Thermonuclear reactions probed at stellar core conditions with laser-based inertial fusion

NIF User Group Meeting
Feb 11th 2025

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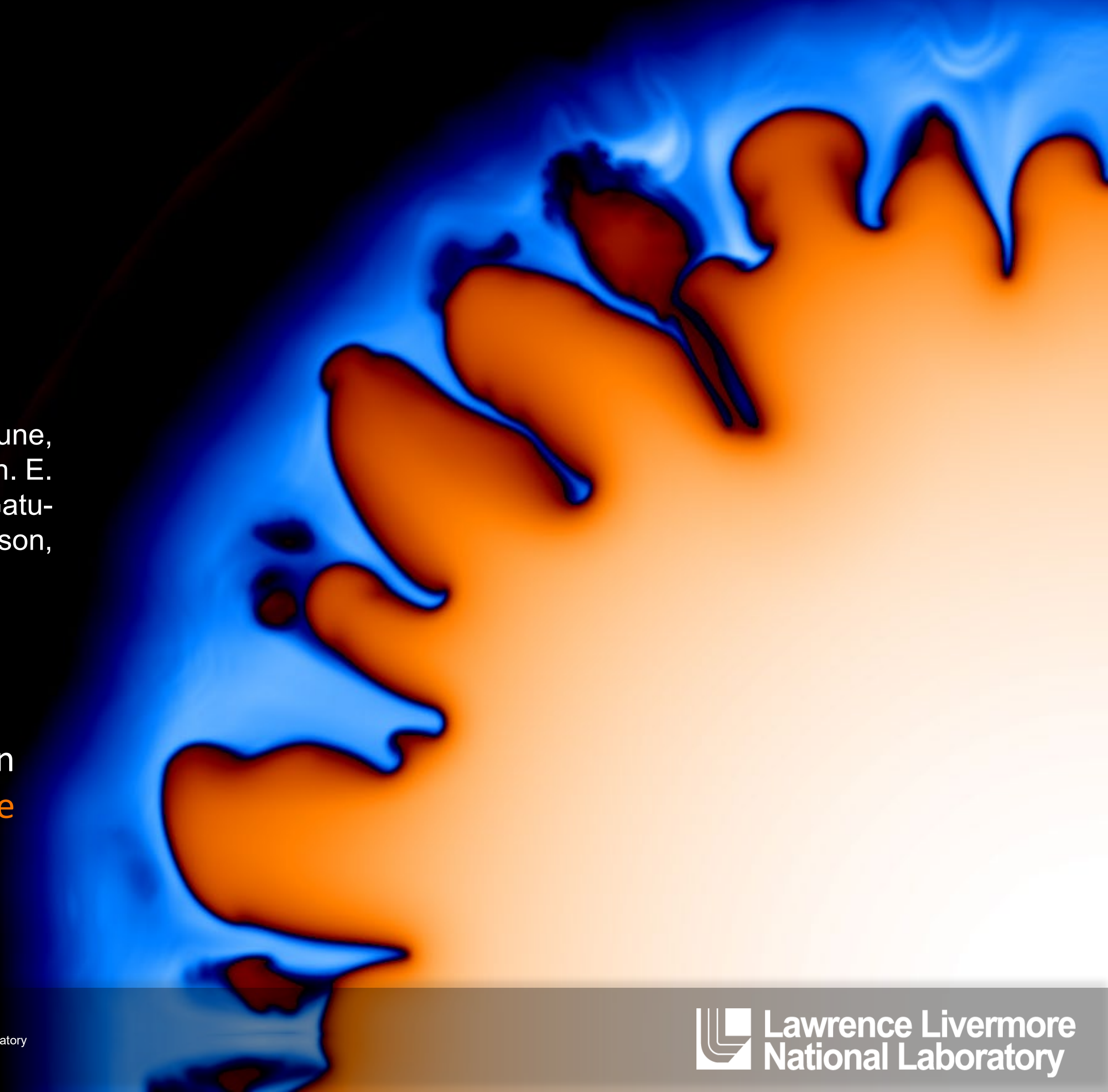


Simulated implosion
density and temperature

LLNL-PRES-774339
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

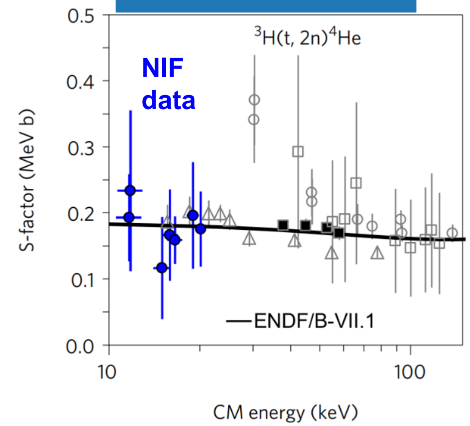
Summary

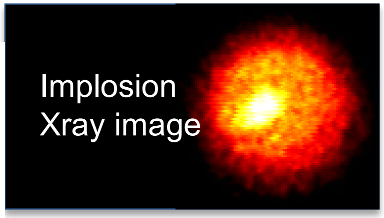
We have performed thermonuclear cross-section measurements at stellar-like conditions for the DD, DT, and D3He reactions

- ICF implosions are complex but can nonetheless be used for nuclear astrophysics
- These measurements are enabling more ambitious measurements in where reaction rates are different in a plasma via terrestrial and plasma screening
- Recent experiments show a path the plasma screening relevant regime but significant challenges remain

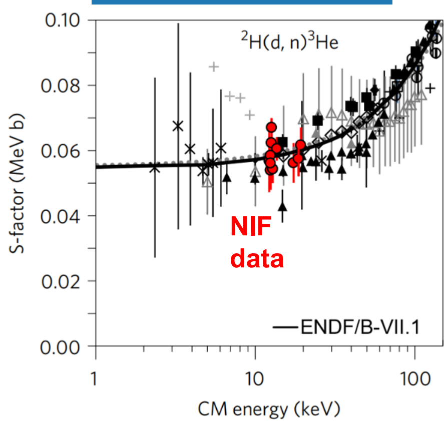
We have made multiple reaction rate measurements and are working toward screening

D+D NIF Sfactor

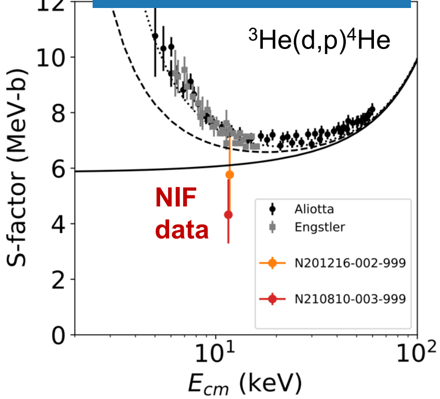




T+T NIF Sfactor

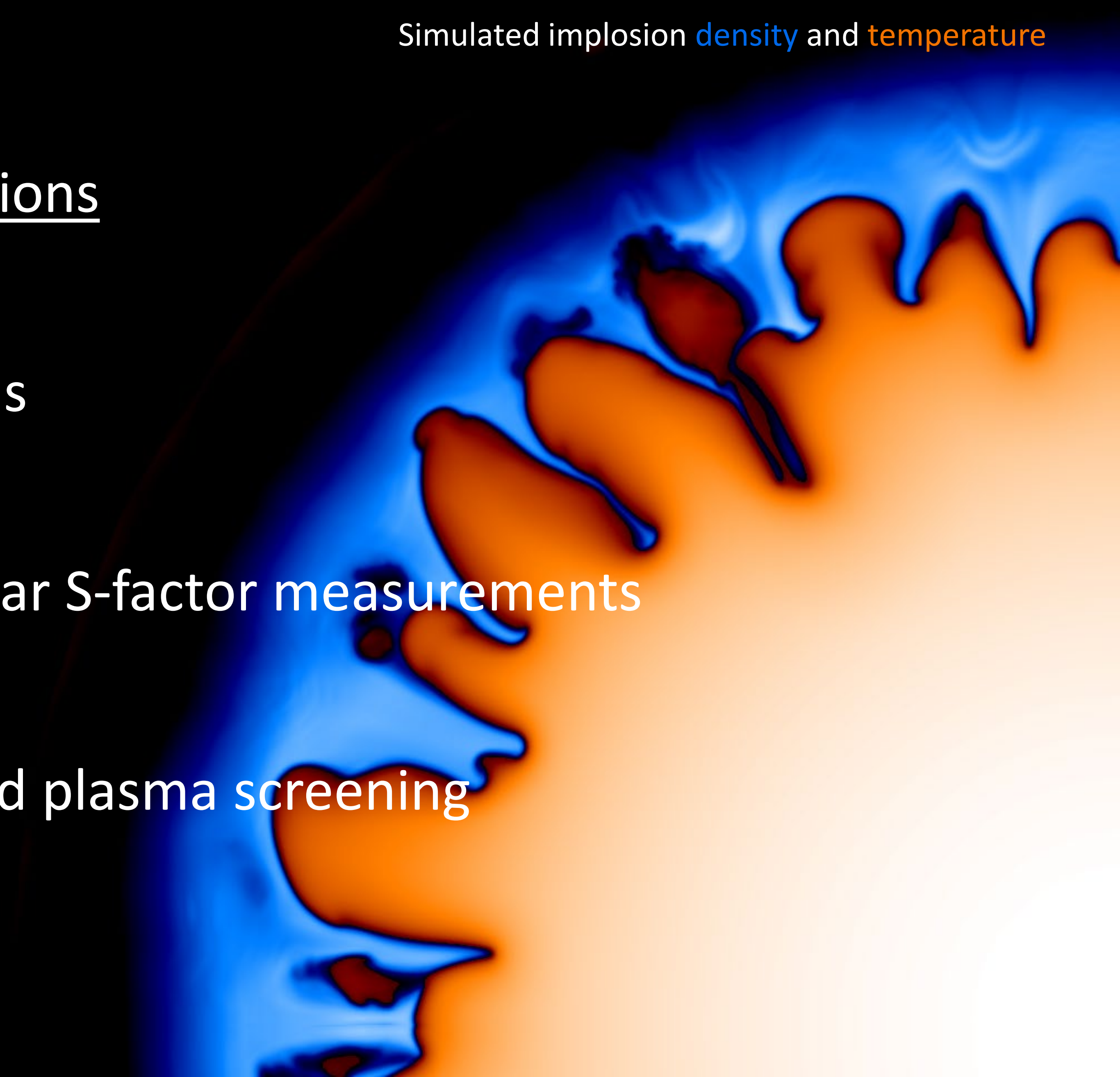


Screening and D+^{3}He NIF Sfactor



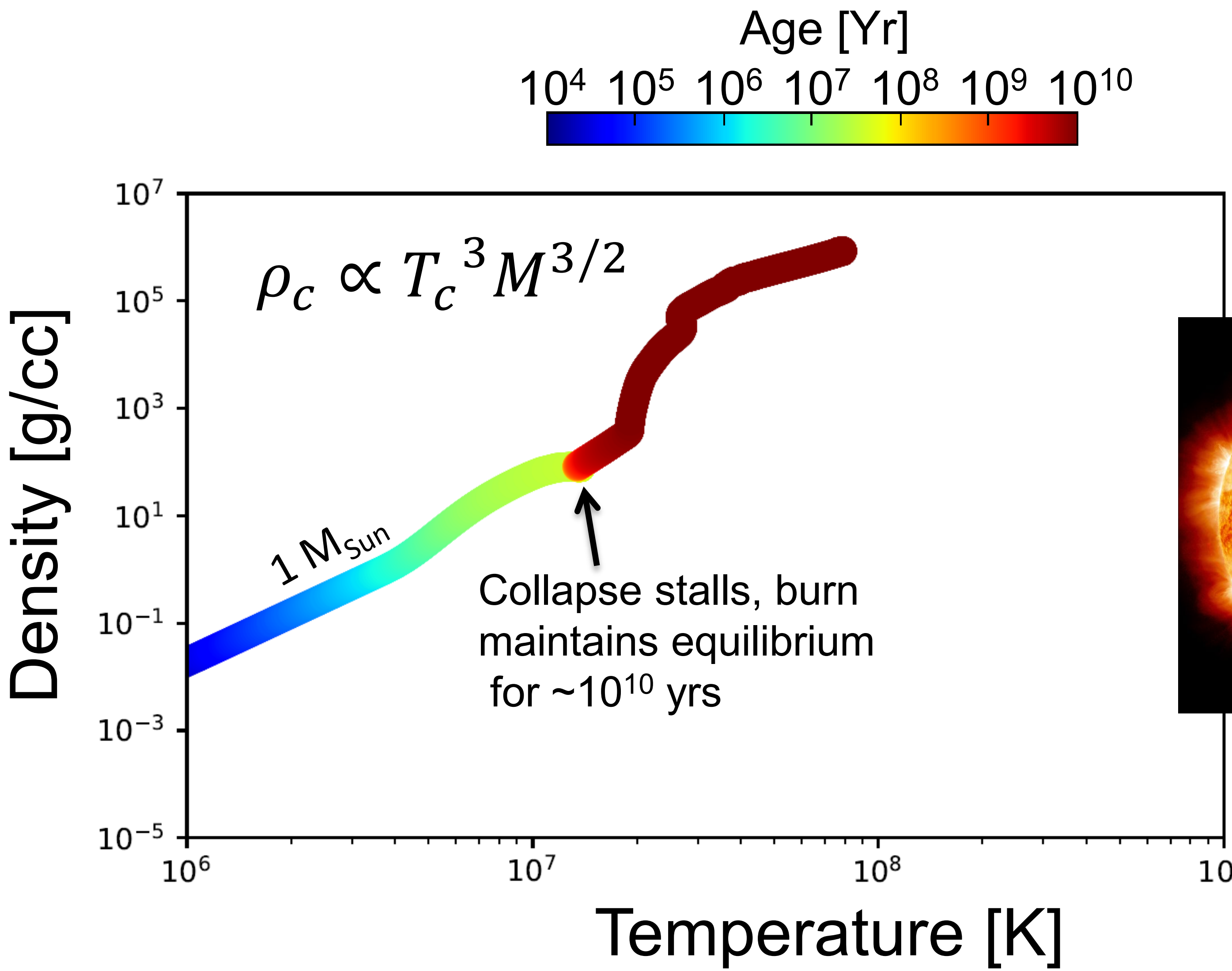
Outline

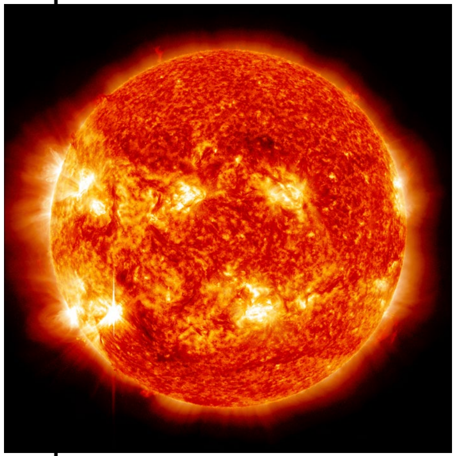
- Stellar conditions
- ICF implosions
- Thermonuclear S-factor measurements
- Terrestrial and plasma screening



Simulated implosion density and temperature

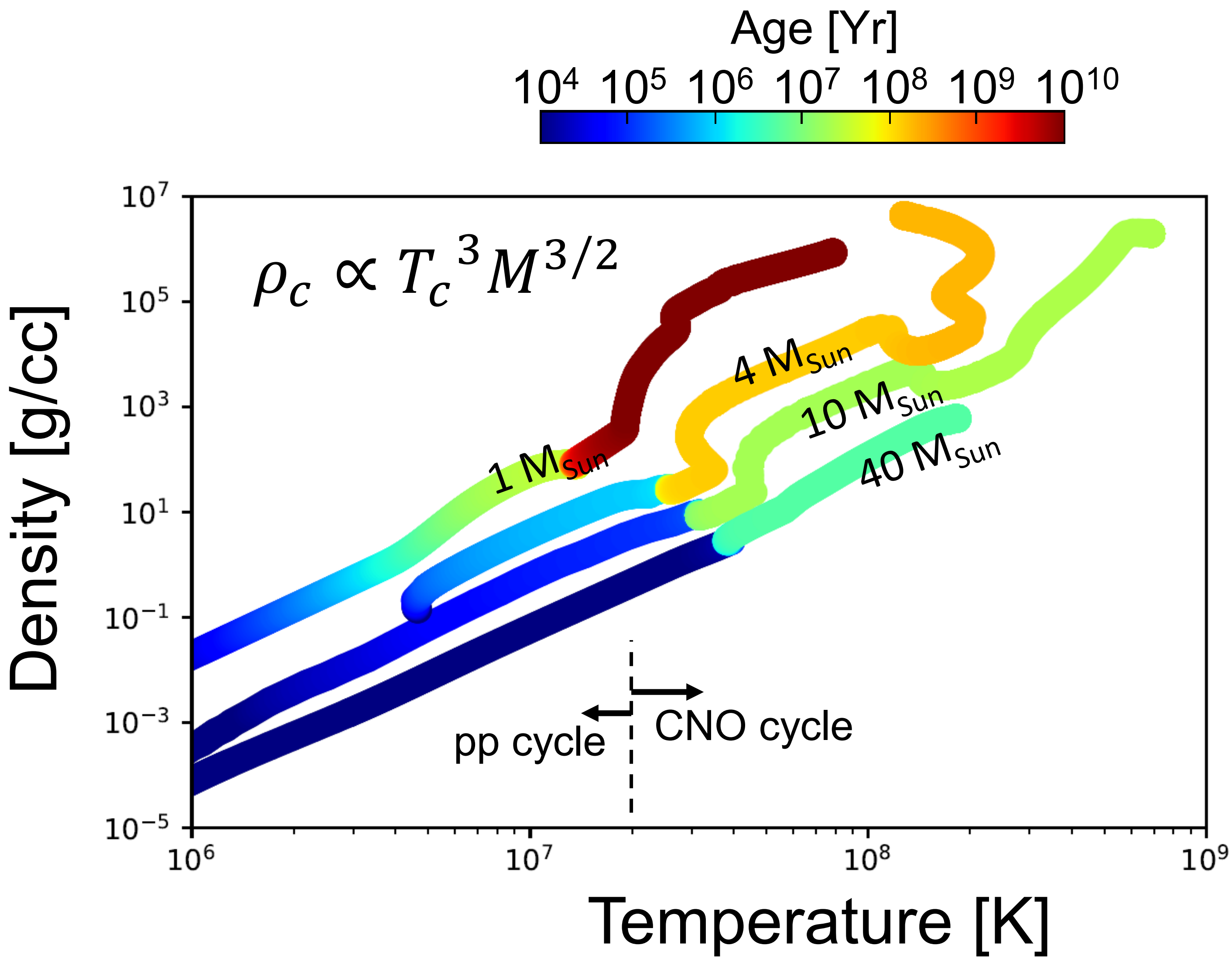
The Sun will spend most of its life burning hydrogen





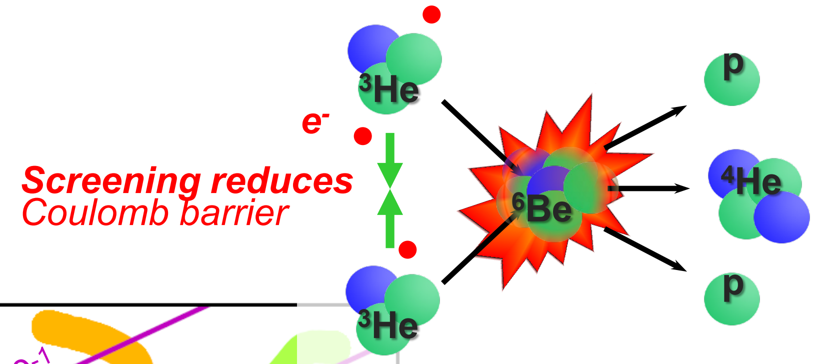
NASA/SDO

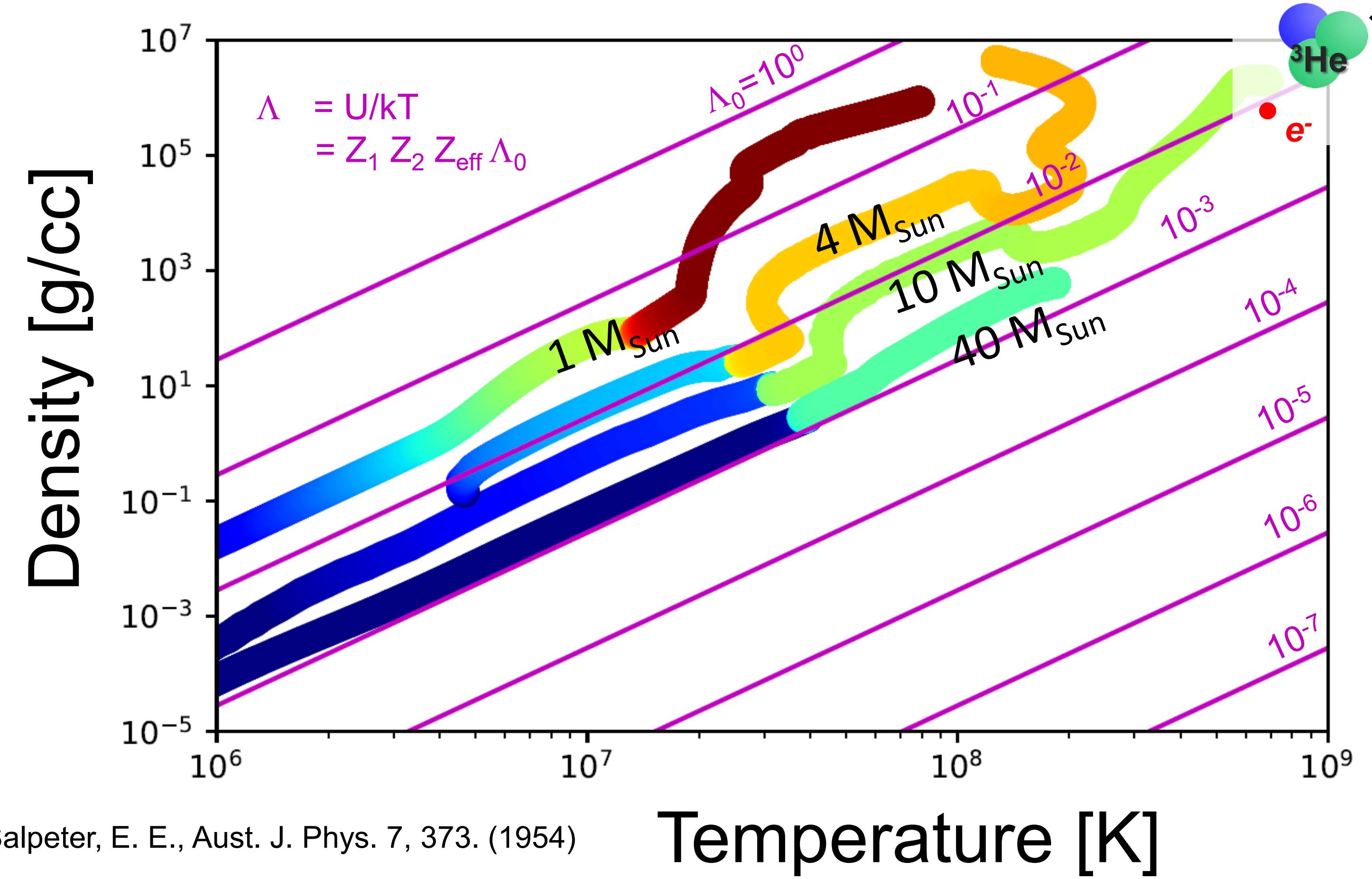
Bigger stars burn hotter and faster



The presence of plasma electrons can shield the Coulomb barrier and enhance reaction rates dependent on the plasma conditions

$$\frac{\sigma_{Screened}(E)}{\sigma(E)} \approx e^{Z_1 Z_2 \tilde{z} \Lambda_0} \approx e^{\frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 T \lambda_D}}$$

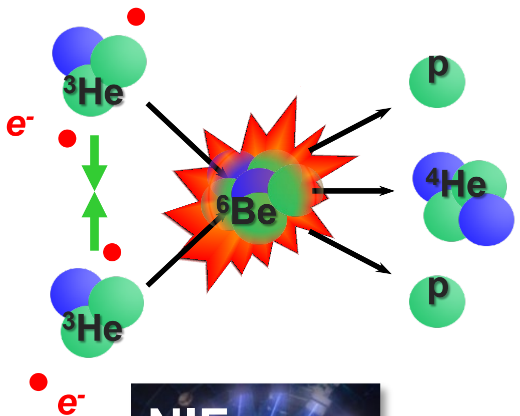


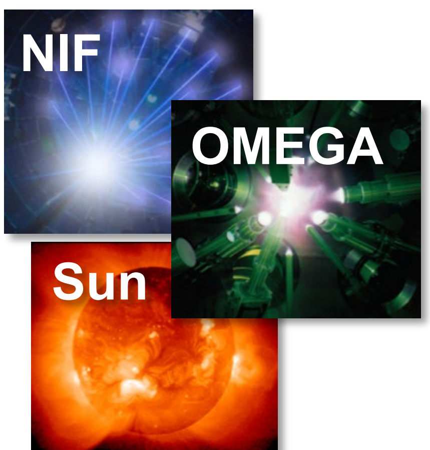


*Salpeter, E. E., Aust. J. Phys. 7, 373. (1954)

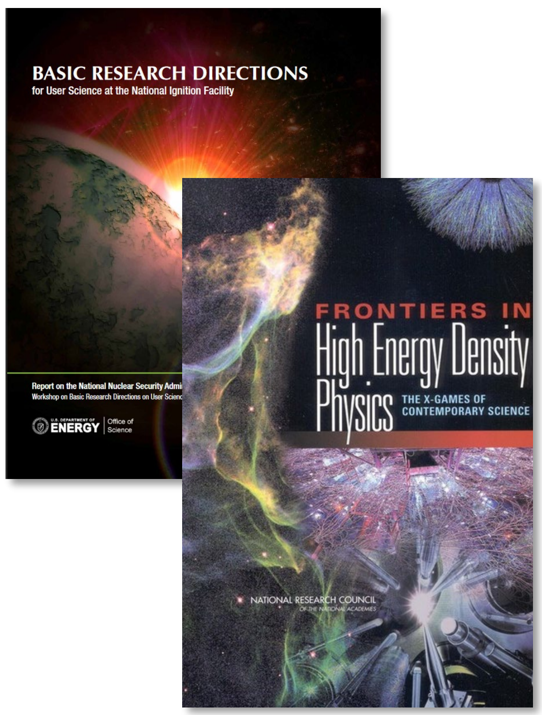
We are interested in studying both "terrestrial" screening and "plasma" screening

Plasma screening

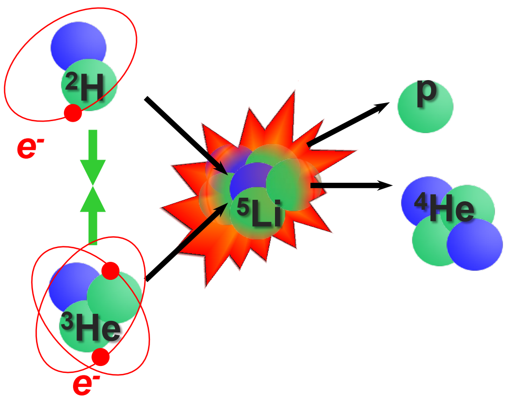




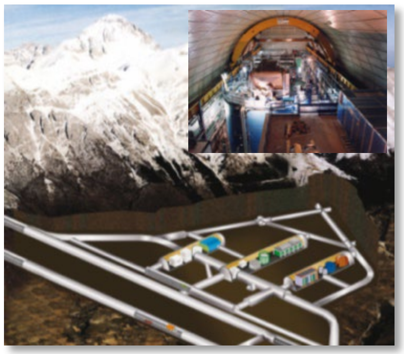
For decades Screening has been identified as a priority for HED



Plasma screening

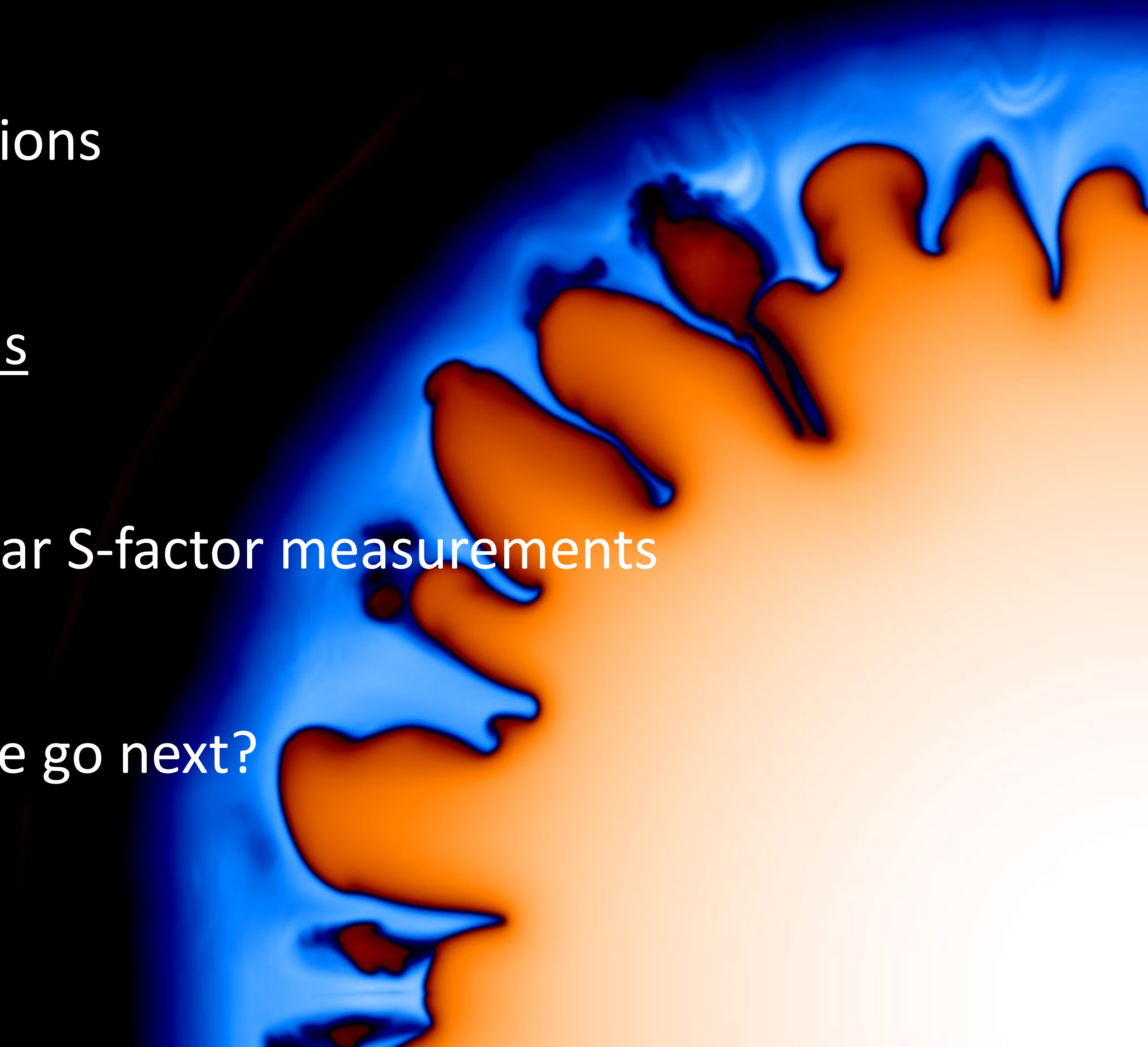


Accelerator experiments



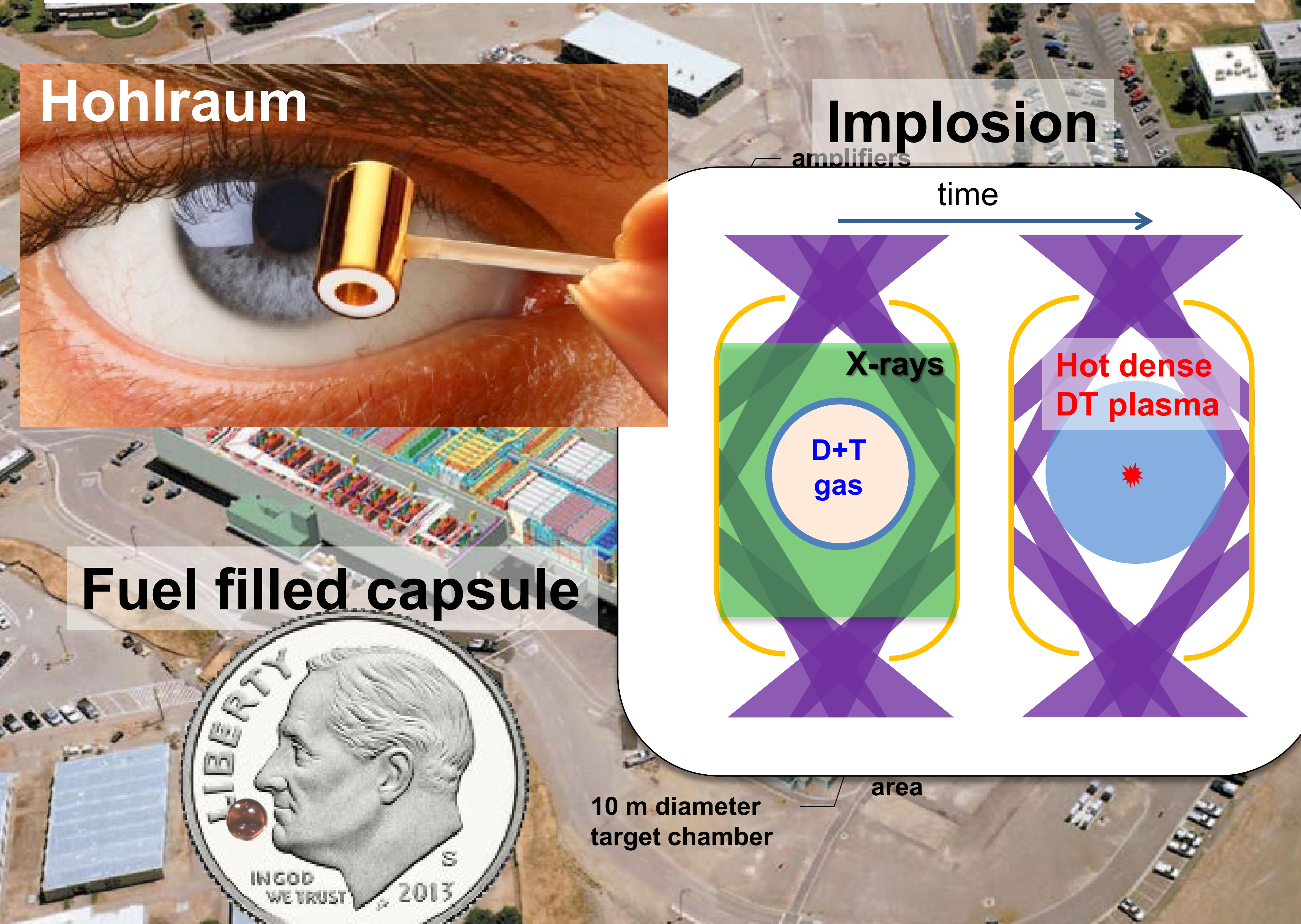
Outline

- Stellar conditions
- ICF implosions
- Thermonuclear S-factor measurements
- Where can we go next?

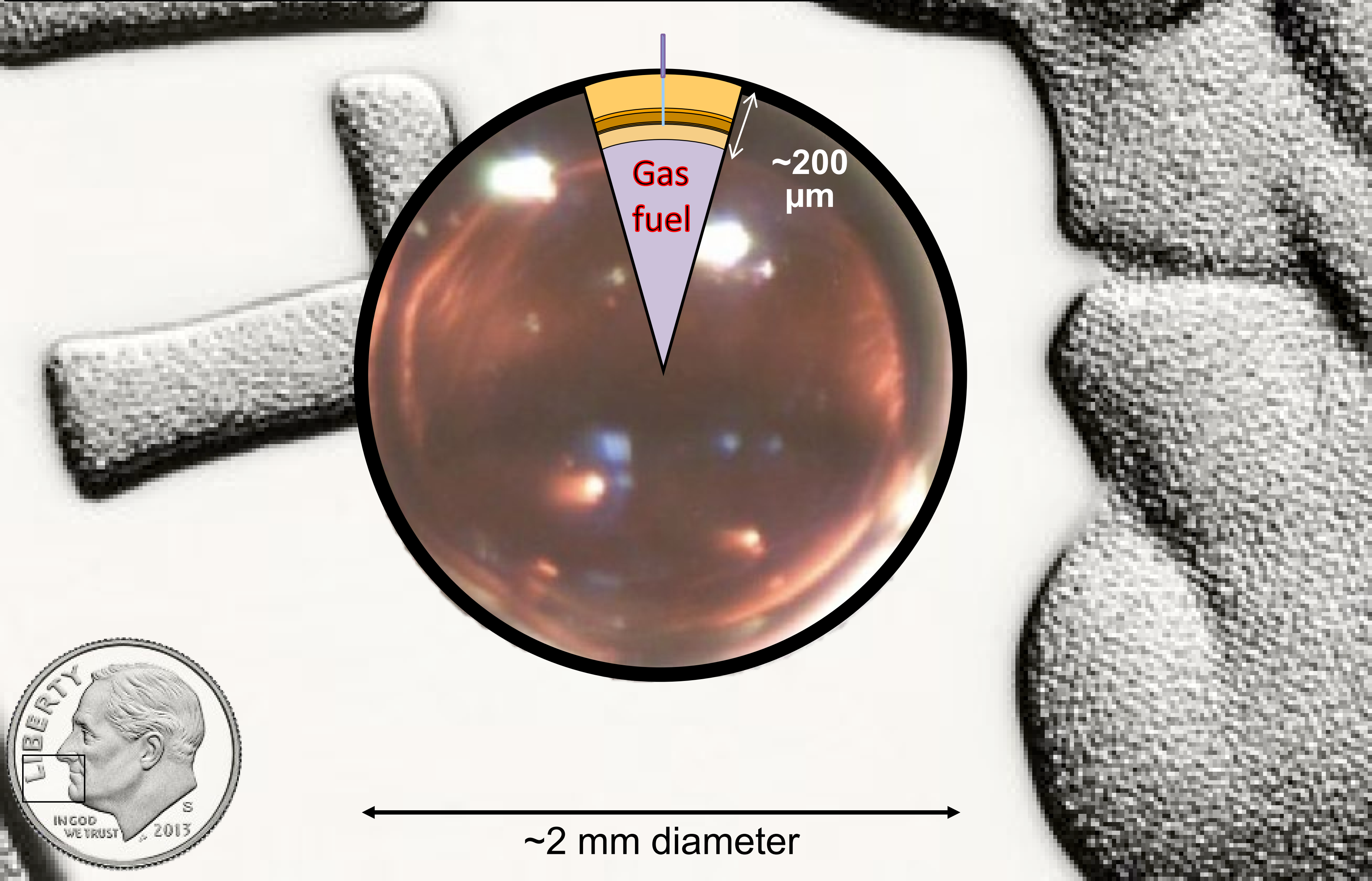


Simulated implosion density and temperature

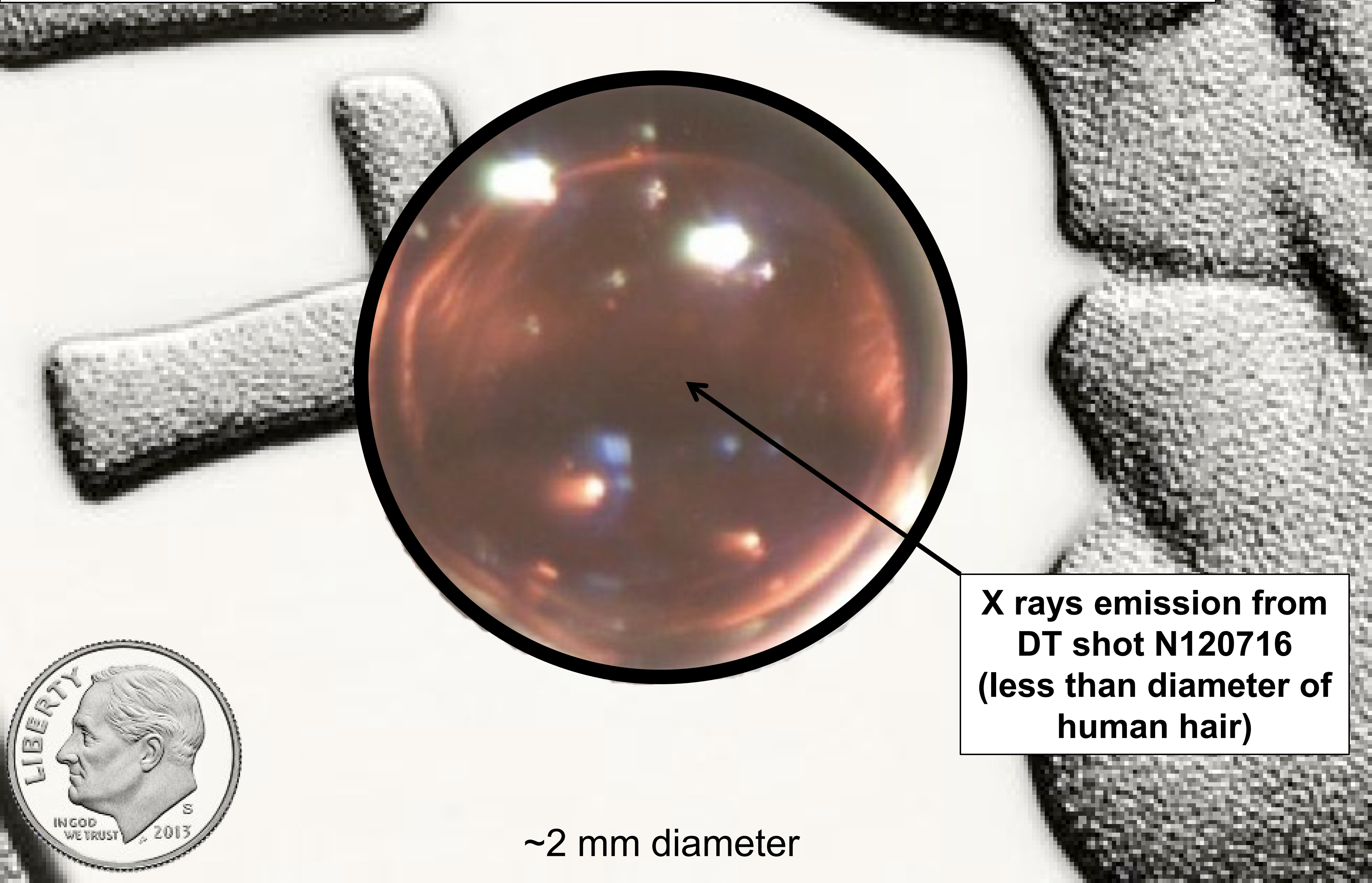
We use gas-filled “symcap” targets with E_{laser} = 0.8-1.5MJ



ICF capsules are shells of CH, HDC, or Be



Spherical convergence of ~35X can produce hotspot pressures of >>100 Gbar



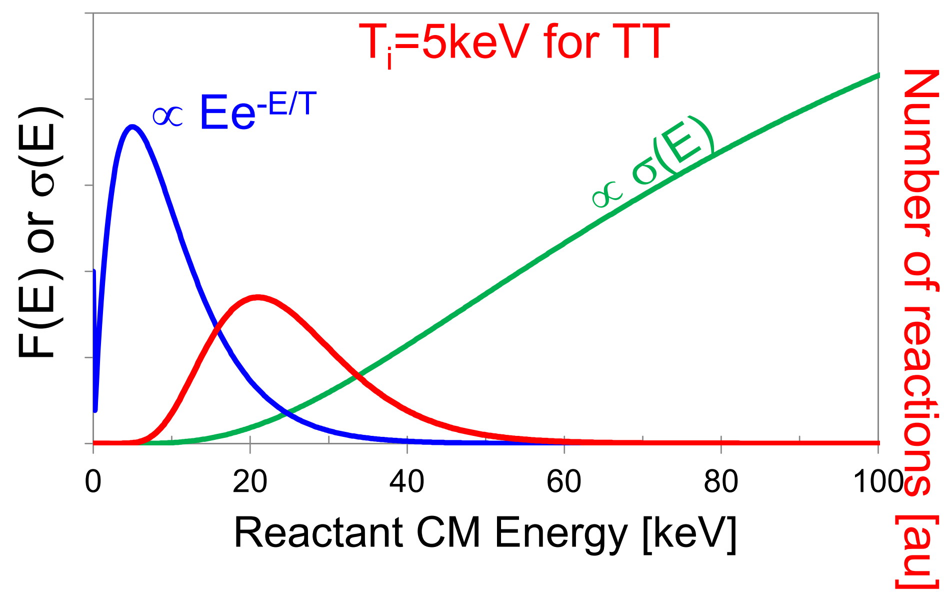
The reaction yield can be expressed in terms of the <σv> or the Maxwellian averaged reactivity

$$Y_{12} = \int \frac{f_1 f_2}{1+\delta_{12}} \frac{\rho(\vec{r},t)^2}{\bar{m}^2} \langle \sigma v \rangle_{12} \, d\vec{r} \, dt$$

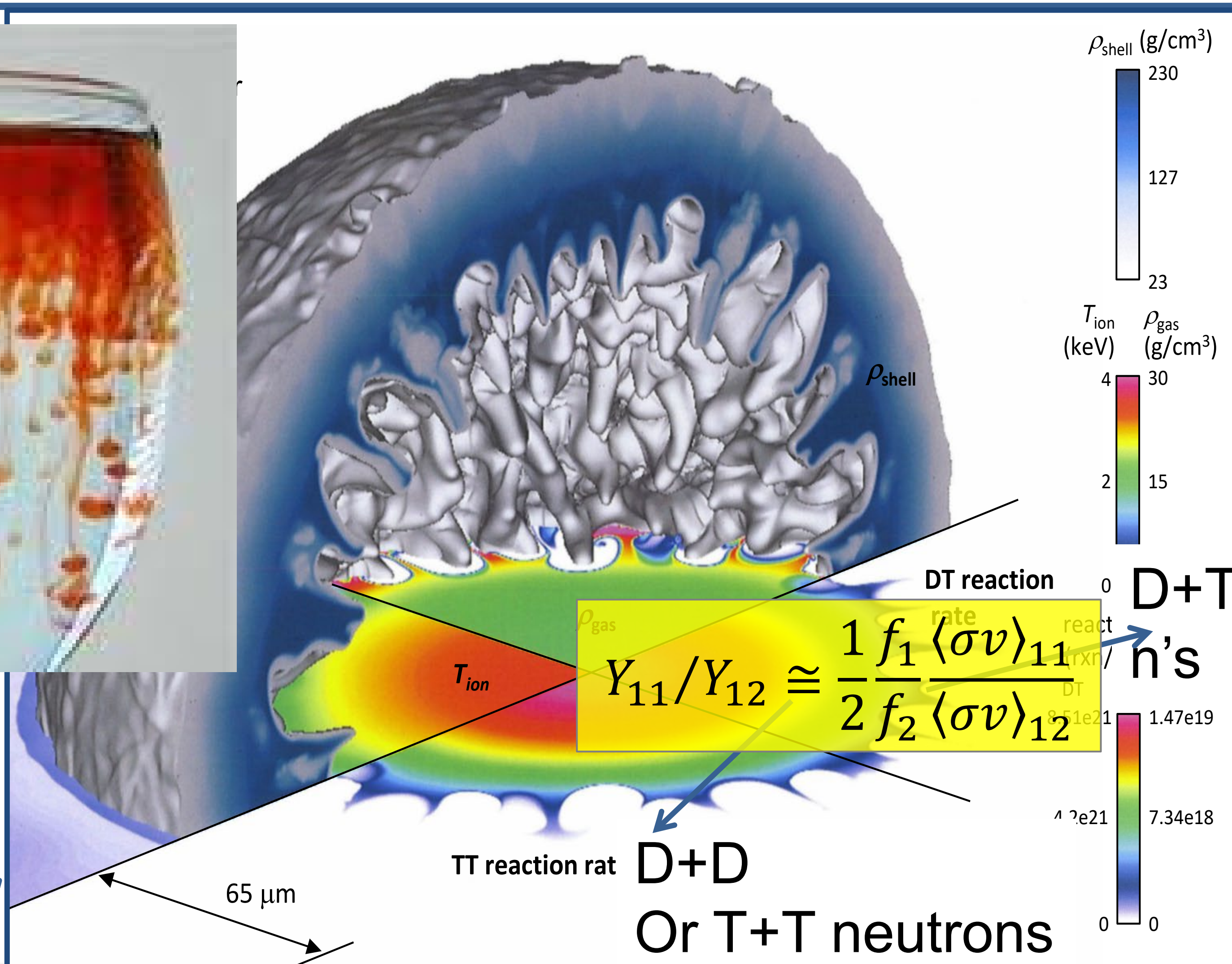
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \, m_r}} \frac{1}{T^{3/2}} \int_0^\infty \boldsymbol{\sigma(E)} \, \boldsymbol{E} \, \boldsymbol{e^{-E/T}} dE$$

For non-resonant reactions:

$$\langle \boldsymbol{\sigma v} \rangle \approx \boldsymbol{S(E_0)} \frac{4}{3} \sqrt{\frac{2\,\tau}{m_r T}} \left(1 + \frac{5}{12\tau}\right) e^{-\tau}$$



However, the yield ratio of two reactions with similar <σv> Ti dependence is independent(!) of detailed Ti($\vec{r}$,t), ni($\vec{r}$,t) profiles



$$Y_{11}/Y_{12} \cong \frac{1}{2}\frac{f_1}{f_2}\frac{\langle\sigma v\rangle_{11}}{\langle\sigma v\rangle_{12}}$$

D+T n's

D+D Or T+T neutrons

Validated by simulation

However, the yield ratio of two reactions with similar <σv> Ti dependence is independent(!) of detailed Ti($\vec{r}$,t), ni($\vec{r}$,t) profiles

$$Y_{12} = \int \frac{f_1 f_2}{1+\delta_{12}} \frac{\rho(\vec{r},t)^2}{\bar{m}^2} \langle\sigma v\rangle_{12}\, d\vec{r}\, dt$$

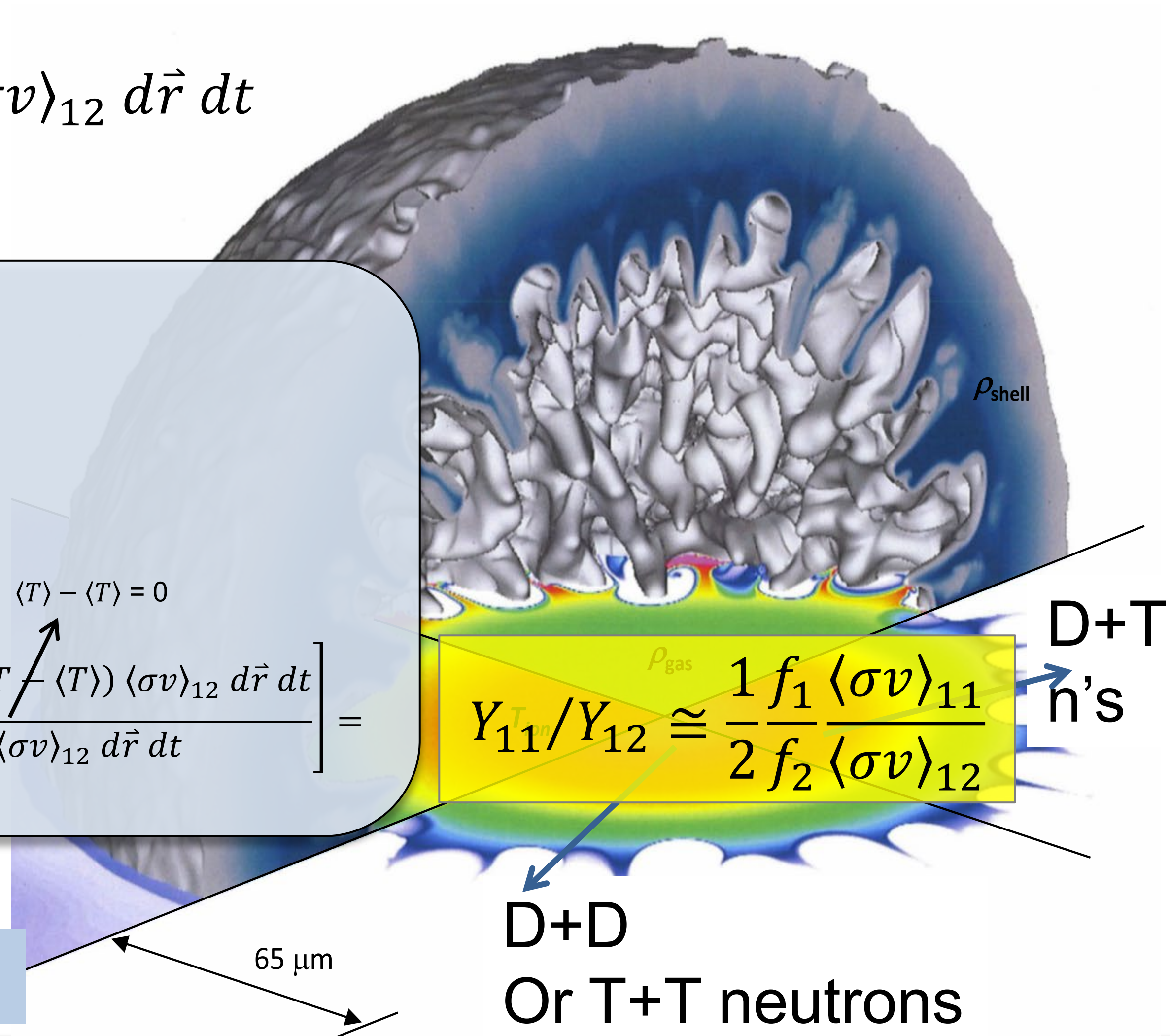
Assume f_1 and f_2 are fixed

Define: $$R = \frac{\langle\sigma v\rangle_{11}}{\langle\sigma v\rangle_{12}}$$

Expand: $$R \approx R_0 + \frac{\partial R}{\partial T}(T - \langle T\rangle)$$

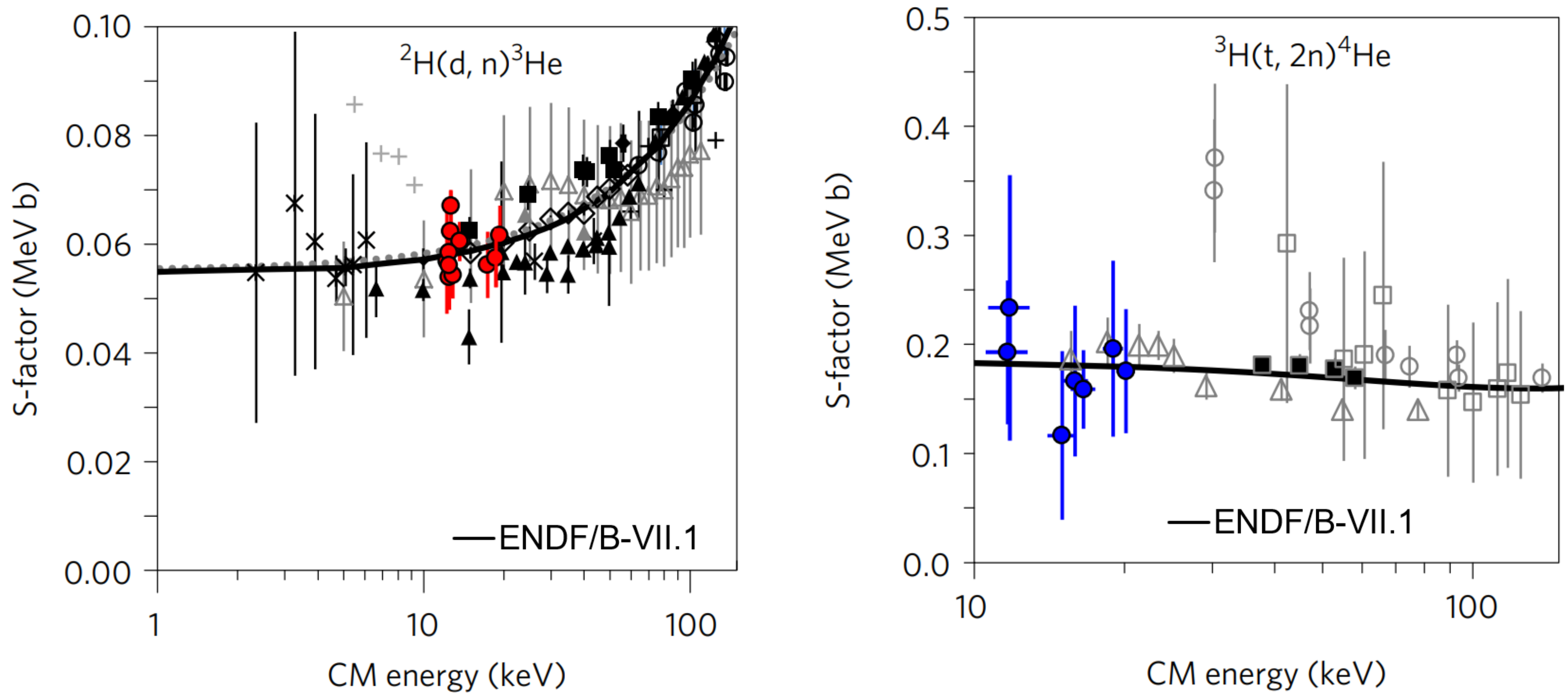
$\langle T\rangle - \langle T\rangle = 0$

$$\frac{Y_{11}}{Y_{12}} = \frac{1}{2}\frac{f_1}{f_2} R_0 \left[1 + \frac{\frac{1}{R_0}\frac{\partial R}{\partial T}\int \rho(\vec{r},t)^2\,(T - \langle T\rangle)\,\langle\sigma v\rangle_{12}\, d\vec{r}\, dt}{\int \rho(\vec{r},t)^2 \langle\sigma v\rangle_{12}\, d\vec{r}\, dt}\right] =$$



Validated by simulation

S-factors for the $^{2}H(d,n)^{3}He$ and $^{3}H(t,2n)^{4}He$ reactions have been measured on the NIF and agree well with accelerator data



D.T. Casey et al, *Nature Physics* **13**, 227–1231 (2017)

Outline

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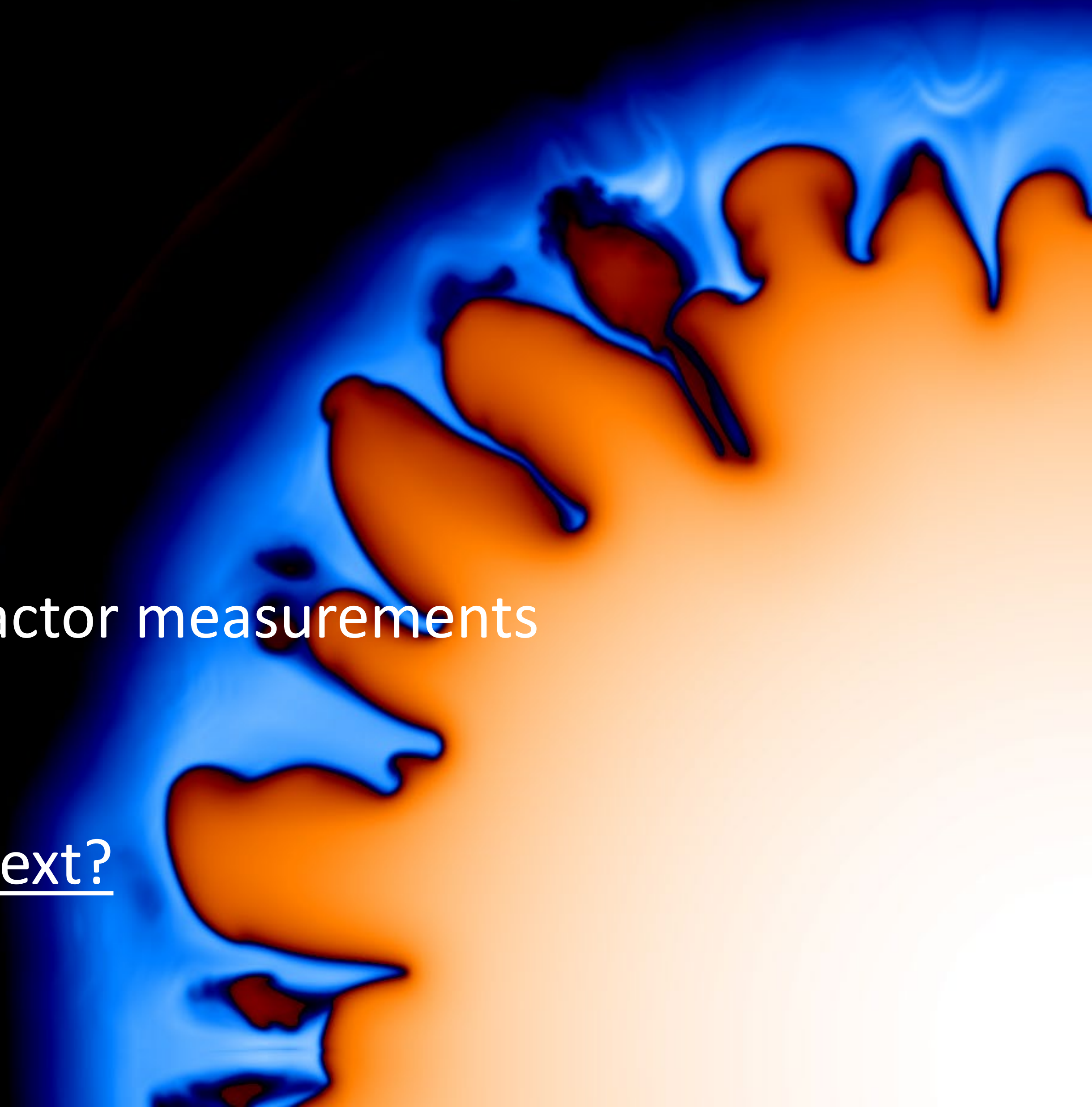

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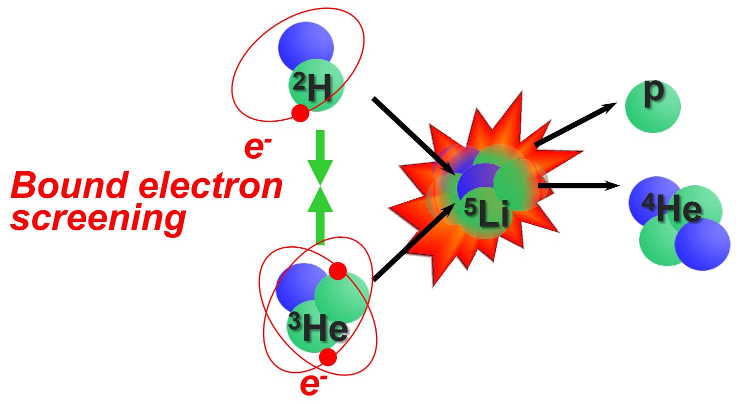
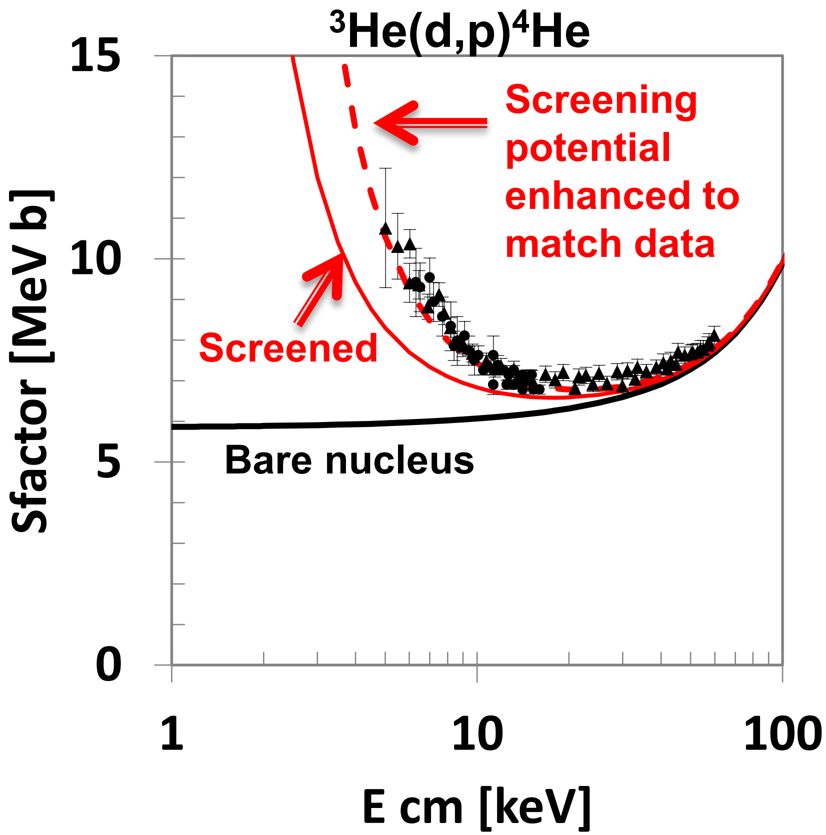
Low energy accelerator experiments are subject to bound electron screening, and discrepancies have been discussed in the literature*



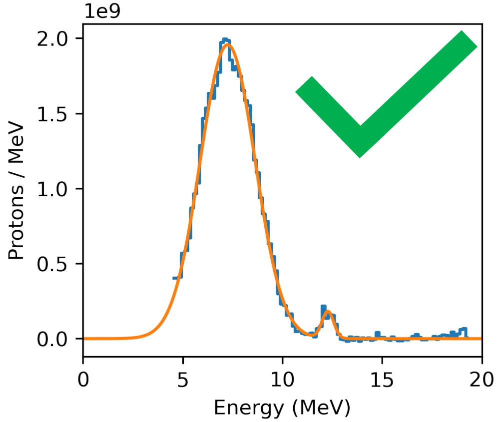


An artificial potential is required to match experiments!

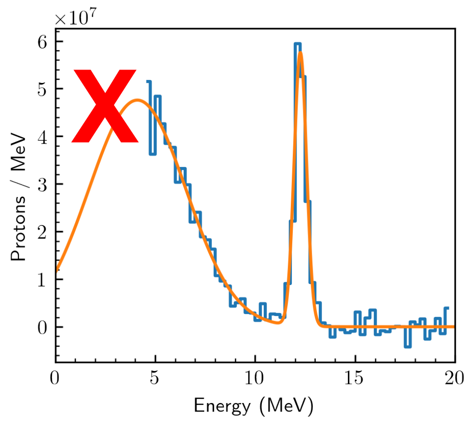
*M. Aliotta *et al.*, Nuclear Physics A 690, 790 (2001).
U. Schröder *et al.*, Nucl. Instr. Meth. B, 40-41, 466 (1989).
H. J. Assenbaum *et al.*, Zeitschrift für Physik A 327, 461 (1987).
M. Barbui, et al., PRL 111, 082502 (2013)

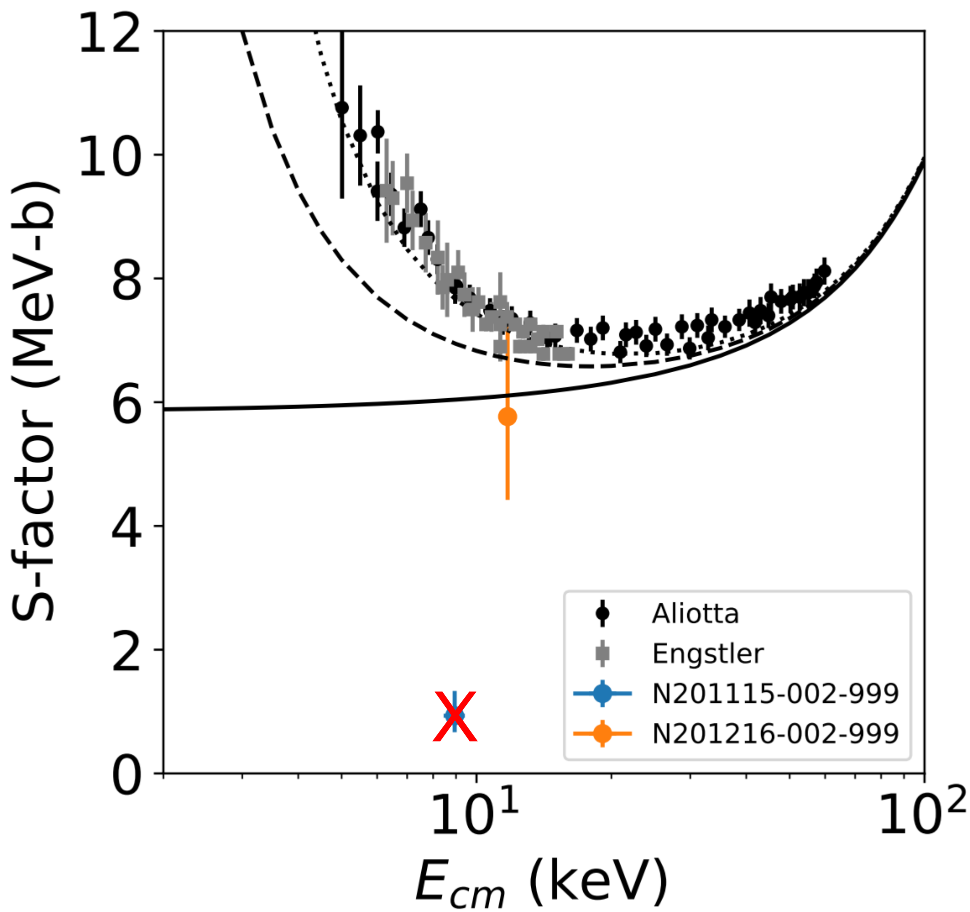
A discovery science campaign was fielded on NIF to measure the bare-nuclear S-factor in the negligible screening regime

N201216 WRF shows clear proton data



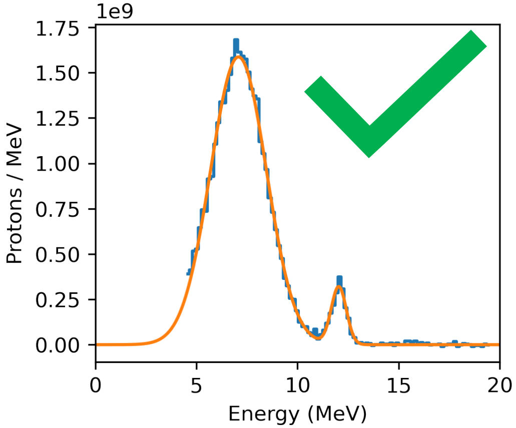
N201216 WRF does not



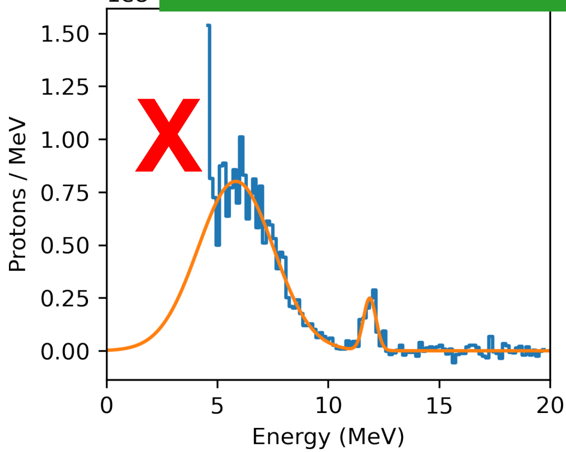


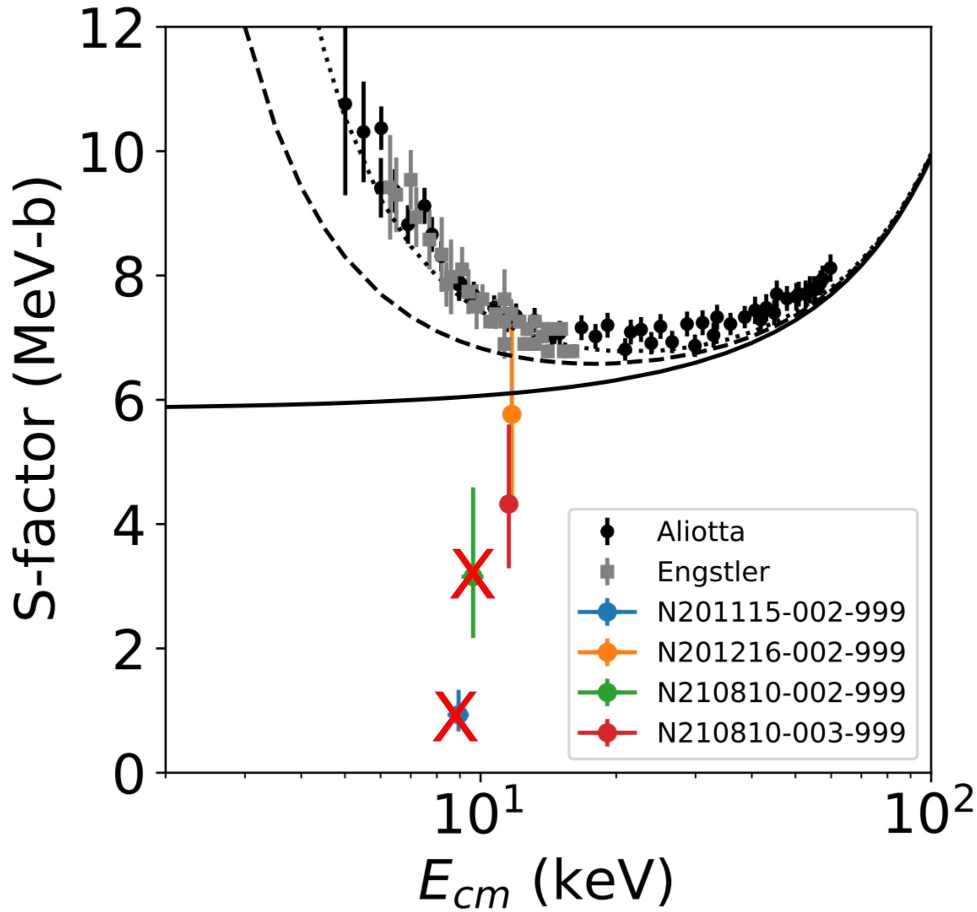
An attempt to repeat the good data was successful, while an attempt to redesign the lower energy point was not

N20810-003 WRF shows clear proton data



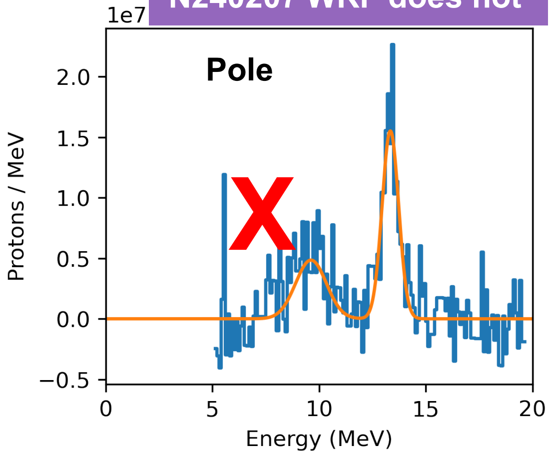
N200810-002 WRF does not



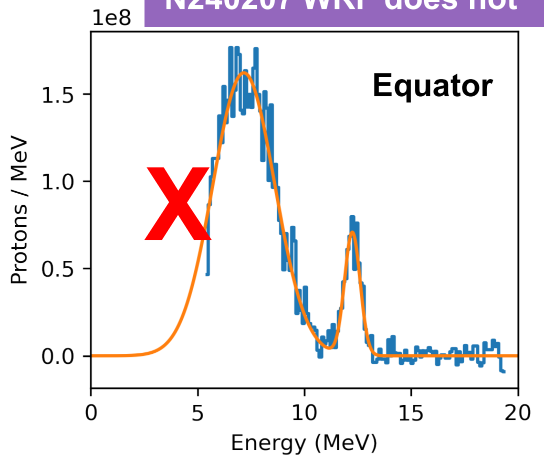


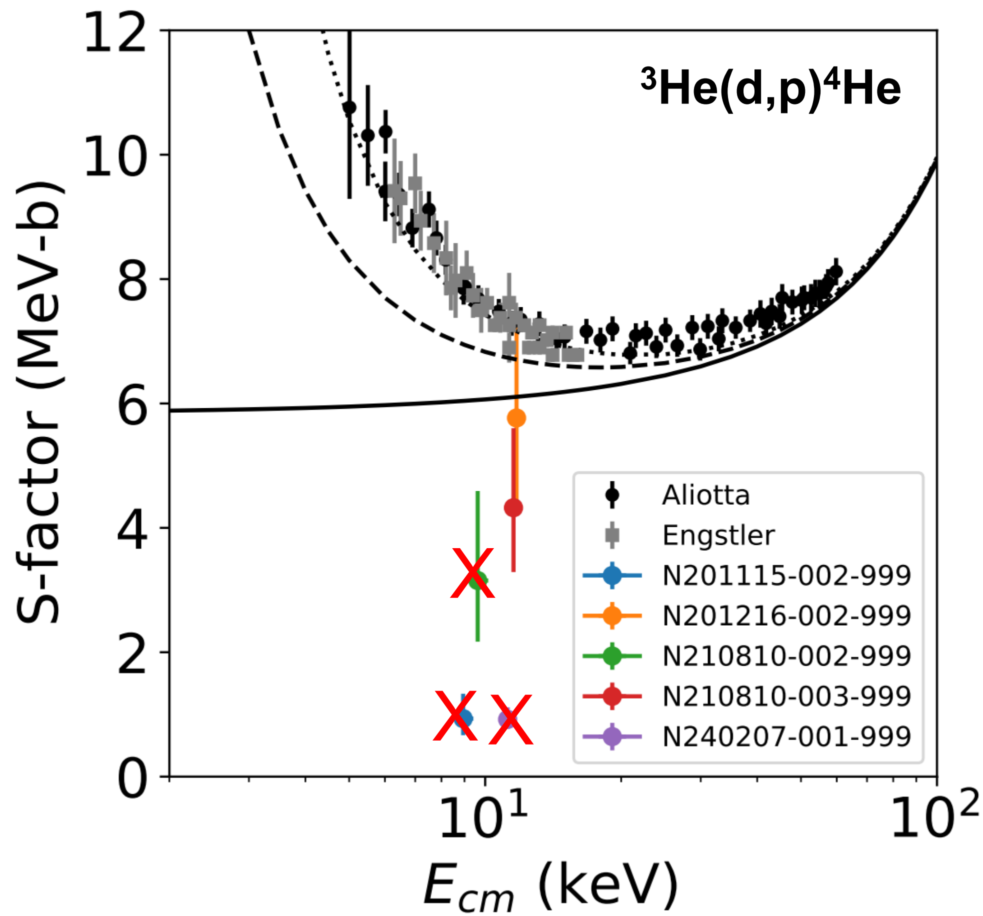
A 3rd repeat the higher energy points showed unexpected variability in yield and ρR – unclear if data can be extracted

N240207 WRF does not



N240207 WRF does not





At least two shots with solid data show encouraging agreement with the $^{3}He(d,p)^{4}He$ bare nucleus S-factor

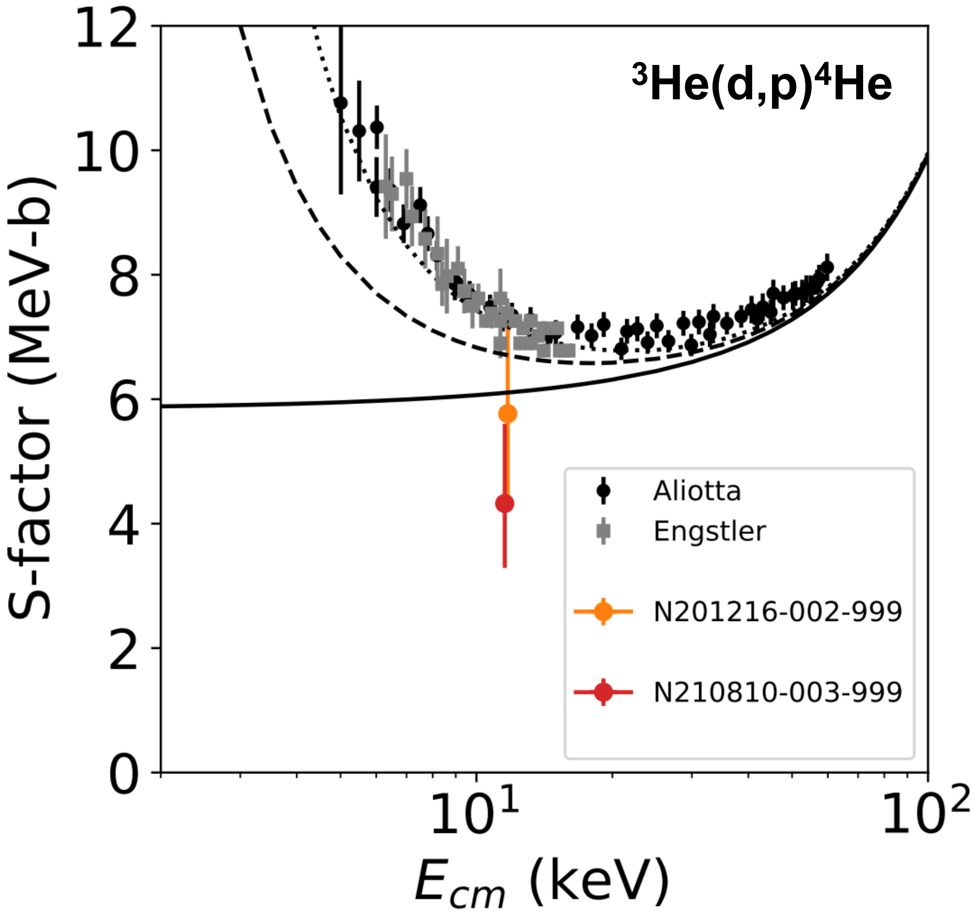
Tim Johnson SRF, Jacob Percy MagSpec

Step range detectors extend proton energy range

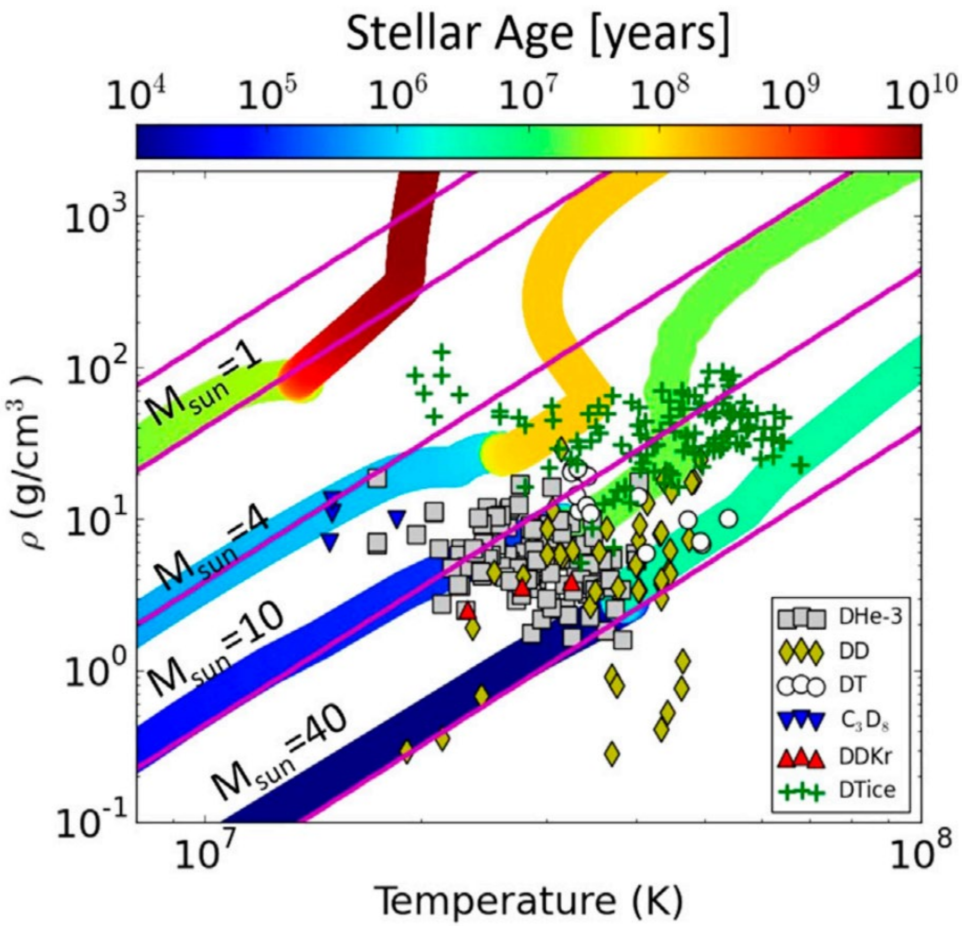
Prototypes were fielded on last screening shot

*T. Johnson submitted to RSI, J. Percy submitted to RSI

This data will help in understanding the accelerator data

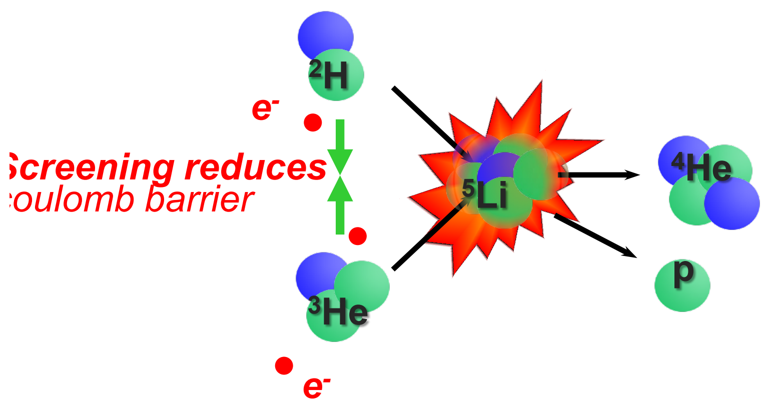


Stellar conditions result in plasma electron screening, a phenomena that has not been observed



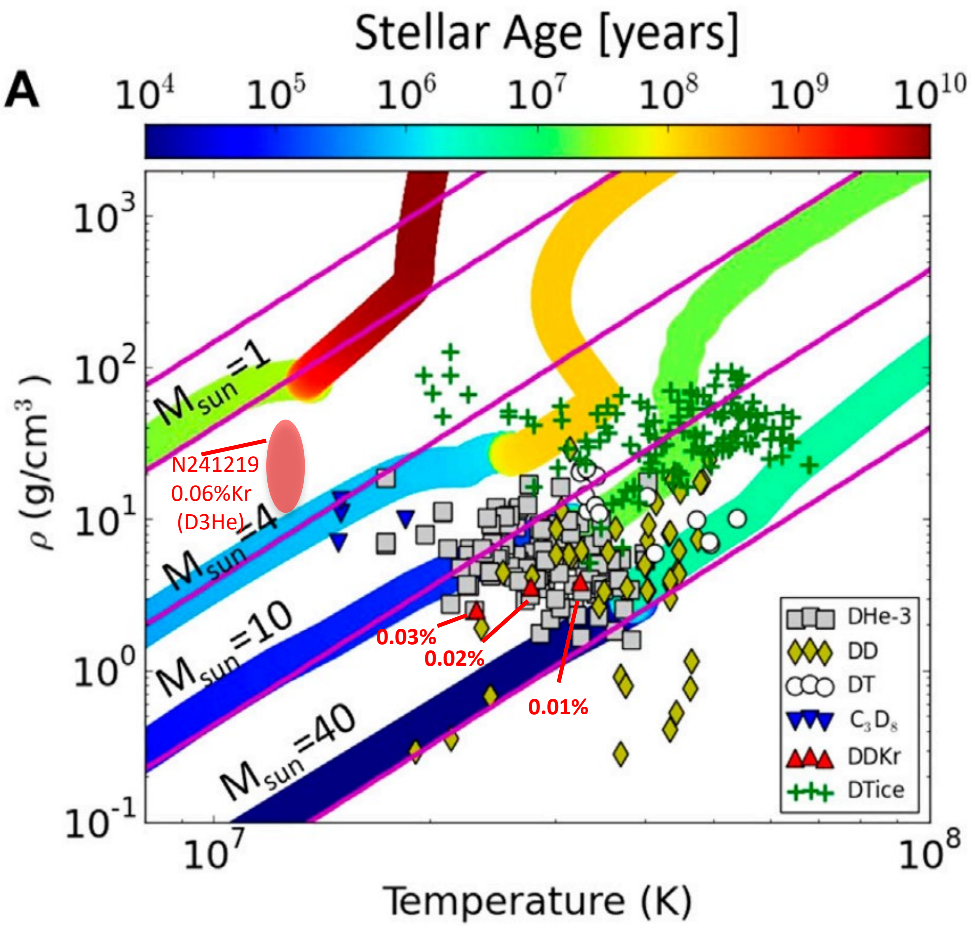
$$\frac{\sigma_{Screened}(E)}{\sigma(E)} \approx e^{Z_1 Z_2 \tilde{z} \Lambda_0} \approx e^{\frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 T \lambda_D}}.$$

Weak screening: Salpeter, Aust. J. Phys. **7,** 373 (1954).



How do we know these untested plasma models are correct?

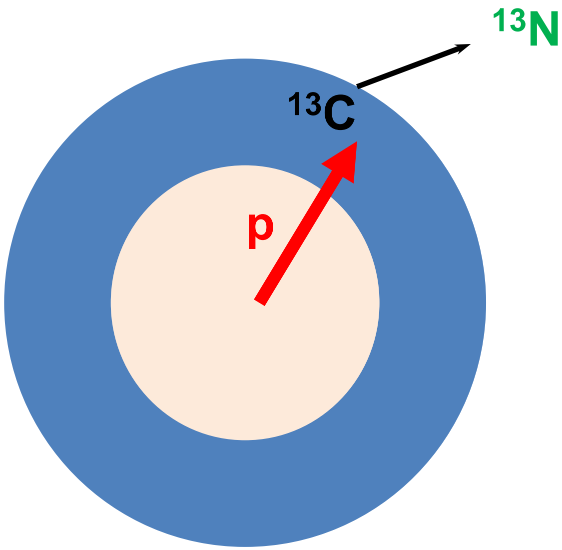
A recent experiment shows a path the plasma screening relevant regime but significant challenges remain

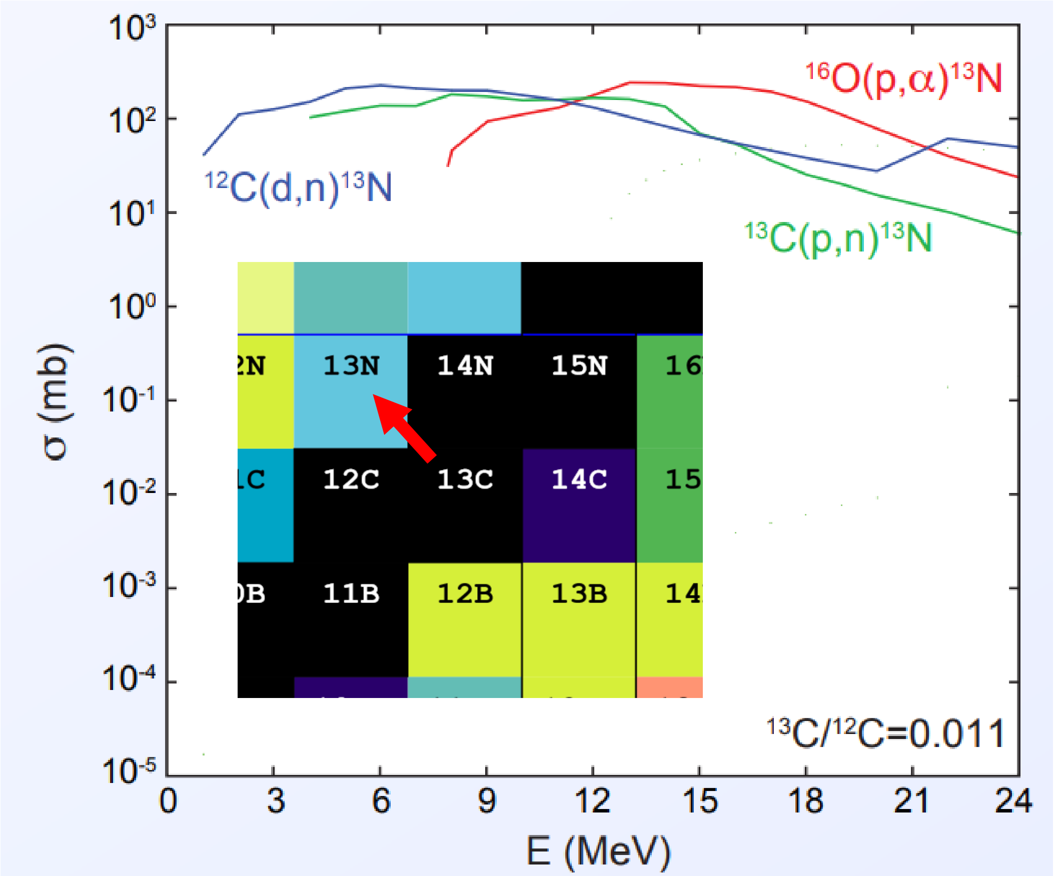


- **Prior experiments show that measuring escaping ^{3}He+d protons is significant challenge**
- **Implosion ρR varied to much for a reliable yield**
- **The region of interest pushes towards higher ρRs where this will just get harder**

So why not measure the protons inside the capsule?

A ^{13}C HDC shell would enable measurement of the proton yield with higher ρR using p+^{13}C -> ^{13}N+n observed with RAGs





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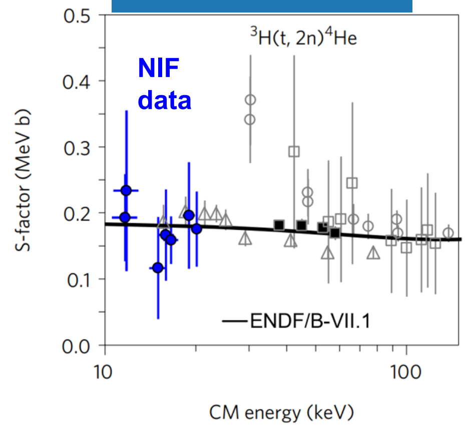
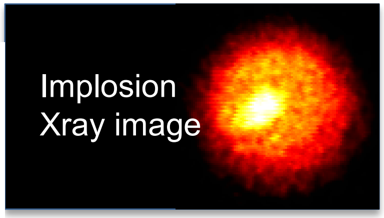
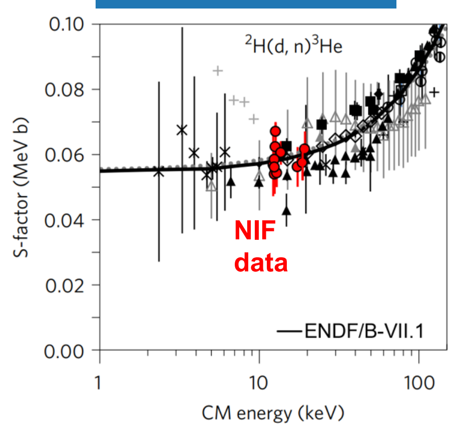
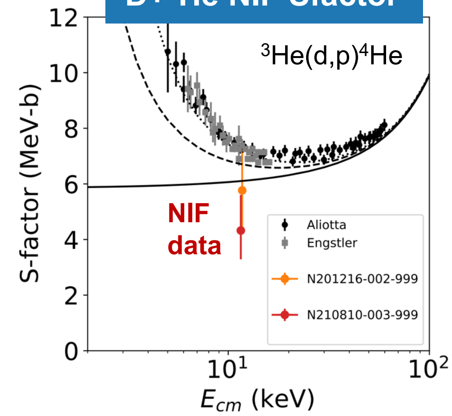


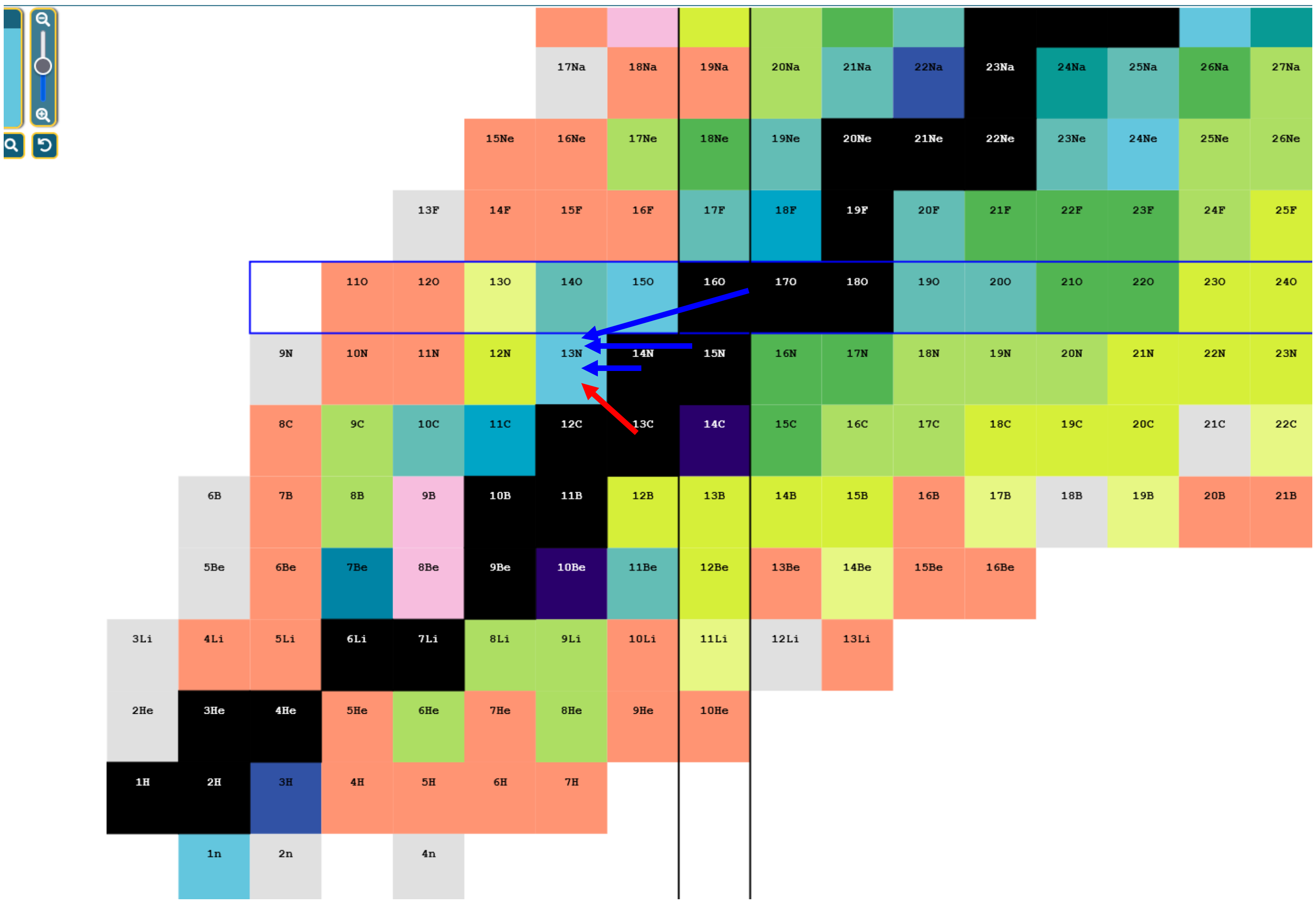


T+T NIF Sfactor



Screening and D+^{3}He NIF Sfactor




17Na 18Na 19Na 20Na 21Na 22Na 23Na 24Na 25Na 26Na 27Na
15Ne 16Ne 17Ne 18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne
13F 14F 15F 16F 17F 18F 19F 20F 21F 22F 23F 24F 25F
11O 12O 13O 14O 15O 16O 17O 18O 19O 20O 21O 22O 23O 24O
9N 10N 11N 12N 13N 14N 15N 16N 17N 18N 19N 20N 21N 22N 23N
8C 9C 10C 11C 12C 13C 14C 15C 16C 17C 18C 19C 20C 21C 22C
6B 7B 8B 9B 10B 11B 12B 13B 14B 15B 16B 17B 18B 19B 20B 21B
5Be 6Be 7Be 8Be 9Be 10Be 11Be 12Be 13Be 14Be 15Be 16Be
3Li 4Li 5Li 6Li 7Li 8Li 9Li 10Li 11Li 12Li 13Li
2He 3He 4He 5He 6He 7He 8He 9He 10He
1H 2H 3H 4H 5H 6H 7H
1n 2n 4n