Melt production models for planetary impacts

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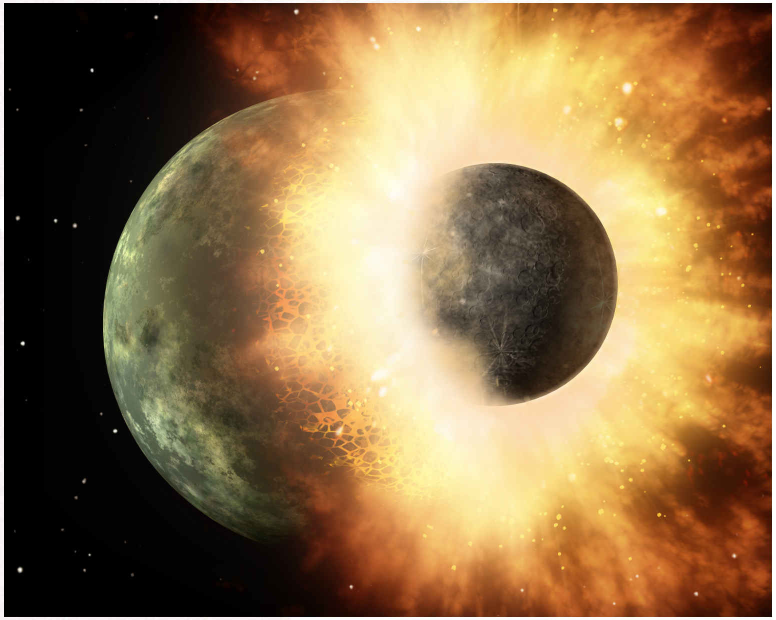
Overview

- Why model melt production?
  - Equillibration conditions (P,T)
- How is it done?
  - From scaling laws to the depth of melting
- Impact angle
  - Critical angle and other problems
- Initial target temperature
  - Depth dependent (liquidus) temperature
- Conclusions & outlook

Why?

- Giant impact
  - Lots of energy
  - Melting/evaporation



- Composition
  - Changes due to equillibration, differentiation and element partitioning
- Equillibration / differentiation / element partitioning
  - Depend strongly on pressure and temperature conditions

How?

- 3D?
  - Time consuming
  - Only small, near vertical impacts due to limited domain size. Otherwise, low resolution
- 2D?
  - Only for vertical impact due to lack of symmetry in non-vertical impacts
- Parametrised models
  - Approximation, but only feasible option for several hundreds of impacts during solar system formation

Theory *(Abramov et al., 2012)*

$$\pi_v = \frac{\rho_t V_{tc}}{\rho_p V_p} \qquad \pi_2 = \frac{3.22 g r_p}{v_i^2}$$

$$\pi_r = R_{tc}\left(\frac{\rho_t}{\rho_p V_p}\right)^{1/3}$$

$$\pi_v = C_v \pi_2^{-\gamma}$$

$$\pi_r = C_r \pi_2^{-\beta}$$

- Scaling laws
  - Pi-scaling
  - Empirical relation from impact/explosion experiments
- Crater volume dependent on impact angle
  - $V_{tc} \sim v_i^{1.3} \sin^{1.3} \theta_i$ (only vertical velocity component)
- Crater radius independent of impact angle (except for very high impact energies)
  - Crater elliptical only for very small impact angles

Theory

- Crater radius and volume as function of projectile size (mass, radius)
  - To determine fraction of melt remaining
- *Pressure / energy* available during impact determines amount of melting
- Certain pressure needed to cause melting upon pressure release after initial shock → Hugoniot equations
  - Conservation of mass, momentum and energy across the shock

Theory

- Isobaric core → constant pressure
  - Pressure decrease quadratically with distance from isobaric core

- Energy available to melt target rock
  - Depends on projectile mass and velocity

Bjorkman & Holsapple, 1987:

$$M_{melt} = k m_p \left(\frac{v_i^2}{E_m} \right)^{3\mu/2}$$

- μ determines whether melt mass scales with energy (μ=2/3), momentum (μ=1/3)
  - Most likely value in between

Theory

- Energy scaling (O'Keefe & Ahrens, 1977)
  - $V_{melt} \sim v^2$ (proportional to kinetic energy)
- μ=0.56 (Abramov et al., 2012)
  - From experiments and later models
  - $V_{melt} \sim v^{1.7}$
- Melt volume/crater volume same dependence on impact angle (3D study)
  - Melt volume ~ $v_i^{1.7} \sin^{1.3} \theta_i$
  - Projectile diameter, densities, melt energy

Depth of melting

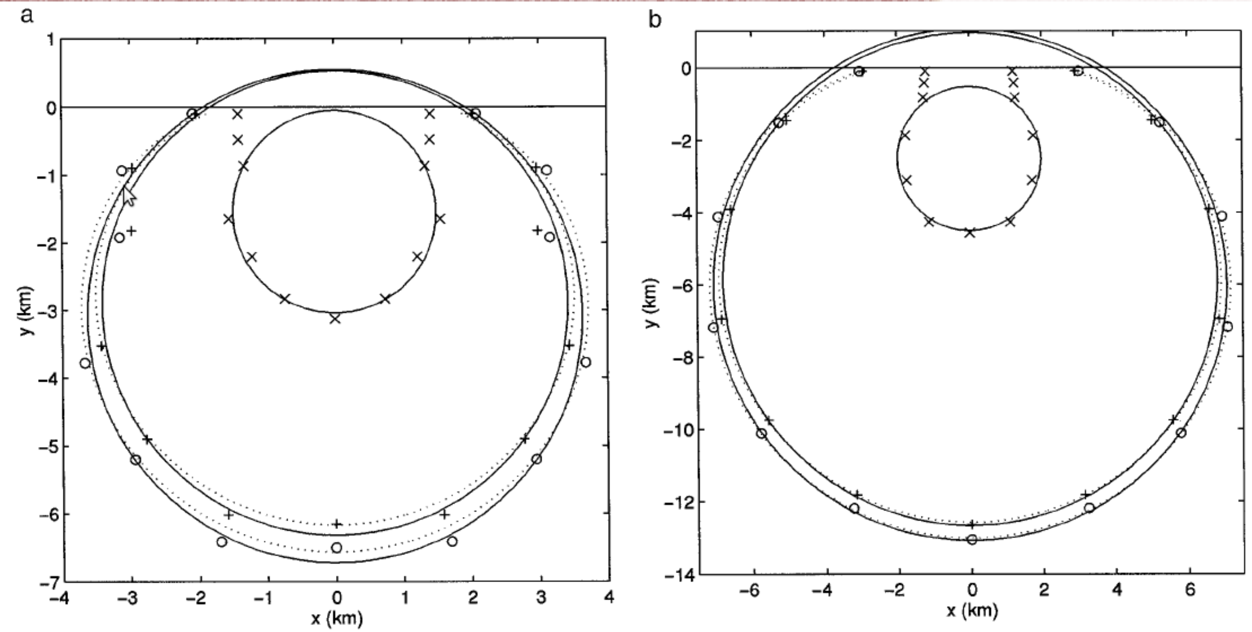
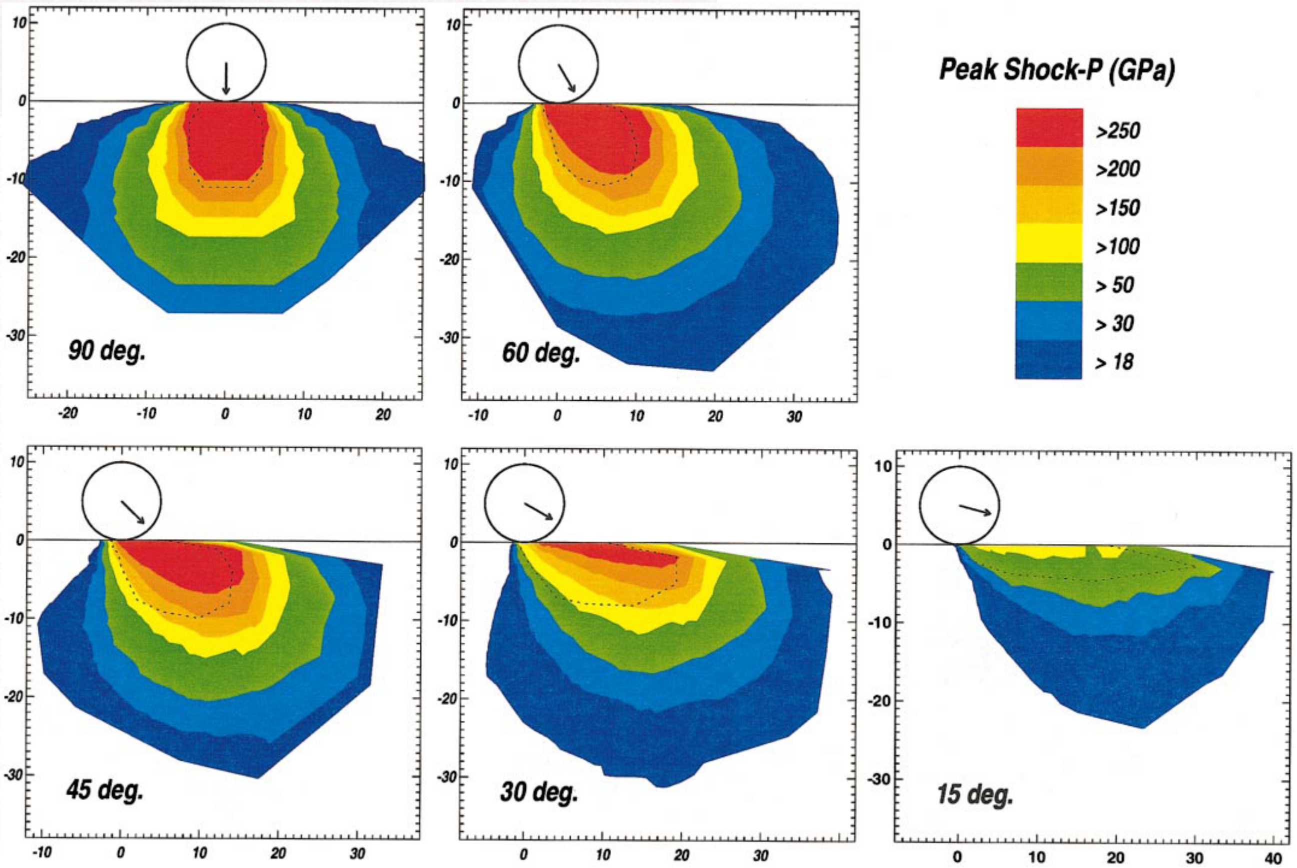


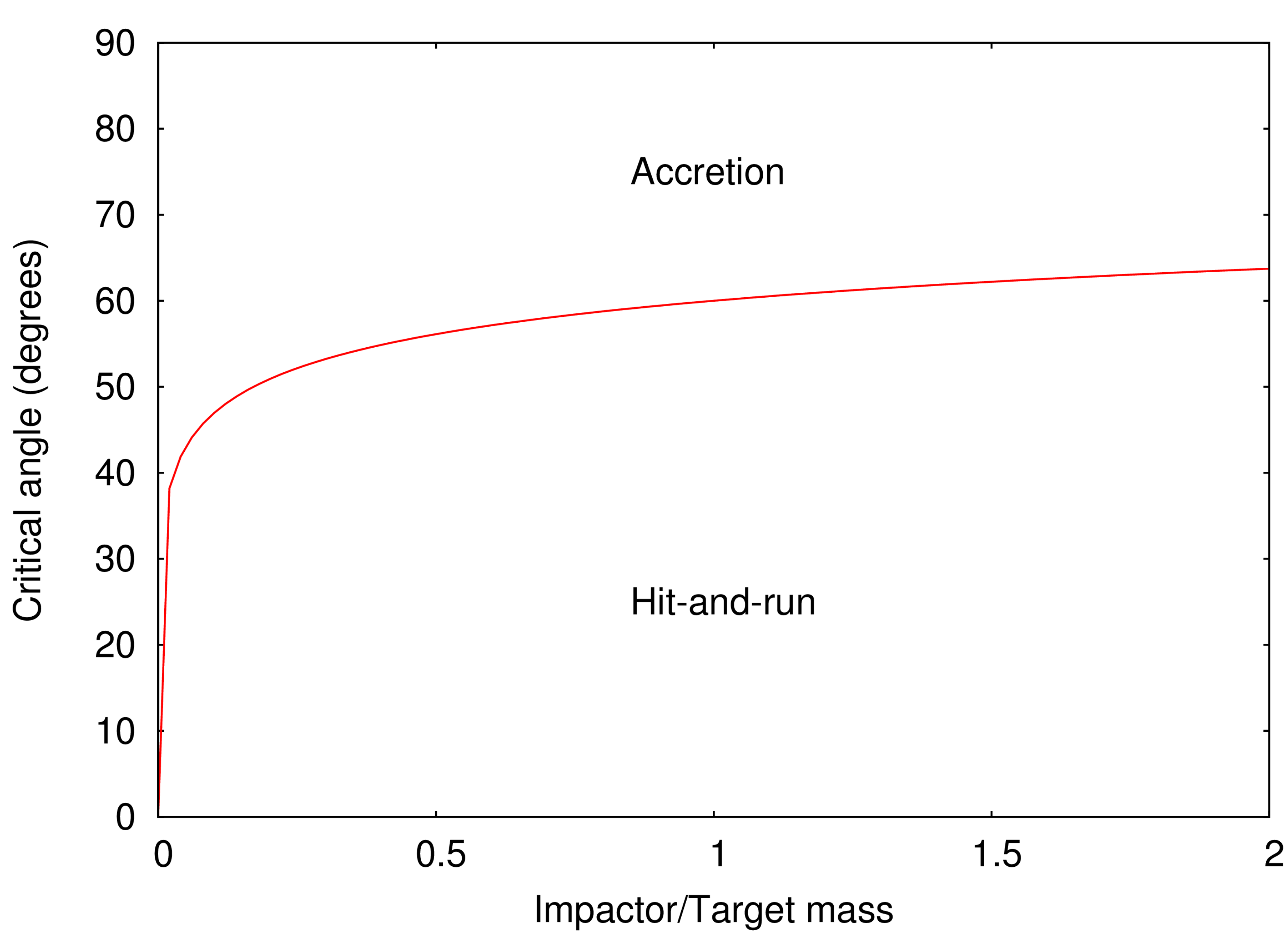
FIG. 7. Melting regions and isobaric core for (a) U = 20 km/sec and (b) U = 50 km/sec. Continuous lines: best fit of the data with a circle; dotted lines: best fit of incipient and complete melting data with a limacon of Pascal. ○, incipient melting; +, complete melting; ×, isobaric core data.

Pierazzo et al., Icarus, 1997

Pierazzo & Melosh, Icarus, 2000

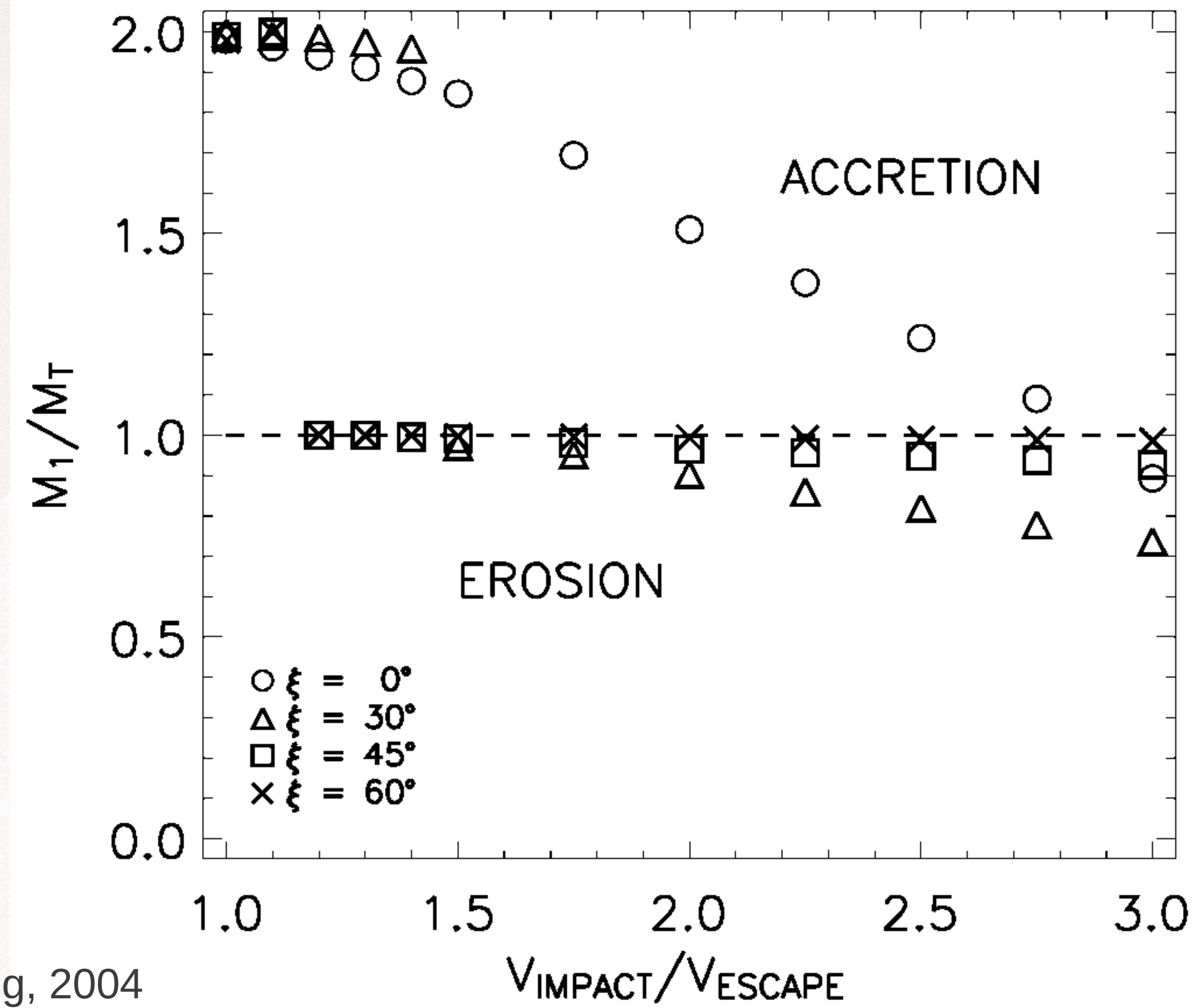


Critical angle



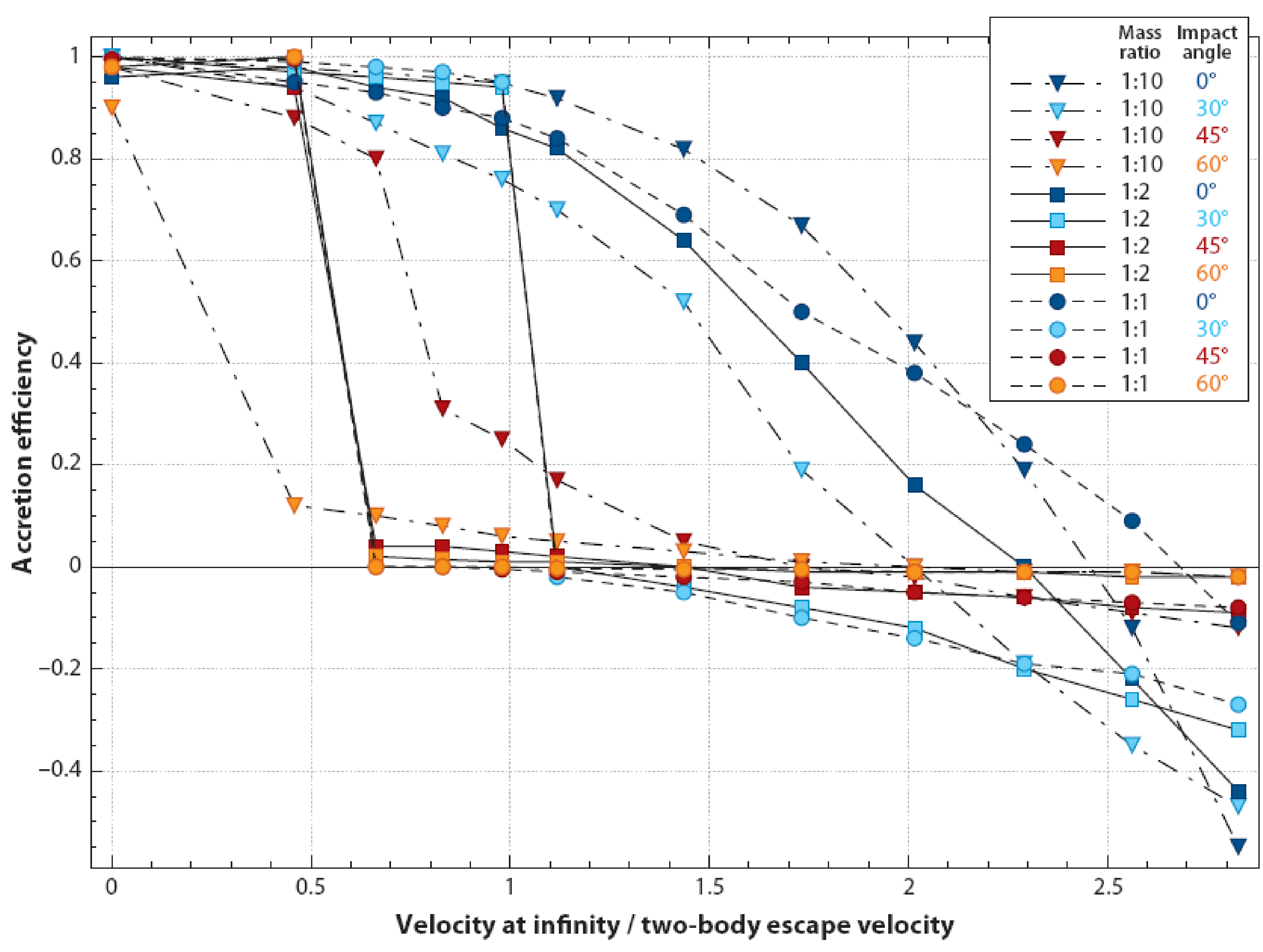
Hit-and-run collisions

- Hit-and-run collisions ($M_{imp} \sim M_t$)



Agnor & Asphaug, 2004

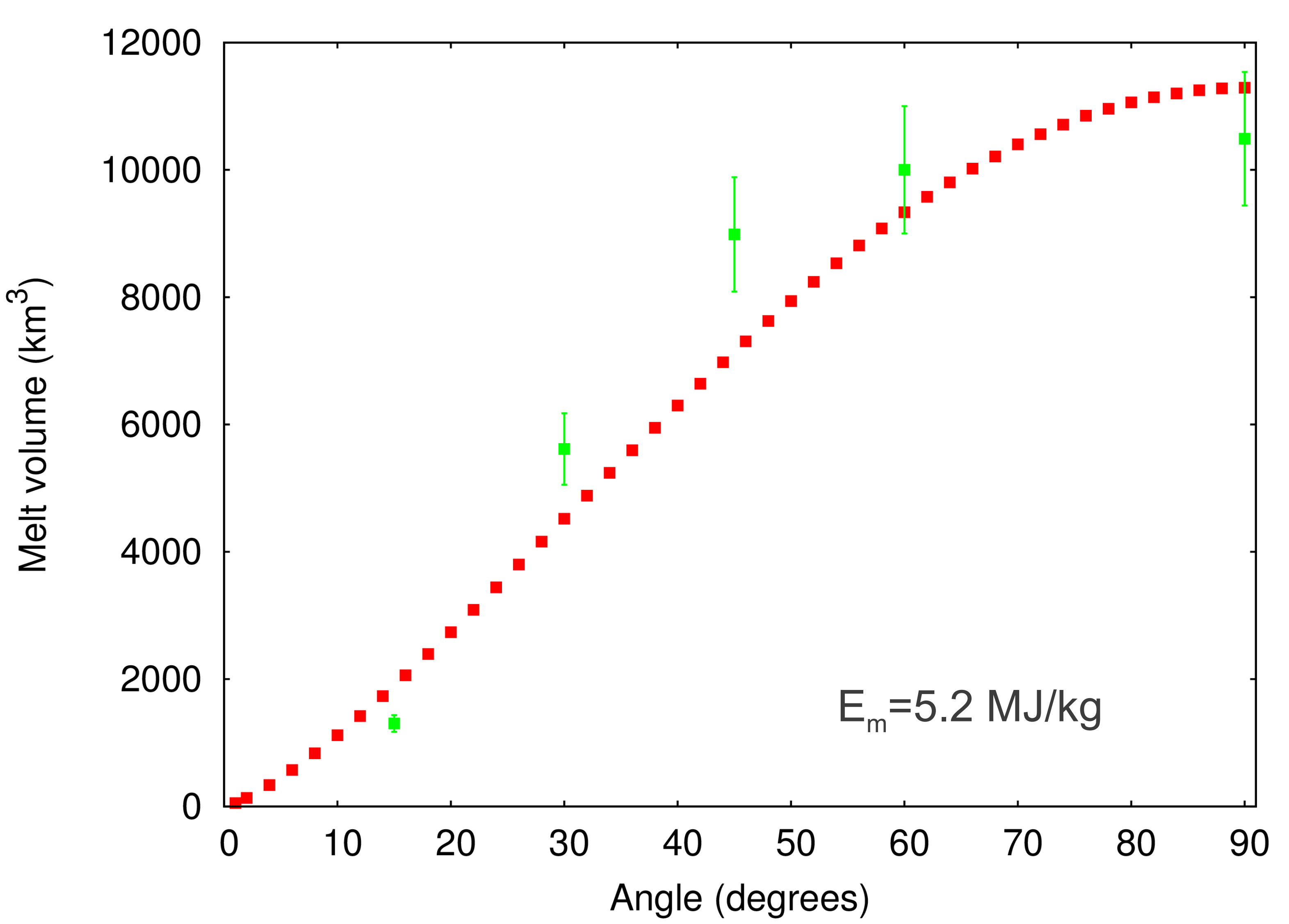
Hit-and-run collision



Asphaug, 2009

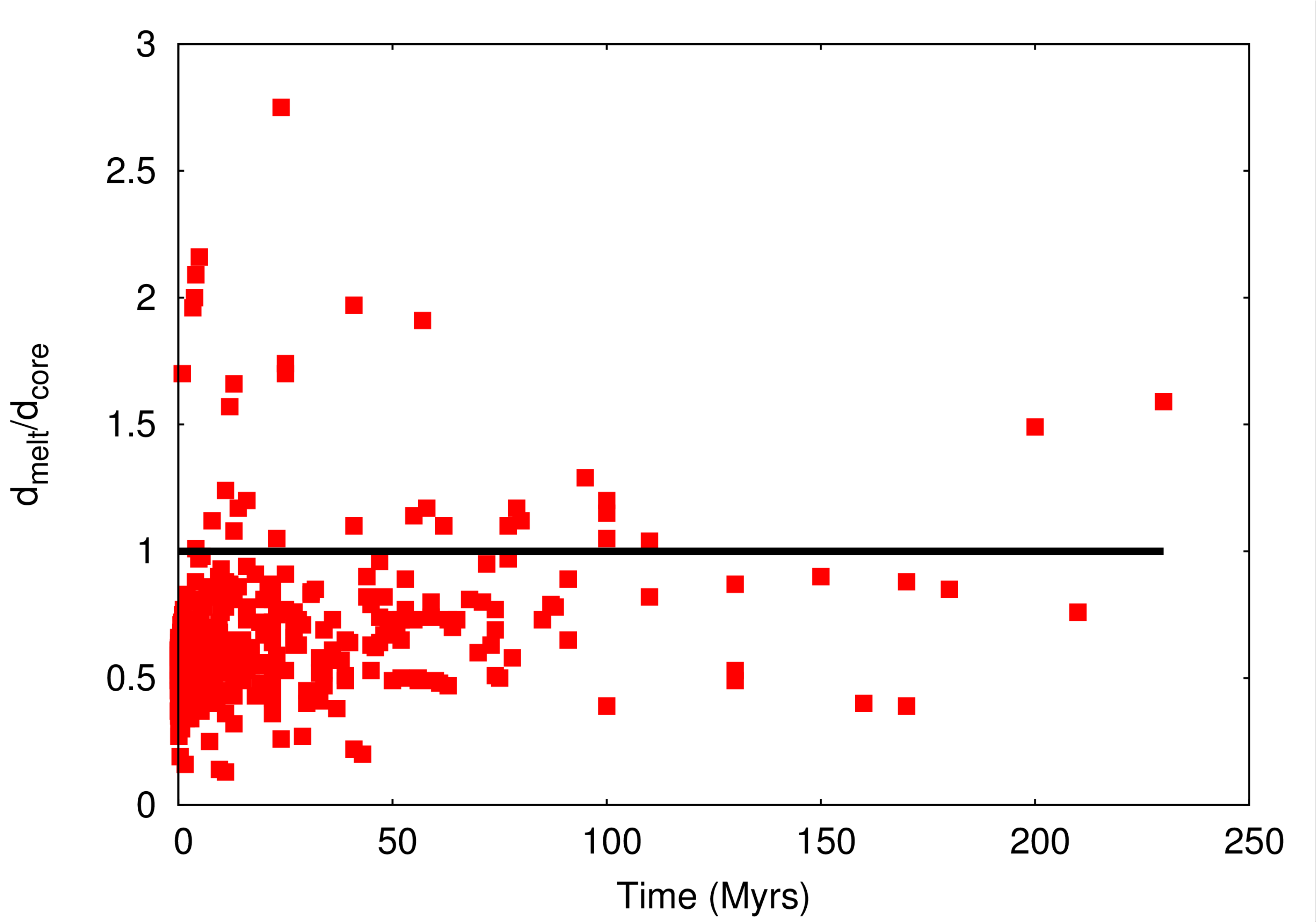
Comparison 3D (Pierazzo & Melosh, 2000)

- Granite, P_m=50 GPa, v_i=20 km/s, r_p=5 km



Melting depth

- Melting depth as function of core depth



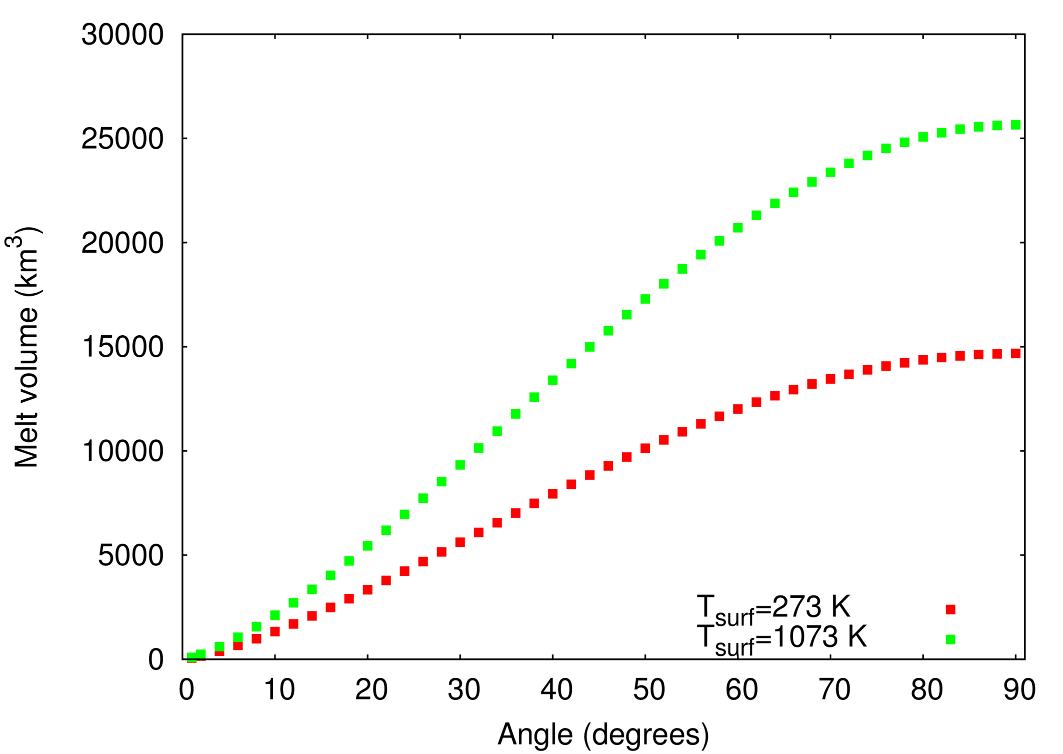
Temperature

- Temperature of target influences amount of melting due to impact
  - Temperature increase with depth
  - Liquidus temperature increase with depth

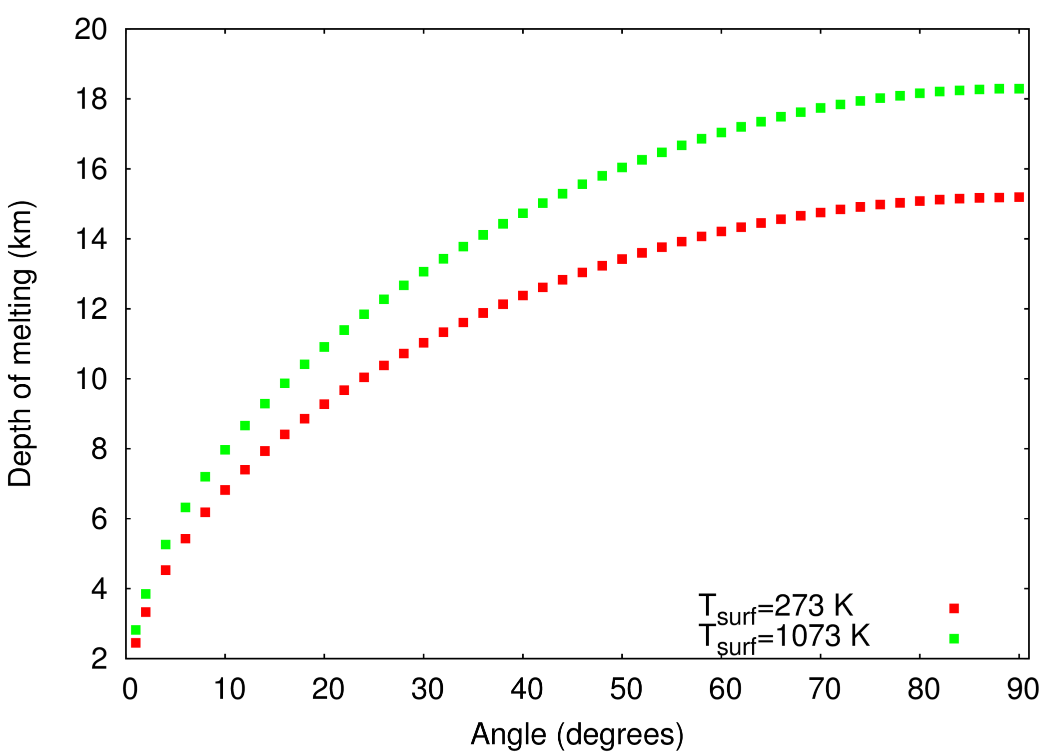
$$E_m\left(1 - \frac{C_p(T_s + \frac{dT}{dz} d_m)}{C_p \frac{dT_L}{dz} d_m + L_m}\right)$$

- Calculation of melting depth too complicated for analytical solution
  - Solved numerically → gives opportunity to add a core to the target (not implemented yet)

Temperature increase



T_{liq} = 1500 K



Conclusions

- Our calculations fit well with 3D data
- From first estimates, most impacts melt up to 0.3-0.9 times the CMB depth
- The initial temperature of the planetesimal may significantly change these results
- Core melting requires a large amount of energy → will likely only happen in some of the large impacts

Future work

- Study influence of different parameters (μ, k, dT_m/dz, dT/dz, L_m, c_p, ...)
- Include core melting via change in liquidus temperature and other material parameters → more consistent with differentiated planetesimals
- Hit-and-run collisions → potential melting but no accretion
- Experiments: Melting parameters where not available yet