FemtoFusion

Nuclear astrophysics at fs laser facilities

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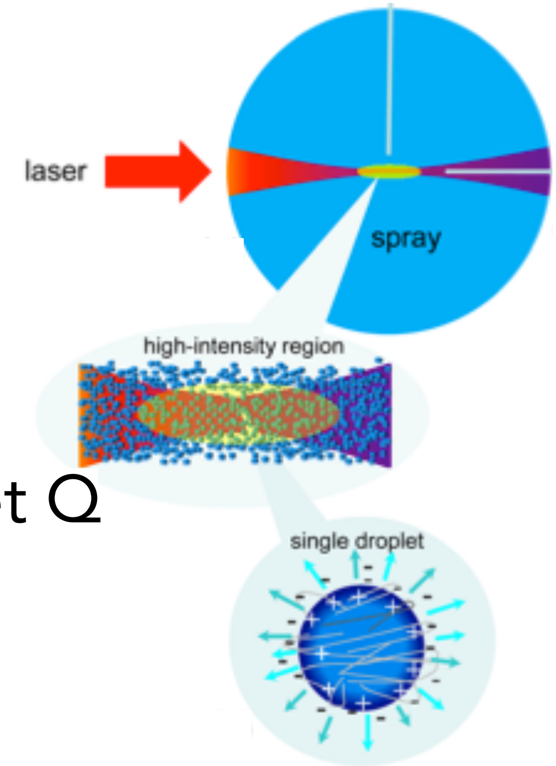
PNPS, colloque de prospective
Montpellier, 26 – 28 mars 2018

Soutien **PNPS : 2014-2016**

fs laser – nano-object interaction

- Measurement principles
  - Nano-object through supersonic gas/liquid high-pressure expansion
  - A few 10 fs laser pulse, focal spot ~ 10 µm diameter $I \sim 10^{18} - 10^{20}$ W/cm^2
  - High-efficiency laser energy absorption in the nano-objects
    →Ionisation, electron stripping → net Q
    →Coulomb + hydrodynamical explosion mechanism
    →Few keV electronic temperature

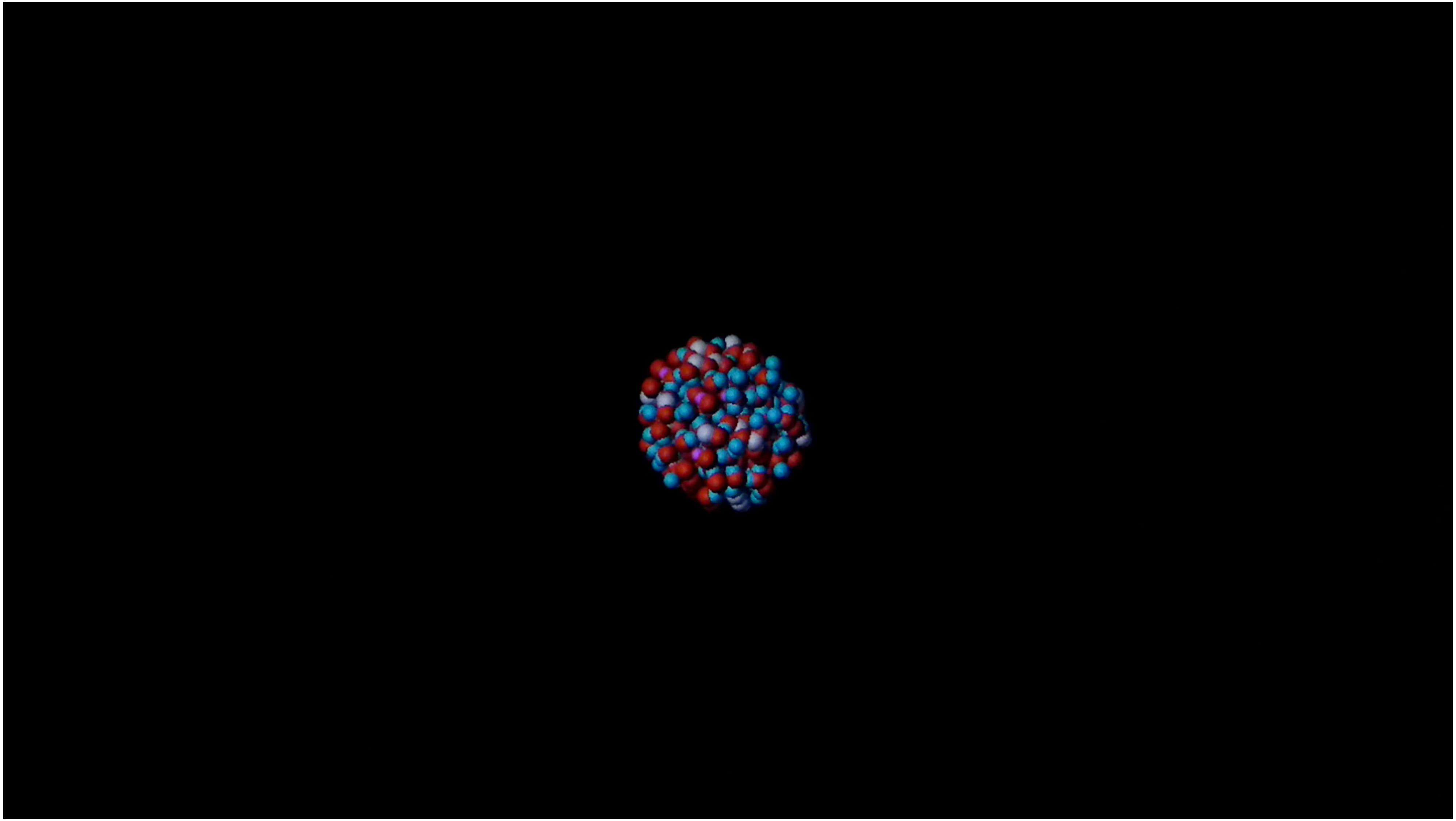


S. Ter-Avetisyan *et al.*, Applied Phys. Lett. **99**, 051501 (2011)

Some orders of magnitude

- Electron response time in the laser high-electric field
  - ~ 20 fs → electron thermalisation
- Nano-object 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 kinetic equations, 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: λ ~ 1 µm

Nano-object Coulomb explosion



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

Nano-objects explosion issues

- Nano-objects as a source of accelerated ions
  - QMD calculations (I. Last & J. Jortner, F. Peano et al.) show narrower energy spectra with
    - Mono-size nano-object distributions
    - Localized ion species inside the nano-objects

S on fully stripped ions

- Nano-objects as a plasma statistics for nuclear astrophysics
  - Structuring nano-objects: lighter ions in the core & heavier ones on the surface
    - Kinematical overtaking to favour light – heavy-ion fusion reactions within the exploding nano-object
  - Increasing the nano-object plasma density
    - Launch nano-shock wave with in-advance laser pulse, ~1 % of I(laser)
    - Triggering fusion reactions at the beginning of the expansion

S in plasma, e^- & i^+ screening

Nano-objects

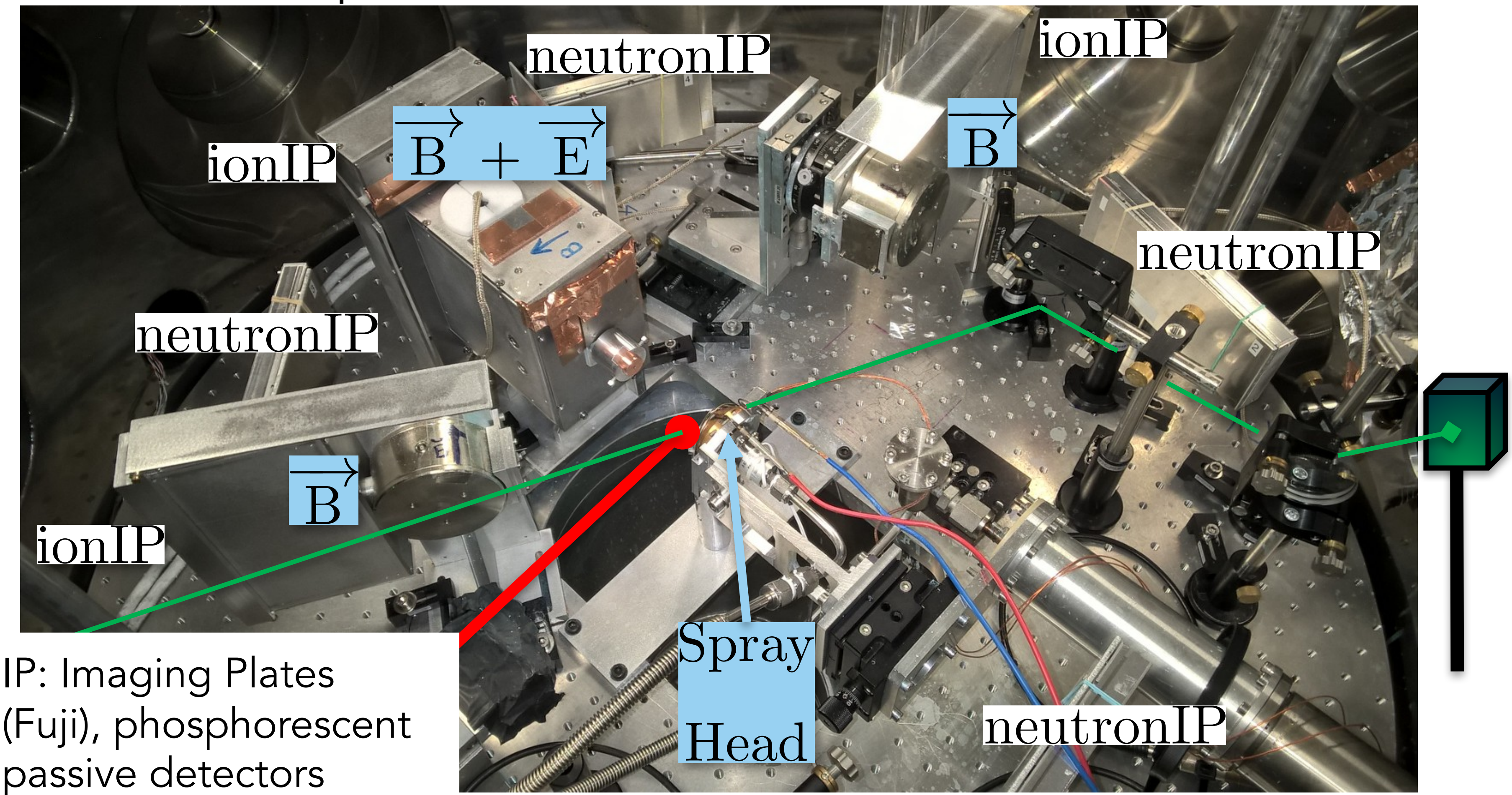
- Atomic clusters
  - Aggregation in the supersonic expansion of a high-P gas
  - Average size = f(P(gas)), ϕ ~ up to a few 10 nm,
  - broad size distribution
- Nano-droplets
  - Supersonic expansion from a spray source
  - ϕ ~ 200 – 300 nm
  - Narrow size distribution
- Sub-micron molecules (organic polymers, chemistry)
  - ϕ up to 1 µm
  - Narrow size distribution
  - e.g. proton-rich core + ^{11}B attached on the surface

Homogeneous ρ(*liquid*)

Heterogeneous, chemistry can enrich the surface, ρ(*solid*)

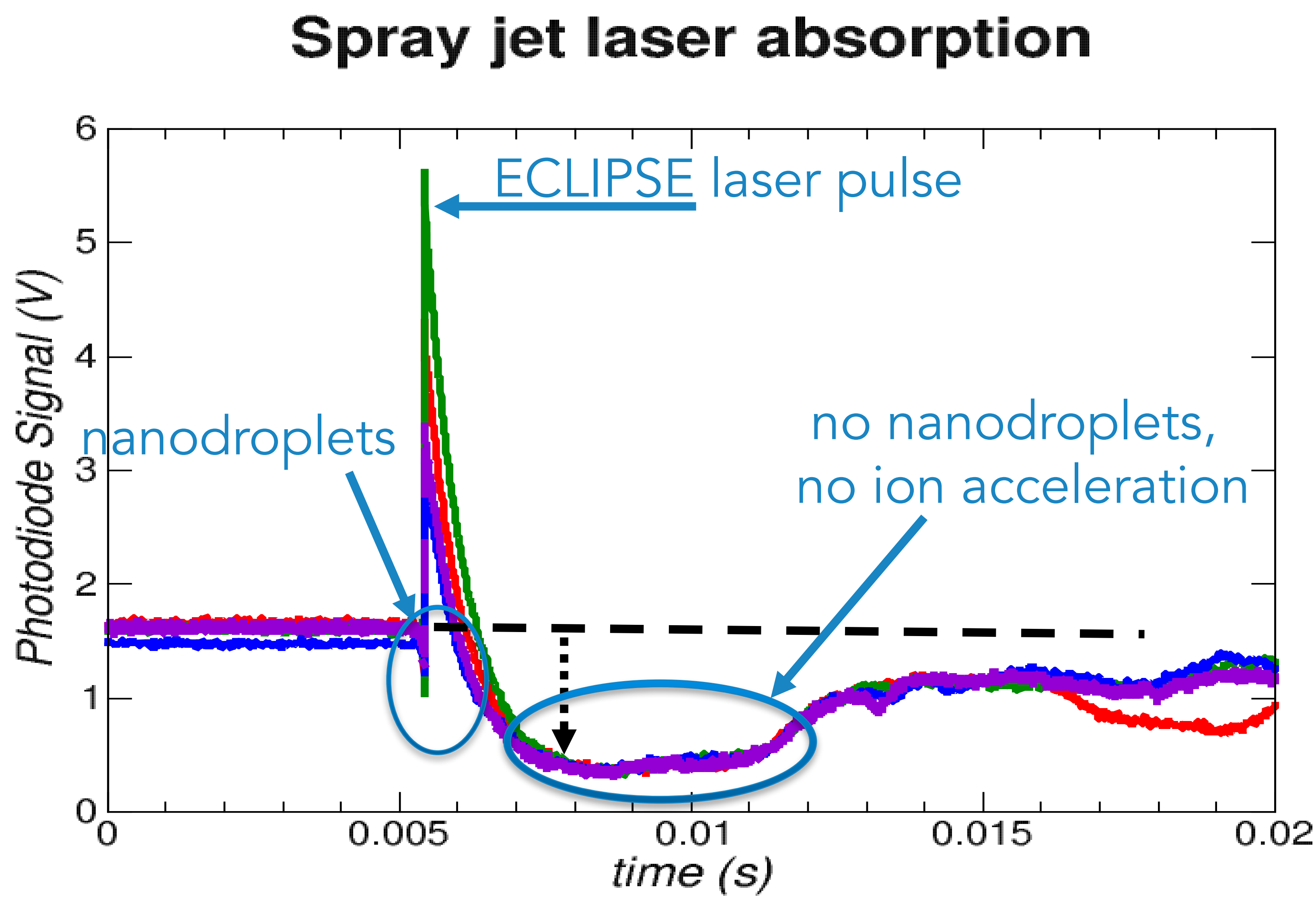
First experiments at CELIA

- ECLIPSE laser: E ~100 mJ on target, 1 Hz, 4 runs from April to December 2017



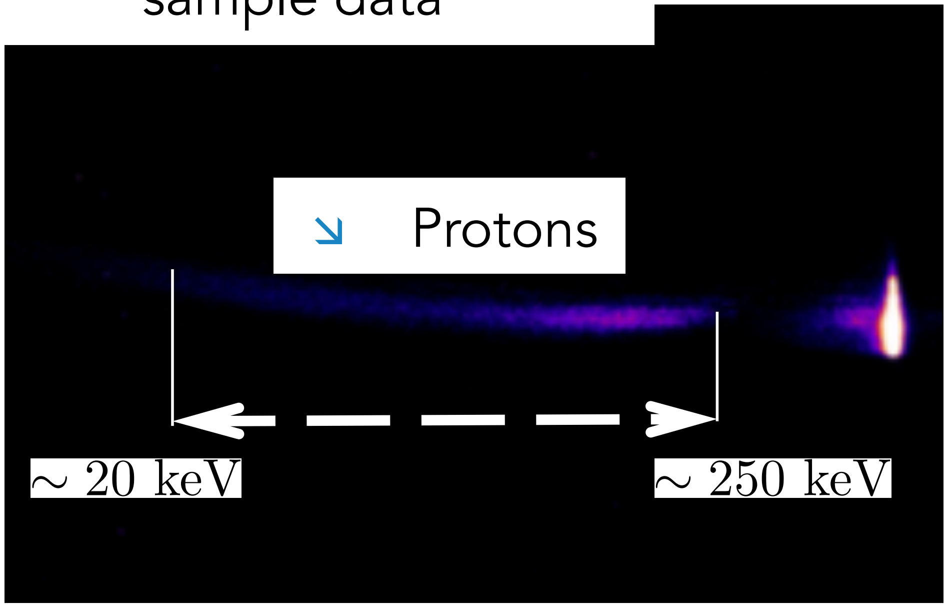
- IP: Imaging Plates (Fuji), phosphorescent passive detectors

Spray laser absorption diagnostic



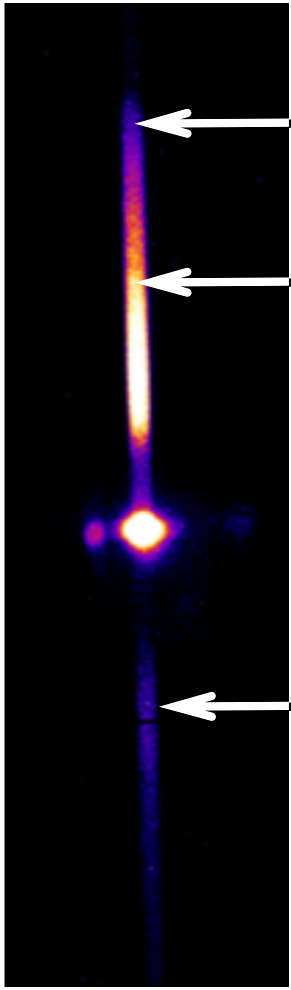
Ion acceleration/detection

- Thomson parabola sample data



- High reproducibility of the ion spectra

$$R(IP) \propto T_K(ion)$$

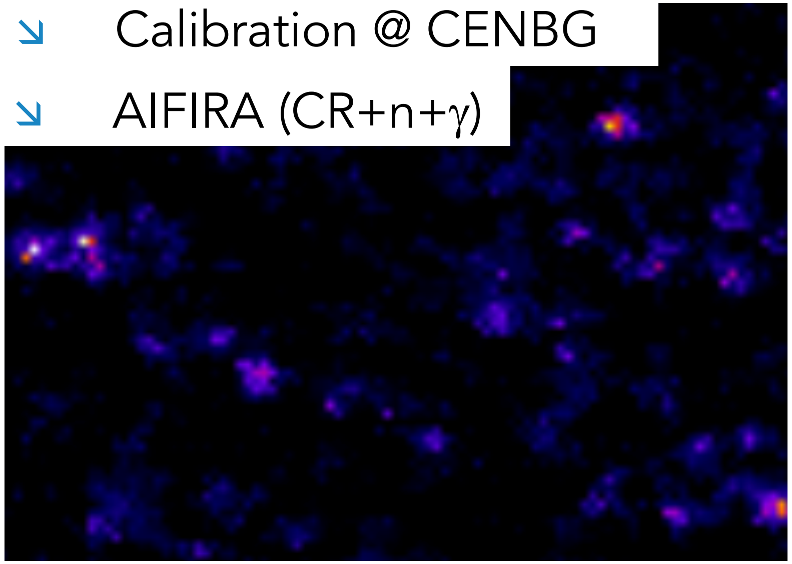


~ 700 eV

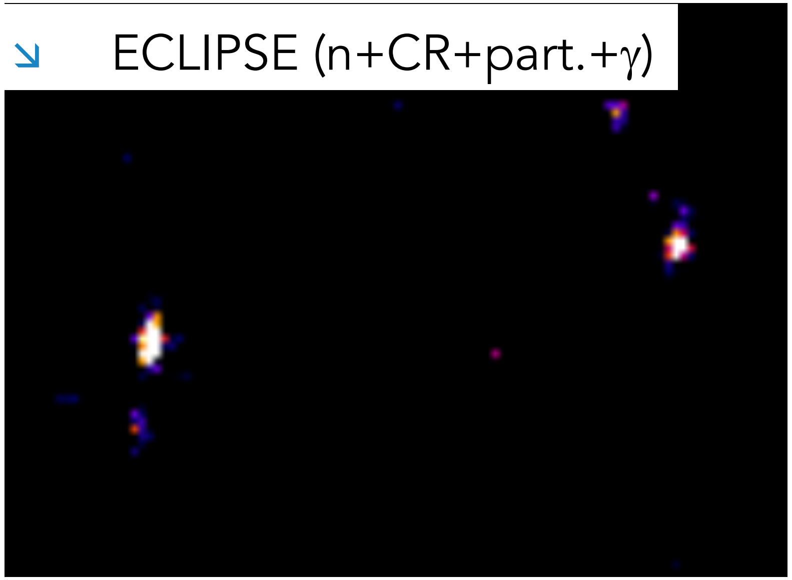
- Positive ions
- Negative ions
- B = 0.1 T magnetic spectrometer sample data

Neutron detectors

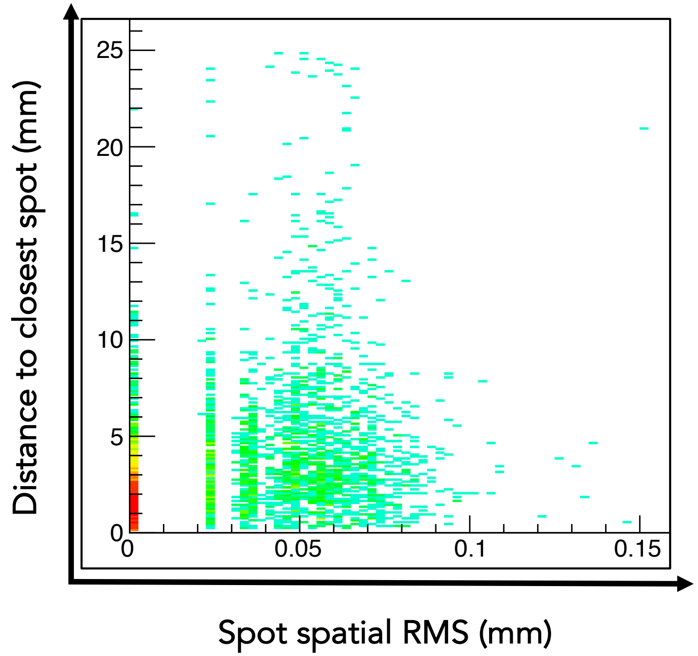
- Calibration @ CENBG
- AIFIRA (CR+n+γ)



- ECLIPSE (n+CR+part.+γ)

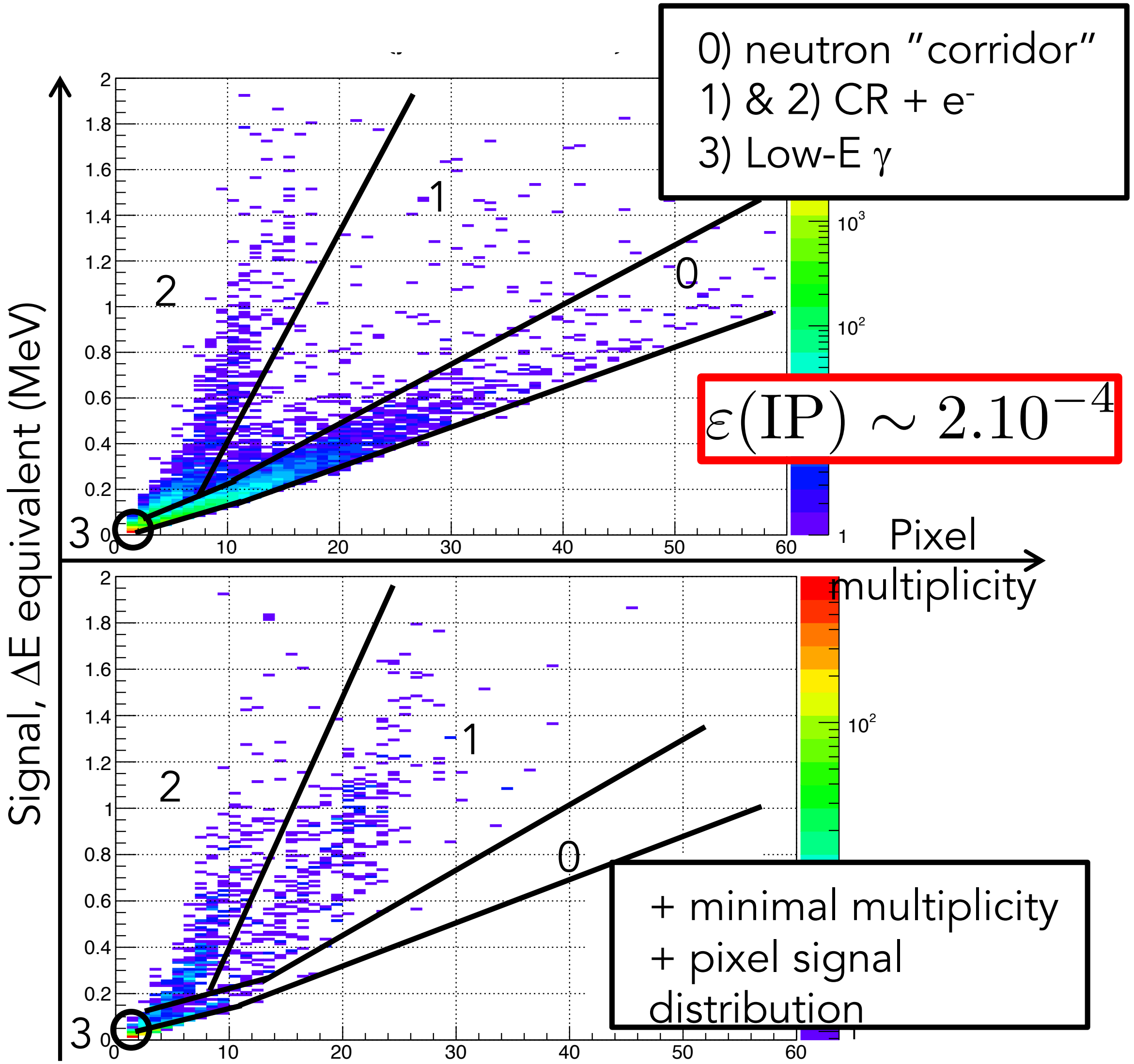


- Imaging Plates are scanned to produce pixel signal distributions, which permits quantitative analysis



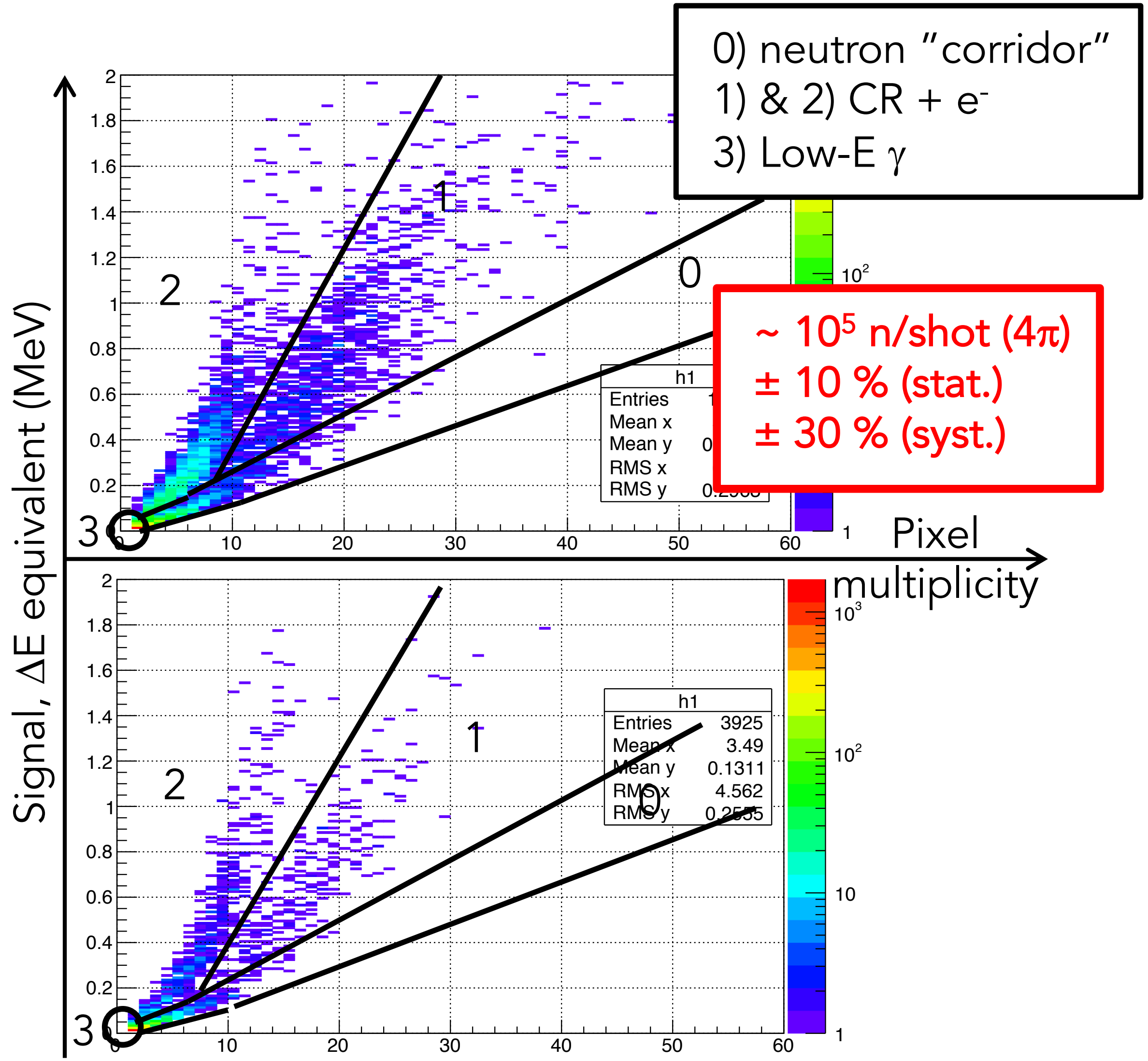
CENBG/AIFIRA measurement

- CENBG/AIFIRA, $\gamma + \text{n}$ production
- CENBG/AIFIRA, run with γ production (no neutrons)



Spray-source measurement

- D_2O in the spray source, for dd fusion
- H_2O in the spray source, no neutrons



FemtoFusion: next steps

- Measurement of the nano-droplet average size (e.g. Mie scattering of laser light)
- Modelling of the spray jet and droplet formation
- Optimization of the spray source to reduce the quantity of matter introduced into the vacuum chamber
  → Increase of the statistics of detected particles with a larger number of laser shots per experiment
- First measurement with latex nanoparticles in C_2H_5OH solution: comparison of the detected ion energy spectra with C_2H_5OH nano-droplets
- Installation of the setup on the upgraded ECLIPSE laser: from 100 mJ to 4 J on target
- Building of a dedicated “large solid-angle” spectrometer for ^{4}He identification from $\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\alpha$

Funding of FemtoFusion

- Initial support from CEA-Saclay/DAp
- PNPS 2014-2016

Charged-particles and neutron detectors

- "mi-lourds" CNRS/INP

Spray-source

- The combination of the three permitted:
  - To build a setup (microscope) for fs high-power lasers with multi-physics purposes (i.e. not only stellar nuclear physics)
  - To obtain our first quantitative results (analysis in progress)
  - To widen the collaboration
- We should be able to build-up on this and ask for funding to improve the set-up.