

# Using lasers for Nuclear Physics: measuring cross-sections in (non) equilibrium plasmas

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*Texas A&M, College Station; INFN-LNS, CATANIA*

## INTRODUCTION:

Create energetic ion beams under specific physical conditions, for basic nuclear science and applications.

*A. Anzalone et al. (LAPLAFUS coll.), **Measuring the astrophysical S-factors in plasmas**,  
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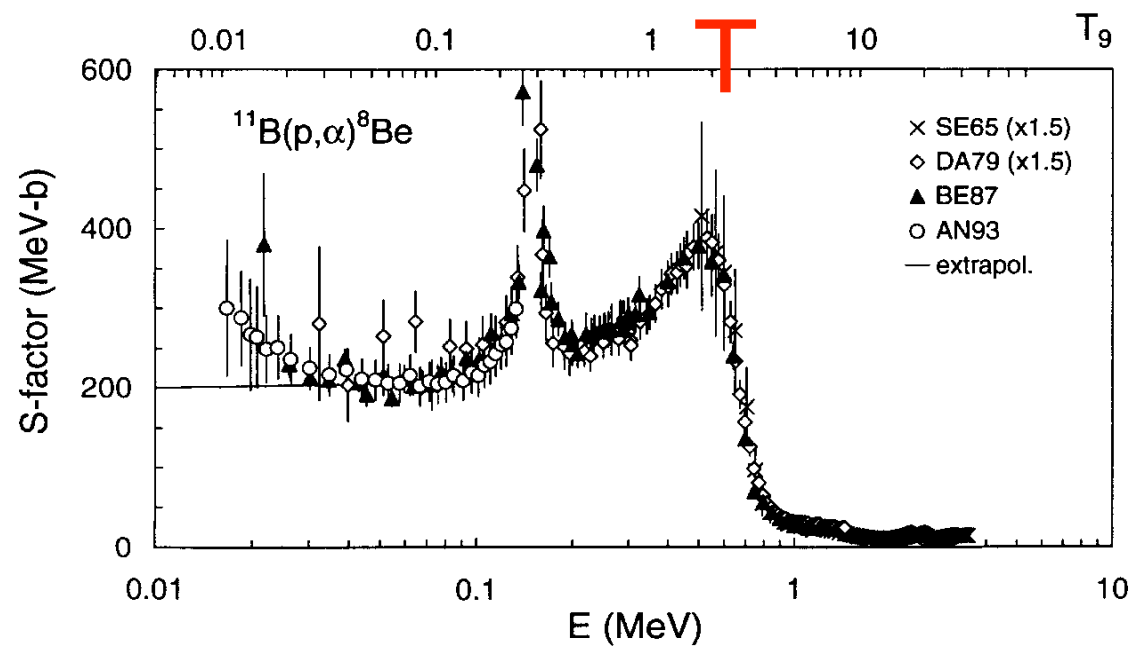
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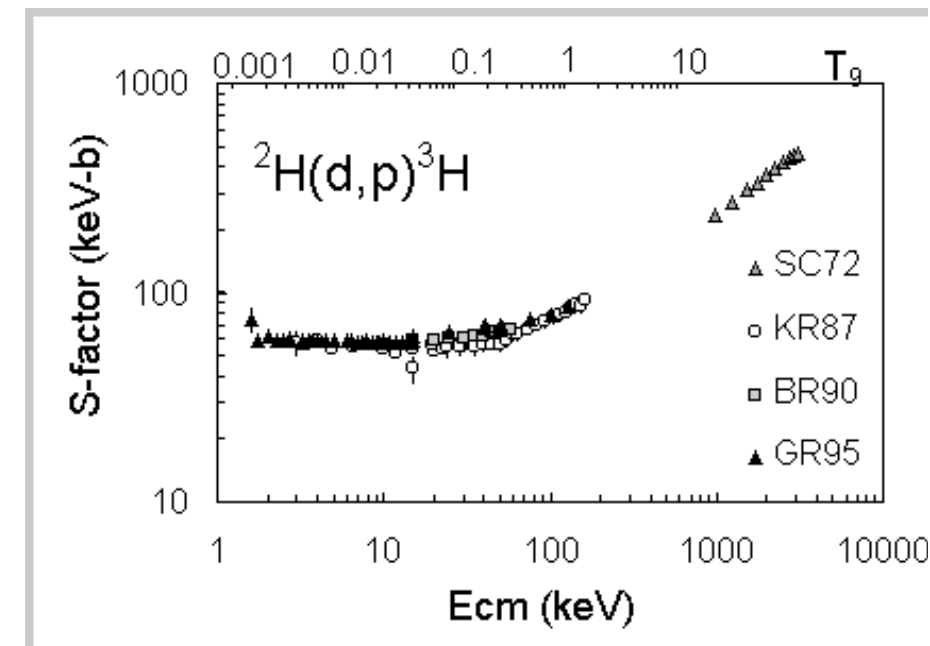
4<sup>th</sup> Int. Conf. on Fission properties of neutron rich nuclei. Sanibel Is. Nov. 2007. J Hamilton et al. eds. P.541.

# Measuring S-factors in hot and dense plasma

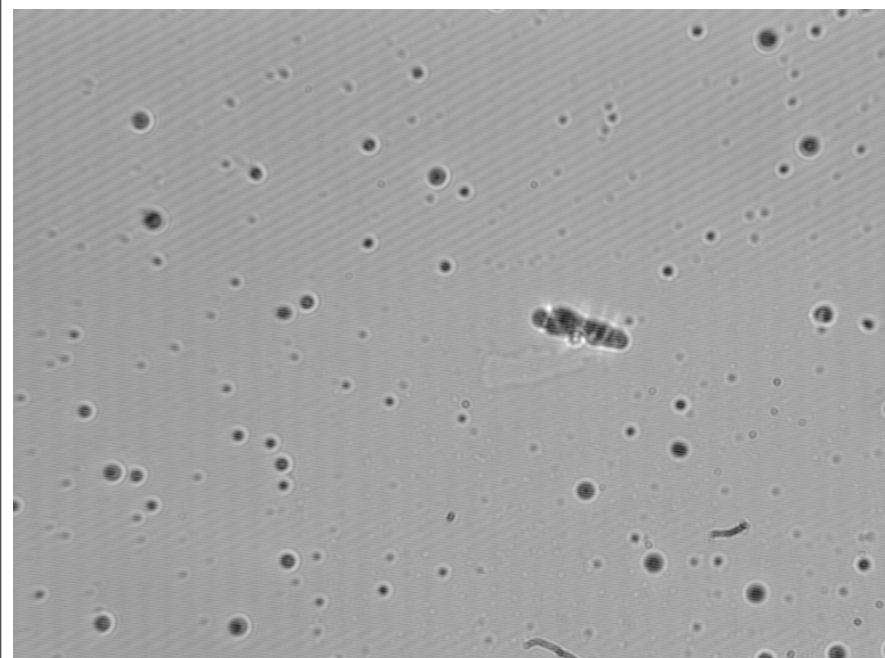
Measure the number of fusion  $N$ , the plasma  
phase space densities (i.e.  $T$ )  $n_1, n_2$  (e.g.  $p+B$ )  
and volumes then recover the cross-section  
(or S-factor)

$$N = \iint dV dt n_1 n_2 \langle \sigma v \rangle,$$
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{k_B T} - \frac{b}{\sqrt{E}}\right) dE$$


Add a third  
axis: density!

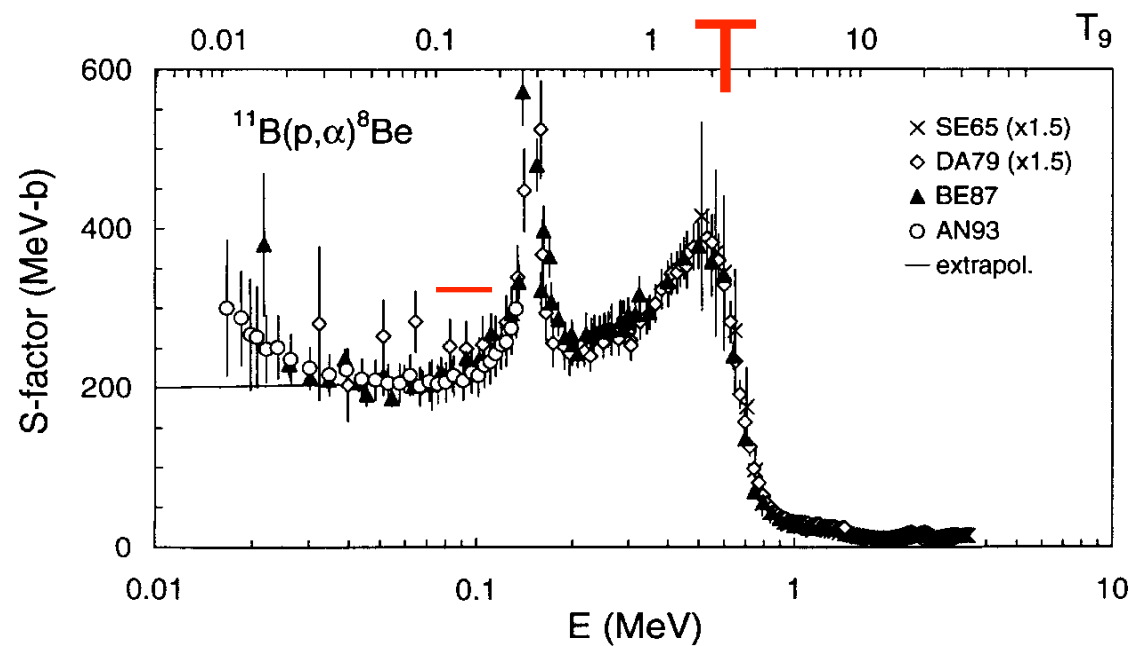


Alpha tracks from laser (p+B) interaction  
at ABC-ENEA (LAPLAFUS coll., W.Sci. in  
press)

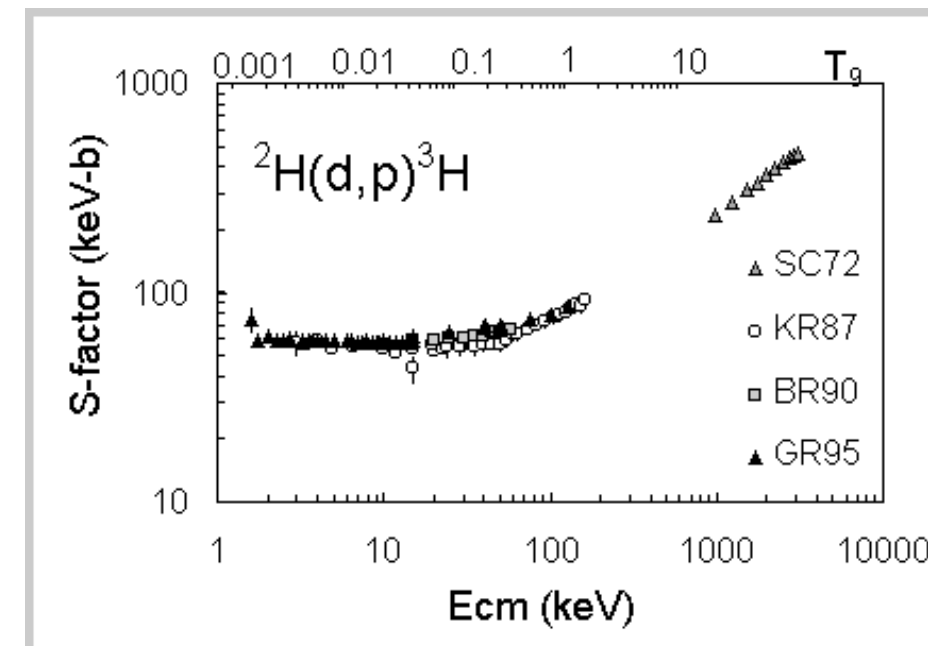


# Measuring S-factors in hot and dense plasma

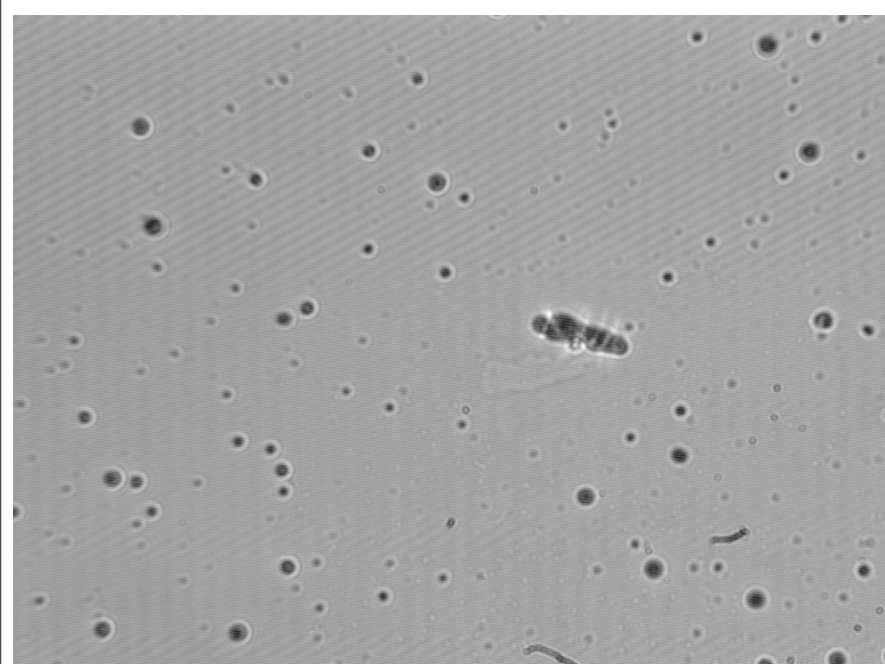
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Add a third  
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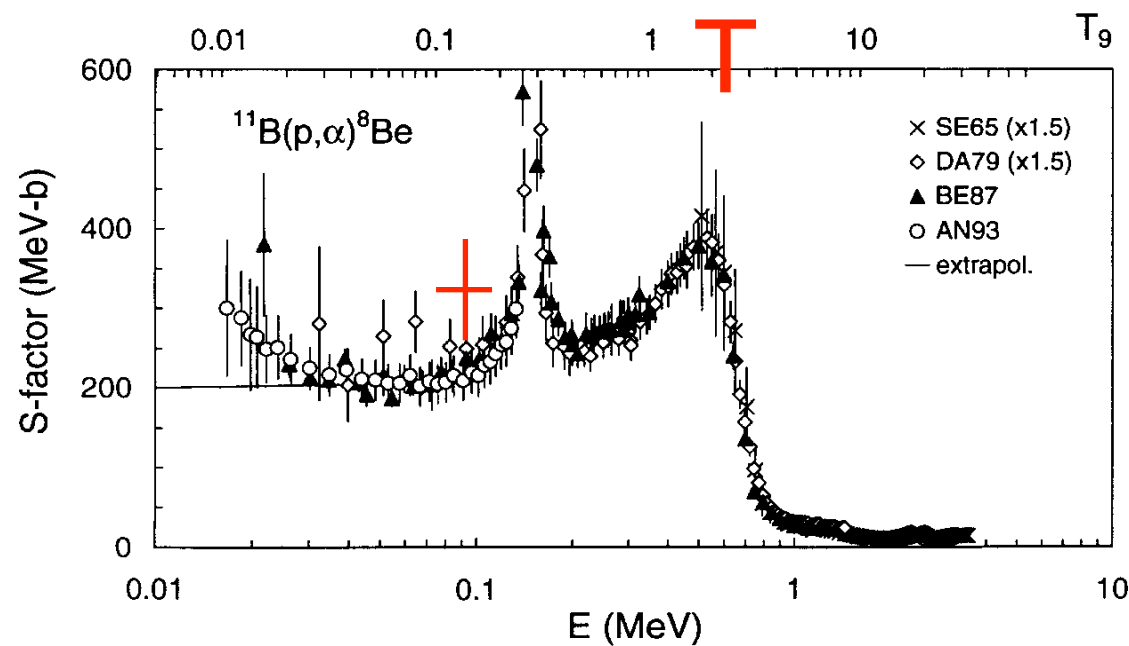


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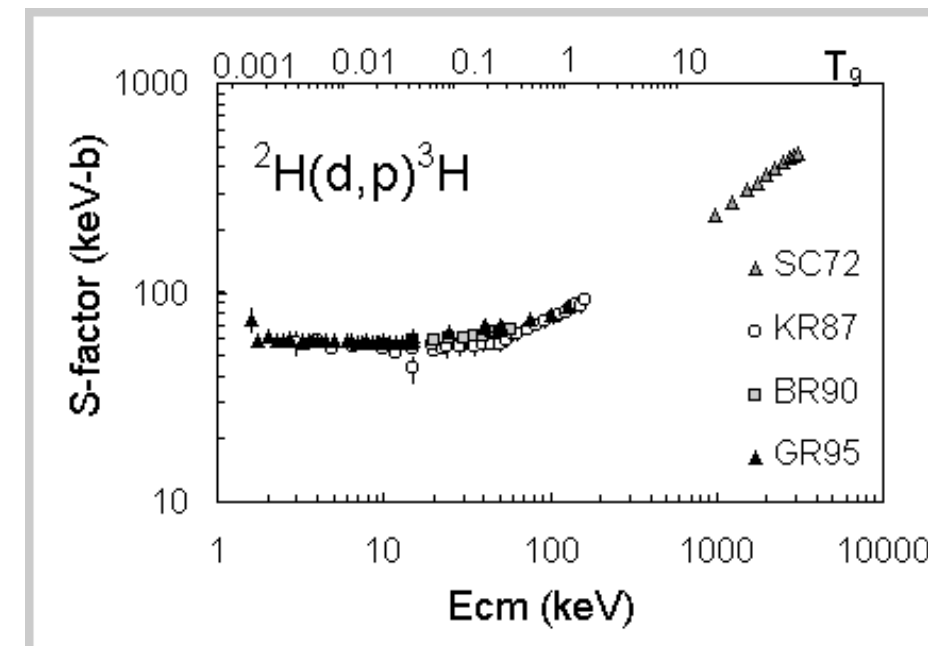


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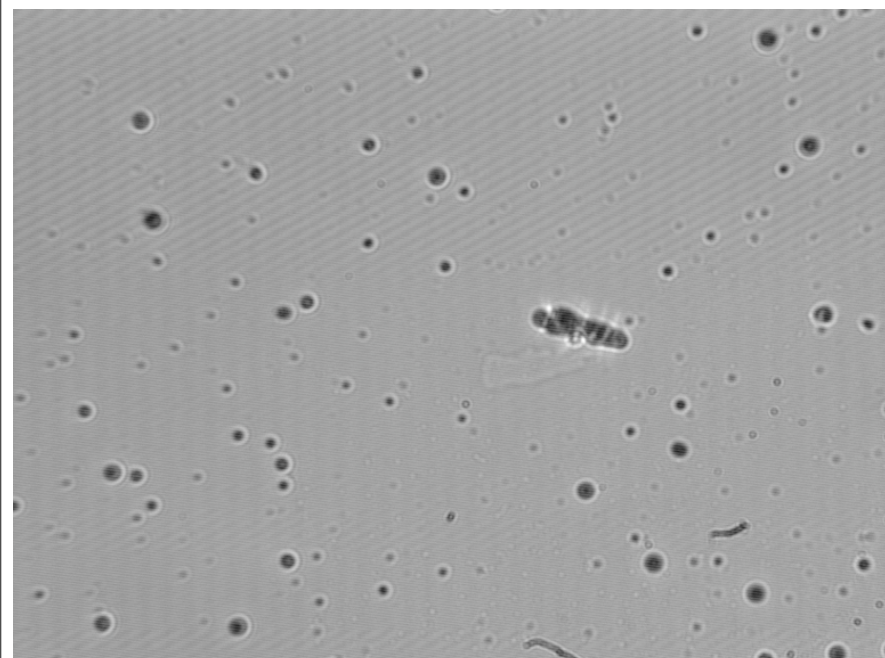
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Add a third axis: density!



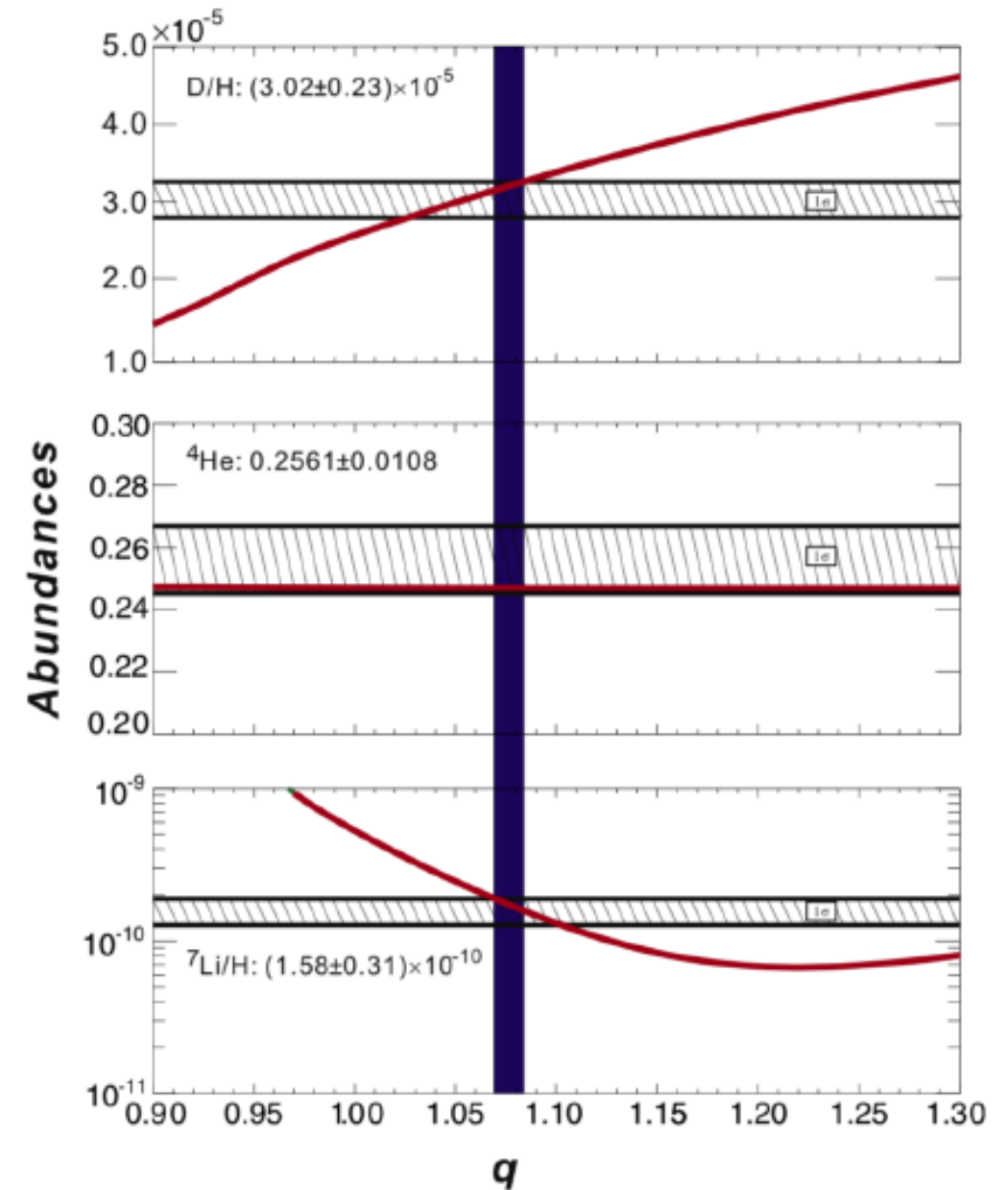
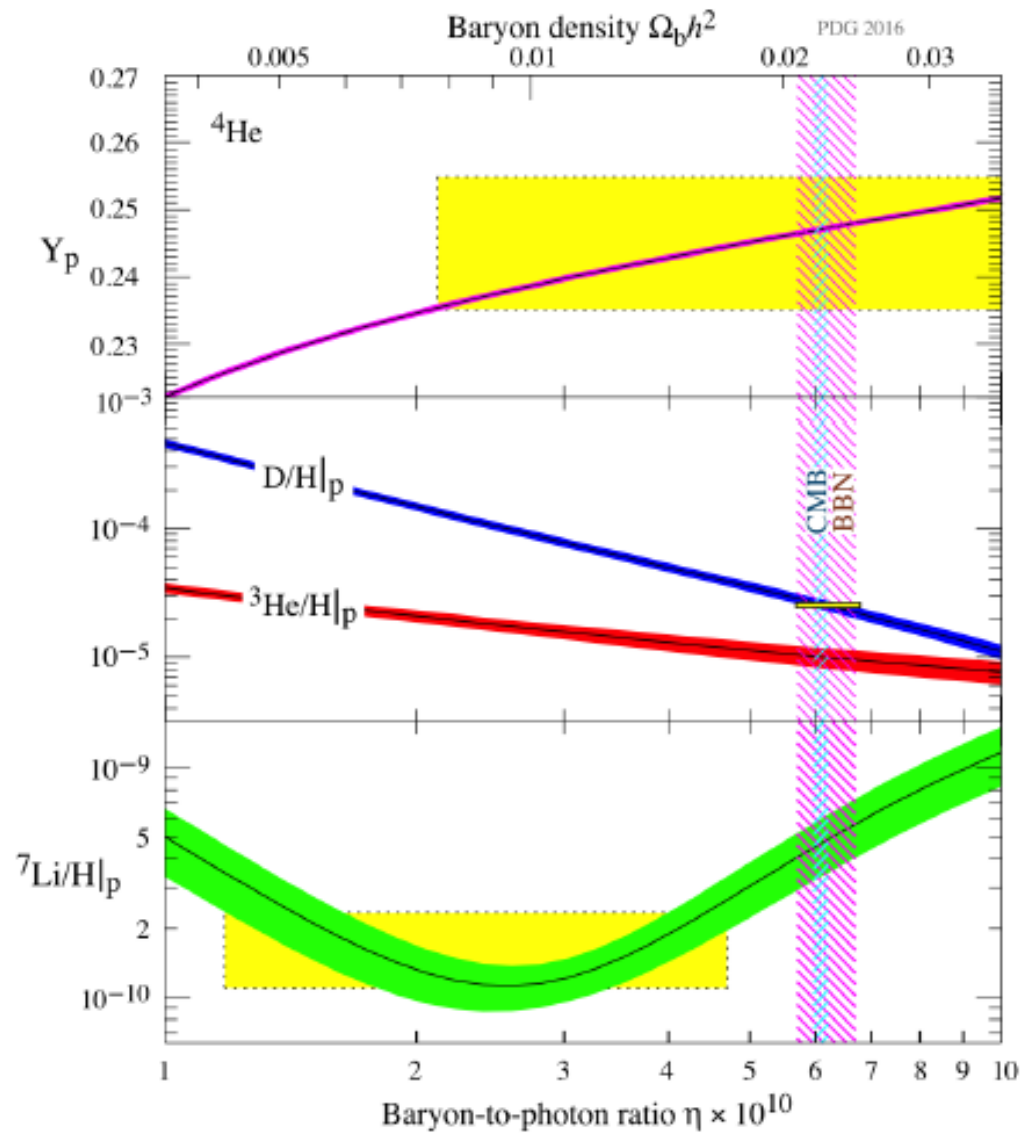
Alpha tracks from laser ( $p+B$ ) interaction at ABC-ENEA (LAPLAFUS coll., W.Sci. in press)





Tally 统计(non-extensive statistics), 或者非平衡, 或者其它问题

$$\langle \sigma v \rangle_{12} = B_q \sqrt{\frac{8}{\pi \mu_{12}}} \times \frac{1}{(kT)^{3/2}} \times \int_0^{E_{\max}} \sigma_{12}(E) E \left[ 1 - (q-1) \frac{E}{kT} \right]^{\frac{1}{q-1}} dE$$



S. Q. Hou, J. J. He et al., The Astrophysical Journal 834, 165 (2017).

# **1.0 Title: Measuring Cluster Fusion Plasma Temperature and Density from $^3\text{He}(\text{d},\text{p})^4\text{He}$ and $\text{d}(\text{d},\text{p})\text{T}$ Reactions**

## **2.0 PI, Co-PI's & Affiliation**

PIs: Todd Ditmire (UT Austin), Aldo Bonasera (Texas A&M, LNS INFN Catania-Italy)

Co-investigators: W. Bang, G. Dyer, H. Quevedo, A. Bernstein (CHEDS, UT Austin)  
M. Barbui, M. Barbarino, G. Giuliani, K. Hagel, Z. Hua, J. Natowitz, K. Schmidt  
(Cyclotron Institute, Texas A&M University, College Station, TX)

A. Caruso (Kore University, Enna-Italy)

J. Sura (Heavy Ion Institute, Warsaw, Poland)

S. Kimura (LNS INFN Catania-Italy)

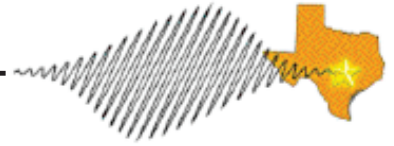
P.Andreoli, R.DeAngelis, F.Consoli, ENEA

## **3.0 Experimental Objectives and Concept**

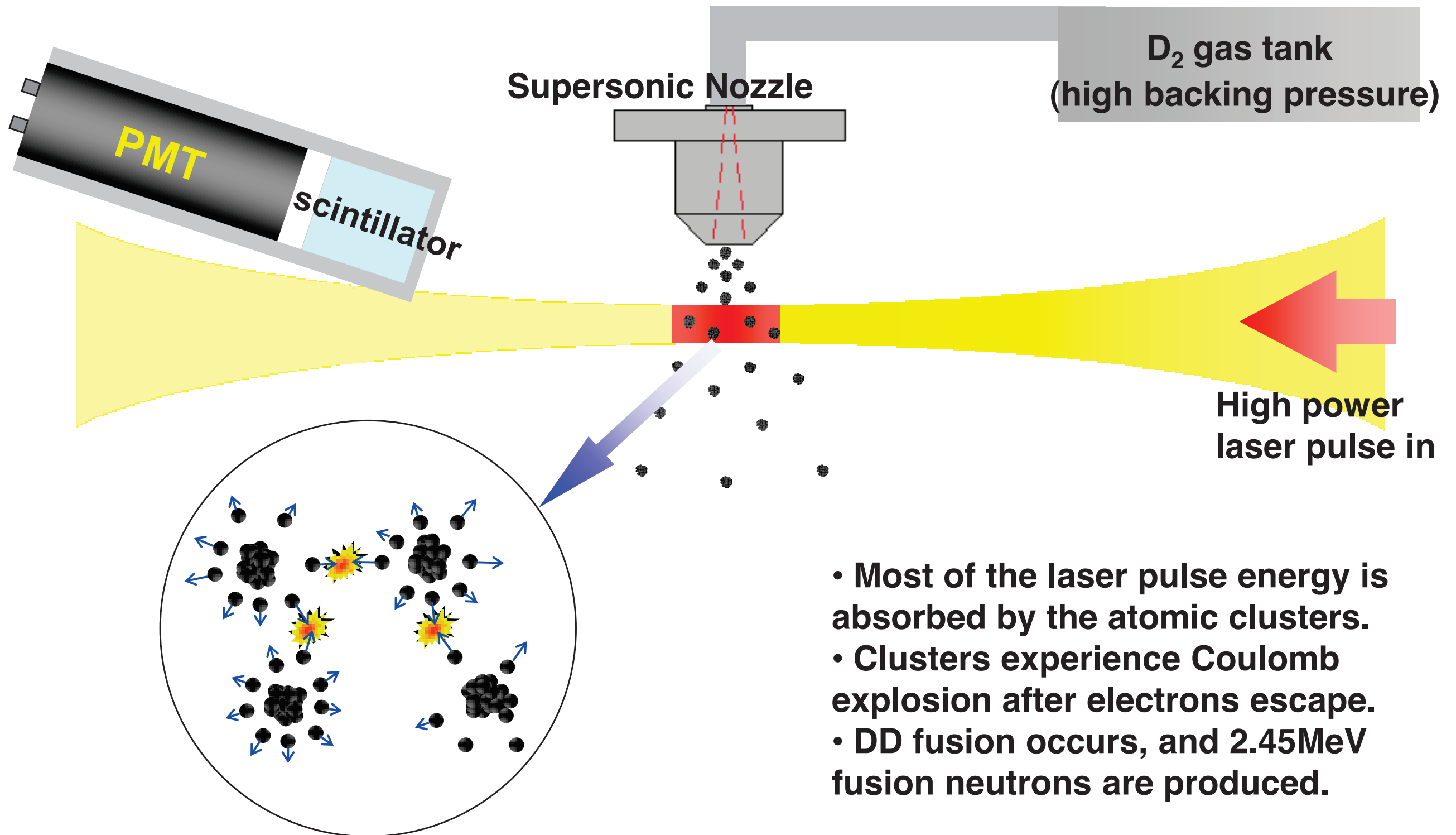
We propose to conduct experiments that follow on from the successful deuterium cluster fusion experiments in early 2011 on the TPW. Specifically we propose a detailed investigation of ion temperature in hot exploding cluster plasmas. To do this we will simultaneously measure the experimental yield from two different nuclear reactions. While our first experiments utilized pure deuterium to drive the  $\text{d}(\text{d},\text{p})\text{T}$  and  $\text{d}(\text{d},\text{n})\text{He}^3$  reactions we now propose to mix  $\text{He}^3$  into the gas jet target to allow us to measure simultaneously yields from the  $\text{He}^3(\text{d},\text{p})\text{He}^4$  and the d-d reactions.

Because these two reactions have different cross sections, measuring the ratio of the yields between these two reactions will allow a precise determination of the plasma temperature at the time when the reaction occurred (assuming thermalization). The measure of the experimental yield from sequential reactions will also make possible a direct measurement of the plasma density at the time of the reaction. Once the

# High power laser can be used to generate neutrons from the fusion reaction



## Nuclear fusion from laser-cluster interaction

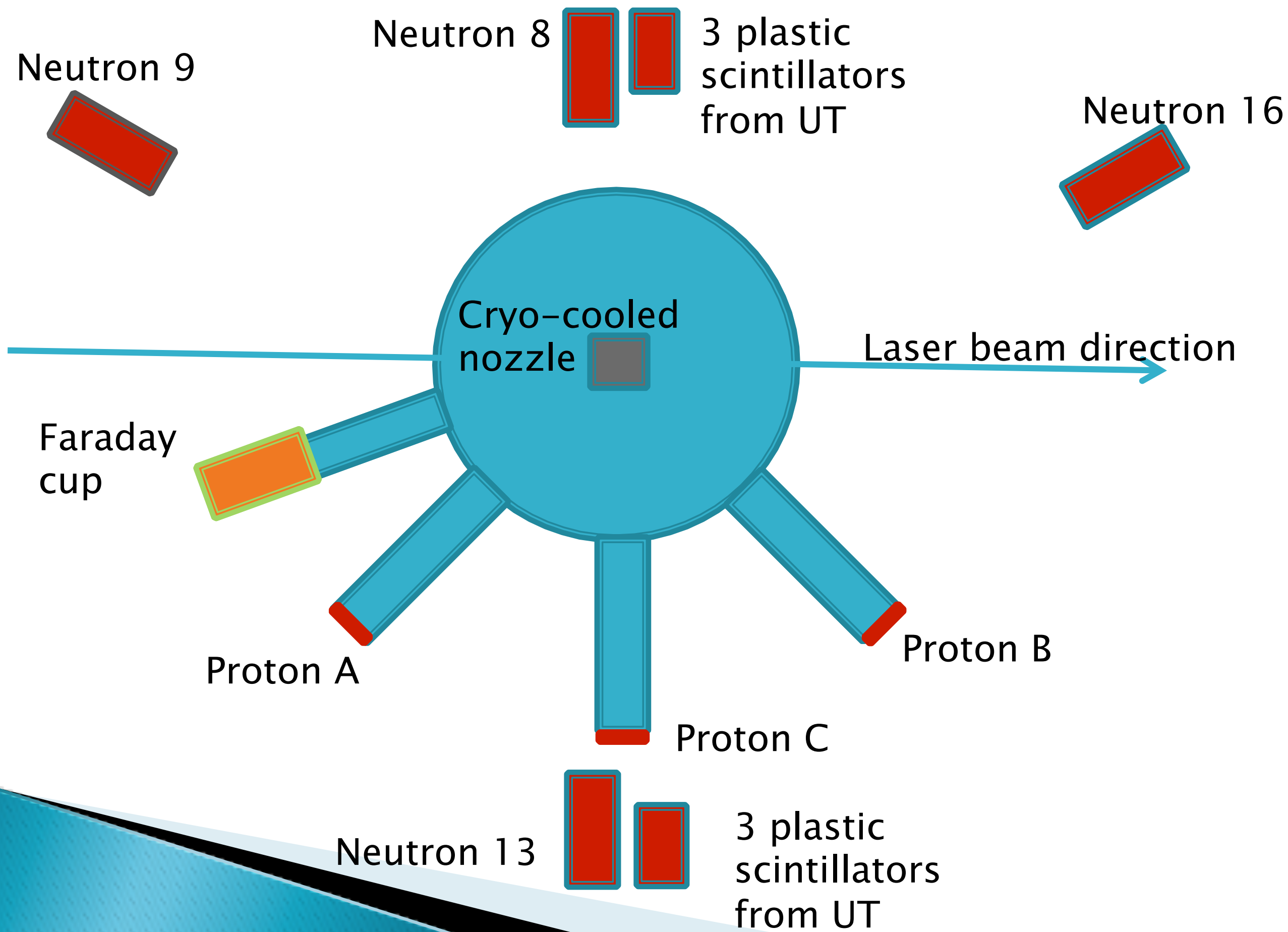


# Expected fusion reactions:





# Experimental setup



92.168.1.101 - Remote Desktop

MultiCam - Multiple Camera Data Acquisition Software

Shot Number

000000 2011-08-29

Exit VI

Acquisition Mode Status and Controls

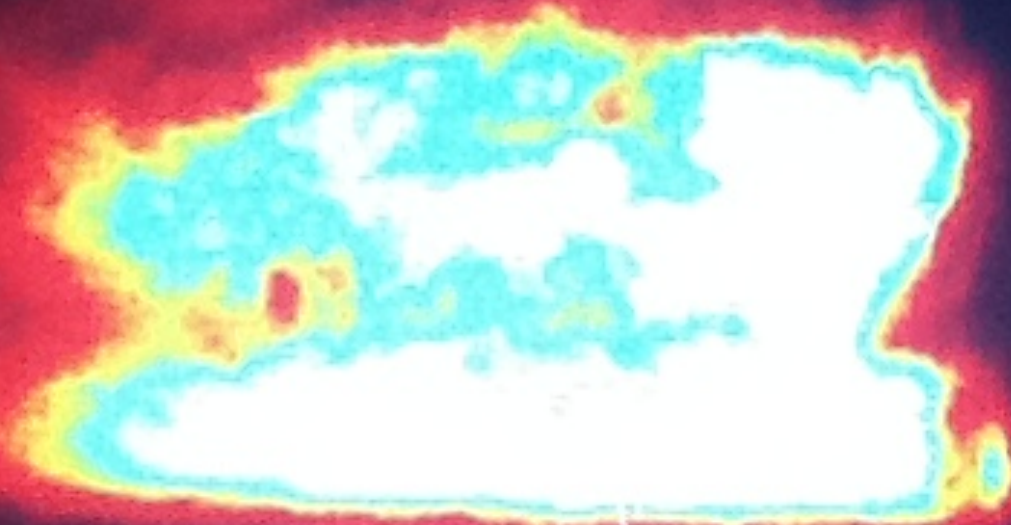
Window Names and Network Shared Variables

SSM

R

Power

Manual Forward



TAFFING

Wakefield Camera

Change MASTERCLOCK  
(SS or Cont. Mode)

Step 7

Change Master Clock



92.168.1.101 - Remote Desktop

MultiCam - Multiple Camera Data Acquisition Software

Shot Number 000000 2011-08-29

Exit VI

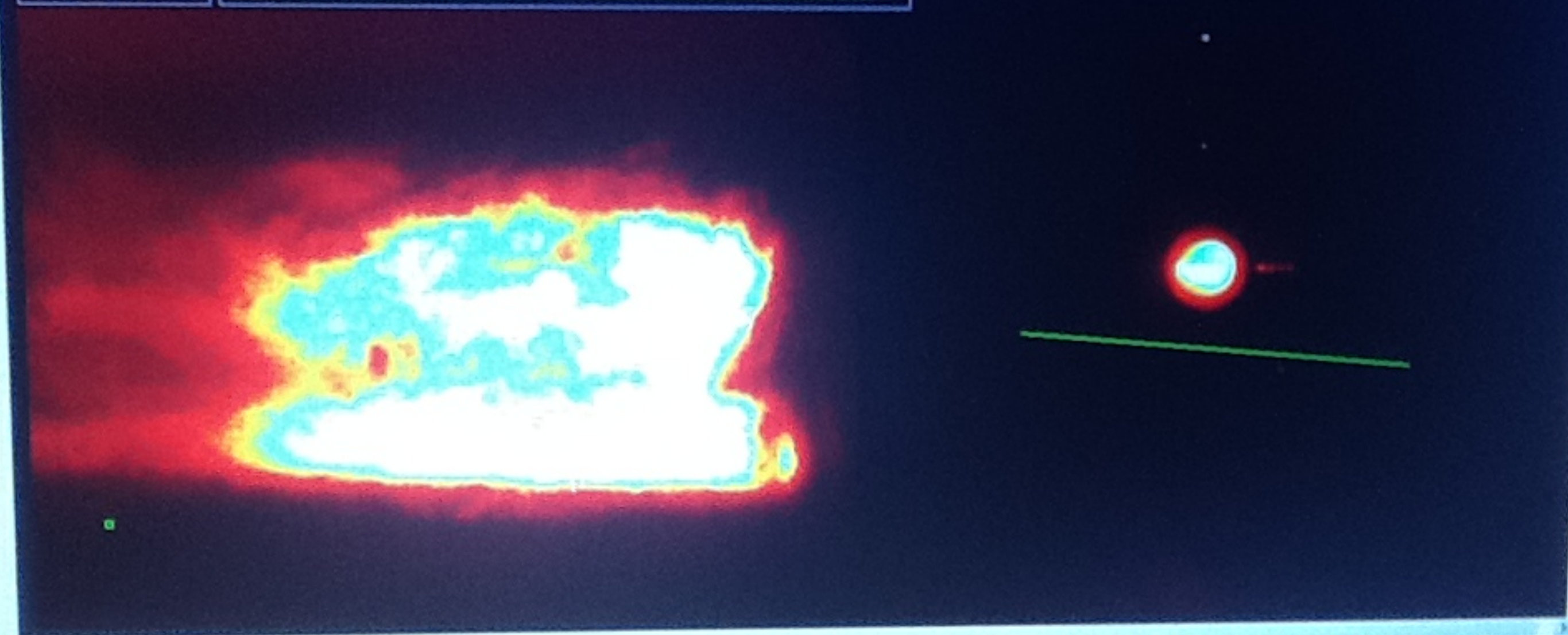
Acquisition Mode Status and Controls Window Names and Network Shared Variables

SSM R

Power

Manual Filtered

Measure V for each event



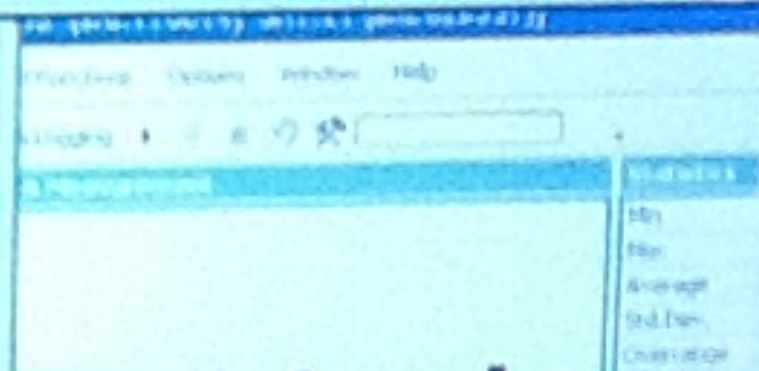
TAFFING

Wakefield Camera

Change MASTERCLOCK  
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Step 7

Display Camera View

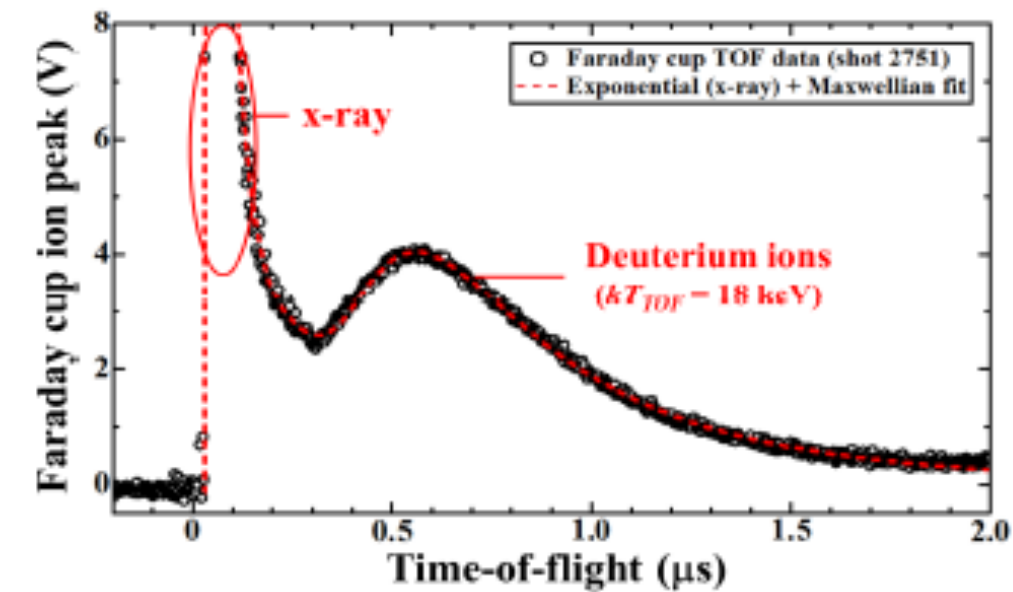


# Measured observables

Temperature and the  
number of the energetic  
ions



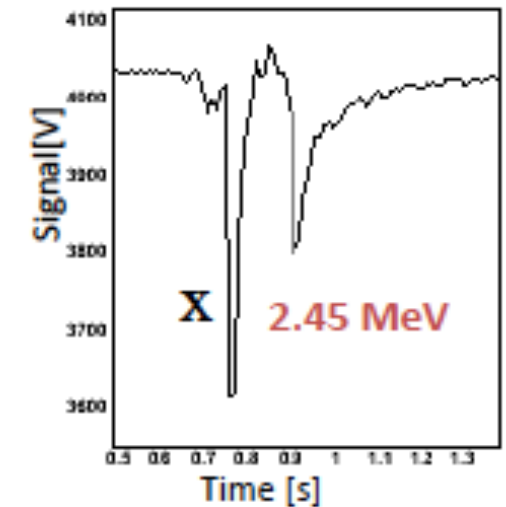
Faraday cup



Yield of 2.45 MeV neutrons



4 liquid scintillators  
NE213 placed at different  
angles and 6 plastic  
scintillators placed at 90  
degrees

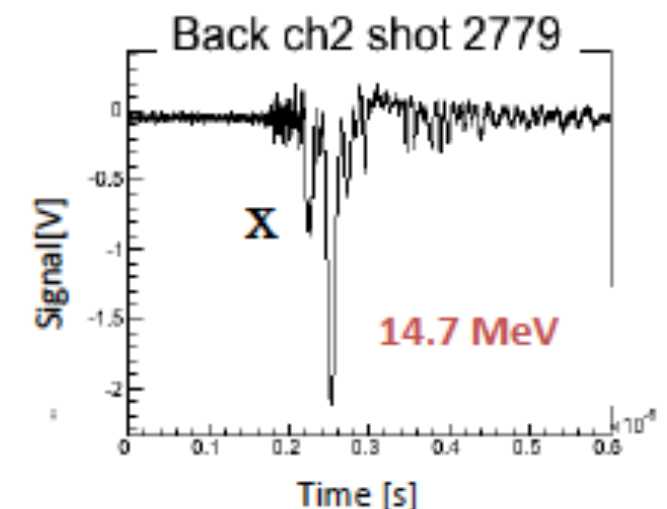
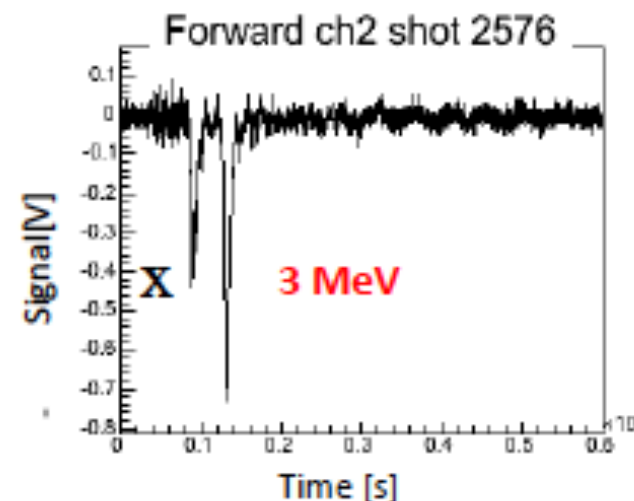


Yield of 3.02 MeV protons



Thin (254  $\mu\text{m}$ ) plastic  
scintillators BC400.

Yield of 14.7 MeV protons





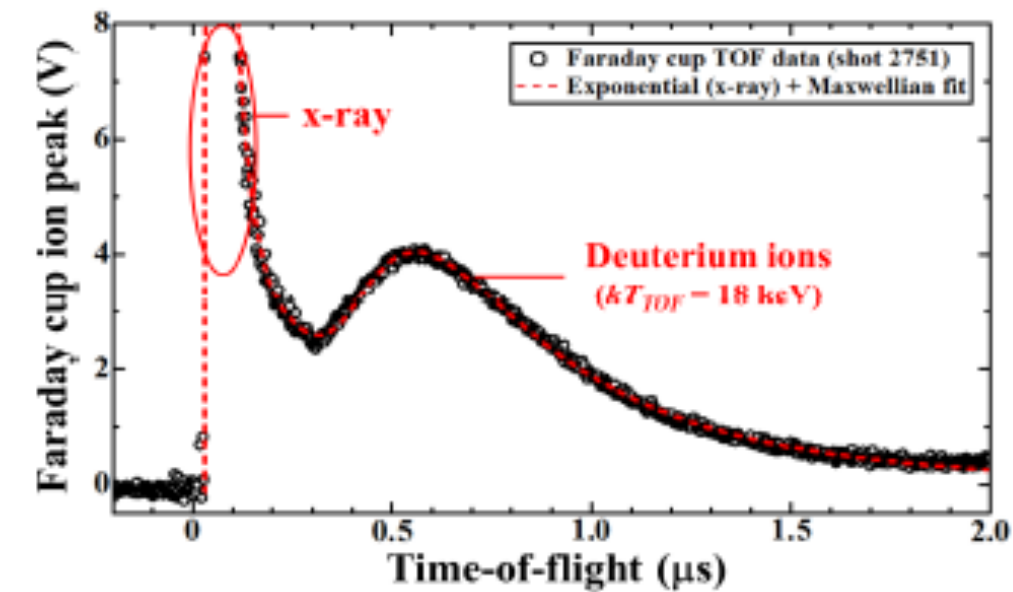
# Measured observables

## Measure N. of ions

Temperature and the number of the energetic ions



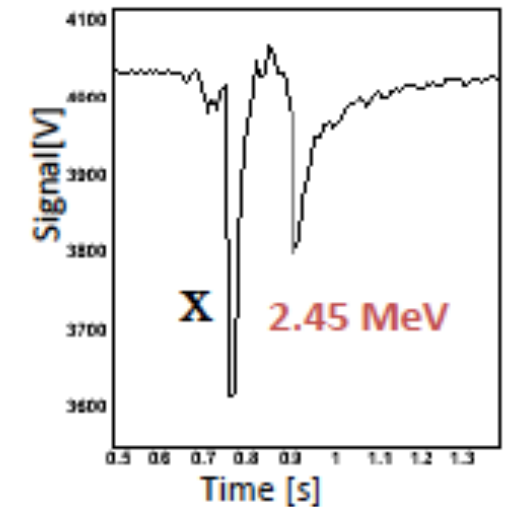
Faraday cup



Yield of 2.45 MeV neutrons



4 liquid scintillators NE213 placed at different angles and 6 plastic scintillators placed at 90 degrees

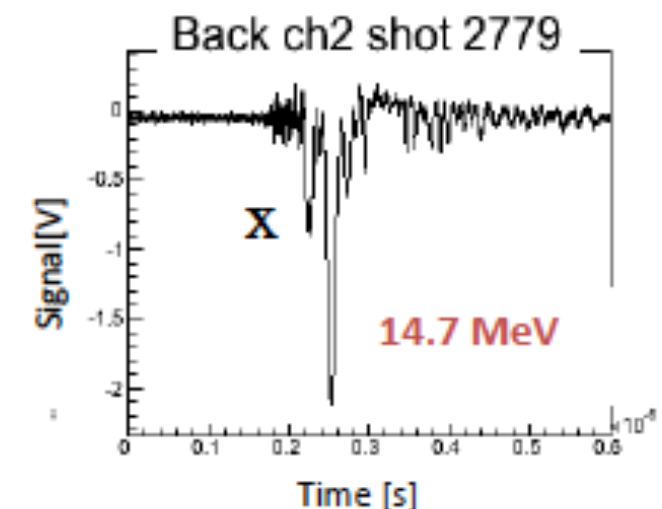
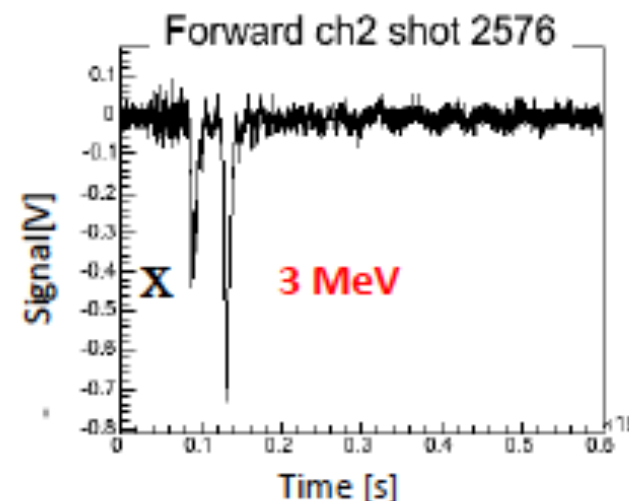


Yield of 3.02 MeV protons



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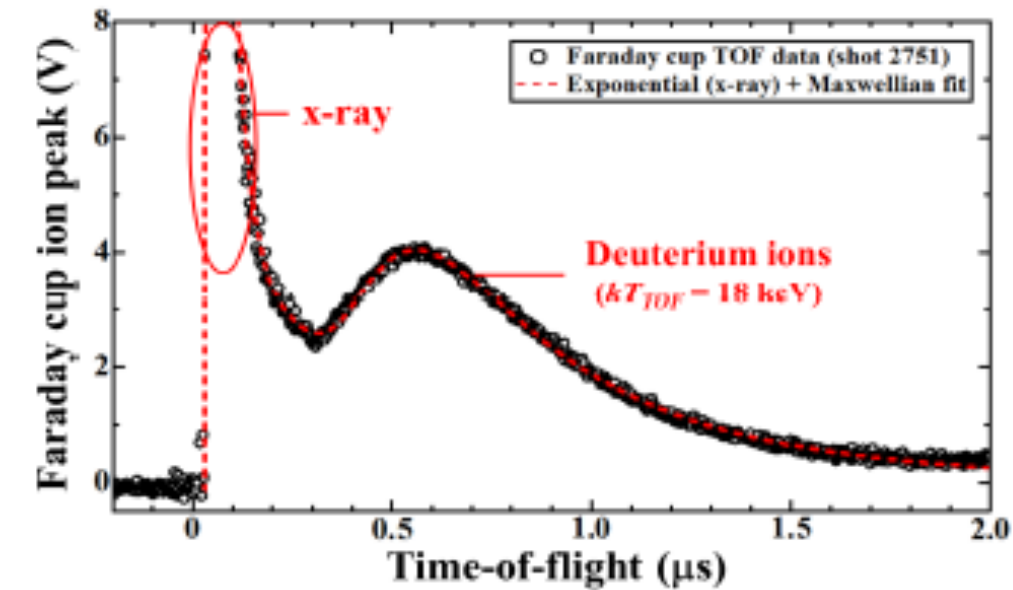
# Measured observables

Measure N. of ions

Temperature and the number of the energetic ions



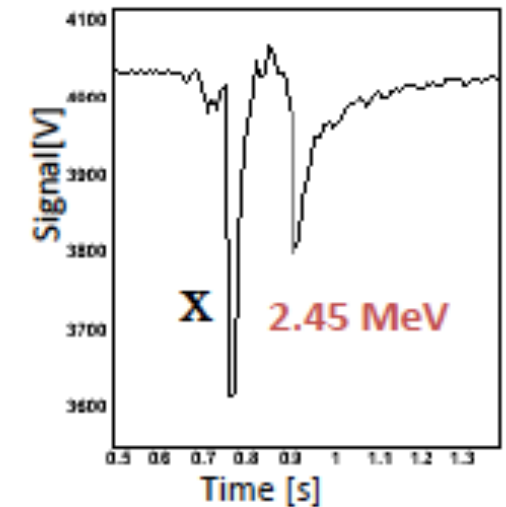
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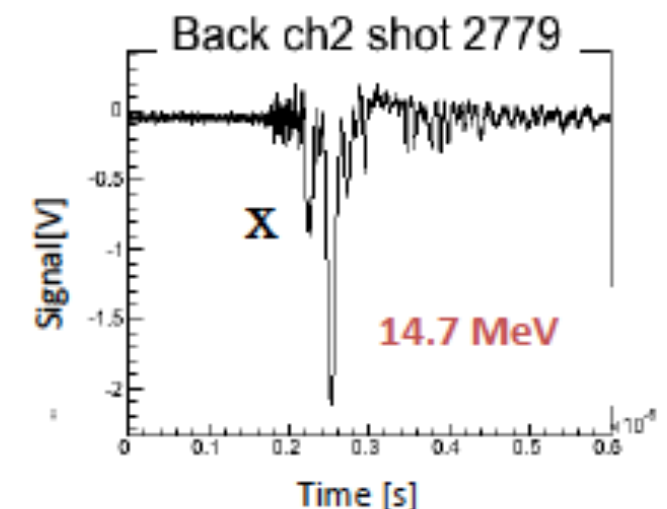
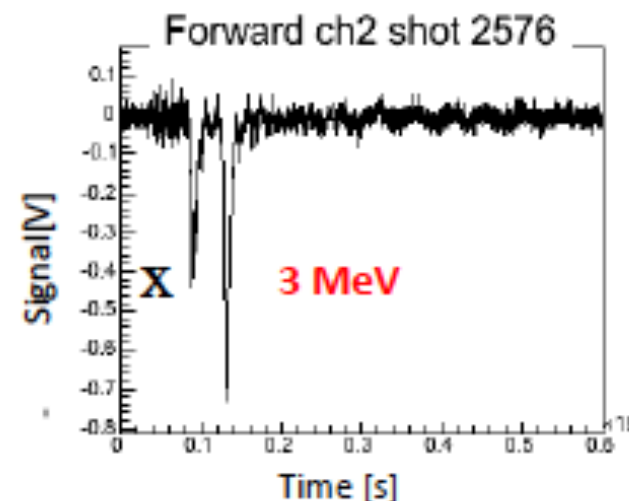


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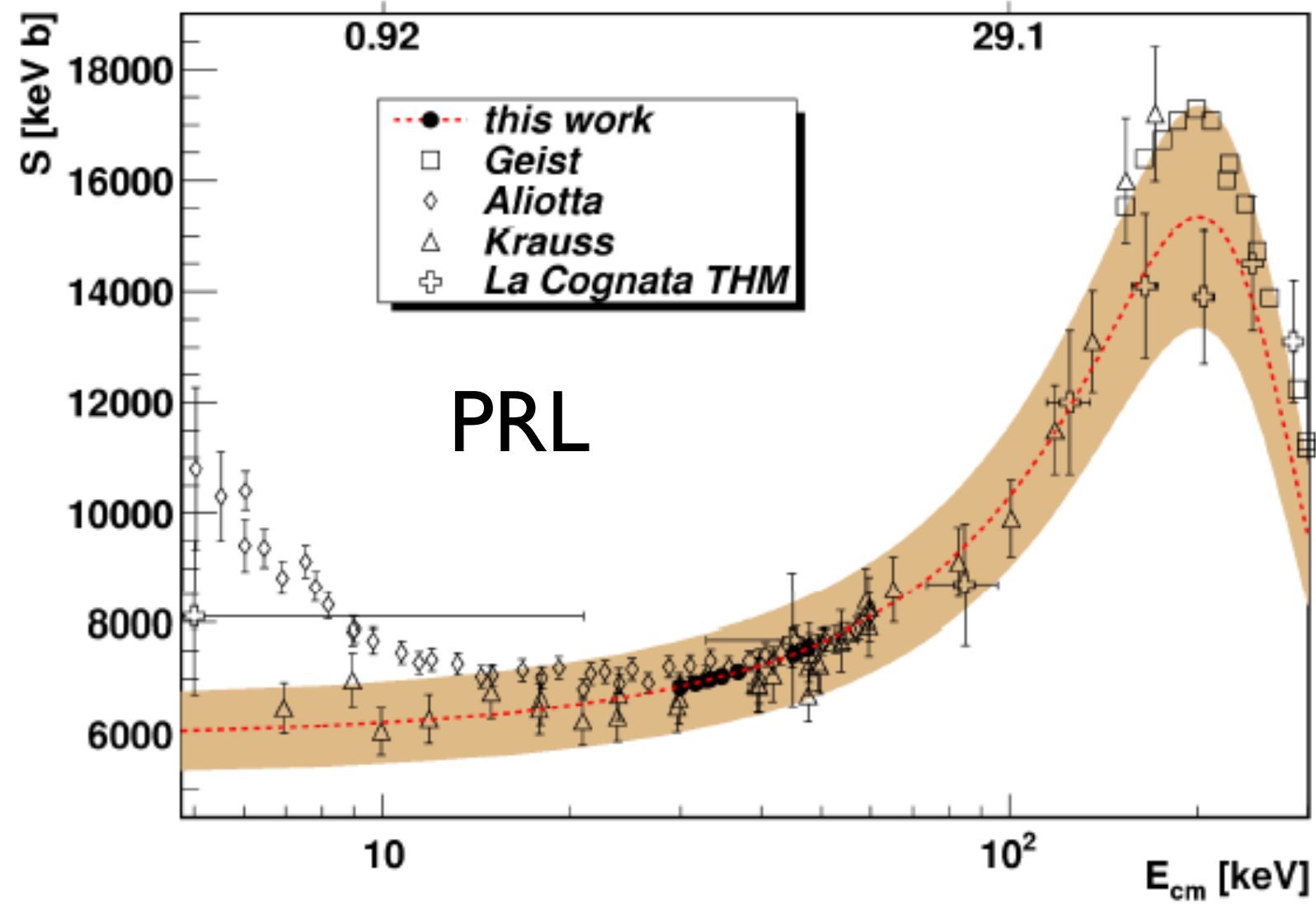
Yield of 14.7 MeV protons

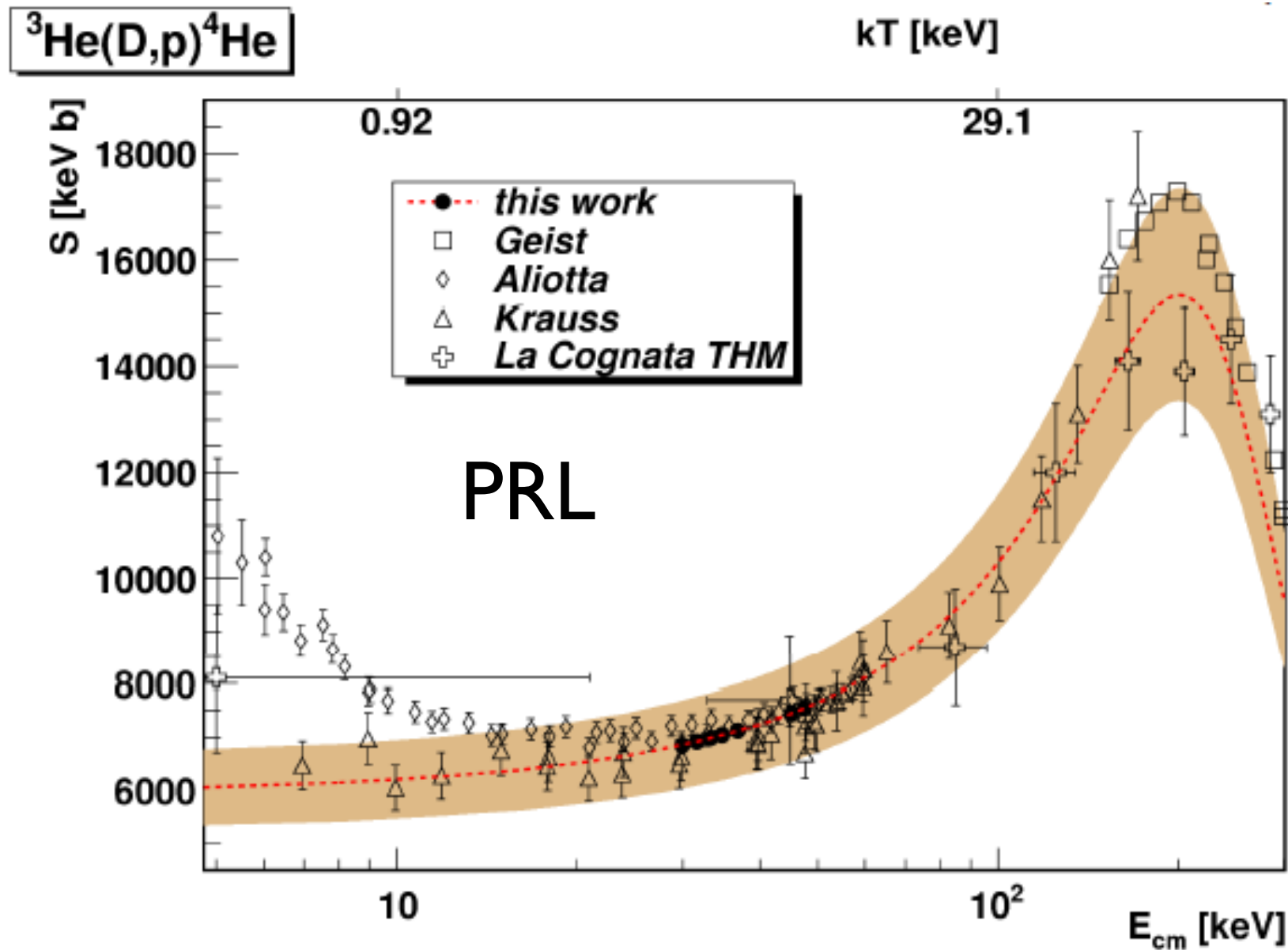


Measure N. of fusions for each channel

$^3\text{He}(\text{D},\text{p})^4\text{He}$

kT [keV]





PHYSICAL REVIEW C **87**, 058801 (2013)

### Gamow peak approximation near strong resonances

Sachie Kimura

*Department of Physics, University of Milano and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy*

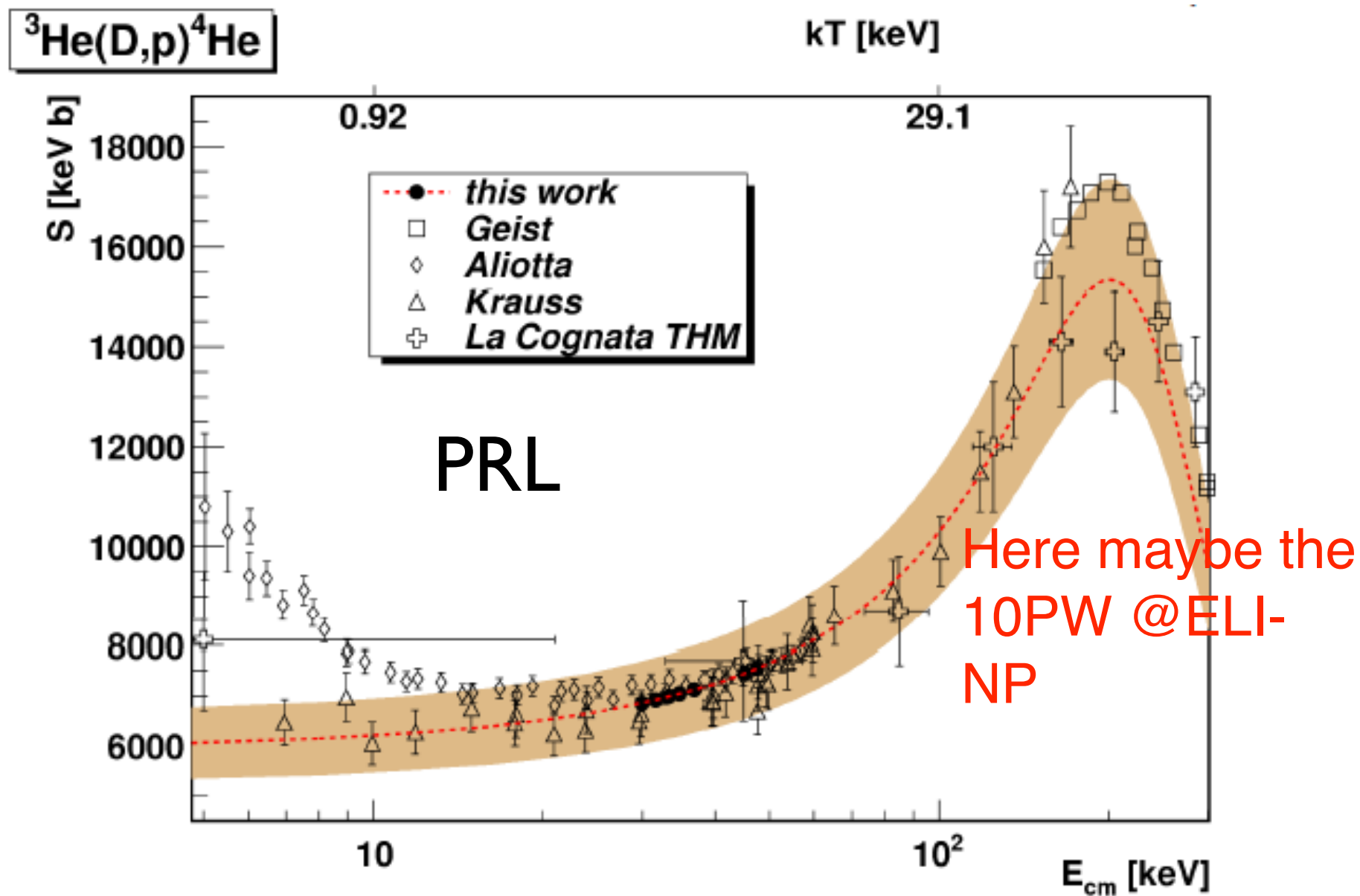
Aldo Bonasera

*Cyclotron Institute, Texas A&M University, College Station Texas 77843-3366, USA and INFN-LNS, via Santa Sofia 62, 95123 Catania, Italy*

(Received 29 November 2012; revised manuscript received 16 April 2013; published 23 May 2013)

We discuss the most effective energy range for charged-particle-induced reactions in a plasma environment at a given plasma temperature. The correspondence between the plasma temperature and the most effective energy should be modified from the one given by the Gamow peak energy, in the presence of a significant incident-energy dependence in the astrophysical  $S$  factor as in the case of resonant reactions. The suggested modification of the effective energy range is important not only in thermonuclear reactions at high temperature in the stellar environment, e.g., in advanced burning stages of massive stars and in explosive stellar environments, as has been already claimed, but also in the application of nuclear reactions driven by ultra-intense laser-pulse





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## Temperature Measurements of Fusion Plasmas Produced by Petawatt-Laser-Irradiated $D_2 - {}^3\text{He}$ or $CD_4 - {}^3\text{He}$ Clustering Gases

W. Bang,<sup>1,\*</sup> M. Barbui,<sup>2</sup> A. Bonasera,<sup>2,3</sup> G. Dyer,<sup>1</sup> H. J. Quevedo,<sup>1</sup> K. Hagel,<sup>2</sup> K. Schmidt,<sup>2</sup> F. Consoli,<sup>4</sup> R. De Angelis,<sup>4</sup> P. Andreoli,<sup>4</sup> E. Gaul,<sup>1</sup> A. C. Bernstein,<sup>1</sup> M. Donovan,<sup>1</sup> M. Barbarino,<sup>2</sup> S. Kimura,<sup>3</sup> M. Mazzocco,<sup>5</sup> J. Sura,<sup>6</sup> J. B. Natowitz,<sup>2</sup> and T. Ditmire<sup>1</sup>

<sup>1</sup>Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA

<sup>2</sup>Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

<sup>3</sup>LNS-INFN, Via S. Sofia 64, 95123 Catania, Italy

<sup>4</sup>Associazione Euratom-ENEA sulla Fusione, via E. Fermi 45, CP 65-00044 Frascati (Rome), Italy

<sup>5</sup>Physics Department, University of Padova and INFN, I-35131 Padova, Italy

<sup>6</sup>Heavy Ions Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093 Warszawa, Poland

(Received 25 February 2013; published 30 July 2013)

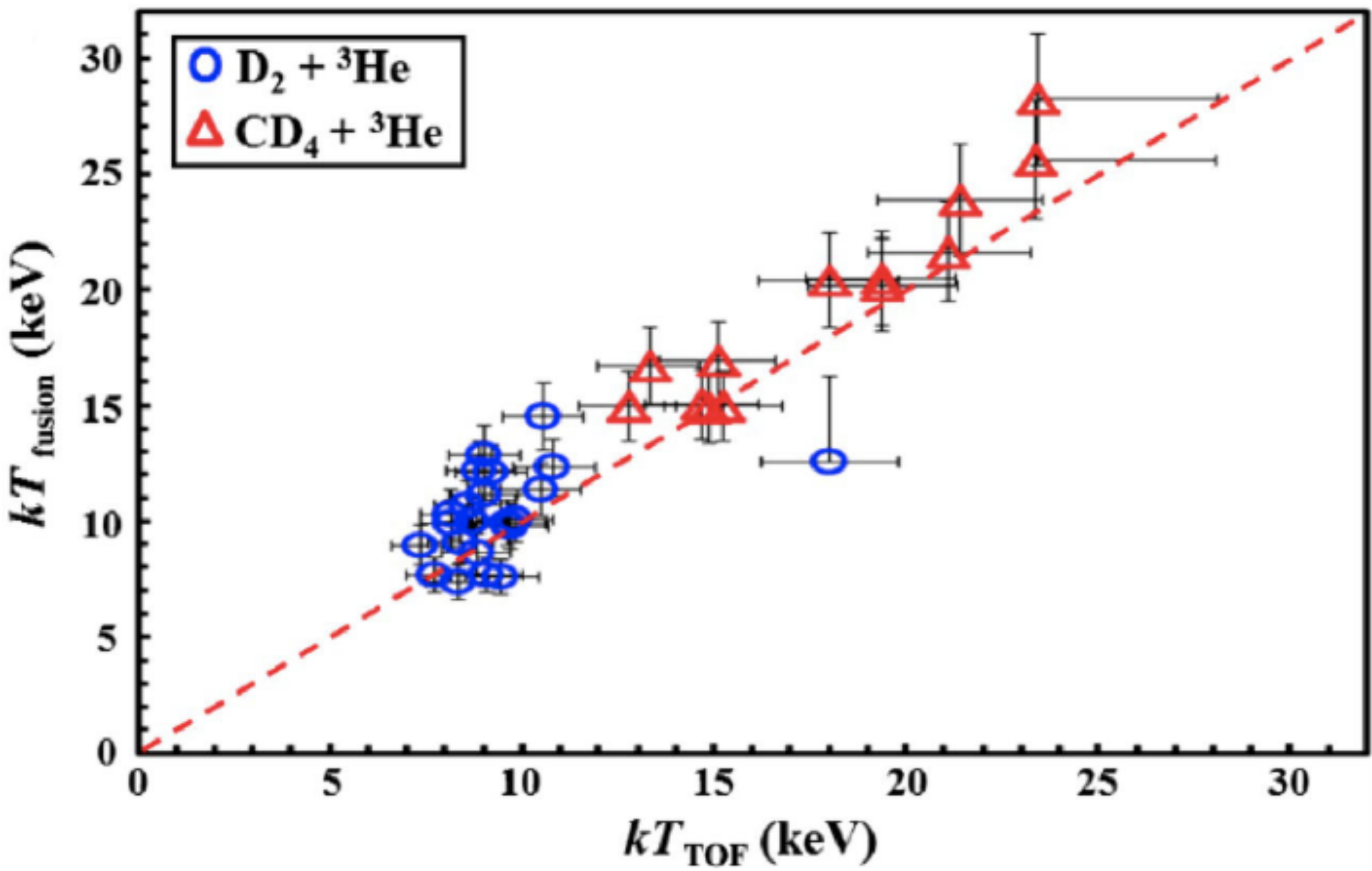
Two different methods have been employed to determine the plasma temperature in a laser-cluster fusion experiment on the Texas Petawatt laser. In the first, the temperature was derived from time-of-flight data of deuterium ions ejected from exploding  $D_2$  or  $CD_4$  clusters. In the second, the temperature was measured from the ratio of the rates of two different nuclear fusion reactions occurring in the plasma at the same time:  $D(d, {}^3\text{He})n$  and  ${}^3\text{He}(d, p){}^4\text{He}$ . The temperatures determined by these two methods agree well, which indicates that (i) the ion energy distribution is not significantly distorted when ions travel in the disassembling plasma; (ii) the kinetic energy of deuterium ions, especially the “hottest part” responsible for nuclear fusion, is well described by a near-Maxwellian distribution.

DOI: 10.1103/PhysRevLett.111.055002

PACS numbers: 52.50.Jm, 25.45.-z, 36.40.Wa

Nuclear fusion from explosions of laser-heated clusters has been an active research topic for over a decade [1–11]. Researchers have used explosions of cryogenically cooled deuterium ( $D_2$ ) cluster targets or near-room-temperature

deuterated methane cluster plasmas produced by the irradiation of a clustering gas jet by 150 fs petawatt peak power laser pulses. We find that the effective ion temperature produced can be in excess of 25 keV.







# Measurement of the Plasma Astrophysical $S$ Factor for the ${}^3\text{He}({}^2\text{H}, p){}^4\text{He}$ Reaction in Exploding Molecular Clusters

M. Barbui,<sup>1,\*</sup> W. Bang,<sup>2,†</sup> A. Bonasera,<sup>3,1</sup> K. Hagel,<sup>1</sup> K. Schmidt,<sup>1</sup> J. B. Natowitz,<sup>1</sup> R. Burch,<sup>1</sup> G. Giuliani,<sup>1</sup> M. Barbarino,<sup>1</sup> H. Zheng,<sup>1</sup> G. Dyer,<sup>2</sup> H. J. Quevedo,<sup>2</sup> E. Gaul,<sup>2</sup> A. C. Bernstein,<sup>2</sup> M. Donovan,<sup>2</sup> S. Kimura,<sup>4</sup> M. Mazzocco,<sup>5</sup> F. Consoli,<sup>6</sup> R. De Angelis,<sup>6</sup> P. Andreoli,<sup>6</sup> and T. Ditmire<sup>2</sup>

<sup>1</sup>*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

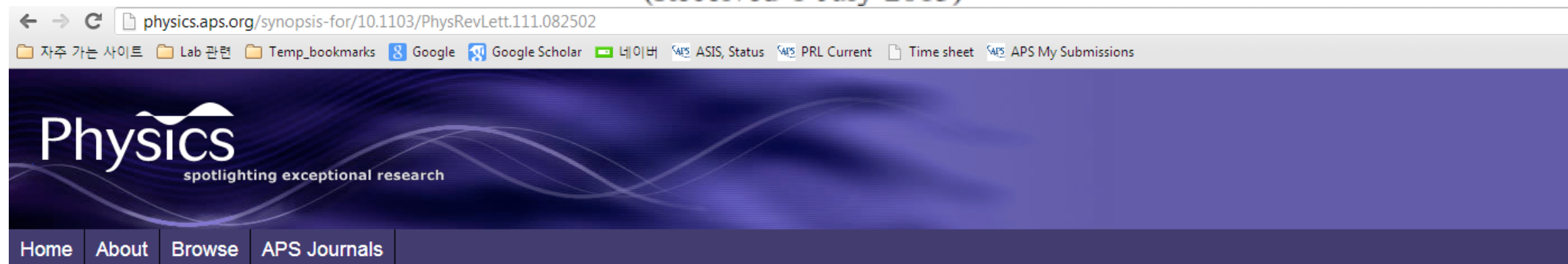
<sup>2</sup>*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*

<sup>3</sup>*INFN- Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy*

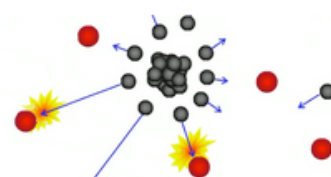
<sup>4</sup>*Department of Physics, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy*

<sup>5</sup>*Dipartimento di Fisica e Astronomia Università degli Studi di Padova and INFN Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*

<sup>6</sup>*Associazione Euratom—ENEA Sulla Fusione, Via E. Fermi 45, CP 65-00044 Frascati, Rome, Italy*  
(Received 1 July 2013)



## Synopsis: Nuclear Reactions in Lab Plasma



Courtesy M. Barbui/Texas A&M University

### Measurement of the Plasma Astrophysical $S$ Factor for the ${}^3\text{He}(d,p){}^4\text{He}$ Reaction in Exploding Molecular Clusters

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

*Phys. Rev. Lett.* **111**, 082502 (2013)

Published August 22, 2013

Many low-energy nuclear reactions in astrophysics occur in plasmas, in which the nuclei are free of electrons. By contrast, most nuclear experiments involve neutral targets, whose bound electrons produce a “screening effect.” A new technique uses lasers to remove these unwanted electrons so that low-energy nuclear reactions can be studied directly in laboratory plasma. The authors demonstrate their approach in *Physical Review Letters* on the deuterium/helium-3 interaction that helped synthesize elements in the early Universe and could potentially be used to power a future nuclear fusion reactor.

In a typical nuclear reaction experiment, an ion beam is directed at a target containing neutral atoms. The bound electrons provide a screen that reduces the Coulomb repulsion between the positive nuclei. Therefore, laboratory measurements tend to predict higher reaction rates than would be expected between ionized nuclei. To obtain astrophysically relevant parameters, researchers try to correct their data by estimating the screening effect of the bound electrons.



**Model-independent determination of the astrophysical  $S$  factor in laser-induced fusion plasmas**

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In this work, we present a new and general method for measuring the astrophysical  $S$  factor of nuclear reactions in laser-induced plasmas and we apply it to  $^2\text{H}(d,n)^3\text{He}$ . The experiment was performed with the Texas Petawatt Laser, which delivered 150–270 fs pulses of energy ranging from 90 to 180 J to  $\text{D}_2$  or  $\text{CD}_4$  molecular clusters (where D denotes  $^2\text{H}$ ). After removing the background noise, we used the measured time-of-flight data of energetic deuterium ions to obtain their energy distribution. We derive the  $S$  factor using the measured energy distribution of the ions, the measured volume of the fusion plasma, and the measured fusion yields. This method is model independent in the sense that no assumption on the state of the system is required, but it requires an accurate measurement of the ion energy distribution, especially at high energies, and of the relevant fusion yields. In the  $^2\text{H}(d,n)^3\text{He}$  and  $^3\text{He}(d,p)^4\text{He}$  cases discussed here, it is very important to apply the background subtraction for the energetic ions and to measure the fusion yields with high precision. While the available data on both ion distribution and fusion yields allow us to determine with good precision the  $S$  factor in the  $d + d$  case (lower Gamow energies), for the  $d + ^3\text{He}$  case the data are not precise enough to obtain the  $S$  factor using this method. Our results agree with other experiments within the experimental error, even though smaller values of the  $S$  factor were obtained. This might be due to the plasma environment differing from the beam target conditions in a conventional accelerator experiment.

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**I. INTRODUCTION**

The nuclear reactions between light nuclei in the low energy region ( $\sim \text{keV}$ ),

$$d + d \rightarrow ^3\text{He}(0.82 \text{ MeV}) + n(2.45 \text{ MeV}), \quad (1)$$

$$d + d \rightarrow p(3.02 \text{ MeV}) + t(1.01 \text{ MeV}), \quad (2)$$

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

have been studied for many decades [1–10]. The role of low-energy nuclear physics is crucial in both astrophysics, playing a key role in the determination of primordial abundances in Big Bang nucleosynthesis (BBN) models, and applied (plasma) physics, as it lies in the energy region of interest for the operation and design of future fusion power plants. Direct and

with bare nuclei and with the ones occurring in astrophysical plasmas [1,6,13,14].

Other physical conditions are possible which might decrease the astrophysical factor, dubbed the dissipative limit (DL) in [11,12]. In a hot plasma, due to the large number of positive and negative charges, fusions occurring in an “electron” cloud might be enhanced. If, however, a large number of positive charges is present in the region where fusion occurs, then the cross section might decrease. In laser-cluster interactions we might be able to create such conditions, thus it would represent a good chance to study the fusion cross sections within stellar plasmas in a laboratory. In particular, we can explore temperatures ranging from few keV up to few tens of keV and a density just above  $10^{18} \text{ atoms/cm}^3$ . These temperatures are similar to those achieved in the BBN and

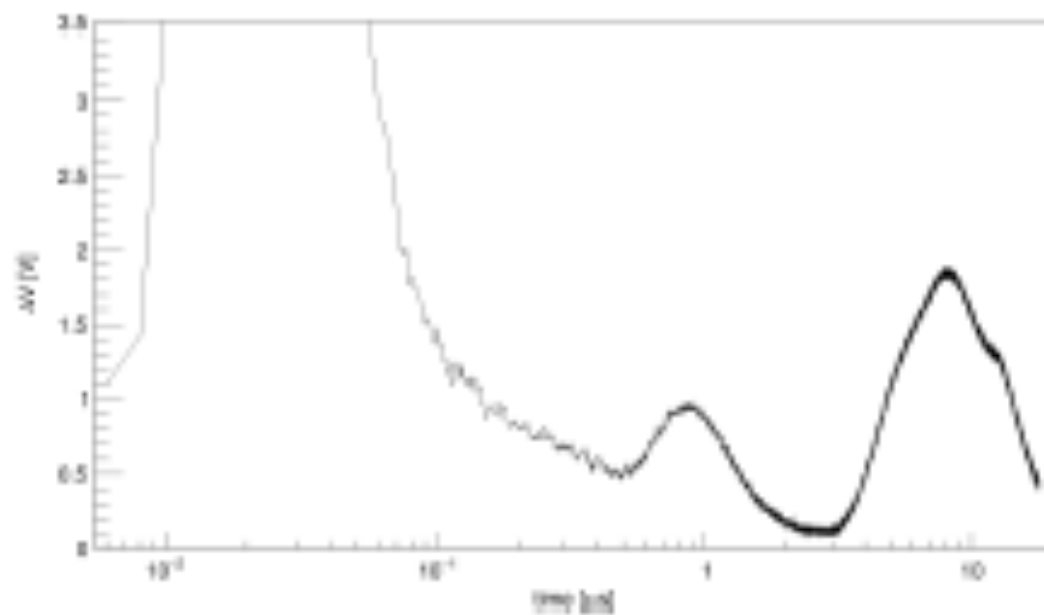


FIG. 1. The Faraday cup signal ( $\Delta V$ ) versus the time of flight of the deuterium ions recorded by the oscilloscope for one experiment of the campaign. The first steep peak whose tail extends to hundreds of ns overlapping with the second peak is due to the X-rays produced by the interaction of the laser inside the vacuum target chamber. The second small peak ( $\lesssim 10^{-6}$  s) is associated with energetic deuterium ions produced in the Coulomb explosion. The big wide double-featured peak at 3-20  $\mu$ s is due to slower sub-keV ions resulting from the plasma wave propagation in the surrounding and cold cluster gas [16, 24]

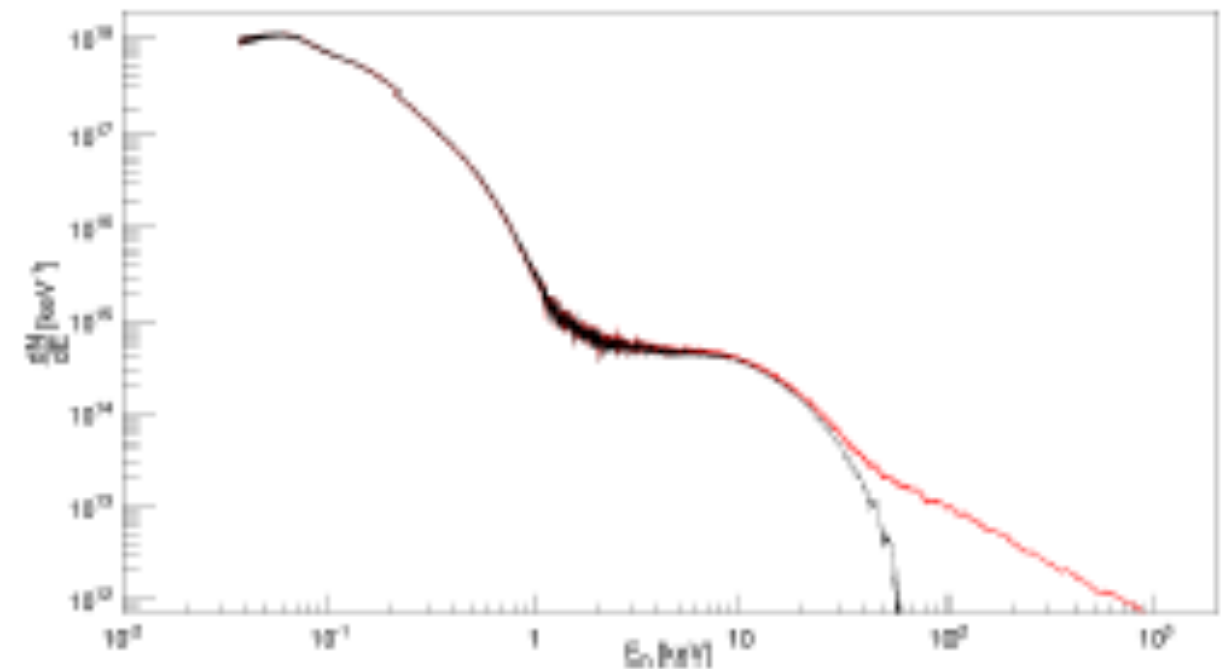


FIG. 2. Deuterium ion energy distribution as recorded in the FC (in red) and after background subtraction (black). The high energy tail is due to the x-ray noise from laser-cluster interaction.

recorded the arrival of energetic deuterium ions for 20  $\mu$ s. The first spike whose tail extends up to hundreds of ns reached the full scale of the oscilloscope for all the shots of the campaign and it is due to the x-rays produced by the interaction of the laser and the target inside the vacuum target chamber. This feature is common in this

Make a good measurement of the ion distributions and get rid of the noise



#### IV. THE METHOD

For each shot, we can derive the S-factor at a given energy defined by the Gamow peak for the nuclear reaction (11) as

$$S_{d-d}(E_G) = \frac{1}{\int \Sigma_{d-d}(E) dE}, \quad (13)$$

where  $\Sigma_{d-d}$  is defined as:

$$\Sigma_{d-d}(E) = \frac{A_{BB} + A_{BT}}{Y_n^{(exp)}}, \quad (14)$$

where, using eq.(4),

$$A_{BB} = \rho_D l \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{dd[BB]} \quad (15)$$

and

$$A_{BT} = \rho_D (R - l) \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{dd[BT]}. \quad (16)$$

Similarly

$$S_{d^3He}(E_G) = \frac{1}{\int \Sigma_{d^3He}(E) dE}, \quad (17)$$

where

$$\Sigma_{d^3He}(E) = \frac{B}{Y_p^{(exp)}}, \quad (18)$$

and

$$B = R \rho_{^3He} \int \frac{dN}{dE} \frac{\exp(-2\pi\eta E)}{E} dE \Big|_{d^3He}. \quad (19)$$

For each event, we assume that the S-factor is nearly constant and the Gamow peak energy is a good representation of the energy at which nuclear reactions mostly occur. Since we have measured the number of fusions and the distribution function, we can easily evaluate the integrand in equations (13) and (17) by using the experimental ion distribution function, after background subtraction, in order to provide an evaluation of the S-factor. This is the essence of the proposed method and it is clear that the major sources of uncertainties are the

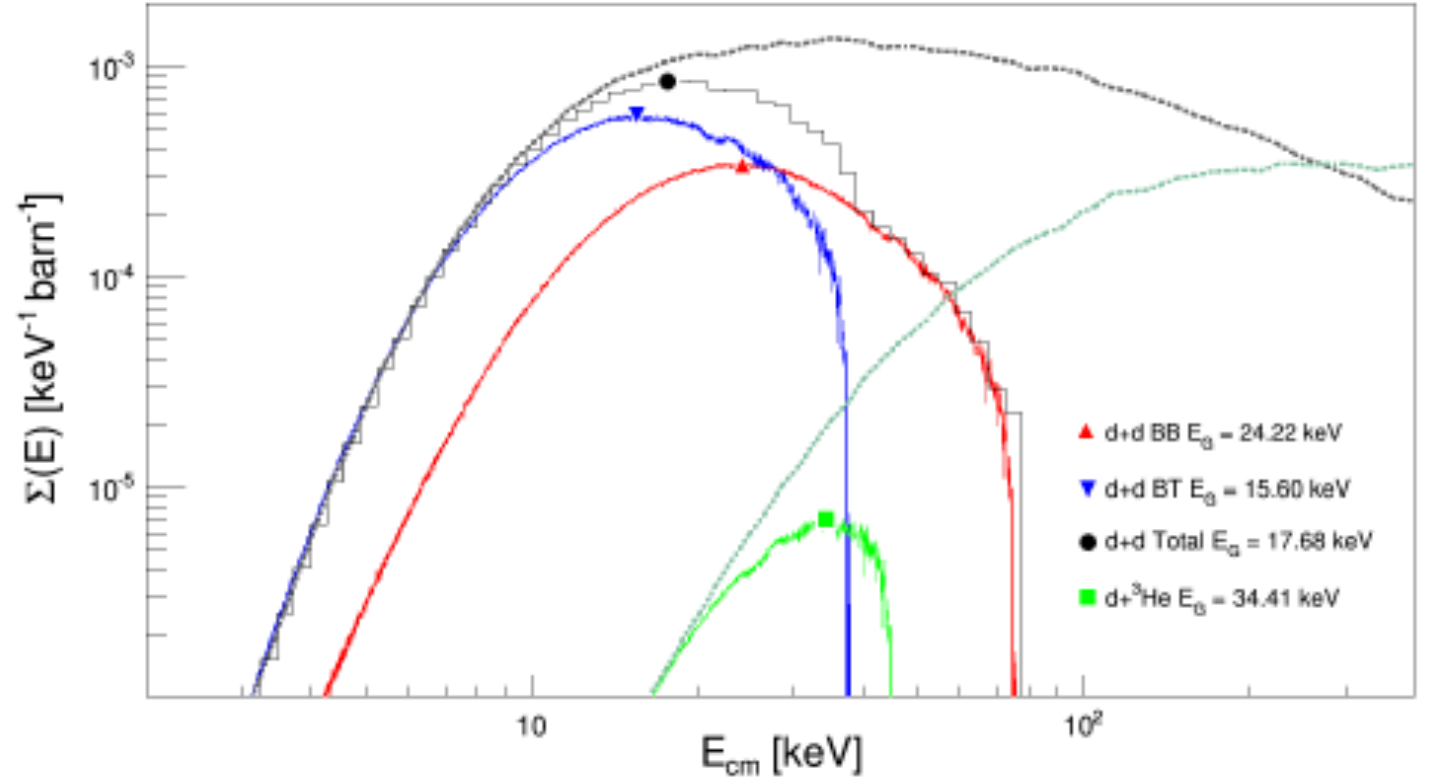
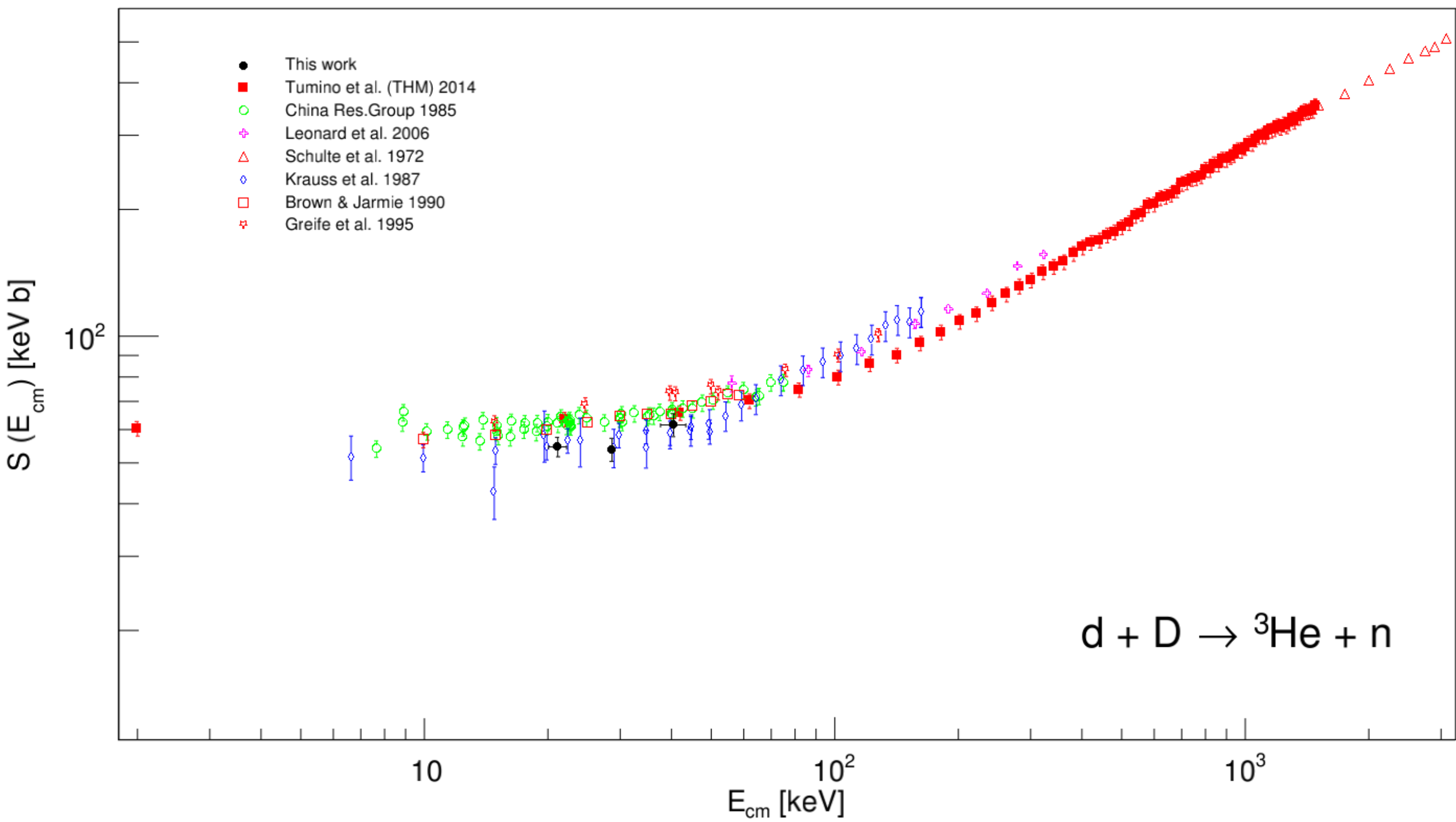
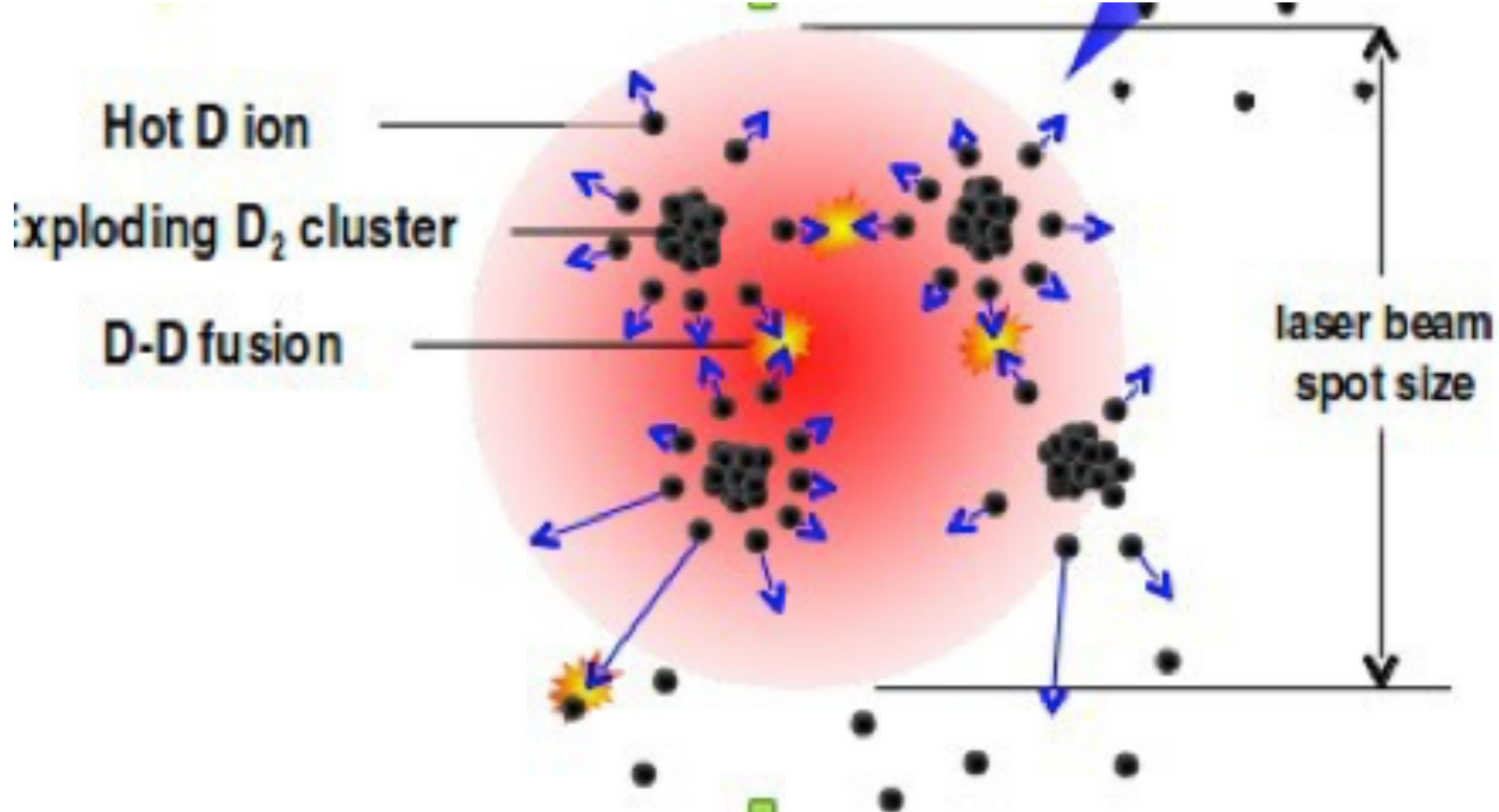
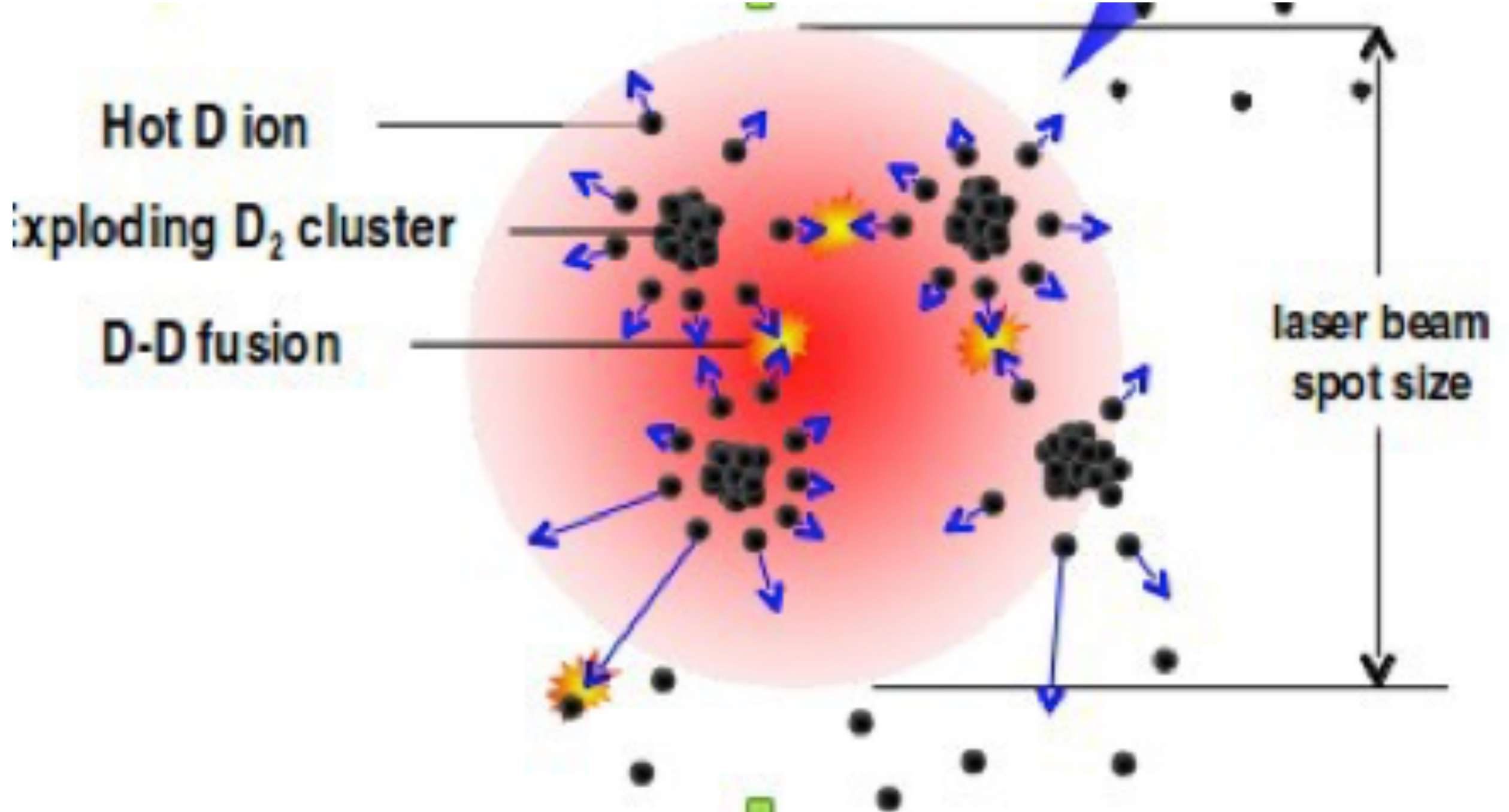


FIG. 4.  $\Sigma(E)$  for the nuclear reactions (1) and (3) is plotted versus the center-of-mass energy of the fusion nuclei. The area under the curves gives the inverse of the S-factor. The d+d *BB* (in red) and *BT* (in blue) contributions are plotted together with their sum (binned, black) and the d+<sup>3</sup>He one (green). The latter are also plotted without applying any background cut (thick dashed grey and cyan lines). The maximum of this quantity locates the Gamow peak energy. The solid (red) up and (blue) down triangles respectively represent the BB and BT contributions of (1), the solid (black) circle is their sum and the solid (green) square is used for the reaction (3).

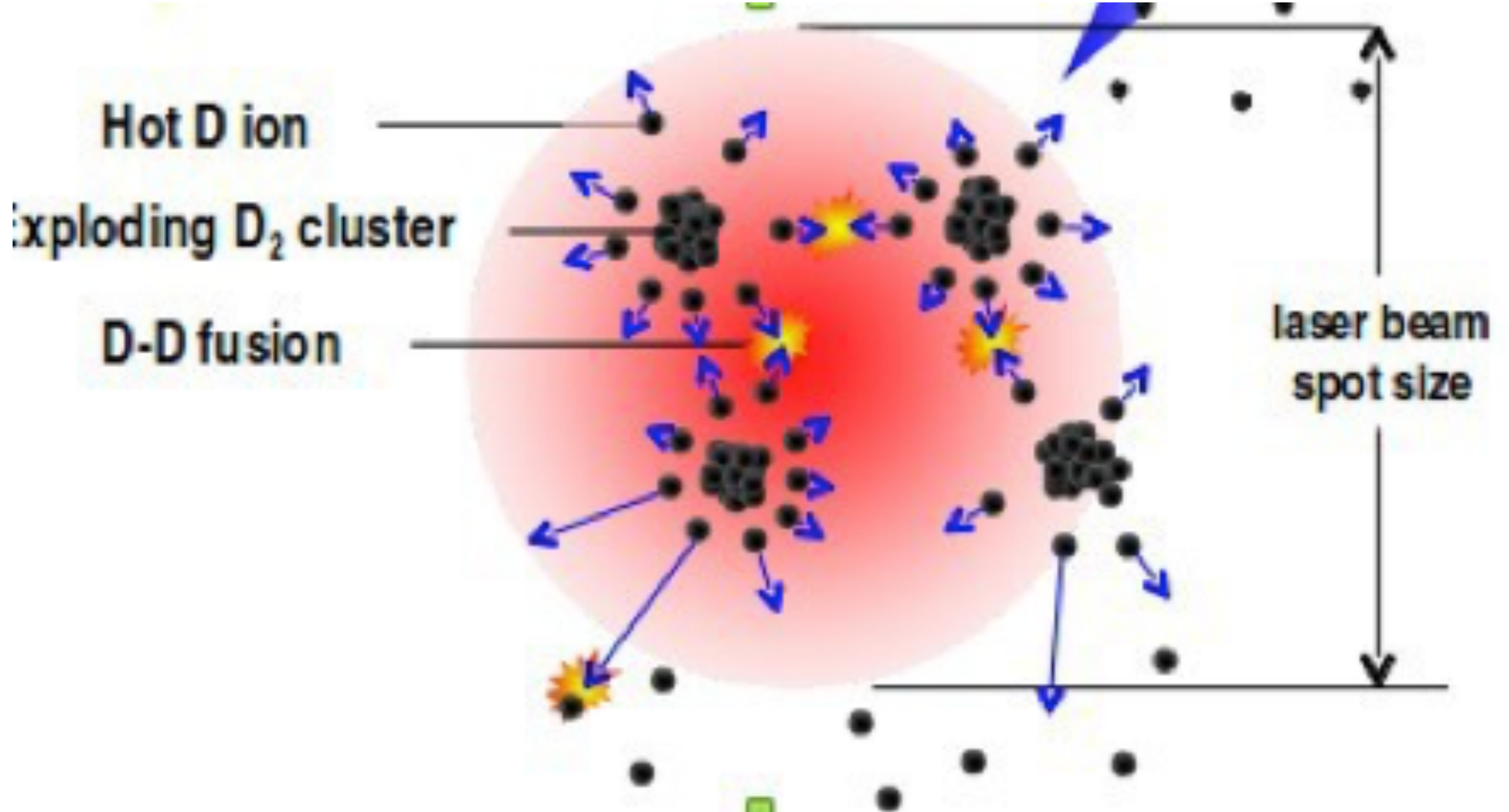






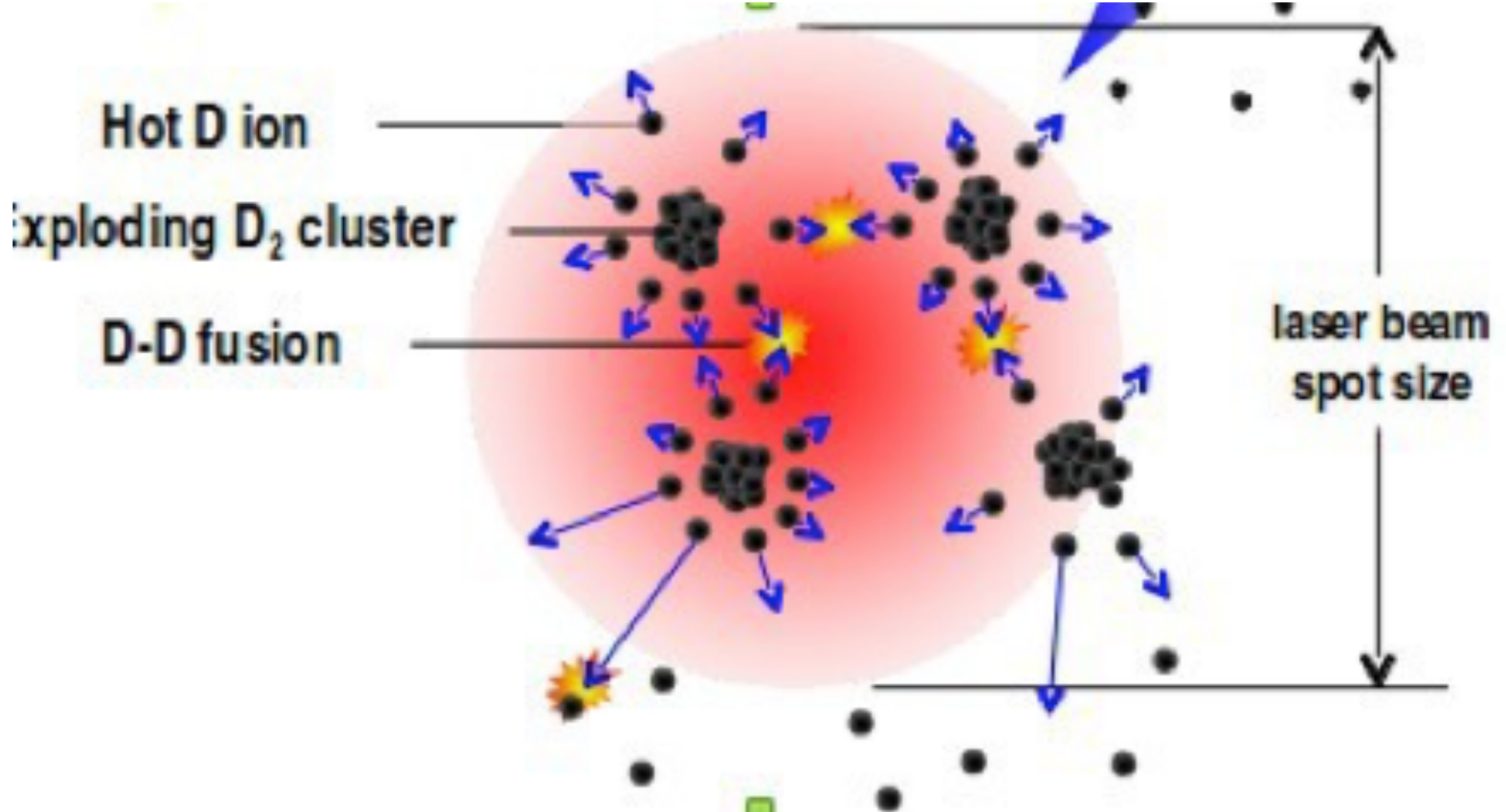


Plasma is a harsh environment. If the collisions occur in the presence of electrons, the probability might go up



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 If they occur in the presence of positive charges, probability might go down: DISSIPATIVE LIMIT<sup>[11]</sup>

S. Kimura, A. Bonasera, Influence of the electronic chaotic motion on the fusion dynamics at astrophysical energies. Nucl. Phys. A 759 (2005) 229244.



## Range of plasma ions in cold cluster gases near the critical point



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## ABSTRACT

We measure the range of plasma ions in cold cluster gases by using the Petawatt laser at the University of Texas–Austin. The produced plasma propagated in all directions some hitting the cold cluster gas not illuminated by the laser. From the ratio of the measured ion distributions at different angles we can estimate the range of the ions in the cold cluster gas. It is much smaller than estimated using popular models, which take only into account the slowing down of charged particles in uniform matter. We discuss the ion range in systems prepared near a liquid–gas phase transition.

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Nuclear fusion from explosions of laser-heated clusters has been an active research topic for over a decade [1–14]. The explosions of cryogenically cooled deuterium ( $D_2$ ) cluster targets or near-room-temperature deuterium-methane ( $CD_4$ ) cluster targets drive fusion reactions. A high intensity femtosecond laser pulse irradiated the cluster gas. This produces energetic explosions of the clusters and tens of keV ion plasma temperature results. DD fusion occurring within this high temperature plasma combined with beam-target fusion, between the ejected ions of the cluster and surrounding cold cluster gas, leads to a burst of fusion neutrons and protons. Following these experiments, we have modified some aspects in order to be able to measure the range of energetic ions in the cold cluster gases. Recall that the range of ions is crucial to estimate the fusion rates in the plasma. We have opportunely focused the laser in such a way that the high-energy pulse drills a “hole” in the target. We found that less than 10% of the laser energy went through the cluster gas for each shot.

A schematic view of this scenario is plotted in Fig. 1a, while an actual experimental result is given in Fig. 1b. Two Faraday cups (FC) were opportunely located: the first one (UTFC) as close as

possible to the incoming laser direction ( $-67.5^\circ$  minimum) thus measuring essentially the hot plasma only; the second one (CTFC) was located at an angle around  $45^\circ$ , see Fig. 1, and compatible to the physical constraints of the laboratory (walls). The ratio of the FC signals gives an indication of the range of the ions in the surrounding cold cluster gas. Our experimental results show that the range of the ions in the cluster gas is almost independent of their energies and it is much shorter than the range calculated using the popular SRIM code for instance [15]. The physics included in SRIM or similar models, is the slowing down of keV ions due to the interaction with electrons in the uniform gas. In our case, the gas has not an uniform density distribution but it is made of drops of different sizes, well explained by a log-normal distribution [16,17], formed during the free expansion into vacuum after the opening of the pulsed valve. Drops can present already inside the valve before the expansion, if the gas is prepared for instance near the critical point of the liquid–gas (LG) phase transition. It is of great interest to study what happens in those cases after the gas expands. Near the second order LG phase transition, the mass distribution of the clusters follows the Fisher’s law and in particular it is a power law at the critical point [18]. The free expansion might change such distribution. Theoretical calculations of a classical interacting gas, which freely expands after has been prepared near the critical point [19], do not display much variation from the predicted Fisher’s cluster distribution. Thus, the cluster size distribution obtained from the

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# Neutron enhancement from laser interaction with a critical fluid



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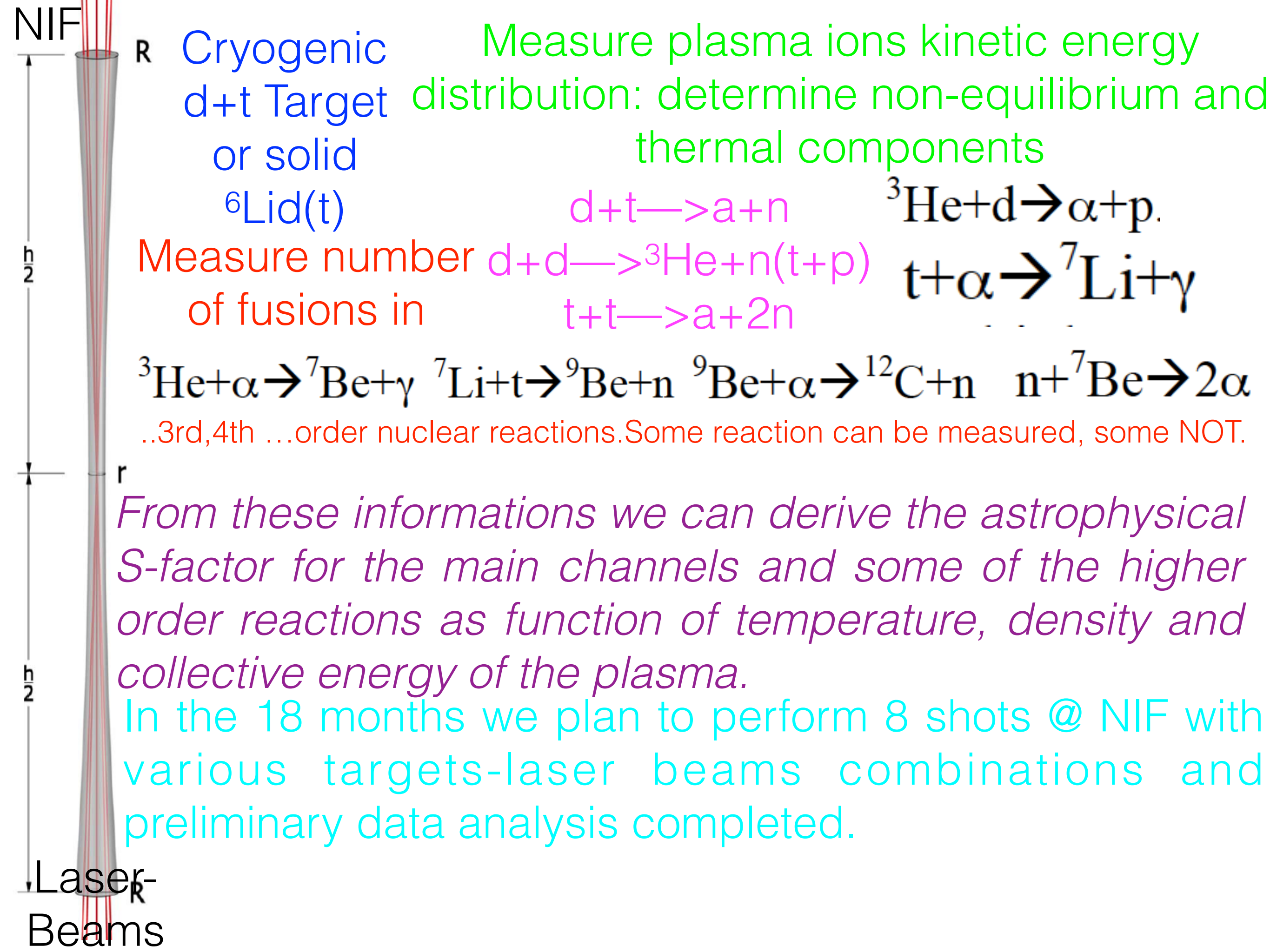
Laser induced plasma

Critical phenomena

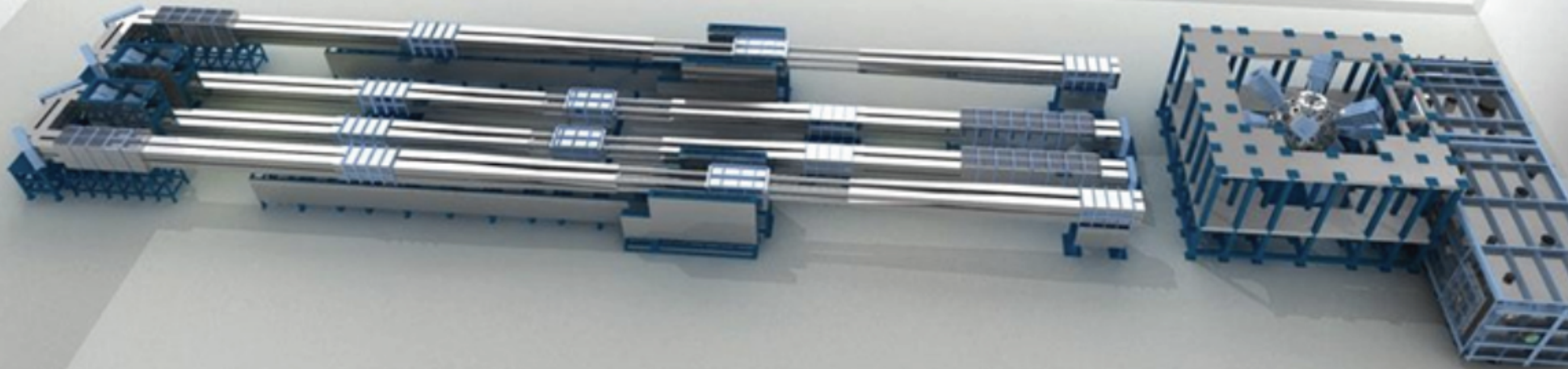
Fusion reactions

## ABSTRACT

We discuss experimentally and theoretically neutron production from the laser driven explosion of gas clusters prepared near the liquid-gas critical point. We let deuterated methane that was prepared very close to its critical temperature and pressure expand through a conical nozzle to create clusters, and then irradiated those clusters with a high intensity pulse from the Texas Petawatt Laser. After ionization, the clusters explode producing energetic ions, some of which fuse with resultant neutron emission. We show that the critical fluctuations present in the nozzle before the expansion influence the dynamics of neutron production. Neutron production near the critical point follows a power law, which is a signature of a second order phase transition and it is consistent with the Fisher model. This result might be relevant for energy production from fusion reactions.







**operating since 2011**

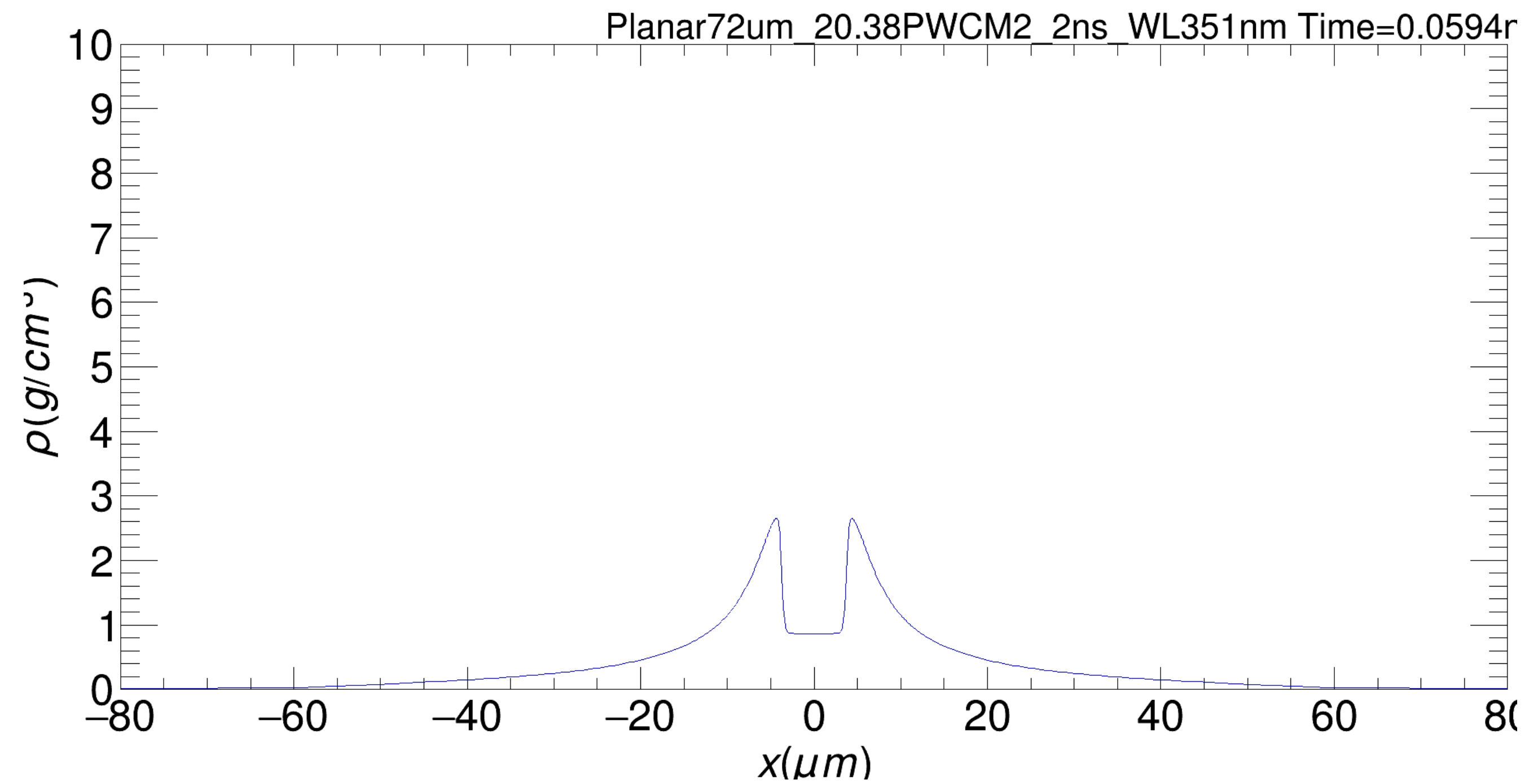
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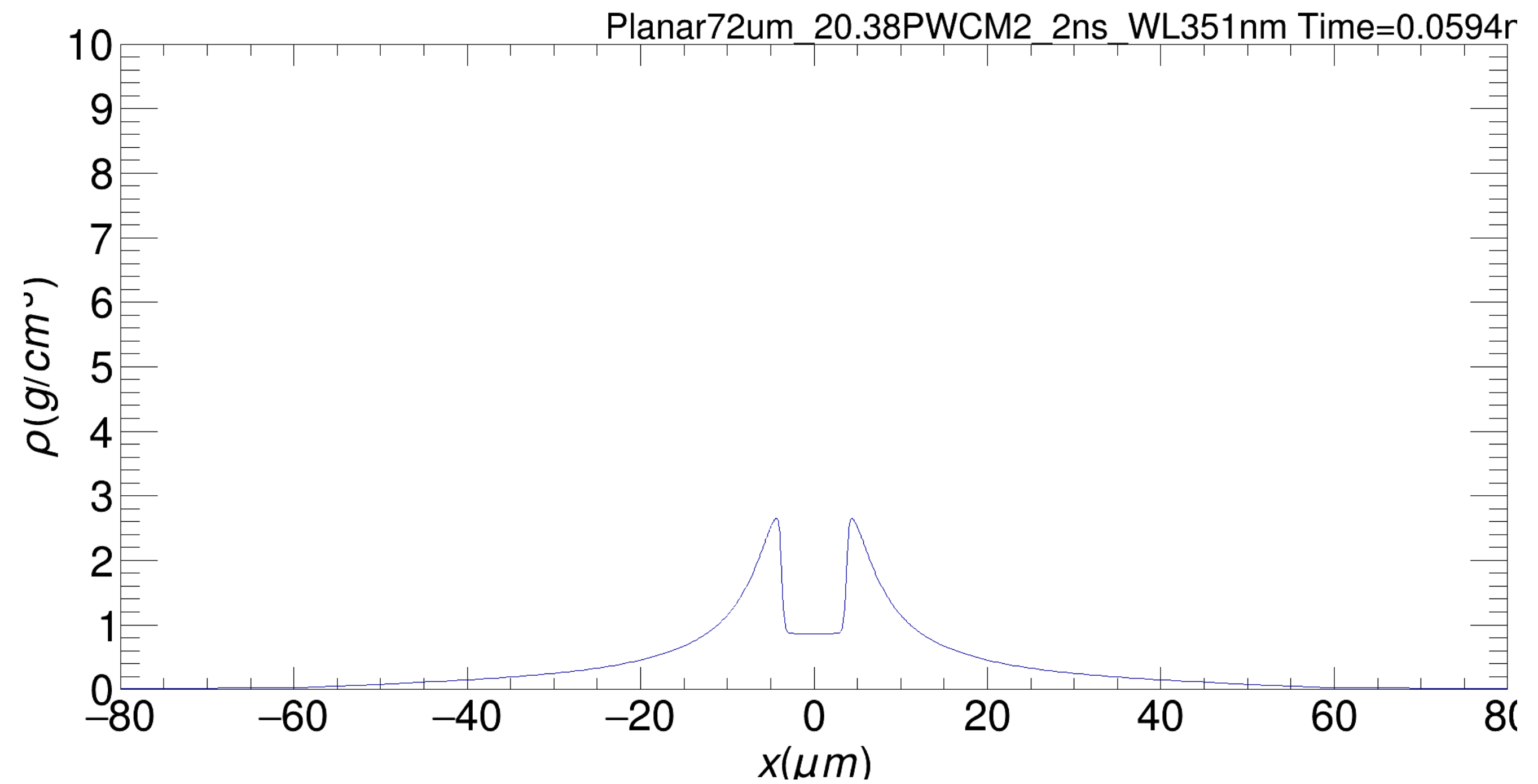
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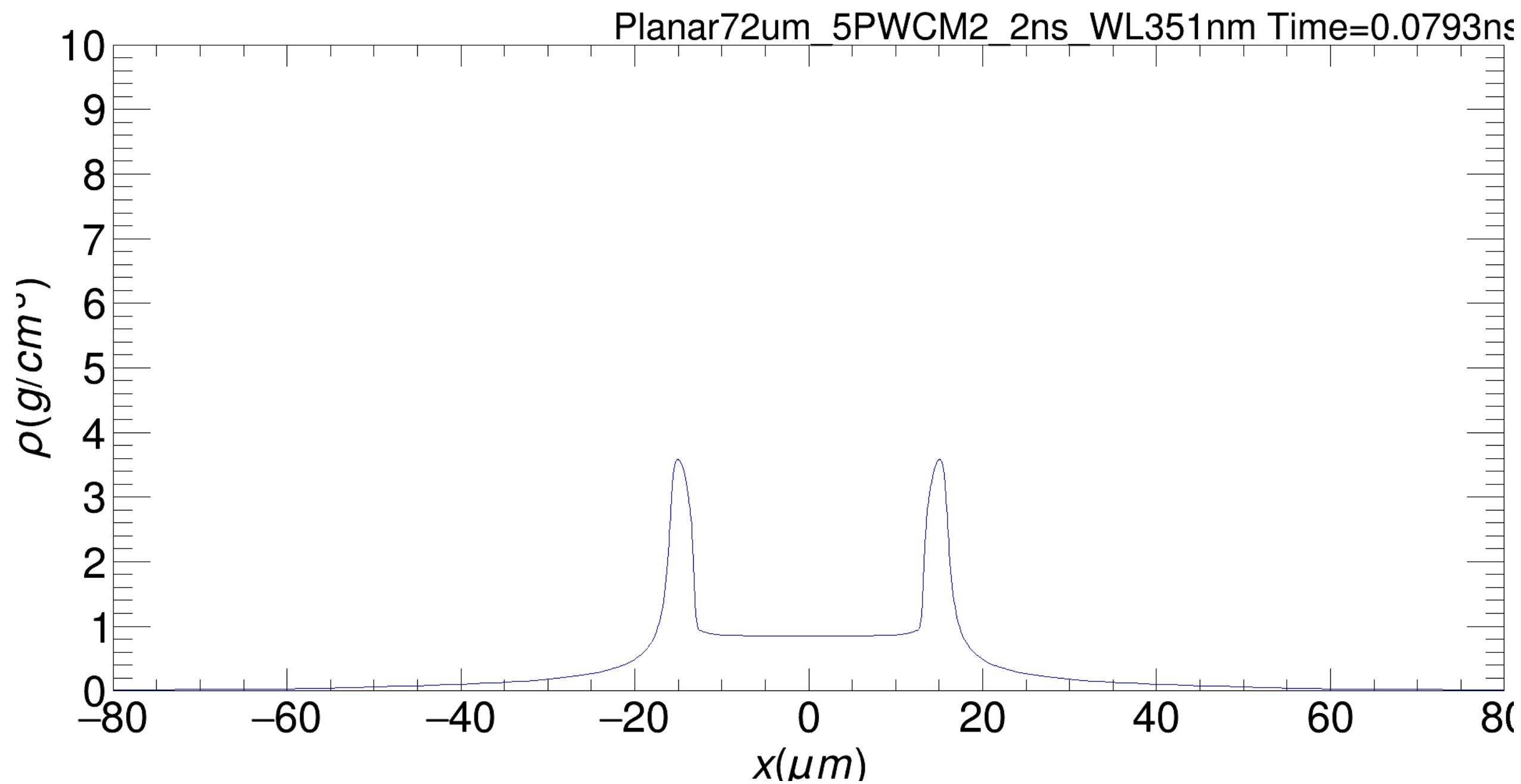
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**Collaboration**









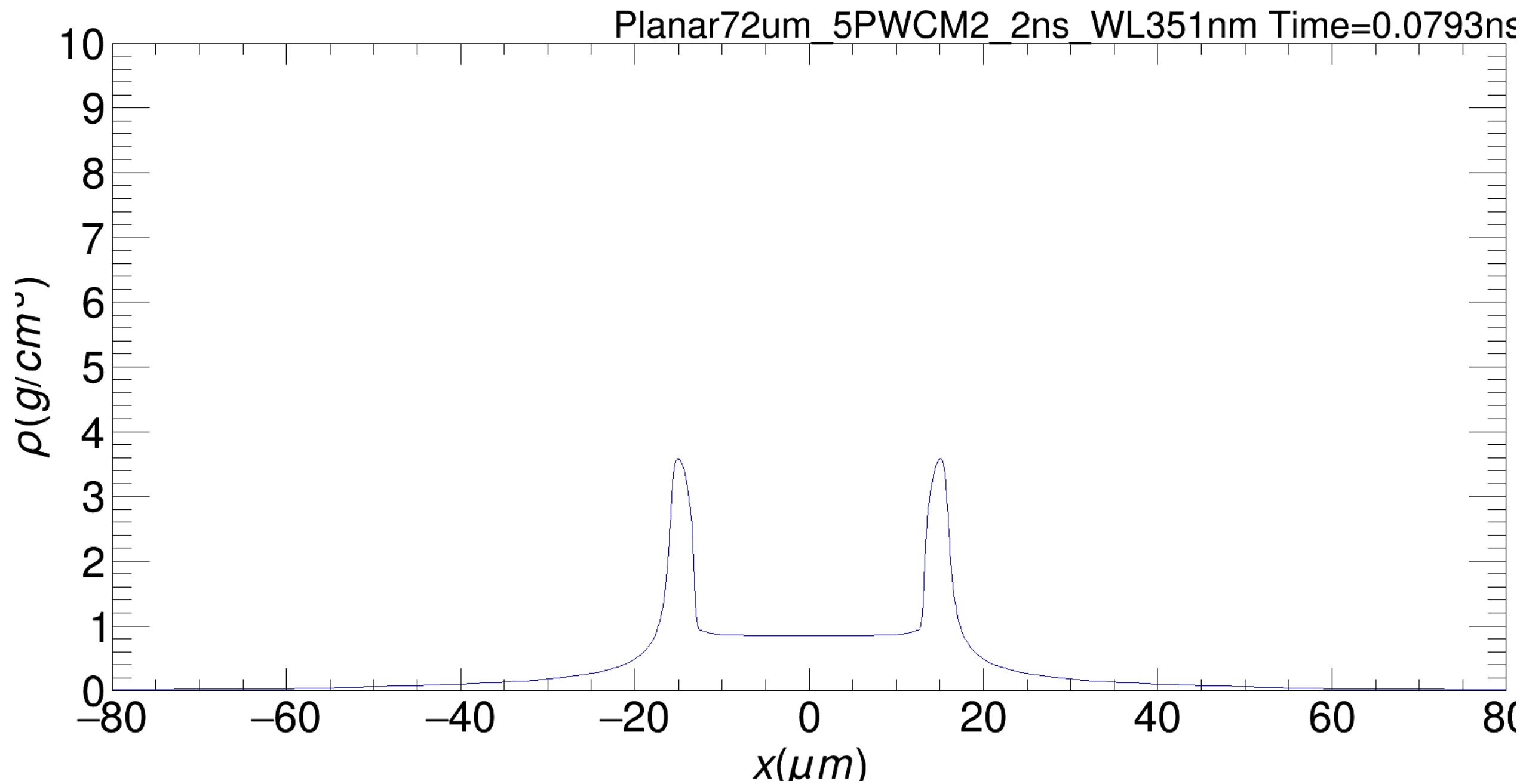
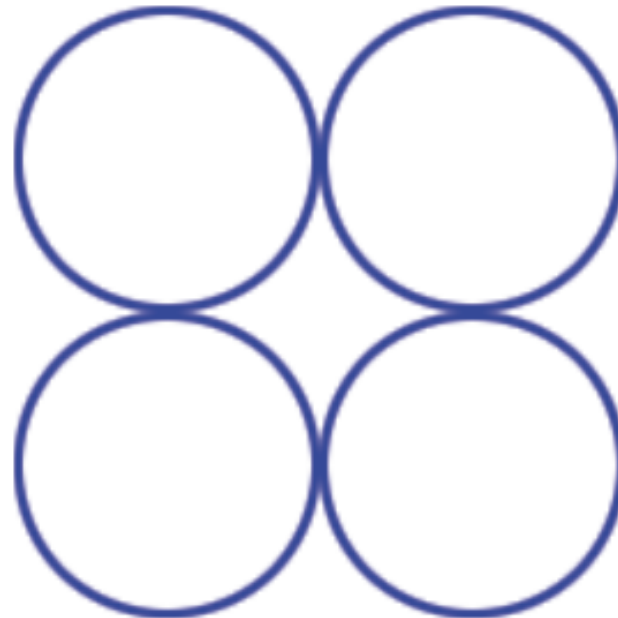
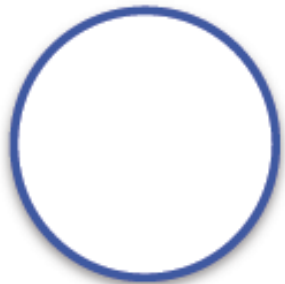


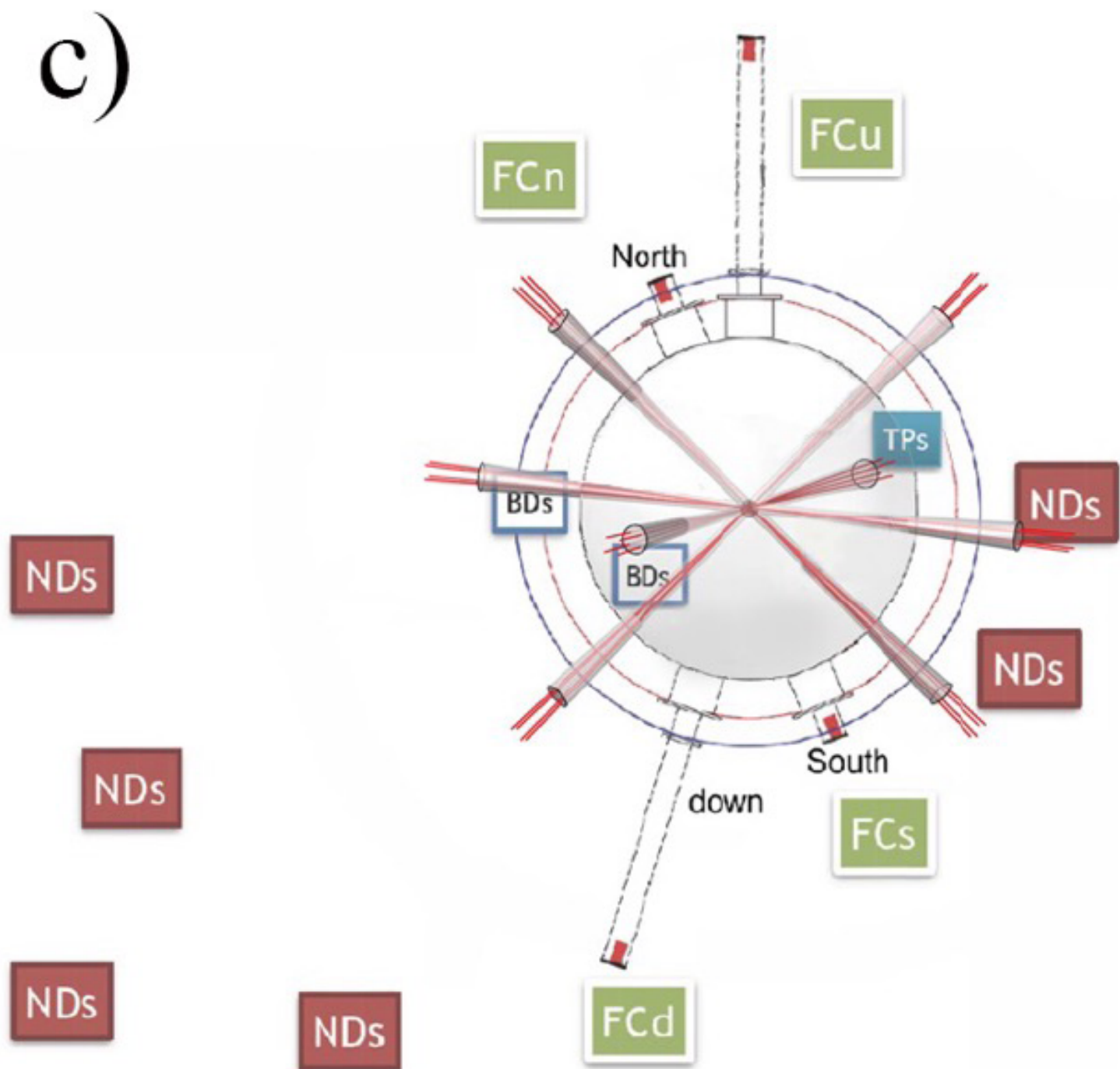
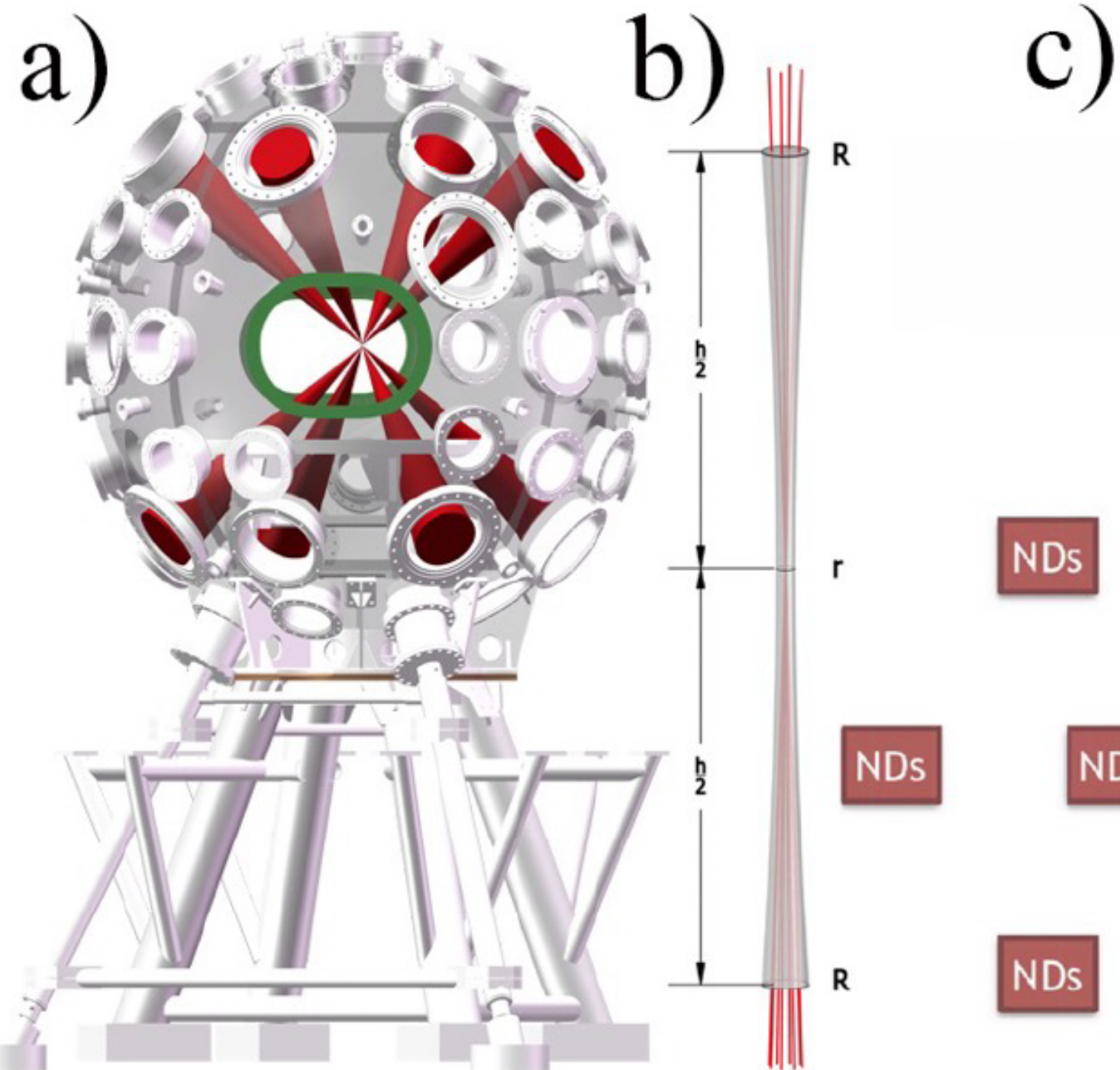


TABLE I. Laser parameters

laser energy(J)	shot 1	shot 2	shot 3	shot 4	shot 5
up	4977.89	5144.29	5026.44	5017.57	6621.55
down	6912.87	7069.24	5525.58	7247.5	7233.71
duration(ns)	2	2	2	2	2
focalization( $\mu\text{m}$ )	200	200	200	150	400
target thickness( $\mu\text{m}$ )	400	905	1095	850	210
target width( $\mu\text{m}$ )	1000	800	1000	1000	1000
laser stucture	center	center	center	center	center
laser energy(J)	shot6	shot 7( $^{13}\text{C}$ )	shot 8(LiD)	shot 9	shot 10
up	6821.62	6435.02	6597.74	6681.29	3554.82
down	7660.26	7495.56	7523.18	7287.12	3883.27
duration(ns)	2	2	2	2	1
focalization( $\mu\text{m}$ )	150	150	150	150	150
target thickness( $\mu\text{m}$ )	2444	300	300	69.56	69.56
target width( $\mu\text{m}$ )	2000	500(hole)	500(hole)	600	600
laser stucture	center	center	center	center	center
laser energy(J)	shot 11	shot 12	shot 13	shot 14	shot 15
up	1672.83	7421.34	9179.14	9569.93	9419.71
down	1729.44	7635.61	9532.21	9775.48	9633.67
duration(ns)	0.5	3	3	3	3
focalization( $\mu\text{m}$ )	150	150	150	150	150
target thickness( $\mu\text{m}$ )	69.56	69.56	79	32	40
target width( $\mu\text{m}$ )	600	600	600	600	4000
laser stucture	center	center	Audi rings	center	borromean



laser energy(J)	shot 16	shot 17	shot 18	shot 19	shot 20
up	9125.03	1805.98	3290.49	3808.78	1441.04
down	9313.11	1916.51	3355.43	4238.80	1638.25
duration(ns)	3	0.5	3	1	0.5
focalization( $\mu\text{m}$ )	150	150	150	150	150
target thickness( $\mu\text{m}$ )	3.6	3.6	10	10	10
target width( $\mu\text{m}$ )	3500	3500	1000	1000	1000
laser stucture	borromean	center	borromean	borromean	borromean
laser energy(J)	shot 21	shot 22	shot 23		
up	6882.84	1487.00	553.29		
down	7042.43	1608.13	733.32		
duration(ns)	2	0.5	0.25		
focalization( $\mu\text{m}$ )	150	150	150		
target thickness( $\mu\text{m}$ )	20	20	20		
target width( $\mu\text{m}$ )	1000	1000	1000		
laser stucture	borromean	borromean	borromean		



# Cross sections\S-factor\reaction rate in plasmas

The effect of ternary fusion reactions

Highly compressed and not so hot plasma

$$Nf1 = Ni * \rho < \sigma v \tau > / 2 = Ni * \rho < \sigma 1 > r1 / 2 \text{-----} (1)$$

$$Nf2 = Nf1 * \rho < \sigma 2 > r2 \text{-----} (2)$$



0	Ni	d	$\rho$	$<\sigma>$	r
1	Nf1	${}^3\text{He} (0.82 \text{ MeV})$ $n (2.45 \text{ MeV})$ $t (1.01 \text{ MeV})$ $p (3.02 \text{ MeV})$			
2	Nf2	${}^4\text{He} (3.5 \text{ MeV})$ $n (14.1 \text{ MeV})$ ${}^4\text{He} (3.6 \text{ MeV})$ $p (14.7 \text{ MeV})$			



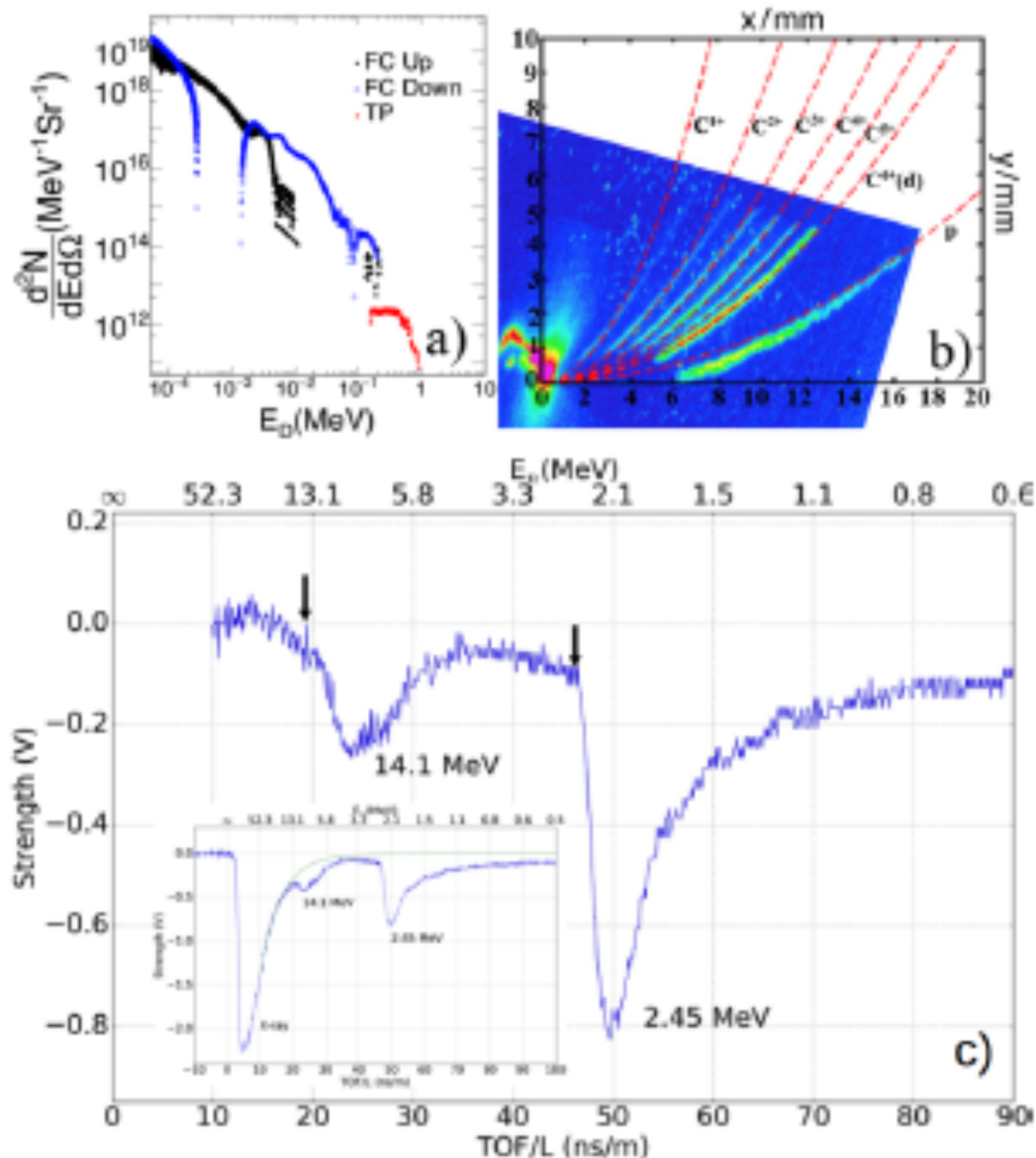


Figure 2: (color online) a) Deuterium energy distribution from the top (full circles) and bottom (open circles) FC, and TP (full triangles). b) TP spectra relative to the laser irradiation of  $\text{CD}_2$  target. c) TOF results for 14.1 MeV and 2.45 MeV neutrons from plastic scintillator detector. The two arrows indicate the 14.1 MeV and 2.45 MeV neutron energies.



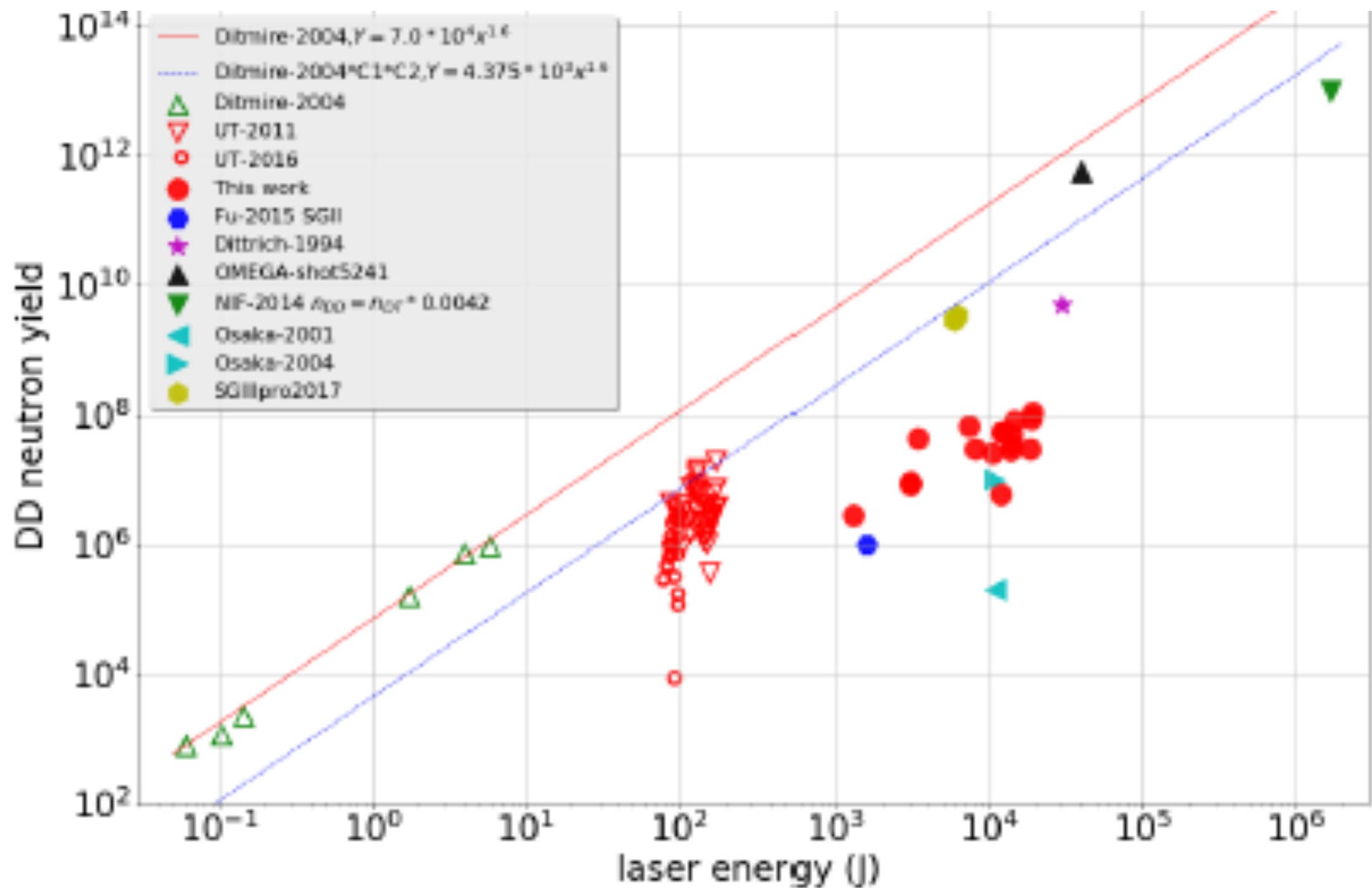


Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-2004<sup>35</sup>, UT-2011<sup>20</sup>, UT-2016<sup>19</sup>, Fu-2015 SGII<sup>40</sup>, Dittrich-1994<sup>44</sup>, NIF-2014<sup>43</sup>, Osaka-2001<sup>41</sup>, Osaka-2004<sup>42</sup>, OMEGA-shot5241<sup>36</sup> and SGIIpro2017<sup>37</sup> are indicated in the inset.

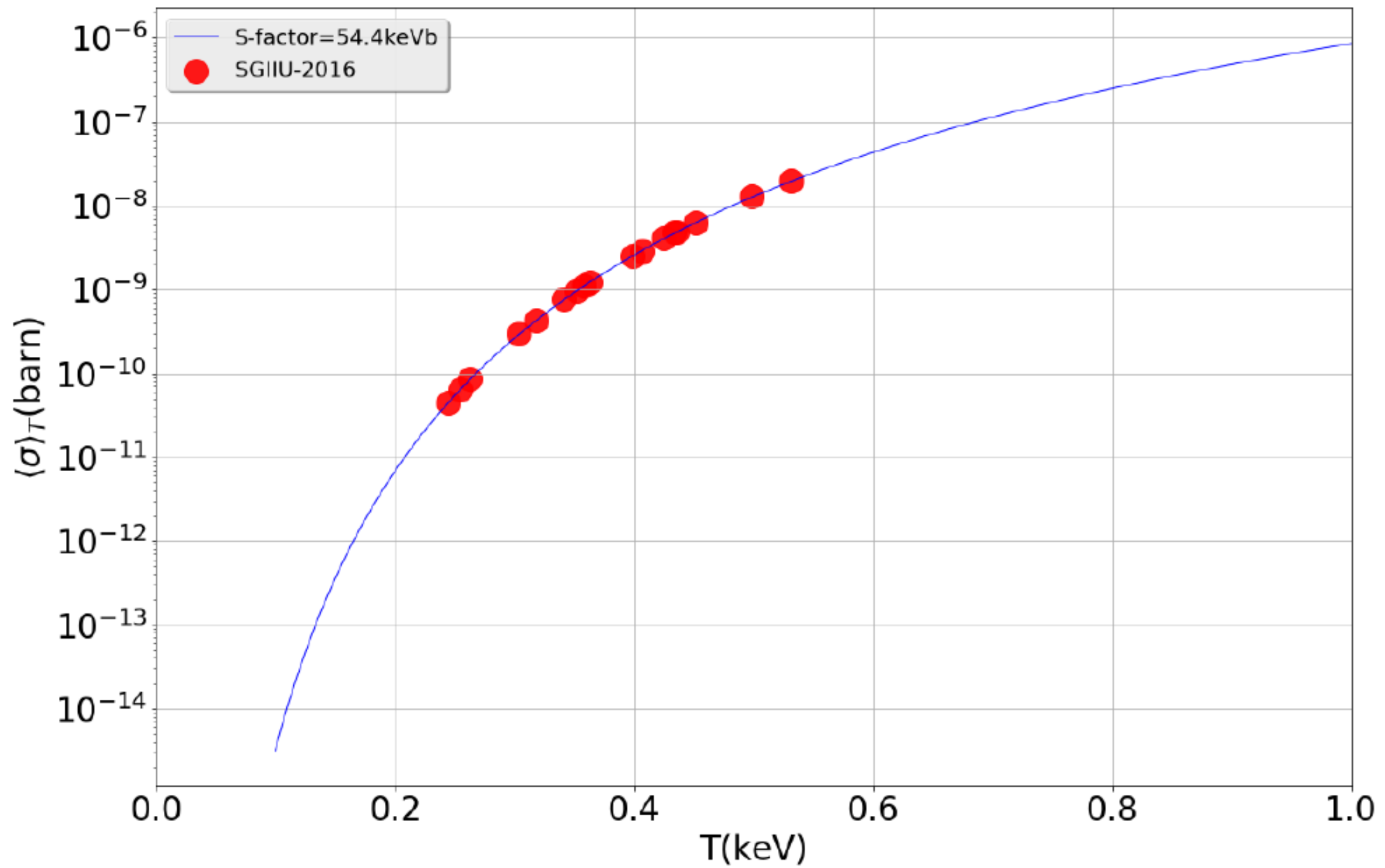


Figure 5: (color online) The average cross section as function of temperature with Maxwell-Boltzmann distribution, expressed by eq. (6) . The red points are the experimental cross section data from eq.(5).

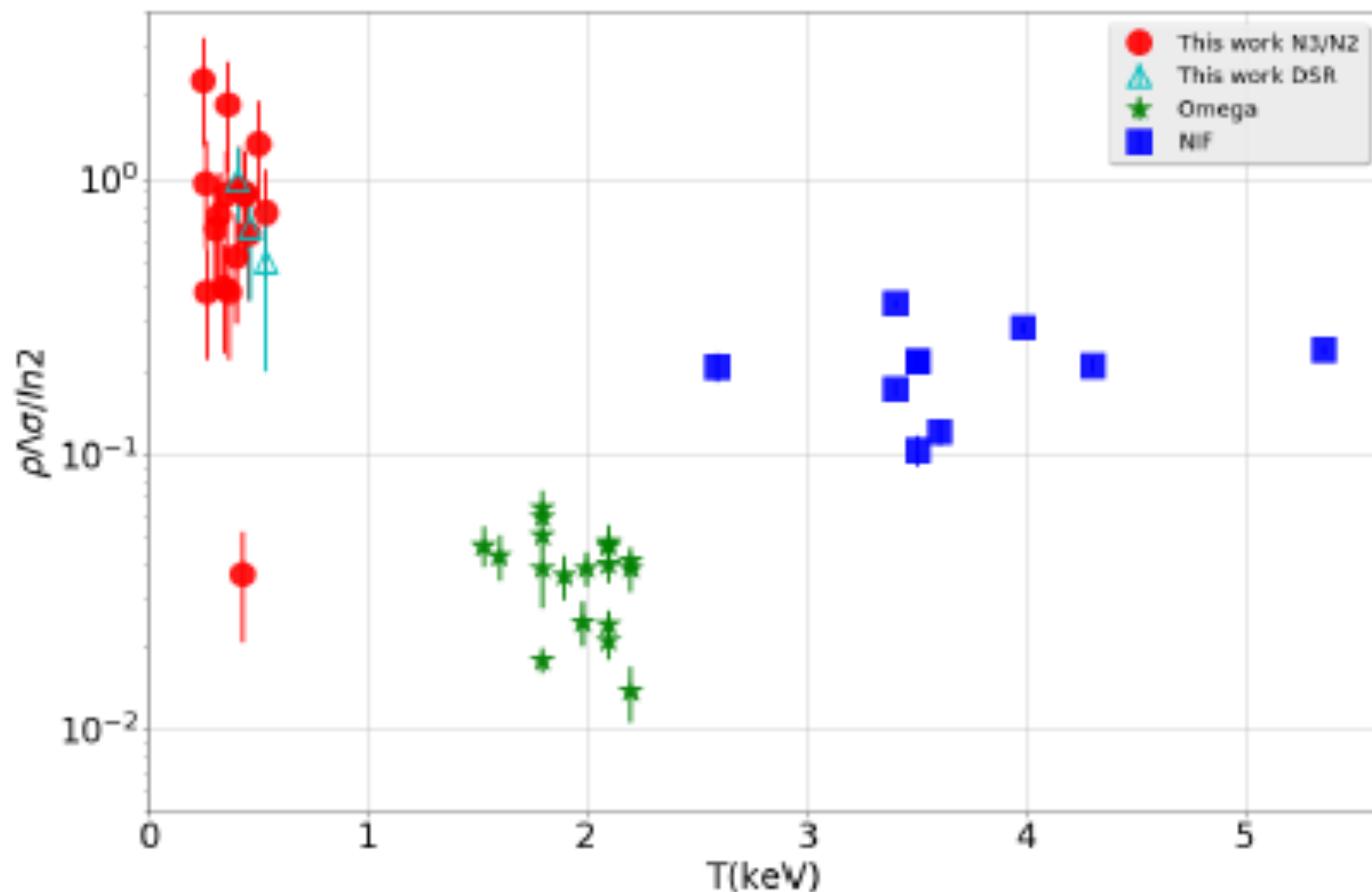


Figure 4: (color online)  $A\rho\sigma/\ln 2$  obtained from eq.(4) vs  $T$  from eq.(1). Omega and NIF data are derived from the experiments<sup>25</sup>, using the Down Scatter Ratio<sup>21,23</sup>. Our results using the DSR method (N4/N3) are given by the open triangle symbols in good agreement with the N3/N2 ratios..

The experimental results can be roughly understood using some simple considerations. We can solve the Rankine-Hugoniot equation assuming a plasma EOS given by:

$$\frac{E}{N} = E_{av} + \frac{A}{2}\bar{\rho} + \frac{B\sigma}{\sigma + 1}\bar{\rho}^\sigma \quad (1)$$

$$P = \rho^2 \frac{d(E/N)}{d\rho} + \rho T \quad (2)$$

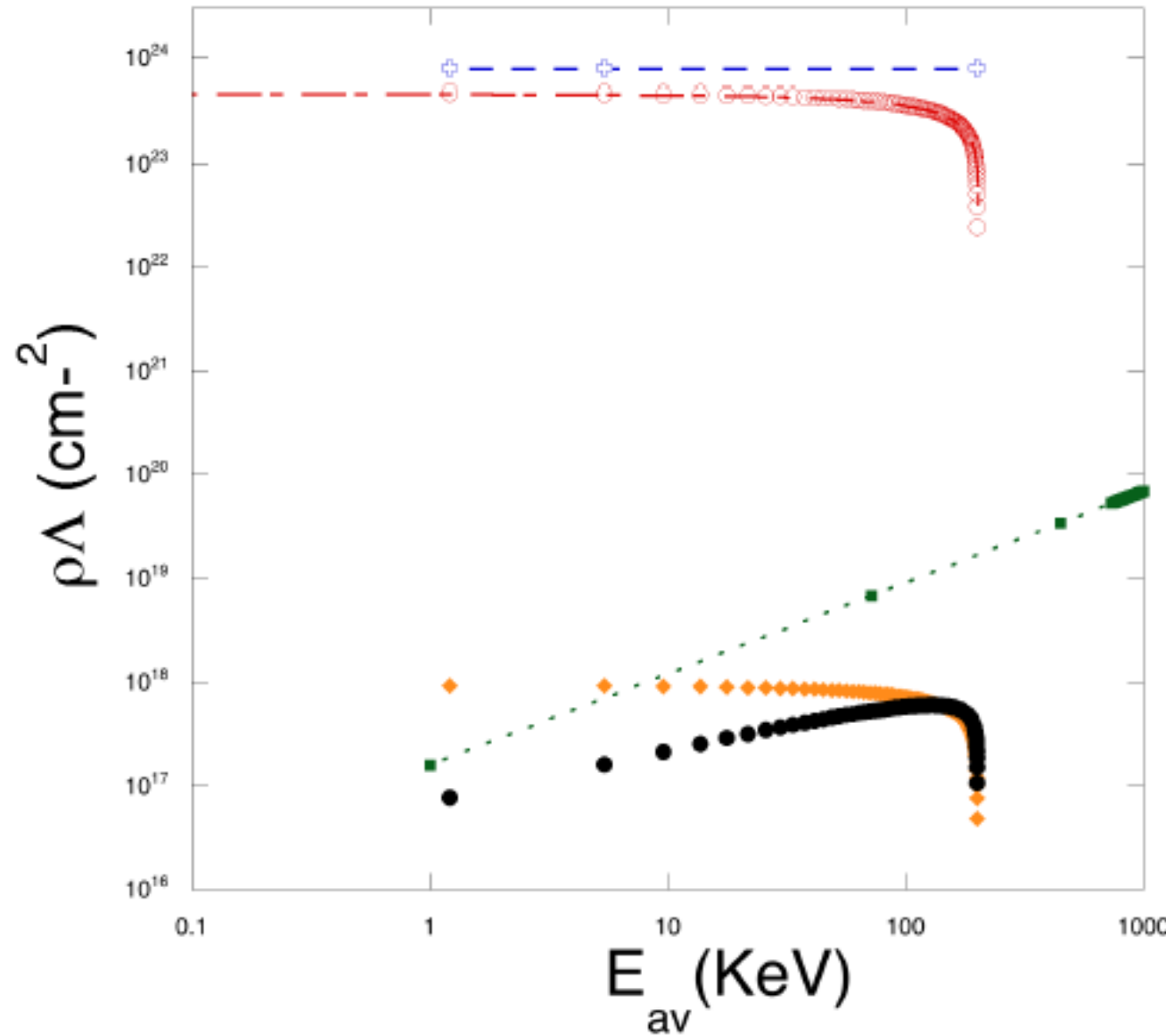
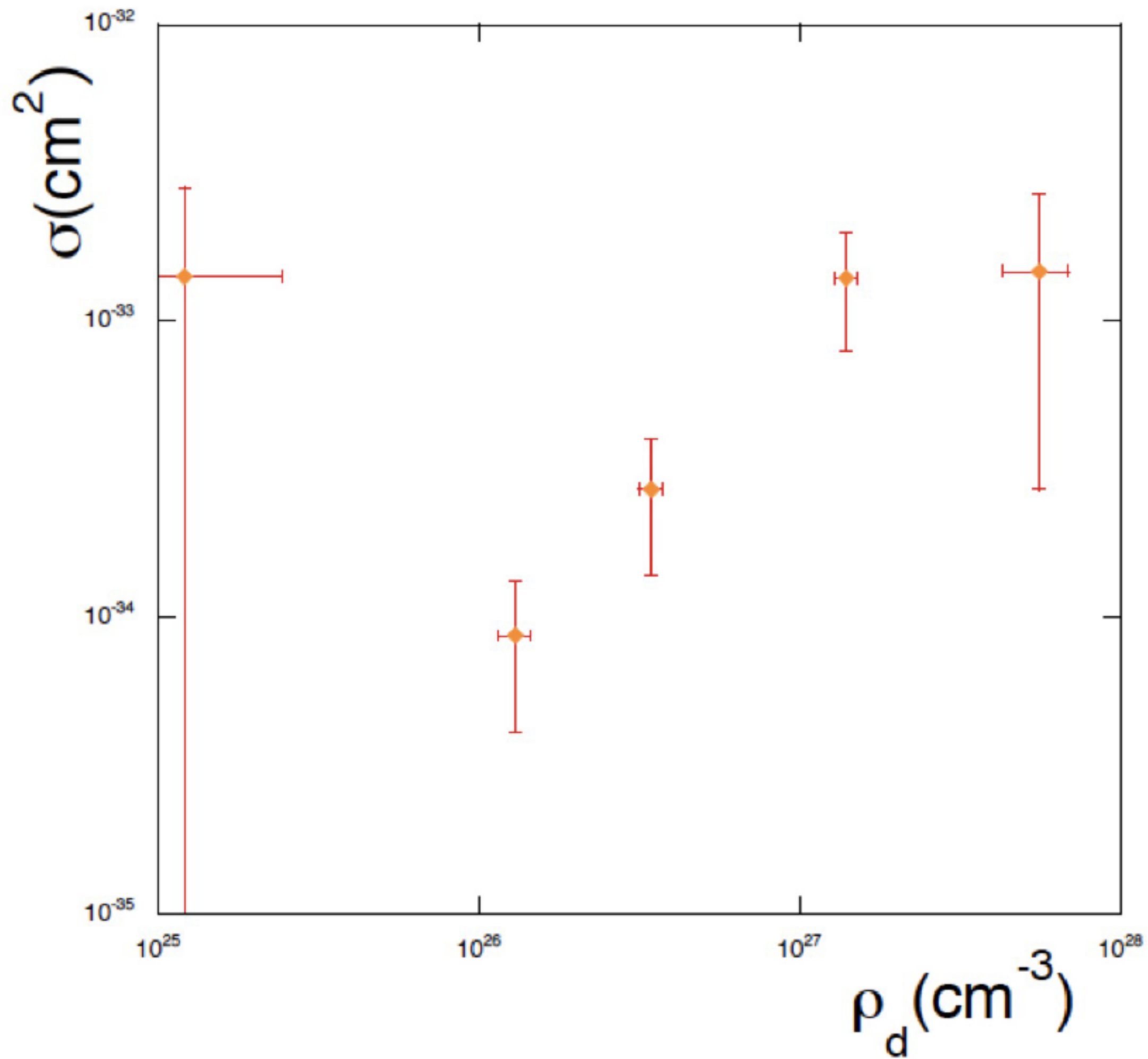


Figure 6: (color online)  $\rho\Lambda$  vs average energy of the plasma. Open cross symbols: experimental result; open circles: range given by the compressed target thickness, full squares: SRIM result; full diamonds: relative distance of plasma particles; full circles: Debye length.





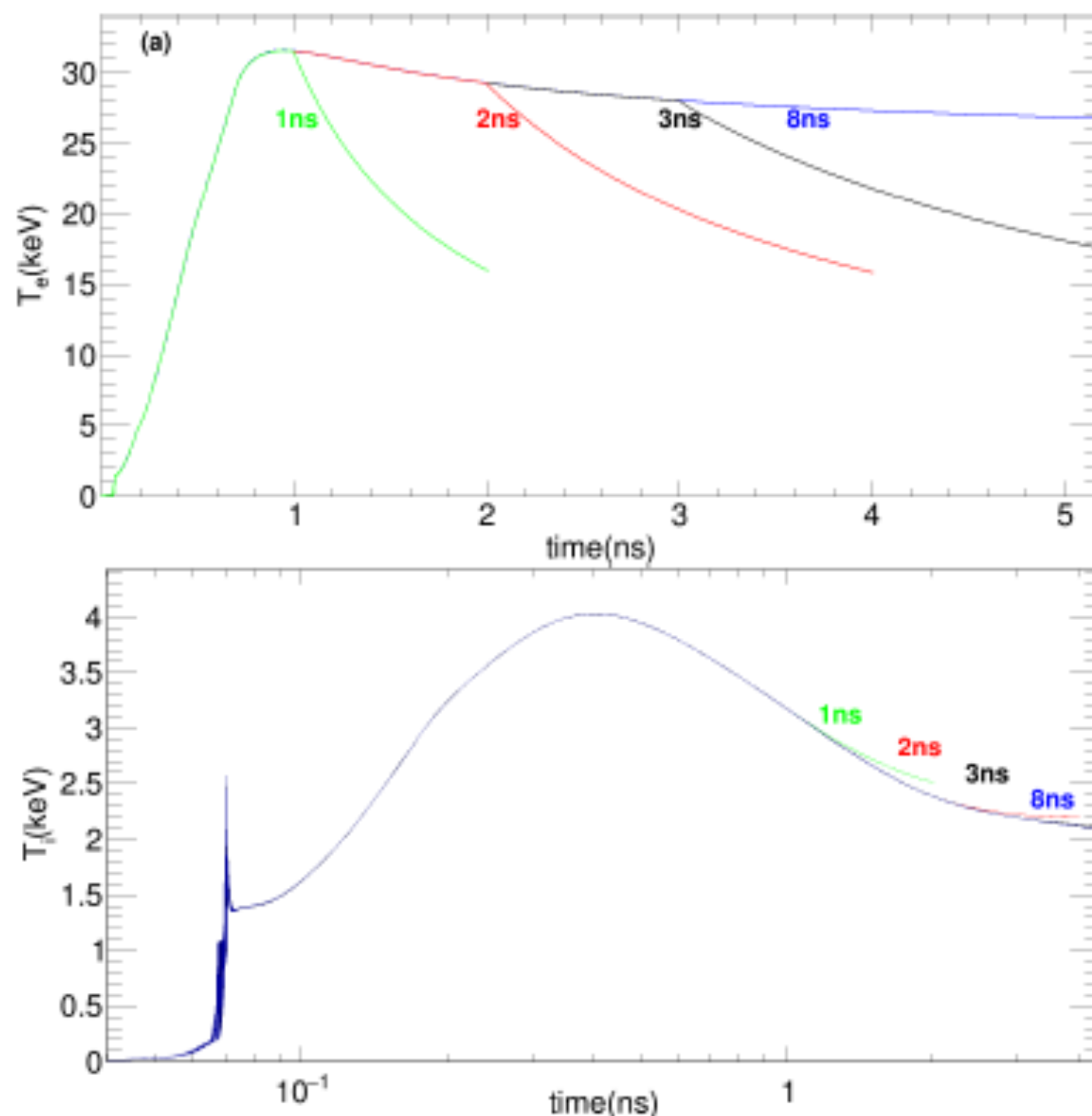


Figure 3: (color online)(a)Electron temperatures time evolution for the parts initially near the center region (23-48 $\mu$ m). The colors label for various of time durations of laser. (b) Ion temperatures vs. time.

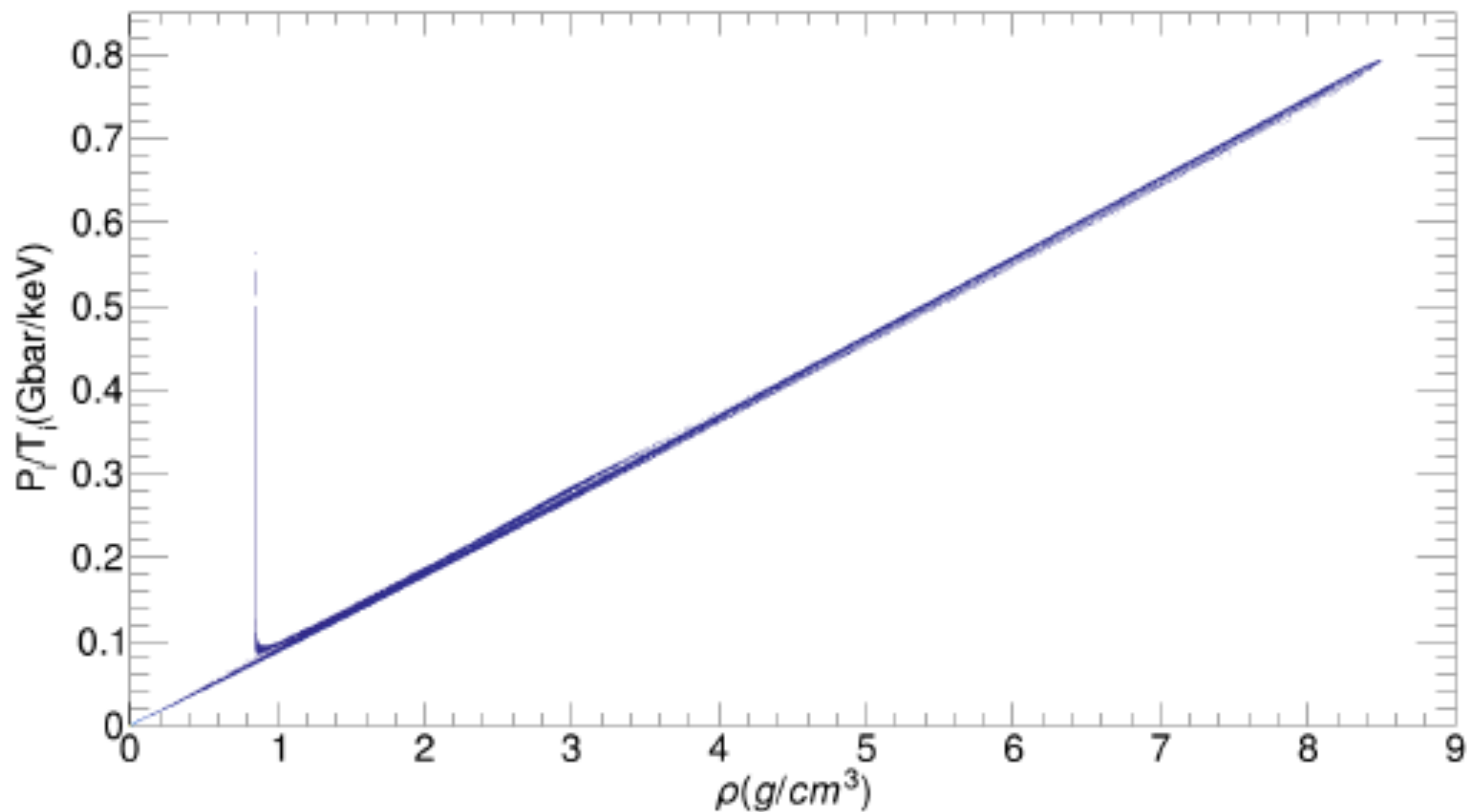


Figure 4: (color online) The phase diagram of ions in the evolution.

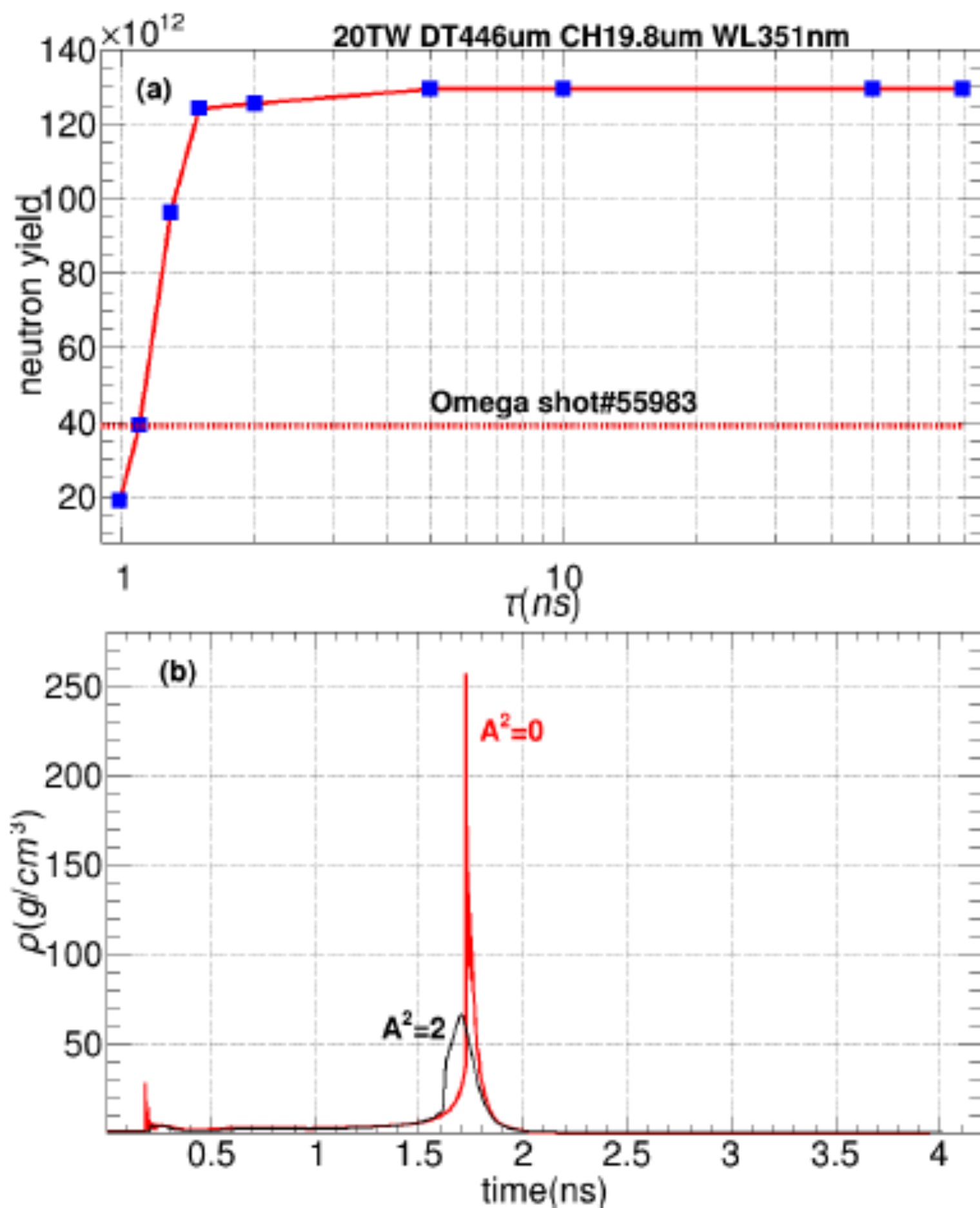
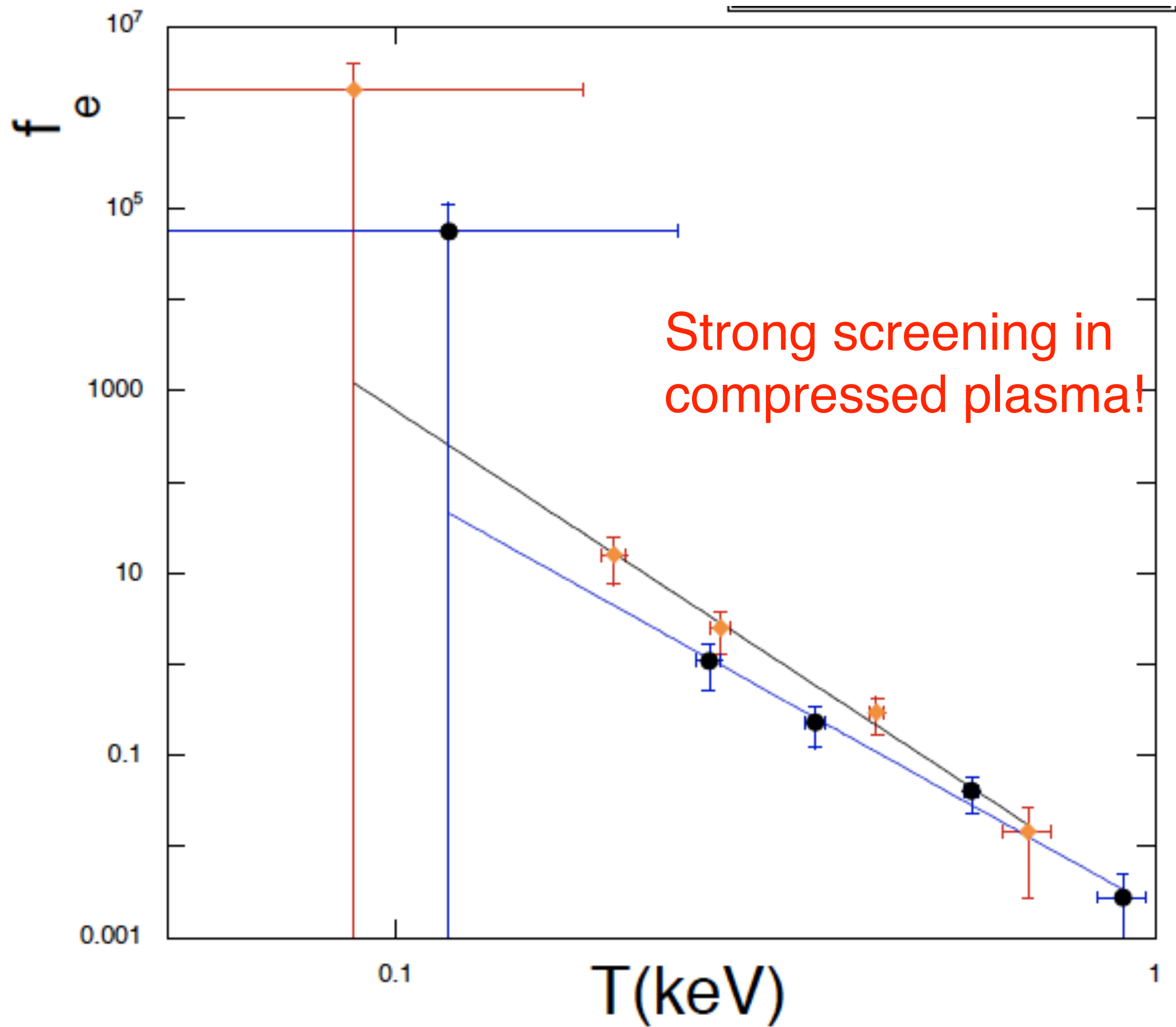


Figure 5: (color online)(a)Neutron yield vs. pulse duration of laser, (b)viscosity effect on the compression.





# Nuclear Physics News

## International

### Nuclear Astrophysics with Lasers

Meirong Huang, Hernan J. Quevedo, Guoqiang Zhang & Aldo Bonasera

A systematic program of investigations of nuclear reactions in laser-produced plasmas is addressed. Such reactions provide an important diagnostic tool for probing the dynamics and thermodynamics in the plasma and understanding laser ion acceleration and neutron production mechanisms. The goal will be to reach the level of knowledge that allows the measurement of fundamental nuclear cross sections at low and high particle densities. The quantitative measurement of fusion probabilities in hot and dense plasmas will contribute significantly to our comprehension of stellar composition and evolution and will provide important information for development of fusion energy production and applications such as medical isotope production and compact neutron source development. All of these are some of the main goals of the European Extreme Light Infrastructure (ELI), the Shanghai Superintense Ultrafast Laser Facility (SULF), the Station of Extreme Light (SEL) in China and similar projects in other countries.



Work in collaboration with:



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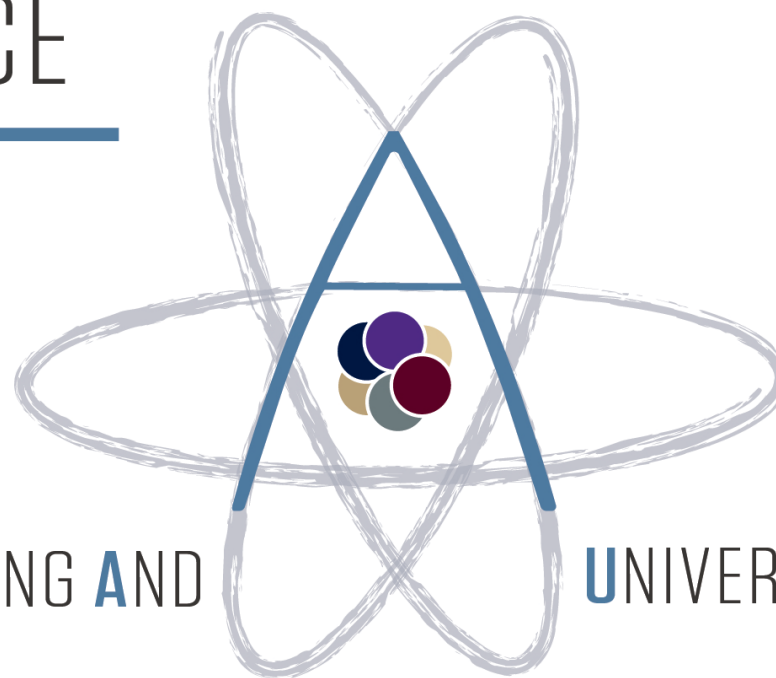
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