Hypervelocity impact experiments to study craterization and catastrophic fragmentation of minor bodies of the Solar System

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http://cisas.unipd.it/lgg/lgg.html

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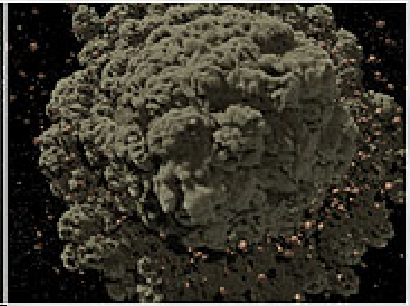
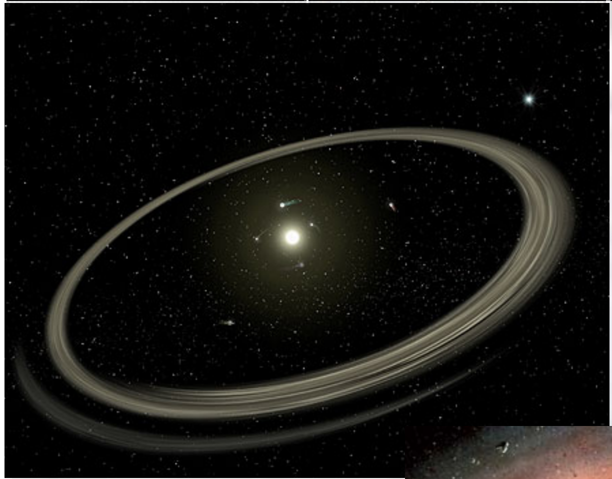
VII Workshopon Catastrophic Disruptionin the Solar System (CD07)
Alicante, Spain 26-29 June 2007

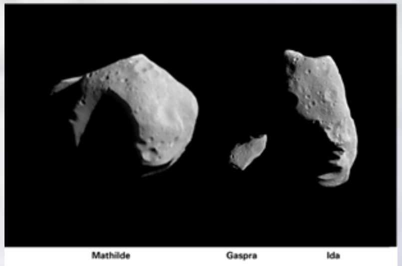
Impacts in the Solar System

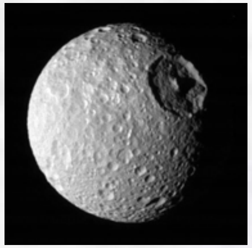


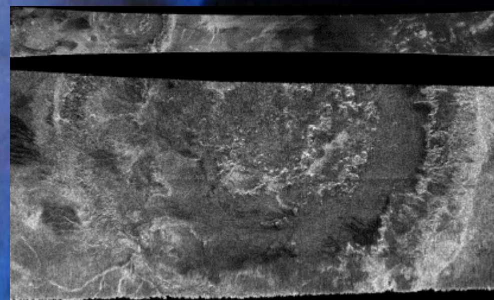


Impact processes play a fundamental role in all phases of planetary formation and evolution, e.g.:
- growth of planets by collisional accretion
- formation of planetary satellites (Moon)
- formation of asteroid families
- cratering of planetary surfaces



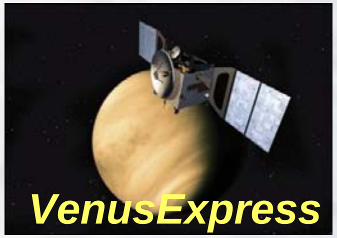


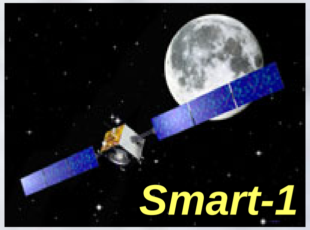




Objectives

- Improve our understanding of impact and collisional processes to study:
  - planetary formation and evolution
  - collisional evolution of minor bodies
  - Comparative planetology
- Support and optimize the scientific return of space missions





Approach: study of impact process on porous targets and planetary surface simulants by **experimental and numerical craterization and catastrophic disruption**

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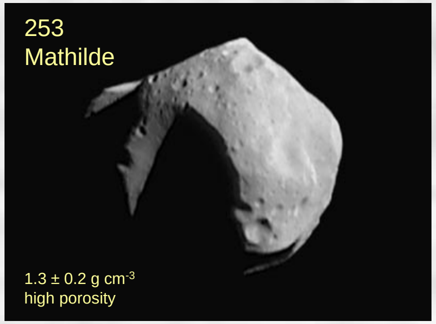
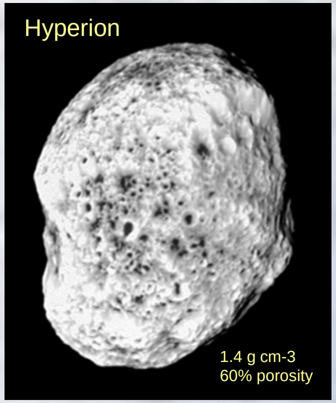
Impacts on porous targets

- Most part of minor bodies and icy satellites of the Solar System show a significant **porosity**.

asteroids **Saturn's moons** **KBO** **Comets**





- Experimental study of impact and catastrophic fragmentation process onto porous targets.
- To extend the available data to ranges of velocity and physical conditions not yet explored.
- Experimental data in support of the interpretation of data from space missions and groundbased observations.

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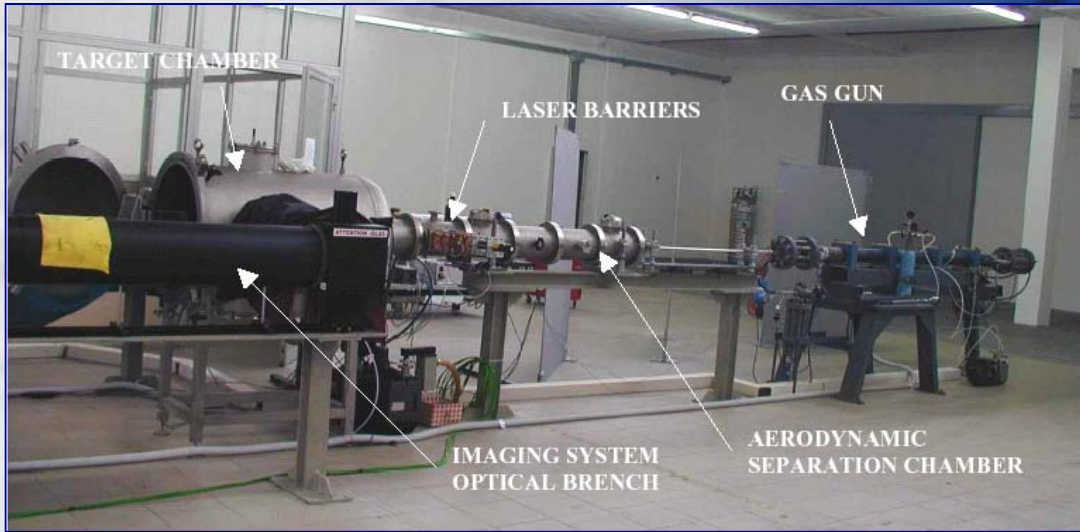
Experimental Set Up

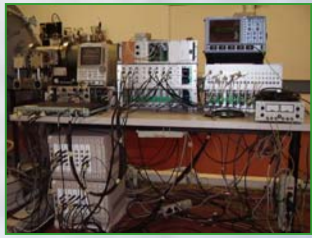


The accelerator:

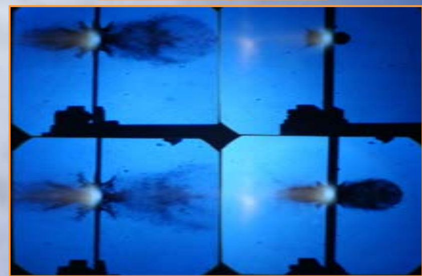
- Two stages light gas gun
- Speed 500 m/s - 5.8 km/s
- Projectiles: Al sphere & nylon cylinder
  mass 1 mg - 1 g
- Repetition = 1shot/15 min

The diagnostics:

- two laser barriers
- optical impact detector
- high speed shadow photography,
  1μs to 100ms frame rate
  exposition time: 10 ns
  4 frames
- fast photometers with dichroic filters
- Acquisition system: up to 38 channels (WE7000 Yokogawa)



Shadowgraphy



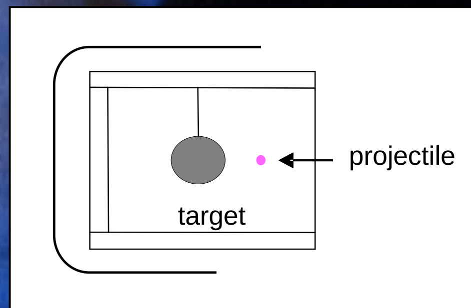
The target chamber:

shot pressure 60 mbar

Target temperature control 120-350 K

The recovery box:

- to suspend targets
- to monitor & collect debris and dust
- metallic box with windows
- equipped with passive detectors



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Target samples

Glass ceramic foam

Target characteristics
Geode shaped (∅~8 cm)
Density 0.73-1.07 g/cm^3
Crushing strength 15-20 MPa

Chemical composition:

66.8%	SiO_2
8.6%	Al_2O_3
3.8%	CaO
2.7%	MgO
9.5%	Na_2O
1.2%	K_2O

Manufacture procedure:
- Powder grinding
  (for 20 min to get a fine well mixed powder)
- Mould filling
- Thermal cycle up to 1100 °C
  (heating rate 10 C°/min)

Porous ice

Chemical composition: 100% H_2
Two types: crushed & shaved ice

Target characteristics
Shape: sphere (∅ 9 cm)
~ "rubble pile" (ice chips)
Density: 0.5 – 0.7 g/cm3
~ snowballs
Density: 0.42-0.69 g/cm^3

Natural pumice

Target characteristics
shape: irregular
Density 0.35 – 0.67g/cm^3

Limestone (Vicenza Stone)

Target characteristics
shape: cube (~7x7x7 cm^3)
Density 2.01 g/cm^3
Crushing Strength 23 MPa

Refractory material

Target characteristics
shape: cube (~6x6x6 cm^3)
Density 0.5 g/cm^3

Natural Marble (Rosso Trento)

Target characteristics
shape: cube (~7x7x7 cm^3)
Density 2.6 g/cm^3
Crushing Strength 137 MPa
MicroHardness 141.1 MPa

Sand

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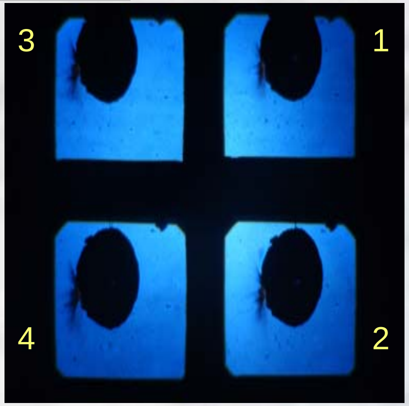
Craterization

Glass-Ceramic Foam



Al sphere 17.2 mg
v=1997m/s

Q=2.2E+06 erg/g

Pumice

Al sphere 1 mm
V=4881 m/s
Crater ∅ 4.55 mm

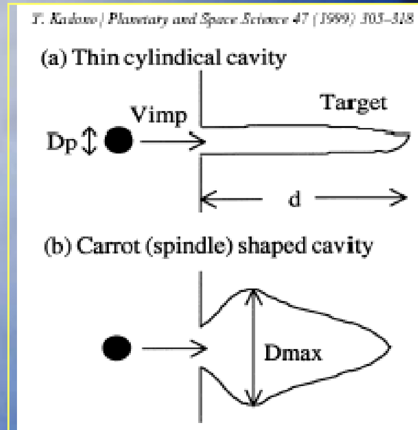


Fig. 1. Typical shapes of cavities produced by the penetration of denser projectiles into lower density targets. (a) Thin cylindrical shaped cavity, observed at low impact velocities. The cavity diameter is almost the same as the projectile diameter and is smaller than its depth d. Recovered projectile is intact. (b) Carrot (spindle) shaped cavity. The maximum cavity diameter D_{max} is larger than the entrance hole diameter. Projectile is usually deformed or fractured.

About **25** shots to analyse craterization of **porous targets**

- Impacts resulted in **compaction of the target material** (as observed by Housen & Holsapple, 2002)
  - Craters in porous materials have **smaller** entrance hole diameter and are **deeper** than those in non porous materials
    - **Carrot shaped cavity** in refractory samples (as observed by Kadono 1999)

Limestone

Al sphere 1.9 mm
V=5000 m/s
Crater ∅ 19 mm

Marble

Al sphere 1.9 mm
V=5192 m/s
Crater ∅ 27 mm

Refractory block

Al sphere 1.5 mm
V=4800 m/s
Crater ∅ 6.80 mm

- about **20** shots on marble and limestone for flash
- **6** grazing impacts on sand

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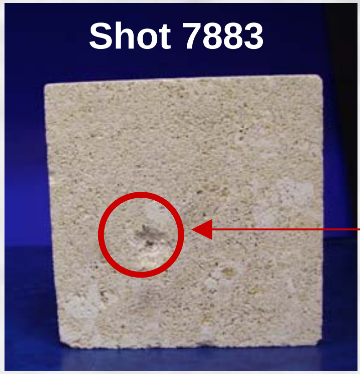
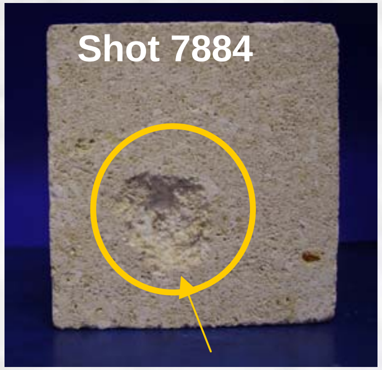
Craterization and impact flash measurements

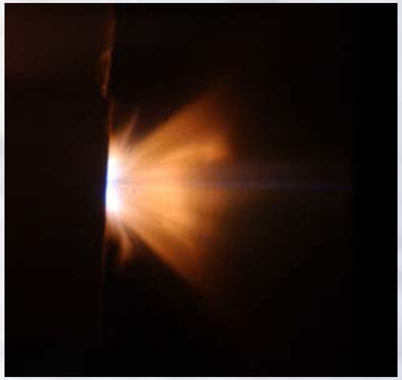
Limestone (Vicenza stone)



Al sphere 1.0 mm
V=5000 m/s
Crater ∅ 10 mm



Al sphere 1.9 mm
V=5000 m/s
Crater ∅ 19 mm



Flash generated by impact

Marble

Al sphere 1.0 mm
V=4916 m/s
Crater ∅ 13 mm

Al sphere 1.5 mm
V=5085 m/s
Crater ∅ 15 mm

Al sphere 1.9 mm
V=5192 m/s
Crater ∅ 27 mm

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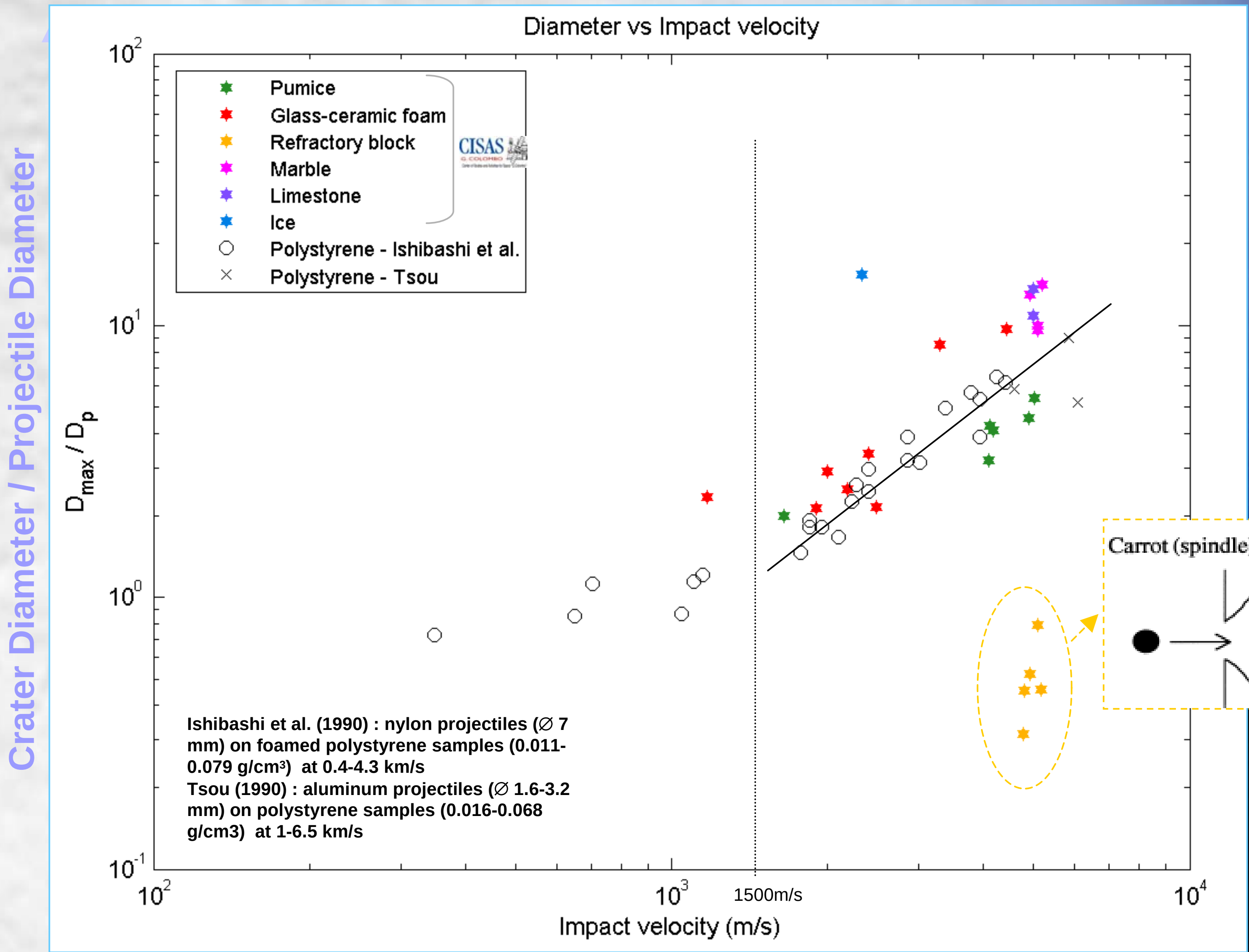
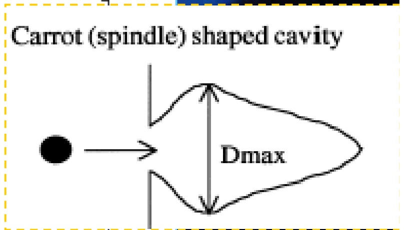
Crater morphology: diameter vs impact velocity





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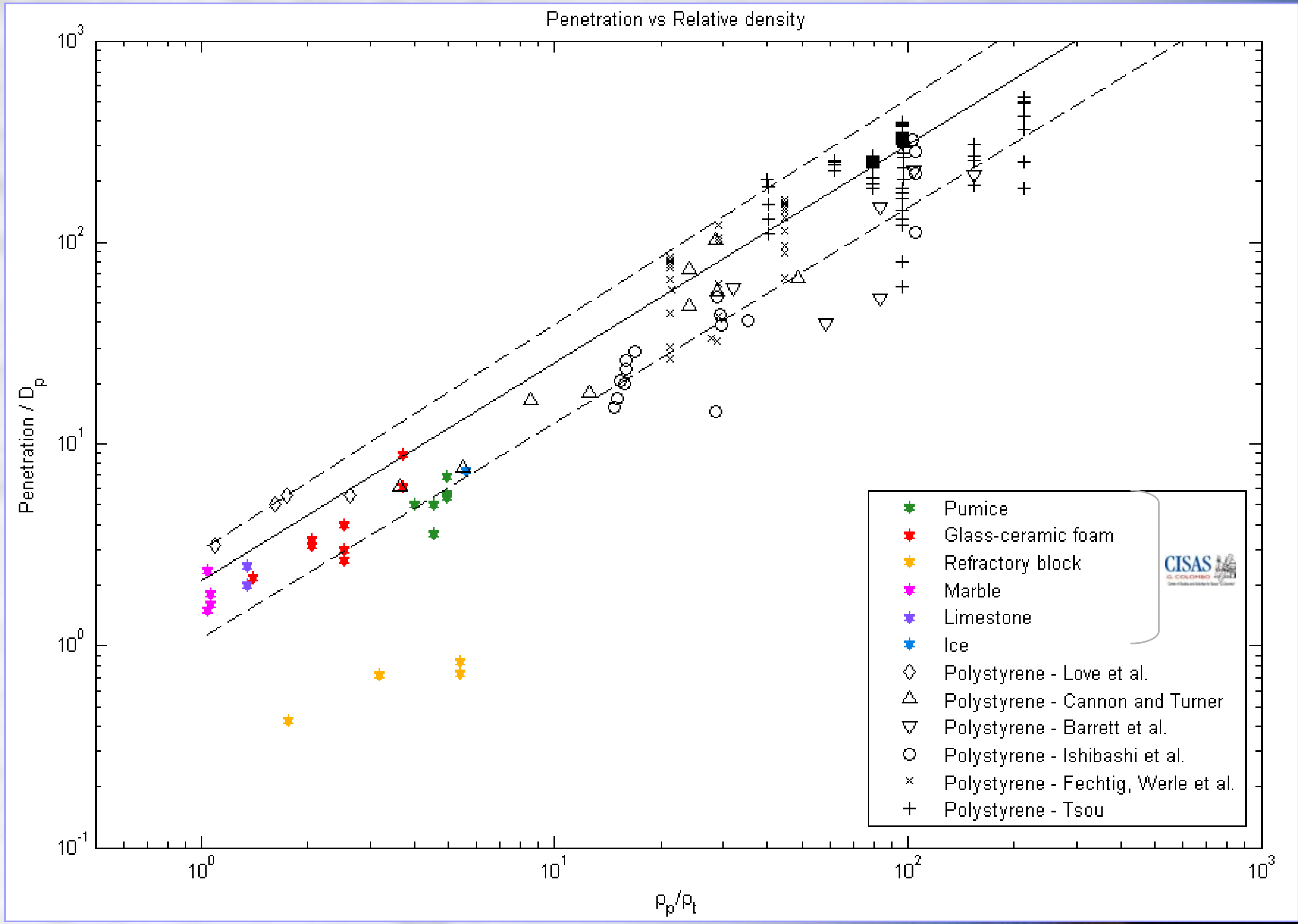
$$D_{max} / D_p = 10^{-0.07 \pm 0.05} V_{imp}^{1.3 \pm 0.1}$$ [Kadono 1999]

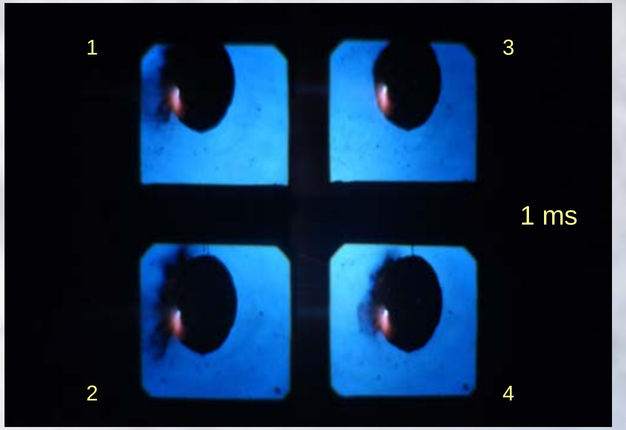
Crater morphology: penetration vs relative density

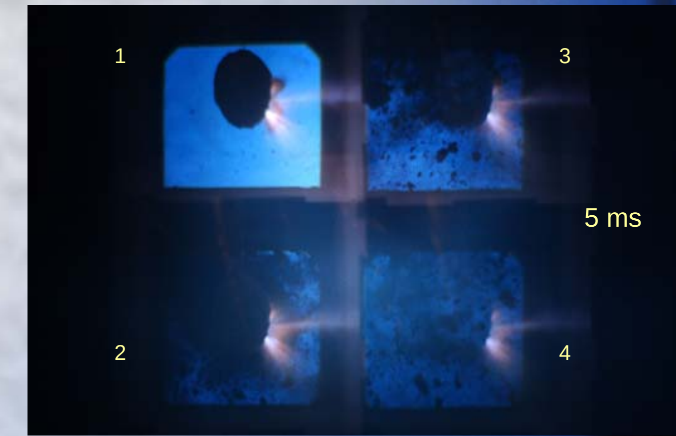


$$p_{max} / D_p = 10^{0.33 \pm 0.31}(\rho_p / \rho_t)^{1.07 \pm 0.17}$$ [Kadono 1999]

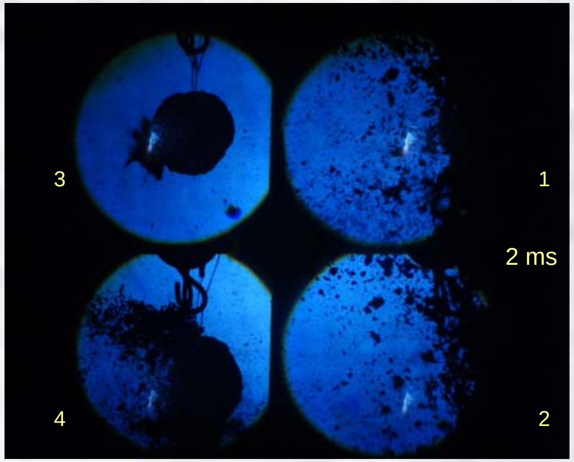
Catastrophic disruption

Glass ceramic foam samples



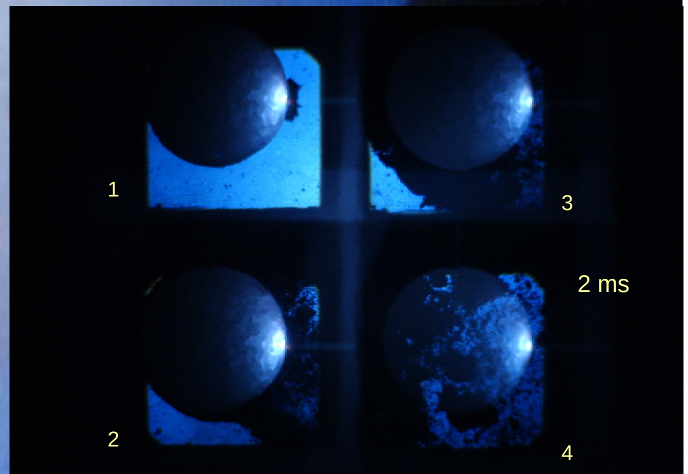


Porous ice



Shaved ice ~ snowball

Crushed ice ~ 'rubble pile' of ice chips



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Catastrophic disruption: almost 30 shots

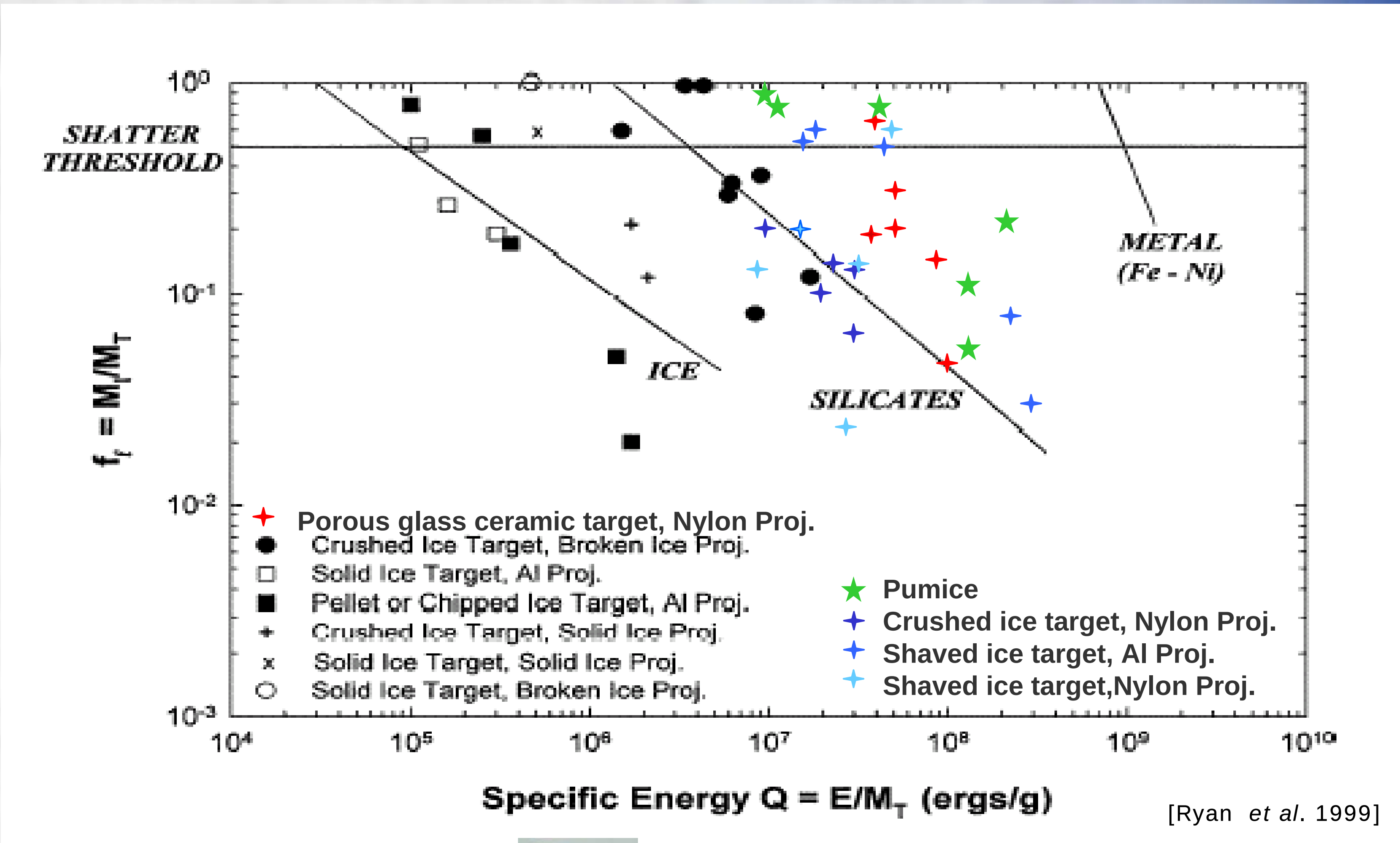
Collisional outcomes

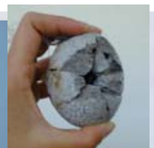
- Debris are recovered after each shattering event
- Each fragments is weighted (down to ~0.005 g)

$$Q = \text{specific energy} = 1/2mv^2/M_T$$

$$f = M_{\text{largest fragment}}/M_{\text{Target}}$$

Disruption: Impact strength



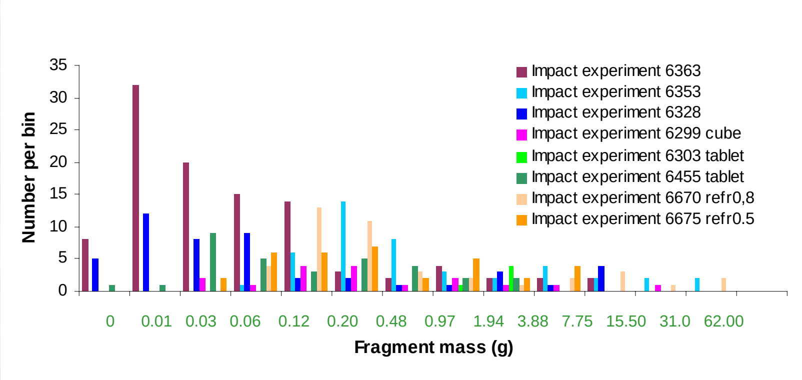


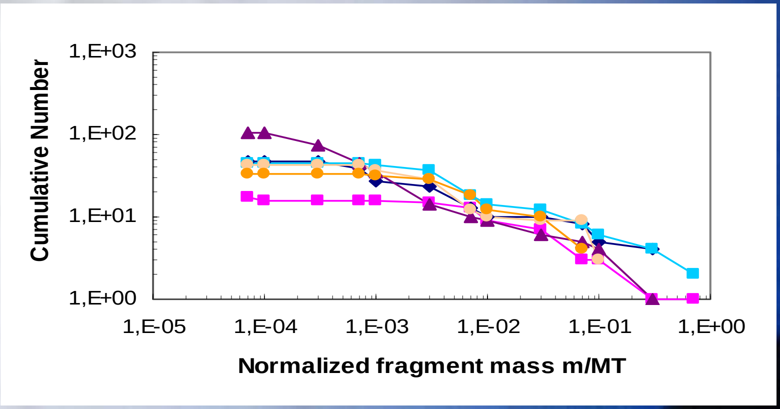
Q_S^*= 4x10^7 erg/g for ceramic foam
6x10^7 erg/g for pumice
Q > values for basalt
>> those typical of solid ice

Fragment mass distribution

Ceramic foam

Ceramic foams





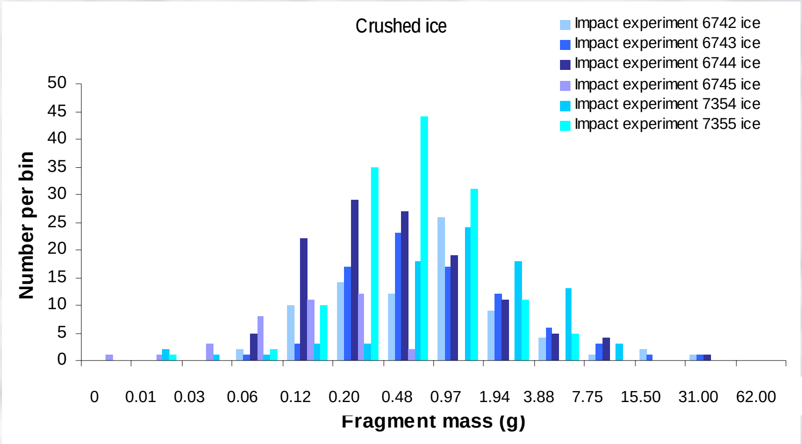
Comparison between shots at specific energy of the same order:

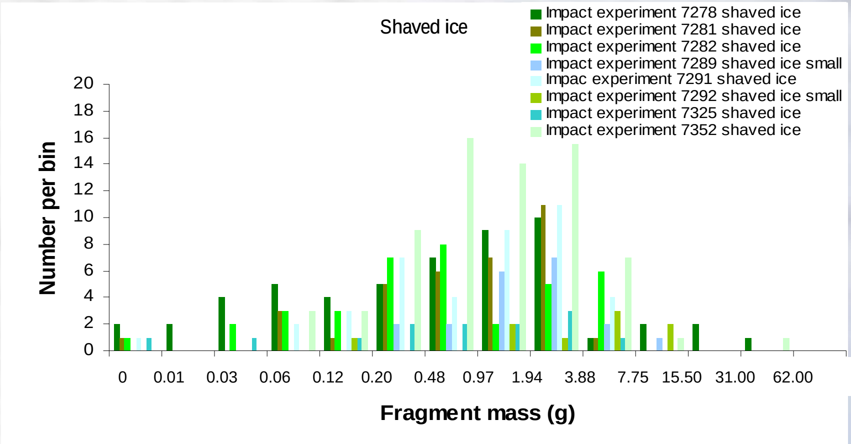
- **Distribution shows no similarities**
- **Fragmentation is not simply governed by energy of impact**

Fragment mass distribution

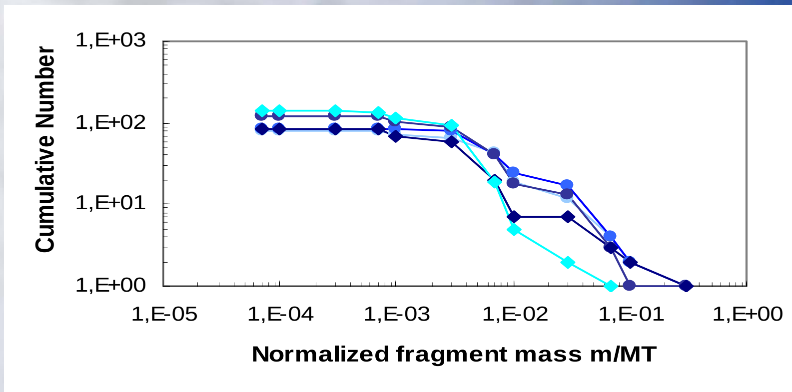
Porous ice

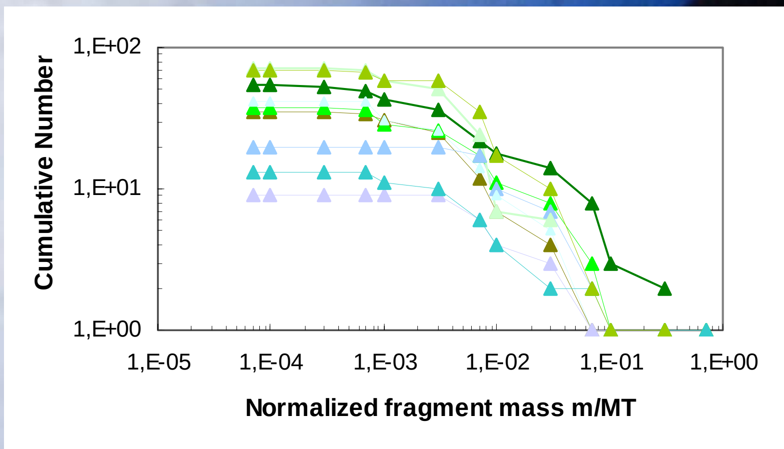
Mass distribution





Cumulative mass distribution





Porous ice

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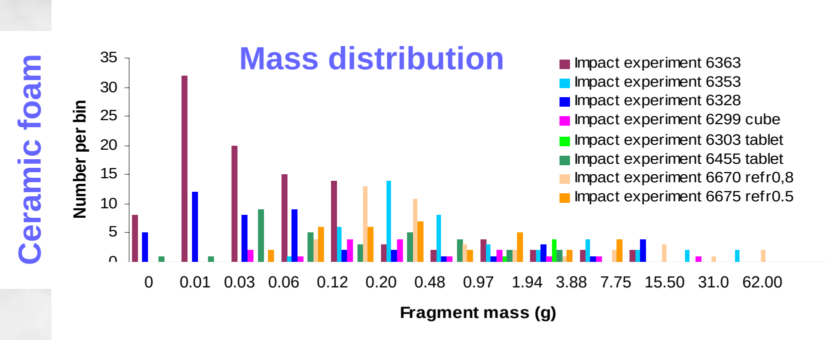
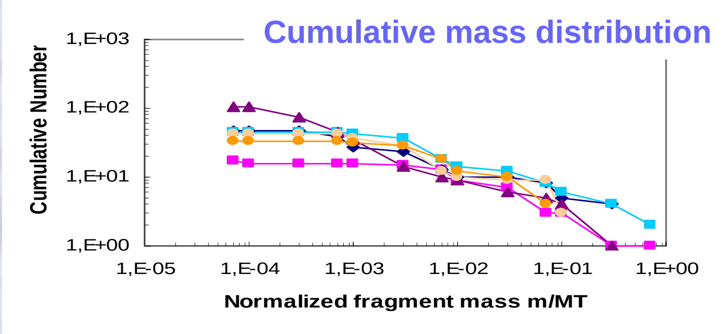
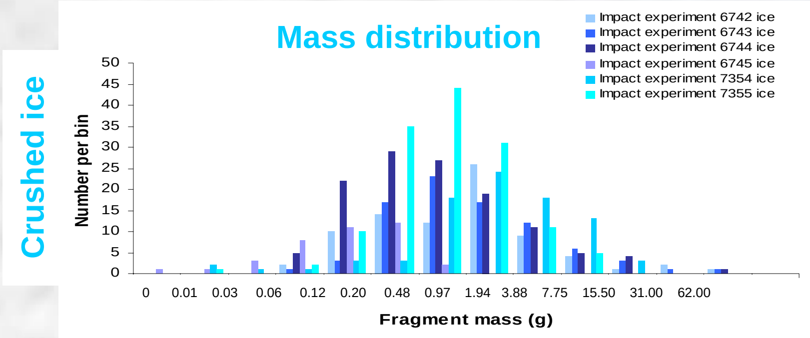
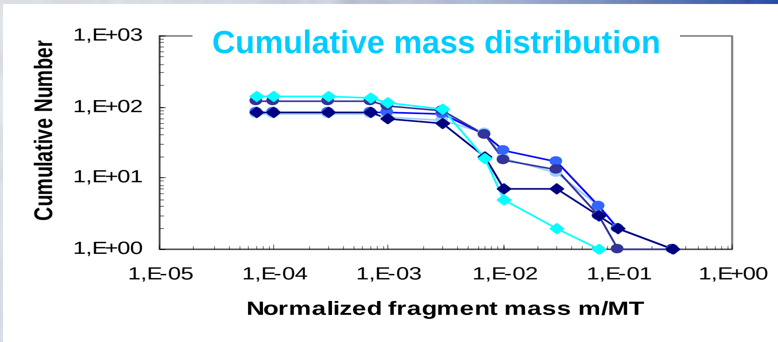
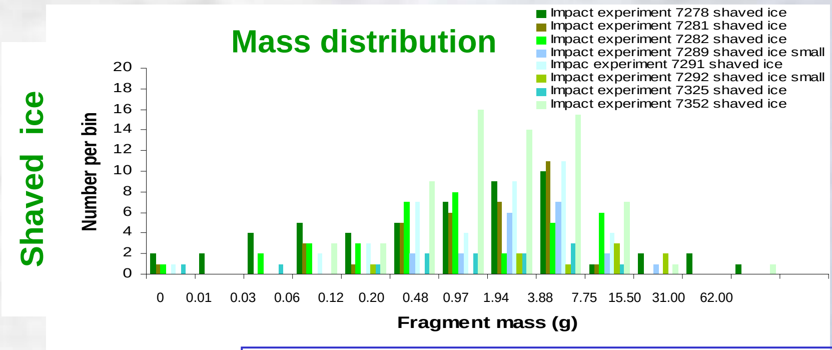
Disruption: Fragment Mass Distribution

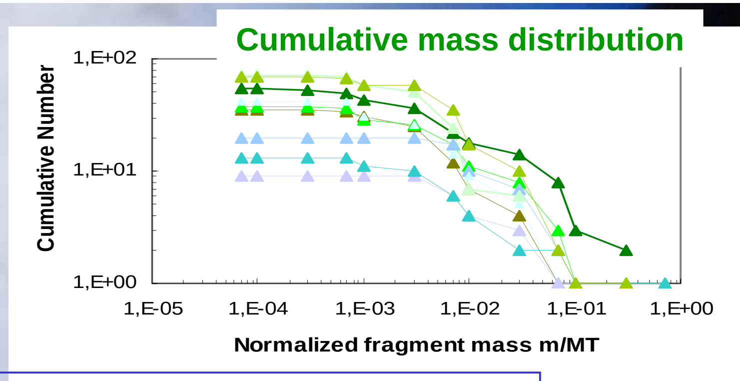












Comparison between shots at specific energy of the same order:
- ➢ Distribution shows no similarities
- ➢ Fragmentation is not simply governed by energy of impact

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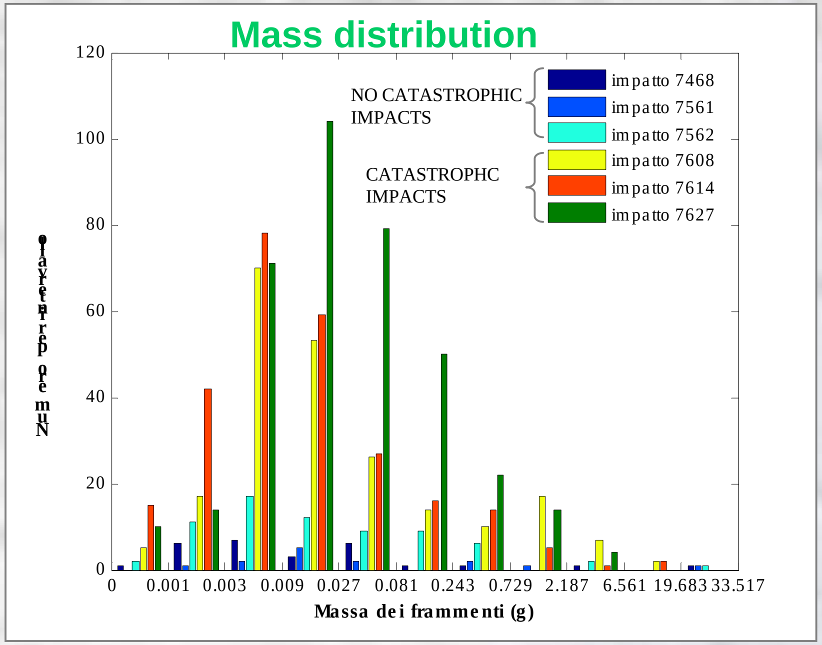
Disruption: dry versus wet-iced



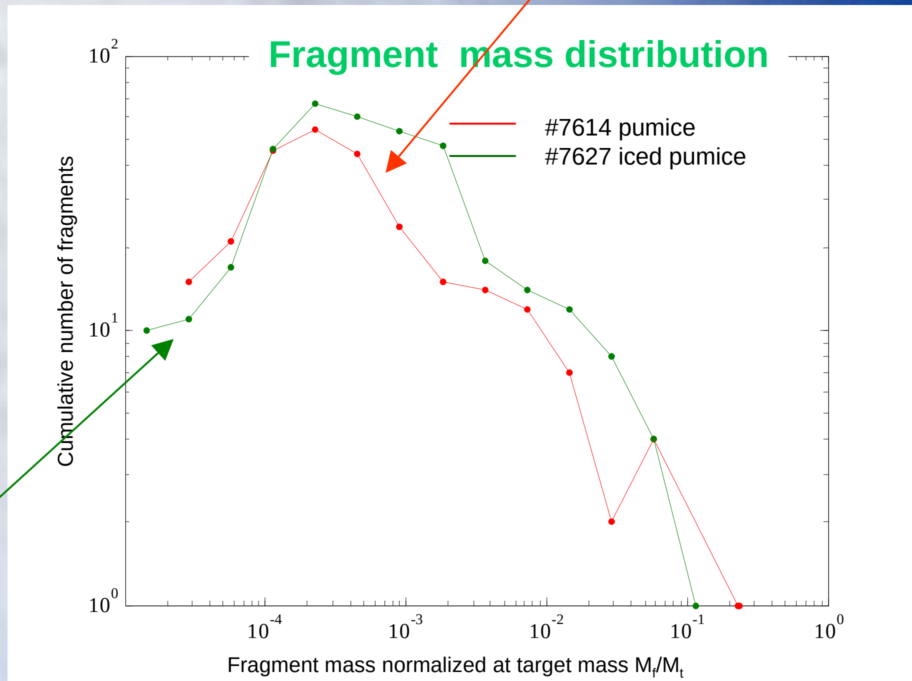
Natural Pumice

Projectile:

Nylon cylinder 4.72mm
V=4400 m/s

7614: dry

7627: wet & iced
water sat 43%



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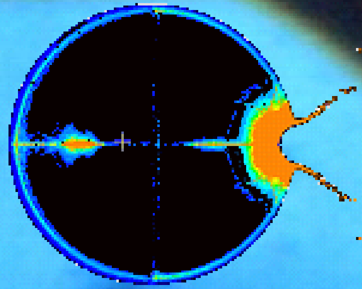
Numerical simulations

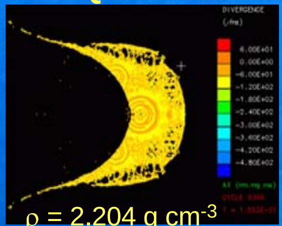


Smooth Particle Hydrodynamics (SPH)

by Autodyn - Century Dynamics

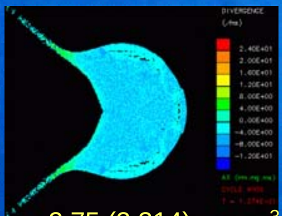
- SPH technique application to different porous and non porous **materials**
- Comparison between **SPH and Lagrangian meshing**
- Comparison between different projectile to target diameter **ratios**
- Good agreement with experimental results

Quartz



$\rho = 2.204$ g cm^{-3}

Porous Concrete 35MPa

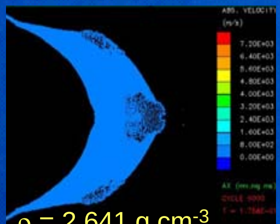


$\rho = 2.75$ (2.314) g cm^{-3}

Sand

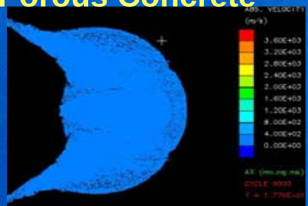
$\rho = 2.65$ g cm^{-3}

Rock



$\rho = 2.641$ g cm^{-3}

Porous Concrete

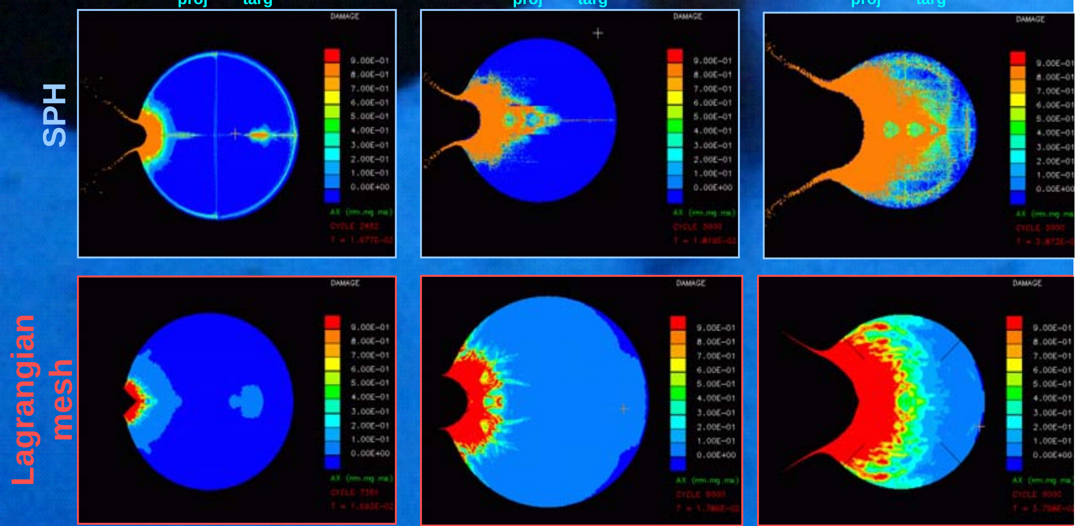


$\rho = 2.44$ g cm^{-3}

Projectile: Al2017 sphere; ∅ 4 mm; V=5 km/s;

Target: sphere ∅ 50 mm

D_{proj} / D_{targ}=0.02 | **D_{proj} / D_{targ}=0.04** | **D_{proj} / D_{targ}=0.08**



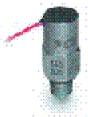
EGU 2007

Wien 16-20 April 2007

Shock wave propagation within the target

Monitoring shock wave
propagation within porous material

⇒ Validation of numerical simulations by SPH



Model **PCB M350B02**

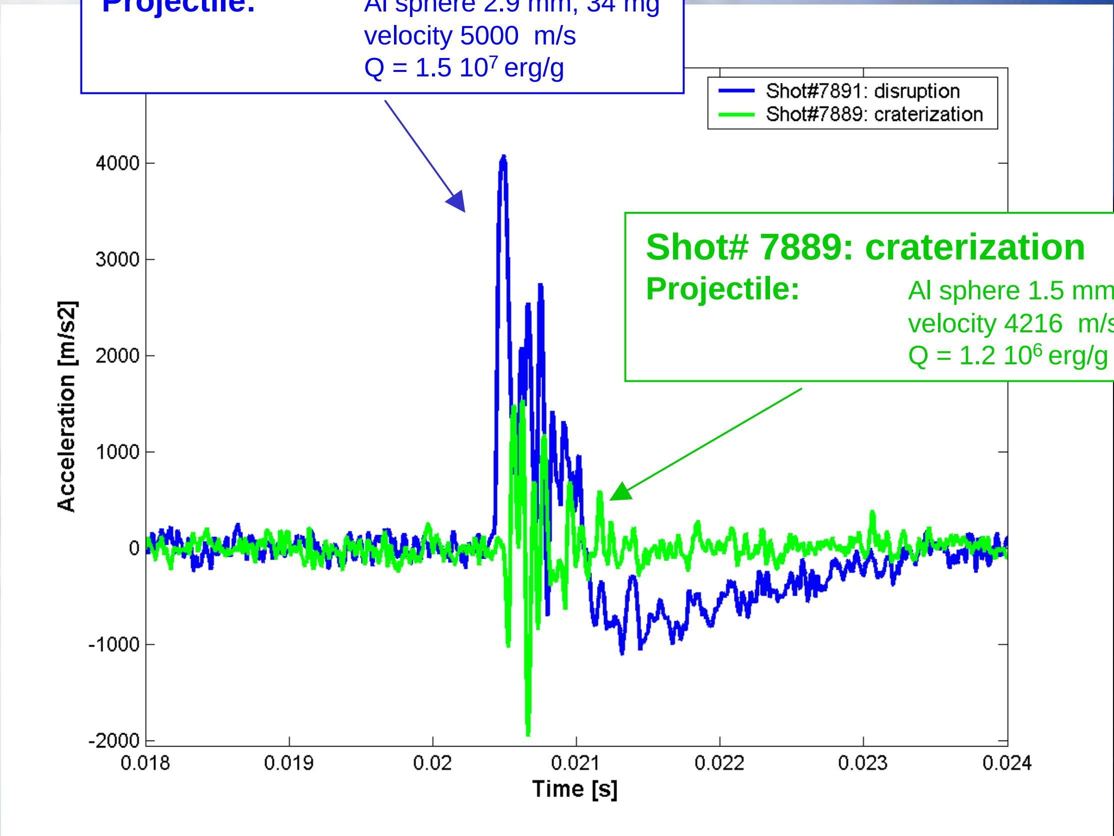
Shock, ceramic-shear, ICP® accel., 0.5 mV/g, 10k g range, filtered integral cable

- Sensitivity: (±30%) 0.5 mV/g (0.05 mV/(m/s²))
- Measurement Range: ±10000 g pk (±98000 m/s² pk)
- Frequency Range: (±1dB) 0.4 to 10000 Hz
- Electrical Filter Corner: (-3dB) 13 kHz
- Mechanical Filter Resonan: 23 kHz
- Weight: 0.16 oz (4.5 gm)

Model 350B24

Shot# 7891: disruption

Projectile: Al sphere 2.9 mm, 34 mg
velocity 5000 m/s
Q = 1.5 10^7 erg/g



Shot# 7889: craterization

Projectile: Al sphere 1.5 mm, 4 mg
velocity 4216 m/s
Q = 1.2 10^6 erg/g

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Impact flashes

- Hypervelocity impacts generate flashes
- Flashes are mainly the result of thermal emission from hot plasma plume created by vaporized projectile and target material.
- At the beginning plasma is optically thick.
  Then temperature drops rapidly, and the gas become optically thin, leading to increased radiation fluxes.
- How much energy is converted into radiation?
  (η luminous efficiency = fraction of initial kinetic energy converted into radiation)
- Very little experimental work on impact flash measurements [e.g. Eichhorn, 1976]
- Few observations of meteorid impacts on the Moon have been performed and intepreted [e.g. Ortiz *et al.* 2000, bellot Rubio *et al.* 2000, Yanagisawa *et al*. 2006].
- Experiments to predict the brightness of the SMART-1 impact flash and to support the interpretation of observational data of impact events.

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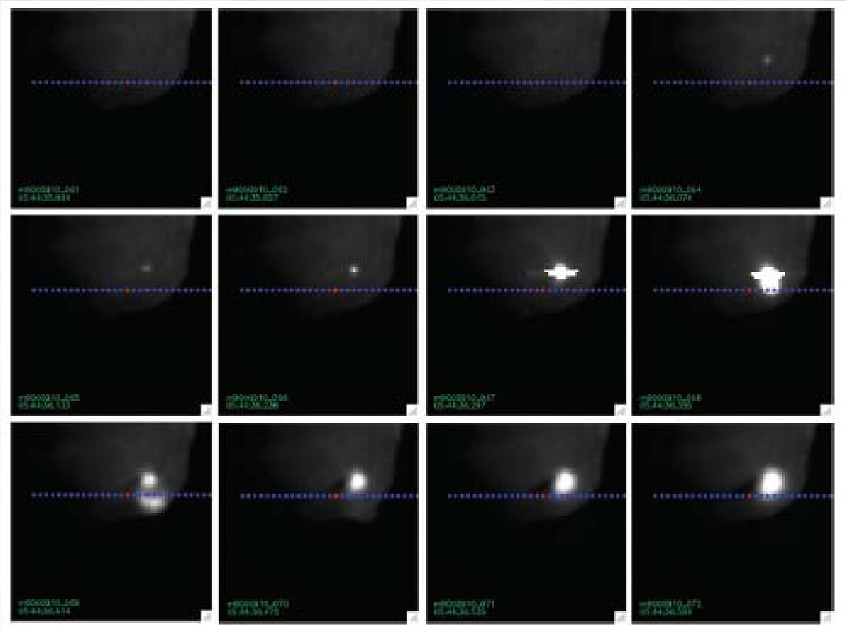
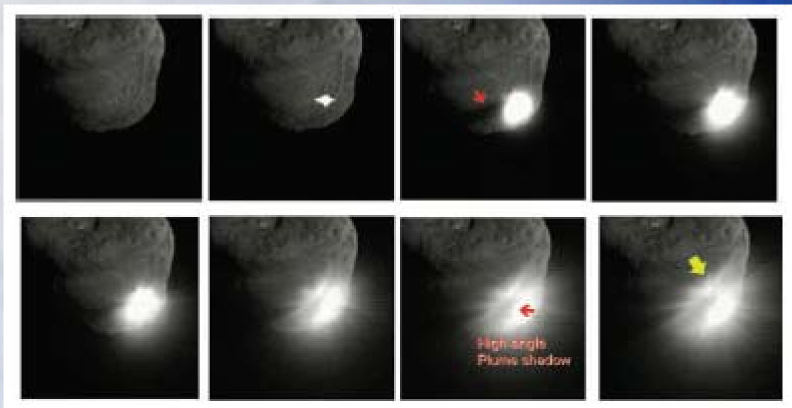
Deep Impact at Comet Tempel 1



Deep Impact at Comet Tempel 1
[O'Hearn et al. *Science* 2005]



Deep Impact at Comet Tempel 1: ejecta development
[O'Hearn et al. *Science* 2005]

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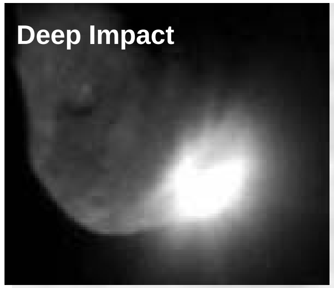
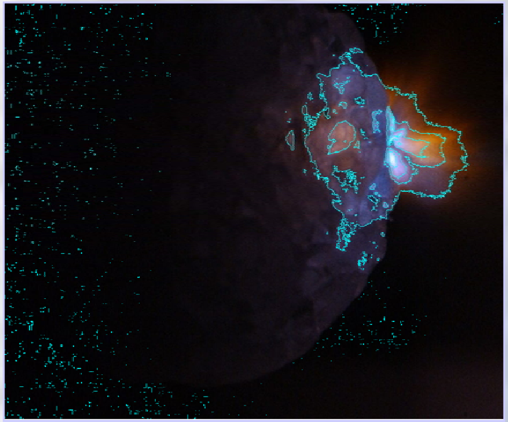


Impact flash

Porous ice

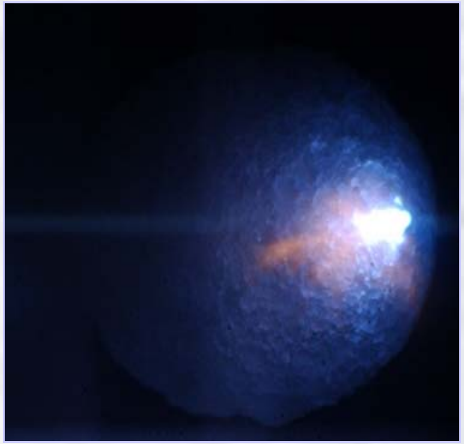
Impact flash generated within the porous target.

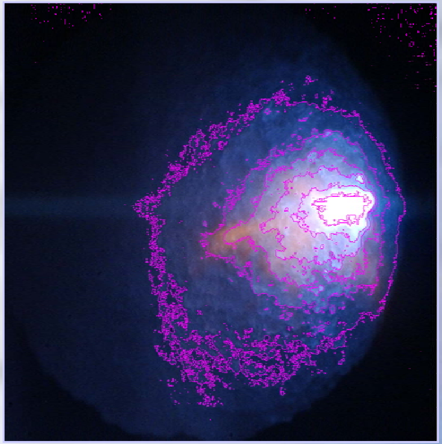
crushed ice

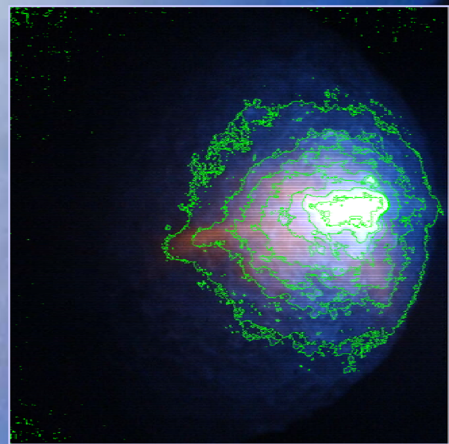


Impact kinetic enery: $5x10^5$ J

shaved ice







Impact kinetic enery: $8x10^5$ J

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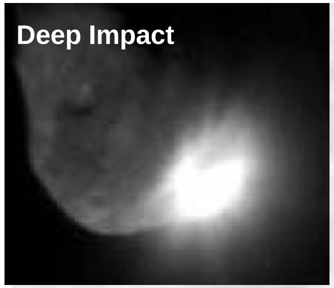
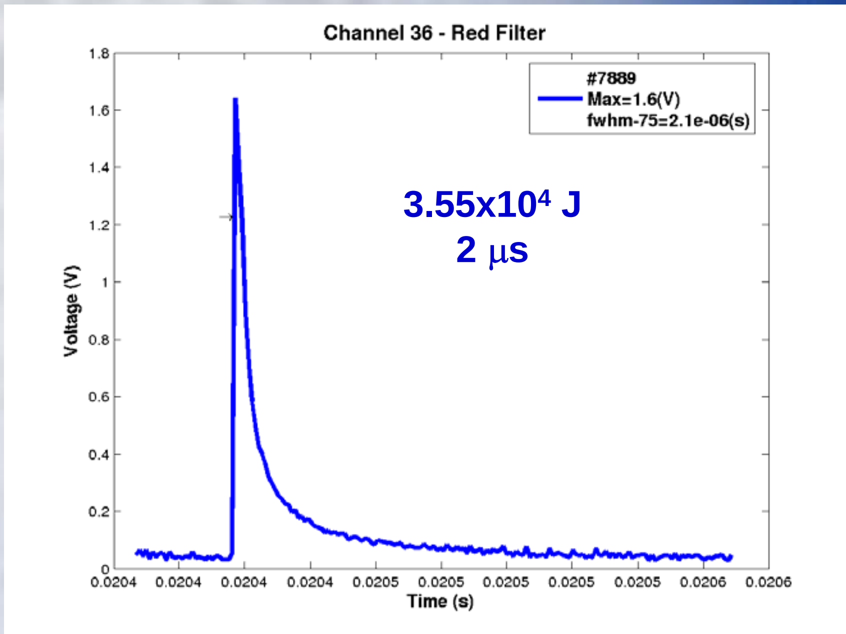


Impact flash

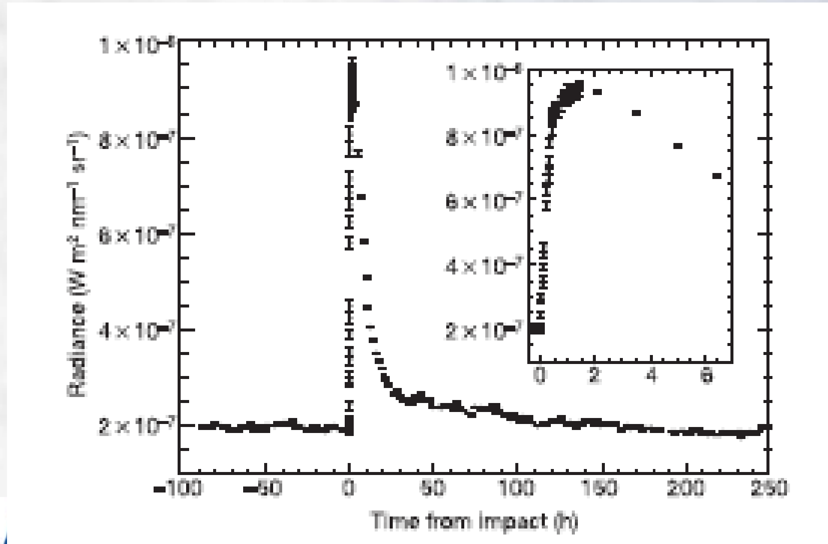
Photo of the flash generated by the impact

Porous ice

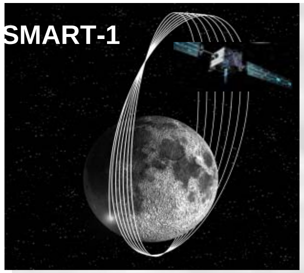
Signal detected by photometer



Impact kinetic enery: 3.55x10^4 J



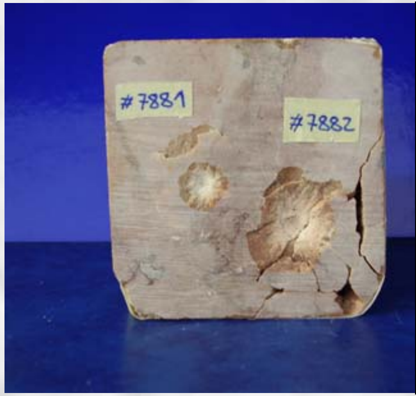
Lightcurve of the cometary dust recorded by Rosetta OSIRIS during Deep Impact
[Kuppers & OSIRIS team, *Nature* 2005]

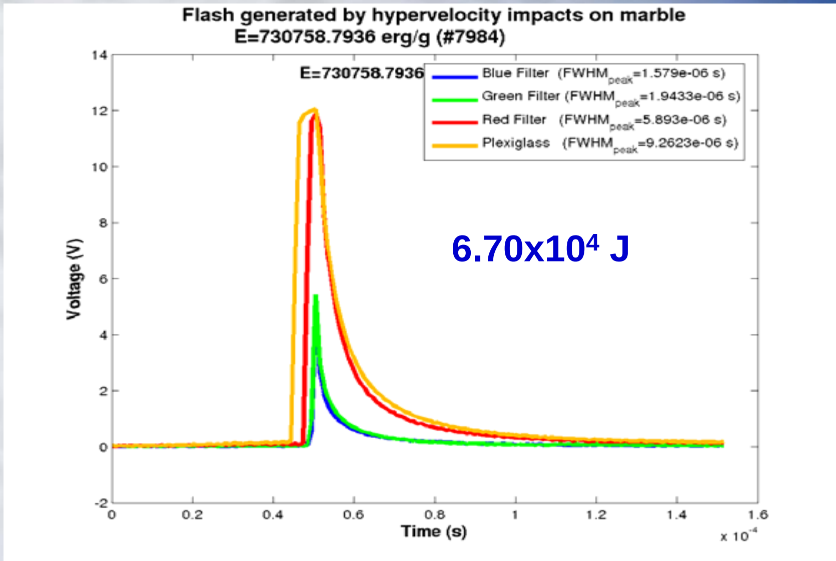


Impact flash

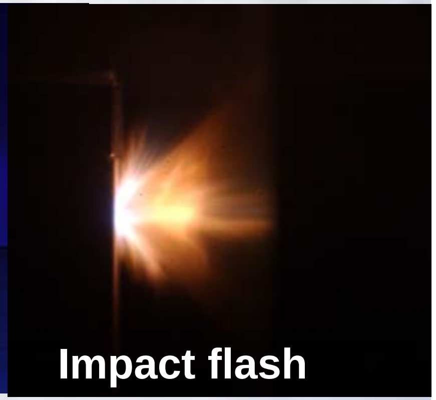
Signal detected by photometers in RGB filters

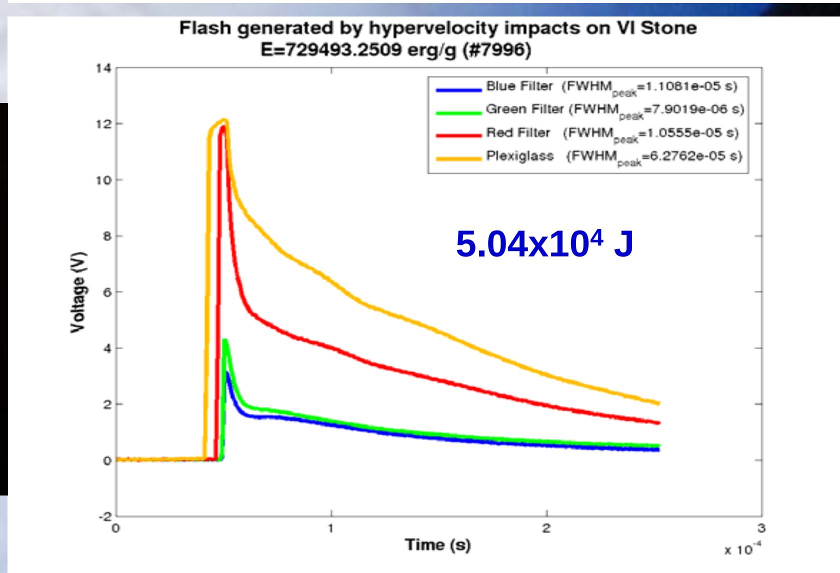
Marble





Vicenza stone





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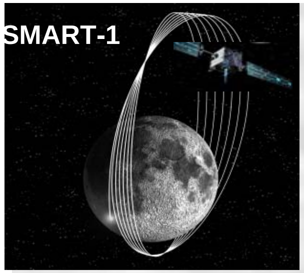
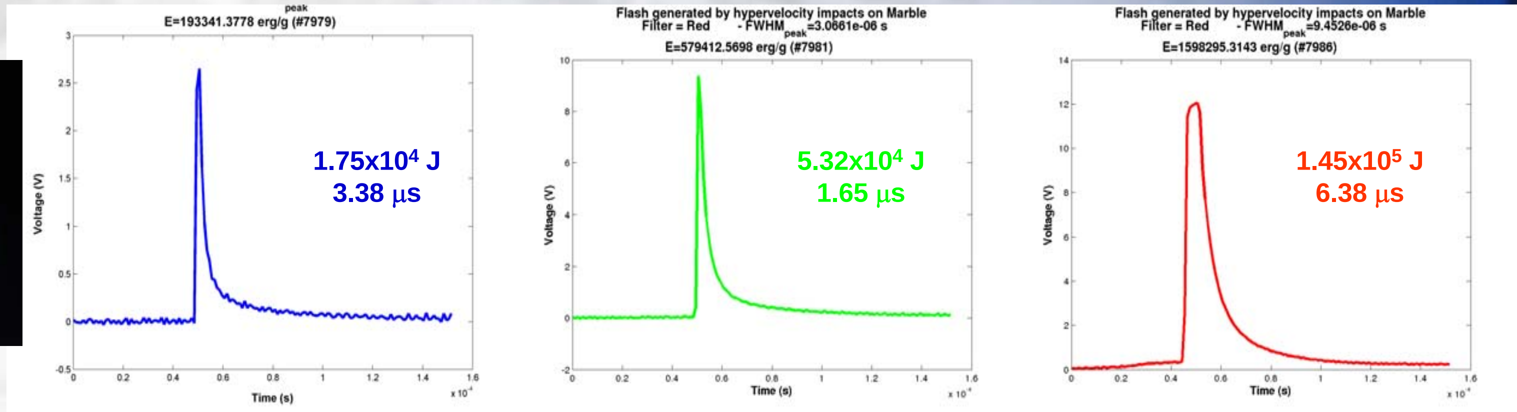


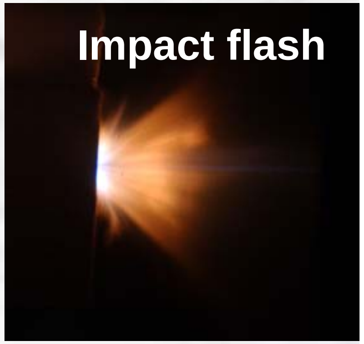
Impact flash

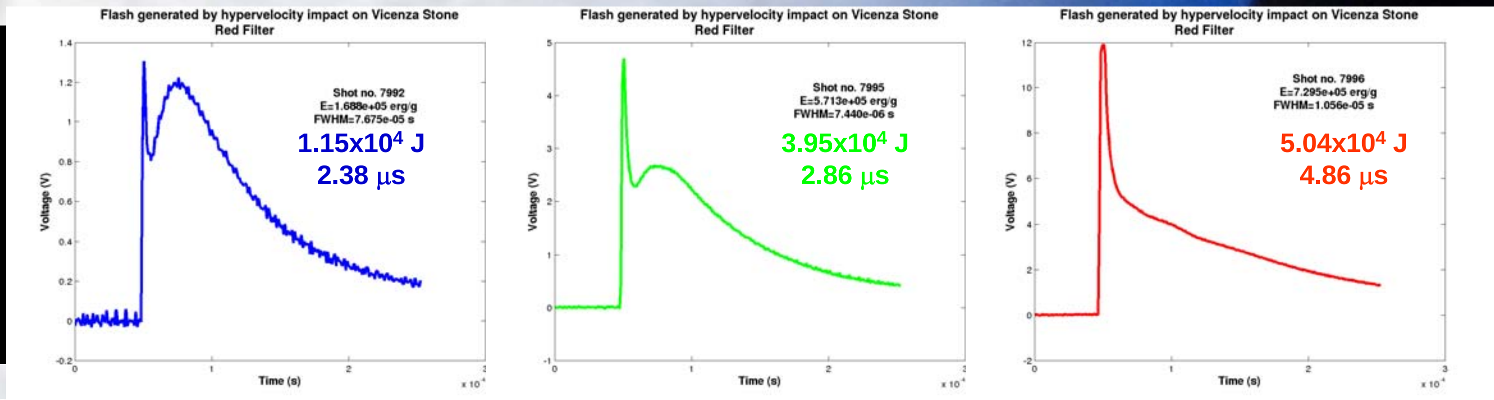
Signal detected by fast photometer (red filter) at different kinetic energies

Marble



Vicenza stone





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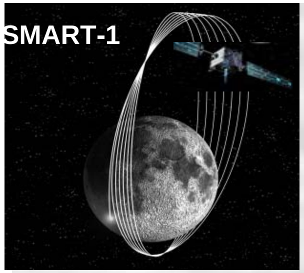
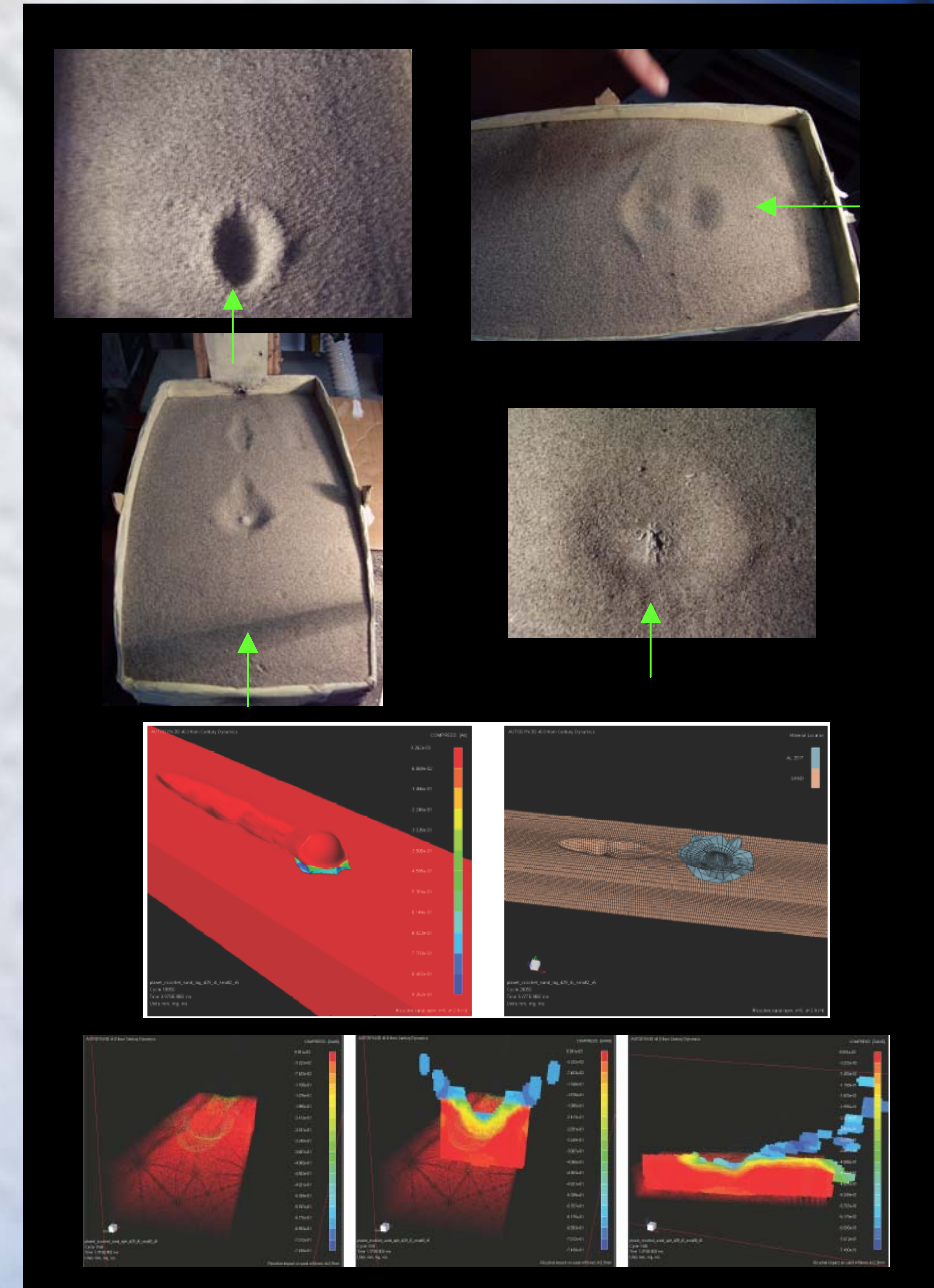


Grazing impacts

- SMART-1 impact on Moon occured at a speed of 2 km/s, at a very shallow angle of incidence
- We simulate SMART-1 impact both by experimental tests and numerical simulations of oblique impacts on sands.
- Grazing impacts with incidence angle between 2°-6° resulted in **elongated craters** and in rebounce (**ricochet**) of the projectile.



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Conclusions

- Porous targets have sound velocity lower than those of non porous target => compaction of initial porous material produces rapid attenuation of the shock, thus affecting energy propagation.
- **Craters** generated by hvi impacts on porous targets are smaller and much deeper than those of non porous targets.
- Target porosity increases the **impact strength**.
  The **shattering critical specific energy Q^*_S** for porous ice samples are much higher than those solid ice and comparable or higher than basalt.
- **Fragment mass distributions** show no similarities. Fragmentation is not simply governed by impact energy, but is more complexly related to geometry and physical properties of the bodies.
- **Impact flash** measurements as function impact kinetic energy to determine luminosity efficiency. -> Energy partition
- **Experimental tests and numerical simulations are essential to support the interpretation of observational data and thus better constraining the current understanding of impact processes.**
  - **Coordination of theoretical and experimental modelling effort.**

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