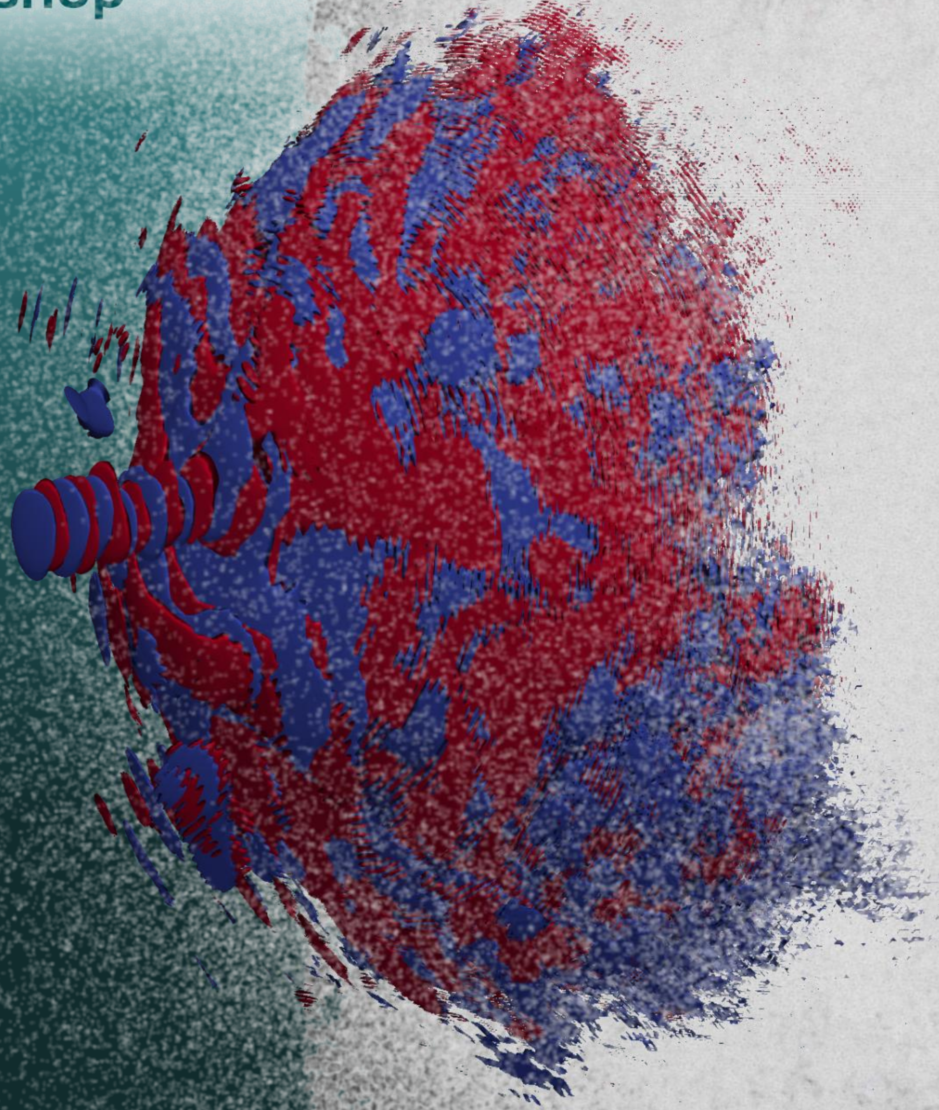
21st Direct Drive and Fast Ignition Workshop
8-11 June - Frascati, Italy

Francesco Mirani

Numerical and experimental activities on nanostructured carbon foams for Inertial Confinement Fusion at Politecnico di Milano

8th June 2026



POLITECNICO
MILANO 1863

NanoLab
DIPARTIMENTO DI ENERGIA

- **Our group** from POLITECNICO MILANO 1863 :


M. Passoni
Principal Investigator


A. Maffini


F. Mirani


K. Ambrogioni


S. De Magistris


M. Iaccarino


D. Orecchia


D. Dellasega


V. Russo


M. Andreoni


F. Piziali


L. Filippi

- **Collaborations:** ENEA RSE Ricerca Sistema Energetico eli

- **Projects:** MUR PRIN 2022 Ministero dell'Università e della Ricerca Nanomaterials for Fusion HiPER+ EUROPEAN LASER FUSION ENERGY EUROfusion

- **Content** of the presentation:

Why are we interested in nanofoams for laser-matter interaction and inertial Direct-drive ICF?

How do we produce the nanofoams, and what characteristics do they have?

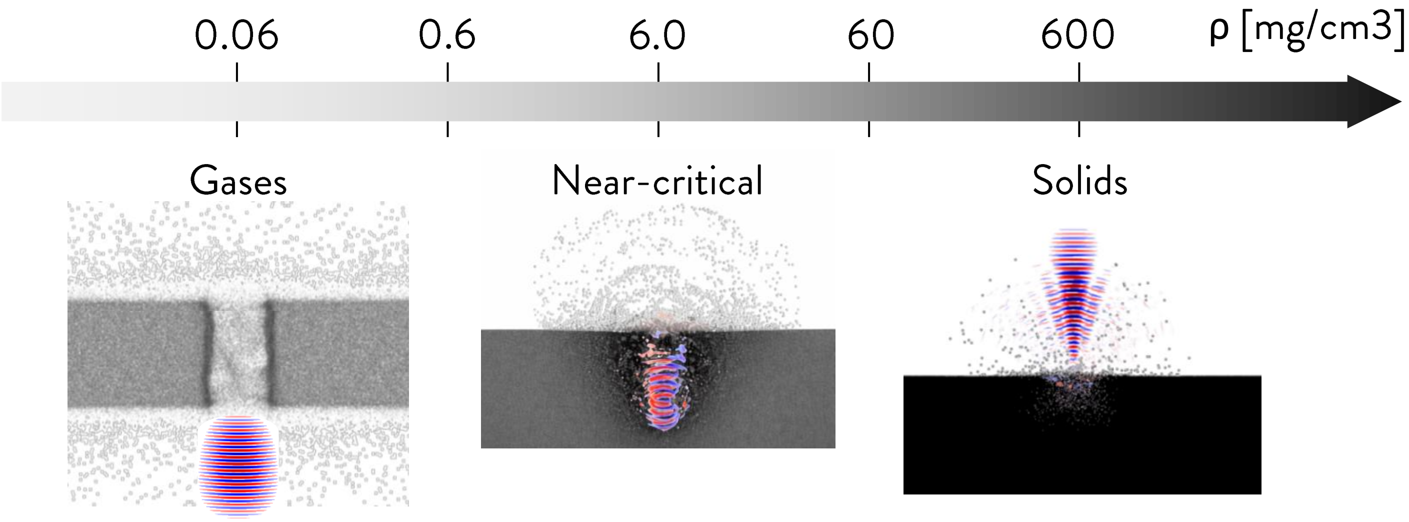
What computational approach are we adopting?

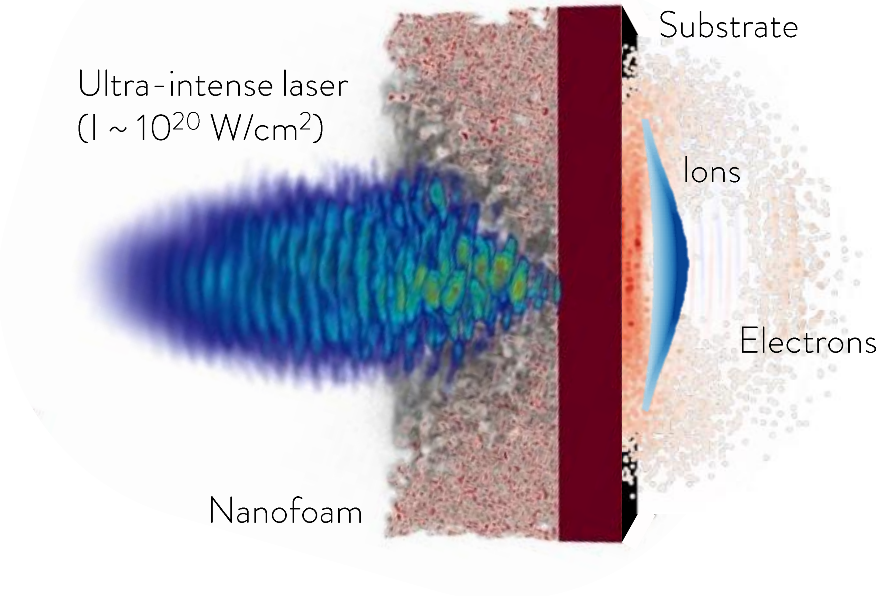
Presentation of some experimental results with the ABC laser.

https://www.laserfusion.eu/category/hiper-plus/

https://www.ensure.polimi.it/journal-papers/

Why are we interested in nanofoams for laser-matter interaction?





High-intensity laser energy interaction with **low-density near-critical materials** allows to:

- Increased **laser conversion into** secondary radiation (**electrons, ions, neutrons, photons**, …) ⬅
- Investigate **warm dense matter** (EOS, astrophysics,…)
- Generate **bright x-ray sources** (e.g. in hohlraum internal walls)

Many years of activities in this framework by our group…

- **Smooth** laser **non-homogeneity** in ICF
- Increase laser conversion into mechanical energy (**shock waves**)

A. Macchi, et al. *Rev. Mod. Phys.* 85.2 (2013): 751-793.

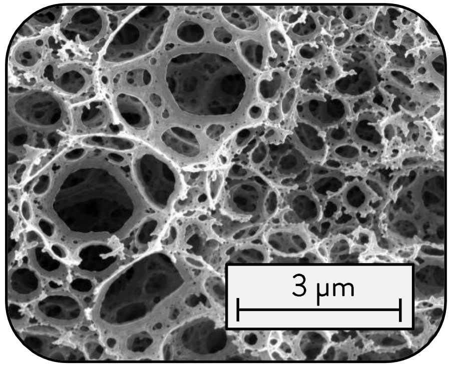
M. Passoni, et al. *PPCF* 62.1 (2020): 014022.

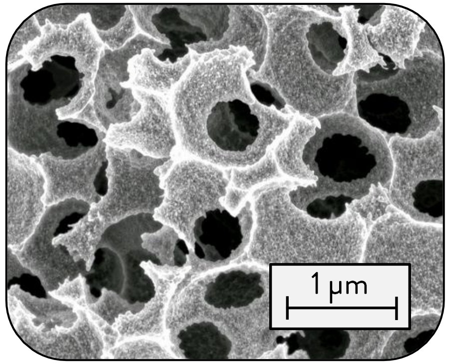
R. S. Craxton, et al. *Phys. Plasmas* 22.11 (2015).

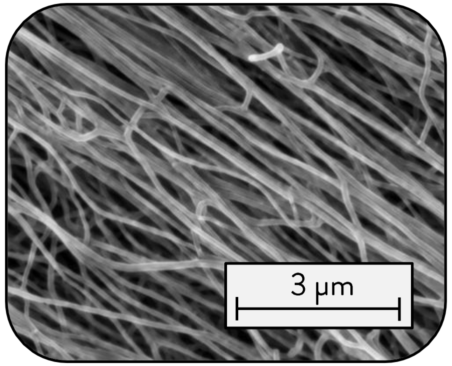
S. X. Hu, et al. *Phys. Plasmas* 25.8 (2018).

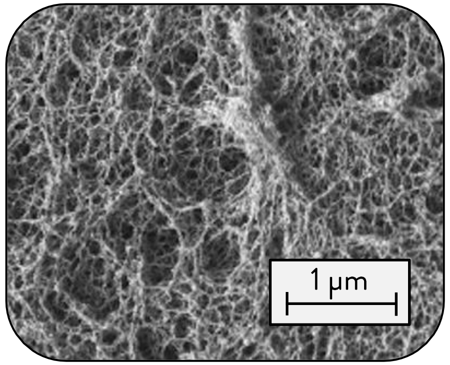
Why are we interested in nanofoams for laser-matter interaction?

- Different kind of “**conventional**” **foams** have been considered **for laser-plasma** experiments including **ICF**


Doped Polymers


Polystyrene


SnO_2 mats


Resorcinol aerogel

- ○ Quasi-periodic networks
- ○ Characterized by “pore size”

K. Nagai, et al. *Phys. Plasmas* 25, 030501 (2018)

C. Yang et al. *Appl. Phys. Lett.* 115, 111901 (2019)

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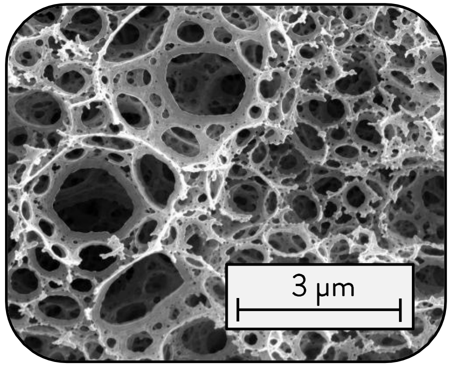
Doped Polymers



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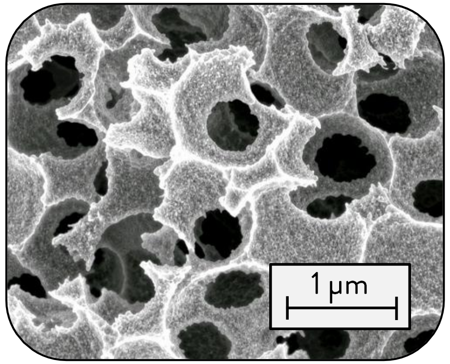

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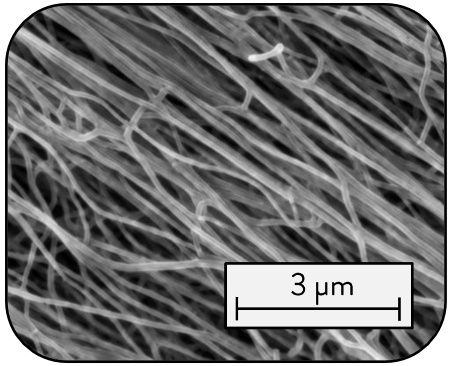

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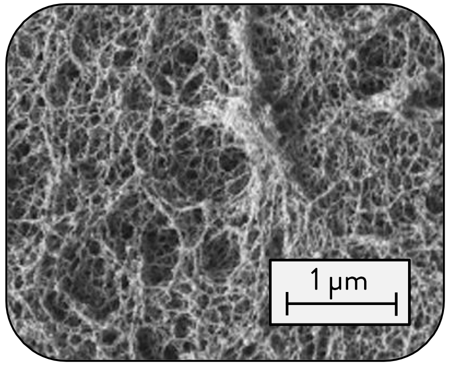
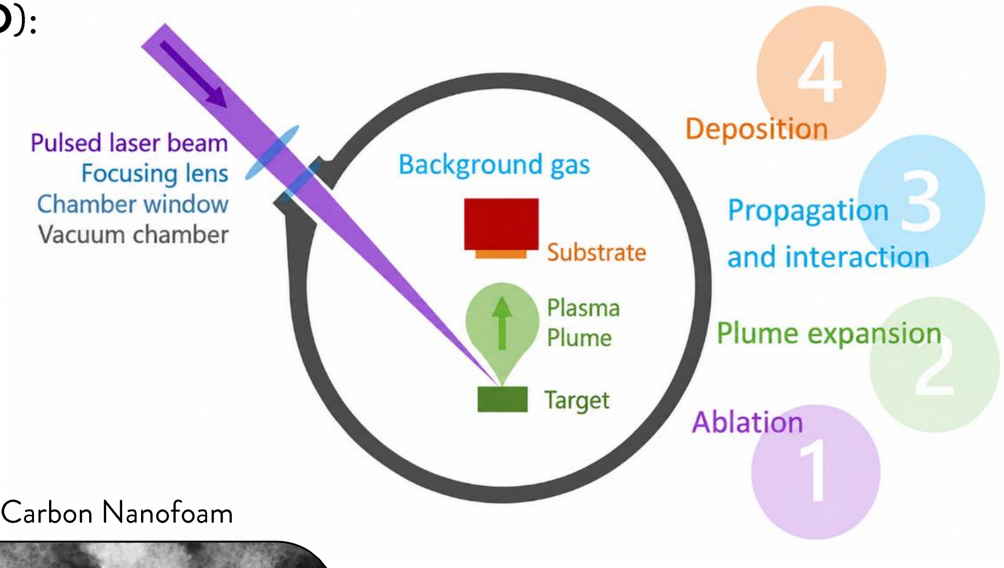
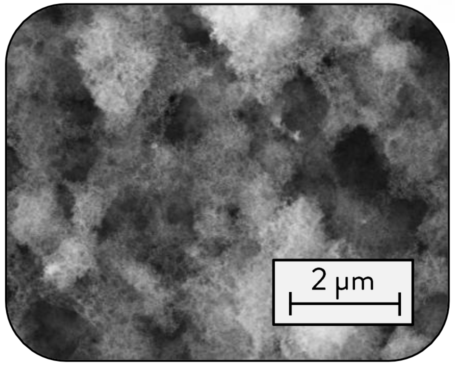


- ○ Quasi-periodic networks
- ○ Characterized by “pore size”

- **Nanofoams produced** via Pulsed-Laser Deposition (**PLD**):



Carbon Nanofoam



PLD process parameters

Control over:

- ○ **Composition**
- ○ **Nanostructure**
- ○ Average **density** and **thickness**
- ○ Any kind of substrate

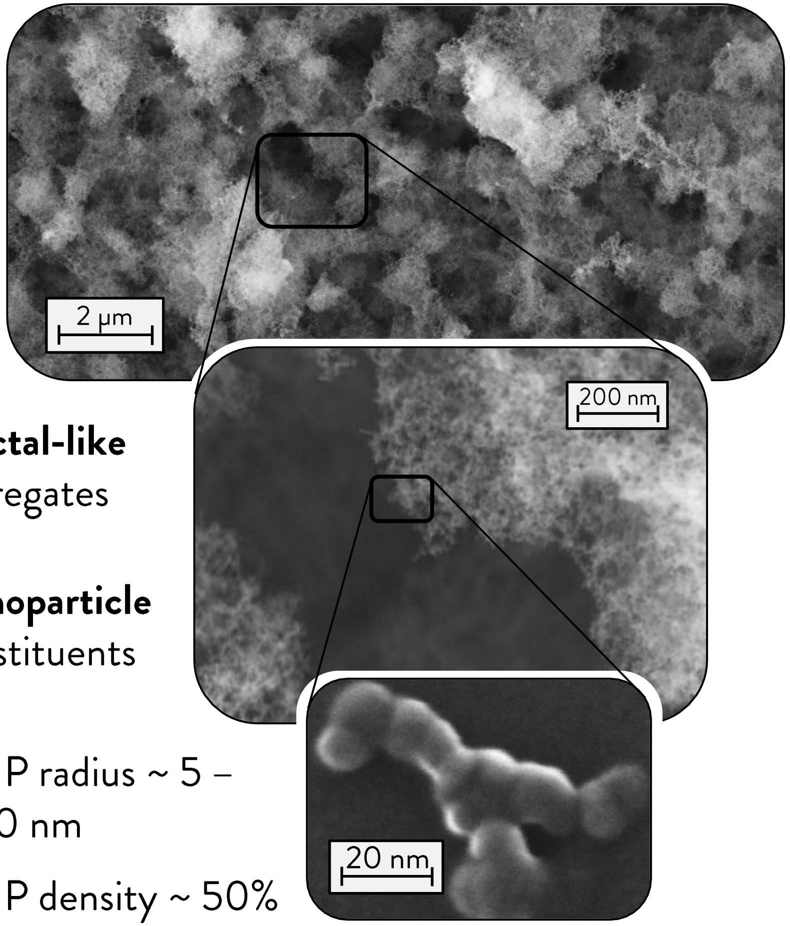
K. Nagai, et al. *Phys. Plasmas* 25, 030501 (2018)

C. Yang et al. *Appl. Phys. Lett.* 115, 111901 (2019)

A. Maffini, et al. *PPCF* 68.3 (2026): 035007.

How PLD nanofoams look like

- **Multi-scale** structure



- **Fractal-like** aggregates
- **Nanoparticle** constituents
    - NP radius ~ 5 – 20 nm
    - NP density ~ 50% – 100% of bulk

D. Orecchia, et al. *Small Struct.* 5.6 (2024): 2300560.

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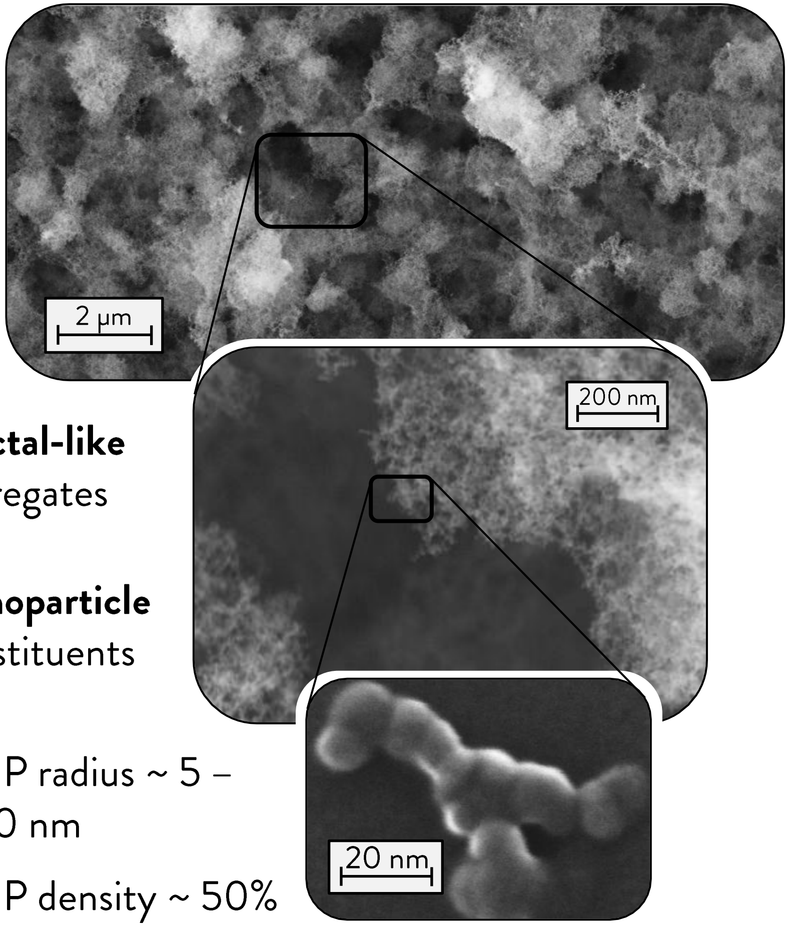

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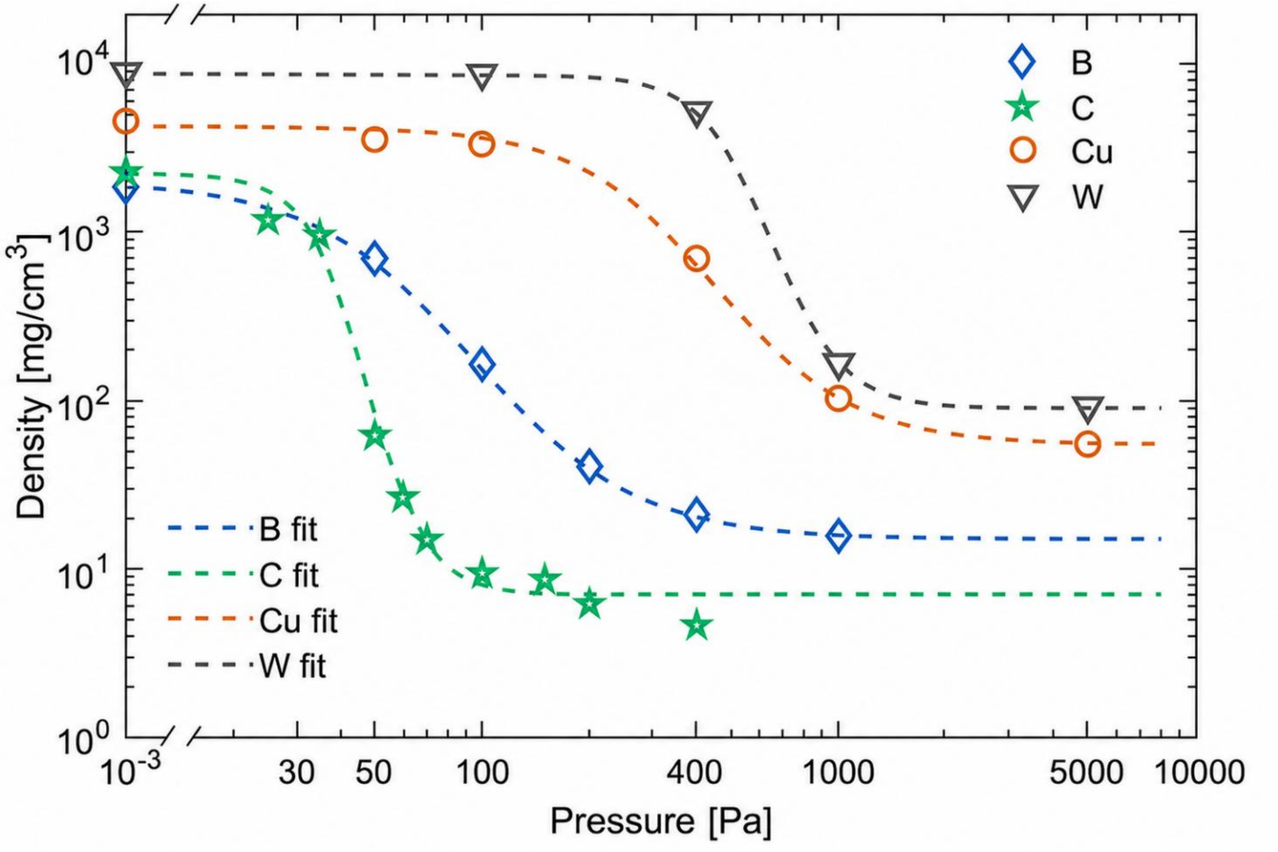
D. Orecchia, et al. *Small Struct.* 5.6 (2024): 2300560.

- **Tune average density** from the bulk to the near-critical value

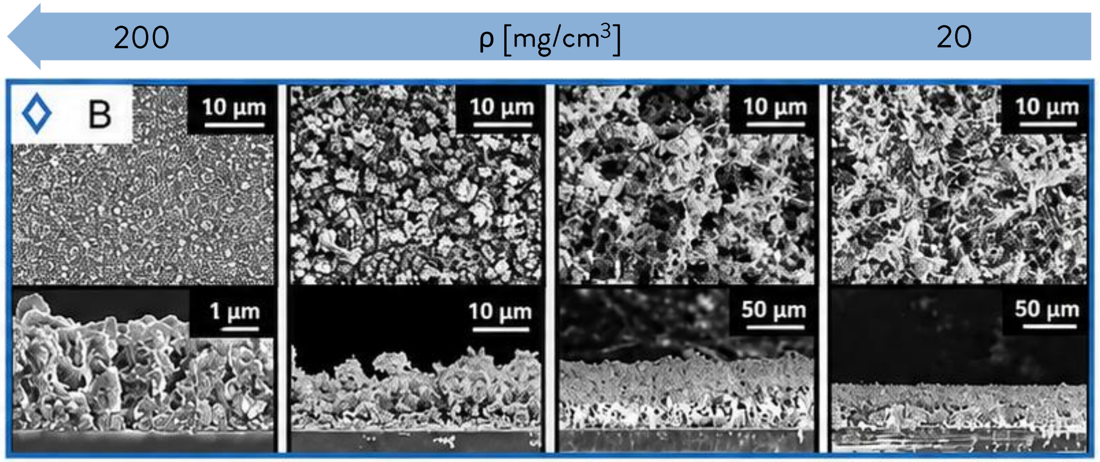


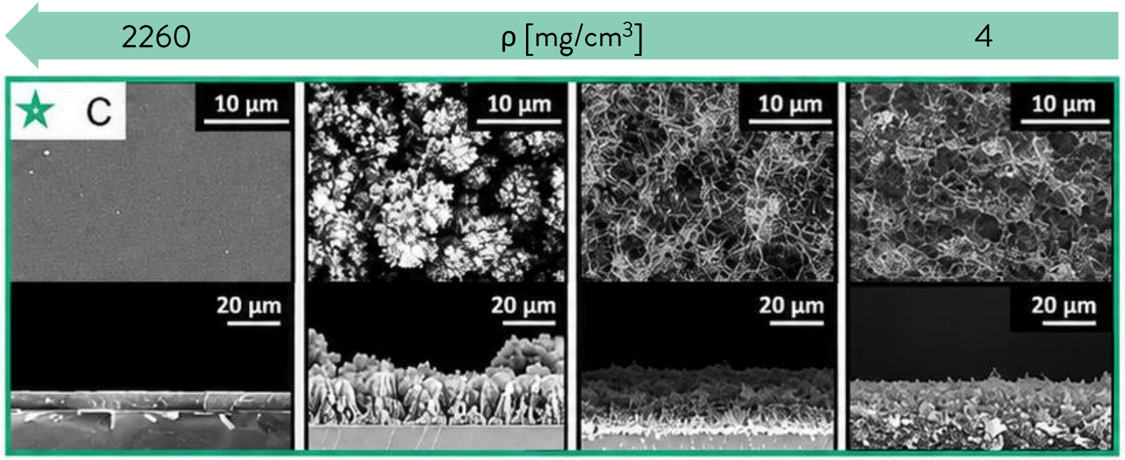
☆ fs-PLD (~ 100 fs, ~ 5 mJ) ◇ ○ ▽ ns-PLD (~ 5 ns, ~ 1 J)

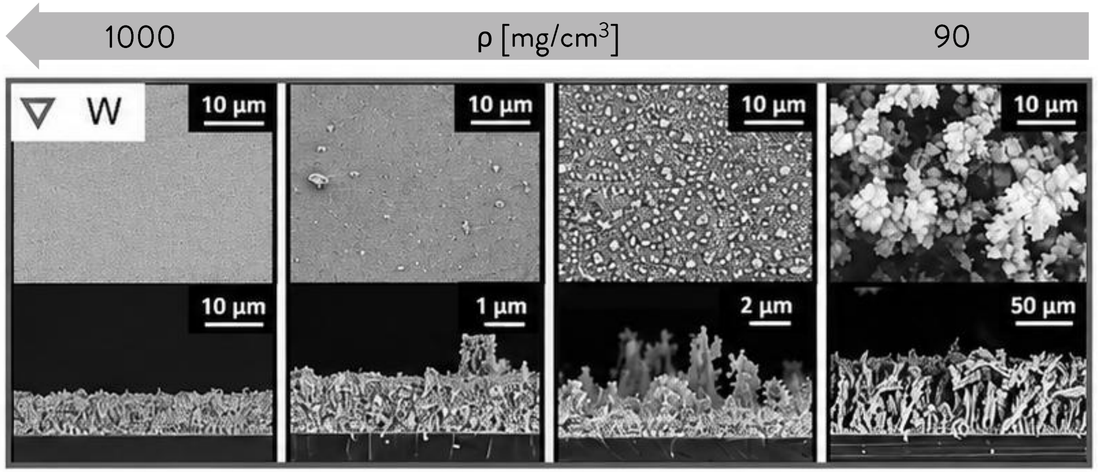
A. Maffini, et al. *PPCF* 68.3 (2026): 035007.

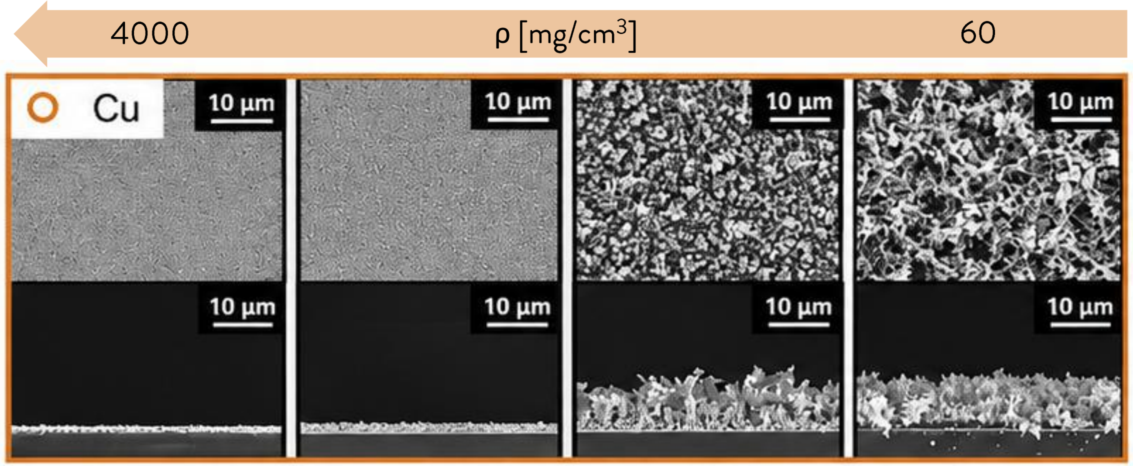
How PLD nanofoams look like

- Different **morphologies according** with **materials** and **densities**
  - Area: from 1 mm^2 to **10 cm^2**
  - Thickness: **1 to 100s μm**









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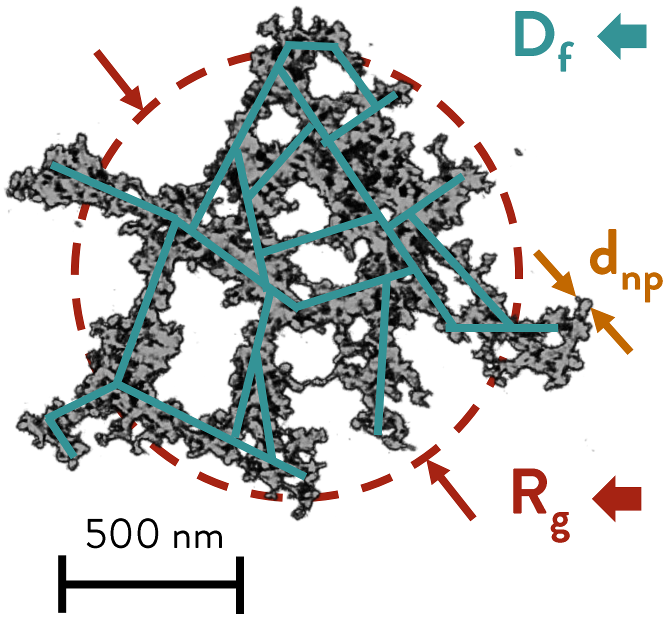
How to model the nanofoam aggregation

Fractal scaling for the **average foam density** from constituents.



Fractal dimension
~ 1.8 – 2.2

Nanoparticle diameter
~ 5 – 40 nm

Gyration radius
~ 0.1 – 5 μm

- Nanofoam **density** is **related** to the **cluster dimension** and **number of nanoparticles**:

$$R_p \sim N_p^{\frac{1}{D_f}} \qquad \rho_{avg} = k\rho_s \left(\frac{d_{np}}{2R_g}\right)^{3-D_f}$$

A. Maffini, et al. *Phys. Rev. Mater.* 3.8 (2019): 083404.

A. Maffini, et al. *Appl. Surf. Sci.* 599 (2022): 153859
M. Galbiati, et al. *Sci. Rep.* Under review (2026).

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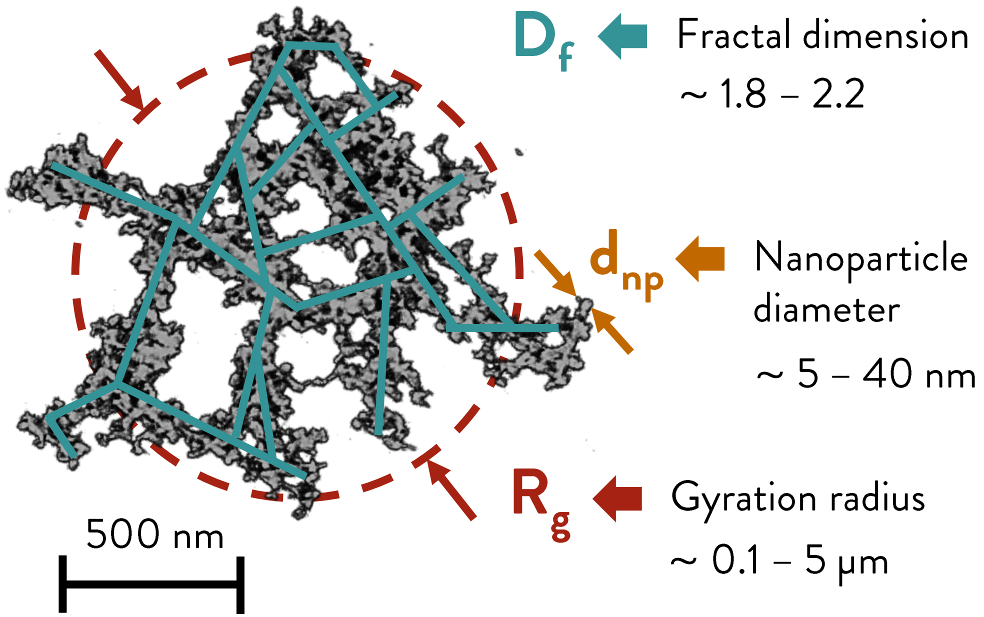

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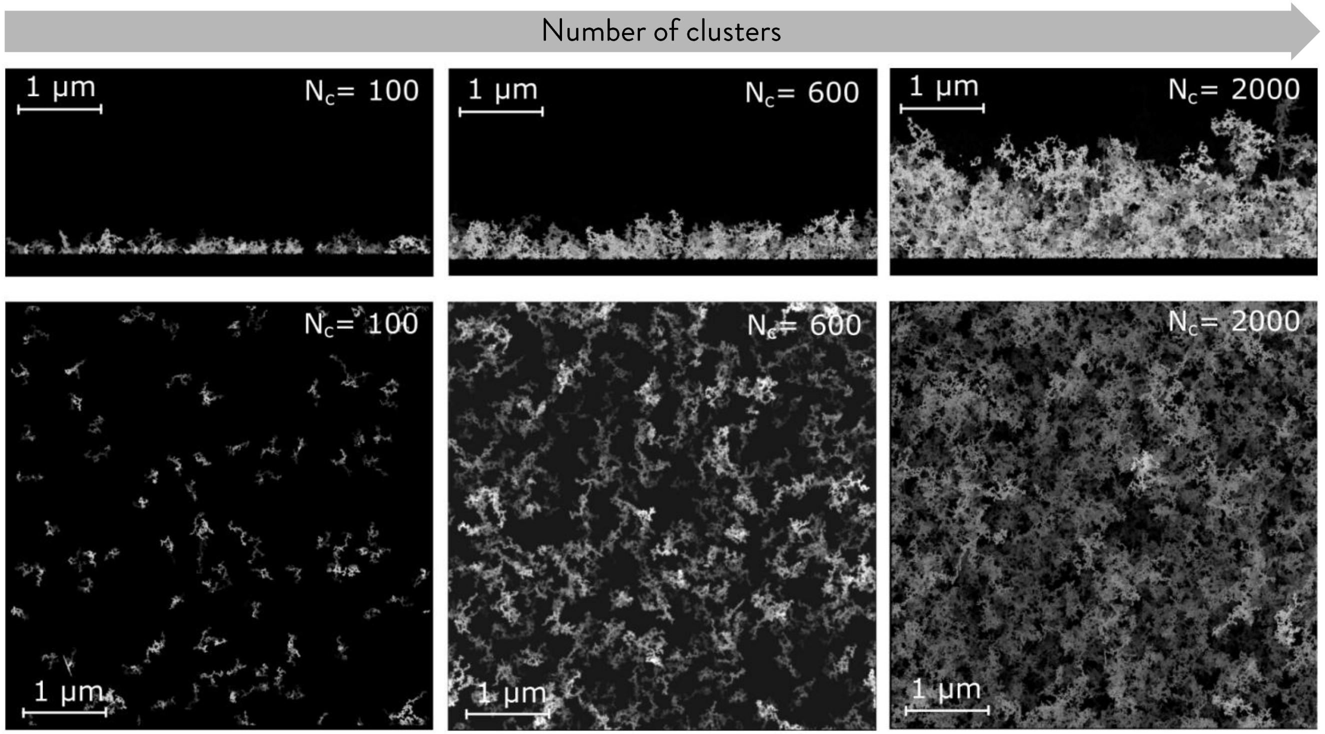
Development of a diffusion-limited cluster-cluster aggregation code to **growth synthetic nanostructures.**



- Nanofoams produced through pulsed-laser deposition **aggregate in a snow-fall-like process**

A. Maffini, et al. *Appl. Surf. Sci.* 599 (2022): 153859

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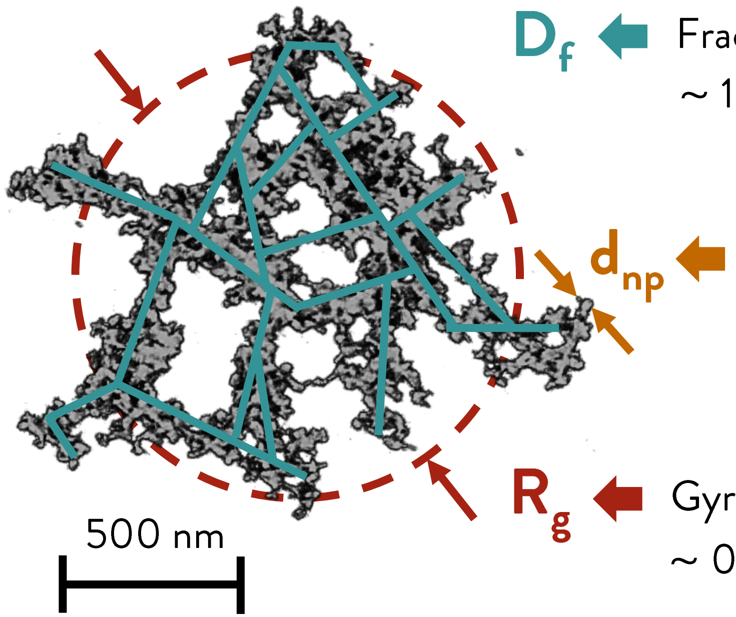

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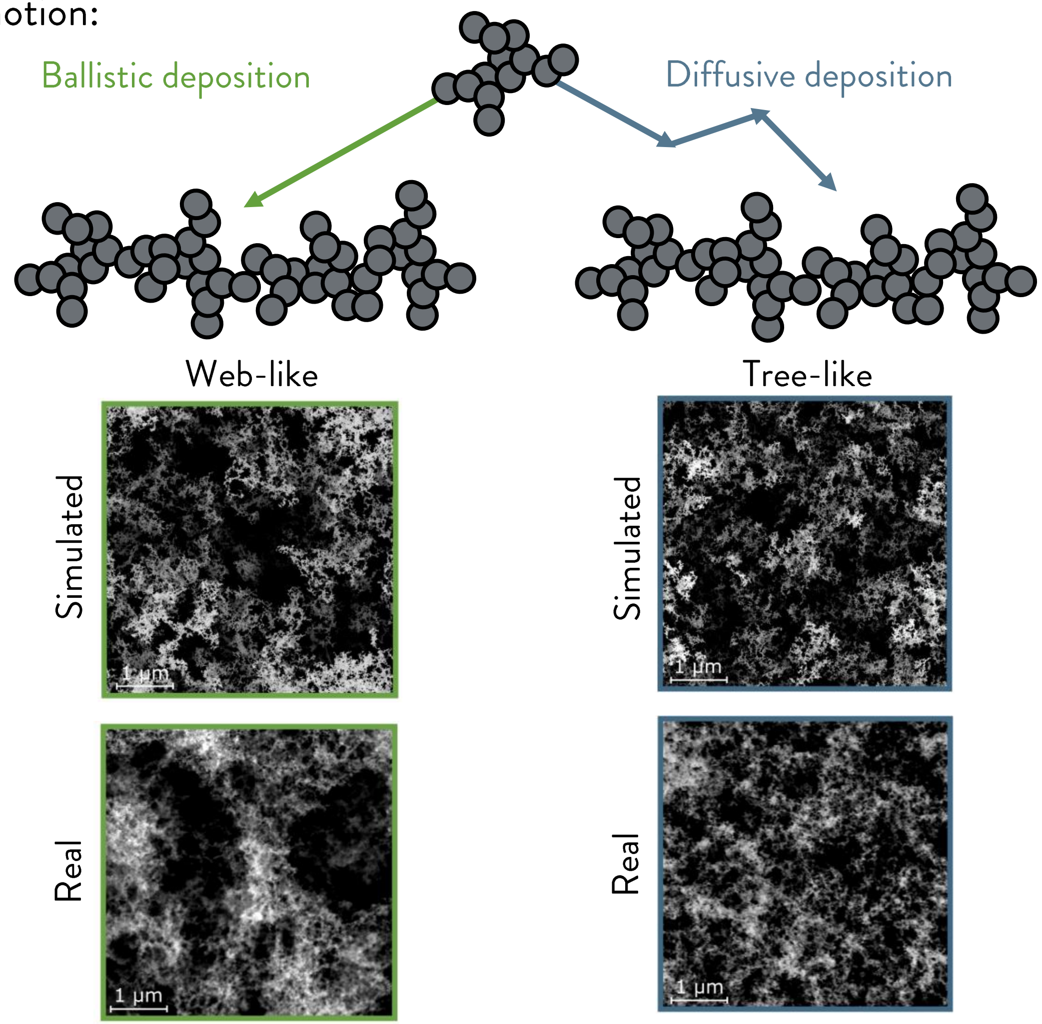
Different morphology correctly reproduced according to cluster motion:



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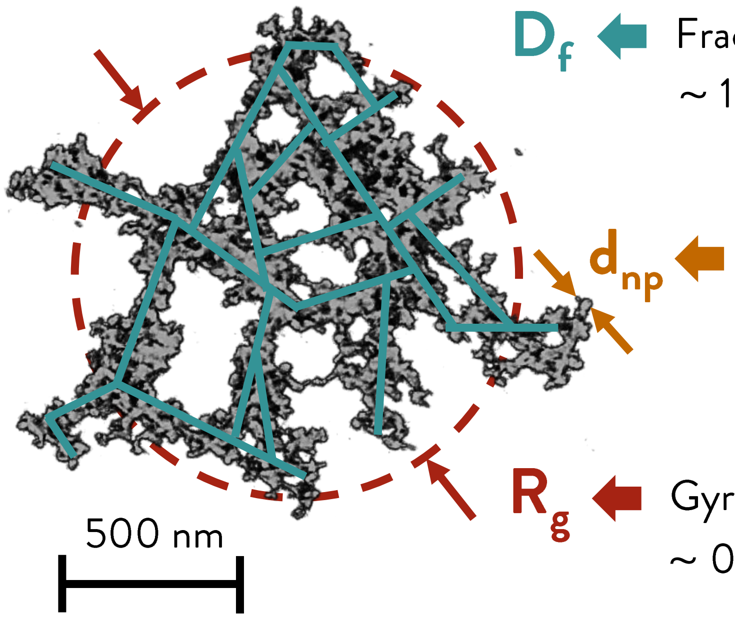

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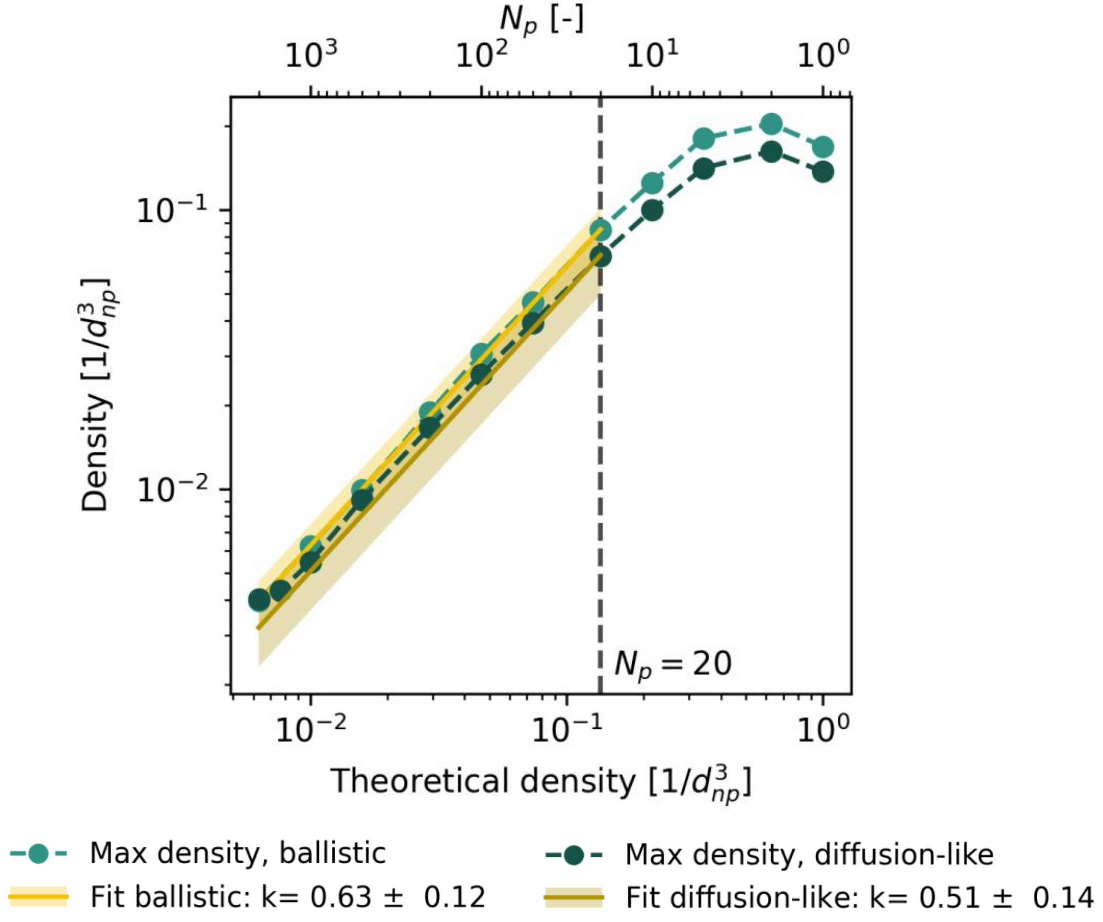
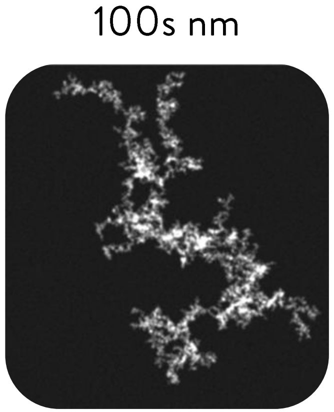
A. Maffini, et al. *Phys. Rev. Mater.* 3.8 (2019): 083404.

Correct density predicted within the range of validity of the fractal scaling



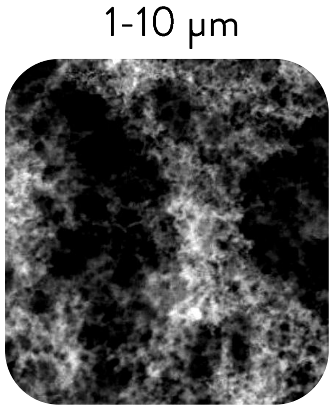
M. Galbiati, et al. *Sci. Rep.* Under review (2026).

Carbon nanofoams for ICF: 1D MULTI-fs hydrodynamic simulations



Sub-wavelength solid parts
(**nanoparticles** and **clusters**)

Affects **laser scattering**
and **absorption**

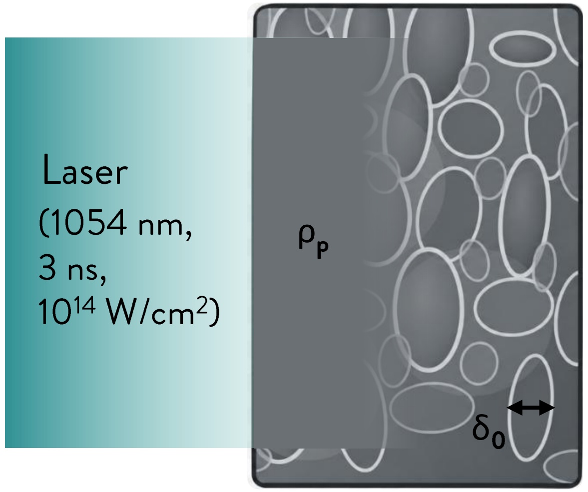


Vaid fractions
and pores

Affects the
homogenisation time

Take into account the effect of the **nanostructure** with a set of effective parameters.

- **1D MULTI validated** for conventional (micrometric, plastic) foams.
- **Carbon nanofoam is an “effective” medium** with fills and gaps.



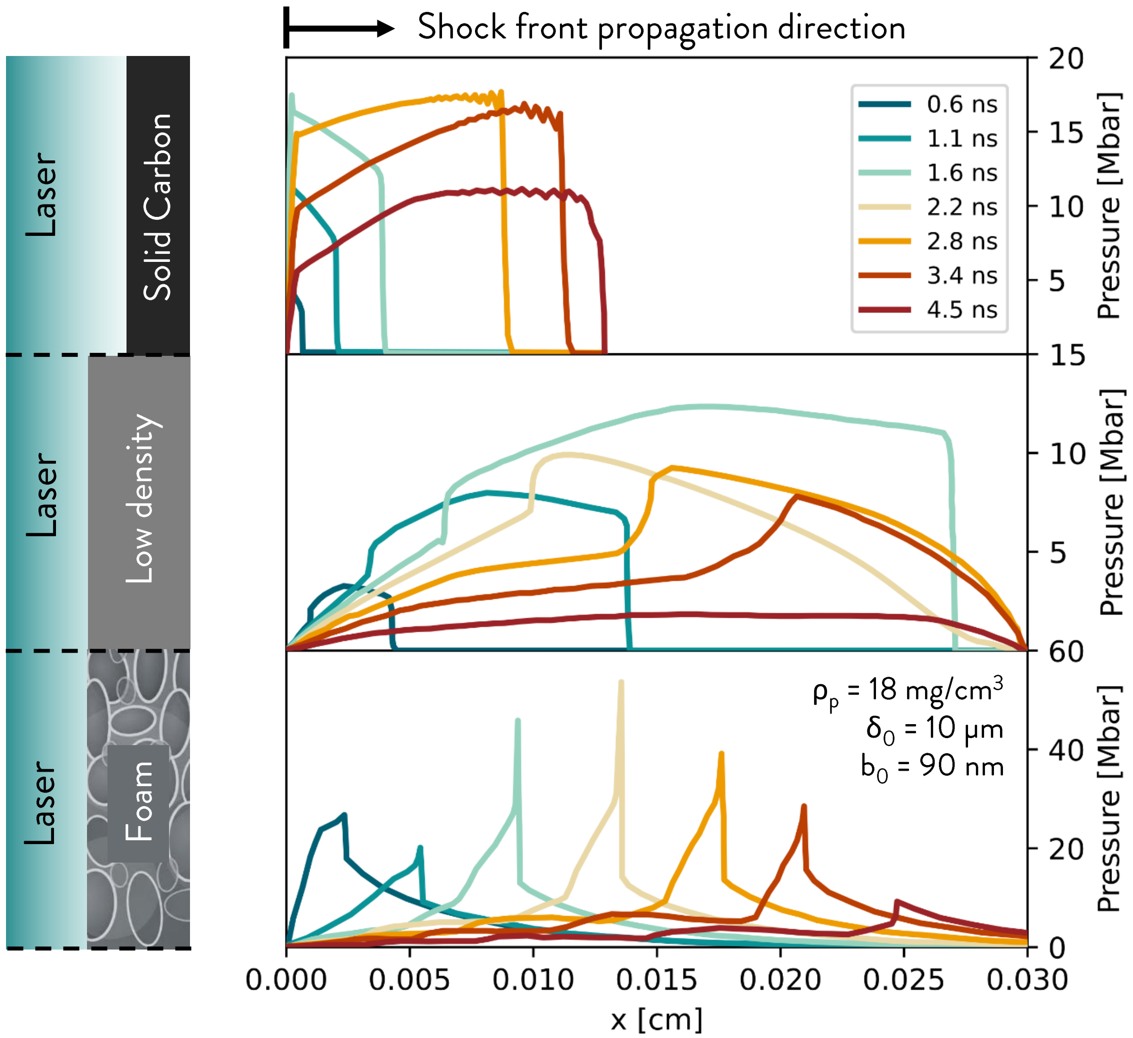
b_0 = Initial solid element size
ρ_s = Density of solid parts

δ_0 = Initial pore size
α = Foam fractal parameter

- Nanofoam **density:** $\rho_p = \rho_s \left(\frac{b_0}{\delta_0}\right)^{\frac{1}{\alpha}}$
- **Degree of plasma homogenization** affects heat conduction
- **Homogenization time** = τ_H (b_0, δ_0, ρ_p, Temperature)

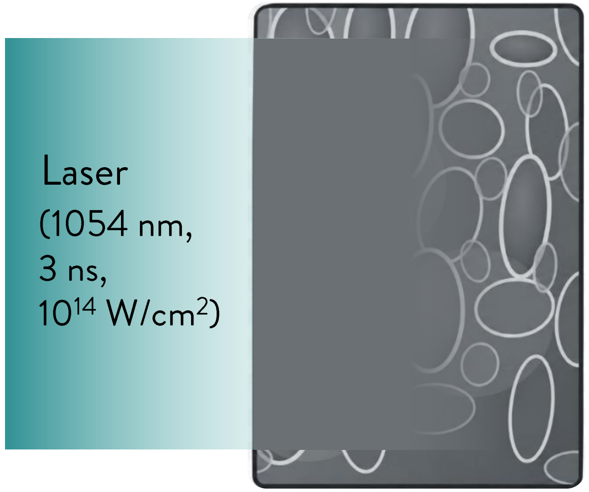
A. Maffini, et al. *LPB* 2023 (2023): e1.

Carbon nanofoams for ICF: 1D MULTI-fs hydrodynamic simulations



A. Maffini, et al. *LPB* 2023 (2023): e1.

- **Foam homogenization delays** heat transport and hydrodynamic **expansion**
- Delayed homogenization **enhances shock-front pressure**
- Higher ρ_p → Higer pressure
- Larger pores → Higer pressure



Laser
(1054 nm,
3 ns,
10^{14} W/cm^2)

- 100s μm required
- Substrate effect not included
- **Experimental validation required**

How to improve the description of the nanostructure?

- Nanofoam **homogenization** is a **complex phenomenon** → **Deeper investigation** should **include the real structure and kinetic effects.**

Simulation of single nanoparticles and clusters **homogenization with Smilei) Particle-In-Cell (PIC)** simulations to **consider kinetic effects** in the homogenization

5-nm-radius ionised graphite

Mean density 26 mg/cm^3 = foam density

Plane wave until homogenisation

10^{12} - 10^{16} W/cm^2 intensity

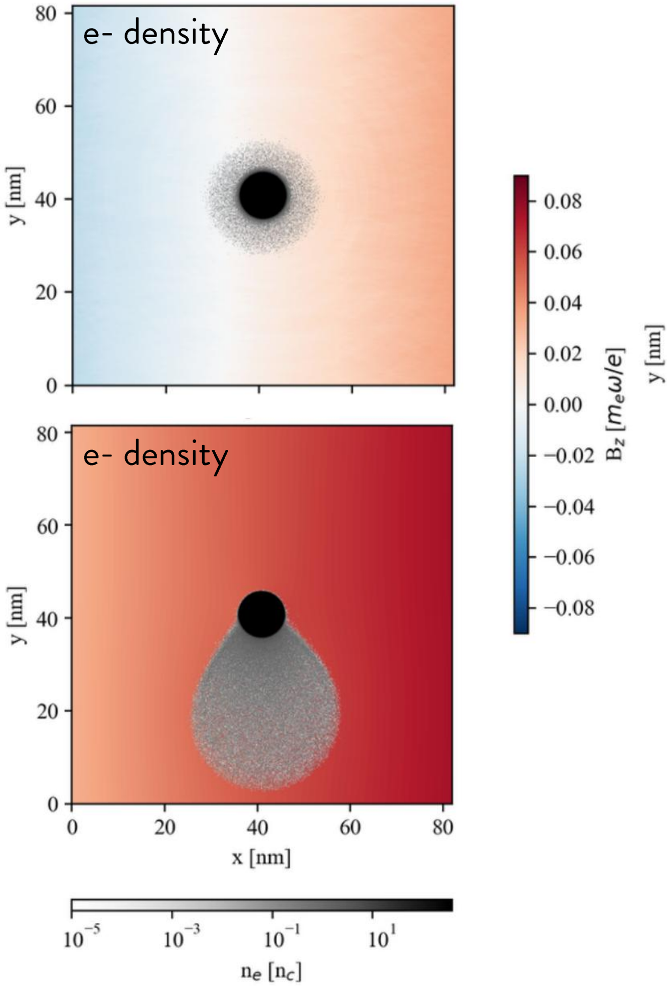
Coulomb collisions included

- **I ≈ 10^{12} W/cm^2**

  Laser absorption dominated by **collisions**

- **I ≈ 10^{16} W/cm^2**

  Non-collisional ablation starts to be dominant



~**180 fs required** for **total homogenization** of single nanoparticle **in 2D**

J. Derouillat, et al. *Comput. Phys. Commun.* 222 (2018): 351-373.
C. Mallimaci, *Master Thesis* (2024).

How to improve the description of the nanostructure?

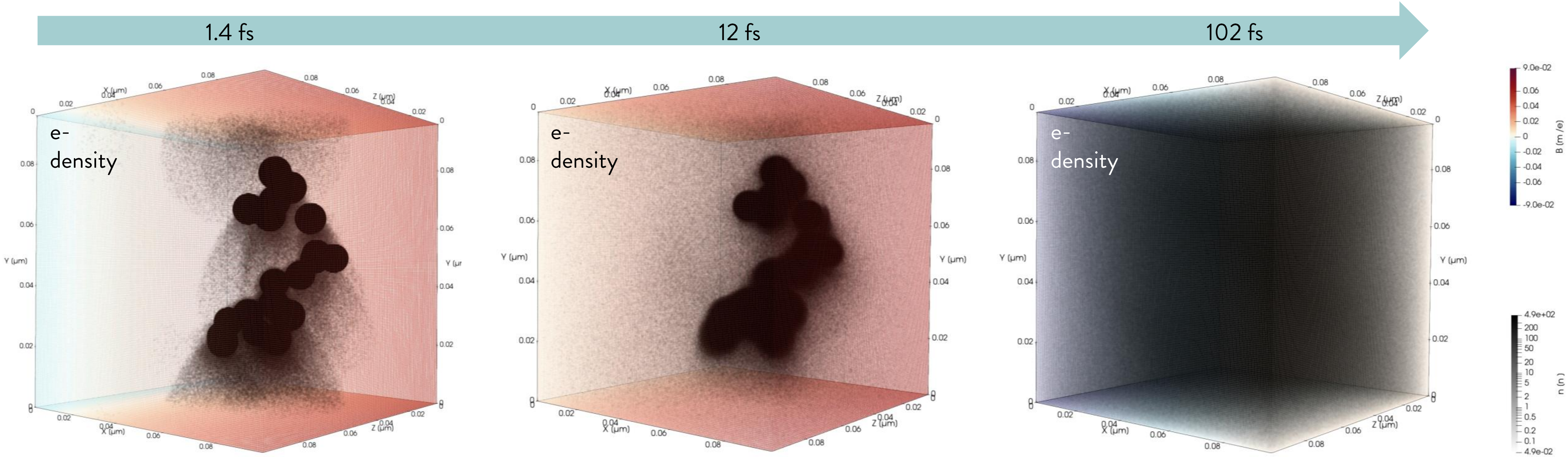
- Nanofoam **homogenization** is a **complex phenomenon** → **Deeper investigation** should **include the real structure and kinetic effects.**

- **I ≈ 10^{16} W/cm^2**

~100 fs required for **total homogenization** of a cluster **in 3D**

WORK IN PROGRESS

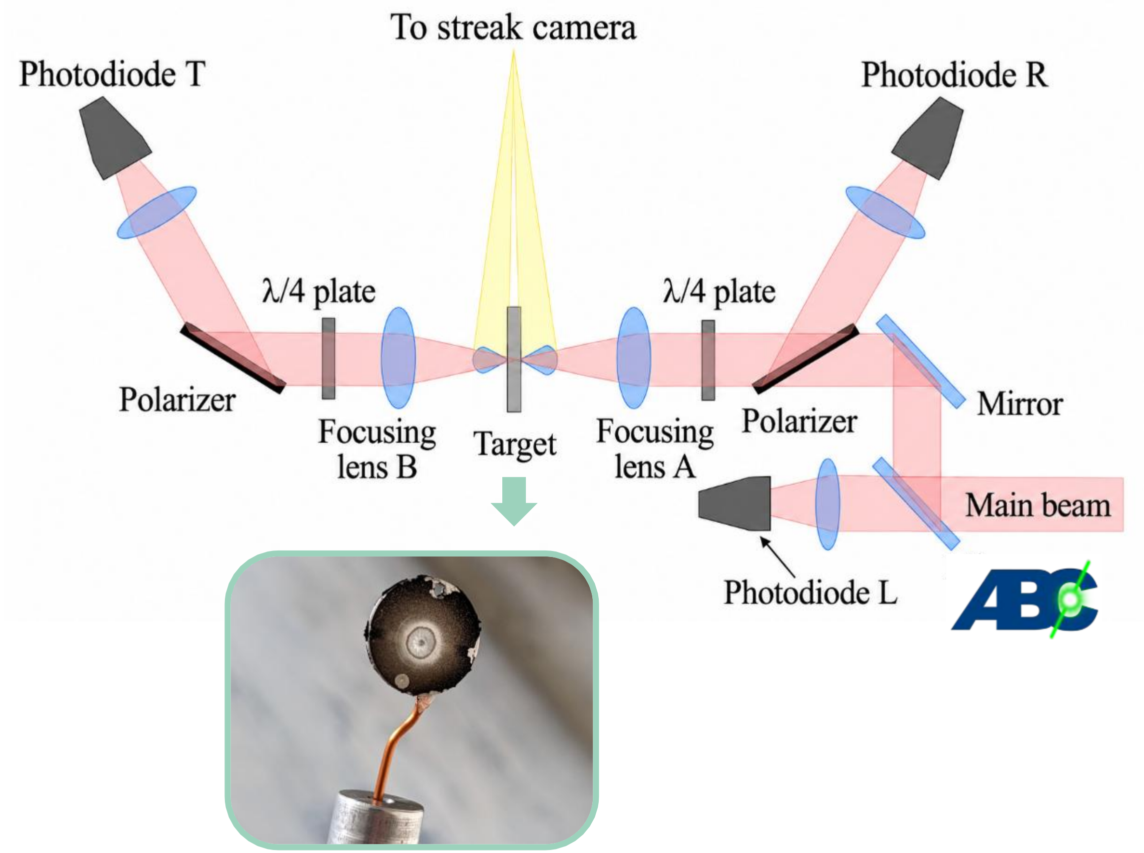
- **Full scan varying the intensity** for single nanoparticles and clusters in 3D
- **Coupling** of kinetic result **to fluid simulations** of nanofoam as ablators for ICF



C. Mallimaci, *Master Thesis* (2024).

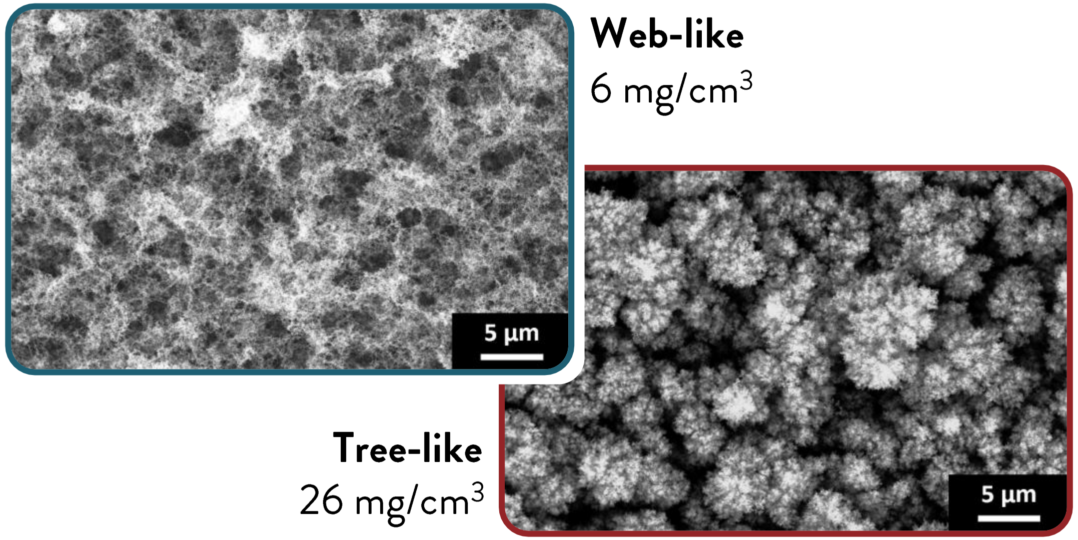
Experimental results from nanofoam irradiation with the ABC laser

- ABC laser: λ = **1054 nm**, τ_{FWHM} = **3 ns**, I = **10^{14} W/cm^2**, E = **40 J**
- Experimental **setup**:



Cipriani, M., et al. *Matter Radiat. Extrem.* 11.4 (2026).

- **Nanofoam targets**:



Web-like
6 mg/cm^3

Tree-like
26 mg/cm^3

- Mass thickness: **78, 156 µg/cm^2**
- Substrates:
- Characterizations:

Bulk Al → **Ablation crater** (post-mortem)

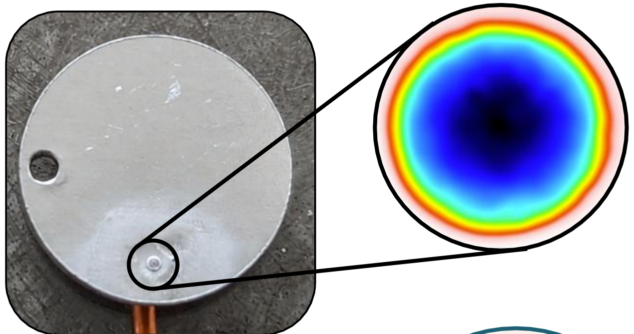
1.5 µm Al foil → **Plasma imaging** with streak camera

Target transmittance and reflectance

Experimental results from nanofoam irradiation with the ABC laser

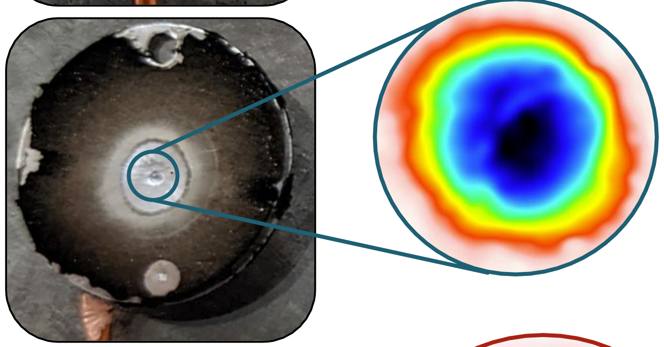
- **Ablation crater** (post-mortem) analysis:
  - ○ **Bulk Al**

    Volume ≈ **3.4 × 10^7 μm^3**



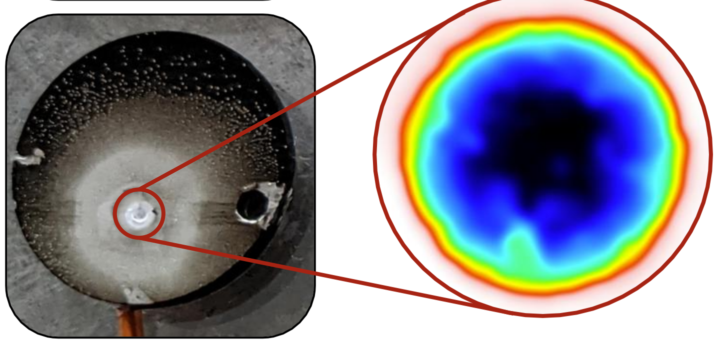
  - ○ **Bulk Al +** **Web-like nanofoam**

    Volume ≈ **4.0 × 10^7 μm^3**



  - ○ **Bulk Al +** **Tree-like nanofoam**

    Volume ≈ **6.0 × 10^7 μm^3**



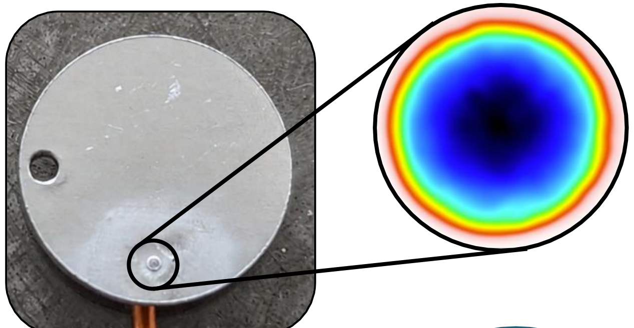
Cipriani, M., et al. *Matter Radiat. Extrem.* 11.4 (2026).

Higer density and thickness → Larger crater size

Experimental results from nanofoam irradiation with the ABC laser

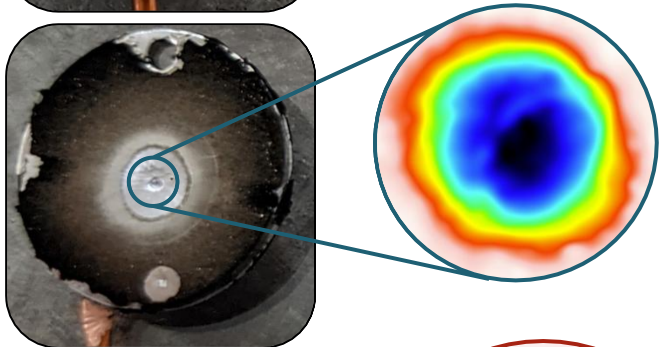
- **Ablation crater** (post-mortem) analysis:
  - **Bulk Al**

    Volume ≈ **$3.4 \times 10^7\ \mu m^3$**



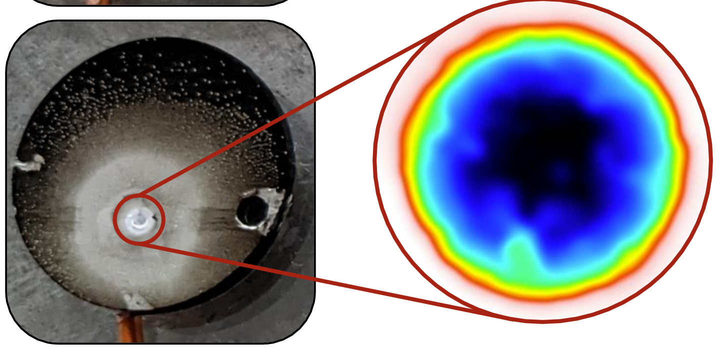
  - **Bulk Al + Web-like nanofoam**

    Volume ≈ **$4.0 \times 10^7\ \mu m^3$**

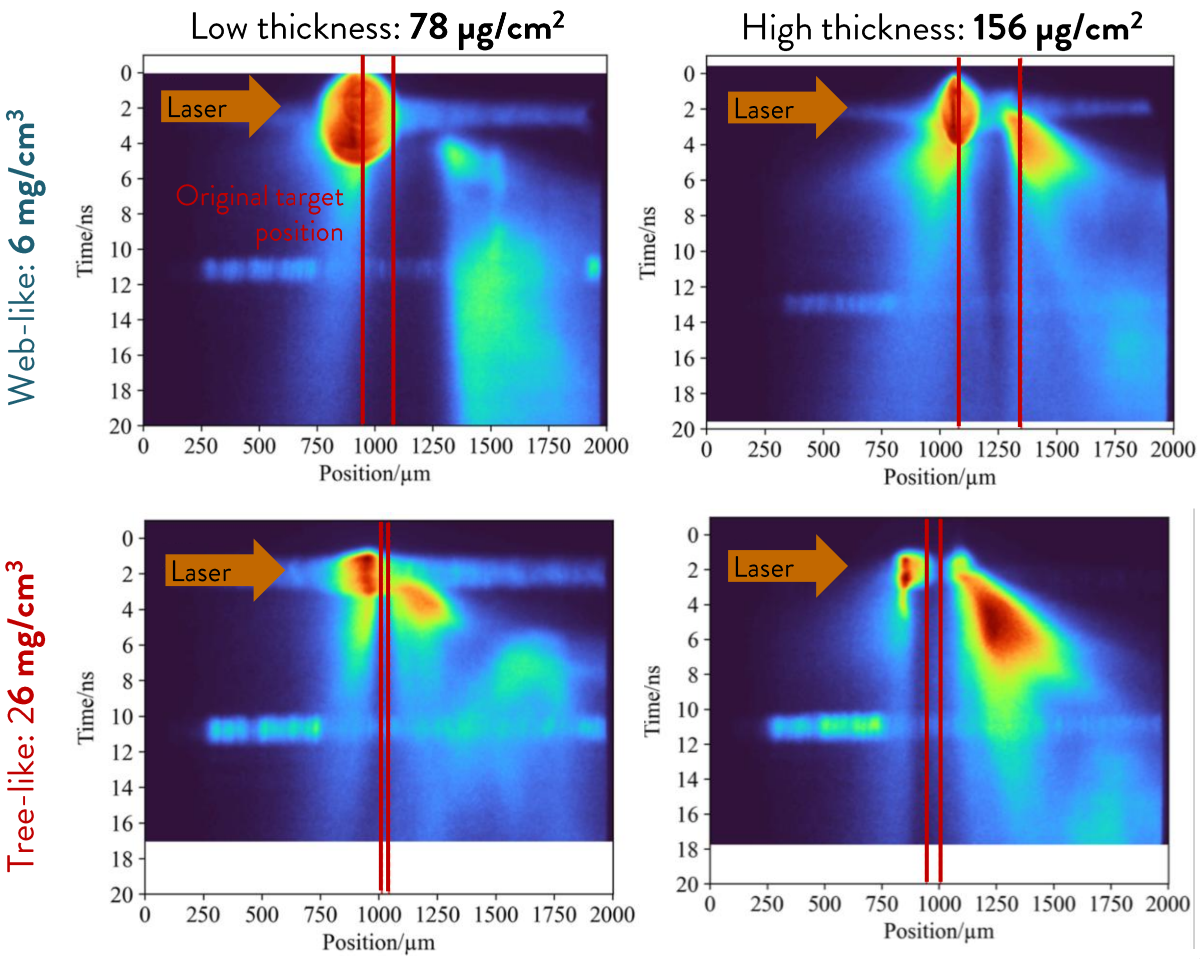


  - **Bulk Al + Tree-like nanofoam**

    Volume ≈ **$6.0 \times 10^7\ \mu m^3$**



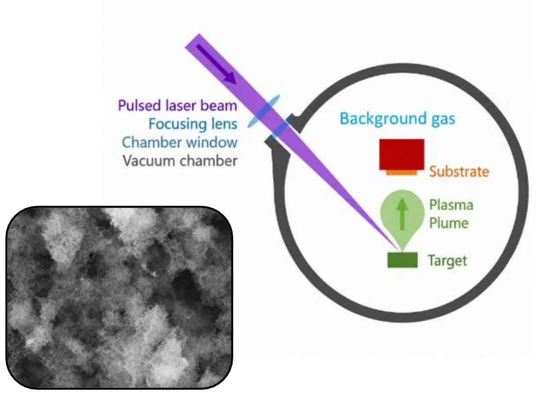
- **Plasma imaging**:



Higer density and thickness → Larger crater size and higher plasma emission from rear side

Cipriani, M., et al. *Matter Radiat. Extrem.* 11.4 (2026).

Conclusions



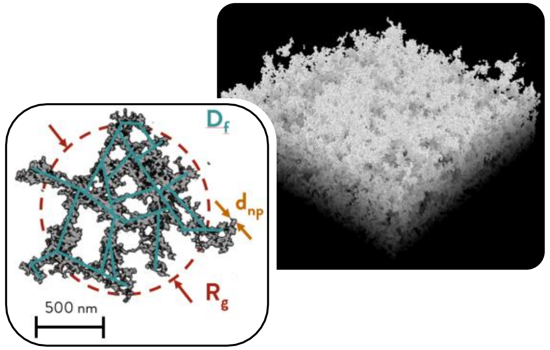
- **PLD** is a **versatile tool** for the **nanofoam** production controlling:
  - Density
  - Thickness
  - Morphology
  - Composition

Talk @ Workshop

WORKSHOP ON MICRO- AND NANO-STRUCTURED MATERIALS FOR EXPERIMENTS WITH HIGH-POWER LASERS

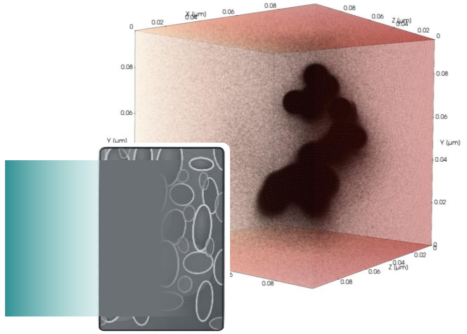
12 June 2026
ENEA Centro Ricerche Frascati, Italy

by S. De Magistris



- **Fractal scaling** and **numerically aggregated nanofoams predict** deposited material **properties**

Thank you for your attention



- **1D MULTI-fs** simulations suggest that **nanofoams** can **enhance** the **ablation loading** @ shock front
- **PIC** simulations allow **studying** the foam **homogenization** in detail

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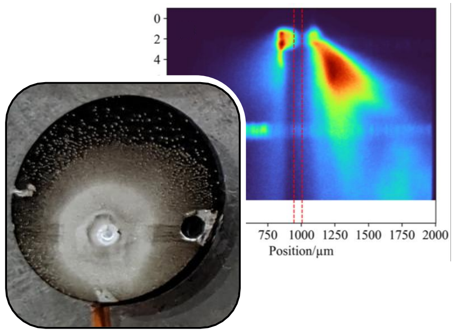
12 June 2026
ENEA Centro Ricerche Frascati, Italy

by K. Ambrogioni



- **Experimental results** with ABC laser indicate that **nanofoam** with **highest density** & **thickness performed best**
- New experiment to test different nanofoams

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