Laser Nuclear Physics

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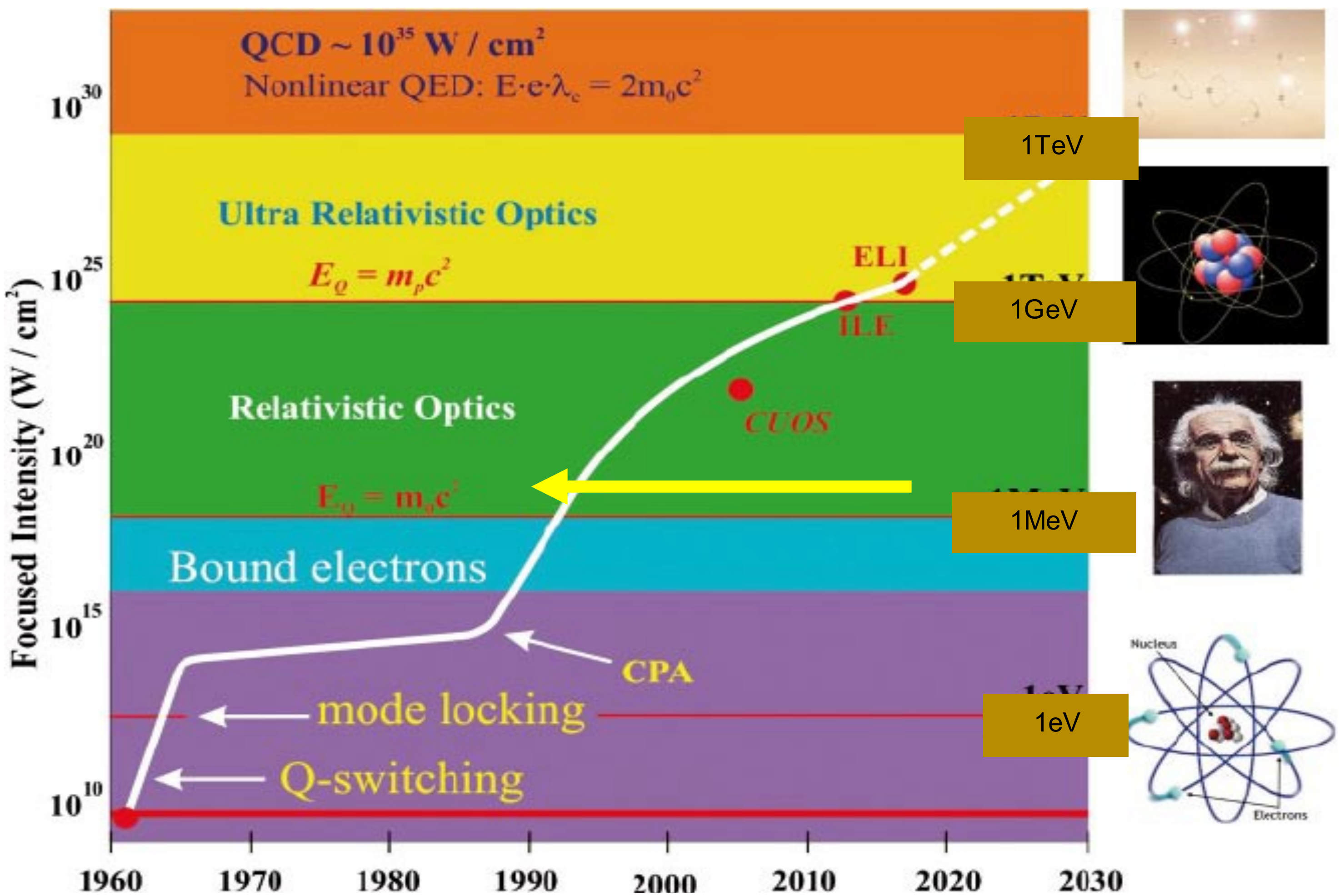
Outline

1. **Laser Nuclear Physics,** the New opportunities
   - Second beams (p/D/e/g/n)
2. Laser for **Applied Nucl. Phys**.
   - Non-destructive detecting
   - Medical Phys.
3. **Laser Nuclear Astrophysics**
   - Nucleosynthesis in stars, in the Big Bang
   - D+D; D+Li
   - EM field and Nucleosynthesis
4. Summary

Higher Intensity Laser→ Nucl. Phys. & Part. Phys.

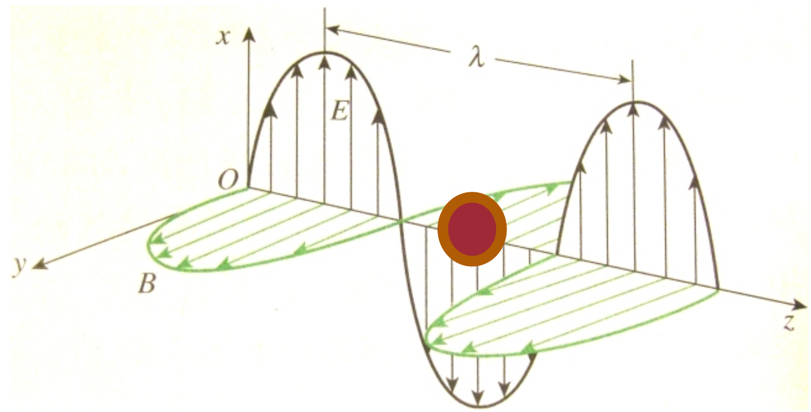


$$E(v/cm)=27.4*I^{1/2}(W/cm^2)$$

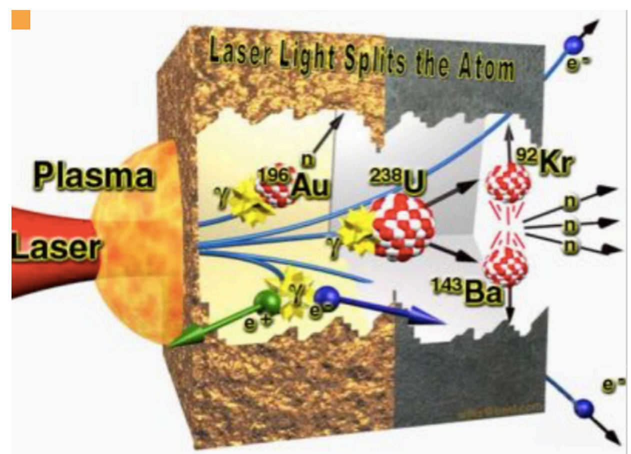
G. Mourou, T. Tajima, Science 331,41 (2011)

Laser +Nucl.

- Laser Nucl. Mech.
  - **Direct Eff.**
    - Energy : ***En=E*q*dL***
    - 10^{22}W/cm^2➔potential=1eV
    - Nucl. “photoelectric eff.”



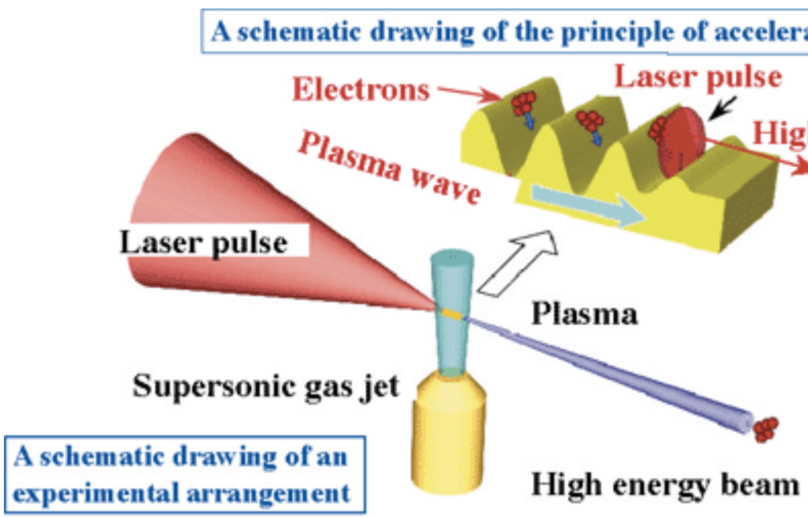
  - **Indirect Eff.**
    - Electron ➔Acc. in Laser
    - ➔2nd beams
    - ➔Nucl. Reaction

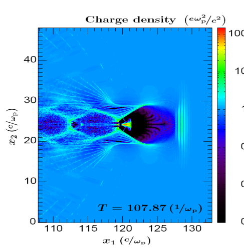


Laser Acc. in Short

e in gas

LWFA (Laser Wake-Field Acceleration)

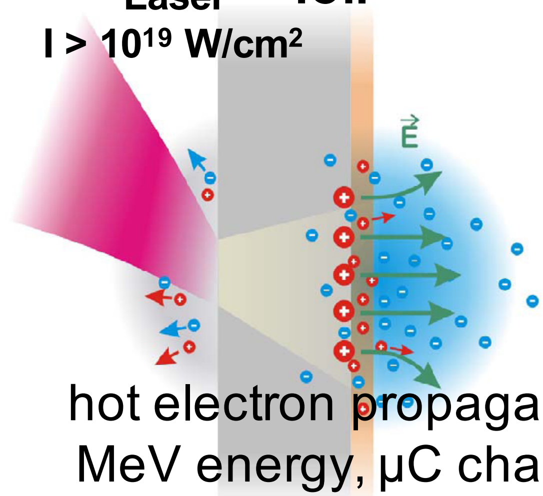




ion in Film

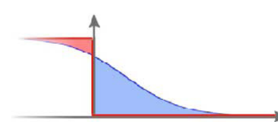
TNSA

(Target Normal Sheath Acceleration)

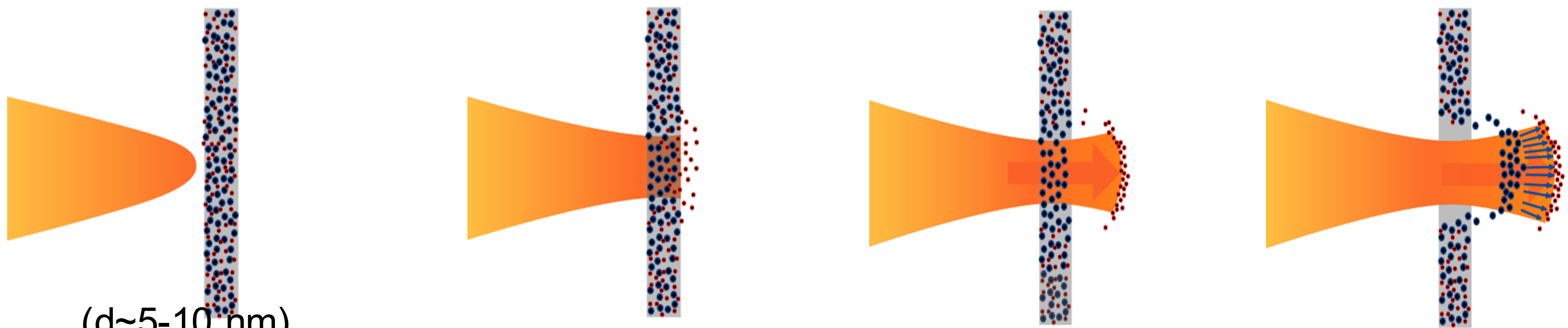


MeV/u protons and ions

hot electron propagation
MeV energy, μC charge

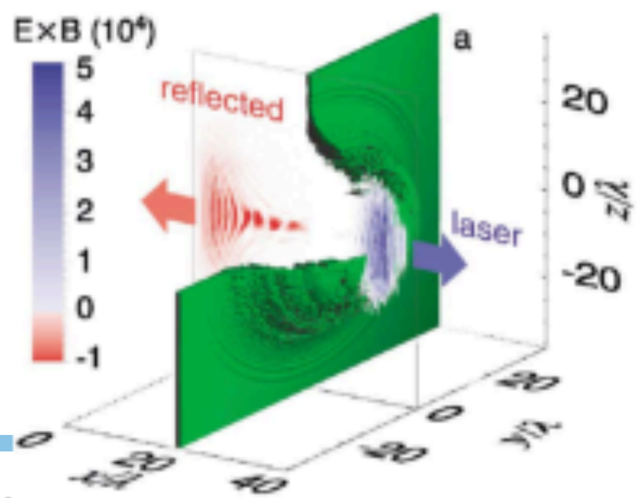


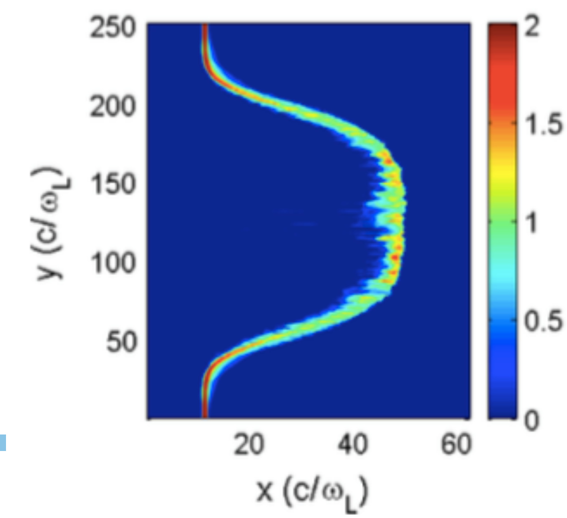
Radiation Pressure Acc. (RPA)



(d~5-10 nm)

laser pulse + ultra-thin foil → fully ionizing the foil. | electrons leave the foil | Light sail | electrons pull ions





Where the New Phys.?

- Extreme conditions brought by High-Intensive Laser
  - Ultra-**Narrow Pulse**(e/p/gamma/n)
  - Ultra-high **E-Field** (10^{11}V/m)
  - Ultra-high **B-Field** (10^{2}-10^{5}T)
  - Ultra-**high pressure**(10^{11} bar)
  - Ultra-**high Temperature** (10^{5}-10^{10}K)
  - **Very high Peak Current (100kA)**

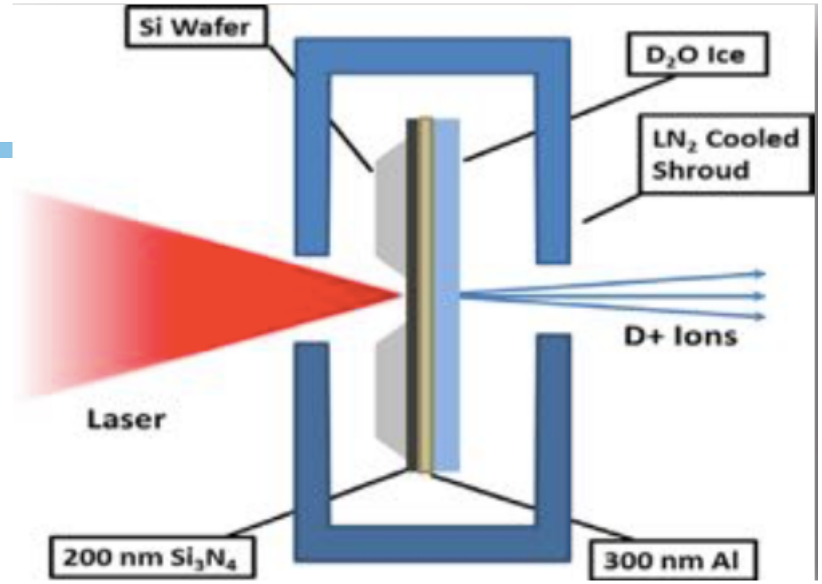
Extreme Conditions can NOT be achieved by traditional Acc.

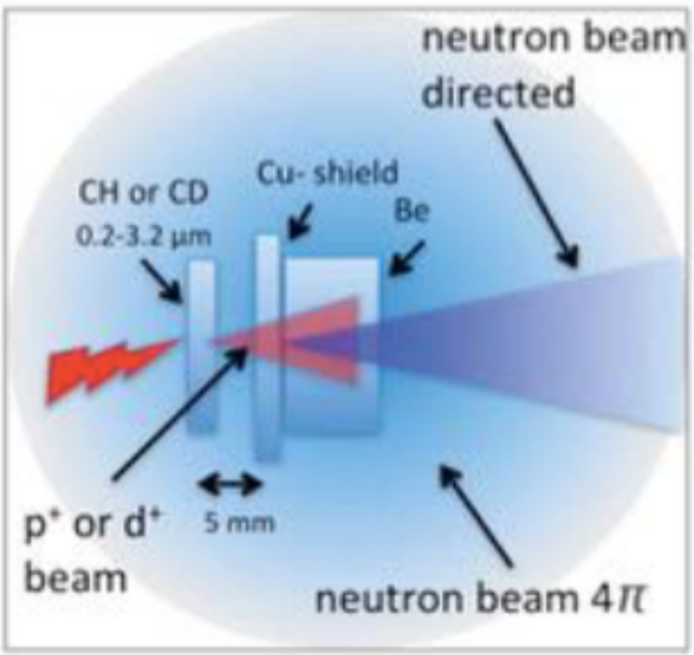
Where the NEW Phys. ?

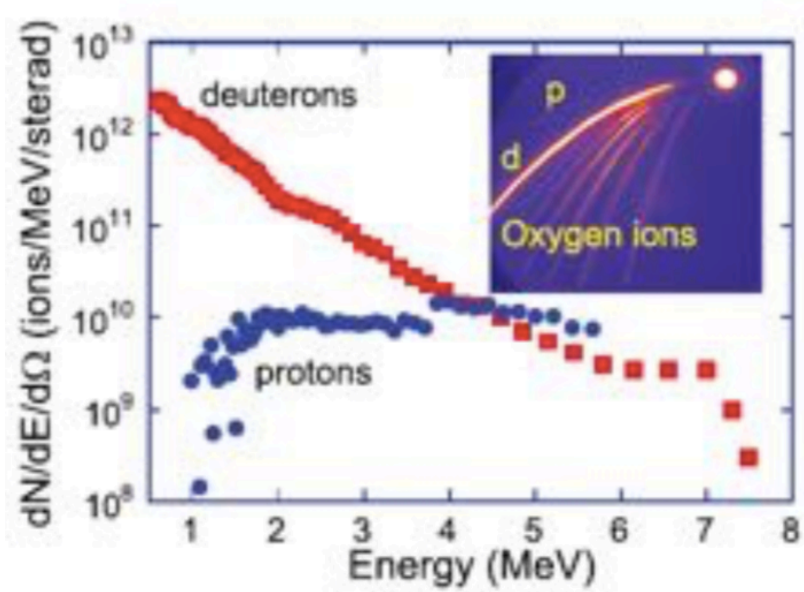
- Extreme Laser → New App.; New Fund. Phys.
  - Second Beam（p, D, alpha, e, e^+、n…)
    - Nucl. Energy
    - Nucl. Waste Processing
    - **n、gamma no-destructive detecting**
    - **Med. isotopes**
  - Strong EM conditions
    - Vacuum properties (QED)
    - **Unruh-Hawking Rad.**
  - Nucl. Astrophys.
    - **in Earth based Labs(?)**

Laser n Source

- p(D)+Be neutron source

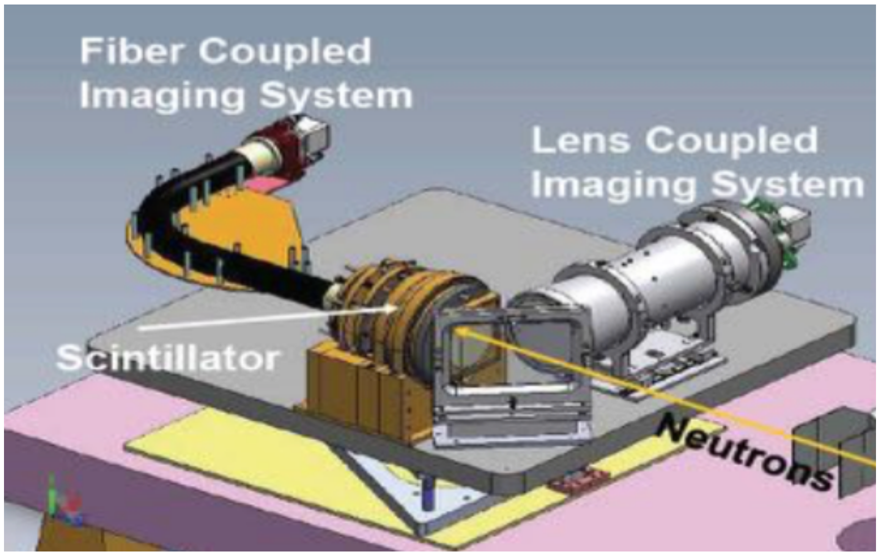


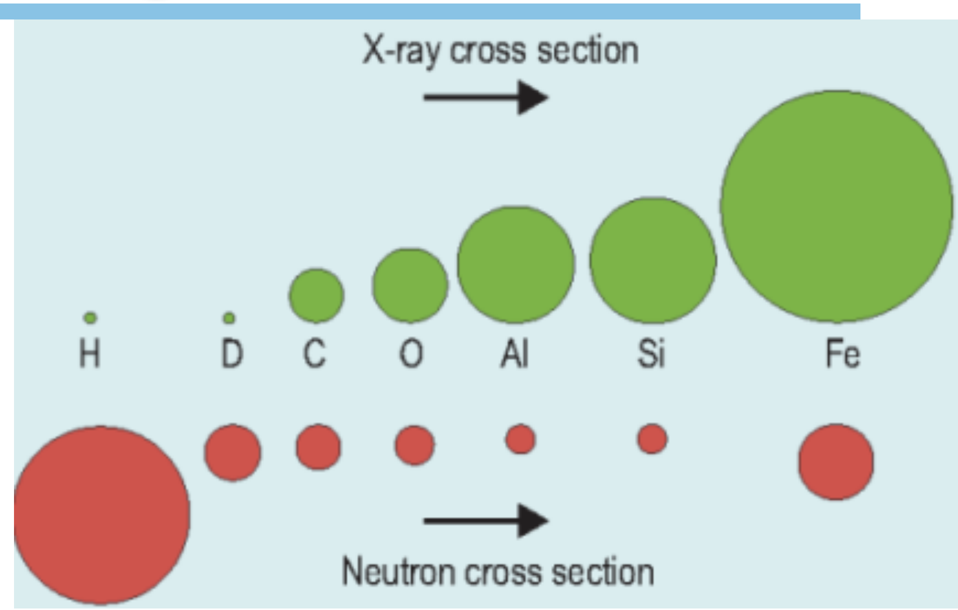


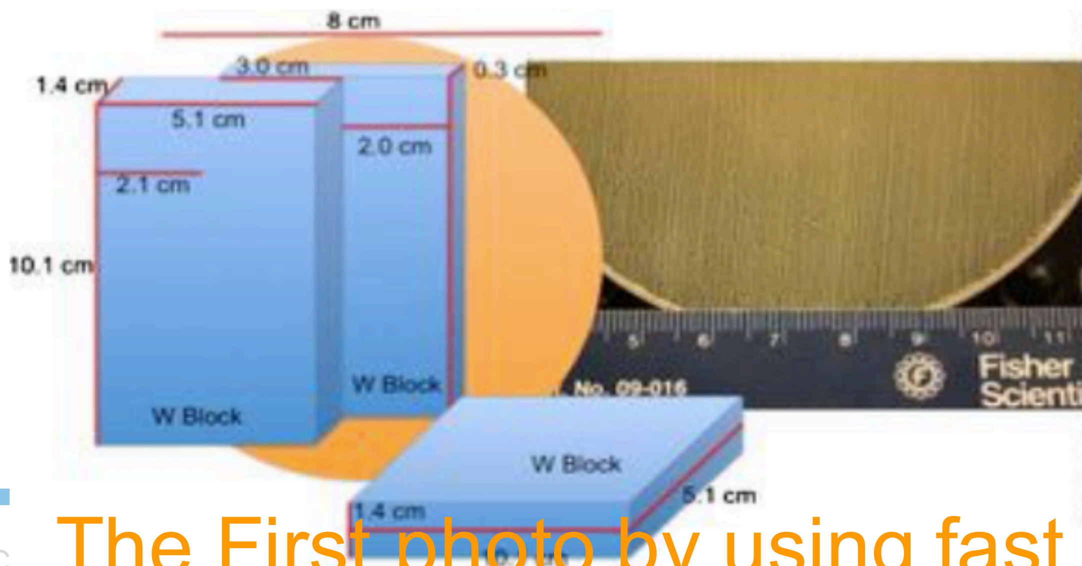


Morrison, J.T., et al., Physics of Plasmas, 2012. ***19****(3)*

Fast n photograph







The First photo by using fast n induced by laser

Laser n source for r-Process

- Extremely high n density!

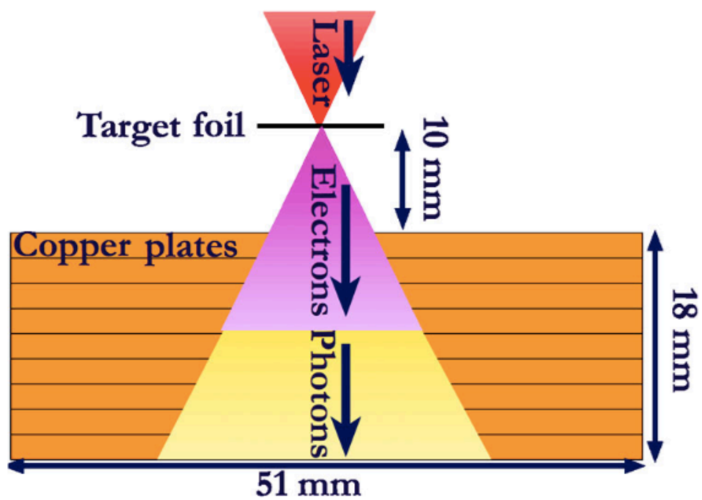


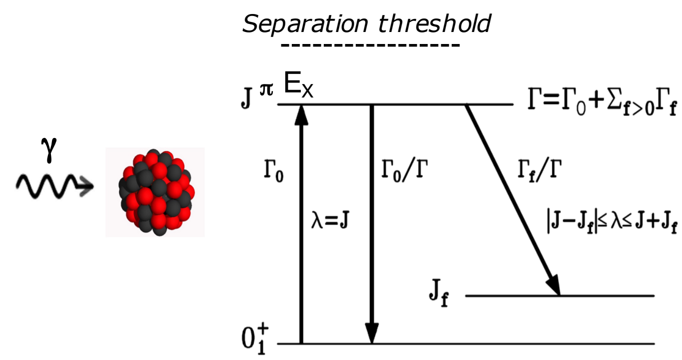
FIG. 1 (color online). Depiction of the experimental setup. The targets are 0.02–3 μm thick plastic foils.

PRL 113, 184801 (2014)

- Texas PW laser
- 150fs,90J,1057nm
- 10um-focus, 0.02-3um target thickness
- 1.1E18 $n/cm^2/s$ achieved, Compared with 1E22 $n/cm^2/s$ in supernova

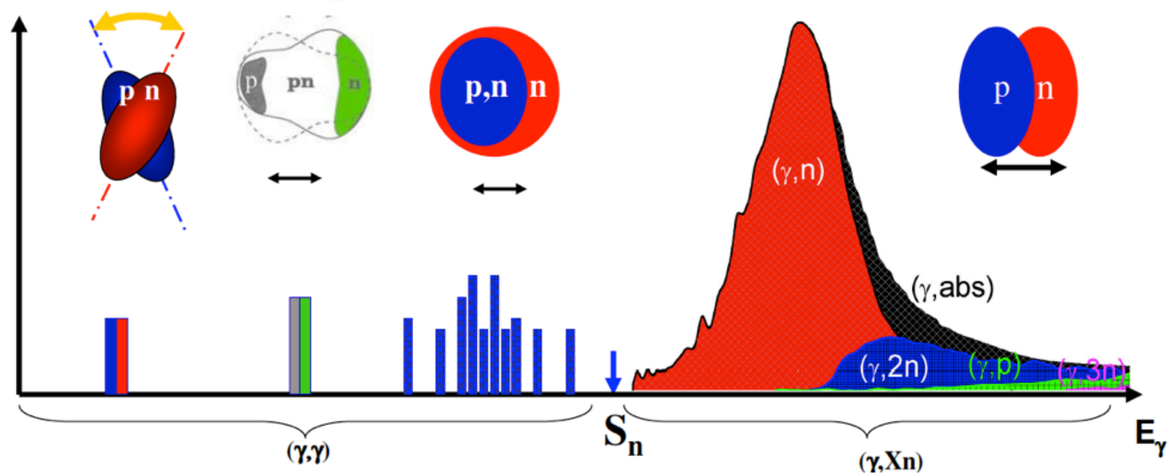
Hopefully, can study r-process with this setup

Nuclear Resonance Fluorescence (NRF)



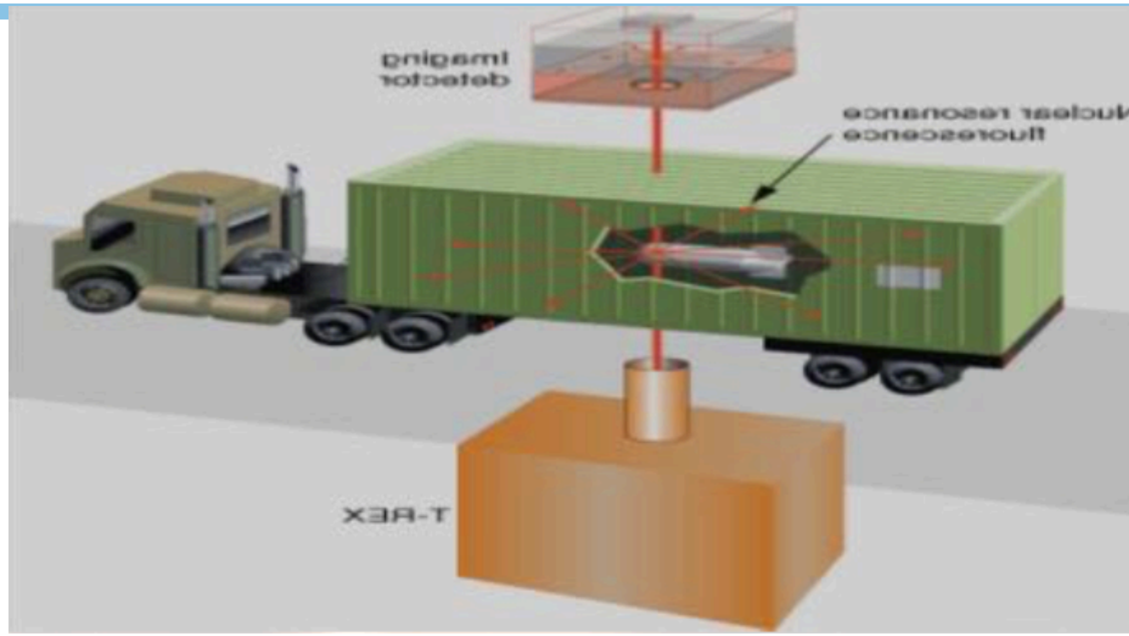
- Very high intensity (10^4 photons/(s*eV)
- Narrow bandwidth (down to 0.5%)
- High degree of polarization (> 99%)
- Small beam diameter (mm range)
- Low duty factor (100 Hz)

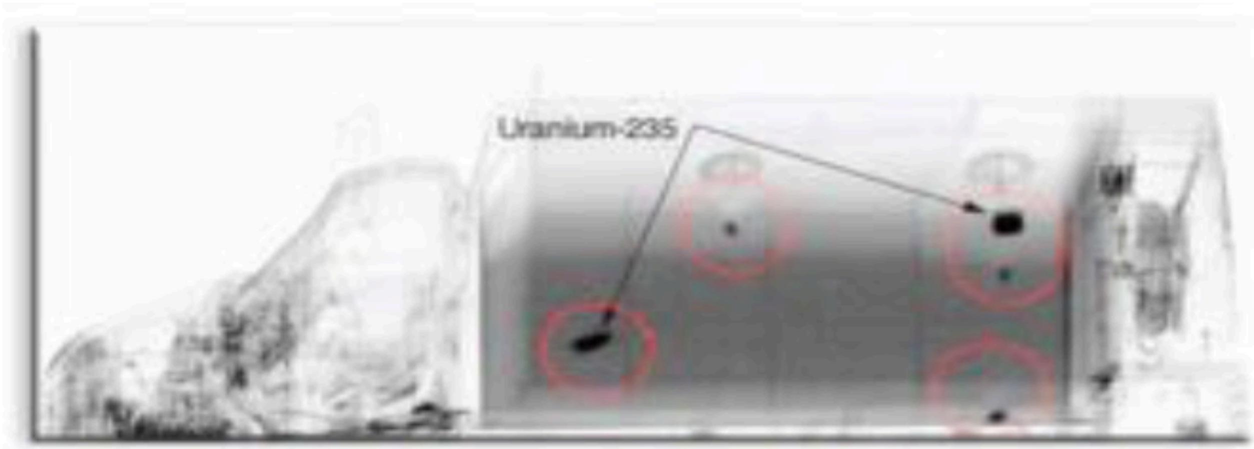
Electromagnetic Dipole Response in Nuclei



Nuclear fluorescence Detecting

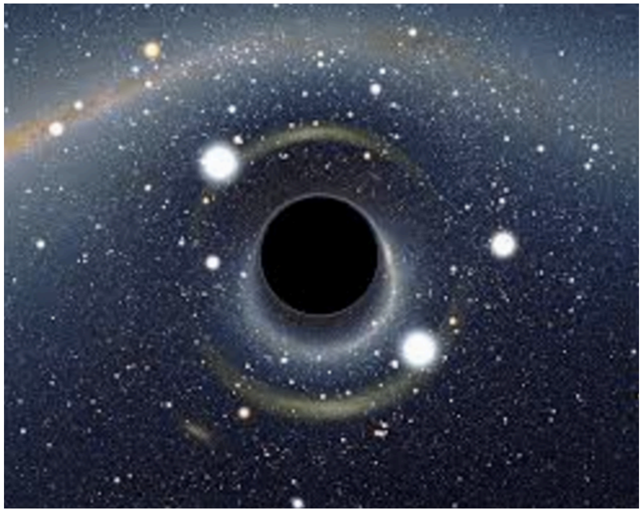
-





MEGa-ray beam absorption technologies currently under development could detect a piece of uranium-235 smaller than 5 millimeters in less than a second. This speed and accuracy would make the MEGa-ray system an excellent tool for examining cargo containers, trucks, and other loads on the move.

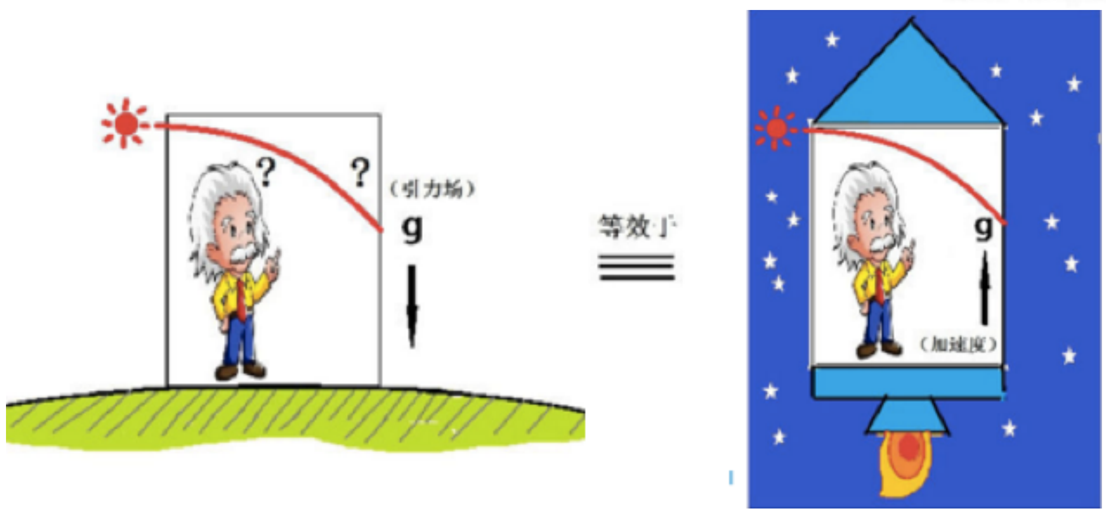
Hawking-Unruh Radiation



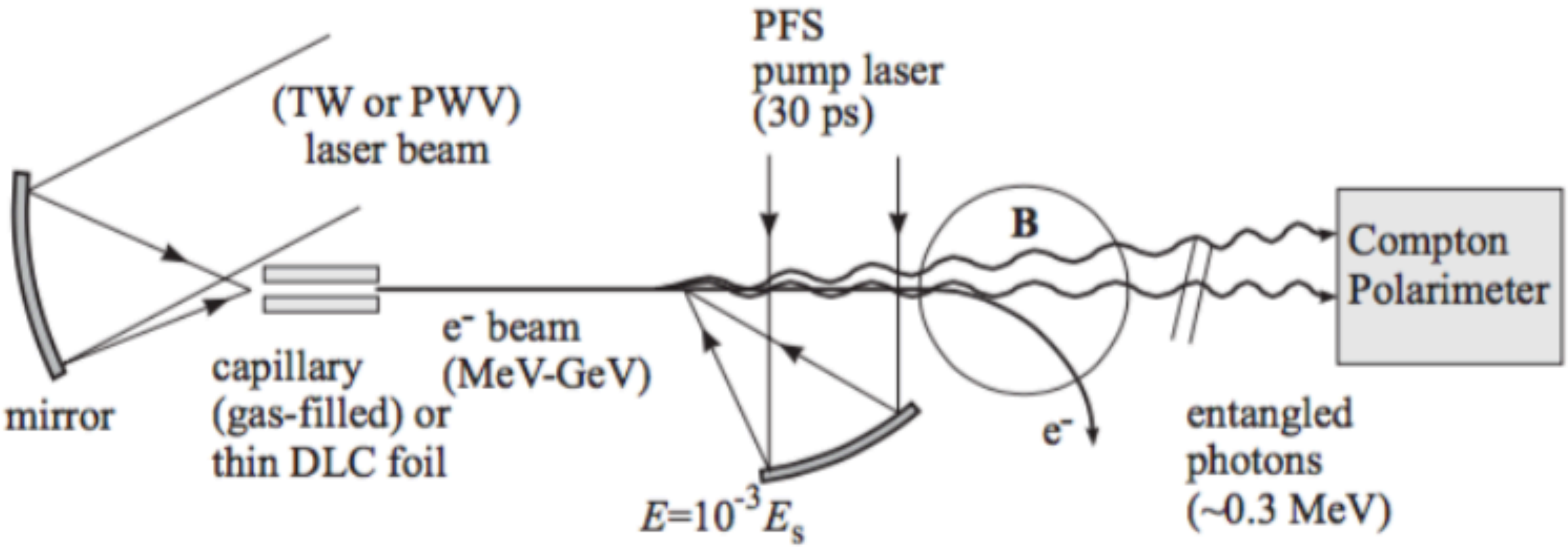
$$T_H = \frac{\hbar c^3}{8k\pi GM} = \frac{\hbar g_s}{2k\pi c}$$

5E23g=5000K

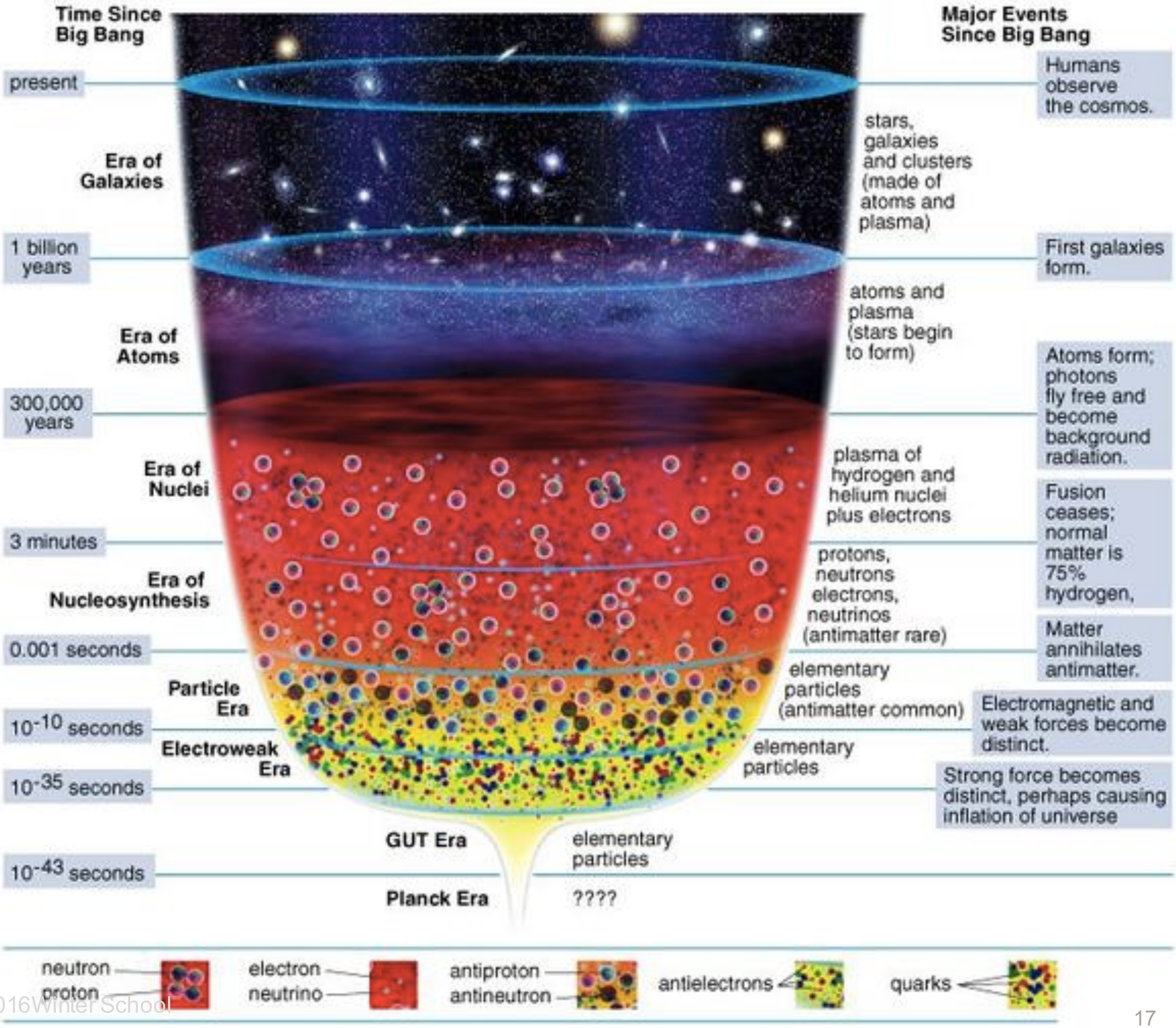
$$T_U = \frac{\hbar a}{2k\pi c}$$



Unruh Rad. Setup

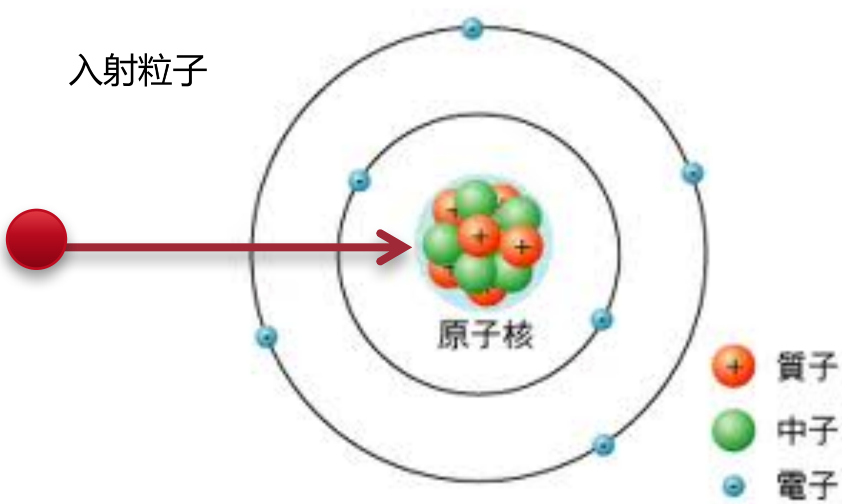


Laser Plasma Collider
for
Nuclear Astrophysics


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10-10 seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10-35 seconds
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10-43 seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

Motivation

- "Full Plasma" Conditions for low nuclear studies?
  - "Full Plasma" is needed for **Nucl. Astrophys. etc**.
  - Traditional Accelerator can not provide "Full Plasma"



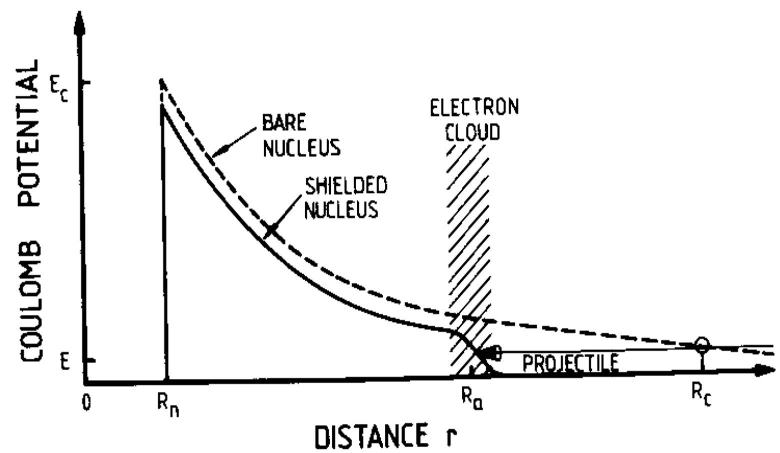


FIGURE 4.8. Shown in an exaggerated and idealized way is the effect of the atomic electron cloud on the Coulomb potential of a bare nucleus. This potential is reduced at all distances and goes essentially to zero beyond the atomic radius R_a. The effect of this electron shielding on an incident projectile is to increase the penetrability through the barrier, and thus also the cross section.

Motivation:

Why Full Plasma?

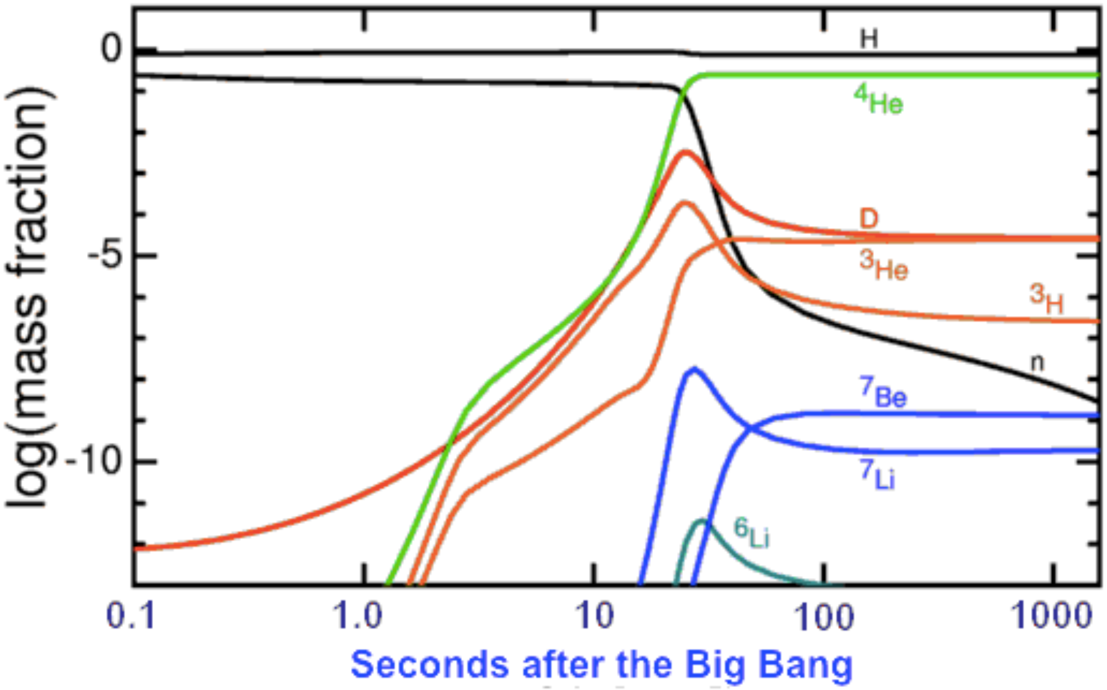
Nuclear Parameters may be also diff in plasma or boundary states.

- ^{7}Be
  - $^{7}Be^{neutral}$ $t_{1/2}$ =52d ;
  - $^{7}Be^{4+}$: Stable !

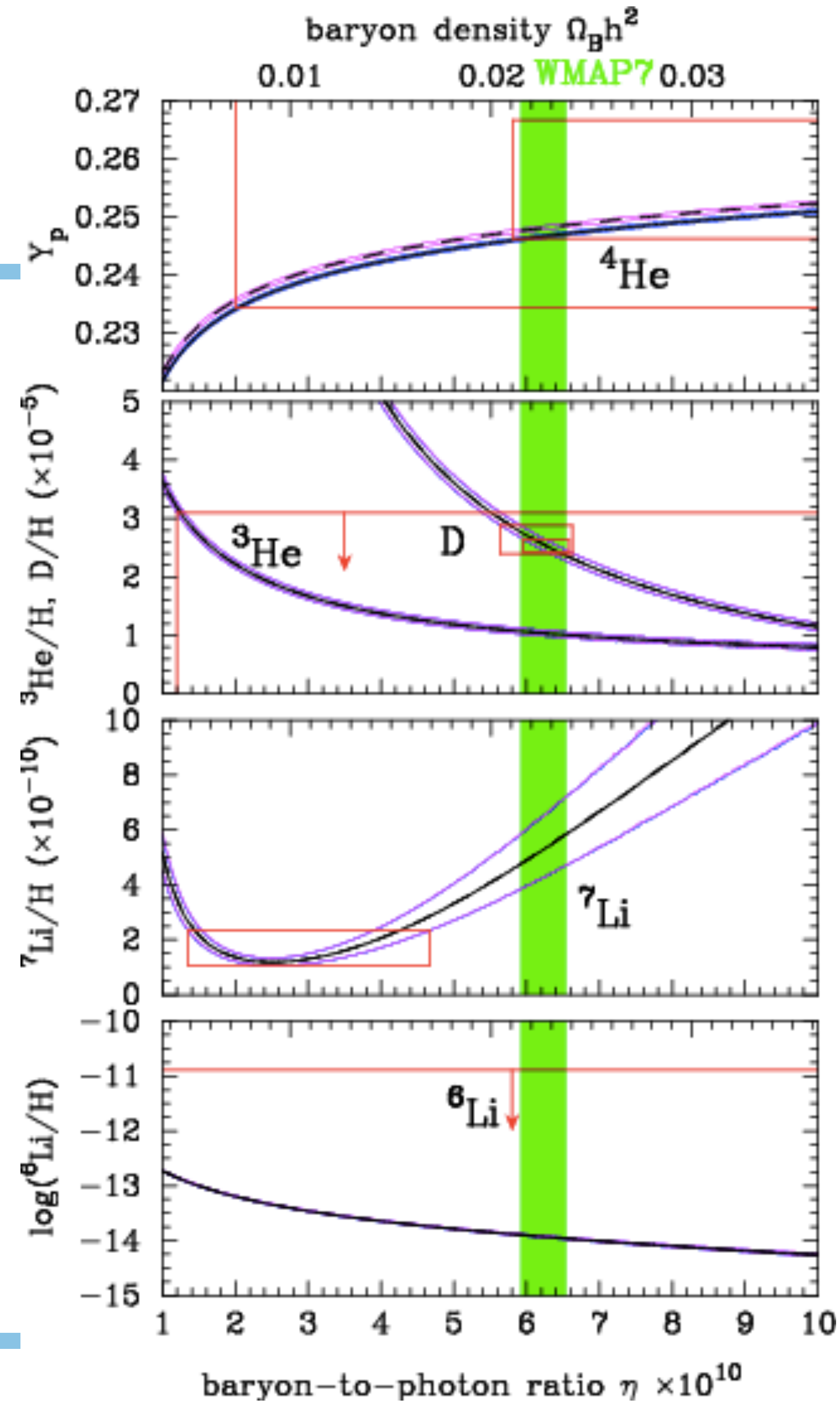
- ^{125}Te 1st ex. st. (Z=52, E=35.5 keV)
  - Q=0 $T_{1/2}$=1.5 ns (internal conversion + M1)
  - Q= 47^{+} $T_{1/2}$ = 6 ± 1 ns F.Attalah et al., Phys.Rev.Lett. 75(1995) 1715

Motivation:

^{6,7}Li abundance

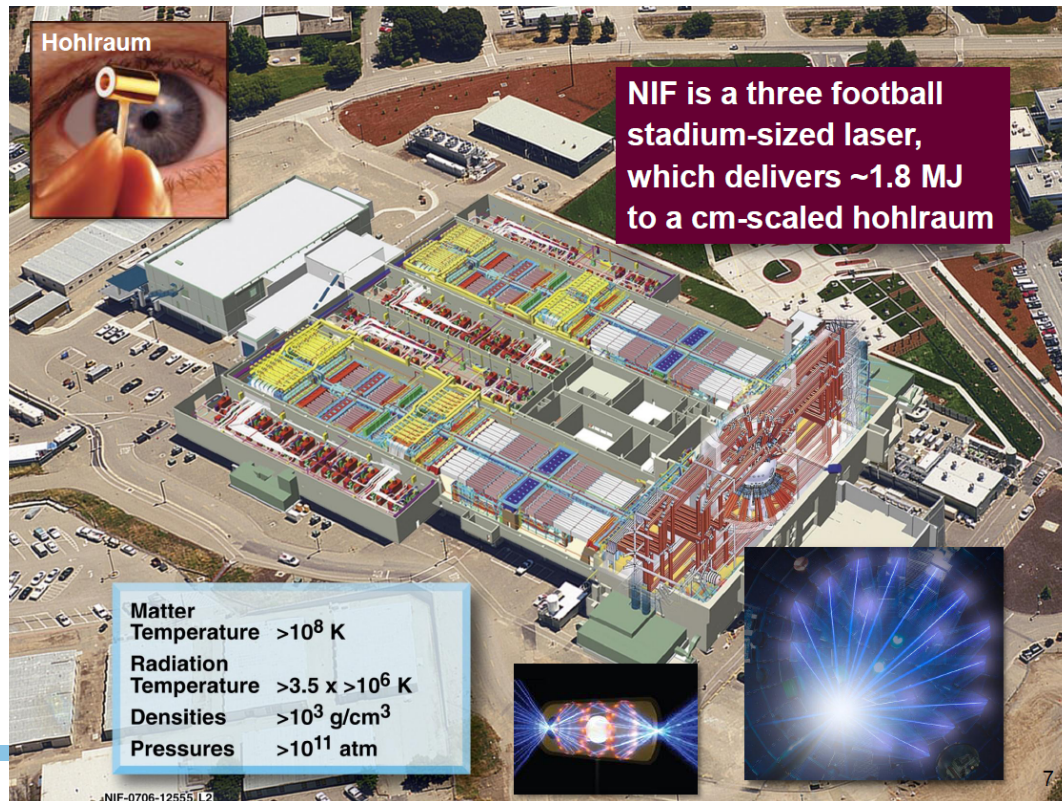


	计算值	观测值
4He	0.248	0.249 ± 0.009
D/p	2.64E-5	$2.78^{+0.44}_{-0.38} \times 10^{-5}$
3He/p	1.06E-5	(0.9—1.3)E-5
7Li/p	4.22E-10	$1.23^{+0.68}_{-0.32} \times 10^{-10}$
6Li/p	1E-5	1×10^{-2}

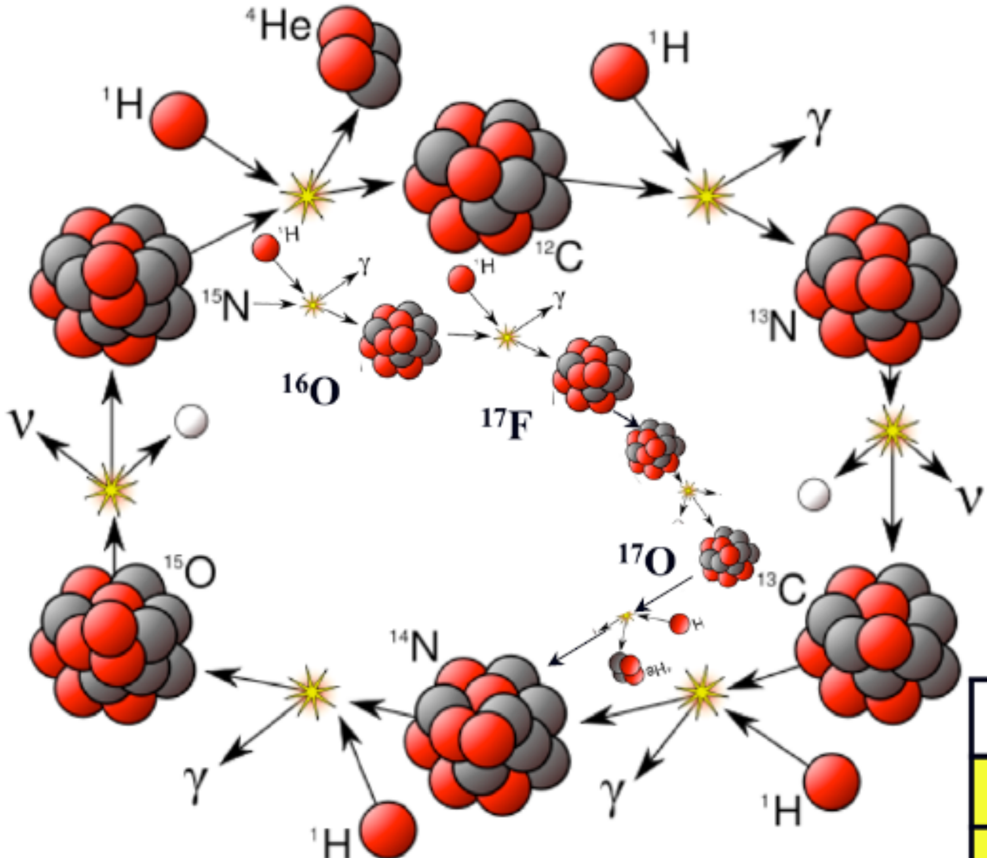


Laser Nucl. Phys.

- NIF (National Ignition Facility)
- ELI-NP (Extreme Light Infrastructure)
- Shen-Guang Laser Facility



CNO Cycle cross section measurements possible at NIF



- First proposed by Bethe in 1938
- Important Hydrogen-burning mechanism in massive stars
  - Makes ≈1.7% of all Helium in low-mass stars like the sun
  - Very massive stars have two other minor CNO cycles
- Measured down to $k_B T \approx 8$ *keV*
  - "Gamow" window near 2 keV
- Reactions that lead to radioactive products are best for NIF

Products formed at $k_B T \approx 6$ keV

Reaction (**cycle #**)	Products/shot
$^{12}C(p,\gamma)^{13}N$ (**I**)	$\approx 1 \times 10^7$
$^{14}N(p,\gamma)^{15}O$ (**I**)	$\approx 2 \times 10^5$
$^{16}O(p,\gamma)^{17}F$ (**II**)	$\approx 7 \times 10^3$
$^{17}O(p,\gamma)^{18}F$ (***III***)	$\approx 7 \times 10^3$

One could study this with a C_6H_6 capsule shot

Positron

Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters

T. Ditmire, J. Zweiback, V. P. Yanovsky, T. E. Cowan, G. Hays & K. B. Wharton

Laser Program, L-477, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

As a form of matter intermediate between molecules and bulk solids, atomic clusters have been much studied[1]. Light-induced processes in clusters can lead to photo-fragmentation[2,3] and Coulombic fission[4], producing atom and ion fragments with a few electronvolts (eV) of energy. However, recent studies of the photoionization of atomic

NATURE | VOL 398 | 8 APRIL 1999 | www.nature.com

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

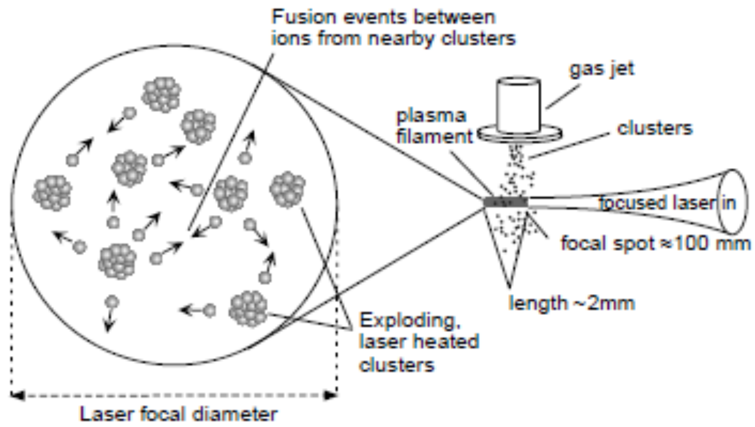


Figure 1 Layout of the deuterium cluster fusion experiment.

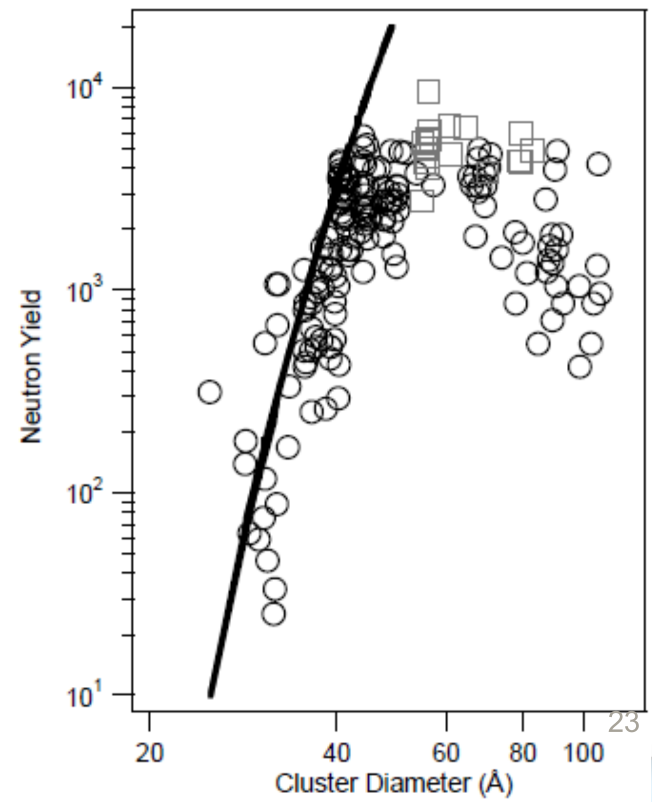
Laser: 120 mJ, 35fs, 10Hz

Laser Intensity: 2×10^{16} W/cm^2

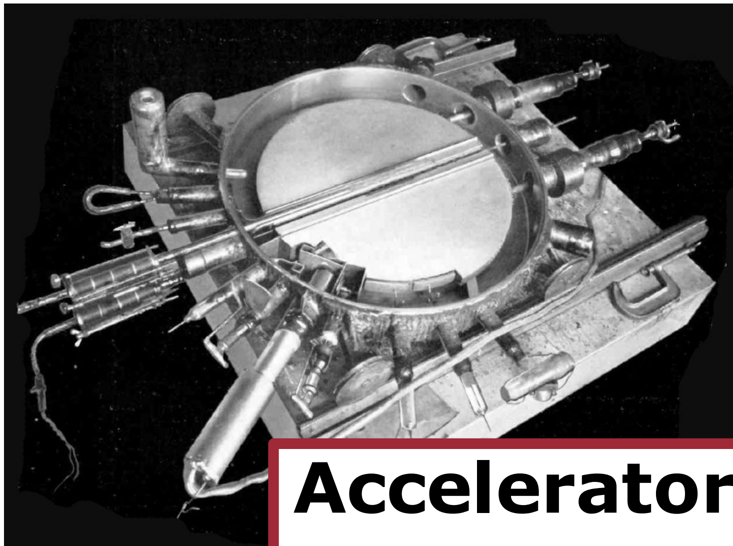
Cluster gas jet: Deuterium, cooled (-170 ^{o}C)

Gas Density: 1.5×10^{19} /cm^3

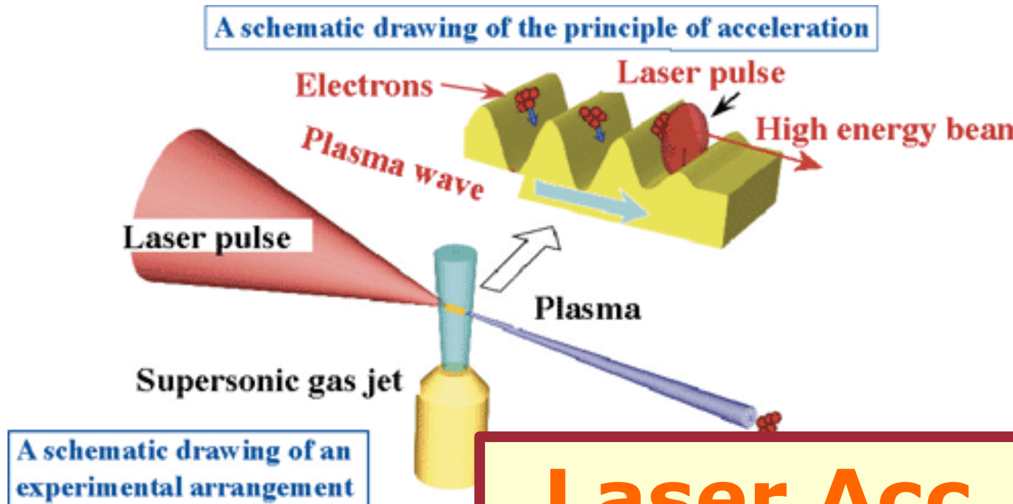
Cluster Size: 50 Angstroms



From Acc. to Collider



Accelerator



Laser Acc

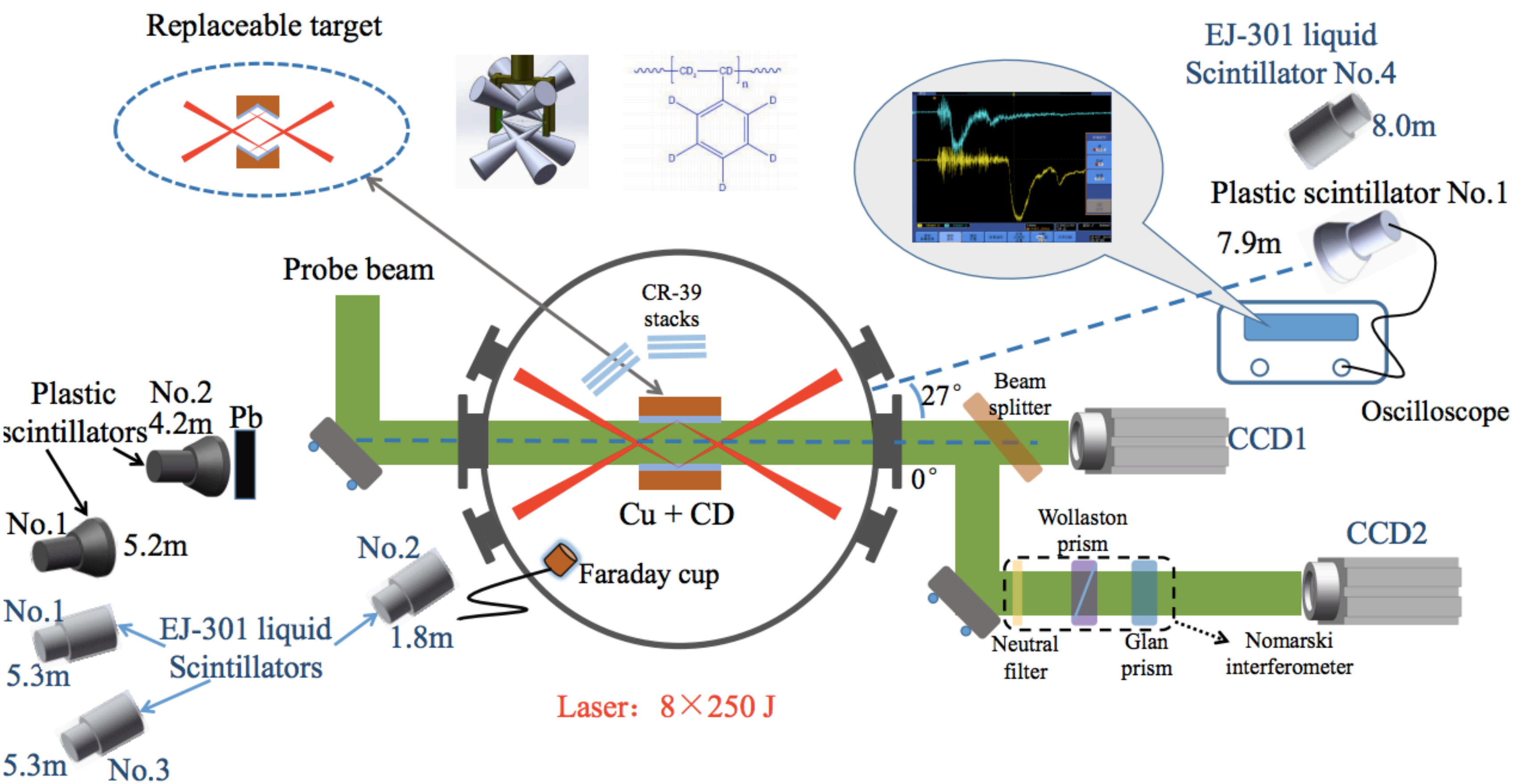
Collider

Laser Collider？

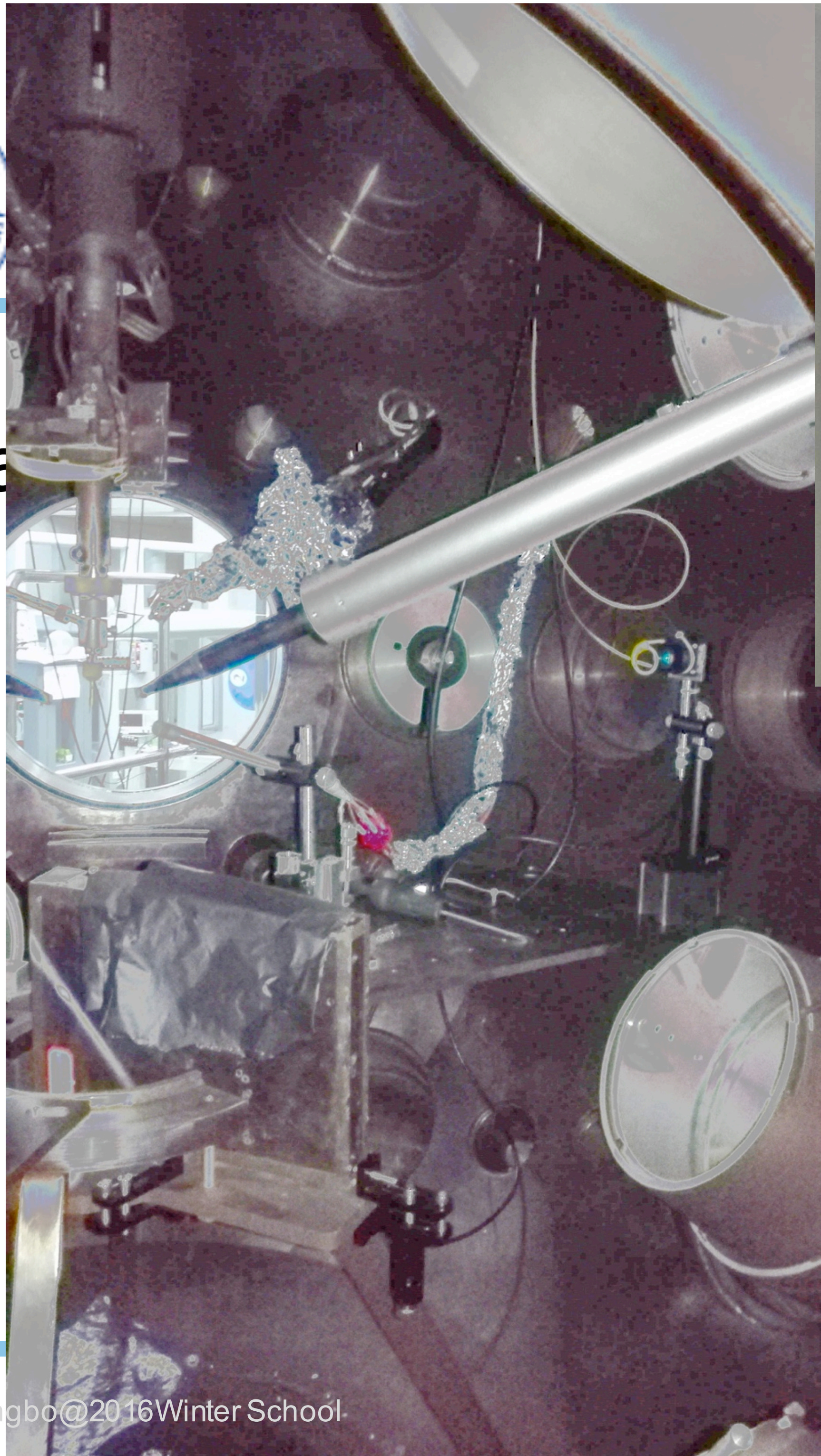
“Laser Plasma Collider”

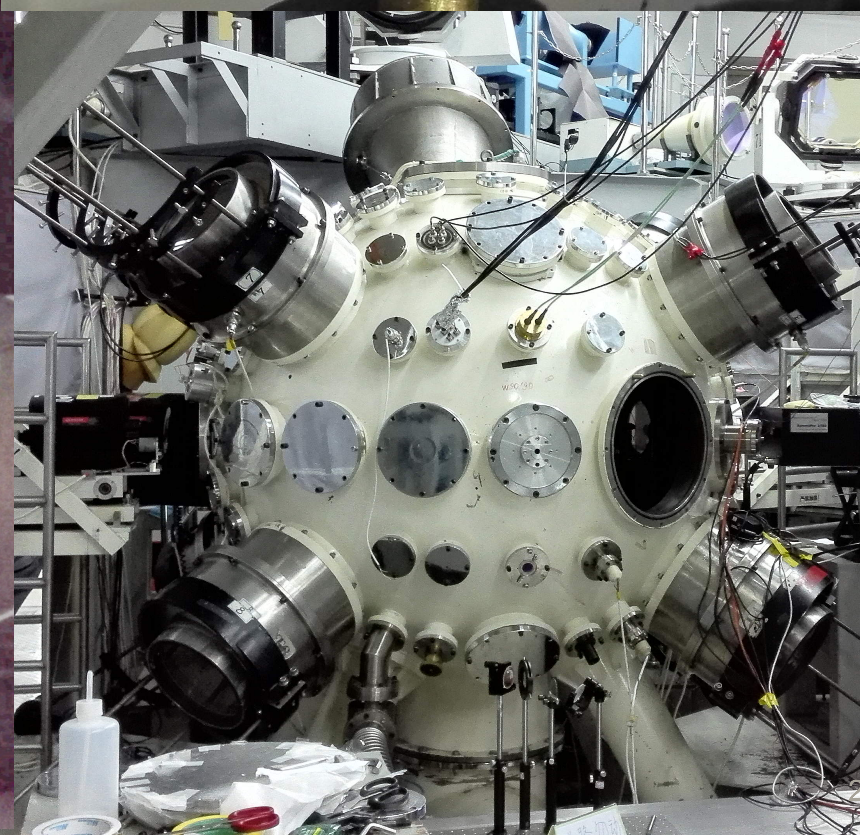
	Laser Plasma Collider	Trad. Collider
Pulse	Very narrow	>ns
Peak Density	Very large	Small
charge	Neutral	charged
Repeat frq.	Very low	High
Cost	Low	High
Size	Small	Large
Beam Quality	Bad	good

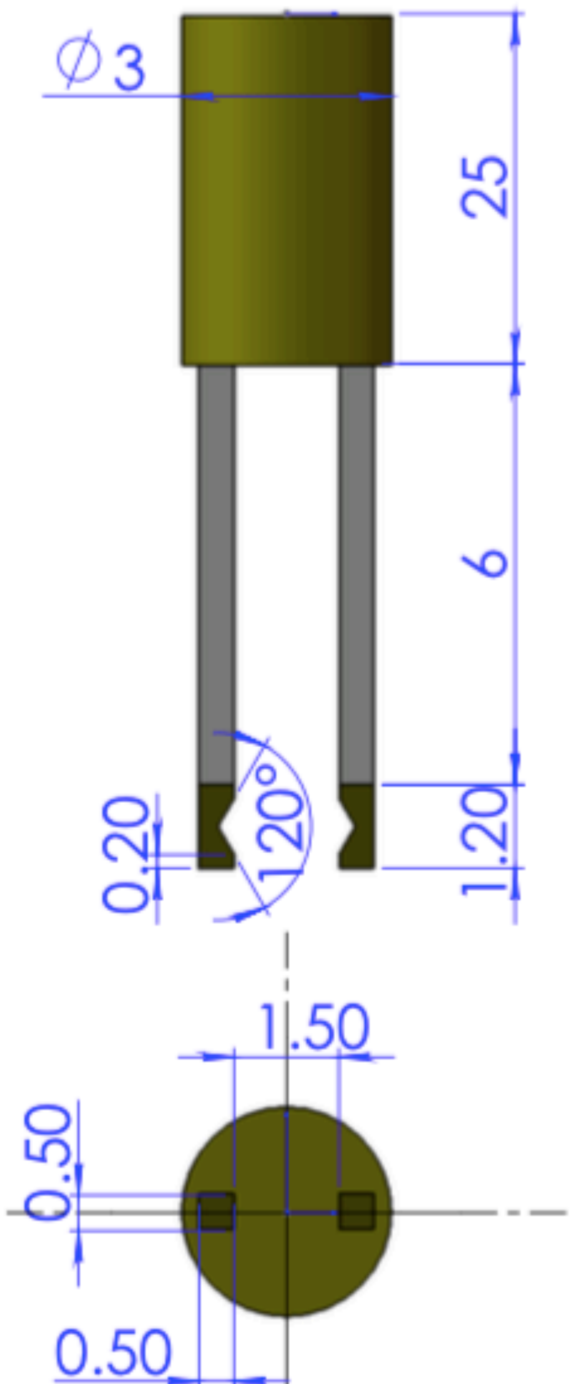
Experimental Setup

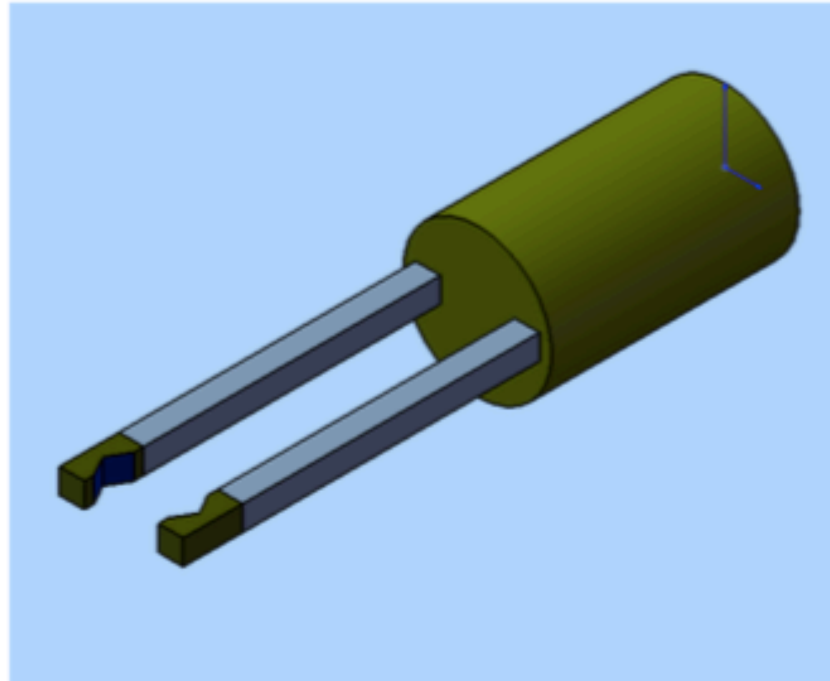


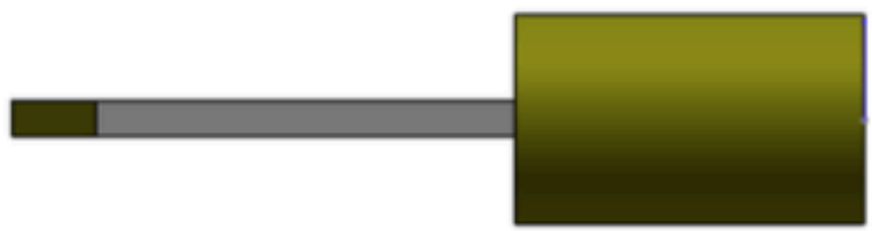
- a

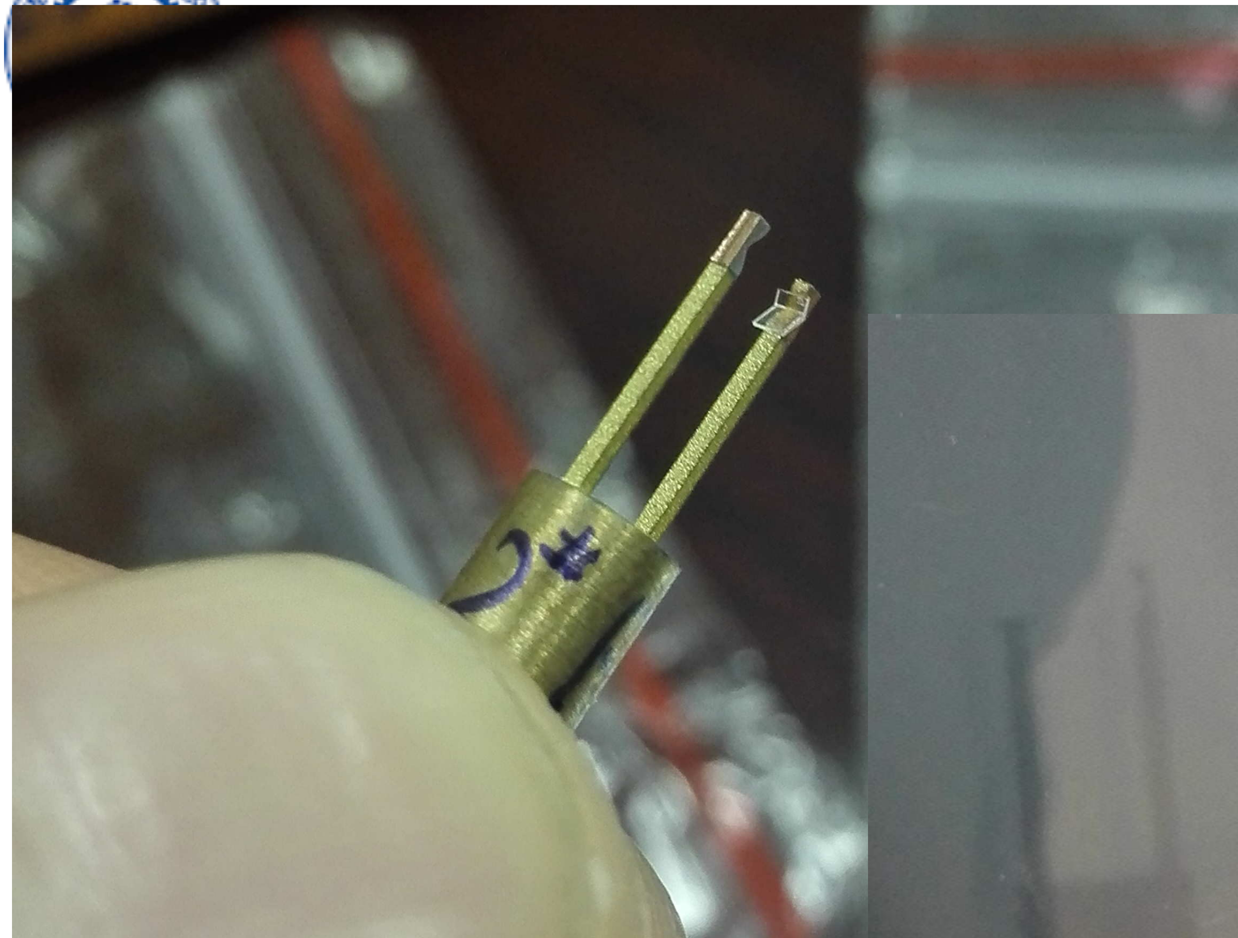




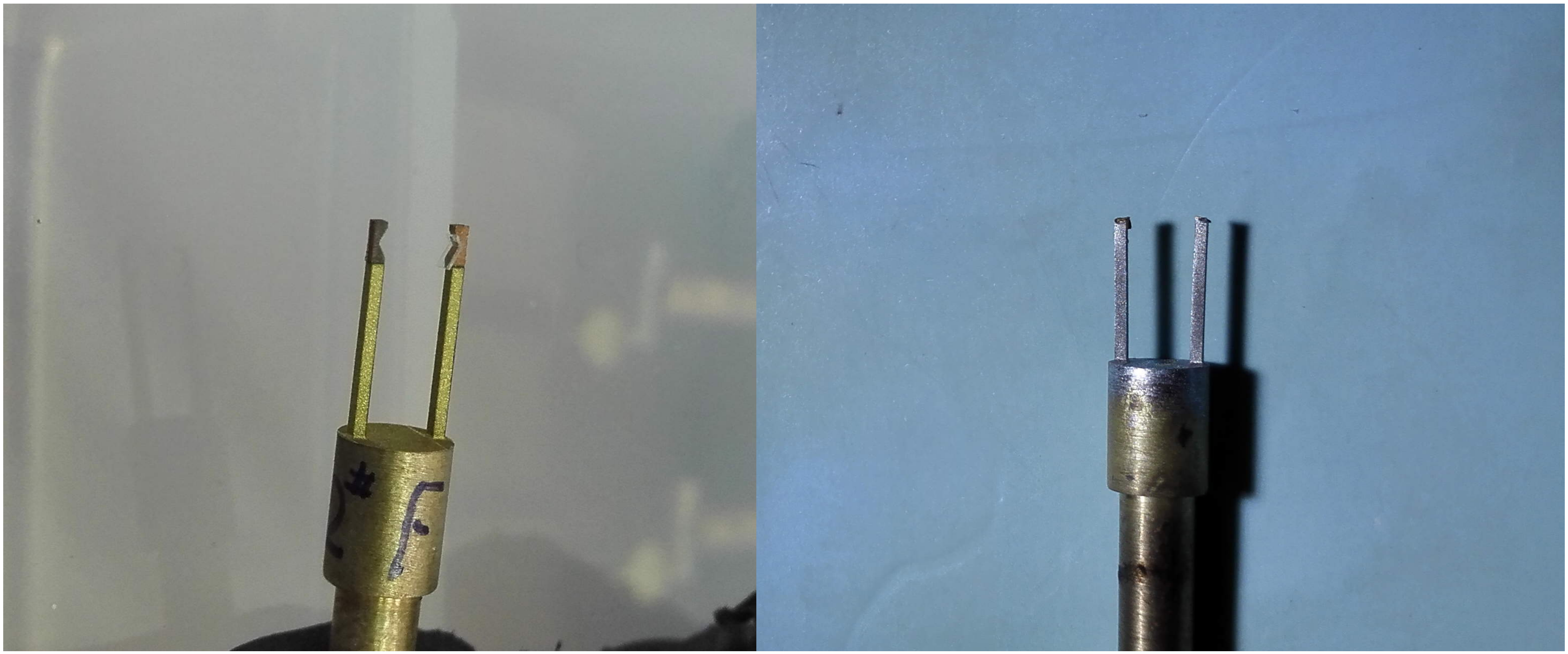

∅3
25
6
1.20
0.20
120°
1.50
0.50
0.50



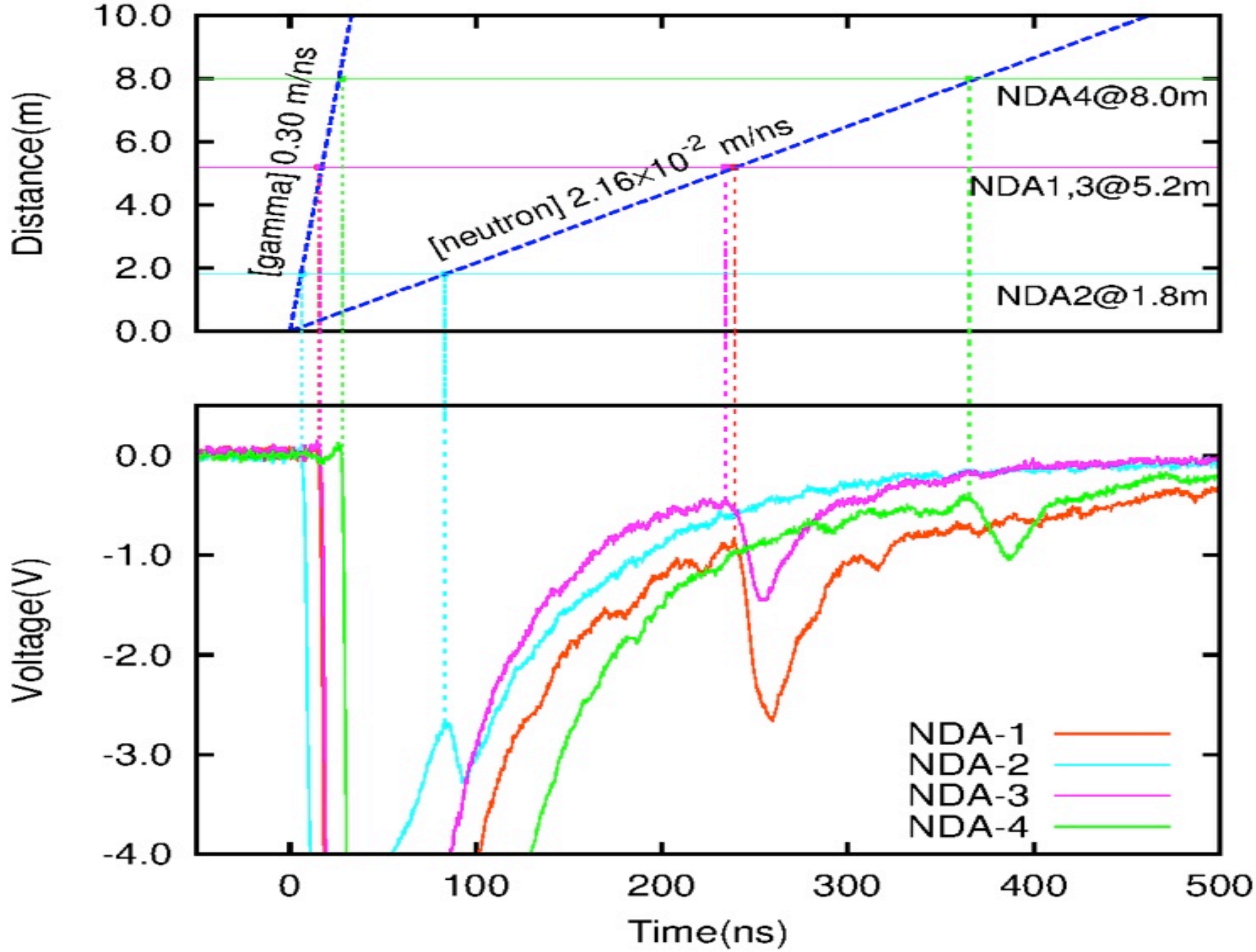




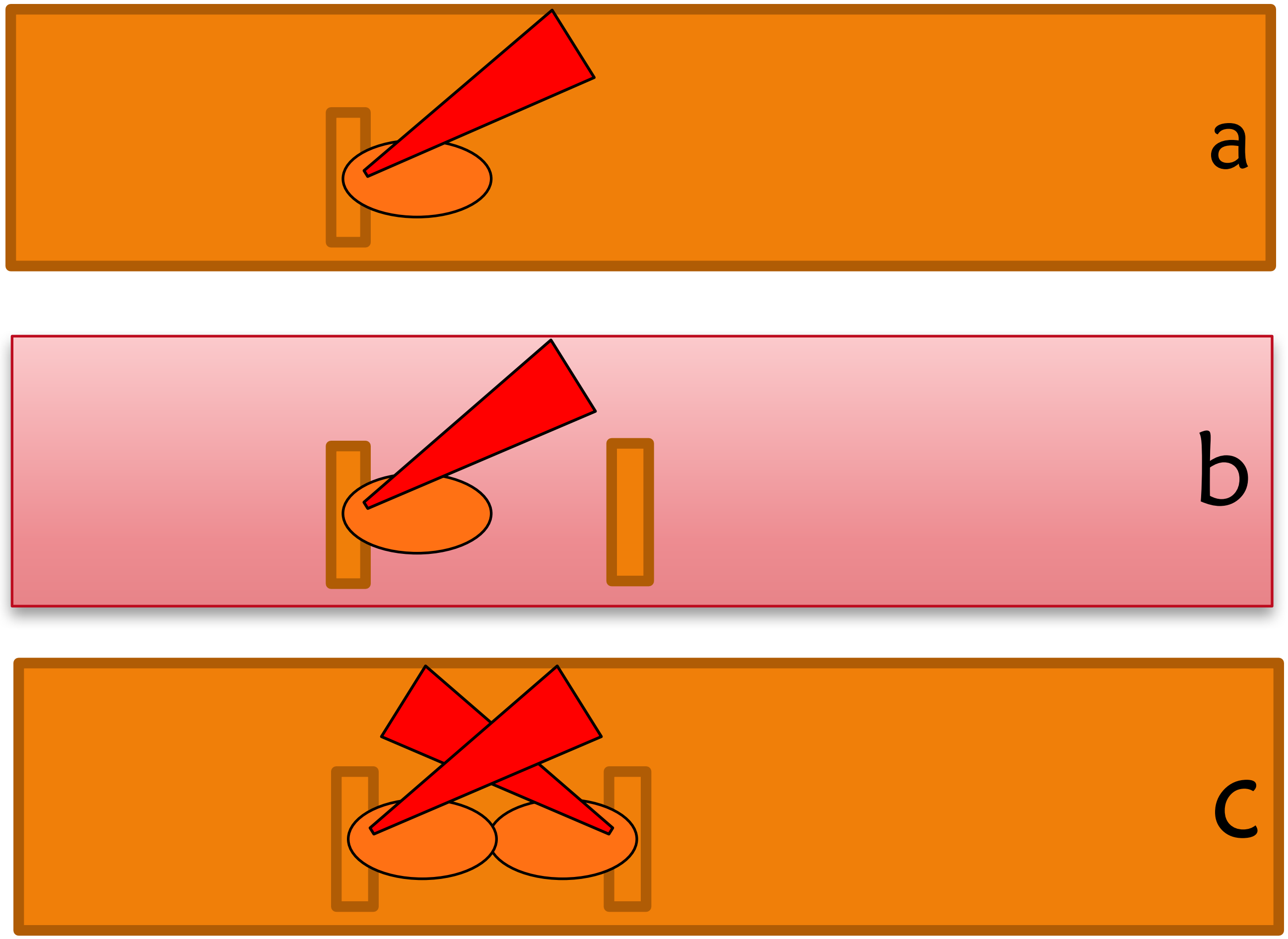
Target before and after shot



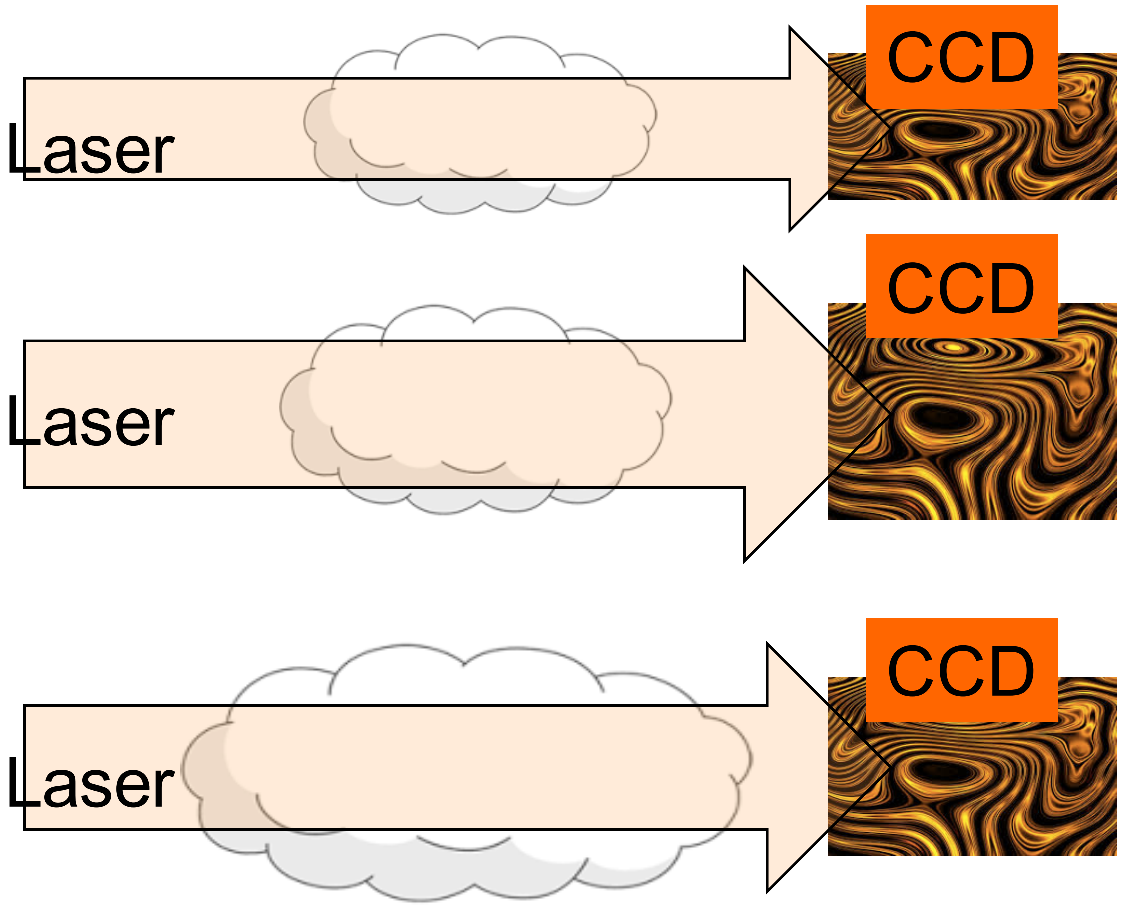
Neutron Spectra

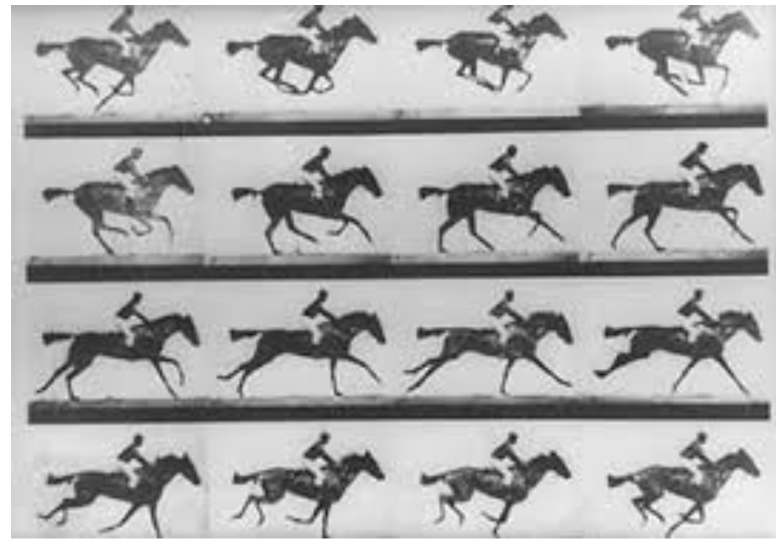


Where did the n products come from?

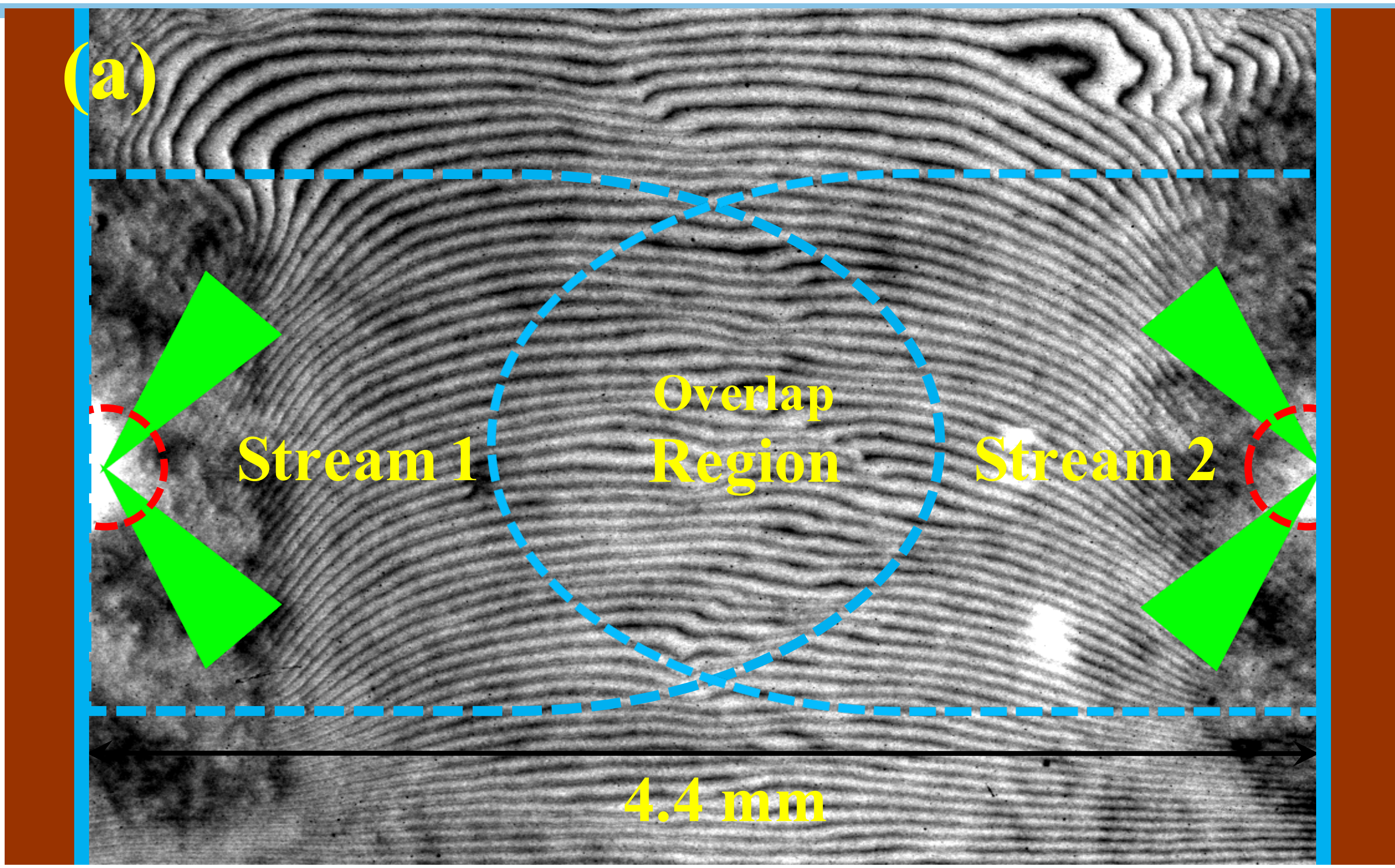


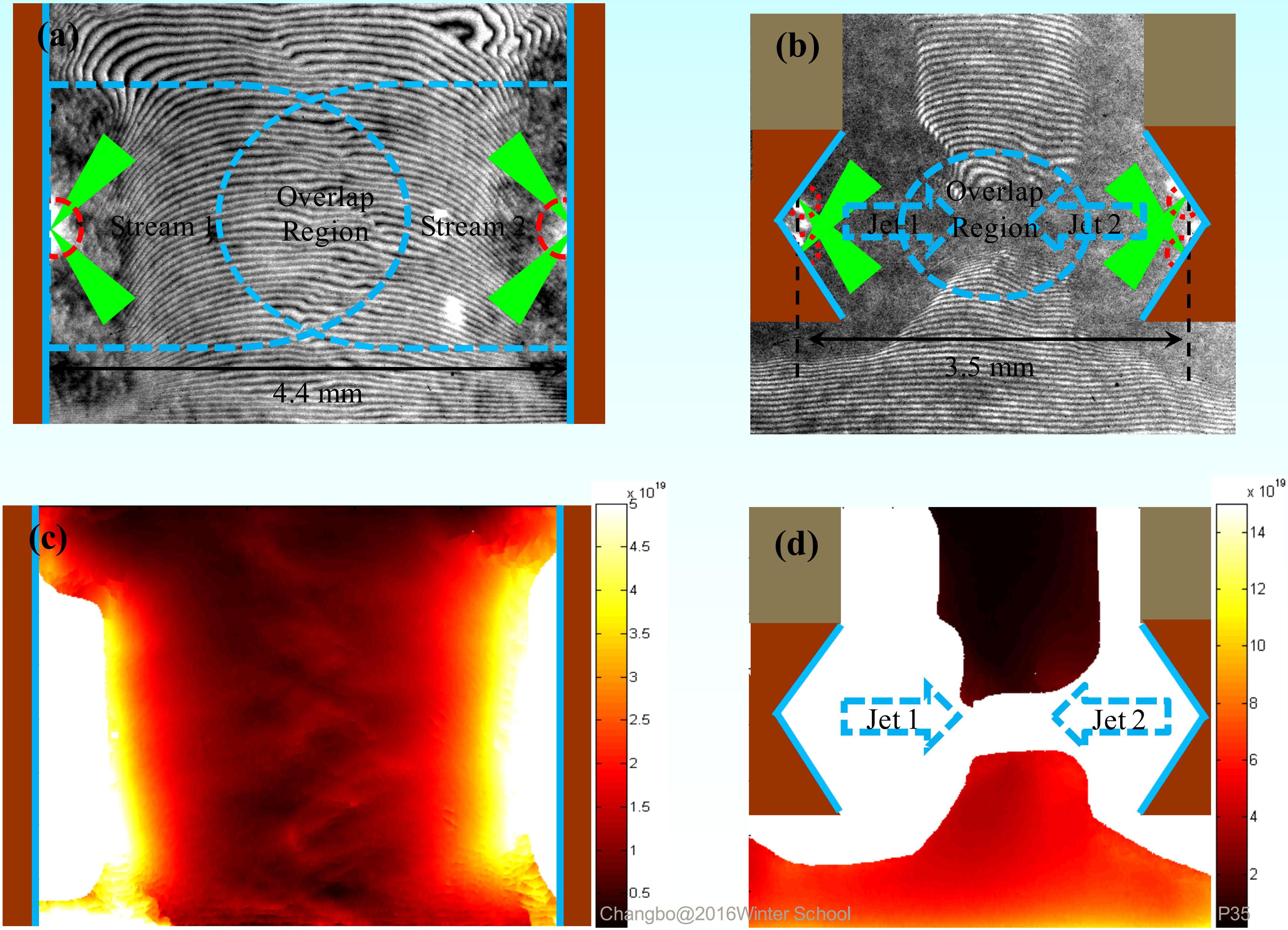
Normasky Interferometer





Jet Density Spectra

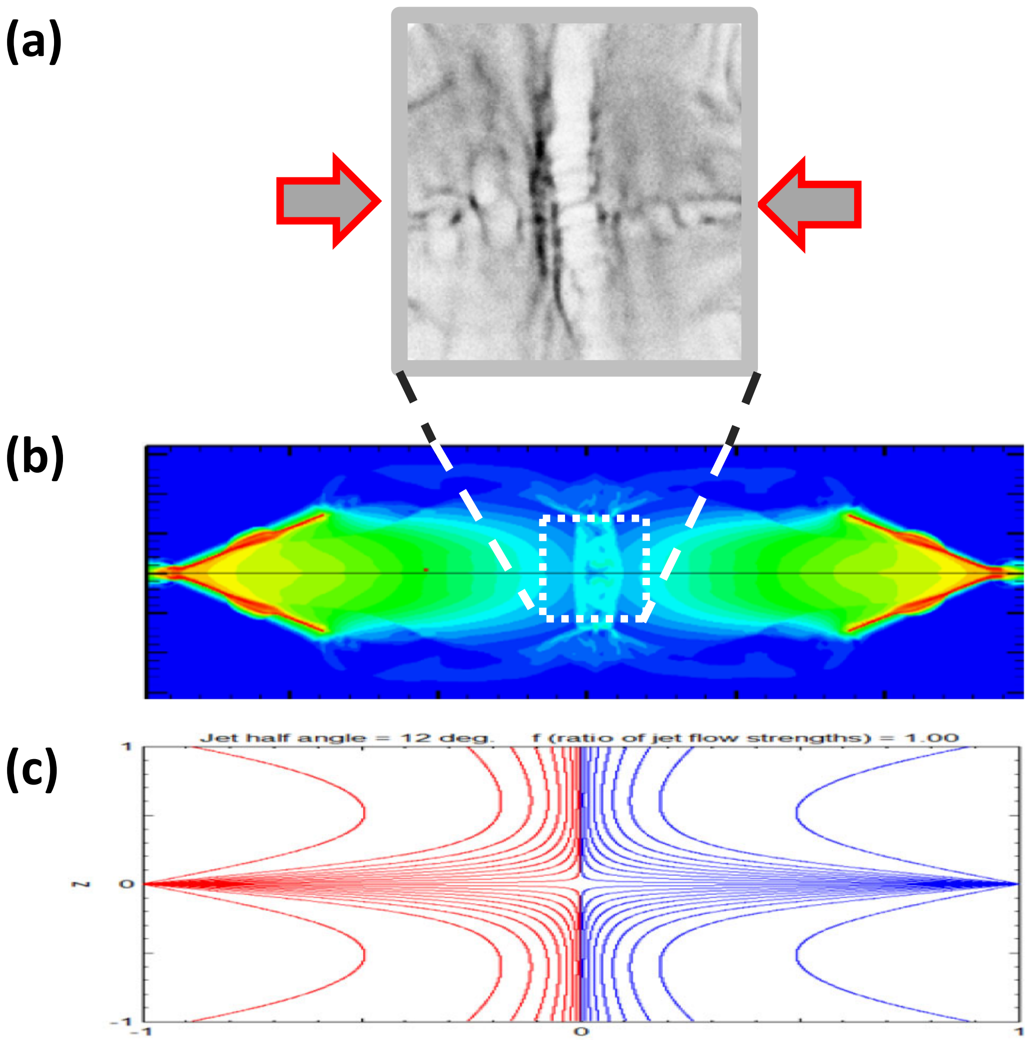



(a)
Stream 1
Overlap
Region
Stream 2
4.4 mm
(b)
Jet 1
Overlap
Region
Jet 2
3.5 mm
(c)
x 10^19
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
(d)
Jet 1
Jet 2
x 10^19
14
12
10
8
6
4
2

Structure of Plasma, ABC

- Driving Force
  - Gradient of Temperature
  - Gradient of Density (Biermann Battery Effect) $\nabla n_e \times \nabla T_e$
  - Scattering (EM, Nuclear Force, Maybe)
  - EM (Large Scale)
  - Laser EM (1E15Hz)

Magnetic Structure

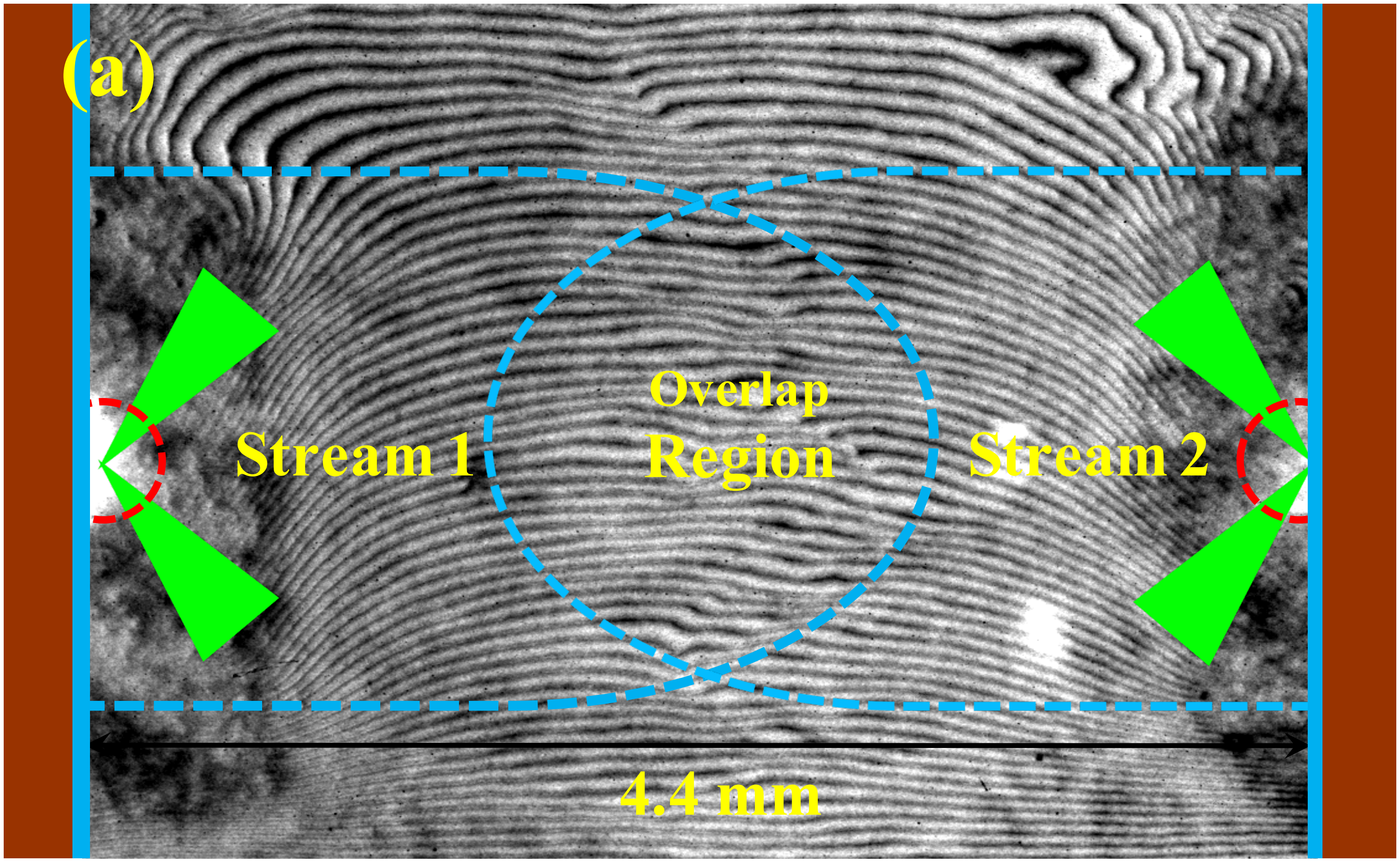


- Electron (NOT Ion) obtains high energy from Laser field
- Electrons fly away, Drag the Ions together
- e-e; e-i; i-i scattering
- E field
- M field strength
- Reynolds Number >20

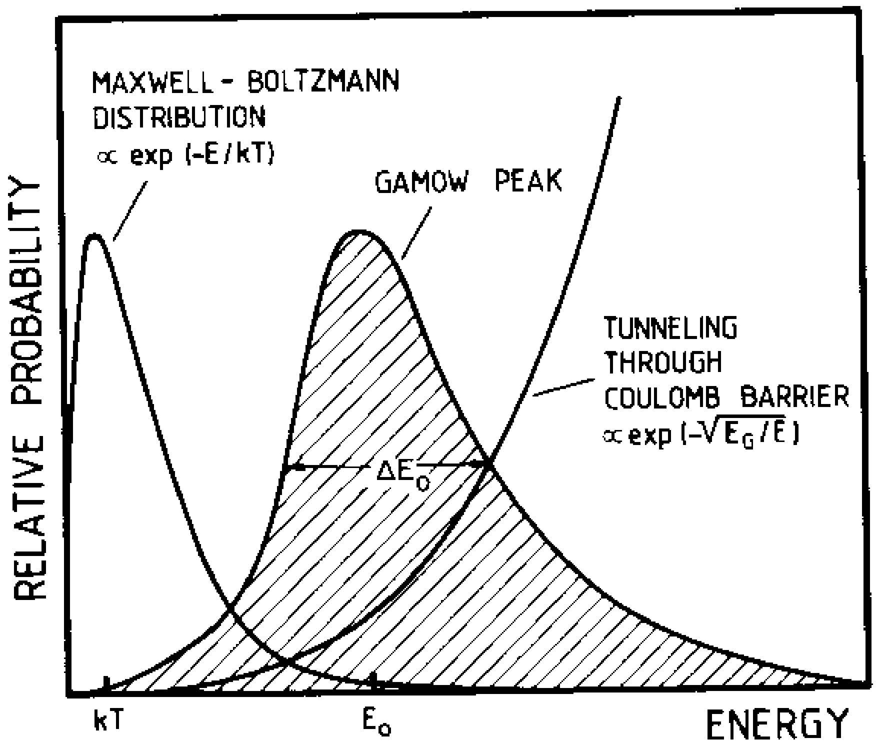
Our neutron Yields consistent with the prediction

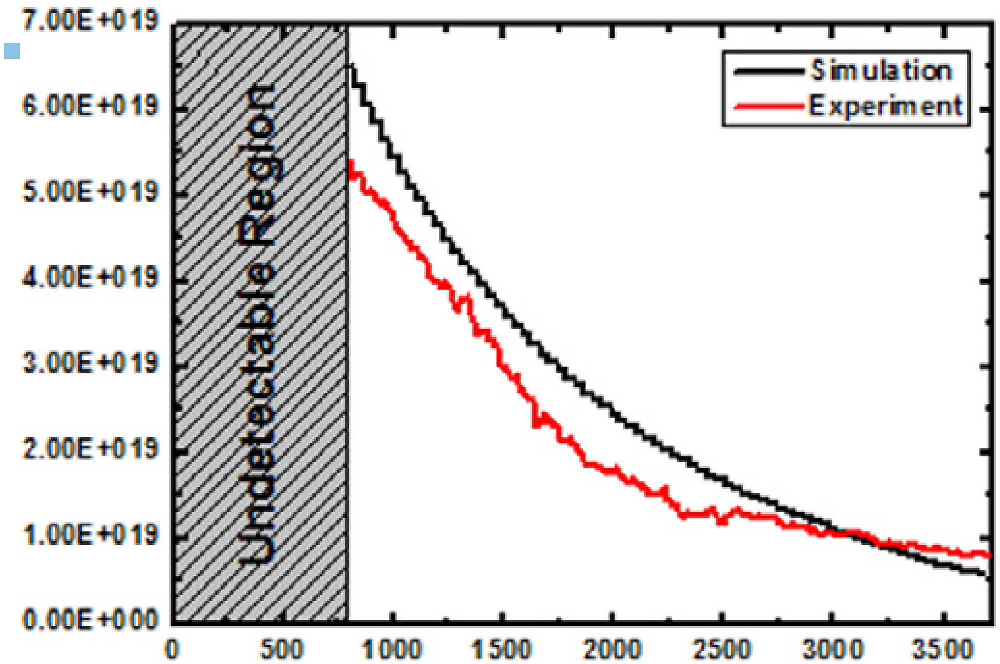
PRL.111(2013)235003

Jet Density Spectra



Measure S-factor Experimentally

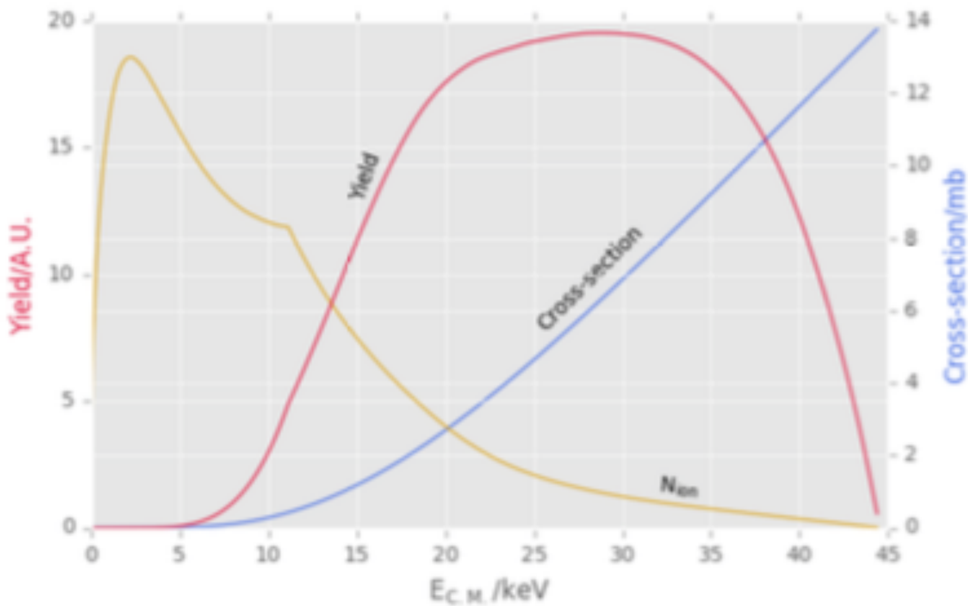


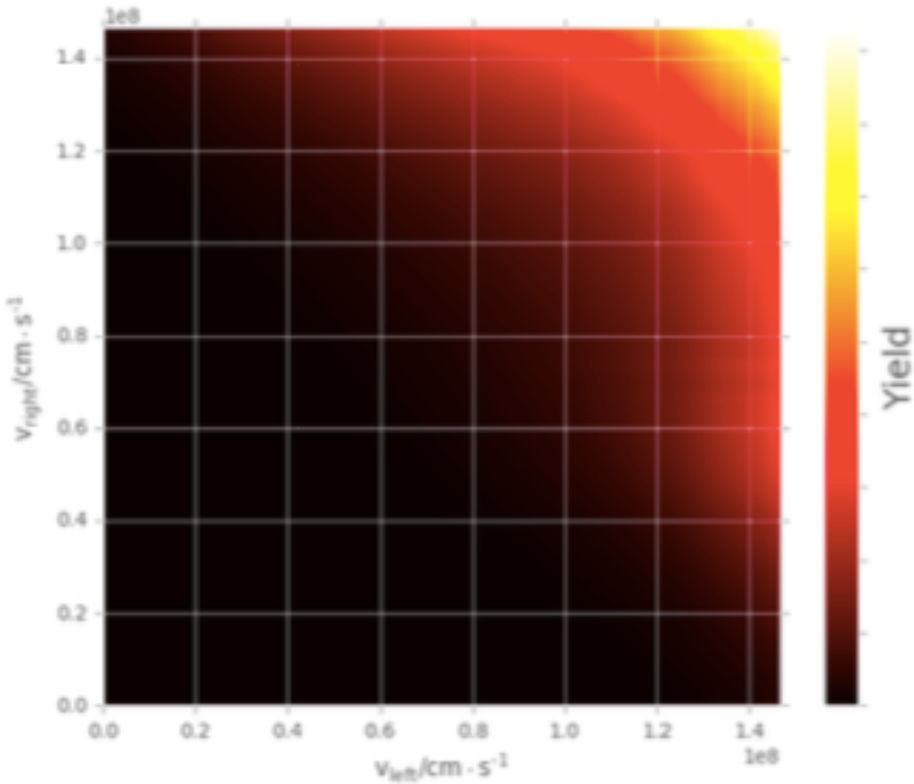


$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE ,$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}} \right) dE .$$

Calculate Neutron products





"Collisionless Plasma (CLP)" & Nucleosynthesis in the cosmos

- Acc. Mech. In CLP
- Plasma Eff. (e shielding)
- Example
  - Li at Sun's surface is 140times lower than th original Sun (Nature464(2009)189
  - Lithium in Stars w/ planets & w/o planets

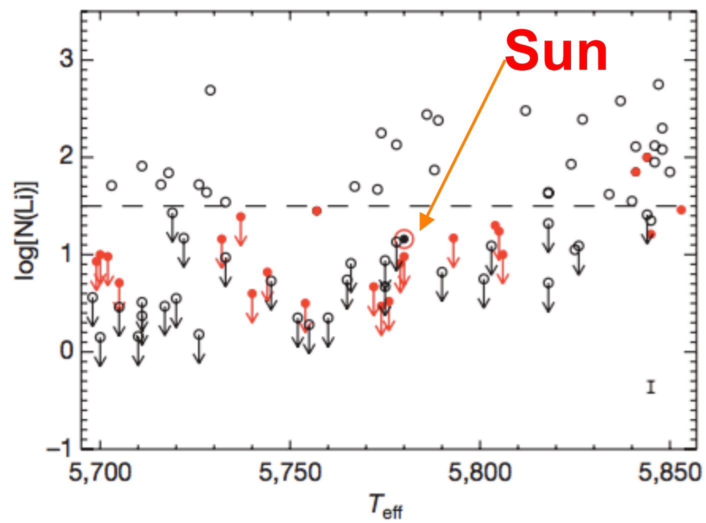
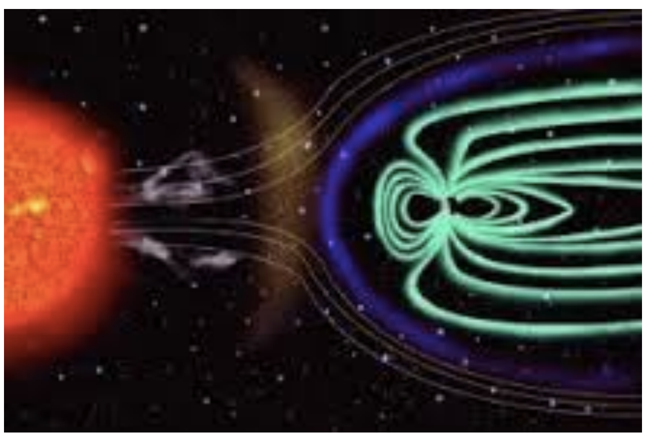


Figure 1 | Lithium abundance plotted against effective temperature in solar-analogue stars with and without detected planets. The planet-hosting and single stars are shown by filled red and empty black circles,

Cosmic Collisionless Plasma



- Astrophysical Shocks:
  - M=2 to relativistic;
  - n=0.01 to 1E10/cm3
- Solar Corona/Wind:
  - M=1.5 to 20;
  - n=1 to 1E8/cm3

X-ray、Gamma-ray
Energetic Particles

Result's Astrophysical Meaning

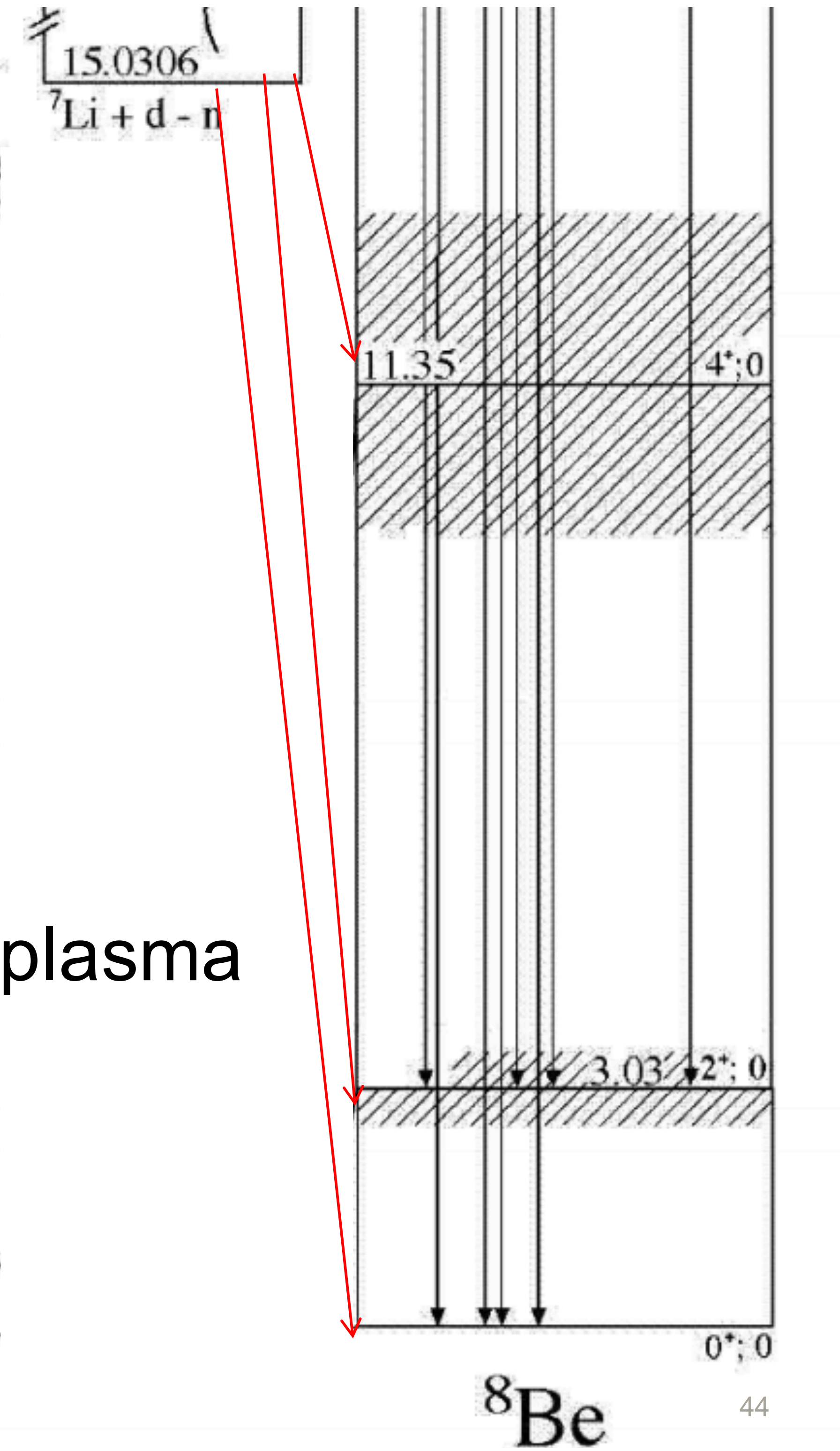
The following may play very imp. roles:

- Thermal Unequ.
  - All obs. (except neutrino) from Surface
- Self-generated EM field
  - Battery eff.
- Neutral Plasma Flux

- Three body reaction?
- D+^{7}Li→g.s. (0+)

  →1st e.s.(2+)

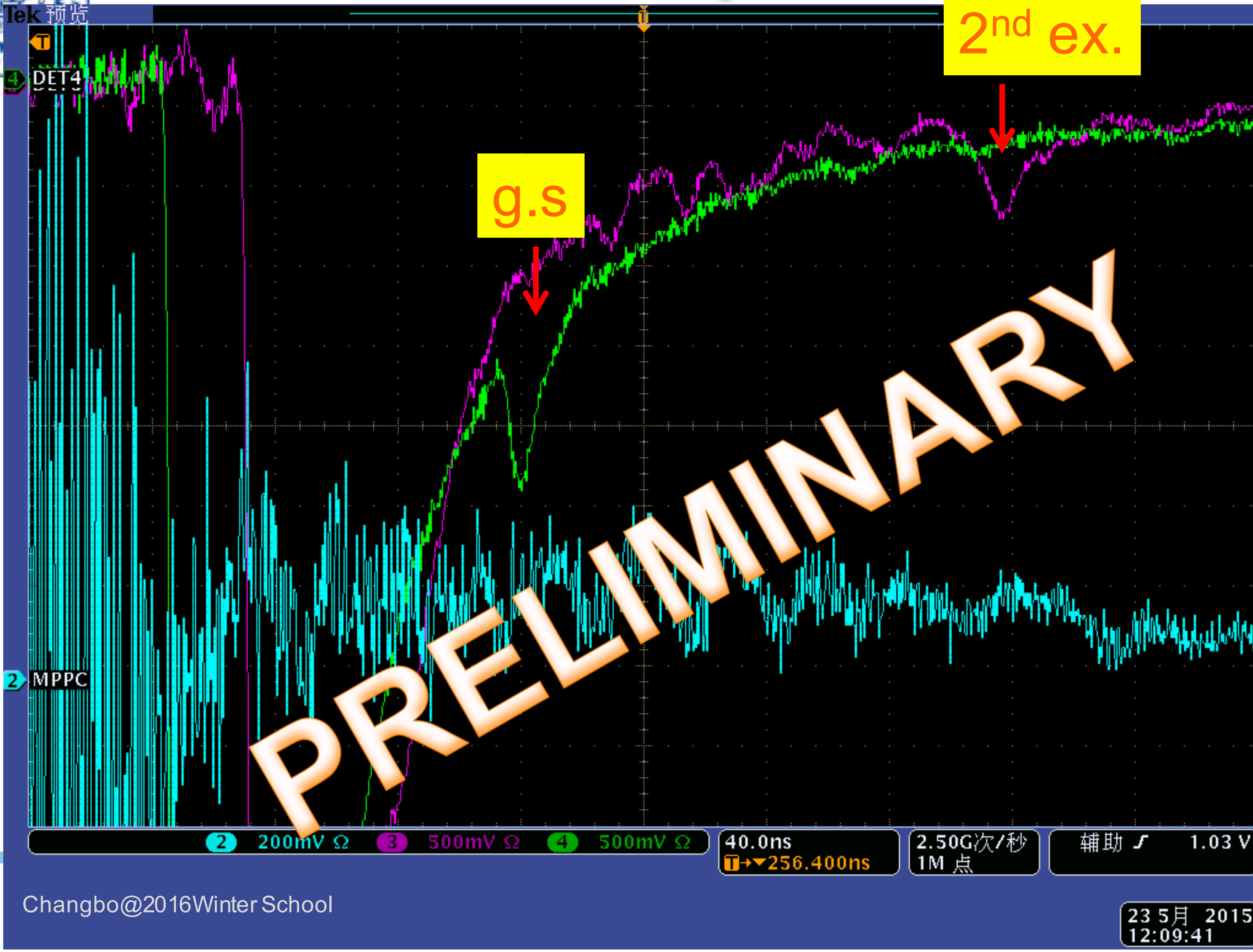
  →2nd e.s.(4+)



We try to find:

- CS diff of bounding states & plasma
  - ^{7}Li structure

D+Li Preliminary Results



Summary and Forecast

- With helps of Lasers, one can study nuclear astrophysics!
- Laser Nucl. Phys.: **Pros**
  - Full Plasma
  - High Peak Intensity ➔ Low Bkg
  - Quasi-thermal Distr.
- Laser Nucl. Phys.: **Cons**
  - Unstable (currently)
  - Repeat Frq. Low
  - difficulties in Product Detecting
  - Quasi-thermal Distr.
  - Plasma Dynamics, Better Understanding needed

Question?

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