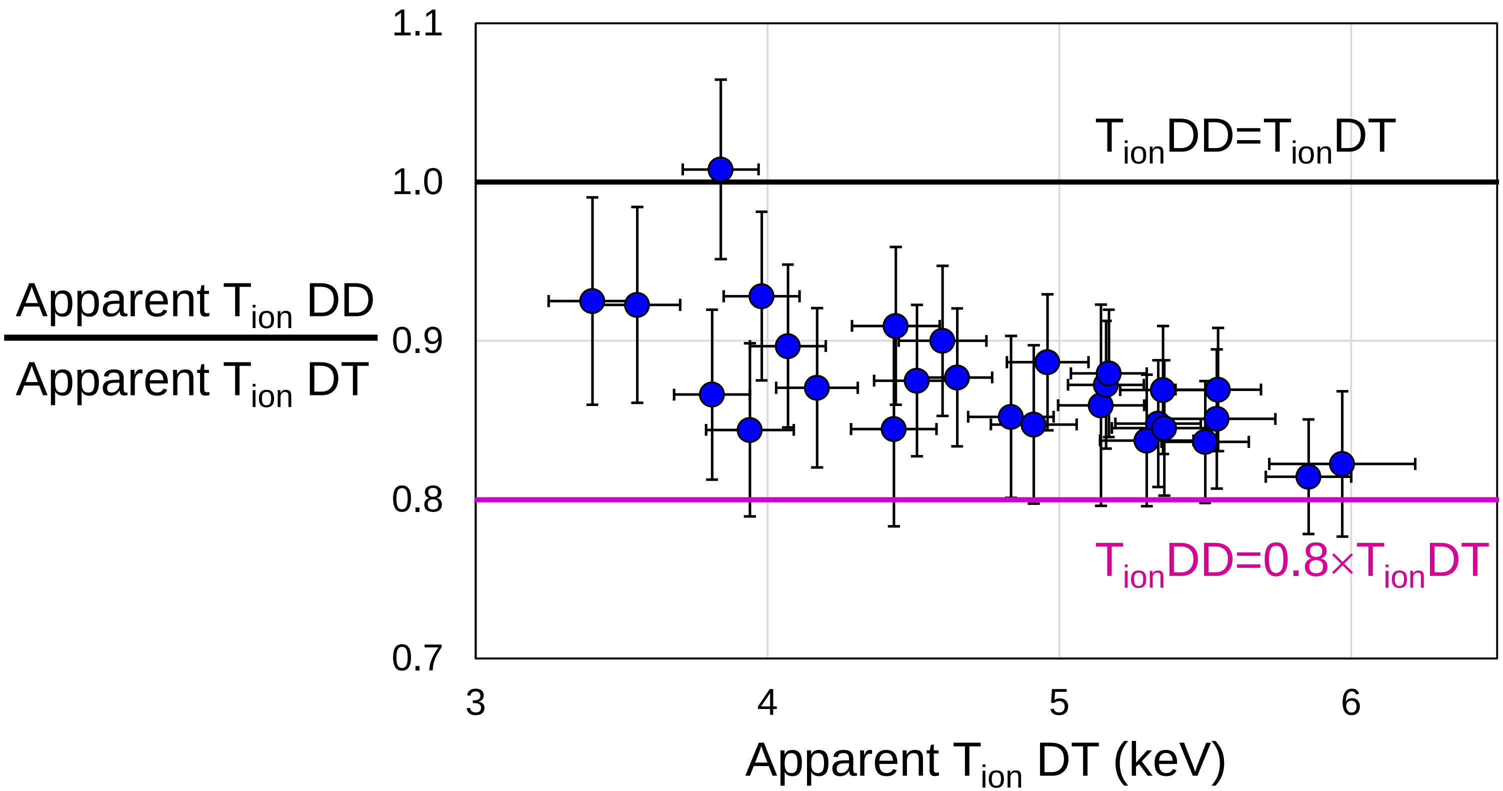
Impact of non-stagnant dynamics on neutron spectrum width in layered DT implosions at the National Ignition Facility



Maria Gatu Johnson
MIT

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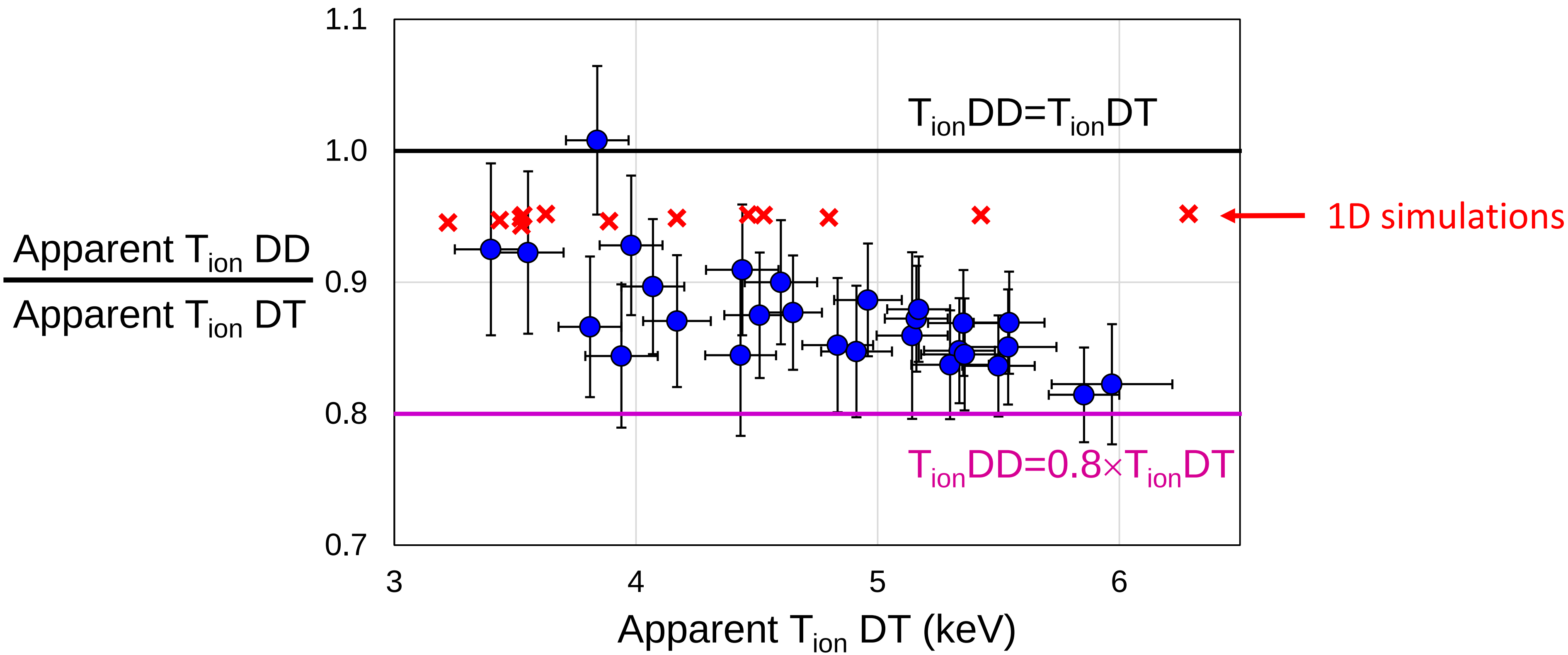

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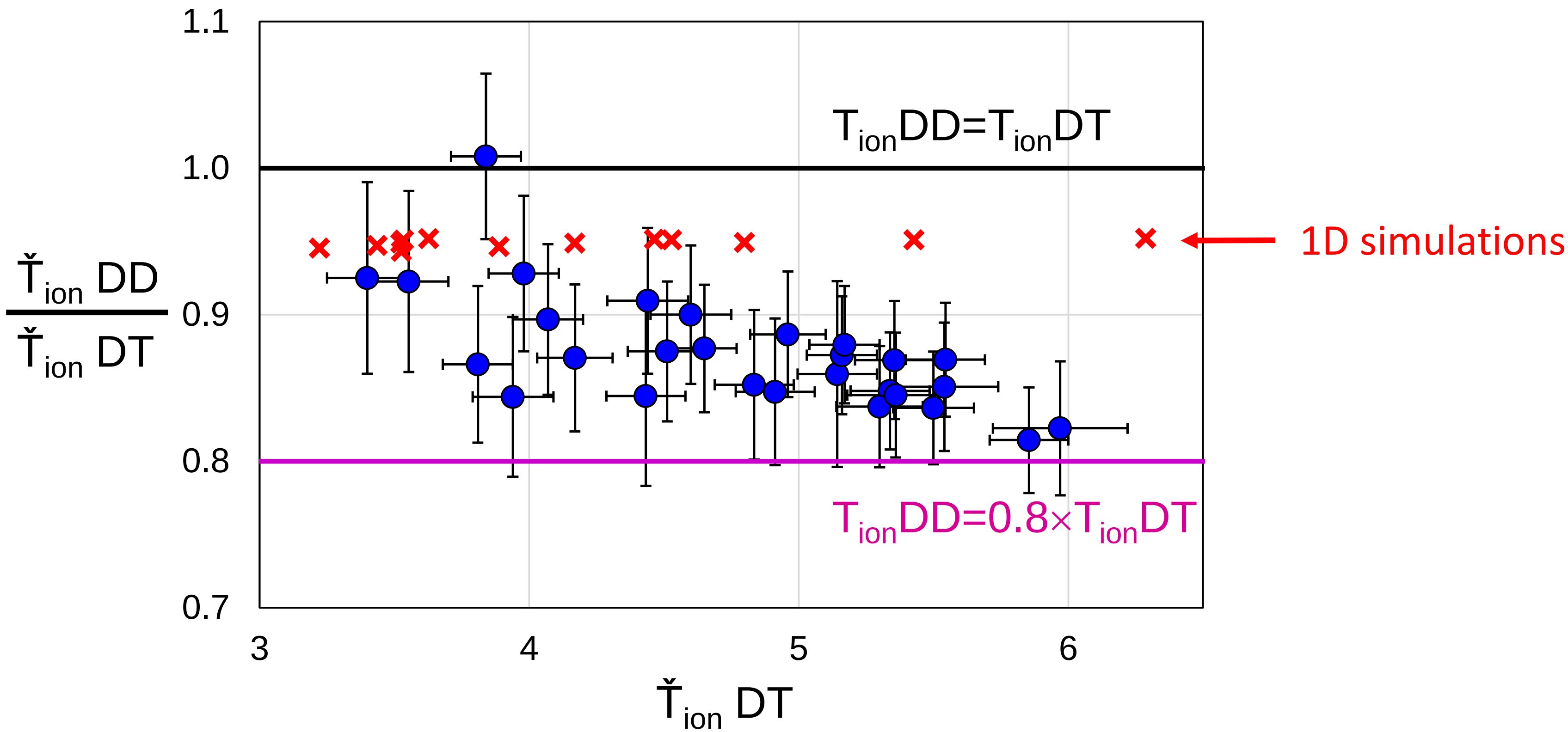


Apparent $T_{ion} \equiv \check{T}_{ion}$

Collaborators

J.P. Knauer, V.Yu. Glebov, T.C. Sangster, ***LLE***

J.D. Kilkenny, ***GA***

E.P. Hartouni, C.J. Cerjan, M.J. Eckart, G.P. Grim, R. Hatarik, A. Kritcher, D.H. Munro, D.B. Sayre, B.K. Spears, C.B. Yeamans, R.M. Bionta, E.J. Bond, D.K. Bradley, J.A. Caggiano, D.A. Callahan, D.T. Casey, T. Doeppner, M.J. Edwards, D.E. Hinkel, O.A. Hurricane, W.W. Hsing, O.L. Landen, S. LePape, T. Ma, A.J. Mackinnon, H.-S. Park, P. Patel, J.E. Ralph, B.A. Remington, ***LLNL***

J.A. Frenje, R.D. Petrasso, ***MIT***

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Anomalously high DT $\check{T}_{ion}$ rel. DD $\check{T}_{ion}$ in NIF implosions suggests significant 3D geometry and residual velocity effects at stagnation

- The observed difference in DT and DD $\check{T}_{ion}$ substantially exceeds the prediction from traditional simulations – this is a clue to understanding stagnation physics
- $\check{T}_{ion}$ is inferred from the neutron spectral width – for a stationary, homogeneous, hydrodynamic plasma where all neutrons escape, this would give thermal T_{ion}
- We examine effects that contribute to neutron spectral width and $\check{T}_{ion}$ DT > $\check{T}_{ion}$ DD:
  - **Profile/reactivity**
  - **Differential scatter**
  - **Residual flow velocities at burn**

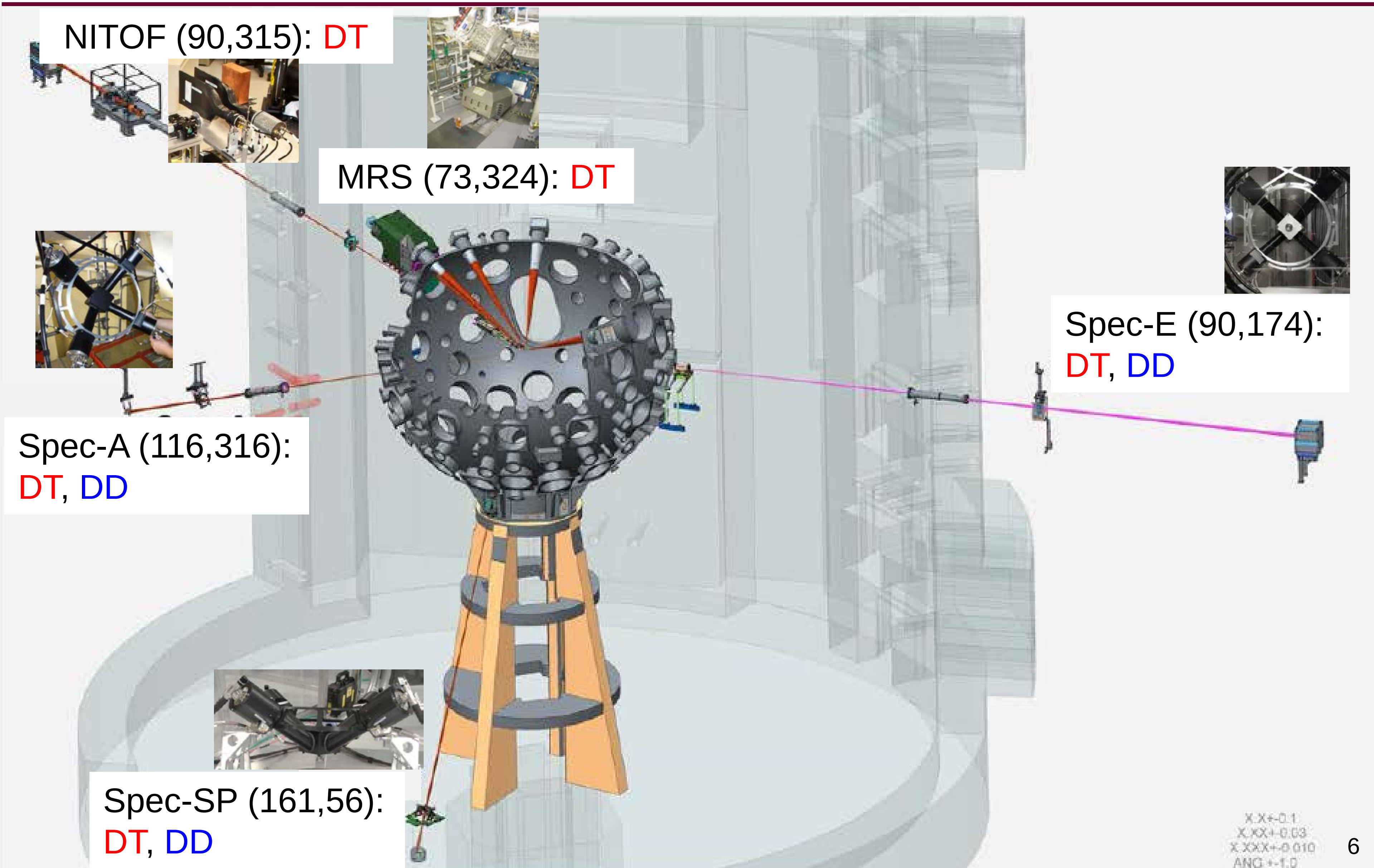
  } *These effects are too small to explain the observations in a simple 1D model*

  - **Stratification**

  } *Does not appear to explain the present observations*

A 3D model considering flows and full implosion geometry appears necessary to explain the observations

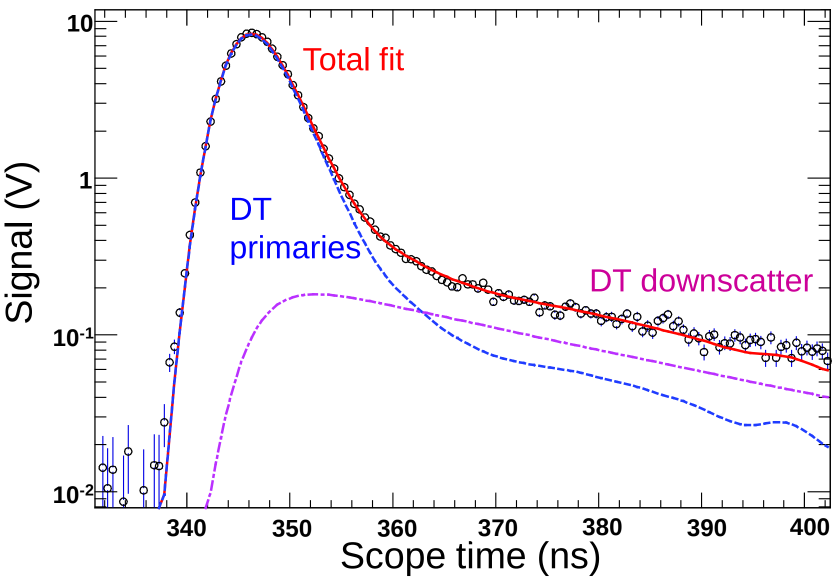
$\check{T}_{ion}$ at NIF are measured by neutron spectrometers in five directions with two different techniques



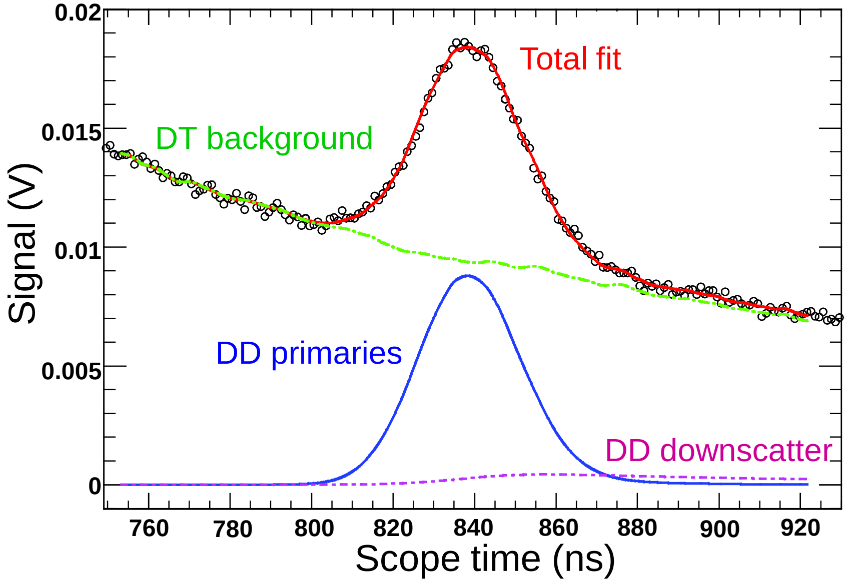
$\check{T}_{ion}$ is inferred from the width of the neutron energy spectrum using the Ballabio* methodology

$$\text{DT variance} \sim 2E_{0,DT} \frac{m_n}{m_n + m_\alpha} \check{T}_{ion}$$

$$\text{DD variance} \sim 2E_{0,DD} \frac{m_n}{m_n + m_{3He}} \check{T}_{ion}$$



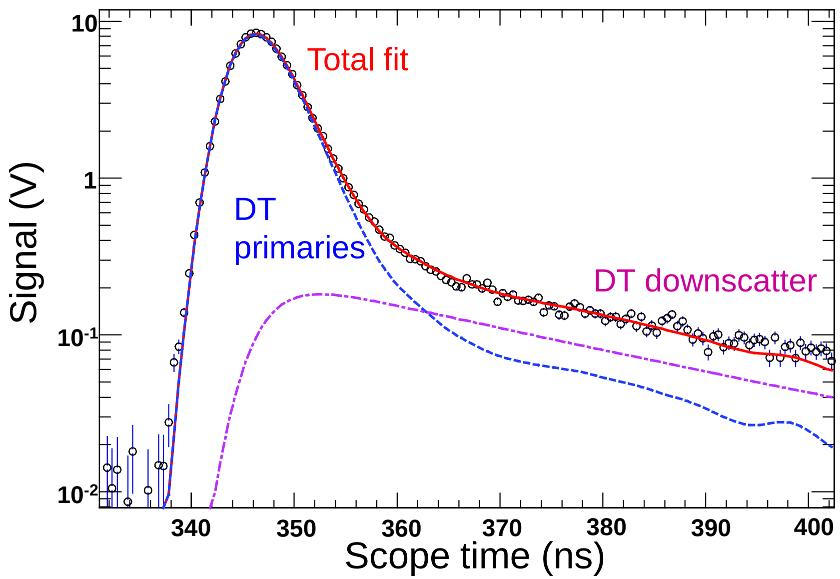
Energy

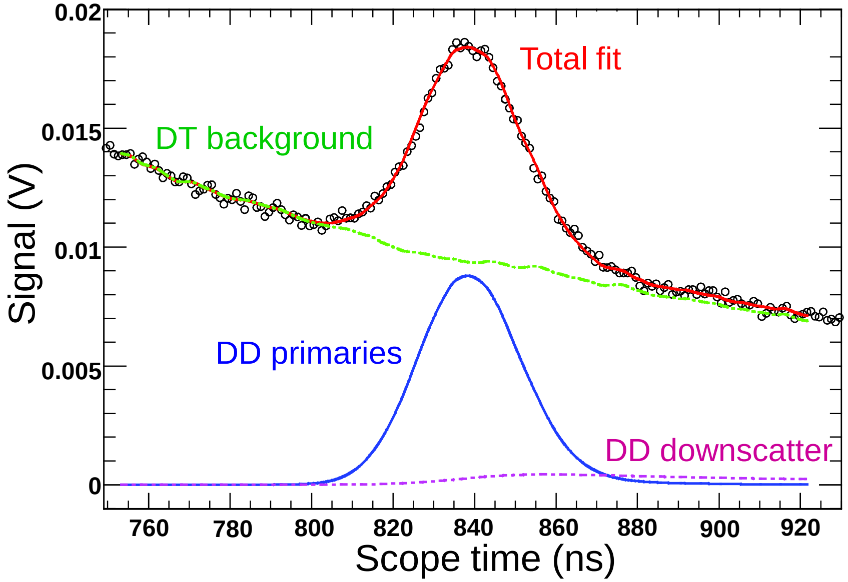


Energy

*L. Ballabio, J. Källne and G. Gorini, Nuclear Fusion **38**, 1723 (1998)
R. Hatarik et al., submitted to Journal of Applied Physics

$\check{T}_{ion}$ is inferred from the width of the neutron energy spectrum using the Ballabio* methodology



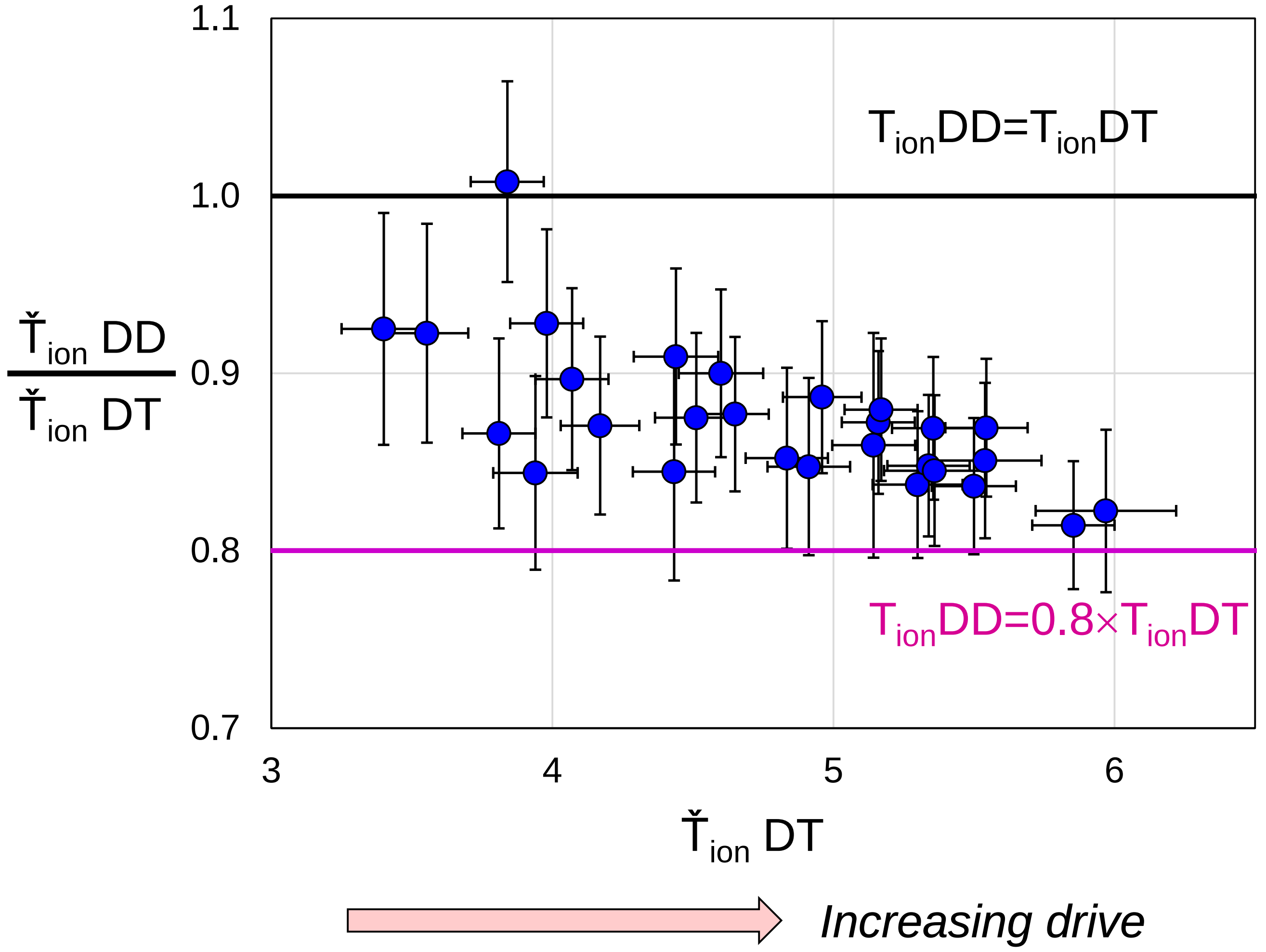


Inferred $\check{T}_{ion} = T_{thermal}$ + other effects:

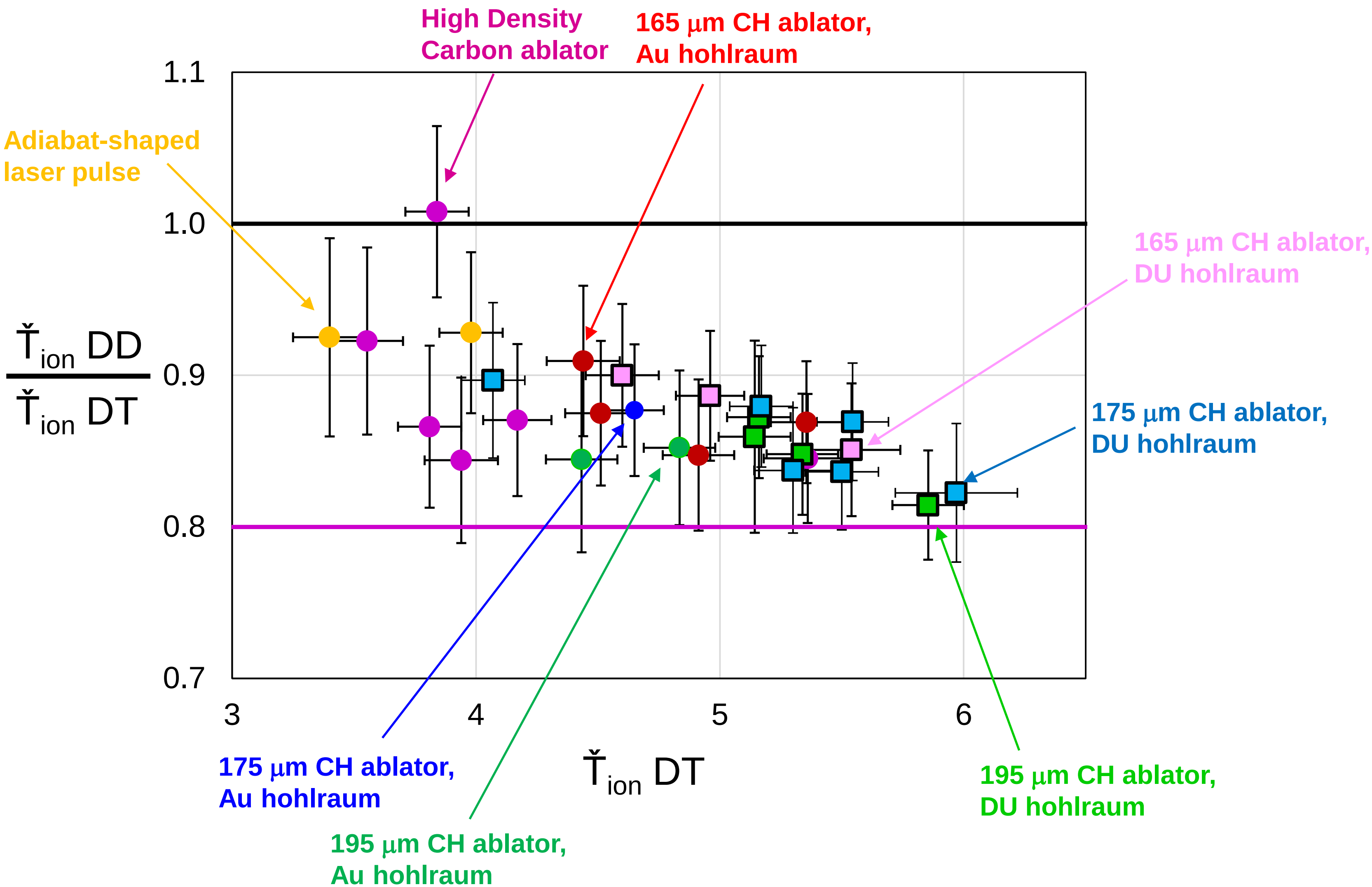
1. Profiles/reactivity
2. Differential scatter
3. Velocity flow effects
4. Stratification

Result

Higher DT than DD $\check{T}_{ion}$ is consistently observed on layered NIF implosions; the difference increases with drive

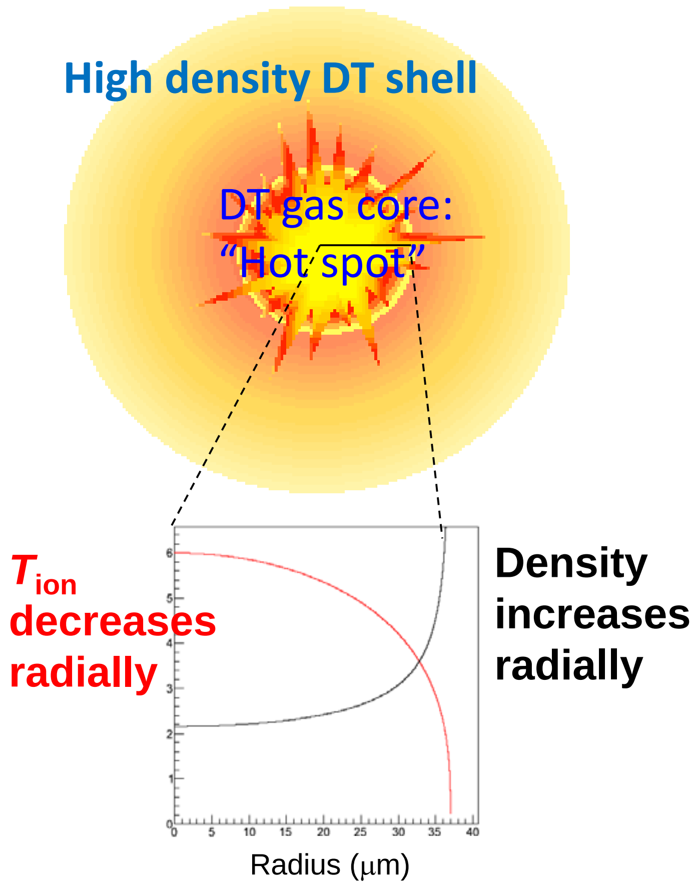


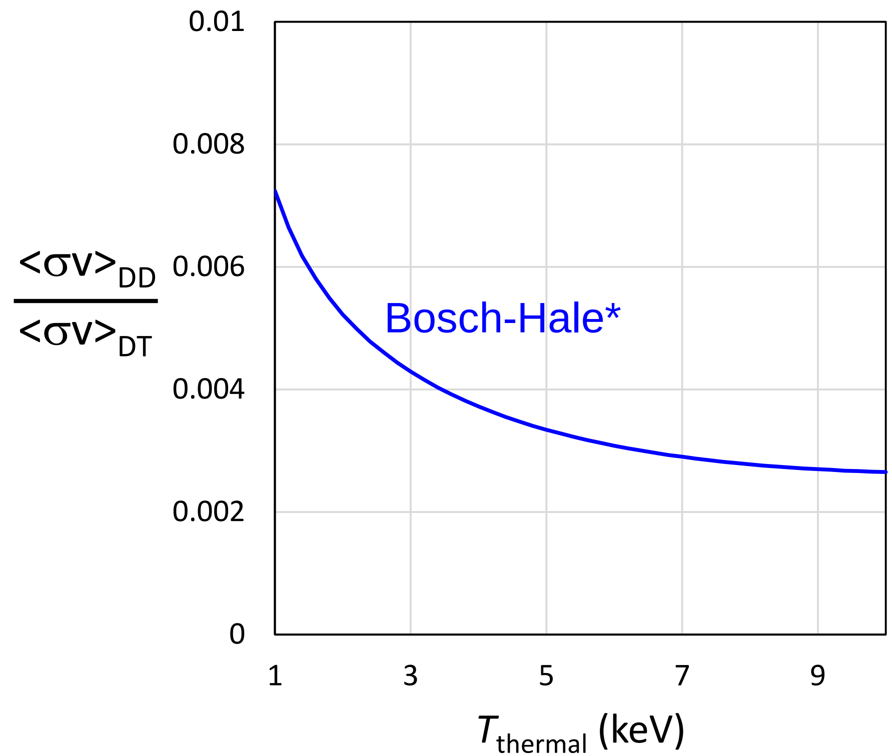
The trend appears independent of ablator and hohlraum



Measured spectra integrate in space and time; a difference in DD and DT $\check{T}_{ion}$ is expected due to profiles and reactivity differences

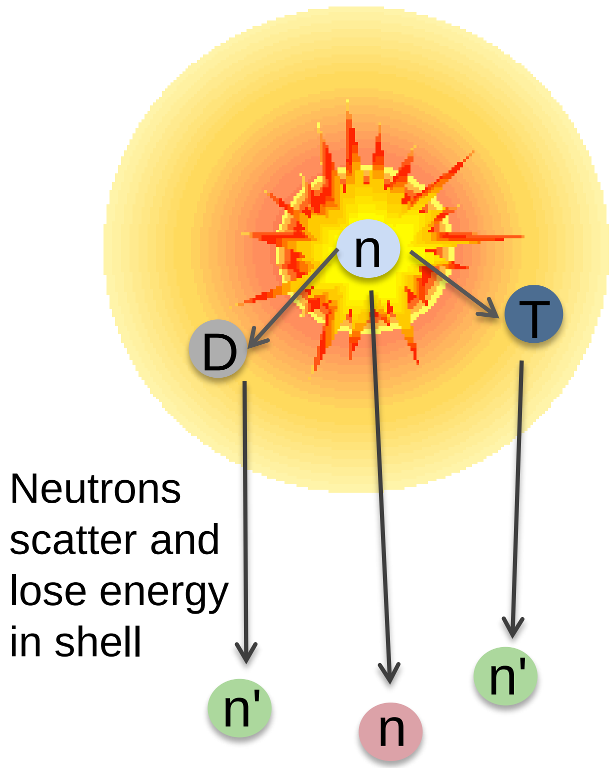
$$\text{Yield} \sim \iint n_i n_j \langle \sigma v(T_{thermal}) \rangle_{ij} \times \text{Volume} \times \text{time}$$

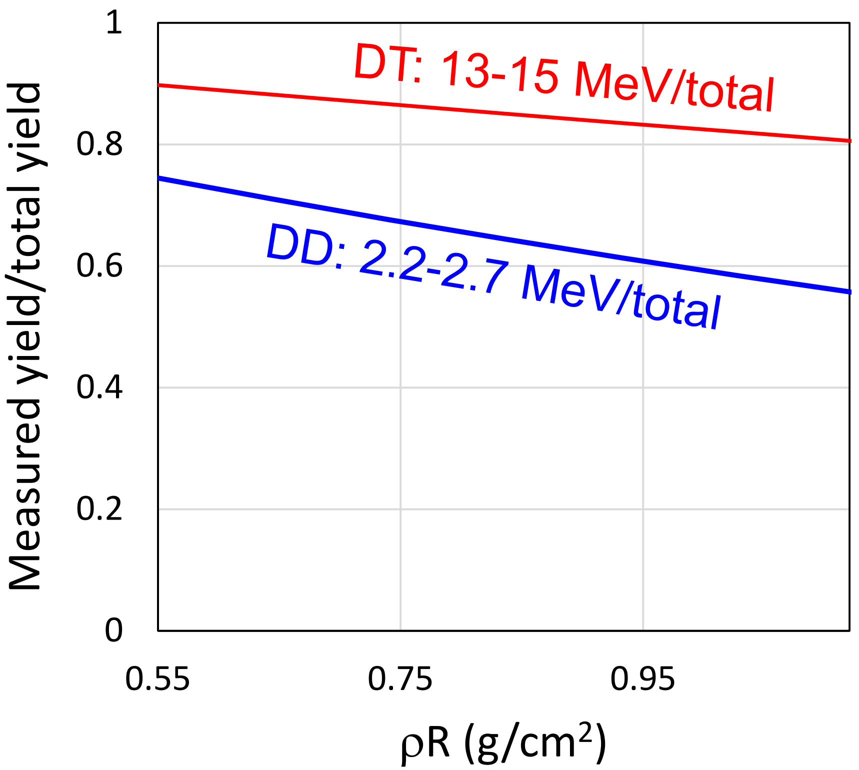




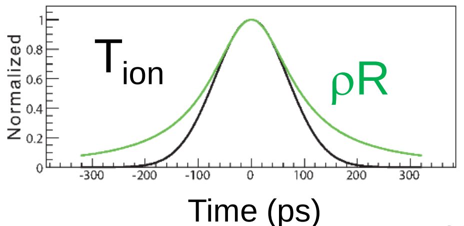
*H.-S. Bosch and G.M. Hale, Nucl. Fusion ***32***, 611 (1992)*

DD neutrons are attenuated more than DT neutrons in the surrounding dense shell; this can also impact $\check{T}_{ion}$ measurements



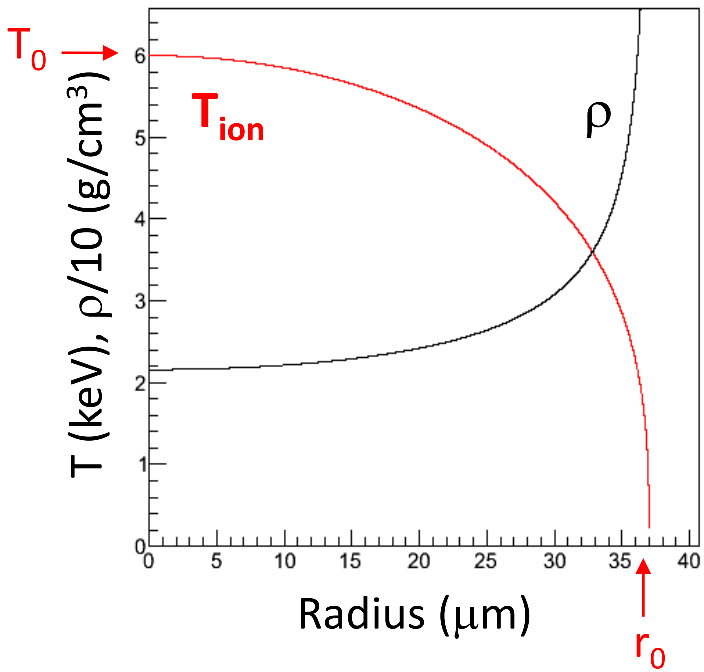


$\check{T}_{ion}$ is determined from the unscattered primary peak → DD may be preferentially weighted to colder times with lower ρR

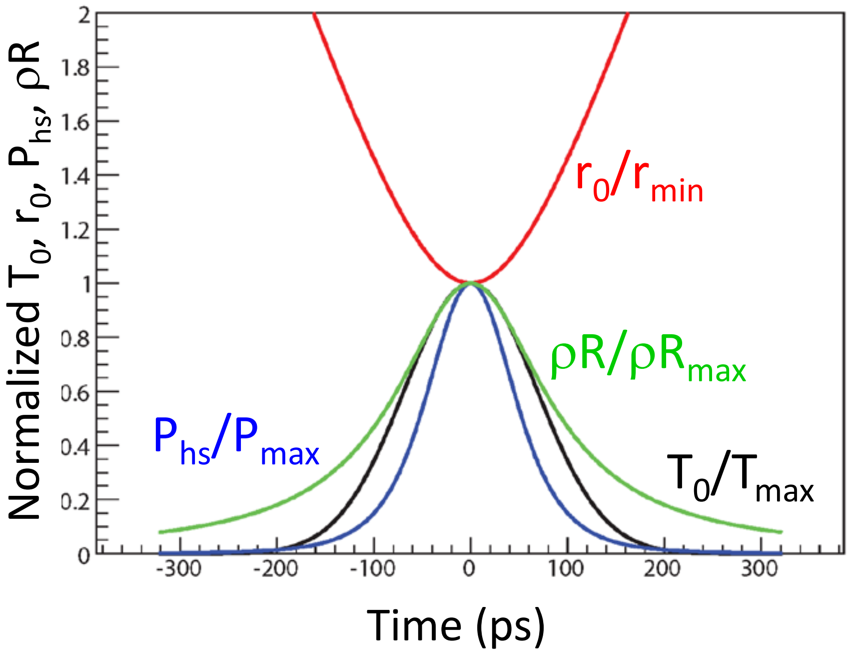


The effect of profiles and differential scatter is estimated using a simple 1D model

Spatial profiles (isobaric assumption*):



Temporal profiles:



Smaller $\tau_{burn} \rightarrow$ larger ΔT_{ion}
Lower $v_{imp} \rightarrow$ larger ΔT_{ion}
Larger $r_{min} \rightarrow$ larger ΔT_{ion}
Larger $\rho R \rightarrow$ larger ΔT_{ion}

**Betti et al., Phys. Plasmas 2010; Cerjan et al, Phys. Plasmas 2013; Springer et al., EPJ 2013; P. Patel et all, Bull. Am. Phys. Soc. 2014*

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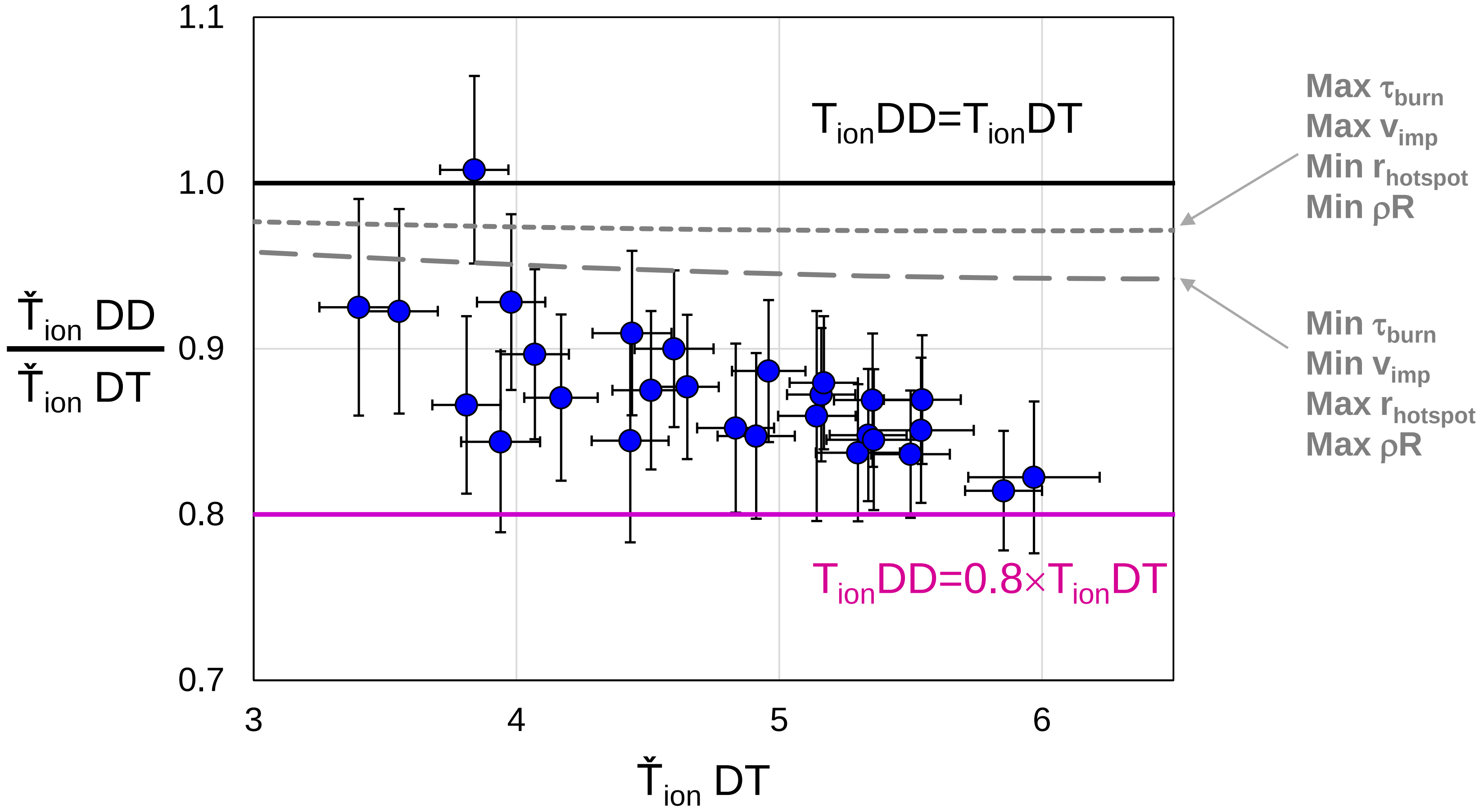
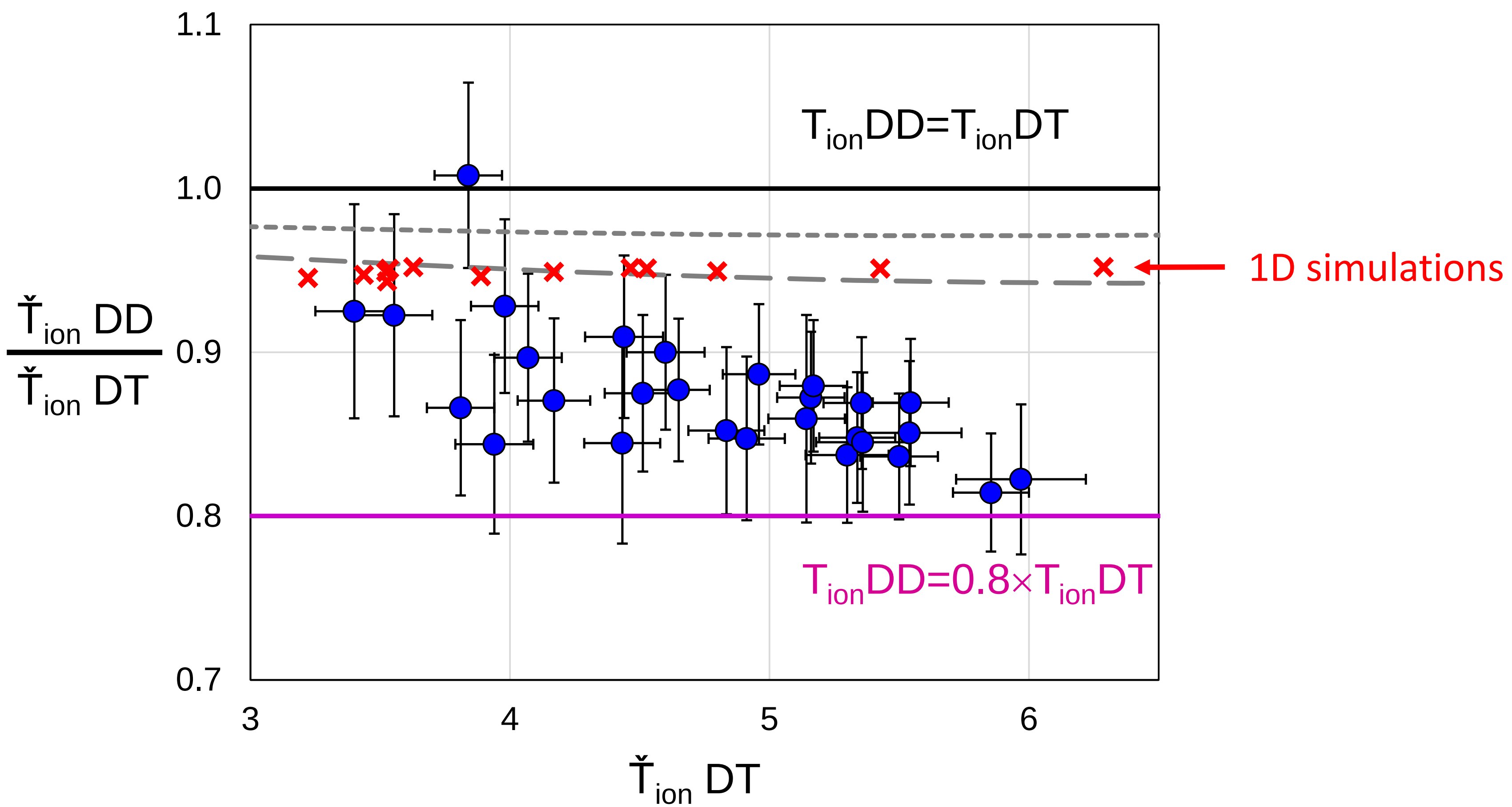


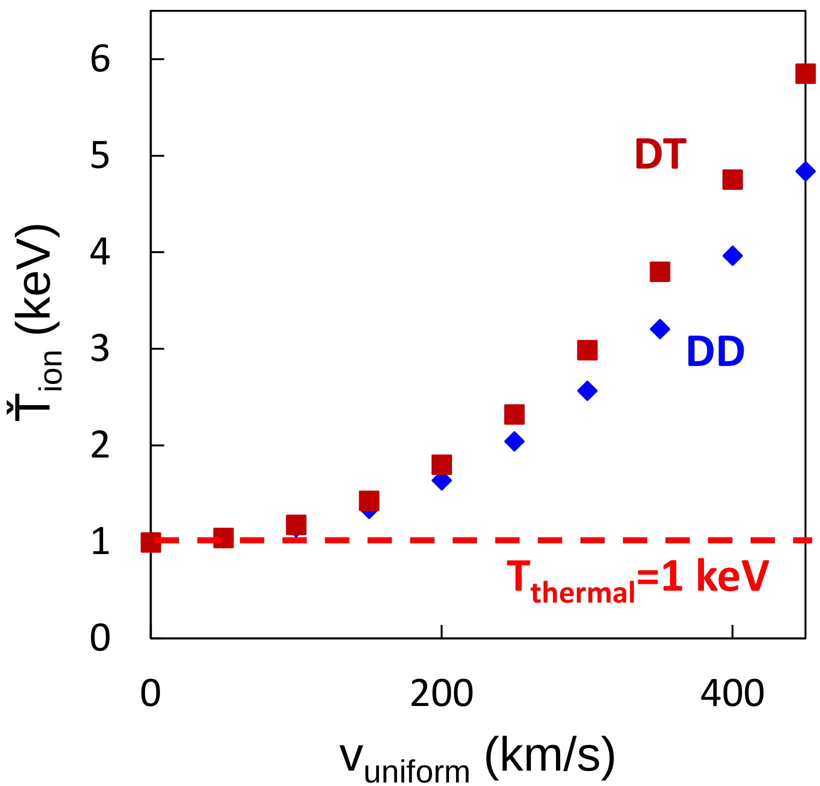
1D hydrodynamic simulations give a $\check{T}_{ion}$ DD vs DT difference of the same magnitude as the 1D model



1D profile and differential scatter effects do not explain the observation

Non-thermal fuel motion at the time of burn leads to additional peak broadening*; the relative impact is larger for DT than for DD

Calculations by B. Appelbe



$$\check{T}_{ion}\,DT = T_{thermal}\,DT + (m_n + m_\alpha)\cdot\sigma_v^2$$

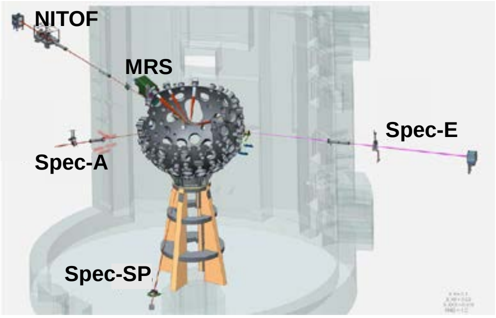
$$\check{T}_{ion}\,DD = T_{thermal}\,DD + (m_n + m_{3He})\cdot\sigma_v^2$$

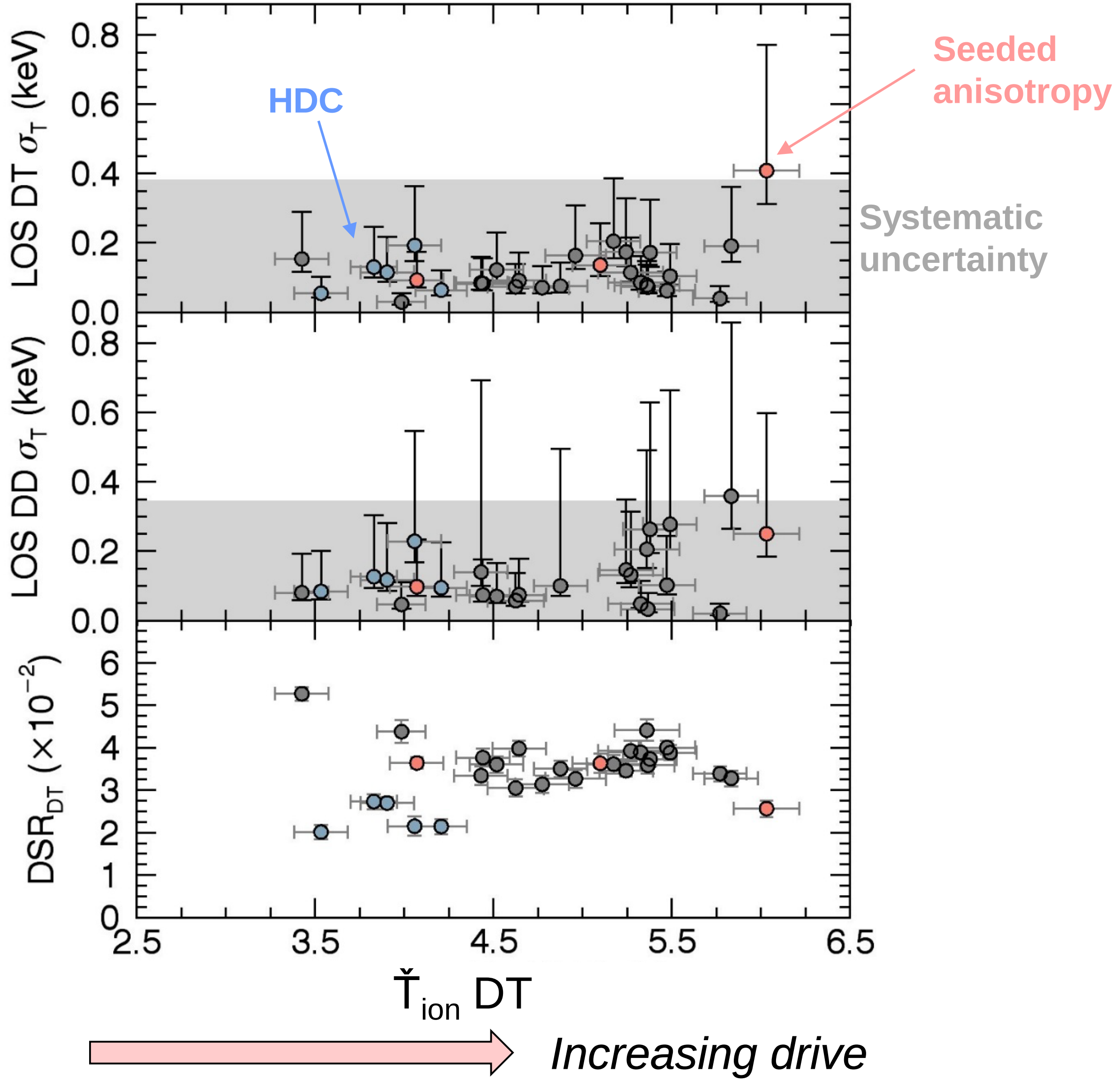
$$T_{thermal} = 0 \rightarrow \check{T}_{DD} = 0.8 \times \check{T}_{DT}$$

- Uniform (radial or turbulent) velocity would result in *isotropy* in the T_{ion} measurements
- Non-uniform velocity would result in *anisotropy* in T_{ion} measurement

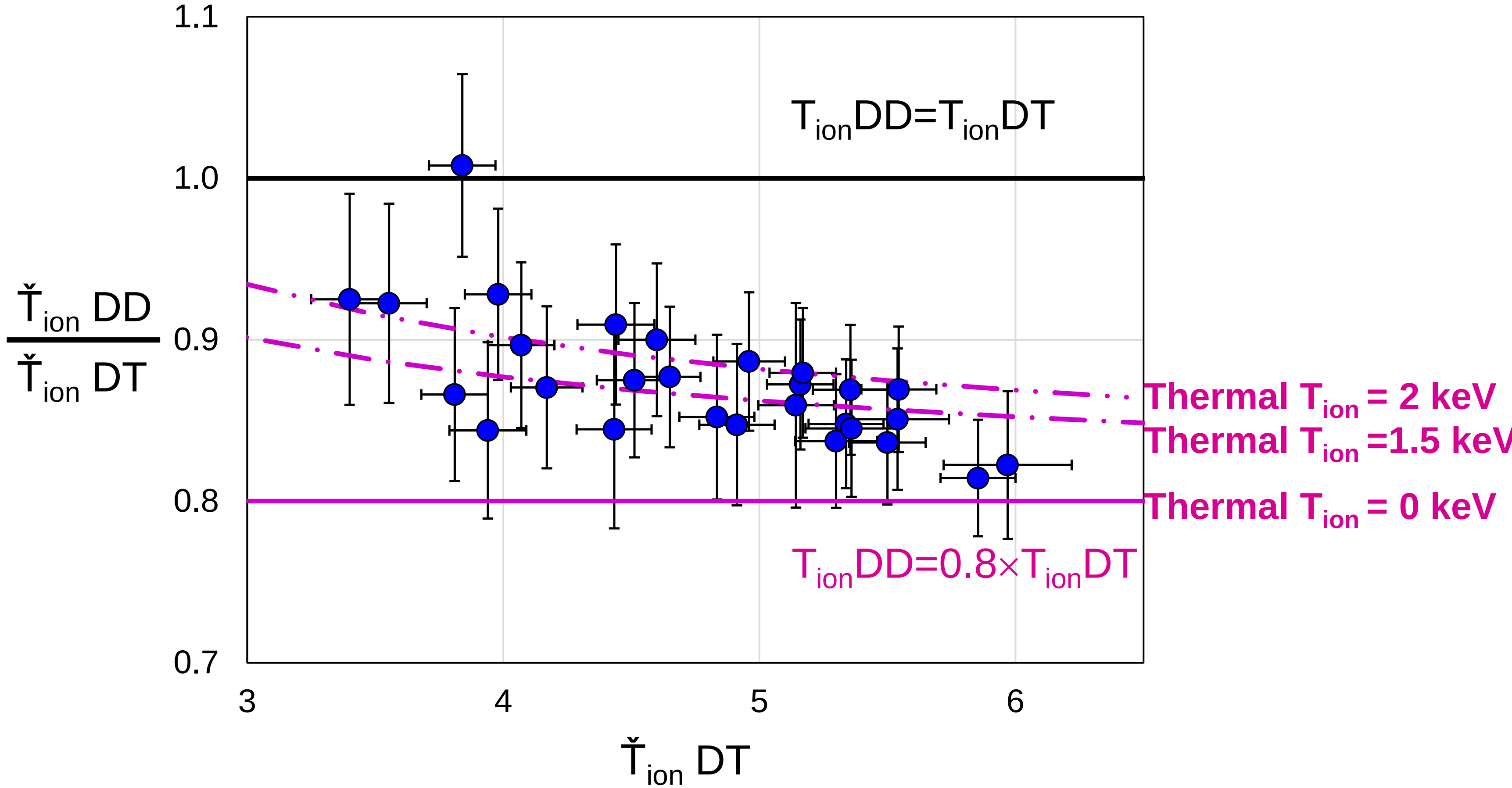
*B. Appelbe and J. Chittenden, PPCF **53**, 045002 (2011)
T.J. Murphy, Phys.Plasmas **21**, 072701 (2014)
D. Munro, submitted to Nucl. Fusion (LLNL-JRNL-676641)
M.M.R. Williams, J. Nucl. Energy **25**, 489 (1971)

Measurements conclusively rule out line-of-sight anisotropy above 0.4 keV, and no anisotropy trend is seen with drive





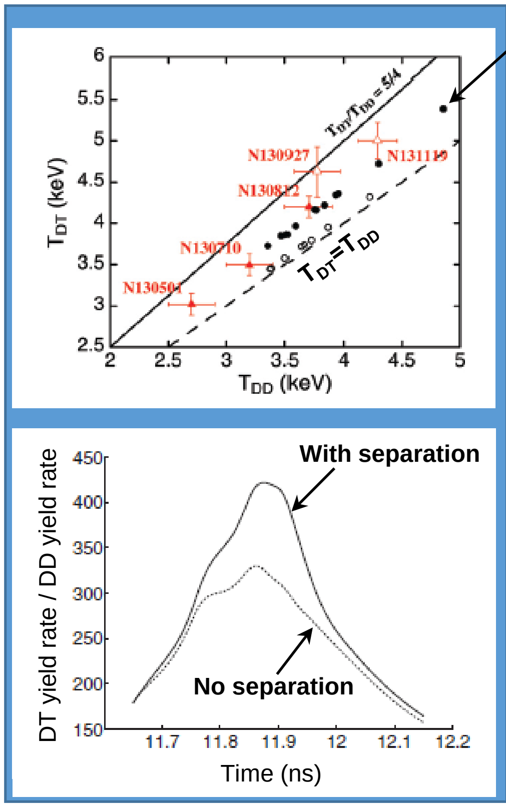
Explaining the full DD-DT $\check{T}_{ion}$ difference with velocity variance leads to unphysically low thermal T_{ion}

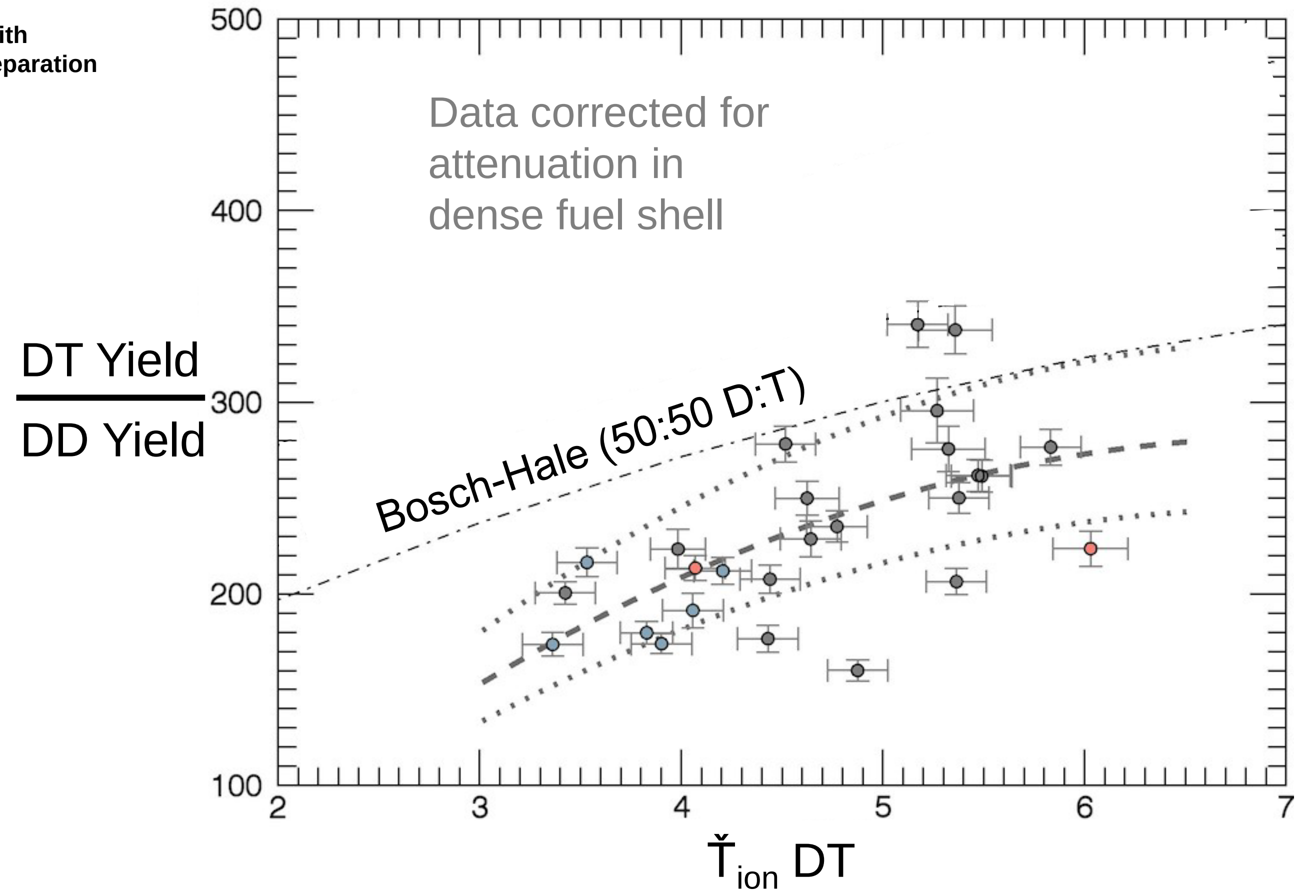


Correcting for profiles and assuming remaining DT/DD difference is due to flows, an average thermal T_{ion} of 2.1 keV is inferred; this is too low to reproduce measured yields

Fuel stratification could give $\check{T}_{ion}$ DT > $\check{T}_{ion}$ DD*; lower than expected DT-to-DD yield ratio on NIF contradicts this hypothesis

**A. Inglebert et al., EPL 107, 65003 (2014):*

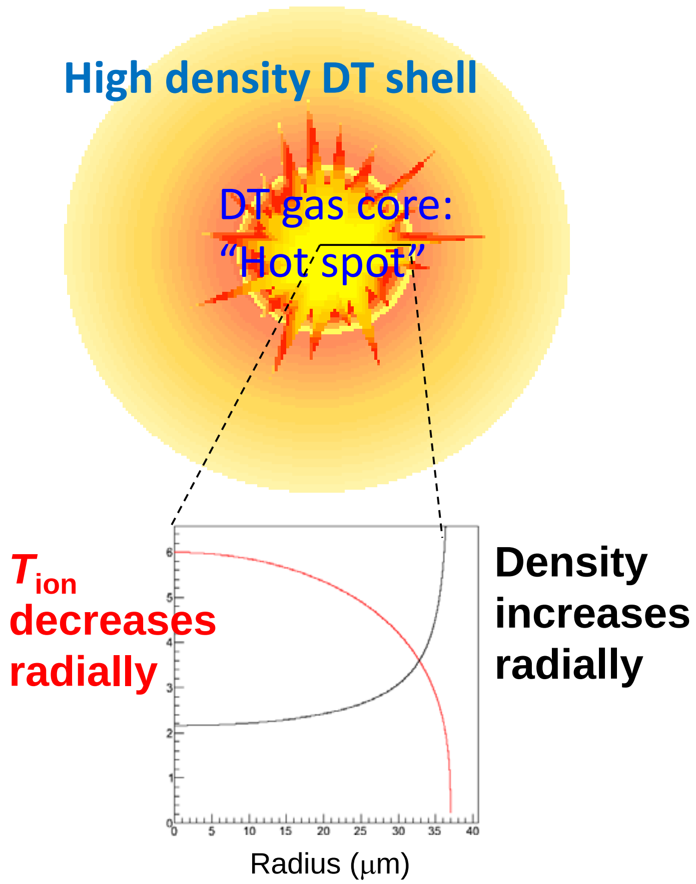




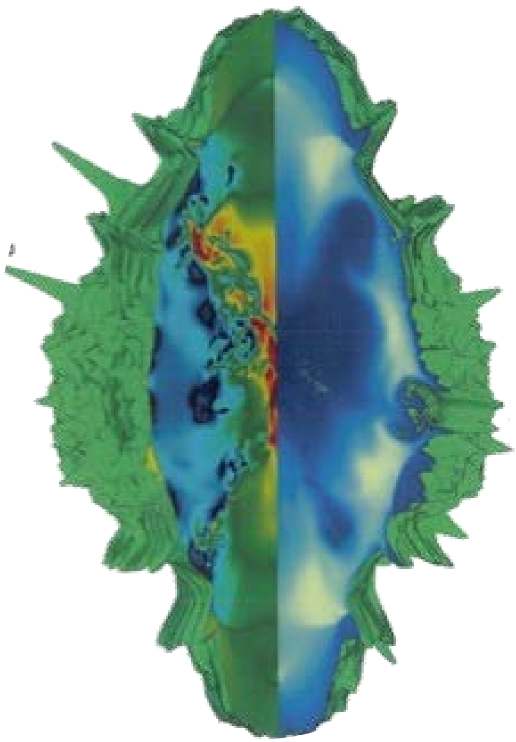
In principle, it should be possible to infer thermal T_{ion} (not impacted by flows) from the DT/DD yield ratio (“ratio method”)

A full 3D simulation accounting for complex geometry and flows looks promising for explaining the data

Naïve model

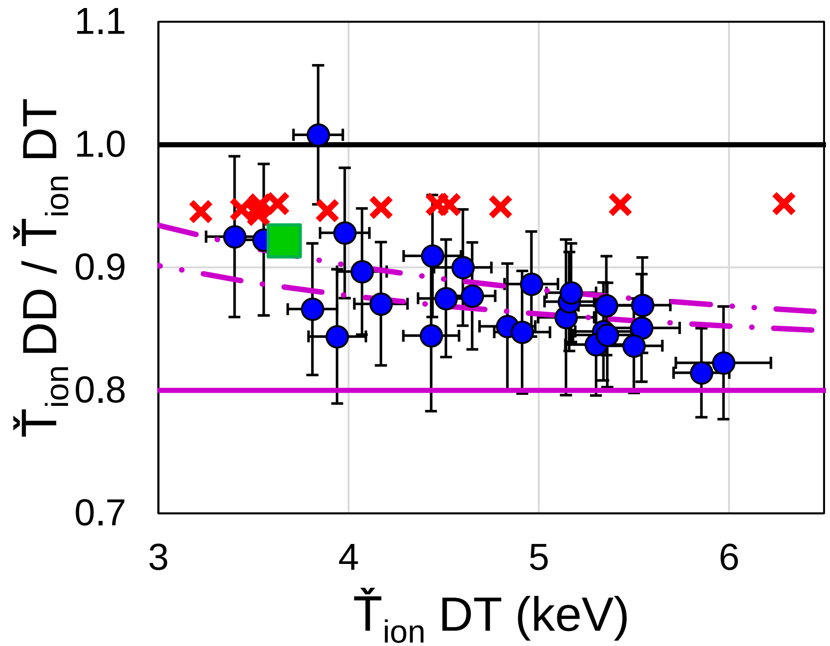


3D simulation



Preliminary 3D simulations by Brian Spears/John Field with drive asymmetry of typical magnitude show the right general trend

Spears/Field/Weber:



$\check{T}_{ion}$ DT=3.7 keV

$\check{T}_{ion}$ DD=3.4 keV

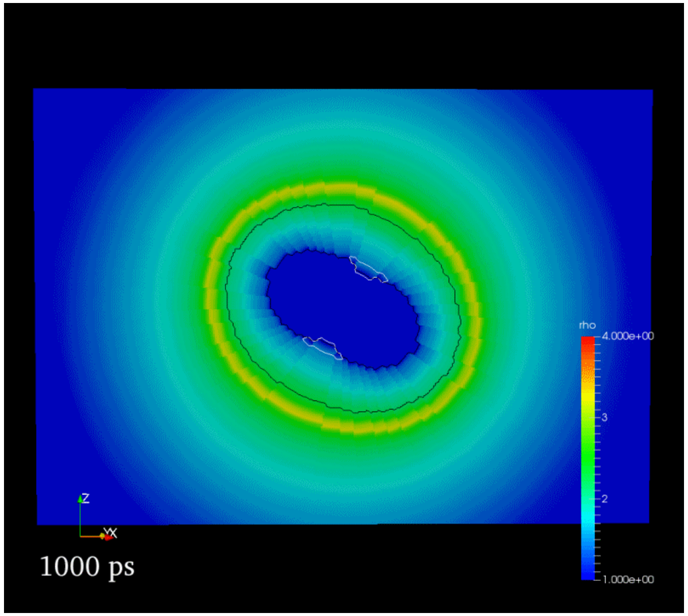
DT r.m.s.=0.09 keV

DD r.m.s.=0.06 keV

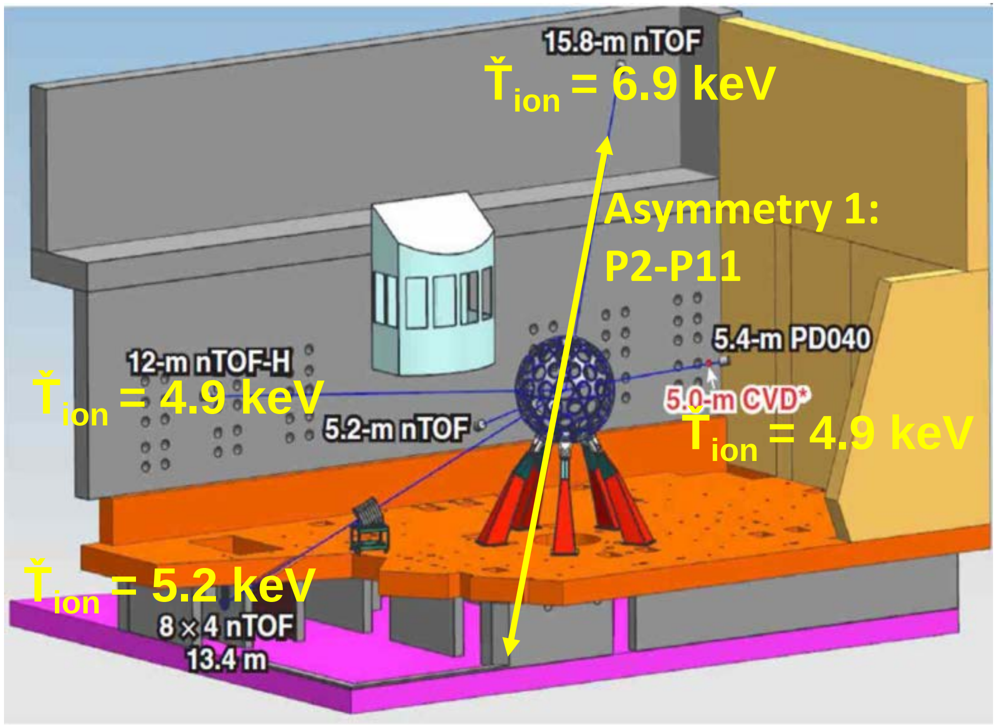
These simulations show substantial DT-DD difference but minimal LOS variation

The capability of simulations to accurately predict the effect of flows on $\check{T}_{ion}$ will be tested in an experiment on OMEGA on Nov 5th

Reduced drive on selected beams will be used to seed a P2 asymmetry along two orthogonal axes; symmetric shots will also be taken for comparison



Simulation by J. Chittenden and B. Appelbe, Imperial College



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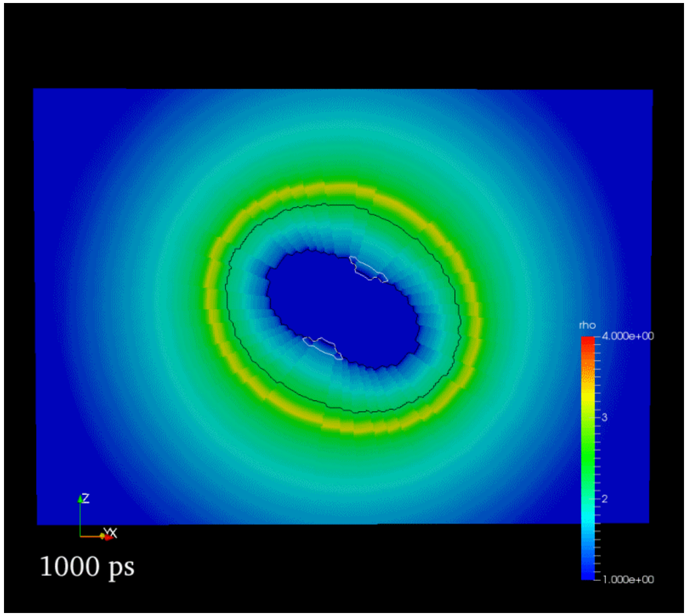

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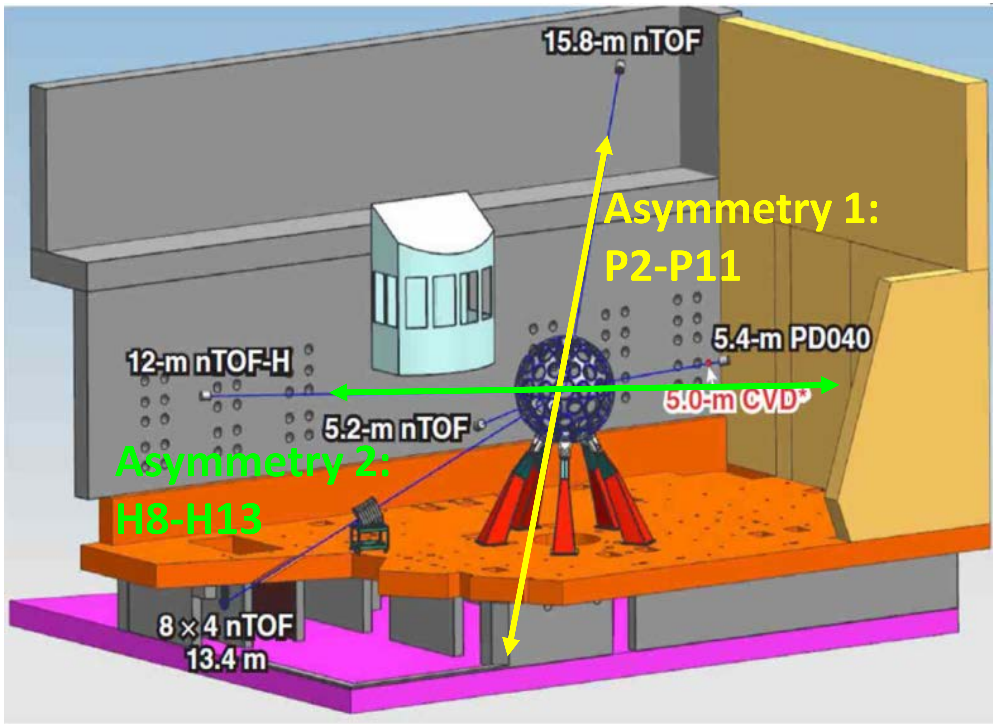

Anomalously high DT $\check{T}_{ion}$ rel. DD $\check{T}_{ion}$ in NIF implosions suggests significant 3D geometry and residual velocity effects at stagnation

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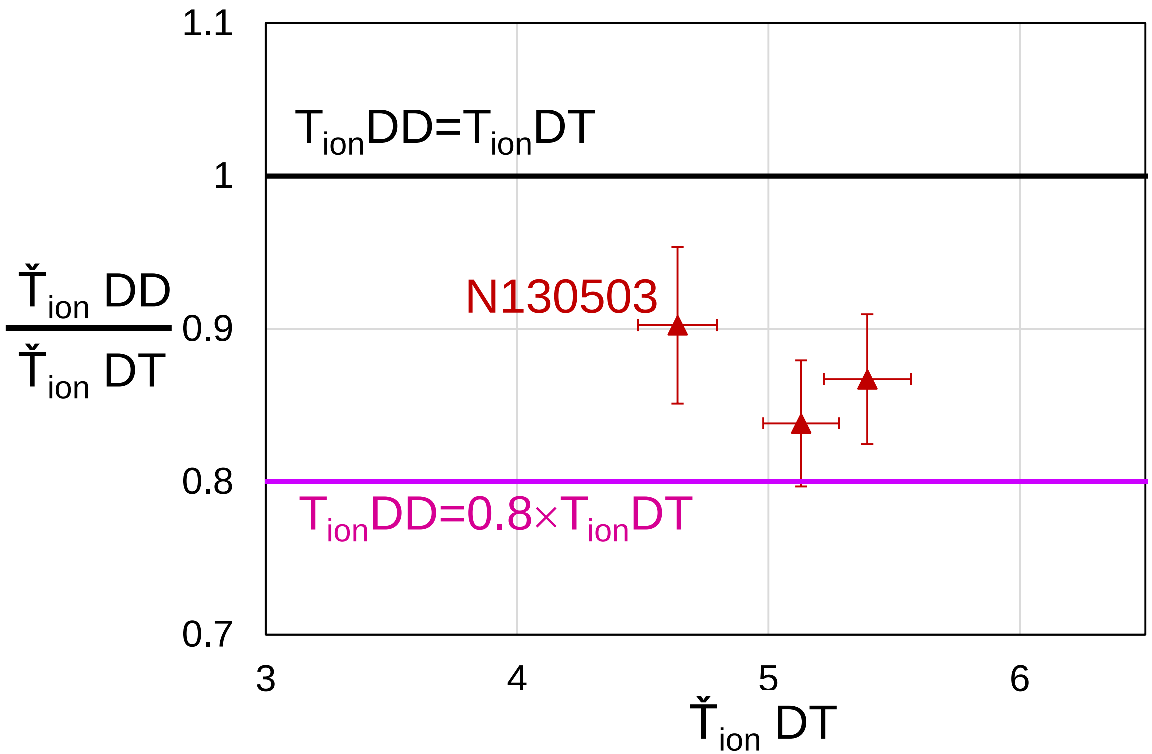
  Does not appear to explain the present observations

A 3D model considering flows and full implosion geometry appears necessary to explain the observations

Measured T_{ion} DT > T_{ion} DD observed for Indirect Drive DT Exploding Pushers* is fully explained by profile effects



N130503	T_{ion} DT (keV)	T_{ion} DD (keV)
Meas	4.64±0.16	4.19±0.19
Sim 1	4.7	4.1
Sim 2	4.6	4.02

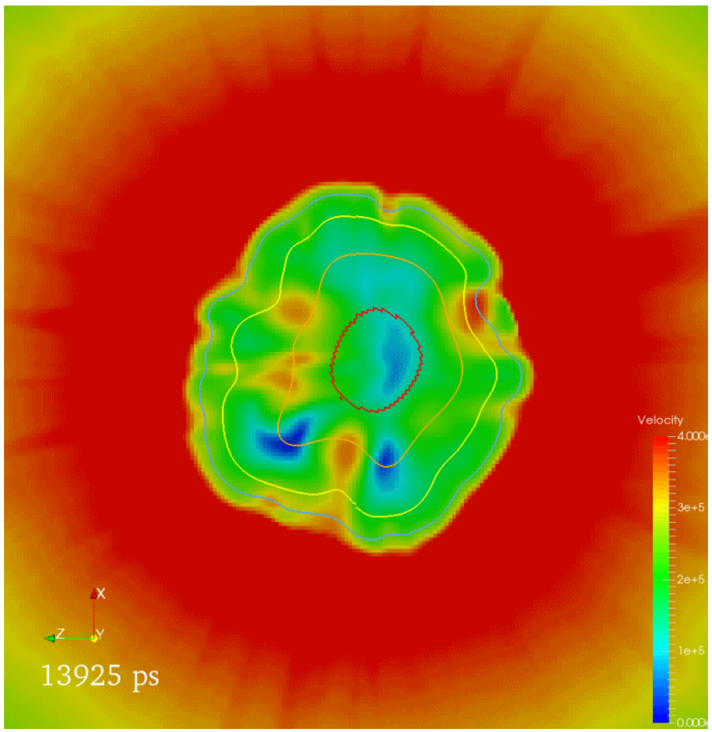
2D Hydra simulations by Rick Olsen (LANL) and Laura Berzak-Hopkins (LLNL). Flows are negligible in these simulations; observed differences are due to profiles in space and time

Y_{DT}/Y_{DD} for these implosions agree with the 50:50 D:T Bosch-Hale prediction

*S. LePape et al., PRL **112**, 225002 (2014)*

Preliminary 3D simulations by Chittenden/Appelbe with small-scale, seeded perturbations* show the right general trend

Chittenden/Appelbe:

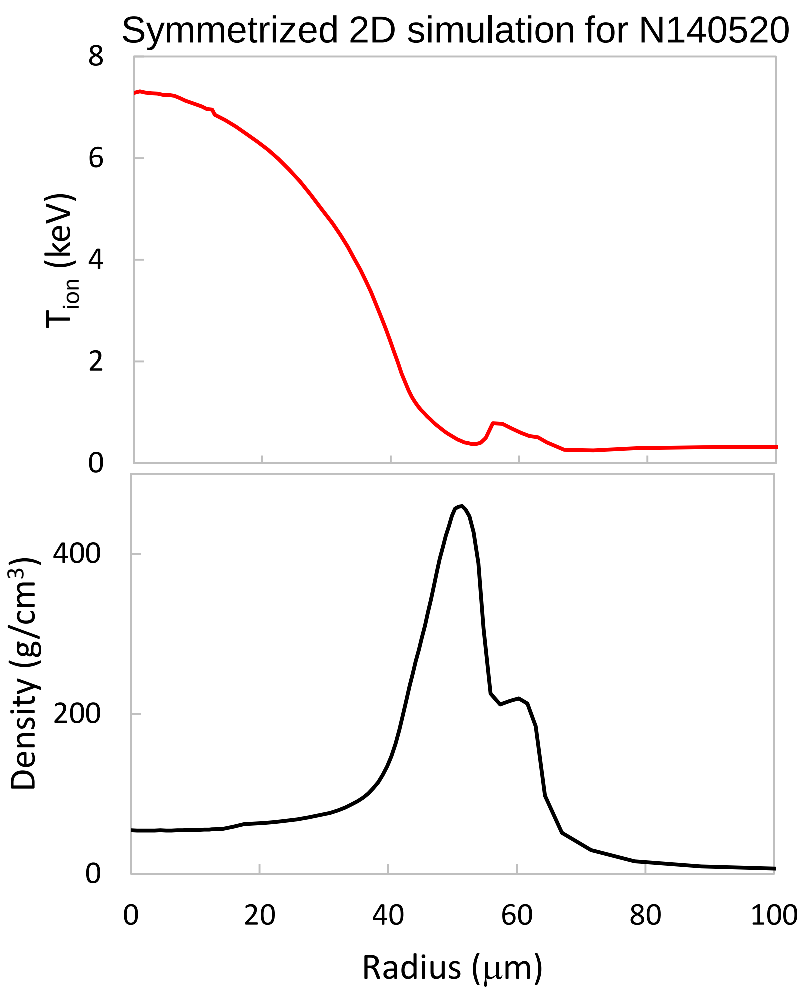


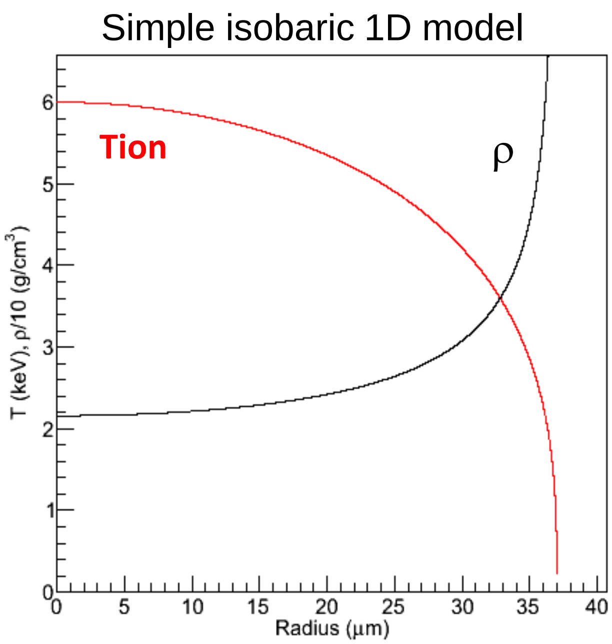
Direction	$\check{T}_{ion}$ (DT)	$\check{T}_{ion}$ (DD)
X	2.92	2.60
Y	2.87	2.57
Z	3.07	2.70
Average	**2.95**	**2.62**
r.m.s.	**0.09**	**0.06**

These simulations show substantial DT-DD difference but minimal LOS variation

**S. Taylor & J. Chittenden, Phys. Plasmas 21, 062701 (2014)*

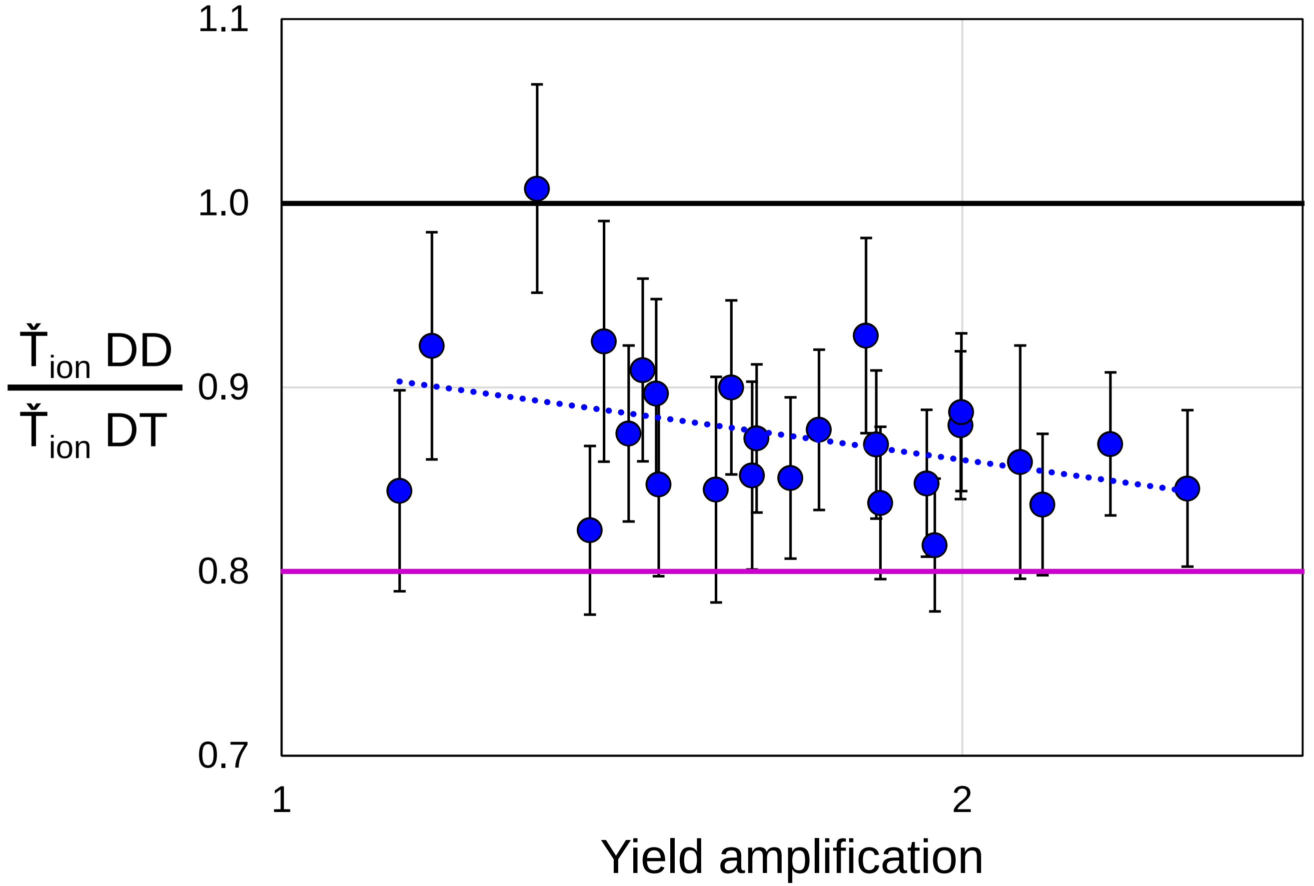
The 1D model is clearly over-simplified – compare with profiles from symmetrized 2D simulations





Non-zero temperature in the dense shell may explain why we are seeing more DD reactions than naively expected relative to DT

There is an apparent trend in DD/DT $\check{T}_{ion}$ with yield amplification due to alpha heating



- Could it be that alpha heating exacerbates the differential scattering effect?
- Does spectral distortion impact Ballabio fit to DT peak?