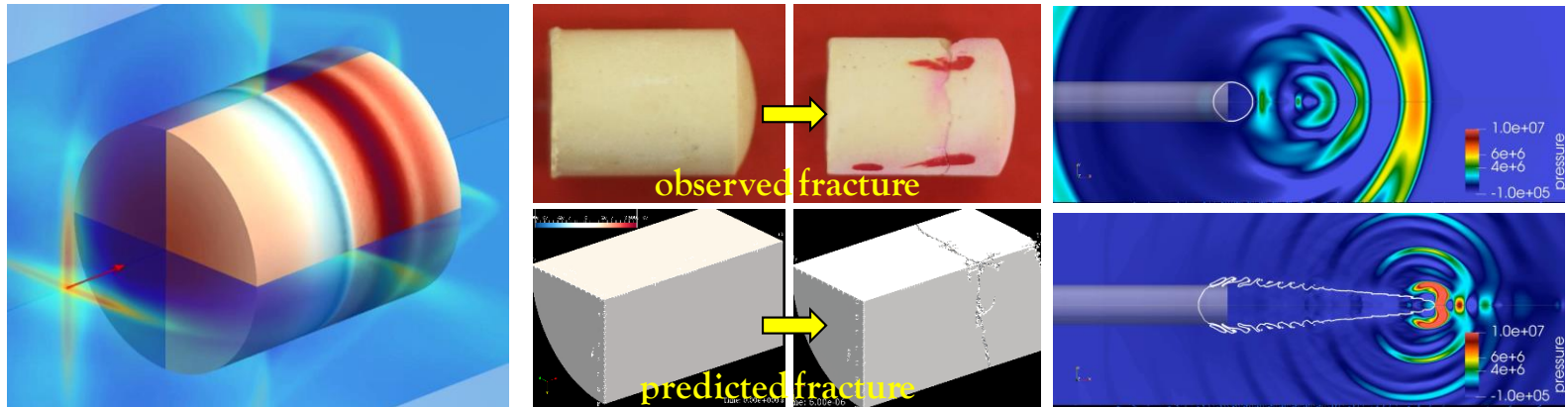


Computational Modeling of Shockwave and Laser Lithotripsy



Kevin Wang[†], John Dolbow[‡], Pei Zhong[‡]

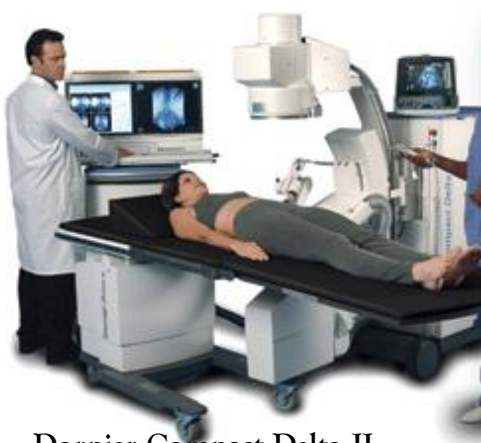
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[‡] Department of Mechanical Engineering and Materials Science, Duke University

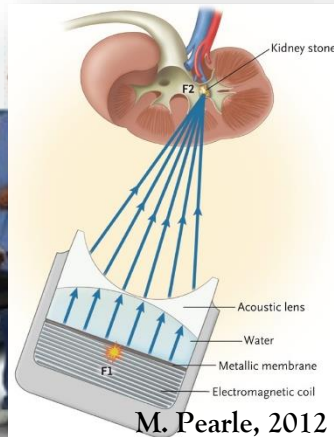


➤ Treatment of urinary stone disease (lifetime risk: ~10%)

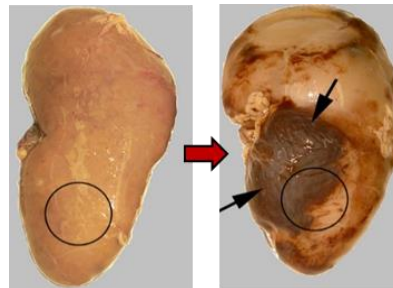
shockwave lithotripsy (SWL)



Dornier Compact Delta II

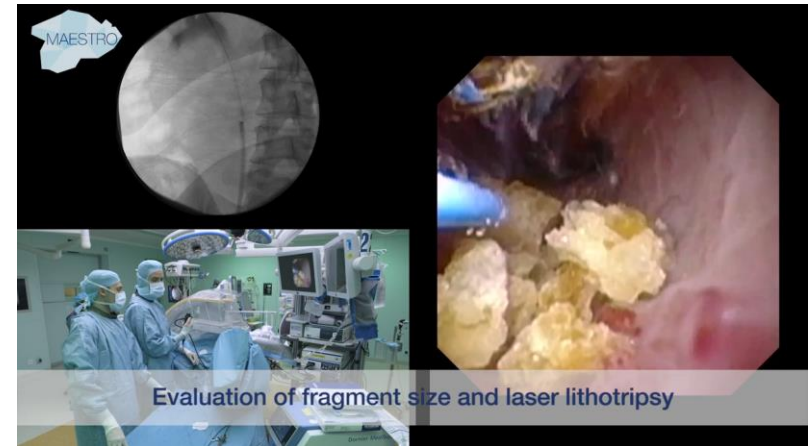


- high-energy acoustic waves focused at the stone ($p_{max} > 10$ MPa)
- non-invasive
- low success rate (~ 50%)
- tissue injury



B. Matlaga

laser lithotripsy (LL)

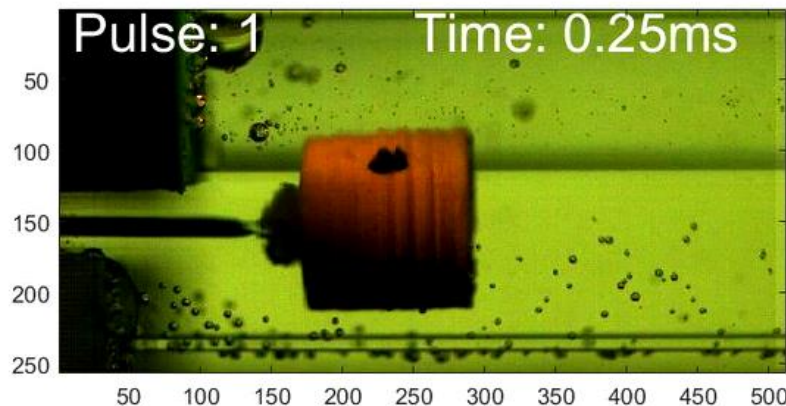


<https://www.youtube.com/watch?v=QDmqgOiYBcc>

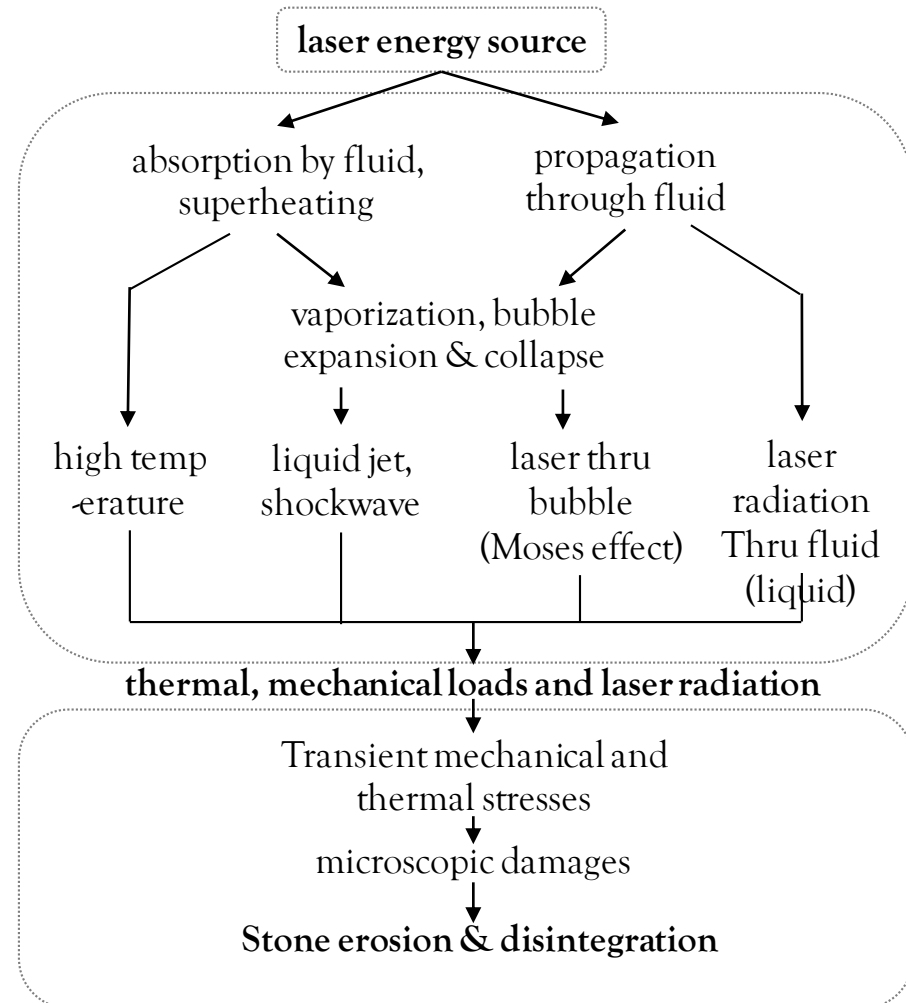
- long-pulsed laser (e.g., Holmium YAG, Thulium) via ureteroscopy
- higher success rate than SWL
- long operating room time
- not recommended for stones > 2 cm (AUA guidelines)

➤ Complex physics, many parameters

- success of treatment depends on many physical parameters
 - stone size, composition (mechanical and thermal properties), geometry
 - energy source (laser or acoustic): pulse energy, frequency, spatial and temporal power distributions



laser lithotripsy experiment in a water tank



➤ Physical models of laser-fluid-solid interaction

- fluid (and soft tissues) governing equations

$$\frac{\partial \mathbf{W}(\mathbf{x}, t)}{\partial t} + \nabla \cdot \mathcal{F}(\mathbf{W}) = \nabla \cdot \mathcal{G}(\mathbf{W}), \quad (\text{Navier-Stokes Eqs.})$$

$$\mathbf{W} = \begin{bmatrix} \rho \\ \rho \mathbf{V} \\ \rho e_t \end{bmatrix}, \quad \mathcal{F} = \begin{bmatrix} \rho \mathbf{V}^T \\ \rho \mathbf{V} \otimes \mathbf{V} + p \mathbf{I} \\ (\rho e_t + p) \mathbf{V}^T \end{bmatrix}, \quad \mathcal{G} = \begin{bmatrix} \mathbf{0}^T \\ \boldsymbol{\tau} \\ (k \nabla T - \mathbf{q}_r + \boldsymbol{\tau} \mathbf{V})^T \end{bmatrix},$$

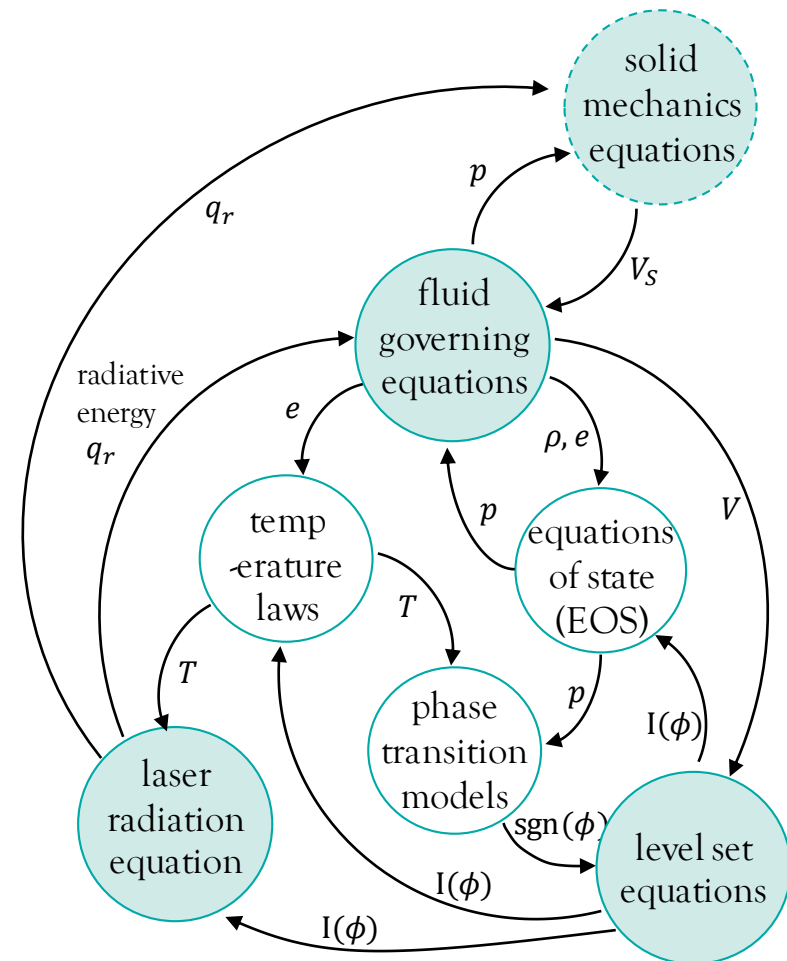
- thermodynamic equations of state (EOS)
- level set equations (interface tracking)

$$\frac{\partial \phi}{\partial t} + \mathbf{V} \cdot \nabla \phi = 0,$$

- laser radiation equation (cf. RTE)

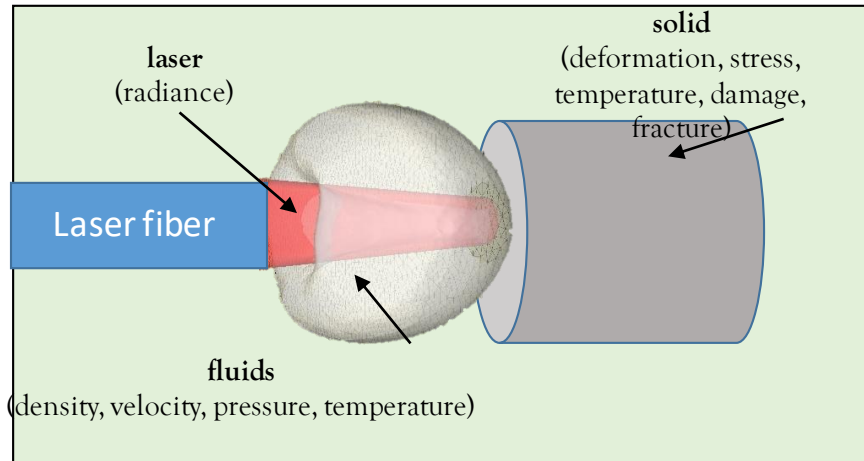
$$\nabla \cdot (L \mathbf{s}) = \nabla L \cdot \mathbf{s} + (\nabla \cdot \mathbf{s}) L = -\mu_\alpha L, \quad \mathbf{q}_r = L \mathbf{s},$$

- phase transition (e.g., vaporization) models
- solid (stone) mechanics: equations of motion, models of elasticity, viscoelasticity, thermomechanical effects, damage, fracture

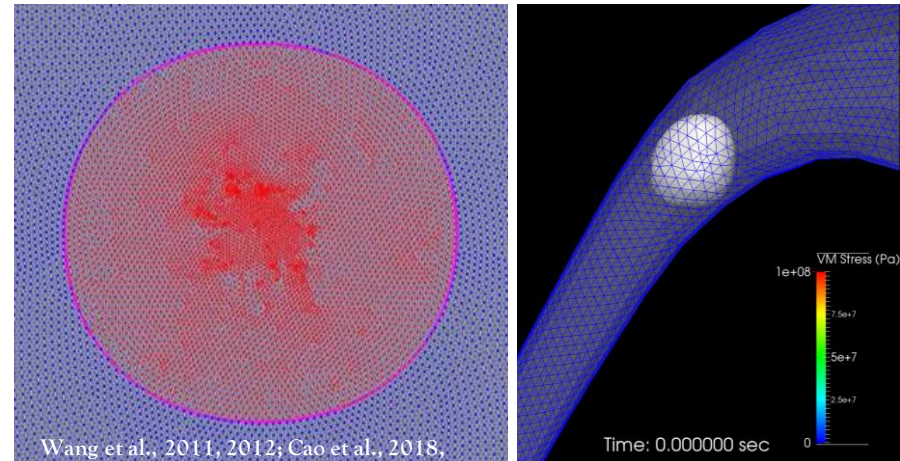


➤ Implicit interface tracking methods

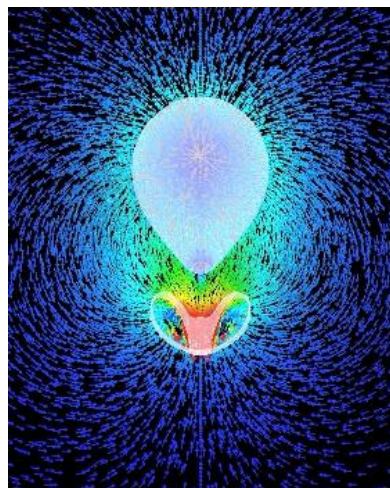
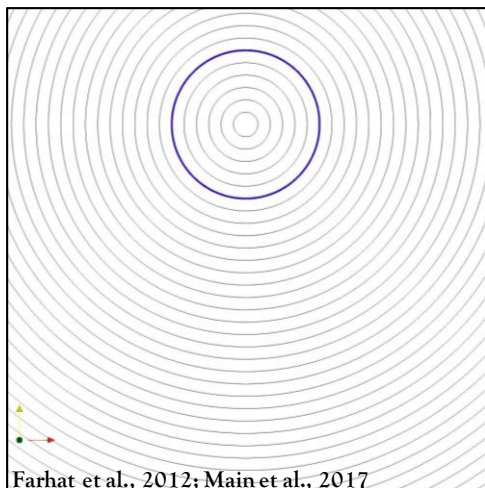
problem setup (LL example)



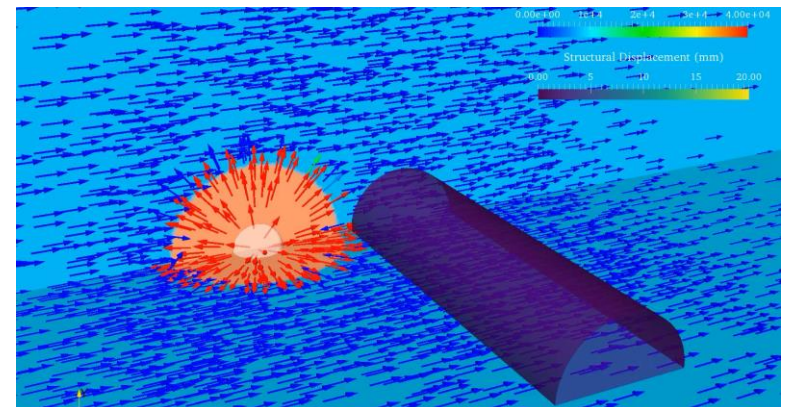
embedded / immersed boundary methods



level set method



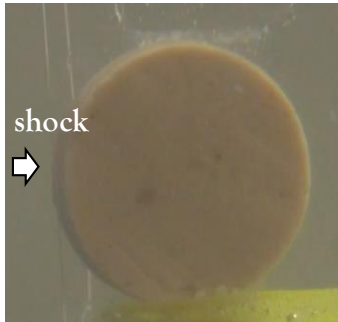
combination (example)



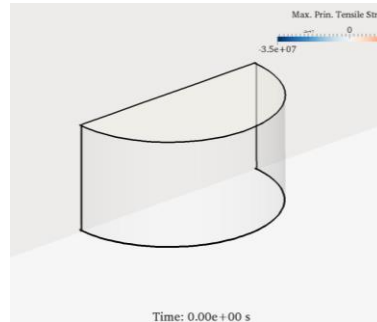
Wang et al., 2015; Ma et al., under review

➤ Prediction of stone fracture in shockwave lithotripsy (SWL)

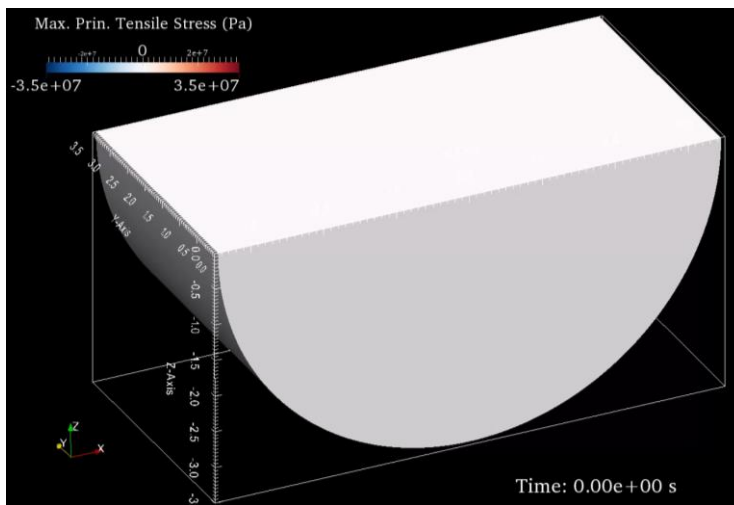
lab experiment



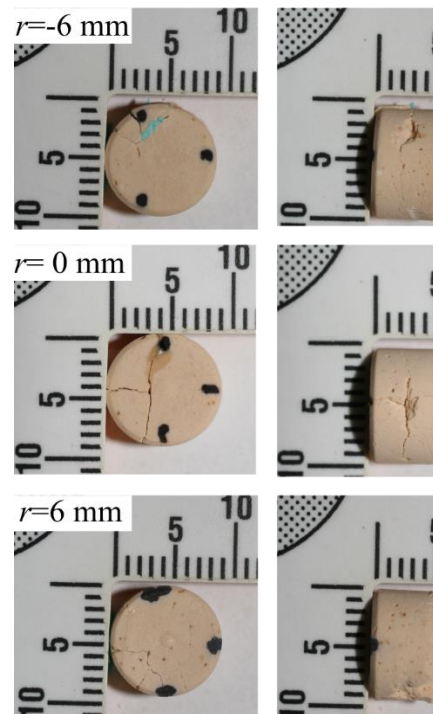
pressure & stress



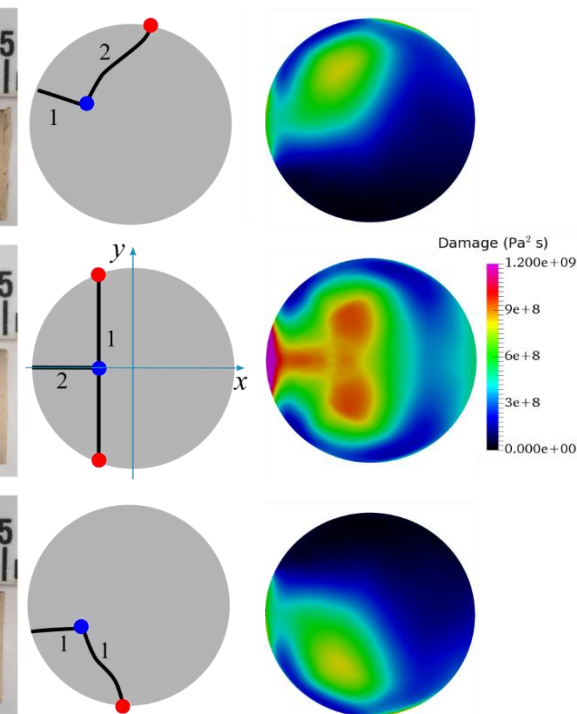
predicted dynamic fracture



lab tests at different off-axis distances



predicted damage



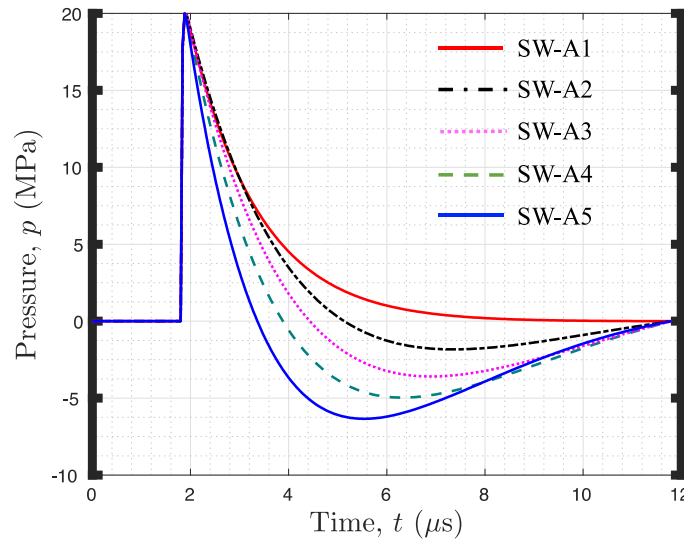
- the computational model captured the location and shape of the fracture observed in laboratory SWL experiments

- S. Cao, D. Liao, Y. Zhang, P. Zhong, and K. G. Wang, "Shock-Induced Damage and Dynamic Fracture in Cylindrical Bodies Submerged in Water," *International Journal of Solids and Structures*, 2019
- G. Xiang, X. Ma, C. Liang, H. Yu, D. Liao, G. Sankin, S. Cao, K. Wang, P. Zhong, "Variations of stress field and stone fracture produced at different lateral locations in a shockwave lithotripter field," *Journal of the Acoustical Society of America*. 2021

Effect of Shockwave Profile

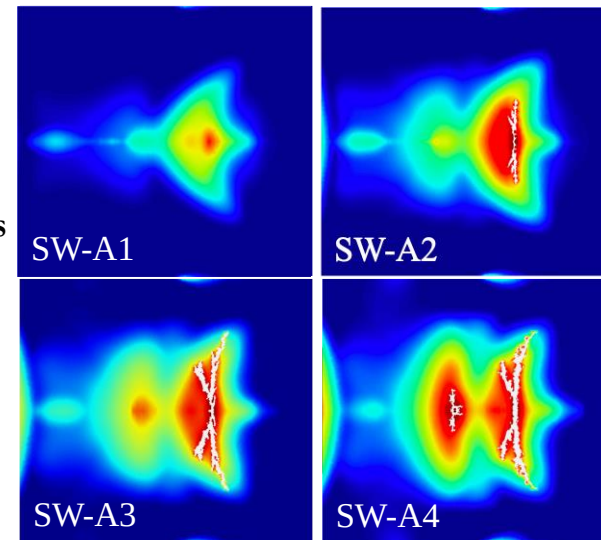
➤ Optimization of shockwave profile for maximum stone damage

same pulse energy, different wave profiles



predicted stone damage and fracture

SWL
simulations



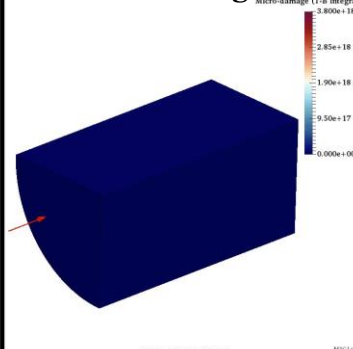
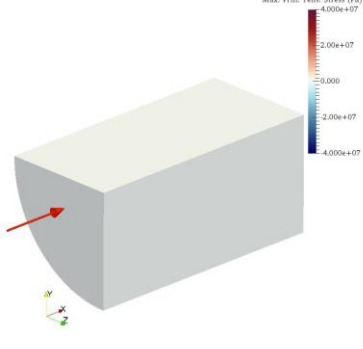
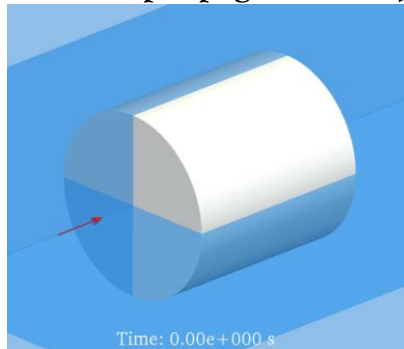
wave propagation



max. tensil stress



stone damage

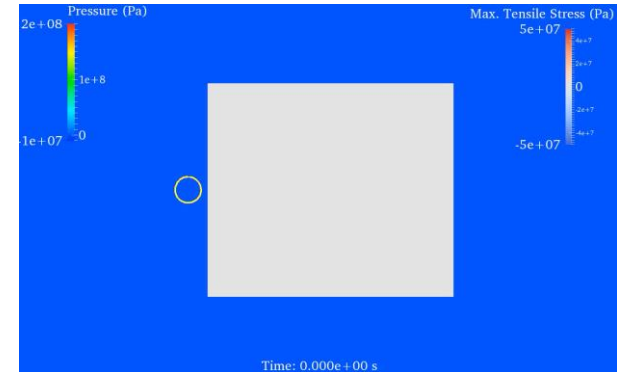


- simulation results suggest that a tensile tail (e.g., SW-A3,A4,A5) in the shockwave profile facilitates stone fracture in SWL

Effects of Cavitation

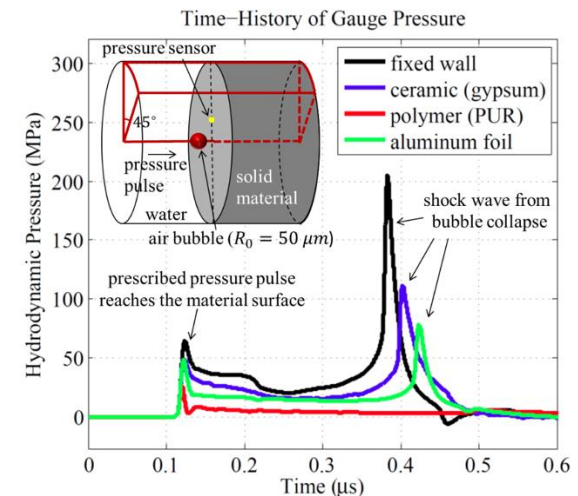
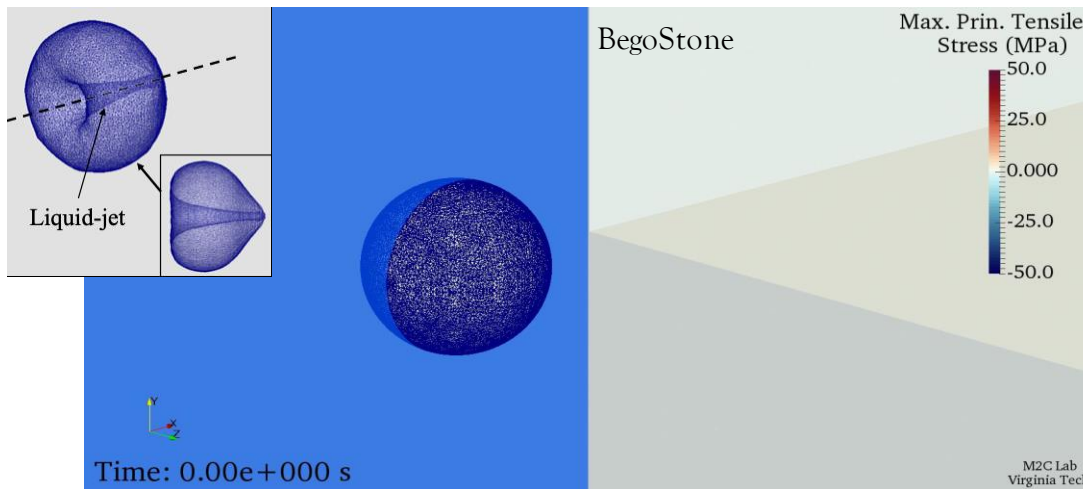
➤ Simulation of cavitation bubble dynamics in SWL and LL

- cavitation occurs due to low pressure (in SWL) and high temperature (in LL)
- many **positive** and **negative** effects:
stone erosion, **wave shielding**, **tissue injury**,
“**Moses effect**”, **stone retropulsion** ...



cavitation
erosion
and wave
shielding
in SWL

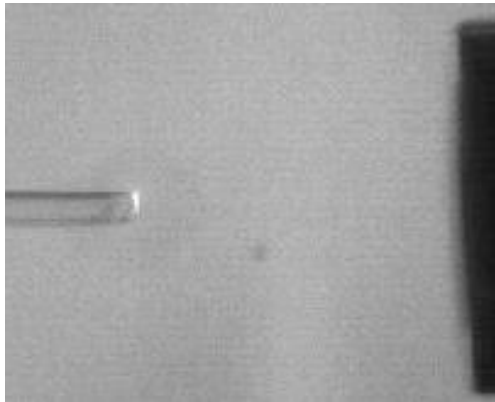
shock-induced bubble collapse near different (solid and soft) materials



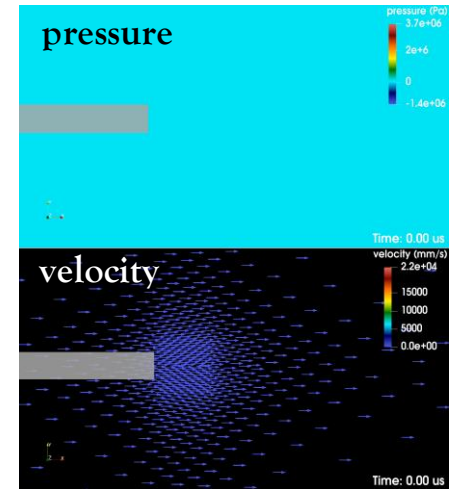
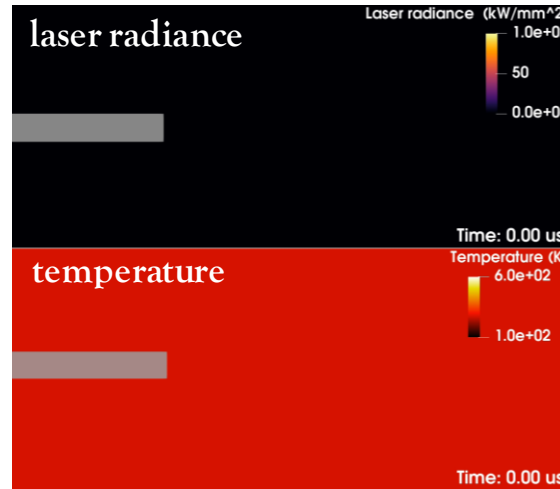
- S. Cao, G. Wang, O. Coutier-Delgosha, K. G. Wang, “Shock-Induced Bubble Collapse Near Solid Materials: Effect of Acoustic Impedance,” *Journal of Fluid Mechanics*; 2020
- K. G. Wang, “Multiphase Fluid-Solid Coupled Analysis of Shock-Bubble-Stone Interaction in Shockwave Lithotripsy,” *International Journal for Numerical Methods in Biomedical Engineering*, 2017

➤ Prediction of laser-induced cavitation and its effects in LL

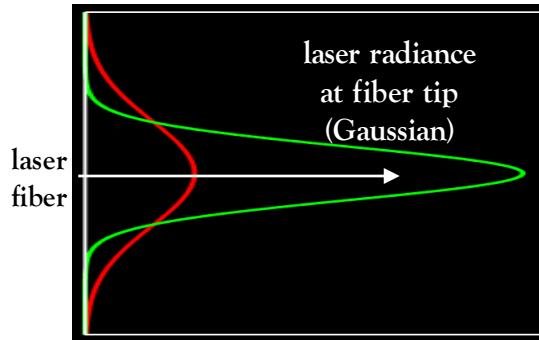
lab experiment
(Holmium:YAG laser)



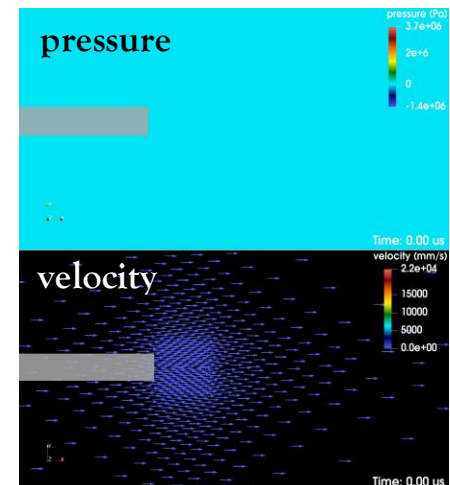
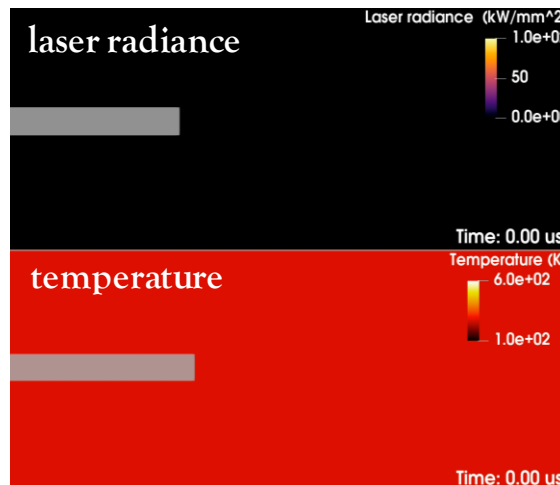
broad laser beam



computational experiment:
broad vs. narrow laser beam



narrow laser beam



- X. Zhao, W. Ma, K. Wang, "An Embedded Boundary Finite Volume Method for Laser-Fluid Coupling and Thermal Cavitation," *Computer Methods in Applied Mechanics and Engineering*, in prep.

➤ Computational modeling of shockwave and laser lithotripsy

- outcome of treatment depends on many physical parameters; some of them are controllable
- a multiphysics (laser-fluids-tissue-stone) model is being developed; codes (in C++) are open-source
 - M2C: <https://github.com/kevinwgy>
 - Aero-F/S: <https://bitbucket.org/frg>
- conducted several case studies

