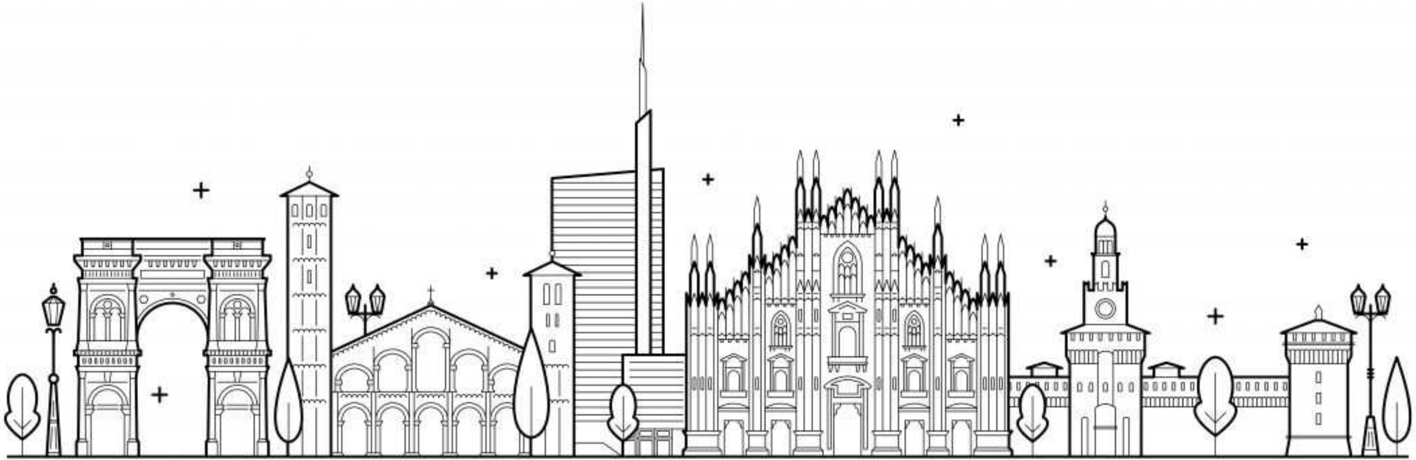
POLITECNICO
MILANO 1863

Interaction between superintense laser fields and nanostructured plasmas

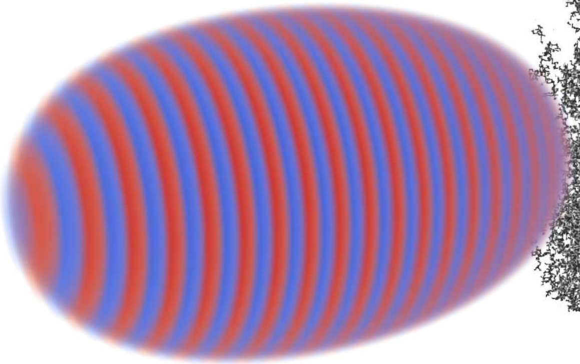
Arianna Formenti

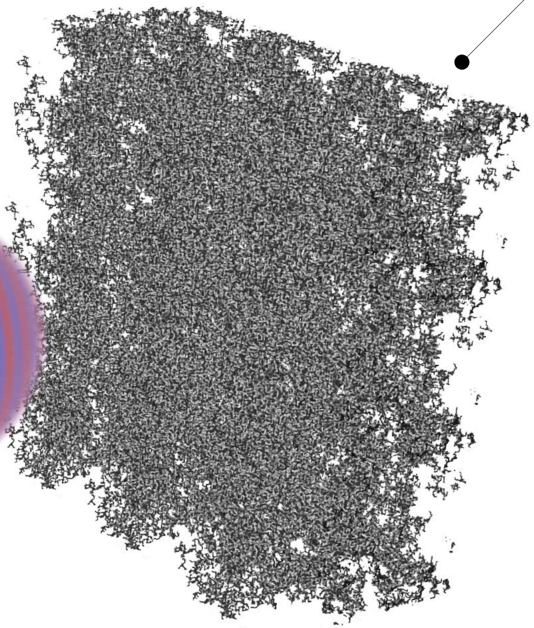
HFLPI Workshop – Milan – July 13rd 2019



Interaction between superintense laser fields and nanostructured plasmas

$$I \geq 10^{18} \frac{\mathrm{W}}{\mathrm{cm}^2}$$

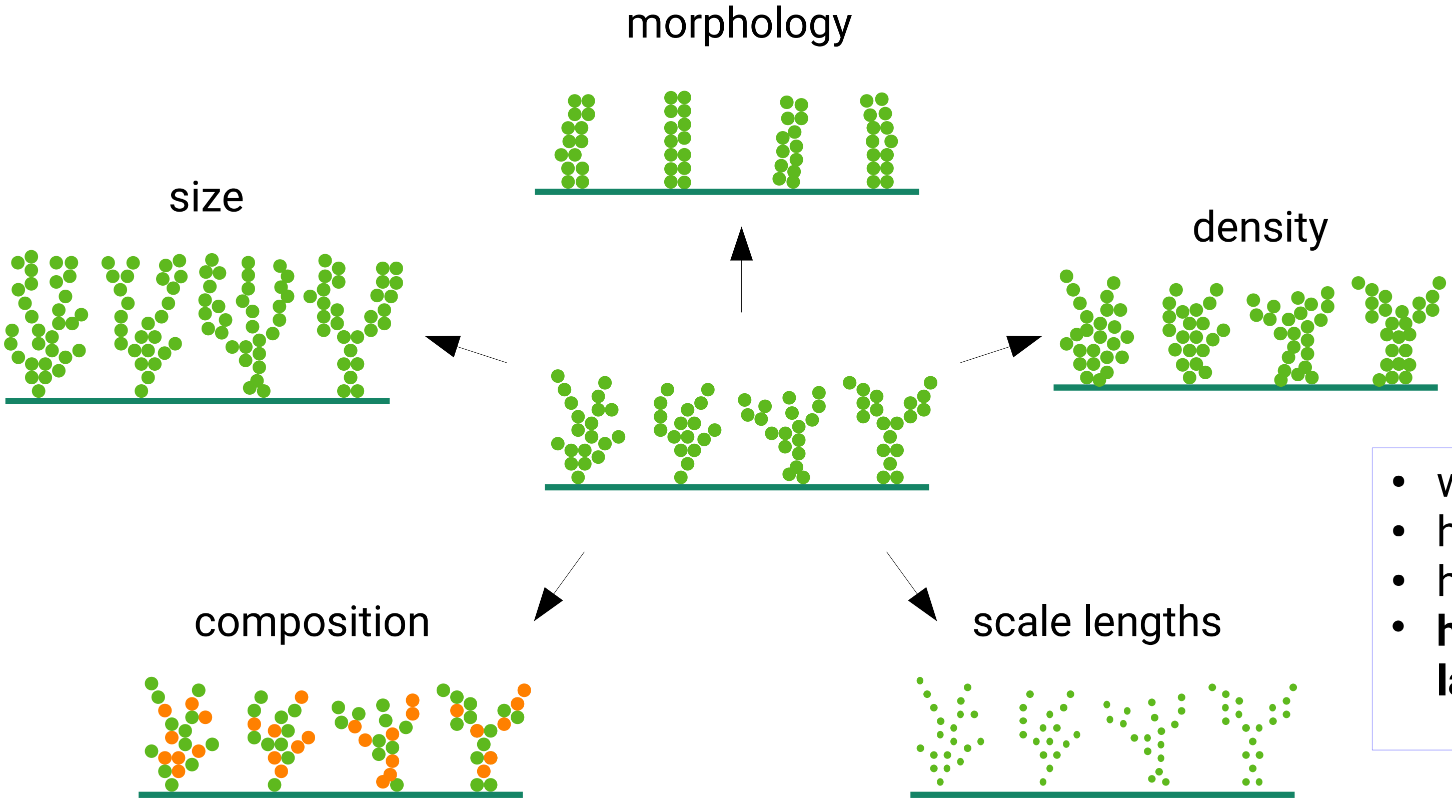




density profile with **characteristic lengths** on **nm – sub-µm scale,** i.e. ~ skin depth - wavelength

why a nanostructure in the first place?

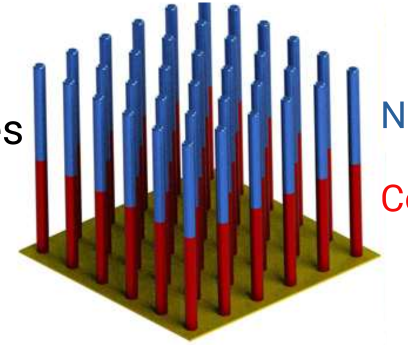
Nanostructured materials give access to a large parameters space



- wide range of regimes available
- high surface-to-volume ratio
- high degree of porosity
- **high conversion efficiency of laser energy into plasma energy!**

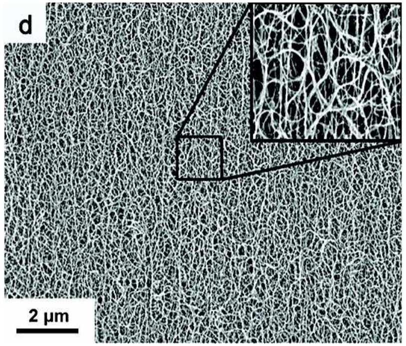
A huge variety of nanostructured materials is interesting for superintense laser-plasma interaction experiments

nanowires



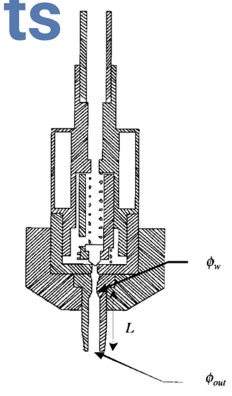
C. Bargsten et al. Sci. Adv. 3.1 (2017)

carbon nanotubes

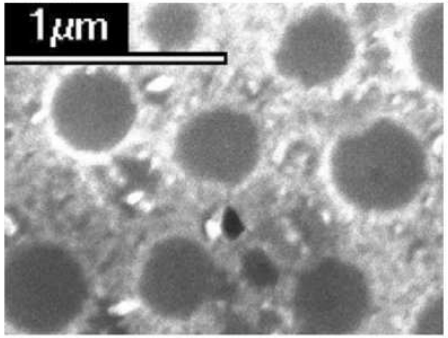


W. Ma et al. Nano Lett. 7.8 (2007)

cluster gas jets

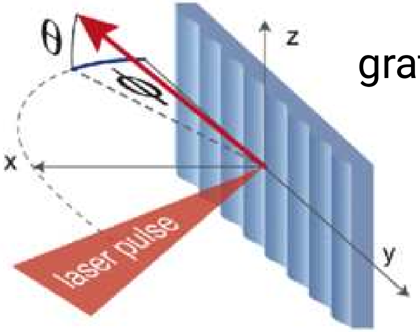


F. Dorchies et al. Phys. Rev. A 68.2 (2003)



gold foam

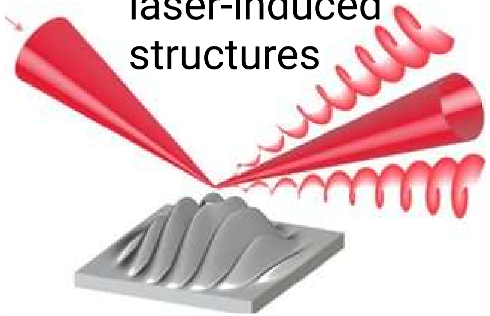
K. Nagai et al. Fusion Sci. Technol. 49.4 (2006)



gratings

L. Fedeli et al. Phys. Rev. Lett. 116.1 (2016)

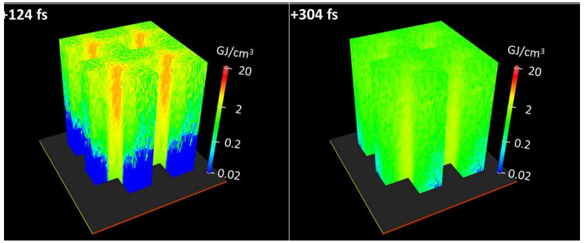
laser-induced structures



A. Leblanc et al. Nat. Phys. 13.5 (2017)

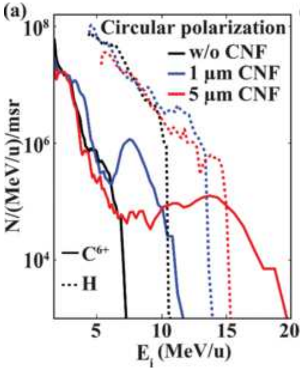
A huge variety of nanostructured materials has been employed in superintense laser-plasma experiments

ultrahigh-energy density matter



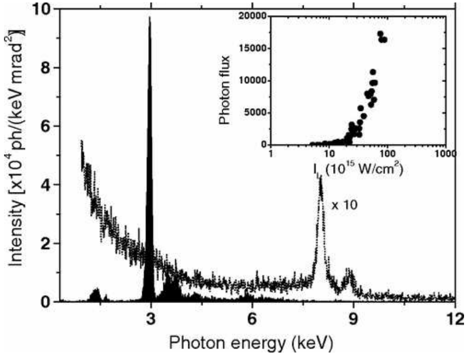
C. Bargsten et al. Sci. Adv. 3.1 (2017)

charged particle acceleration



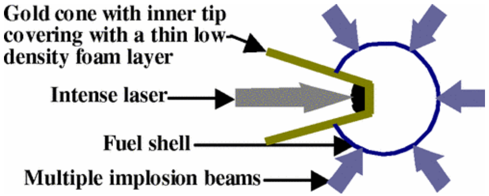
J. H. Bin et al. Phys. Rev. Lett. 115.6 (2015)

photon sources



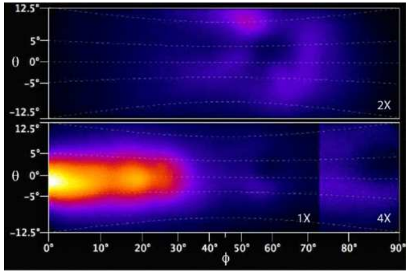
L. M. Chen et al. Phys. Rev. Lett. 104.21 (2010)

fast ignition for inertial confinement fusion



A. L. Lei et al. Phys. Rev. Lett. 96.25 (2006)

high field plasmonic

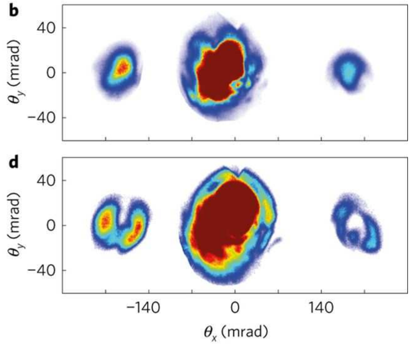


flat target

grating target

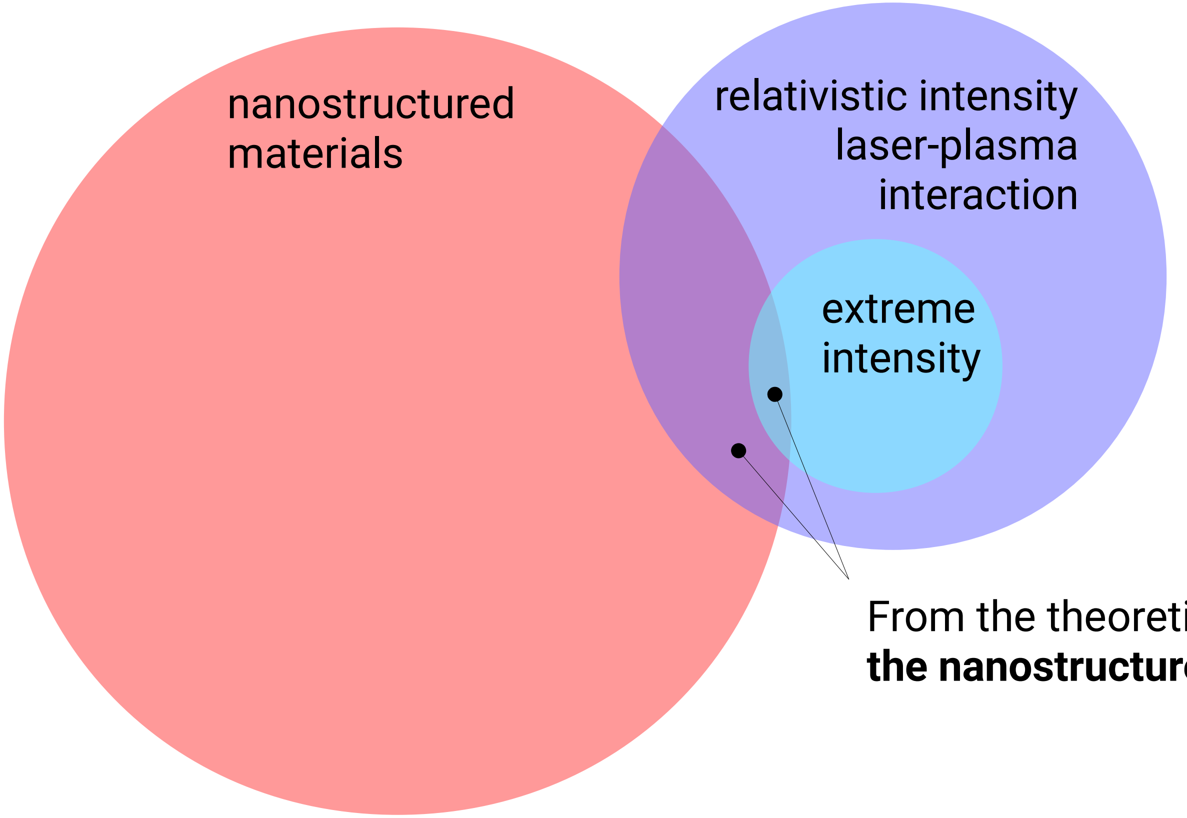
L. Fedeli et al. Phys. Rev. Lett. 116.1 (2016)

plasma optics



A. Leblanc et al. Nat. Phys. 13.5 (2017)

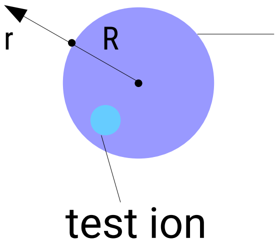
A key issue is to provide accurate modeling of both the laser and the nanostructured plasma in their interaction



From the theoretical standpoint,
the nanostructure is often disregarded!

It is worth trying to include the nanostructure, even if it will soon be destroyed by the intense light

lifetime of the nanostructure: simple estimation



nanoparticle, as the brick of the nanostructure

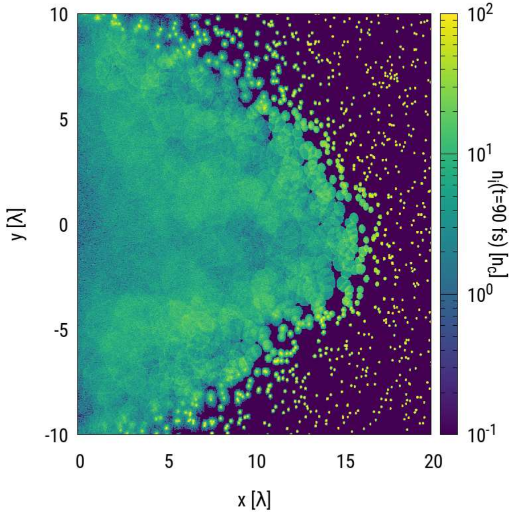
hypothesis: a_0 is high enough that all electrons are ejected from the nanoparticle

characteristic velocity of a test ion

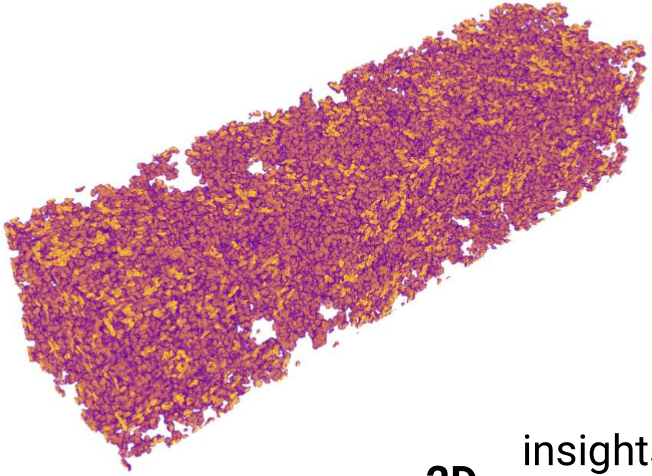
$$\beta = \sqrt{\frac{2}{3}}\frac{\omega_{p,i}R}{c}\sqrt{\frac{r-R}{r}} \sim 10\frac{\mu\text{m}}{\text{ps}}$$

→ nanostructure washed away in ~ 100 fs

ion density @ 90 fs



We have studied laser-nanostructured plasma interaction with PIC simulations to assess the role of the nanostructure itself



WHAT

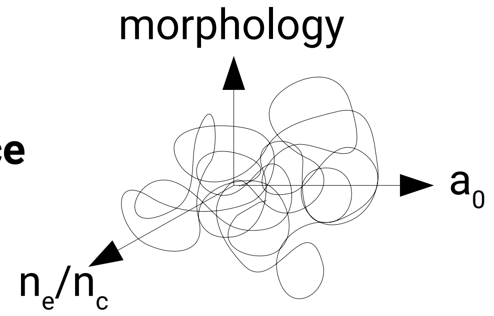
study the role of the nanostructure

2D insights on a wide range of regimes

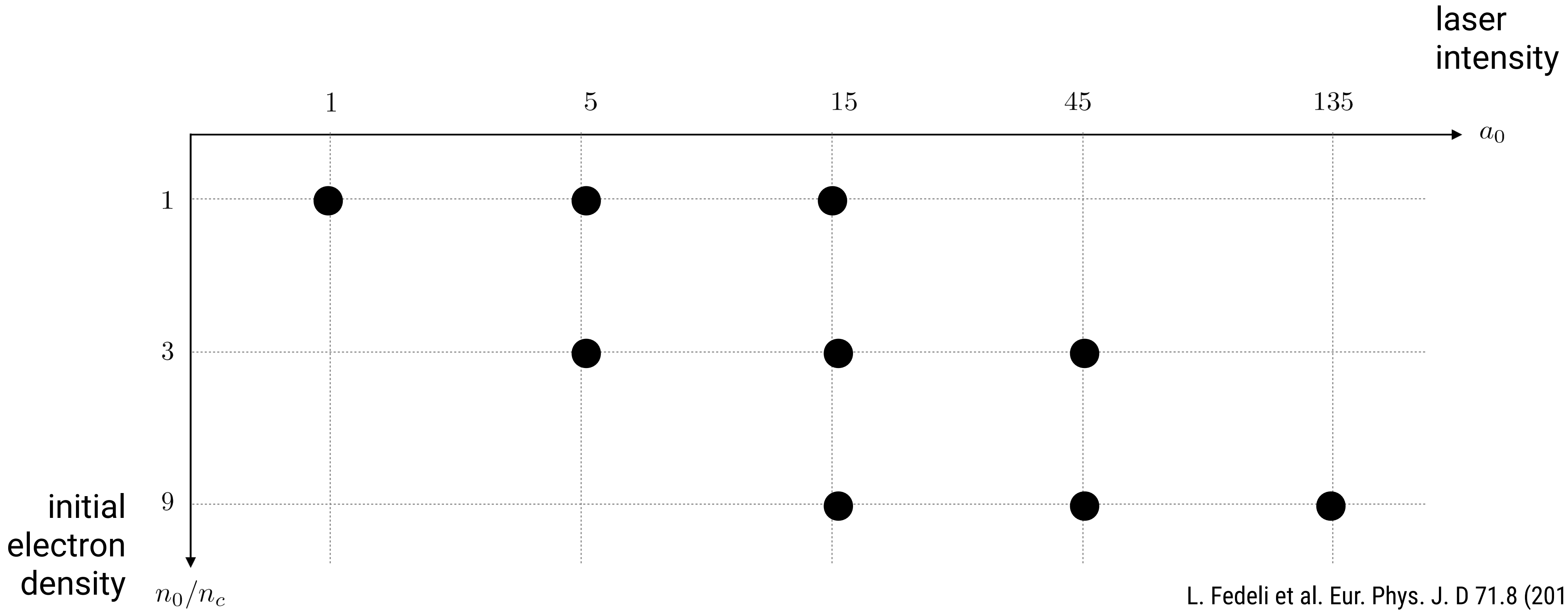
accurate description of the nanostructure **3D**

combined use of 2D and 3D simulations to explore the parameter space

HOW



First, we explored a wide range of laser & plasma parameters with 2D PIC simulations

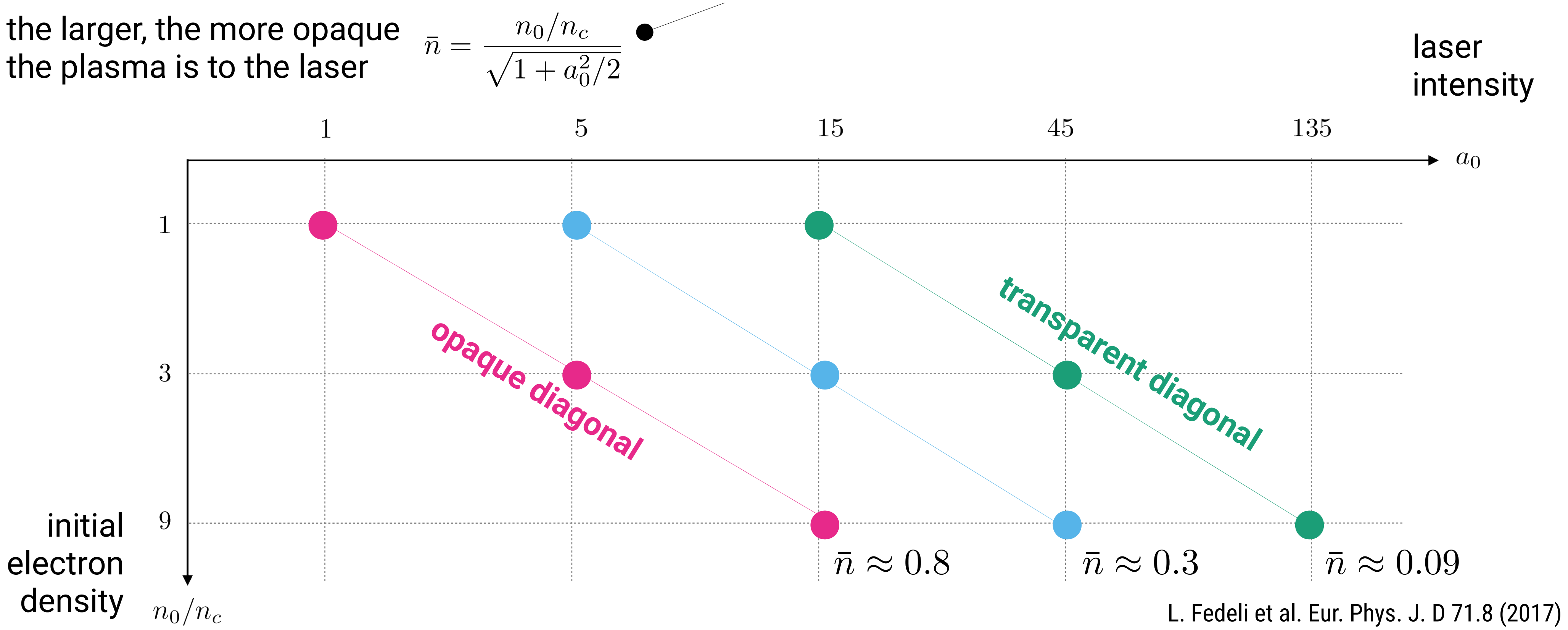


L. Fedeli et al. Eur. Phys. J. D 71.8 (2017)

Each diagonal has a its own value of the "opacity parameter"

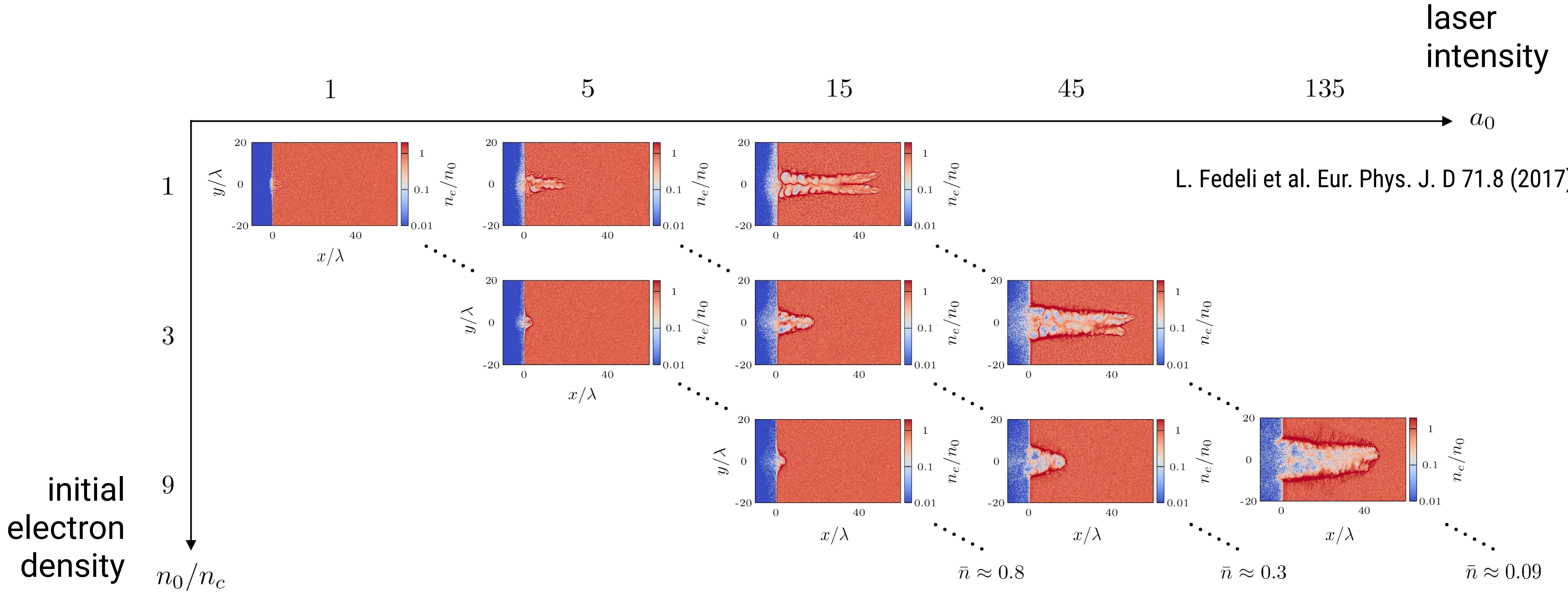
the larger, the more opaque the plasma is to the laser

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



L. Fedeli et al. Eur. Phys. J. D 71.8 (2017)

We simulated semi-infinite homogeneous plasma slabs



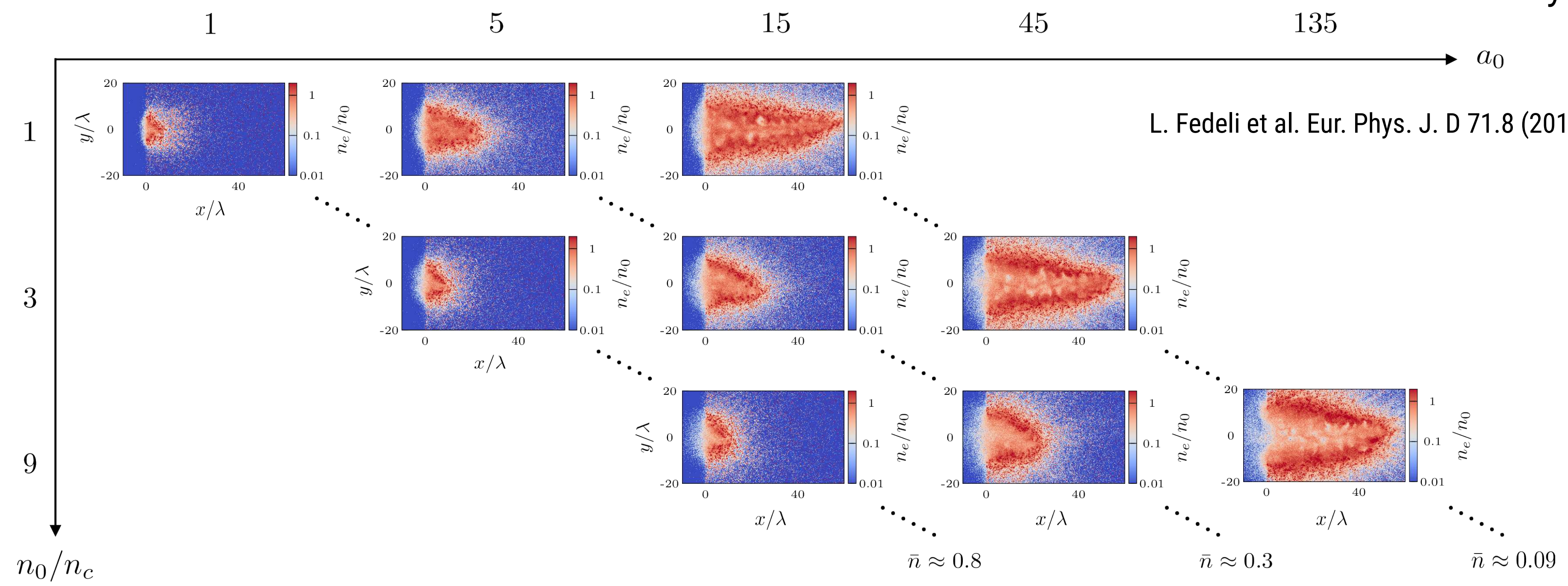
L. Fedeli et al. Eur. Phys. J. D 71.8 (2017)

And also semi-infinite nanostructured plasma slabs

nanospheres
r_s ~ 40 nm
n_e ~ 90 n_c
d_s ~ 13 nm

here the nanostructure is simply a collection of **nanospheres randomly arranged in space**

laser intensity

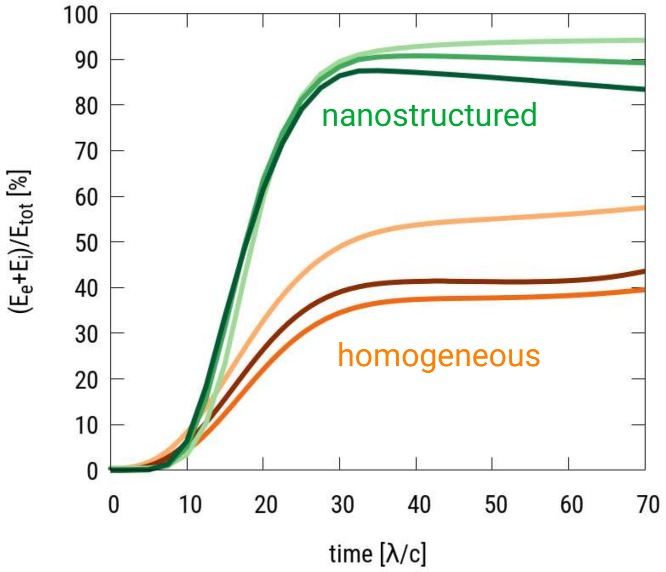


L. Fedeli et al. Eur. Phys. J. D 71.8 (2017)

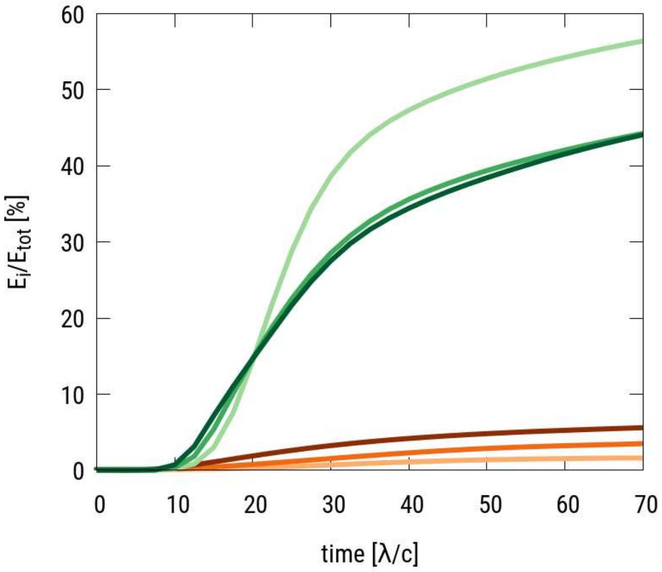
We found out that in the opaque diagonal the nanostructure allows for a much higher laser absorption

1

total absorption



ion absorption



a_0	n_0/n_c
1	1
5	3
15	9

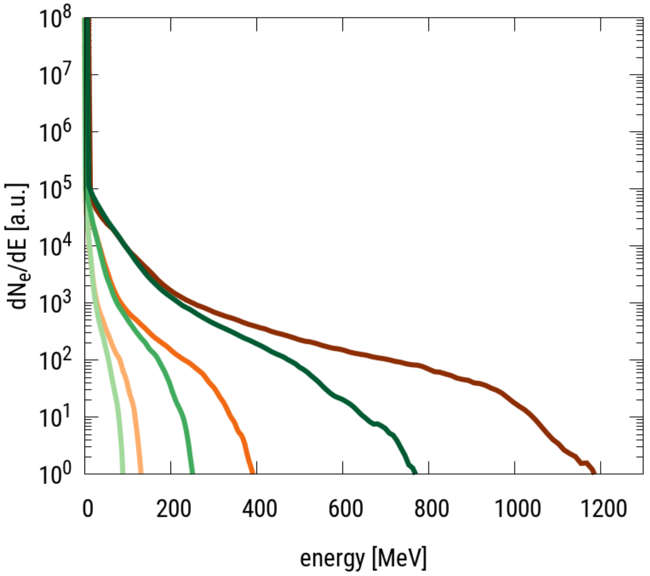
enhanced absorption mostly because ions absorb much more

L. Fedeli et al. Eur. Phys. J. D 71.8 (2017)

We found out that in the transparent diagonal the nanostructure damps the maximum electron energy

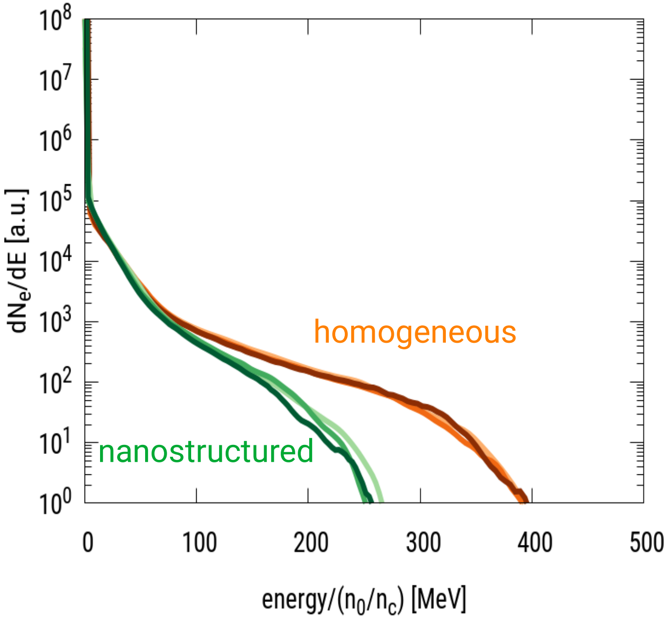
2

electron spectra



re-scale energy axis

re-scaled electron spectra



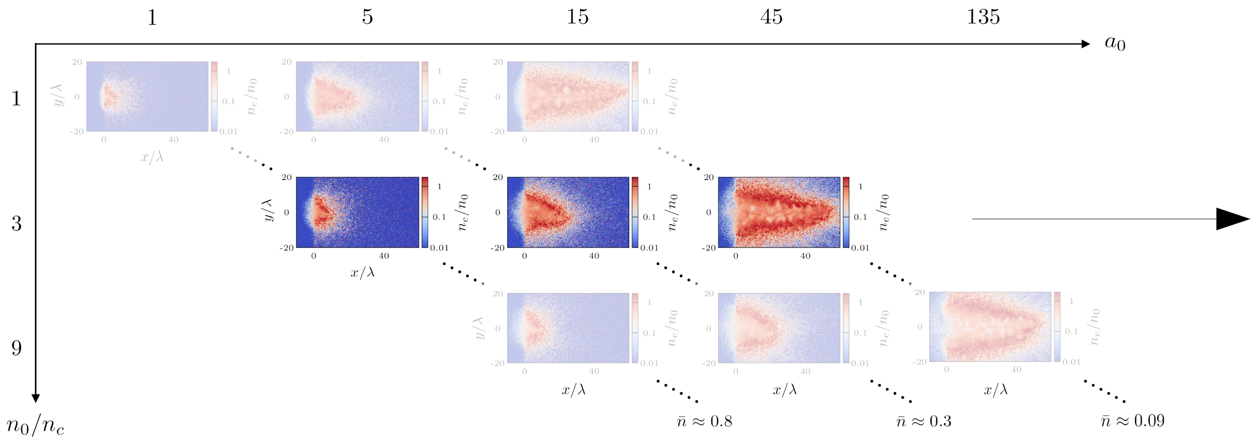
a_0	n_0/n_c
15	1
45	3
135	9

indications of a self-similar behavior even with a nanostructure

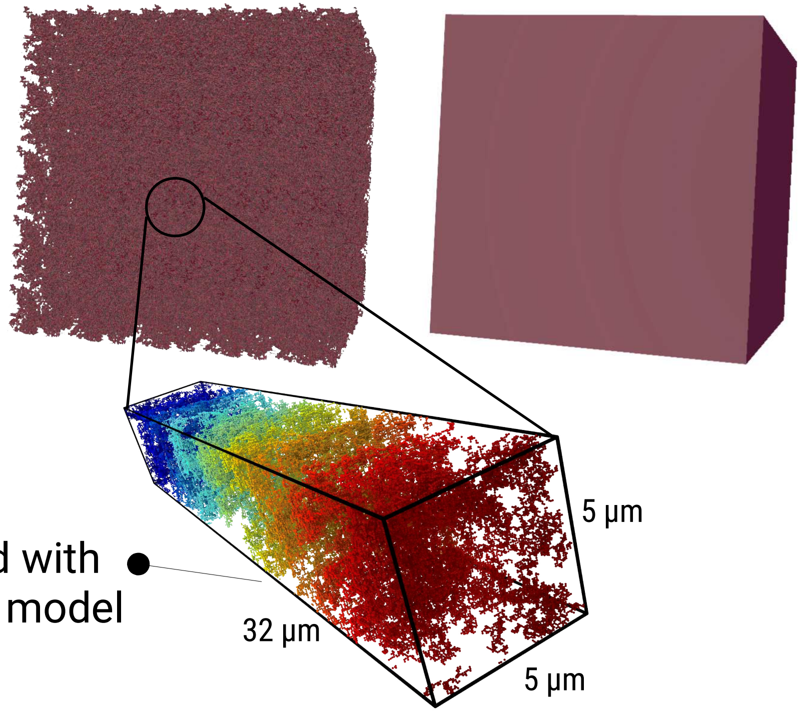
S. Gordienko et al. Phys. Plasmas 12.4 (2005)

Then, we selected the most interesting cases to be simulated with 3D PIC

L. Fedeli et al. Sci. Rep. 8.1 (2018)



nanostructured vs. homogeneous



nanoparticles
$r_s \sim 40$ nm
$n_e \sim 60\ n_c$
$d_s \sim 16$ nm

foam-like structure: obtained with a cluster-cluster aggregation model (see poster for more details)

3D

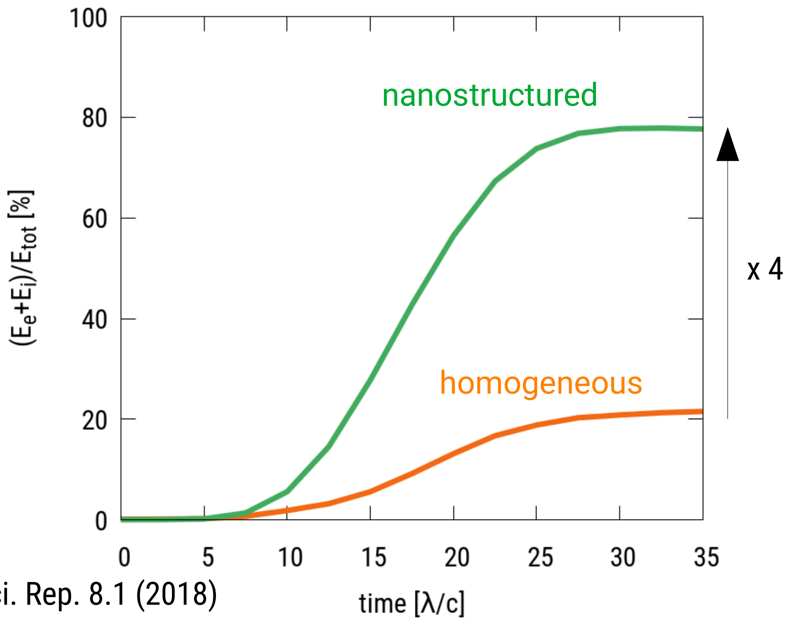
We found out that previous 2D simulations caught well the behavior of the irradiated nanostructure

1 **opaque diagonal**

transparent diagonal 2

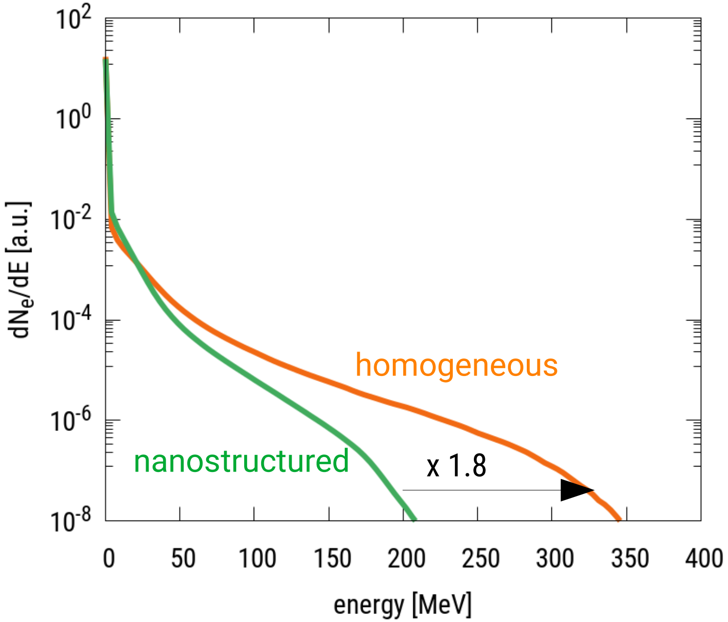
$a_0 = 5$
$n_e = 3$

total absorption



L. Fedeli et al. Sci. Rep. 8.1 (2018)

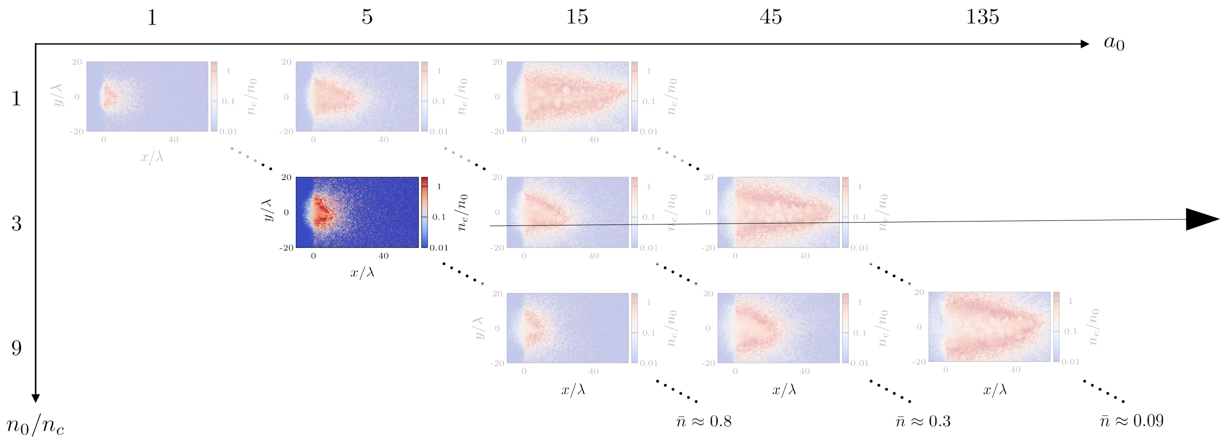
electron spectra



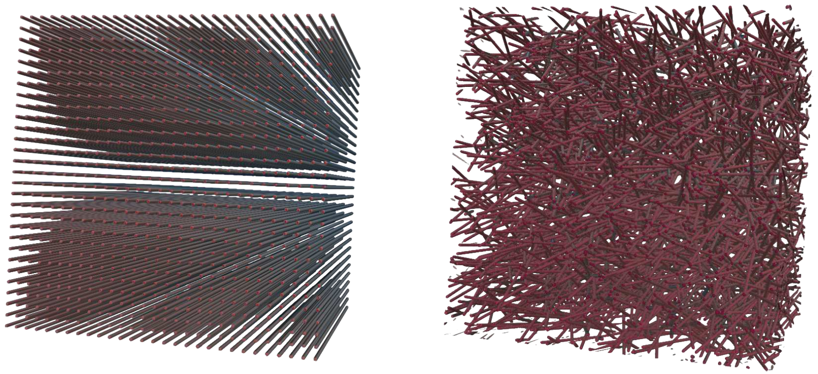
$a_0 = 45$
$n_e = 3$

3D

Then, we selected the most interesting (a_0, n_e) case to be simulated with 3D PIC using several different morphologies



ordered nanowires vs. random nanowires

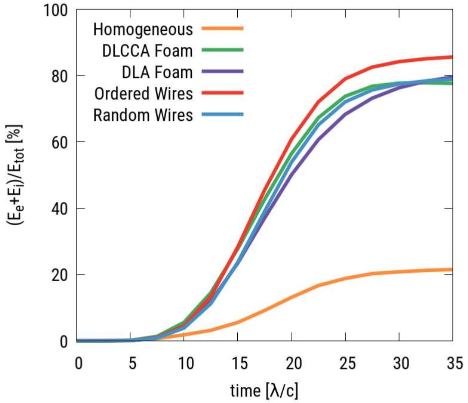


most interesting because it's the closest to the transparency threshold

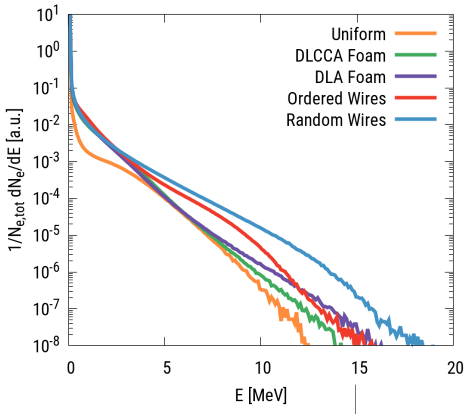
L. Fedeli et al. Sci. Rep. 8.1 (2018)

We found out that the details of the nanostructure can deeply affect the energy and angular distributions

for all nanostructures ~ 80% of laser energy absorption



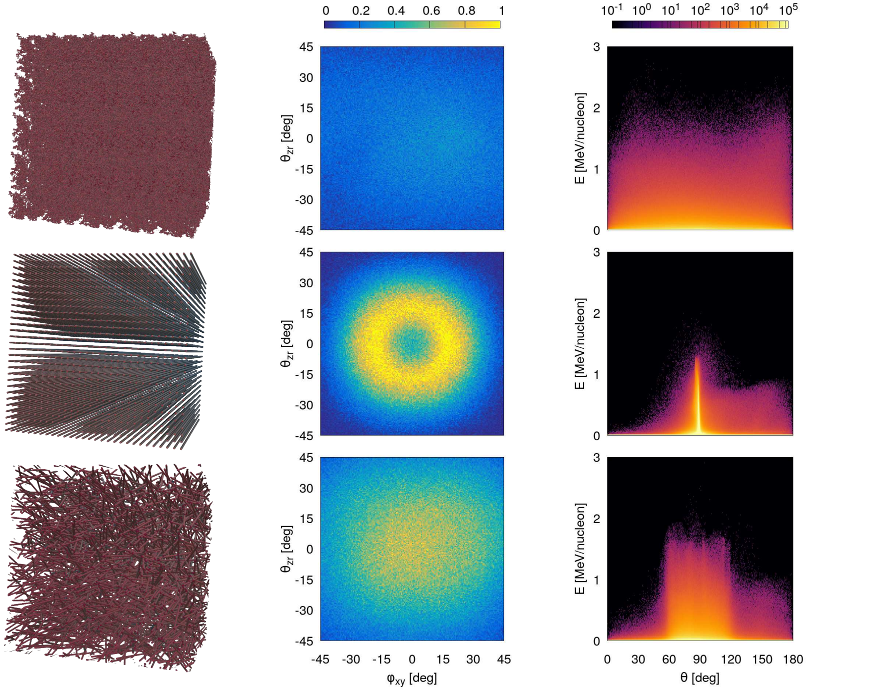
different absolute number of energetic electrons



if we assume the self-similarity, it would be 300 MeV for a_0=100, n_e=60 n_c

electron angular distribution

ion energy-angle distribution



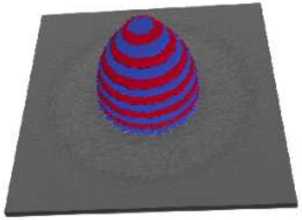
L. Fedeli et al. Sci. Rep. 8.1 (2018)

Lastly, we studied the role of the nanostructure in double-layer targets for enhanced laser-driven ion acceleration

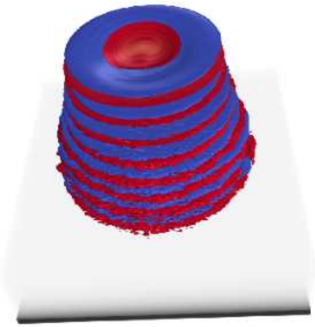
solid foil coated with a near-critical layer

ion spectra

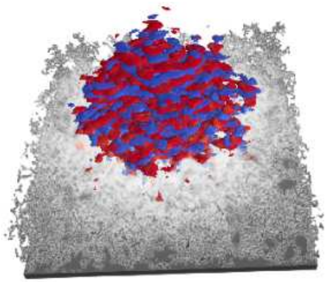
bare solid foil



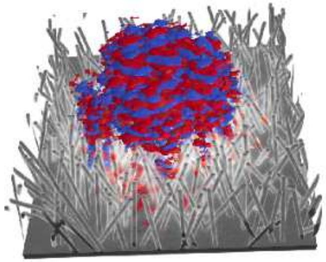
homogeneous

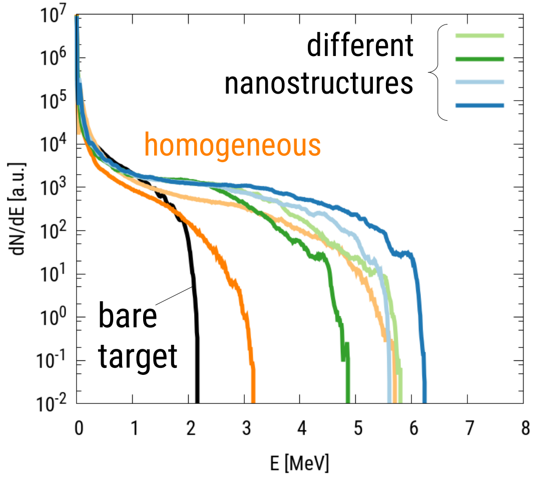


foam-like



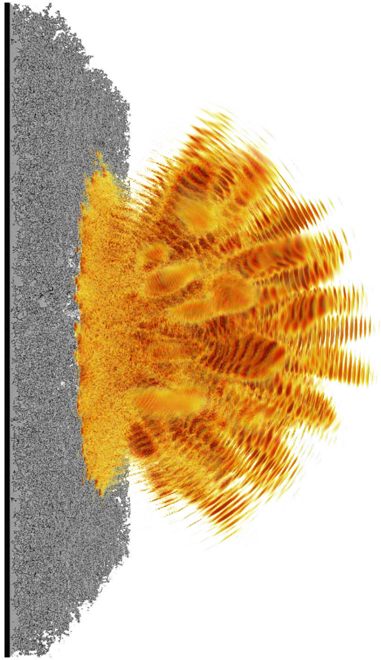
random nanowires





nanostructures and homogeneous near-critical layers do not necessarily work the same way

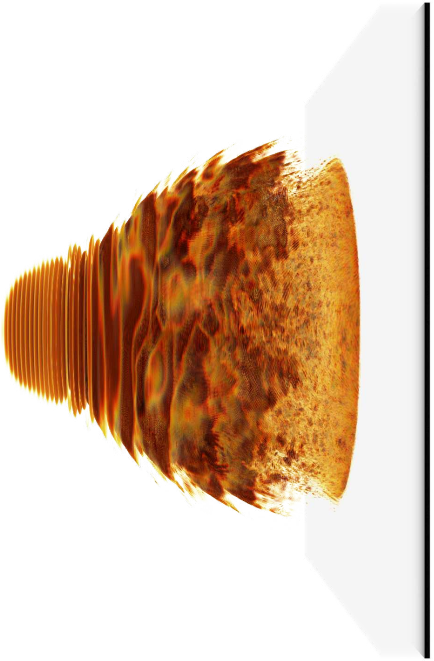
more details in poster



Conclusions

NANOSTRUCTURE MATTERS!

- include it for a complete description
- not including it, leads to “wrong” results depending on the regime of interaction



Perspectives

What happens at extreme intensities?
→ Rafael Caprani, MSc Thesis in collaboration with LULI

How reliable and predictive?
→ compare with experiments

Applications?
→ radiation sources

Analytical modeling?
→ To be developed

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L. Cialfi

Acknowledgments

NanoLab

erc

ERC-2014-CoG No. 647554

ENSURE

THANK YOU!