SHOCKWAVE COMPRESSION PHYSICS OF CONDENSED MATTER LATTICE BOLTZMANN METHOD WITH APPLICATION TO GLASS UNDER HYPERVELOCITY IMPACT

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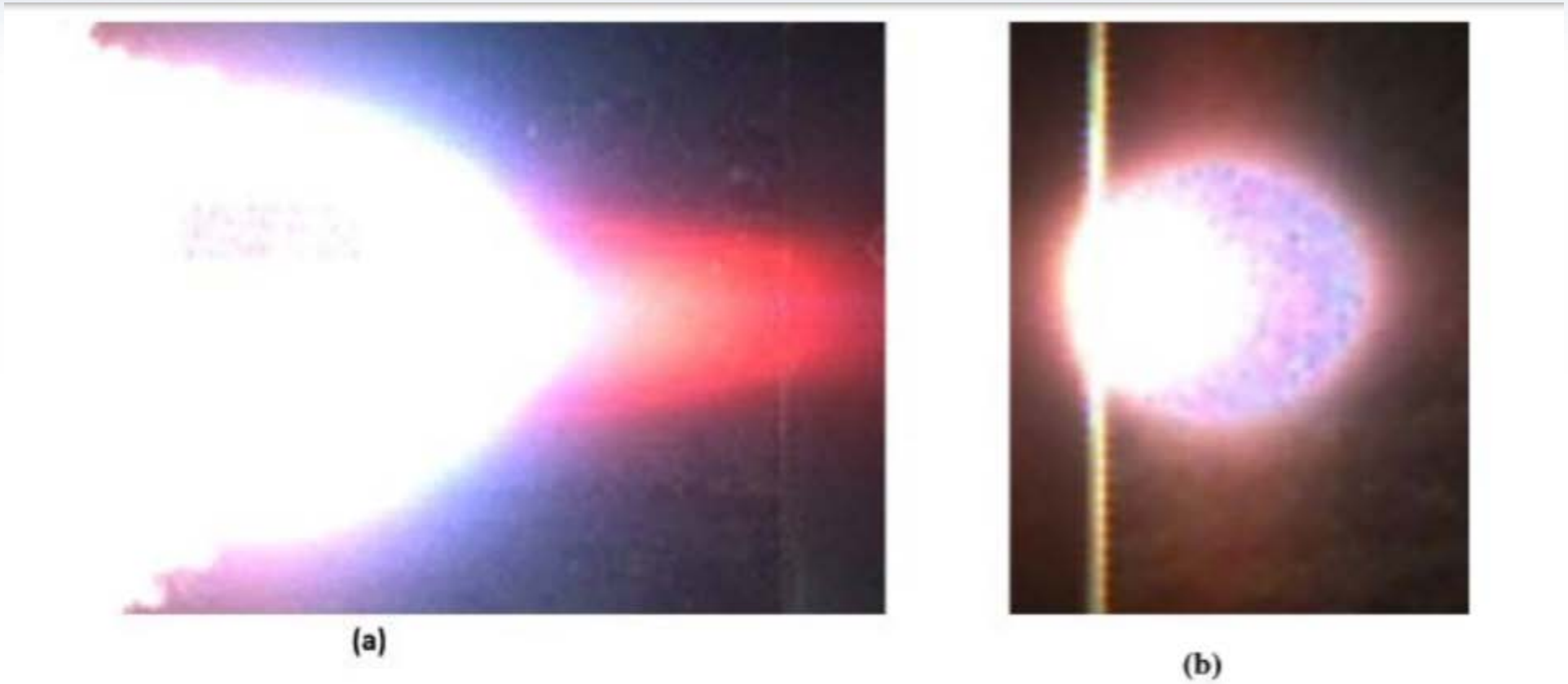
ACCELERATING TO THE NAVY & MARINE CORPS AFTER NEXT

Hypervelocity Impact on Soda Lime Glass results in Cherenkov Radiation and X-Rays and Gamma Rays

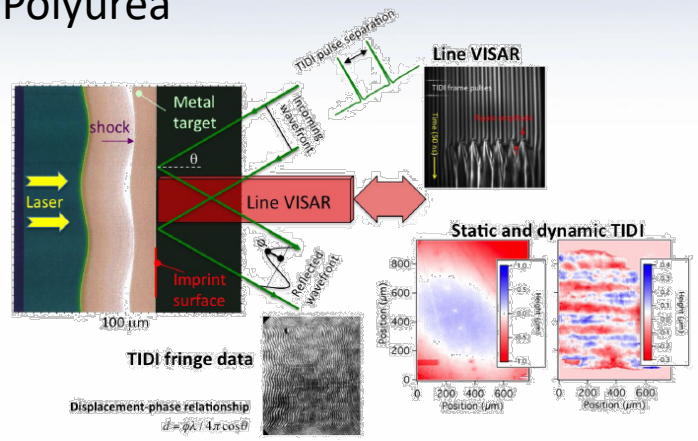


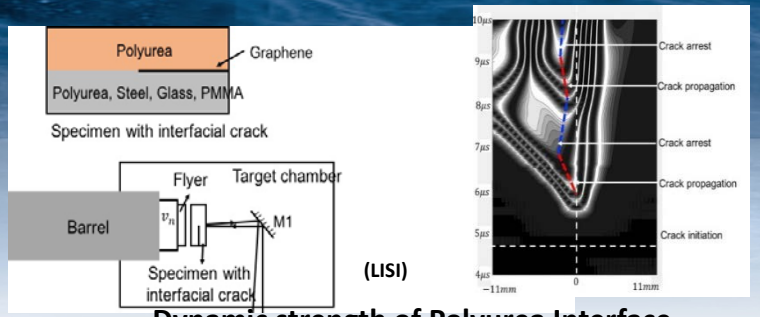
(a)

(b)

Cherenkov Radiation plume in Hypervelocity Impact of SLG distinct CR Spectrum followed by charge particle. (a) Gamma Rays and (b) X-Ray radiation

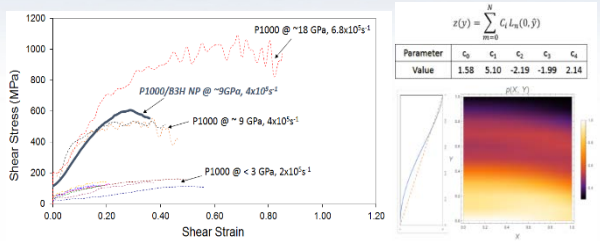
Laser Shock LANL and LLNL Polyurea





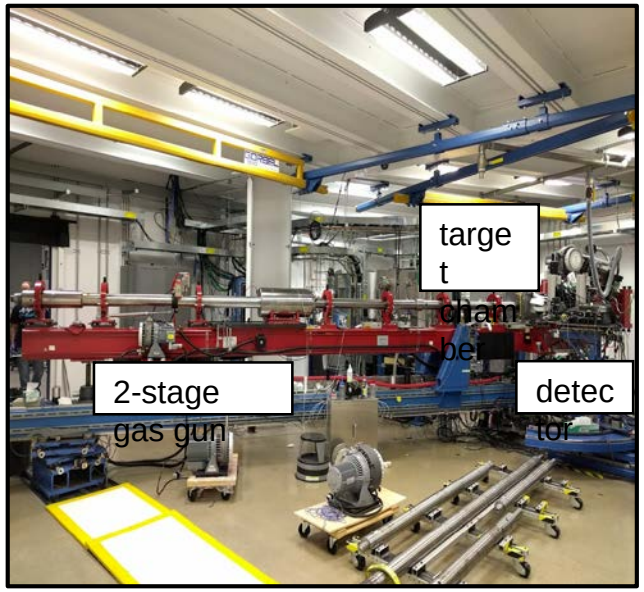
(LISI)

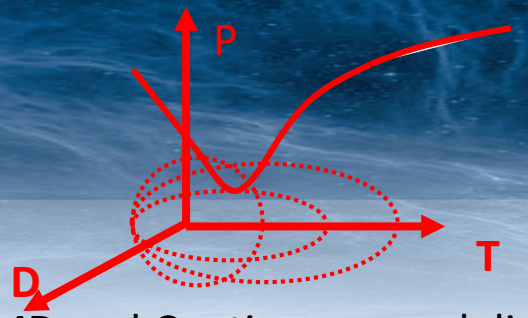
Dynamic strength of Polyurea Interface



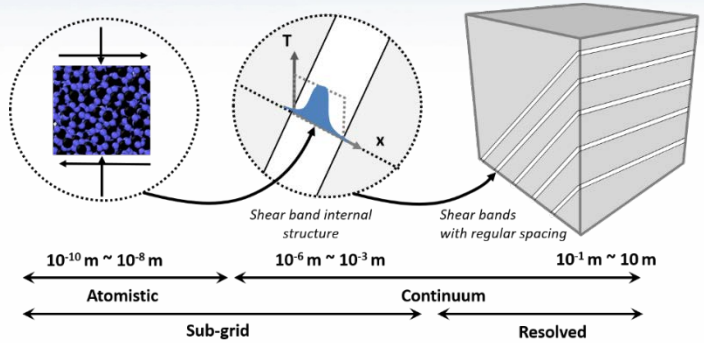
Shearing Resistance of nano particle reinforced polyurea

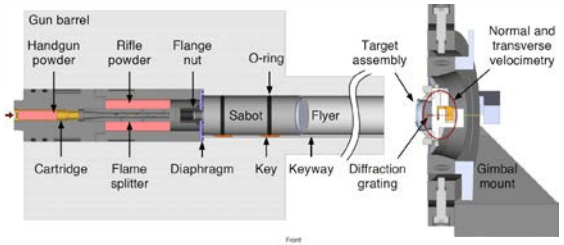
Design of diffractive optic

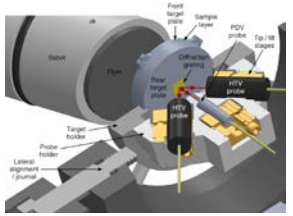




MD and Continuum modeling Shear banding in glass at extreme pressure







Pressure-Shear Plate Impact

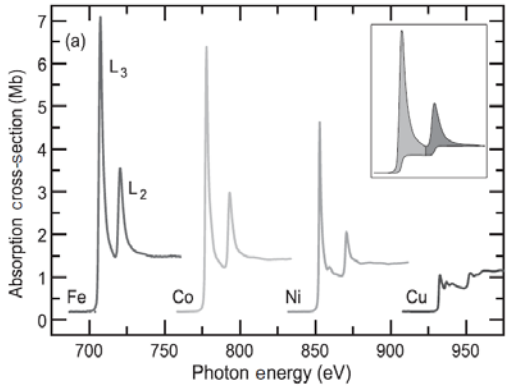
Unclassified

Stanford XFEL Time-resolved X-ray Femtosec

X-ray Free Electron Laser (XFELs)
Linac coherent Light Source (LCLS)

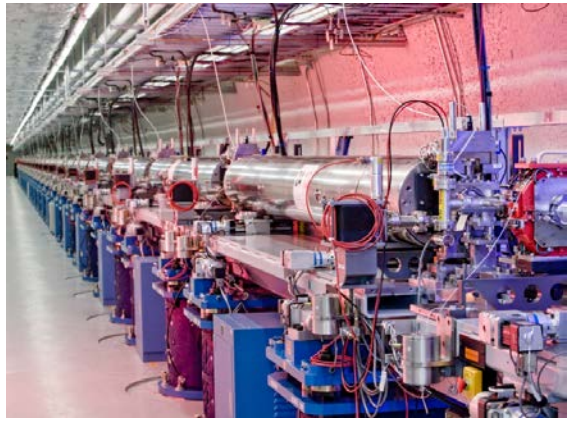
- ✓ Spatial Resolution (10-15 nm)
- ✓ Temporal Resolution (50 fs)
- ✓ Increased Peak Brilliance
- ✓ Penetration Depth
- ✓ Elemental Specificity

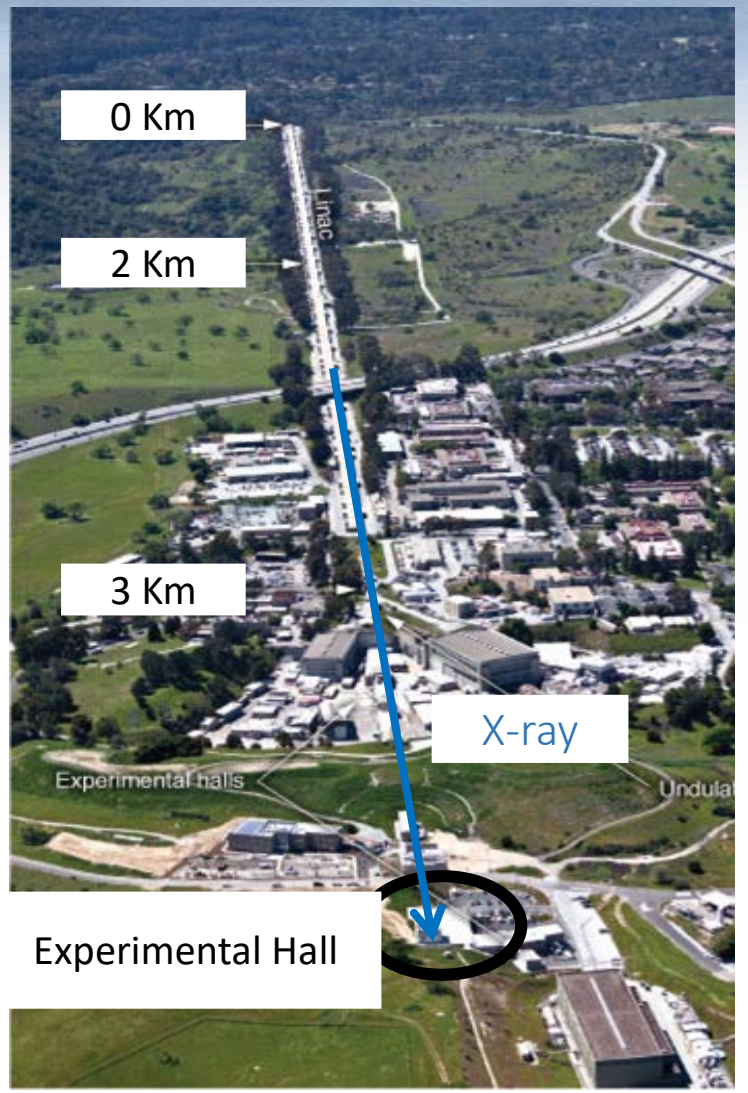
Unclassified



X-ray Absorption Spectra (XAS)

Undulator Hall



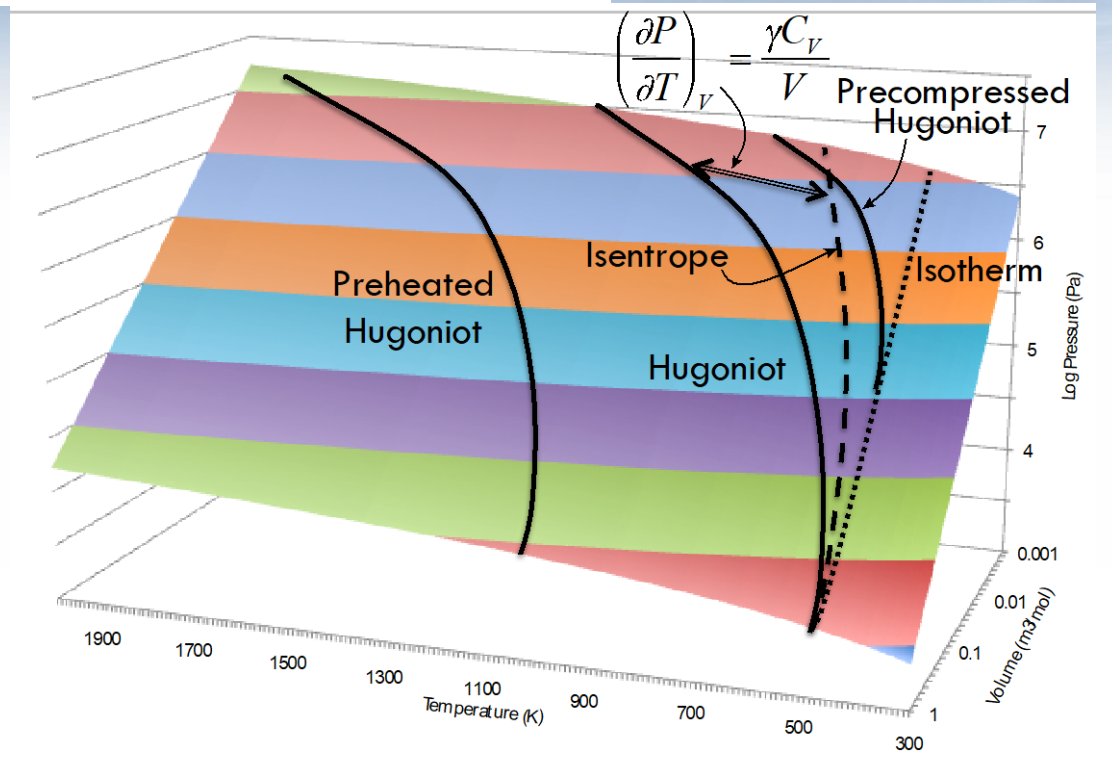


UC Davis
MIT

Unclassified

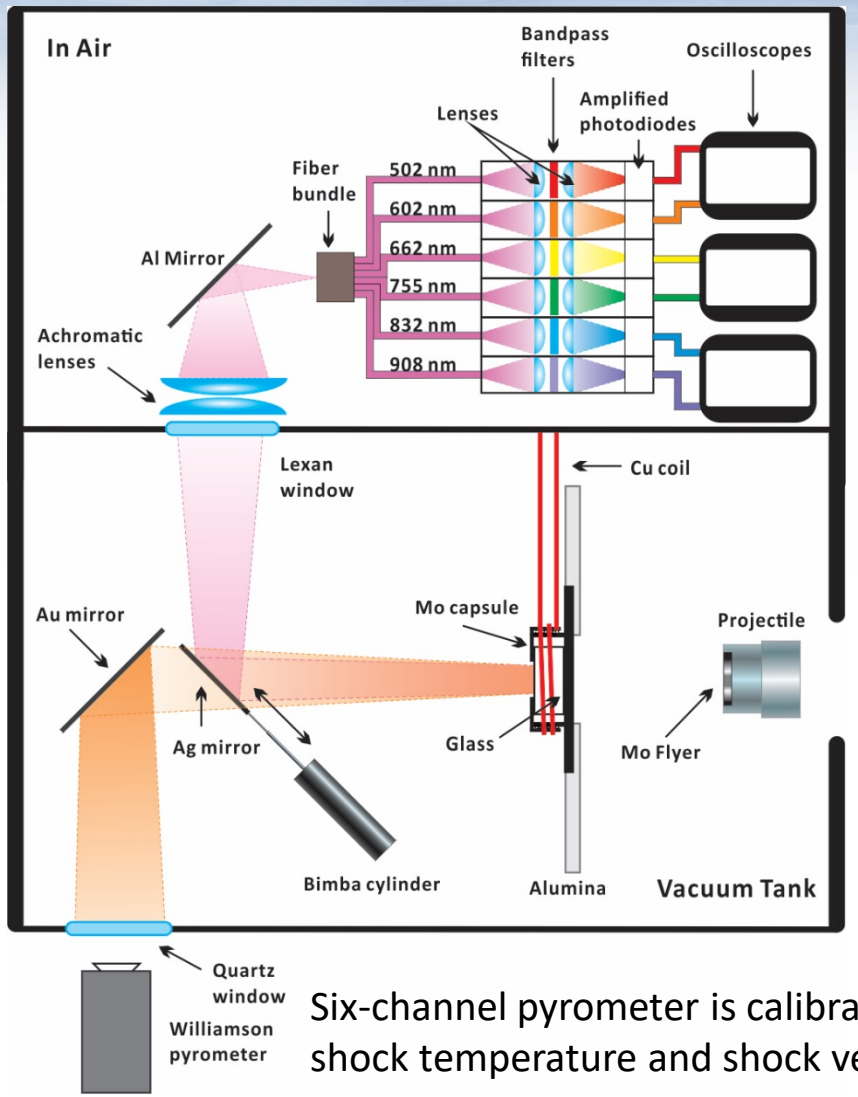
Experiments: Shock temperature and sound speed-Caltech

Thermodynamic Constraint:
Mie-Gruneisen Eqn. and Hugoniot



Hugoniot

Sound speed and temperature in SODA-LIME GLASS



Six-channel pyrometer is calibrated to give both shock temperature and shock velocity

Development of AI to exploit data and Design Hybrid protection systems

AI for exploration of Protection Systems Design Space:

Big-data:

Universities: Generated from experiments at National-Lab facilities (Argonne, LLNL XFEL-SLAC), and benchtop YAG Laser shock, diamond anvil (DA) testing, and Pressure-Shear Plate Impact testing.

Multiscale from MD to Continuum modeling to generate additional data for glassy materials in extreme conditions

Sandia and LANL (DOE Facilities) recent test data

NSWCCD: Full Scale testing against various weapons and threats,

NSWCDD: Large Gas Gun Testing,

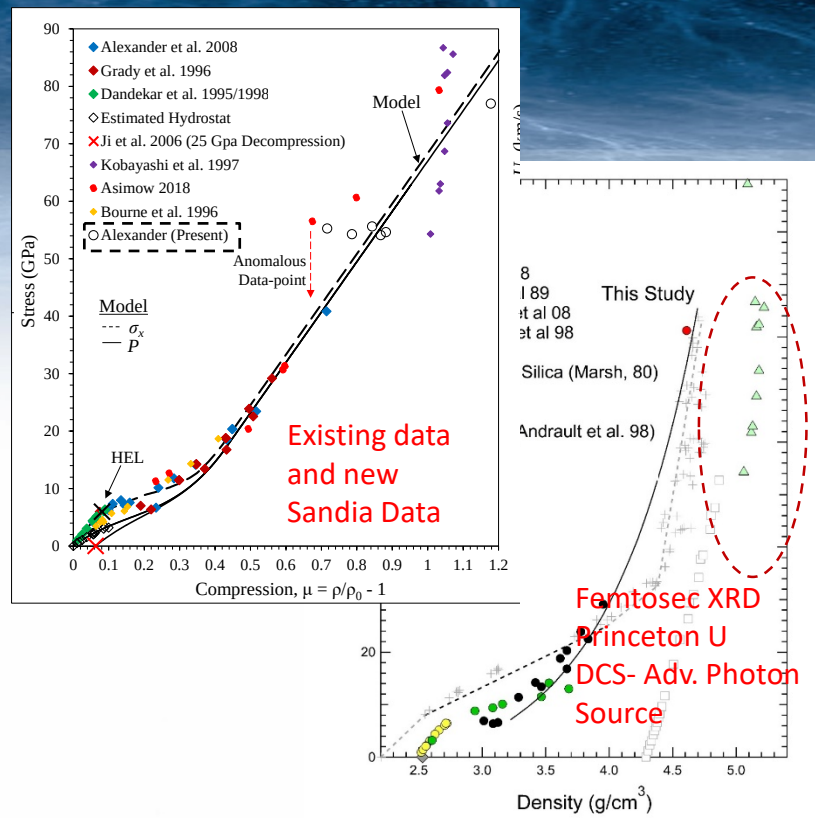
NRL: Polymers subject to ballistic and shock, DA, and blast testing

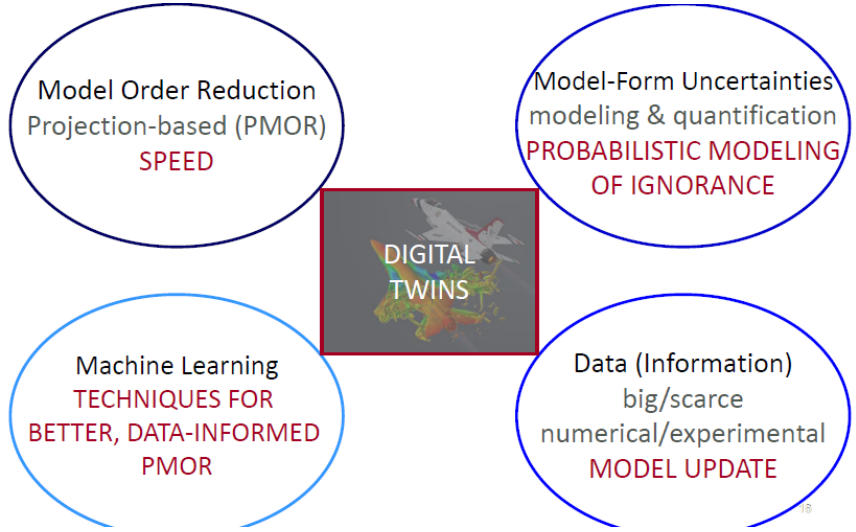
APS: Computer Generated materials and protection systems data for glassy materials and polymers

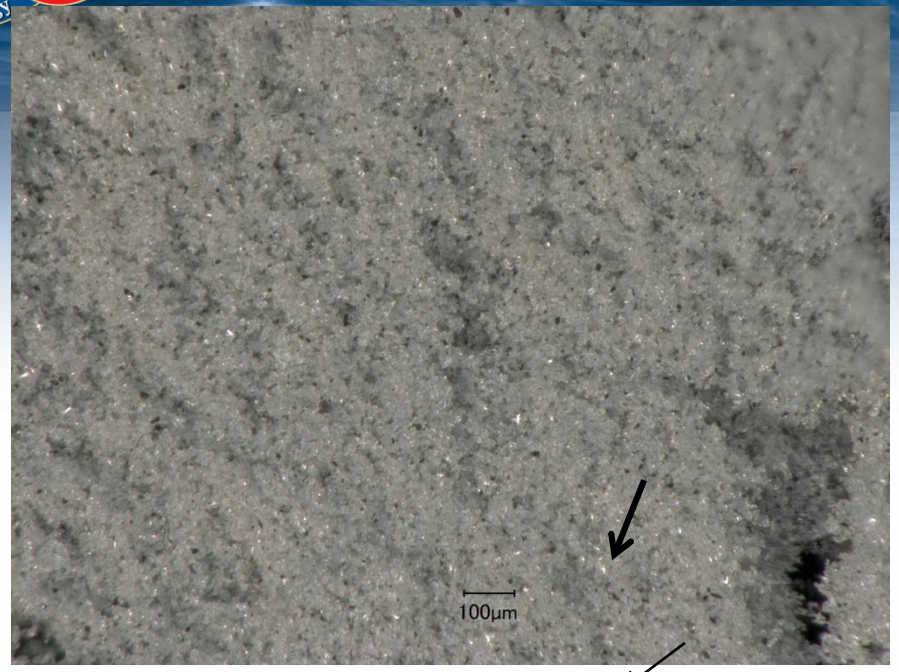
AI – is driven by a Digital Twins with Thermodynamics Constraints:

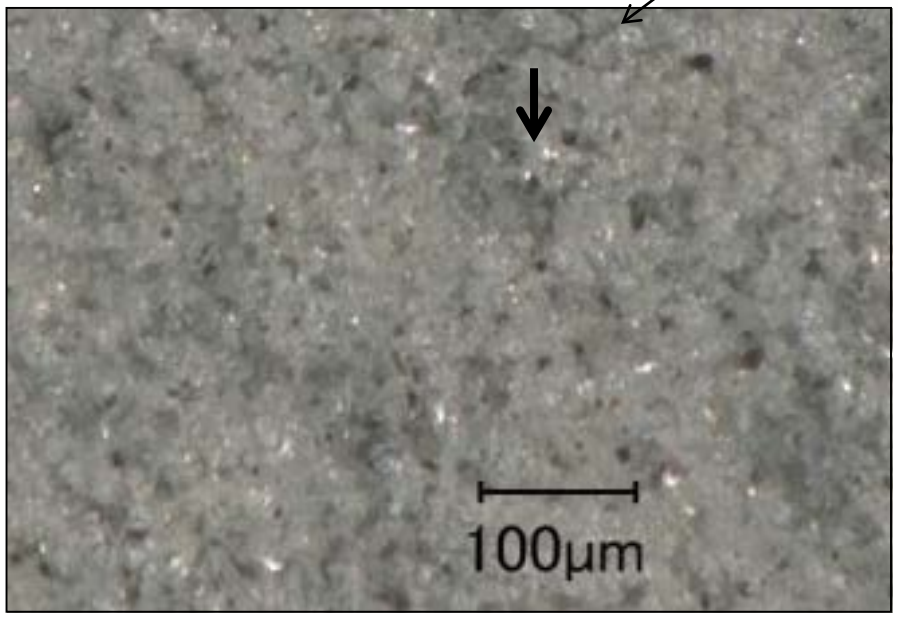
Projection based Model –Order Reduction (PMOR) to satisfy Thermodynamic Constraints. ***Data sampling and clustering: PMOR, (DT): Machine Learning(ML), Model form Uncertainties, and Big Data.***

Achieve Hybrid Protection Module for Multi-Threats. AI will cut the design process from weeks to minutes and seconds, and provide decision makers,



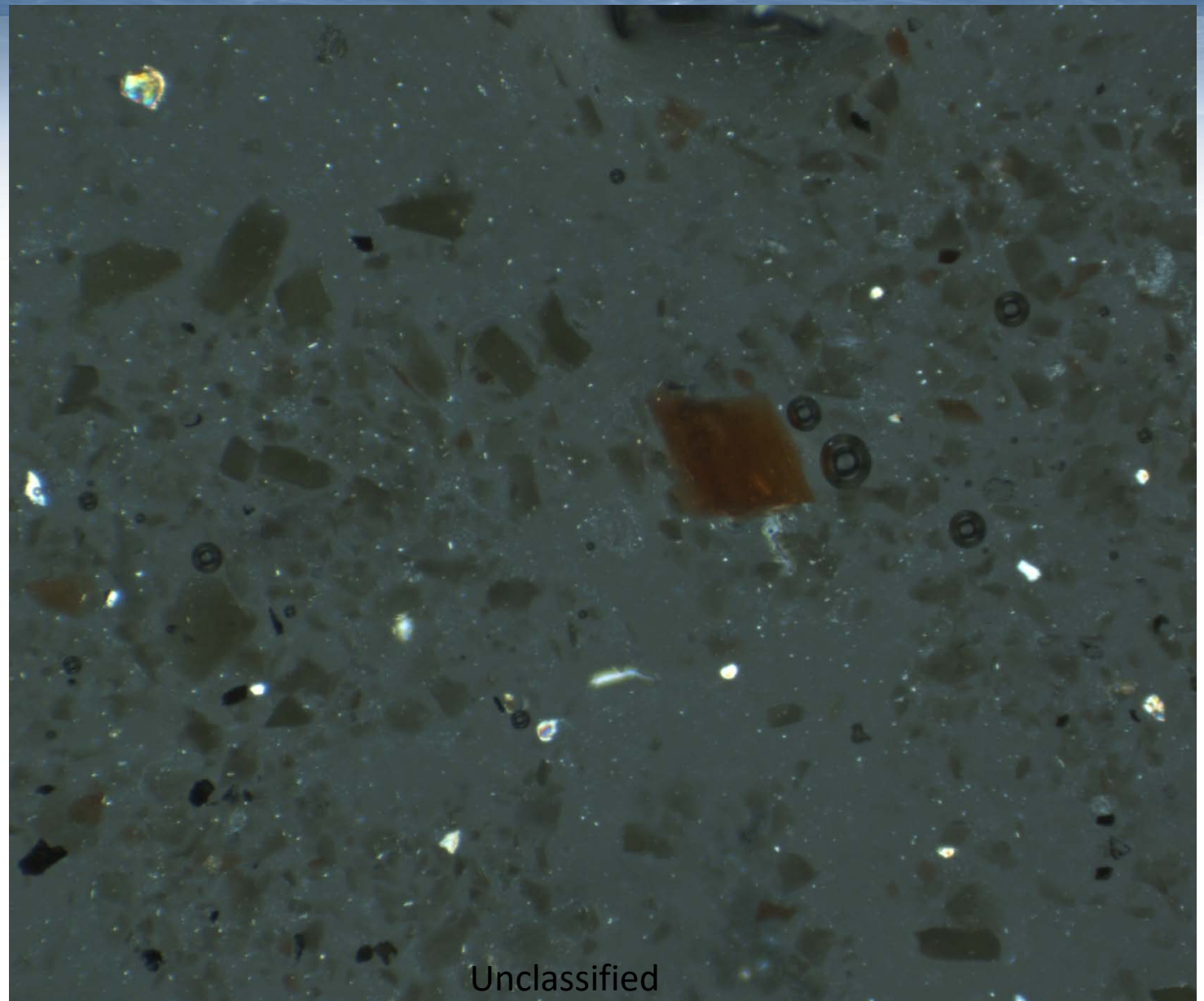






Sieved Glass Powder < 10 microns

Polarized-Contrast Microscopy to identify Crystalline Phases



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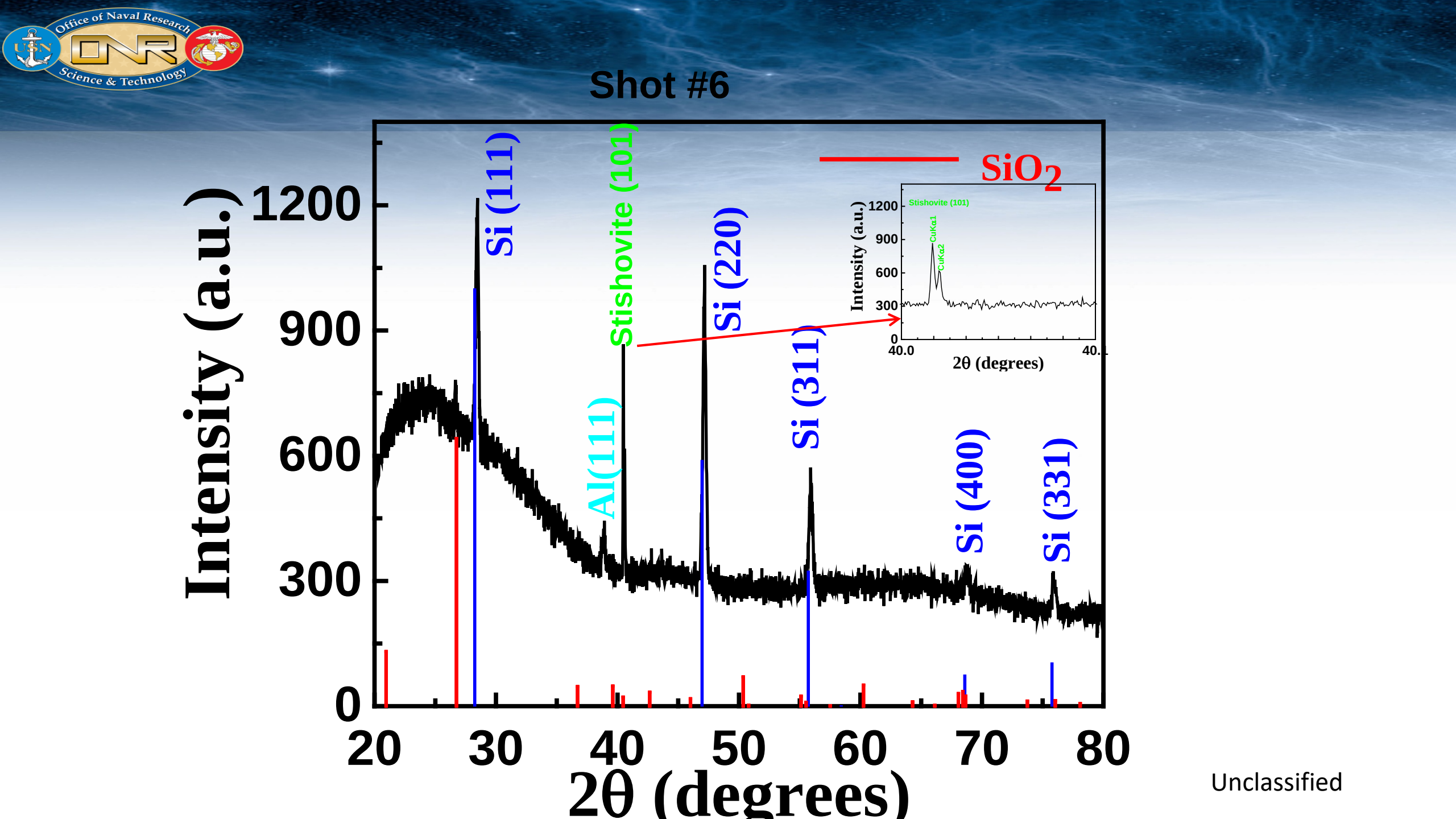

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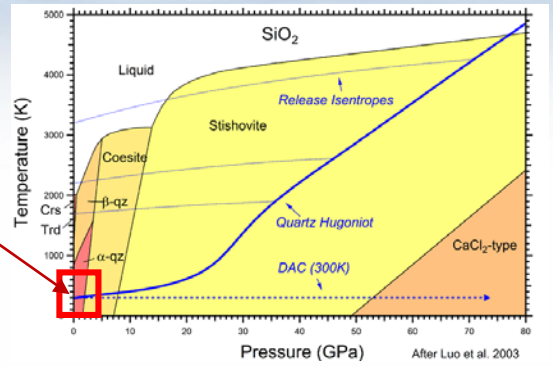
Lattice Boltzmann Method (LBM) and Shock Compression of Glass subject to Hypervelocity Impact

- In hypervelocity impact, the total time for glass as amorphous Continuum compared to that in Polymorphic states, is miniscule!
- Polymorphic states are particles *(distribution in nano to micron sizes),* rather than a continuum, due to the incompatibility of lattice parameters (can't satisfy "co-factor" crystal-to-crystal)!
- Single crystals found in powders (confirmed by crossed polarized Microscopy and XRD)
- Proton Radiography could reveal other fluid like behavior (e.g. Bubbly flows), which can be captured easily by LBM.



- LBM of Phase transition -- ***compressible flows with high Mach number*** (sound speed in glass 1.2 Km/s and much higher in polymorphic crystals)
- LBM couples with MD and meso-scale and MD- molecular scale
- LBM can deal with statistical particle distribution (for evaluating W in Boltzmann's entropy equation), and address particle impact in Statistical Mechanics.
- LBM is a particle based method (Boolean algebra is used for operation of particle numbers distribution-functions), a discrete solver for Boltzmann Eqn.
- LBM can deal with chemical reactions, e.g. CaSiO3 Perovskite and Crystalline Silicon Monoxide reactions in Soda Lime Glass, and may be other reactions, and not yet discovered in testing.
- LBM increases the efficiency of computations and can be easily coupled w. SPH
- SPH (Smooth Particle Hydrodynamics)-CTH Sandia Code can deal with continuum and particles at boundaries of LBM (compressible flow/high Mach number)-- ALE Codes
- The macroscopic *Entropic Force*, requires the statistical nature as the entropy increases in the system.

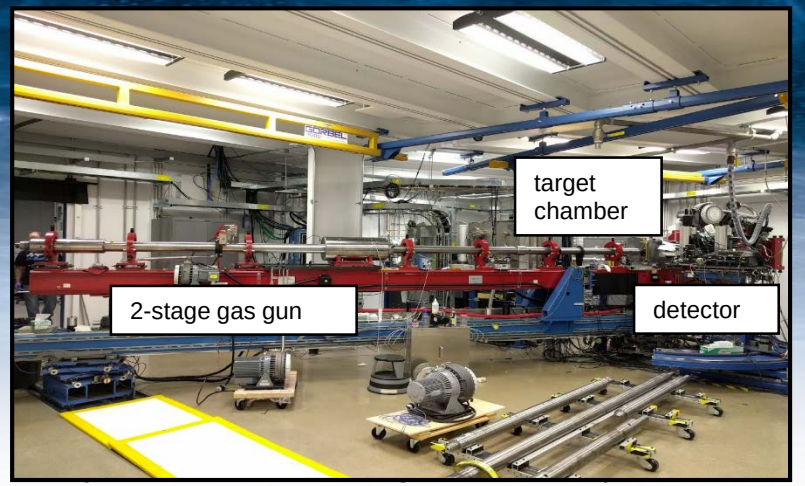
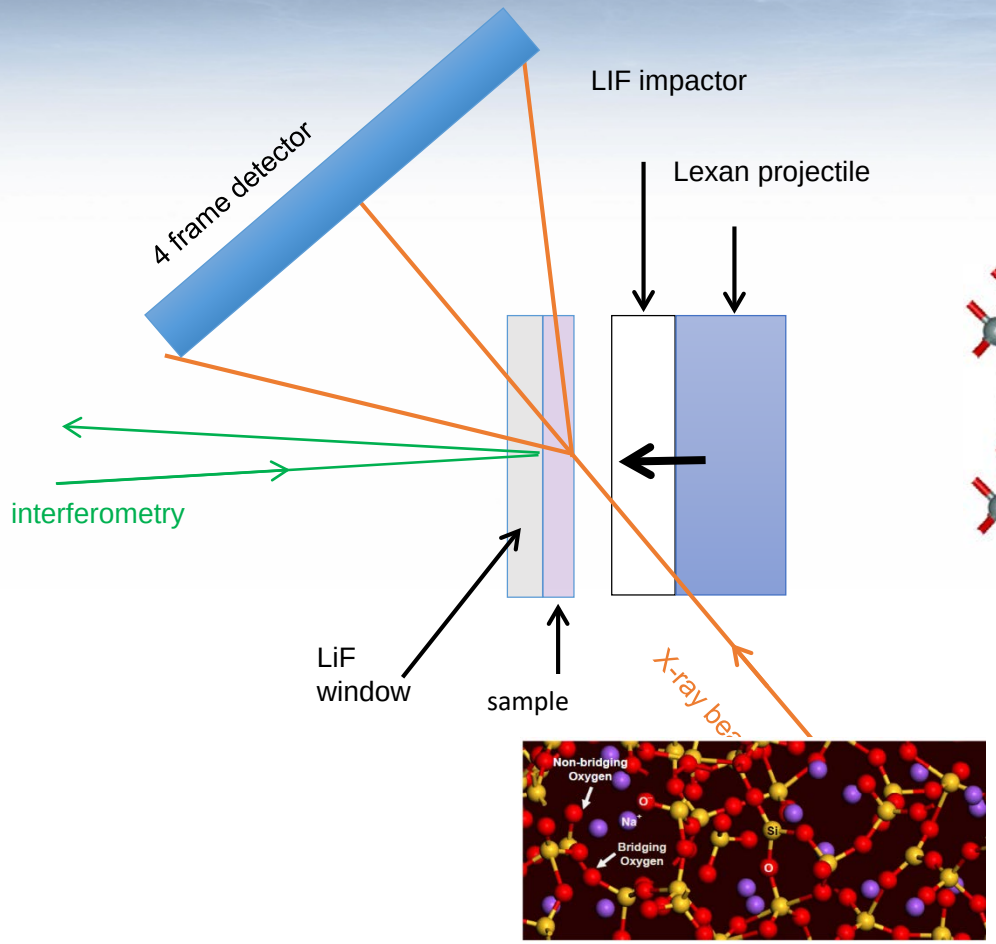
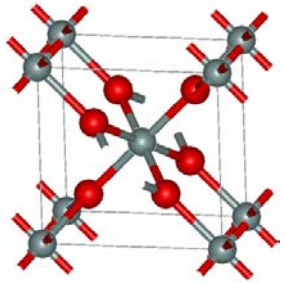
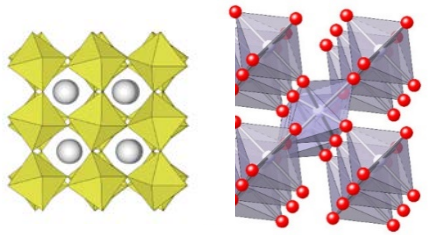


Image: ANL

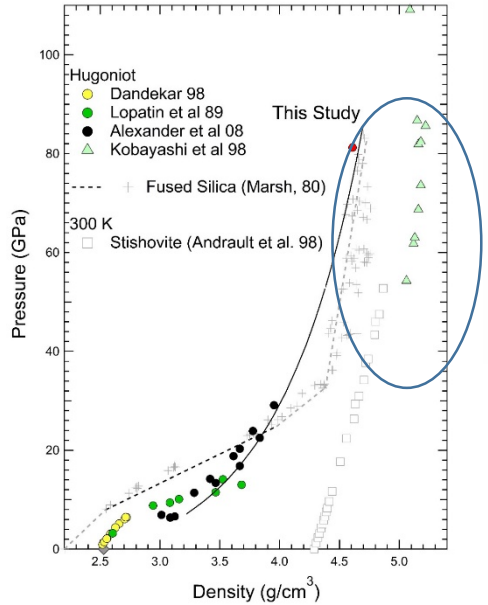




Stishovite



$\underline{CaSiO_3}$

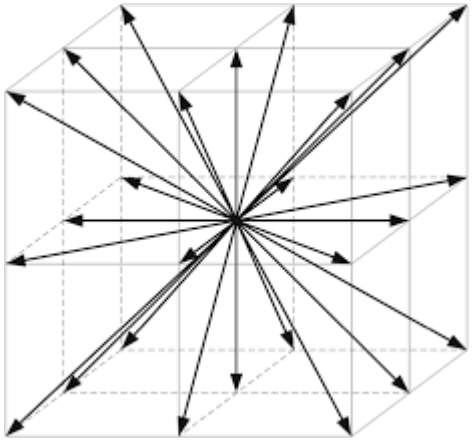


Temp. Reaching 5700 deg K

Amorphous Soda-Lime Glass transformation. Temp 5700 deg. K

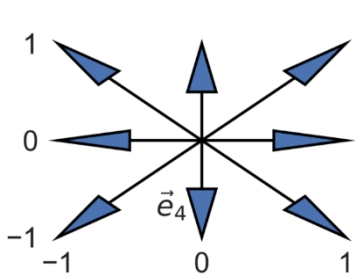
Tom Duffy, Princeton U., Yogi Gupta, U. Washington

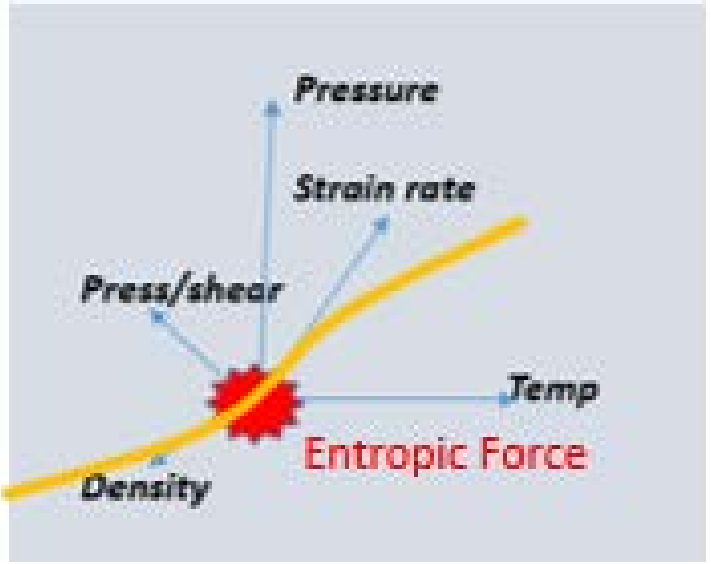
LBM of Phase transition -- *compressible flows with high Mach number*
(sound speed in glass 10 Km/s and much higher in polymorphic crystals)



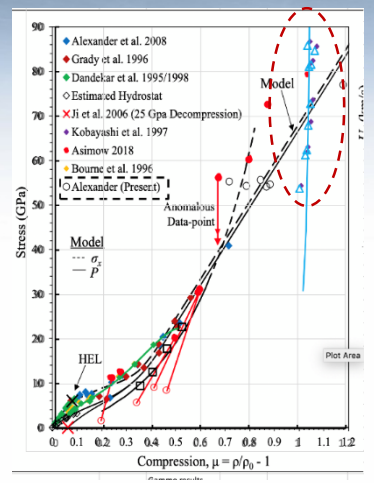
3D LBM

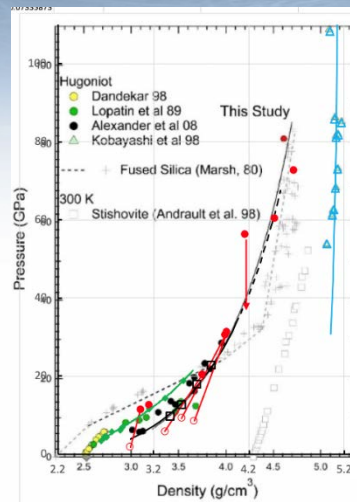
2D LBM

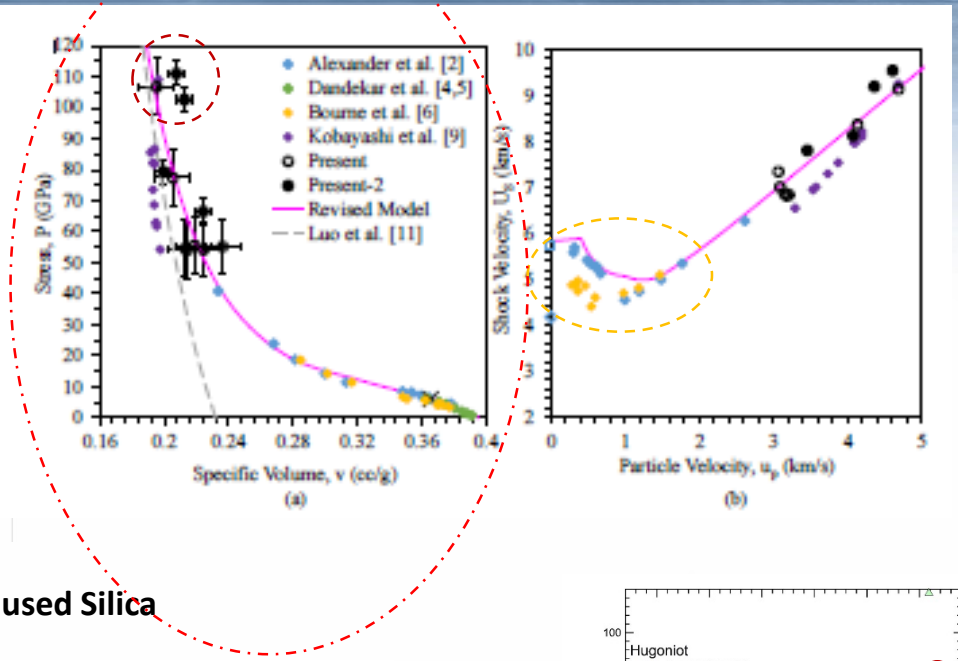




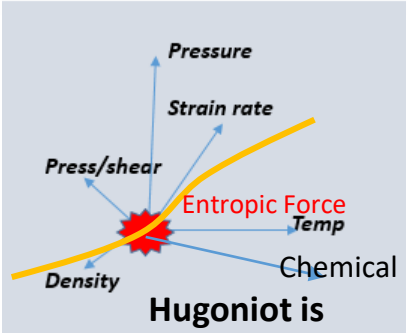
Shock Compression Test Results-Large Scatter of data and Thermodynamics based Computations w. Entropic Force to deal with data in Multi-dimensional space surface manifold



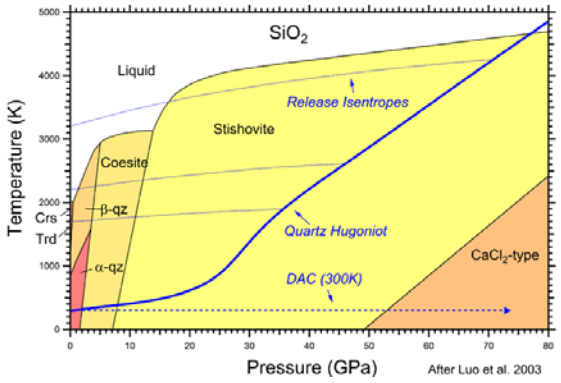




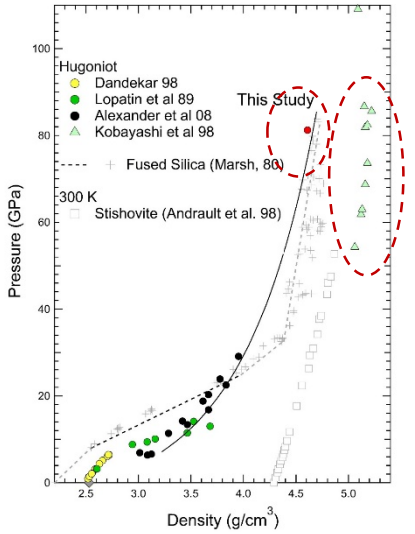
Fused Silica



Hugoniot is not a single curve, it is a surface manifold



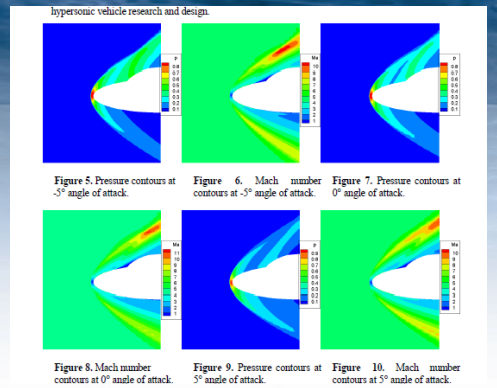
Phase Transformation

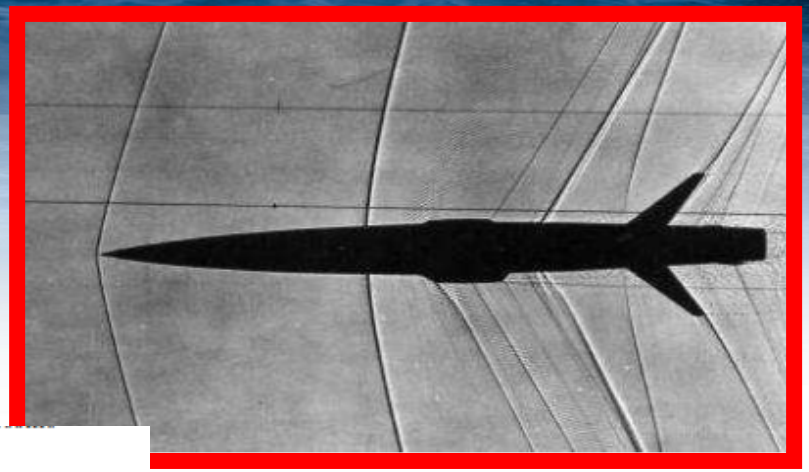


Entropic Forces

Hypersonic Compressible Flow-LBM

1-D LBM
Nat. Def. Univ.
China





3D LBM

Plasma

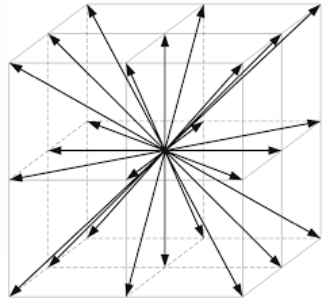
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \,, \qquad (17.1a)$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (P\mathbf{g} + \rho \mathbf{v} \otimes \mathbf{v} - 2\eta\boldsymbol{\sigma} - \zeta\theta\mathbf{g}) = \rho g \qquad (17.1b)$$

$$\frac{\partial}{\partial t}\left[(\frac{1}{2}v^2 + u + \Phi)\rho\right] + \boldsymbol{\nabla} \cdot [(\frac{1}{2}v^2 + h + \Phi)\rho\mathbf{v} - 2\eta\boldsymbol{\sigma} \cdot \mathbf{v} - \zeta\theta\mathbf{v}] = 0 \,, \qquad (17.1c)$$

$$\frac{\partial (\rho s)}{\partial t} + \boldsymbol{\nabla} \cdot (\rho s \mathbf{v}) = \frac{1}{T}\left(2\eta\boldsymbol{\sigma} : \boldsymbol{\sigma} + \zeta\theta^2\right) . \qquad (17.1d)$$

Here $\boldsymbol{\sigma} : \boldsymbol{\sigma}$ is index-free notation for $\sigma_{ij}\sigma_{ij}$.



3-D LBM

Plus Maxwell's Equations

Equation of State
Mie-Grueneiseen Eqn.
MD and Testing at Nat. Labs

ss u and the enthalpy per unit mass h in terms of the sound speed

$$C = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s} = \sqrt{\frac{\gamma P}{\rho}} \qquad (17.2c)$$

l. (16.48)]. A little algebra gives

$$\rho = \left(\frac{C^2}{\gamma K}\right)^{1/(\gamma-1)} \,, \quad u = \frac{C^2}{\gamma(\gamma-1)} \,, \quad h = u + \frac{P}{\rho} = \frac{C^2}{\gamma - 1} \,. \qquad (17.2d)$$

CONCLUSIONS

- Hypervelocity Impact results in polymorphic behavior in soda lime glass (SLG)
- Hypervelocity impact on SLG results in temperature of 5700 Deg. K (the temperature at the surface of the sun).
- Hypervelocity Impact results in Cherenkov Radiation, X-Rays and Gama Rays.
- Sandia NL CTH code is used to predict the shape of the cavity
- Lattice Boltzmann method is ideal in computing the shockwave reflections from the cavity
- Since data from CTH is very expensive and time consuming, AI Artificial Intelligence Digital Twin is used to populate the results with additional information
- Powders resulting from Hypervelocity Impact on SLG show complex phases that were never identified before (Using Polarized-Contrast Microscopy followed by X-Ray Diffraction (XRD).
- Testing at Stanford Linear (SLAC) accelerator and Argon NL will provide extremely valuable information at Femtosecond for testing the CTH code results.