PDF version of talk presented at the Lunar Volatiles Workshop Without Walls, May 2013.

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Collisional Processes and Parameters Influencing the Delivery of Volatiles to Lunar Cold Traps after a Comet Impact

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Background

- Spectral/radar signatures detected by several missions- from Clementine (1994) and Lunar Prospector (1998) to LCROSS (2010) and others- suggest presence of water in permanently shadowed regions (cold traps) near the lunar poles.
- Origins of lunar water?
  - Primordial water in the lunar interior.
  - Interaction of surface minerals with solar wind protons.
  - Volatile-rich comet/meteorite impacts.
- Our focus: comets as a source for cold-trapped water.
  - ~10^{17} kg of material delivered through comet impacts over 4 b.y. [1]
  - Analytical[2]/numerical[3] models predict a significant fraction remains gravitationally bound; could migrate to cold traps.
  - Given a site indicative of a comet impact, what can we say about the associated volatile fallout? How much water could comets have contributed to the lunar volatile inventory?

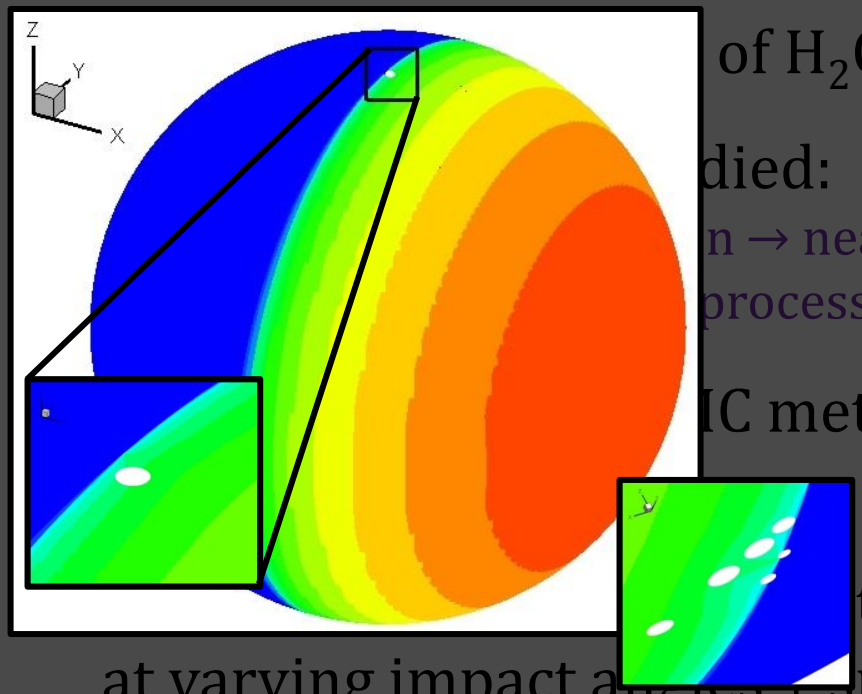
[1]Morgan and Shemansky, 1994; [2]Moses *et al.*, 1999; [3]Ong *et al.*, 2010 and Stewart *et al.*, 2011.

Approach & Method

- Post-impact transport of H_2O: global in scale + takes months.
- Prior models have studied:
  - Initial volatile retention → near-field, short-term simulations[1].
  - Global transport/loss processes → ballistic (collisonless) hopping[2].
- Our hybrid SOVA/DSMC method can handle both limits + the intermediate stage.
- Simulations consider impact of comet (pure H_2O ice; r = 1 km) at varying impact angles + speeds.
- Problem-specific features of the DSMC code:
  - Diurnally varying surface temperature[2].
  - 7 cold traps[3]: 1 North Pole (1257 km^2) + 6 South Pole (4575 km^2).
  - Temperature-dependent residence times[4] for H_2O on H_2O ice matrix[5].
  - Photo-destruction probability[6].

[1]Ong *et al.*, 2010; [2]Butler, 1997; [3]Elphic *et al.*, 2007 and Noda *et al.*, 2008; [4]Langmuir, 1916 and Frenkel, 1924; [5]Sandford and Allamandola, 1993; [6]Huebner, 1992.

Approach & Method



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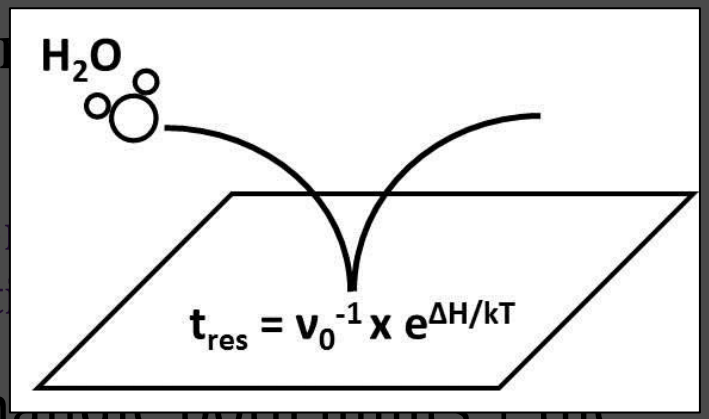

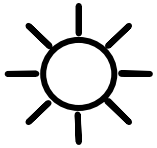

$$P_{ionize} = e^{-\Delta t/2.45\times10^6}$$
$$P_{dissociate} = e^{-\Delta t/8.3\times10^4}$$

- Problem-specific features of the DSMC code:
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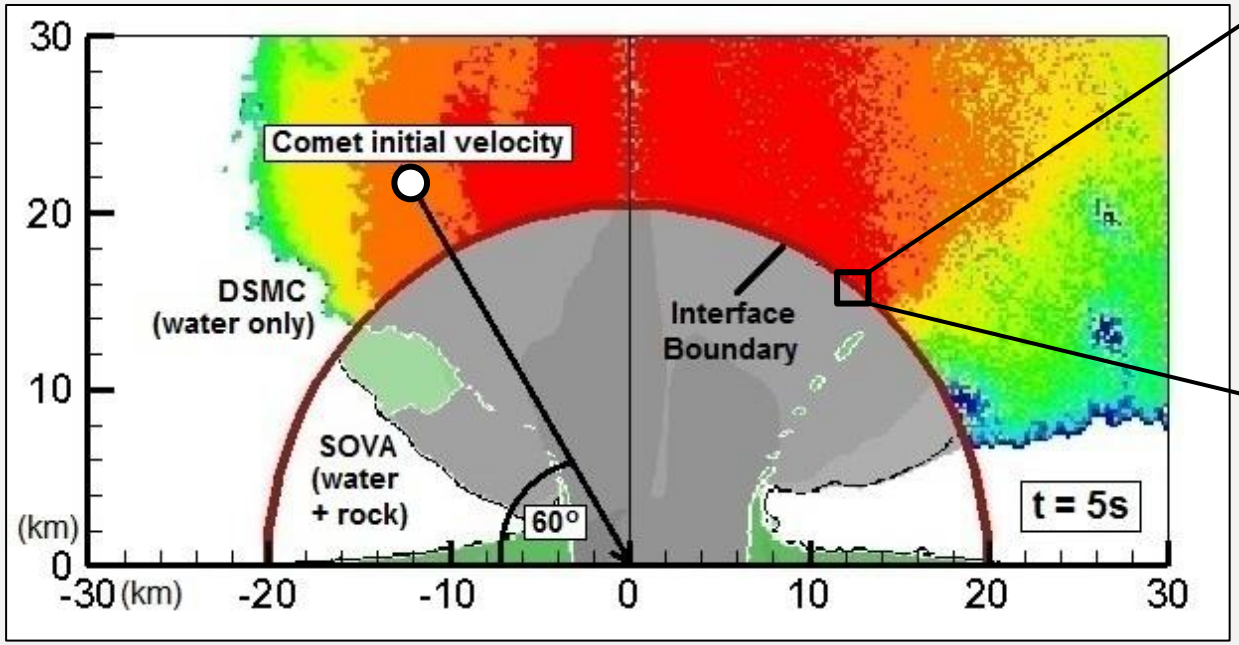
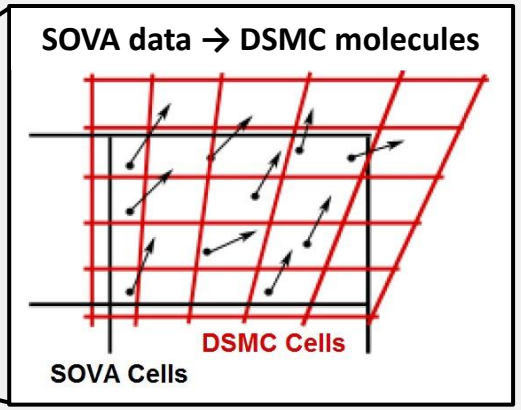
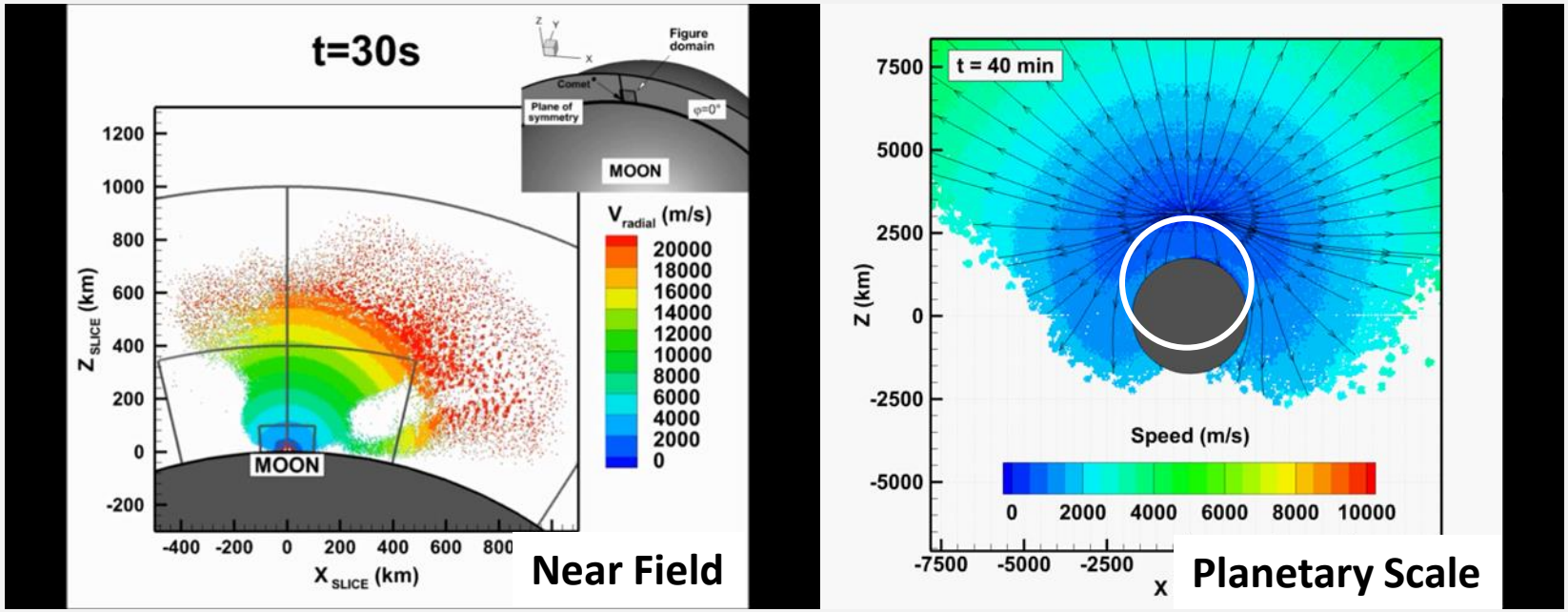




Supersonic speeds ∴ only SOVA → DSMC coupling, none vice versa.

- **SOVA** hydrocode: Simulates impact and hydrodynamic flow of relatively dense vaporized/molten comet and target material.
- **DSMC** (Direct Simulation Monte Carlo):
  - Simulates water vapor only. Particle based method- create, move, index, collide and sample 'molecules' (Bird, 1994).
  - Transition to rarefied but collisional expansion into vacuum.
  - DSMC is highly parallelizable.

Initial Expansion Flow

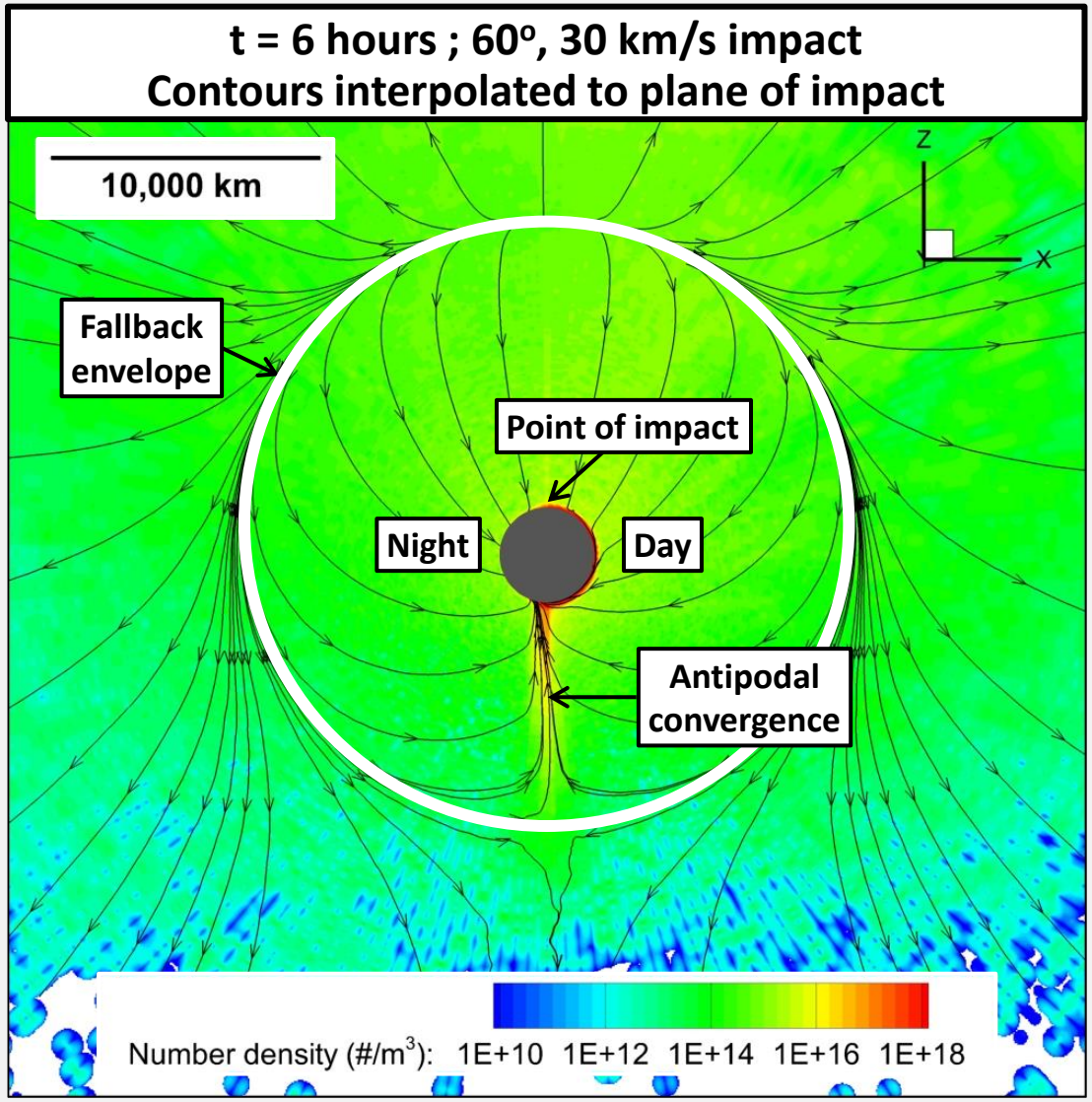


60°, 30 km/s impact. Contours interpolated to plane of impact.

- Rapid initial expansion at speeds ≥ v_{escape} (2380 m/s at surface).
- At later times, material traveling at < v_{escape} begins to fall back.
- Later simulations neglect escaping vapor.
- Due to scale of problem, our simulations are under-resolved, but our DSMC implementation[1] should achieve reasonable accuracy.

[1]Stewart *et al.*, 2009. 'Parallel 3D Hybrid Continuum/DSMC Method for Unsteady Expansions into a Vacuum' (AIAA Aerospace Sciences Meeting).

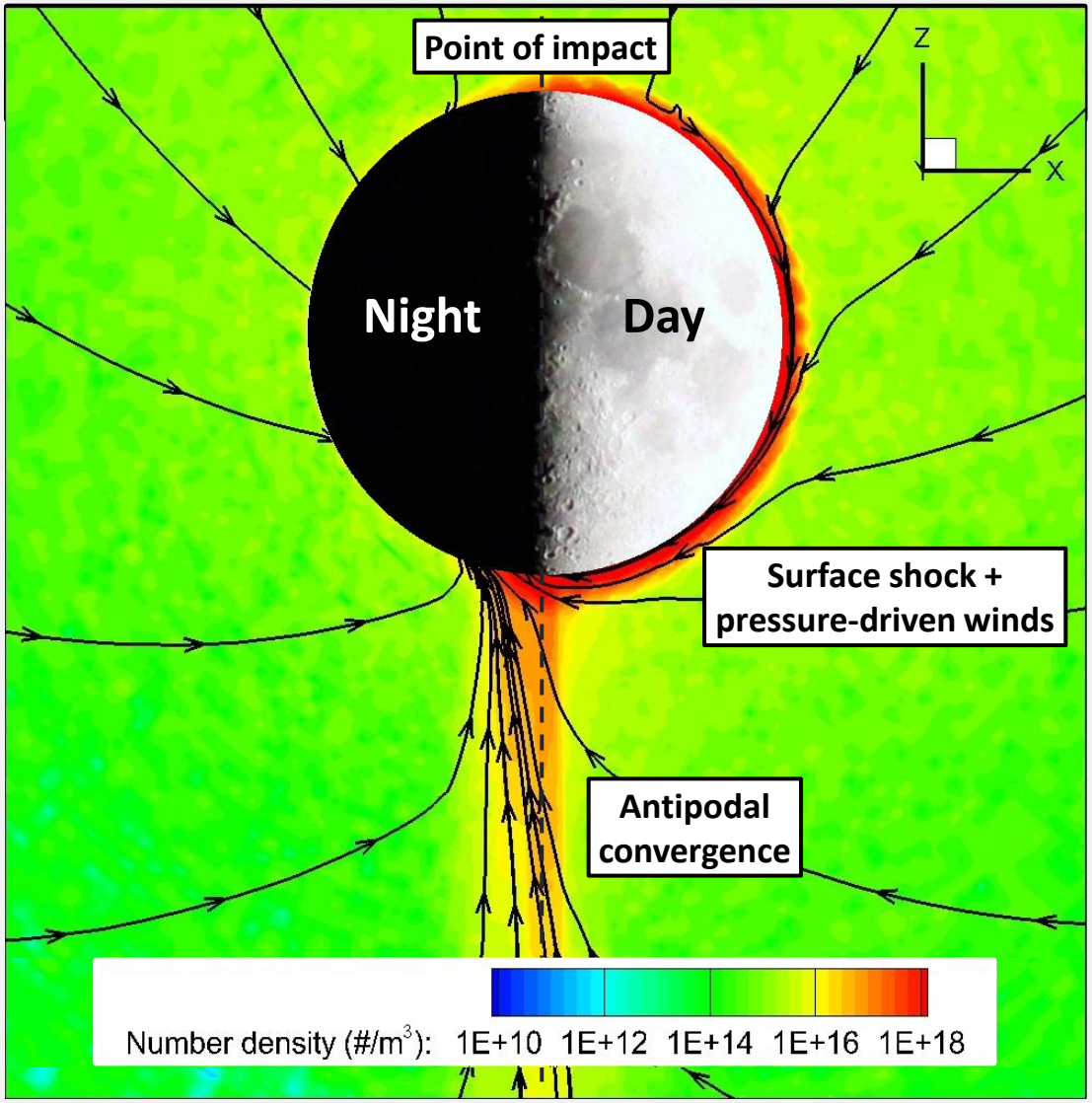
Transient Atmosphere



Computational cells: 1° lat. x 2° long. x 2.5 km at surface (increasing exponentially to 100 km).

- Collisional but cold vapor at altitude falls back along nearly ballistic trajectories. Slower outflow at later times → growing spherical fallback envelope.
- Convergence of streamlines at antipode.
- Vapor pressure over day side → surface shock.
- Vapor transport through day-side winds, driven by North-South + day-night pressure gradients. Reach South Pole within 1-3 hours.

Transient Atmosphere



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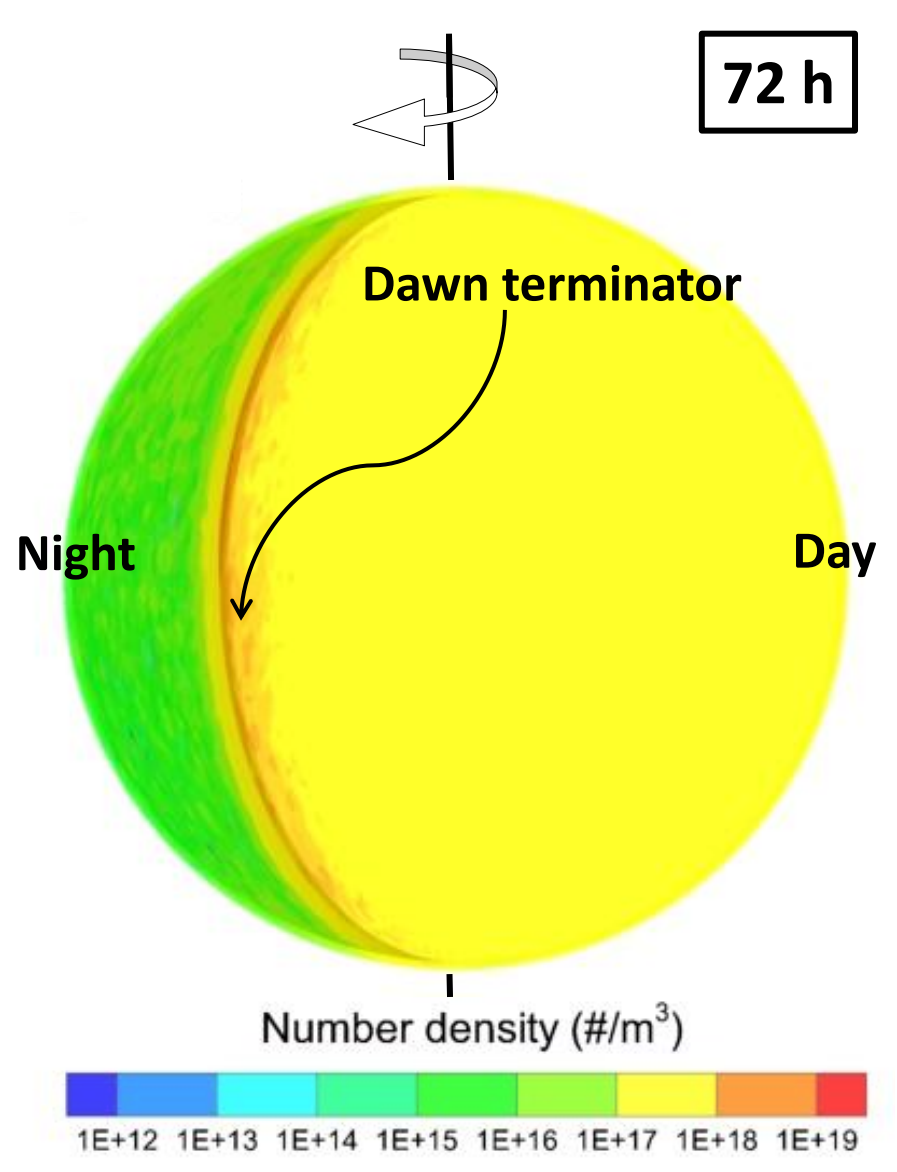
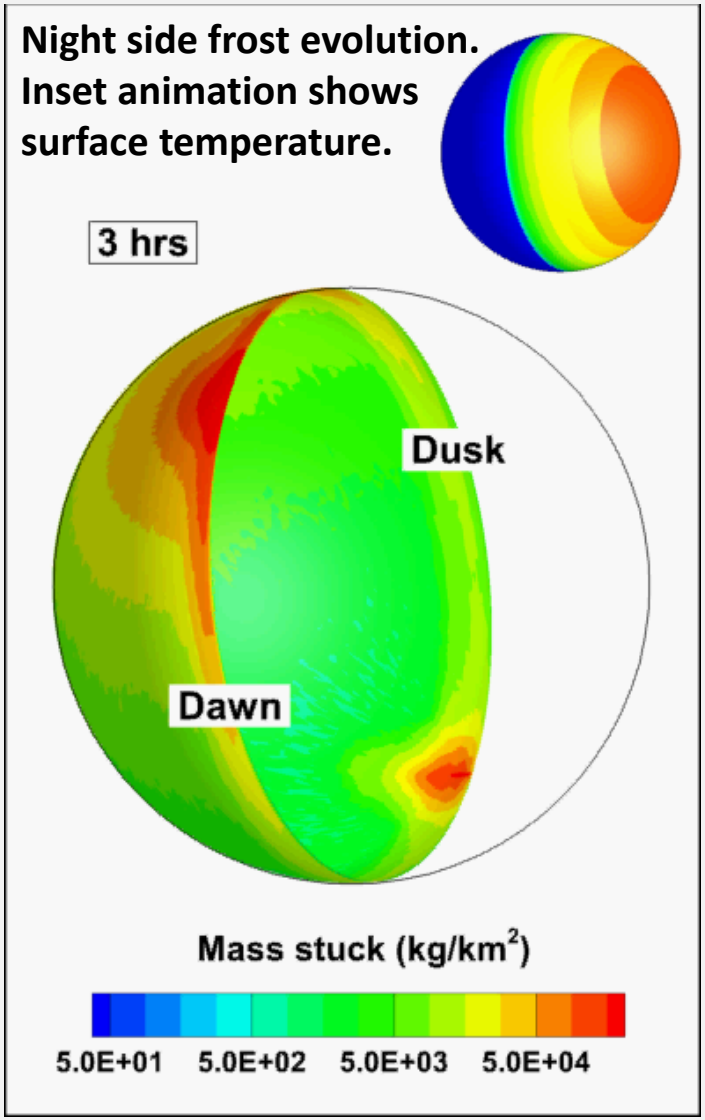


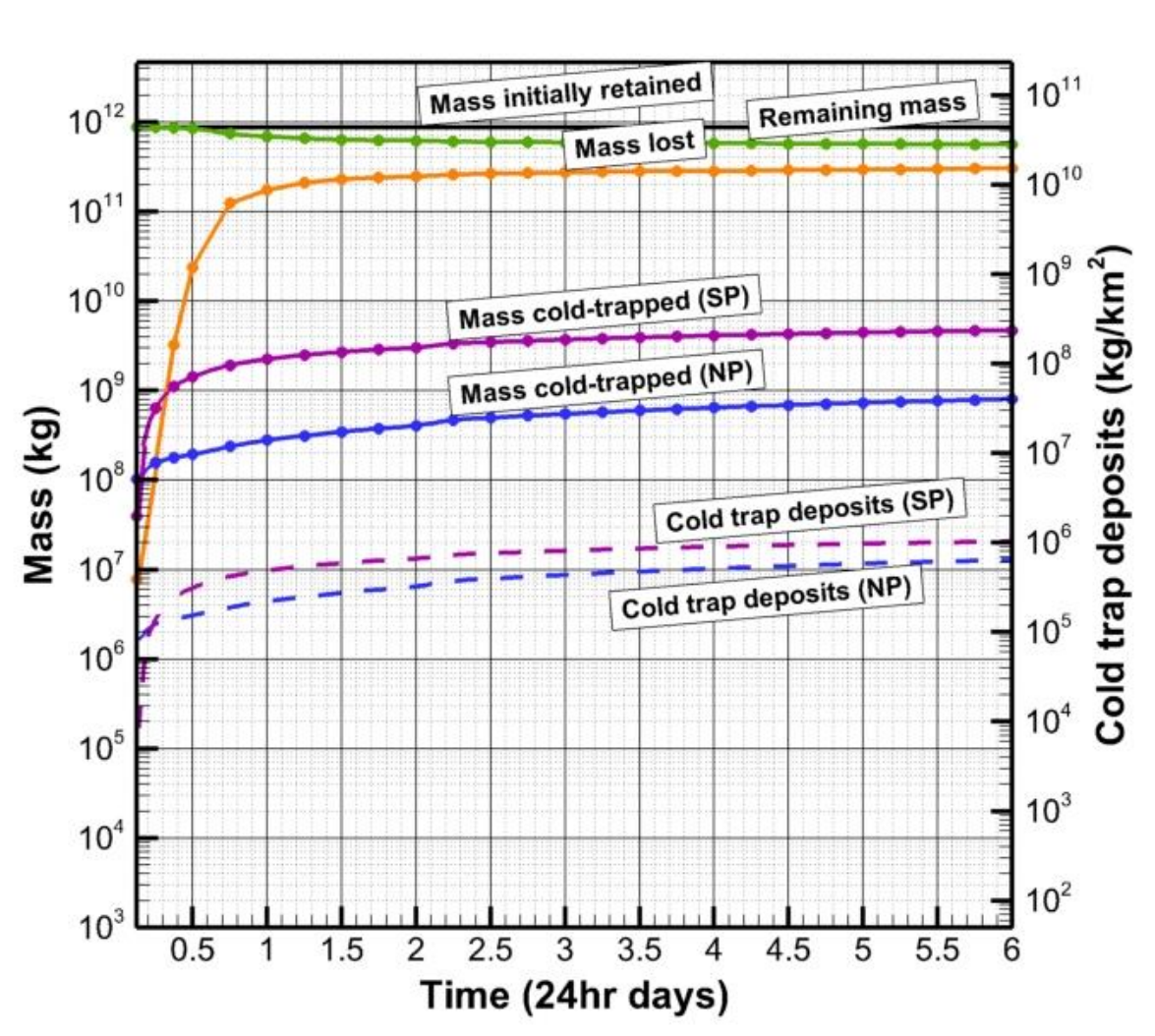
- Only vapor at < 100 km altitude shown. Fallback intensity diminishes with time.
- Convergence of streamlines sustains a temporarily thick atmosphere around antipode.
- Over days to months: loss to photo-destruction + deposition on night side and in cold traps.
- Sublimation of night-side frost rotating into sunlight sustains locally thick atmosphere along dawn terminator.

Surface Frost Evolution



- Night-side residence time ~ 38 h → frost cover, with some, though not significant, migration.
- $O(10^5)$ kg/km^2 ≡ $O(0.1)$ mm H_2O ice (assuming $\rho \approx 10^3$ kg/m^3). Cold traps not shown here.
- Day-side winds and antipodal convergence → concentration of ice at poles and terminators. Dusk/dawn difference due to fallback on to regolith with and without ice cover.
- Progressively decreasing fallback preserves band along initial dusk longitude.

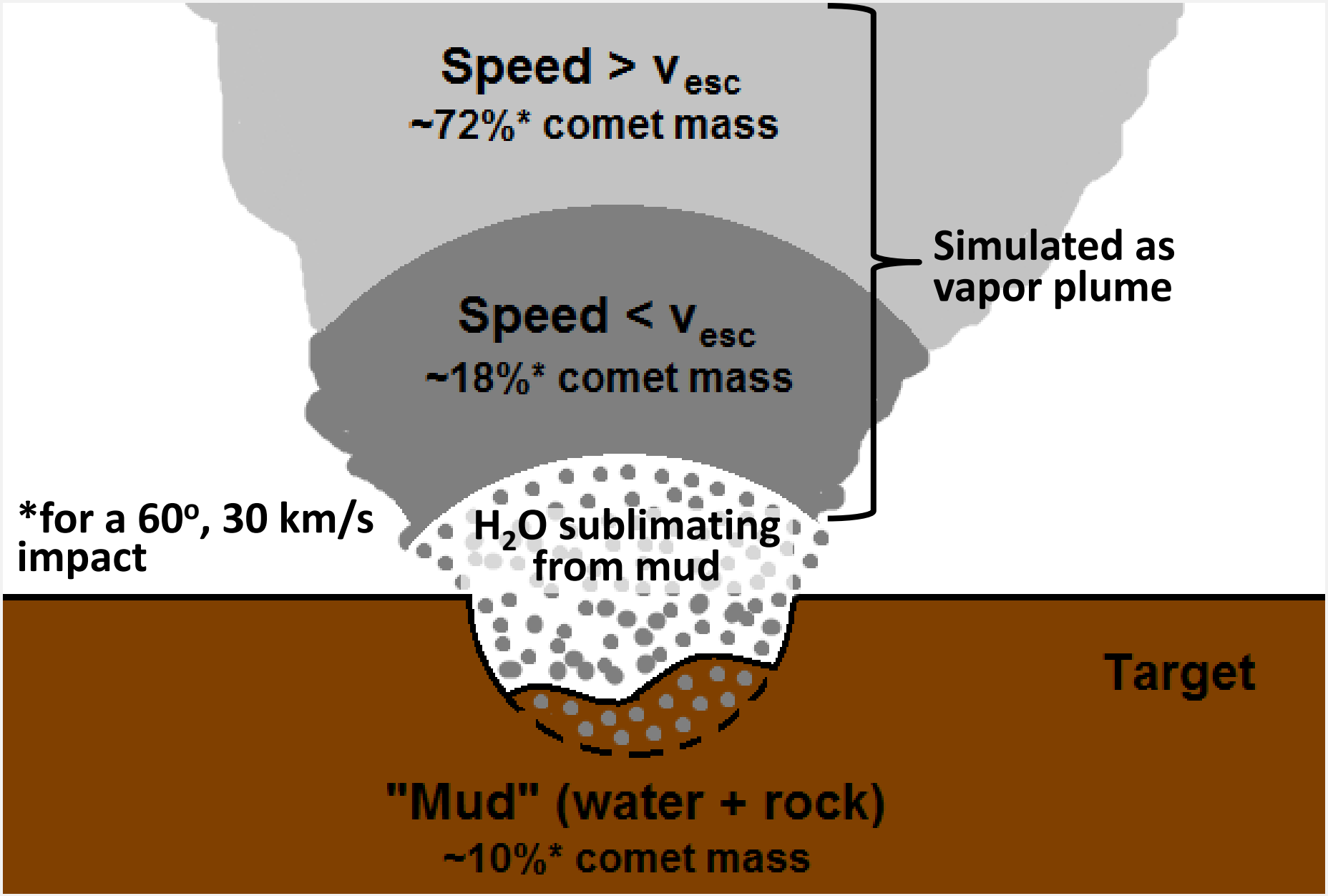
Cold Trap Deposition



Temporal evolution of vapor plume water (~18% comet mass)

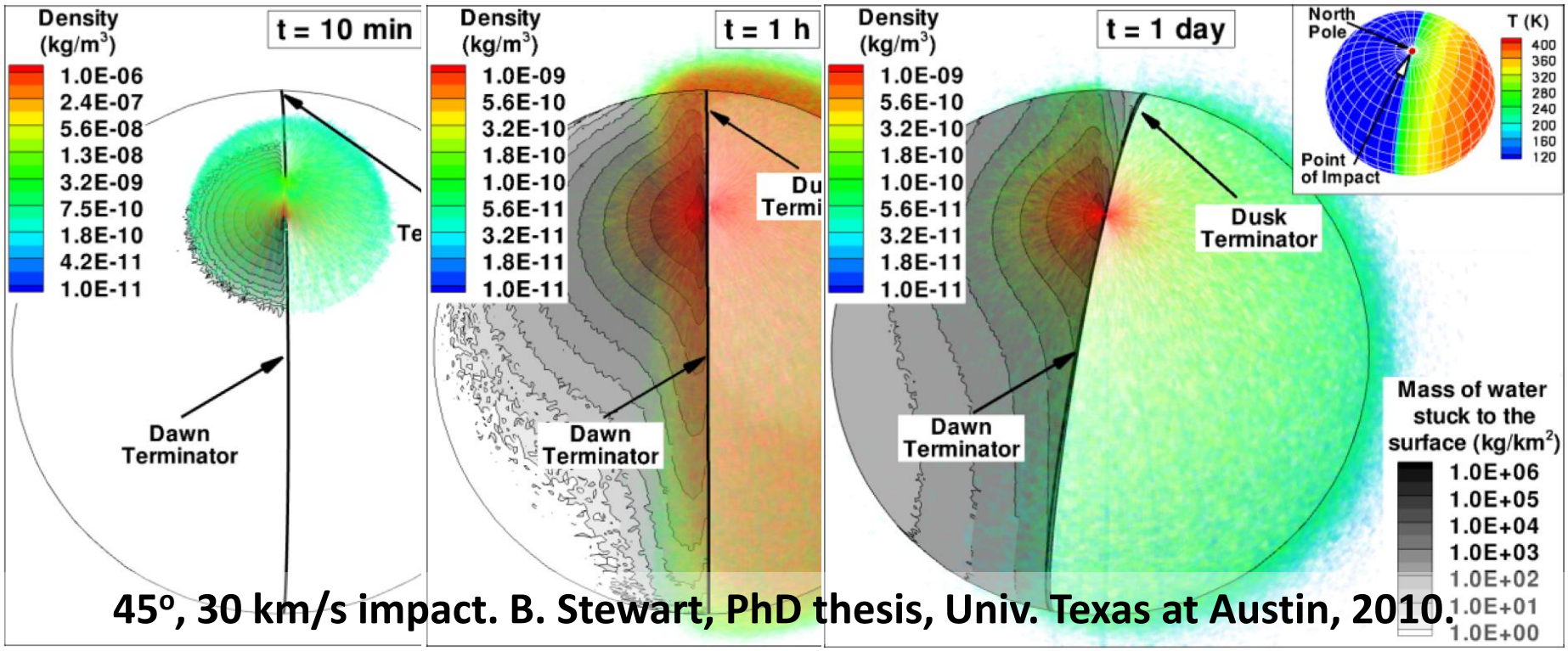
- ~28 % of comet mass is gravitationally bound after 30 min for 60°, 30 km/s impact.
- Molecules that are photo-destroyed or cross Hill sphere- considered lost.
- In 6 days, O(1 mm) ice at cold traps. Deposits are thicker at antipode.
- Simulations continued over months. Long loss time scales ⇒ varying location of impact does not influence *total* cold-trapped mass.

Remaining Water



*for a 60°, 30 km/s impact

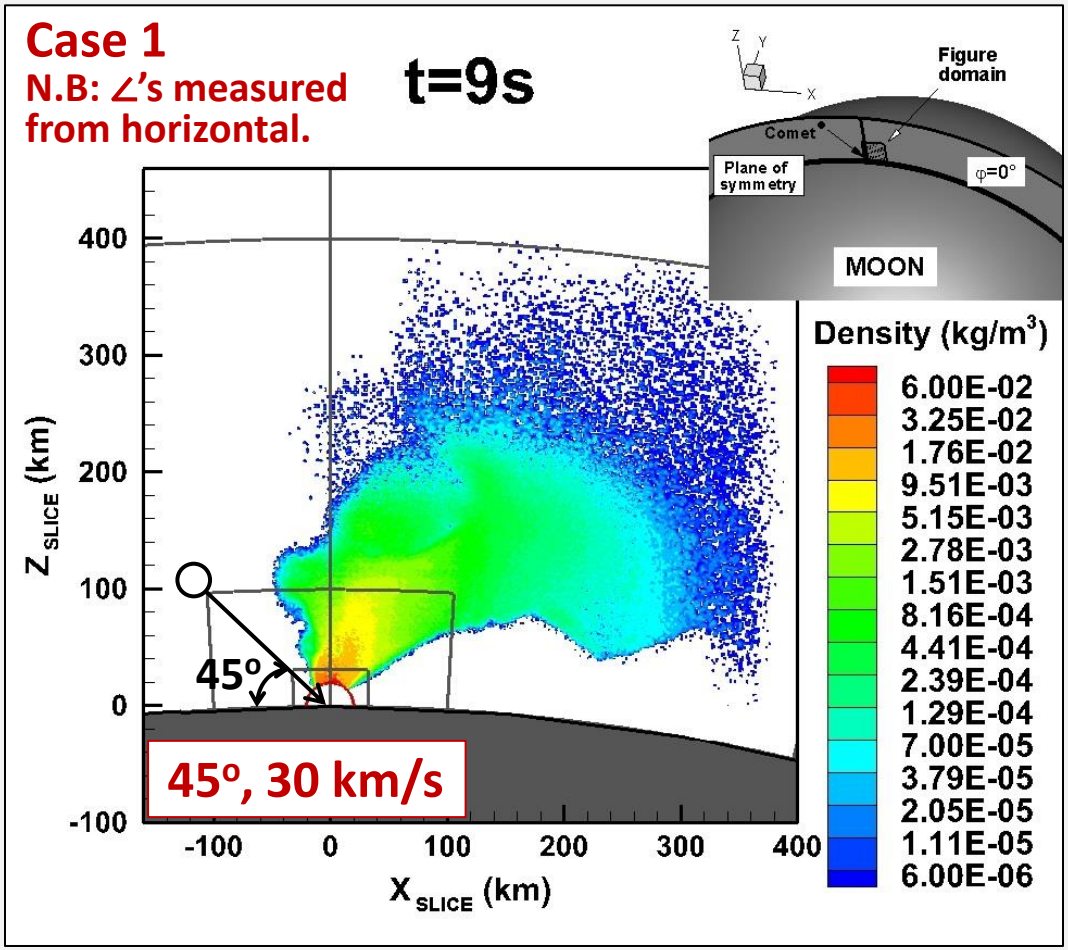
Remaining Water

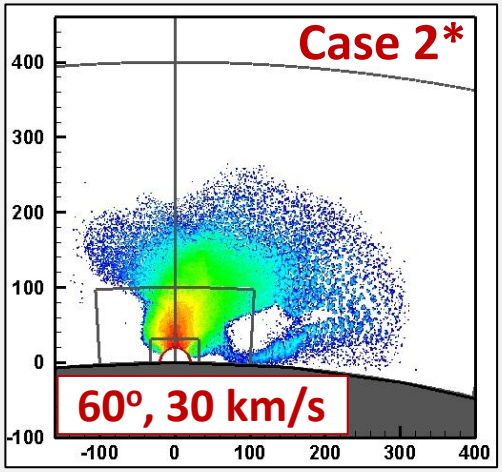


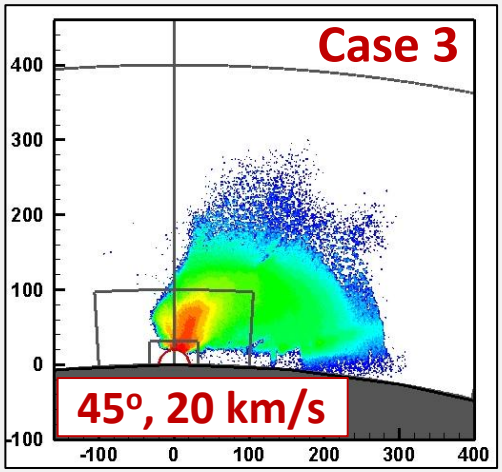
45°, 30 km/s impact. B. Stewart, PhD thesis, Univ. Texas at Austin, 2010.

- SOVA simulations stopped when:
  - Outflow → subsonic.
  - Flux asymptotes → 0.
- Remaining water independently sublimated from 'crater' centered at point of impact.
- Thickest deposits near point of impact. Shocks/antipodal convergence absent; evolves to localized flow at terminator.
- Relative contribution of vapor plume + remaining water to cold trap deposits - impact parameter dependent.

Influence of Impact Parameters



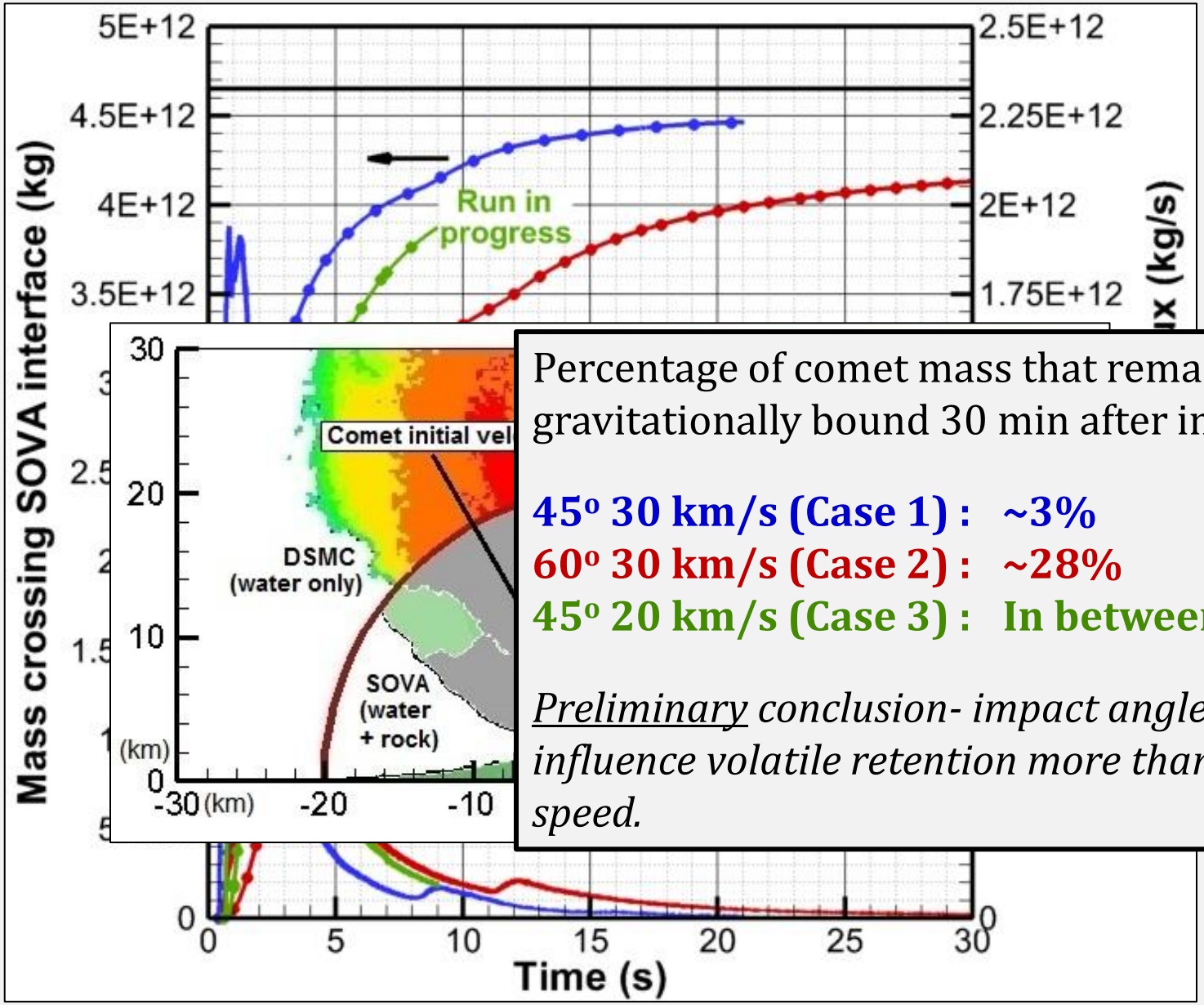




- More oblique impact → more downrange focusing + more kinetic energy partitioned to vaporized projectile. (Consistent with Pierazzo & Melosh, 2000 and Gisler *et al.*, 2006).

*Case shown in the previous slides.

Influence of Impact Parameters



Percentage of comet mass that remains gravitationally bound 30 min after impact:

45° 30 km/s (Case 1) : ~3%
60° 30 km/s (Case 2) : ~28%
45° 20 km/s (Case 3) : In between (?)

<u>Preliminary</u> conclusion- impact angle seems to influence volatile retention more than impact speed.

Summary & Conclusions

- Given a site indicative of a comet impact, what can we say about the associated volatile fallout? Pressure-driven winds + antipodal effects → post-impact transport processes qualitatively different from largely collisionless transport through ballistic hops. Can lead to preferential or enhanced deposition of volatiles.

- How much water could comets have contributed to the lunar volatile inventory at cold traps*? Preliminary discussions in **Stewart *et al.*, 2011 (Icarus 215, 1-16)**. Requires us to further quantify sensitivity to impact parameters (work in progress).

- Future work:
  - Modeling: More realistic comet; more detailed temperature maps + topography (local differences between specific cold traps; non-polar shadows); better model for diffusion of water through overburden.
  - Physics: Optical shielding, condensation.

*Note: Post-deposition processes such as space weathering (e.g. Crider & Vondrak, 2003), sub-surface migration (Schorghofer & Taylor, 2007) influence retention over geological times.