LASER-INDUCED NUCLEAR ASTROPHYSICS

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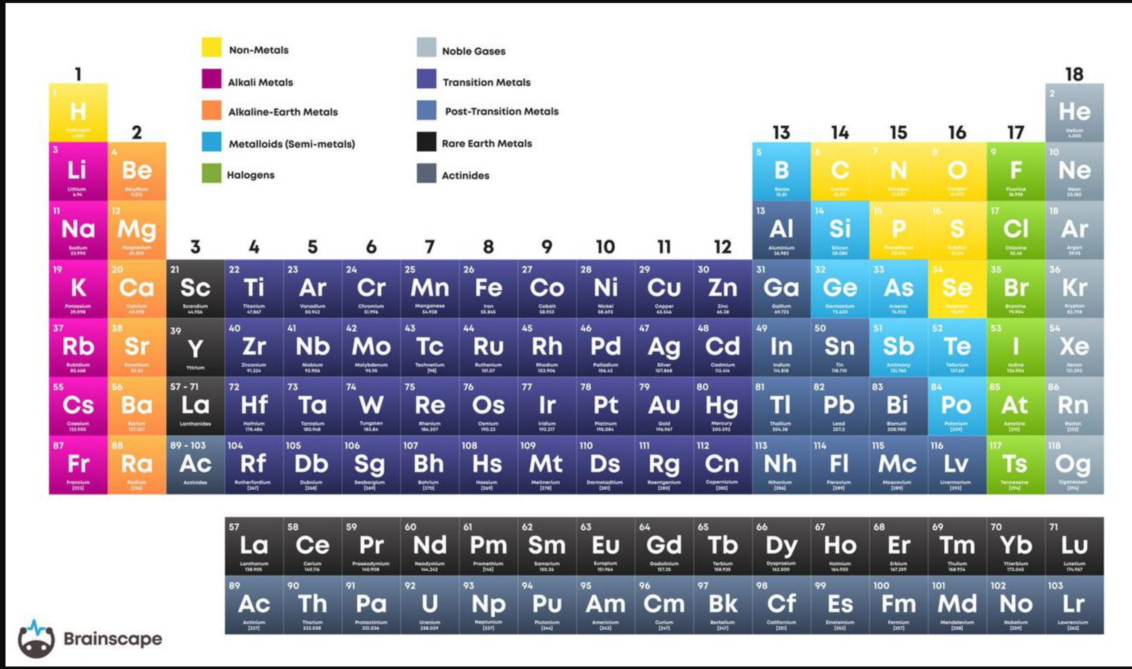
NUCLEAR ASTROPHYSICS

Focus:

- nucleosynthesis of the elements
- energy production in stars
- …

Questions:

- what is the origin of the elements?
- how do stars/galaxies form and evolve?
- what powers the stars?
- how old is the universe?
- …



NUCLEOSYNTHESIS

Stars are cosmic cauldrons (loosely quoting C. Rolfs) and they *cook*!

for a reaction: $1+2 \rightarrow 3+4$

N_i = number density

Total reaction rate: $R_{12} = (1+\delta_{12})^{-1} N_1 N_2 <\sigma v>_{12}$ reactions $cm^{-3}\ s^{-1}$

$$\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv$$

Energy production rate: $\varepsilon_{12} = R_{12}\ Q_{12}$ $Q=[(m_1+m_2)-(m_3+m_4)]c^2$

Mean lifetime of nucleus 1 against destruction by nucleus 2

$$\tau_2(1) = \frac{1}{N_2 < \sigma v >}$$

energy production as star evolves ⟵ $<\sigma v>$ KEY quantity ⟶ change in abundance of nuclei X

STELLAR REACTION RATE

$$\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv$$

cross section $\sigma(v)$ **velocity distribution $\Phi(v)$**

velocity distribution:

interacting nuclei in plasma are in thermal equilibrium at a **temperature T**

we assume non-degenerate and non-relativistic plasma.. so

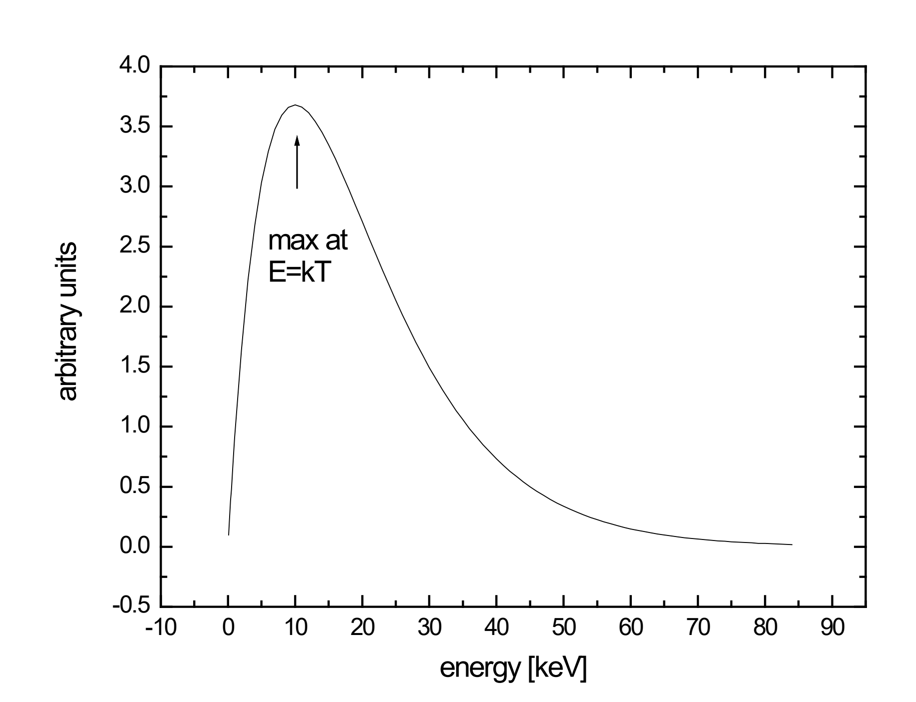
→ **Maxwell-Boltzmann velocity distribution**

$$\phi(v) = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} v^2 \exp\left(-\frac{\mu v^2}{2kT} \right)$$

with $\mu = \frac{m_p m_T}{m_p + m_T}$ reduced mass

v = relative velocity

example: Sun T ~ 15×10^6 K $\Rightarrow$ kT ~ 1 keV



kT ~ 8.6×10^{-8} T[K] keV

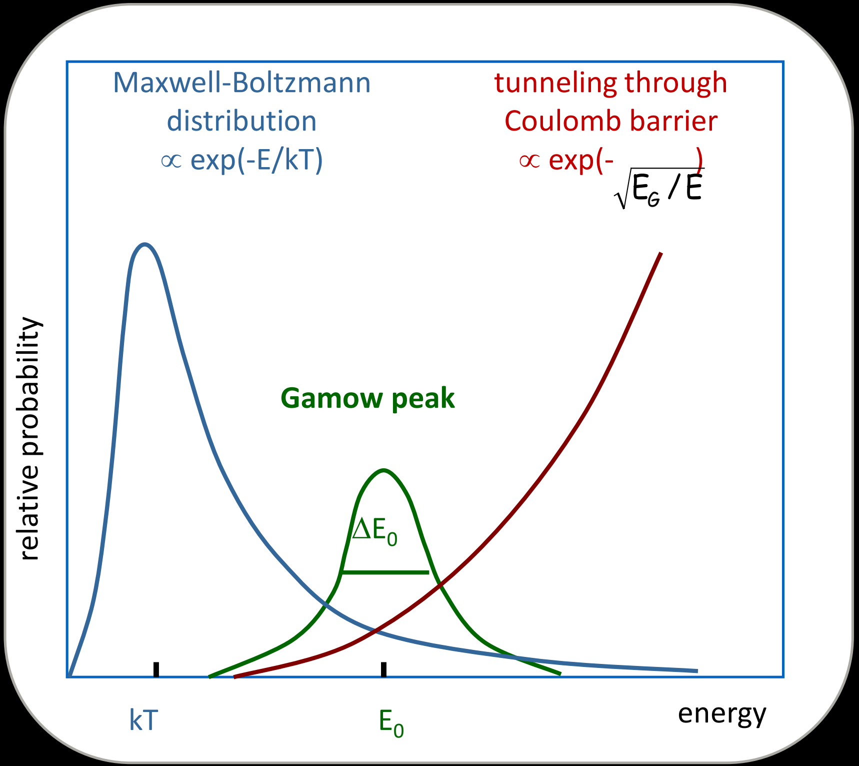
THE GAMOW PEAK

The most effective energy region for thermonuclear reactions (i.e. the energy region at which most of reactions occur).

$E_0 \pm \Delta E_0/2$ energy window of astrophysical interest

$E_0 = f(Z_1, Z_2, T)$

depends on the reaction and temperature



Examples:
$T \sim 15\text{x}10^6$ K
($T_6 = 15$)

reaction	Coulomb barrier (MeV)	E_0 (keV)	area under Gamow peak $\propto \langle\sigma v\rangle$
p + p	0.182	5.9	$7.0\text{x}10^{-6}$
$\alpha + {}^{12}C$	2.242	56	$5.9\text{x}10^{-56}$
${}^{16}O + {}^{16}O$	10.349	237	$2.5\text{x}10^{-237}$

STRONG sensitivity to Coulomb barrier → separate stages: H-burning, He-burning, C/O-burning …

IN-PLASMA MEASUREMENTS

TH Method is complementary to direct measurements as well as other indirect methods.

But what about stars? We need to study directly in a star-like environment.

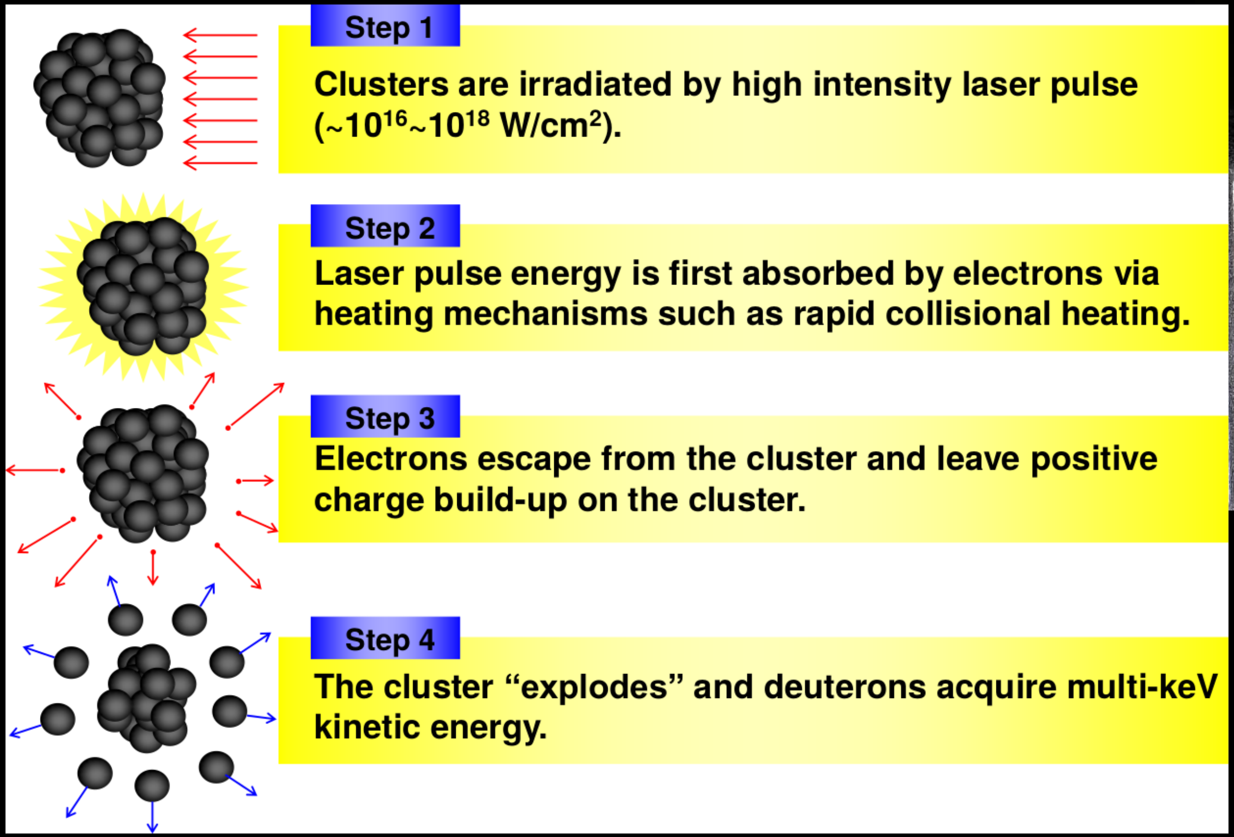
Plasma affects nuclear reactions and decays in a non-negligeable way (electron screening and beta decay half-lives).

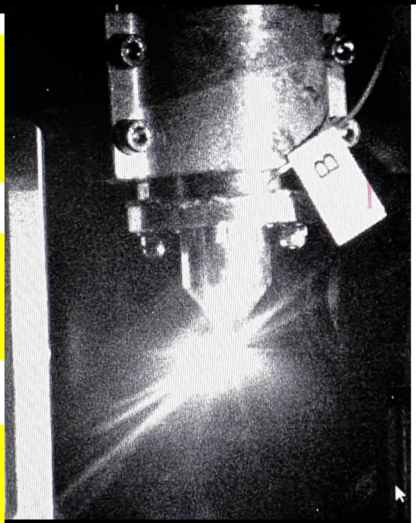
We need a Laboratory Plasma.

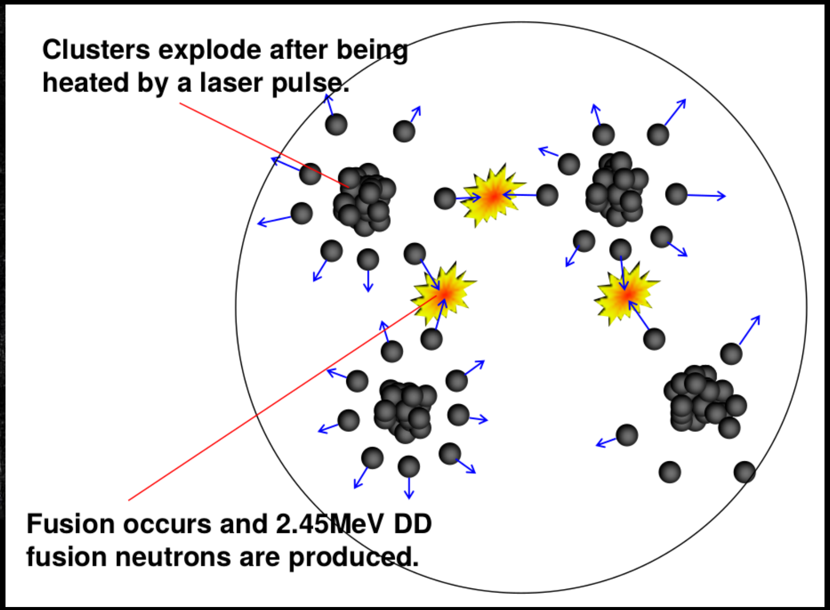
The plasma commonly used in Tokamak(-like) or magnetic trap experiments can be confined for long timescales but it has usually very low density and/or temperature. This practically hinders electron screening studies, but laser amplification technology has now advanced enough to enable these studies with high-power high-intensity and high-repetition lasers.

THE LASER-CLUSTER PARADIGM

The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of plasmas with multi-keV temperature. These energies overlap with the typical temperatures of stellar environments where thermonuclear reactions occur, thus making this paradigm a ***perfect scenario for nuclear astrophysics research***.

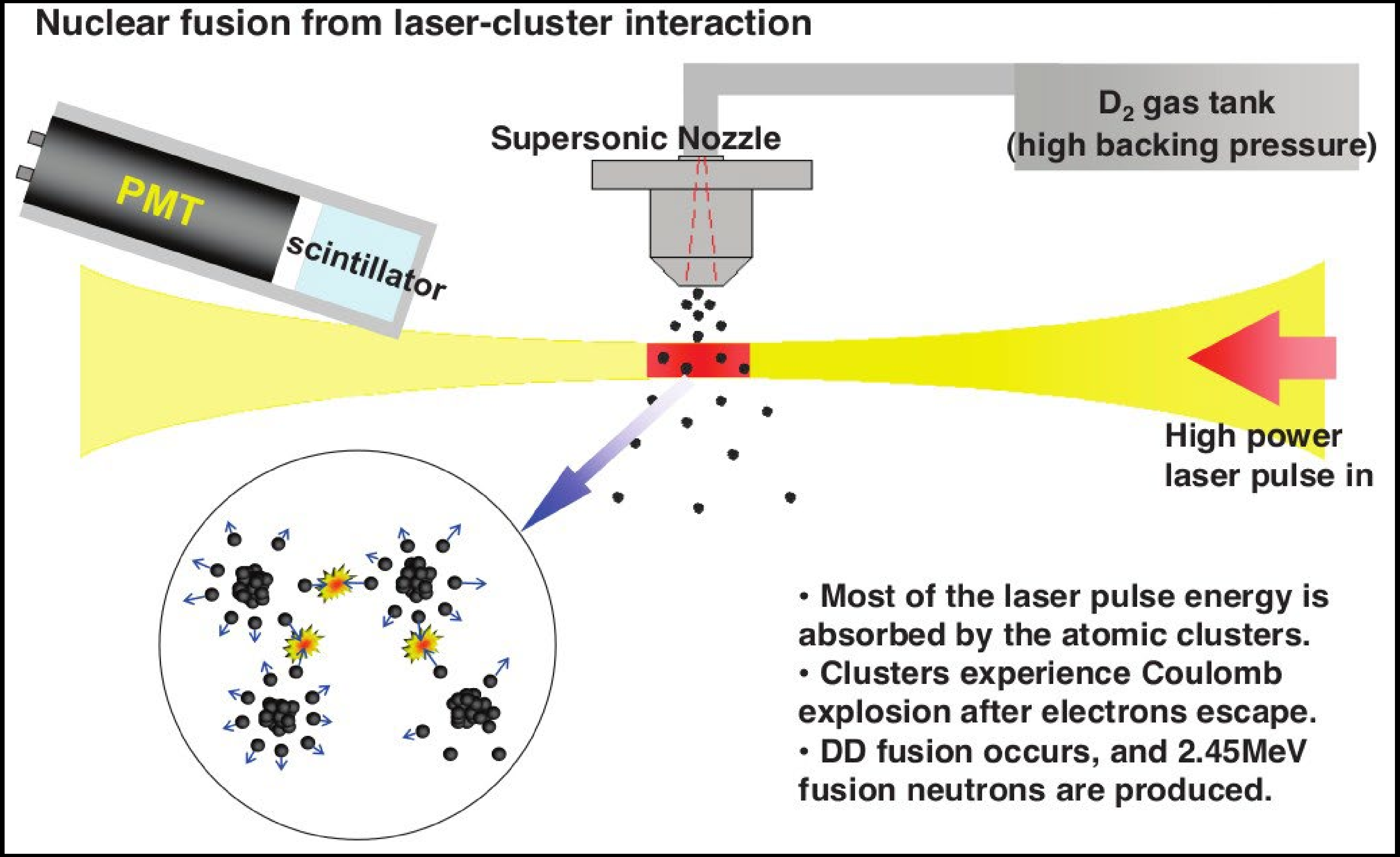






$$\langle \sigma v \rangle_{accelerator} \neq \langle \sigma v \rangle_{plasma} \approx \langle \sigma v \rangle_{stars} \neq \langle \sigma v \rangle_{bare}$$

DEUTERIUM-DEUTERIUM FUSION @ TPW



$$d + d \rightarrow {}^{3}\mathrm{He}(0.82MeV) + \boxed{n(2.45MeV)}$$

$$d + d \rightarrow \boxed{p(3.02MeV)} + t(1.01MeV)$$

$$d + {}^{3}\mathrm{He} \rightarrow \boxed{p(14.7MeV)} + {}^{4}\mathrm{He}(3.6MeV)$$

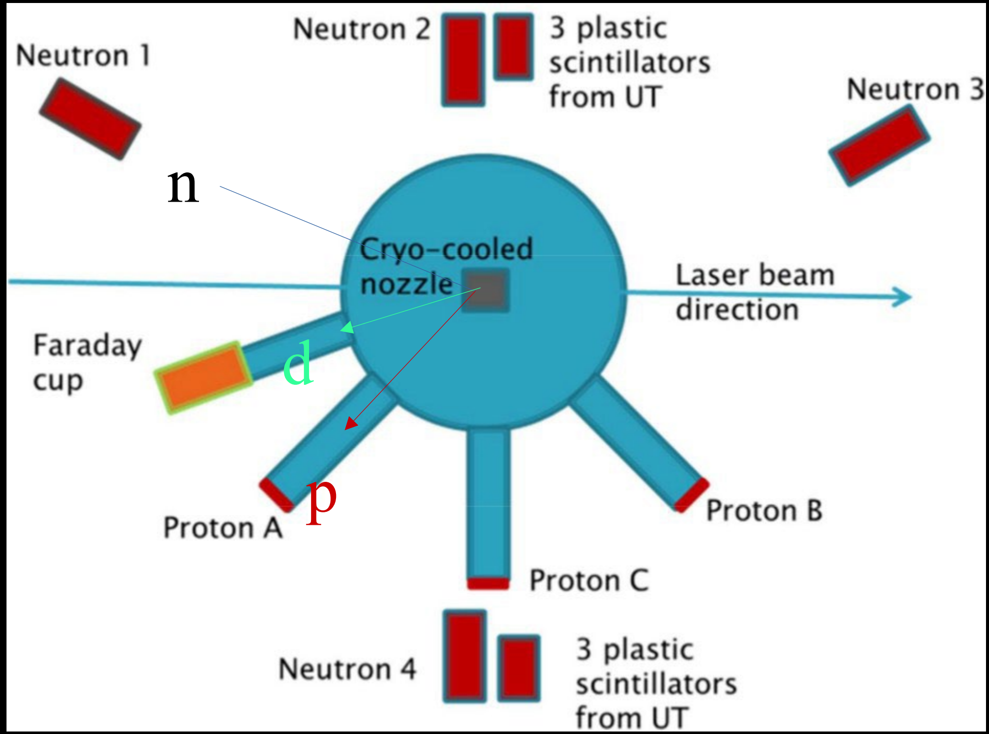
E = 100-140 J
Pulse duration: 140 fs
Rep. Rate: ~ 1/hour
CW: 1057 nm
Intensity ~ 10^{21} W/cm^2

D ions energy: 1-10^2 keV
Density ~ 10^{18} atoms/cm^3
Yield: 10^{5} – 10^{7} n/shot

THE EXPERIMENT

$$Y = \frac{\rho_1 \int \frac{dN}{dE} S(E) \exp[-2\pi \eta(E)] v \tau \, dE}{1+\delta_{12}}$$

$$= l\rho_D \int \frac{dN}{dE} \sigma_{BB}(E) dE$$



fusion products, n & p →scintillators ToF

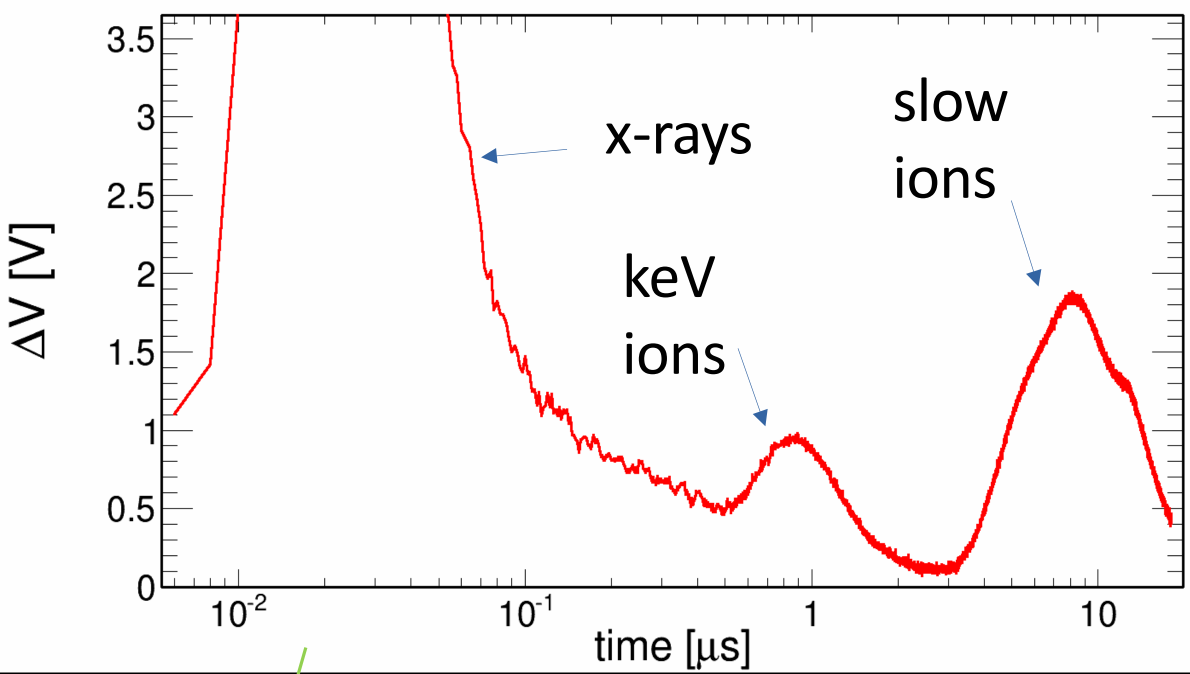
deuteron spectrum →FC ToF

gas-cluster and plasma diagnostics → interferometry, CCD, previous Rayleigh scattering measurements

$$d + d \rightarrow {}^3\mathrm{He}(0.82MeV) + n(2.45MeV)$$

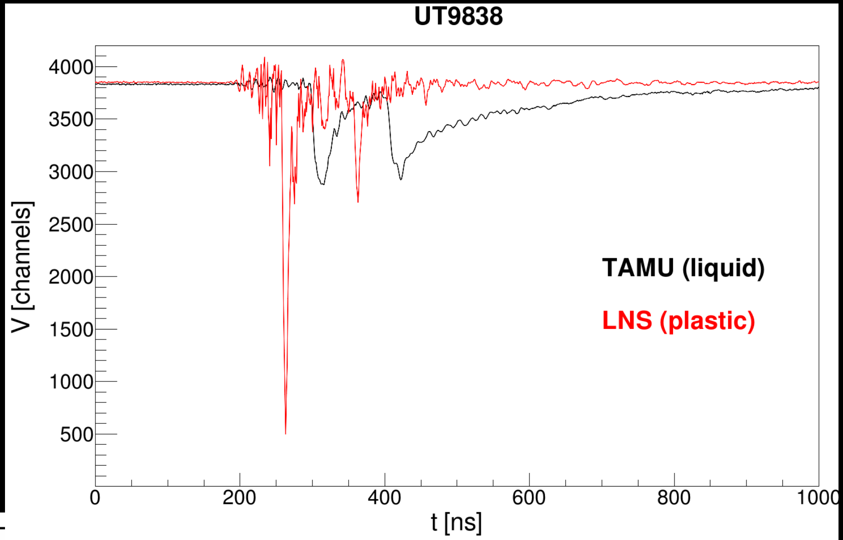
$$d + {}^3\mathrm{He} \rightarrow p(14.7MeV) + {}^4\mathrm{He}(3.6MeV)$$

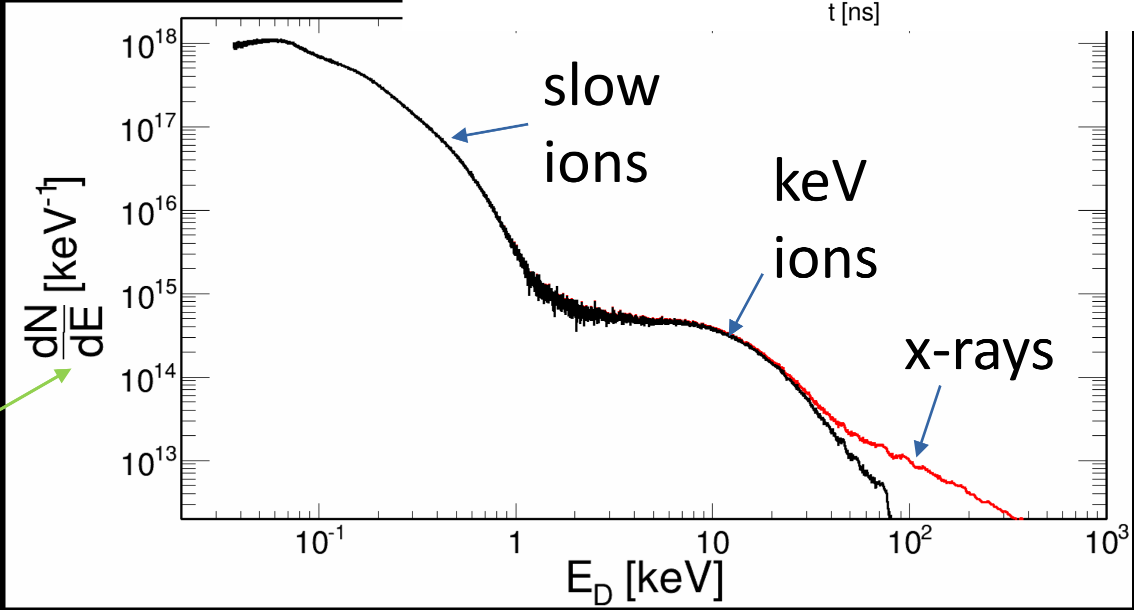
SOME DATA ANALYSIS



$$\frac{d^2N}{dt\,d\Omega} = \frac{\Delta V}{qeR_\Omega \Delta\Omega}$$

$$\frac{d^2N}{dE\,d\Omega} = \frac{s^3}{m_D v_D^3 \pi r_F^2} \frac{\Delta V}{qeR_\Omega}$$

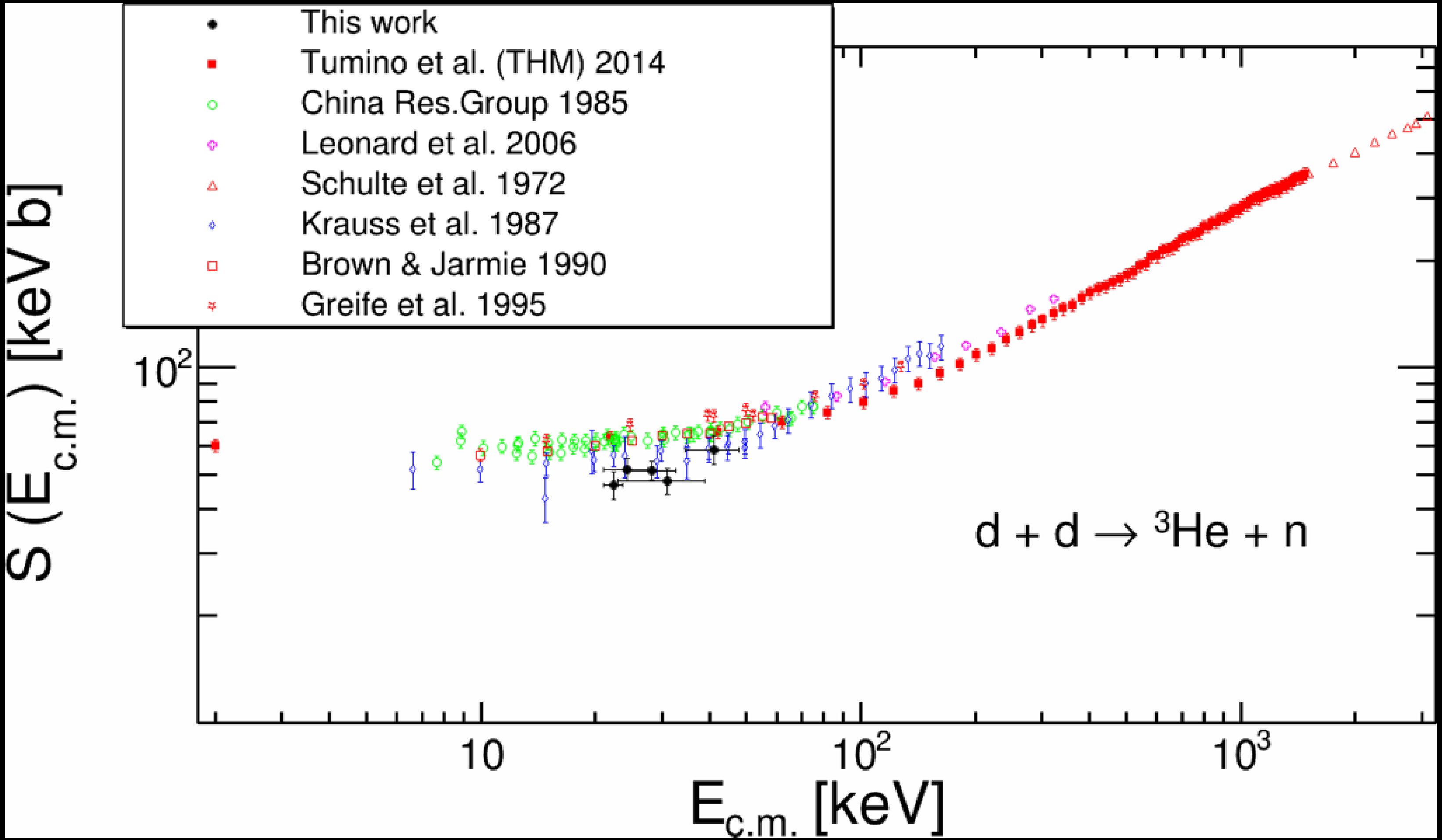




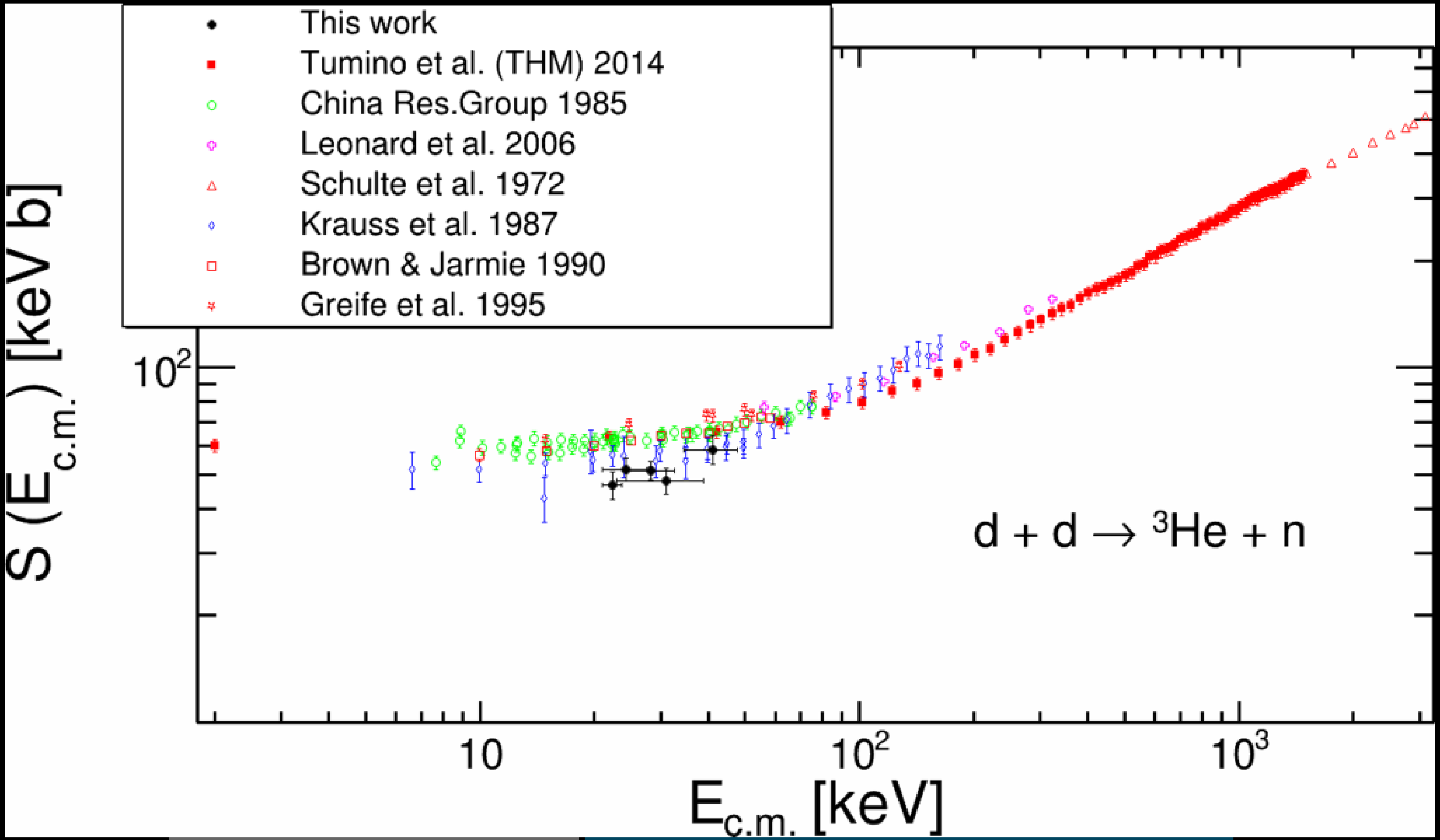
WHAT DID WE LEARN?

Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas
D. Lattuada et al.
Phys. Rev. C **93**, 045808 **2016**
DOI: https://doi.org/10.1103/PhysRevC.93.045808

- we need statistical signficance → reproducibility
- we need to better measure the high energy tail of the D ToF signals
- we need more target control



DD-FUSION EXPERIMENT @ GIST 2023-24



screening

Big Bang Nucleosynthesis

Expected shots

Temp [keV]	Livetime [h]	Shots
1-2	8	~ 500
2-3	4	~ 150
3-5	1	~ 100
5-10	1	~ 100
> 10	2	~ 200

D(d,p)t also!
BR = 50%

DD-FUSION EXPERIMENT @ GIST 2023-24

E = 4 J

Pulse duration: 25 fs

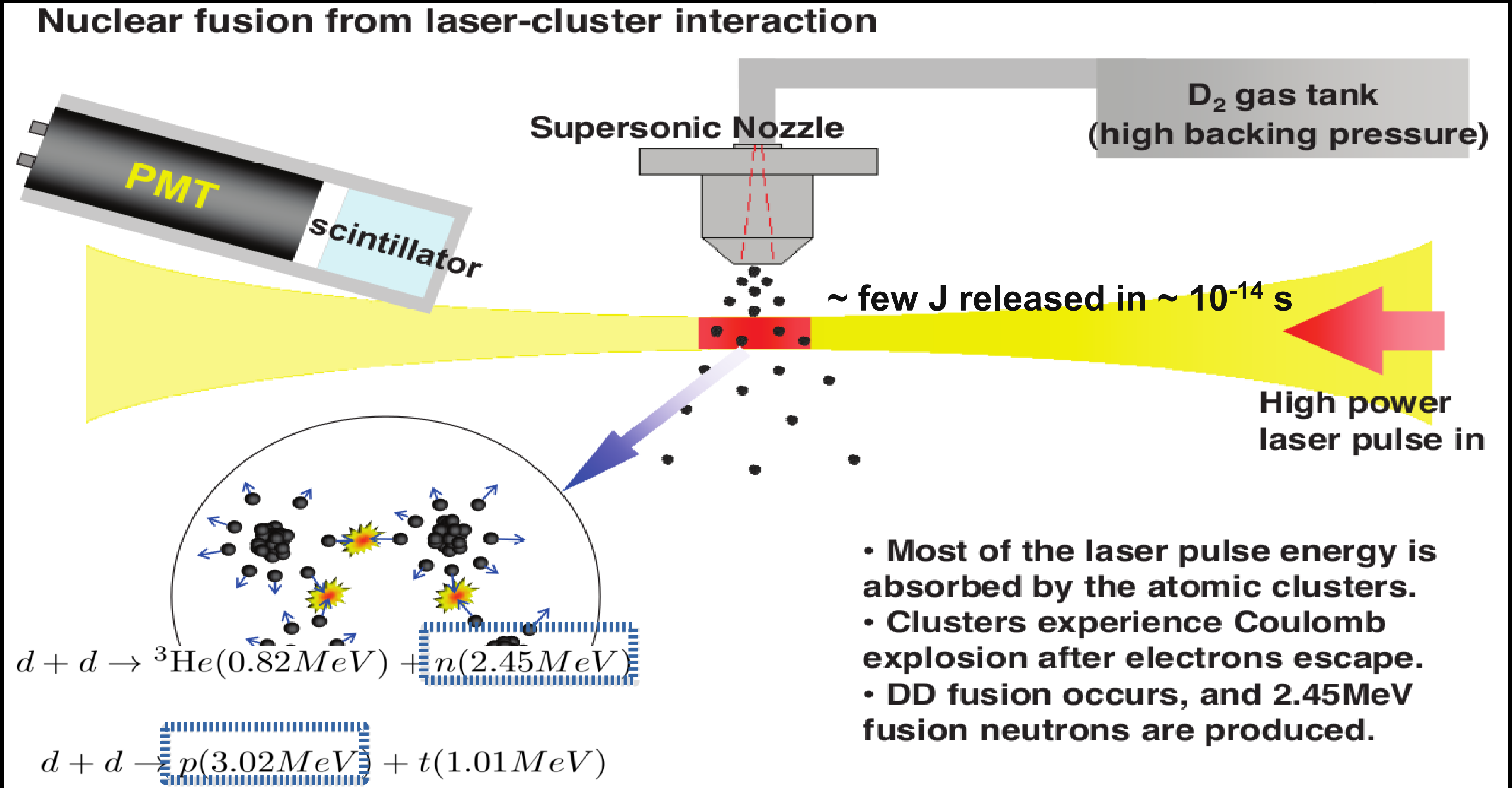
Rep. Rate: 5Hz (but 1/20s)

CW: 800 nm

Intensity ~ 10^{20} W/cm^2

deuterium ions
Kinetic Energy 1-100 keV
Density ~ 10^{18} atoms/cm^3

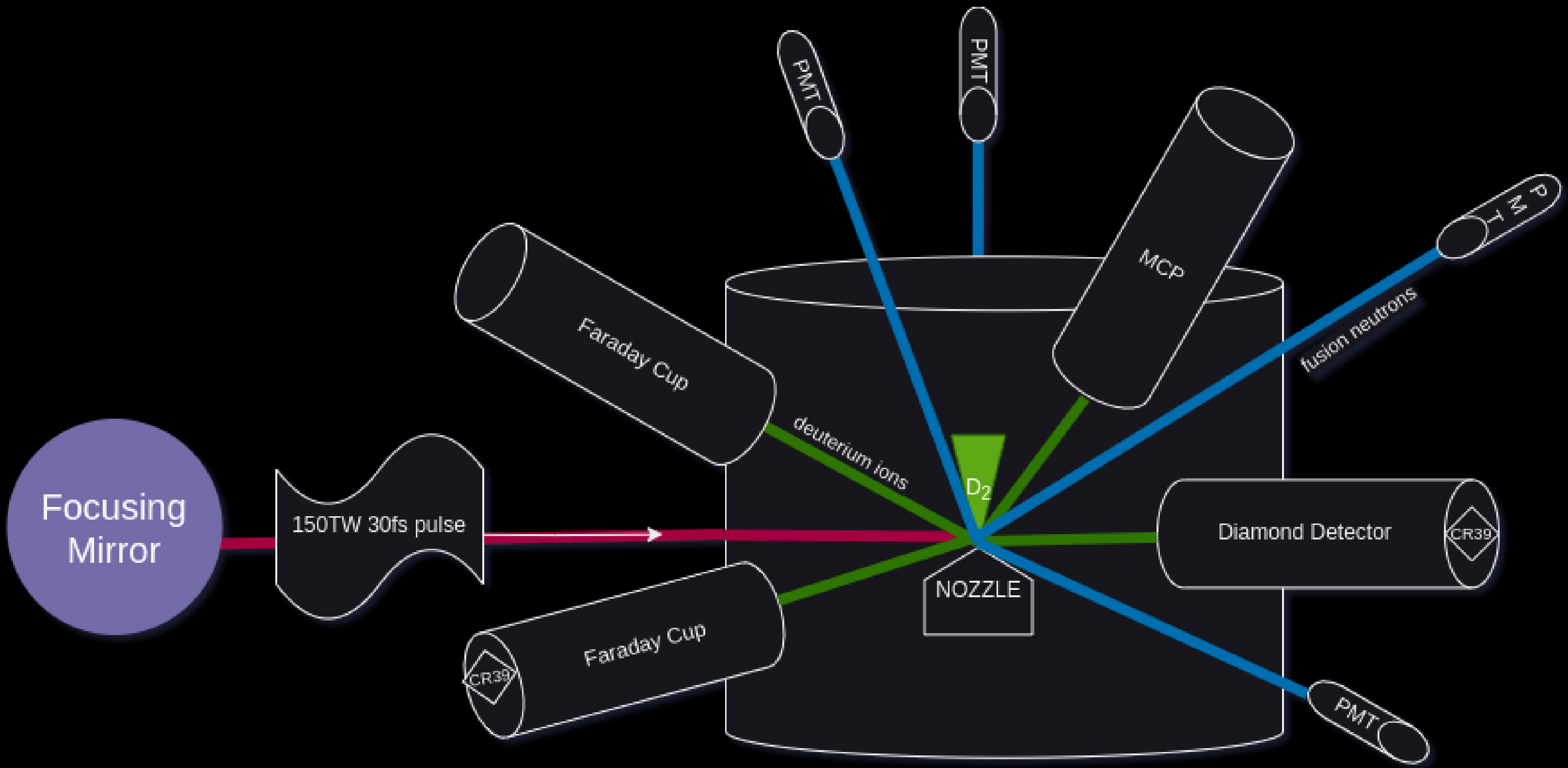
10^4 - 10^5 neutrons per shot



GIST Laser Fusion Laboratory, Prof. W. Bang

https://laserfusion.gist.ac.kr/laserfusion/

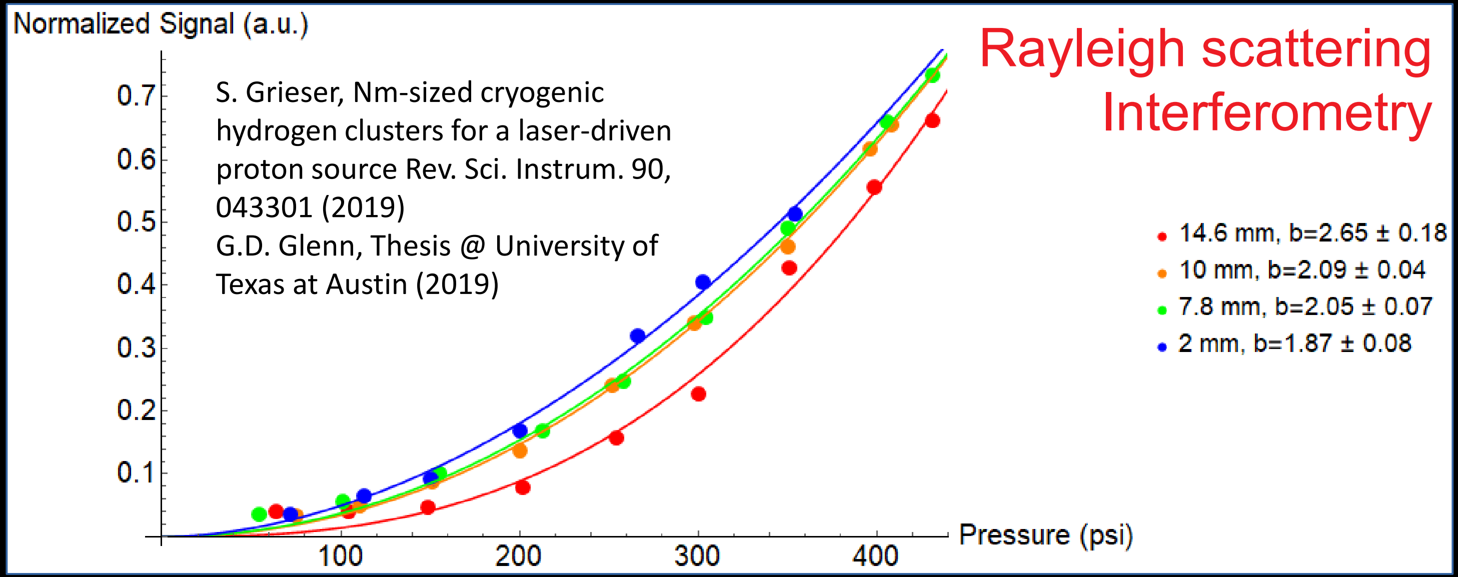
DD-FUSION EXPERIMENT @ GIST 2023-24

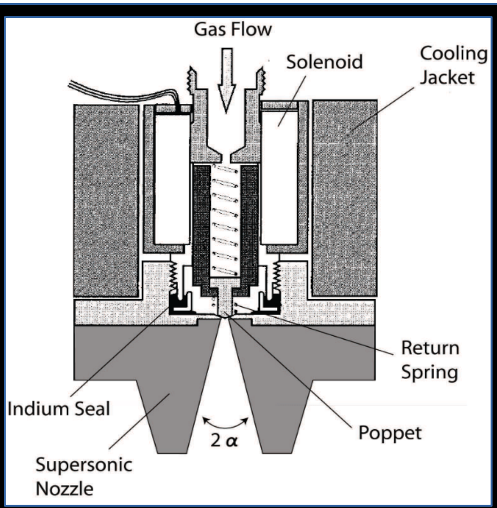


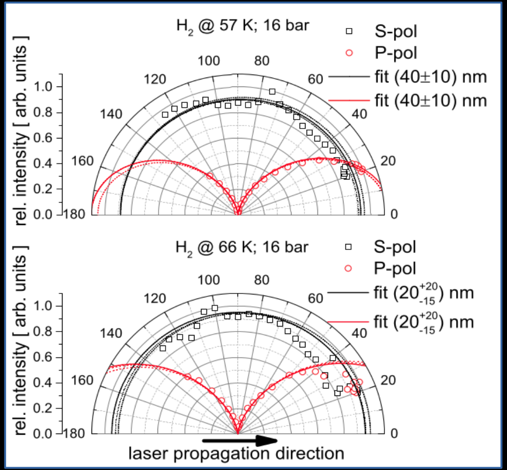
Plasma temperature control and reproducibility for over 3k shots 1-40 keV (kT)
Deuteron spectra measured with excellent accuracy

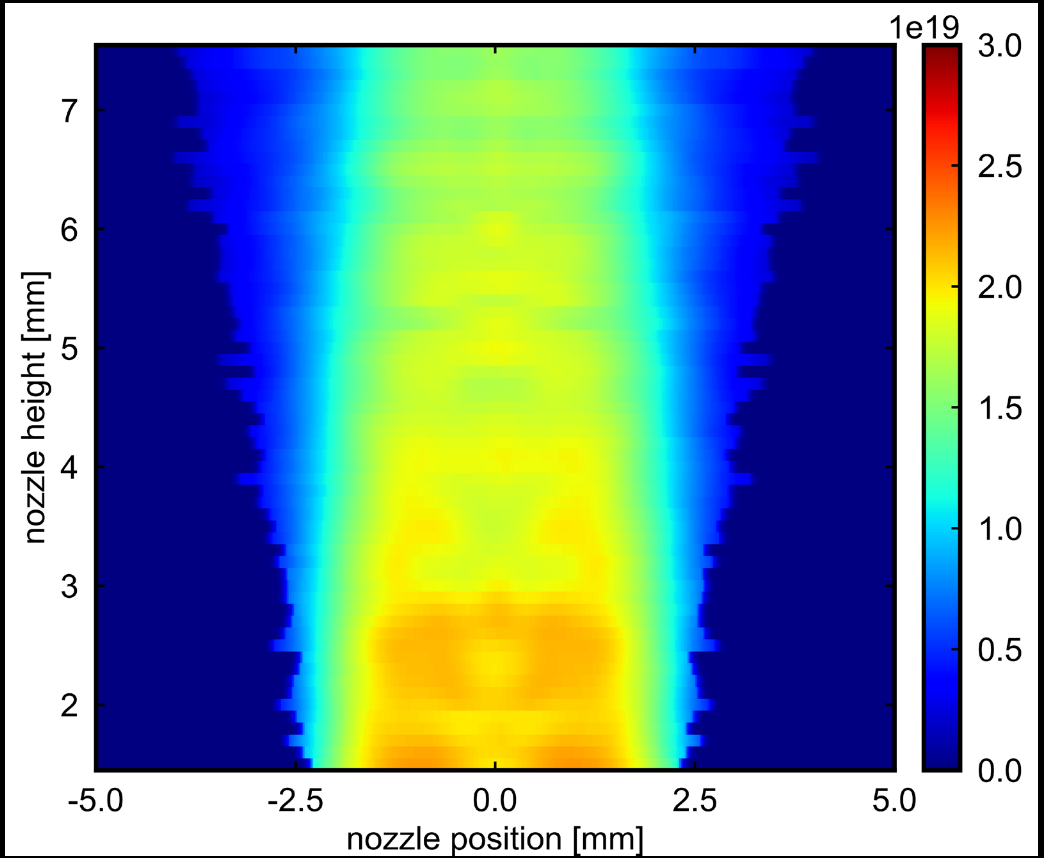
Neutron detection inefficient for low energies..
Target not perfect for very low temperatures..

TARGET CHARACTERIZATION









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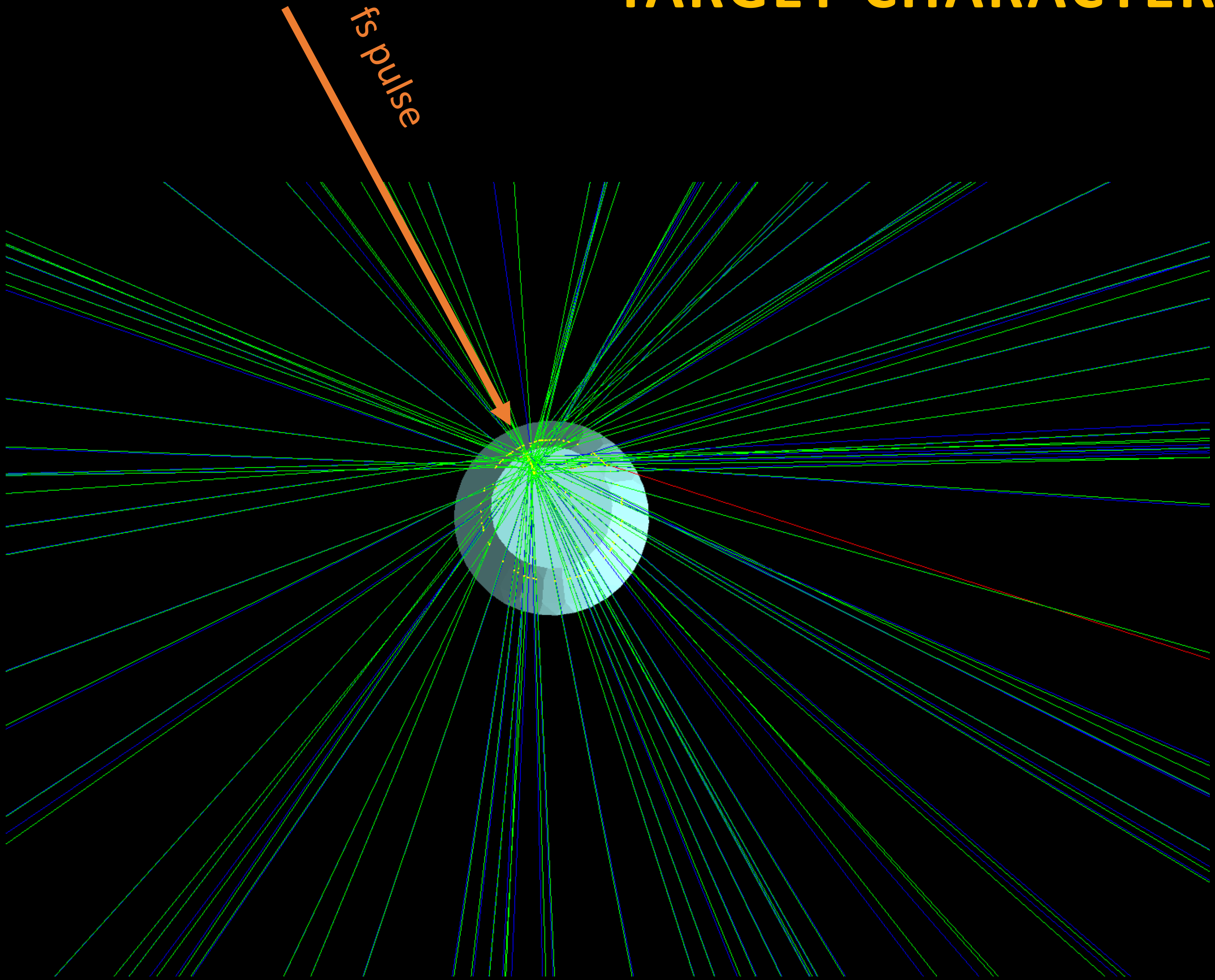
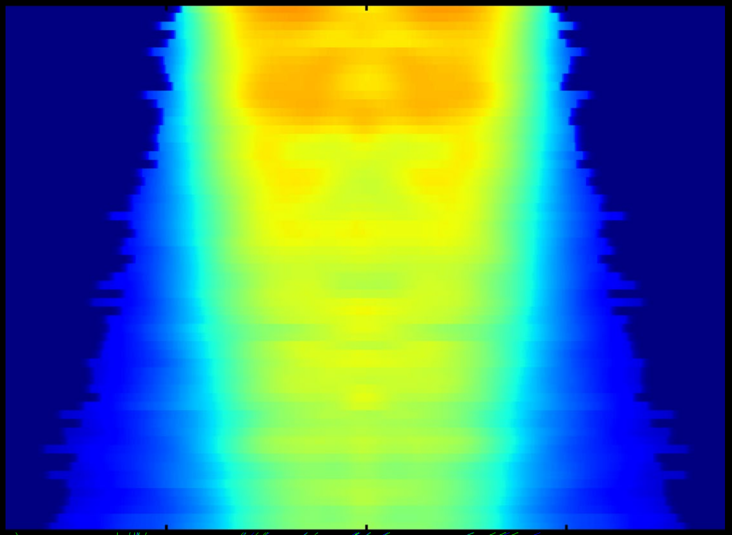
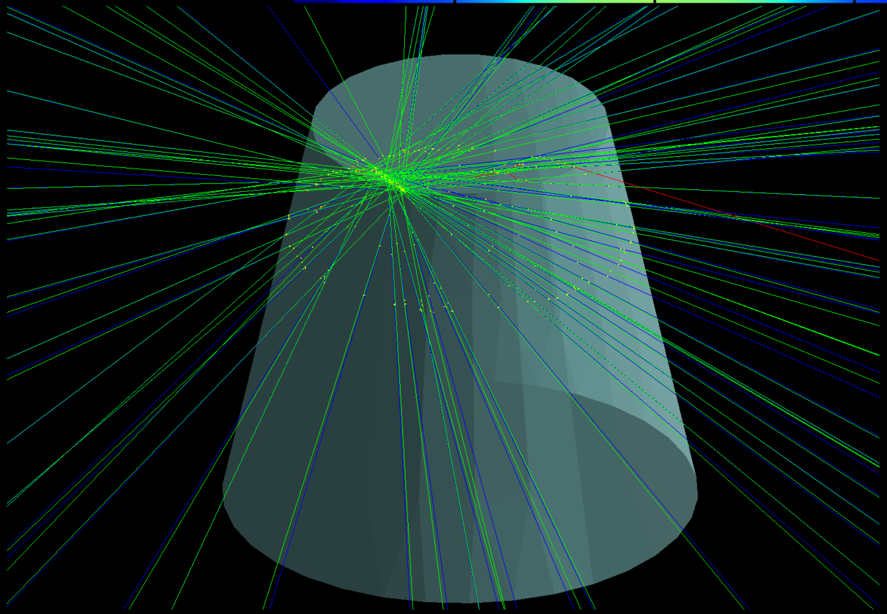
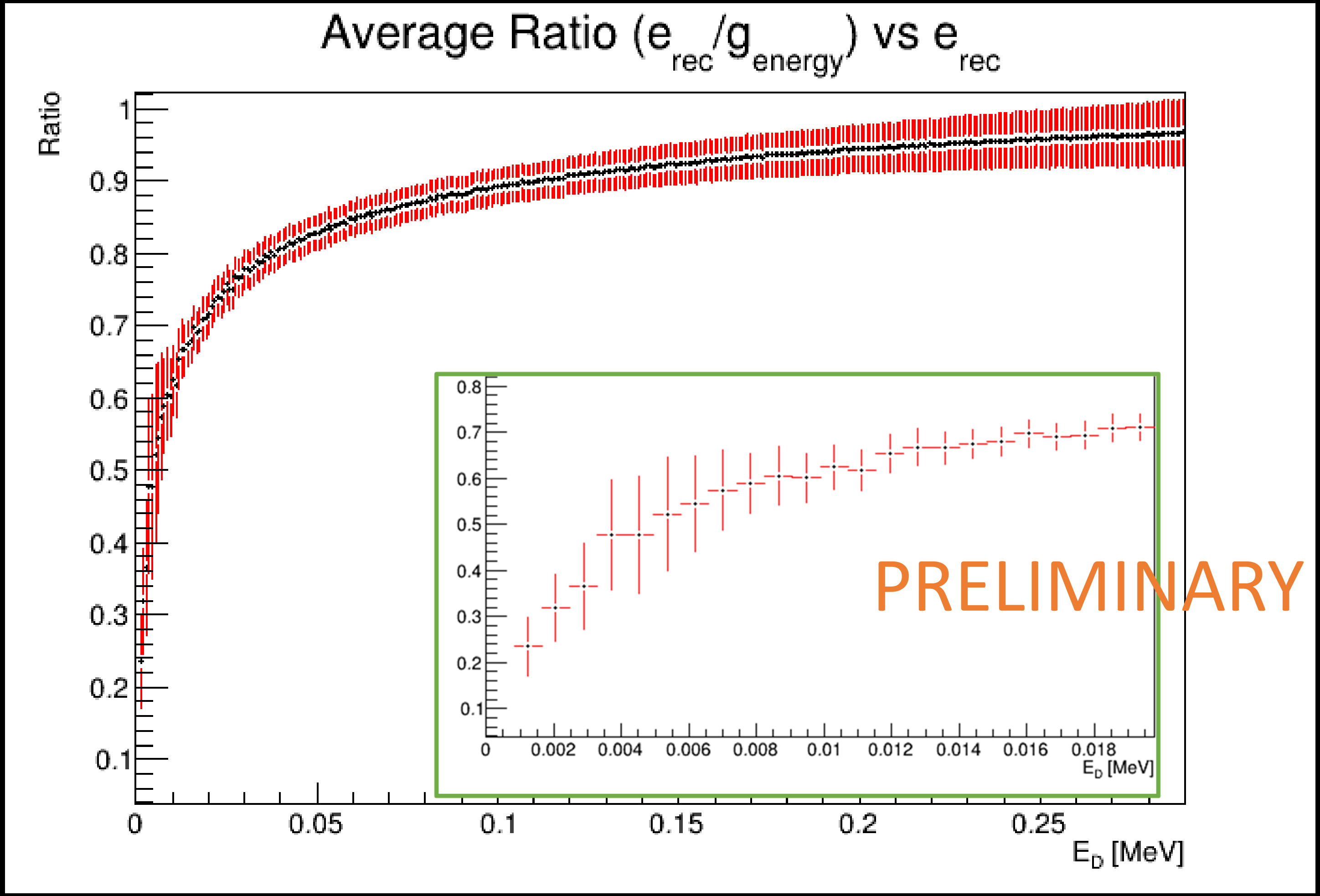


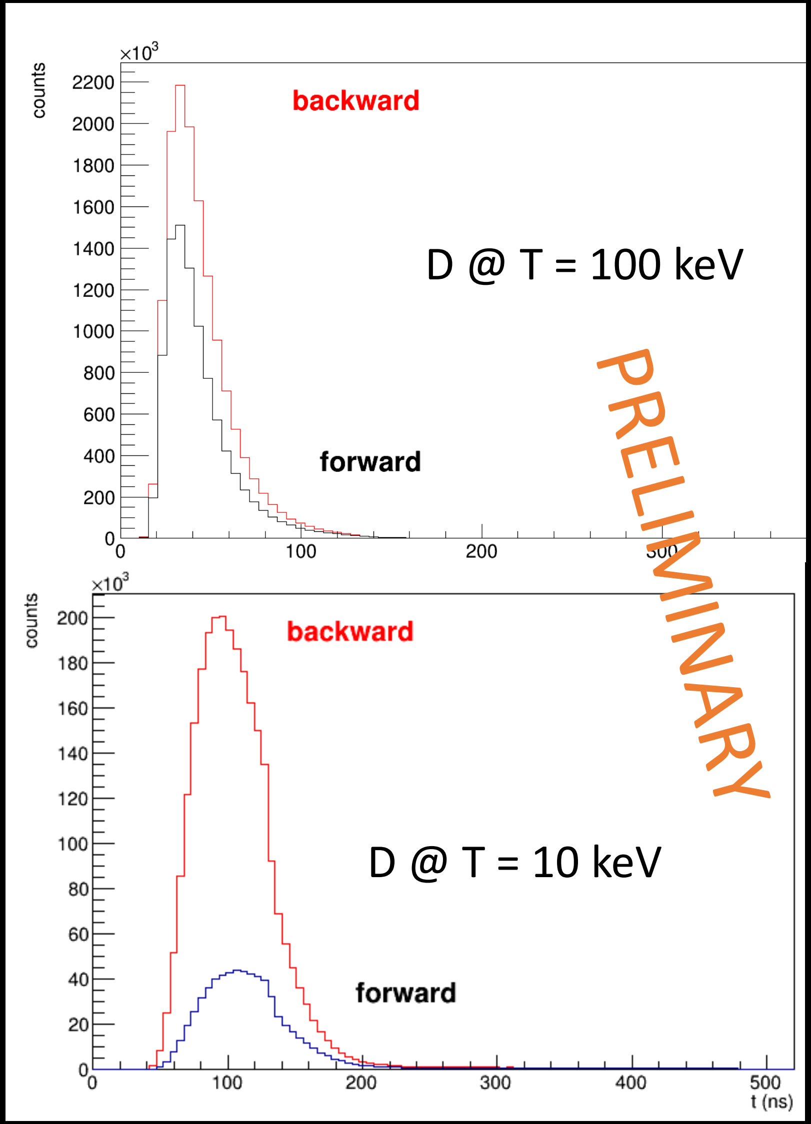




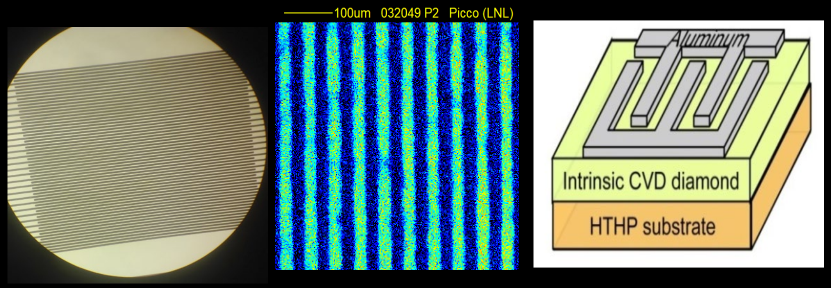
GROOT 10.1051/epjconf/201716501034

TARGET CHARACTERIZATION WITH GEANT4 (LIMITATIONS)



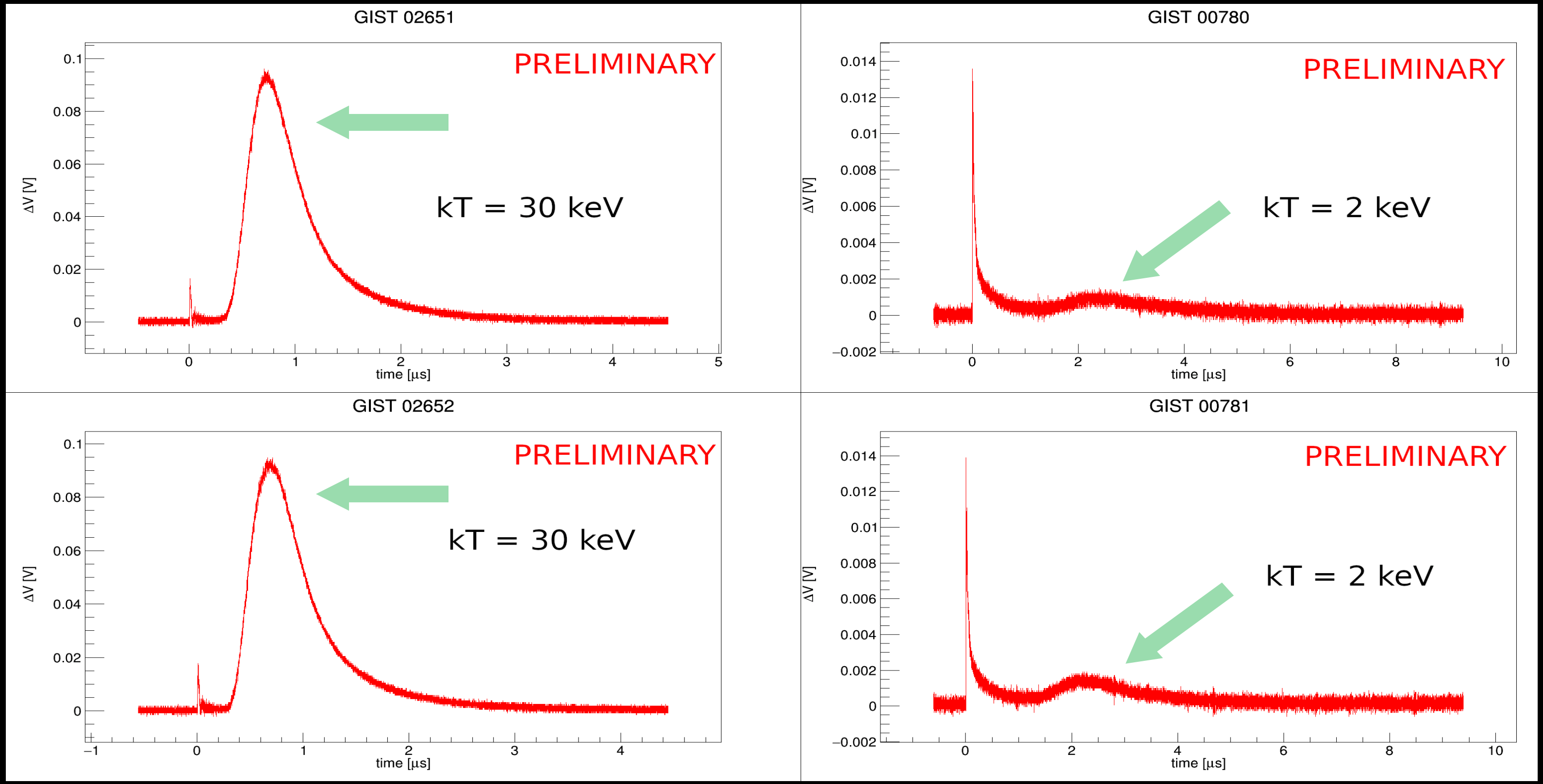


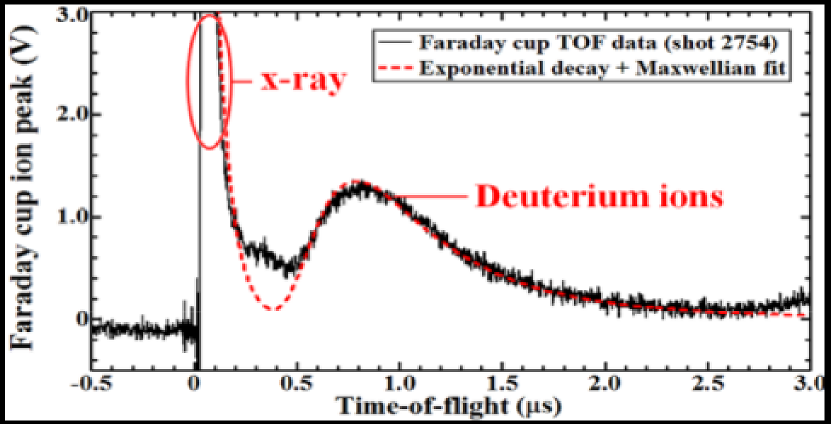
DIAMOND DETECTORS



Interdigitated CVD
Prof. Claudio Verona
Tor Vergata University

Diamond thickness	25 µm
Interdigitated electrodes	20 µm - 20 µm
Active area	~0.8 mm^2
CCE	100% up to 1 MeV H^+
Time resolution	~0.5 ns

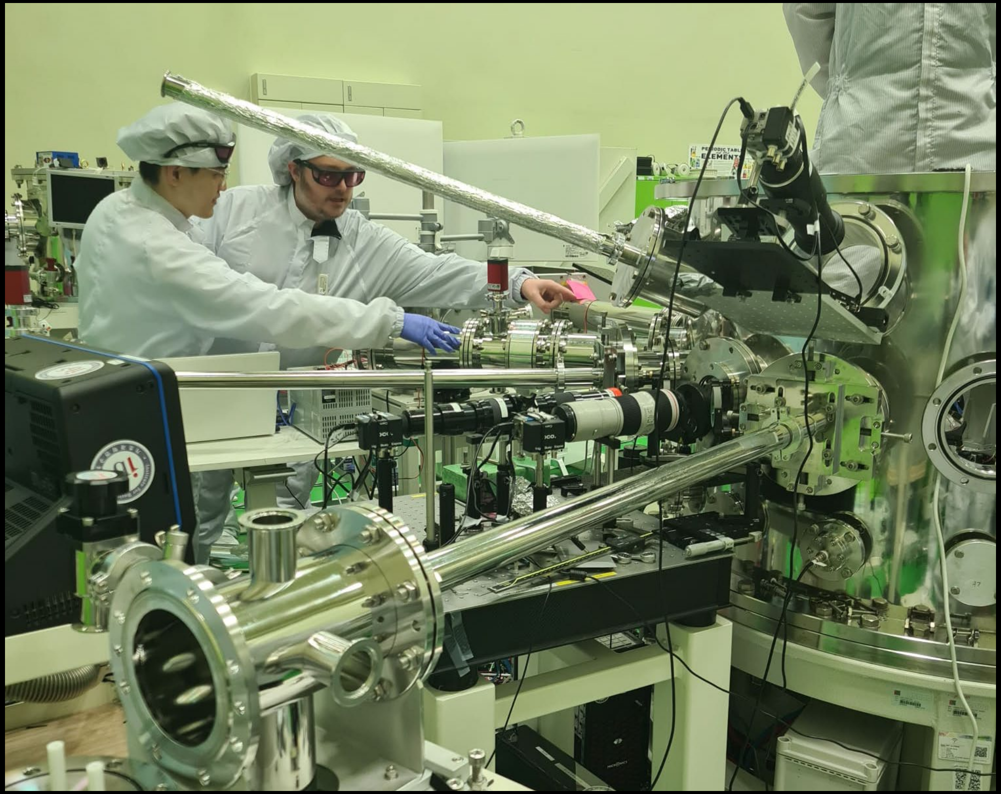




2011 & 2016 UT Faraday cup

DD-FUSION EXPERIMENT @ GIST 2023-24

Over 3000 shots, with T control between kT~ 1 - 40 keV



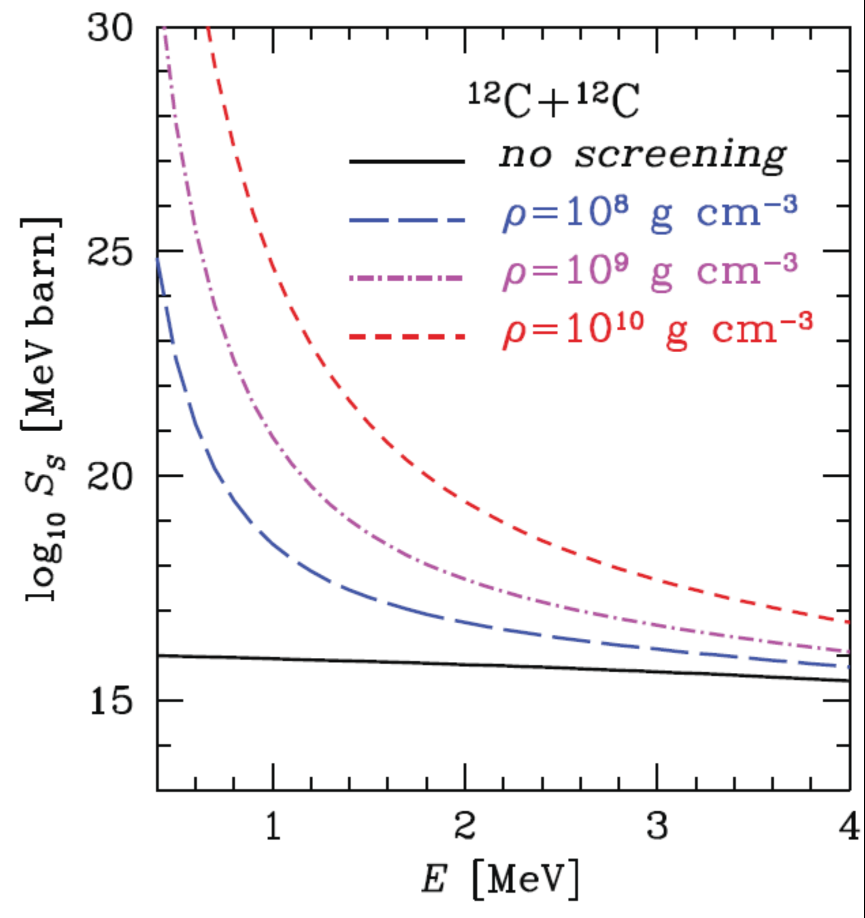
TOWARDS A SYSTEMATIC STUDY OF ELECTRON SCREENING

Carbon burning is a key stage of stellar evolution.

A measurement with the THM was performed in the entire astrophysical region of interest, but.

Preliminary studies both with deuterated methane (CD_4) and with solid targets point towards the new possibility of studying the carbon burning with laser-induced plasmas.

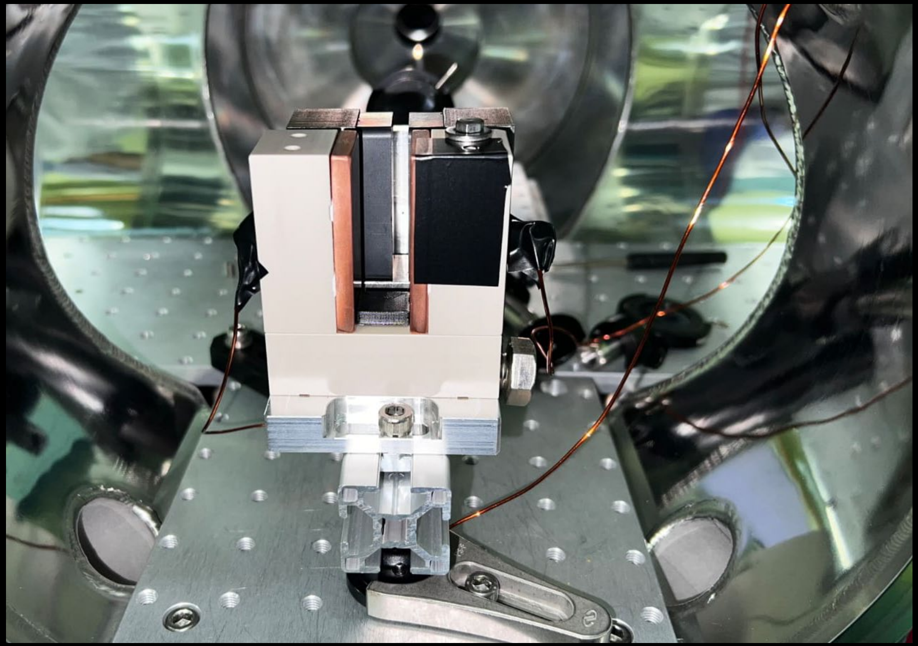
High-repetition rate high-power high-intensity lasers could provide an independent determination of the reaction rate.



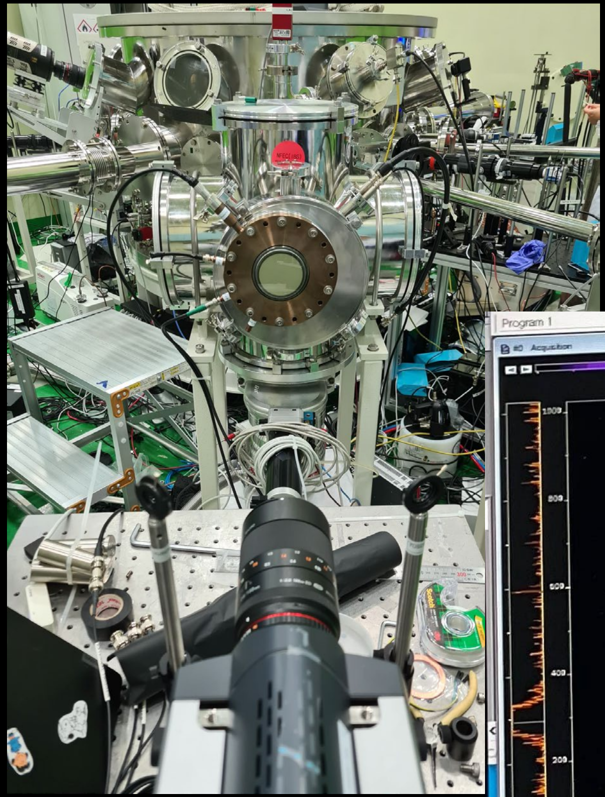
P. A. Kravchuk and D. G. Yakovlev, "Strong plasma screening in thermonuclear reactions: Electron drop model," Physical Review C, vol. 89, no. 1, p. 015802, Jan. 2014, doi: 10.1103/PhysRevC.89.015802.

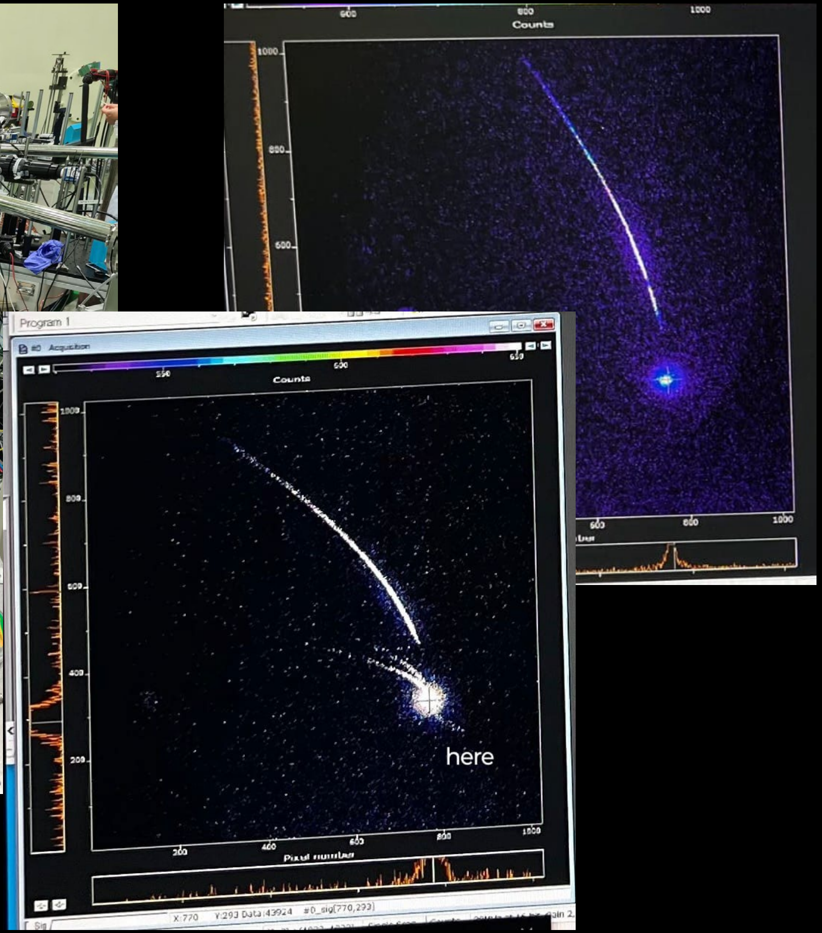
DD-FUSION EXPERIMENT @ GIST 2023-24

Online Thomson Parabola with MCP-readout developed in collaboration with ELI-NP (D. Doria et al.) and GIST for CH_4 test.



A. Russo, M. Costa (LNS)

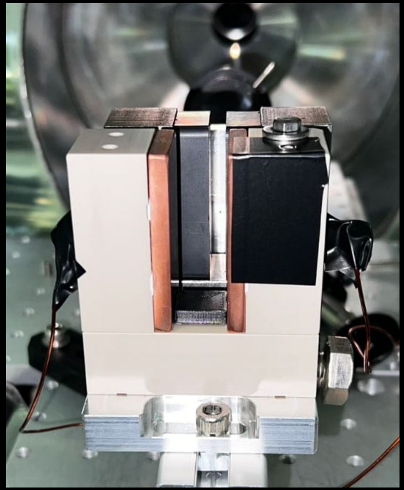




VERSATILE ARRAY FOR LASER-INDUCED NUCLEAR ASTROPHYSICS RESEARCH

Science-driven, portable, cost-efficient. *And partially funded*.

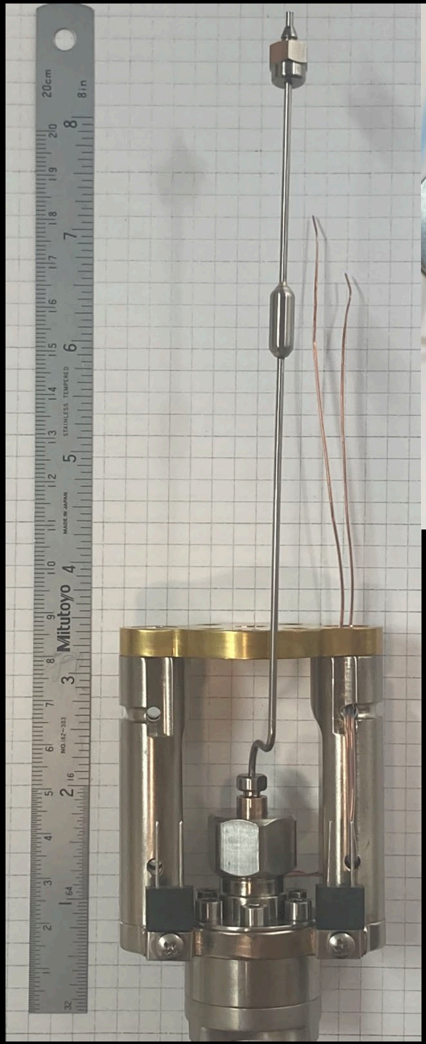
- cryo-cooled supersonic nozzle (ready to be characterized in 2026 in collaboration with INFN-LNF, Eupraxia) ;
- compact interaction chamber (CAD ready, *need money*) ;
- neutron ToF fast plastic scintillators (preliminary tests ok, collaboration with CHINEXT@LNS group) ;
- charged particle ToF detectors: CVD diamonds (1 realized and tested in collaboration with Rome TVU, R&D on DE/E); FCs are LNS-ready to be optimized;
- 2 TPS (prototype realized and tested in collaboration with ELI-NP, need mechanical optimization and *need money*).

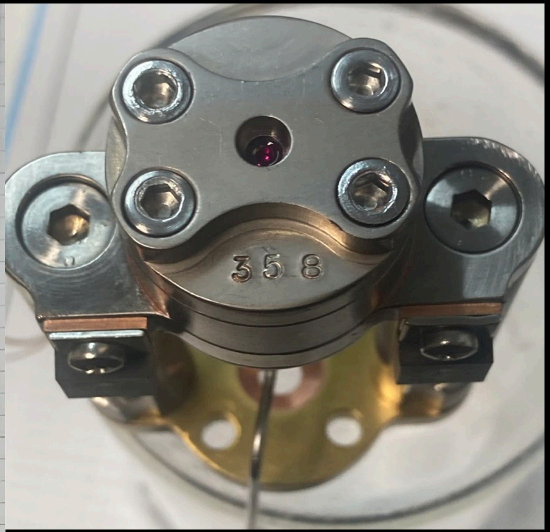


VERSATILE ARRAY FOR LASER-INDUCED NUCLEAR ASTROPHYSICS RESEARCH

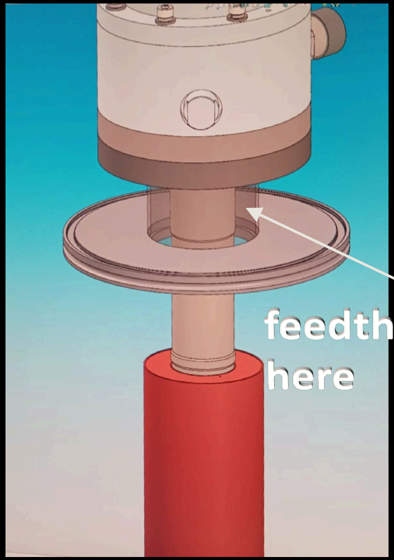
Current status

- Cryogenic EVEN-LAVIE valve for the production of gas jet at 10 K with high density (> 10^{19} cm^{-3}), highly collimated with high repetition rate (> 100 Hz);
- Sumitomo CH-202 two-stage Gifford-McMahon (GM) cryocooler (Helium, closed-cycle)
- Lake Shore Model 336 temperature controller with 2 calibrated sensors and heaters





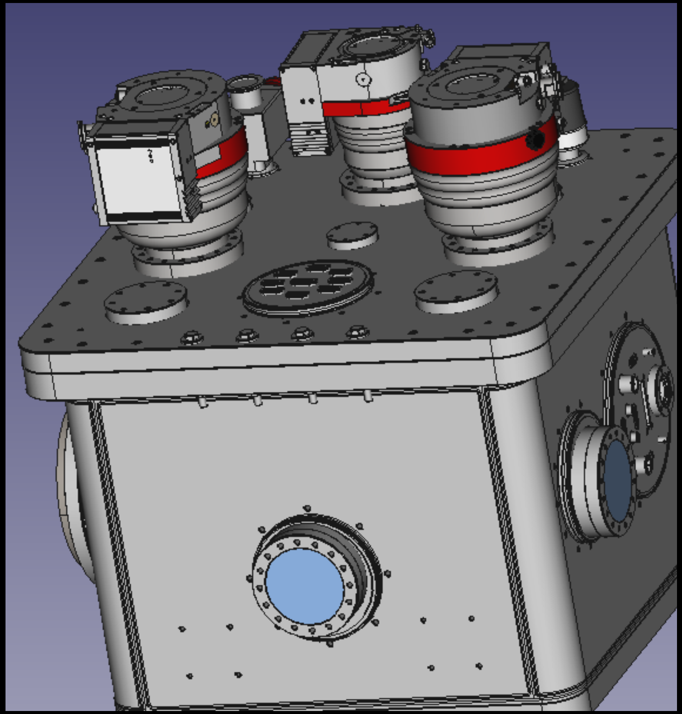
VERSATILE ARRAY FOR LASER-INDUCED NUCLEAR ASTROPHYSICS RESEARCH



M. Costa (LNS)

Current status

- compact interaction chamber (CAD submitted for final quotation, *need money*) ;
- test @ FLAME (LNF) probe beam in 2026;
- adapters and cable management under optimization



FLAME GEM-AREA chamber (LNF)

CONCLUSIONS

High power lasers technology is advancing rapidly → opportunity for systematic in-plasma measurements

Laser-cluster experiments provide a promising paradigm for Nuclear Astrophysics, in-plasma cross-section measurements and electron screening studies are possible

Preliminary results at GIST with high repetition rate confirm reproducibility

Analysis for low energy points is ongoing..

PID is not easy & MCP+CCD is expensive (90k€?) → Idea of using Timepix3-QuadPIX as spectrometer readout (G. Claps, LNF)

Is EMP destroying all sensitive electronics? Shielding for spectroscopic amplifier?

Prompt gammas detectable? Gas Cherenkov Detectors (NIF) or..?


THE 13TH EUROPEAN SUMMER SCHOOL ON
EXPERIMENTAL NUCLEAR ASTROPHYSICS
Primordial Nucleosynthesis and Early Stars, Stellar Evolution, Hydrostatic and Explosive Nucleosynthesis, Plasmas in Stars and Laboratories, Detectors and Facilities for Nuclear Astrophysics, Experiments with rare and radioactive isotopes, Indirect Methods
14-20 JUNE 2026
ACI TREZZA (CT)

THANK YOU