Numerical simulations of nanostructured plasmas

Luca Fedeli

Chalmers University, 05/10/2016

The group at Politecnico di Milano

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Matteo Passoni
Associate professor

erc **ENSURE**

Numerical team

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Associate professor

The group at Politecnico di Milano

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Research interests

Laser-driven **ion acceleration**

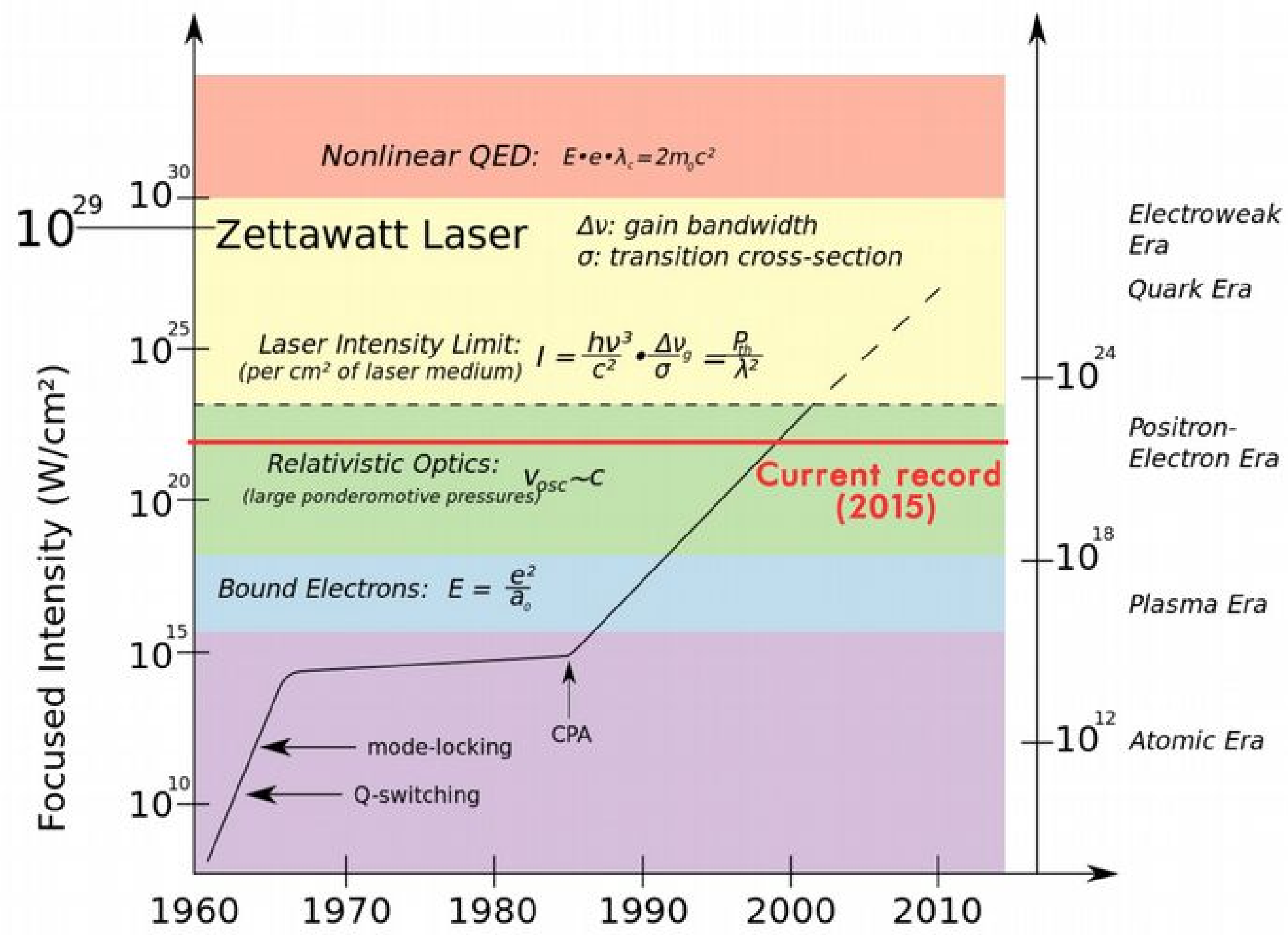
Applications of laser-driven ions in **material science**

Secondary sources (e.g. laser-driven **neutron sources**)

Advanced targets for laser-plasma experiments (near-critical foams)

Nanostructured plasmas

Ultra-intense, ultra-short, ultra-high contrast lasers



Ultra-short (10s fs), **ultra-intense** (up to ~10^{22} W/cm^2) laser systems

Ti:sapphire-based: **λ~800 nm**

Very high temporal contrast, even **10^{10} @ps** timescale

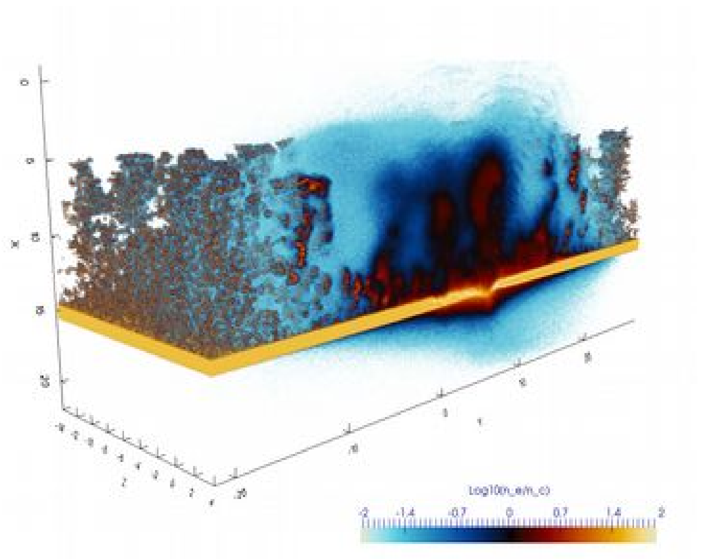
Nanostructured plasmas

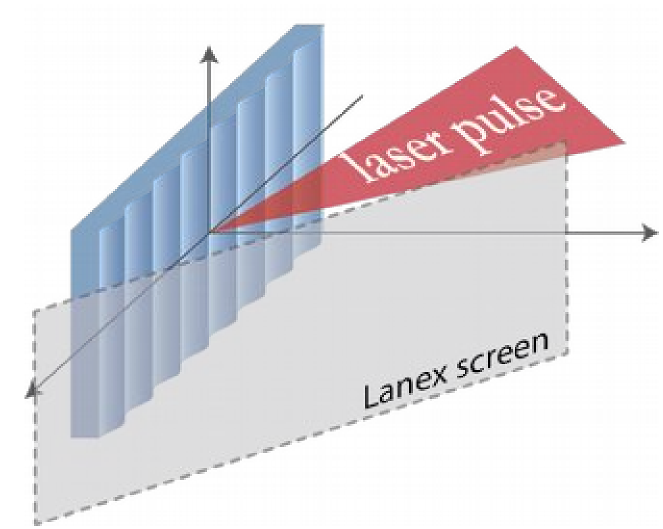
Nanostructured plasmas

If we irradiate a solid, nanostructured, target with these lasers, **the structures might survive**

In some cases this is **incidental**

In other cases it is **desirable**





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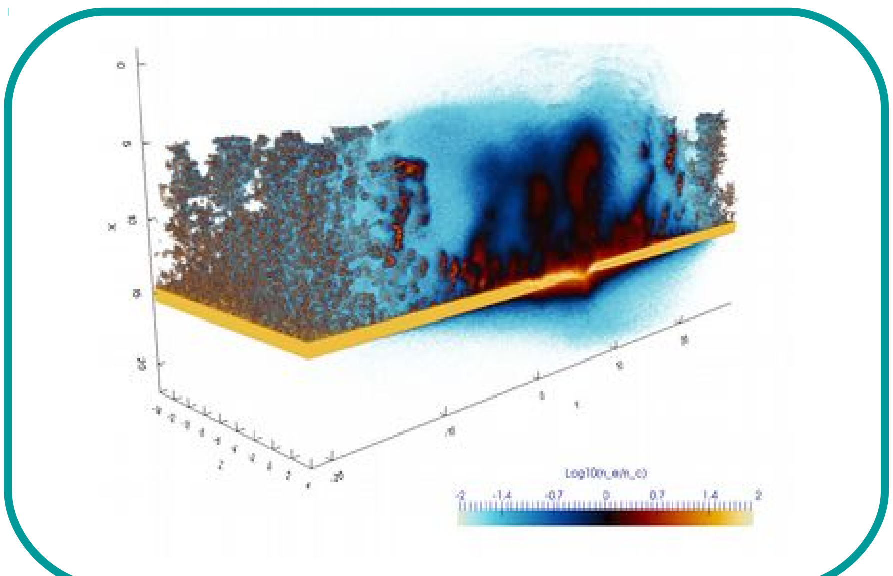
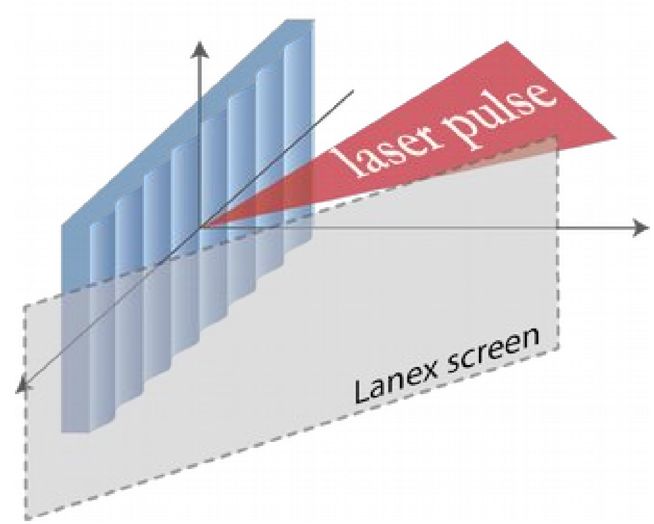




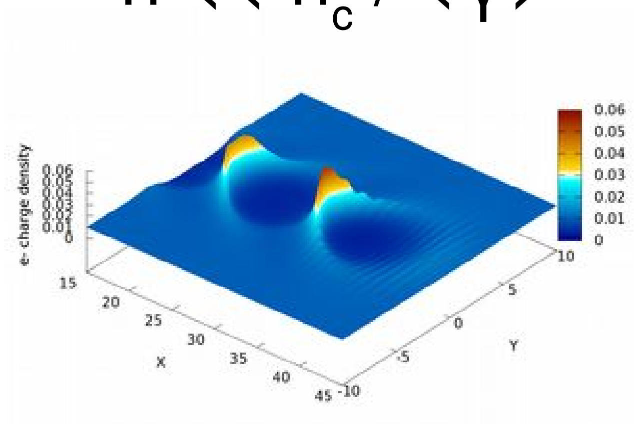
Nanostructured near-critical density plasmas

Why bother with low density porous materials?

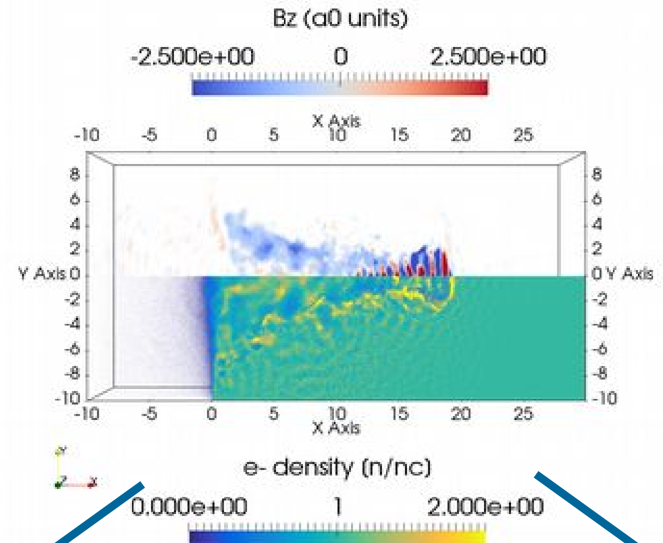
Essentially because we care about laser-interaction with **near-critical plasmas**

Near-critical plasmas

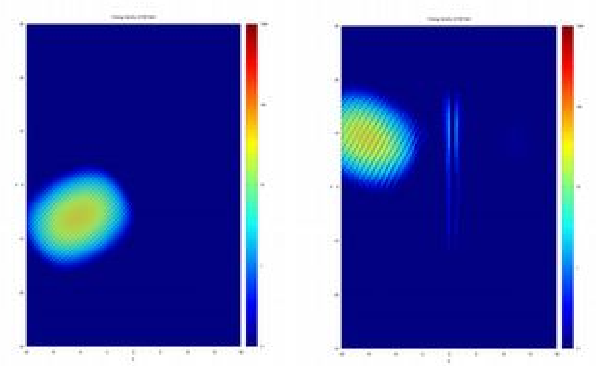
$n \ll n_c / \langle \gamma \rangle$



$n \sim n_c / \langle \gamma \rangle$



$n \gg n_c / \langle \gamma \rangle$



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

$$\langle \gamma \rangle = \sqrt{1 + a_0^2/2}$$

$$a_0 = \frac{e E_0}{m_e \omega c}$$

Near-critical plasmas

Collisionless shocks

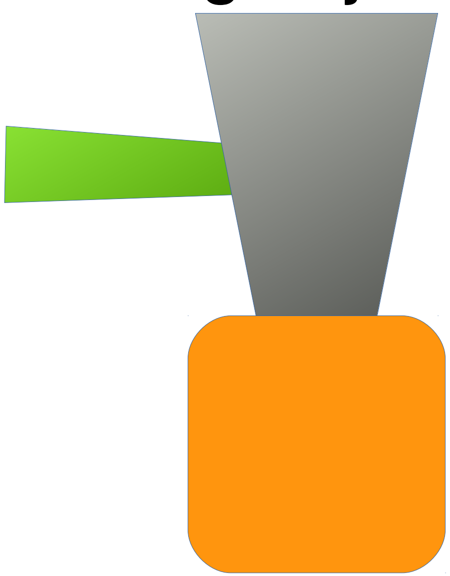
Synchrotron emission

Laser-driven ion acceleration

Near-critical plasmas

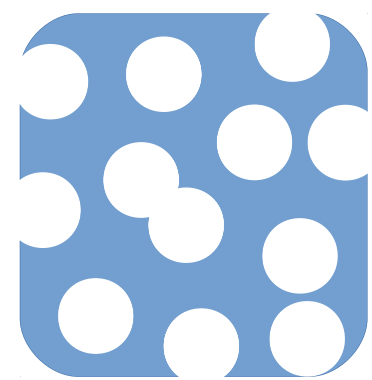
We don't really have many strategies
to explore that density range
1 n_c means few mg/cm^3 !

High-density gas-jets



Pre-heating

Low-density porous materials



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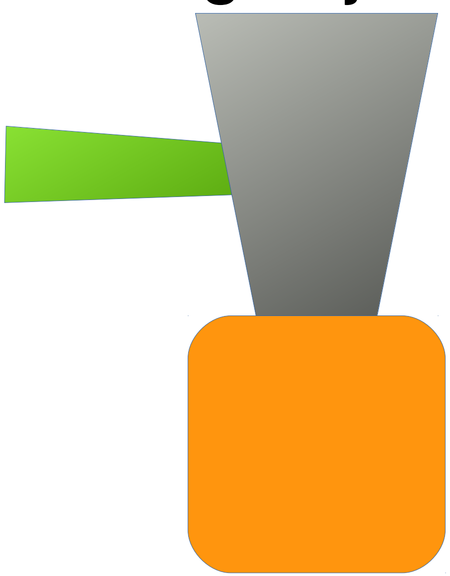

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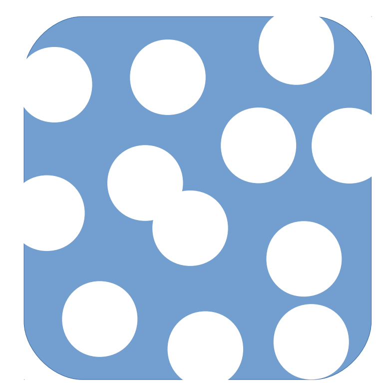
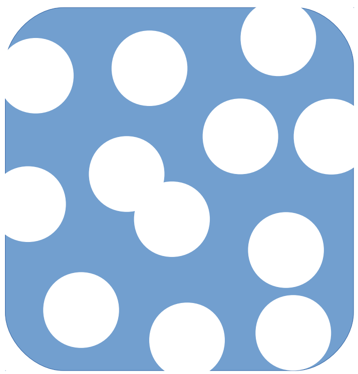
Low-density porous materials

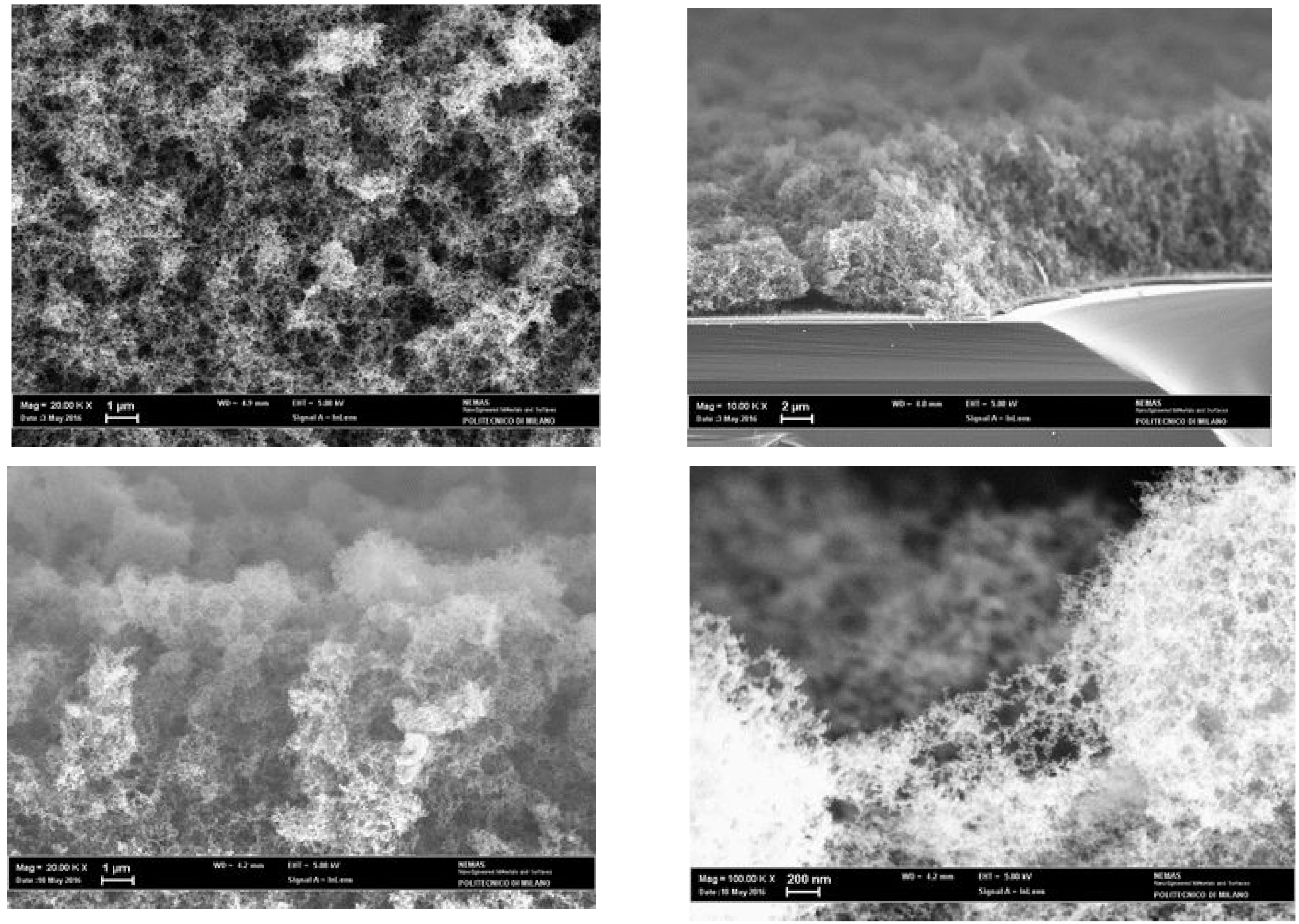


Near-critical plasmas



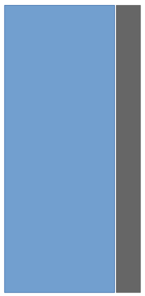
Low-density carbon foam

Tunable density, down to ~ $1n_c$ (fully ionized)



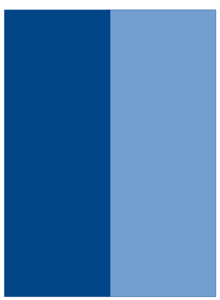
Zani et al. Carbon 56 (2013)

Near-critical plasmas



Can be attached onto a solid foil

Proven.
Thickness range: ~4-60 μm



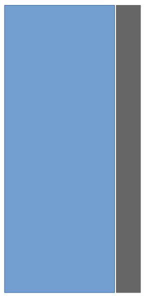
Abrubt density change (but still low density)

Proven.
But, better control is needed

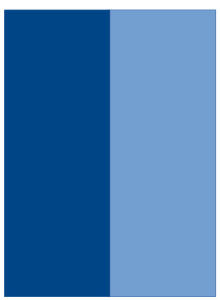
Density gradient

Proven.
But,challenging to control

Near-critical plasmas



Can be attached onto a solid foil



Abrubt density change (but still low density)

Density gradient

→ A lot of “freedom” in target design

(e.g. density taylored for Magnetic Vortex acceleration, Collisionless Shocks generation...)

Experiments with foam-attached targets

I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

Experiments with foam-attached targets

In 2014/2015 we perfomed experiments with foam-attached targets

Gwangju PW-class laser facility

Aim: enhancing laser-driven ion acceleration with better laser-target coupling

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I.Prencipe et al., PPCF 58 (2016)
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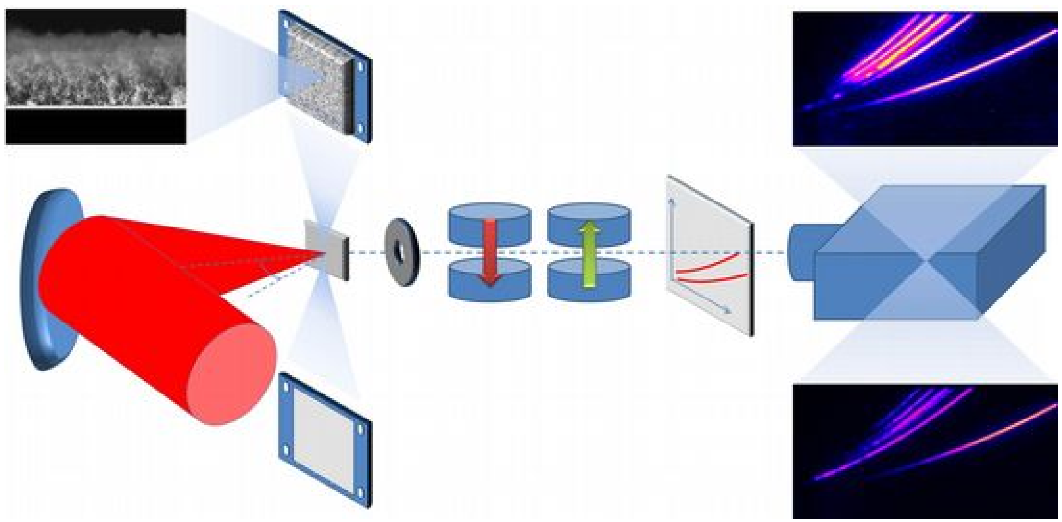
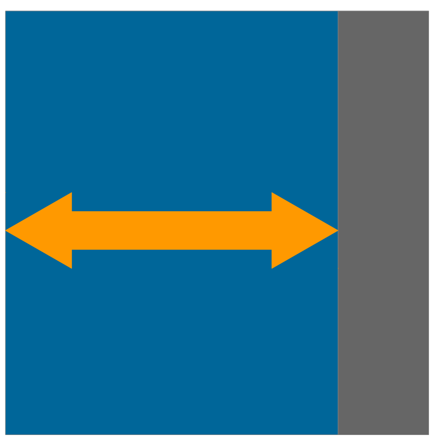
Experiments with foam-attached targets



Up to 5×10^{20} W/cm^2
30 fs, 30° pulse incidence
C-,P-,S- polarization

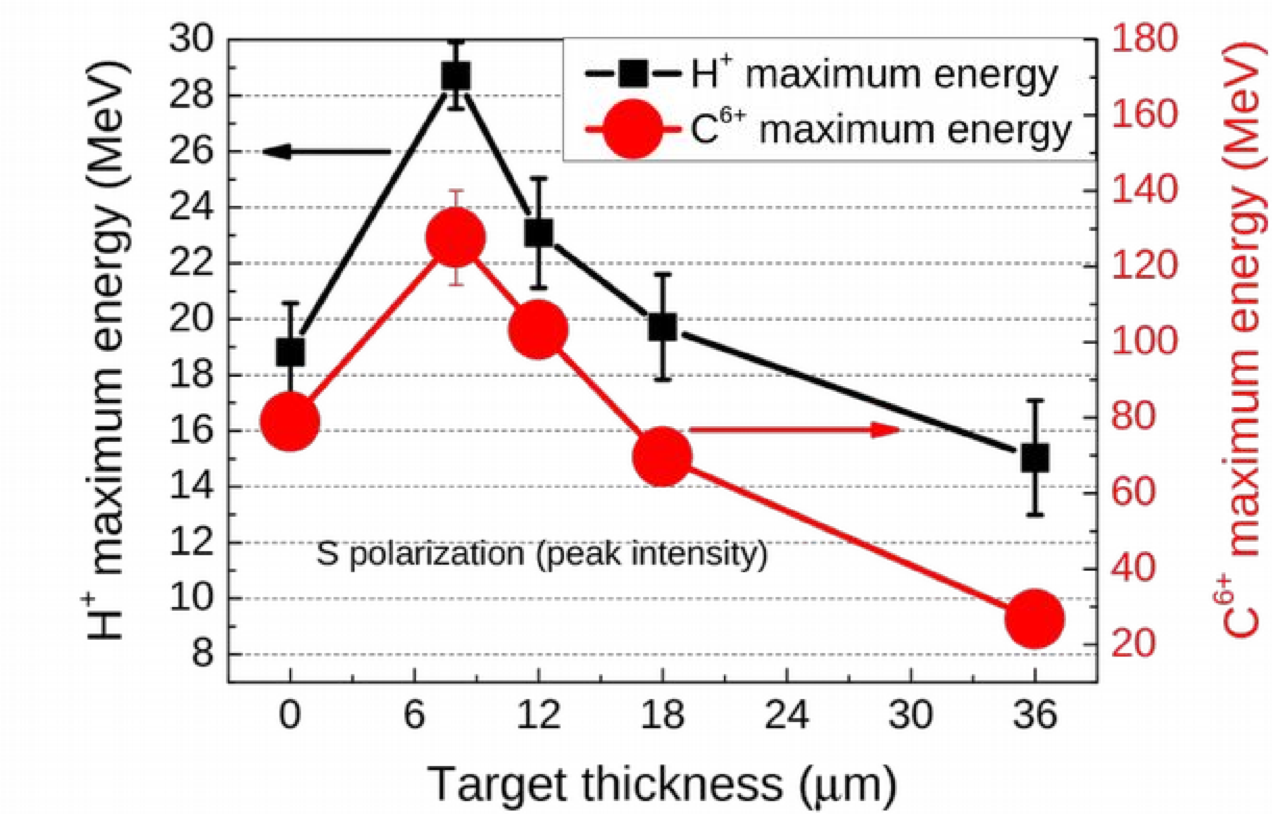
Thomson Parabole to look at ion spectra



Targets made of **0.75 µm Al** + **0-36 µm Carb. foam (~ 1 n_c)**

I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

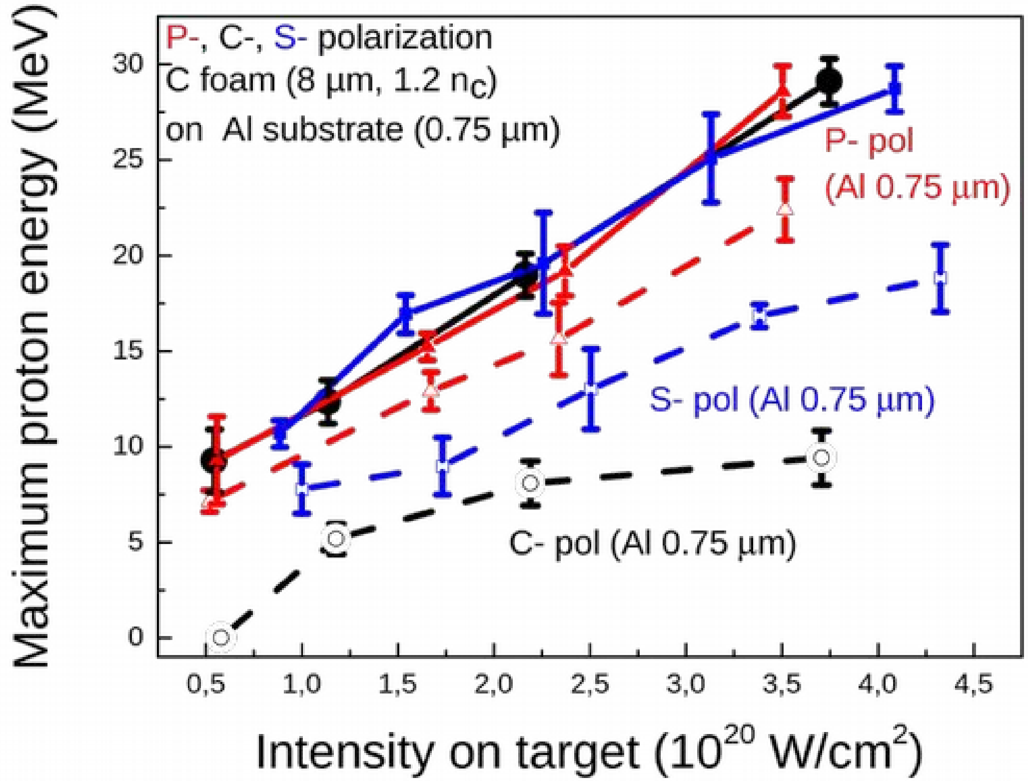
Experiments with foam-attached targets



Optimal foam thickness

I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

Experiments with foam-attached targets



With foam no effects of pulse polarization

I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

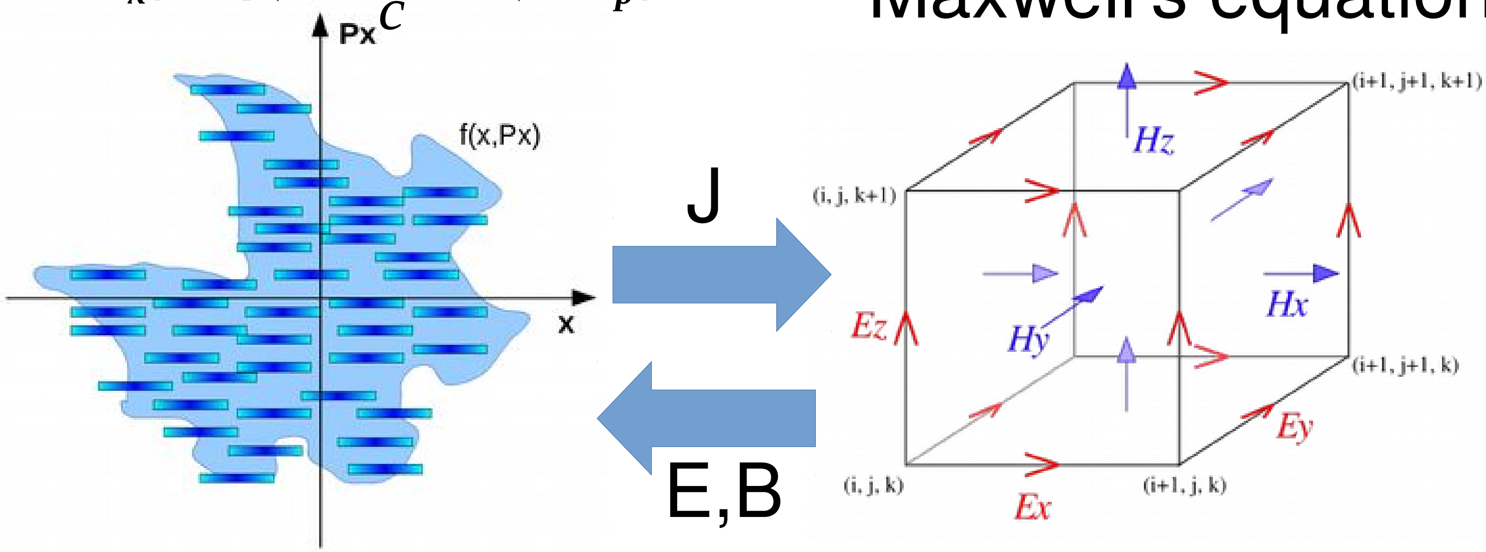
How do we simulate these plasmas?

How do we simulate these plasmas?

Particle-In-Cell codes

$$\partial_t f + \boldsymbol{v} \cdot \nabla_x f + q\left(\vec{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right) \cdot \nabla_p f = 0$$

Maxwell's equations



$$f(\boldsymbol{x}, \boldsymbol{p}, t) \approx \sum_i S(\boldsymbol{x} - \boldsymbol{x}_i(t))\, \delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

We need to simulate these **complex structures** in Particle-In-Cell (**PIC**) codes

How do we simulate these plasmas?

We've used and we'll use foam-attached targets in forthcoming experiments

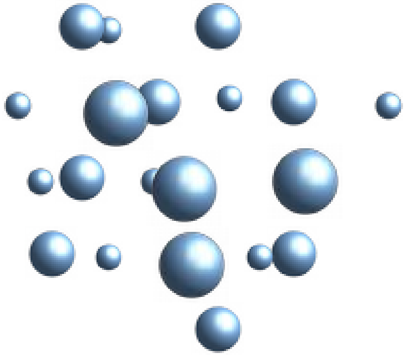
We need **numerical support**

How do we model these structures?

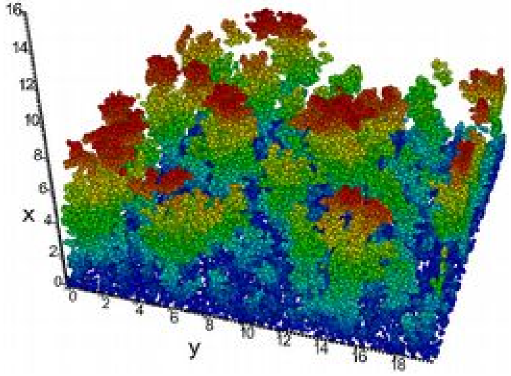
Models

Uniform plasmas

Idealized model

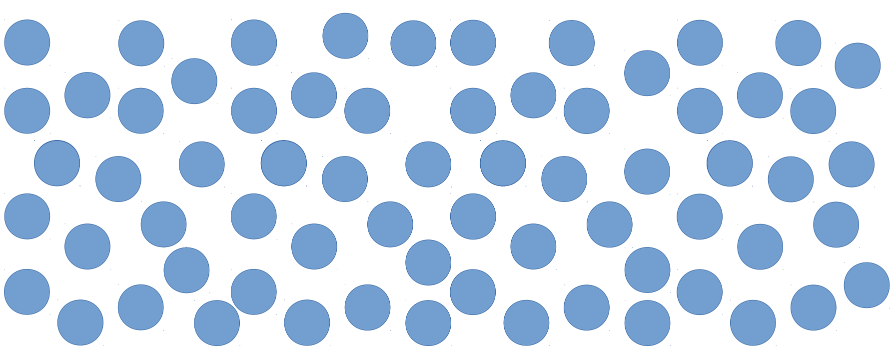


More realistic model



Simplified models

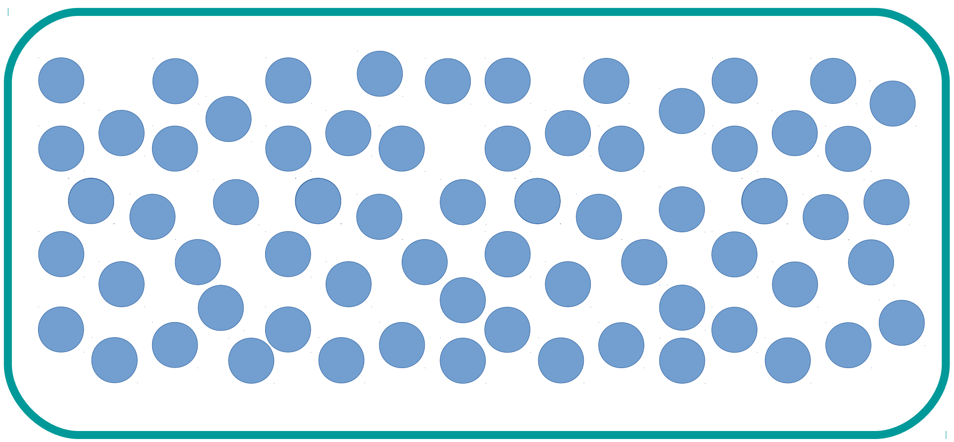
Instead of using a **uniform plasma** (as typically done in the literature)



We can try to use a **“random balls”** model

A.Sgattoni et al. PRE 85 (2012) S.Okihara et al. PRE 69 (2004)

Simplified models

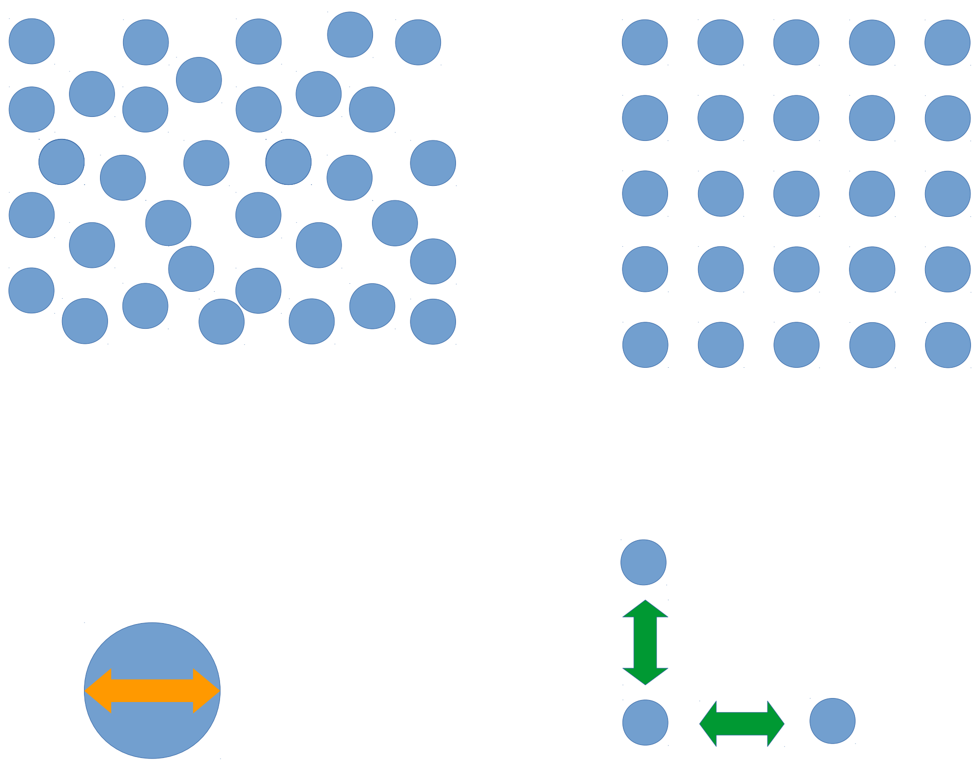


Very **crude model**

No μm-scale structure

Spheres are not connected

Simplified models

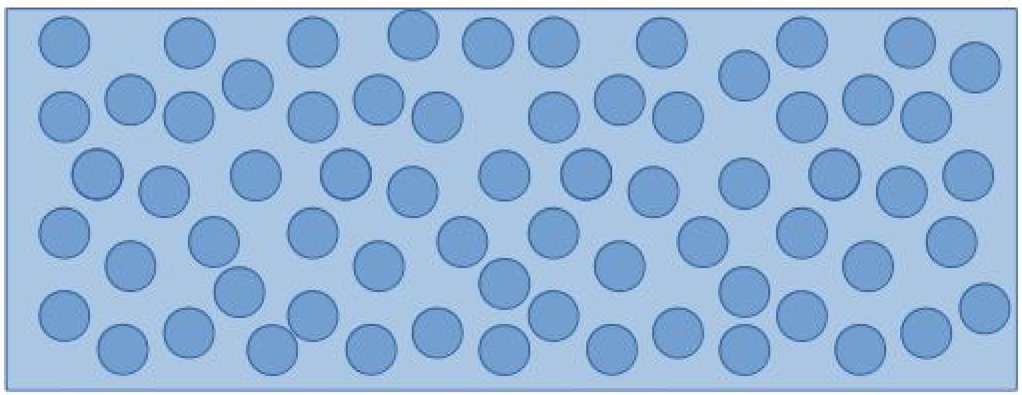


Few parameters to play with

Ordered vs Disordered

Radius and average distance

Simplified models

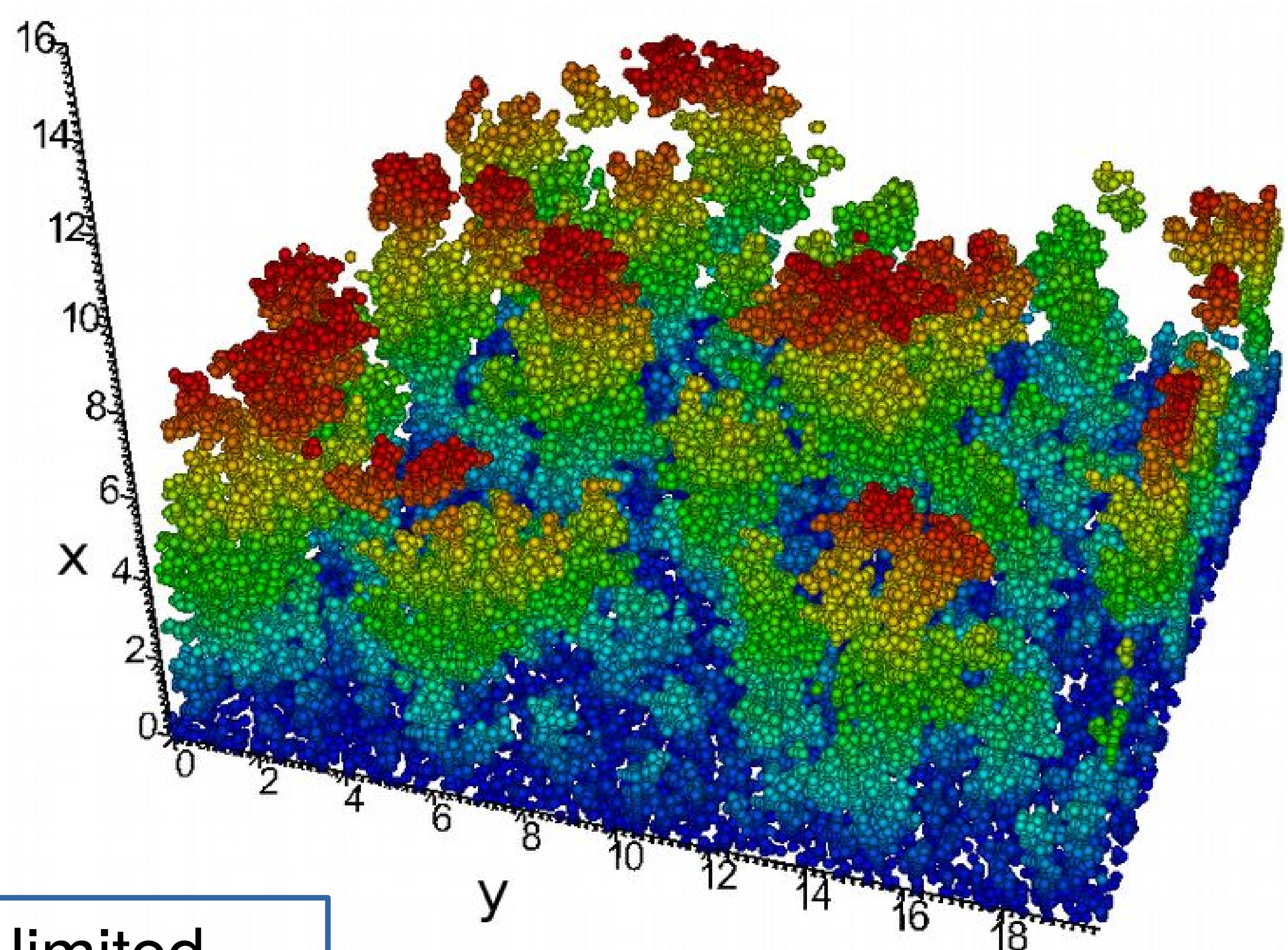


We can even mix a uniform plasma with a random balls plasma

Might simulate partial pre-heating

More realistic models

More realistic models



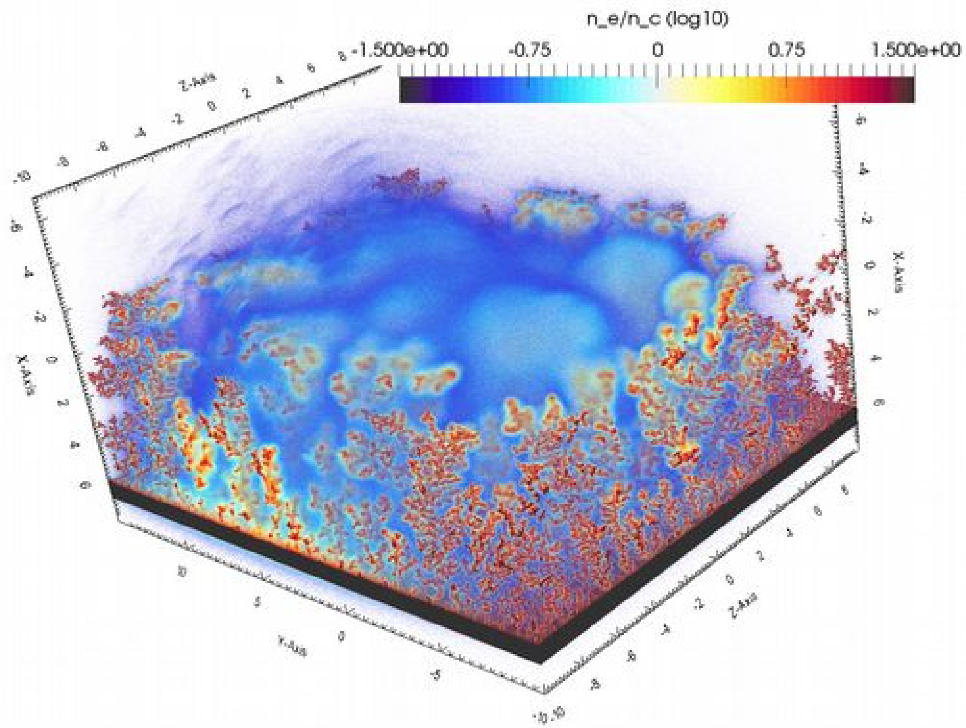
Diffusion limited aggregation model

T.A. Witten & L.M. Sanders PRL 47 (1981)

Experiments with foam-attached targets

Experiments with foam-attached targets

We used a realistic model to support our experimental activity on foam-attached targets



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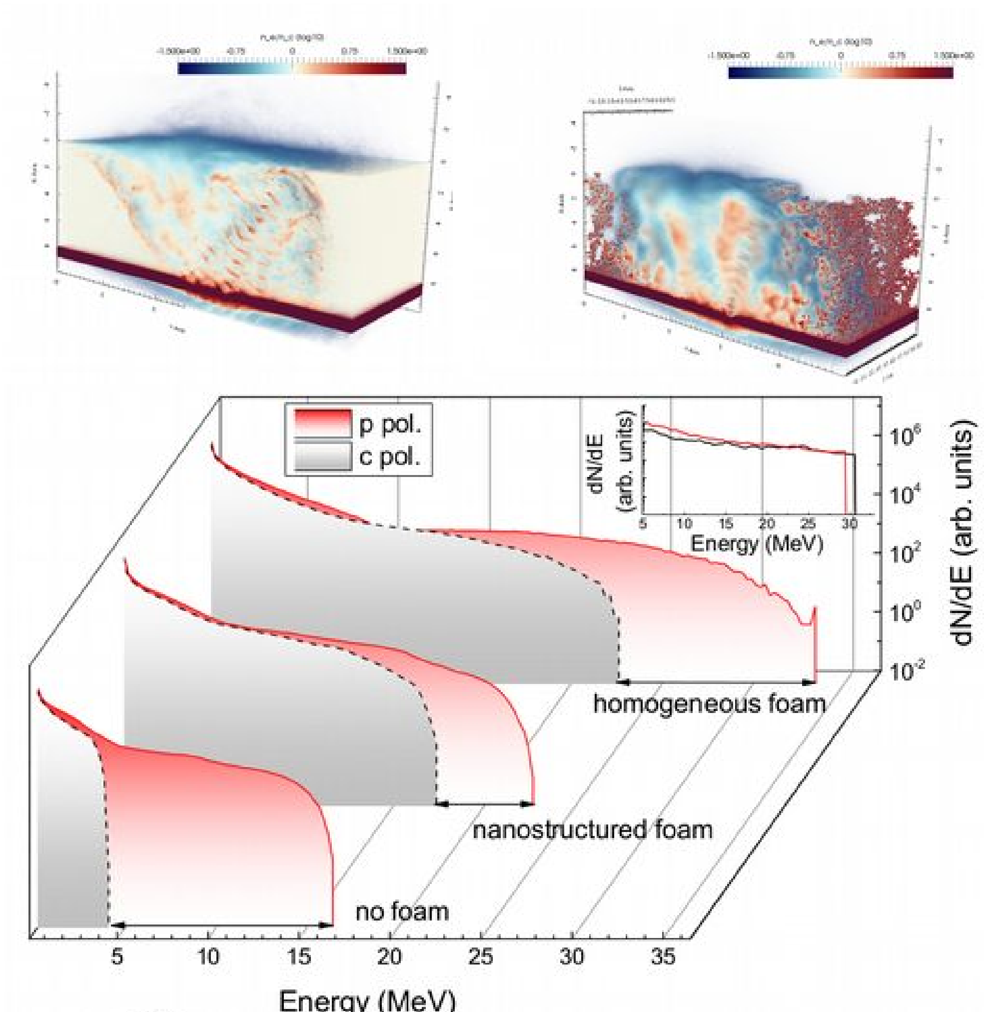
I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

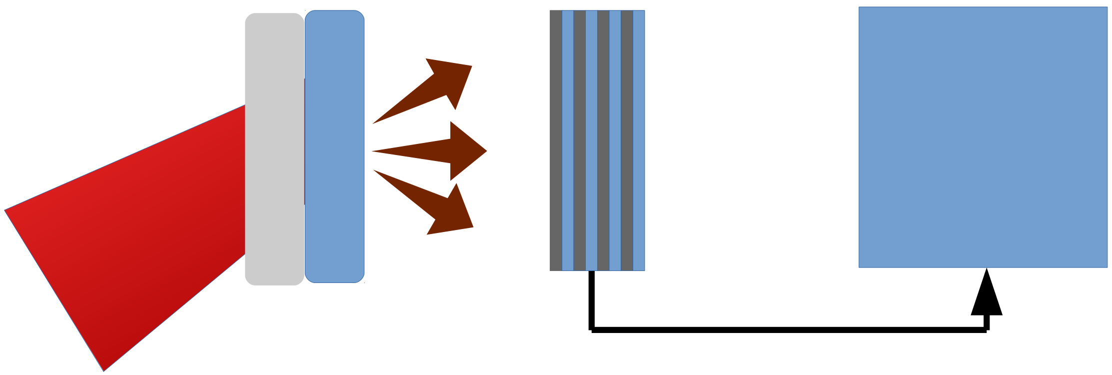
How do we simulate these plasmas?



Simulations with realistic foams allowed to reproduce essential features observed in the experiments

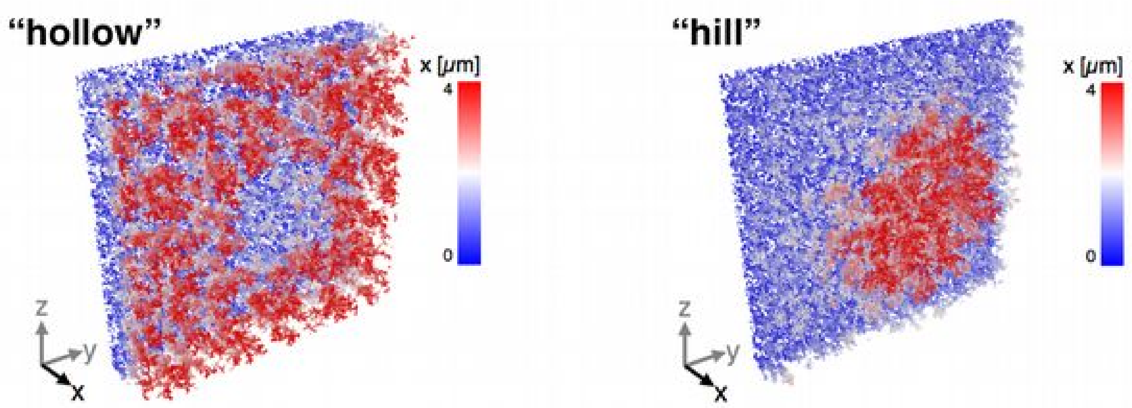
I.Prencipe et al., PPCF 58 (2016)
M.Passoni et al., PRAB 19(2016)

Some recent developments



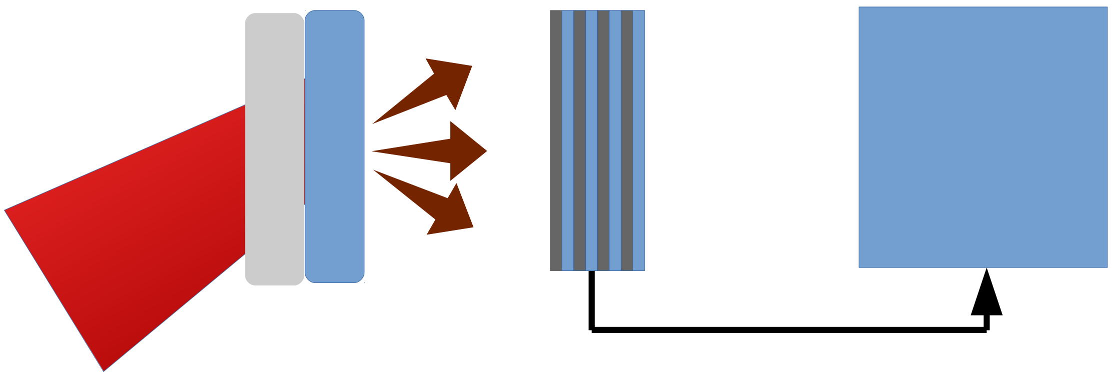
Synthetic RadioChromic Films for direct comparison with experimental results.

Also to understand the effect of foam inhomogeneities



Simulations done by A. Formenti

Some recent developments



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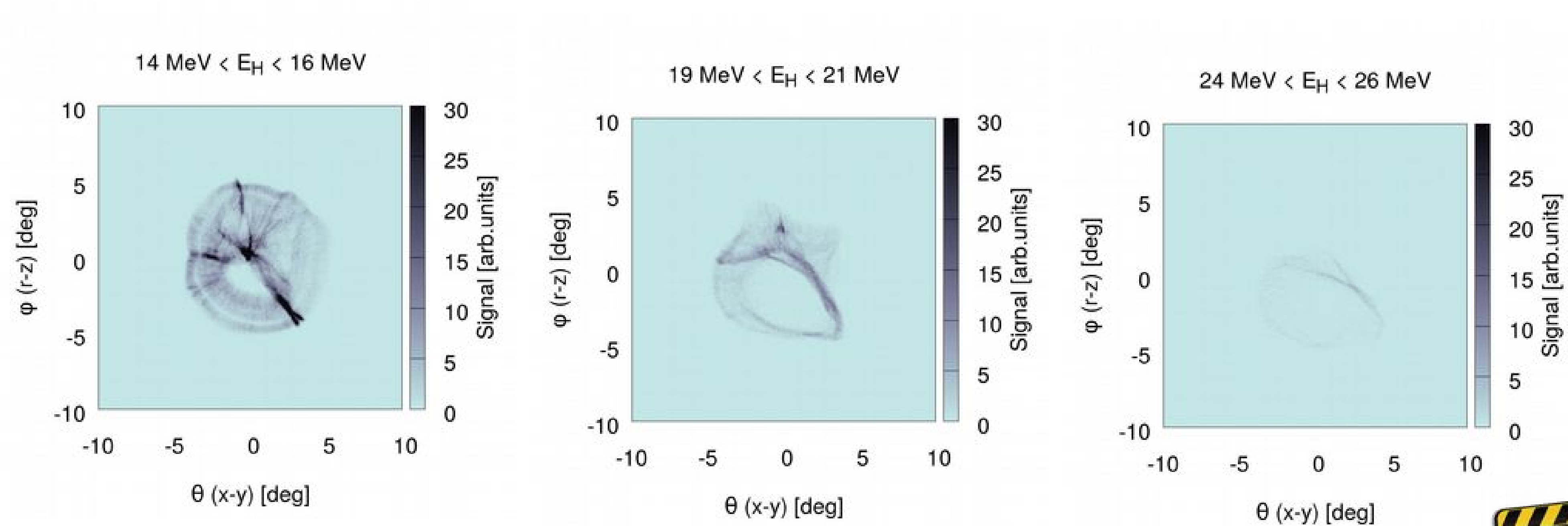

Simulations done by A. Formenti

Simulations of nanostructured plasmas: some examples with simplified models

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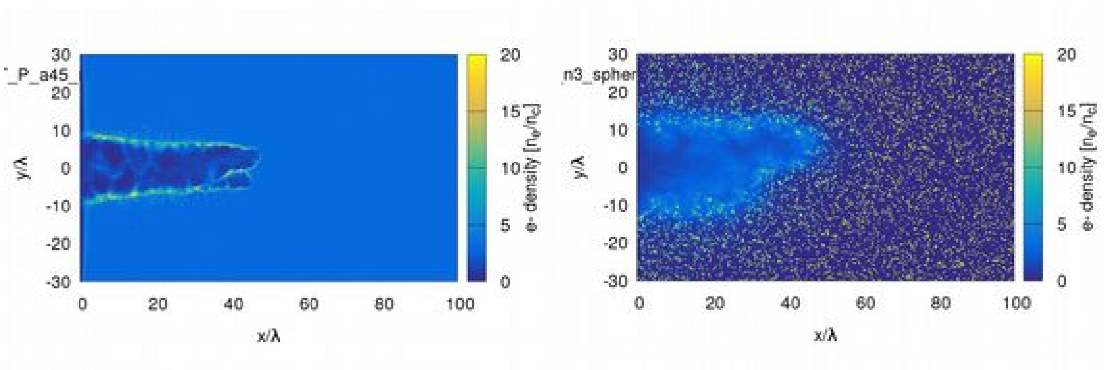
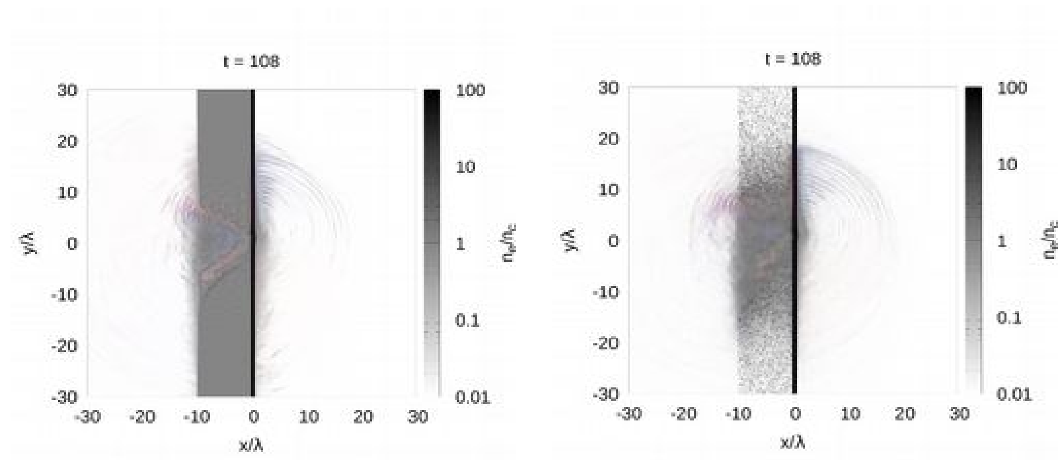


Laser propagation in near-critical foams

WORK IN PROGRESS

Enhanced electron heating with foam-attached targets



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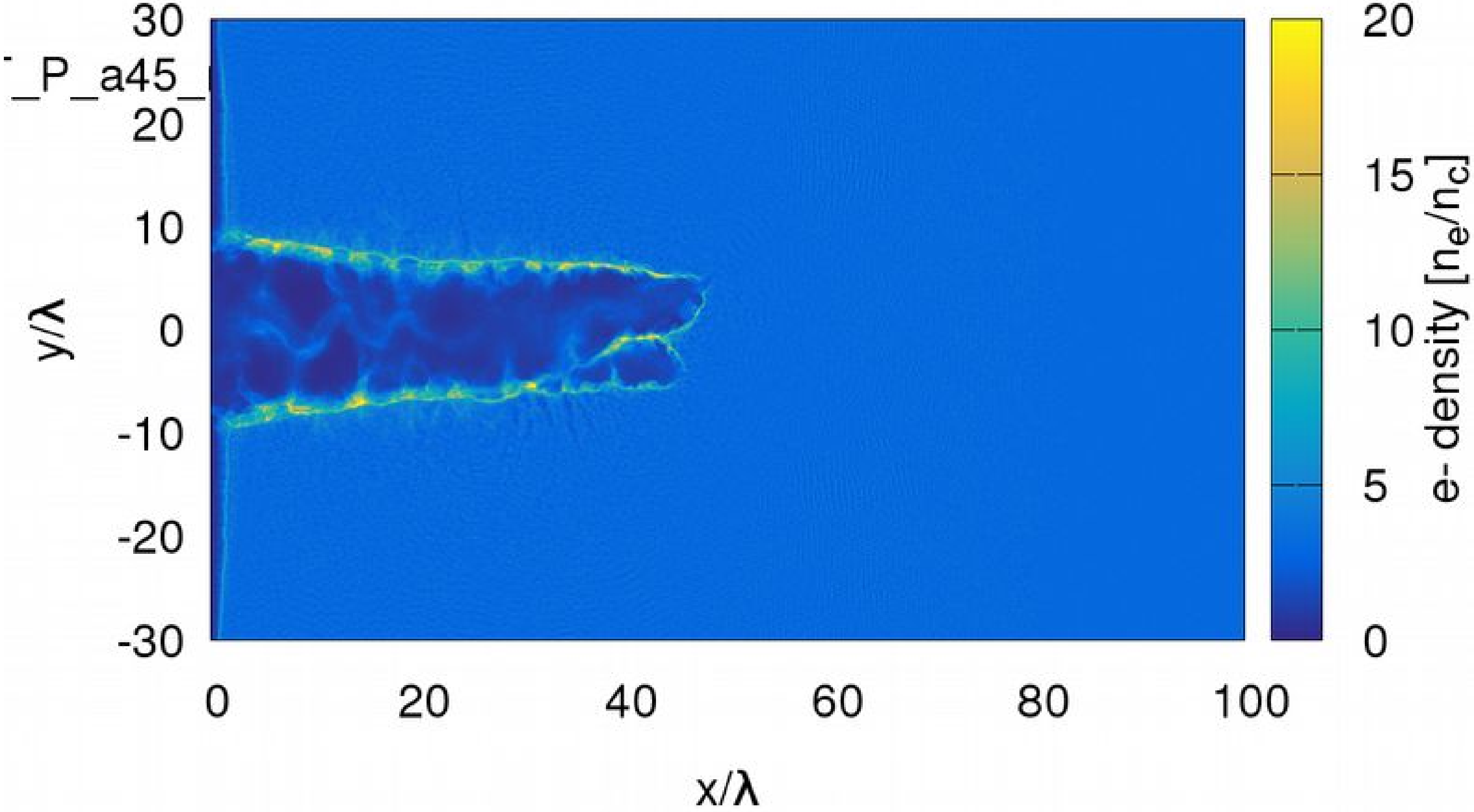

Laser propagation in near-critical plasmas

The numerical setup

P-polarized, gaussian
a_0=45, w=5λ, τ_{FWHM}=15λ/c

Uniform, n = 3 n_c
30 part.p.cell (for e^-)

Box: 220λ x 60λ
Resolution: 30 ppλ

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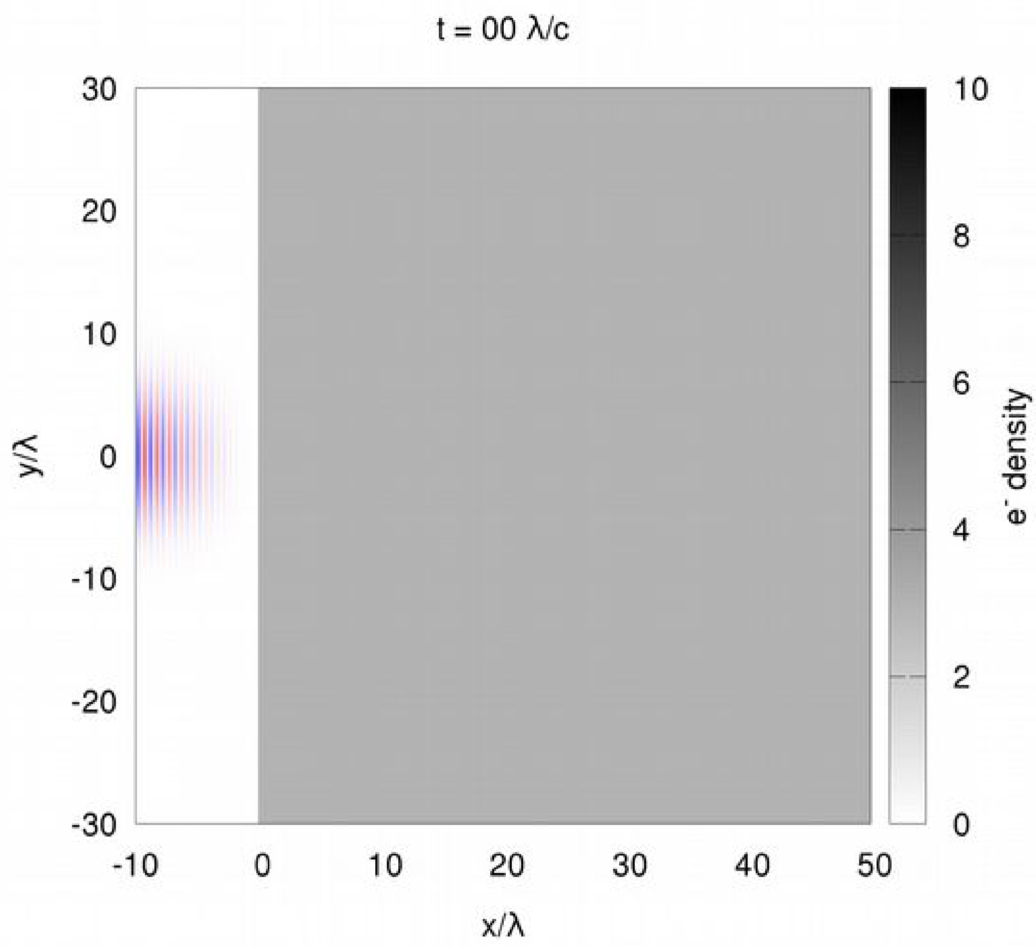
Laser propagation in near-critical plasmas



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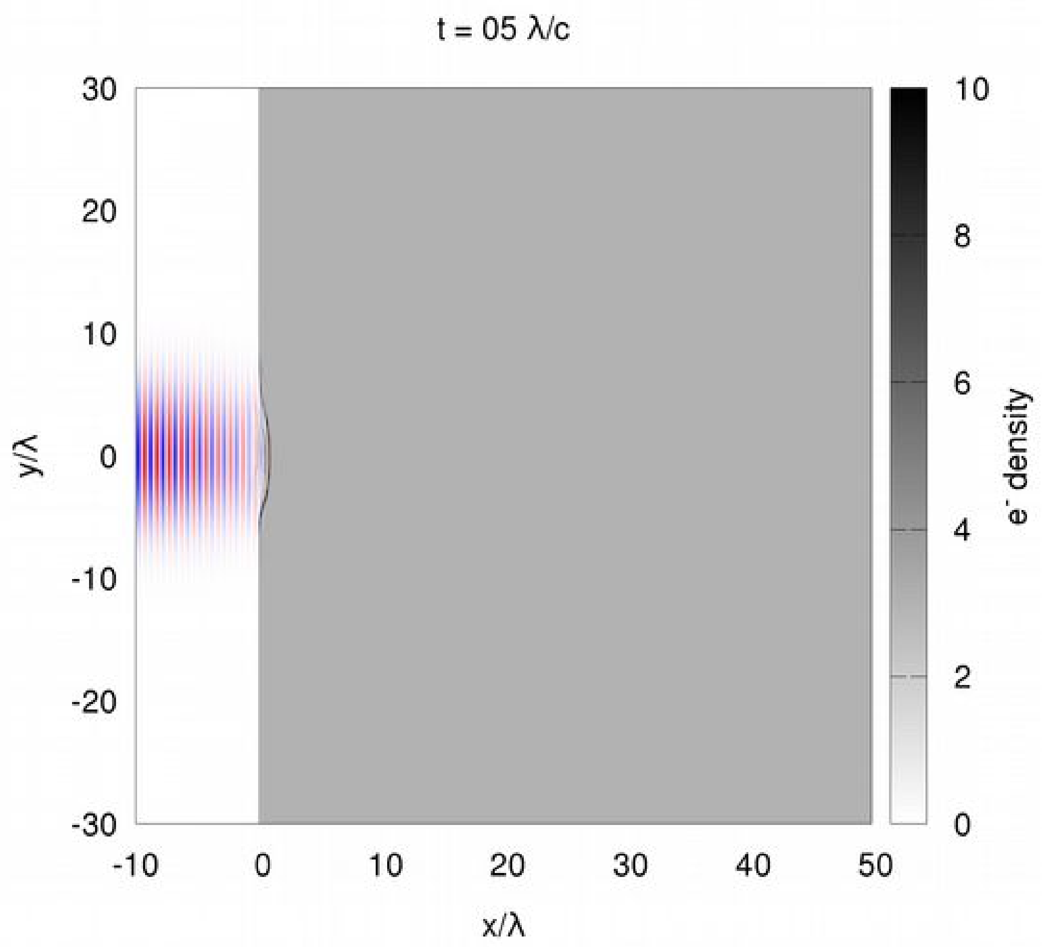

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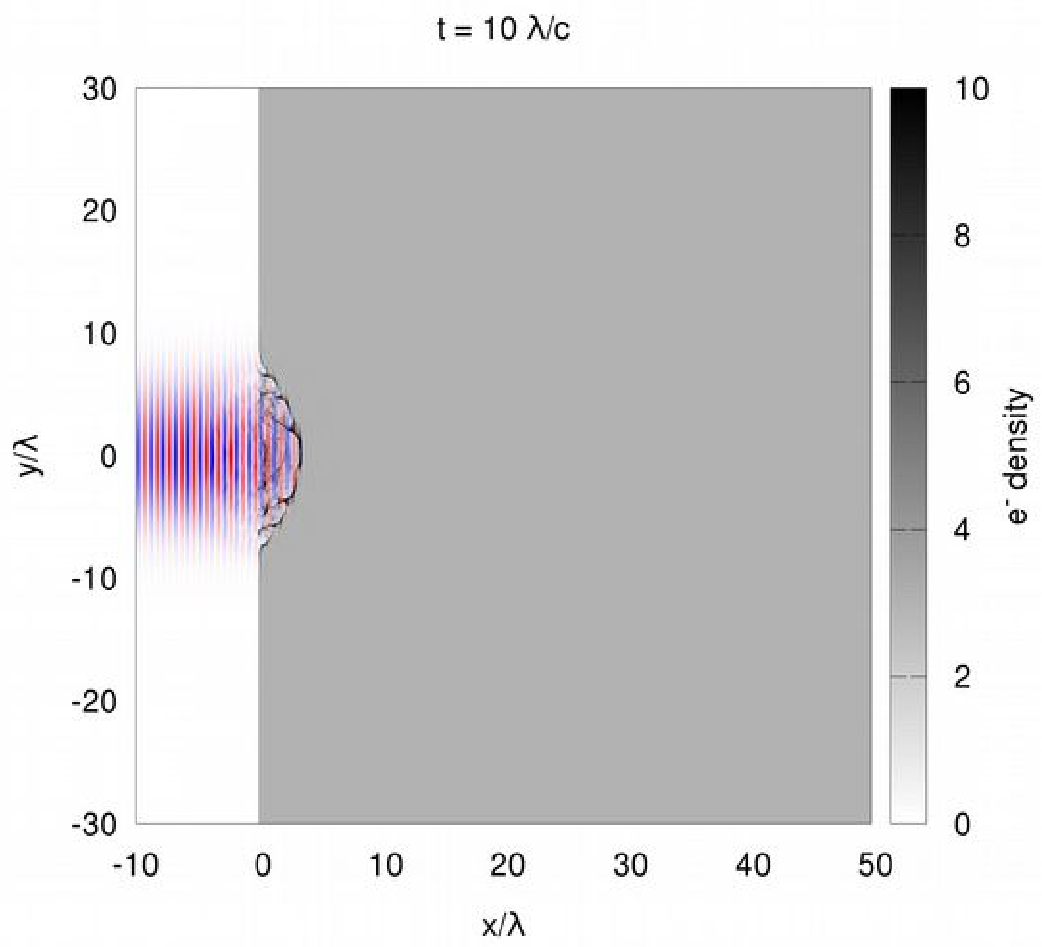

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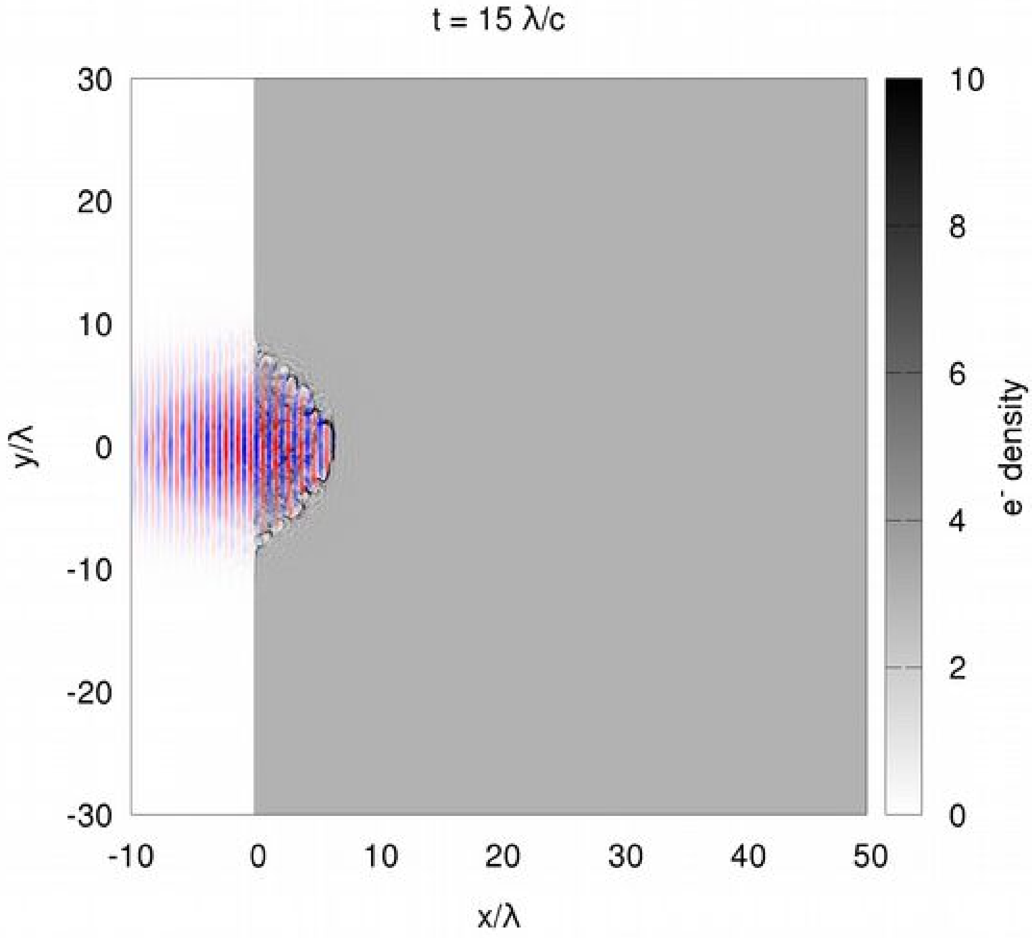

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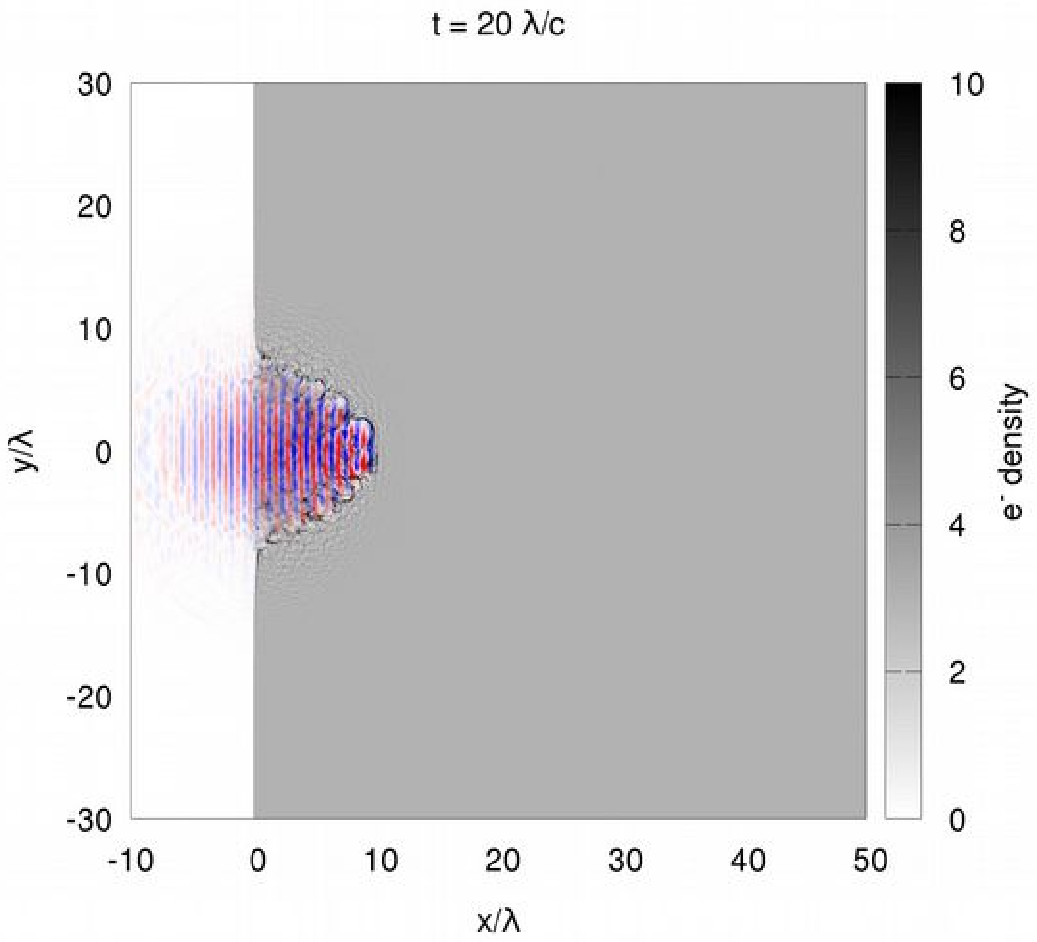

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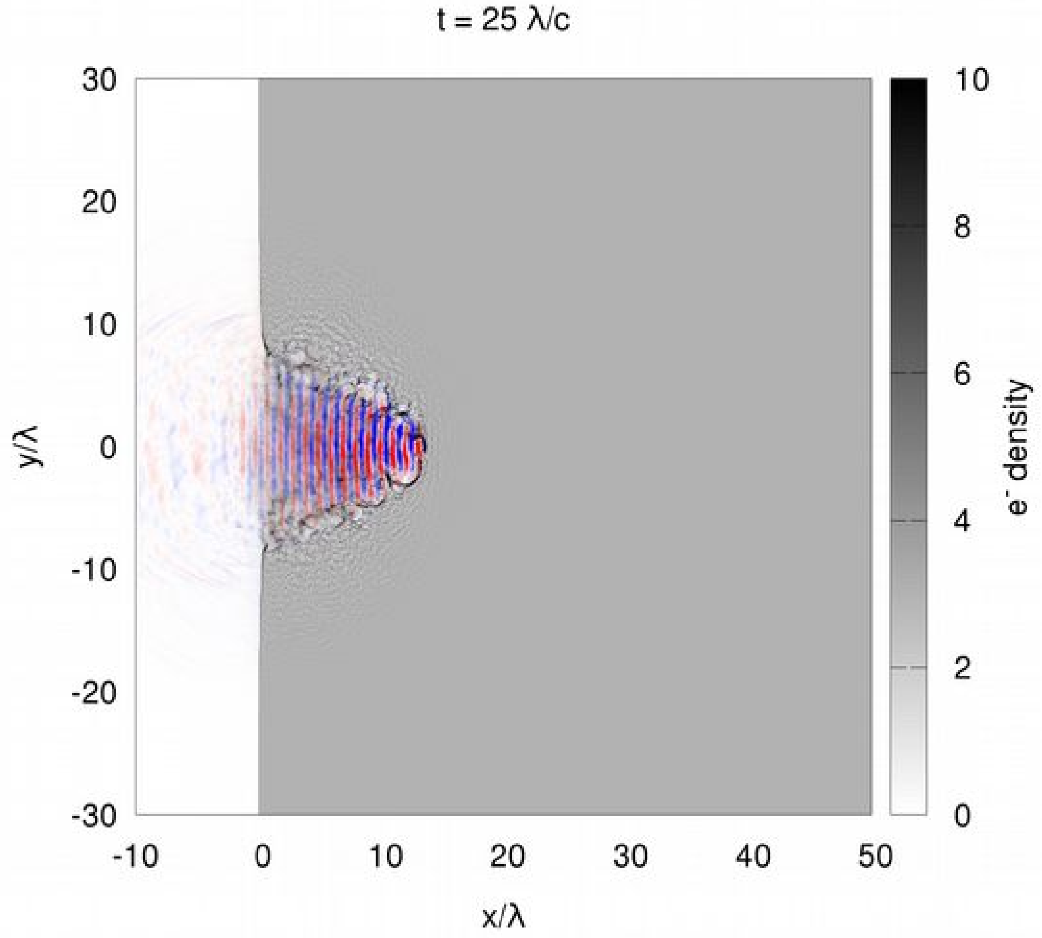

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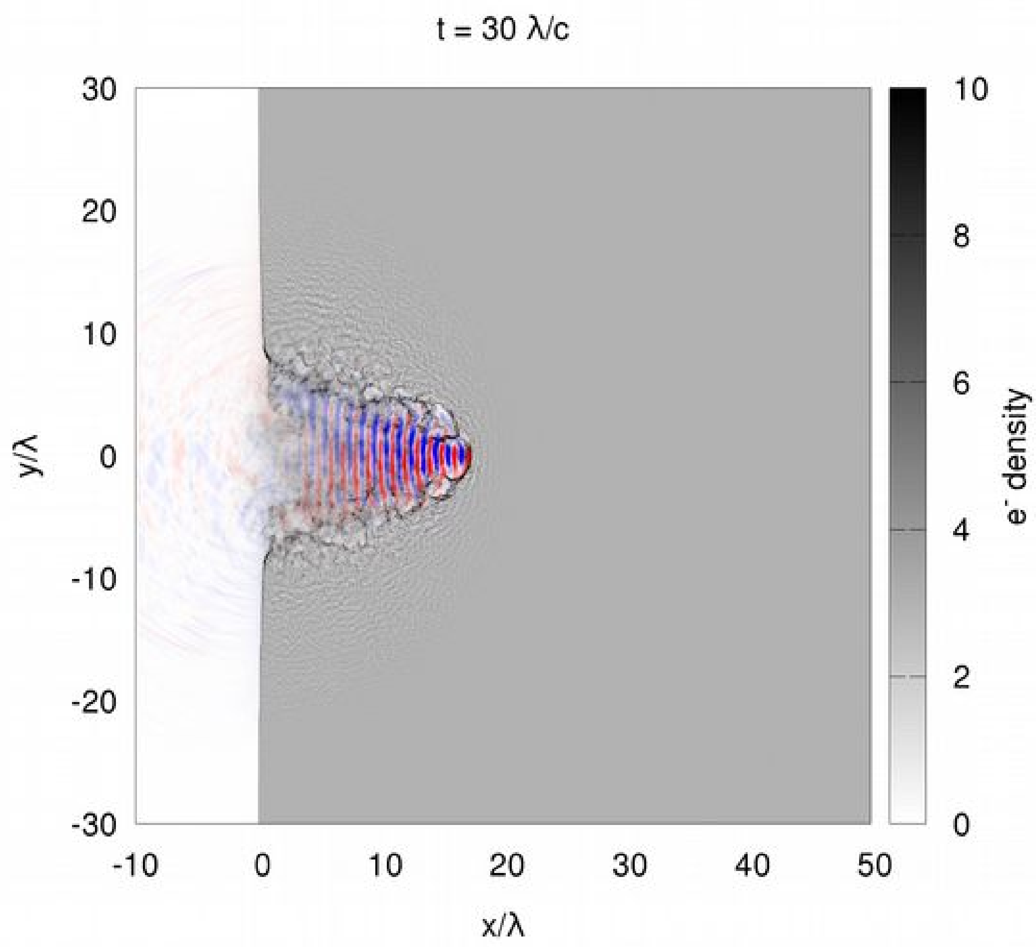

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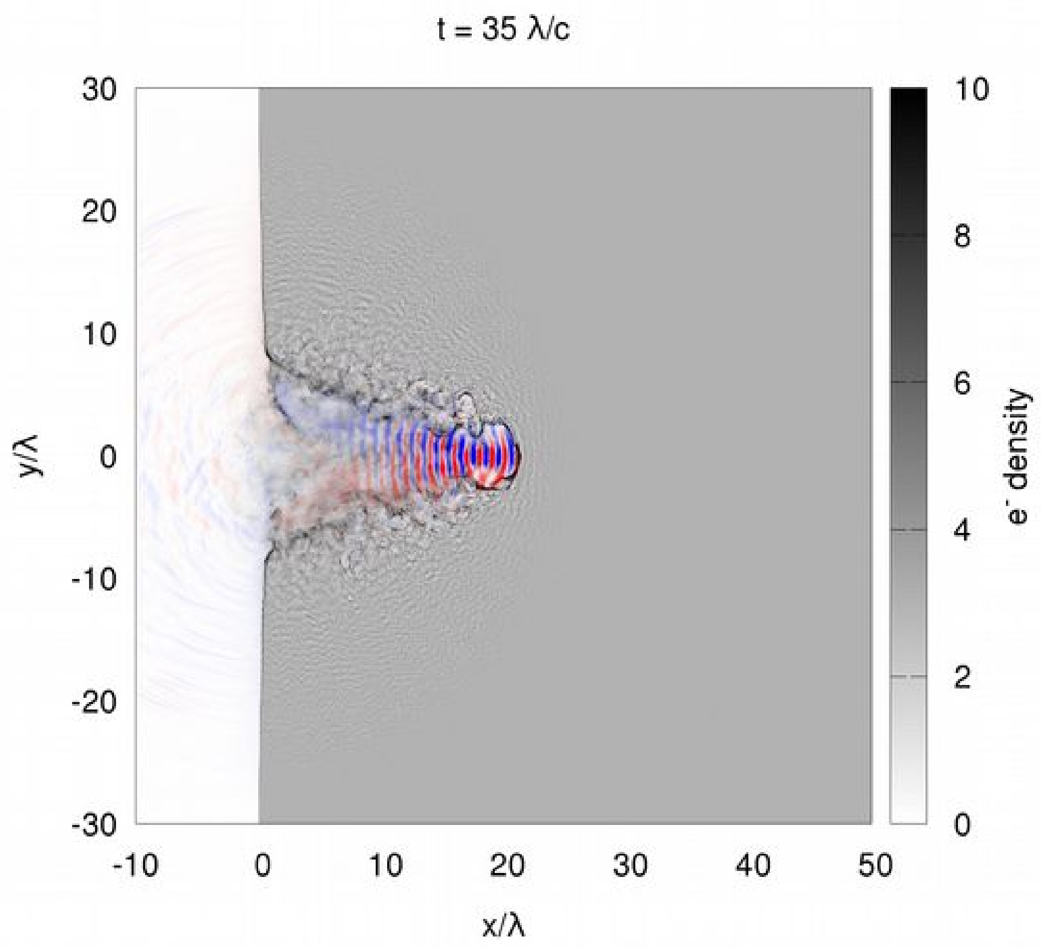

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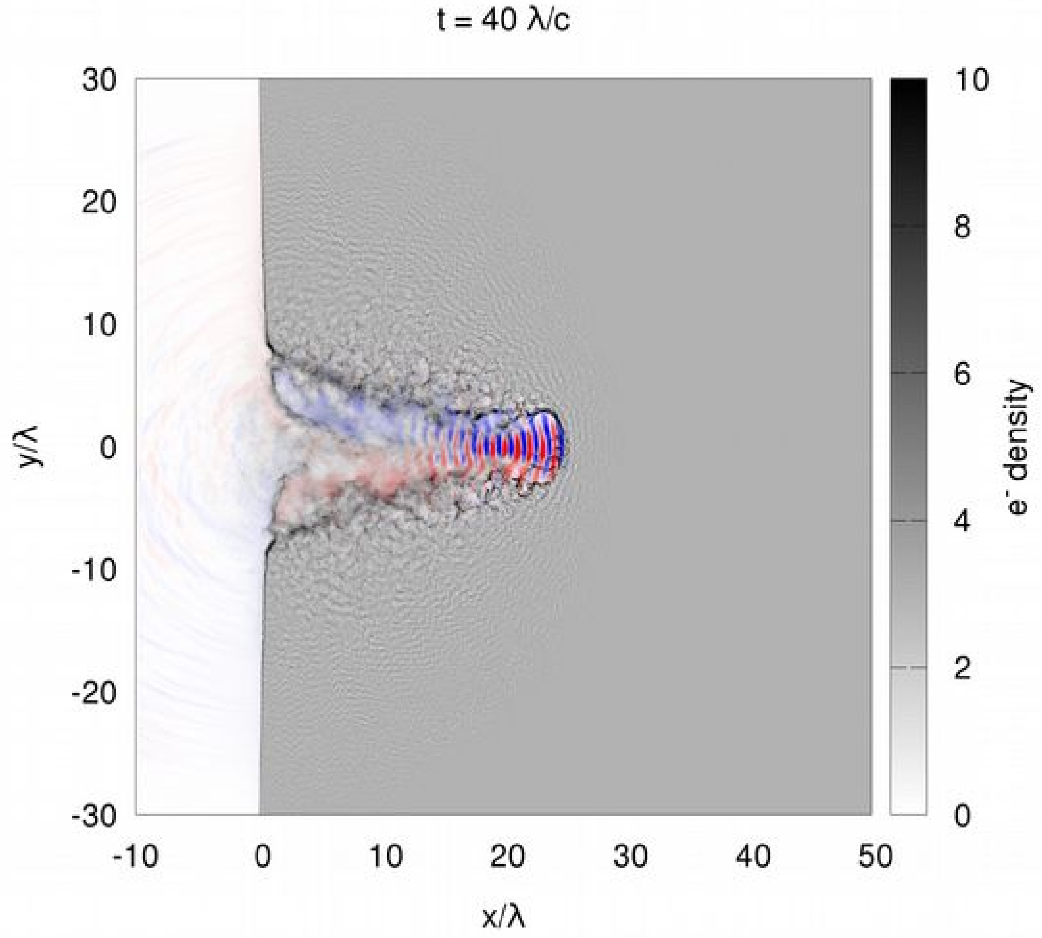

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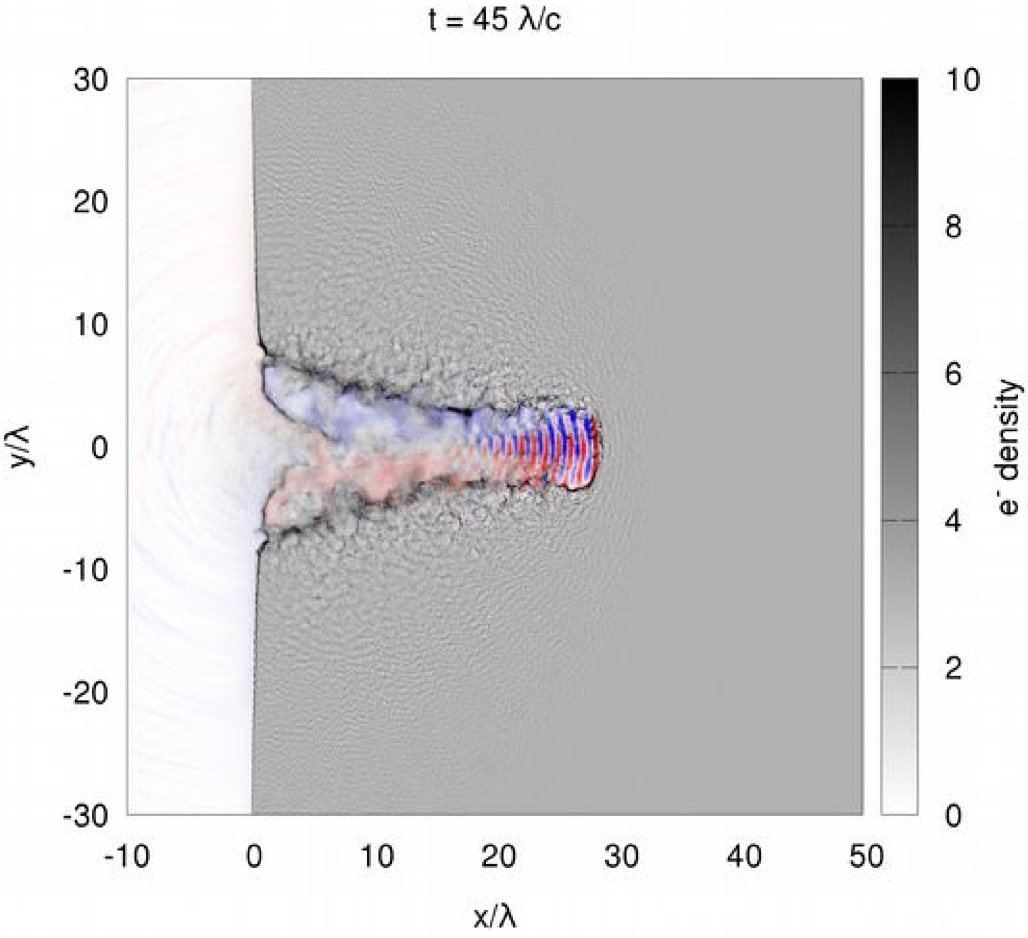

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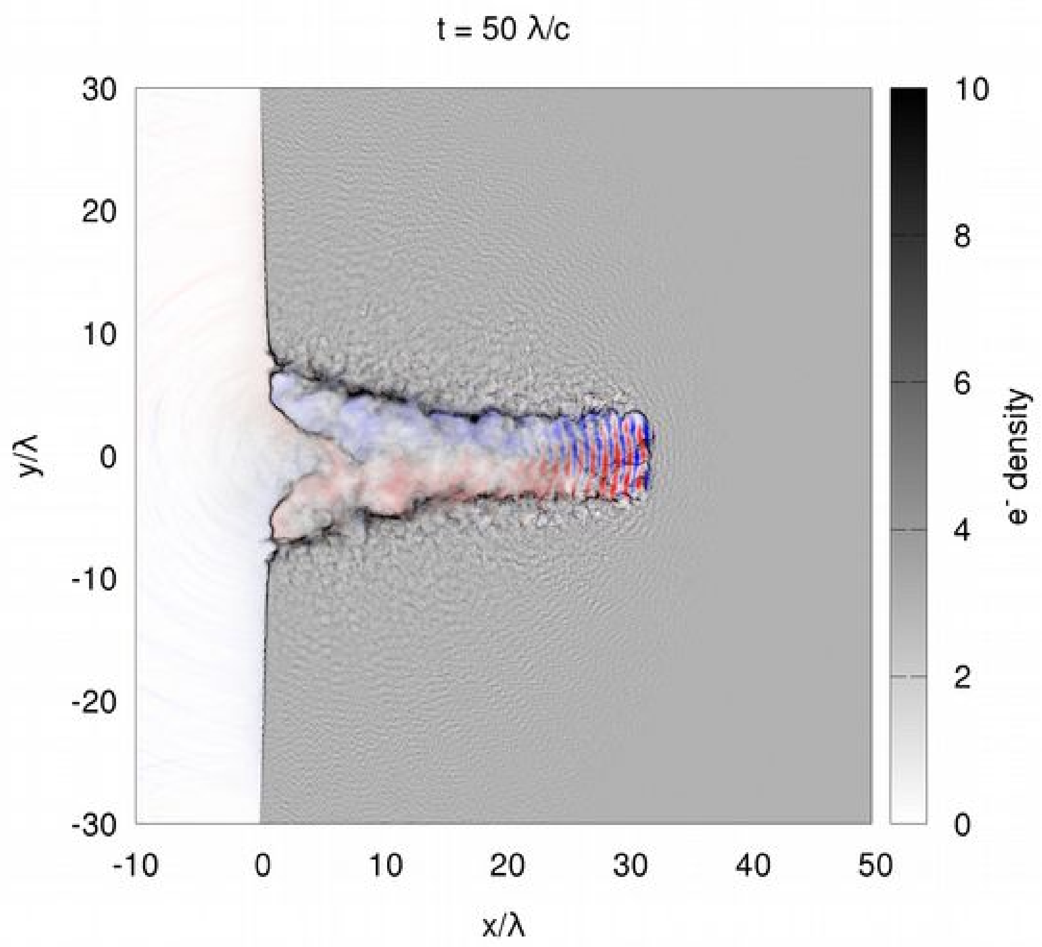

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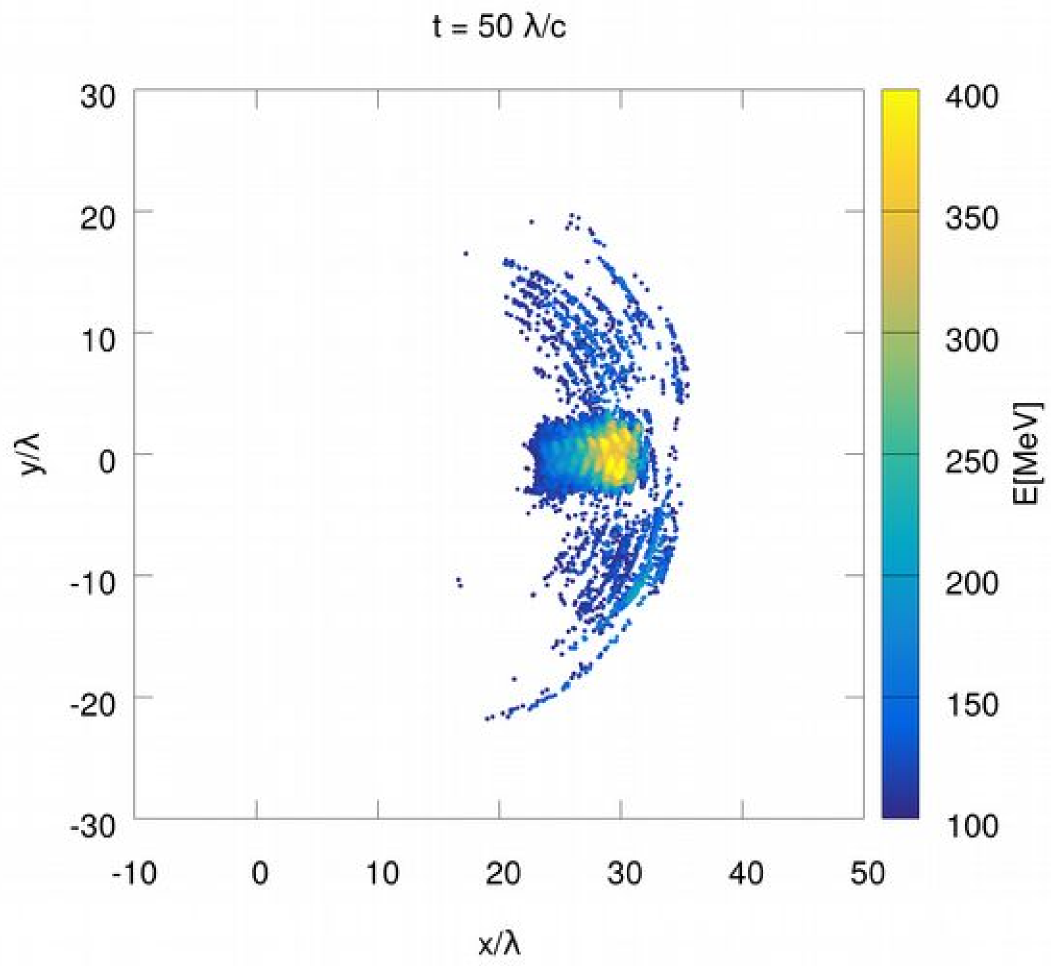
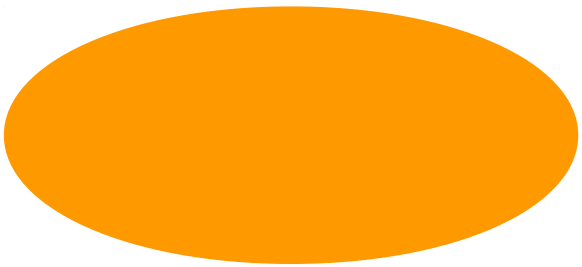


H.Wang et al. PoP 22 (2015)
D. J. Stark et al. PRL 116 (2016)

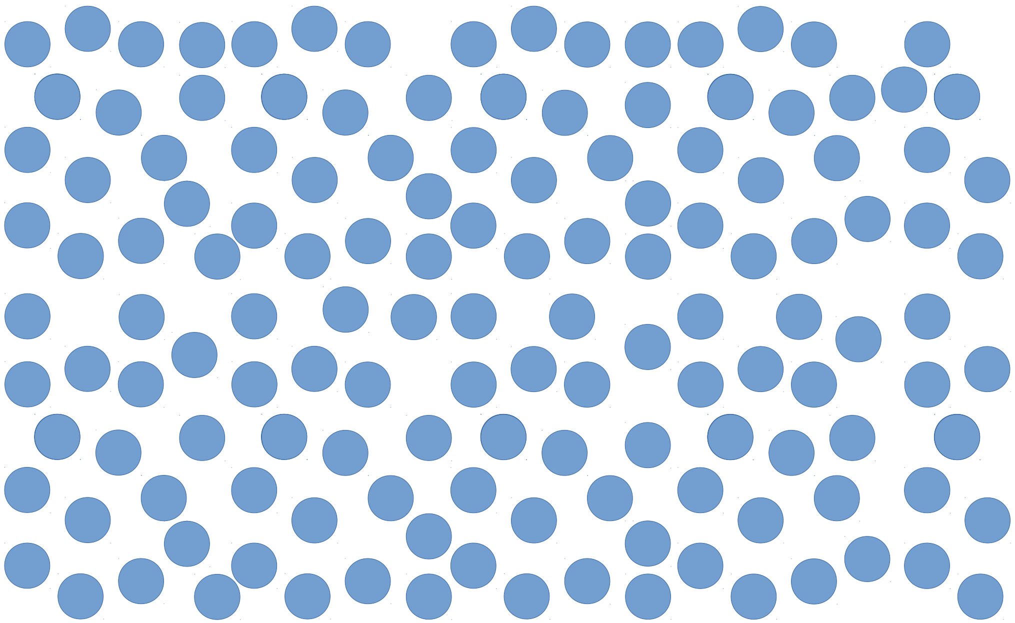
Laser propagation in near-critical plasmas

The numerical setup



P-polarized, gaussian

a_0=45, w=5λ, τ_{FWHM}=15λ/c



Rnd. spheres, $\langle n \rangle = 3\ n_c$

r = 0.178 λ , filling=0.1

270 part.p.cell (for e^-)

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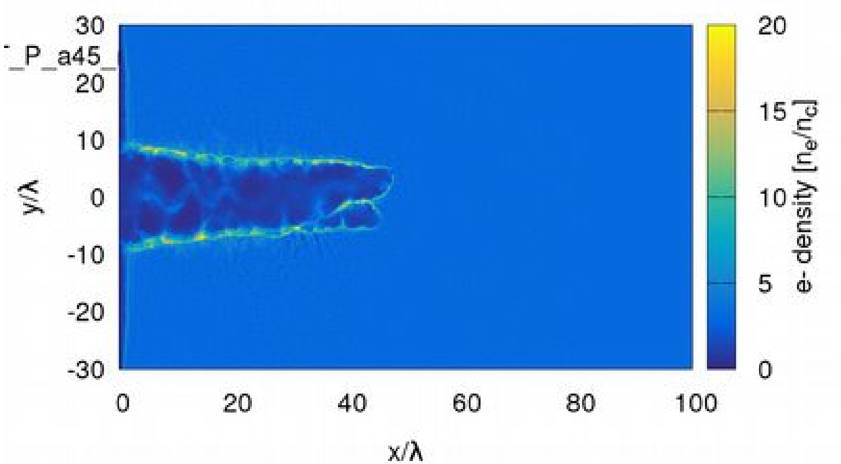
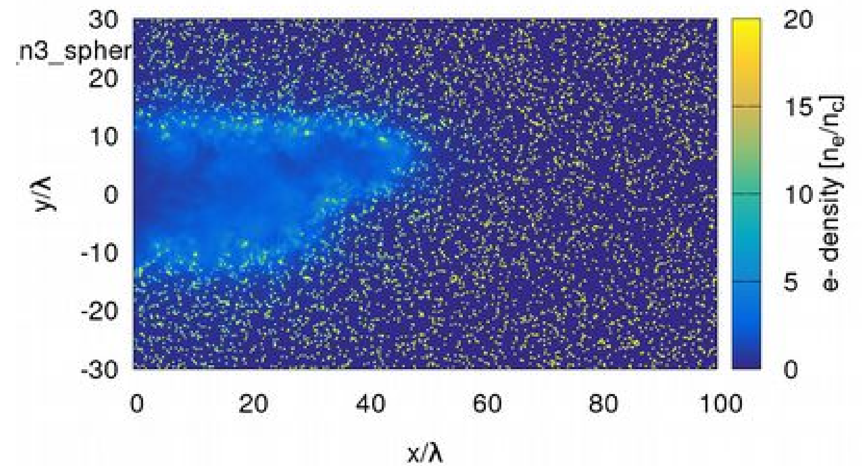
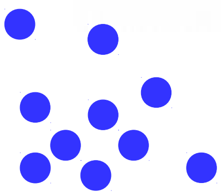
Numerical simulations

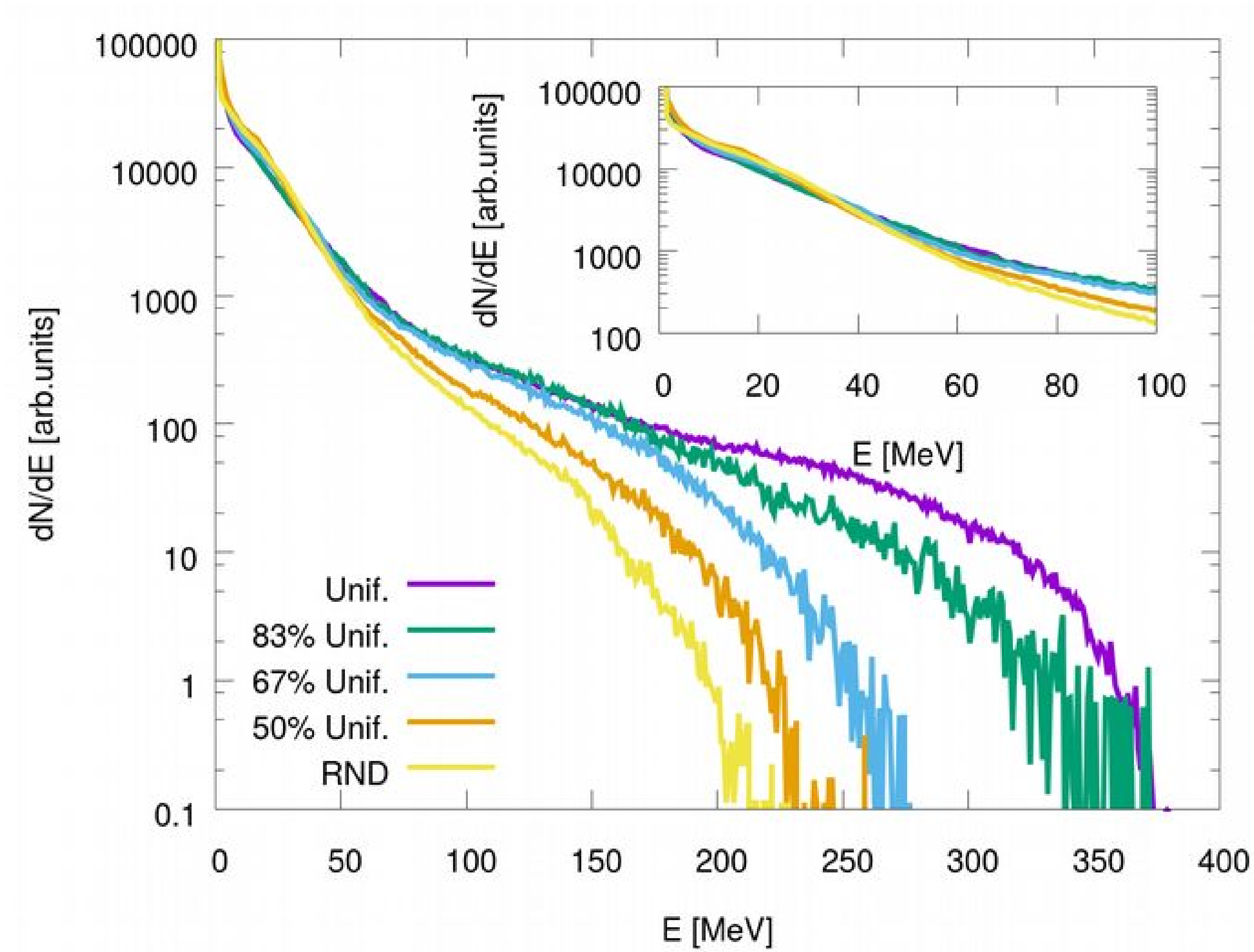




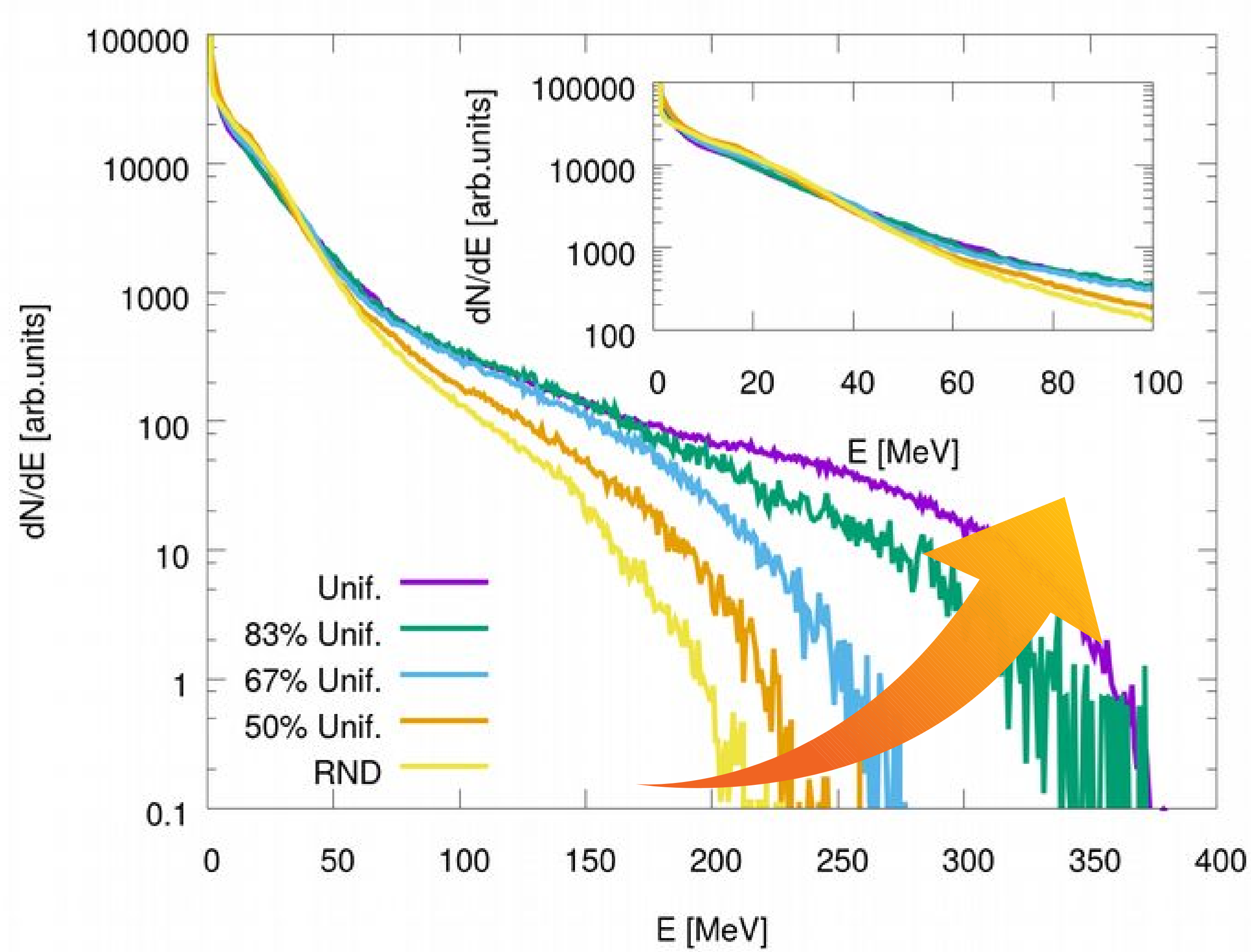
67%  + 33%  = 3 n_c on avg.

I can mix the two plasmas, going from a fully uniform plasma to a fully disconnected random spheres - plasma

Numerical simulations

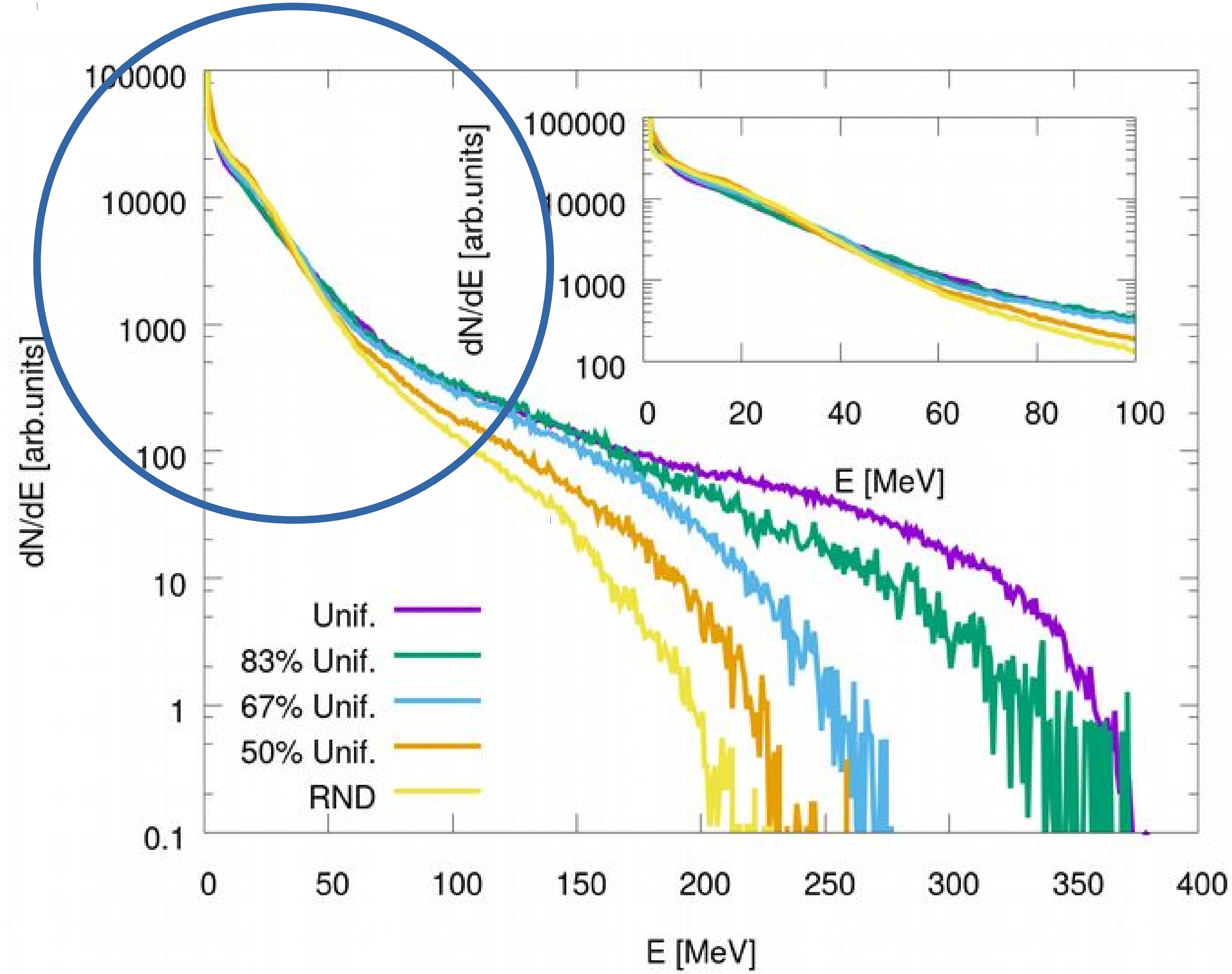


Numerical simulations



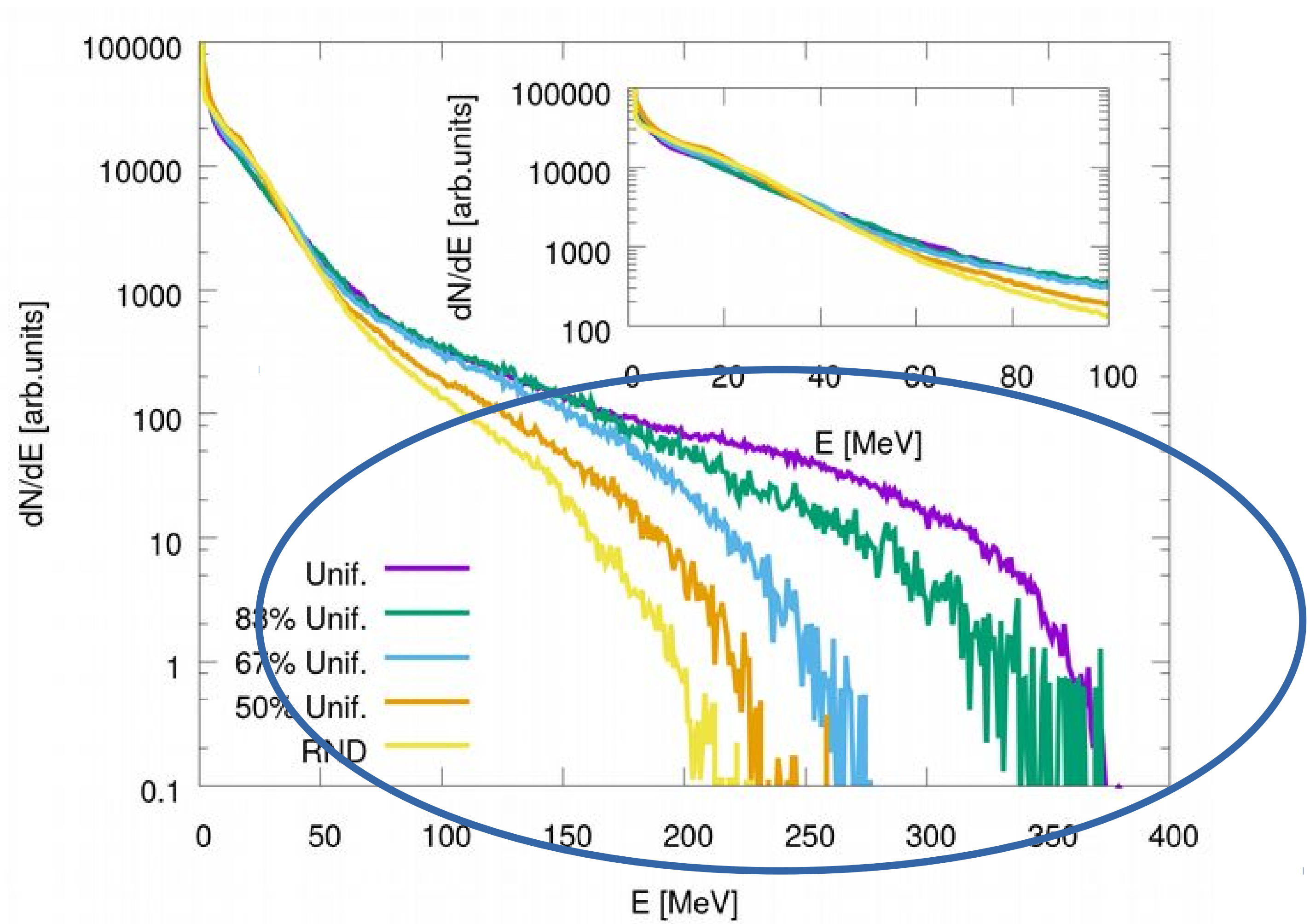
From "completely random spheres" to completely uniform

Numerical simulations



“Some” temperature difference here

Numerical simulations



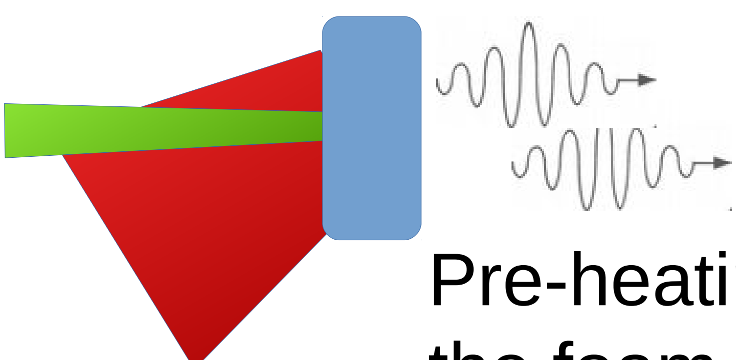
Significant cut-off energy difference

Numerical simulations

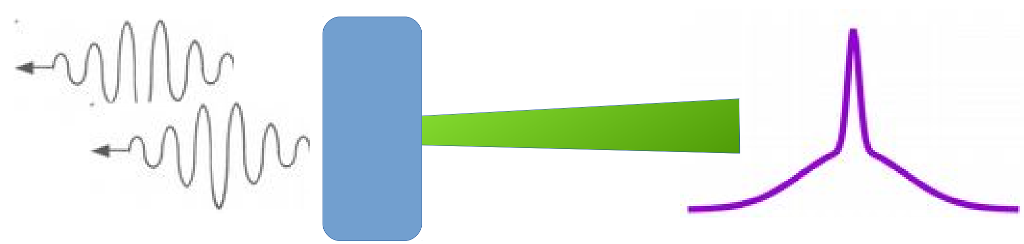
This is observable if we look at the spectrum of synchrotron emission. Peak scales as ~ $\gamma^3 \omega_c$

According to the model, “uniform is probably better” for synchrotron emission

In principle we could see if the model makes any sense with a simple experiment



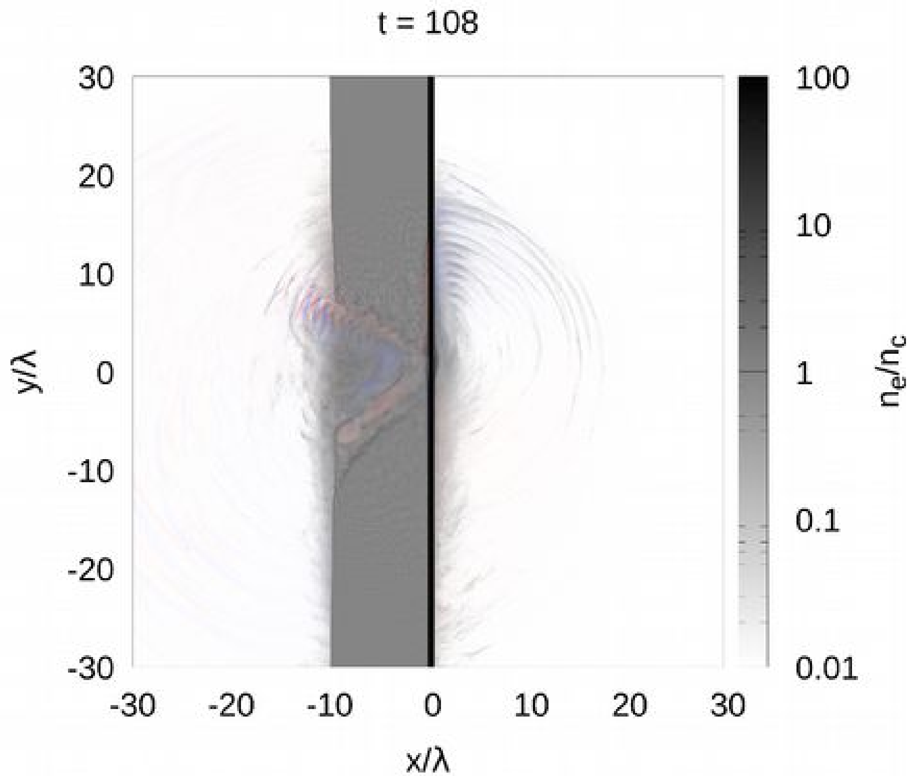
Pre-heating of the foam

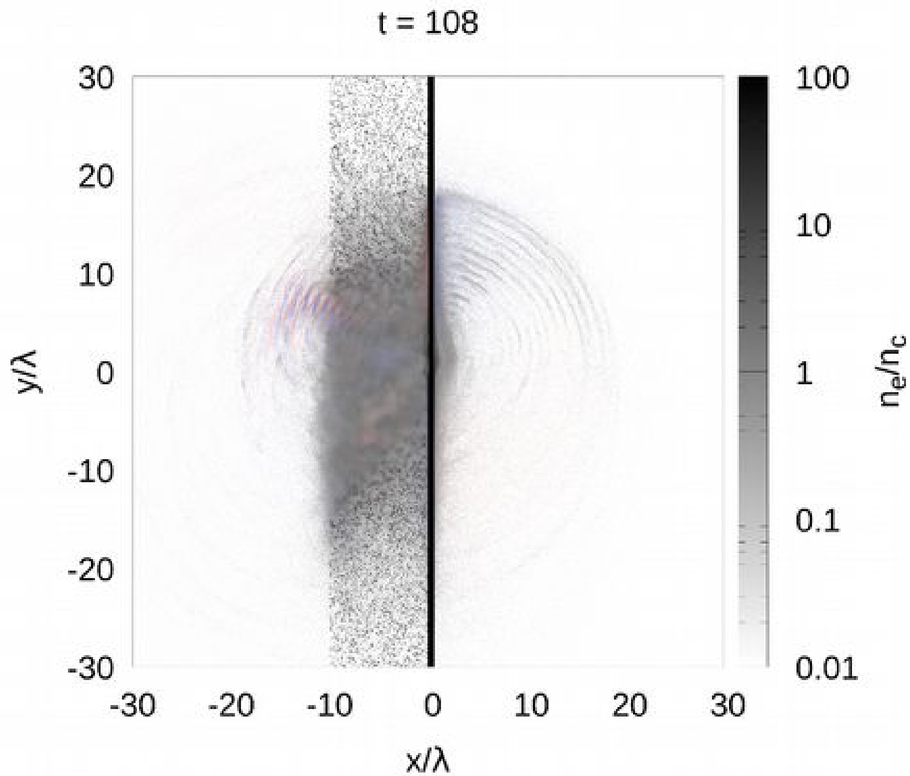


Reduce the contrast

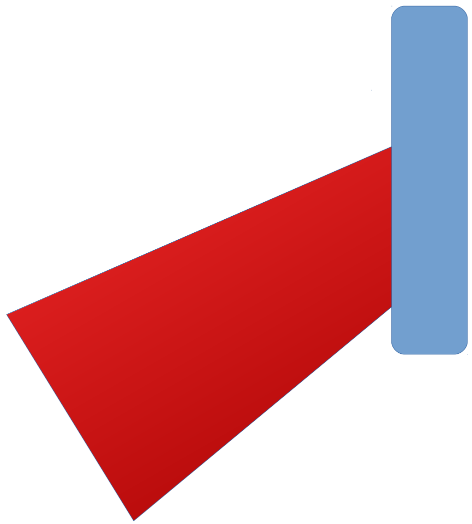
Electron heating in foam-attached targets

Electron heating in foam-attached targets





Electron-heating in foam-attached targets

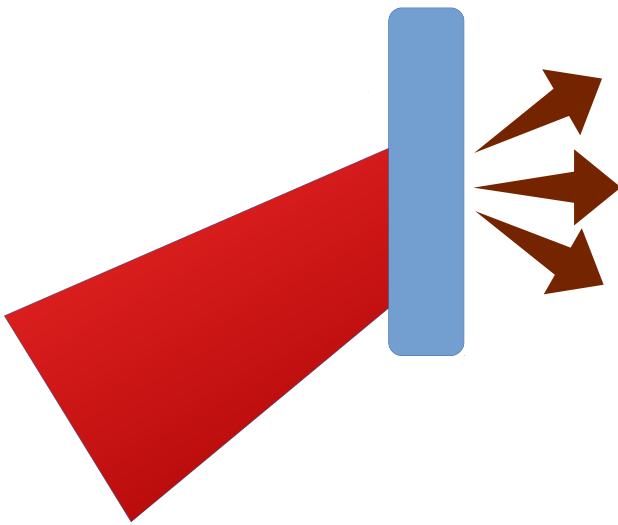


A lot of existing literature!
Interesing for several reasons:
ion acceleration, electron/positron beams, electron transport...

However, several issues of existing models (Angular dependence, polarization dependence…) and **no models for foam-attached targets**

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in foam-attached targets

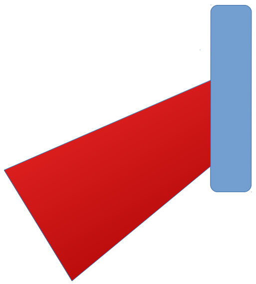


Not easy to find parametric scans for e^- temperature

But a **lot of data on laser-driven ion acceleration**

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in simple targets



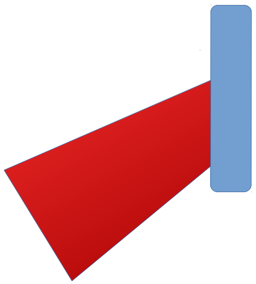
Write a model for Te(a_0,pol)

JxB heating

Vacuum heating

$$T_e[MeV]=0.511\cdot C_1(pol)\cdot\left(\sqrt{1+\frac{a_0^2}{2}}-1\right)+0.511\cdot C_2(pol)\cdot\left(\sqrt{1+2\,a_0^2\sin^2\theta}-1\right)\cdot\tan\theta$$

Electron-heating in simple targets



Write a model for Te(a_0,pol)

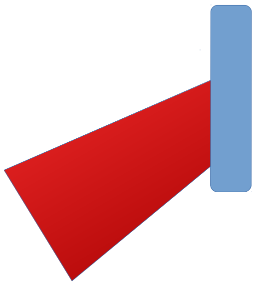
JxB heating

Vacuum heating

$$T_e[MeV] = 0.511 \cdot C_1(pol) \cdot \left(\sqrt{1 + \frac{a_0^2}{2}} - 1 \right) + 0.511 \cdot C_2(pol) \cdot \left(\sqrt{1 + 2 a_0^2 \sin^2\theta} - 1 \right) \cdot \tan\theta$$

2D/3D simulations to check model and fit parameters

Electron-heating in simple targets



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2D/3D simulations to check model and fit parameters

Plug T_e into existing model for ion acceleration

$$E_{max}(ions)=Z_i k_b T_e\left[\phi'-1+\frac{\beta(\phi',\zeta)}{l(\phi',\zeta)e^{\phi'+\zeta}}\right]$$

M.Passoni, M. Lontano. PRL 101 (2008)

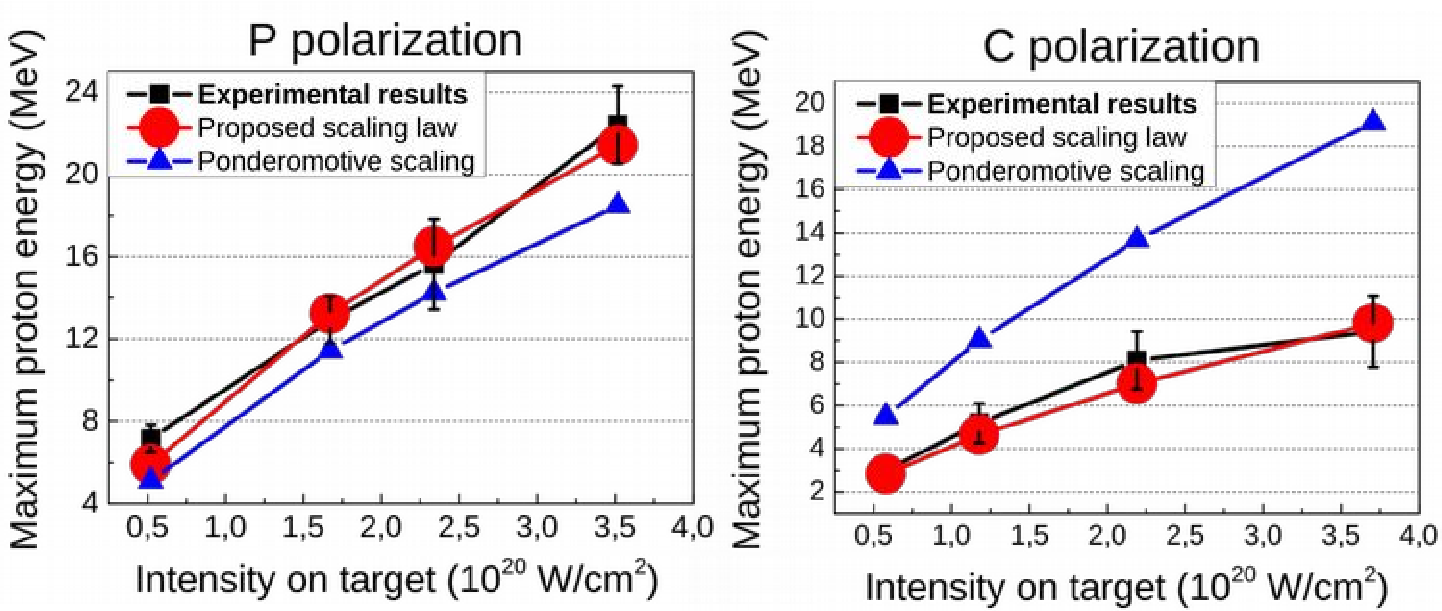
Electron-heating in simple targets

JxB heating

Vacuum heating

$$T_e[MeV]=0.511\cdot C_1(pol)\cdot\left(\sqrt{1+\frac{a_0^2}{2}}-1\right)+0.511\cdot C_2(pol)\cdot\left(\sqrt{1+2a_0^2\sin^2\theta}-1\right)\cdot\tan\theta$$

Benchmark with experiments

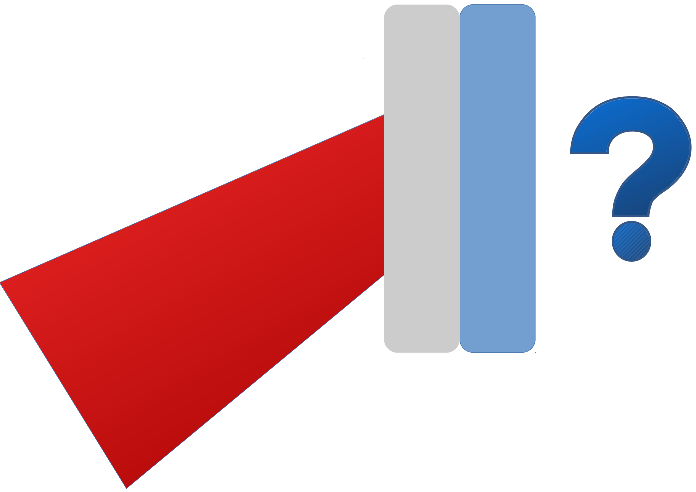


Exp. data

I.Prencipe et al. PPCF 58 (2016)

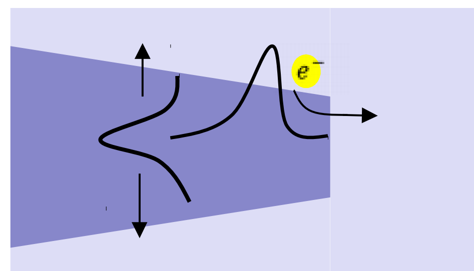
M.Passoni et al. PRAB (2016)

Electron-heating in near-critical plasmas



What about foam-attached targets?

APL Robinson et al, PPCF 53 (2011)



Pulse erosion
$T_e \sim a_0^2$

Ponderomotive expulsion $T_e \sim a_0$

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in near-critical plasmas

What about foam-attached targets?

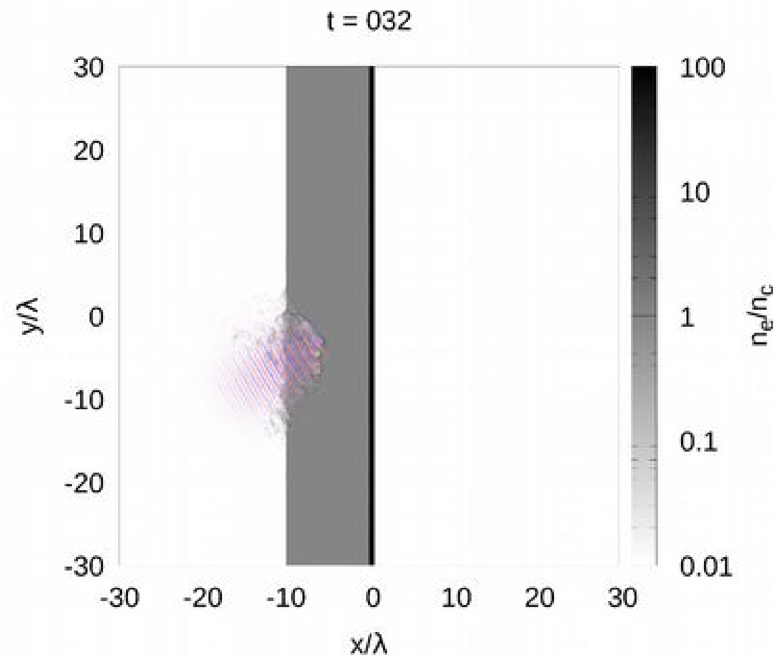
2D Particle-In-Cell simulations to obtain T_e

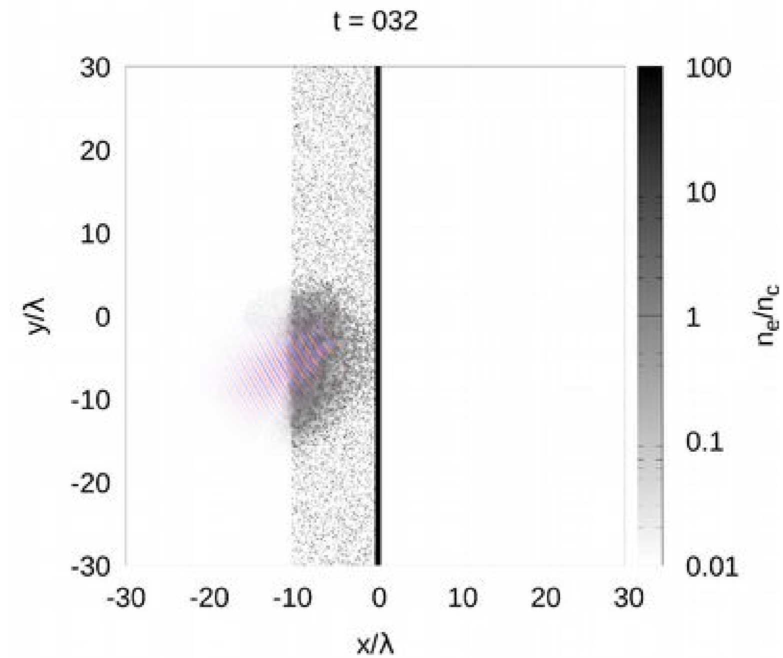
Investigation limited to one particular setup

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in near-critical plasmas

Two models for the foam





Homogeneous foam $n_e = n_c$

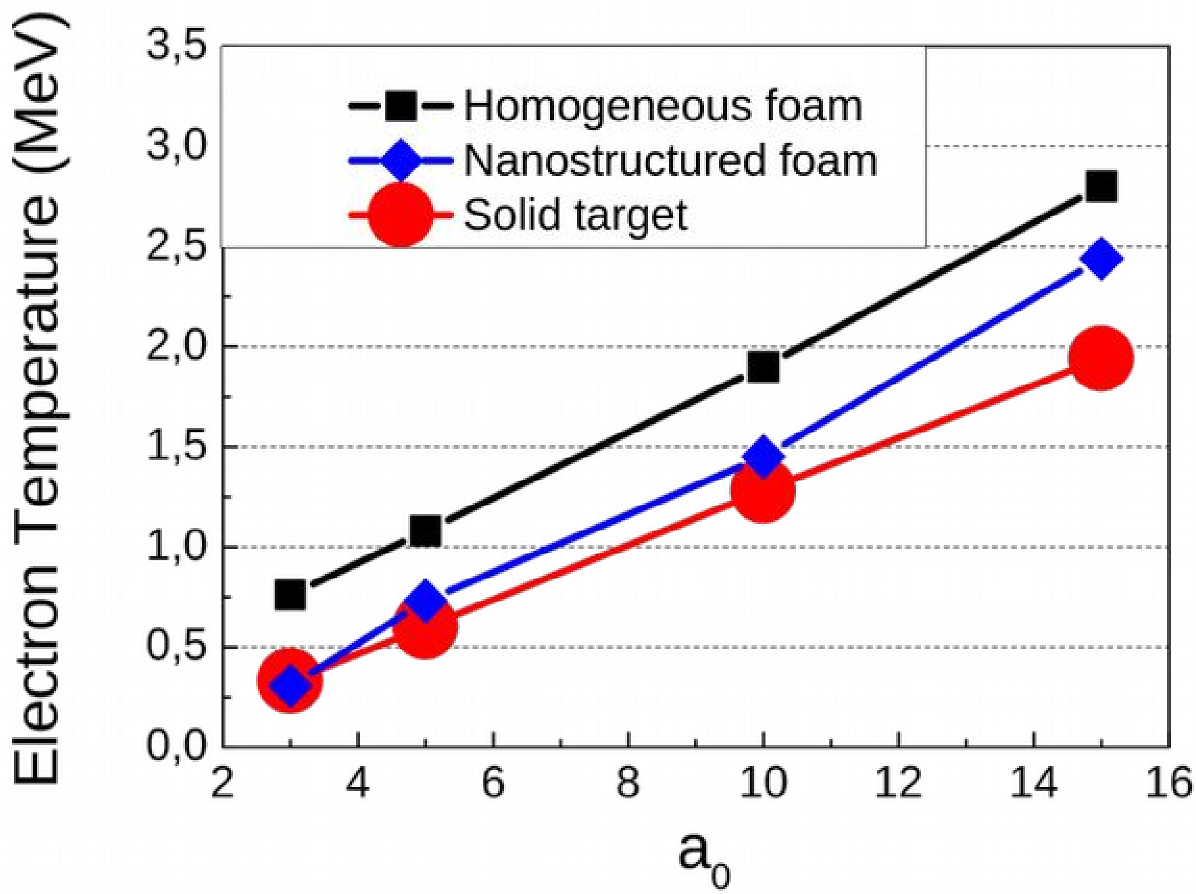
Rnd. Spheres $\langle n_e \rangle = n_c$

$r = 10\,\mathrm{nm}$, $n_e = 100\ n_c$

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in near-critical plasmas

Simple linear fit: $T_e[MeV] = C_1 + C_2 a_0$

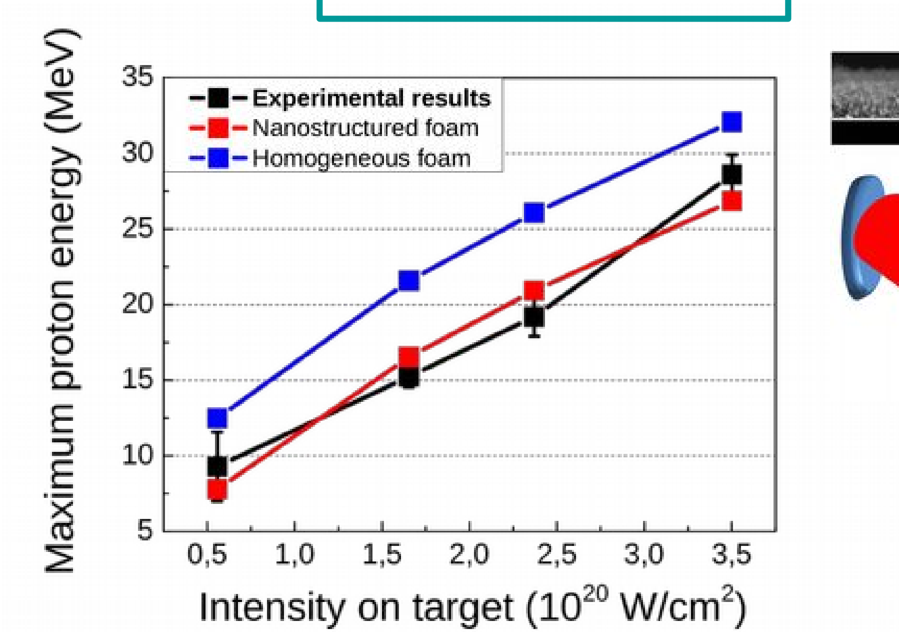


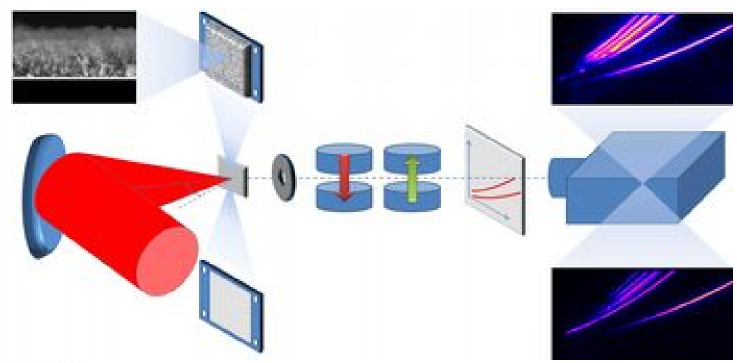
L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

Electron-heating in near-critical plasmas

Same idea of flat targets

T_e → Ion acceleration model → Estimation of E_{max} → Benchmark





L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE

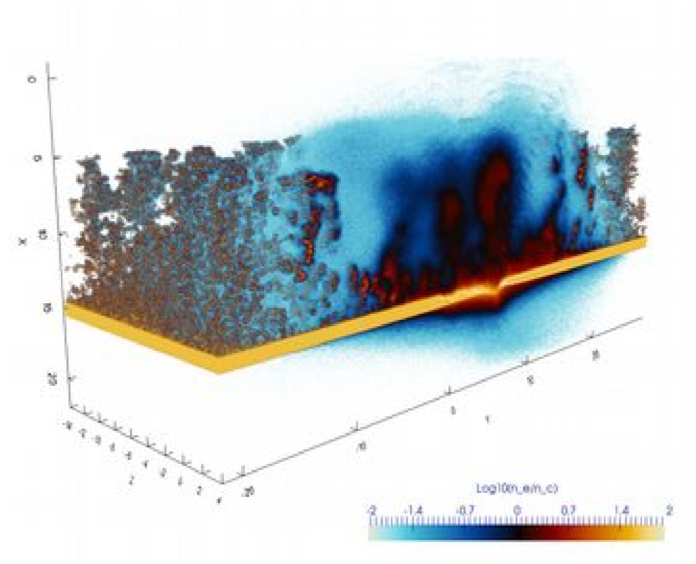
Nanostructured plasmas

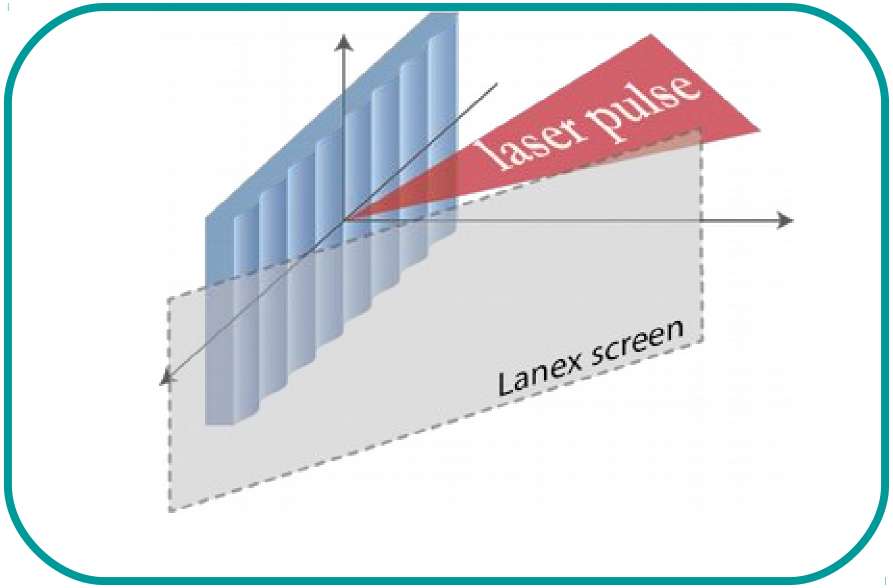
Nanostructured plasmas

If we irradiate a solid, nanostructured target with these lasers, **the structures might survive**

In some cases this is **incidental**

In other cases it is **desirable**



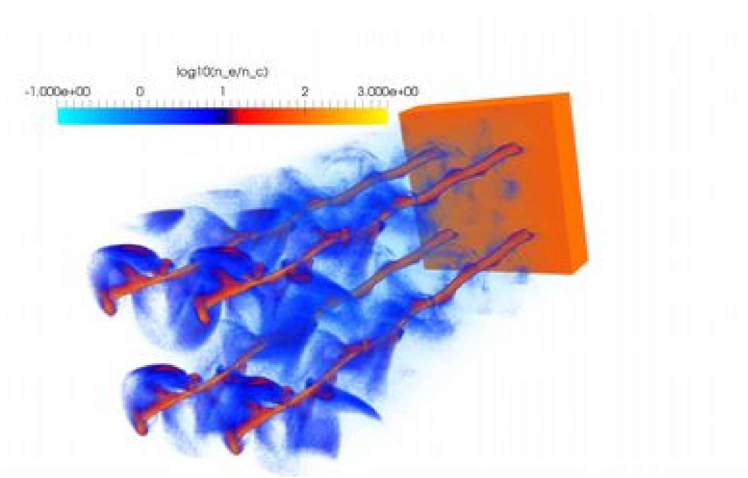


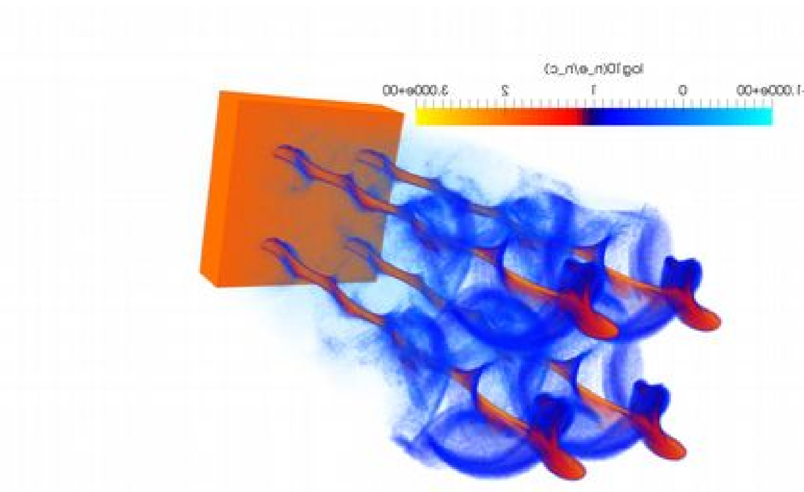
Nanostructured plasmas

Wide topic, growing interest in the community.

L.Fedeli et al. PRL 116 (2016)
T.Ceccotti et al. PRL 111 (2013)
V.Kaymak et al. PRL 117 (2016)
S. Jiang et al. PRL 116 (2016)
K.Q.Pan et al. PoP 23 (2016)
M.A.Purvis et al. NatPhot 7 (2013)

...

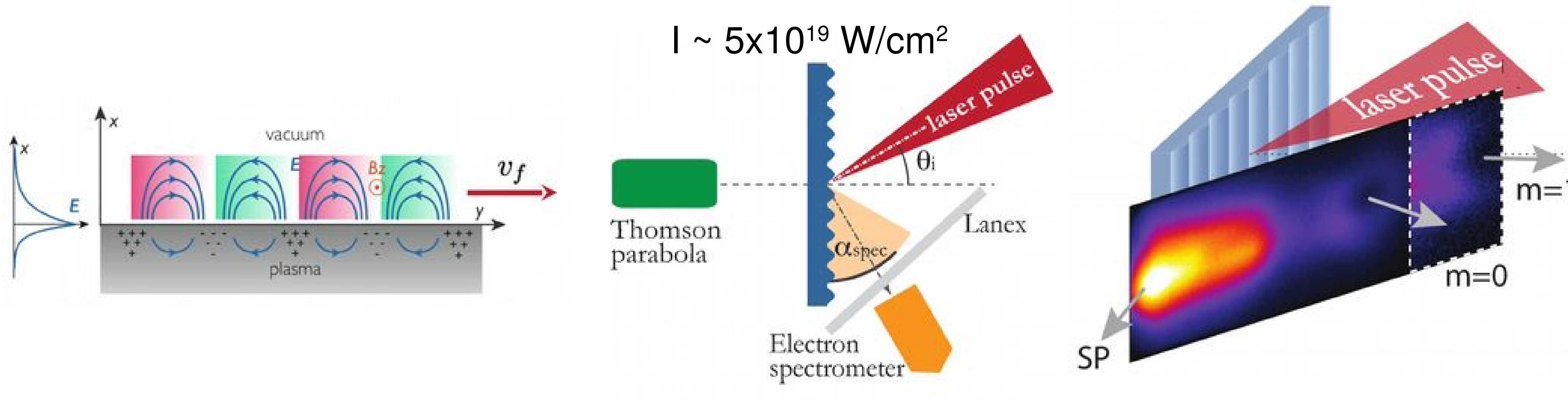




Nanostructured plasmas

High Field Plasmonics

Electron acceleration with a relativistic surface plasmon

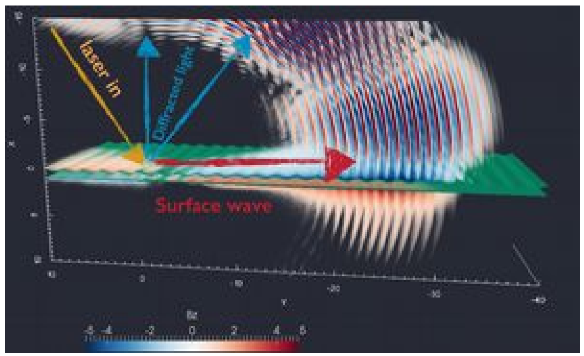


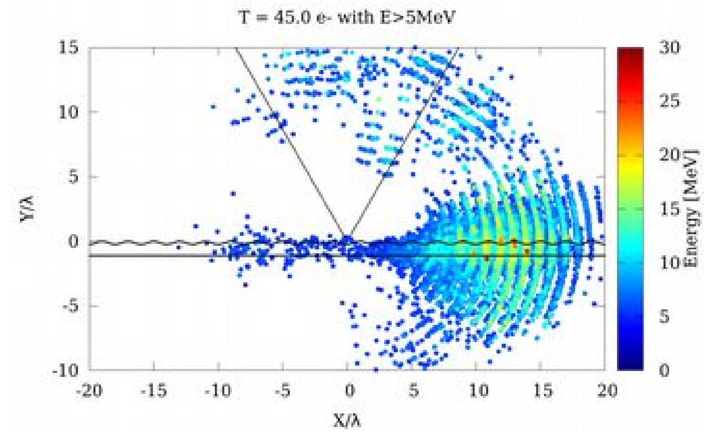
$$\frac{\omega}{c}\sin(\theta)=\frac{\omega}{c}\sqrt{\frac{1-\omega_p^2/\omega^2}{2-\omega_p^2/\omega^2}}\pm n\frac{2\pi}{d}$$

L.Fedeli et al. PRL 116 (2016)

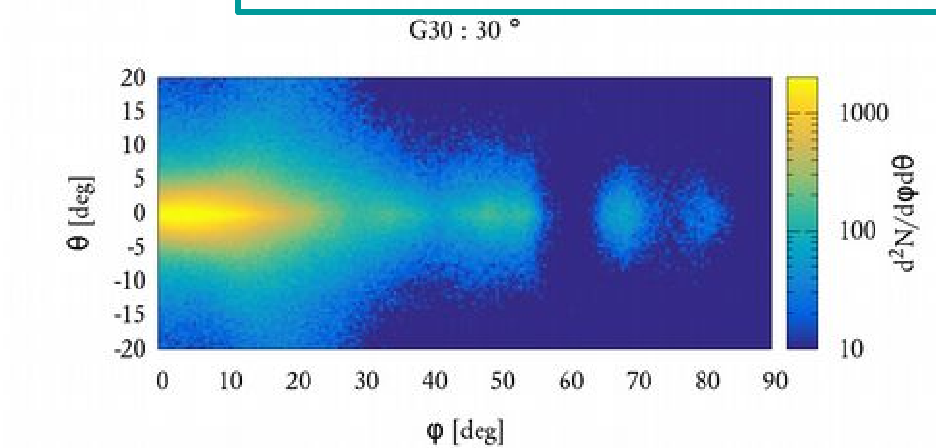
Nanostructured plasmas

2D/3D PIC simulations confirmed the picture

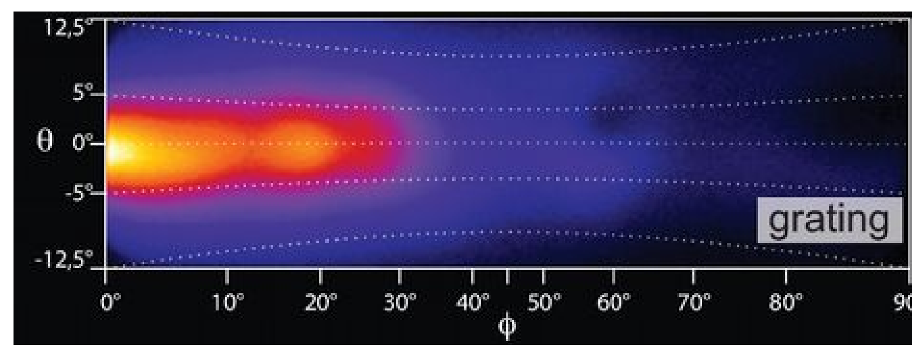




And were able to reproduce exp.results



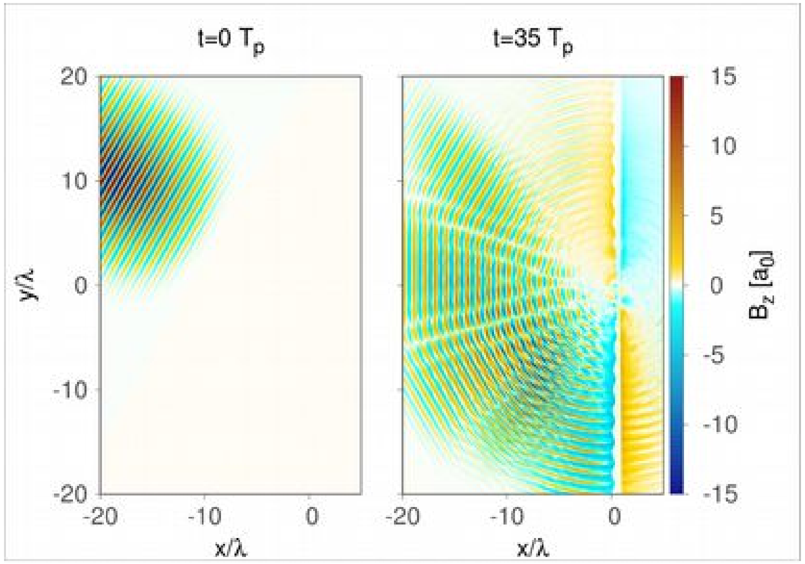
3D PIC Simulation



Exp. results

Other kinds of nanostructures plasmas

High Field Plasmonics
Enhanced high-order harmonic emission from irradiated grating targets



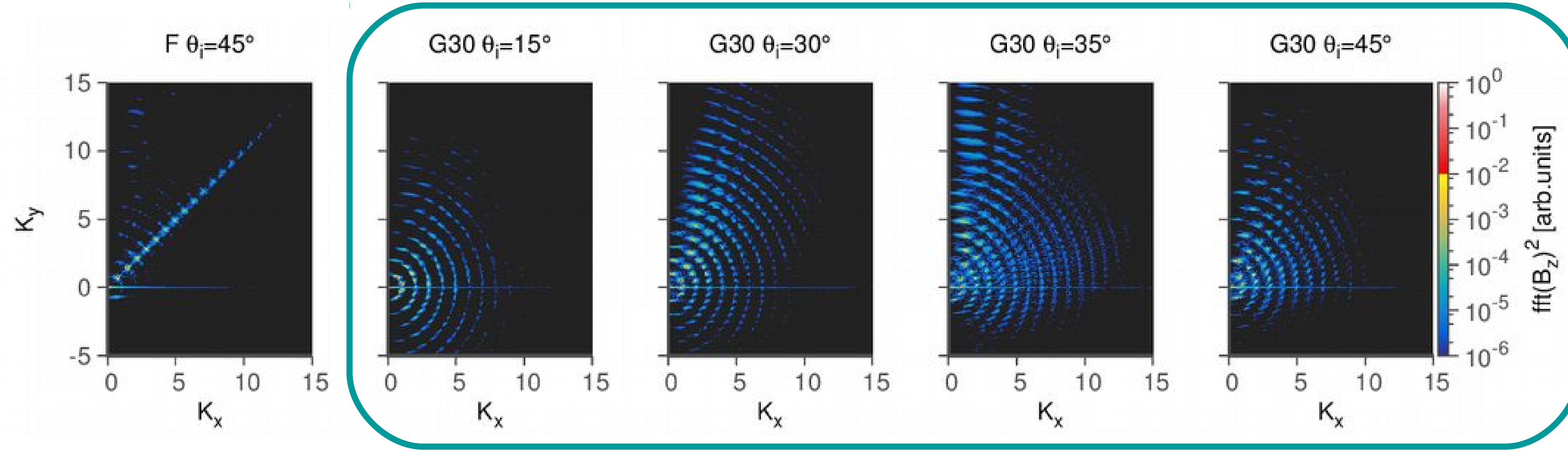
Dr A.Macchi

Dr A.Sgattoni

L.Fedeli et al. (to be submitted soon)

Other kinds of nanostructures plasmas

High Field Plasmonics
Enhanced high-order harmonic emission from irradiated grating targets



Exp. Resonance @ 30°

Dr A.Macchi

Dr A.Sgattoni

L.Fedeli et al. (to be submitted soon)

Conclusions

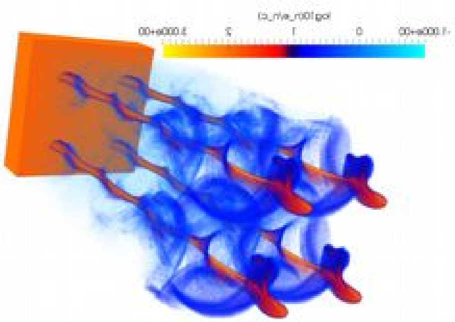
Conclusions

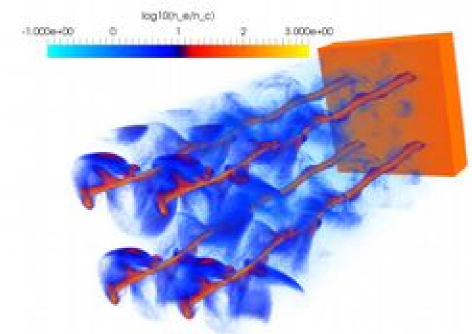
Ultra-intense, ultra-short, ultra-high contrast lasers allow to study **nanostructured plasmas**

Sometimes this is **desirable** (e.g. for gratings), sometimes it is **accidental** (e.g. for foams).

Nanostructure can strongly affect laser-plasma interaction and we **need simulations** to support and guide experimental activities

Since only recently ultra-short, ultra-high contrast lasers have become available, there are **many possible scenarios to study**.

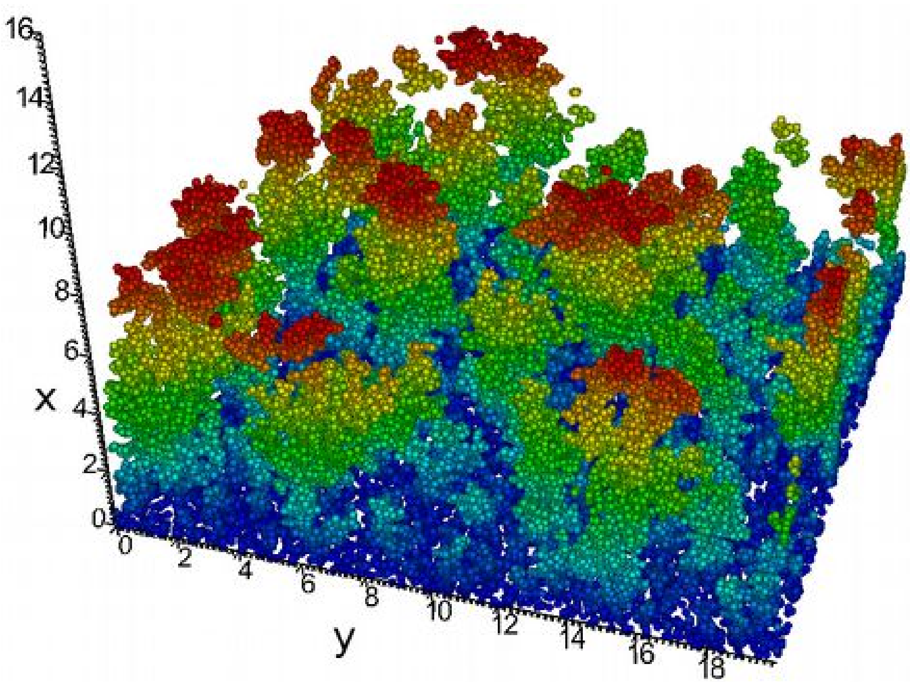




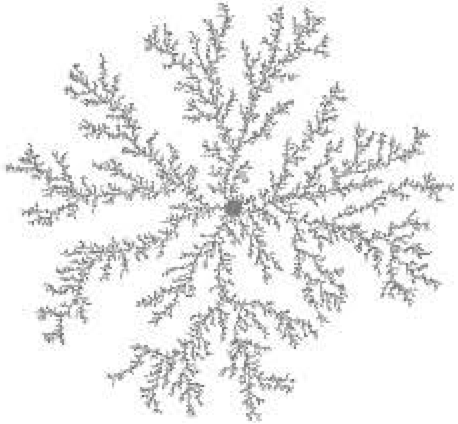
Thank you for your attention!

Diffusion-limited aggregation

How do we "build these structures"?



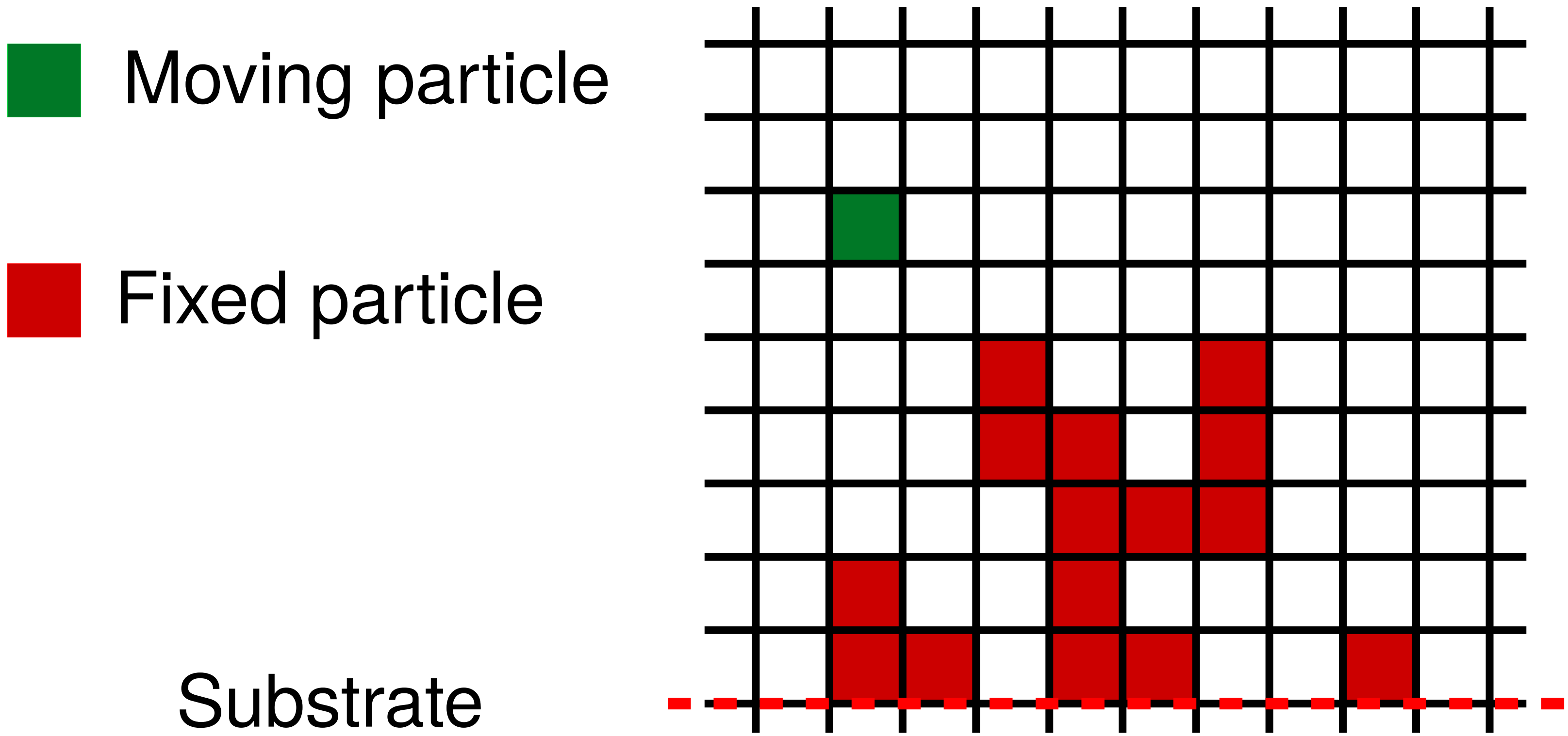
A very simple model



Which accurately describes many natural structures

T.A. Witten & L.M. Sanders PRL 47 (1981)

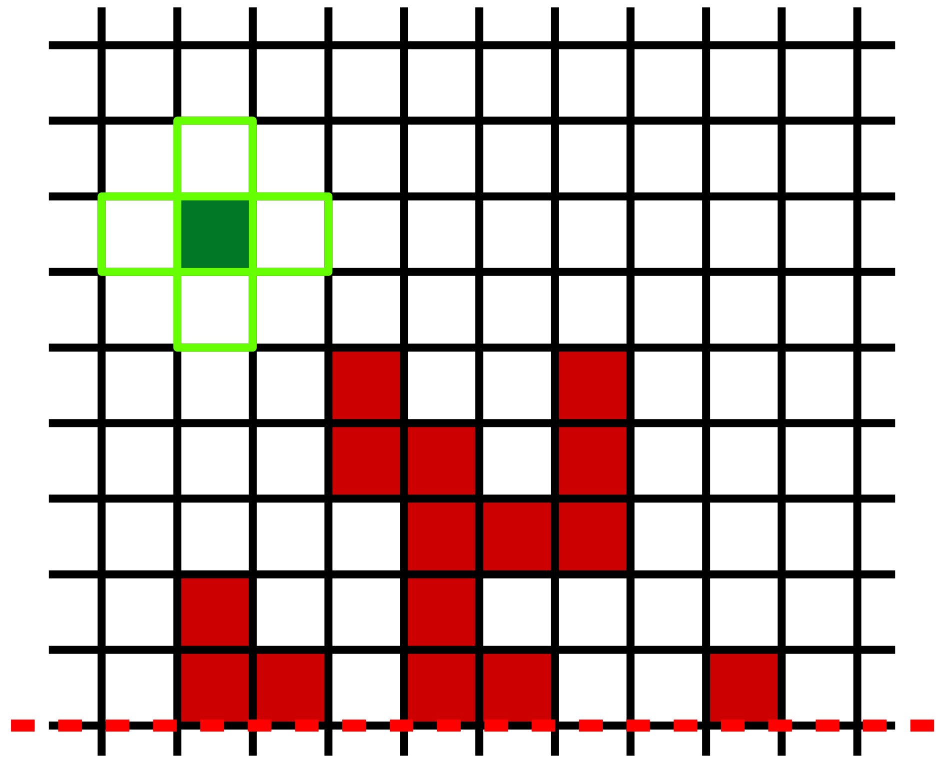
Diffusion-limited aggregation



Diffusion-limited aggregation

Moving particle

Fixed particle

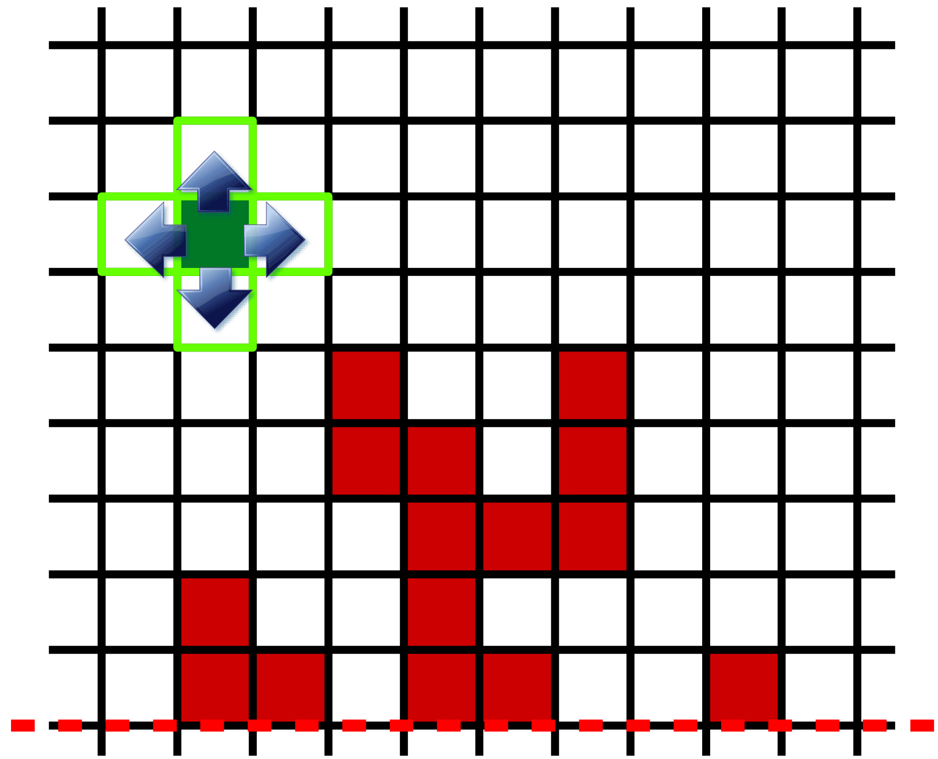


Check if surrounding
cells are free

Diffusion-limited aggregation

Moving particle

Fixed particle

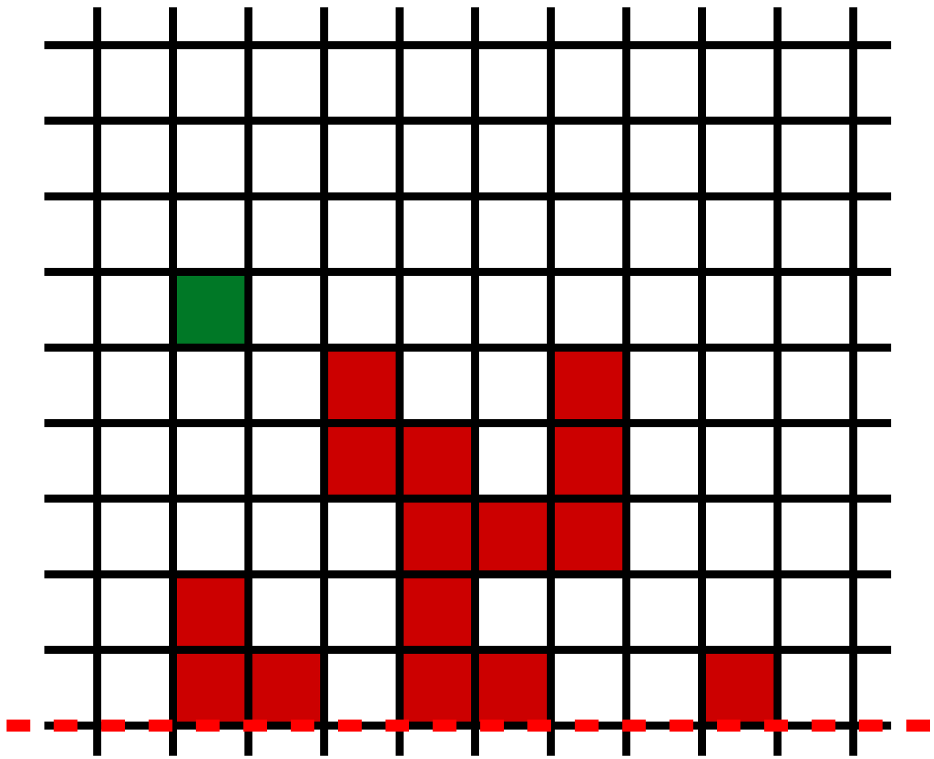


Random movement
on the grid

Diffusion-limited aggregation

Moving particle

Fixed particle

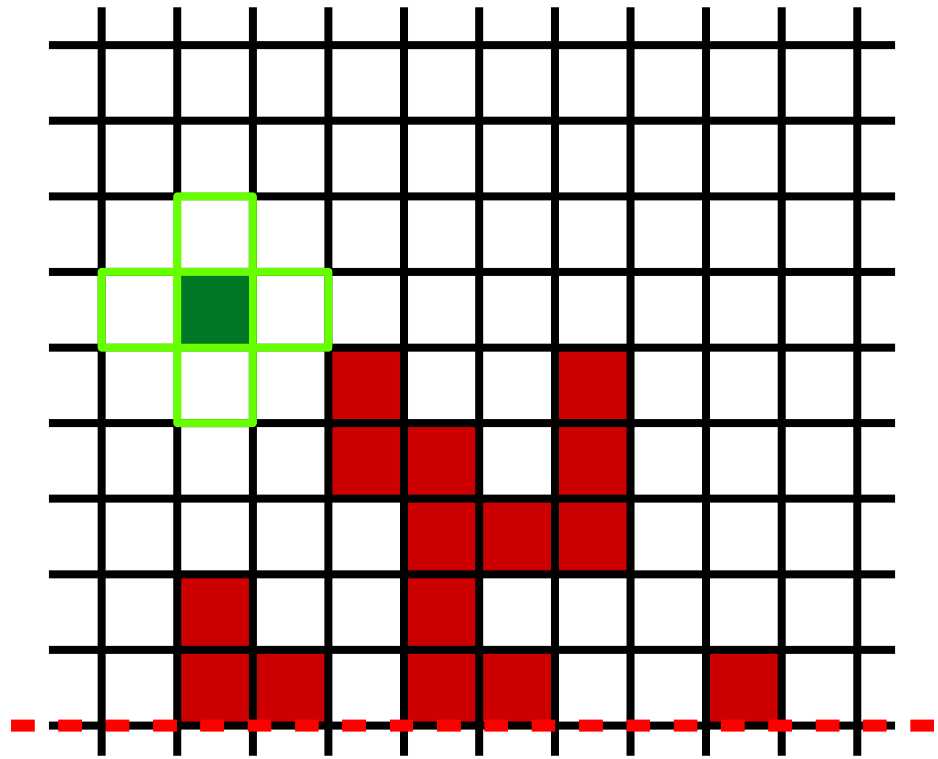


The particle moves

Diffusion-limited aggregation

Moving particle

Fixed particle

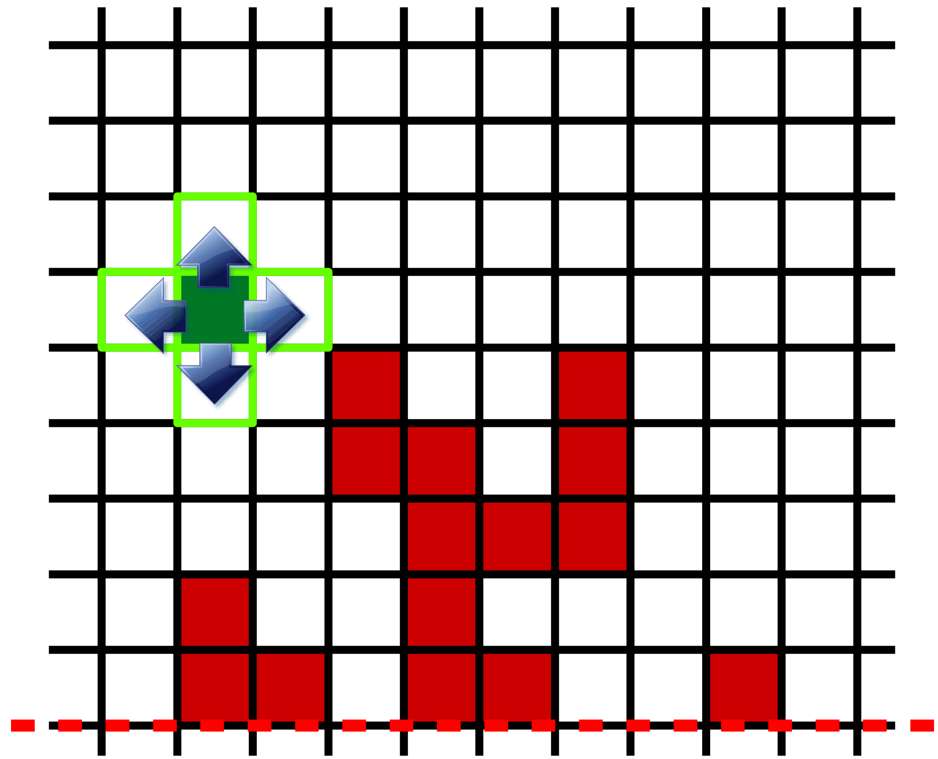


Check if surrounding
cells are free

Diffusion-limited aggregation

Moving particle

Fixed particle

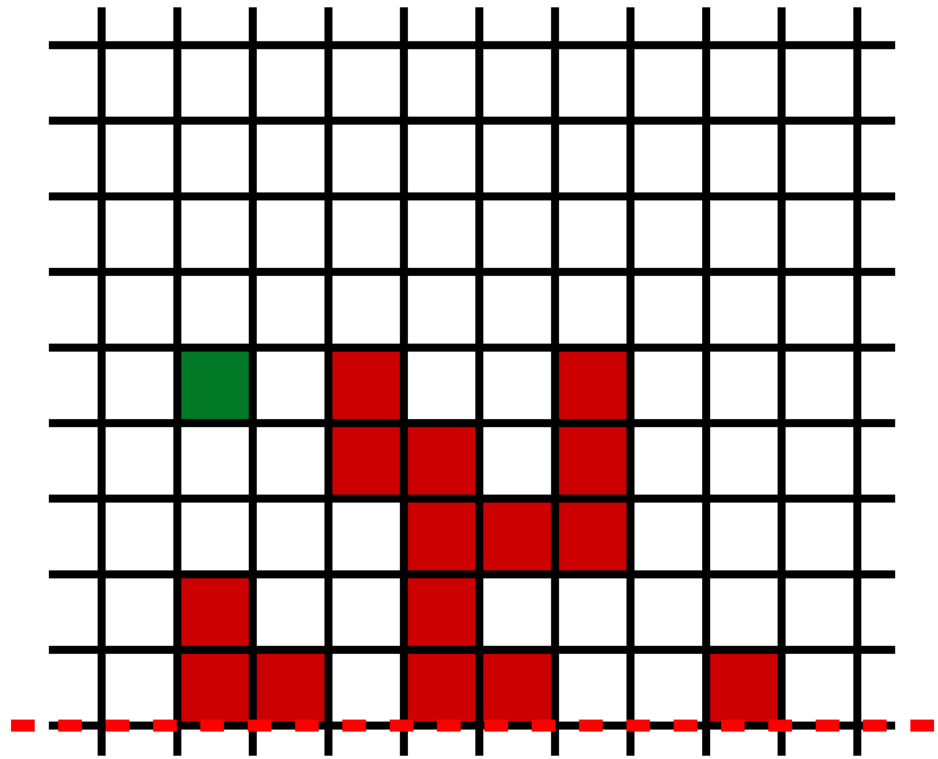


Random movement
on the grid

Diffusion-limited aggregation

Moving particle

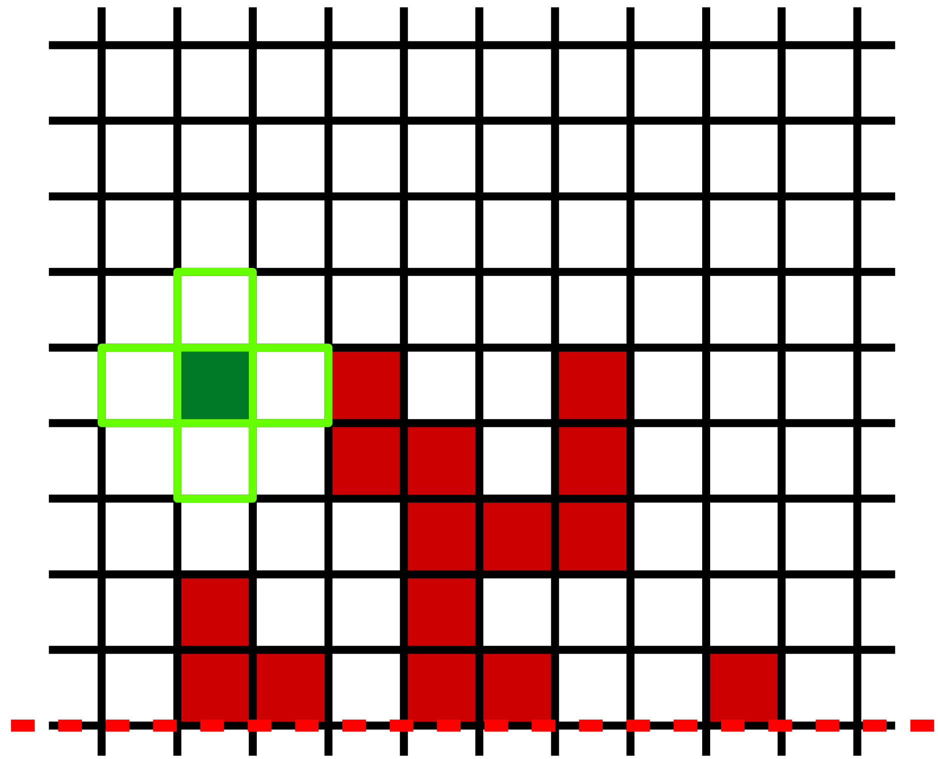
Fixed particle



Diffusion-limited aggregation

Moving particle

Fixed particle



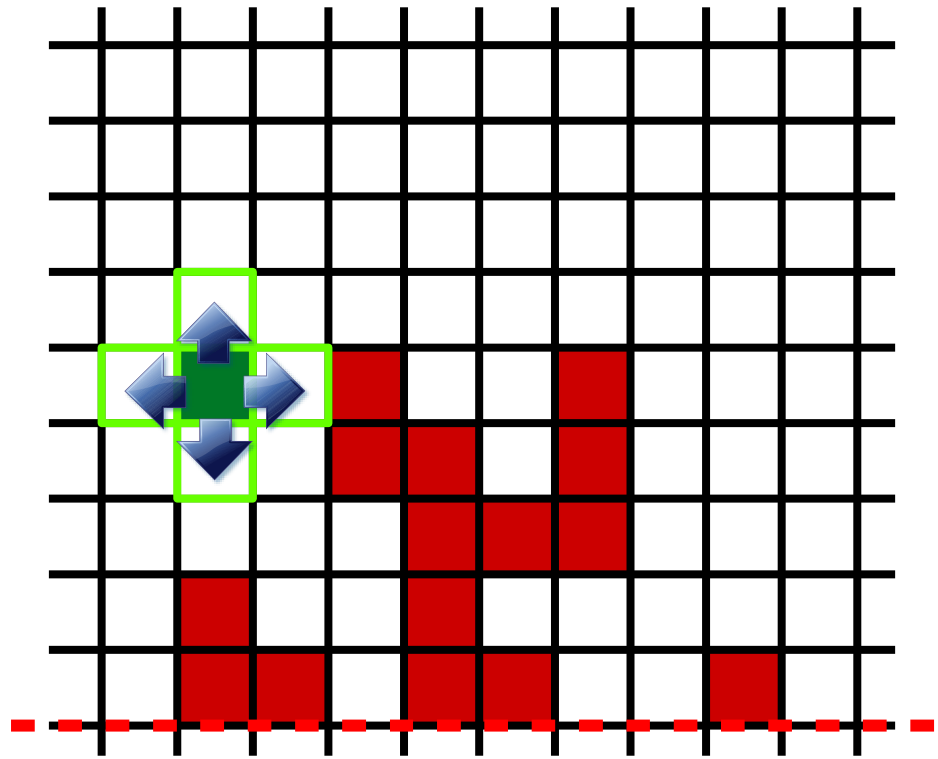
?

Check if surrounding cells are free

Diffusion-limited aggregation

Moving particle

Fixed particle

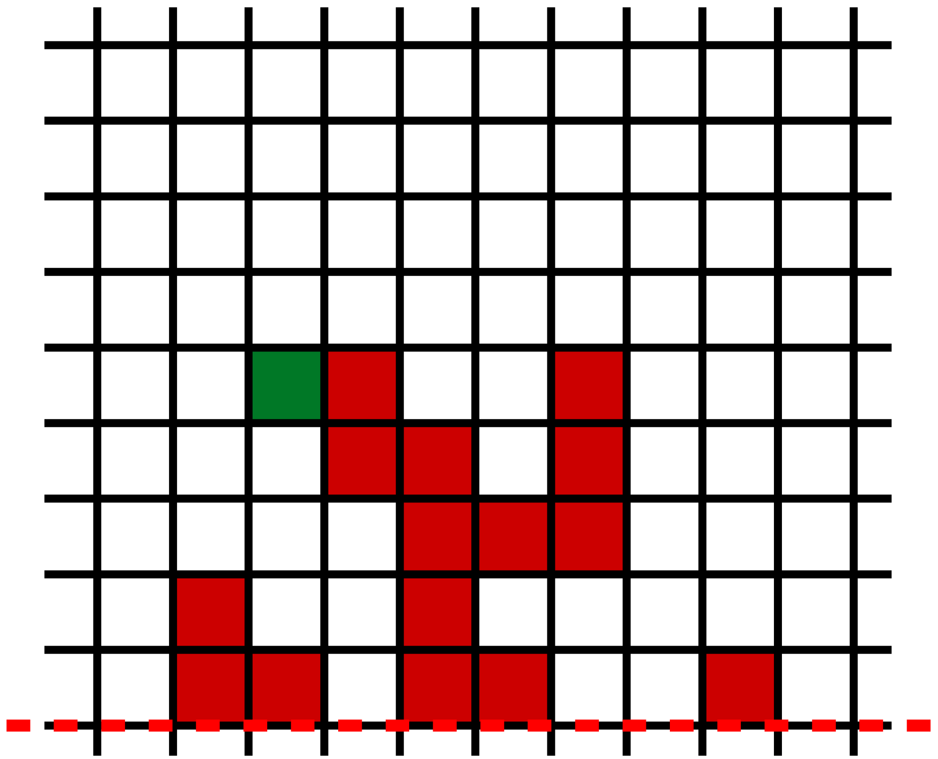


Random movement
on the grid

Diffusion-limited aggregation

Moving particle

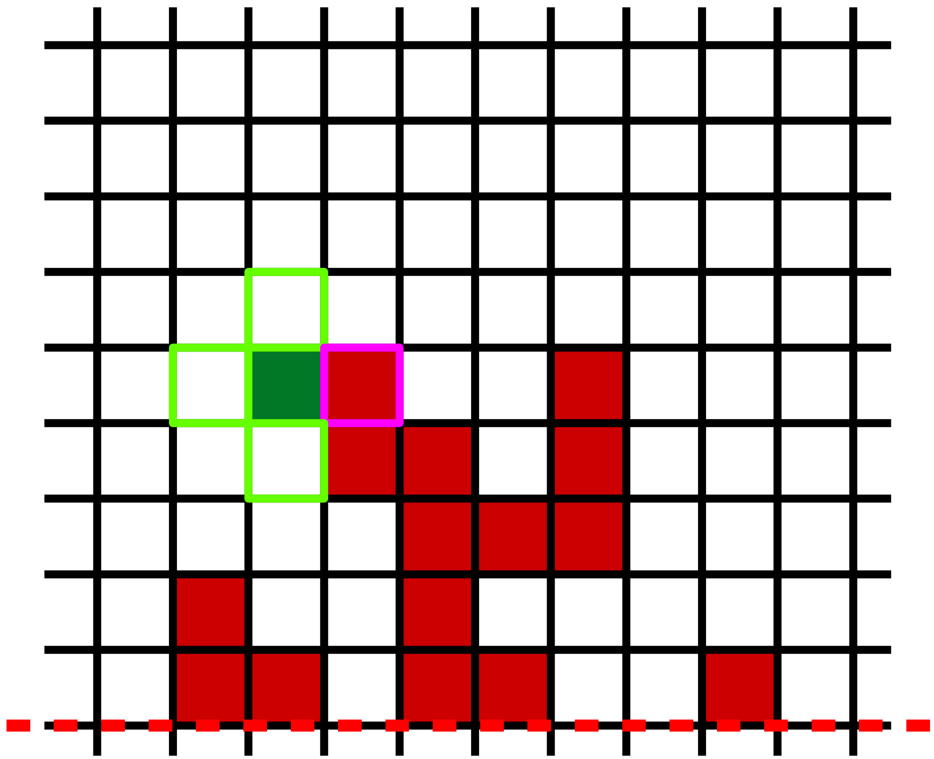
Fixed particle



Diffusion-limited aggregation

Moving particle

Fixed particle

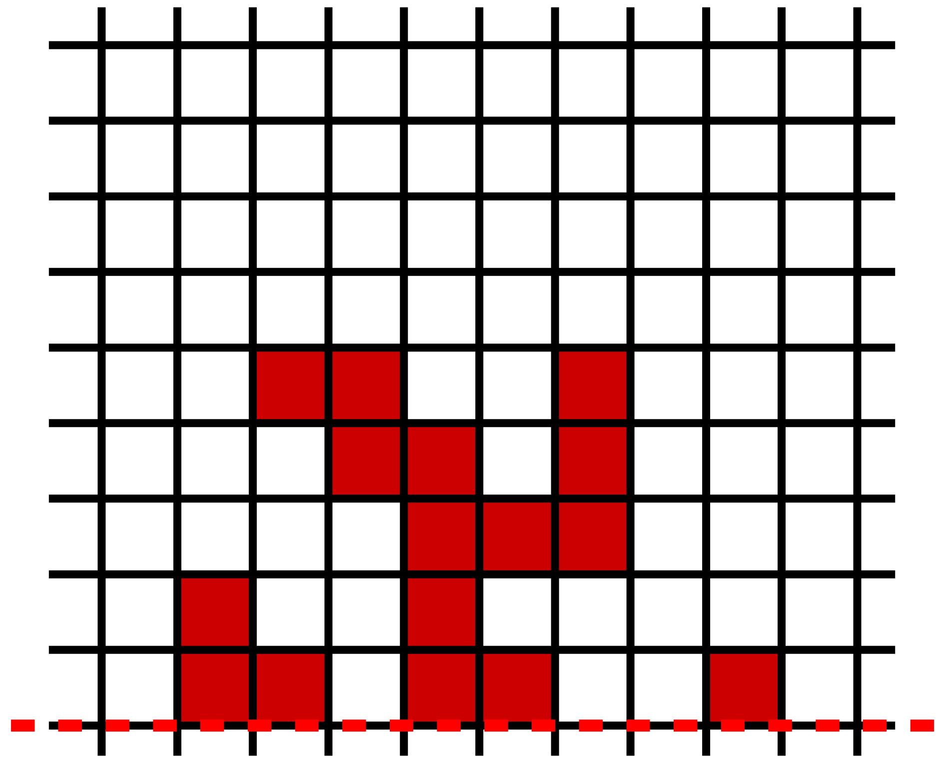


The particle touches a filled cell. It stops there

Diffusion-limited aggregation

Moving particle

Fixed particle

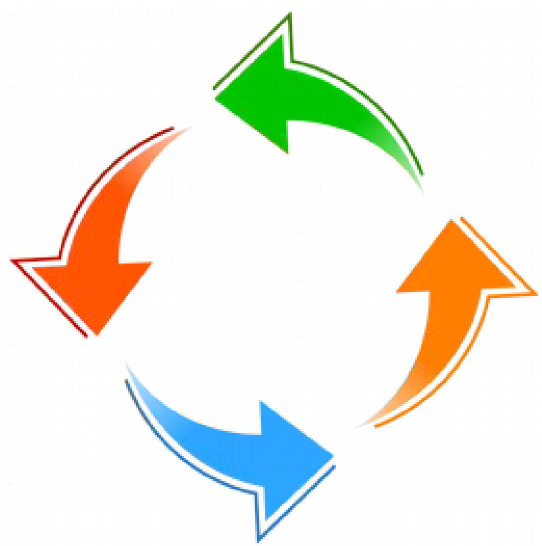


The particle touches a filled cell. It stops there

Diffusion-limited aggregation

Moving particle

Fixed particle



A new particle starts from the edge of the grid