PROPAGATION OF IMPACT-INDUCED SEISMIC WAVES INTO THE INTERIOR OF A RUBBLE-PILE ASTEROID

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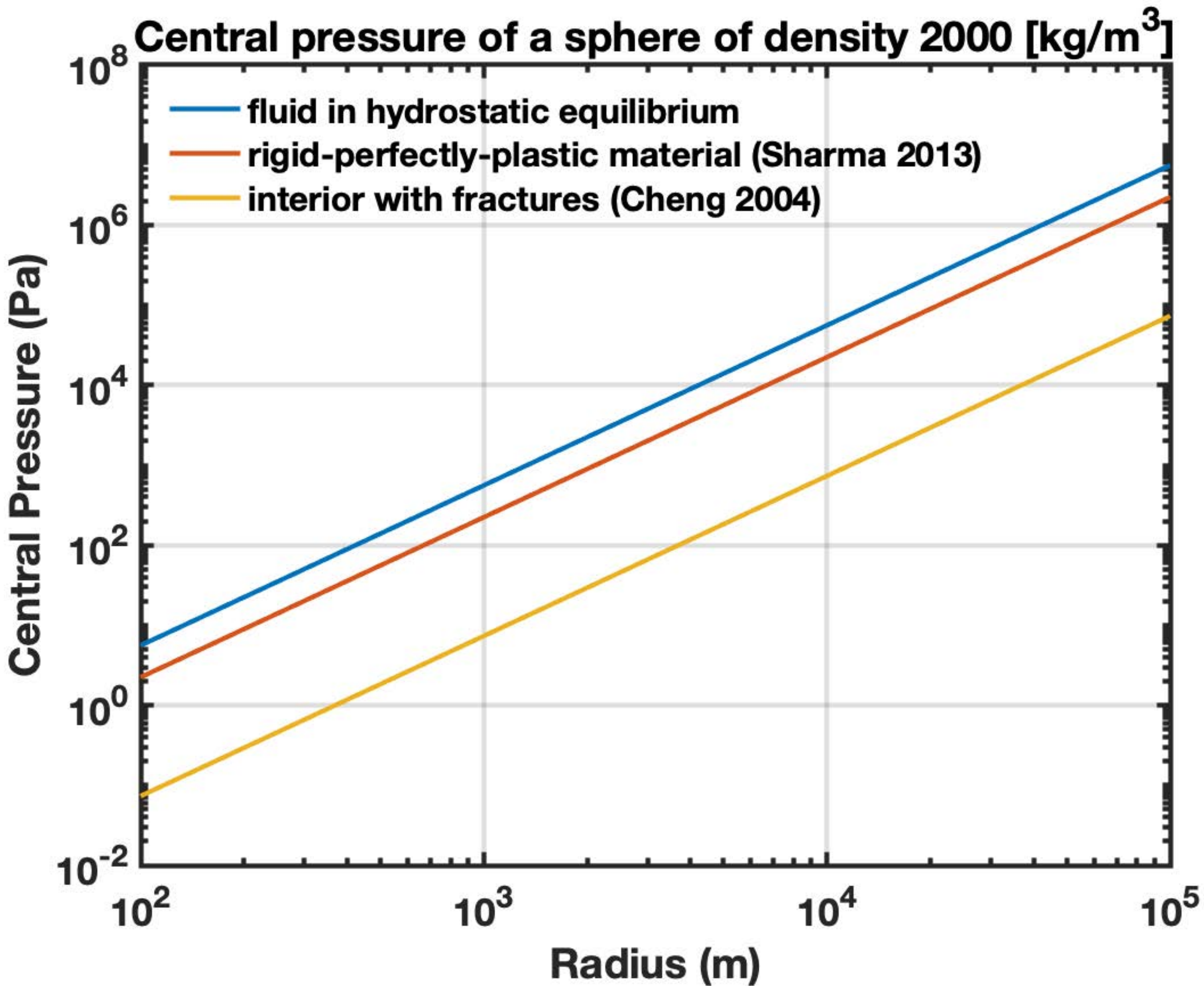
MOTIVATION

- Effects of impact induced seismic waves into the interior of a selfgravity body
- Dependence of wavespeed with the increasing pressure in the interior
- Effects on the relocation of the material in the interior
- Visible effects on the surface far from the impact point

PRESSURE IN THE INTERIOR OF AN ASTEROID (THEORETICAL MODELS)

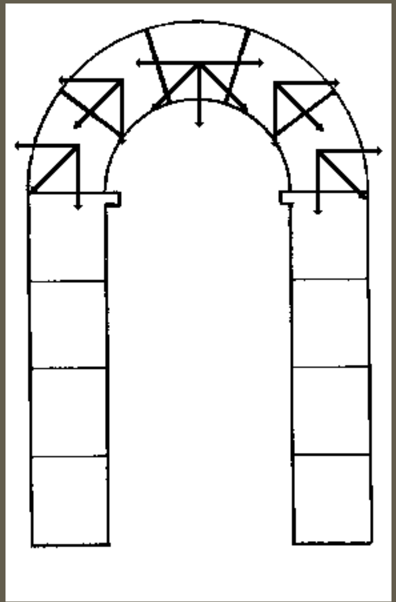
Variation of the pressure inside an agglomerated asteroid computed with three methods:

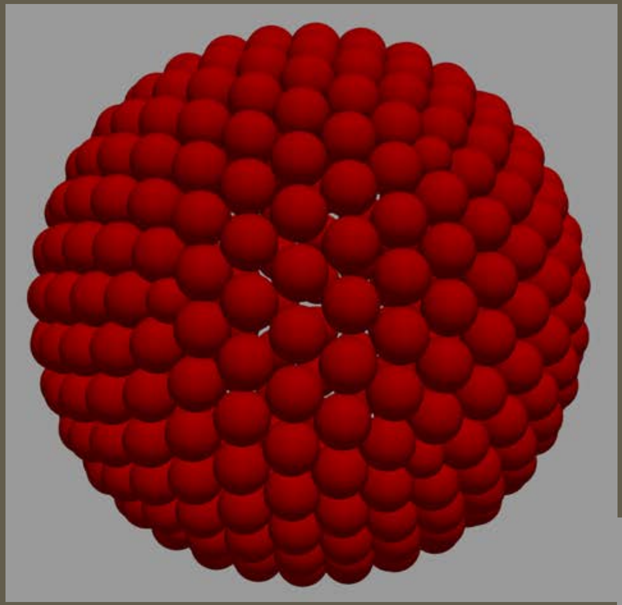
- A fluid in hydrostatic equilibrium
- A rigid perfectly plastic material, according to eqs. from Sharma (2013)
- An asteroid with vessels in the interior filled with granular material (Cheng 2004)



PRESSURE IN THE INTERIOR OF AN ASTEROID (RUBBLE PILE MODELS)

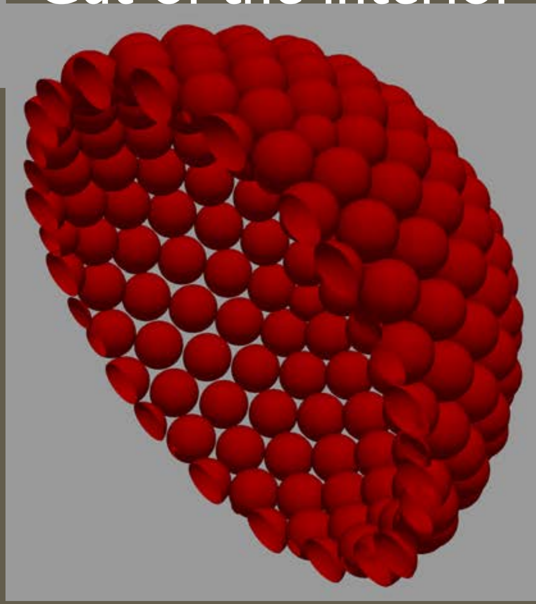
An agglomerated asteroid could have chain forces among the particles that hold the weight of the overlaying material, like an architectural arc or dome.





Hypothetical extreme object, with one layer of particles, maintained by self-gravity

Cut of the interior



The pressure in the interior will be 0.

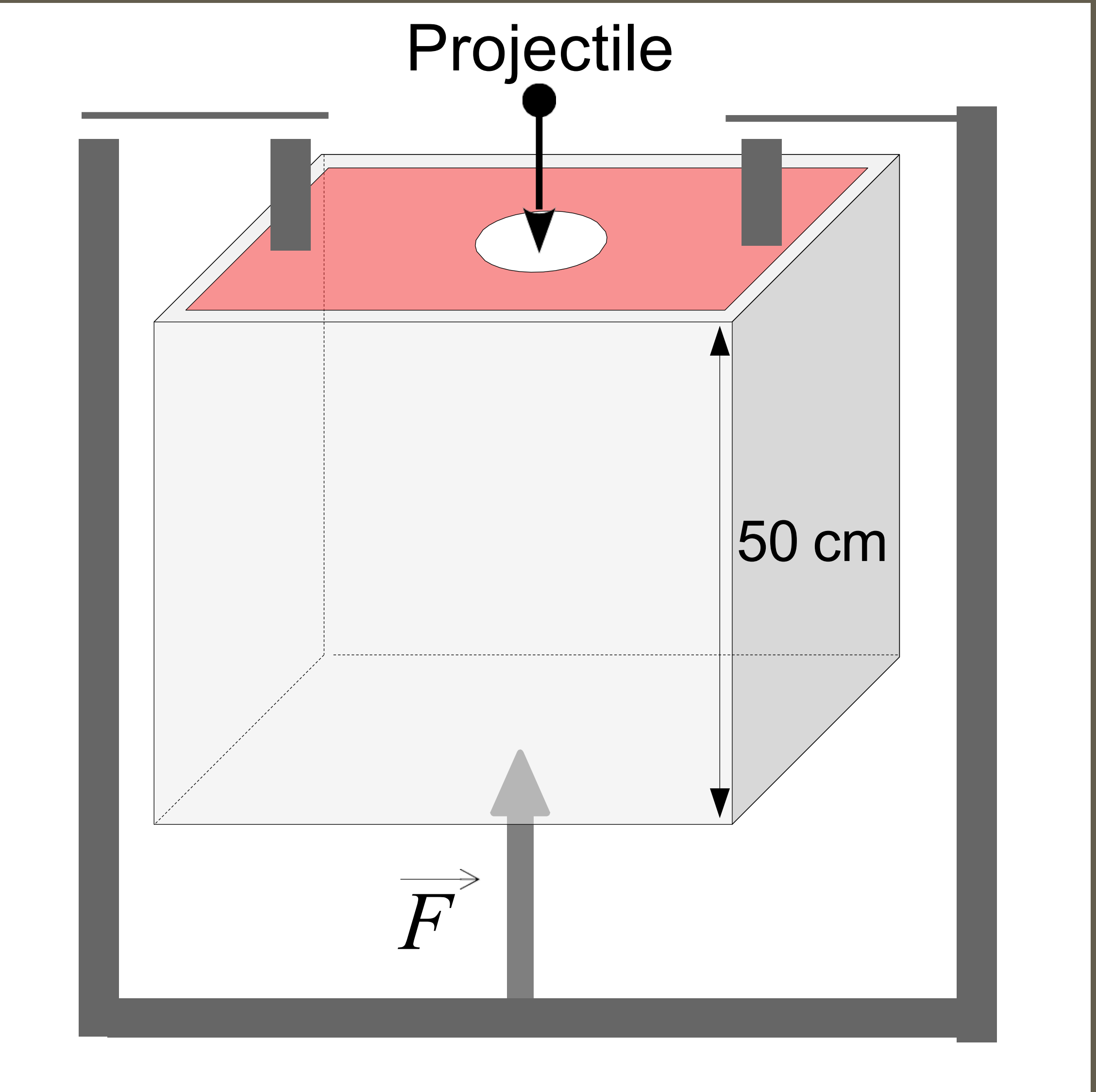
HOW MIGHT THIS EFFECT AFFECT THE PROPAGATION OF IMPACT-INDUCED WAVES INTO THE INTERIOR?

TWO APPROACHS

Laboratory experiments in Earth-gravity with different granular materials and a wide range of velocities.

Numerical simulations with a DEM code, with different elastic material properties, velocities up to the sound speed of the solid material and a wide range of gravity regimes.

EXPERIMENTAL SETUP

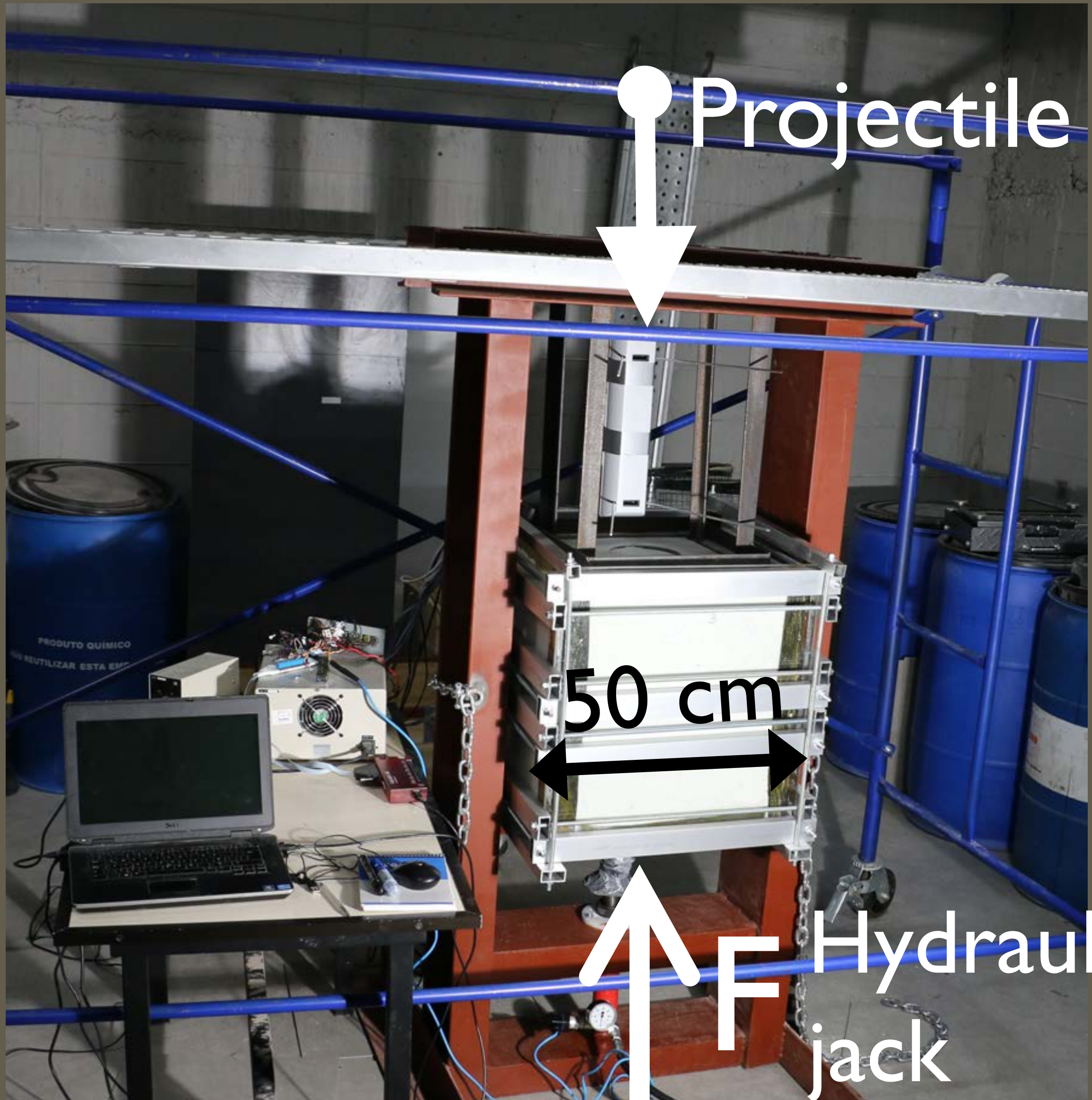


- Granular media in a movable cubic box with a hydraulic jack
- Top cover cannot move
- Small aperture on top for impact

Previous similar experiments:

- Yasui et al. 2015
- Van den Wildenberg et al. 2013
- Delage et al. 2017

EXPERIMENTAL SETUP



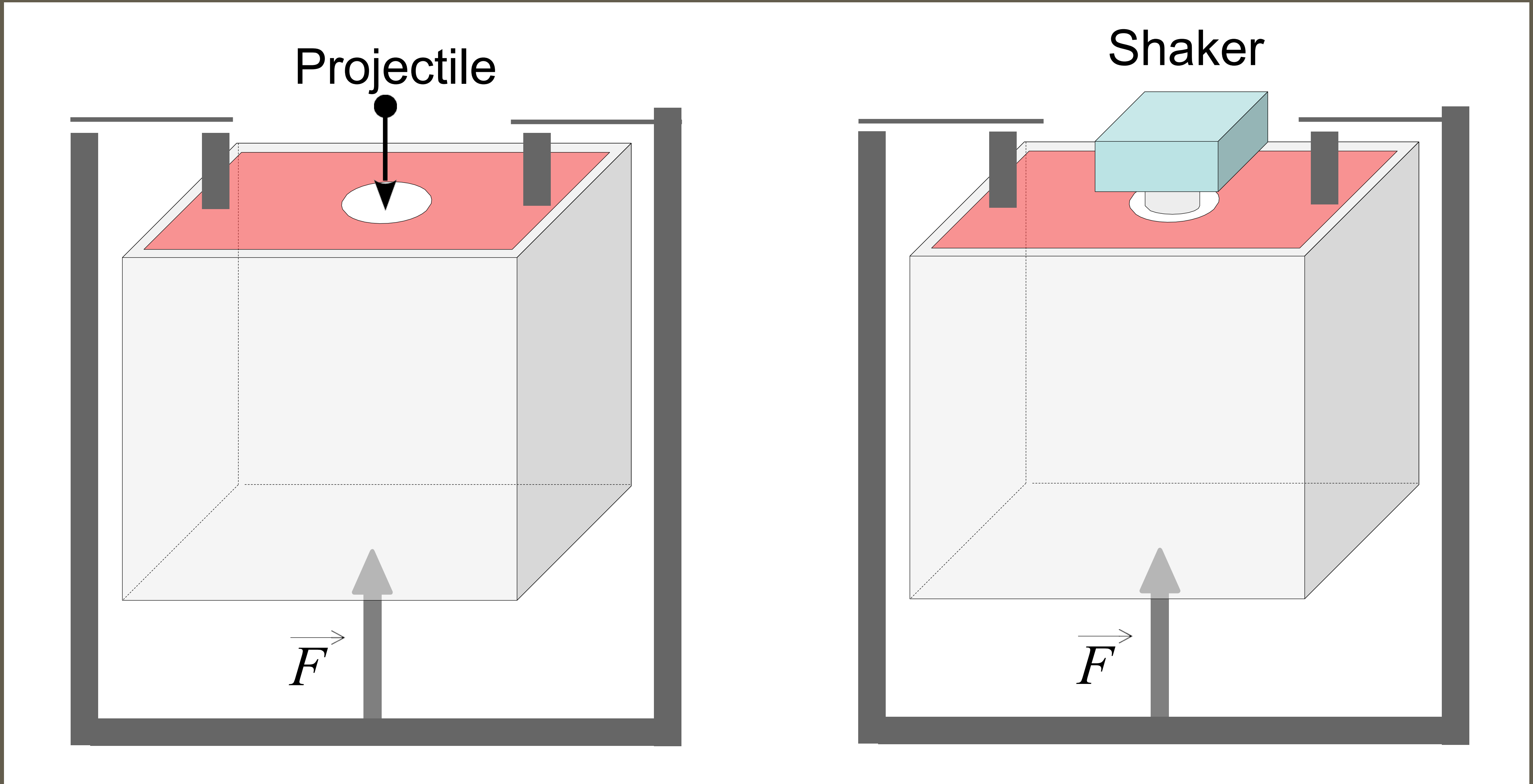
Selfgravity is mimicked by static loading

Top view

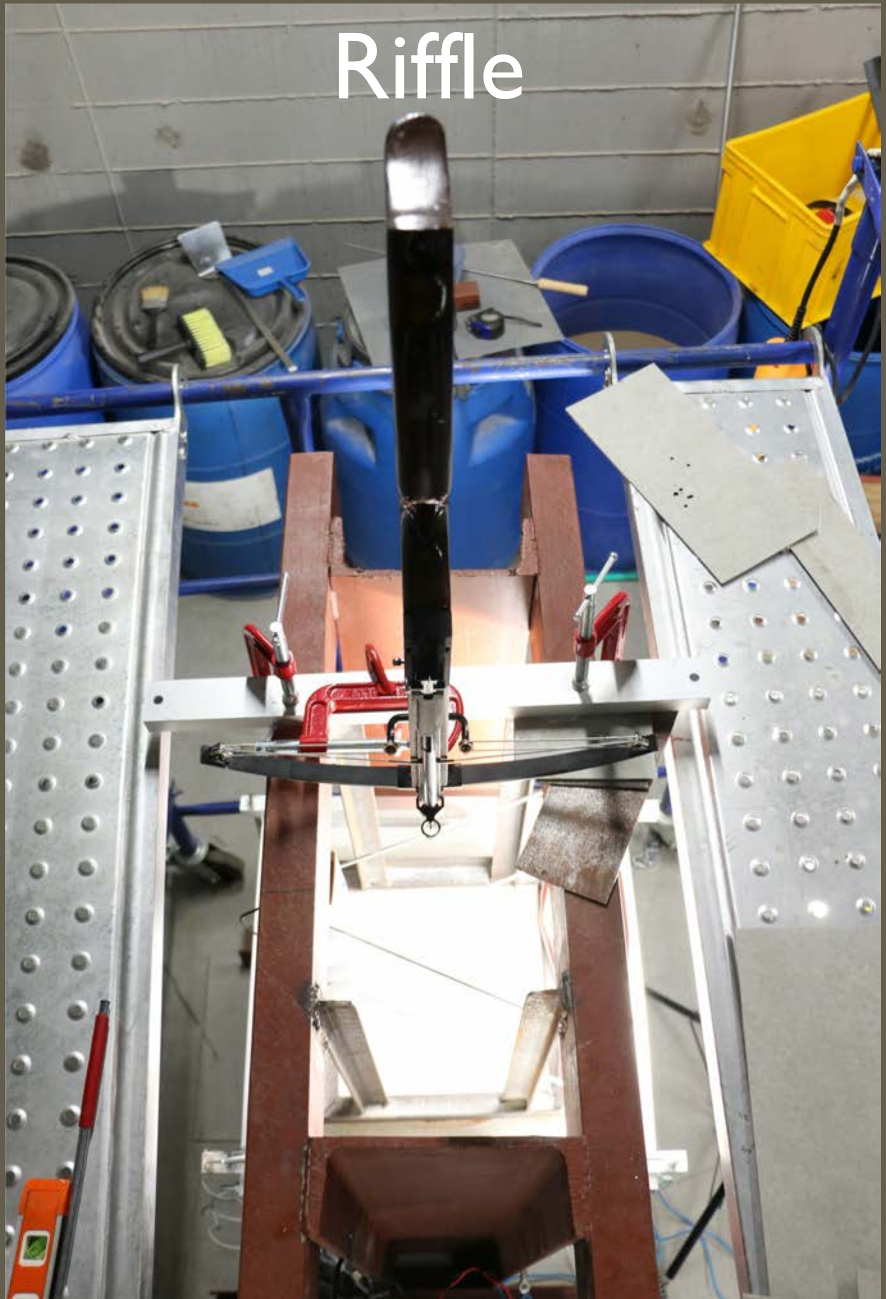
EXPERIMENTAL LIMITATION AND QUESTIONS

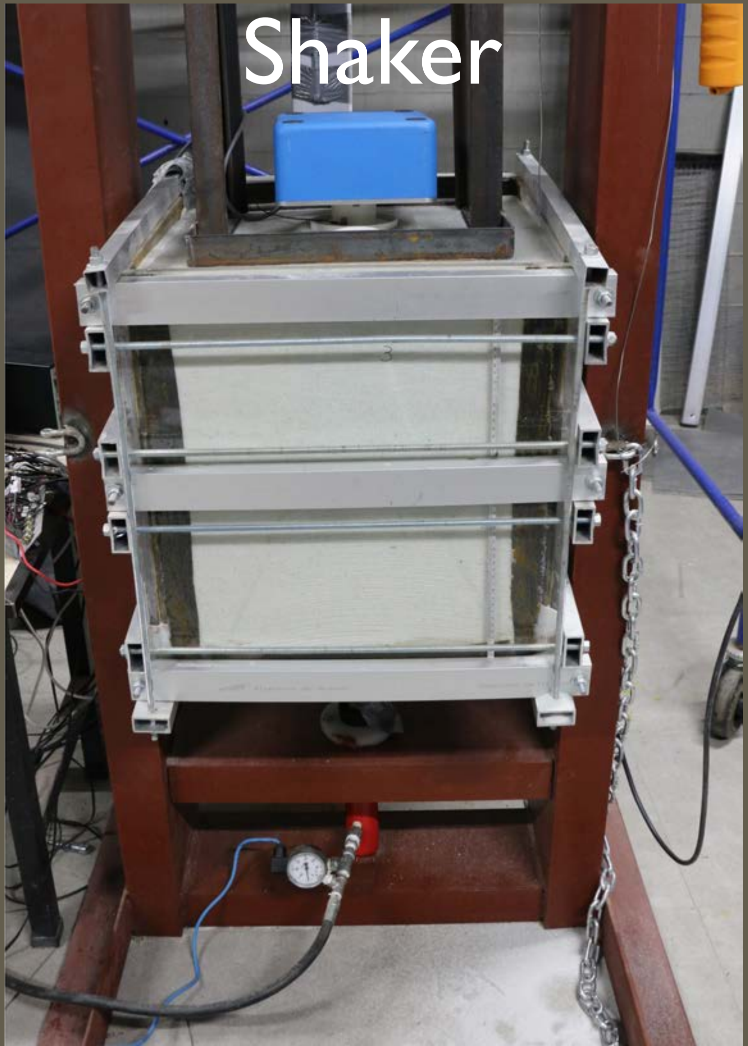
- Does confining pressure mimic selfgravity? (min= *atm.*)
- How can we extrapolate our results to micro-g?
- Are non-impact induced waves equivalent? e.g. waves produced by vibrations (relevant for a microgravity experiment in orbit)

TWO TYPES OF GENERATED WAVES
IMPACT AND SHAKER



IMPACT vs. SHAKER





GRANULAR MEDIA

Natural: granite gravel

Irregular shapes

Type	mm	Porosity (%)
Gravel	1 - 4	35
Sand	0.25 - 2	38

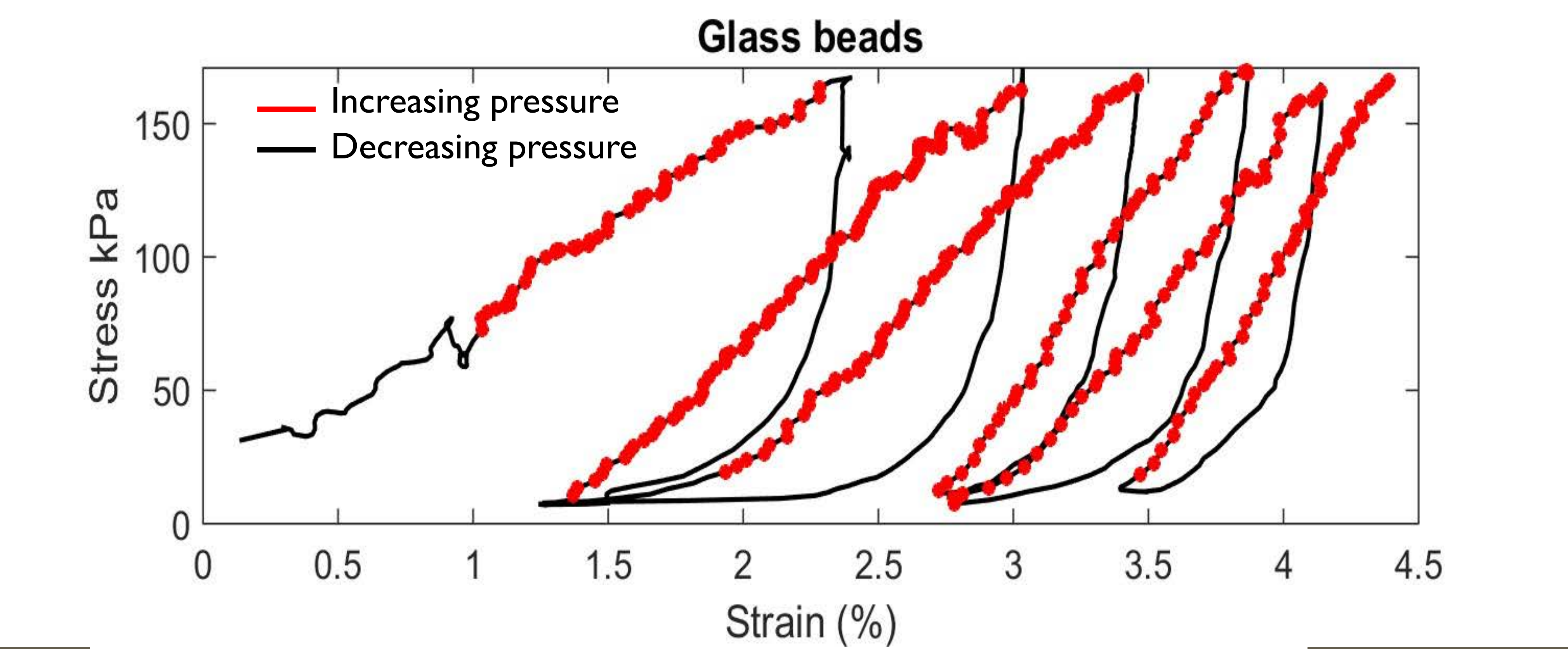
Artificial: Glass beads

Spherical shapes

Type	mm	Porosity (%)
Glass	0.125 - 1	15

STRESS-STRAIN QUASI-STATIC RELATIONSHIP

After loading the material into the box, we perform a set of increase and release of pressure with the hydraulic jack.
We study the hysteresis of the granular material.



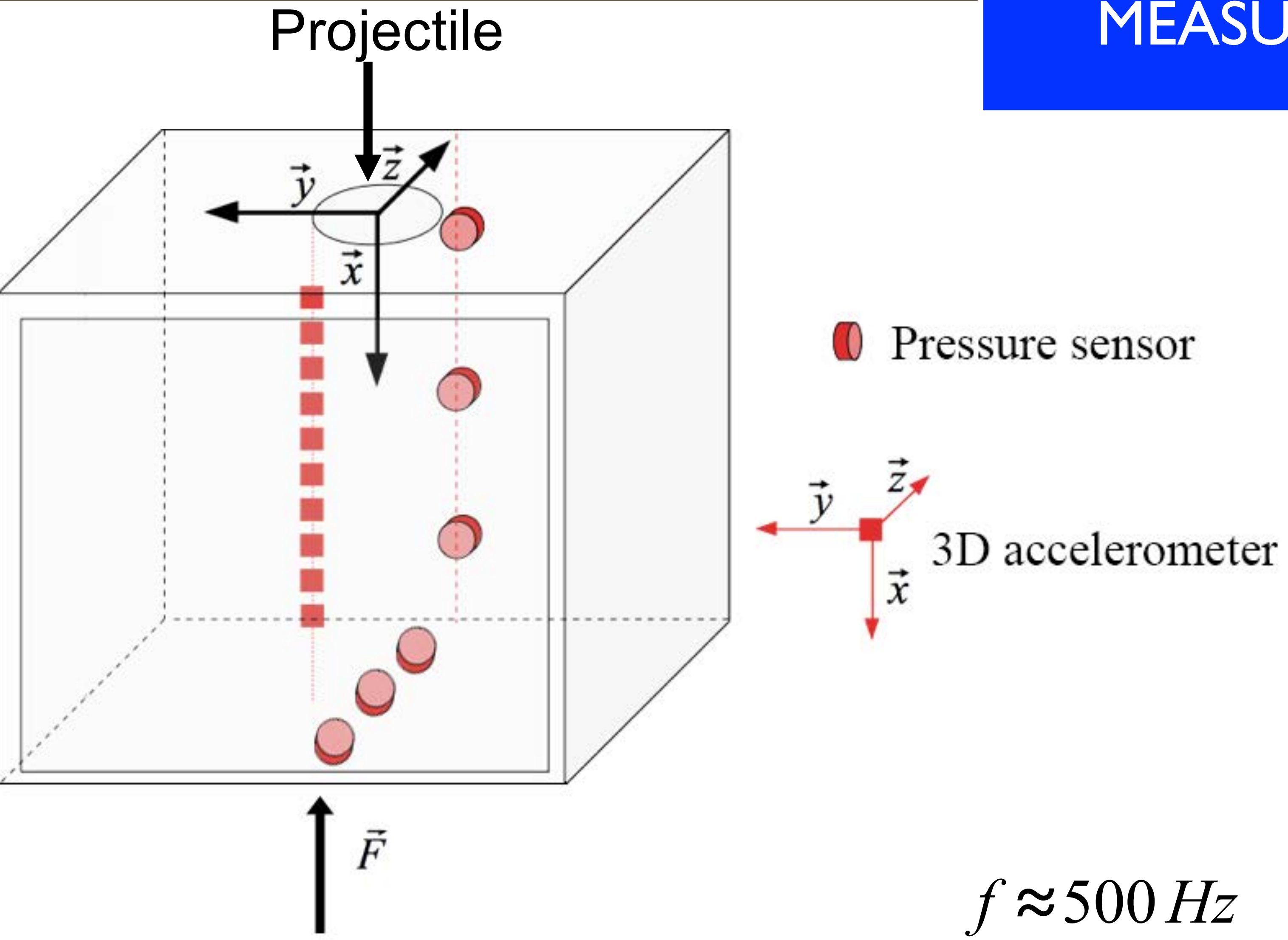
- Strong hysteresis (non-reversible motions of grains)
- Several loading to “stabilize the system”

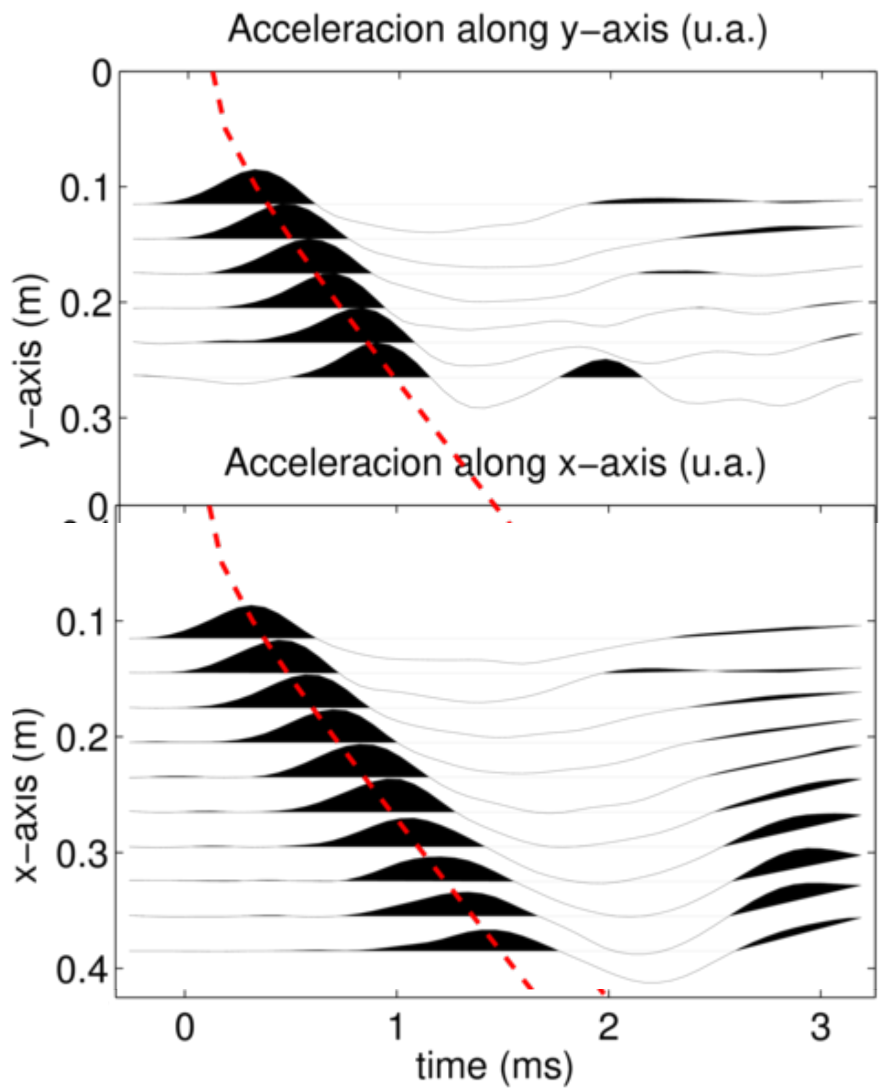
PROJECTILES

Spherical bullets

GUNS

MEASUREMENTS INSIDE THE BOX



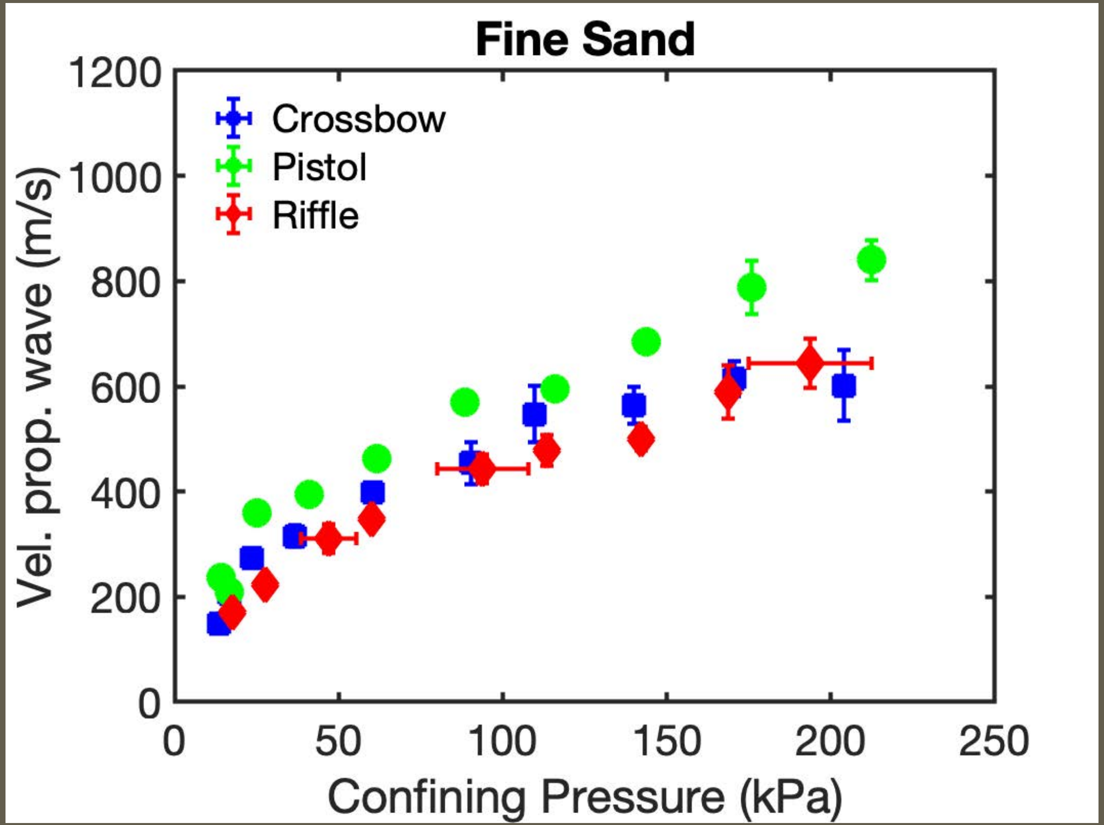


$$f \approx 500\,Hz$$
$$\lambda \approx 0.4\,m$$

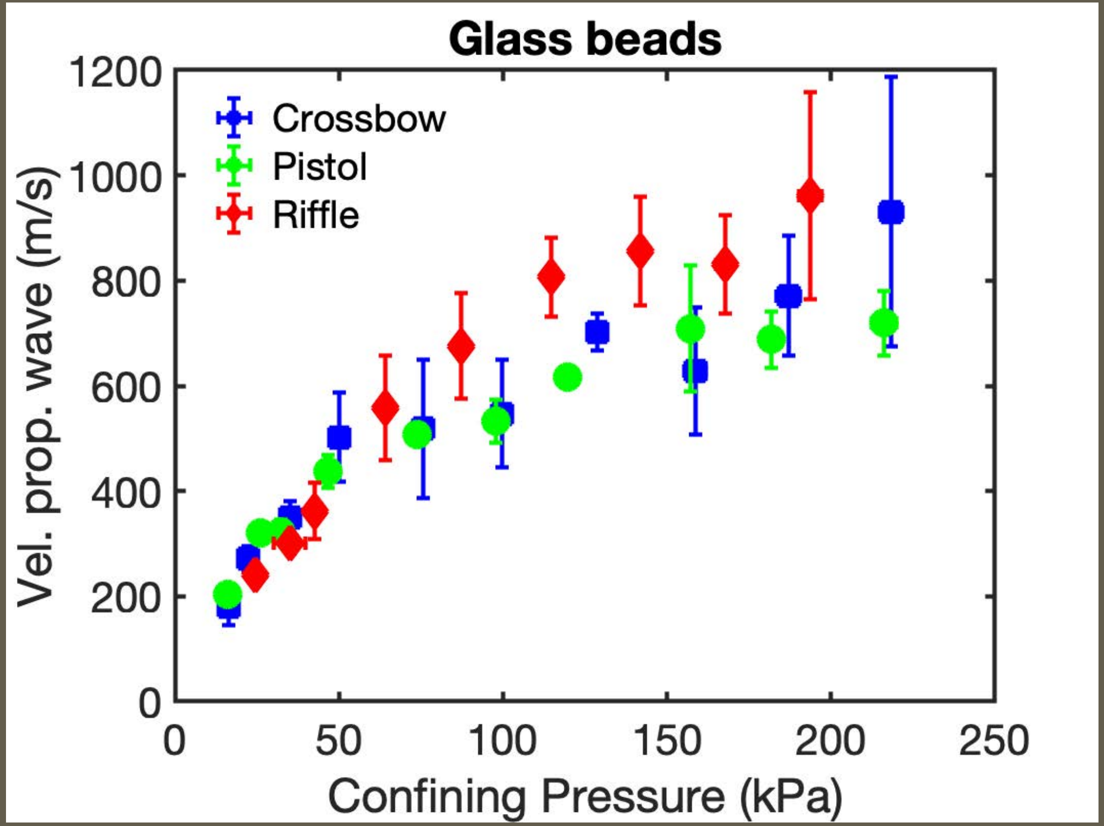
From the analysis of the polarization → P-Wave

VELOCITY OF THE IMPACT INDUCED WAVE vs CONFINING PRESSURE

Fine Sand 0.5-1 mm



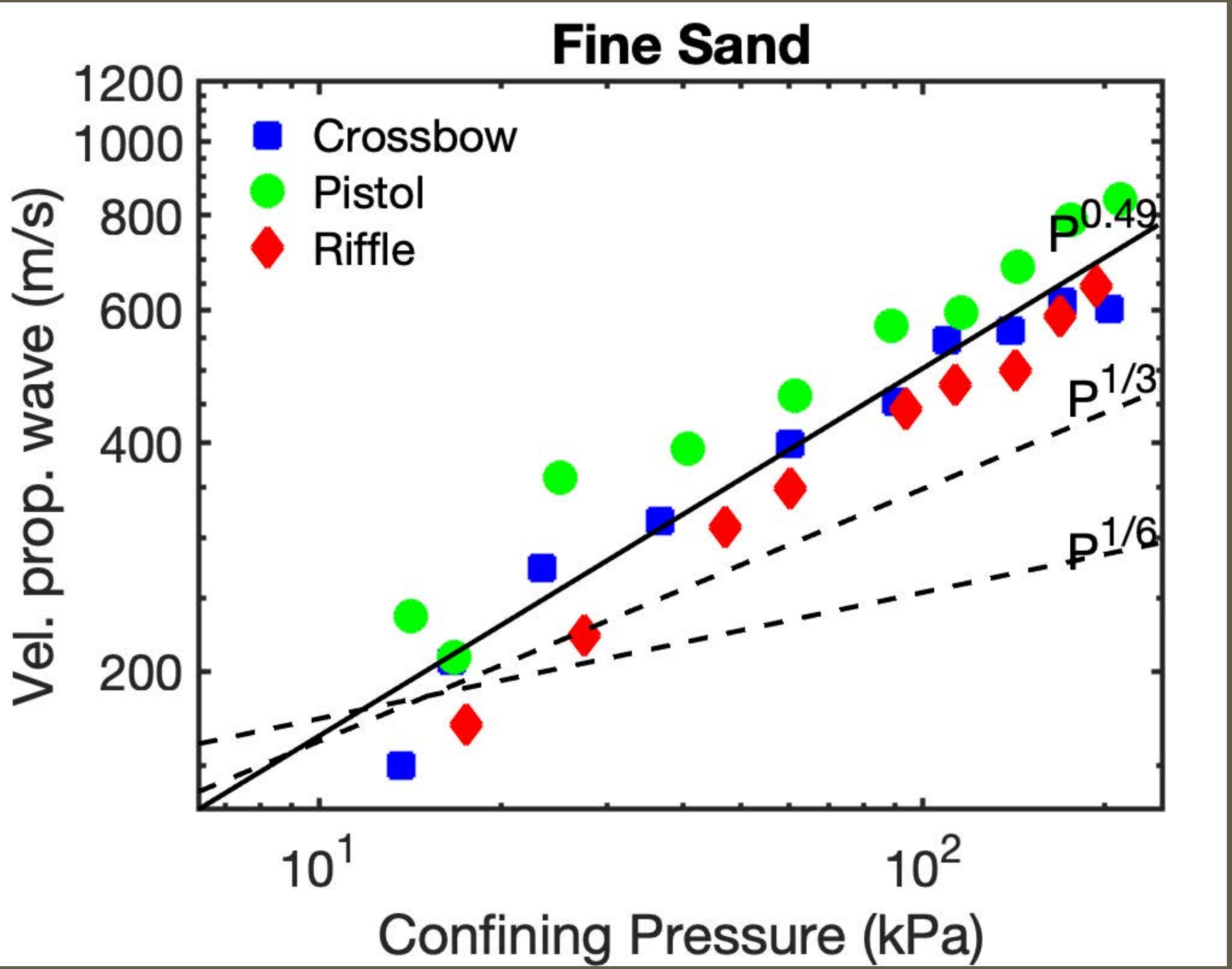
Glass beads 0.25-1 mm



→ No clear dependency on kinetic energy

→ bulk material more significant than grain size

VELOCITY OF THE IMPACT INDUCED WAVE vs. CONFINING PRESSURE OBS. vs. THEORY

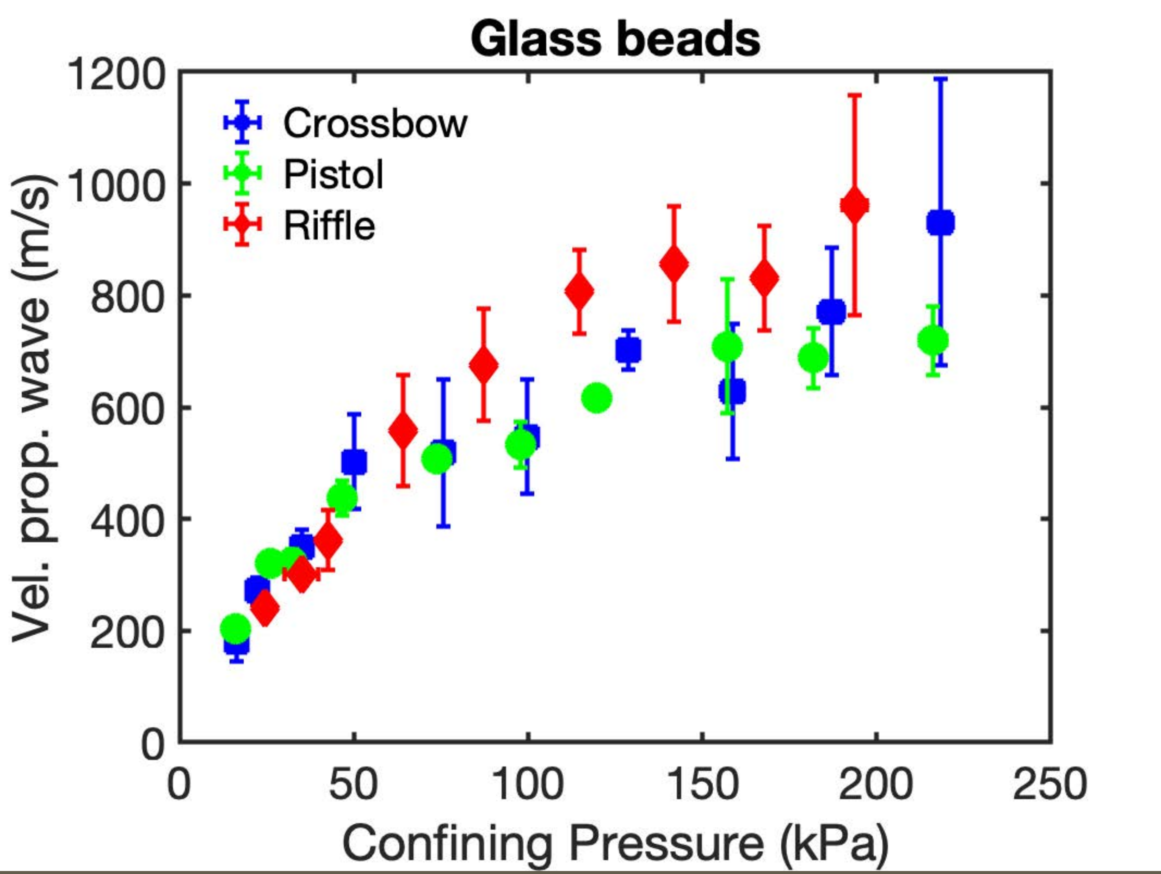


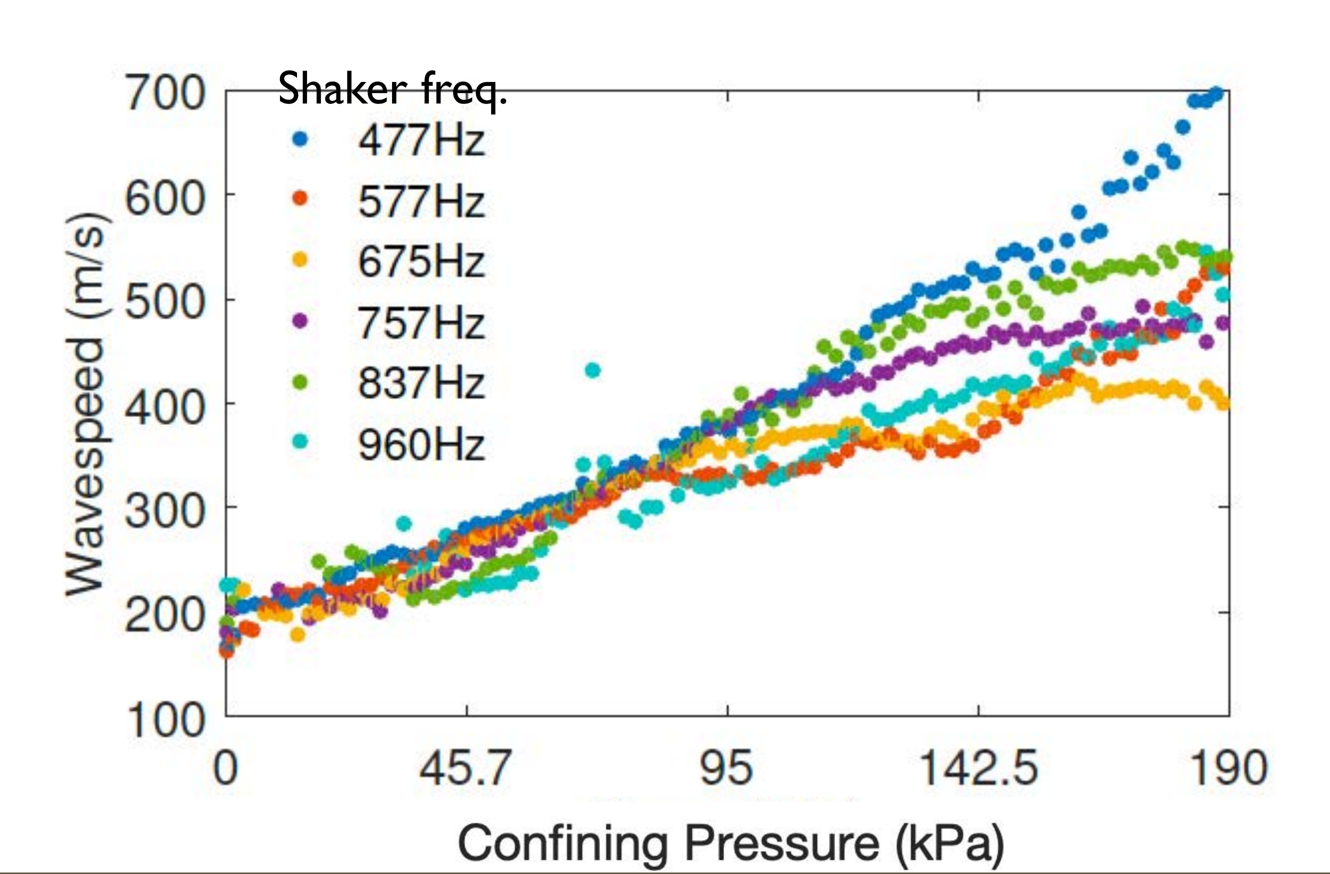
→ close to linear-like relationship

→ ≠ Hertz-Mindlin theory

$$V \propto P^{1/3-1/6}$$

IMPACT VS SHAKER - LABORATORY





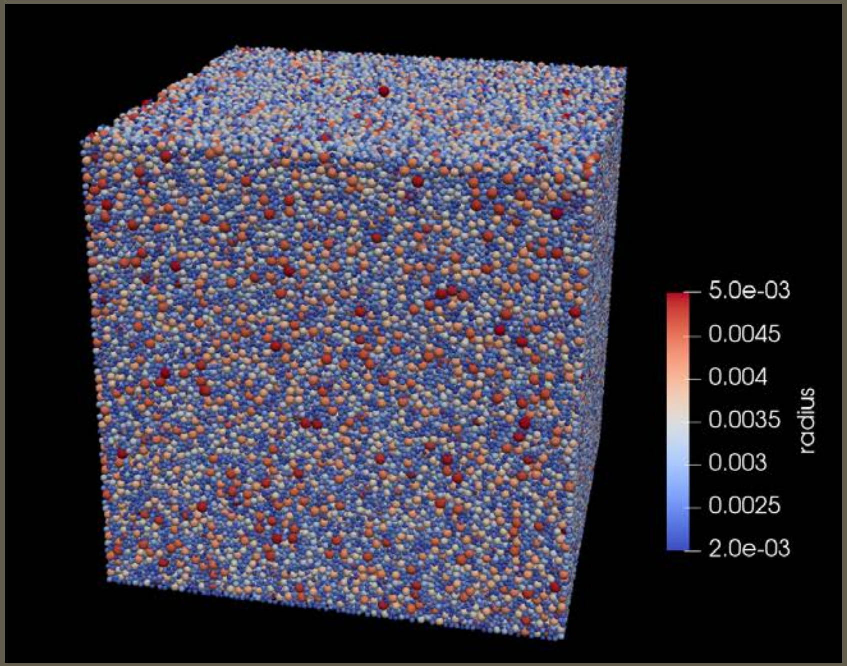
IMPACT / SHAKER COMPARISON

	Impact	Shaker
Acceleration	> 3,5 m/s^2	~ 0,2 m/s^2
Frequency	~ 500 Hz	~ 500 Hz
Polarization	P-Wave	P-Wave
Wavespeed	Similar dependence with pressure	

Implications: Possibility to conduct safe experiments in orbit (micro-g) with granular media & shaker to study the wave propagation

NUMERICAL SIMULATIONS

- Code: ESyS-Particle
- Create initial conditions:
  - Generate block of particles
    - Cube 0.4x0.4x0.4 m
    - Particles: sizes between 2-5 mm
    - Particle density: 3000 kg/m^3
    - ~300.000 particles
  - Several settling steps under different gravity conditions.

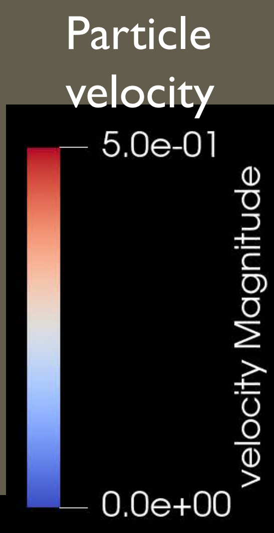


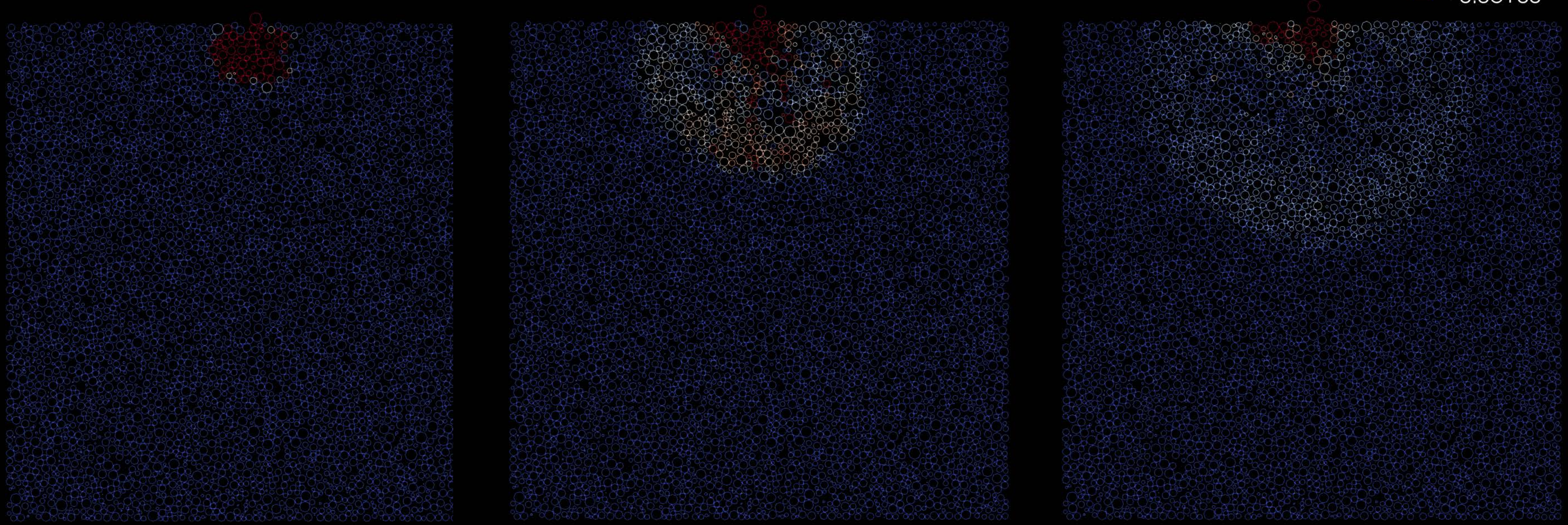
PROPAGATION OF IMPACT INDUCED WAVES

Impact of a 5mm projectile at v_{imp}=50,200,500 m/s.

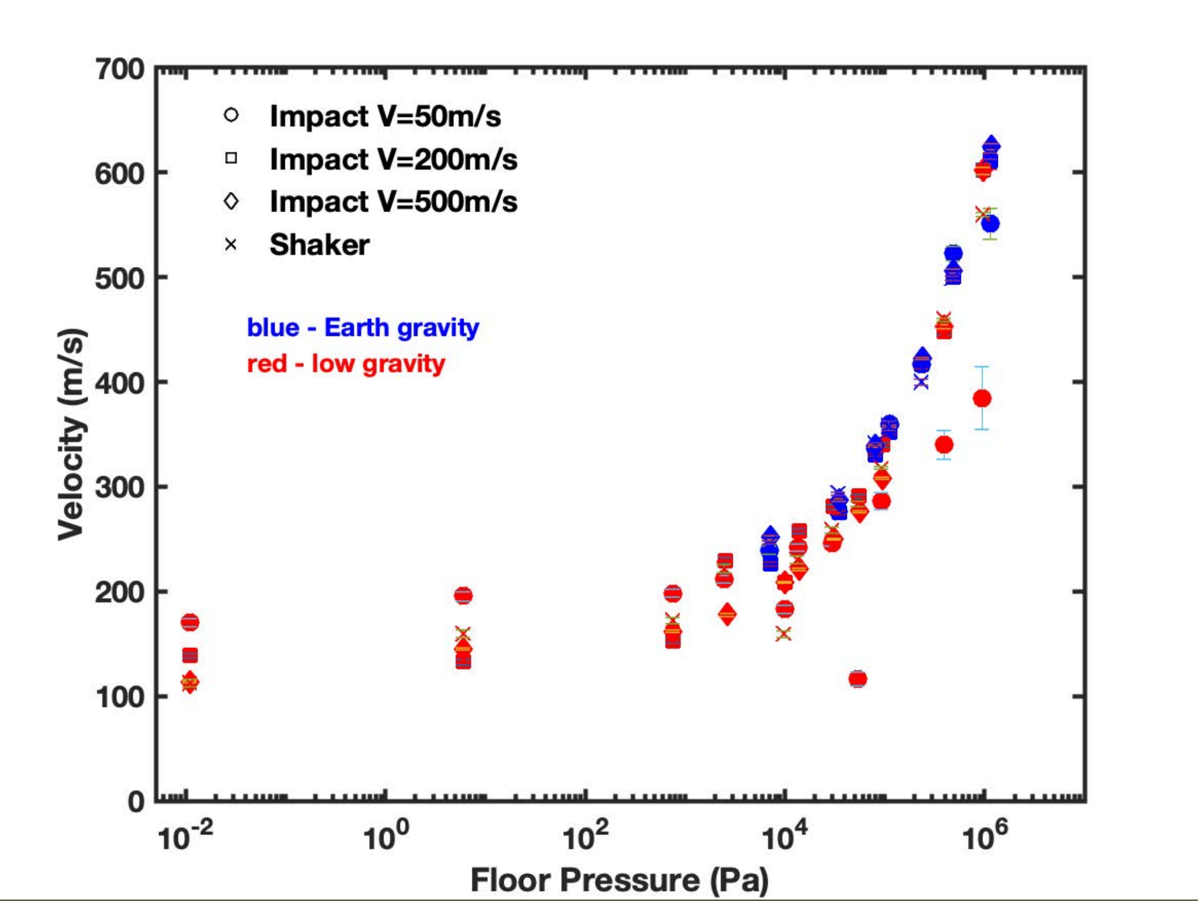
We also perform similar experiments with a simulated shaker.

Snapshots of a slice in the interior below the impact point at 3 different times separated by 10^{-5}s (v_{imp}=200).

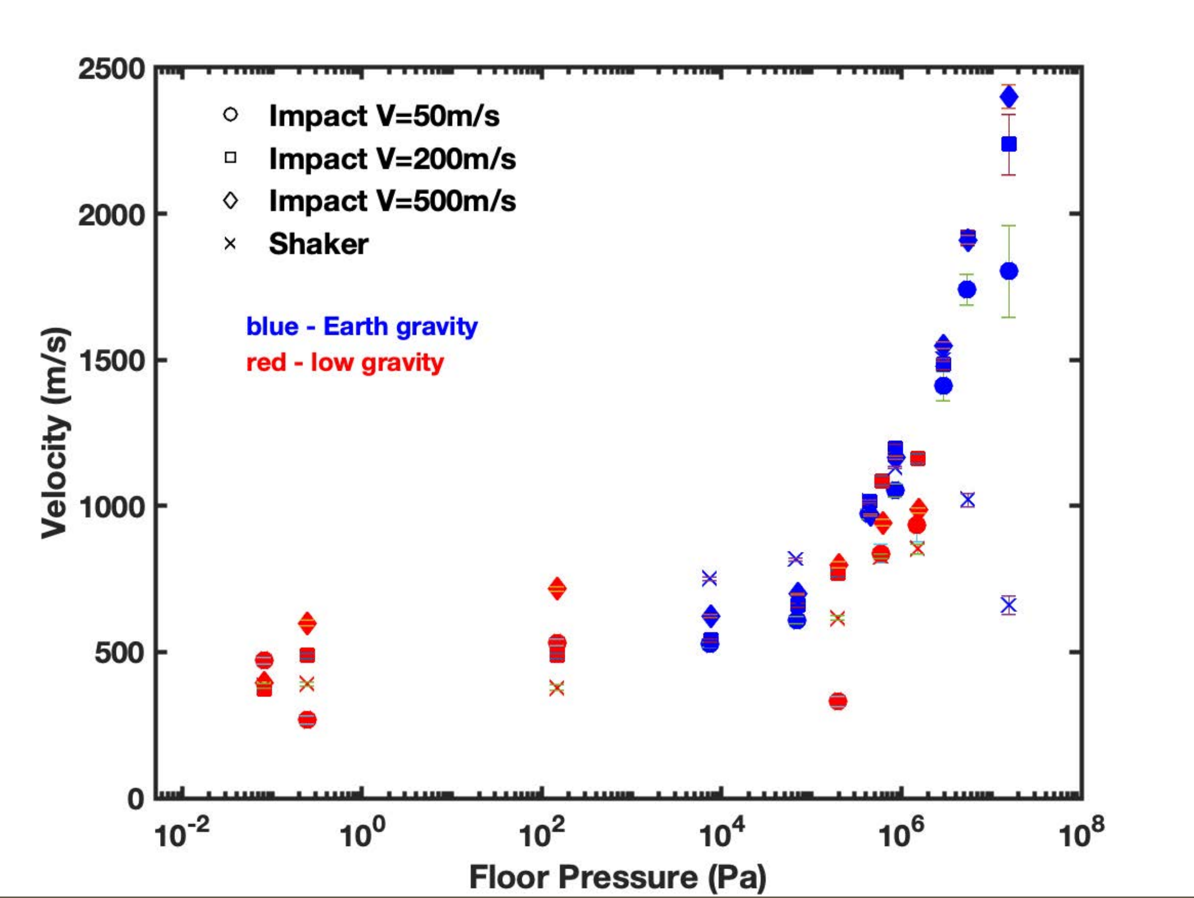




WAVE PROPAGATION OVER 7 ORDERS IN PRESSURE

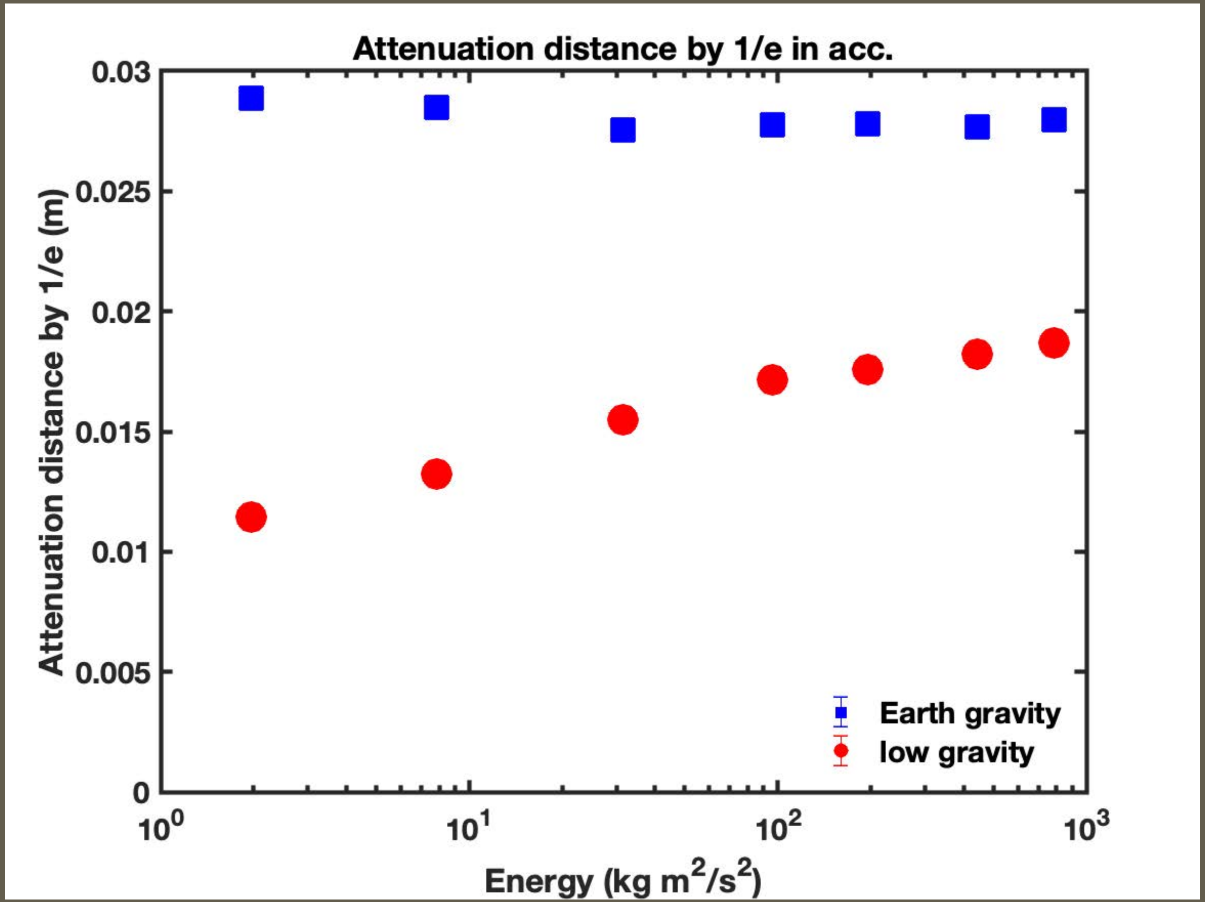


Material type I (Y=10^{10} Pa)

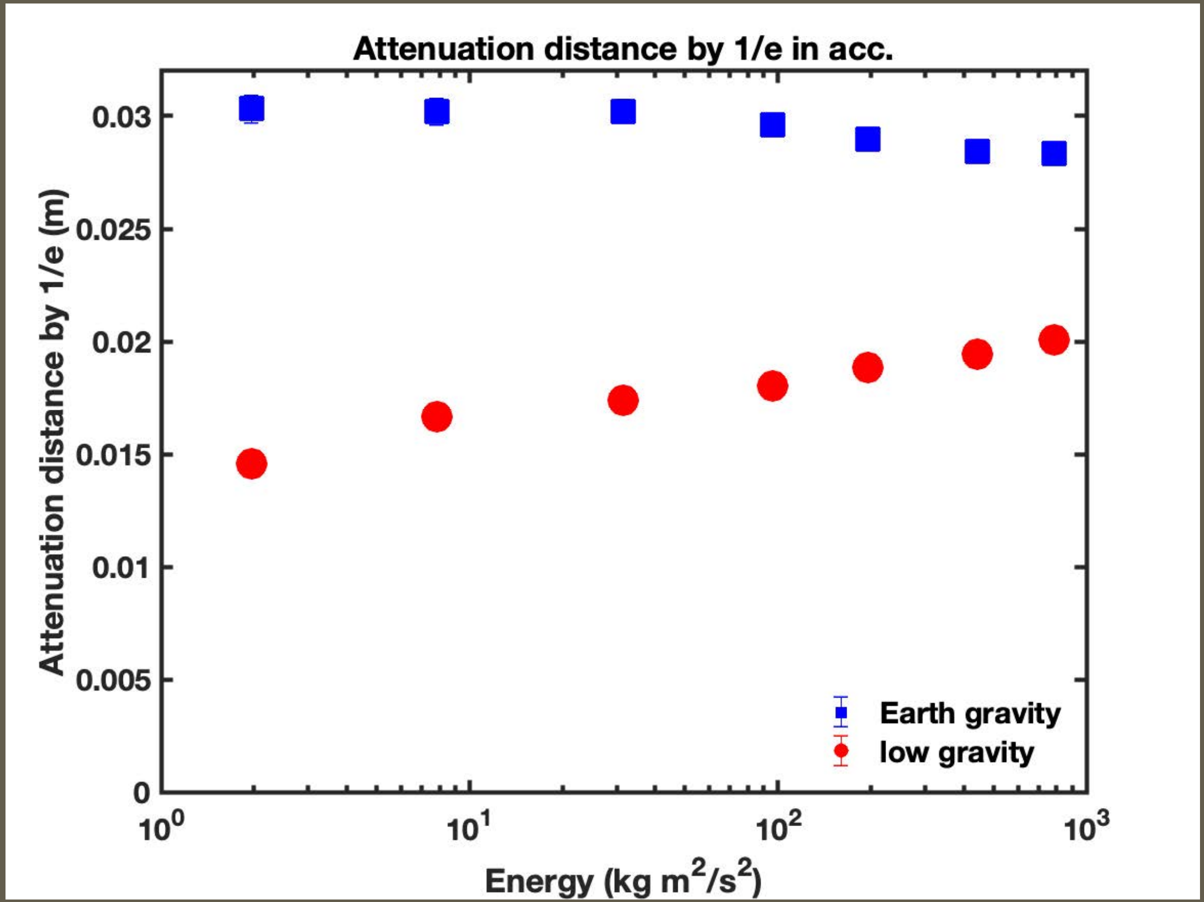


Material type II (Y=10^{11} Pa)

ATTENUATION OF THE WAVE



Material type I (Y=10^{10} Pa)



Material type II (Y=10^{11} Pa)

SIMULATION RESULTS

- The propagation speed does not depend on the speed of the projectile or the generation mechanism (impact vs shaker).
- There is exponential dependence of propagation speed (v) with the confining pressure (P) with a similar factor b for materials with different strengths.

$$v = a\,10^{bP} + v_0$$

	a	***b***	***v_0 (m/s)***
$Y = 10^{10}$ Pa	**3.15**	**0.36**	**141**
$Y = 10^{11}$ Pa	**4.2**	**0.36**	**447**

- Asymptotic speed at $P \rightarrow 0$: for low strength material ~140 m/s

  for high strength material ~ 450 m/s

CONCLUSIONS

- Impacts induce a P-compression wave
- Equivalence between impact and shaker
- Increase of wavespeed with confining pressure

IMPLICATIONS FOR DART

- For a 160m granular asteroid (like Didymos B), pressures at the interior $\lesssim$ 10 Pa. Very low P-wavespeed.
- The seismic wave induced by the DART impact will take ~1 sec. to travel across the body.
- Very high attenuation. Could very low-speed ejecta be produced far for the impact point?

FUTURE WORK

- Extend lab. experiments with hypervelocity projectiles

  Electrothermal accelerometer is under construction.
  Impact speeds of 2-4 km/s.

- Lab. experiments with a shaker in low-g are desirable

  (Hermes facility in ISS)