



# Asteroid Impact Risk Assessment

**Donovan L. Mathias**

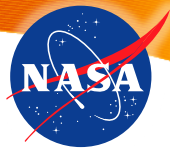
Asteroid Threat Assessment Project  
NASA Ames Research Center

USGS Seminar  
Menlo Park, CA  
February 27, 2018



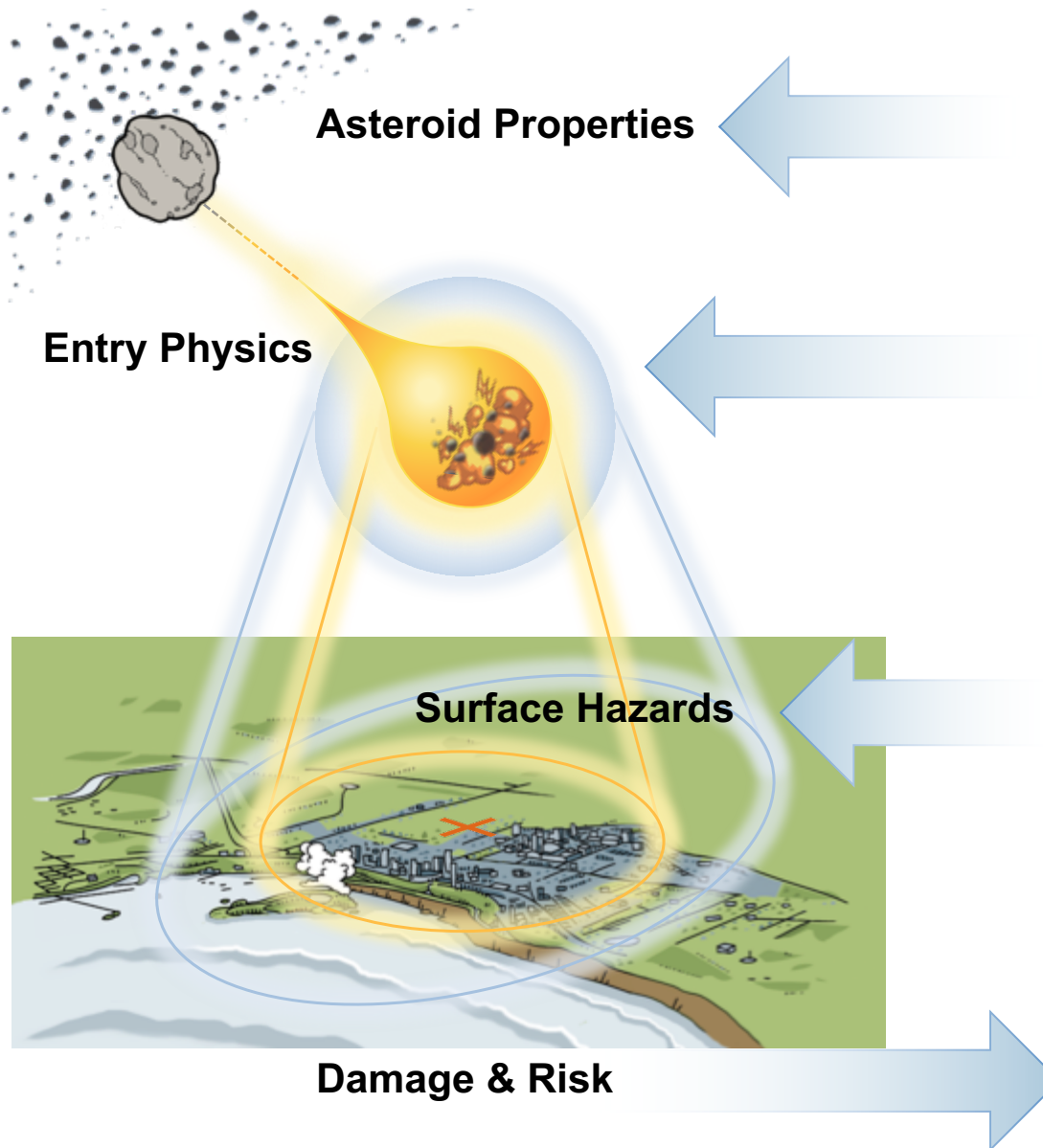


# ATAP Presentation Contributors



- Michael Aftosmis
- Jessi Dotson
- Marian Nemec
- Darrel Robertson
- Eric Stern
- Lorien Wheeler

# Asteroid Threat Assessment



## Characterization

- Measurements
- Inference
- Data aggregation
- Property database website

## Entry Simulations & Testing

- Coupled aerothermodynamics
- Ablation & radiation modeling
- Arc jet testing

## Hazard Simulations

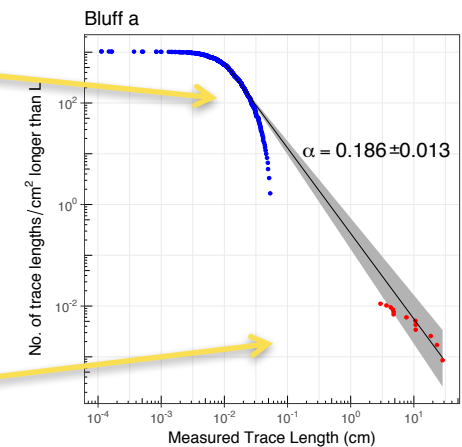
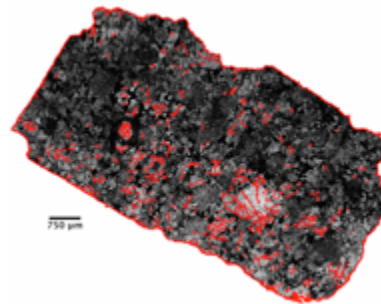
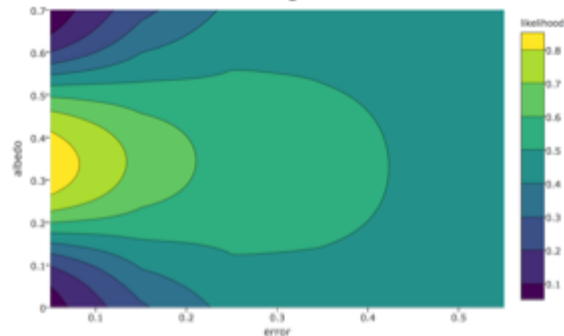
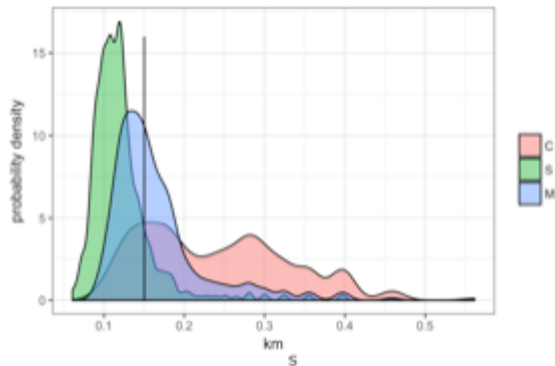
- 3D blast simulations
- Impact crater simulations
- Tsunami simulations
- Thermal radiation models
- Global effects

## Probabilistic Risk Assessment

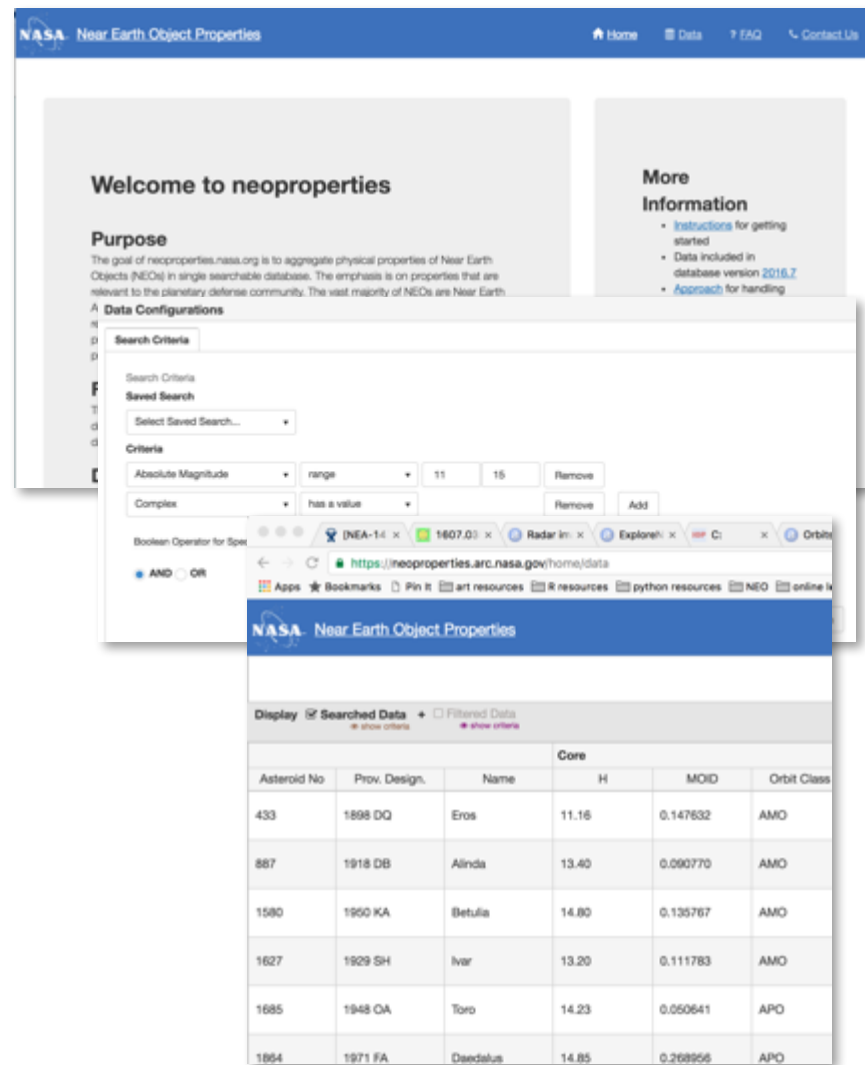
- Analytic physics-based entry and damage models
- Probabilistic Monte Carlo simulation using uncertainty distributions

# Asteroid Characteristics

- Inferring characteristics and distributions
  - Developed distributions of key asteroid characteristics for use in risk models
  - Developing methodology to quantitatively infer characteristics given limited information.
- Meteorites as asteroid samples
  - Bulk density
  - Grain density
  - Thermal emissivity
  - Acoustic velocity
  - Quantifying observed fractures as analog of “aerodynamic strength”



- neoproperties website
  - Aggregates physical properties of NEOs and meteorites into a searchable database
  - Emphasis on properties of interest to the planetary defense community.
- Asteroid contents include:
  - Taxonomic class
  - Diameters & albedos
- Meteorite contents include:
  - Density & porosity
  - Compressive & tensile strength
  - Elastic & shear moduli
  - Heat capacity & thermal conductivity



The screenshot shows the NASA Near Earth Object Properties website. The top navigation bar includes links for Home, Data, FAQ, and Contact Us. The main content area is divided into sections: Welcome to neoproperties, Purpose (explaining the goal of aggregating physical properties of NEOs), More Information (with links for instructions, data version 2016.7, and approach for handling), and Data Configurations. The Data Configurations section includes a Search Criteria panel with a Saved Search dropdown, a Criteria panel with filters for Absolute Magnitude (range 11 to 15) and Complex (has a value), and a Boolean Operator for Spec (AND/OR). Below the search criteria, a table of NEO data is displayed, showing Asteroid No., Prov. Design., Name, H, MOID, and Orbit Class.

| Asteroid No. | Prov. Design. | Name     | H     | MOID     | Orbit Class |
|--------------|---------------|----------|-------|----------|-------------|
| 433          | 1898 DQ       | Eros     | 11.16 | 0.147632 | AMO         |
| 887          | 1918 DB       | Alinda   | 13.40 | 0.090770 | AMO         |
| 1580         | 1950 KA       | Betulia  | 14.80 | 0.135767 | AMO         |
| 1627         | 1929 SH       | Ivar     | 13.20 | 0.111783 | AMO         |
| 1685         | 1948 OA       | Toro     | 14.23 | 0.050641 | APO         |
| 1864         | 1971 FA       | Daedalus | 14.85 | 0.268956 | APO         |

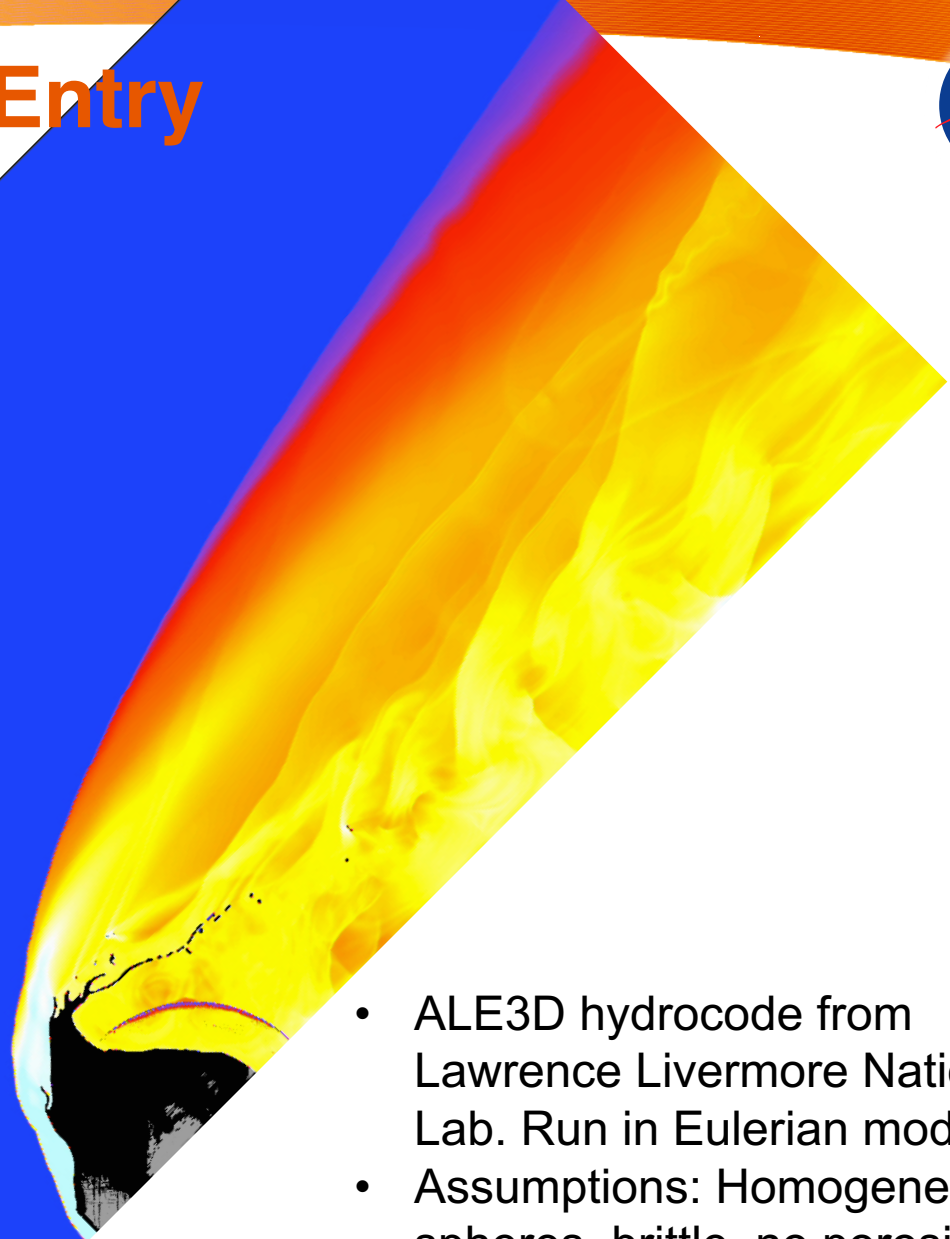
Feedback? Suggestions? Email [jessie.dotson@nasa.gov](mailto:jessie.dotson@nasa.gov)

# Atmospheric Entry

Asteroid  
 $\varnothing 50\text{m}$ ,  $45^\circ$ ,  $20\text{km/s}$ ,  $2\text{g/cc}$ ,  $0.1\text{MPa}$

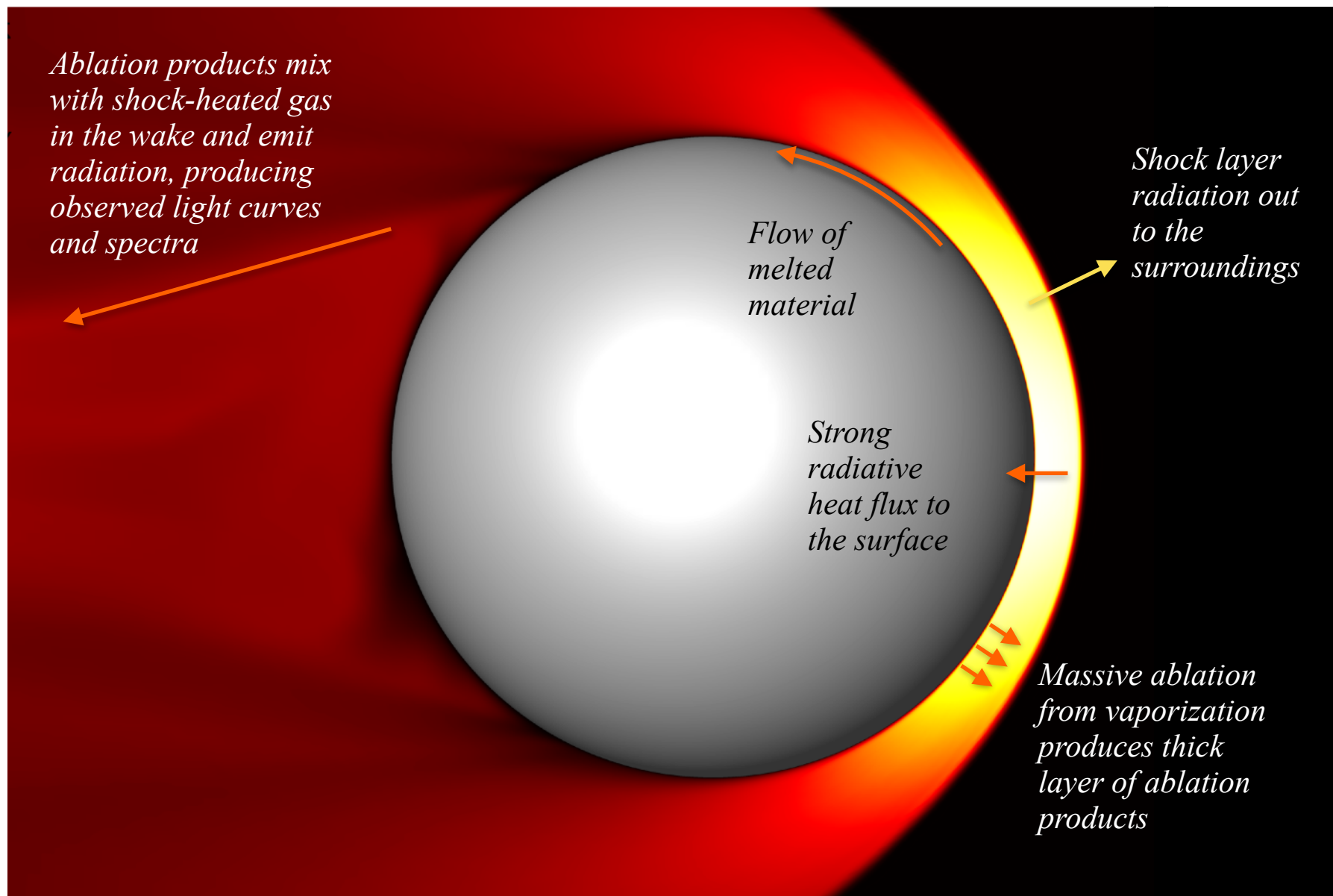
Altitude (km)

60.00



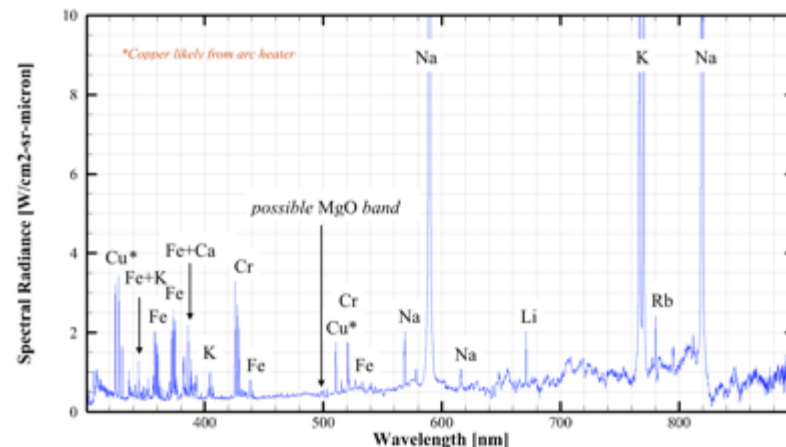
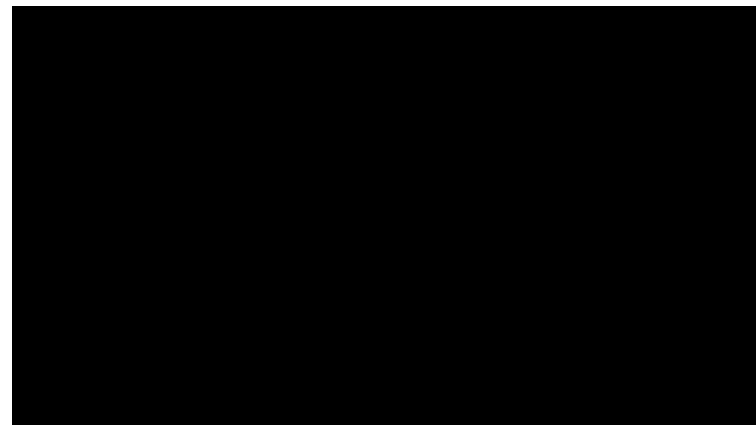
- ALE3D hydrocode from Lawrence Livermore National Lab. Run in Eulerian mode
- Assumptions: Homogeneous spheres, brittle, no porosity, no ablation
- Provided by Darrel Robertson

# Large Meteoroid Entry Environment



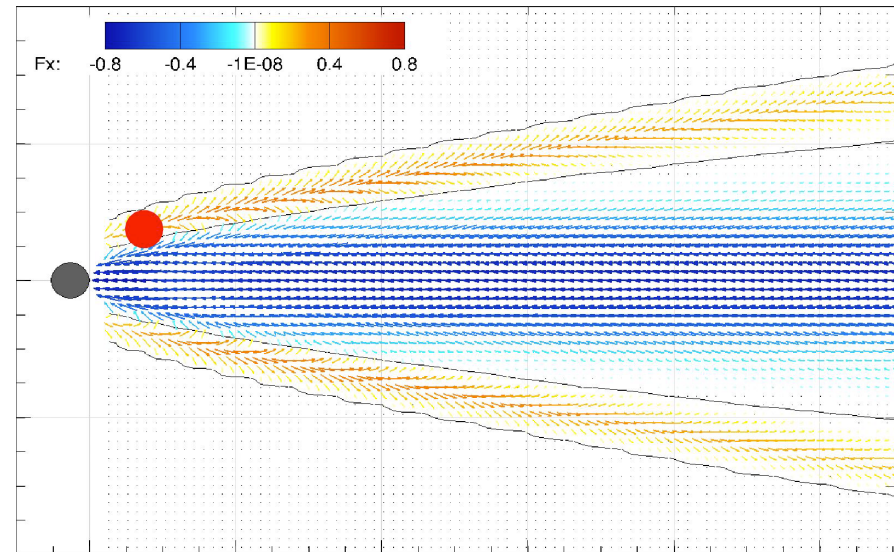
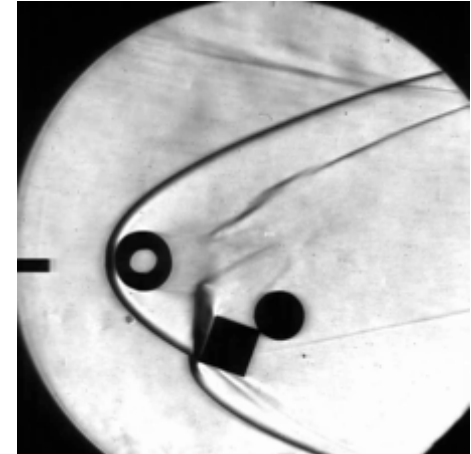
# Meteoroid Ablation Experiments

- Asteroid ablation models:
  - State of the art asteroid energy deposition code uses single parameter to account for mass loss due to ablation
  - Ablation physics for large meteoroids and asteroids is poorly understood
- Development of detailed ablation model:
  - Laser scans of pre- and post-test model shapes have provided data for developing and validating melt flow ablation models
  - Results indicate much lower melt viscosity than previously assumed
  - Widespread melt flow results in significantly lower effective heat of ablation than state of the art
- Looking ahead: luminosity models
  - High-resolution spectra of ablation products from arc jet experiment provides unique data for development and valuation of meteoroid luminosity models



# Asteroid Fragment Spreading

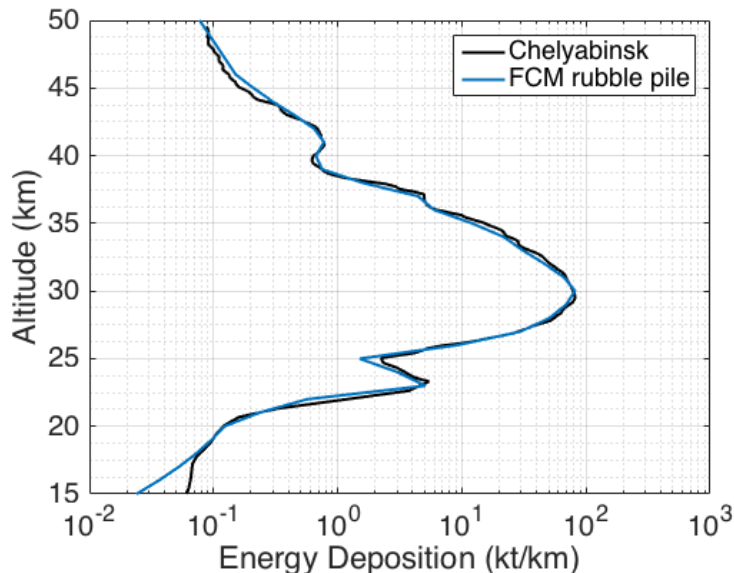
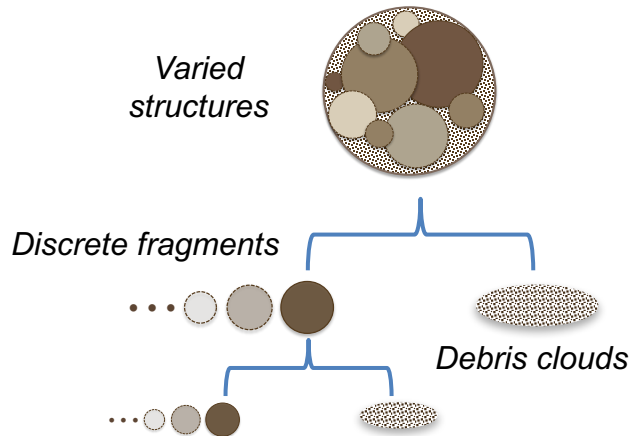
- Asteroid fragment spread-rate:
  - Current atmospheric energy deposition code requires model for the rapid increases in aerodynamic drag area to produce realistic energy deposition profiles
  - Recent studies (Laurence et al.) have suggested that there may be significant uncertainty in the assumed historical model
- Collaboration with DLR to study multi-body aerodynamics:
  - DLR wind tunnel facility allows for free-flight experiments of multiple bodies in hypersonic flow
  - Utilize wind tunnel data to validate ATAP numerical simulations
  - Single-body simulations performed to-date show very good agreement with DLR experimental data
- Looking ahead:
  - Developing analytic model for asteroid fragment spreading based on database approach



Cart3d static force database for trajectory simulation.

# Fragment-Cloud Model (FCM)

## FCM Breakup Modeling

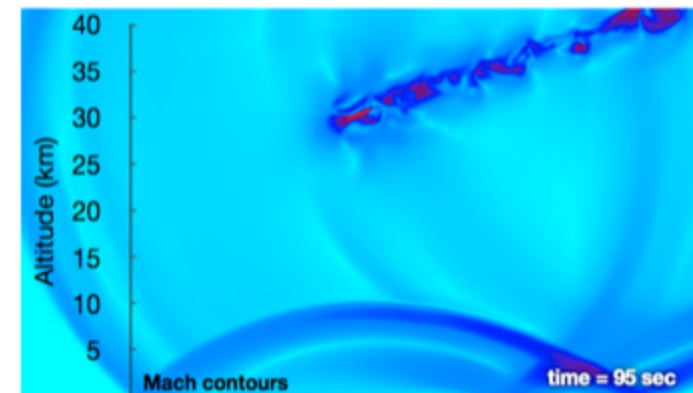
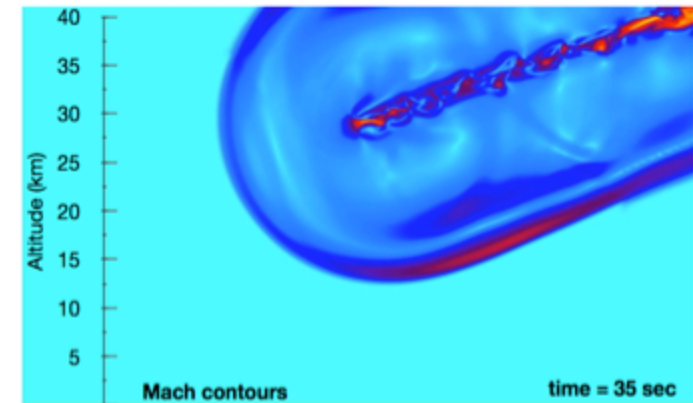


## FCM Approach

- Analytic model of energy deposited in the atmosphere during entry and breakup
- Represents breakup process using a combination of discrete fragments and aggregate debris clouds
- Can represent range of asteroid structures and breakup characteristics
- Energy deposition used to estimate airburst altitudes and ground energies for risk modeling
- FCM results can match observed meteor light curves to:
  - Infer pre-entry asteroid properties
  - Investigate breakup characteristics
  - Guide model refinements

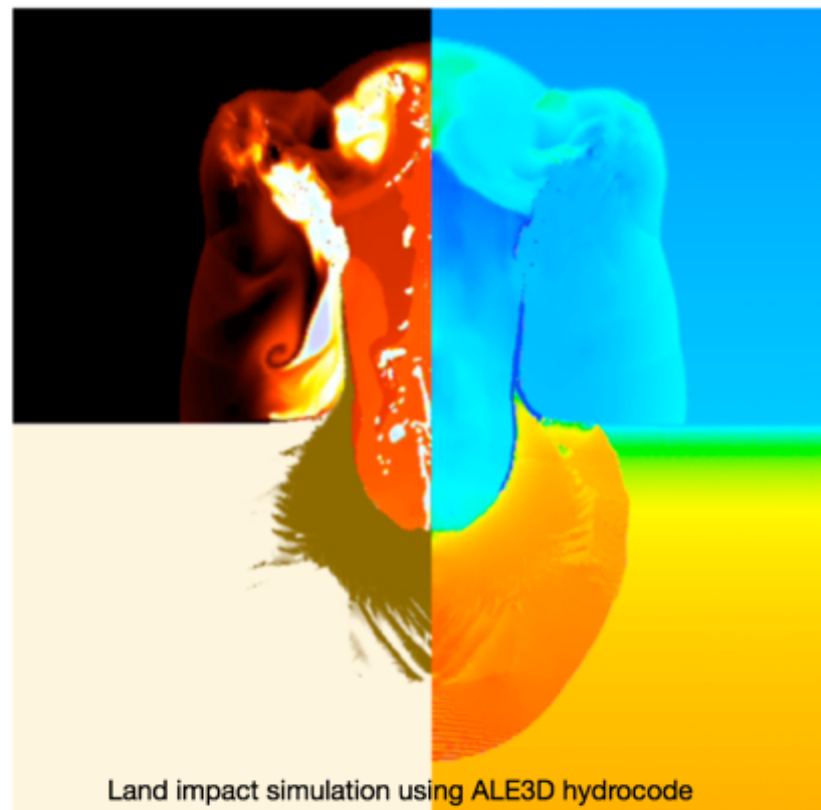
# Hazard Simulation

- High-fidelity simulations of key impact hazards:
  - Tsunami Modeling
  - Surface Impact Modeling
  - Blast Overpressure Modeling
- Used to anchor and refine analytic models used in risk analysis
- Uses entry conditions and energy deposition from asteroid characterization and entry modeling efforts



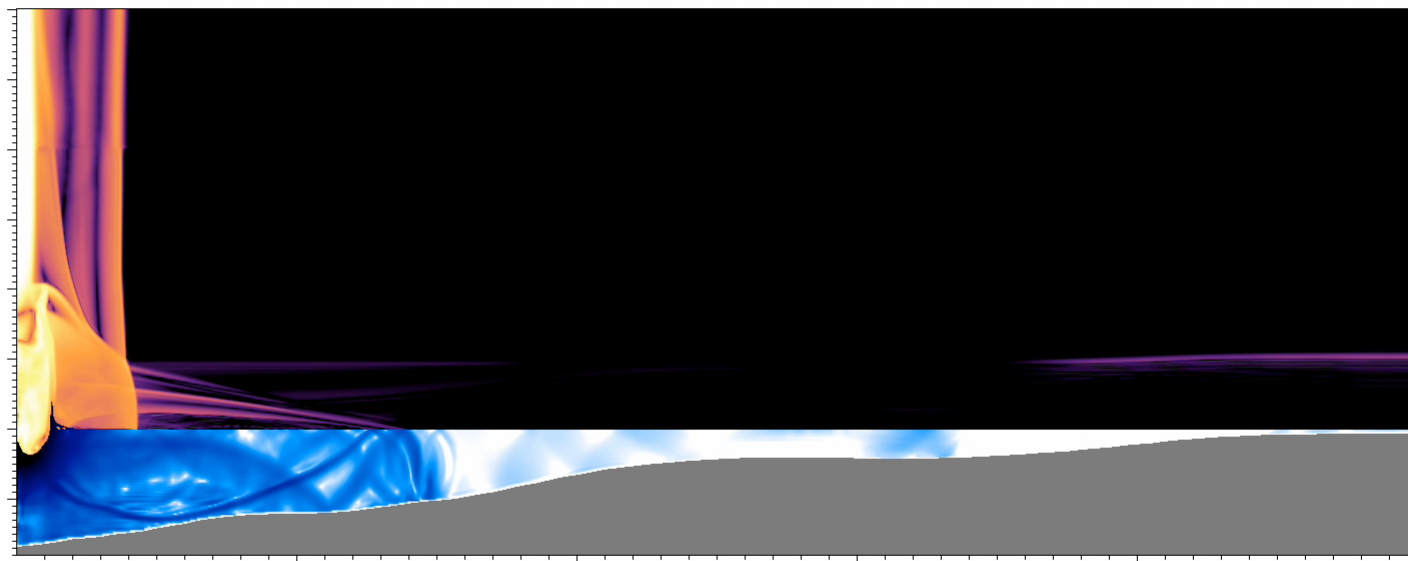
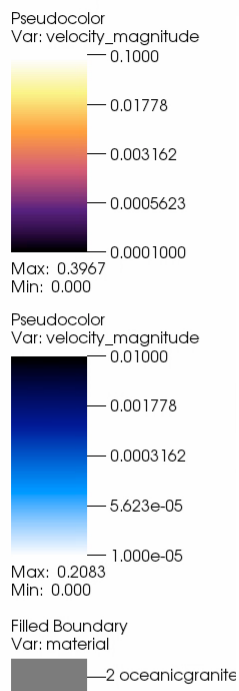
# Surface Impact Modeling

- Land Impacts
  - Nearfield: Hydrocode simulations of impactors up to 1 gigaton conducted for PDC17 impact scenario (Tokyo, Japan, May 2017)
  - Farfield Propagation: Coupling with NASA's Cart3D aerodynamic simulation code for far field blast propagation.
  - Includes both energy deposited in atmosphere and energy released at impact site.
- Water Impacts (Splashing)
  - High-fidelity hydrocode (ALE3D) simulations provide cavity size and salt water plume ejection, but expensive for long distance propagation
  - Provides initial waves for long distance propagation performed with developmental version of GeoClaw tsunami code
  - Formation of traveling wave trains from initial water cavities using different modeling approaches/wave equations
- Analytic model development/validation:
  - Impressive results for water impacts using engineering method based on use of Hankel functions (currently in development)



# Deep Water Impact

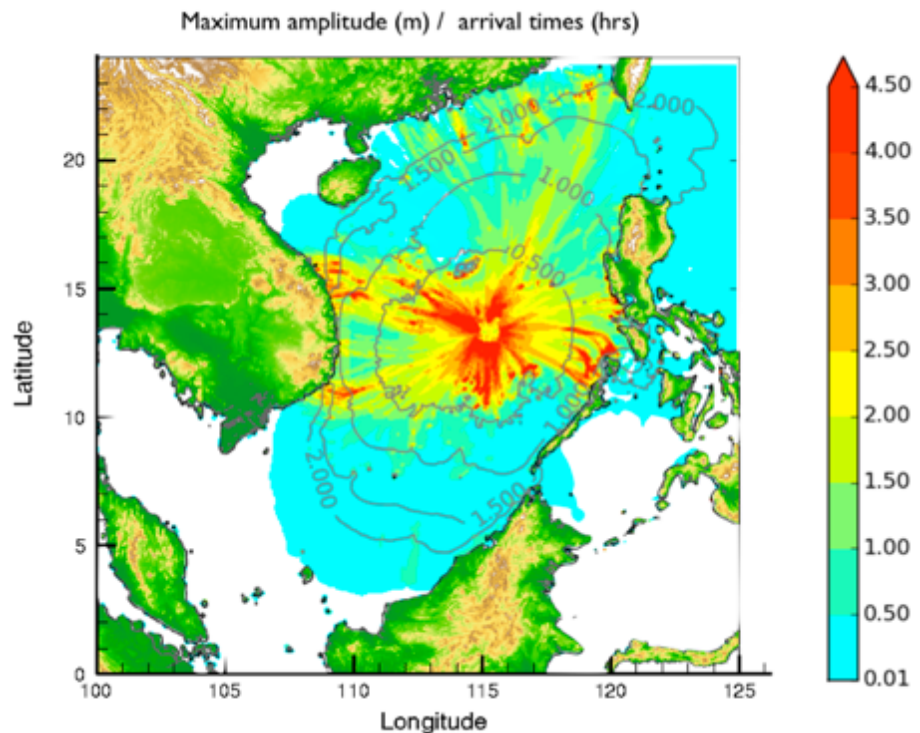
DB: 1GT\_JapanTrench\_240.008086146  
Cycle: 8086146 Time: 2.1e+07



ALE3D simulations by Darrel Robertson

# Tsunami Modeling

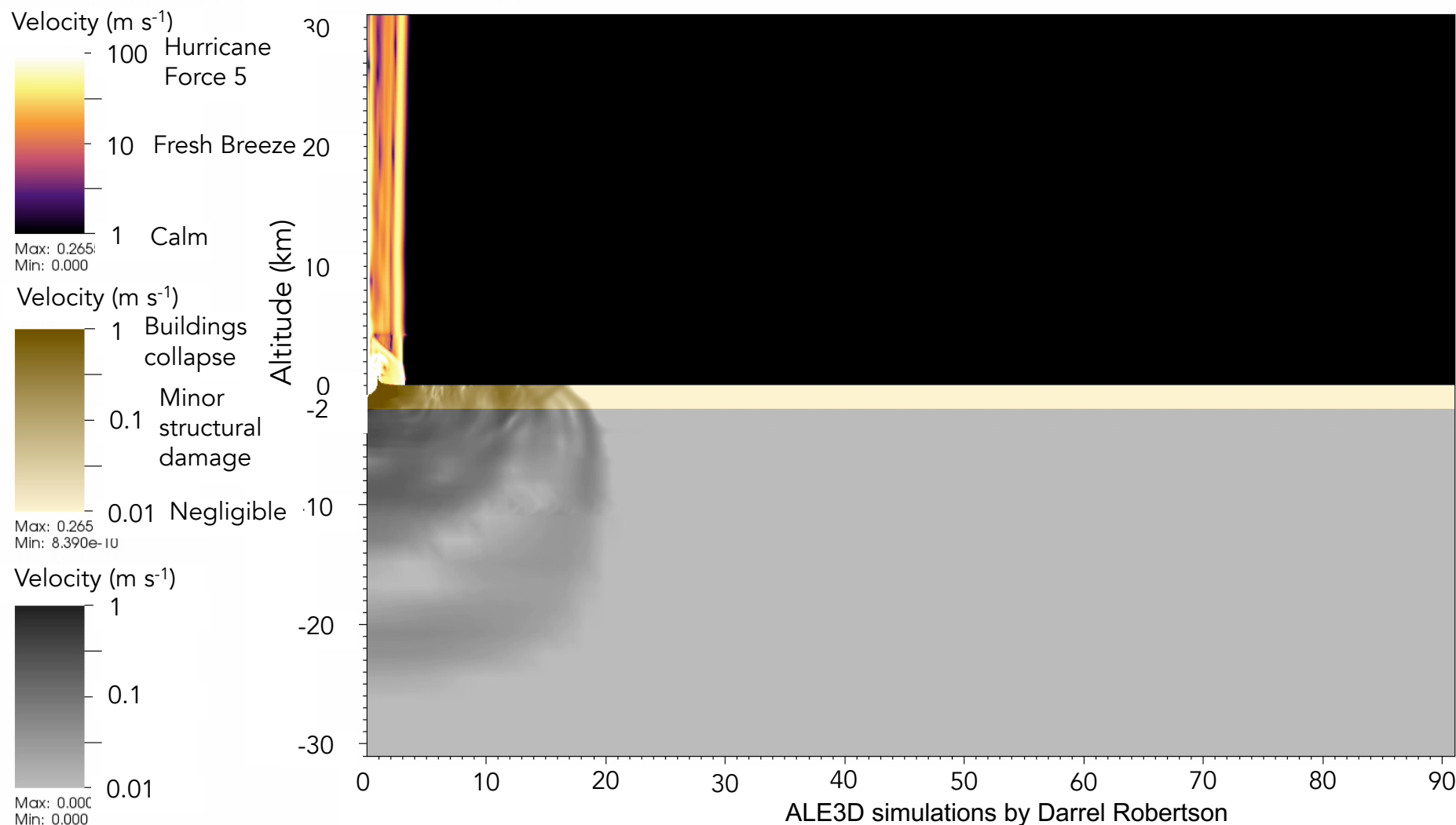
- Tsunami Workshop (Aug. 2016)
  - Sponsored the NASA/NOAA Workshop on Asteroid Threat Assessment: Asteroid-generated Tsunami (AGT) and Associated Risk, held in Seattle WA
  - Included head-to-head comparisons of tsunami simulations from NASA, DOE, NOAA and academia for a range of water impact and airburst cases (5, 100 & 250 MT)
- Outcome
  - 2003 SDT report may have overstated tsunami risk from asteroid airburst
  - Large airbursts may be reasonably modeled with Shallow Water Equations (SWE)
  - Higher frequencies associated with water impacts may merit study with Boussinesq or Linearized Euler solvers
- Follow-up
  - Parametric studies of SWE, Boussinesq, and Linearized Euler methods
  - Developing improved analytic models for tsunami run-up and run-in



# 100Mt iron into sandstone

DB: 100MT\_GobiDesert\_280.006890070

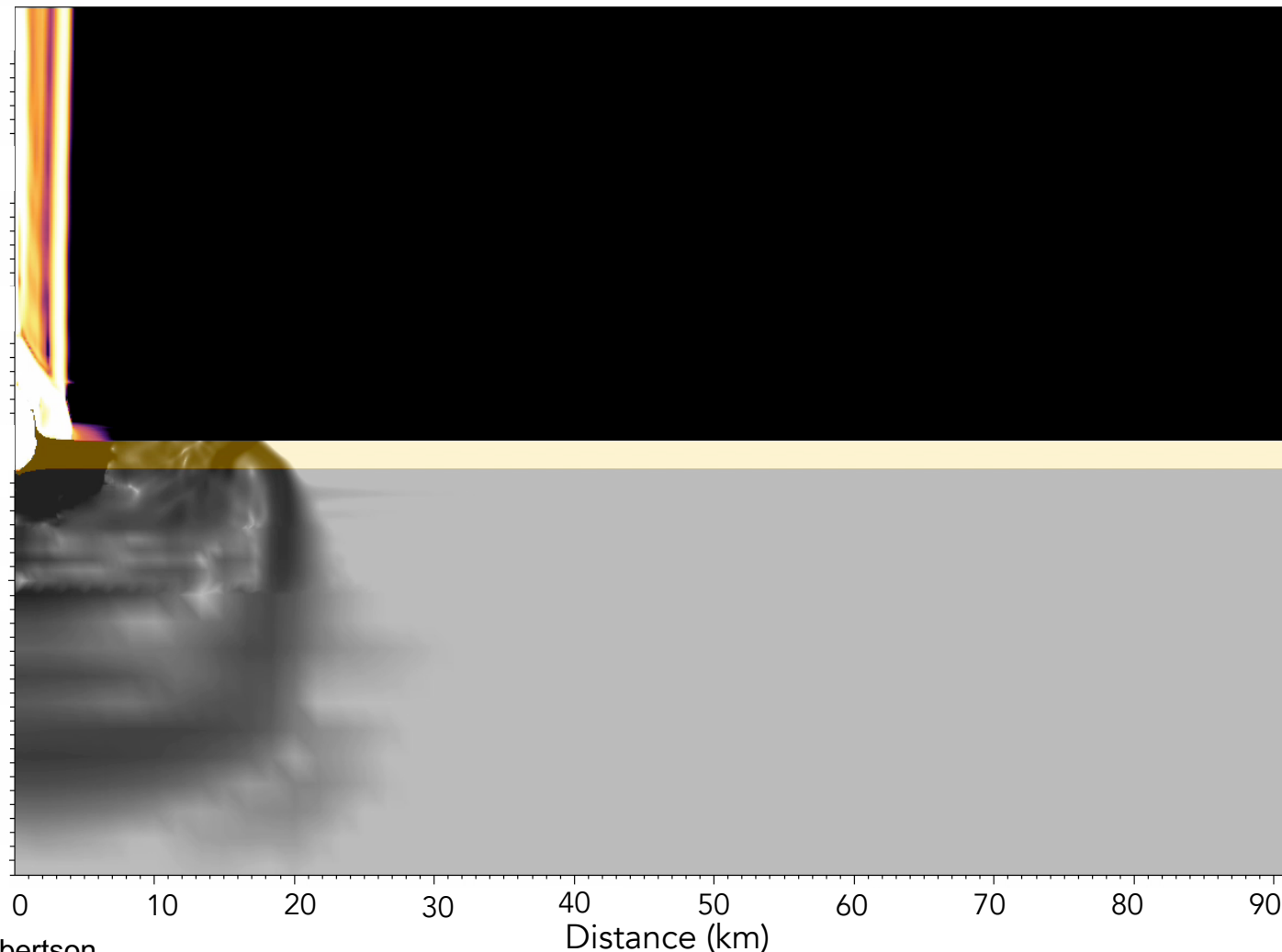
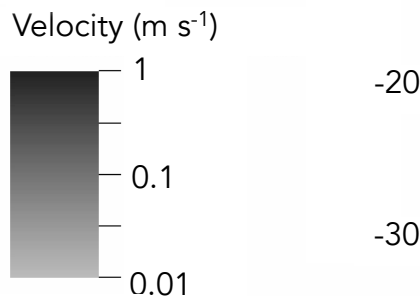
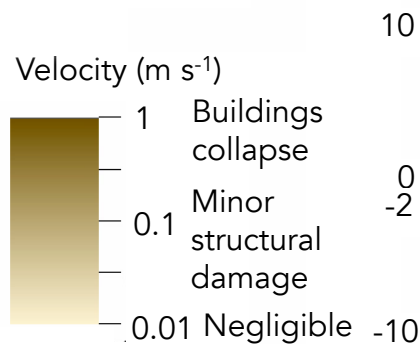
Cycle: 6890070 Time: 9.30001e+06



# 1Gt iron into sandstone

DB: 1GT\_GobiDesert2\_280.006036221

Cycle: 6036221 Time: 9.50001e+06

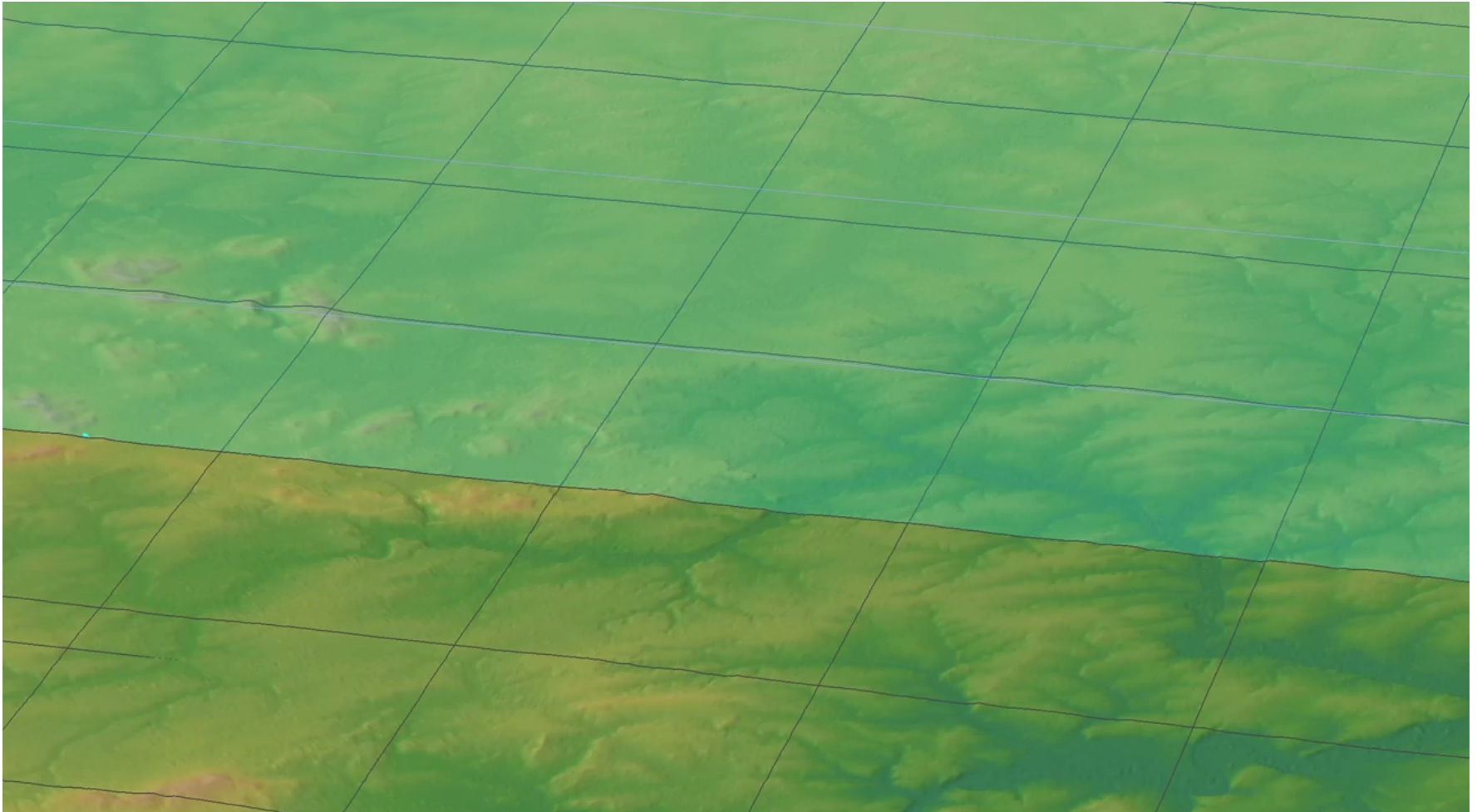


ALE3D simulations by Darrel Robertson

# Simulated Airburst

Cart3d simulations by Michael Aftosmis and Marian Nemec

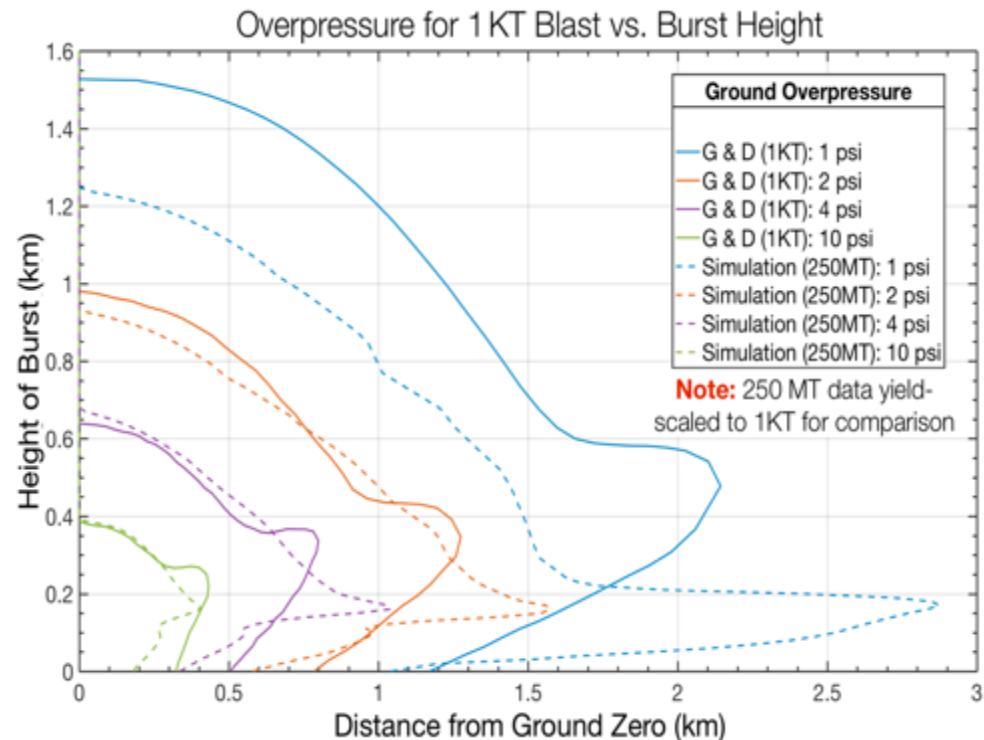
# Airburst over Tunguska



Cart3d simulations by Michael Aftosmis and Marian Nemec

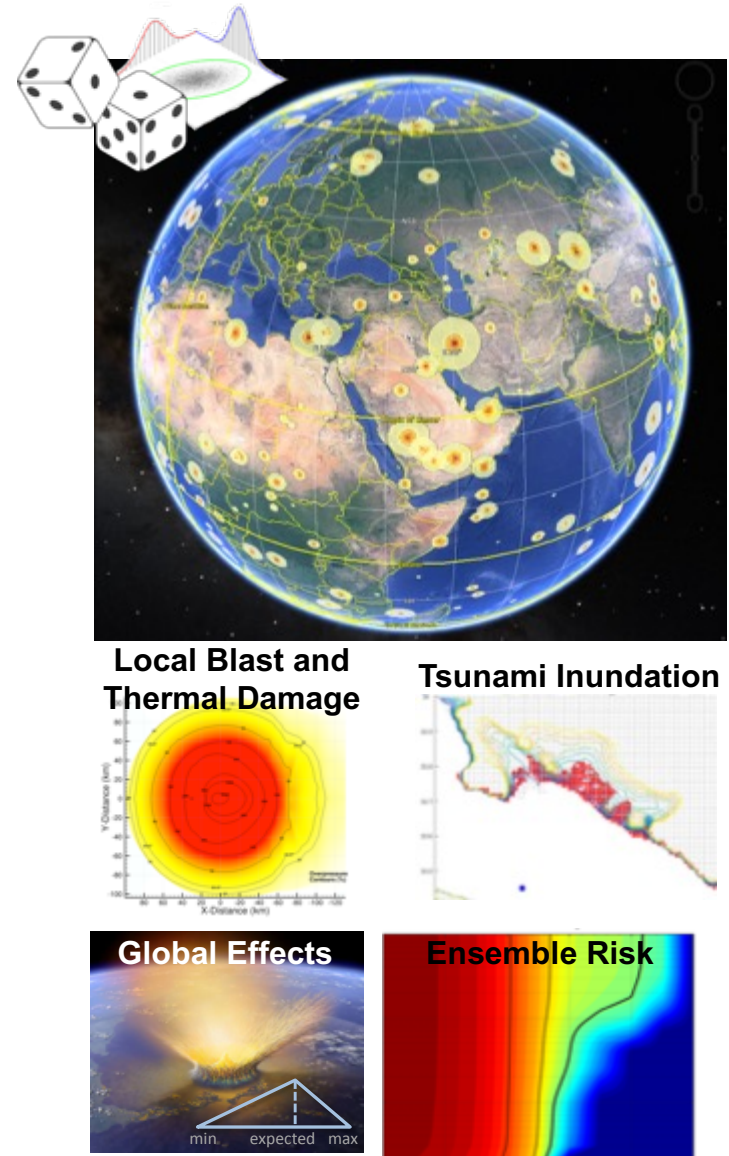
# Blast Overpressure Modeling

- Computational fluid dynamics (CFD) simulations of blast propagation from asteroid airburst to overpressure levels on the ground.
- Height-of-Burst (HOB) map for risk assessment
  - HOB maps estimate blast damage areas for bursts of different energies and altitudes.
  - Yield-scaling based on smaller nuclear sources (Glasstone & Dolan)
  - Yield-scaling becomes inaccurate due to buoyancy effects for higher impact energies (KE >10-50 megatons, diameter > 50-80m)
- Used CFD simulations to generate improved HOB map for large impactors.
  - PAIR risk model interpolates between appropriate HOB maps to give improved prediction of ground footprint
  - Excellent example of high-fidelity analysis informing the fast-running methods for probabilistic risk assessment

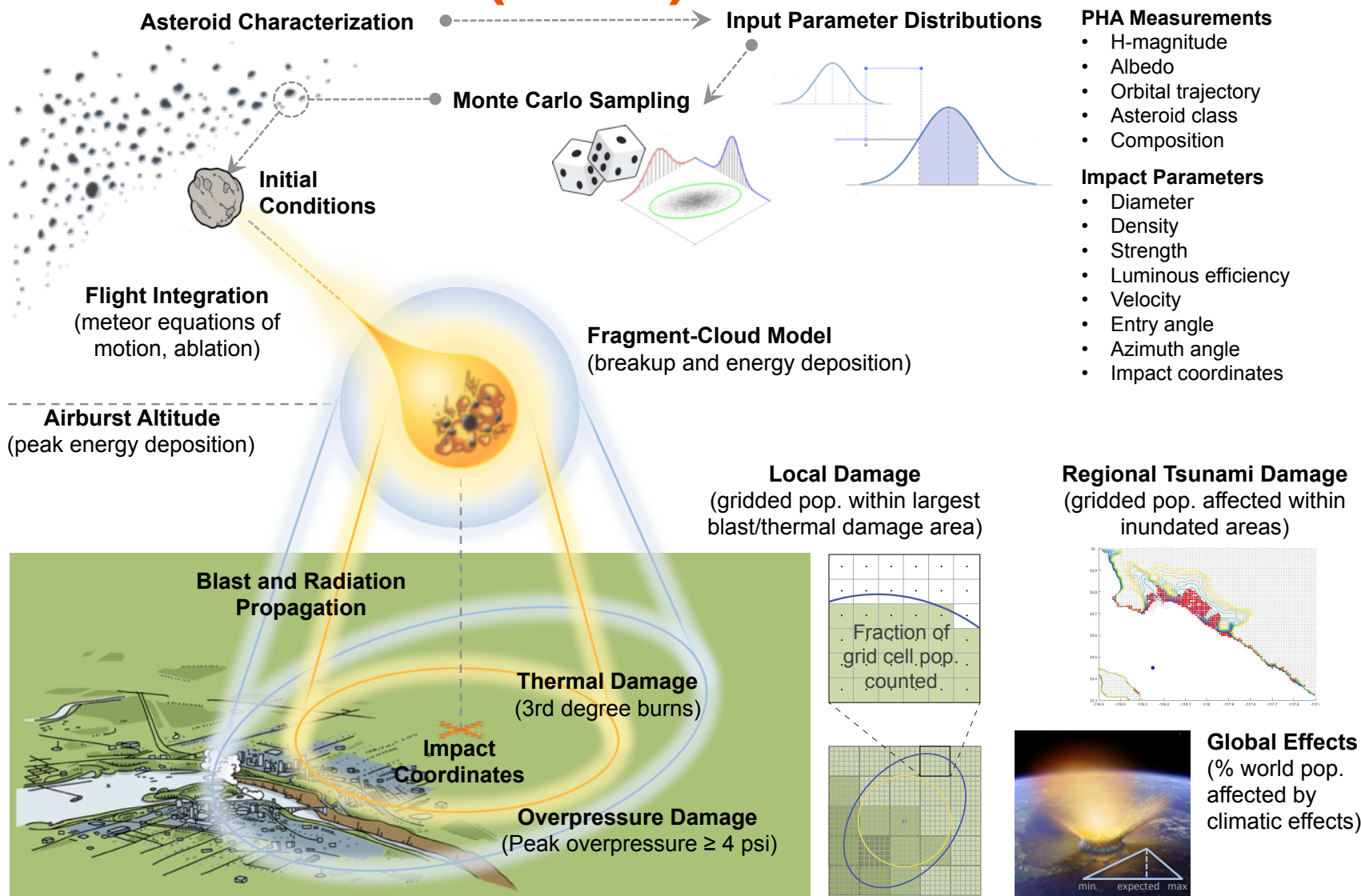


# Probabilistic Asteroid Impact Risk (PAIR) Model

- PAIR model approach:
  - Uses analytic models of asteroid entry and hazards to assess damage from millions of impact cases
  - Samples uncertainty distributions of asteroid properties developed by characterization team
  - Location-specific affected populations capture range of consequences
  - Hazard models include blast overpressure, thermal radiation, tsunami, and global effects
  - Models anchored with high-fidelity simulations.
- Results & Applications
  - 2017 NEO Science Definition Team
  - Impact corridor risk assessment (TTX3 and PDC impact exercises)
  - Hypothetical TC4 scenario.

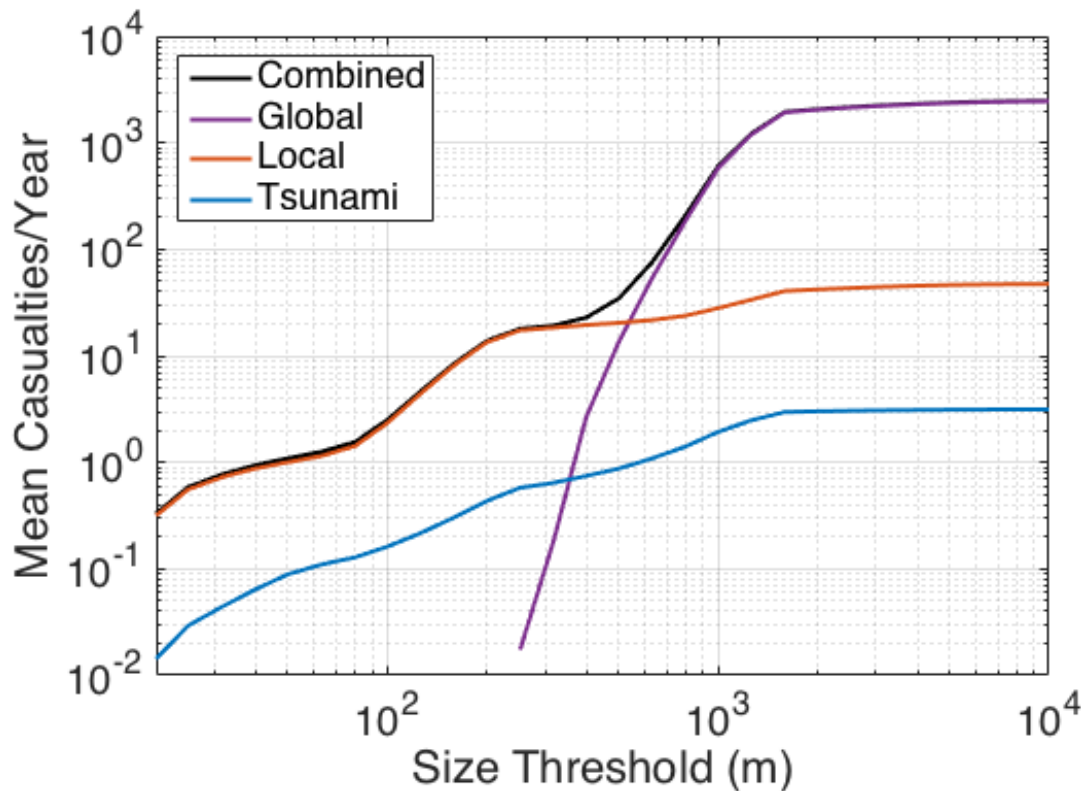


# Probabilistic Asteroid Impact Risk (PAIR) Model



# Expected Casualties from Asteroid Impacts

## 2017 NEO SDT Report



**Global effects from large impacts dominate the risk**

**Local effects drive the risk for impactors smaller than 500 m.**

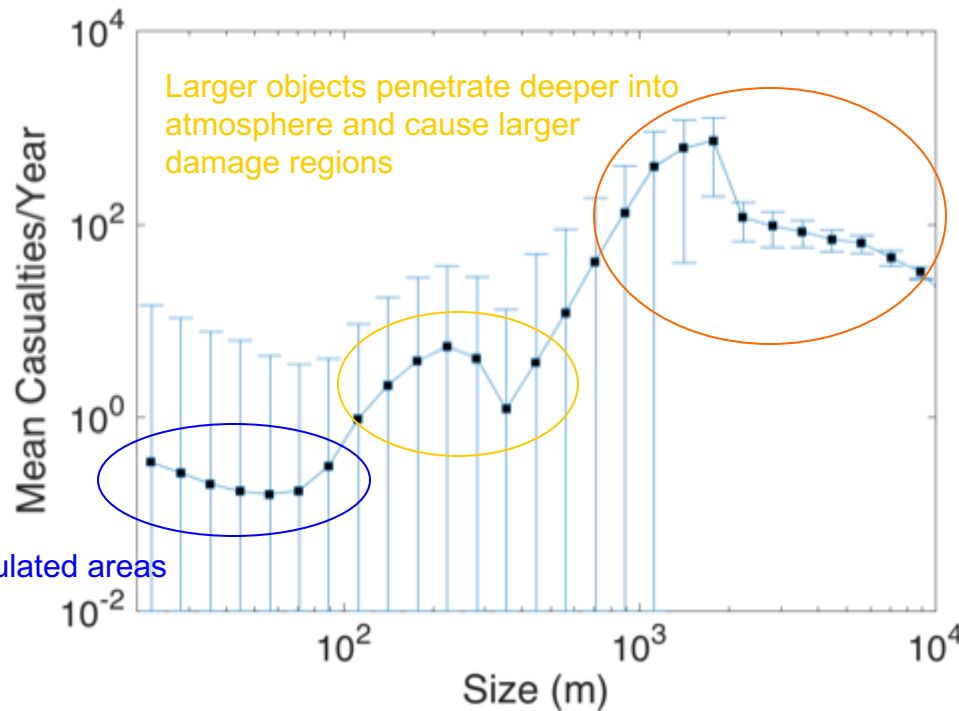
**Tsunami effects can be important for specific scenarios, but on average contribute ~10x less risk than local effects.**

**Cumulative average annual casualties, by hazard, for the total PHO population.**

# Differential Casualty Estimates

## 2017 NEO SDT Report

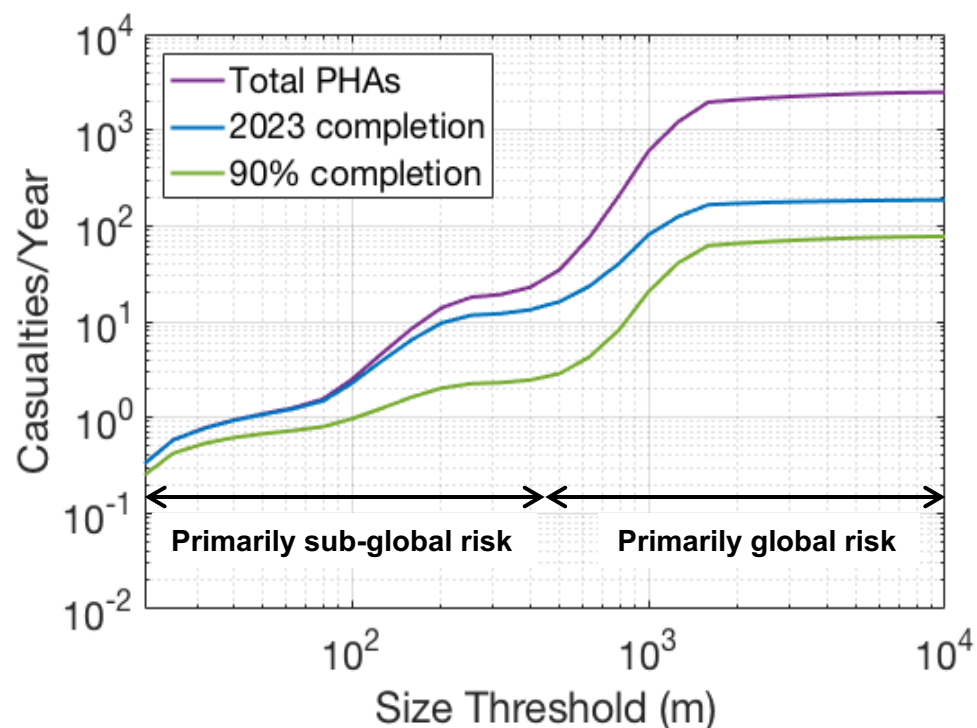
- Average (total) casualty estimates plotted for each size bin for total PHO population
- Vertical bars represent one standard deviation uncertainty bounds
  - Bars that extend to bottom of plot indicate that zero casualty results fall within one standard deviation of the mean



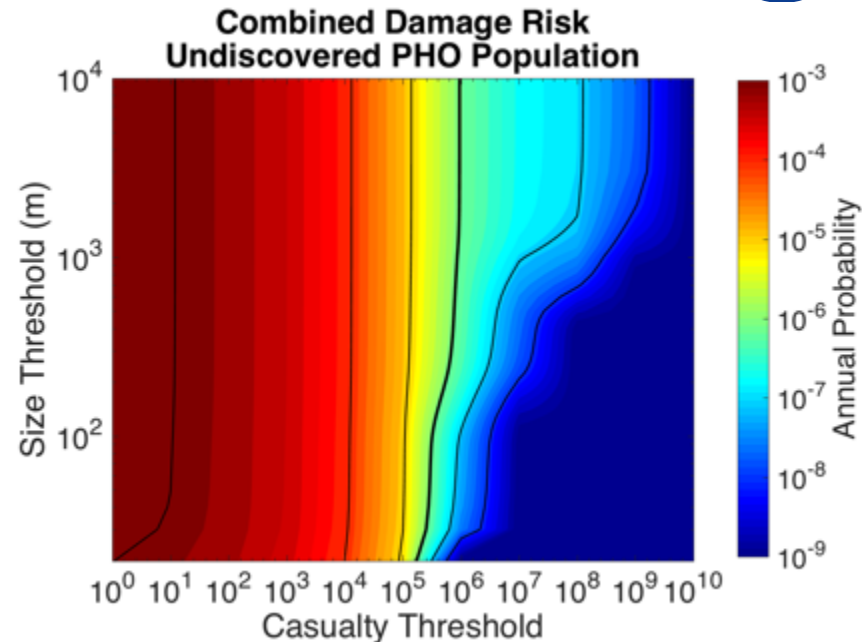
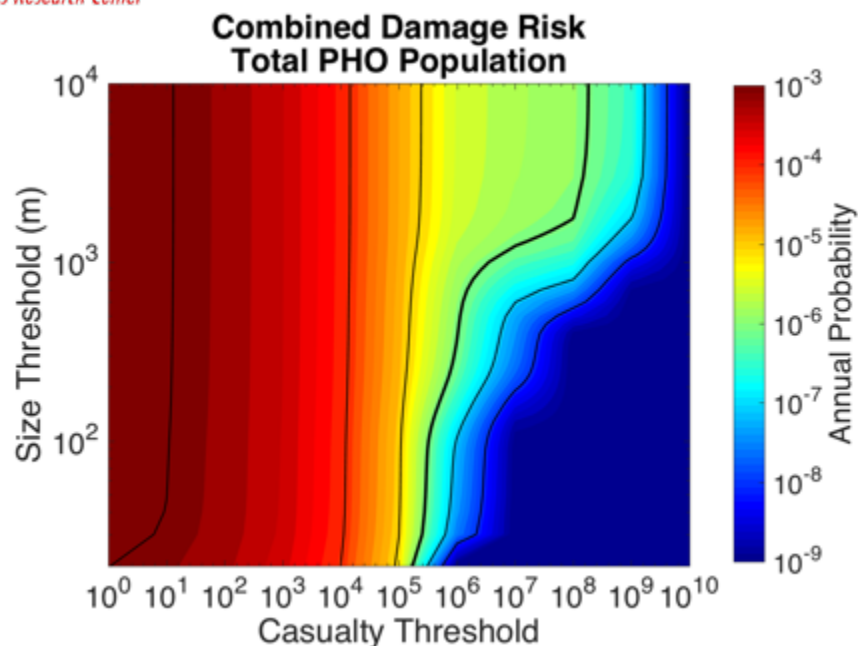
Largest objects result in global effects. The fall off with size  $> 2\text{km}$  occurs because the impact frequency decreases with size while damage per strike remains constant

# Cumulative Expected Casualties 2017 NEO SDT Report

- Cumulative expected casualties per year
  - Total PHO population
  - Assuming current survey discovery rate up to 2023
  - At point where 90% of the sub-global risk uncertainty has been reduced
- In 2023, largest risk uncertainty reduction associated with large objects
- At 90% completion
  - Additional large-object risk uncertainty reduced
  - Largest uncertainty reduction occurs in the “hundreds of meter” size range



# 2017 SDT Combined Risk Results



- Combined (local, tsunami, and global effects) risk profiles are shown for total PHO population (left) and undiscovered (2023) PHO population (right).
- Comparative risk is unchanged below ~250 m.
- AT sizes above ~1 km, undiscovered PHO risk is ~ 10x less than that for the entire PHO population.
- Annual casualty risk still dominated by large impactors.

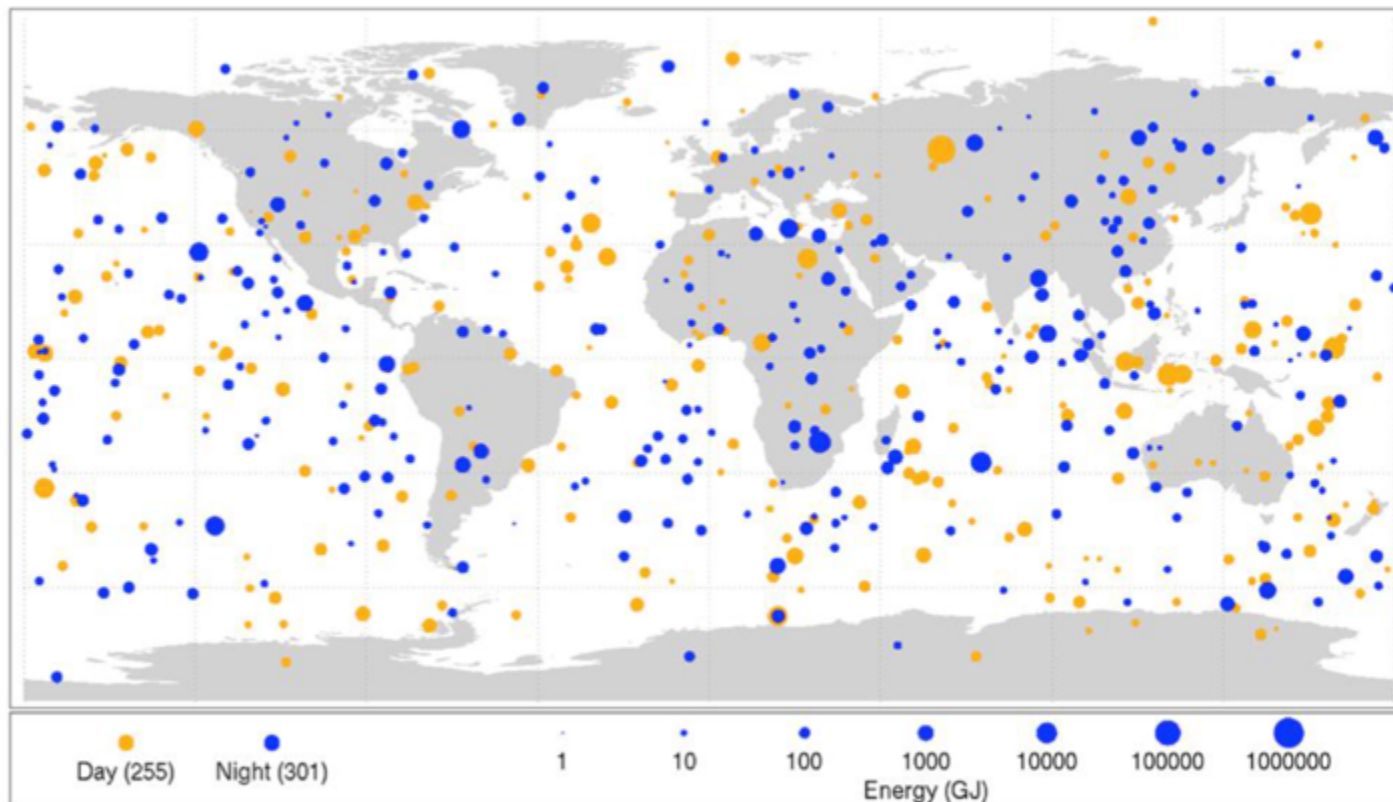
# 2017 NEO SDT Risk Results Summary

- Total nominal risk from PHO impact ~ 2500 casualties/year
  - Dominated by global effects of large objects
- Risk associated with undiscovered PHO (2023) ~ 180 casualties/year
  - 10 casualties/year for land impact
  - <1 casualties/year for water impact
  - 170 casualties/year for remaining global effects
- At 90% survey completeness, undiscovered objects pose risk ~ 80 casualties/year
  - Risk dominated by the small chance of undiscovered objects in the 500m-2km size range
  - Local and tsunami damage combine for ~ 2 casualties/year



# Bolide Events 1994 – 2013

## Small Asteroids that Disintegrated in Earth's Atmosphere



This diagram maps the data gathered from 1994-2013 on small asteroids impacting Earth's atmosphere and disintegrating to create very bright meteors, technically called "bolides" and commonly referred to as "fireballs". Sizes of orange dots (daytime impacts) and blue dots (nighttime impacts) are proportional to the optical radiated energy of impacts measured in billions of Joules (GJ) of energy, and show the location of impacts from objects about 1 meter (3 feet) to almost 20 meters (60 feet) in size.

# THANKS!