ECLIM 2026 | 38TH EUROPEAN CONFERENCE ON LASER INTERACTION WITH MATTER

Nanofoams in action: a versatile tool for laser-matter interaction experiments

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[1] Dipartimento di Energia, Politecnico di Milano
[2] Laboratoire pour l'Utilisation des Lasers Intenses (LULI),
[3] ELI Beamlines Facility

POLITECNICO MILANO 1863

NanoLab

Why foams in laser-matter interaction?

Why are PLD nanofoams special?

How to tune nanofoam properties

A few examples of applications

Open issues & perspectives

Why foams in laser-matter interaction?

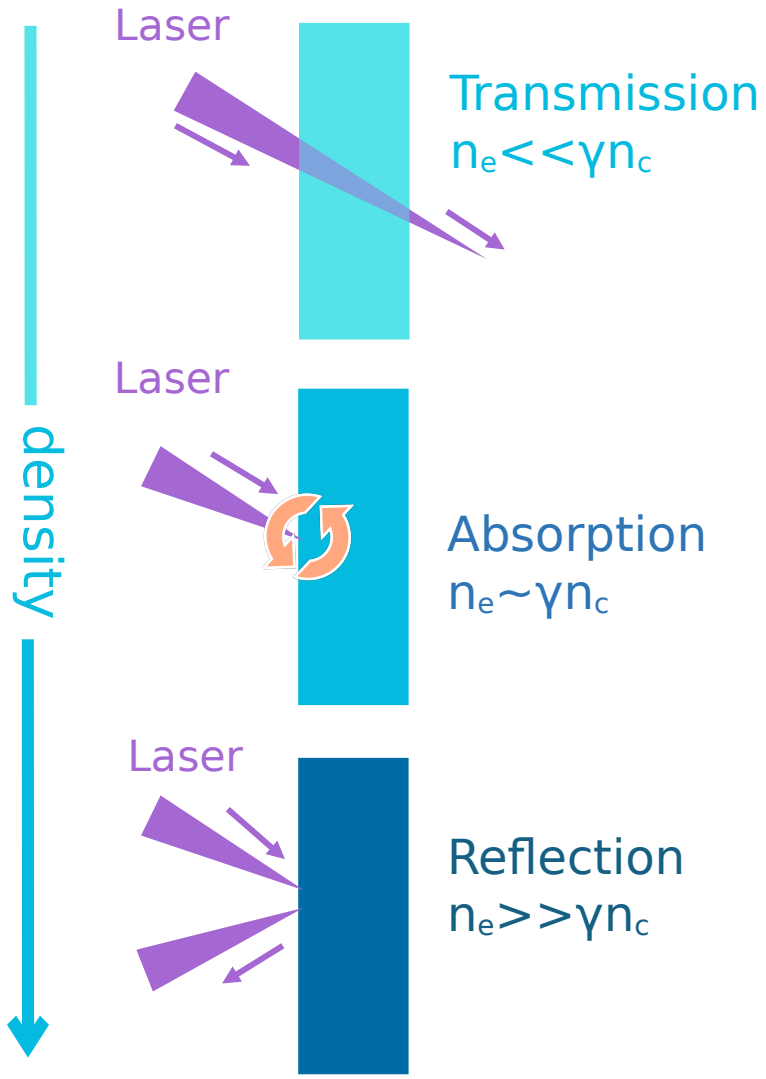
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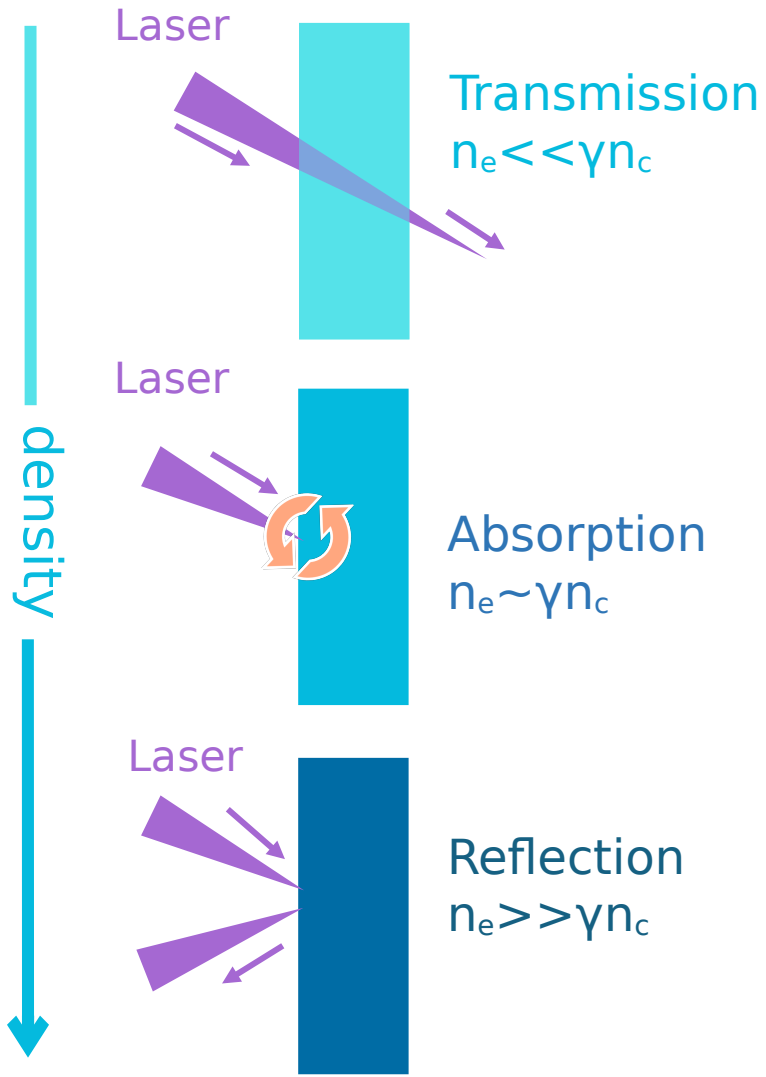
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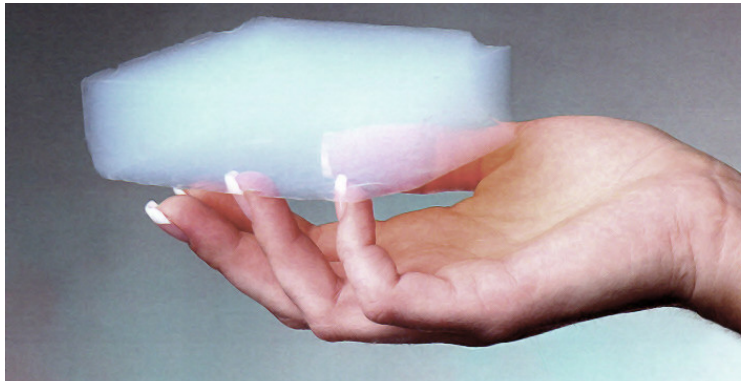


$$n_c = \frac{m_e \omega_L^2}{4 \pi e^2}$$

Near-critical density / regime

Why foams?

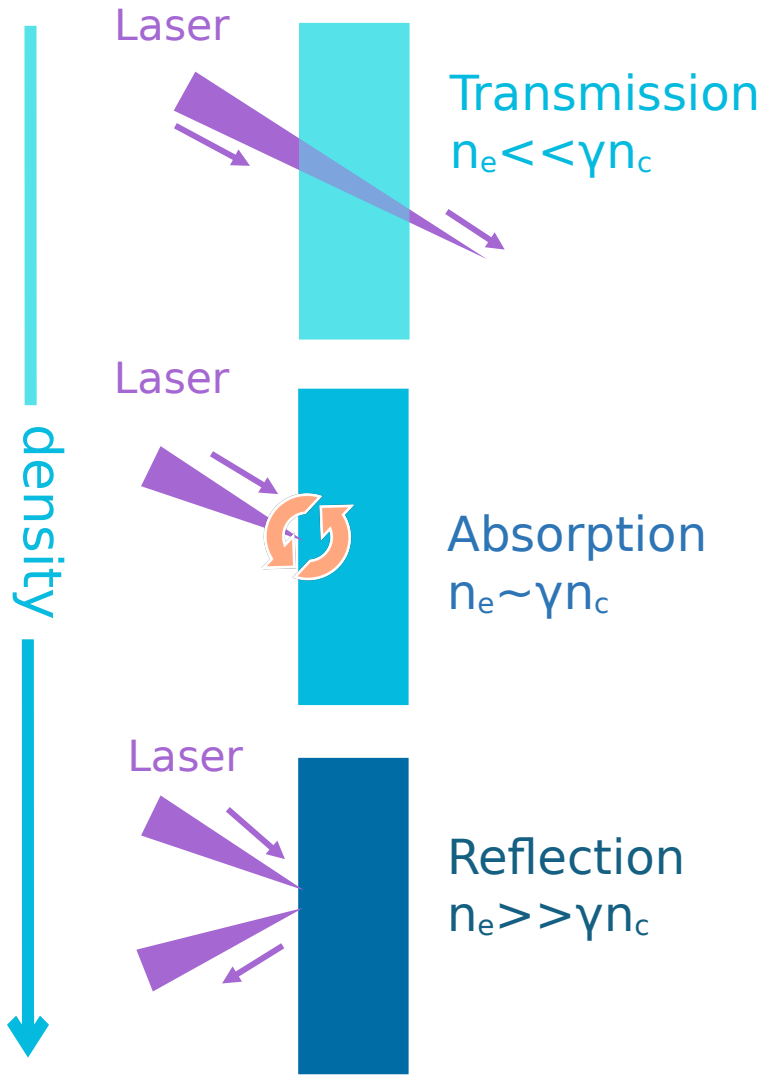


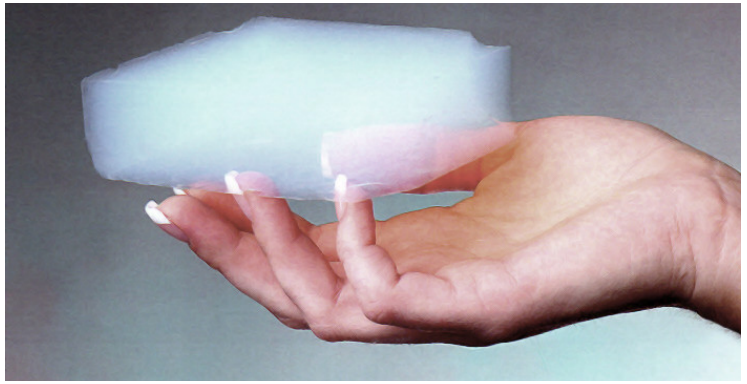


$$n_c = \frac{m_e \omega_L^2}{4\pi e^2} \approx \text{few } \frac{\text{mg}}{\text{cm}^3}$$

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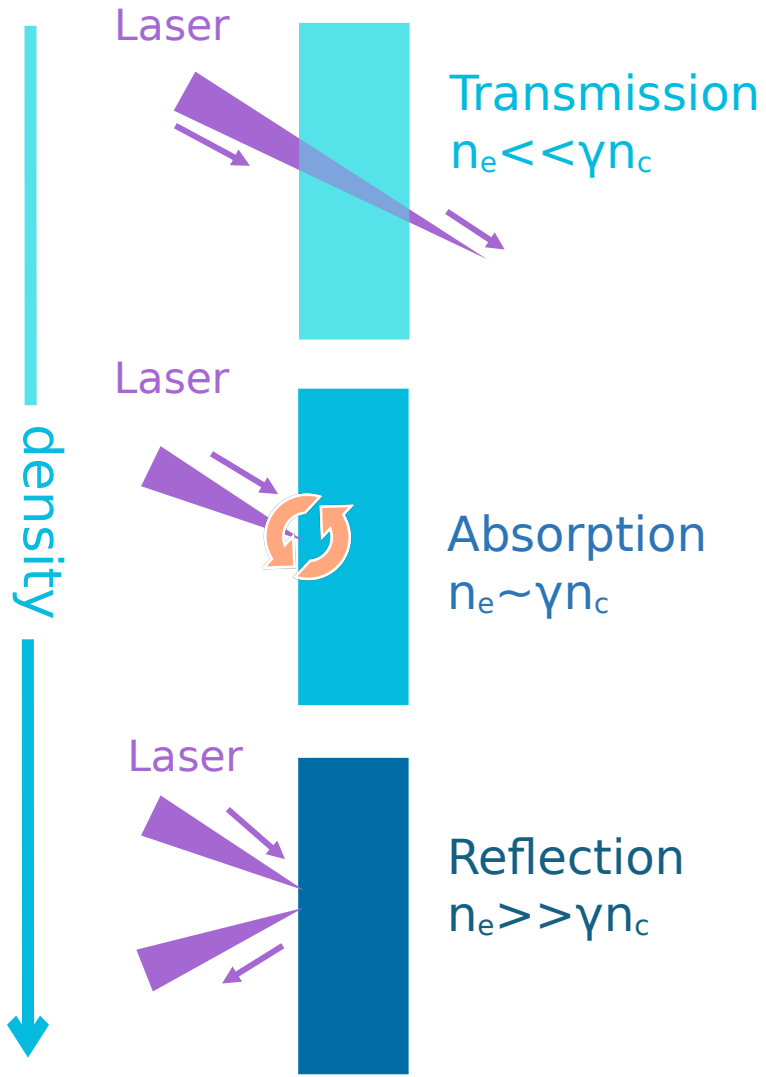


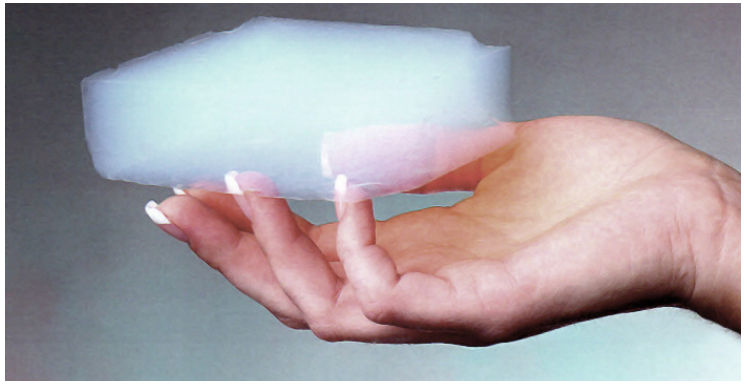


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- Density & composition **shaping**

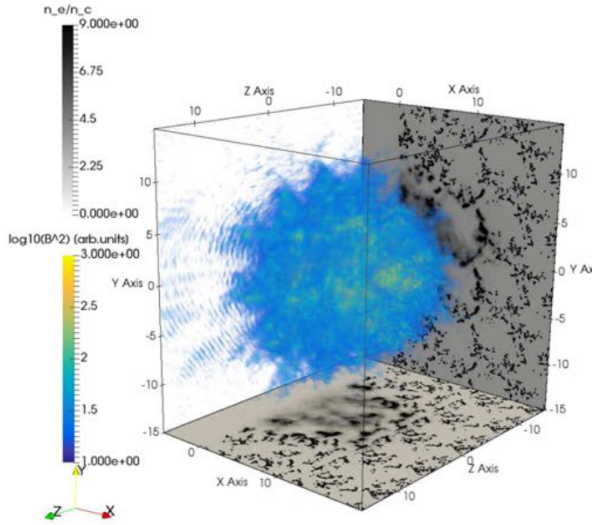
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- **Near-critical** density / regime
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- **Morphology** (& size) **matters!**



L. Fedeli et al., *Scientific reports* **8.1**, (2018)

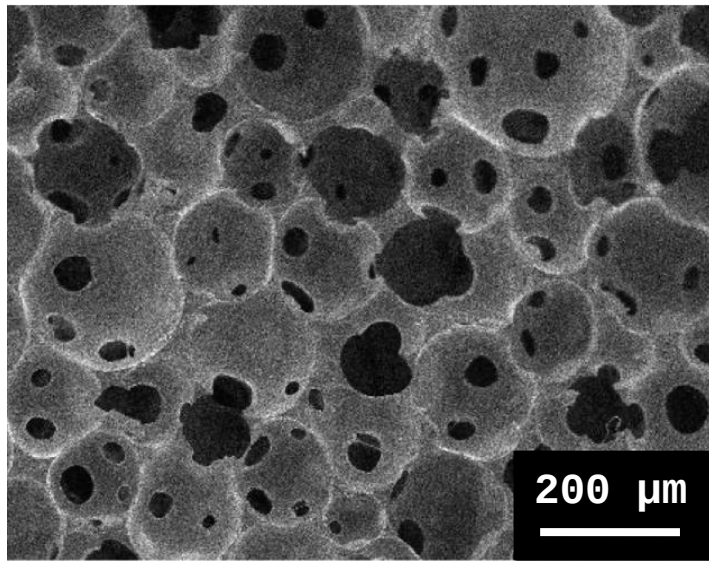
How to make foams targets

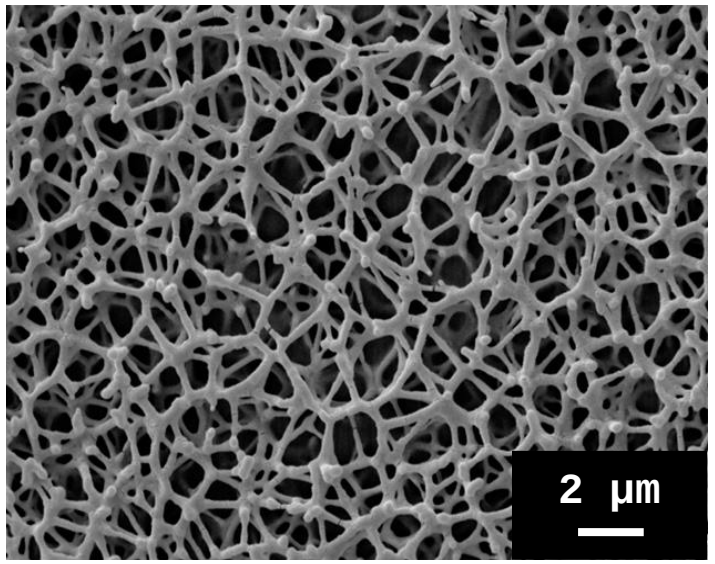
Chemical Synthesis

- ✓ Cheap & easy manufacturing
- ✓ Easily scalable
- × Limited control over properties

Additive Manufacturing

- ✓ Precise & reproducible
- ± Hard to get to the nanoscale
- × Limited control over composition



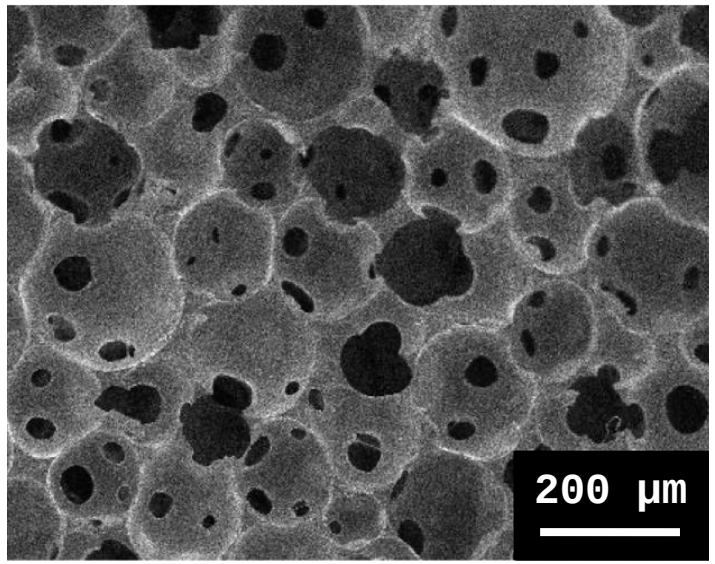


A. Maffini, et al. Plasma Physics and Controlled Fusion 68 (2026): 035007

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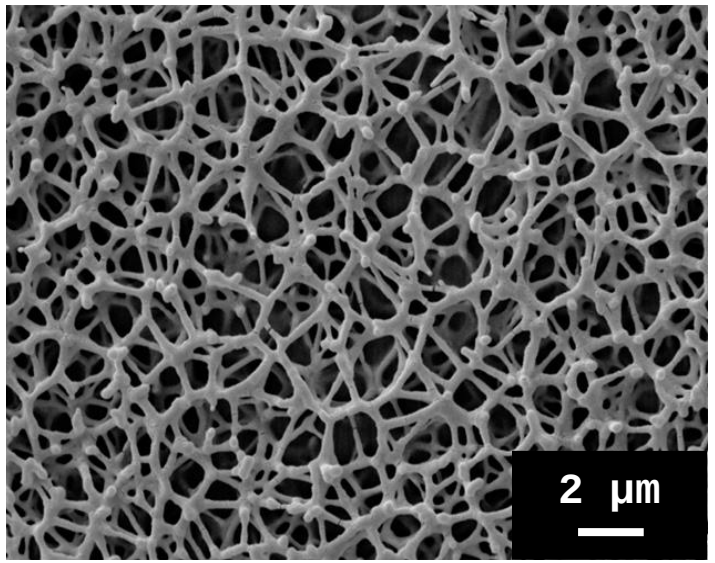
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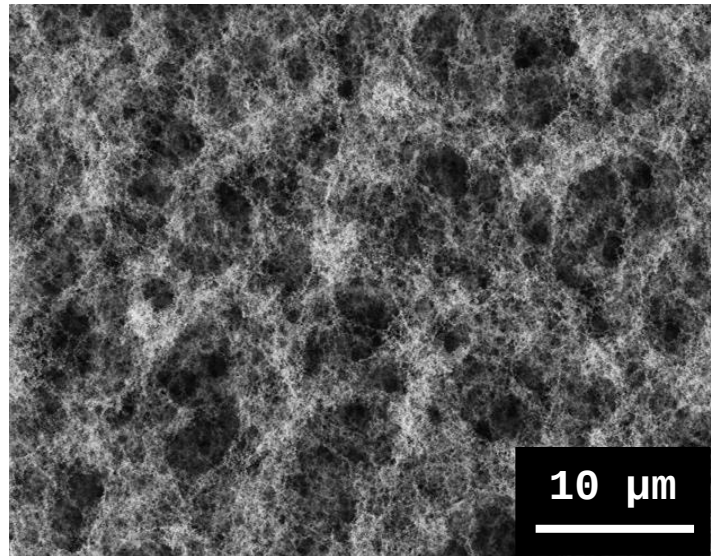
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Pulsed Laser Deposition

- ✓ Extreme versatility
- ✓ High control over properties
- ✓ Nanostructured morphology



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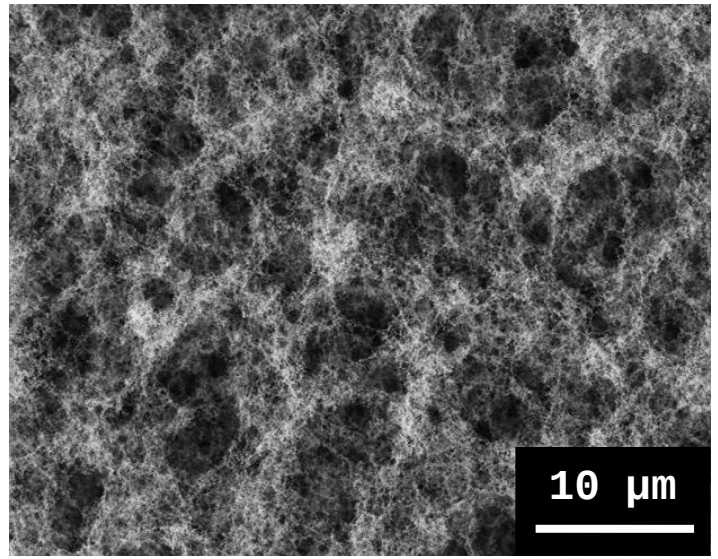
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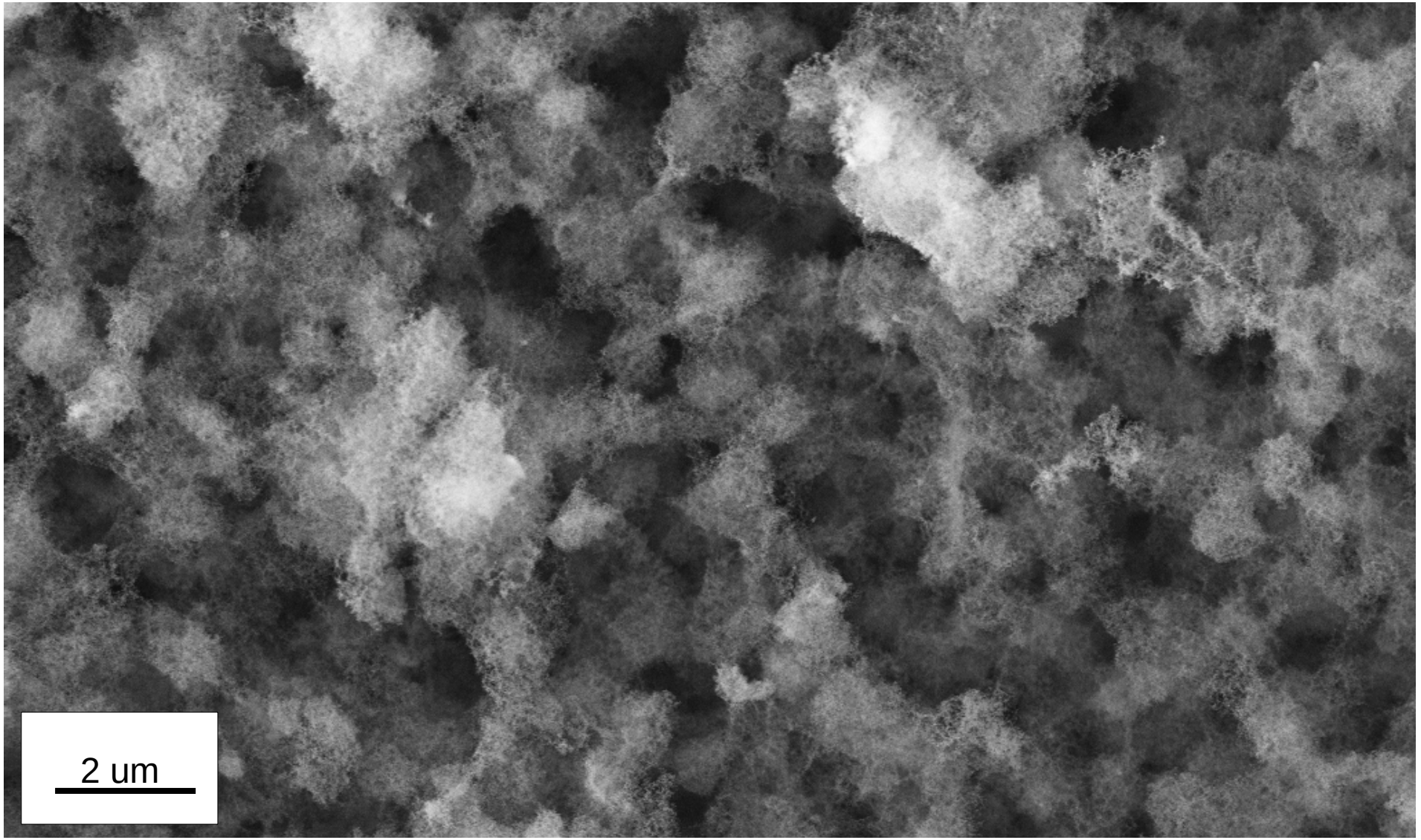
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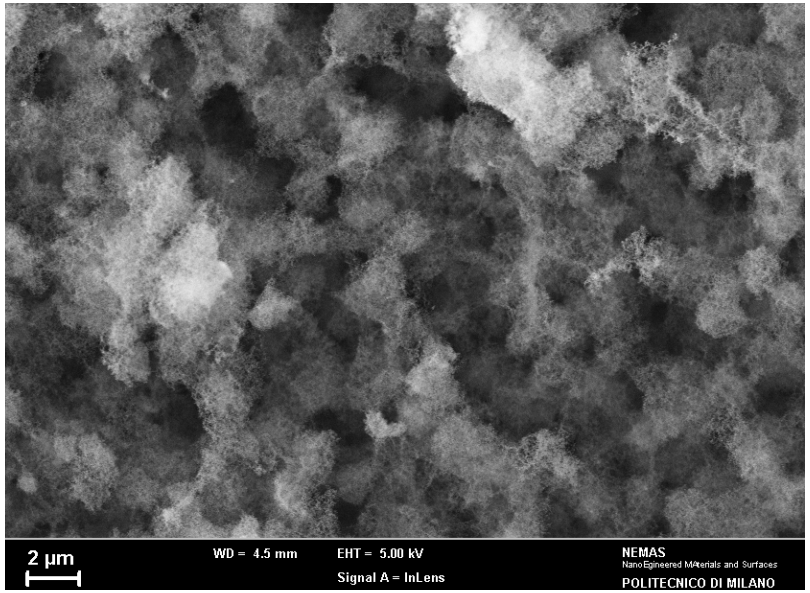
A few examples of applications

Open issues & perspectives

A closer look to PLD nanofoams



A closer look to PLD nanofoams



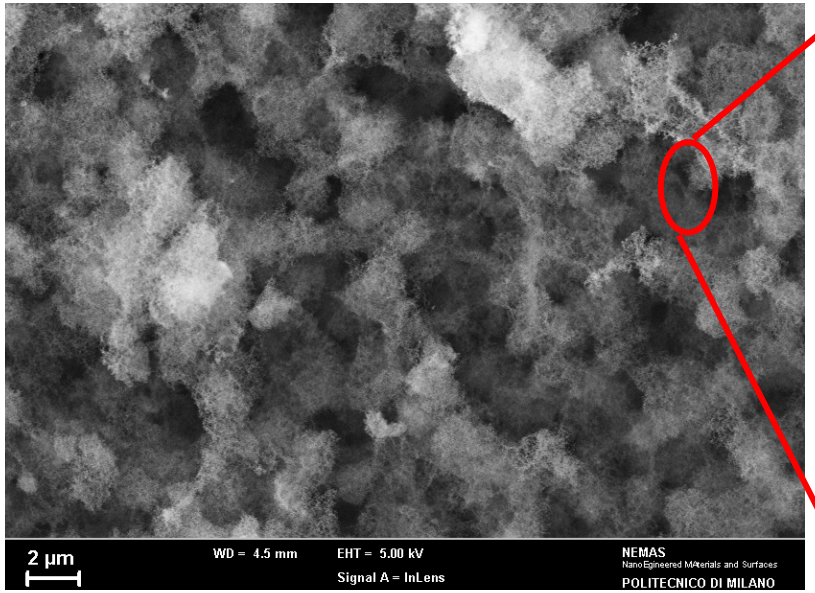
Multi-scale structure

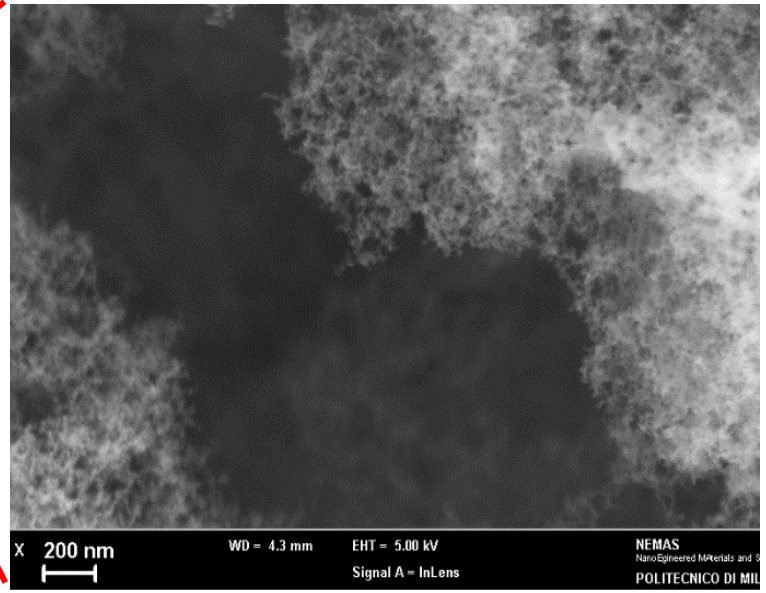
Thickness: 1 to 100s µm

Area: from 1 mm^2 to 10 cm^2

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

A closer look to PLD nanofoams



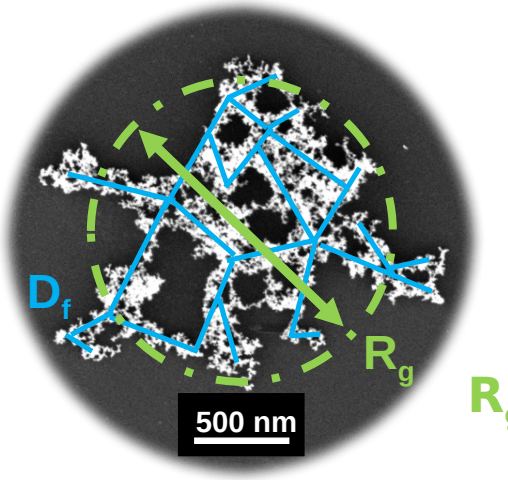


Multi-scale structure

Thickness: 1 to 100s µm

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Fractal-like aggregates

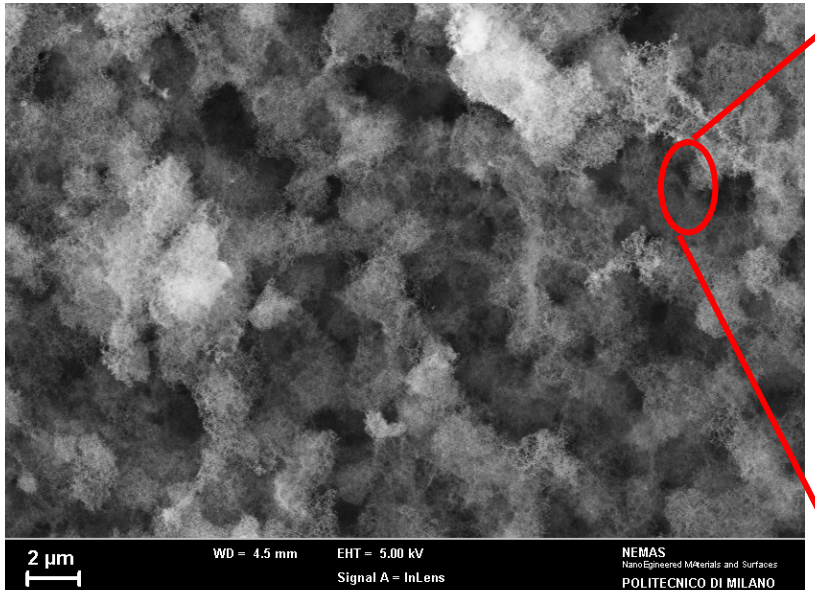


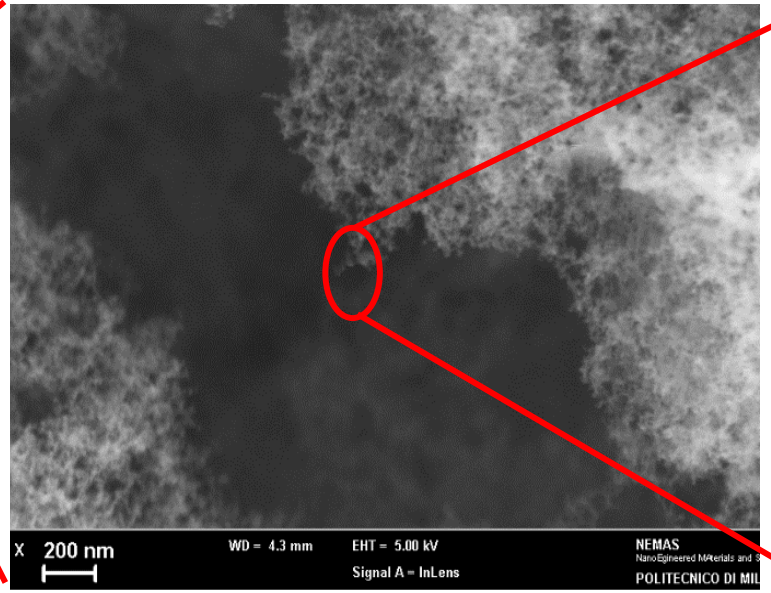
D_f Fractal dimension: ~ 1.8 – 2.2

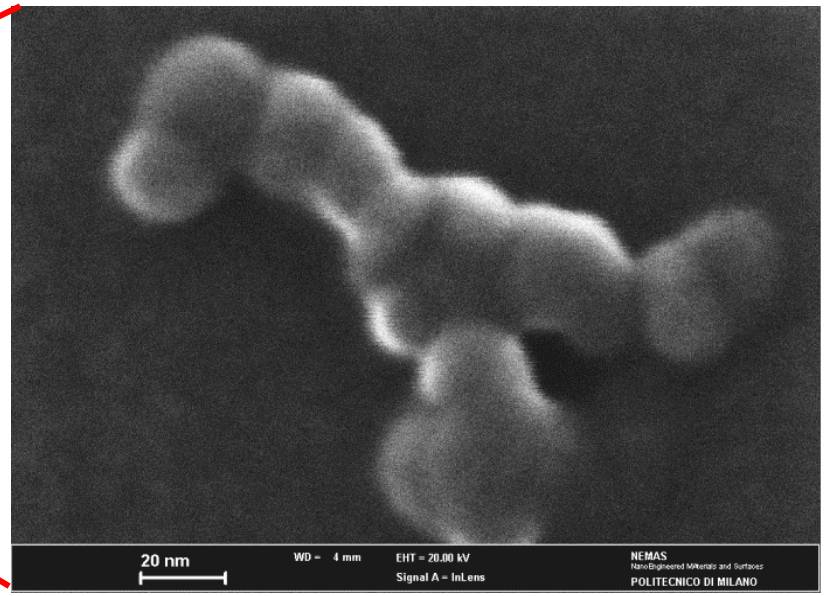
R_g Gyration radius: 0.1 µm – 5 µm

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A closer look to PLD nanofoams







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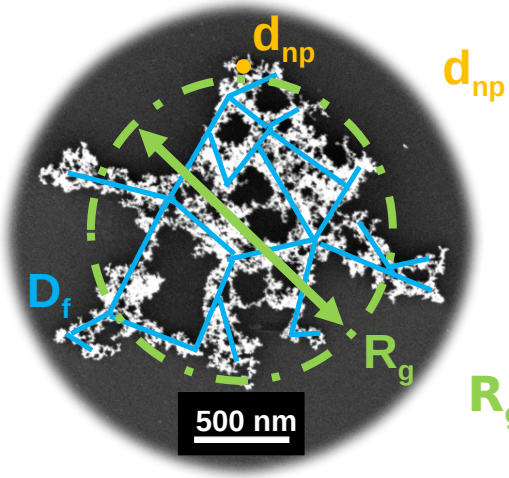
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Fractal-like aggregates

Nanoparticle constituents

$$\rho_{th} \cong k\rho_{np}\left(\frac{d_{np}}{2R_g}\right)^{3-D_f}$$



d_{np} Nanoparticle diameter: 5 nm – 40 nm

Nanoparticle density: ~ 50% – 100% of bulk

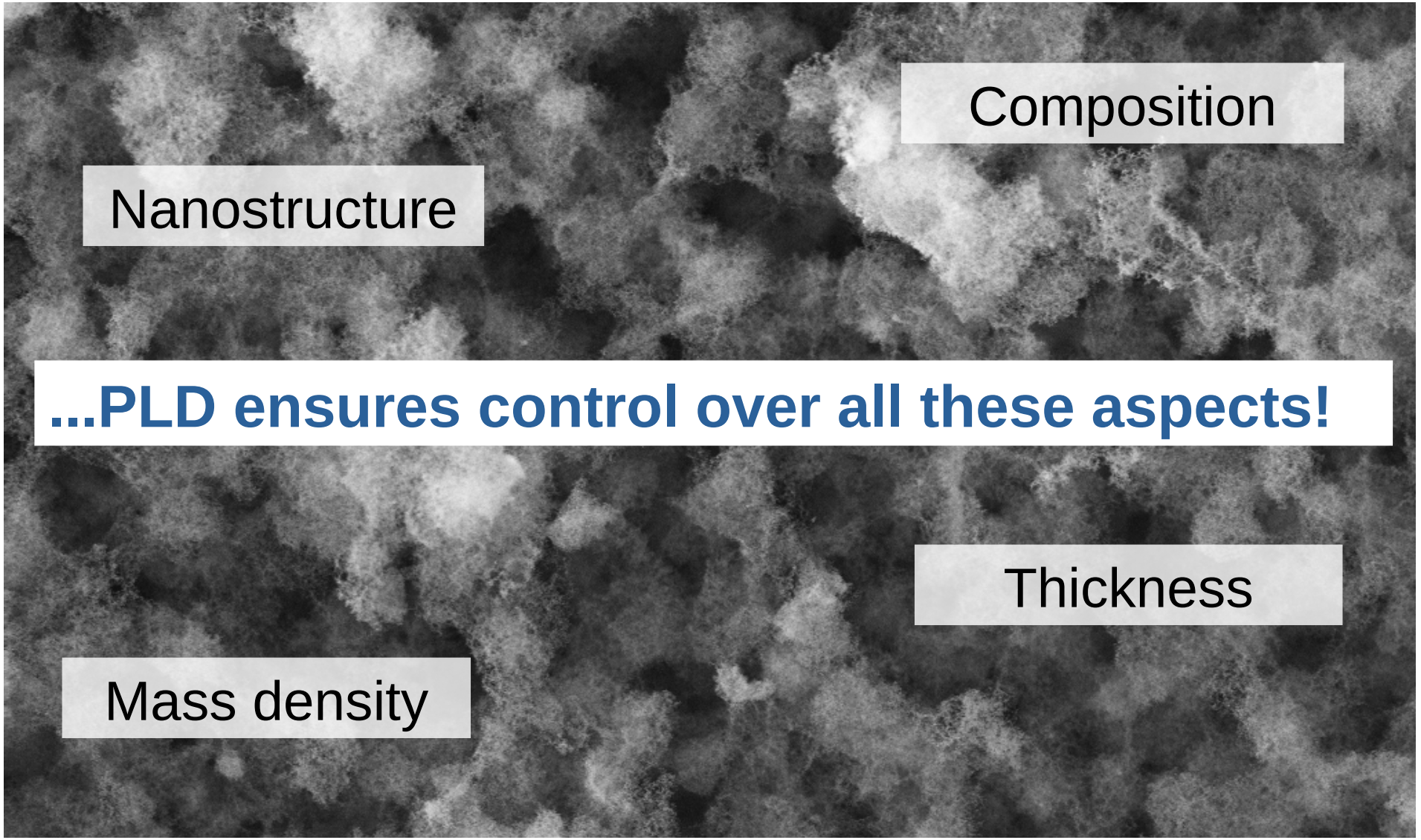
Nanoparticle composition: any!

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Why Pulsed Laser Deposited Nanofoams?



Why foams in laser-plasma interaction?

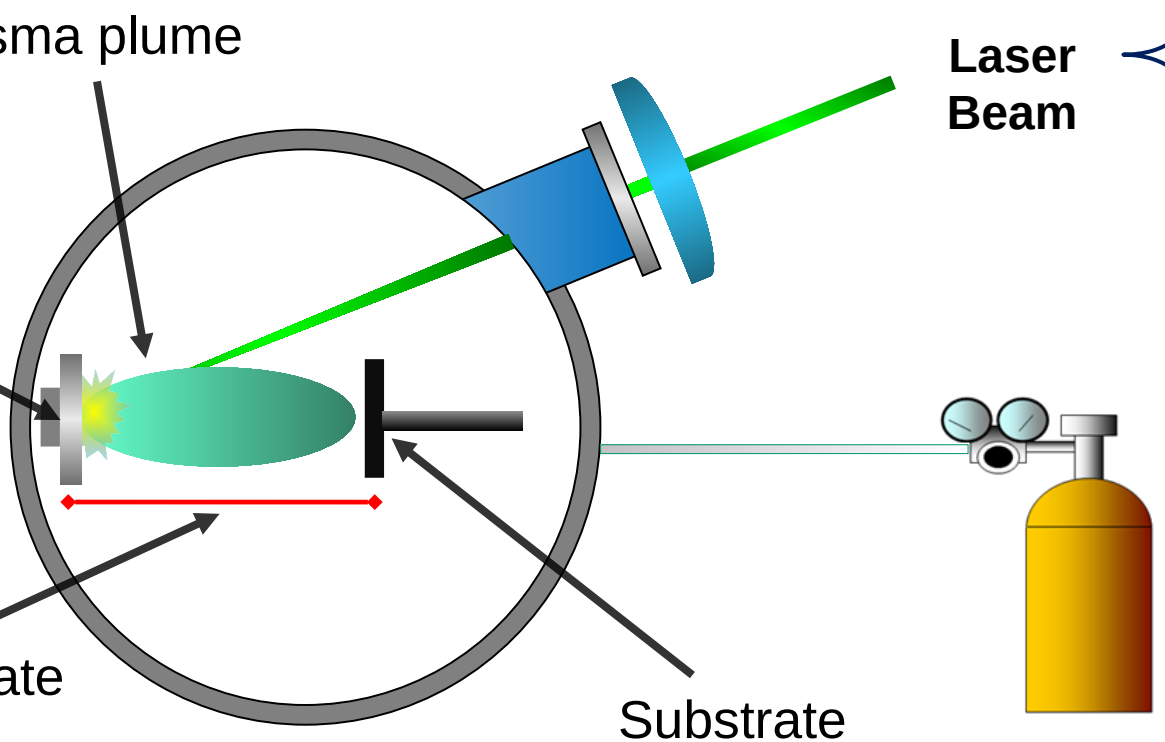
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Pulsed Laser Deposition in a nutshell



Laser Beam

Conventional ns-PLD:
- ~ 5 ns pulse duration
- ~ 1 J pulse energy

Alternative fs-PLD:
- ~ 100 fs pulse duration
- ~ 5 mJ pulse energy

Background Gas
- Inert (He, Ar,...)
- Reactive (N_2, O_2, ...)

Nanofoam properties control

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

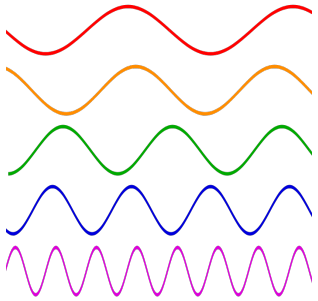
Micro-scale

- Average density
- Morphology

Macro-scale

- Uniformity
- Thickness profile

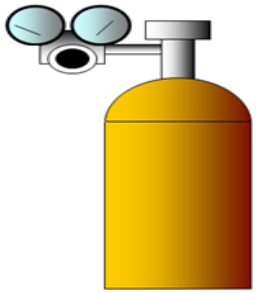
Pulse Duration



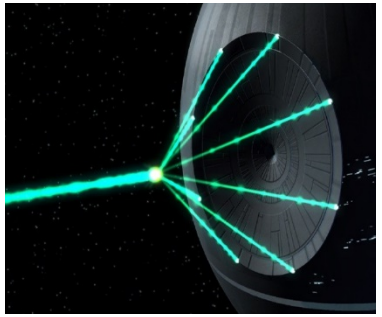
Target composition



Gas pressure



Laser Fluence



Deposition time



PLD process parameters

Nanofoam properties control

Nano-scale

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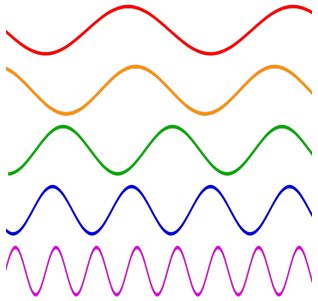
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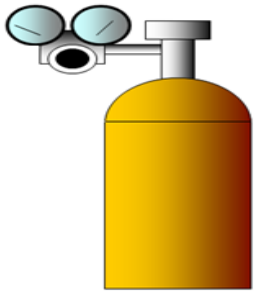
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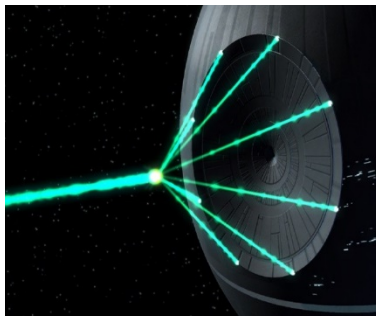
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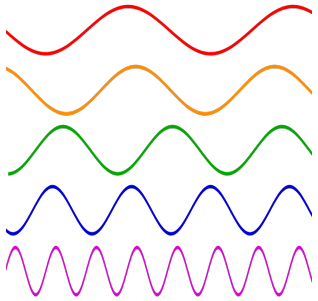
Macro-scale

- Uniformity
- Thickness profile

Complex, non-linear process

Many degrees of freedom

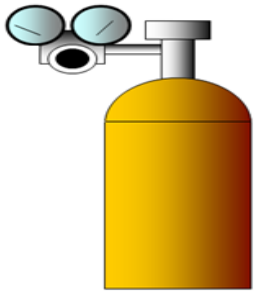
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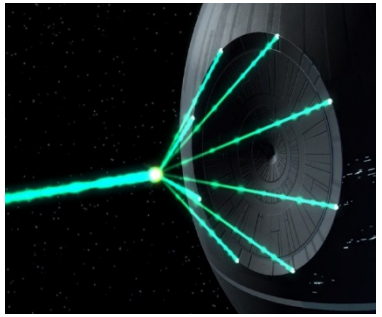
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PLD process parameters

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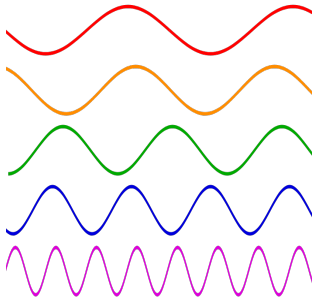
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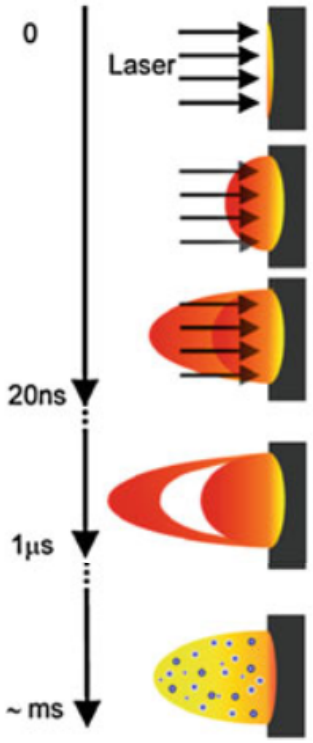
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PLD process parameters

A “snowfall model” for nanofoam growth

Nanosecond PLD

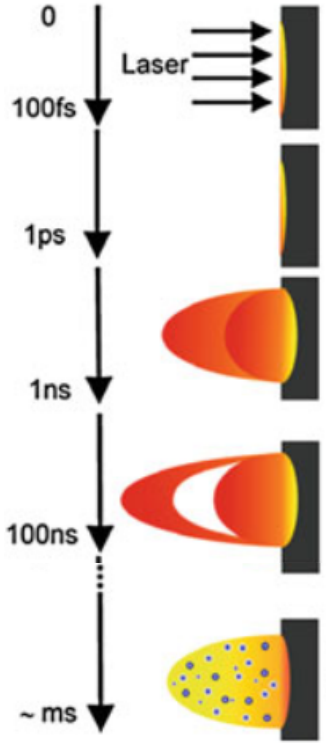


Thermal evaporation of atoms & ions

Laser-plasma plume interaction

Ablation

Femtosecond PLD

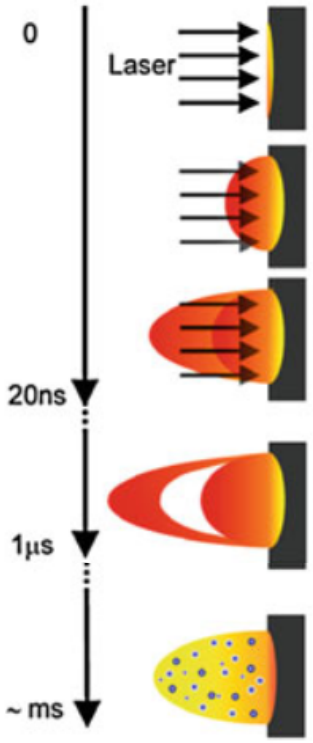


Laser-electron interaction

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

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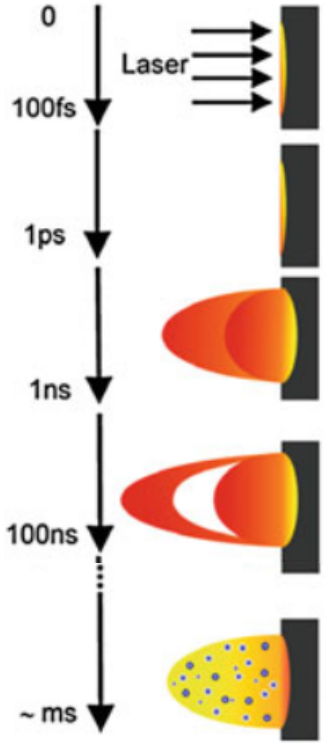
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Nanoparticle nucleation

Ablation

Nanoparticle Synthesis

Femtosecond PLD



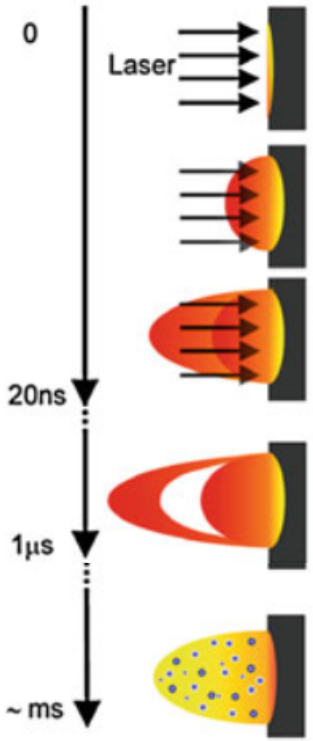
Laser-electron interaction

Direct ejection of nanoparticles

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

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Nanosecond PLD



Thermal evaporation of atoms & ions

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Nanoparticle nucleation

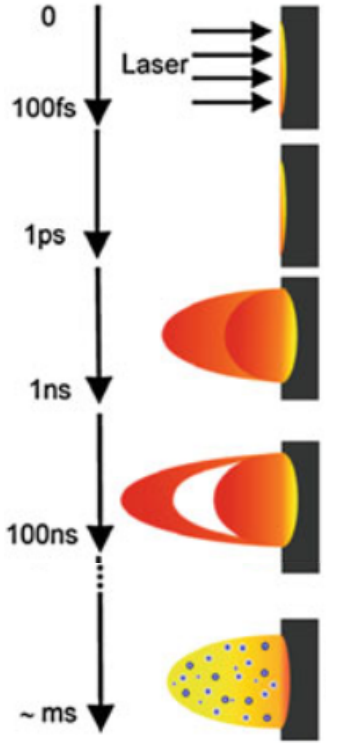
Diffusion-limited Cluster-Cluster aggregation

Ablation 1

Nanoparticle Synthesis 2

Aggregate formation 3

Femtosecond PLD



Laser-electron interaction

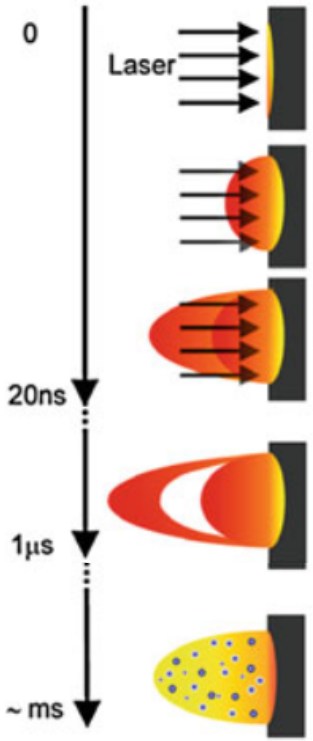
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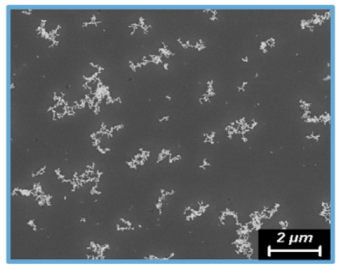


Thermal evaporation of atoms & ions

Laser-plasma plume interaction

Nanoparticle nucleation

Diffusion-limited Cluster-Cluster aggregation



Aggregate landing

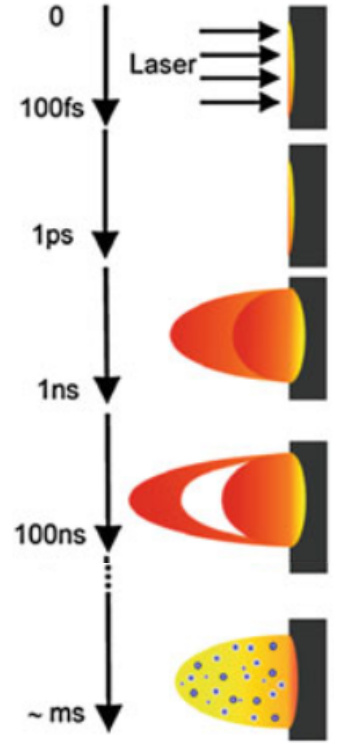
Ablation 1

Nanoparticle Synthesis 2

Aggregate formation 3

Foam growth by aggregate layering 4

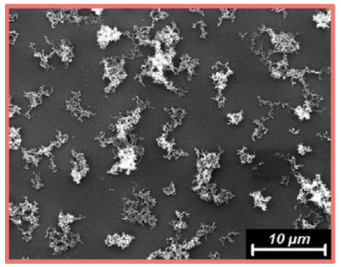
Femtosecond PLD



Laser-electron interaction

Direct ejection of nanoparticles

Diffusion-limited Cluster-Cluster aggregation



Aggregate landing

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

Nanofoam properties control

Nano-scale

- Crystalline structure & composition
- **Nanoparticle** size

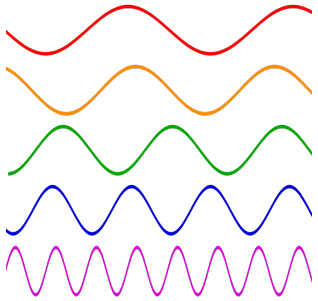
Micro-scale

- Average **density**
- **Morphology**

Macro-scale

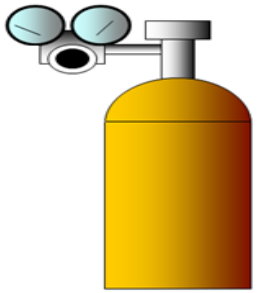
- Uniformity
- Thickness profile

Pulse Duration



Target composition

Gas pressure



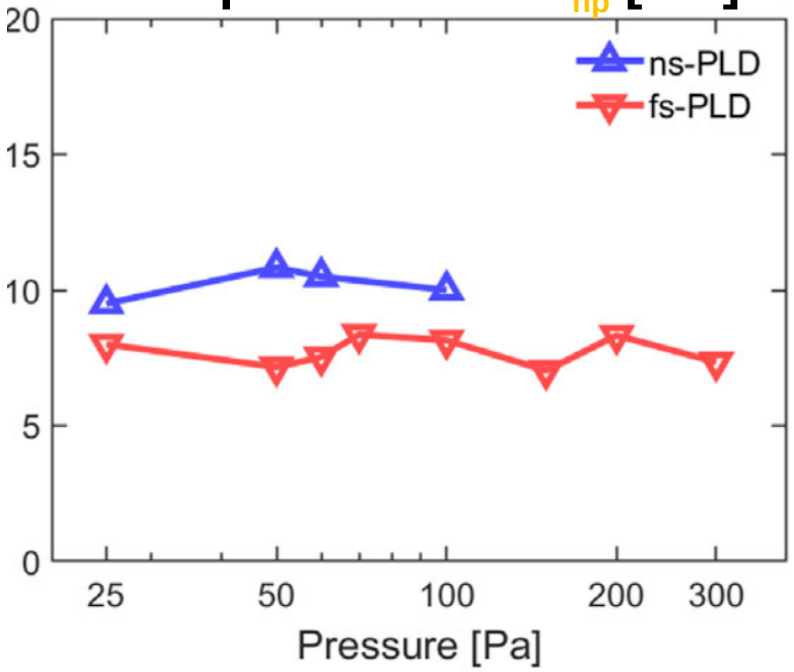
Laser Fluence

Deposition time

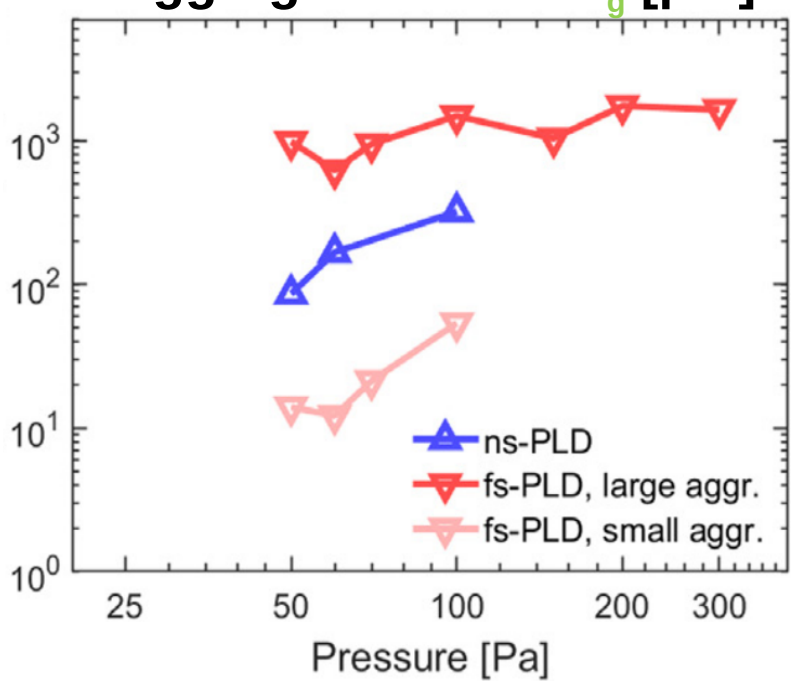
PLD process parameters

Nanofoam analysis at nano- and micro-scale

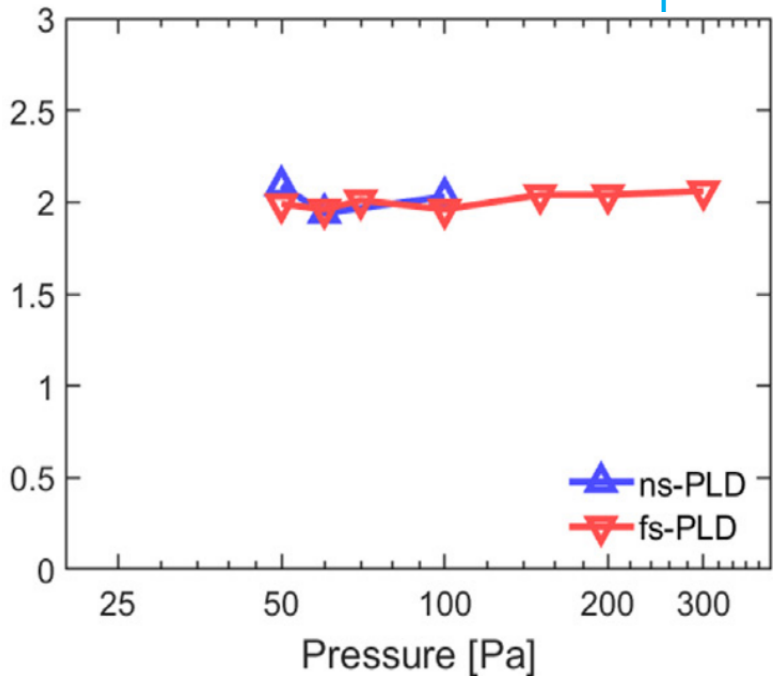
Nanoparticle size d_{np} [nm]

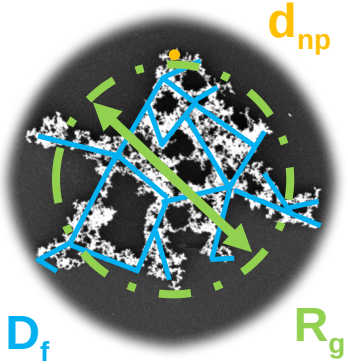


Aggregate radius R_g [μm]



Fractal dimension D_f



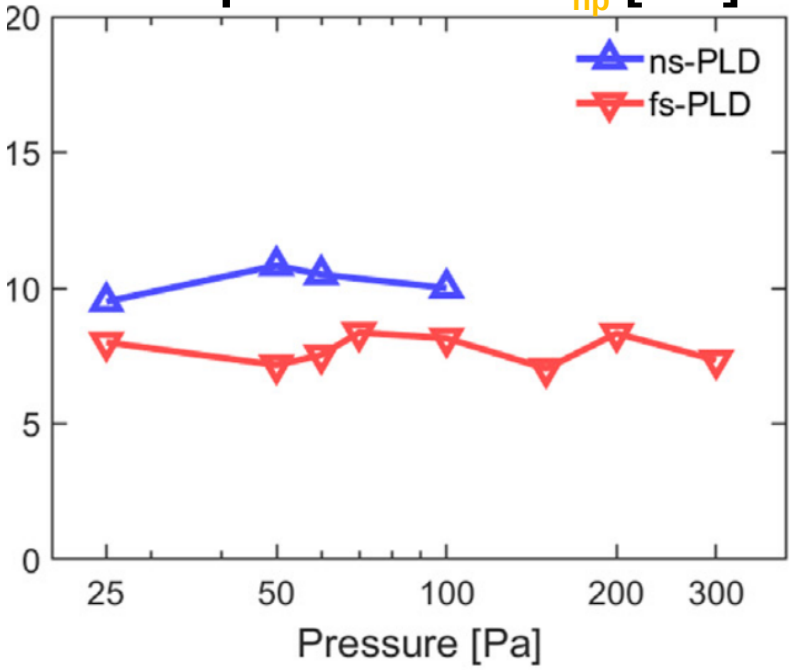


$$\rho_{th} \cong k\rho_{np}\left(\frac{d_{np}}{2R_g}\right)^{3-D_f}$$

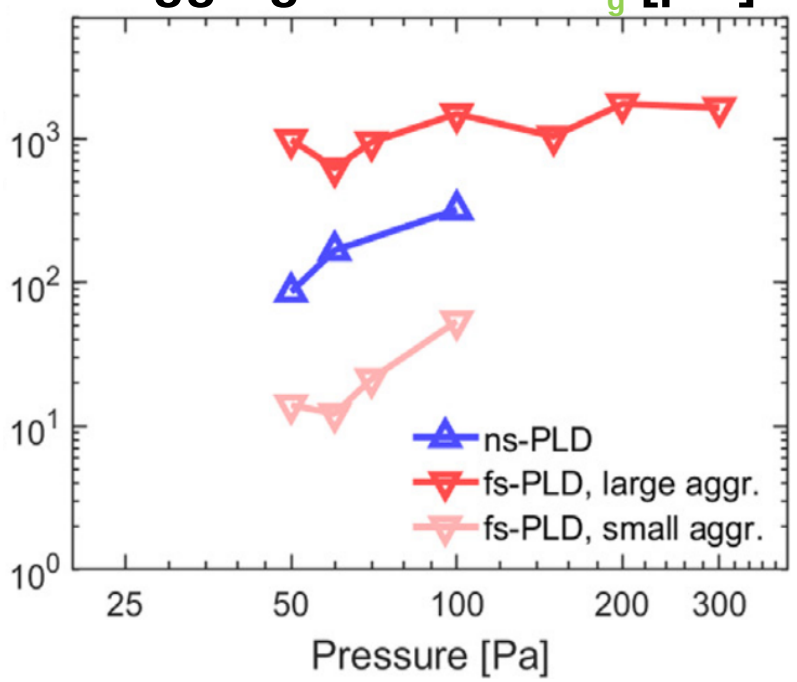
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Nanofoam analysis at nano- and micro-scale

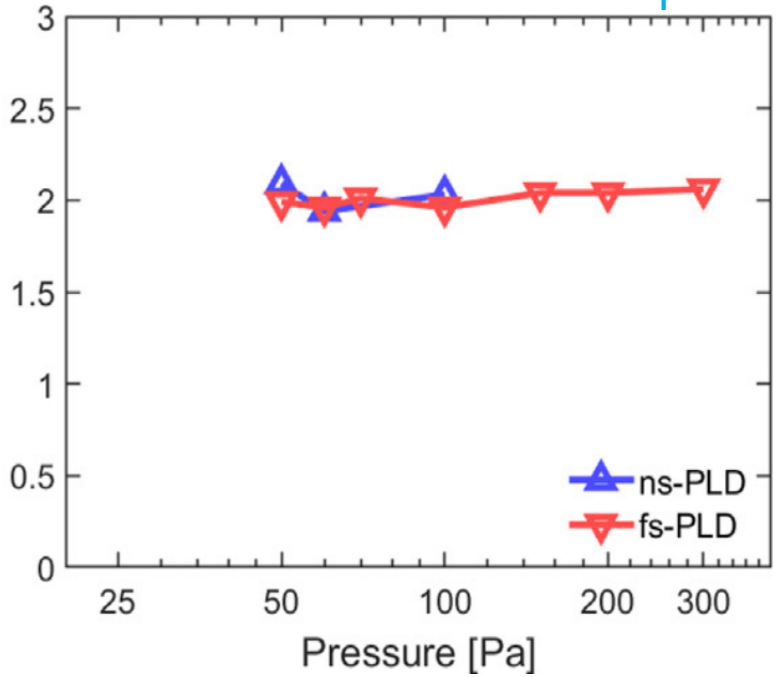
Nanoparticle size d_{np} [nm]

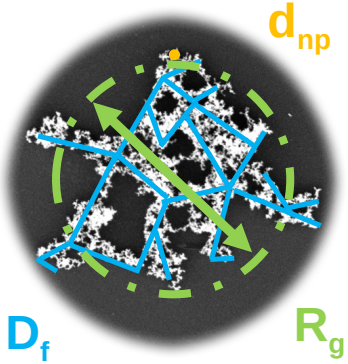


Aggregate radius R_g [μm]



Fractal dimension D_f





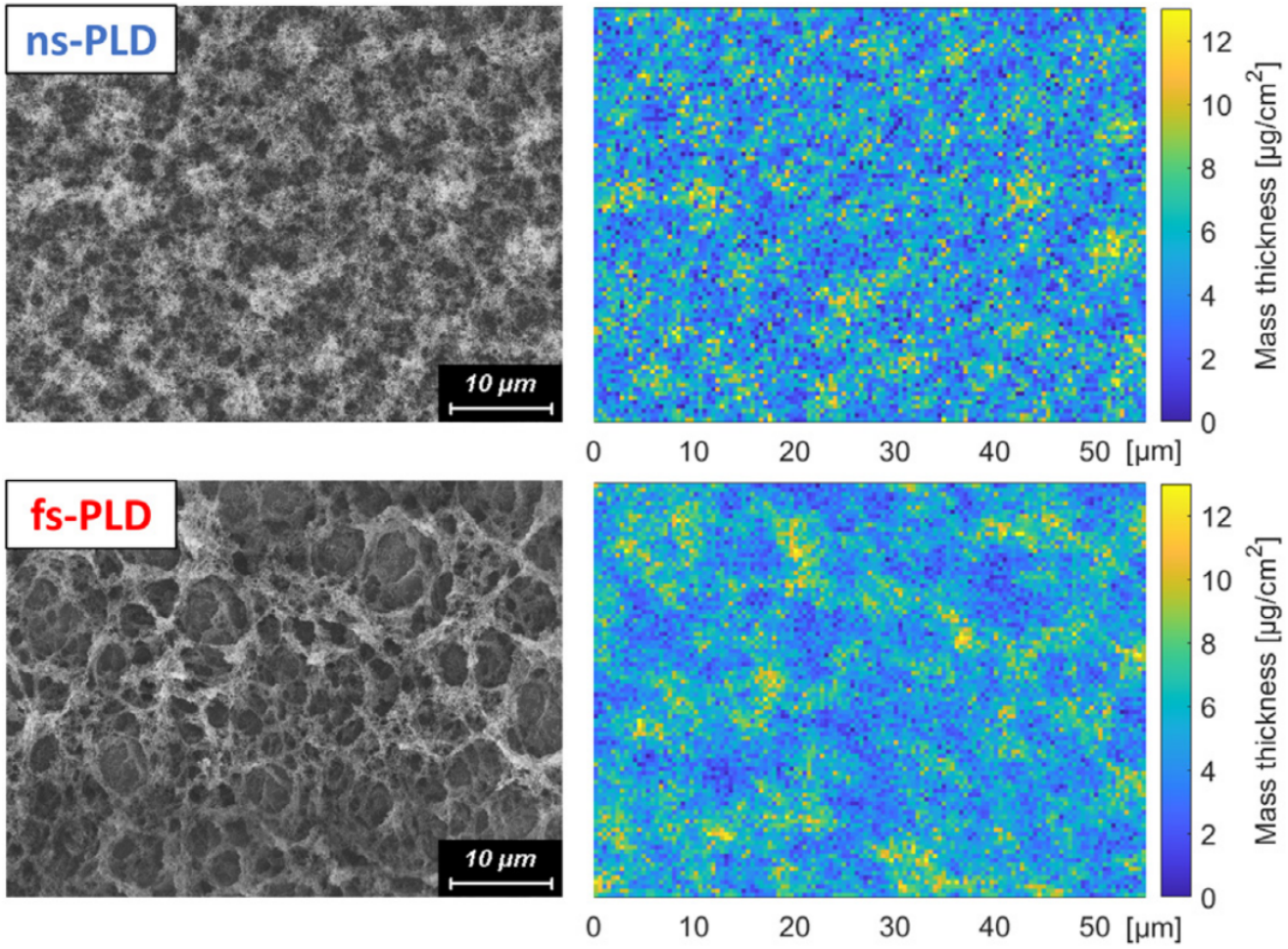
$$\rho_{th} \cong k\rho_{np}\left(\frac{d_{np}}{2R_g}\right)^{3-D_f}$$

Prediction of nanofoam density!

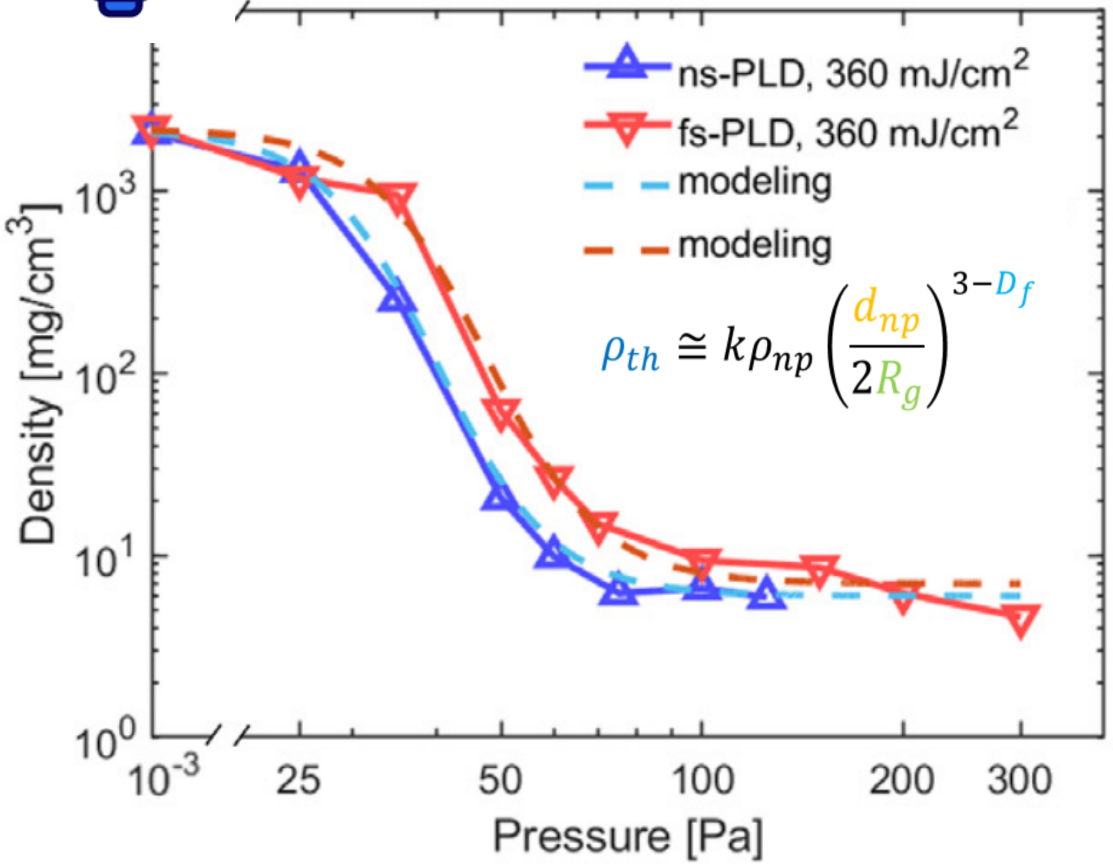
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Fine tuning of nanofoam density and morphology

Density maps of carbon nanofoams



Carbon nanofoam density [experiments and model]



A. Pazzaglia et al., *Material Characterization* **153** (2019) 92-102
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Nanofoam properties control

Nano-scale

- Crystalline structure & **composition**
- Nanoparticle size

Micro-scale

- Average density
- Morphology

Macro-scale

- Uniformity
- **Thickness** profile

Pulse Duration

Target composition



Gas pressure

Laser Fluence

Deposition time

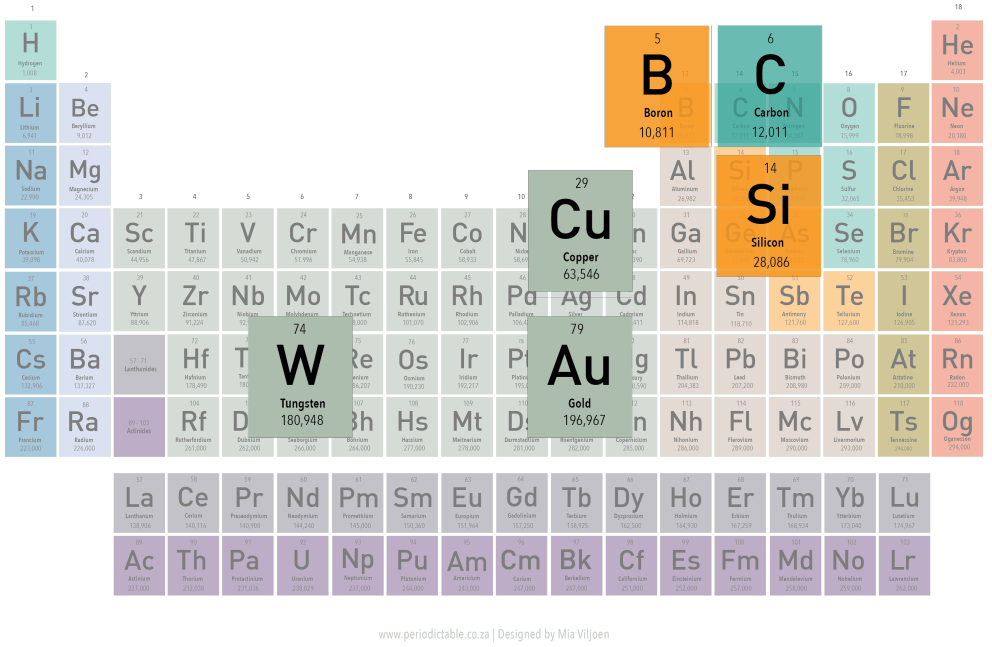


PLD process parameters

A lot of elements to play with…

Deposition with fs-PLD:

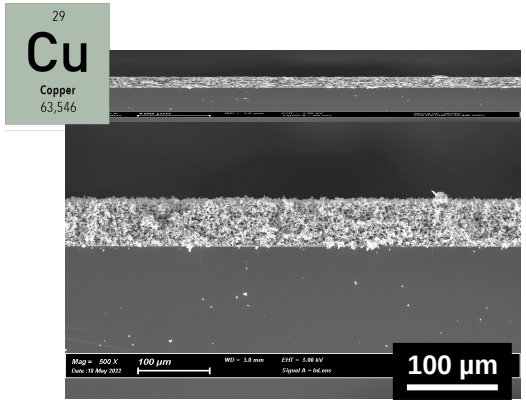
- Same fluence, 0.1 J/cm²
- Different pressure & time

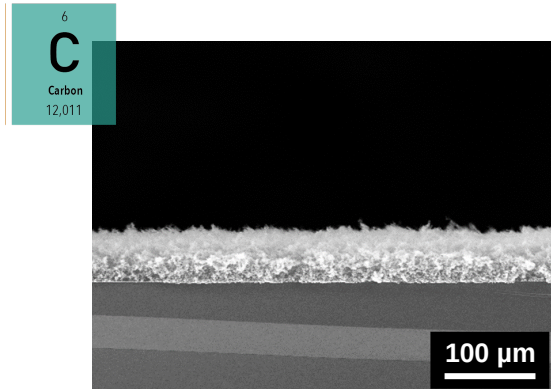


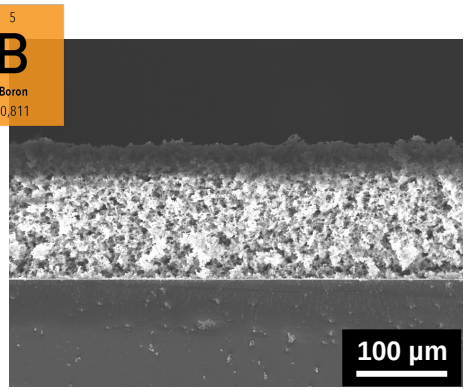
D. Orecchia et al., *Small Structures* **5**, 2024

A lot of elements to play with…

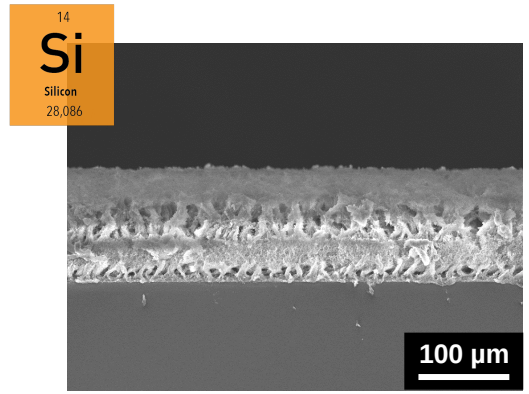
Deposition with fs-PLD:
- Same fluence, 0.1 J/cm²
- Different pressure & time

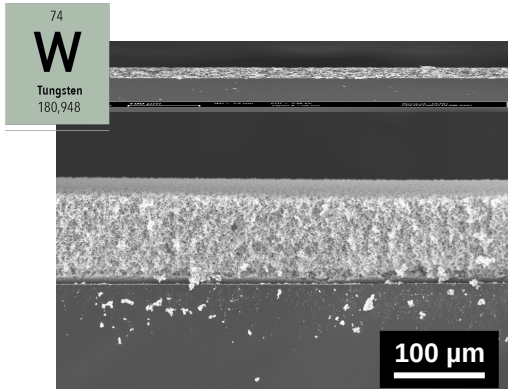


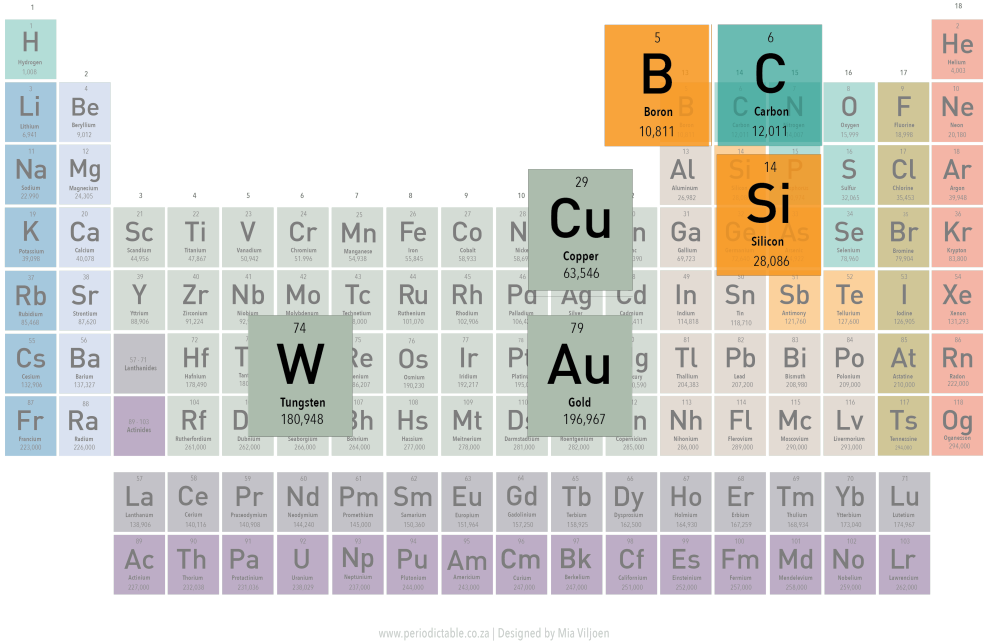


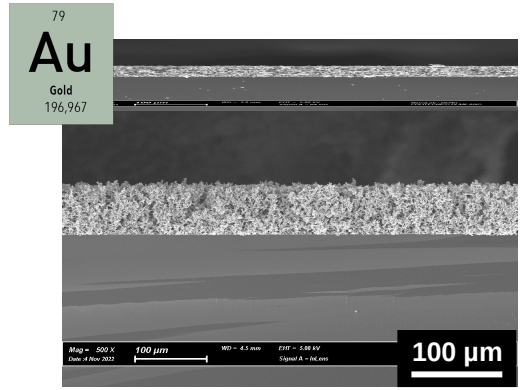


Thickness > 100 µm









D. Orecchia et al., *Small Structures* **5**, 2024

Nanofoam properties control

Nano-scale

- Crystalline structure & **composition**
- Nanoparticle size

Micro-scale

- Average density
- **Morphology**

Macro-scale

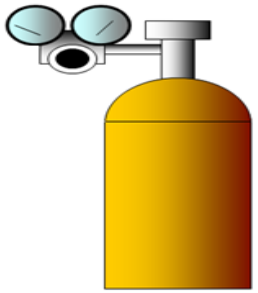
- Uniformity
- Thickness profile

Pulse Duration

Target composition



Gas pressure



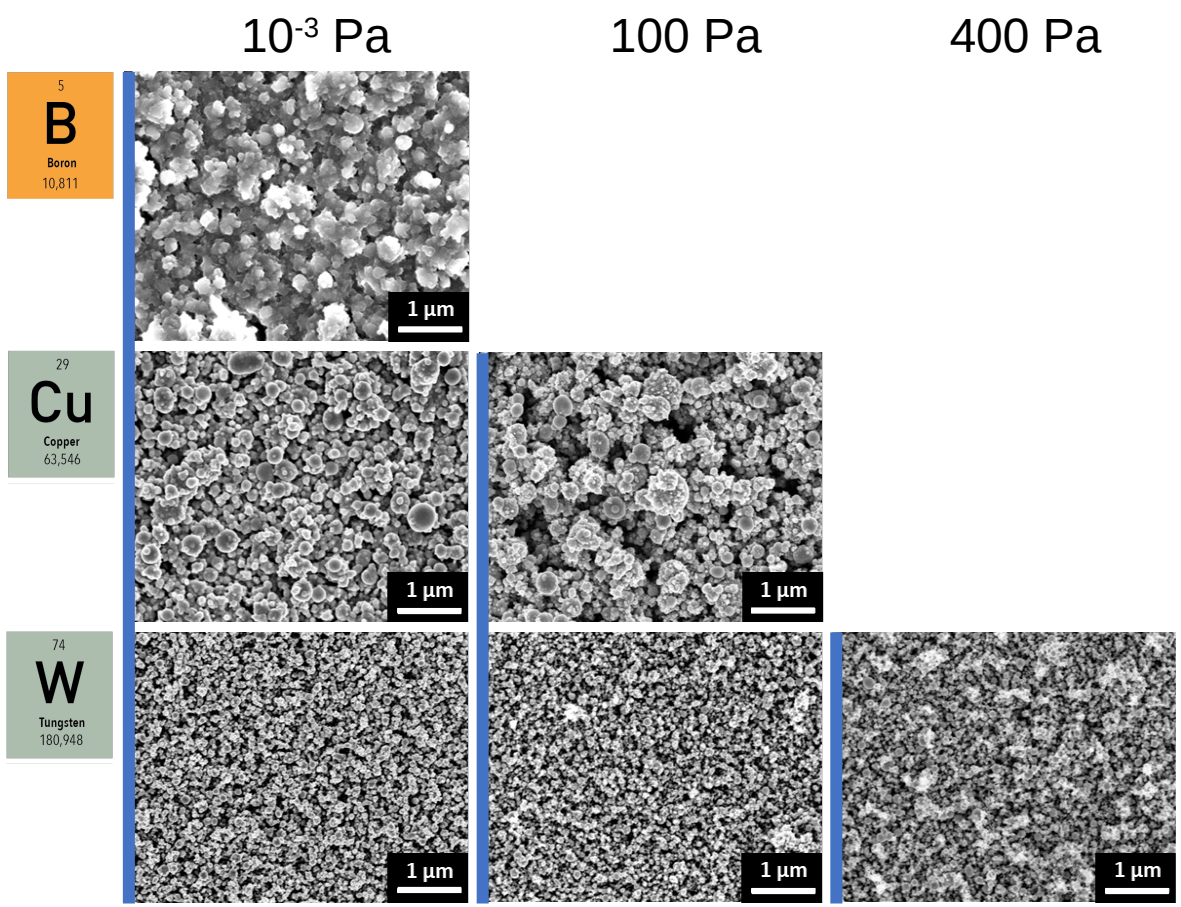
Laser Fluence

Deposition time

PLD process parameters

A nearly-universal behaviour

Argon gas **pressure**

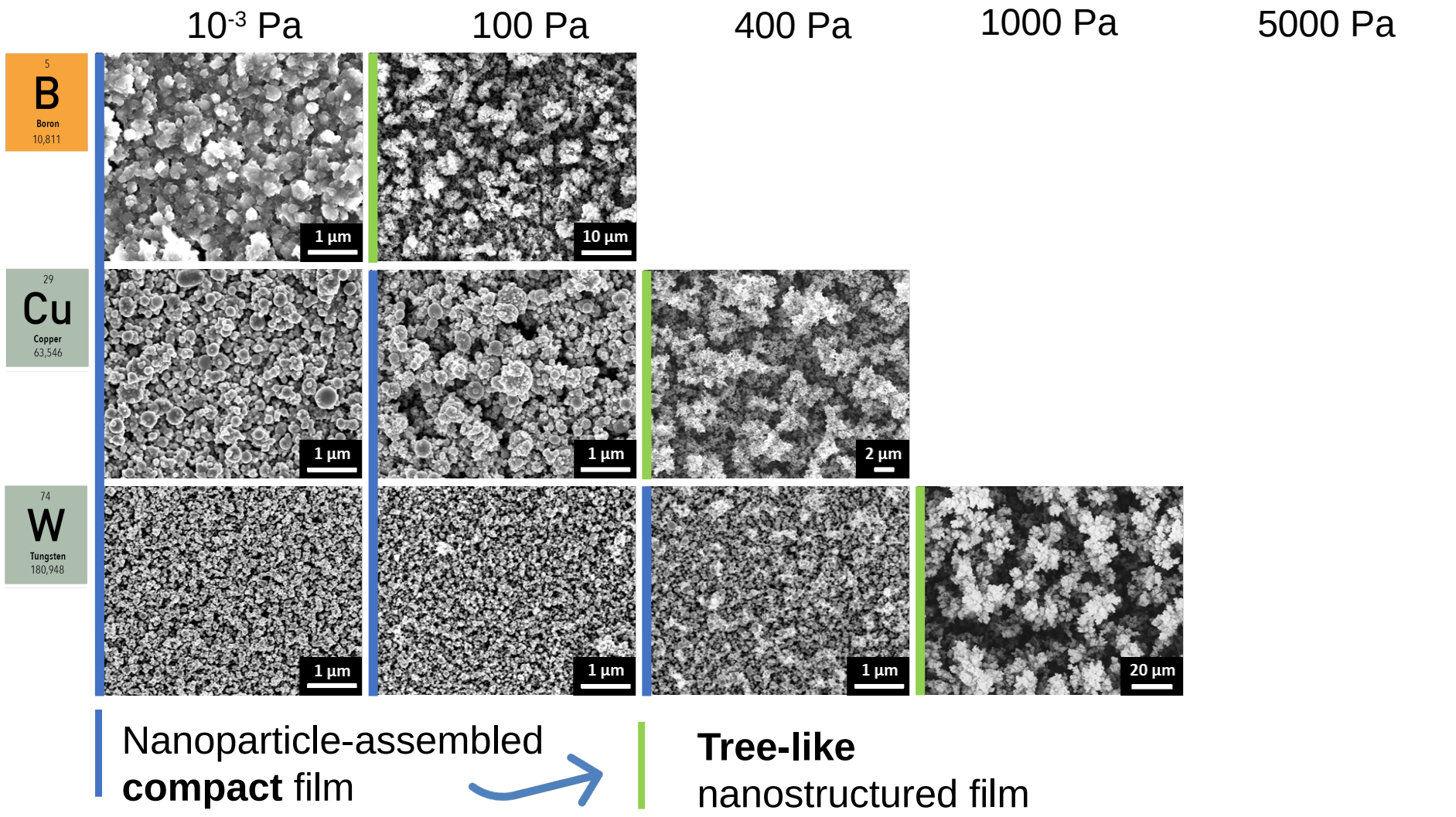


Nanoparticle-assembled
compact film

D. Orecchia et al., *Small Structures* **5**, 2024

A nearly-universal behaviour

Argon gas **pressure**



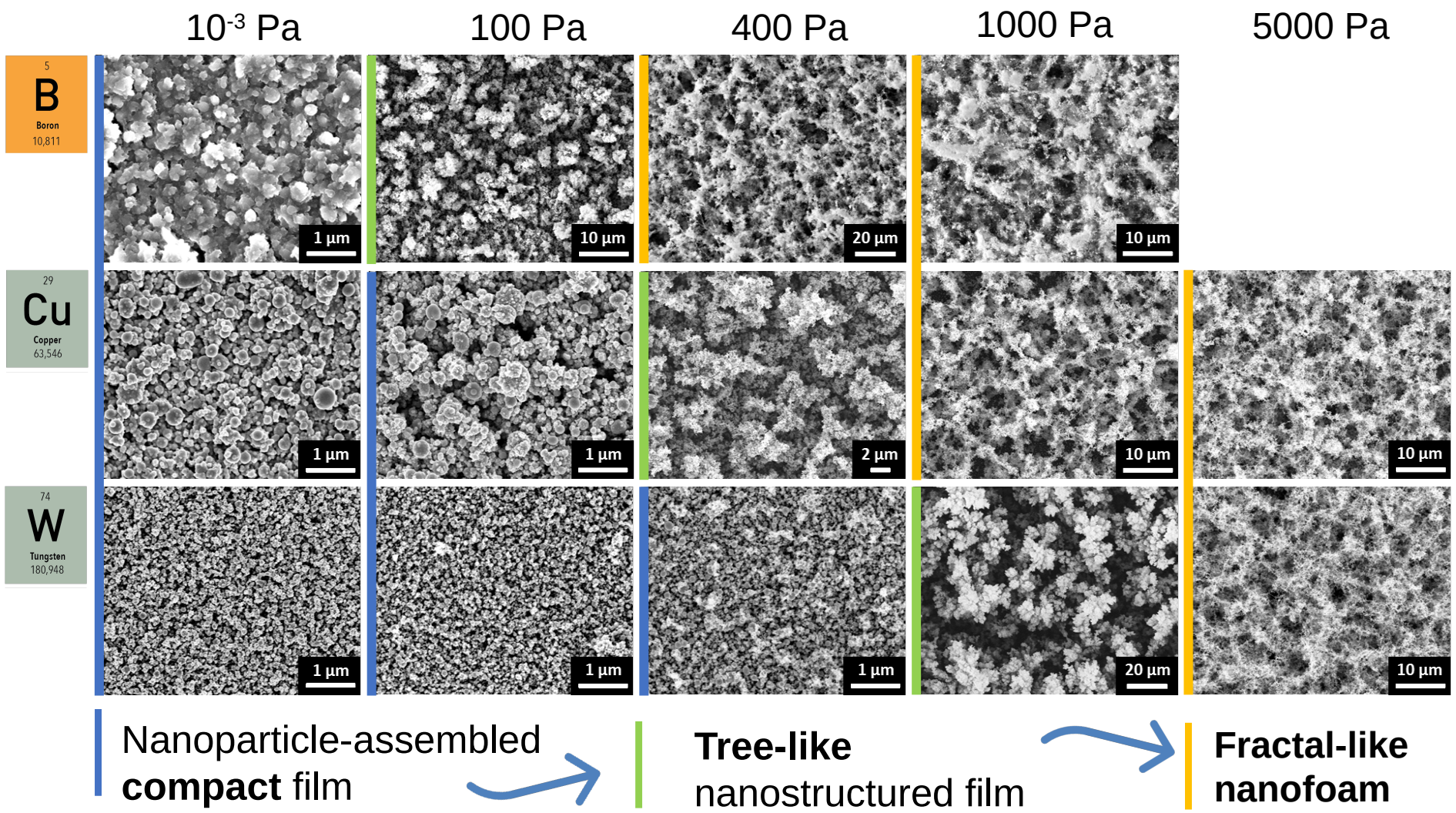
Nanoparticle-assembled **compact** film

Tree-like nanostructured film

D. Orecchia et al., *Small Structures* **5**, 2024

A nearly-universal behaviour

Argon gas **pressure**



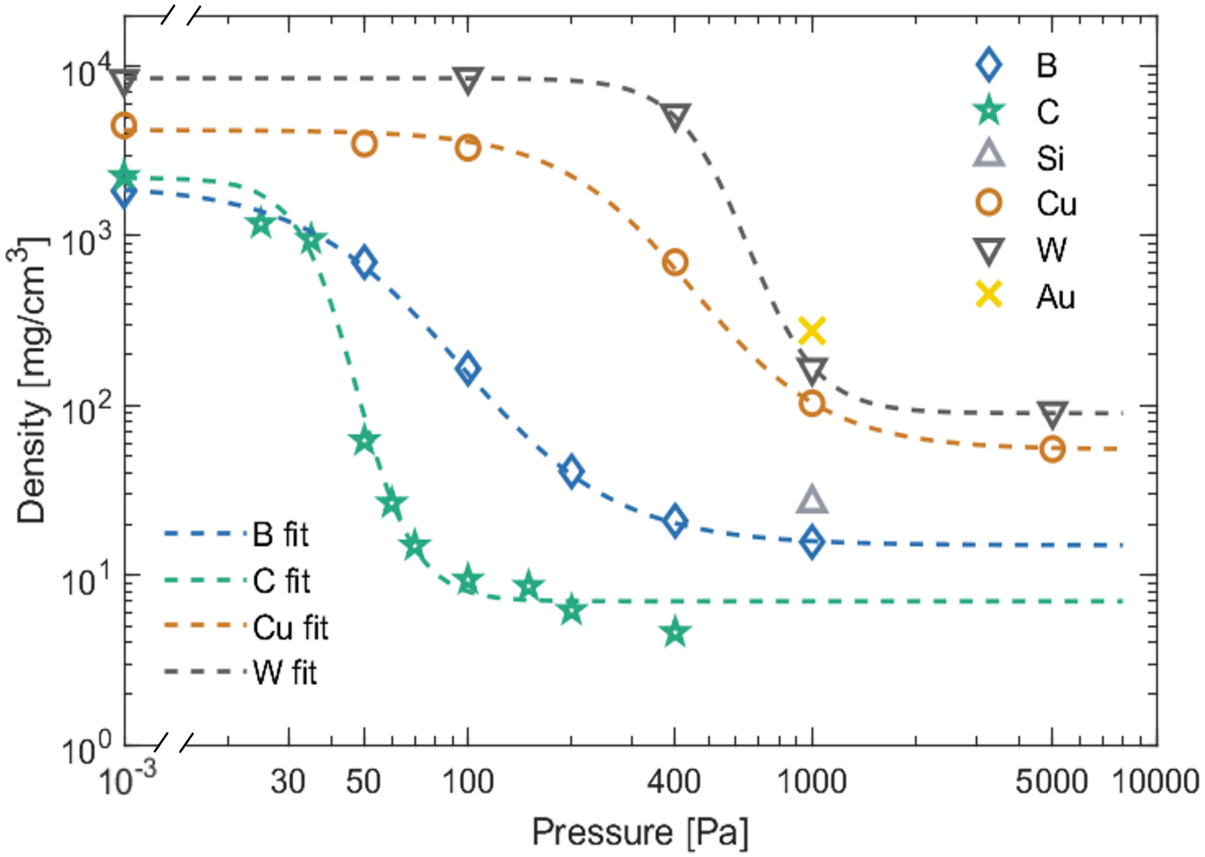
Nanoparticle-assembled **compact** film

Tree-like nanostructured film

Fractal-like nanofoam

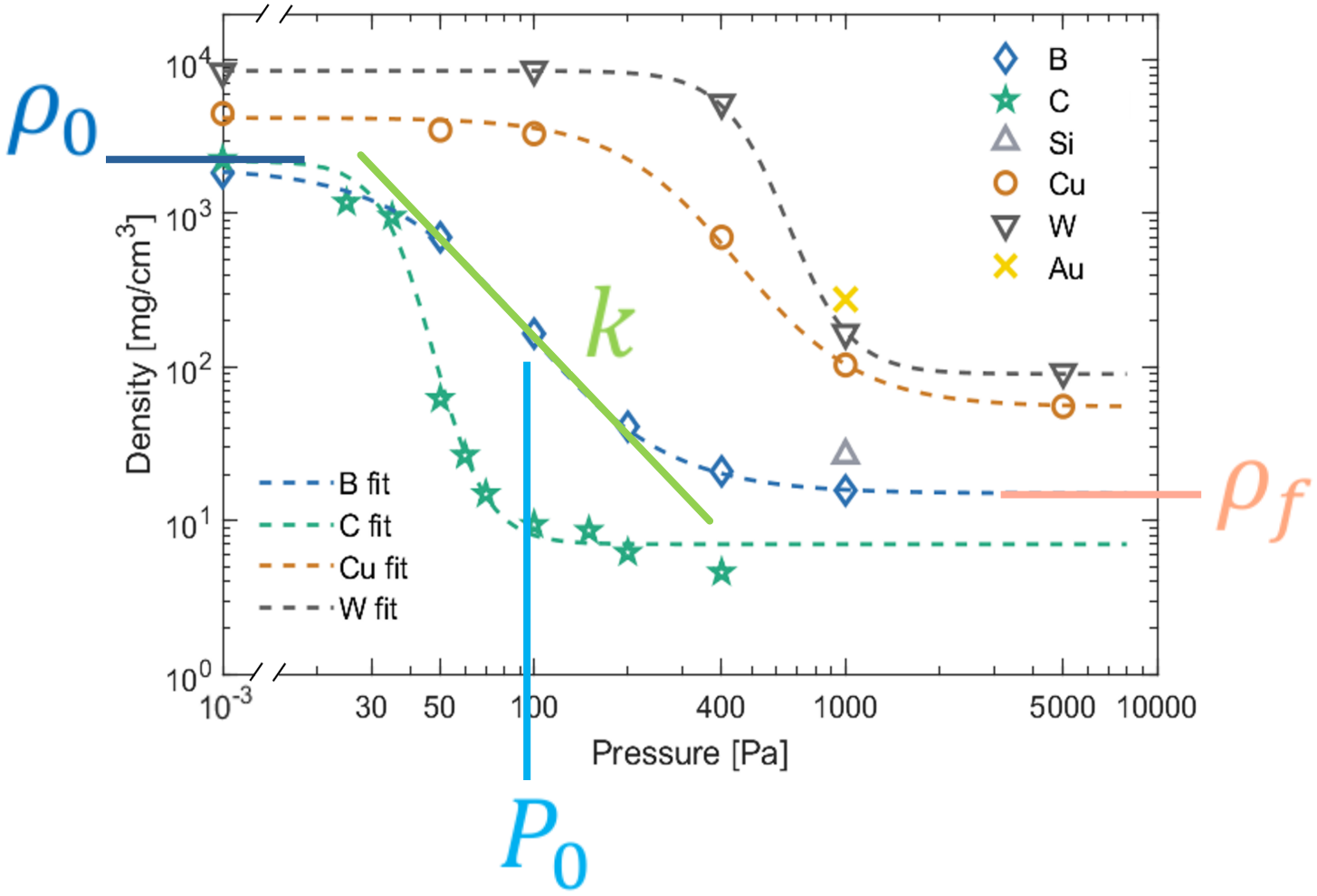
D. Orecchia et al., *Small Structures* **5**, 2024

A nearly-universal behaviour

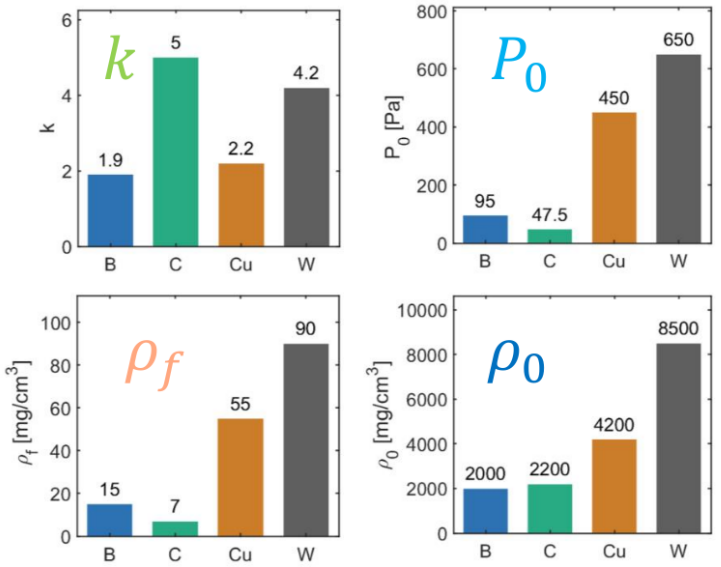


D. Orecchia et al., *Small Structures* **5**, 2024

A nearly-universal behaviour

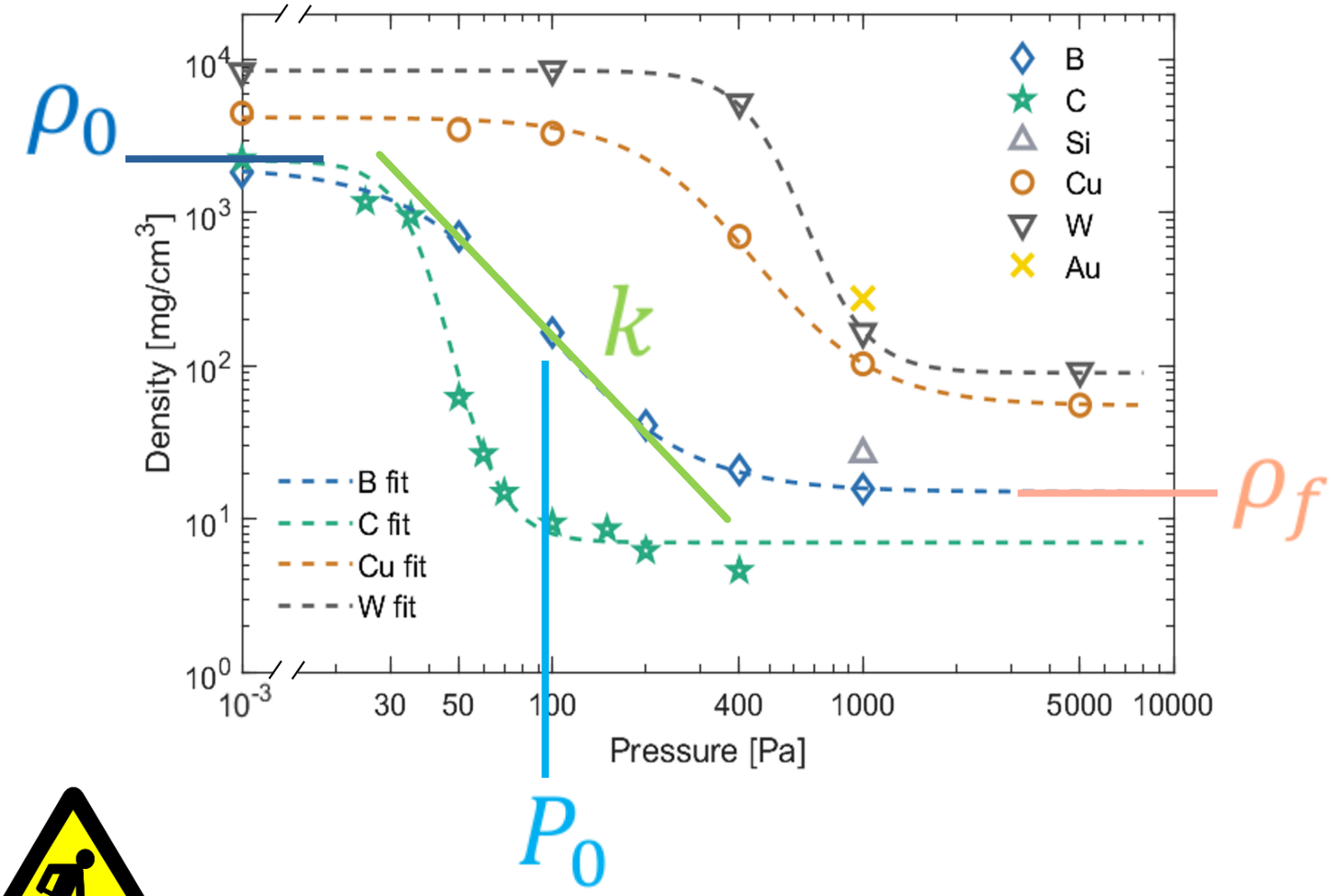


$$\rho(P) = \rho_0 \left(\frac{\rho_f}{\rho_0}\right)^{\left[\frac{P^k}{P^k + P_0^k}\right]}$$

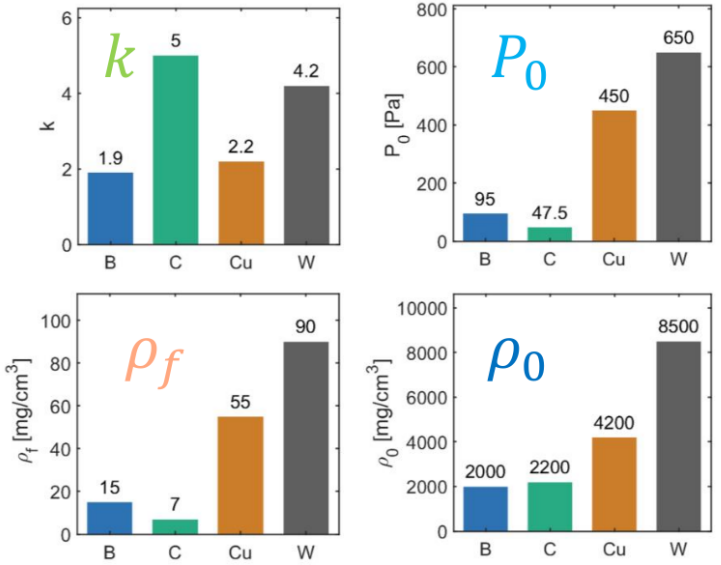


D. Orecchia et al., *Small Structures* **5**, 2024

A nearly-universal behaviour



$$\rho(P) = \rho_0 \left(\frac{\rho_f}{\rho_0}\right)^{\left[\frac{P^k}{P^k + P_0^k}\right]}$$





Is a **first-principle deduction** of the free parameters possible?

D. Orecchia et al., *Small Structures* **5**, 2024

Why foams in laser-plasma interaction?

A closer look to nanofoams

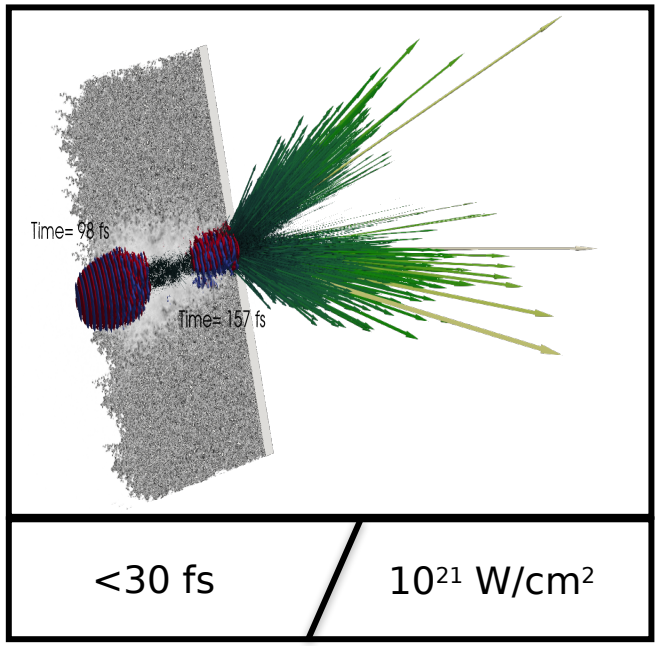
How to tune nanofoam properties

A few examples of applications

Open issues & perspectives

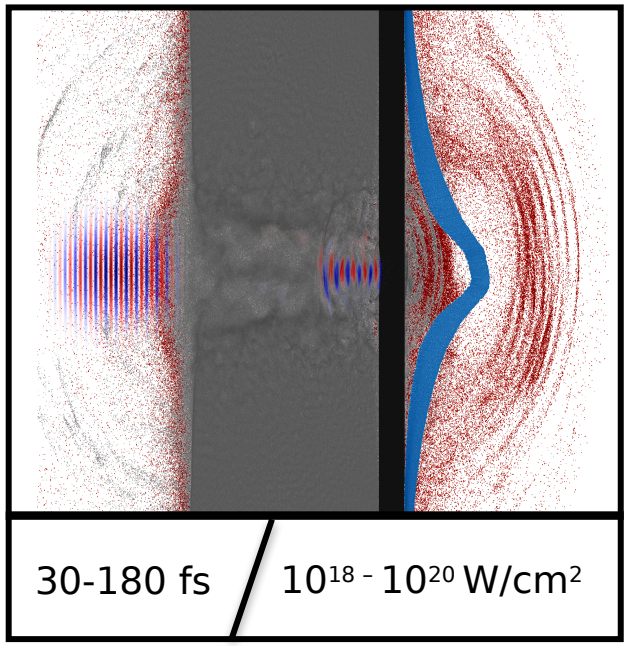
A few examples of application

γ-rays generation



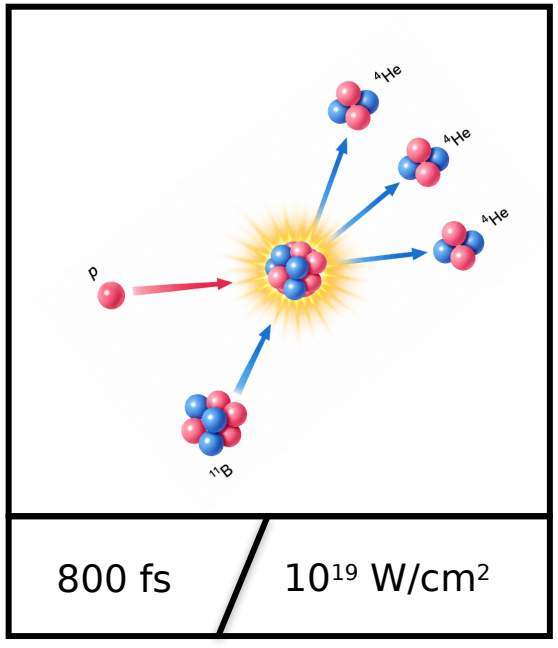
<30 fs | 10^{21} W/cm²

Ion acceleration



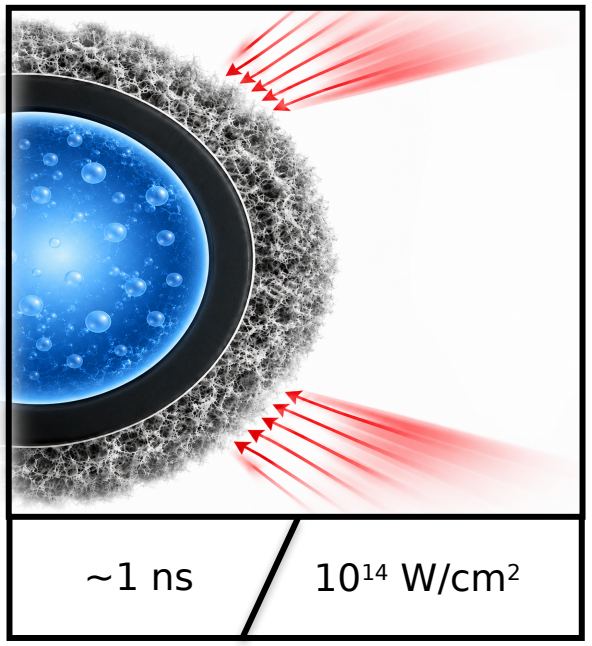
30-180 fs | 10^{18} - 10^{20} W/cm²

p-^{11}B fusion



800 fs | 10^{19} W/cm²

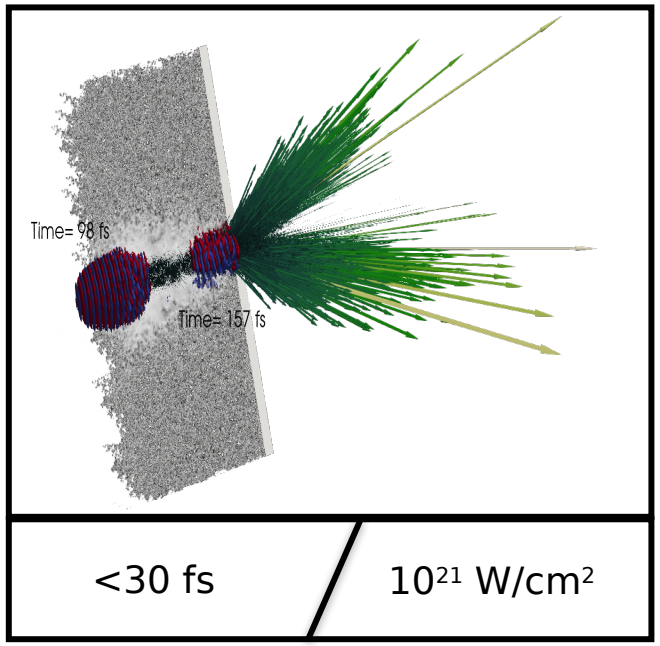
Direct Drive ICF



~1 ns | 10^{14} W/cm²

A few examples of application

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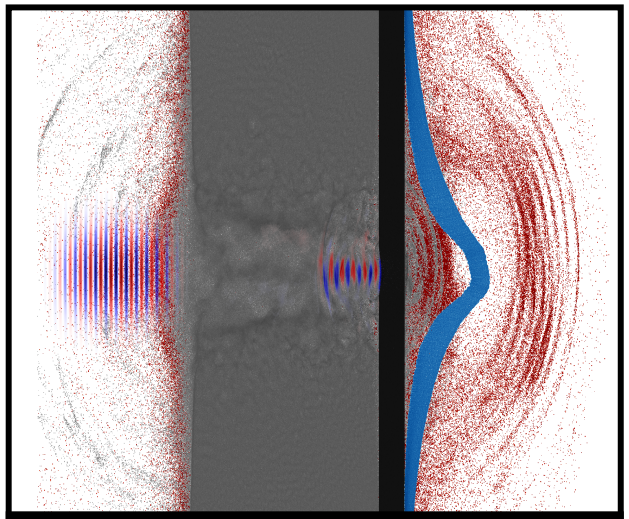
Two experiments (2025, 2026) @ Apollon (LULI).
See M. Galbiati talk at 15:20!

A few examples of application

γ-rays generation

<30 fs | 10^{21} W/cm²

Ion acceleration



30-180 fs | 10^{18} - 10^{20} W/cm²

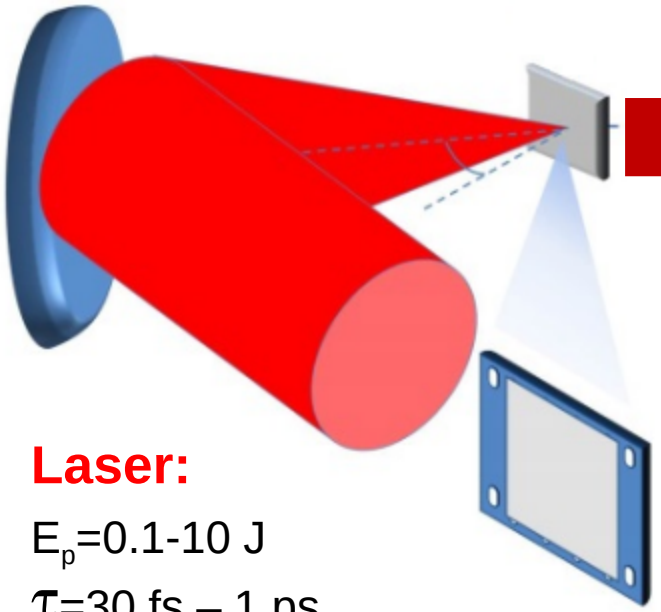
p-^{11}B fusion

800 fs | 10^{19} W/cm²

Direct Drive ICF

~1 ns | 10^{14} W/cm²

Nanofoams for advanced TNSA



Laser:

E_p=0.1-10 J

τ=30 fs – 1 ps

I=10^{18} – 10^{22} W/cm^2

Accelerated p

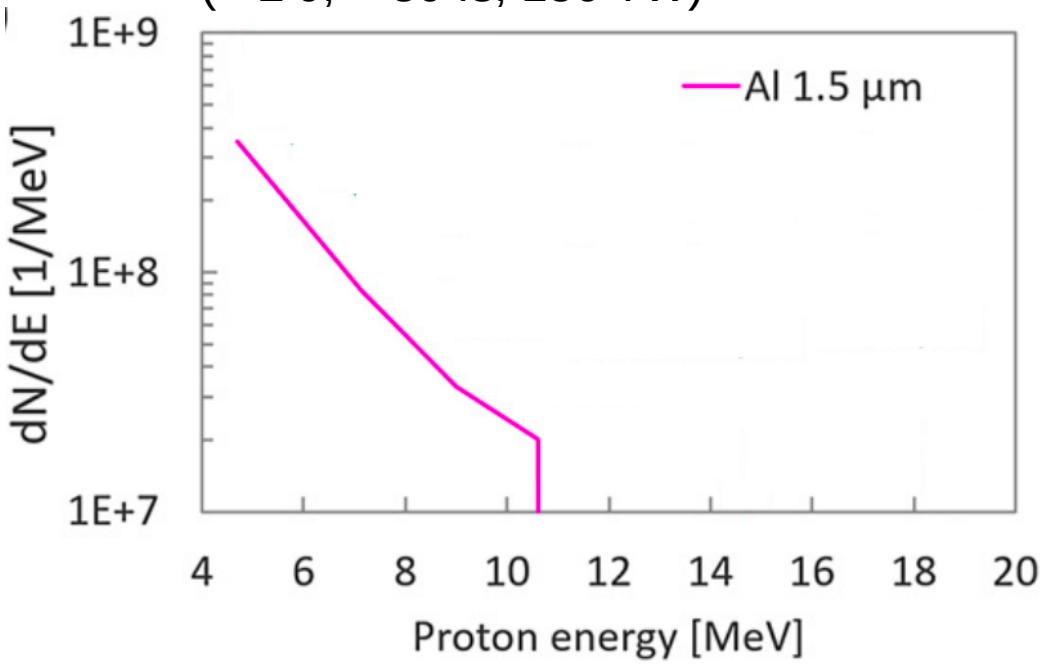
E_{max} ≈ 10s MeV

10^{10}-10^{12} ions/bunch

~ ps duration

Experiments @ Draco
(~ 2 J, ~ 30 fs, 150 TW)

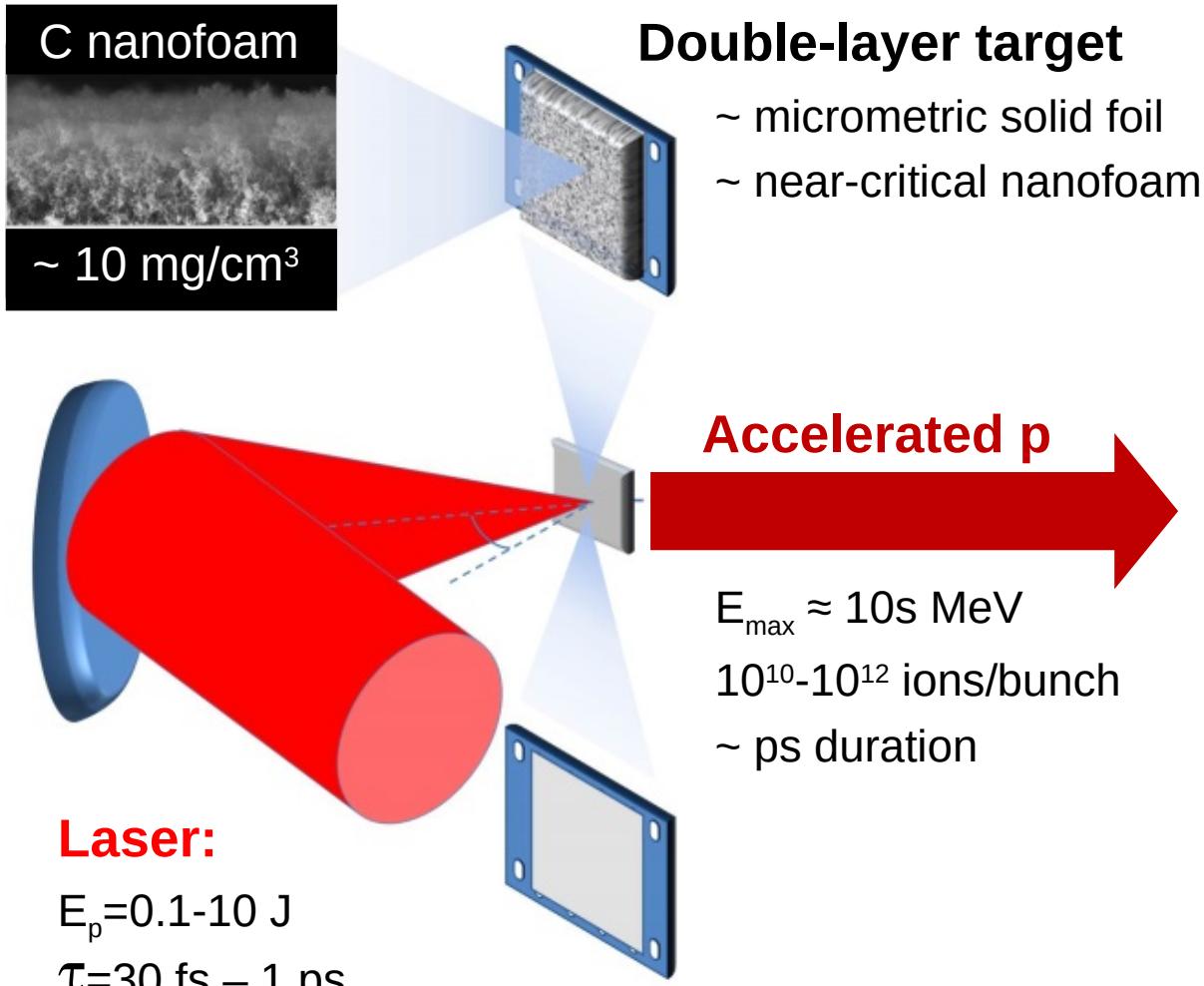
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



F. Mirani et al., *Phys. Rev. Applied* **24** 014017 (2025)

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
I. Prencipe et al., *New Jour. Physics* **23.9** (2021)

Nanofoams for advanced TNSA



Double-layer target

~ micrometric solid foil

~ near-critical nanofoam

Accelerated p

E_{max} ≈ 10s MeV

10^{10}-10^{12} ions/bunch

~ ps duration

Laser:

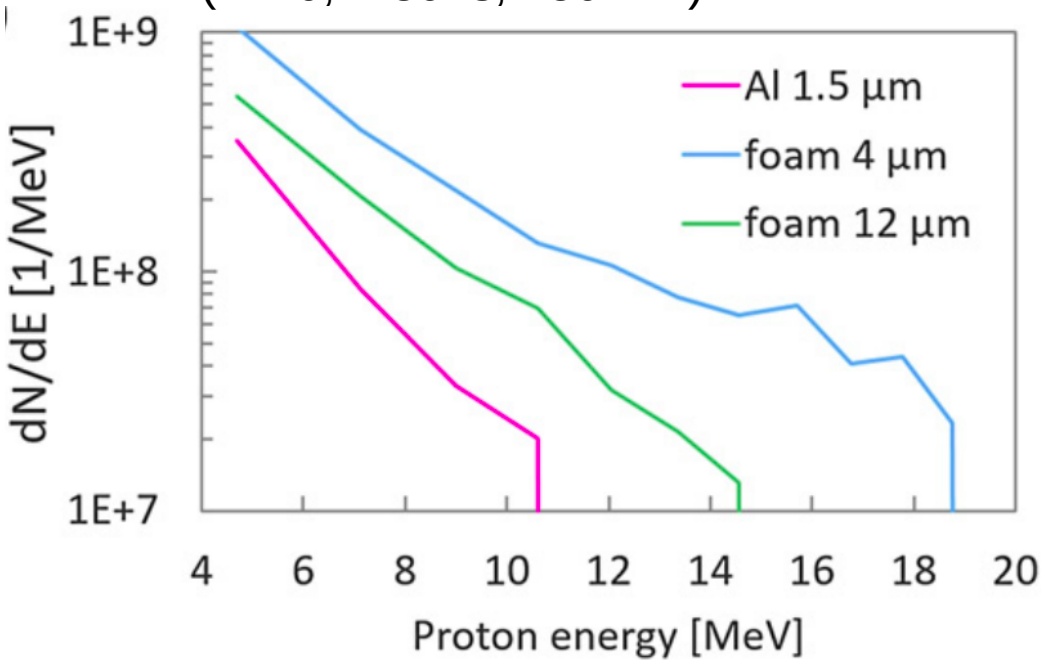
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(~ 2 J, ~ 30 fs, 150 TW)

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



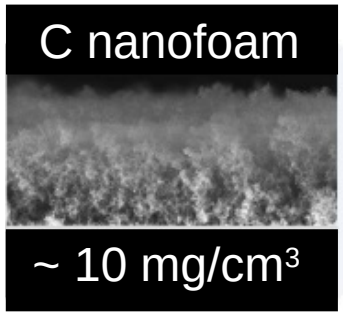
~ x **2** in maximum **energy**!

~ x **4** in **number** of protons!

F. Mirani et al., *Phys. Rev. Applied* **24** 014017 (2025)

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
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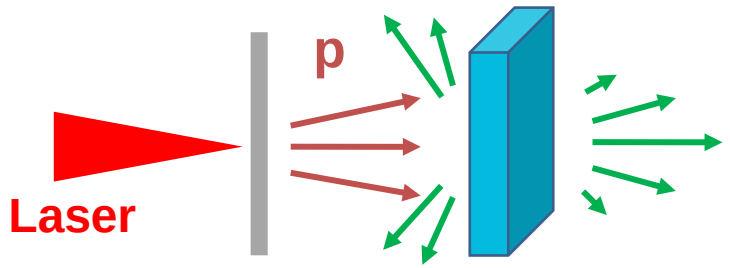
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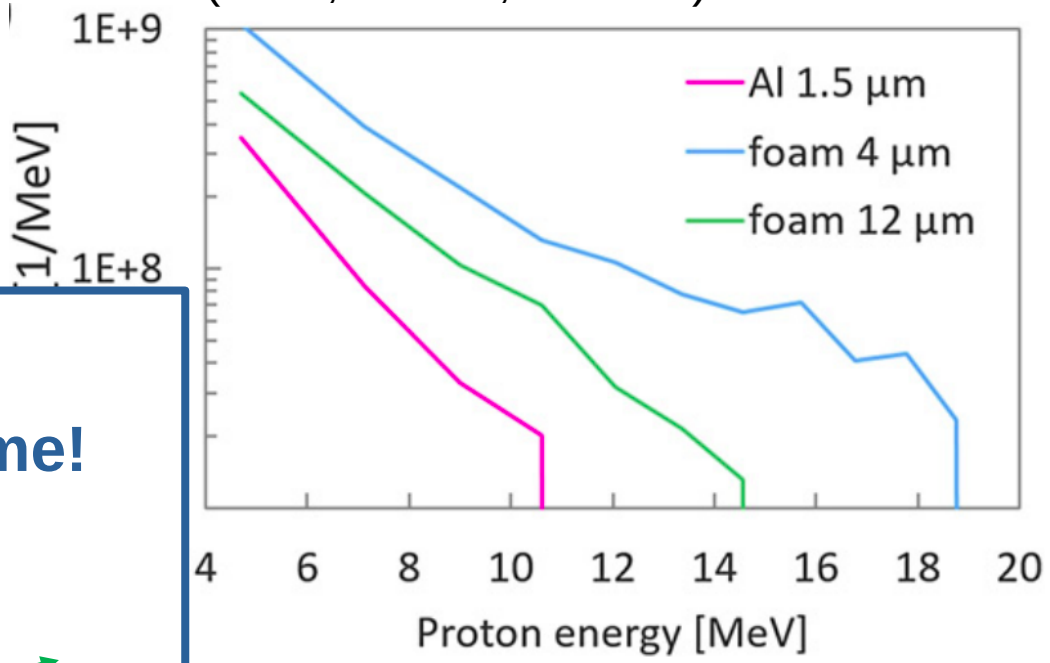
I=10^{18} – 10^{22} W/cm^2

Will work in any pitcher-catcher scheme!



Experiments @ Draco
(~ 2 J, ~ 30 fs, 150 TW)

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



~ x **2** in maximum **energy**!

~ x **4** in **number** of protons!

F. Mirani et al., *Phys. Rev. Applied* **24** 014017 (2025)

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
I. Prencipe et al., *New Jour. Physics* **23.9** (2021)

A few examples of application

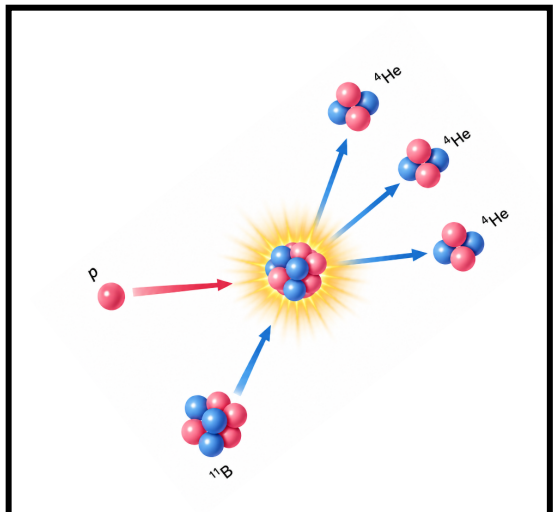
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p-^{11}B fusion



800 fs | 10^{19} W/cm²

Direct Drive ICF

~1 ns | 10^{14} W/cm²

First experiment in 2024 @ Taranis (QUB): in-foam fusion, α flux ~ 5 × 10^{7} sr^{-1} J^{-1} [1]

Next experiment in November 2026 @ ELI Beamlines

[1] D. Molloy et al., Phys. Rev. Res, 7, 013230 (2025)

A few examples of application

γ-rays generation

<30 fs | 10^{21} W/cm²

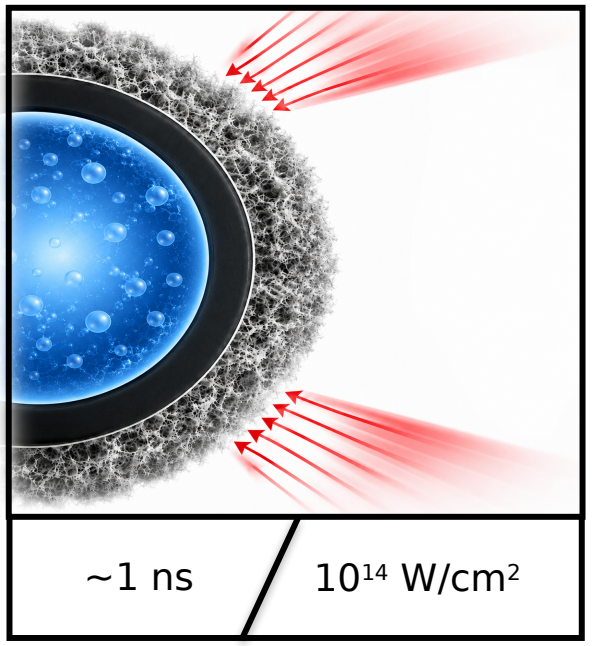
Ion acceleration

30-180 fs | 10^{18} - 10^{20} W/cm²

p-^{11}B fusion

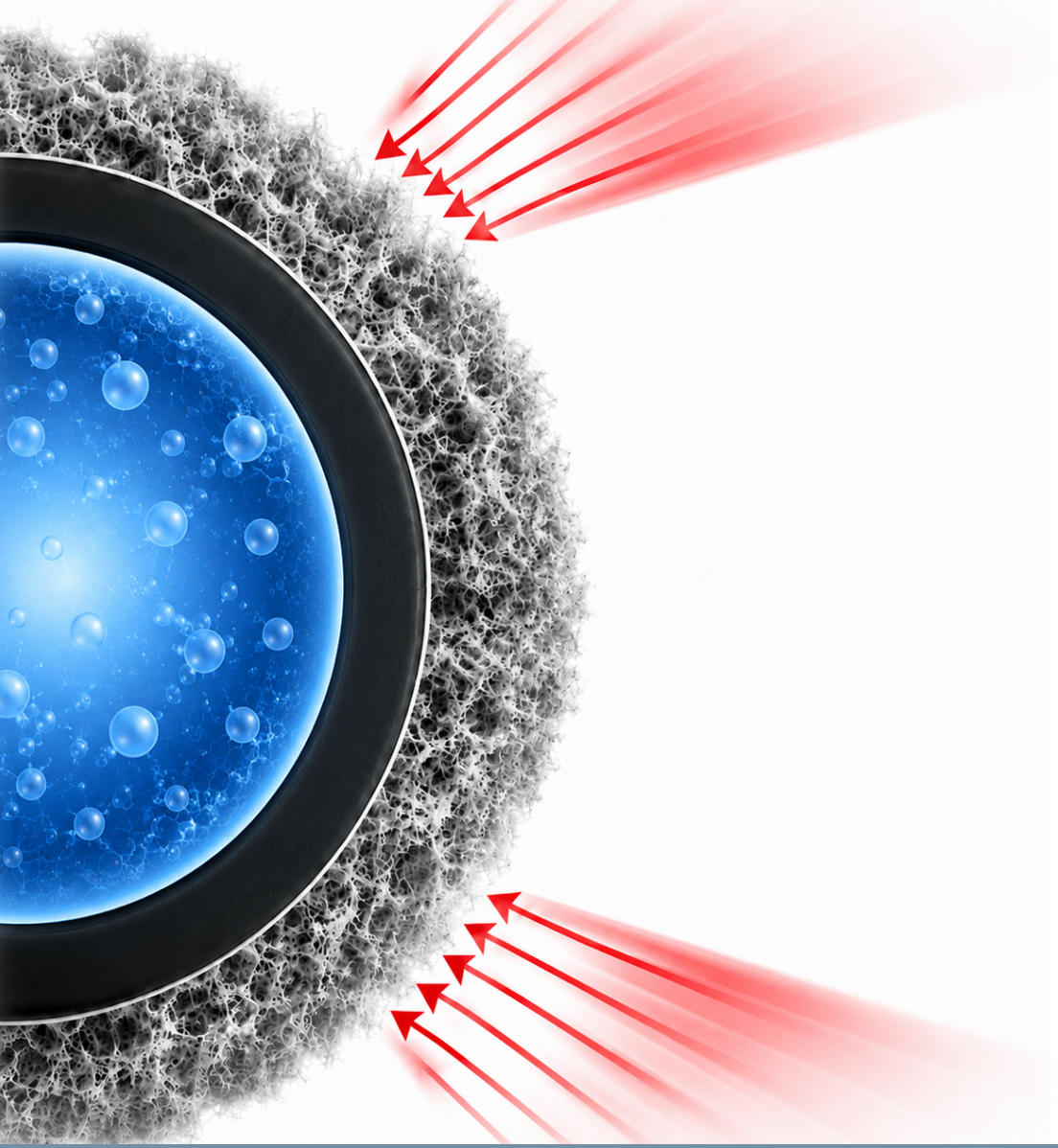
800 fs | 10^{19} W/cm²

Direct Drive ICF



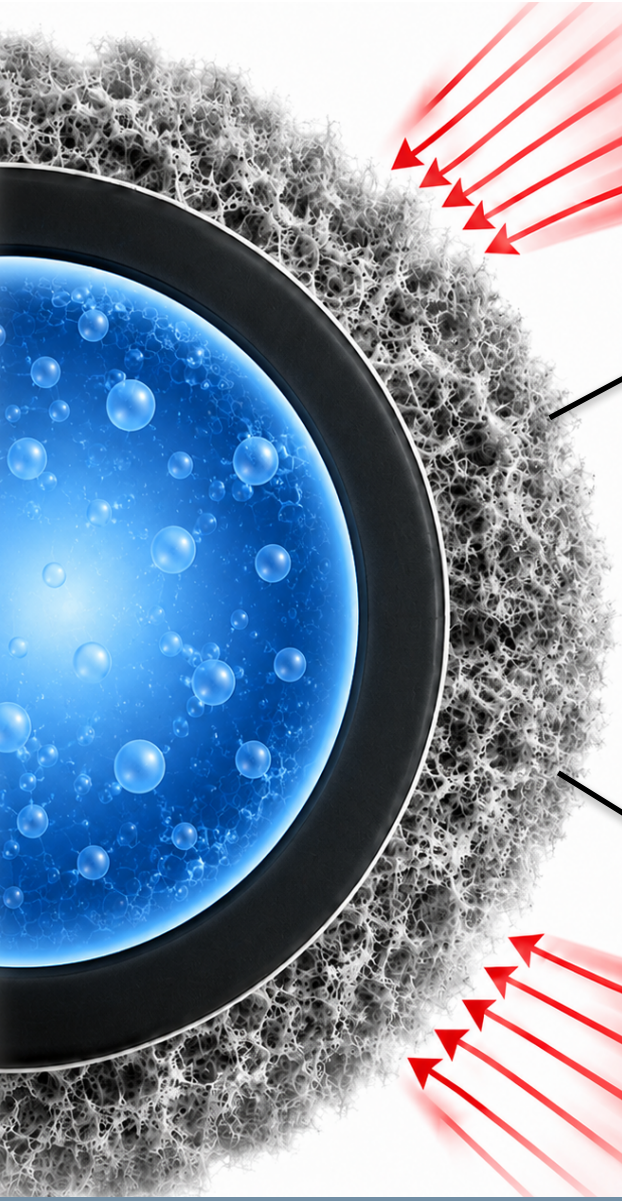
~1 ns | 10^{14} W/cm²

Nanofoams for Direct Drive ICF

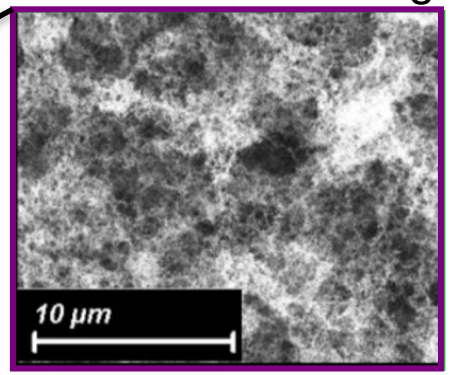


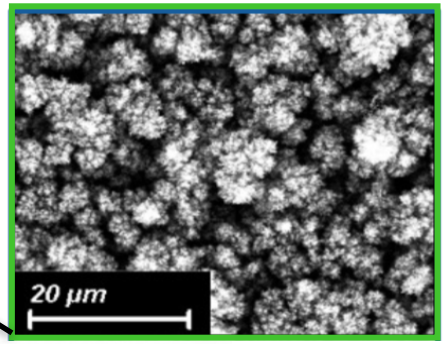
A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., Matter Radiat. Extrem. 11, 047402 (2026)

Nanofoams for Direct Drive ICF



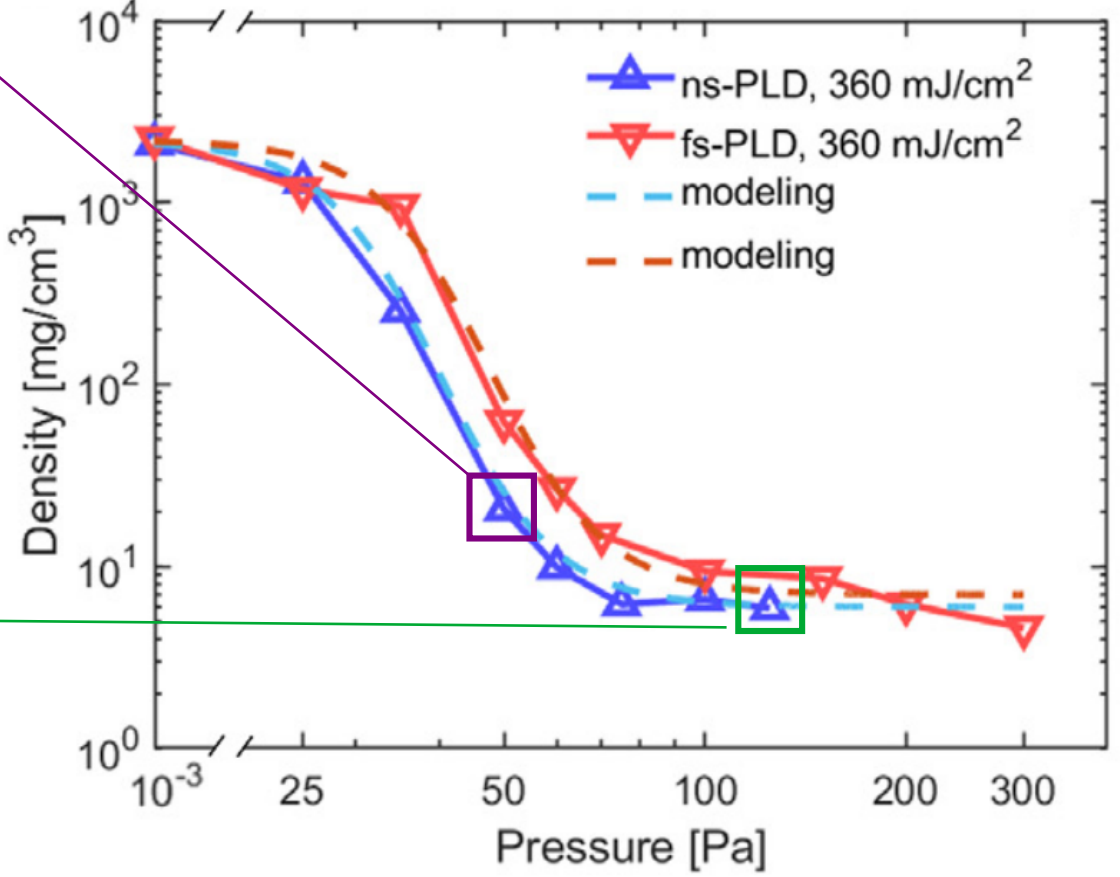
Fractal-like 6 mg/cm³





Tree-like 26 mg/cm³

Carbon nanofoam density [experiments and model]



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A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)

M. Cipriani et al., Matter Radiat. Extrem. 11, 047402 (2026)

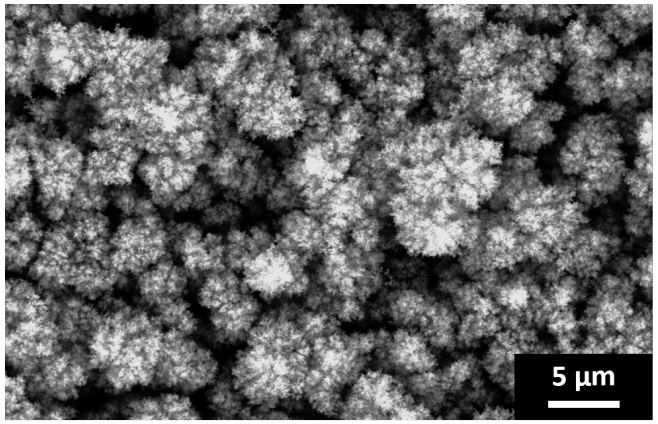
Nanofoams for Direct Drive ICF

Tree-like nanofoam

Average **density**~
- 26 mg/cm^3 (~7.8 n_c)

Geom. thickness~
- 30 µm, 60 µm

Mass thickness~
- 78 µg/cm^2, 156 µg/cm^2

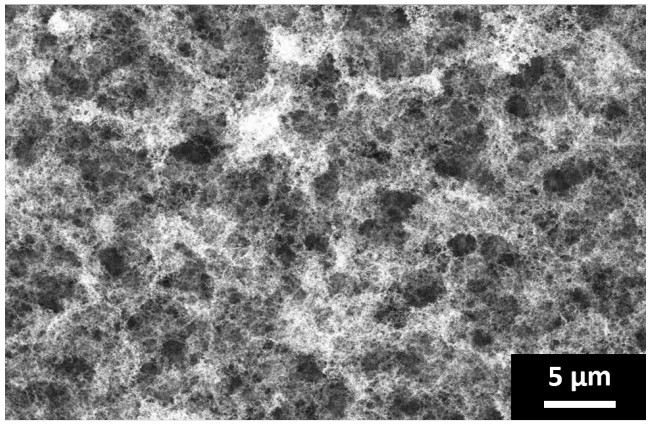


Fractal-like nanofoam

Average **density**~
- 6 mg/cm^3 (~1.8 n_c)

Geom. thickness~
- 130 µm, 270 µm

Mass thickness~
- 78 µg/cm^2, 156 µg/cm^2



A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., Matter Radiat. Extrem. 11, 047402 (2026)

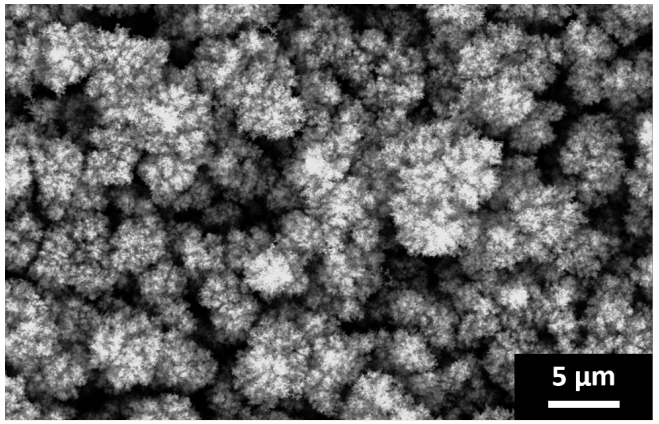
Nanofoams for Direct Drive ICF

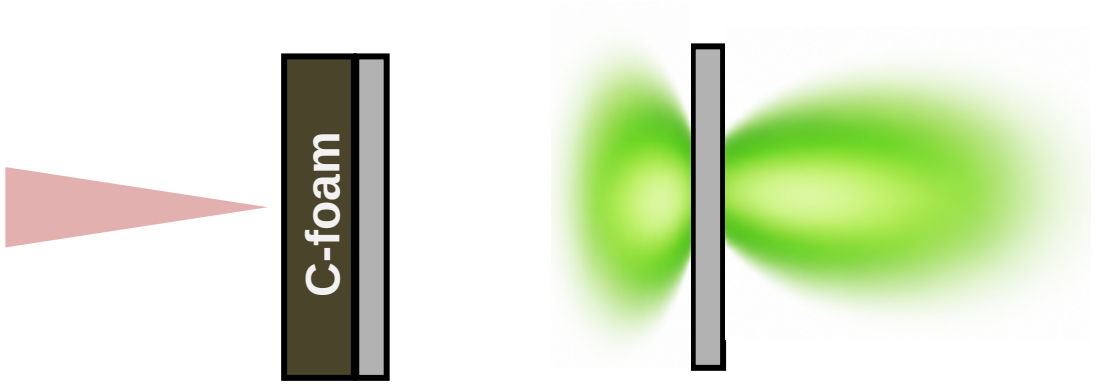
Tree-like nanofoam

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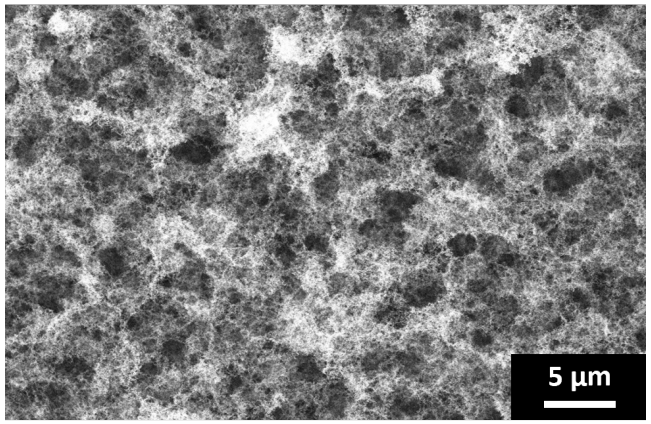
Compare plasma evolution

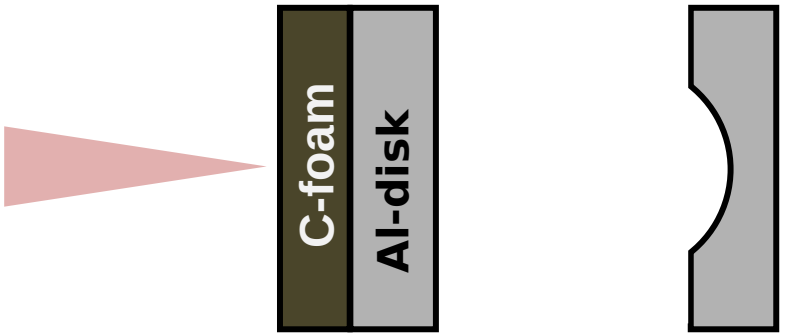
Fractal-like nanofoam

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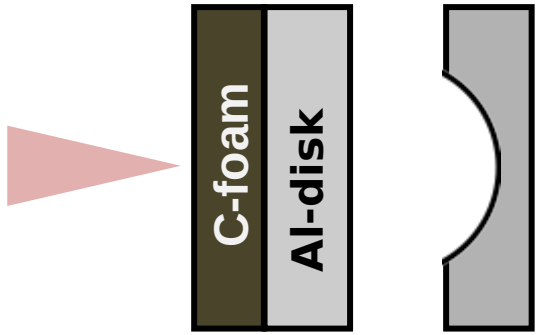


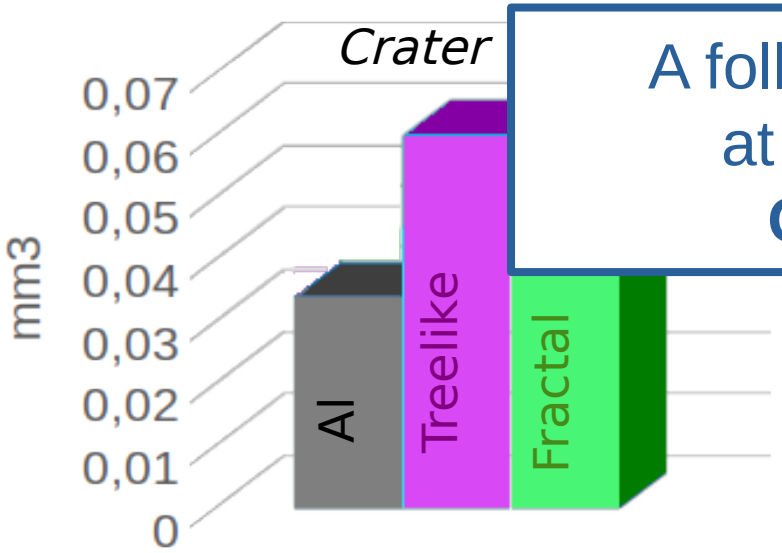
Compare crater volumes to have info on **relative enhancement** of **ablation efficiency**

A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., Matter Radiat. Extrem. 11, 047402 (2026)

Nanofoams for Direct Drive ICF

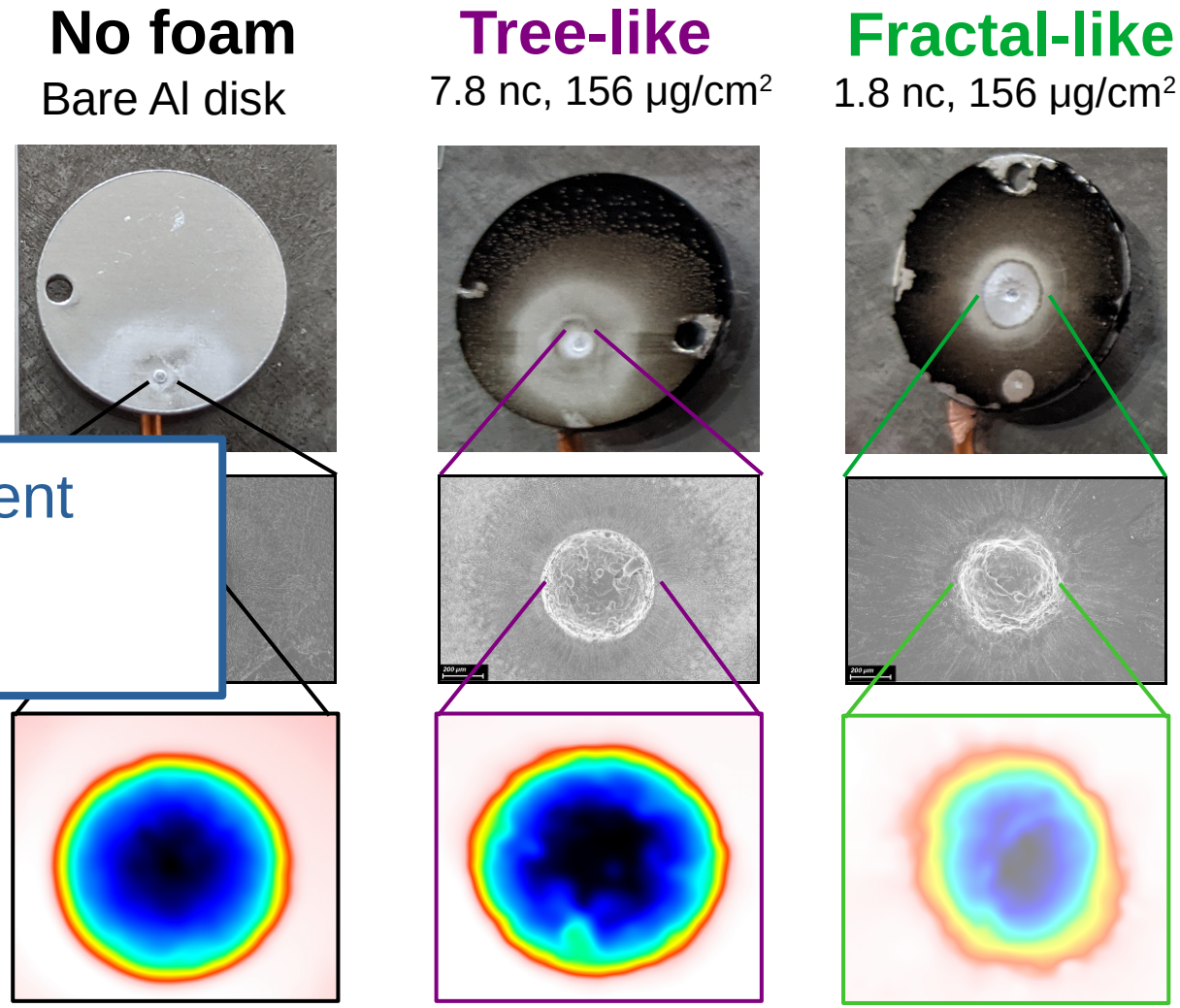
Wavelength = 1054 nm
Temporal FWHM = 3 ns
Intensity = 10^{14} W/cm^2
Ep = 40 J





A follow-up experiment at ABC (ENEA) in **October 2026!**

Tree-like foam ~ 170 % bare target!



A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., Matter Radiat. Extrem. 11, 047402 (2026)

Why PLD nanofoams for laser-matter interaction?

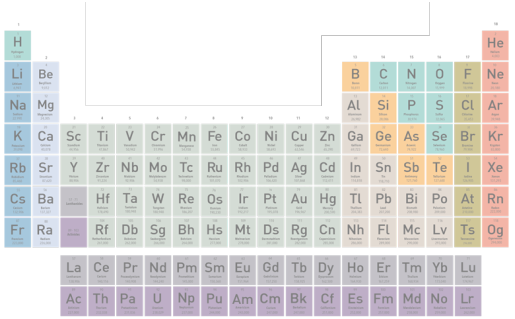
Why are PLD nanofoams special?

How to tune nanofoam properties

A few examples of applications

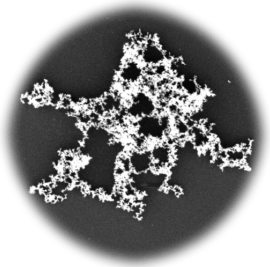
Open issues & perspectives

...What is coming next



1

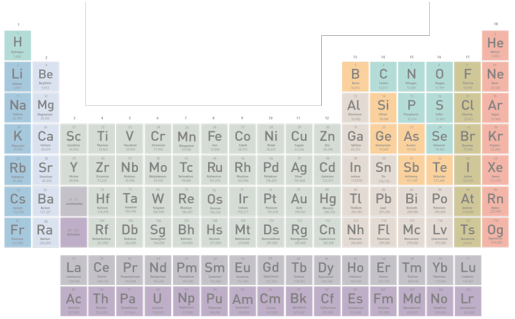
Explore **other elements** of interest & **compounds**



2

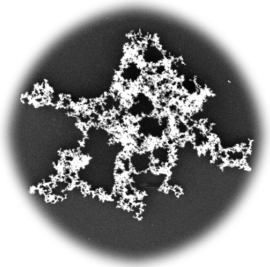
Predict nanofoam **properties** from the deposition conditions

...What is coming next



1

Explore **other elements** of interest & **compounds**



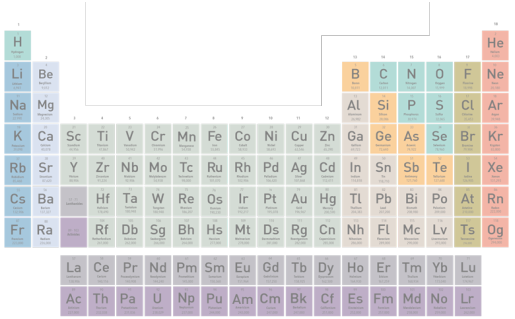
2

Predict nanofoam **properties** from the deposition conditions

3

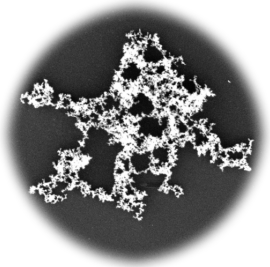
Advance the **modeling** & **simulation** of laser-foam interaction in fs and ns regime

...What is coming next



1

Explore **other elements** of interest & **compounds**



2

Predict nanofoam **properties** from the deposition conditions

3

Advance the **modeling** & **simulation** of laser-foam interaction in fs and ns regime

4

Address **high rep. rate** and **high throughput** feasibility

CA25144

ICED

Inertial fusion energy: supply Chain of laser-targets from Exploration to Delivery

Create a sustainable laser-target supply chain to tackle:

(i) **production of large batches** of targets and **production standards** towards a sufficient supply for Inertial Fusion Energy,

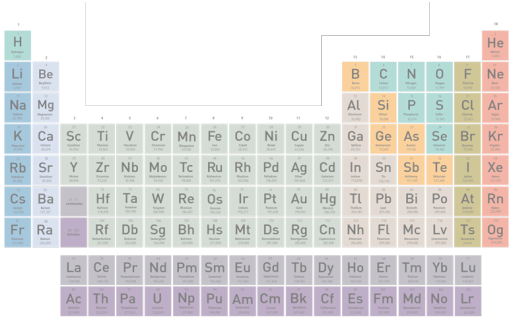
(ii) development of **targets for parametric studies** that advance the understanding of laser-plasma interactions and burning plasmas,

(iii) **interdisciplinarity** all across the chain.

You can NOW **apply to join** the Working Groups!!

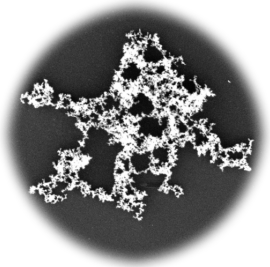
Working Groups				
WG1	WG2	WG3	WG4	WG5
Training, networking and dissemination	**Fuel Supply at Interdisciplinary Crossroads**	**Efficient Fuel at Interdisciplinary Crossroads**	**Fuel Metrology at Interdisciplinary Crossroads**	**Target supply chain for IFE**

...What is coming next



1

Explore **other elements** of interest & **compounds**



2

Predict nanofoam **properties** from the deposition conditions

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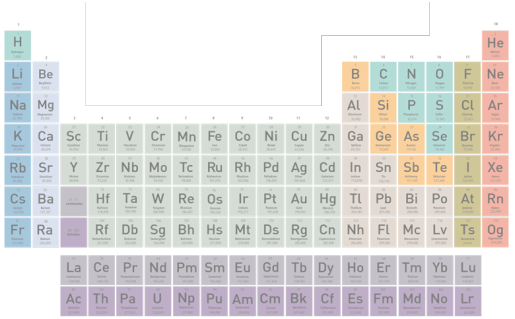
5

Assess nanofoams for **HED** & **Stopping Power**

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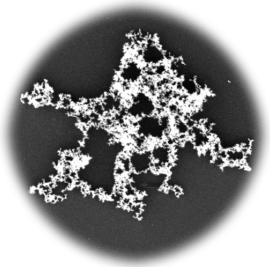
P4P Plasma Stopping Power

...What is coming next



1

Explore **other elements** of interest & **compounds**



2

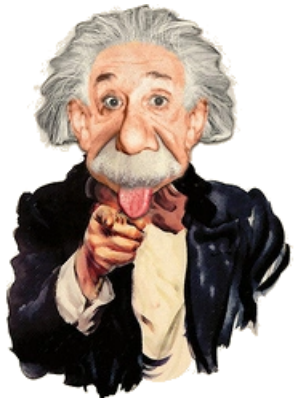
Predict nanofoam **properties** from the deposition conditions

3

Advance the **modeling** & **simulation** of laser-foam interaction in fs and ns regime

4

Address **high rep. rate** and **high throughput** feasibility



6

Your suggestions!
We are **looking for collaborations**

5

Assess nanofoams for **HED** & **Stopping Power**



Lawrence Livermore National Laboratory





NanoLab

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PRIN 2022 programme
NANOMATERIALS FOR FUSION
CUP D53D23002840006

CA25144 ICED

CA 21128 PROBONO

HiPER+ EUROPEAN LASER FUSION ENERGY

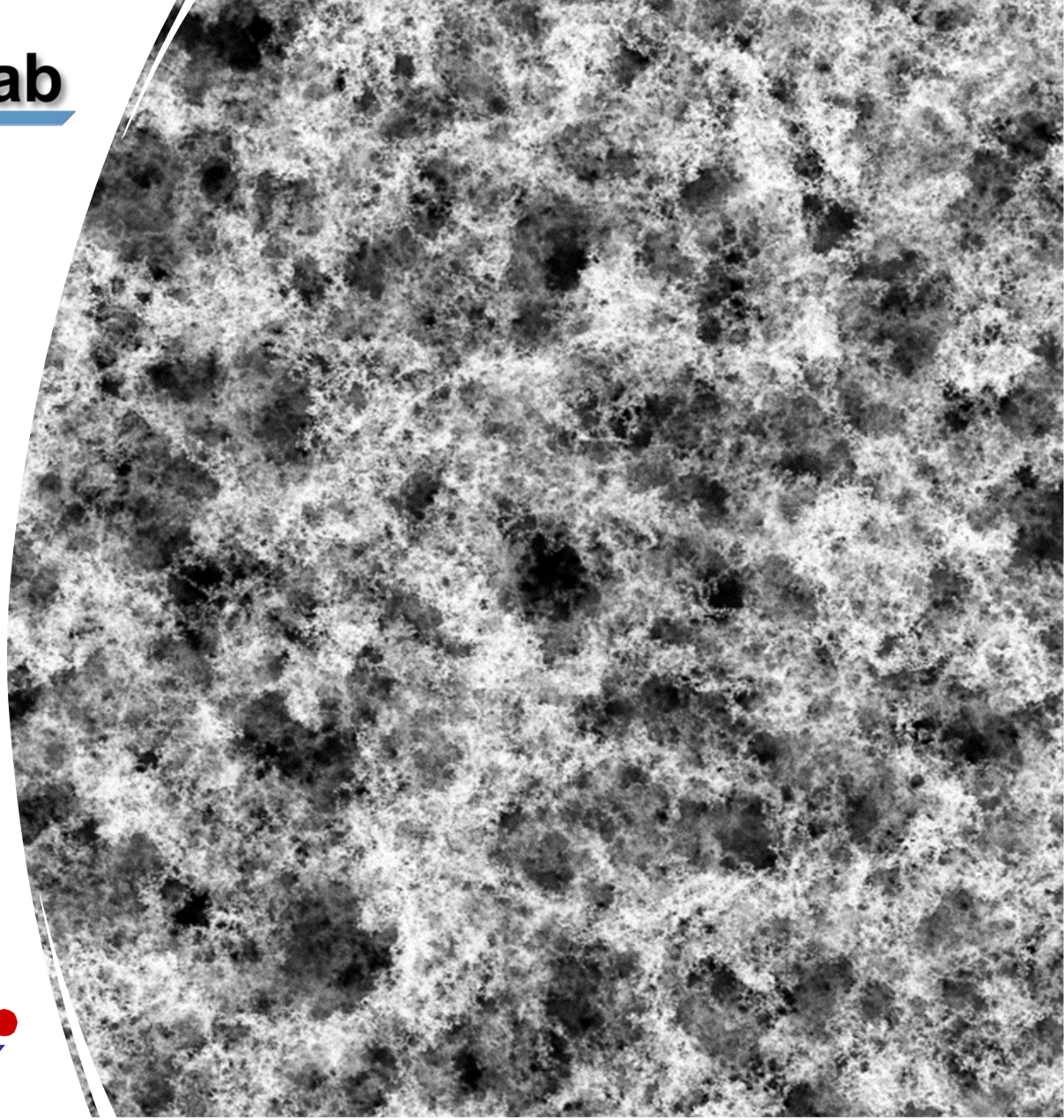
ENEA

eli

EUROfusion

RSE Ricerca Sistema Energetico

CLPU CENTRO DE LÁSERES PULSADOS





NanoLab

Thank you for your attention!

POLITECNICO MILANO 1863

PRIN 2022 programme
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HiPER+ EUROPEAN LASER FUSION ENERGY

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CLPU CENTRO DE LÁSERES PULSADOS