What do we know about asteroid interiors?

What matters for mitigation?

I consider only the most likely primary method: 
A kinetic Impact

And focus on the smaller objects:
  a few hundred meters.

Keith Holsapple, 
University of Washington
Kevin Harison, Boeing
An impactor of up to 10 tons may impart sufficient velocity to deflect a 100-500 m object..

Ref: NRC Report, 2010
The ejecta from an impact may greatly enhance the direct effect of moving the asteroid (β factor).
Next?

- Continue to study
- Plan Missions

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So, with all the uncertainty, and indirect inference, what do we actually do??

- Multiagency collaboration
  - Scientifically interactive
  - Electrically interacting
- Multi-craft collaboration
  - Interagency
  - Interchange
  - Interdisciplinary

Consequence of a collision: 
- unknown trajectory
- wide-ranging effects
- insufficient preparedness

Phenomena:
- detection
- warning
- response
- recovery
What matters for the impact deflection of a 100-500 m asteroid?

- The three most important features are the porosity, the porosity, and the porosity.
  - Low porosity: Spall strength (rocks) or shear strength (soils) are important.
  - Highly porous: Little else matters, $\beta$ is essentially unity.
So our present conclusions about impact deflections are:

- **Hard rock asteroid:**
  - Crater will be a *spall crater*
  - It is determined by the *tensile strength*..
  - Large $\beta$ (5-20??)

- **Rubble Pile, density 1.5-2 g/cm$^3$**
  - Crater will be "simple crater", determined by *shear strength* via *angle of friction*
  - Smallish $\beta \sim 1.5-2$

- **Highly porous material, 0.5-1.5 g/cm$^3$**
  - Crater determined by *crush strength*
  - $\beta \sim 1$
  - But it does not matter a lot anyway...
Tensile strength, Craters on small bodies.

BUT: On small bodies, all impact craters will be spall craters!!

The impacts we consider into a hard rock object will most certainly form a spall crater.

Ref: Holsapple LPSC 2013
A spall crater in a lab rock target
Tensile strength, Craters.

A spall crater in a lab rock target
Tensile strength, Craters.

On Earth, small craters in brittle materials are spall craters.

In the lab that has been treated primarily as an annoyance: we cannot make 'real' craters.
Shear strength, Fireball Breakup.

Fig. 4. Estimated apparent bulk strength (=ram pressure in Table 4) at first, second, and third breakups as a function of mass for our 13 cases (Pr—Příbram; LC—Lost City;...)

Chelyabinsk

Fireballs break up at atmospheric pressure of a few to a few tens of Mpa.

Ref: Popova, Hartmann, et al., 2011, M&PS
Shear strength, Spin Limits

For rubble piles, max spin depends on angle of friction: (Holsapple, 2001, 2004)

And determines the paths followed for shape changes due to Yorp spin-up (Holsapple, 2010, Sanchez and Scheeres, 2012)
Shear strength, Spin Limits.

This is the only direct data on the global strength of actual asteroids. The theory is consistent with the data if the small-scale strength is ~few Mpa.

Gravity dominates irrespective of strength when D > few km

The origin of that strength is under debate: rocks with cracks (Holsapple), or rubble piles with van der Walls (Scheeres, Sanchez)?

Ref: Holsapple, Icarus, 2007
Shear strength, Planetary cratering.

Transition from strength->gravity craterers indicates value of shear strength.

Figure 3  The regimes of cratering for a material with strength. In the strength regime the cratering efficiency depends on the impact velocity, but is independent of gravity-scaled size. For increasing size at a fixed velocity, there is a transition to the gravity regime in which the cratering efficiency has a power law decrease with increasing size. Most experiments in geological materials are by necessity in the strength regime.

Holsapple, 1993
What is the strength of GEOLOGICAL MATERIALS?

Mohr-Coulomb or Drucker-Prager envelopes

1. Highly porous materials: crush strength
2. Sand craters: shear strength
3. Large rock and ice craters: shear strength
4. Small rock and ice craters: tensile strength
Mathilde’s crush strength is consistent with other geological materials.
Example: Mathilde

- Centrifuge experiments: ejecta blankets are suppressed when \[ \rho gh = 0.01 Y_c \]
  
  \[ \rho = \text{density} \ (1300) \]
  \[ g = \text{gravity} \ (10^{-3} \ G) \]
  \[ h = \text{crater depth} \]
  \[ Y_c = \text{crush strength} \]

- On Mathilde, the transition crater depth is less than 5 km.

- Thus, Mathilde’s crushing strength must be < 6 MPa.
And the Crush strength determines crater morphologies

Crater transition size from external ejecta to retained ejecta indicates crush strength

Ref: Housen and Holsapple, Icarus, 2012
The Crush strength determines porosity limits.

The distribution of the porosity of small bodies is as predicted from lab experiments.
Lab measurements of porosity and crushing
We know something of the *global* porosity of the small bodies.

From Carry, B., 2012, by way of Housen, K.
And especially, what is the structure the top 10m?

Regolith or not?
Eros: 10's of meters, from impact ejecta

Regolith or not?
Itokawa: Reaccumulated rubble?
What porosity can we expect?
So the important questions about an asteroid are:

1. What is the porosity of the top 10 meters?
2. What is its "strength"?
   1. Spall strength
   2. Shear strength
   3. Crush strength

And what do we know about those?

The rest of this talk will focus on that question..
From these experimental and numerical results, we can make tentative predictions...

- **Low porosity rock or ice asteroid:**
  - Crater will be a *spall crater*
  - It is determined by the *tensile strength*...
  - Large $\beta$ (5-20??)

- **Rubble Pile, porosity 30-40%**
  - Crater will be "simple crater",
    determined by *shear strength* via *angle of friction*
  - Smallish $\beta \sim 1.5-2$

- **Highly porous material, porosity 40-90%**
  - Crater determined by *crush strength*
  - $\beta \sim 1$ in any case
So what is $\beta$??

Brittle, low porosity
Rubble Pile, 30-40% porous
Highly porous, 50-90%

Ref: Holsapple and Housen, Icarus, 2012; & Presentation by Kevin Housen tomorrow
Our experiments have showed three types of results.

A deep crater with no ejecta
Let me explain that...

Assumptions:
- ~1 meter impactor
- 5->20 km/s impact velocity
- Makes a crater in the top 10+ m structure

Then, how much change in velocity can we achieve with a given impactor?

The velocity increment is determined by the impactor momentum times the momentum multiplication factor $\beta$. 
So, what matters for the deflection of a 100-500m object?

Characterization!

- velocity
- spin
- mass
- albedo
- orbit
- taxonomy
- companions
- porosity
- regolith
- shape
- density
- families

It is the strength and porosity of the top 10 m that matters...