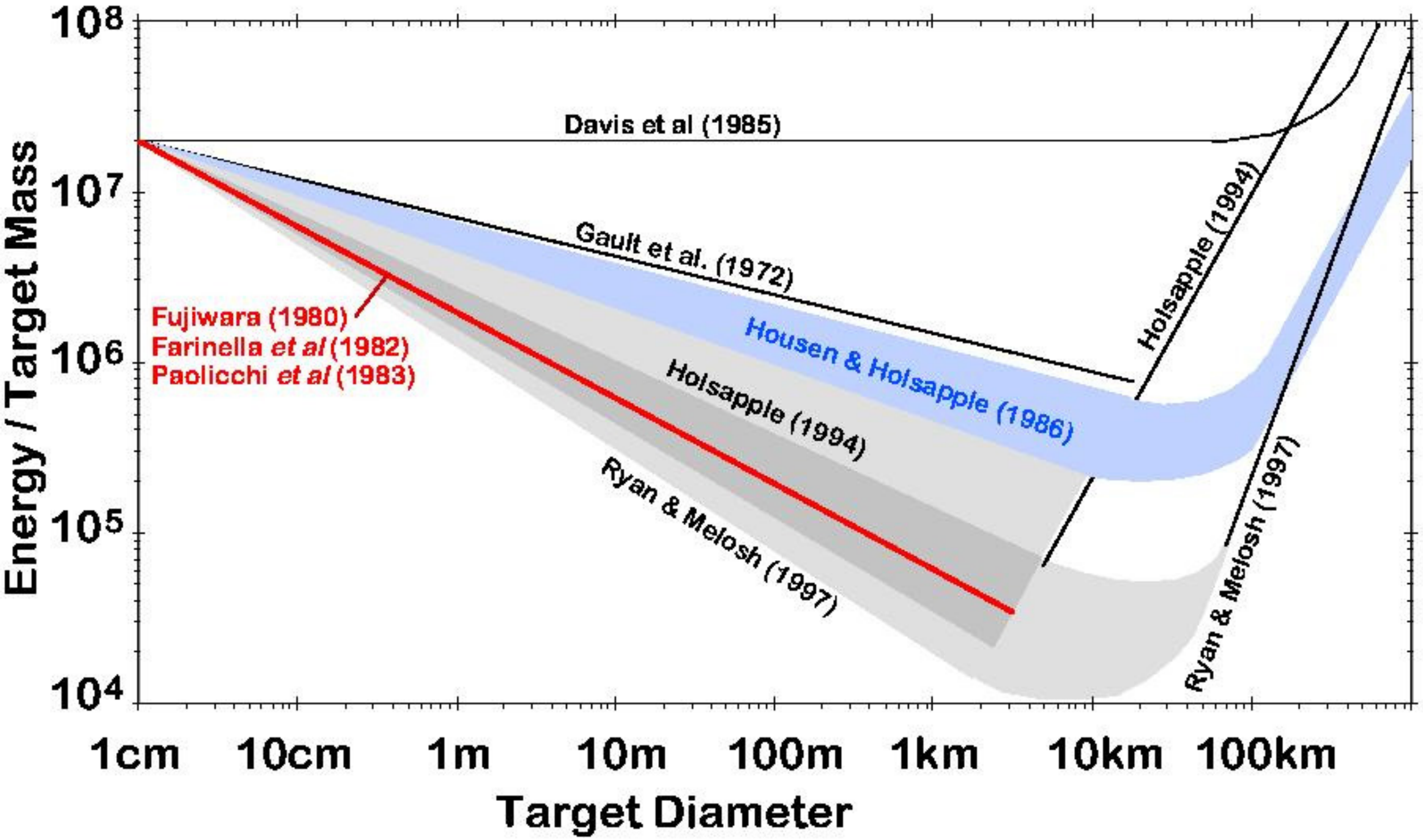
Simulating the collisional disruption of a small body: what do we need to know?

- Balance Laws (easy: continuum mechanics: balance of mass, momentum, energy)
- Material behavior (very hard: 100 Mbar down to partial bars!)
- Robust computer codes

Comparison of scaling models

5th Catastrophic Disruption Workshop, Mt. Hood, June 30 - July 1, 1998

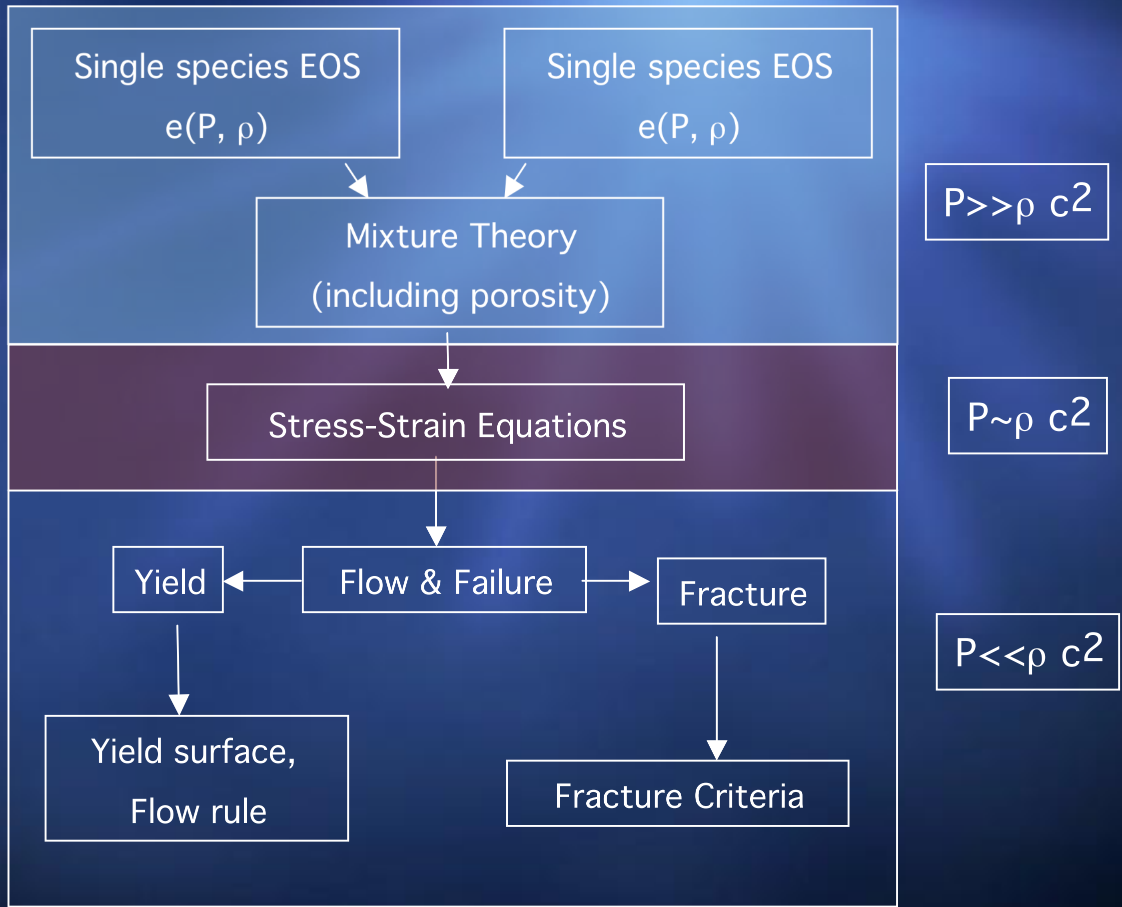


Material Behavior: Three regimes

EOS

Solids

Flow, fracture, failure



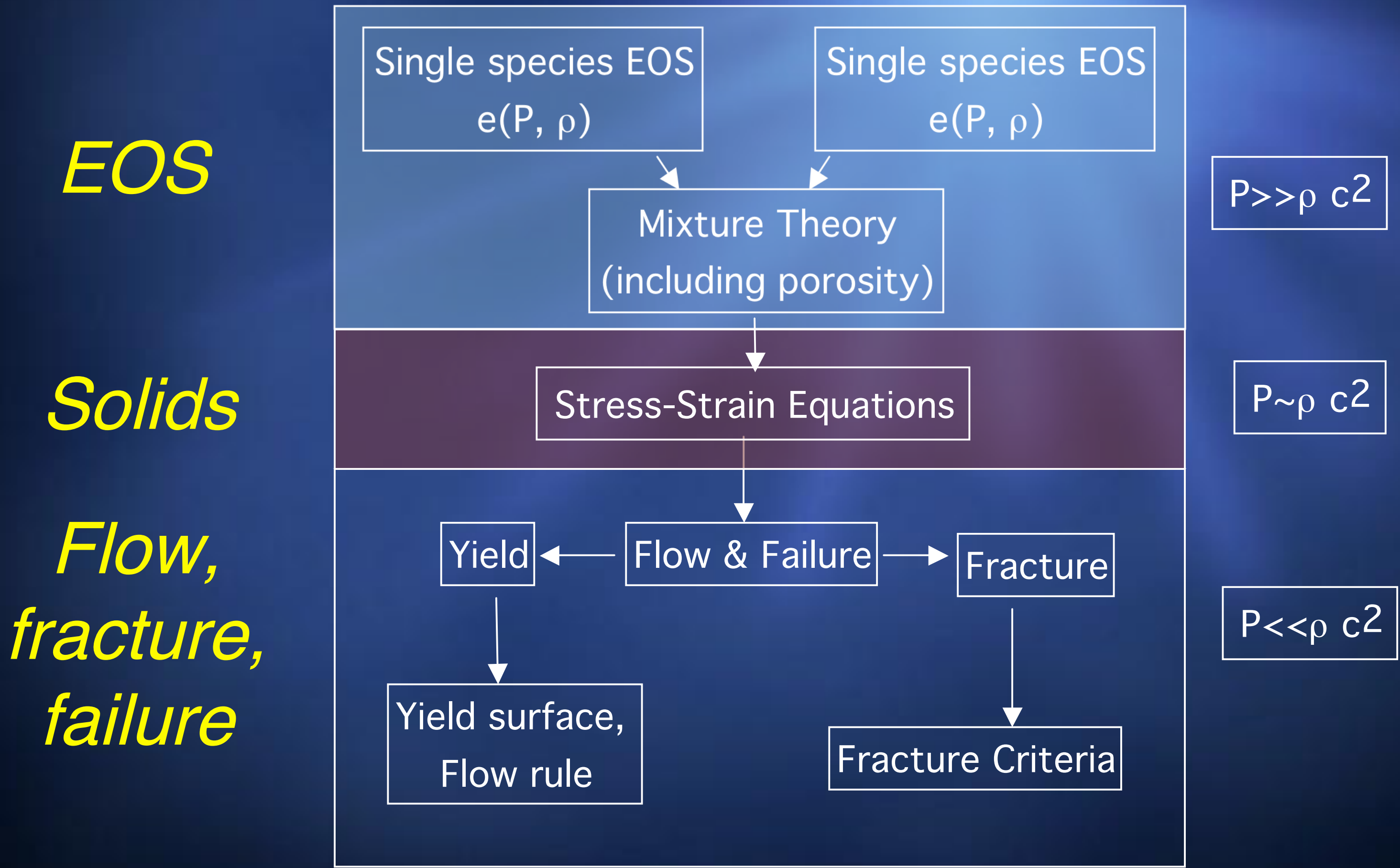
Stress-Strain behavior

- When $\mathbf{P \approx \rho c^2}$ the material no longer behaves as a fluid.

- Then we need a constitutive equation for the stress-strain behavior

- Almost always, in wave codes that is simply an isotropic linear elastic relation (which is undoubtedly extremely crude).

Which brings us to the strength parts..

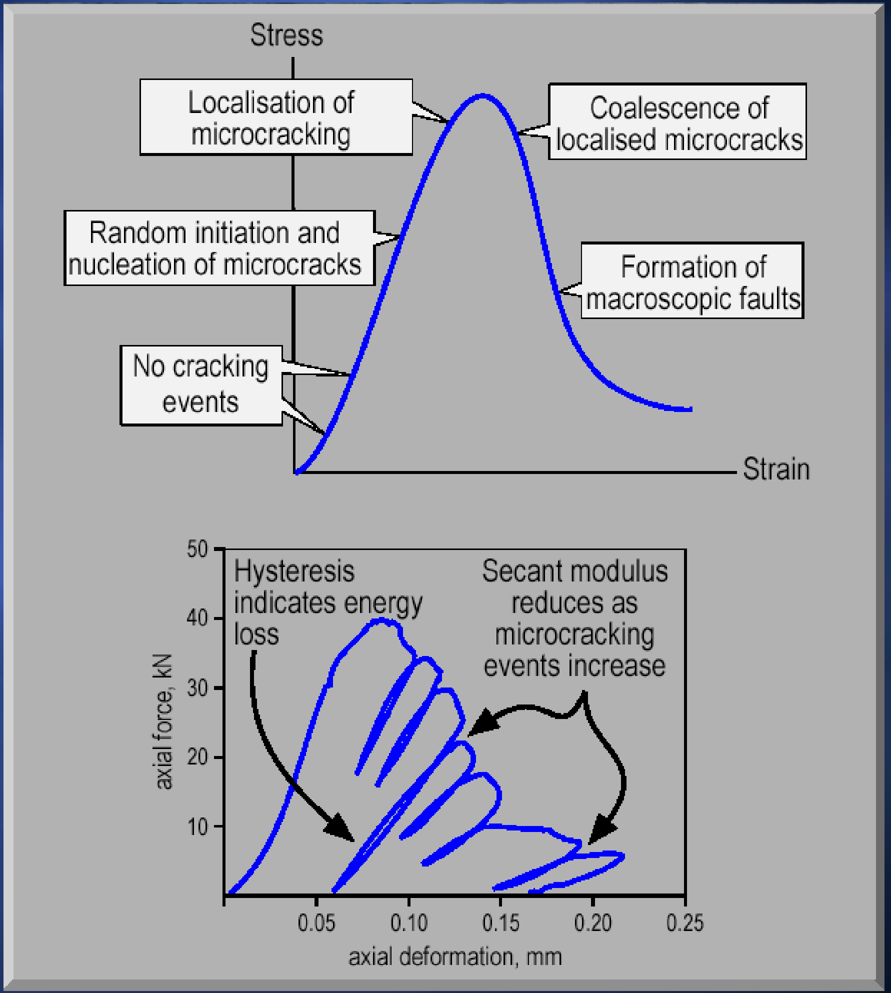


The "F" words: Flow, Fracture and Failure

- Models for these fall into three groups:
  - *"Degraded Stiffness", no explicit flow or fracture.*
  - *"Flow" including plasticity and damage, used to model microscopic voids and cracks leading to an inability to resist stress.*
  - *"Fracture", involving actual macroscopic cracks and voids which are tracked, leading to an inability to resist stress.*

In a continuum theory, the first two can be included directly, the latter is difficult, unless some statistical approach is used to smear them out.

Damage and degradation leading to ultimate failure occur at some limiting strain



Flow and Fracture: Yielding and Cracking

Initial Yield=F(stresses) or G(strains)

- Isotropic=> σ_1, σ_2, σ_3
  (Or three stress invariants)
- Commonly only 2, e.g.
  J_2=F(P)
  Or max shear=f(pressure)

The Grady-Kipp Model

Special nature

- It is a Tensile Brittle Fracture Mechanism
  - For fragmentation in mining
- One-Dimensional Model
- Synthesized for constant strain rate histories only

- Governed by Crack Distributions (Weibull) and growth
- Implies rate and size-dependent strength

But Attractive Physics

There exists an initial distribution of incipient flaws in the target

- Weibull distribution:

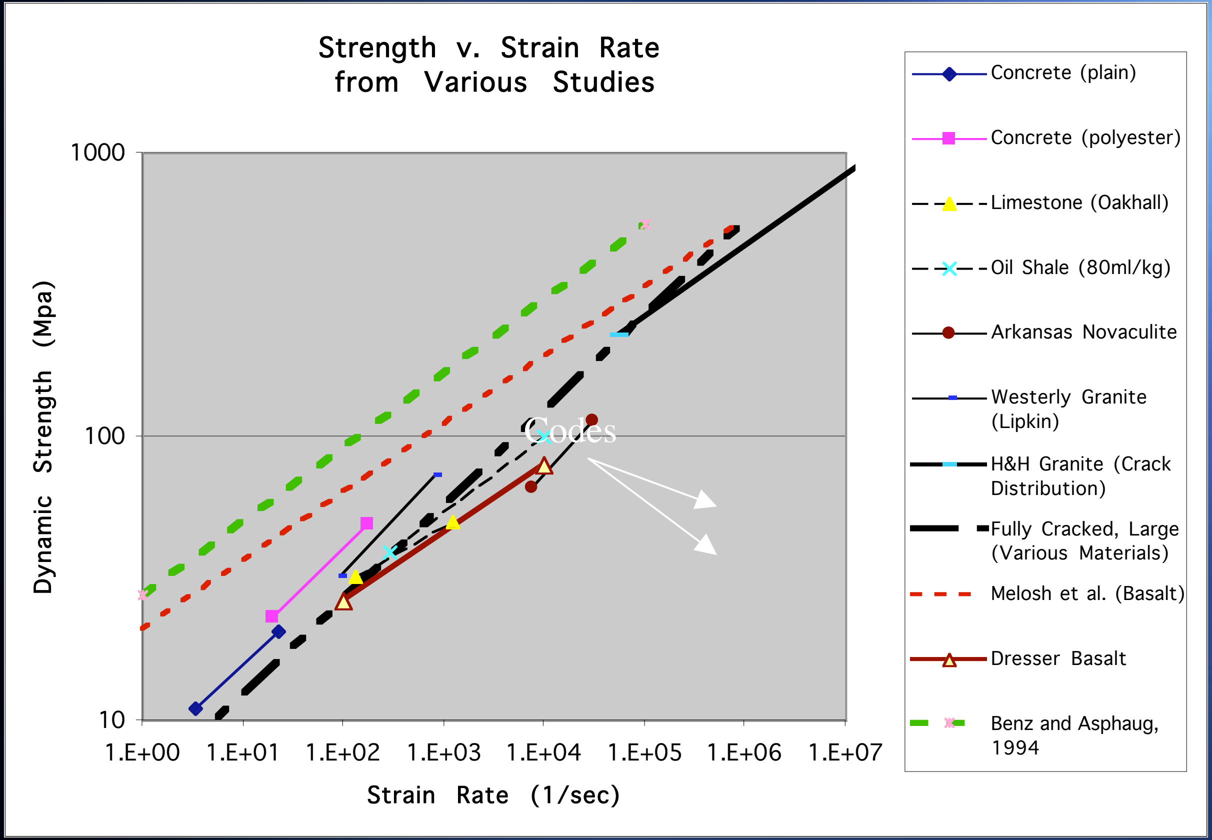
$$N(\varepsilon) = k\ \varepsilon^m$$

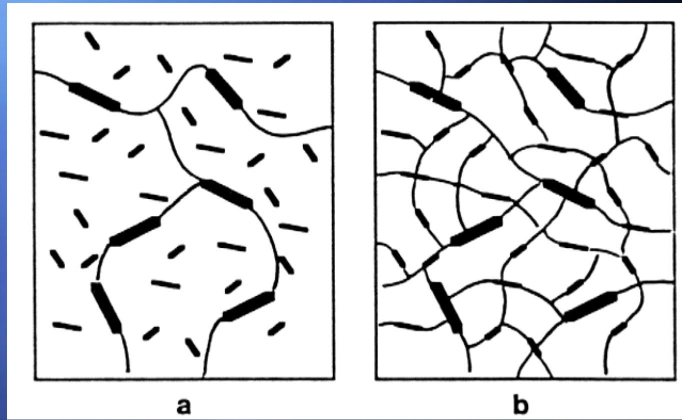
where:
N = density number of flaws activating at or below the strain ε
k, m: Weibull parameters (large m= more homogeneous material)

$$\varepsilon_{min} = (1/\ kV)^{-m}$$

Larger targets (volume V) activate largest crack at lower strain
$\Rightarrow$ Larger targets are weaker

Tensile fracture depends strongly on strain rate





Low strain rate

High strain rate

(From Asphaug)

A Grady Kipp Implementation in 3D

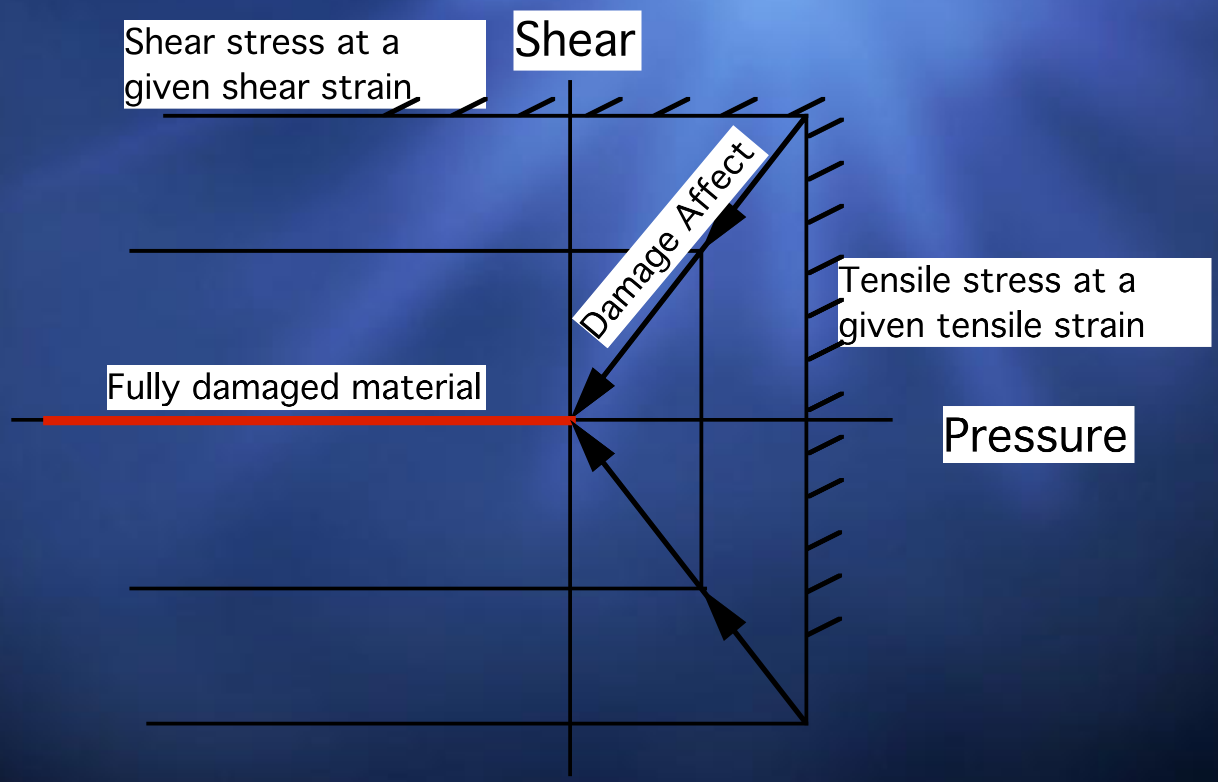
•Damage is isotropic, so that when a crack is formed in one directions, all directions lose stiffness

•As damage accumulates, the stiffness in both tension and in shear decrease, eventually to zero.

•Therefore, material failed by the outgoing shock behaves as water.

•*Calibrated to disruption test, by adjusting the strength (Weibull) parameters*

The Grady-Kipp Approach



Fragmentation phase: principles

Equation of state
P=f(E,ρ)

Model of brittle Failure

Stress tensor

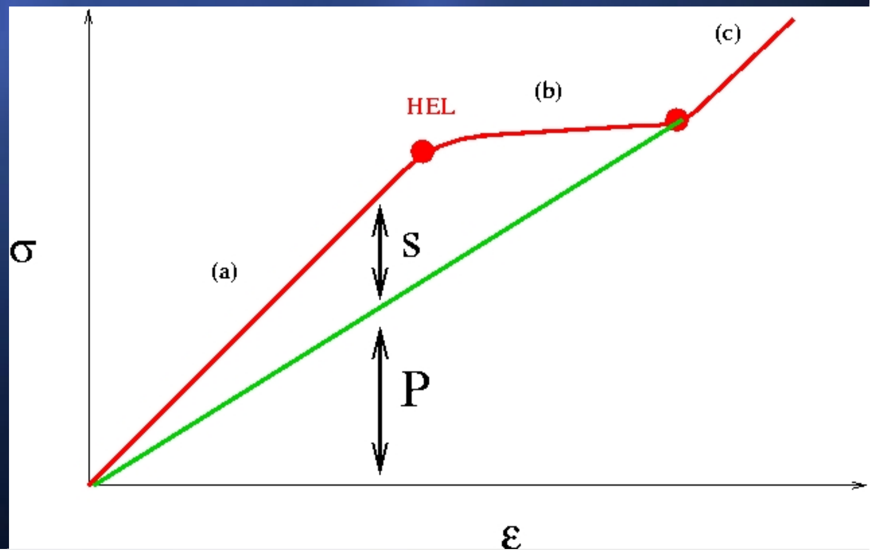
$$\sigma_{\alpha\beta} = -P\,\delta_{\alpha\beta} + S_{\alpha\beta}$$

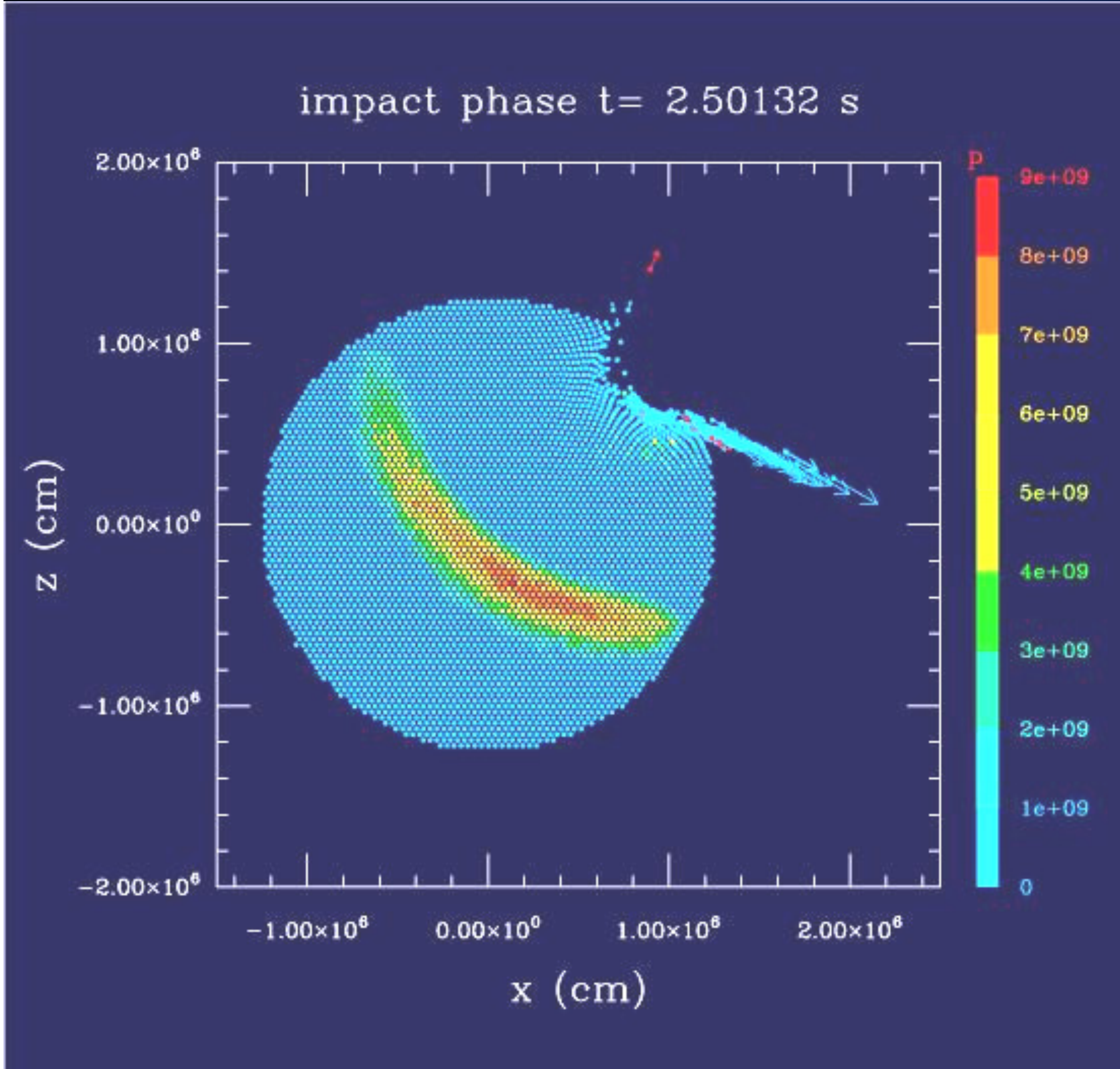
$$S_{\alpha\beta} = \mu(\varepsilon_{\alpha\beta} - 1/3\,\varepsilon_{\gamma\gamma}\delta_{\alpha\beta})$$

Yielding criterion:
$S_{\alpha\beta} \rightarrow f\,S_{\alpha\beta}$

Conservation equations

SPH techniques





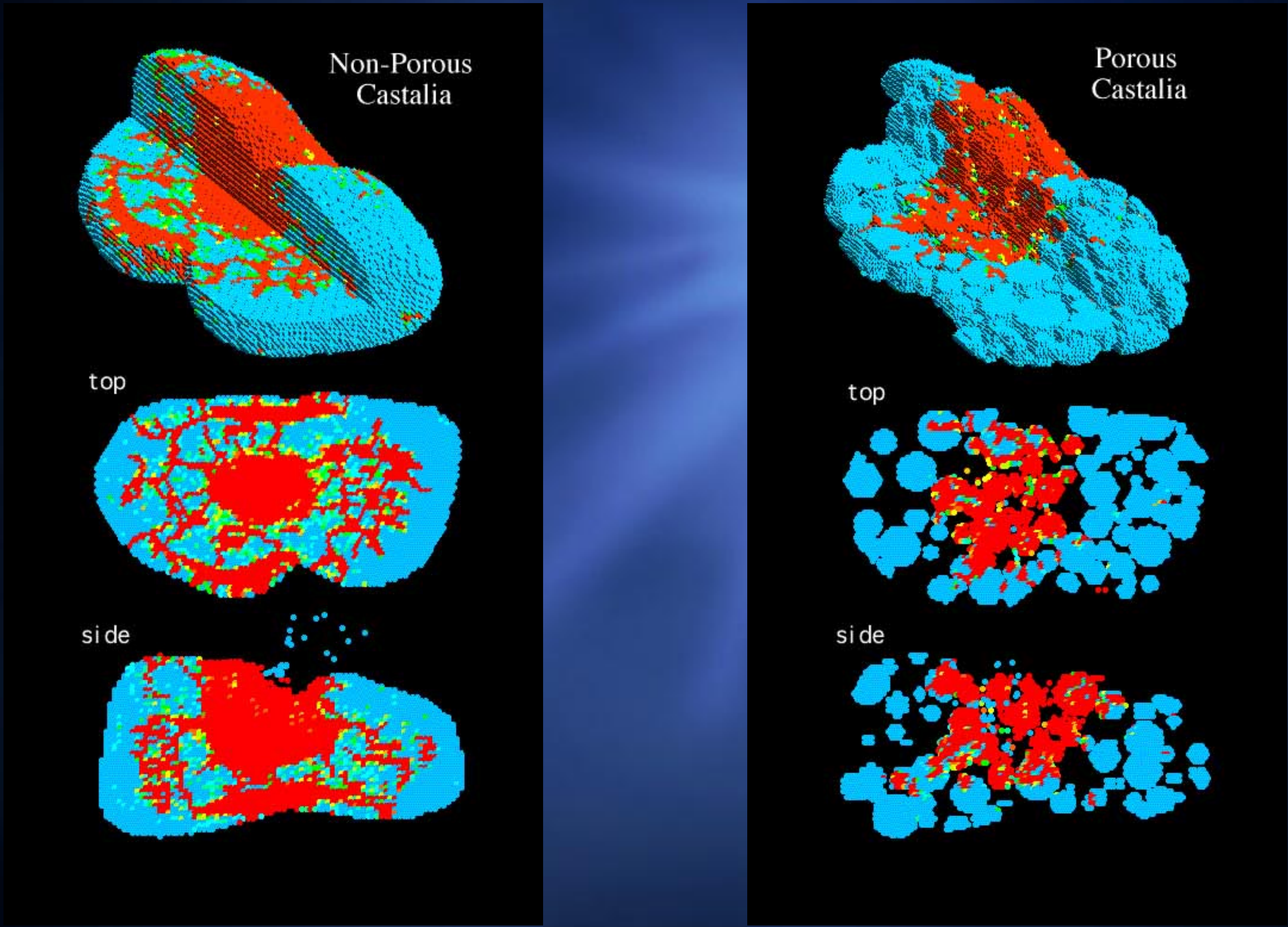
Fragmentation Phase

Shock wave Propagation

Impact velocity: 5 km/s

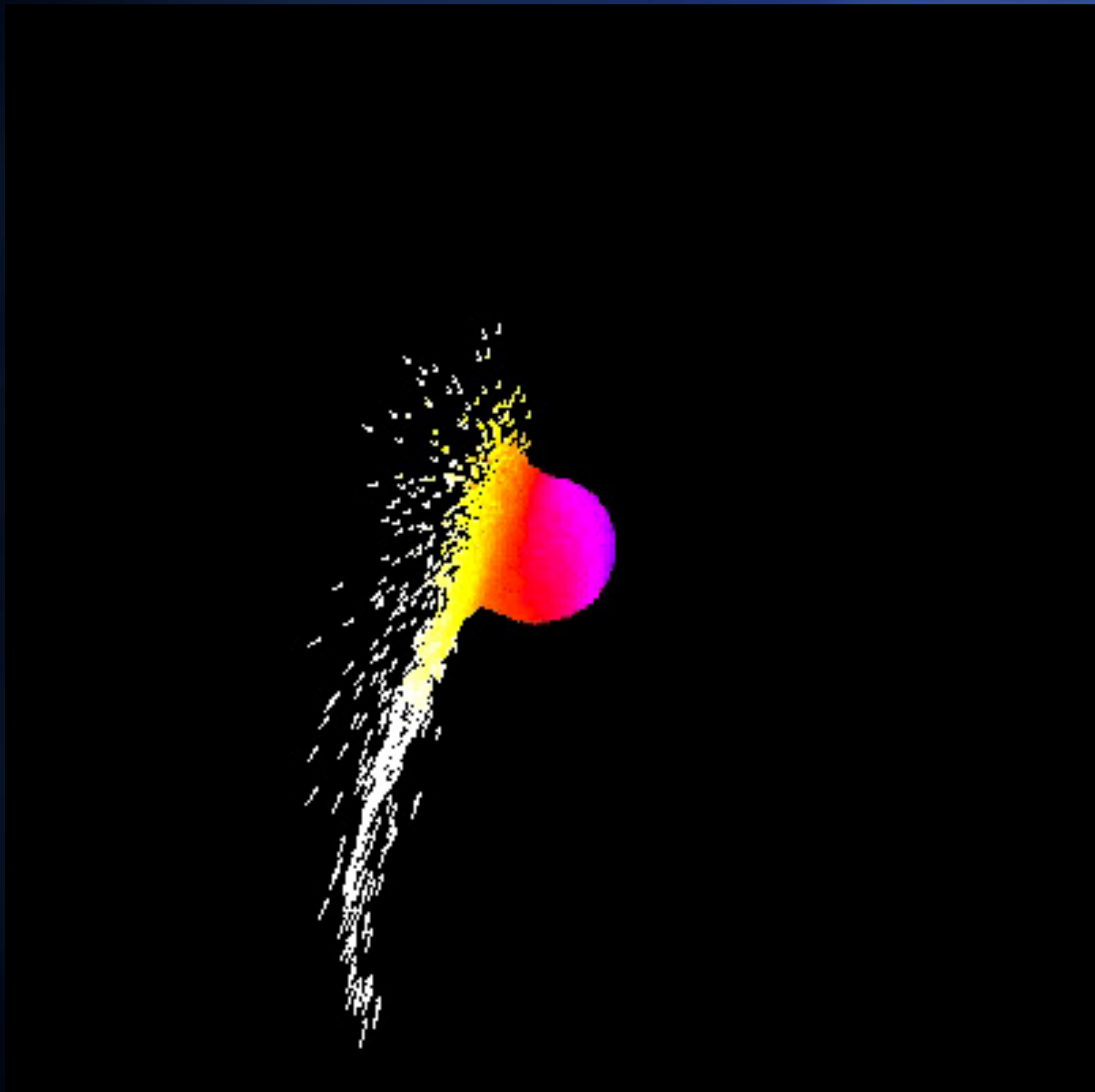
Impact angle: 45°

P. Michel & W. Benz



From Asphaug et al. 1998, Nature **393**.

Impact angle: 66°, V = 5 km/s D=164 km



Velocity distribution At the end of the fragmentation phase

Colors from Yellow to Blue indicate velocities from large to small

Intermediate impact regime

Gravitational Phase: parallel N-Body simulations

- Several hundreds of thousands km-size fragments can be generated by the fragmentation phase

⇒ Impossible to compute their gravitational interaction by classical methods:

The CPU time required to compute N interactions between N particles is of O(NxN) !!

Using the so-called hierarchical tree method (tree code):

CPU Time = O(N log N)

Gravitational Phase: parallel N-Body simulations

- Parallel N-Body code: *pkdgrav* (Parallel K-D tree GRAVity code); developed at UW by T. Quinn, J. Stadel, D.C. Richardson

- Detects and handles collisions between massive particles. Several options:

1. Systematic particle merging
2. Merging/Bouncing of particles depending on impact speed and spins.

Particle shape: spherical

Simulations of Collisions in the Gravity Regime

- SPH hydrocode → crack propagation through the target
- Nbody code → gravitational interaction between intact fragments

↓

Simulation of target shattering + fragment dispersion and/or reaccumulation

Michel et al. (2001), Science Vol. 294, pp 1696-1700.

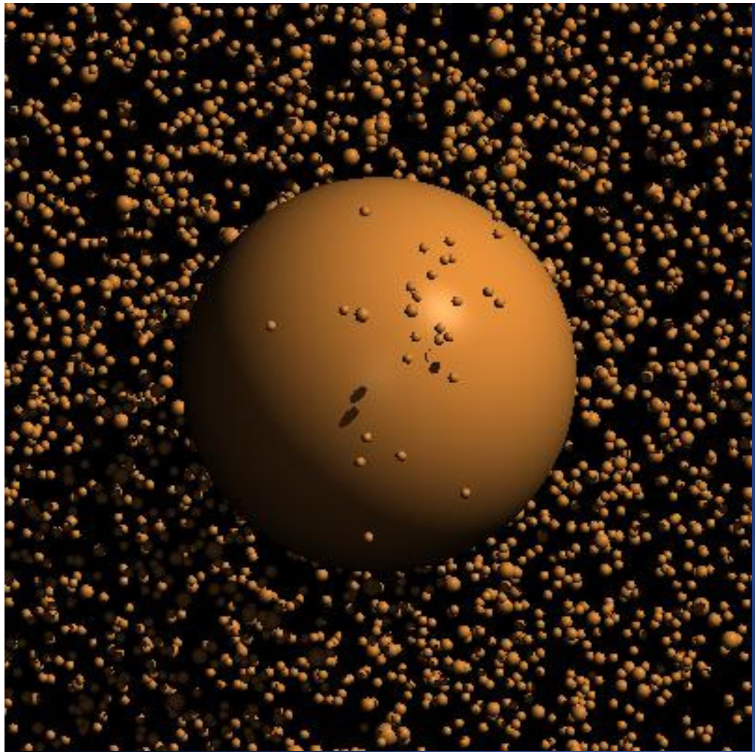
Results!

Simulations of asteroid disruptions have
1. successfully reproduced asteroid families
2. suggest that most kilometer-sized objects are gravitational aggregates

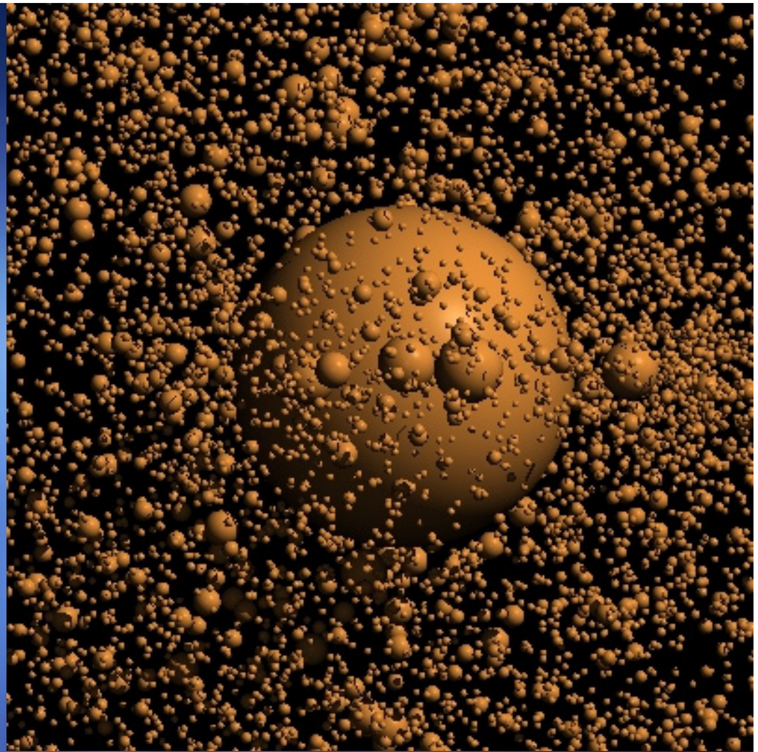
Michel et al., *Science* 294 (2001)

Impact energies and collisional outcomes depend highly on the internal structure of the parent body

Michel et al., *Nature* 421 (2003)

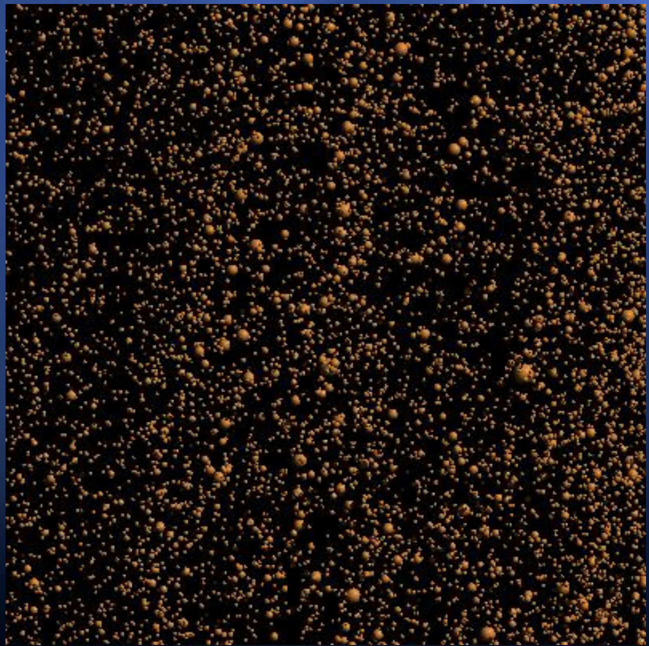


Michel, Benz, Tanga, Richardson, *Icarus*, **160**, 2002.



T=84 minutes

T=2 minutes

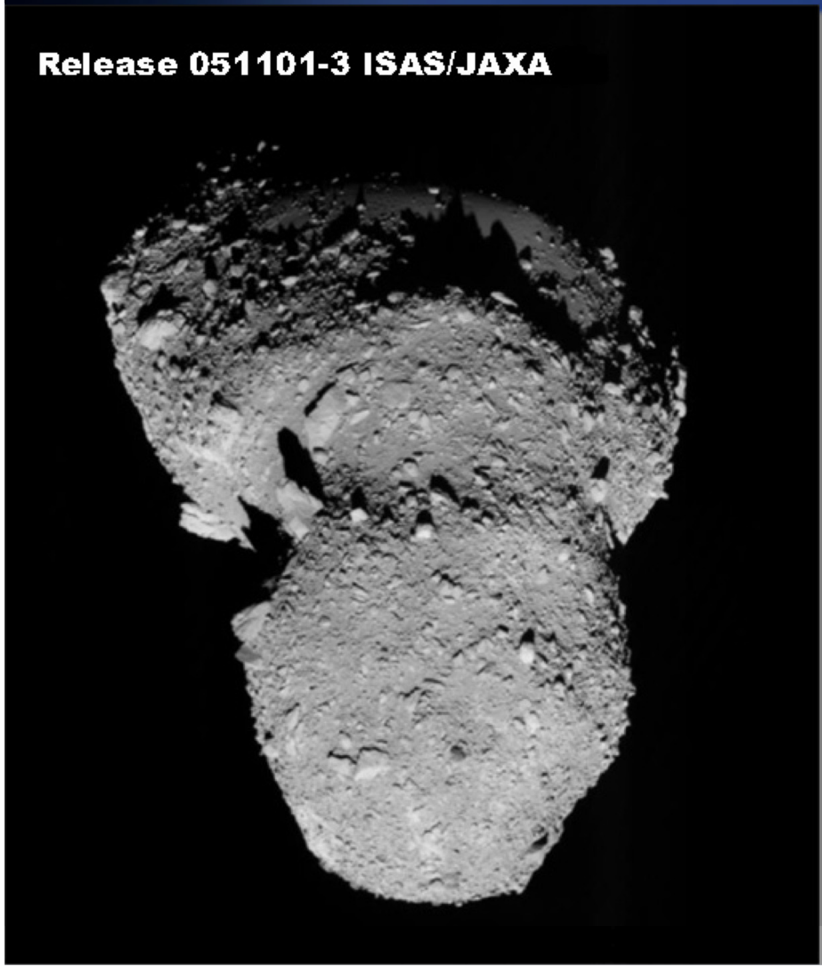


T=2 seconds

Different phases of the reaccumulation process

Implication: most asteroids originating from the disruption of a larger one - such as most NEOs - should be rubble piles

The japanese mission Hayabusa brought us some evidence in this direction: where are the craters?? why so many debris ?? What about the small bulk density (< 2 g/cm3)



From Velocities to Orbital Elements

Gauss Formulae: transformation velocities to orbital elements

$$\frac{\partial a}{a} = \frac{2}{na\sqrt{1-e^2}}[(1+e\cos f)V_t + e\sin f\, V_r]$$

$$\partial e = \frac{\sqrt{1-e^2}}{na}[\frac{e+2\cos f + e\cos^2 f}{1+e\cos f}V_t + \sin f\, V_r]$$

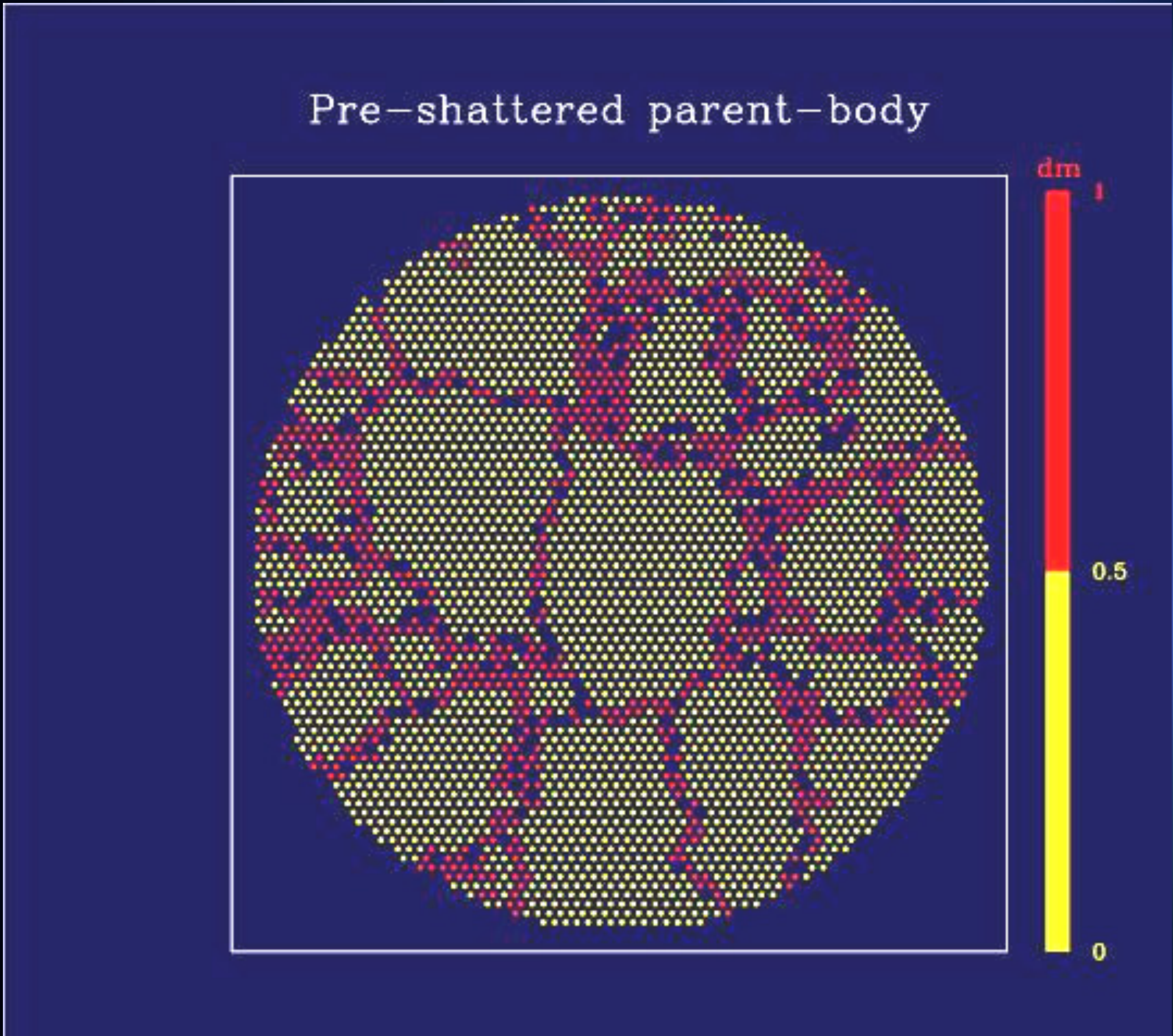
$$\partial i = \frac{\sqrt{1-e^2}}{na}[\frac{\cos(\omega + f)}{1+e\cos f}V_w]$$

(a, e, i, w, f, n)=orbital elements of Parent body (family barycenter)

Requires to assume *a priori* ω and f of the parent body at the impact instant

Effect of the Parent Body's Internal Structure

- Previous simulations assumed monolithic parent bodies
- Large asteroids are likely to undergo shattering events before disruptive ones
- **What is the outcome of the disruption of a pre-shattered parent body?**



Yellow zones= fragments

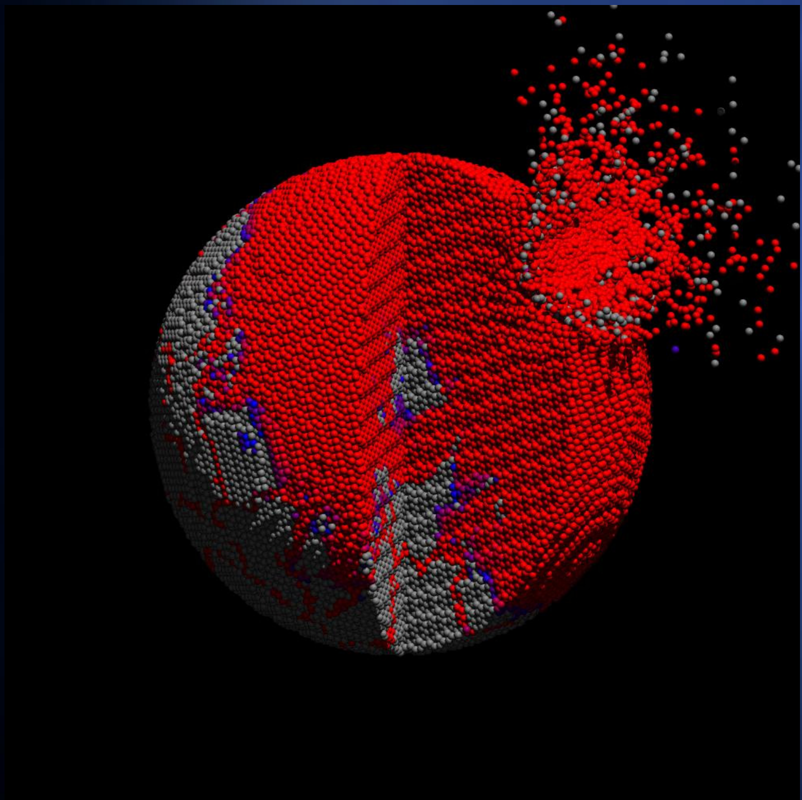
Red zones= dammage (separation between fragments)

Black points= void

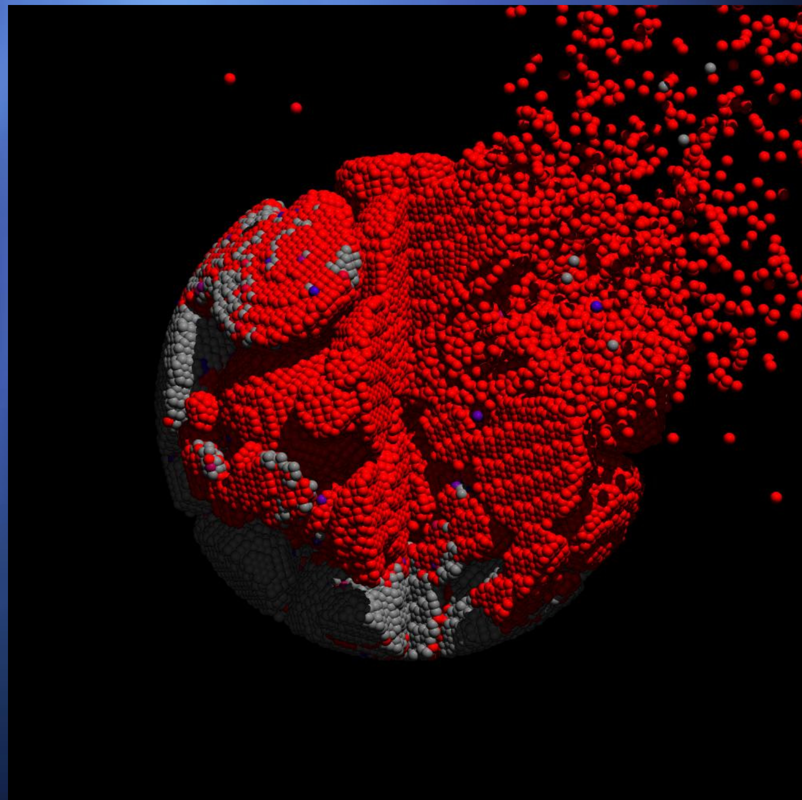
W. Benz & P. Michel

Two types of pre-shattered internal structures

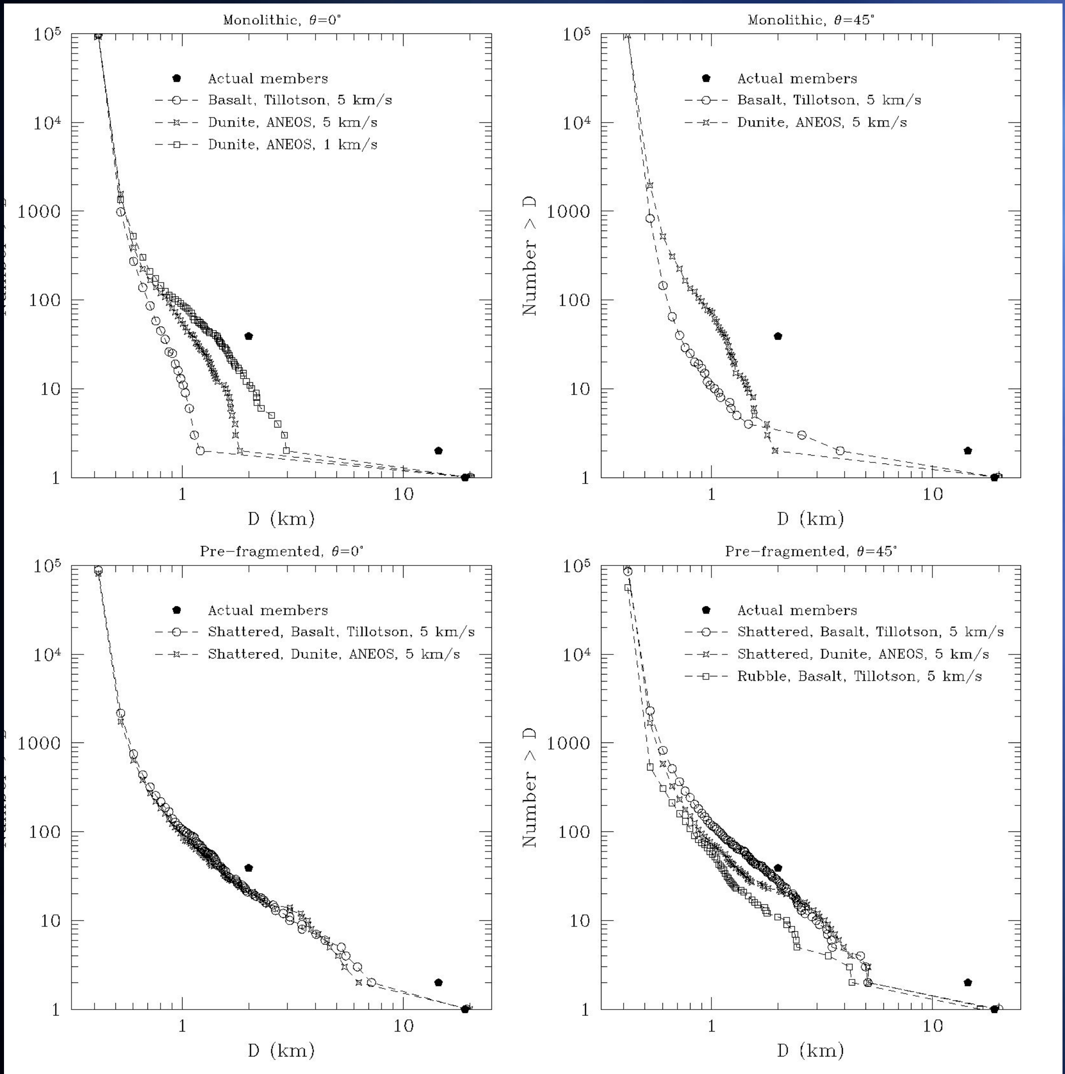
Presence of damage zones



Presence of damage zones + voids



Monolithic/Pre-shattered Parent Body



Monolithic Parent Body

N>D vs D (km)

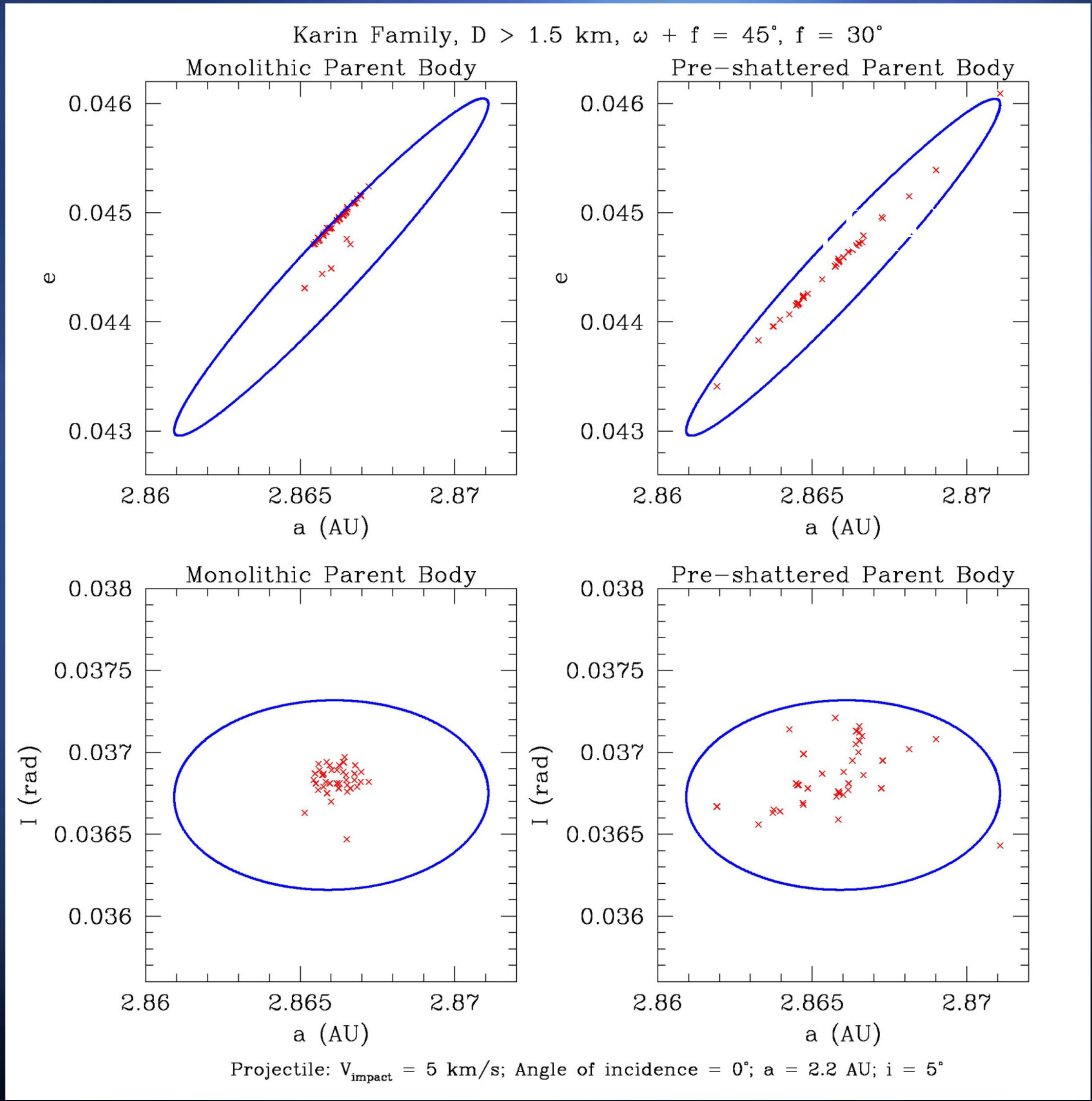
Pre-shattered Parent Body

Monolithic/Pre-shattered Parent Body

Ellipses = spreading of the real family

Crosses = simulation

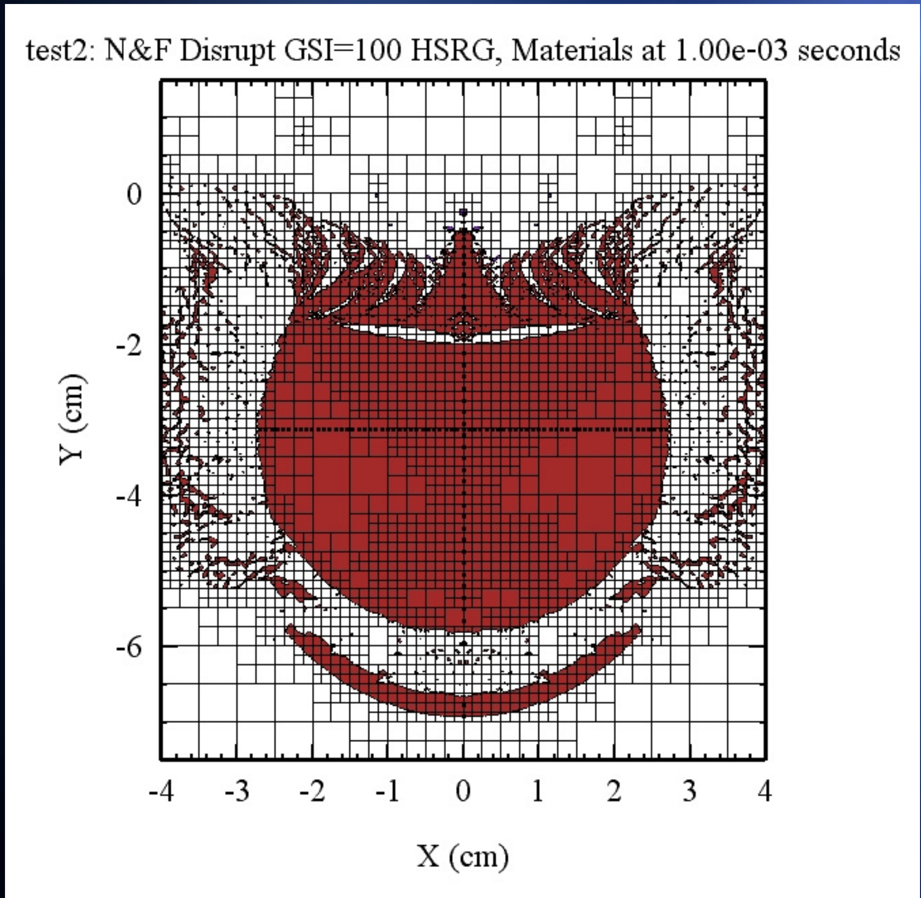
I (rad) vs a (UA)



So how can we improve the models?

- Compare, Compare, Compare
  - to real experiments
    - Large explosive field tests
    - Carefully controlled lab tests
  - to impact craters
    - (but what was the impactor?)
- Test, Test, Test
  - real materials
    - Crushability
    - Strength in different states

Experiments = first and crucial step for code validation



Example:

Simulation by an Hydrocode of the Impact experiment on basalt of Nakamura & Fujiwara in 1992

The core fragment is successfully reproduced

"Some" Current Shortcomings:

- Most strength models do not address all types of "strength"
- Codes often have "hidden features"
- Equations of state of some materials are still uncertain
- We do not often enough make comparisons to any experiments

Some more specific shortcomings

- We cannot model well enough to distinguish details for a particular crater
- *We cannot handle mixtures well*
- *Mixing rocks and atmospheres, and porosity makes for very difficult code calculations*
- *We don't do chemistry*

However, on the positive side

- In the gravity regime: we were able to reproduce qualitatively the main properties of asteroid families → reaccumulation processes may dominate and « accurate » modeling of fragmentation may not be so crucial (needs to be checked) for qualitative studies
- In the strength regime: the SPH hydrocode including a model of brittle failure has at least reproduced successfully some experiments on basalt targets
- Future challenge: characterizing the behavior of porous materials and differentiated objects, first in the strength regime (with confrontation to experiments) and then in the gravity regime (formation of C-type asteroid families, impact response of comets, KBOs …)

Arigato Gozai-Masu
Thank you for your attention
Merci beaucoup …