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ENSURE

Theoretical investigations of laser-driven ion acceleration with nanostructured materials

Arianna Formenti

NanoLab Talk, Milan, April 23rd, 2018

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Theoretical investigations of **laser-driven ion acceleration with nanostructured materials**

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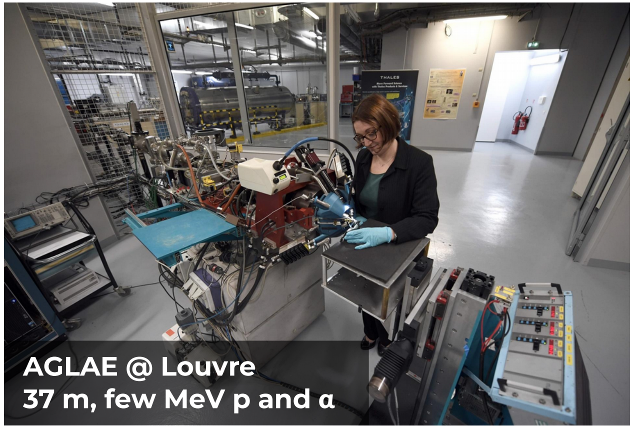
NanoLab Talk, Milan, April 23rd, 2018

Many different kinds of conventional (ion) accelerators exist

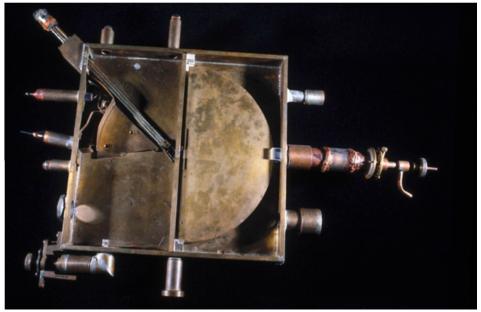
LHC @ CERN
27 km, from 450 GeV to 6.5 TeV p



AGLAE @ Louvre
37 m, few MeV p and α

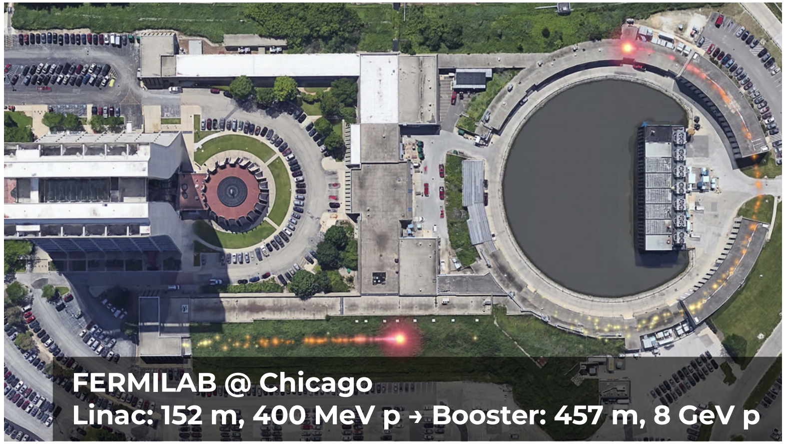
CNAO @ Pavia
80 m, 250 MeV p and 400 MeV C^{6+}

CN @ Padova
7 m, 5.5 MV



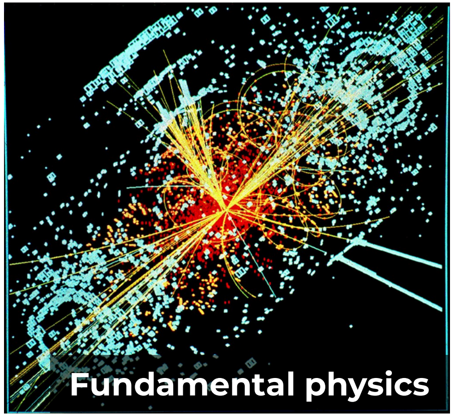
11-inch cyclotron @ Berkeley (1932)
30 cm, 1.2 MeV p

Commercial cyclotron
2 m, 18 MeV p

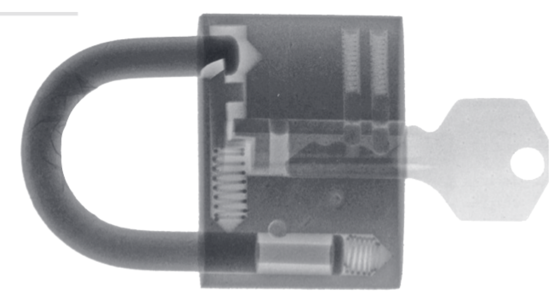


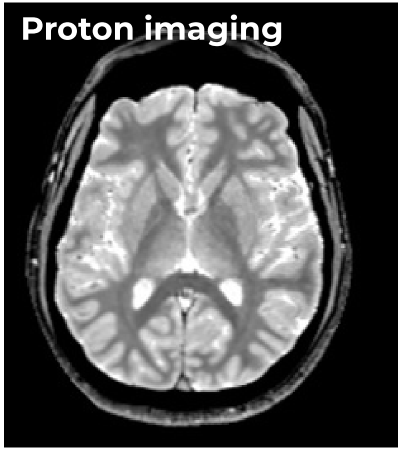
FERMILAB @ Chicago
Linac: 152 m, 400 MeV p → Booster: 457 m, 8 GeV p

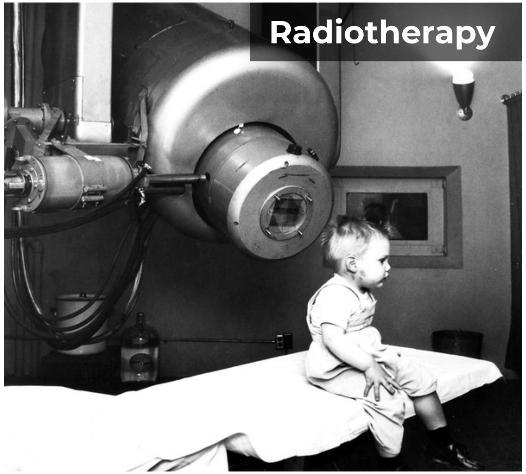
Accelerated ions have a lot of applications

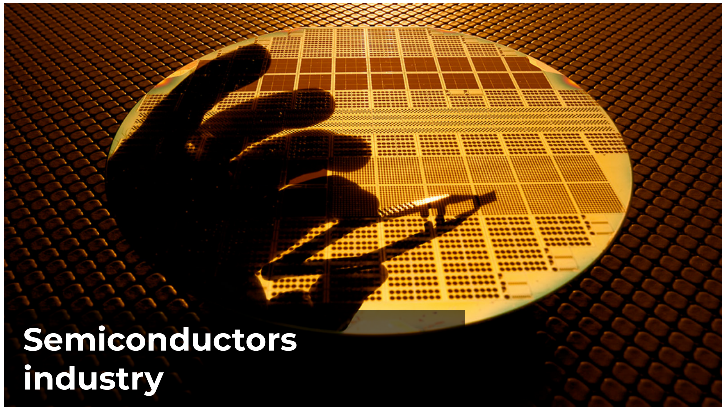


Secondary neutron sources for imaging









But potentially there's a non-conventional, appealing and promising way to accelerate ions

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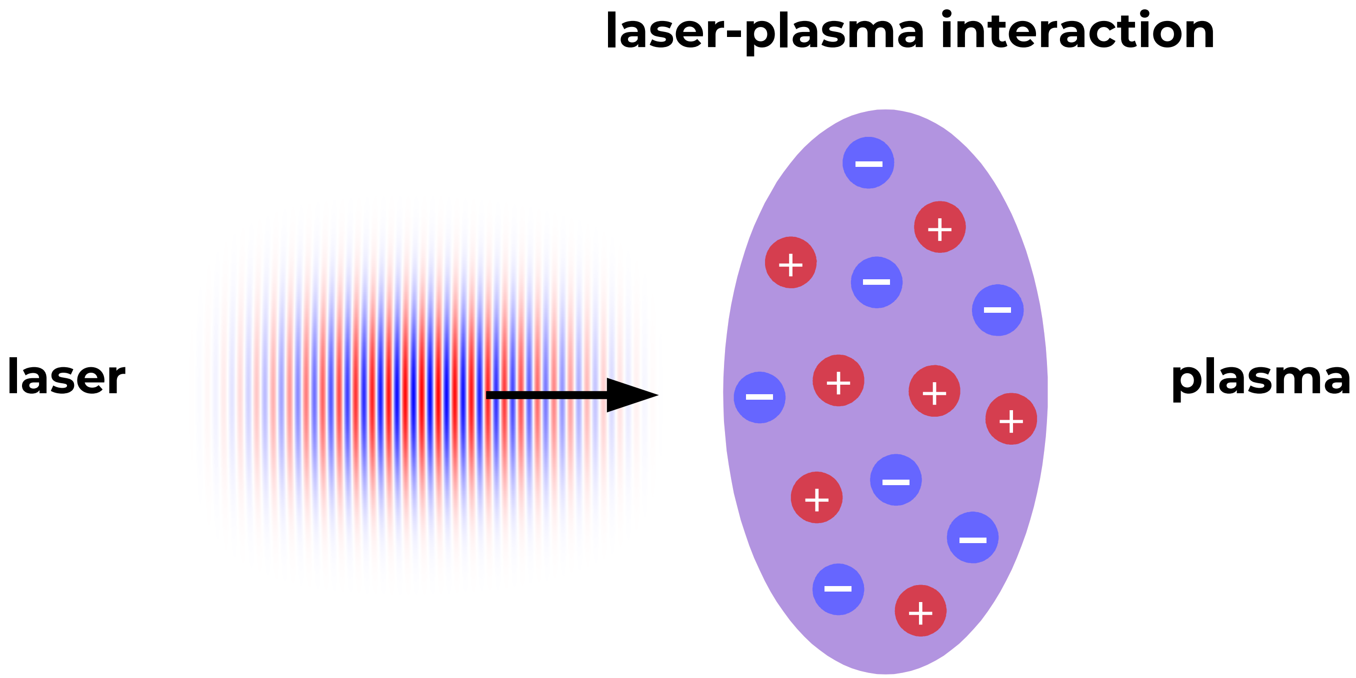
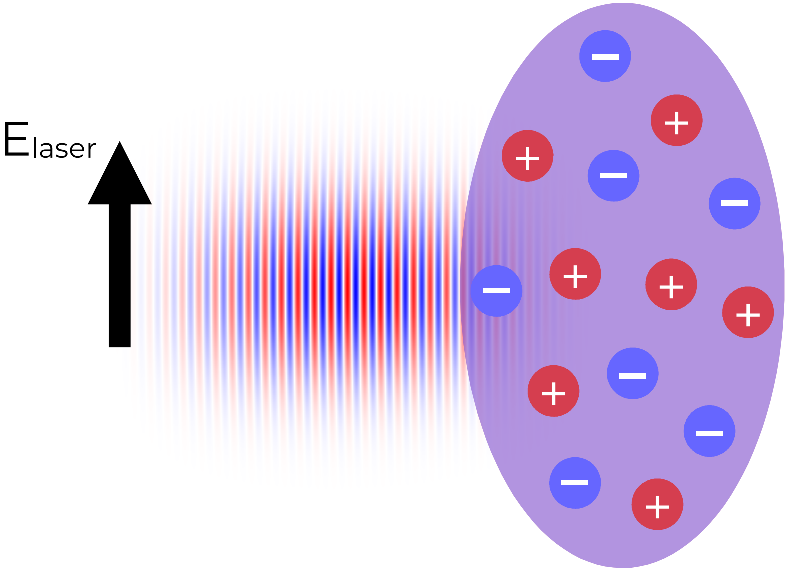


Plasmas as non-conventional accelerators

PLASMA

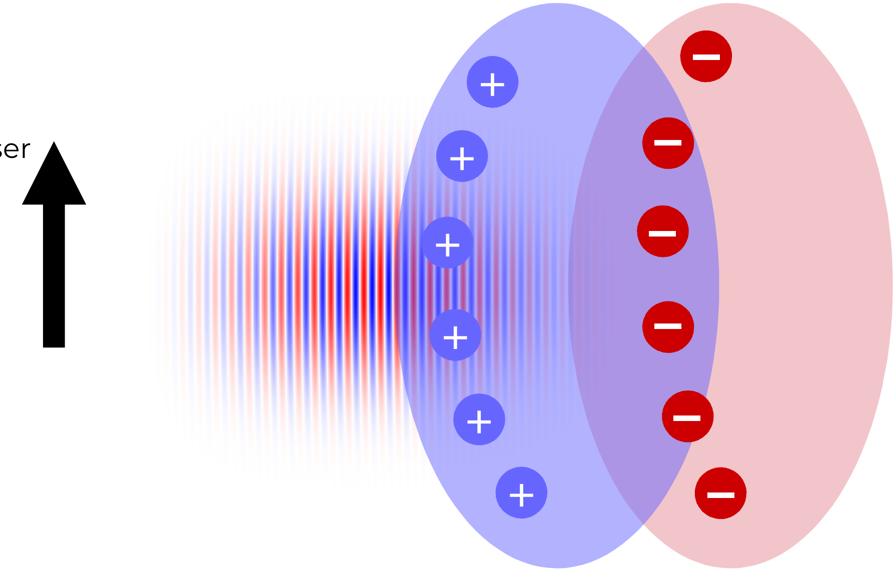


E_{laser}
- transverse
- oscillating

Plasmas as non-conventional accelerators

PLASMA → **strong charge separation**

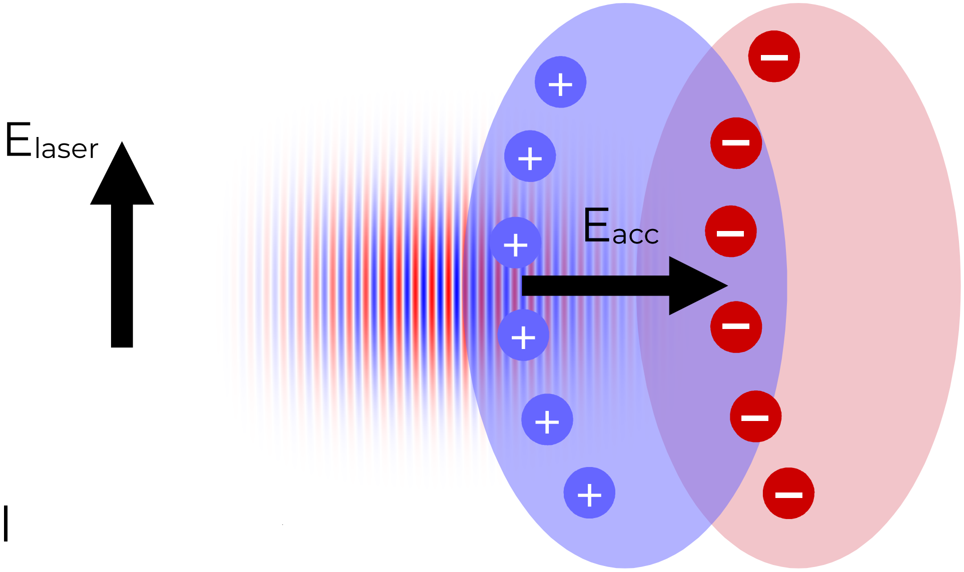
E_{laser}



E_{laser}
- transverse
- oscillating

Plasmas as non-conventional accelerators

PLASMA → strong charge separation → **huge electric field generation**



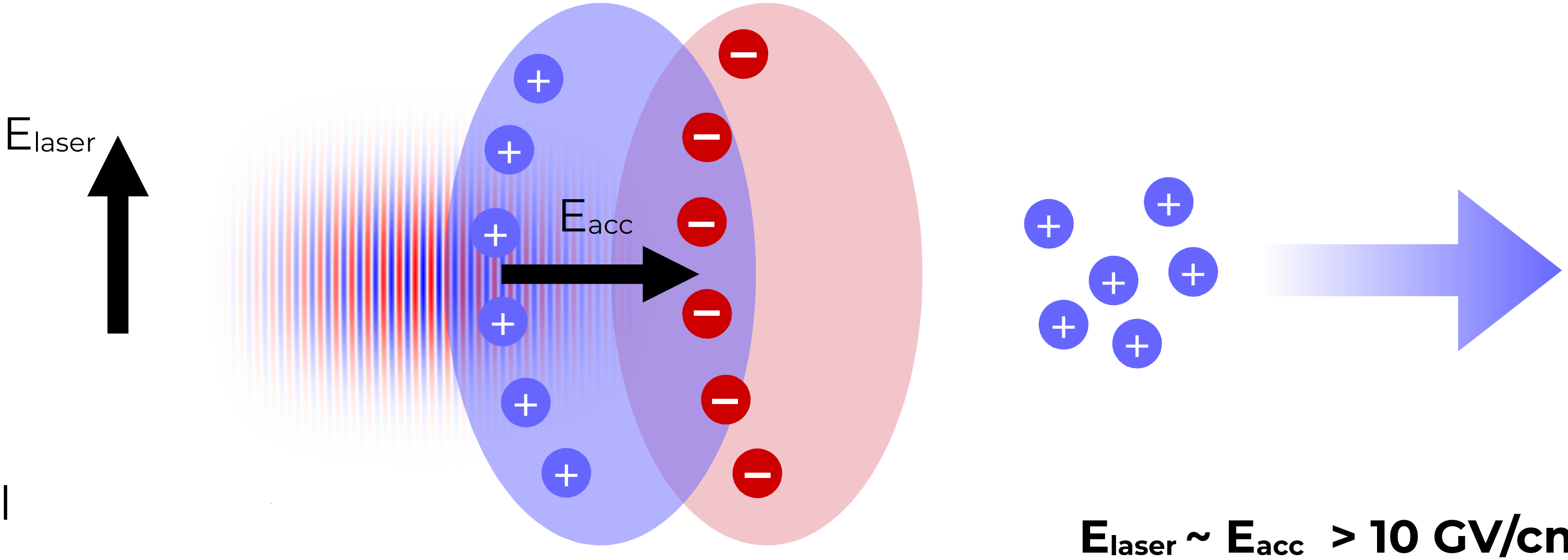
E_{laser}
- transverse
- oscillating

E_{acc}
- longitudinal
- quasi-static

E_{laser} ~ E_{acc} > 10 GV/cm

Plasmas as non-conventional accelerators

PLASMA → strong charge separation → huge electric field generation → **charged particle acceleration**



E_{laser}
- transverse
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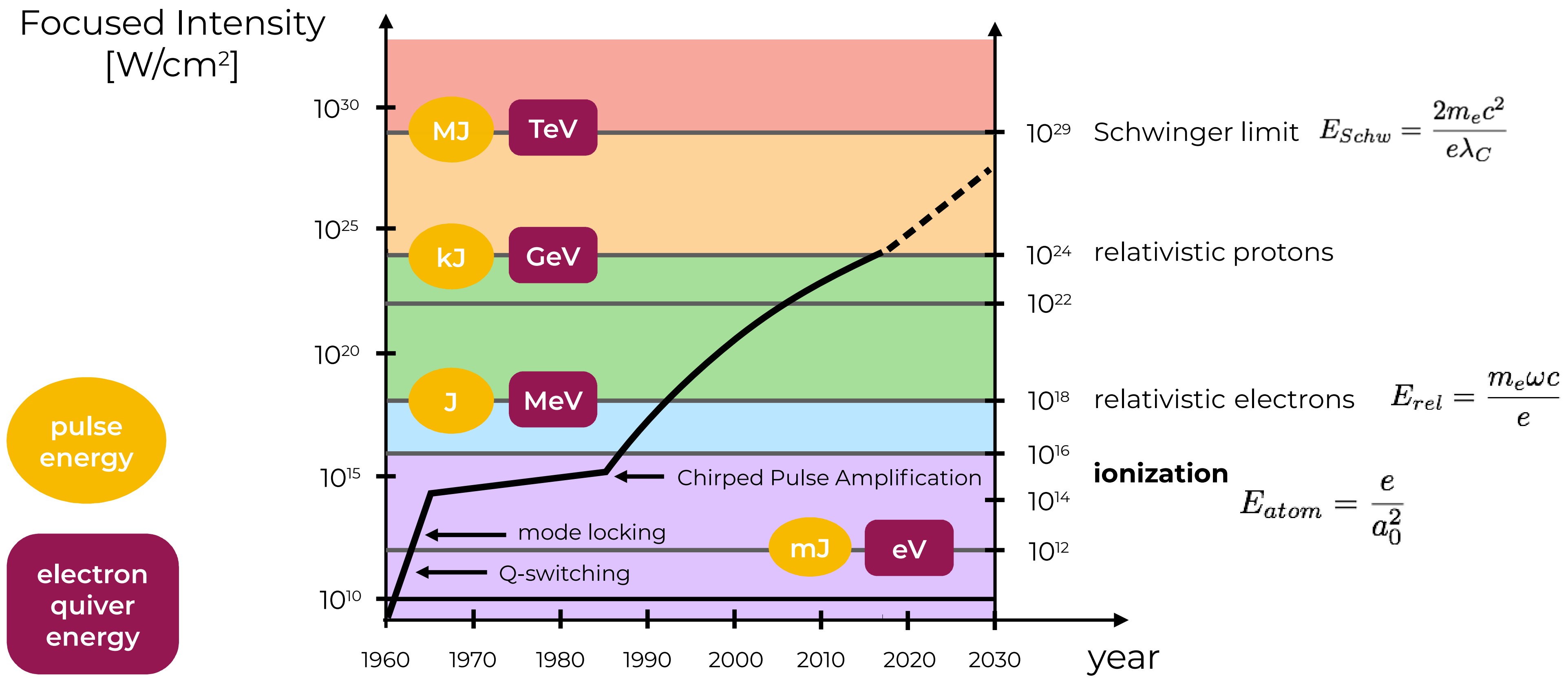
E_{laser} ~ E_{acc} > 10 GV/cm

We need ultra-intense laser pulses



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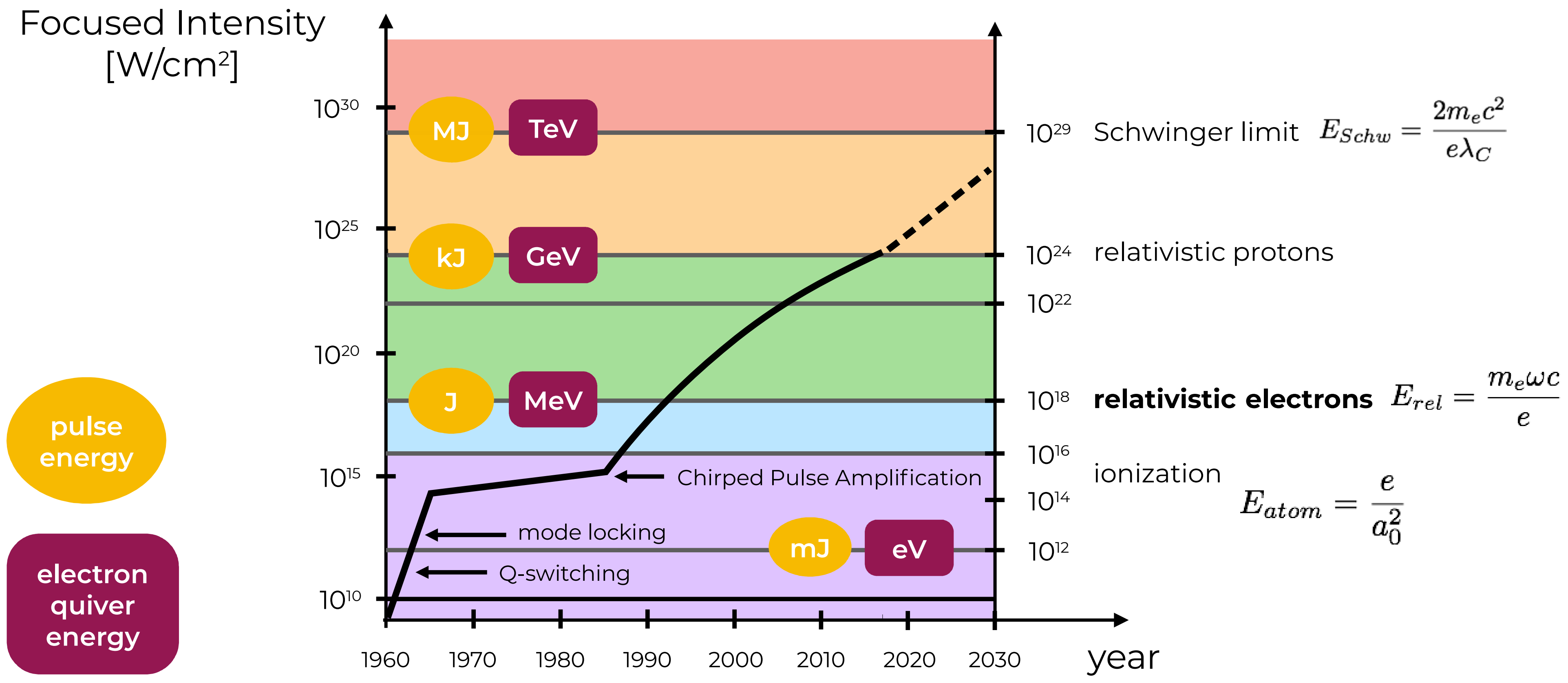
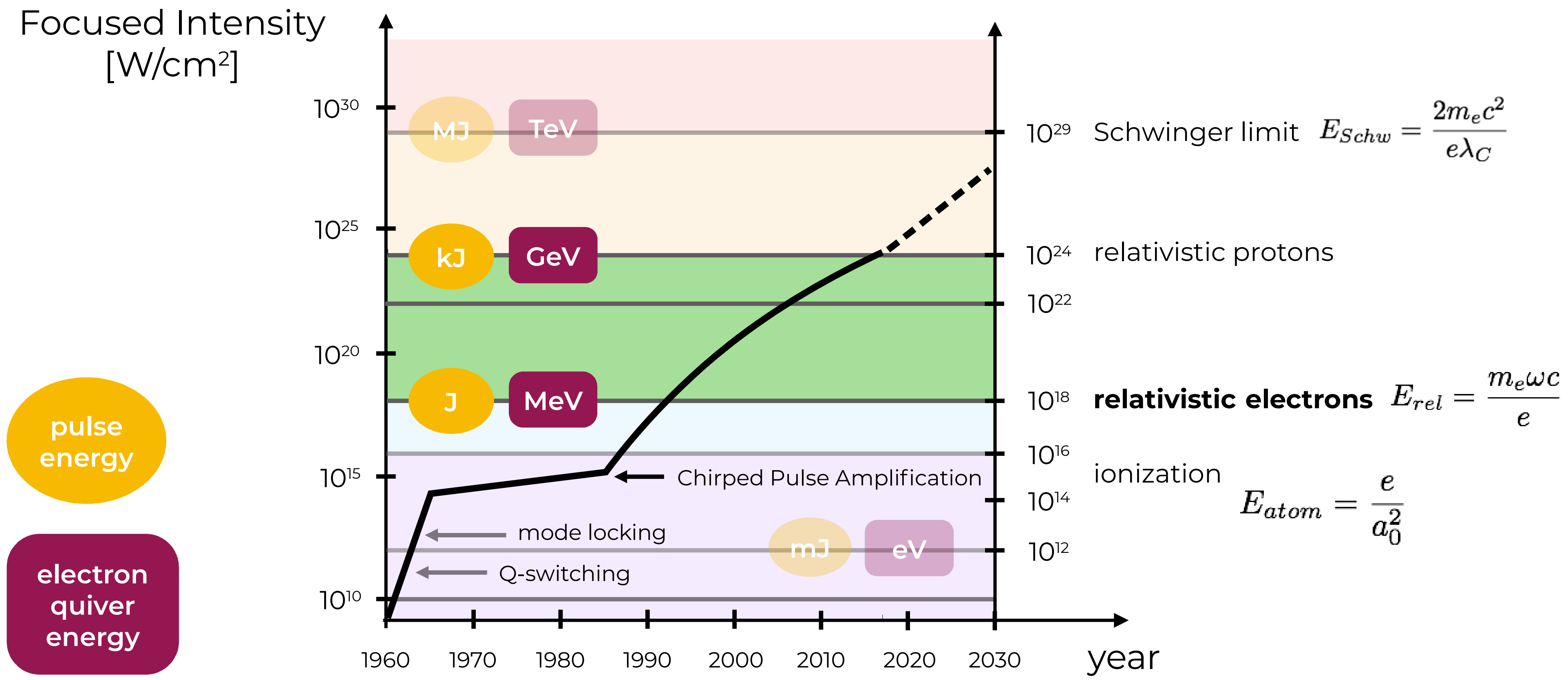


We need ultra-intense laser pulses



They can go from huge facilities to table-top systems, depending on other parameters

Typical CPA laser pulse parameters

- Wavelength ~ 1 - 10 μm
- Energy ~ 10^{-1} - 10^{3} J
- Power ~ 10 TW - few PW
- **Duration ~ 10 - 10^{3} fs**
- Spot size Ø < 10 μm
- **Intensity ~ 10^{18} - 10^{22} W/cm²**

full ionization → plasma

Many challenges to be faced, but it's worth it

Why bother?

Many challenges to be faced, but it’s worth it

Why bother?

Conventional acceleration: E_{acc} < 100 MV/m
Laser-plasma acceleration: E_{acc} > 10 GV/cm

Many challenges to be faced, but it’s worth it

Why bother?

Potentially

- Compact
- Cost-effective
- Flexible
- Reduced radioprotection

Conventional acceleration: E_{acc} < 100 MV/m
Laser-plasma acceleration: E_{acc} > 10 GV/cm

Many challenges to be faced, but it’s worth it

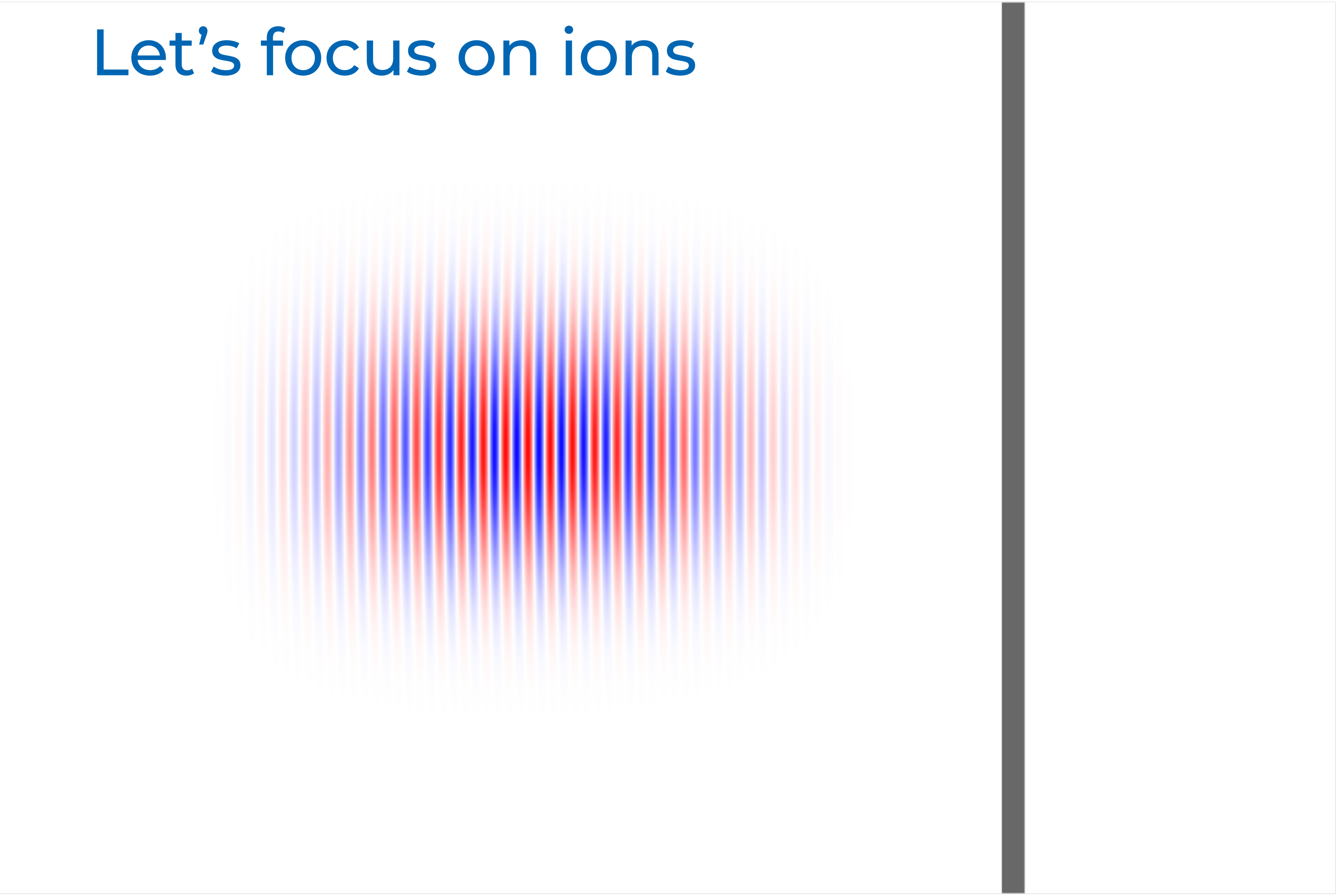
Why bother?

Potentially
- Compact
- Cost-effective
- Flexible
- Reduced radioprotection

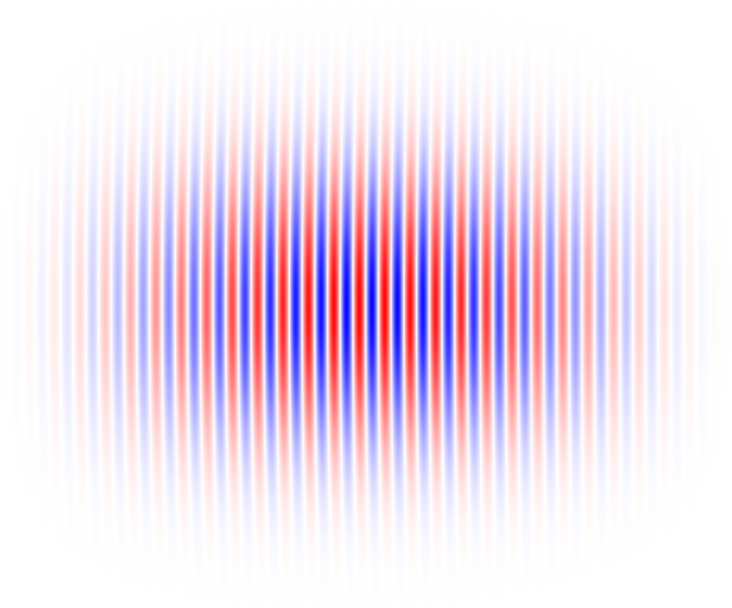
But still many issues
- Control?
- Stability?
- Reproducibility?
- Lower maximum energy

Conventional acceleration: E_{acc} < 100 MV/m
Laser-plasma acceleration: E_{acc} > 10 GV/cm

Let’s focus on ions



This is the conventional scheme



laser pulse

- ultra-high intensity
- ultra-short duration

target

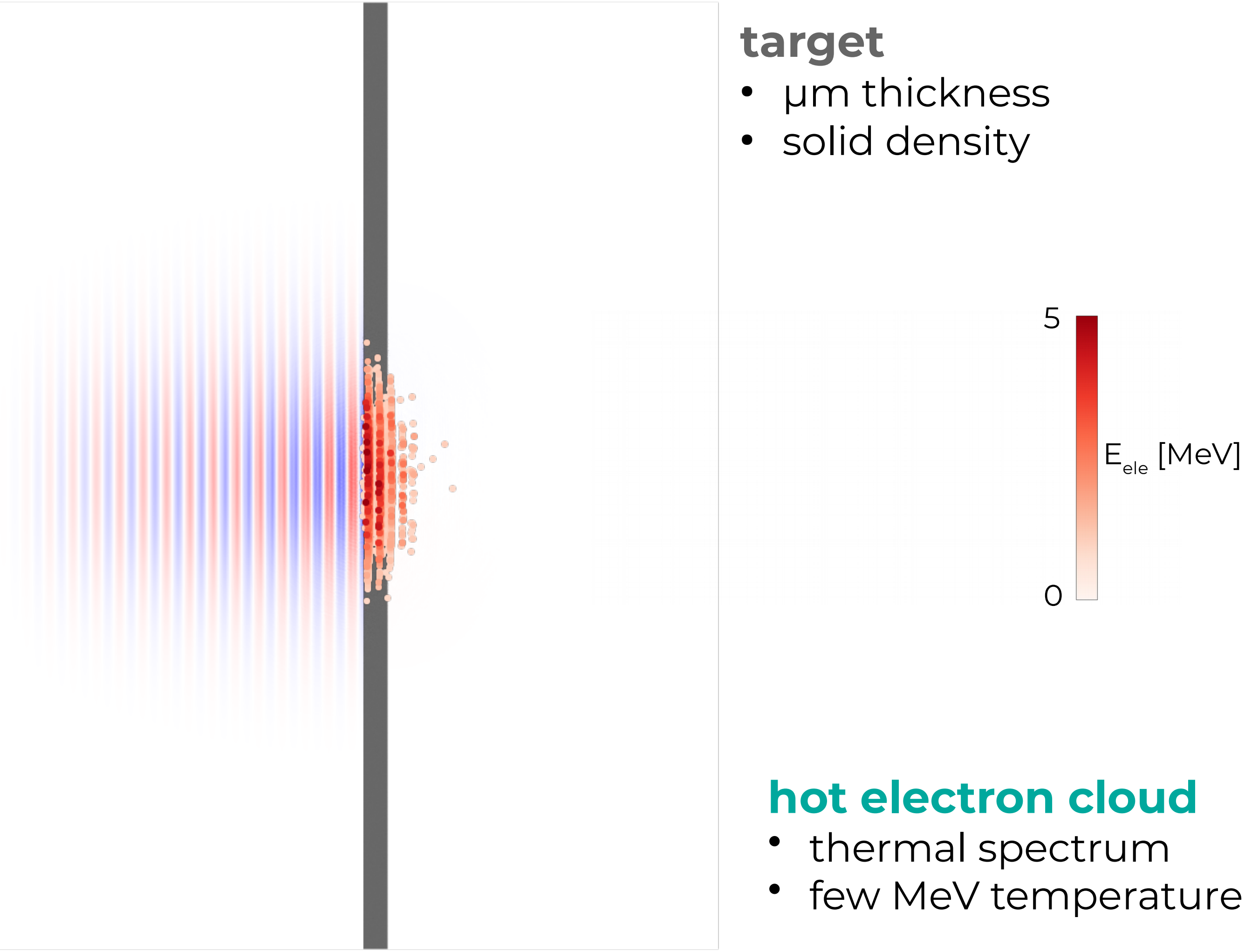
- μm thickness
- solid density

The pulse is arriving

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

target
- μm thickness
- solid density

Hot electrons are generated

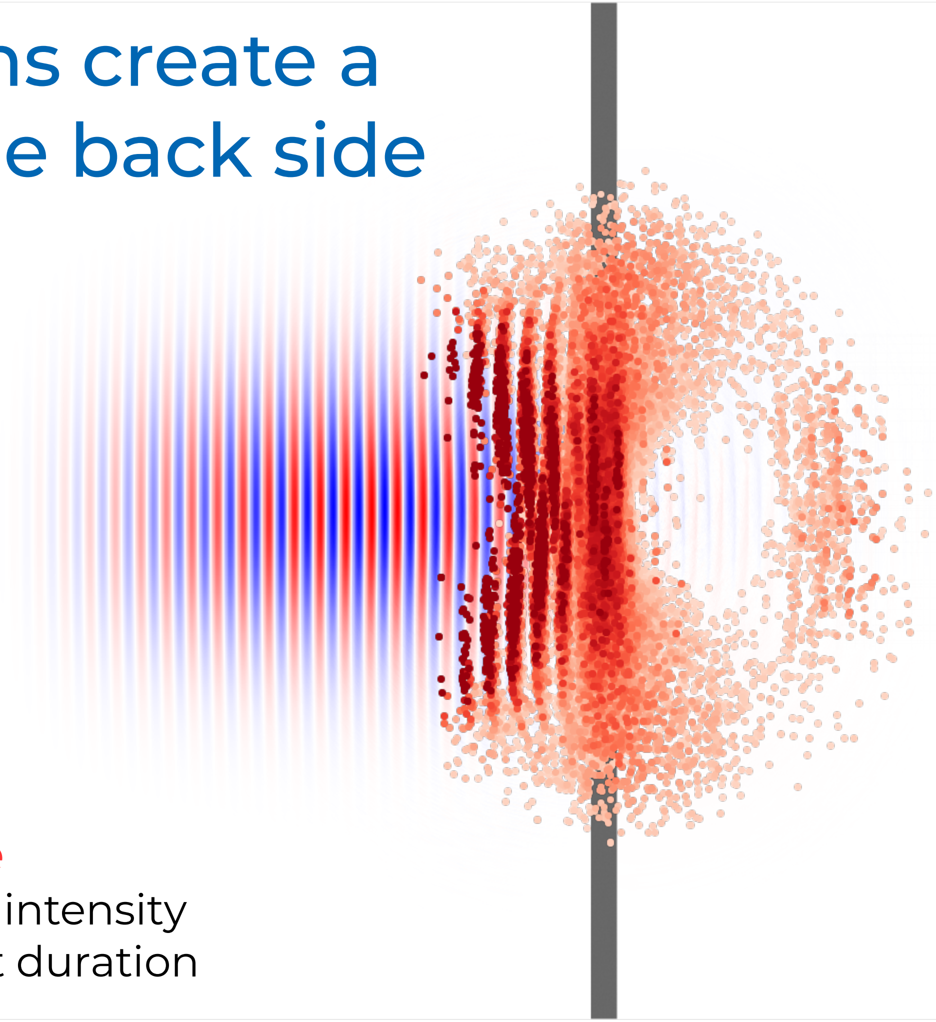


target
- µm thickness
- solid density

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

hot electron cloud
- thermal spectrum
- few MeV temperature

Hot electrons create a **sheath** in the back side

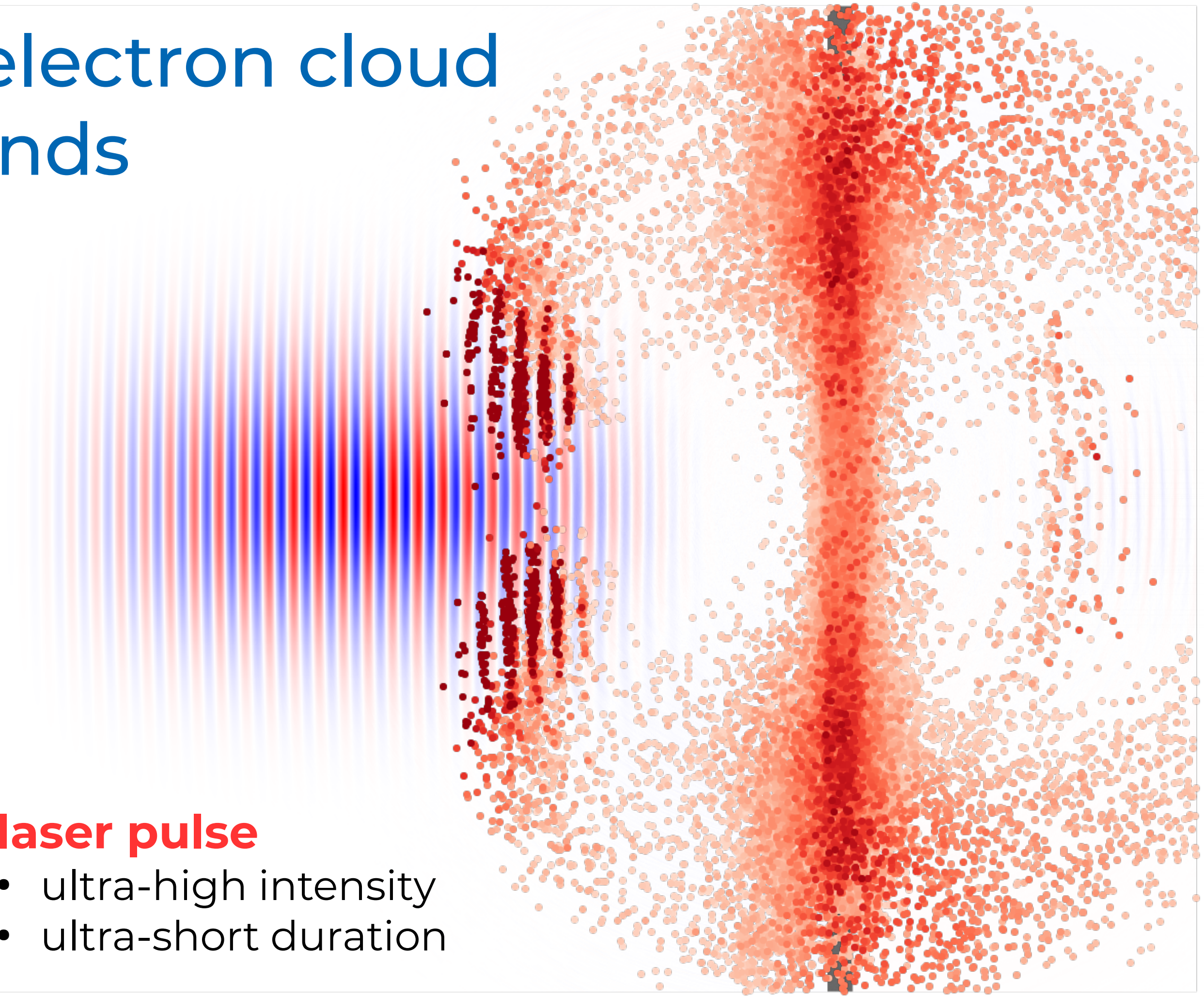


target
- μm thickness
- solid density

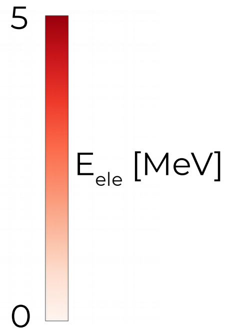
laser pulse
- ultra-high intensity
- ultra-short duration

hot electron cloud
- thermal spectrum
- few MeV temperature

Hot electron cloud expands



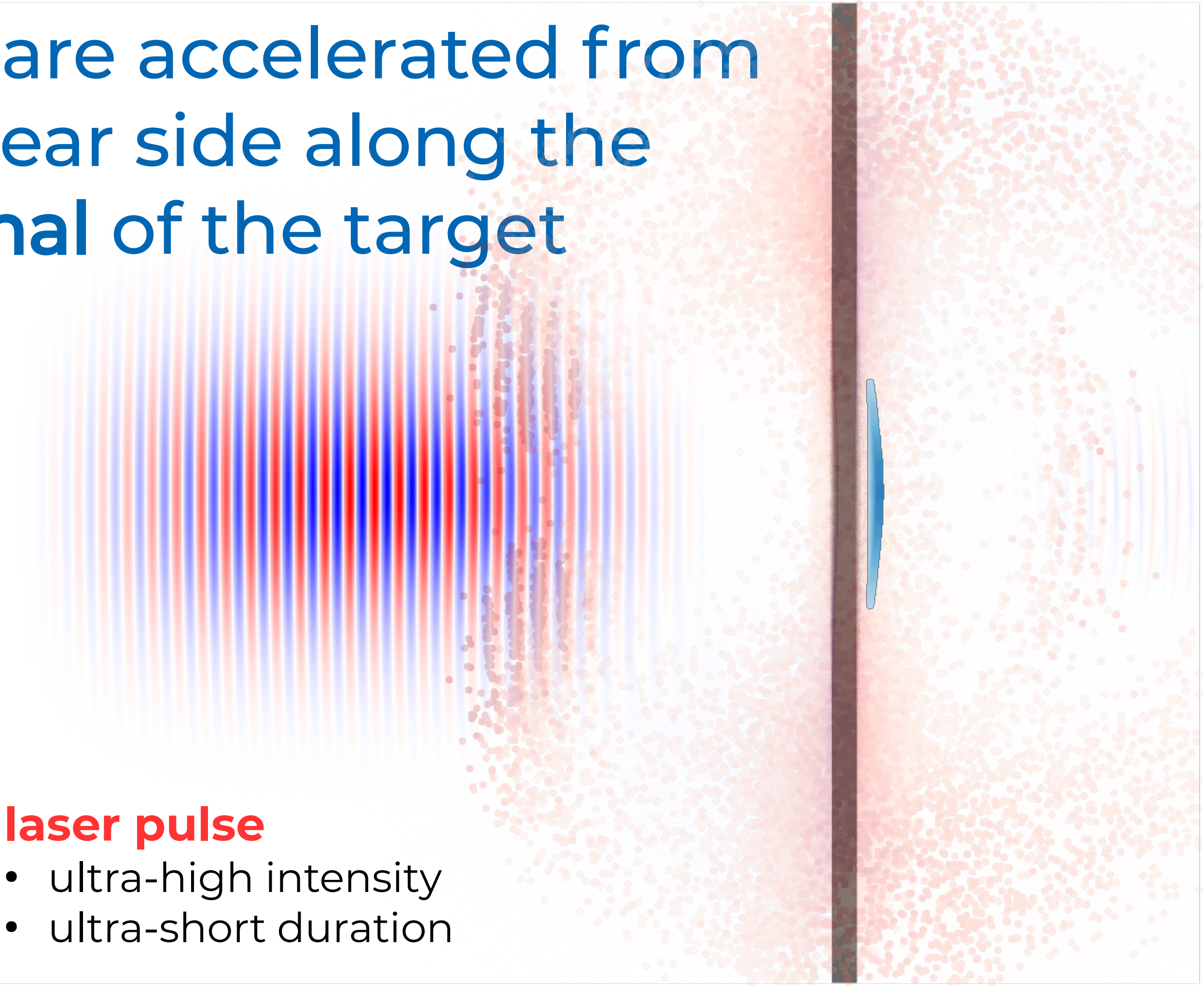
target
- μm thickness
- solid density



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

hot electron cloud
- thermal spectrum
- few MeV temperature

Ions are accelerated from the rear side along the **normal** of the target



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

target
- μm thickness
- solid density

E_{ions} [MeV]
3 — 0

hot electron cloud
- thermal spectrum
- few MeV temperature

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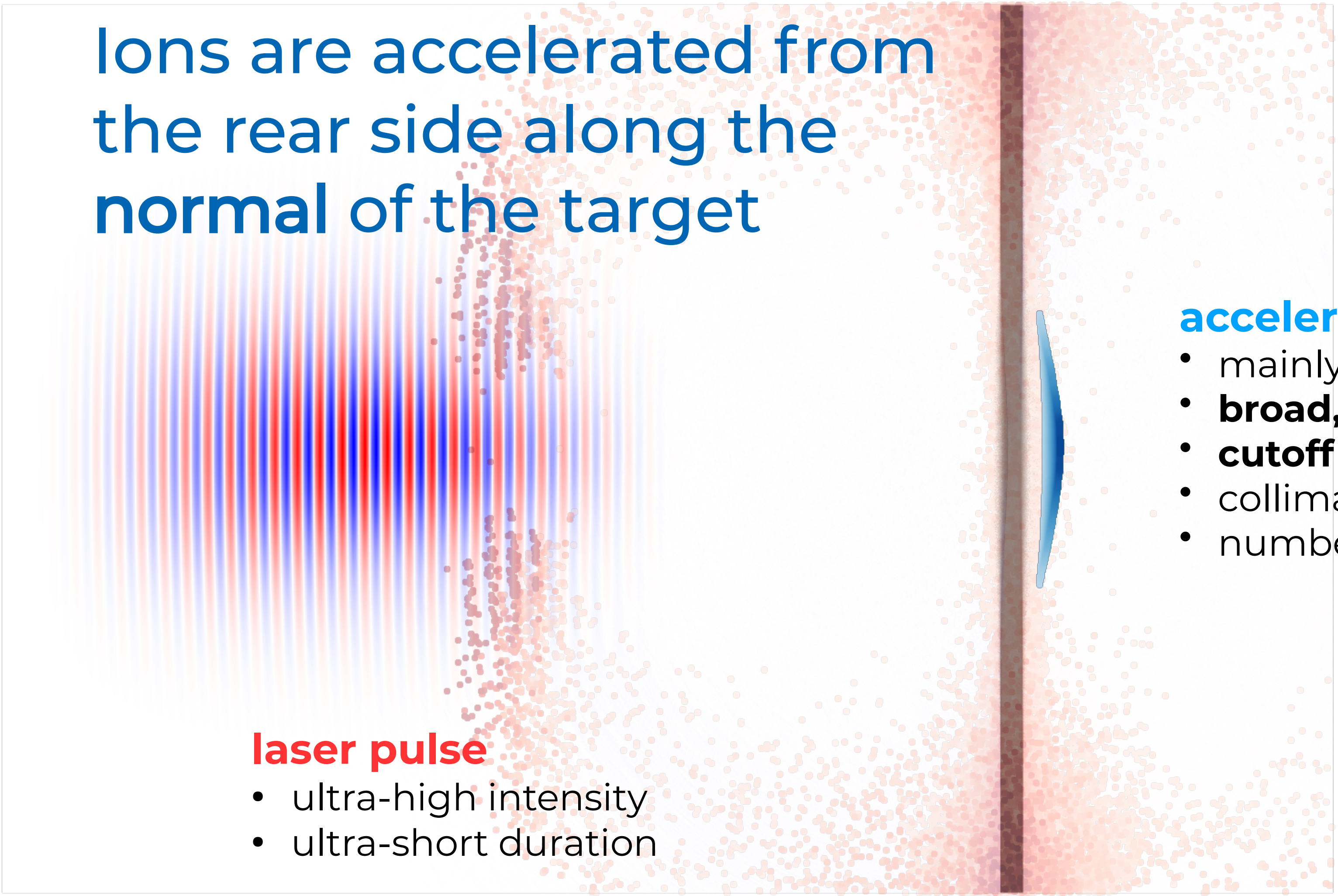


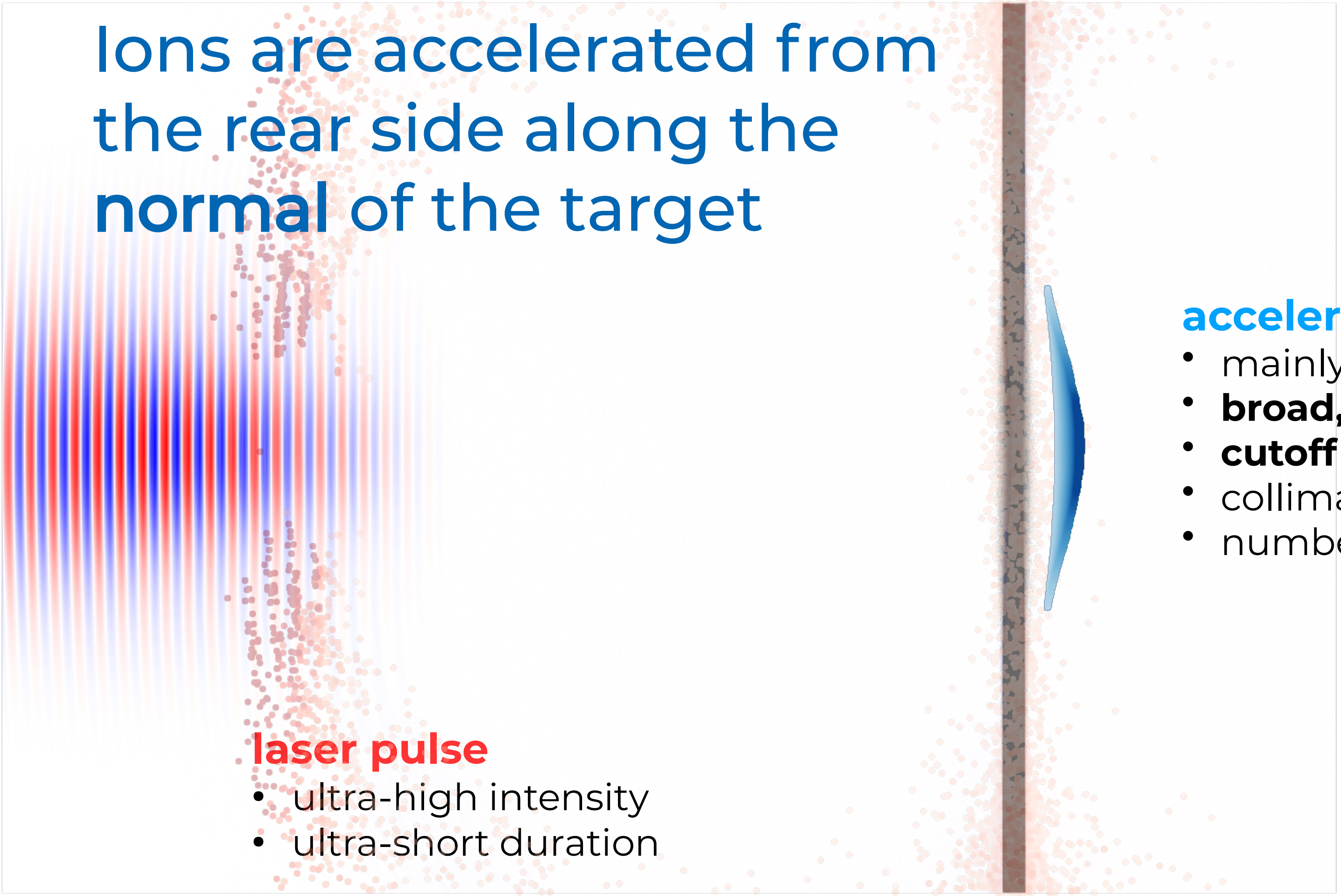
laser pulse
- ultra-high intensity
- ultra-short duration

target
- μm thickness
- solid density

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

hot electron cloud
- thermal spectrum
- few MeV temperature

Ions are accelerated from the rear side along the **normal** of the target



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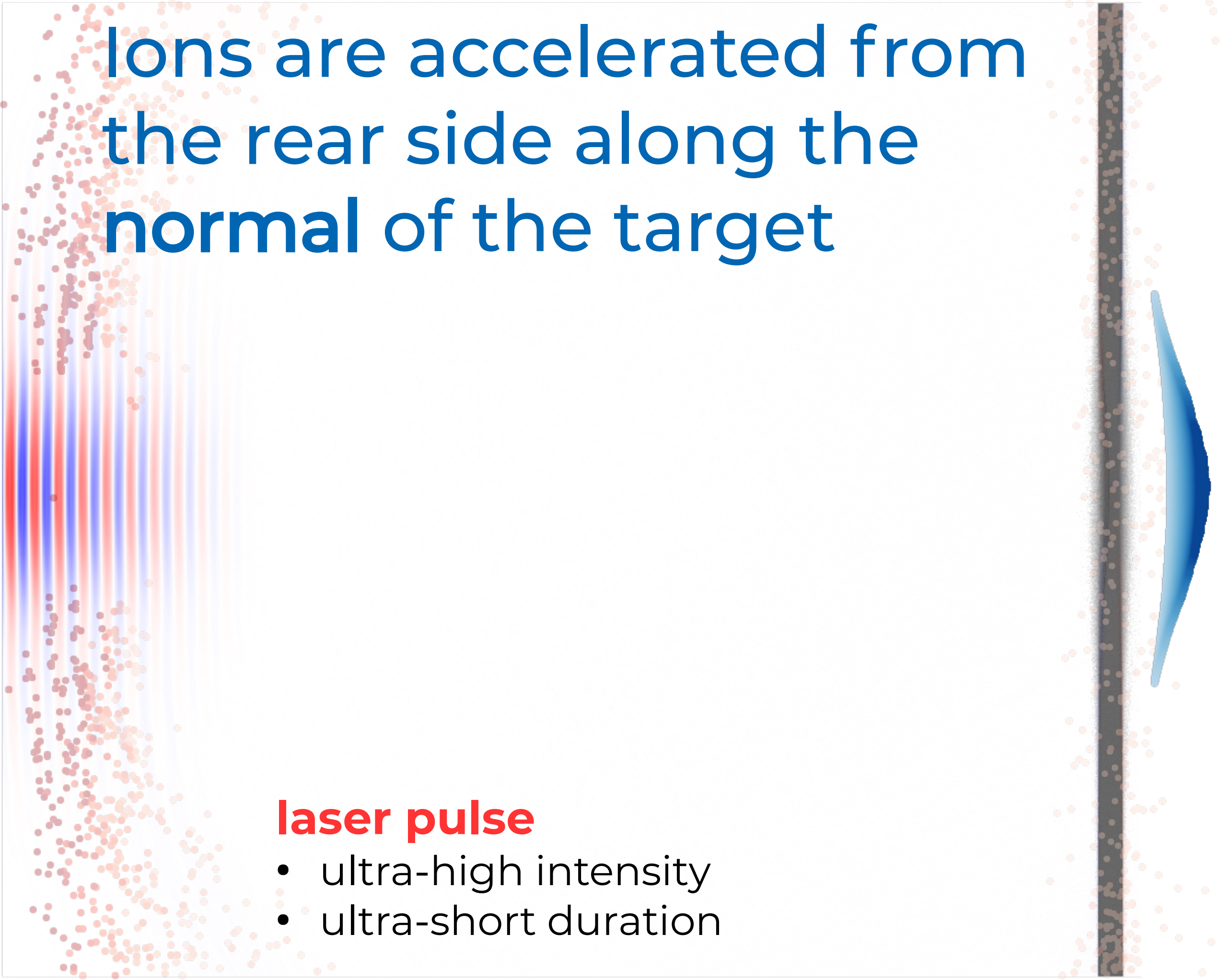

laser pulse
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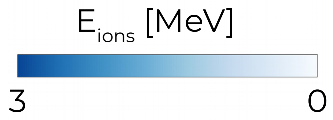


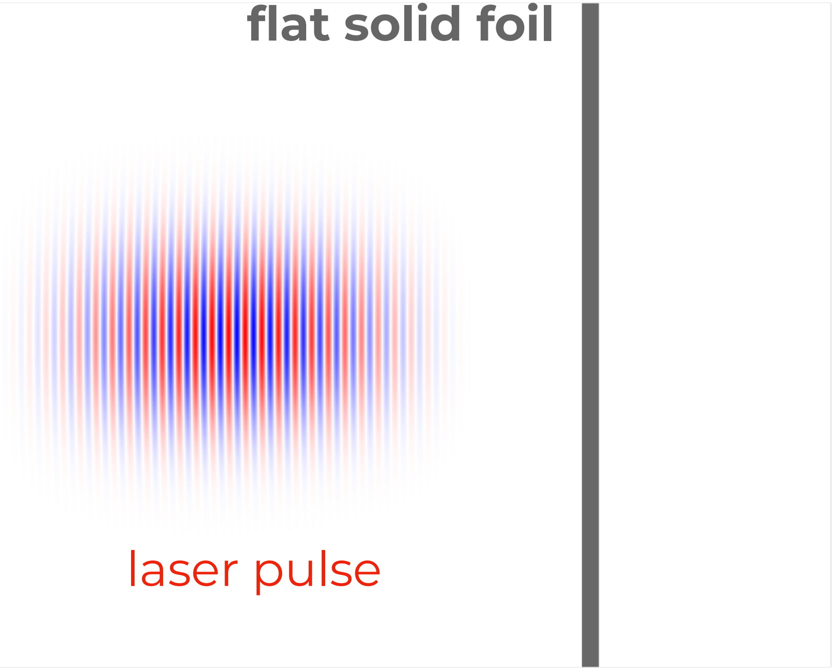
hot electron cloud
- thermal spectrum
- few MeV temperature

The target is crucial

A smart target improves the acceleration process

Conventional

"**T**arget-**N**ormal **S**heath **A**cceleration"



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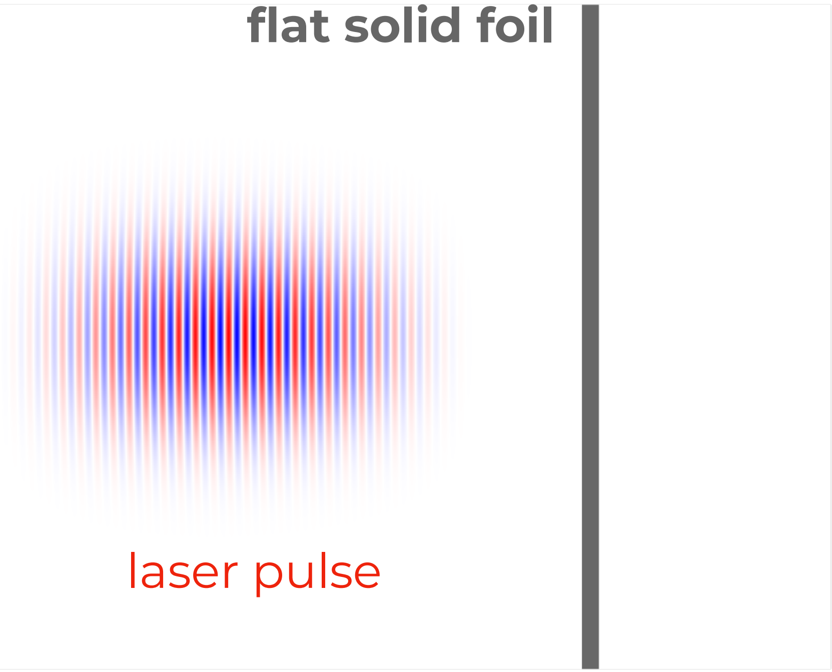
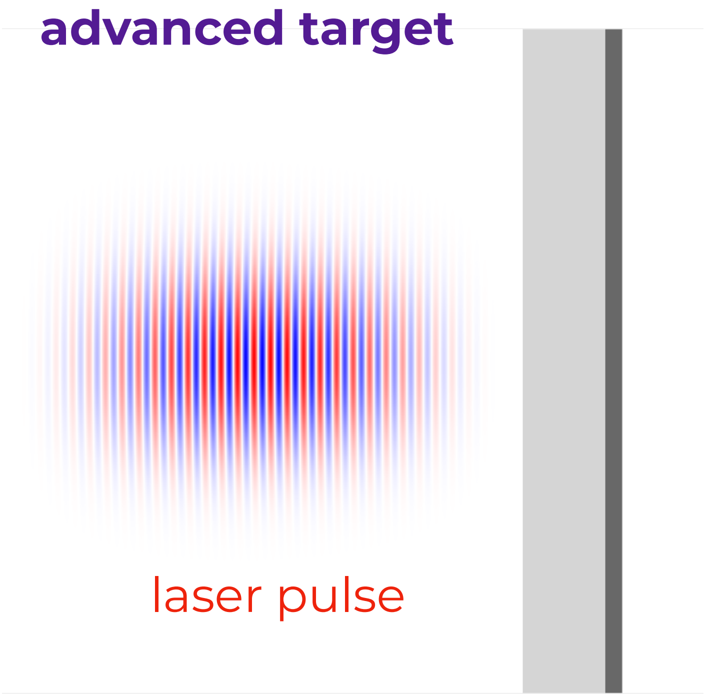


Enhanced



A smart target improves the acceleration process

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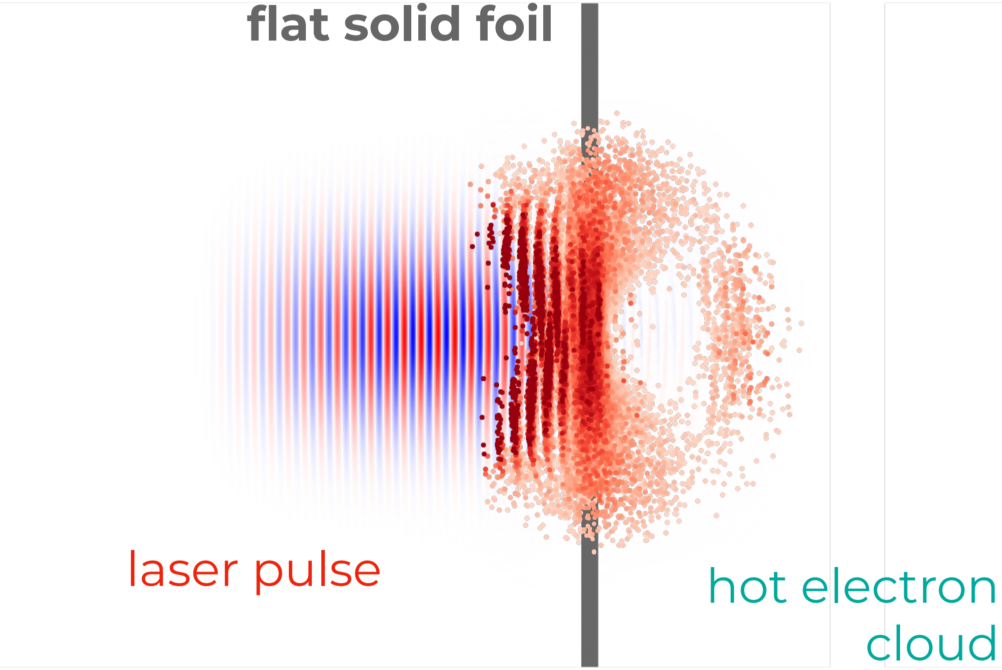
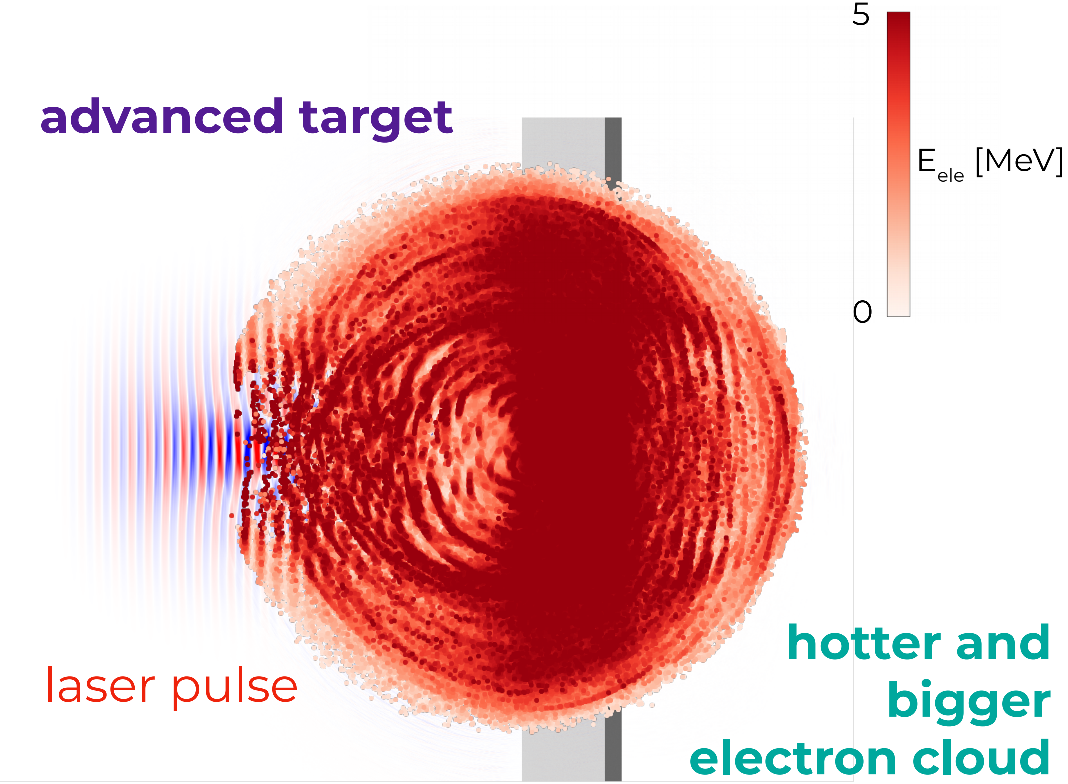


Enhanced



The target is the key

Conventional

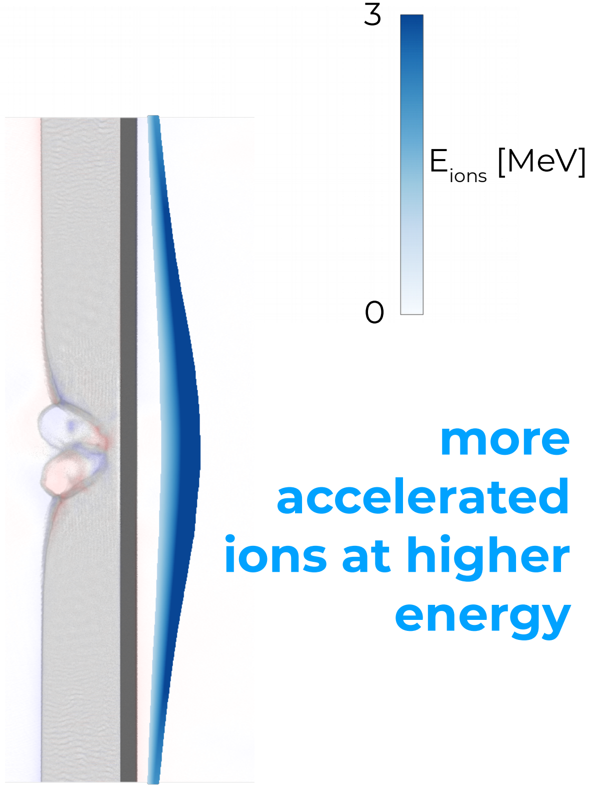
"**T**arget-**N**ormal **S**heath **A**cceleration"

flat solid foil

accelerated ions

Enhanced

advanced target

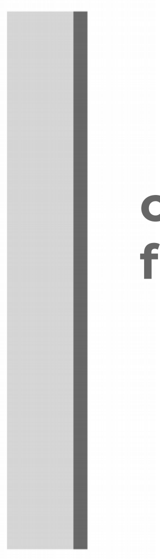


more accelerated ions at higher energy

How can an additional layer enhance the TNSA process? Mainly because of its density...

advanced target

near-critical density layer



conventional flat solid foil

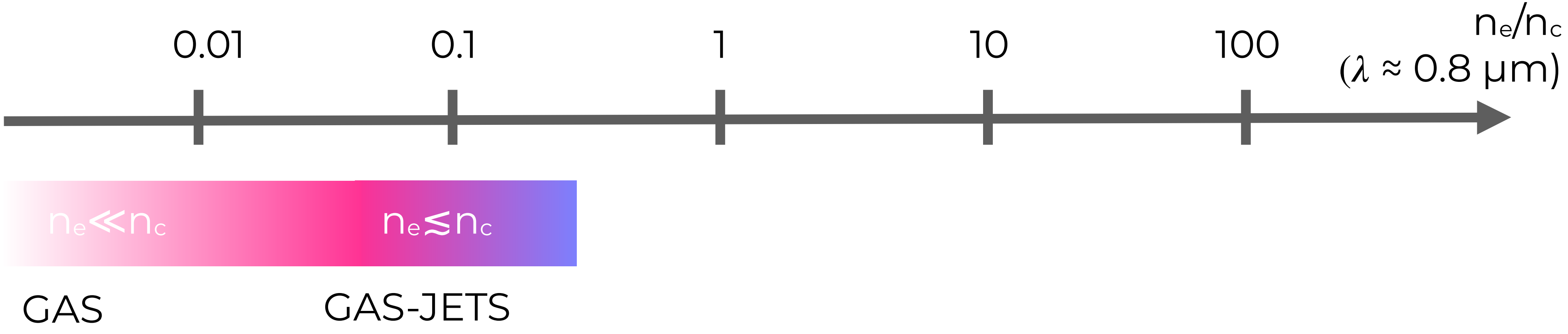
$$n_e \approx n_c = \frac{\pi m_e c^2}{e\lambda^2}$$

plasma frequency **matching** laser frequency → **stronger coupling**

The laser-plasma coupling is enhanced in the near-critical regime

underdense plasmas

- laser propagation
- low absorption
- volume interaction



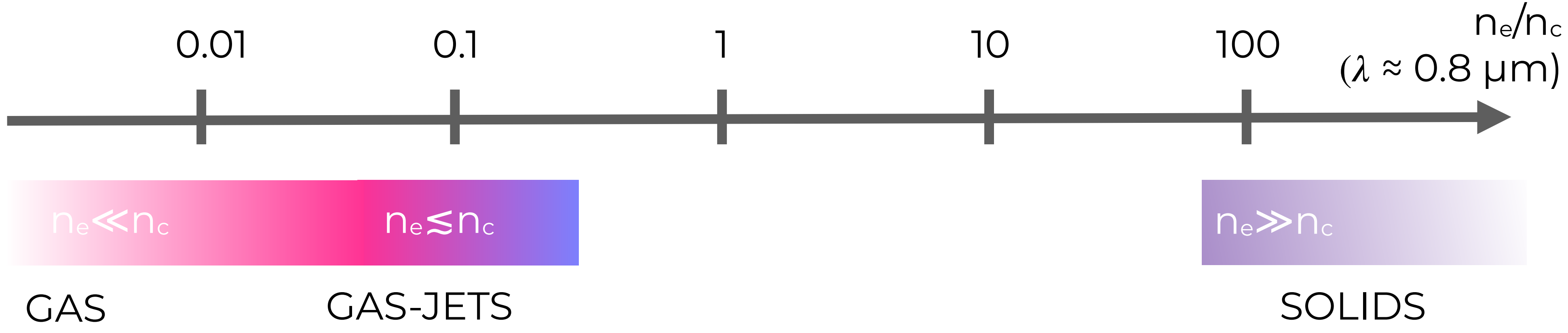
The laser-plasma coupling is enhanced in the near-critical regime

underdense plasmas

- laser propagation
- low absorption
- volume interaction

overdense plasmas

- laser reflection
- laser damping
- surface interaction



The laser-plasma coupling is enhanced in the near-critical regime

underdense plasmas

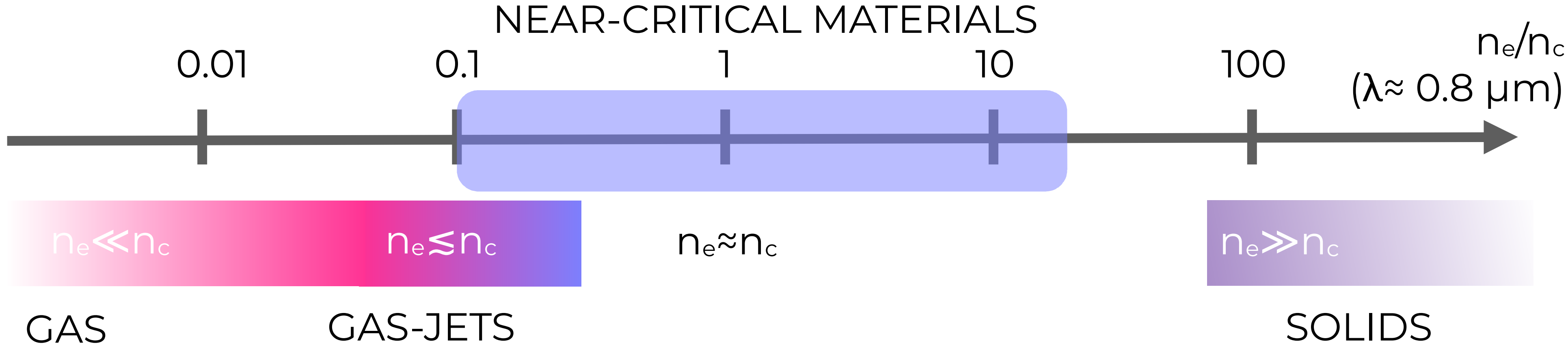
- laser propagation
- low absorption
- volume interaction

near-critical plasmas

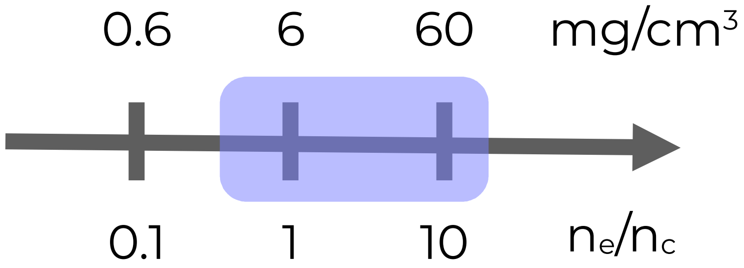
- **strong interaction**
- **complex regime**
- **extremely interesting**

overdense plasmas

- laser reflection
- laser damping
- surface interaction



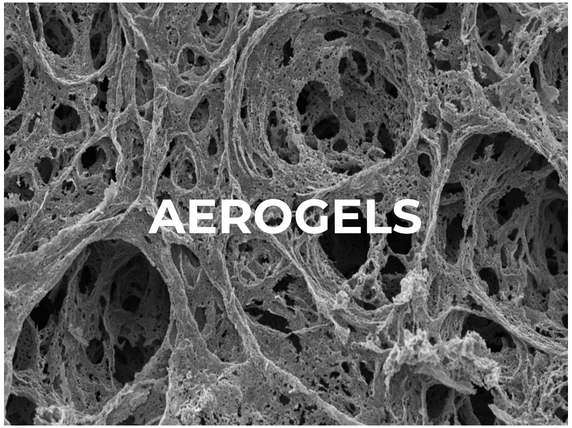
Producing near-critical materials is challenging because of their very low average density

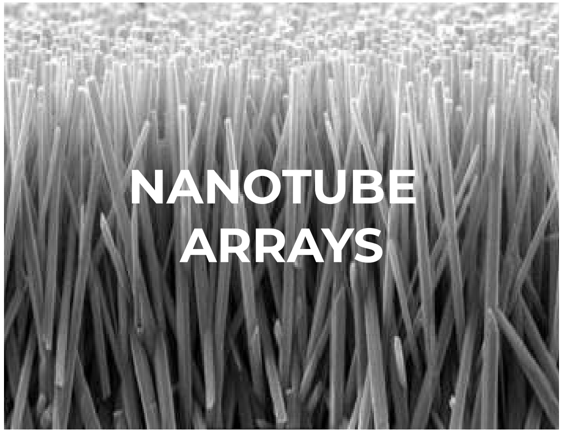


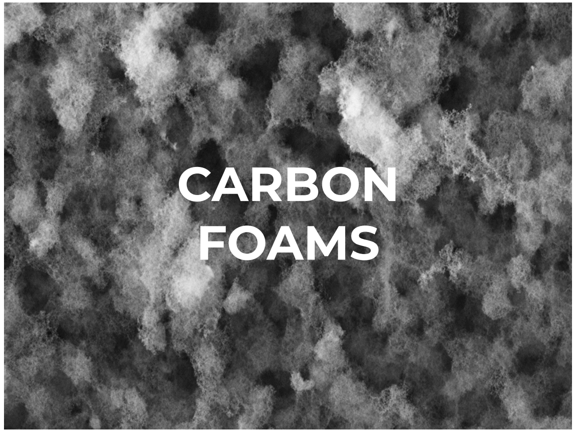
$\lambda \approx 0.8\ \mu m \rightarrow$ **$n_c \approx 6\ mg/cm^3$ = 6 x density of air**

<u>ultra-low density</u>

very few option other than pre-heating







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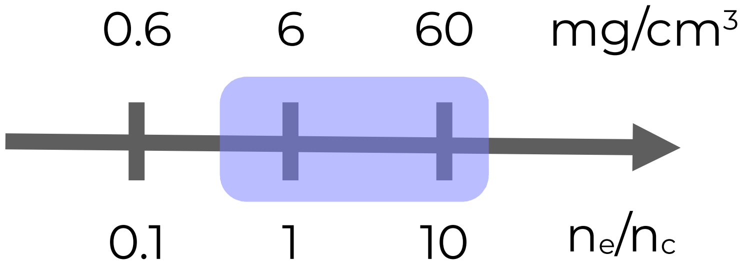

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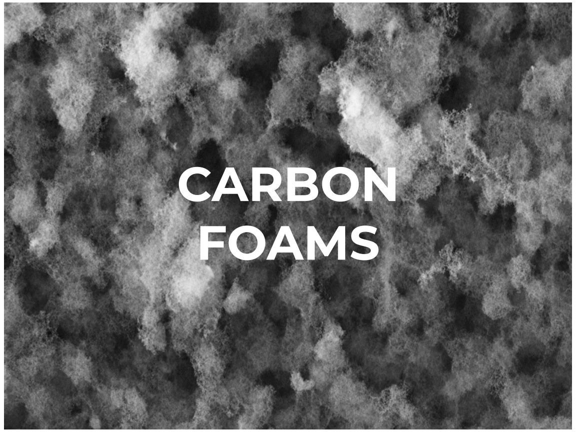
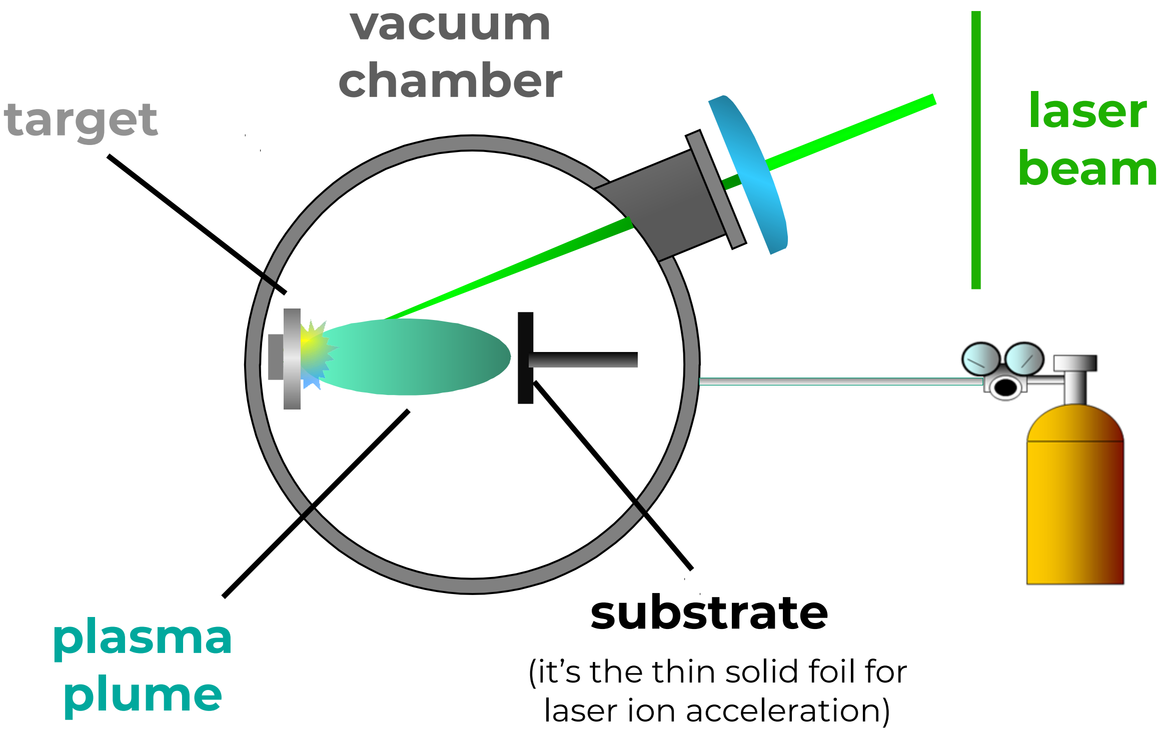


Foams are grown directly on a substrate by means of the Pulsed Laser Deposition technique



- 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)

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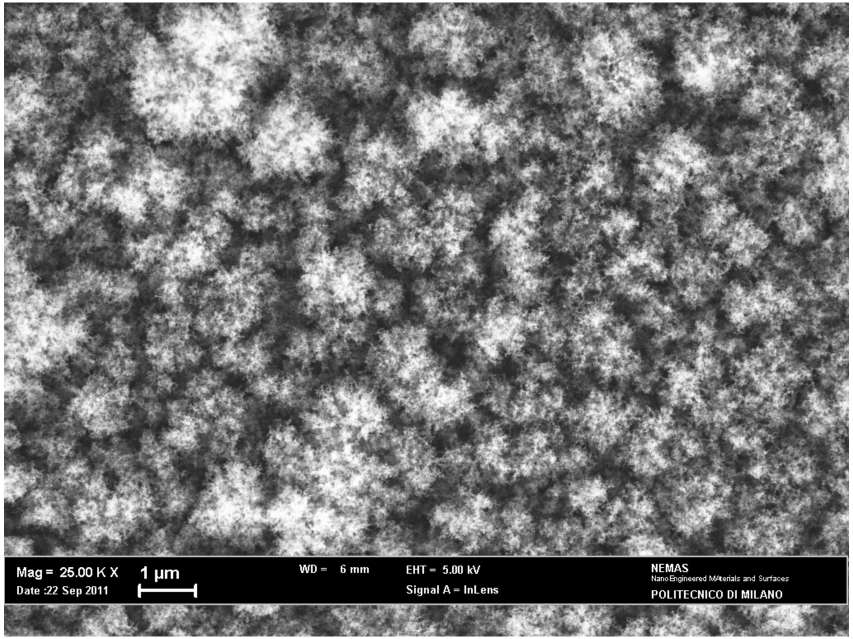
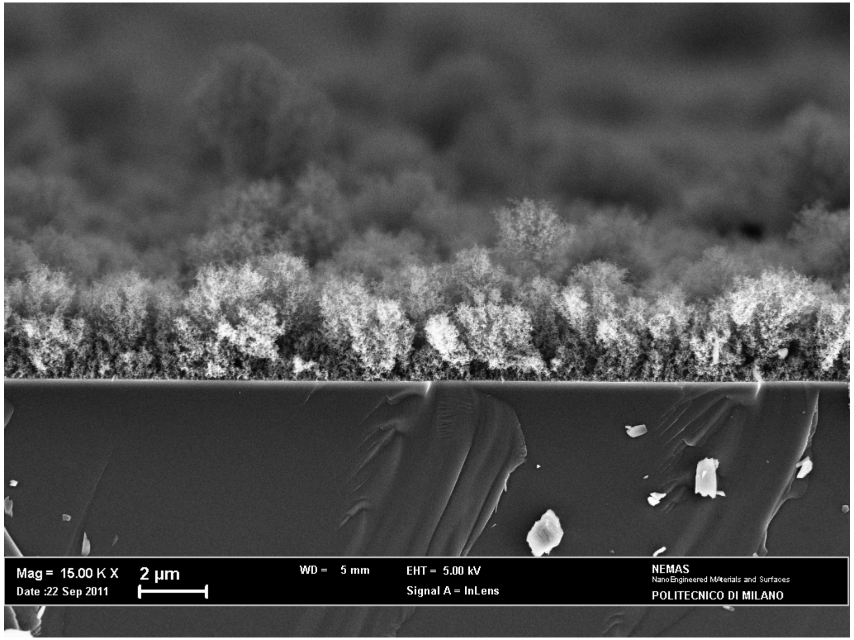
Carbon foams can have very complex morphology and structure at the nanoscale

top-view

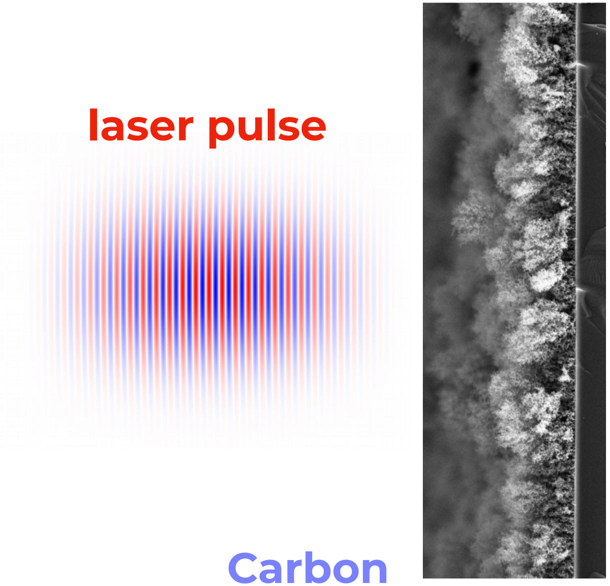


cross-section



Scanning Electron Microscopy images NanoLab

There are still many open issues



?

- How does a **foam behave upon irradiation** by a high-intensity laser?
- Do the **nanostructure** and the **morphology** affect the interaction and the acceleration?
- How can we **tune** the properties of the **foam**-attached target to **optimize** ion acceleration?
- …

Theoretical studies

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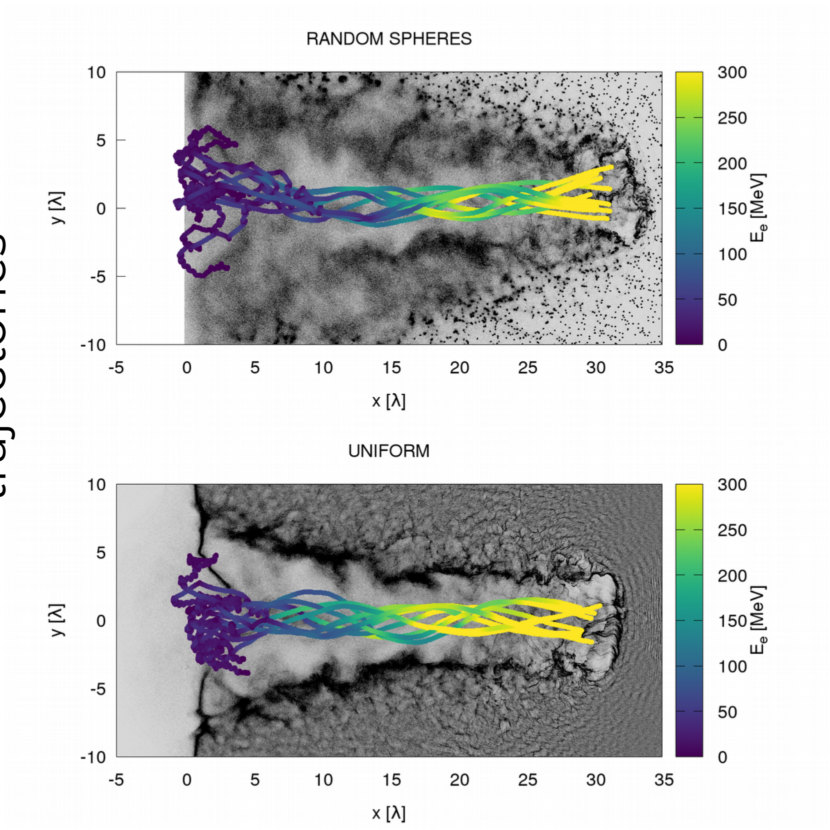
Theoretical investigations of laser-driven ion acceleration with nanostructured materials

Arianna Formenti

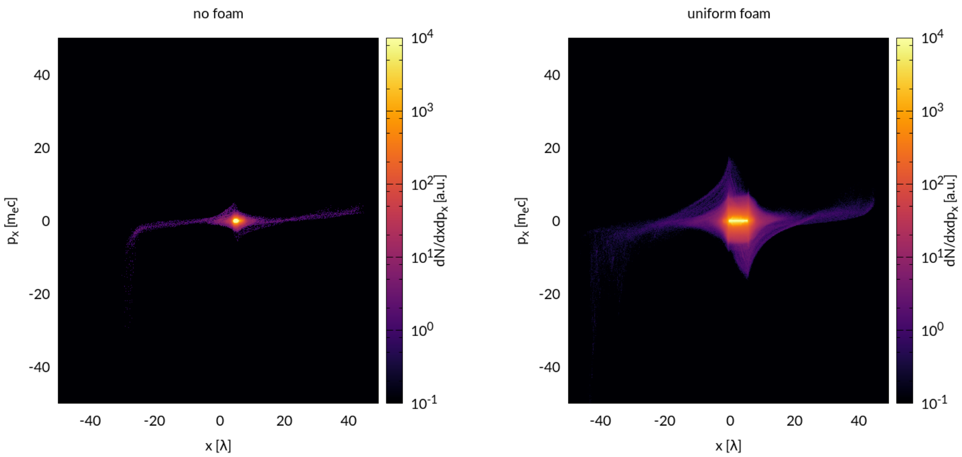
NanoLab Talk, Milan, April 23rd, 2018

Kinetic, relativistic, Particle-In-Cell simulations are a powerful numerical tool

trajectories

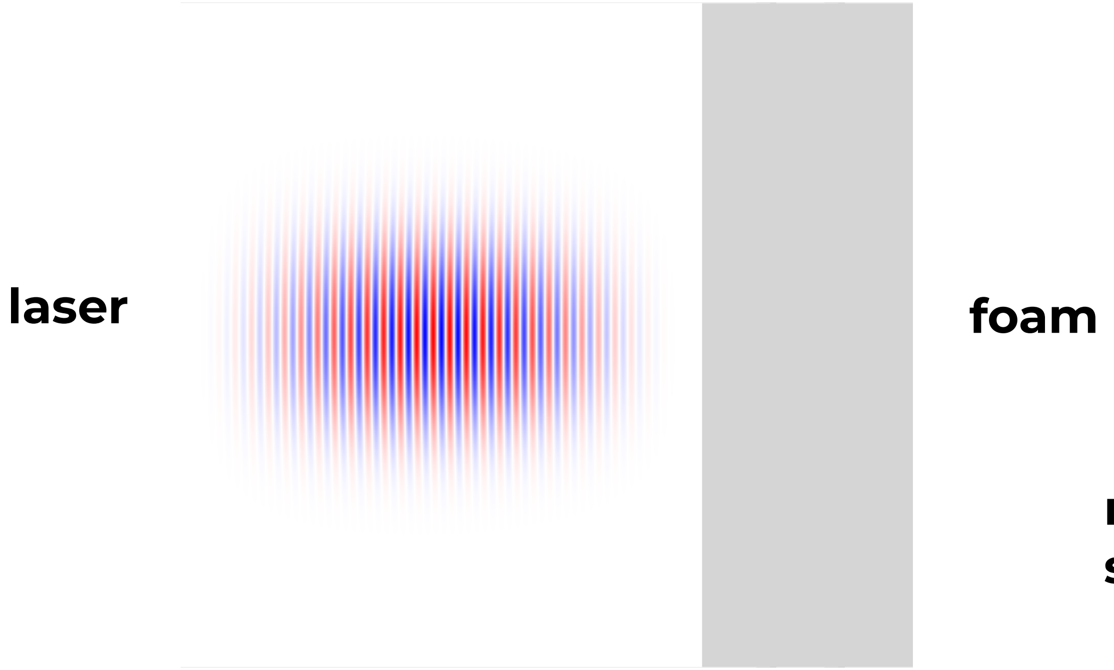


phase space



PIC codes

We started investigating the interaction rather than the acceleration

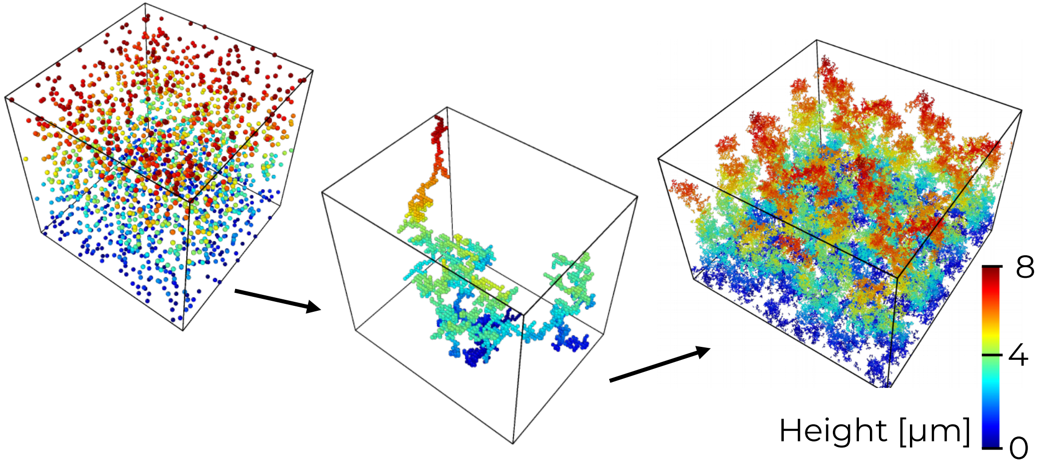


no substrate,
so no ion acceleration!

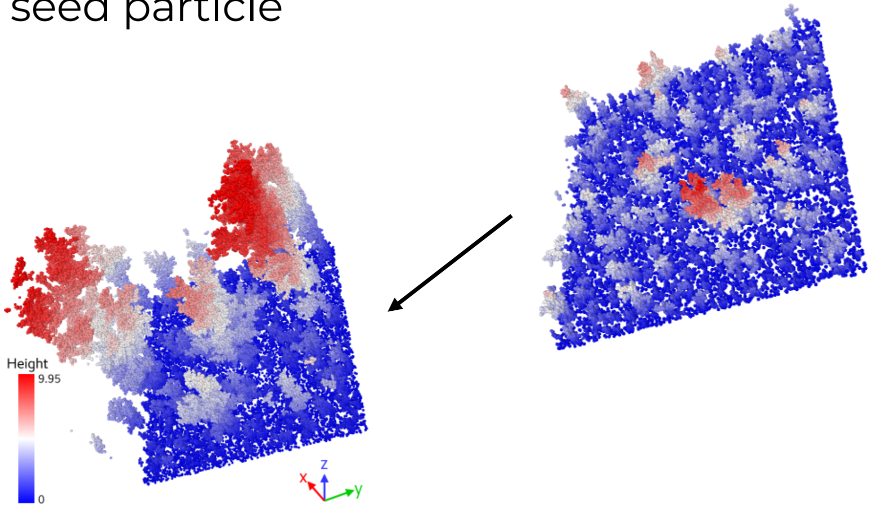
but first, pick a **model** for the **foam material**

Quite realistic aggregation models that can mimic the foam growth

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

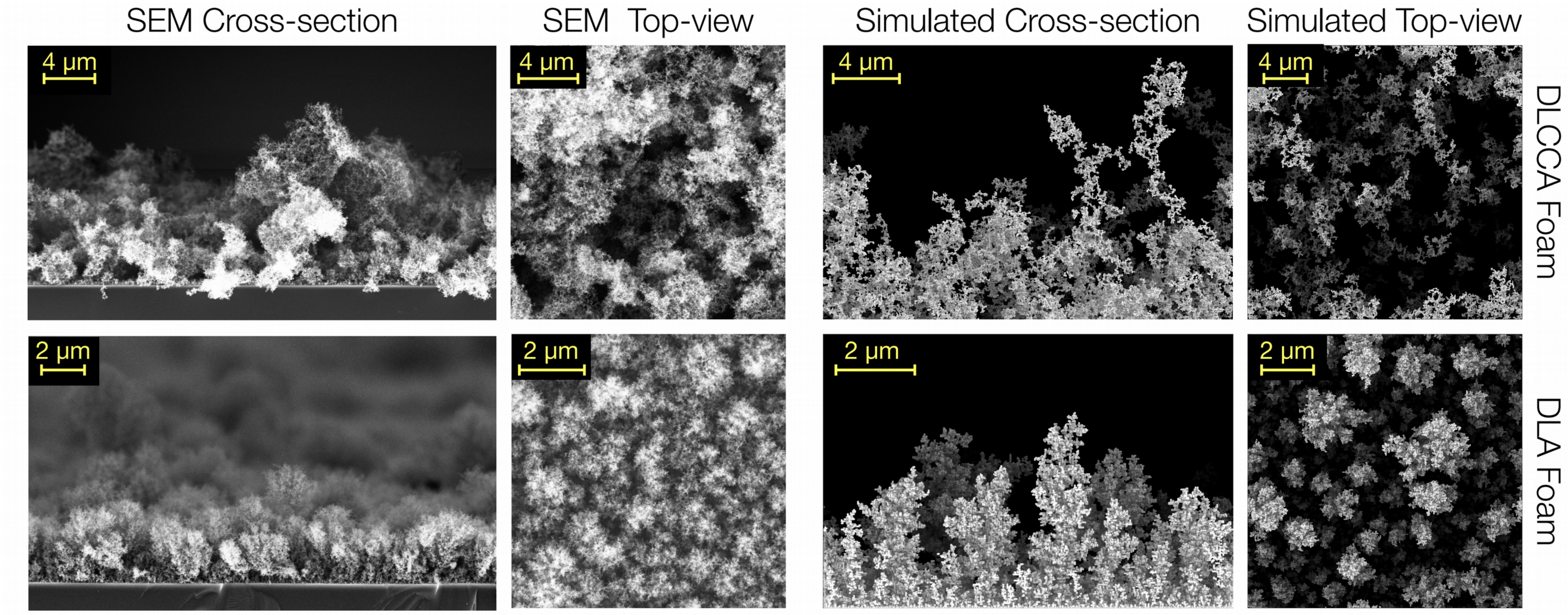


Diffusion-Limited (DLA)
- Brownian motion of particles
- particle deposition in clusters by irreversible sticking starting from a seed particle



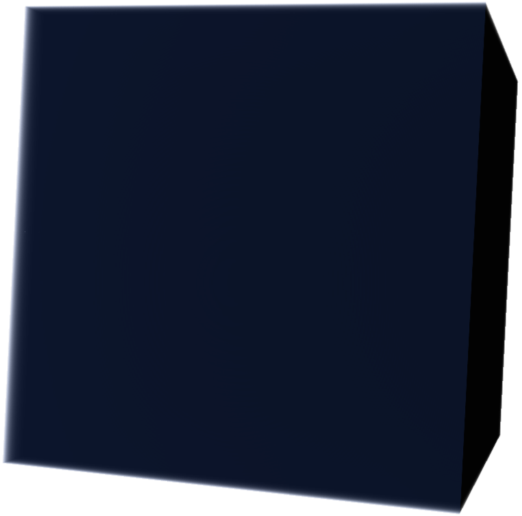
Witten and Sander. *Phys Rev Lett* 47 (1981)
Meakin. *Phys Rev Lett* 51 (1983)

Quite realistic aggregation models that can mimic the foam growth

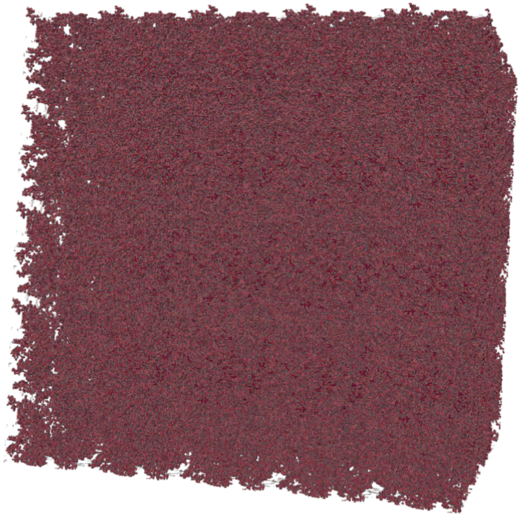


We used some of these models to investigate laser-foam interaction

homogeneous

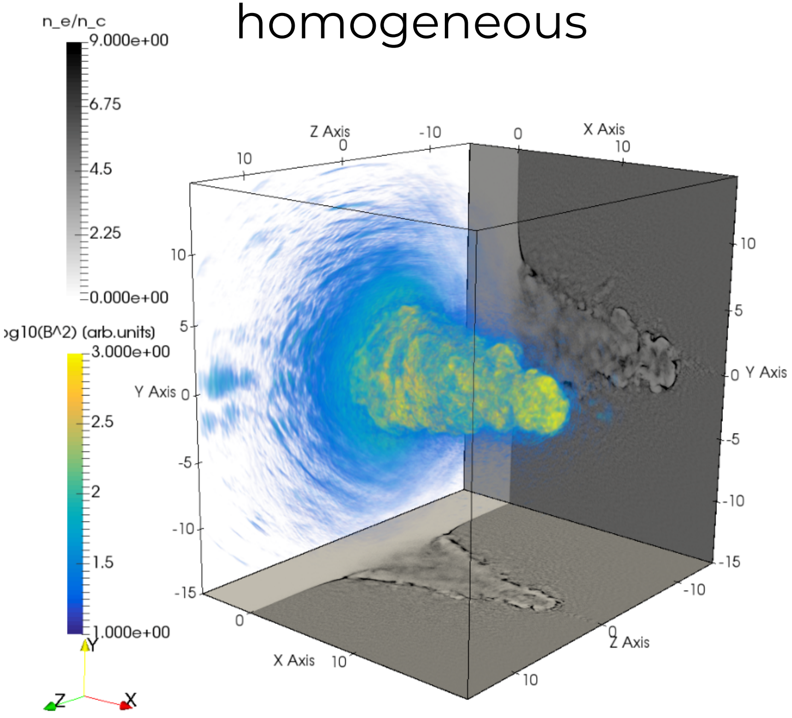


DLCCA foam

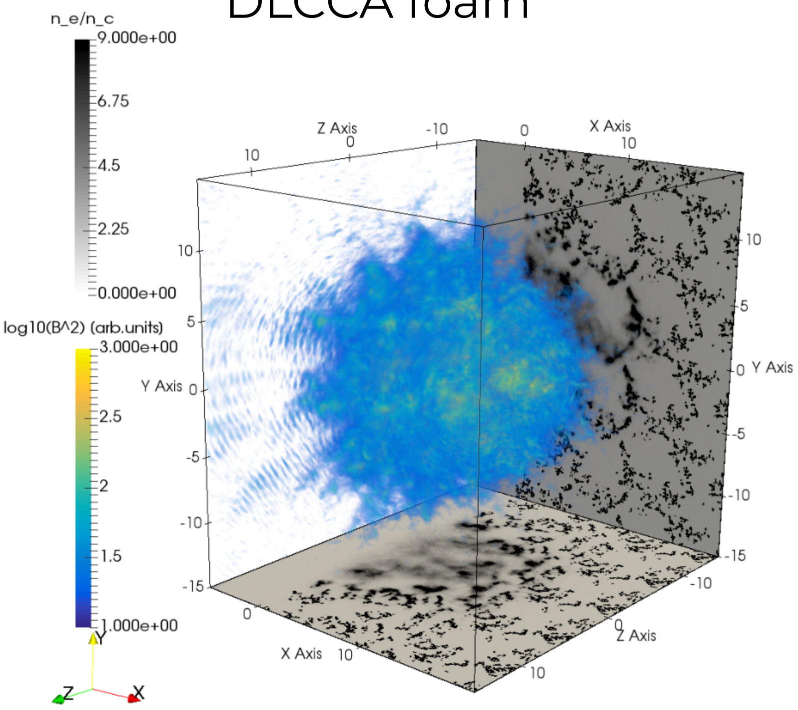


Pulse propagation is influenced by a nanostructure

homogeneous



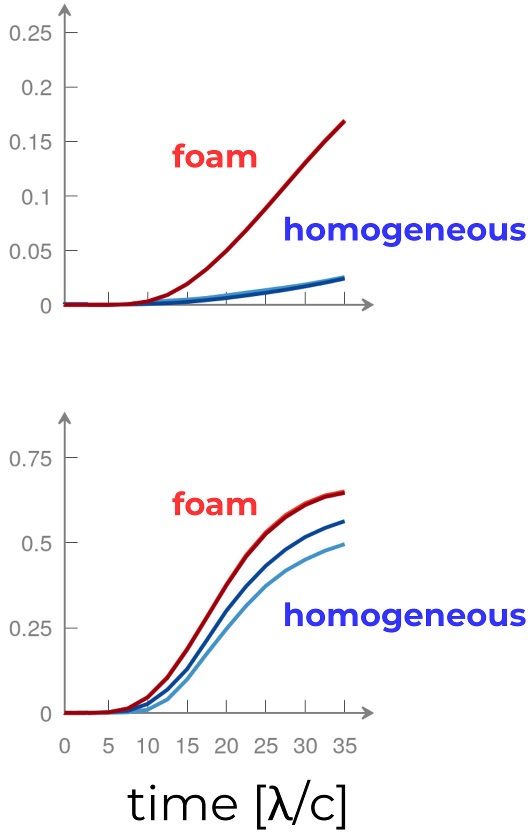
DLCCA foam



The nanostructure strongly enhances total and ion laser absorption

ion absorption

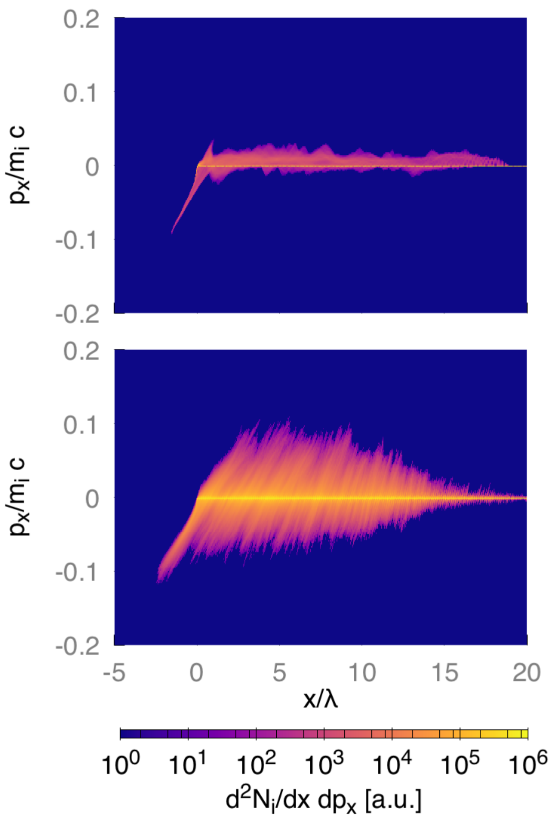
electron absorption



a_0=15, n_0=3n_c

(especially at "low" intensity)

ion phase space p_x vs. x

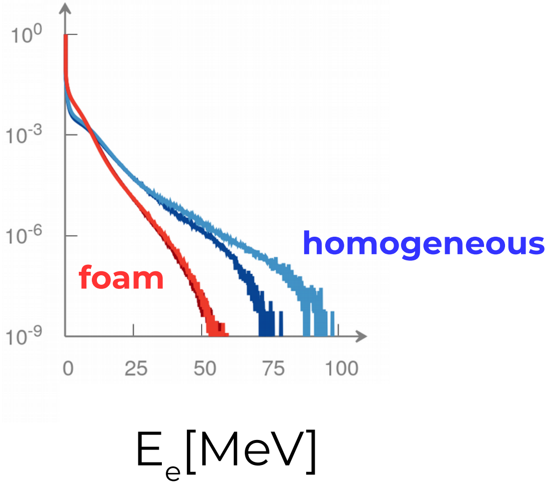


homogeneous

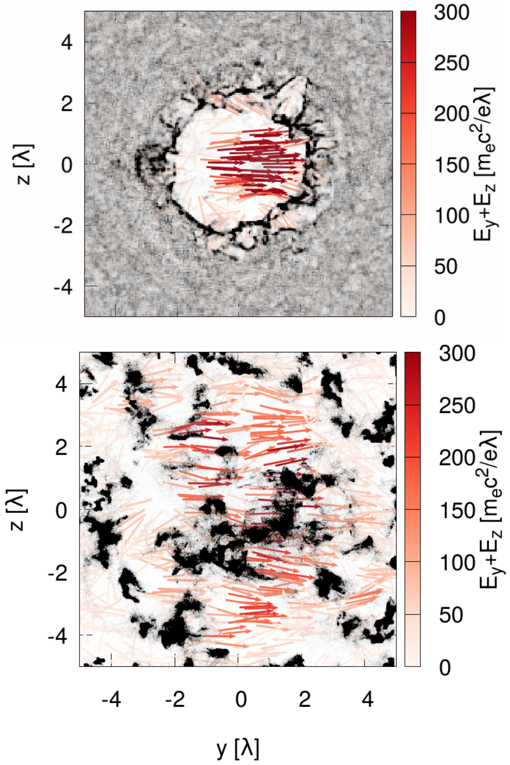
DLCCA foam

The nanostructure has a detrimental effect on high-energy electrons, beneficial on the mildly energetic ones

normalized electron spectrum



transverse electric field



homogeneous

DLCCA foam

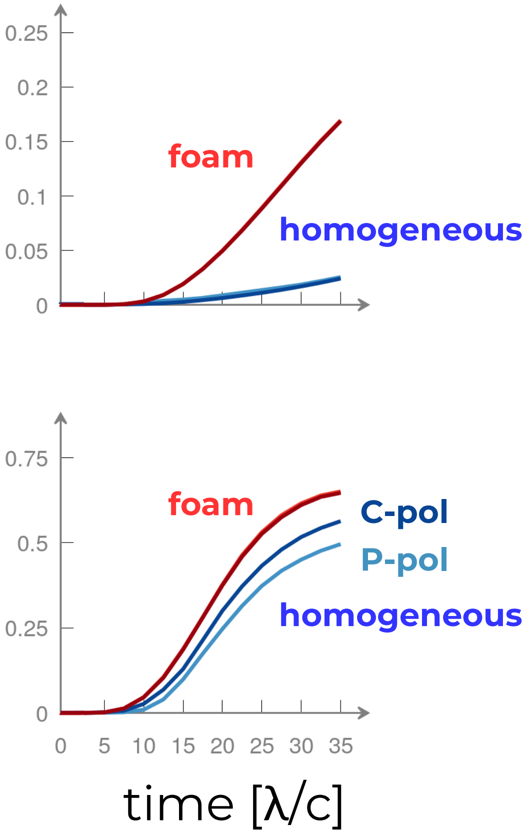
a_0=15, n_0=3n_c

(especially at “high” intensity)

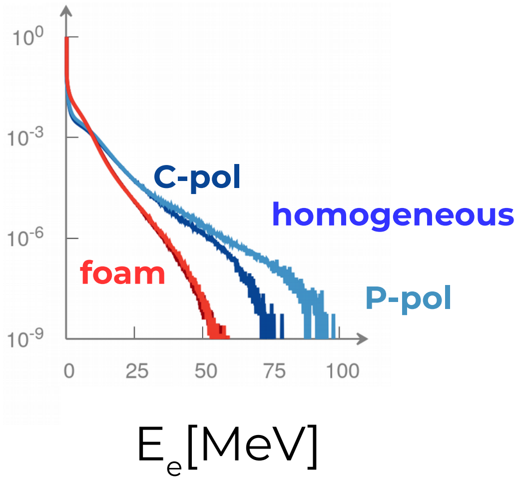
The nanostructure kills polarization dependence

ion absorption

electron absorption



normalized electron spectrum

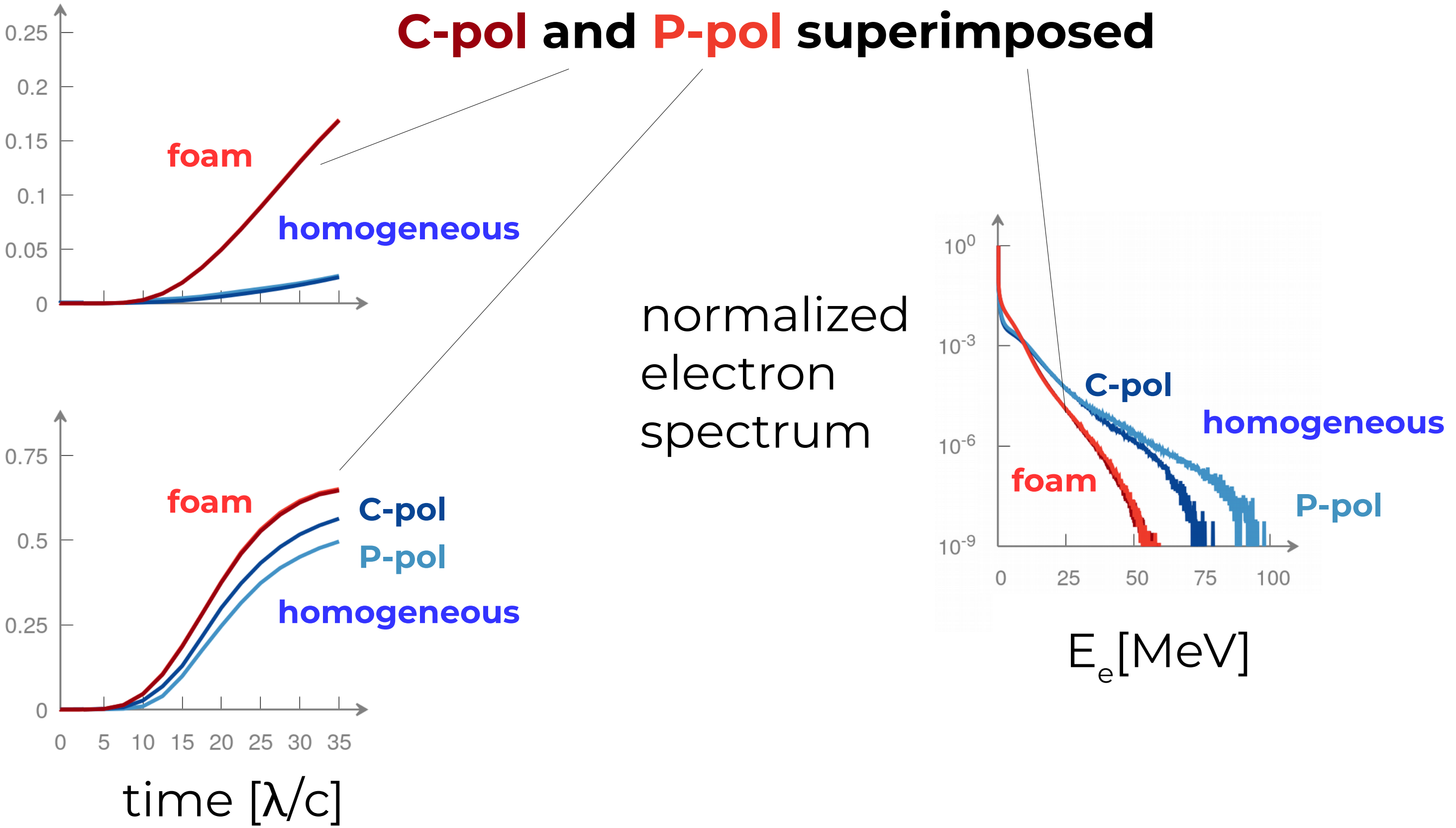


a_0=15, n_0=3n_c

The nanostructure kills polarization dependence

ion absorption

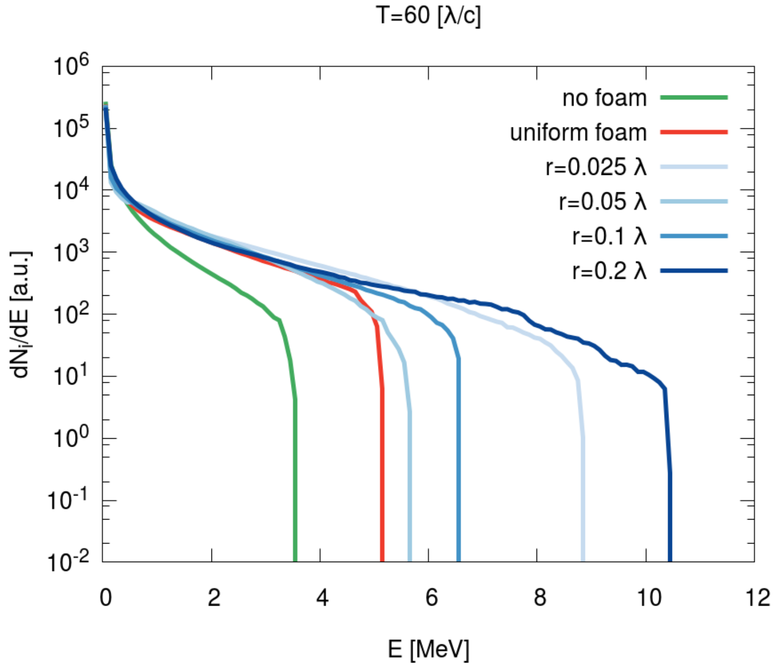
electron absorption



a_0=15, n_0=3n_c

What do we expect from ion acceleration?

one might expect that homogeneous is better for laser-driven ion acceleration...well maybe...



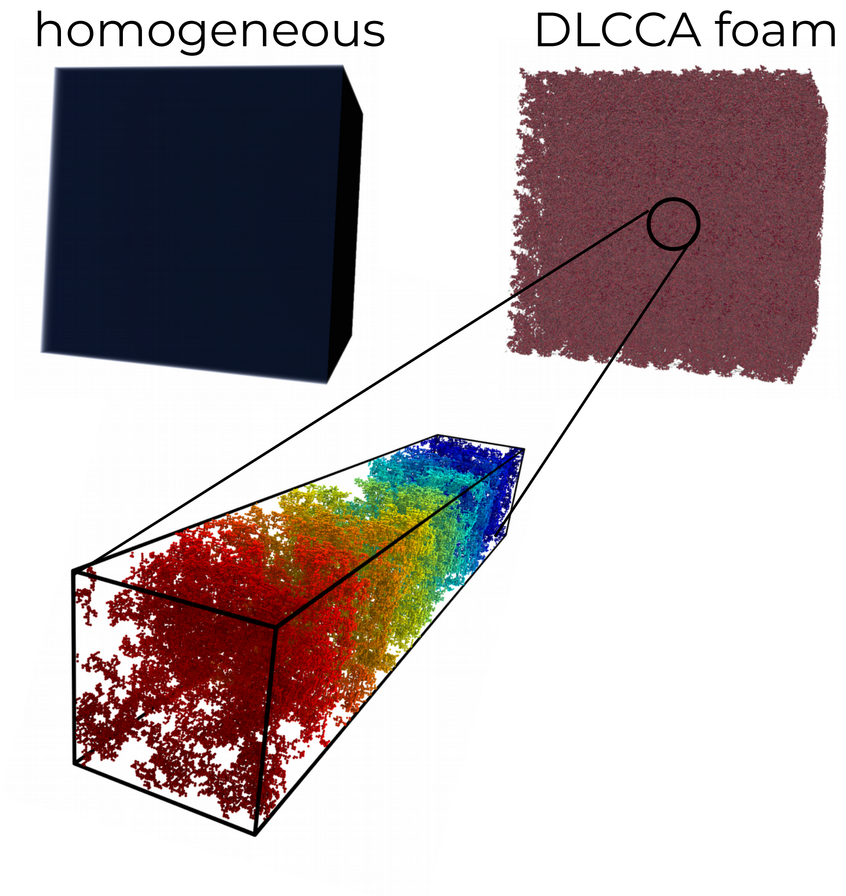
EXTREMELY PRELIMINARY

2D

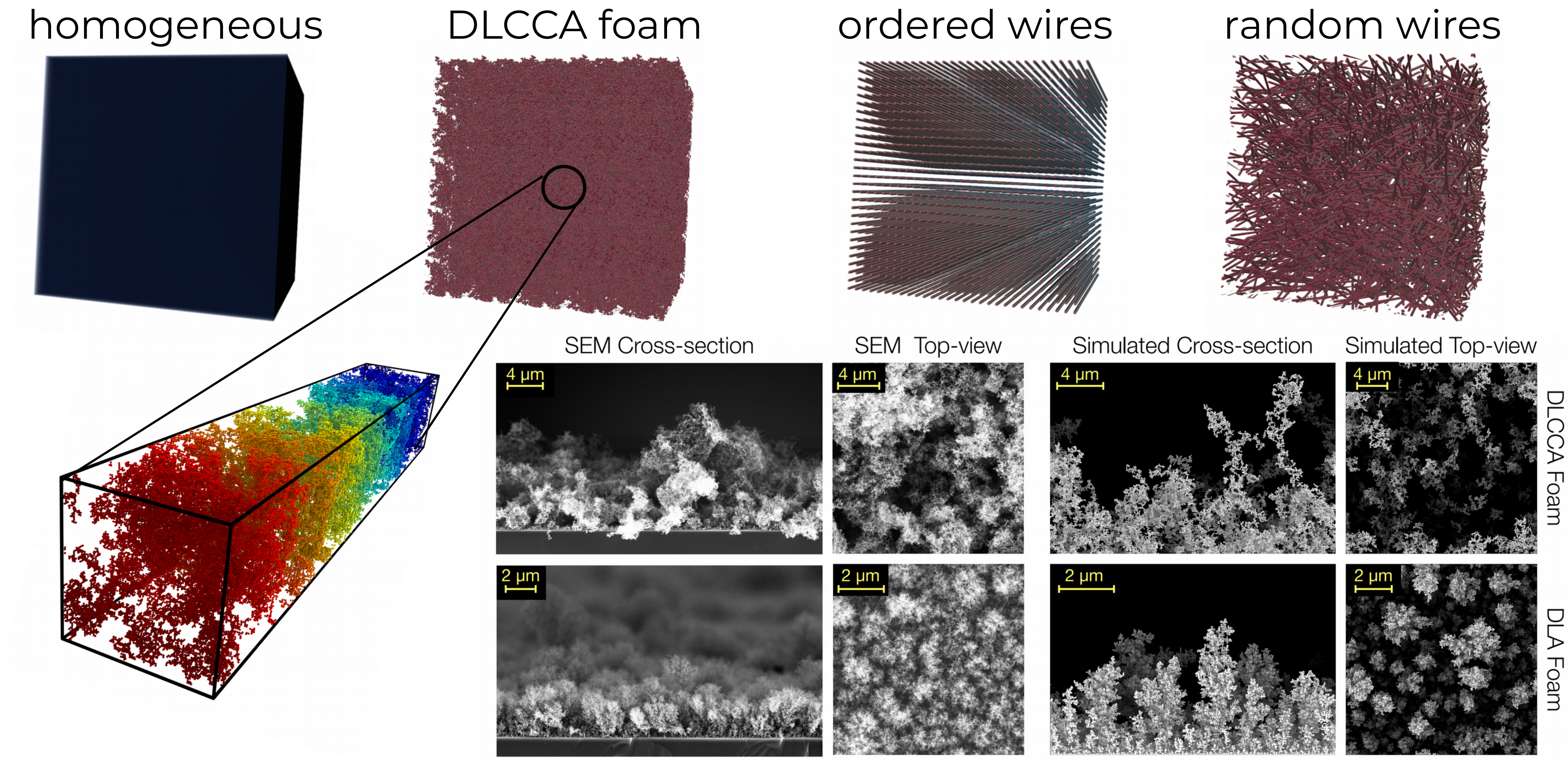
$a_0=5$, $n_0=3n_c$

random spheres foam

We also investigated different morphologies



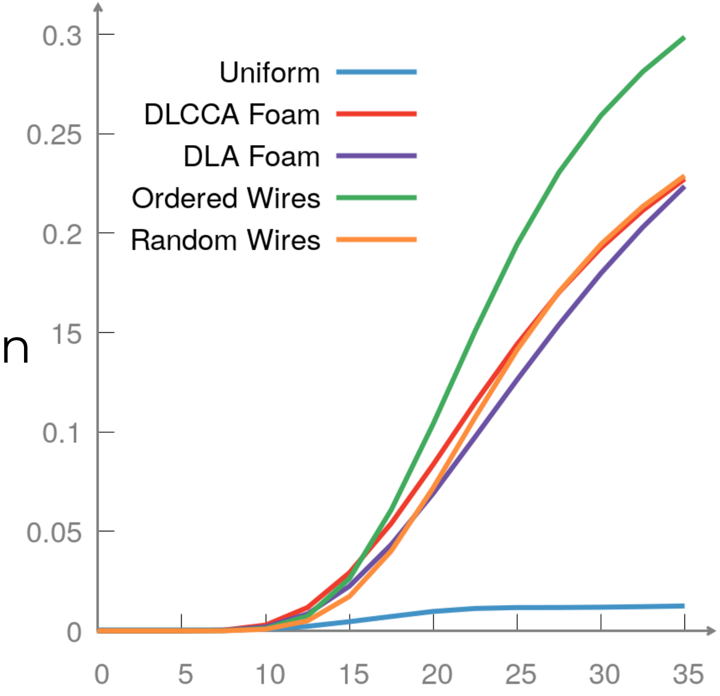
We also investigated different morphologies



L. Fedeli et al. *Sci Rep* 8.1 (2018): 3834.

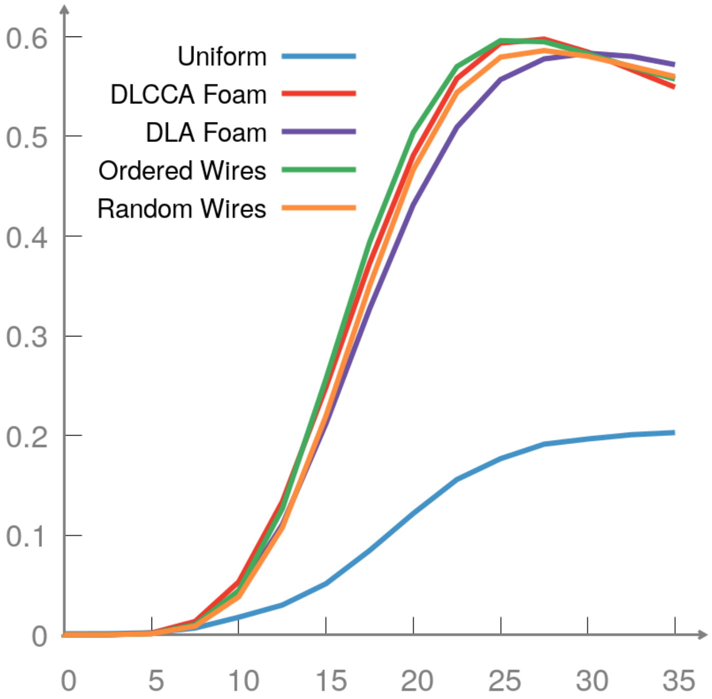
The morphology does not affect much total and ion absorption

electron absorption



time [λ/c]

ion absorption

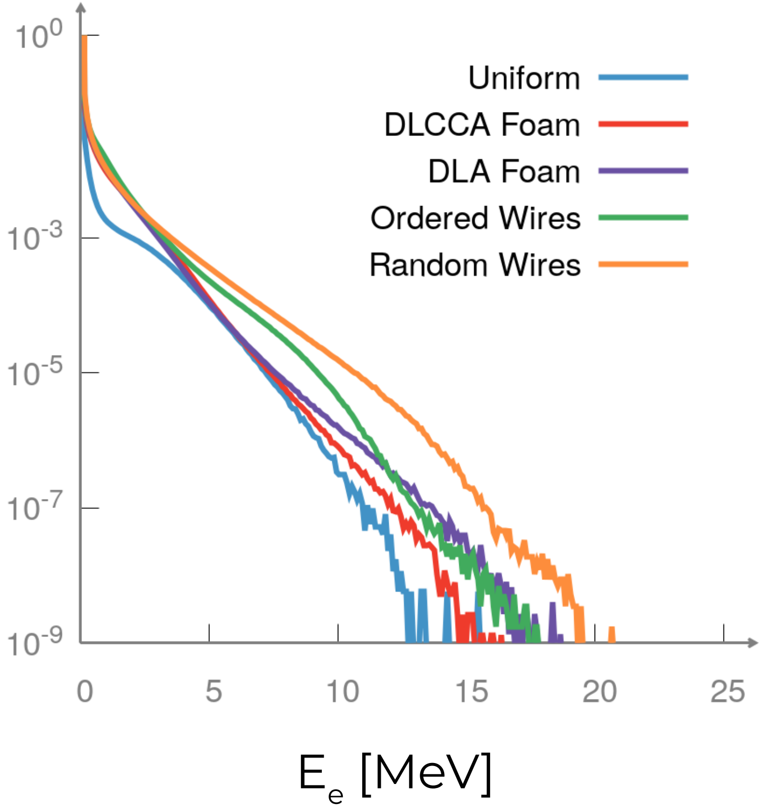


time [λ/c]

L. Fedeli et al. *Sci Rep* 8.1 (2018): 3834.

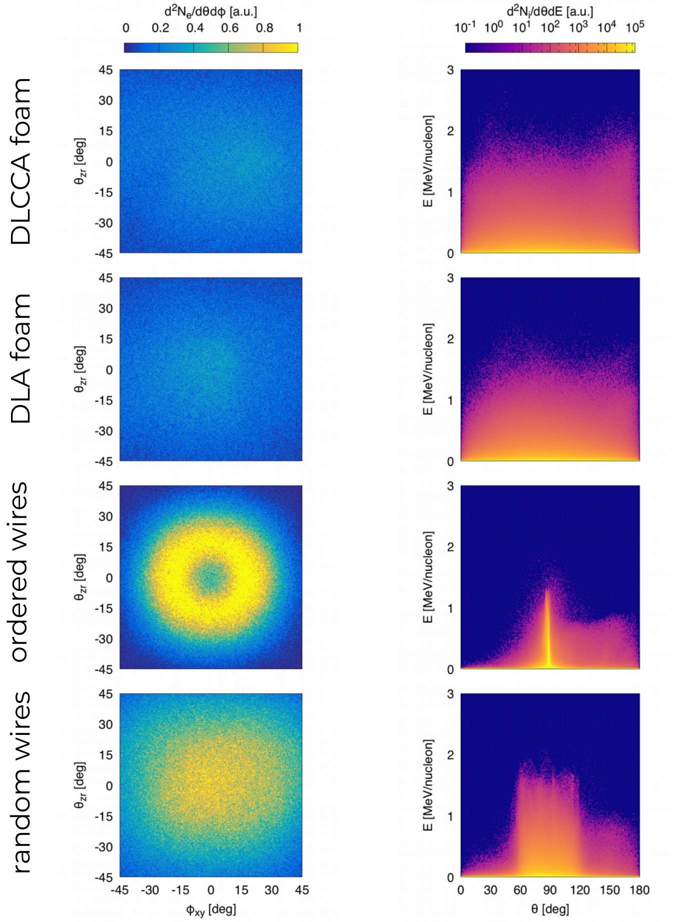
The morphology affects electron spectra and angular distribution

normalized electron spectrum



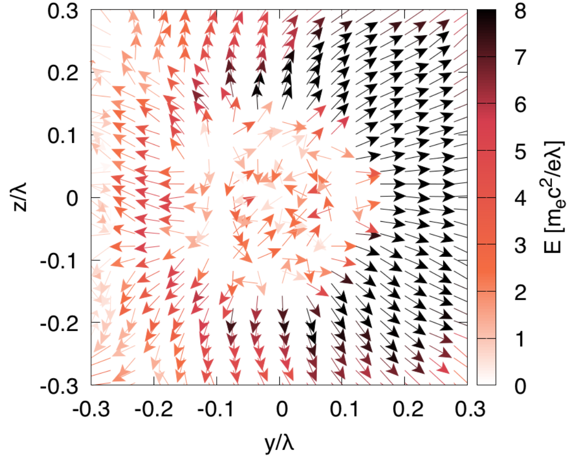
Electron angular distribution of propagation direction

Ion distribution energy vs. angle

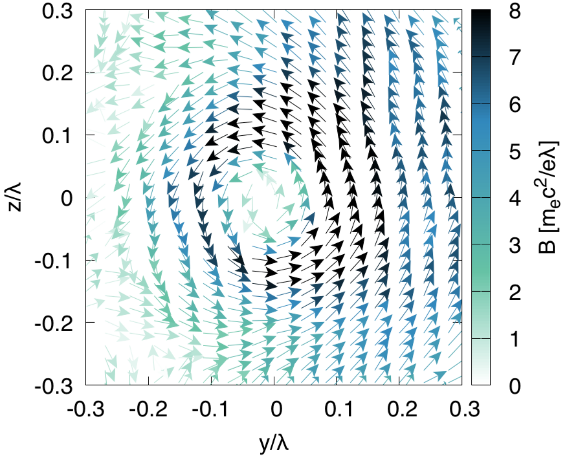


The morphology affects electron spectra and angular distribution

transverse electric field

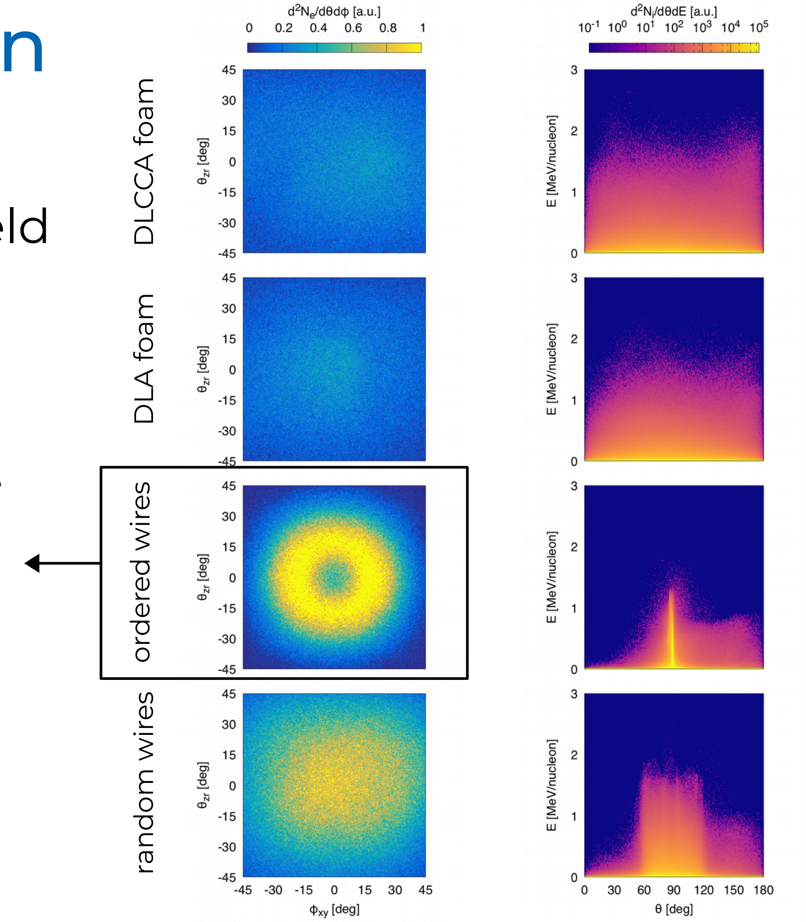


transverse magnetic field



Electron angular distribution of propagation direction

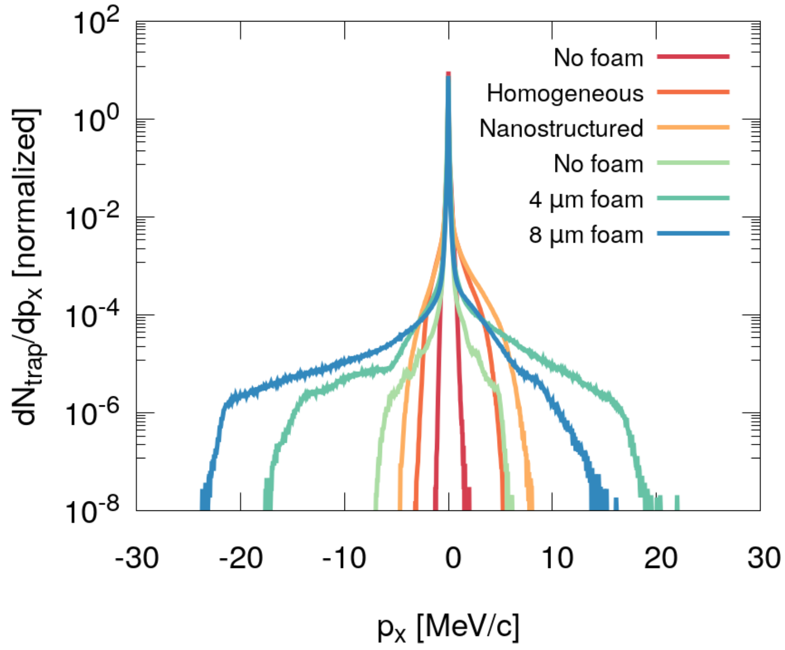
Ion distribution energy vs. angle



Simplified analytical models help grasp the main features of the acceleration process

3D simulations show that the **hot electron** population is **non-Maxwellian** (especially with foams)

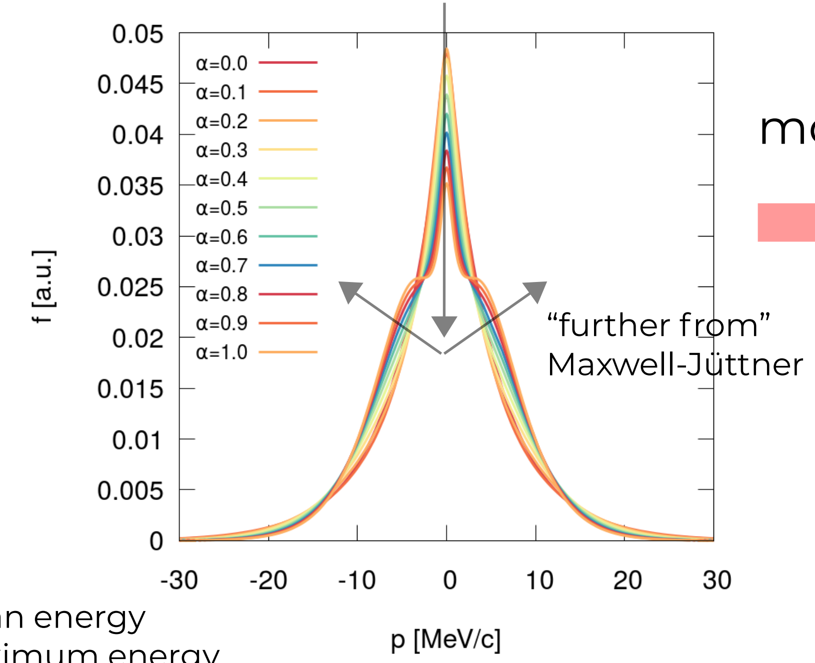
hot electron longitudinal momentum distribution



fix the **maximum hot electron energy**, then **calculate** the **ion spectra** using a self-consistent, quasi-static, 1D, relativistic analytical model

We can consider a non-Maxwellian hot electron distribution via a suitable distribution function

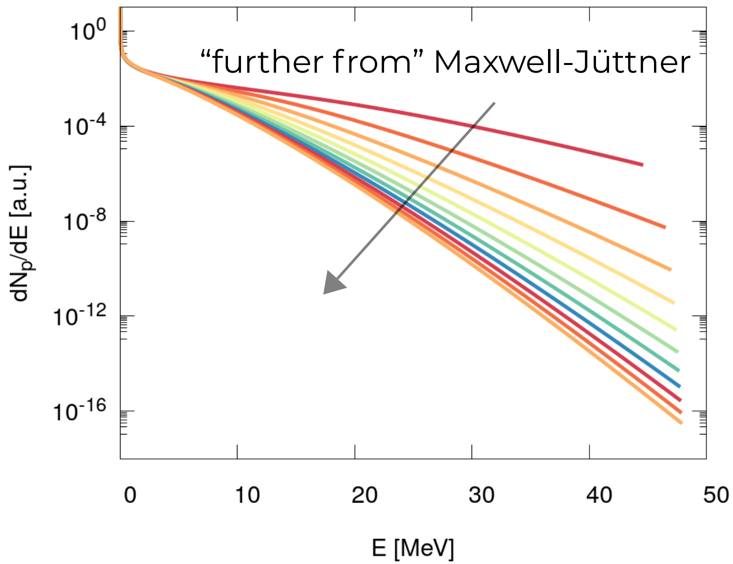
hot electron longitudinal momentum distribution



same mean energy
same maximum energy

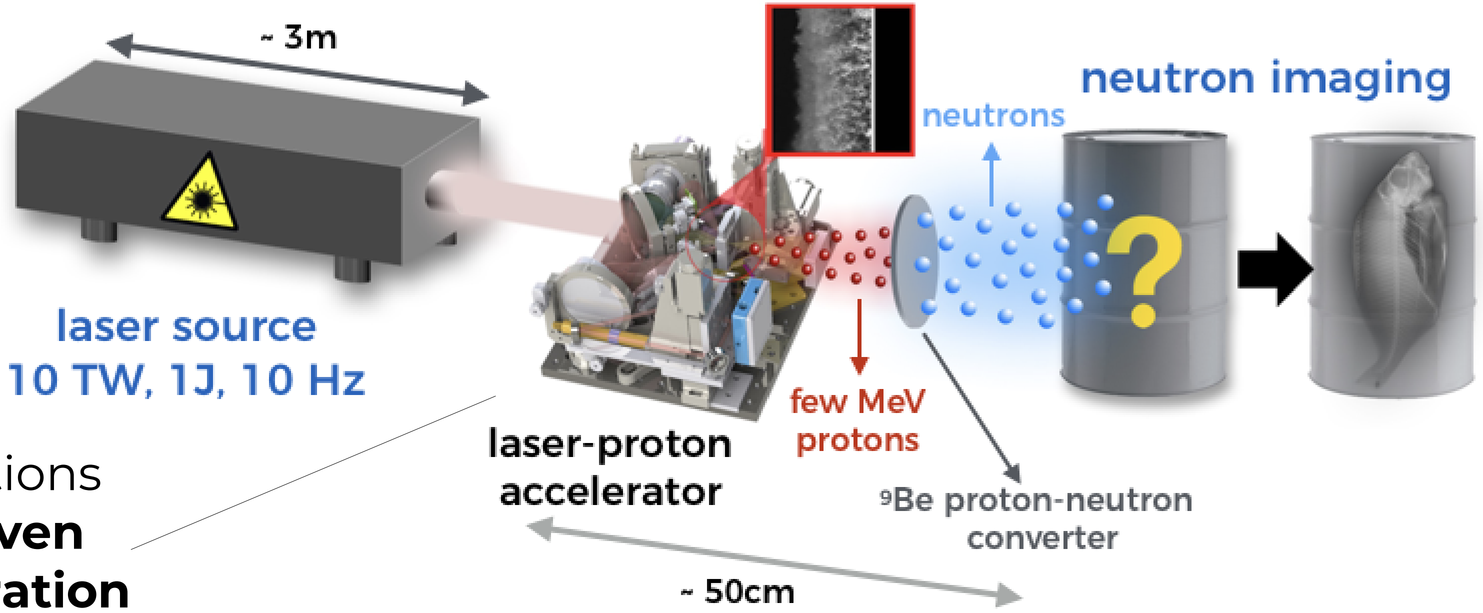
model

accelerated ions spectrum



Looks like the details of the distribution may count

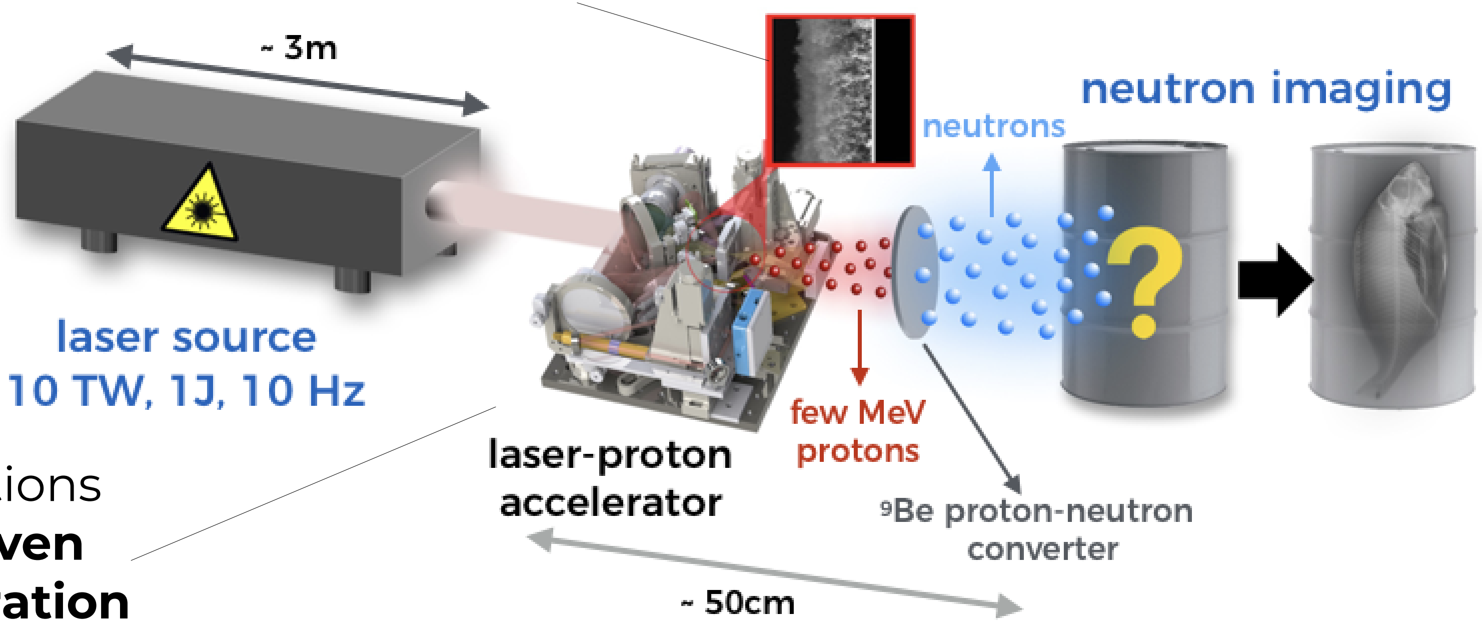
Multi-stage simulations to study secondary neutron generation from laser-driven ions



PIC simulations of **laser-driven ion acceleration**

Multi-stage simulations to study secondary neutron generation from laser-driven ions

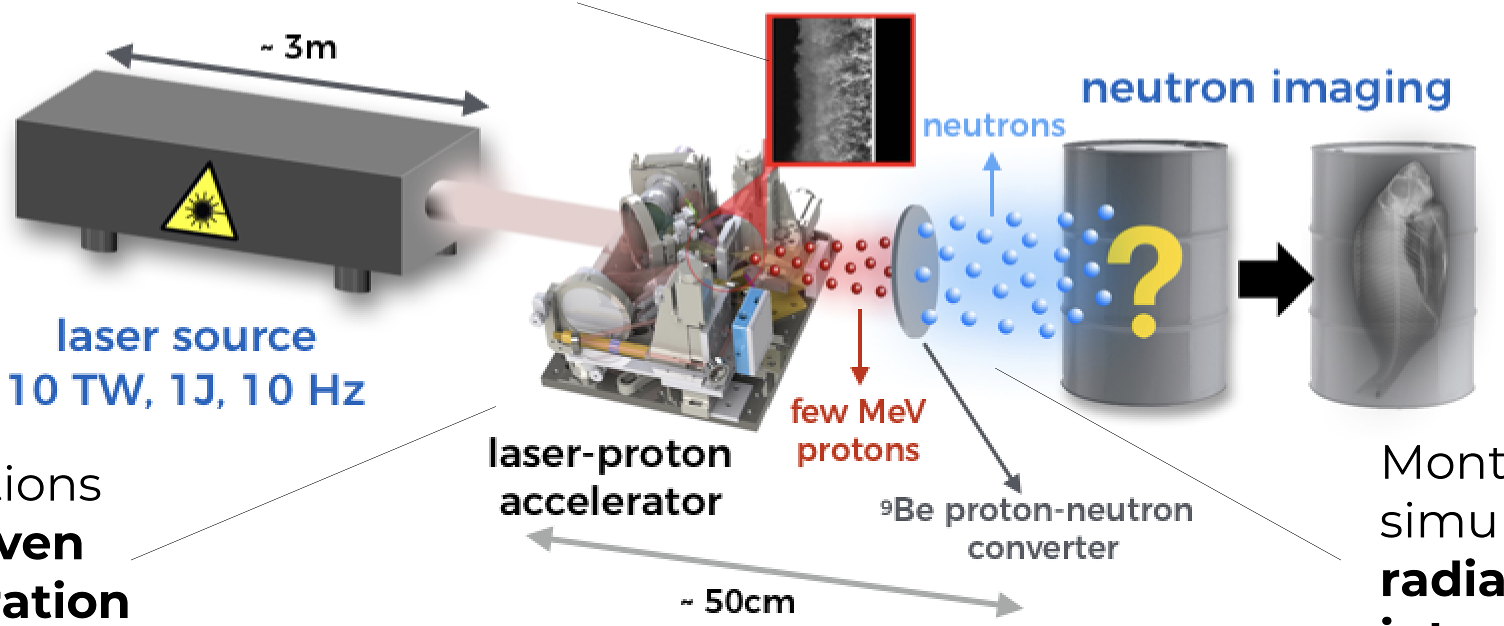
Foam model



PIC simulations of **laser-driven ion acceleration**

Multi-stage simulations to study secondary neutron generation from laser-driven ions

Foam model

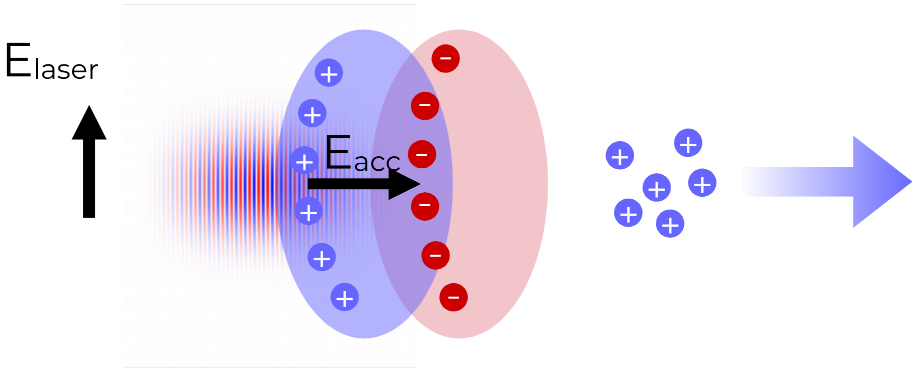


PIC simulations of **laser-driven ion acceleration**

Monte Carlo simulations of **radiation-matter interaction**

Brief summary

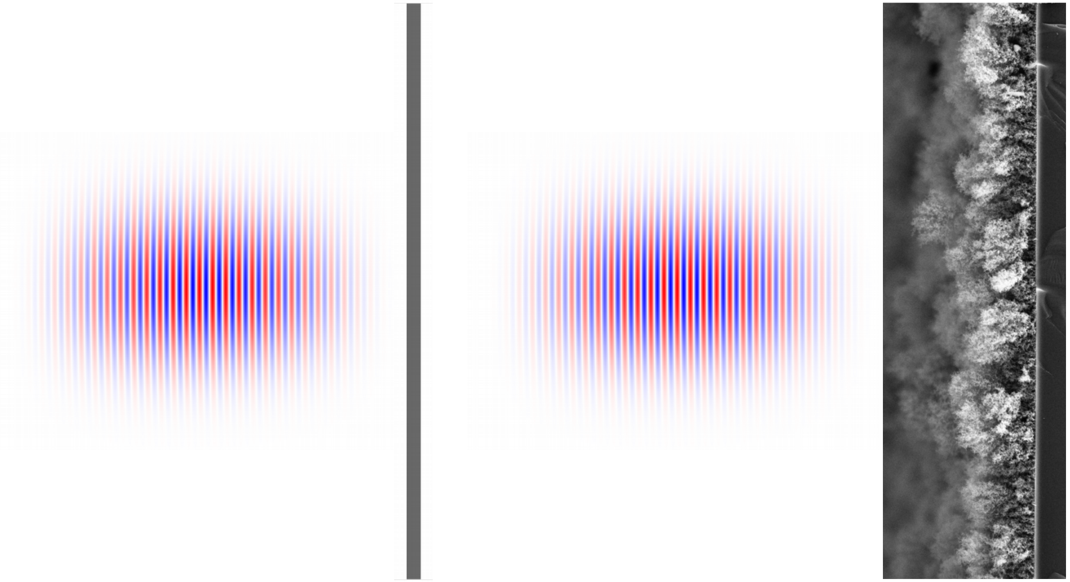
Laser-plasma acceleration



Laser-driven ion acceleration

Conventional

Enhanced

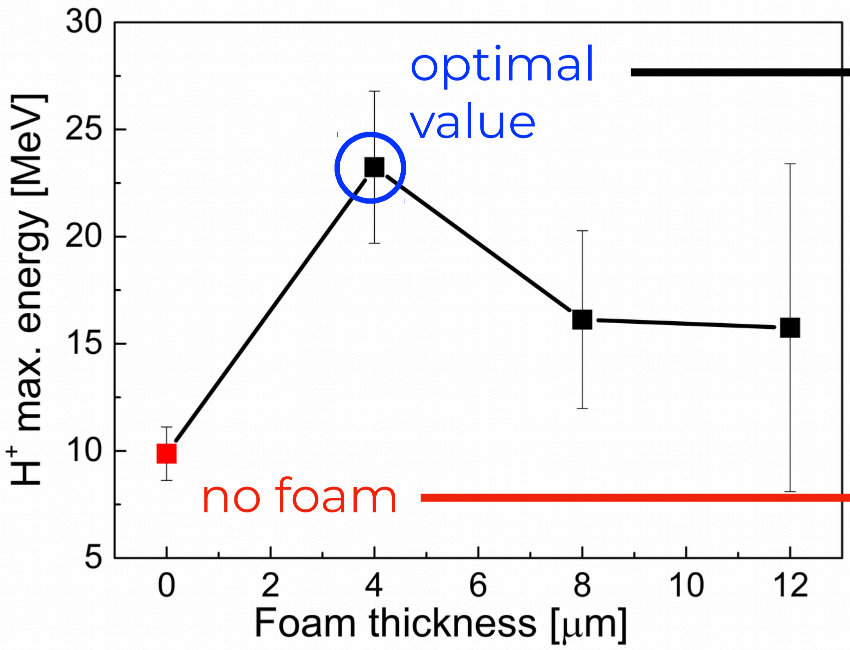


It is important to include a realistic description of the foam nanostructure and morphology

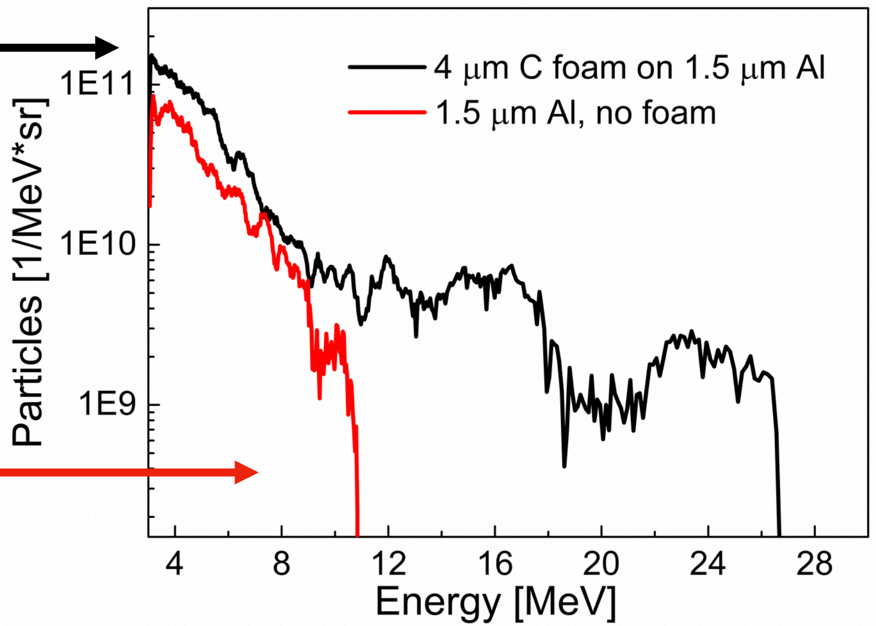
So what about the accelerators? We are working on it and we can say that foams are pretty cool…

@ HZDR

maximum proton energy vs. foam thickness



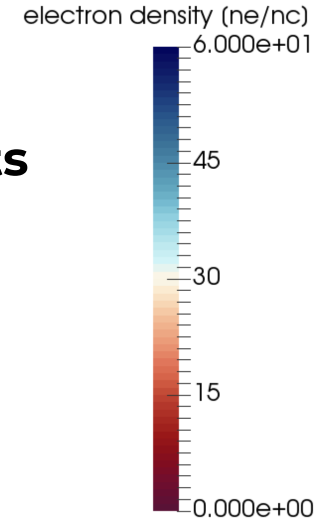
proton energy spectra

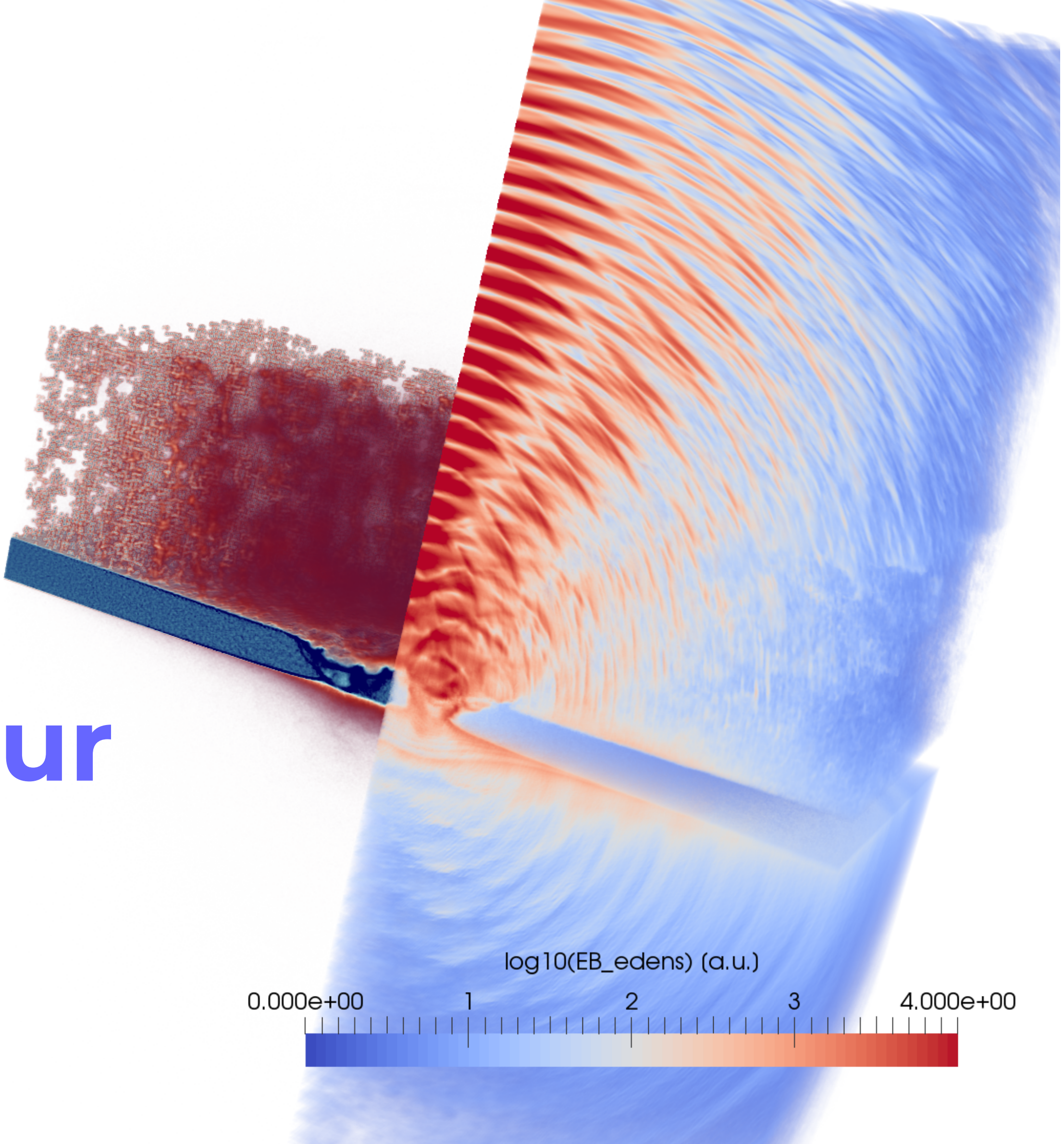


Acknowledgments

ERC-2014-CoG No. 647554

ENSURE





Thanks for your attention!