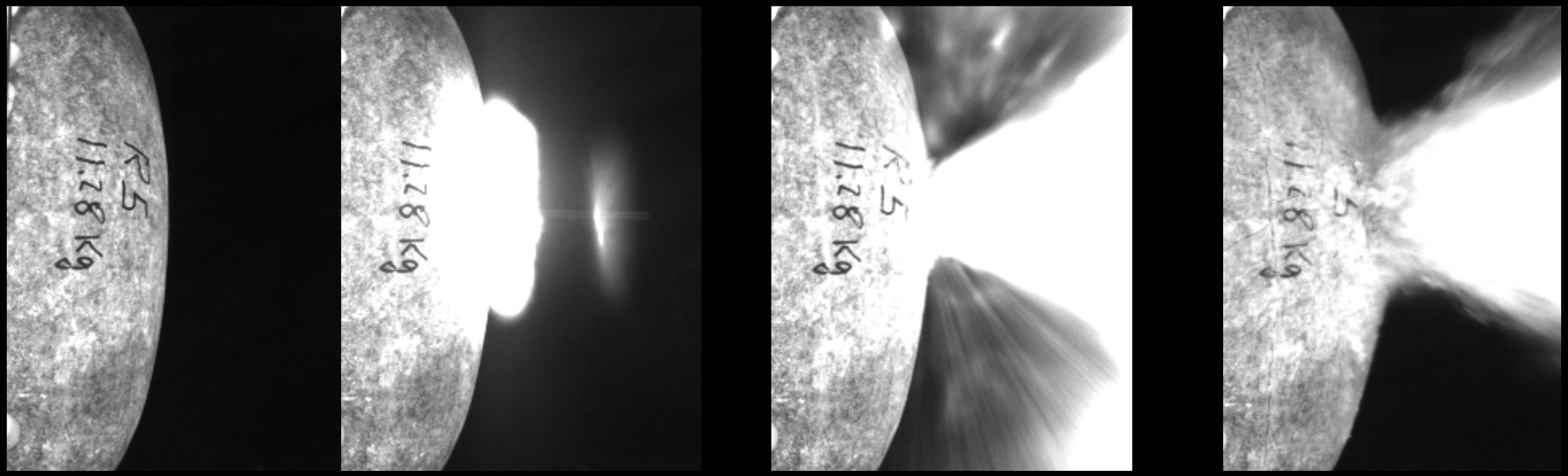
Momentum transfer via direct impact: Experimental measurements



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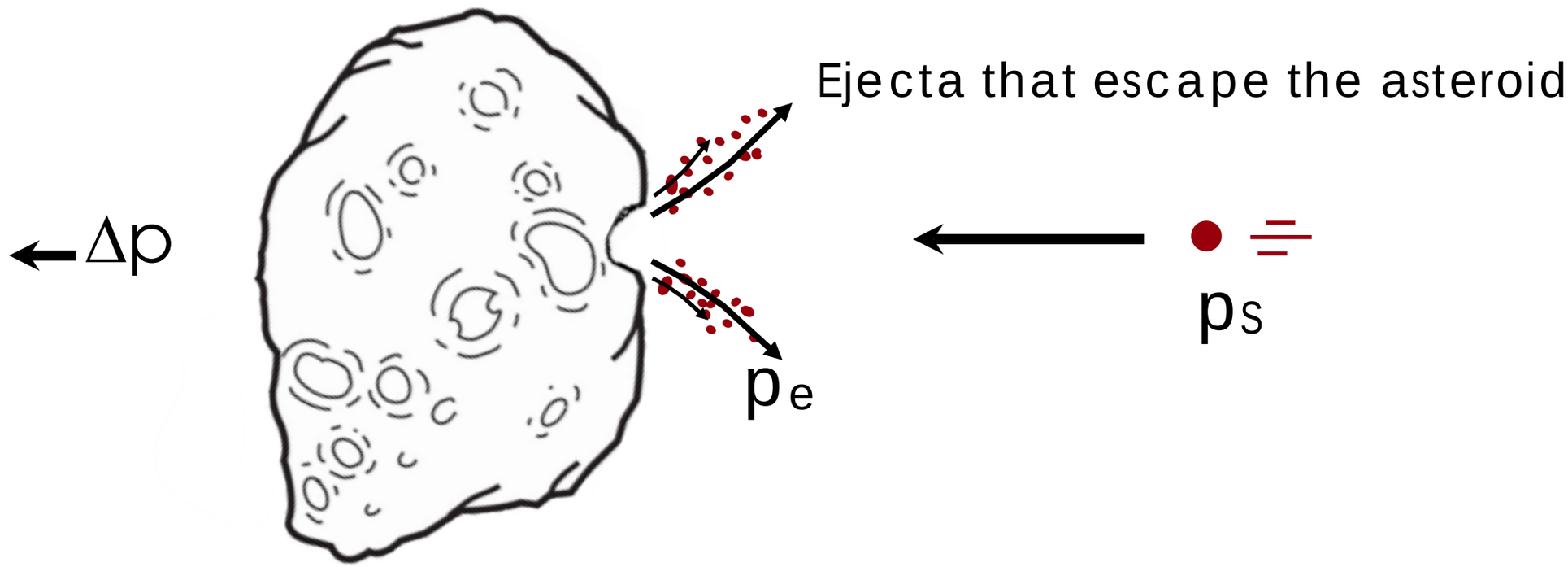
The central question

- How effective is the direct impact method?
  - What is the largest asteroid we could expect to deflect?

Momentum multiplication factor



Change in asteroid momentum: $\Delta p = p_s + p_e$

Define $\beta = \dfrac{\Delta p}{p_s}$

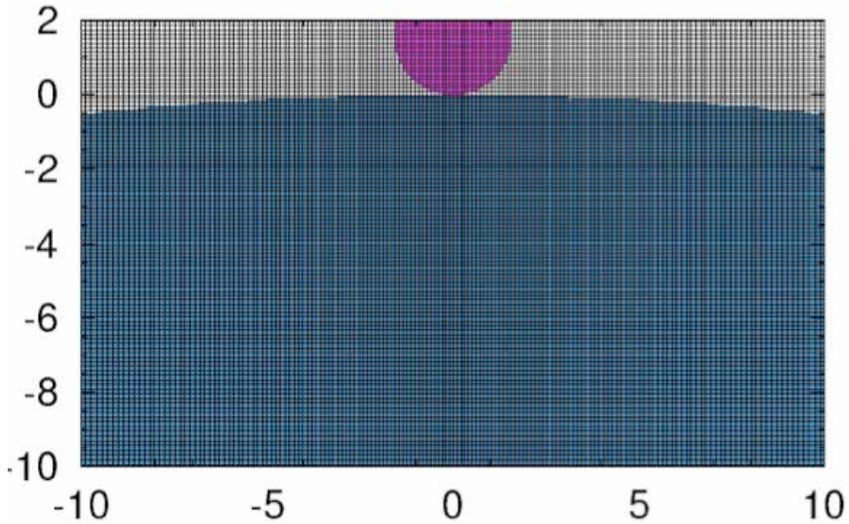
$$\boxed{\beta = 1 + \frac{p_e}{p_s}}$$

$\beta > 1$, unless there is no escaping ejecta

Our approach

- Conduct impact experiments to directly measure β.
  - But can't do experiments under the conditions of an actual mission.
  - So, the experiments are "scaled" to the mission conditions.

- Numerical simulations
  - Validate against experiments
  - Extend the reach of experiments



Scaling of ejecta momentum

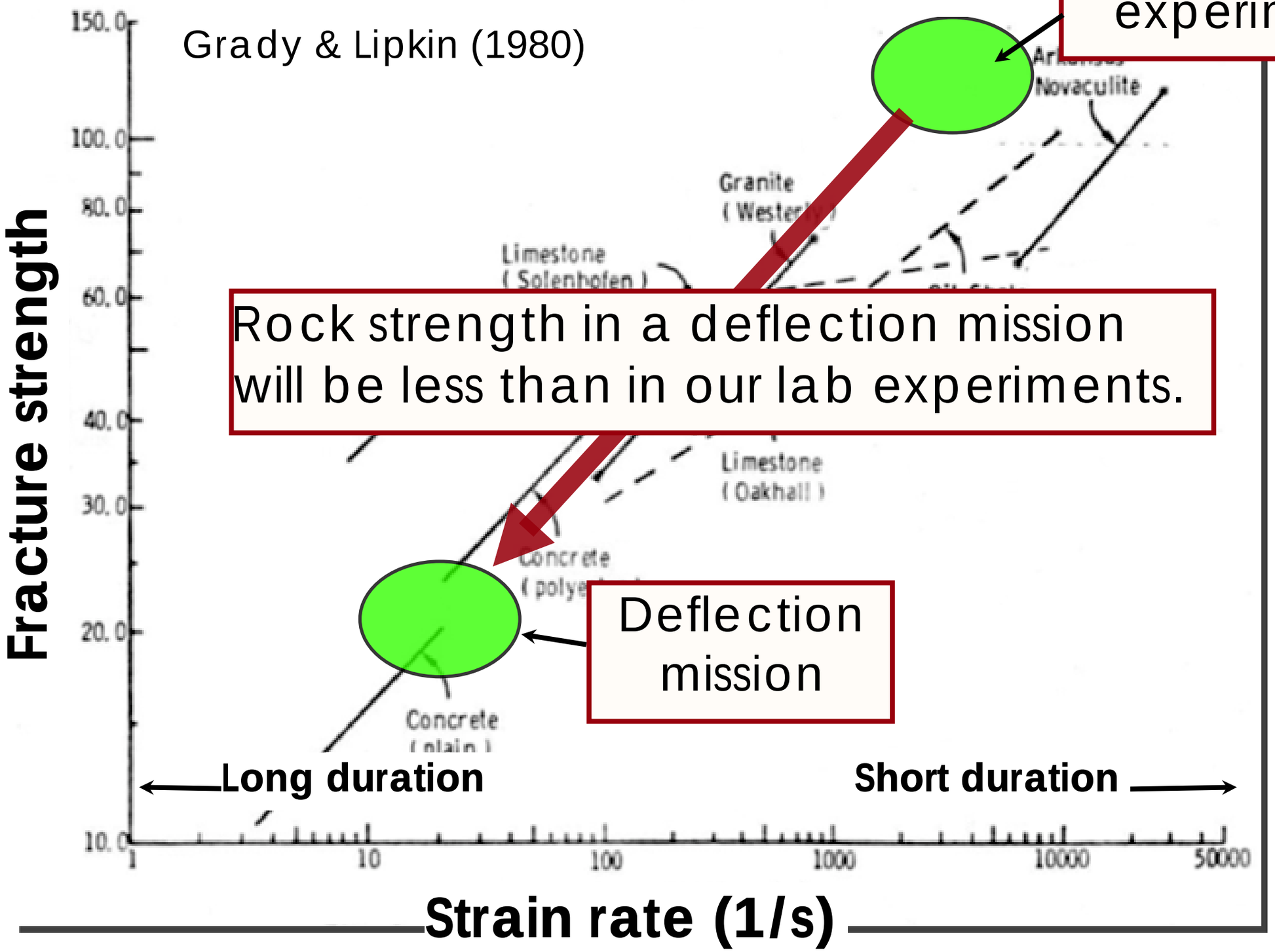
$$\beta = 1 + \frac{p_e}{p_s}$$

- Understanding β is just a cratering and ejecta problem.
- We know how ejecta scales from point-source theory of cratering.
  - (Housen et al 1983, Holsapple & Schmidt 1987, Housen & Holsapple 2011)

Two regimes of crater formation

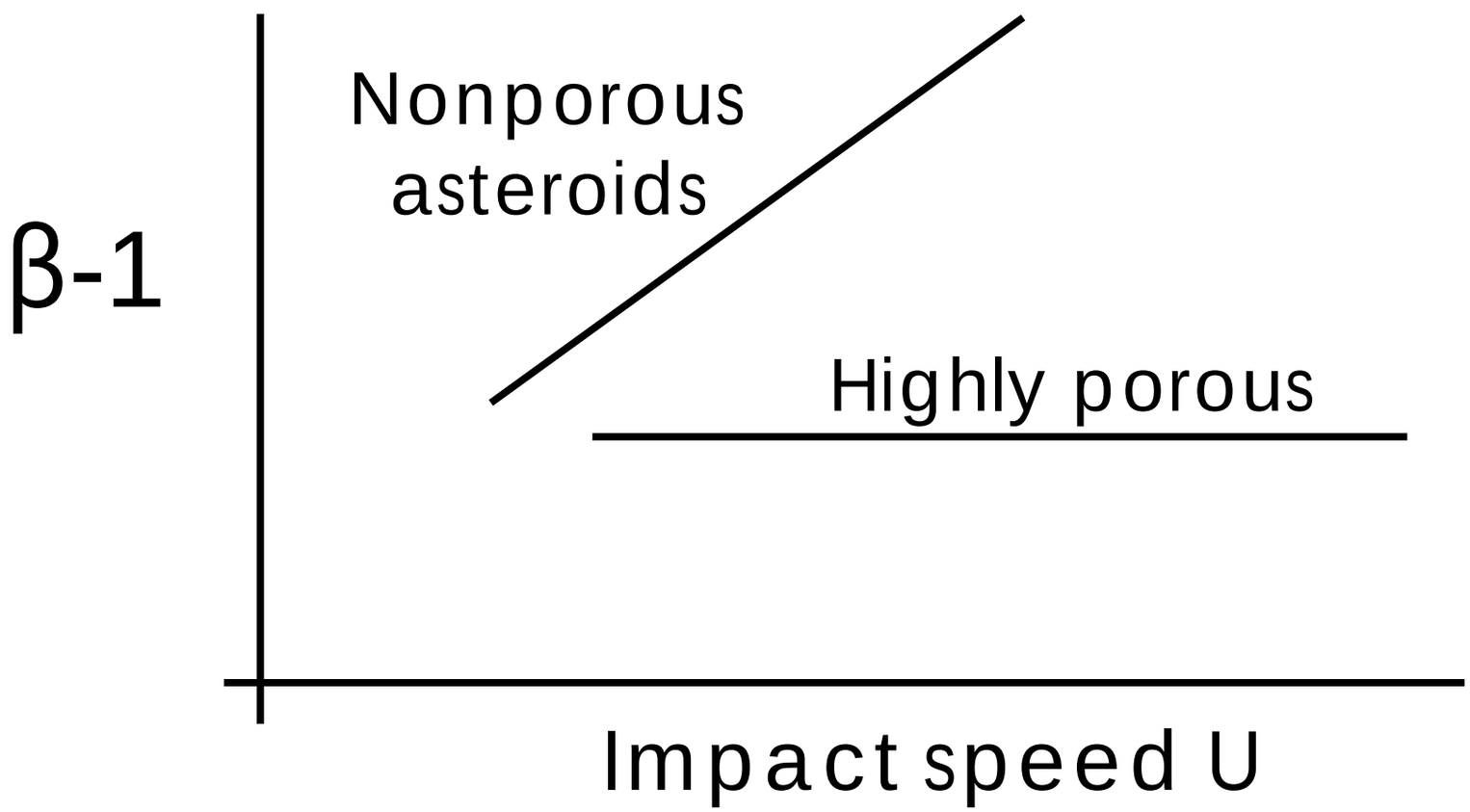
- Gravity regime $\rho gh >> \text{cohesion}$
  - Large-scale impacts, or craters formed in very low strength materials (e.g. sand)
- Strength regime $\rho gh << \text{cohesion}$
  - “Small” impacts in rocky targets
  - And perhaps “cohesionless” soils at micro-G
- Applying lab results to a mission requires knowing which regime you’re in.

Rock strength is rate dependent



Scaling of β

	Nonporous	Moderate porosity	Highly porous
Strength	$\beta - 1 \propto a^{0.15} U^{0.73}$	$\beta - 1 \propto U^{0.2}$	$\beta - 1 \approx \text{constant}$
Gravity	$\beta - 1 \propto (ga)^{-0.25} U^{0.5}$	$\beta - 1 \propto (ga)^{-0.08} U^{0.16}$	$\beta - 1 \approx \text{constant}$



Low-porosity materials have the strongest velocity dependence

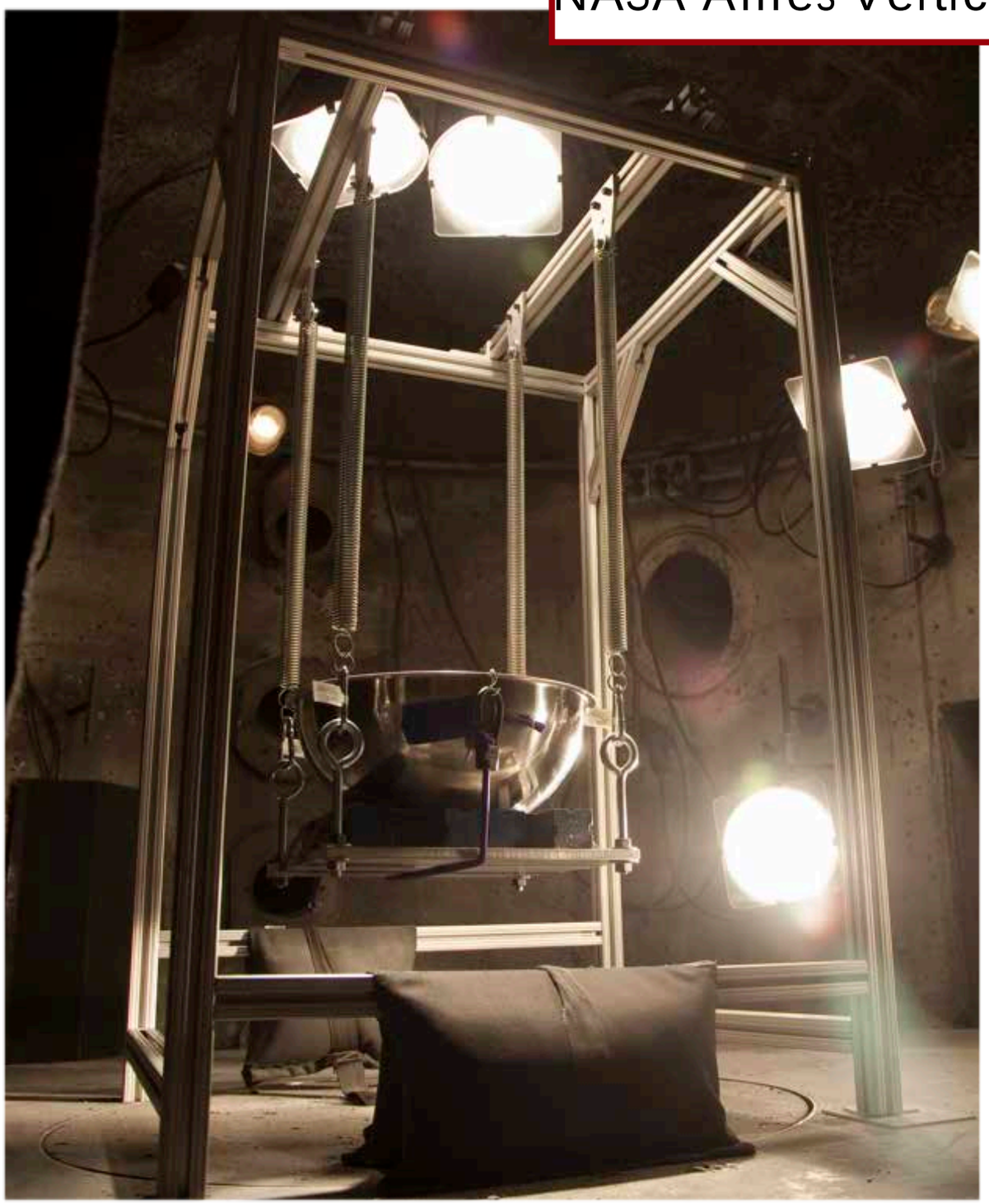
Experiments to measure β

- Ballistic pendulum
  - Works, but granular materials need to be shot vertically
- Force transducers
  - Uncertainty when integrating force-time history to get impulse
- Suspend target from springs

Impact chamber in Boeing Shock Physics Lab

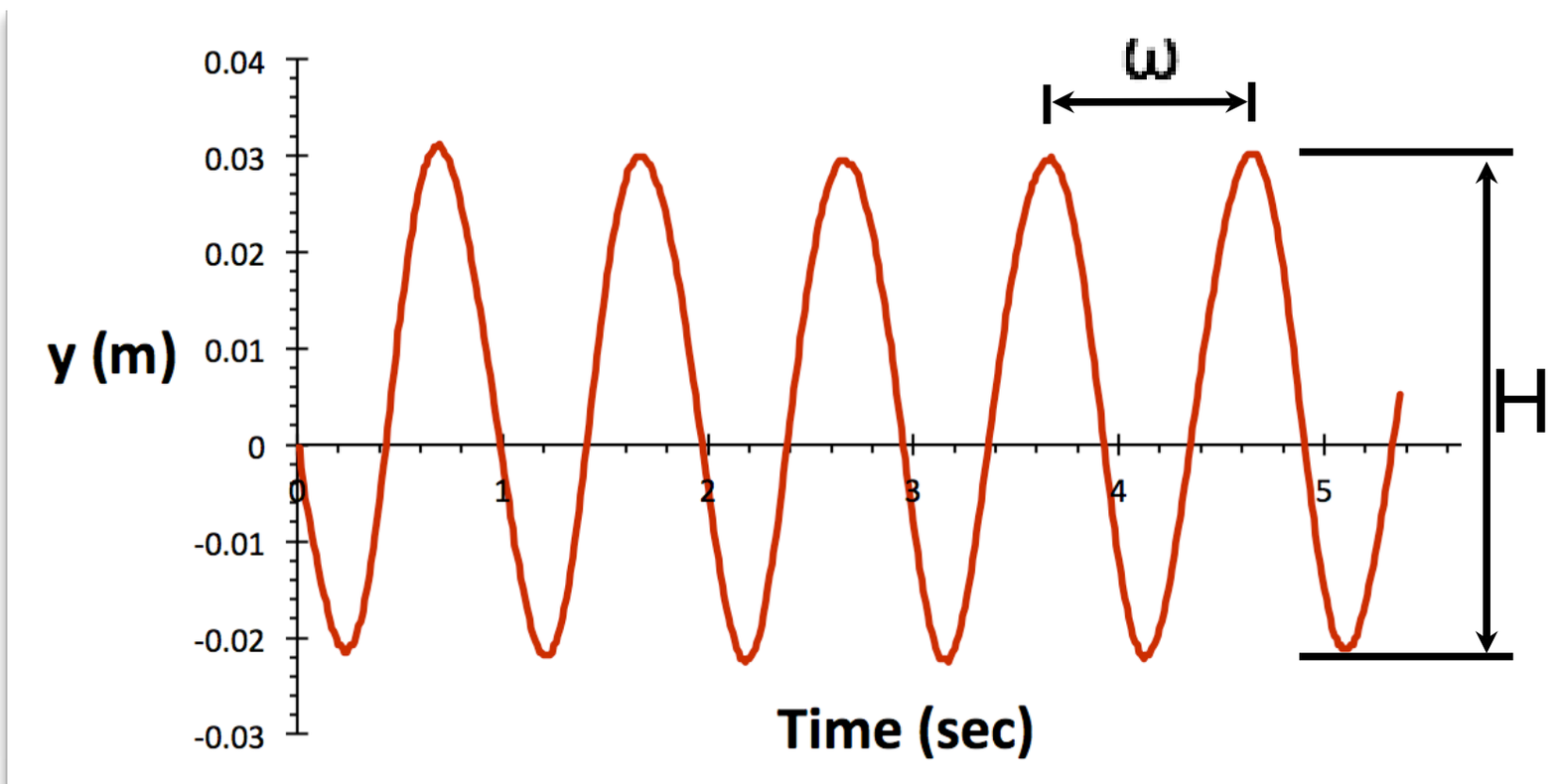
Experiments to measure β

NASA Ames Vertical Gun Range



How we measure β

Sand target
5.7 km/s impact
6.4 mm Al sphere



Impulse delivered to target:

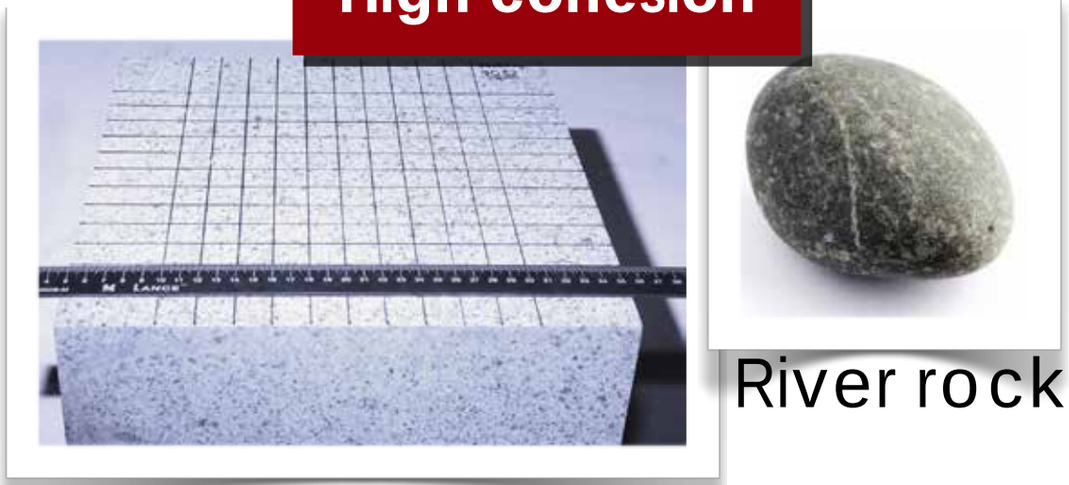
$$I = \frac{H\omega M}{2}$$

$$\beta = \frac{I}{mU}$$

m,U = projectile mass, speed

Target materials used to-date

Low porosity
High cohesion



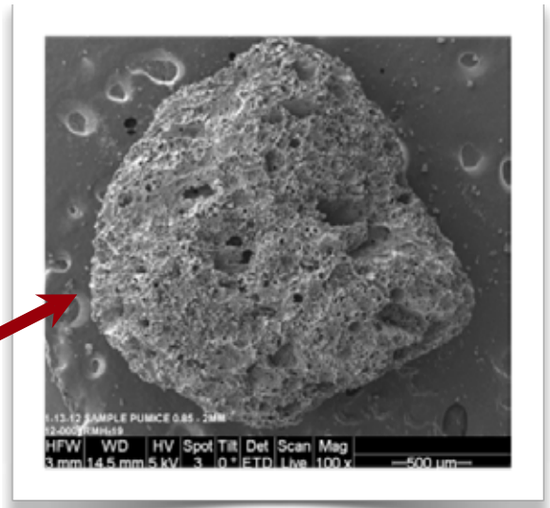
Granite & basalt blocks

River rock

High porosity
Medium cohesion

Cohesive pumice

High porosity
No cohesion

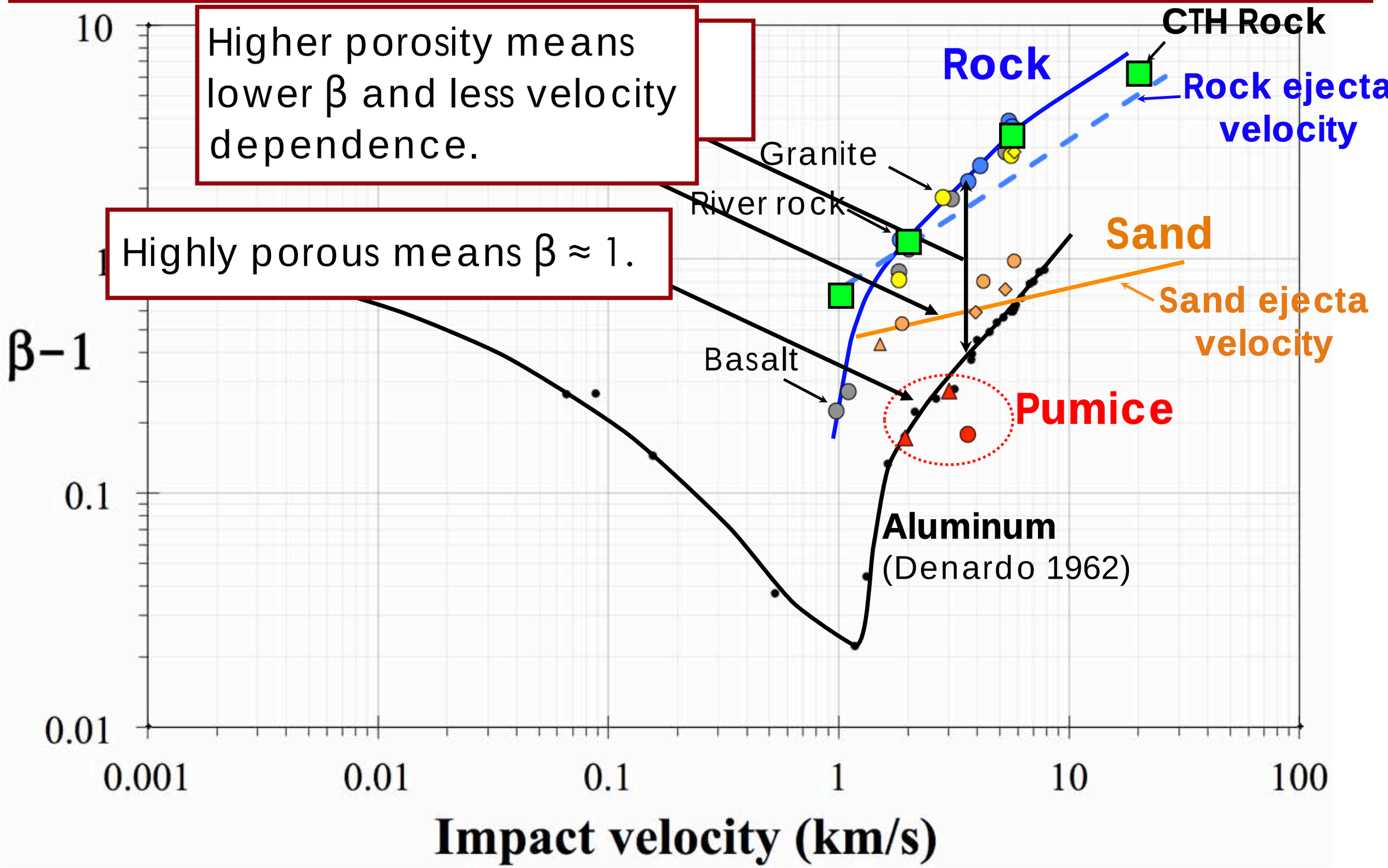


Granular pumice
84% porosity

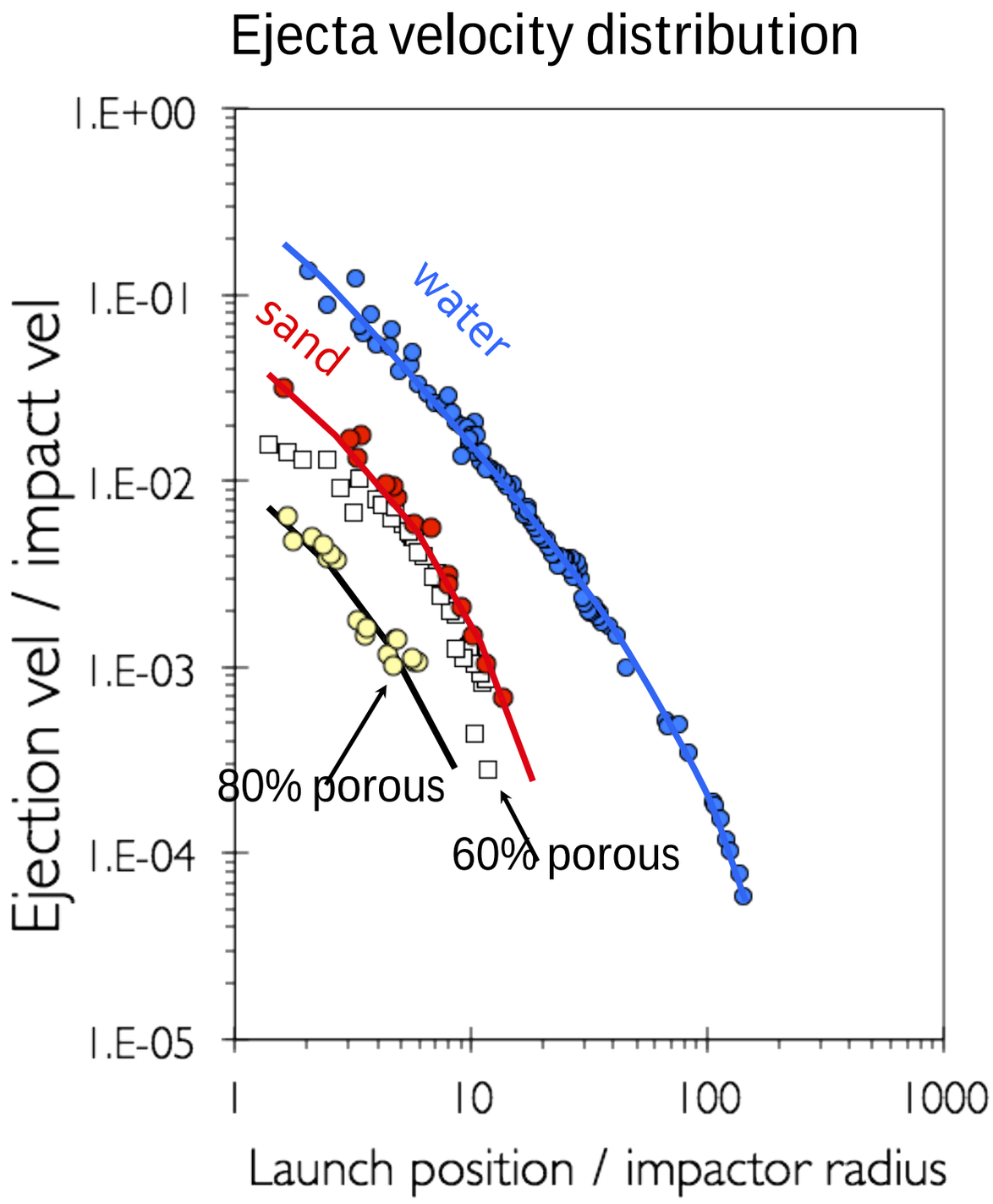
Medium porosity
No cohesion

Dry sand
35% porosity

Results


Higher porosity means lower β and less velocity dependence.
Highly porous means β ≈ 1.
CTH Rock
Rock
Rock ejecta velocity
Granite
River rock
Sand
Sand ejecta velocity
Basalt
Pumice
Aluminum
(Denardo 1962)
β−1
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
Impact velocity (km/s)

High porosity reduces ejecta velocity



Applications to asteroids

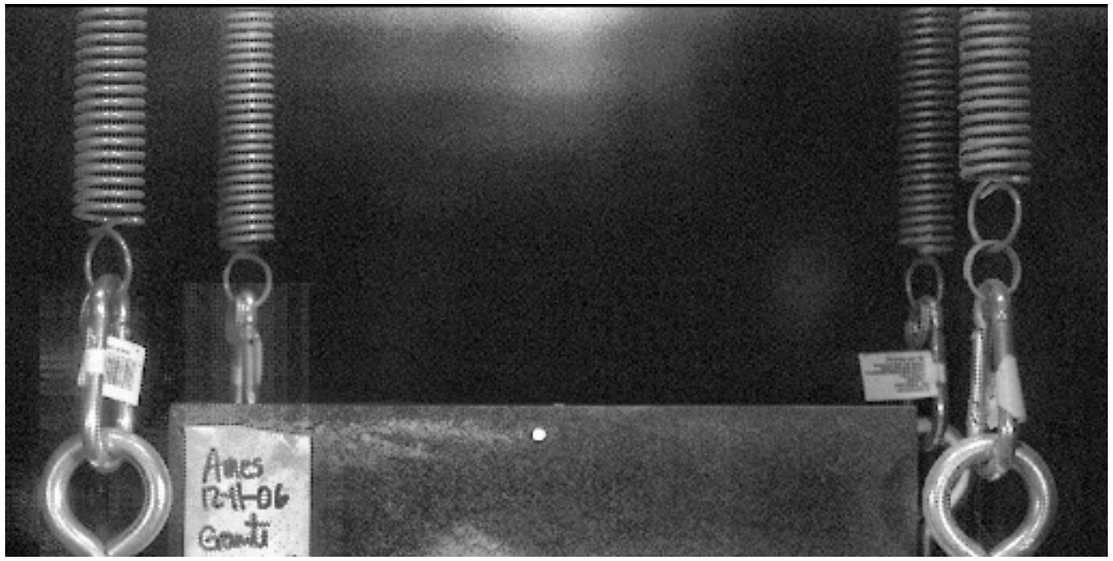
- Is the event strength or gravity dominated?
  - The crater scaling is different in these two regimes.

- How much of the ejecta escapes the asteroid, and how much momentum does it contain?

Rocky targets

- Strength dominated at all size scales of interest.
- All ejecta would escape an asteroid.
  - Slowest ejecta has m/s speeds.
  - Escape speed for 500 m asteroid = 0.2 m/s

Granite target
5 km/s impact
6.4 mm Al sphere

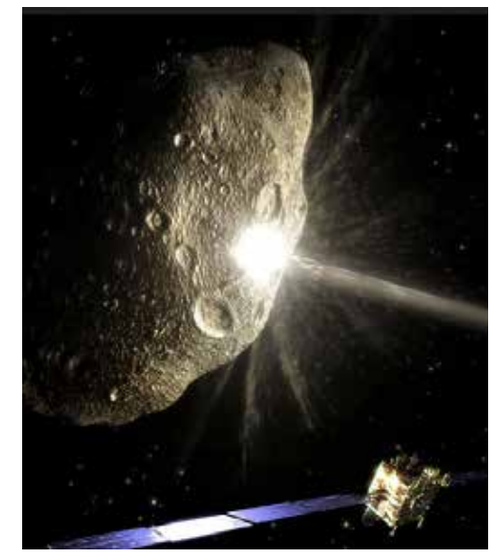


Scaling to higher impact speed

5 km/s lab experiment

Measured
$\beta \approx 4 - 5$

20 km/s mission



4x higher velocity

$$\beta - 1 \propto U^{0.73}$$

β = 9-12

CTH @ 20 km/s: β = 7.5

Conservative: $\beta \approx 8$

Strain rate effect

$$\beta - 1 \propto a^{0.15}$$

Impactor size

- Strength of rock depends on strain rate.
  - Rock is weaker for large-scale impacts.
  - Lower strength means bigger craters, more ejecta.
- For a 1-m impactor, we get a factor of 2x increase in β-1.

20 km/s mission to a rocky asteroid: $\beta \approx 15$

Implications for deflection

ΔV = 0.01 m/s for 1-decade warning (Ahrens & Harris, 1992)

$$\beta = \frac{M\Delta V}{mU} = 15$$

5-ton spacecraft, 20 km/s

A 5-ton impactor at 20 km/s imparts $\Delta V \geq 0.01$ m/s for rocky asteroids up to ~500m diameter.

1-ton spacecraft could deflect a ~300m diameter body.

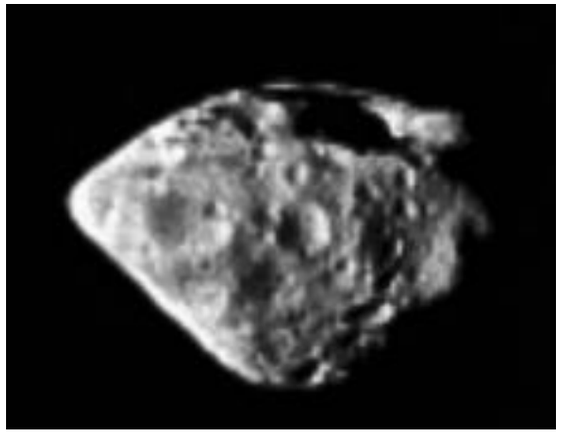
Additional conservatism - assume no rate dependence:
5-ton spacecraft could deflect a ~300m diameter body.

Sand targets

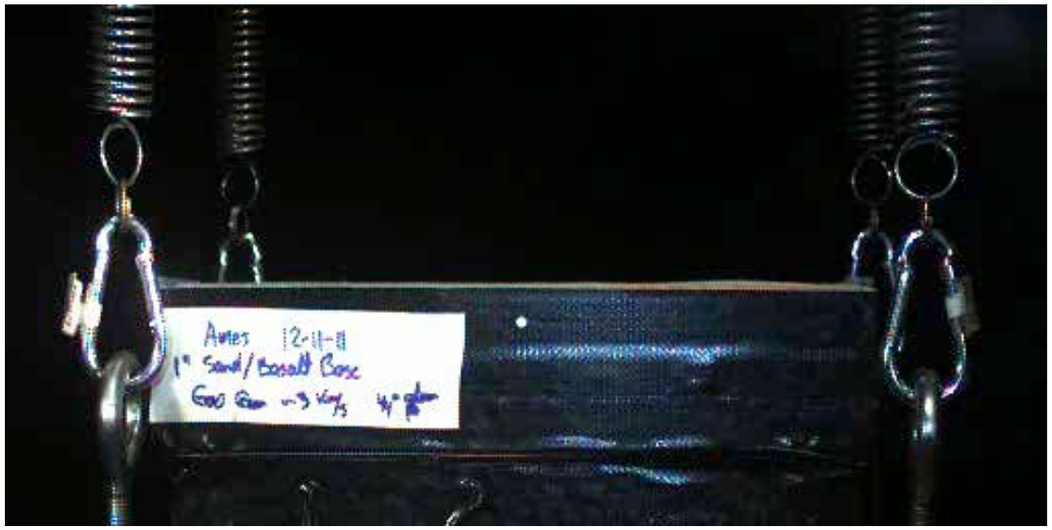
- Lab experiments are gravity dominated.
- Assume gravity dominated for a small asteroid as a bounding case.
- Must account for ejecta that are retained.
  - Holsapple and Housen (2012) Icarus 221.
- Bottom line:
  - $\beta \approx 1$ to 2 for a 20 km/s deflection mission.
  - Deflection of 200 to 300m bodies is possible.

Regolith-covered rock

Asteroid Steins ~5 km dia



- All asteroids imaged to date show signs of a regolith-covered surface.
  - So bare rock may be an unlikely case.
- What is the effect of a regolith layer?
- Impacted basalt target covered by a layer of sand
  - Only have 1 experiment.



Summary

- We find significant momentum multiplication for rocky targets, or regolith-covered rock.
- Increased target porosity causes
  - dramatic decrease in β as target porosity increases
  - weaker dependence on impact speed
- For a decade of warning deflection is possible for
  - Rocky bodies up to ~500 m diameter
  - “Balls of sand” up to 200-300 m diameter

Open questions

- Effect of a regolith layer
  - How does the layer thickness affect β?
  - What is the impact velocity dependence?
- Strain rate effects should be evaluated directly in momentum transfer experiments with rock targets.
- How does the "fabric" of the target affect β?
- What is the cohesive strength of granular materials at μ-G gravity?
  - How does that affect β?