7th IAA Planetary Defense Conference

High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC

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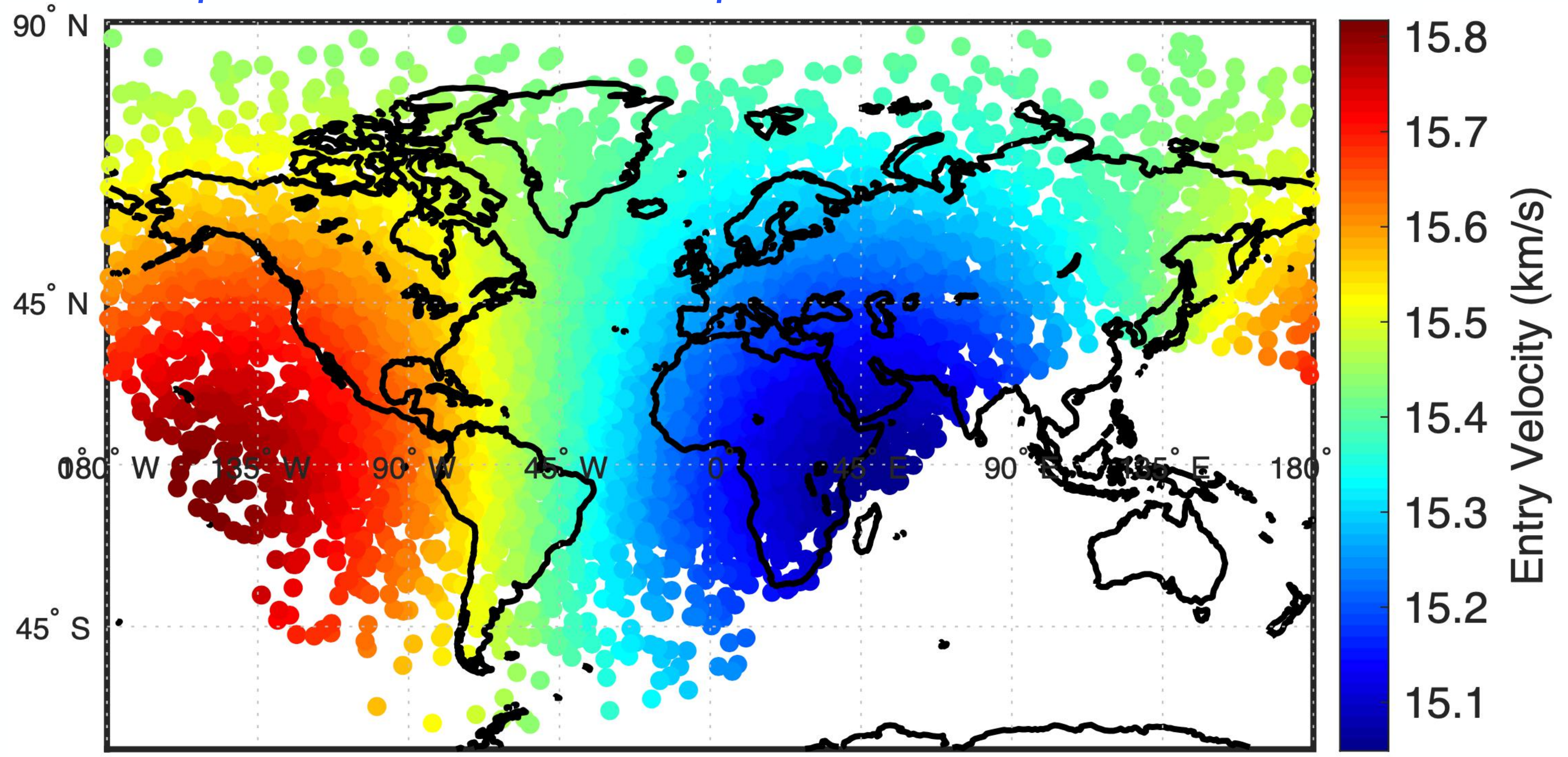
2021 PDC asteroid impact scenario Day 0 information

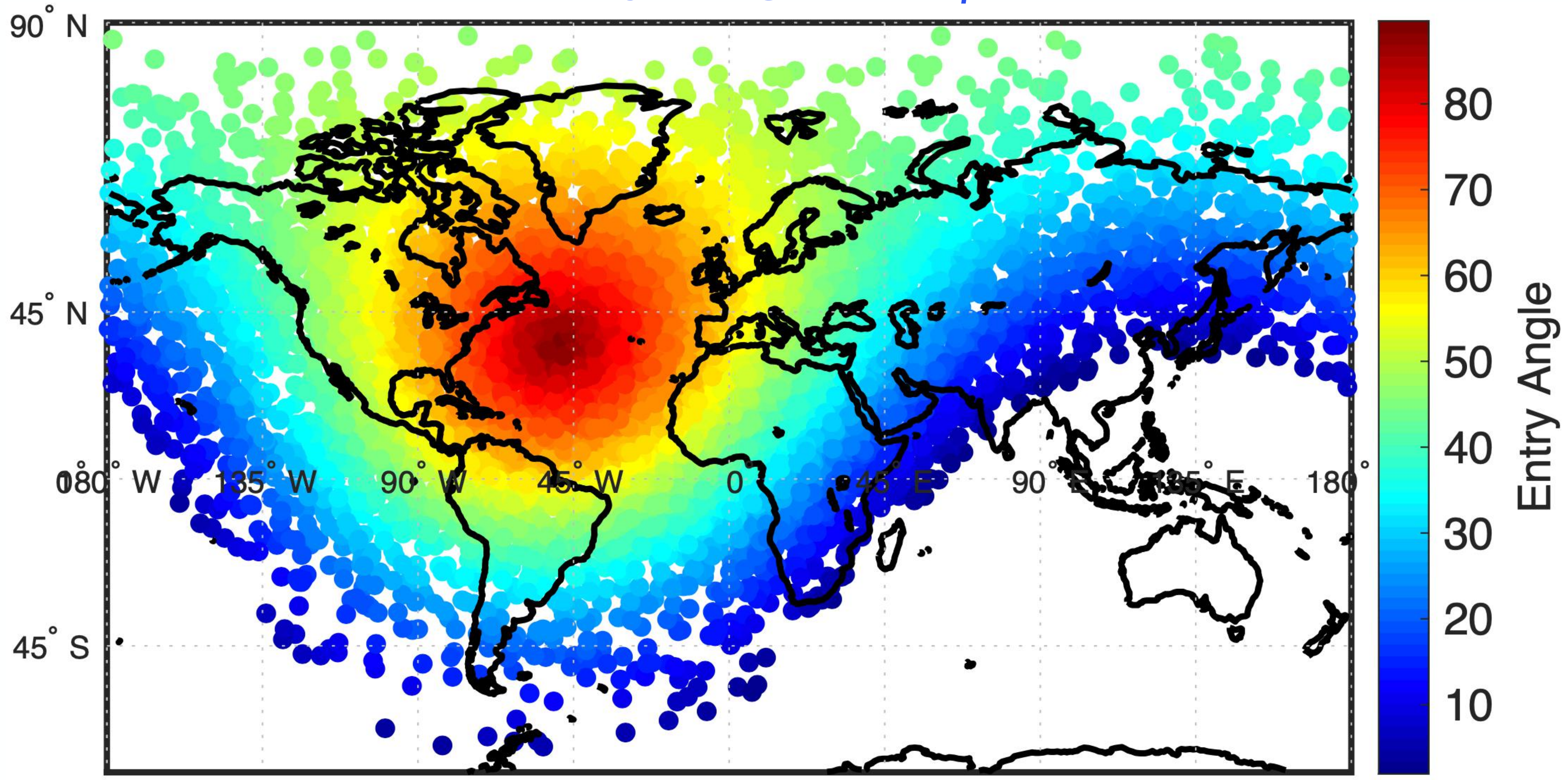
Entry modeling and probabilistic risk assessment

- Absolute magnitude H = 22.4 ±0.3, albedo unknown - used full NEOWISE distribution giving a range of diameters between 25 m – 700 m
- Energy range from 1.2 Mt – 13 Gt
- Wheeler et. al (2021) used probabilistic risk assessment to determine that Velocity = 15.2 km/s covers major population centers accounting for majority of risk

Map of 100km entry points from Day 0 data



Entry angle map



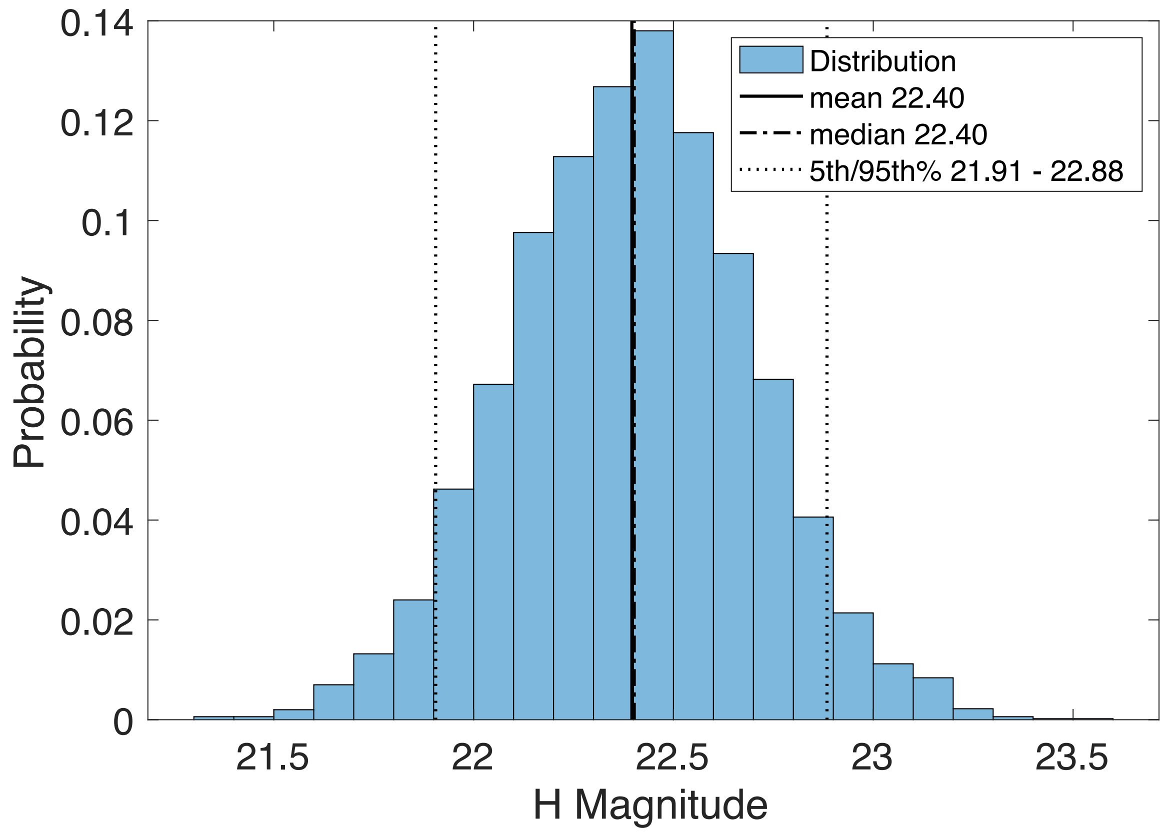
See Wheeler et al. 2021 for details of Day 0 analysis

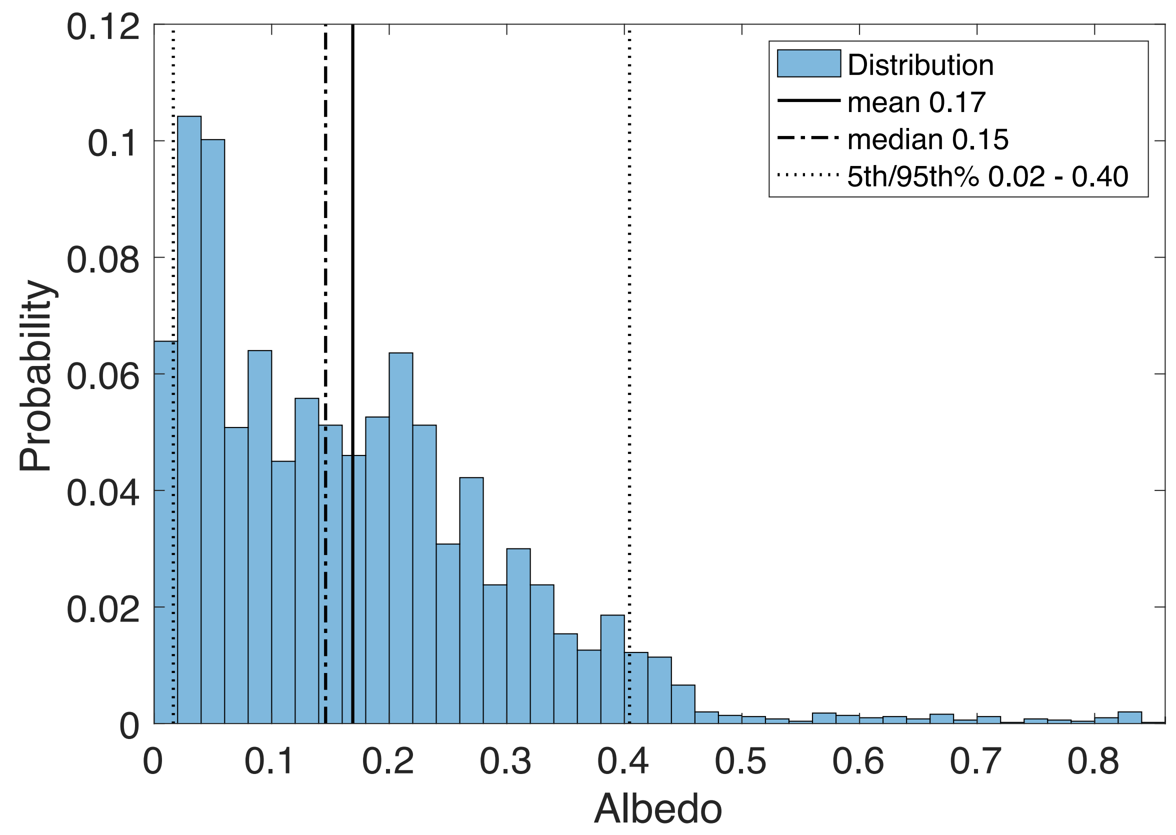
Asteroid properties

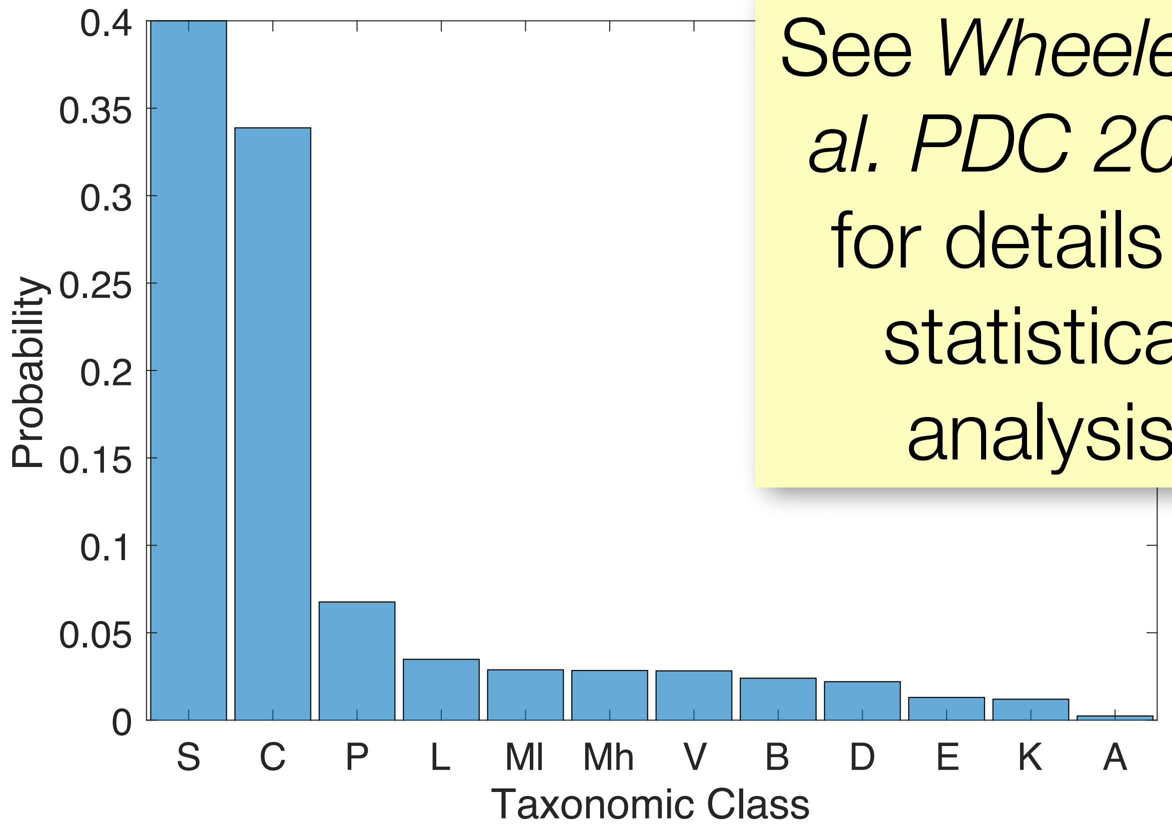
Statistical analysis and Bayesian inference to determine likely asteroid properties

- No typing or other specifications known. Generic NEA distributions used for taxonomic class, density, strength, etc.
- High-fidelity simulations focus on the median and mean cases

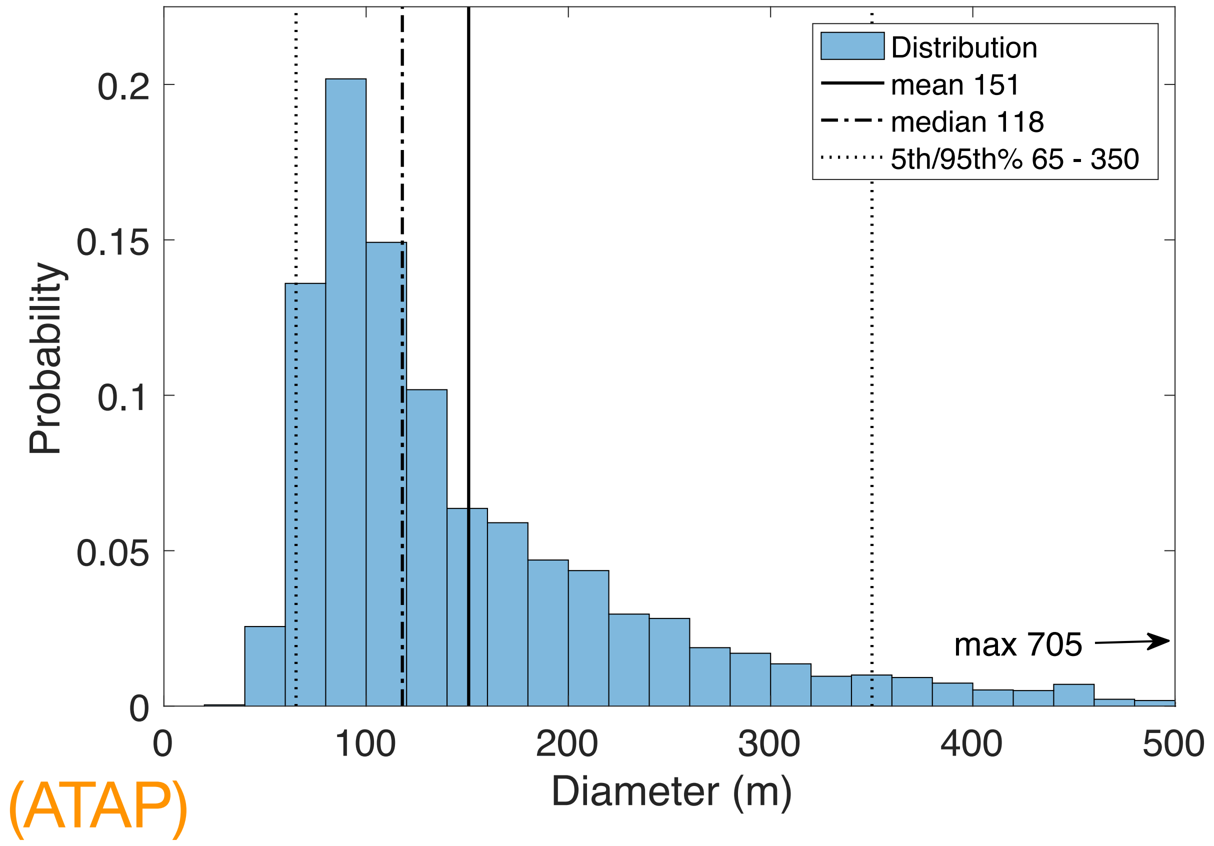
	Mean	25%	50% (Median)	75%
H magnitude	22.40	22.19	22.40	22.60
Albedo	0.17	0.05	0.15	0.24
Diameter Ø [m]	151	88	118	186
Density [g/cc]	2.166	1.694	2.066	2.500
Mass [kg]	9.08×10^9	7.6×10^8	1.83×10^9	6.58×10^9
Energy [Mt]	256	21	52	185

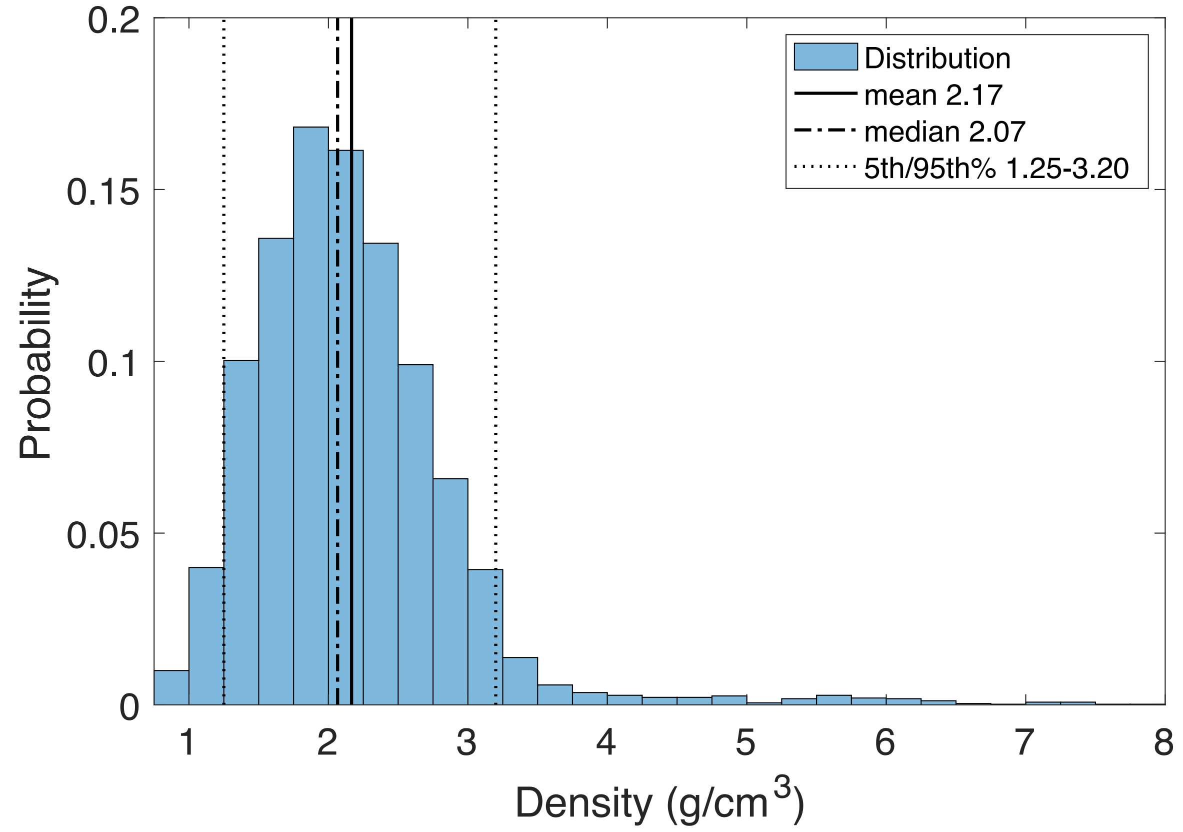


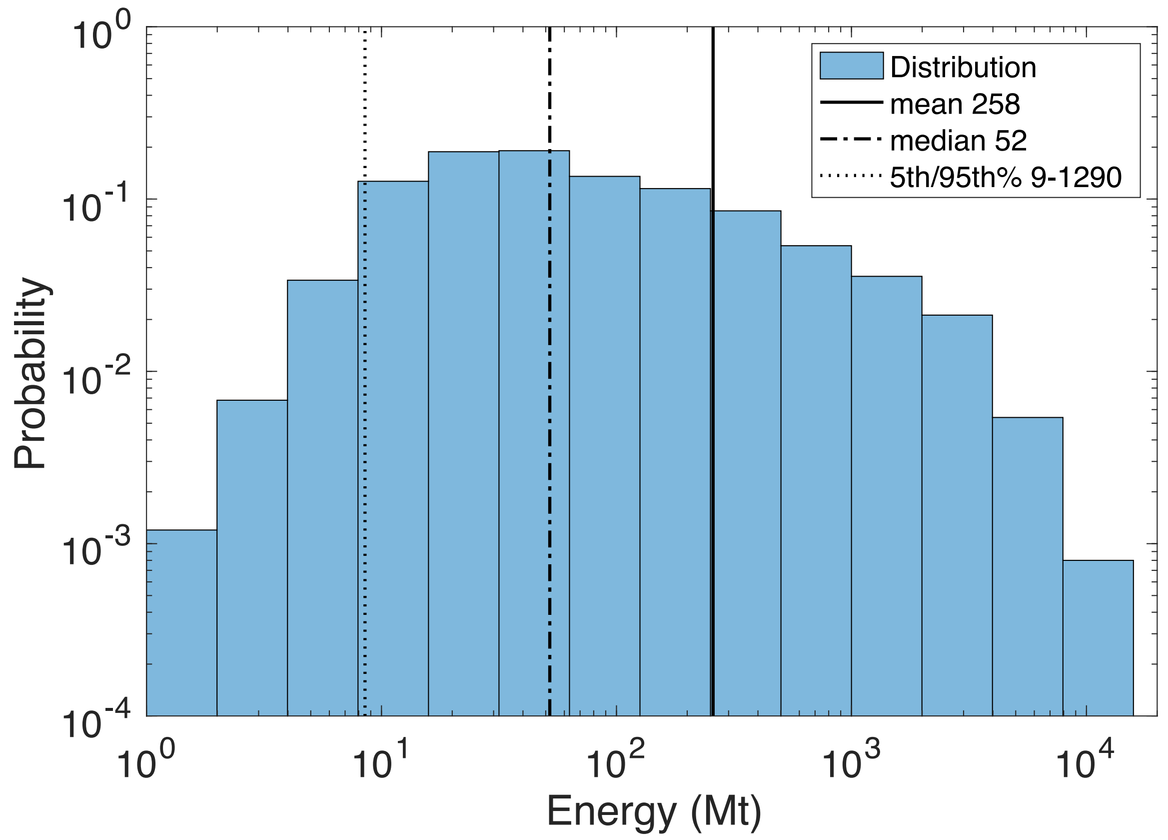




See *Wheeler et al. PDC 2021* for details of statistical analysis







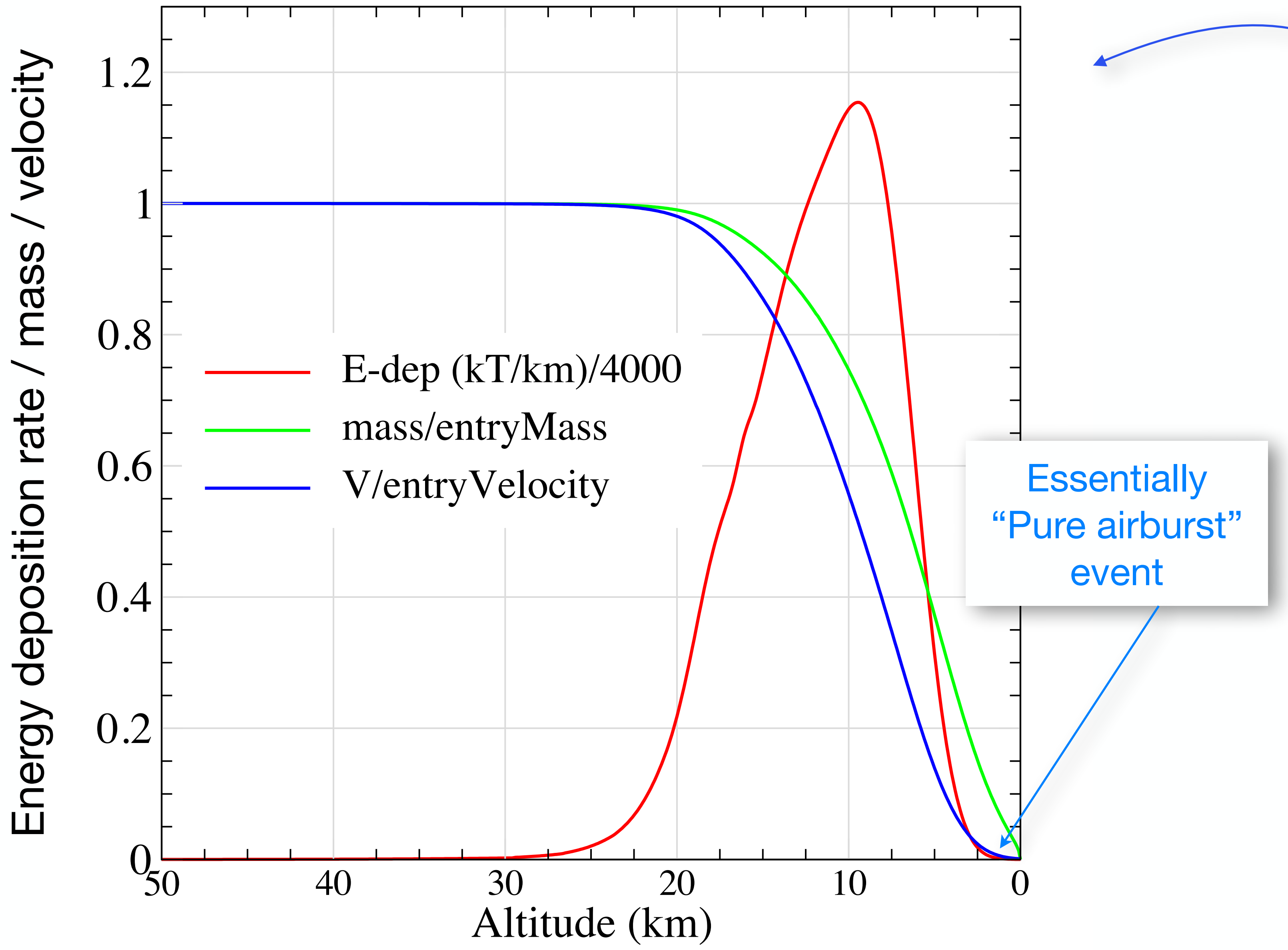
Median asteroid properties

ARC/TNA

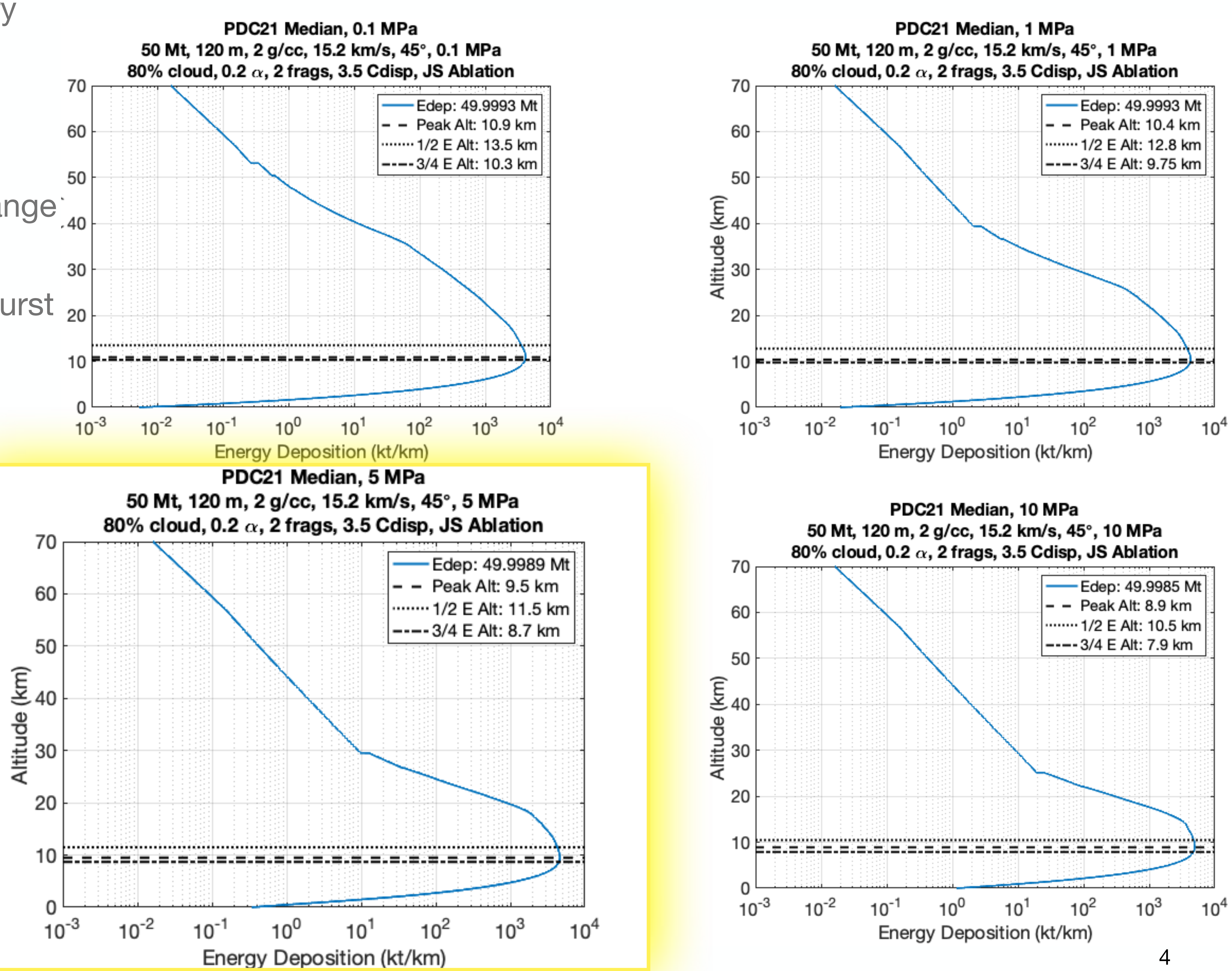
Detailed selection of properties for median impact case

- Selected rounded median energy of 50 Mt (actual 52 Mt) and computed consistent diameter based on density of 2 g/cc & entry velocity of 15.2 km/s
- 45° entry angle selected based on entry angle over population centers with high mean affected population
- Ran entry profiles with FCM (ATAP Fragment Cloud Model) for range of strengths from 0.1-10 MPa.
- **Selected 5MPa strength** (median ~2MPa) since more compact burst is near optimal height of burst for 50Mt.

Entry Profile for 5MPa Aero. Strength



Variation of Energy Deposition Profile with Aerodynamic Strength



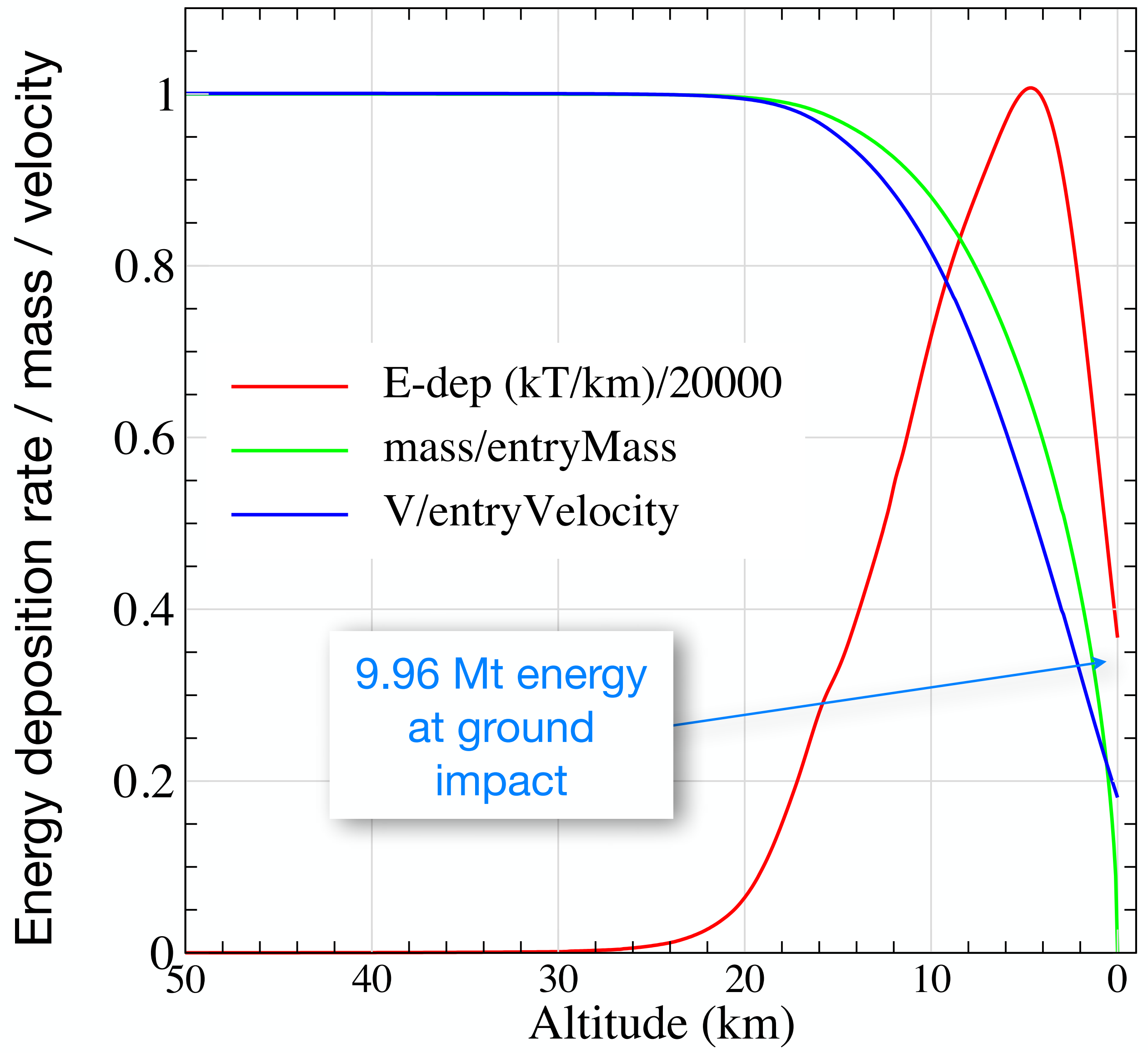
Mean asteroid properties

Detailed selection of properties for mean impact case

ARC/TNA

- Selected rounded mean energy of 250 Mt (actual 252 Mt) and computed consistent diameter based on density of 2 g/cc & entry velocity of 15.2 km/s
- 45° entry angle selected based on entry angle over population centers with high mean affected population
- Ran entry profiles with FCM (ATAP Fragment Cloud Model) for range of strengths from 0.1-10 MPa.
- Selected 5MPa strength since it includes energetic burst and relatively large (~10Mt) ground impact which is likely at 250 Mt.

Entry Profile for 5MPa Aero. Strength



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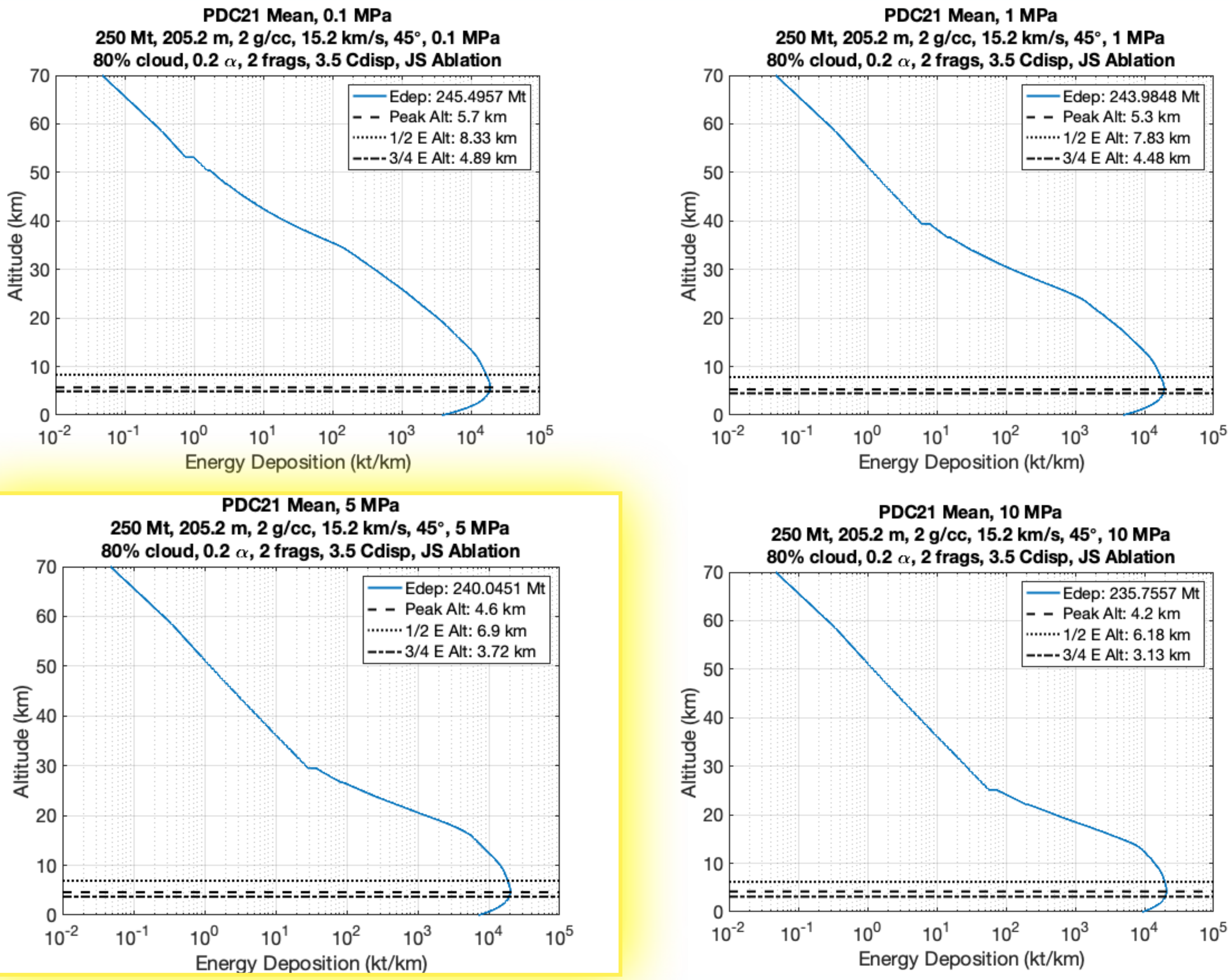
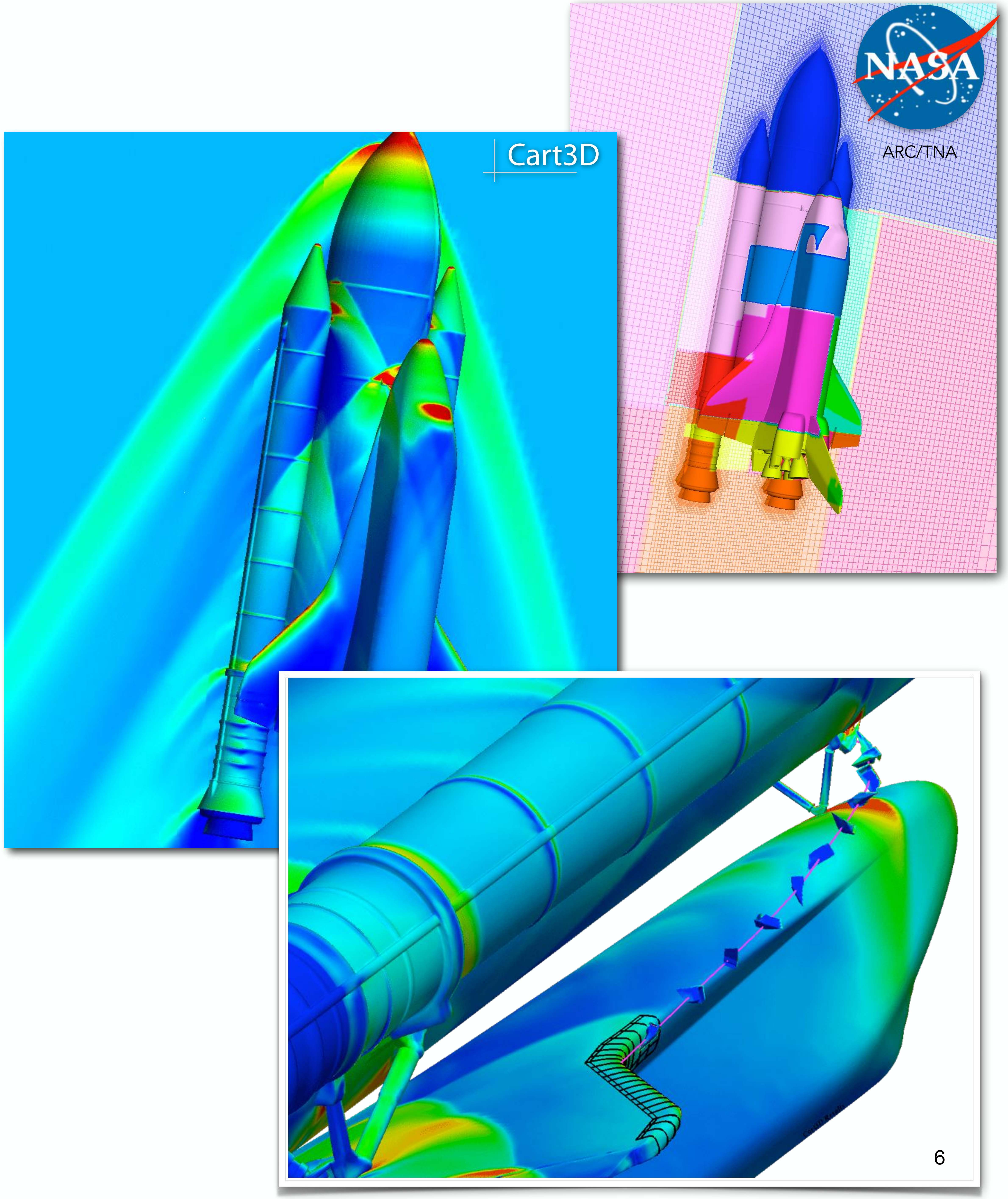


Solver overview: Cart3D

Production solver based on cut-cell Cartesian mesh method

- 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
  - Domain-decomposition for good parallel scalability
- All runs are full 3D
  - 270-380 M cells with 20-30 k time steps
- Excellent scalability
  - Typical airburst simulations take 8-16 hrs on ~4000 cores
- One of NASAs most heavily used production solvers, large validation database, 700+ users
- Good comparisons w/ *CTH*, *xRAGE* & *ALE3D* at the 2016 Tsunami Workshop



Solver overview: Cart3D

Extensive Validation for airburst and entry simulations

- 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
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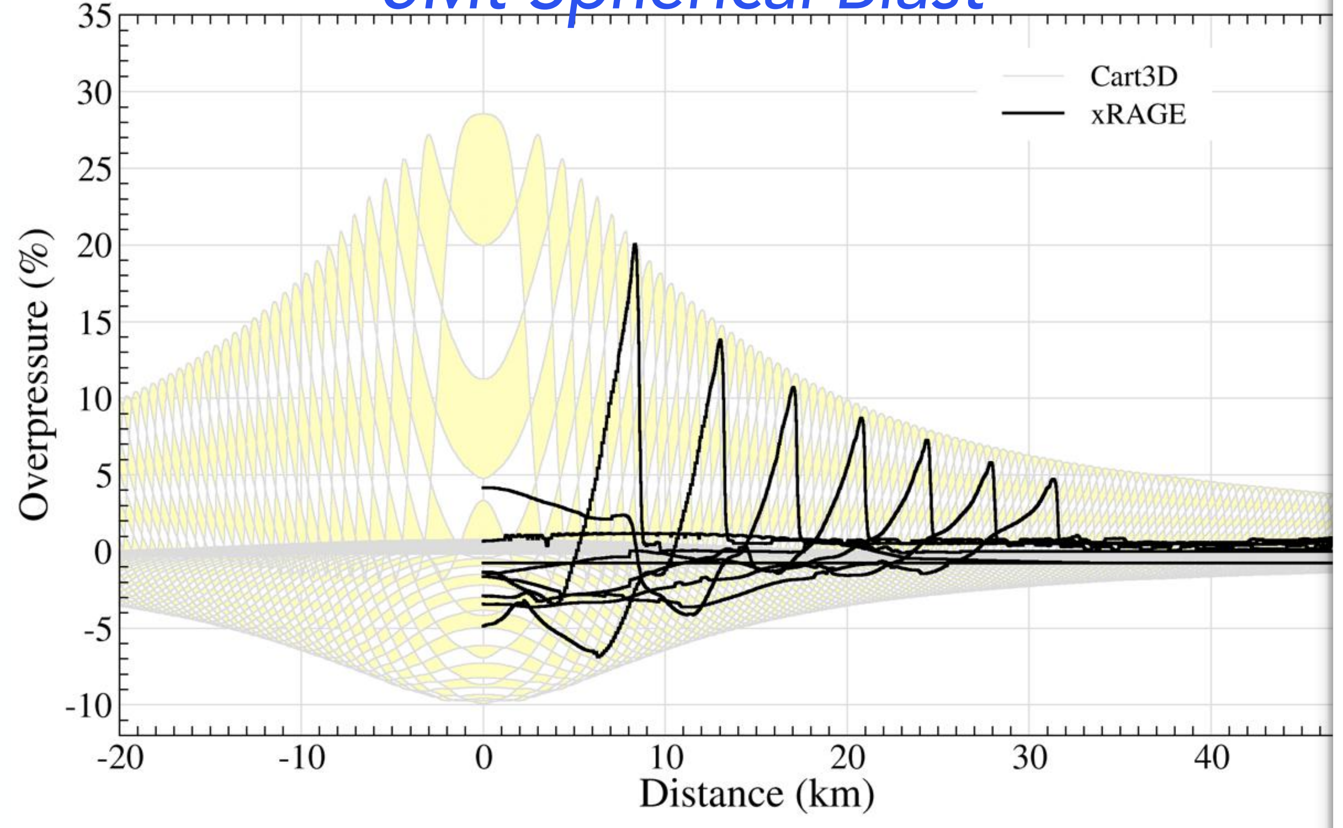
5Mt Spherical Blast



Comparison with xRAGE (DoE) at 2016 Tsunami Workshop

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Chelyabinsk Ground Footprints

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

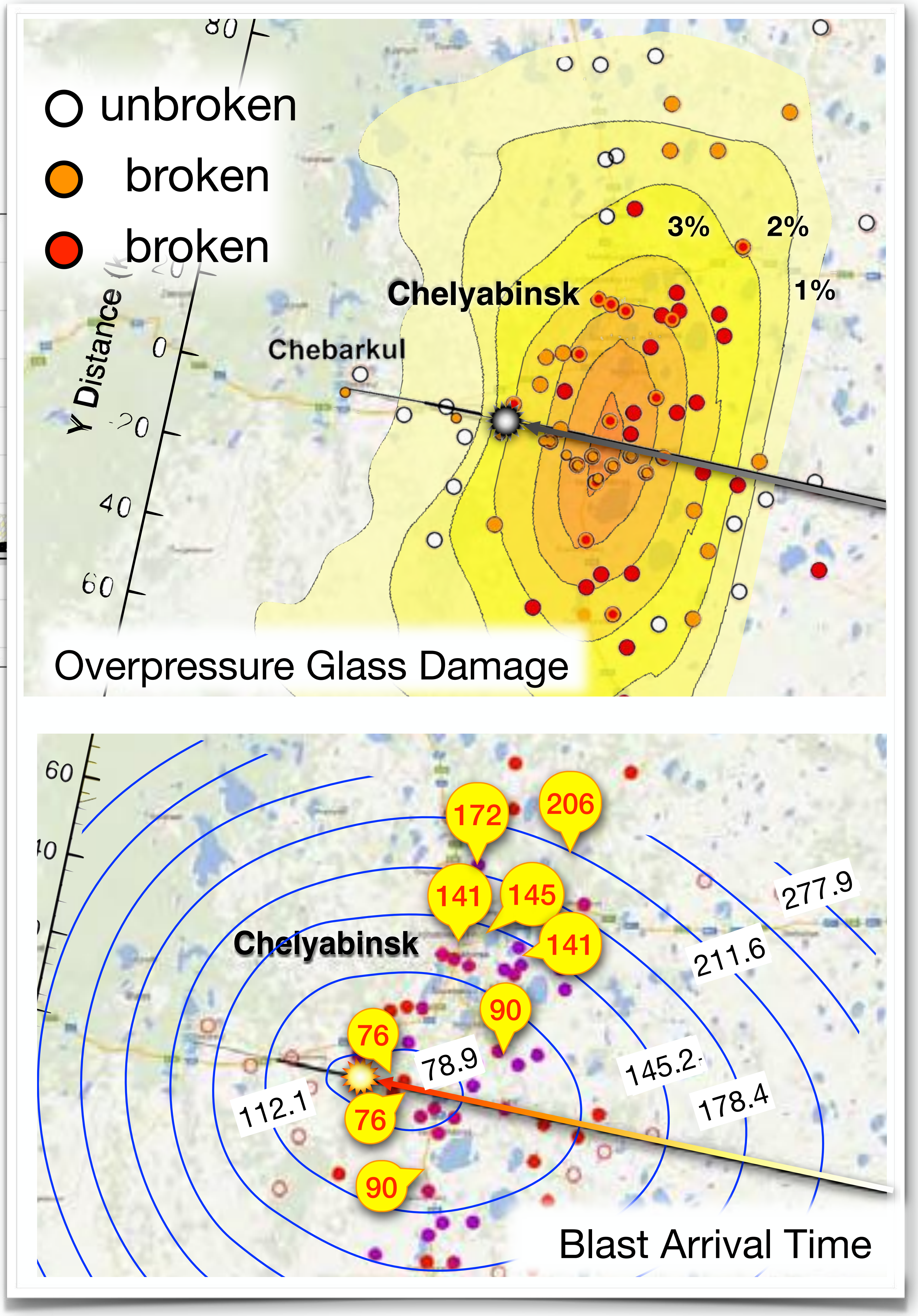
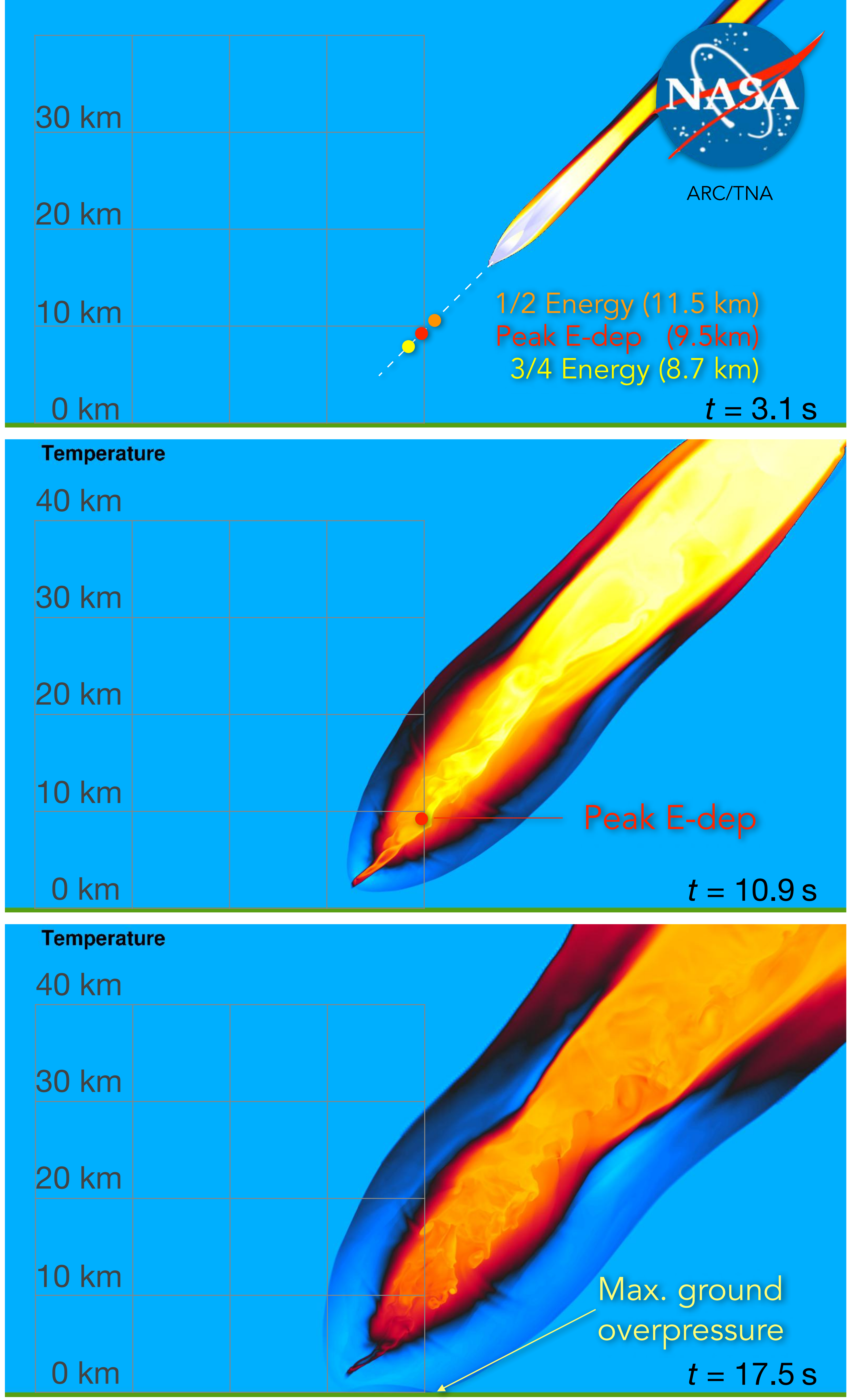


Image credit *AIAA 2016-0998, used with permission.*

Median Case: 45° entry, 50 Mt

45° entry of Ø 120 m, asteroid at 15.2 km/s, ρ = 2000 kg/m^3

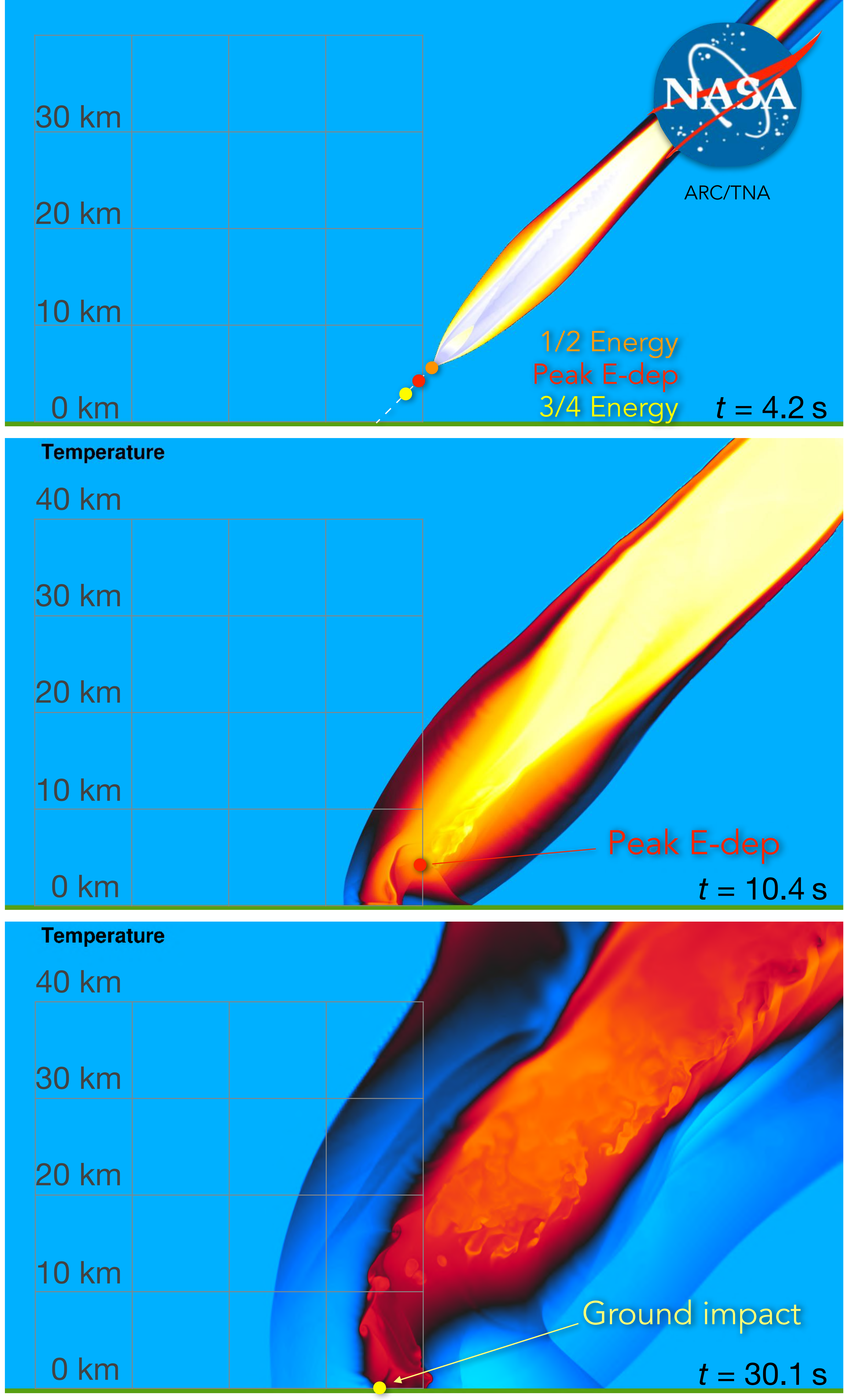
- Choose 5MPa strength case
  - 1/2 Energy altitude = 11.5 km
  - 3/4 Energy altitude = 8.7 km
  - Peak energy deposition @ 9.5 km
  - Near “optimal” burst height for maximum ground overpressure
- Full 3D, half-domain simulation, entry corridor r = 125m
- Mesh has 272 M cells with 16 m resolution of entry corridor & near max overpressure, coarsens by factors of 2
- Simulation covers 6:45 min total time after entry interface
  - Time step adjusted from Δt = 0.002 s (entry) to Δt = 0.015 s (late propagation) to maintain roughly constant wave propagation per step
- Domain
  - Extent [km]: (-128, 0, 0) ➝ (128, 120, 80)
  - Reflecting wall ground BC @ z = 0
- Record ground pressures and winds
- CPU: 8 hours on 200 nodes (8000 Intel cascade cores)



Mean Case: 250 Mt, 45° entry

45° entry of Ø 205 m, asteroid at 15.2 km/s, ρ = 2000 kg/m³

- Ground impact case — over 10Mt KE remaining at impact
  - Choose 5 MPa aerodynamic strength as representative
  - 1/2 Energy altitude = 6.9 km
  - 3/4 Energy altitude = 3.72 km
  - Peak energy deposition @ 4.6 km
  - Still has over 10Mt of KE at ground impact
- Approx. 3% of KE at impact goes into air blast
  - Model as surface detonation
- Larger domain — 380 M cell mesh with 16 m resolution of entry corridor & near max overpressure, coarsens by factors of 2
  - Extent [km]: (-128, 0, 0) ➛ (128, 120, 80)
  - Reflecting wall ground BC @ z = 0
- Simulation covers 7:50 min total time after entry interface
  - Time step adjusted from Δt = 0.002 s (entry/impact) to Δt = 0.016 s (late propagation)
- Record ground pressures and winds
- CPU: 8 hours on 200 nodes (8000 Intel cascade cores)



Median Case: 50 Mt, 45° entry

45° entry of Ø 120 m, asteroid at 15.2 km/s, ρ = 2000 kg/m³

ARC/TNA

Static Temperature

Mean Case: 250 Mt, 45° entry

45° entry of Ø 205 m, asteroid at 15.2 km/s, ρ = 2000 kg/m³

ARC/TNA

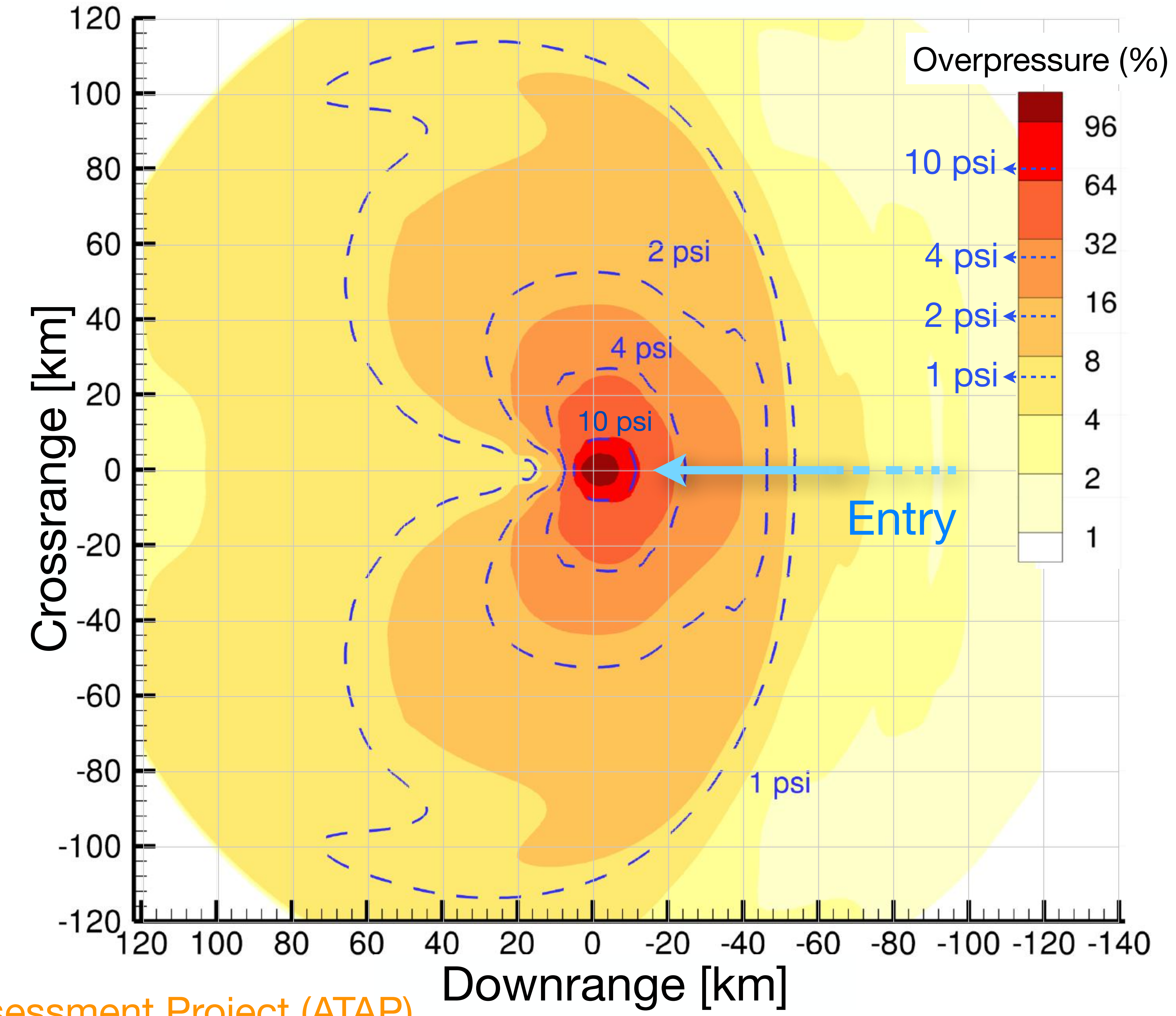
Static Temperature

Median Case: 50 Mt, 45° entry

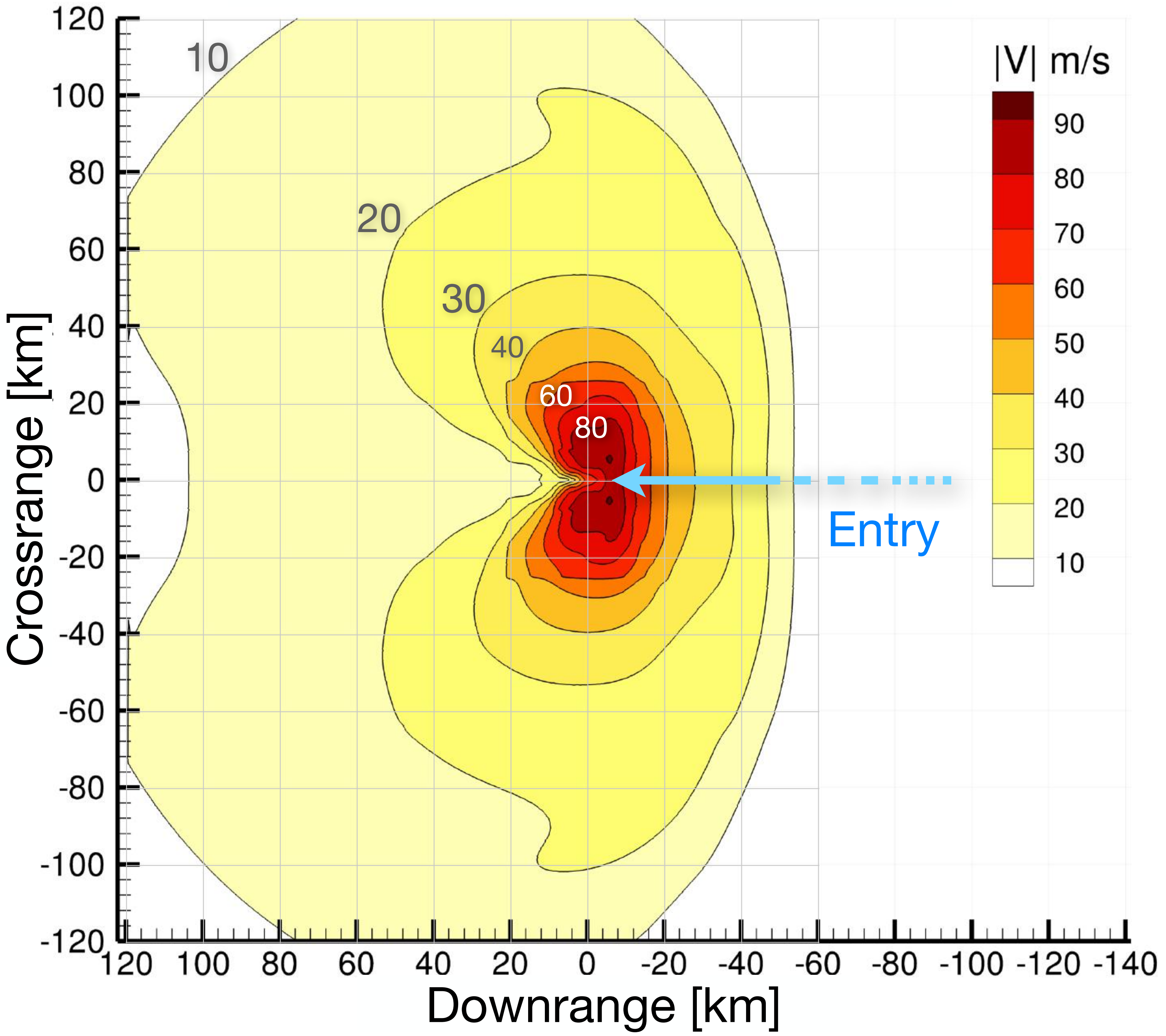
Ground footprints

- Footprint of maximum ground overpressure and surface wind speed captured over the duration of the simulation. Peak energy deposition near (0, 0). Entry is from right to left.
- The correlation between wind speed and overpressure level follows closely those of Glasstone and Dolan (1977)
- 1 psi overpressure exceeds ±115 km crossrange, and 10 psi contour is nearly circular with a radius ~9km

Peak ground overpressure



Peak surface wind speed

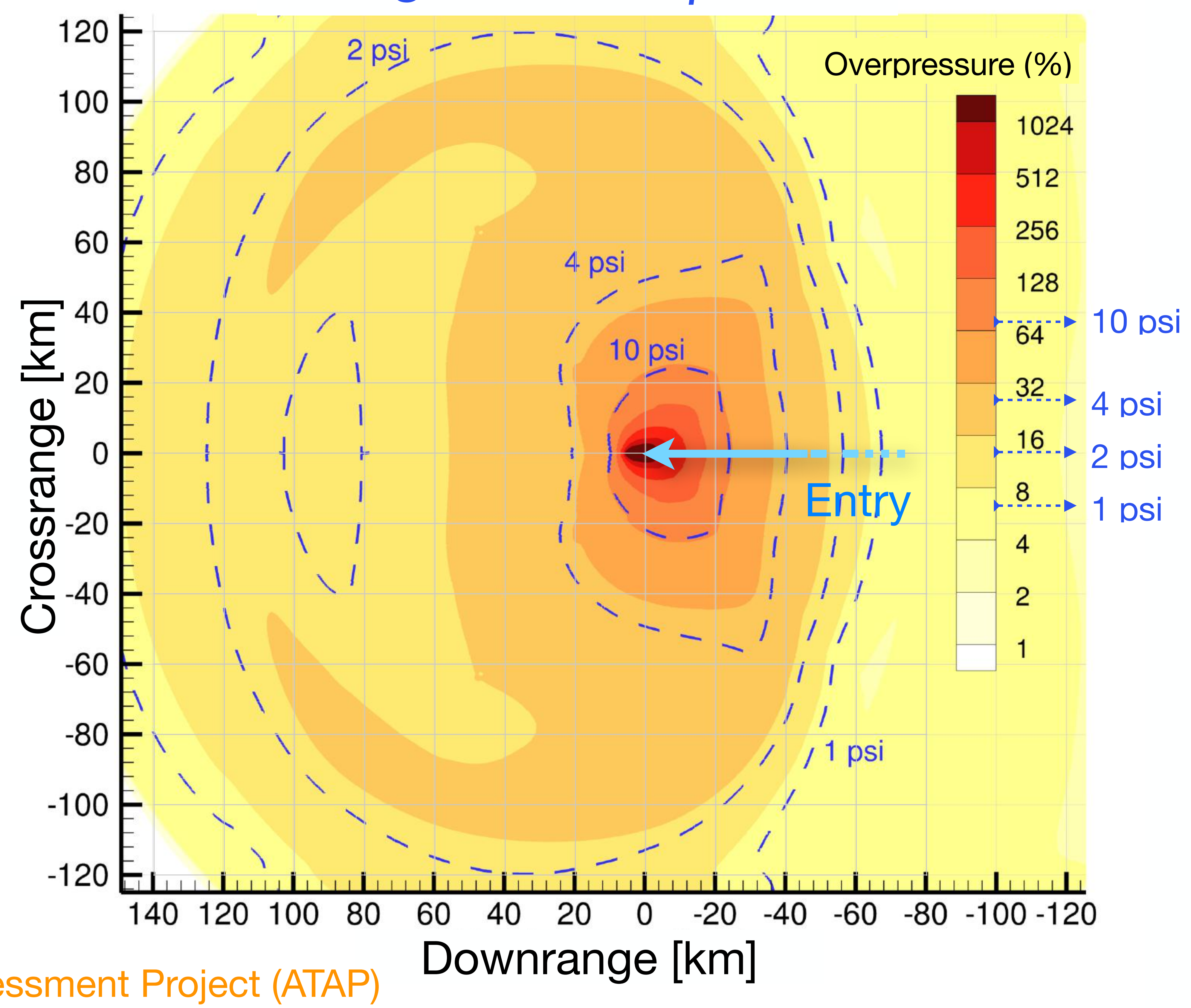


Mean Case: 250 Mt, 45° entry

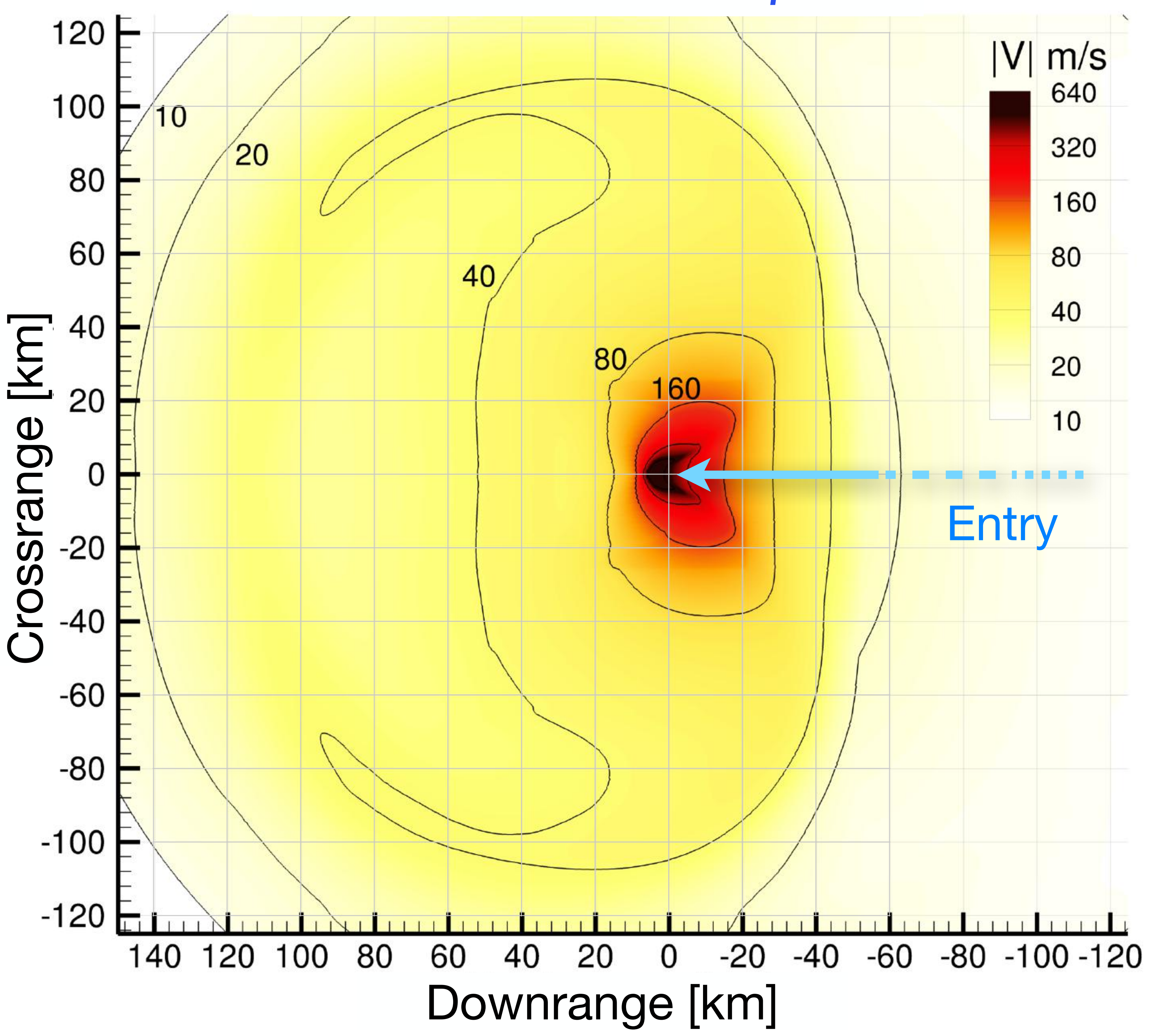
Ground footprints

- Footprint of maximum ground overpressure and surface wind speed captured over the duration of the simulation. Peak energy deposition near (0, 0). Impact is at +5 km downrange. Entry is from right to left.
- The correlation between wind speed and overpressure level follows closely those of Glasstone and Dolan (1977)
- The 2 psi contour extends to ±120 km crossrange. The 1psi contour extends beyond domain boundary at ±155 km

Peak ground overpressure



Peak surface wind speed

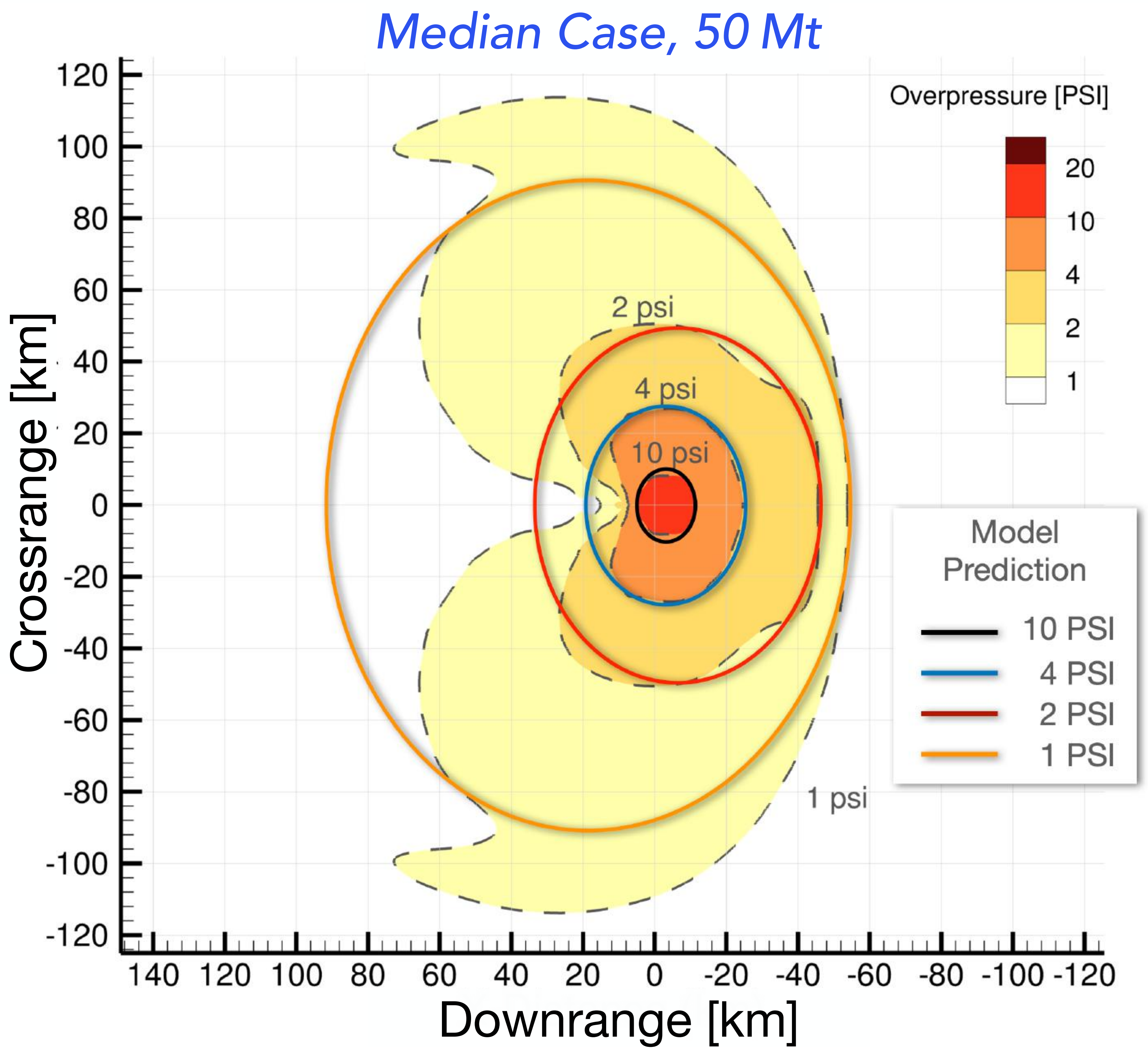


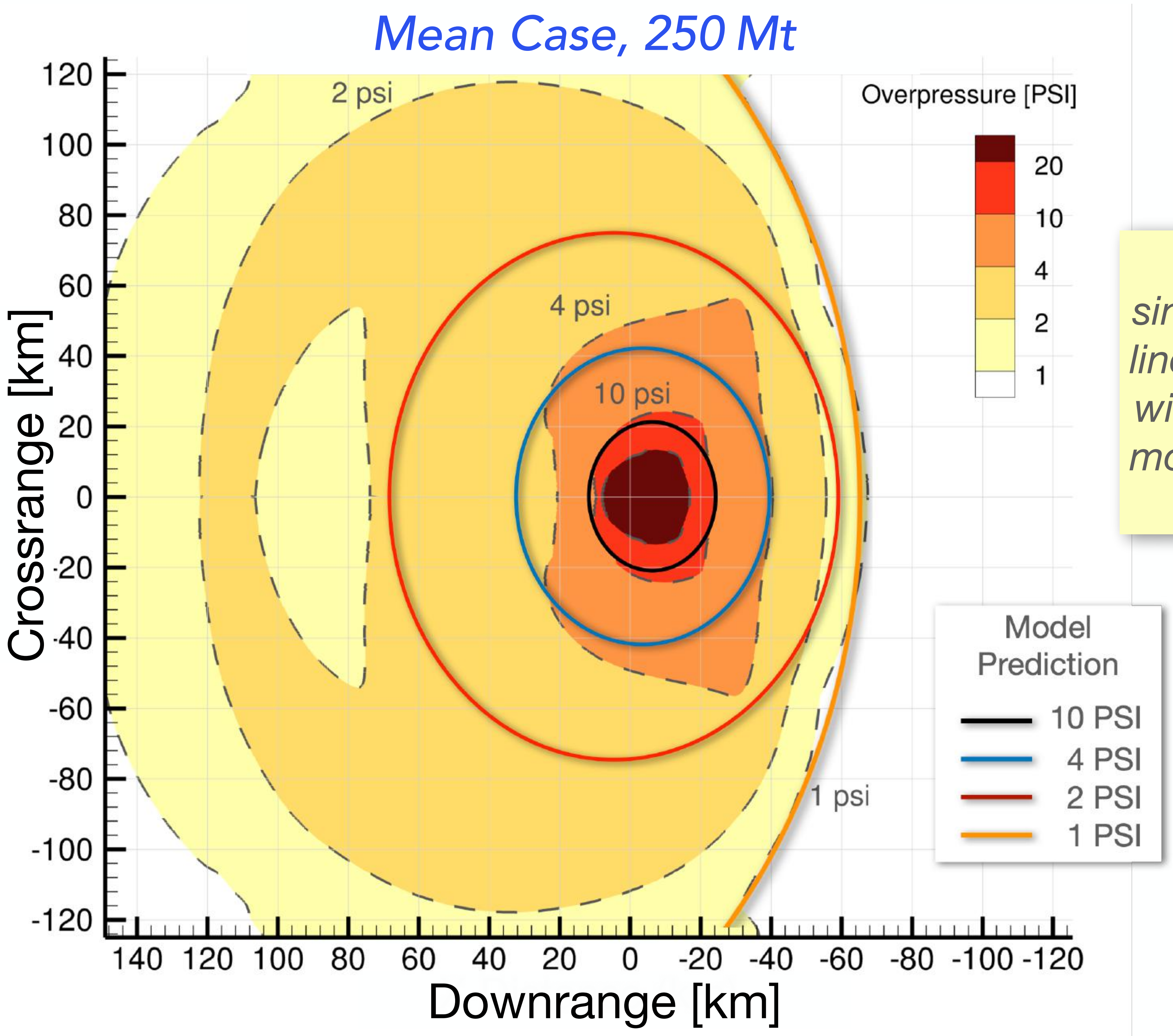
Ground footprint comparison with HoB model

ARC/TNA

Comparison of 3D simulation with fast-running engineering model

- Model does a very good job of predicting ground footprint for the 50 Mt (median) case. Model predictions of the mean blast radius, $\sqrt{\mathrm{Area}/\pi}$, are within 10% for all (1, 2, 4, 10 psi) overpressures
- At 250 Mt, model predictions are reasonable for 4 & 10 psi, but less accurate at lower overpressures. This is not surprising since the HoB model assumes a point source, which is a poor analog for this larger case which continuously sheds energy as it approaches the ground.





Dashed lines show simulation results. Solid lines show comparisons with HoB & eccentricity models (Aftosmis et al., 2017; 2019)

Summary

ARC/TNA

- Probabilistic risk assessment for hypothetical asteroid 2021 PDC was used to develop maps of mean ground damage radii and affected population.
- These maps were used to select nominal entry properties and combined with statistical inference techniques for asteroid properties to develop a range of entry profiles with sufficient detail to enable high-fidelity simulation.
- Performed high-fidelity 3D entry simulations for self-content median (50Mt) and mean (250Mt) entry profiles to compute ground overpressure footprints and maps of local maximum wind speed to drive hazard modeling using NASA's Cart3D simulation package.
- Results for the median (50 Mt) and mean (250 Mt) showed that critical or unsurvivable damage areas covered 1,734 and 5,940 km^2 respectively, with serious damage covering 23,700 km^2 for the median and 55,242 km^2 for the mean.

	Full Simulation Results - (downrange x crossrange)		Fast Running HoB Model	
Damage Level	Median (50 Mt)	Mean (250 Mt)	Median (50 Mt)	Mean (250 Mt)
Serious (1 PSI)	147 x 232 km	220 x 320 km (est)	142 x 176 km	299 x 350 km
Severe (2 PSI)	78 x 111 km	180 x 240 km	79 x 98 km	115 x 135 km
Critical (4 PSI)	39 x 56 km	65 x 113 km	45 x 56 km	65 x 75 km
Unsurvivable (10 PSI)	18 x 17 km	35 x 49 km	15 x 18 km	33 x 38 km

- Comparisons with the fast-running height-of-burst & eccentricity model revealed that predictions for the 50 Mt median case were very good for all damage levels. For the larger (250 Mt) case, agreement was good at the higher damage levels, but less accurate for more moderate damage.

References

- "Planetary Defense Conference Exercise - 2021" Center for Near Earth Object Studies, JPL, *https://cneos.jpl.nasa.gov/pd/cs/pdc21/*, accessed Jan. 2021.
- Dotson, Mathias, Wheeler, Wooden, Bryson and Ostrowski, "Near Earth Asteroid Characterization for Threat Assessment", IAA-PDC-17-03-14, May 2017
- Wheeler, Dotson and Mathias "Impact Risk Summary for the PDC 2021 Hypothetical Impact Exercise: Day 0", 3 Dec. 2020
- Wheeler, L., Register, P., Mathias, D., A fragment-cloud model for asteroid breakup and atmospheric energy deposition, *Icarus* **295**:149–169, 2017
- Aftosmis, M. Nemec, M., Mathias, D., and Berger, M., Numerical simulation of bolide entry with ground footprint prediction, *AIAA Paper 2016-0998*, Jan. 2016.
- Mathias, D., Wheeler, L., Dotson J., 2017. A probabilistic asteroid impact risk model: assessment of sub-300m impacts. *Icarus* 289:106–119. 2017.
- Aftosmis, M.J., Mathias, D.L., and Tarano, A.M., "Simulation-based height of burst map for asteroid airburst damage prediction." *Acta Astronautica*, **156**:278- 283, 2017.
- Aftosmis, Nemec & Wheeler, A Ground Footprint Eccentricity Model For Asteroid Airbursts. IAA-PDC-19-06.01, 2019 April 2019.