Laser-induced Nuclear Astrophysics @ LNS

D. Lattuada
University of Enna KORE
Laboratori Nazionali del Sud - INFN

The AsFiN group

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The AsFiN Collaboration

@Catania: A. Bonasera, S. Cherubini, G. D'Agata, A. Di Pietro, P. Figuera, G.L. Guardo, M. Gulino, M. La Cognata, **L. Lamia**, D. Lattuada, A.A. Oliva, **R.G. Pizzone**, G.G. Rapisarda, G.M.Restifo, S. Romano, D. Santonocito, M.L. Sergi, R. Spartà, C. Spitaleri, A. Tumino

@Napoli M. La Commara **@Padova**_M. Mazzocco

@Perugia M. Busso, S. Palmerini, M. Limongi, A. Chieffi, M.C. Nucci

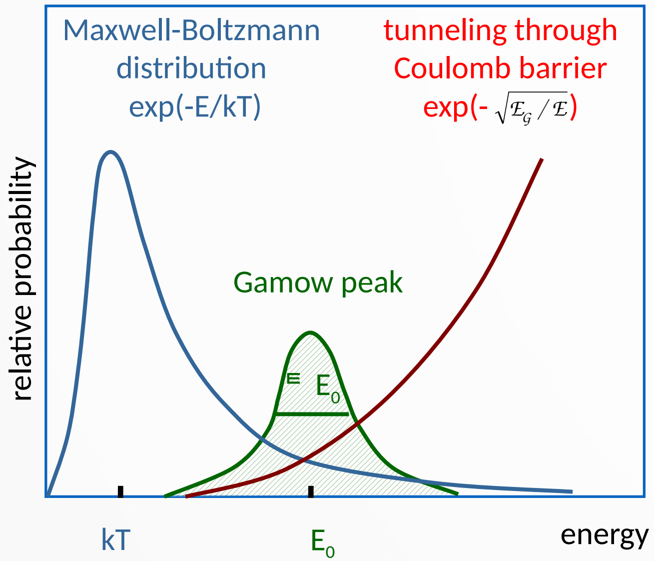
Collaborations

Cyclotron Institute,Texas A&M,US: R. Tribble, V. Goldber
Texas A&M Commerce US: C. Bertulani
Florida State University US: I. Wiedenhofer
Notre Dame University US: M. Wiescher, M. Couder
C.N.S. Riken, Wako, Japan: S. Kubono, H. Yamaguchi, S. Hayaka
University of Taskent: B. Irgaziev, R. Yarmukhanmedov
CIAE, Beijing, China: S. Zhou, C. Li, Q. Wen
Nuclear Physics Institute, ASCR, Rez, Czech Rep.: V. Kroha, V. Burjan, J. Mrazek
Nipne IFIN Bucharest: L. Trache
ELI-NP Bucharest: C. Matei, D. Balabanski
Atomki, Debrecen, Hungary: G. Kiss
CSNSM, Orsay, France : A. Coc , F. Hammache, N. De Sereville
University of Catalunya: J. Jose
Rudjer Boskovic Institute Zagreb Croatia: N. Soic, M. Milin
INFN Sez. Napoli e UniNA: D. Pierroutsakou, C. Parascando
University of Pisa: S. Degl'Innoccenti, P. Prada Moroni
GIST, Gwangju, South Korea: W. Bang

Outline

- Nuclear Astrophysics
- Why lasers?
- How?
- Why at LNS?
- What next?

Nuclear reactions in stars..



Example: T ~ 15x10^6 K (T_6 = 15)

reaction	C.barrier (MeV)	E_0 (keV)	area under Gamow peak
p + p	0.5	5.9	7.0x10^{-6}
^{12}C + ^{12}C	2.242	56	5.9x10^{-56}
^{16}O + ^{16}O	10.349	237	2.5x10^{-237}

For T ~ 200x10^6 K, E_0 ~ 320 keV
(KT ~ 17 keV)

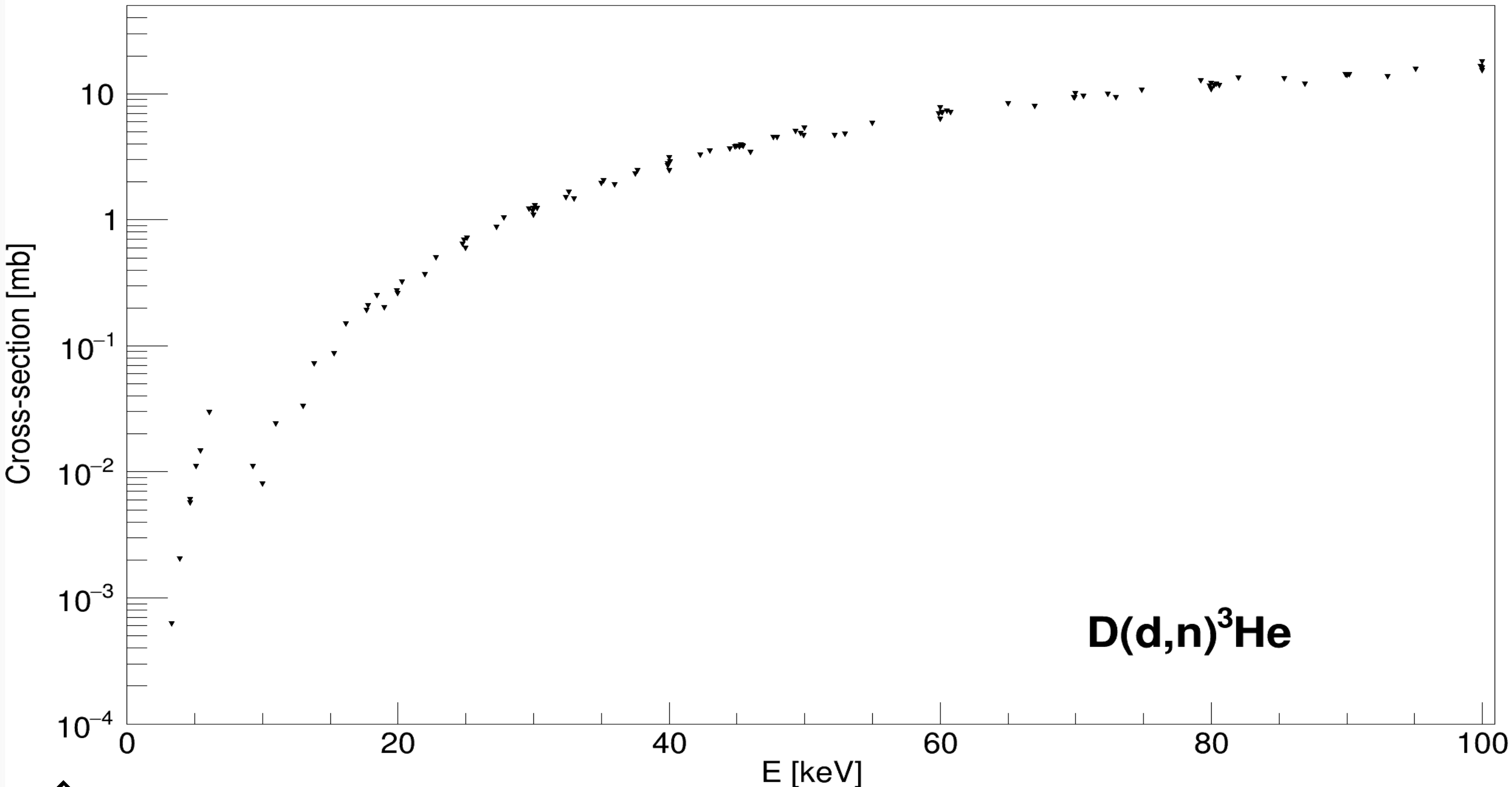
Gamow peak: most effective energy region for thermonuclear reactions
It is where measurements should be carried out

10^{-18} barn < σ < 10^{-9} barn →

- EXTRAPOLATION
- LUNA, JUNA (background suppression)
- INDIRECT METHOD (THM, ANC)

.. explore directly in a laboratory plasma!

0-day exp: Deuterium burning



GIST23 plan

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: 50/50

Electron screening

Big Bang Nucleosynthesis

Electron screening

$$\sigma_s(E)=\sigma_b(E+U)$$

$$f(E)=\frac{\langle\sigma_s v\rangle}{\langle\sigma_b v\rangle}\approx e^{\frac{\pi\eta U}{E}}$$

$$U\approx\frac{Z_1 Z_2 e^2}{R_o}$$

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

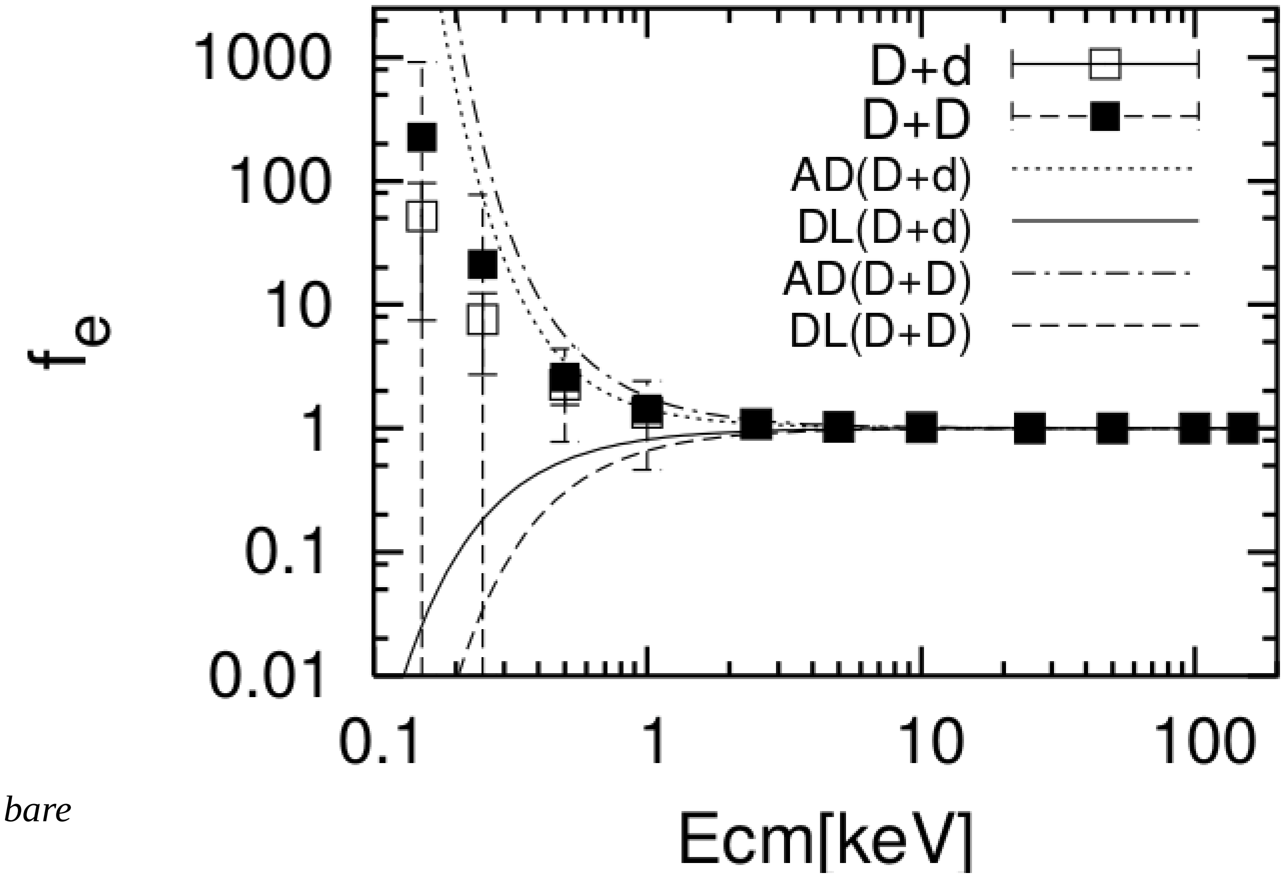


Fig. 1. Enhancement factor as a function of incident center-of-mass energy for the reactions D+*d* and D+D. Error-bars represent the variances obtained from the events generated for each beam energy.

Electron screening

Relatively small enhancements due to electron screening at energies E/U = 100 could cause significant errors in the extrapolation to lower energies, if the cross section curve is forced to follow the trend of the enhanced cross sections without correcting for screening

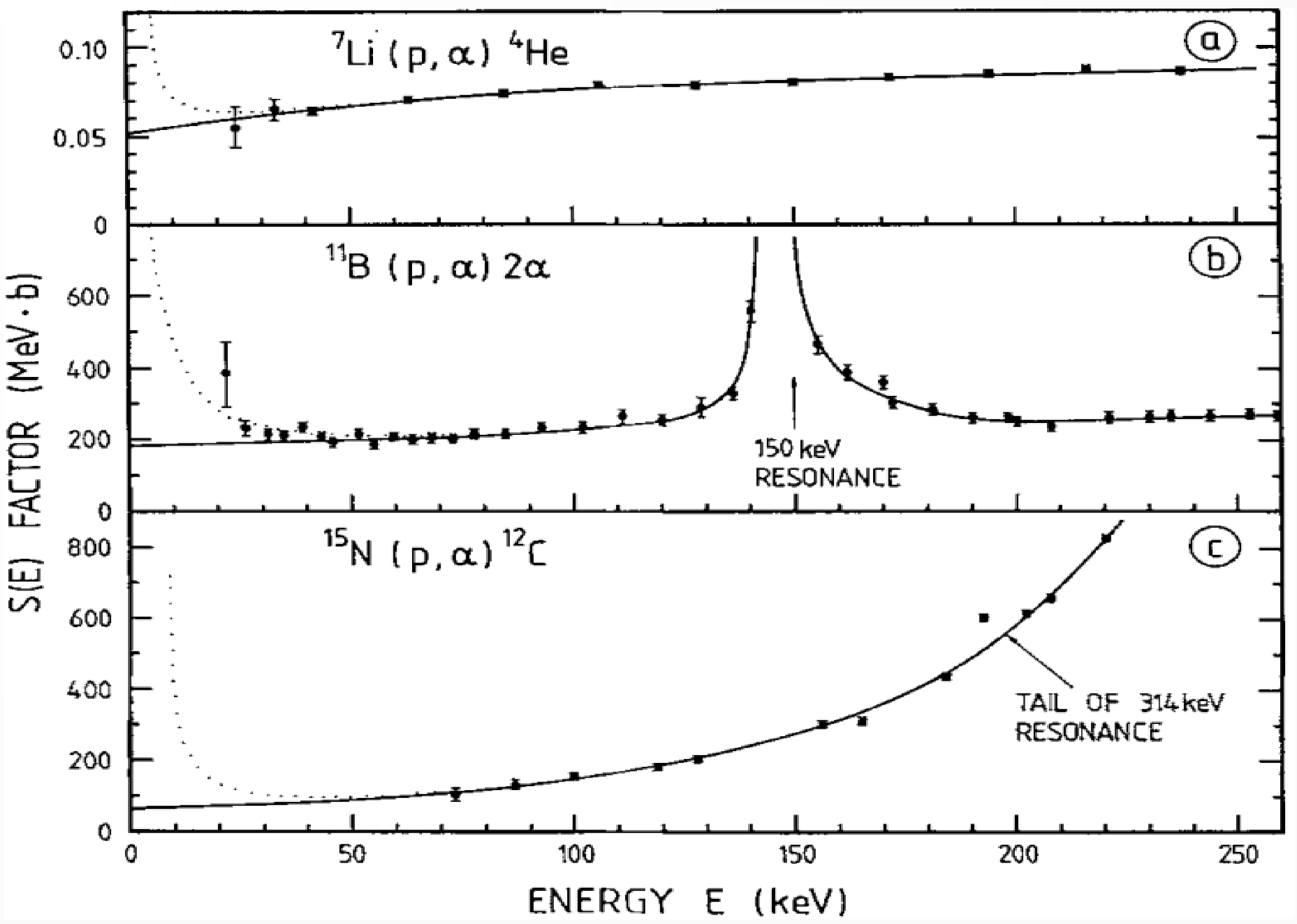
The whole effect of screening in this case ($U_0 << E_{max}$) *is then that the reaction rate with screening neglected has to be multiplied by the factor* $e^{-\frac{U_0}{KT}}$

$$R_D = 2.812 \, x \, 10^{-7} \rho^{-1/2} T_9^{1/2} \zeta^{-1} (cm)$$

$$Weak\ screening: R_D \gg dist_{nuclei} (stars)$$

$$Intermediate\ screening: \langle E_C \rangle \approx KT$$

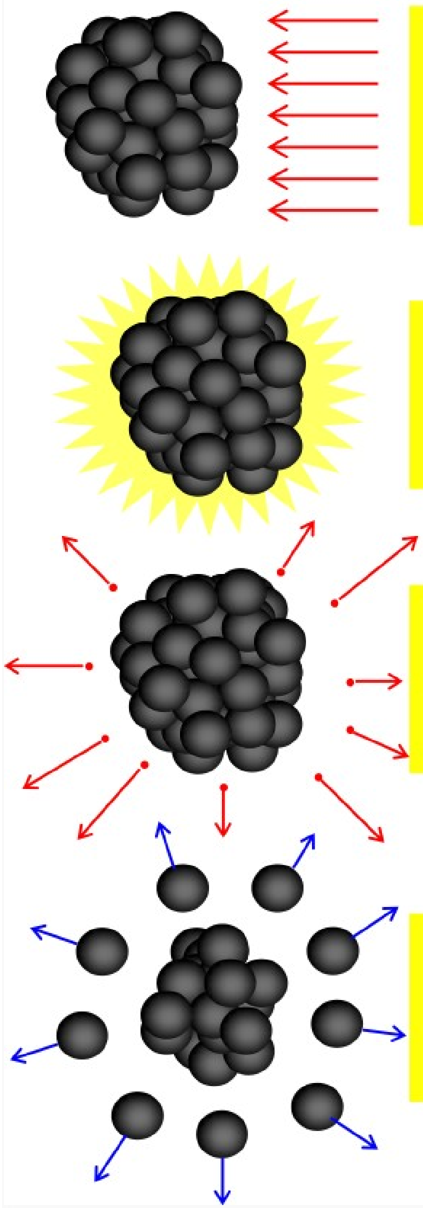
$$Strong\ screening: \langle E_C \rangle \gg KT$$



Effects of electron screening on low-energy fusion cross sections Assenbaum, H. J., Langanke, K., & Rolfs, C. 1987

ELECTRON SCREENING AND THERMONUCLEAR REACTIONS E. E. SALPETER 1954

How? Coulomb explosion of cryo-cooled molecular clusters



Step 1

Clusters are irradiated by high intensity laser pulse (~10^{16}~10^{18} W/cm^2).

Step 2

Laser pulse energy is first absorbed by electrons via heating mechanisms such as rapid collisional heating.

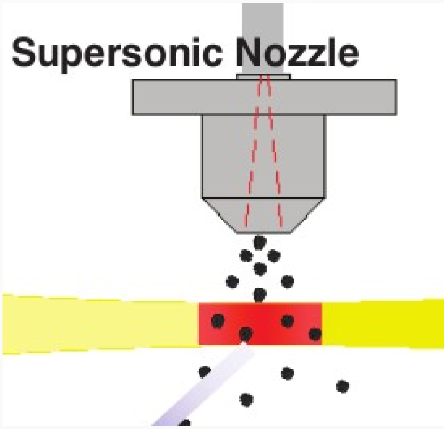
Step 3

Electrons escape from the cluster and leave positive charge build-up on the cluster.

Step 4

The cluster "explodes" and deuterons acquire multi-keV kinetic energy.

- Enhanced laser absorption
- Thermal distribution of accelerated species
- (no ponderomotive force)
- 4π isotropic
- Control over the MB temperature by changing the focus and/or the temperature of the nozzle



How?

E = 100-140 J

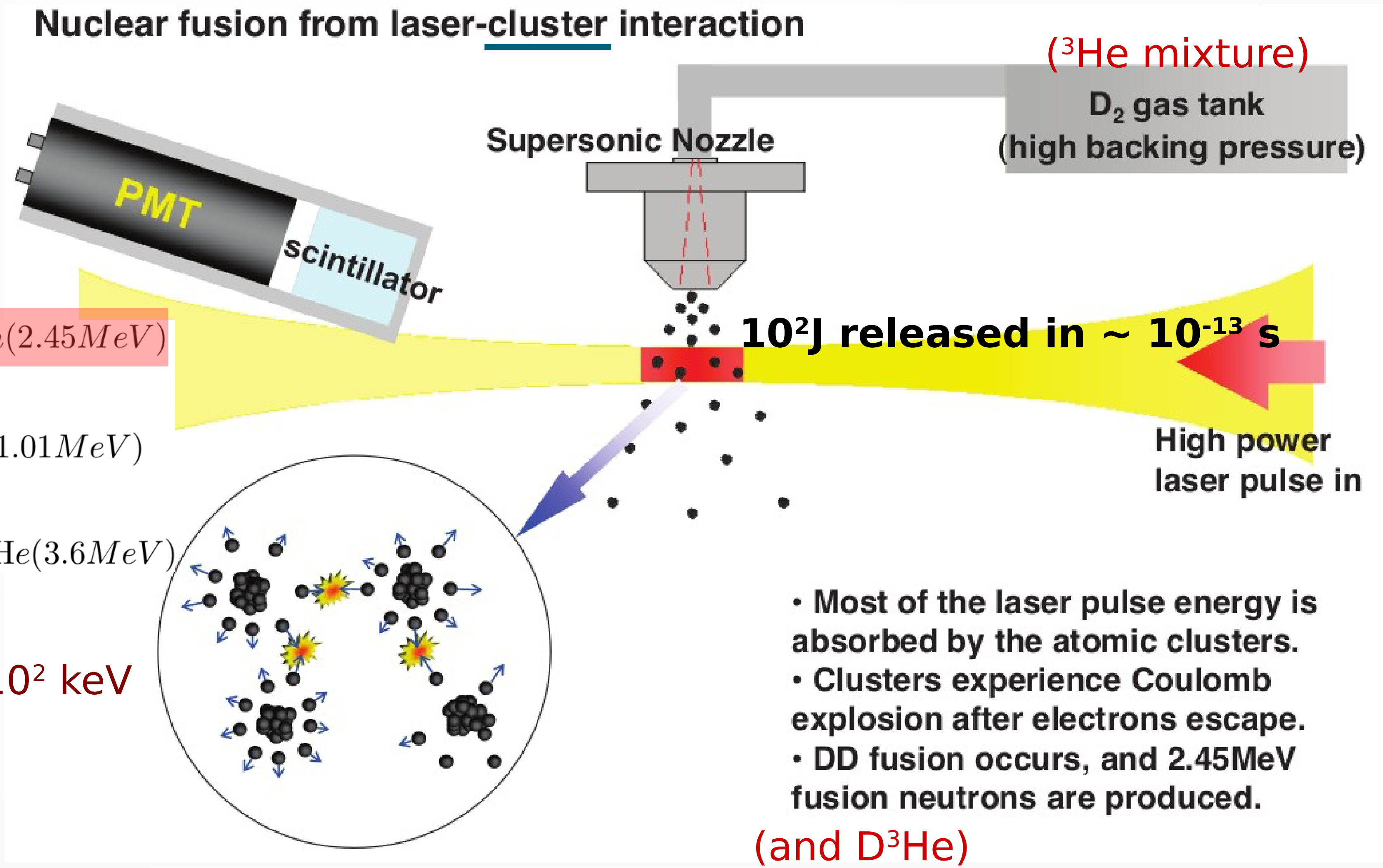
Pulse duration: 140 fs

Rep. Rate: ~ 1/hour

CW: 1057 nm

Intensity ~ 10^{21} W/cm^2

UT Petawatt Laser 2011



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

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

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

Deuteron Kinetic Energy < 10^2 keV
Density ~ 10^{18} atoms/cm^3

10^5-10^7 neutrons per shot

Ditmire, T. et al. Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters. Nature 398, 489–492 (1999).

How?

D(d,n)^{3}He   D(d,p)t

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

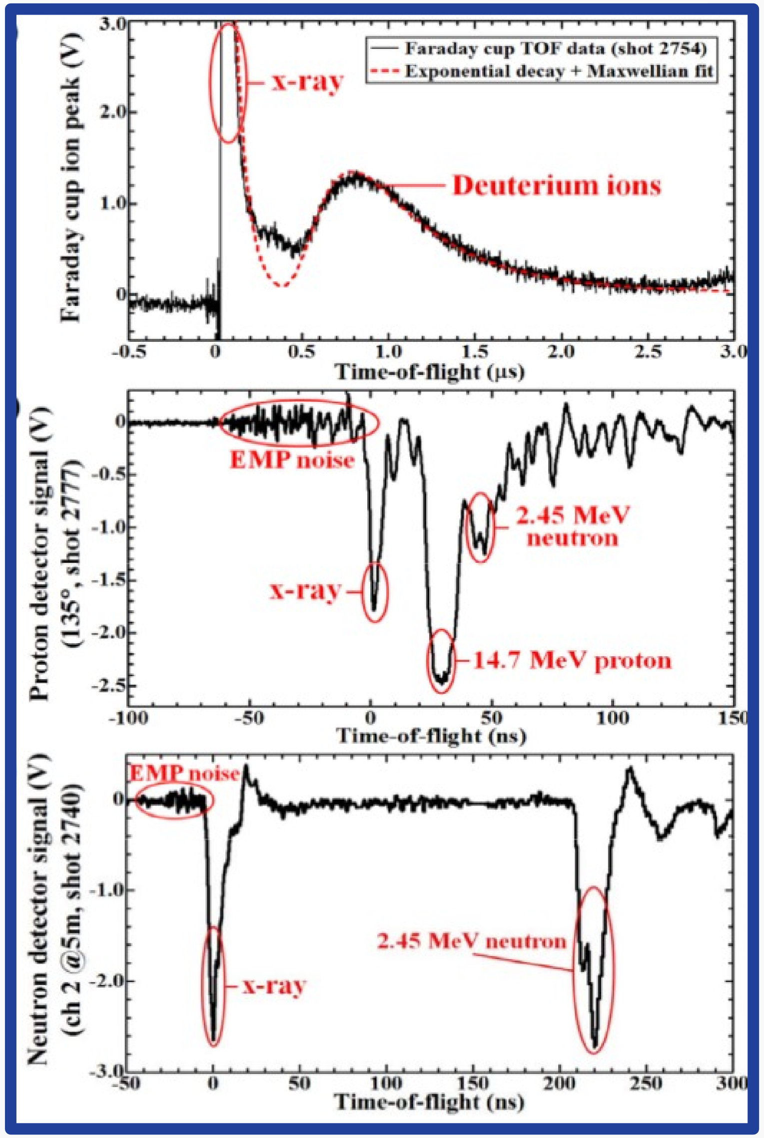
$$= l\rho_D \int \frac{dN}{dE} \sigma_{BB}(E) dE$$

$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{E_G/E}}$$

$$2\pi\eta = b/\sqrt{E}$$

$$b = 0.9898 Z_i Z_j \sqrt{A}\ \mathrm{MeV}^{1/2}$$

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta(E))$$

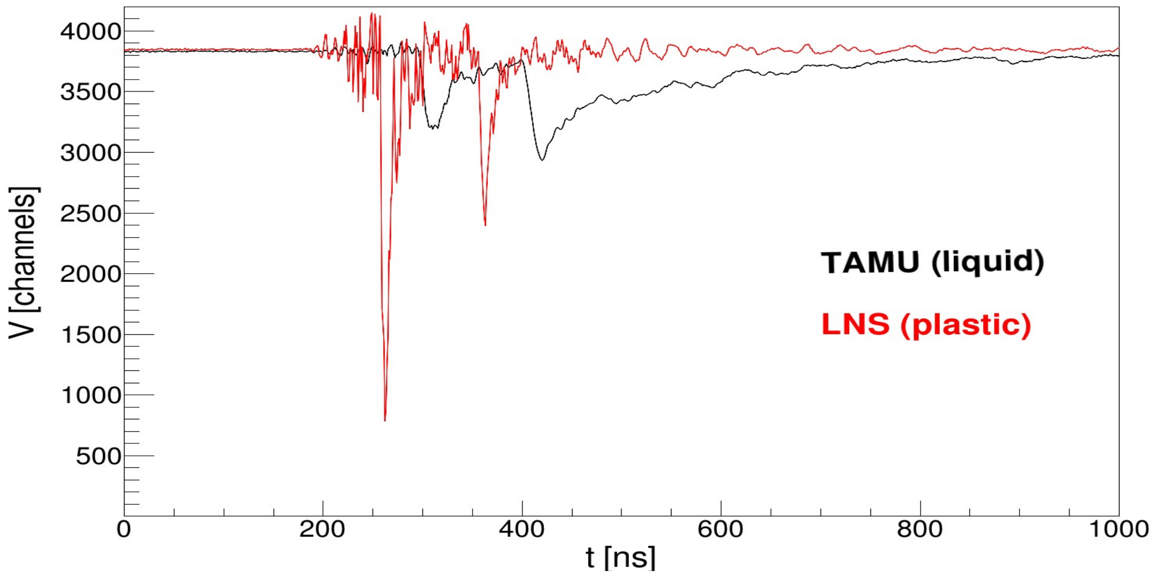


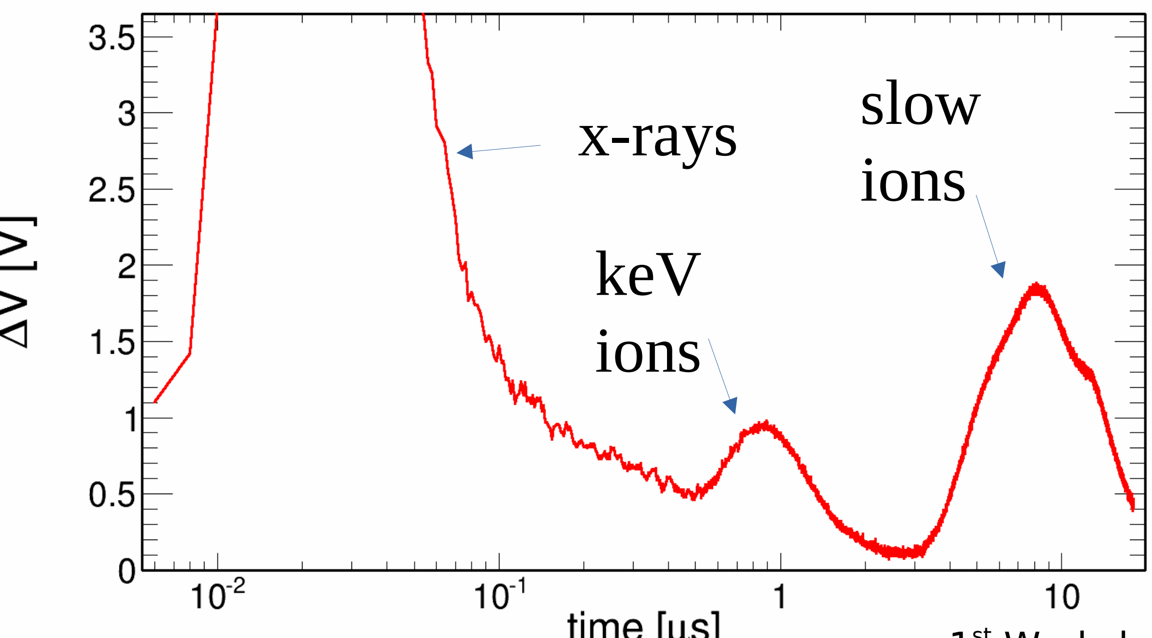
n & p → scintillators, diamond, CR39

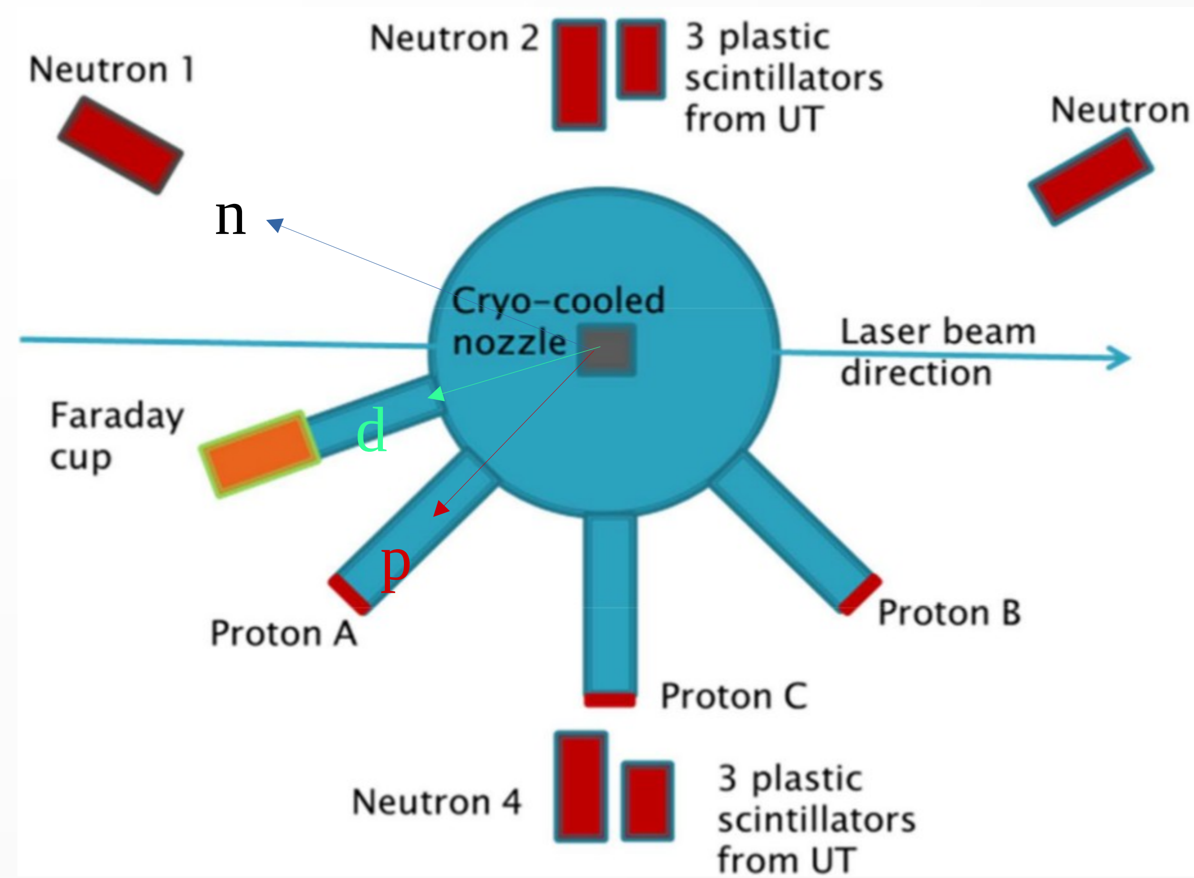
Deuteron spectrum → MCP, FC, diamond, CR39

Gas and plasma diagnostics → interferometry, CCD, previous Rayleigh scattering measurements

2011 & 2016 experiments







PHYSICAL REVIEW C
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Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

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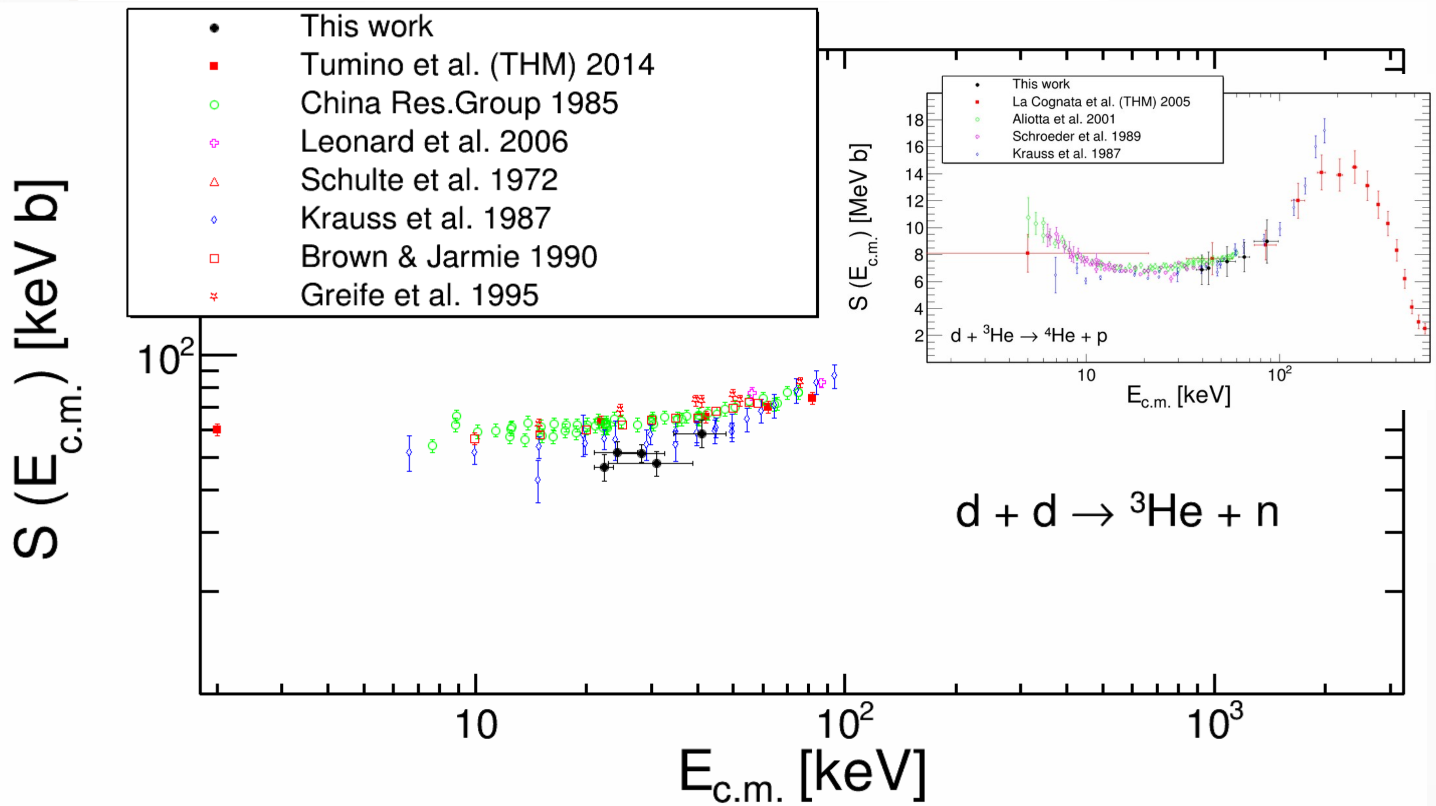
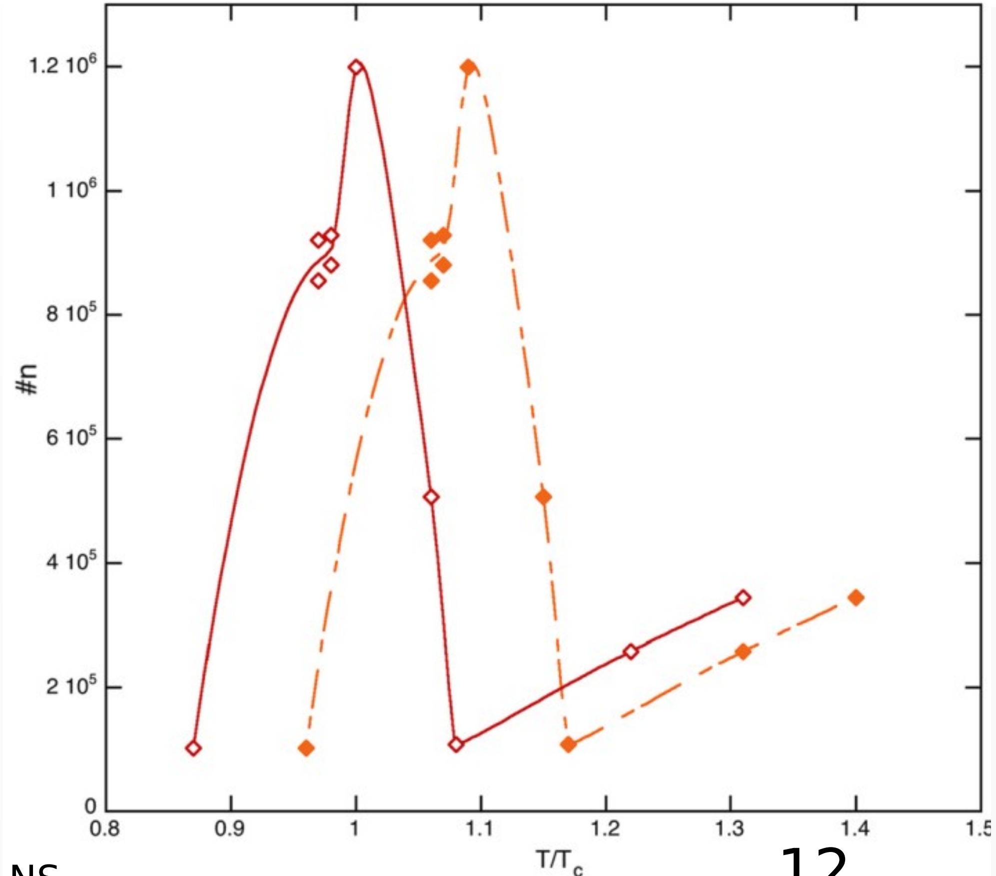
Neutron enhancement from laser interaction with a critical fluid

H.J. Quevedo[a], G. Zhang[b,1], A. Bonasera[b,c,*], M. Donovan[a], G. Dyer[a], E. Gaul[a], G.L. Guardo[c], M. Gulino[c,d], M. La Cognata[c], D. Lattuada[c], S. Palmerini[e,f], R.G. Pizzone[c], S. Romano[c], H. Smith[a], O. Trippella[e,f], A. Anzalone[c], C. Spitaleri[c], T. Ditmire[a]

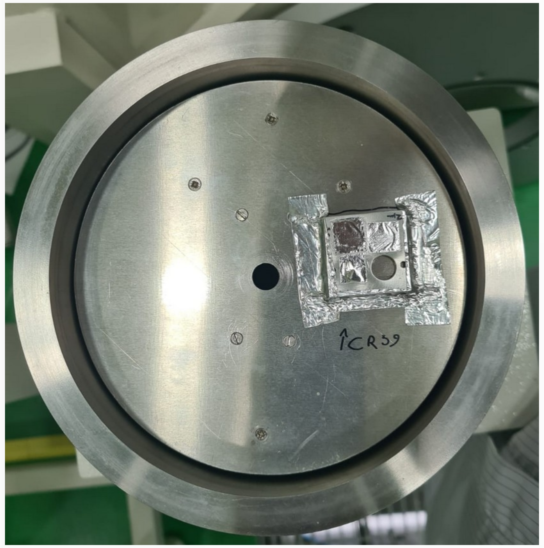


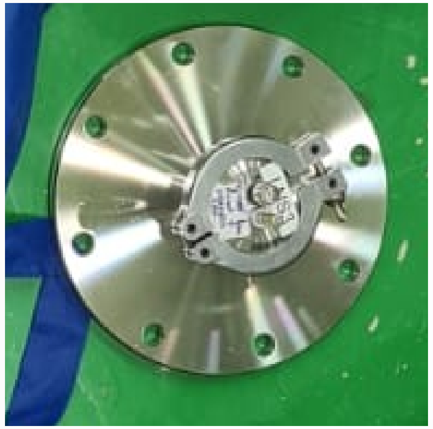


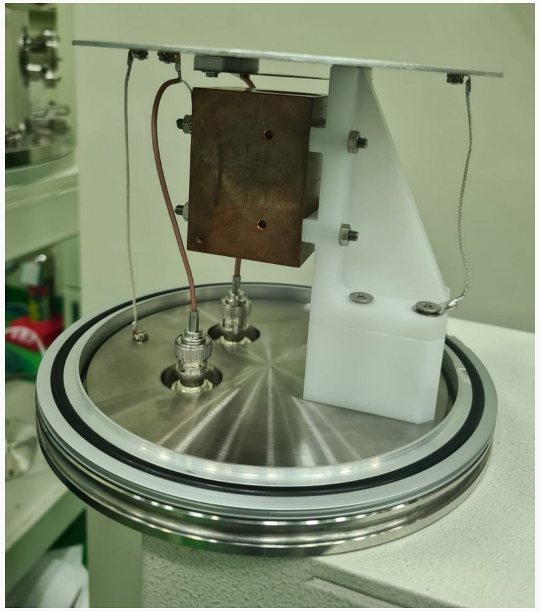
Where

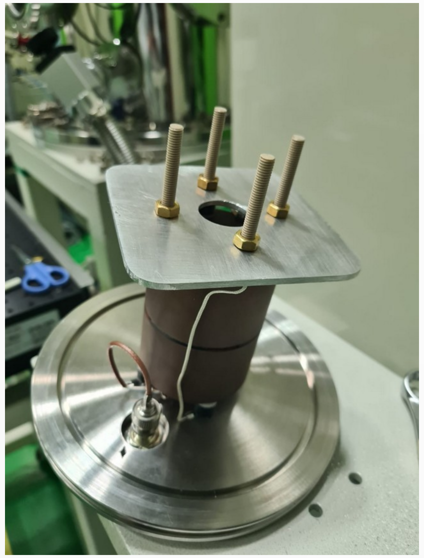
- iLUCE perfect candidate for future high repetition studies
- Long-standing expertise on nuclear physics, accelerators, detectors, electronics, cryogenics, target development, etc.. @LNS (and @LNF)
- Optimization of the setup while under construction (tests @ FLAME)
- Unique possibilities of new paradigm of interaction in synergy with standard accelerators

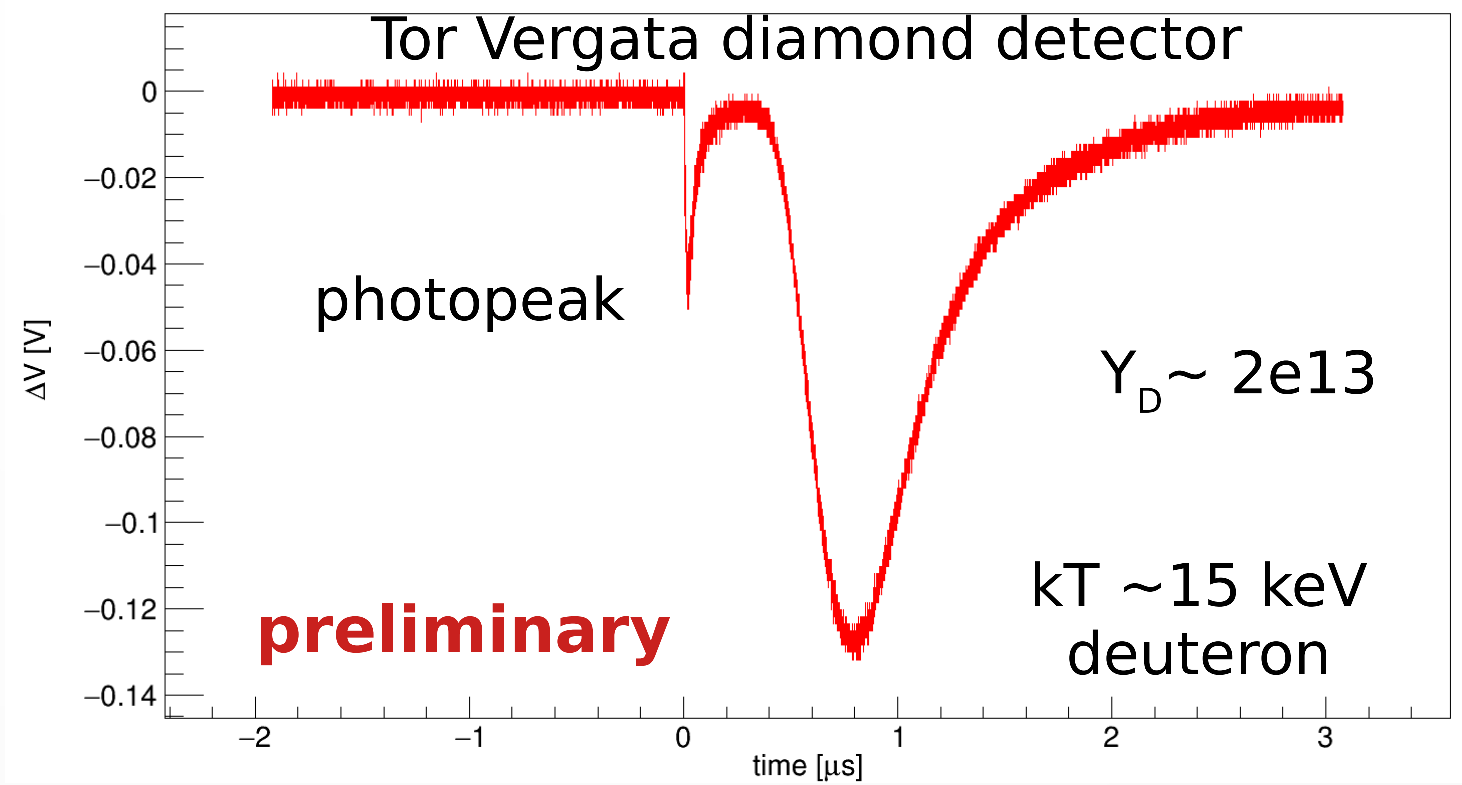
The Dec23 GIST experiment







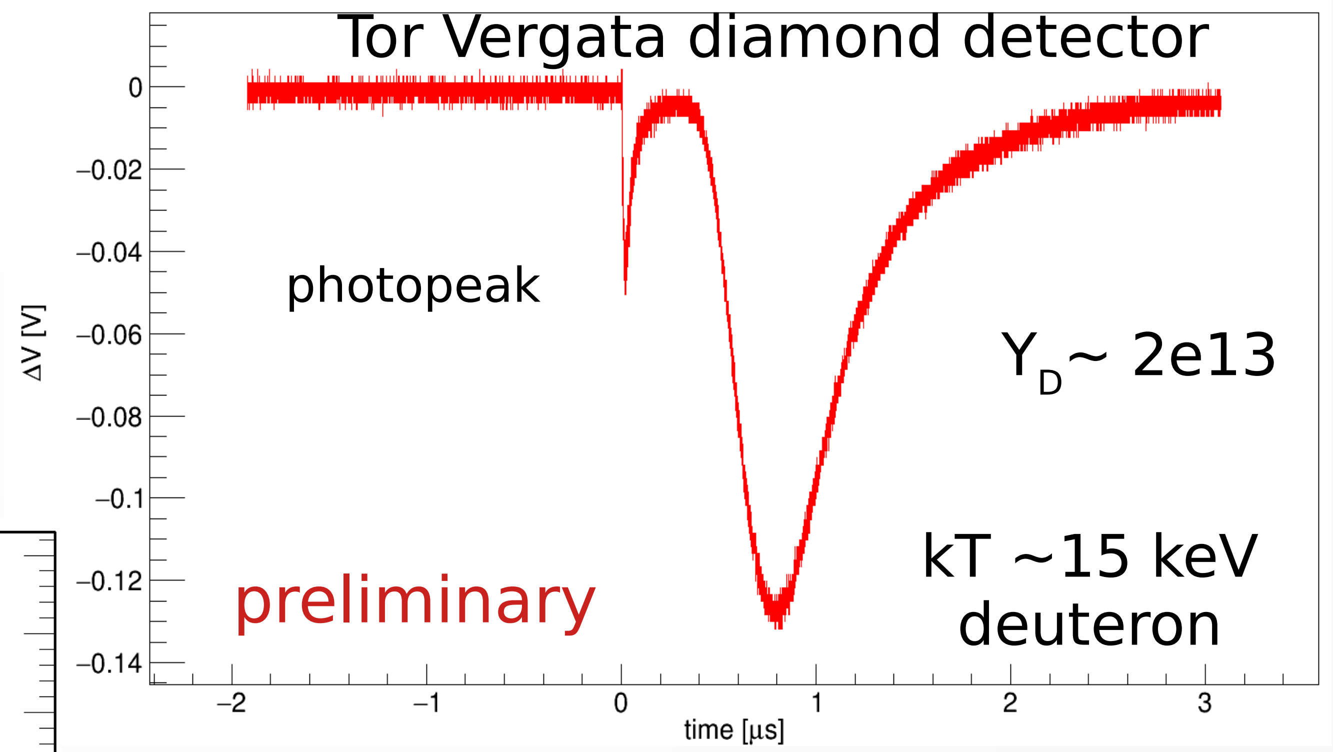




Over 3000 shots, with T control between kT ~ 1 keV and kT ~ 40 keV

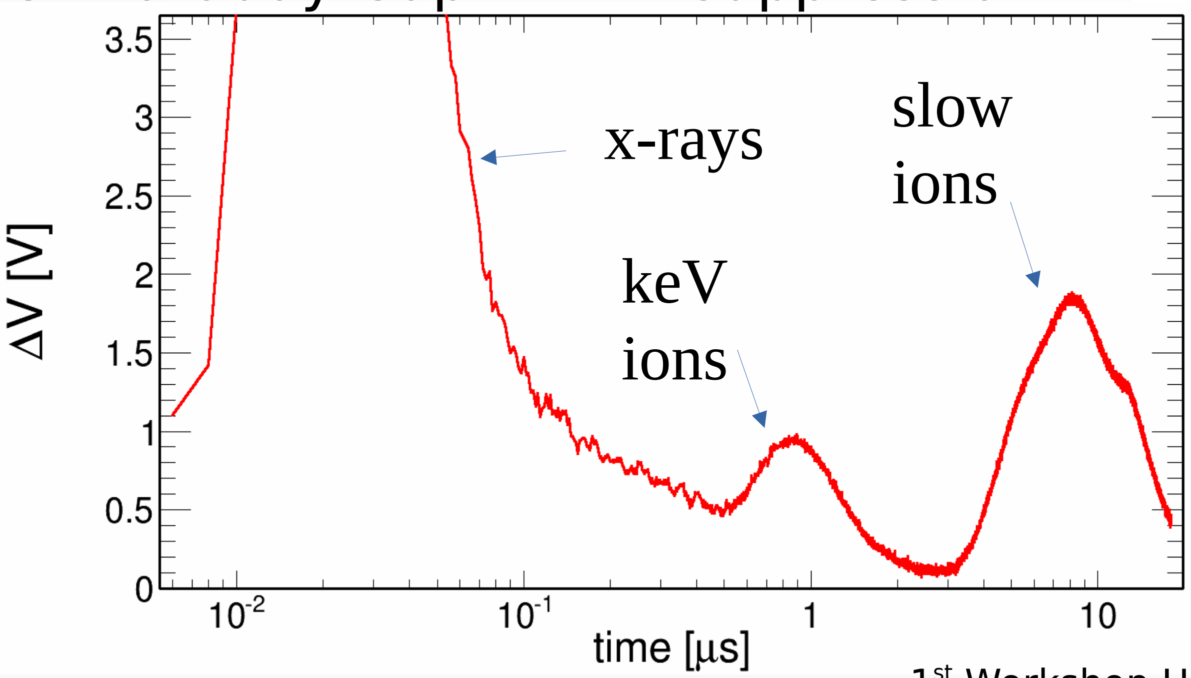
Experimental Faraday cup with magnetic suppression (LNS)

GIST23 & UT2011/16

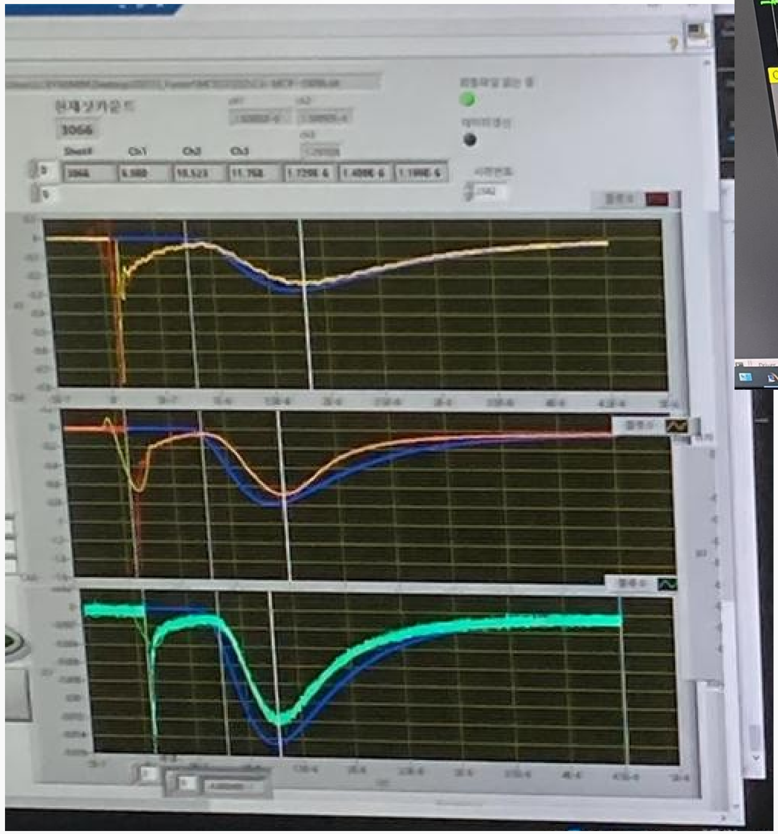


GIST

UT Faraday Cup with V suppression



The Dec23 GIST experiment



What next?

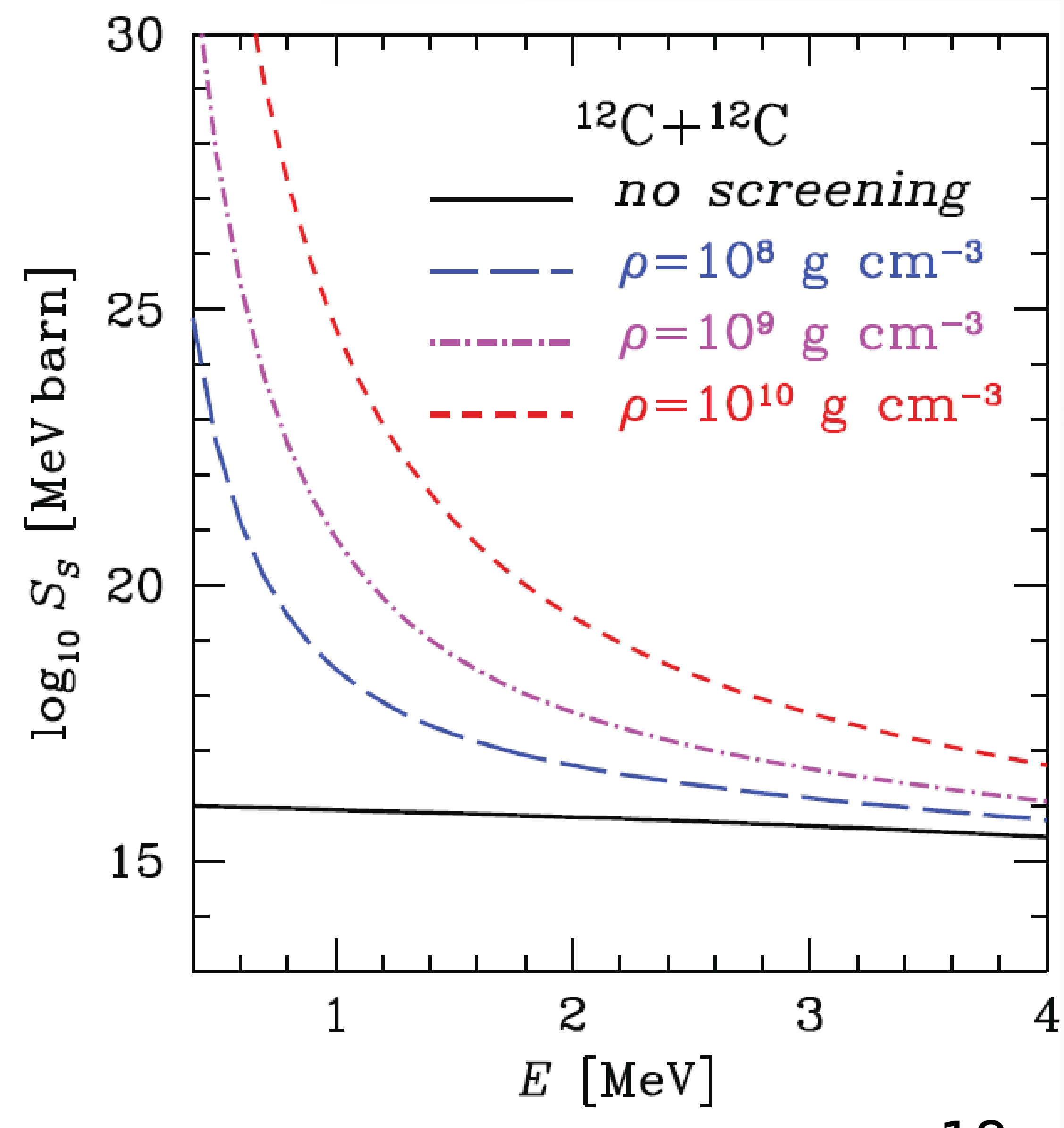
What next?

Can we accelerate ^{12}C?

Up to which energies?

We can detect them in ToF with FC and diamond detectors, but can we deconvolute the signals?

We would need a Thomson Parabola Spectrometer or..



What else?

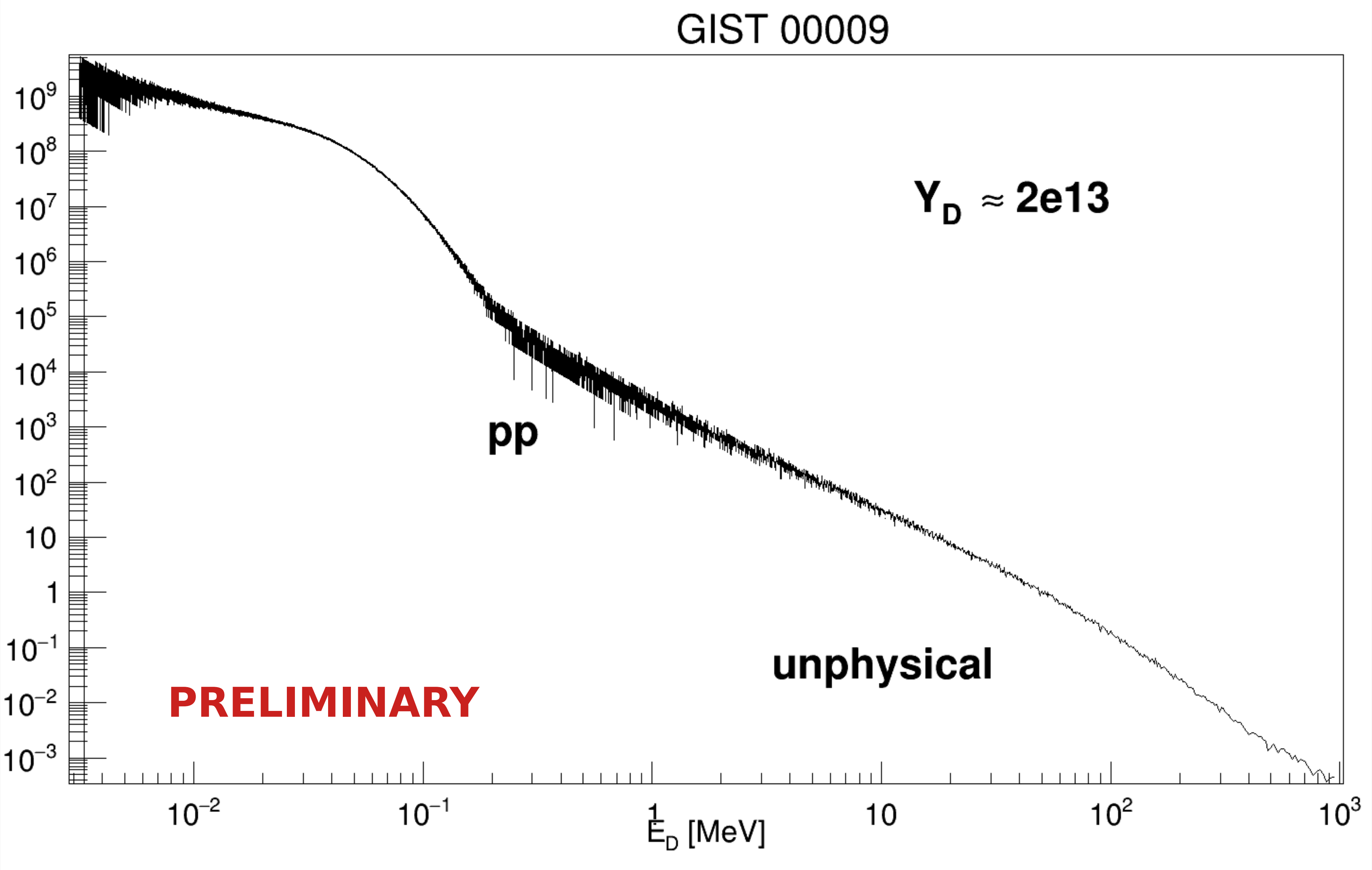
- LASER + TANDEM unique possibility at LNS
- In-plasma measurement of nuclear reactions relevant for astrophysics with a tandem-like beam profile impinging on a laser-induced plasma target, with high repetition
- SETBACKS: synchronization and reproducibility? Exploring a different paradigm: continuous beam + 1 laser shot per second/minute and compare → background evaluation can be tricky
- Need for intense R&D and careful planning

Conclusions

- High power lasers technology is steeply advancing
- Huge window of opportunity for Nuclear Astrophysics in-plasma studies
- Laser-cluster experiments provide a perfect paradigm
- In-plasma cross-section measurements have been performed
- In-plasma electron screening studies are possible (synergy with others)
- Need for systematic and multi-diagnostics approach
-
- ..so? Money and people.

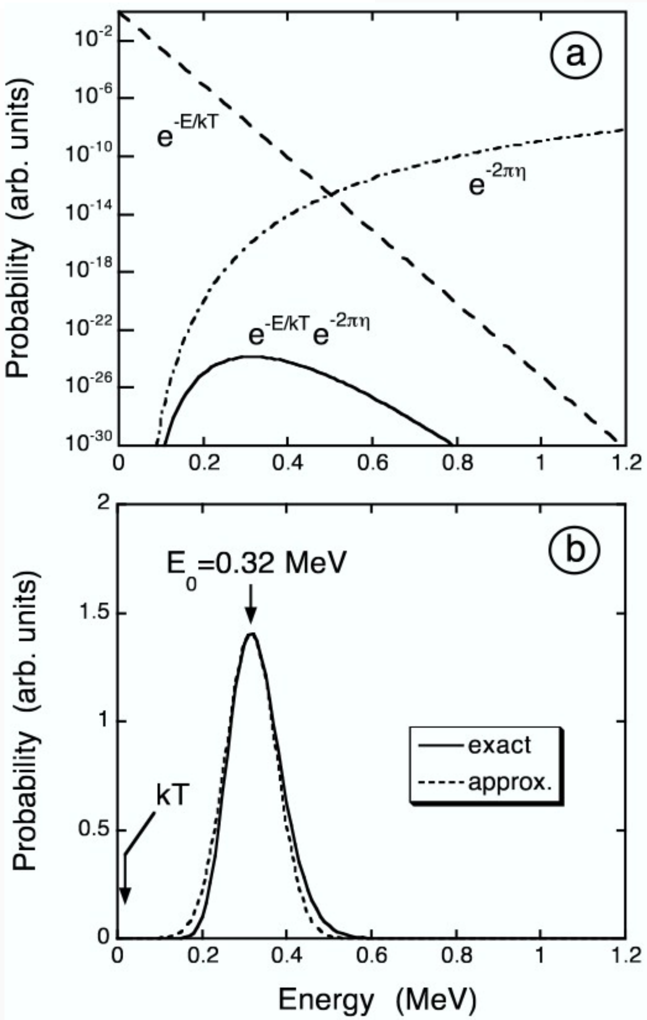
Q&A

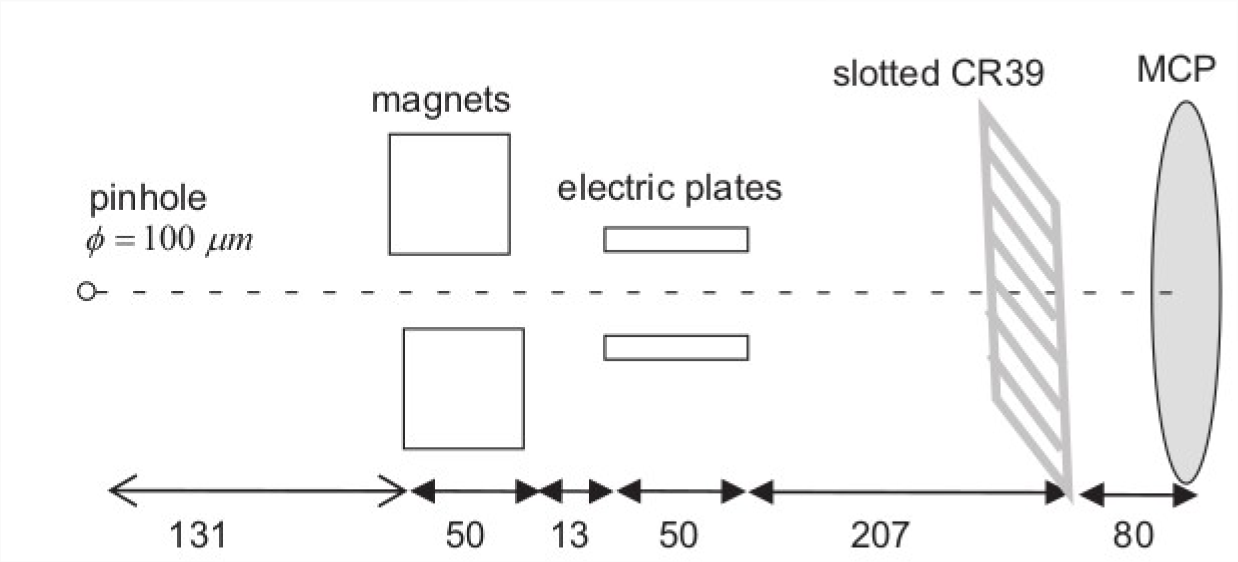
BACKUP

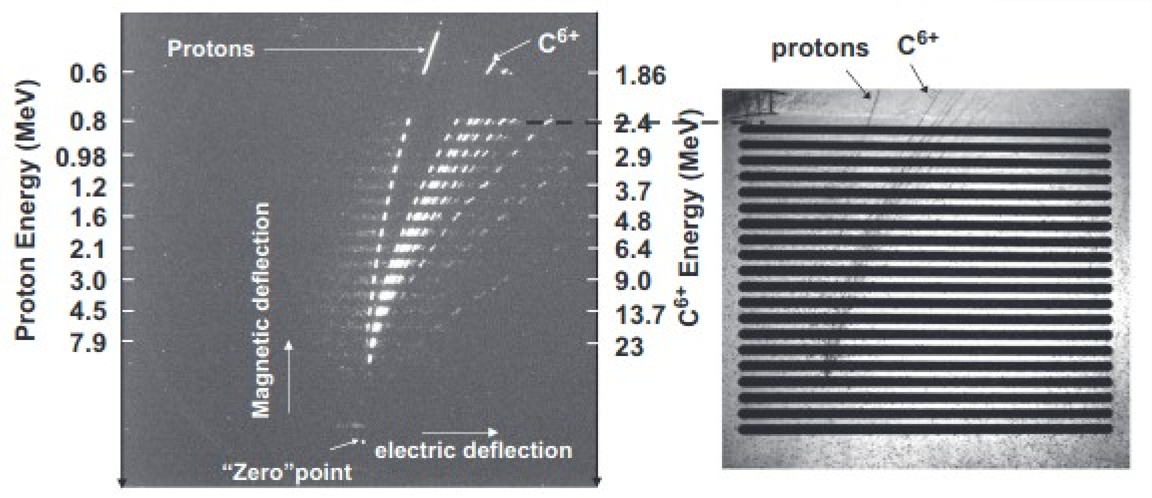

GIST 00009
$Y_D \approx 2e13$
pp
unphysical
PRELIMINARY
E_D [MeV]
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}

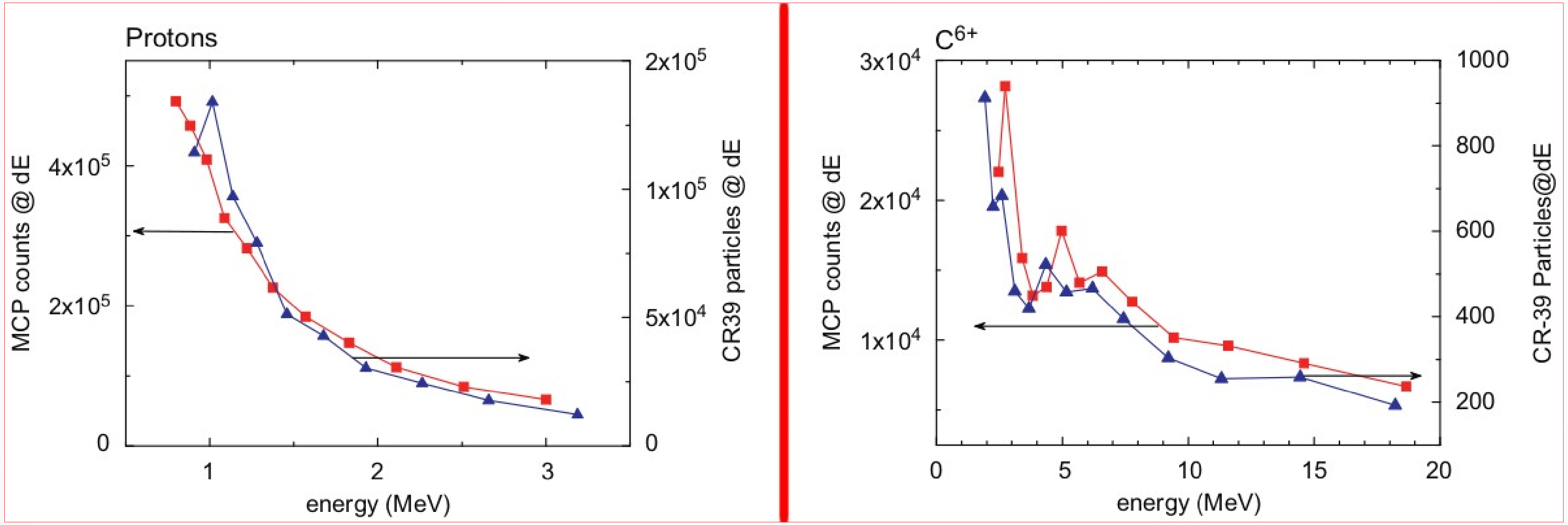
$$Y \approx \frac{t_d}{2} \int n_D^2 \langle \sigma_{D(D,n)^3He} v \rangle_{kT} dV + N_{ion} \int n_D \langle \sigma_{D(D,n)^3He} \rangle_{kT/2} dl$$

$^{12}C(\alpha,g)^{16}O$ - Nuclear Physics of Stars, C. Iliadis









Read by IP, MCP, LANEX, CMOS ..

R. Prasad et al., Calibration of Thomson parabola—MCP assembly for multi-MeV ion spectroscopy, Nuclear Instruments and Methods in Physics Research A 623 (2010)