Nuclear astrophysics at laser facilities

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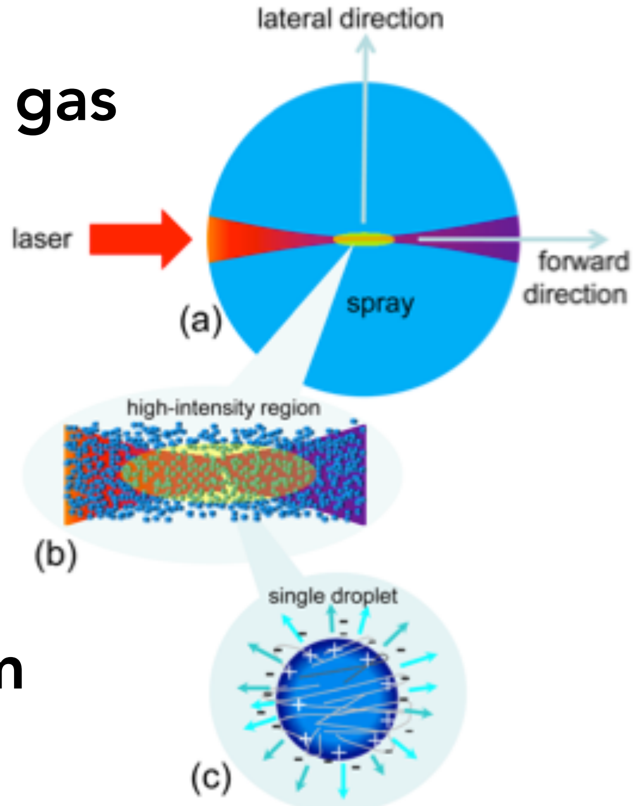
irfu.cea.fr – celia.u-bordeaux.fr

Nuclear physics with lasers

- Two tracks for reactivity/low-energy fusion probability measurements
  - Fusion reactions at femtosecond (fs) high-power lasers
    - Reacting species accelerated in the laser absorption mechanism
    - Determination of fusion probability corresponding to a certain energy spectrum
  - Large facilities with nanosecond (ns) lasers
    - Plasma reaching high temperature & density, species reacting inside the plasma
    - Reactivity/fusion probability determined corresponding to the Gamow window of the laser plasma
    - Going-on program at NIF

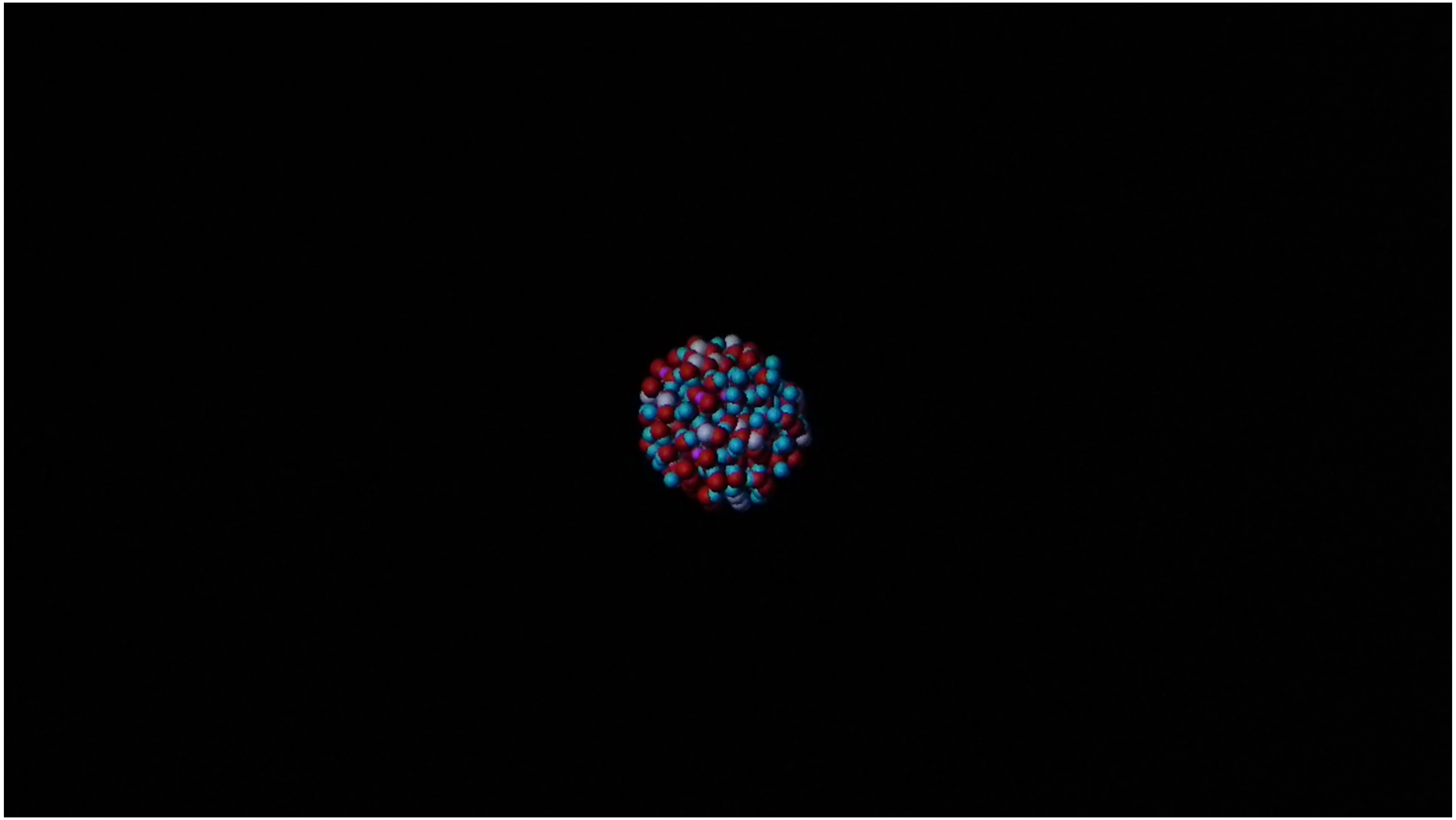
fs laser – nano-object interaction

- **Measurements of S factors or nuclear rates**
- Principle of the experiment
  - Atom cluster through supersonic gas expansion (nozzle)
  - A few 10 fs laser pulse,
    focal spot ~ 10 µm diameter
    I ~ 10^{18} – 10^{20} W/cm^2
  - High-efficiency laser energy absorption in the clusters
    → Coulomb explosion mechanism
  - 1 – 10 Hz repetition rate



S. Ter-Avetisyan *et al.*,
Applied Phys. Lett. **99**, 051501 (2011)

Nano-object Coulomb explosion



Calculation by François Bayard (CPE/C2P2, Univ. Claude Bernard, Lyon)

Nano-objects

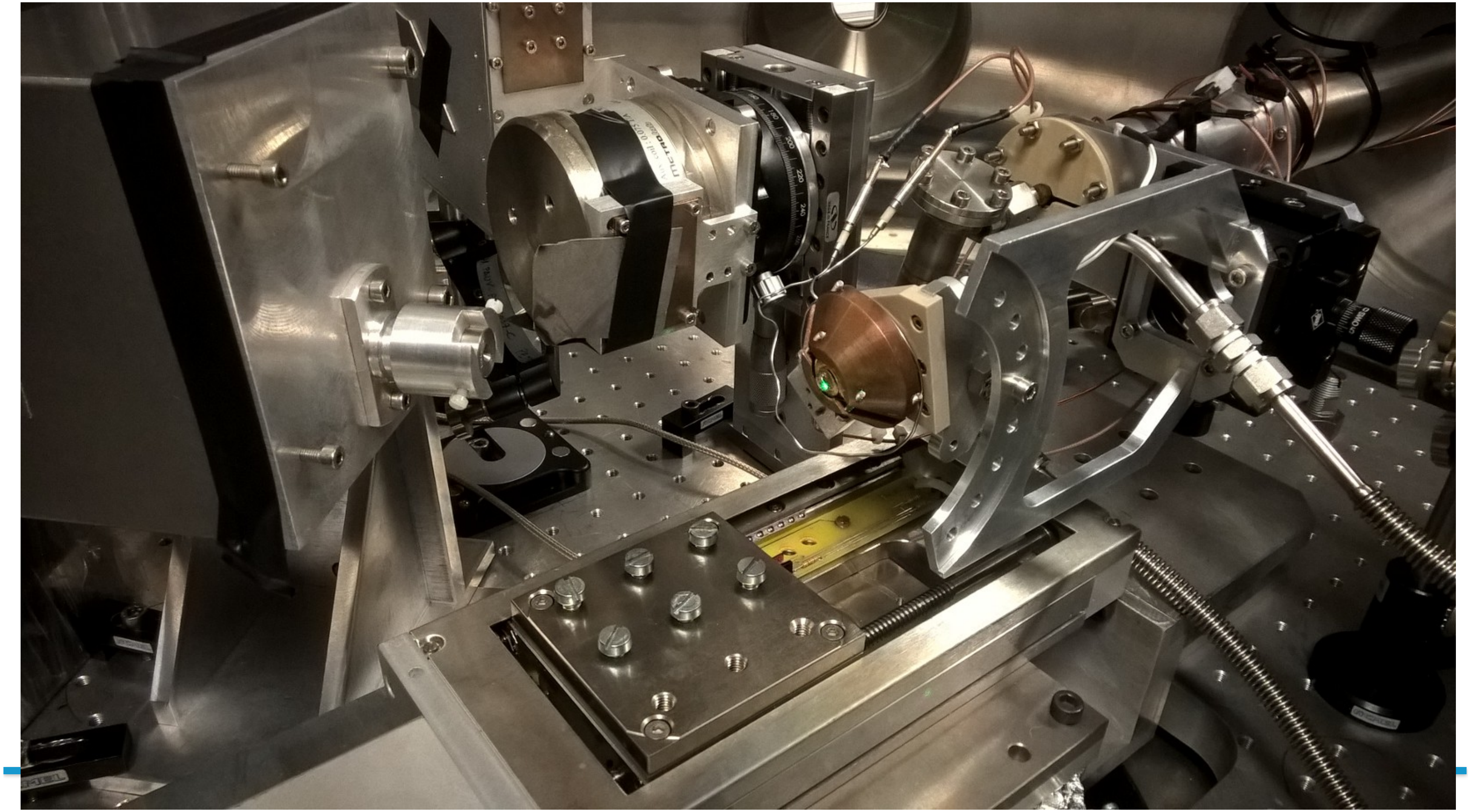
- ↘ **Atomic clusters**
  - Clusterisation in the supersonic expansion of a high-P gas
  - Average size ←→ gas pressure
  - Φ a few nm to a few 10 nm, homogeneous, ρ(*liquid*)
- ↘ **Nano-droplets**
  - From the supersonic expansion of a liquid of a spray
  - Φ ~ 200 – 300 nm, homogeneous, ρ(liquid)
- ↘ **Sub-micron molecules**
  - From chemistry
  - Φ ~ a few 100 nm
  - Homogeneous, chemistry can enrich the surface

Some orders of magnitude

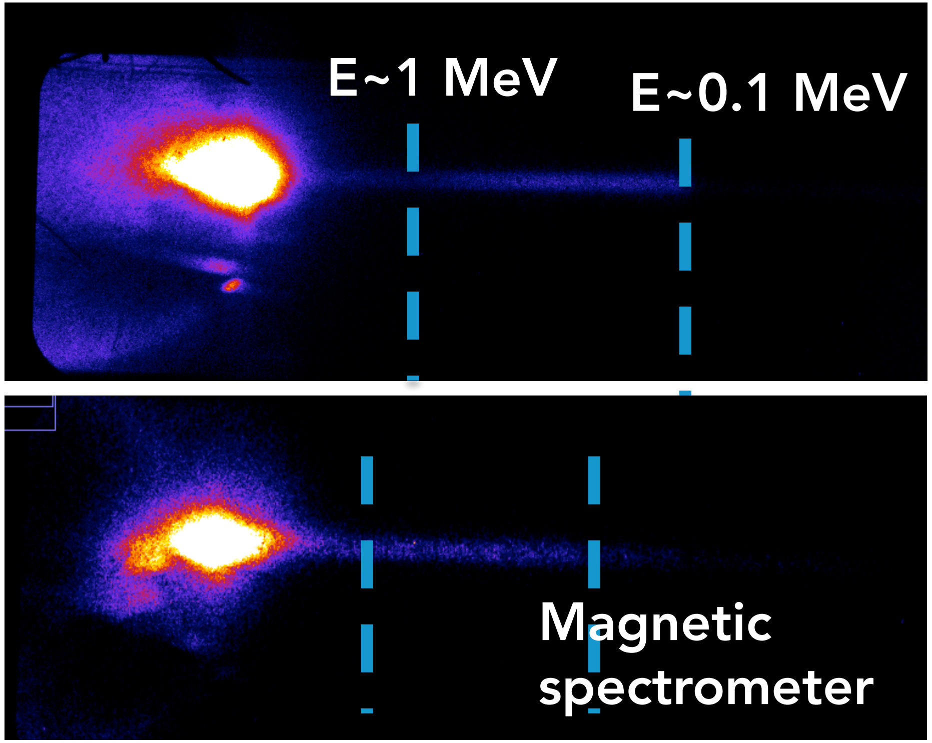
- **Electron response time in the laser high-electric field**
  - ~ 20 fs → thermalisation
- **Coulomb explosion time**
  - A few 10 ps (ion acceleration)
- **Relaxation ion/electron**
  - Electron – ion collision frequency: ~ a few 10/fs
  - Fully out-of-equilibrium plasma → description with kinetics equation, molecular dynamics or particle-in-cell models
- **Lasers**
  - Pulse duration: a few 10 fs → ~ 200 fs
  - Pulse energy: a few 100 mJ to a few J
  - Intensity: from 10^{16} to 10^{20} W/cm^2 → E = 10^9-10^{11} V/cm
  - Contrast: 10^6 to 10^{12}, at 1 ps, 10^1 to 10^4 at 100 fs
  - Wavelength: $\lambda \sim 1$ µm

Test experiment at CELIA July 2016

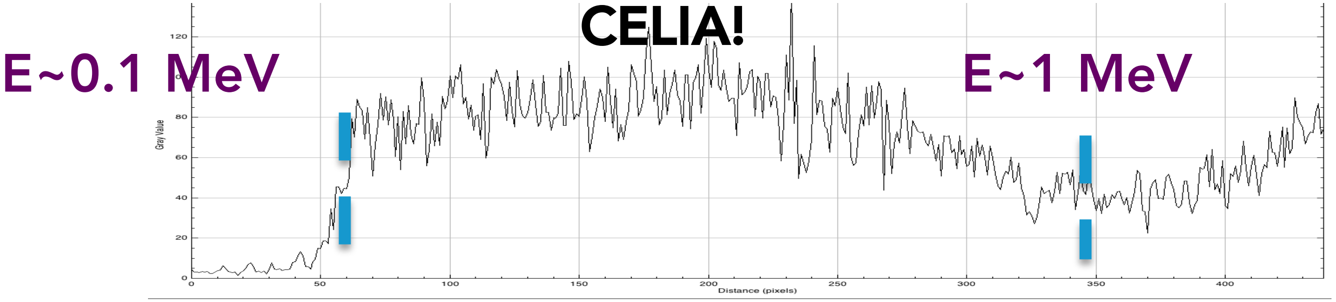
- With G. Andrianaki, G. Boutoux (CELIA) & A. Soleihac (ILM, Lyon)



Test experiment at CELIA July 2016

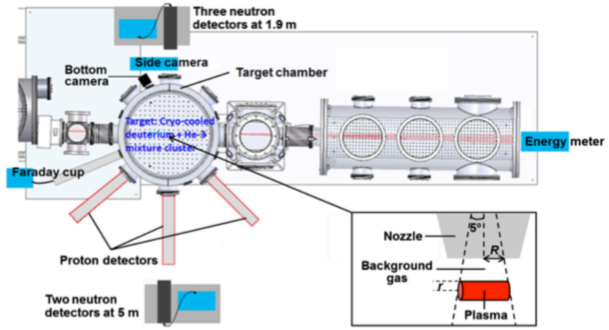


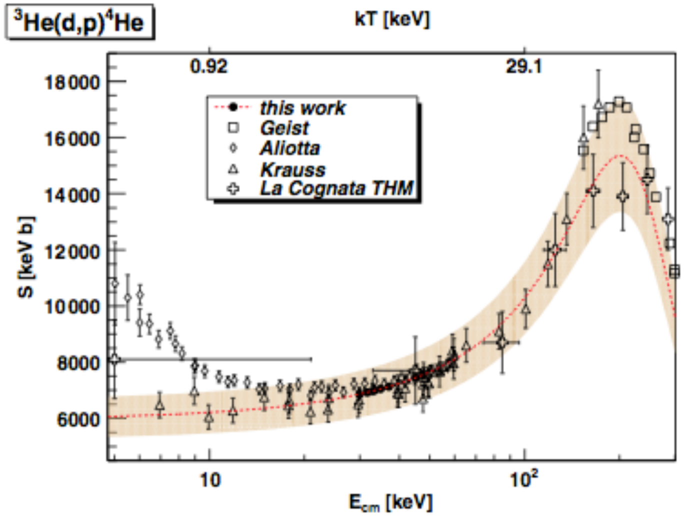
- Reproducible signal
- Approx. the same energy range in both detectors
- Spectra seem different
- A few shots are needed to generate enough signal on the imaging plates
- Improvements of the detectors are needed for the protection against photons
- 1 MeV protons: local record at CELIA!

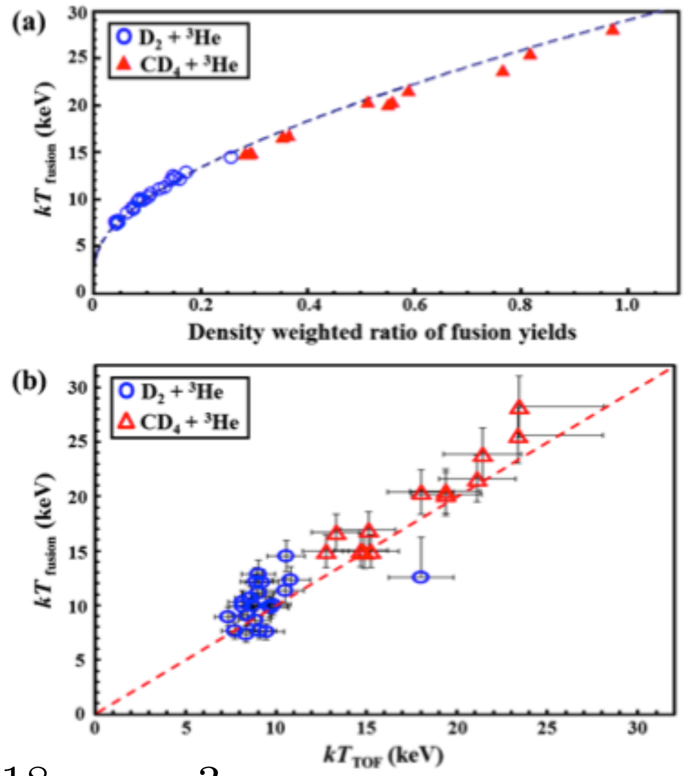


fs laser – nano-object interaction

- M. Barbui *et al.*, Phys. Rev. Lett. **111**, 082502 (2013)
- W. Bang *et al.*, Phys. Rev. Lett. **111**, 055002 (2013)







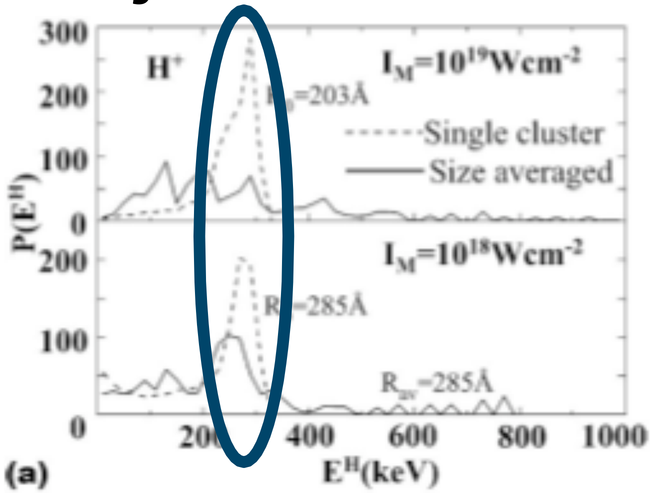
$$\rho(^3\mathrm{He}) \quad \sim \quad 10^{18}\ \mathrm{cm}^{-3}$$

fs laser – nano-object interaction

↘ Possible evolutions of the field

- Use of narrow size distributions of clusters
  vs log-normal for gas expansion
  → A more precise definition of the target
  → Nanodroplets
  → Nano-objects synthesised by chemistry
- Shaping of the fs pulse
  → Shock-wave into the cluster
  → Trigger fusion reactions
  in higher density plasmas

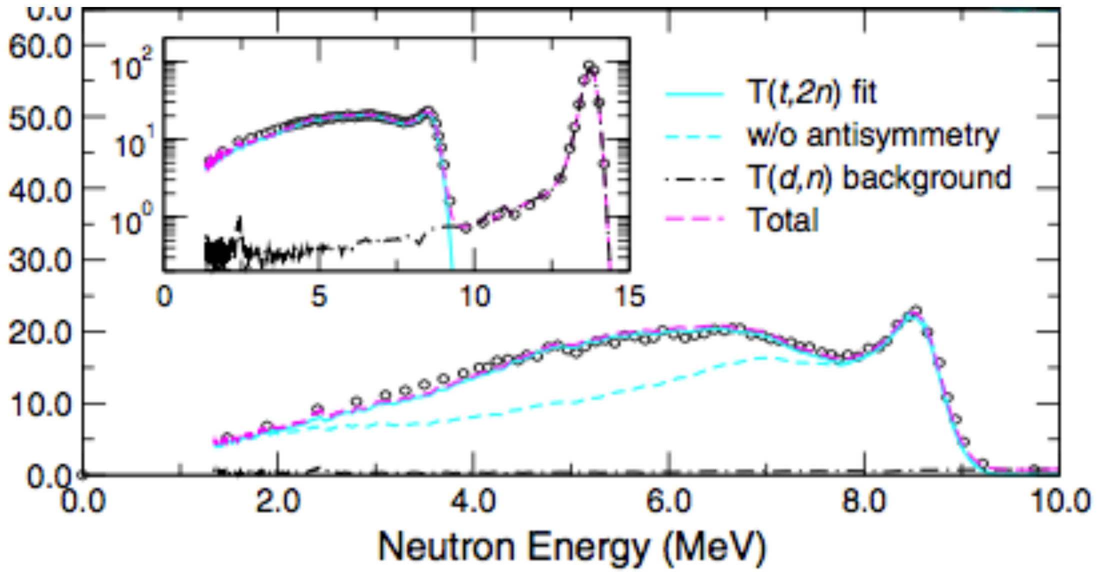
$$\rho(\text{ions}) \quad \sim \quad 10^{21} - 10^{23}\ \text{cm}^{-3}$$



I. Last & J. Jortner,
PoP 14, 123102 (2007)

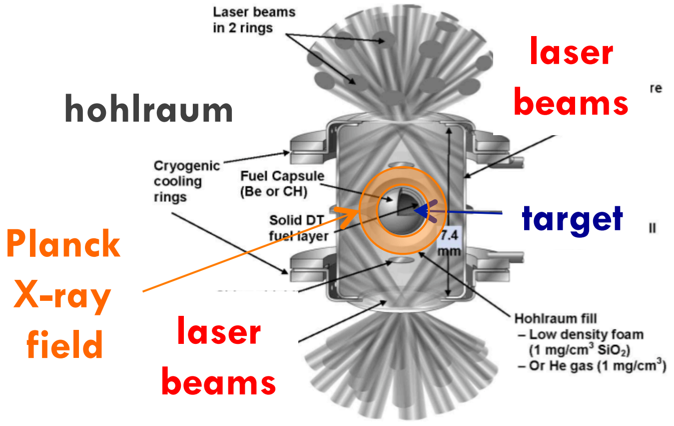
Example of an on-going programme on NIF

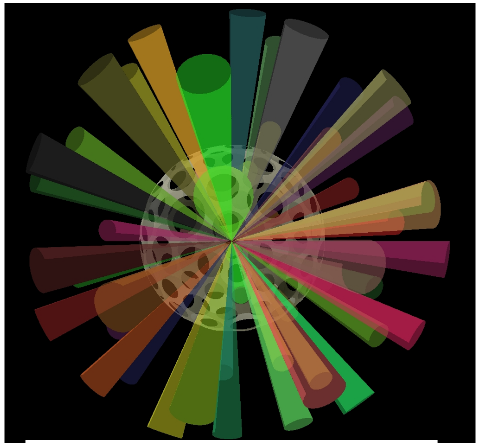
- Measurements of S factors of *tt* & *dd* fusion rates
- NIF on-going experiment
  - D.T. Casey *et al.*, Phys. Rev. Lett. **108**, 075002 (2012)
  - D.T. Casey *et al.*, Phys. Rev. Lett. **109**, 025003 (2012)
  - D.B. Sayre *et al.*, Phys. Rev. Lett. **111**, 052501 (2013)



An experiment @ HE multi-beam laser facility

NIF experiment indirect drive

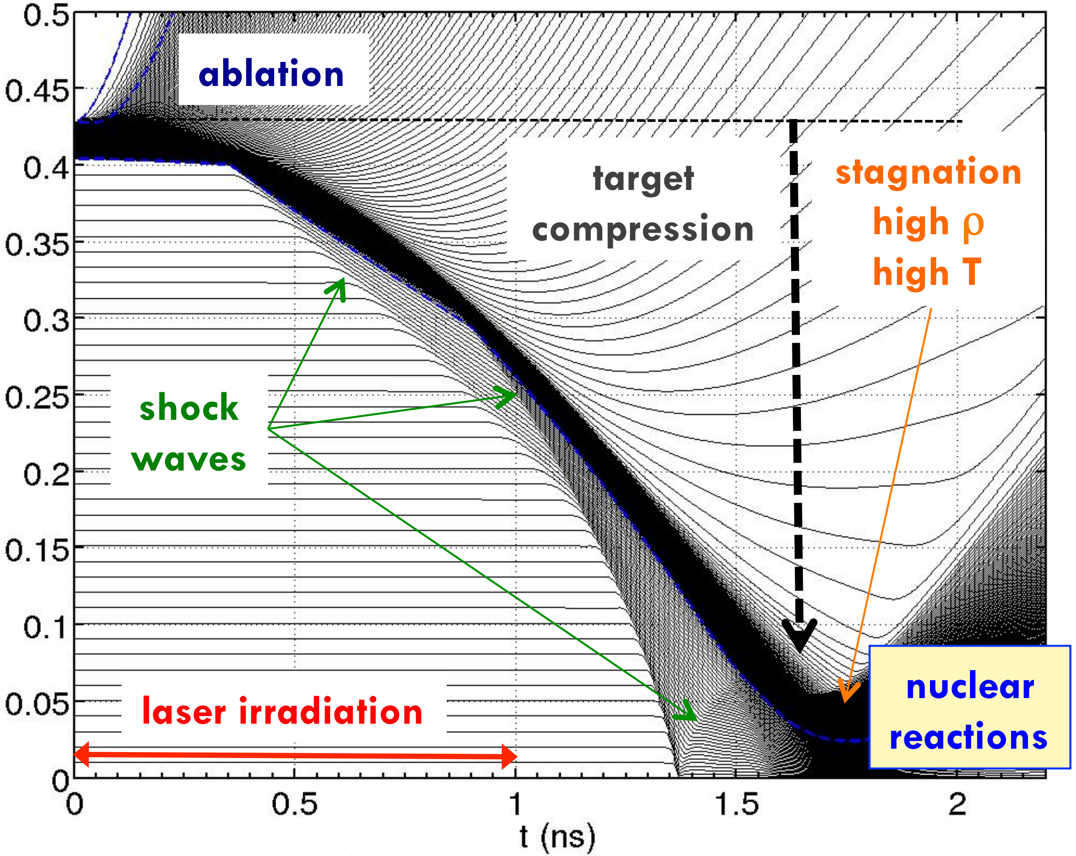




VisRad Prism Corp

OMEGA experiment direct drive

Laser experiment



Courtesy of X. Ribeyre (CELIA, Bordeaux)
Calculation with CHIC hydrodynamics
spherical symmetry

Measurement of fusion reactions

$$\mathrm{N_{fp}(E_D)} = \frac{\Delta\Omega}{4\pi}\int \mathrm{dt\ d^3}\vec{r}\,\langle\sigma\nu\rangle(\mathrm{T}(\vec{r},\mathrm{t})) \times$$

$$\rho_\mathrm{A}(\vec{r},\mathrm{t})\rho_\mathrm{B}(\vec{r},\mathrm{t}) \times \int \mathrm{dE_F P(E_F, E_D,}\vec{r},\mathrm{t})$$

$\mathrm{N_{fp}(E_D)}$ → Detected fusion products

$$\left.\begin{array}{r}\mathrm{T}(\vec{r},\mathrm{t}) \\ \rho_\mathrm{A}(\vec{r},\mathrm{t}),\ \rho_\mathrm{B}(\vec{r},\mathrm{t})\end{array}\right\}$$

→ From plasma hydrodynamics calculations & additional diagnostics (Doppler, neutrons)

$\int \mathrm{dE_F P(E_F, E_D,}\vec{r},\mathrm{t})$ → From Monte-Carlo transport

→ **Experimentally, the method of reaction yield ratios is used to improve the accuracy on the determination of the reactivity**

Conclusions

- High-energy laser facilities (will) permit exploring “in-plasma” nuclear physics, from low to rather high ρ & k_BT
- Existing & being-built facilities provide a continuum of experiments from Hz repetition rate measurements to single – shot laser experiments
- For nuclear astrophysics, $p+^{11}B$ reaction can be studied, in search for electron screening effects (as for $p+^{8}Be \rightarrow ^{8}B+\nu$)
- Experiments for astrophysics in close relationship with laser fusion physics for energy
- Experiments on fs lasers for astrophysics aim also at other physics goals such as negative ion sources…
- fs laser experiments as a program of their own but also as a test bench of diagnostics for large-scale facilities