# Diagnosing Implosion Performance at the NIF by Means of Neutron-Spectrometry and Neutron-Imaging Techniques

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**Massachusetts Institute of Technology**



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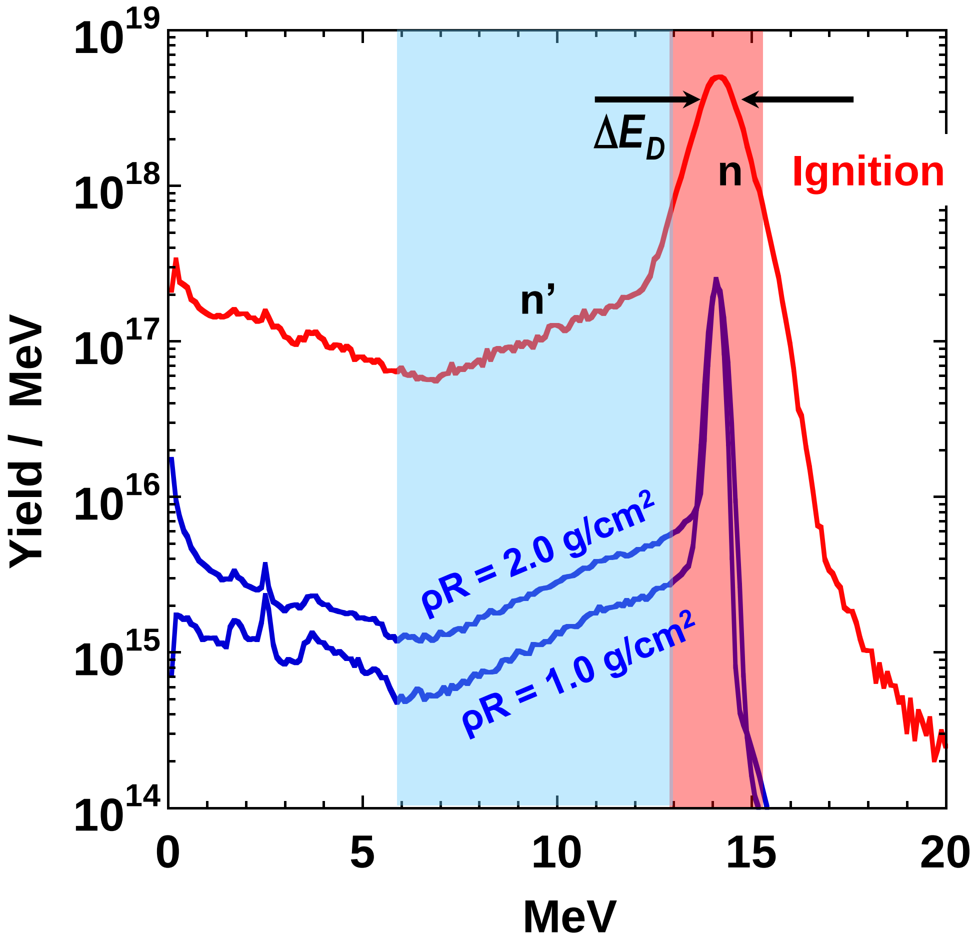
# The neutron data have been essential to the progress of the experiments on the NIF

- The neutron-spectrometry data indicate that the tuning campaigns have improved the implosion performance by ~50× since the 1st shot in Sept 2010.
- We have achieved a radial convergence of ~35, fuel *ρR* values up to ~1.3 g/cm$^2$, and inferred hot-spot pressures up to ~150 Gbar.
- The maximum pressure is ~2× lower than point design, and the observed neutron yields are 3-10× lower than expected.
- The pressure and yield deficits are most likely explained by higher than predicted fuel-ablator mix and *ρR* asymmetries often observed in the implosions.
- A path forward to address these issues has been defined.

# The neutron spectrum is used to diagnose neutron yield ($Y_n$), ion temperature ($T_i$) and areal density ($\rho R$)




**Primary neutrons (n):**

- $Y_n$
- $T_i$ $\quad T_i \propto \Delta E_D^{\,2}$
- *Residual kinetic effects*

**Scattered neutrons (n'):**

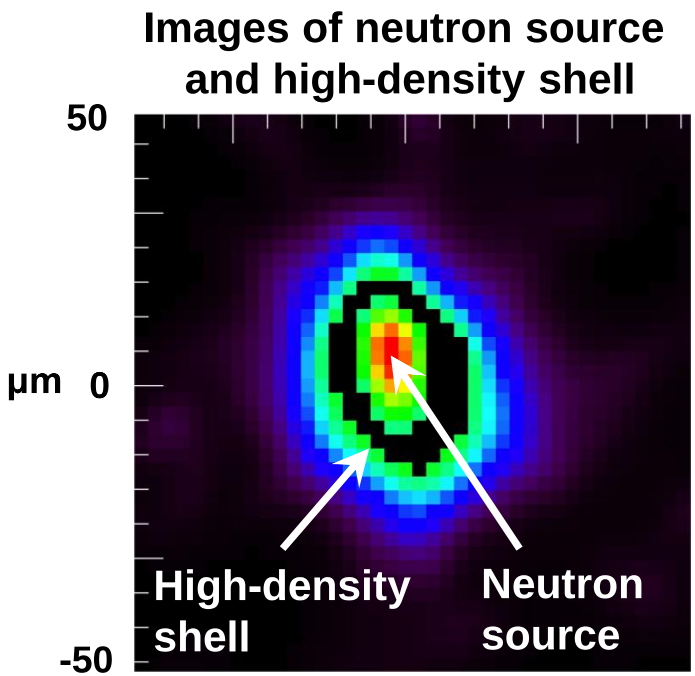
- $\rho R$ $\quad \rho R \propto \frac{Y_{n'}}{Y_n} = dsr$

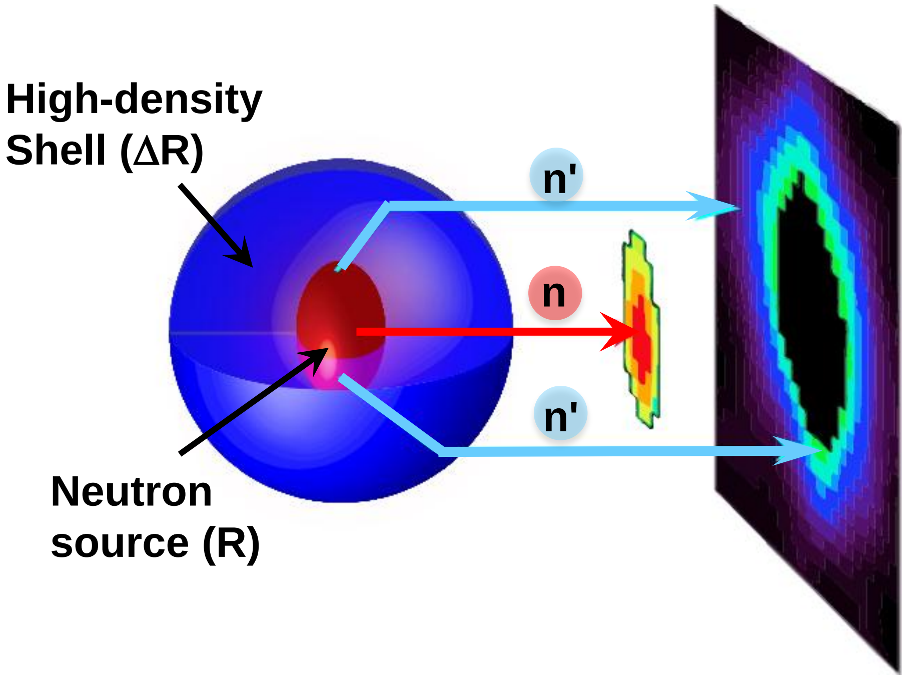
$\rho R$ (g/cm$^2$) $\approx 21 \times dsr_{10\text{-}12\ \text{MeV}}$ [1)]

**Measurement of the detailed shape of the low-energy part of neutron spectrum provides 3D information about implosion**

[1)] J.A. Frenje et al., these proceedings; to be submitted to Nucl. Fusion.

# Primary and scattered neutrons are imaged to diagnose neutron-source size (R) and thickness of high-density shell (ΔR), resp.




**Primary neutrons (n):**

- *R* of neutron source

**Scattered neutrons (n'):**

- *ΔR* of high-density shell

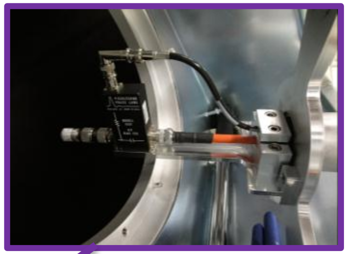
G. Grim et al., APS invited (2012).

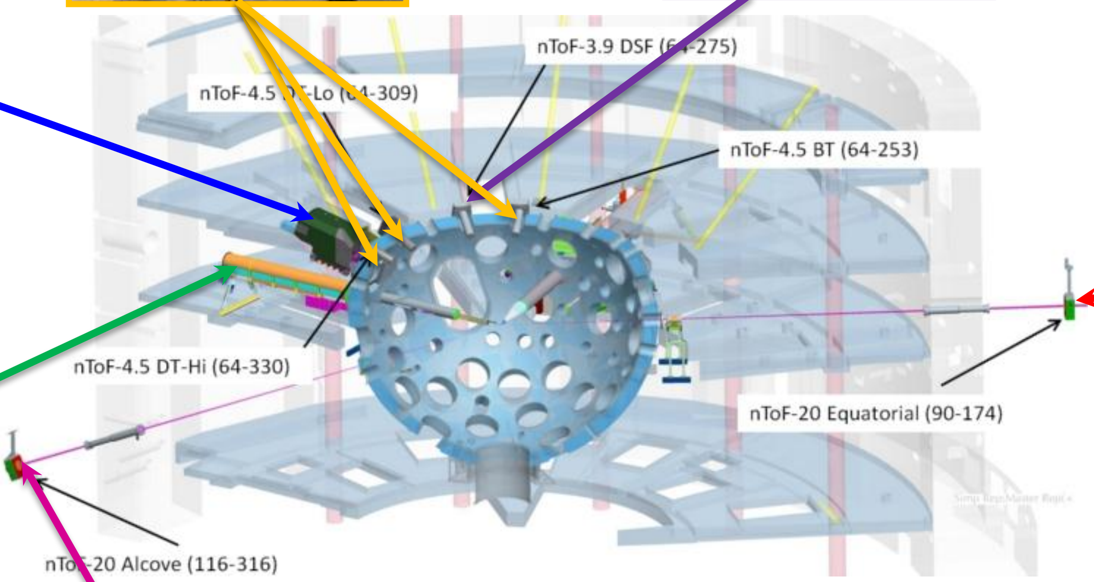
# Several neutron spectrometers and an imaging system have been fielded at various locations on the NIF

**MRS (77-324)**

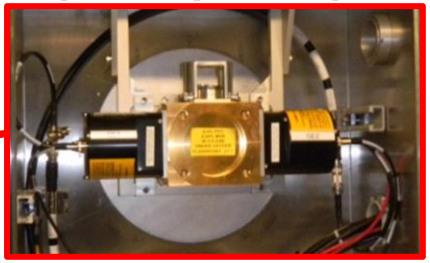
**nTOF4.5m (64-330)**

**nTOF3.9m (64-275)**

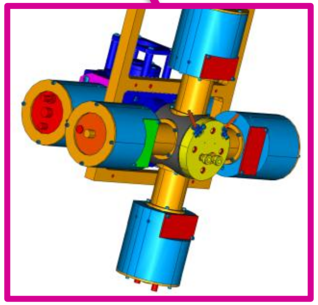





**Spec-E (90-174)**



**NITOF/NIS (90-315)**

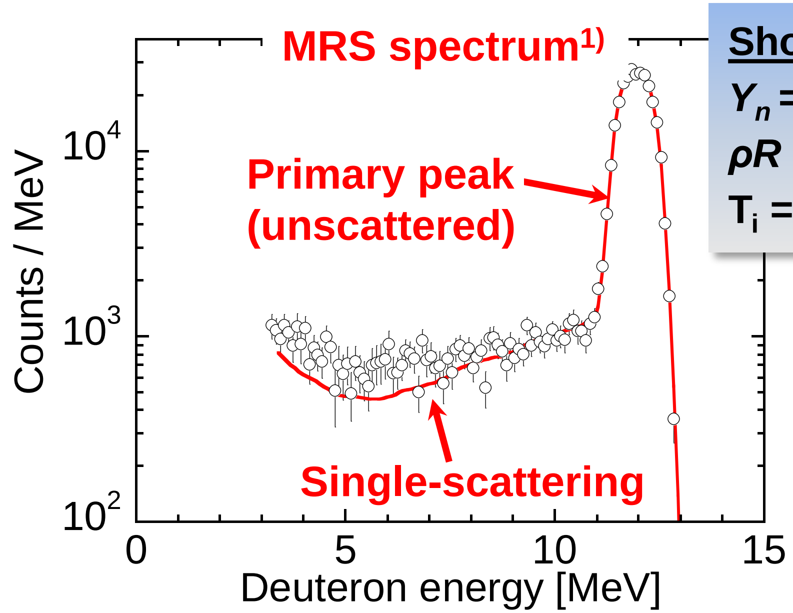


**Spec-A (116-316)**

**This provides good implosion coverage for reliable measurements of $Y_n$, $T_i$, $\rho R$, and $\rho R$ asymmetries**

M. Gatu Johnson et al., RSI (2012).
F.E Merrill et al., RSI (2012).

# Spectra and images are now measured routinely on the NIF (Example: DT shot N120205)

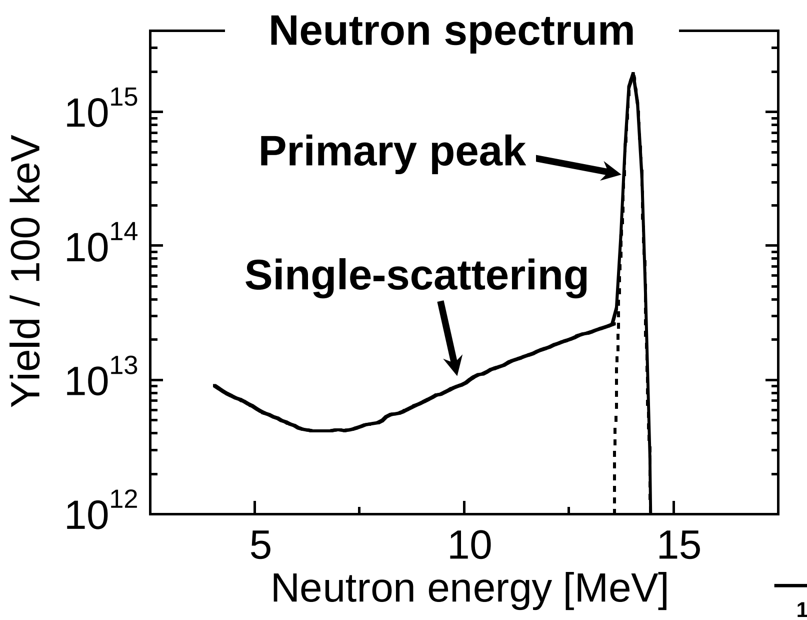


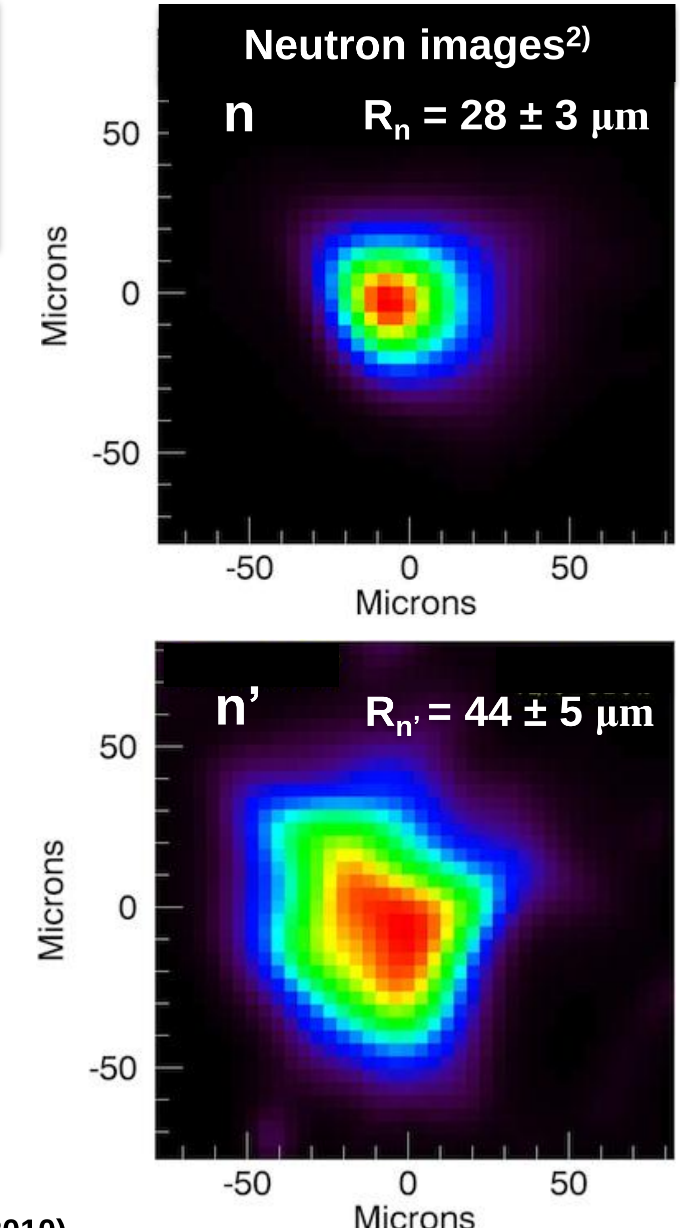

**Shot N120205**

$Y_n = (5.6 \pm 0.2)\times10^{14}$

$\rho R = 900 \pm 40$ mg/cm$^2$

$T_i = (3.4 \pm 0.1)$ keV

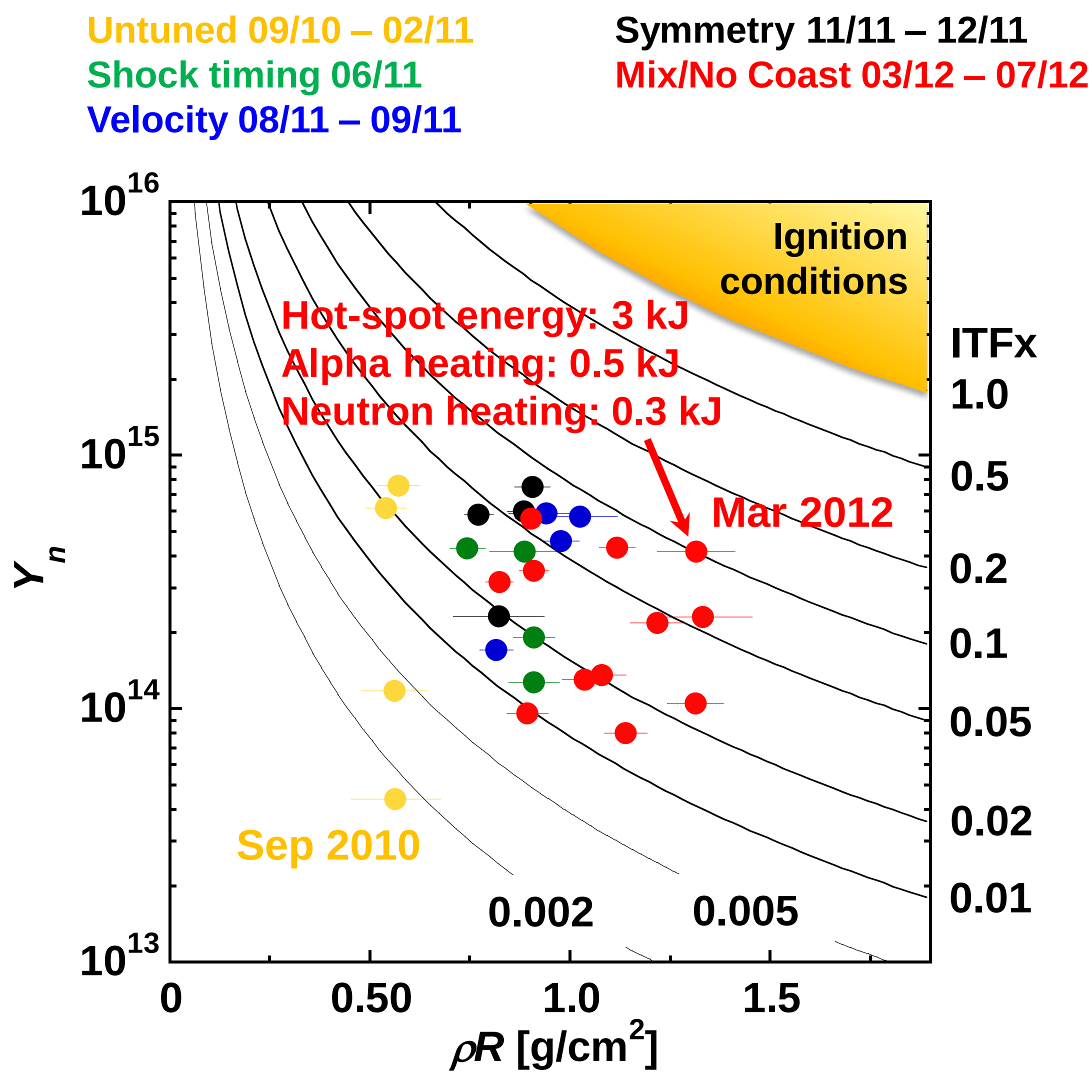



[1] J.A. Frenje et al., PoP (2010).

[2] G. Grim APS invited, PoP (2012).

# The spectrometry data indicate that the tuning campaigns have improved the implosion performance by ~50× since Sept 2010




**Implosion performance[1]:**

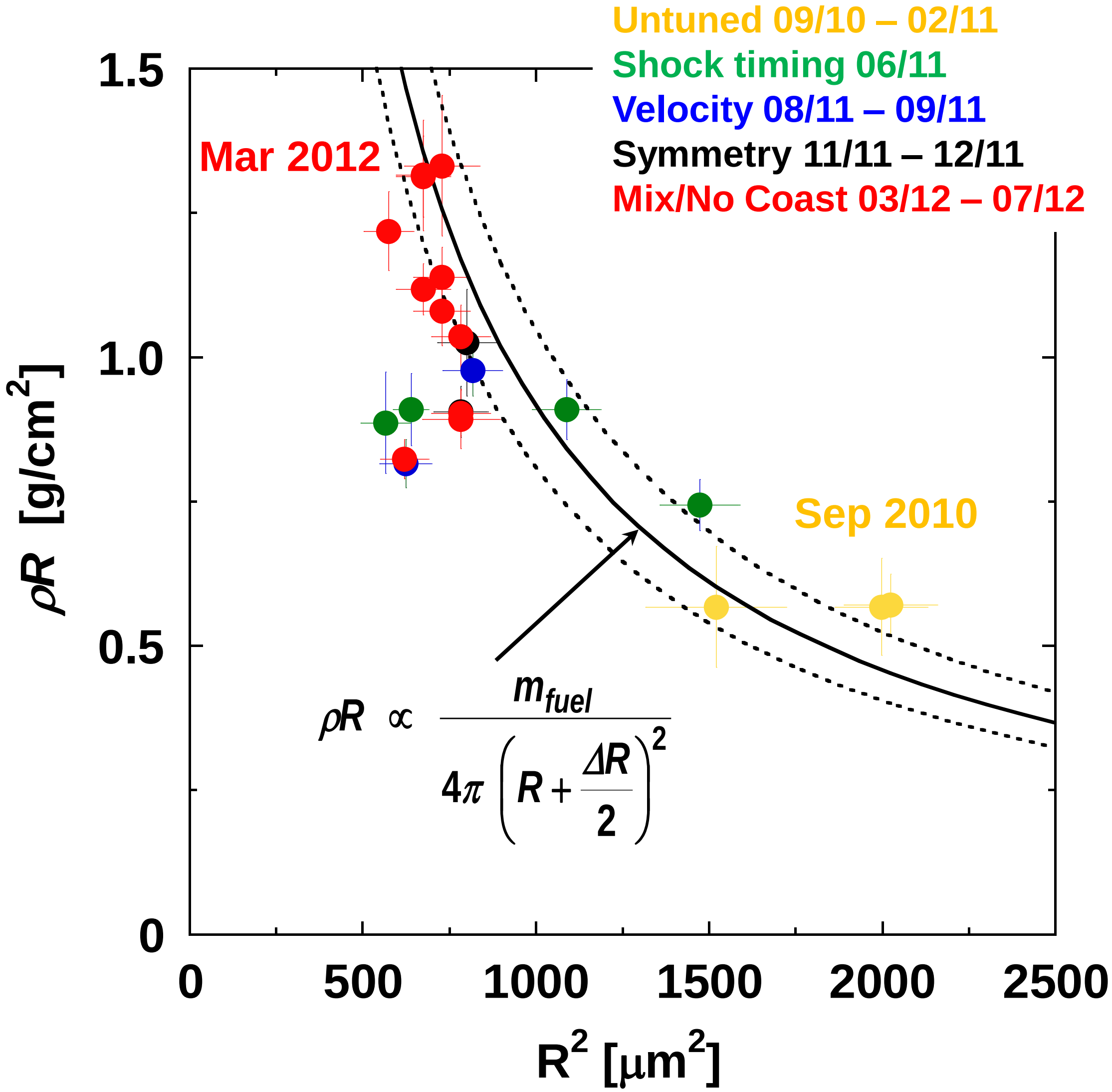
$$ITFx \approx \left(\frac{Y_n}{3.2e15}\right)\left(\frac{\rho R}{1.47}\right)^{2.3}$$

**Lawson-type parameter[2]:**

$$\frac{E_\alpha}{E_{losses}} \approx \sqrt{ITFx}$$

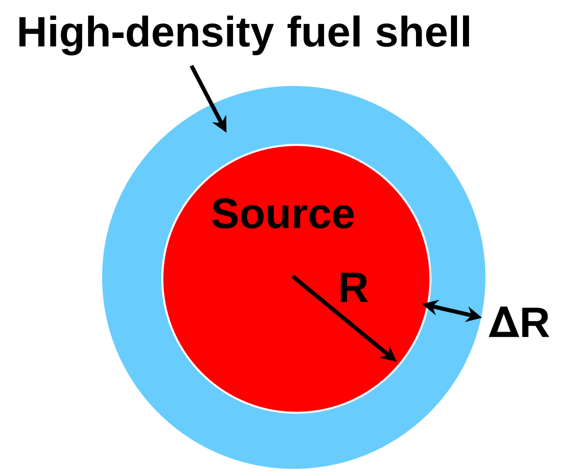
[1] M .J. Edwards et al., PoP (2011); A.J. Mackinnon et al., PRL (2012).
[2] R. Betti et al., OV/5-3

# Spectrometry and imaging data self-consistently indicate that the tuning campaigns have improved the convergence by ~2×




$$\frac{\Delta R}{R} = 0.49 \pm 0.16$$

(fit to all neutron-imaging data)

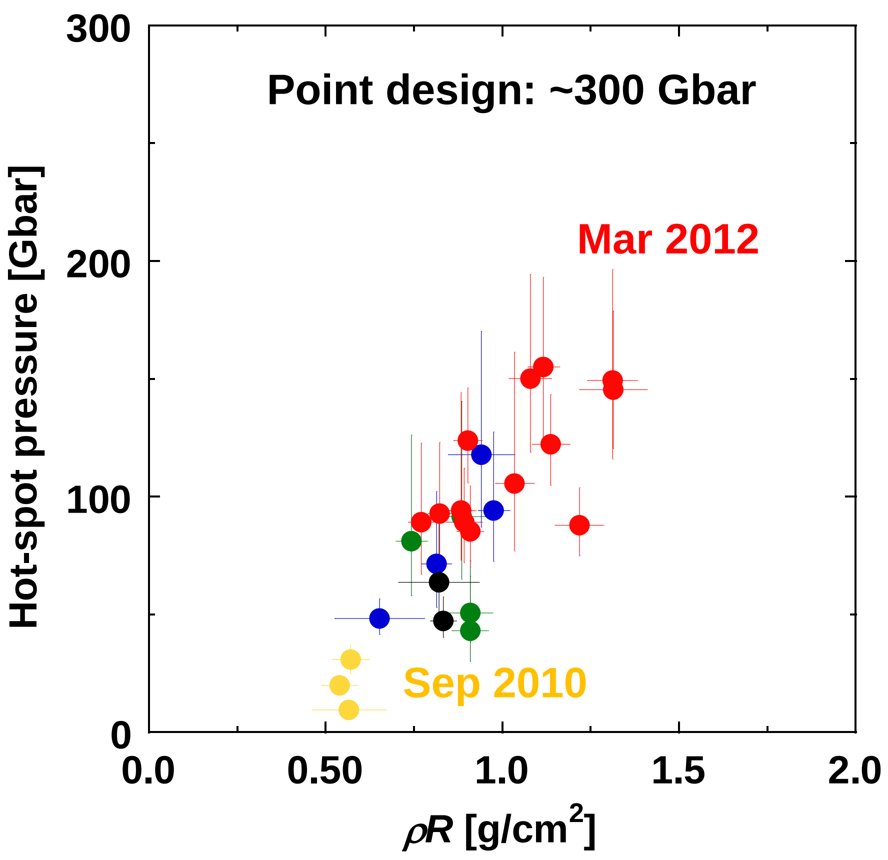


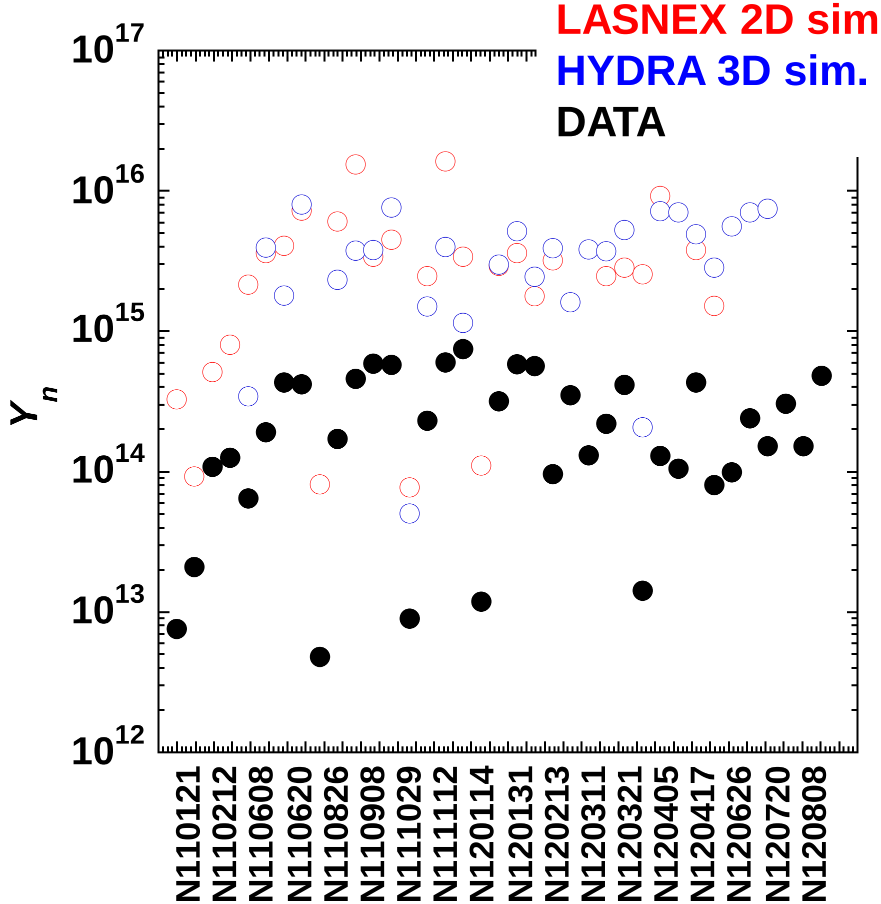

Sept 2010 $R^2$ data inferred from x-ray images.

NIF

# Inferred hot-spot pressure is ~2× lower than point design, and yields are ~3-10× lower than predicted

Untuned 09/10 – 02/11
Shock timing 06/11
Velocity 08/11 – 09/11
Symmetry 11/11 – 12/11
Mix/No Coast 03/12 – 07/12

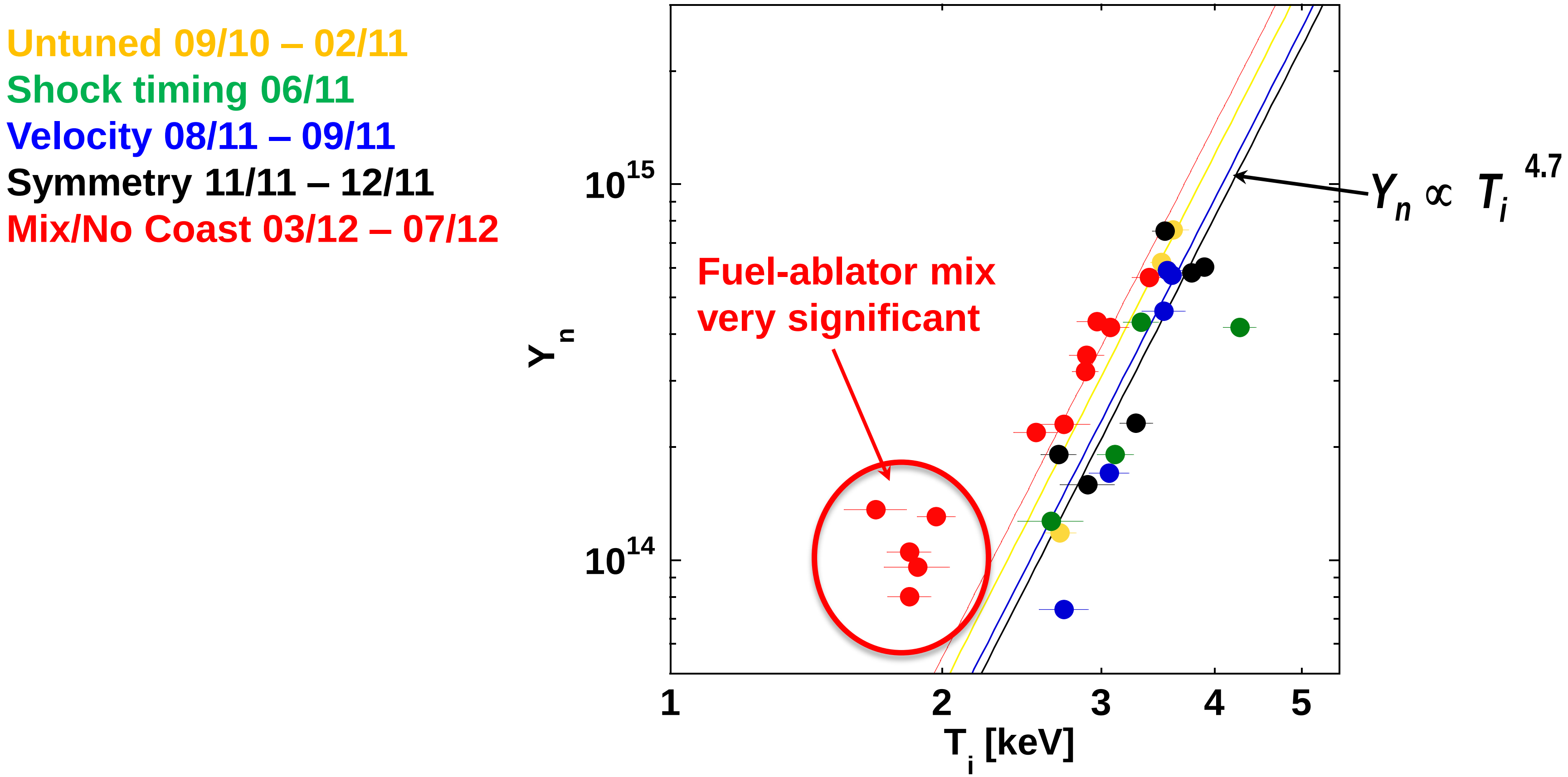



**What's causing this pressure and yield deficit?**

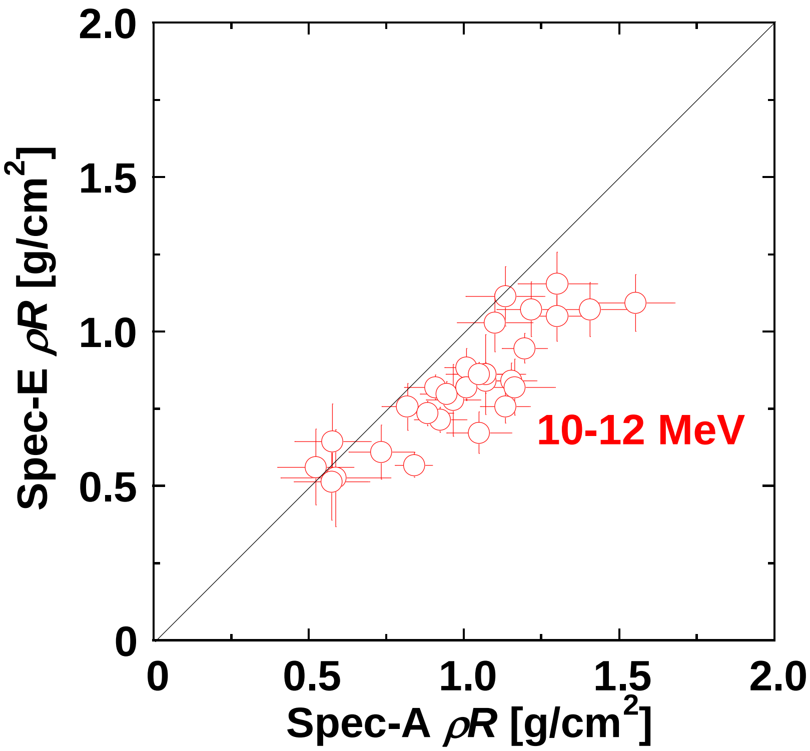
1) P. Springer et al., IFSA (2011).

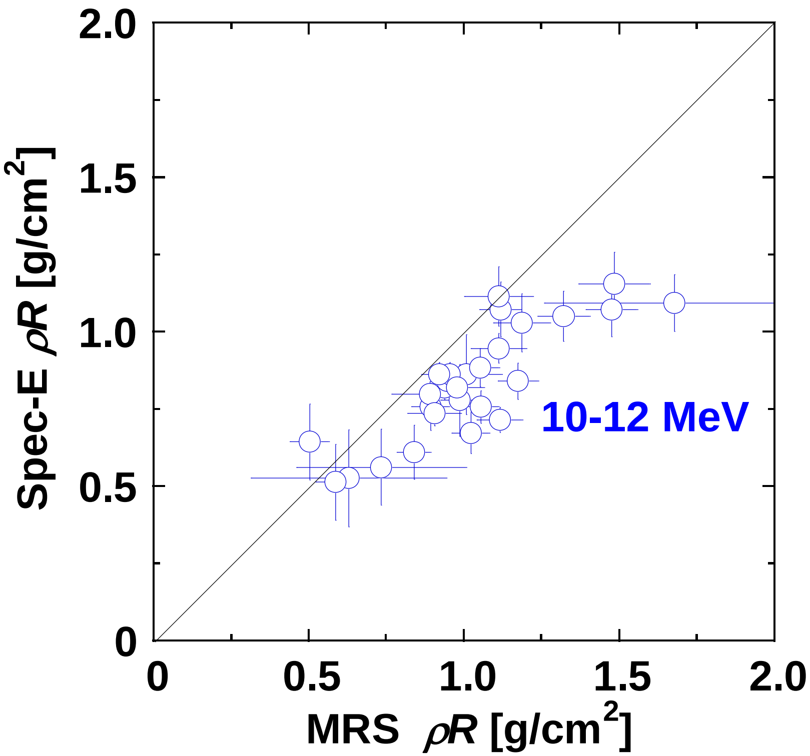
# The pressure and $Y_n$ deficits can be explained partly by larger than predicted CH-ablator mixed into the hot spot



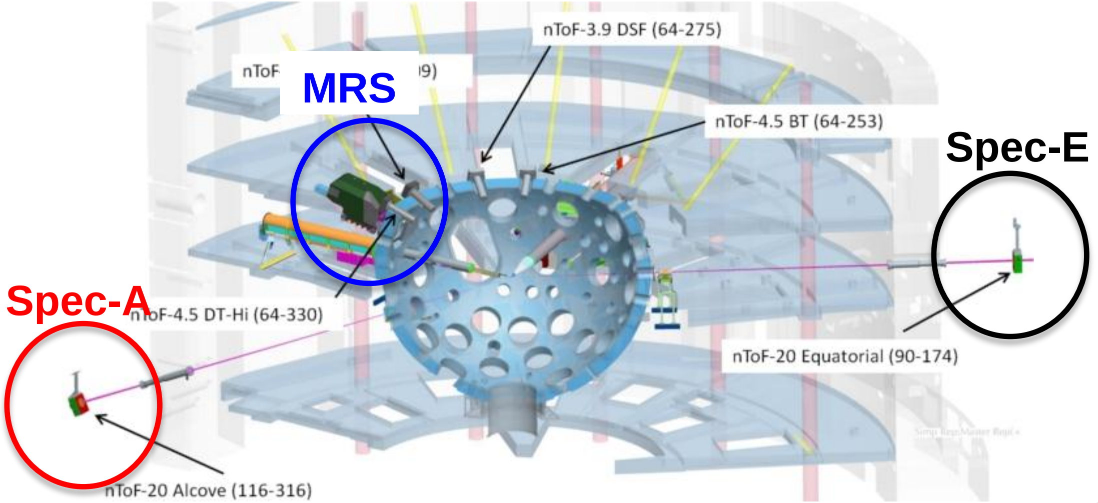

The higher-convergence implosions display more mix, which reduces $T_i$ and $Y_n$. Other data indicate that the "mix-performance cliff" occurs at a remaining shell mass that is ~30-40% larger than the point design

# The $Y_n$ and pressure deficits can also be explained partly by the systematic low-mode *ρR* asymmetries often observed

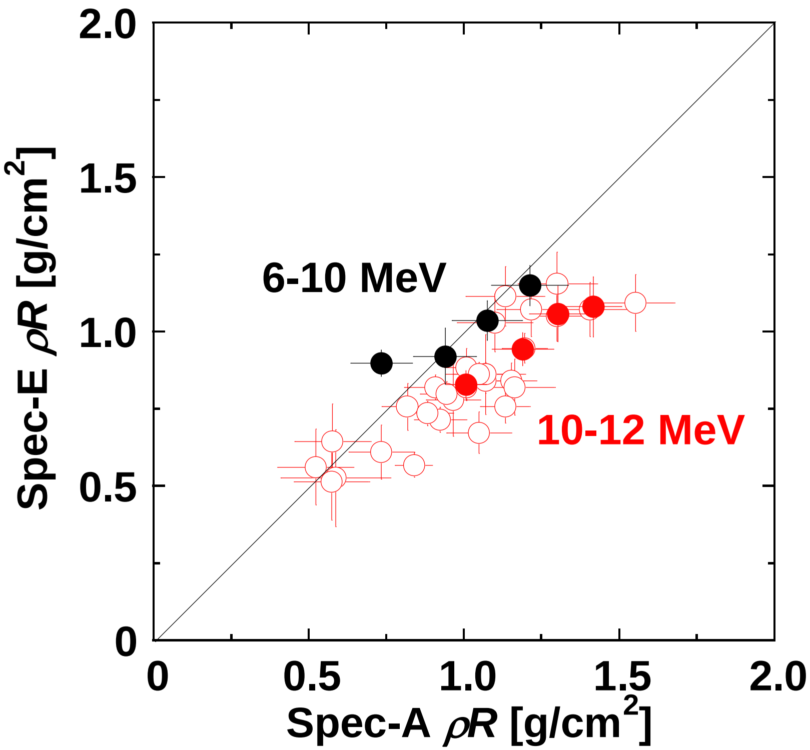


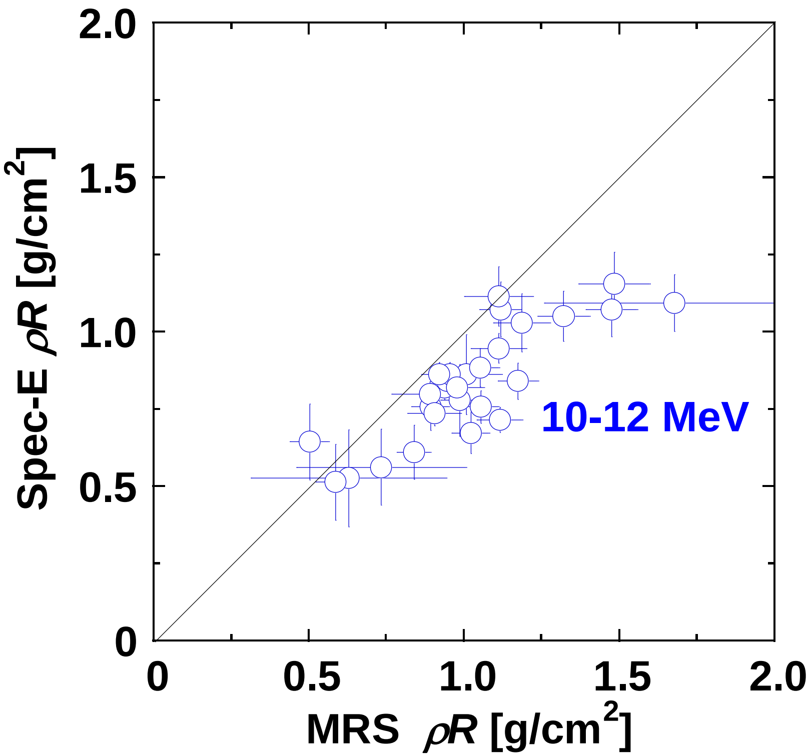




**Neutron measurements of un-scattered neutrons also indicate similar low-mode *ρR* asymmetries**

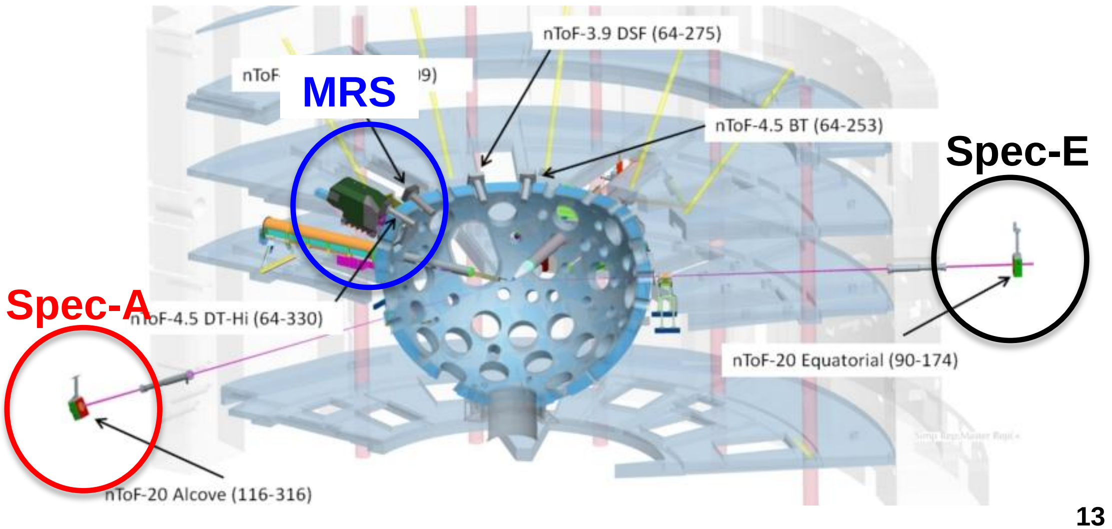


# When using the 6-10 MeV range, Spec-E and Spec-A nTOFs probe similar portion of the implosion, and provide similar *ρR* values




**Neutron measurements of un-scattered neutrons also indicate similar low-mode *ρR* asymmetries**



# Need to address the observed higher-than-predicted levels of mix and low-mode *ρR* asymmetries

- **Understand the origin and structure of mix and low-mode *ρR* asymmetries.**
- **Lower CR implosions (more 1D) should be examined and understood to improve the modeling capabilities before conducting the high CR implosions necessary for ignition.**
- **Engineering solutions and new diagnostic capabilities need to be implemented:**
  - Implement in-flight 2D x-ray radiography of the ablator.
  - Implement in-flight Compton radiography of the fuel.
  - Implement a new nTOF-neutron spectrometer for probing *ρR* on the south pole.
  - Reduce size and/or patch up diagnostic holes and star burst, and reduce diameter of the fill tube to improve drive symmetry.

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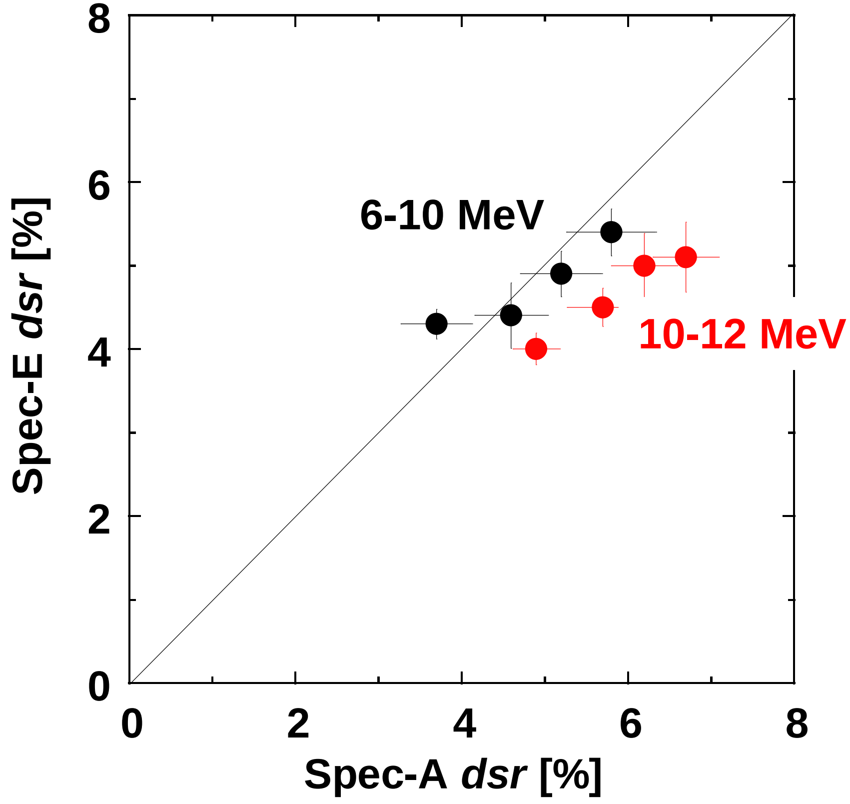
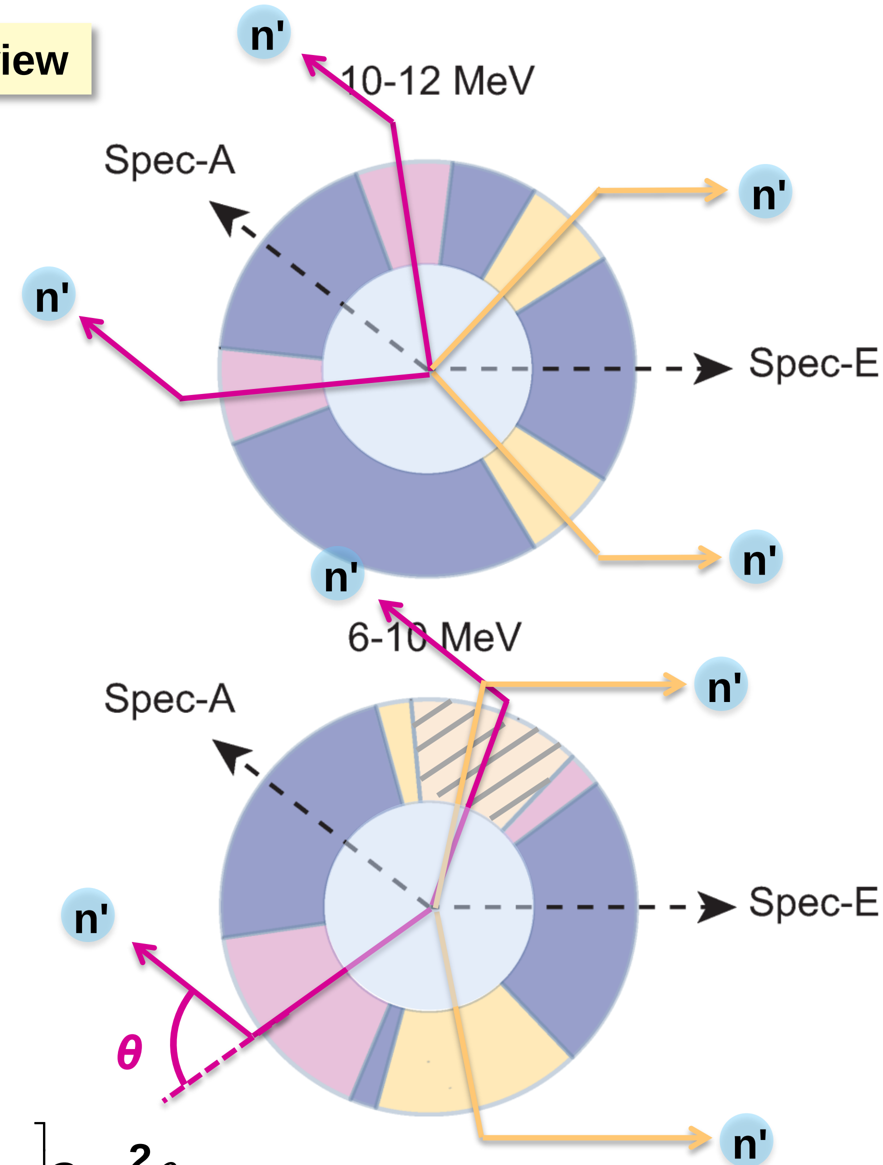
NIF

# In contrast to the 10-12 MeV *dsr* data, the 6-10 MeV *dsr* data show no "$\rho R$ asymmetries"



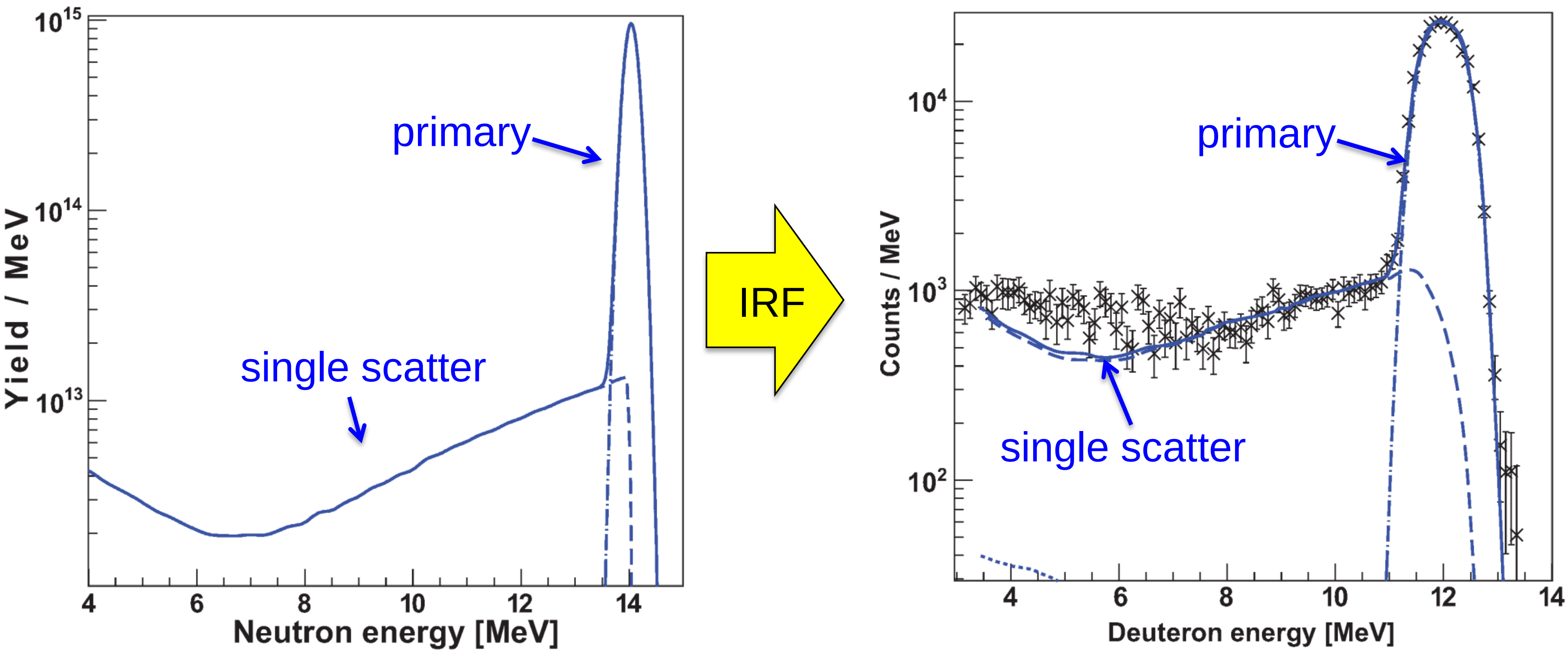

Top view




$$E_{n'} \approx E_n \left[1 - \frac{4A}{(A+1)^2}\right] Cos^2\theta$$

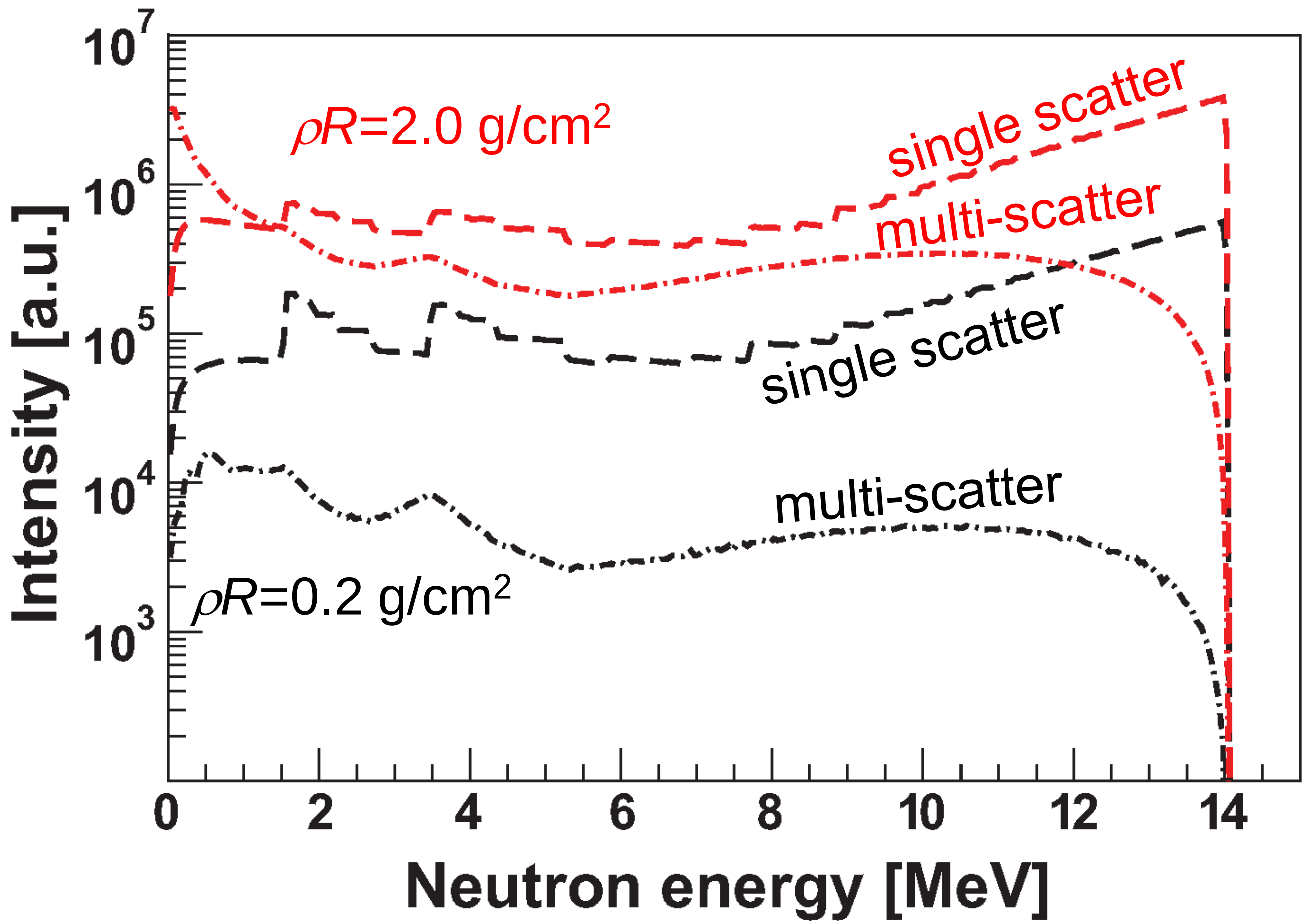
# A single scattering model cannot explain the low-energy neutron spectrum in high-$\rho R$ implosions

**MRS data for Cryo DT, Nov. 12, 2011**



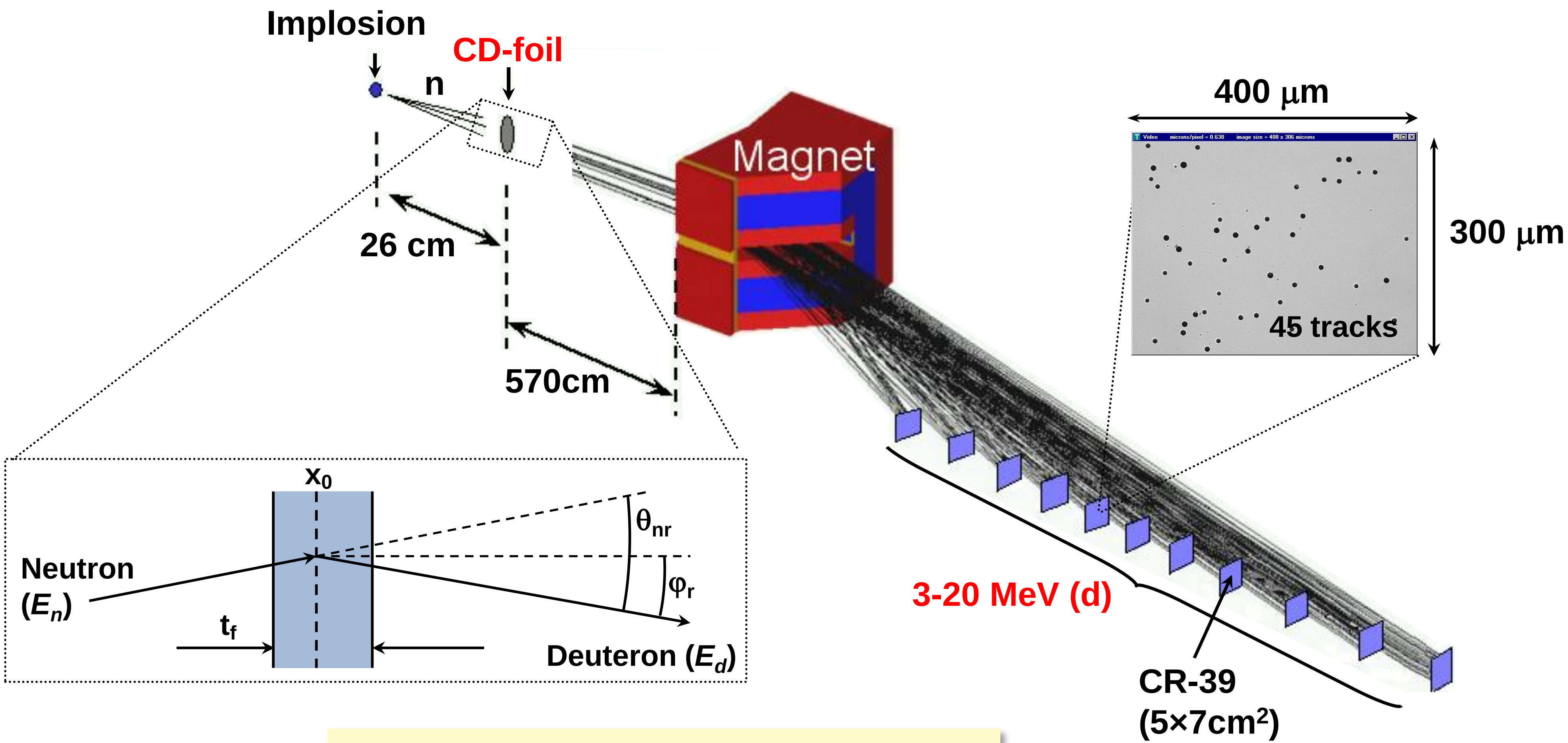

**$\rho R$ asymmetries and multiple scattering may be important at energies below ~9 MeV, and will be considered**

# Neutron spectrum simulations indicate that multiple scatter is important in high ρR implosions




**More sophisticated analysis of the neutron spectrum is currently being developed**

# The MRS measures the neutron spectrum, using the recoil technique combined with a magnetic spectrometer




$$E_d \approx \frac{8}{9} E_n Cos^2\theta_{nd} - \frac{1}{Cos\varphi_r} \int_{x_o}^{t_f} \frac{dE(E_d)}{dx} dx$$

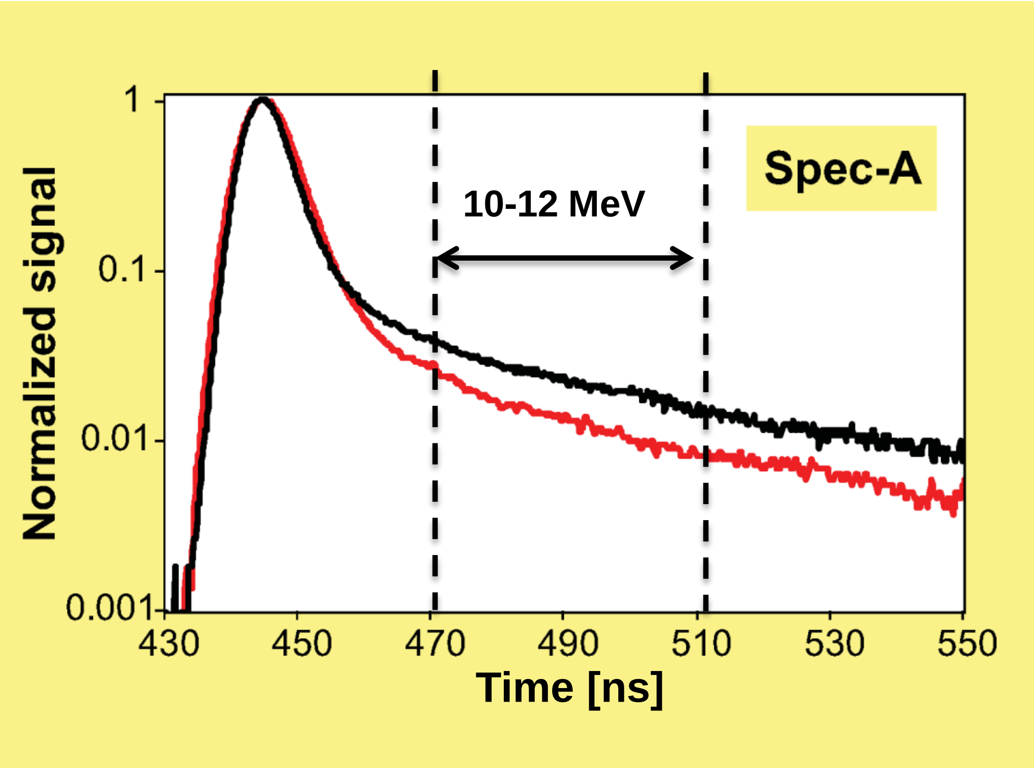
J.A. Frenje et al., Phys. Plasmas 17, 056311 (2010)

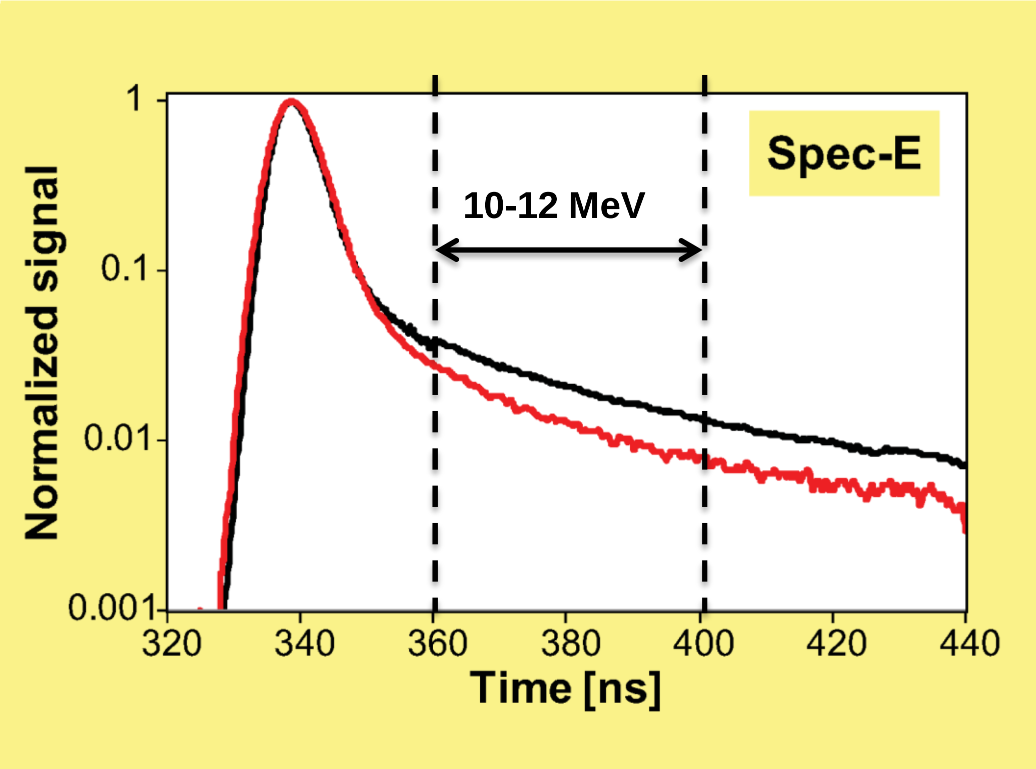
Spec-A/Spec-E/IgnHi

# The background in the *dsr* region is determined from DT exploding pushers, then subtracted to get *dsr* for DT cryo shots

**Cryo DT, Nov. 12, 2011**

**DT Exp Push, Nov. 21, 2011**



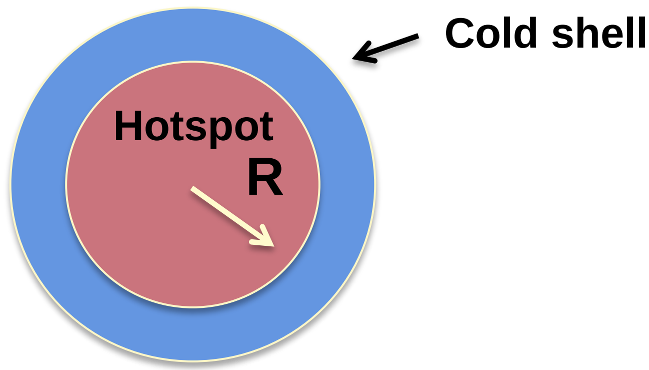




**$dsr$ = 4.8±0.4%**
**$T_i$=3.49±0.40 keV**
**$T_i$=5.68±0.64 keV**

**$dsr$ = 3.9±0.2%**
**$T_i$=3.53±0.38 keV**
**$T_i$=5.35±0.59 keV**

# To gain insight about the implosions, a simple model can be used to infer hot-spot properties from emitted neutrons, X-rays and γ-rays

**Measured hot spot quantities**




neutrons γ-rays X-rays

$$Y \sim Vol \times t_{burn} \times \langle\sigma v\rangle \times n^2$$

Density, $\rho \sim nA$
Mass, $M_{HS} \sim \rho V$
Pressure, $P \sim nT$
Energy, $E \sim PV$

**Derived hot spot quantities**

- More sophisticated model uses isobaric assumption (n~1/T)
- Allows 3D spatial profiles to be fit to match all observables
- Time dependence not yet included

From P. Springer et al., IFSA (2011).