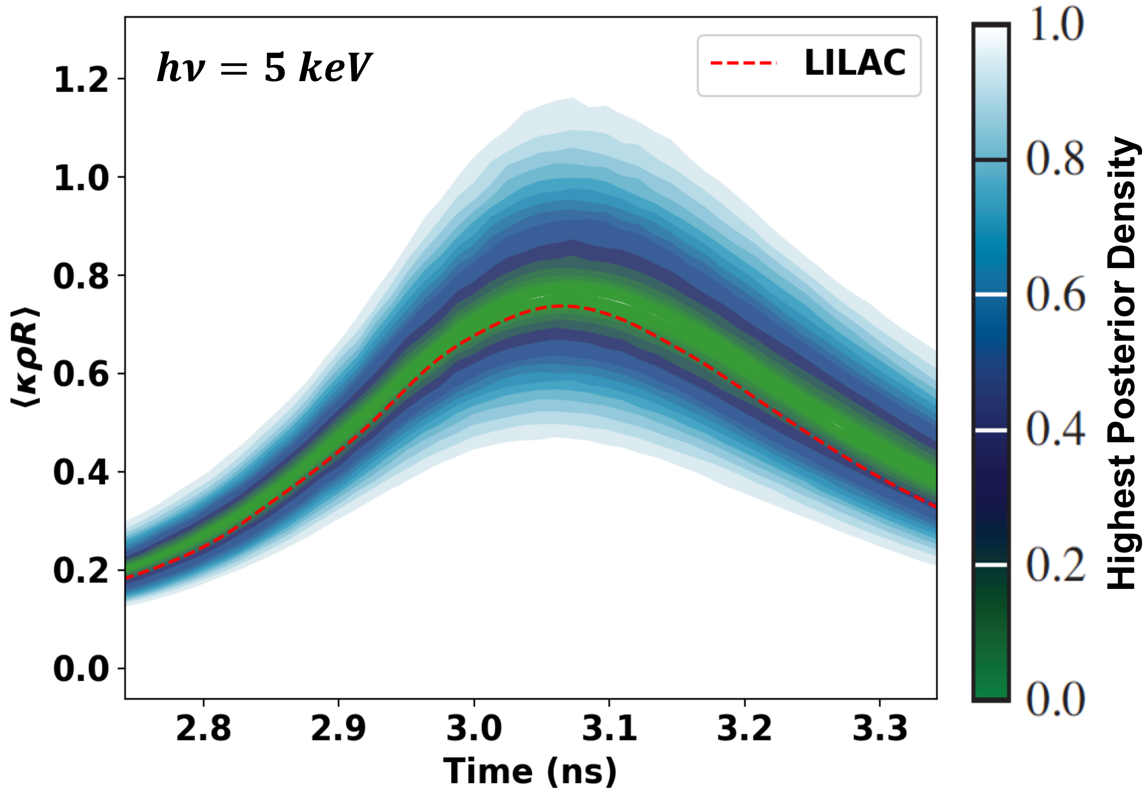
Constraining Energy Transport in Compressive Implosions



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Self-emission measurements of OMEGA 60 spherical implosion experiments constrain transport properties at Gbar pressures

- Convergent high energy density (HED) experiments are able to assemble materials to Gbar pressures.

- The measured self-emission from these experiments strongly depends on energy transport quantities such as the opacity of the shell and the thermal conductivity of the hotspot.

- A semi-analytic model in a Bayesian inference framework is used to perform a synthetic study to understand the sensitivity of the measured emission to the underlying transport.

Collaborators

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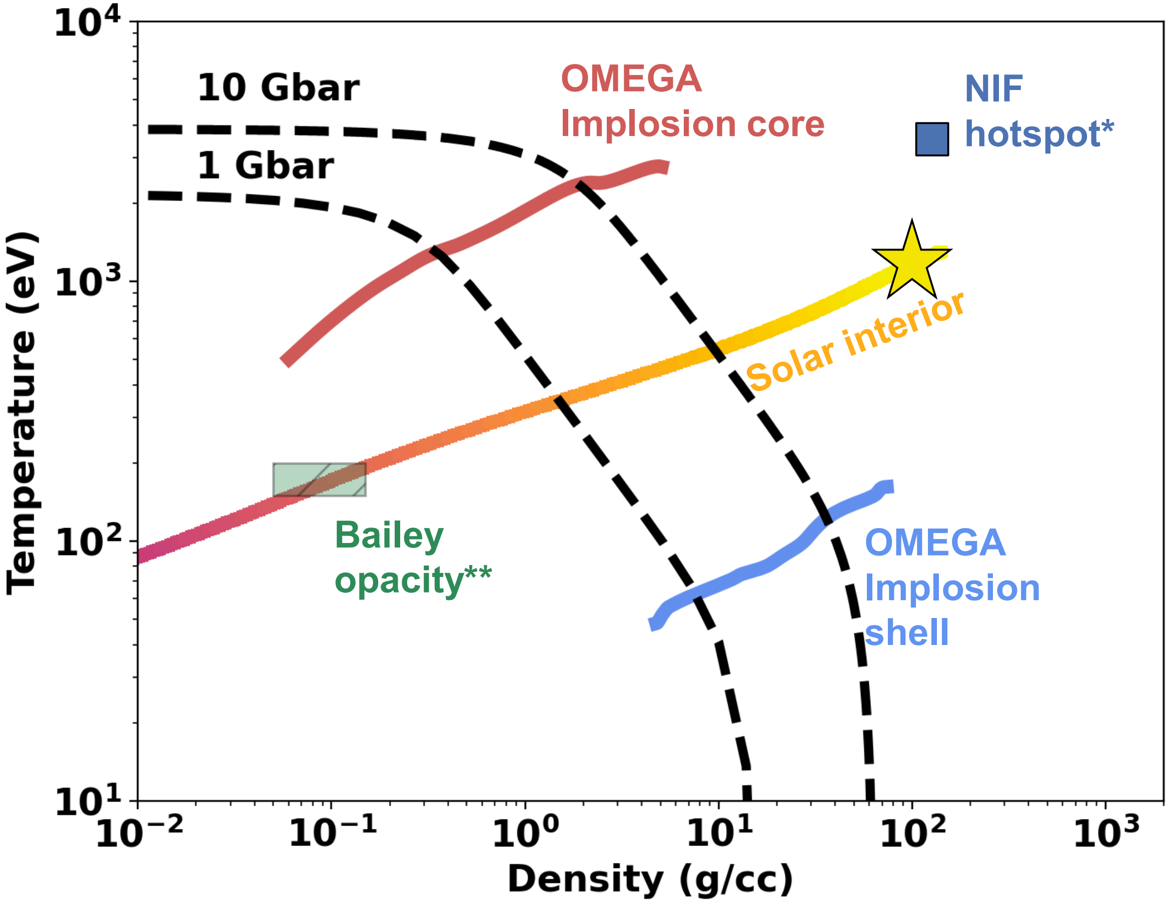
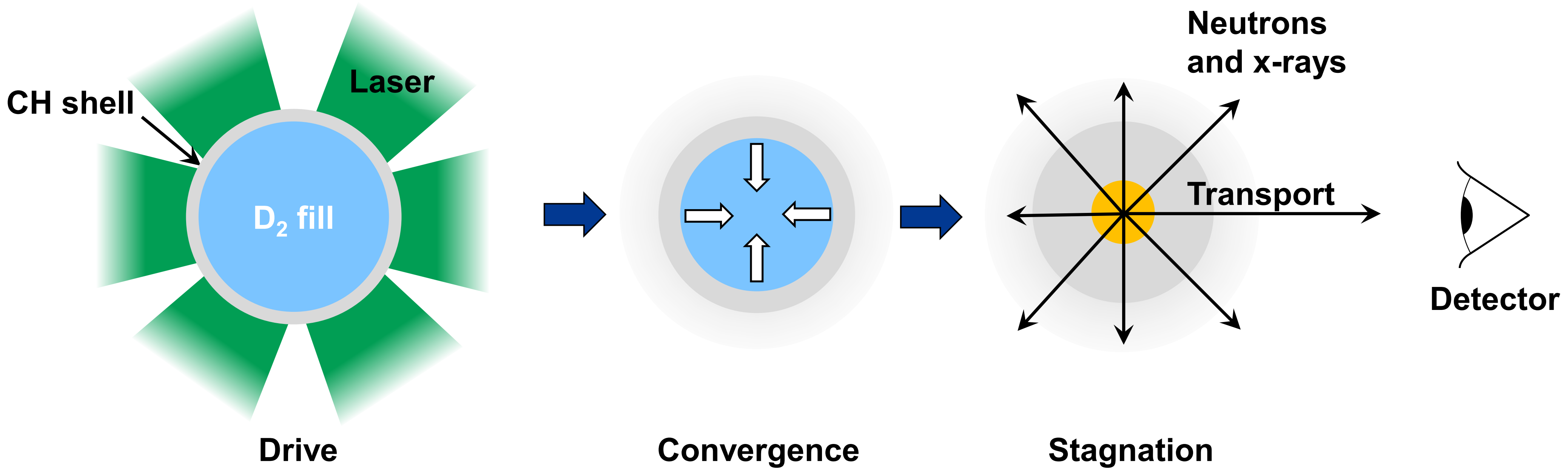
Implosion experiments access some of the most extreme states of matter achievable in a laboratory setting.

- The Gbar conditions reached in implosion experiments are relevant to solar interiors, fusion plasmas, etc.
- Material properties are not well-known at Gbar conditions**, which makes characterizing these extreme states challenging
- Much effort has gone into diagnostic development for implosion experiments for ICF applications



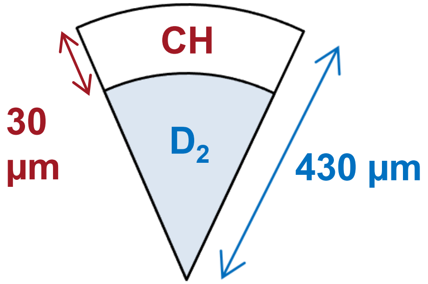
* P.K. Patel, et. al. *Phys. Plasmas* 27 (2020).
** J.E. Bailey, et. al. *Nature* 517 (2015).

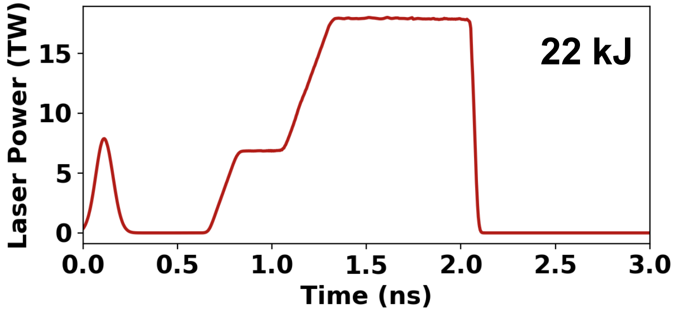
In OMEGA-60 convergent HED experiments, a gas-filled plastic capsule is directly driven by 60 beams in a spherical geometry, causing it to implode.



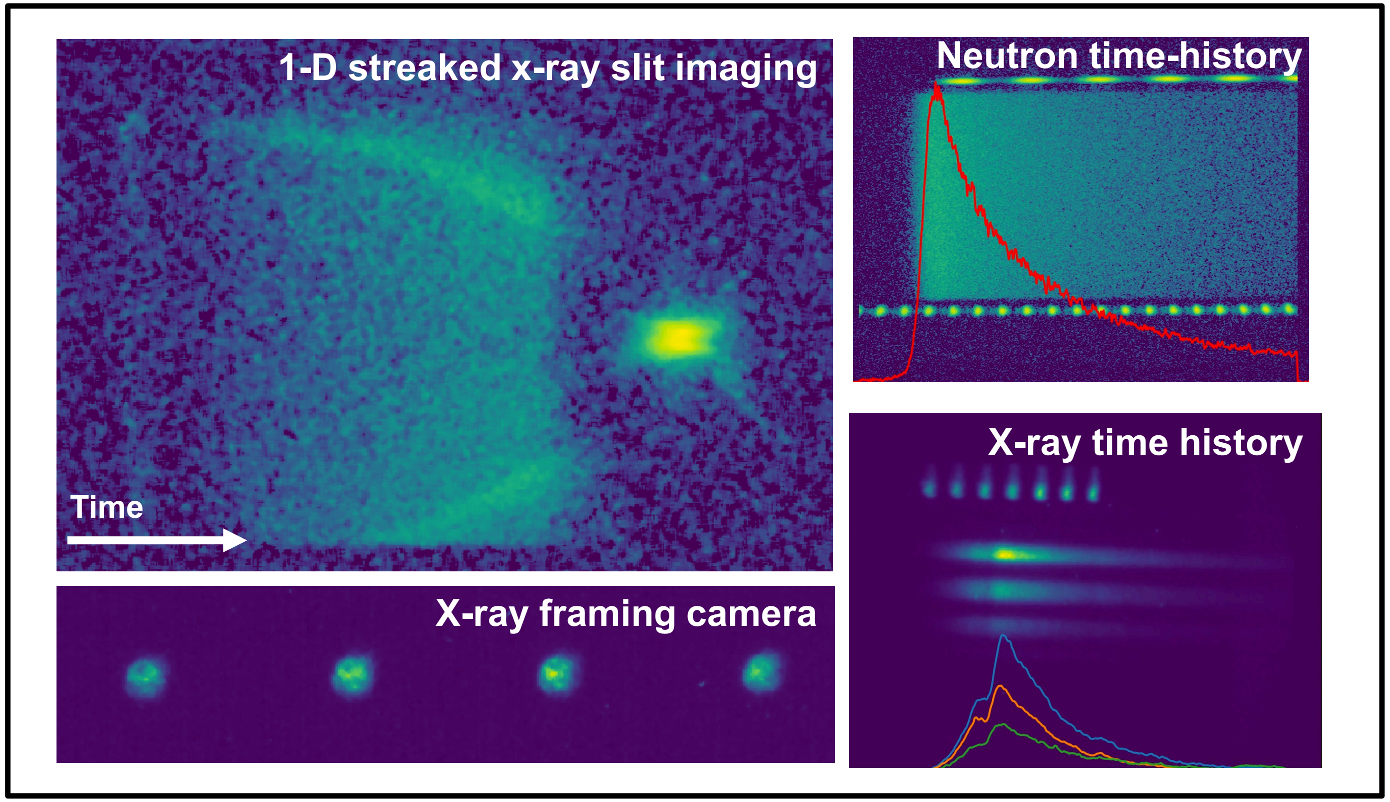
Self emission carries information about the transport properties of the hotspot and the dense shell

Self-emission data was obtained for deuterium-filled 30 μm thick plastic shell implosions on the OMEGA 60 laser system.



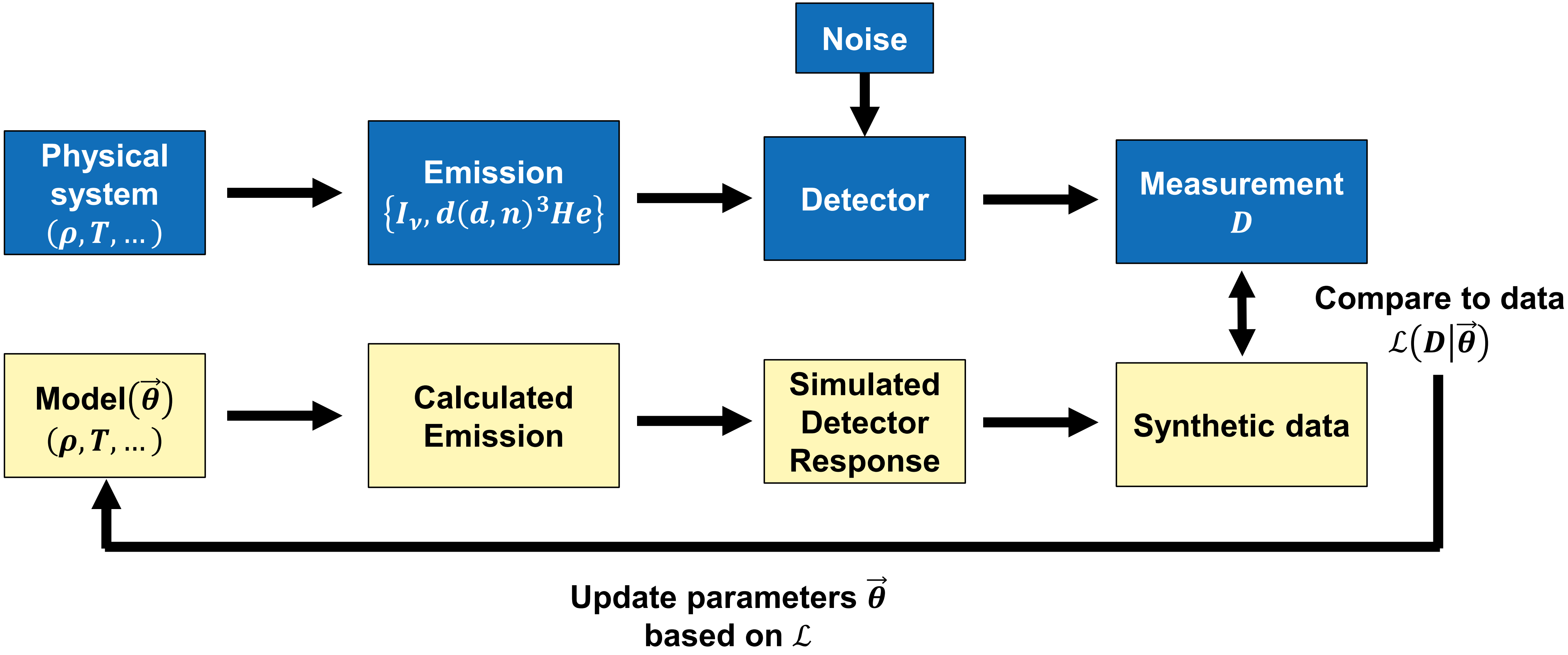


Experimental Data



Datasets from implosion experiments are highly-integrated but information-rich

A parameterized model in a Bayesian inference framework can be used to constrain the underlying states and rigorously quantify uncertainties.*



We need to develop a parameterized model of the system

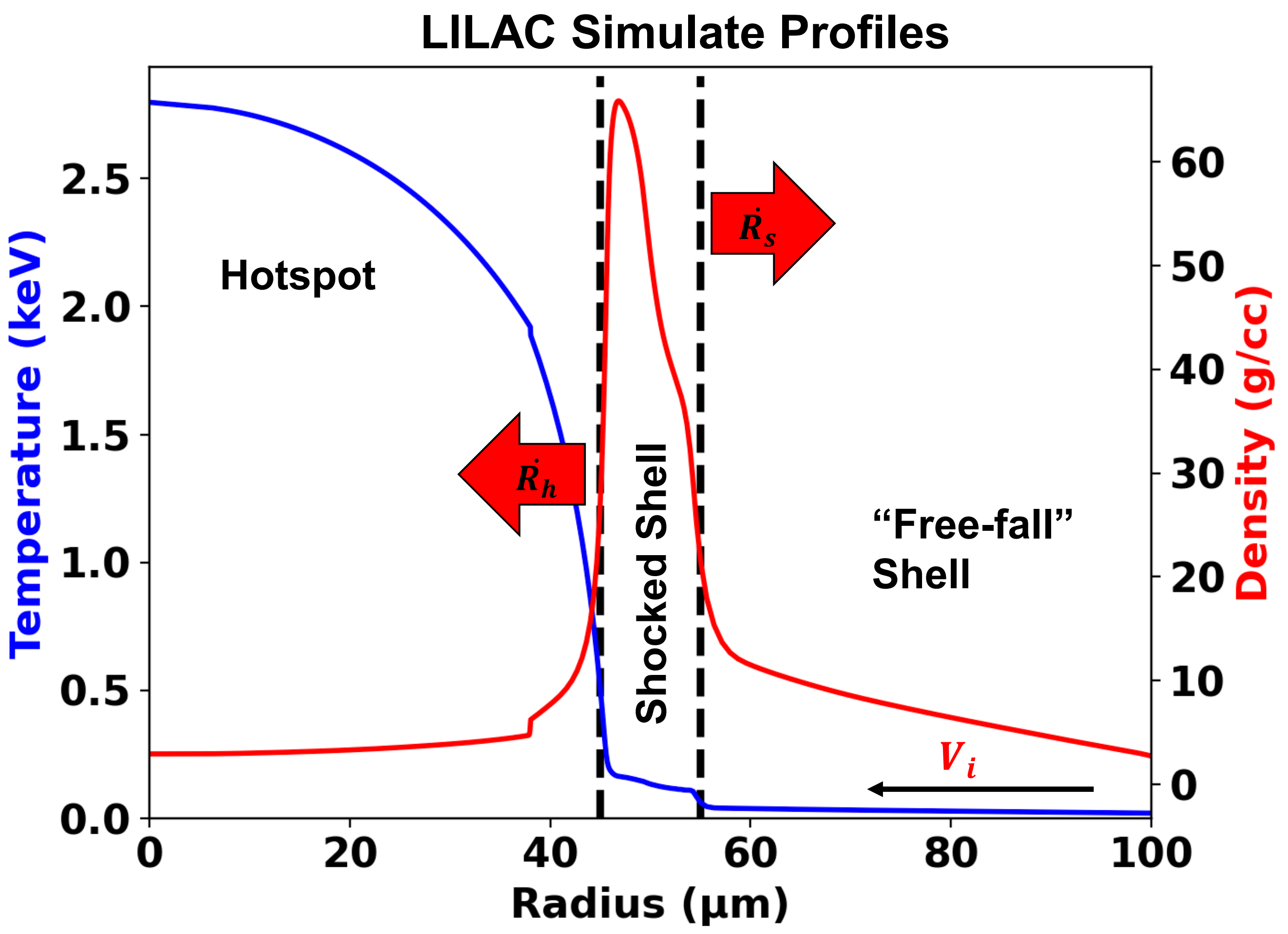
* J.J. Ruby et. al. *Phys Rev E*, 102(5):53210 (2020).

A simplified picture of the system can be constructed by dividing the system into three regions wherein a different energy transport mechanism dominates

- The system is governed by a set of computationally-expensive coupled PDEs:

$$
\begin{aligned}
&i. && \frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \\
&ii. && \frac{\partial \rho \vec{u}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) + \vec{\nabla} p = 0 \\
&iii. && \frac{\partial \epsilon}{\partial t} + \vec{\nabla} \cdot \left(\vec{u} \cdot (\epsilon + p)\right) = S
\end{aligned}
$$

- The system can be broken into three regions*:
  - Hot spot $0 < r < R_h$
  - Shocked shell $R_h < r < R_s$
  - "Free-fall" shell* $r > R_s$
- In each region, the PDEs can be simplified under some assumptions



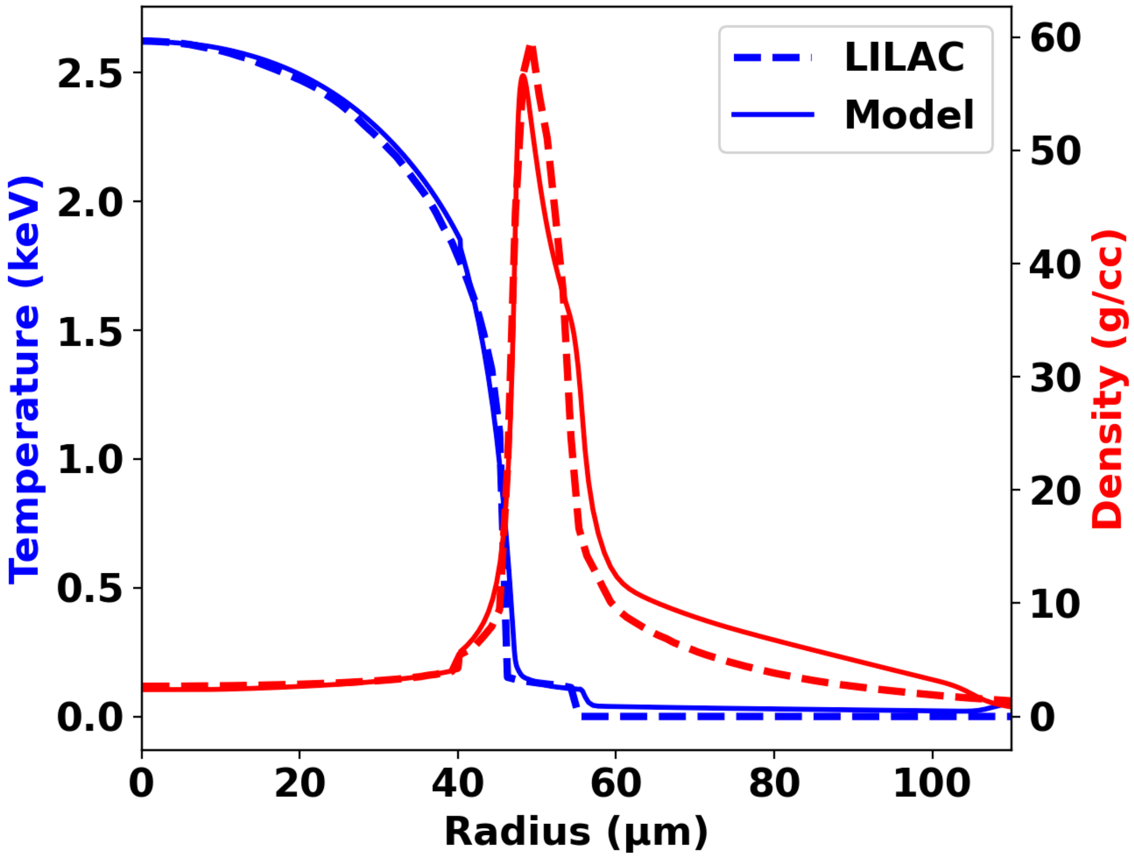
* R. Betti, et. al. *Phys. Plasmas* 9, 2277 (2002).

A semi-analytic, parameterized model that reproduces the full hydrodynamics calculation can be derived using this simplified picture

- The PDES can be simplified into a system of 5 ODEs with 12 parameters[*, **, †]

1. $\frac{d}{dt}\left(pR_h^{3\gamma_{D_2}}\right) = 0$	Adiabatic compression
2. $\frac{d}{dt}\left(\frac{pR_h^3}{T}\right) = \kappa_0 R_h T^{\alpha}$	Energy conservation
3. $\frac{dM_{ss}}{dt} = M_{in} - M_{out}$	Mass conservation
4. $\frac{d(M_{ss}\langle U_{ss}\rangle)}{dt} = \Sigma \mathrm{F_{sh}}$	Momentum conservation
5. $\frac{dR_s}{dt} = -\frac{\gamma_{CH}-1}{2} u_{ff} + \frac{\gamma_{CH}+1}{2} U_{ss}\|_{R_s}$	Rankine-Hugoniot
6. $\langle U_{ss}\rangle = f\left(R_h, \dot{R}_h, R_s, \dot{R}_s, \ldots\right)$	Closure relation

The reduced model emphasizes the flow of energy between regions.



* R. Betti, et. al. *Phys. Plasmas* 9, 2277 (2002).
** J. Sanz, et. al. *Phys. Plasmas* 12, 112702 (2005).
† A.R. Christopherson, et. al. *Phys. Plasmas* 25, 012703 (2018).

The parameterized model can be used to generate synthetic self-emission data

- The spectral radiance is calculated by solving the equation of radiative transfer:

$$\vec{\Omega}\cdot\vec{\nabla}I_\nu = \rho\kappa'_\nu(T,\rho)(S_\nu(T,\rho) - I_\nu)$$

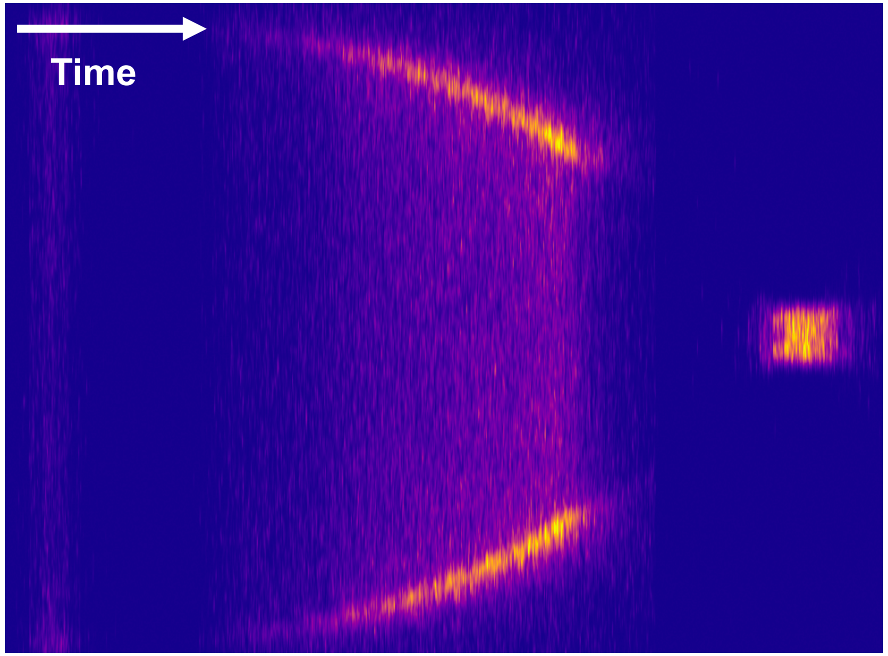
- Neutron emission is computed from the reaction rate:

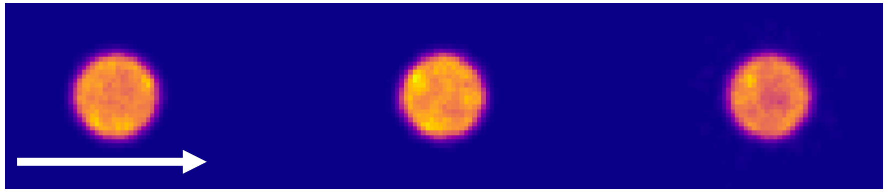
$$\frac{dN}{dt} = \frac{\rho^2}{2m_D}\int_0^\infty \sigma v f(v)dv$$

- The emission is fed through realistic detector responses to generate a synthetic dataset

We conduct synthetic study using data generated from LILAC to understand sensitivities to transport quantities

Synthetic Data

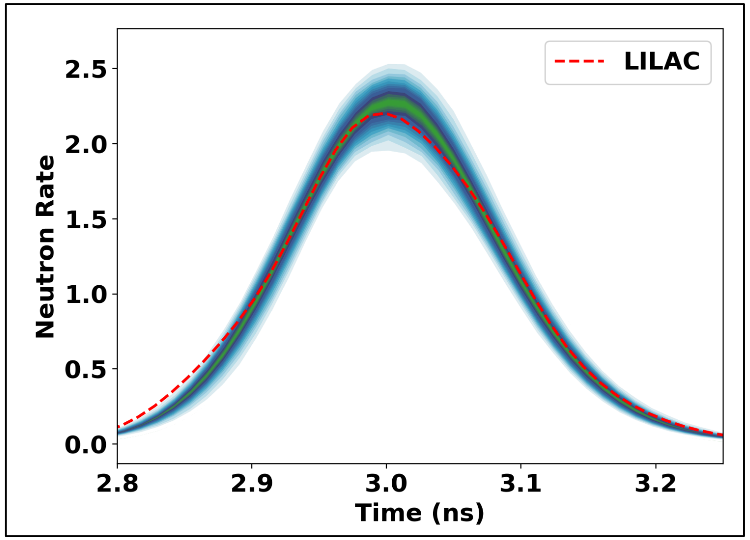




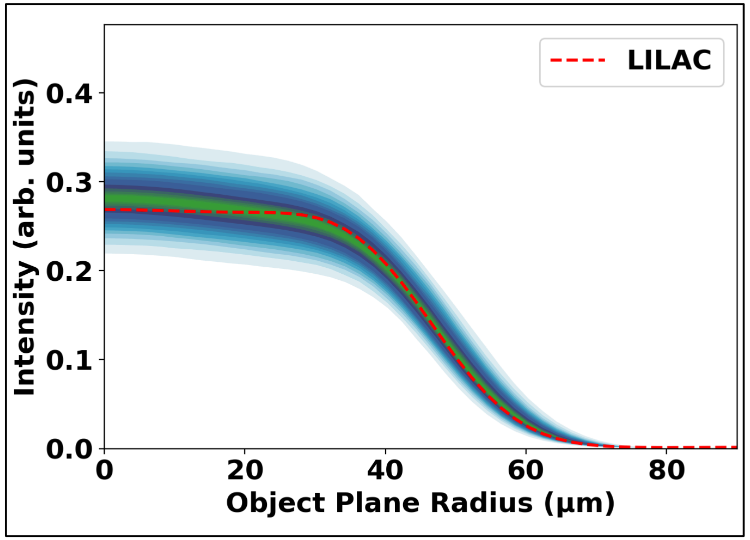
*T. Hilsabeck, *PYRIMADS PYthon Radiation IMaging And Detection Simulation,* Prompt Radiation Detection and Imaging Workshop *(2022)* LLNL-PRES-829846

The reduced model and Bayesian inference is able to reproduce the synthetic data from LILAC.

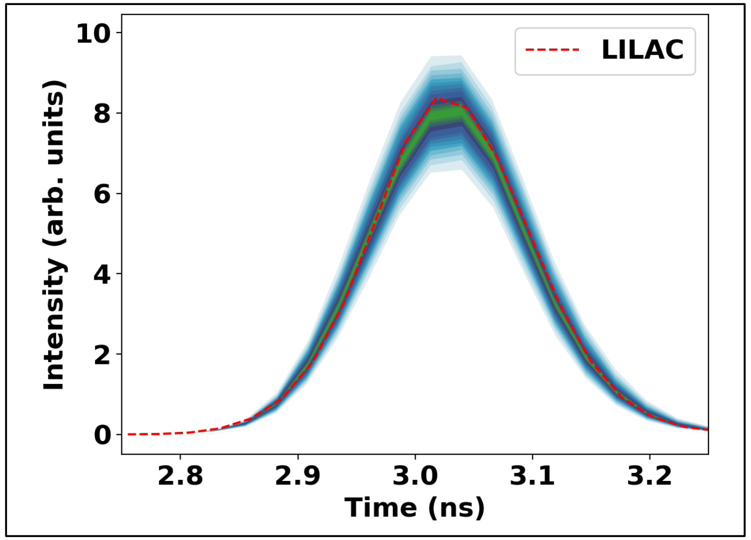
Neutron Time History



Framing Camera Lineout

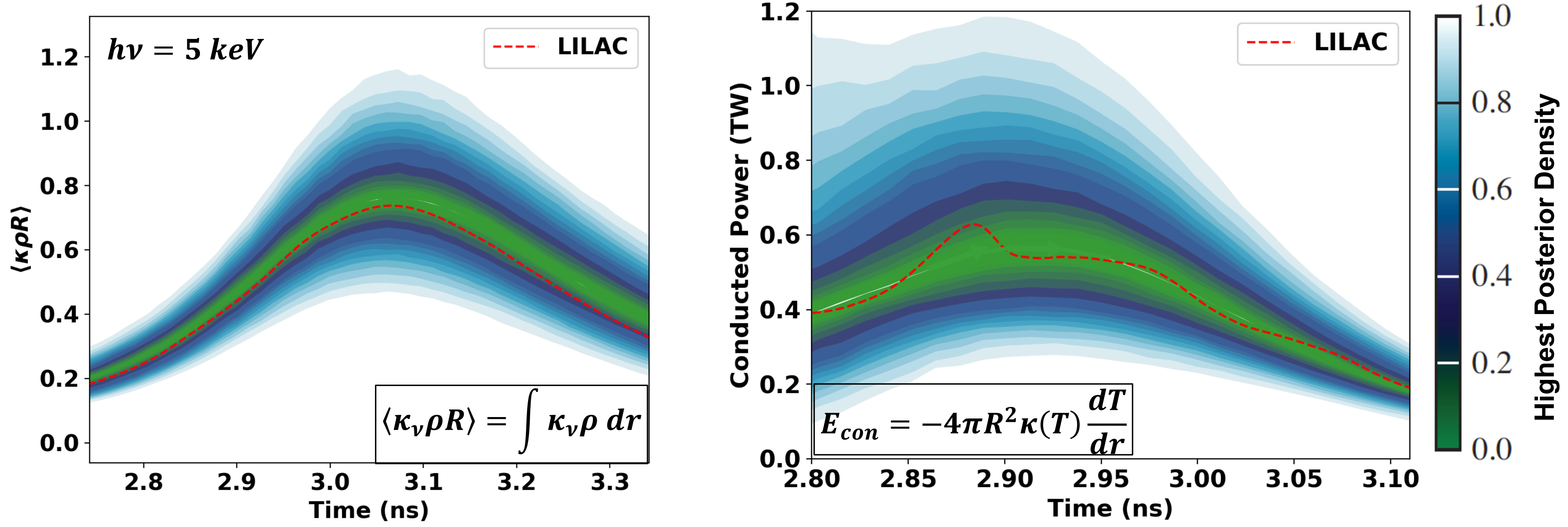


X-ray Time History



The data is well-explained by the simplified model

The reduced model and synthetic data constrain key transport quantities of the system.



Self-emission measurements of CH shell implosions are sensitive to energy transport properties at Gbar conditions

Summary

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Self-emission measurements of CH shell implosions are sensitive to energy transport properties at Gbar conditions