Theoretical Studies, selected topics

- Formation: coagulation vs. concentration
  - need for development of hybrid hydrodynamic codes that can fully capture the interaction of gas and particles in proto-planetary disks
- Impact physics
  - calibrated SPH/CTH impact codes with realistic materials and physics
  - determine fragmentation/accretion laws for a range of impact speeds, material properties, rotation, etc.
- Physical evolution
  - coupling between shapes of small asteroids and their rotational states
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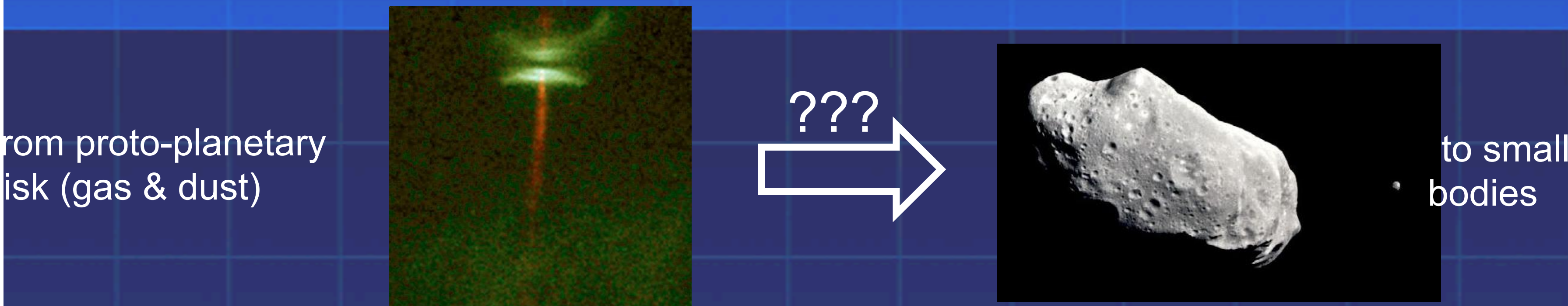
  - radiation torques on meteorite-sized bodies
  - meteorite delivery models including fragmentation and radiation effects
- Thermal modelling/interiors
  - branch the gray area between cometary (<100 km) and standard geodynamics codes (>1000 km)

Formation: coagulation vs. concentration

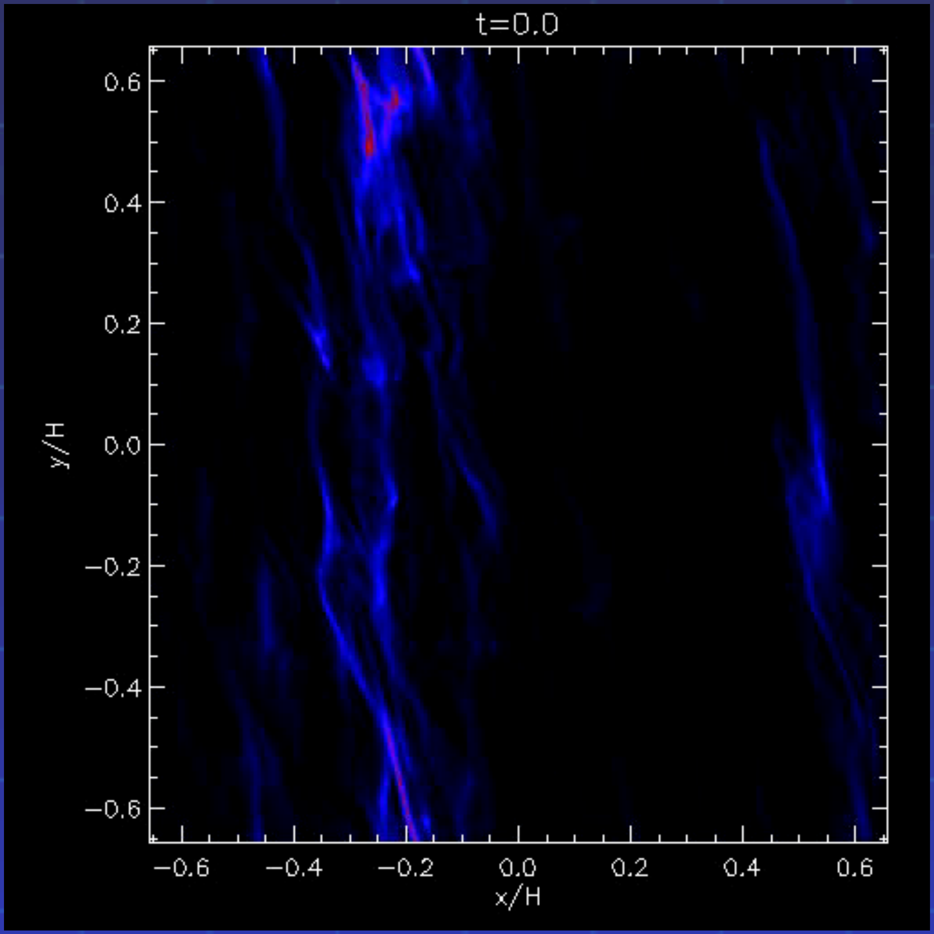


- Coagulation model postulates that planetesimals form by two-body collisions from smaller constituents of the disk (e.g., Kenyon & Luu)

- Possible problems: 1 meter barrier, size distribution of main belt asteroids (*Morbidelli et al. 2009*), inefficient in low-mass environment

Concentration/Gravitational Instability (GI)

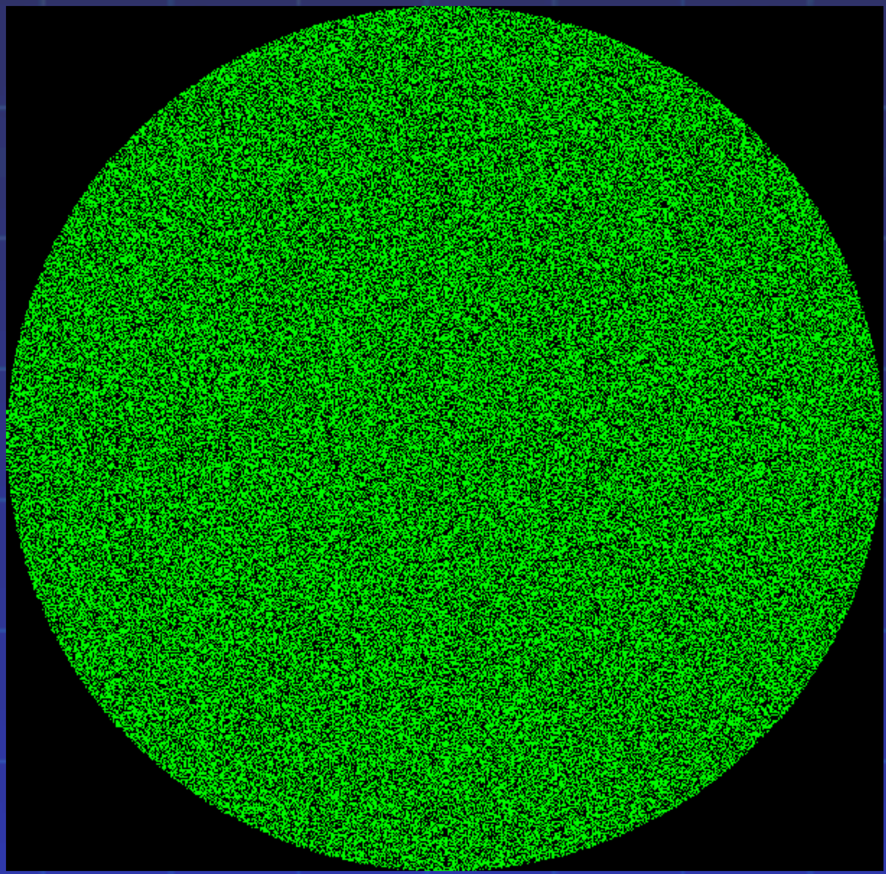
- Concentration/GI model invokes gas-particle interactions to concentrate solids, followed by local gravitational collapse
- Existing grid codes need to resolve global features of disk dynamics and do not have good resolution on the scale of individual clumps
- Gravitational *N*-body interaction between particles only very approximate (!)
- CPU expensive (unlike coagulation codes)



Johansen et al. (2007)

Concentration/Gravitational Instability (GI)

- Final phase of collapse treated by an efficient tree N-body code
- Simplified physics, e.g., no gas, initial conditions uncertain
- Can explain high fraction (>30%) of binaries in Kuiper belt
- Implications for the initial mass function of asteroids and Kuiper belt objects uncertain
- Implies fast formation, implications for thermal evolution due to short-lived radioisotopes



Nesvorny (2008)

Formation: coagulation vs. concentration

- Priority: Need for development of hybrid hydrodynamic codes that fully capture the interaction of gas and particles in proto-planetary disks
- Existing Pencil code solves magnetohydrodynamic equations on a three-dimensional grid, solid particles interact with gas by aerodynamic forces
- To include self-gravity, particle density is mapped on the grid and potential is found by Fourier transform - 1st code of this kind but lacks resolution on sub-grid scale
- This major theoretical issue needs to be resolved
- Future codes need to make predictions on the initial mass function of asteroids and Kuiper belt objects, binary fraction, etc.

Theoretical Studies

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Impact physics

Ida and Dactyl

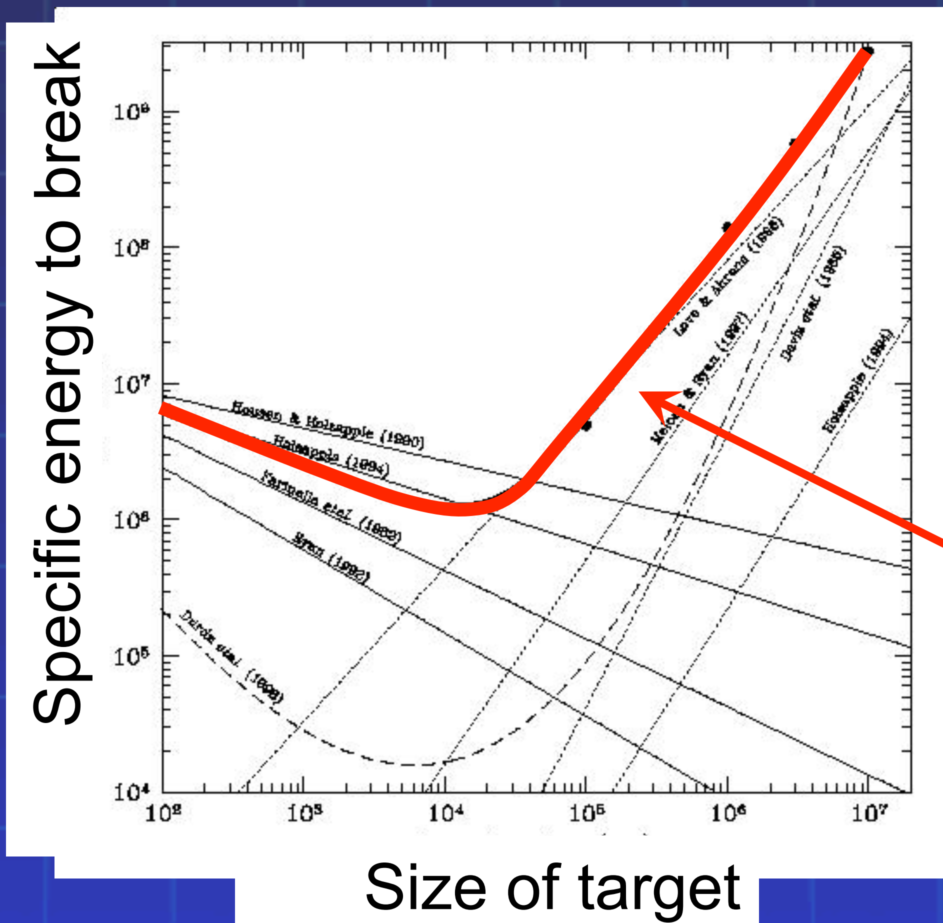
Asteroid P/2010 A2

Important for a number of reasons:

- formation conditions (impact speed, thermal evolution)
- collisional histories of different populations
- constraints on planet evolution (Late Heavy Bombardment)
- relation to the interplanetary dust complex

Impact physics

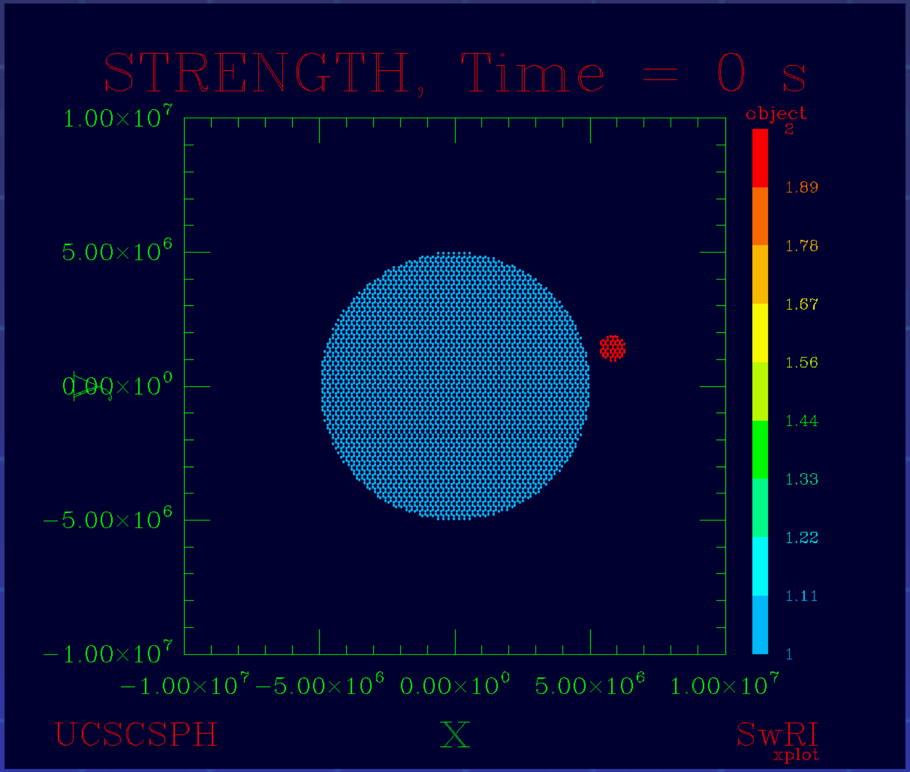
So far fragmentation/accretion laws developed for monolithic & non-rotating targets, and very few impact speeds



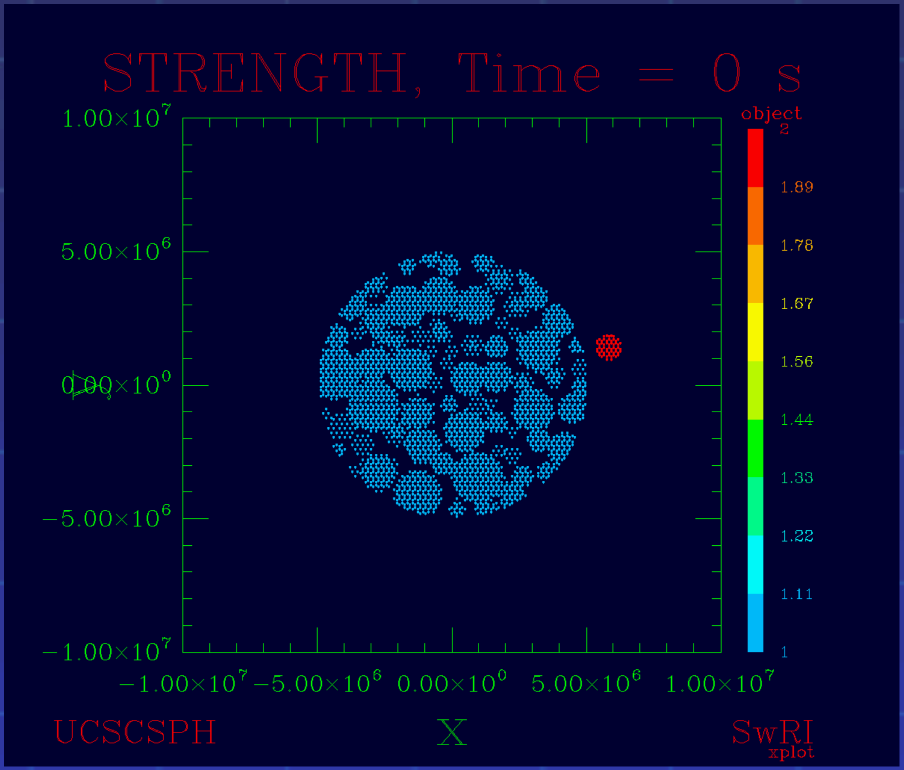
Benz & Asphaug (1999)
- basalt and pure ice
- 0.5, 3 and 5 km/s

Effects of macro-porosity

Monolithic target



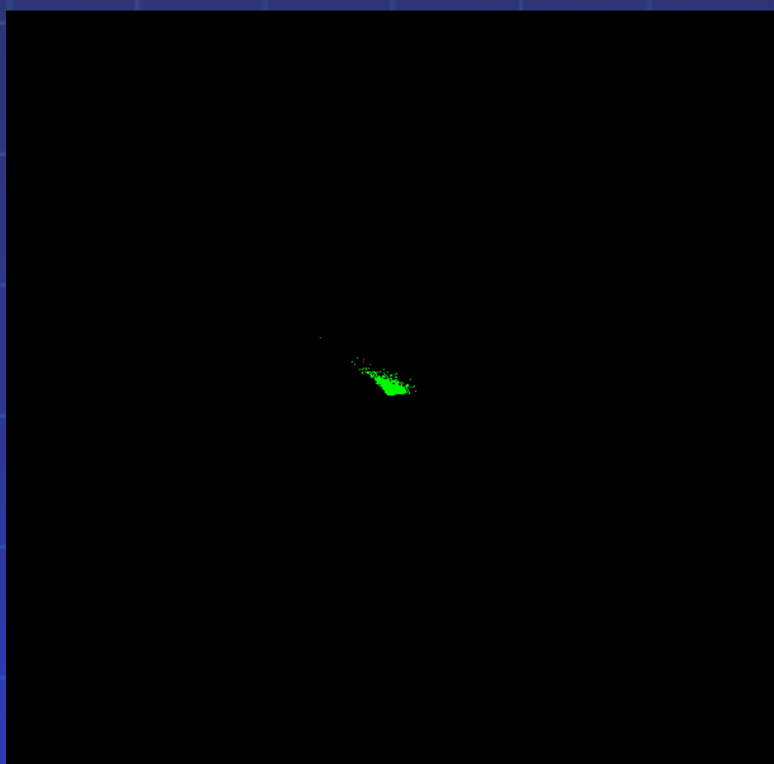
Porous target



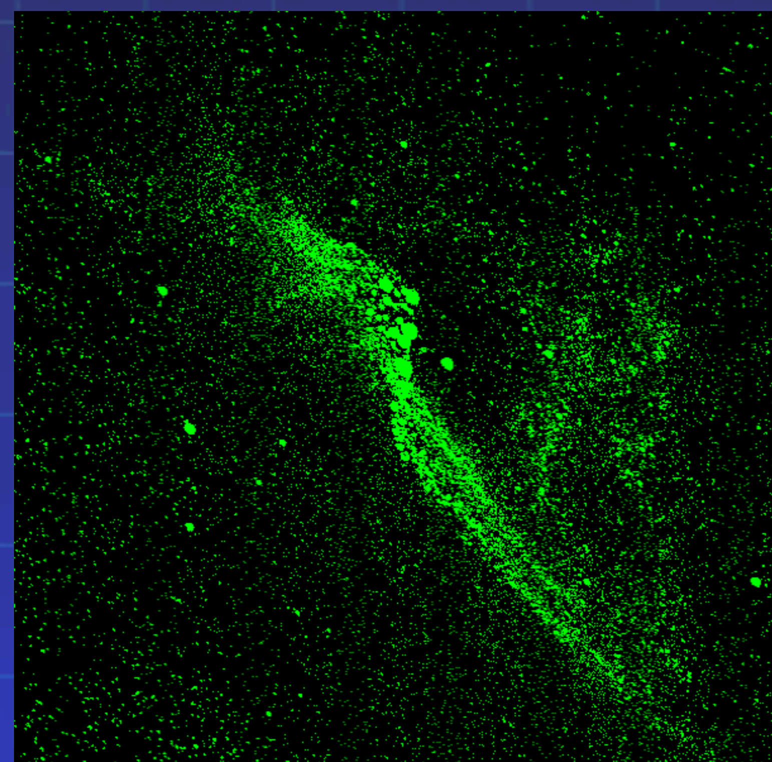
Transition to N-body solver

Used SPH codes do not treat gravity self-consistently,
k for the initial phases of impact but not later, need for hand-over

Far view



Close view



Impact Physics, priorities

- Self-consistent gravity
- Realistic macro- and/or micro-porosity
- Pre-impact rotation of target
- Real equations of state –no monoatomic or diatomic gas, vapor (no granit or basalt) – part experimental, part analytic
- Resolve convergence issues! Scalability and recalibration.

- Once codes are in place, use them to develop general scaling laws that can be used to understand accretion & fragmentation stages
- Predictions for size distribution, binarity & post-impact spins of fragments (compare to families)

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Dynamical & Physical Evolution

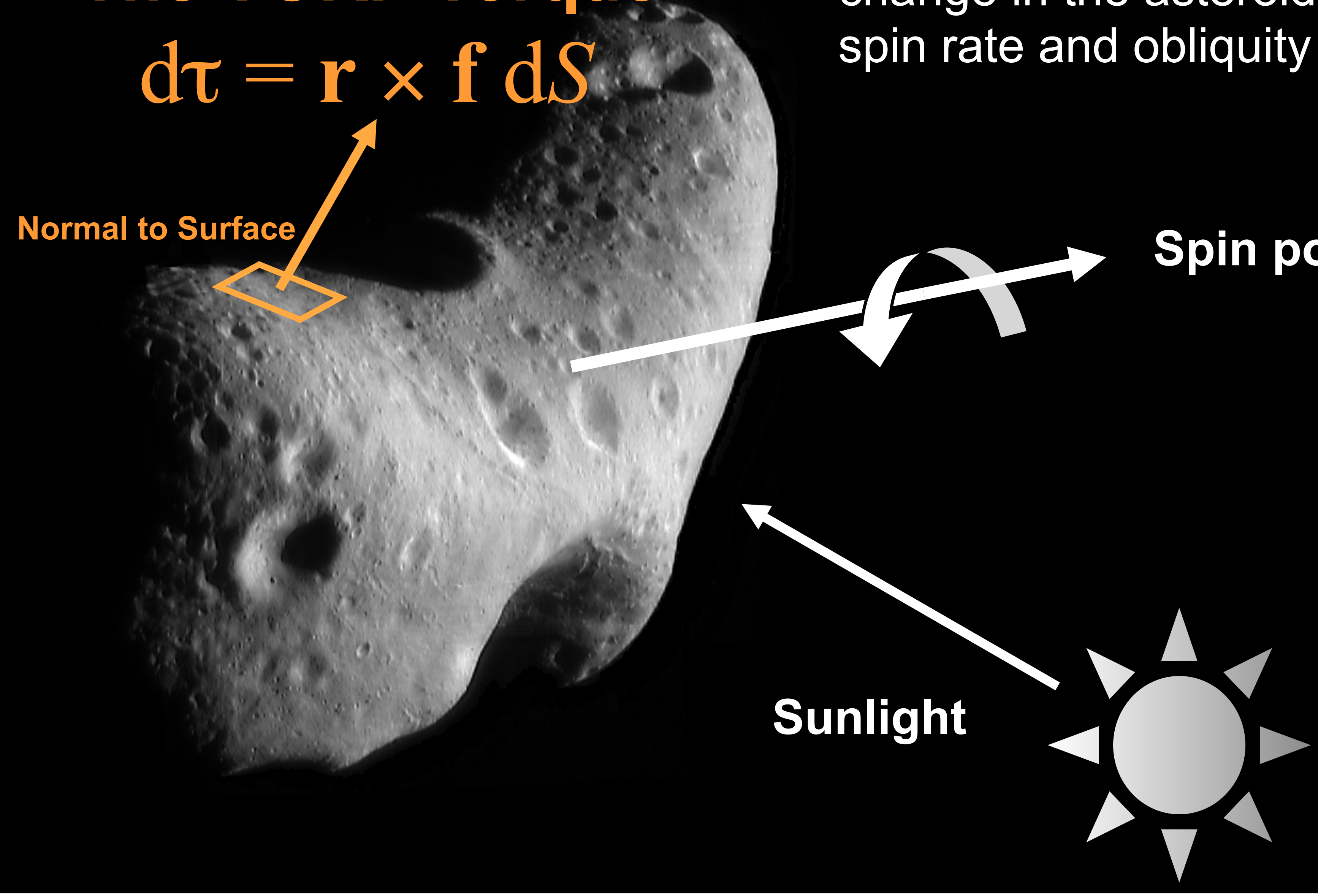
Asteroid binary (66391) 1999 KW4

New observations show that the top-like shape and binarity should be common among small asteroids

The YORP Torque

$$d\tau = \mathbf{r} \times \mathbf{f}\, dS$$

- Absorbed and reemitted sunlight produces a change in the asteroid's spin rate and obliquity



Dynamical & Physical Evolution

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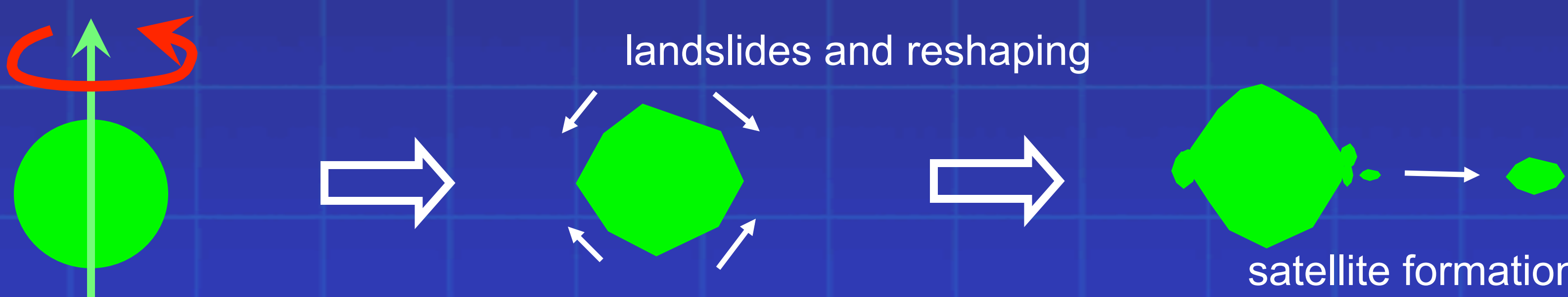
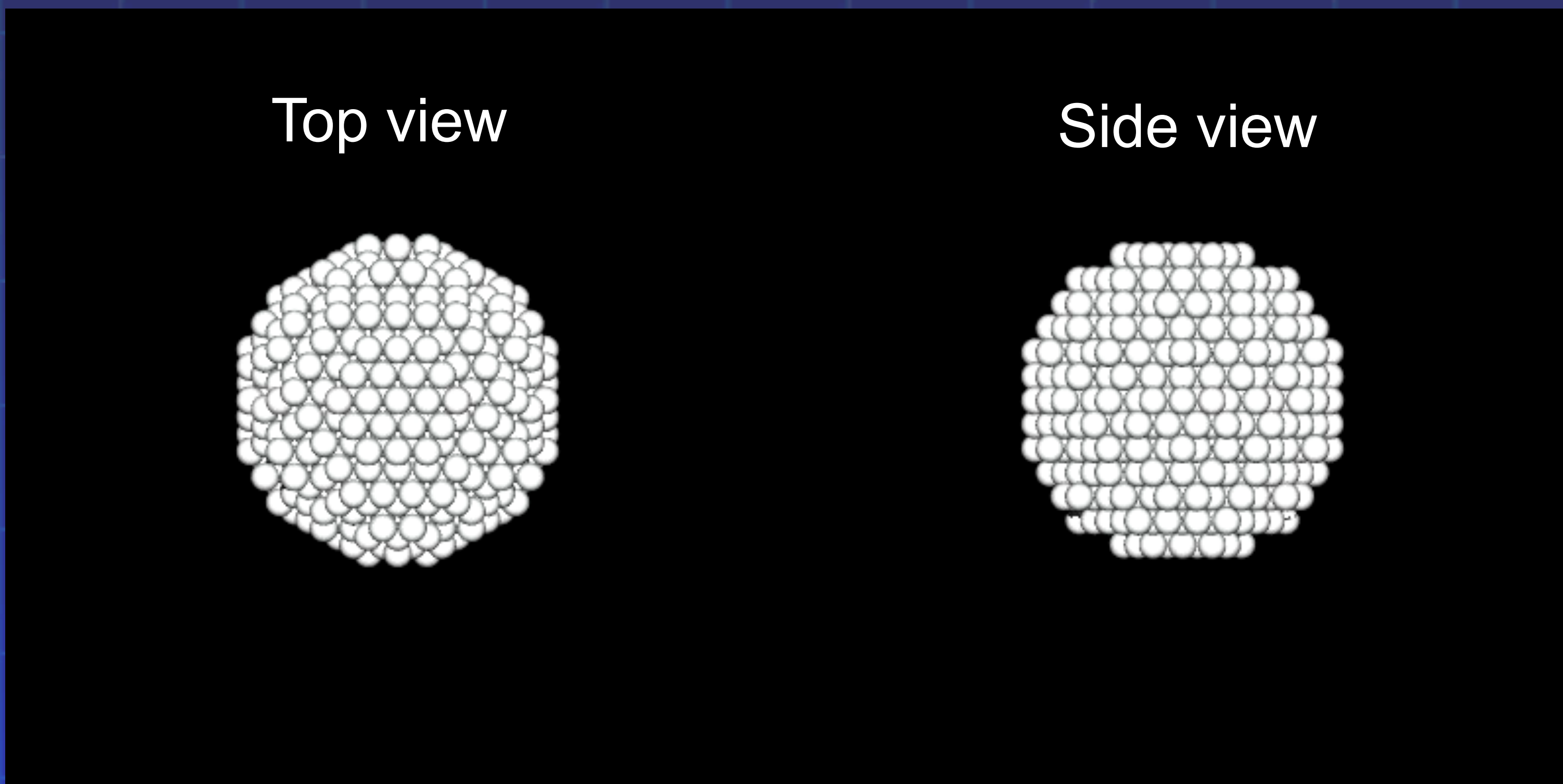


Dynamical & Physical Evolution

Spin-up by radiation forces leads to reshaping of a small asteroid and satellite formation



Walsh et al. (2009)

Dynamical & Physical Evolution

- Priority: develop finite-element/particle codes that are capable of following shape changes of objects that undergo spin-up by YORP
- Since YORP is sensitive to small scale surface features, determine feedback of shape changes on the magnitude of the YORP torque (asteroid Itokawa)
- Apply these future codes to satellite formation (two theories: gradual mass shedding and accretion of satellite in orbit, fission of a monolithic fragment)
- Determine radiation torques on meteorite-sized bodies. Finite element code for thermal conduction. (Problem: existing calculations indicate that rotation speed should increase beyond limits)
- Meteorite delivery models including fragmentation and radiation effects (existing models still suffer from many limitations)

Theoretical Studies

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Thermal Modeling

- Two kinds of computer codes co-exist in the community:

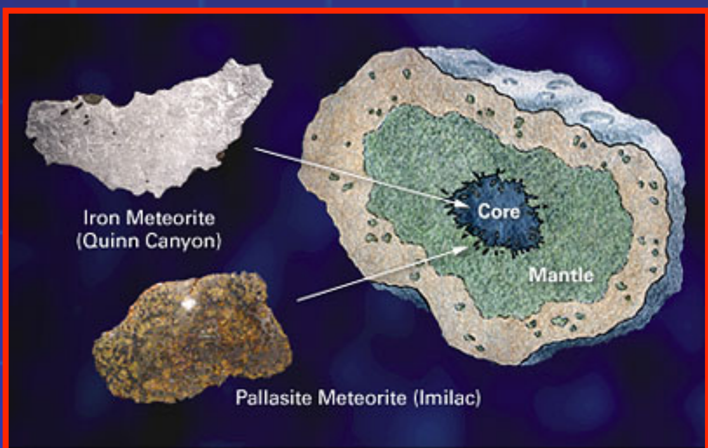
  1) ‘cometary’ code appropriate for <100 km objects, deals with issues such as hydrothermal alteration, degassing, etc. *(Prialnik et al.)*

  2) standard geodynamic codes appropriate for >1000 km objects, issues related to differentiation, cryovolcanism, etc.

- The gray zone at ~100-1000 km, many small bodies fall into this category, appropriate codes do not exist
- Relevant to KBOs (from density to composition, relative role of rock and hydrocarbons), Ceres and other large asteroids
- Funding problems for developing appropriate codes may exist

Thermal Modeling

Example of physical processes studied by 'cometary' codes (hydrothermal circulation, aqueous alteration, etc.)



Grimm & McSween (1989)

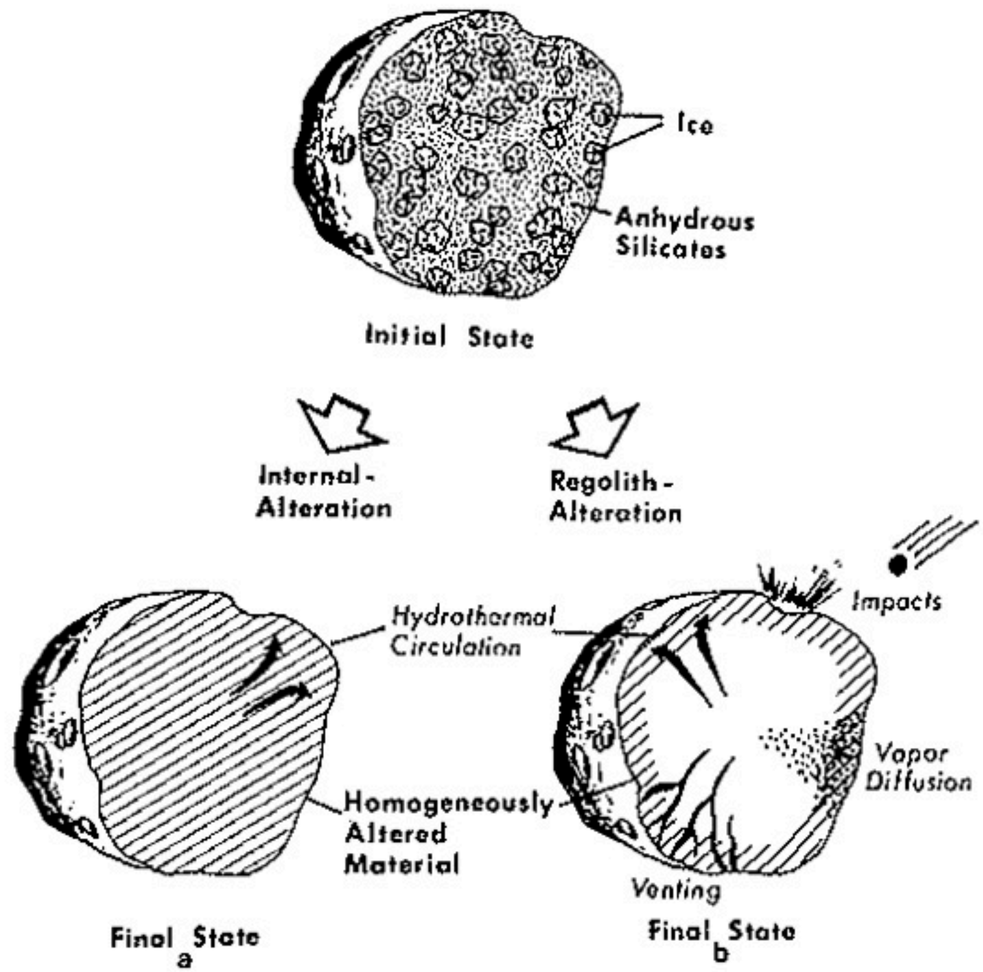
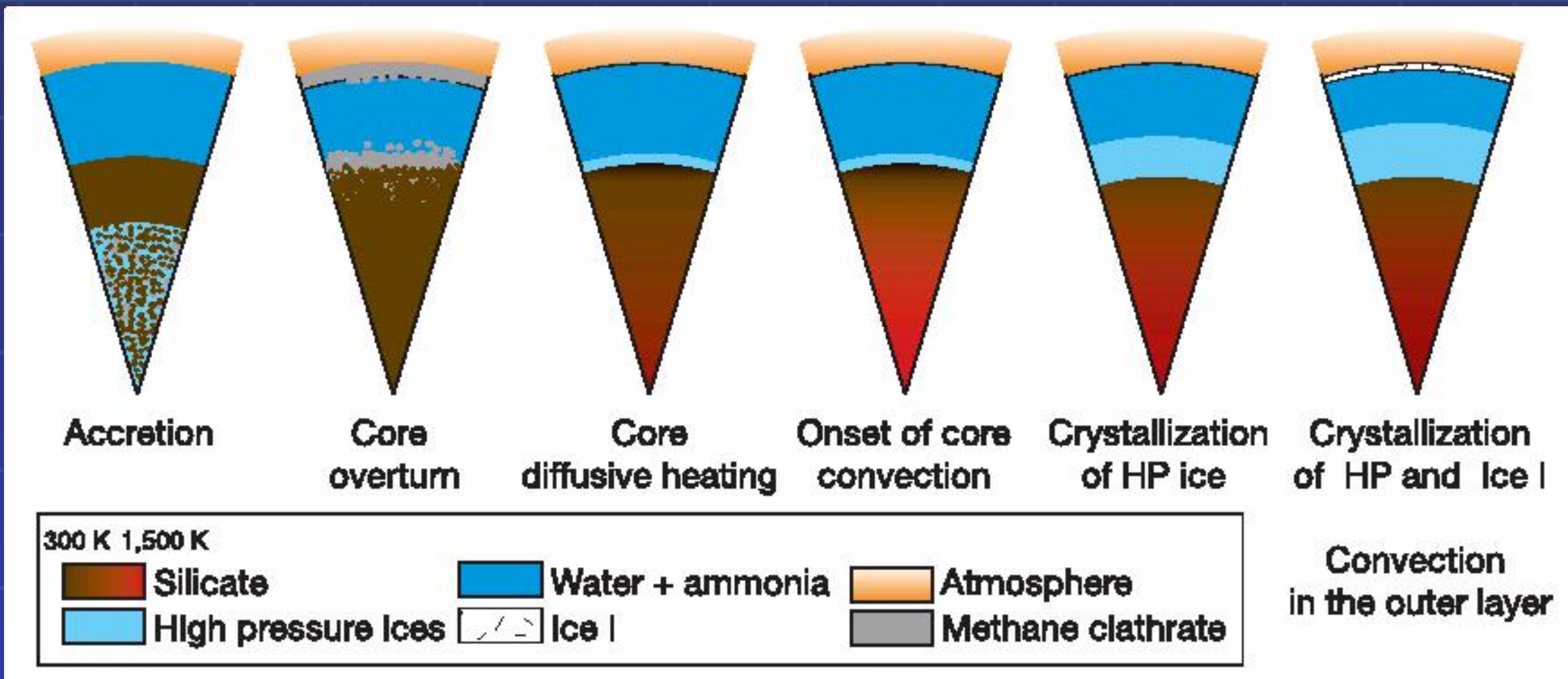


FIG. 1. Schematic illustration of the alternative models tested in this paper for aqueous alteration of

Thermal Modeling

Example of physical processes studied by a standard geodynamic code (core formation, convection, etc.)



Tobie et al. (2006)

Summary

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