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Title: Modeling Hydrodynamic Instabilities, Shocks, and Radiation Waves in High Energy Density Experiments

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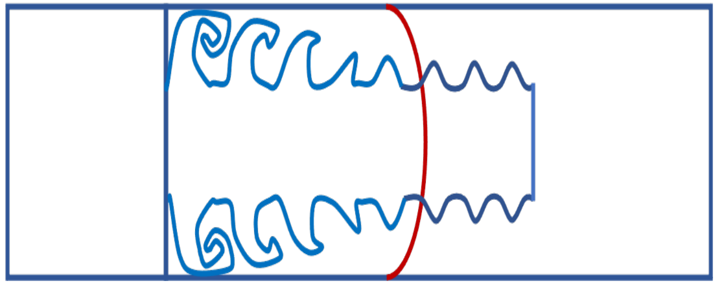
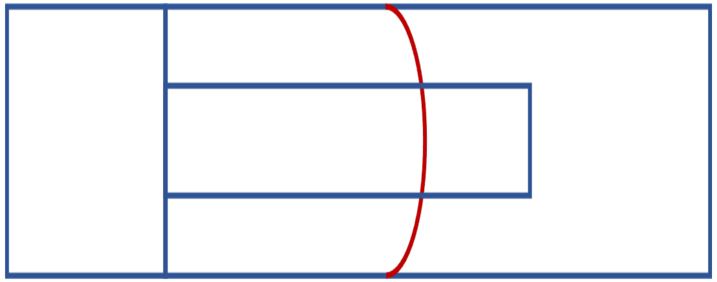
Modeling Hydrodynamic Instabilities, Shocks, and Radiation Waves in High Energy Density Experiments

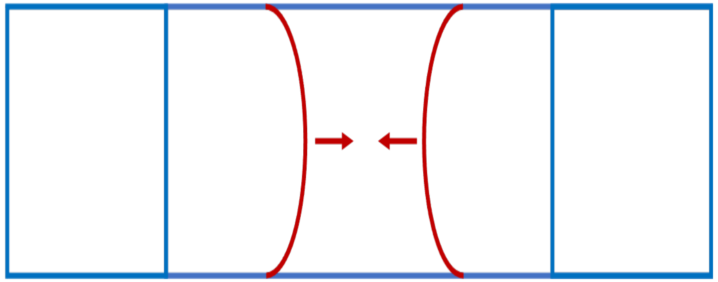
Shock seeding instabilities



Subsonic transitioning wave



Shock and wave interaction



Shane X. Coffing

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My friends and family, and so many others, esp.:

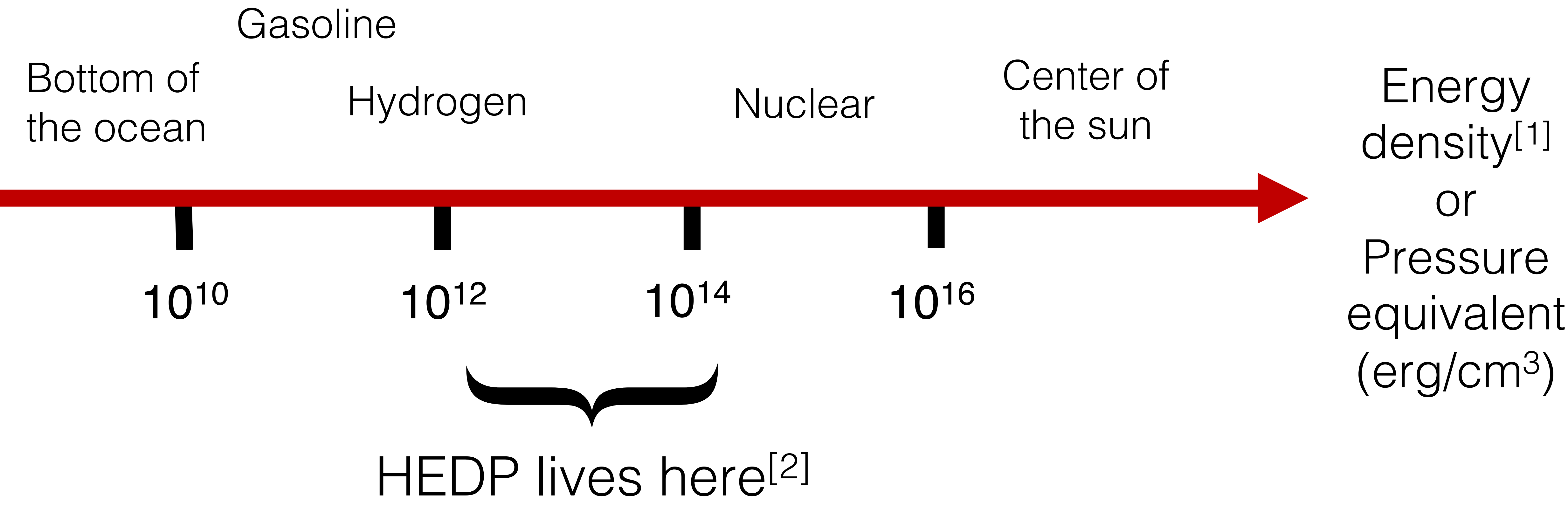
Gertrude

What we are going to talk about

- Intro to relevant high energy density physics (HEDP) (5)
- Three different HEDP experiments (~12 each)
    - Instabilities on galactic filaments
    - Subsonic radiation waves in COAX
    - Shocks interacting with radiation waves in Radishock
- What they study, how/why we model them, results
- Summary: the products of my research (5)

Brief introduction to HEDP

What is high-energy density physics?



In this realm, we often deal with the micron, the nanosecond, the eV

How do we *model* HEDP phenomenon?

- (Euler) Equations of hydrodynamics[2]
    - + Add radiation
    - + Add gravity/energy terms
    - + Add electromagnetism
    - + Add sub-grid models
    - + More models

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot \rho \cdot \mathbf{u} = 0$$ mass

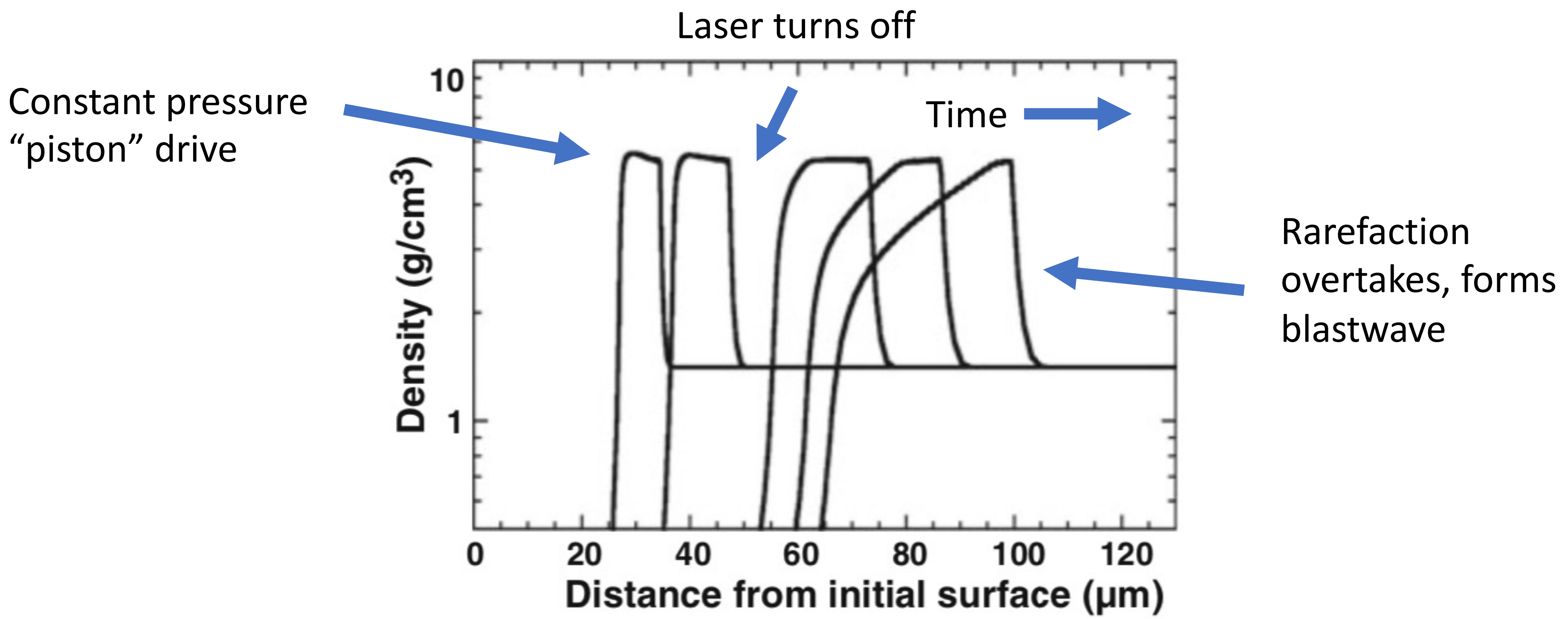
$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} \mathbf{u}\right) = -\boldsymbol{\nabla} p$$ momentum (force)

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} p = -\gamma p \boldsymbol{\nabla} \cdot \mathbf{u}$$ energy

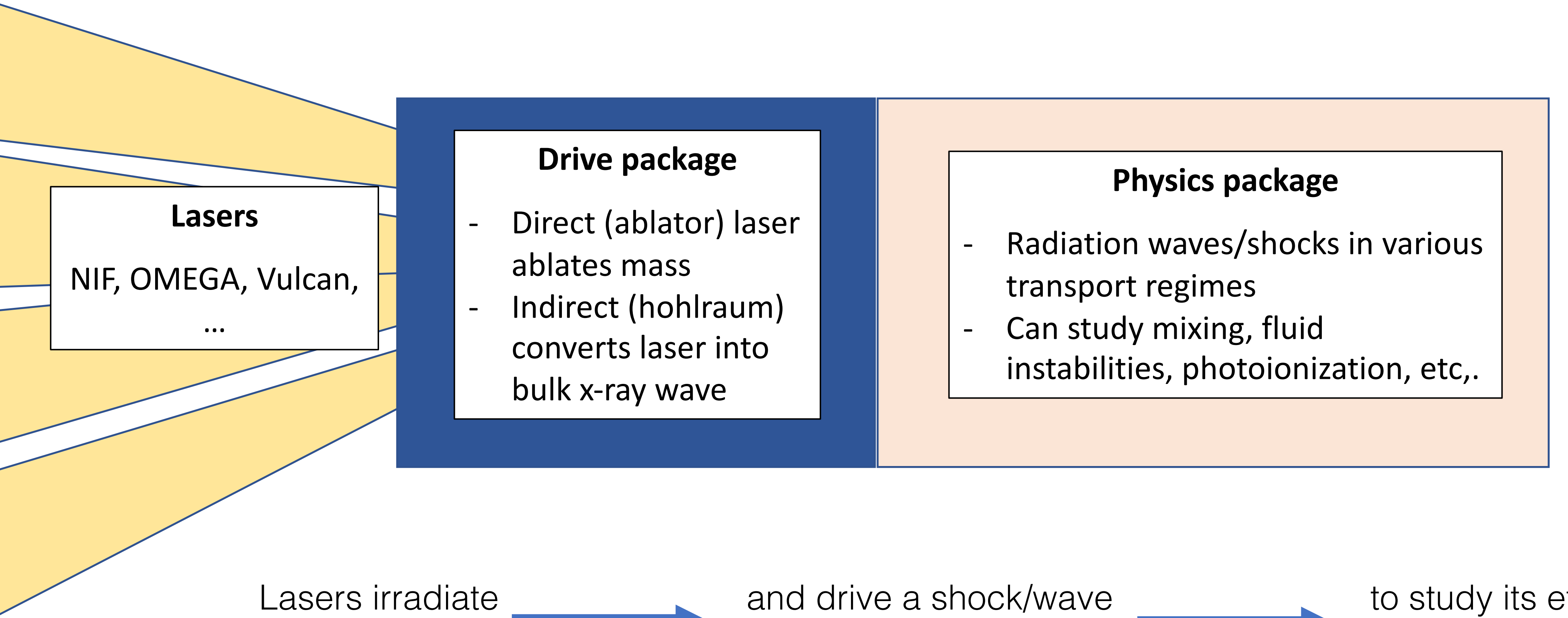
- We use hydro codes to model these eqs.
    - CRASH (University of Michigan)[3]
    - Cassio (Los Alamos National Laboratory)[4]
    - Need analytical solutions to verify HEDP relevant eqs.

How do we *make* HEDP phenomenon?

- Laser facilities, pulsed-power facilities, accelerators, …
- Make **shocks**, **radiation flows**, …, to drive physics studies



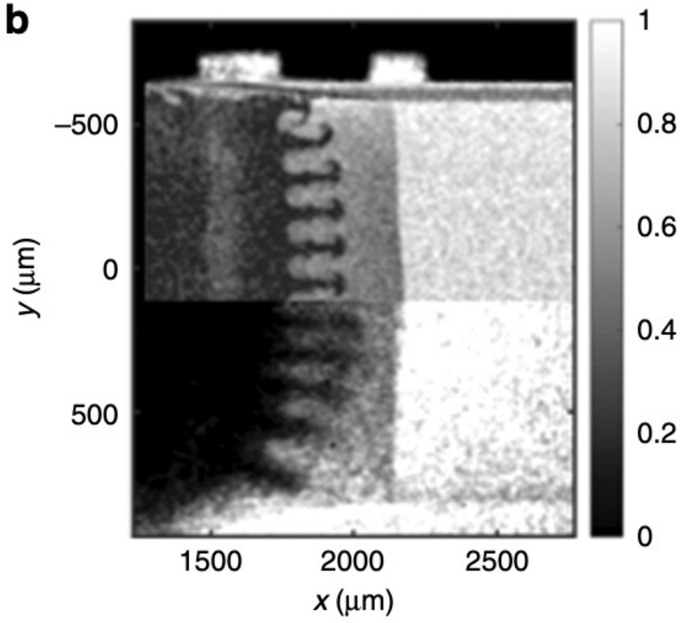
Radiation/shock tube experiments



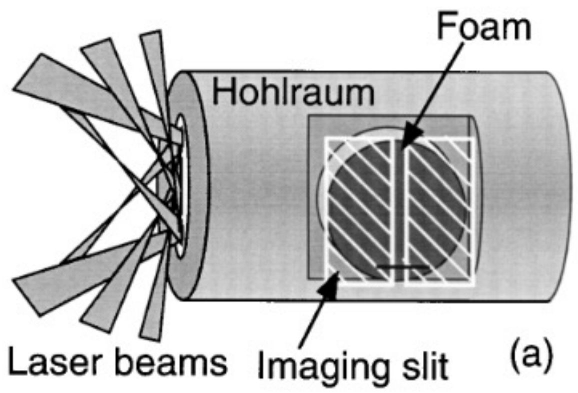
Lasers irradiate something → and drive a shock/wave into a target → to study its effects on a variety of scenarios

Why do we model HEDP phenomenon?

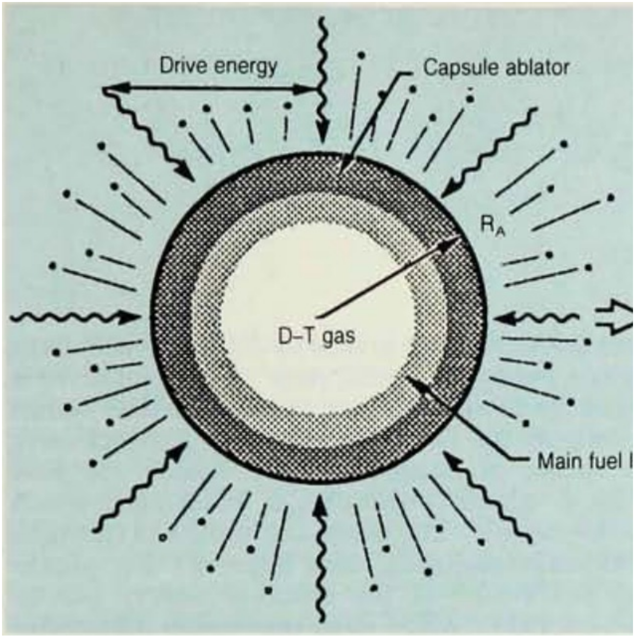
We need high precision experiments to validate HEDP models



HEDLA: A supernova RT experiment[5]

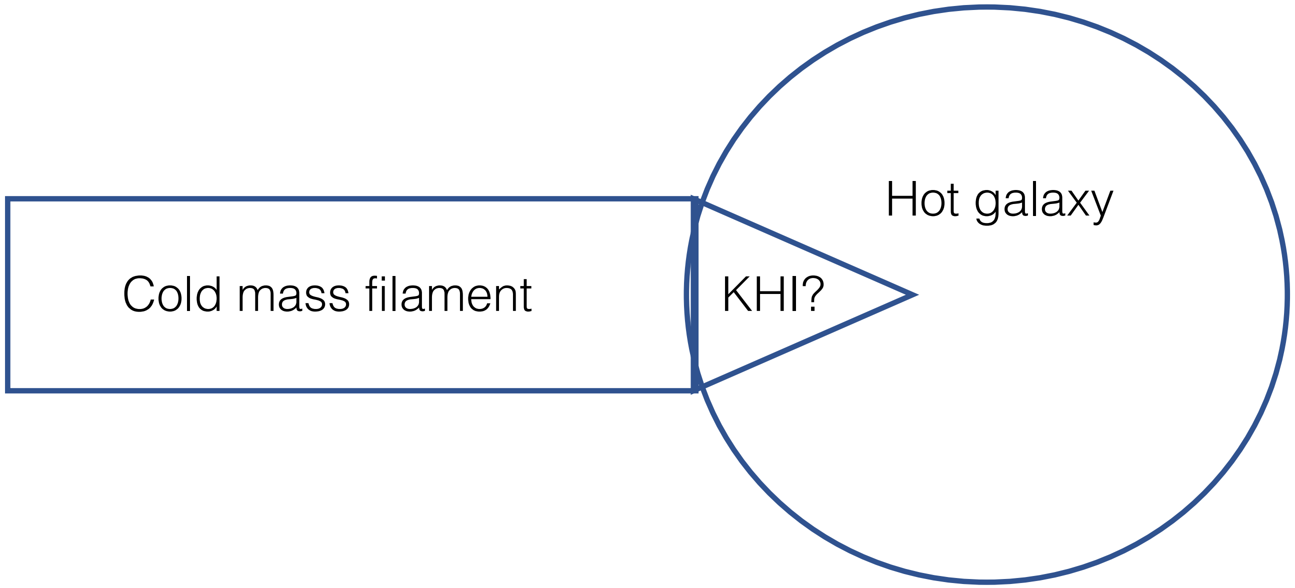


Fundamental science: a radiation wave exp[6]



Energy: inertial confinement fusion[7]

The HEDP experiments



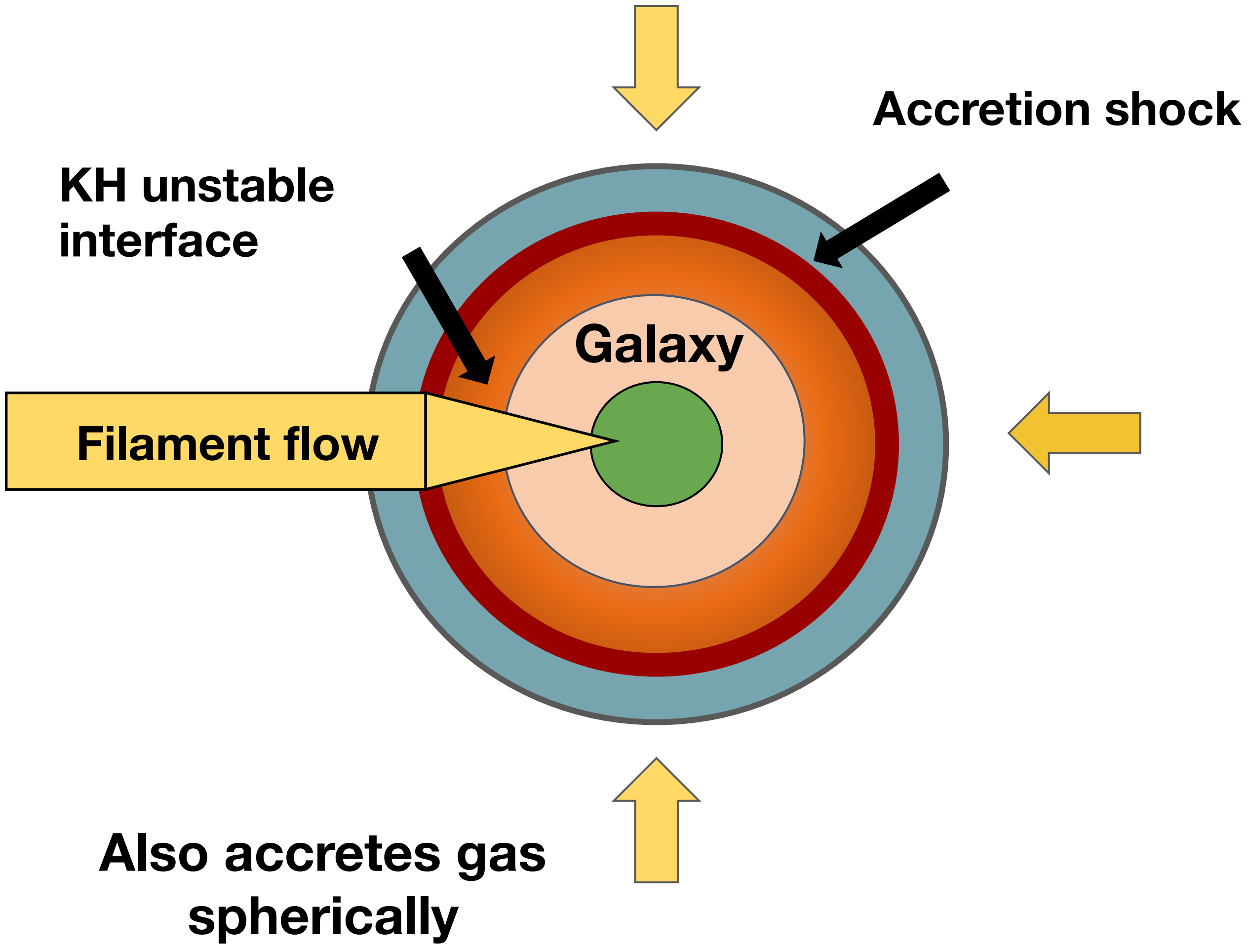
Instability on cosmic filaments

Does the Kelvin-Helmholtz instability (KHI) hinder galaxy formation?

How does radiative cooling affect the KHI?

Can an experiment illuminate this phenomenon?

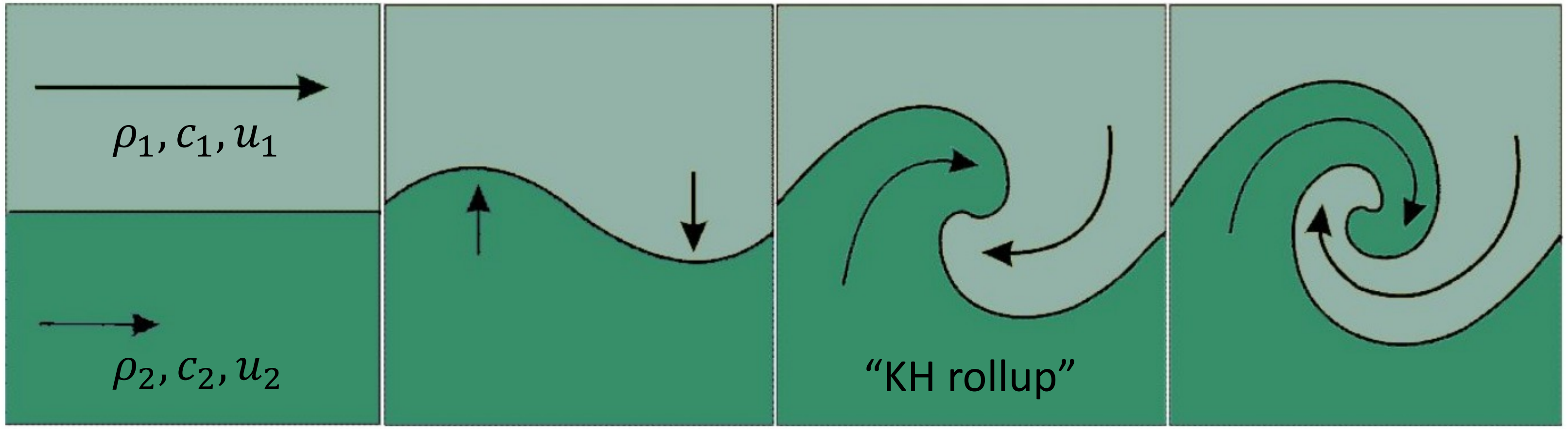
Filaments give cold gas to galaxy centers[10]



- A halo accretes gas spherically
- A shock eventually forms from building accretion pressure
- The filament flow is now shocked!
- The shock-collapsed filament is KH unstable.

What is the Kelvin-Helmholtz instability?

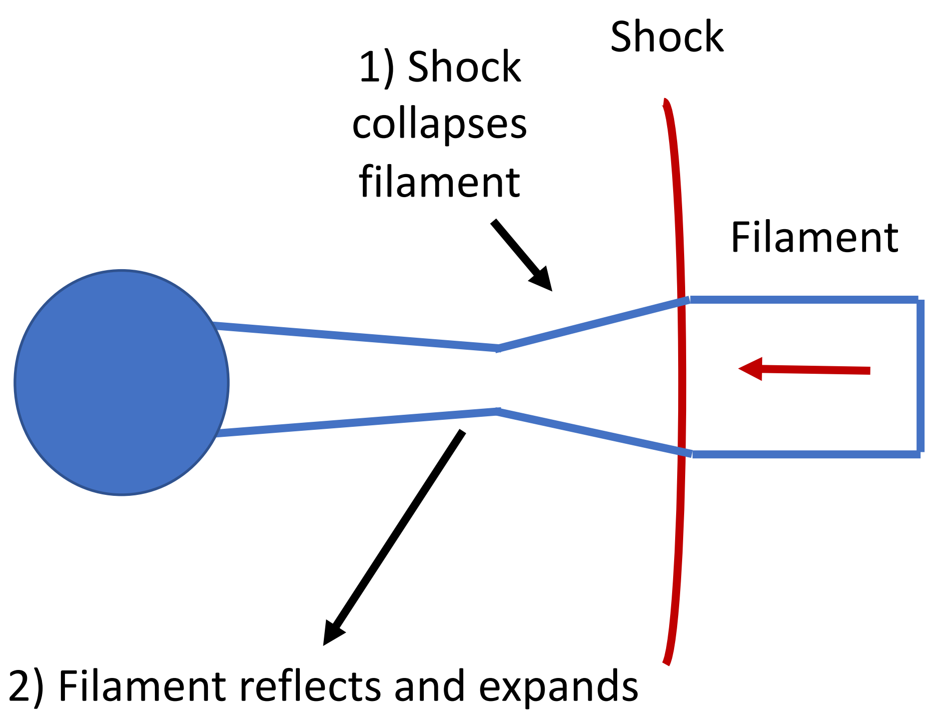
Two fluids flowing past one another, can shear and mix via KHI[8]:



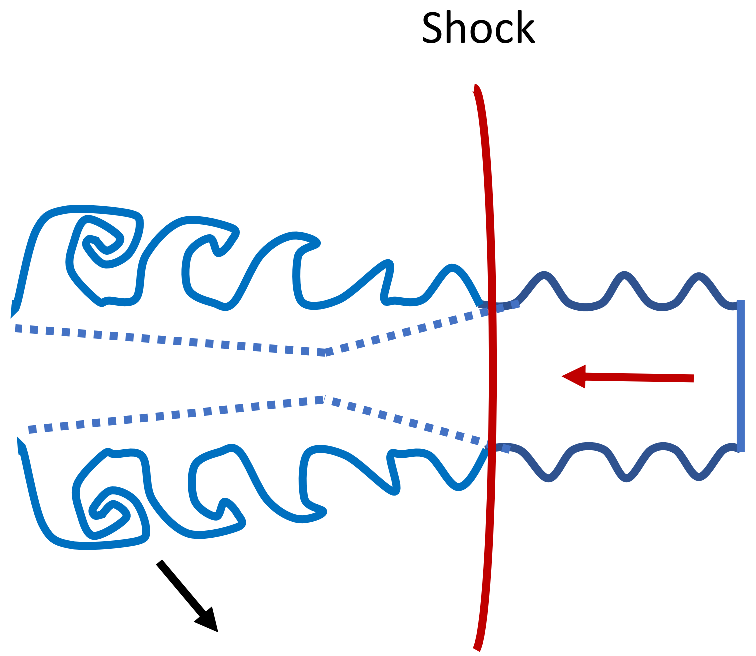
$$\gamma_c = -i\gamma_{ic}\frac{\sqrt{-1 - M_c^2 + \sqrt{1 + 4M_c^2}}}{M_c}, \quad M_c = \Delta u/(c_1 + c_2)$$

Growth dictated by densities and sound speeds of each material, and the convective Mach.

Then how does KHI change the picture?

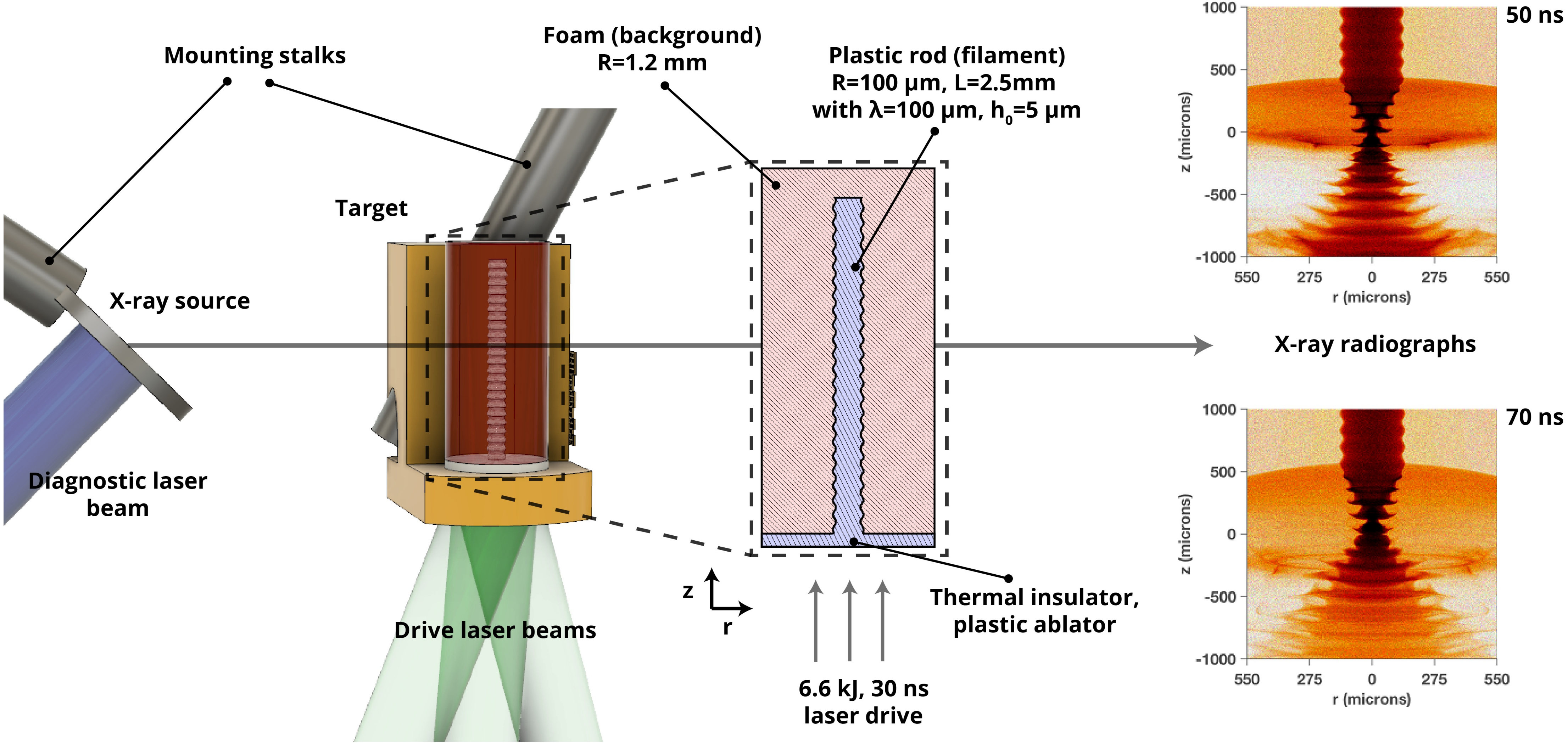


No KH = more concentrated, cold mass



KHI = mixing! Reduces cold mass delivered.

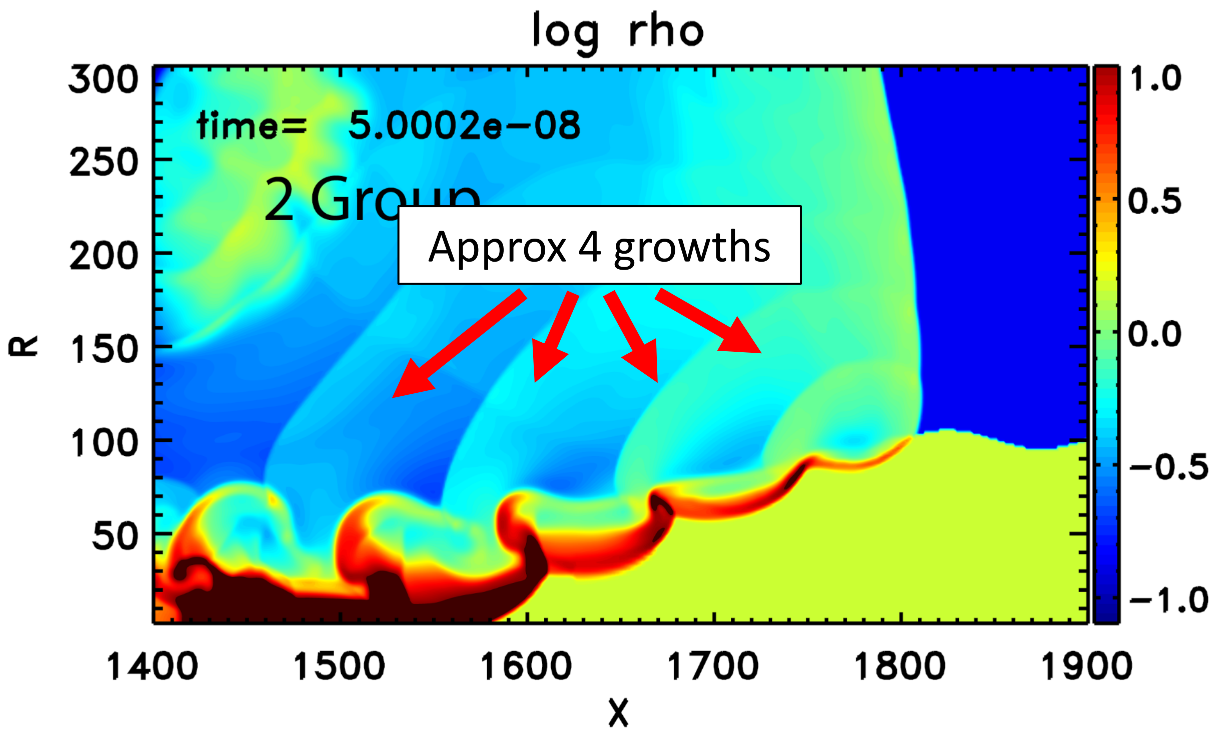
We designed an exp. to test KHI importance[11]



Exp. shock frame is the astrophysical analog

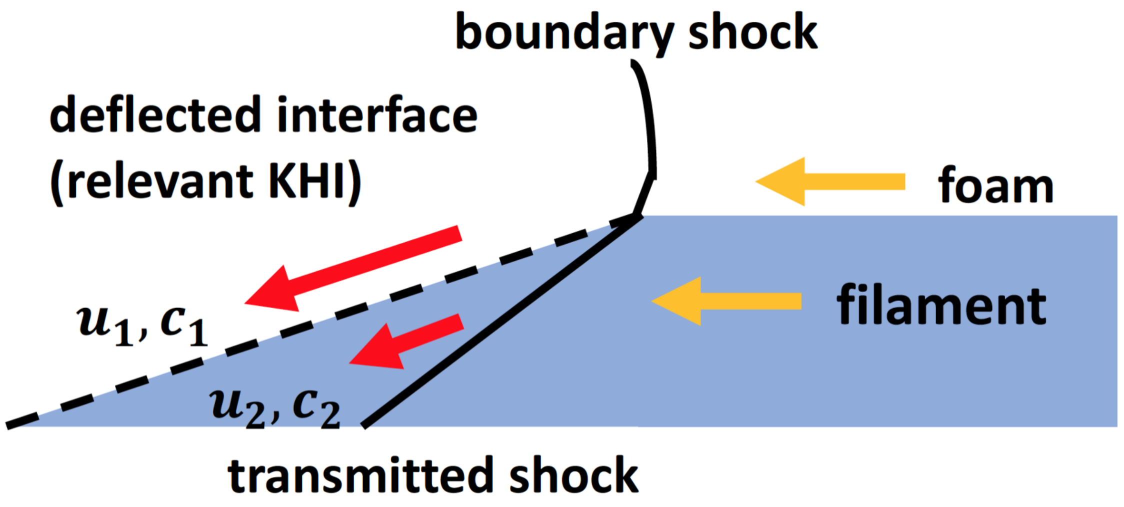
Simulations of the experiment (CRASH code)

In exp. shock travels

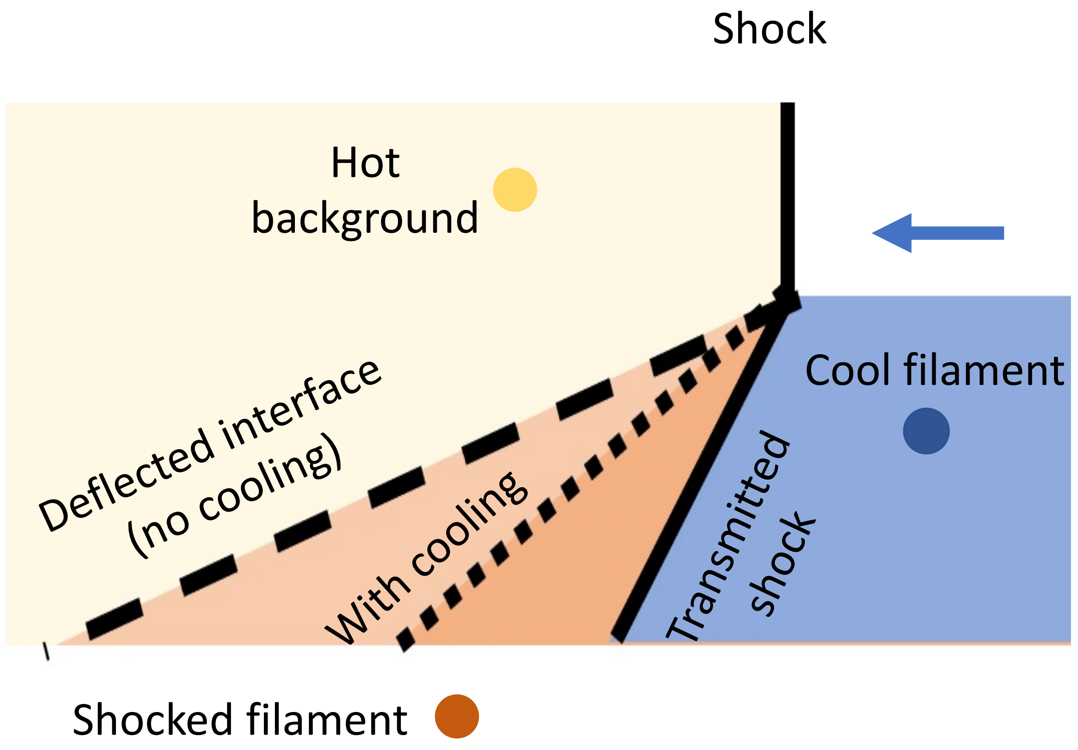


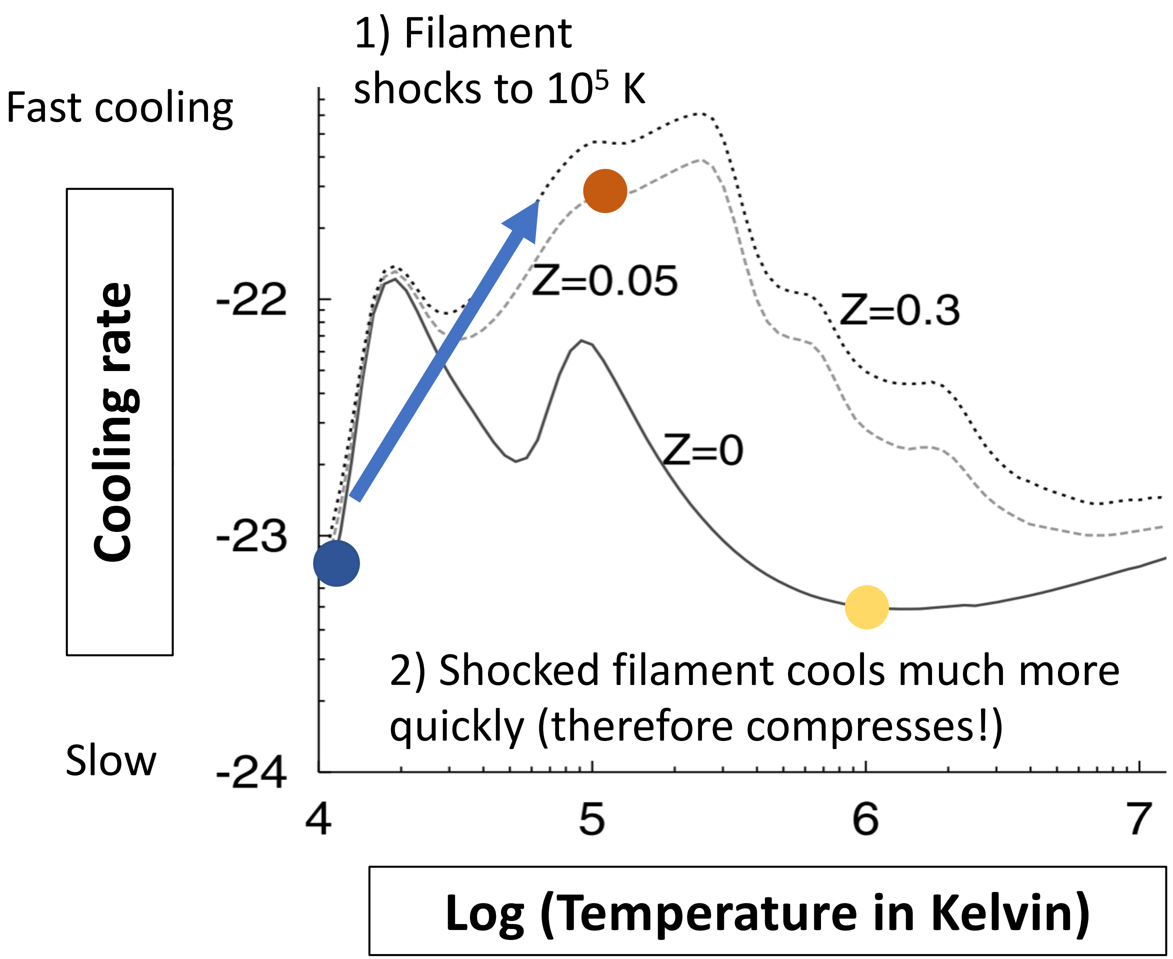
Astrophysical analog

In astro/stationary shock frame, filament travels



Radiative cooling affects KHI growth

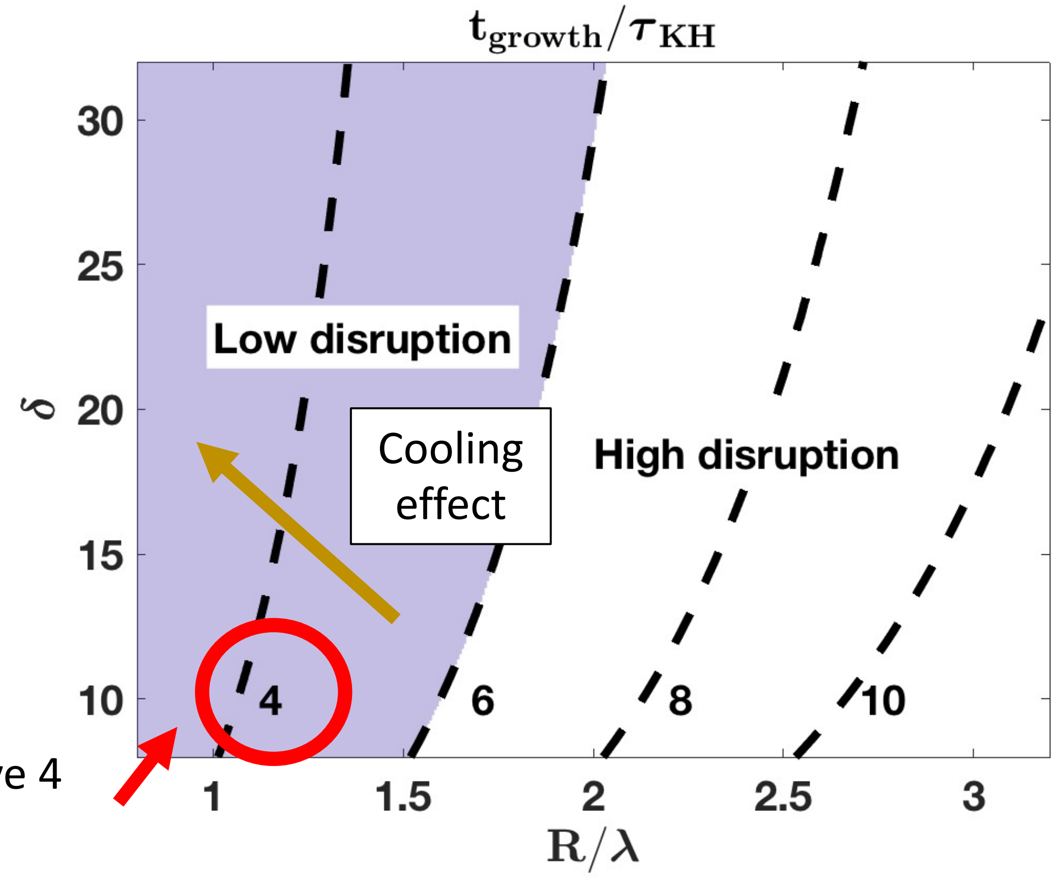




We assess the disruption of KHI on the filament

More time allowed for KHI to grow

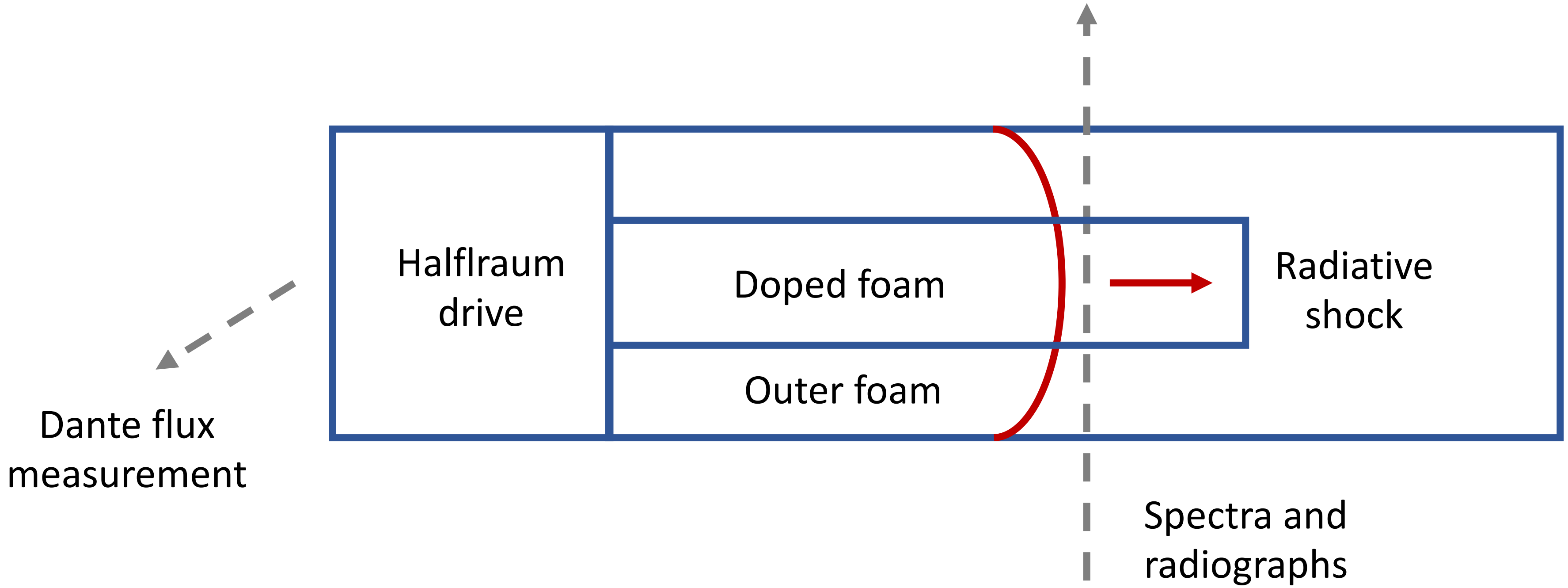
Filament becomes more dense than background



Experiment will observe 4 KHI growths periods

Adiabatic case is best case scenario for disruptive growth.

Rad. cooling helps stabilize - - filaments can deliver more concentrated mass!



The COAX experiment

An indirectly driven radiative shock platform with a spectral temperature diagnostic.

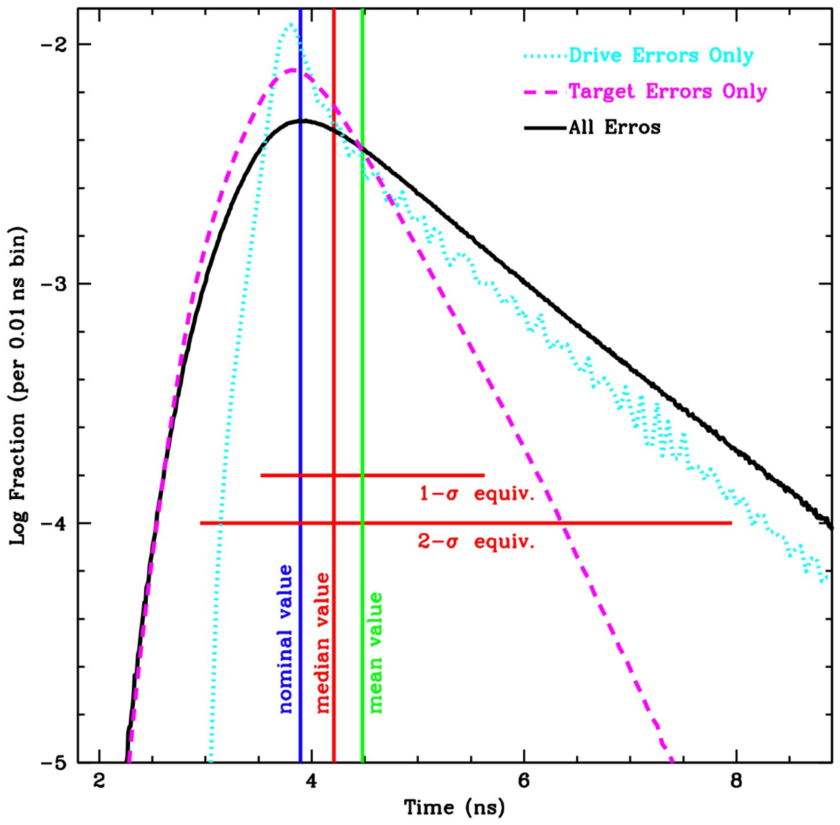
Can we simultaneously verify three diagnostics and maximize their data usage?

Is this a good platform for studying other physics, e.g. shock breakout?

The goal is to understand modeling uncertainties

- Uncertainty quantification (UQ) framework for Pleiades exp.[12]
- Showed that shock breakout measurement alone insufficient
- **Valid for all radiation flow exp.**
- **Key modeling uncertainties:**
  - **Drive modeling**
  - **Target (density, homogeneity)**
  - **Physics (EOS, transport, 3T, etc)**

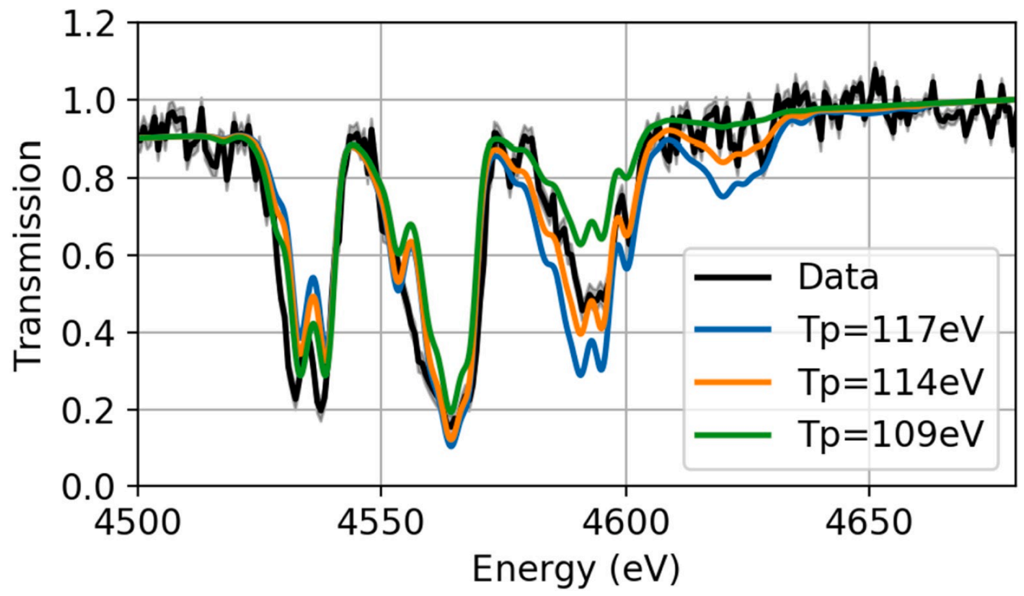
Fryer, 2016.



Breakout measurement time after uncertainty and error propagation. Combined errors lead to a 1-sigma error of +/- 1 ns!

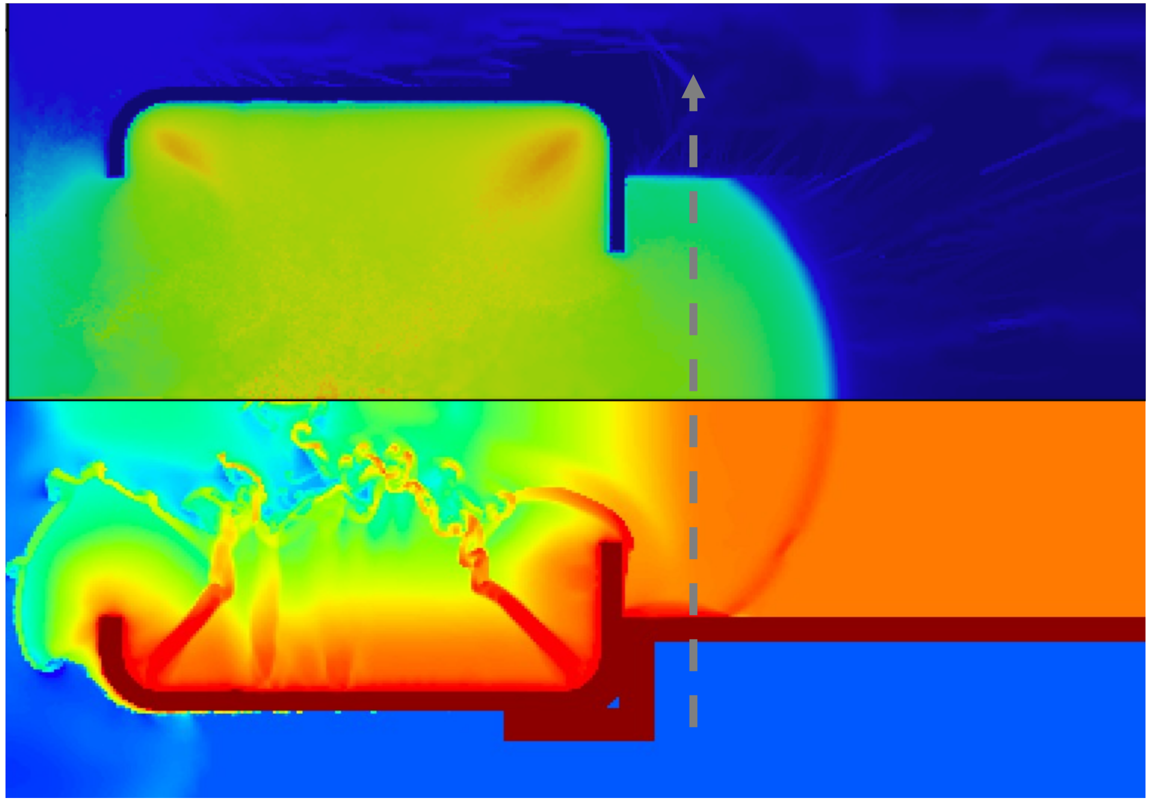
We've developed COAX for a spectral temperature diagnostic with similar UQ goals

- Similar modeling uncertainties as Pleiades
- **COAX has 3 diagnostics: Dante flux, spectroscopy, and radiography[13]**
- Initial estimates suggest an +/- 8 eV error in temperature estimation from spectra[16]

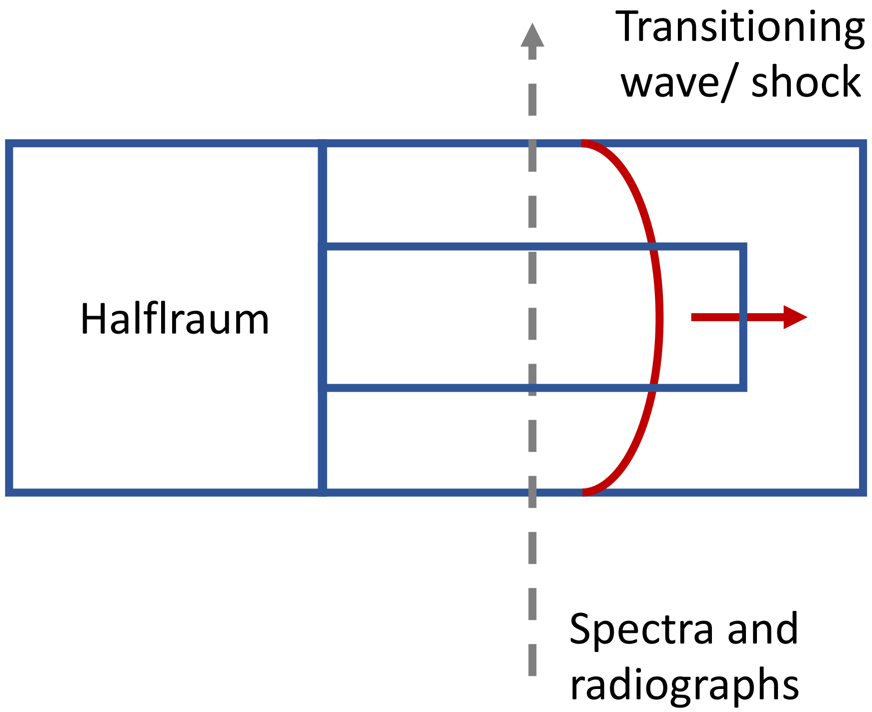


We model COAX with LANL's Cassio code

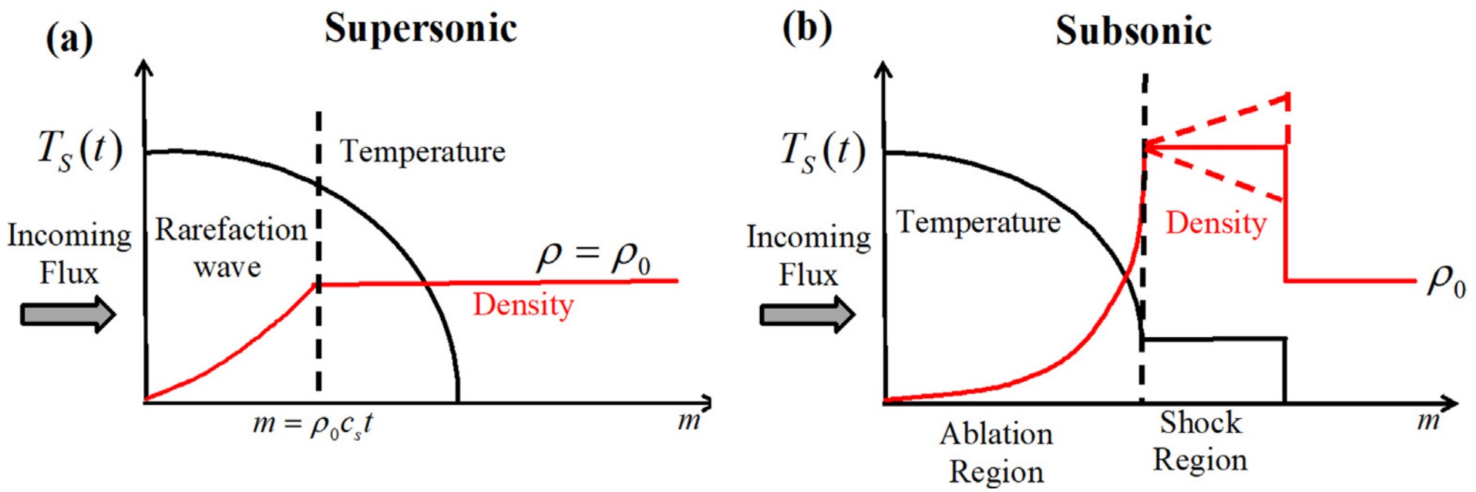
Temperature (120 eV wave)



Density (70 mg/cm^3 foam)



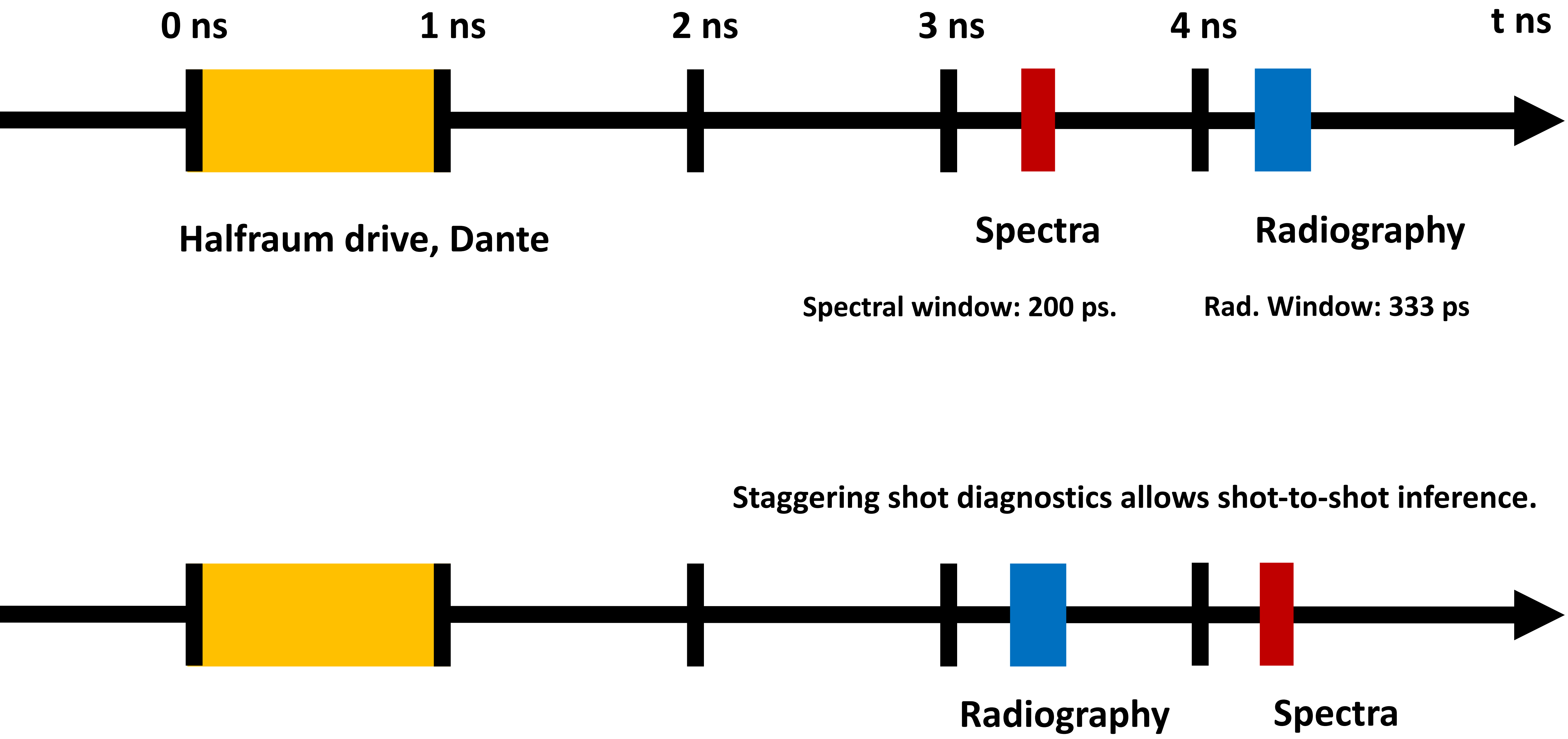
COAX: transitioning radiation waves



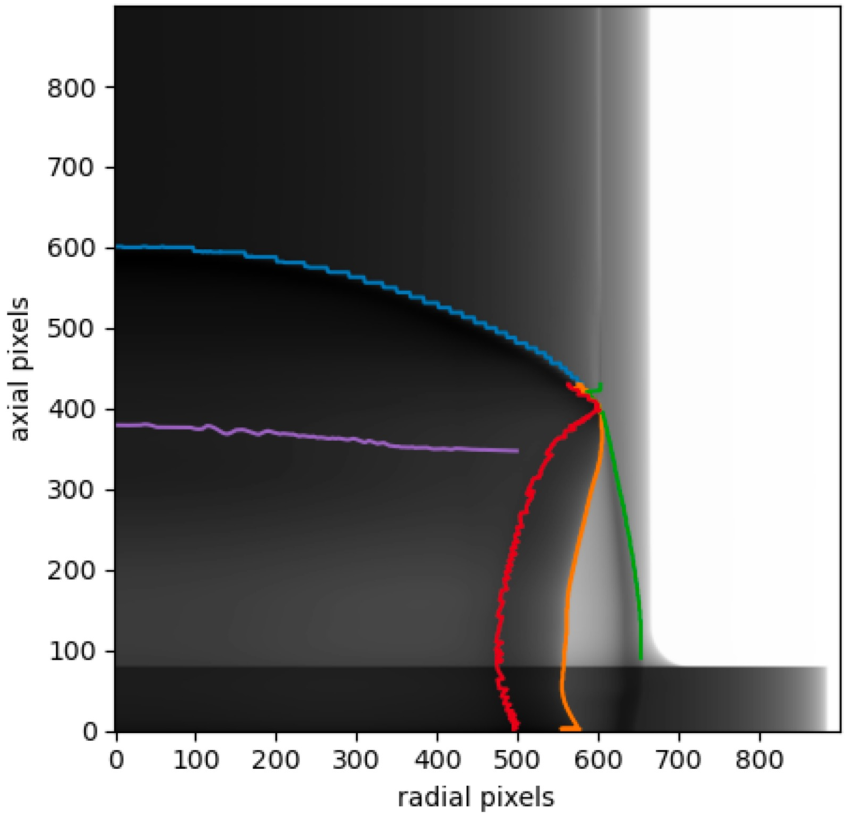
A temperature source travels as a heat (radiation) wave through an initially cold, constant density field. Supersonic case, no material fluxes:

$$\rho c_V \frac{\partial T}{\partial t} = -\boldsymbol{\nabla} \cdot \frac{4\sigma}{3\rho\kappa} \boldsymbol{\nabla} T^4$$

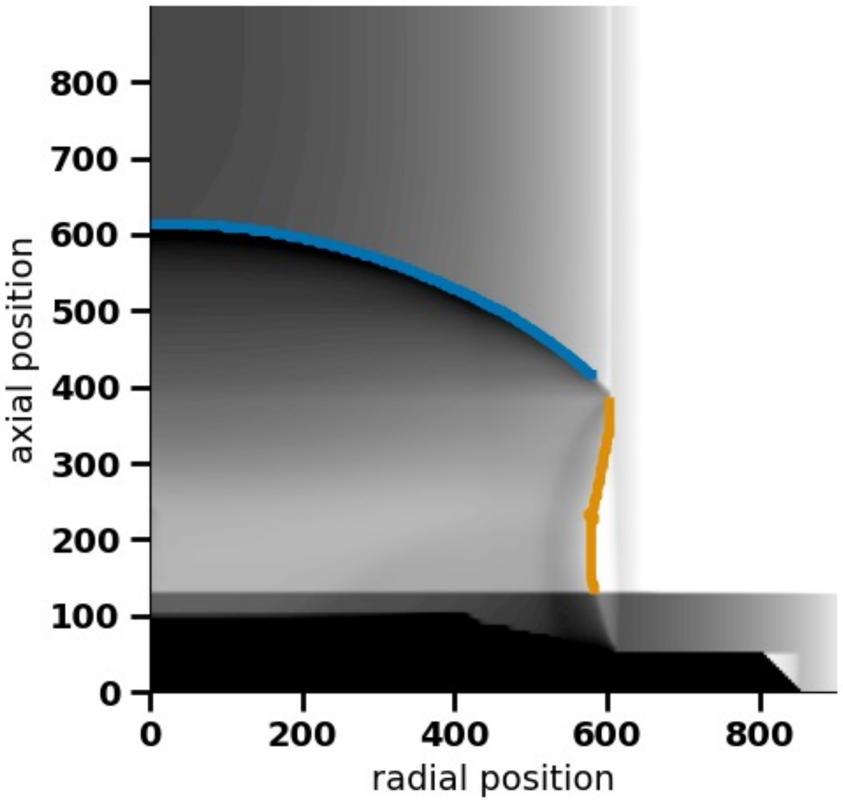
COAX radiation waves start supersonic (a), then become subsonic and form a shock (b).


0 ns
1 ns
2 ns
3 ns
4 ns
t ns
Halfraum drive, Dante
Spectra
Radiography
Spectral window: 200 ps.
Rad. Window: 333 ps
Staggering shot diagnostics allows shot-to-shot inference.
Radiography
Spectra

We first match features in radiography

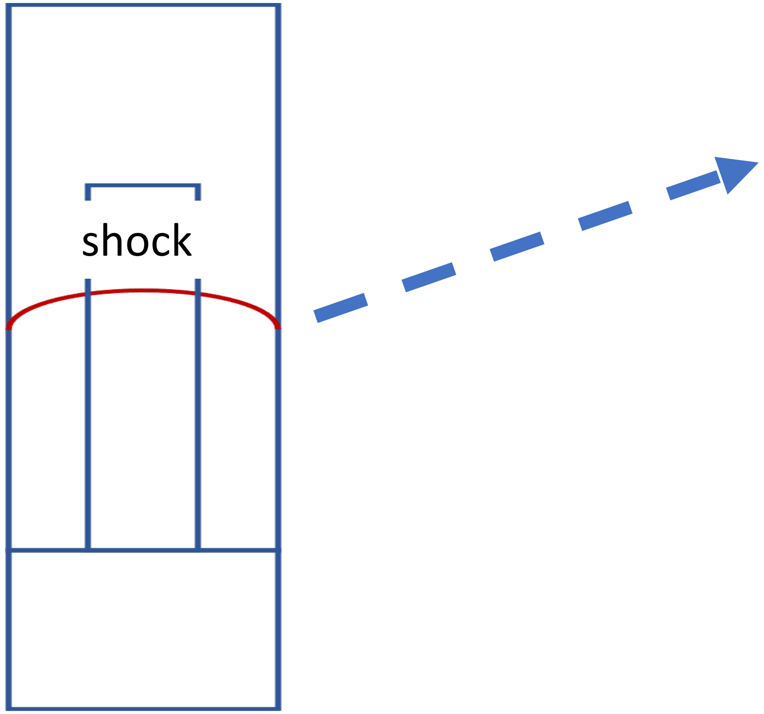


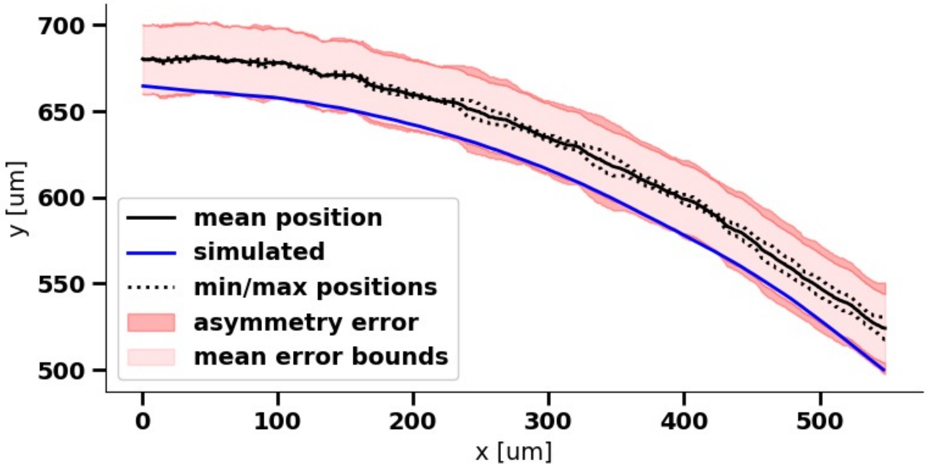
Detectable and prominent features with Canny edge detection. Wealth of information!



Selected features for analysis: the primary shock and reflected wall shock.

Minimizing errors in curvature constrains density



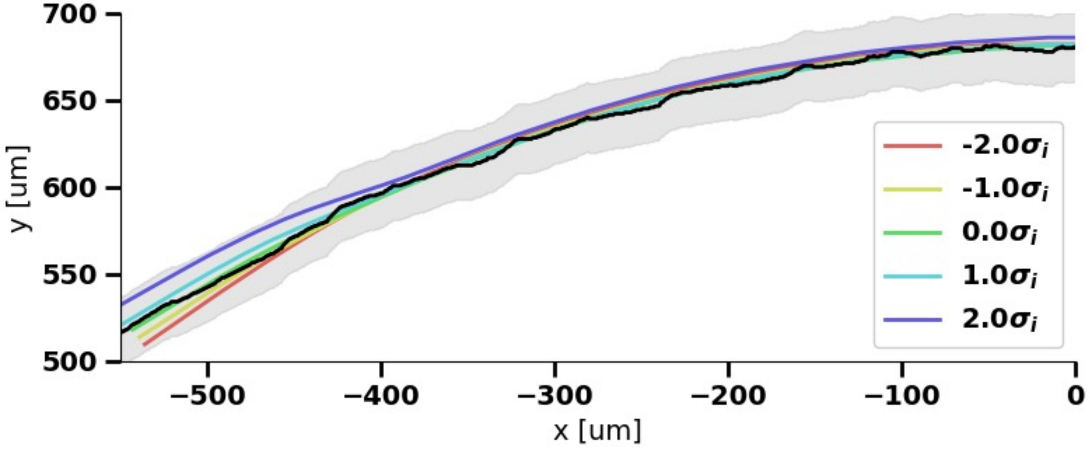


If our modeling choices are correct, we systematically predict higher outer foam densities.

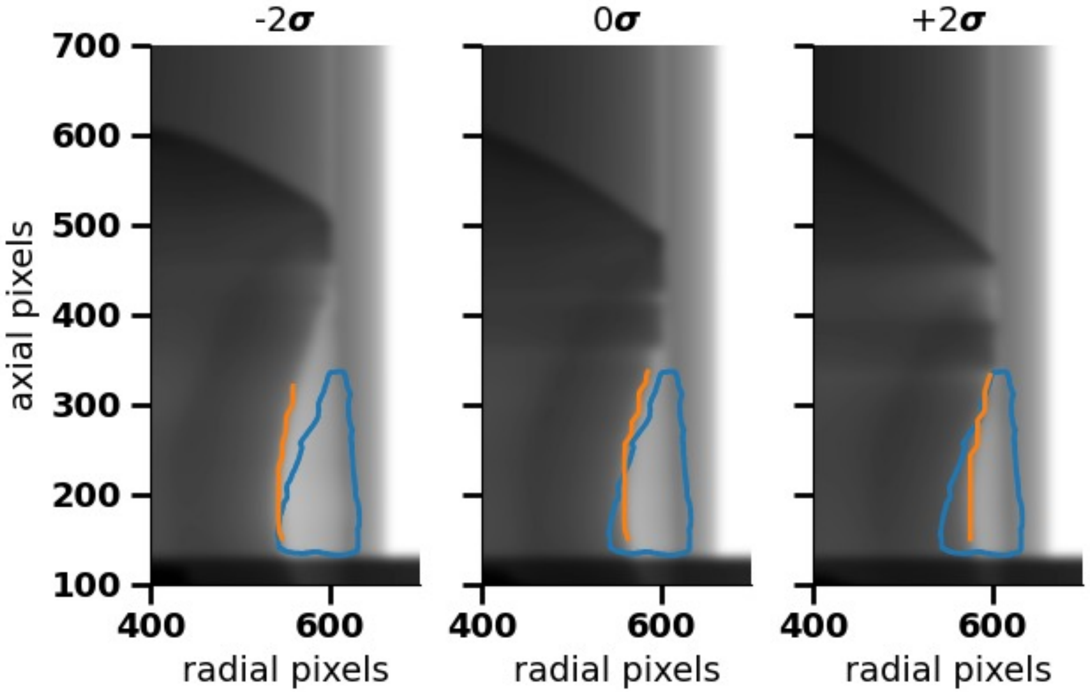
Shot	Shock position (μm)	Outer density range
86456	680	0 to 1 σ_o
86459	844	1 to 2 σ_o
86462*	503.5	-2 to 2 σ_o

We can look at wall shocks and outer foam features to constrain density/drive

Inner and outer foam density uncertainties lead to changing drive (laser power) settings too! More power needed to drive a stronger shock to match same position.

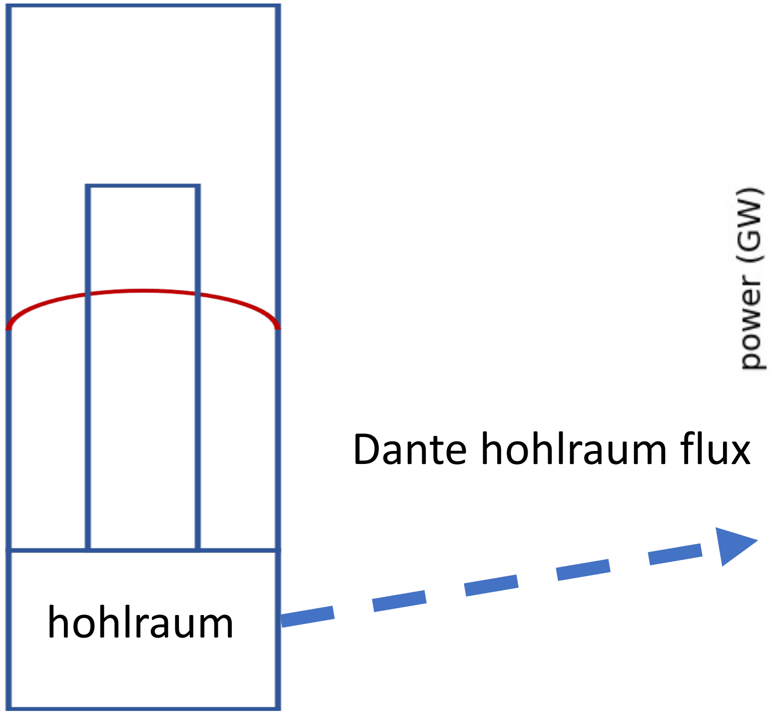


We can produce nearly identical shock structure in the inner foam by changing drive settings. But big difference in spectra!

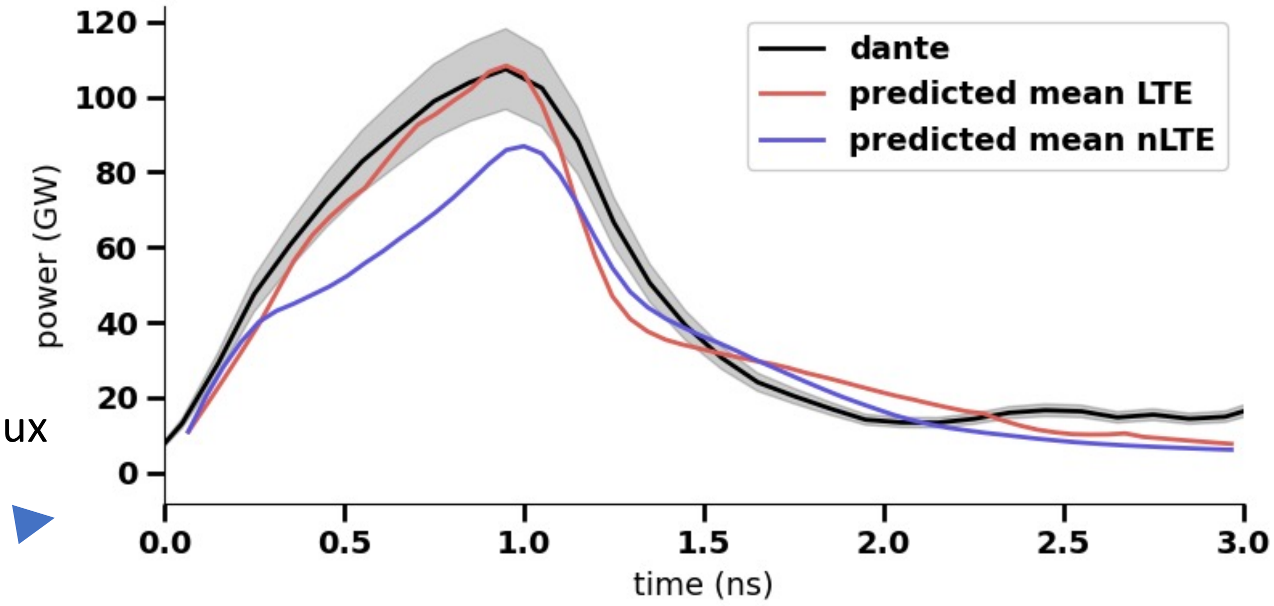


Matching wall shocks reveal a stronger constrain on outer foam density.

Drive fluxes provide a qualitative comparison of simulated hohlraum drive

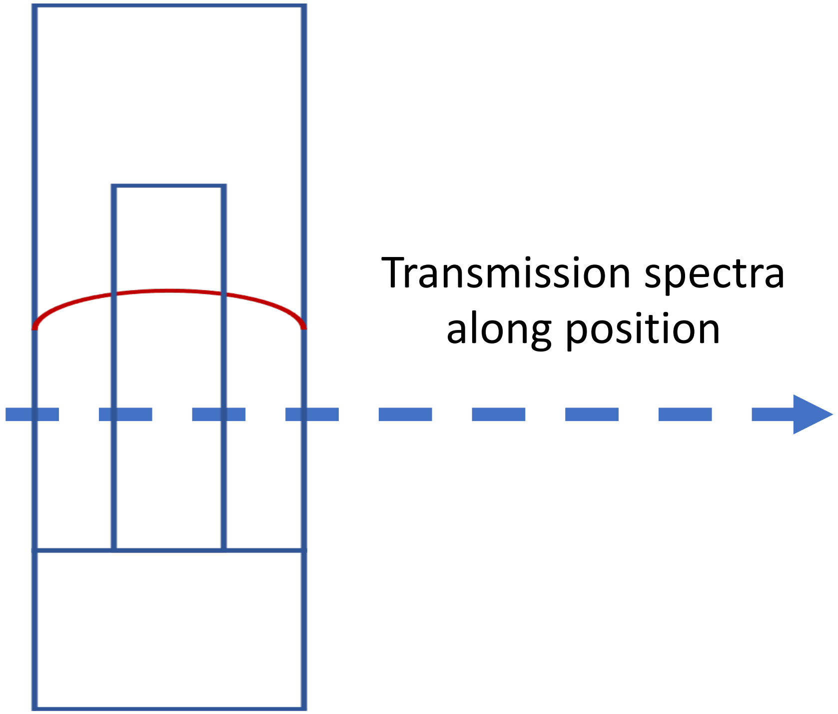


Dante hohlraum flux



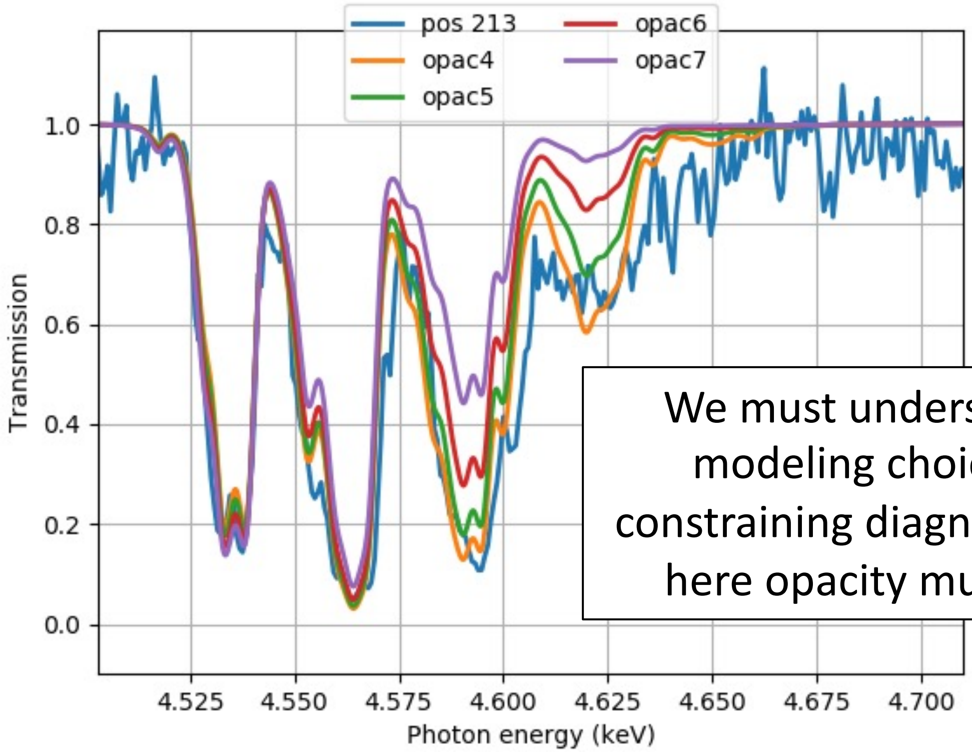
Models employing LTE physics tend to approximate flux well, while nLTE models may underpredict.

Once drive, density choices selected, we turn to spectral comparison



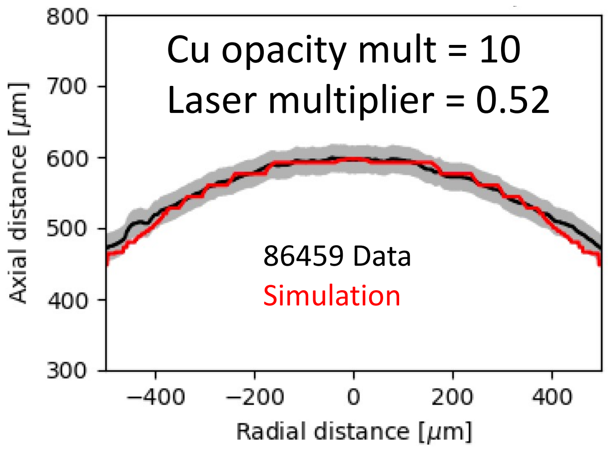
Transmission spectra
along position

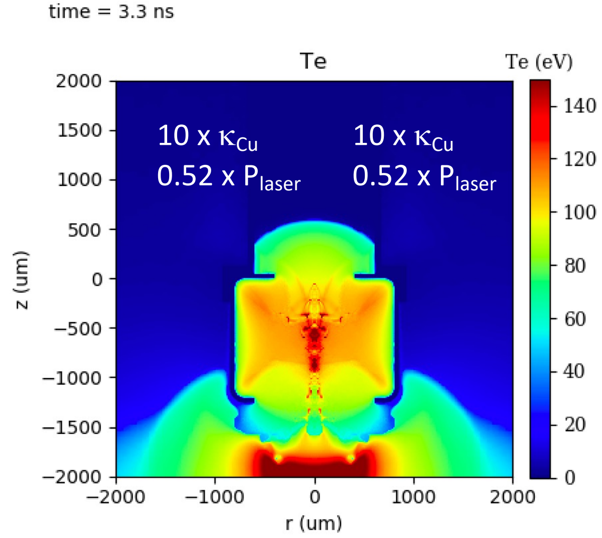
Hohlraum opacity multipliers of 4 to 7.



We must understand all modeling choices for constraining diagnostics, e.g. here opacity multipliers

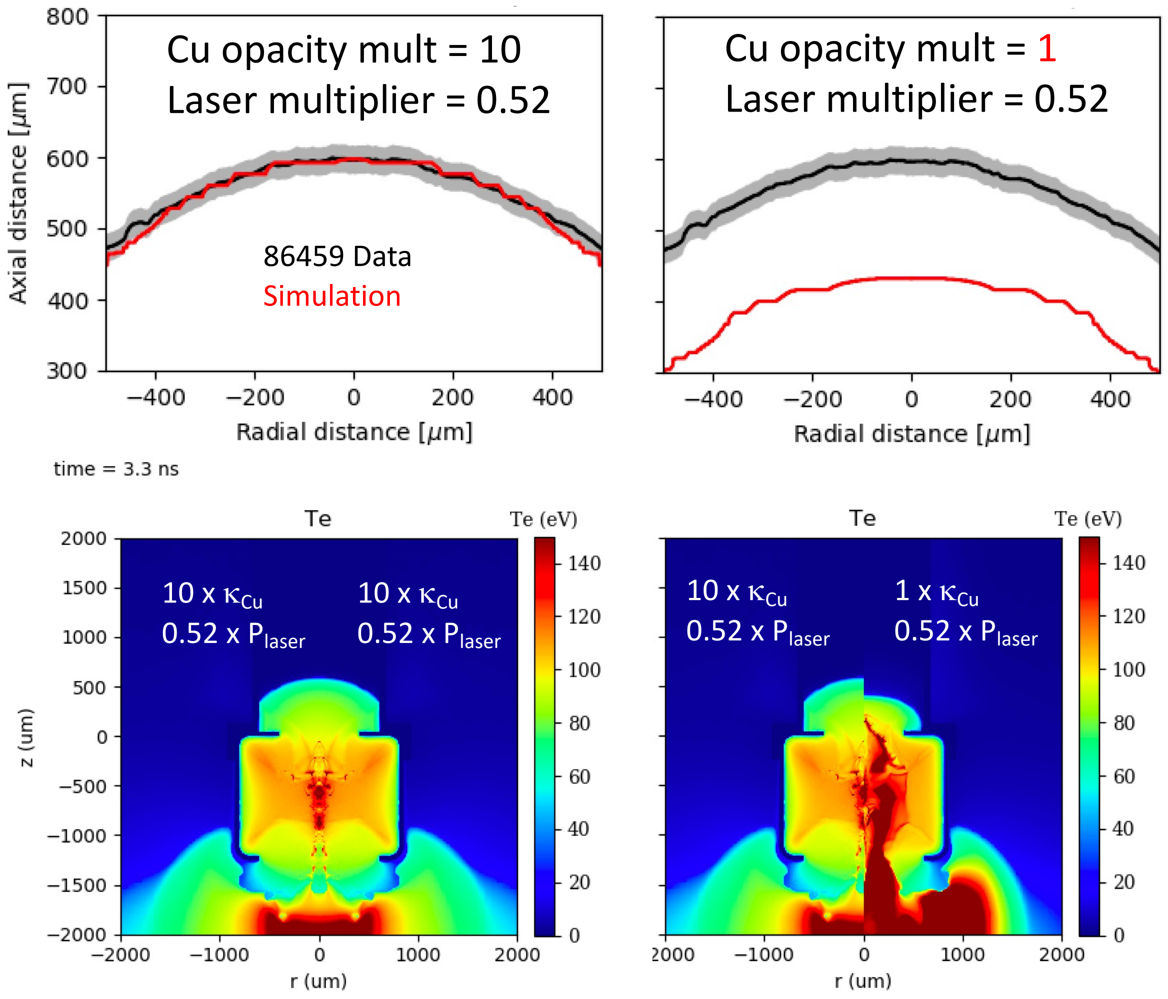
Simulations with enhanced Cu opacities & reduced laser power can match shock positions



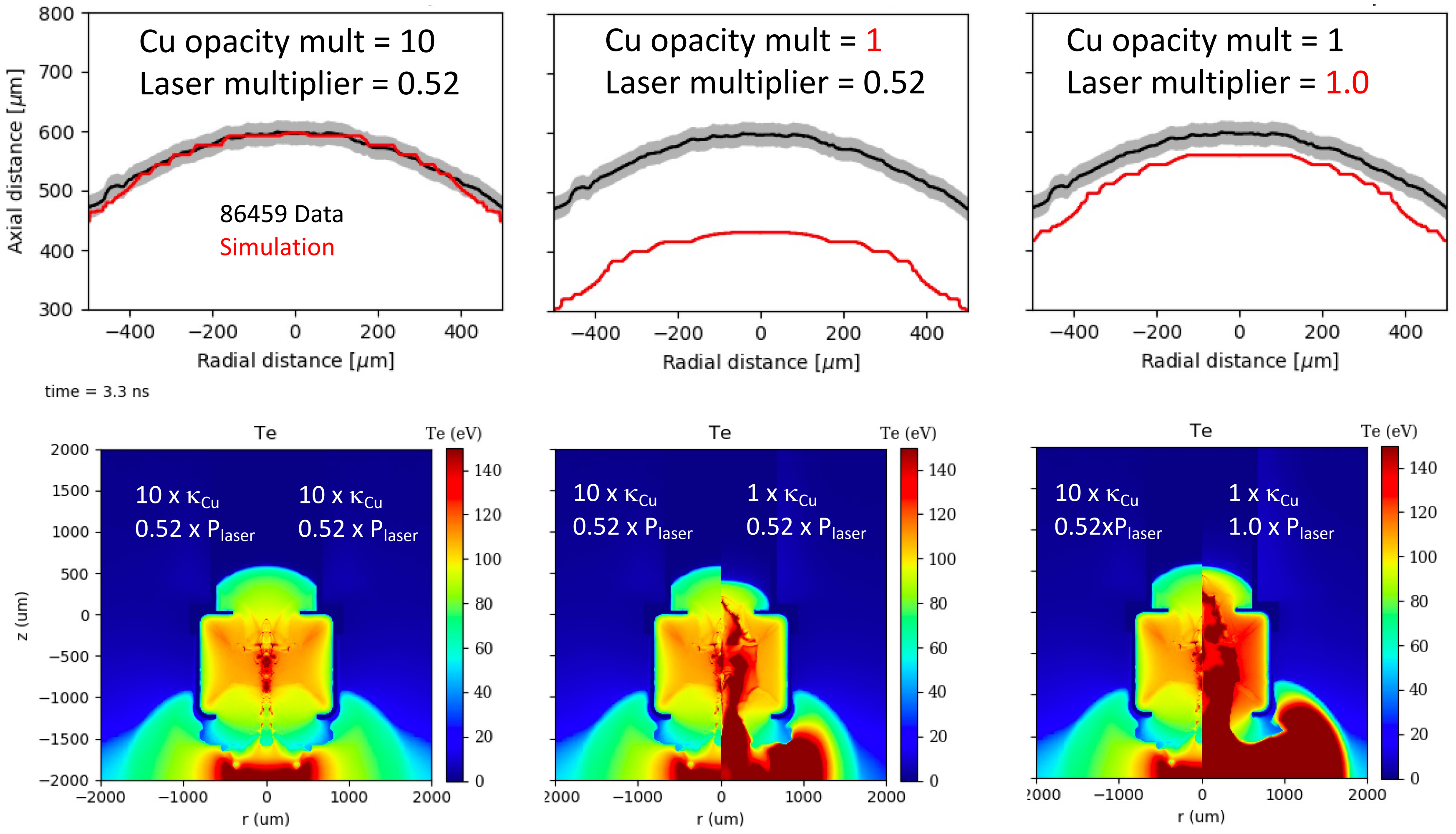


H. Robey, 2021.

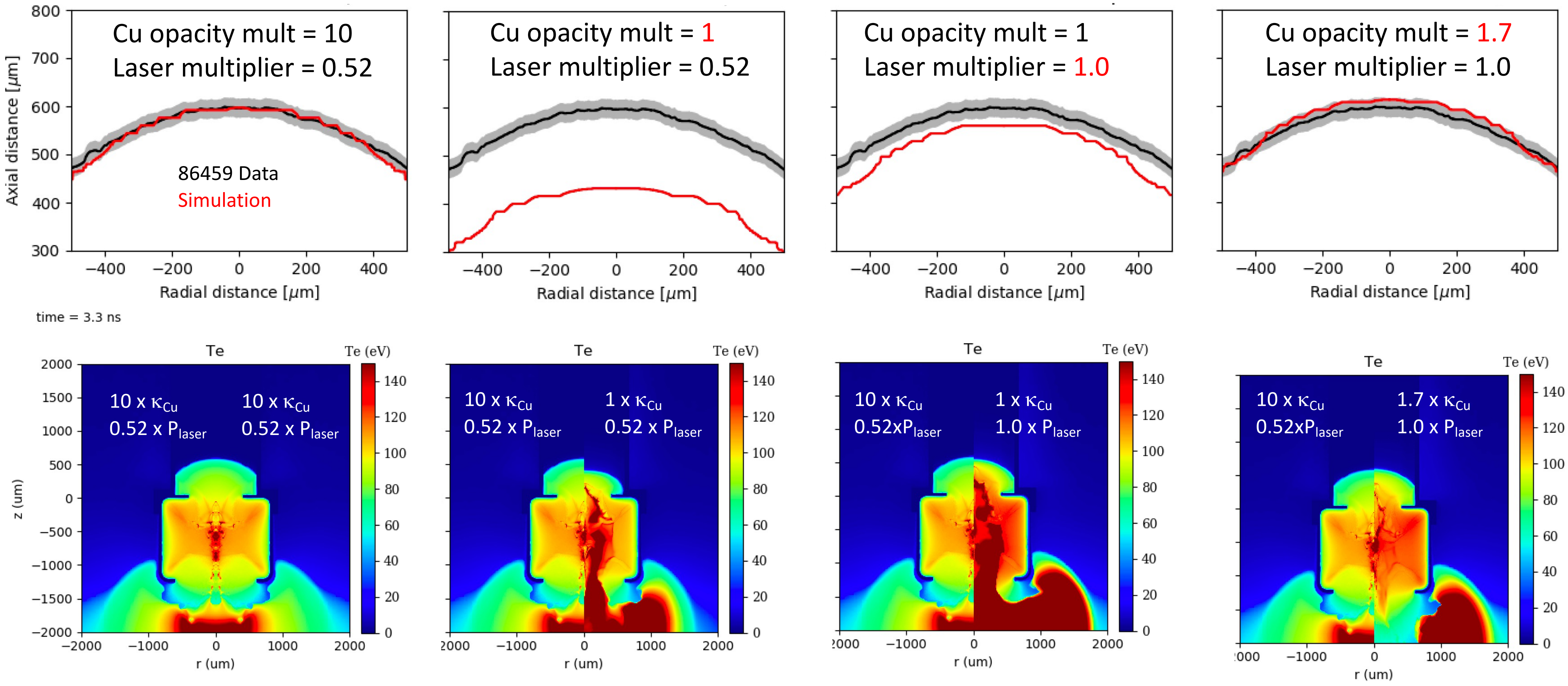
We can modify these Cu opacities and find necessary laser power multipliers



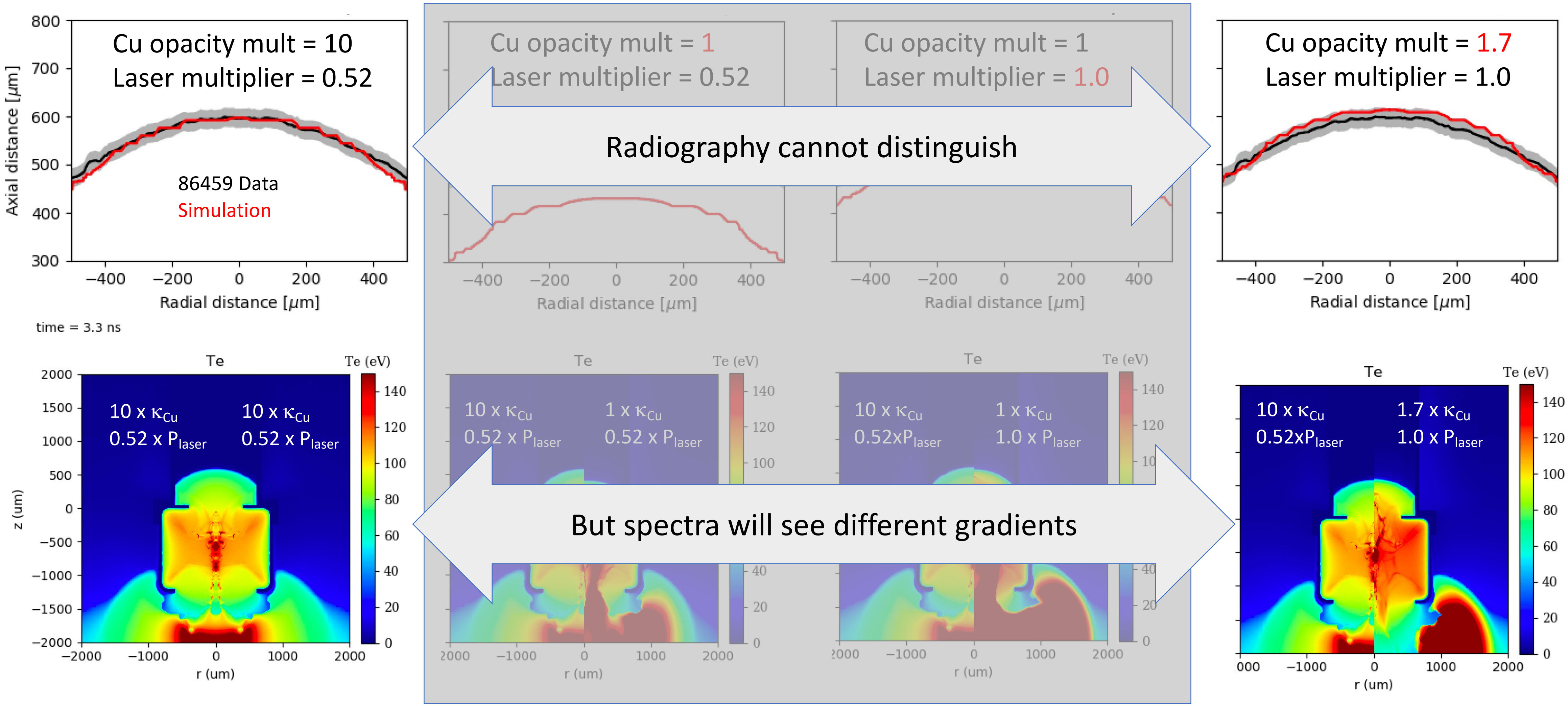
With the Cu opacity at its nominal value, the laser drive can now be increased back to its nominal delivered value



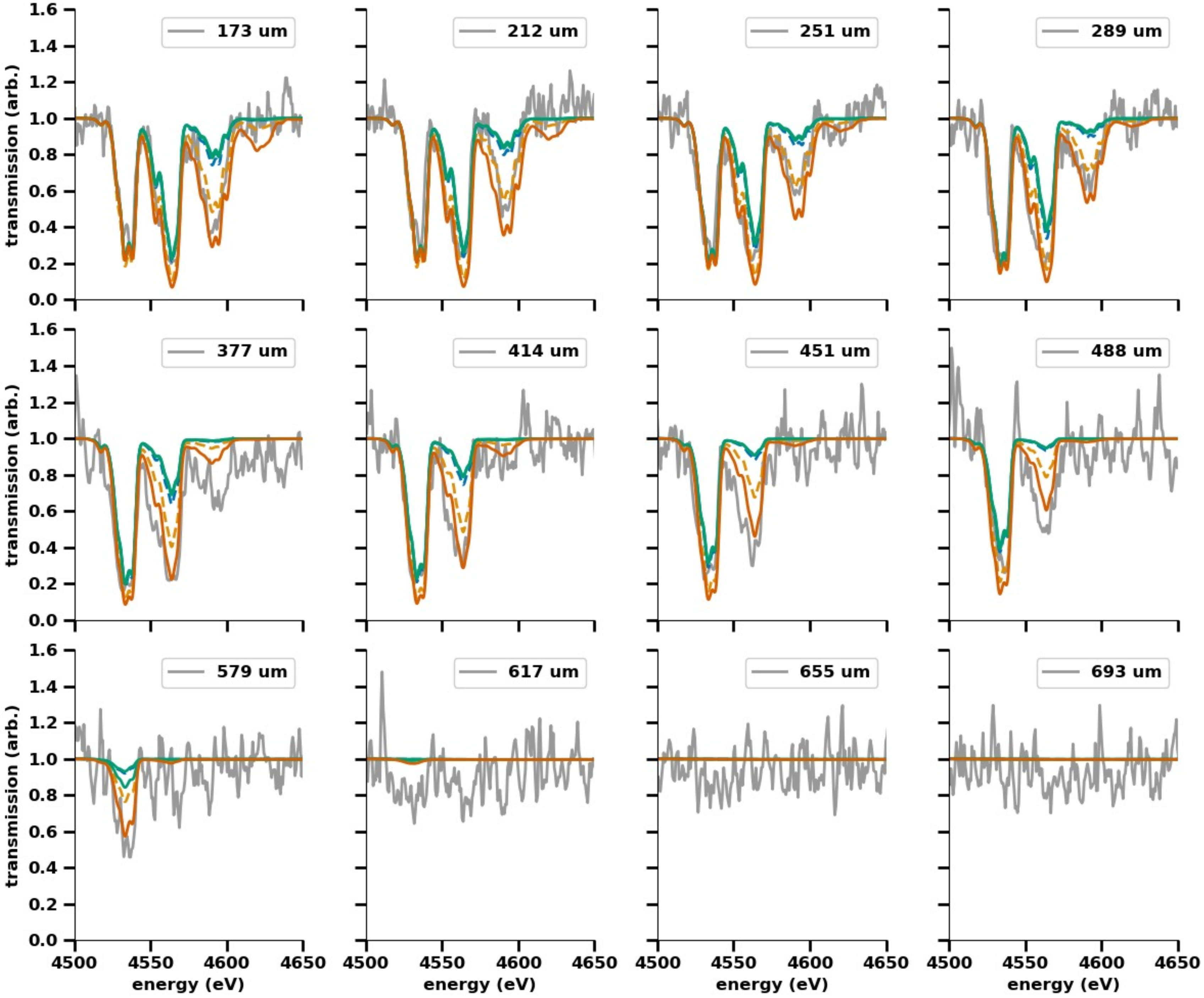
A Cu opacity multiplier of 1.7 and the full nominal laser power agree with the measured shock position



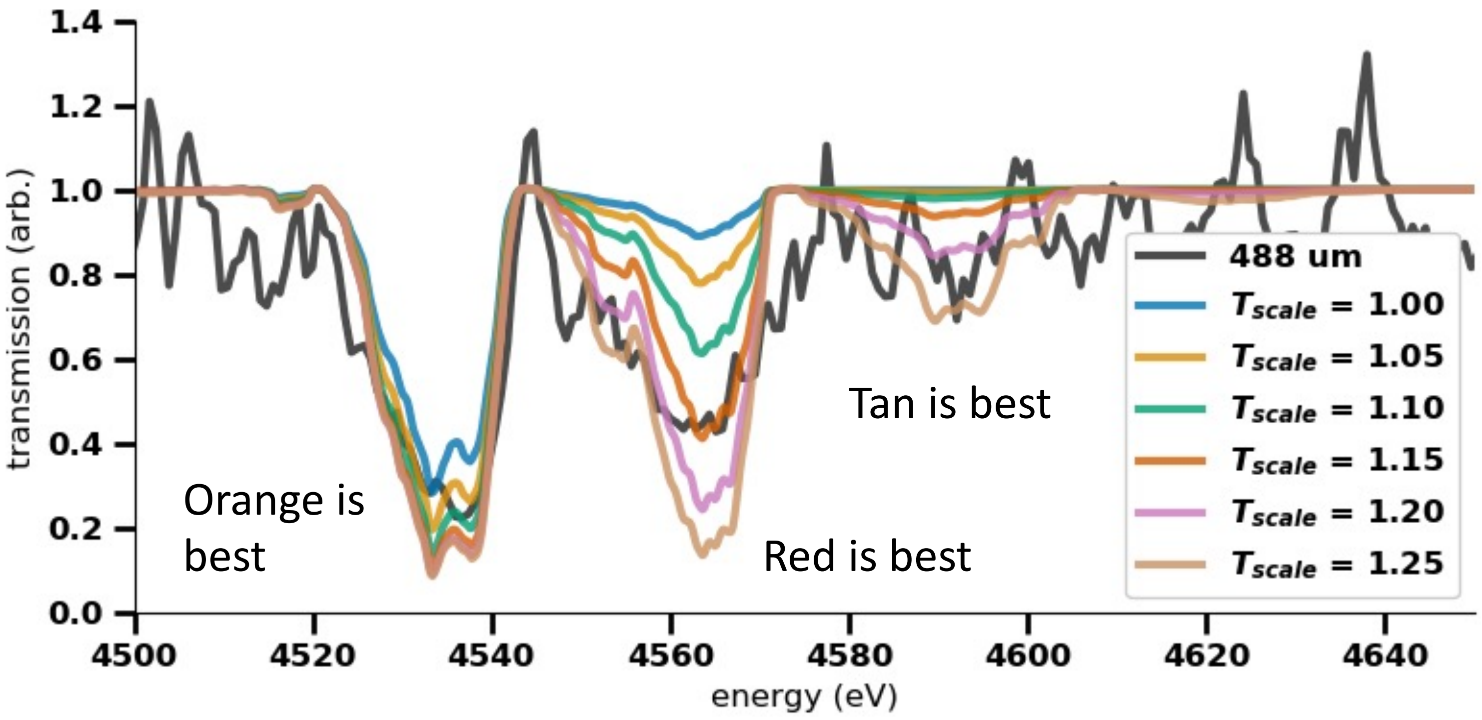
Degenerate solutions may be eliminated with multiple diagnostic constraints



A look at LTE vs NLTE models for all lineouts of shot 86456

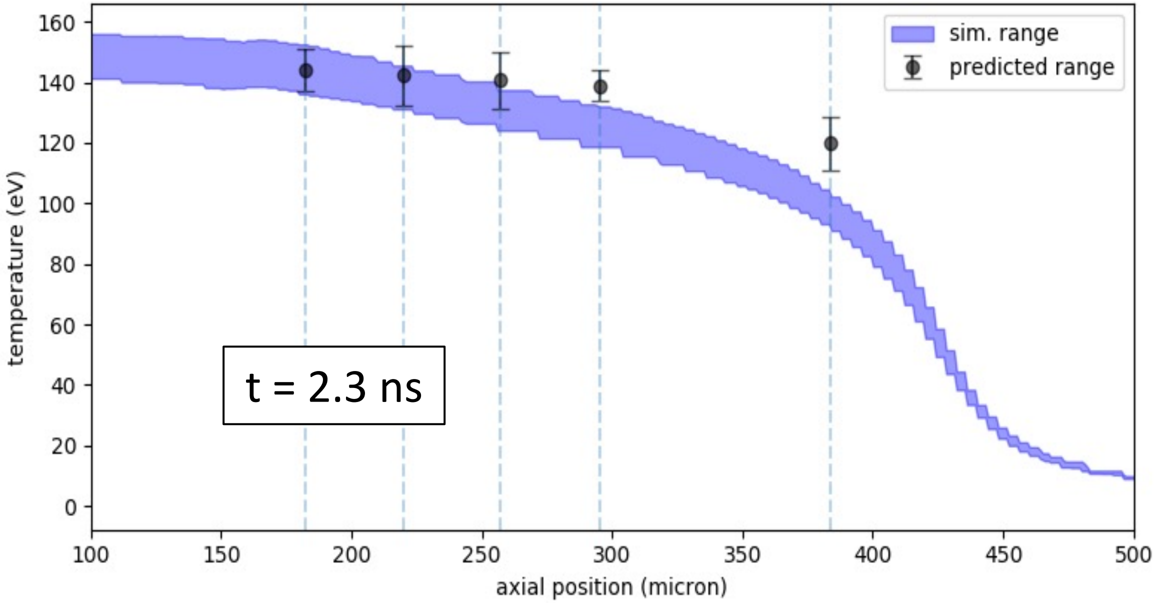


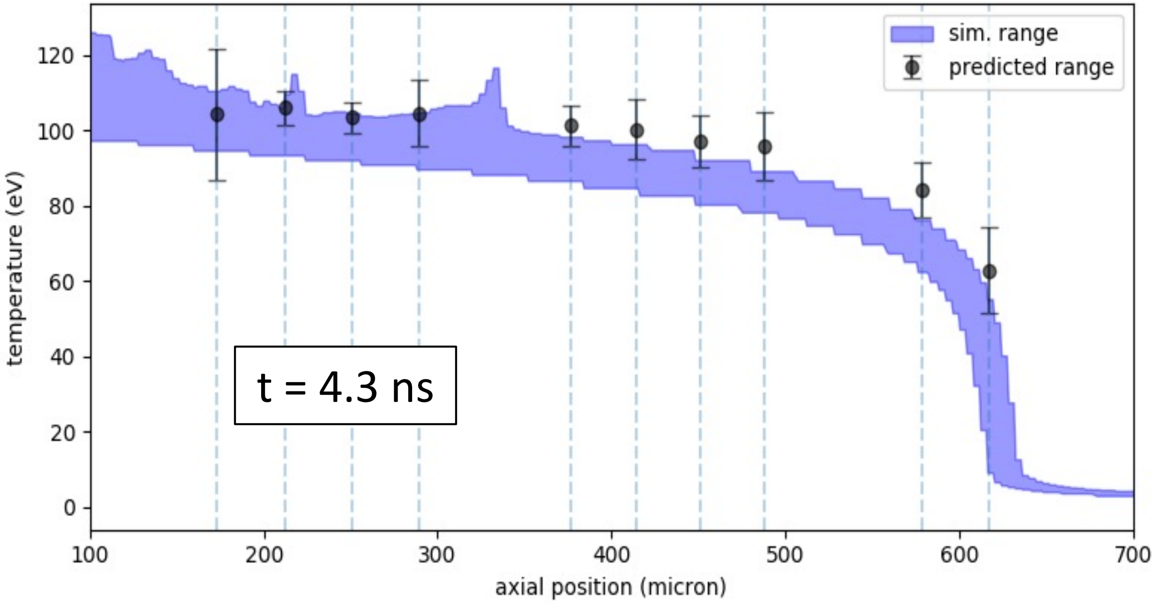
We can scale the temperature profile to seek better fits and infer “correct” T



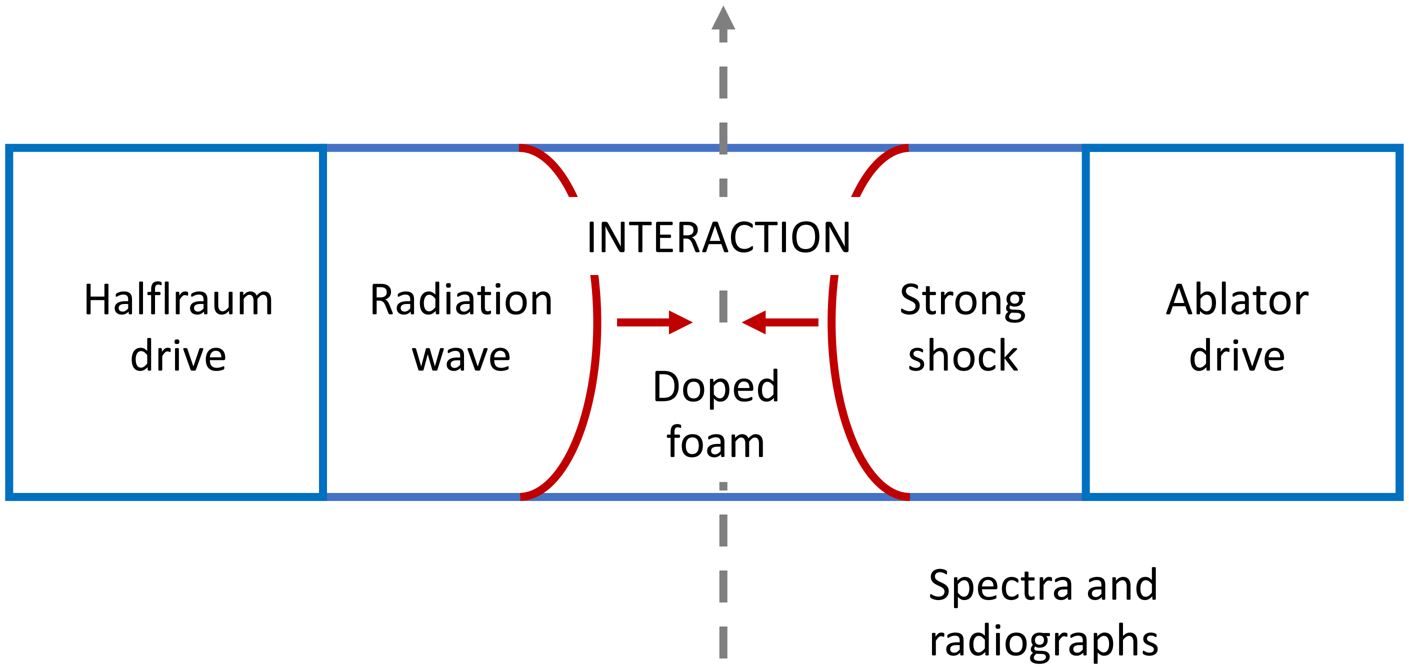
The fact that different temperature scalings fit best for different features indicates a large profile (density, temperature, concentration, etc.) uncertainty!

Temperature reconstruction of all models reveals some limitations[14]





Both simulation sets underpredict the spectral temperature by a few eV on average, at most 20 eV in the earlies case.

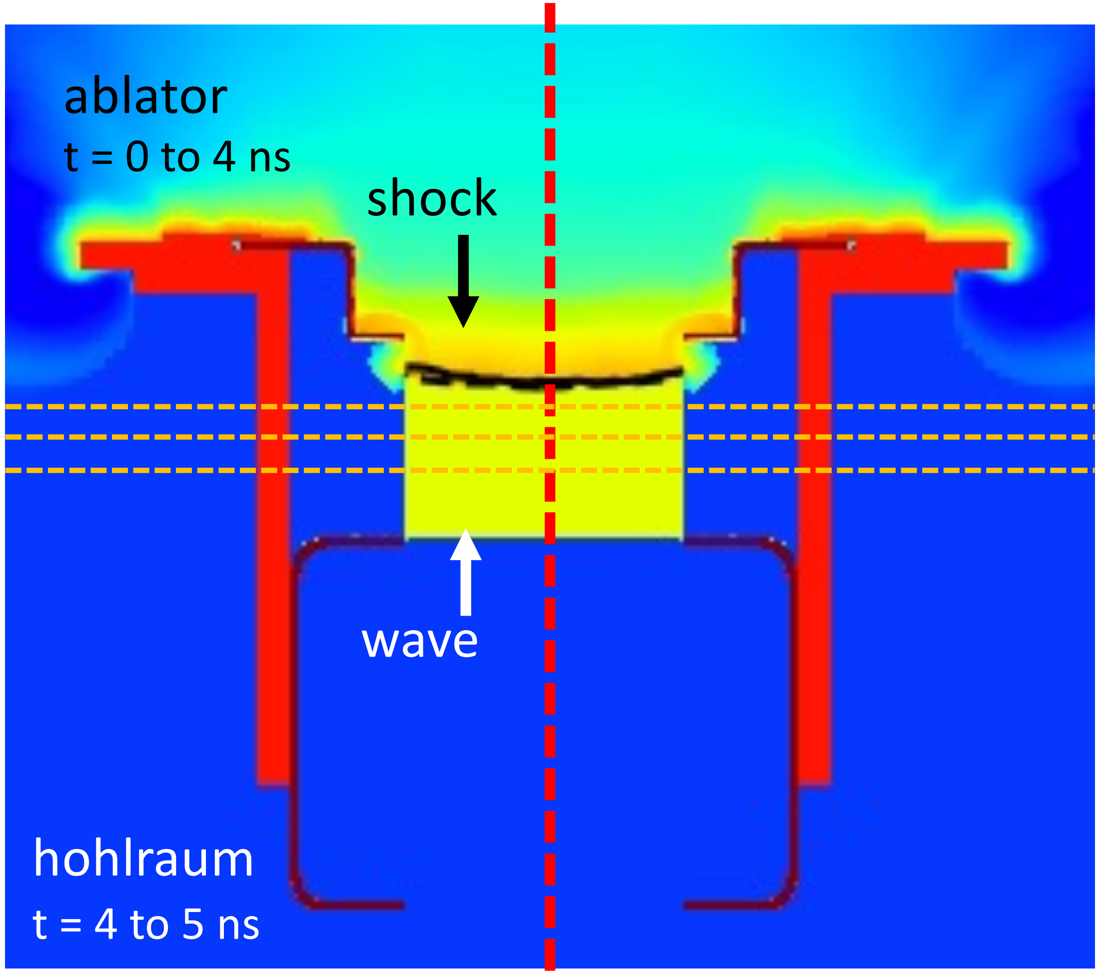


The Radishock experiment

Can we build from COAX to investigate the head-on collision of a radiation wave and shock?

Can we develop and verify theory for this phenomenon?

Cassio, 2D, axisymmetric simulations of Radishock[15]



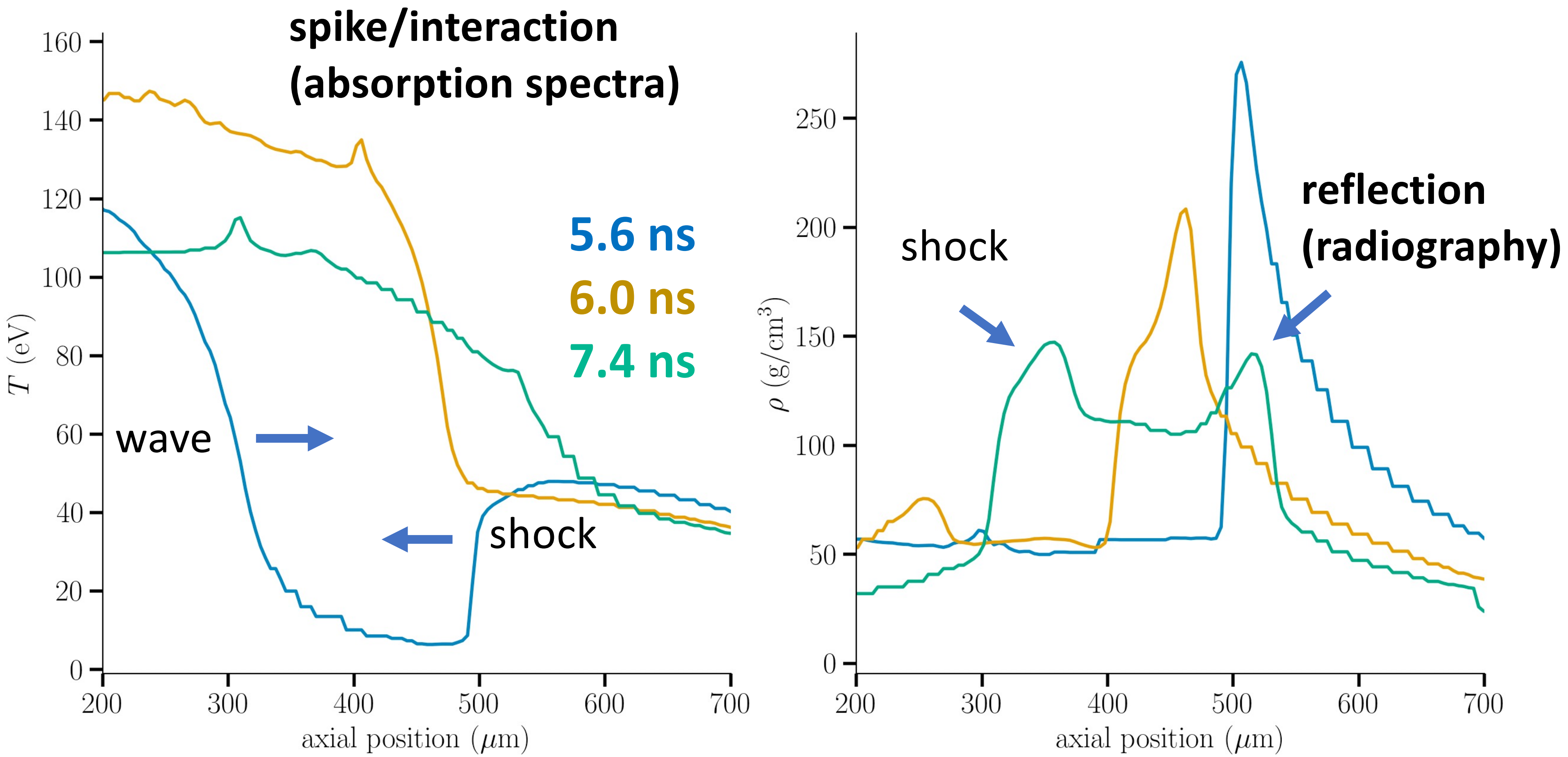
This line is the **axial center.**

We will look at 1D density, temperature data along this center.

These are example lines of sight for radiographs and spectra. They are called **lineouts and represent integrations through 3D geometry.**

The interaction of the shock and radiation wave creates a temperature spike

Note: 1D axial data of 2D simulations

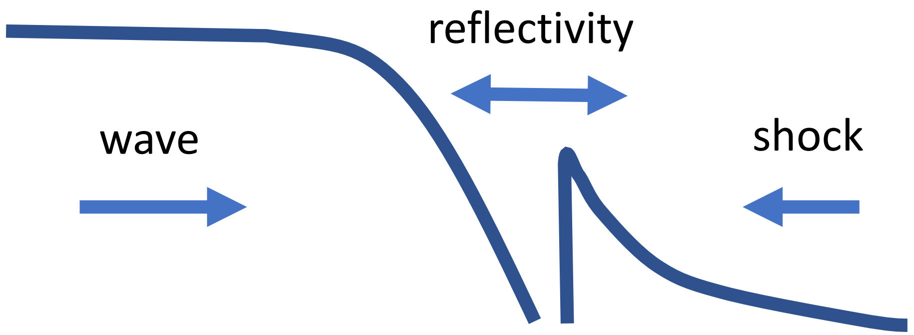


Can model a supersonic Marshak wave interacting with a moving, reflective boundary

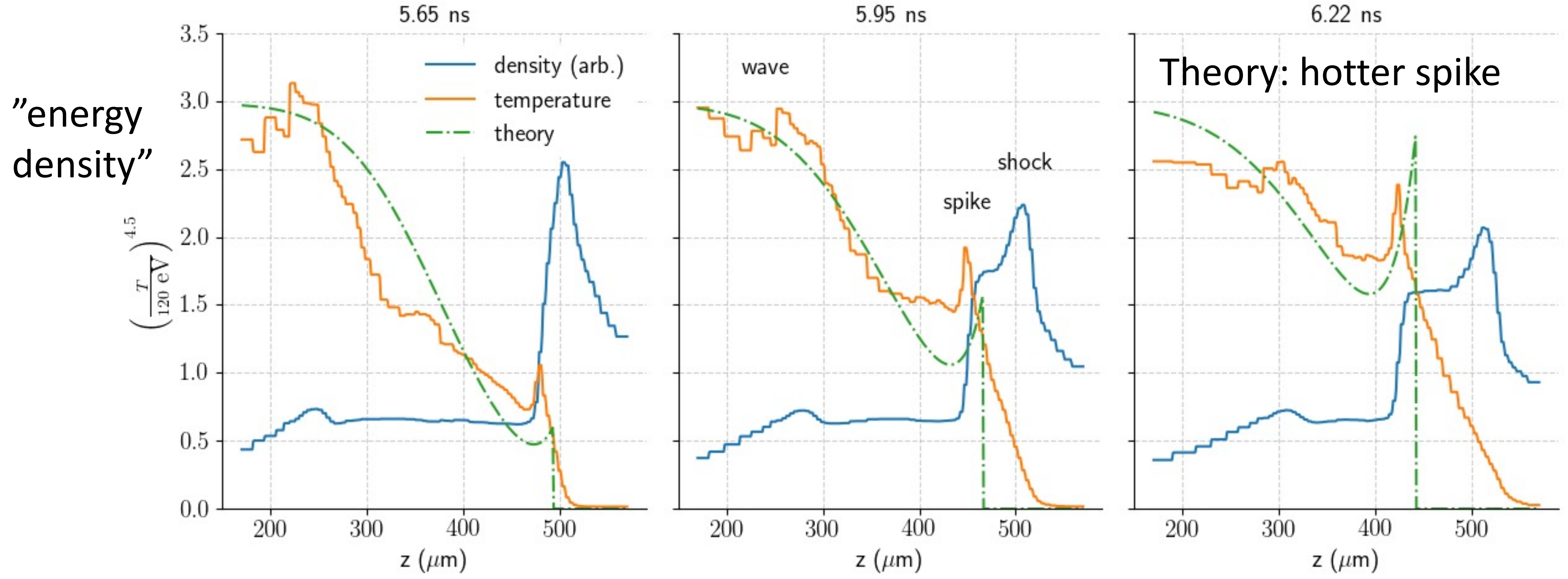
- Linearize the radiation-diffusion equation in opacity

$$\frac{\partial T}{\partial t} = \nabla \frac{1}{\kappa} \nabla T, \ \kappa \sim T^{-7/2}$$

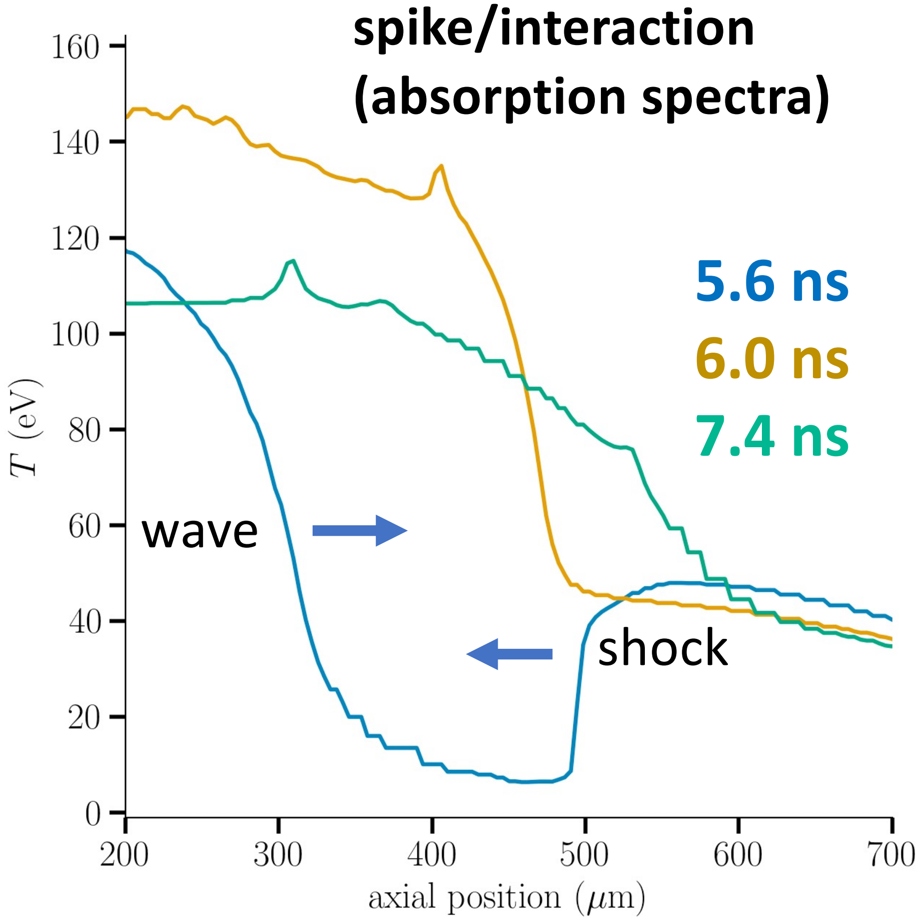
- Apply Laplace transform with boost, moving boundary, Forrest Doss[16]
- Reflectivity parameter (e.g. 90% of heat flux is reflected back into wave)



Theory well-predicts the spike at early times, but over-predicts speed and spike T at later times

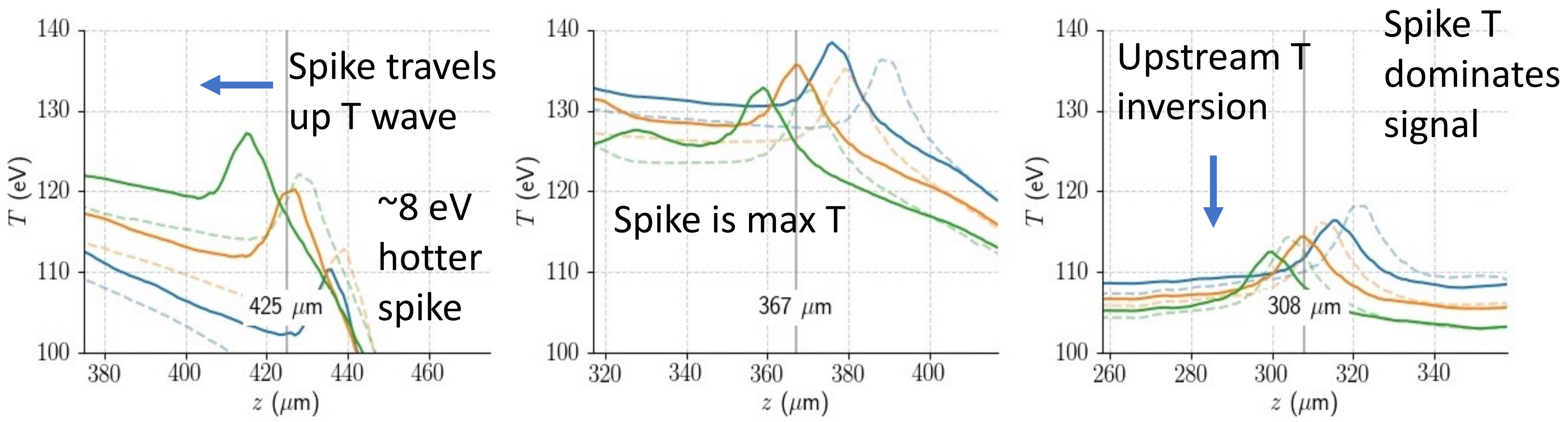


Detection: spectra is dominated by temperature profile

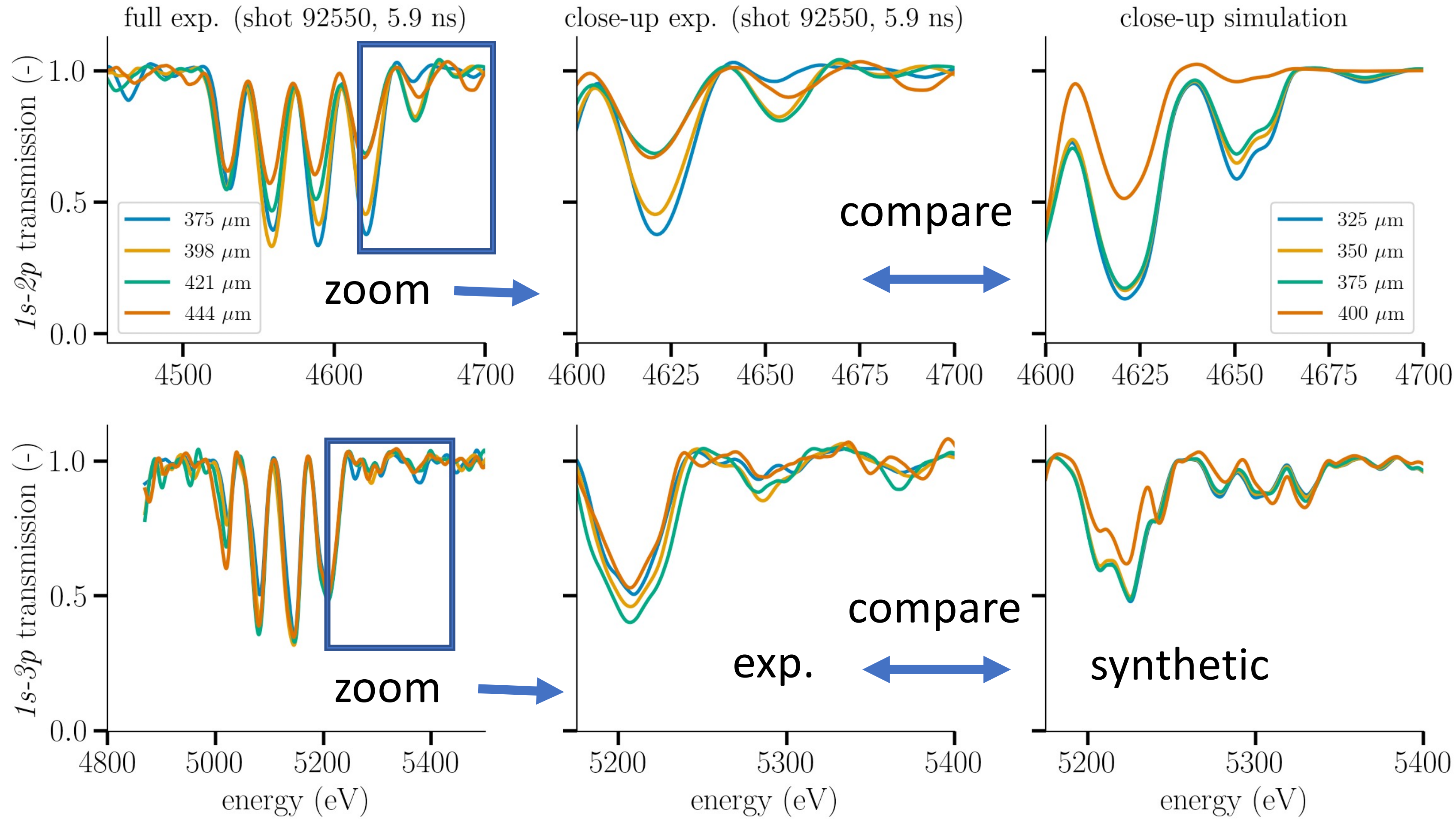


We identify regimes of evolution of the spike feature

Early: 5.8 ns **Peak: 6.4 ns** **Late: 7.2 ns**



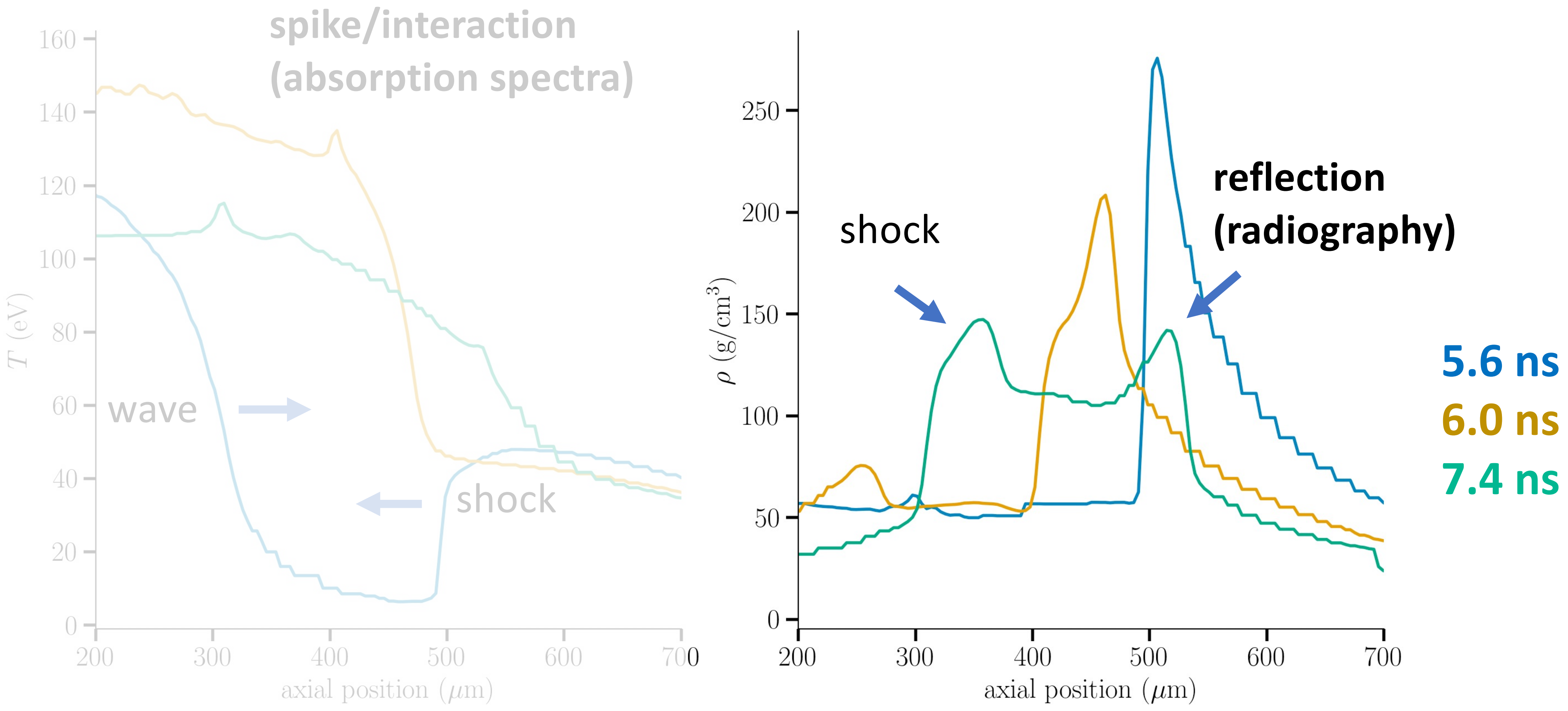
Against experimental spectra, we can identify lineout positions where the spike passes through



Very difficult to infer (noise, incomplete data, lower baseline, etc).

Exp. shot at 5.9 ns compares well with simulation.

Detection: radiography is dominated by density profile



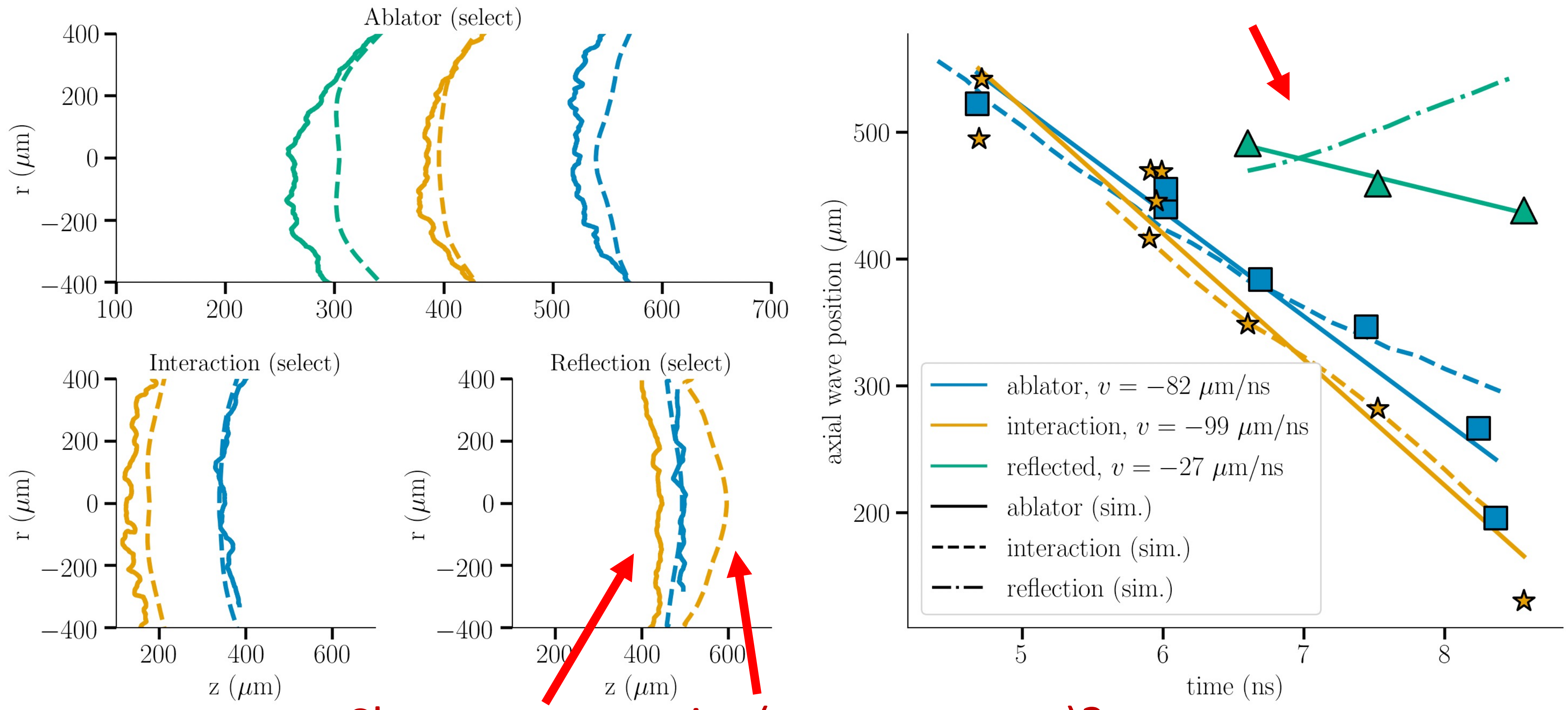
Against experimental radiography, we can identify “reflection” feature unique to interaction

Wave shape/position compare well!

Some disagreement!

Solid are experimental

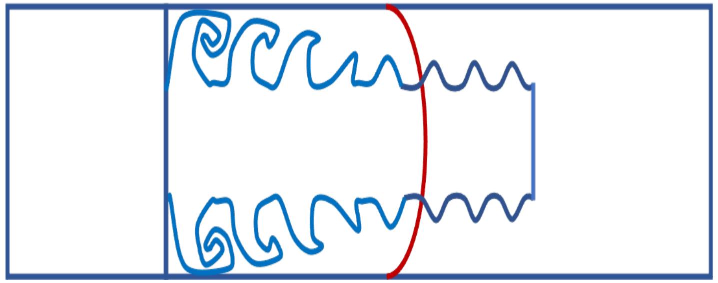
Dashed are simulation



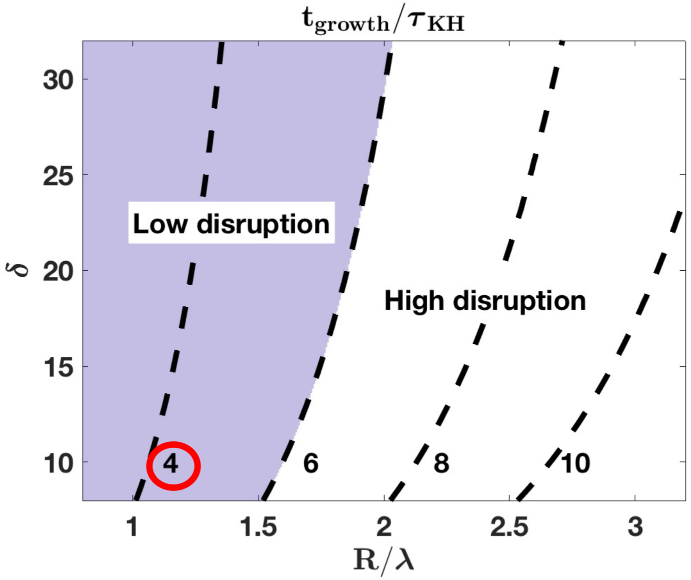
Slower exp. vs. sim (orange curves)?

Summary

Galactic filament experiment



Designed a well-scaled laboratory astrophysics experiment studying the role of KHI on cosmic filaments.



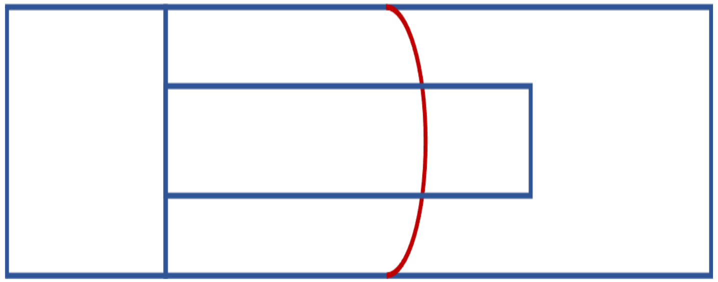
Success:

1. Developed thorough scaling analysis
2. Argued for best-case growth scenario
3. Provided prescriptions for studying more advanced growth.

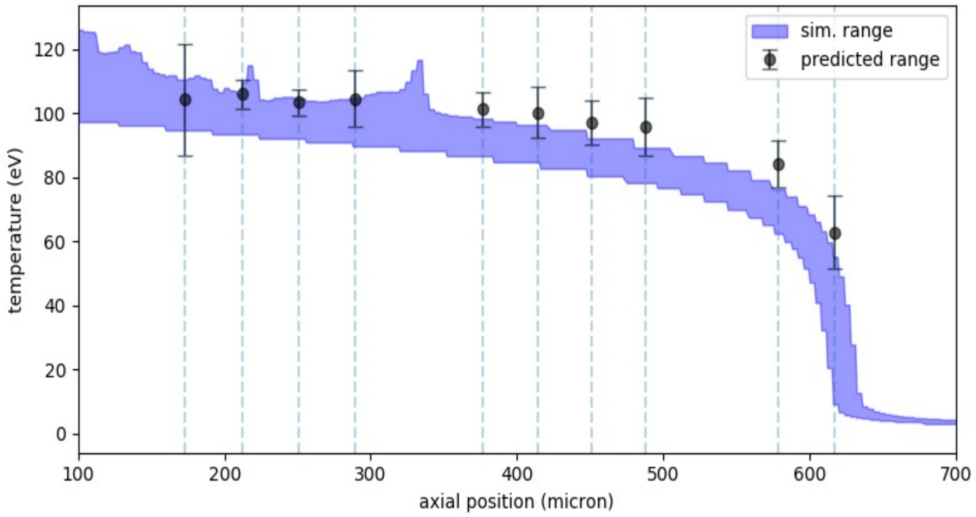
Future:

1. Analyze current experimental data
2. Implications for area mass-flow rate
3. Develop radiative case

COAX: Subsonic transitioning wave



Simultaneously constrained three-diagnostics on a radiation tube experiment studying transitioning subsonic radiation waves.



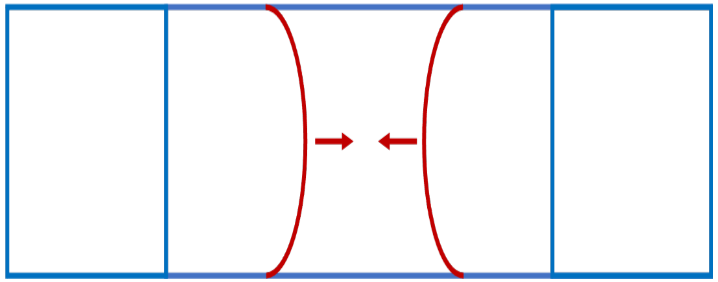
Success:

1. Developed UQ methods for radiation experiments
2. Advanced synthetic ray trace platform
3. Spatial temperature inference

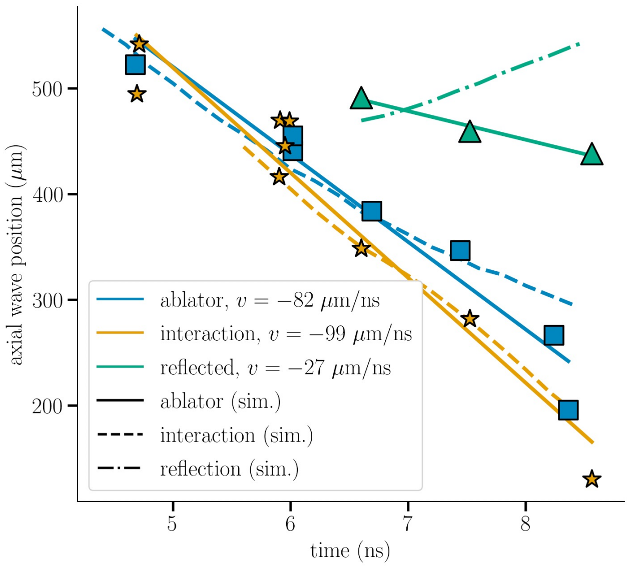
Future:

1. Repeat experiment for edge cases (supersonic)
2. Apply physics-informed learning techniques to learn noise distributions

Radishock: Shock and wave interaction



Developed simulation, theory, and experimental pipeline for an experiment studying the head-on collision of radiation waves and shocks.



Success:

1. Demonstrated new theory for interaction
2. Provided several pieces of evidence for detection of interaction

Future:

1. Use UQ development and analysis for new experiments
2. Refine theoretical development

Final thoughts

- The ultimate products:
  - Three+ collaborative publications demonstrating novel research in laser-driven experiments studying hydrodynamic phenomenon
  - HEDLA scaling experience
  - Computational modeling of HEDP
  - A deeper understanding of validation and UQ
- These experiences inform future work in novel learning-based UQ methods in my post-doc

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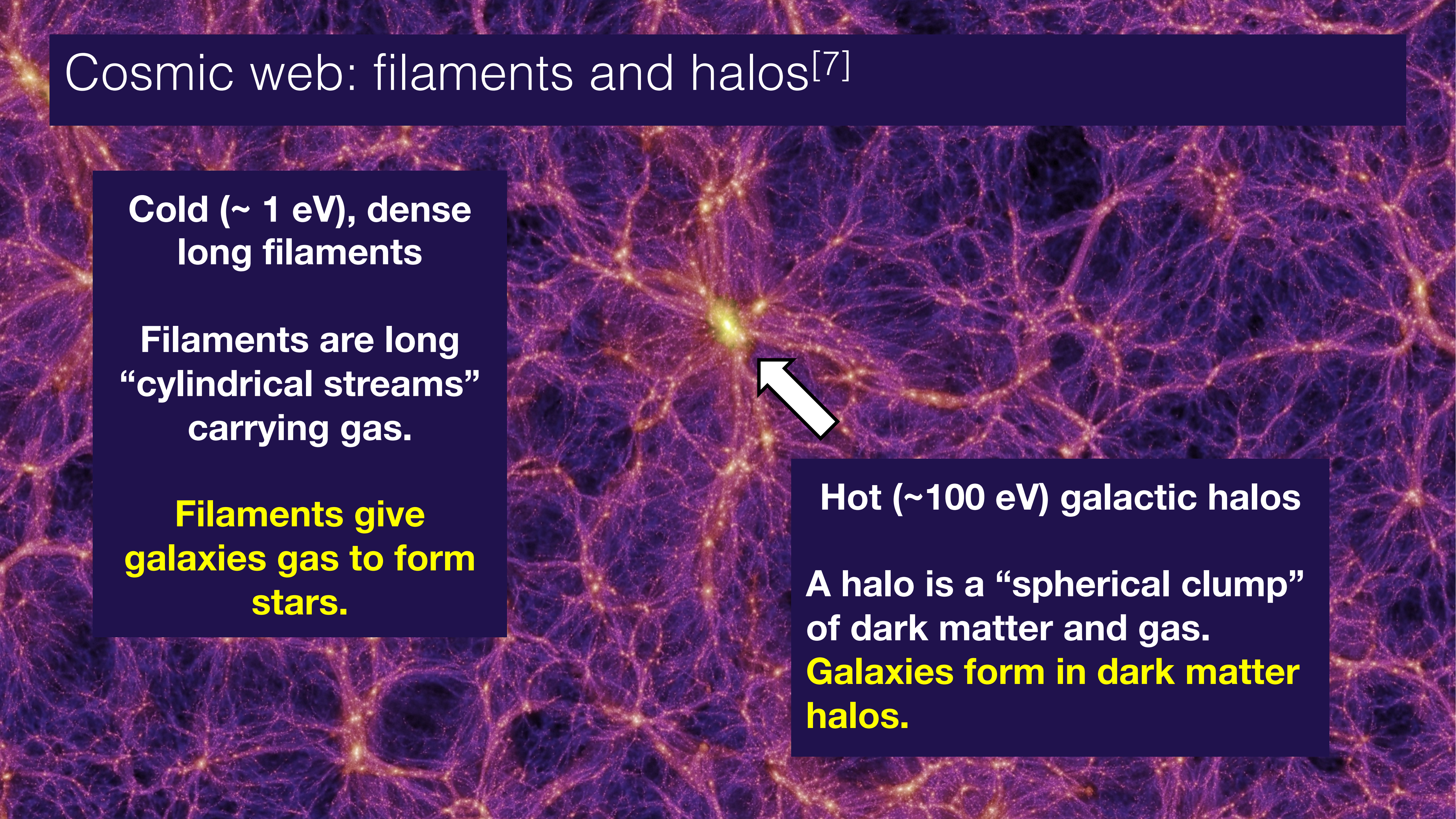
12. Coffing, Shane X., et al. "Design and scaling of an Omega-EP experiment to study cold streams feeding early galaxies." The Astrophysical Journal Supplement Series 245.2 (2019): 27.
13. Fryer, C. L., et al. "Uncertainties in radiation flow experiments." High energy density physics 18 (2016): 45-54.
14. Coffing, Shane X., et al. "Inferring the temperature profile of the radiative shock in the COAX experiment with shock radiography, Dante, and spectral temperature diagnostics." Physics of Plasmas 29.8 (2022): 083302.
15. Johns, Heather Marie, et al. "A temperature profile diagnostic for radiation waves on OMEGA-60." High Energy Density Physics 39 (2021): 100939.
16. Fryer, Chris L., et al. "Designing radiation transport tests: Simulation-driven uncertainty-quantification of the COAX temperature diagnostic." High Energy Density Physics 35 (2020): 100738.
17. Radishock paper (in prep).
18. Doss, F. W., "Exact results on intrinsic gradients in the compression of heat," Pro- ceedings of the International Conference on Mathematics and Computational Meth- ods Applied to Nuclear Science and Engineering, ANS M&C 2021, 2021, p. 1134.

Supplementary slides for discussion

Cosmic web: filaments and halos[7]



Cold (~ 1 eV), dense long filaments

Filaments are long "cylindrical streams" carrying gas.

Filaments give galaxies gas to form stars.

Hot (~100 eV) galactic halos

A halo is a "spherical clump" of dark matter and gas.
Galaxies form in dark matter halos.

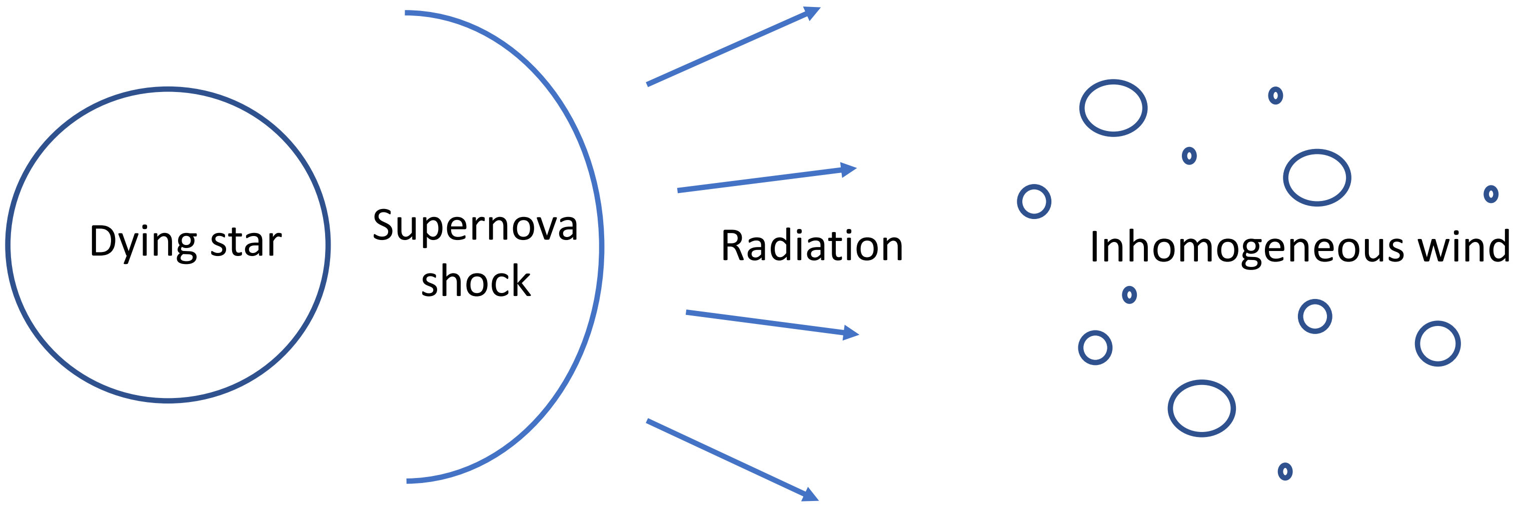
Why a cosmic filament exp.?

- High impact theory that helps answer fundamental questions about our origin[8]
- Galaxy formation is difficult to observationally explore
- Simulations can resolve filament formation or fine-scale hydrodynamic instabilities, **but often not both**
- HEDP provides a unique opportunity to investigate firsthand this hydrodynamic phenomenon

CRASH code[3]

- AMR, 3 T
- Multigroup, flux limited radiation diffusion
- Uses Hyades to model laser drives
- Roe solver (exact Riemann)
- Operator split (implicit energy update)

$$\frac{\partial \mathbf{U}}{\partial t} = \mathbf{R}_{\text{hydro}}(\mathbf{U}) + \mathbf{R}_{\text{frequency}}(\mathbf{U}) + \mathbf{R}_{\text{diffusion}}(\mathbf{U}),$$



Shock breakout

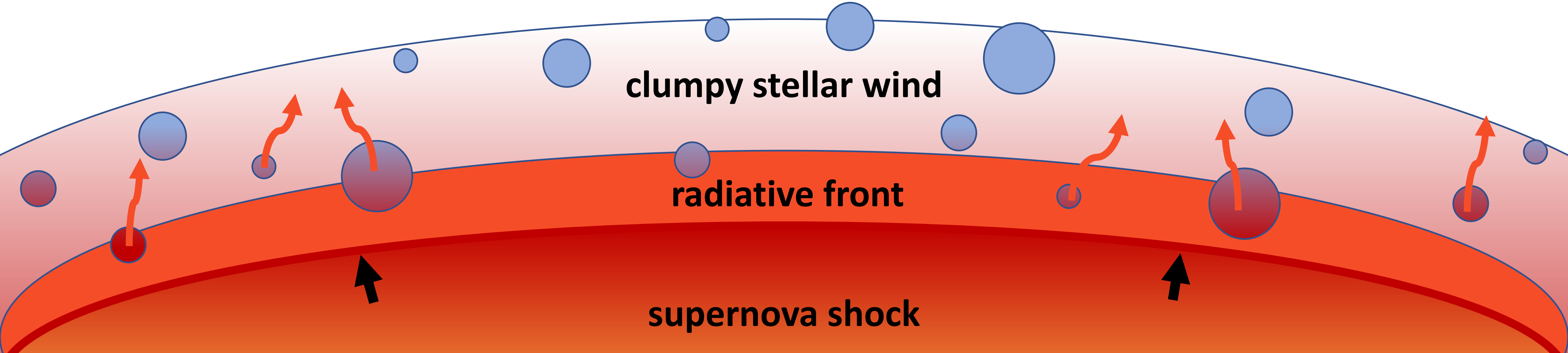
How does radiation from a shock flow through irregular distributions of matter?

Can this process provide us a unique spectral signature for supernovae? For other transient phenomena?

Breakout front turns clumps into emitters

- Radiative shock (~20-60 eV) heats up clumps
- Non-uniform heating, “bright” irregular flow structures
- **Unique spectral signatures? Ingredients:**

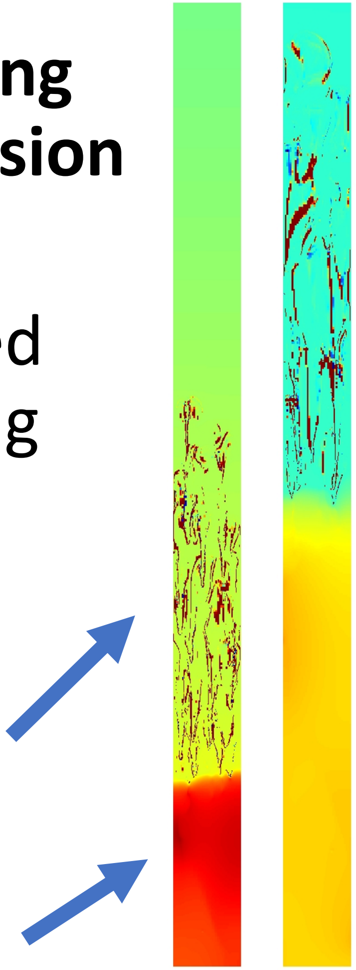
$$\text{luminosity} = f(\text{photon energy}, \text{mass}, \text{opacity}, \text{gas temperature})$$



We’ve shown enhanced emission in first-look work

- **Fryer et al. (2020): Strong extreme UV, x-ray emission features in spectra [2]**
- Simulations show heated clump “strands” evolving

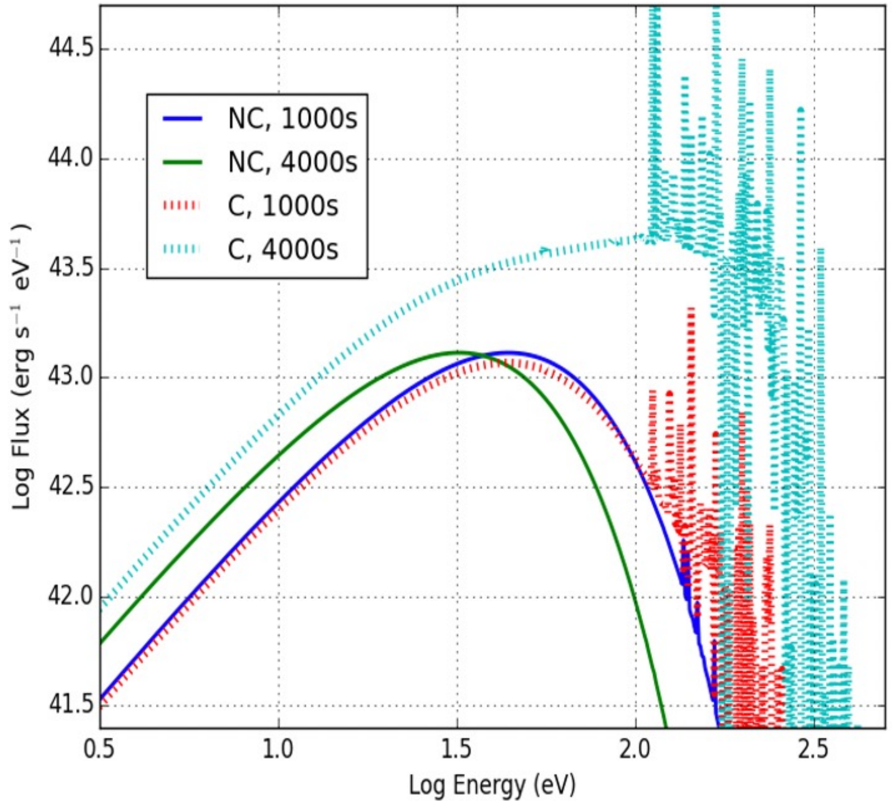
r = 1e13 cm



Heated clumps

SN shock

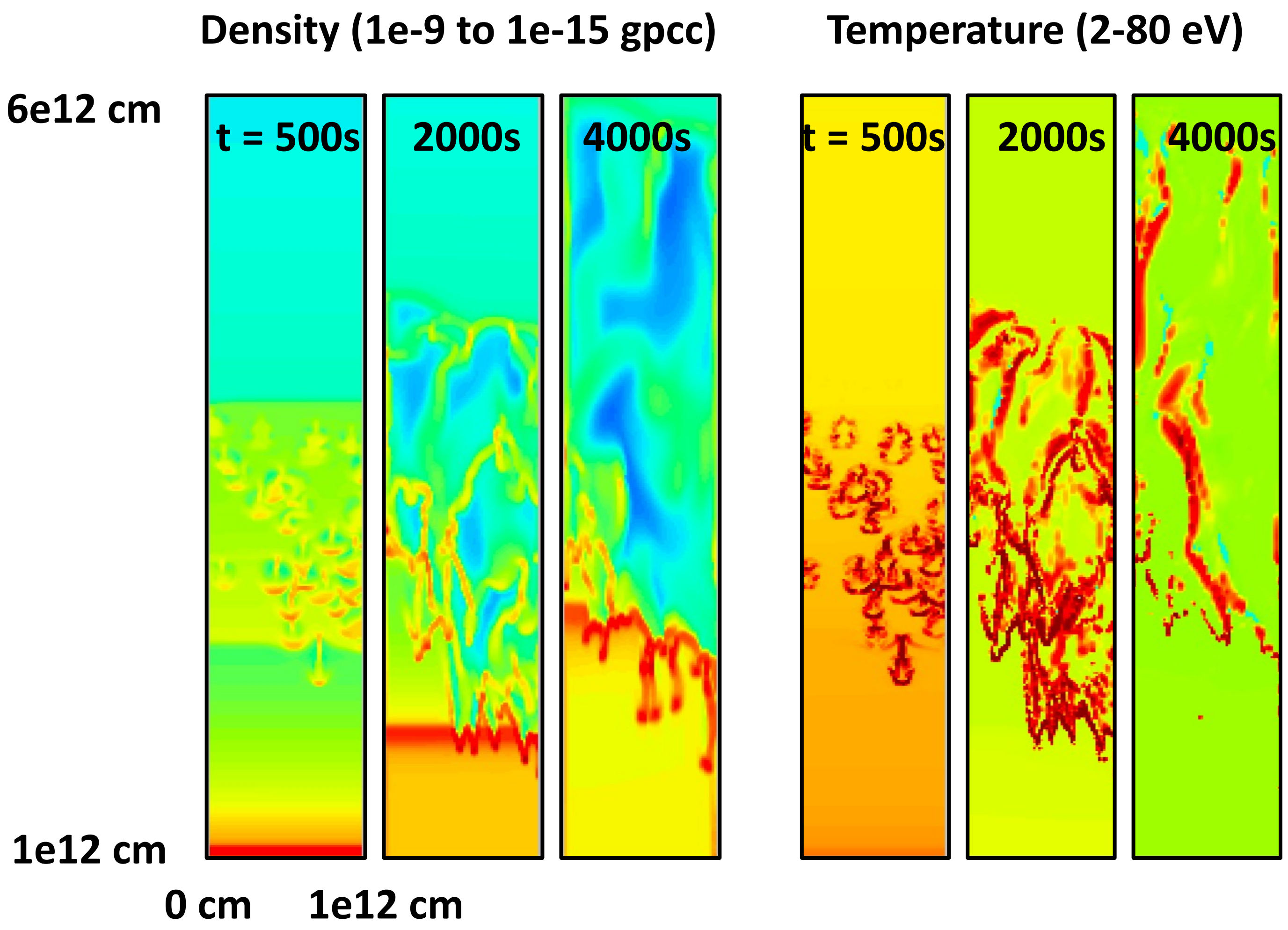
R = 1e11 cm



Clumped vs smooth run spectra, note high energy features

Porous SBO flow creates hot EUV+ emission

- Short lived flow structures
- Radiative acceleration and mixing can shred the clumps, mixing also a cooling process
- **With porous shell, EUV+ temperatures, similar features as pure clumped**
- **More research to be done to discern between spectra**



Current and *past* collaborators on LANL Radiation Flow Experiments (COAX, Radishock, OUTI, XFOL)

Experimental
- Heather Johns
- Pawel Kozlowski
- Ted Perry
- *Colin Brown*
- *J. D. Hager*
- *J. Kline*

Program Support
- *Melissa Douglas*
- Todd Urbatsch
- Sean Finnegan
- *Aimee Hungerford*

Diagnostics
- *R Gonzales*
- J. Cowan
- J. Jorgenson
- T. Archuleta
- *T. Sedillo*

Design
- *Nick Lanier*
- Chris Fryer
- Tom Byvank
- *John Morton*
- *Suzannah Wood*
- *Andy Liao*
- Harry Robey
- **Shane Coffing**
- ***Timothy Araujo***
- ***Joseph Coale***

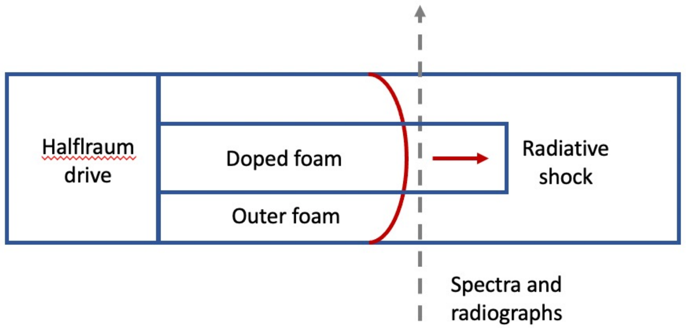
Theory
- Chris Fontes
- Peter Hakel
- Manolo Sherrill

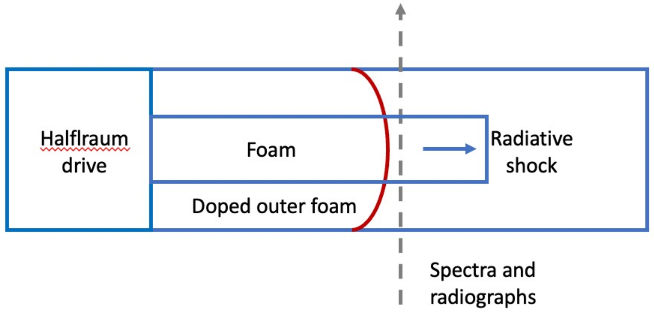
Target Fab
- Kevin Love
- Nikolaus Christiansen
- *Alex Strickland*
- Derek Schmidt
- *Tana Morrow*
- Theresa Quintana
- Chris Hamilton
- Lynne Goodwin
- Frank Fierro
- Chris Wilson
- Blaine Randolph
- Patrick Donovan
- Stephanie Edwards
- *Deanna Capelli*

***Students**

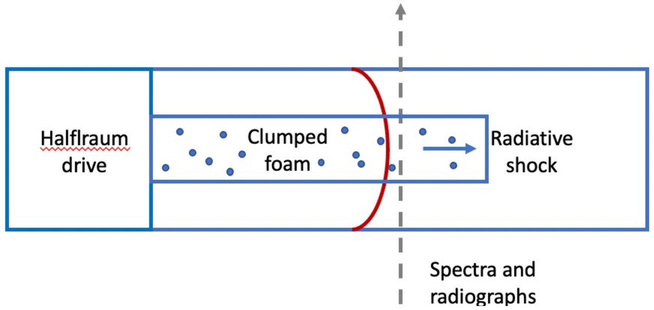
COAX is just the beginning

COAX

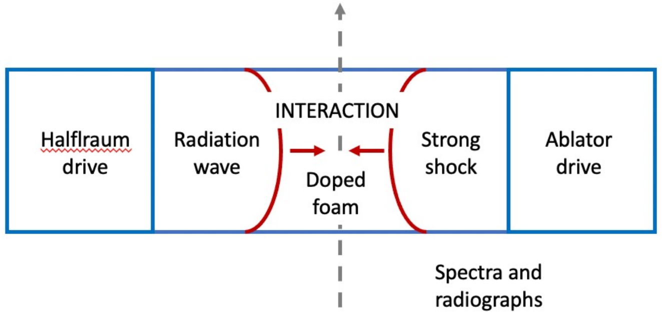




Outer doped foams, **OuTI**



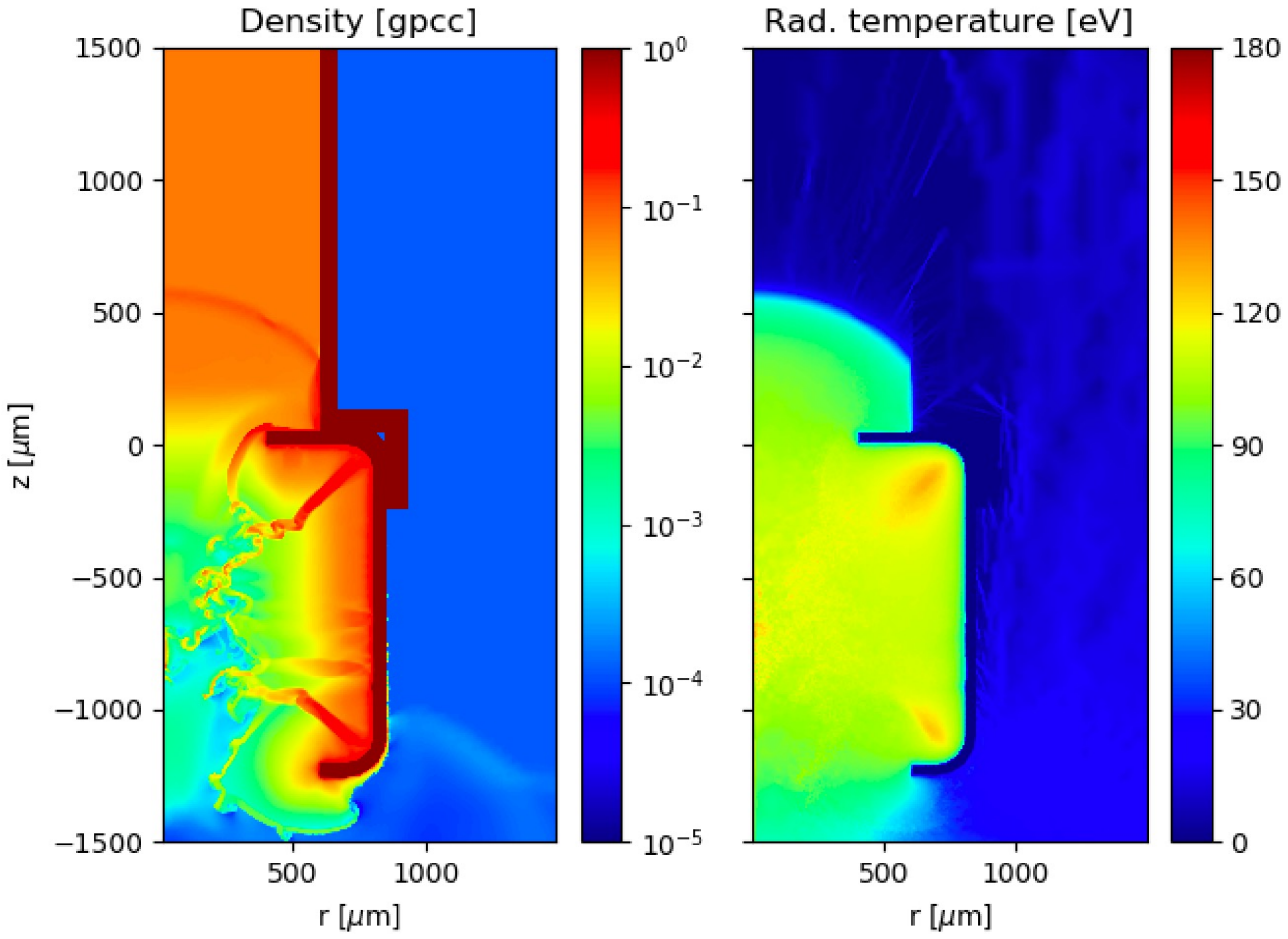
Stochastic media, **XFOL**



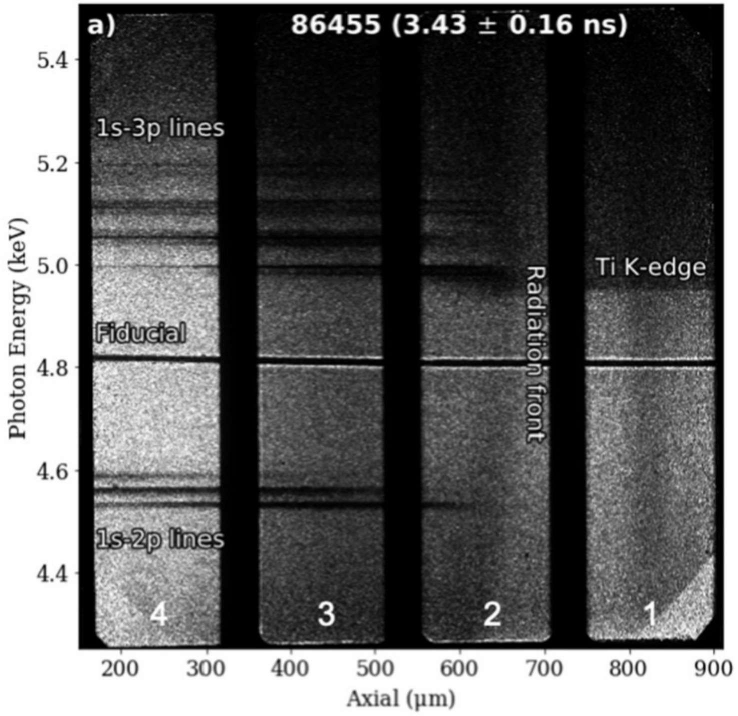
Interacting shocks and waves, **Radishock**

Cassio is our primary modeling tool

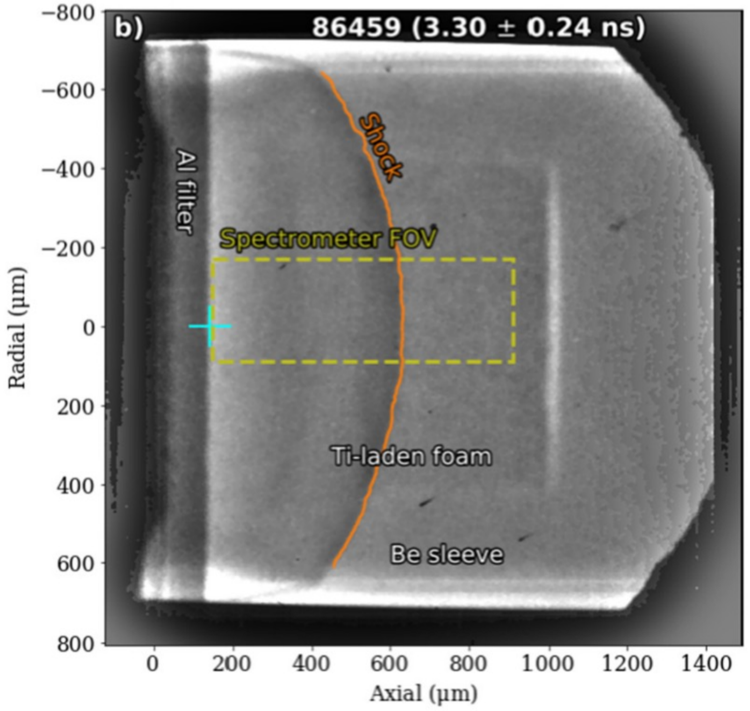
- AMR, 3 temperature models
- Mazinisin laser package[5]
- SESAME opacities
  - nLTE opacities based on the linear response method[6]
  - LTE solutions with opacity multipliers
- Radiation transport solvers: SN or IMC [7,8]



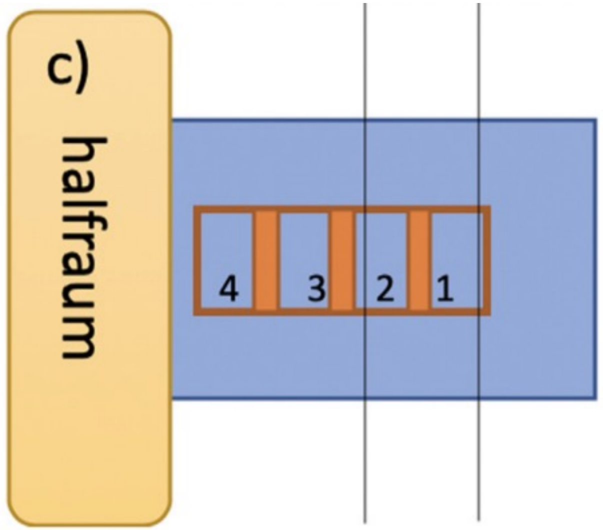
COAX spectroscopy configuration



a) raw film showing frames

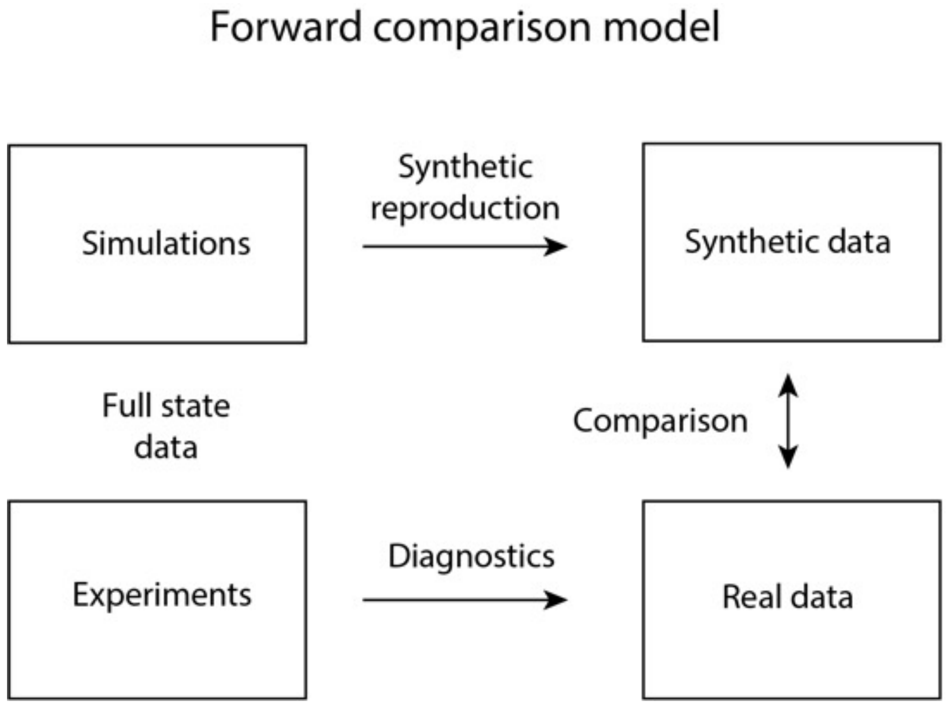


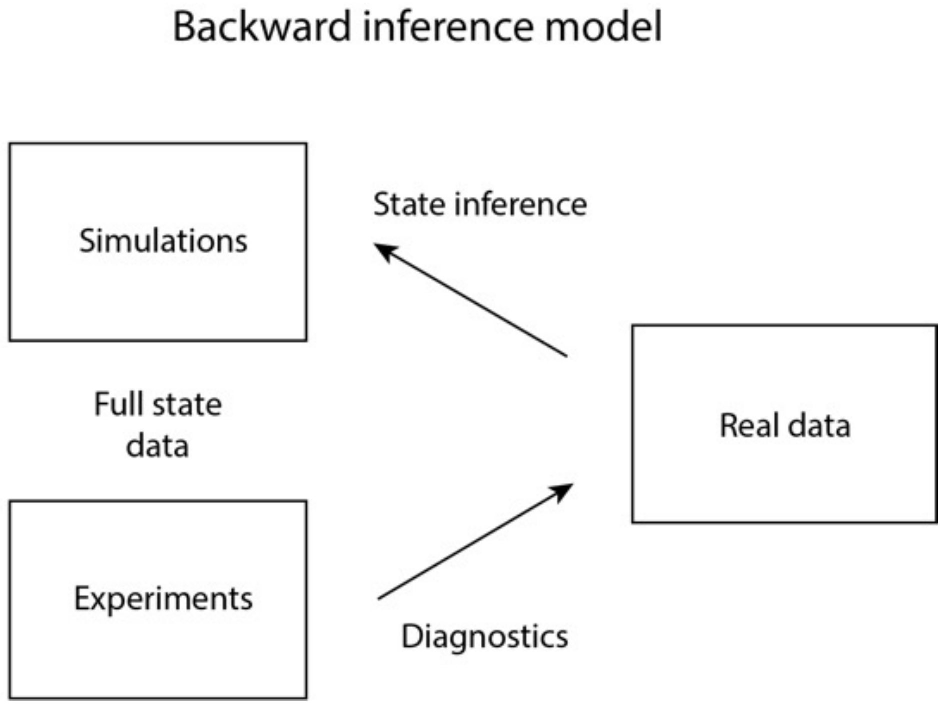
b) FOV



c) Diagram of imaging window

There are broadly two comparison methods





A simplified design and UQ process

MODELING CHOICES

Physics

Radiation models, plasma models, opacity physics, EOS

Target

Densities, inhomogeneities, clumps and mixing

Drive

Hohlraum/laser modeling, power and timing uncertainties

INITIAL TEST

Does radiography match?
Position, curvature, *timing*

Produce similar Dante flux?
Physical **solution?**
Peak, distributions, *late time flux*

FINAL TESTS

Does the spectra make sense?
Best fits, reconstruct T profile

Propagate uncertainties.

Broader applications for the physical regimes?

Astrophysical shocks, shock breakout

NIF, ICF/HED

Radishock, OuTI, XFLows

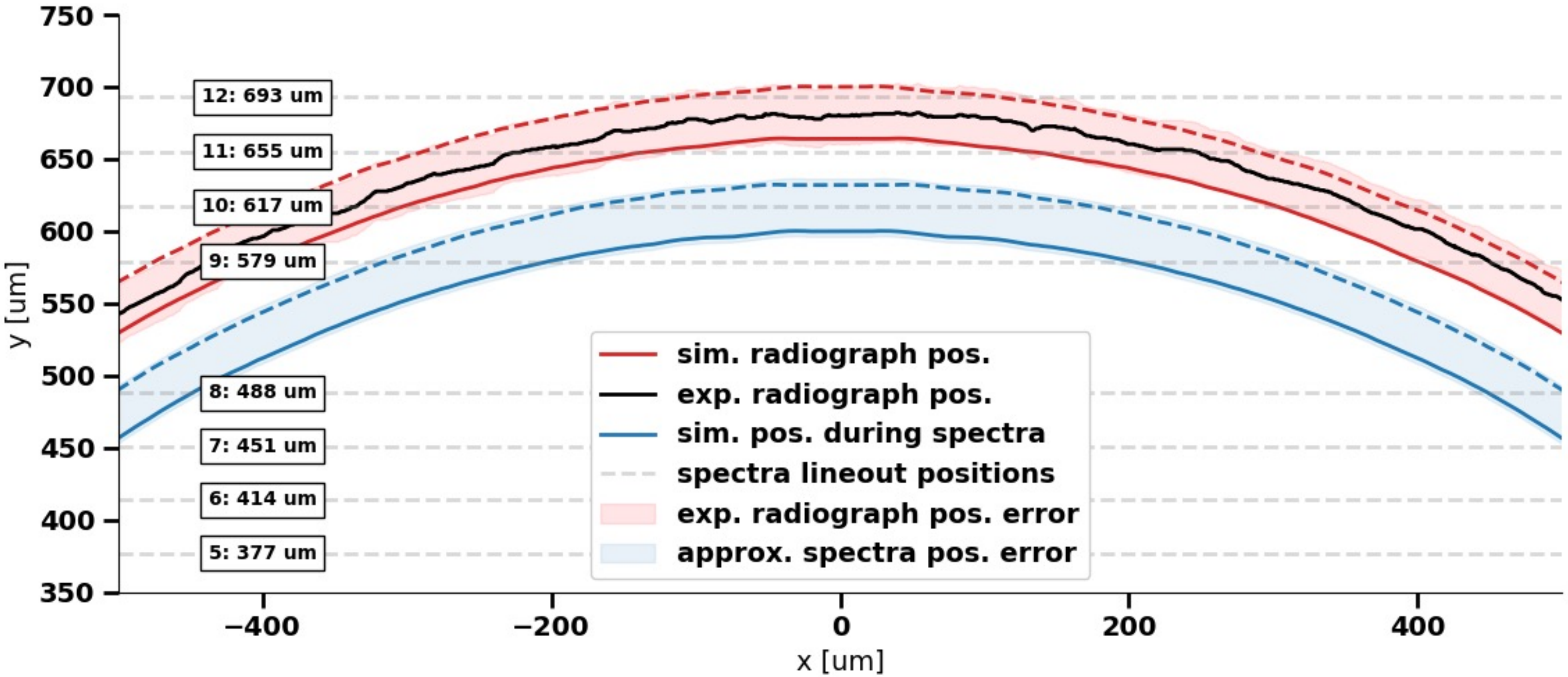
We use radiography to match shock positions[5]

We take spectra at these positions.

Red: where shock is during radiography.

Blue: where it may be during spectra.

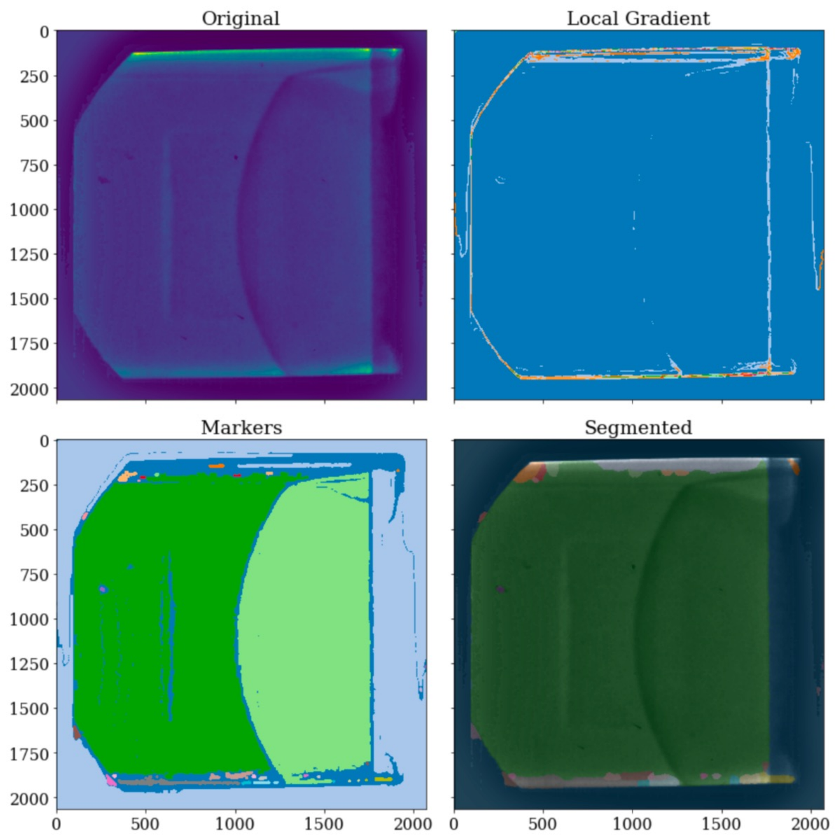
+/- 20 micron error

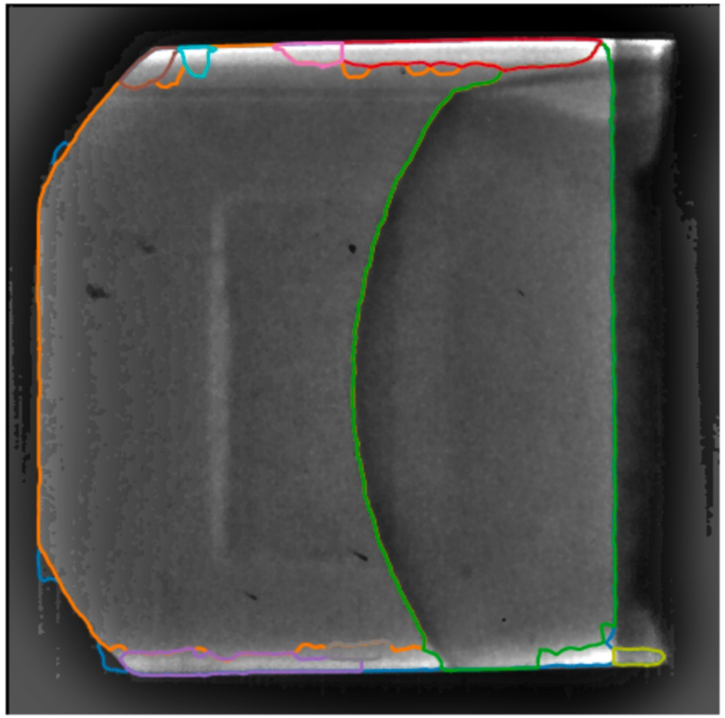


We do not (directly) know the shock position during spectra. But by performing experiments with staggered timings, we can infer the conditions through modeling.

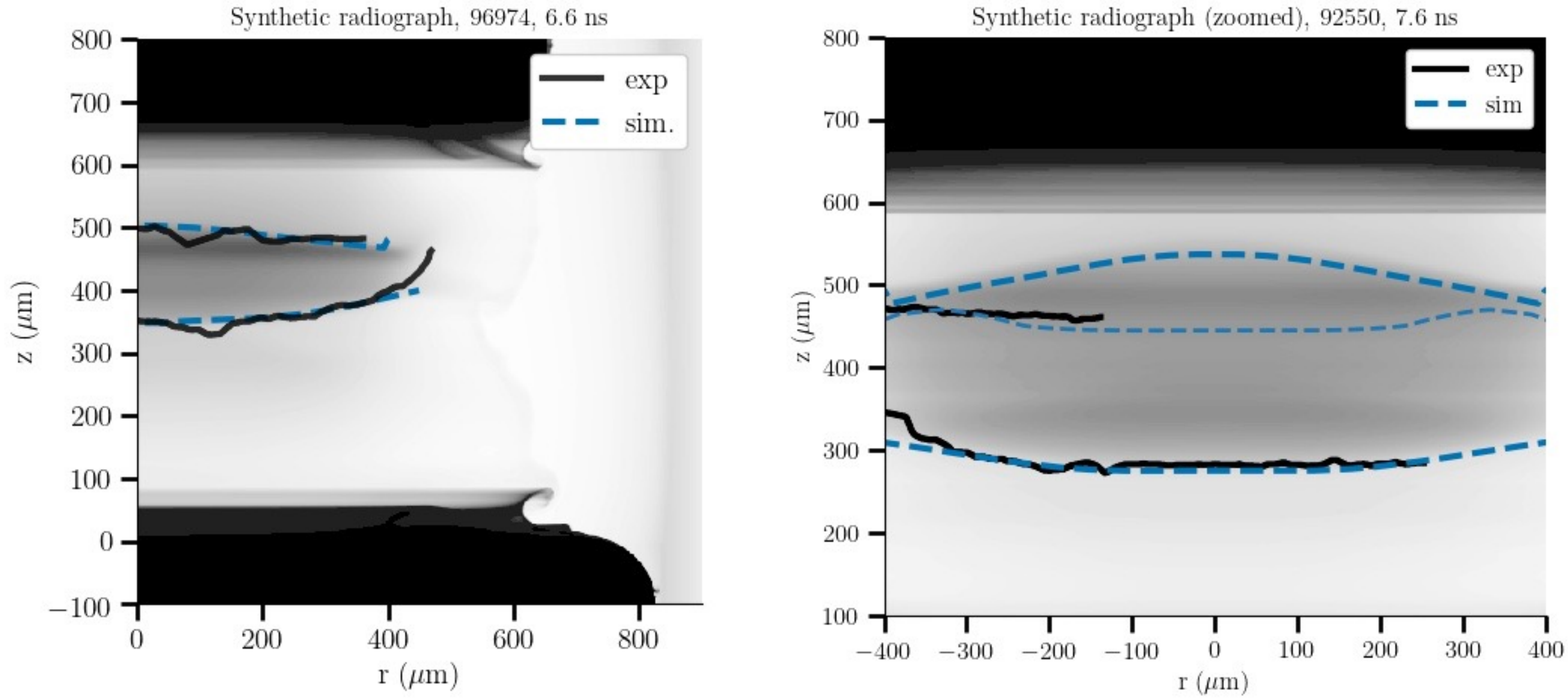
XRIPL images and contours our experimental radiography

- (P. Kozlowski, 2021) XRIPL uses watershedding to segment and select contours.[6]
- **Experimental data for an example COAX shot**





Radiographed transmitted feature in Radishock



Synthetic spectra informs the signatures of the spike

Deeper transmission lines are hotter T