Constraining the 3He+3He Gamow Energy Probed in High Energy Density Plasmas at the National Ignition Facility

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NIF Users Group

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Integrated analysis of NIF DS experiments demonstrated T_{3He} = 12.4 ± 3.2 keV, or Gamow energy of 95 ± 14 keV, which is significantly lower than previous experiments

- Experiments were conducted at NIF to generate ^{3}He+^{3}He reactions, which is important for the proton-proton-I chain reaction in the Sun

- Previous experiments with the mirror ^{3}H+^{3}H reaction observed nuclear reaction pathway dependence upon the Gamow energy

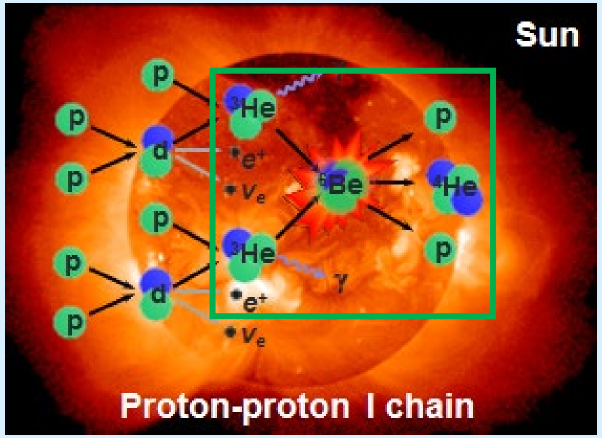
- A wholistic analysis of the data constrained a static hot-spot model which inffered
  - Hot spot volume
  - Electron temperature
  - Electron density
  - Flows

- This data was used to understand the D^{3}He proton spectrum which was used to constrain the energy balance in the implosion

Stellar Nucleosynthesis experiments have focused on probing three-body nuclear reactions

^{3}He+^{3}He

^{3}He+^{3}He $\rightarrow \alpha$ + p + p is responsible for nearly half the energy generation in our sun:



- The ^{3}He^{3}He S-factor determines the pp-I/(pp-II + pp-III) branching ratio and is important for neutrino oscillation physics[1)]

T+^{3}He

T+^{3}He can proceed through several different branches:

T+^{3}He $\rightarrow \alpha$ + p + n
T+^{3}He $\rightarrow \alpha$ + d
T+^{3}He $\rightarrow$ ^{6}Li + γ

- An anomalously high S-factor for the gamma branch has been hypothesized to explain ^{6}Li abundance in primordial material **– this was ruled out (Zylstra et al., PRL 117, 035002 (2016))**

T+T

T+T $\rightarrow \alpha$ + n + n is a mirror reaction to ^{3}He^{3}He

- Basic nuclear physics governing few-body reactions with 3 particles in final state not well understood
- Also important for ICF (contributes to the neutron spectrum)

The unique ensemble of T+T, T+^{3}He and ^{3}He+^{3}He spectra provides insight into final-state interactions in six-nucleon systems

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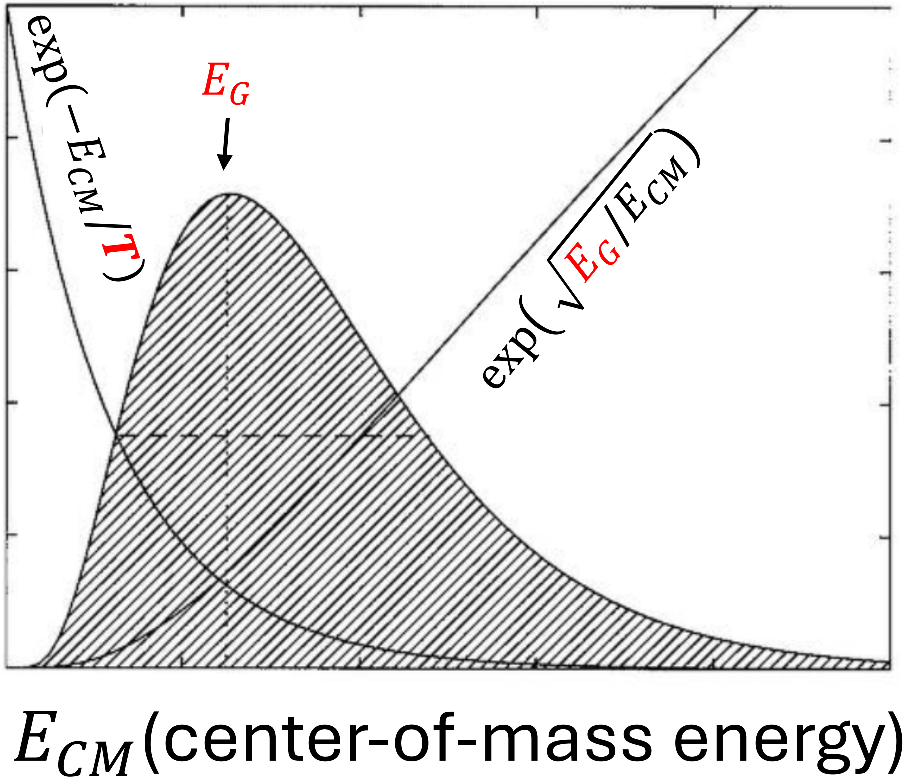
[1)] Adelberger et al., Rev. Mod. Phys 83, 2011

Fusion reactions occur over a continuum of center-of-mass energies, but the most probable energy is called the Gamow Energy



Probability to find a particle: $\exp(-E_{CM}/T)$

Probability to fuse : $\exp\left(\sqrt{\boldsymbol{E_G}/E_{CM}}\right)$

The Gamow Energy is only a function of temperature for a given reaction

$$\boldsymbol{E_G} = \left(b\,\frac{T}{2}\right)^{2/3}$$

$$b = \sqrt{\frac{\mu_{12}}{2}}\,Z_1 Z_2\,\frac{e{\wedge}2}{2\,\varepsilon_0\,\hbar}$$

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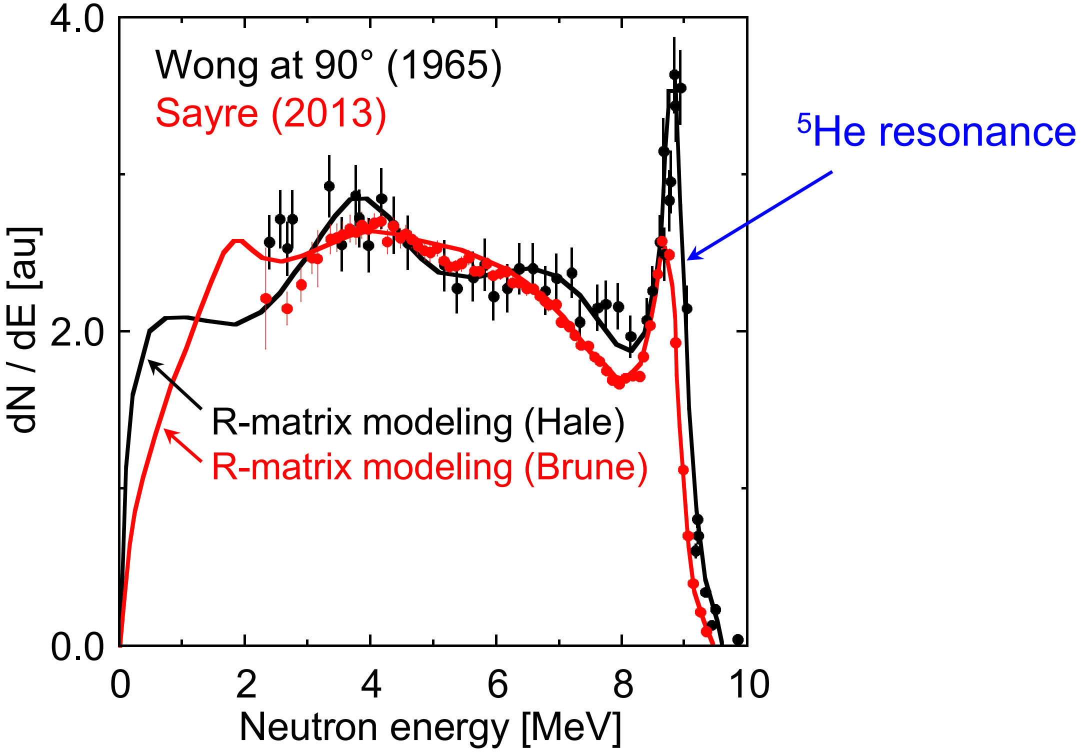
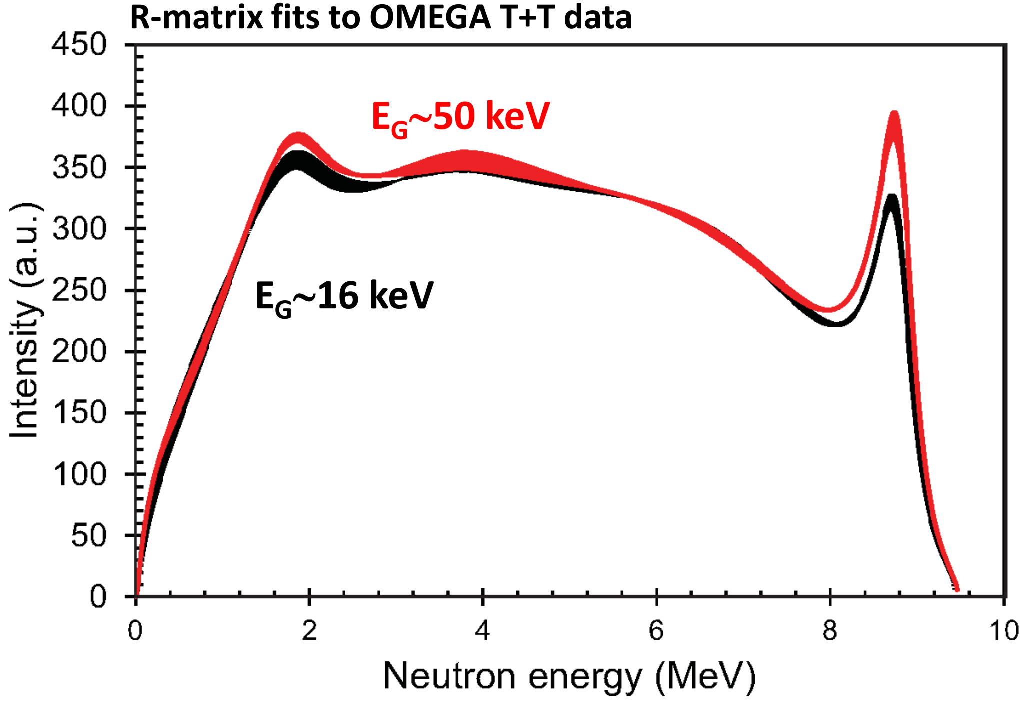
[1] Figure adapted from Choudhuri *Astrophysics for Physicists*

Motivation

Previous experiments on T+T saw variations product spectra as a function of Gamow energy, suggesting the possibility that the ^{3}He+^{3}He reaction might do the same





The Sayre (ICF) and Wong (accelerator) spectra indicate that the reaction mechanism is changing with E_G

The Gatu-Johnson (ICF) verified that the reaction mechanism changes with E_G

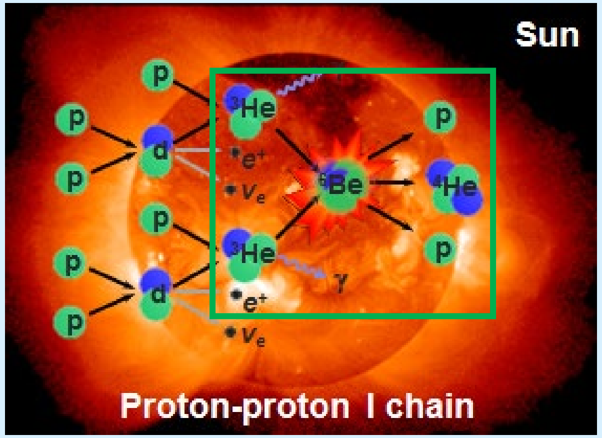
[1] Sayre et al, PRL (2013).
[2] Wong et al, NP (1965).
[3] Bacher et al, FewBody Meeting (2015)

[1] Gatu-Johnson et al, PRL (2018)

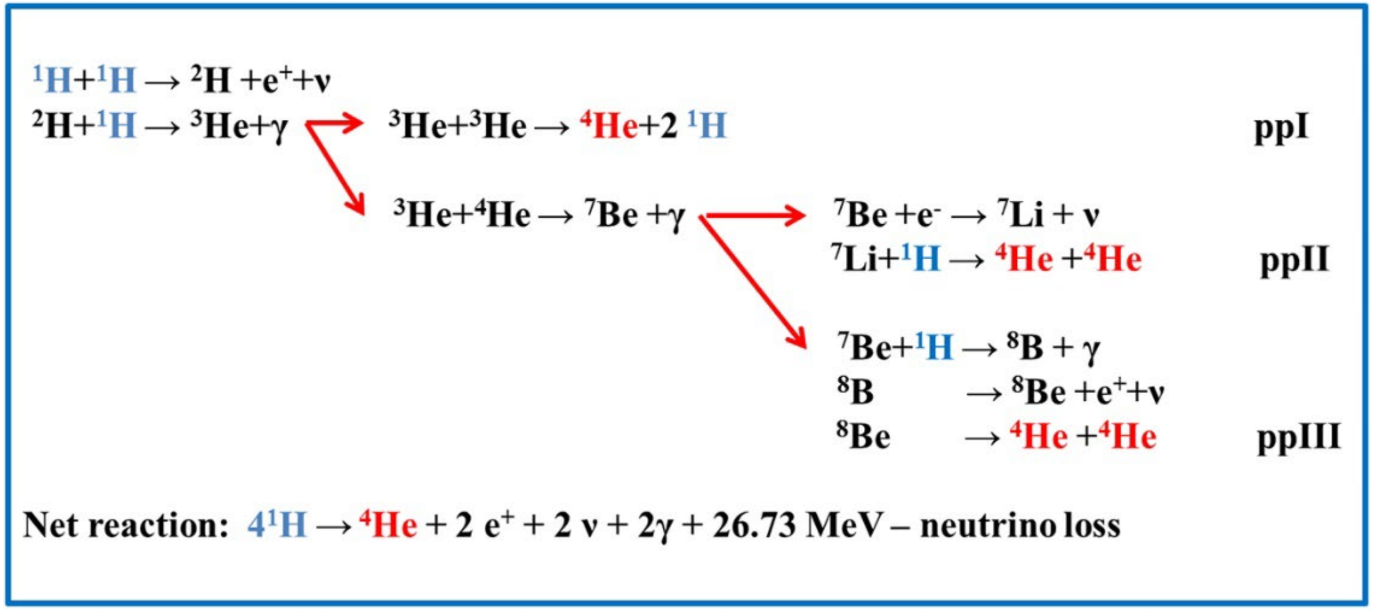
ICF experiments can address the Gamow Energy dependence of the ^{3}He+^{3}He reaction which is important for understanding nuclear physics of many-body reactions and solar neutrinos

^{3}He+^{3}He

$^3\text{He}+^3\text{He} \rightarrow \alpha + p + p$ is responsible for nearly half the energy generation in our sun:



- The ^{3}He^{3}He S-factor determines the pp-I/(pp-II + pp-III) branching ratio and is important for neutrino oscillation physics[1)]



$^1\text{H}+^1\text{H} \rightarrow ^2\text{H} + e^+ + \nu$

$^2\text{H}+^1\text{H} \rightarrow ^3\text{He}+\gamma$ → $^3\text{He}+^3\text{He} \rightarrow ^4\text{He}+2\,^1\text{H}$ ppI

$^3\text{He}+^4\text{He} \rightarrow ^7\text{Be}+\gamma$ → $^7\text{Be}+e^- \rightarrow ^7\text{Li}+\nu$

$^7\text{Li}+^1\text{H} \rightarrow ^4\text{He}+^4\text{He}$ ppII

$^7\text{Be}+^1\text{H} \rightarrow ^8\text{B}+\gamma$

$^8\text{B} \rightarrow ^8\text{Be}+e^+ + \nu$

$^8\text{Be} \rightarrow ^4\text{He}+^4\text{He}$ ppIII

Net reaction: $4\,^1\text{H} \rightarrow ^4\text{He} + 2\,e^+ + 2\,\nu + 2\gamma + 26.73\text{ MeV}$ – neutrino loss

Uncertainty in the ^{3}He^{3}He S-factor directly impacts uncertainty in calculated neutrino fluxes from solar models

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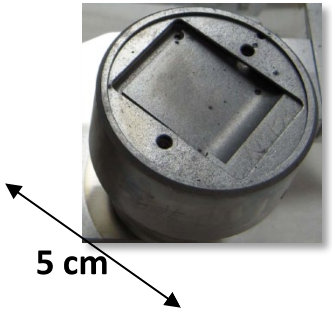
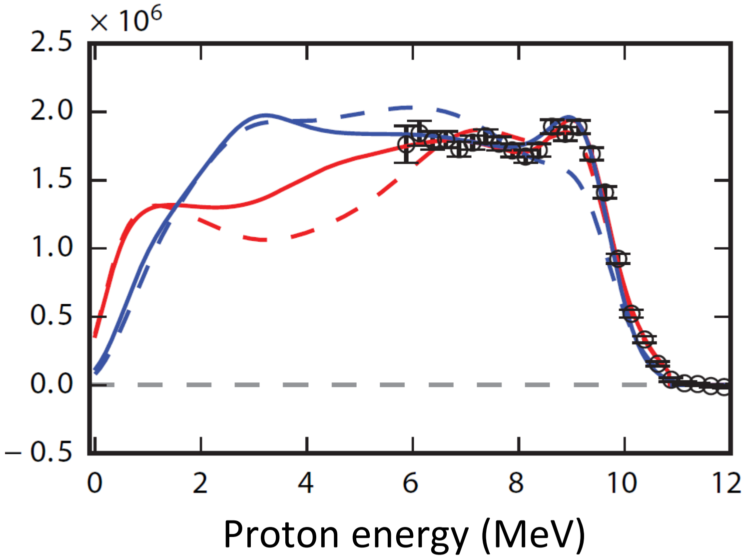
[1)] Vinyoles, Ap. J 2017

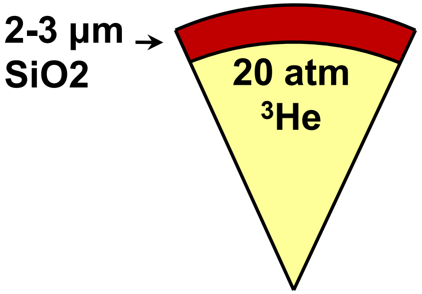
[2)] Brune, Solar Fusion III workshop, 2022

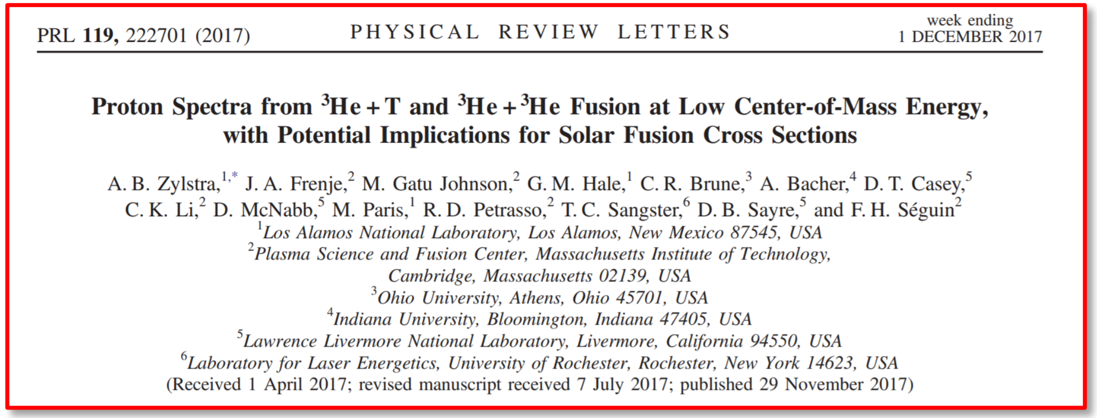
Previous OMEGA experiments observed the ^{3}He+^{3}He proton spectrum at E_G=165 keV

$$^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \alpha + \mathrm{p} + \mathrm{p} \quad Q = 12.86\mathrm{MeV}.$$








PRL **119,** 222701 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Proton Spectra from ^{3}He + T and ^{3}He + ^{3}He Fusion at Low Center-of-Mass Energy, with Potential Implications for Solar Fusion Cross Sections

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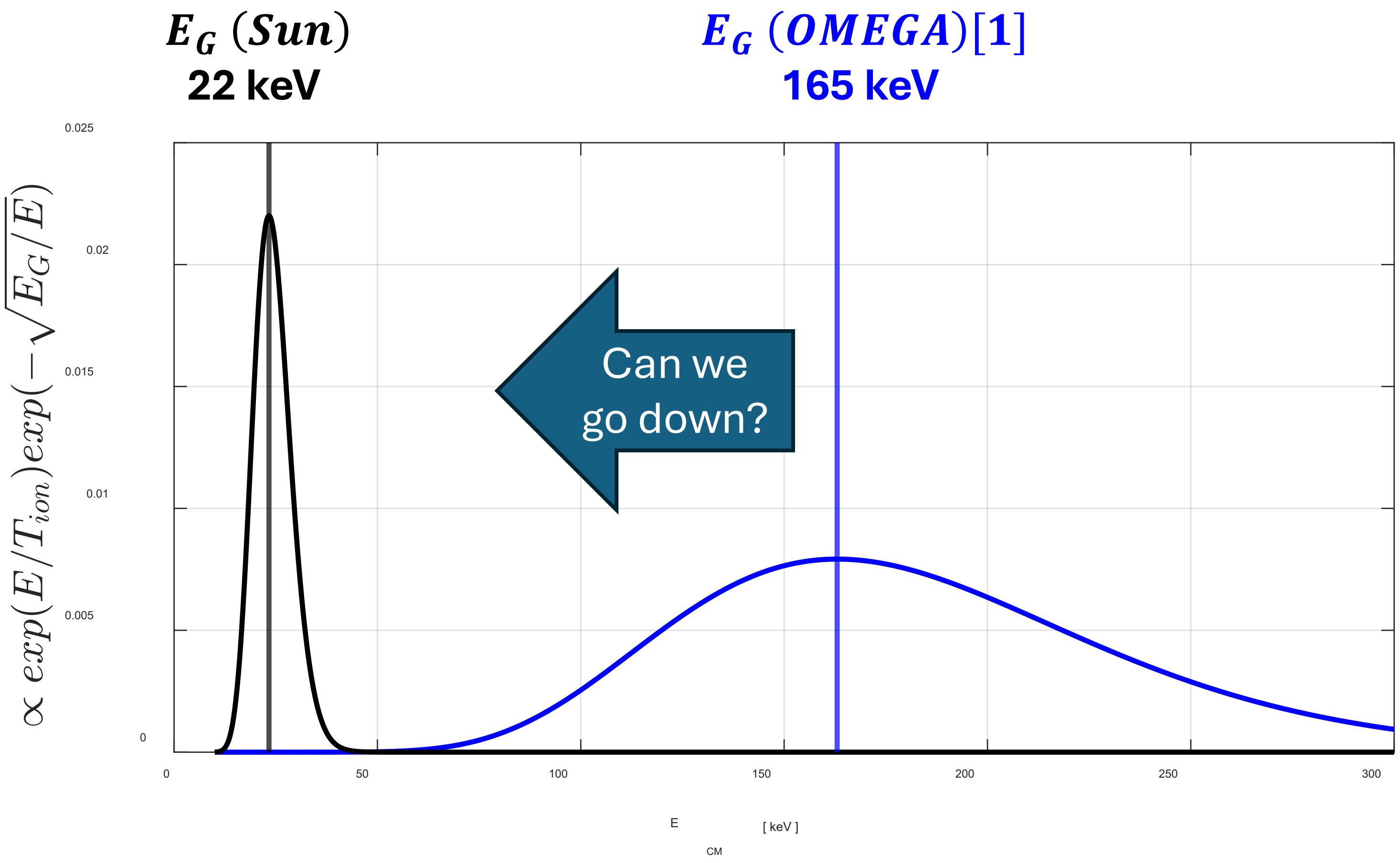
Previous experiments probed the ^{3}He+^{3}He reaction at high CM Energies

NIF experiments were conducted to lower the ‘Gamow’ Energy

$$^3\mathrm{He} + ^3\mathrm{He} \rightarrow \alpha + \mathrm{p} + \mathrm{p} \quad \mathrm{Q} = 12.86\mathrm{MeV}.$$

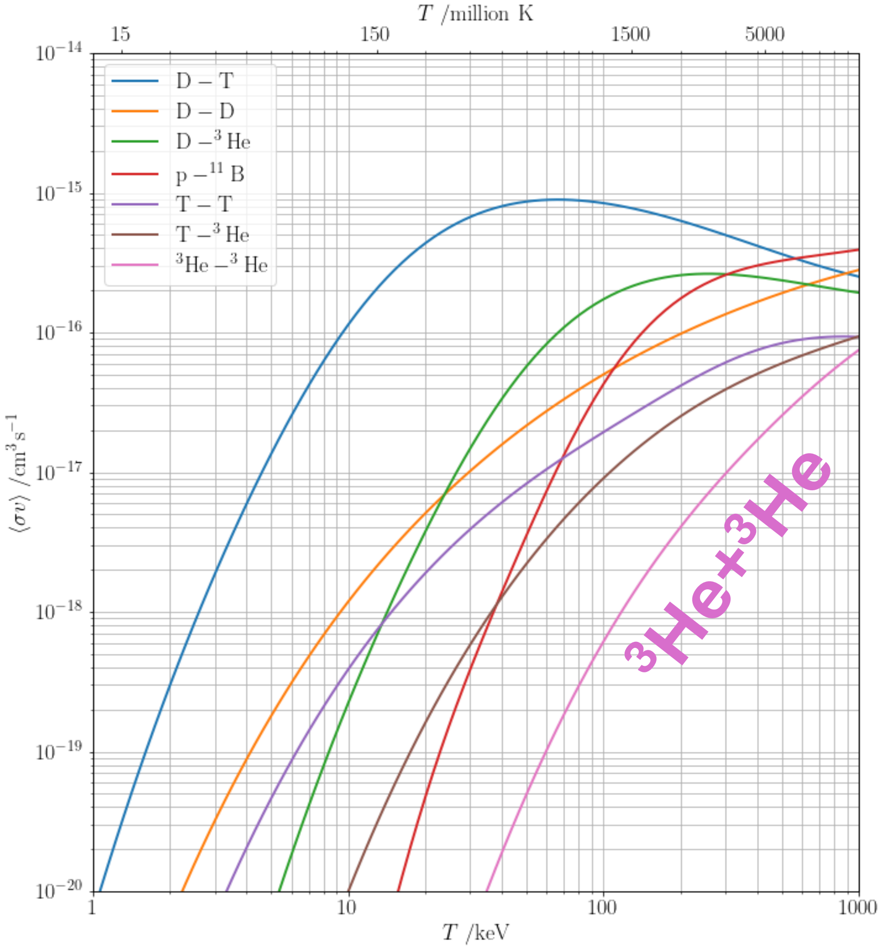


[1] A. B. Zylstra et al. Physical Review Letters 119.22 (Nov. 2017).

Motivation

Lowering the Gamow Energy, i.e. plasma temperature, severely impacts the total yield

Experiments were pursued at NIF to drive larger plasma at high density to compensate



$$Y_{3He3He} \propto n_{3He}^2 < \sigma v > (T)\, V_{HS}$$

We want :

↓ T temperature decrease

↑ n_{3He}^2 density increase

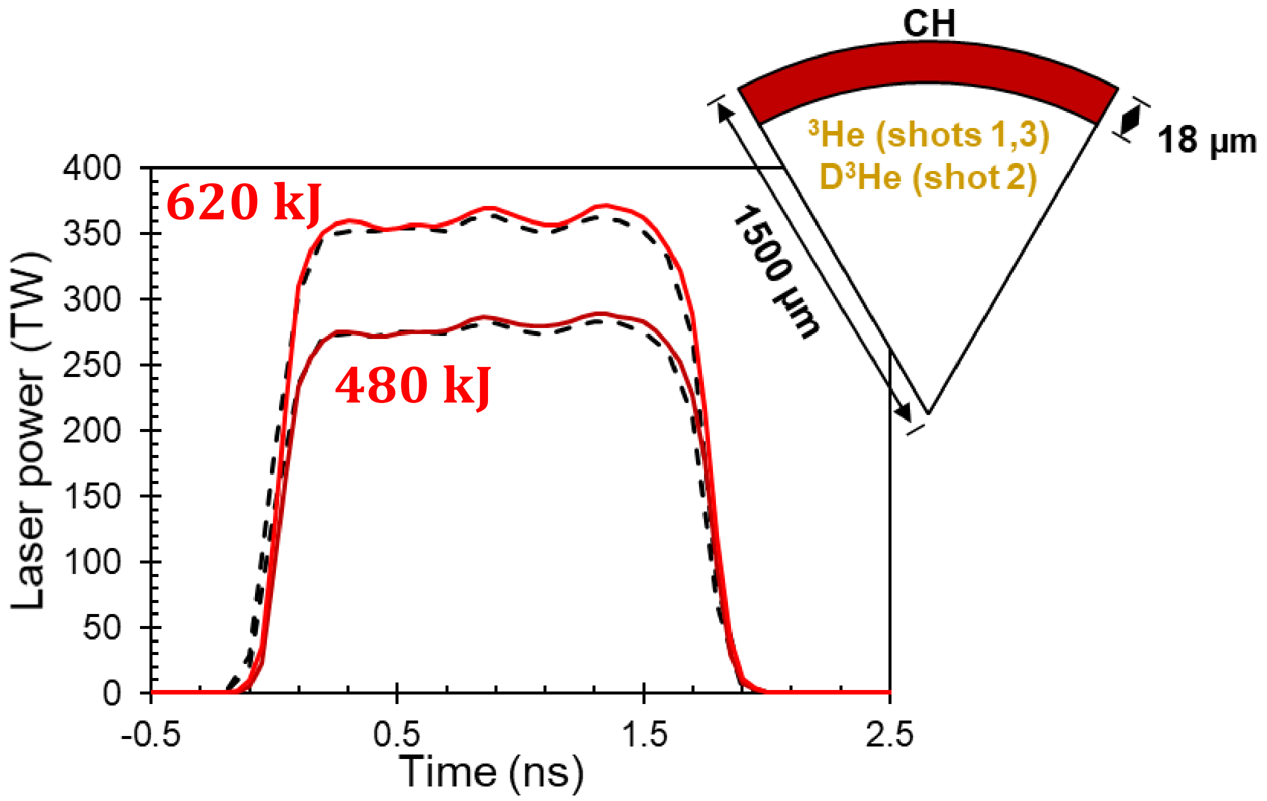
↑ V_{HS} volume increase

This required NIF drive energies for the implosions

https://scipython.com/blog/nuclear-fusion-cross-sections/

Experiments

A NIF DS day was acquired to generate implosions at lower temperature, but bigger plasma volumes to detect the ^{3}He+^{3}He-proton spectra at lower Gamow energy



Shot	Laser Energy	Fill pressure (torr)	Fill pressure (Pa)	D fraction	3He fraction	rho_init (g/cm^3)	OD(µm)	wall thickness(µm)	Density(g/cc)
N200211-002	480 kJ	7590	1.01E+06	0.128	99.87	1.25E-03	2929.3	17.7	0.978
N200211-003	480 kJ	7582	1.01E+06	19.46	80.54	1.17E-03	2920.0	17.8	0.973
						1.25E-			

Fusion product spectroscopy is sensitive to the ion temperature generated

We want to know”

$$T_{3He}$$

But we can only get”

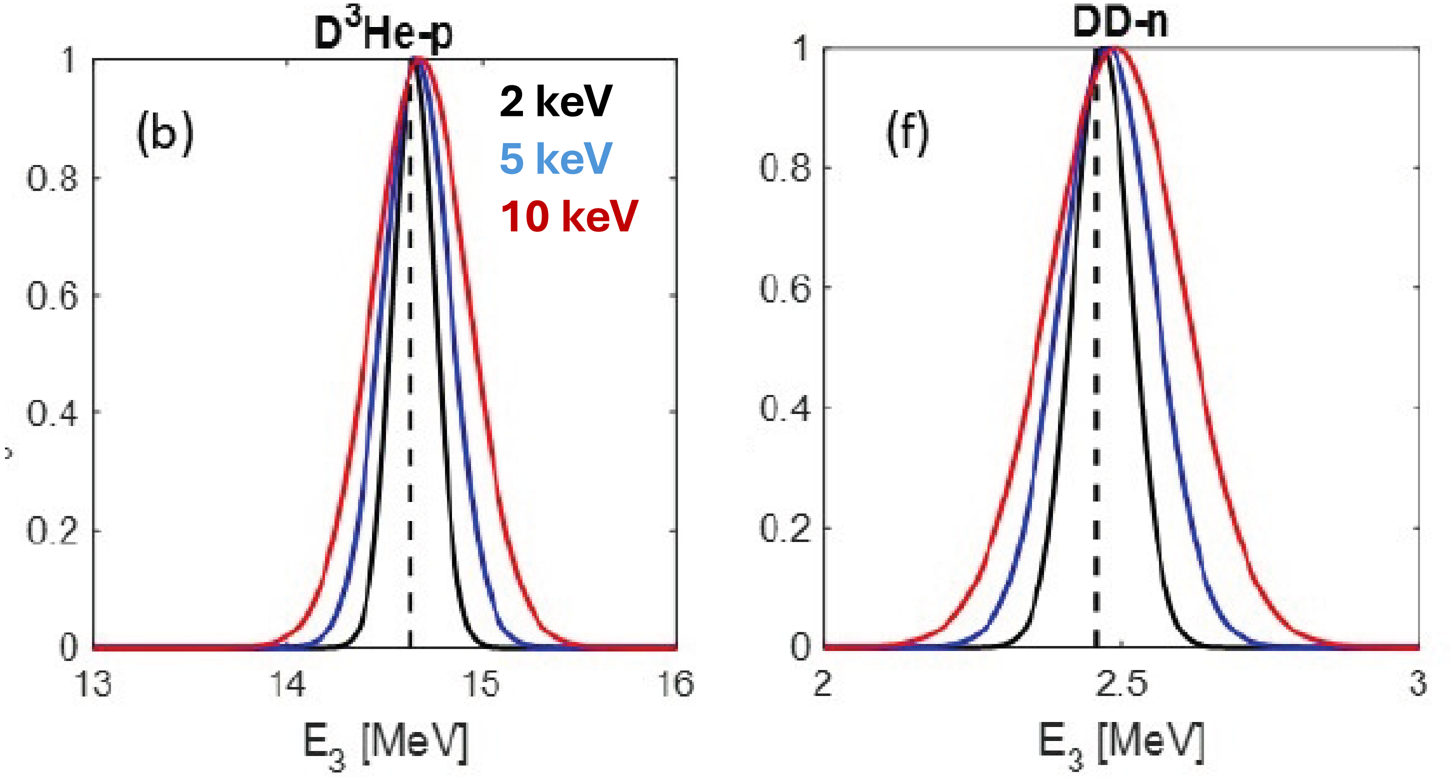
T_D and T_{D3He}

DD-n are measured with nTOFs

D3He-p are measured with wedge range filters

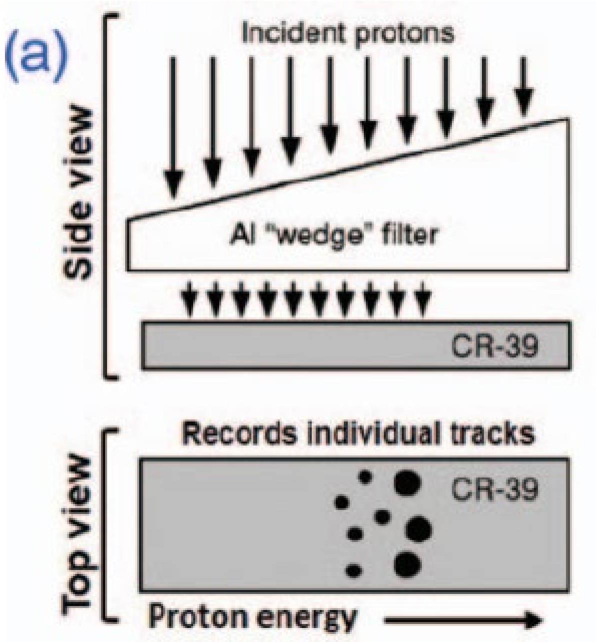
The ‘thermometer’ reactions are:

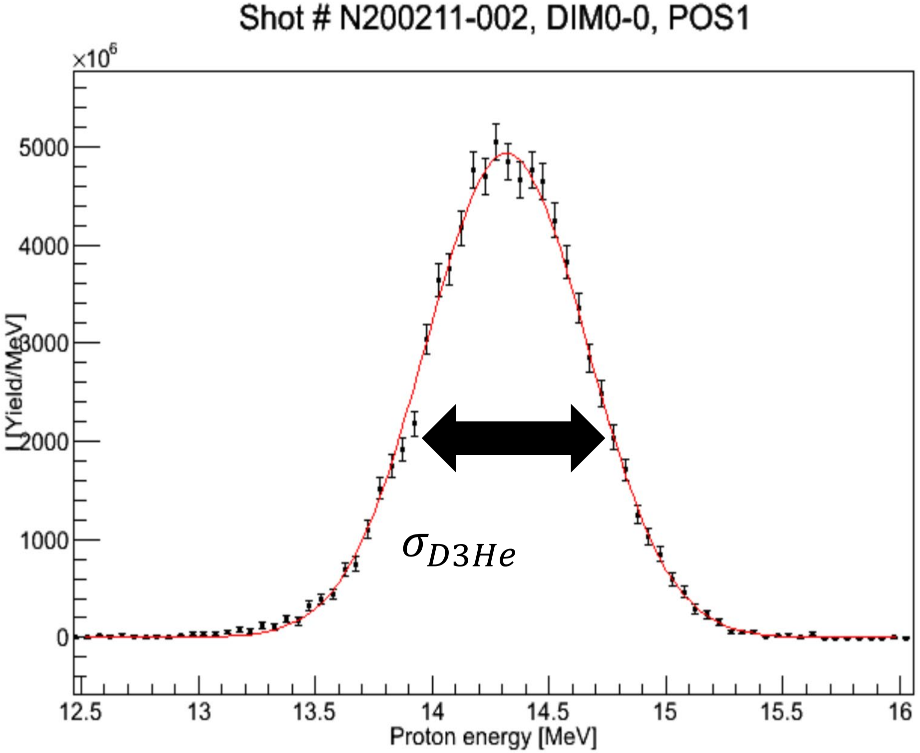
$$D + D \rightarrow n$$
$$D + 3He \rightarrow p$$



The temperature measured with WRFs is a composition of the deuterium and helium-3 temperature plus stopping power, flow, and detector broadening

Wedge Range Filter
(WRF) concept :





flows[3]

$$\sigma^2_{D3He} = \left(\frac{(m_{3He}\, \boldsymbol{T_{3He}} + m_D\, \boldsymbol{T_{DD}})}{m_D + m_{3He}}\right)^2 + \boldsymbol{\sigma^2_{dE/dx}}(\boldsymbol{T_e}, \boldsymbol{n_e}, \boldsymbol{V_{HS}}) + \boldsymbol{\sigma^2_{flows}} + \boldsymbol{\sigma^2_{Det}}$$

Nuclear kinematics [1]

Charged particle stopping [2]

Detector response [4

[1] Ballabio et al, Nuc. Fusion 1998
[2] Adrian et al, PRE 2022
[3] Murphy PoP 2014
[4] Seguin et al 2003

Solution

Additional diagnostics and inference techniques are required to interpret the D³He proton spectrum for the underling temperture

$$\sigma_{D3He}^2 = \left(\frac{(m_{3He}\,\boldsymbol{T_{3He}} + m_D\,\boldsymbol{T_{DD}})}{m_D + m_{3He}}\right)^2 + \boldsymbol{\sigma_{dE/dx}^2}(\boldsymbol{T_e}, \boldsymbol{n_e}, \boldsymbol{V_{HS}}) + \boldsymbol{\sigma_{flows}^2} + \boldsymbol{\sigma_{Det}^2}$$

σ_{D3He}^2 - measure directly from WRFs

$\boldsymbol{T_{DD}}$ - constrain from nTOFs

$\boldsymbol{T_e}, \boldsymbol{n_e}, \boldsymbol{V_{HS}}$ - measure from x-ray penumbral imaging

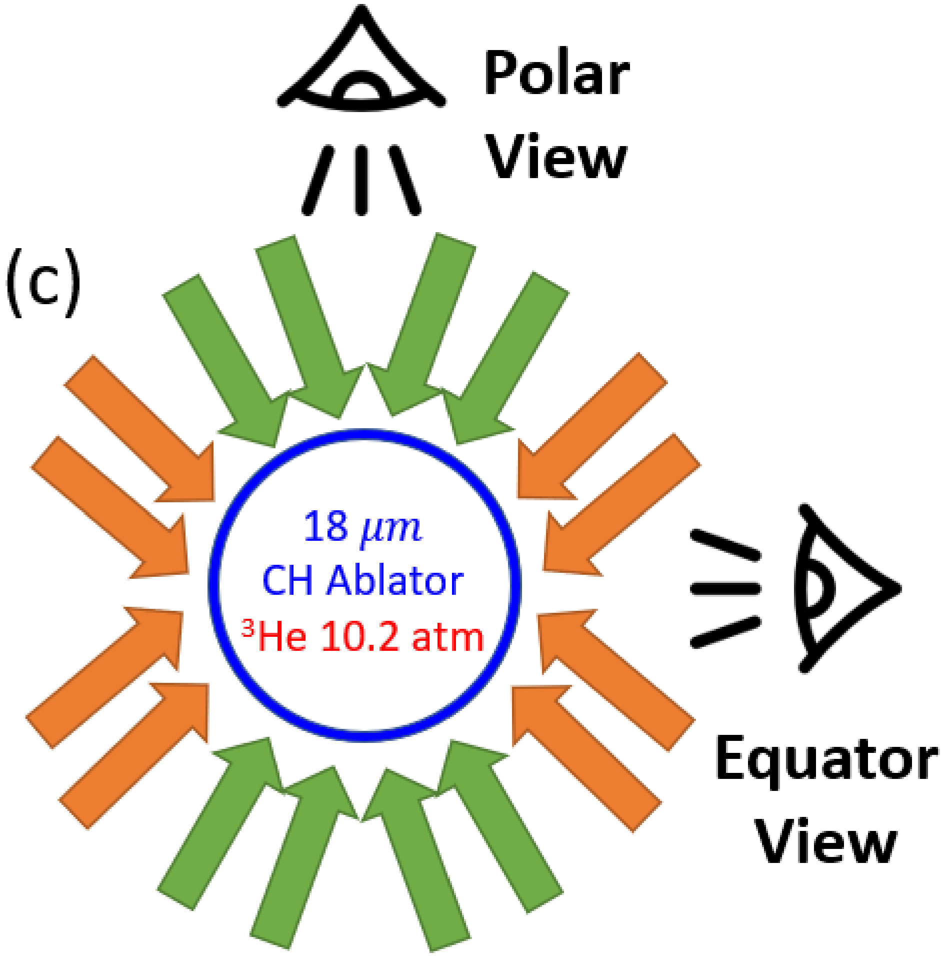
$\boldsymbol{\sigma_{flows}^2}$ - constrain from yield degradation

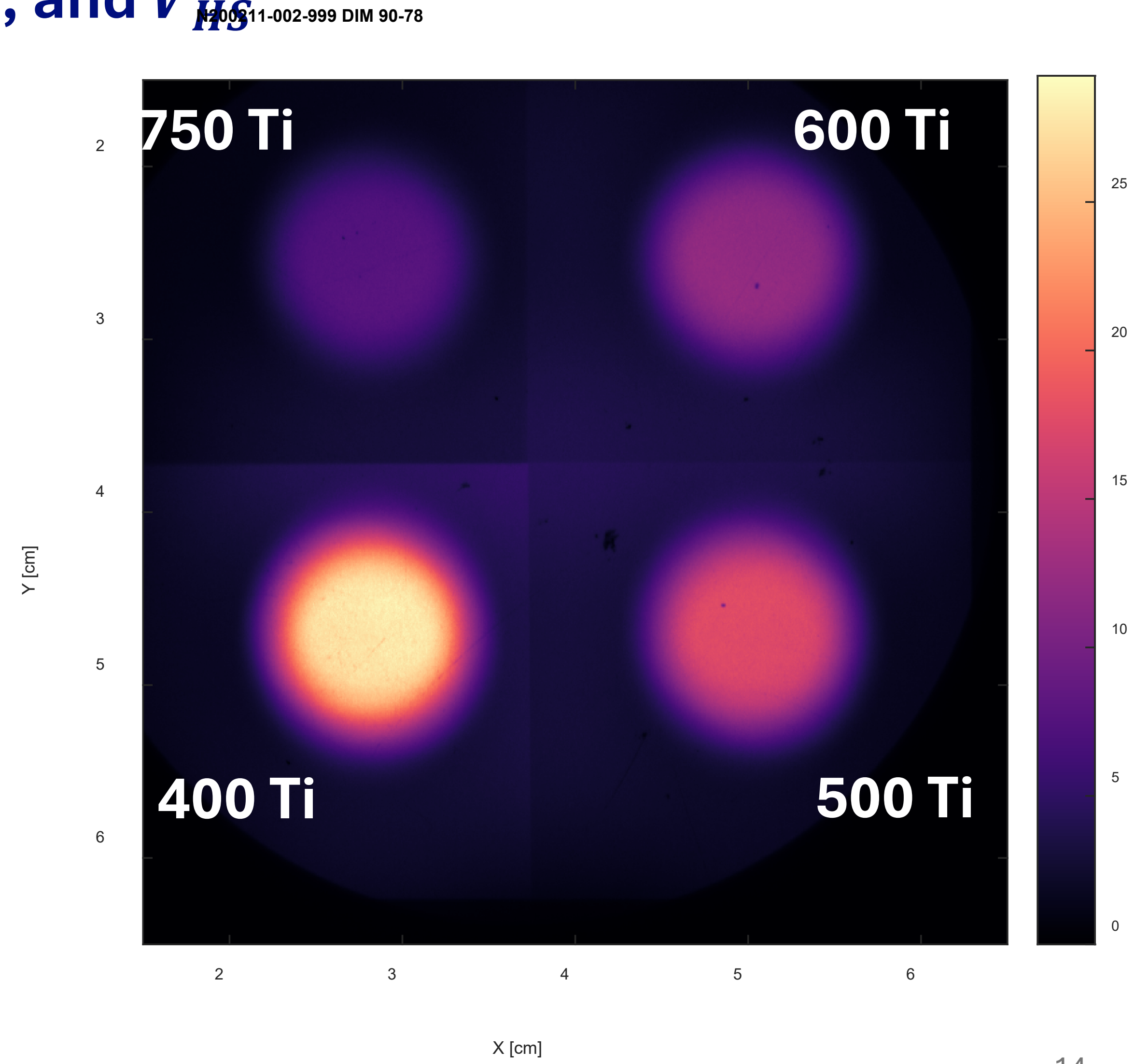
$\boldsymbol{\sigma_{dE/dx}^2}$- model broadening due to charge particle stopping

$\boldsymbol{\sigma_{Det}^2}$ - calibration

$\boldsymbol{T_{3He}}$ - constrain once everything else is diagnosed

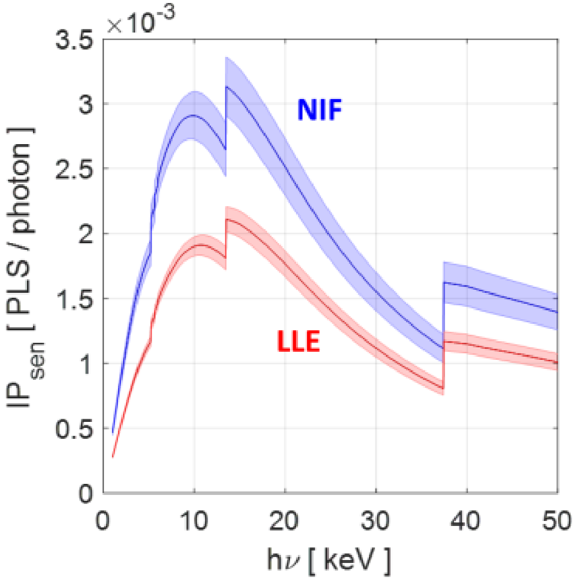
X-ray penumbral imaging was done in the polar and equatorial directions to help constrain T_e, n_e, and V_{HS}

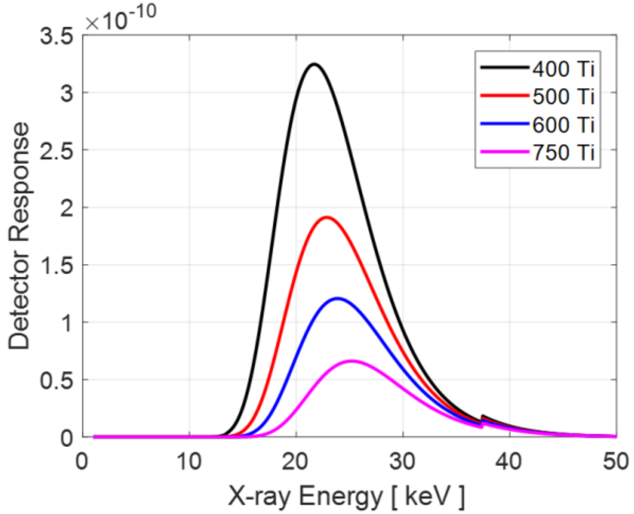




The penumbral images were used to determine the emission averaged n_e and T_e

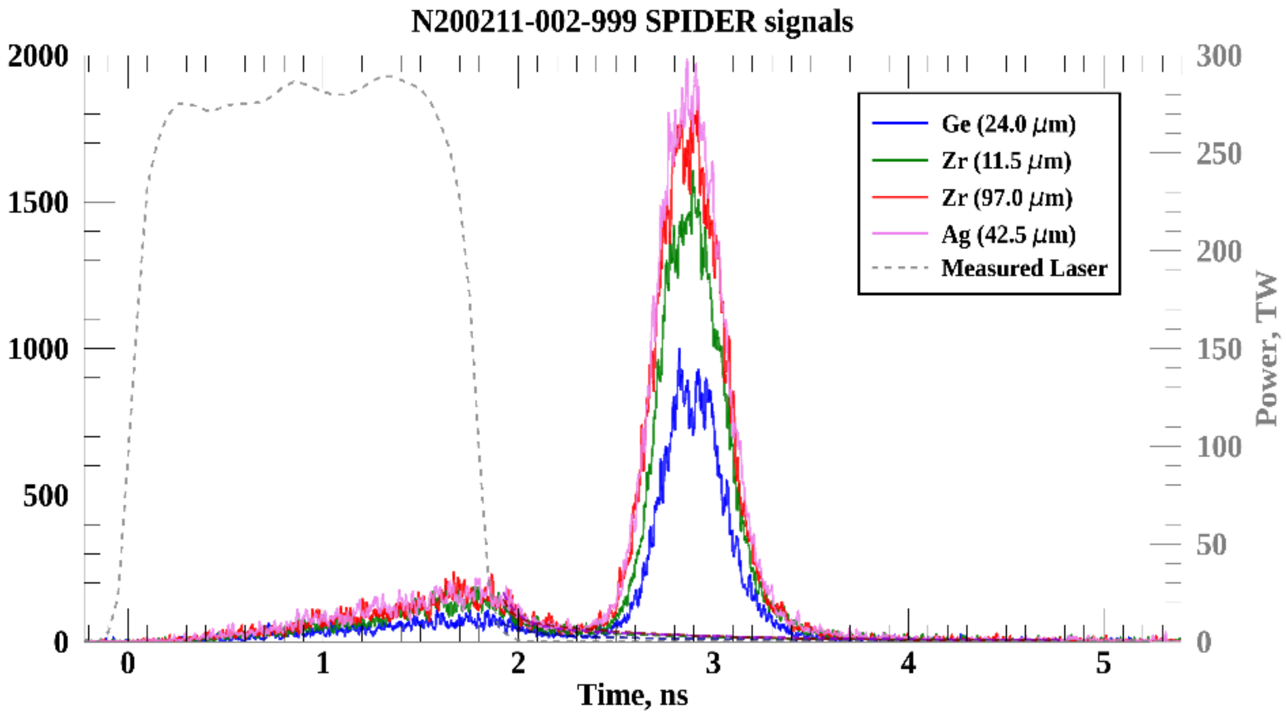
$$PSL_k = \underbrace{3 \times 10^{15}}_{\text{Bremsstrahlung Emission Factor}} \left[\underbrace{\int \frac{Z_{eff} n_e^2}{\sqrt{T_e/k_B}} \langle g_{ff} \rangle e^{-h\nu/T_e} T_k IP_{sen} dh\nu}_{\text{X-ray Emission and Image Plate Detection [PSL / cm}^3\text{ / s]}} \right] \underbrace{\Omega}_{\text{Solid Angle}} \underbrace{V_{HS}}_{\text{Hot Spot Volume}} \underbrace{2\sqrt{\frac{\ln 2}{\pi}}\tau}_{\text{Burn duration}},$$





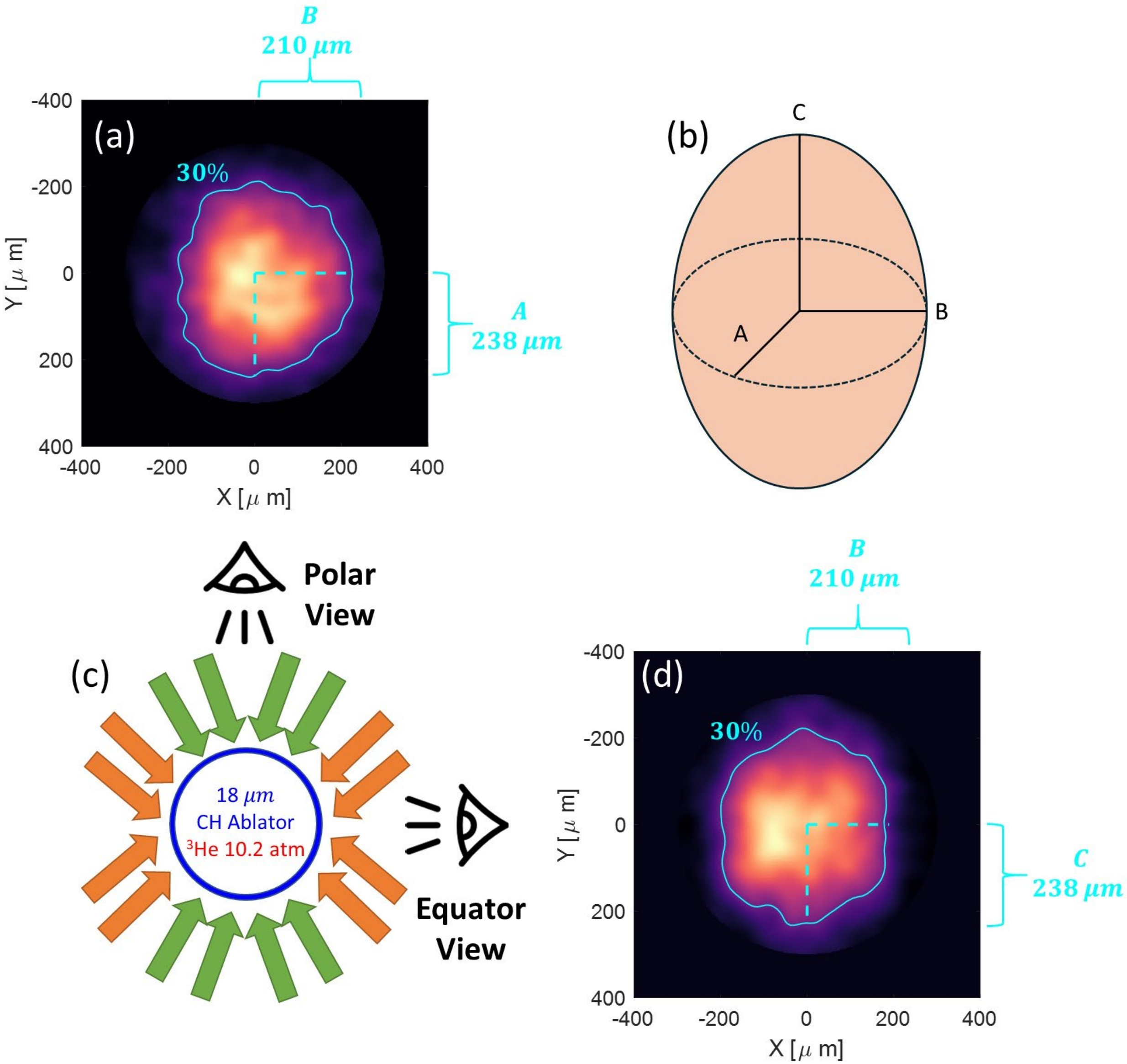
Emission History

The burn width was determined from SPIDER data where we averaged the 100 um slit measurements together



BT~2.89ns; BW~364ps

The hot spot volume was determined by determined the major and minor axis of a ellipsoid model from the polar and equatorial images



The probability distributions for n_e , T_e , and V_{HS} were determined by including sources of uncertainty from image plate calibrations and penumbral reconstruction

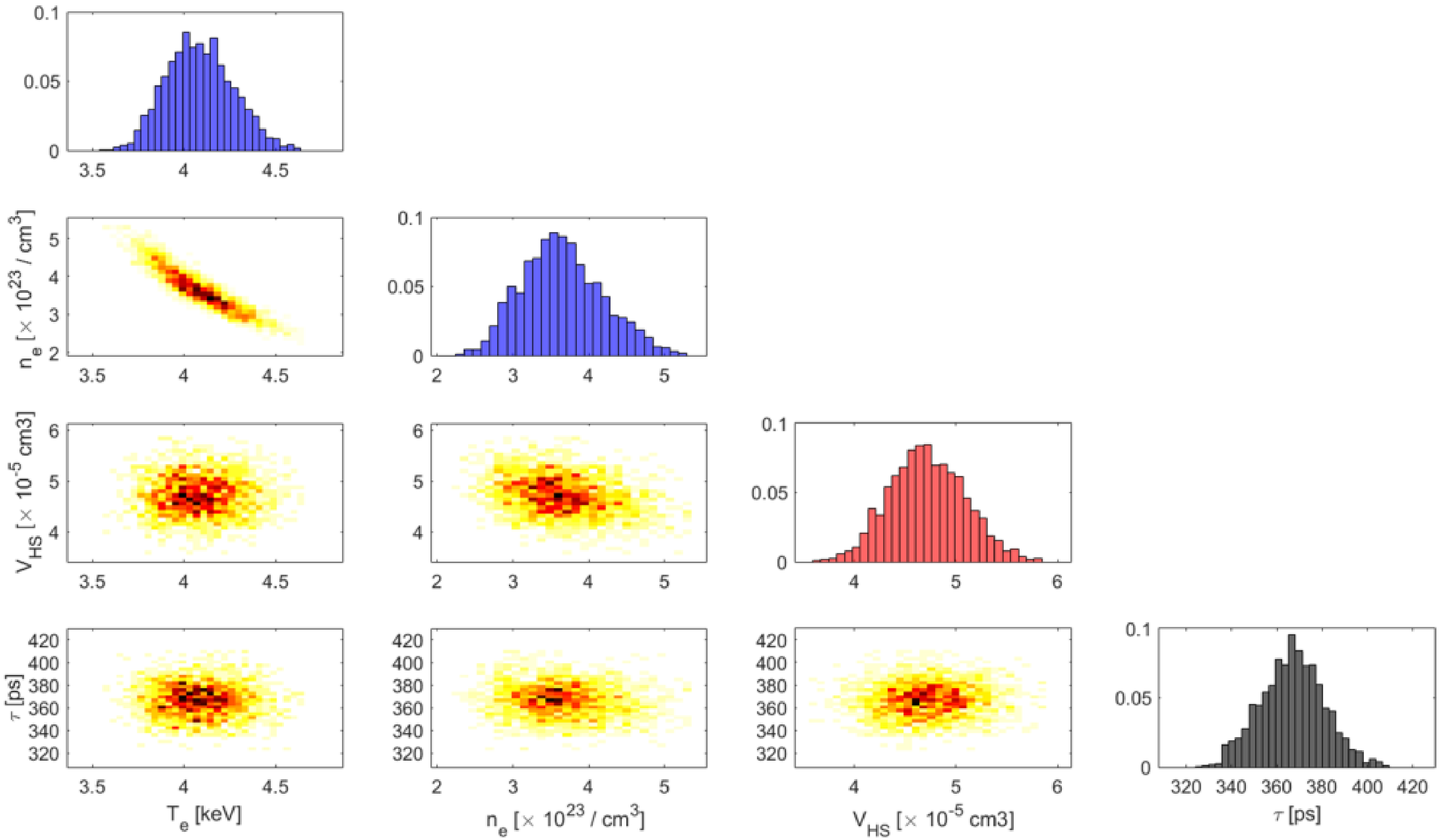
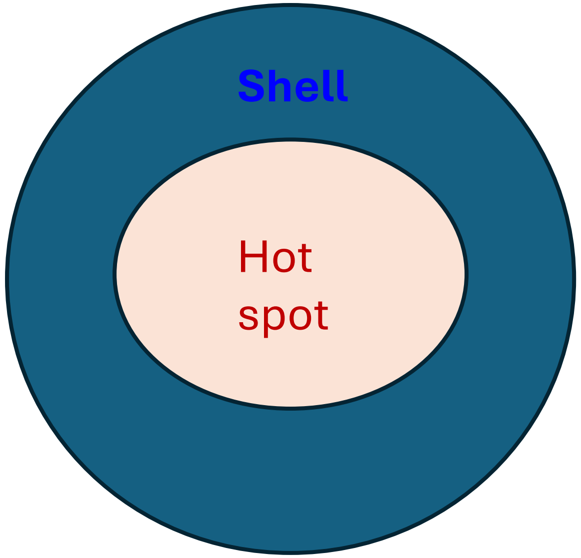


FIG. 3. Probability distribution of n_e, T_e, V_{HS}, and τ that best fit the x-ray penumbral imaging measurements from implosion N200211-003. The diagonal plots display the marginal probability distributions for the four parameters, while the off-diagonal plots show the bi-variate distributions.

A 3D proton tracing model computed the energy loss of D3He-p as they escaped the hot-spot and remaining shell and sampled the uncertainty in n_e , T_e , and V_{HS}



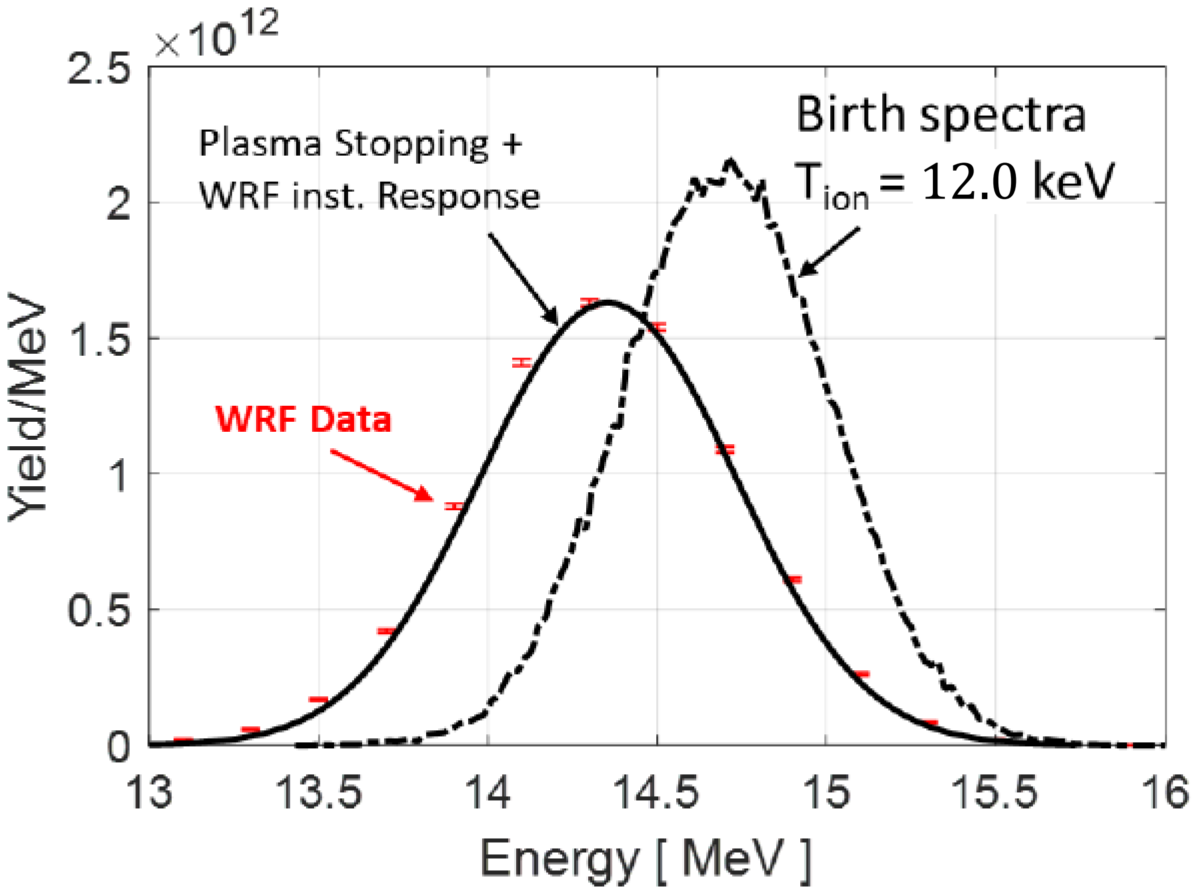
$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{v}_i \delta t + (1/2)\mathbf{a}_i \delta t^2$$

$$\mathbf{v}_{i+1} = \mathbf{v}_i + \mathbf{a}_i \delta t,$$

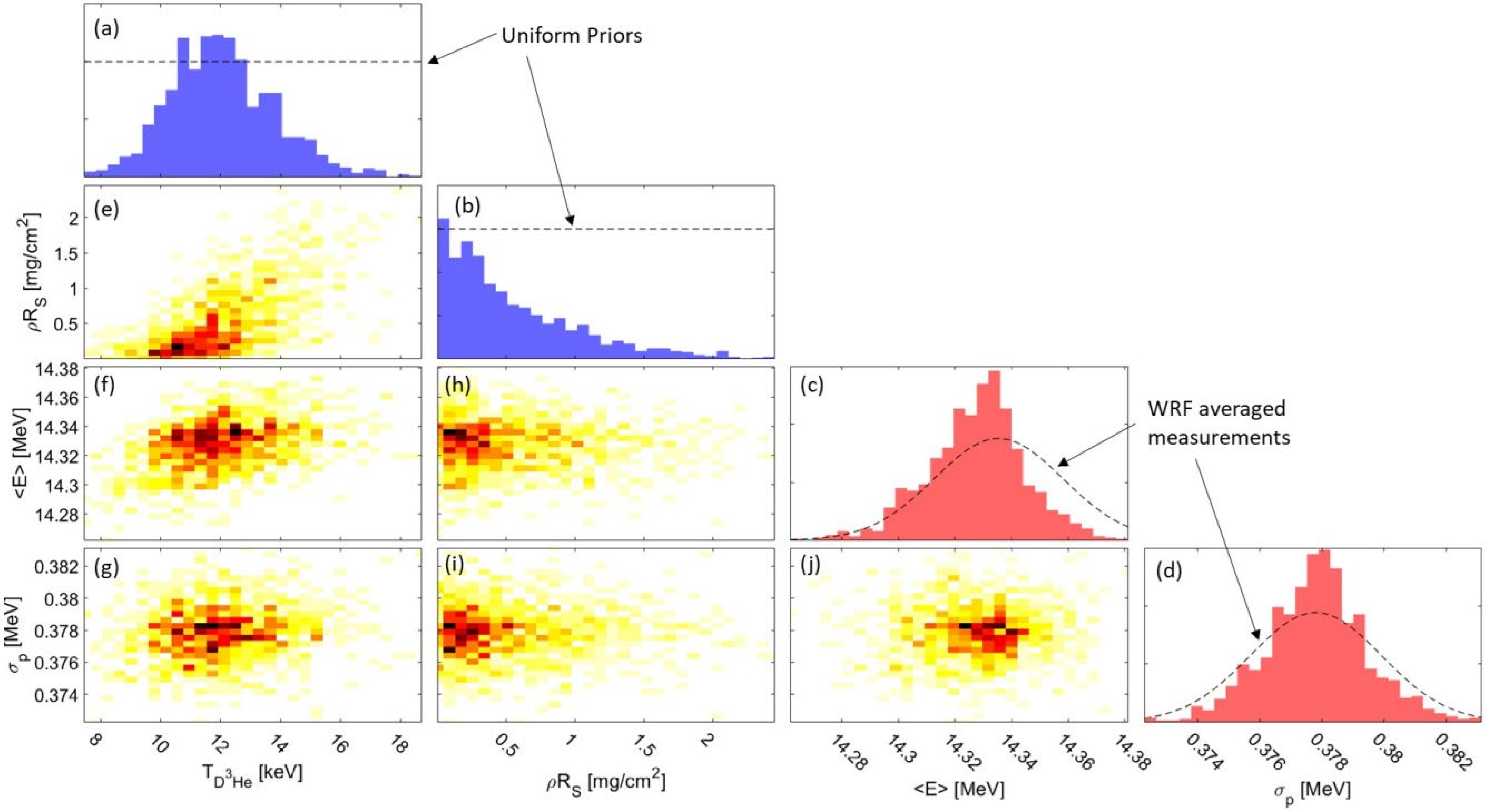
$$\mathbf{a}_i = \frac{1}{m_p} \frac{\mathbf{v}}{|\mathbf{v}|} \frac{dE}{dx}(E_i, n_e, T_e).$$

The protons were sourced with different T_{D3He}

$$\langle E \rangle_B = 14.630 + 3.02 \times 10^{-2} (T_{D^3He}/5)^{0.744} \text{ [MeV]}$$
$$\sigma_B = 172.31 (T_{D^3He}/5)^{0.503} \text{ [keV]}. \quad (7)$$



The 3D model computed $< E >$ and σ_P by varying the n_e , T_e , and V_{HS} of the hot spot as well as the T_{D3He} and ρR_{shell} to fit he WRF measurements



Update

The x-ray penumbral imaging data enabled us to constrain the broadening associated with energy loss of the D3He-protons

$$T_{WRF} = \underbrace{\frac{(m_{3He}\, T_{3He} + m_D\, T_{DD})}{m_D + m_{3He}} + T_{flows}}_{T_{D3He} \,=\, 12.0 \pm 1.8\ \text{keV}} + T_{dE/dx}\underset{\overset{\uparrow}{\approx\ 7\ \text{keV}}}{(T_e, n_e, V_{HS})}$$

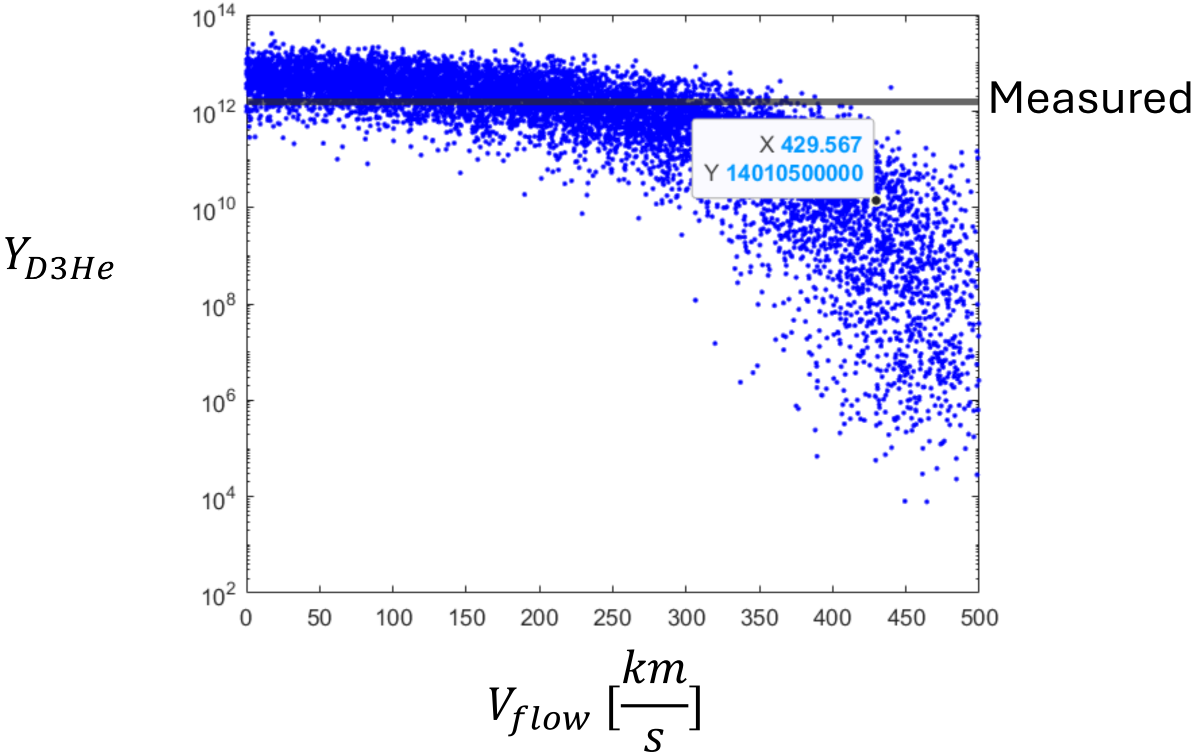
Flows were constrained by examining the yield degradation of D3He

$$Y_{D^3He} \propto N_D N_{^3He} \langle \sigma v(T_{D^3He}) \rangle V_{HS}^{-1} \tau \qquad (10)$$

Know from fill

Measured

Measured (SPIDER)

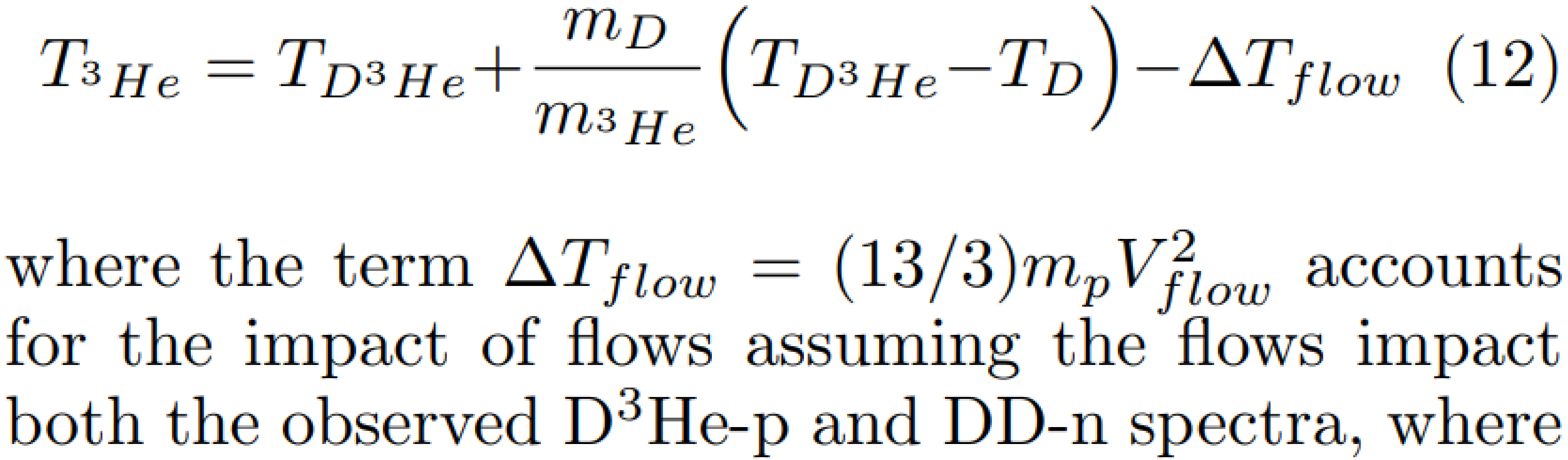


Profile effect also impact yield

Assume V_{flow} is equally likely from 0 to ~320 km/s

Summary

Integrated analysis of NID DS experiments demonstrated T_{3He} = 12.4 $\pm$ 3.2 keV



$$T_{^3He} = T_{D^3He} + \frac{m_D}{m_{^3He}}\left(T_{D^3He} - T_D\right) - \Delta T_{flow} \quad (12)$$

where the term $\Delta T_{flow} = (13/3) m_p V_{flow}^2$ accounts for the impact of flows assuming the flows impact both the observed D^{3}He-p and DD-n spectra, where

T_{D3He} = 12.0 ± 1.8 keV

T_{DD} = 9.32 ± 0.18 keV

$v_{flow} = 0\text{–}320$ km/s

$$T_{3He} = 12.4 \pm 3.2\ keV$$

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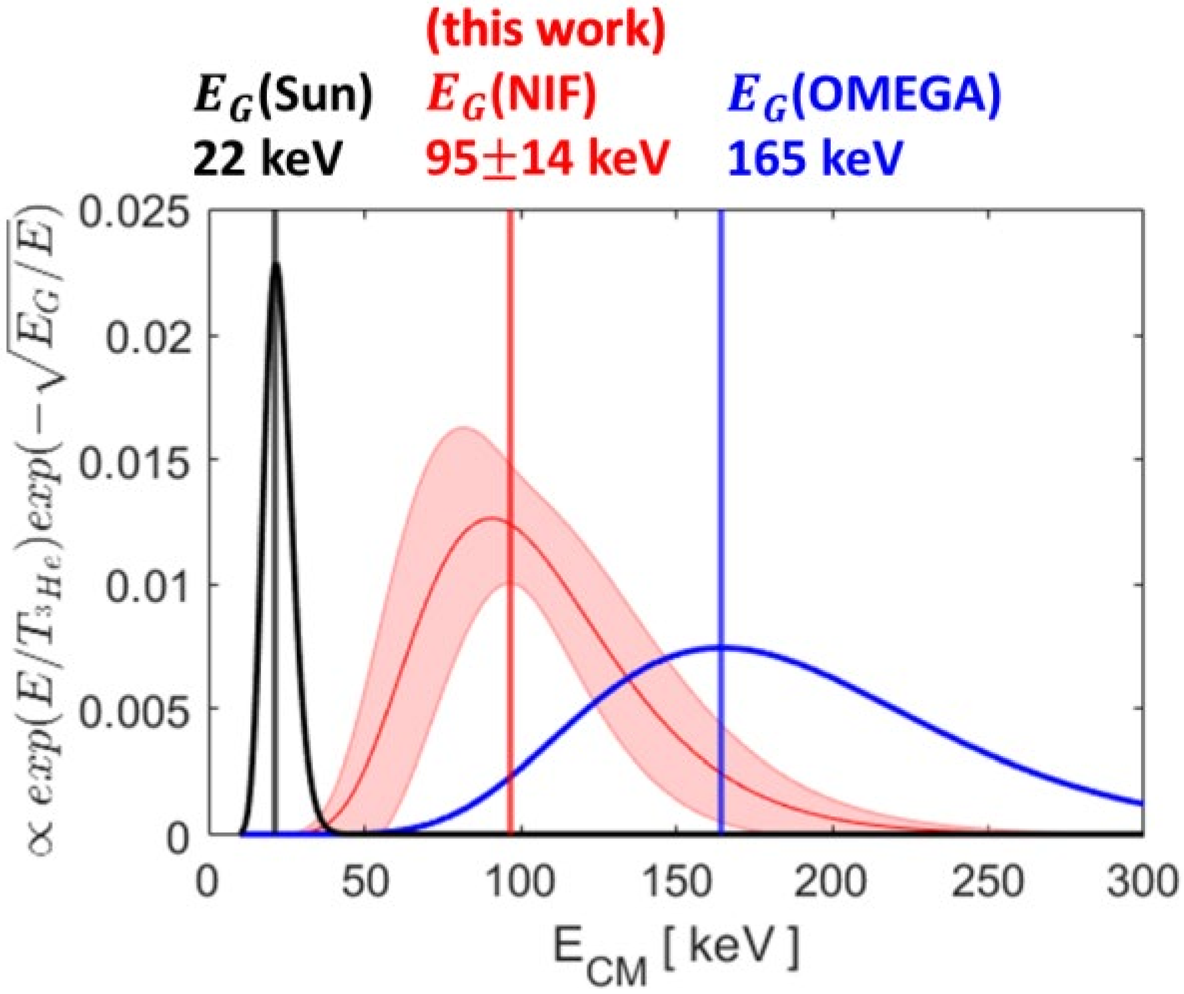


Gamow Energy was corrected for :

Stopping power of D3He-p ~30% effect

Flows ~20% effect

Future Work

Temperature / Gamow Peak Analysis:

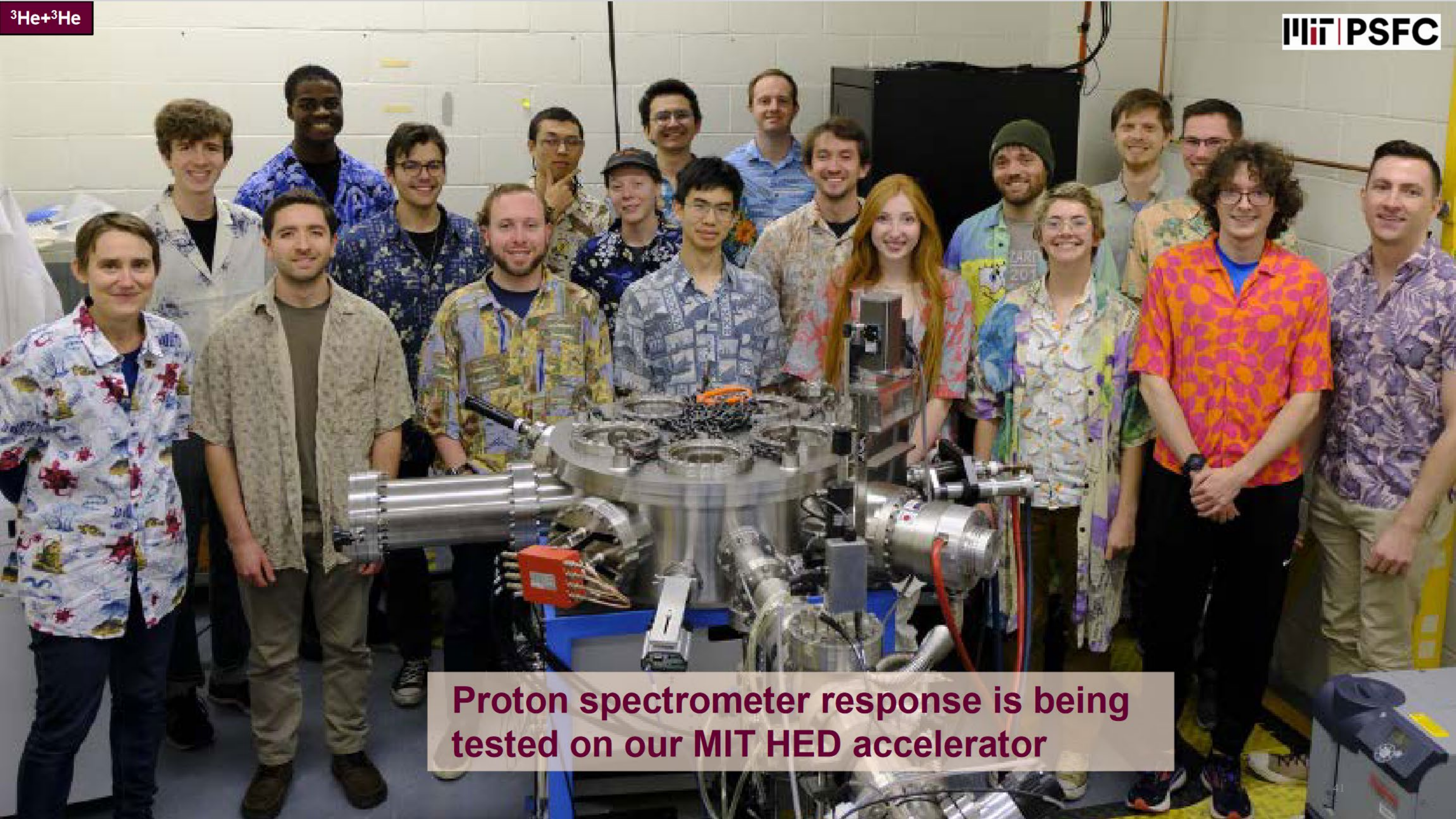
1. a full 3-dimensional (3D) reconstruction of the x-ray emission region can be done to constrain the plasma volume

2. a full Bayesian error analysis including the uncertainties of the x-ray image reconstruction process, profile inference, and proton tracing model would better explore the complex relationships between the data and model

^{3}He+ ^{3}He proton spectrum:

1. Proton spectrum is under active analysis

2. Issues were encountered due to the short distances from detector to impolosion



Proton spectrometer response is being tested on our MIT HED accelerator

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