Ion Kinetic Dynamics in Strongly-Shocked Plasmas Relevant to ICF

IFE/1-5

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Ion kinetic physics affects the dynamics of plasmas relevant to Inertial Confinement Fusion experiments

- Strongly-shocked ($M > 10$) thin-shell implosions produce conditions similar to the DT-vapor in ICF experiments.
- Implosions with D+^{3}He gas were used to study ion kinetic mechanisms over a wide range of Knudsen numbers ($N_K = \lambda_{ii}/R$):
  - Yield from slightly kinetic implosions (N_K = 0.01—0.05) is dominated by the loss of long mean-free-path ions.
  - Yield from highly kinetic implosions ($N_K > 0.5$) is dominated by multi-species physics: ion species separation, thermal decoupling.
- The observed physics mechanisms will impact the formation of the ICF hotspot.

Many thanks to my coauthors:

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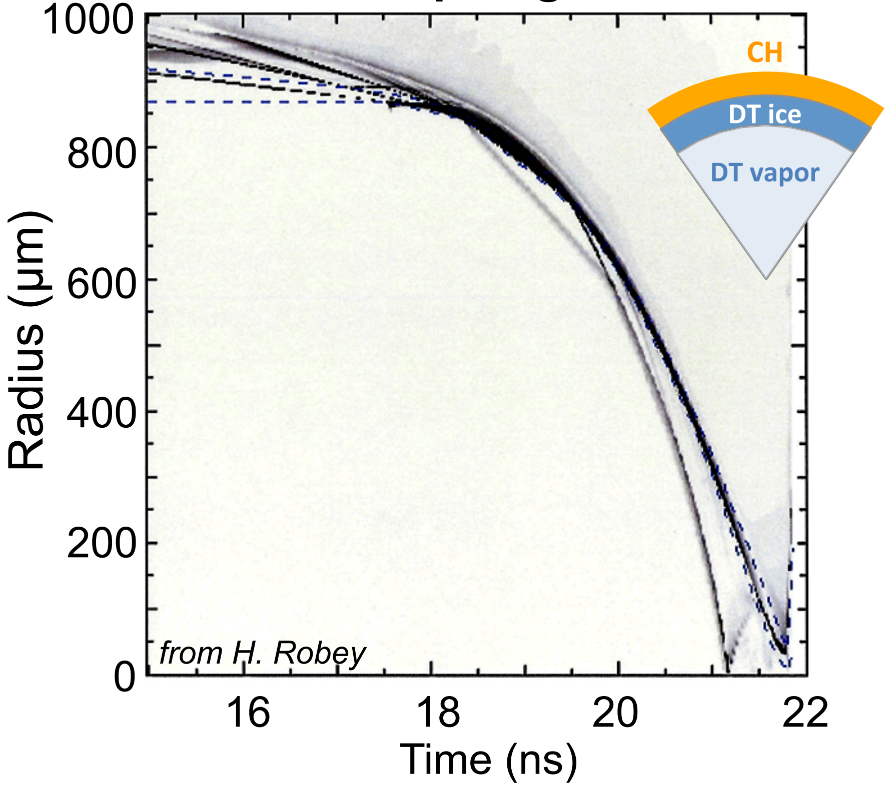
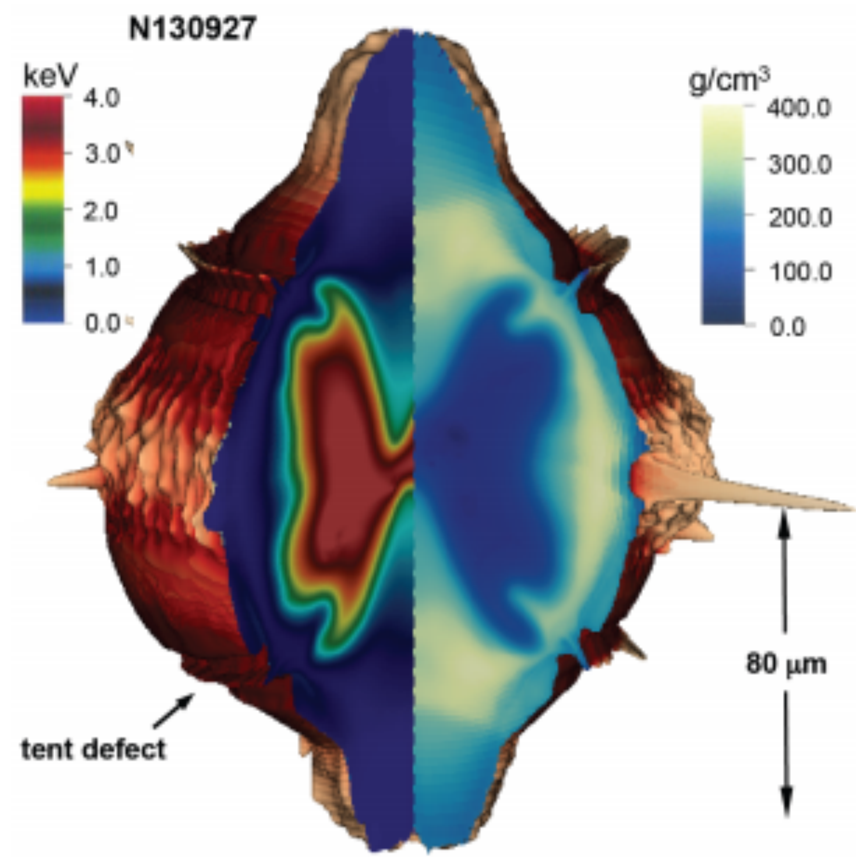
Hydrodynamic simulations are used to design and understand Inertial Confinement Fusion (ICF) implosions

1D Hydrodynamic simulation of hot-spot ignition

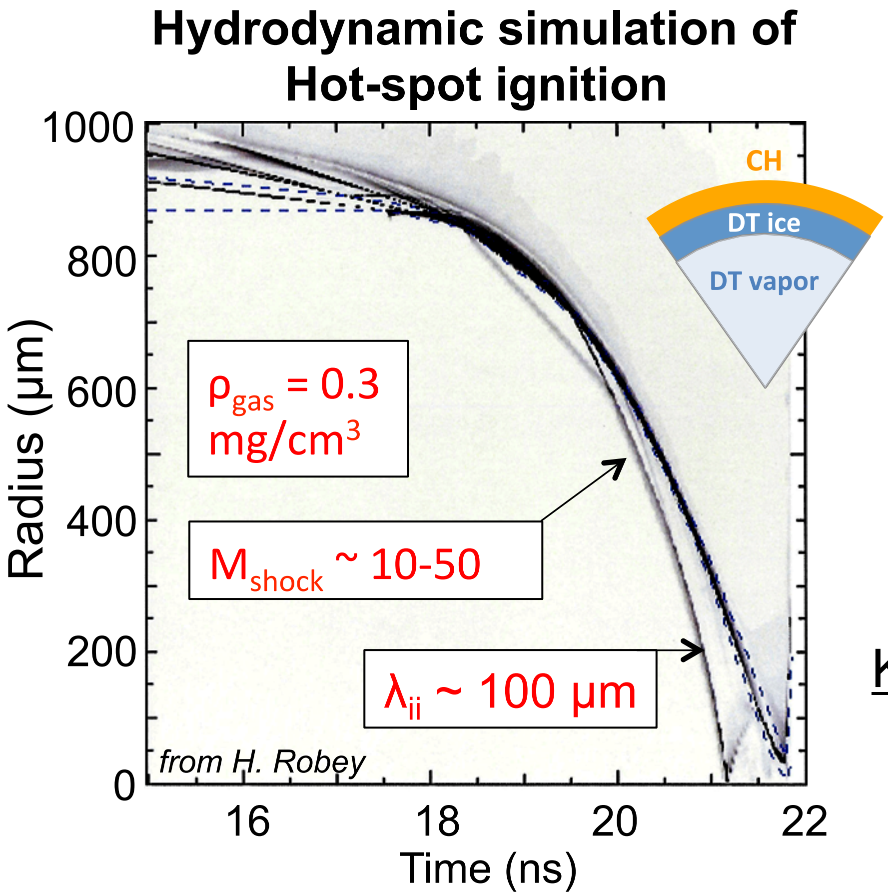


3D simulation of sub-igniting implosion



D. Clark, J. Phys. Conf. Series 717, 012011 (2016)

However, the shock phase of cryogenic ICF implosions can generate plasmas in which *kinetic physics* becomes important



$$\lambda_{j,k} = \frac{3}{4\pi}\left(\frac{4\pi\epsilon_0}{e^2 Z_j Z_k}\right)^2 \frac{T^2 m_j}{n_k m_r \ln\Lambda} \propto M^4$$

<u>Kinetic regime</u>: λ_{ii} ~ Radius of implosion

In this regime, hydrodynamics can break down

Additionally, hydrodynamic codes used to design ICF implosions only model a single ion species

Experiment

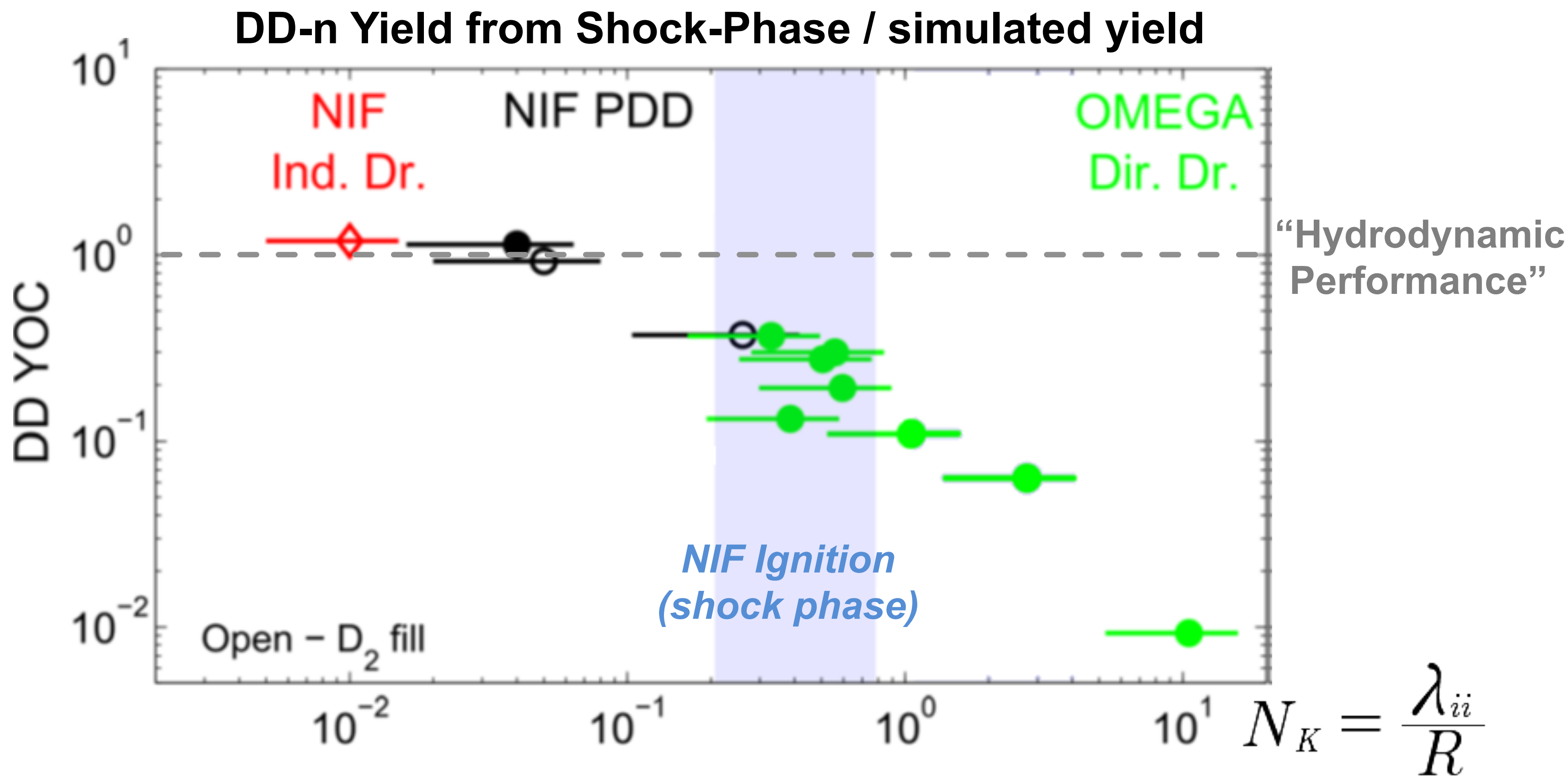
Species (%)		Mass	Charge
D (50%)		**2 amu**	**+1 e**
T (50%)		**3 amu**	**+1 e**

Hydrodynamic Simulation ("Single-ion fluid")

Species	Mass	Charge
"DT"	**2.5 amu**	**+1 e**

***Multiple-ion kinetic physics* may produce unexpected behavior**

Recent experiments relevant to the ignition shock-phase disagree systematically with hydrodynamic simulations



Performance drops with increased Knudsen number, N_K.

If mean-free-paths are long, this condition will affect each ion species differently

Example: Consider a D, ^{3}He plasma with constant mass density ρ:

$$\lambda_D = \left[\frac{1}{\lambda_{D,D}} + \frac{1}{\lambda_{D,{}^3He}}\right]^{-1} = \lambda_C \frac{10(3-f_D)}{24-19f_D}$$

$$\lambda_{{}^3He} = \left[\frac{1}{\lambda_{{}^3He,D}} + \frac{1}{\lambda_{{}^3He,{}^3He}}\right]^{-1} = \lambda_C \frac{5(3-f_D)}{8(5-4f_D)}$$

$\lambda_D/\lambda_{3He} \approx 3.2$!

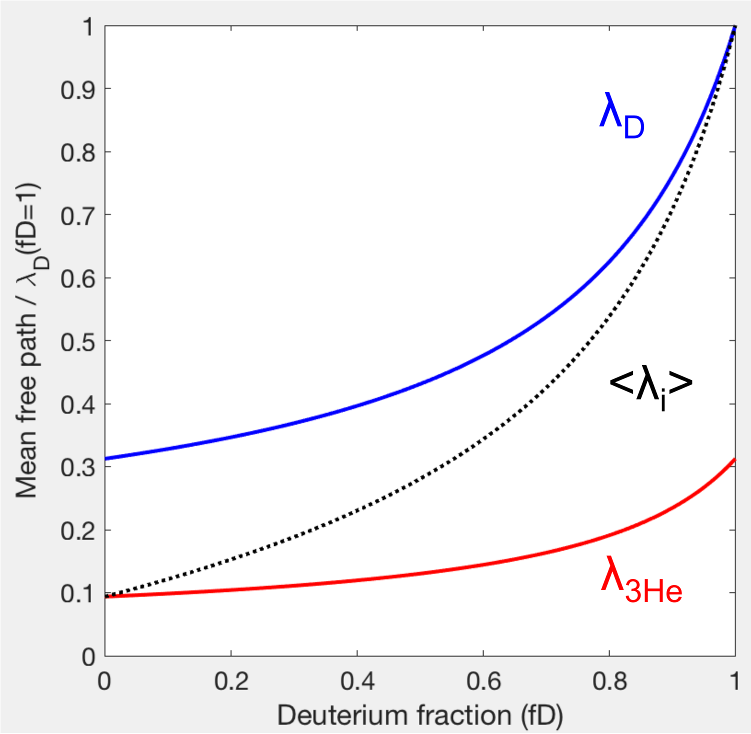
where $\lambda_C = \left(\frac{3}{4\pi}\right)\left(\frac{4\pi\epsilon_0}{e^2}\right)^2 \frac{T^2 m_p}{\rho \log\Lambda}$

→ $\langle\lambda_i\rangle = f_D\lambda_D + f_{{}^3He}\lambda_{{}^3He}$

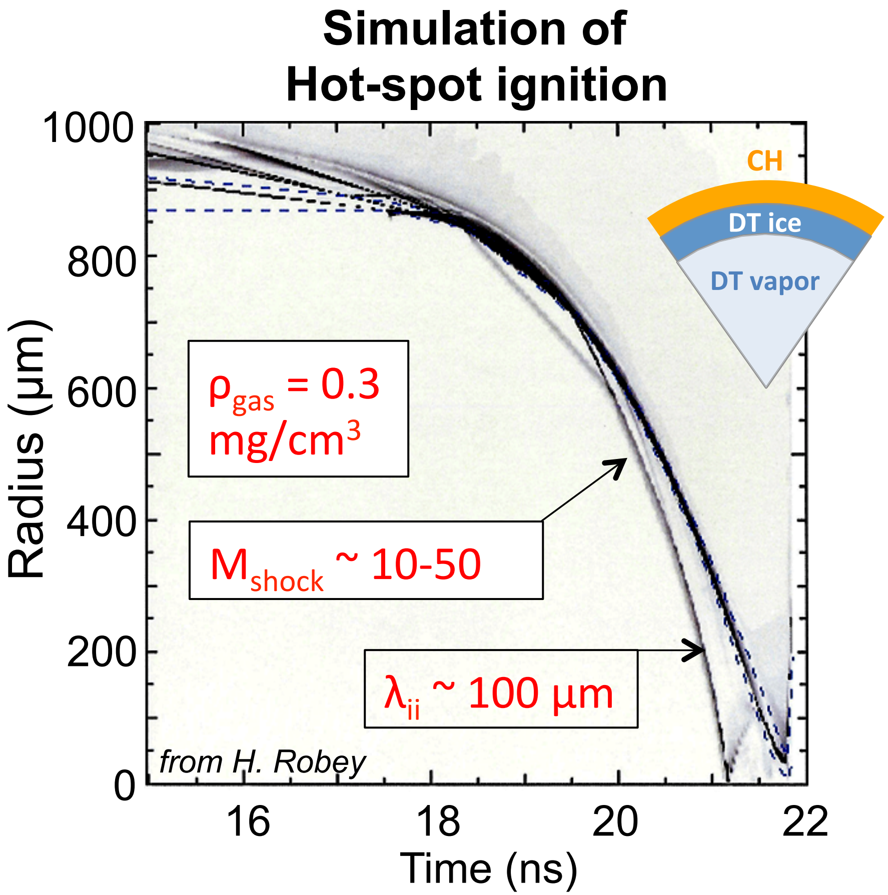
$$= (3-f_D)\frac{24+37f_D-45f_D^2}{(24-19f_D)(5-4f_D)}\frac{5\lambda_C}{8}$$

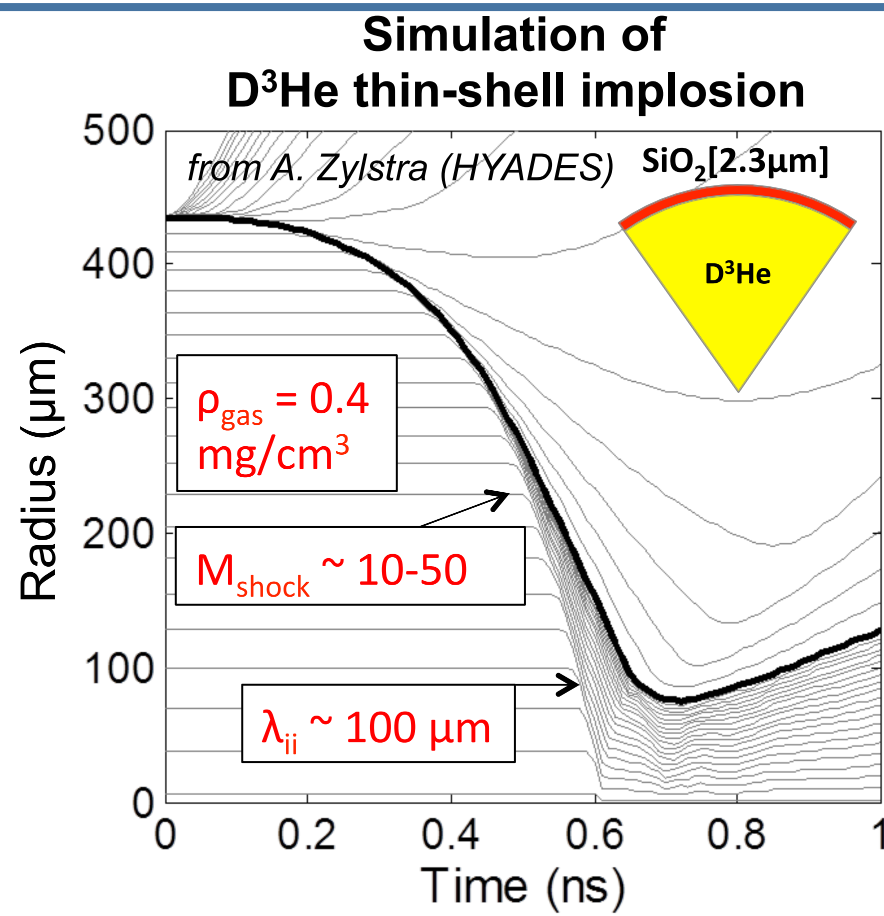
<λ_i> varies by ~10x!

Theoretical mean-free-path scaling



Kinetic conditions in shock-driven, thin-shell implosions are similar to the shock phase of ignition experiments



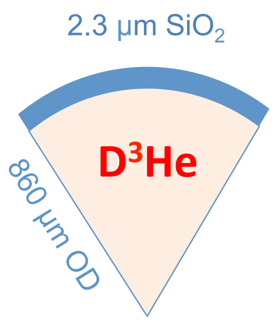


Kinetic regime:

λ_{ii} ~ Radius of implosion

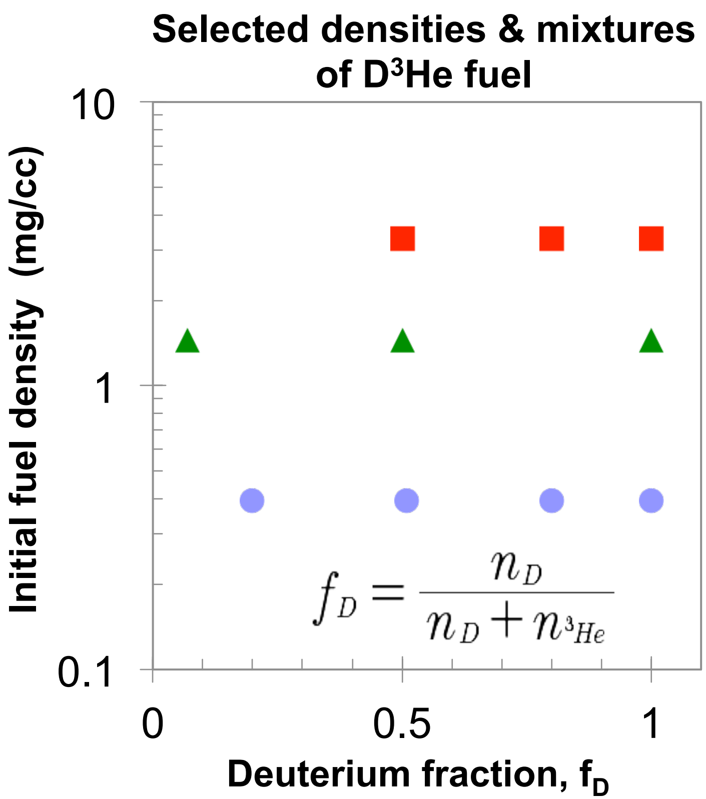
To explore the importance of multiple-ion and kinetic physics, D:^{3}He fuel ratio scans were performed in shock-driven implosions

Direct Drive



Fuel density:
3.3, 1.45 or 0.4 mg/cc

Laser:
60 beams, 23 TW,
0.6 ns (1.0 ns) square



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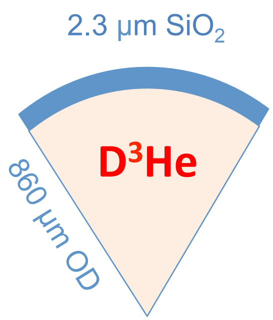

Fuel density:

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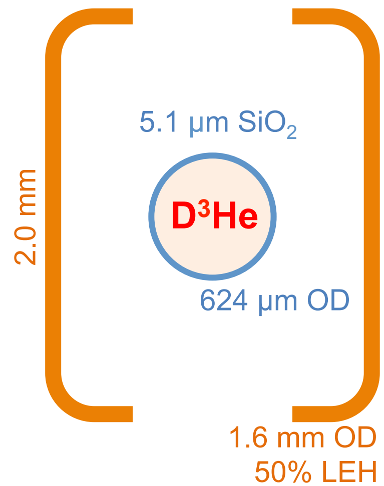
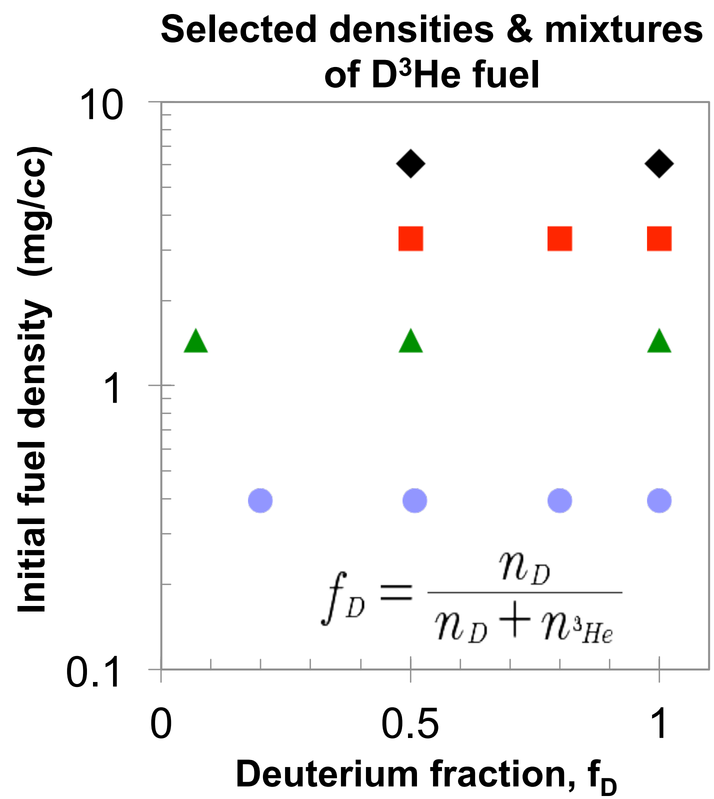
Indirect Drive



6.1 mg/cc

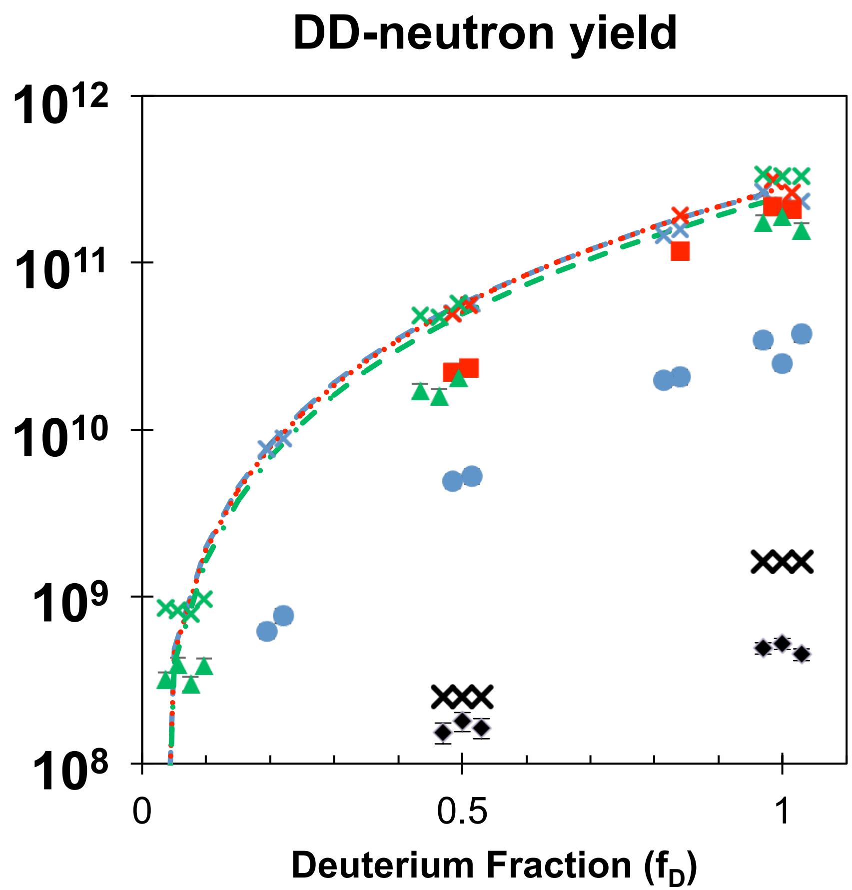
40 beams, 17.5 TW,
1 ns square

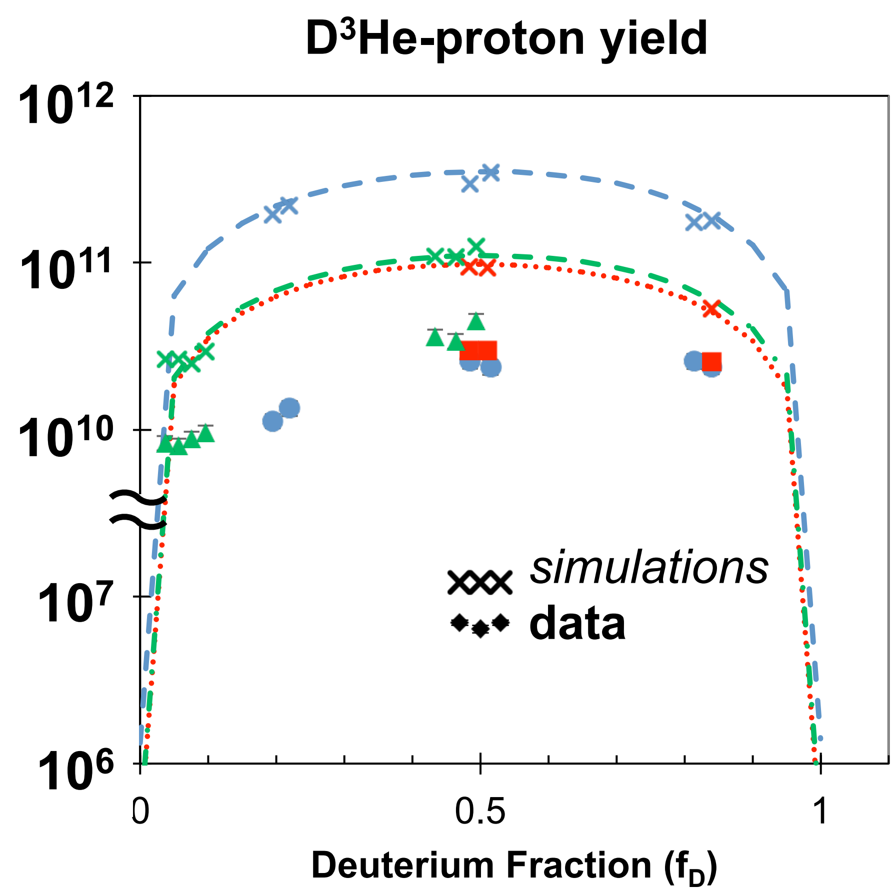


We measure:
Yield, Spectral width → <T_i>, Bang-time, Burn duration, Burn radius
… for the D-D *and* D-^{3}He fusion reactions.

H. G. Rinderknecht, et al. *Phys Rev Lett* **114**, 025001 (2015)

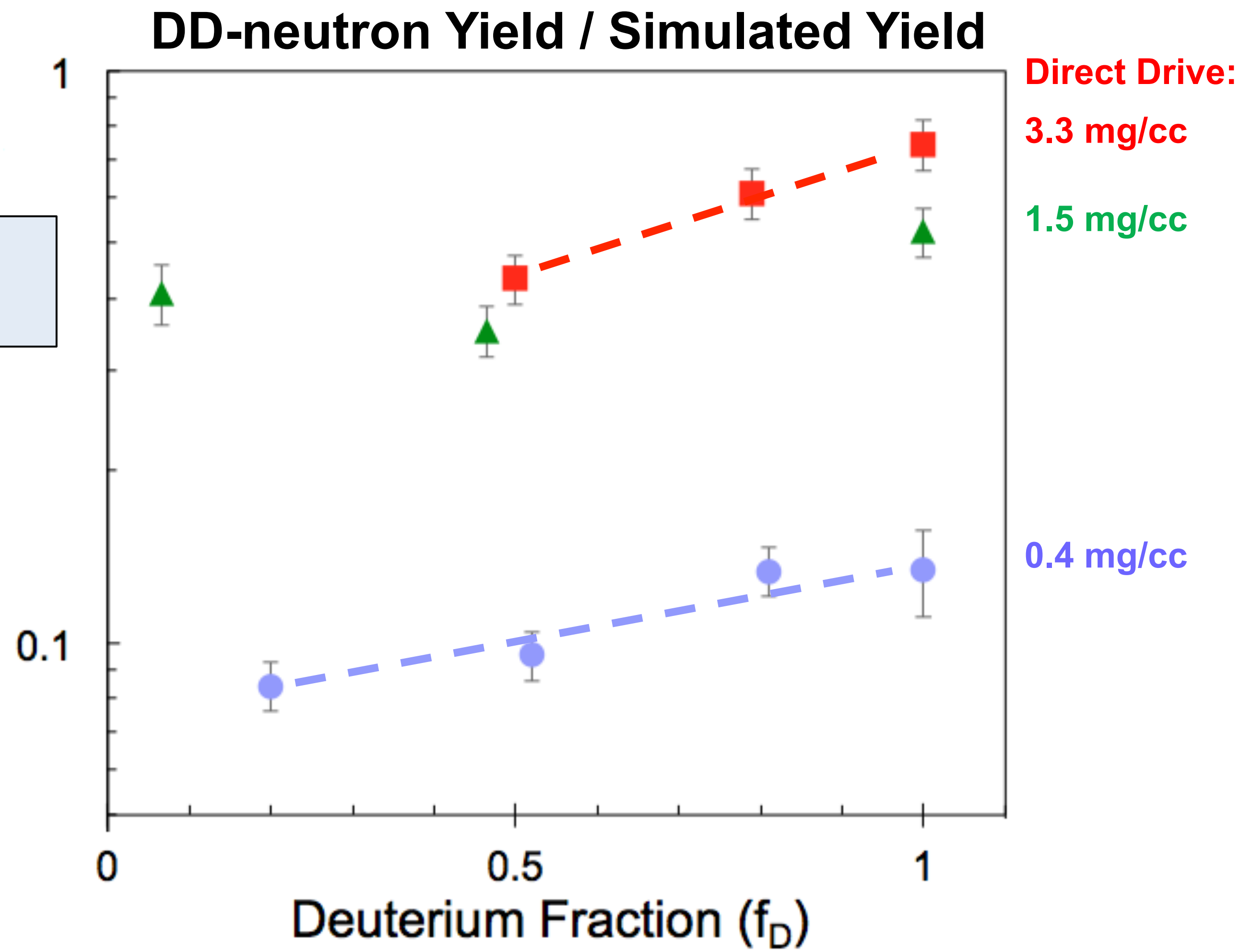
Yields vary by many orders of magnitude with deuterium fraction, gas pressure, and drive conditions





Nuclear performance exhibits anomalous trends with fuel composition ($f_D = n_D/n_{tot}$)

- Low-density:
  YOC ~ f_D



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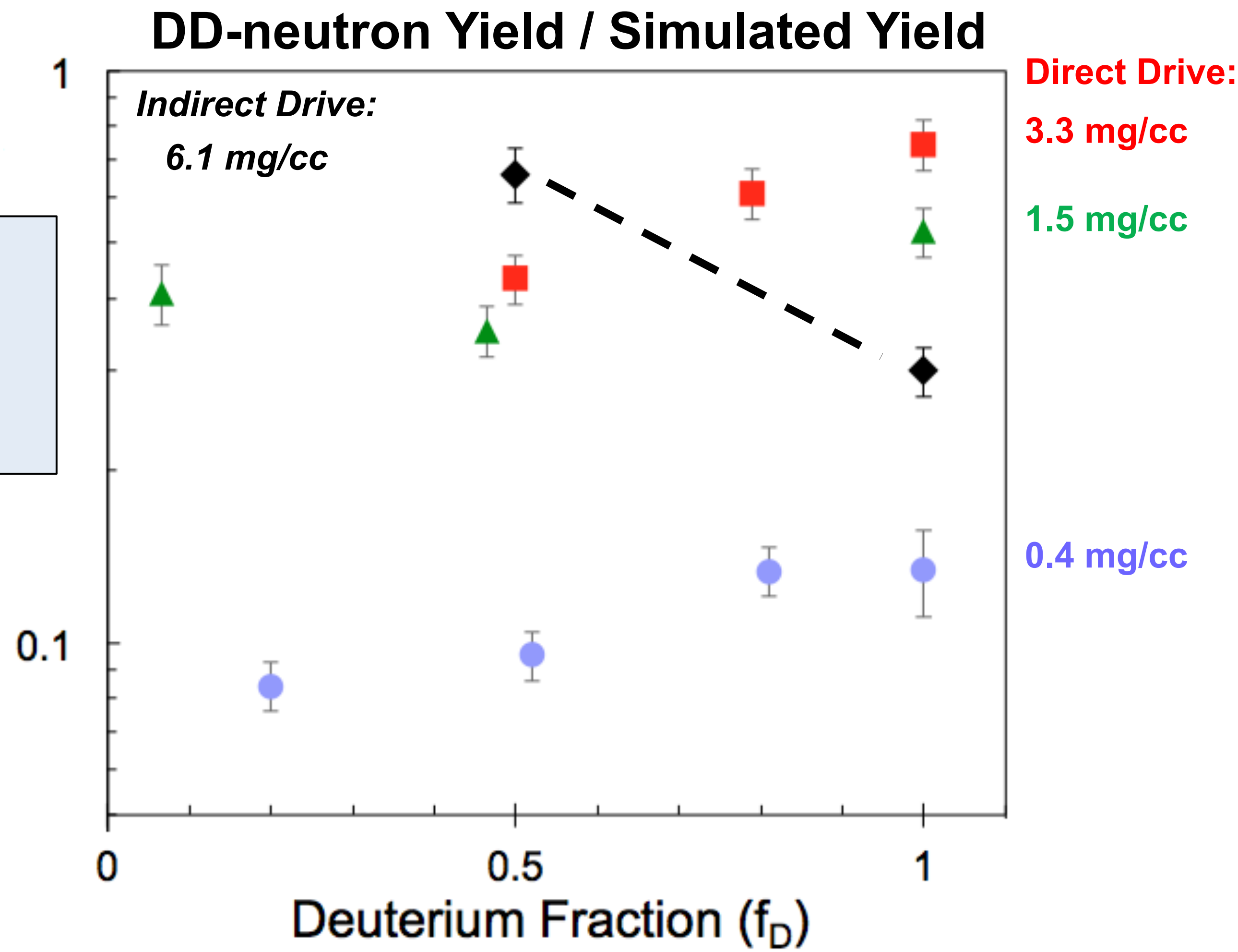
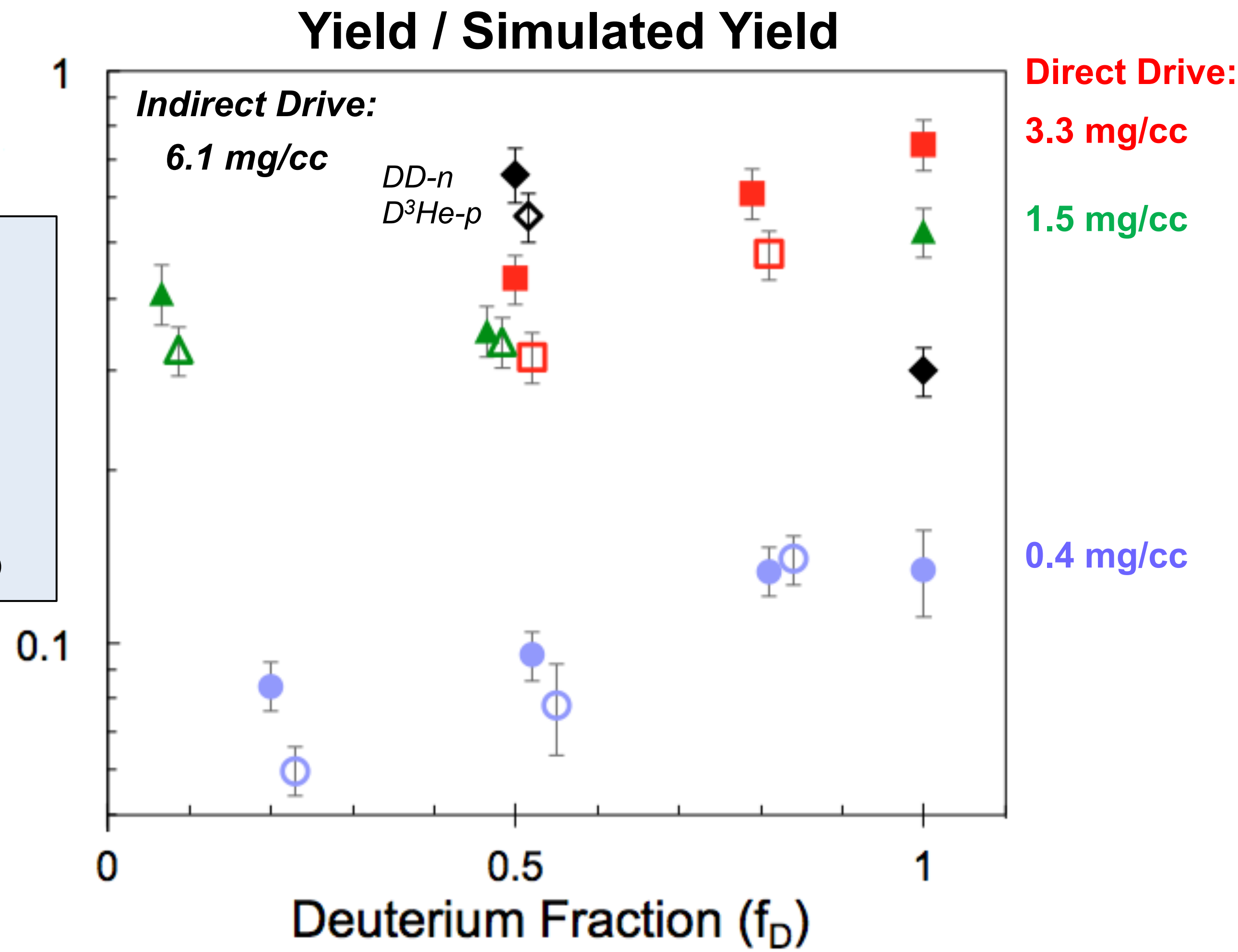


- Low-density: $YOC \sim f_D$
- High-density: $YOC \sim f_D^{-1}$

Nuclear performance exhibits anomalous trends with fuel composition ($f_D = n_D/n_{tot}$)

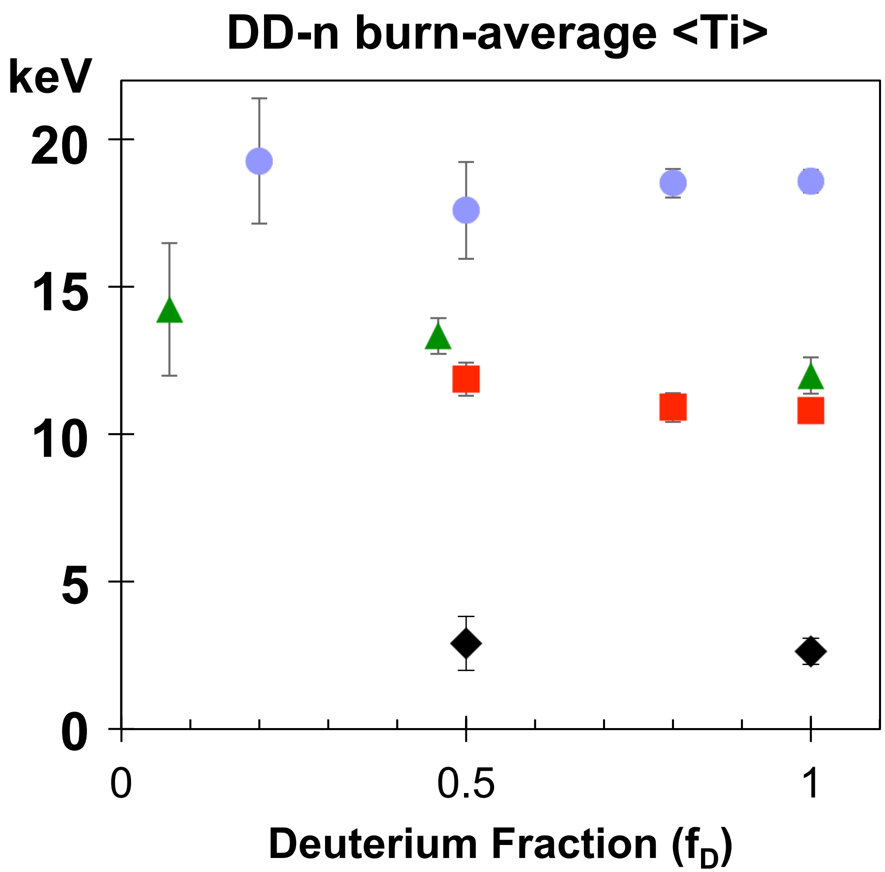
- Low-density: $YOC \sim f_D$
- High-density: $YOC \sim f_D^{-1}$
- Same trend in DD-n, D^3He-p



A "burn-averaged" Knudsen number $\langle N_K \rangle$ is calculated from the measured temperature and density

$$\langle N_K \rangle \equiv \frac{\langle \lambda_i \rangle}{R} \propto \frac{\langle T_i \rangle^2}{\langle n_i \rangle R}$$

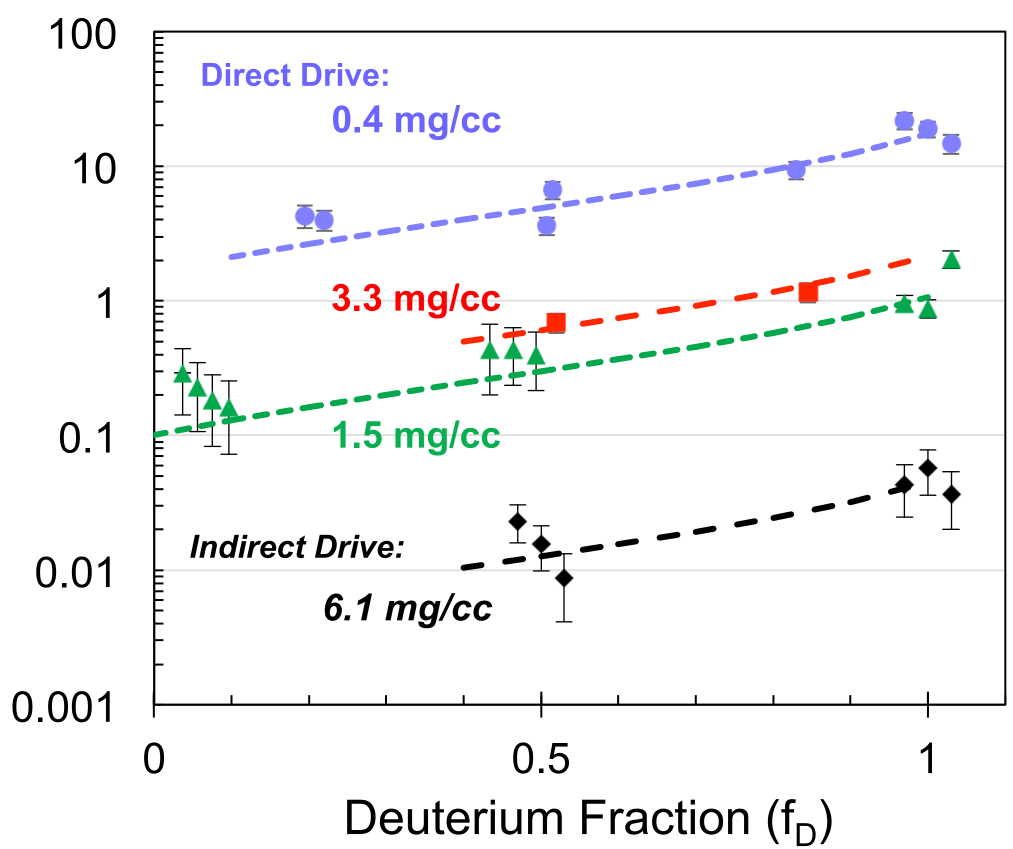
- $\langle T_i \rangle$ inferred from fusion product spectra[1]
- **R** inferred from x-ray self-emission
- $\langle n_i \rangle$ inferred from comprehensive nuclear data[2], secondary nuclear yields[3], or x-ray self-emission



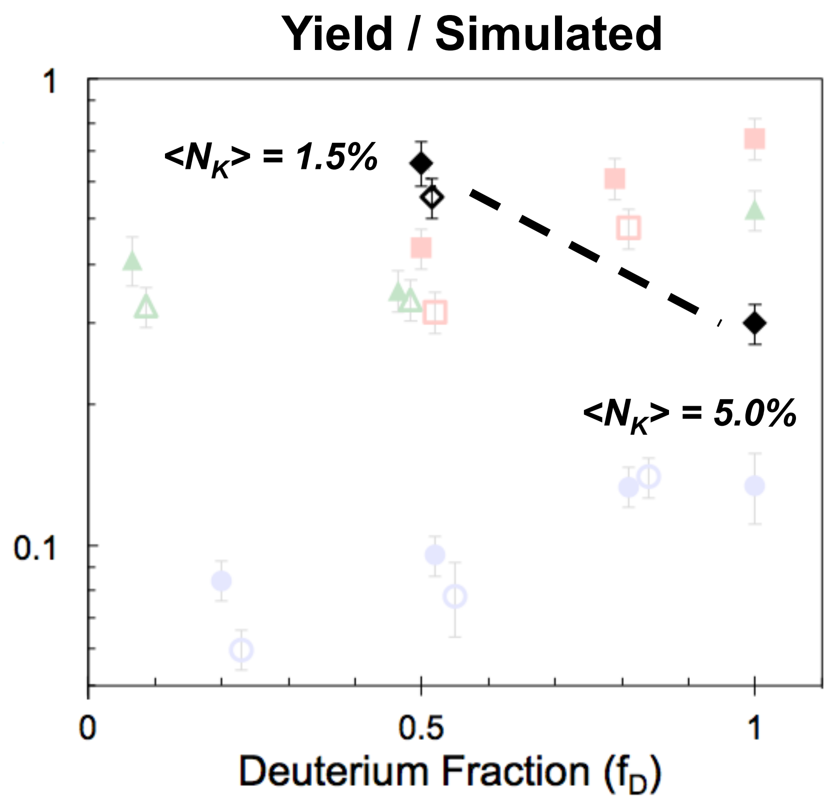
[1]Brysk PP 15, 611 (1973); Ballabio NF 38, 1723 (1998)
[2]Rinderknecht PRL 114, 025001 (2015)
[3]Cable JAP 62, 2233 (1987)

<N_K> varies over 3 orders of magnitude, and increases with f_D for all experiments, as expected

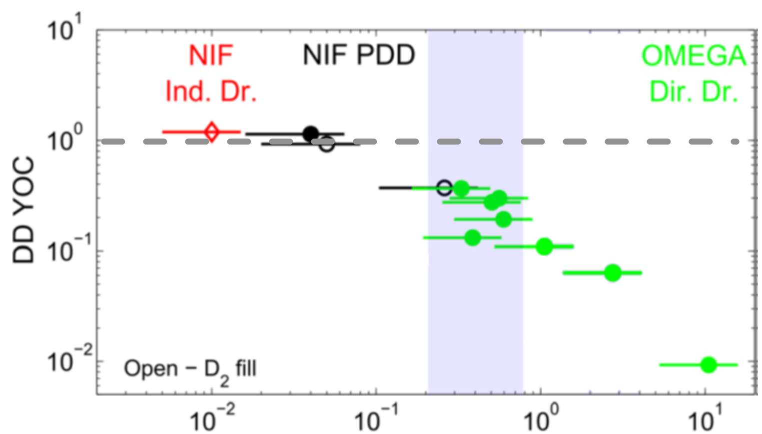
$$\langle N_K \rangle = \langle \lambda_{ii} \rangle / R_{burn}$$



Low $\langle N_K \rangle$ experiments follow expected yield trend with $\langle N_K \rangle$: large λ_{ii} effects dominate



- Rosenberg, et al., demonstrated reduced performance: YOC ~ $1/N_K$



[1]Albright POP 20, 122705 (2013)
[2]Kagan PRL 115, 105002 (2015)

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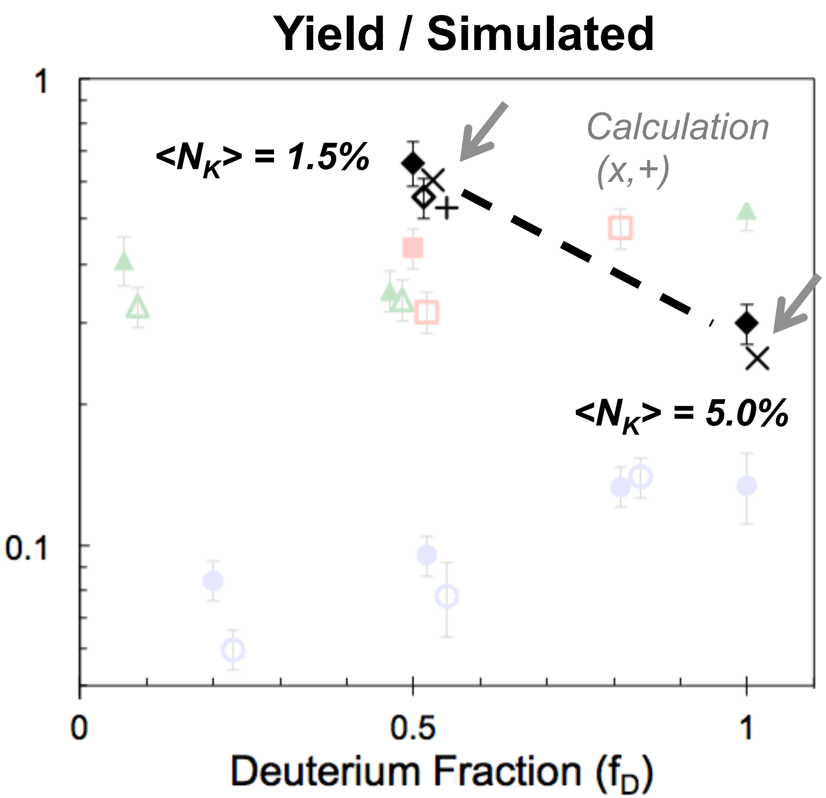

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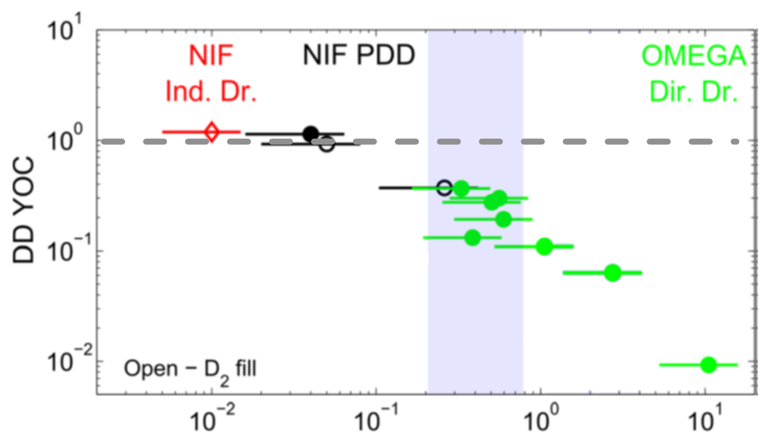
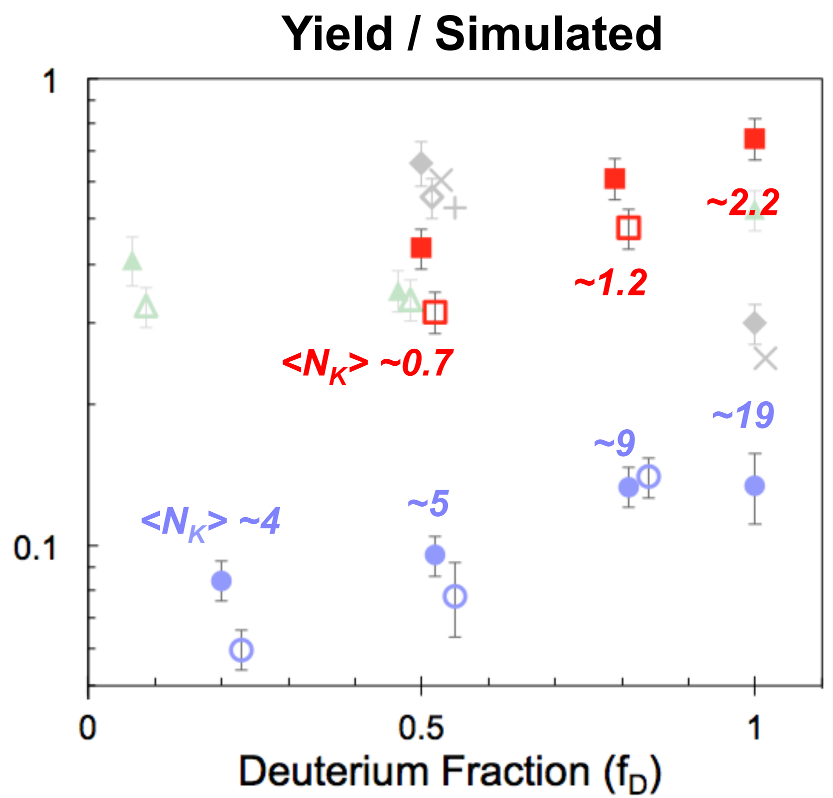


- Calculated reactivity reduction due to perturbed ion distribution functions[1,2] (DD-n: **x**, D^3He-p: **+**) agree with data.

[1]Albright POP 20, 122705 (2013)
[2]Kagan PRL 115, 105002 (2015)

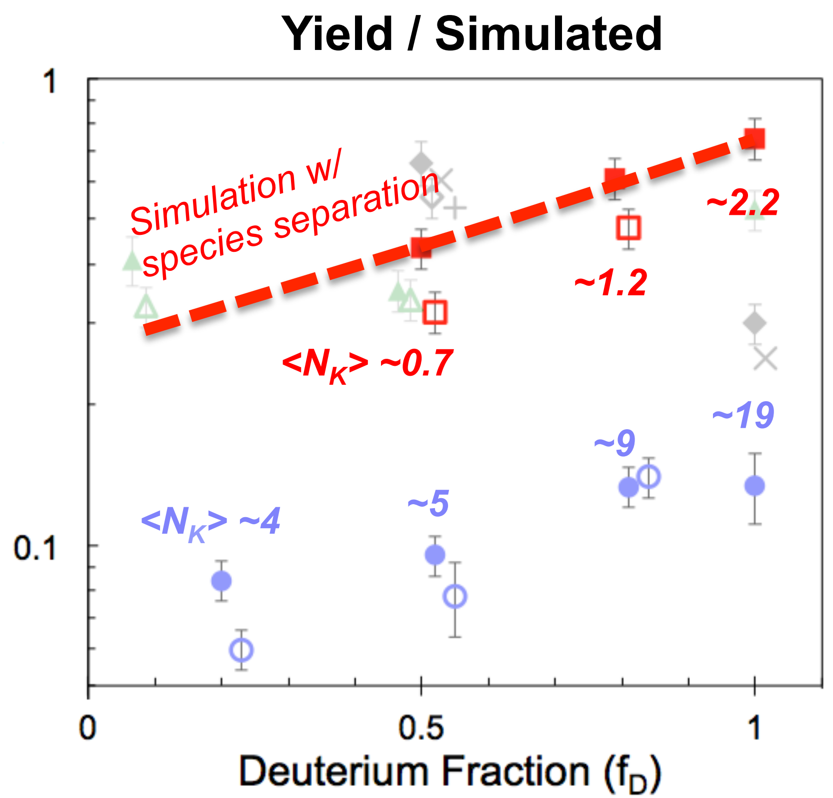
High <N_K> experiments follow a different trend: multi-species effects dominate



- For $\langle N_K \rangle \gtrsim 1$, distribution functions are far from Maxwellian, and fusion is not predominantly thermal.
- Yield trends are dominated by *multispecies effects*[1], which alter concentration and energy balance:
  -
  -

[1]Rinderknecht PRL 114, 025001 (2015)

High <N$_K$> experiments follow a different trend: multi-species effects dominate



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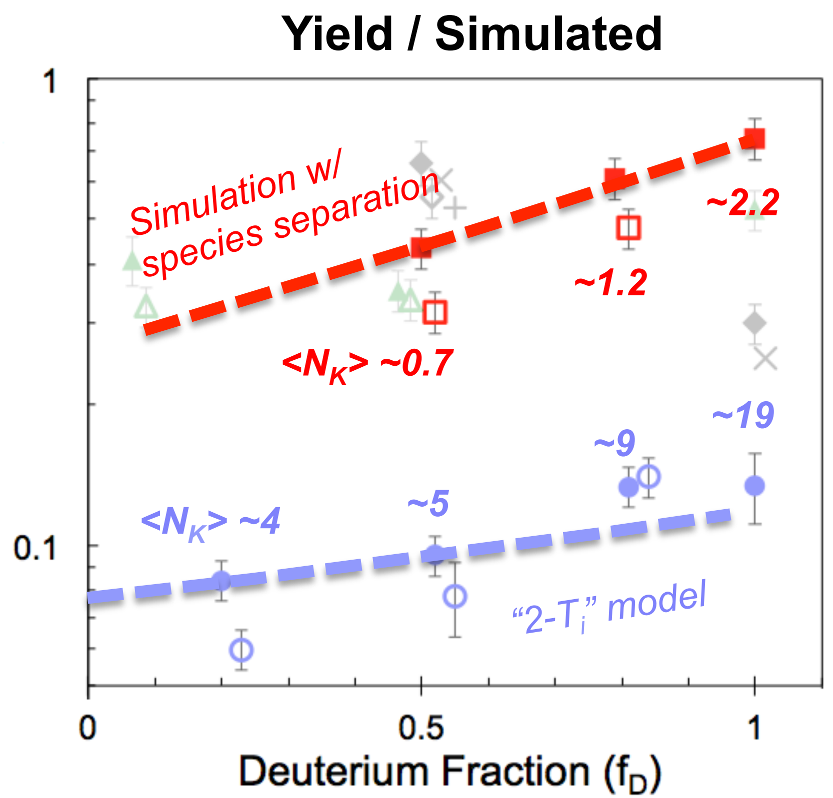
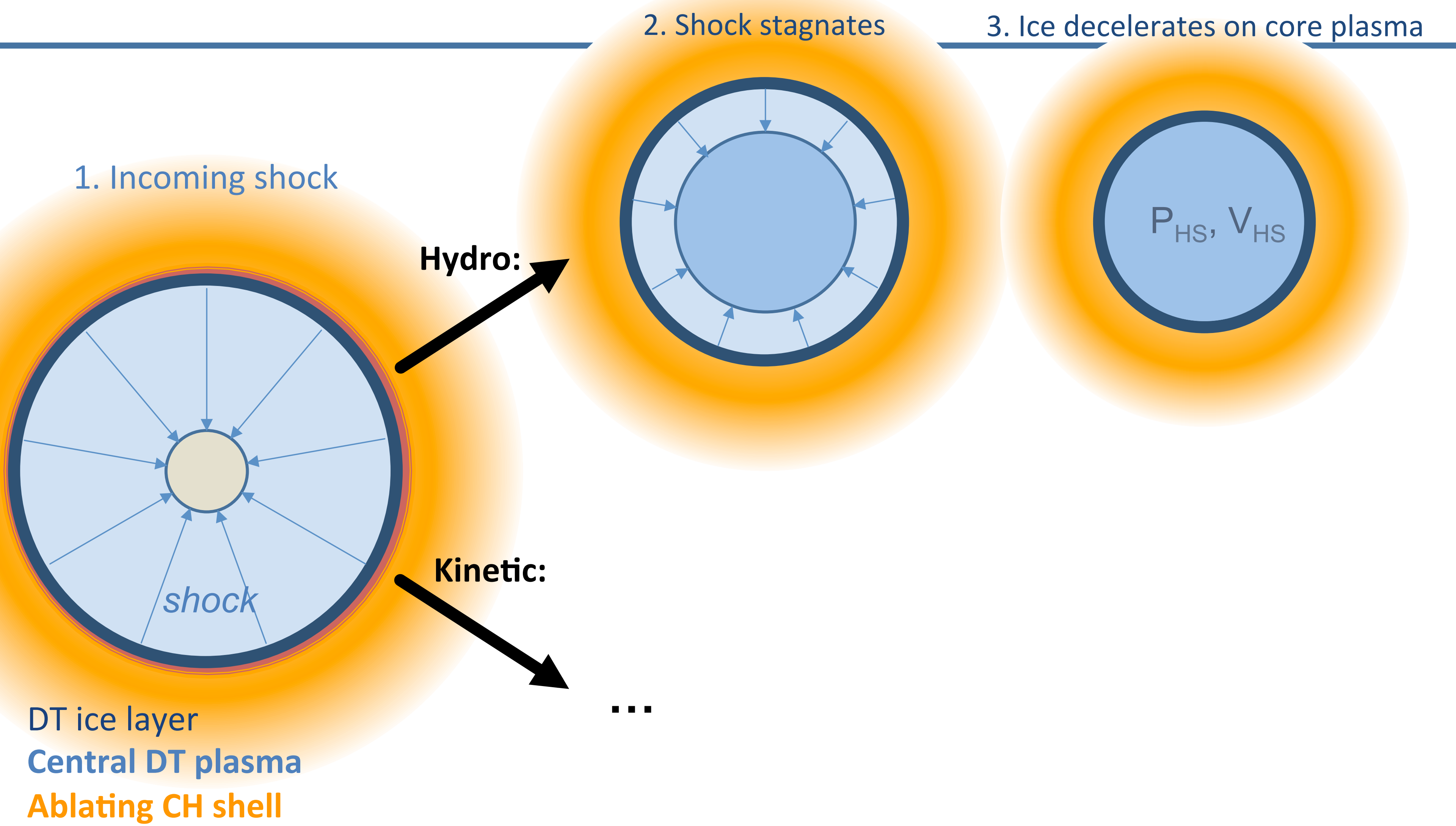


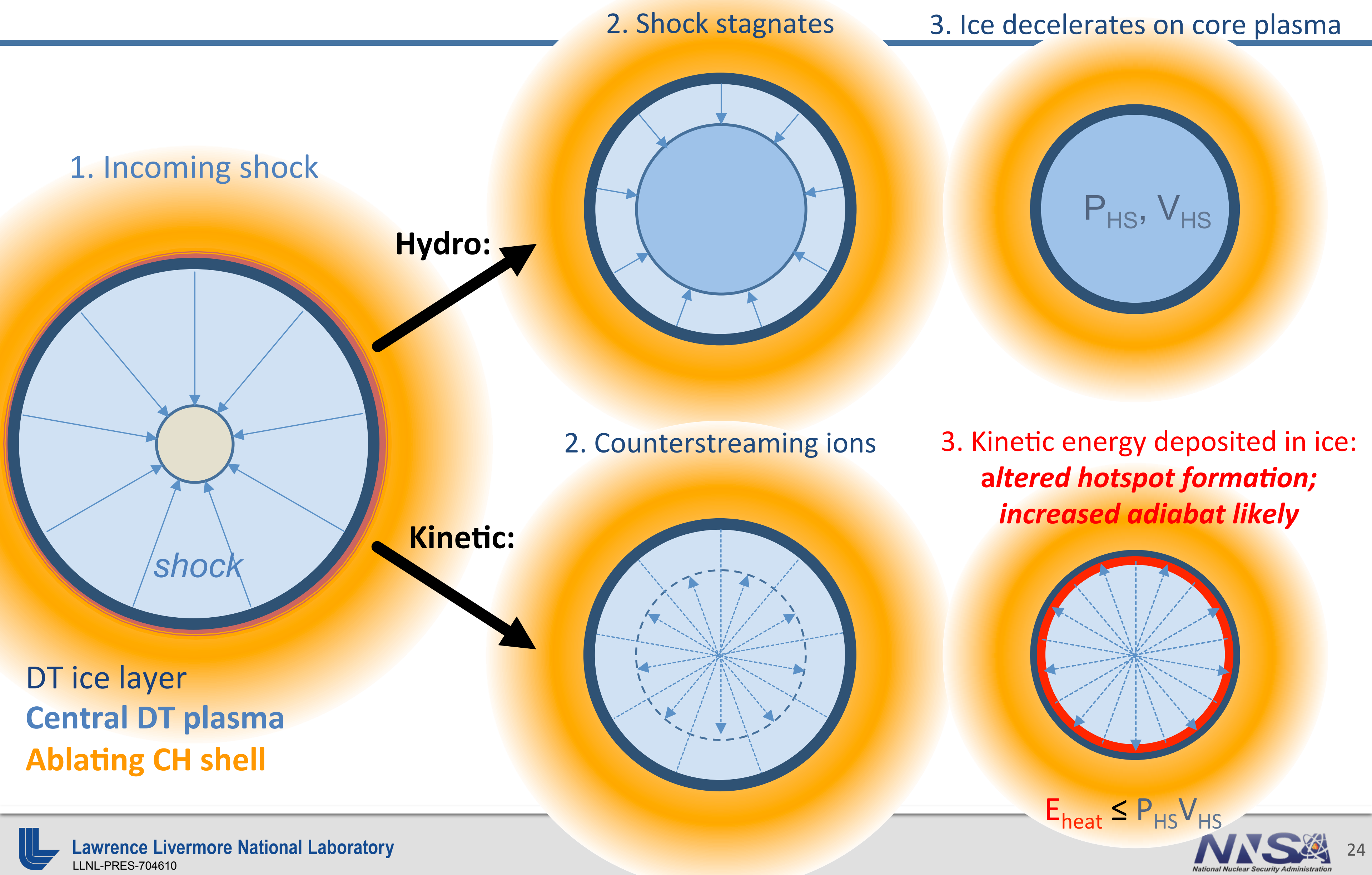
- For $\langle N_K \rangle \gtrsim 1$, distribution functions are far from Maxwellian, and fusion is not predominantly thermal.
- Yield trends are dominated by *multispecies effects*[1], which alter concentration and energy balance:
  - D, ^{3}He species separation for higher density
  - D, ^{3}He thermal decoupling for lower density

[1]Rinderknecht PRL 114, 025001 (2015)

Hydrodynamic codes form the hotspot by the DT-ice decelerating on the stagnated central DT-plasma



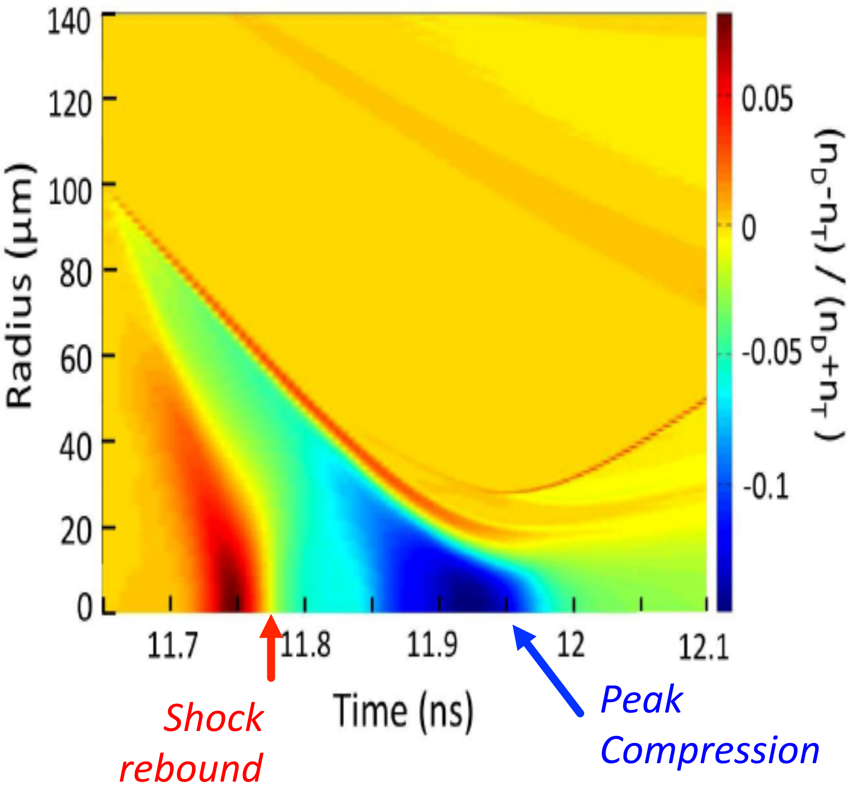
A *fully kinetic* (i.e. collisionless) low-density DT plasma inside the DT ice layer could alter deceleration trajectory and hotspot formation



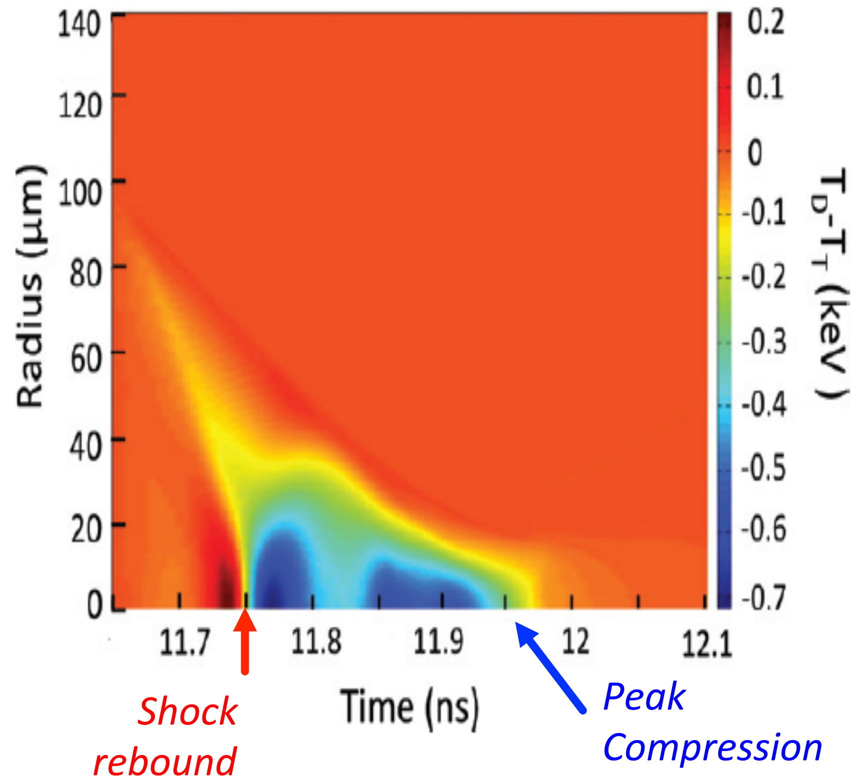
Kinetic physics is simulated to affect the DT fuel during shock propagation and fuel assembly in ignition-scale implosions

Vlasov-Fokker-Planck simulations of ignition-scale NIF implosion*

Ion density difference (deuterium – tritium)



Ion temperature difference (deuterium – tritium)



*from A. Inglebert, EPL 107, 65003 (2014)

The Kinetic Physics in ICF Workshop at LLNL on April 5—7 brought together 90+ researchers from 20 worldwide institutions

Goals of the Workshop:

1. **Assemble and present the evidence** for non-fluid-like phenomena in ICF
2. **Summarize the status of analysis and numerical techniques** for studying these phenomena
3. **Map out an experimental and computational plan** that enables informed judgment and quantitative assessment on the role of kinetic phenomena in ICF pertaining to the NIF

A white paper summarizing the findings of the workshop is forthcoming.

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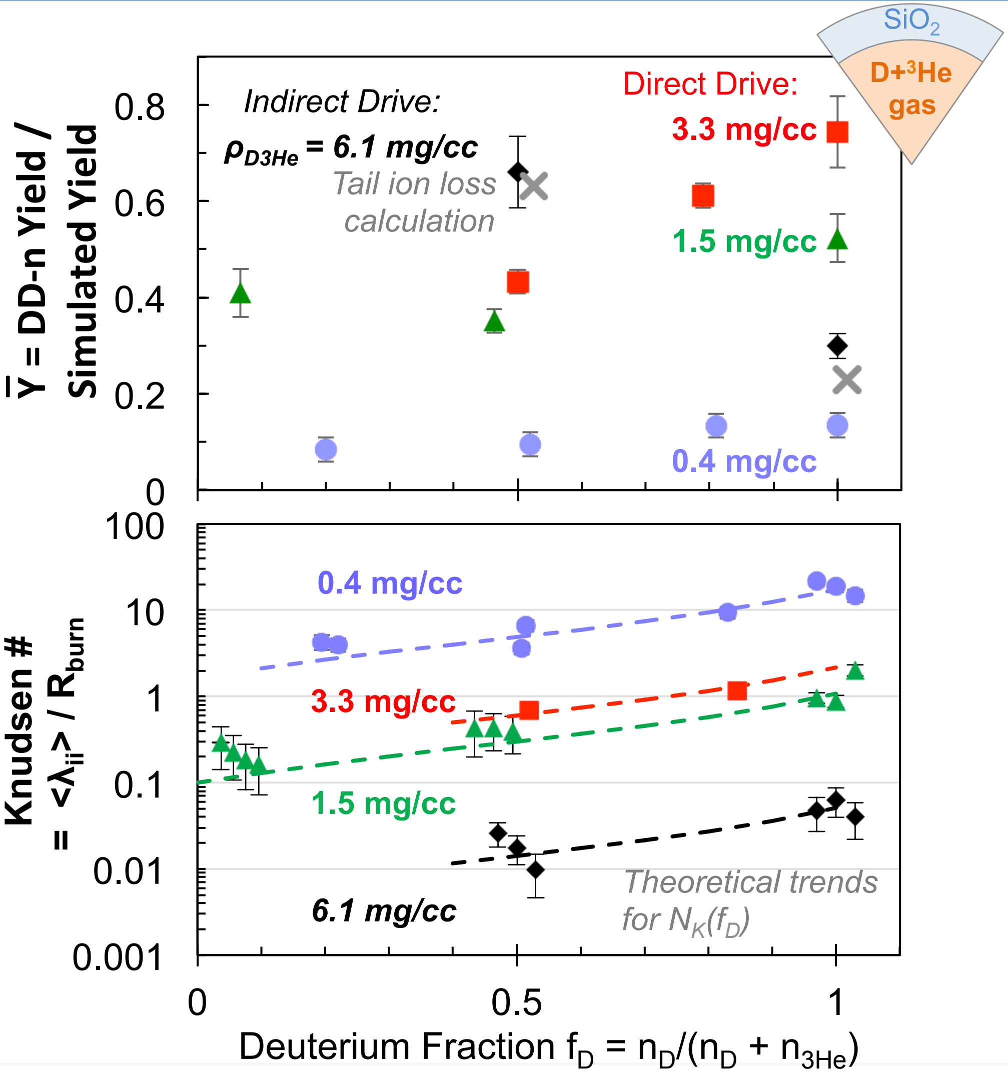
- Implosions with D+^{3}He gas were used to study ion kinetic mechanisms over a wide range of Knudsen numbers ($N_K = \lambda_{ii}/R$):
  - Yield from slightly kinetic implosions (N_K = 0.01—0.05) is dominated by the loss of long mean-free-path ions.
  - Yield from highly kinetic implosions ($N_K > 0.5$) is dominated by multi-species physics: ion species separation, thermal decoupling.
- The observed physics mechanisms will impact the formation of the ICF hotspot.

Appendix

Ion kinetic physics mechanisms impact plasmas relevant to shock-phase DT-vapor in ICF experiments

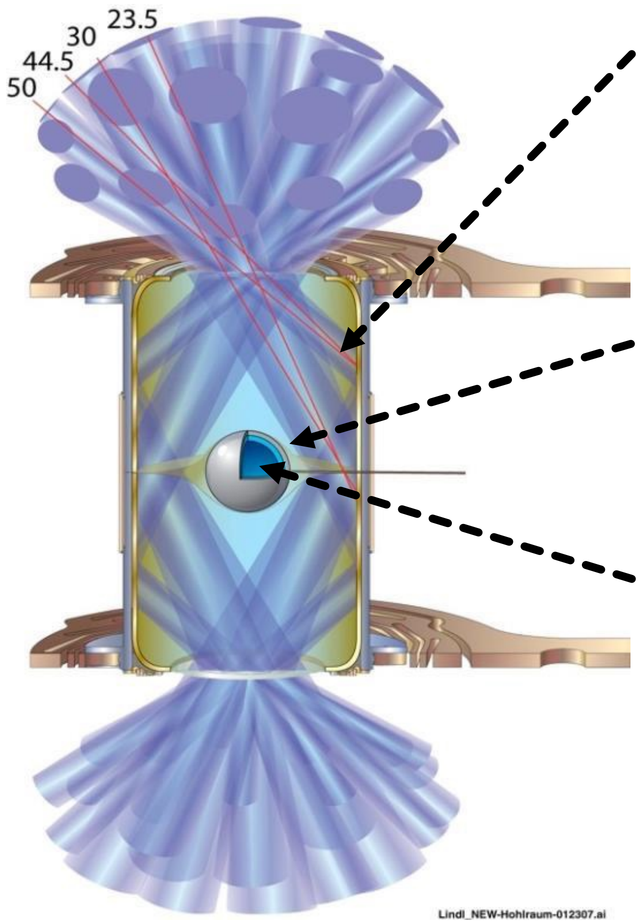


- Strongly shocked (M > 10), low-density (ρ ~ 1 mg/cc), hot (T_i > 1 keV) plasmas are produced in laser-driven capsule implosions to study the effects of *long mean-free-paths* (**$N_K = \lambda_{ii}/R > 0.01$**) and *multiple ion species.*
- Trends in nuclear performance are dominated by different effects in three regimes of N_K:
  - **$N_K < 0.1$**: Nuclear yield matches predictions of reactivity reduction due to suprathermal "tail" ion loss.[1] *Trend:* $\bar{Y}(f_D = 1) < \bar{Y}(f_D = 0.5)$
  - **0.1 < NK ≈ 1:** Nuclear data implies separation of D, ^{3}He by diffusion.[2] $\bar{Y}(f_D = 1) > \bar{Y}(f_D = 0.5)$
  - **NK >> 1:** Ion temperatures imply thermal decoupling of D, ^{3}He.[2] $\bar{Y}(f_D = 1) > \bar{Y}(f_D = 0.5)$
- During shock-phase of ICF ignition implosions, DT-vapor has **$0.2 < N_K < 0.8$**, implying distributions are strongly non-thermal.

[1]*Albright POP 20, 122705 (2013); Kagan PRL 115, 105002 (2015)*
[2]*Rinderknecht PRL 114, 025001 (2014)*

This work performed under the auspices of the U.S. DoE by LLNL under Contract DE-AC52-07NA27344.

Plasmas with multiple ion species are common in ICF, and multi-ion species physics significantly affects plasma dynamics



Recent work: [Theory, Experiment]

Hohlraums:

Issues: Multipliers needed to match drive; Low-mode drive asymmetry

- Au bubble formation and evolution (thermodiffusion) [Amendt, Kagan]
- Plasma interpenetration in ablator/gas/Au bubble region [LePape, Kemp]

Ablator:

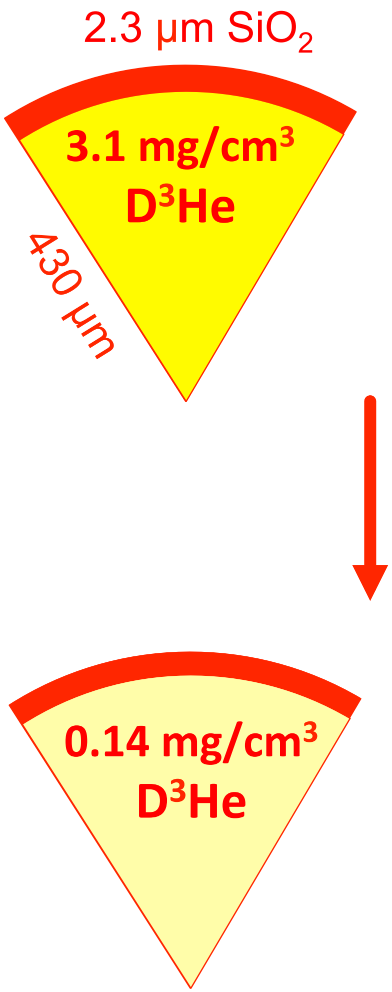
- Species separation in ablated plasma [Ross]
- mix at ablator/DT interface (proton/ion transport into ice) [Fernandez, Murillo, Bellei]

Shock Physics & Fuel Assembly:

Issues: simulations predict higher ρR (DSR), lower <Ti> than observed

- Ion species separation and/or "multi-fluid" effects:
  - Dominant for $N_K > 0.01$ [Rygg, Rosenberg, Herrmann, Hsu, Casey, Schmitt]
  - Effect for $N_K < 0.01$? "No": [Casey, Ho]; "Yes": [Inglebert, Peigney]
- Multi-species + fields shock-front structure [Sio, Hua, Hoffman, Le, Taitano]
- Collisionless behavior during shock phase (energy/entropy distribution, initial conditions for deceleration) [Rinderknecht]

A fuel density scan in D^3He exploding pushers was used to explore the transition between hydro and kinetic regimes

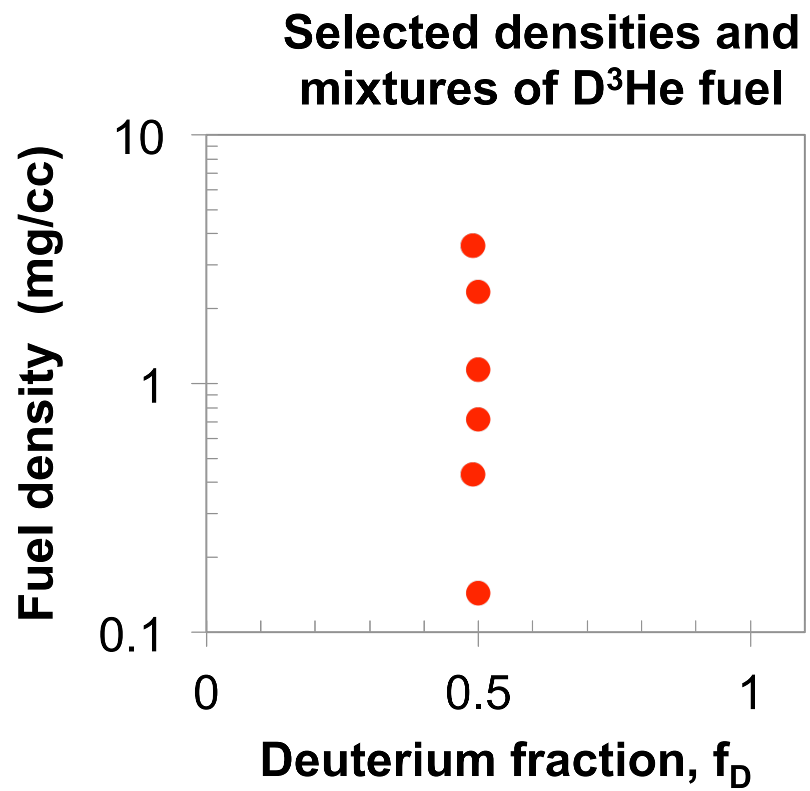


Hydro regime

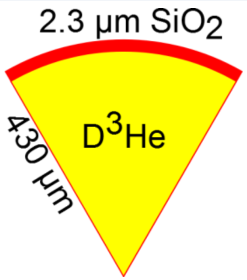
$\lambda_{ii} < R_{fuel}$
(at bang time)

Kinetic regime

$\lambda_{ii} >> R_{fuel}$
(at bang time)

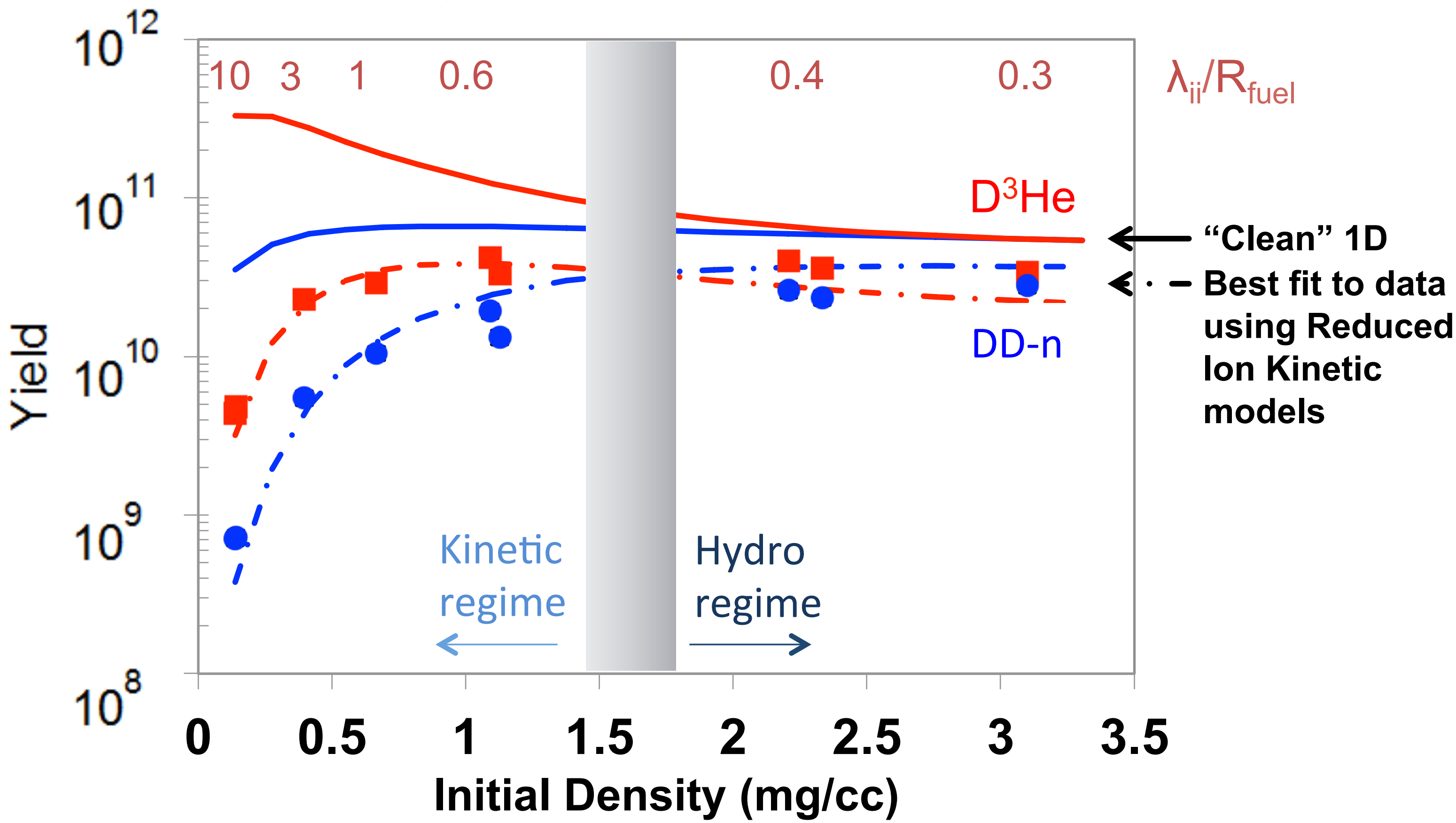


Including "Reduced Ion Kinetic" models in the hydro simulations, they are able to fit the measured yield trend



3 Kinetic models included:

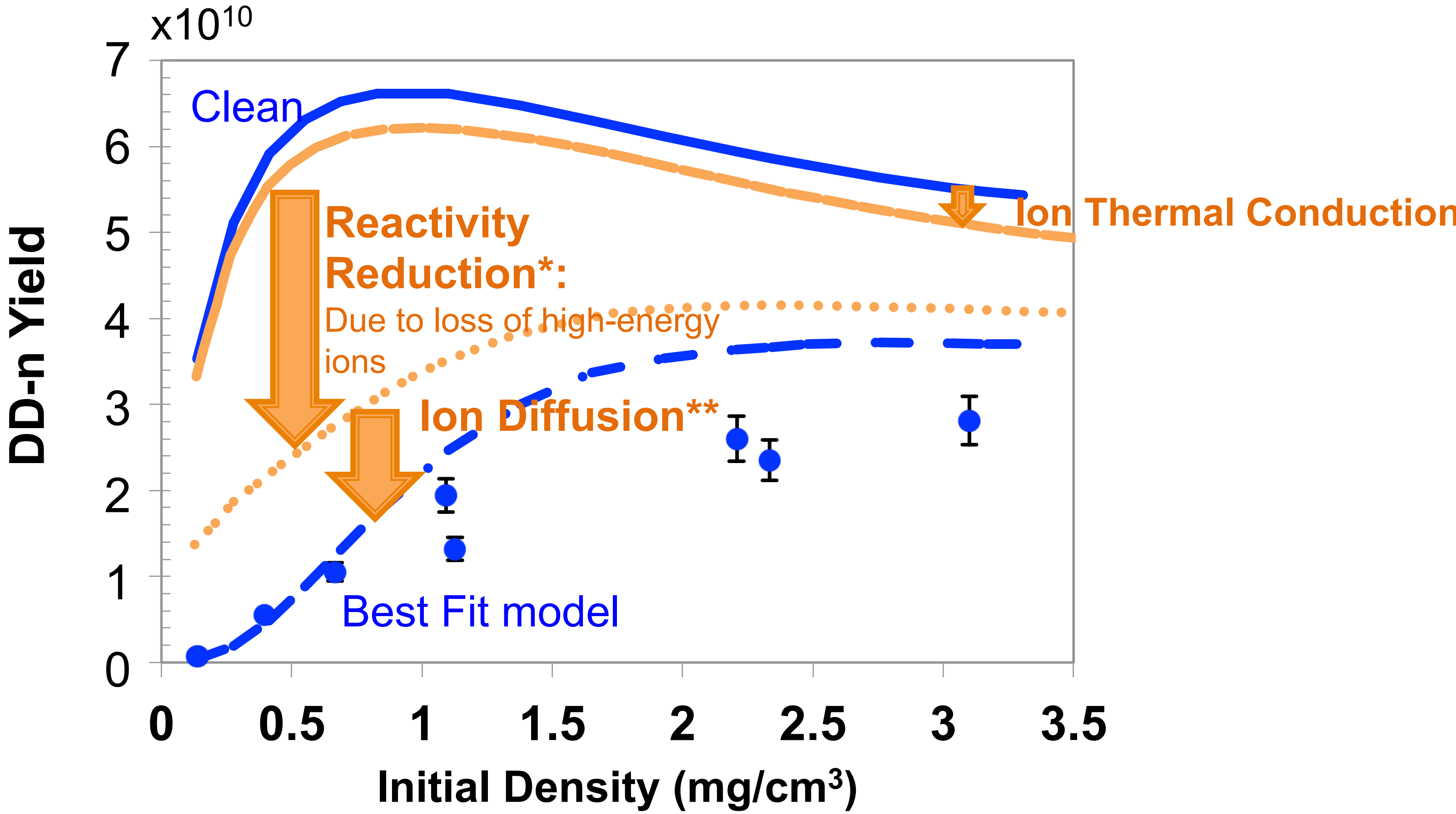
Tail ion loss, ion diffusion, ion thermal conduction



Simulations by N. Hoffman, LANL

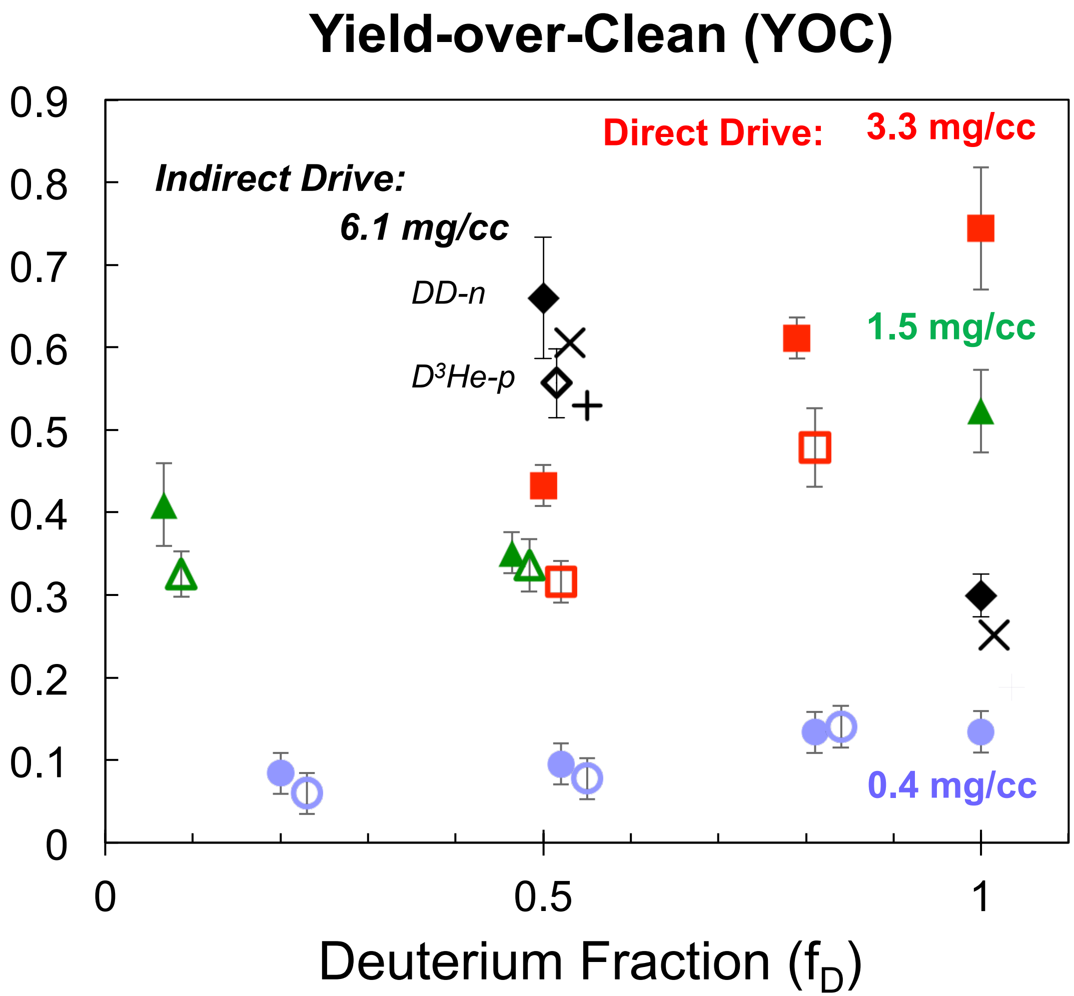
- 3 free kinetic parameters (5 total)
- fit to 25 independent observables (5 on each shot)

In Reduced Ion Kinetic fit, yield reduction is dominated by loss of high-energy tail ions from the plasma and ion diffusion

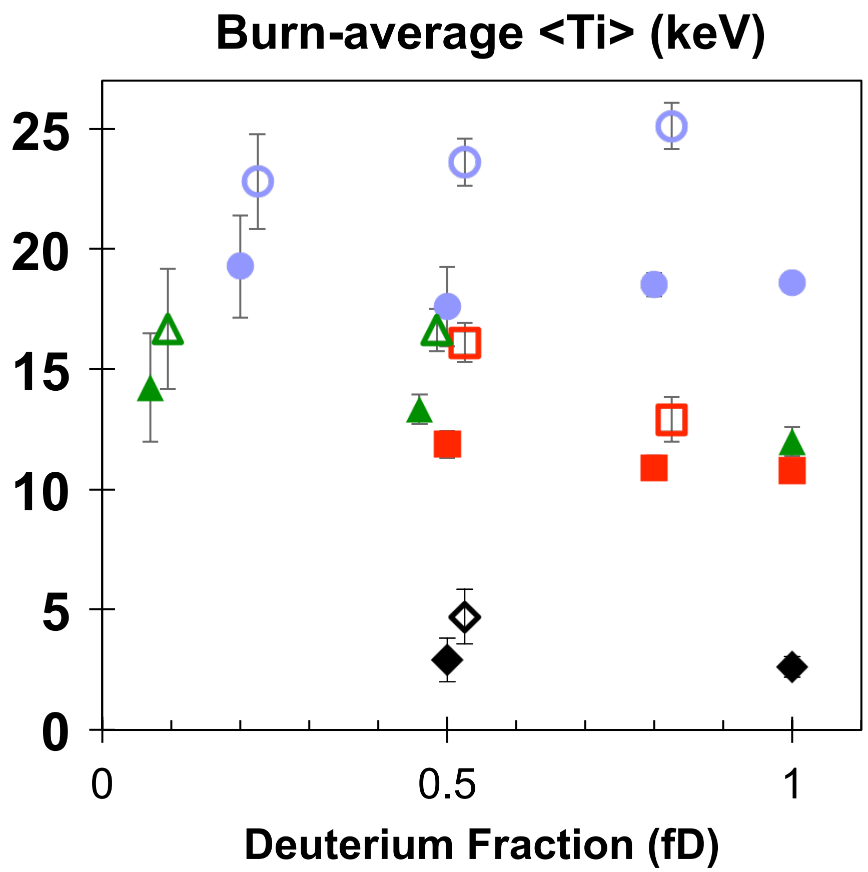


*K. Molvig, et al. PRL 109, 095001 (2012)
**Similar to Zel'dovich & Raizer, Ch. VII §4 (Dover, 2002);
G. Zimmerman, private communication (2000)

Plotting yield relative to simulated yield demonstrates reduced performance as a function of composition



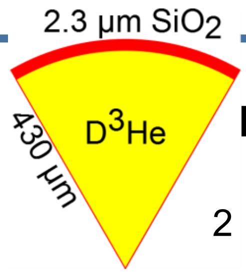
Temperatures vary from ~2—25 keV with deuterium fraction, gas pressure, and drive conditions



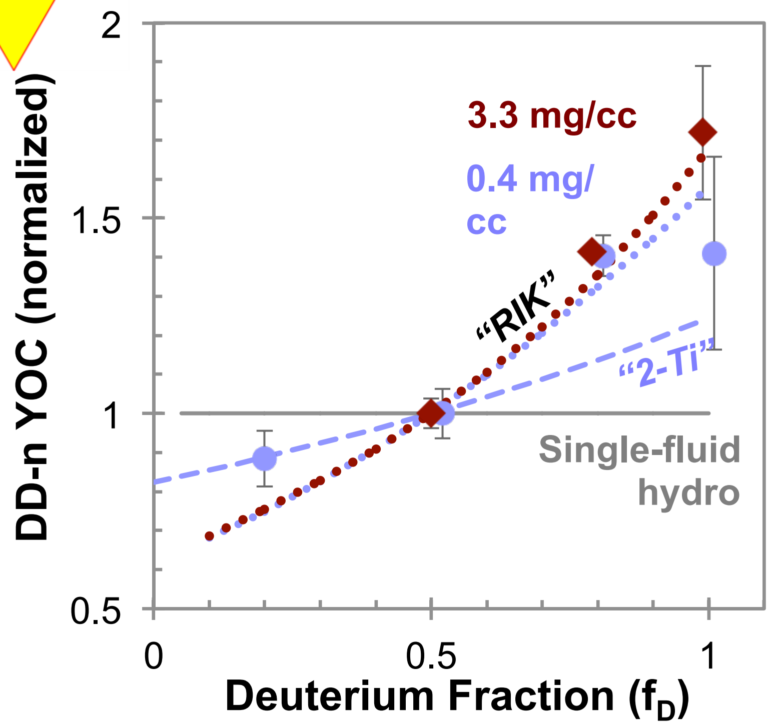
Summary of yields, temperatures, and <N_K>

Density mg/cc	f_D	# shots	Yields DD-n	Yields D^3He-p	$\langle T_i \rangle_{DDn}$ keV	$\langle N_K \rangle$
6.08	1	3	(4.9±0.4)e8		2.6±0.4	0.046±0.015
(Indirect)	0.5	3	(1.7±0.2)e8	(6.8±0.4)e6	2.9±0.9	0.016±0.008
3.29	1	2	(2.1±0.2)e11		10.8±0.4	
	0.8	1	(1.2±0.1)e11	(2.6±0.3)e10	10.9±0.5	1.16±0.19
	0.5	2	(2.3±0.2)e10	(3.0±0.2)e10	11.9±0.6	0.69±0.11
1.45	1	3	(1.7±0.2)e11		12.0±0.6	1.30±0.67
	0.46	3	(1.8±0.2)e10	(3.8±0.6)e10	13.3±0.6	0.42±0.12
	0.07	4	(3.5±0.5)e8	(8.7±0.8)e9	14.2±2.3	0.22±0.08
0.39	1	3	(3.2±0.6)e10		18.6±0.4	18.5±3.8
	0.8	1	(2.0±0.2)e10	(2.5±0.2)e10	18.5±0.5	9.4±1.4
	0.5	2	(5.1±0.3)e9	(2.5±0.2)e10	17.6±1.7	5.1±2.2
	0.2	2	(7.0±1.1)e8	(1.2±0.2)e10	19.3±2.1	4.1±0.6

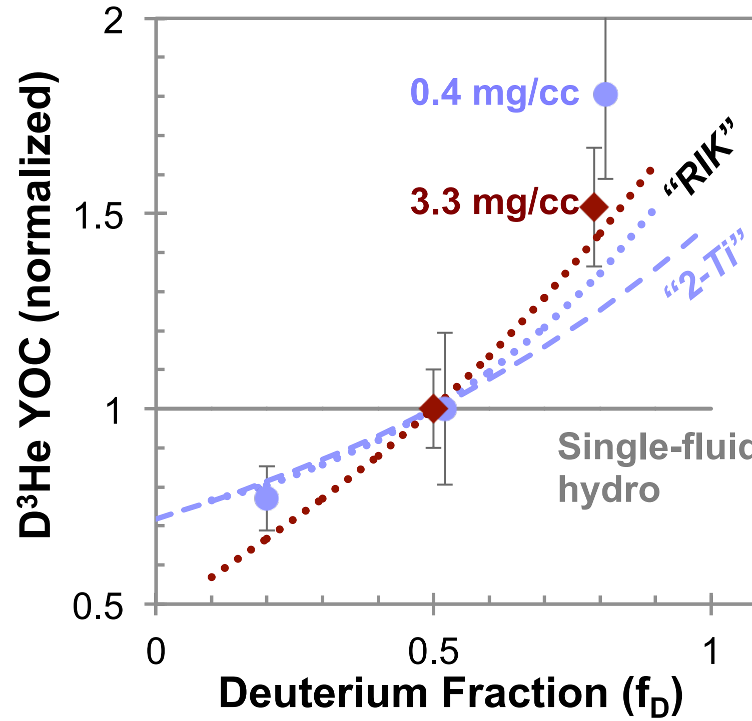
Yields vary by over 50% as a function of deuterium fraction relative to single-fluid simulations



DD-neutron Yield / simulated yield normalized to f_D = 0.5



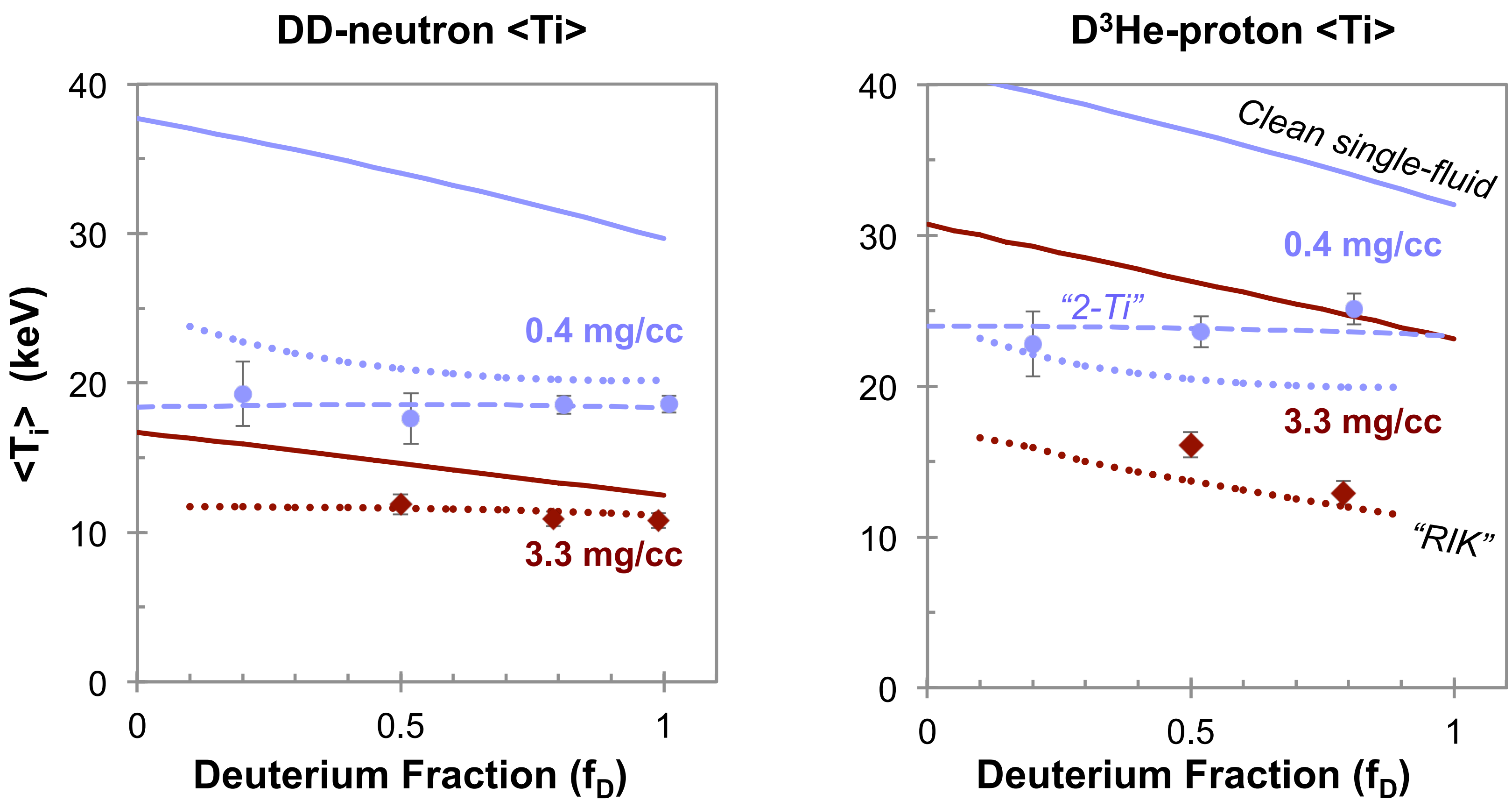
D³He-proton Yield / simulated yield normalized to f_D = 0.5



Reduced Ion Kinetic modeling ("RIK") by Nels Hoffman
Two-ion temperature ("2-Ti"): post-processed 1D-HYADES model

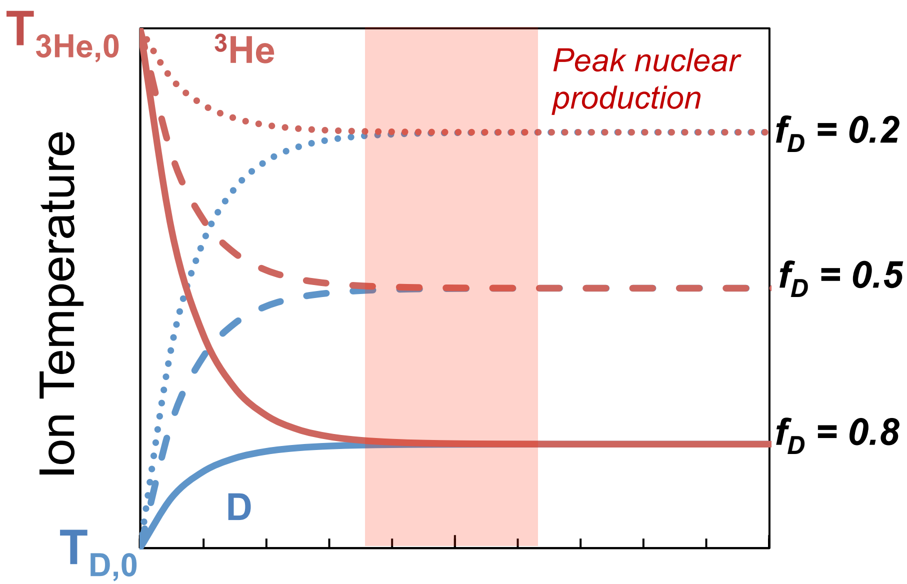
H. Rinderknecht, et al. *Phys Rev Lett* **114**, 025001 (2015)

Ion temperatures also exhibit unexpected trends: <Ti> is *anomalously constant* with f_D in low-density implosions



Since the shock heats the ion species differentially, equilibration rate affects the burn-averaged ion temperature

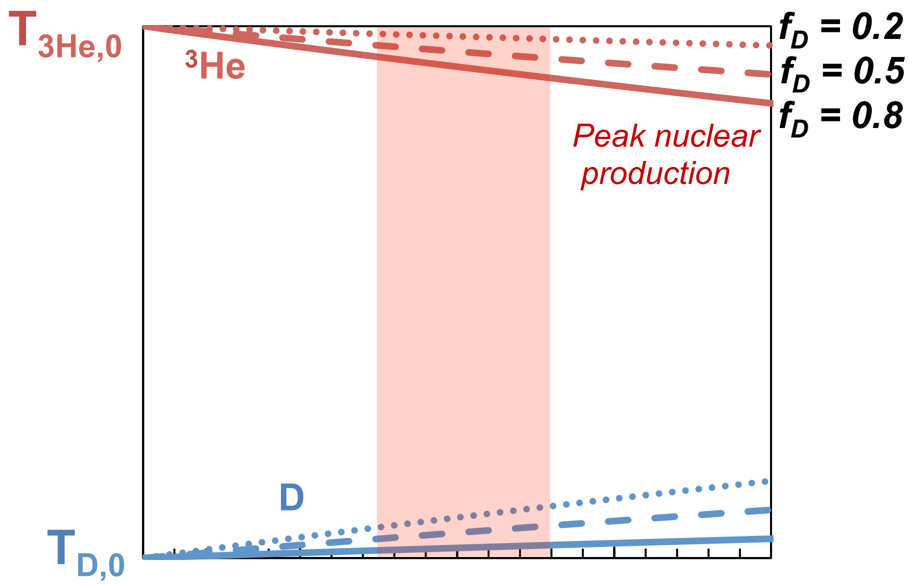
Rapid equilibration (fluid):
$\tau_{eq} << \tau_{burn}$



Time after shock rebound

$$\langle T_i \rangle \propto (3 - f_D)$$

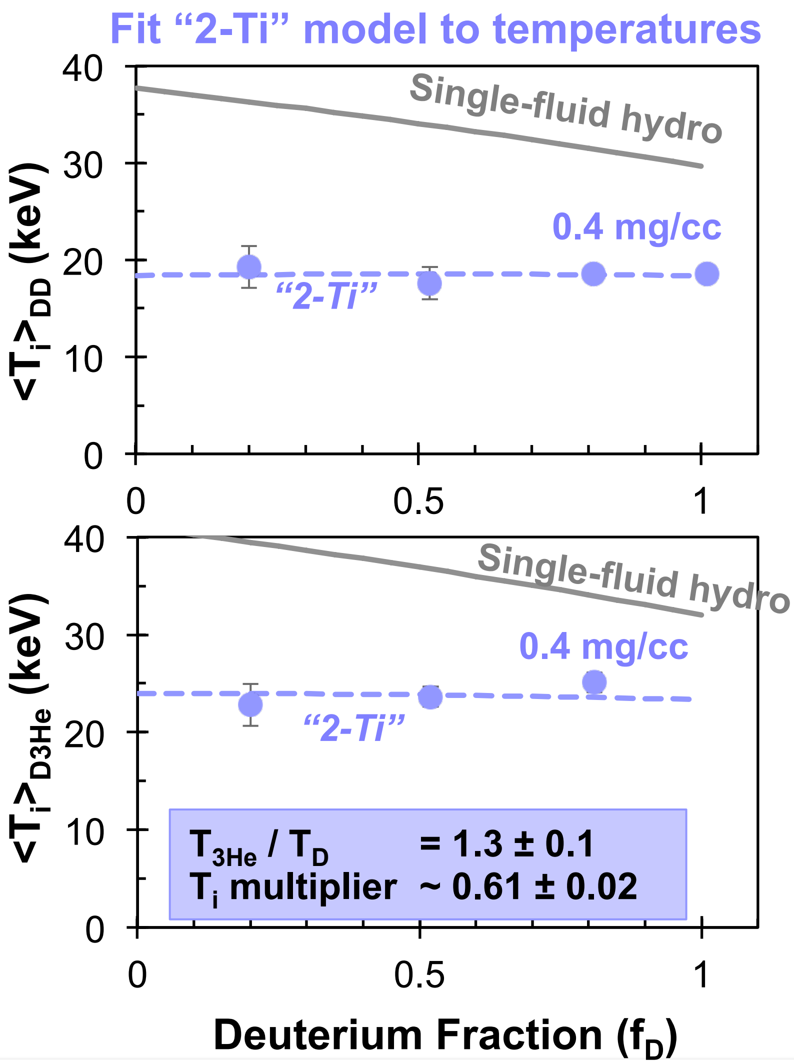
Slow equilibration (kinetic):
$\tau_{eq} >> \tau_{burn}$

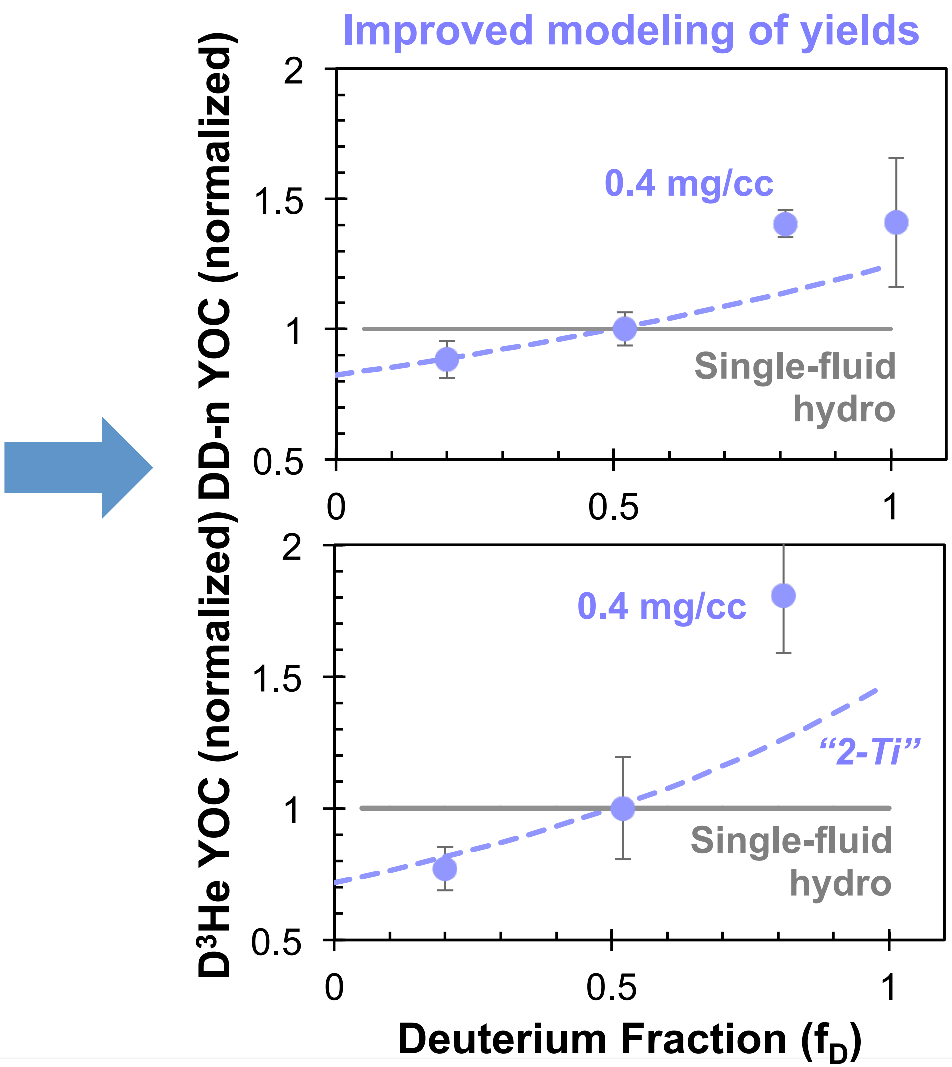


Time after shock rebound

$\langle T_i \rangle \approx$ ***constant***
(as observed)

For low gas-density implosions, an empirical thermal decoupling model ($T_{3He} \neq T_D$) was fit to the temperature data; yields are better reproduced





Data from multiple diagnostics was used to determine whether the fuel composition had changed during the implosion

$$Y_{jk} = \int \frac{n_j n_k}{1+\delta_{jk}} \langle \sigma v \rangle_{jk} dV d\tau$$

"Invert" the equation

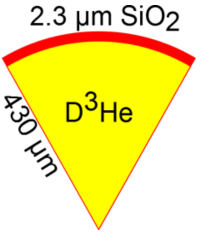
$$\langle n_j n_k \rangle \approx \frac{(1+\delta_{jk}) Y_{jk}}{\langle \sigma v \rangle_{jk} \left(\langle T \rangle_{ij} \right) \left(\frac{4\pi}{3} R_{50,ij}{}^3 \right) \tau_{burn,ij}}$$

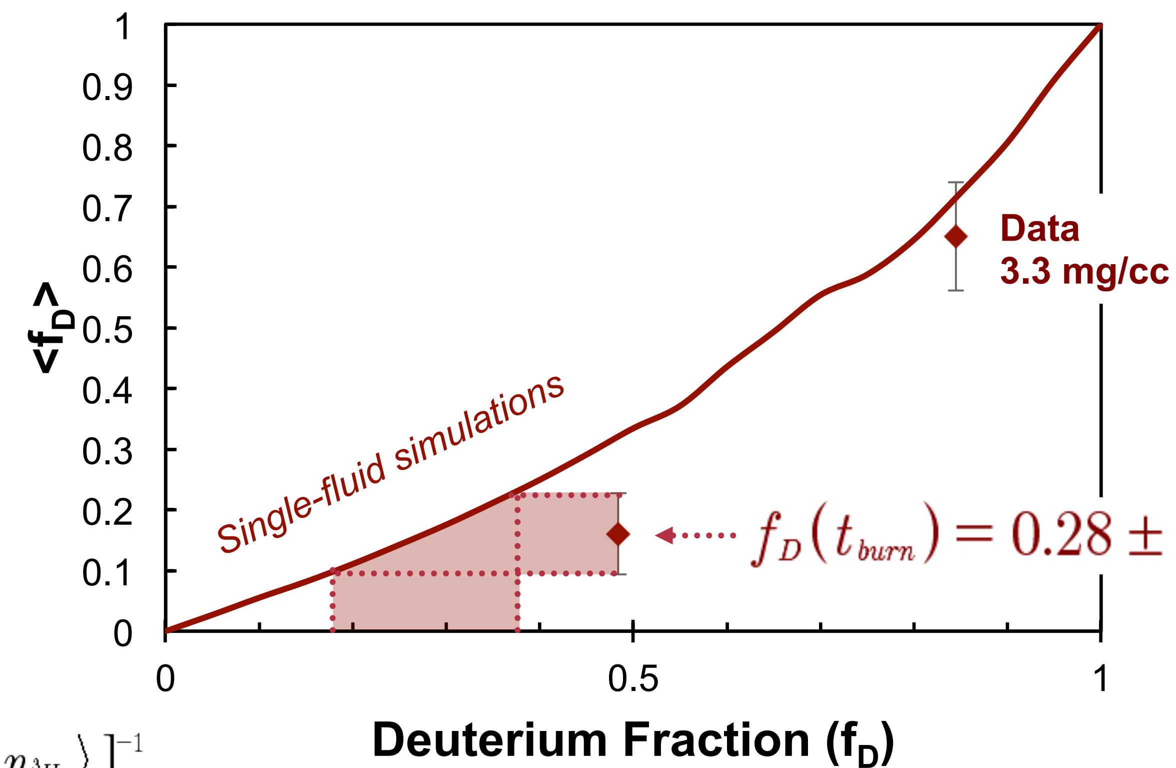
measured quantities

All quantities are measured for both the **DD-** and the **D^3He-fusion** reaction. Then from the definition of f_D:

$$f_D = \frac{n_D}{n_D + n_{^3He}} \quad \Rightarrow \quad \langle f_D \rangle = \left[1 + \frac{\langle n_D n_{^3He} \rangle}{\langle n_D n_D \rangle} \right]^{-1}$$

The "burn-averaged deuterium fraction" was calculated from nuclear observables, indicating species separation prior to burn





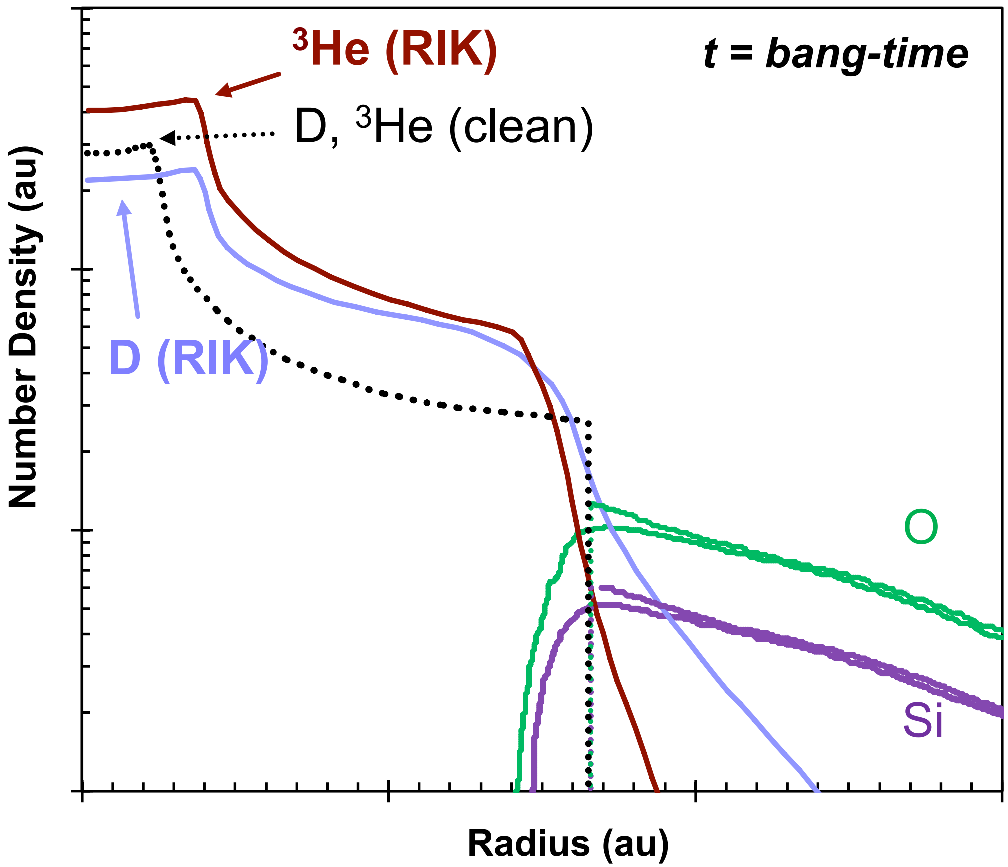
$$f_D(t_{burn}) = 0.28 \pm 0.10$$

$$\langle f_D \rangle = \left[1 + \frac{\langle n_D n_{^3He} \rangle}{\langle n_D n_D \rangle} \right]^{-1}$$

$$\langle n_j n_k \rangle \approx \frac{(1+\delta_{jk}) Y_{jk}}{\langle \sigma v \rangle_{jk} (\langle T \rangle_{ij}) (\frac{4\pi}{3} R_{50,ij}{}^3) \tau_{burn,ij}}$$

This is the first direct evidence of *ion species separation* in an ICF implosion

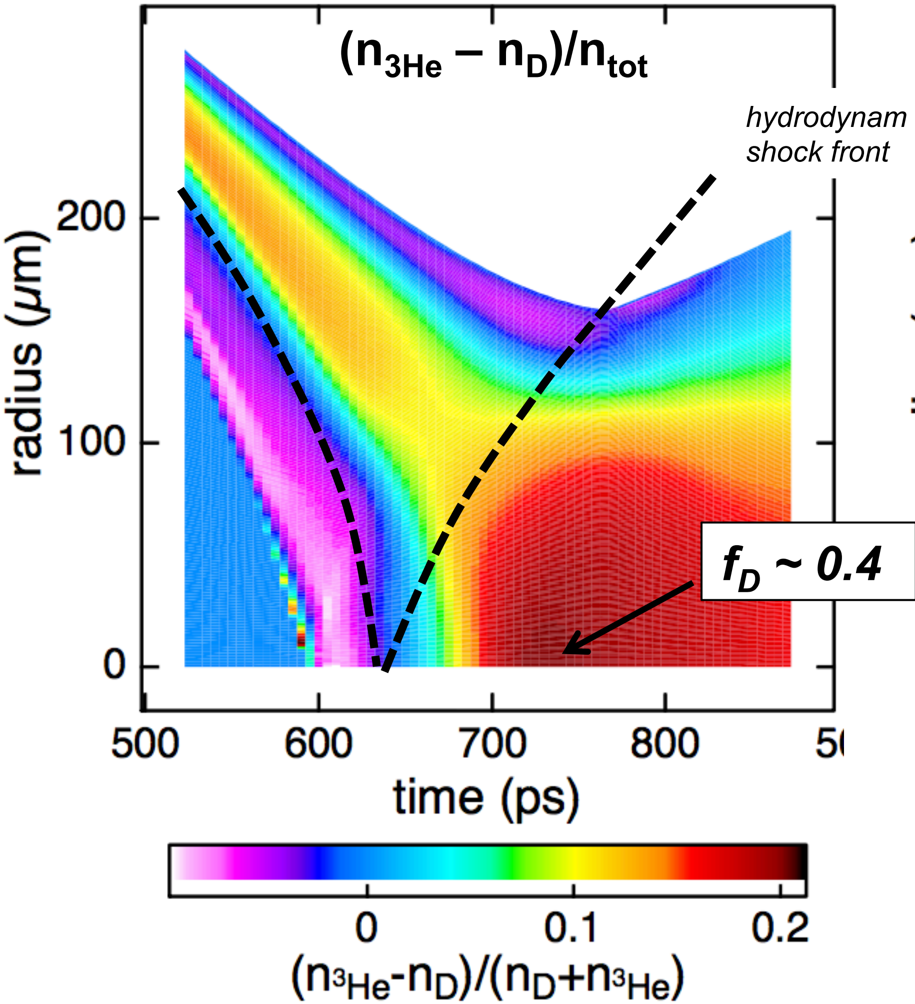
Simulations including ion diffusion ("Reduced Ion Kinetic") predict a comparable amount of species separation to that observed

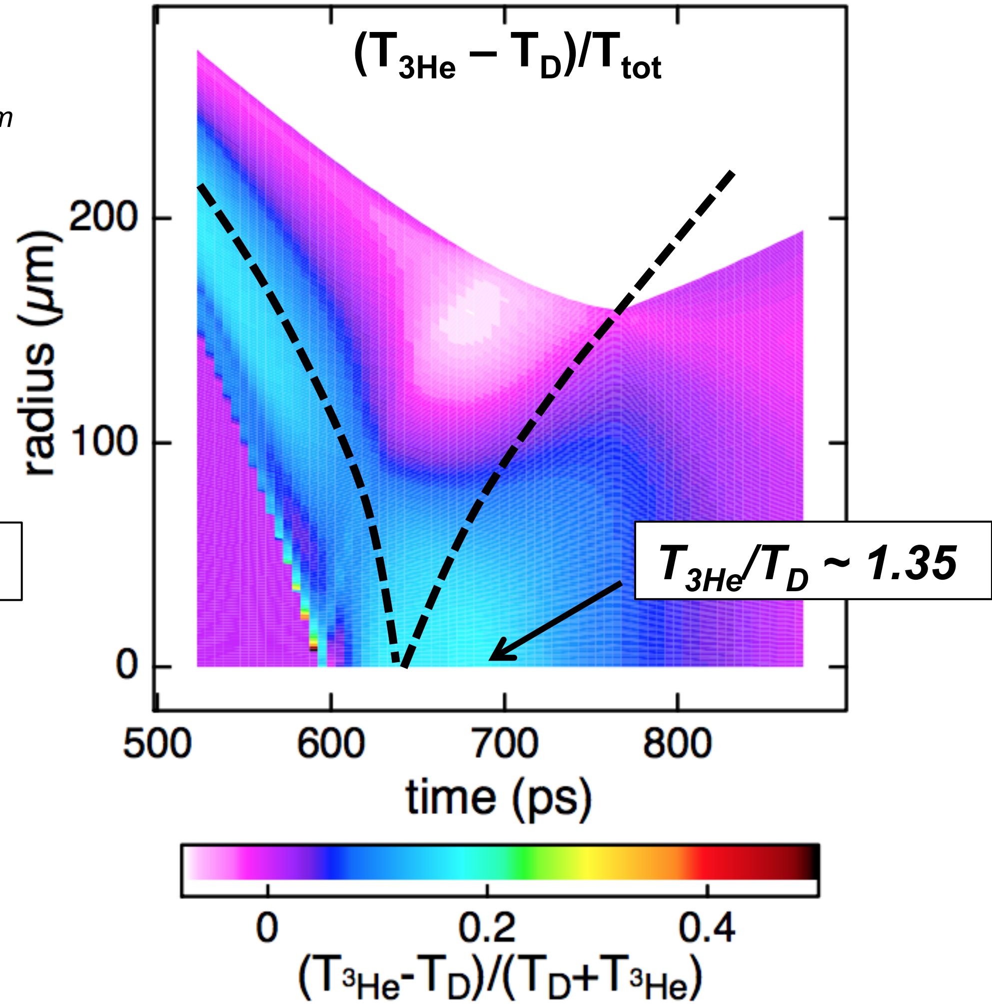


$f_D(t_0) = 50\% \rightarrow f_D(t_{burn}) = 33\%$

See Hoffman, et al. Phys. Plasmas ***22****, 052707 (2015)*

Fully kinetic simulations indicate both the density and temperature of the ion species differ during burn





O. Larroche, et al., POP 23, 012701 (2016)