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CIFS

Neutron backscatter edges – a novel diagnostic for Inertial Confinement Fusion

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3 – Lawrence Livermore National Laboratory

**Currently at Sandia National Laboratories*

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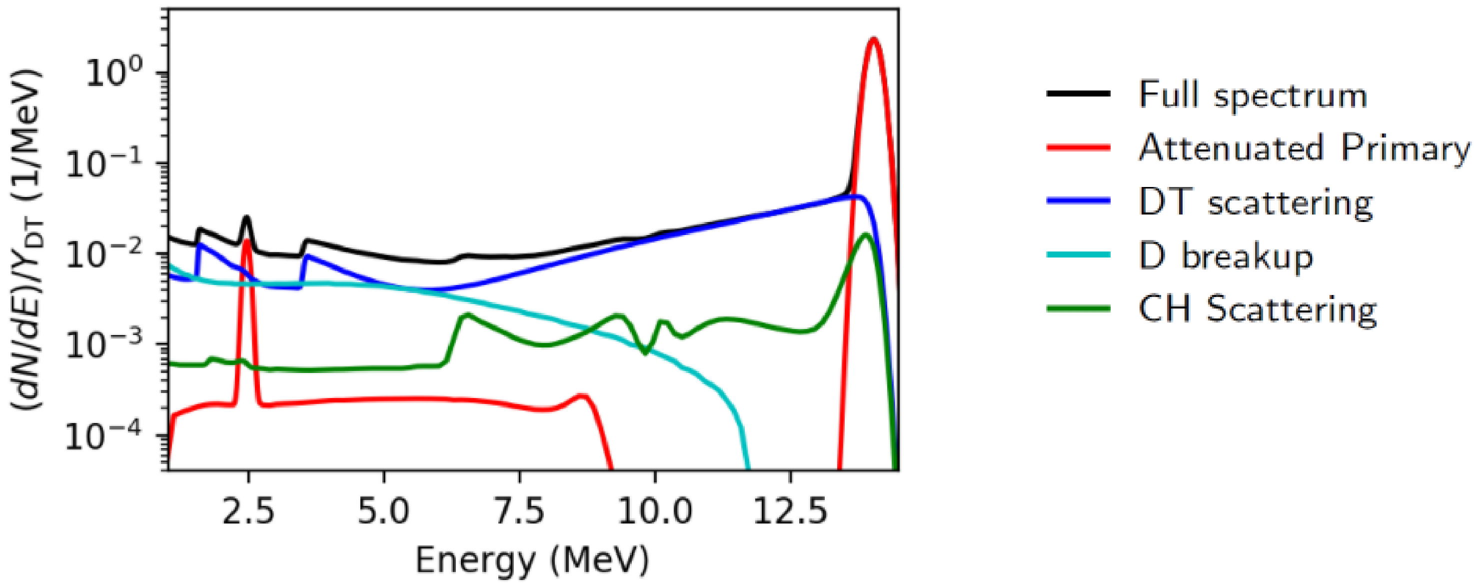
Overview

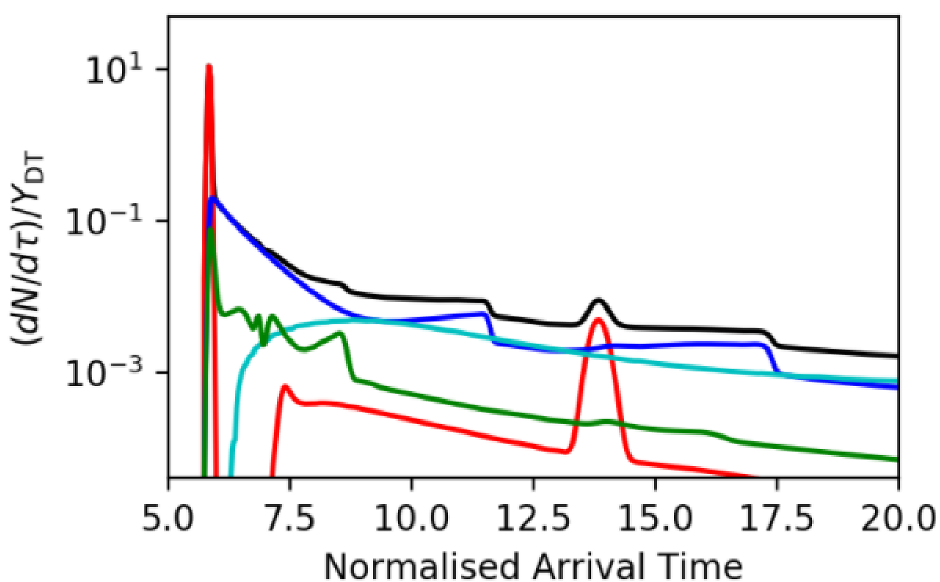
- Scattered neutron spectroscopy
- Why backscattered neutrons?
- Experimental results from OMEGA
- Outlook:
  - Multiple lines of sight and asymmetry
  - Edge measurements in an igniting capsule

Example neutron spectrum

Energy spectrum



Time of flight signal

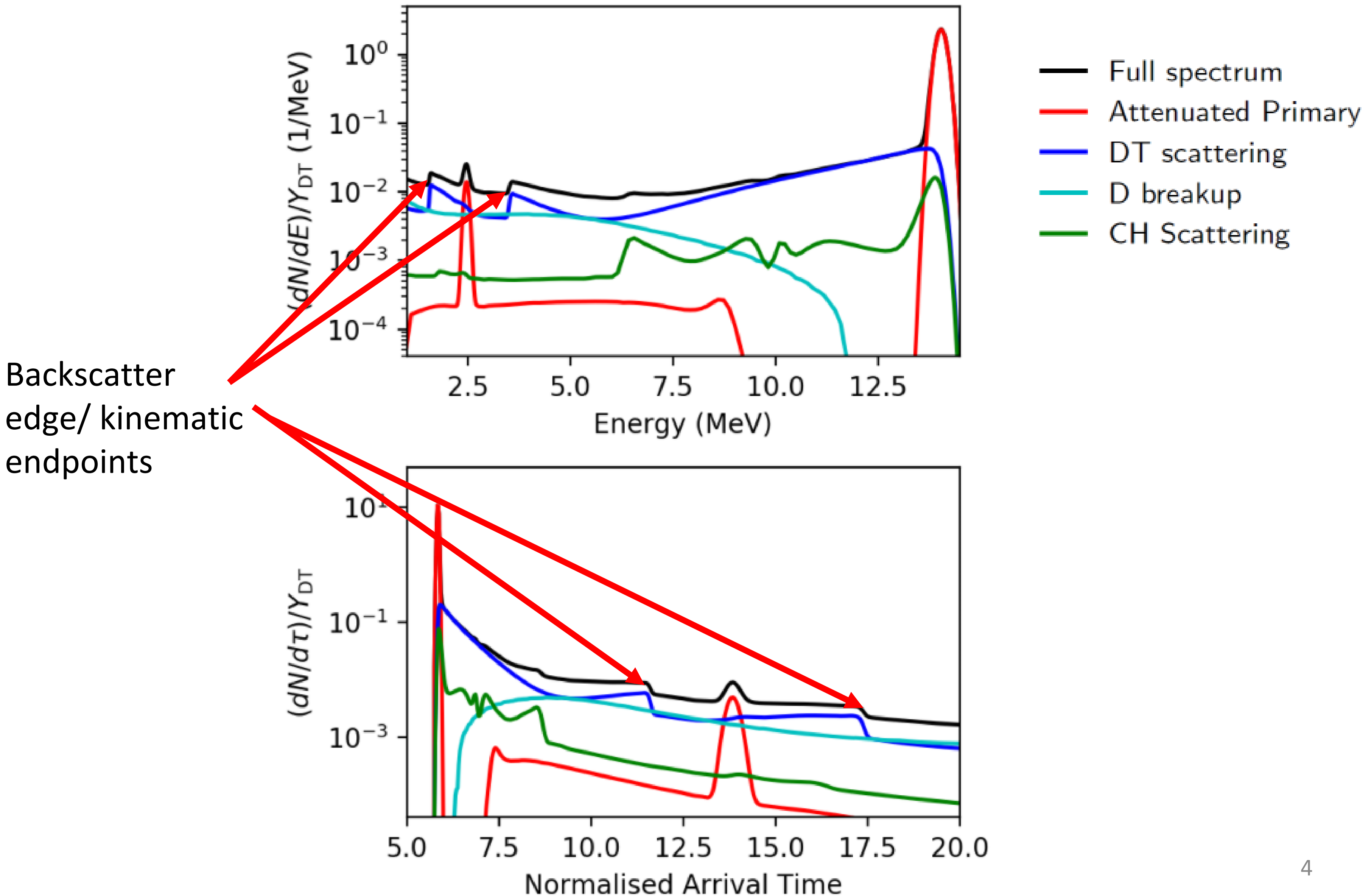


$$\rho R_{\text{tot}}(\text{g/cm}^2) = (20.4 \pm 0.6) \times dsr_{\text{10-12MeV}},$$

$$\rho R_{\text{fuel}}(\text{g/cm}^2) = (18.8 \pm 0.5) \times dsr_{\text{10-12MeV}}.$$

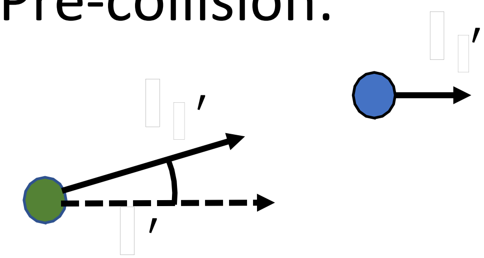
Johnson et al., RSI (2012)
Crilly et al., PoP (2018)

Example neutron spectrum

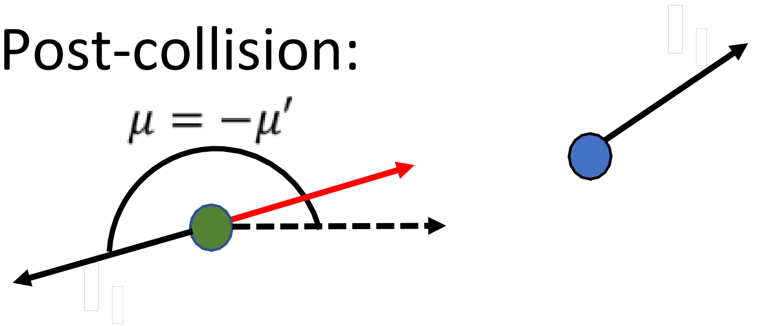


Backscatter

Pre-collision:



Post-collision:

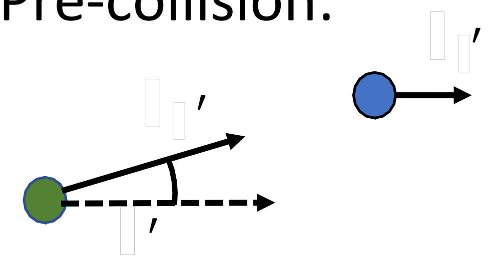


$$v_n = \frac{A-1}{A+1} v_n' - \frac{2A}{A+1} v_i' \mu'$$

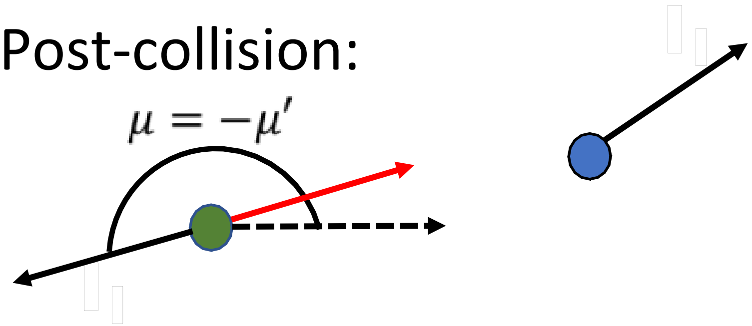
- Backscatter velocity related to the component of the ion motion in direction of neutron

Backscatter

Pre-collision:



Post-collision:



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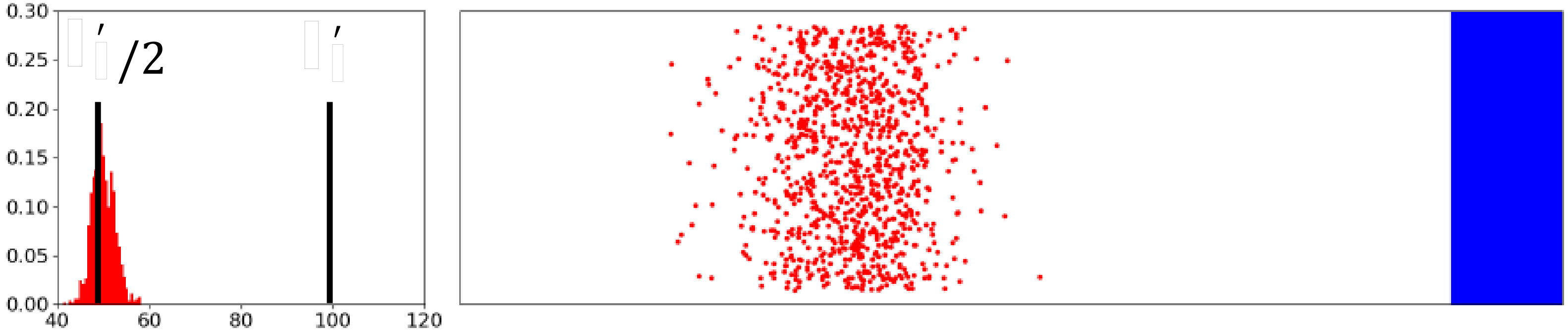
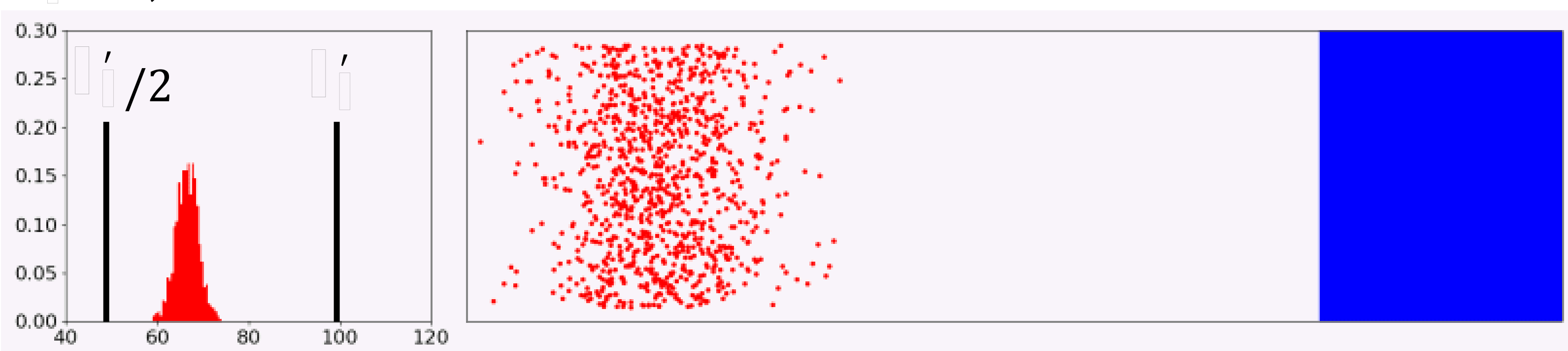
- Backscatter velocity related to the component of the ion motion in direction of neutron

$$v_n = \frac{A-1}{A+1} v_n' - \frac{2A}{A+1} v_i' \mu'$$

$= 0, \; = 0$



$\neq 0, \; = 0$



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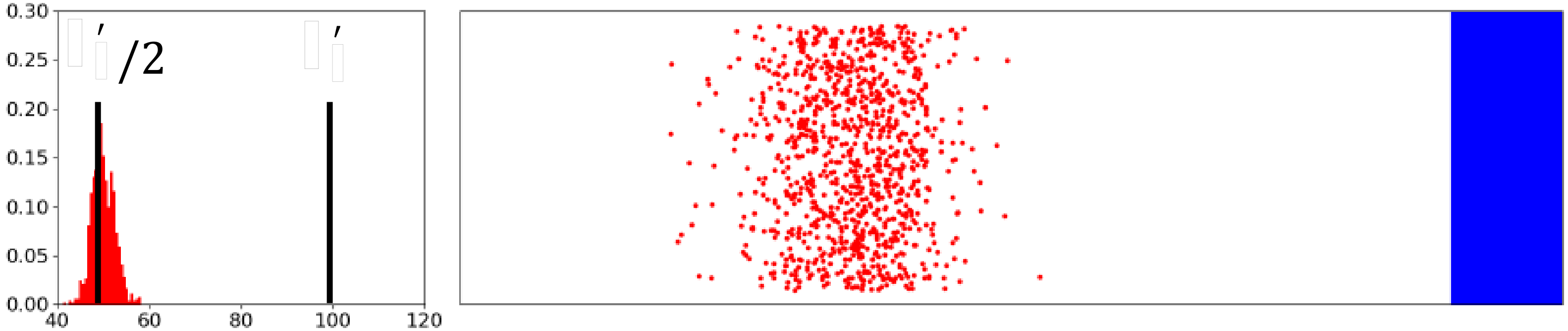

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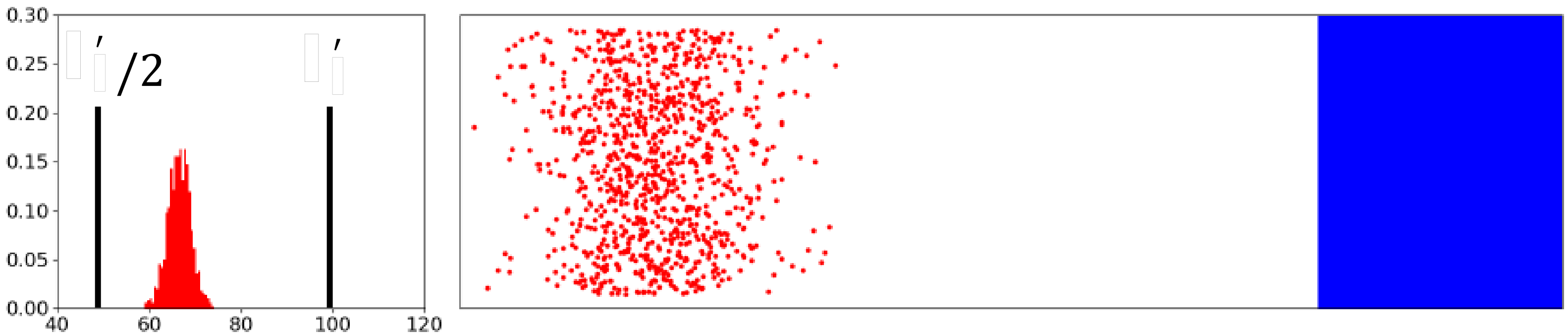

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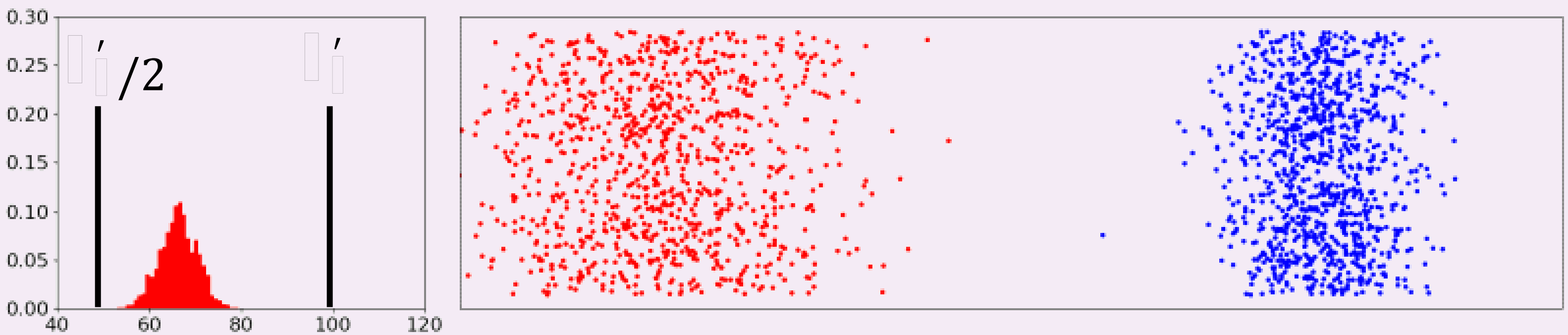
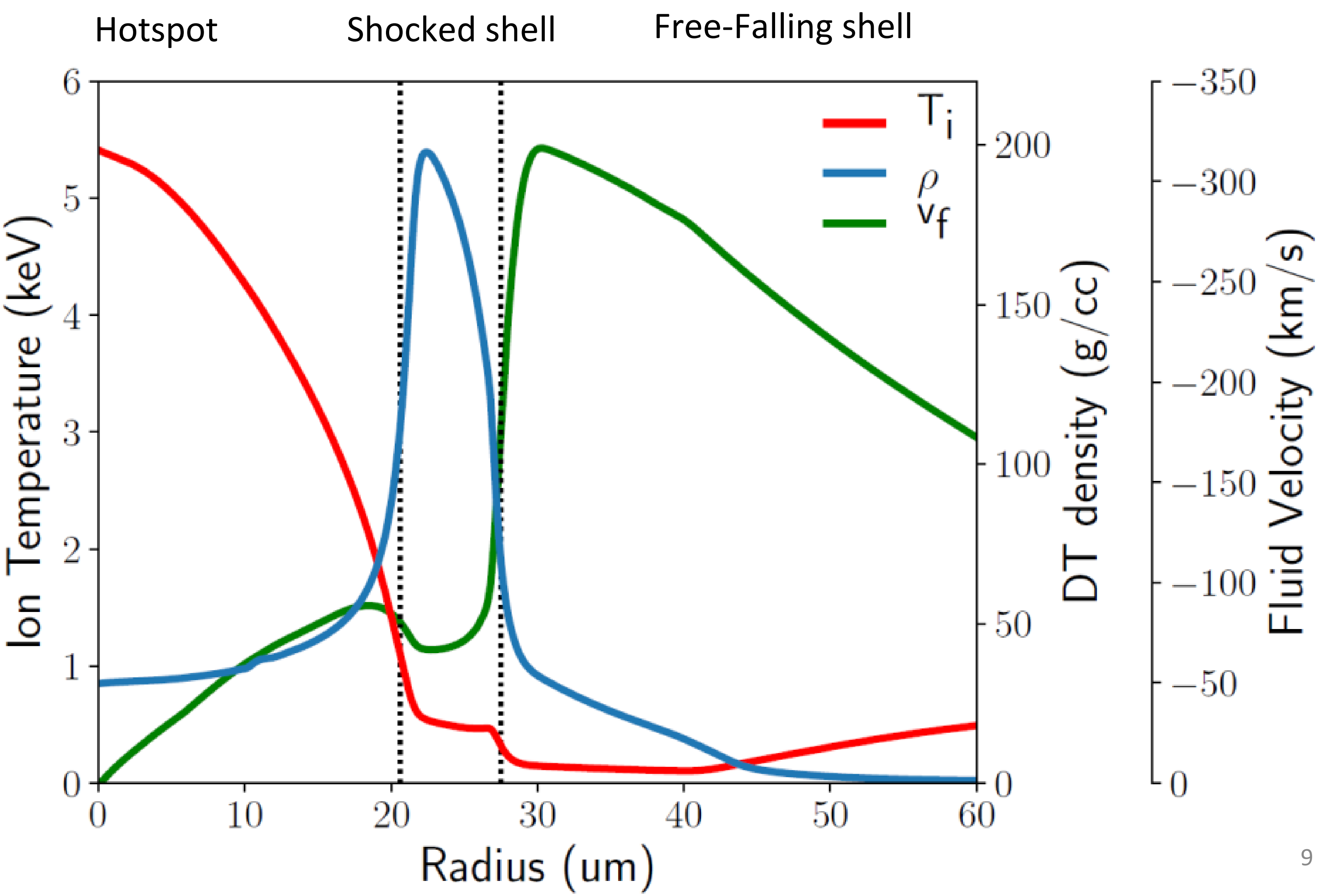


Where do neutrons scatter



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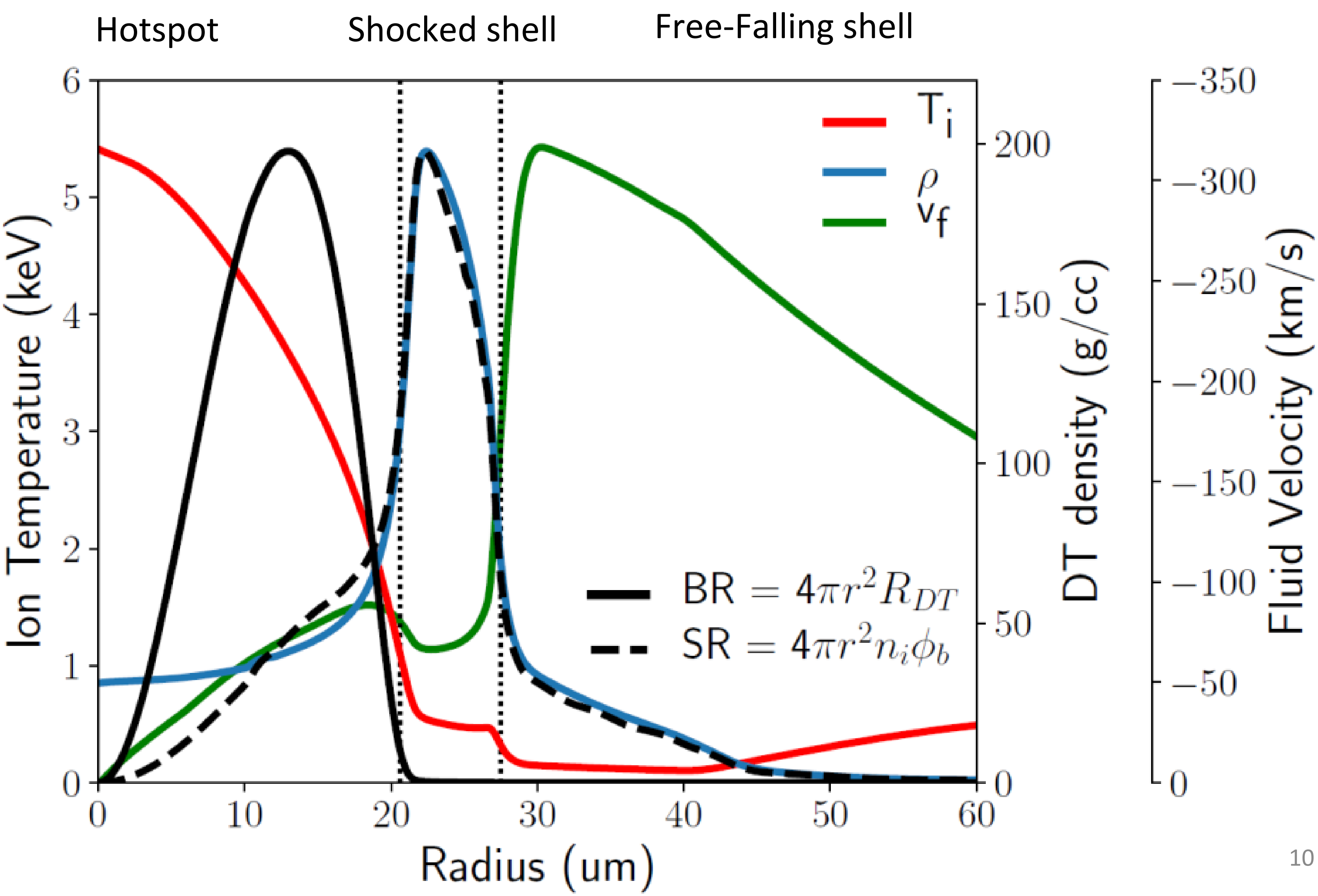

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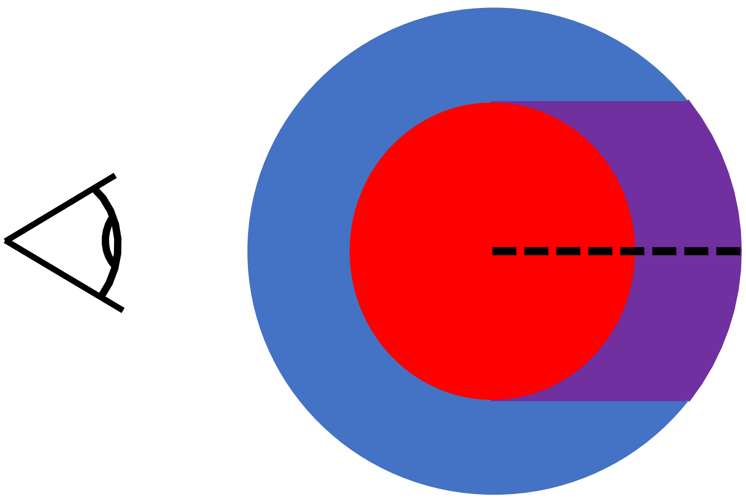
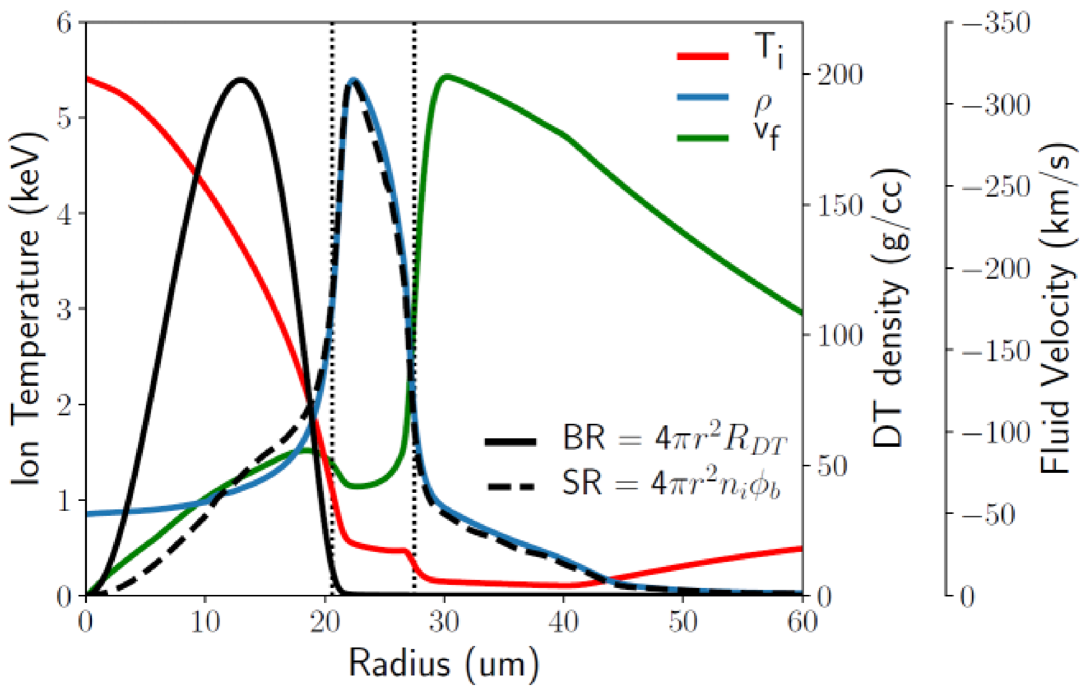
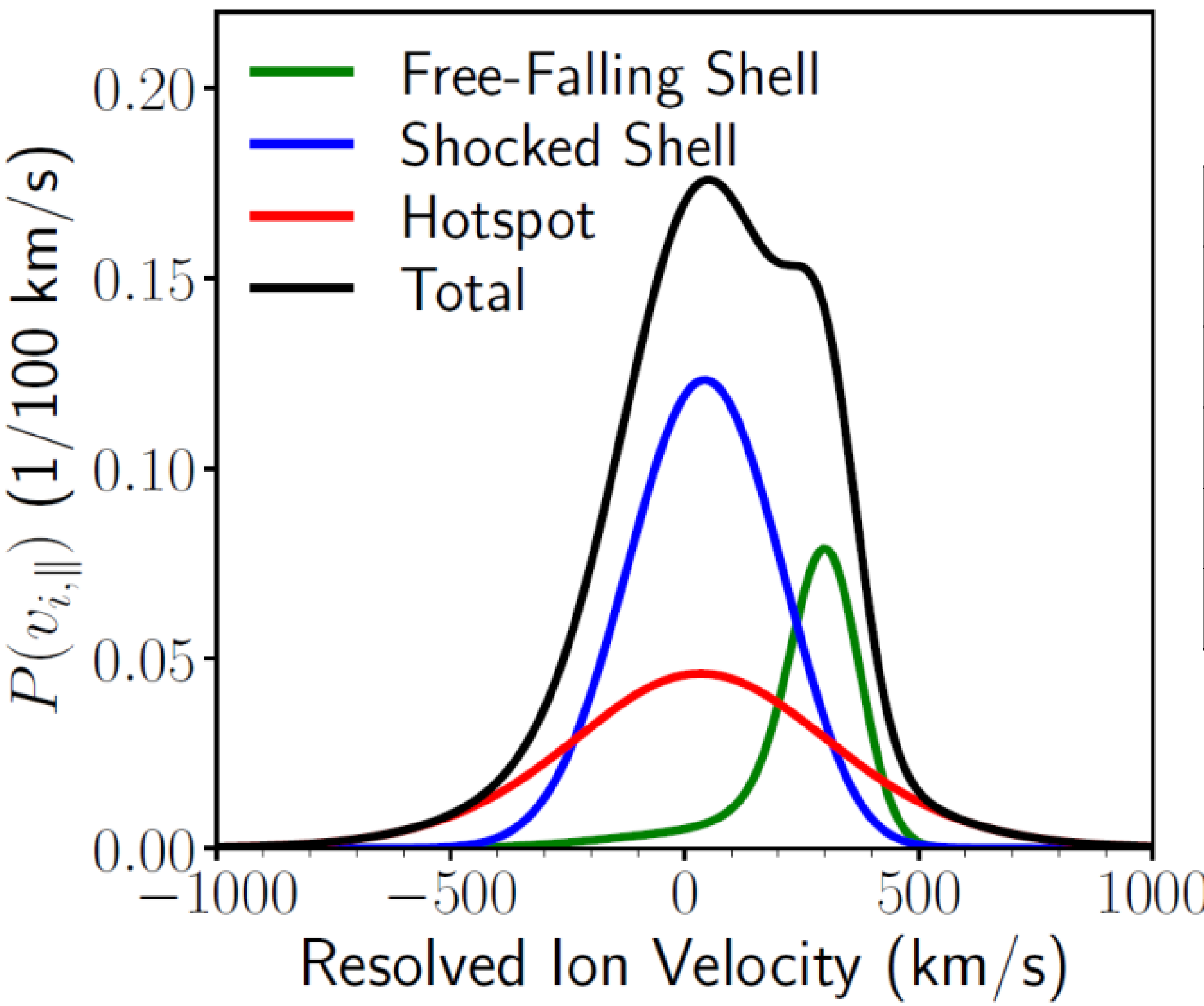
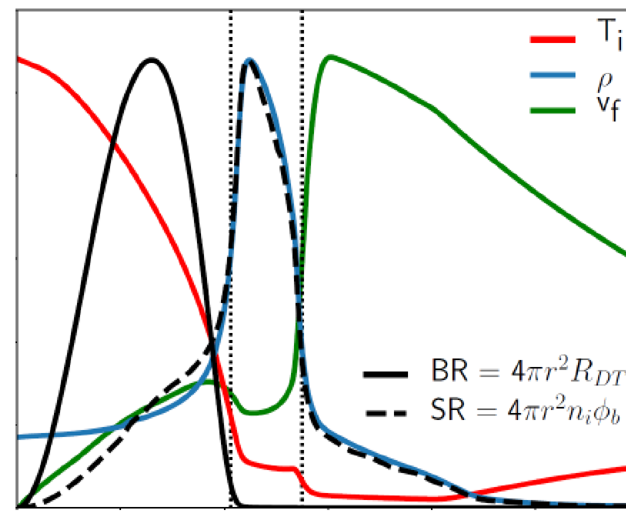




Scattering triton velocity distribution





Scattering triton velocity distribution

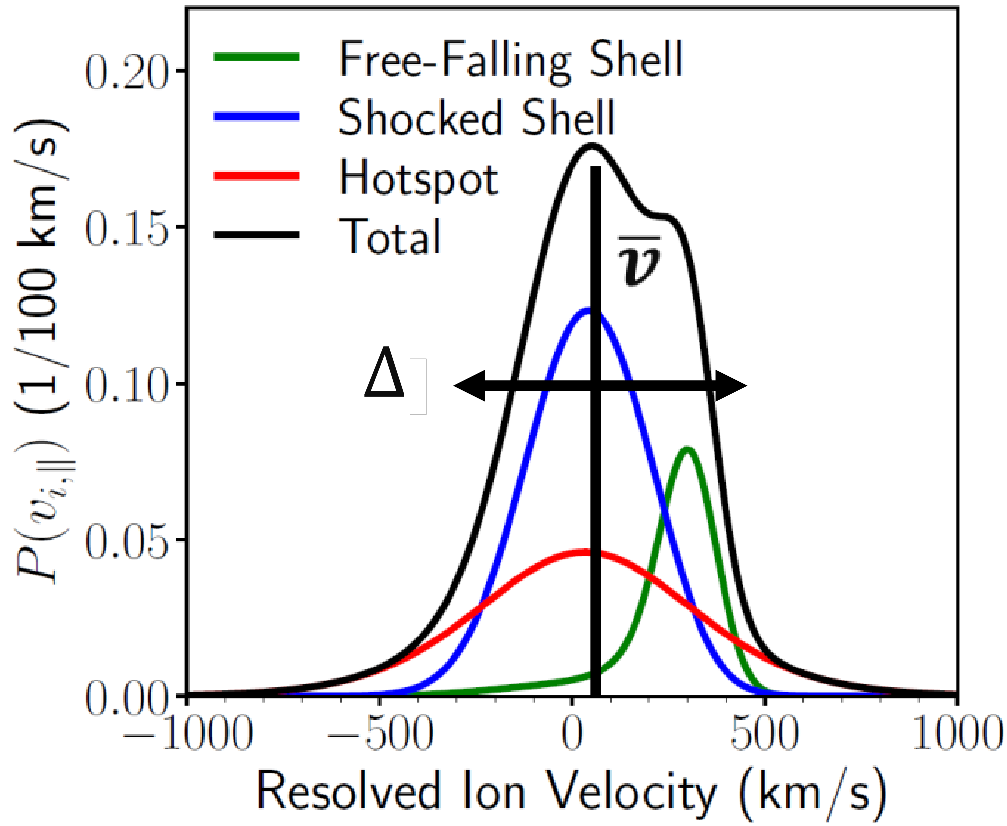
Taking moments (averaging is scatter weighted):
Mean scatter bulk flow:

$$\bar{v} = -\langle v_f \mu' \rangle$$

Apparent scatter temperature:

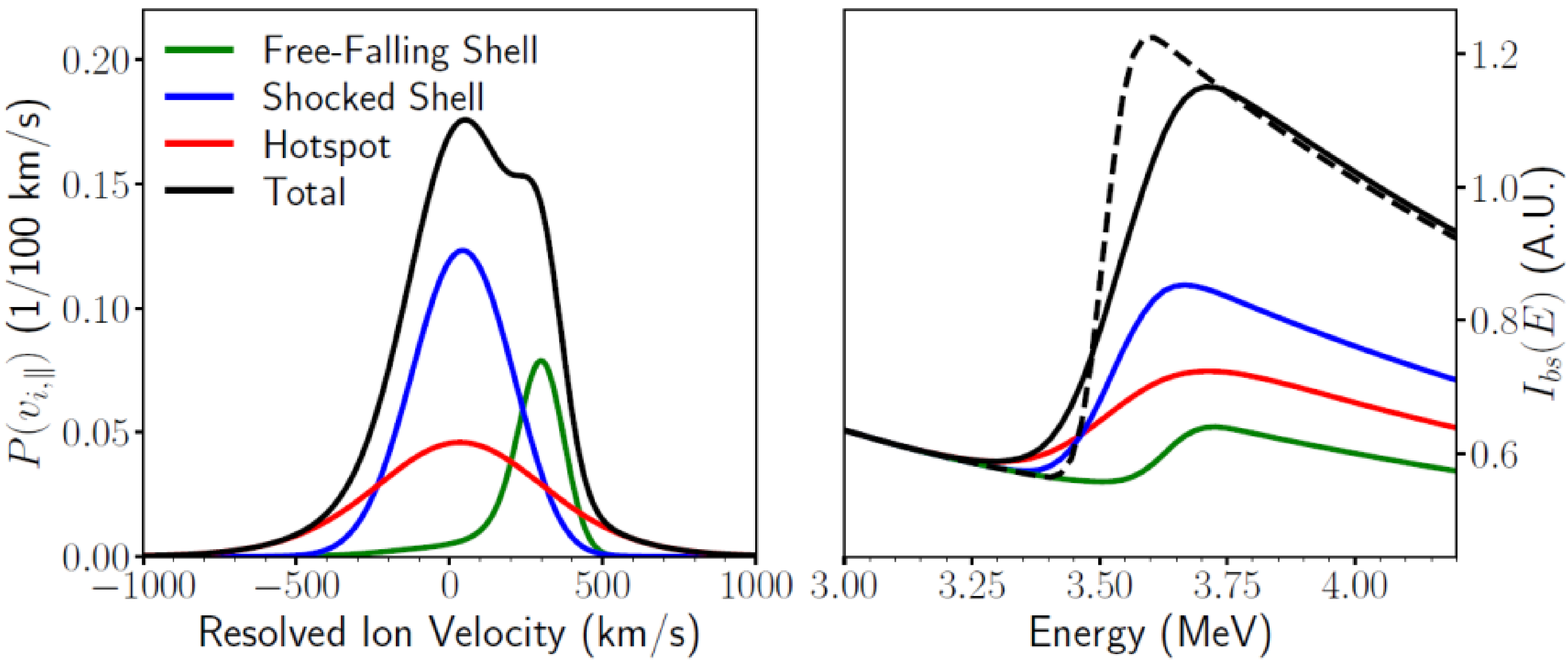
$$\Delta_v^2 = \left\langle \frac{T_i}{m_i} \right\rangle + \underbrace{\langle v_f^2 \mu'^2 \rangle - \bar{v}^2}$$

Fluid velocity variance (deceleration, spatial profiles, etc.)



Translation to a spectral shape

- Shift in edge position = average scattering triton velocity
- Slope of edge = variance in scattering triton velocity (thermal + non-thermal)



Experimental Results on OMEGA

nT edge analysis (single line of sight):

1. Measure and fit the primary DT spectrum

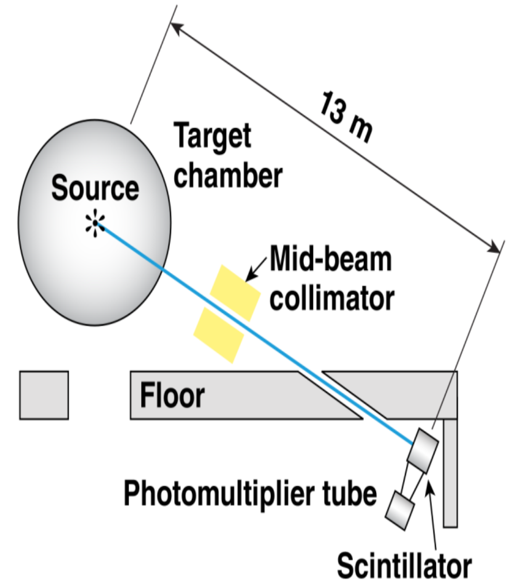
   [illegible] , [illegible]

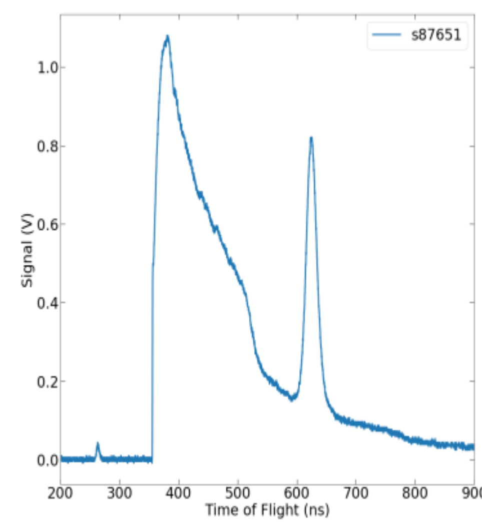
2. Measure and fit the nT edge (using v_{HS}, T_{ion})

$$\bar{v}, \Delta_v$$

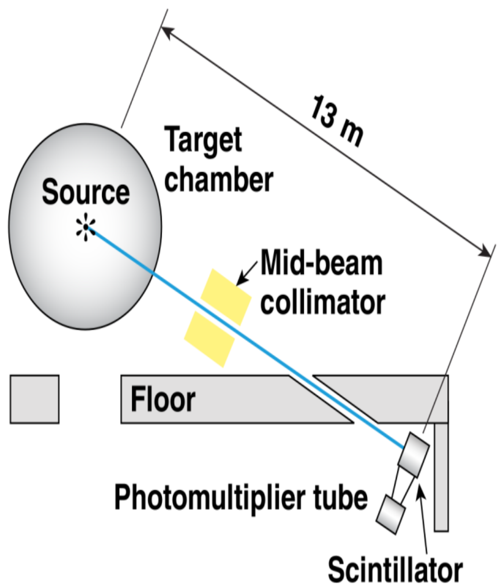
3. Use hotspot measurements to extract shell contribution

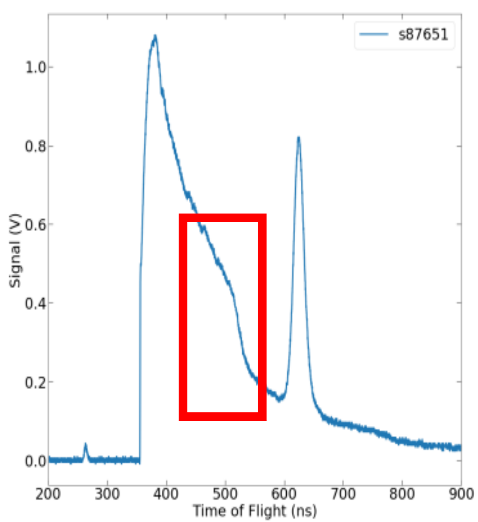
   [illegible] h [illegible] , [illegible] h [illegible]

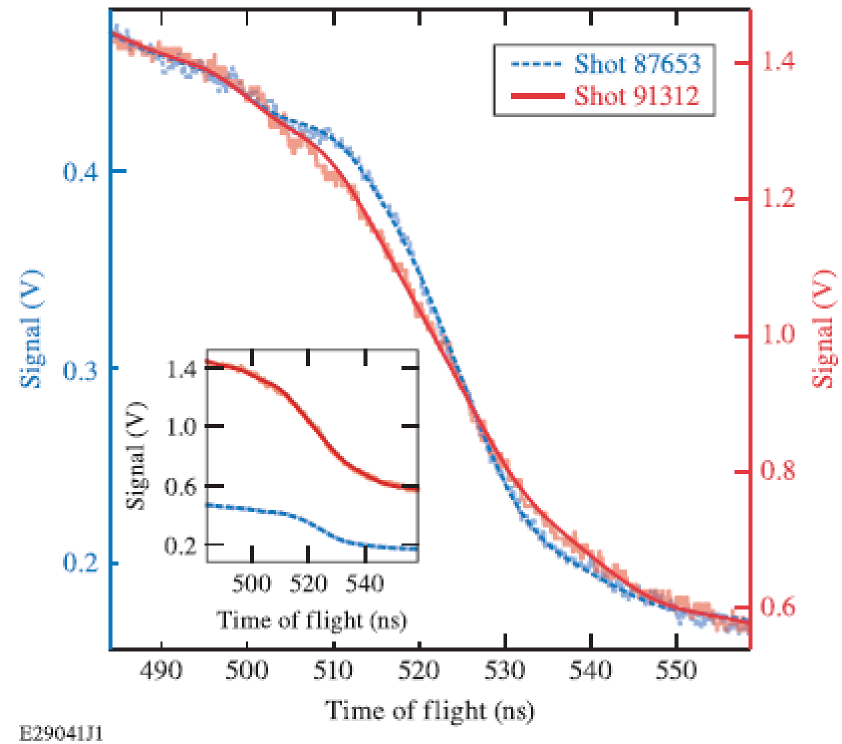




Experimental Results on OMEGA





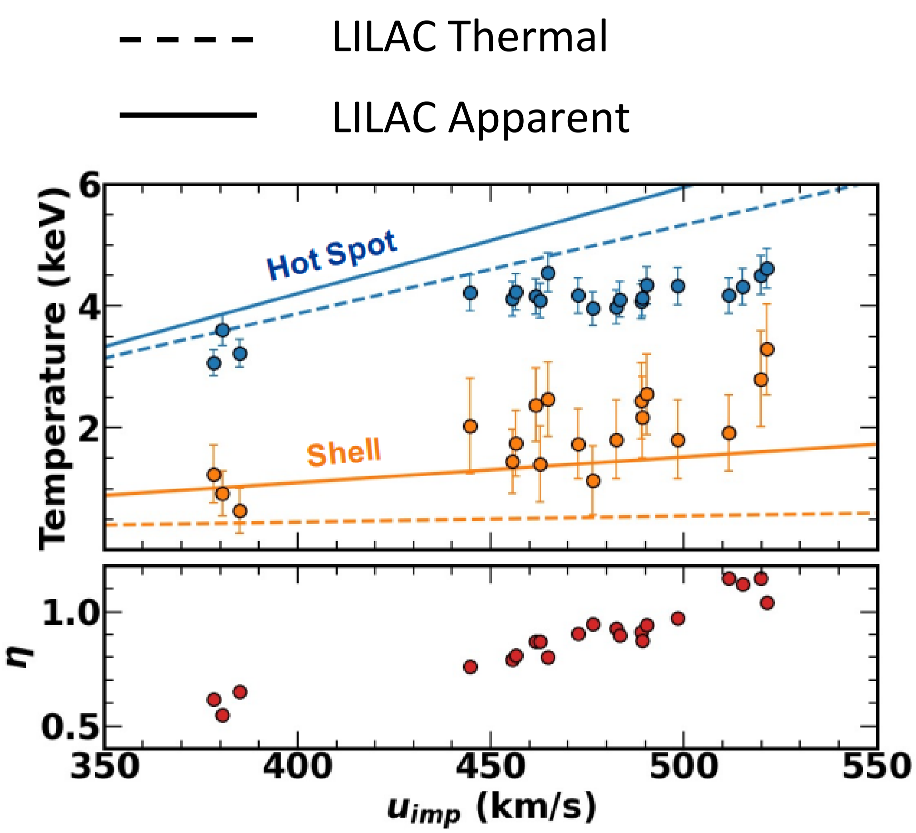


Mannion et al., PRL (in sub.)
C. J. Forrest et al., RSI (2016)

Experimental Results on OMEGA

- Shots were down-selected based on hotspot symmetry metrics
- Measured shell velocities of ~ 70km/s
- Temperatures trend with u_{imp}

$$\eta_{sim} = \frac{\text{RT bubble height}}{\text{Inflight shell thickness}}$$

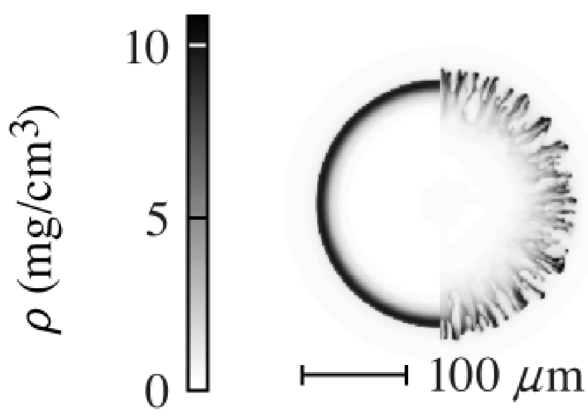


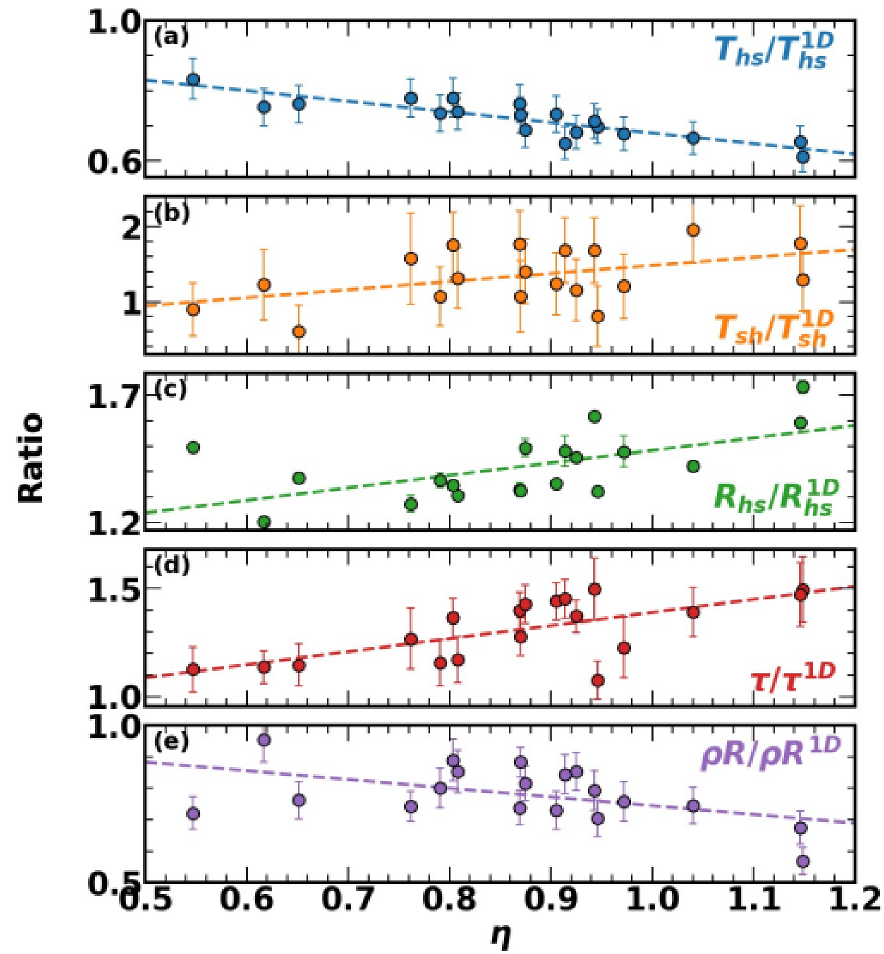
Mannion et al., PRL (in sub.)

Experimental Results on OMEGA

$$\eta_{sim} = \frac{\text{RT bubble height}}{\text{Inflight shell thickness}}$$

- Considered trends of inferred hotspot and shell parameters with shell decompression



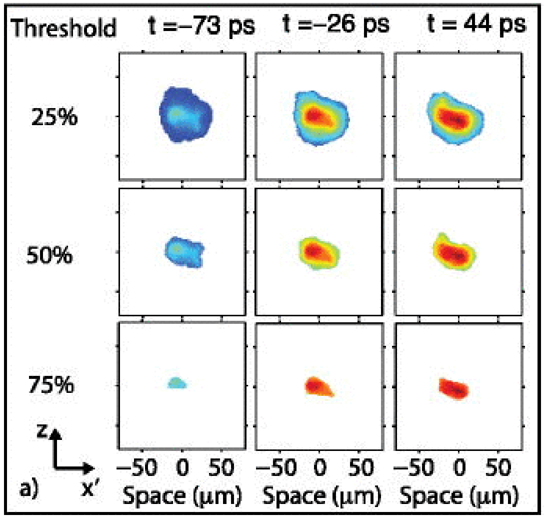


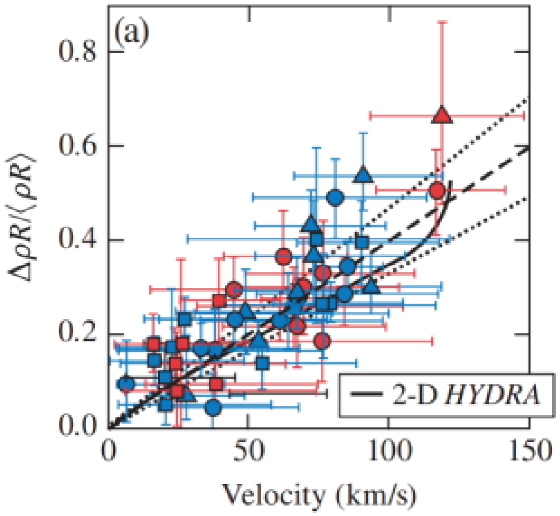
Shah, Phys. Rev. E., (2021)
Mannion, PRL, (in sub.)

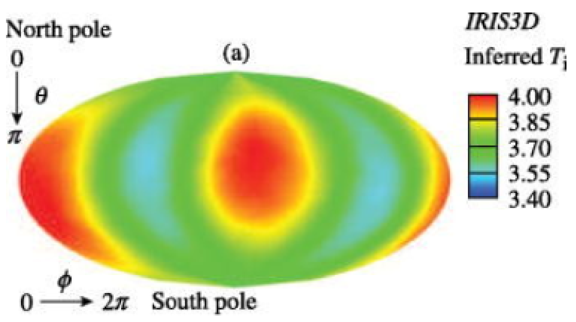
Asymmetry

- Substantial experimental evidence for mode 1 drive asymmetries at both OMEGA and NIF:
    - Motion in time-resolved X-ray images
    - Hotspot velocity
    - Apparent temperature anisotropy

- Theory, simulation and some experimental measurements suggest that mode 1 drive → mode 1 areal density

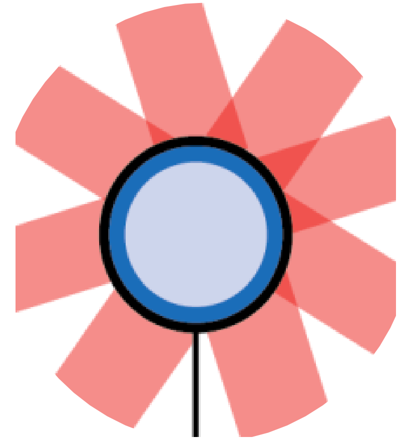




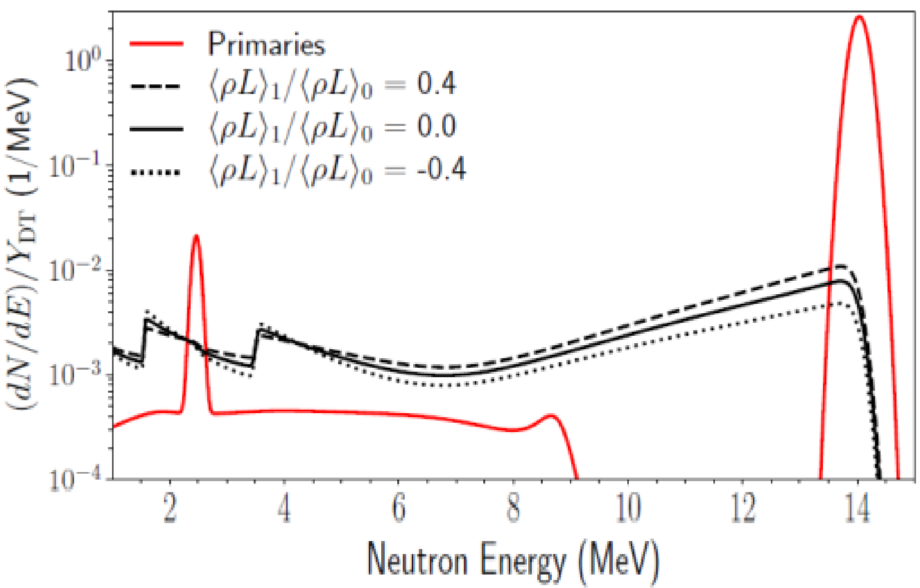


Cyro-offset series

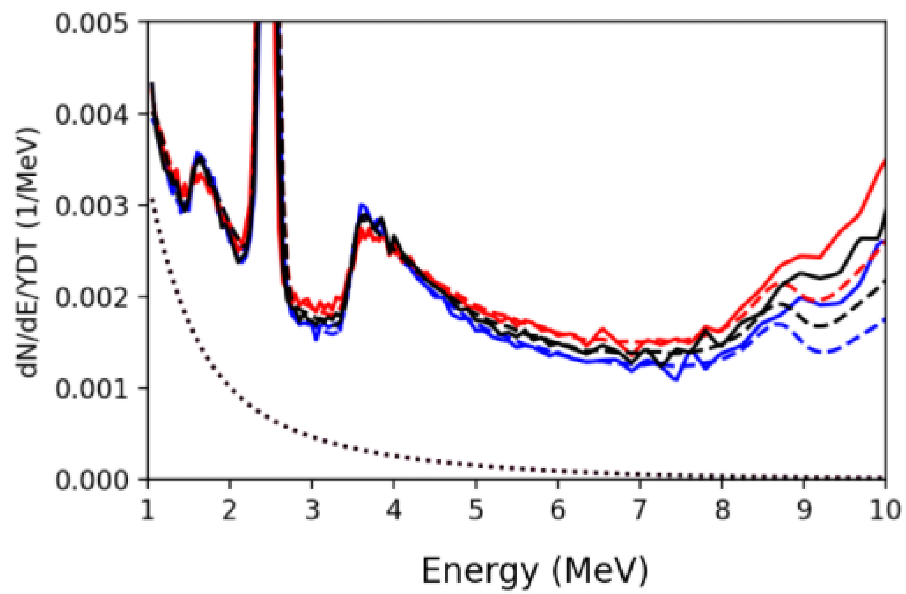
- Target offsets introduce mode 1 drive asymmetry



Trends in mode 1 model reflected in experimental data



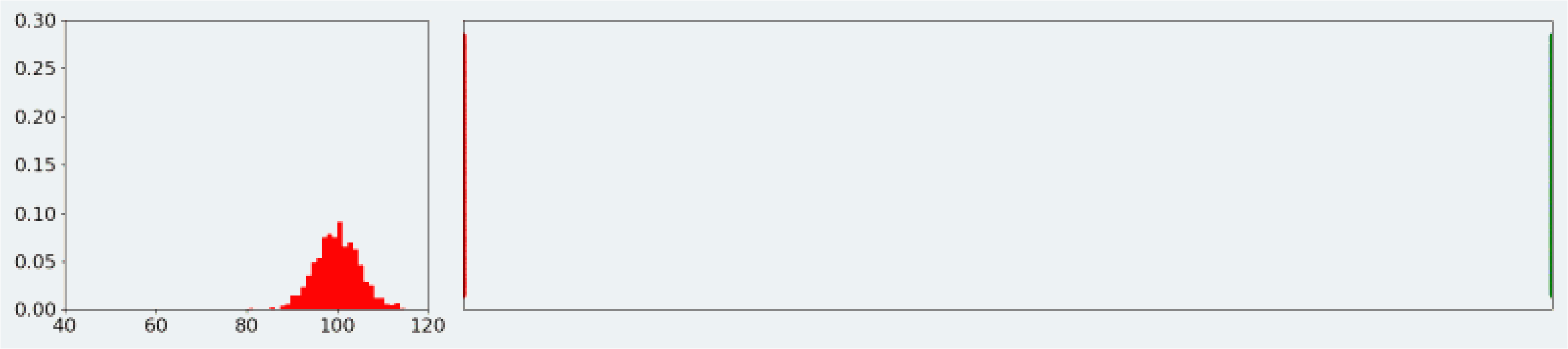
Experimental data deconvolved using evolution algorithm by Forrest



nD and nT edges

- With measurements of both the nT and nD edges we can separate thermal and non-thermal components

$$\Delta_v^2 = \left\langle \frac{T_i}{m_i} \right\rangle + \left\langle v_f^2 \mu'^2 \right\rangle - \bar{v}^2$$



Burn Regimes

- Using hydro-scaled 1D simulations we can access the different burn regimes

Based on N161023
R_{out} = 909 um
t_{peak} = 6.25 ns
$Y_{amp,Chimera}$ = 4
"Self-heating"

Scale x1.1
R_{out} = 1000 um
t_{peak} = 6.88 ns
$Y_{amp,Chimera}$ = 9
"Robust Ignition"

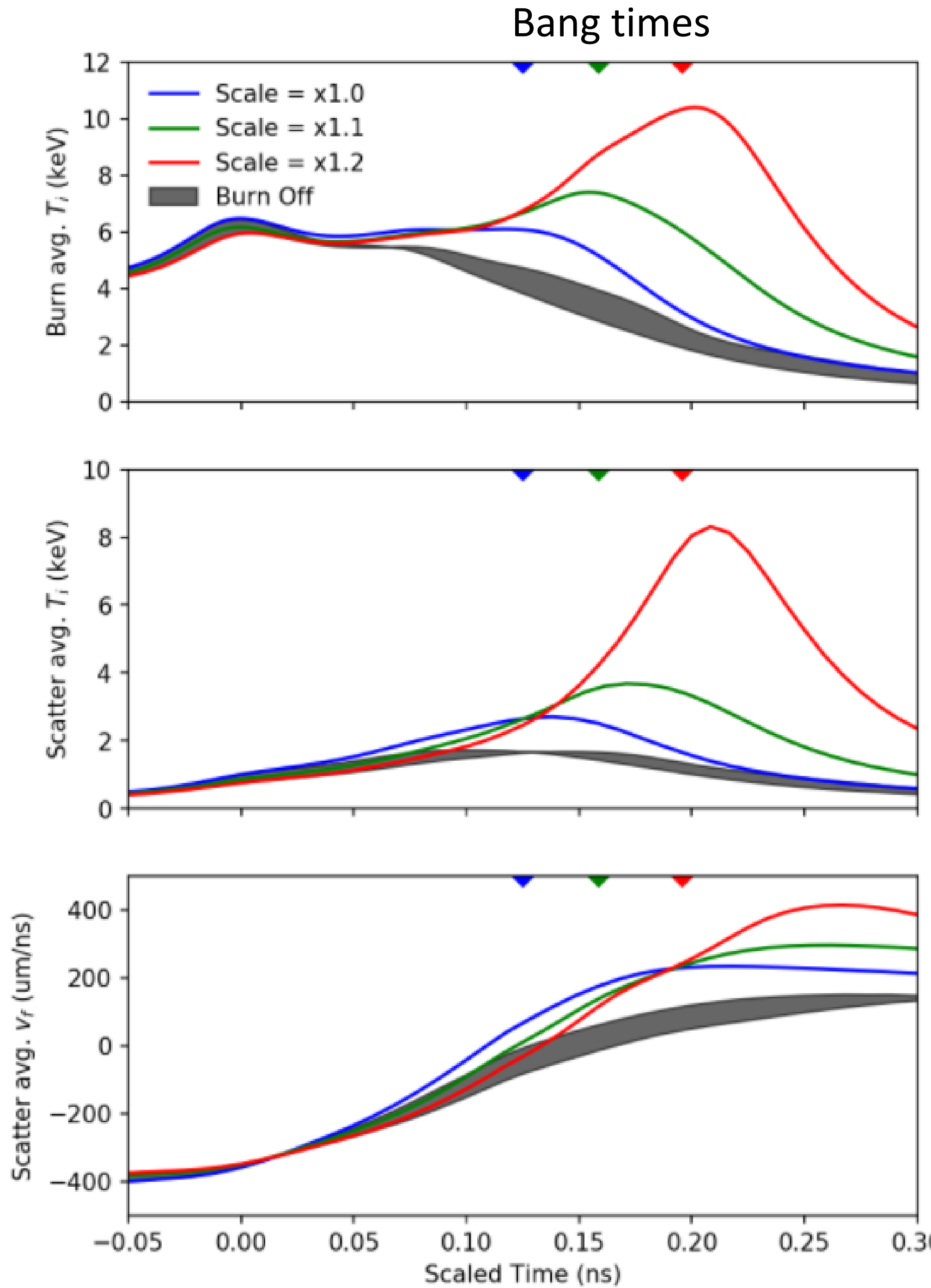
Scale x1.2
R_{out} = 1090 um
t_{peak} = 7.50 ns
$Y_{amp,Chimera}$ = 40
"Propagating Burn"

McGlinchey et al., PoP, (2018)
Tong et al., Nuc. Fus., (2019)

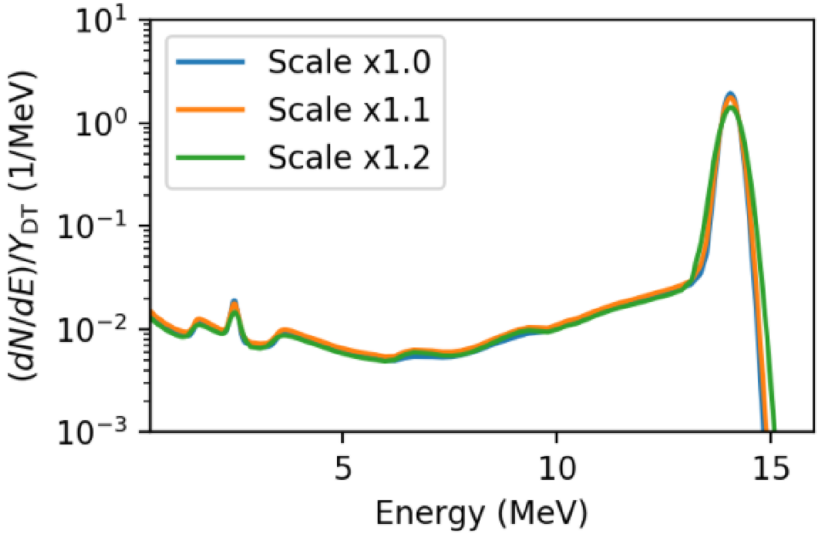
Hydrodynamic differences

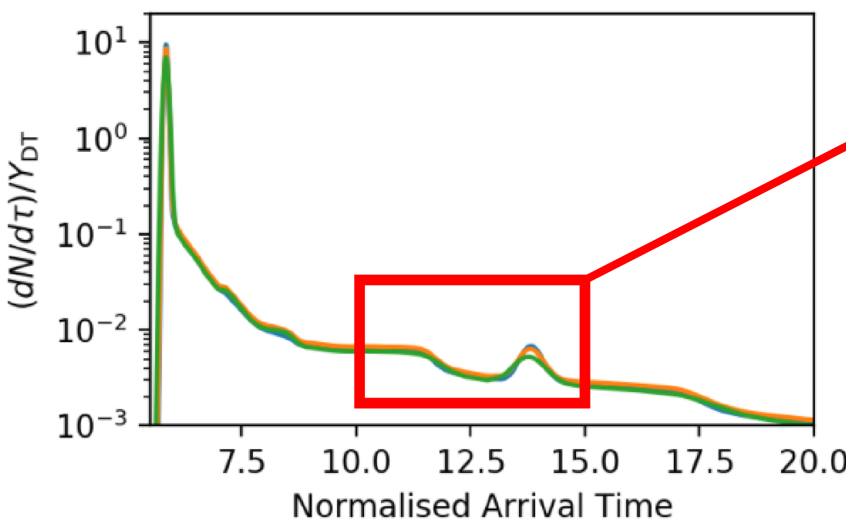
As the degree of fusion burn increases:

1. Larger burn average temperatures
2. Larger scatter average temperatures
3. Larger scatter average expansion velocities

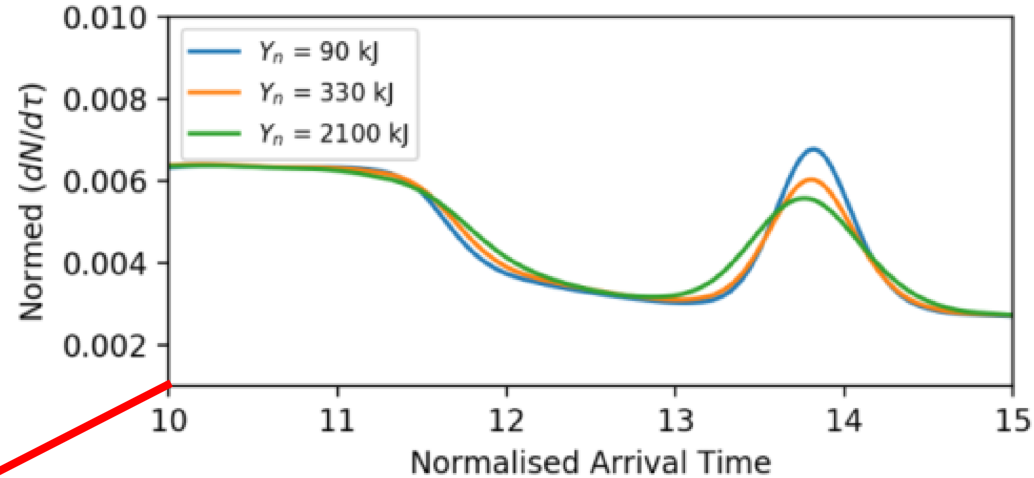


Synthetic neutron spectra



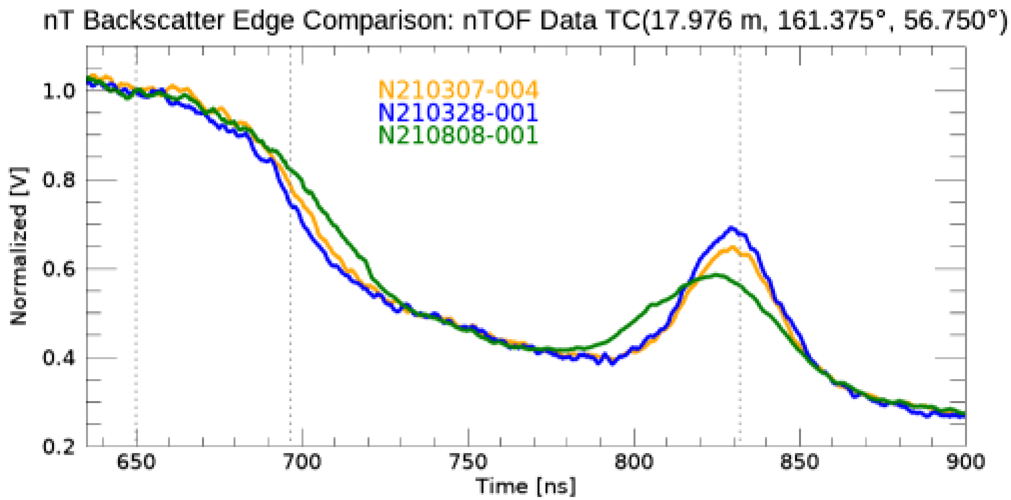


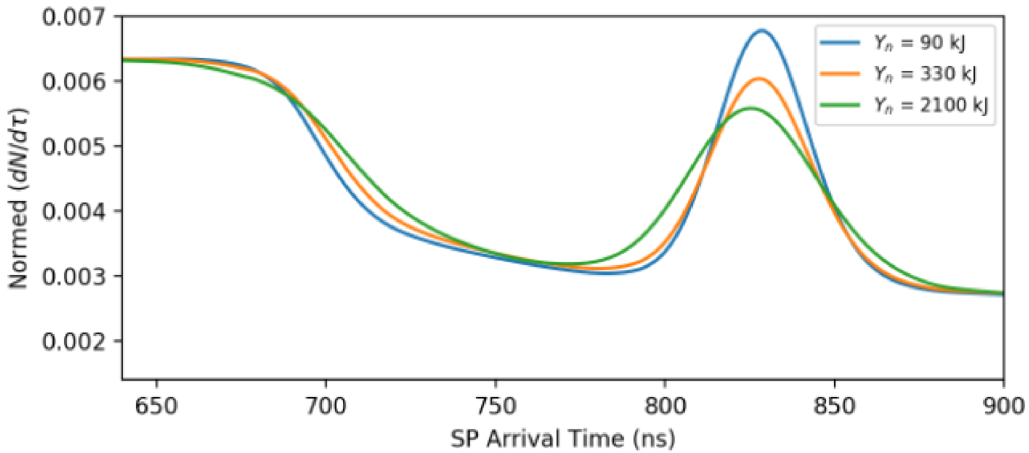
Neutron transport calculations performed by Minotaur on 1D Chimera hydrodynamic profiles



1. Later arrival = expanding shell
2. Broader edge = higher fuel temperature

NIF Experimental Data





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Conclusions

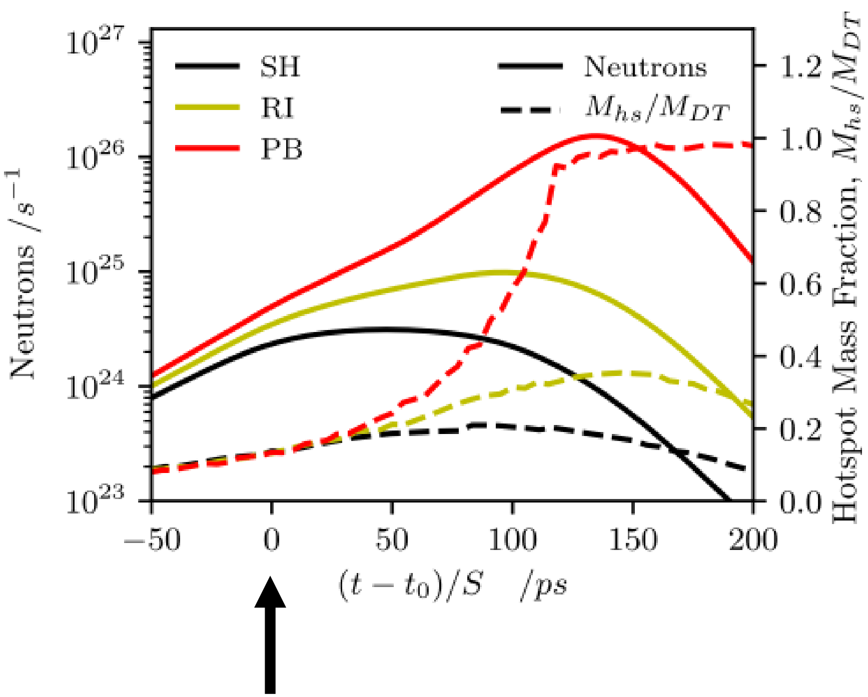
- Scattered neutron spectra contain a wealth of information about dense fuel conditions
- Experimental data from OMEGA has shown that the backscatter edge is sensitive to key implosion physics
- Model development will allow us to explore 3D backscatter spectroscopy
- The backscatter edges could prove to be a key diagnostic of burn propagation into the dense fuel

Extras

Burn Regimes

- Self-heating
  - Hotspot temperature drops after peak compression
- Robust Ignition
  - Increase in hotspot temperature but insufficient confinement
- Propagating Burn
  - Large fraction of DT mass heated to thermonuclear temperatures

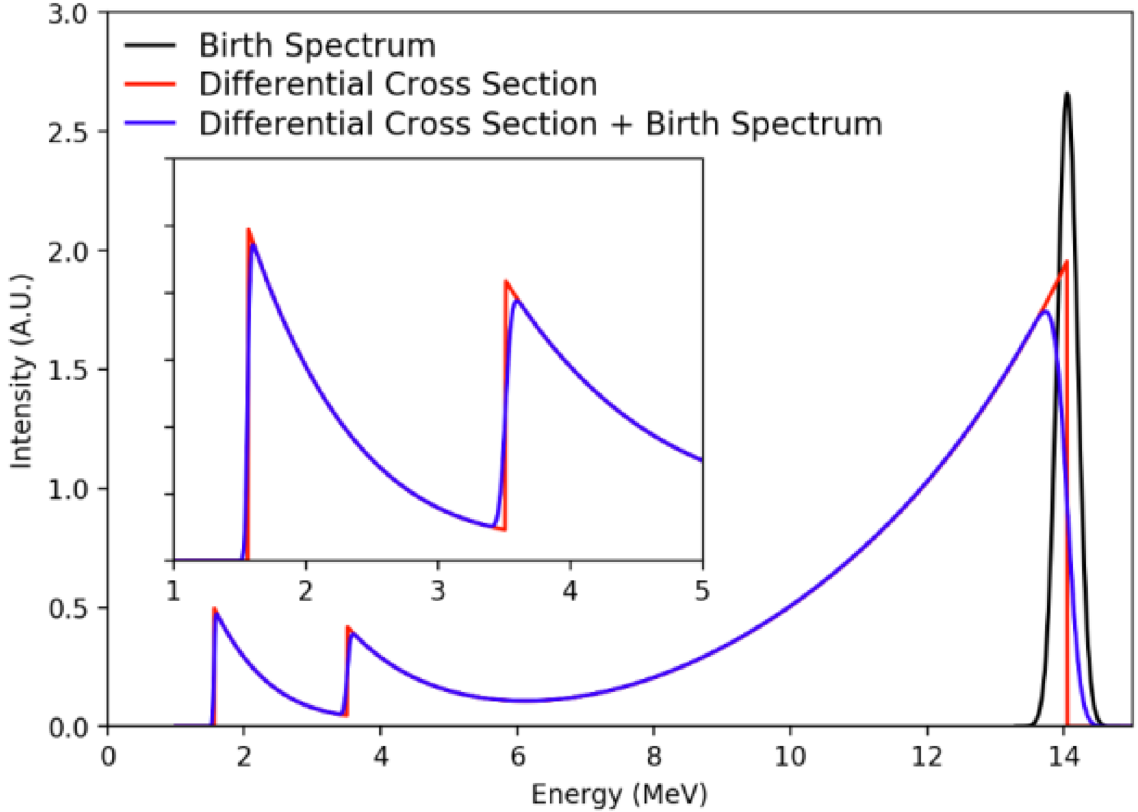
Tong et al., Nuc. Fus., (2019)



Time at which mechanical work on hotspot = 0

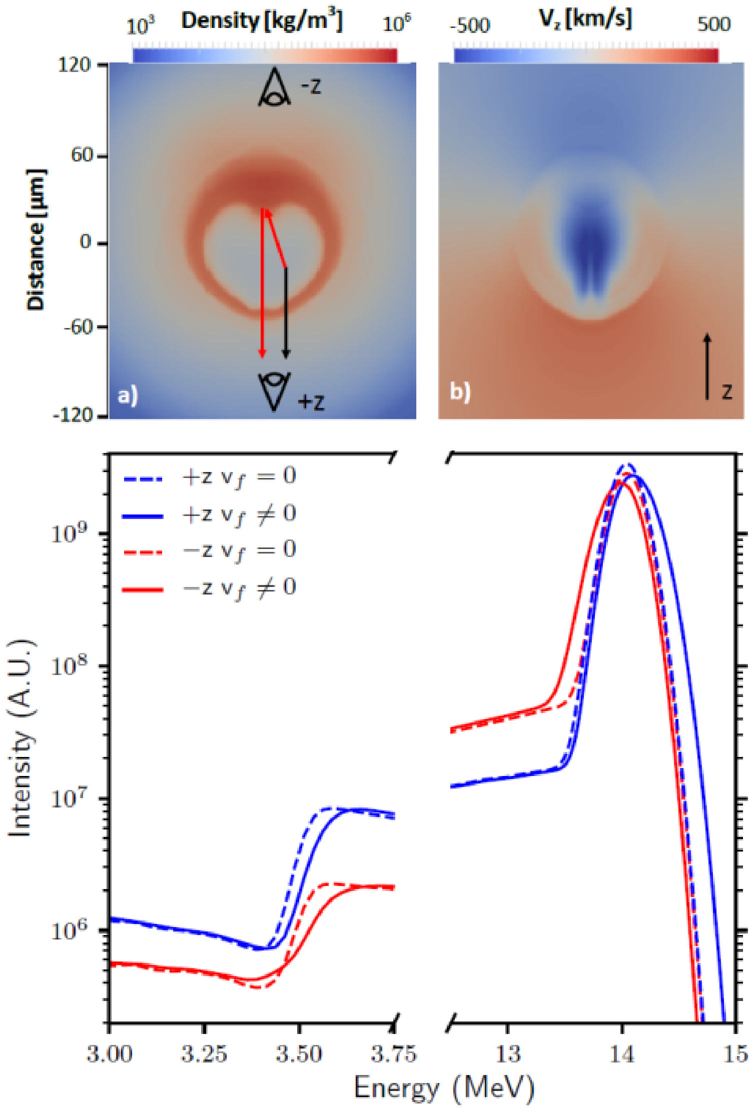
Translation to a spectral shape

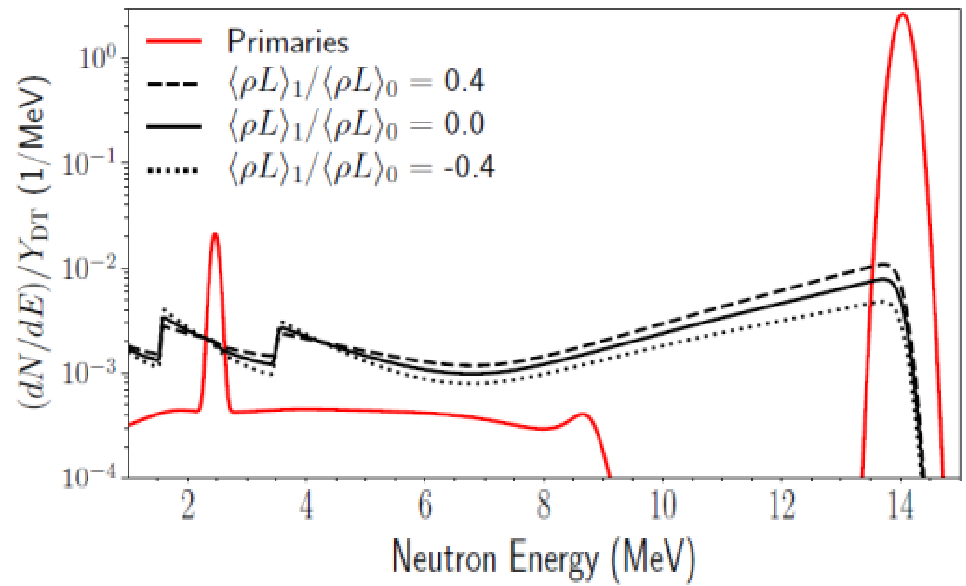
- Single scattered neutron spectrum requires:
  - Differential cross section (ENDF + Experiment*)
  - Birth neutron spectrum (Measured DT spectrum)
  - Scattering ion velocity distribution



* Frenje et al. PRL 2011

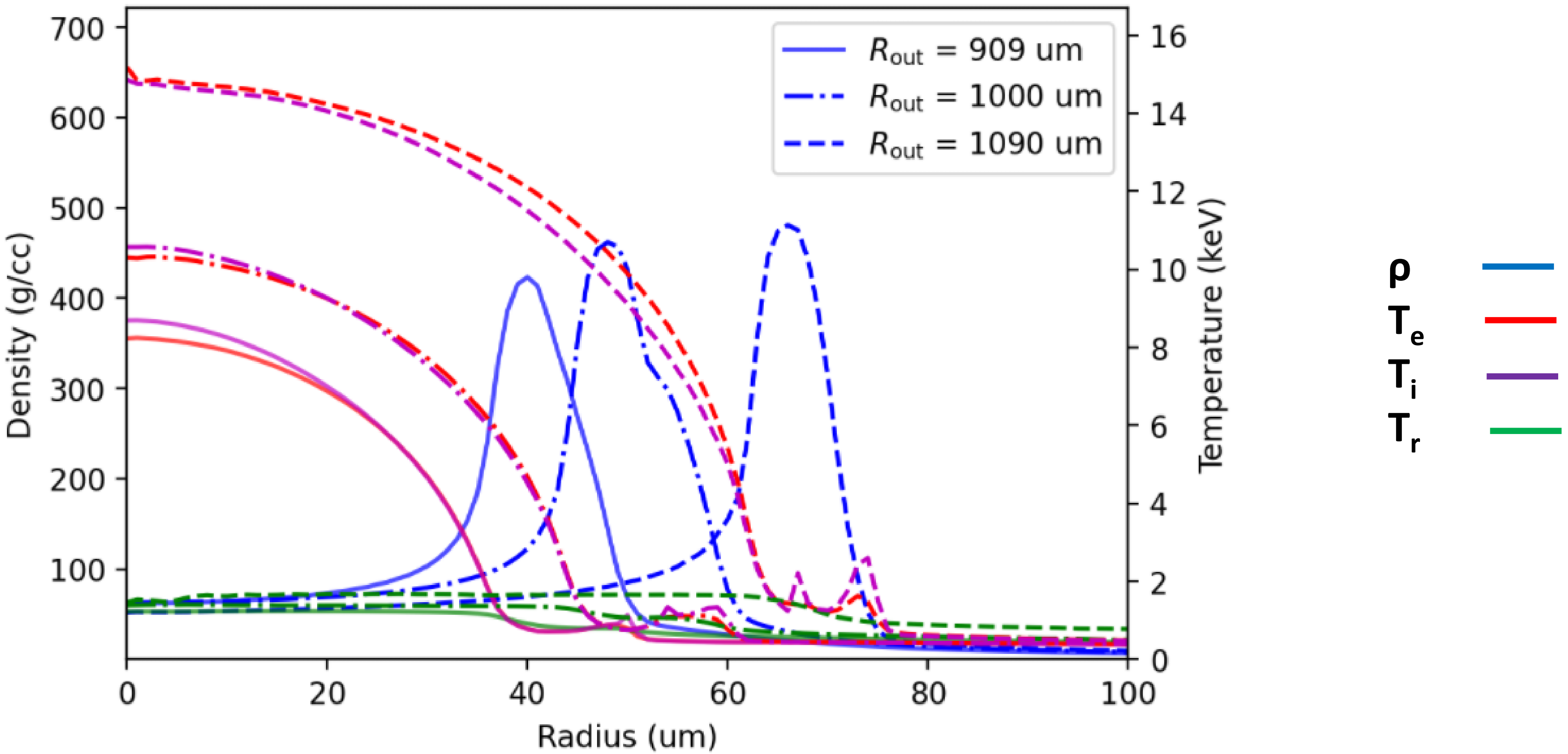
Mode 1 simulations and models



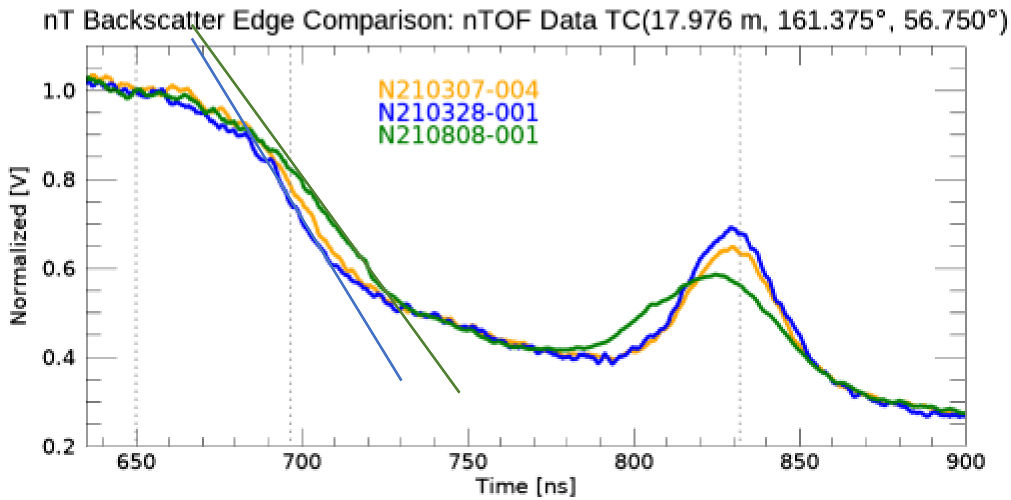


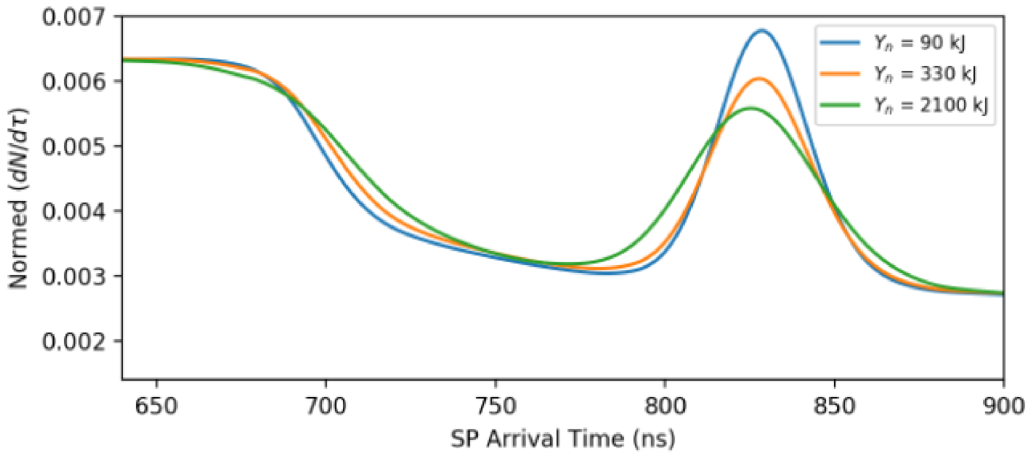
Crilly et al., PoP (2018)
Crilly et al., PoP (2021)

Bang Time Profiles



Synthetic neutron spectra





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