POLITECNICO MILANO 1863

ERC-2014-CoG No. 647554
ENSURE

Foam-Based Multi-Layer Targets for Laser-Driven Ion Acceleration

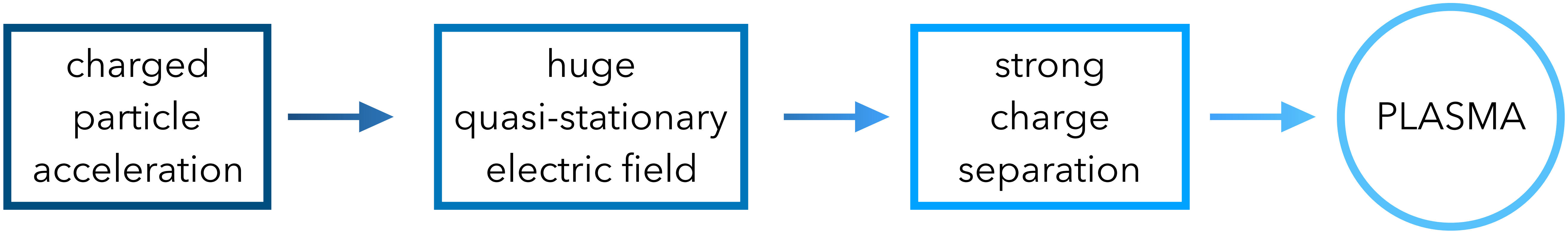
Arianna Formenti

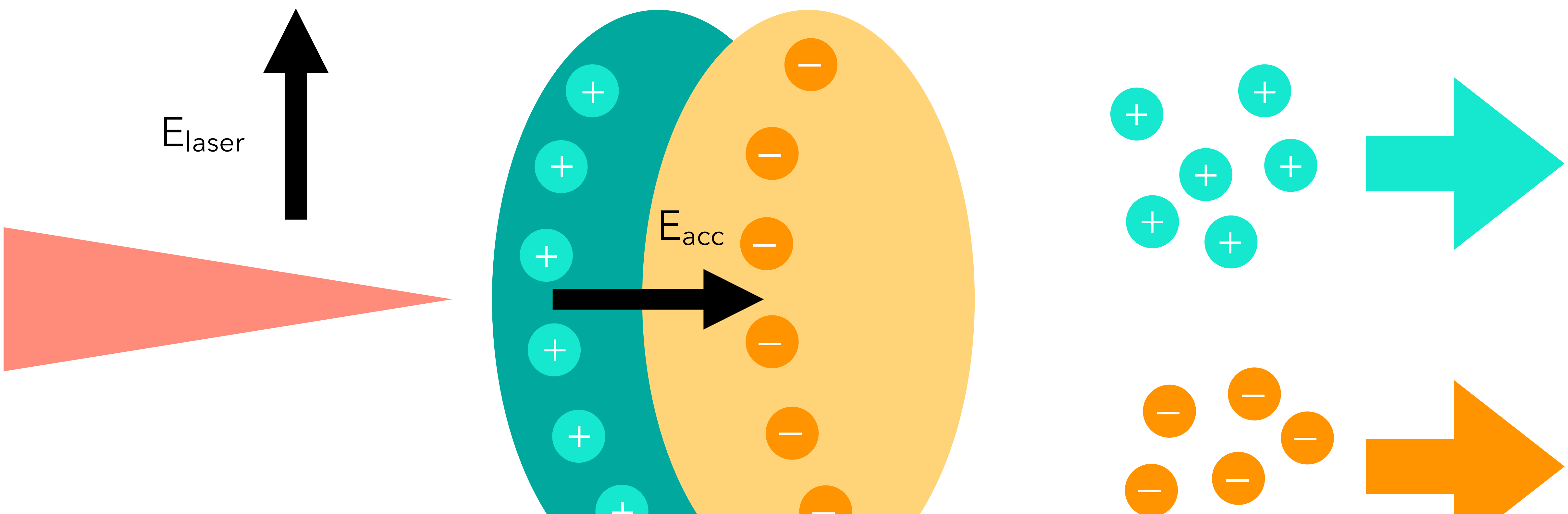
Isola d'Elba, September 27th, 2017

3rd European Advanced Accelerator Concepts Workshop

Plasmas as non-conventional accelerators

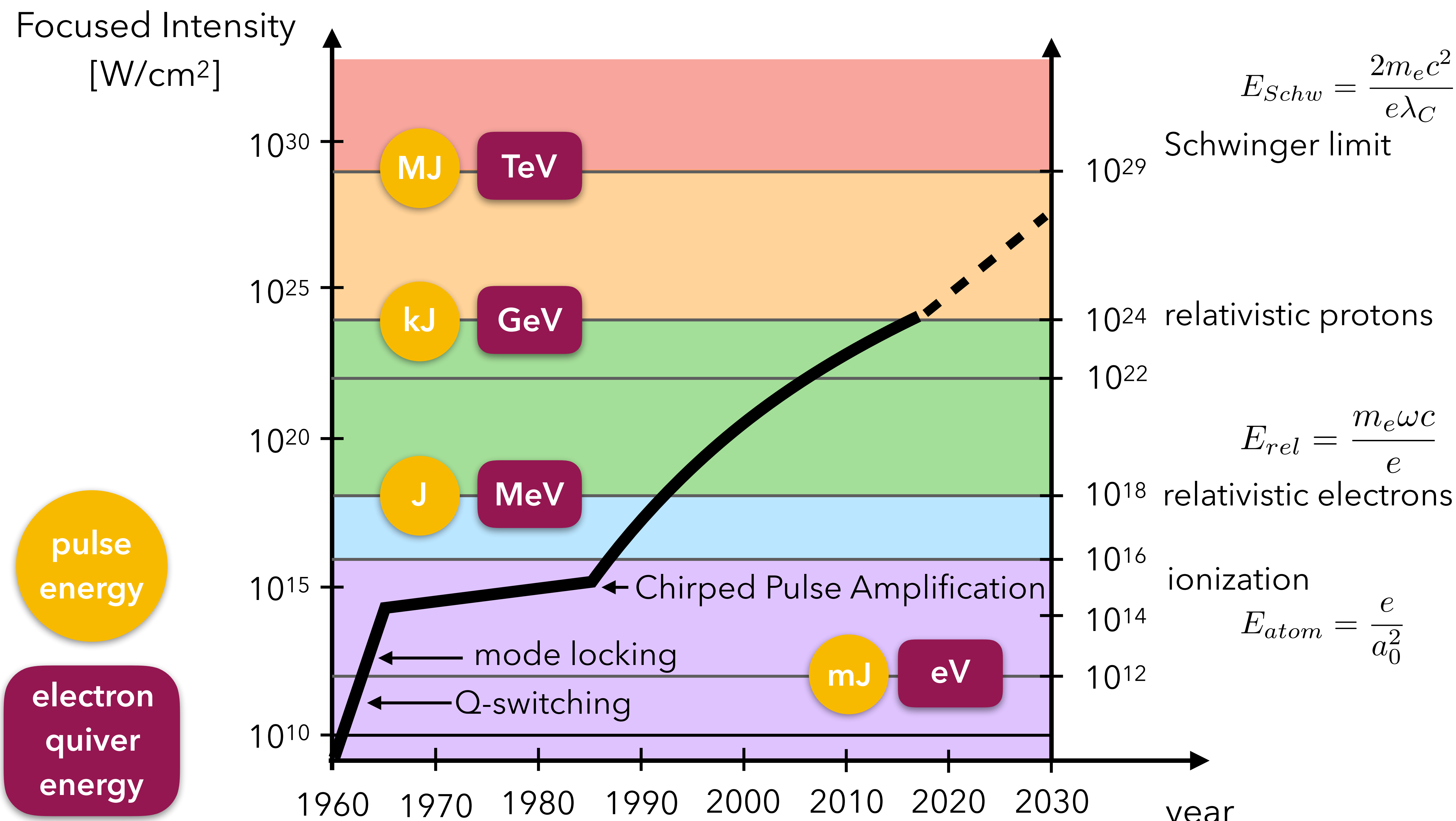
Idea of laser-plasma accelerators



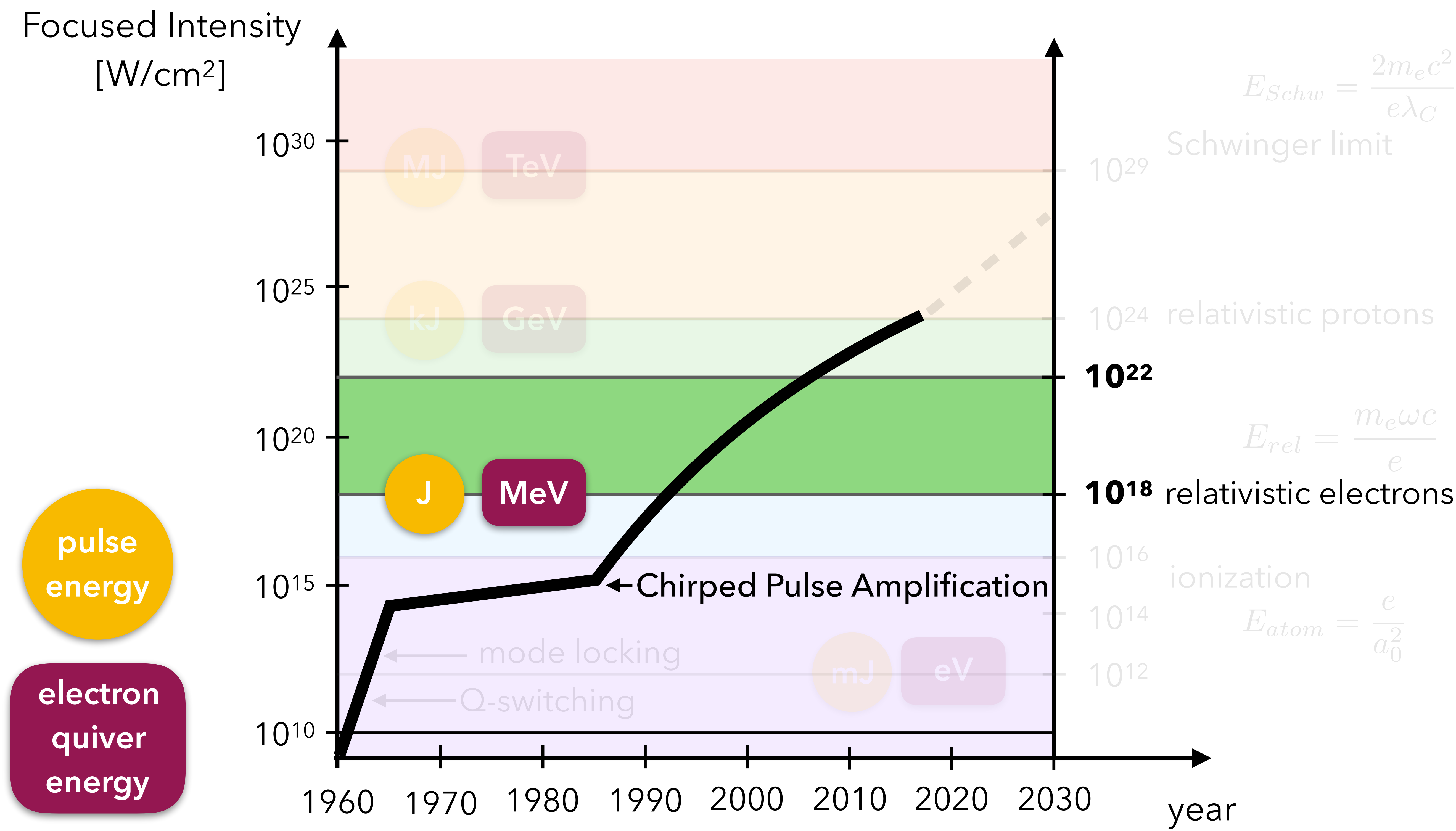


$\mathbf{E_{laser} \sim E_{acc} > 1\ GV/cm}$

What kind of lasers?



Already available ultra-intense lasers



Ultra-intense lasers turn matter into plasma

$$I = \frac{cE_{max}^2}{8\pi}$$

$$v_{osc} = \frac{eE_{max}}{m_e\omega}$$

relativistic electrons in one laser cycle

$$I \geq \frac{1.4 \times 10^{18}}{\lambda^2(\mu m^2)} \frac{W}{cm^2}$$

Typical CPA laser pulse parameters

- Wavelength ≈ 1 - 10 μm
- Energy ≈ 10^{-1} - 10^{-3} J
- Power ≈ 100 TW - few PW
- Duration ≈ 10 - 10^3 fs
- Spot size ∅ < 10 μm
- Intensity ≈ 10^{18} - 10^{22} W/cm^2

full ionization!

From huge facilities…

…to table-top systems.

Laser-plasma accelerators: a great challenge

www.engineeringchallenges.org

Why bother?

Laser-plasma accelerators: a great challenge

www.engineeringchallenges.org

Why bother?

Potentially
- compact!
- cheap!
- flexible!

Laser-plasma accelerators: a great challenge

www.engineeringchallenges.org

Why bother?

Potentially
- compact!
- cheap!
- flexible!

LHC ring, Geneva, Switzerland

Isola d'Elba, Italy

Laser-plasma accelerators: a great challenge

www.engineeringchallenges.org

Why bother?

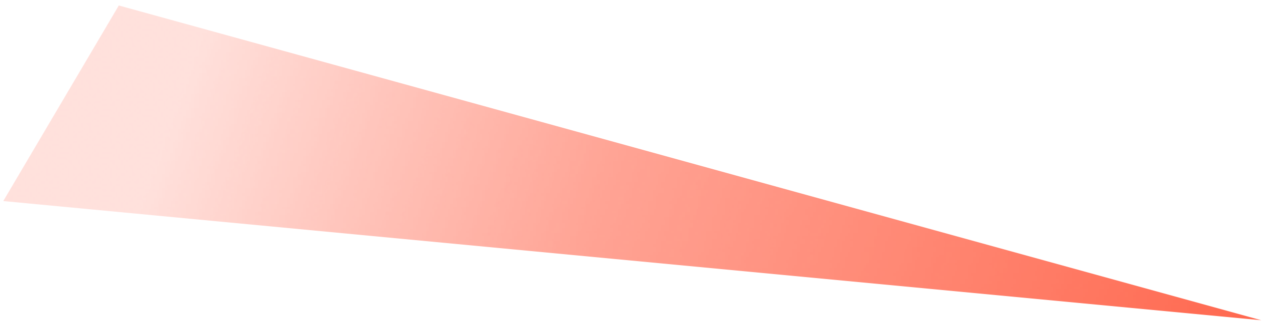
Potentially
- compact!
- cheap!
- flexible!

However
- controlled process?
- reproducibility?
- reduced performances…

LHC ring, Geneva, Switzerland

Isola d'Elba, Italy

Ions can be accelerated by laser-matter interaction

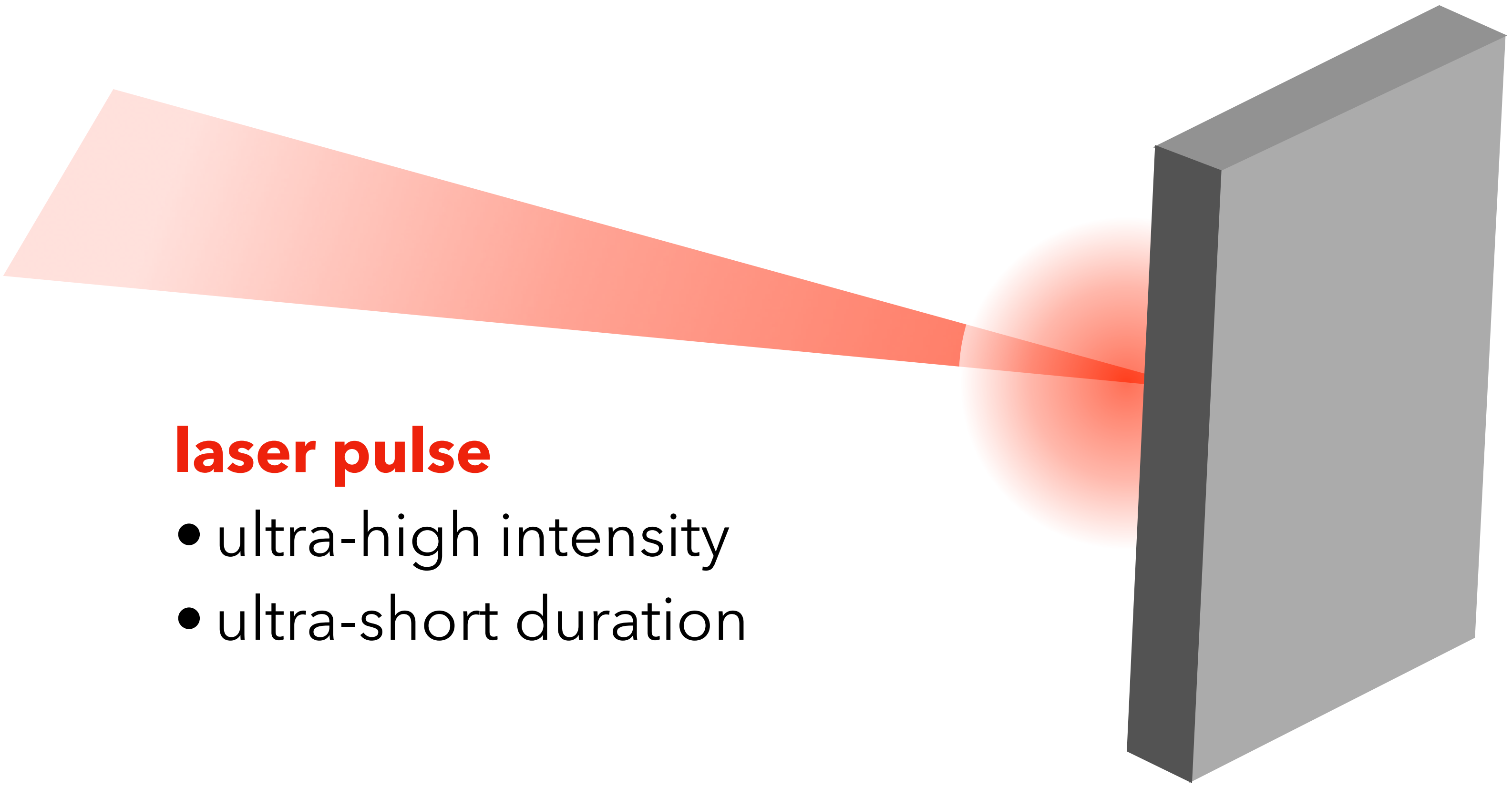


laser pulse

- ultra-high intensity
- ultra-short duration

Macchi et al. *Rev Mod Phys* 85.2 (2013): 751.
Daido et al. *Rep Prog Phys* 75.5 (2012): 056401.

Ions can be accelerated by laser-matter interaction

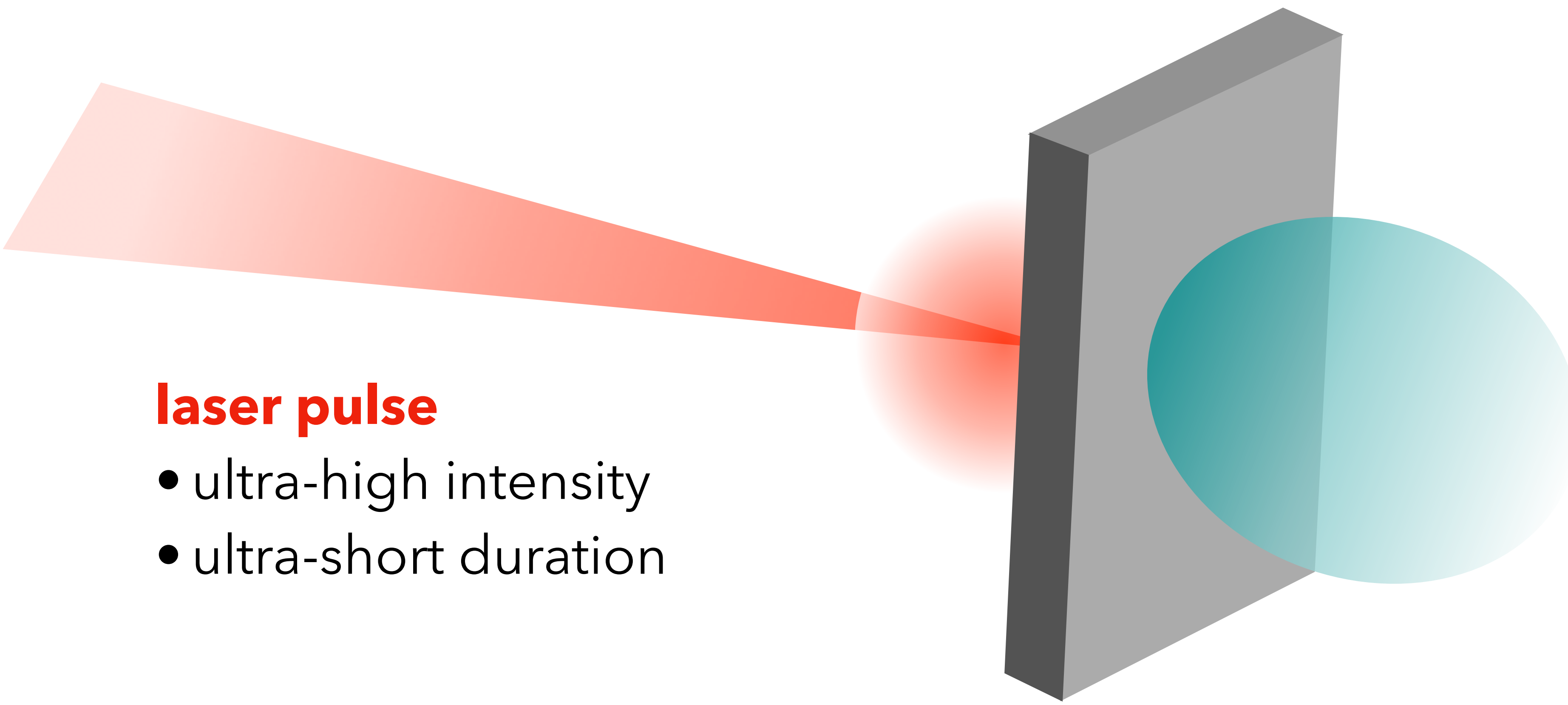


laser pulse
- ultra-high intensity
- ultra-short duration

target
- μm thickness
- solid density

Macchi et al. *Rev Mod Phys* 85.2 (2013): 751.
Daido et al. *Rep Prog Phys* 75.5 (2012): 056401.

Ions can be accelerated by laser-matter interaction



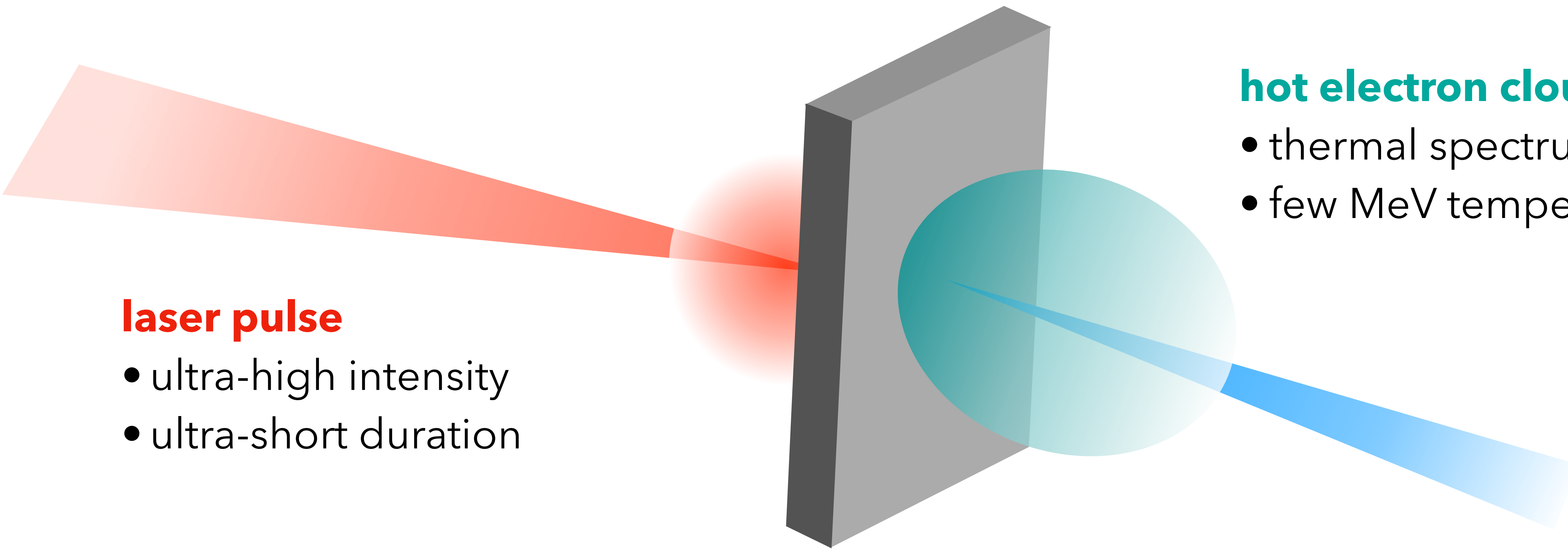
hot electron cloud
- thermal spectrum
- few MeV temperature

laser pulse
- ultra-high intensity
- ultra-short duration

target
- μm thickness
- solid density

Macchi et al. *Rev Mod Phys* 85.2 (2013): 751.
Daido et al. *Rep Prog Phys* 75.5 (2012): 056401.

Ions can be accelerated by laser-matter interaction



hot electron cloud
- thermal spectrum
- few MeV temperature

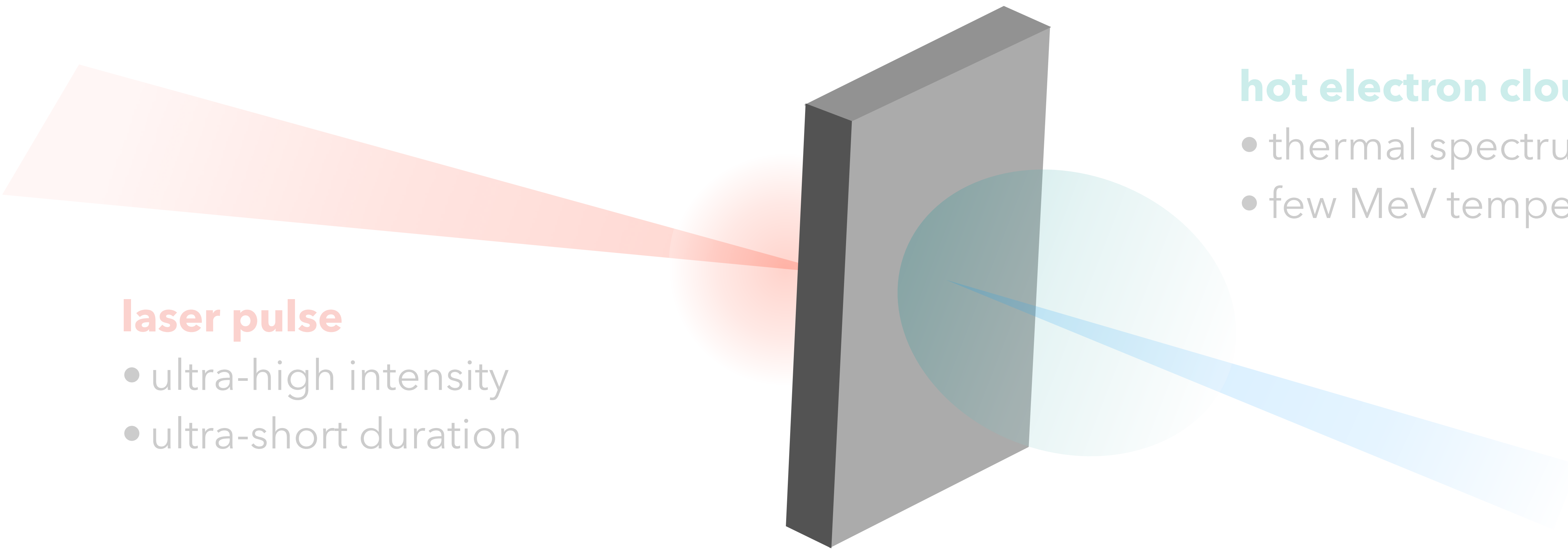
laser pulse
- ultra-high intensity
- ultra-short duration

target
- μm thickness
- solid density

accelerated ions
- mainly *p* and C^{6+} from impurities
- **broad, exponential spectrum**
- **cutoff energy < 100 MeV**
- collimation along target normal
- number 10^9 - 10^{13}

Macchi et al. *Rev Mod Phys* 85.2 (2013): 751.
Daido et al. *Rep Prog Phys* 75.5 (2012): 056401.

The target is crucial



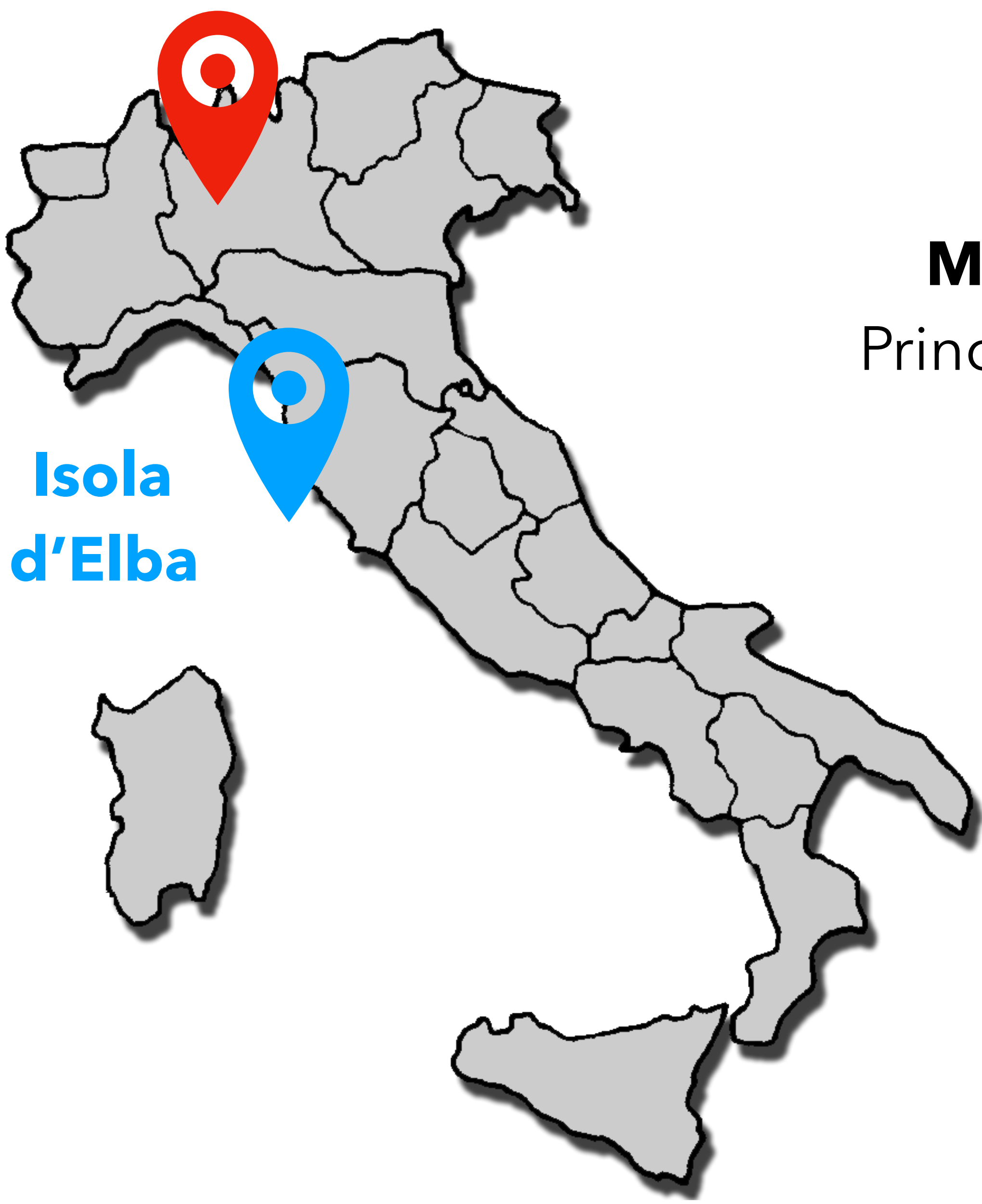
Macchi et al. *Rev Mod Phys* 85.2 (2013): 751.
Daido et al. *Rep Prog Phys* 75.5 (2012): 056401.

Our group @ Politecnico di Milano

NanoLab

POLITECNICO
MILANO 1863

Milano



Matteo Passoni
Principal Investigator

erc

ENSURE project

ERC-2014-CoG No. 647554

www.ensure.polimi.it

Ongoing Collaborations

HZDR
SourceLAB
INFN
Queen's University Belfast
大阪大学 OSAKA UNIVERSITY
CLPU CENTRO DE LÁSERES PULSADOS

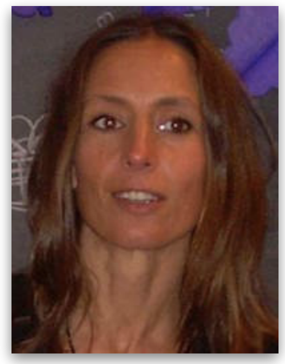
The ENSURE team

Associate Professors

Matteo Passoni

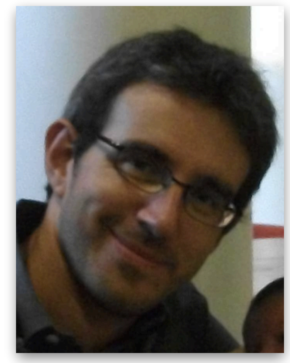
Margherita Zavelani Rossi

Researcher



Valeria Russo

Post-docs



David Dellasega

Alessandro Maffini

Luca Fedeli

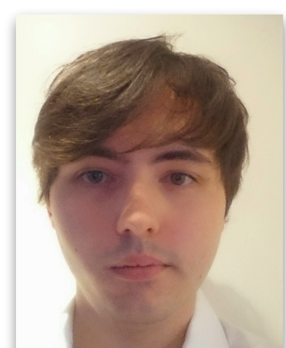
Lorenzo Cialfi

PhD students

Andrea Pazzaglia

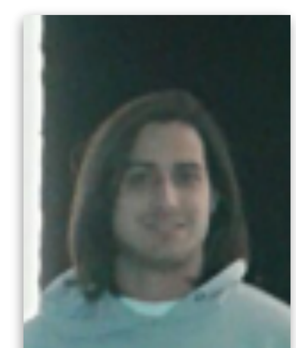
Arianna Formenti

Francesco Mirani



Michele Sala

MSc student



Alessandro Tentori

The ENSURE team

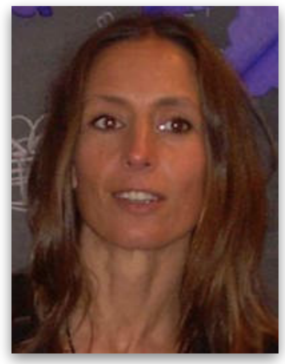
Experimental team

Associate Professors

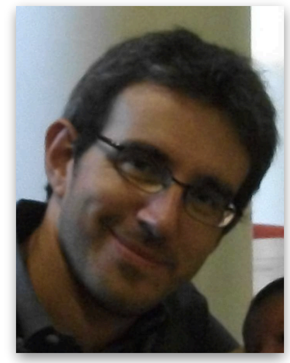

Matteo Passoni


Margherita Zavelani Rossi

Researcher


Valeria Russo

Post-docs


David Dellasega


Alessandro Maffini


Luca Fedeli

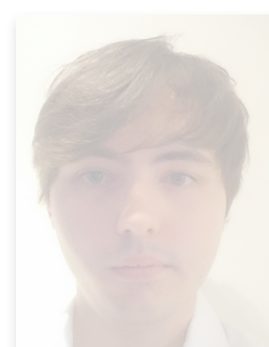

Lorenzo Cialfi

PhD students


Andrea Pazzaglia


Arianna Formenti


Francesco Mirani


Michele Sala

MSc student


Alessandro Tentori

POLITECNICO
MILANO 1863

The **ENSURE** team

Numerical team

Associate Professors

Matteo Passoni

Margherita Zavelani Rossi

Researcher

Valeria Russo

Post-docs

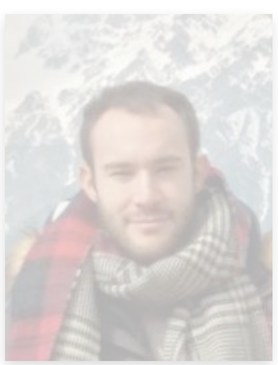
David Dellasega

Alessandro Maffini

Luca Fedeli

Lorenzo Cialfi

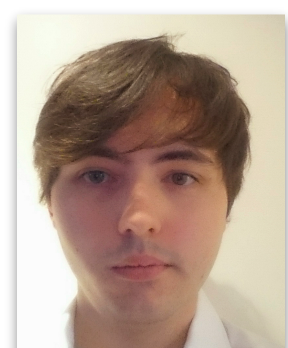
PhD students



Andrea Pazzaglia

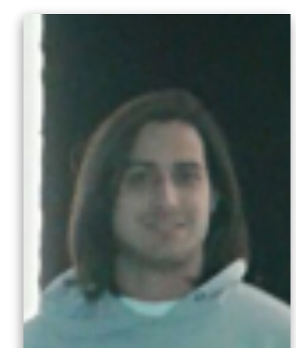
Arianna Formenti

Francesco Mirani



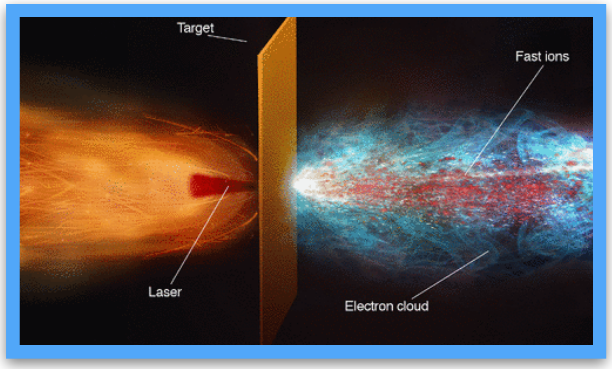
Michele Sala

MSc student

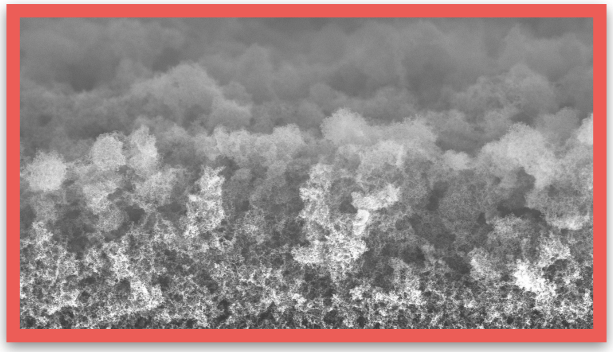


Alessandro Tentori

ENSURE research interests

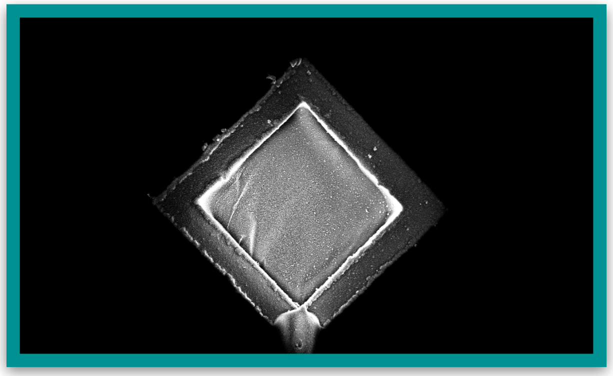


Laser-driven ion acceleration
- theoretical/numerical investigations
- experimental campaigns



Materials science
- development of low-density foams
- advanced targets for laser-plasma experiments

Applications in materials and nuclear science
- materials characterization with laser-driven ions
- secondary neutron sources for applications

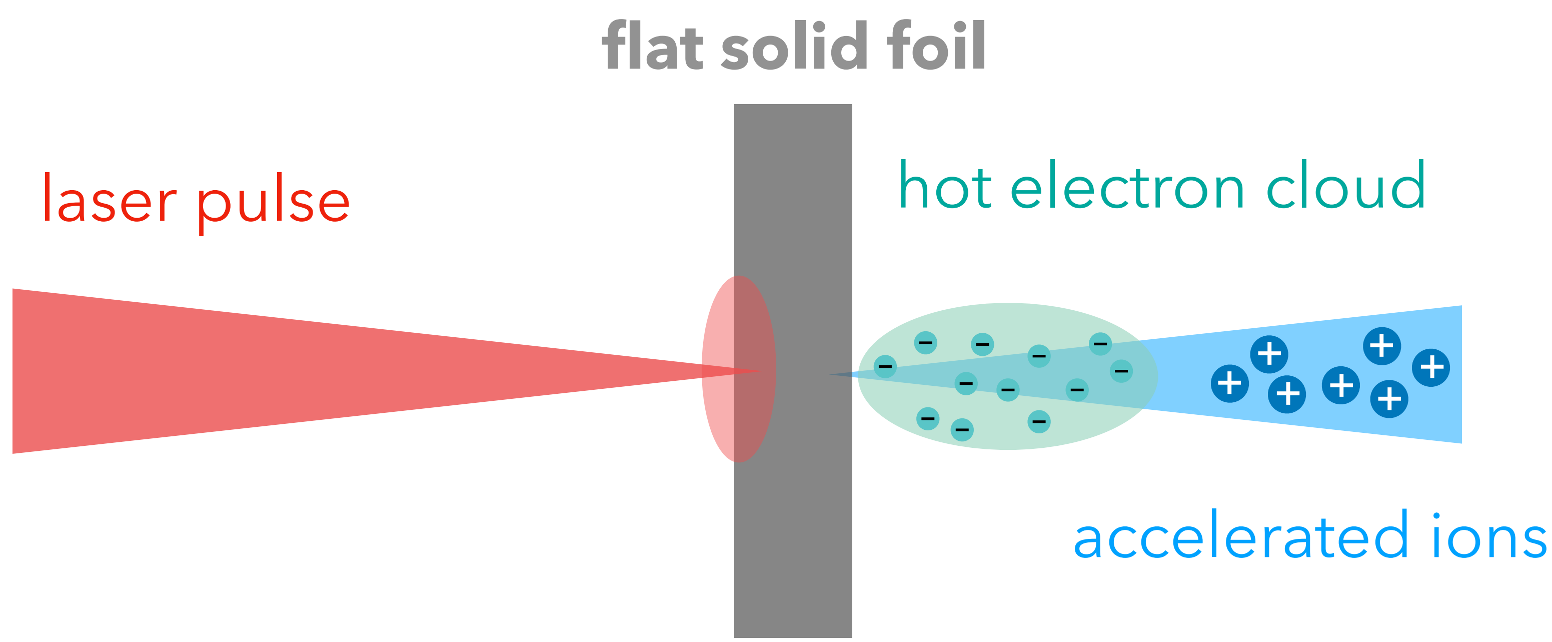


Fundamental physics and laboratory astrophysics
- laser interaction with nanostructured plasmas
- collisionless shock acceleration of ions

A smart target improves the acceleration process

Target Normal Sheath Acceleration (TNSA)

Conventional

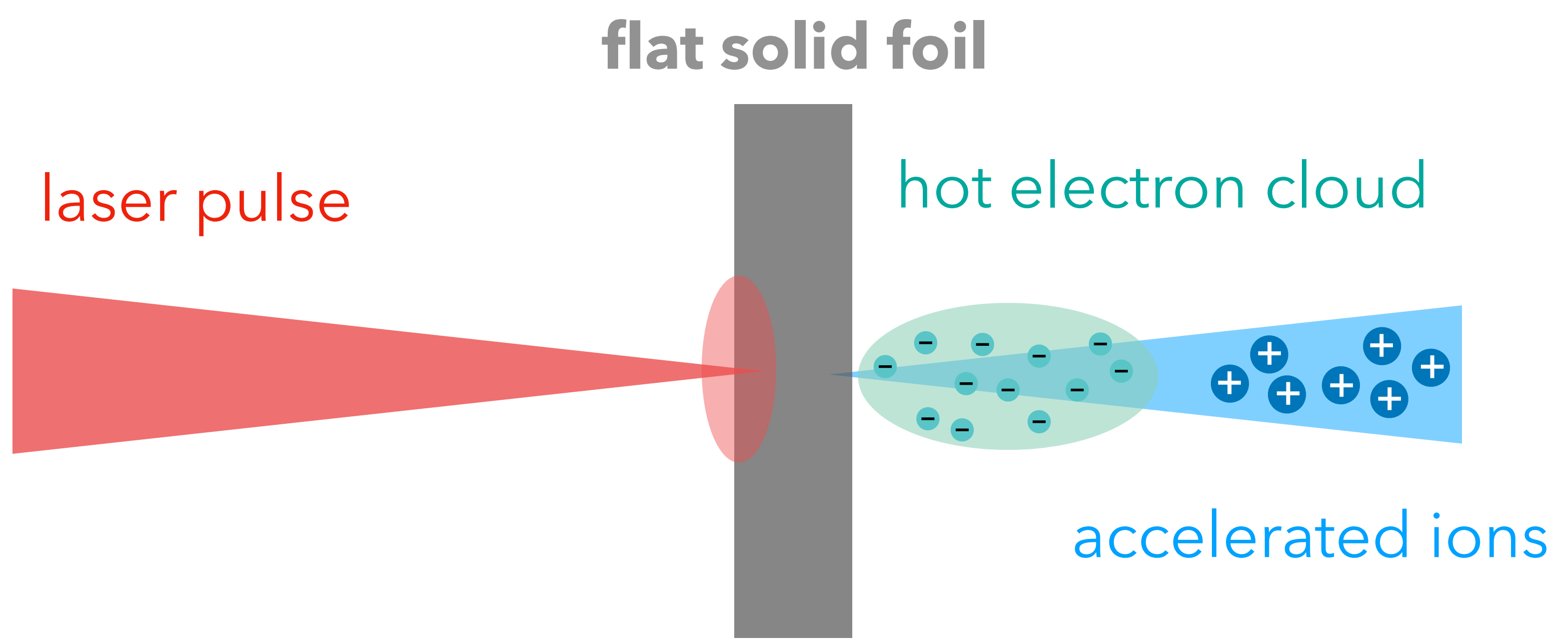


Wilks et al. *Phys Plasmas* 8 (2001)

A smart target improves the acceleration process

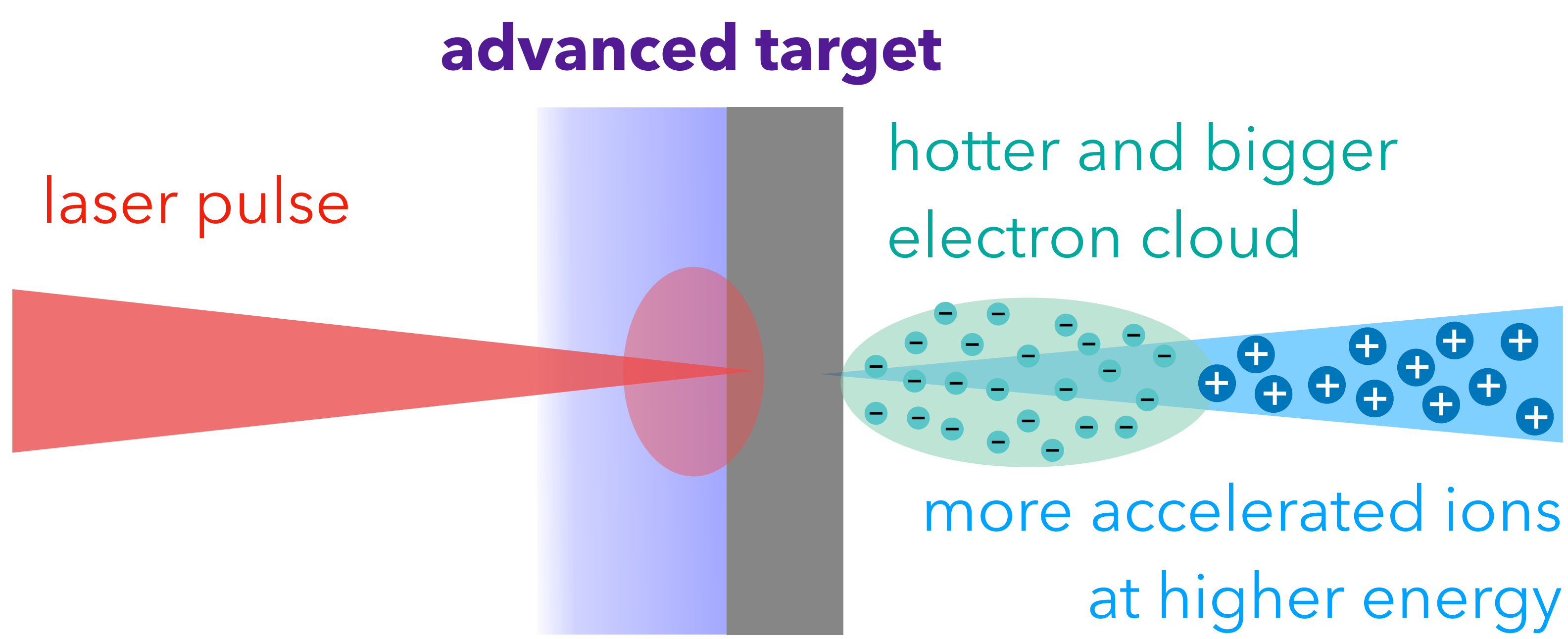
Target Normal Sheath Acceleration (TNSA)

Conventional



Wilks et al. *Phys Plasmas* 8 (2001)

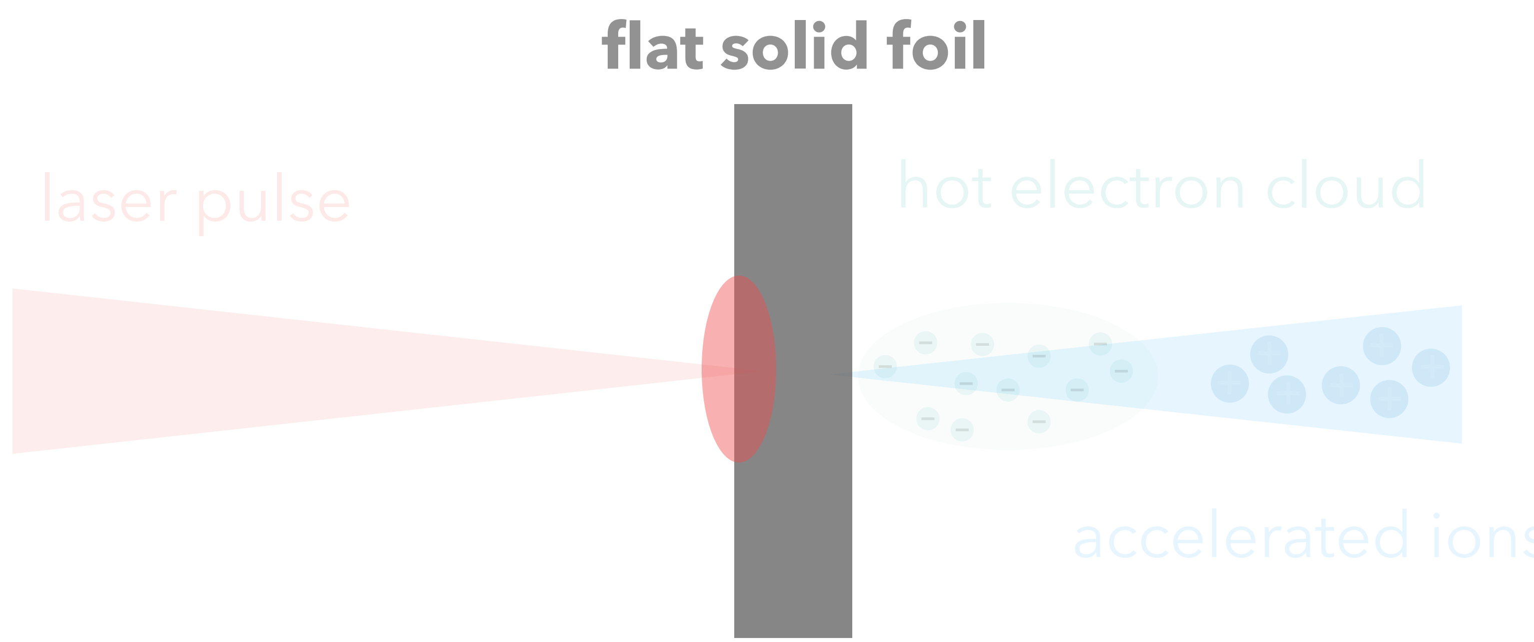
Enhanced



A smart target improves the acceleration process

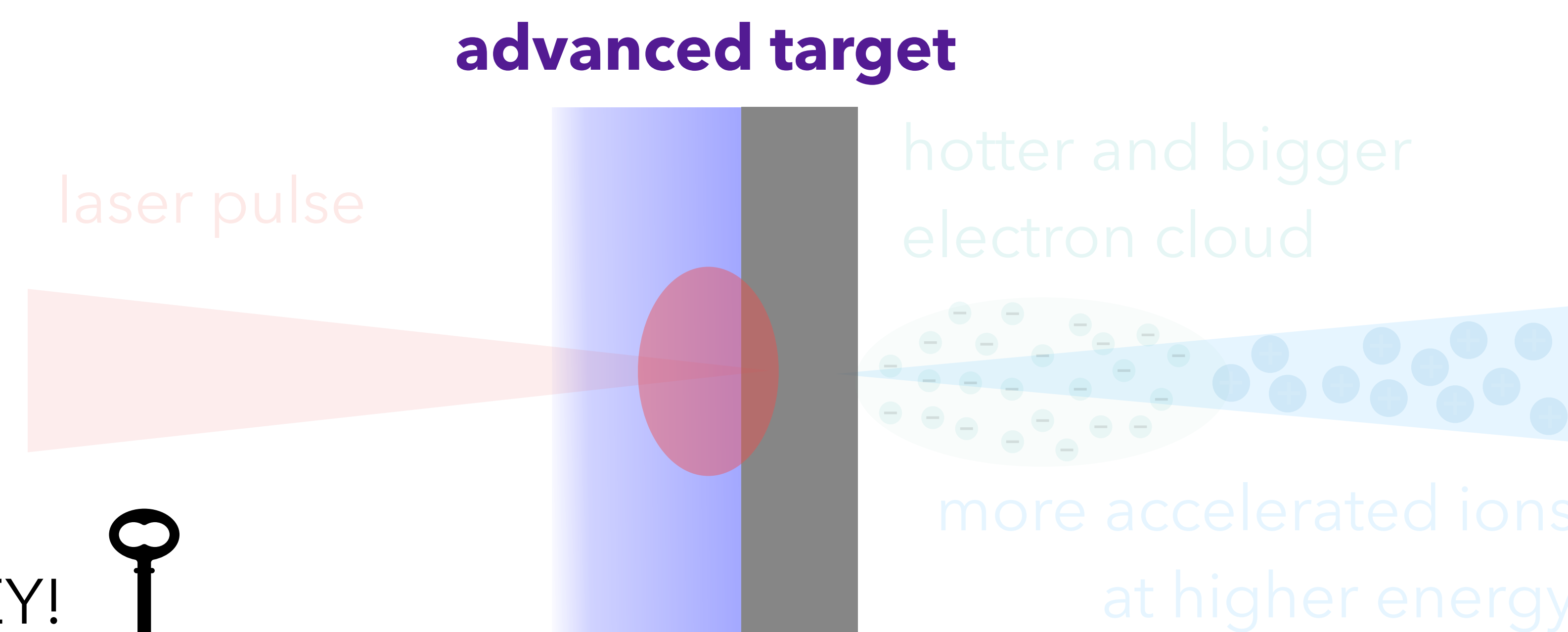
Target Normal Sheath Acceleration (TNSA)

Conventional



Wilks et al. *Phys Plasmas* 8 (2001)

Enhanced

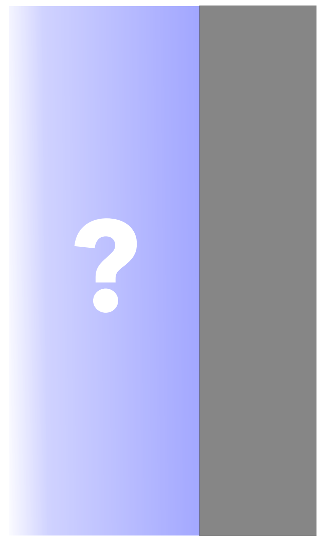


THE TARGET IS THE KEY!

But not any target material is ok

advanced target

What kind of material?
With what properties?



conventional
flat solid foil

Two requirements:

1. **attached** to solid foil → **TNSA-like** process
2. **near-critical** density → stronger **coupling**

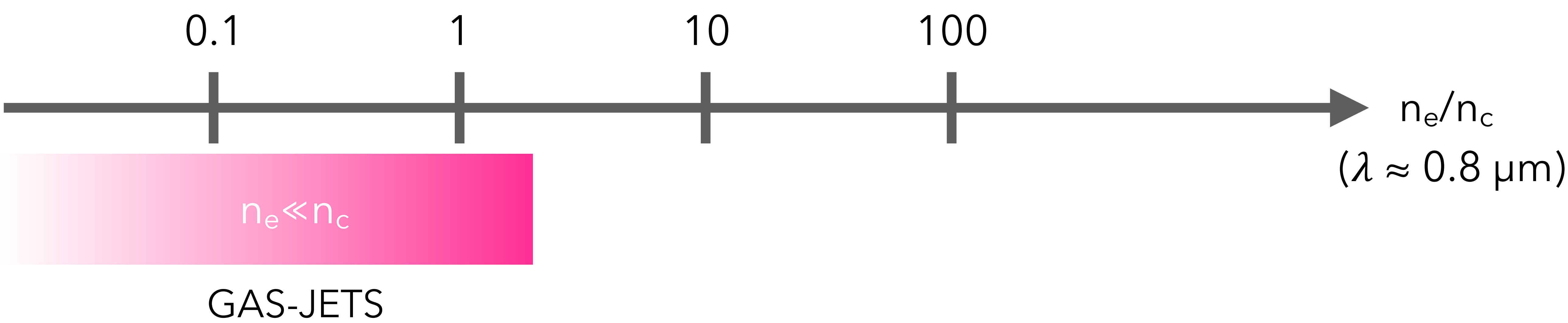
critical density

$$n_c = \frac{\gamma_e \pi m_e c^2}{e\lambda^2}$$

Near-critical materials is what we need

underdense plasmas

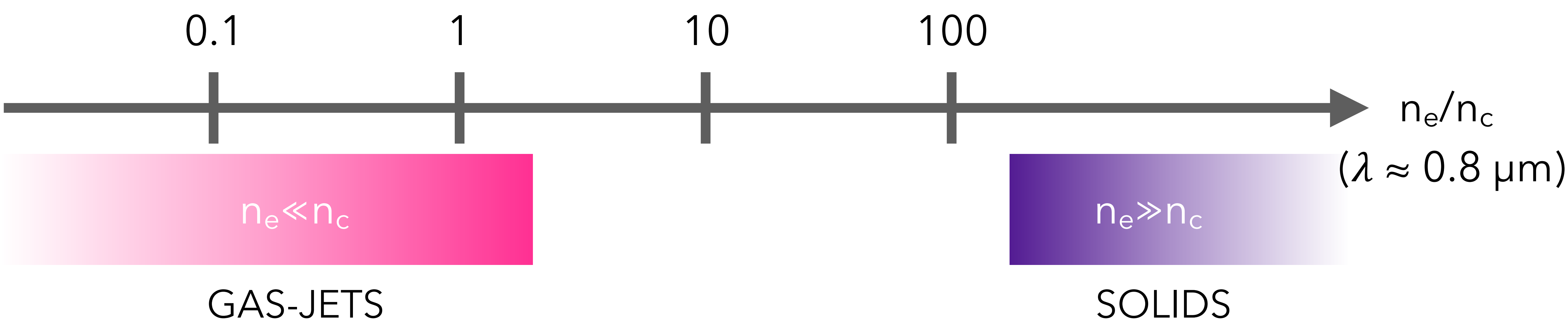
- laser propagation
- low absorption
- volume interaction



Near-critical materials is what we need

underdense plasmas
- laser propagation
- low absorption
- volume interaction

overdense plasmas
- laser reflection
- laser damping
- surface interaction



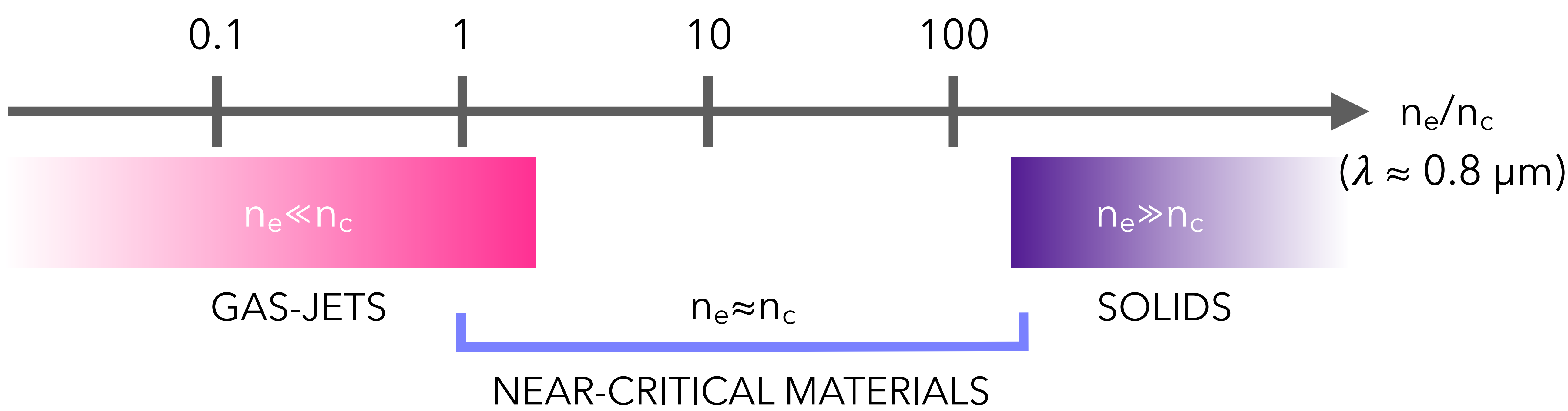
Near-critical materials is what we need

underdense plasmas
- laser propagation
- low absorption
- volume interaction

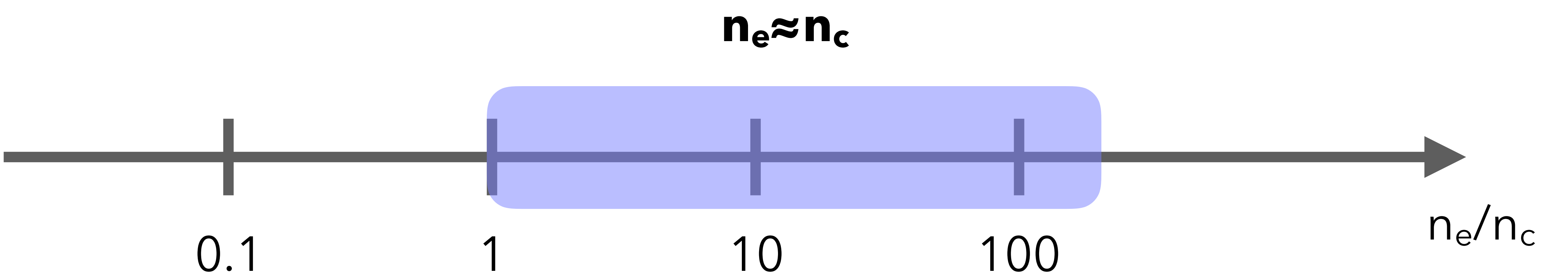
near-critical plasmas
- plasma density **matching** laser frequency
- **strong interaction**

overdense plasmas
- laser reflection
- laser damping
- surface interaction

complex regime



Producing near-critical materials is challenging

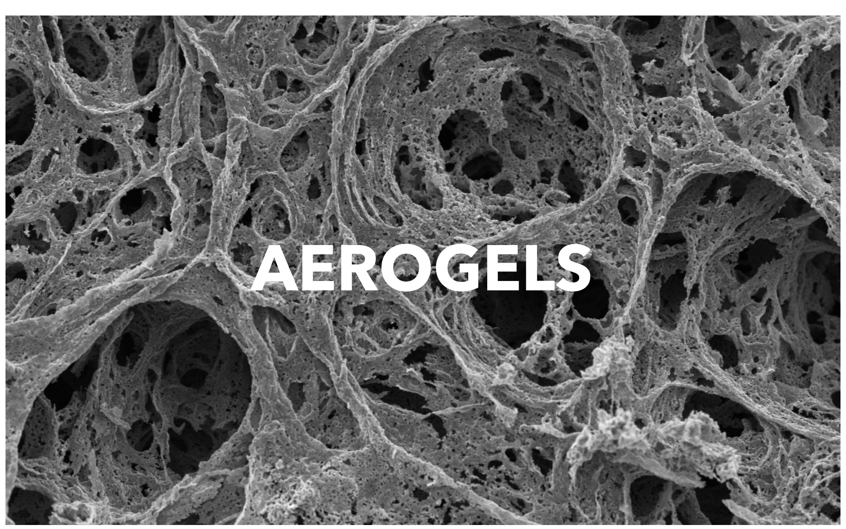


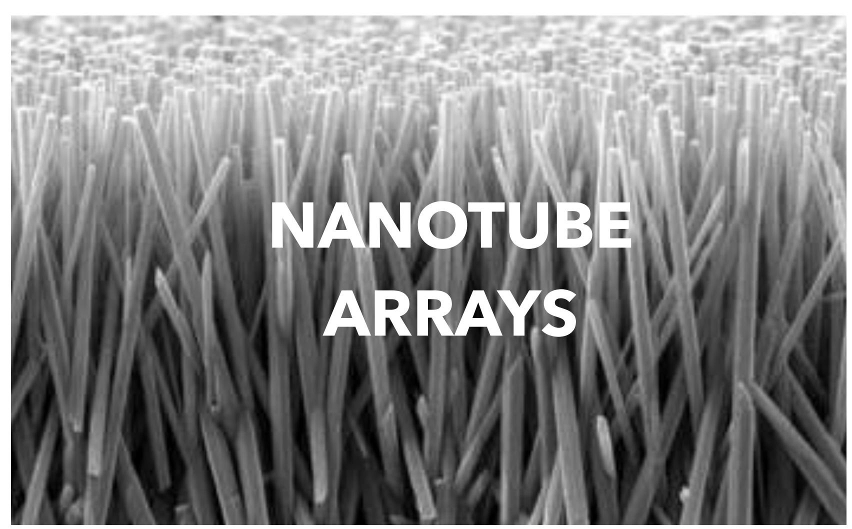
for $\lambda \approx$ **0.8 μm** & γ_e**=1 - 30**

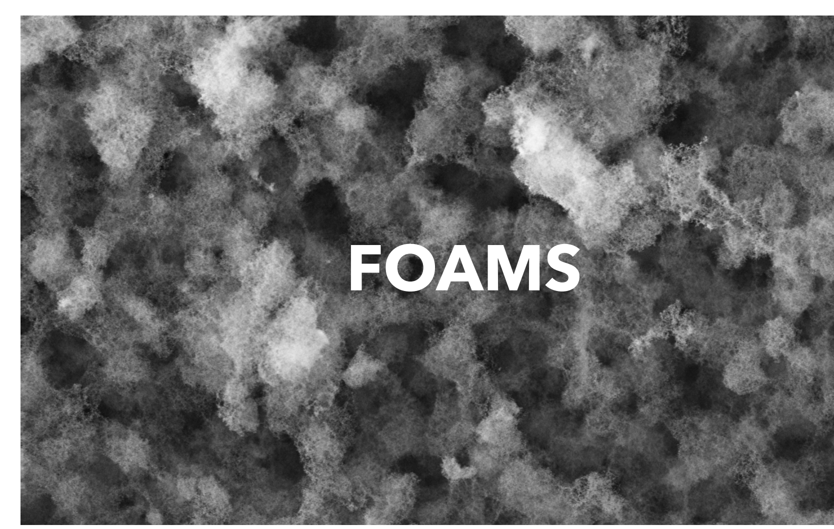
$n_c \approx$ **6 - 180 mg/cm³**

VERY LOW DENSITY:

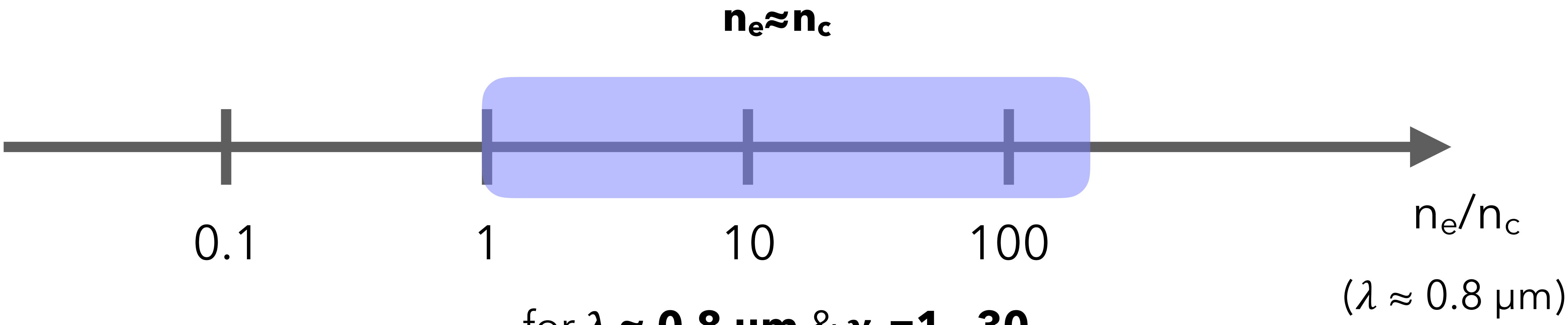
few options other than pre-heating







We focus of Carbon foams

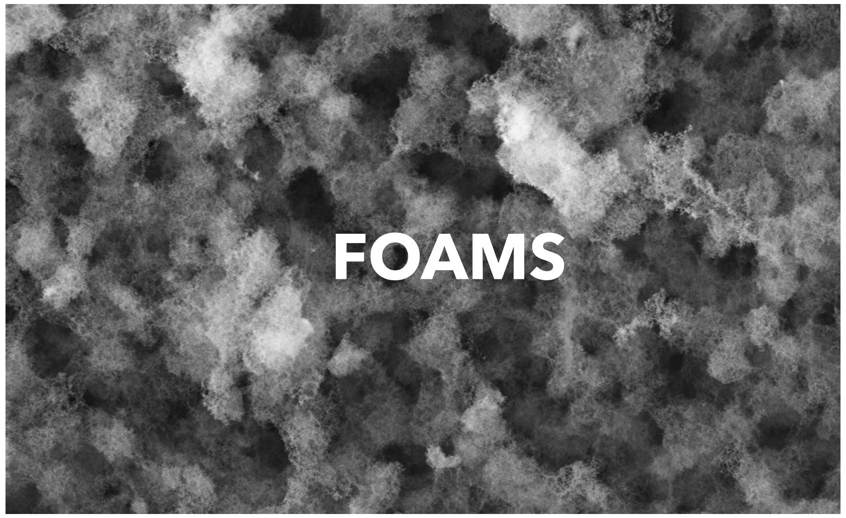


for **$\lambda \approx$ 0.8 μm** & **γ_e=1 - 30**

$n_c \approx$ 6 - 180 mg/cm³

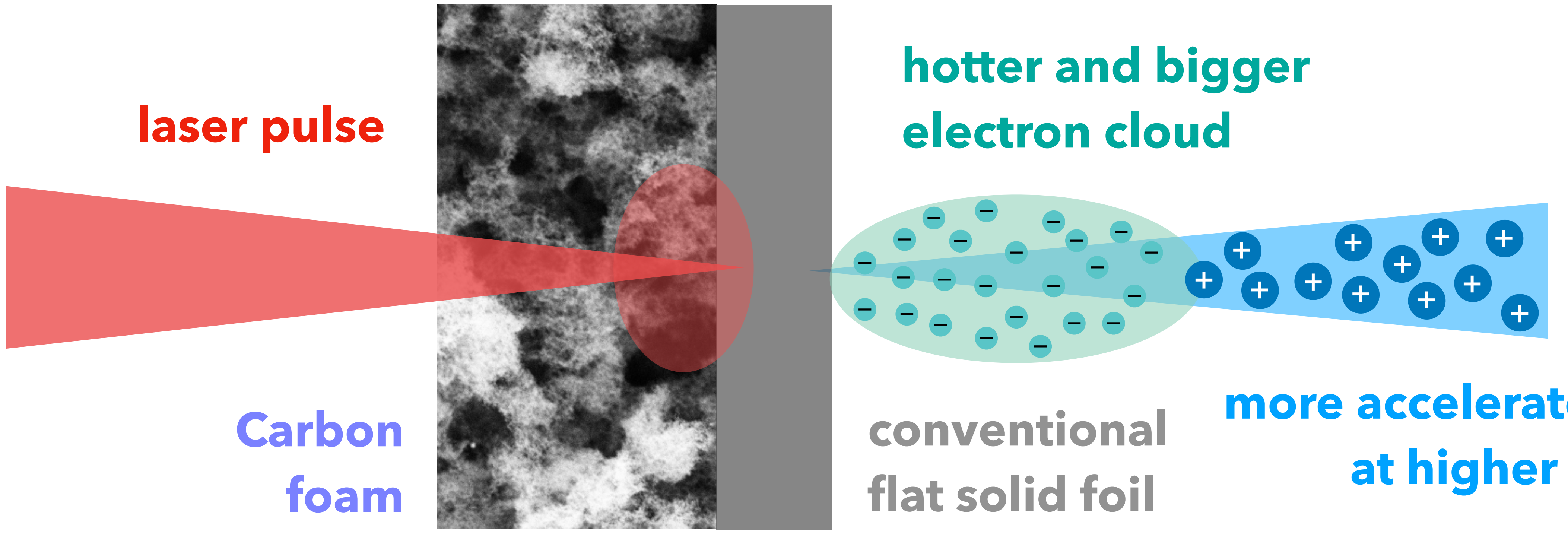
VERY LOW DENSITY:

few options other than pre-heating



Foams improve ion acceleration performances

foam-based multi-layer target



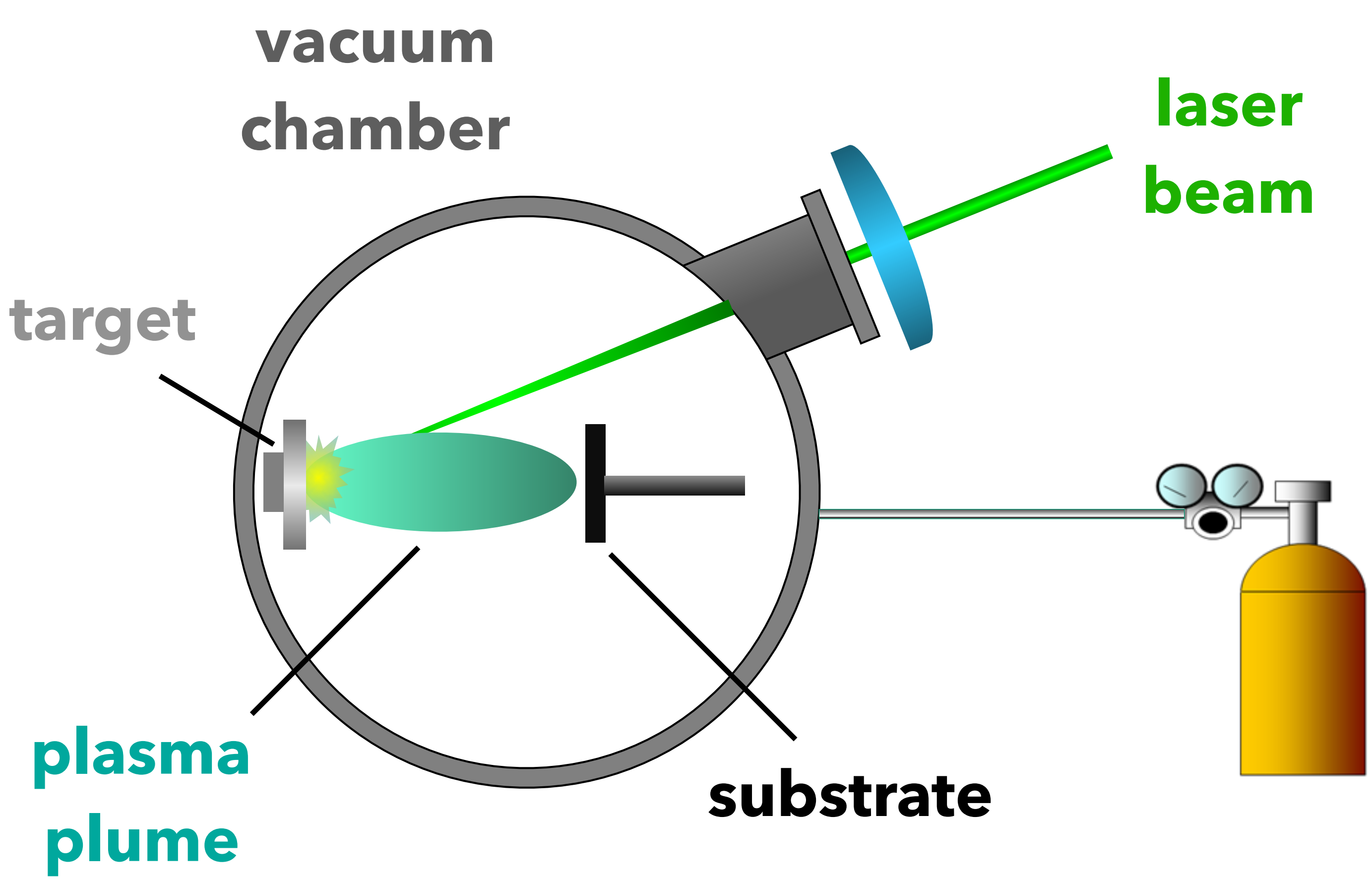
WITH FOAM

- stronger laser energy absorption
- more hot electrons
- higher hot electrons temperature
- increased maximum ion energy
- more accelerated ions
- enhanced robustness

ENHANCED TNSA PROCESS!

Foams are directly grown on the substrate

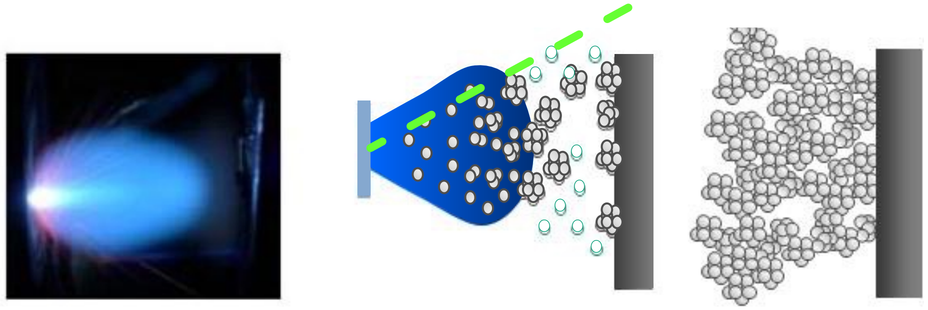
production by **Pulsed Laser Deposition (PLD)** technique



- λ = 266, 532, 1064 nm
- τ = 7 ns
- E = 0.1 - 2 J
- RR = 10 Hz
- F = 0.1 - 20 J/cm^2
- I = 10^7 - 2 x 10^9 W/cm^2

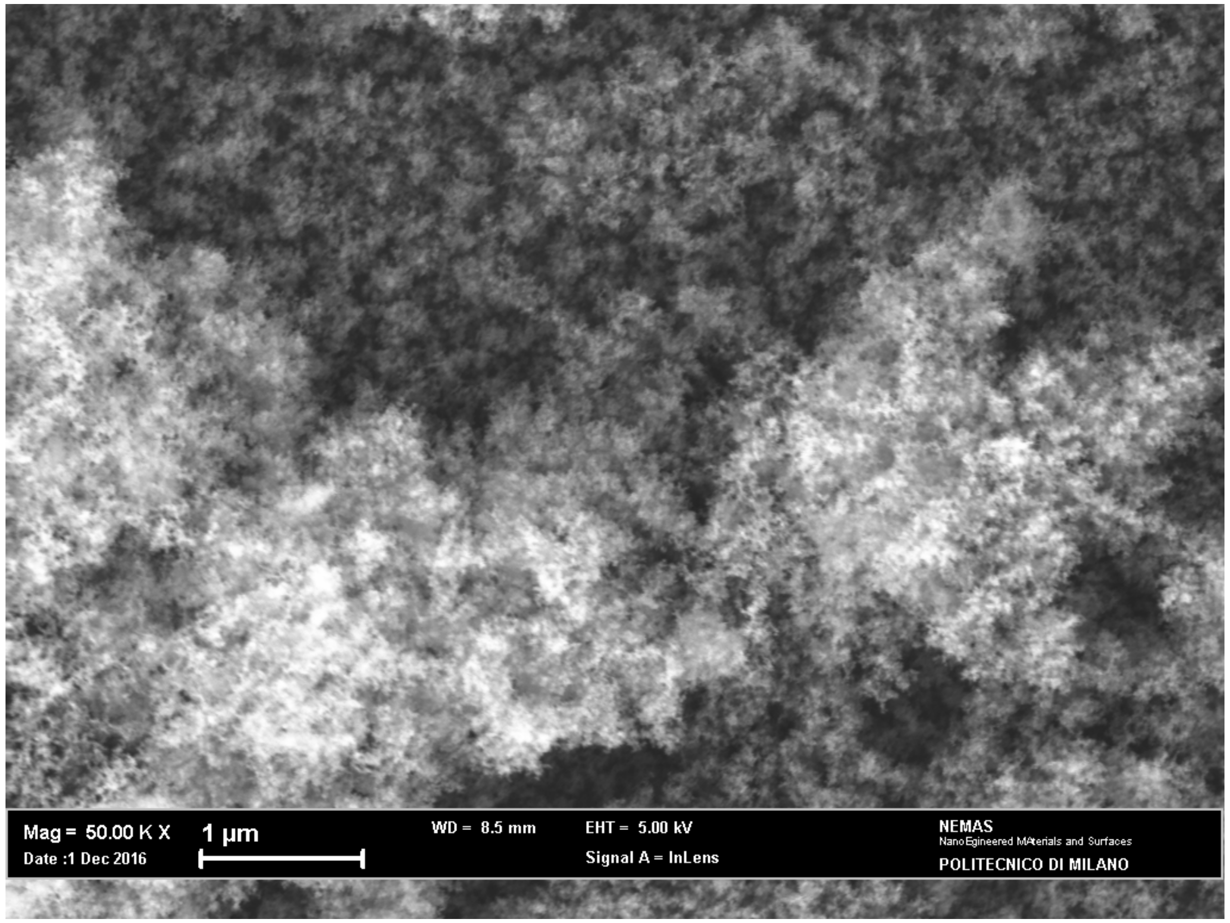
background gas

- Inert (He, Ar…)
- Reactive (O_2)

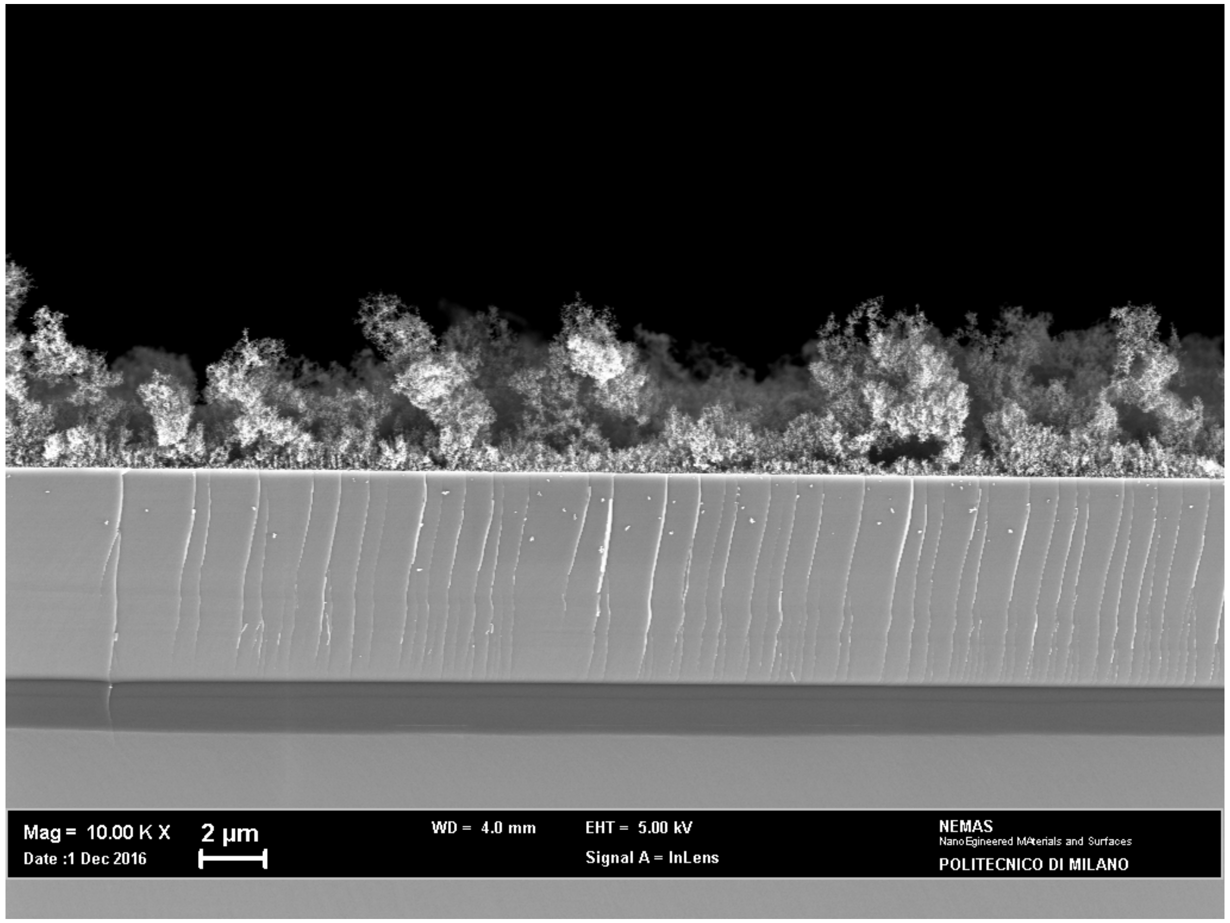


NanoLab

Foams are non-ordinary materials



top view



cross-section

SEM images

Foams are non-ordinary materials

NanoLab

nanostructure

aggregates on the µm-scale

high porosity

low density

complex morphology

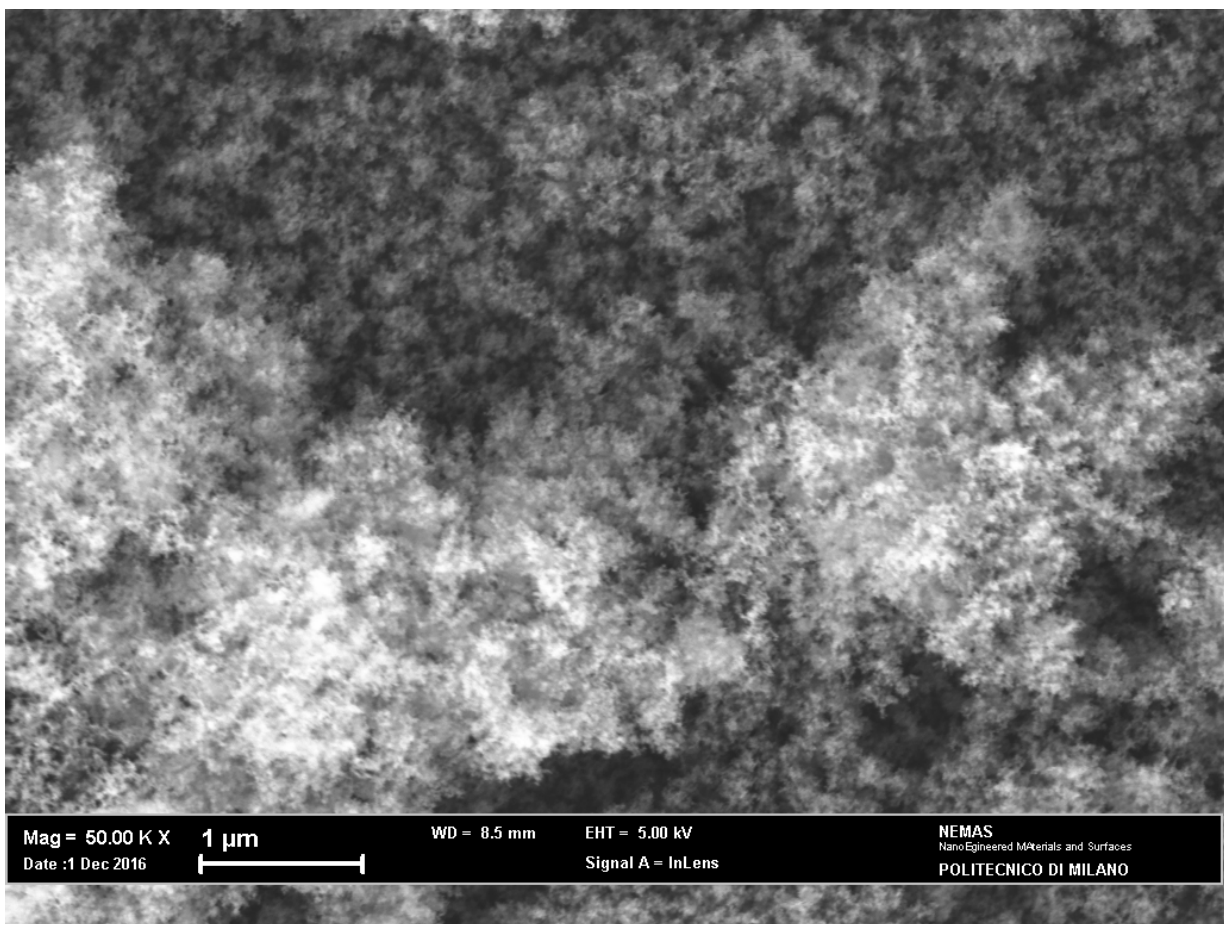
self-similar features

non-uniform density profile

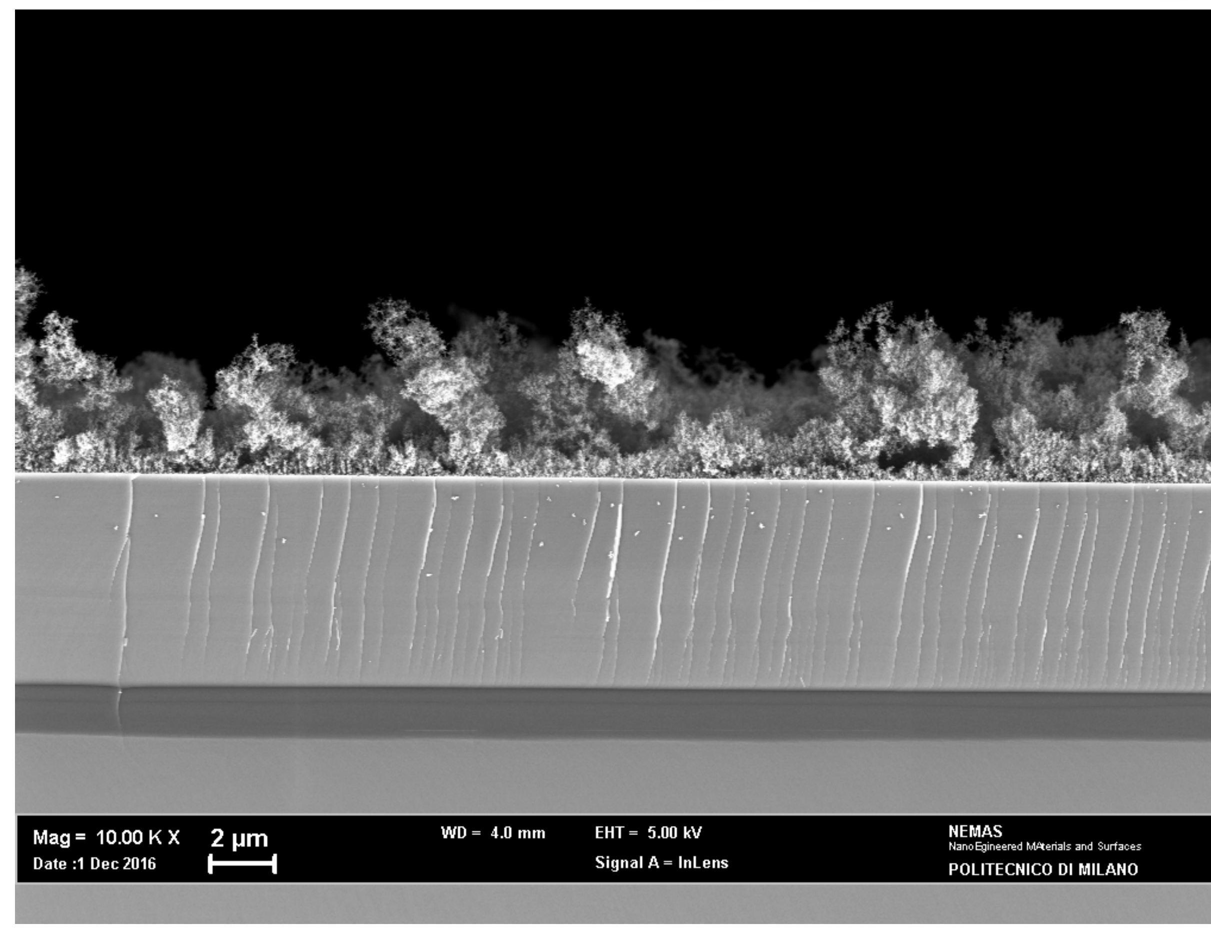
non-uniform thickness profile

solid-density building-blocks

tunable



top view



cross-section

SEM images

Foams are non-ordinary materials

nanostructure

aggregates on the μm-scale

high porosity

low density

complex morphology

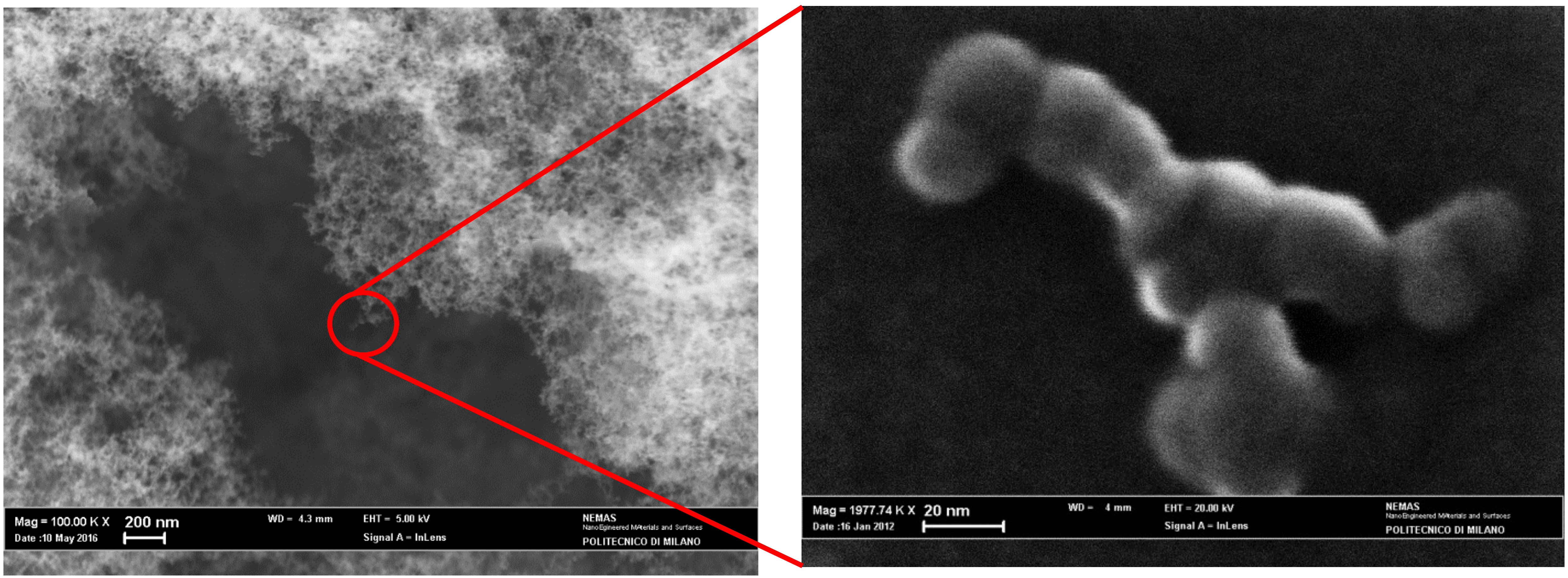
self-similar features

non-uniform density profile

non-uniform thickness profile

solid-density building-blocks

tunable



top view

SEM images

building-blocks

Foam features can be tuned on different scales

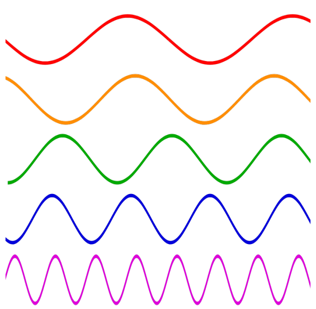
Foam property control

Nano-scale

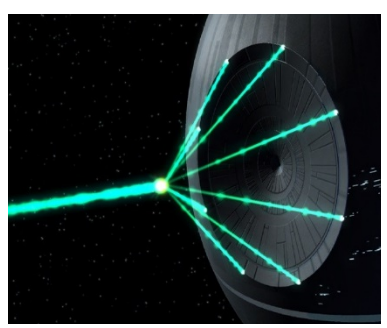
Micro-scale

Macro-scale

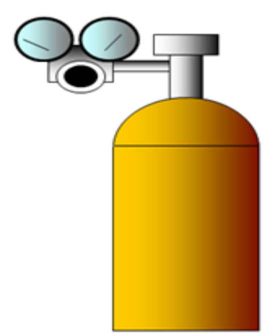
Laser wavelength



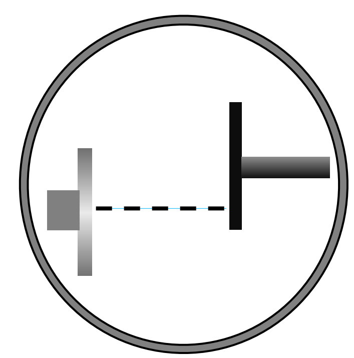
Laser fluence



Gas pressure



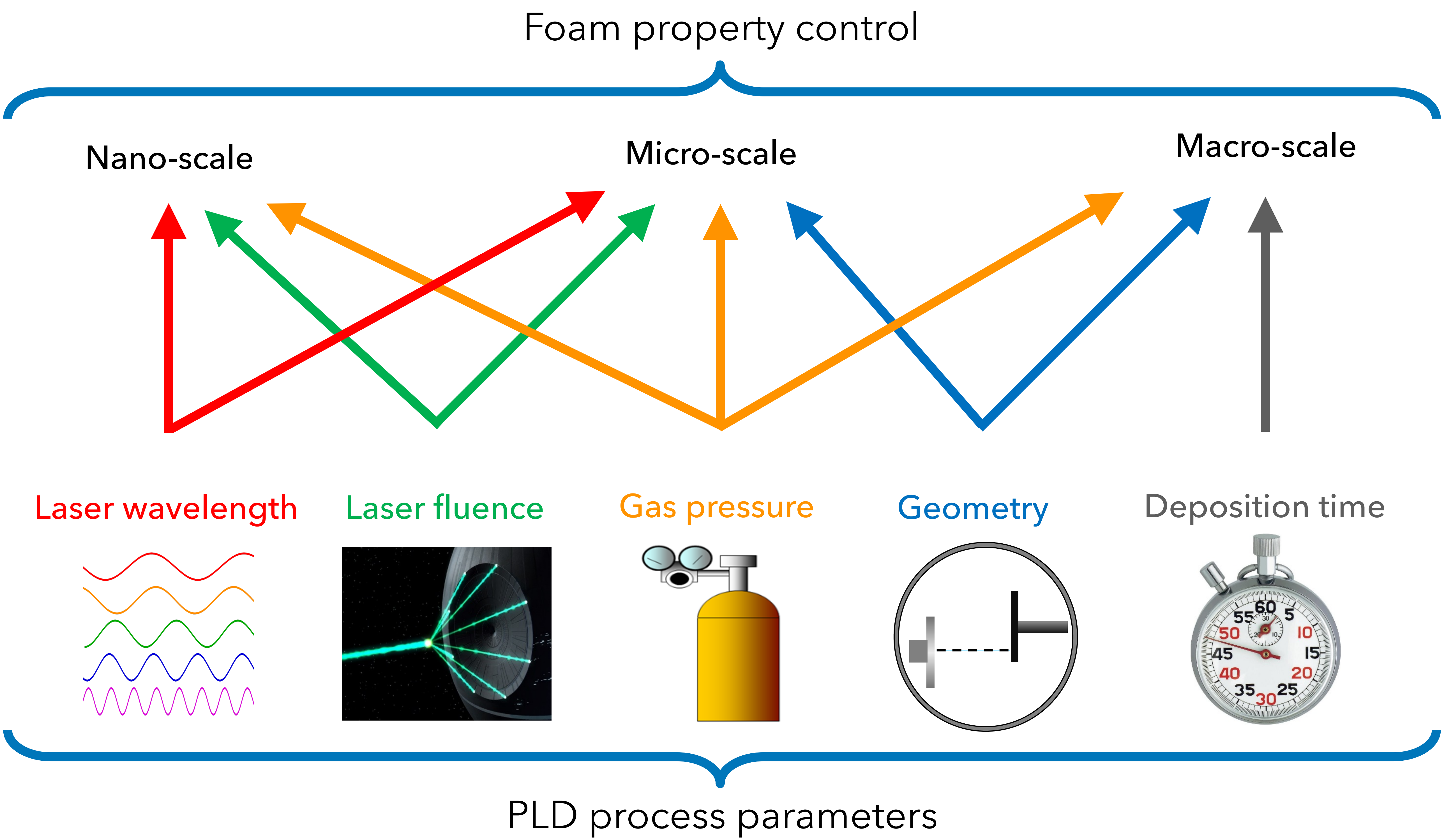
Geometry



Deposition time

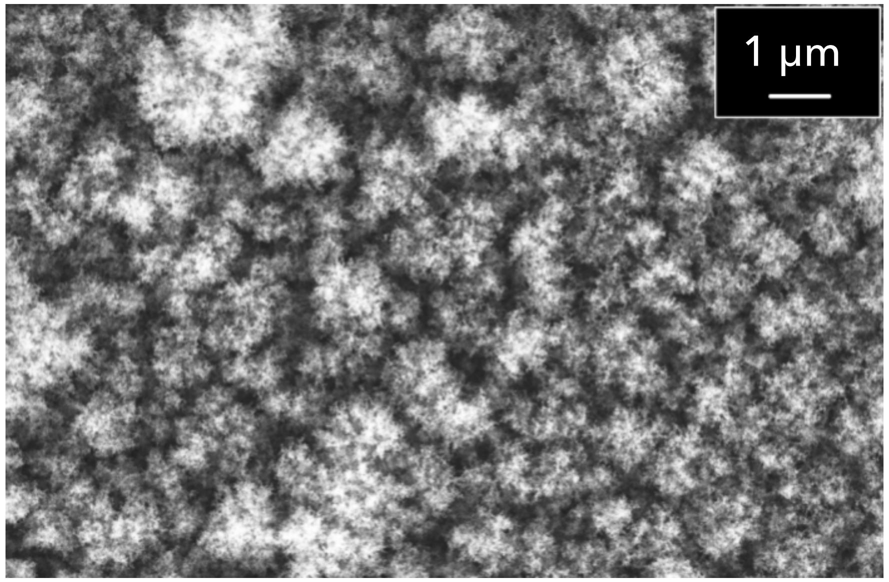
PLD process parameters

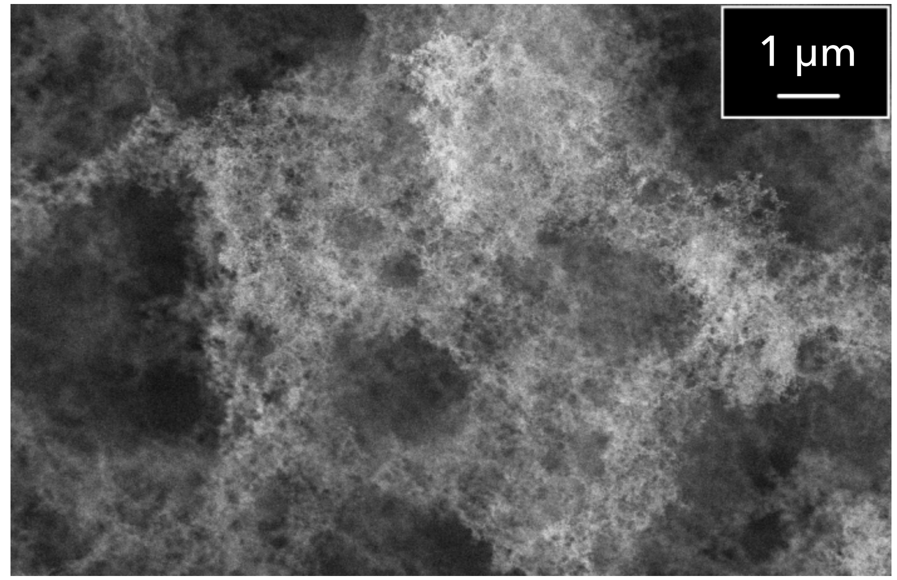
Foam features can be tuned on different scales

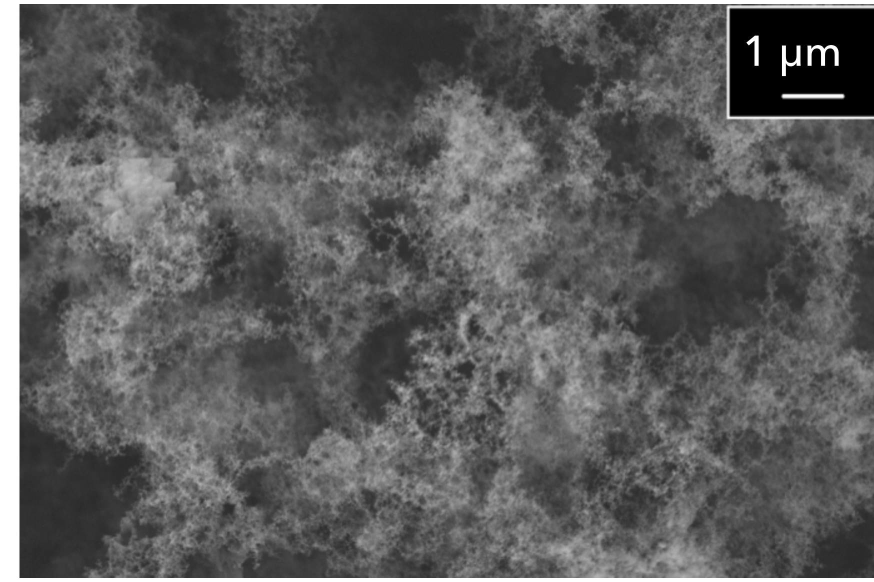


Foam morphology depends on gas pressure

Argon

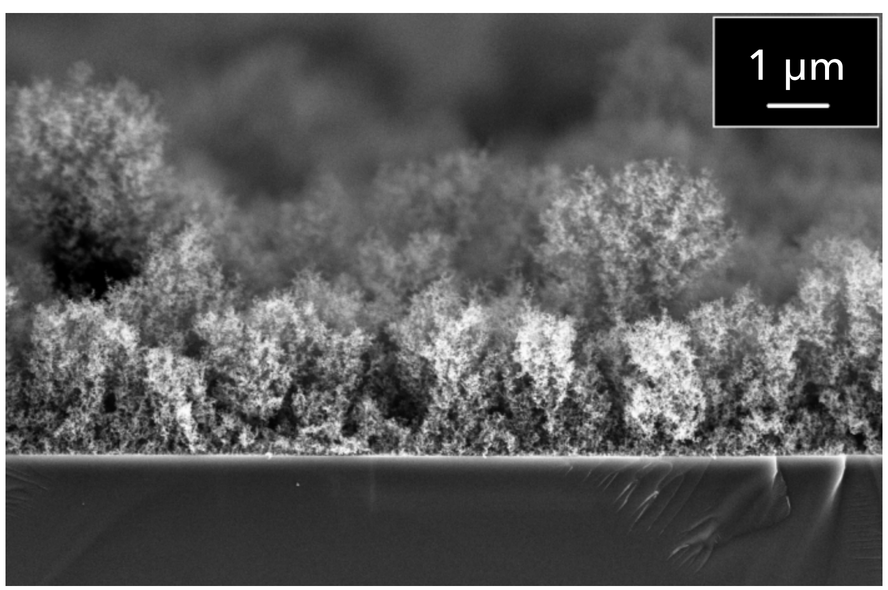


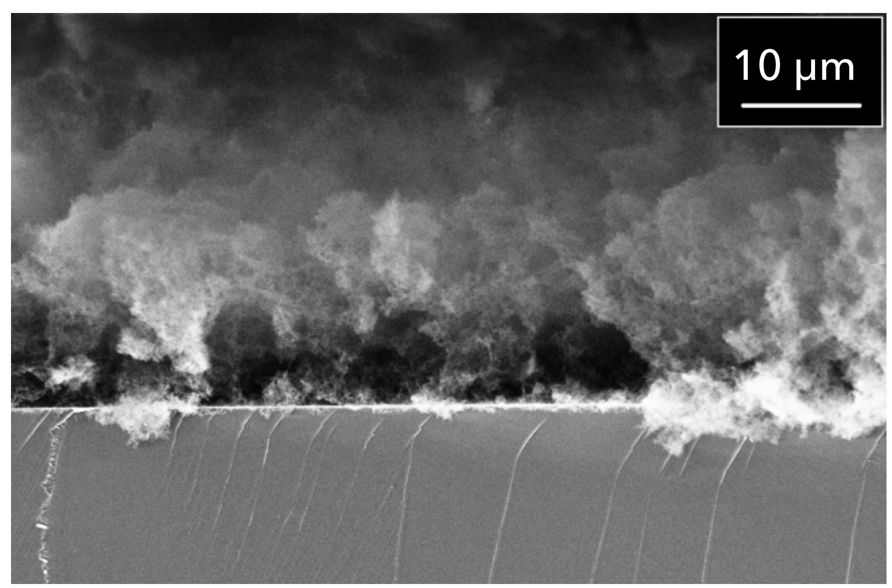


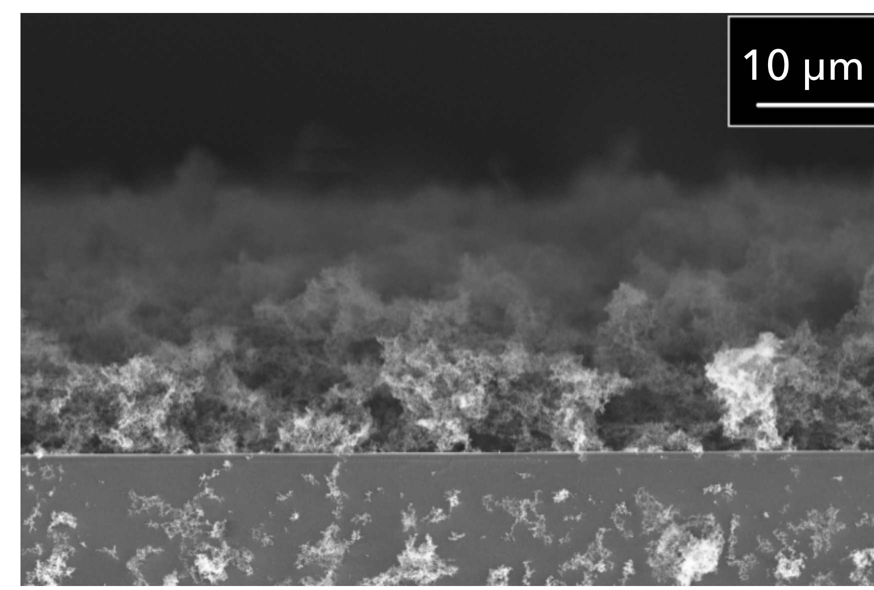


30 Pa | 100 Pa | 150 Pa

Gas pressure →



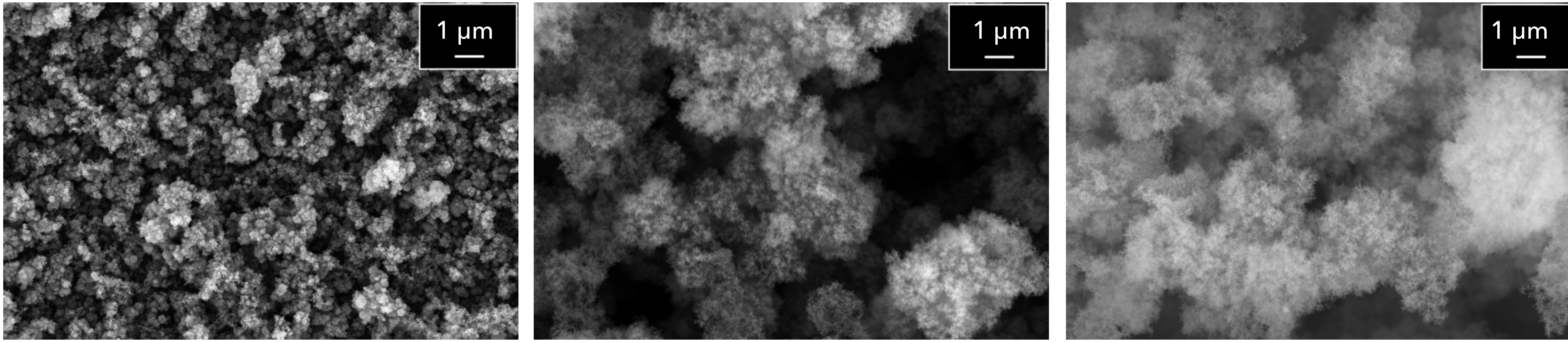




Zani et al. *Carbon* 56 (2013)

Foam morphology depends on the gas type

Helium

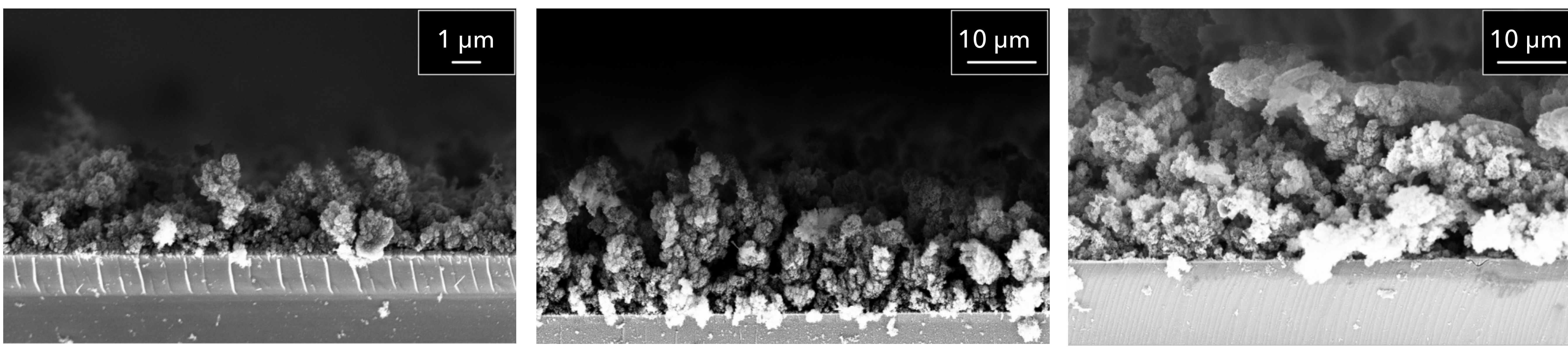


30 Pa

100 Pa

150 Pa

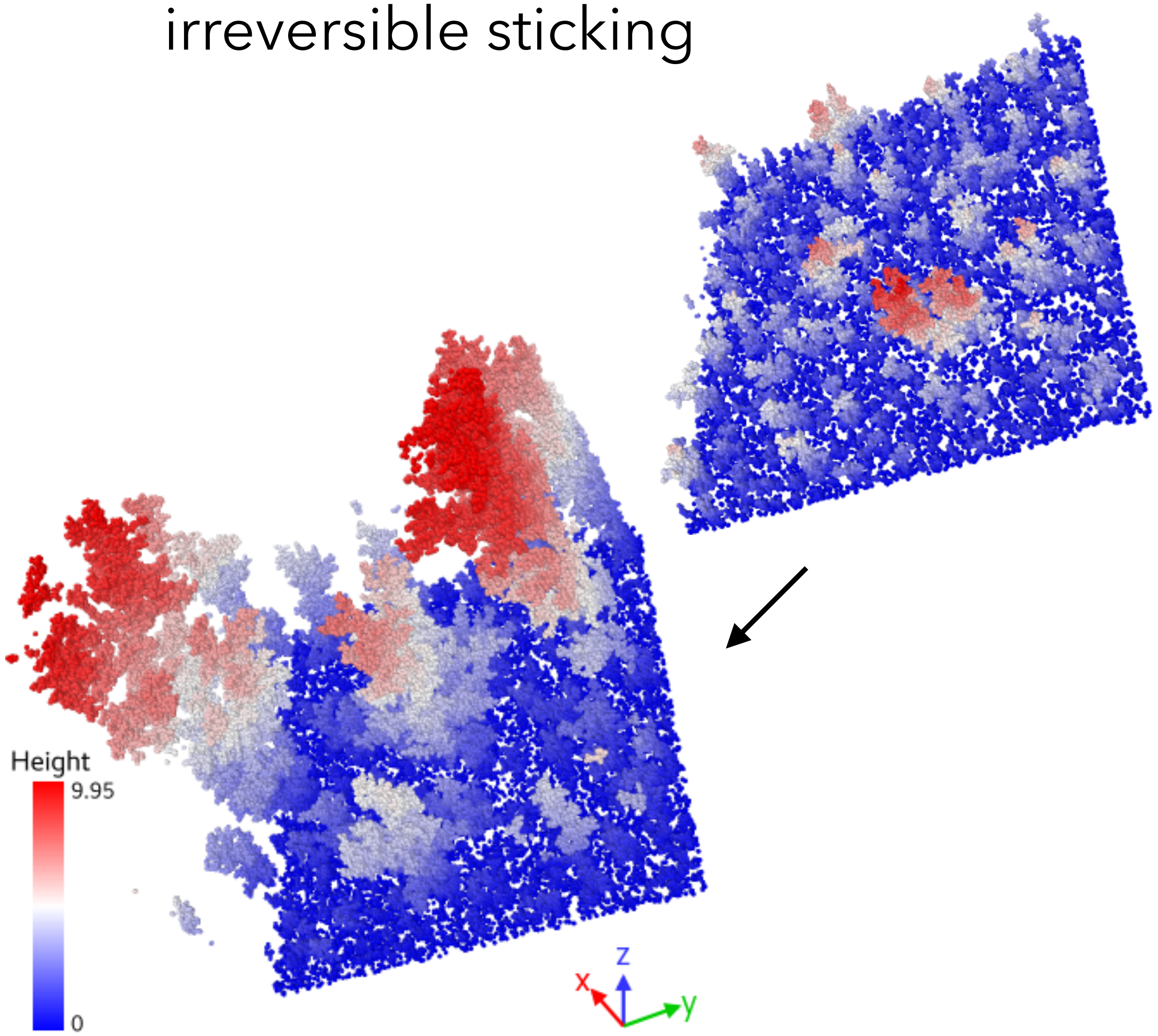
Gas pressure



Zani et al. *Carbon* 56 (2013)

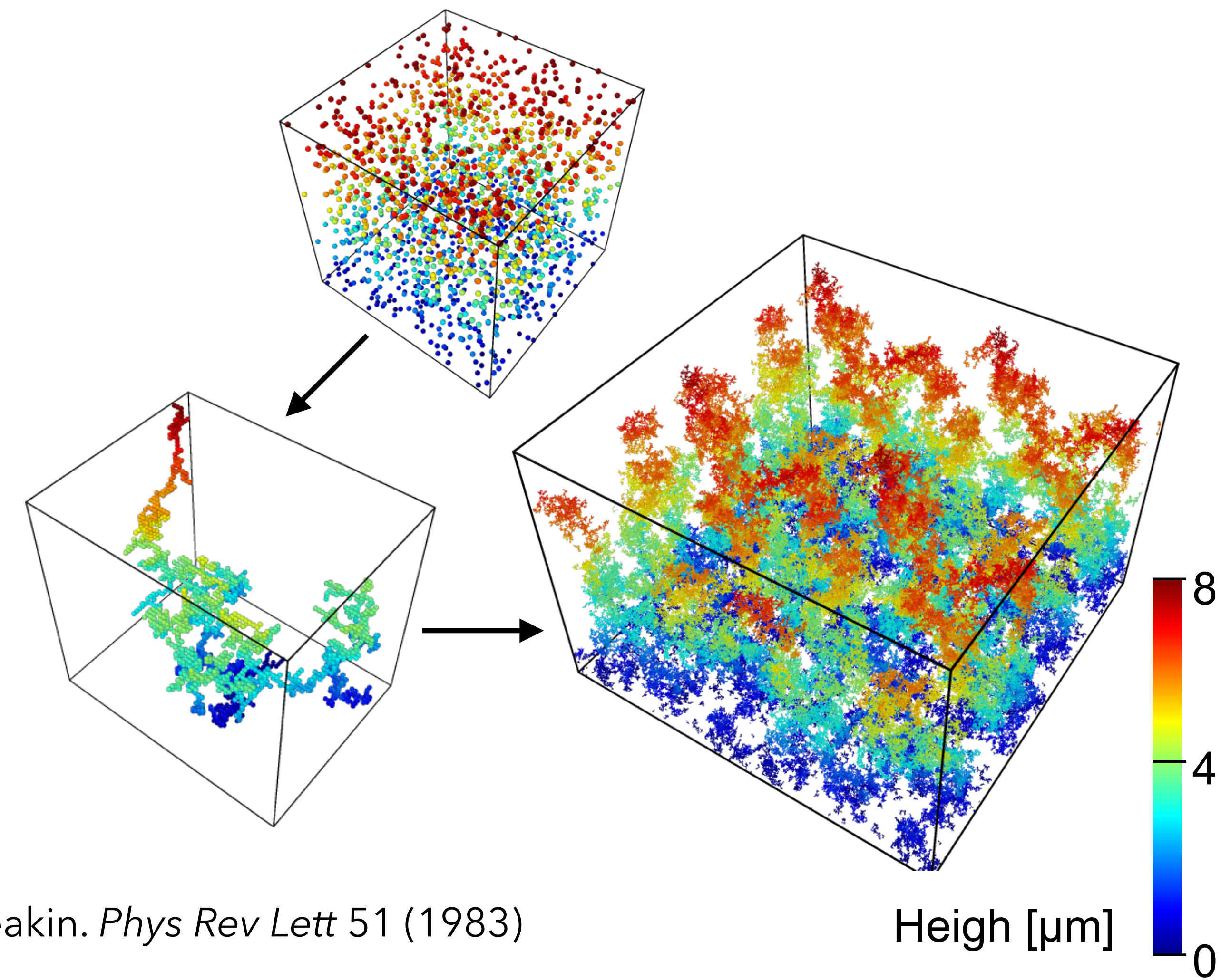
Aggregation models can mimic foam growth

Diffusion-Limited (DLA)
- Brownian motion of particles
- particle deposition in clusters by irreversible sticking



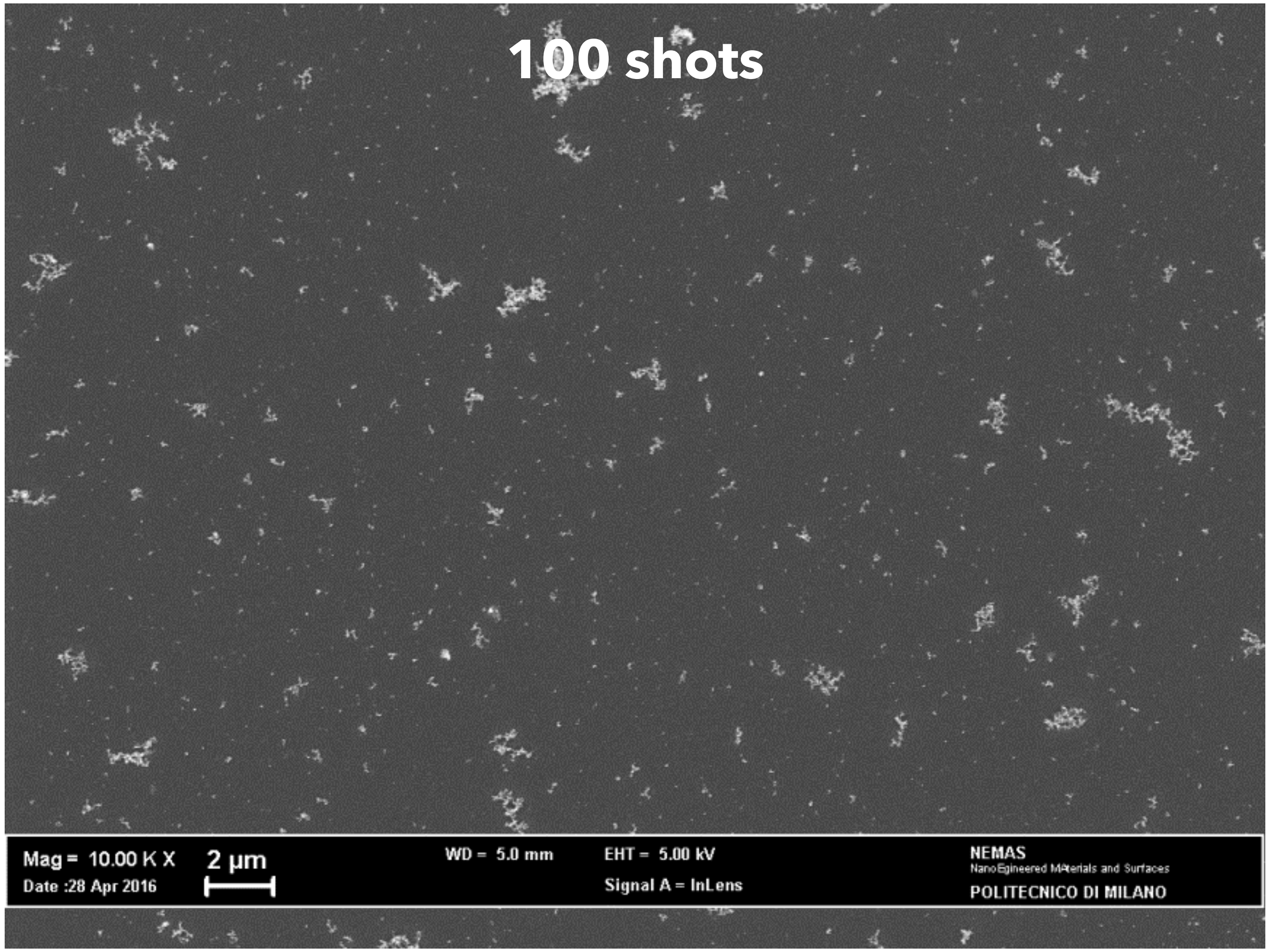
Witten and Sander. *Phys Rev Lett* 47 (1981)

Diffusion-Limited Cluster-Cluster (DLCCA)
- Brownian motion of particles
- particle aggregation in clusters by irreversible sticking
- clusters deposition on substrate

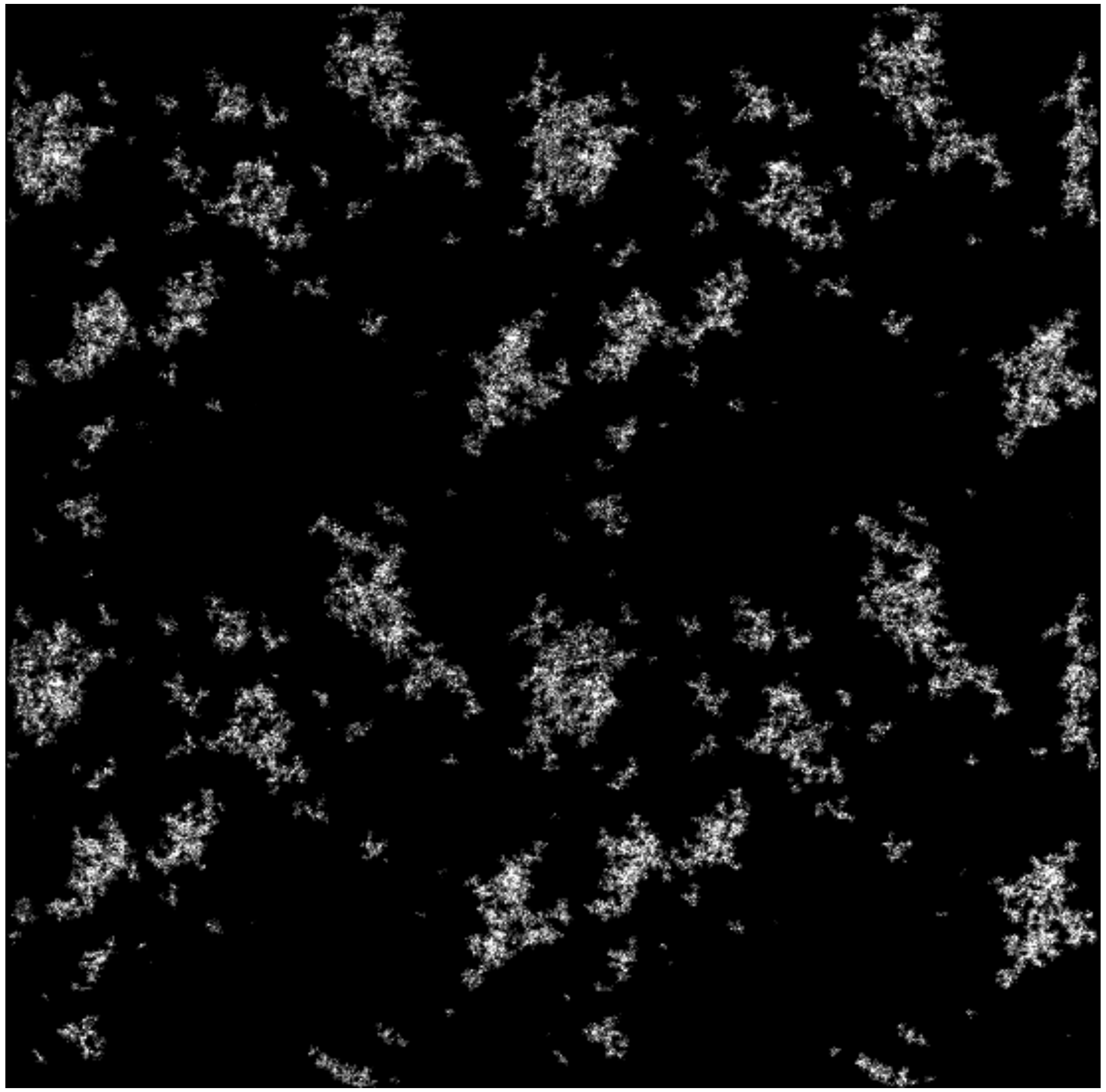


Meakin. *Phys Rev Lett* 51 (1983)

Real vs. synthetic foam growth

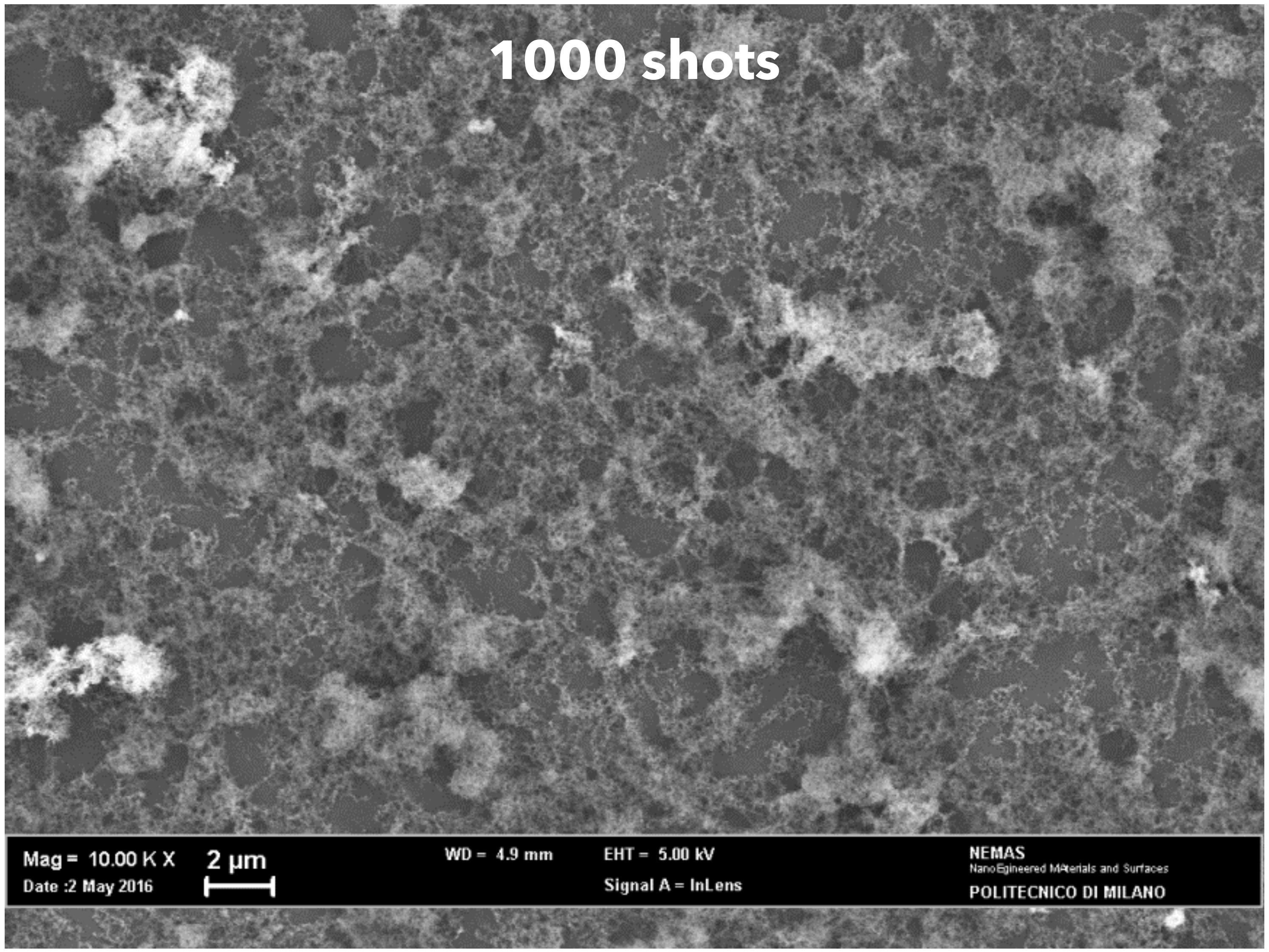


REAL

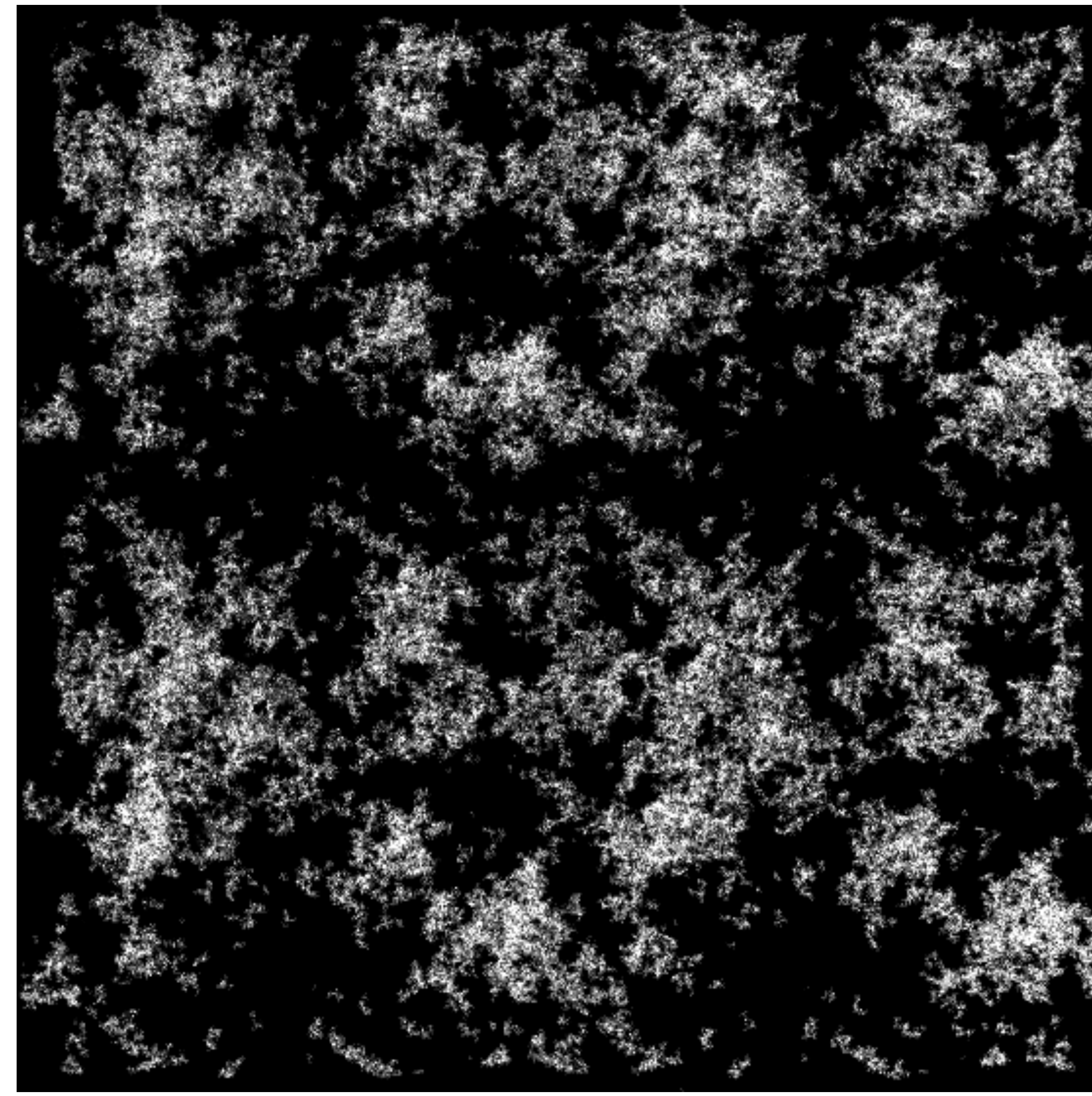


DLCCA MODEL

Real vs. synthetic foam growth

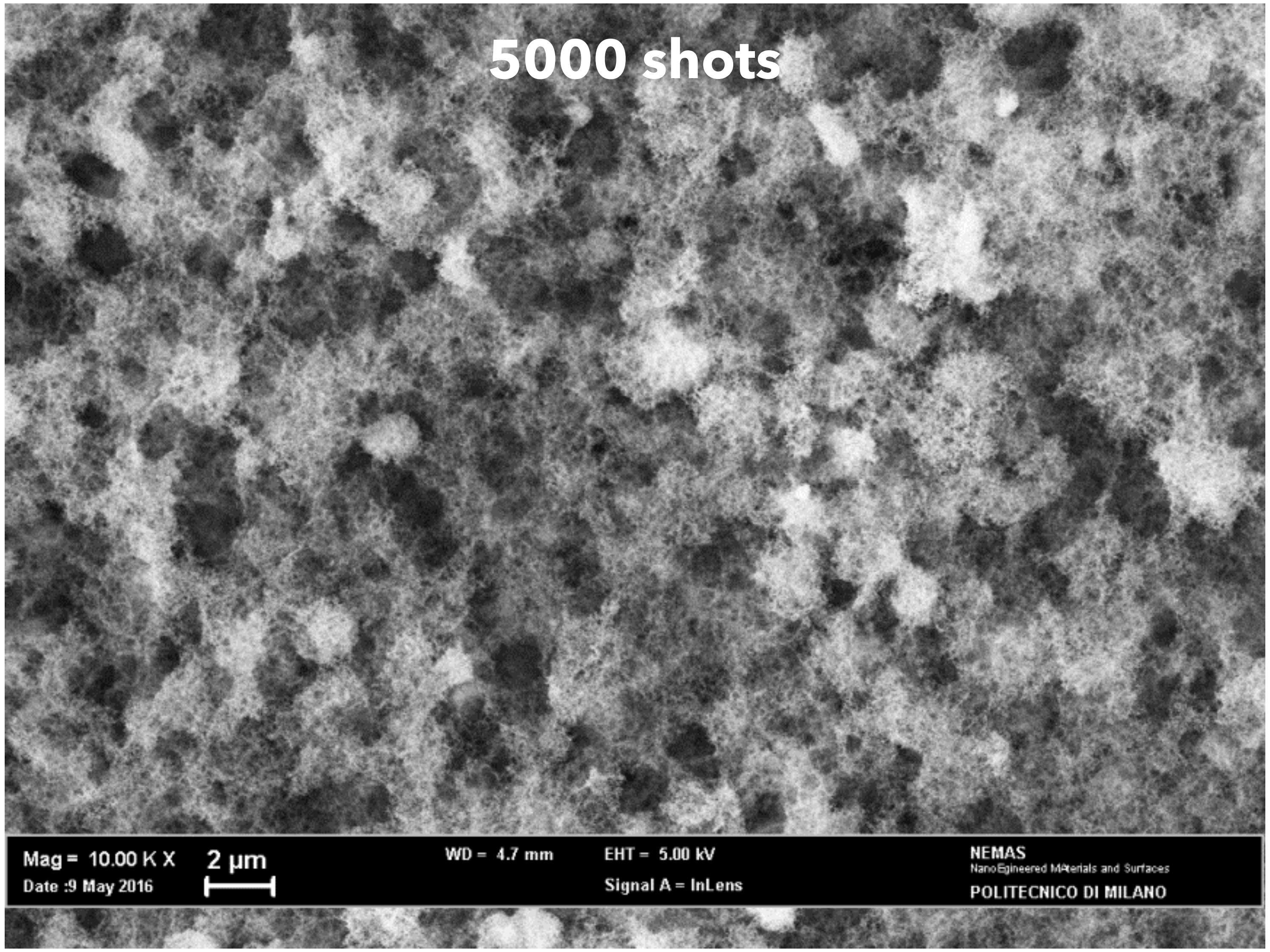


REAL

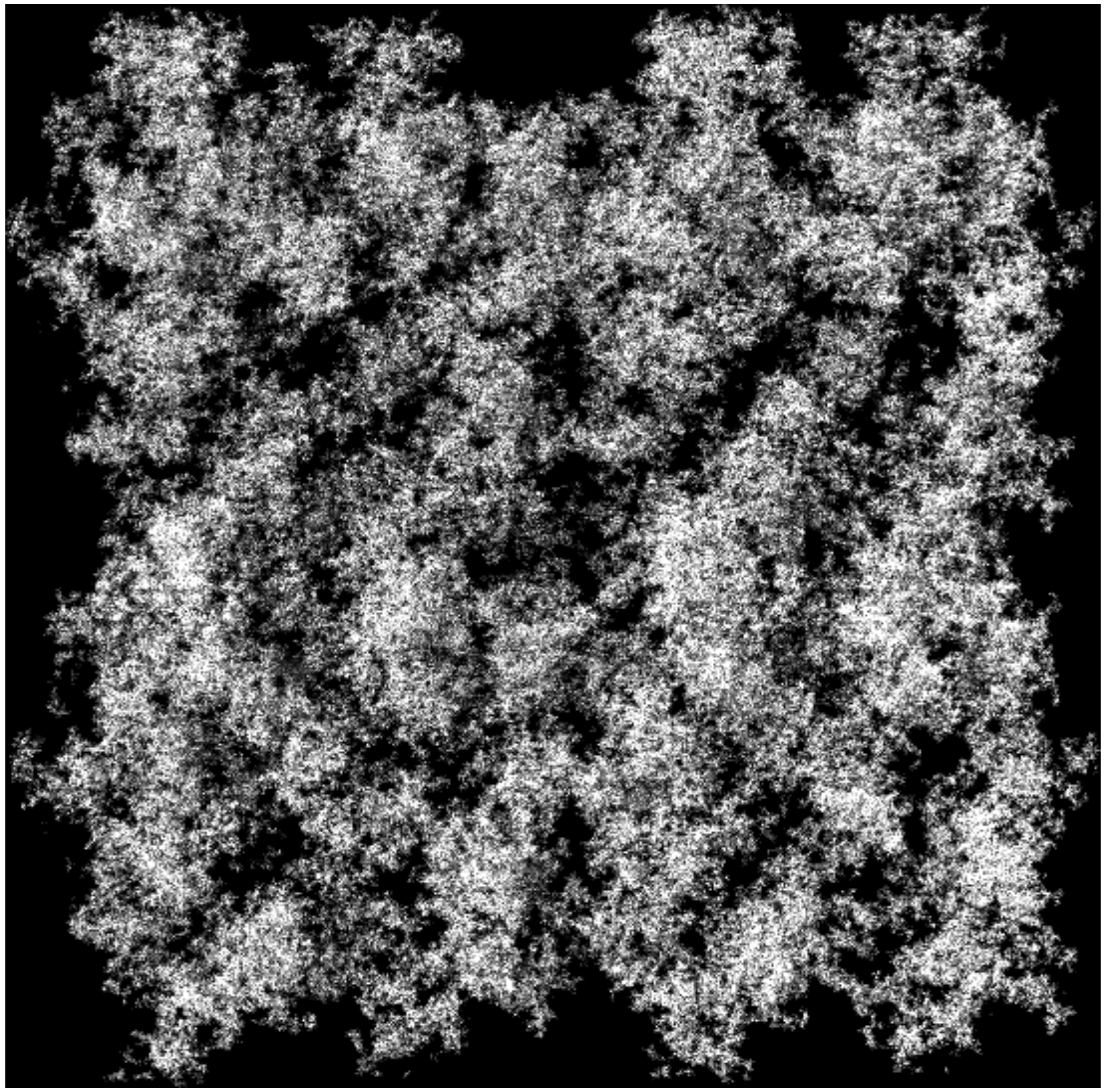


DLCCA MODEL

Real vs. synthetic foam growth



REAL



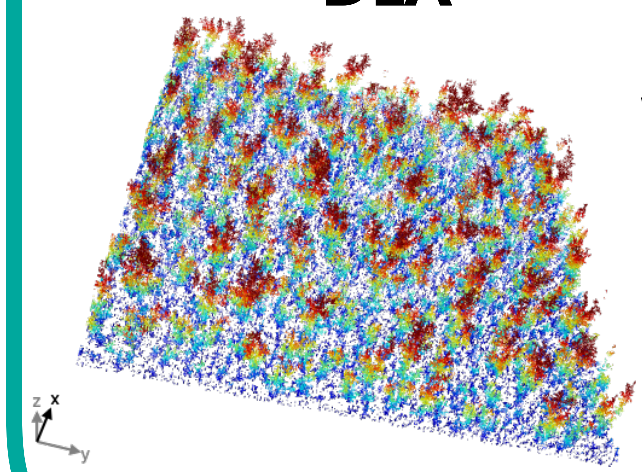
DLCCA MODEL

Choose a foam model to simulate the acceleration

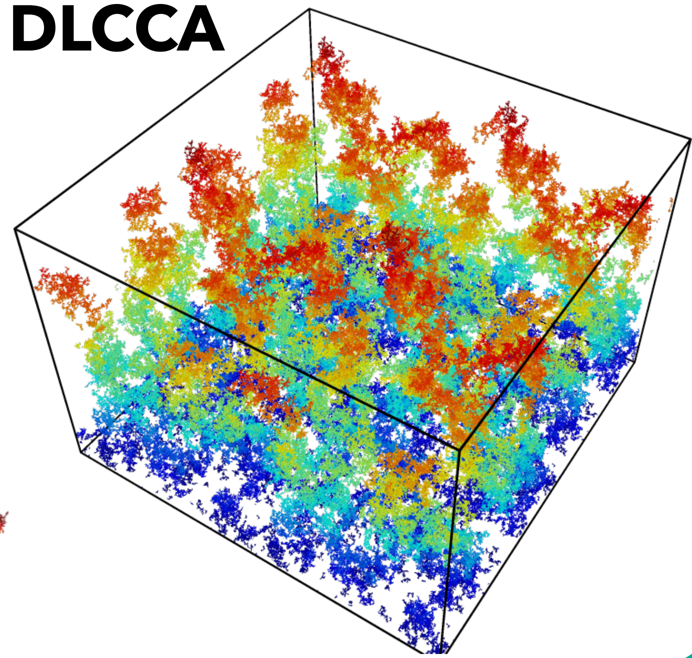
3D

quite realistic

DLA

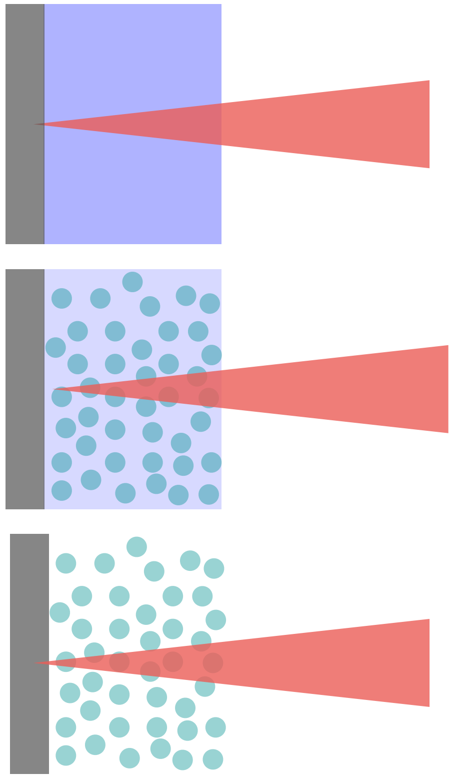


DLCCA



2D

very idealized



homogeneous

mixed

random spheres

Particle-In-Cell codes
for laser-plasma interaction

github.com/ALaDyn/piccante

github.com/SmileiPIC/Smilei

piccante Open Source PIC Code

Smilei)

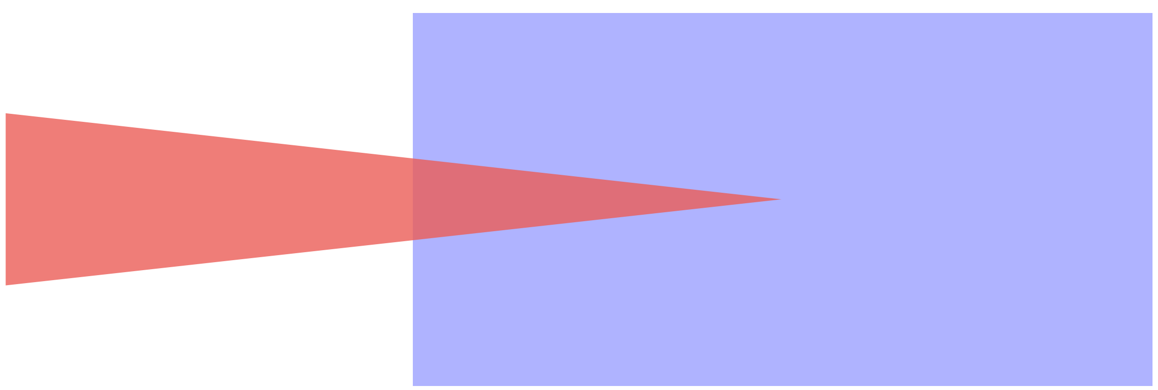
CINECA

But first we investigated the interaction only

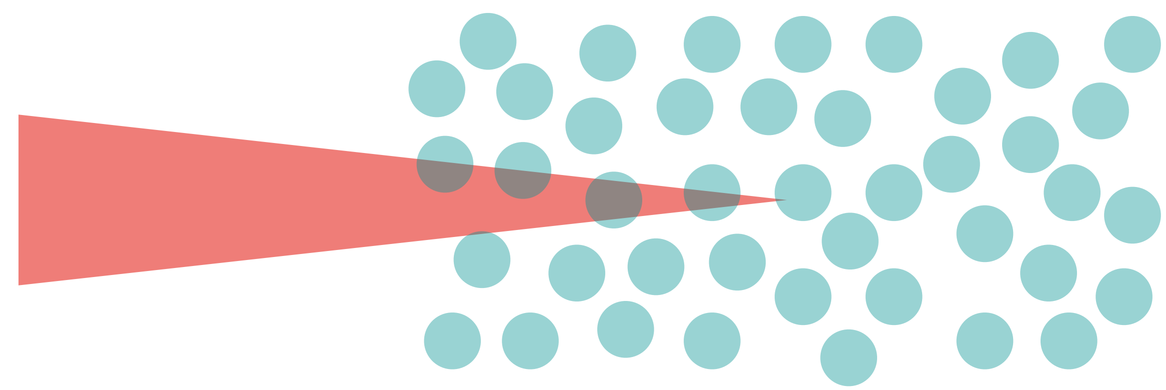
2D

near-critical plasmas

homogeneous



random spheres

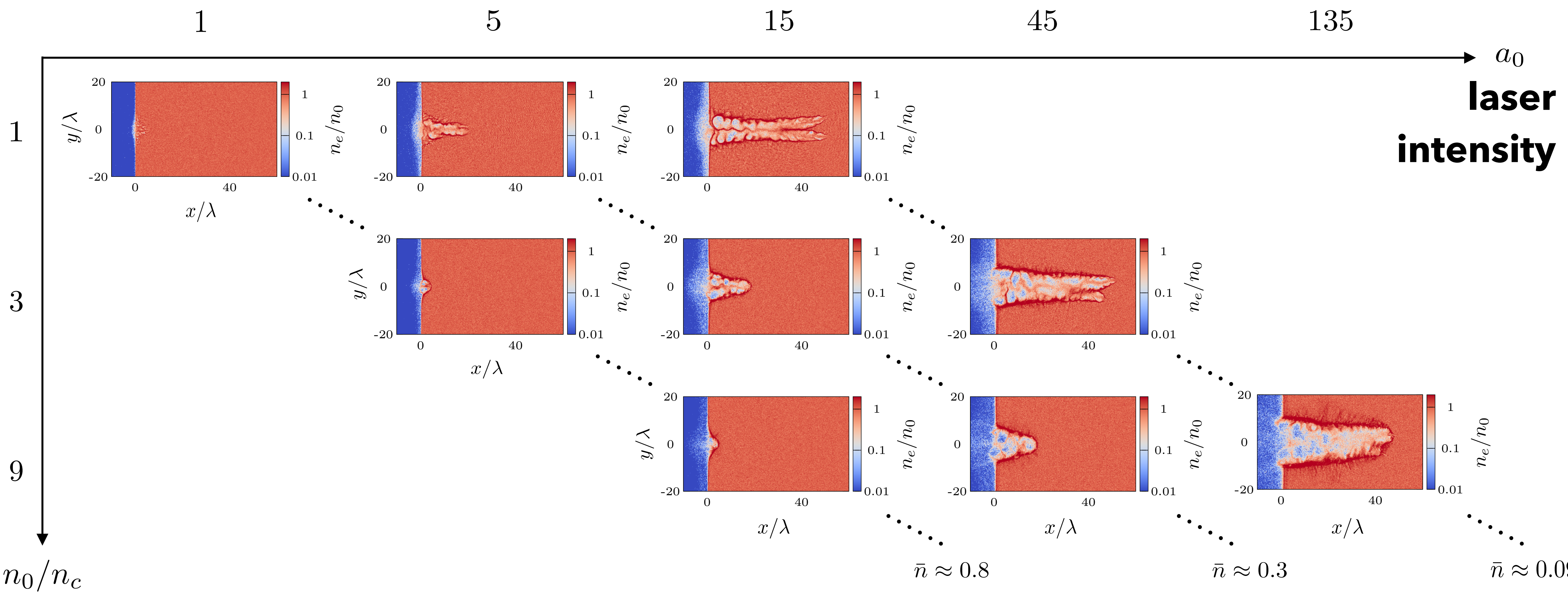


no substrate, so no ion acceleration!

Compare simulations of homogeneous plasmas…

2D

electron density plots



laser intensity

unperturbed average density

relativistic transparency

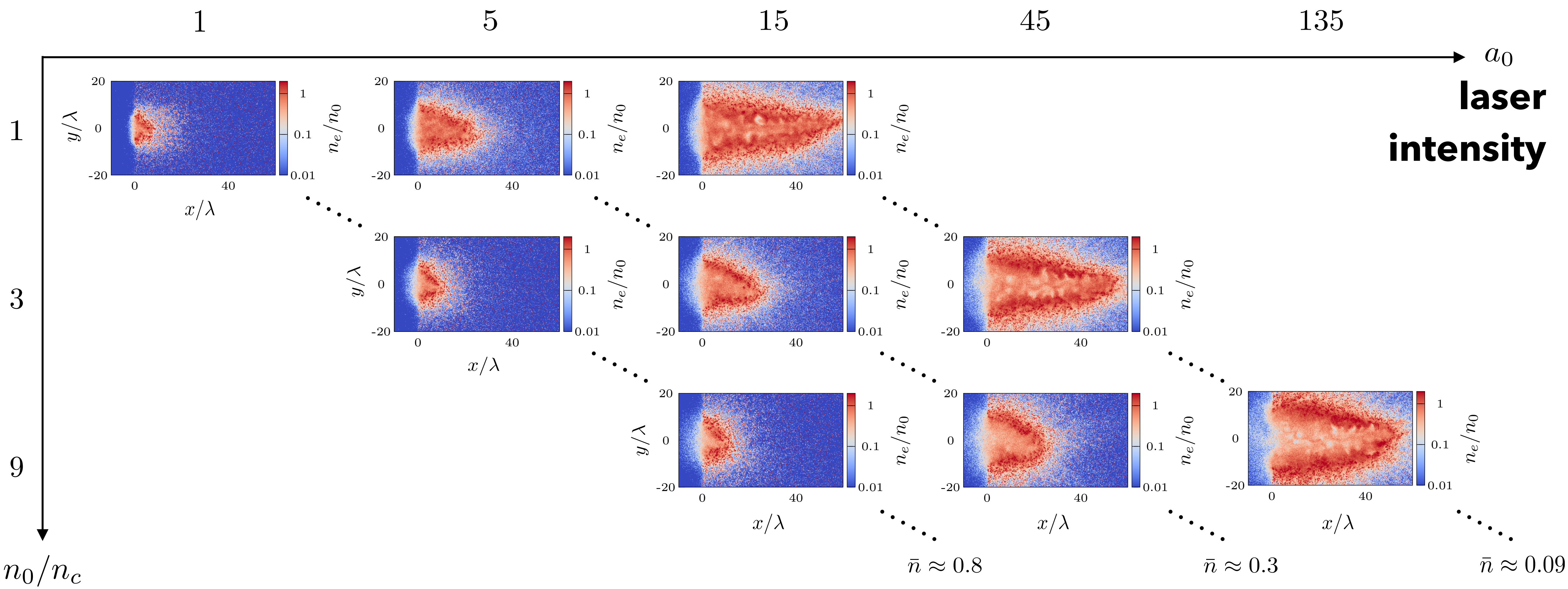
$$\bar{n} = \frac{n_0/n_c}{\sqrt{1+\frac{a_0^2}{2}}}$$

Fedeli et al. *Eur Phys J D* 71 (2017)

…with simulations of random spheres plasmas

2D

electron density plots



laser intensity

unperturbed average density

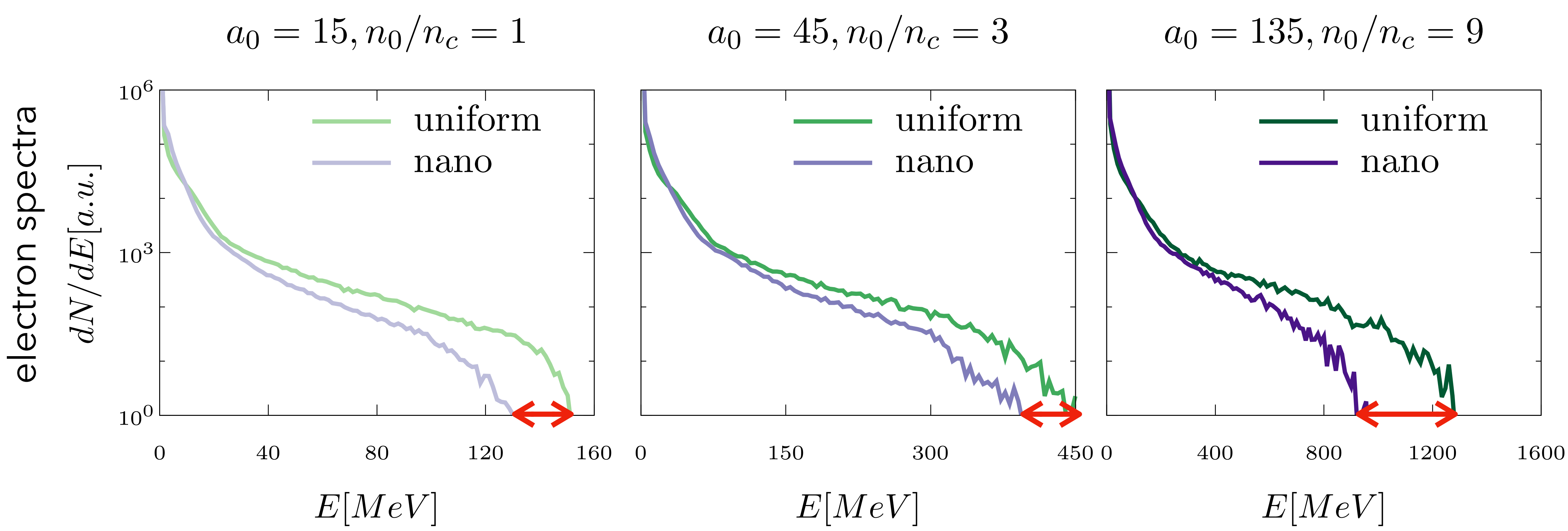
relativistic transparency

$$\bar{n} = \frac{n_0/n_c}{\sqrt{1 + \frac{a_0^2}{2}}}$$

Fedeli et al. *Eur Phys J D* 71 (2017)

Main difference is energy repartition

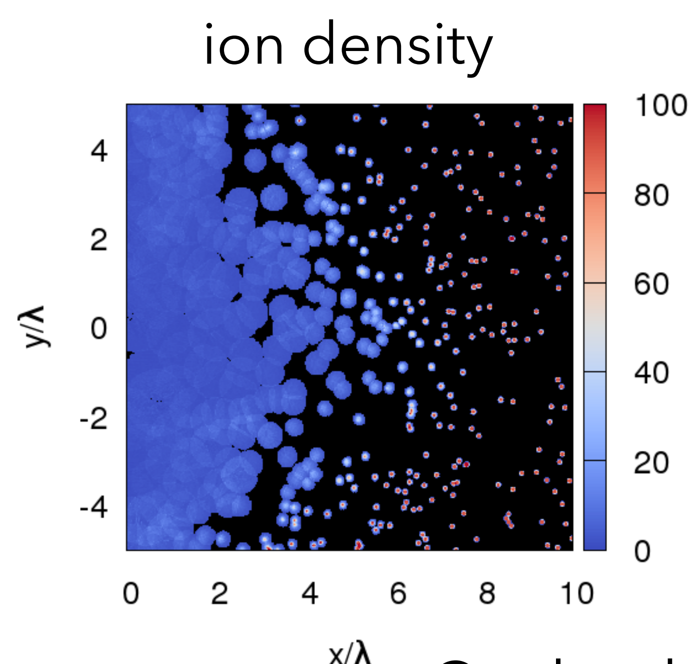
2D

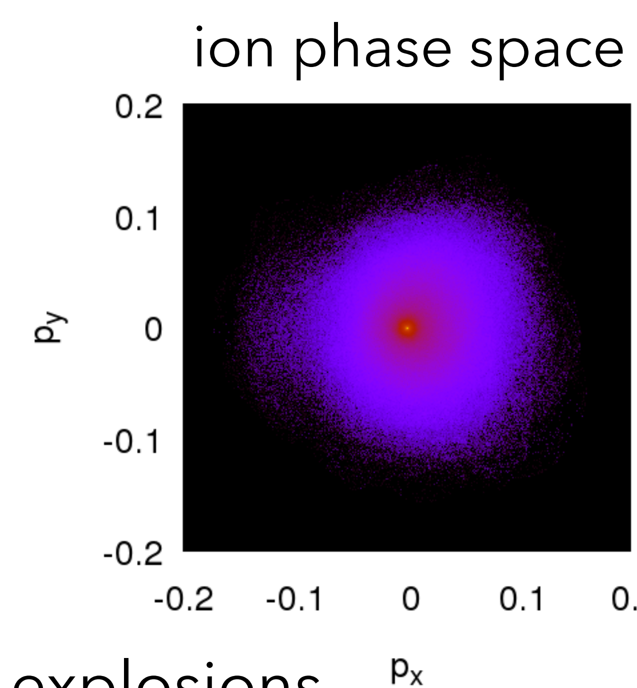


WITH STRUCTURE

less energy to hot electrons

Homogeneous foam should be better for ion acceleration!





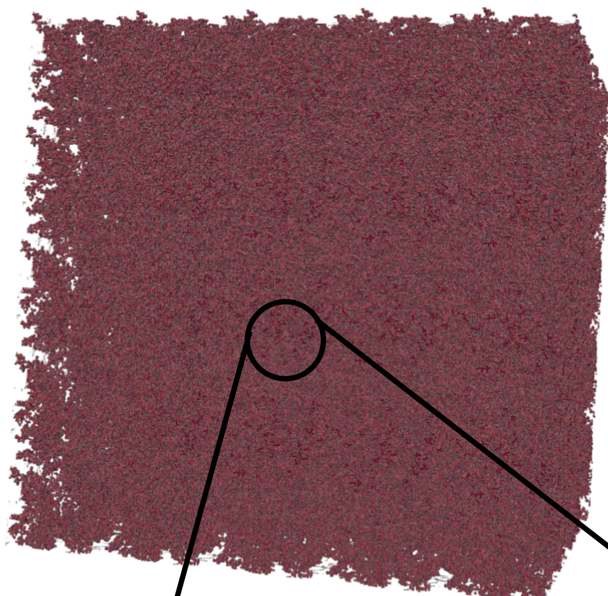
Coulomb explosions

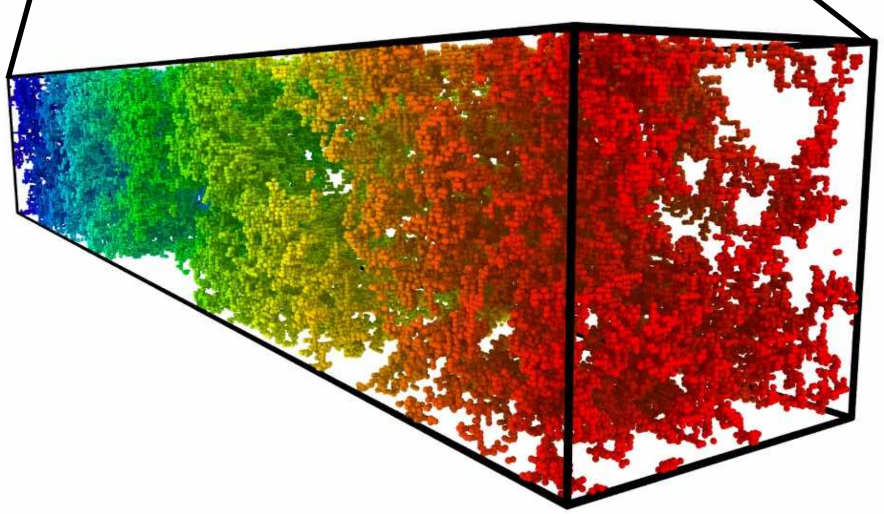
Fedeli et al. *Eur Phys J D* 71 (2017)

Next: compare different kinds of nanostructures

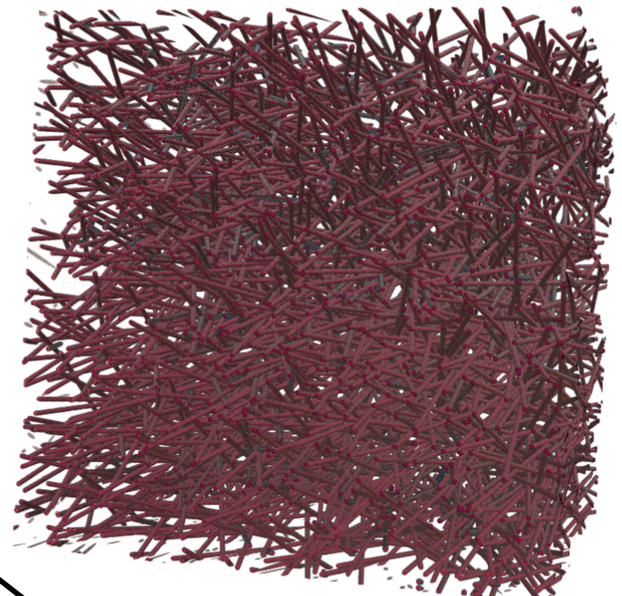
3D

DLCCA

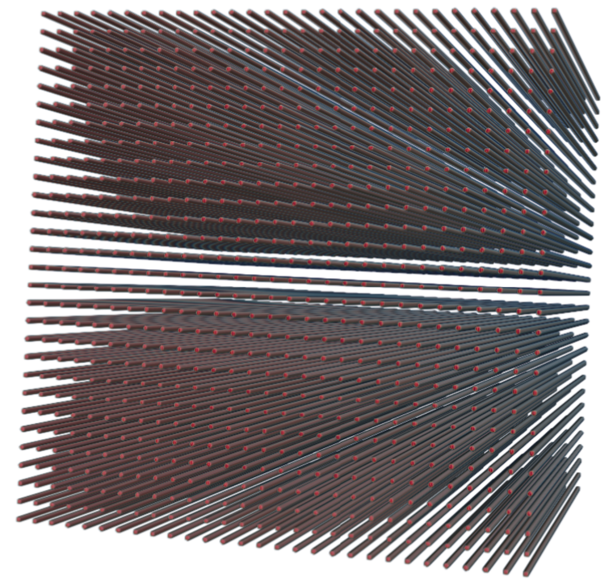




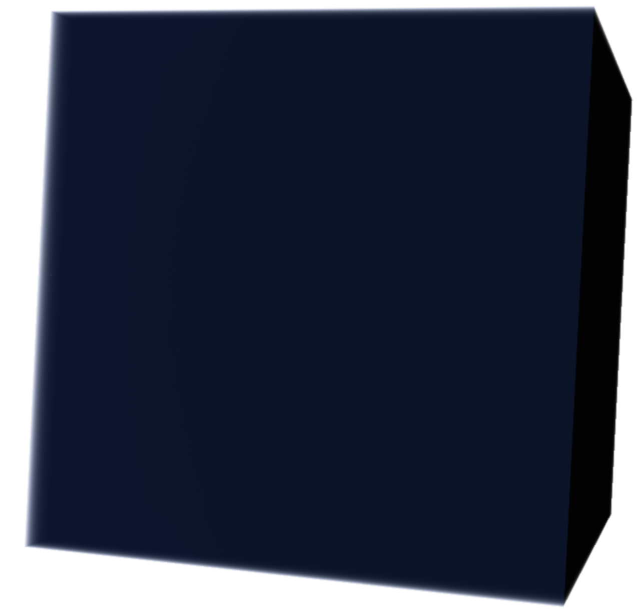
random wires

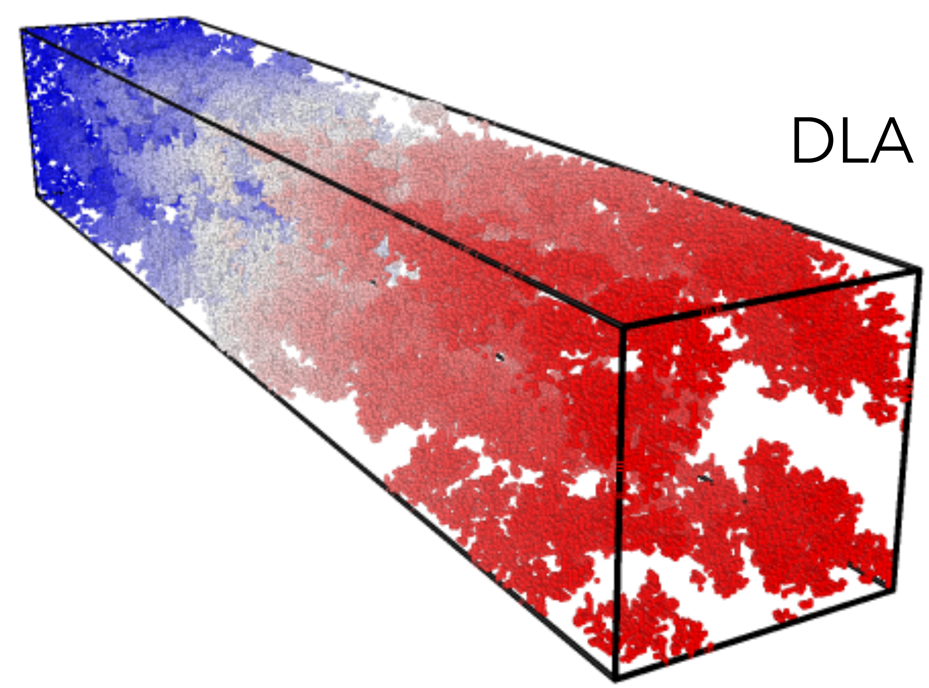


ordered wires



homogeneous

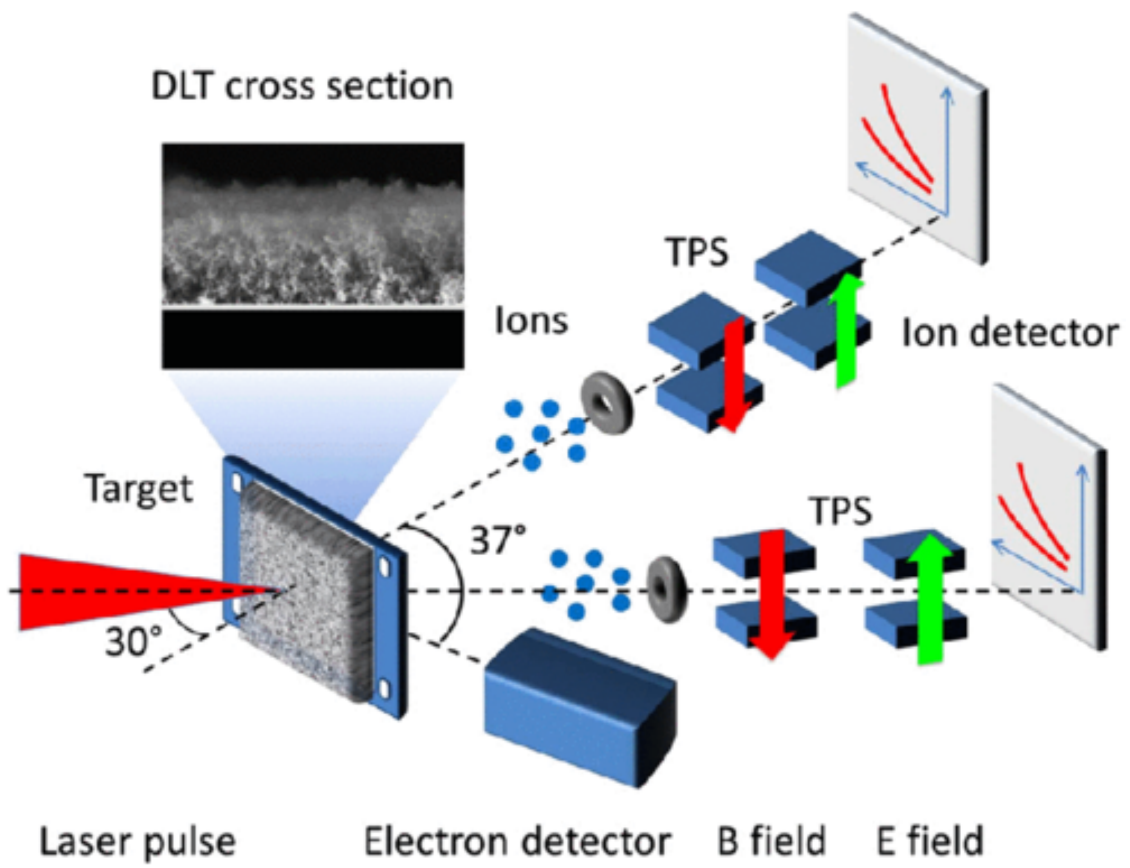




Ion acceleration experiments in laser facilities

3 recent campaigns:
- **GIST**, Gwangju, South Korea, 2015-2016
- **HDZR**, Dresden, Germany, 2017
- **ILE**, Osaka, Japan, 2017

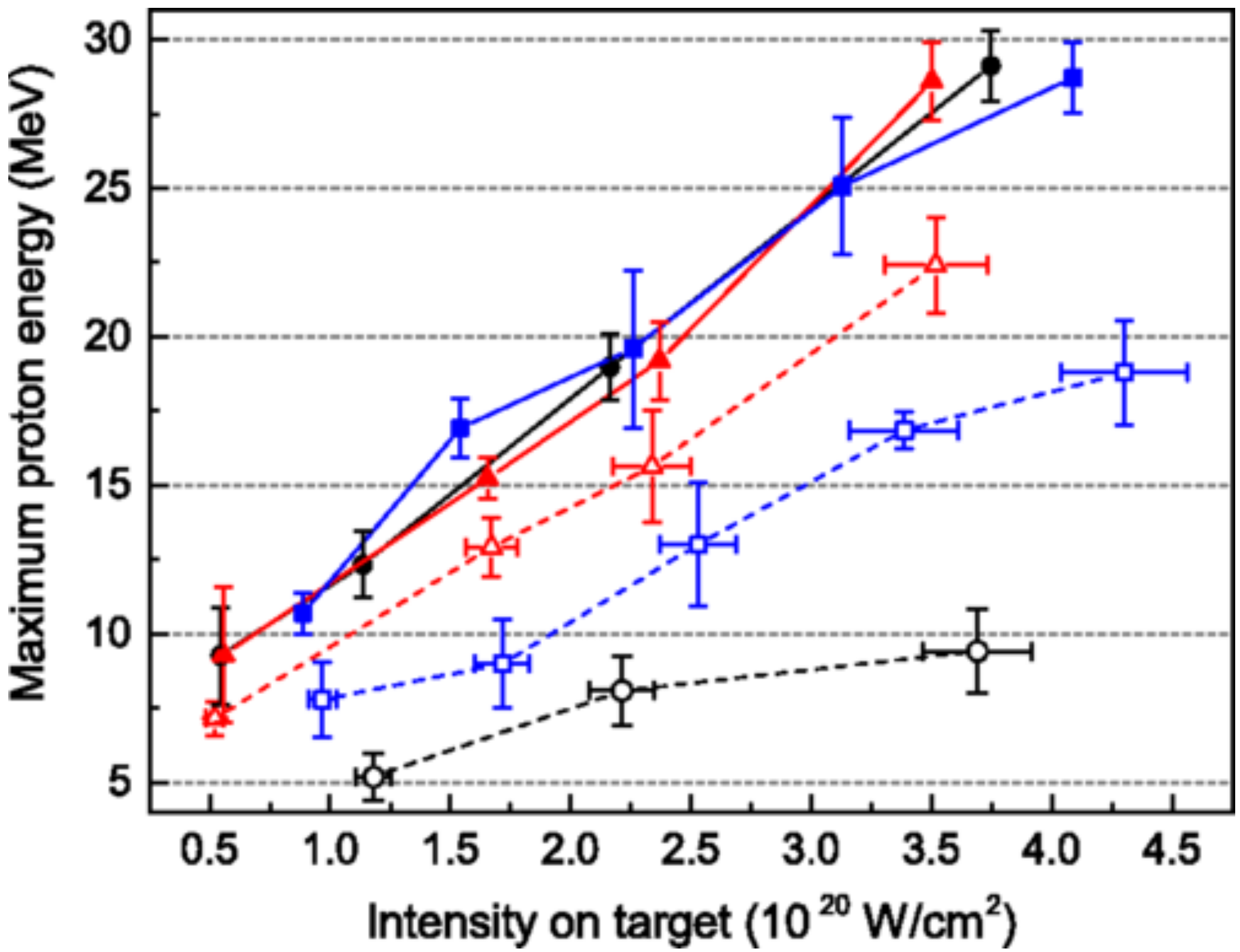
experimental setup



Foams wipe out polarization dependance

Gwangju Institute of Science and Technology

maximum proton energy vs. intensity



P-polarization

S-polarization

C-polarization

solid line: foam-attached target

dashed line: flat solid foil

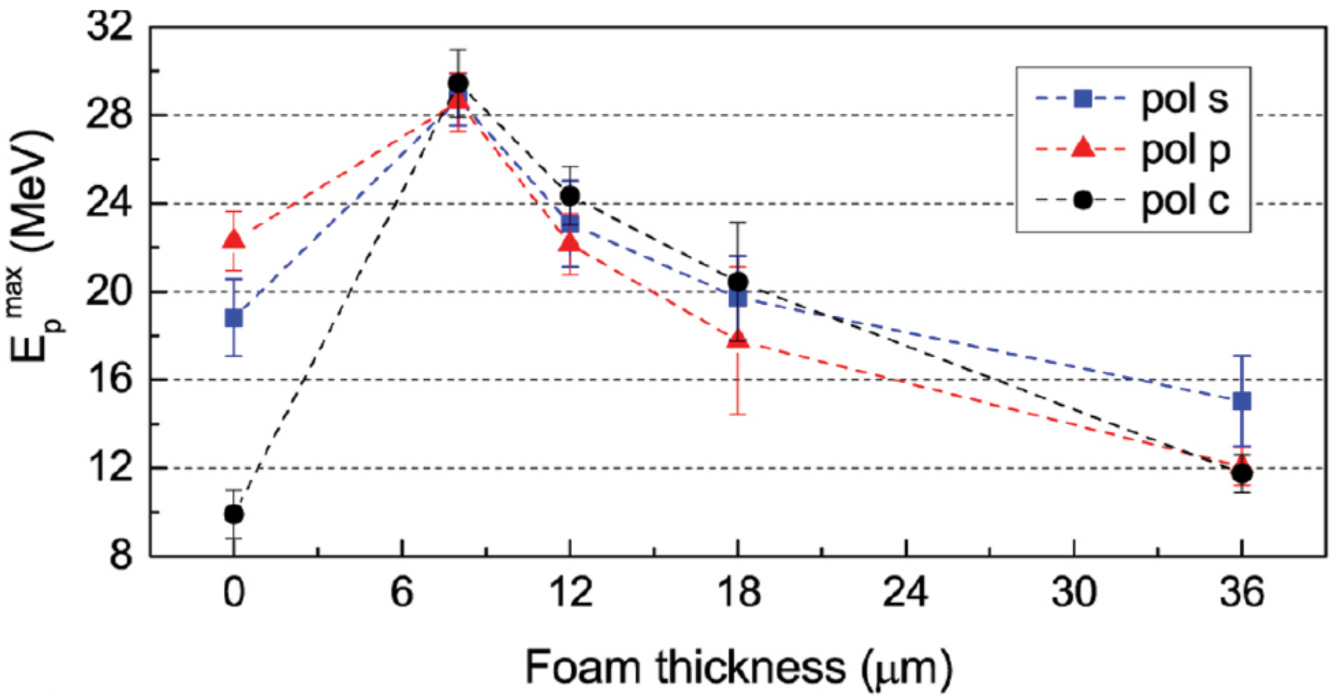
Some parameters:

- substrate = Al 0.75 µm
- foam = C 8 µm
- energy on target = 8 J
- angle of incidence = 30°
- duration = 25 fs

Passoni et al. *Phys Rev Accel Beams* 19 (2016)

The thinner the foam the better?

maximum proton energy vs. foam thickness

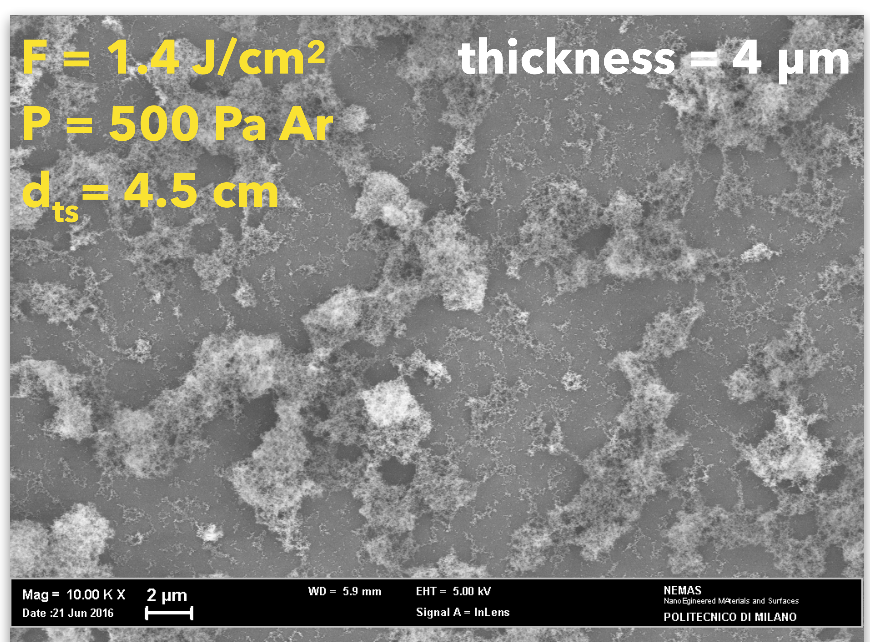


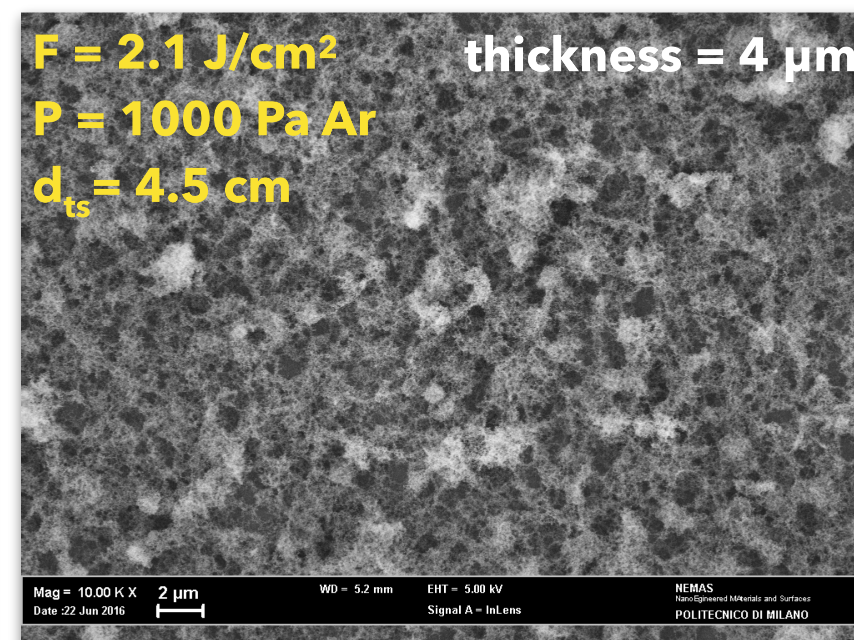
Some parameters:

- substrate = Al 0.75 μm
- **foam thickness = 8, 12, 18, 36 μm**
- energy on target = 8 J
- angle of incidence = 30°
- duration = 25 fs
- intensity = 4.5 x 10^{20} W/cm^2

Remark: reducing foam thickness is not trivial!

Prencipe et al. *Plasma Phys Contr F* 58 (2016)



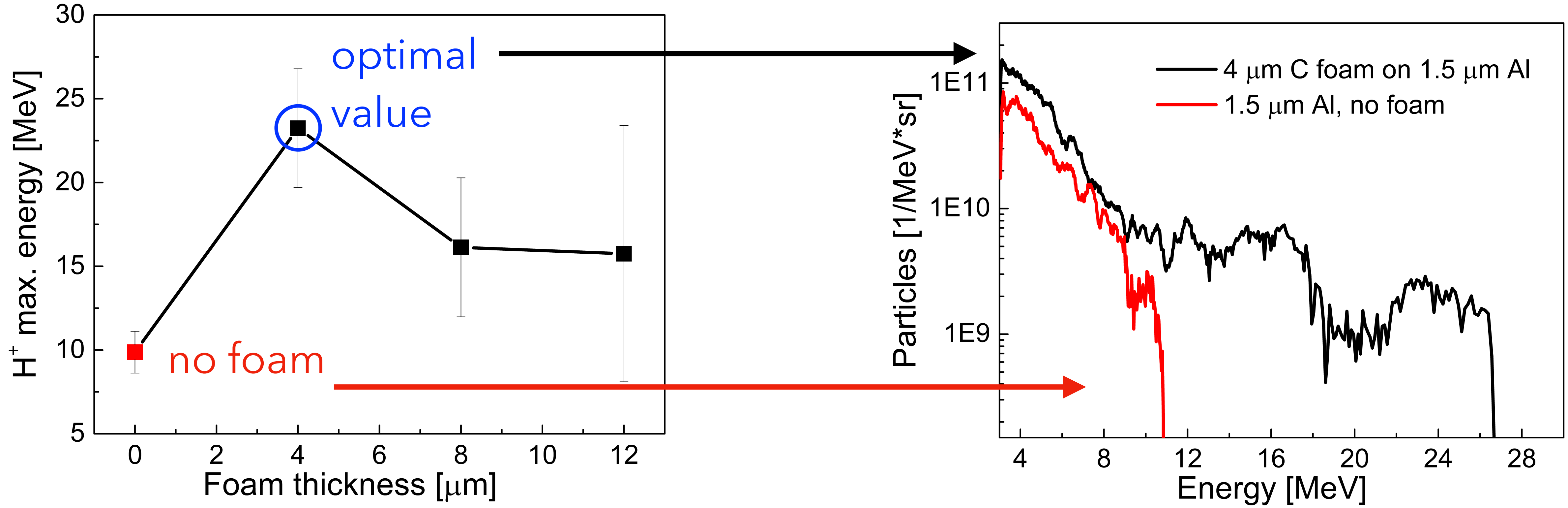


preliminary

So far the thinner the foam the better

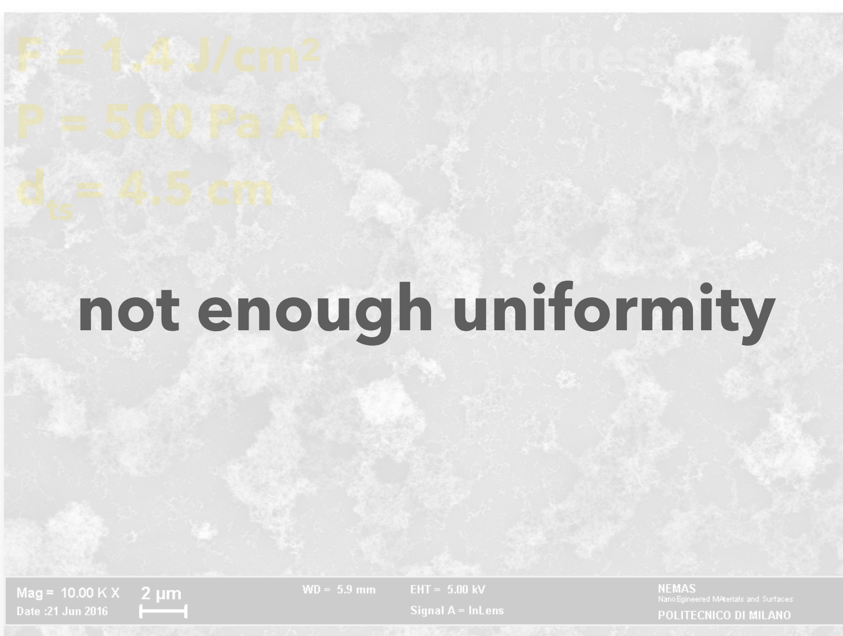
HZDR

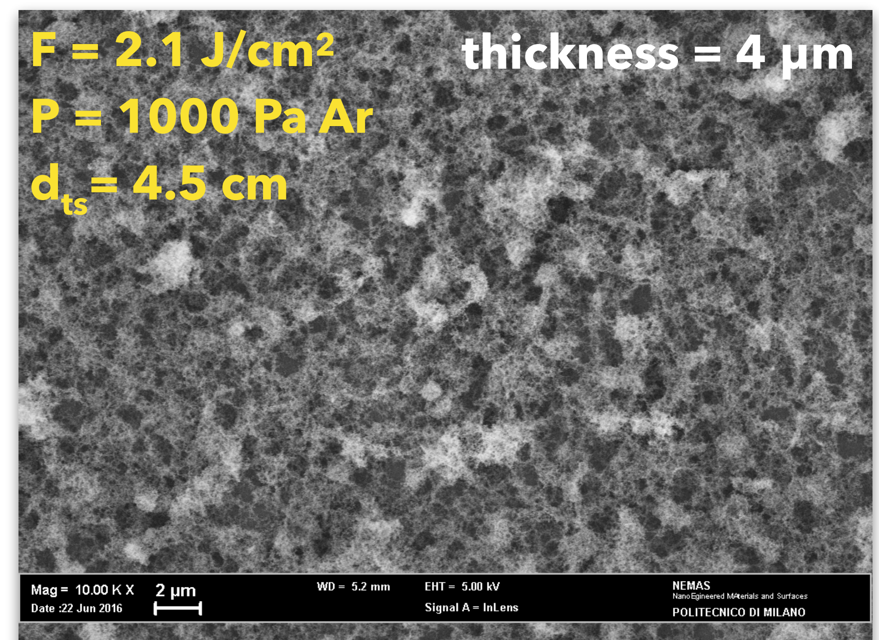
maximum proton energy vs. foam thickness **proton energy spectra**



Some parameters:

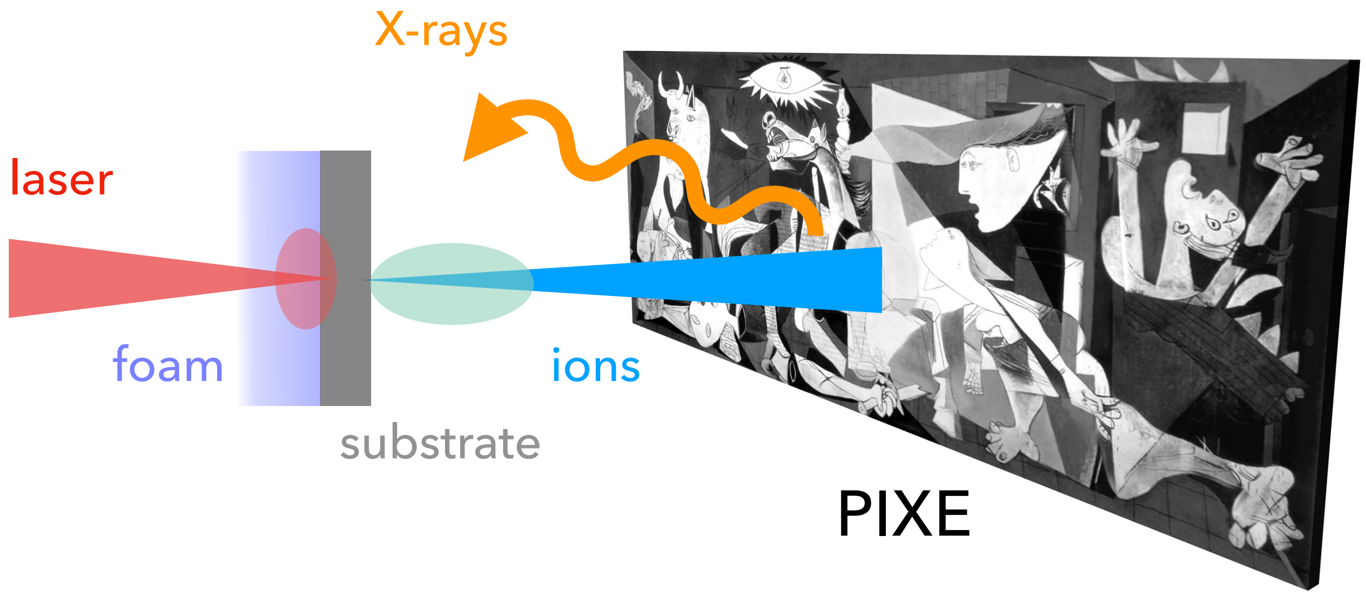
- Energy on target = 2 J
- Intensity ≤ 5 x 10^{20} W/cm²
- Power = 150 TW
- Angle of incidence = 2°
- Substrate = Al 1.5 μm
- Foam = C 4,8,12 μm



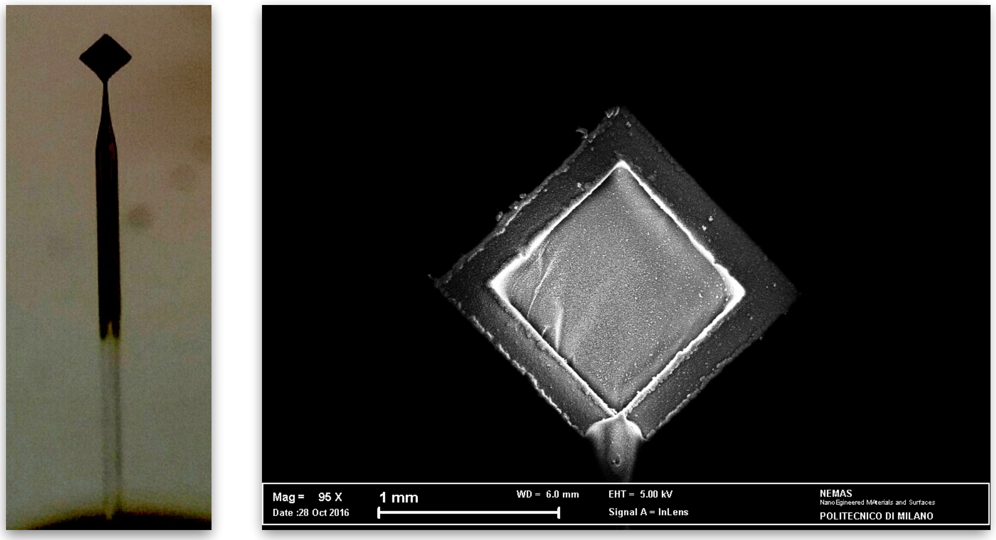


Some applications of laser-induced ions…

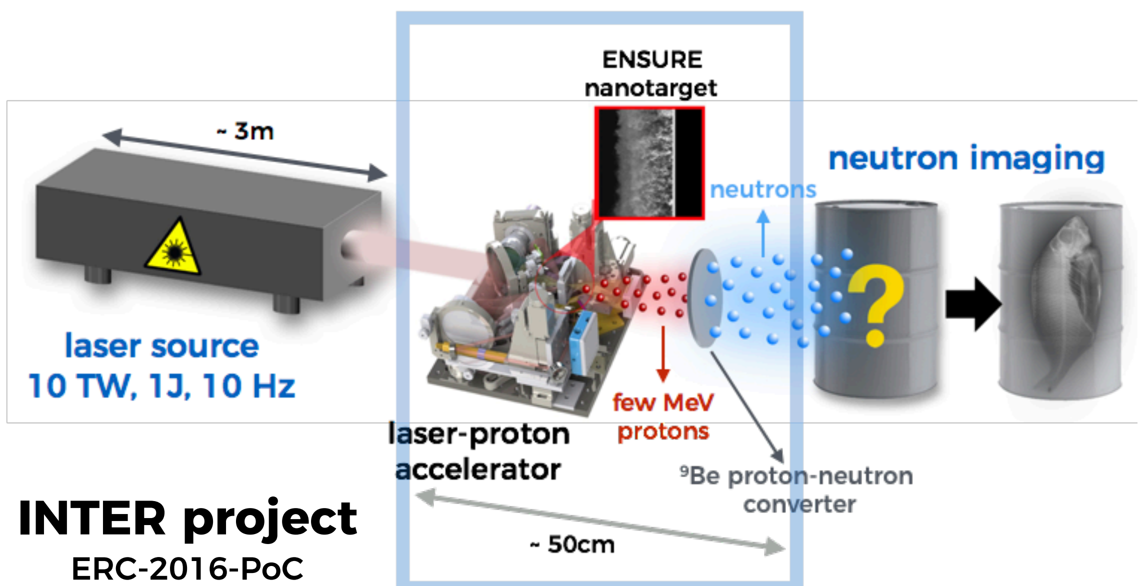
materials characterization



laser-induced collisionless shock



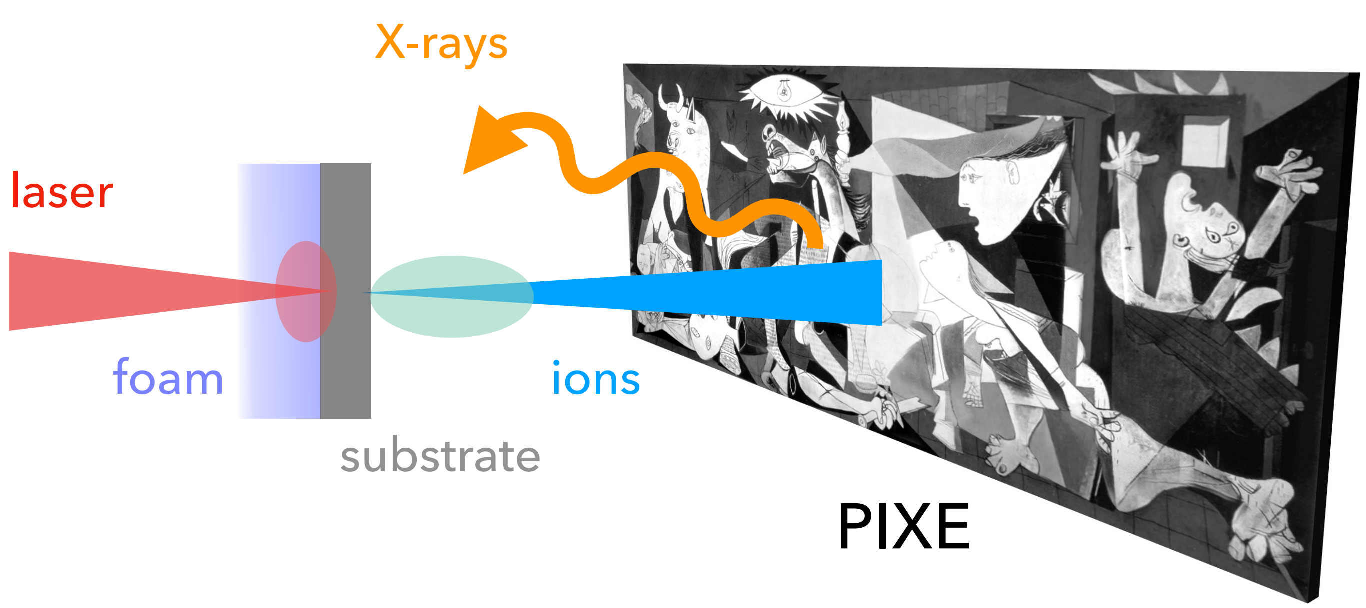
secondary neutron sources



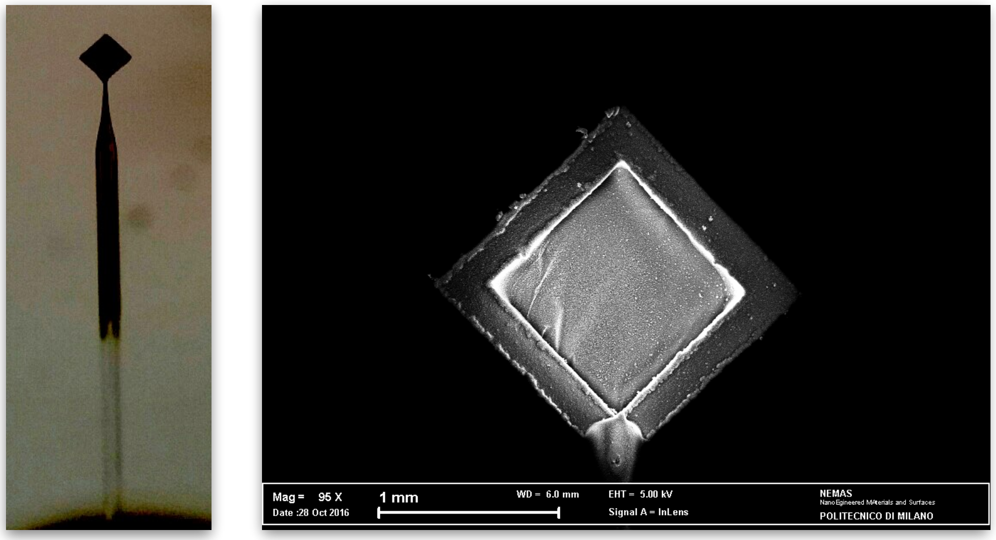
INTER project
ERC-2016-PoC

...and of foam-based multi-layer targets

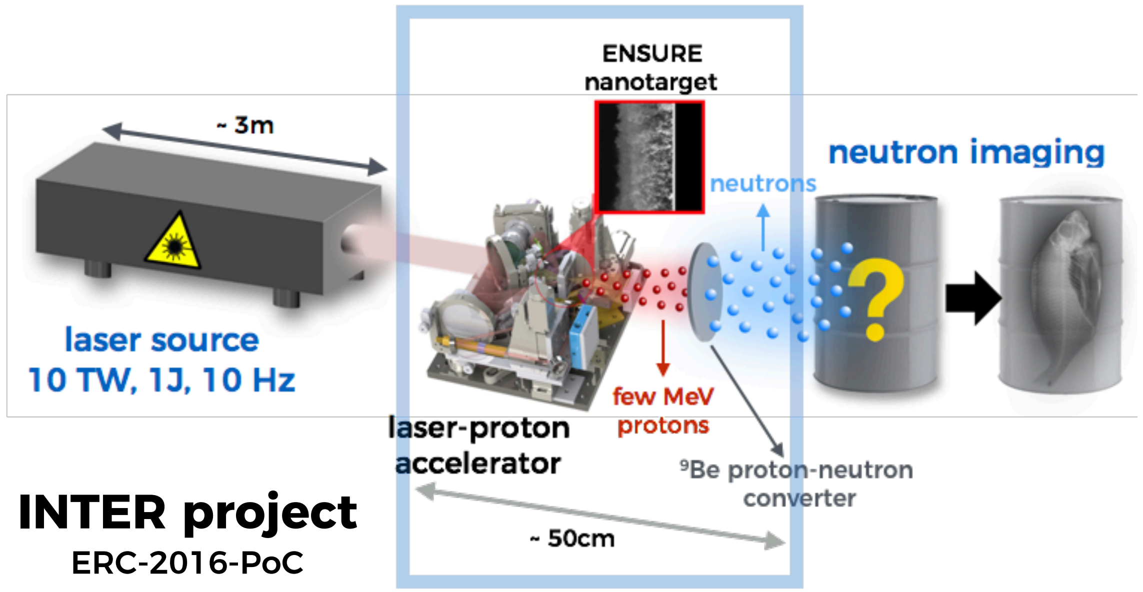
materials characterization



laser-induced collisionless shock

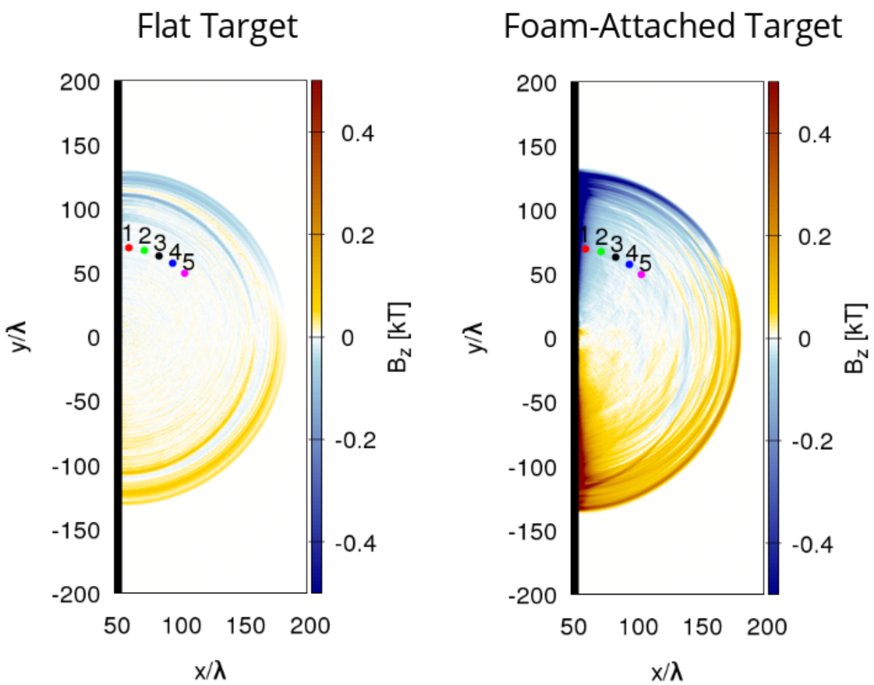


secondary neutron sources

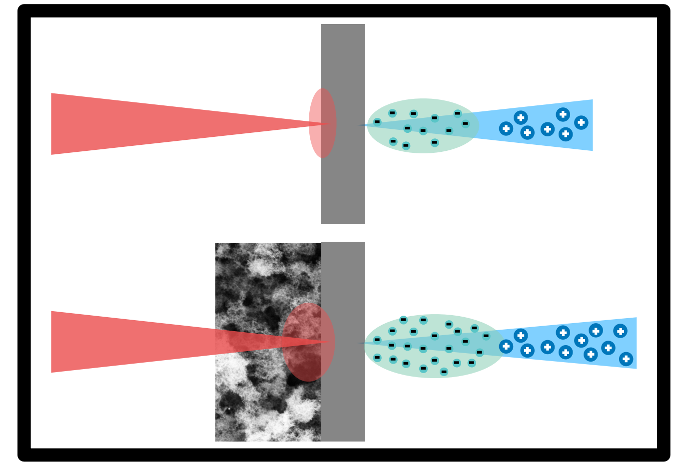


INTER project
ERC-2016-PoC

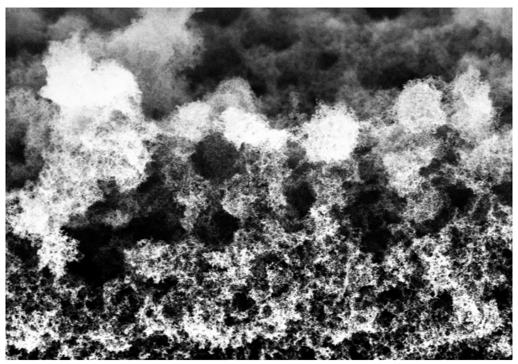
THz radiation enhancement



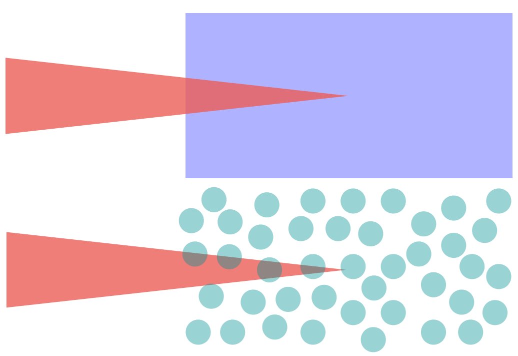
Conclusions



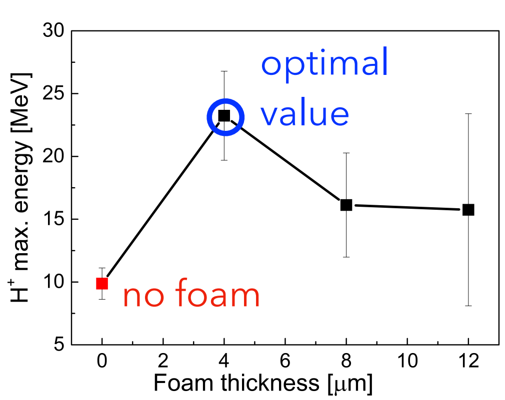
Near-critical nanostructured foams are complex materials useful to enhance laser-driven ion acceleration.



Production of foam materials with novel properties:
low thickness, down to 4 μm



Simulations to investigate foam behavior in the interaction:
uniform should be better for ion acceleration



Ion acceleration experiments with foam-attached targets:
promising results, thinner foams are more efficient

Thank you!

arianna.formenti@polimi.it
www.ensure.polimi.it
www.nanolab.polimi.it