Research in the Center for Radiative Shock Hydrodynamics (CRASH)

Center for Laser Experimental Astrophysics Research

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Center for Radiative Shock Hydrodynamics

Department of Atmospheric Oceanic & Space Sciences

Applied Physics Program
Department of Physics

Michigan Institute for Plasma Science and Engineering

Many individuals contribute to the CRASH Team

- **Co-Principal Investigators**
  - **UM: James P. Holloway, Kenneth G. Powell, Quentin Stout**
  - **TAMU: Marvin L. Adams**

- **Participants**
  - **UM: Eight departments (Math, Stats + six in Engineering)**
    - **Ten instructional faculty**
    - **Eight research faculty**
    - **Twenty graduate students**
    - **Engineers, administrators, undergraduates**
  - **TAMU: Three departments (Nuclear, CompSci, Stats)**
    - **Six instructional faculty**
    - **Eight graduate students**
    - **Technical staff**
  - **Simon Frazer U.: Prof. Derek Bingham and one graduate student**

We value our scientific and financial collaborators

Scientific collaborators (partial list):

LLE/Rochester – *Knauer, Boehly, Nilson, Froula, Fiskel, others*

LLNL – *Park, Remington, Glenzer, Fournier, Doeppner, Miles, Ryutov, Smalyuk, Hurricane, others*

LANL – *Montgomery, Lanier, others*

Florida State – *Plewa*

France – *Bouquet, Koenig, Michaut, Loupias, others*

Britain -- *Lebedev*

Texas – *Wheeler*

Arizona – *Arnett, Meakin*

Negev – Shvarts, Malamud

Chicago – Abarzhi, others

Financial collaborators:

CRASH:

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CLEAR:

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Los Alamos Nat. Lab.

Laboratory for Laser Energetics

Past support:

Lawrence Livermore Nat. Lab.

Naval Research Lab.

CRASH is focused on *predictive science*

- **What CRASH is about:**
  - **Our goal is to test methods**

    that evaluate our predictive capability

    to model complex behavior
    - **The predictor is a multiphysics computer code**
    - **Radiation hydrodynamic experiments are modeled**
  - **Our approach is to predict the behavior of a more complex system based on measurements of simpler systems**
- **This talk:**
  - **Our radiative shock system and experiments**
  - **The CRASH code**
  - **Predictive science studies**

Shocks become radiative when …

- **Radiative energy flux would exceed incoming material energy flux**

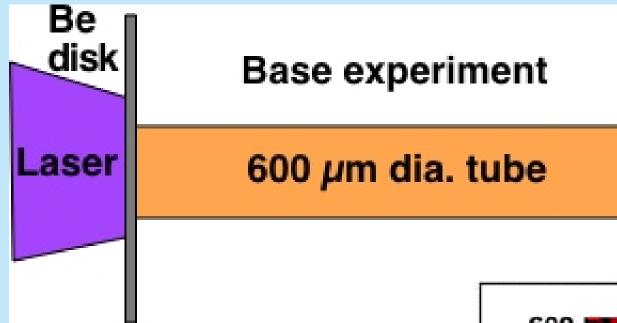
where post-shock temperature is proportional to u_s^2.

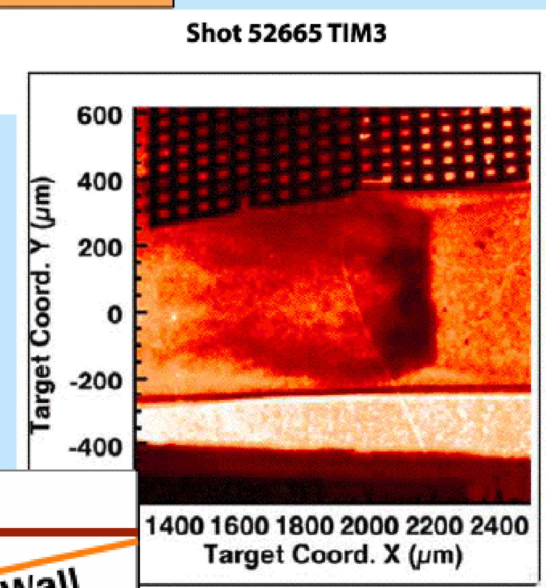
- **Setting these fluxes equal gives a threshold velocity of 60 km/s atmospheric-pressure xenon:**

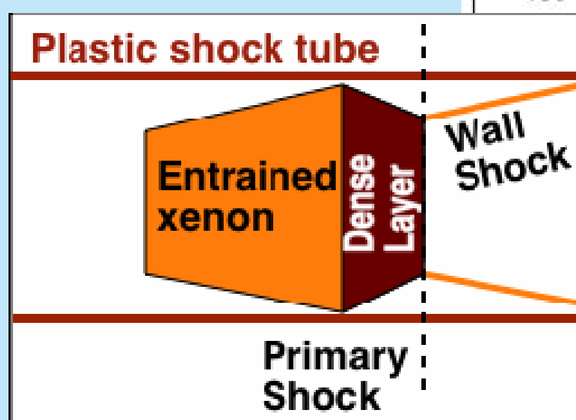
Material	xenon gas		
Density	6.5 mg/cc	Initial ion temperature	2 keV
Initial shock velocity	200 km/s	Typ. radiation temp.	50 eV

Our simple system is a radiative shock in a circular tube

- 1 ns, 3.8 kJ laser irradiates Be disk
- Drives shock down Xe-filled tube
- Radiation ablates wall of tube -> wall shock
- Ongoing CRASH experiments chosen first to improve then to test predictive capability







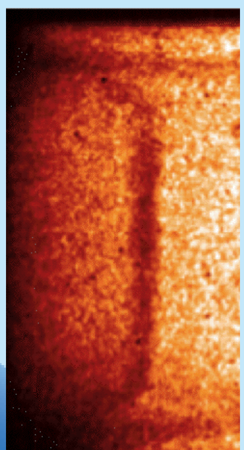
CRASH essential physics: Drake et al HEDP 2011

We have used radiography to investigate the lateral structure of these shocks

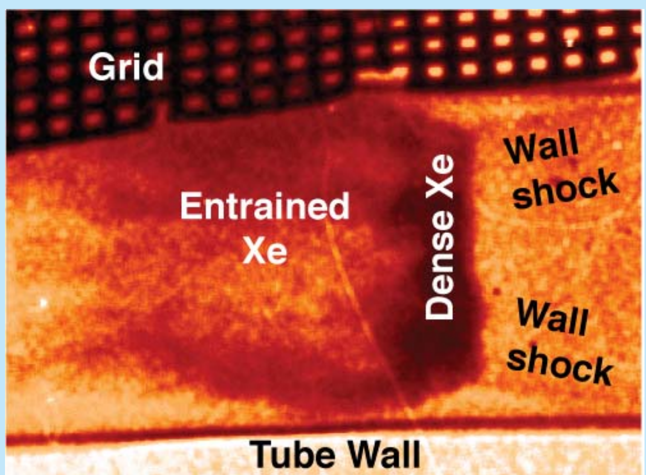
- Bayesian analysis of tilt gives compression ~ 22
  - Doss HEDP, A&SS 2010
- Shock-shock interactions give local Mach number
  - Doss PoP 2009
- Shape of entrained flow reveals wave-wave dynamics
  - Doss PoP 2011
- Thin layer instability; scaling to supernova remnants
  - Doss thesis & to be pub.

Radiographs

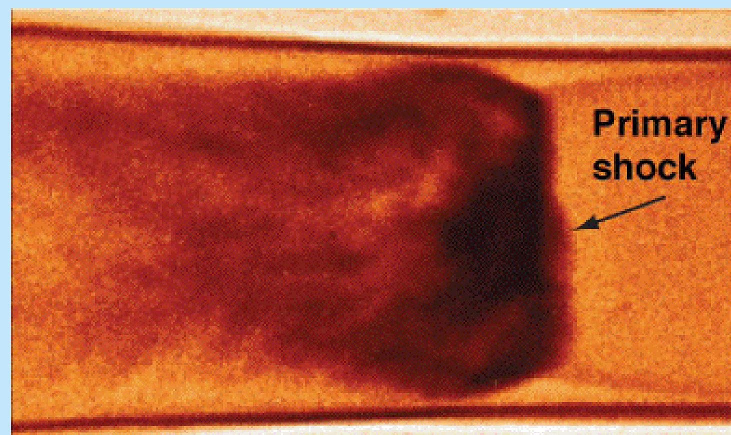
3.5 ns



13 ns



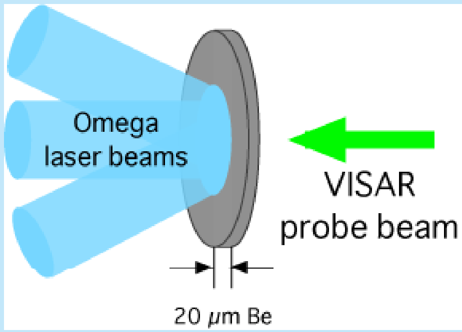
26 ns

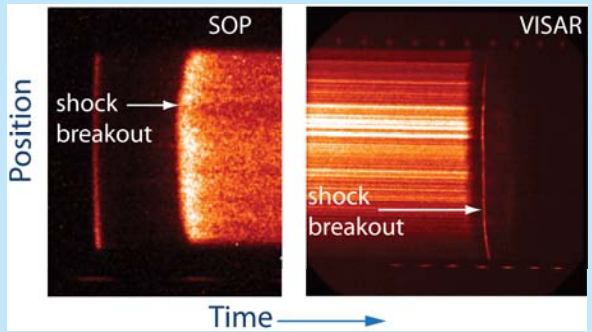


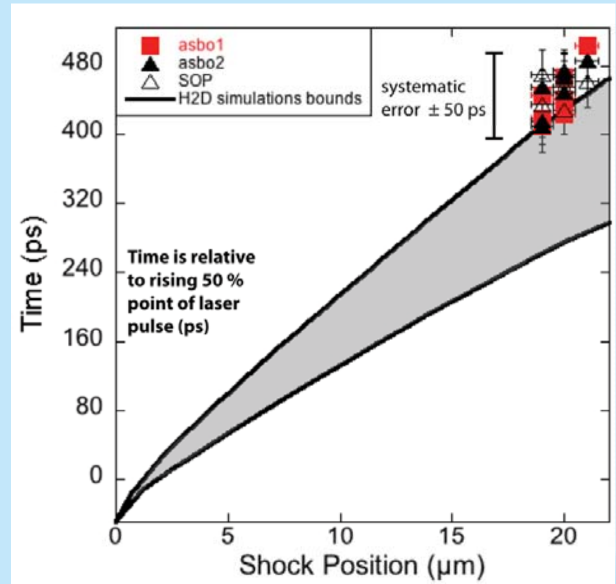
Credit:
Carolyn Kuranz

We are also making other measurements

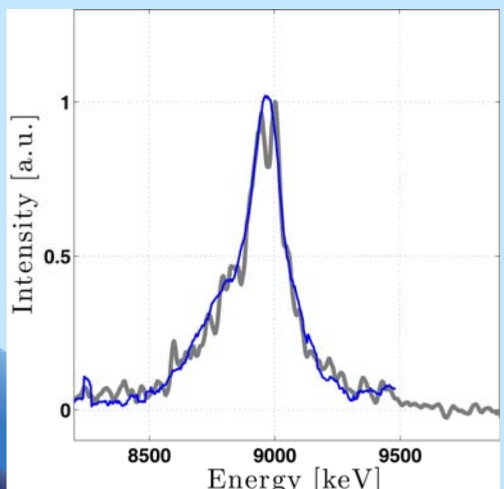
- **Shock breakout from the Be disk**

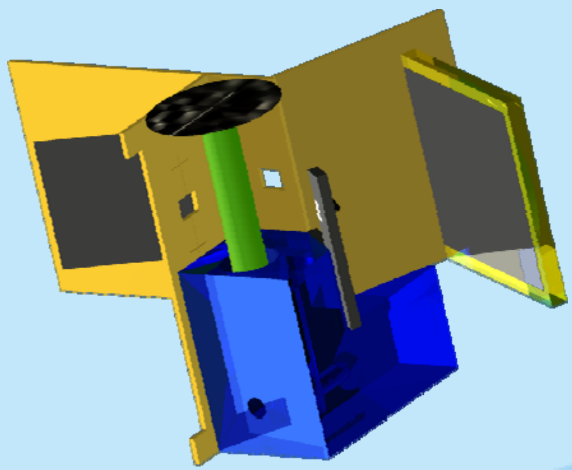






- **X-ray Thomson scattering**





- Papers in prep
  - Kuranz et al.
  - Stripling et al.
  - Visco et al.
  - Huntington et al.

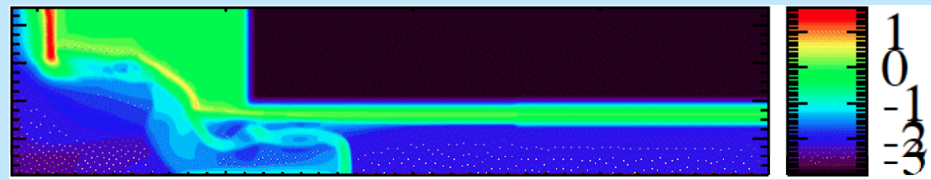
CRASH

We simulate the experiments using the CRASH code

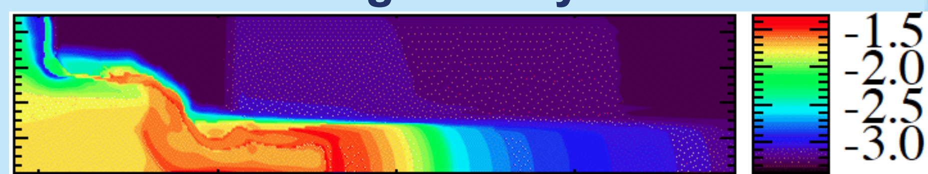
- Dynamic adaptive AMR
- Level set interfaces
- Self-consistent EOS and opacities or other tables
- Multigroup-diffusion radiation transport
- Electron physics and flux-limited electron heat conduction
- Laser package
- Ongoing
  - Multigroup preconditioner
  - I/O performance upgrade

3D Nozzle to Ellipse @ 13 ns

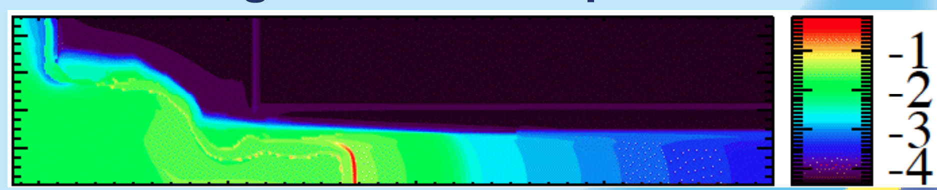
Material & AMR



Log Density



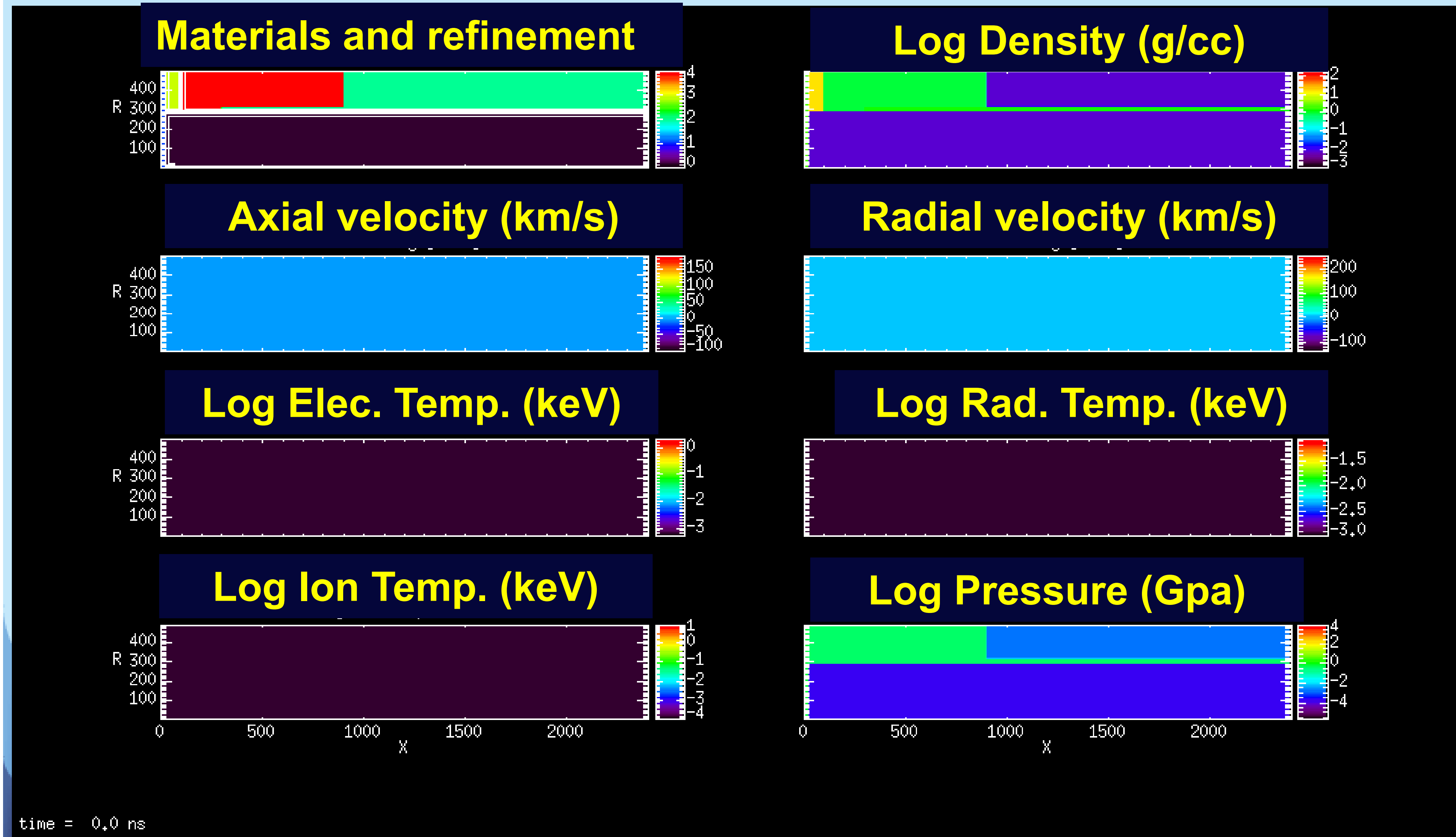
Log Electron Temperature



Log Ion Temperature

CRASH code: Van der Holst et al, Ap.J.S. 2011

The CRASH 3.0 simulation of the simple experiment reproduces many observed aspects



- All physics, 10 hours on 100 cores

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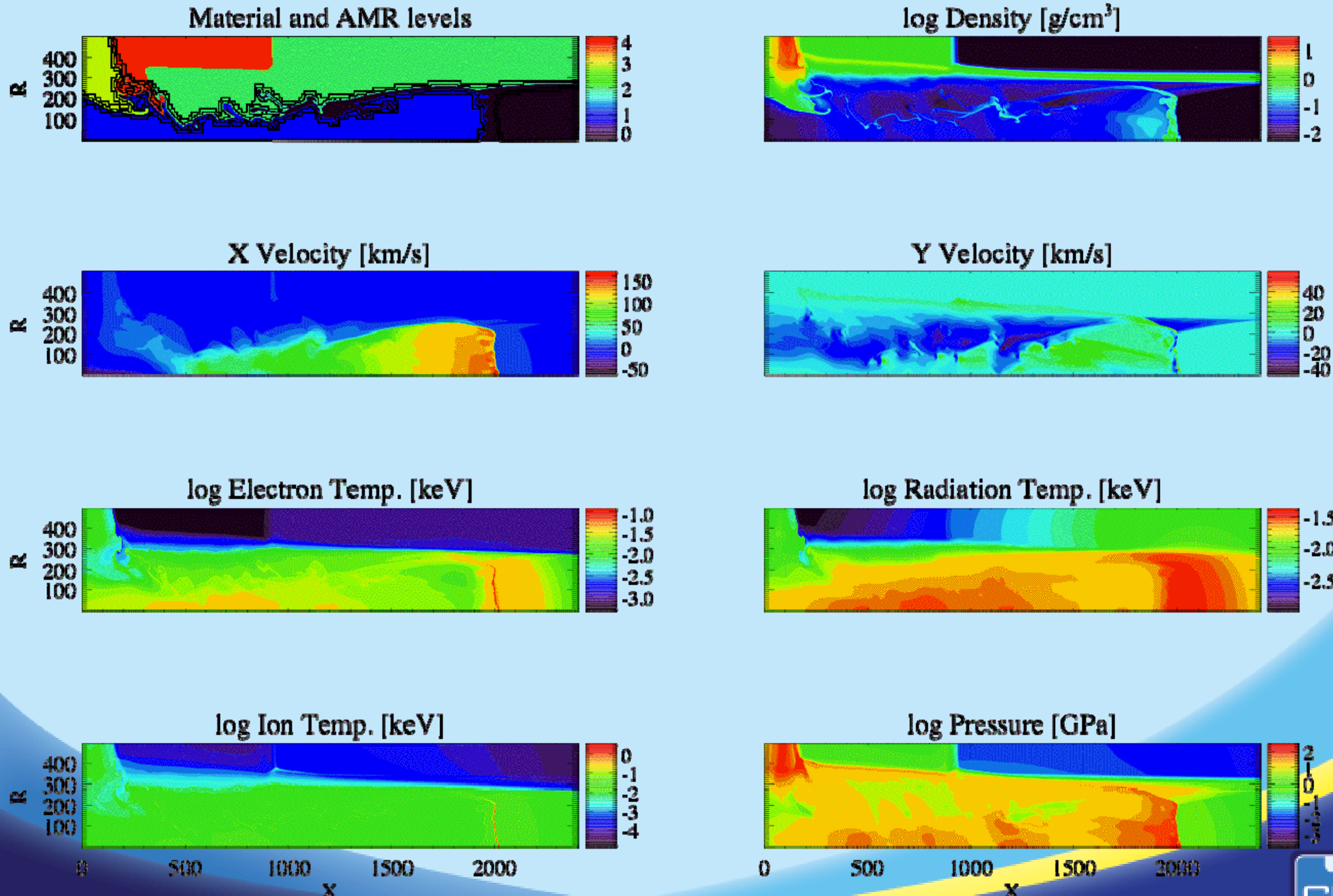
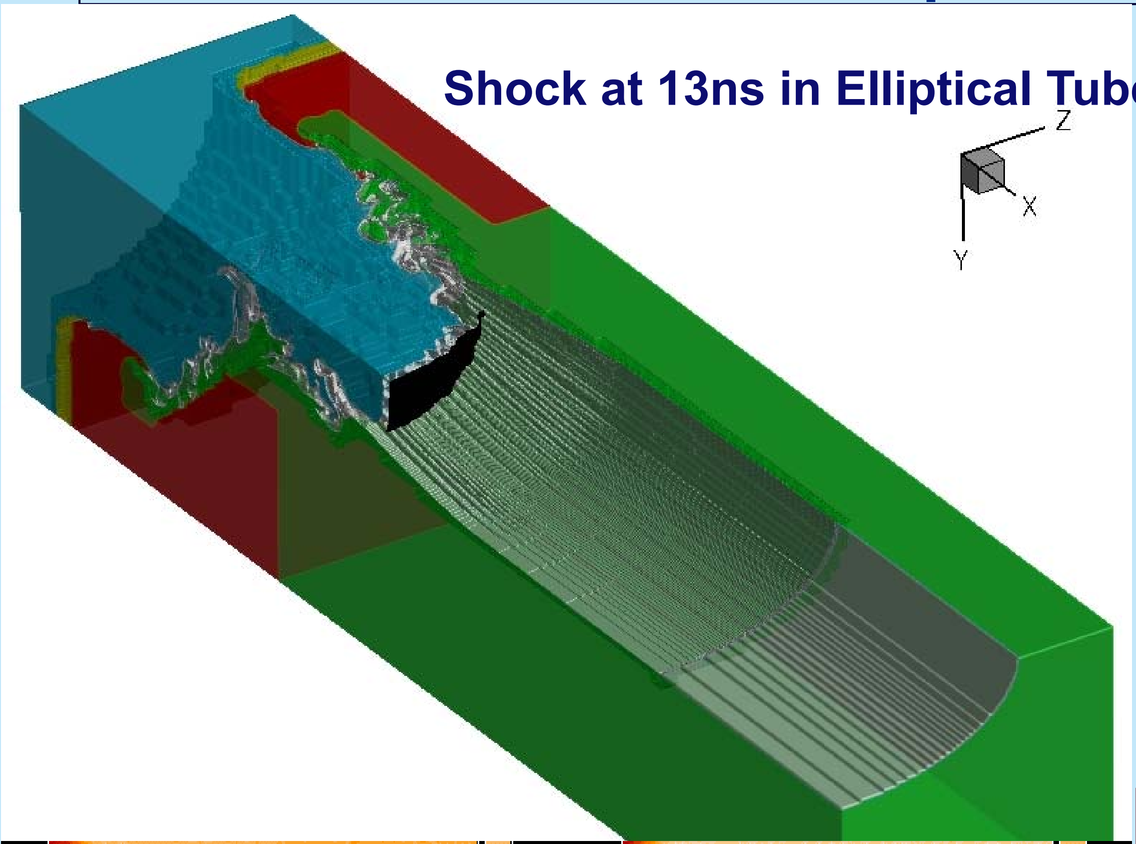
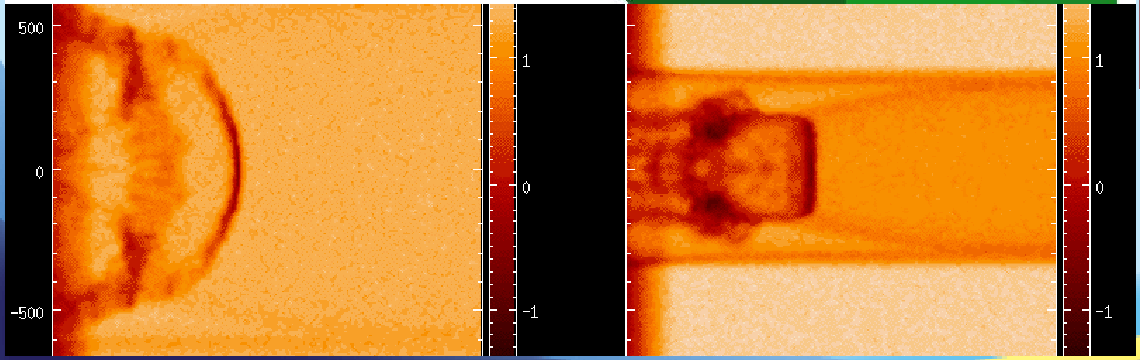
The shock at 13 ns looks much like the data



Our complex system drives such a shock into an elliptical tube





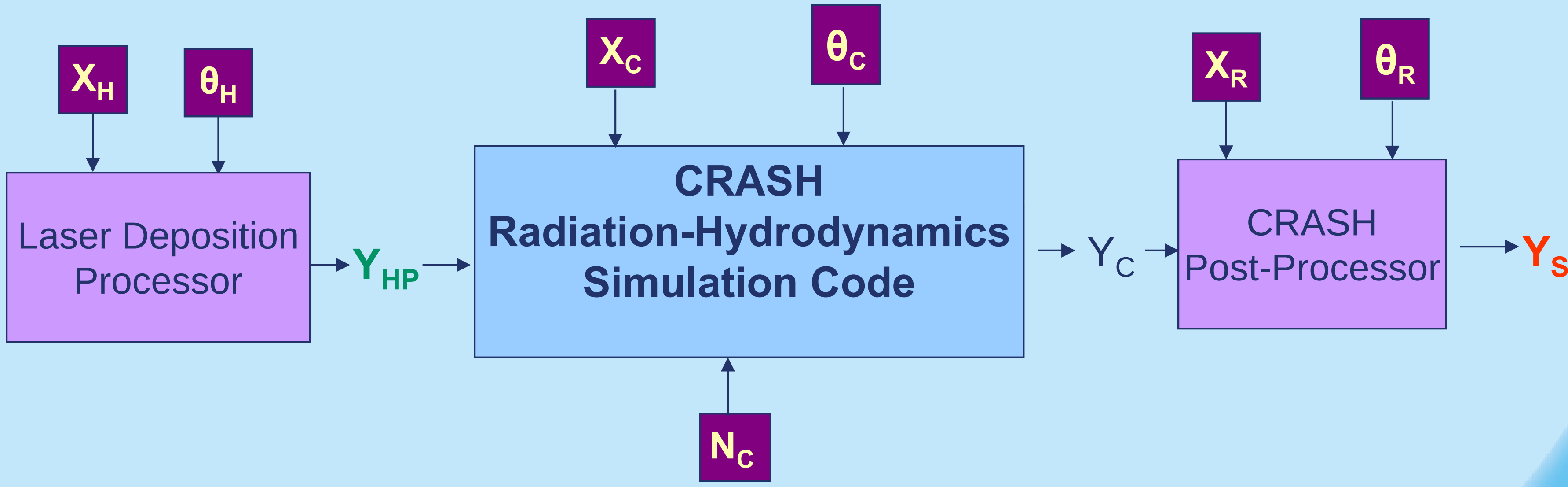
This is the system we want to predict

Elliptical simulations:

Van der Holst et al, HEDP Submitted 2011

First experiments next month
Variability study in 2012

Our work in predictive science revolves around inputs and outputs of the code



X - Experiment parameters
θ - Physical Constants
N - Numerical Parameters

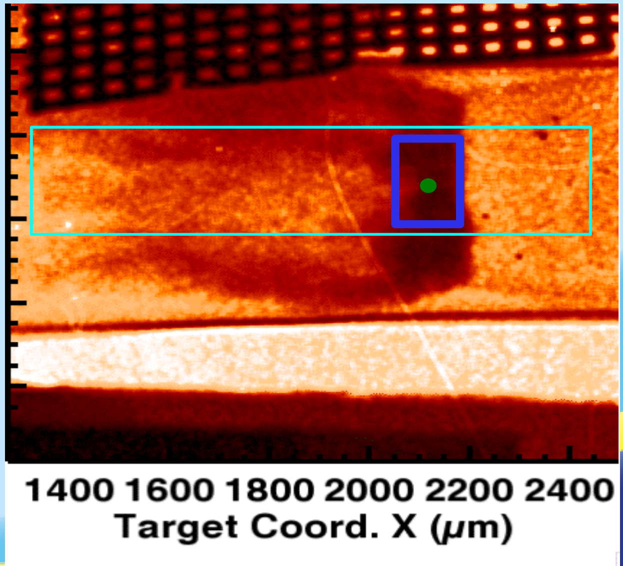
Y - Results passed forward and/or analyzed with data by statistical methods

Our inputs and outputs reflect the specifics of our experimental system

Inputs

- Experimental (x)
  - Laser energy
  - Be disk thickness
  - Xe fill gas pressure
- Model parameters (θ)
  - Vary with model
  - Examples:
    - electron flux limiter, laser energy scale factor,
    - opacity or group scale factor
- Form of model
  - e.g. 2D vs 3D

- Outputs (y)
  - Integrated Metrics
    - Shock location (SL)
    - Axial centroid of dense Xe (AC)
    - Area of dense Xe (A)
    - Radial moments
  - Shock breakout time (BOT)



We draw conclusions by comparing run sets in which we vary the inputs with experimental outputs

- Typical multi-D run sets are 128 runs, limited by available cycles
- Run sets are space-filling Latin Hypercube designs
- Current analysis is via Gaussian-process Bayesian modeling

(Sorry for the opaque jargon – no time to explain)

We use a model structure for calibration, validation & uncertainty assessment

x : **experimental input**

θ : **physics or calibration input**

Measured in calibration experiments with specific x and unknown theta (few of these)

Fits code over input space

$$y_m = \eta(x,\theta) + \delta(x) + \epsilon$$
$$y_c = \eta(x,\theta_c)$$

$$\Rightarrow \begin{cases} \eta(x,\theta) \\ \delta(x) \quad \epsilon \\ \pi(\theta | y_m, y_c) \end{cases}$$

Computed with specific values of x and theta (lots of these)

Models discrepancy between reality and code – speaks to validation

Replication error

First CRASH application: Holloway et al RESS 2011

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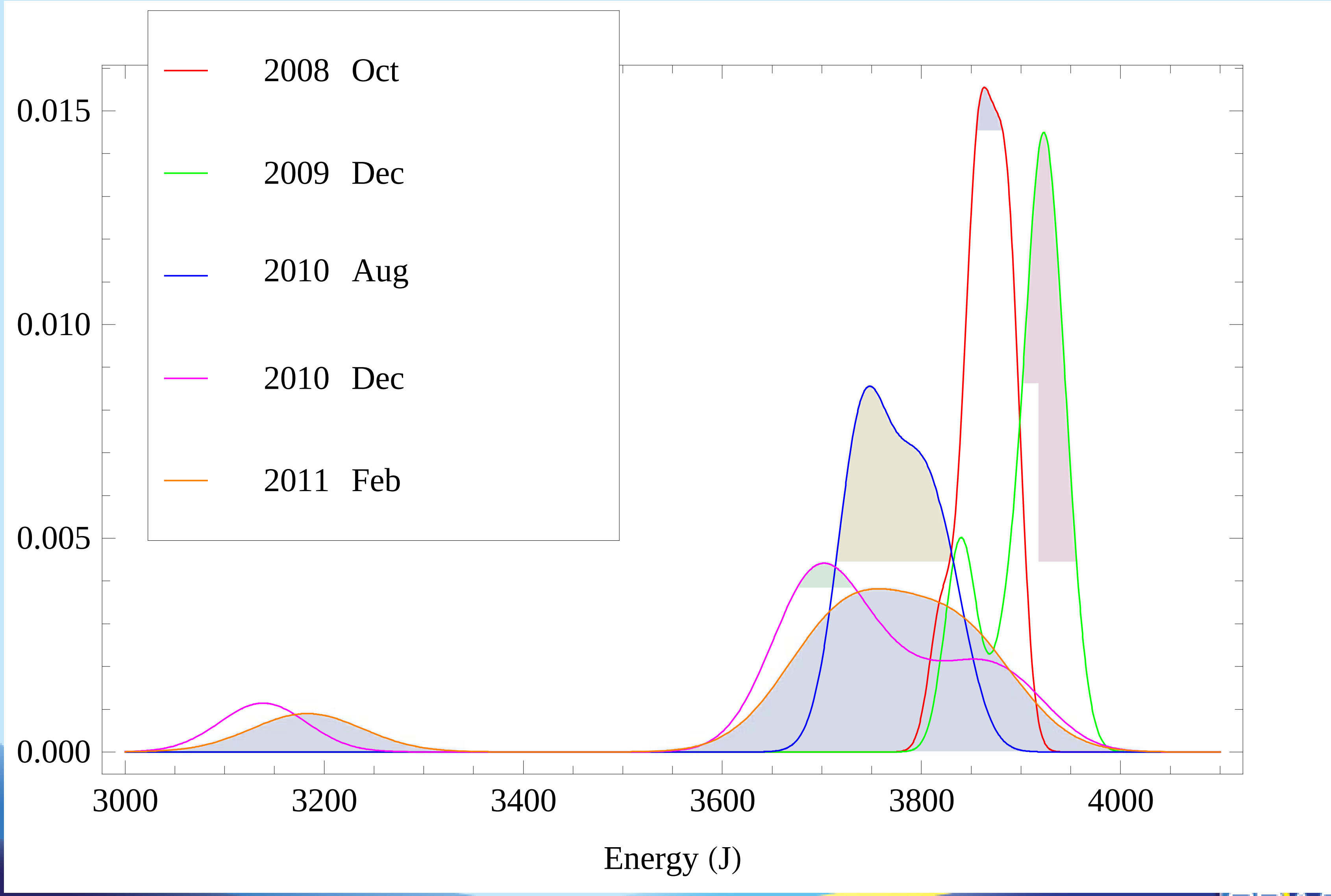
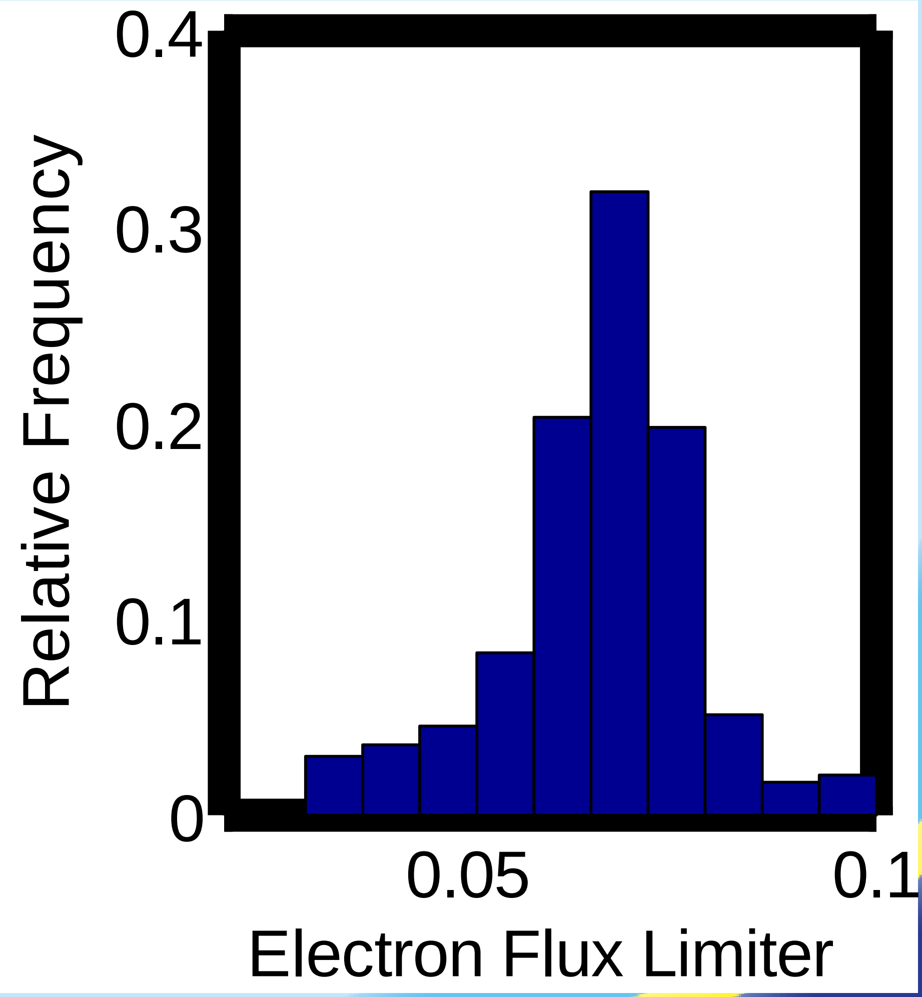
Kennedy & O'Hagan 2000, 2001

Laser energy is an experimental input and is uncertain, especially in advance



Flux limiter is an uncertain model parameter

- **Need to evaluate probability distribution of such parameters**
- **This can represent calibration or tuning**
- **If the residual discrepancy is small, we get calibration**
- **If not, we get tuning**



We combine such models …

- In sequence:
  - One set of experiments can be used to calibrate parameter probability distributions
  - These can be used in another model to predict
- Jointly:
  - Allows use of cheap and expensive models
  - Model-model discrepancy corrects the cheap model to the expensive one
  - Use a field-model discrepancy as before
  - Jointly fit both and calibrate/tune

The mathematical structure for joint models using two simulation codes is not too complex

Common theta values put in M1 & M2

M1-theta tuned to model M2

Theta values put in model M1 only

Theta values in M2 only

$$
\begin{aligned}
\mathrm{BOT}_1 &= \eta_{\mathrm{BOT}}(x, t_1, t_c) \\
\mathrm{BOT}_2 &= \eta_{\mathrm{BOT}}(x, \theta_1, t_c) + \delta_{1\to 2}(x, t_2, t_c) \\
\mathrm{BOT}_m &= \eta_{\mathrm{BOT}}(x, \theta_1, \theta) + \delta_{1\to 2}(x, \theta_2, \theta) \\
&\quad + \delta(x) + \epsilon
\end{aligned}
$$

Tuned values of theta

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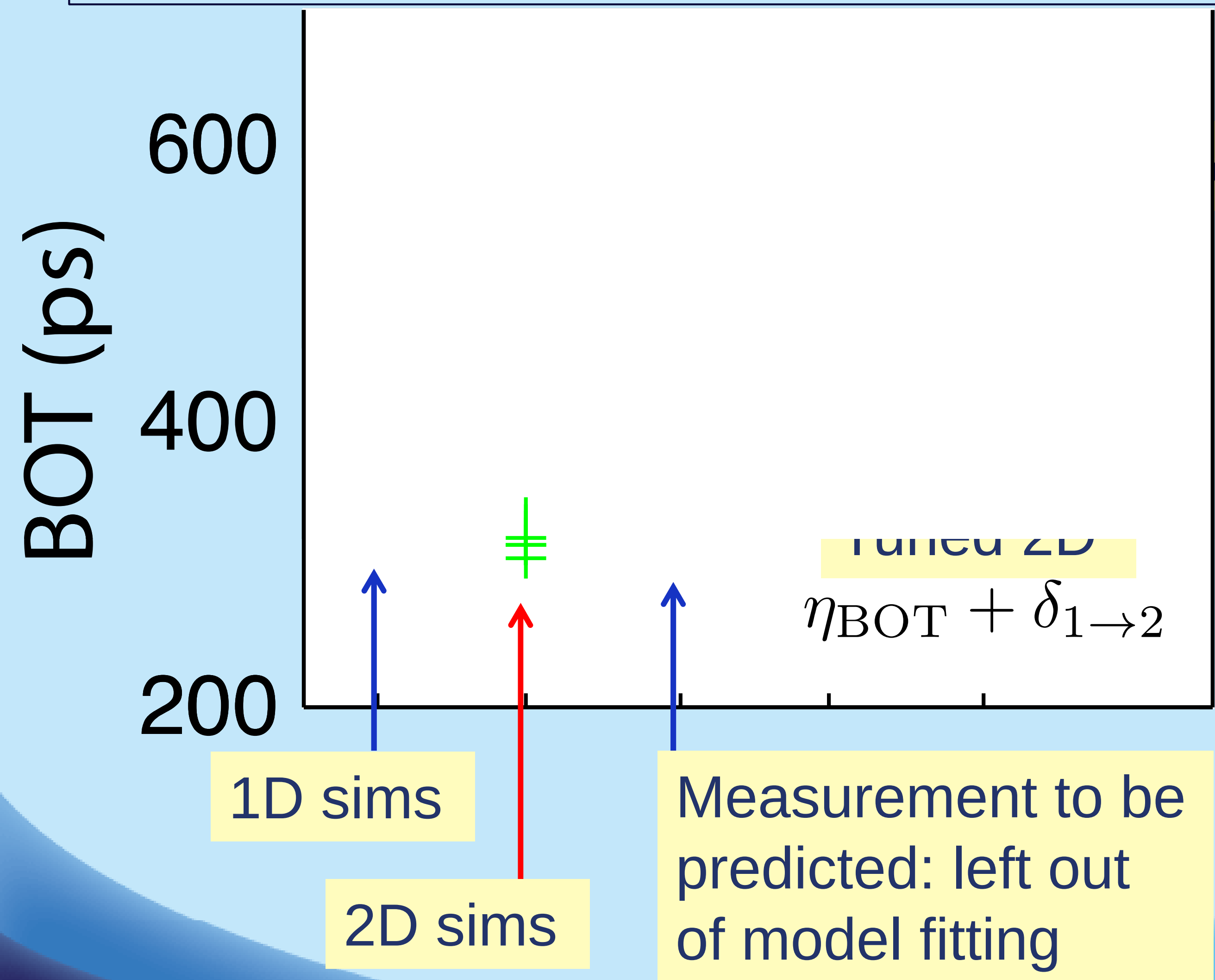
Using this structure we predicted shock breakout time (BOT) using 1D & 2D codes



This was preparation for jointly using 2D multigroup and 3D gray

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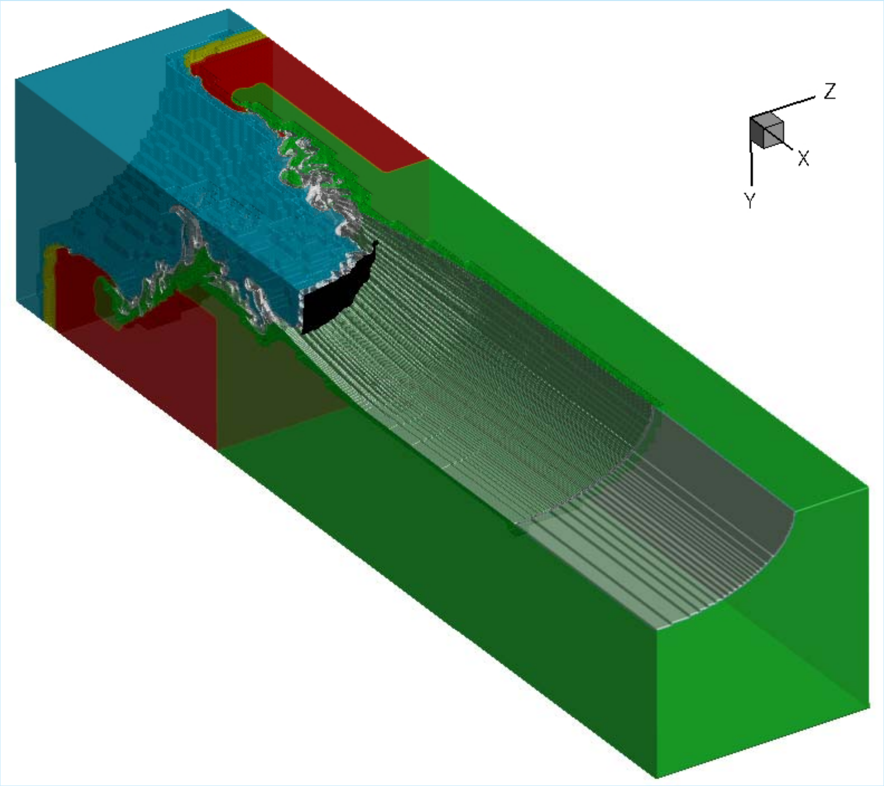
We are now working to combine complex models and predict our complex experiment

- Combine predictions from multiple integral models that are not a strict hierarchy
  - Faster running models can help explore the dependence on the input variables
  - Jointly use multigroup 2D and Gray 3D
- Tune faster running models to slower, better models
  - e.g. 2D circular tube to 3D oval tube
- Better understand calibration in combined models
- Propose best next sets of runs to optimally reduce expected integrated MSE in fitting
- Predict year 4/5 experiment

Thanks



http://aoss-research.engin.umich.edu/crash/