

Laser-plasma experiments (at LULI) relevant to kinetic modeling

Frédéric Perez

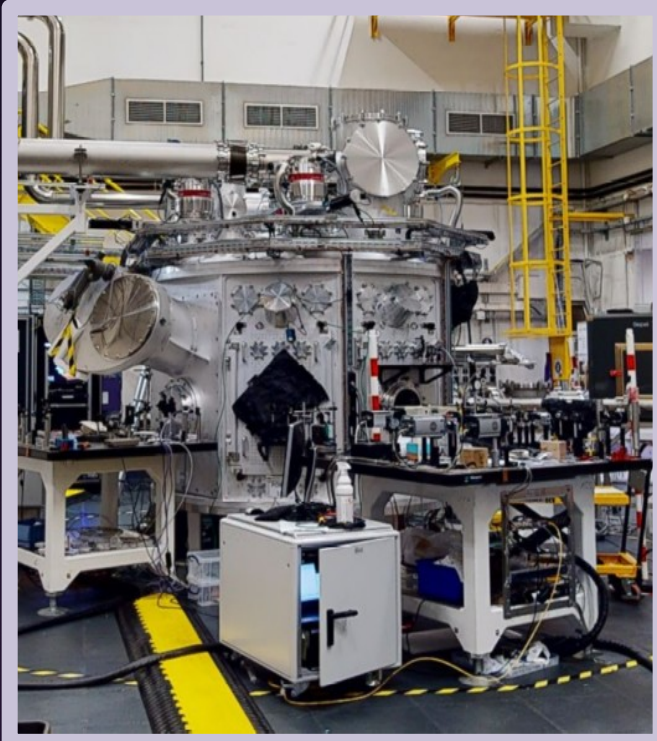
LULI laboratory, CNRS, Ecole Polytechnique, France



**supported by Project ELI-RO/DFG/2025_013 IATP-NP 2.0
funded by the Institute of Atomic Physics, Romania**

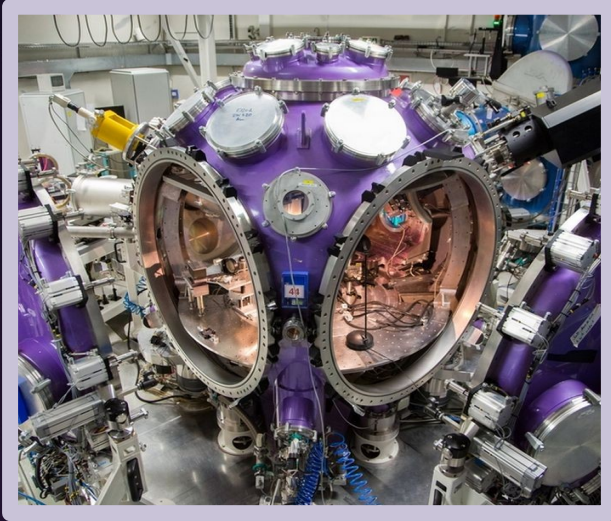
- Atomic physics
- Ion acceleration
- QED
- Instabilities
- ...

Three laser facilities at LULI



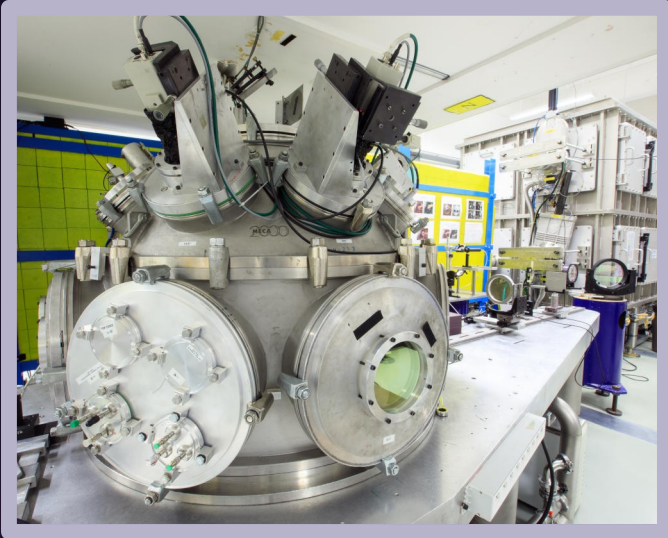
- **Apollon:** 2 beams, 25 fs, 70J, short-focal or long-focal
→ laser wakefield, high-harmonics, ion acceleration, gamma-ray production, atomic physics, ...

Three laser facilities at LULI



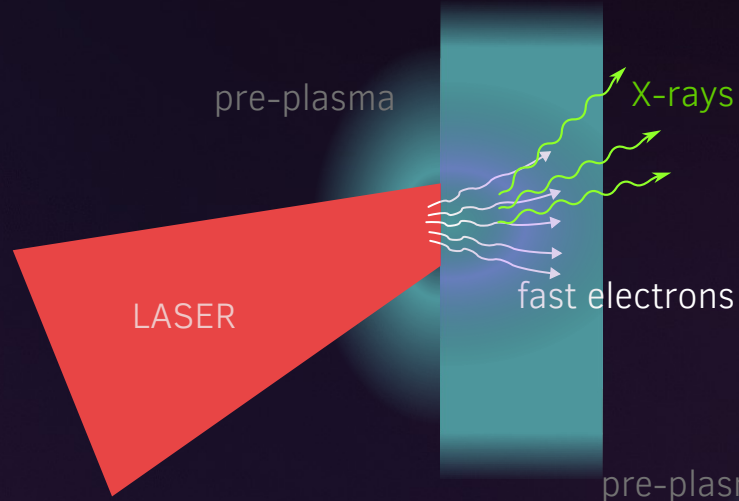
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- **LULI2000:** - 2x nanosecond beams, 1 kJ
- 1 ns (1kJ) + 1 ps (100 J)
→ ion acceleration, atomic physics, laser-plasma interaction, warm-dense matter, planetology, laboratory astrophysics, ...

Three laser facilities at LULI

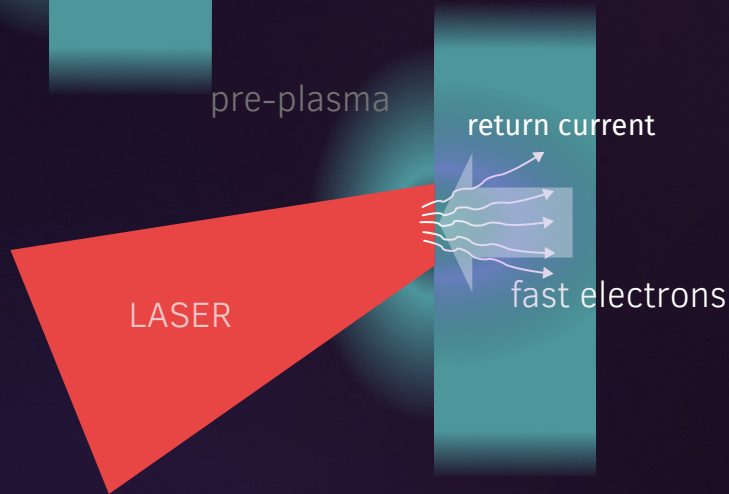


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→ ion acceleration, atomic physics, laser-plasma interaction, warm-dense matter, planetology, laboratory astrophysics, ...
- **HERA:** 2x nanosecond beams, 200 J
→ shock-driven material testing, equations of state, ...

Short-pulse interaction with solid targets

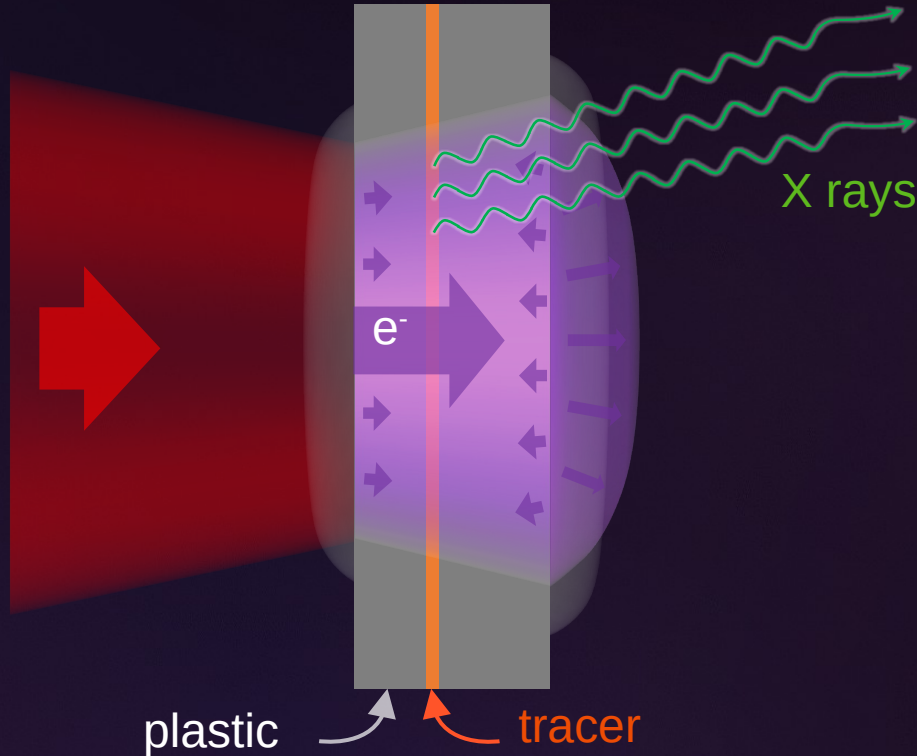


- Relativistic intensity $\sim 10^{18} \text{ W/cm}^2$
 - electrons accelerated $> \text{MeV}$
 - electrons interact with other electrons and ions
 - ionisation, recombination, ...
 - X-ray production → used as backlighter



- Direct heating by electrons
 - Return current by slow electrons
 - indirect heating
 - Other sources of heating?
- temperature up to several keVs
→ exotic atomic physics

Atomic physics using short pulses



- Experiments at LULI2000, Apollon, ...
- Solid targets
- Tracer layer = Al, Ti, Cu, ...
- Temperature up to 2 keV

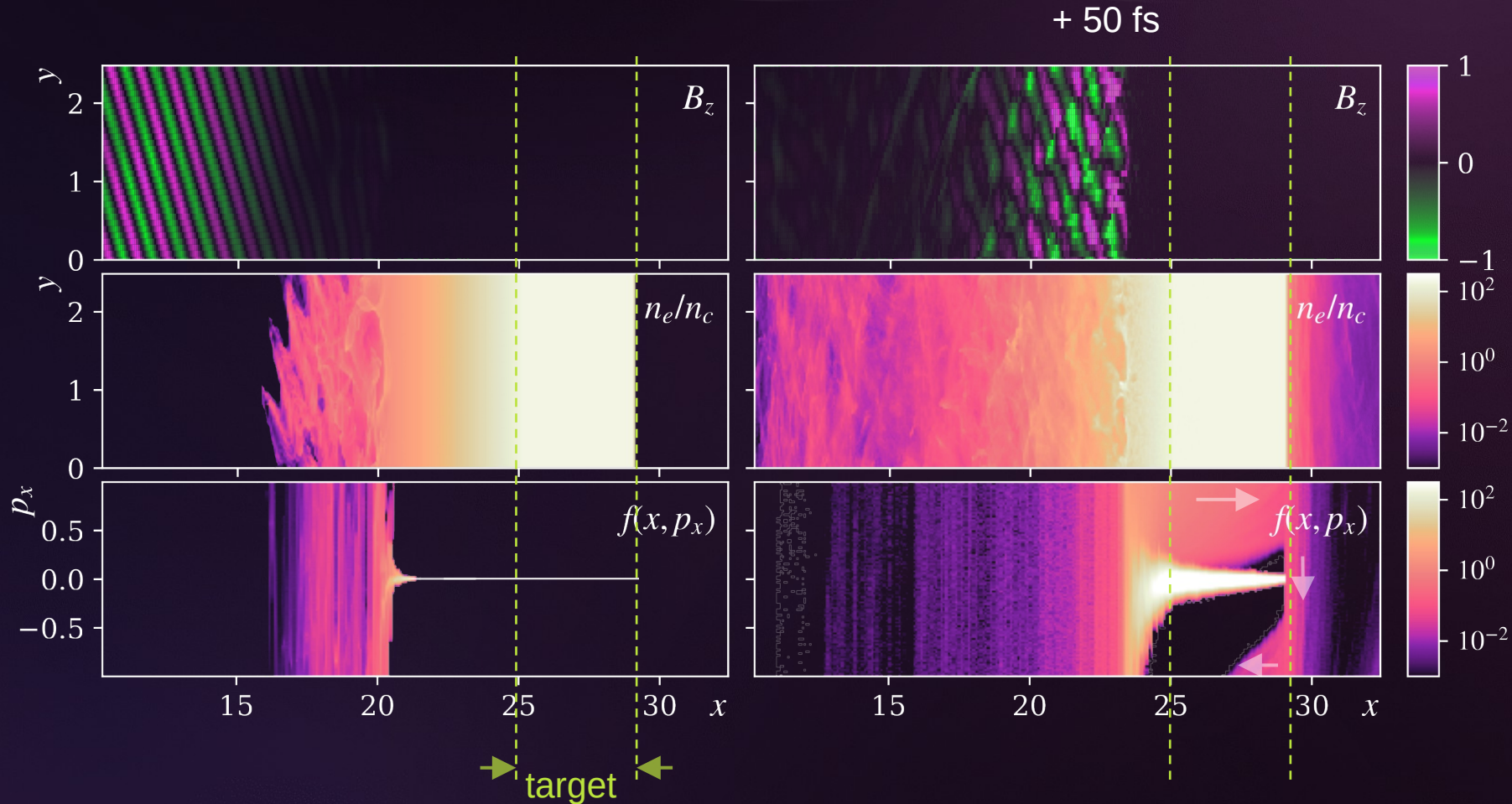
Conditions relevant to fusion plasma

- X-rays contain atomic physics data (electronic transitions)

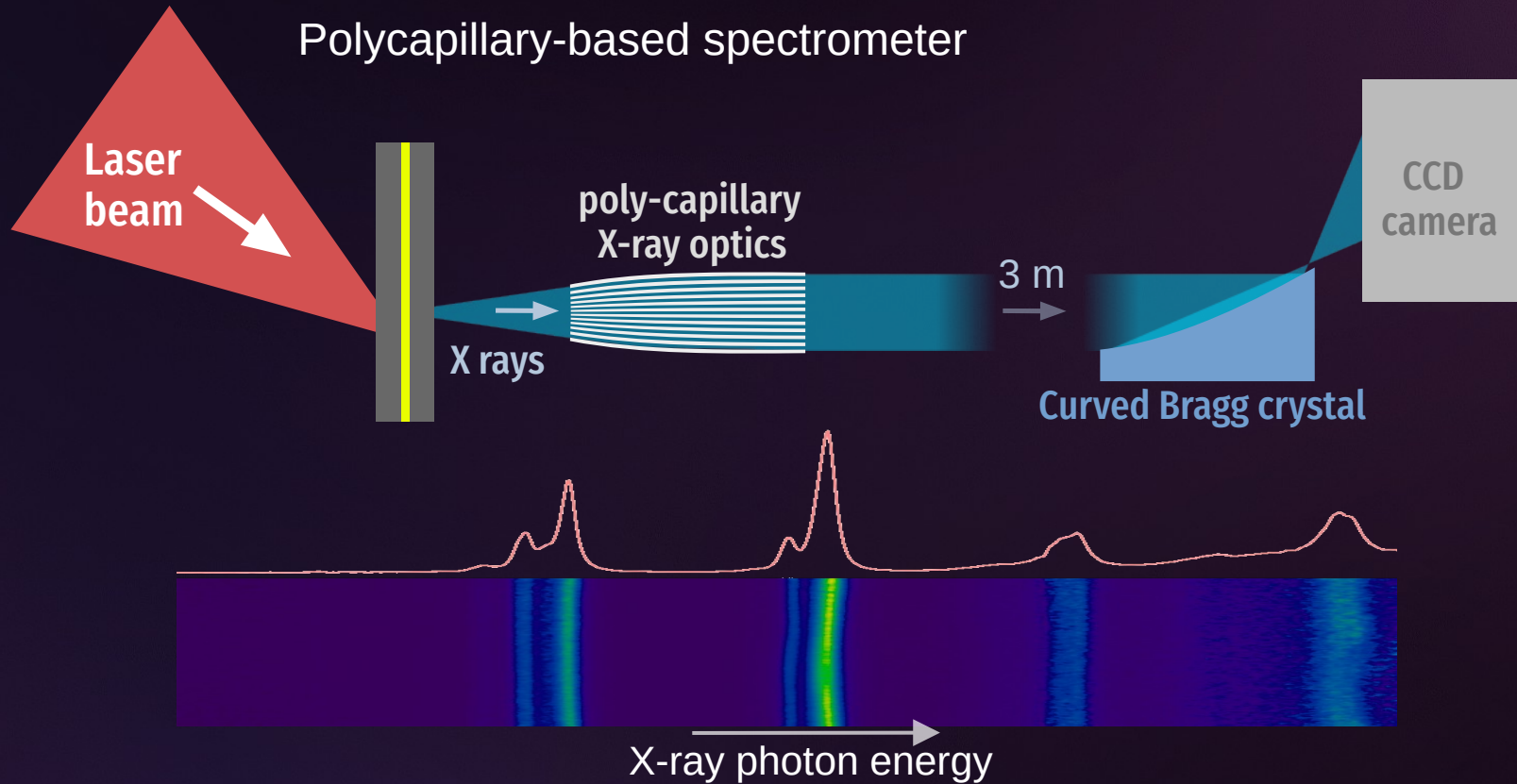
Illustration with PIC simulation



Hanna Lahmar
Frederic Perez

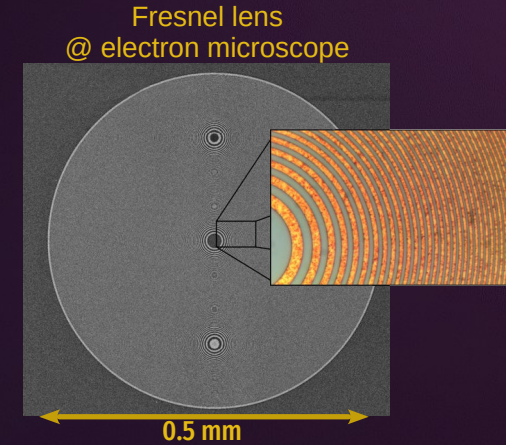
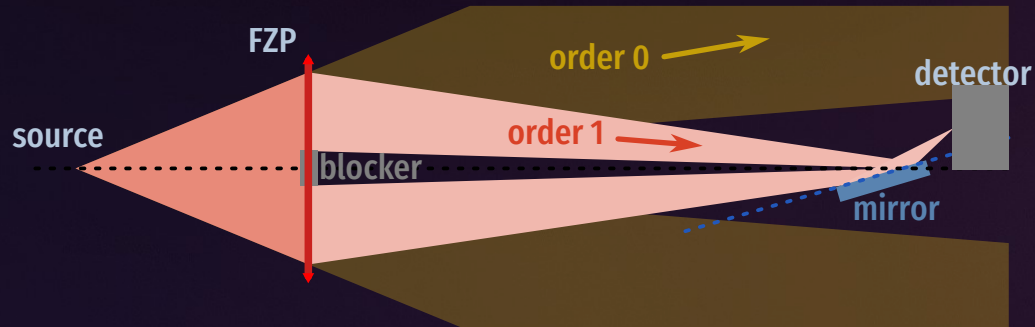


X-ray diagnostics in extreme conditions



X-ray diagnostics in extreme conditions

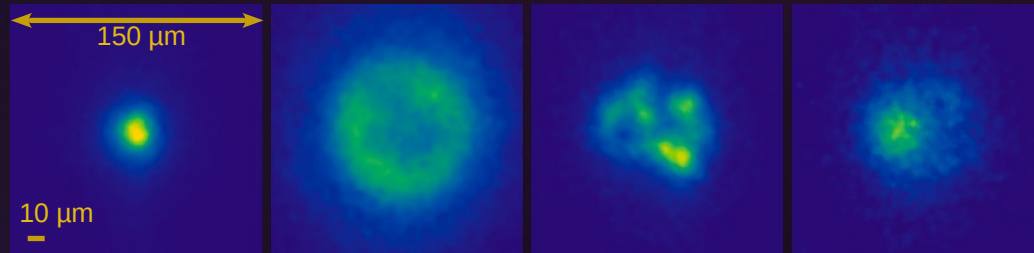
Fresnel-lens X-ray imaging



PhD: Alexandre Do

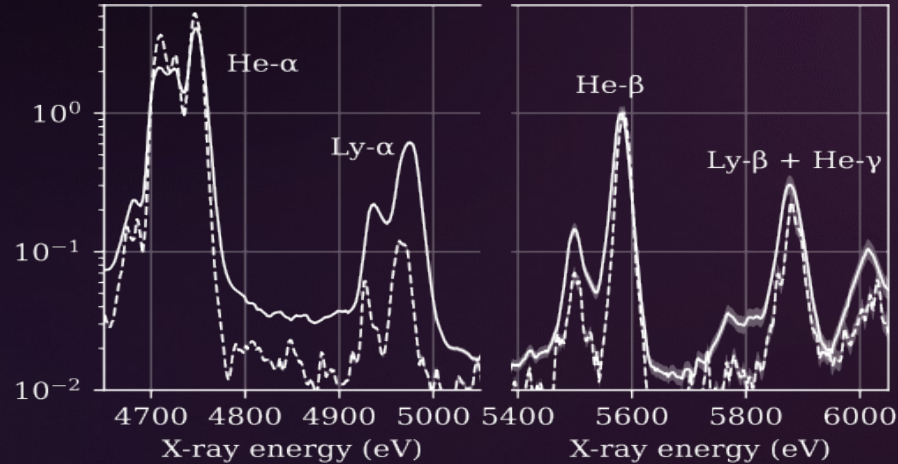
Do et al. RSI **88**, 013701 (2017)

Do et al. RSI **89**, 113702 (2018)

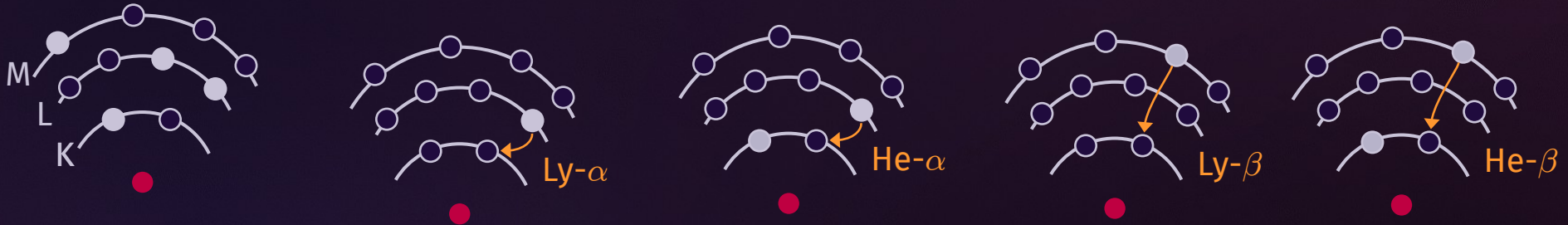


Interpretation of X-ray spectrum

Spectrum from
titanium tracer layer



Atomic configuration

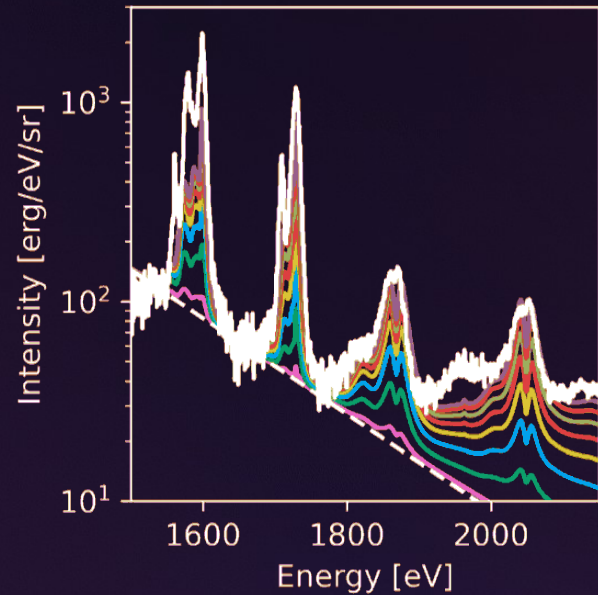


Spectra indicate statistical distribution of states
→ ionisation level, temperature, density, ...

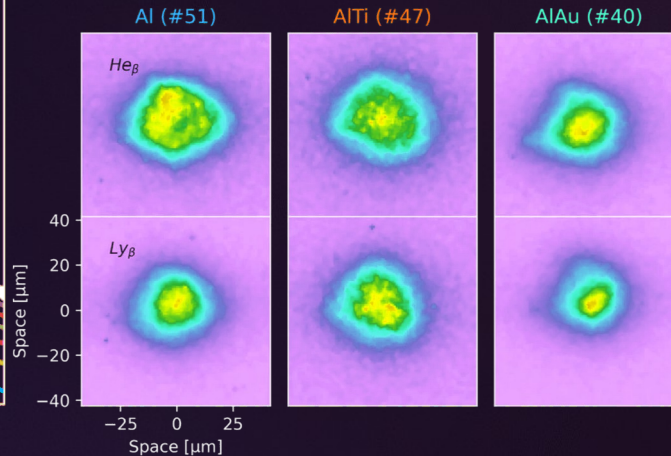
Experiment on mixtures to investigate high-Z

Tracer made of **Al** or **Al+Ti** or **Al+Au**
Compared to hydro+rad+atomic simulations

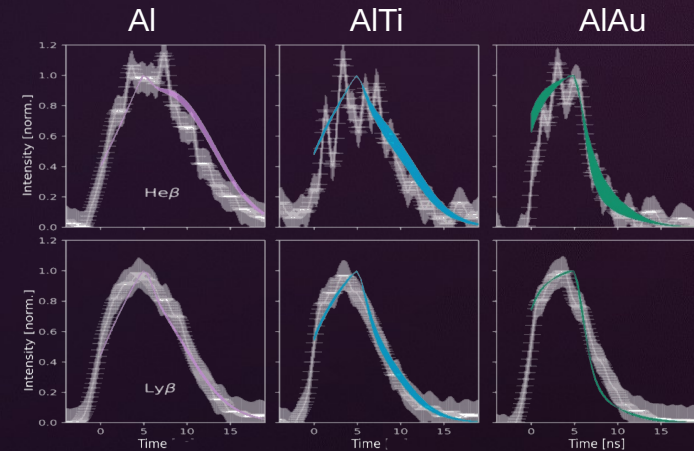
Spectral



Spatial



Time-resolved



Lecherbourg et al.
PoP 32, 092706 (2025)

radiative cooling matching simulation results

New experiments on absorption spectroscopy

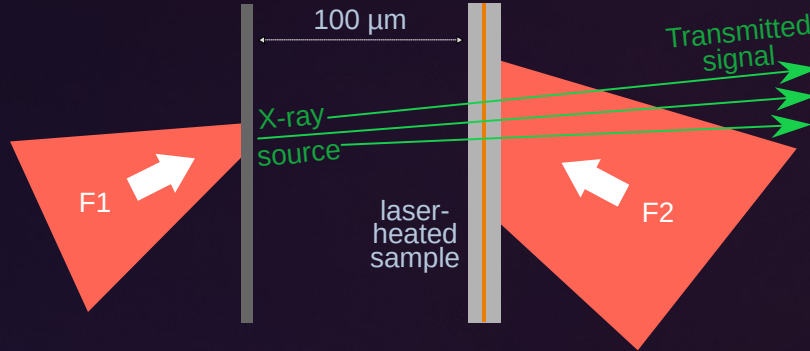


Benjamin Guery
Frederic Perez
Patrick Audebert
Sophie Baton

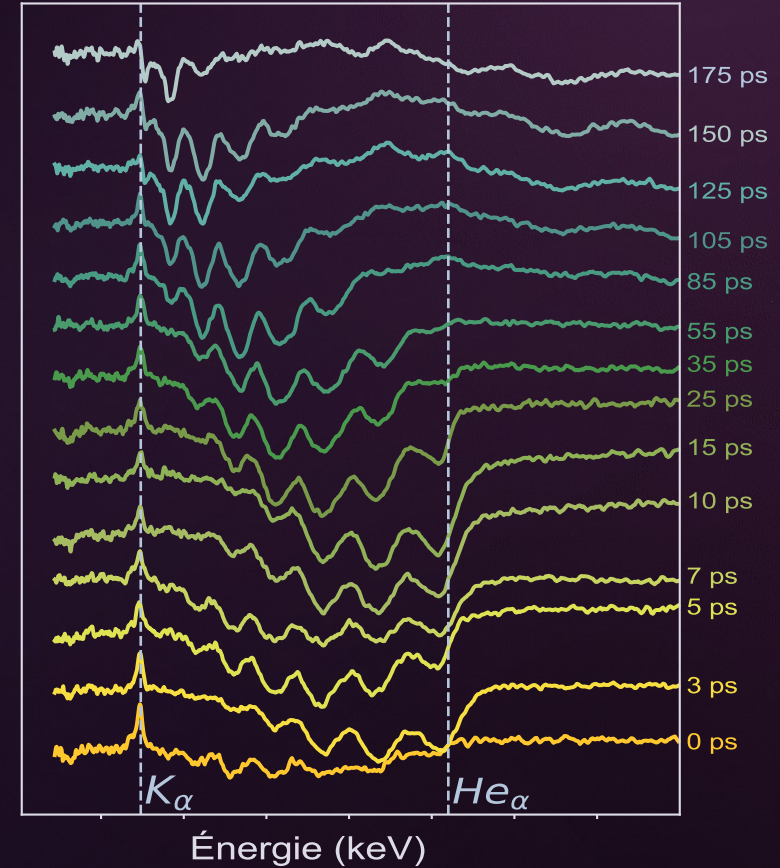


LIRA

- Heating + probing by 2 different lasers
- Al included in target



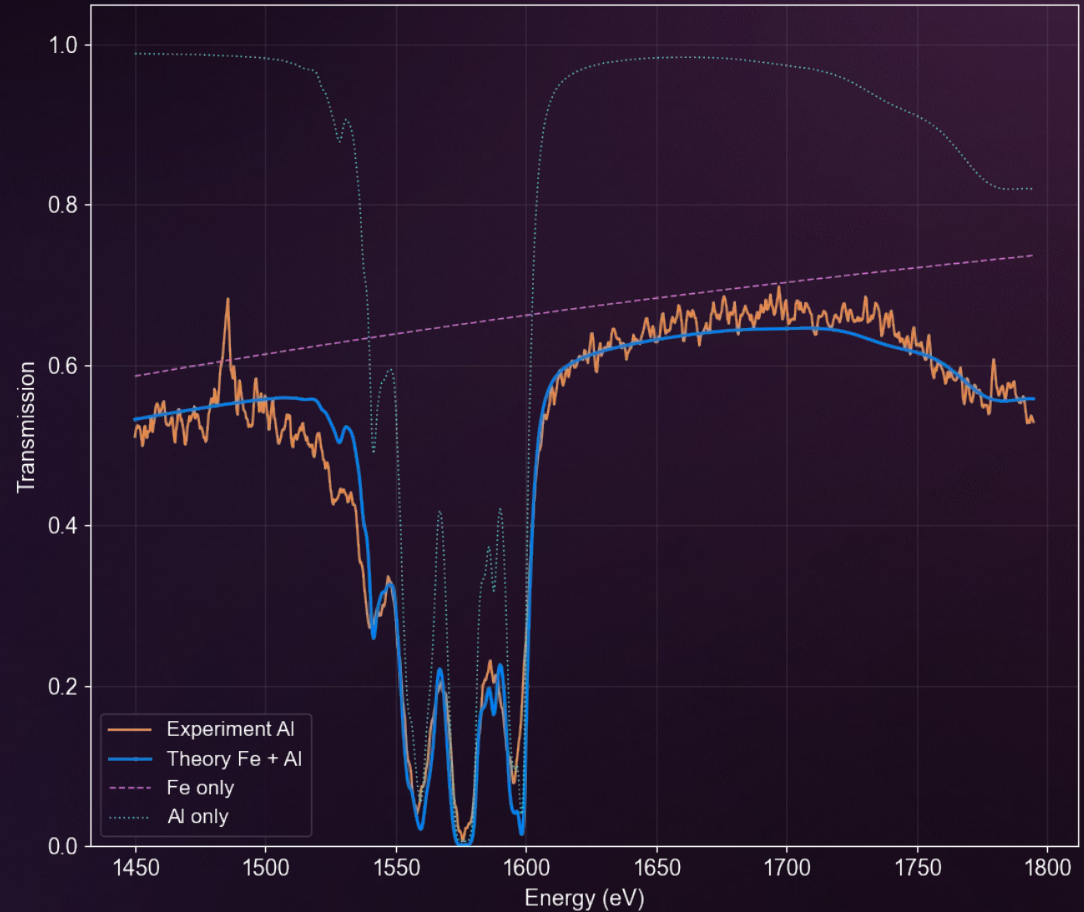
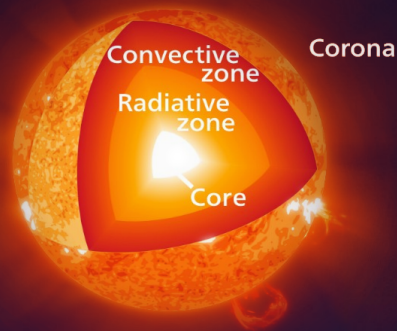
- Excellent results on Al absorption
- Temperature evolution as plasma expands



Precise agreement with atomic simulations

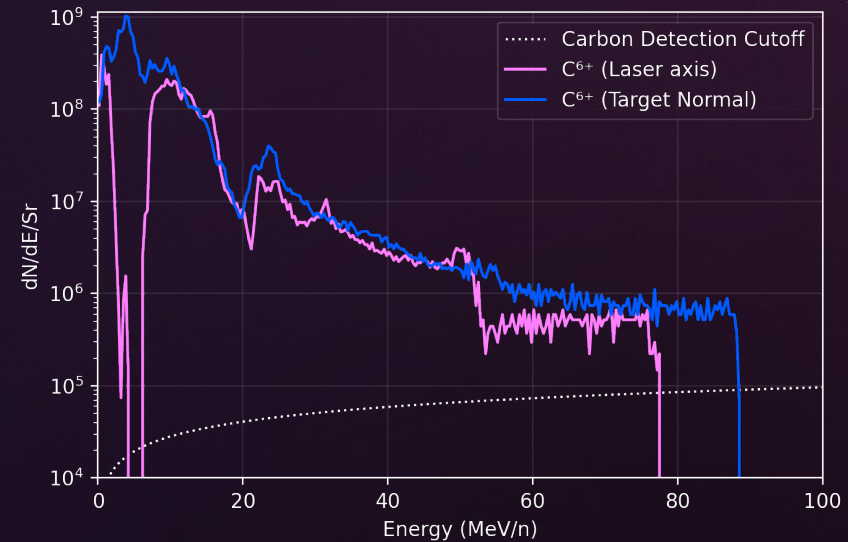
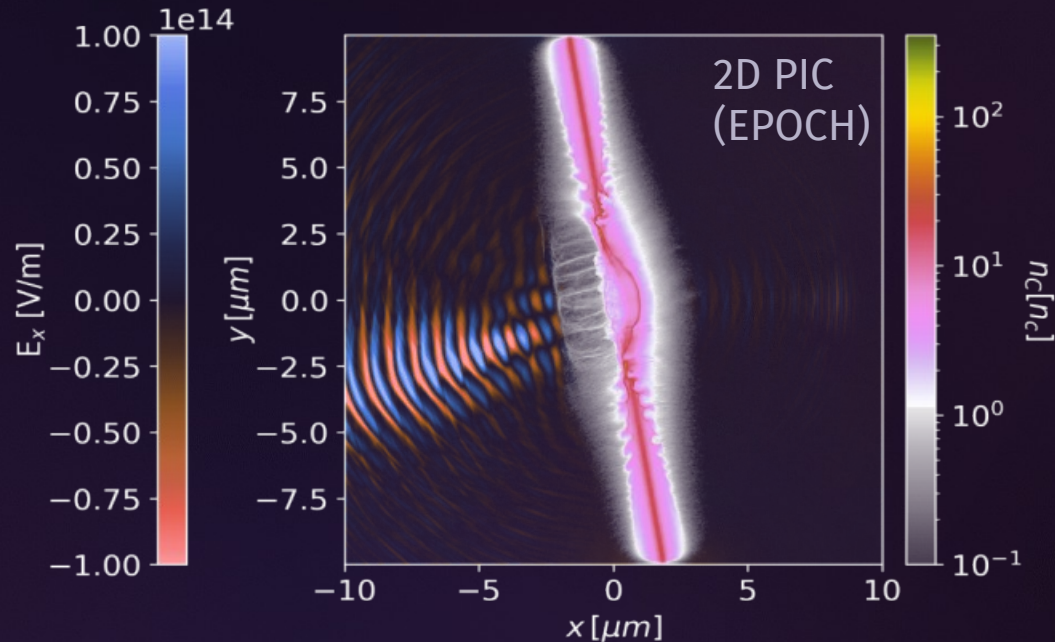
- First absorption spectroscopy with high-intensity laser
- ~ first absorption spectroscopy @ solid density + 250 eV
- Uniform in space and time

→ Next: apply to the opacity of Fe in the Sun's interior

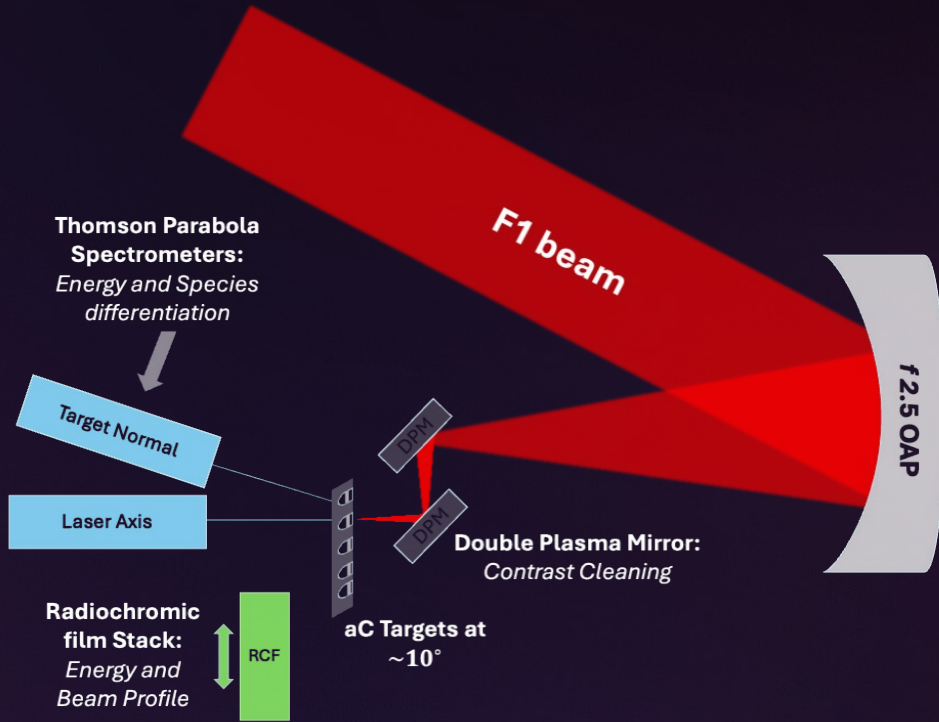


Ion acceleration with ultra-thin foils

Radiation pressure acceleration (RPA)
Best with circular polarization
~ few 100 nm foils

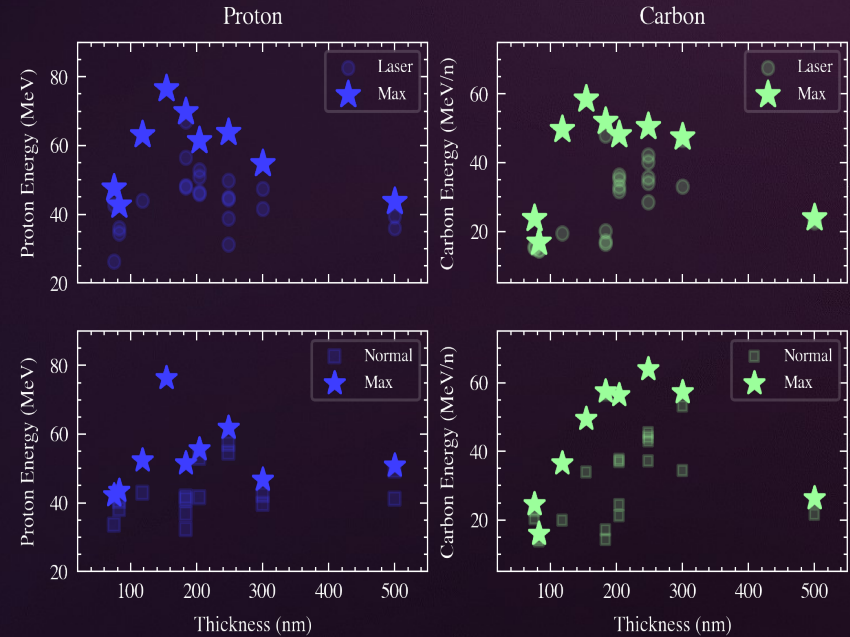


Apollon campaign in 2025



Along
laser
axis

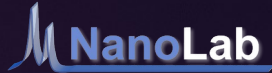
Along
target
normal



Gamma-photon generation in foam



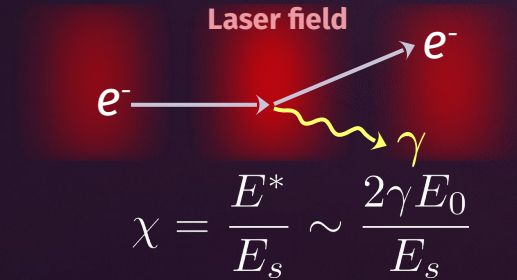
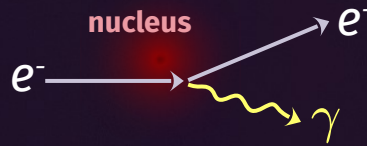
Marta Galbiati
Livia Lancia
Lorenzo Romagnani
Jean-Raphaël Marquès
Soig Turban
Maria Vagianni
Mickael Grech
Caterina Riconda
Arseny Mironov
Julie Cardon



- Get efficient gamma sources
- Explore strong-field QED
- Apollon $\sim 10^{22}$ W/cm²

Two dominant processes

- Non-linear inverse Compton scattering
- Bremsstrahlung



$$\chi = \frac{E^*}{E_s} \sim \frac{2\gamma E_0}{E_s}$$

→ enhance Compton vs. Bremsstrahlung?

Interaction with foam → self-focusing, direct acceleration

Smilei)

Time= 95 fs

Time= 180 fs

3D PIC simulation

laser Intensity = 8.65×10^{20} W/cm²

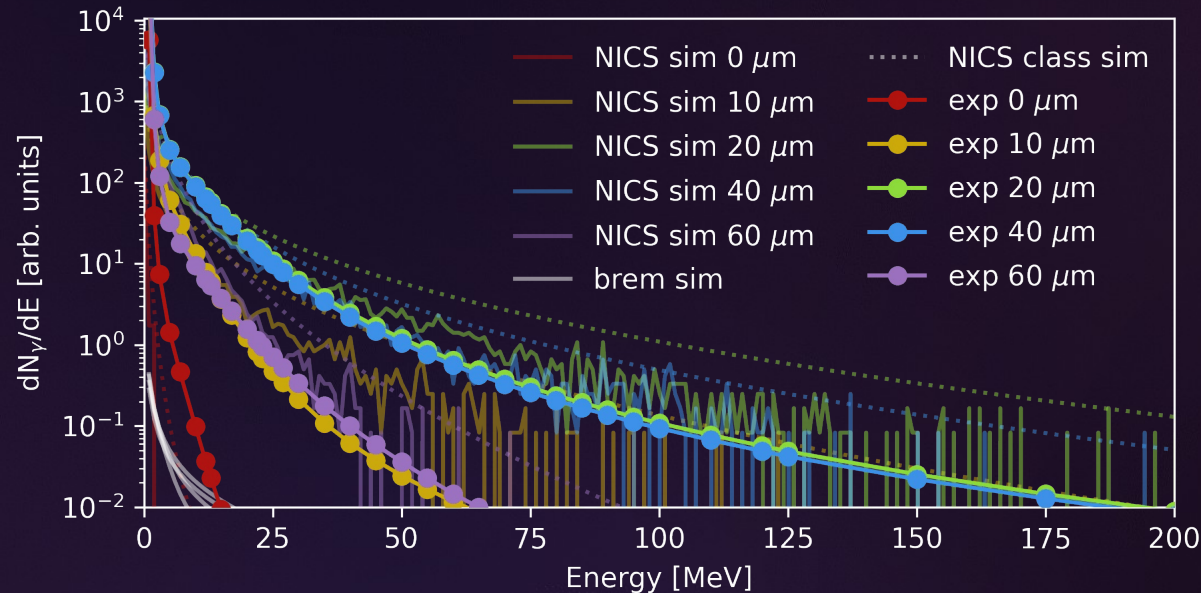
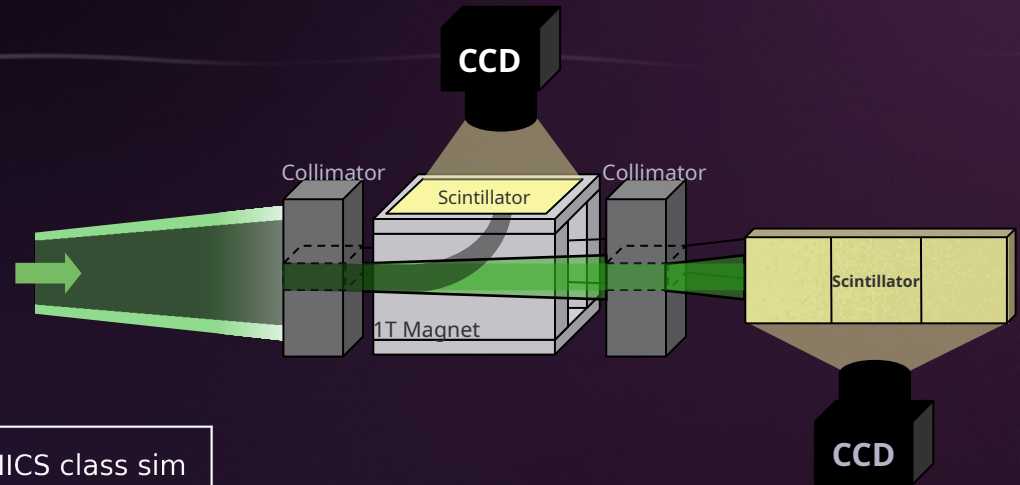
$a_0 = 20$ waist = 3 μ m FWHM = 25 fs

carbon foam density $\sim 1 n_c$

5

Measured gamma spectrum

- New electron + gamma spectrometer



- Spectra vary by foam thickness
- Trend matches self-focusing effect
- Corresponds to $\chi \sim 0.3$

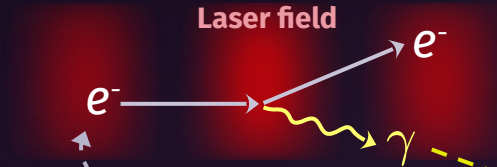
At higher intensities ... electromagnetic showers?



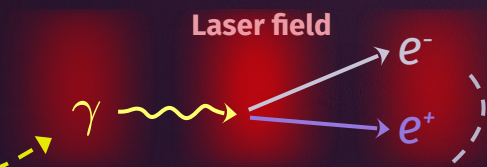
Mattys Pouyez
Samuel Hoyos-Aristizabal
Giuseppe Nicotera
Anthony Mercuri-Baron
Anna Grassi
Caterina Riconda



Inverse Compton



Breit-Wheeler



- Theory group works on EM showers in strong-field QED
- Applications:
 - electron-positron pair plasma found in astro scenarios
 - Testing strong-field QED
- Challenge: pair plasma in the laboratory

Theory compared to Monte-Carlo simulations

Successive
generation of
particles

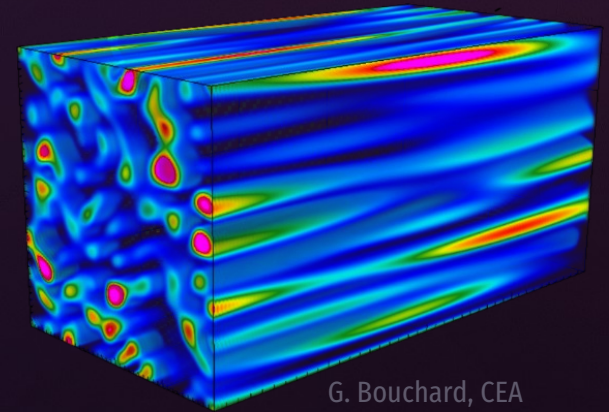
→ matches
analytical solution
for electron-laser
collision

Achievable
experimentally?



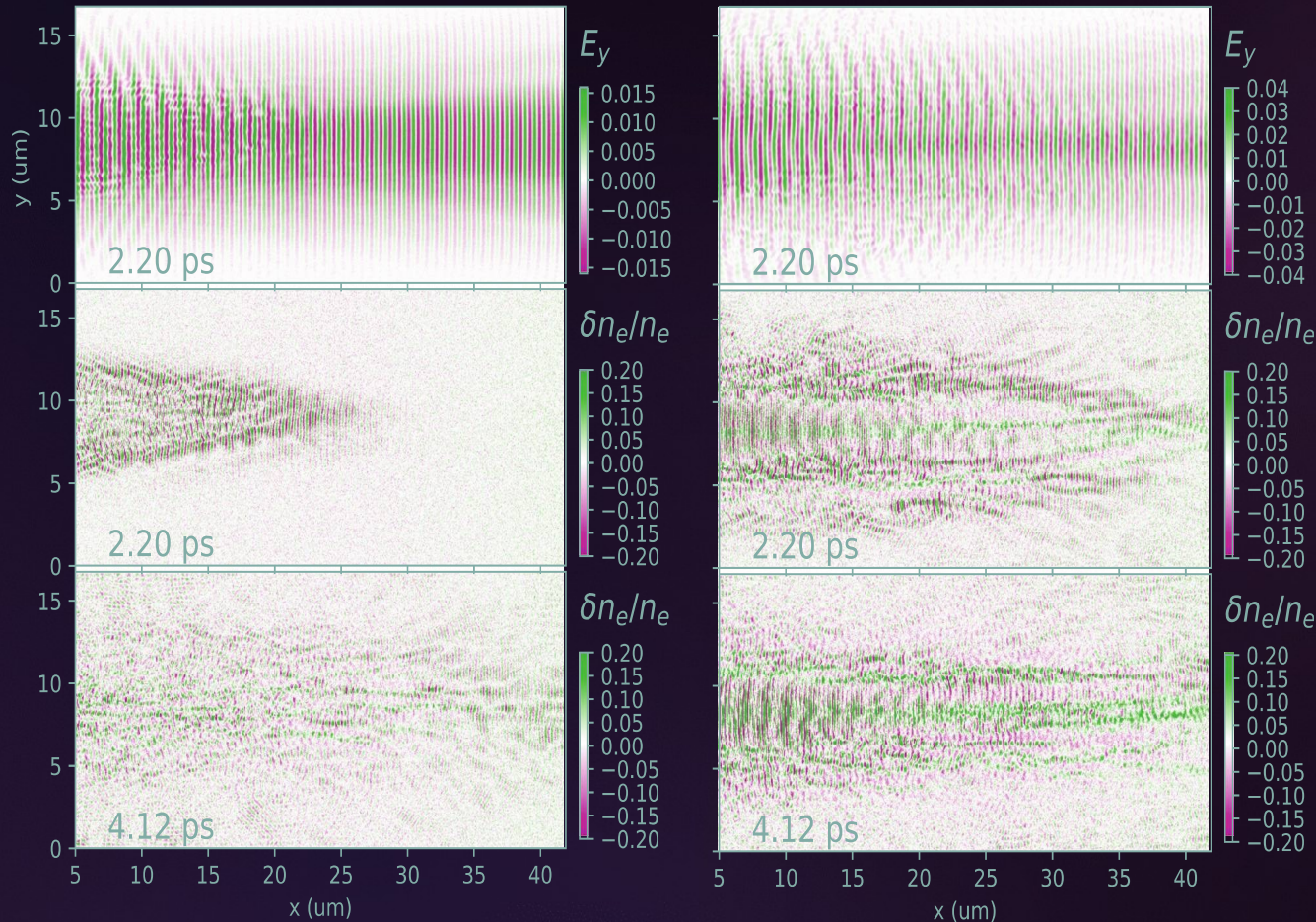
Long-pulse interaction (ns) can show short-scale physics!

- Nanosecond $\gg$ collision time scale
→ equilibrium? No kinetic effects?
 - **Short time scales exist:**
Laser oscillation
Plasma waves
(Local gradients) / (speed of sound)
- kinetic effects! → PIC simulations!



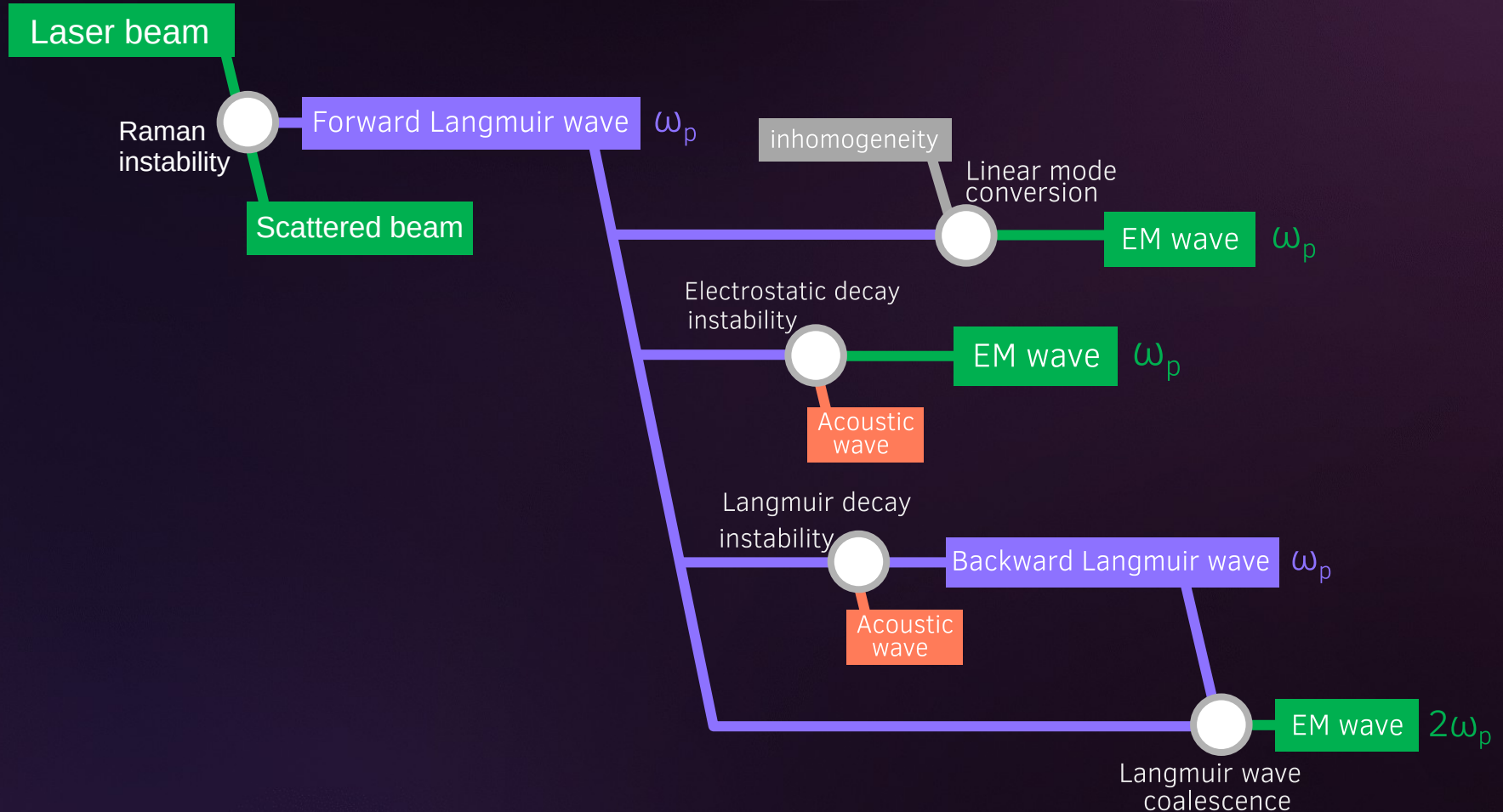
G. Bouchard, CEA

PIC simulations @ several picoseconds

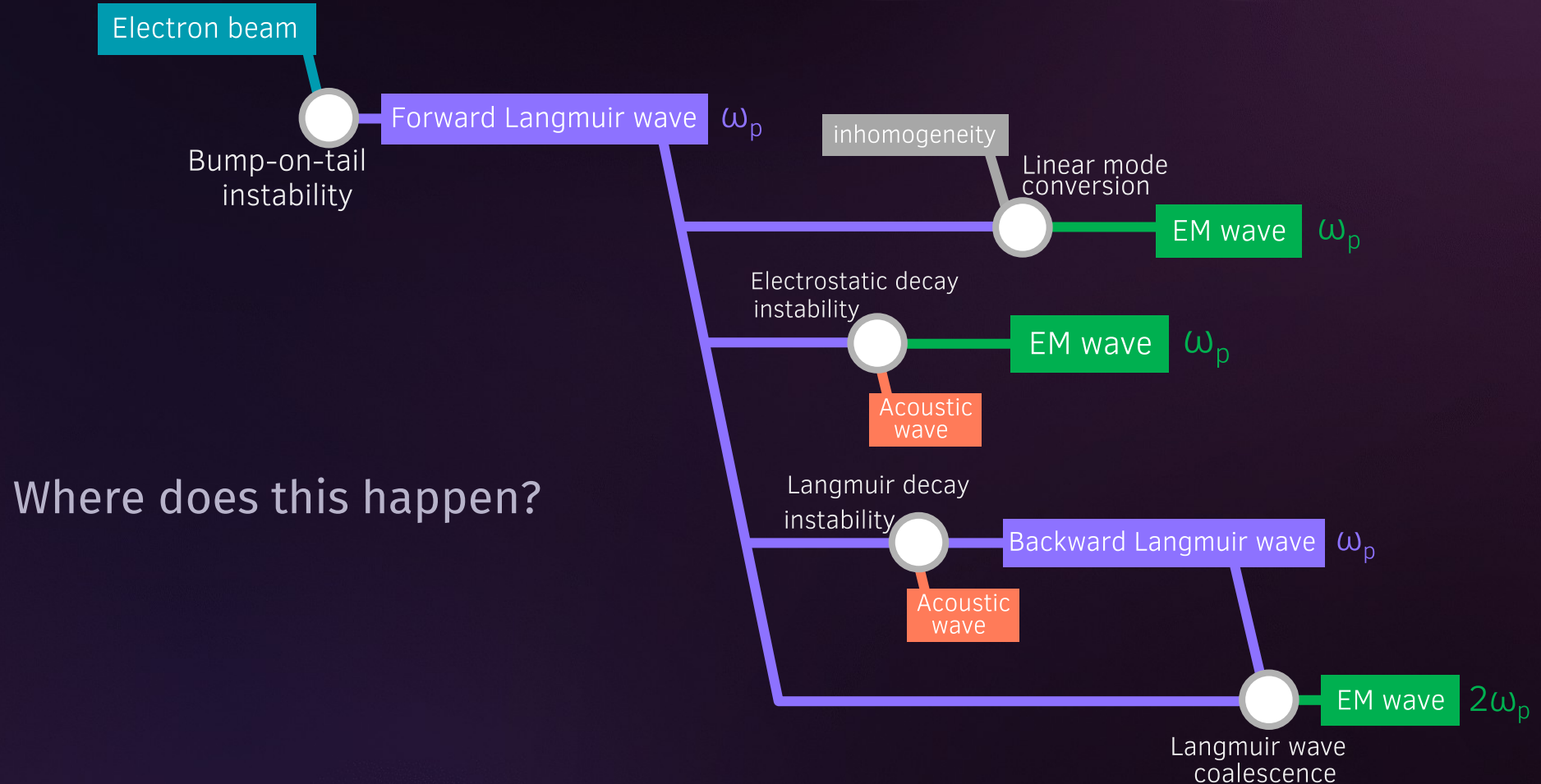


- Laser through plasma
- Instabilities generate plasma waves + EM waves
- Turbulence?
- Importance of laser-plasma interaction for fusion

Laser-plasma interaction cause many couplings

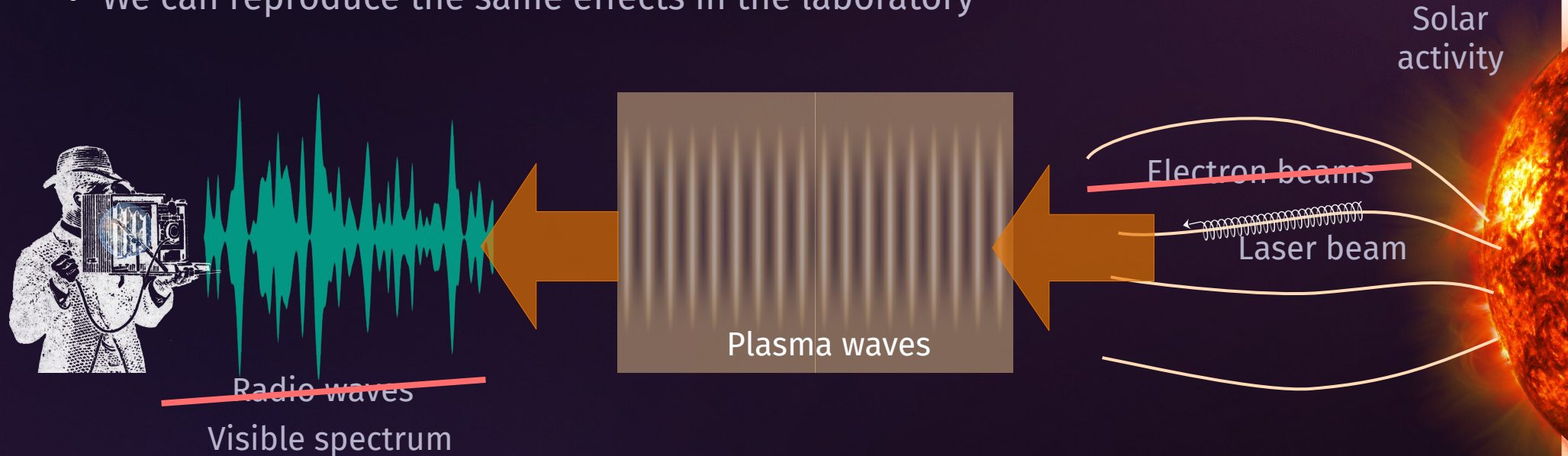


The same couplings exist in space physics!



Solar bursts!

- Solar bursts are radio-wave emissions associated to Solar activity
- We can reproduce the same effects in the laboratory



Experiments on solar radio bursts at LULI

- Experiments started in 2018
- ~ 1 kJ on solid or gas targets
- Recently added magnetic field ~ solar conditions



Louise Cornet
Jean-Raphaël Marquès
Frederic Perez
Livia Lancia
Bruno Albertazzi



Sylvie Depierreux
Pascal Loiseau



Carine Briand

Summary of a few applications of kinetic plasma @ LULI

- Heating with short pulse → atomic physics
- Ion acceleration
- QED (gamma generation)
- Parametric instabilities → application to solar bursts
-

Thank you for your attention!