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High-Fidelity Blast Propagation for PDC25 Impact Scenarios

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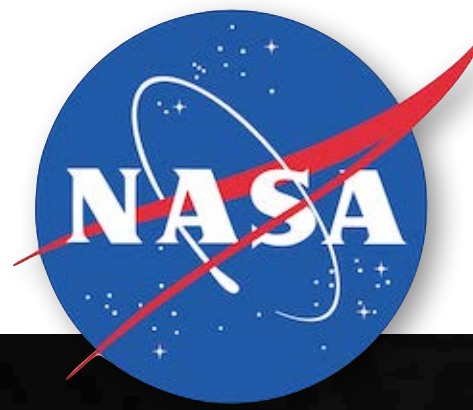
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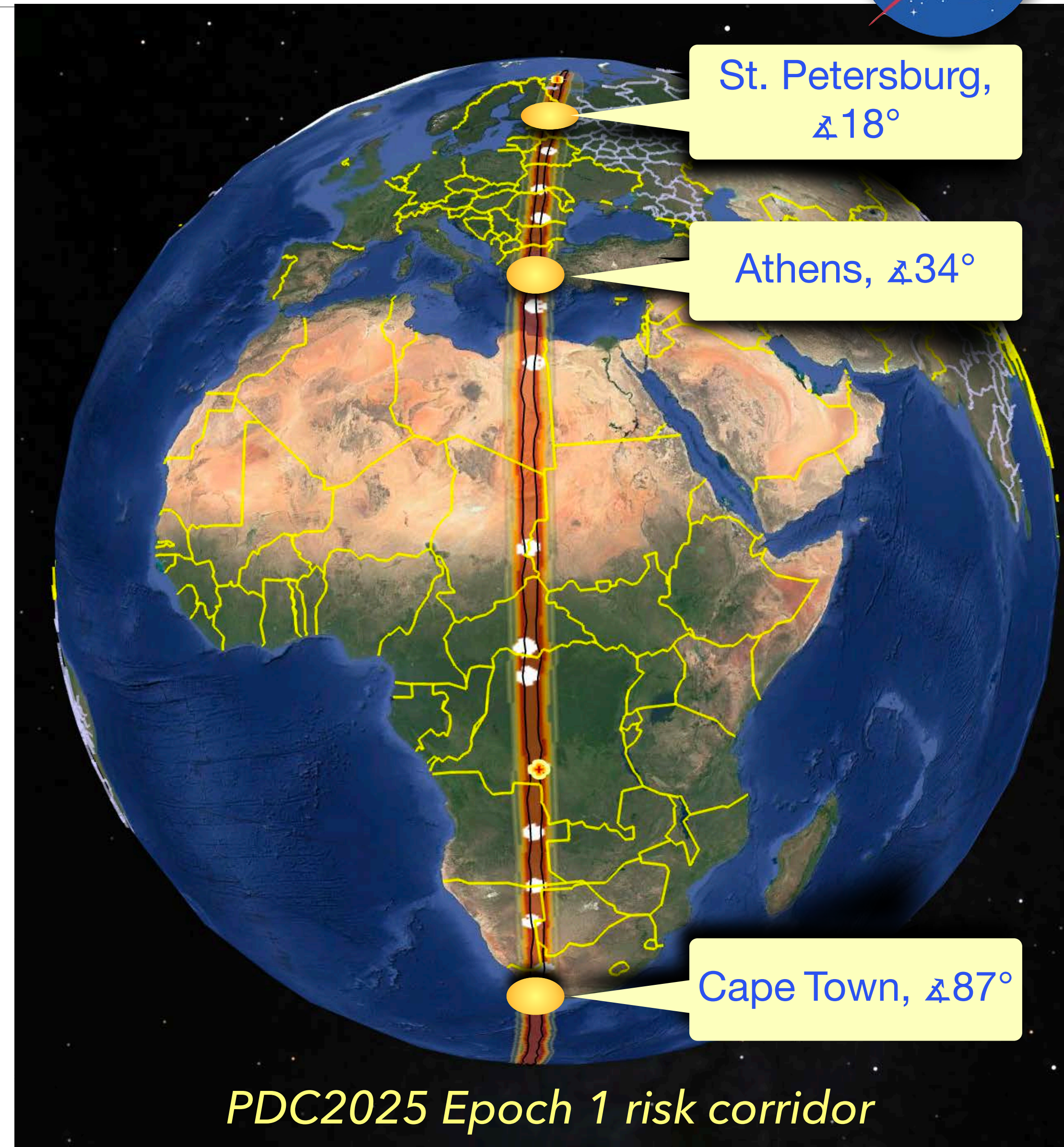
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May 5–9, 2025

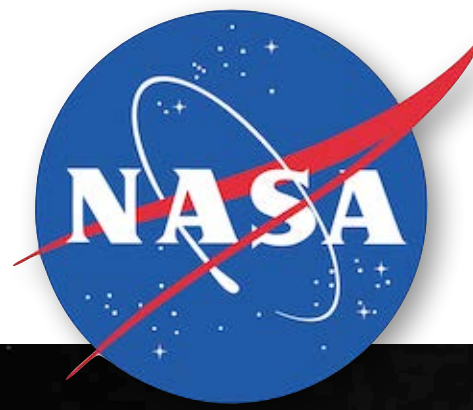
PDC25 impact scenarios



- Epoch 1 impact scenarios
- Cases considered
- Numerical simulations
 - Setup
 - Simulation results
- Summary



PDC25 impact scenarios

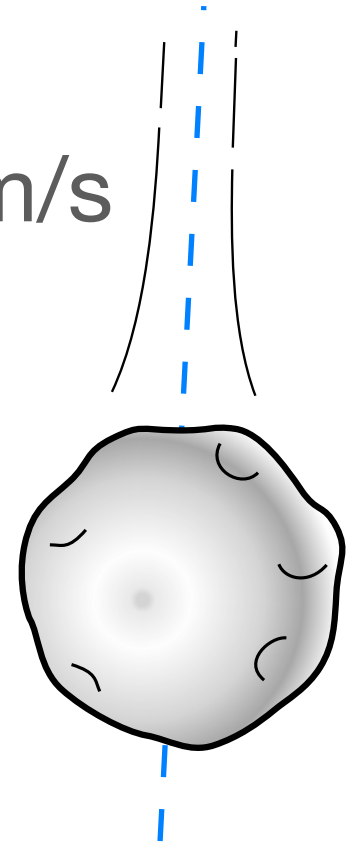


Investigation of PDC 2025 Epoch 1 cases & trends

Cape Town

$V = 13.75 \text{ km/s}$

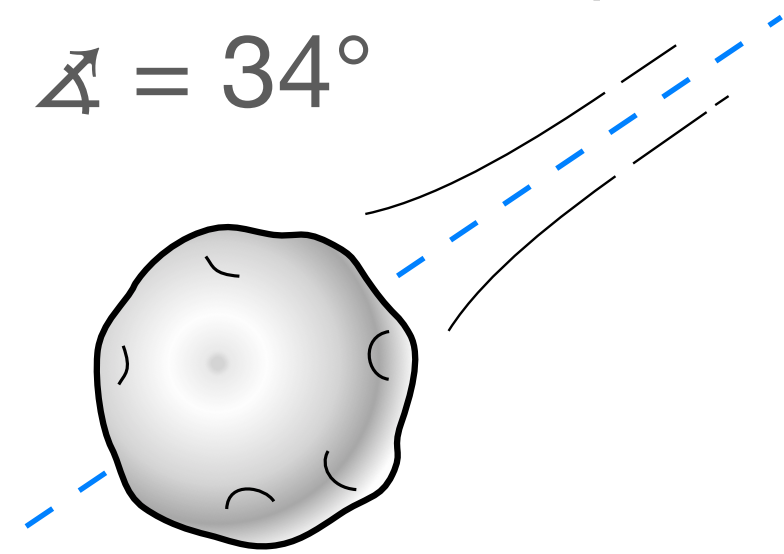
$\Delta = 87^\circ$



Athens

$V = 13.70 \text{ km/s}$

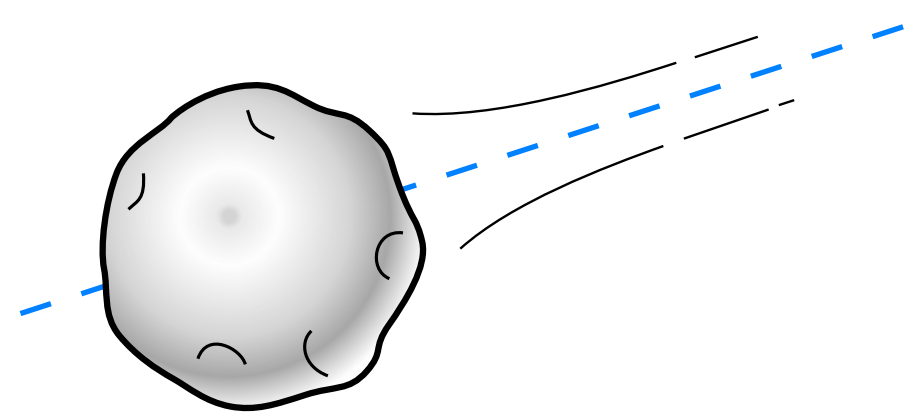
$\Delta = 34^\circ$



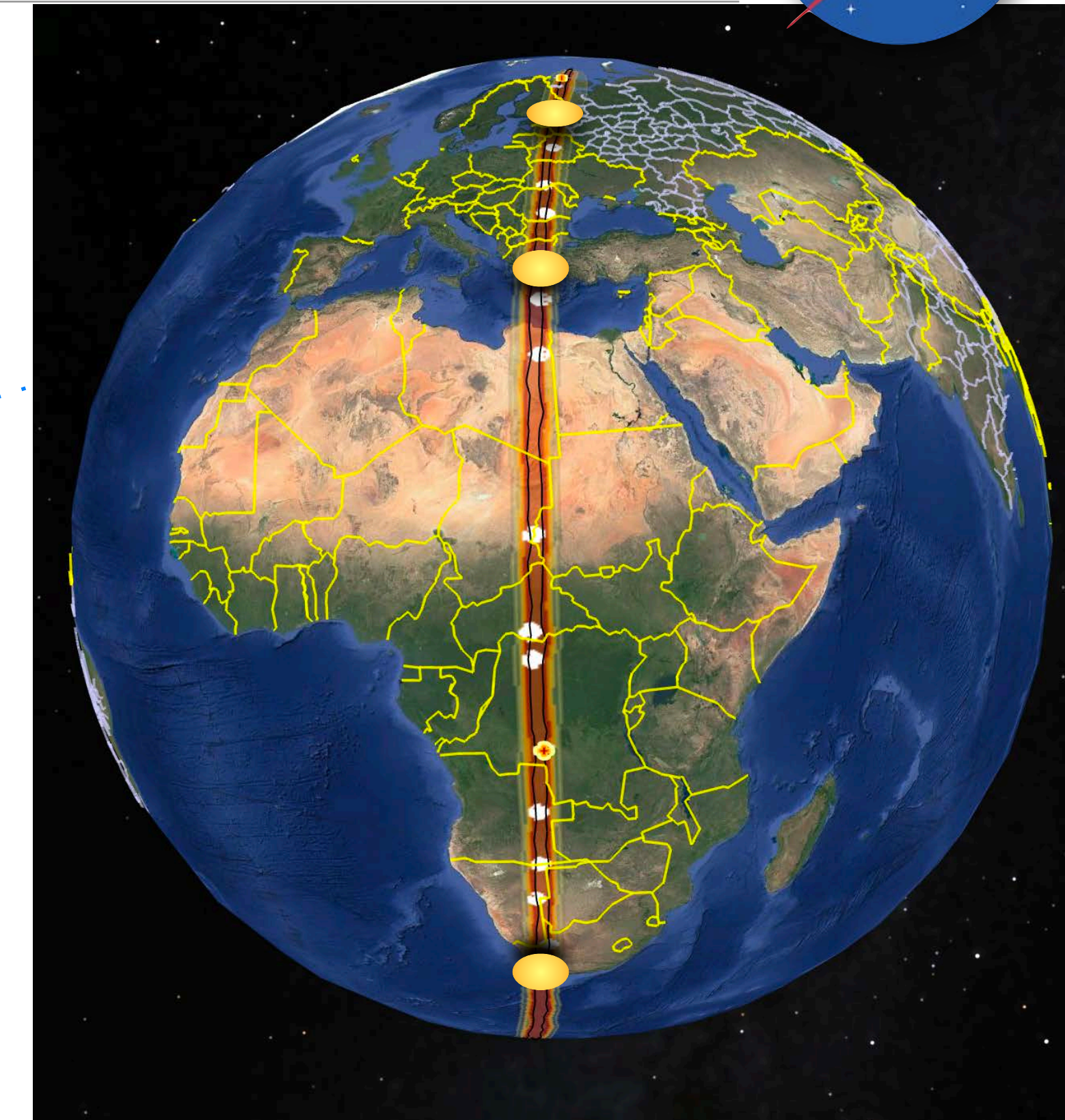
St. Petersburg

$V = 13.70 \text{ km/s}$

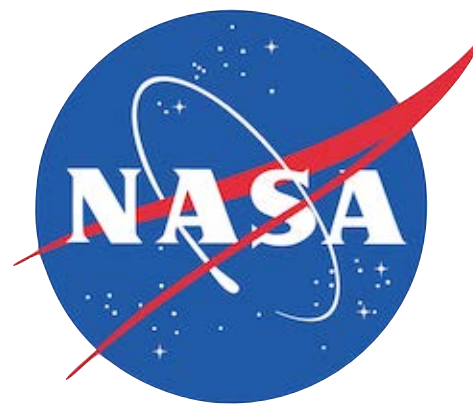
$\Delta = 18^\circ$



- Consider 3 asteroids at these 3 locations
 - $\emptyset = [119.12, 189.09, 272.71] \text{ m}$
 - With entry kinetic energy of $E_{\text{Tot}} = [50, 200, 600] \text{ Mt}$
 - Correspond to median (50 Mt), 95% (200 Mt) and ~99.9% (600 Mt)
- Assume moderate strength & density
 - $\rho = 2.5 \text{ g/cc}$, $\text{Str} = 2 \text{ MPa}$
- Perform high-fidelity simulations & compare with HoB predictions



PDC2025 Epoch 1 risk corridor



Impact Scenarios: Entry profiles & energy deposition

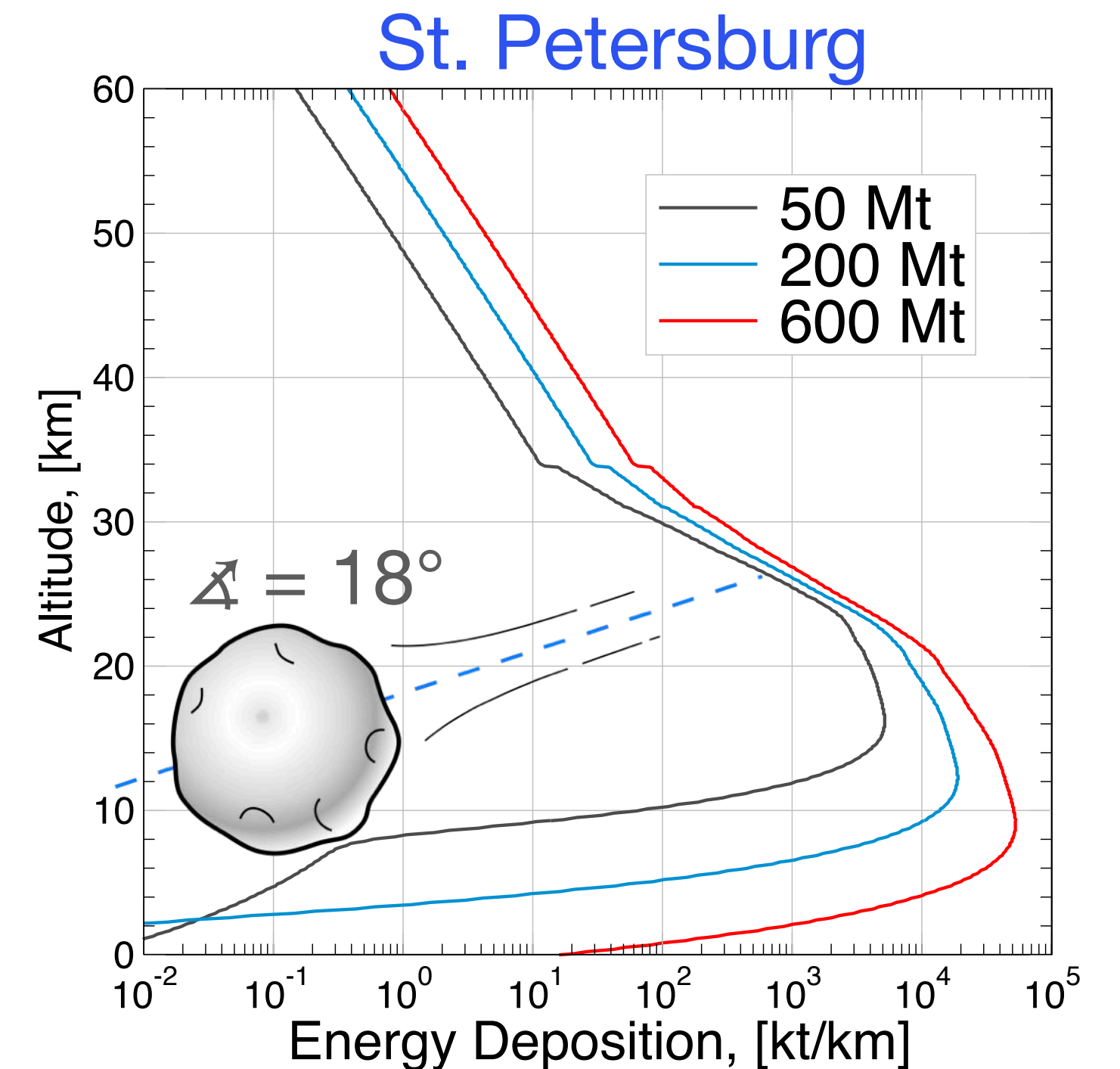
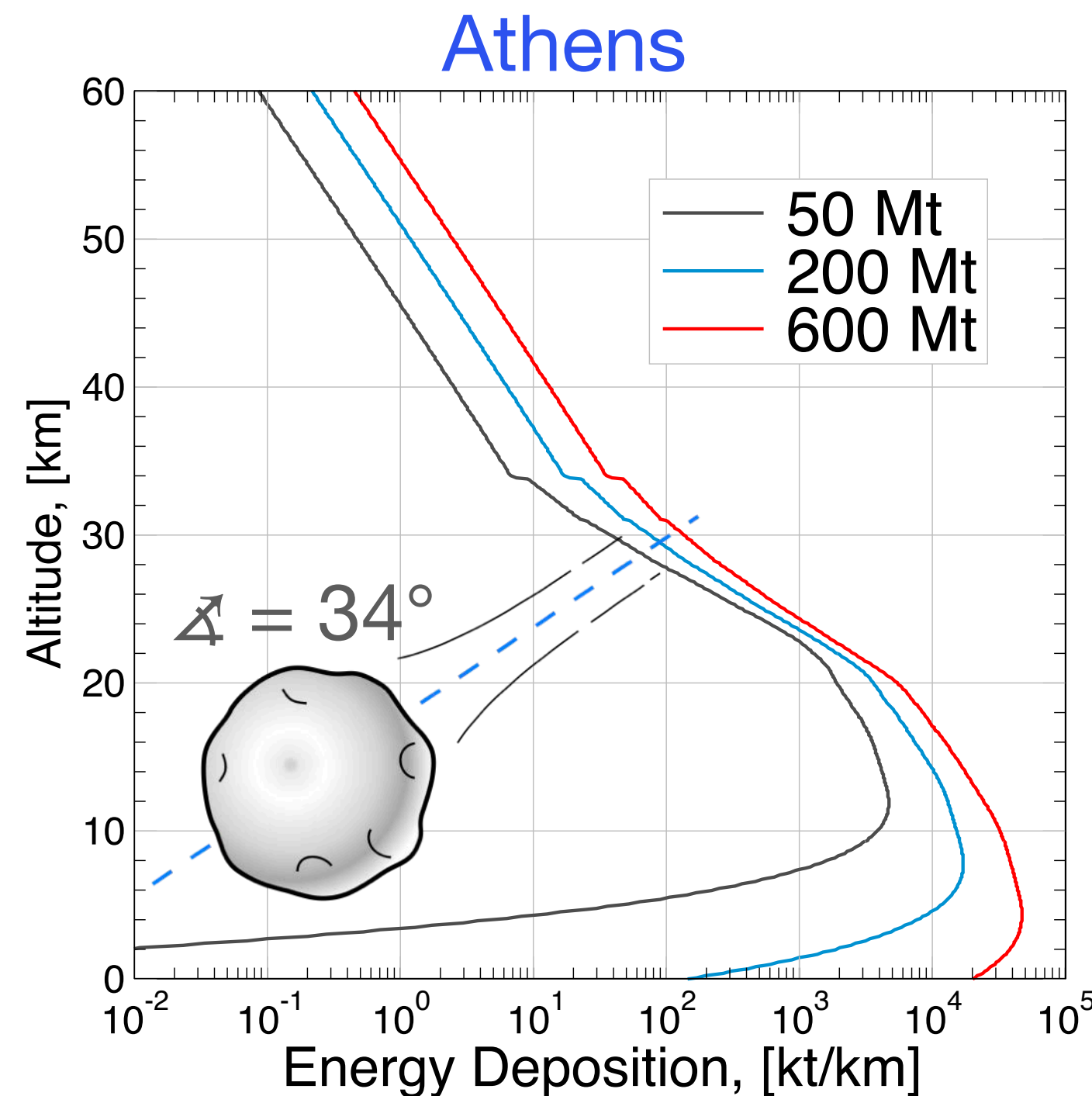
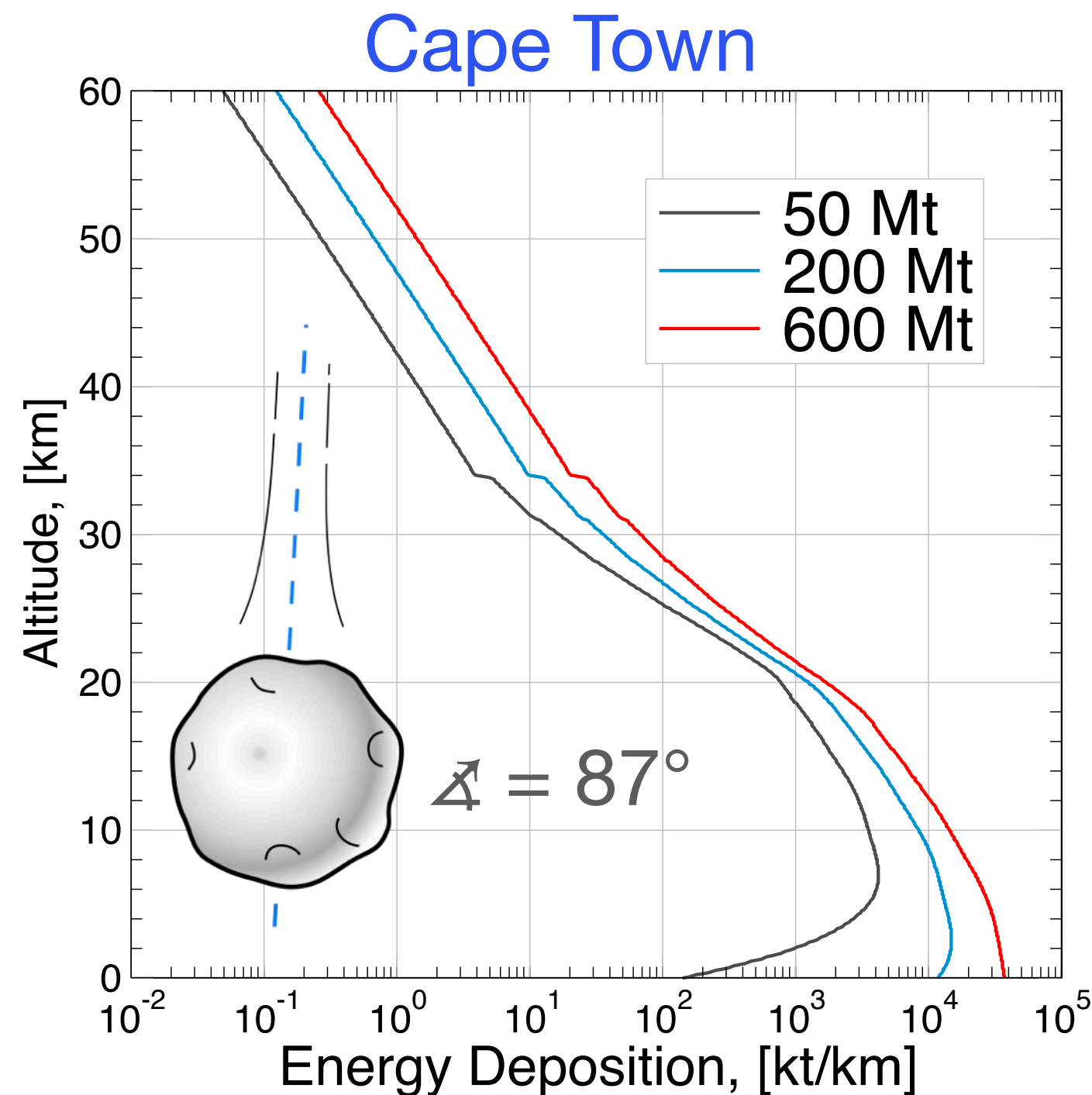
Height of burst varies with entry angle and size

Entry profiles reveal the expected trends, for similar compositions:

- Larger objects penetrate more deeply
- Shallower entries burst higher

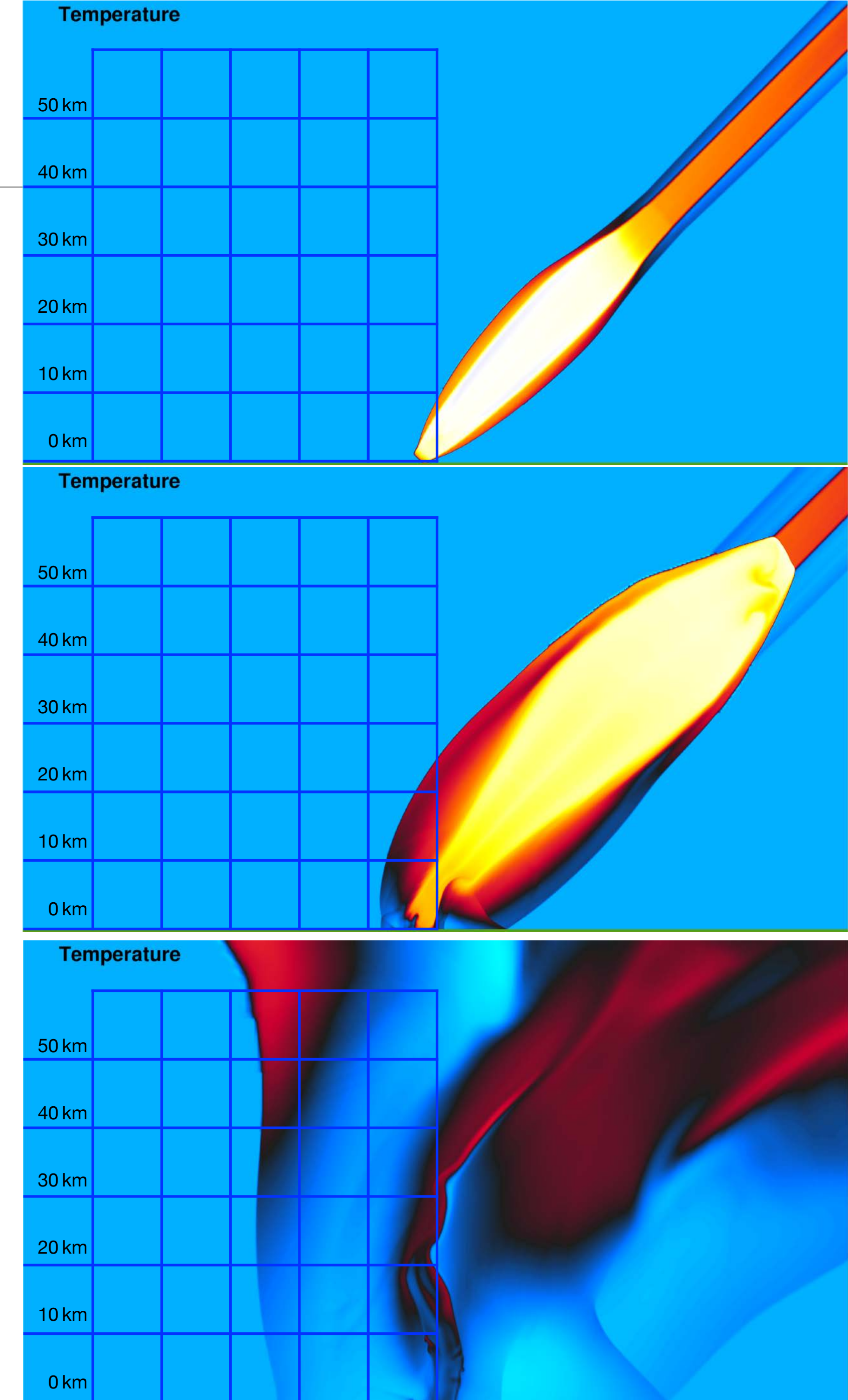
Moderate strength, Peak Edep altitude, [km]

Energy [Mt]	Cape Town 87°	Athens 34°	St. Petersburg 18°
50	7.0	11.9	16.2
200	2.6	7.8	12.4
600	0.0	4.4	9.1

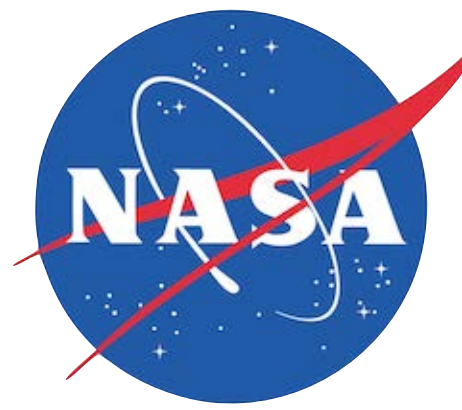


Numerical simulations & results

- Solver overview
- Overview of entry & impact simulations
- Ground footprints & comparisons

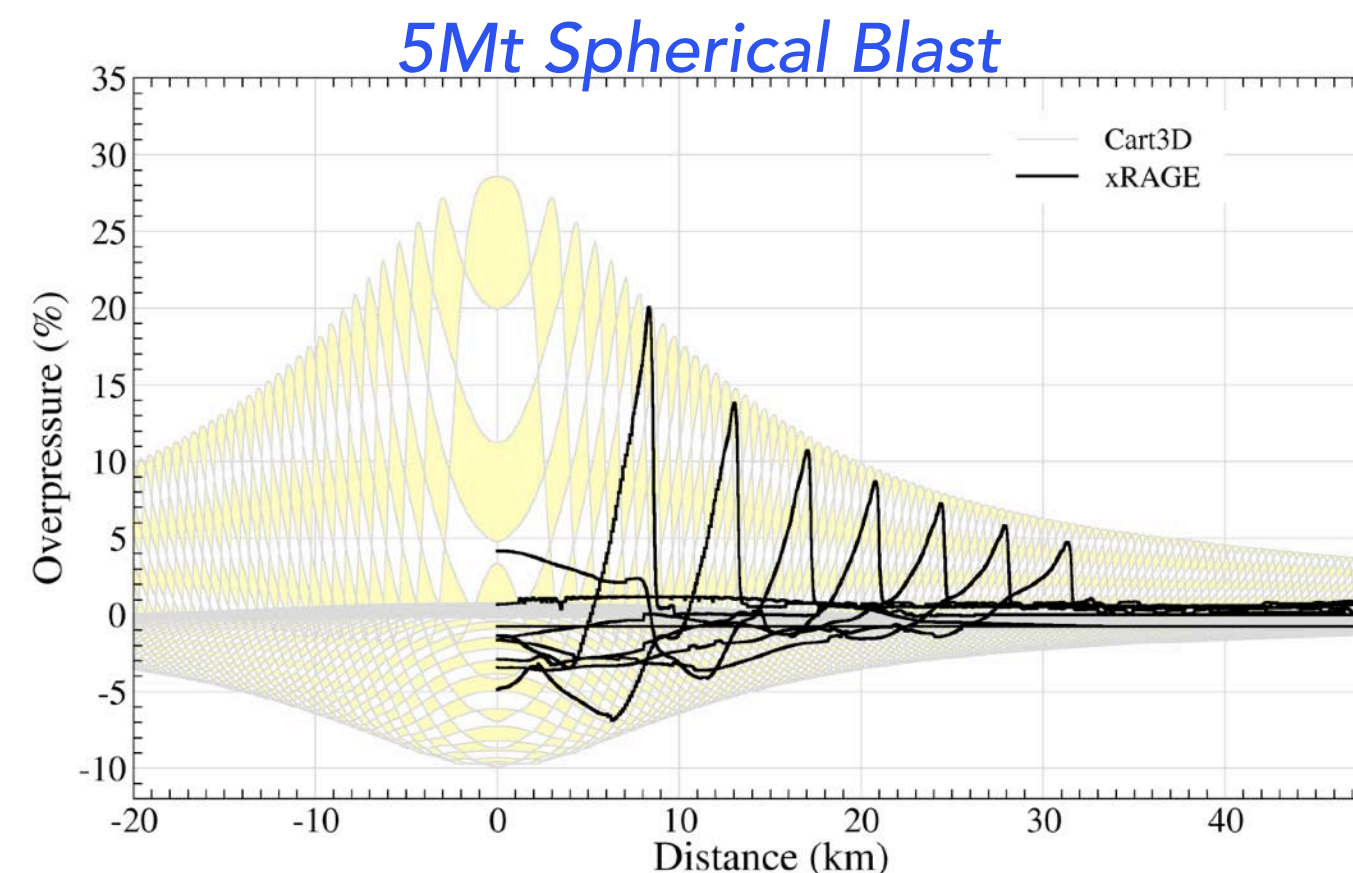


Numerical simulations & results



Solver Overview: Cart3D

- Originally developed for aerospace applications
- Fully-automated mesh generation for complex geometry
- Inviscid solver using Cartesian cells
 - Fully-conservative finite-volume method
 - Multigrid accelerated 2nd-order upwind scheme
 - Dual-time approach for unsteady simulations
 - Domain-decomposition for good parallel scalability
- All runs are full 3D
 - 220-330M cells with 20-30k time steps
- Excellent scalability
 - Typical airburst simulations take 8-16 hrs on ~4000 cores
- One of NASA's most heavily used production solvers, large validation database, 900+ users
- Good comparisons w/ *CTH*, *xRAGE* & *ALE3D* at the 2016 Tsunami Workshop



Comparison with *xRAGE* (DoE)
at 2016 Tsunami Workshop

Chelyabinsk Ground Footprints

Chelyabinsk airburst: *AIAA Paper 2016-0998*, Jan 2016

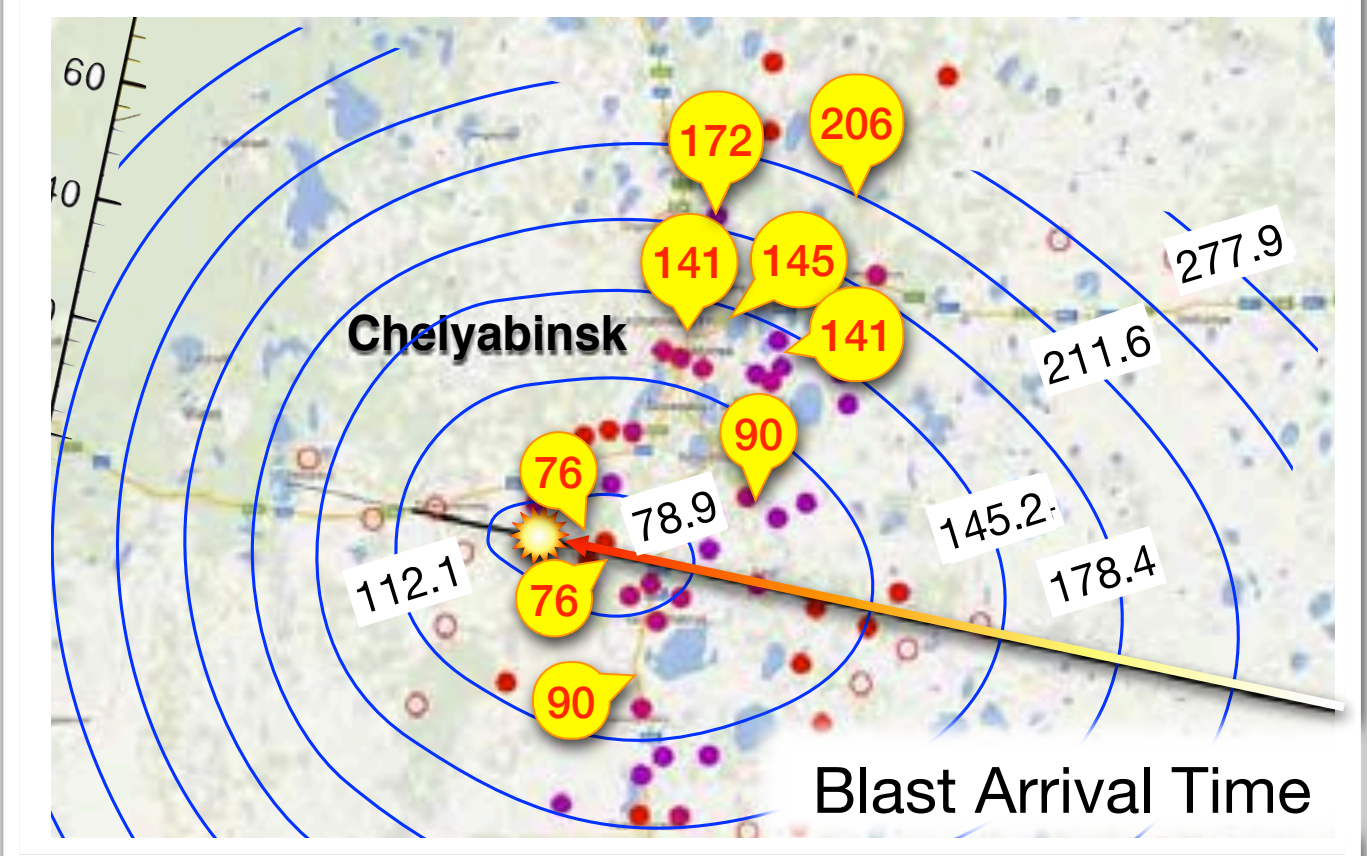
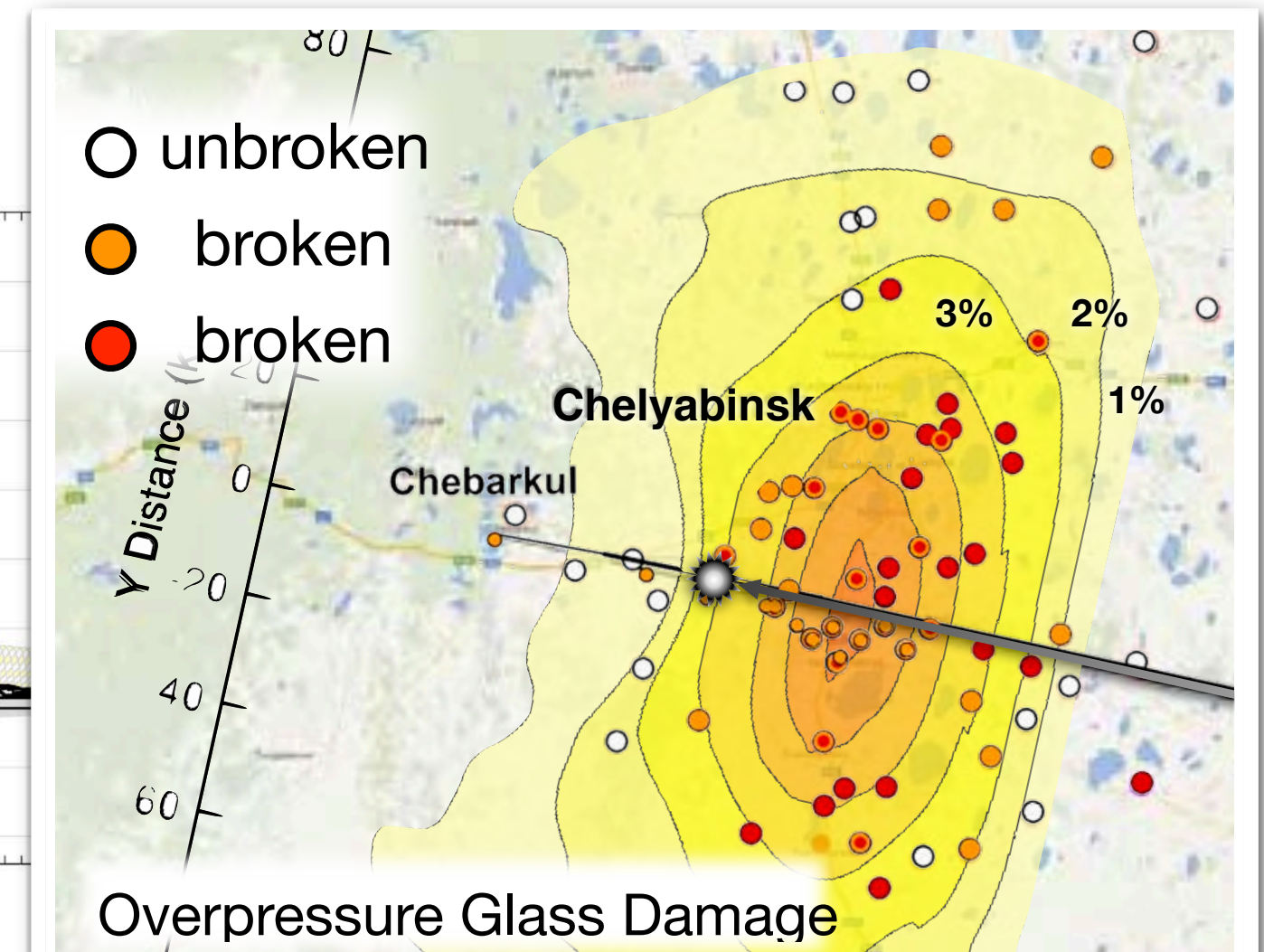
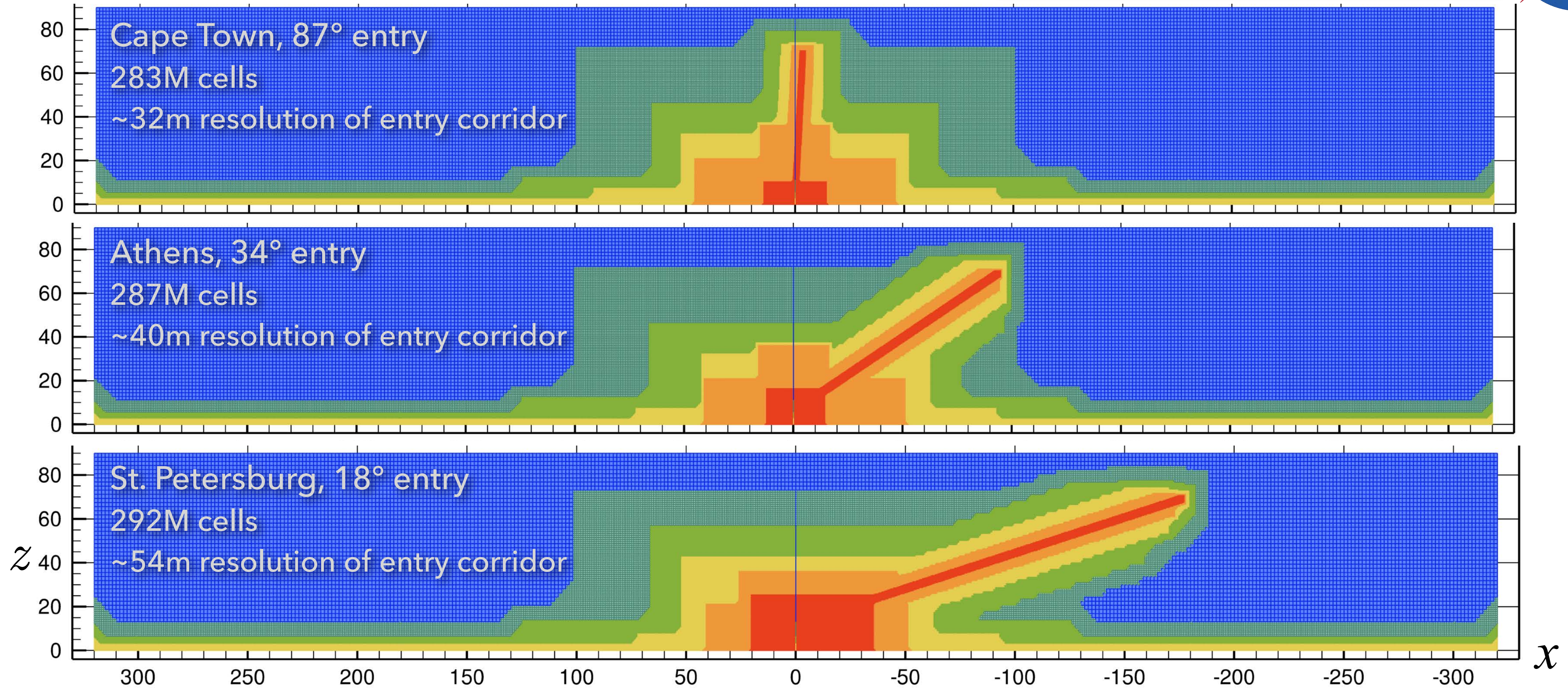
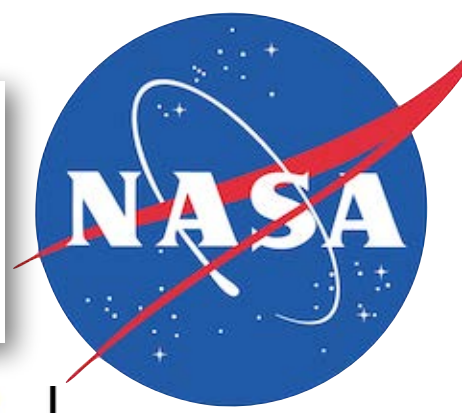
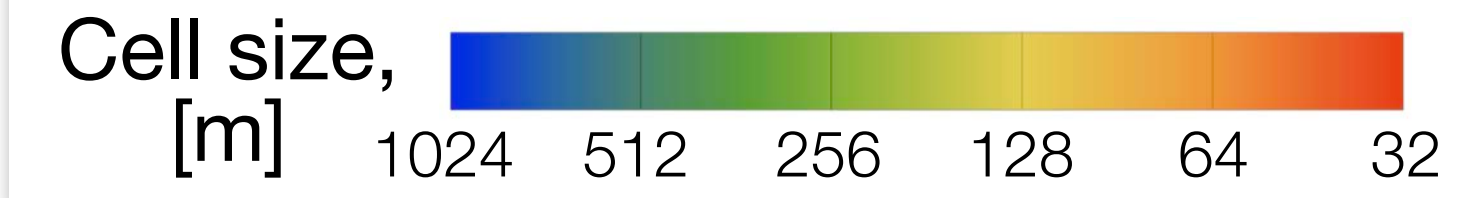


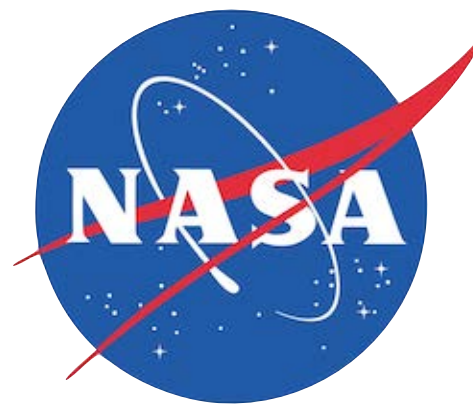
Image credit *AIAA 2016-0998*, used with permission. 6

Computational Meshes

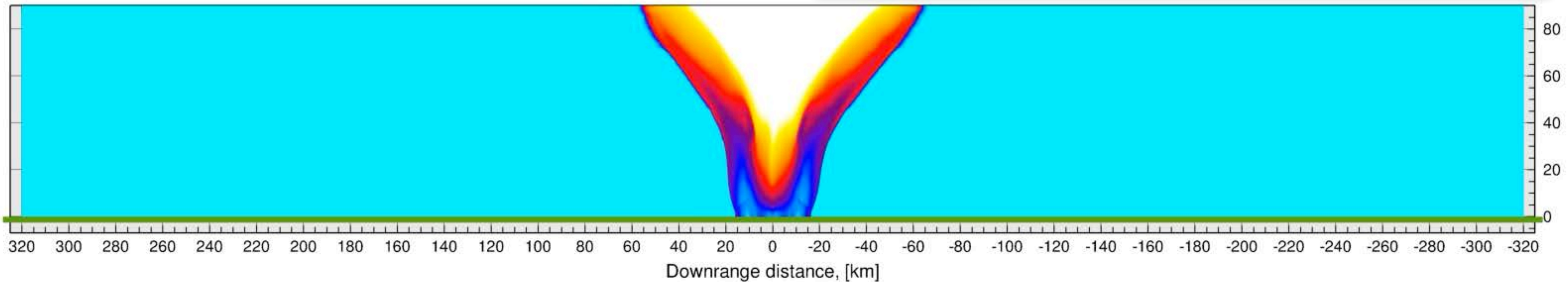
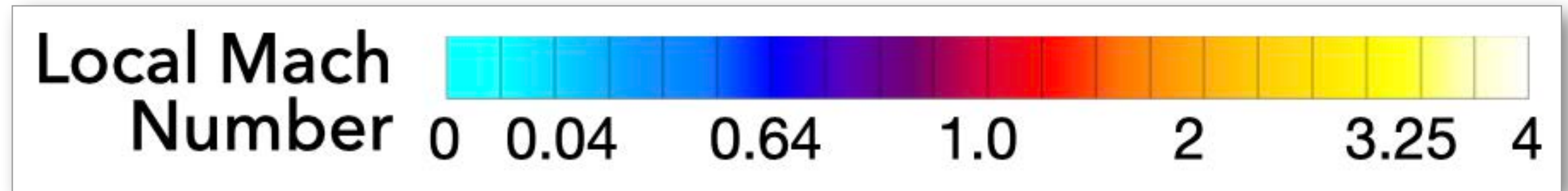


- Domain extends ± 320 km along (x, y) ground plane x 90 km altitude (z)
- All simulations 3D with cross-range symmetry (y)

Sample of entries

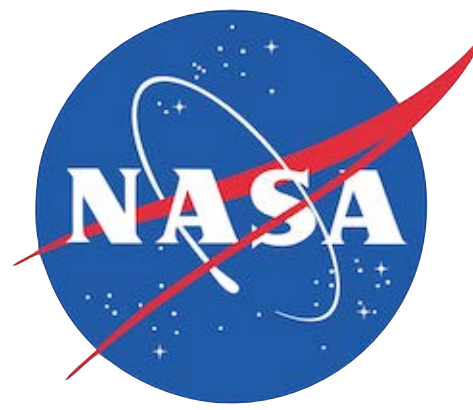


200Mt at Cape Town

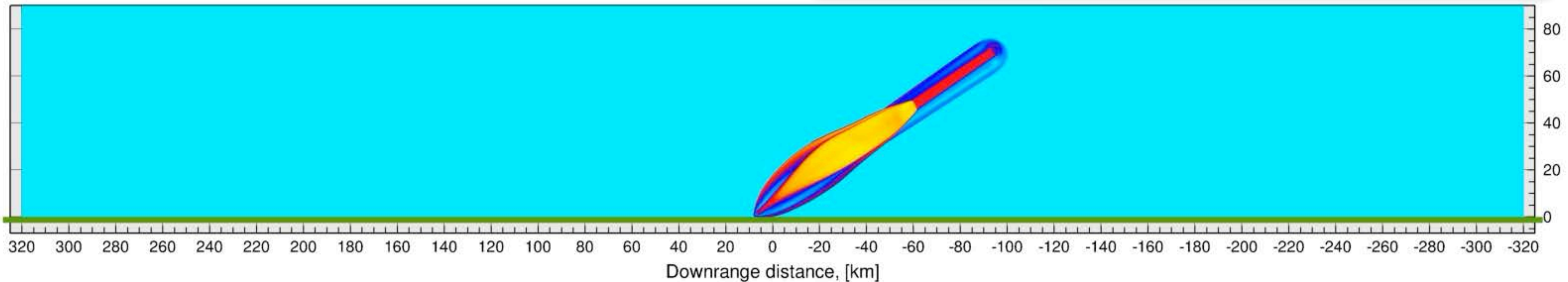
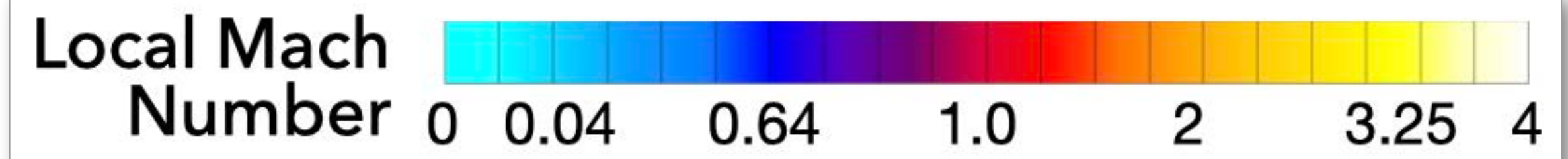


- Entry: $\angle 87^\circ$, $|V| = 13.75$ km/s
- Peak energy deposition occurs at 2.7 km, just before impact
- ~ 170 Mt of energy goes into atmosphere, ~ 30 Mt into ground
- Ground impact 5.3s after entry

Sample of entries

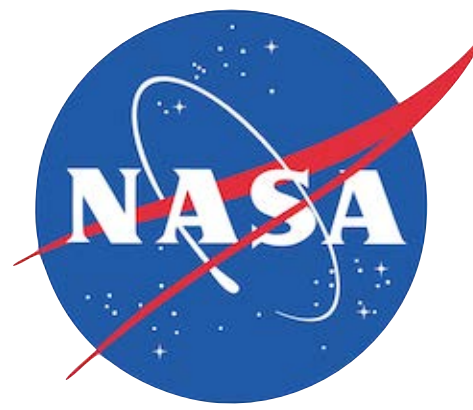


200Mt at Athens

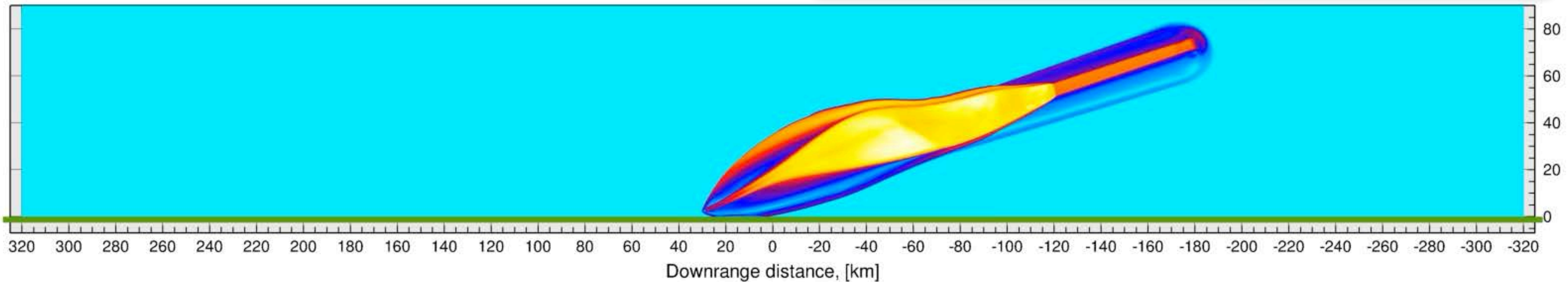
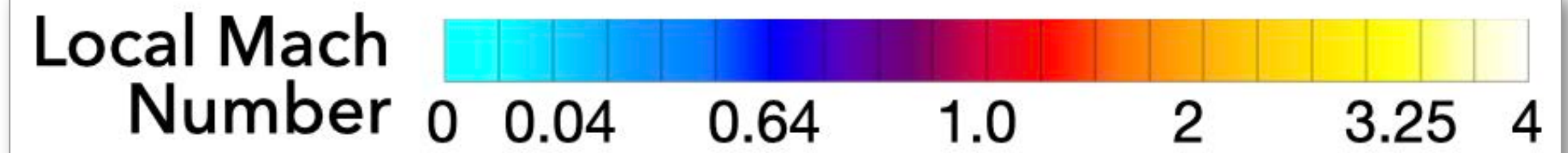


- Entry: $\angle 34^\circ$, $IVI = 13.7$ km/s
- Peak energy deposition occurs at 7.8 km
- Essentially airburst event:
 - ~ 199.9 Mt of energy goes into atmosphere,
 - ~ 0.1 Mt into ground impact
- Ground impact 15.3s after entry, about same time as blast wave from main airburst

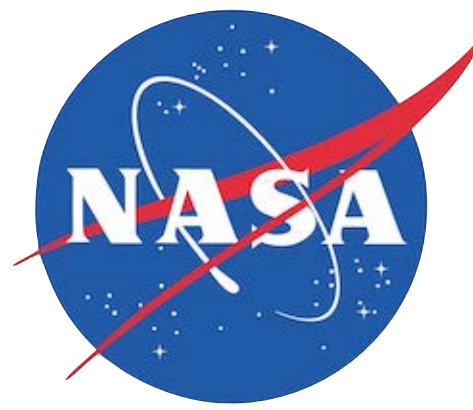
Sample of entries



200Mt at St. Petersburg



- Entry: $\angle 18^\circ$, $|V| = 13.7$ km/s
- Peak energy deposition occurs at 12.4 km
- Pure airburst event, 200 Mt into atmosphere
- Blast wave first hits ground ~ 29.4 s after entry



Cape Town, 87°: Snapshots of entry & impact

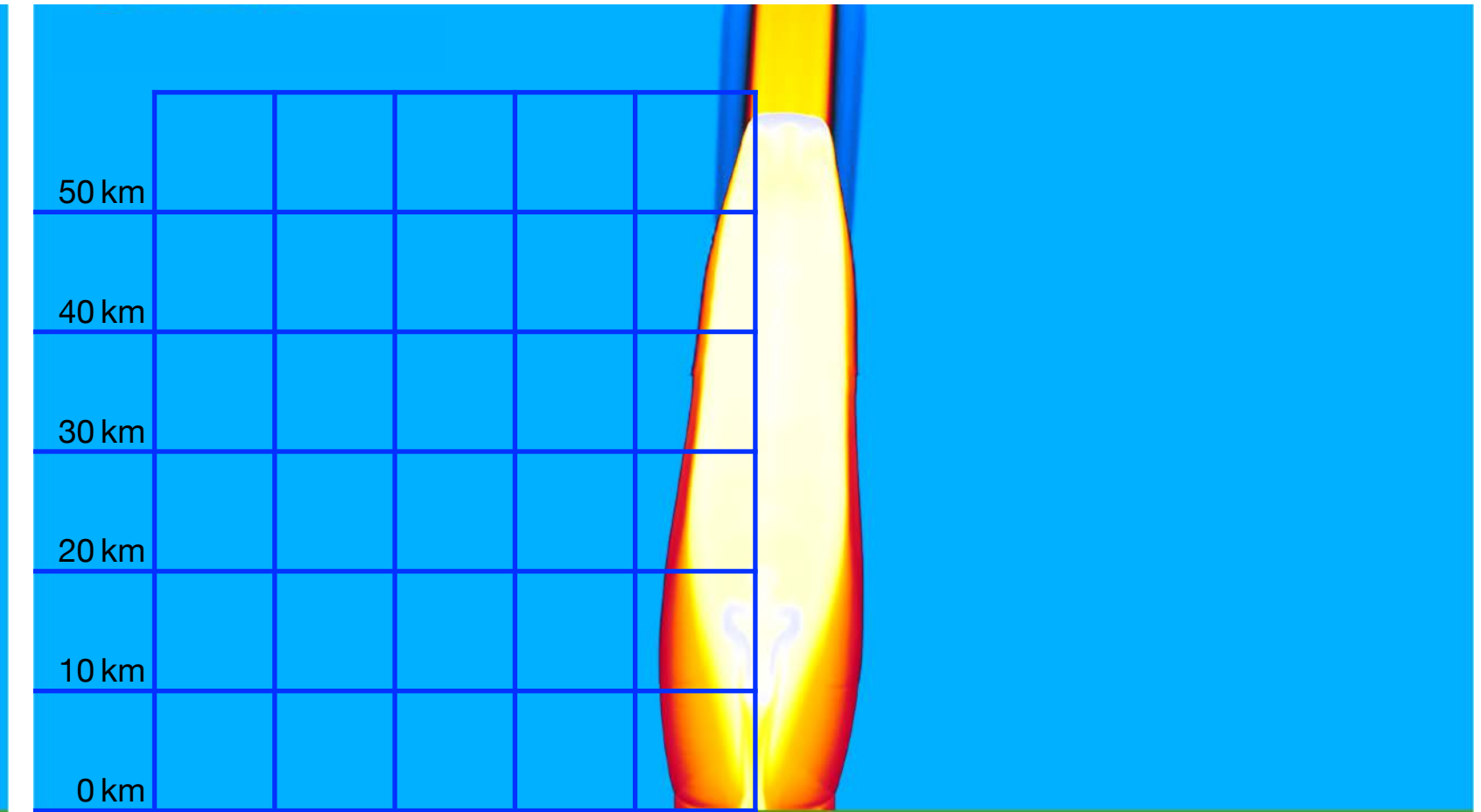
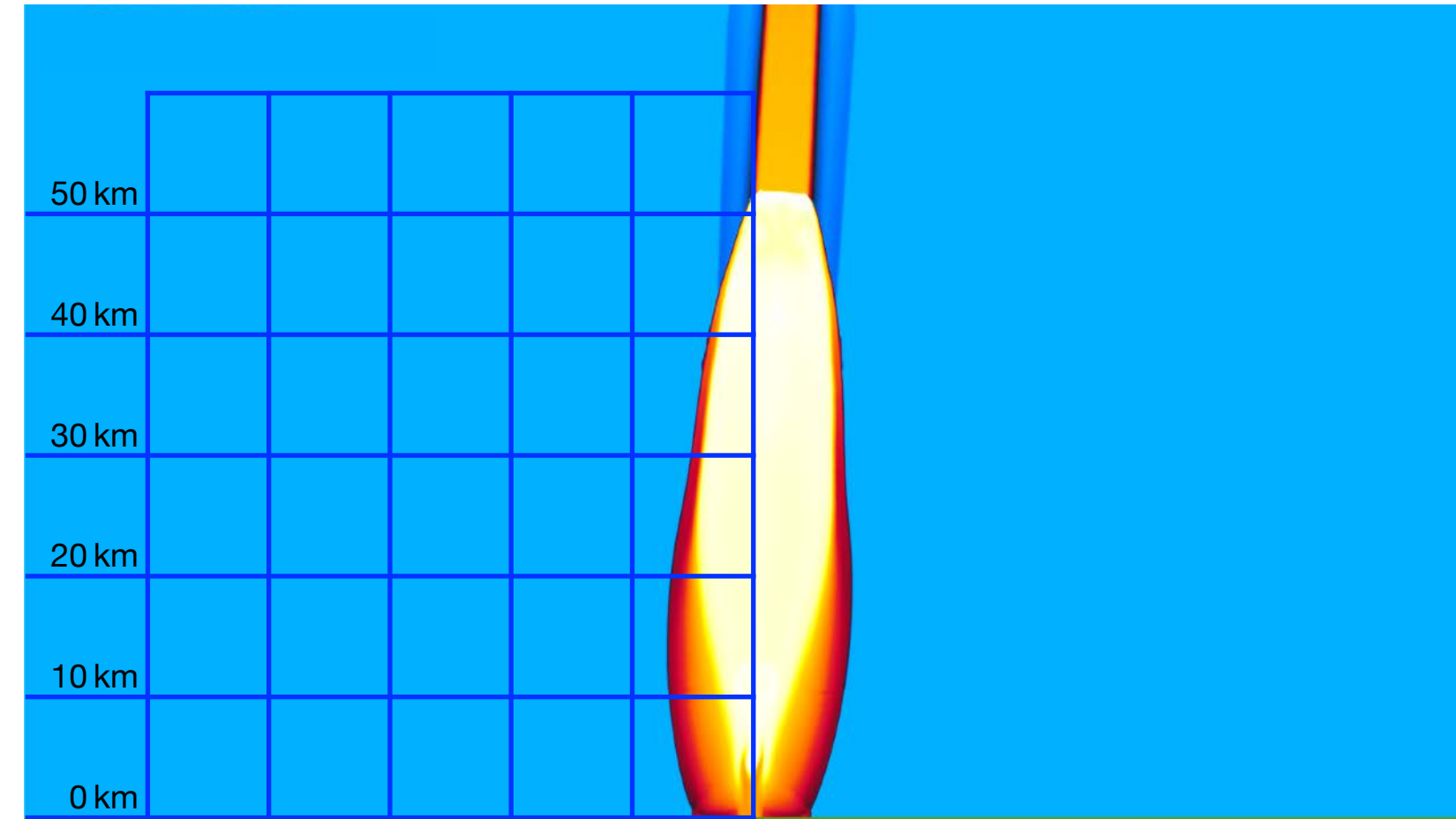
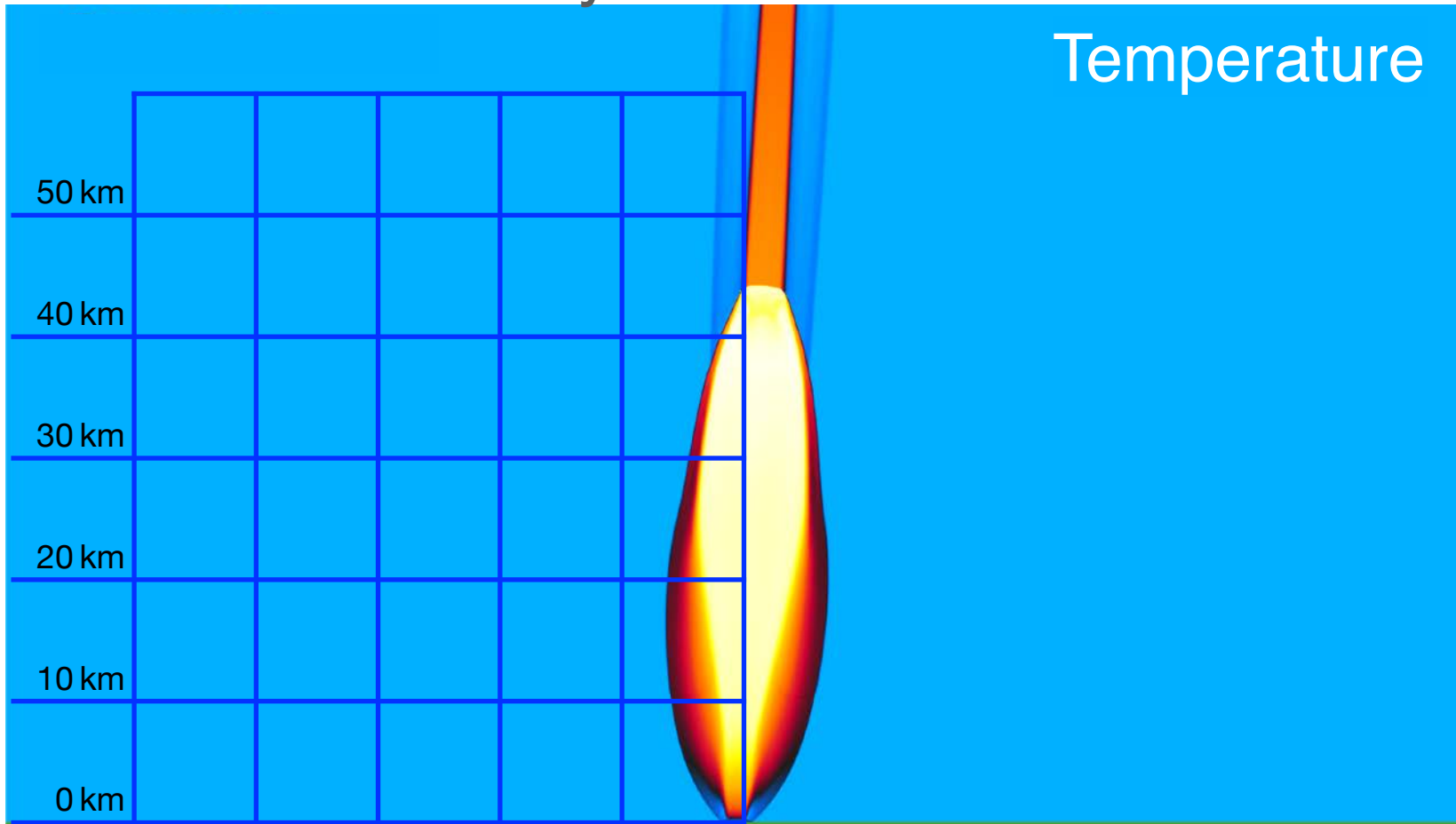
50 Mt is a low airburst, 200 & 600 Mt both impact

$t = 8.4$ s after entry

50 Mt
Temperature

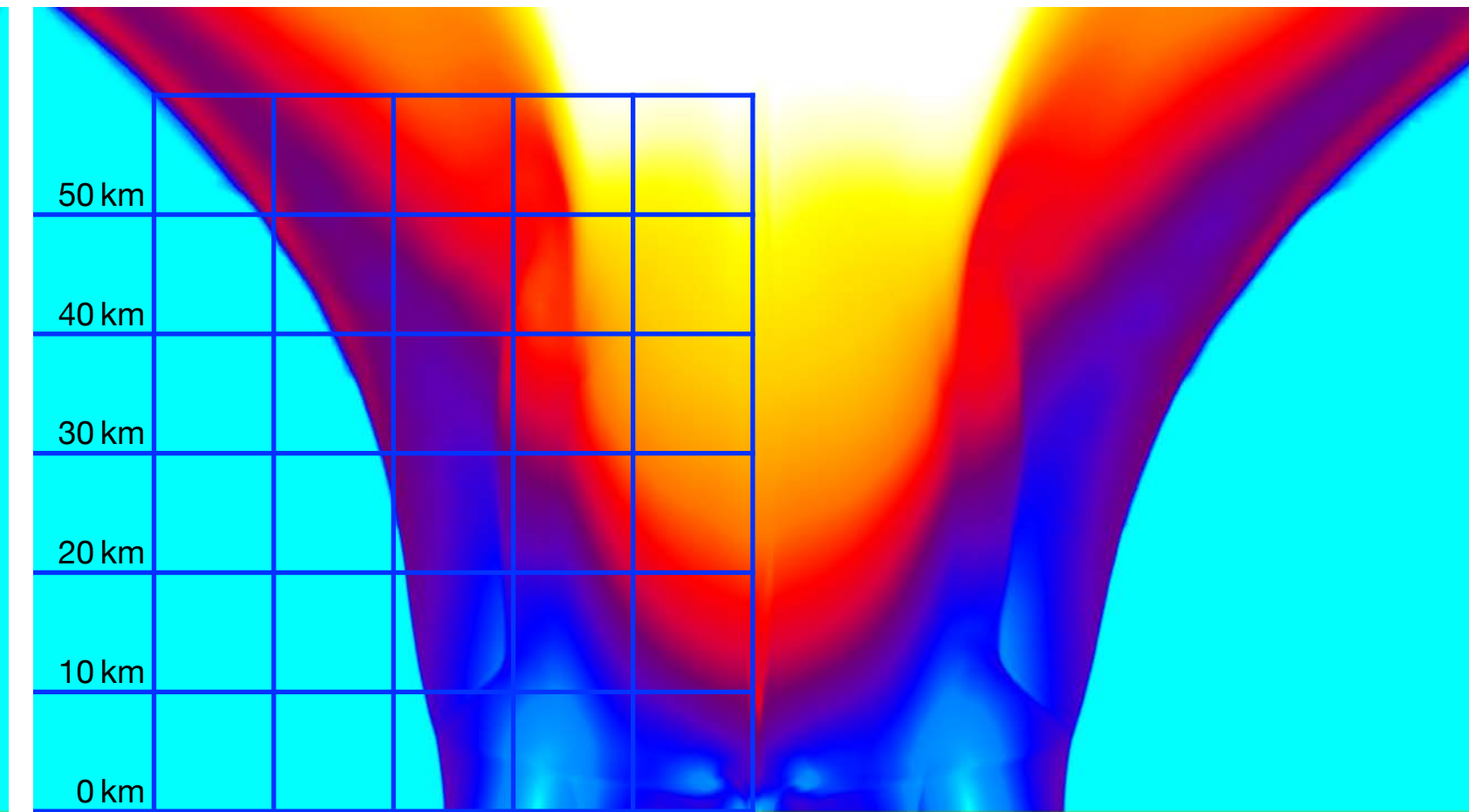
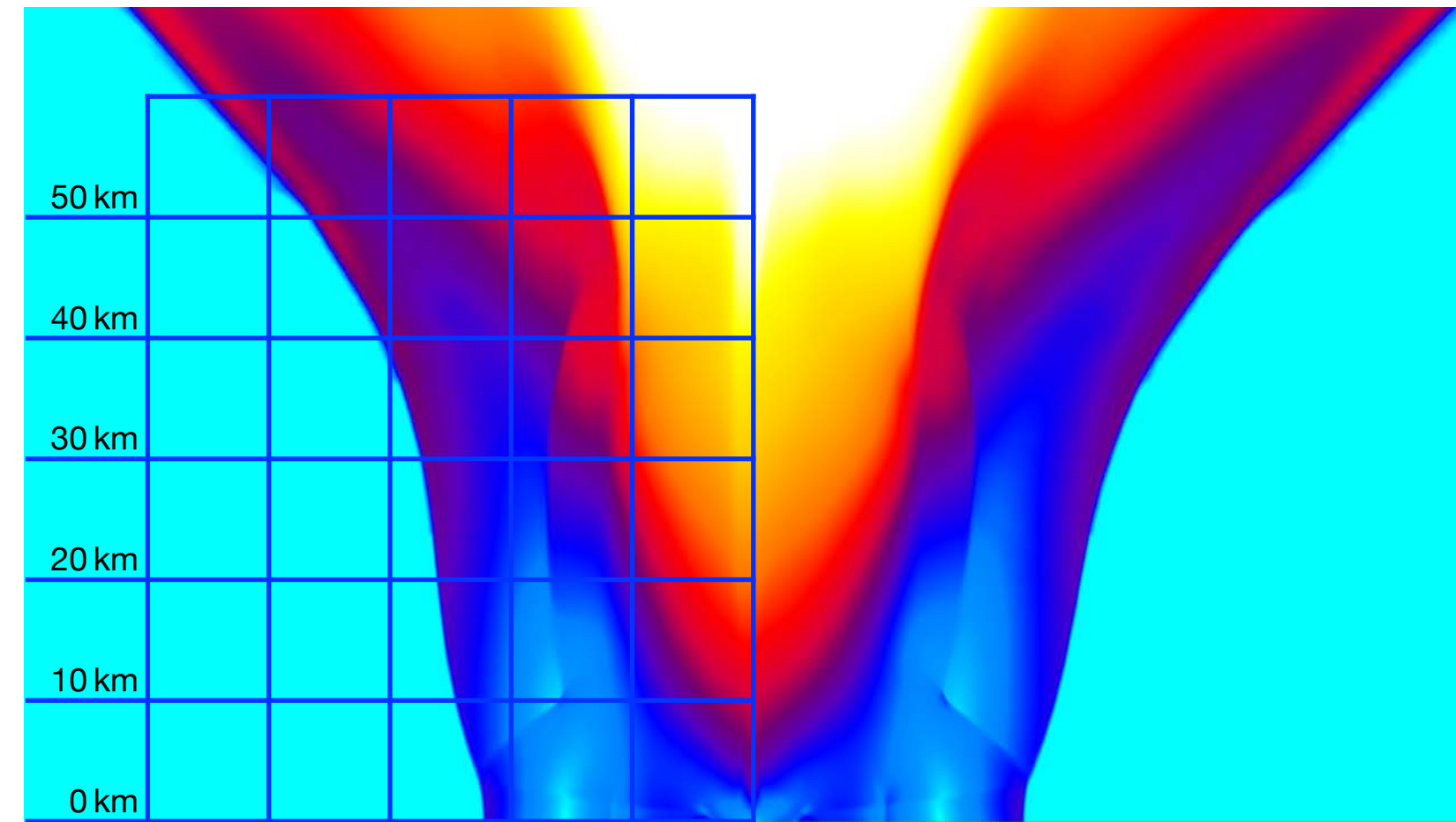
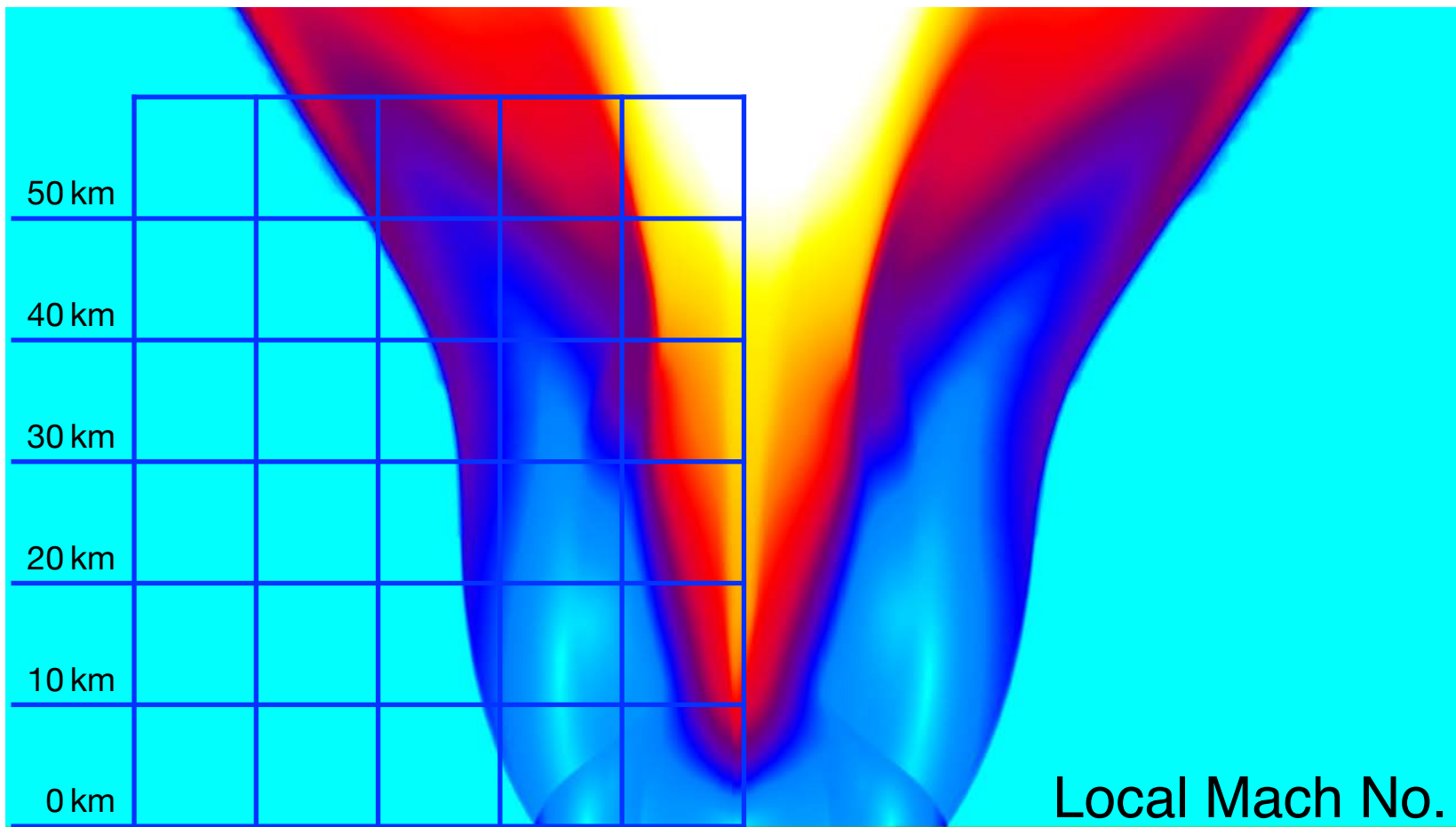
200 Mt

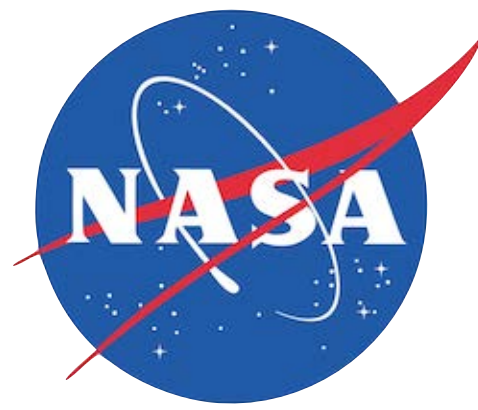
600 Mt



$t = 35.7$ s

Local Mach No.





Athens, 34°: Snapshots of entry & impact

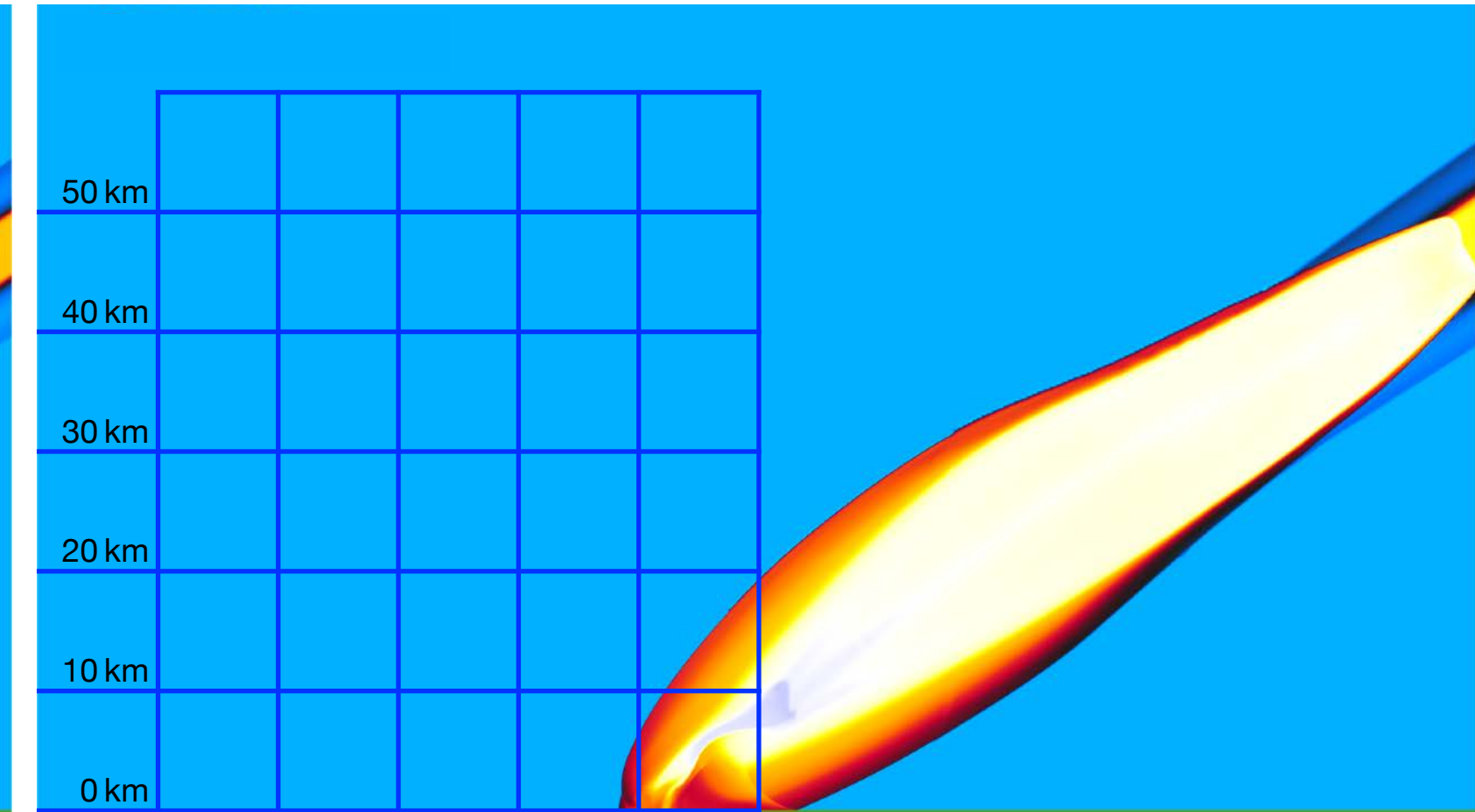
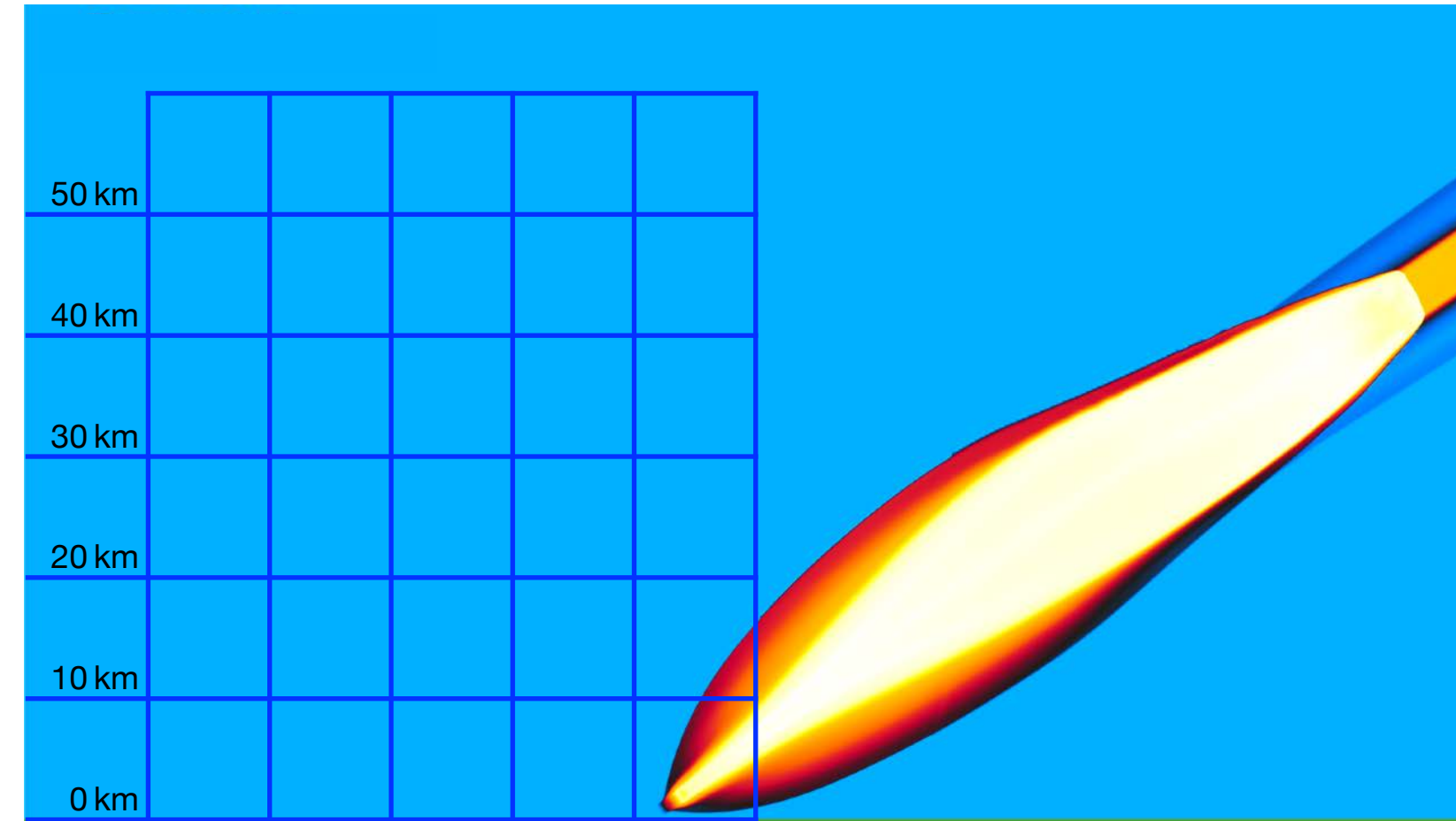
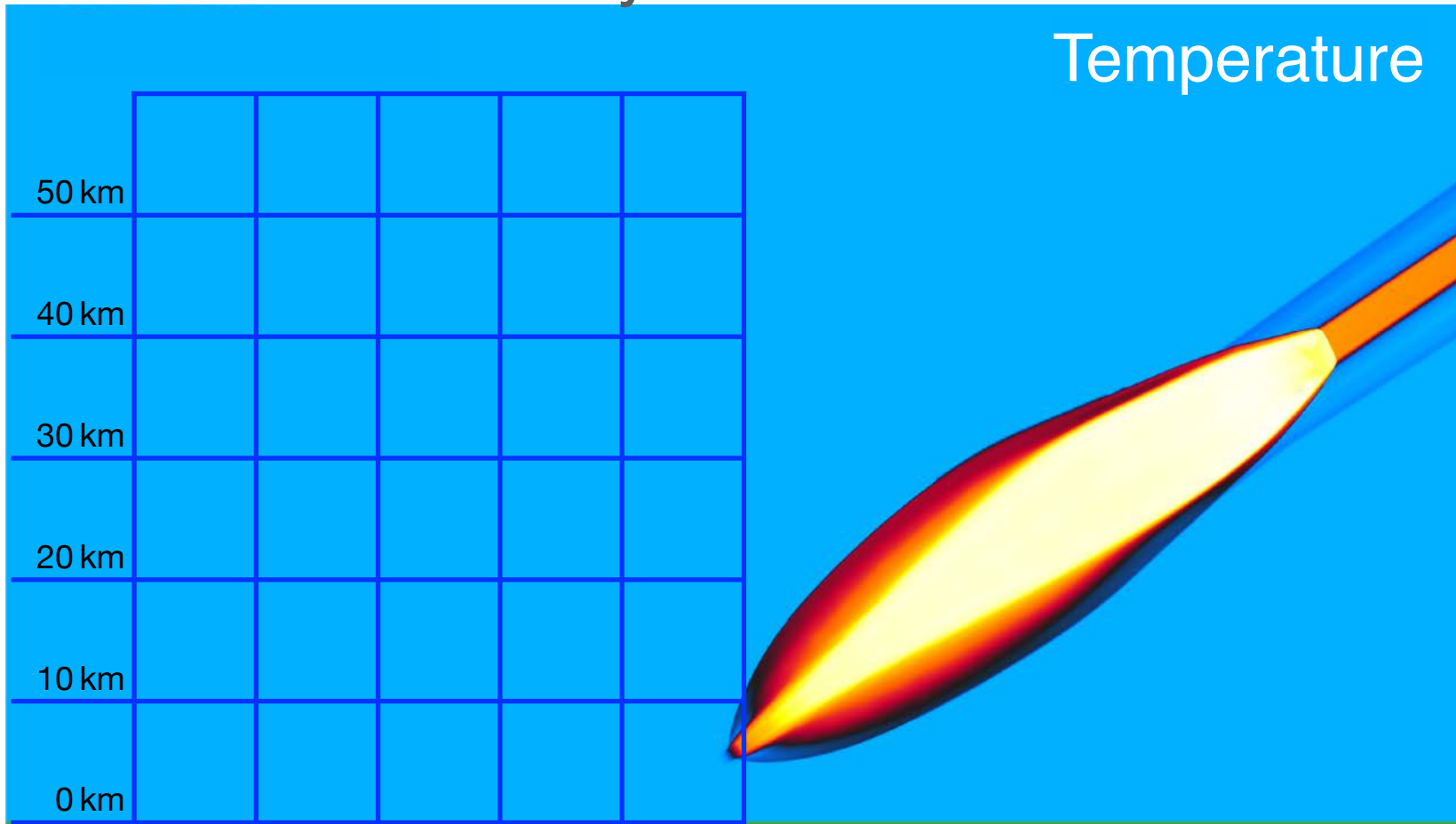
50 & 200 Mt are airburst dominant, 600 Mt is impact

$t = 12.3$ s after entry

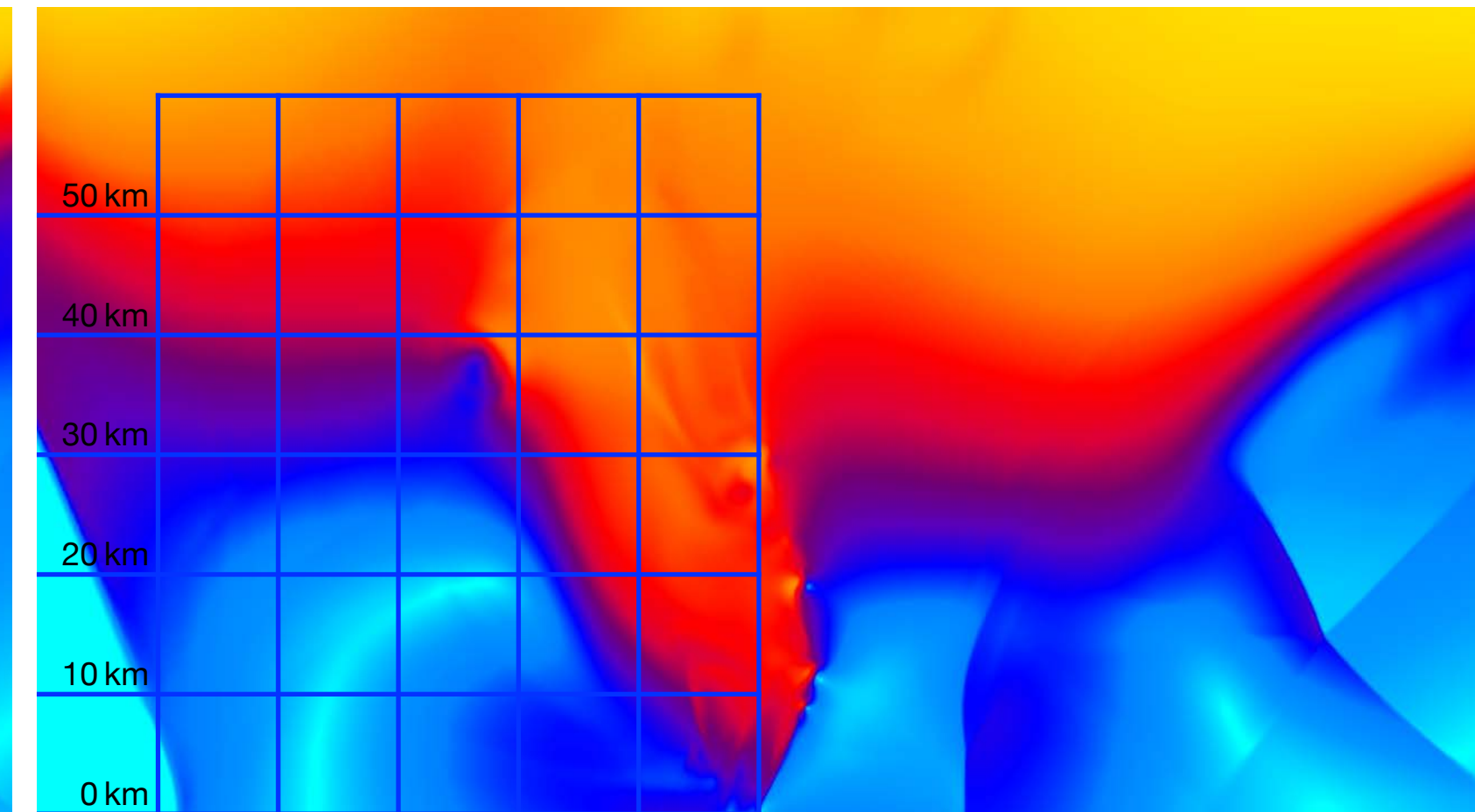
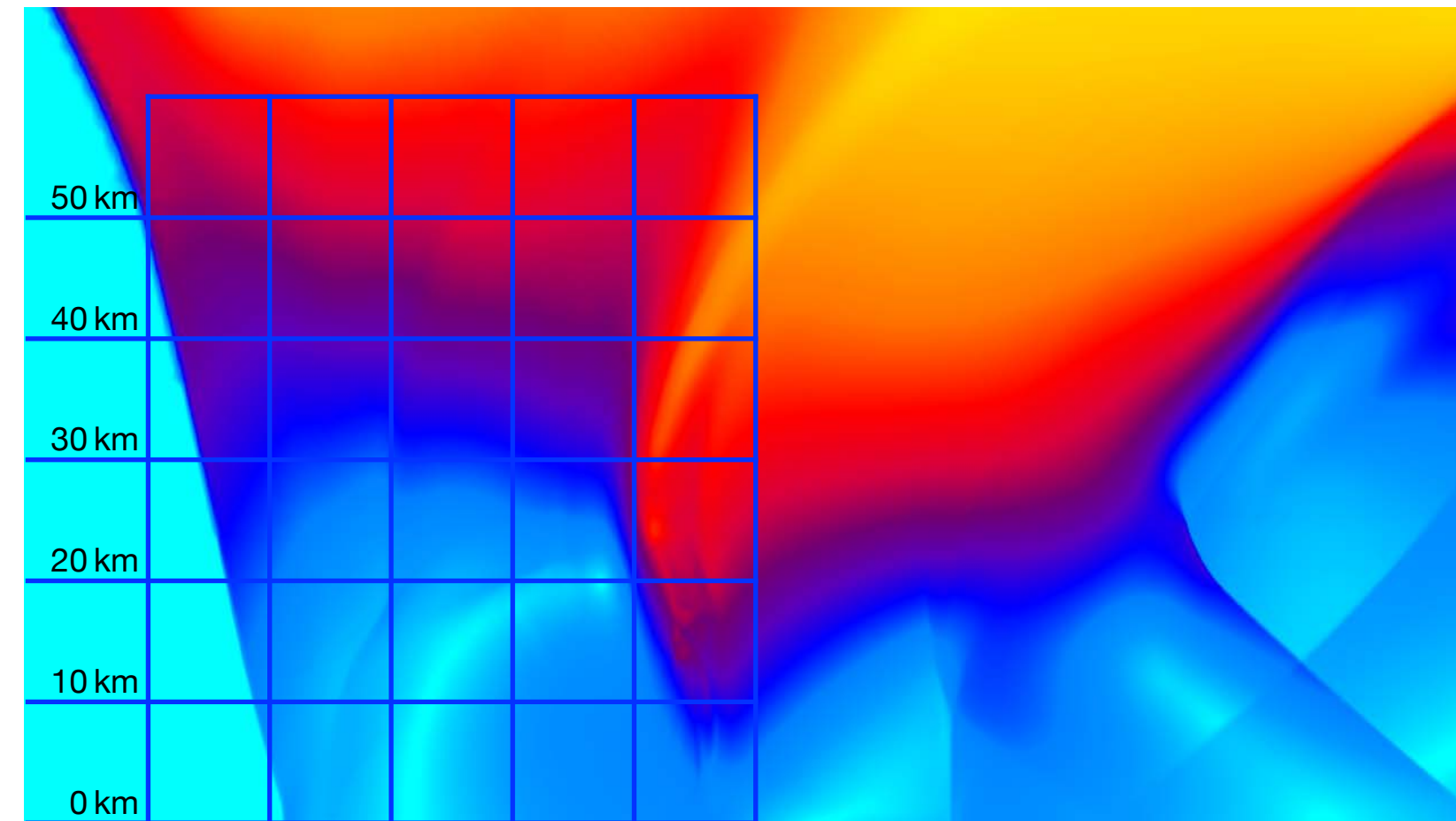
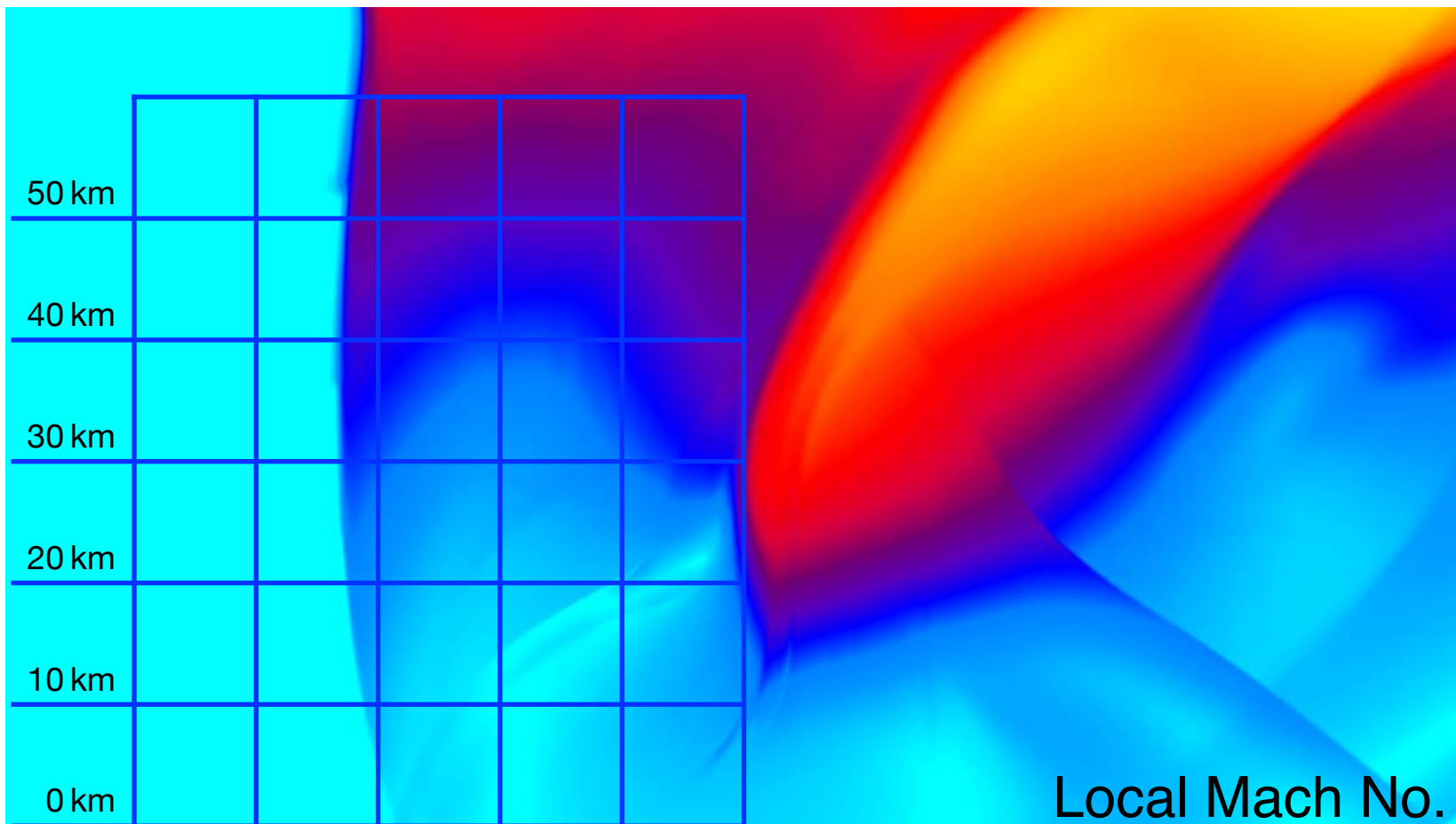
50 Mt
Temperature

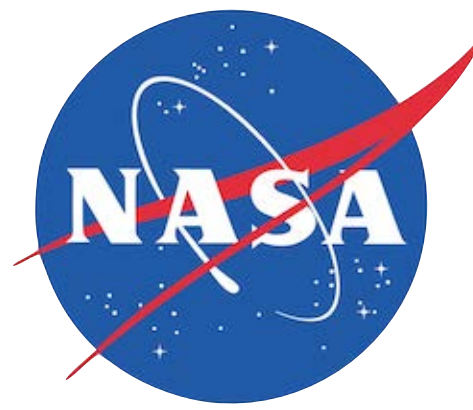
200 Mt

600 Mt



$t = 86$ s



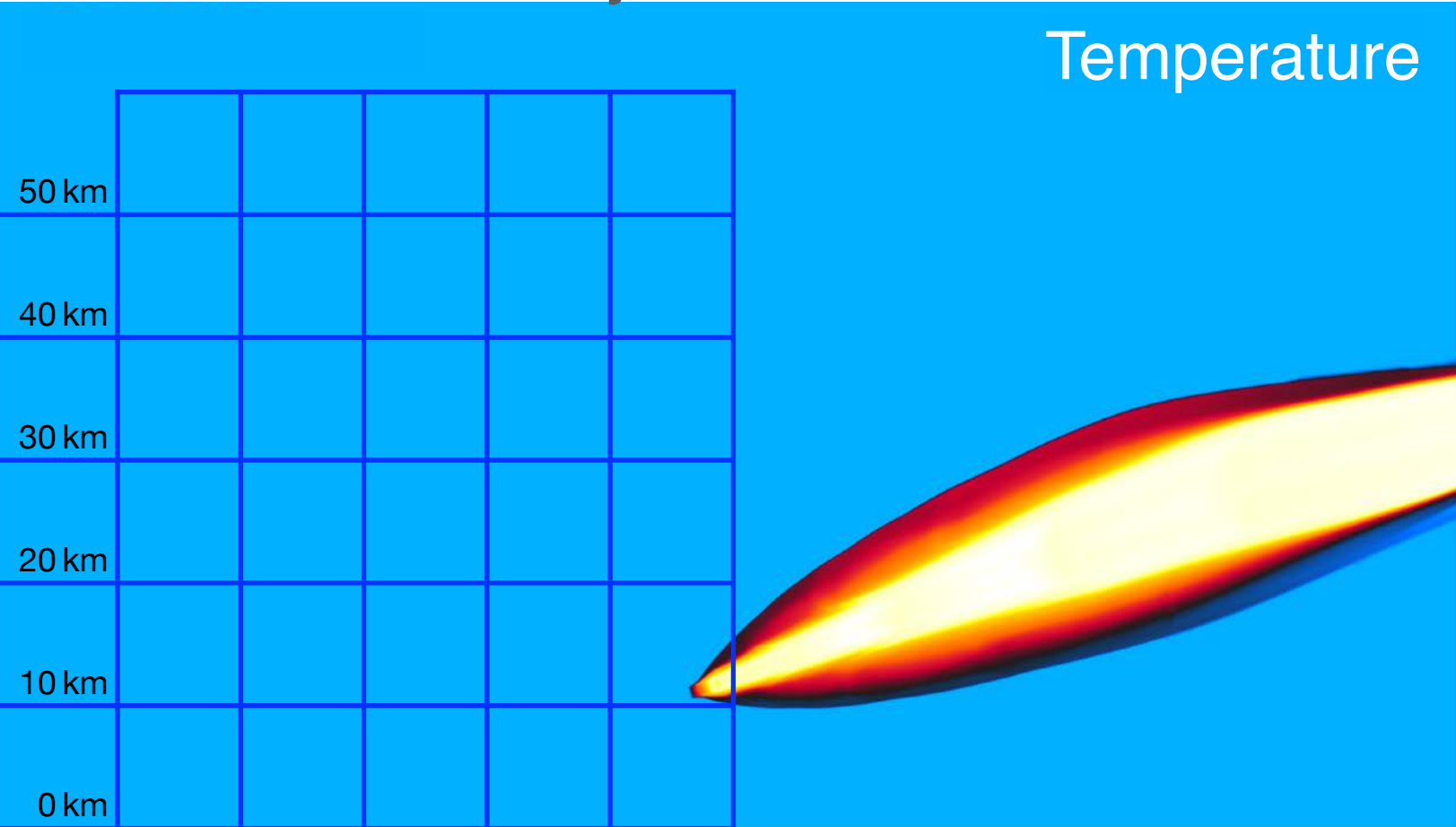


St. Petersburg, 18°: Snapshots of entry & impact

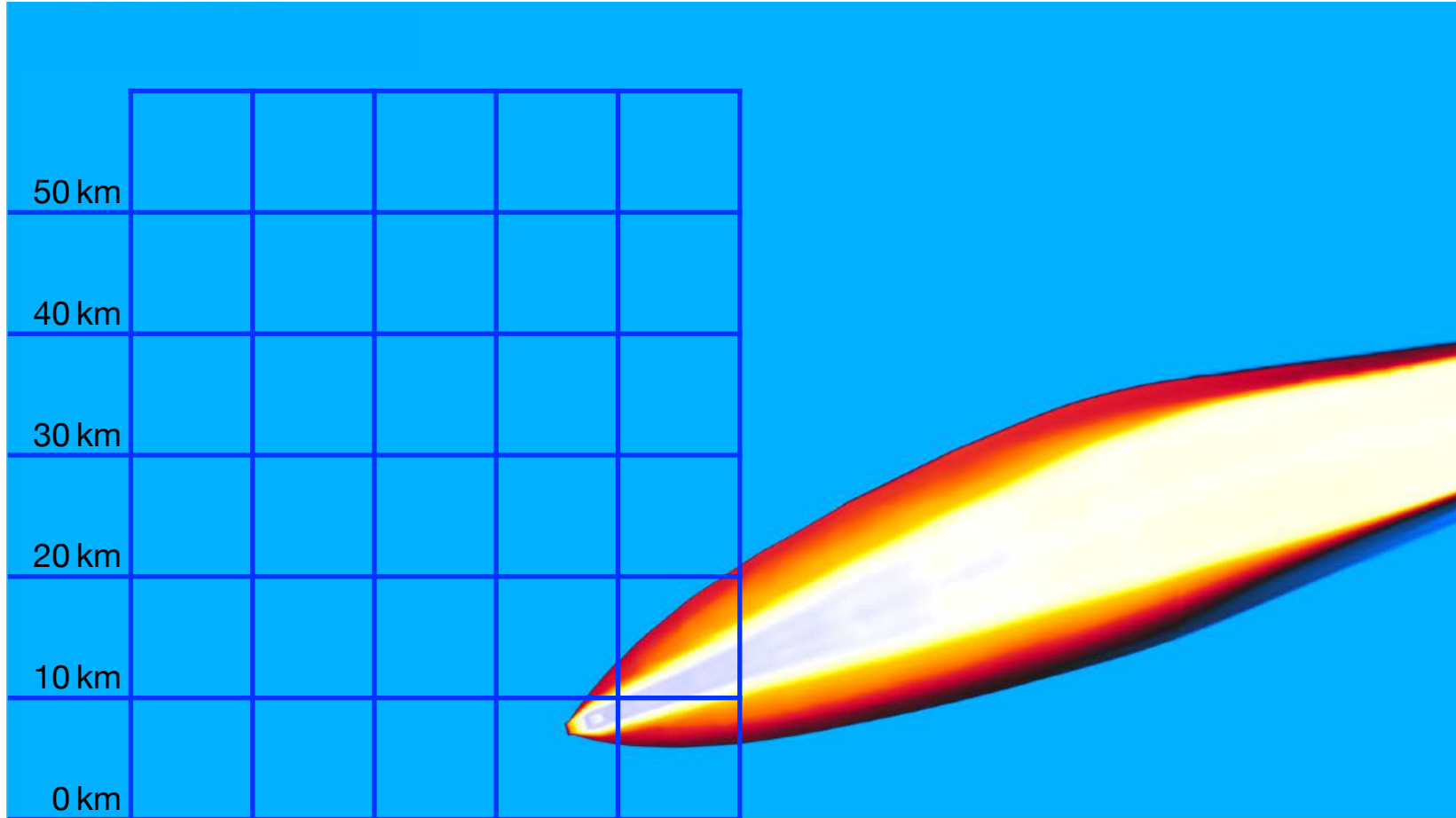
50 & 200 Mt are airburst dominant, 600 Mt is impact

$t = 17.8$ s after entry

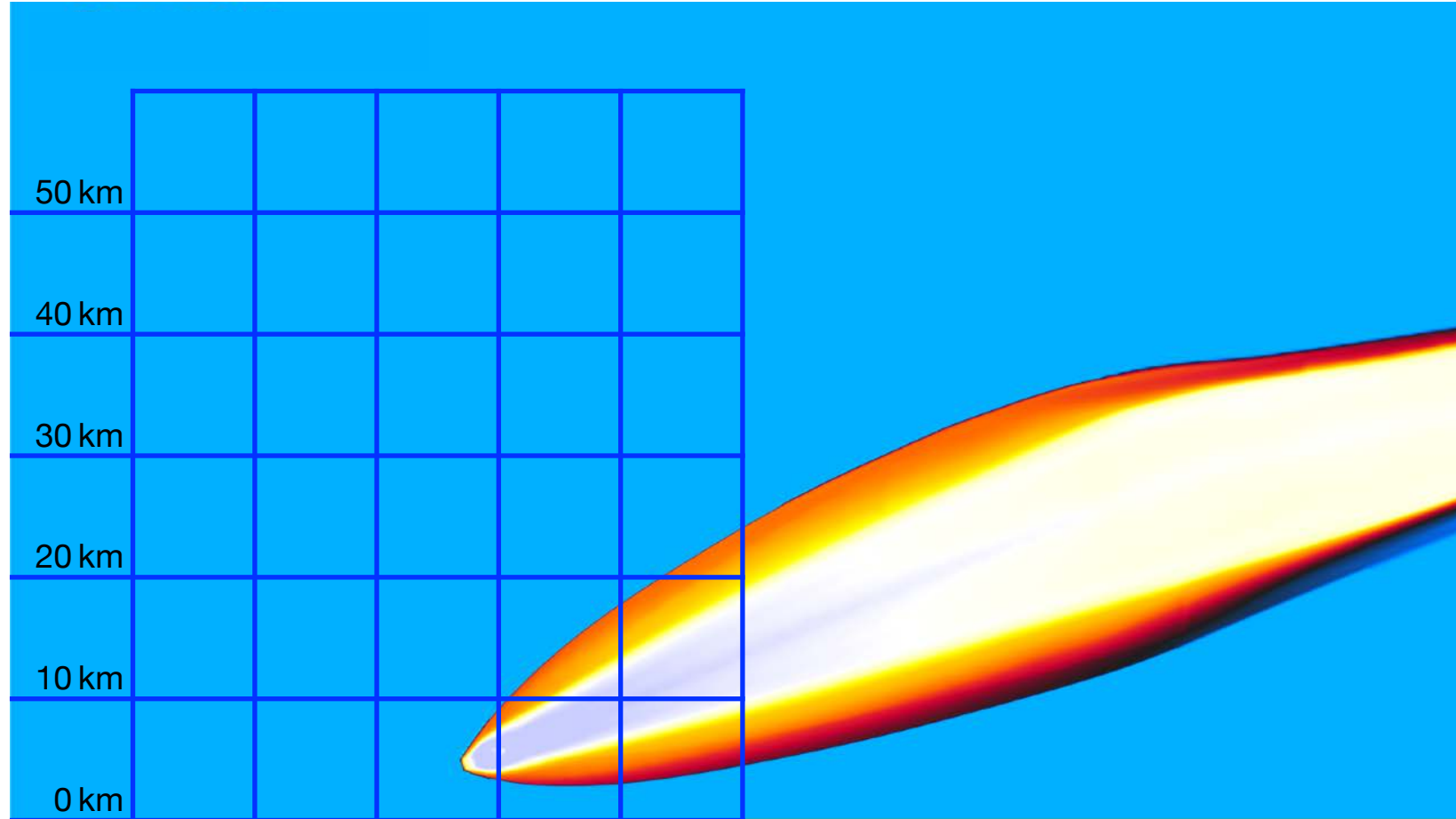
50 Mt
Temperature



200 Mt

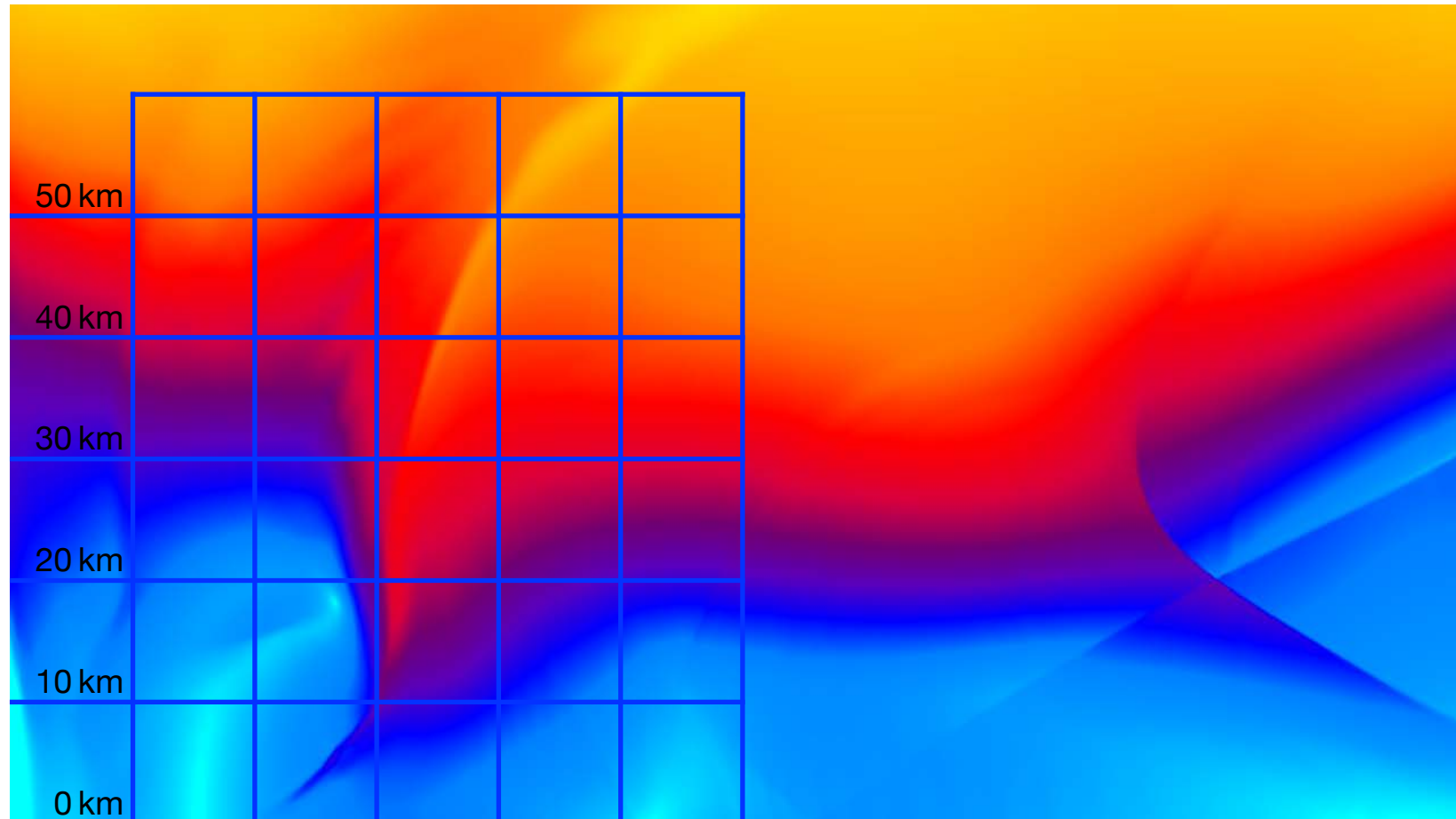
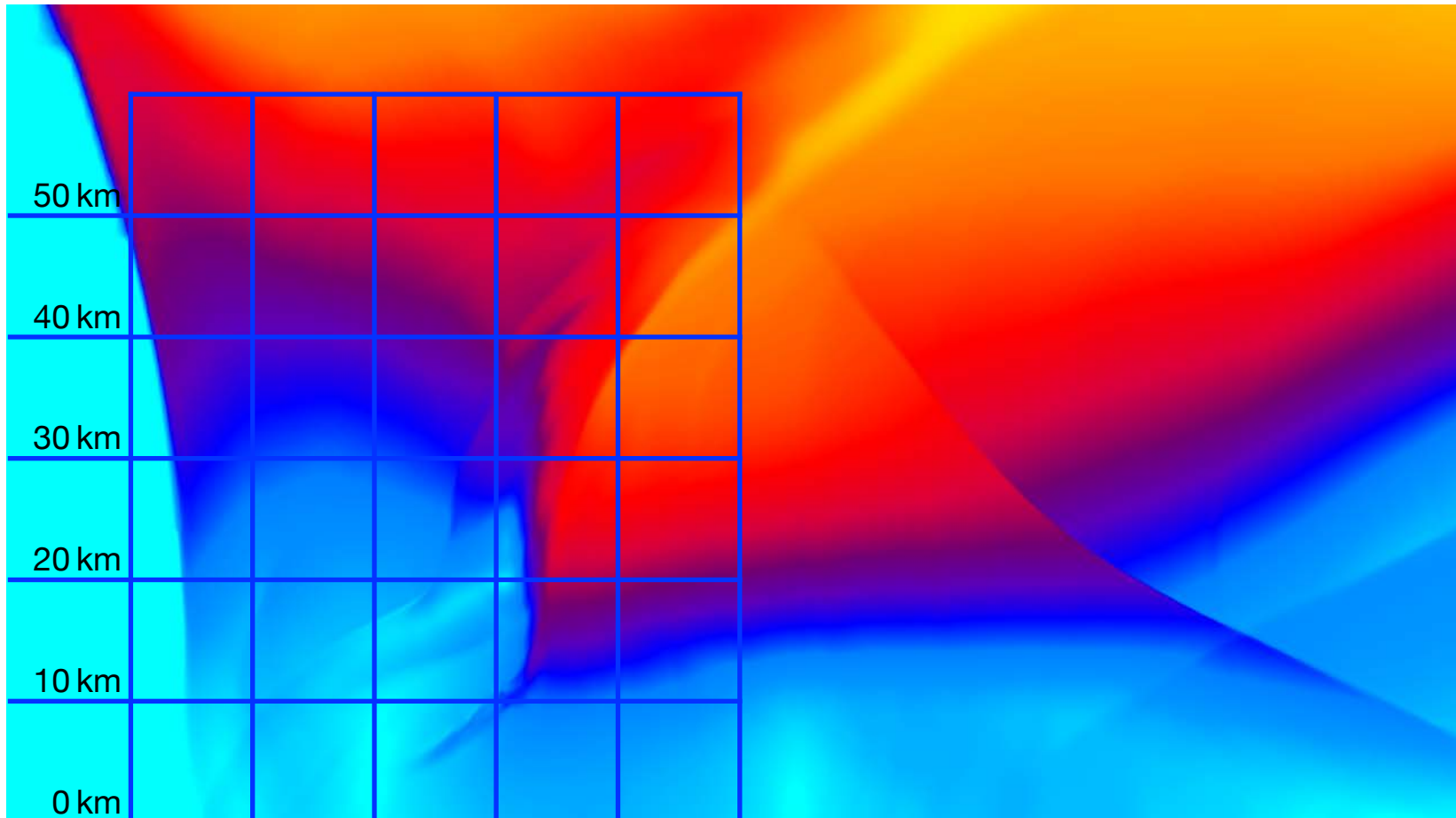
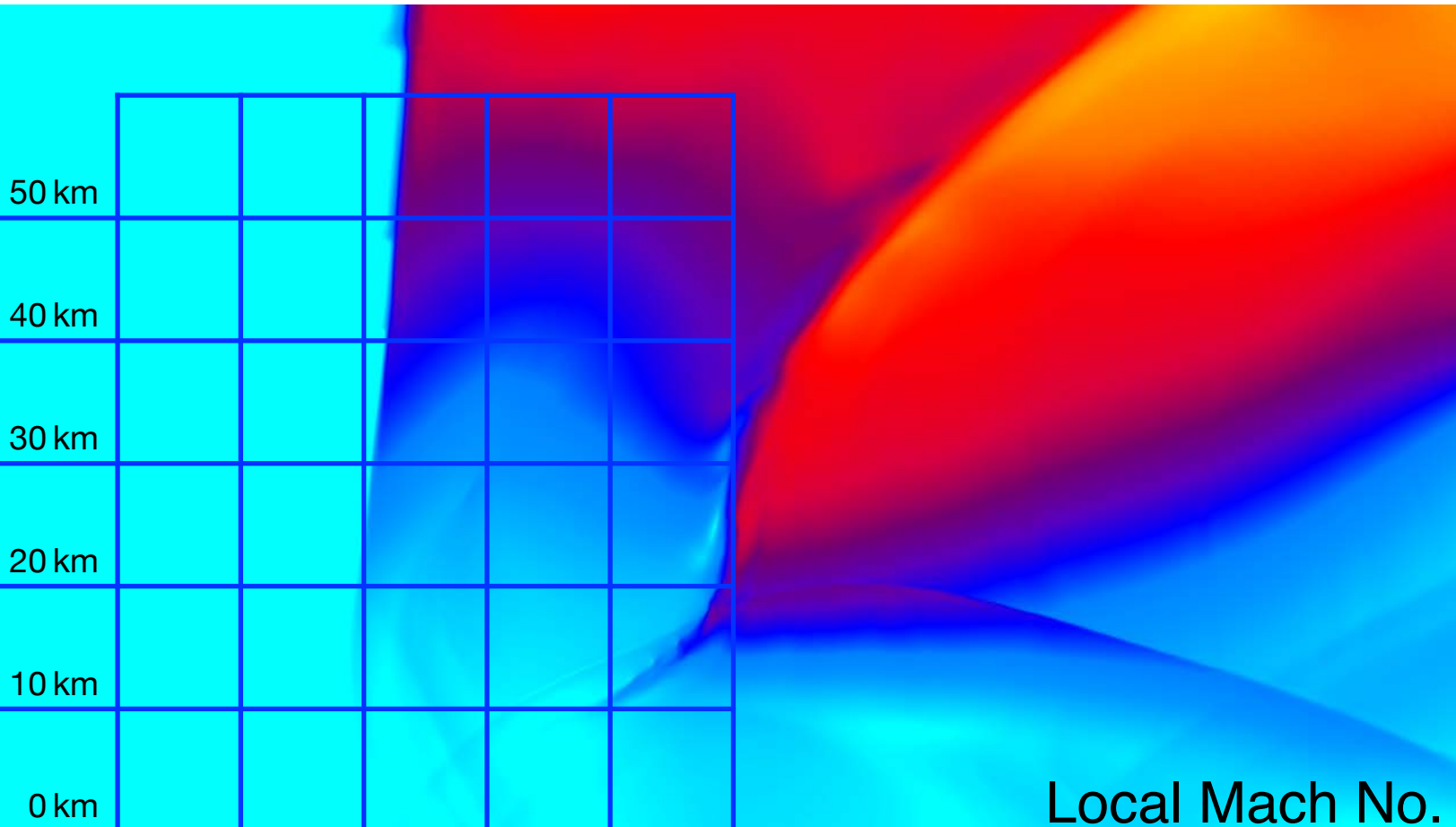


600 Mt



$t = 86$ s

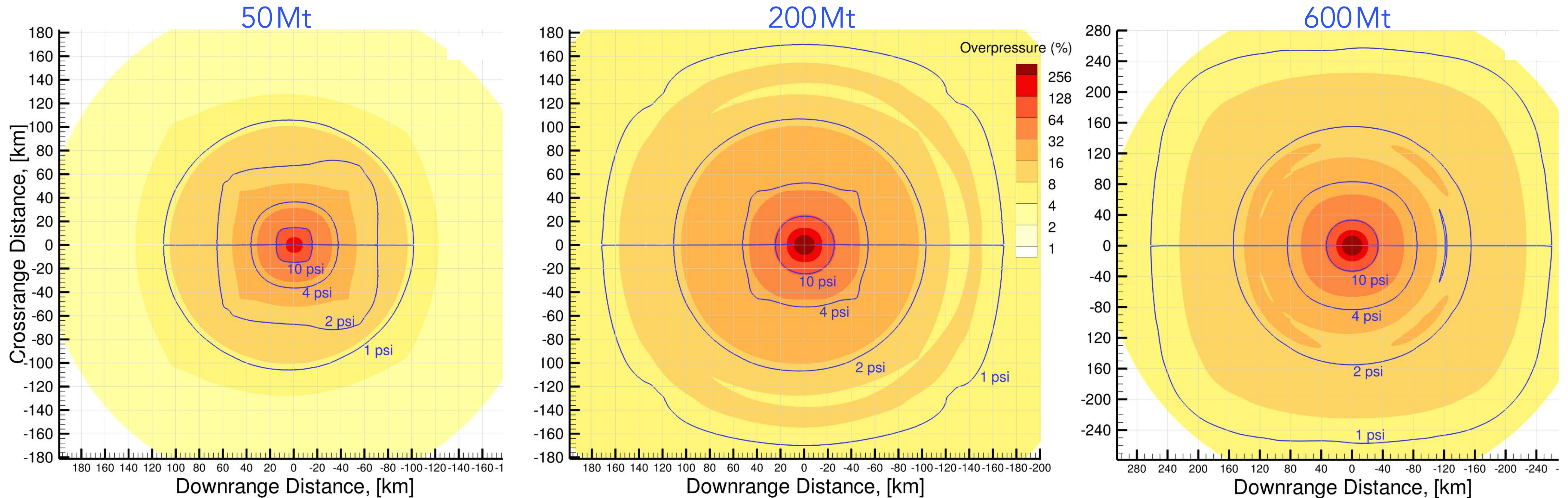
Local Mach No.



Ground overpressure footprints

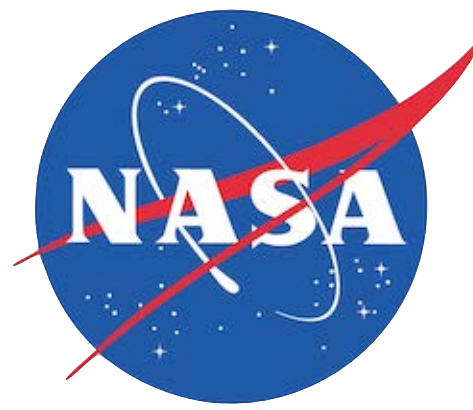


Cape Town, 87°: Local peak overpressure

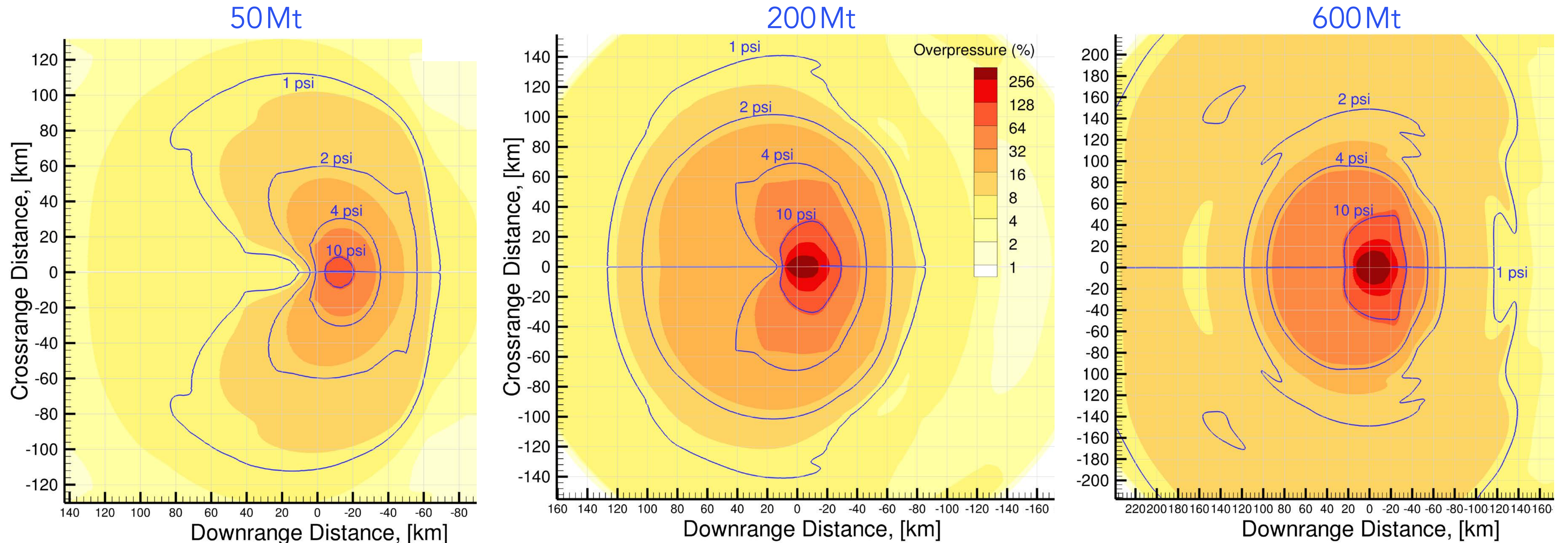


- Largely circular contours, consistent with near vertical impact
- Some grid effects are apparent, but unlikely to change comparison significantly

Ground overpressure footprints

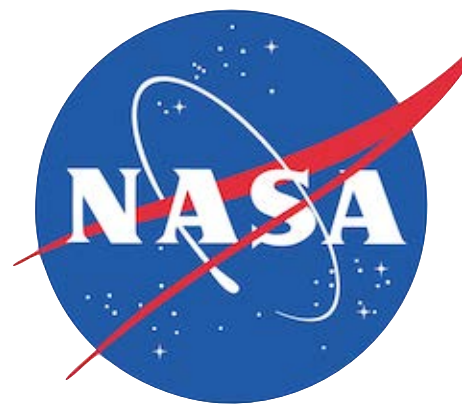


Athens, 34°: Local peak overpressure

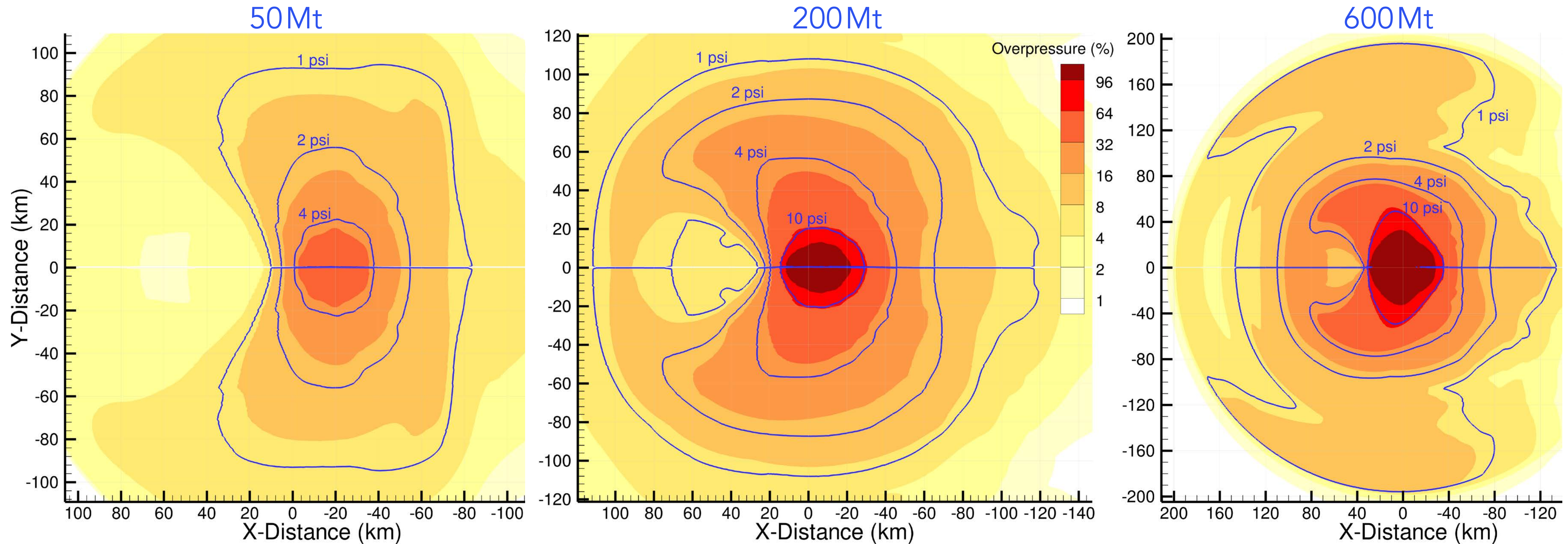


- “Butterfly” shaped contours, typical of oblique entries
- Highest aspect ratios of ~ 1.5 - consistent with earlier studies
- High overpressures more circular (also typical), evidence of shadow region downstream of ground zero

Ground overpressure footprints

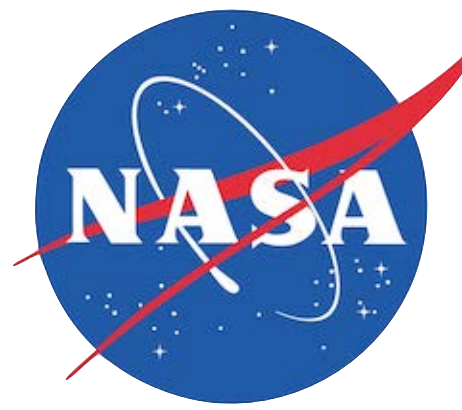


St. Petersburg, 18°: Local peak overpressure



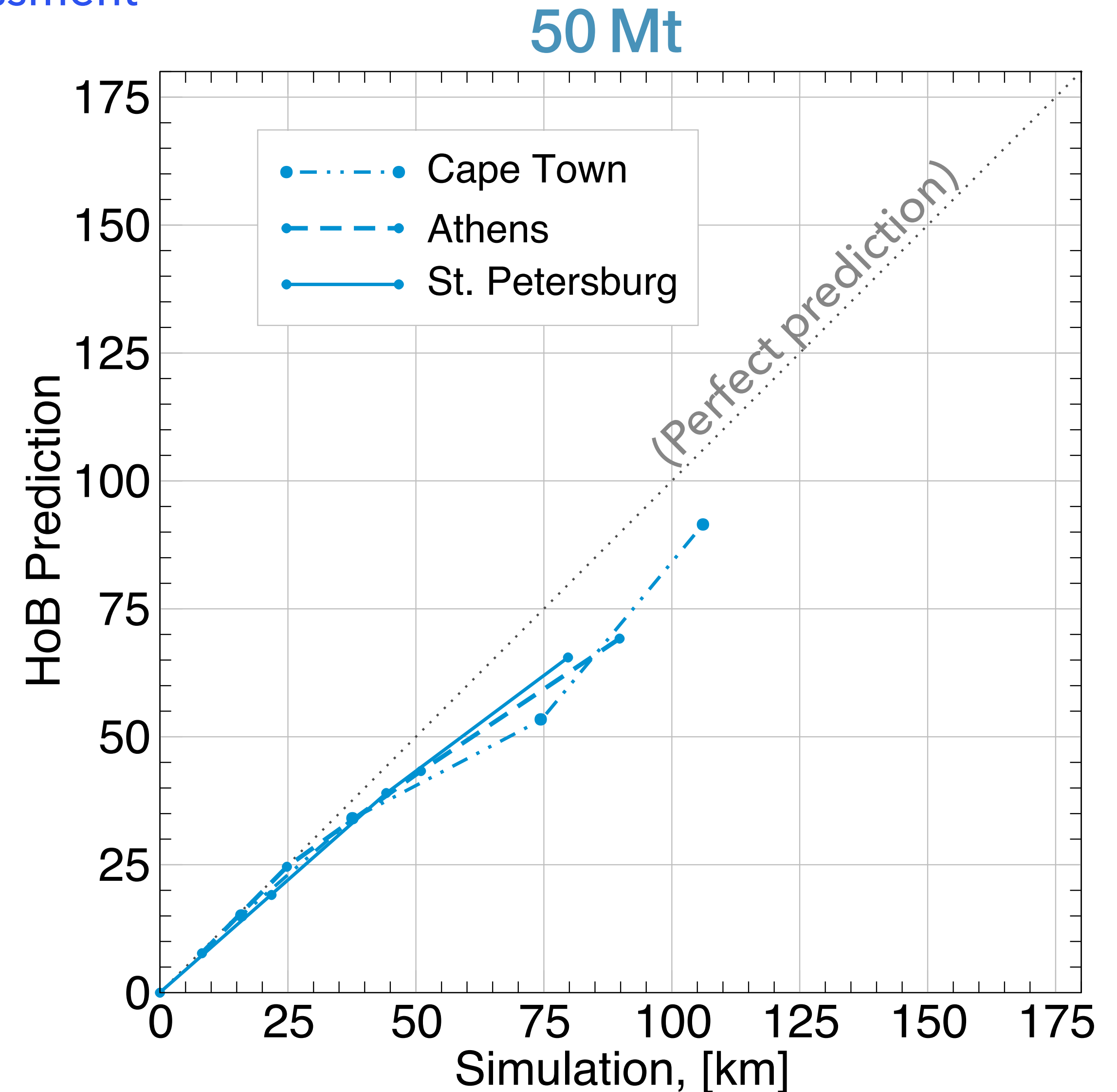
- “Butterfly” shaped contours, typical of oblique entries, evidence of shadow region
- Highest aspect ratios of ~ 1.6 , although low psi contours in 200Mt are somewhat surprising
- 600 Mt simulation not quite done for 1psi

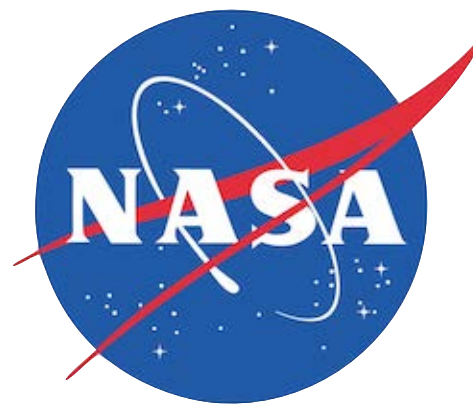
Numerical simulations & results



Compare simulations with HoB model in PAIR Risk-Assessment

- Plot simulation results vs HoB prediction
 - Perfect prediction falls on diagonal
 - Higher overpressures (smaller damage radii) are near origin
- All entries are predominantly airbursts
- Predictions are all reasonable
 - Slight underprediction of lower overpressures
 - HoB most accurate at Athens (34°) and St. Petersburg (18°)

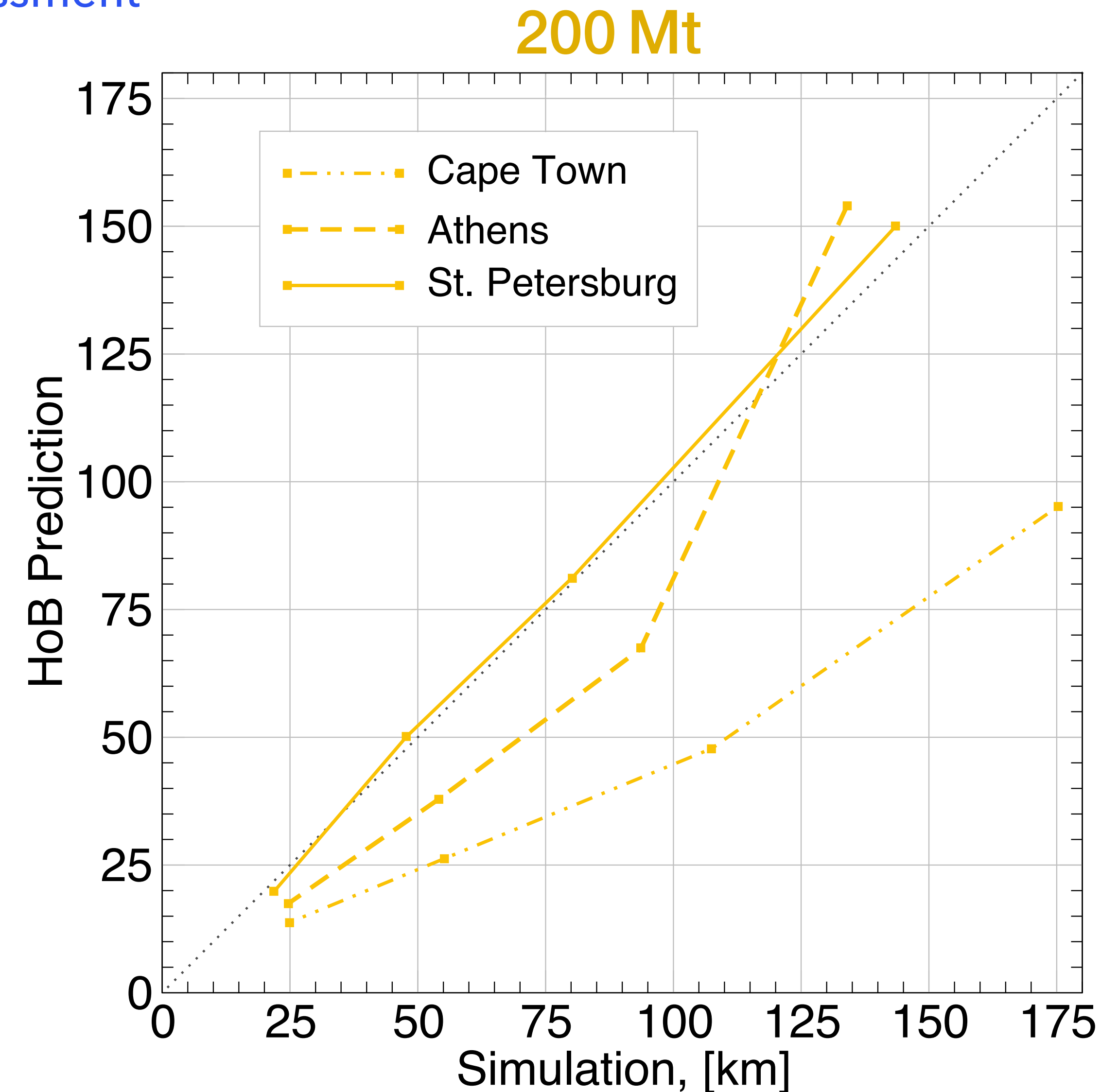




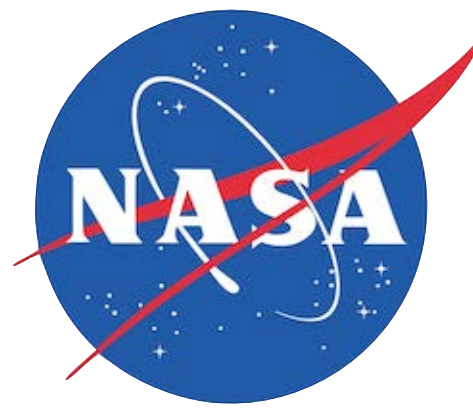
Numerical simulations & results

Compare simulations with HoB model in PAIR Risk-Assessment

- Airburst in St. Petersburg (18°) & Athens (34°)
- Post-peak ground impact in CapeTown (87°)
- HoB shows best prediction of highest overpressures
- HoB generally less accurate farther from ground zero and for steeper entries where ground impact occurs (e.g. Cape Town)
- St. Petersburg is “pure” airburst and well predicted

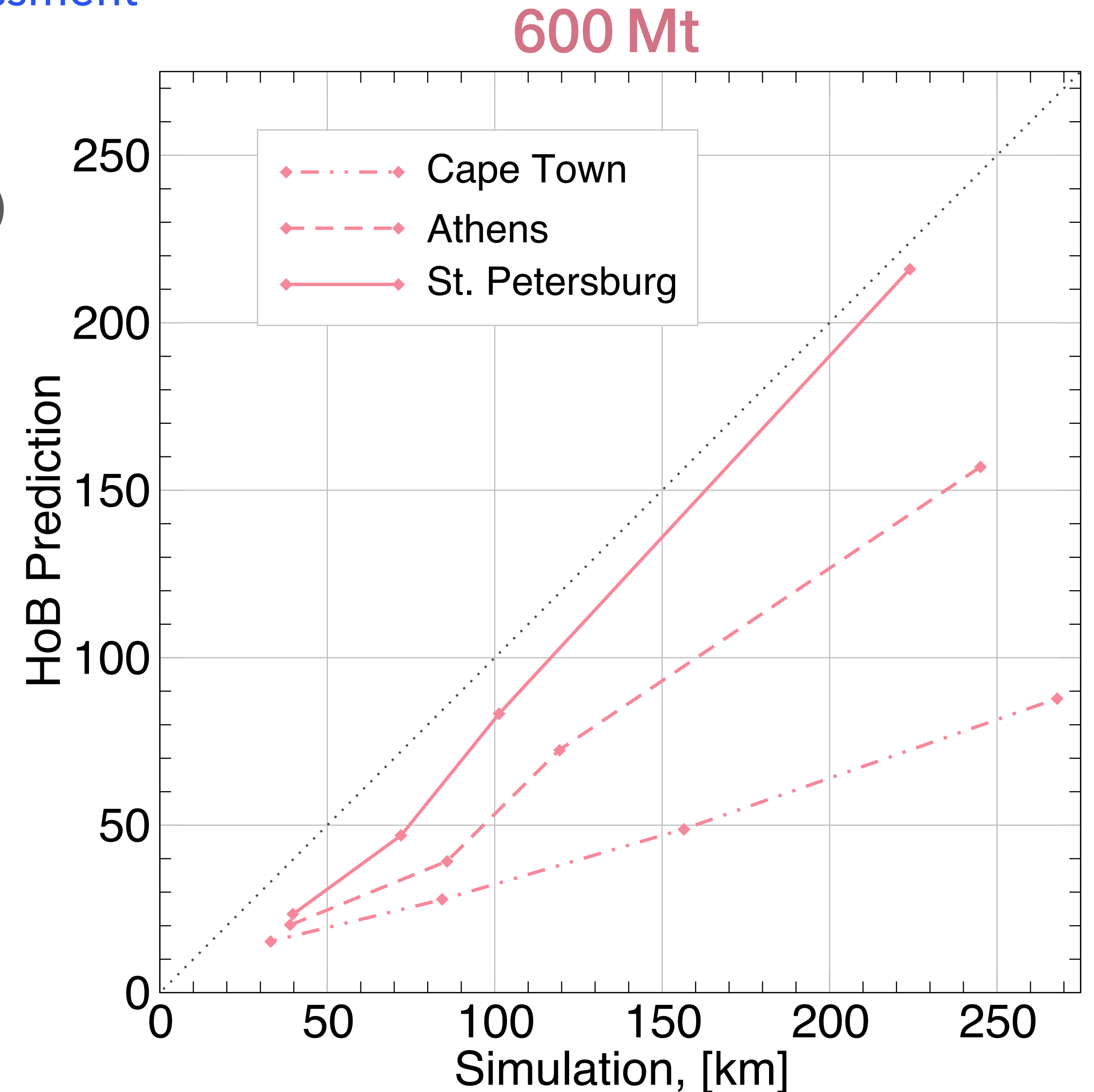


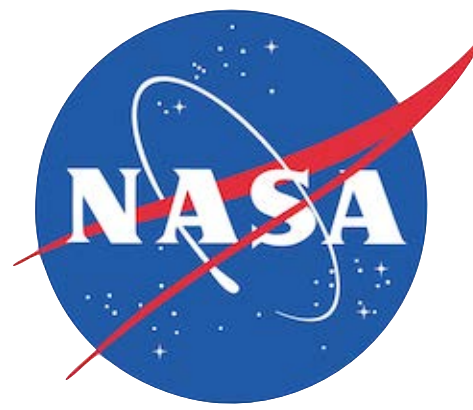
Numerical simulations & results



Compare simulations with HoB model in PAIR Risk-Assessment

- Ground impact at Cape Town (87°) & Athens (34°)
- Airburst at St. Petersburg (18°) shows best prediction
- Extent of ground damage is under predicted for both ground impacting cases
- Underprediction is most severe for Cape Town which has the largest ground impact



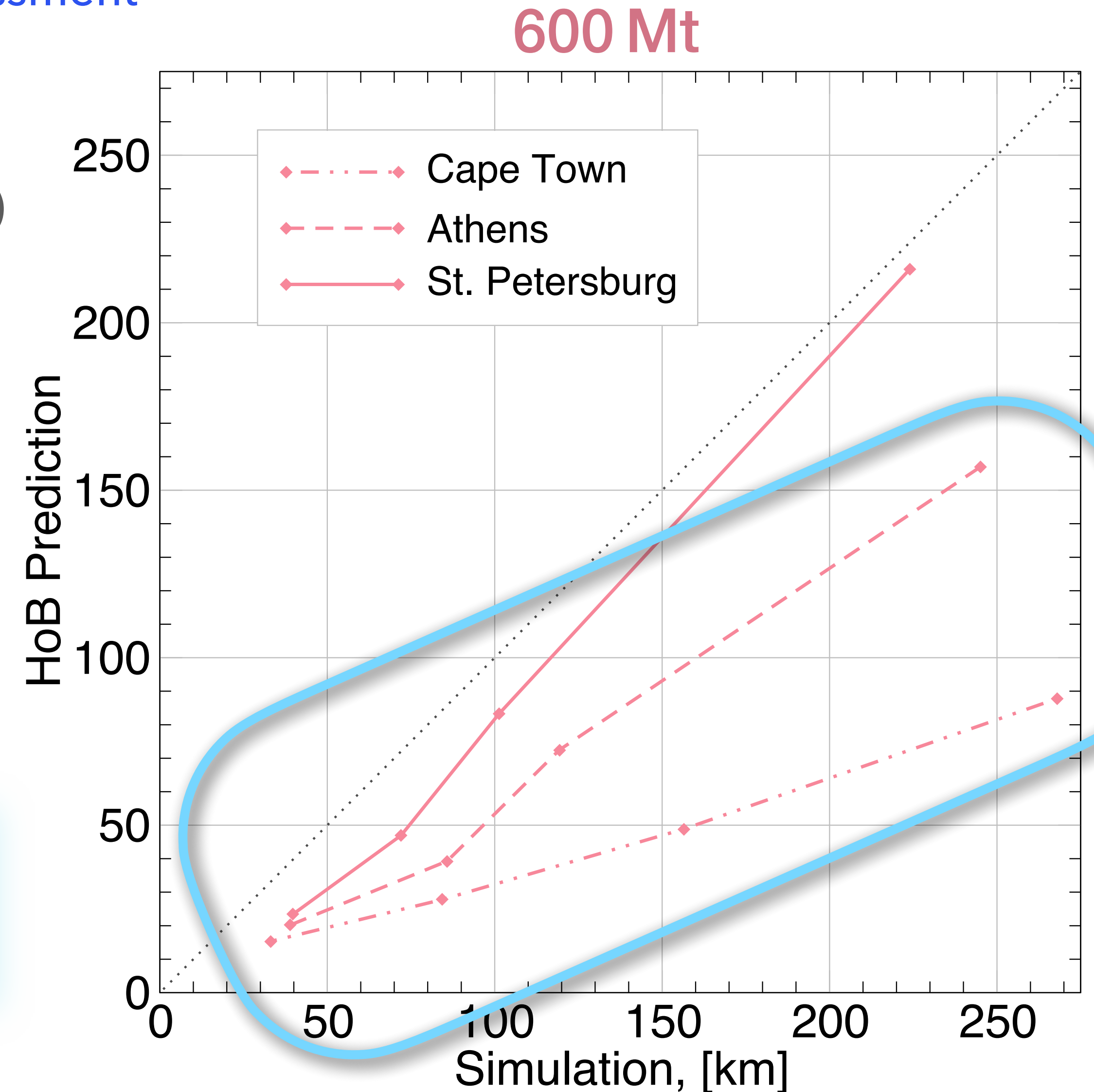


Numerical simulations & results

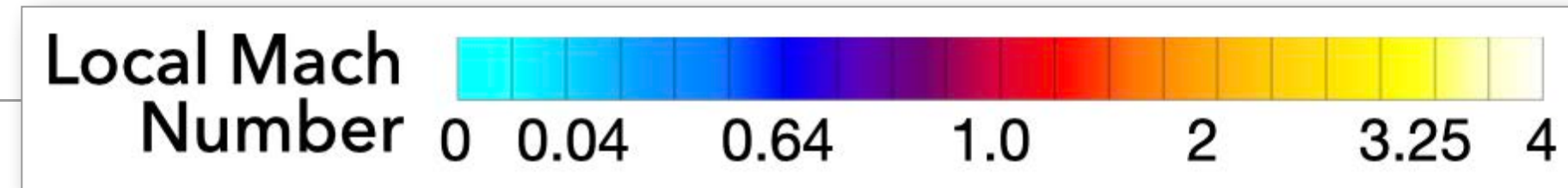
Compare simulations with HoB model in PAIR Risk-Assessment

- Ground impact at Cape Town (87°) & Athens (34°)
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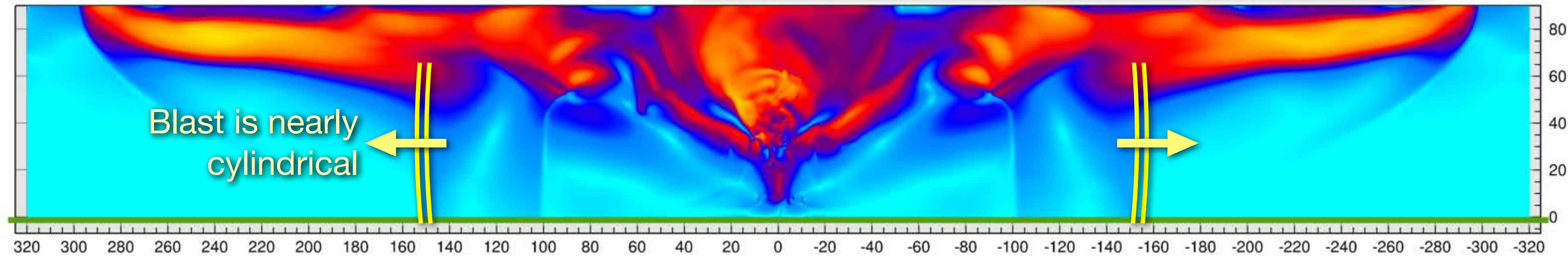
Look at Cape Town & Athens more closely



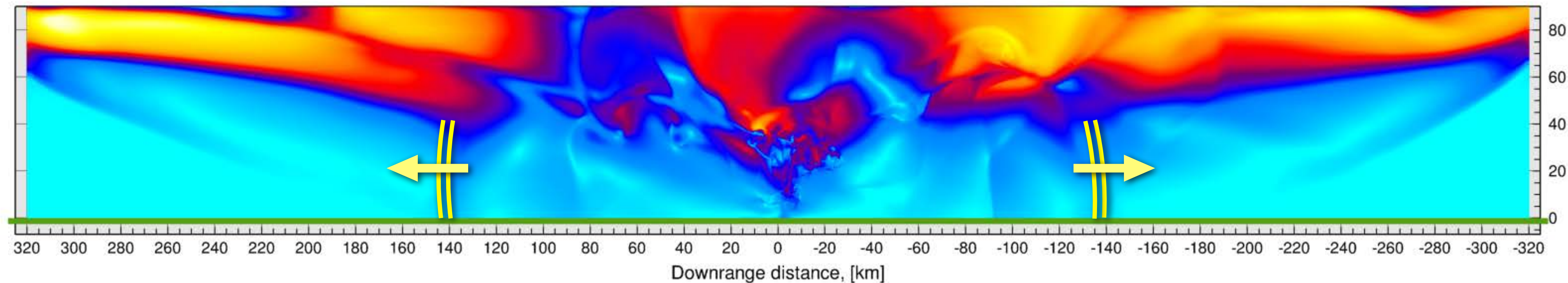
Numerical simulations & results



Cape Town, 600Mt
(380s after entry)

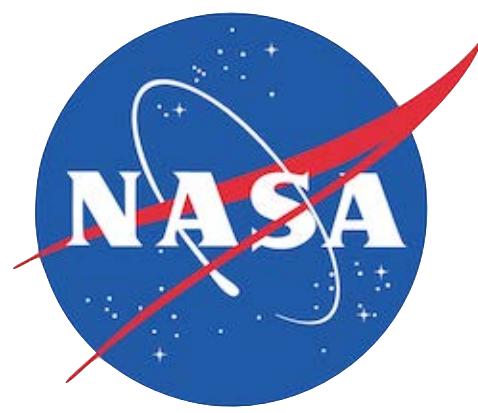


Athens, 600Mt
(320s after entry)

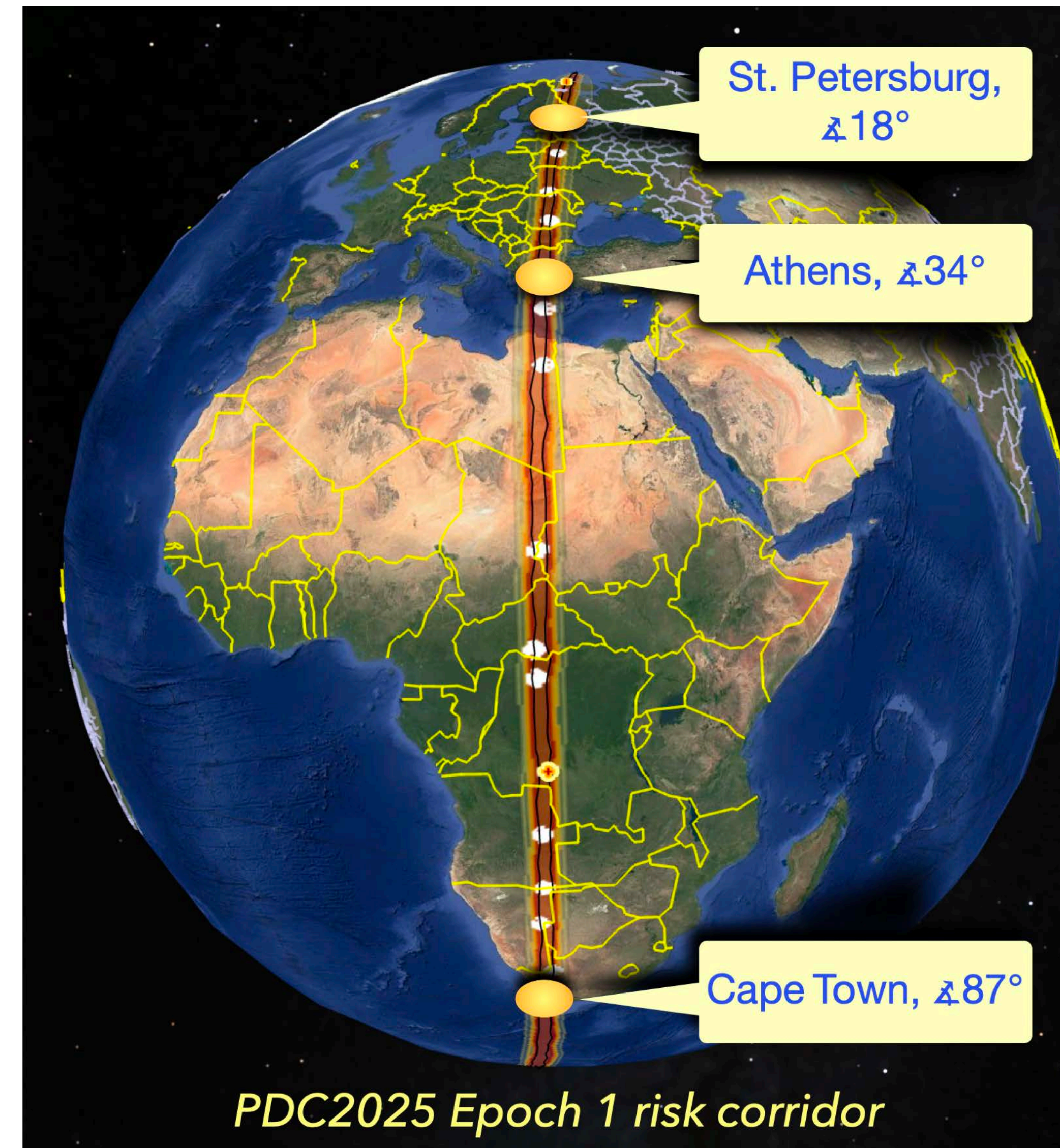


- Blast waves far from impact are essentially cylindrical shocks, confined between upper atmosphere and ground
- Dominant decay rate is cylindrical, not spherical, especially far from impact
- Once the blast becomes similar in scale to the thickness of the atmosphere, overpressures decay slower than predicted by classical spherical blast-based methods

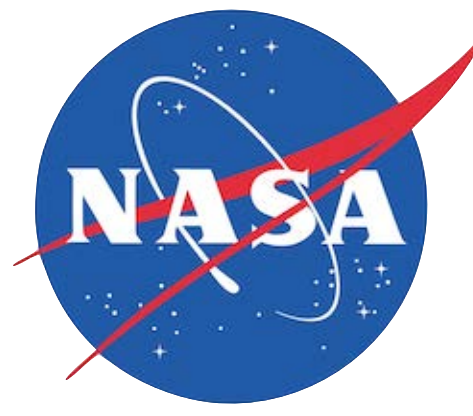
Summary



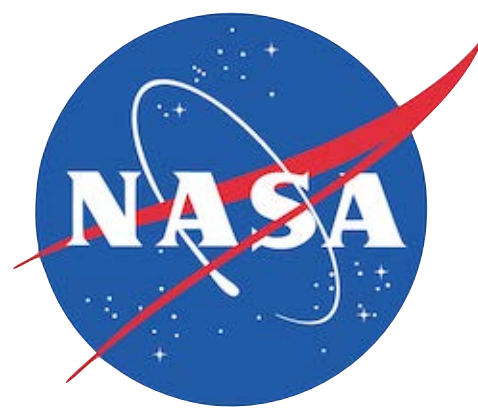
- Performed high-fidelity blast modeling for PDC25 Epoch 1 asteroids
 - Examined median, 95th and 99th-percentile asteroids
 - Compared blast overpressure predictions with those of the fast-running HoB-based tools used in Risk Assessment
- HoB-based predictions for airburst events were generally very accurate
 - Ground-impacting cases were less well predicted
 - Predictions for median sized 50Mt blast was accurate at all locations
 - 200 & 600Mt (95 & 99th-percentile) showed good agreement where blast was airburst-dominant
- At distances comparable to the thickness of the atmosphere, large blasts get confined between the surface of the earth and the upper atmosphere
 - This confinement results in essentially cylindrical blast expansion which slows decay of ground overpressure with distance
 - HoB predictions are based on spherical blast decay and therefore under-predict damage radii for large blasts at large distances



Backup



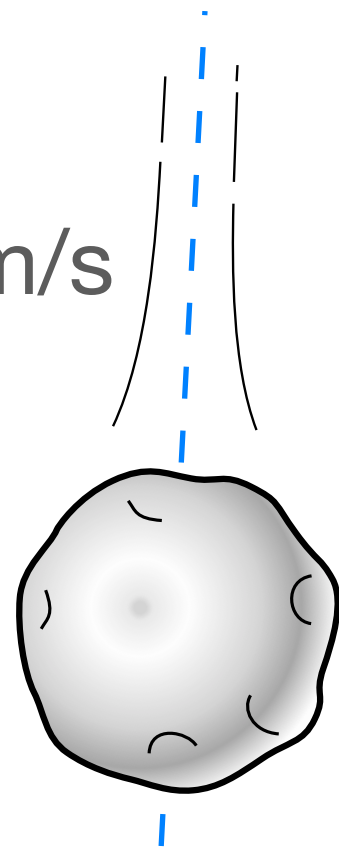
Impact Scenarios: Entry profiles & energy deposition



Height of burst varies with entry angle and size

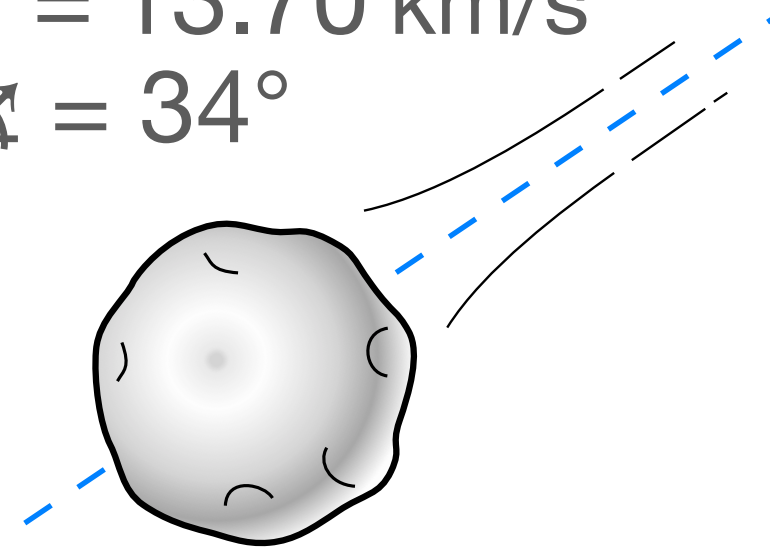
Cape Town

$V = 13.75 \text{ km/s}$
 $\Delta = 87^\circ$



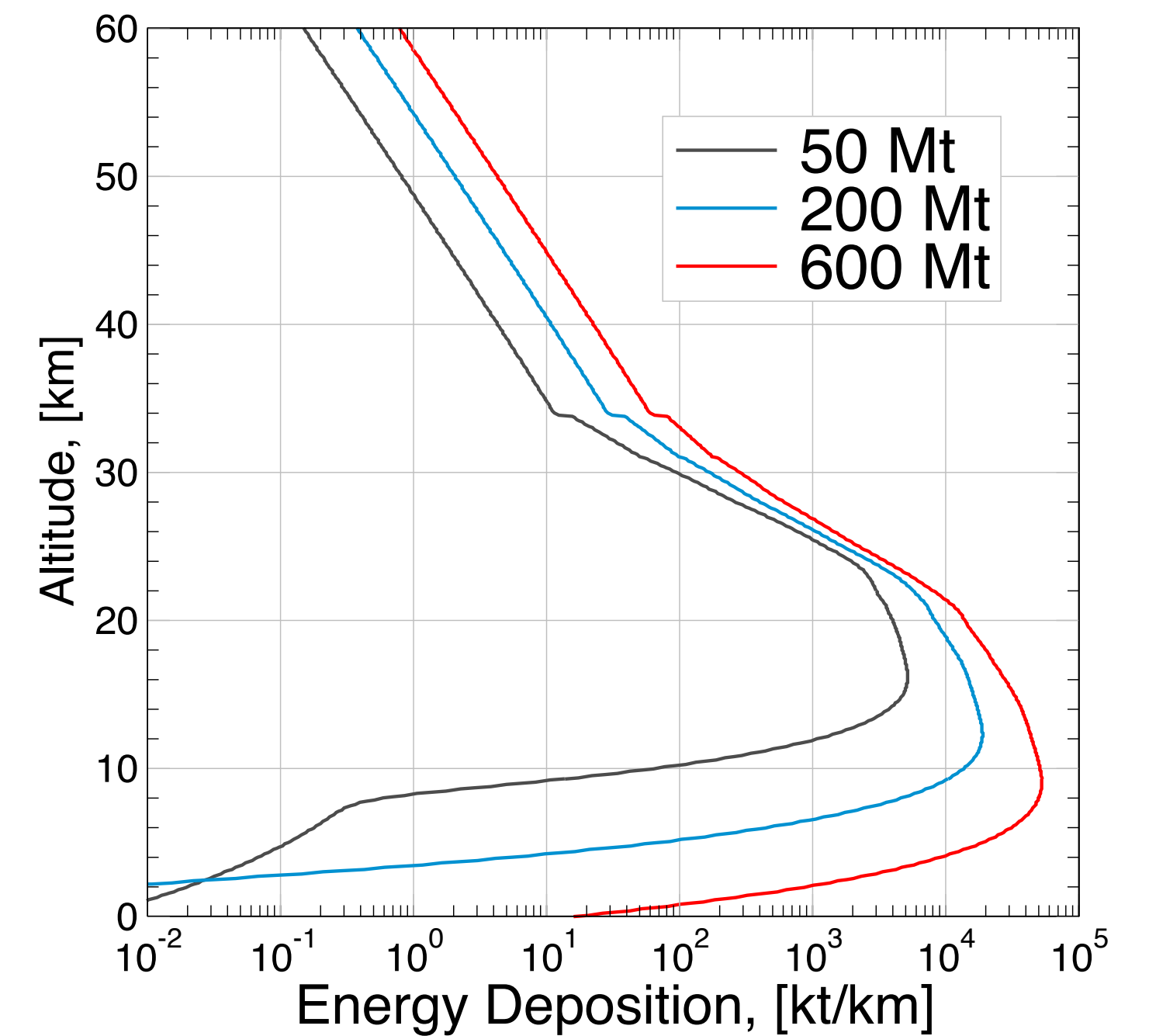
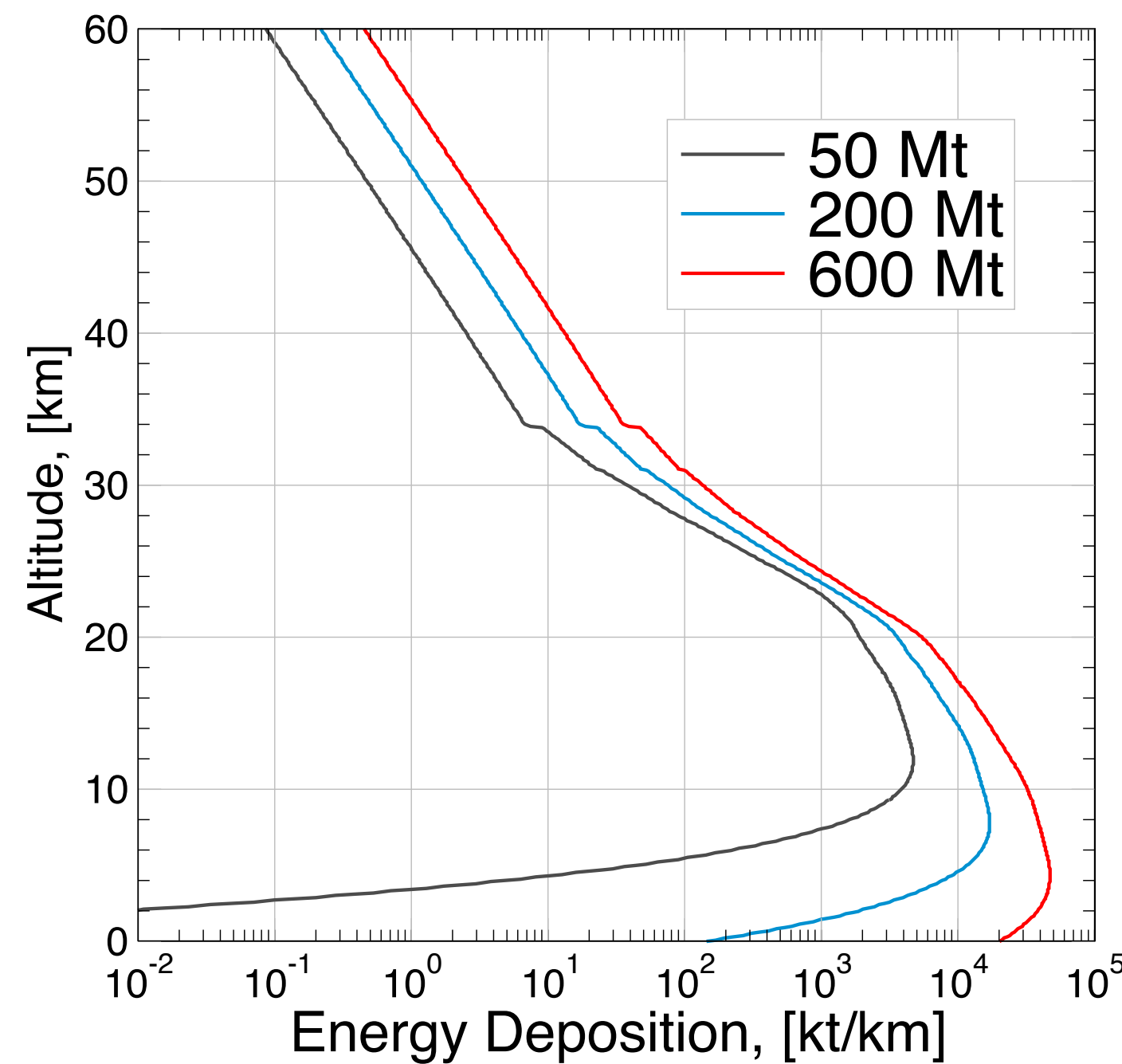
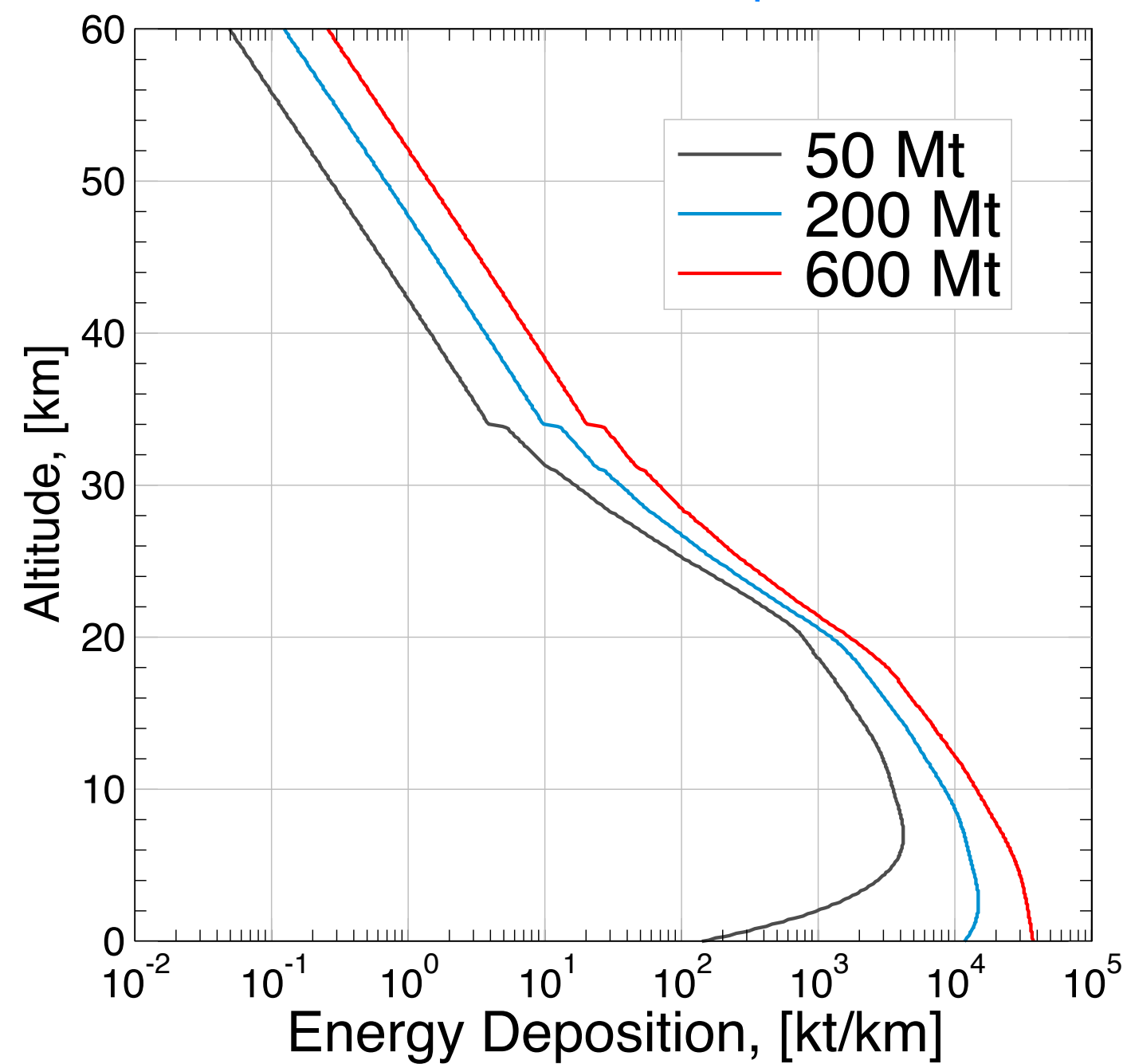
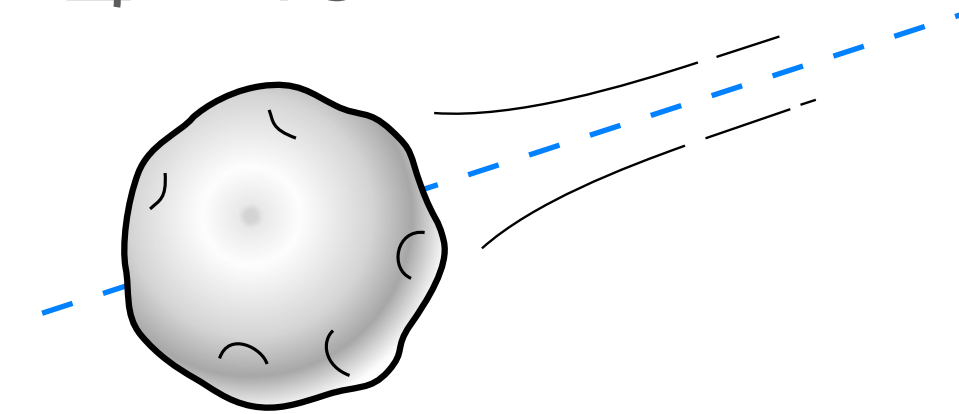
Athens

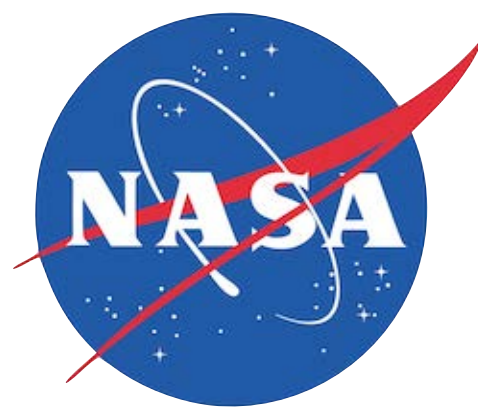
$V = 13.70 \text{ km/s}$
 $\Delta = 34^\circ$



St. Petersburg

$V = 13.70 \text{ km/s}$
 $\Delta = 18^\circ$





Impact Scenarios: Entry profiles & energy deposition

Height of burst varies with entry angle and size

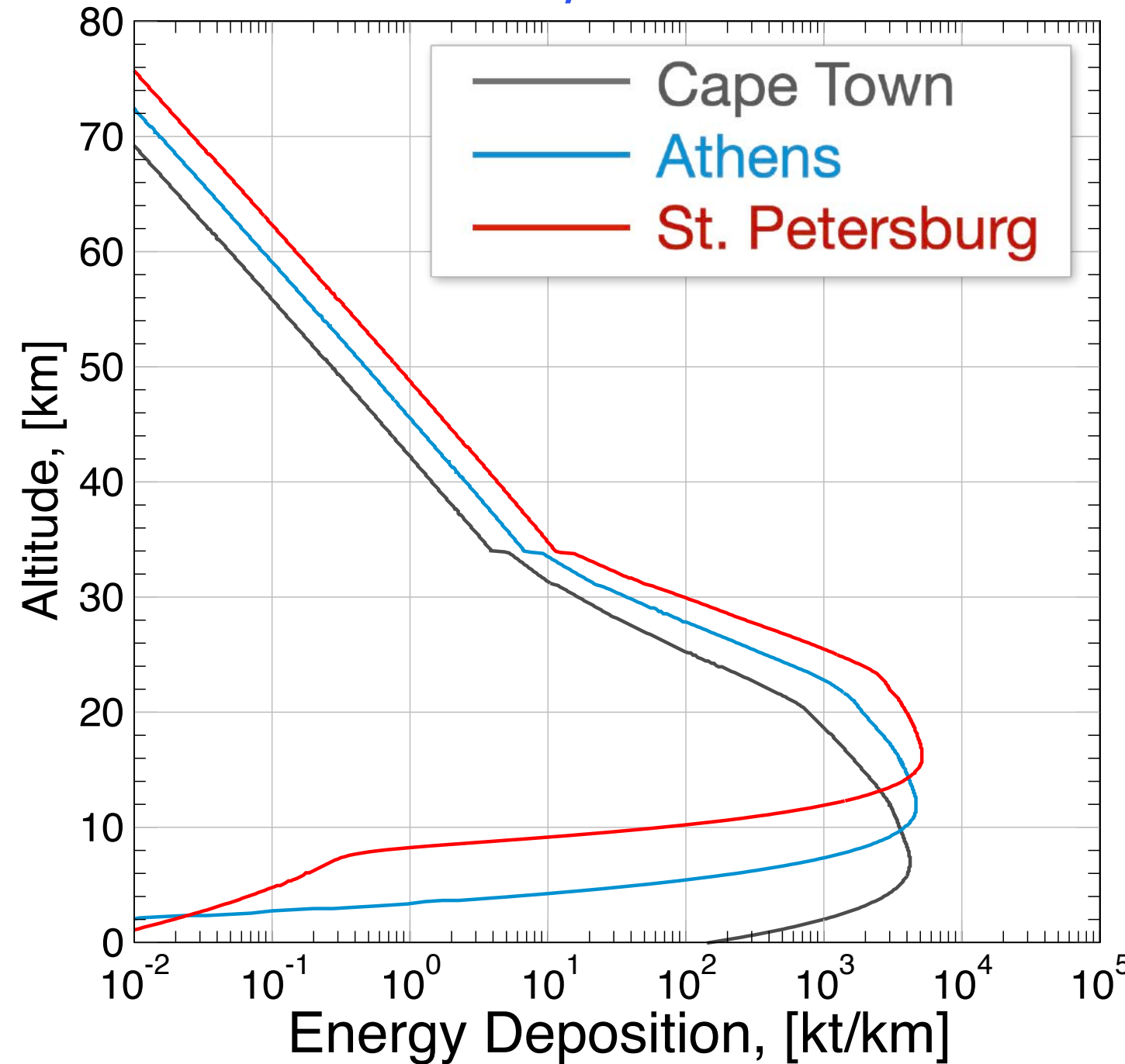
Entry profiles reveal the expected trends, for similar compositions:

- Larger objects penetrate more deeply
- Shallower entries burst higher

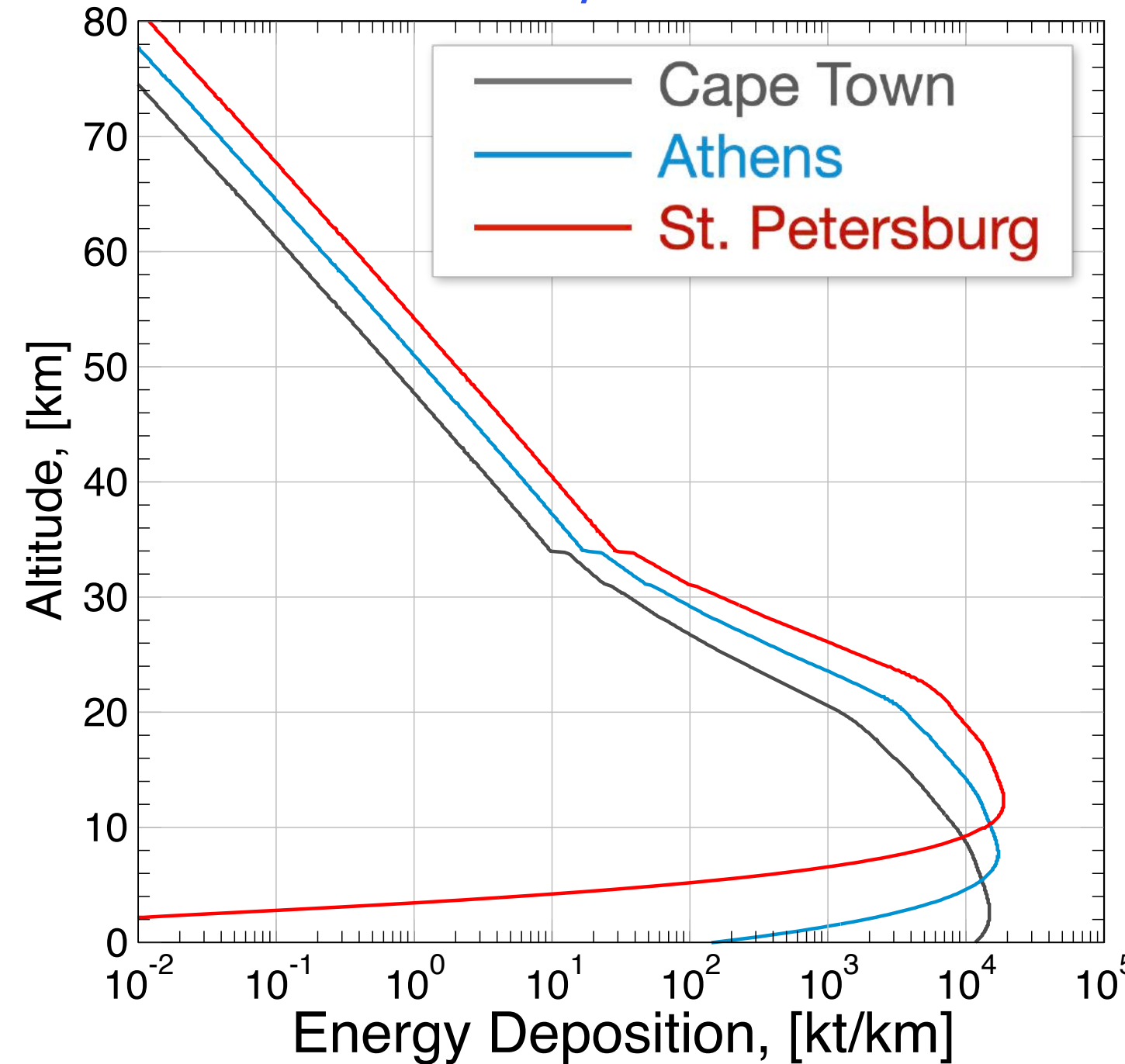
Moderate cases, Peak Edep altitude, [km]

Energy [Mt]	Cape Town 87°	Athens 34°	St. Petersburg 18°
50	7.0	11.92	16.23
200	2.6	7.8	12.37
600	0.0	4.36	9.13

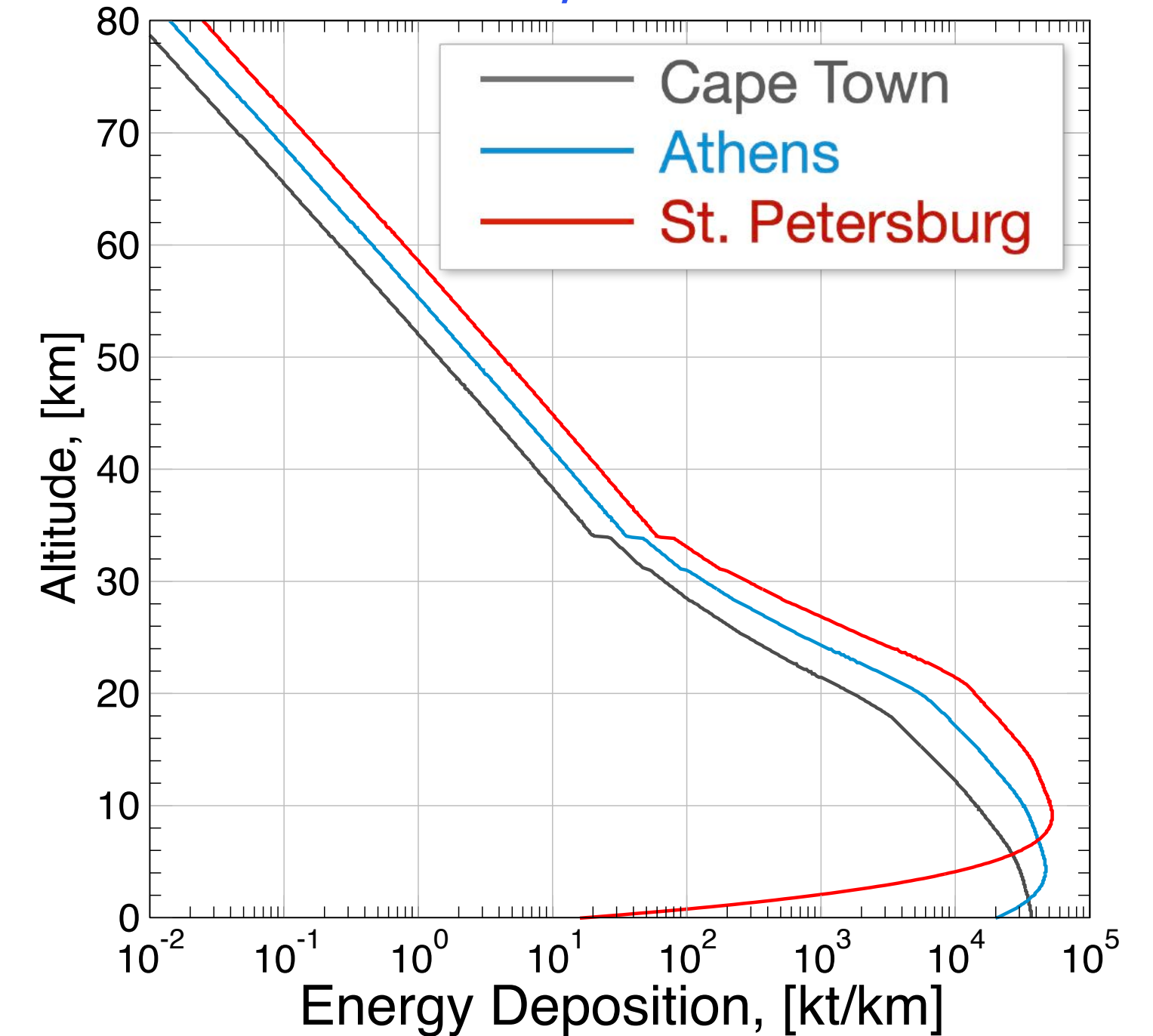
50 Mt, Ø119 m



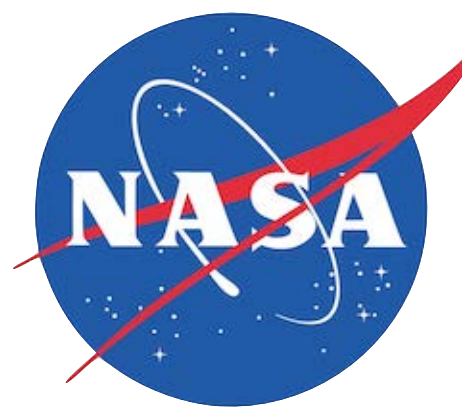
200 Mt, Ø198m



600 Mt, Ø279m



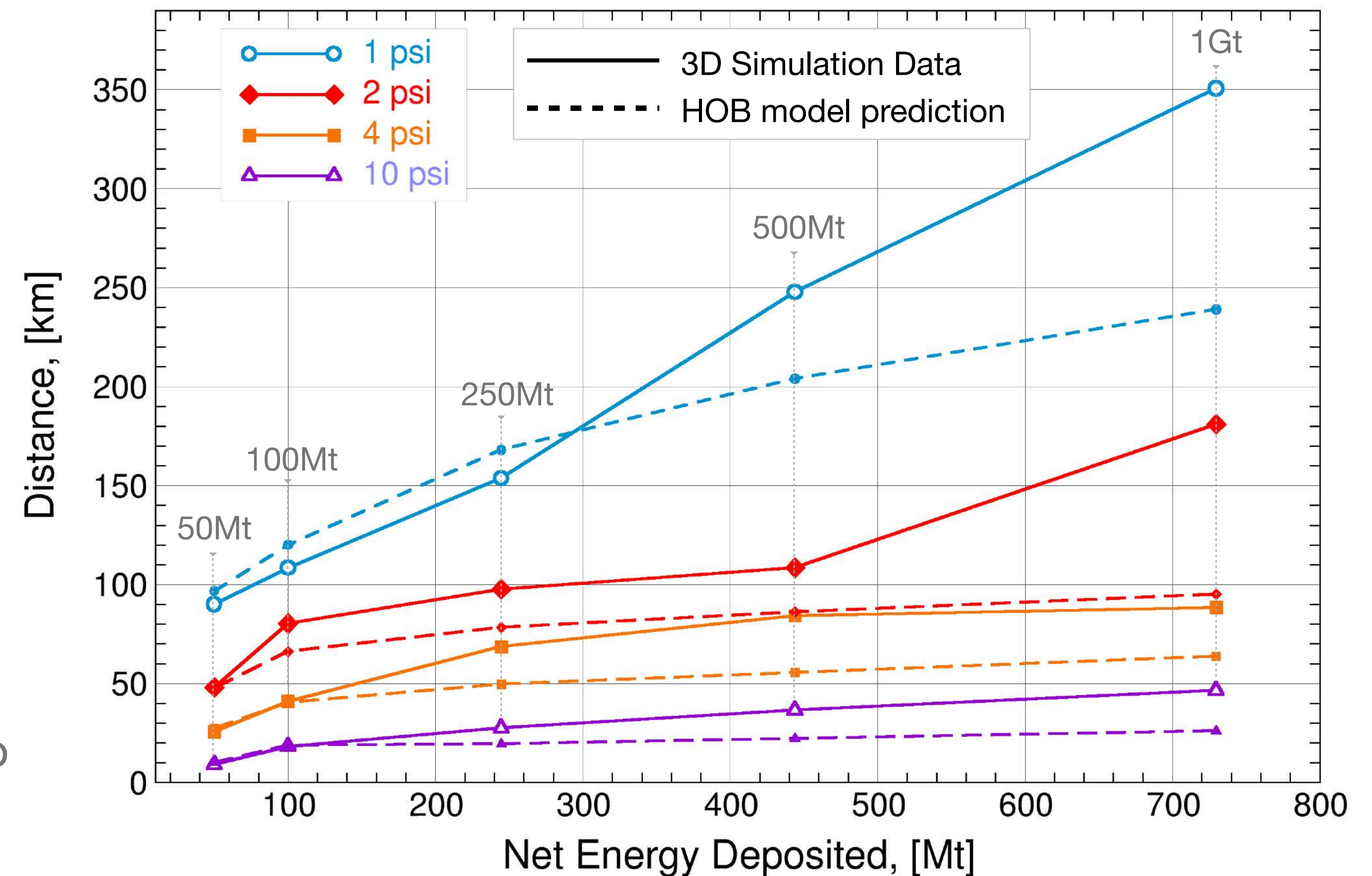
Overpressure Decay & Damage Radii



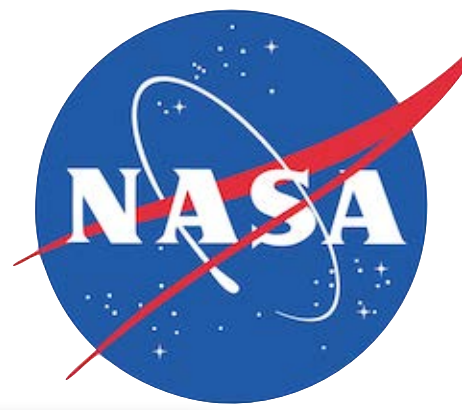
Damage radii prediction

- Fast running Height of Burst (HOB) methods are based on self-similar spherical blast theory
- Compare with simulation results of parametric entries at 45°
- The approach clearly becomes inappropriate when impact energy is large
- The buoyancy corrected* HOB-model:
 - Excellent at ~50Mt and below
 - Very good at 100Mt
 - Deteriorates rapidly above 250Mt
- Parametric studies showed that this was linked to the transition to more cylindrical behavior as the blast got stronger and overpressure distances become similar to the height of the atmosphere

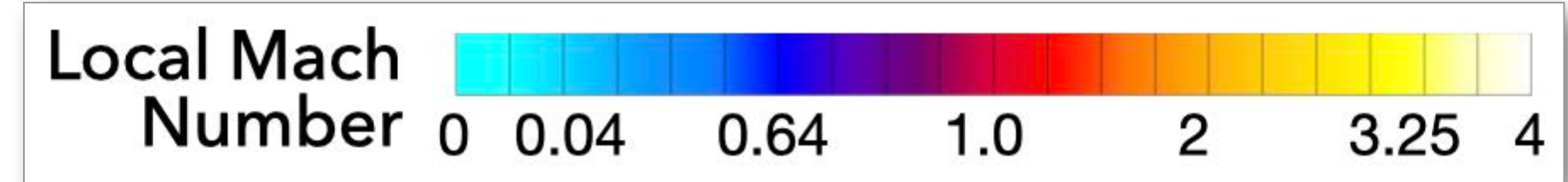
3D simulation vs HOB prediction of damage radii



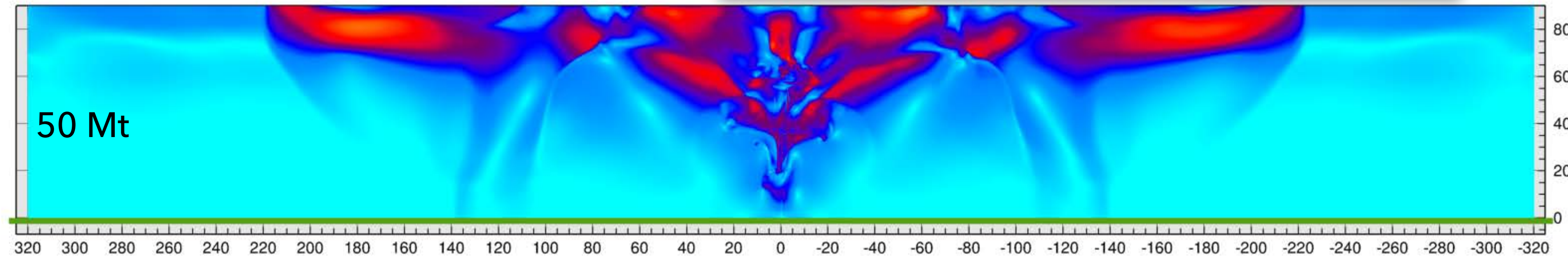
Numerical simulations & results



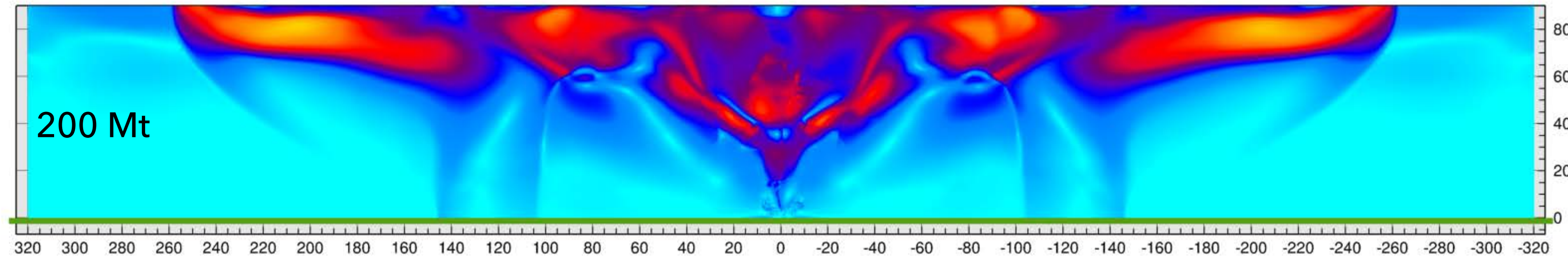
Cape Town at late time (~7.5 min, ~150km)



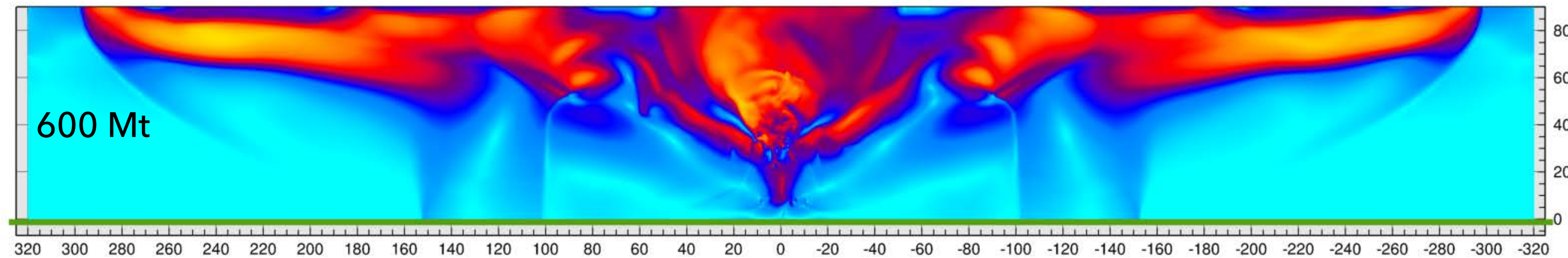
- 50 Mt: Still has elements of spherical blast near ground



- 200 Mt blast near ground clearly cylindrical

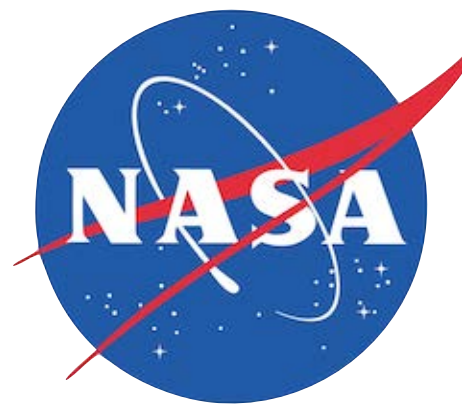


- 600Mt: Confinement makes blast even more cylindrical

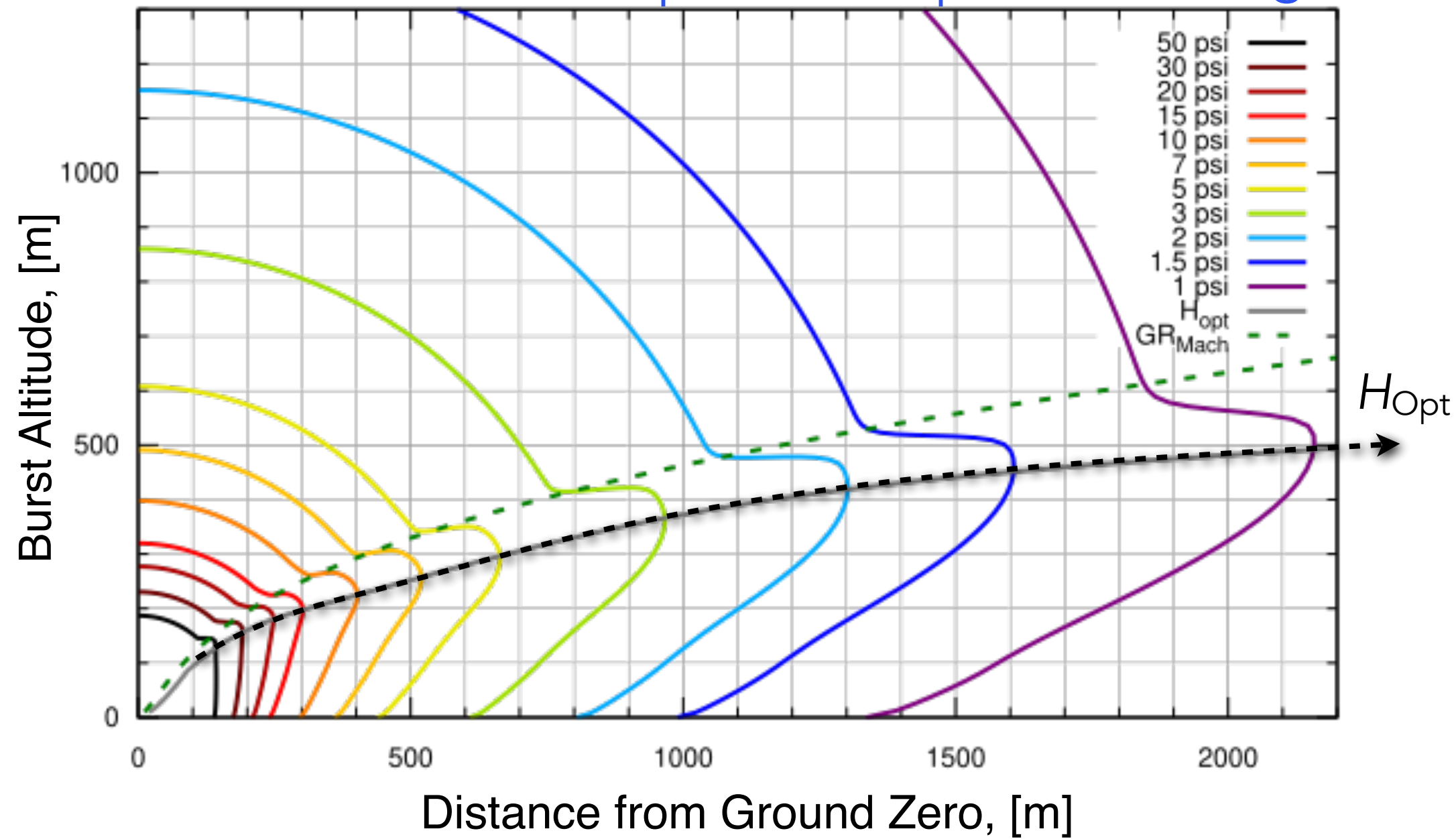


Downrange Distance, [km]

Height of Burst maps



Canonical HoB map for 1kt spherical charge

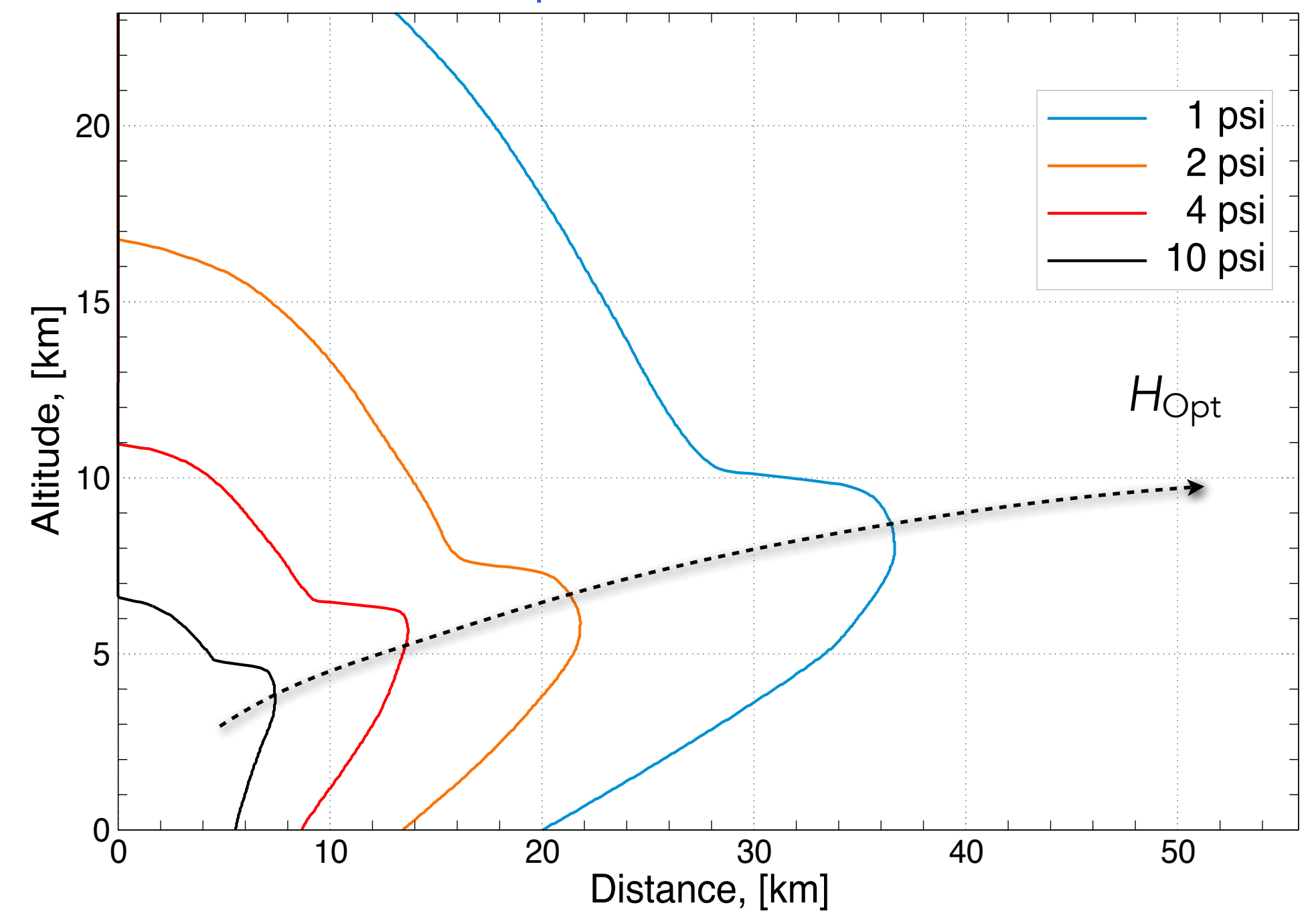


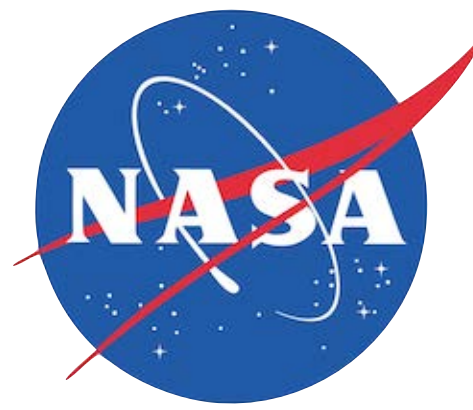
For any overpressure level, there exists a burst height that maximizes the extent of a given overpressure, H_{Opt} , that maximizes a given overpressure level on the ground

Yield Scaling:
$$\frac{d_1}{d_2} = \left(\frac{E_1}{E_2} \right)^{\frac{1}{3}}$$

- Scale the map for 1kt spherical charge to any size
- 8x increase in energy corresponds to a 2x increase in distance to given overpressure
- Therefore, H_{Opt} increases with yield

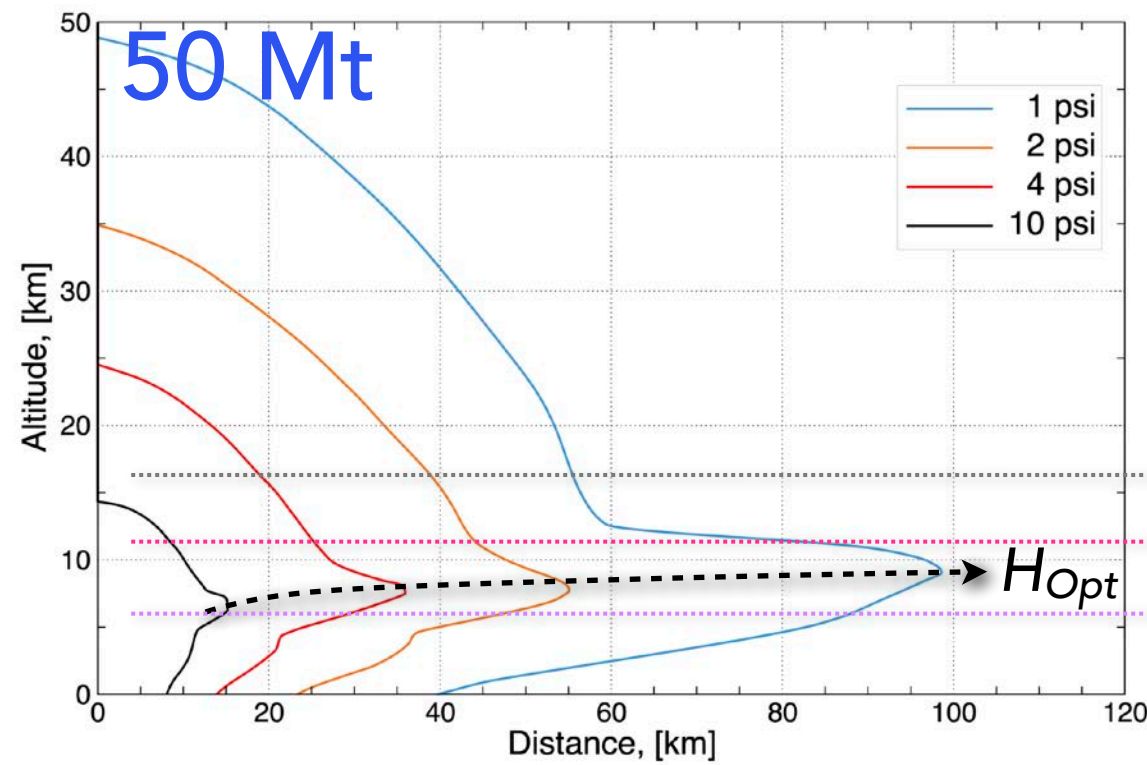
HoB map scaled for 5 Mt



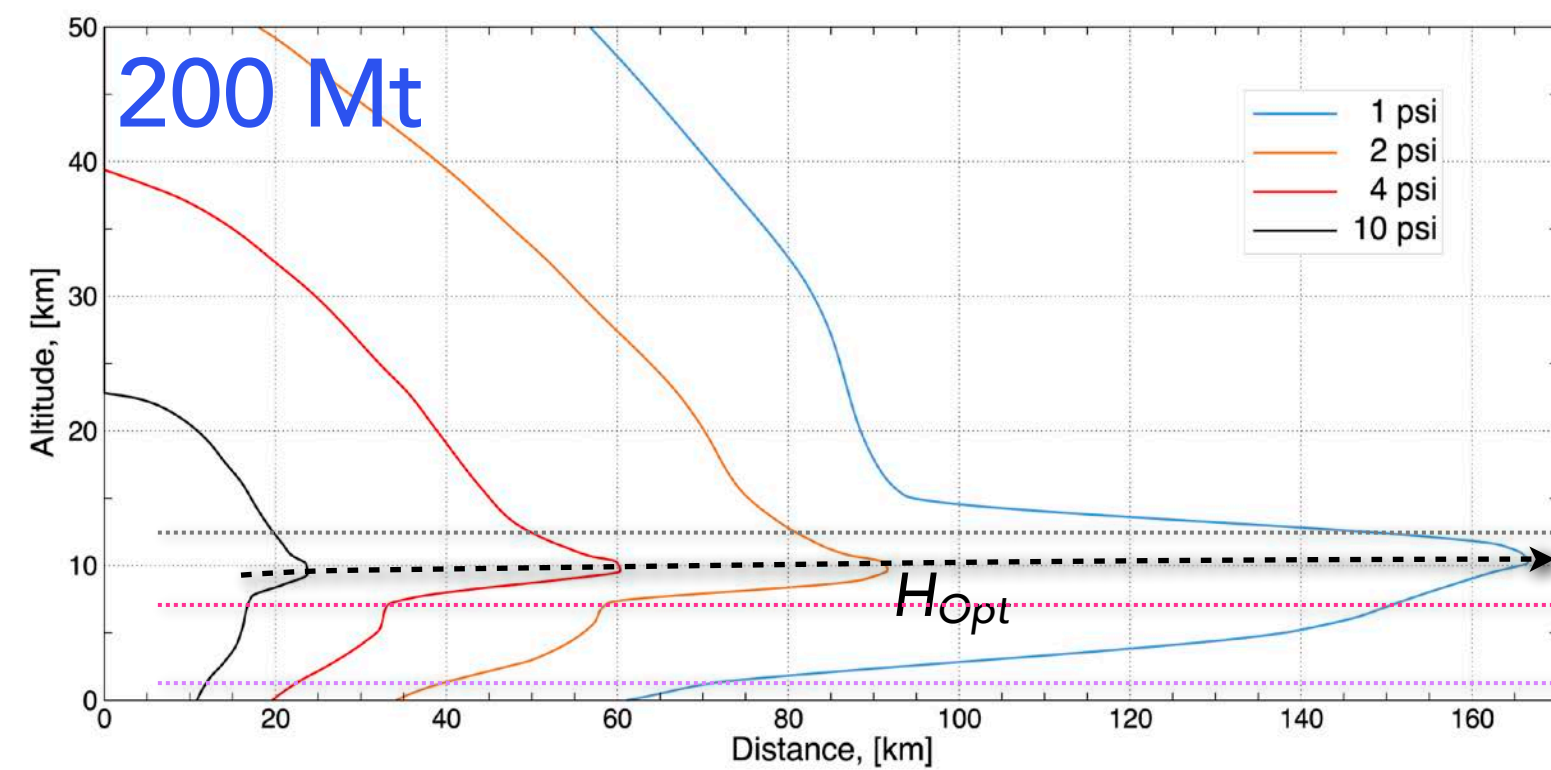


Height of Burst maps for 50, 200 & 600 Mt airbursts

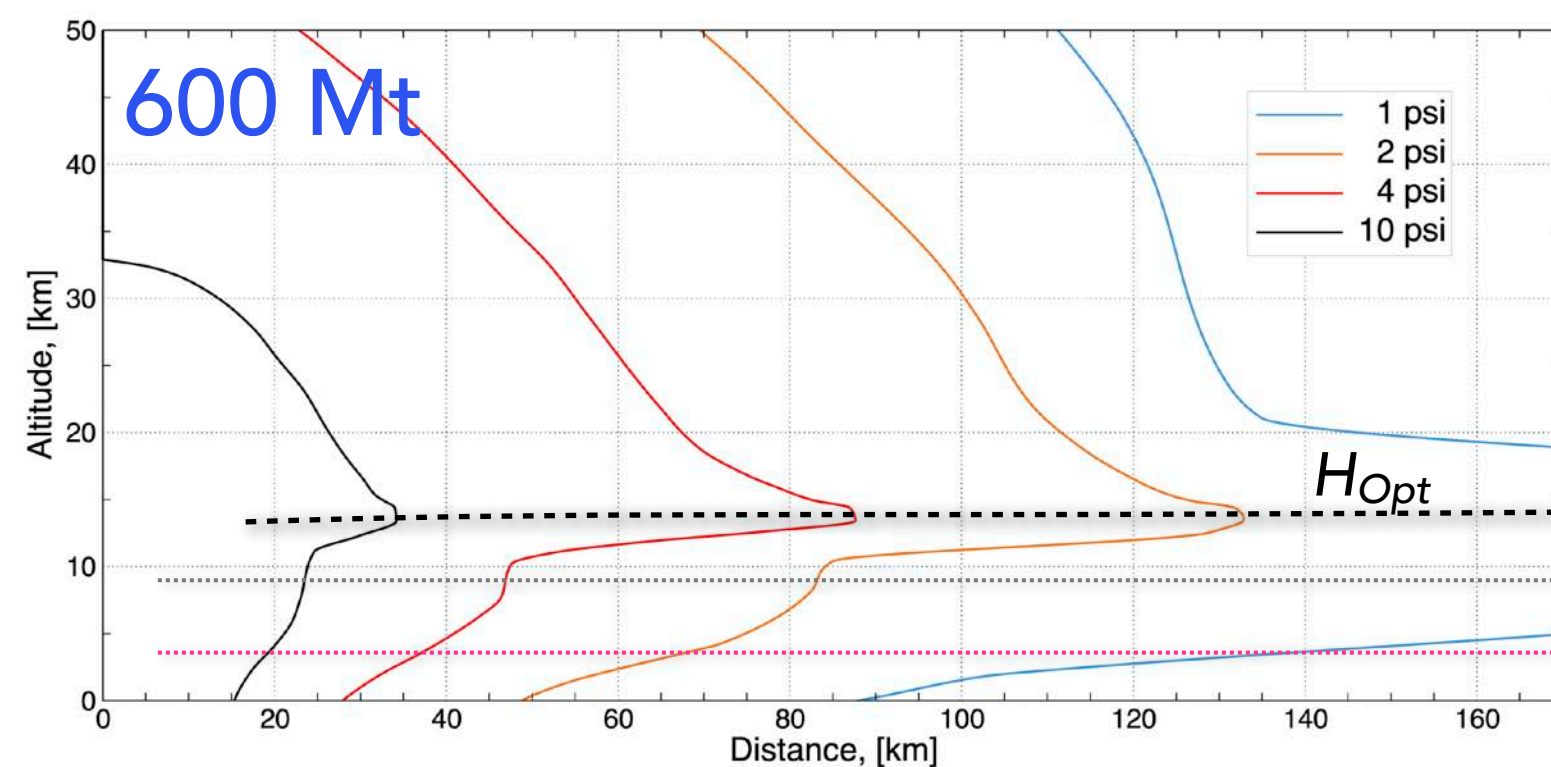
For large blasts, buoyancy causes a flattening of the H_{Opt} curve as yield increases, but trends stay the same



St. Petersburg
Athens
Cape Town



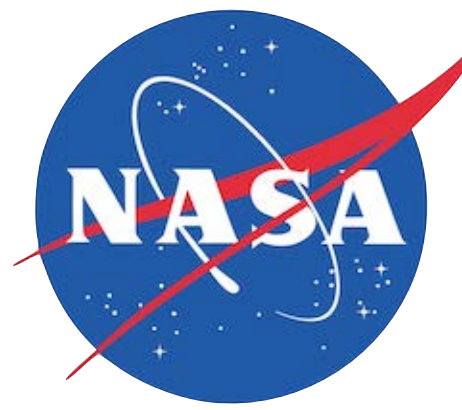
St. Petersburg
Athens
Cape Town



St. Petersburg
Athens
Cape Town (impact)

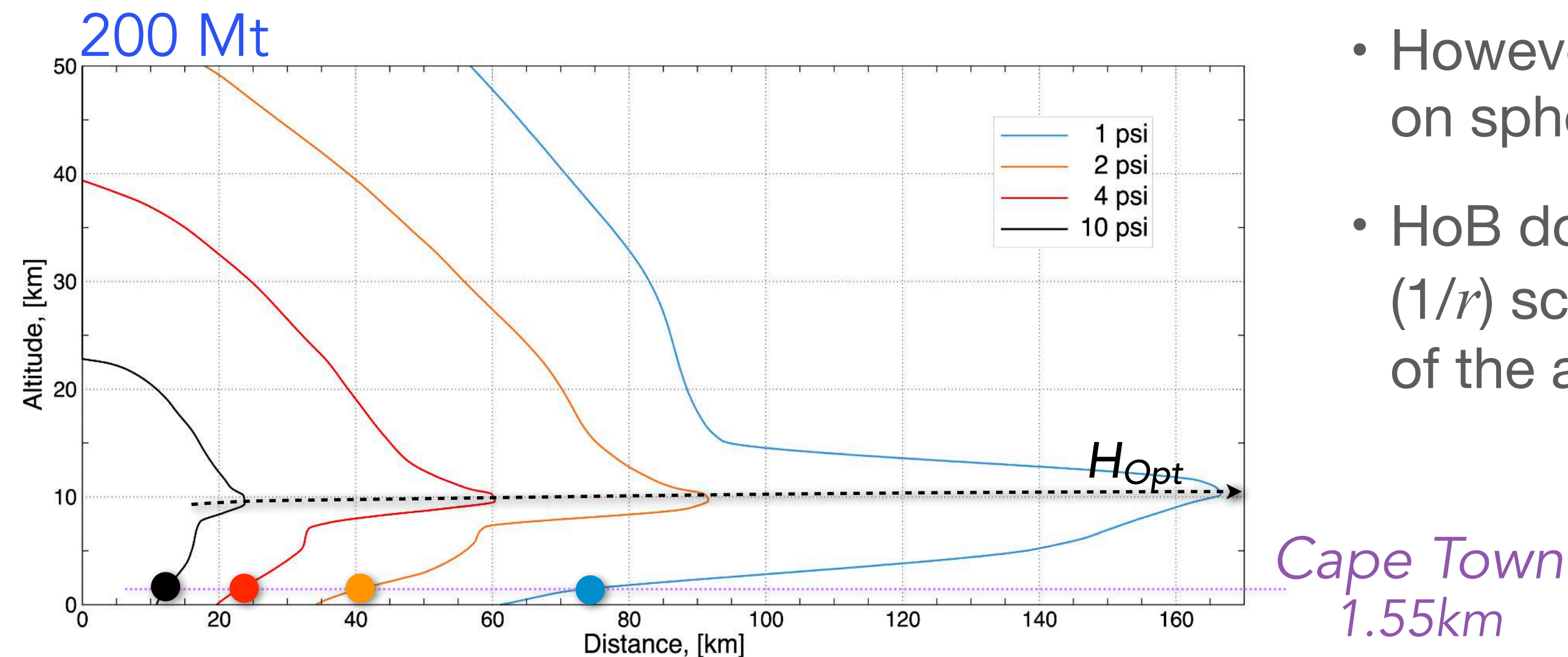
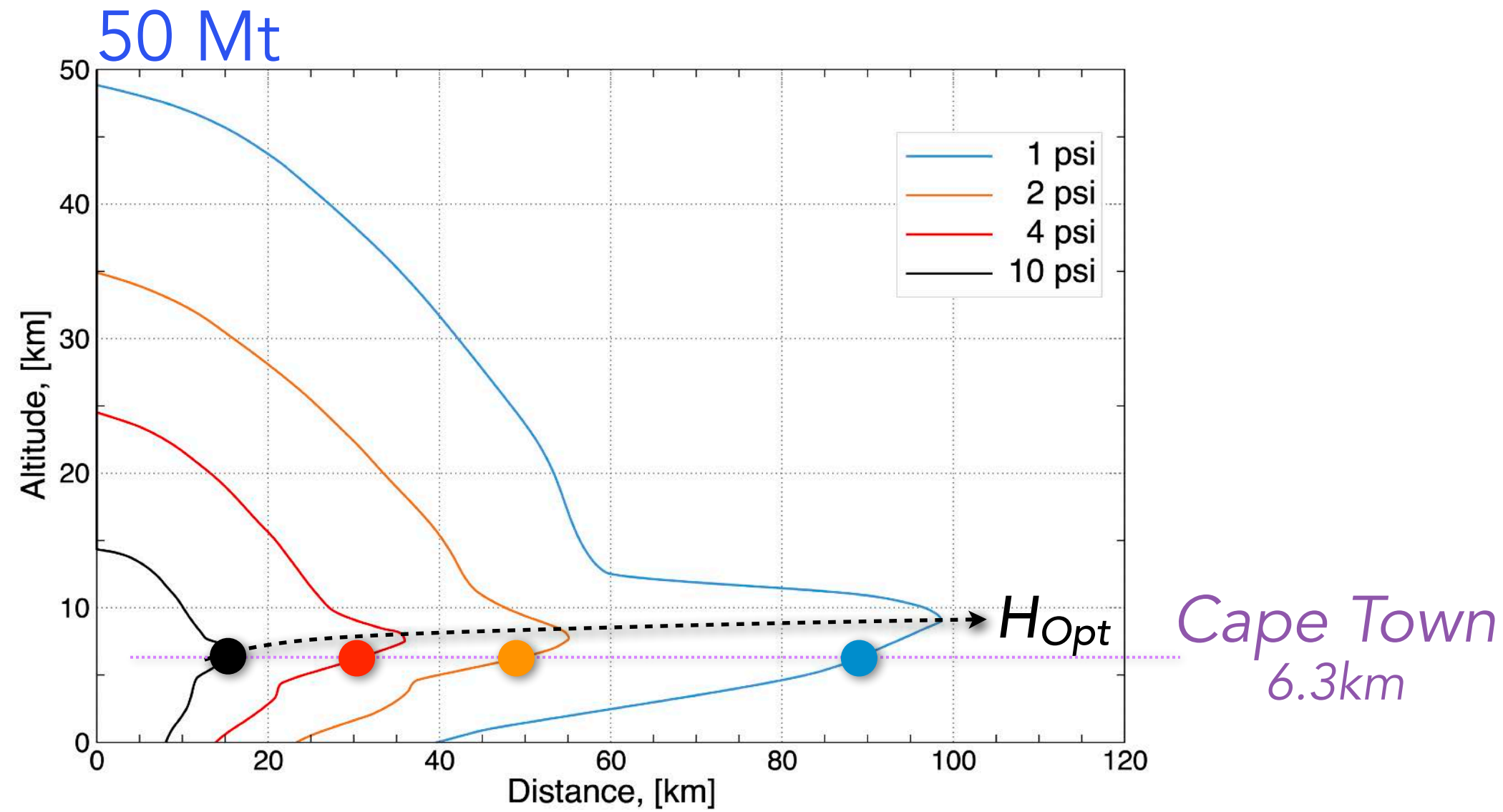
Moderate cases, Peak Edep altitude, [km]			
Energy [Mt]	Cape Town 87°	Athens 34°	St. Petersburg 18°
50	7	11.92	16.23
200	2.6	7.8	12.37
600	0	4.36	9.13

- Trend in H_{Opt} vs yield is opposite that of burst height vs yield
 - H_{Opt} increases with yield
 - For asteroid entries, burst height generally decreases with size
- Ground overpressure can be very sensitive to burst height
 - Larger objects may “over penetrate” with airbursts that are significantly below H_{Opt} (e.g. 600 Mt case)
 - Oblique trajectories may result in airbursts that are too high
- “Ground impact” = not all entry energy goes in the atmosphere



Height of Burst maps for 50, 200 & 600 Mt airbursts

HoB sensitivities can lead to counterintuitive results



HoB Prediction @ Cape Town damage radius [km]

KE at entry [Mt]	10 psi	4 psi	2 psi	1 psi
50 MT @ 6.27km	15.2	30.7	49.2	89
200 MT @ 1.55 km	12.2	23.2	41.2	75

- HoB predicts larger damage radius for 50Mt than for 200Mt for all damage levels
- However, even with buoyancy correction, HoB is based on spherical charge and not real entry (& impact)
- HoB does not account for transition from 3D ($1/r^2$) to 2D ($1/r$) scaling as blast radius becomes similar to thickness of the atmosphere