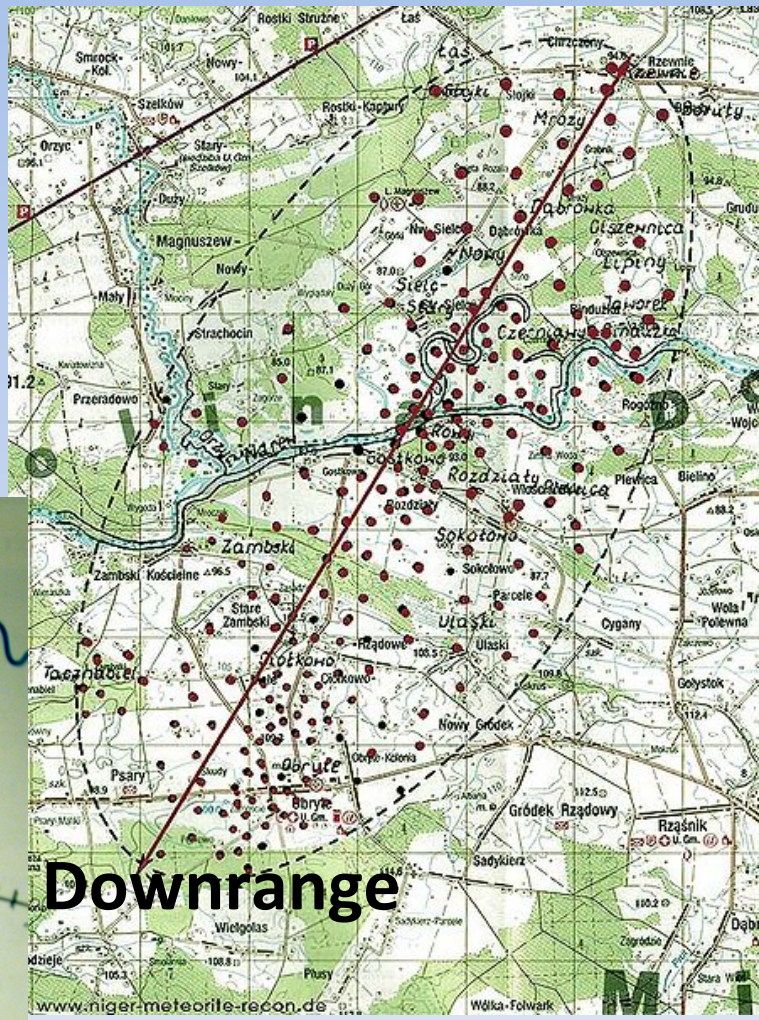
Note that some masses and number of fragments are estimates

From: Cat. of Meteorites, 5th Ed

Strewnfields

- This pattern is produced by breakup, atmospheric drag, and winds.
- Larger pieces fall downrange

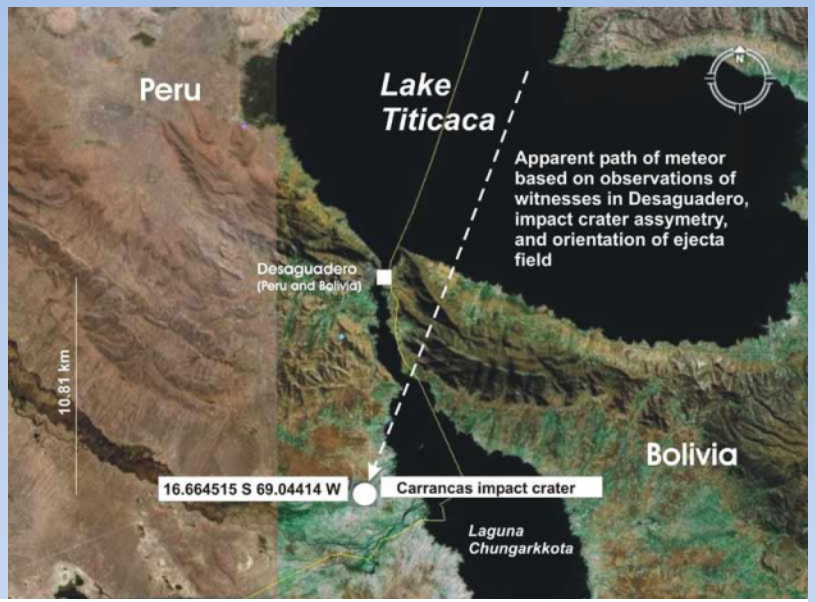




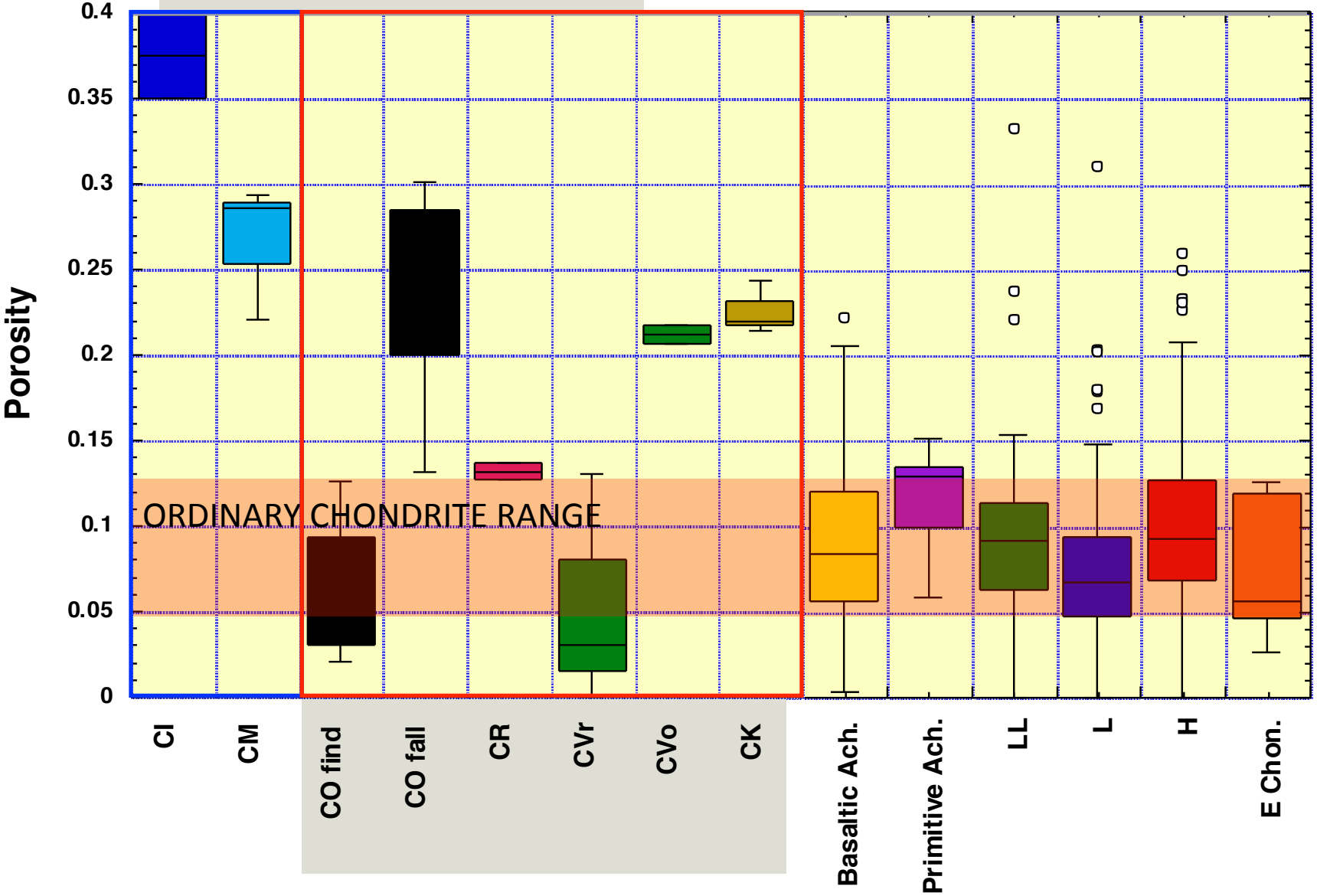
Pultusk

Carancas (H4-5)

- Carancas, Peru (Near Lake Titicaca), 3800 m (12,500 ft.) elevation.
  - Fall: 15 September 2007, ~16:45 UT
- Crater 4.5 m (15 ft) deep, 13 m (43 ft) wide
  - Meteorite was estimated at ~ 3 m in diameter before impact (largest recovered fragment 350 g)
- Residents complained of illness from the impact-produced vapors
  - Turns out that the local ground water is rich in arsenic (and close to the surface).



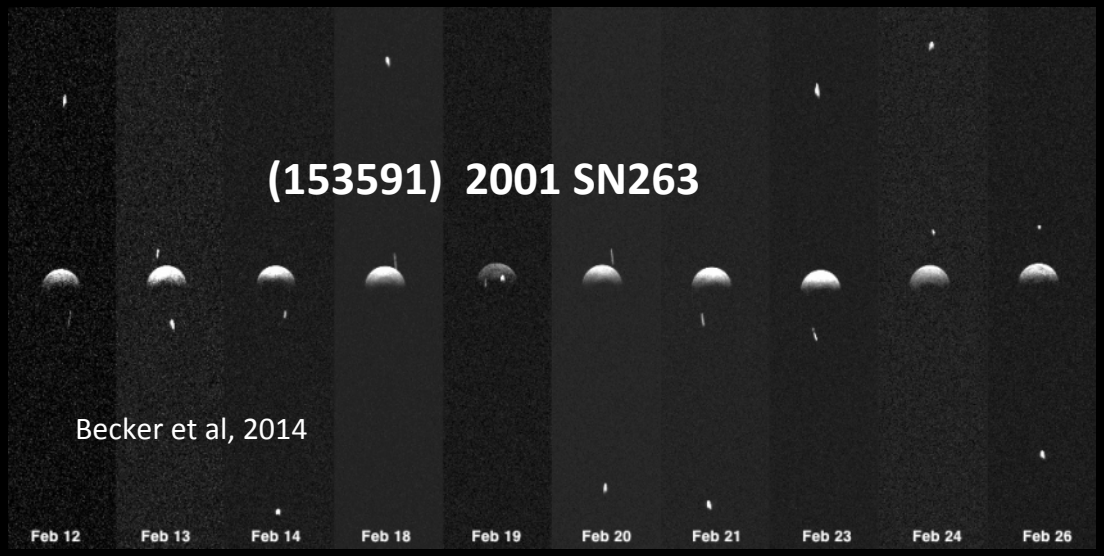
Meteorite Porosity

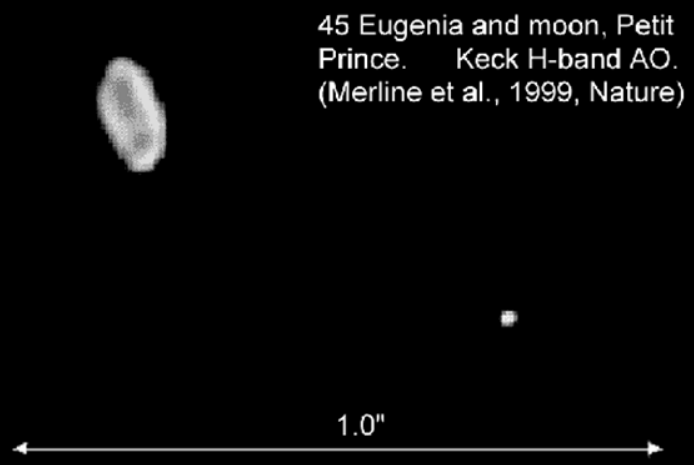


Asteroid/Meteorite Strength

- Most ordinary chondrites (Q or Itokawa type asteroids) are very tough when they are coherent.
  - Compressive strengths as much as 20 times greater than concrete
- Volatile rich carbonaceous chondrites tend to be much weaker.
- Volatile poor carbonaceous chondrites (CV, CO, CR) can be as strong as ordinary chondrites
- While some meteorites are strong in hand sample, they often the come from VERY weak rubble pile asteroids that break up high in the atmosphere.
  - Based bolides and strewnfields, small asteroids are often rubble piles

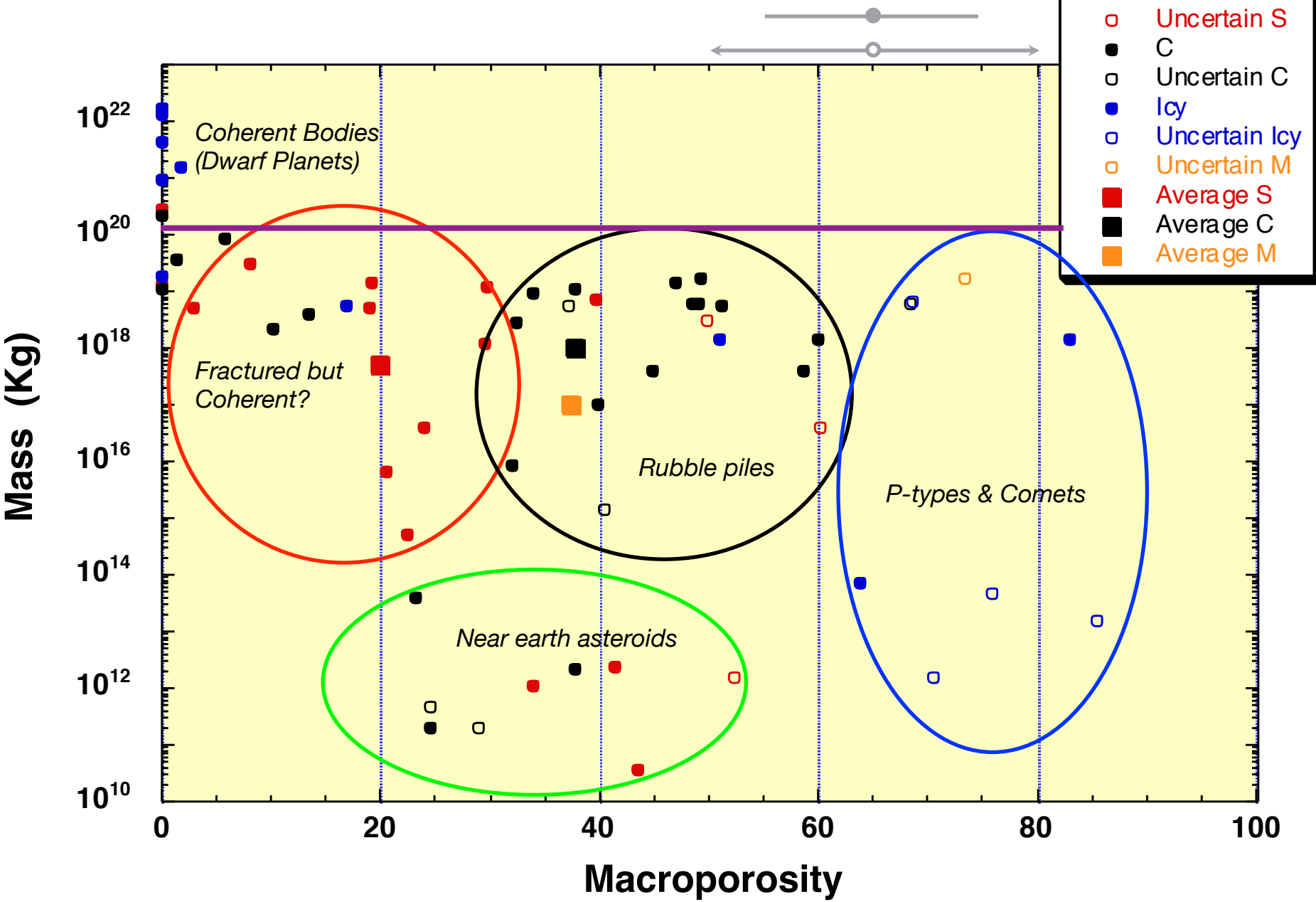
Observations of NEAs





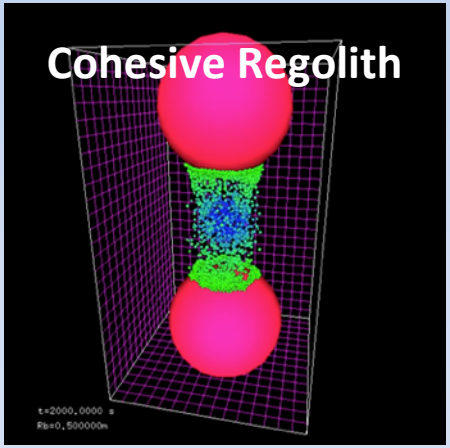
- **For physical properties studies we want to know asteroid density.**
  - **That is mostly determined by observations of binary asteroids**
  - **Orbital period of the secondary provides system mass.**
  - **Other observations give volume.**
  - **Compare asteroid bulk density with meteorite analogues to get an estimate of porosity.**
- **Rotation rate allows us to assess cohesion.**

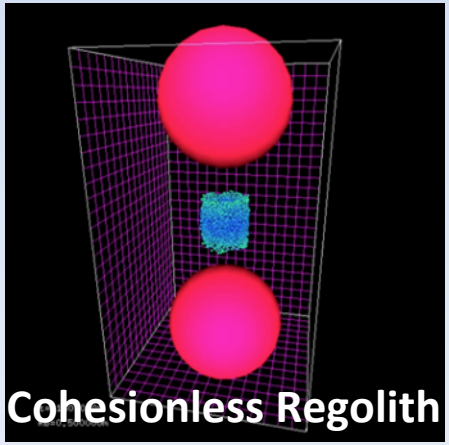
ASTEROID POROSITY

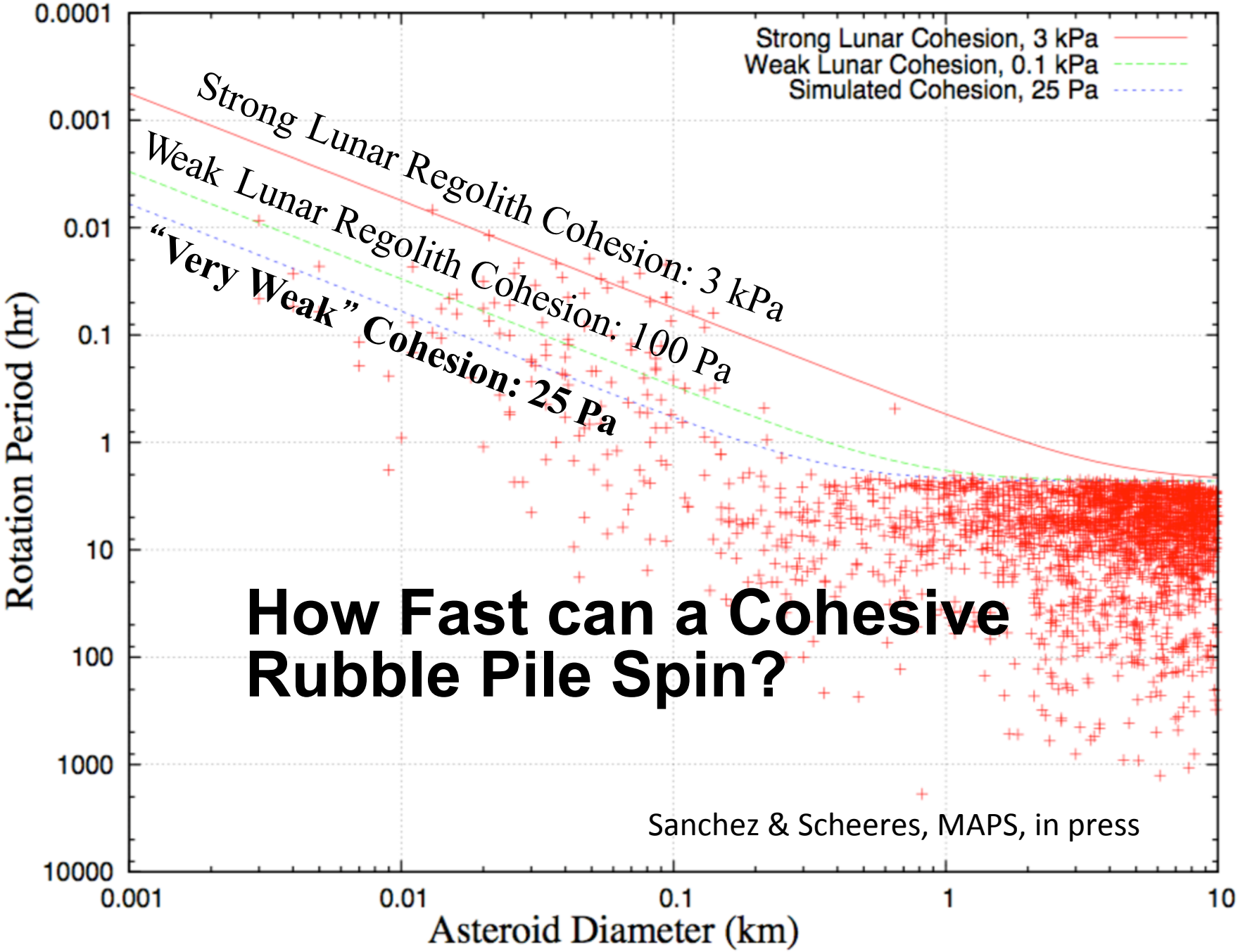


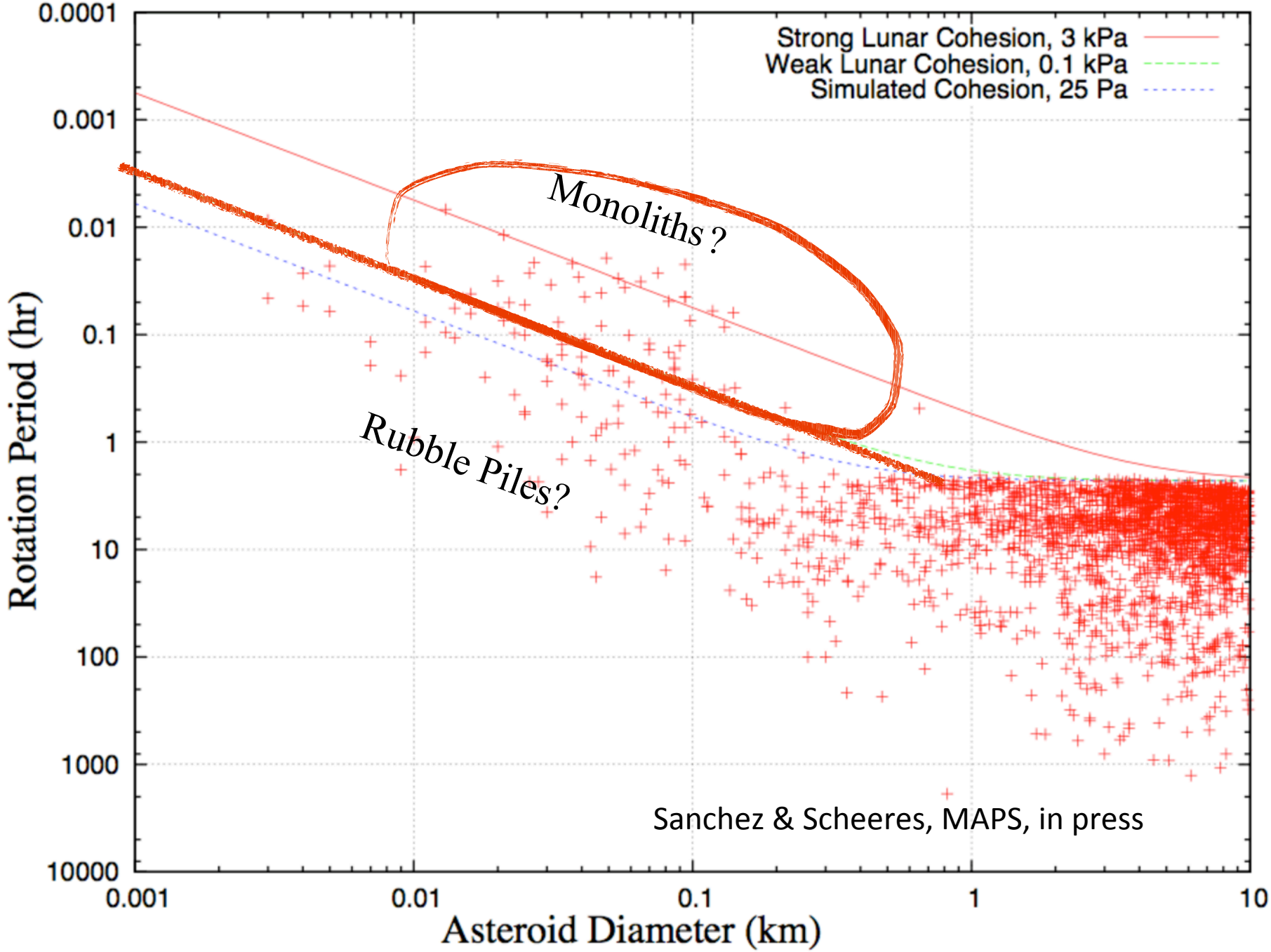
The Physics of Rubble Piles

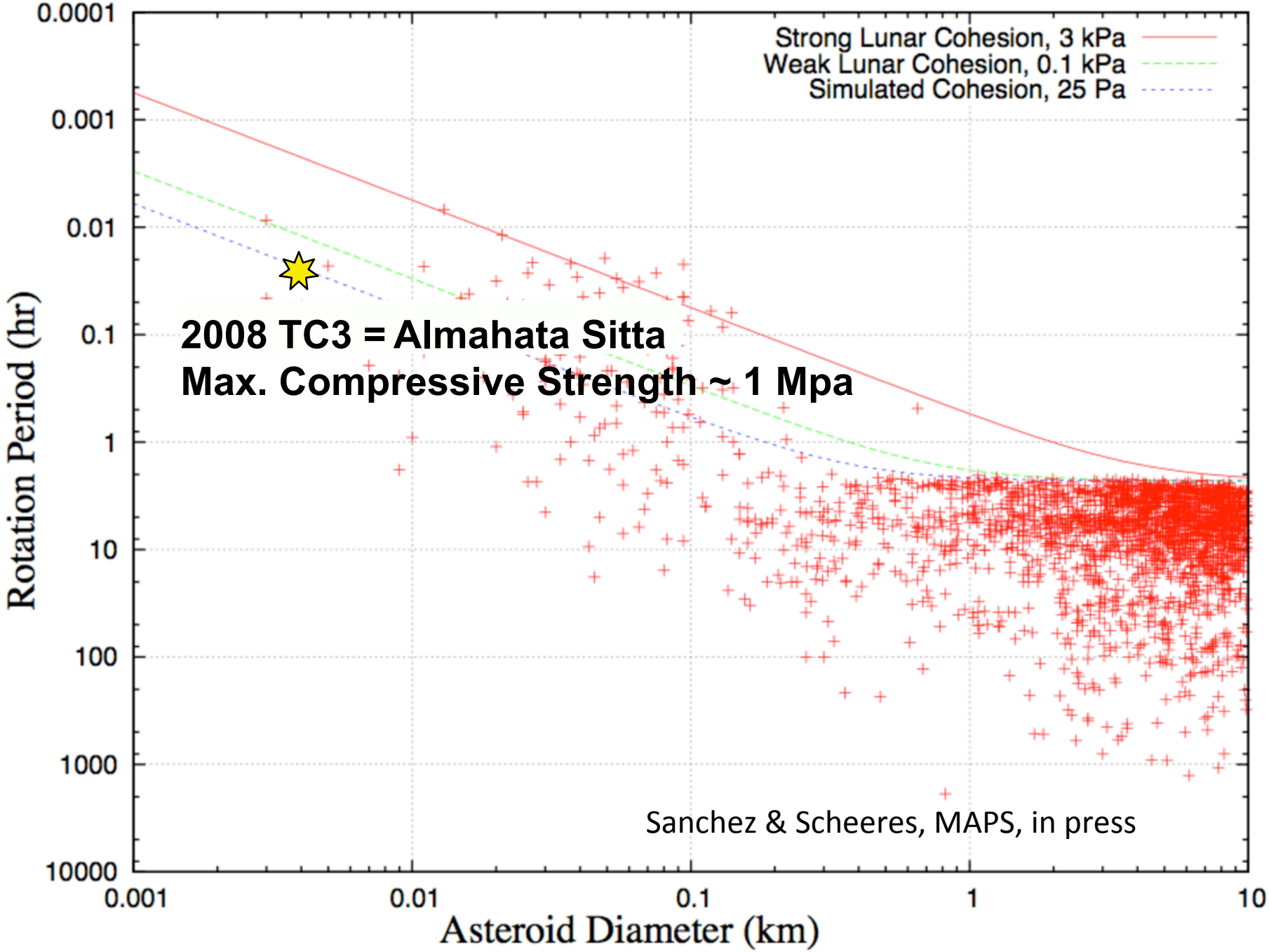
- A rubble pile has a size distribution of boulders and grains, from ~microns to decameters
  - Small regolith "dominates" in surface area but not volume.
  - Larger boulders and grains are coated in a matrix of finer grains.
- Implications of cohesion for small body strength and surfaces
  - Rubble pile asteroids can be strengthened by cohesive forces between their smallest grains.
  - Cohesive strength less than found in the upper lunar regolith can allow ~10 m rubble piles to spin with periods less than a few minutes.
  - "Monolithic boulders" ~10 m and spinning with periods much faster than ~1 minute can retain millimeter to micron grains on their surfaces



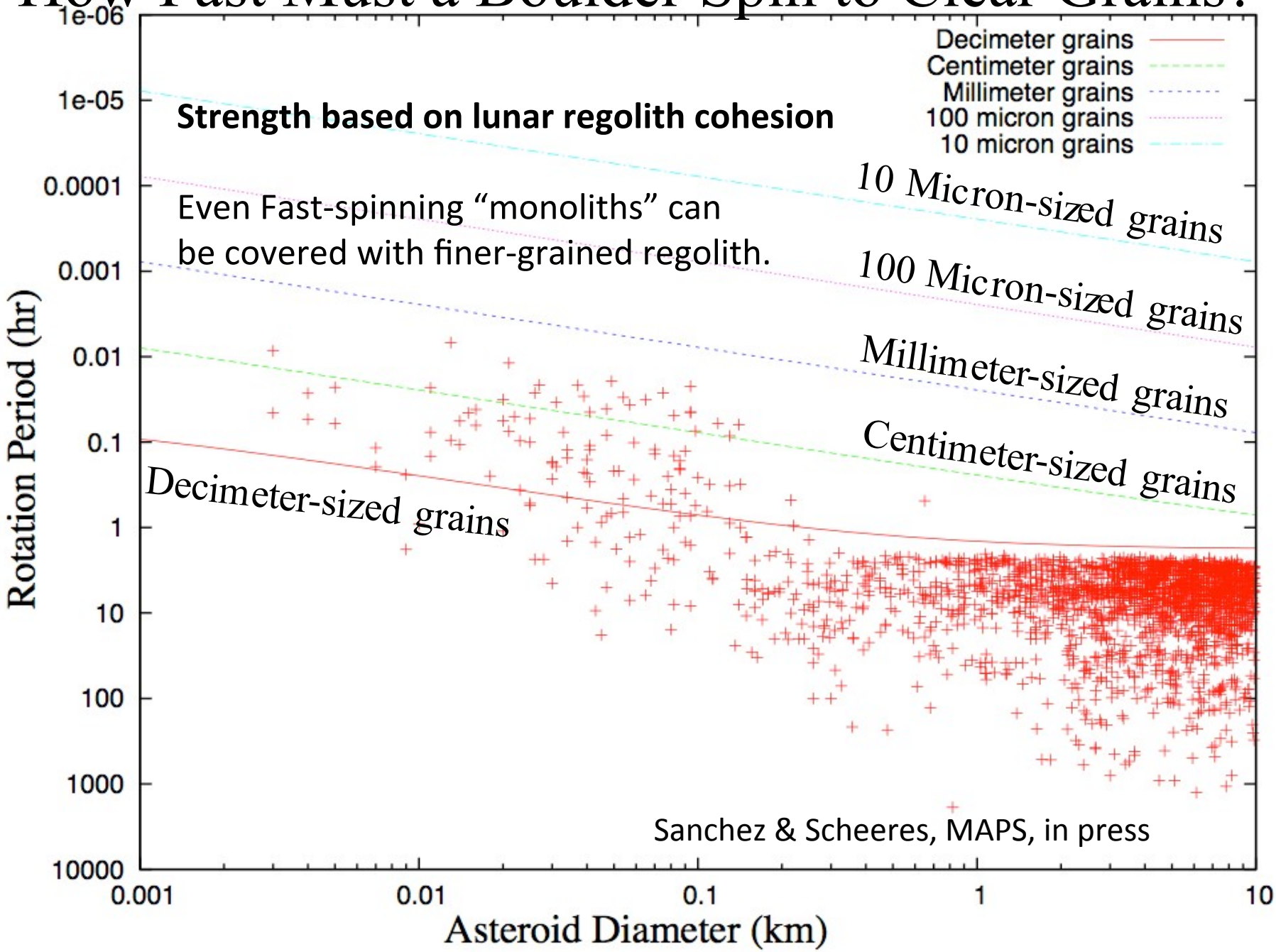



Strong Lunar Cohesion, 3 kPa
Weak Lunar Cohesion, 0.1 kPa
Simulated Cohesion, 25 Pa
Strong Lunar Regolith Cohesion: 3 kPa
Weak Lunar Regolith Cohesion: 100 Pa
"Very Weak" Cohesion: 25 Pa
How Fast can a Cohesive Rubble Pile Spin?
Sanchez & Scheeres, MAPS, in press
Rotation Period (hr)
Asteroid Diameter (km)
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0.001
0.01
0.1
1
10


Strong Lunar Cohesion, 3 kPa
Weak Lunar Cohesion, 0.1 kPa
Simulated Cohesion, 25 Pa
Monoliths ?
Rubble Piles?
Sanchez & Scheeres, MAPS, in press
Rotation Period (hr)
Asteroid Diameter (km)
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0.001
0.01
0.1
1
10

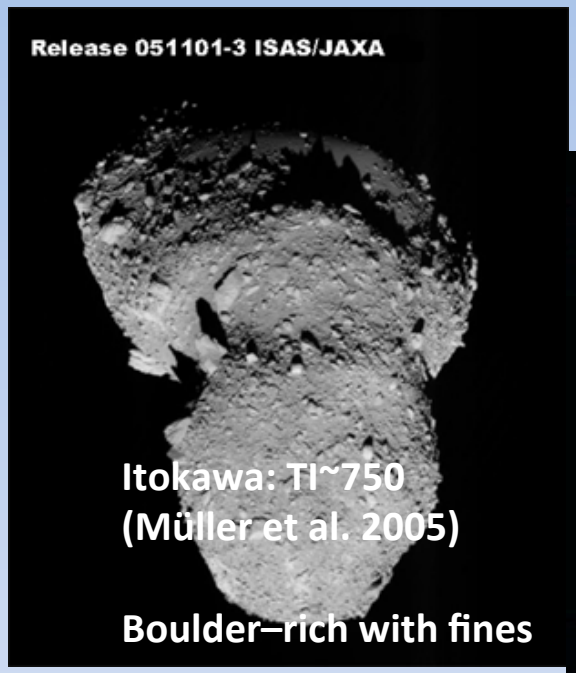

Strong Lunar Cohesion, 3 kPa
Weak Lunar Cohesion, 0.1 kPa
Simulated Cohesion, 25 Pa
2008 TC3 = Almahata Sitta
Max. Compressive Strength ~ 1 Mpa
Sanchez & Scheeres, MAPS, in press
Rotation Period (hr)
Asteroid Diameter (km)
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0.001
0.01
0.1
1
10

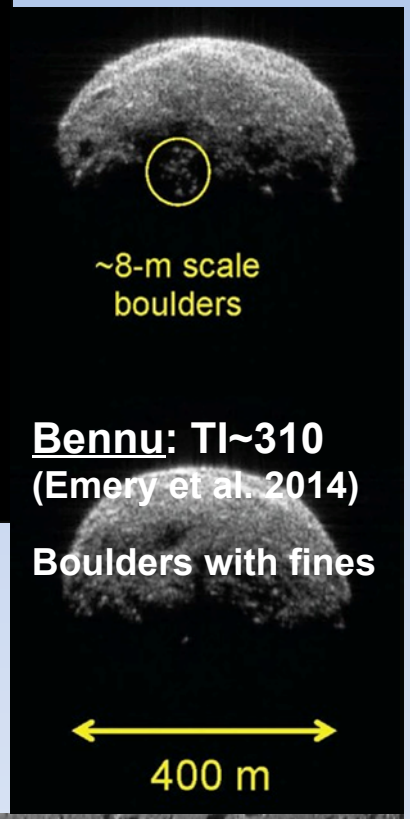
How Fast Must a Boulder Spin to Clear Grains?

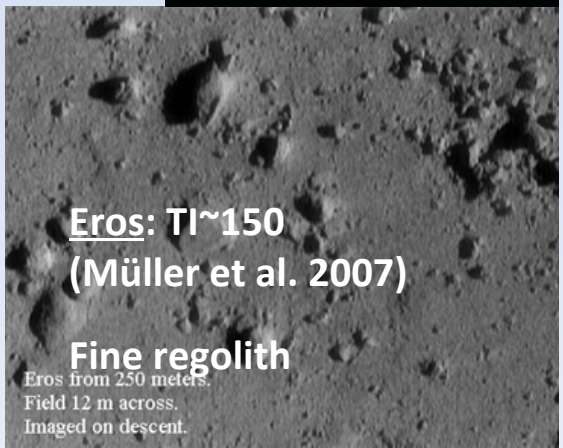


Thermal Inertia

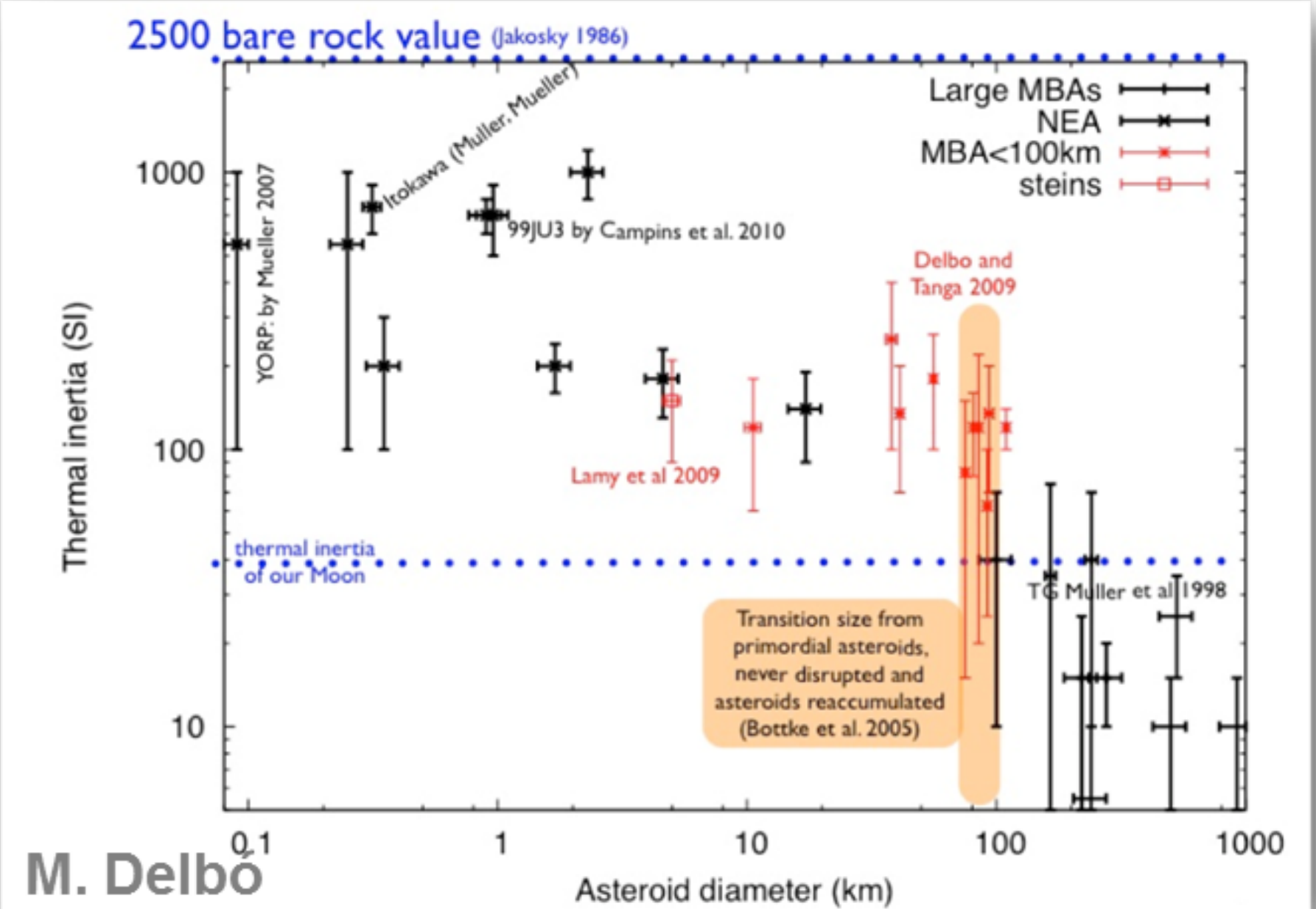
- Thermal Inertias of NEOs range from ~100 to ~1000 J $m^{-2}K^{-1}s^{-1/2}$
  - Moon: ~50
  - Large Main Belt asteroids: 10 to 40
  - Bare rock: 2500
- Implications for regolith grain sizes
  - NEO regoliths likely all coarser than the Moon's
  - Lower end likely "pebble" size (~mm)
  - Upper end has abundant boulders (> 0.5 m)





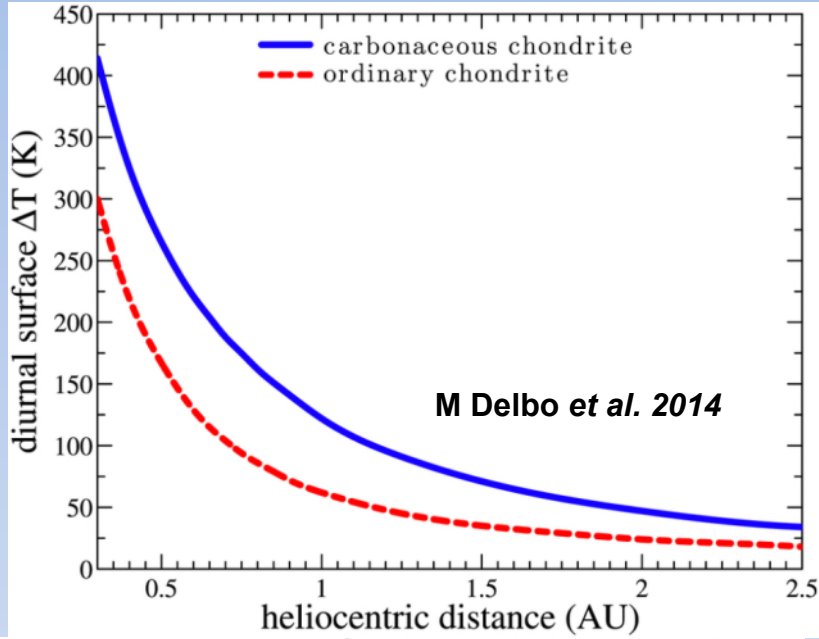


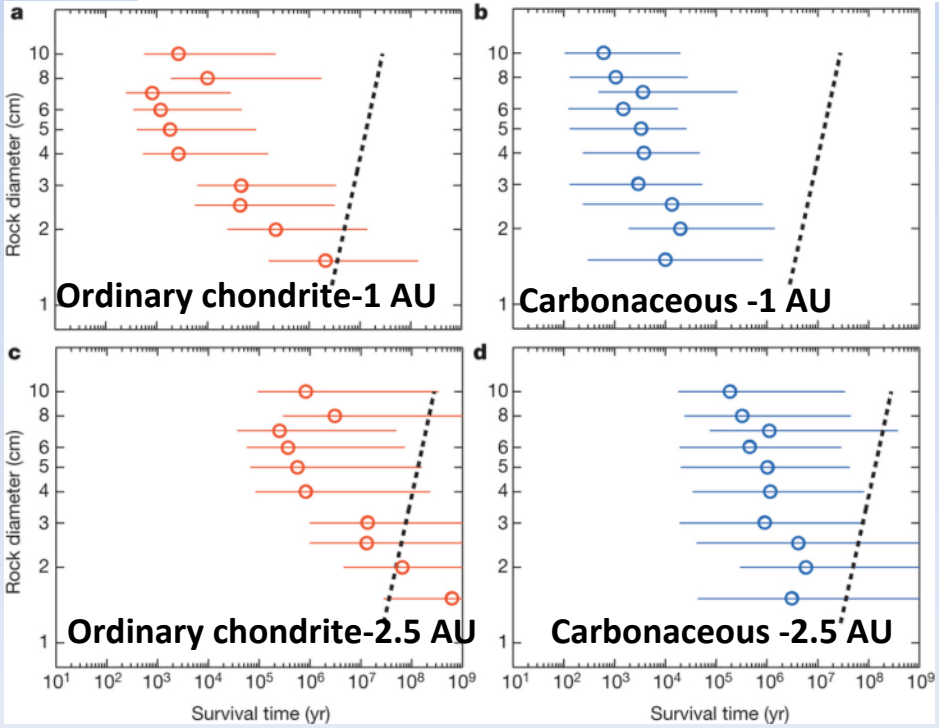
Thermal Inertia



Where do the fines come from?

- Turns out that thermal fragmentation from diurnal temperature variations breaks up rocks more quickly than micrometeoroid impacts, without the problem of ejection from the low-gravity body, creating fine-grained fragments.
- This effect works more strongly on the darker, carbonaceous asteroids (and more strongly with solar distance).





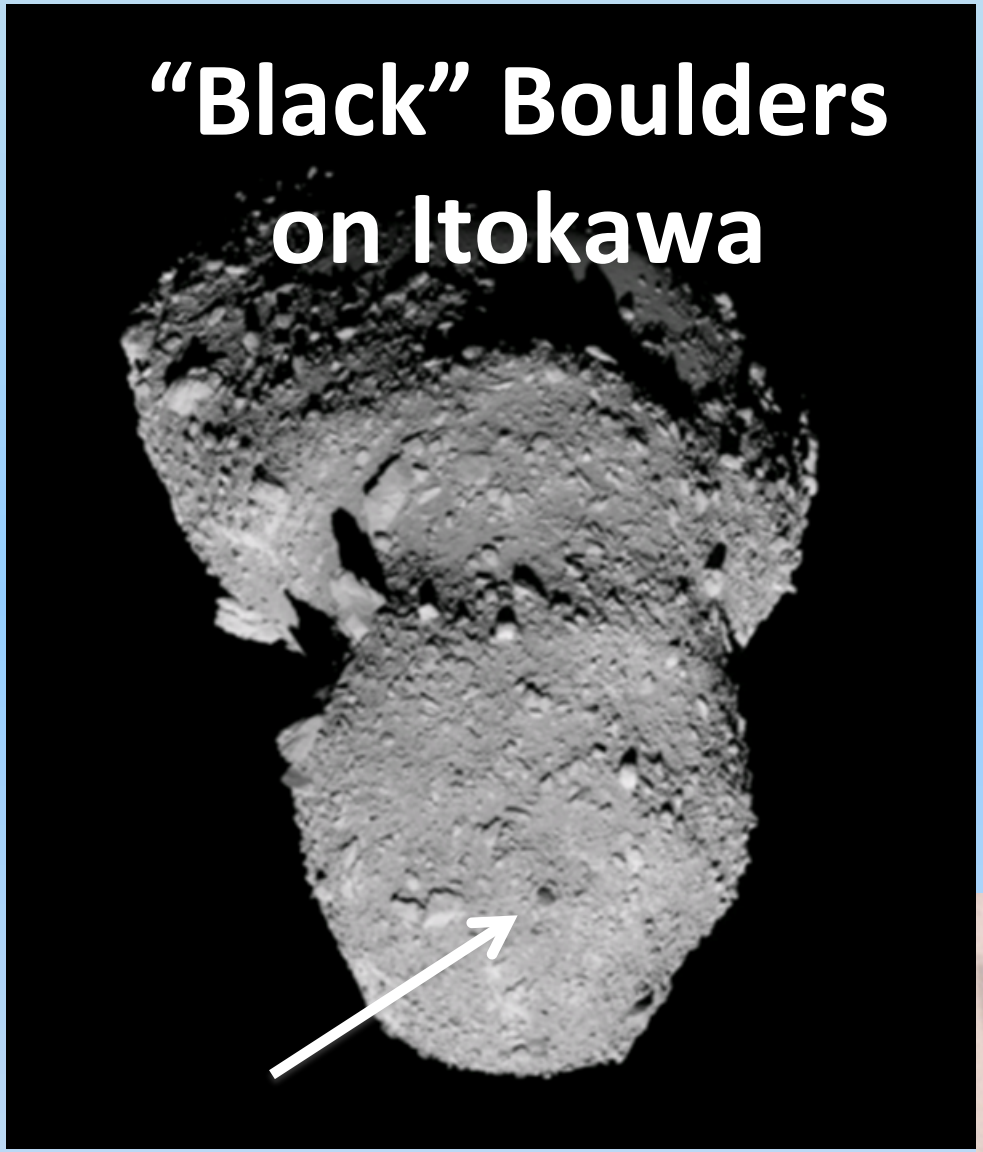
An Aside on ISRU

Element (wt.%)	Volatile-rich Carbonaceous Chondrites (CI, CM)	Other Carbonaceous (CO, CV, CK, CR, CH)	Ordinary Chondrites (LL, L, H)	Enstatite Chondrites (EL, EH)
Water	15.3	1.9	0	0
Carbon	2.7	0.7	0.1	0.4
Iron	19.6	27.3	22.5	25.5
Magnesium	10.7	14	14.7	12.4
Nickel	1.1	1.4	1.3	1.5
Sulfur	4.6	1.5	2.2	4.6
Oxygen	31	32.7	38.2	29.5
Silicon	11.7	15	18.1	17.7

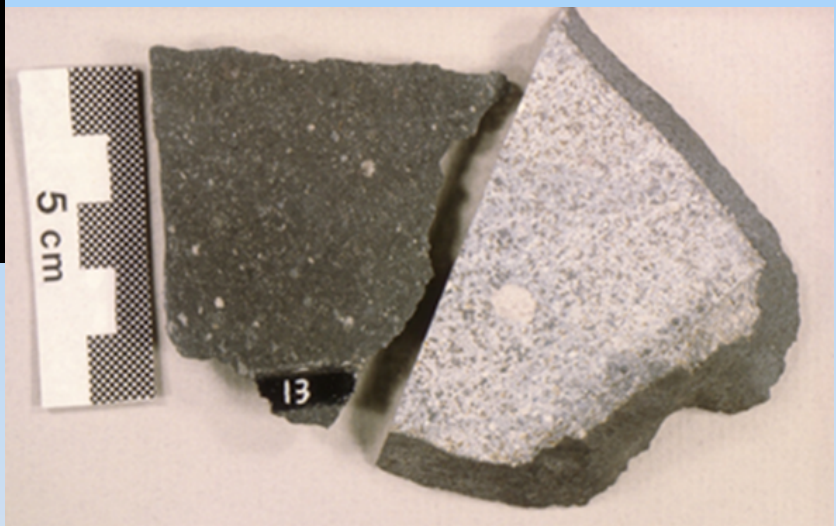
From Hutchison, 2004

- Most stones are very tough and poor in water and carbon.
- The oxygen in stones is mostly locked in very tough silicates.
- If you want to mine an asteroid for volatiles, it is not a good idea to grind up something that is 10X harder than concrete and has essentially no volatiles.

“Black” Boulders on Itokawa



- Most likely a “Black Chondrite”
- Black chondrites are 15% of the ordinary chondrite fall population
  - We should expect black chondrites on ordinary chondrite asteroids.
- Shown below are OCs Farmington and Farmville
  - Similar chemistry and mineralogy
  - factor of three difference in albedo



NEA Physical Properties

- Almost all NEAs are rubble piles.
  - Fall, bolide, spin rate, bulk density, and physics data all point to that conclusion.
  - Rubble pile NEAs are very porous.
- Weak cohesion is still enough to keep NEAs together.
  - Dusty regoliths are the glue of rubble piles.
- Thermal fragmentation can be a major source of fine particles on small bodies.
- The components of NEAs (meteorites) vary hugely in strength.
  - From steel to soggy dirt clods.
- Most NEAs (even very small NEAs) have some dusty regolith.