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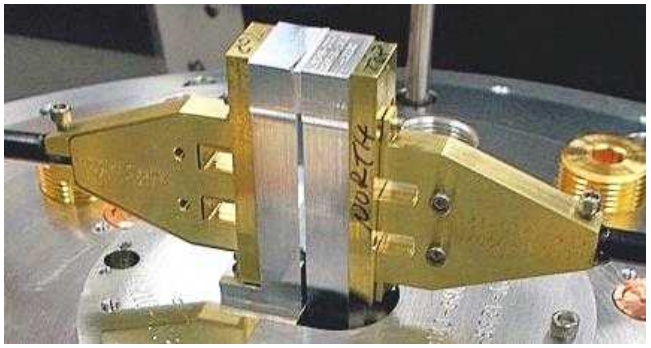

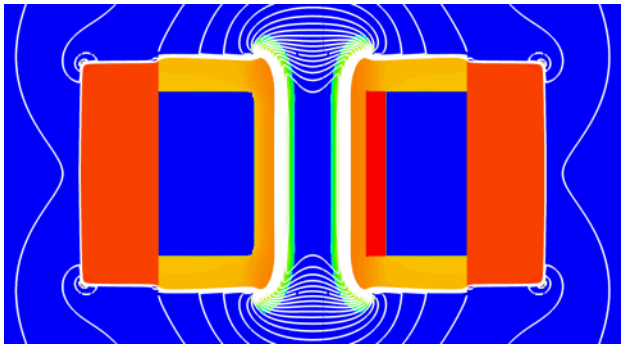

New Multi-Megabar Shockless Compression Experiments at the Z Machine

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Iterative Lagrangian Analysis (ILA) extracts quasi-isentropic material response from velocimetry

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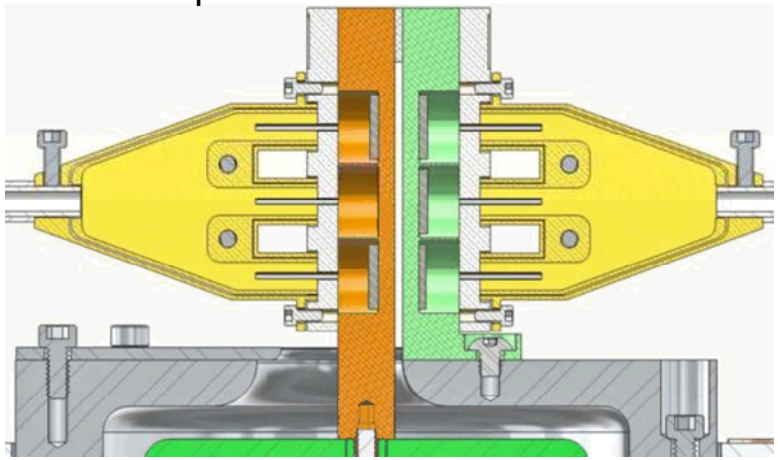
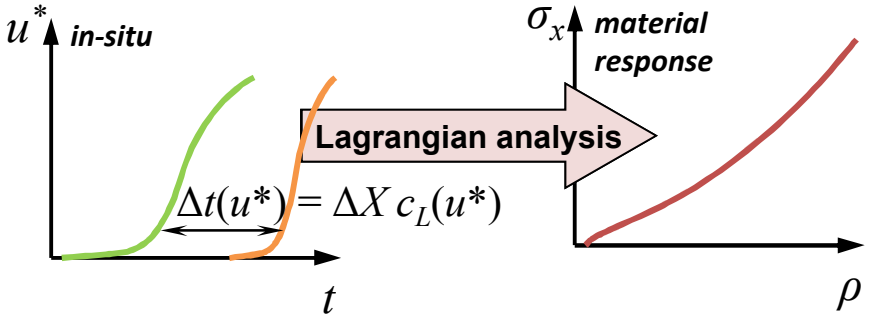
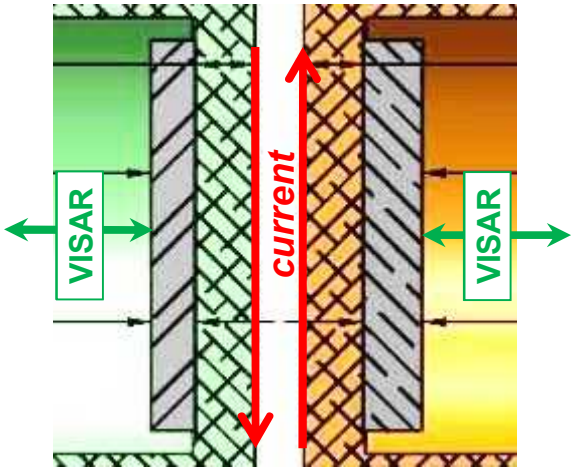
Stripline load on the Z machine





u^* = "compression velocity" (mechanical-EOS variable)



- In-situ measurements → Direct Lagrangian Analysis (DLA)
- Real measurements are free-surface or window-interface
  → Iterative Lagrangian Analysis (ILA)
  - map measured $\boldsymbol{u(t)}$ into in-situ $\boldsymbol{u^*(t)}$, then apply DLA
  - typically map by iterative characteristics technique[1]
  - dual-sample and single-sample approaches
  - ***assumes single-valued material response***

[1] *S. D. Rothman & J. Maw, J. Physique IV **134**, p745 (2006)*

Localized unloading in high-strength materials violates ILA assumption of single-valued response

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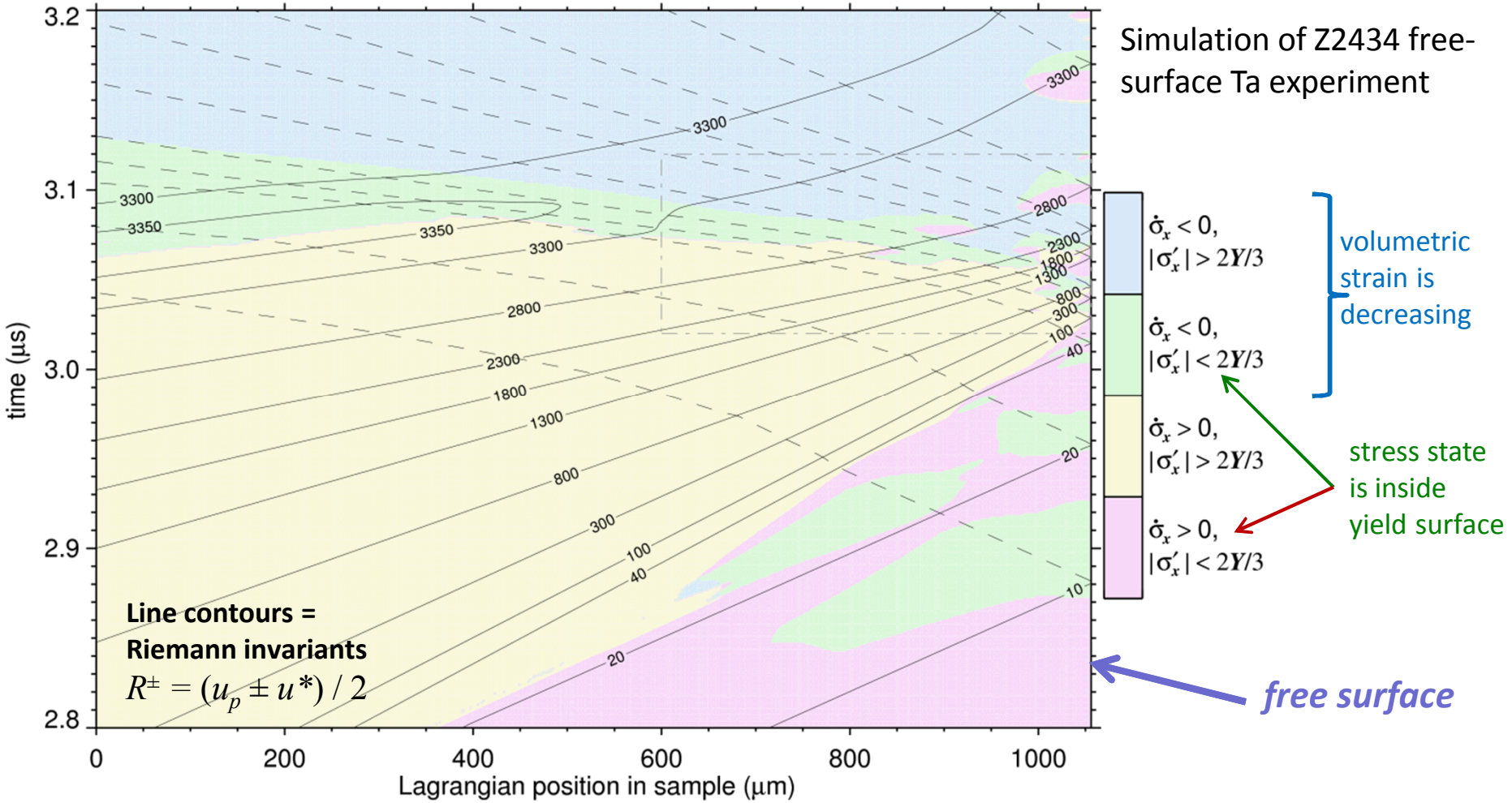
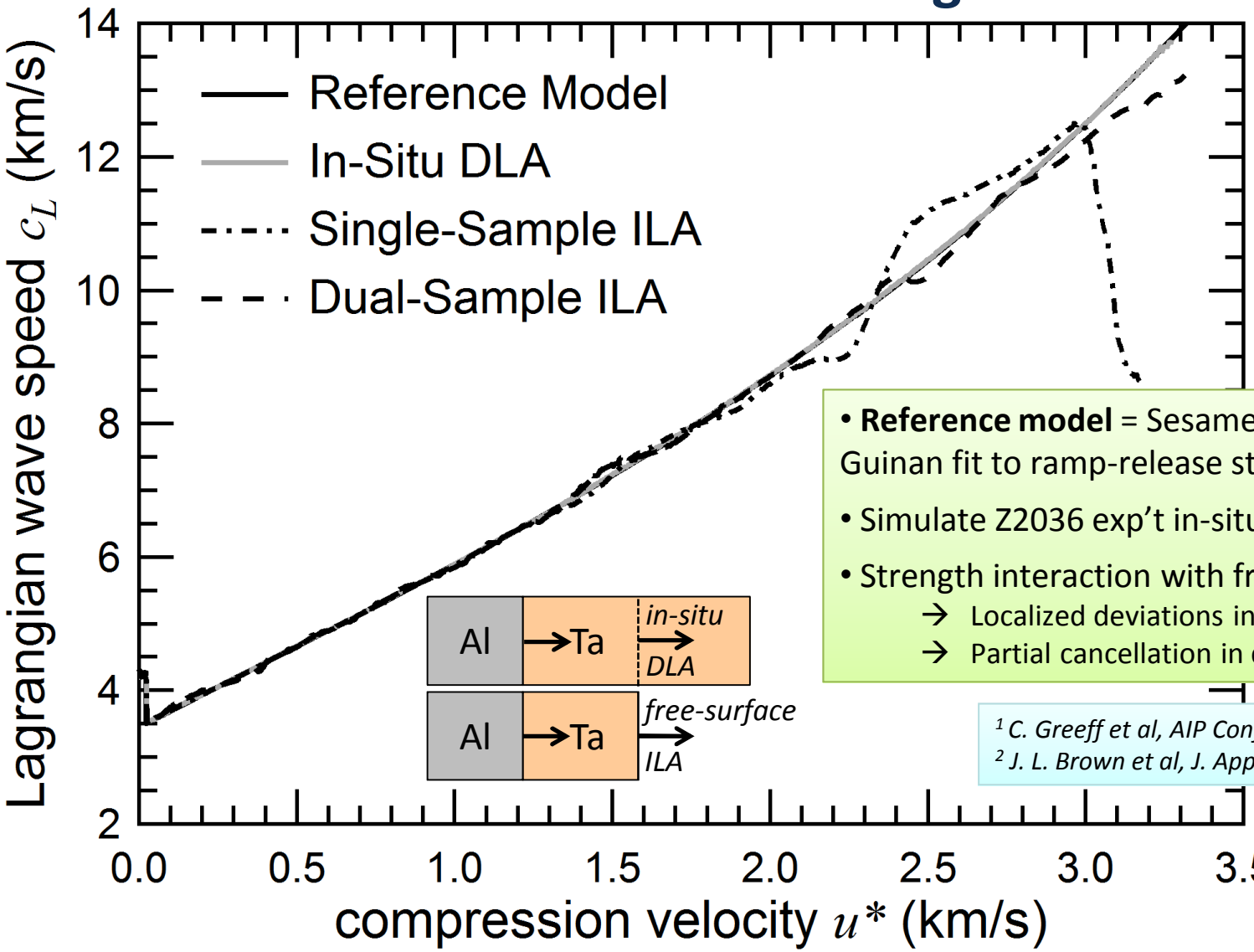


- High-pressure pseudo-characteristics traverse regions in ***t-x*** that are inside the yield surface
- Elastic propagation speed in these regions increases apparent wave speed measured across sample

J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

Analysis of synthetic data quantifies systematic deviations due to violation of single-valued response

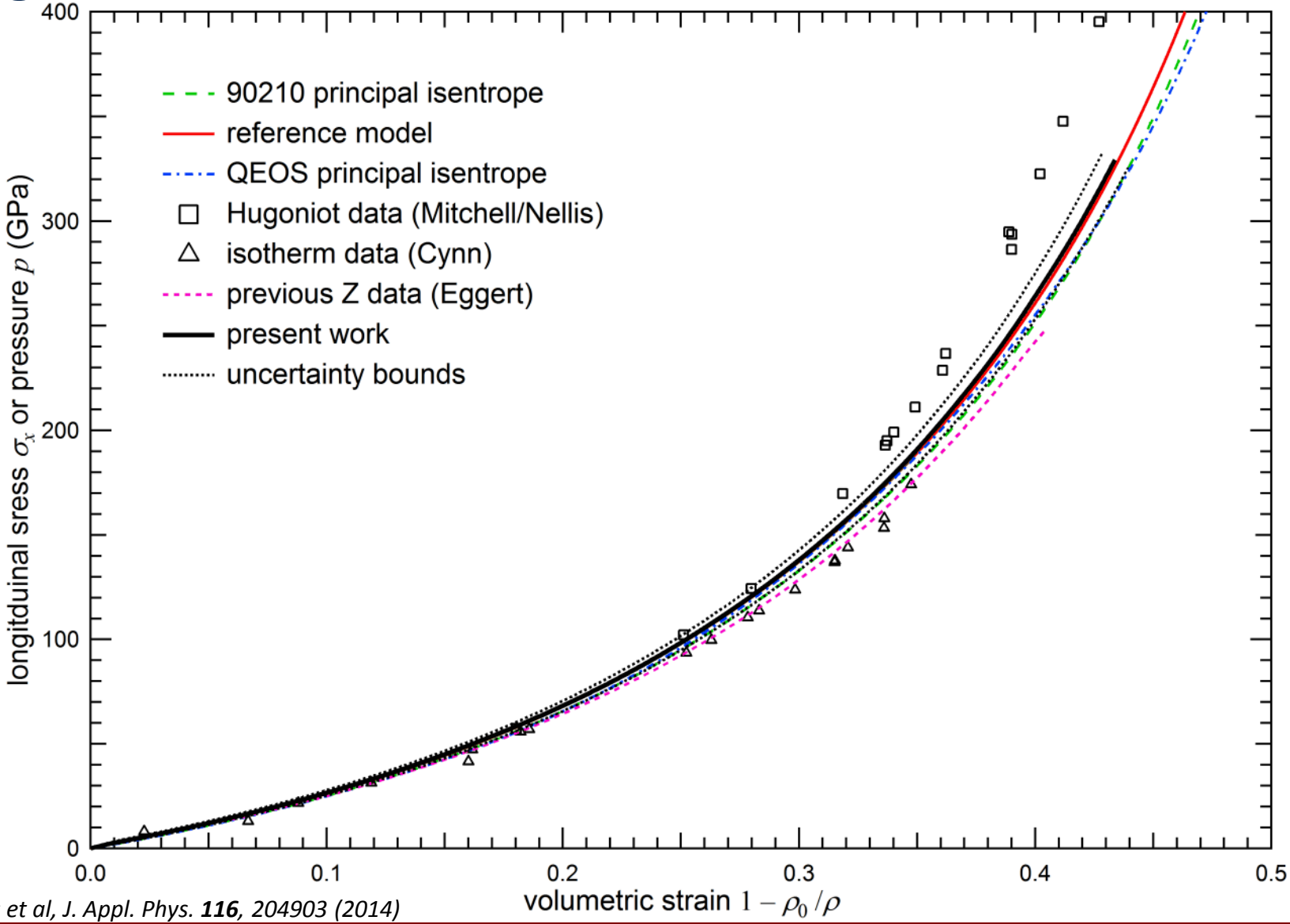


- **Reference model** = Sesame 90210[1] + Steinberg-Guinan fit to ramp-release strength data[2]
- Simulate Z2036 exp't in-situ & free-surface
- Strength interaction with free surface (ILA)
  - → Localized deviations in apparent $c_L(u^*)$
  - → Partial cancellation in dual-sample case

[1] *C. Greeff et al, AIP Conf. Proc.* ***1195****, 681 (2009)*
[2] *J. L. Brown et al, J. Appl. Phys.* ***115****, 043530 (2014)*

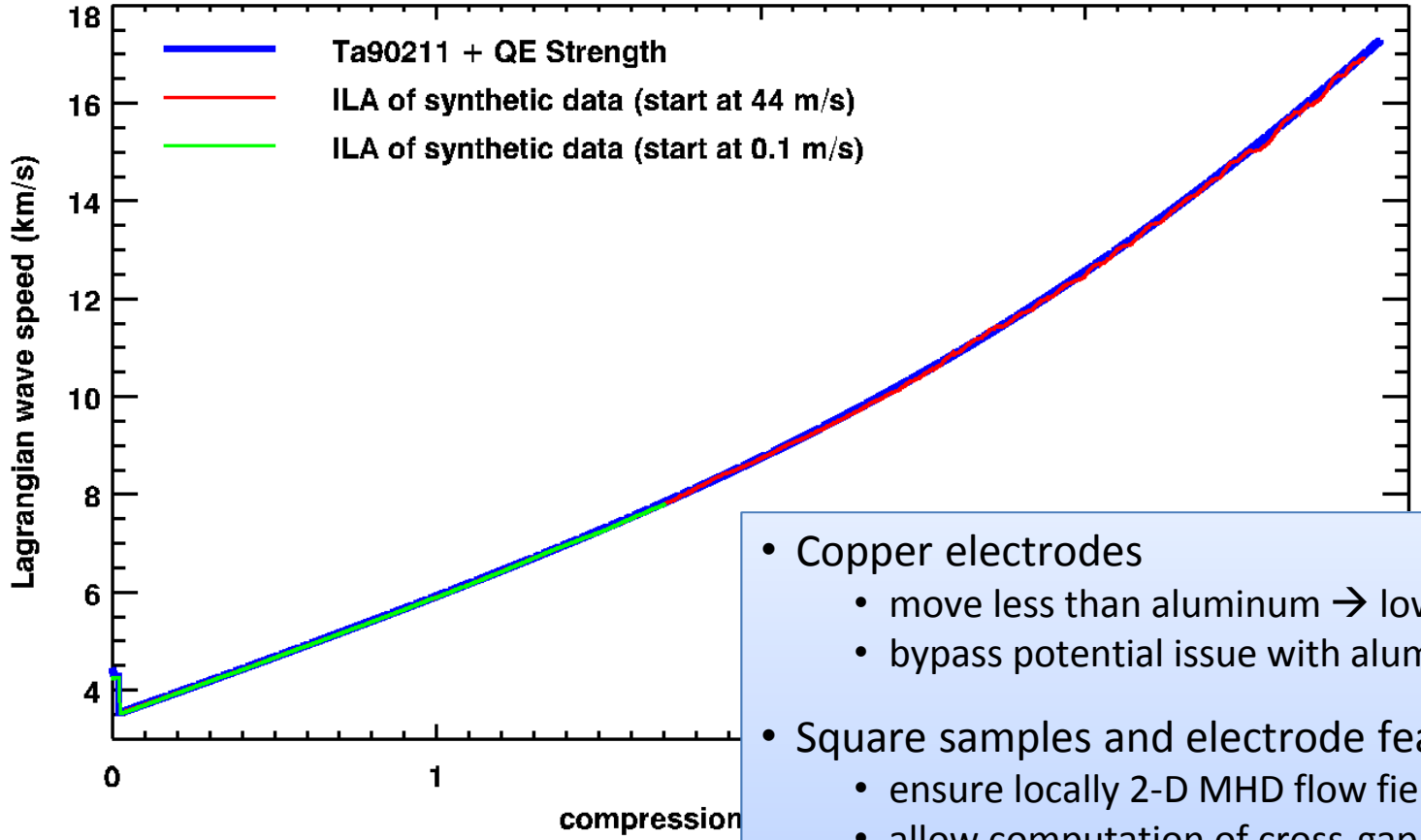
J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

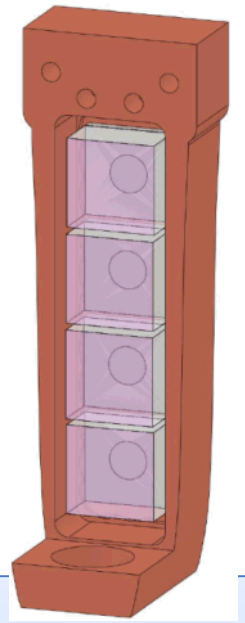
Averaged stress-strain of 15 Ta experiments agrees well with the reference model



J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

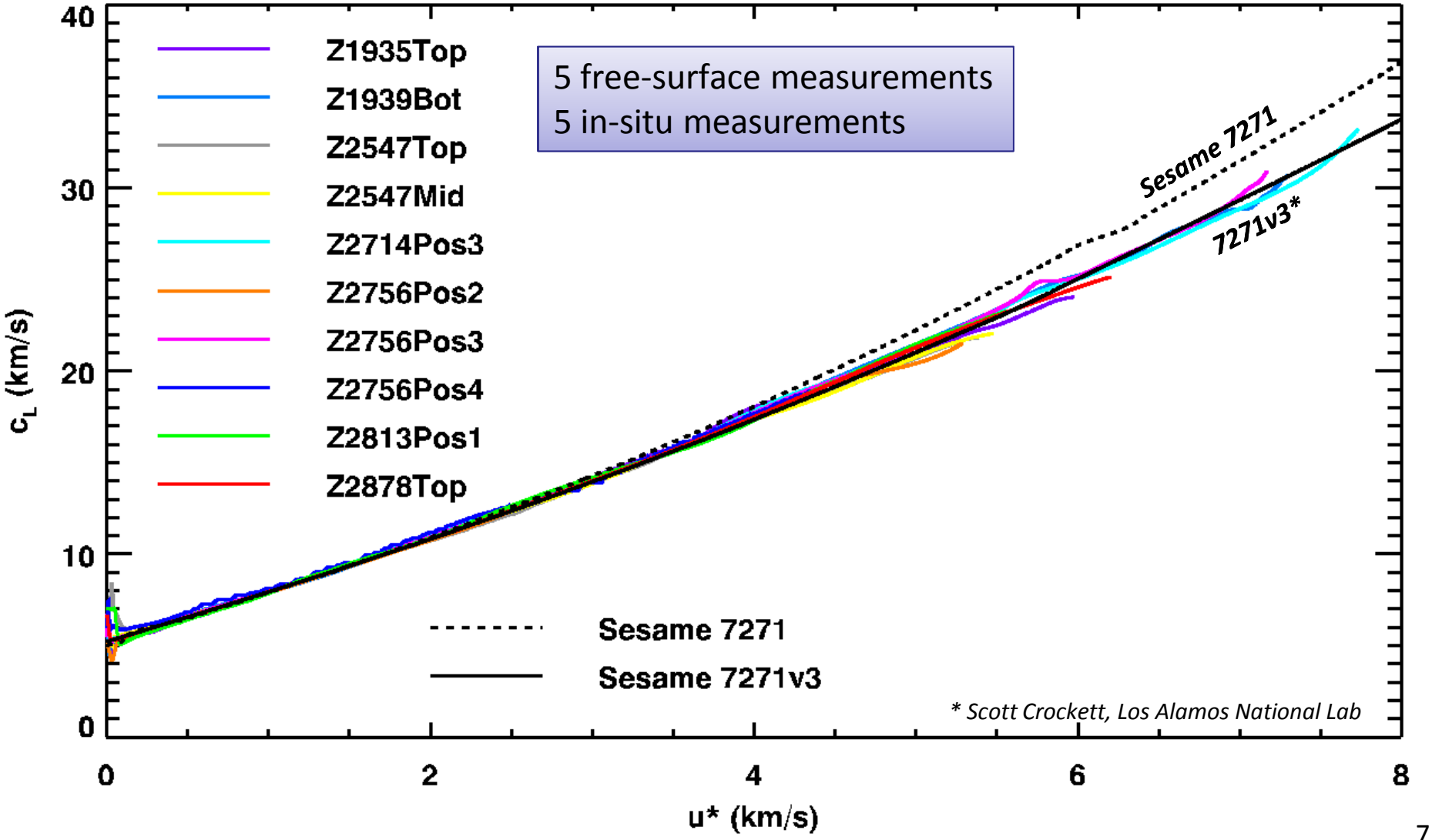
Improvements to experiment design are enabling quasi-isentrope measurements to higher stress



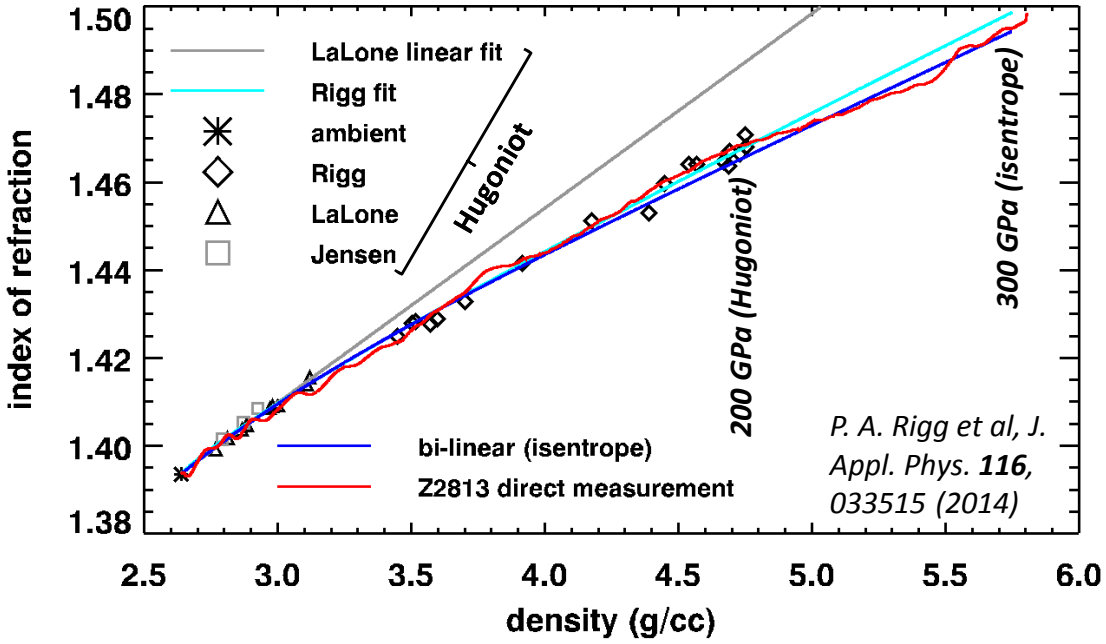


- Copper electrodes
  - move less than aluminum → lower dI/dt, higher B/I
  - bypass potential issue with aluminum phase transitions
- Square samples and electrode features
  - ensure locally 2-D MHD flow field
  - allow computation of cross-gap non-uniformity
- LiF windows
  - significantly reduce errors due to local unloading
  - uncertainty in stress-strain response at multi-megabars
  - uncertainty in index of refraction (nonlinear in density)

Collection of 10 results on LiF mechanical response indicate LANL 7271 EOS is too stiff



True velocity deduced from non-linear index of refraction with temperature correction



- 1-D hydrocode computes $u_{apparent}$ from given u_{true}
- update u_{true} from measured $u_{apparent}$
- iterate until simulation matches measured $u_{apparent}$

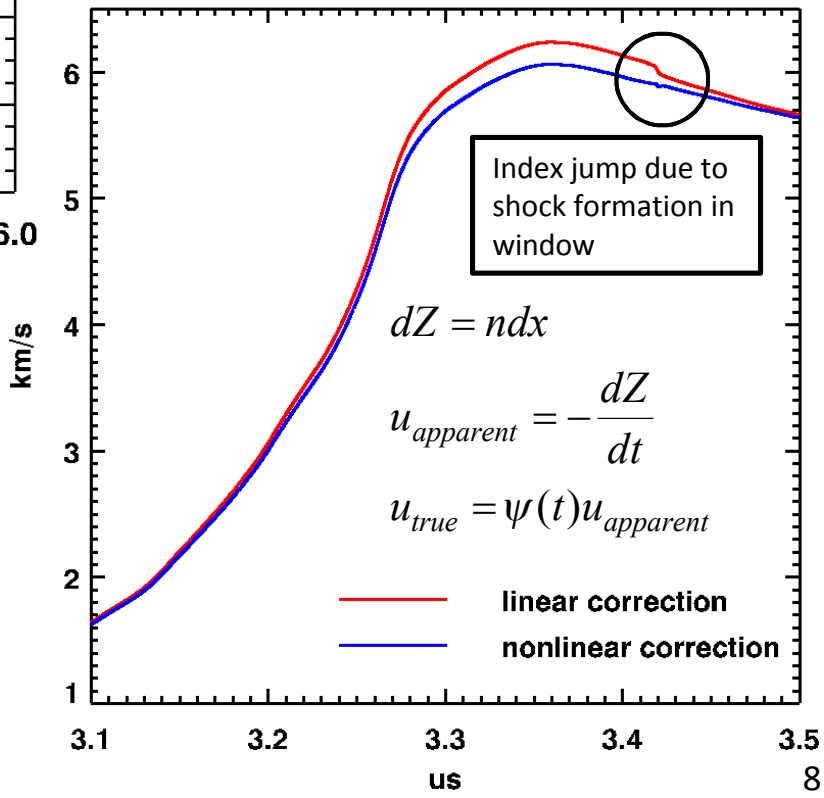
$$n_{isentrope} = \frac{a_1 + a_2\rho}{1 + e^{a_3(\rho - a_4)}} + (a_5 + a_6\rho)\left(1 - \frac{1}{1 + e^{a_3(\rho - a_4)}}\right)$$

$$n = n_{isentrope} + c\left(T - T_{isentrope}\right)$$

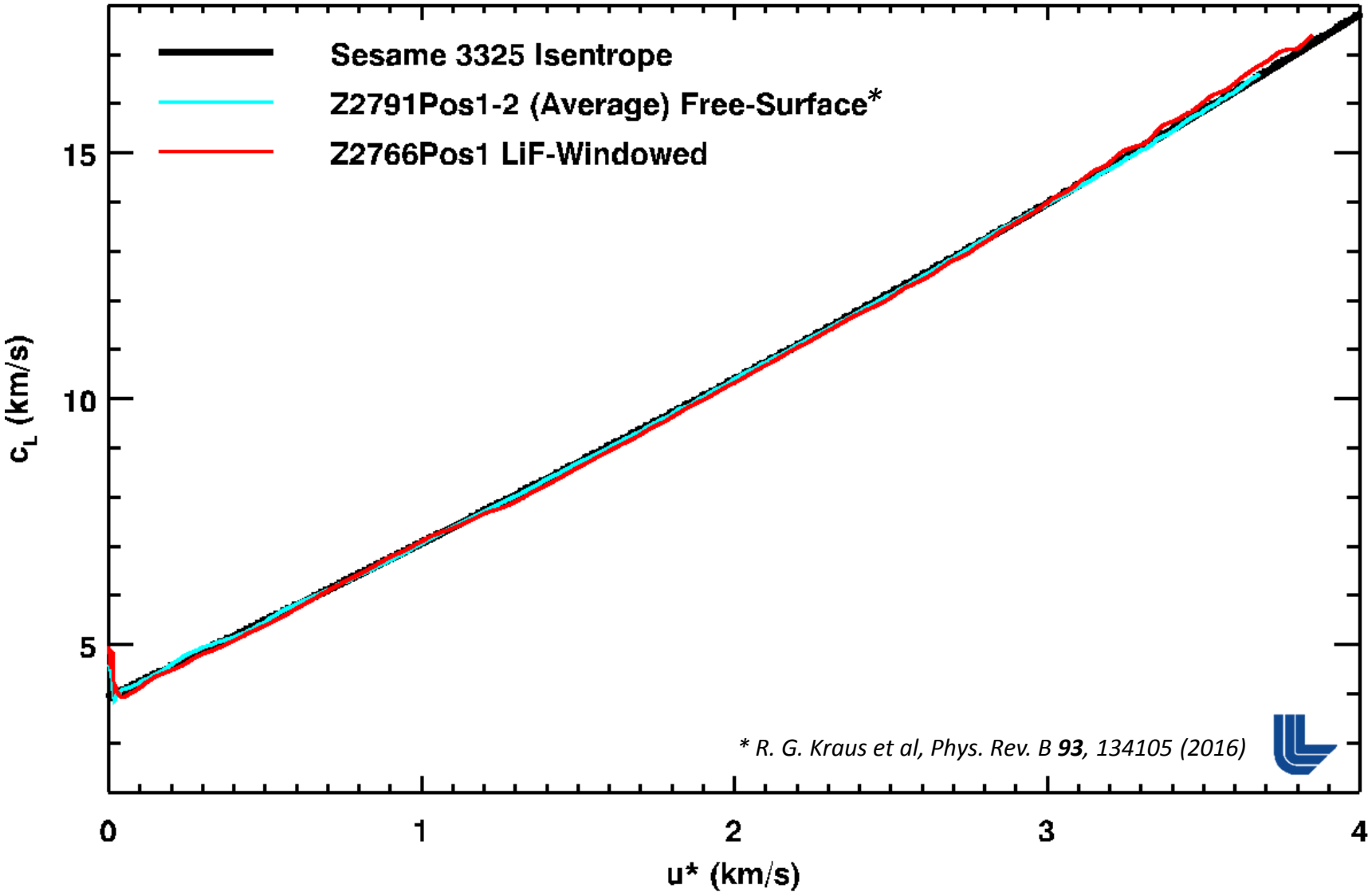
Direct measurement:
Measure $u_{apparent}$
Simulate u_{true}

$$\frac{dn}{d\rho} = \frac{1}{\rho}\left(n - \frac{du_{apparent}}{du_{true}}\right)$$

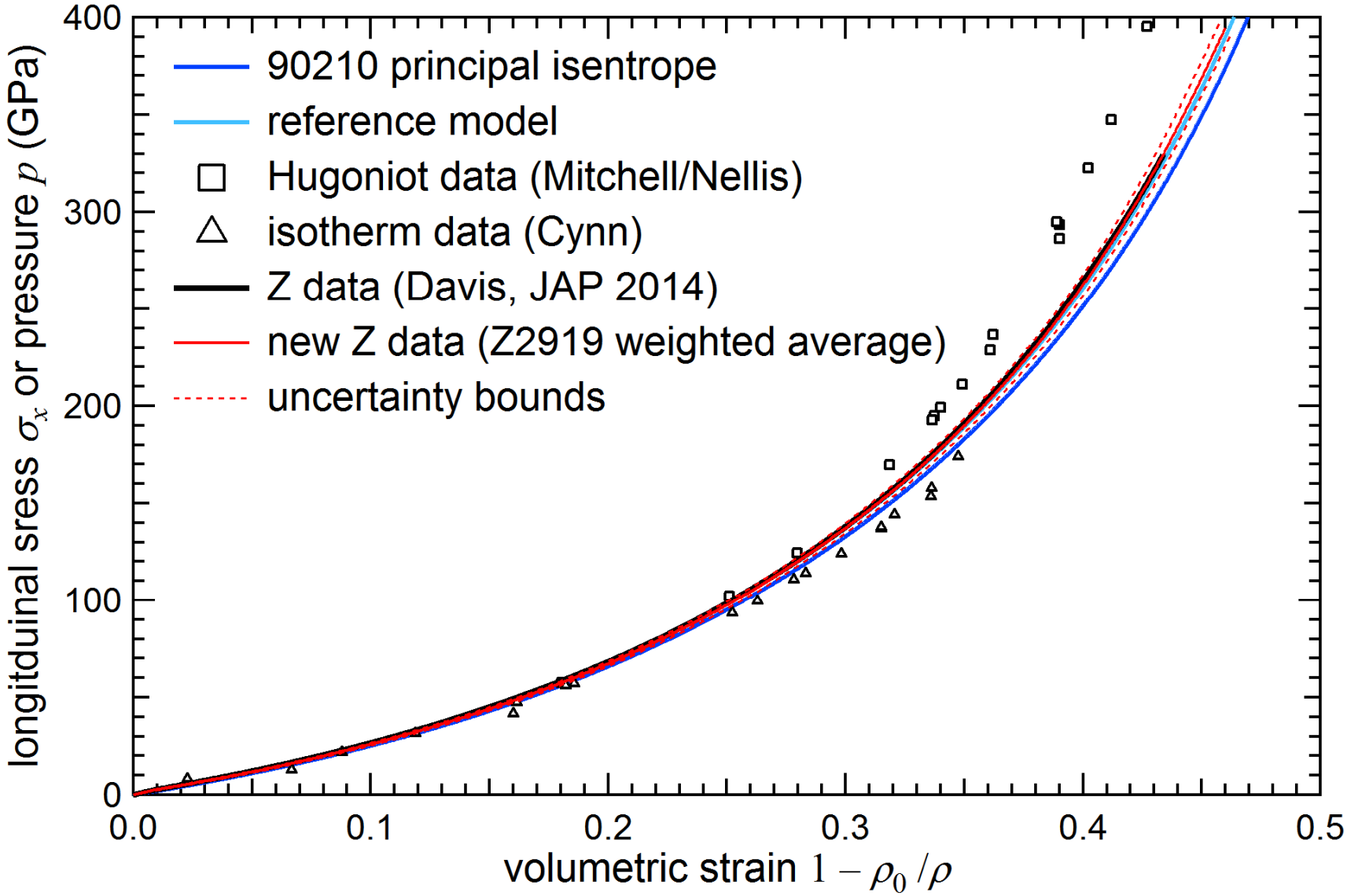
D. Hayes, J. Appl. Phys. **89**, 6484 (2001)



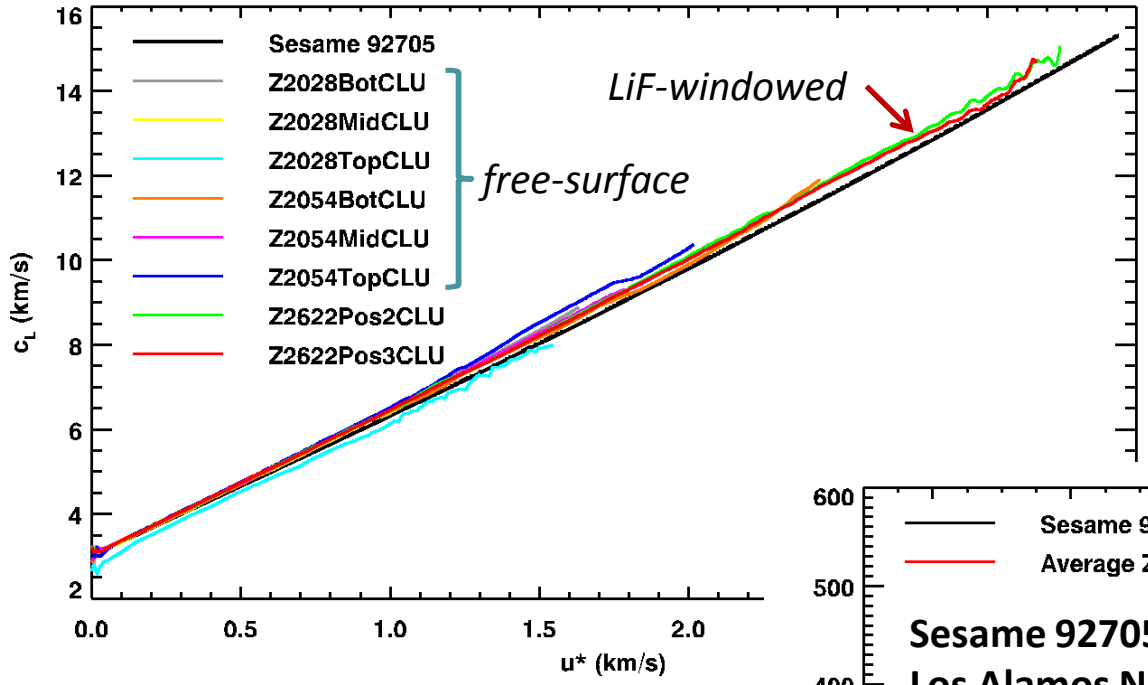
LiF-windowed Cu data agree with results from free-surface experiments

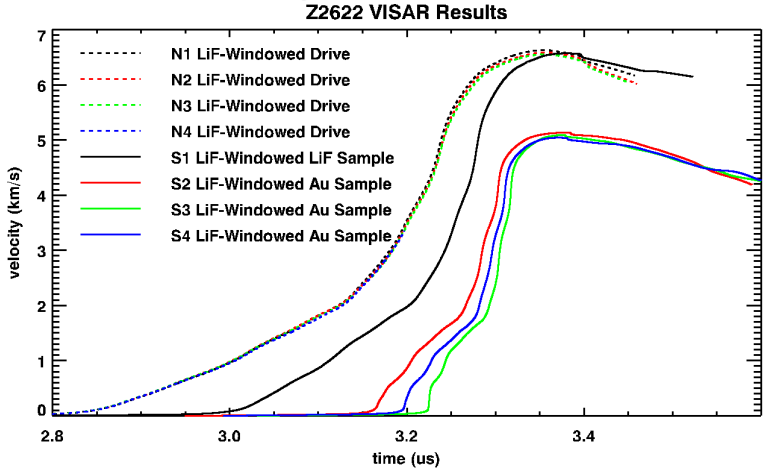


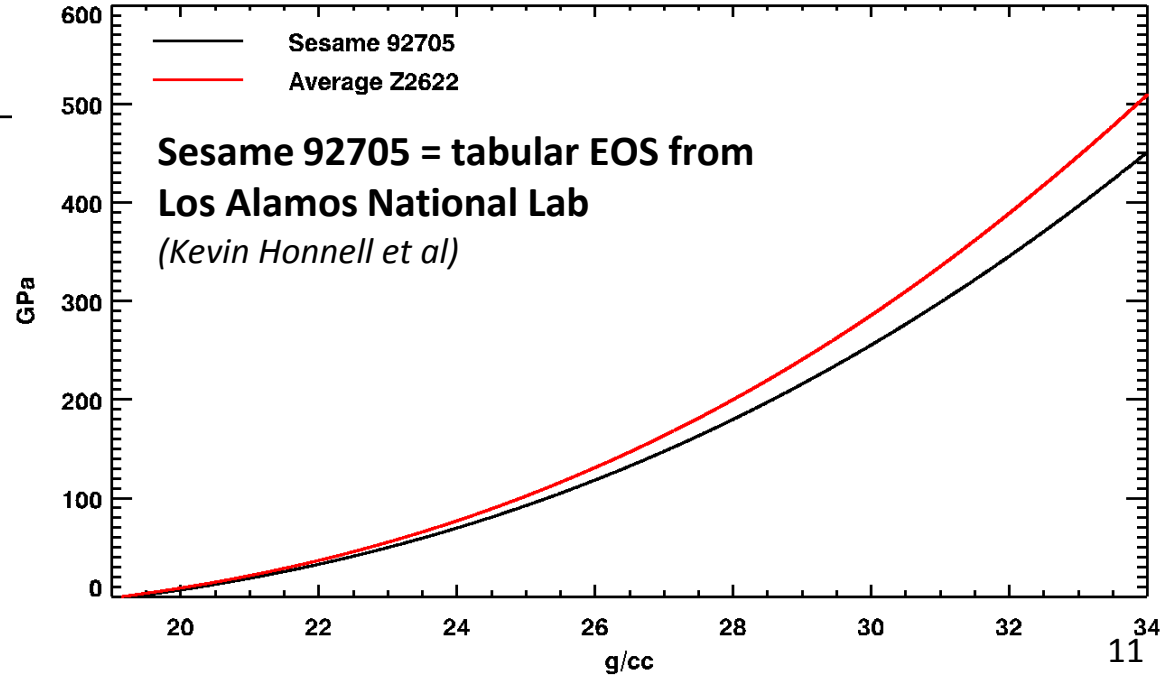
LiF-windowed Ta experiment extended measurement to near 400 GPa



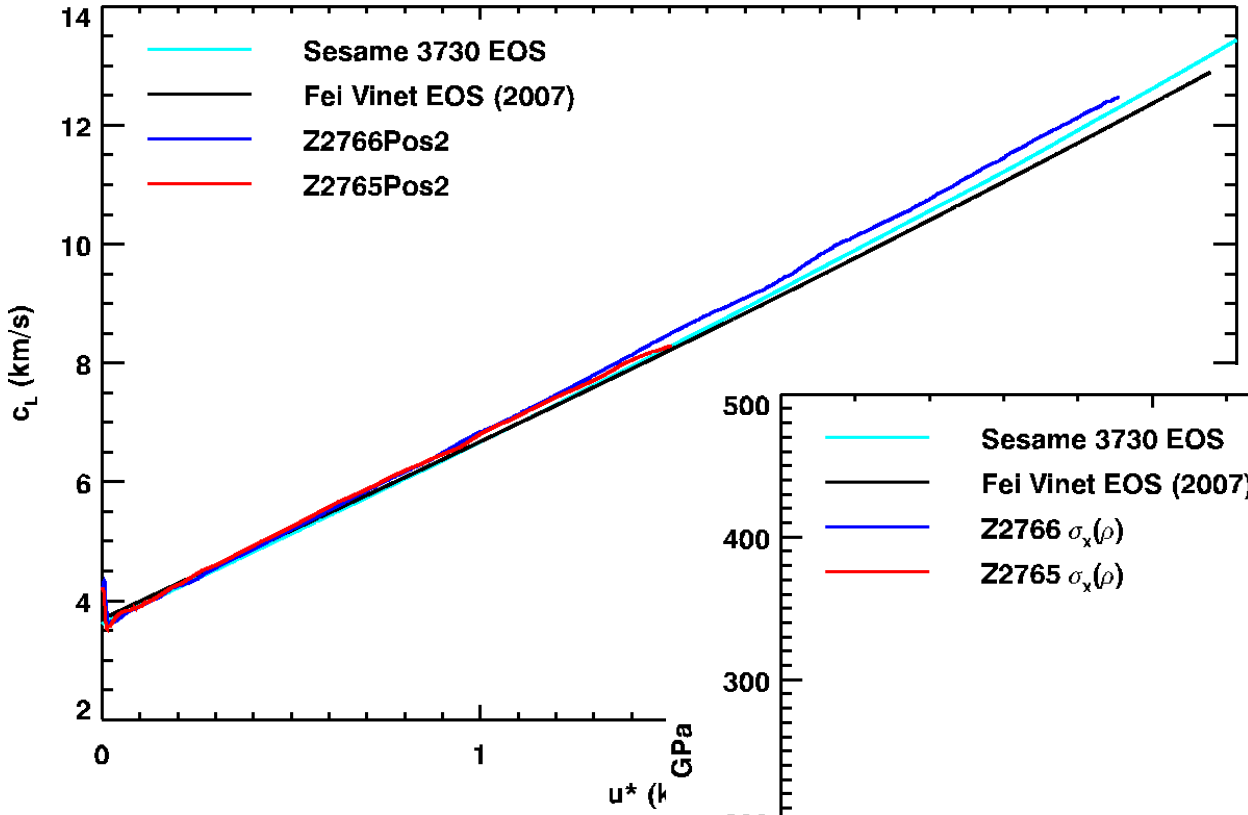
Preliminary analysis of Au data to 500 GPa suggests lower compressibility than leading model

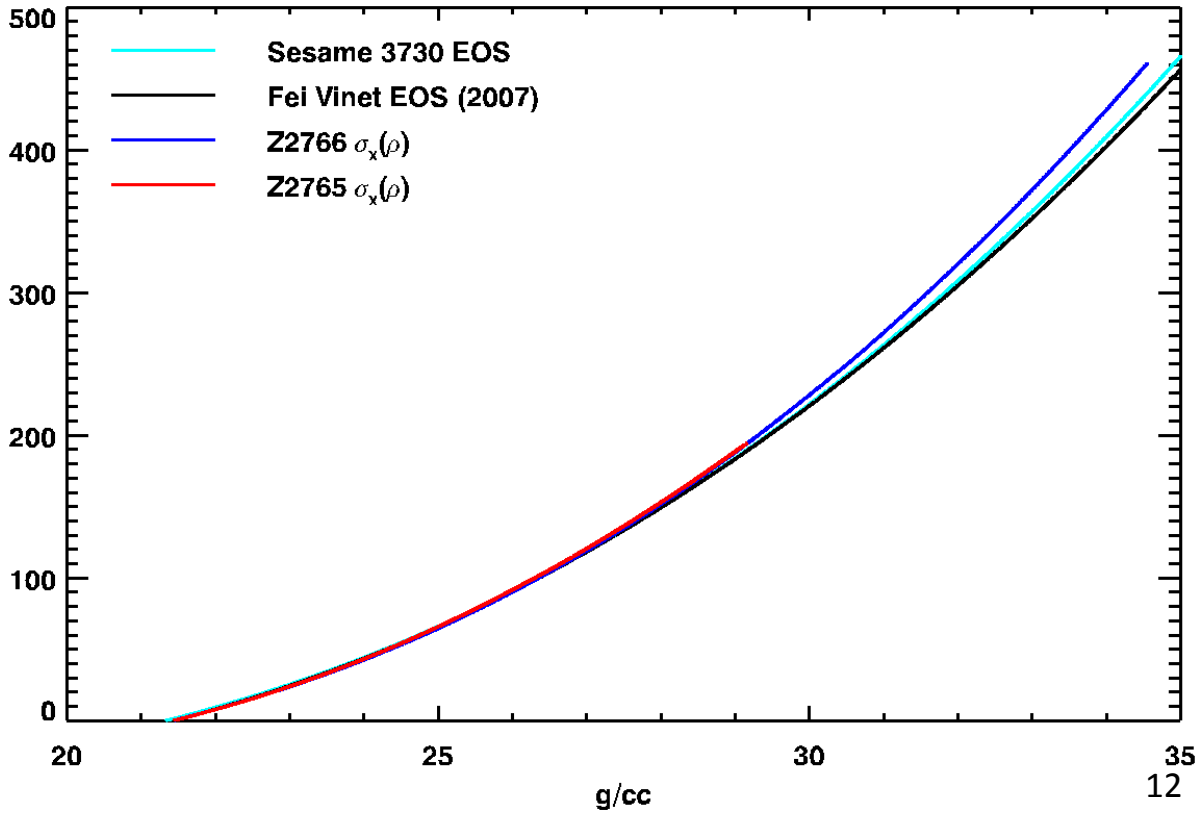




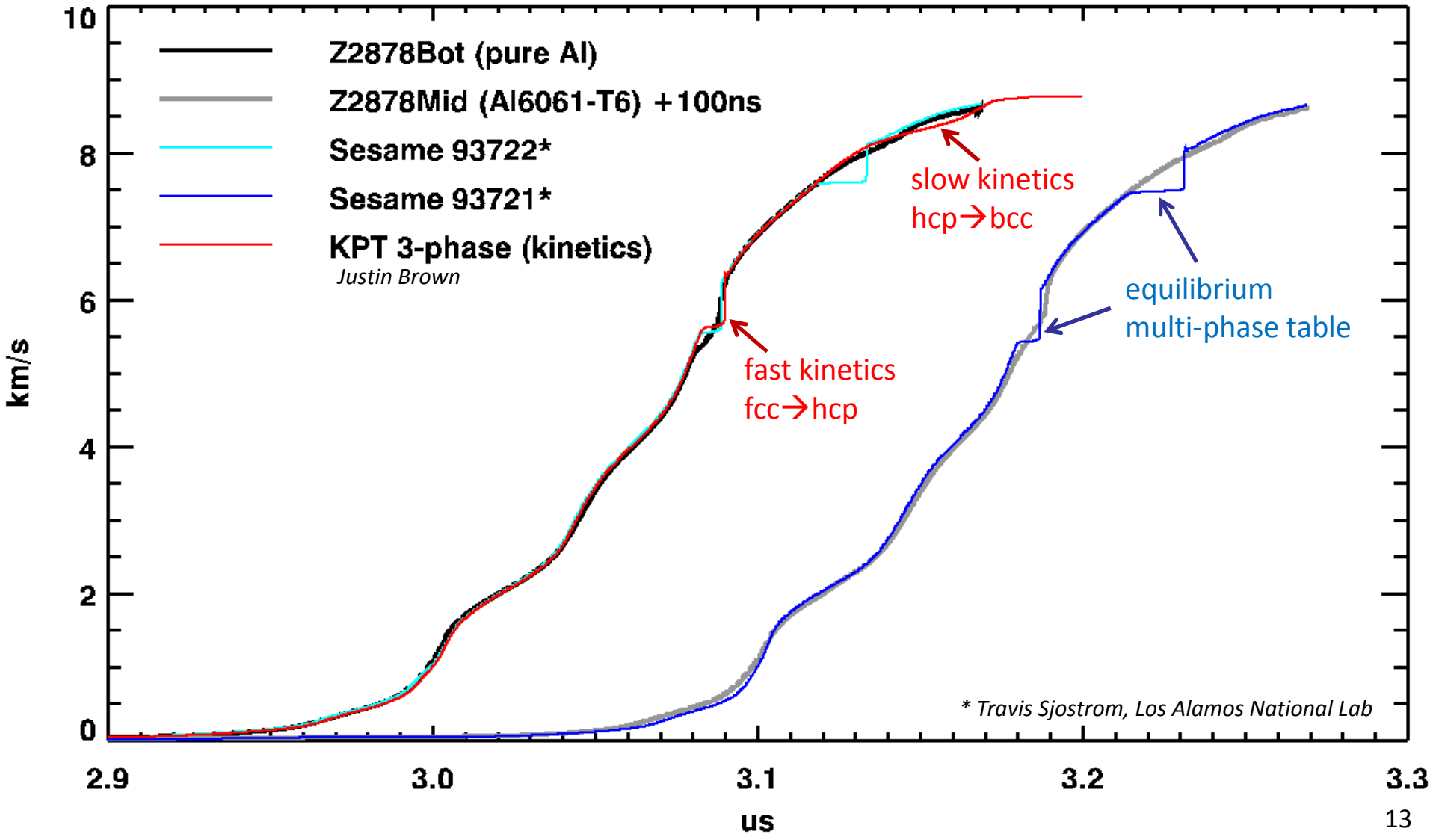


LiF-windowed Pt data also show stiffer response





LiF-windowed Al data show fcc→hcp transition



Concluding Remarks

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- Systematic deviations in ILA apparent wave speed for free-surface experiments with high-strength materials
- Averaged free-surface Ta data agree well with Sesame 90210 to 330 GPa
- Recent experiments use LiF windows, Cu electrodes, and square samples
- LiF quasi-isentrope softer than previous models
- Must account for nonlinear density dependence of LiF index of refraction
- Preliminary results for quasi-isentropes of Au (500 GPa), Pt (450 GPa), Ta (400 GPa), and Cu (350 GPa), plus data on phase transitions in Al (400 GPa)

Future Work:

- Independent measurements of strength at shocklessly-compressed states
- Optimization of EOS/strength models using forward simulations

Extra Slides

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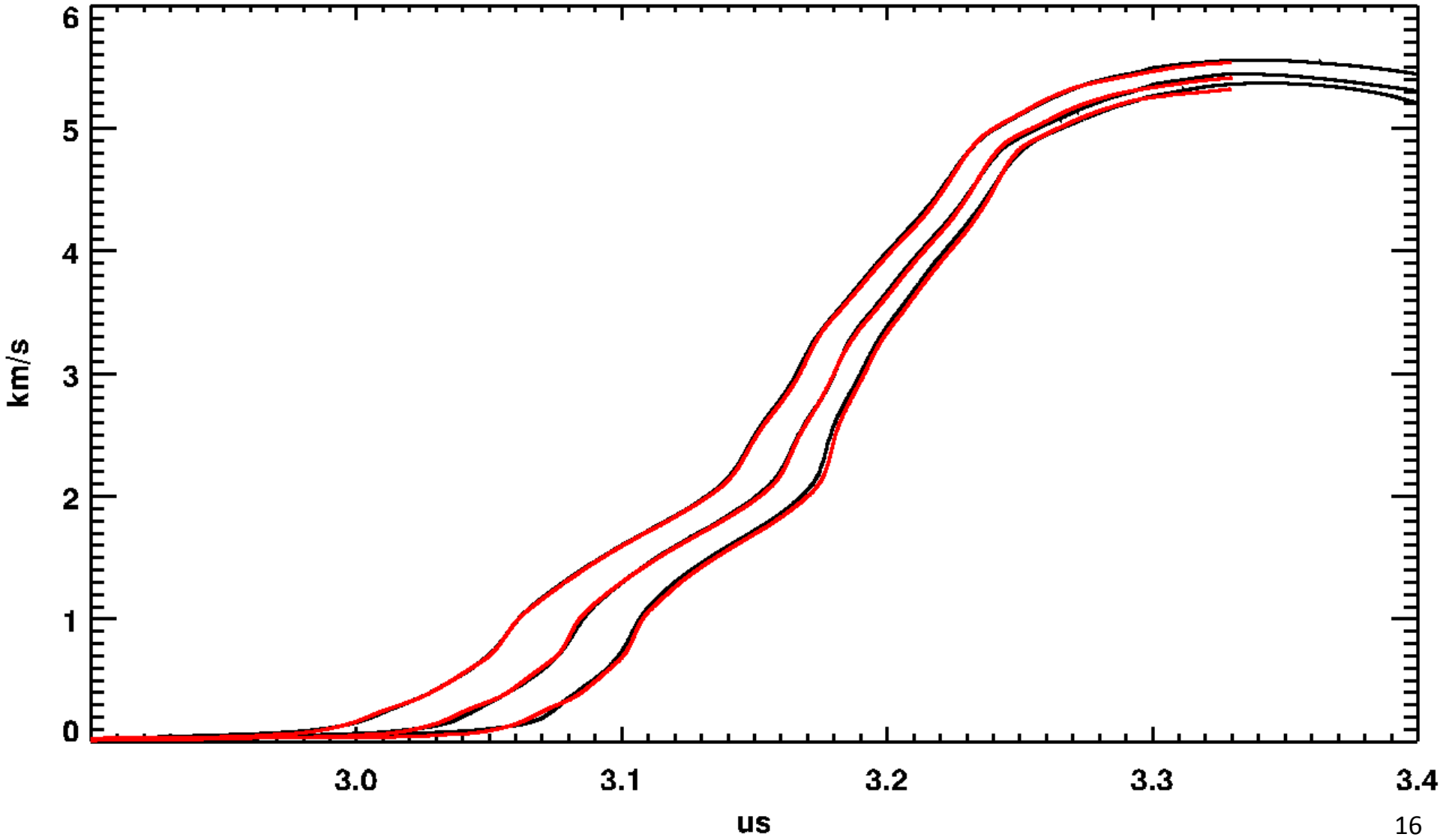
Reference Ta model gives excellent agreement to measured velocities on Z2919



2-D MHD calculations elucidate late-time cross-gap non-uniformity of driving B-field

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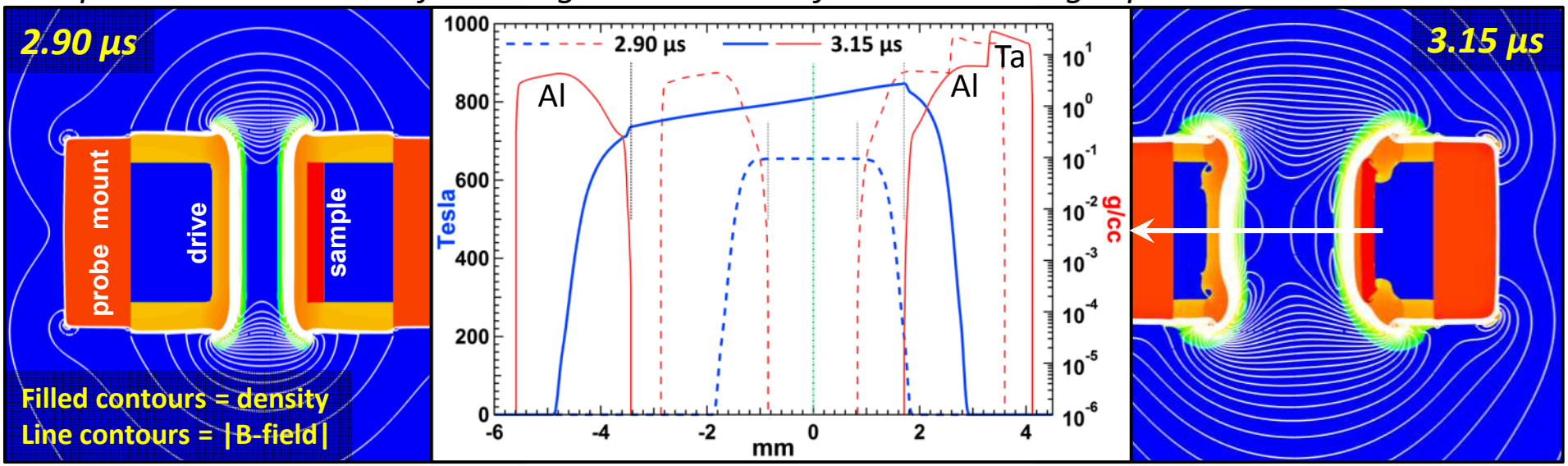
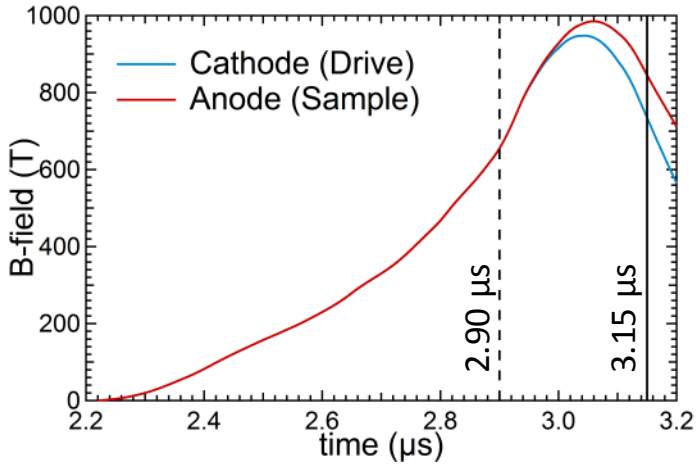
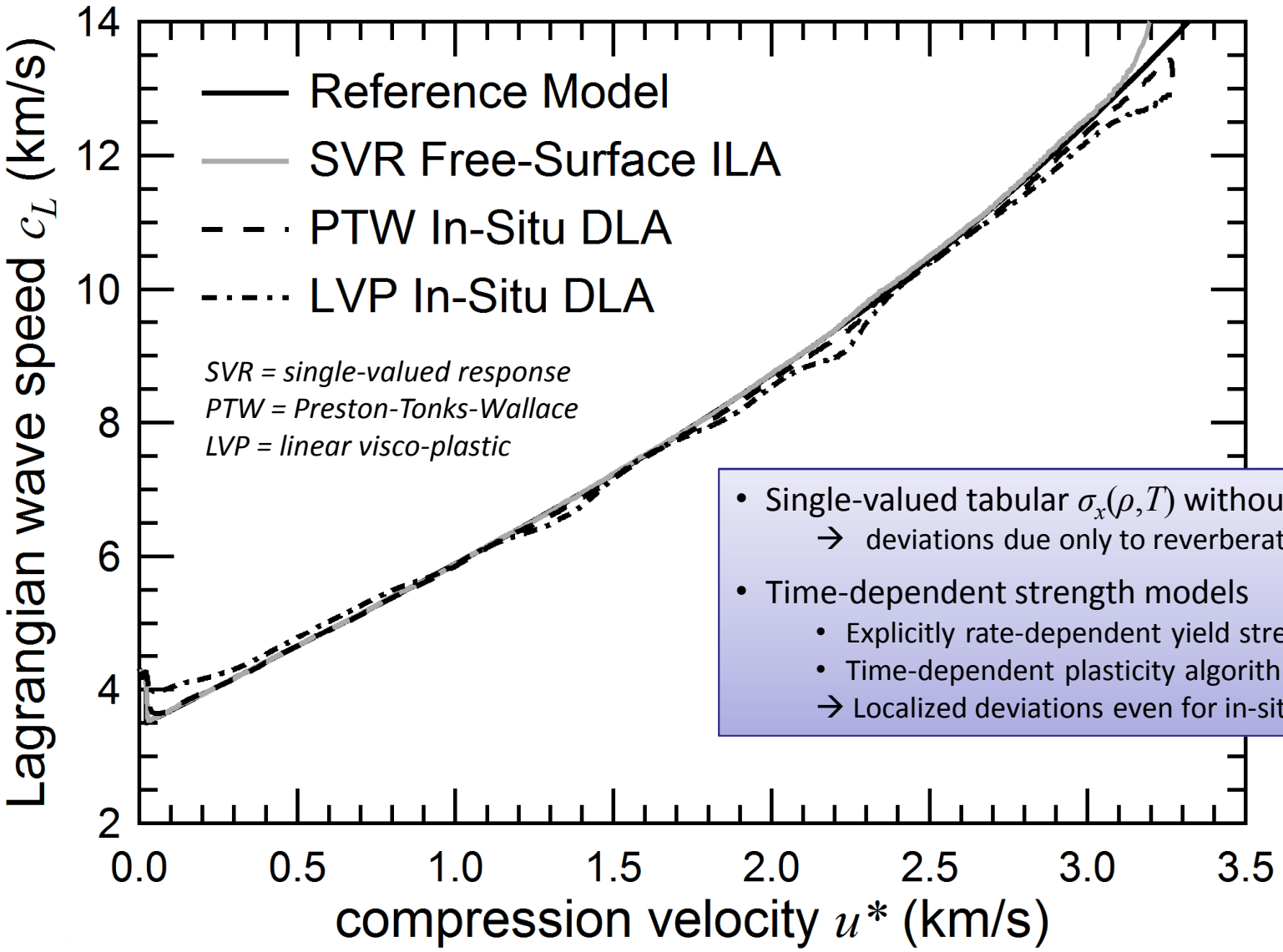
Snapshots with line-outs from Alegra simulation of Z2434 mid-height position





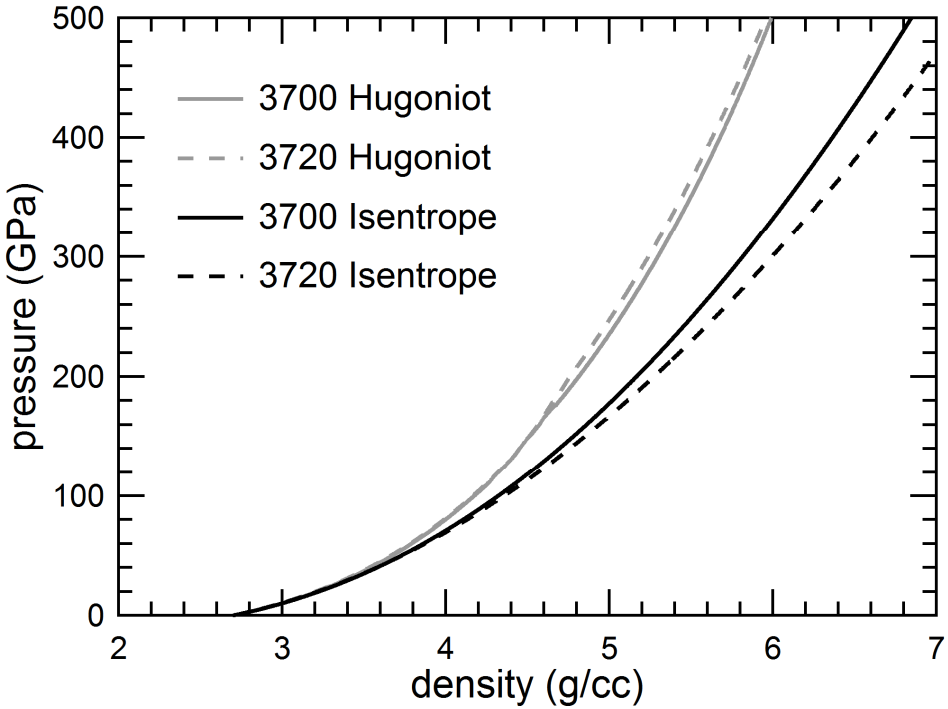
- Asymmetric wave reverberations in electrodes
  - Left (drive): reflection from free surface
  - Right (sample): reflection from high-impedance material
- Resulting 2-D effects cause asymmetric B-field topology
- Can occur prior to time of peak current
- Use 2-D B-field Sample/Drive ratio to correct 1-D B-field
  - Only if experiment is really 2-D!
  - For cylindrical samples, discard beyond divergence

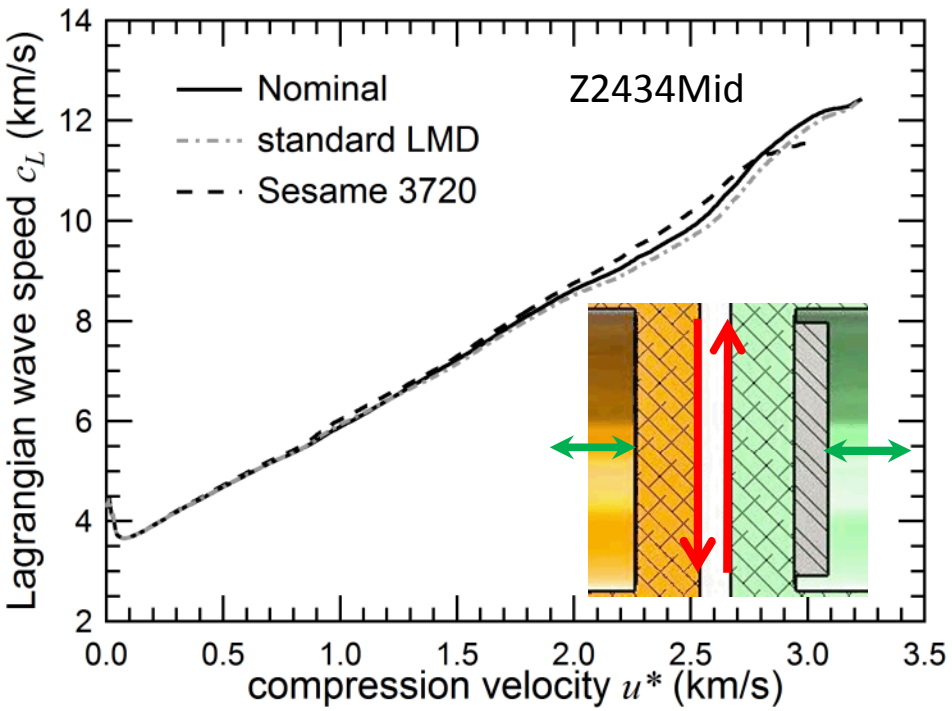
Time dependence in strength can cause small systematic deviations in apparent wave speed



- Single-valued tabular $\sigma_x(\rho,T)$ without strength
  - → deviations due only to reverberation
- Time-dependent strength models
  - Explicitly rate-dependent yield stress (PTW)
  - Time-dependent plasticity algorithm (LVP)
  - → Localized deviations even for in-situ DLA

Single-sample ILA has sensitivity to models used for electrode standard material





- Aluminum electrode sees different states in drive-side and sample-side electrodes
- Reanalyzed Z2434Mid changing only Al conductivity model, and again changing only Al EOS model
- Off-nominal models known to be inaccurate (nominal models largely validated)
- True uncertainty expected to be smaller than deviations shown here