POLITECNICO
MILANO 1863

Plasmonics at relativistic laser intensities:

particle acceleration and HHG

Luca Fedeli

Szeged, 12/10/2017

The ENSURE group at Politecnico di Milano

Matteo Passoni
Associate professor

ERC-2014-CoG No.647554
ENSURE

Collaborations with:

HZDR SourceLAB
OSAKA UNIVERSITY Queen's University Belfast

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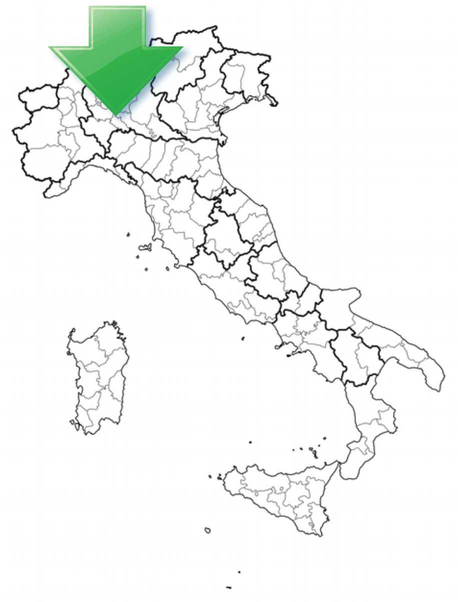

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We are interested in:

- Intense Laser-driven sources
- Material science applications of laser-driven sources
- Advanced targetry

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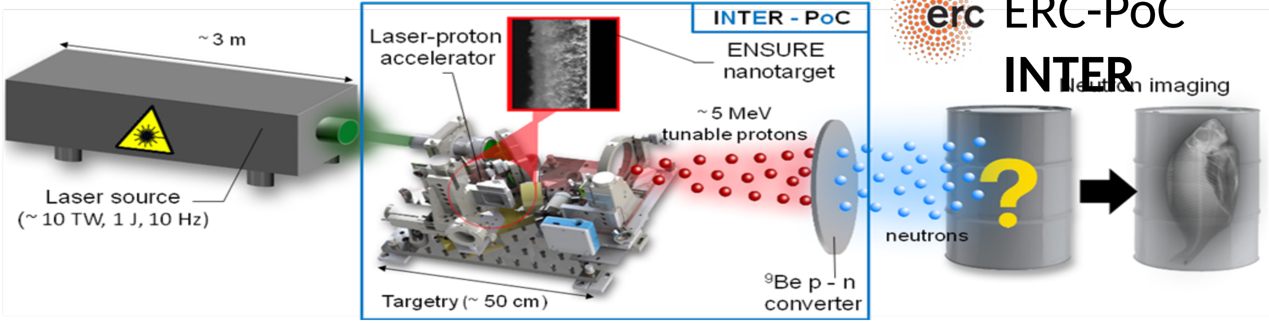
erc ERC-PoC
INTER



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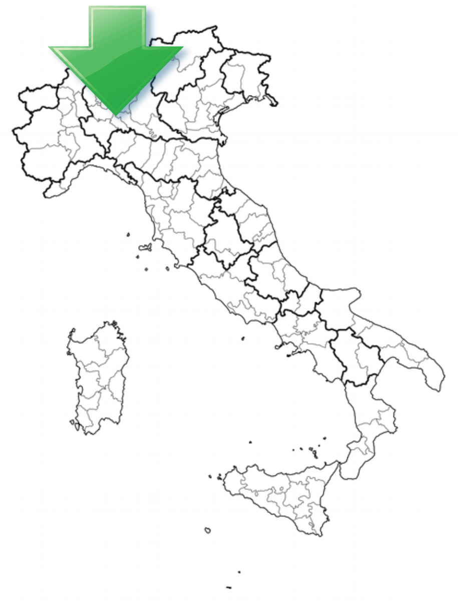

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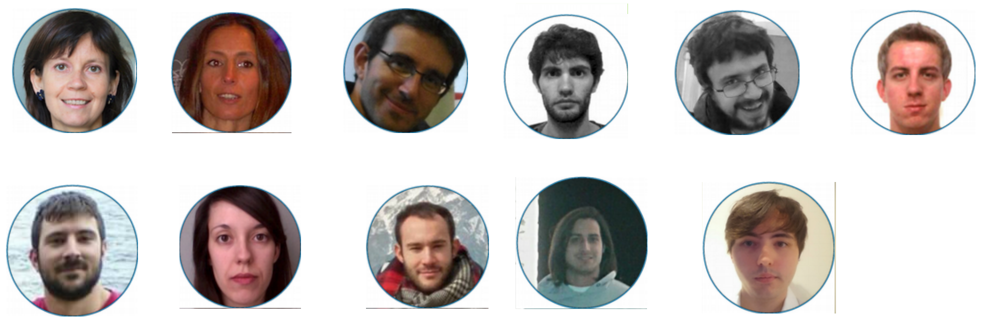
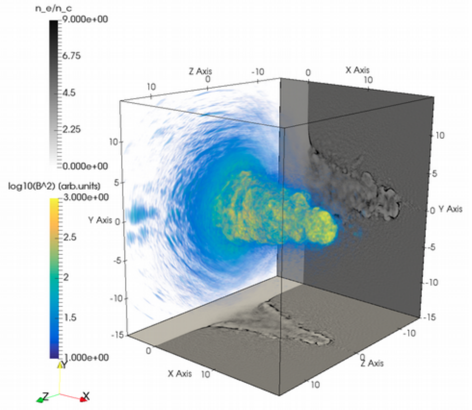


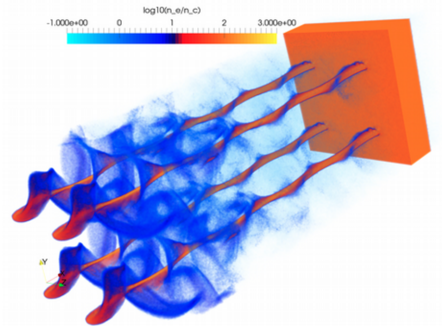
Our expertise:

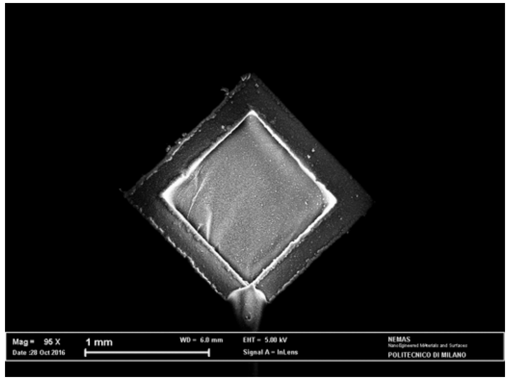
- Materials science
- Theory & sim of intense laser-plasma interaction

Collaborations with:

HZDR · SourceLAB · OSAKA UNIVERSITY · Queen's University Belfast







Plasmonics at relativistic laser intensities

Plasmonics at **relativistic laser intensities**

At I ~ 10^{18} W/cm^2 electrons become relativistic in one laser cycle

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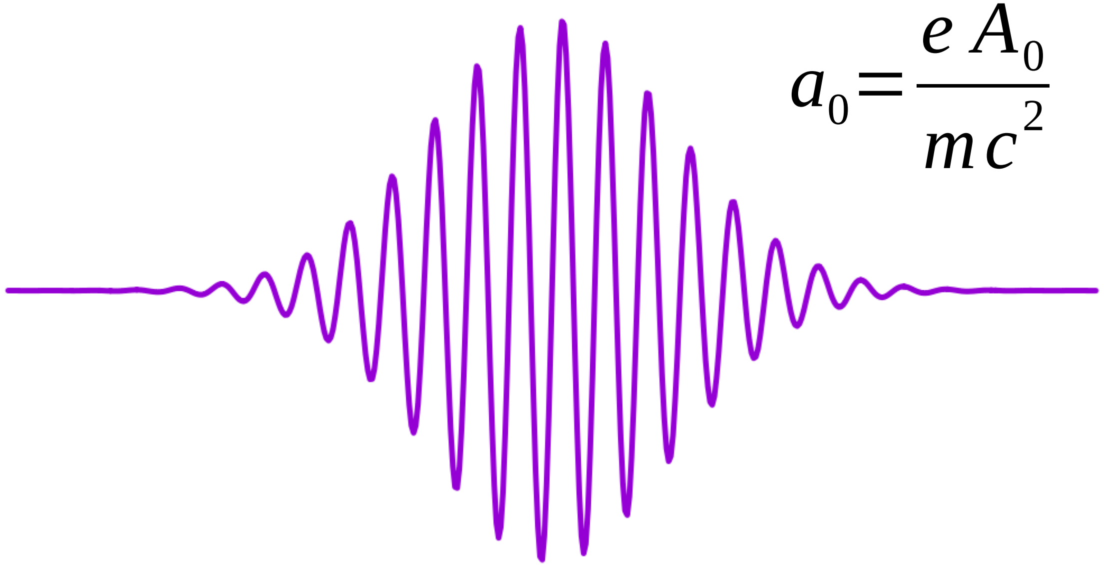

$$a_0 = \frac{e A_0}{m c^2}$$

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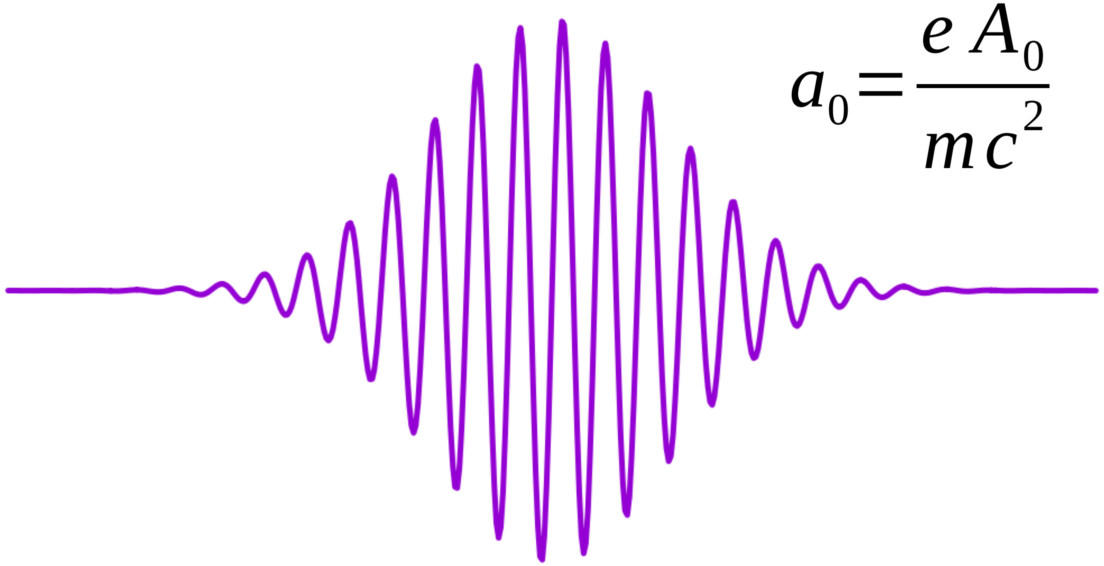

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Relativistic regime: $a_0 > 1$

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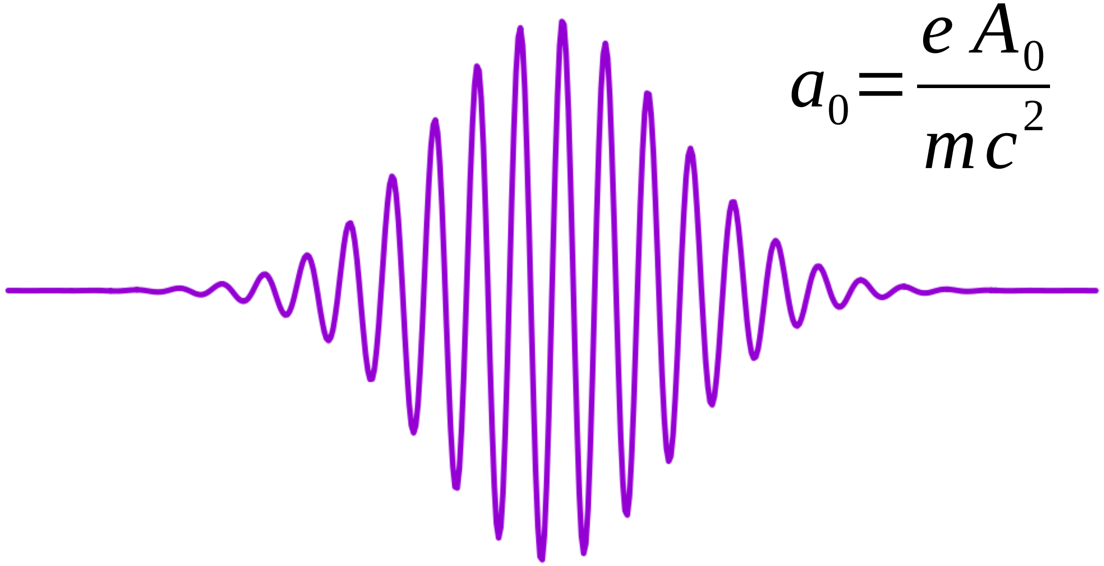
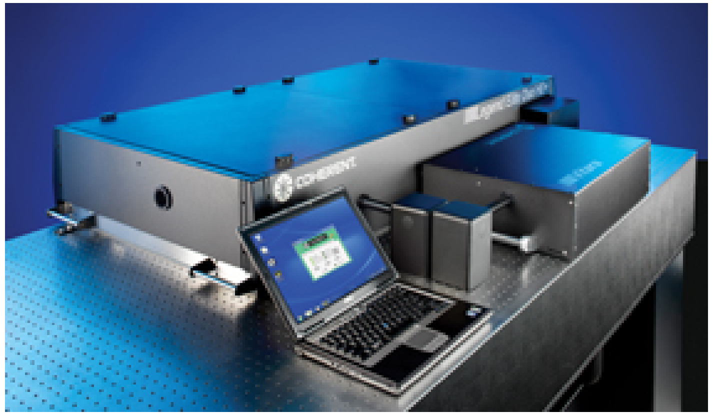


$$a_0 = \frac{e A_0}{m c^2}$$

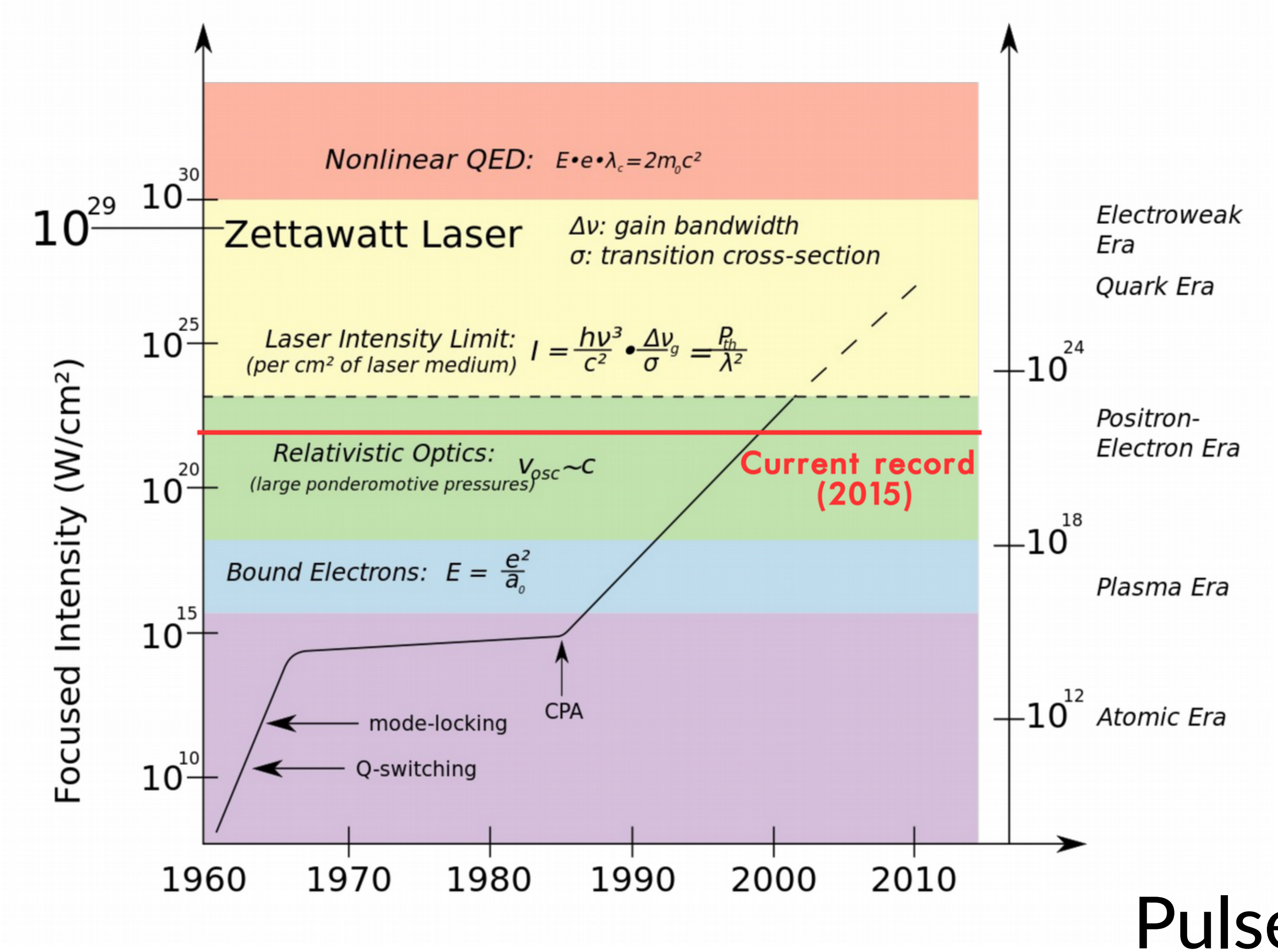
Relativistic regime: $a_0 > 1$

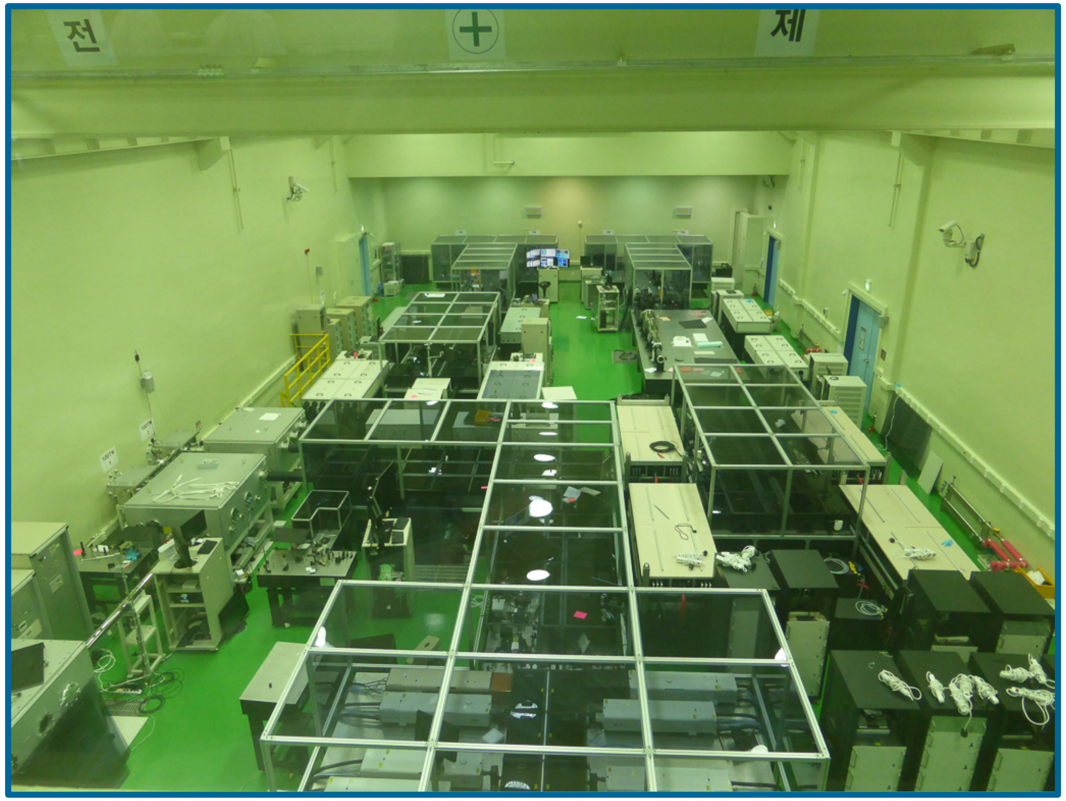
Mainly Ti:Sapphire-based systems



Nowadays these intensities can be obtained with table-top setups

Laser facilities can reach intensities of ~ 10^{22} W/cm^2

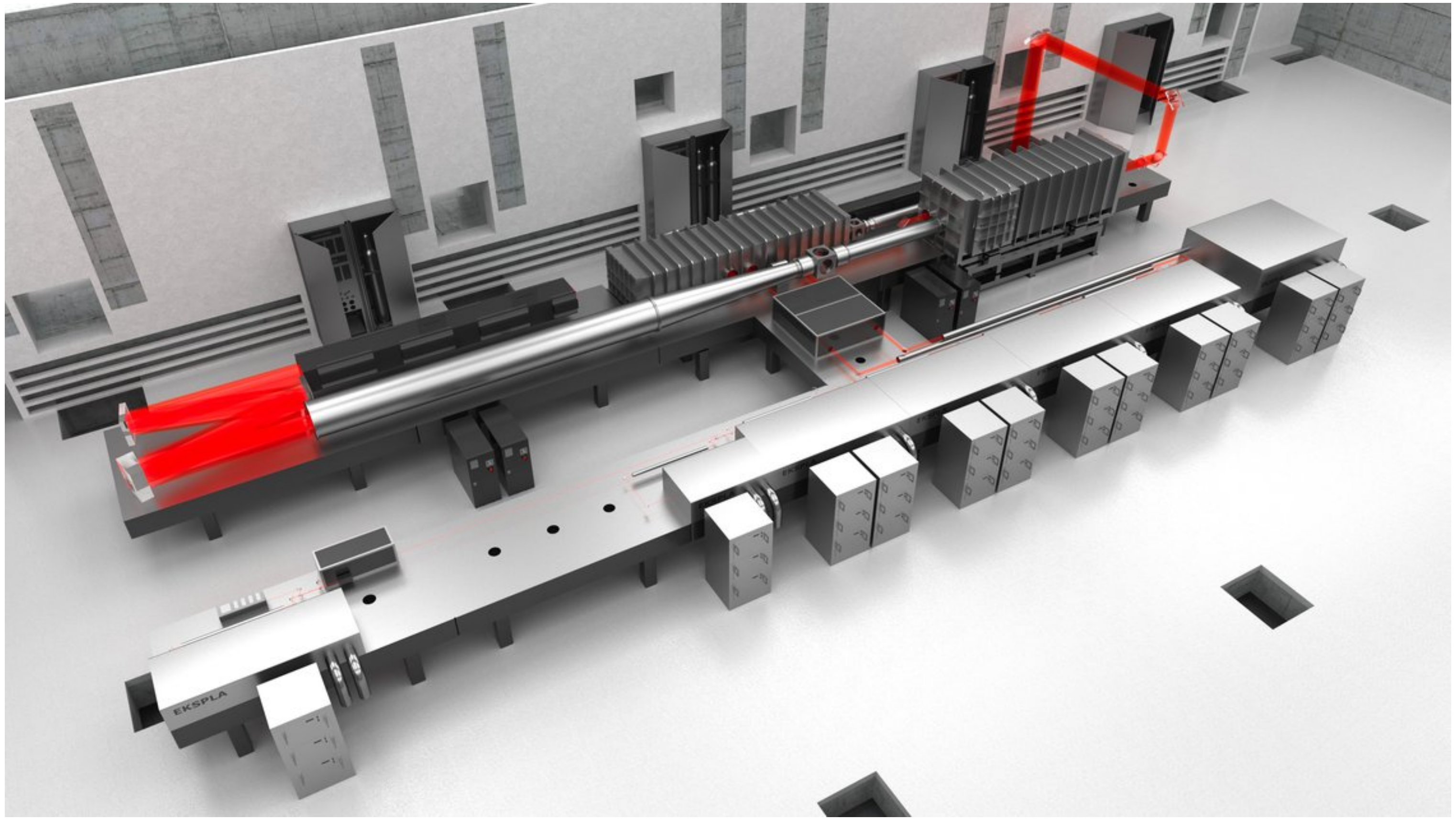




Pulser PW laser (Gwangju, Rep.of Korea)

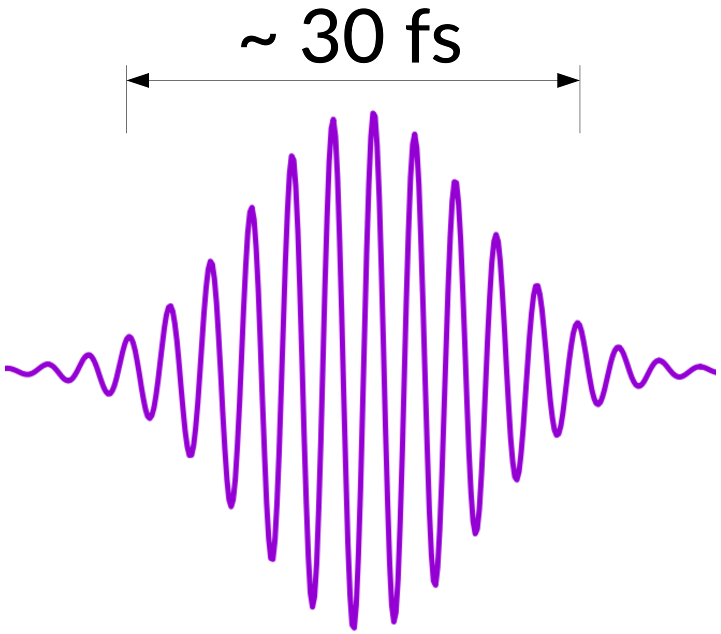
ELI-beamlines, Apollon...
aim at > 10^{23} W/cm^2

eli beamlines

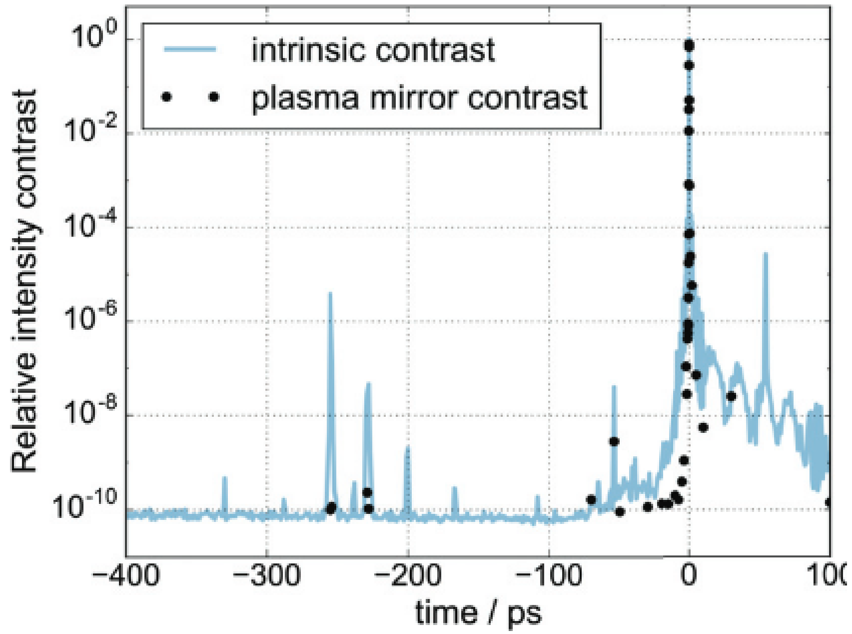


These ultra-intese lasers are:

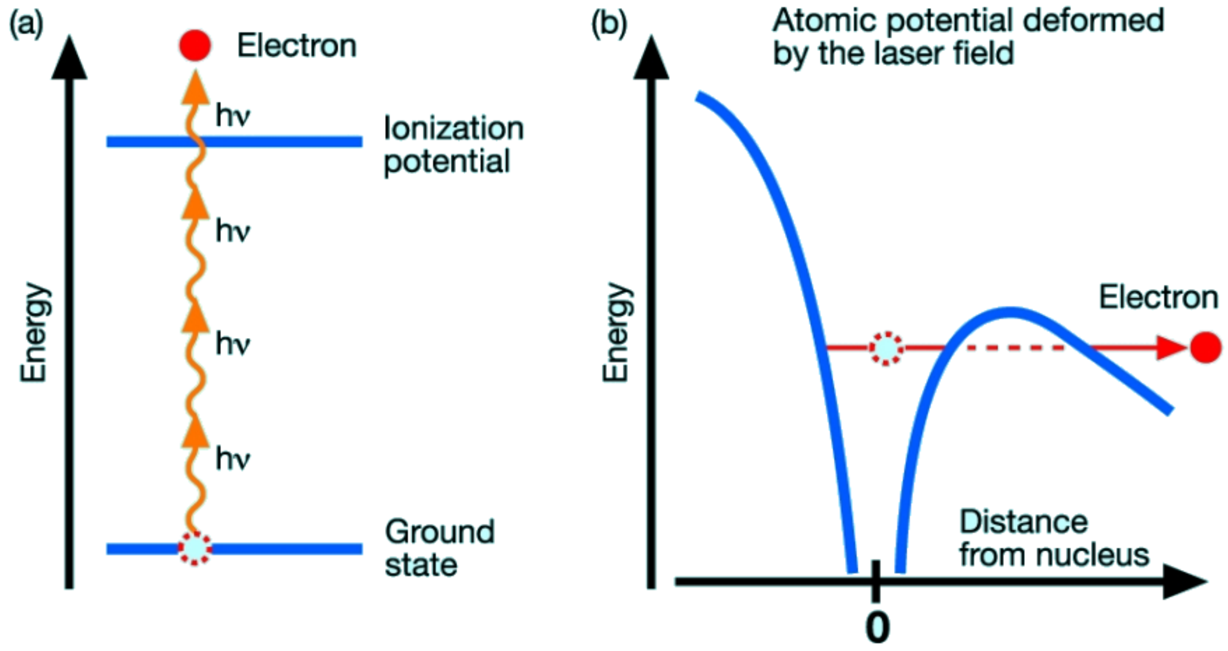
- Ultra-short



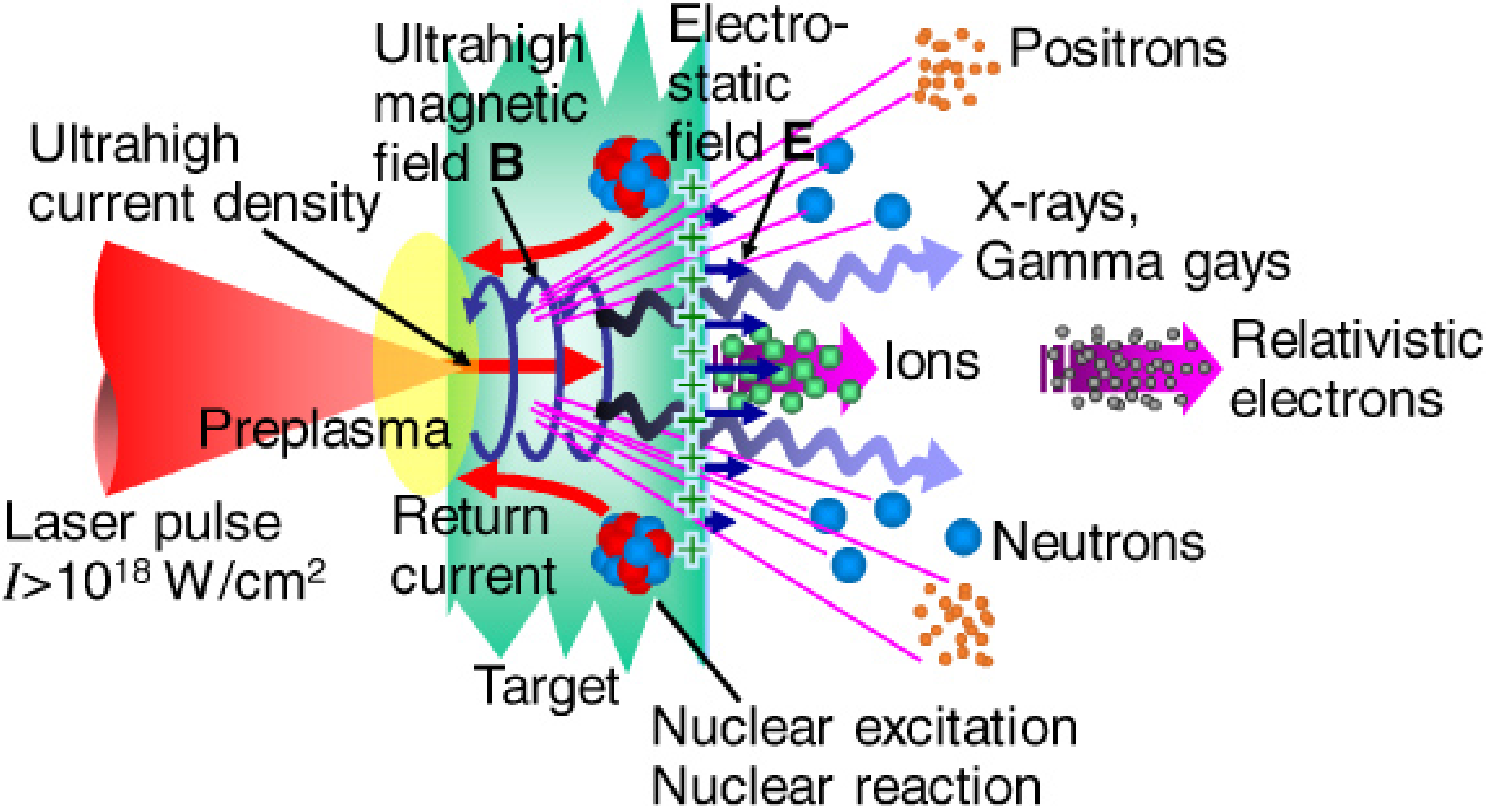
- Ultra-high contrast



At these intensities everything becomes a plasma in few cycles



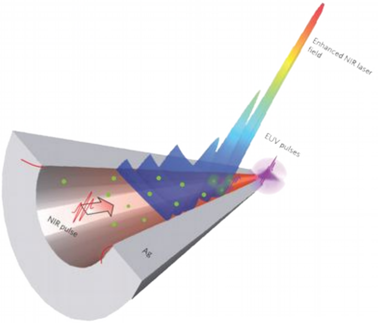
Applications: accelerating particles, photon sources, laboratory astrophysics

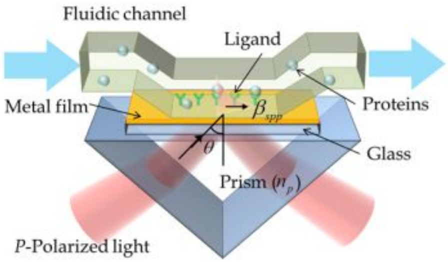


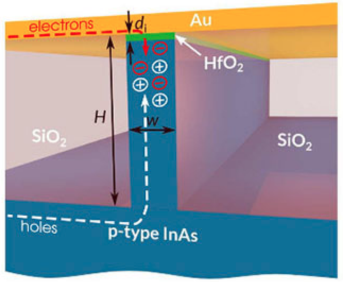
Plasmonics at **relativistic laser intensities**

Plasmonics at relativistic laser intensities

Plasmonics is a vibrant research field







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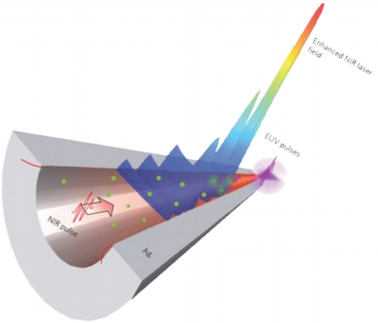
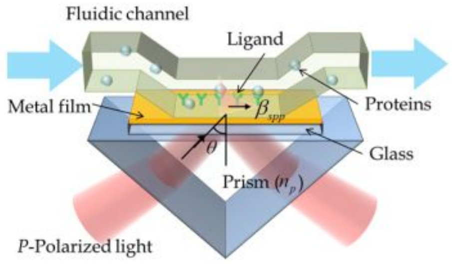
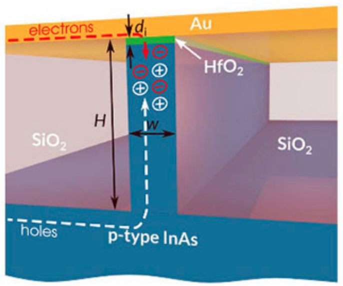
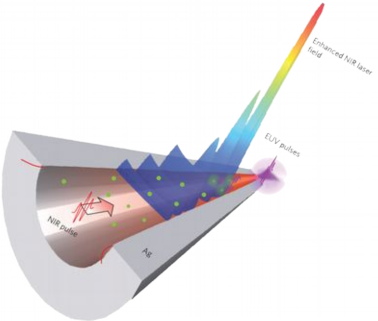


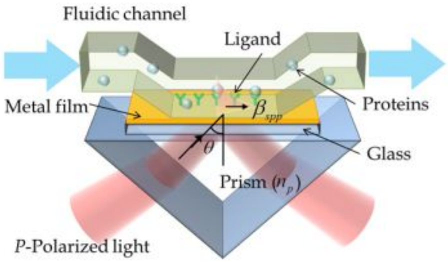


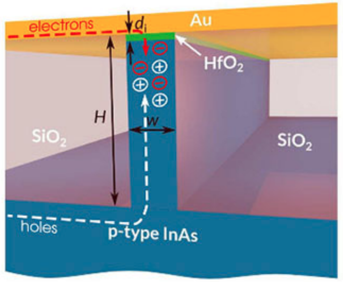


Can we port some of its ideas in the relativistic regime?

Plasmonics is a vibrant research field







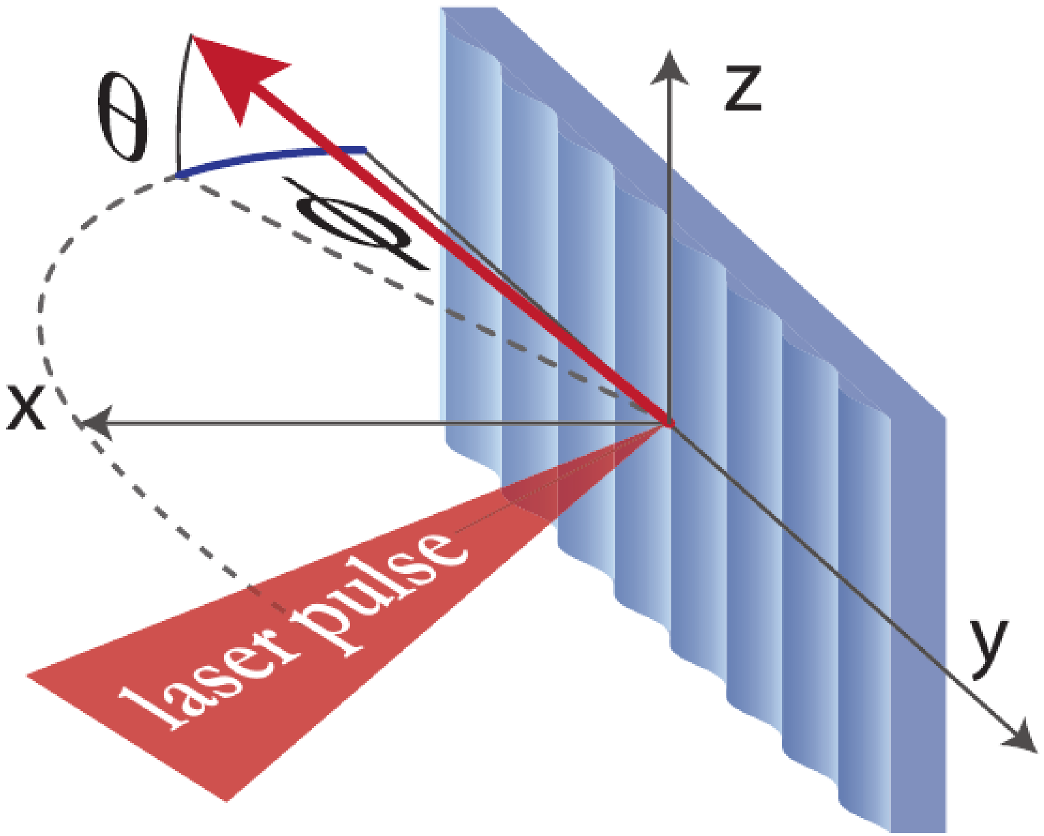
Can we port some of its ideas in the relativistic regime?

Almost unexplored topic

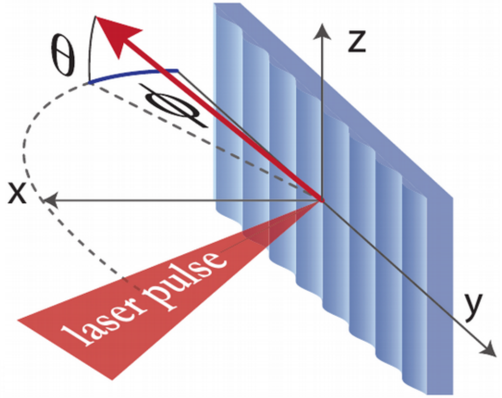
What schemes from plasmonics might be suitable?

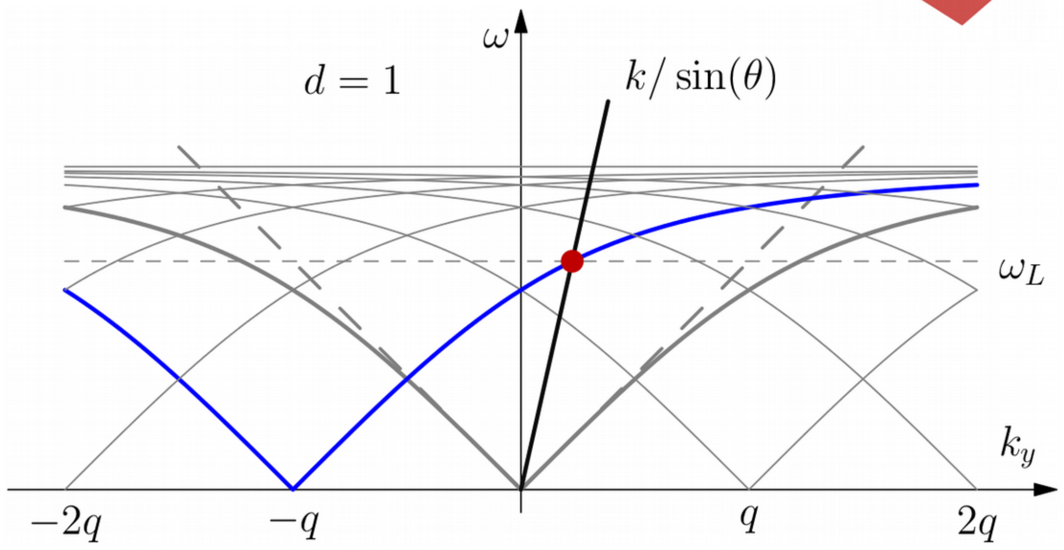
❗ we don’t have dielectrics at ultra-high intensity

We might use a grating target



Gratings allow to excite surface plasmons if resonance is satisfied





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

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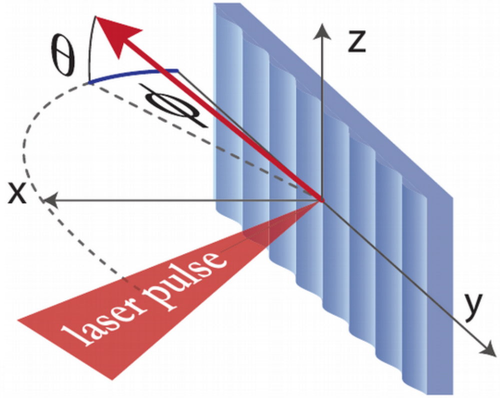

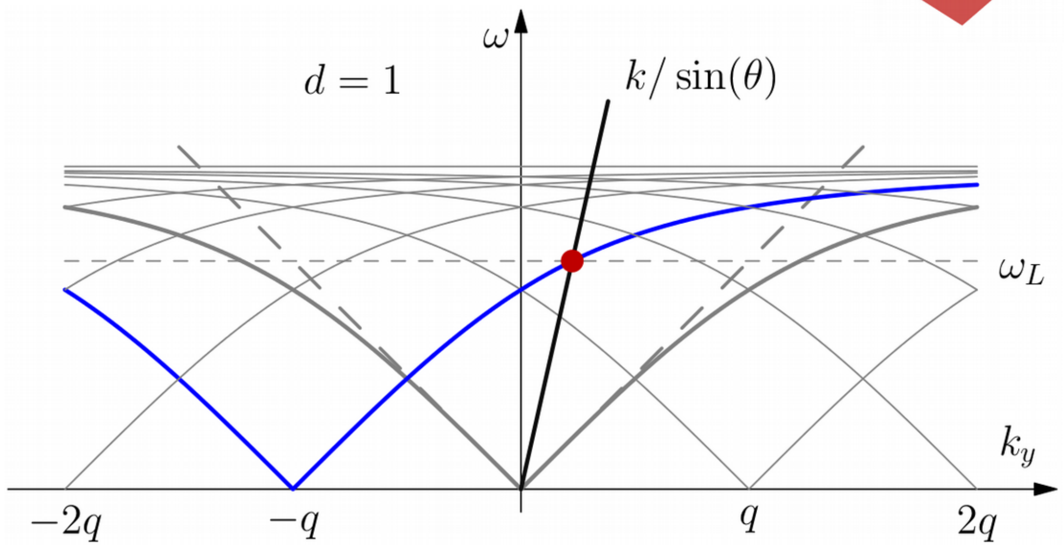

$$\frac{\omega}{c}\sin(\theta)=\frac{\omega}{c}\sqrt{\frac{1-\omega_p^2/\omega^2}{2-\omega_p^2/\omega^2}}\pm n\frac{2\pi}{d}$$

$$\frac{\omega}{c}\sin(\theta)\approx\frac{\omega}{c}\pm n\frac{2\pi}{d} \qquad (\omega_p \gg \omega)$$

How can we find if we are actually exciting surface plasmons?

We may have a look at several “observables”

- Resonant enhancement of laser-driven ions
(Ceccotti et al. PRL 111 2013)

- Acceleration of electrons along target surface by surface plasmon
(Fedeli et al. PRL 116 2016)

- Resonant enhancement of High-order Harmonic generation
(Fedeli et al. App.Phys.Lett. 110 2017)

Irradiated solid foils emit multi-MeV ions

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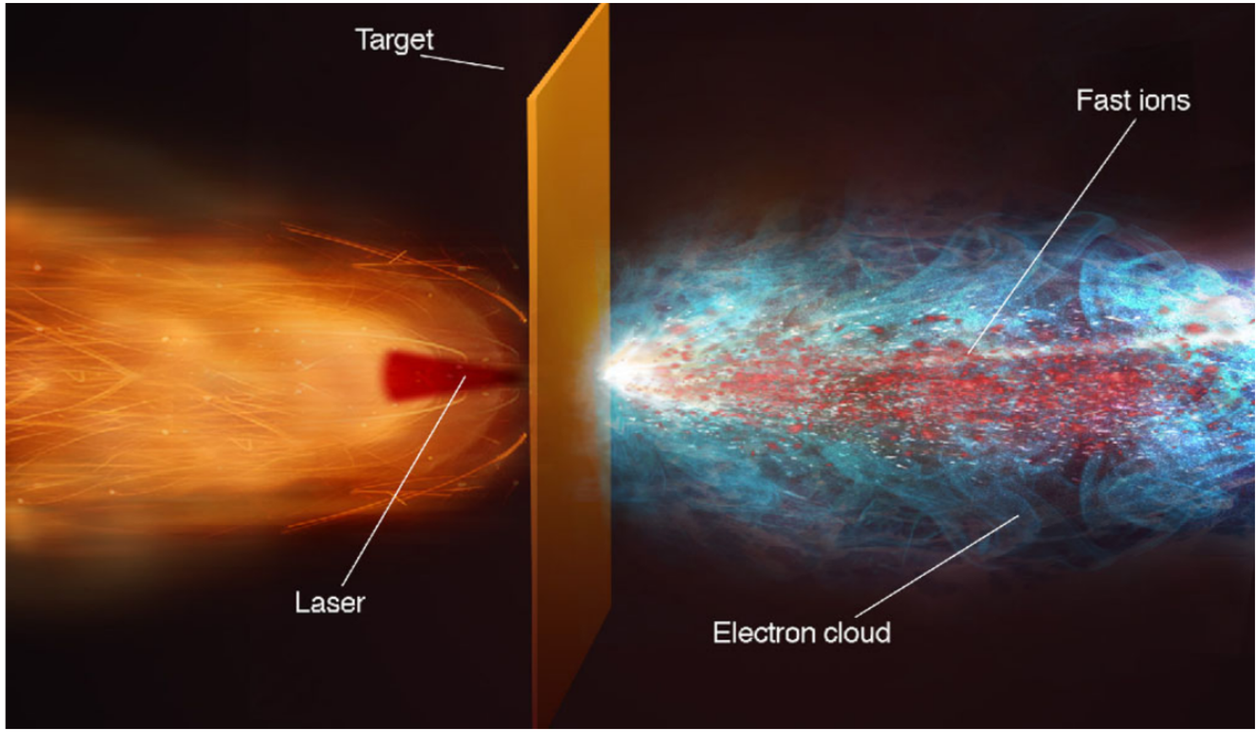
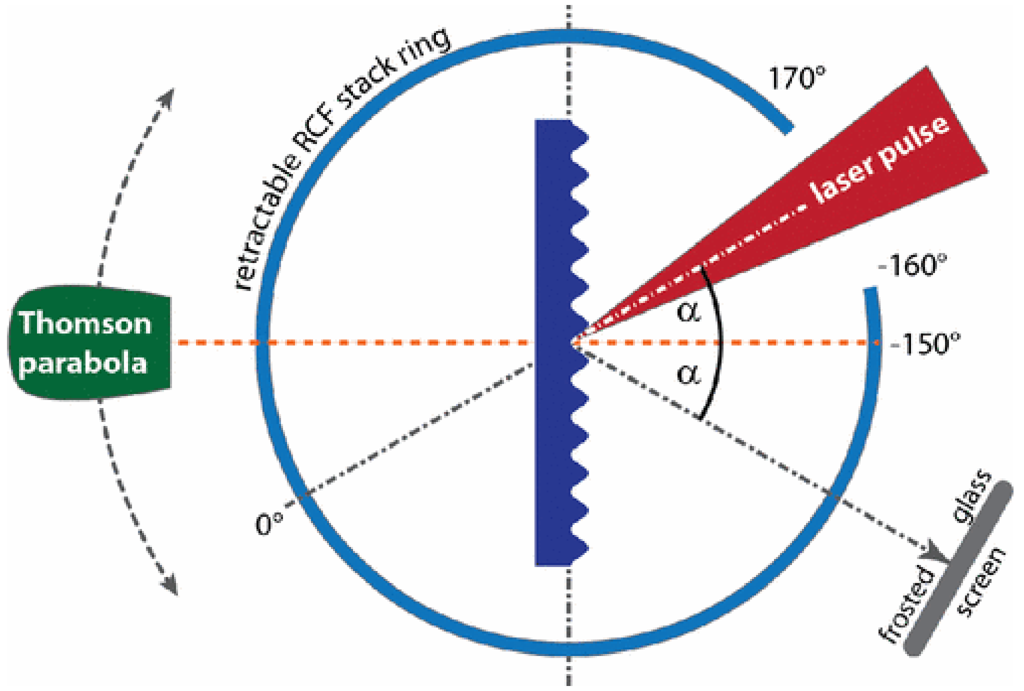


from Macchi et al. 2013. Rev.Mod.Phys.

Grating targets show resonant enhancement of ion acceleration



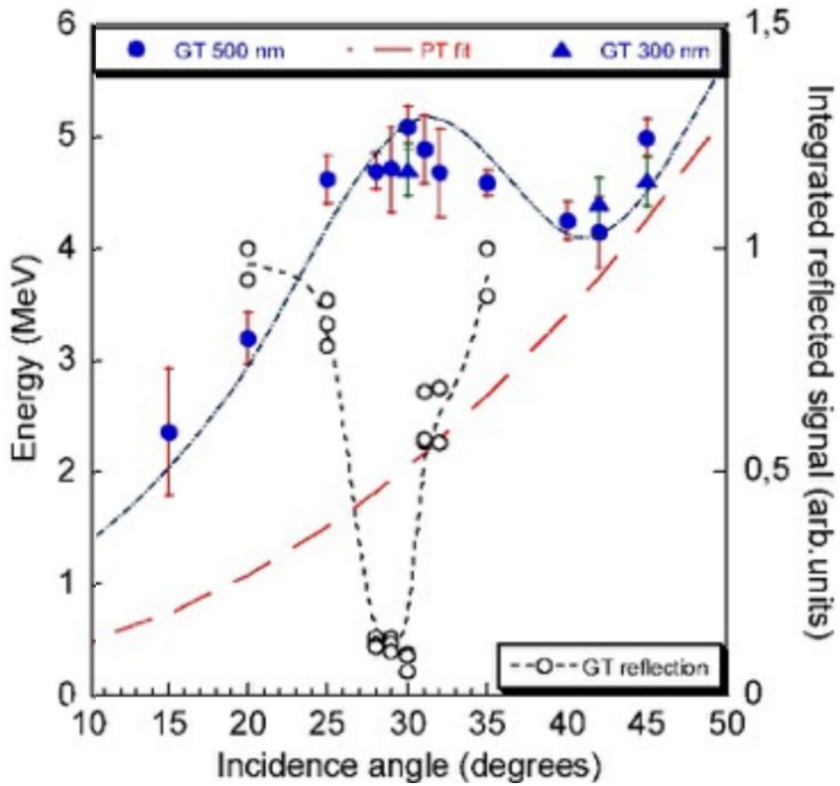
T.Ceccotti et al. PRL 111 (2013)

100 TW UHI laser
CEA-Saclay, Paris

I ~ 5×10^{19} W/cm^2
10^{12} pulse contrast

Gratings d = 2λ, 250 nm height
Expected resonance @ 30°

Grating targets show resonant enhancement of ion acceleration



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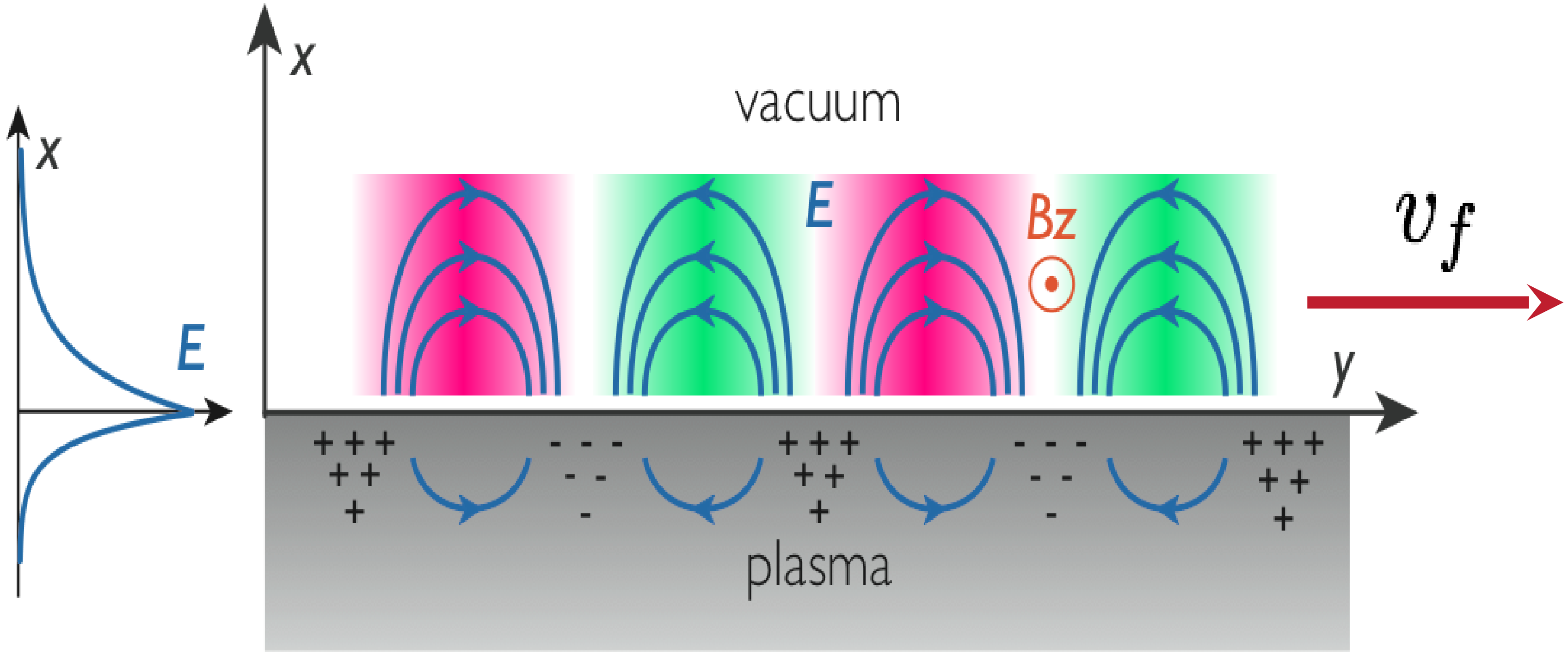
Relativistic fields can accelerate electrons at multi-MeV energies

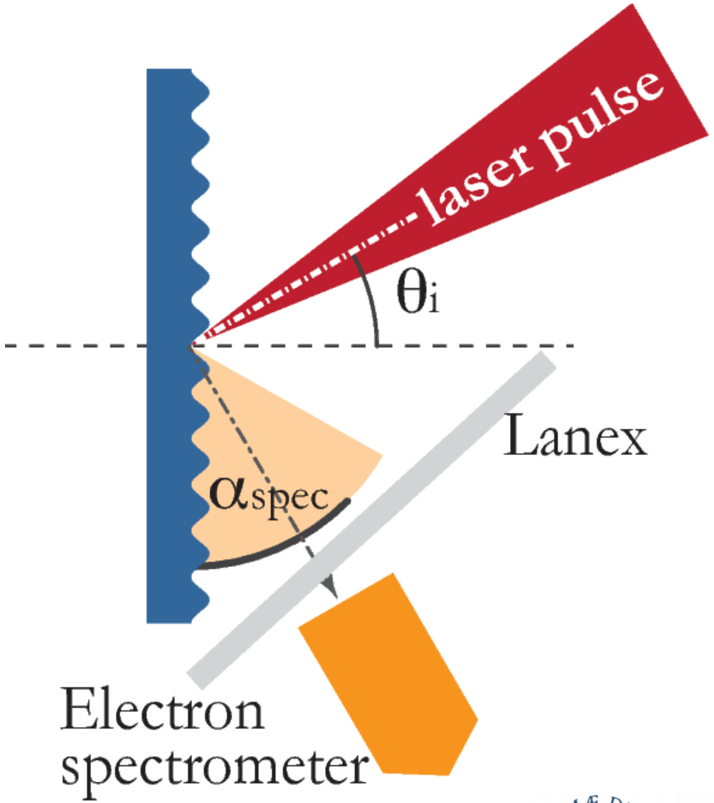
Can we use the fields of a Surface plasmon to accelerate e^- ?



M.Raynaud et al. Physics of Plasmas 14 (2007)

C.Riconda et al. Physics of Plasmas 22 (2015)

We irradiate again gratings, but with diagnostics for e⁻



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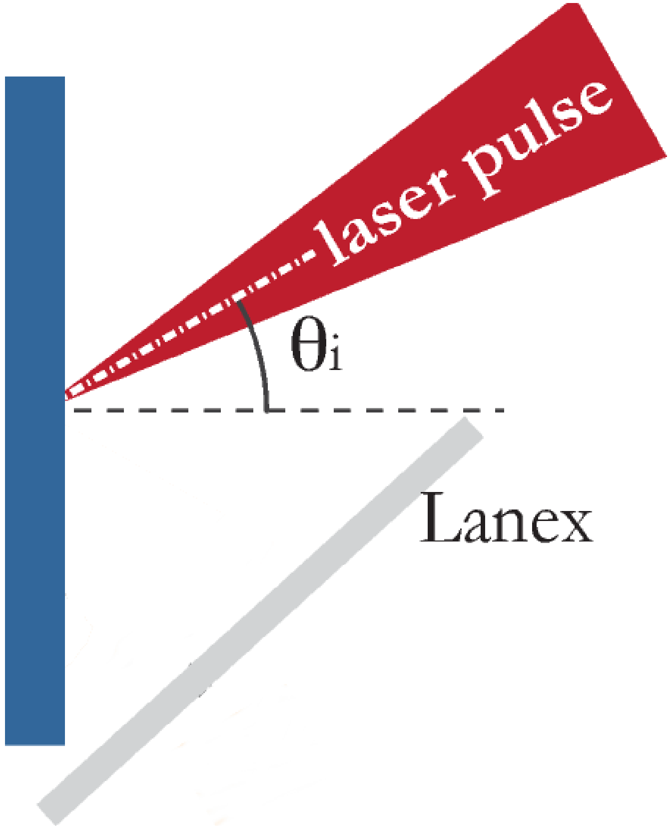
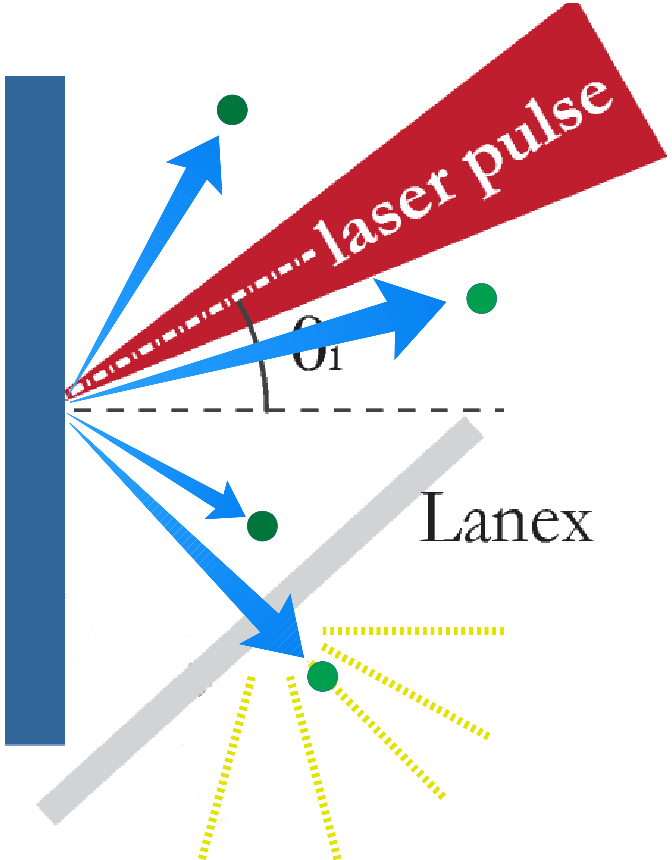
L.Fedeli et al. PRL 116 (2016)

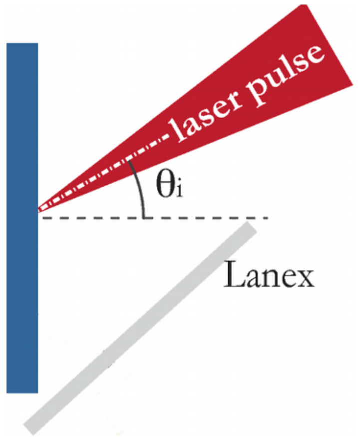
Lanex allows to image the emitted electrons

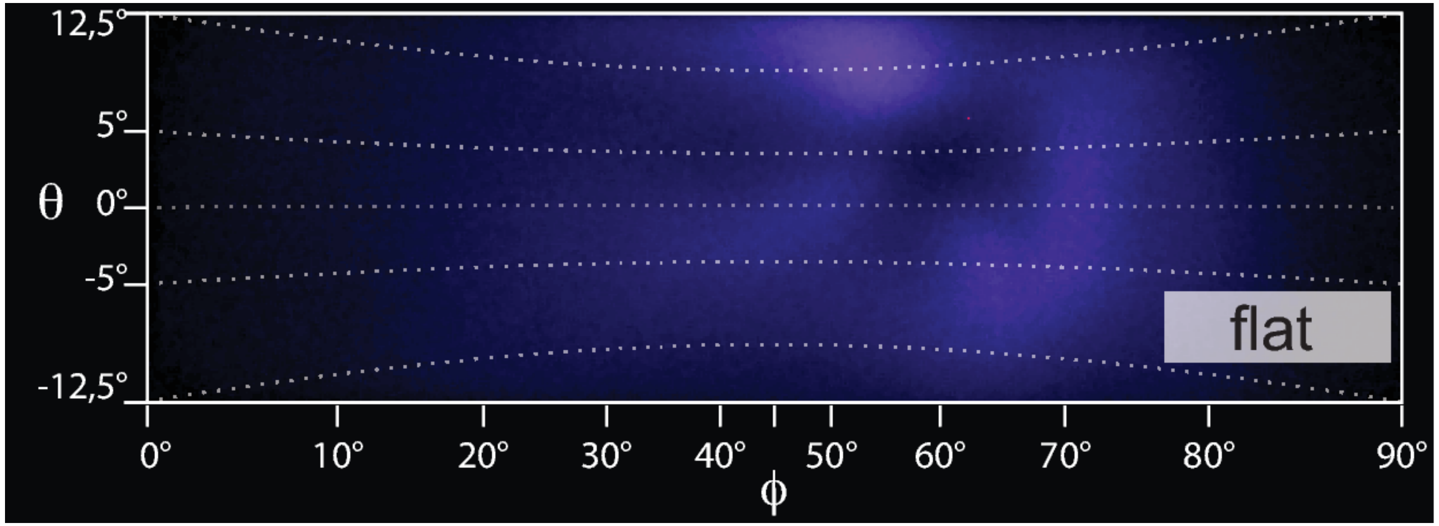


Lanex allows to image the emitted electrons

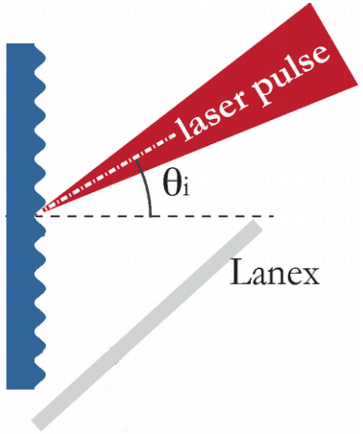


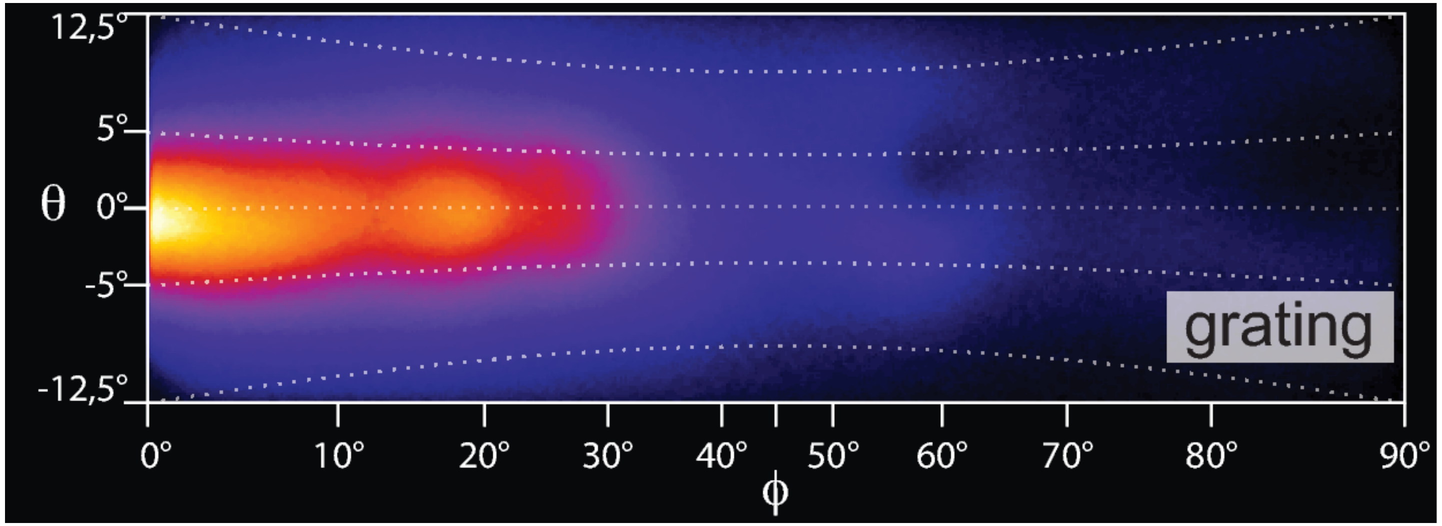
No particular features with flat targets



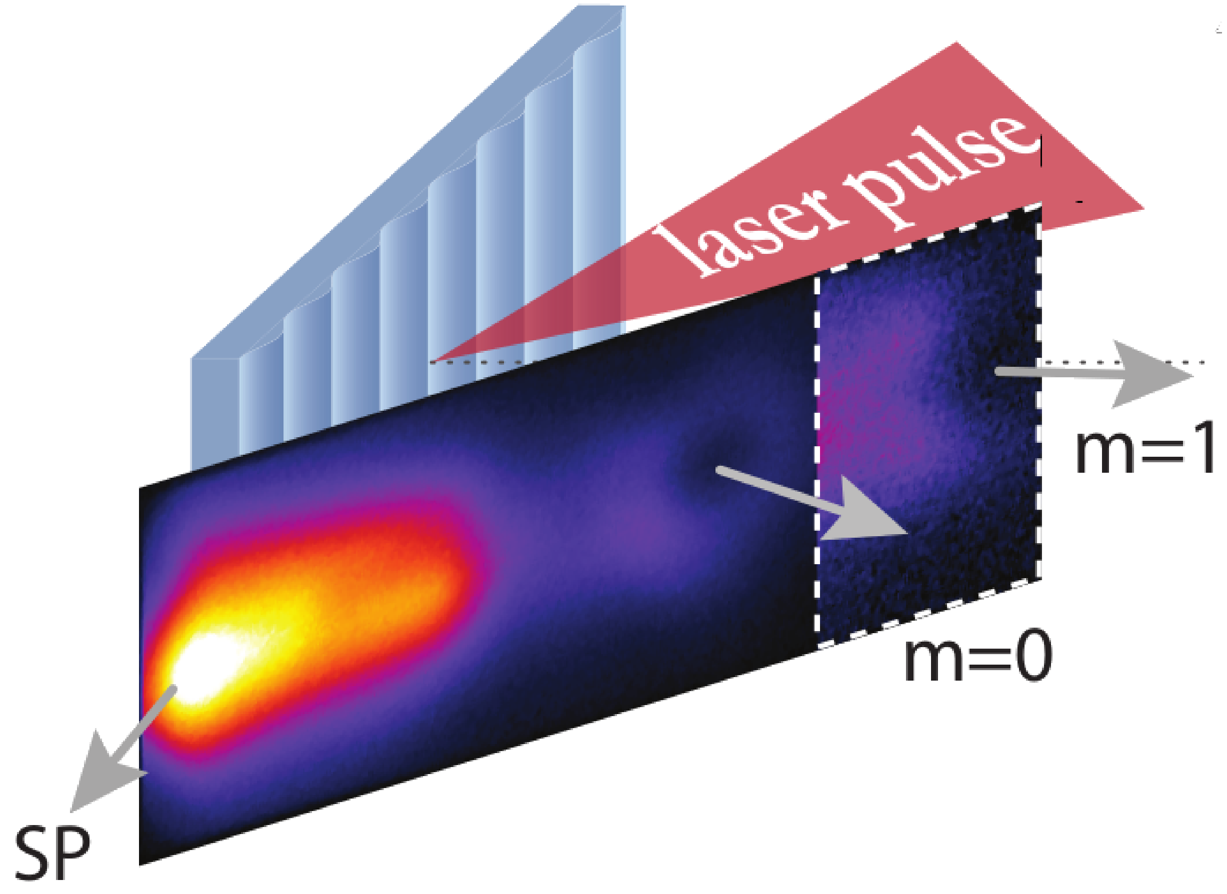


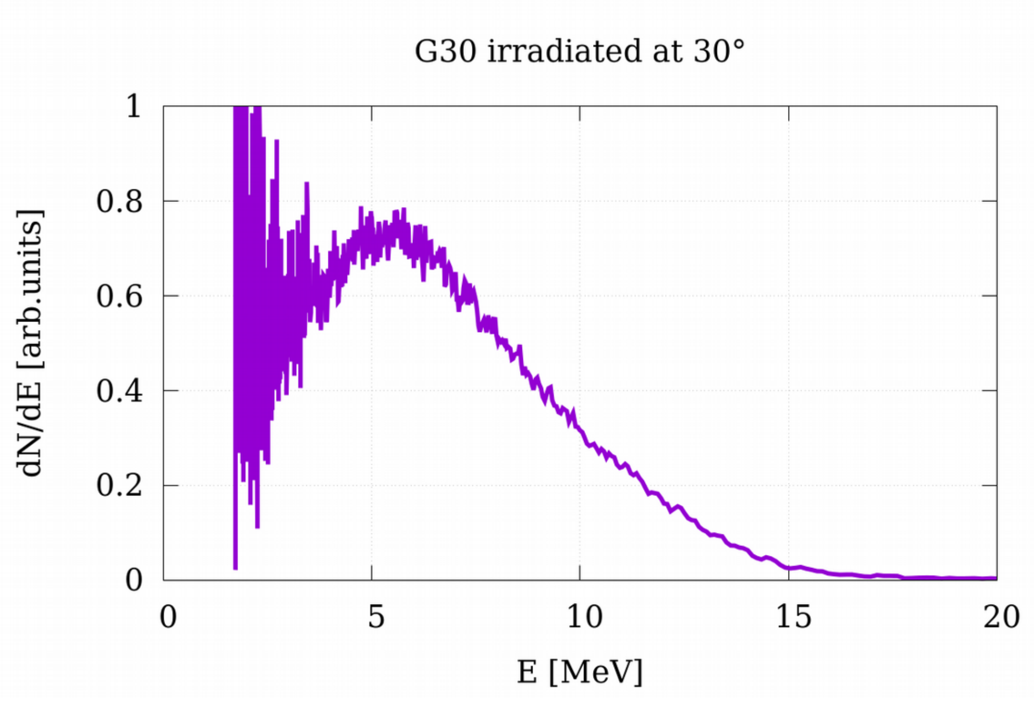
Collimated emission with gratings!



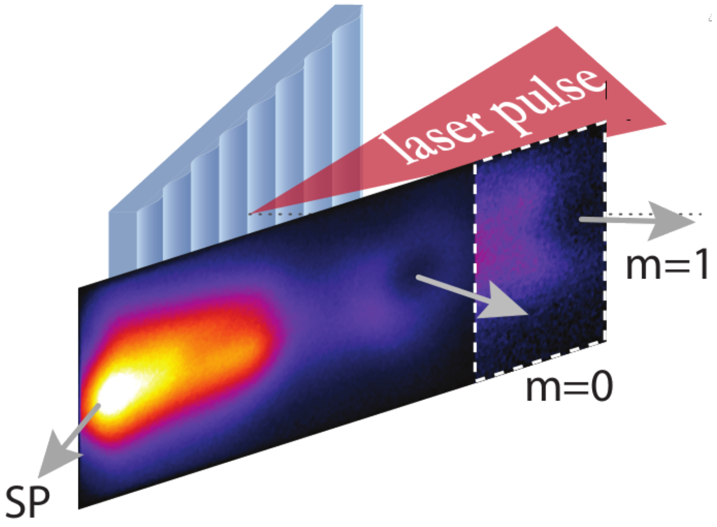


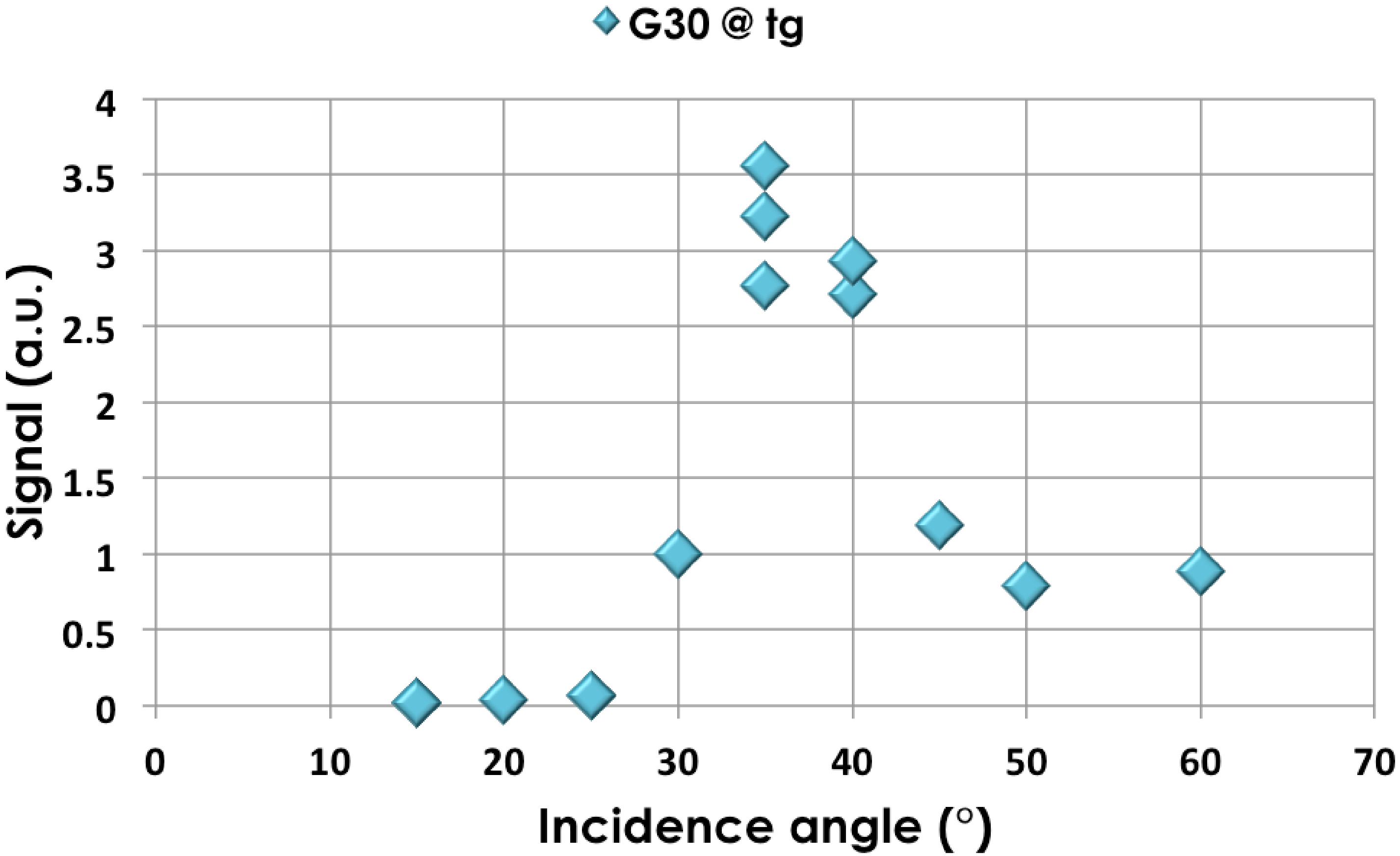
100s pC with energy up to 15 MeV





Resonant enhancement of electron emission





Numerical simulations can help to visualize what’s going on

Particle-in-cell codes in a nutshell

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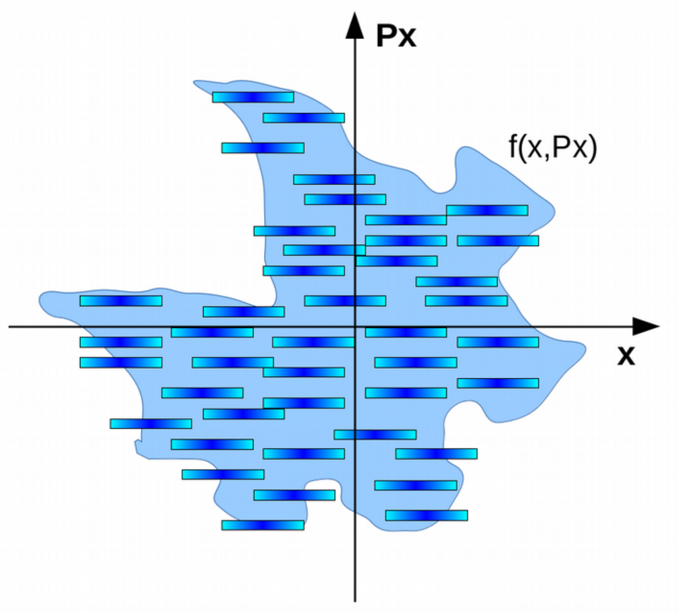
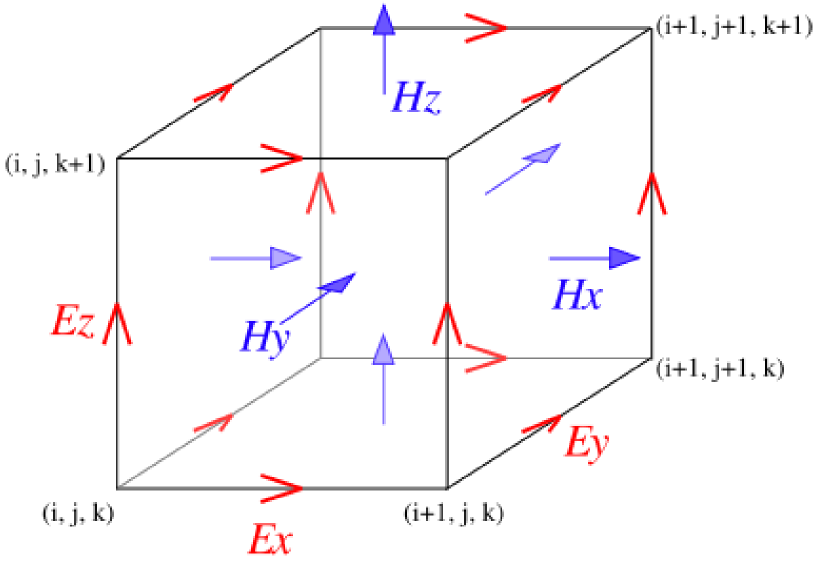


Distribution function

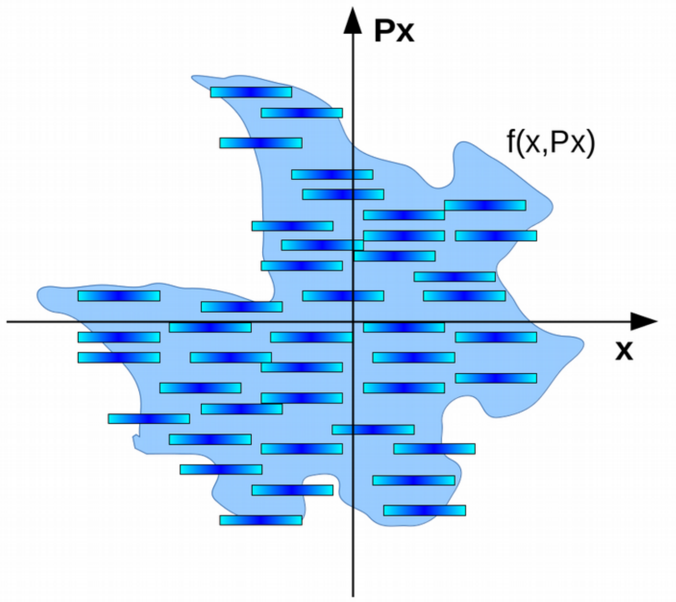
Sampled with “macroparticles”

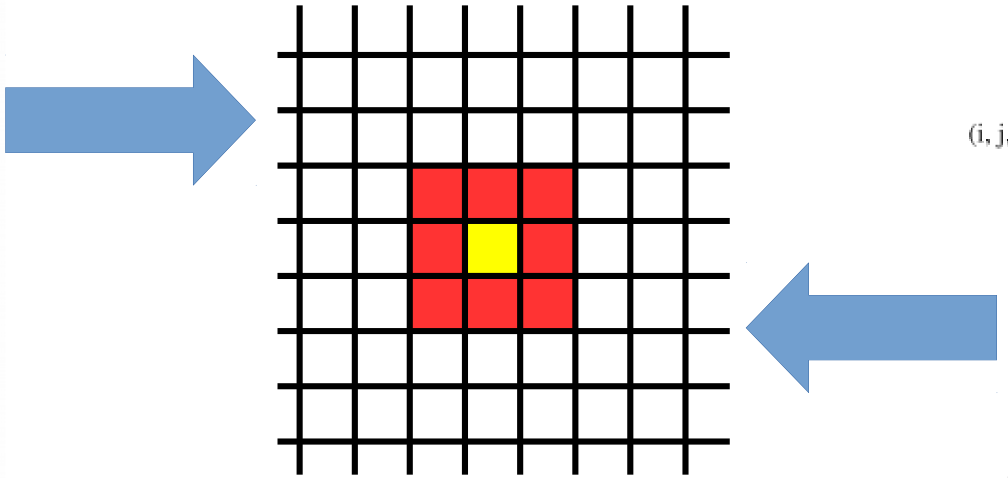


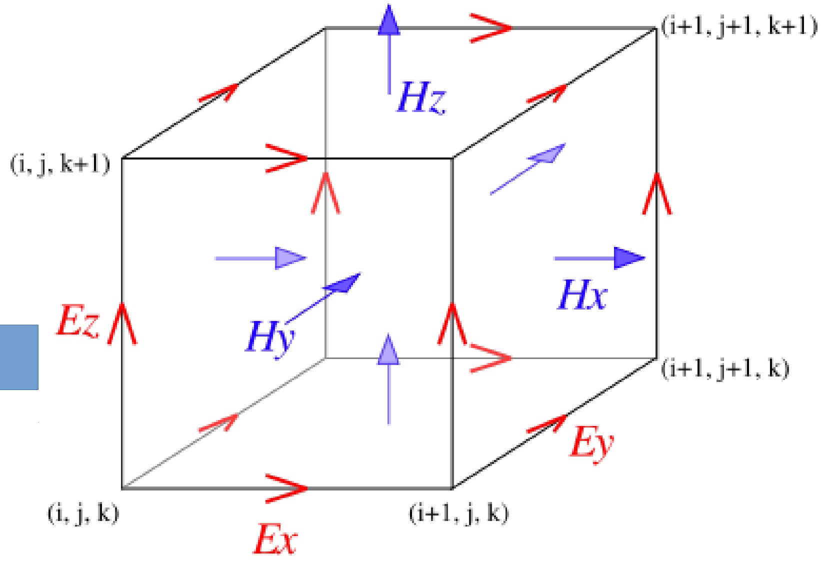
Maxwell’s equations

Solved on a grid

Particle-in-cell codes in a nutshell







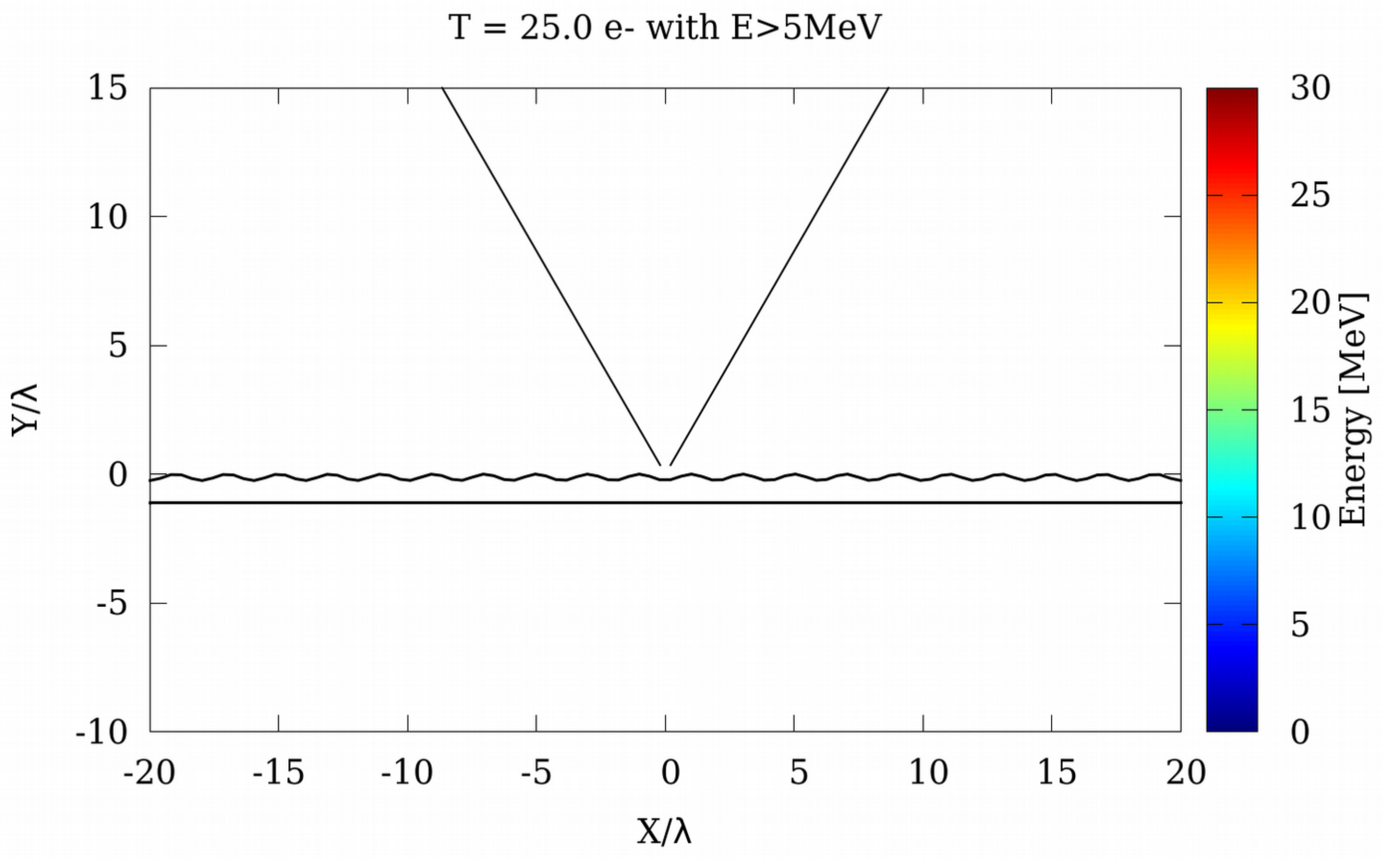
Current deposition & interpolation of EM field

Use of shape functions to reduce noise

piccante Particle-In-Cell code

Piccante: `https://github.com/ALaDyn/piccante`

2D simulations offer insights on the physical process at play



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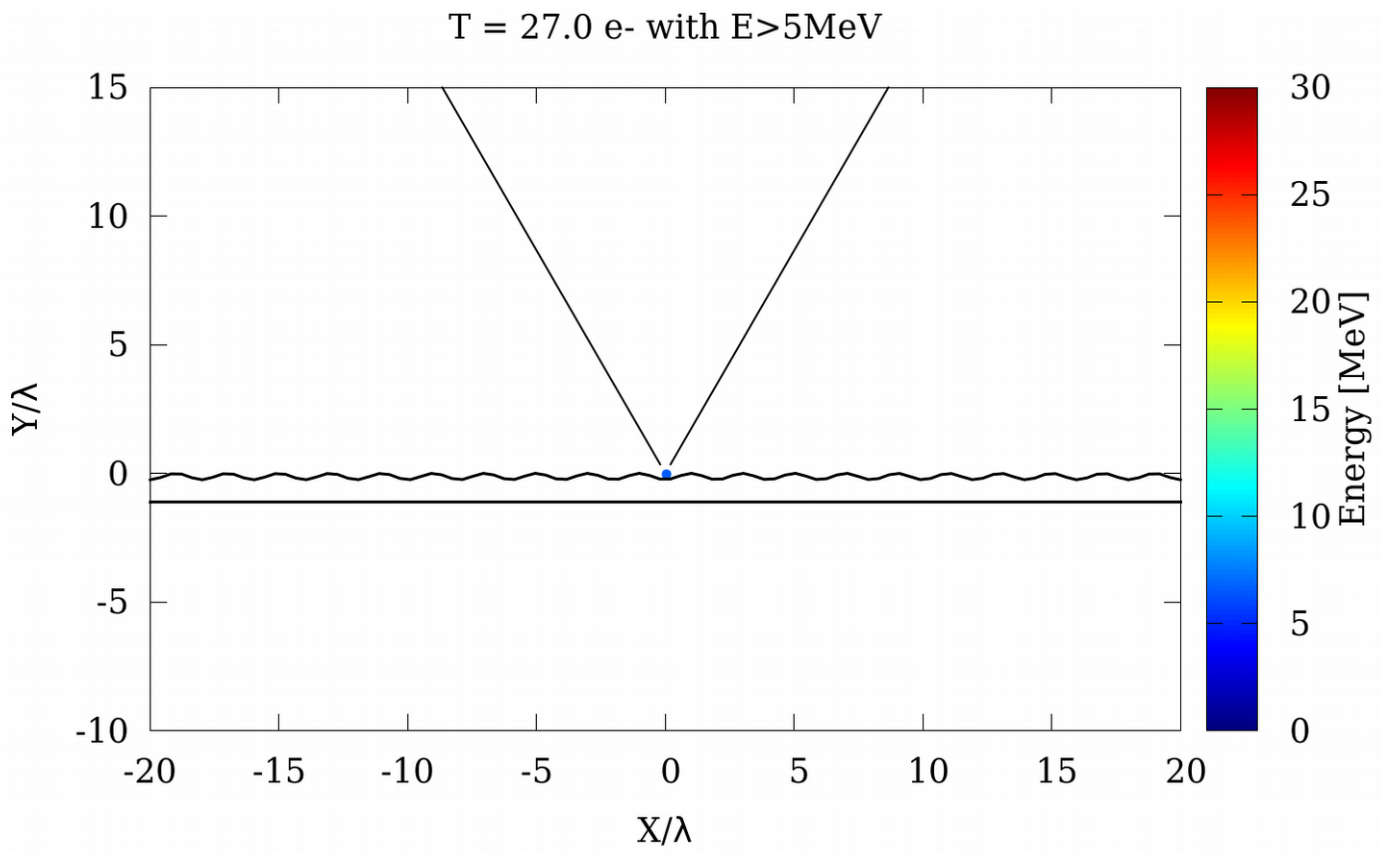

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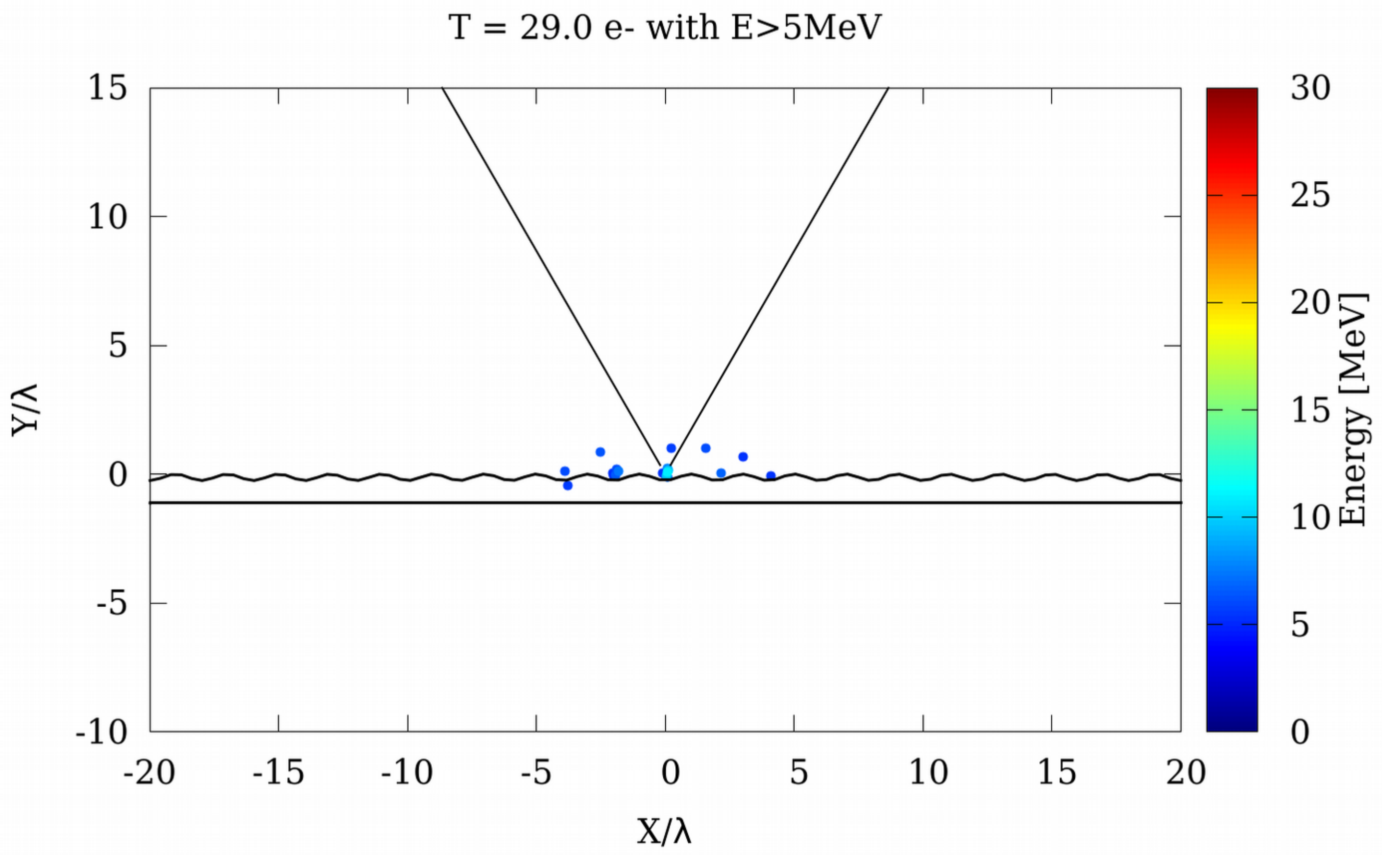

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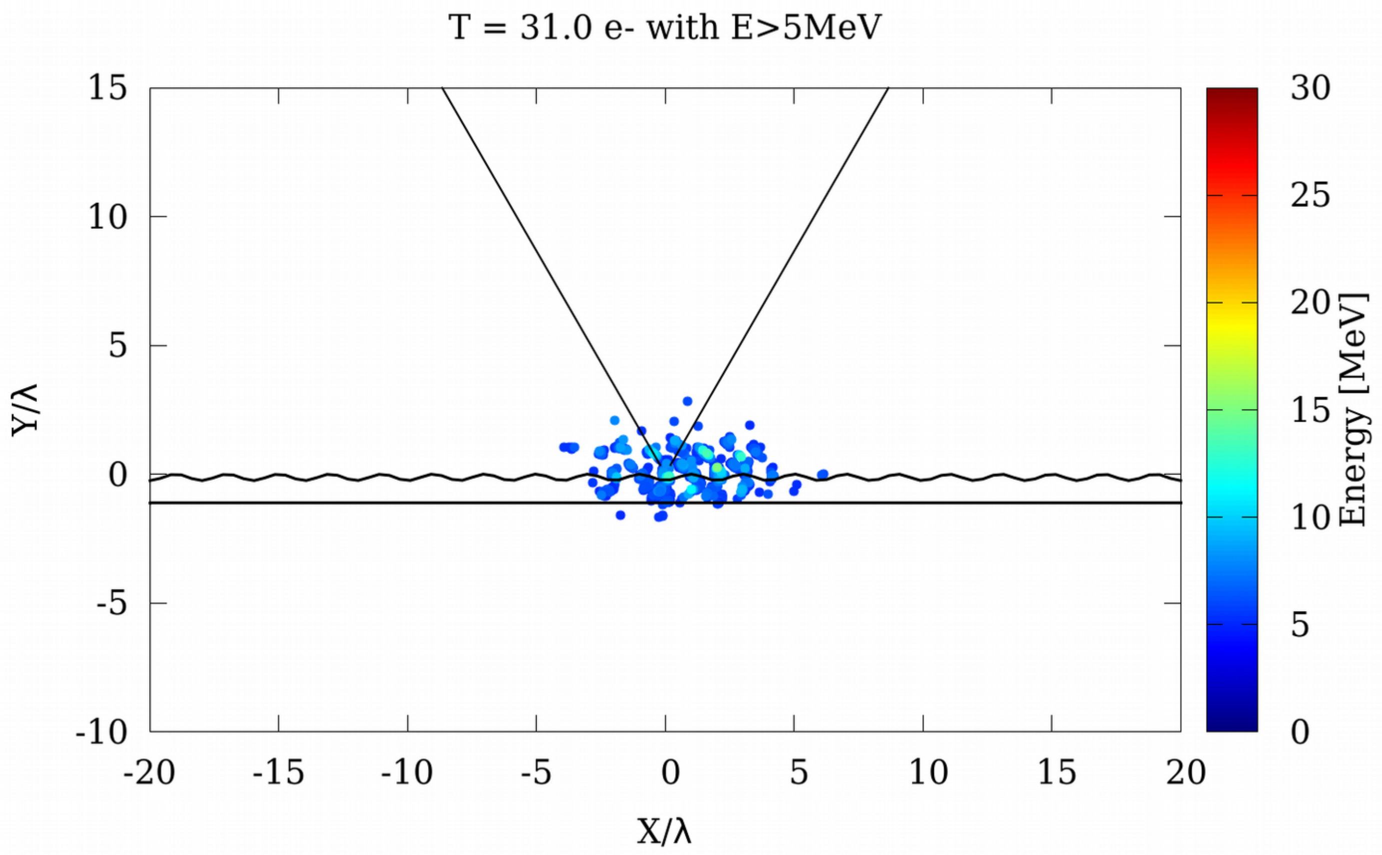

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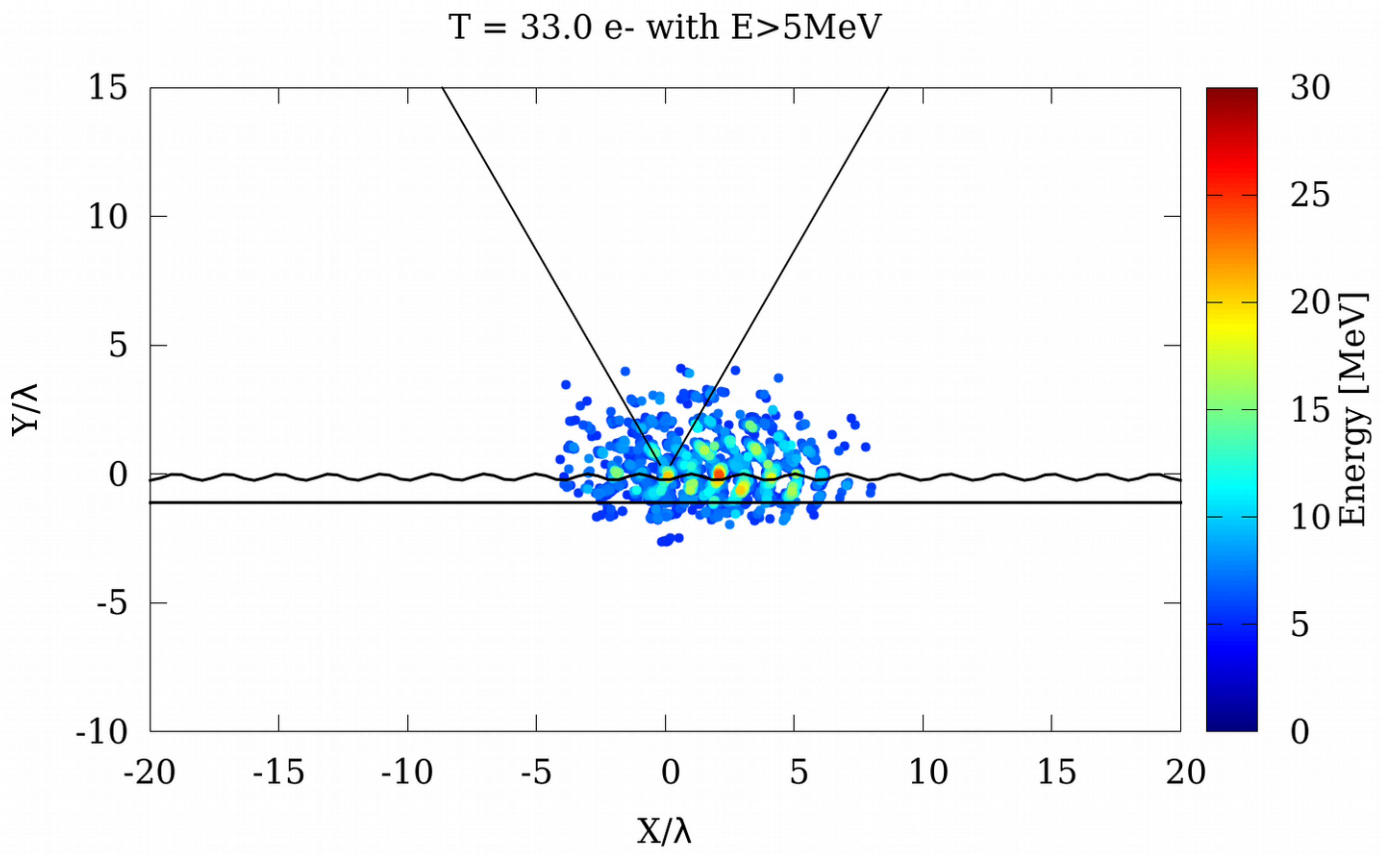

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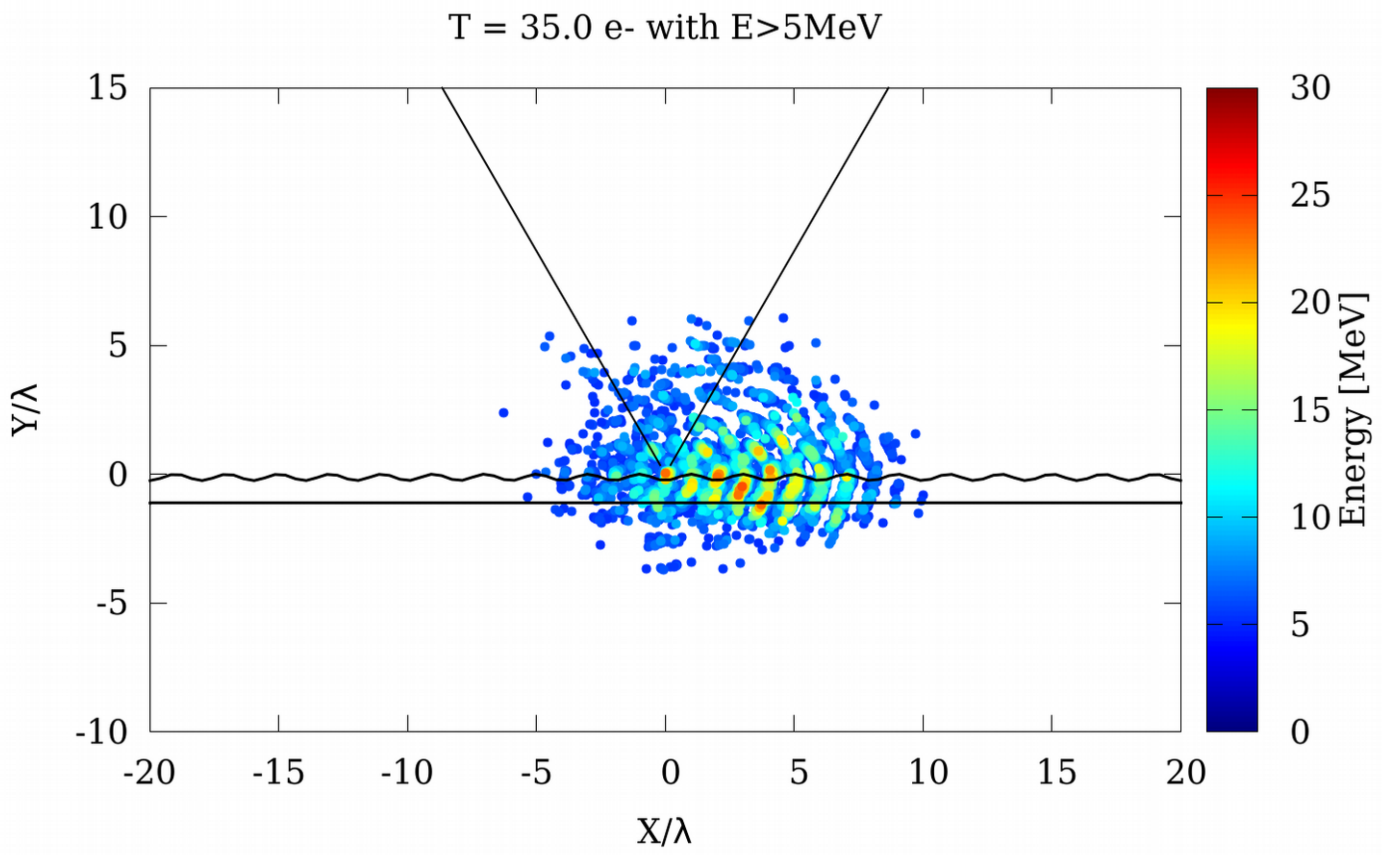

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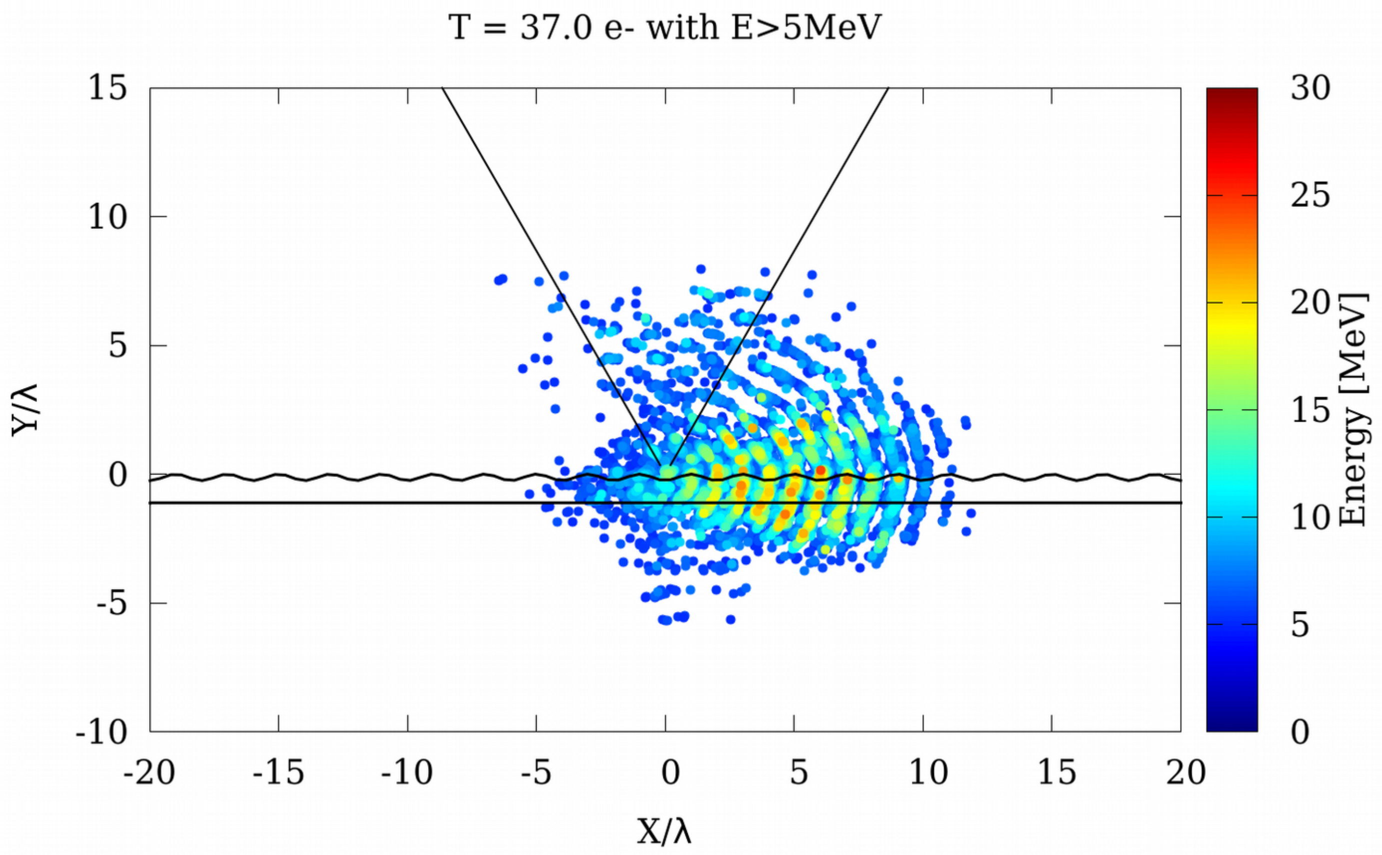

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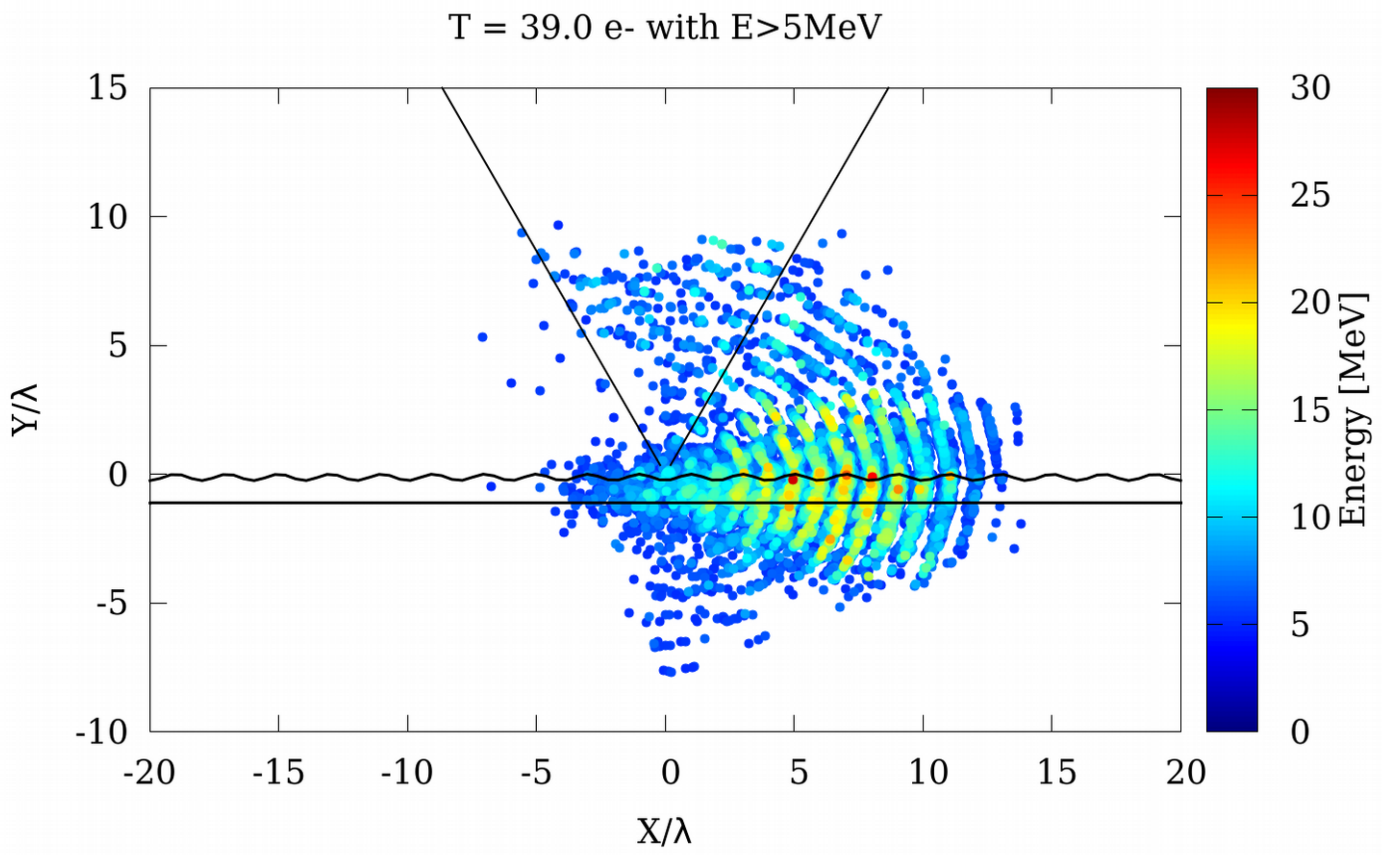

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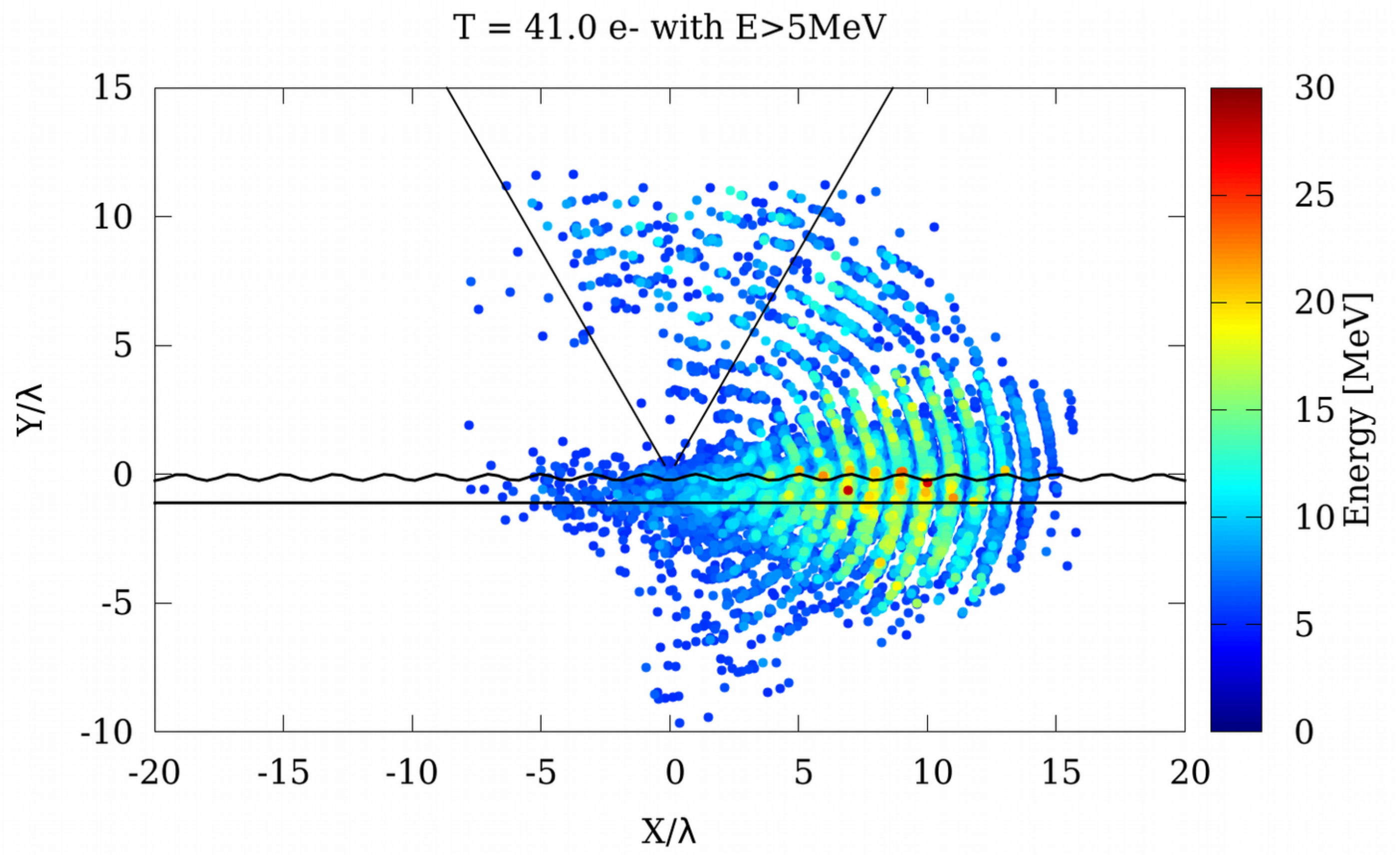

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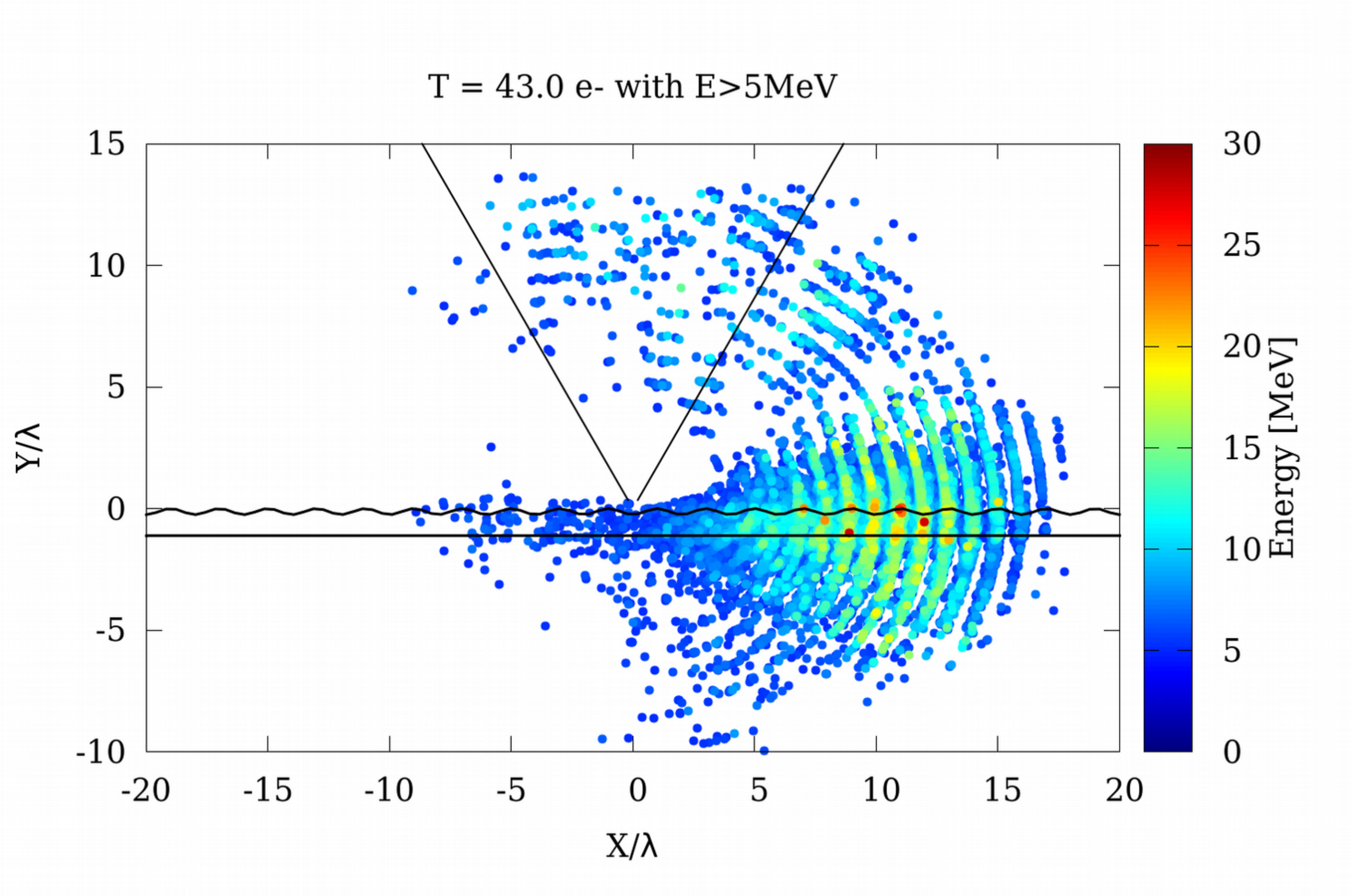

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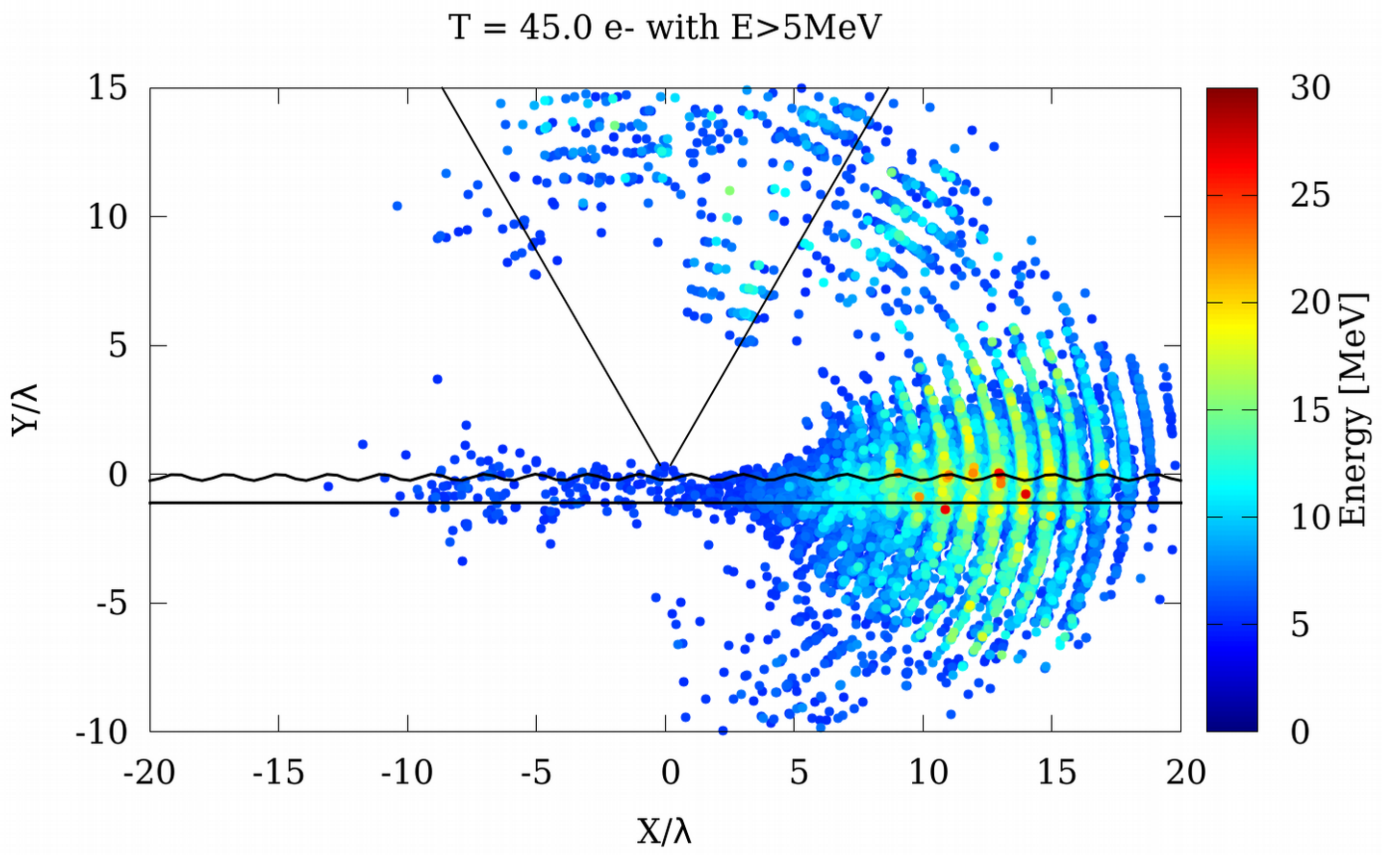
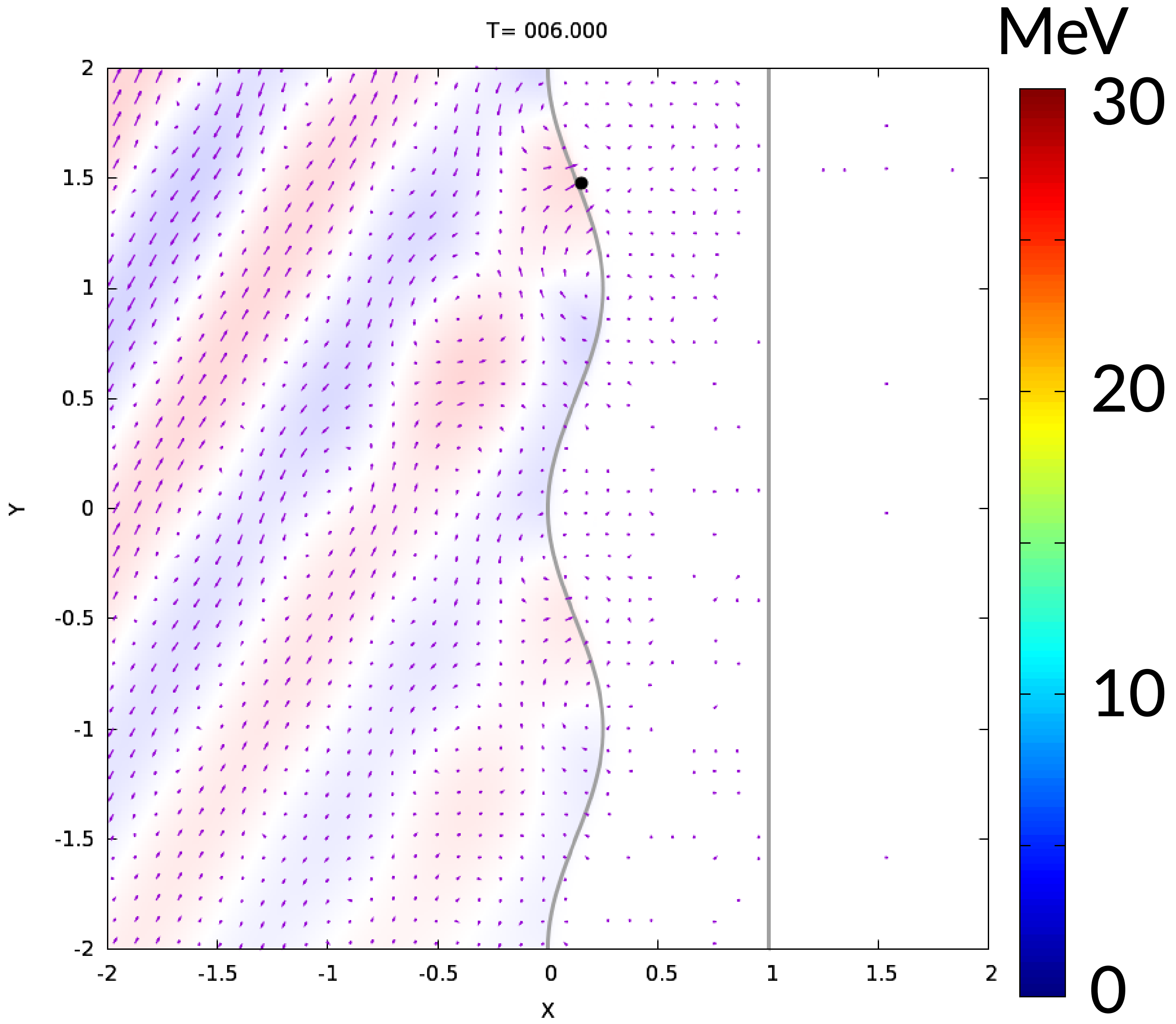


A more detailed look on a selected electron



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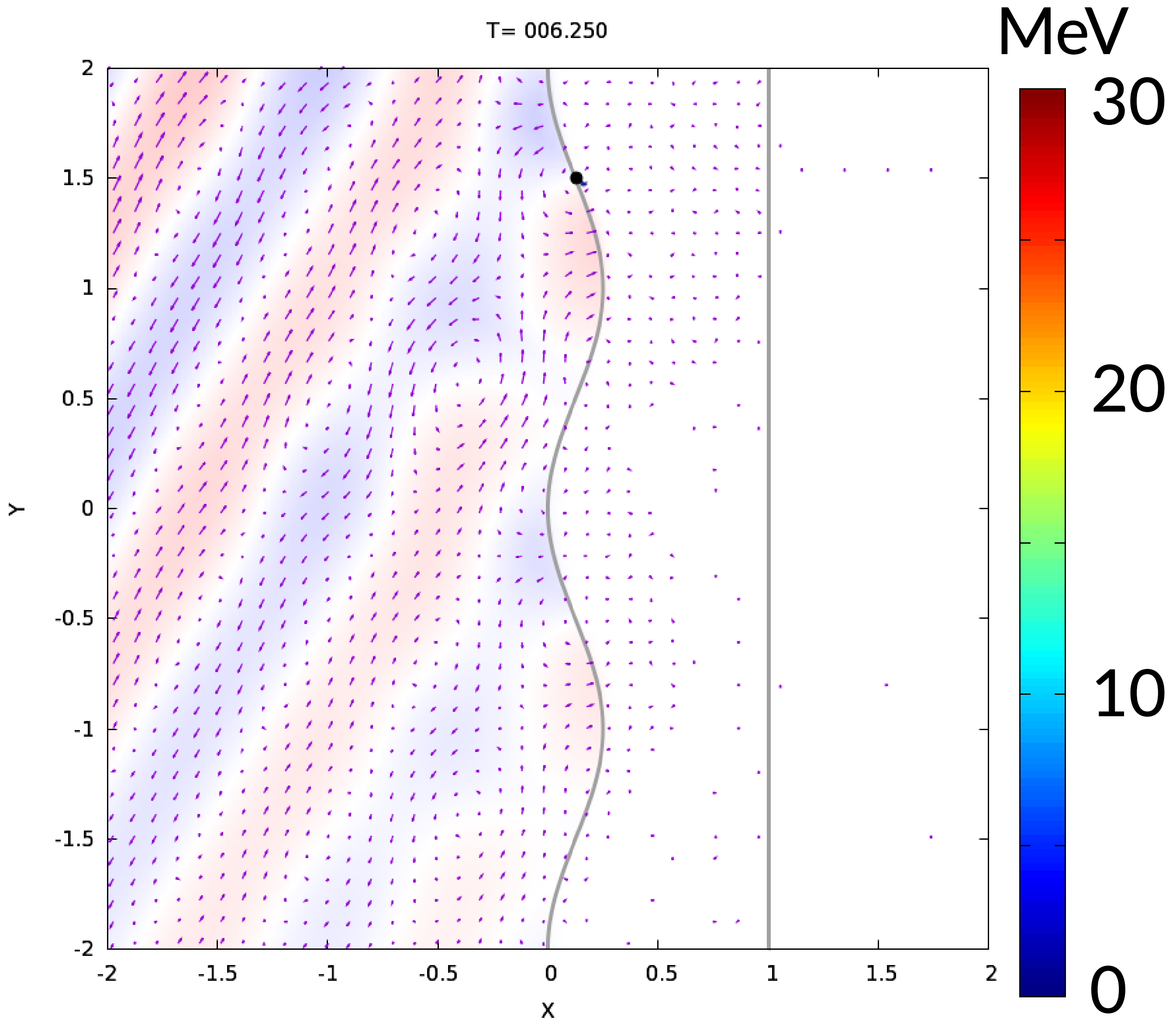

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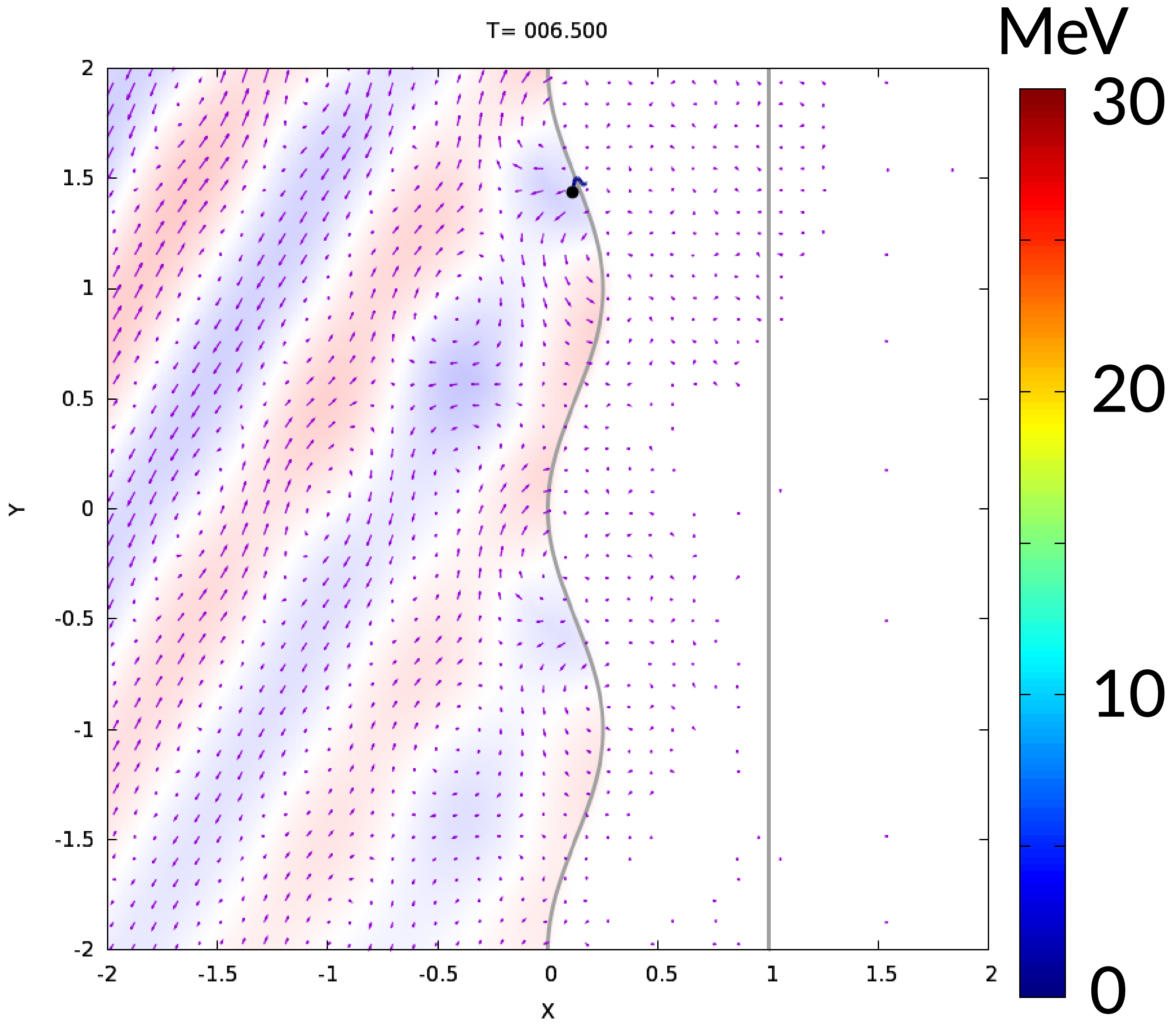

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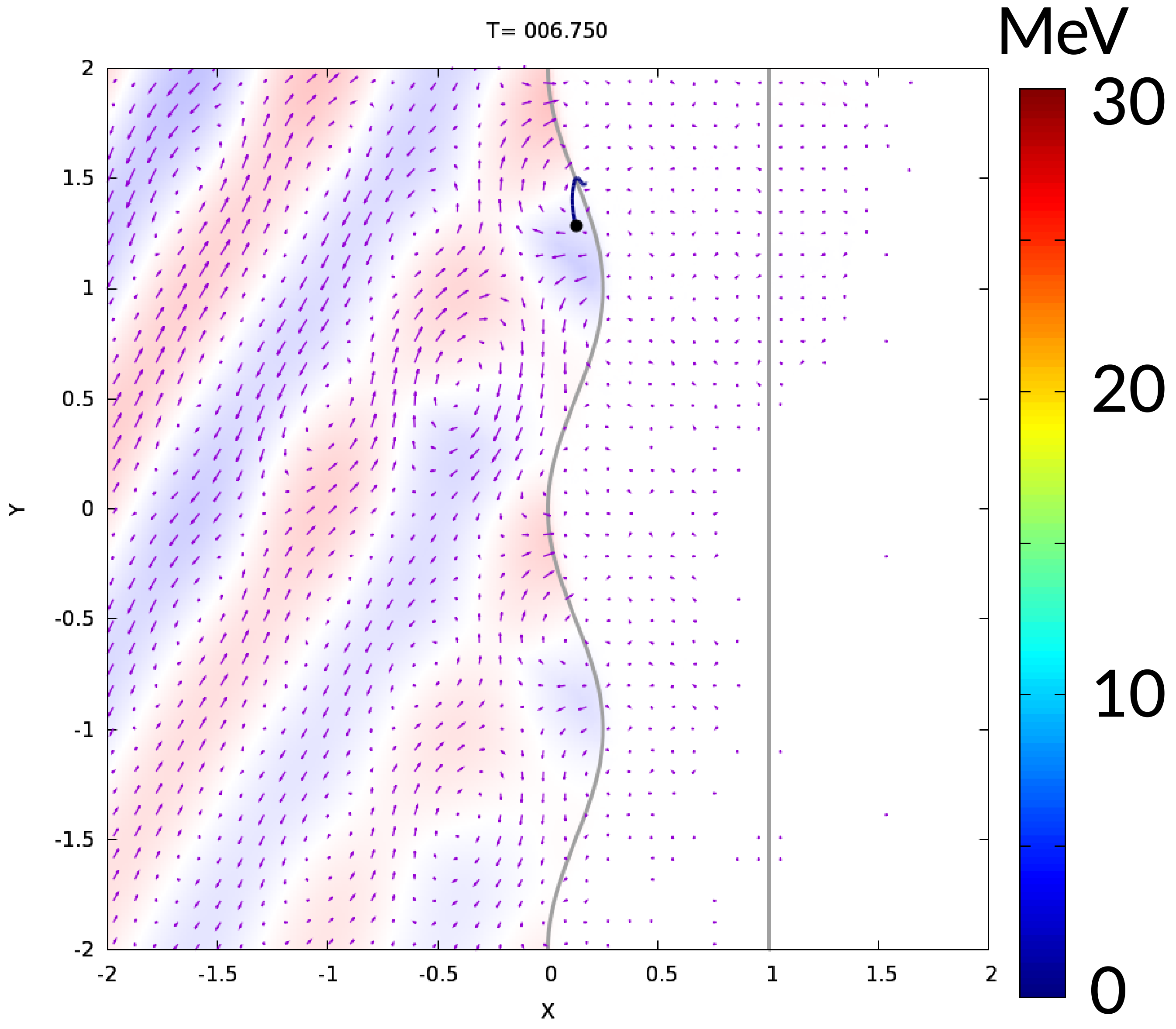

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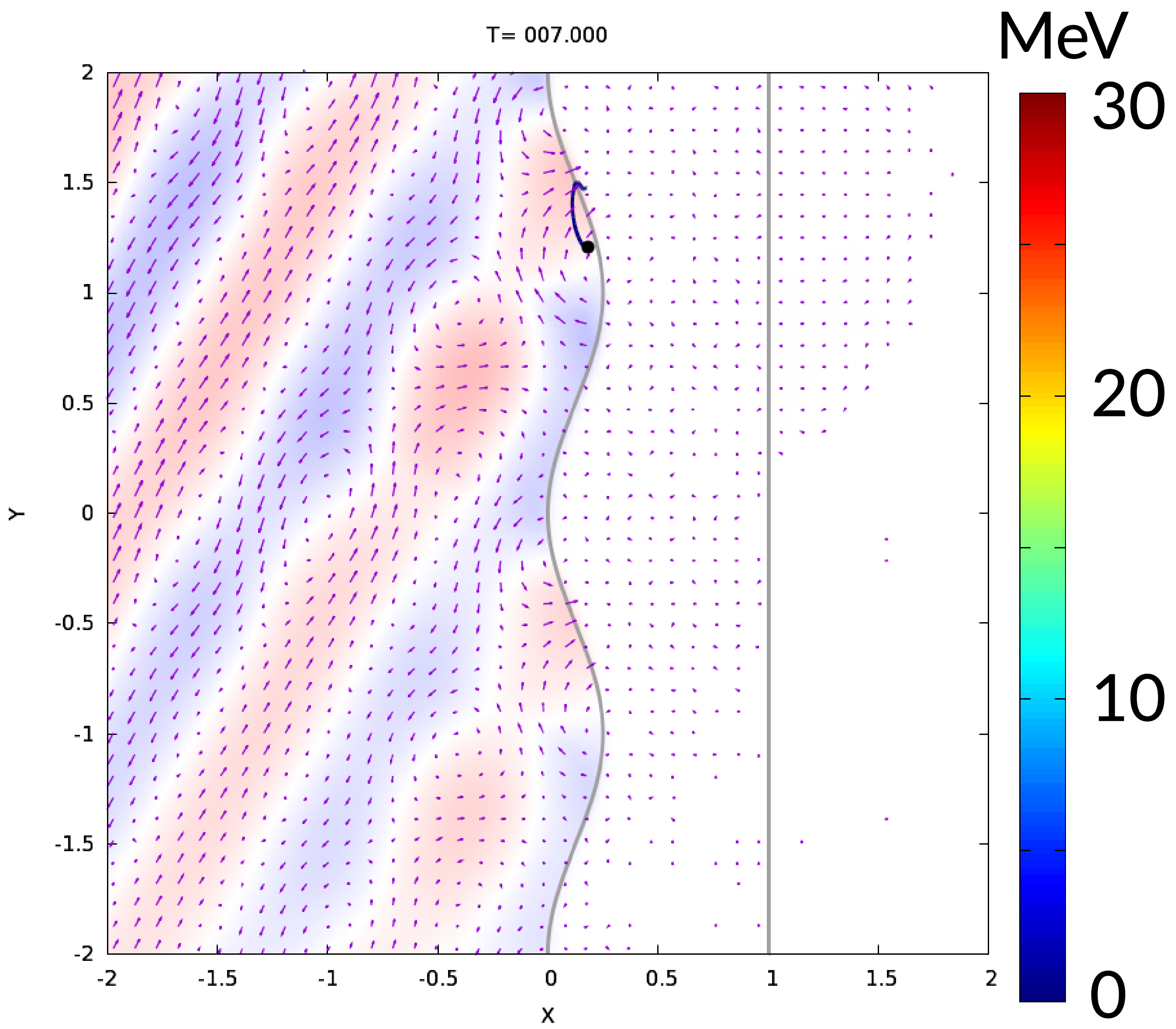

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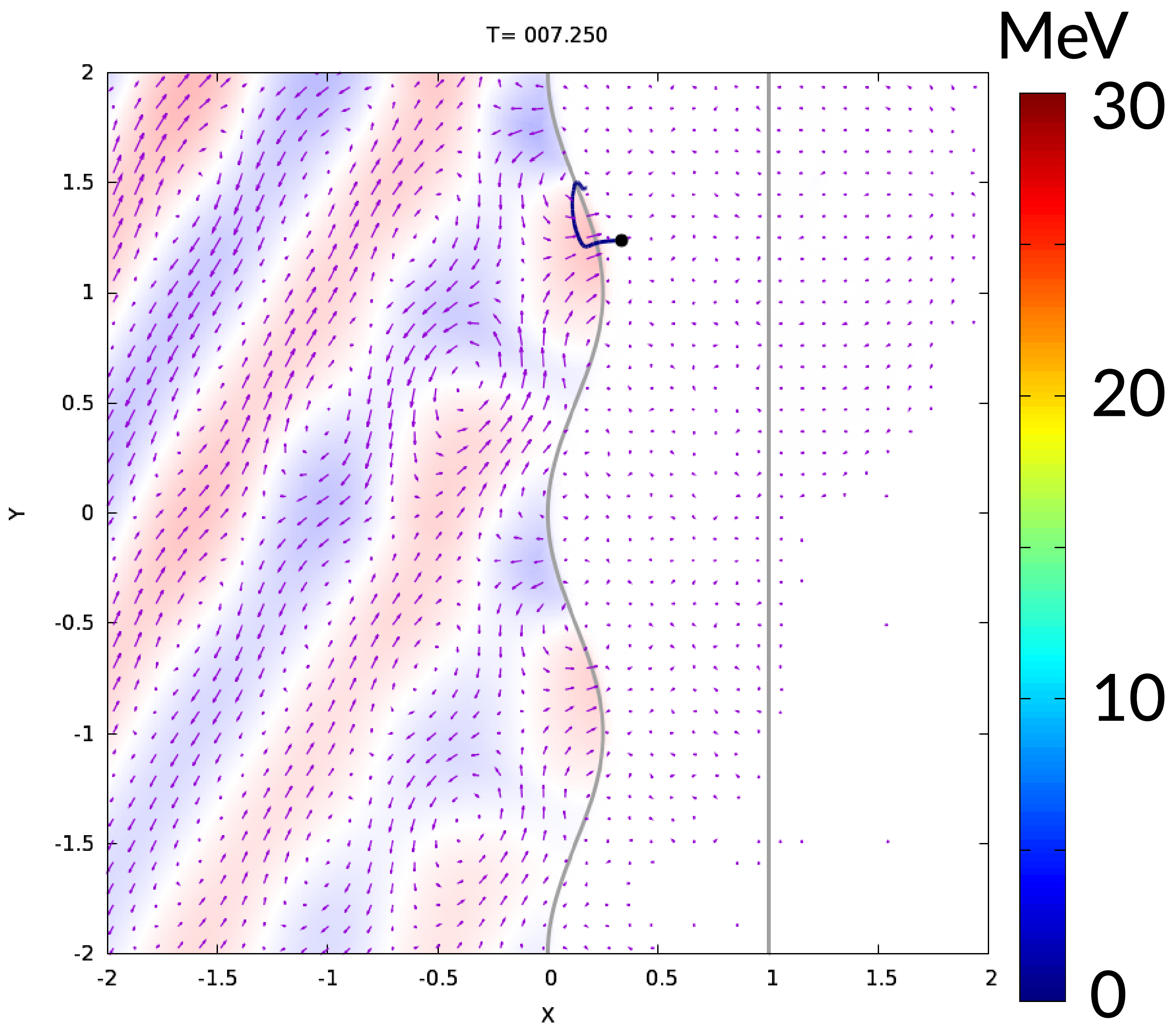

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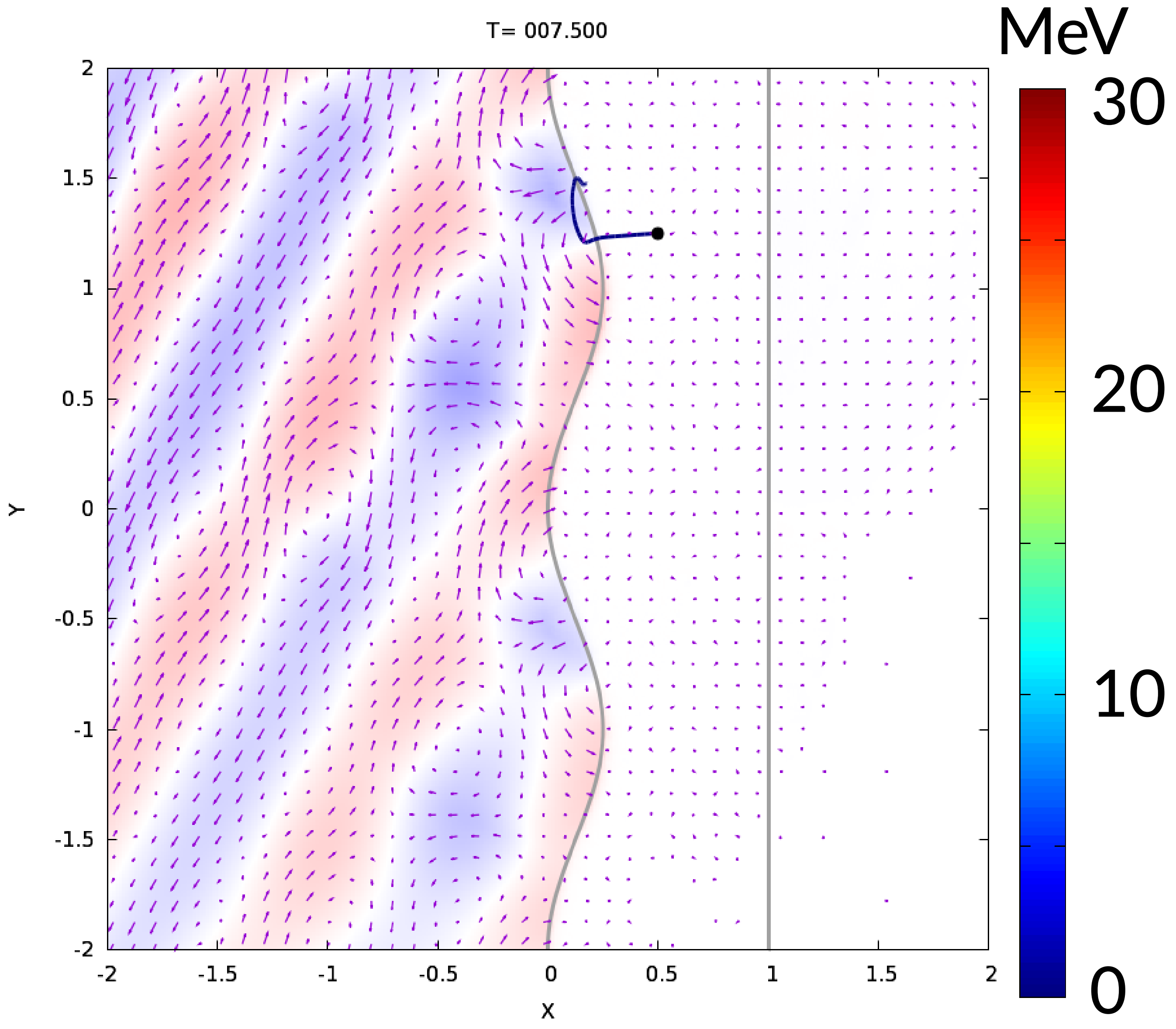

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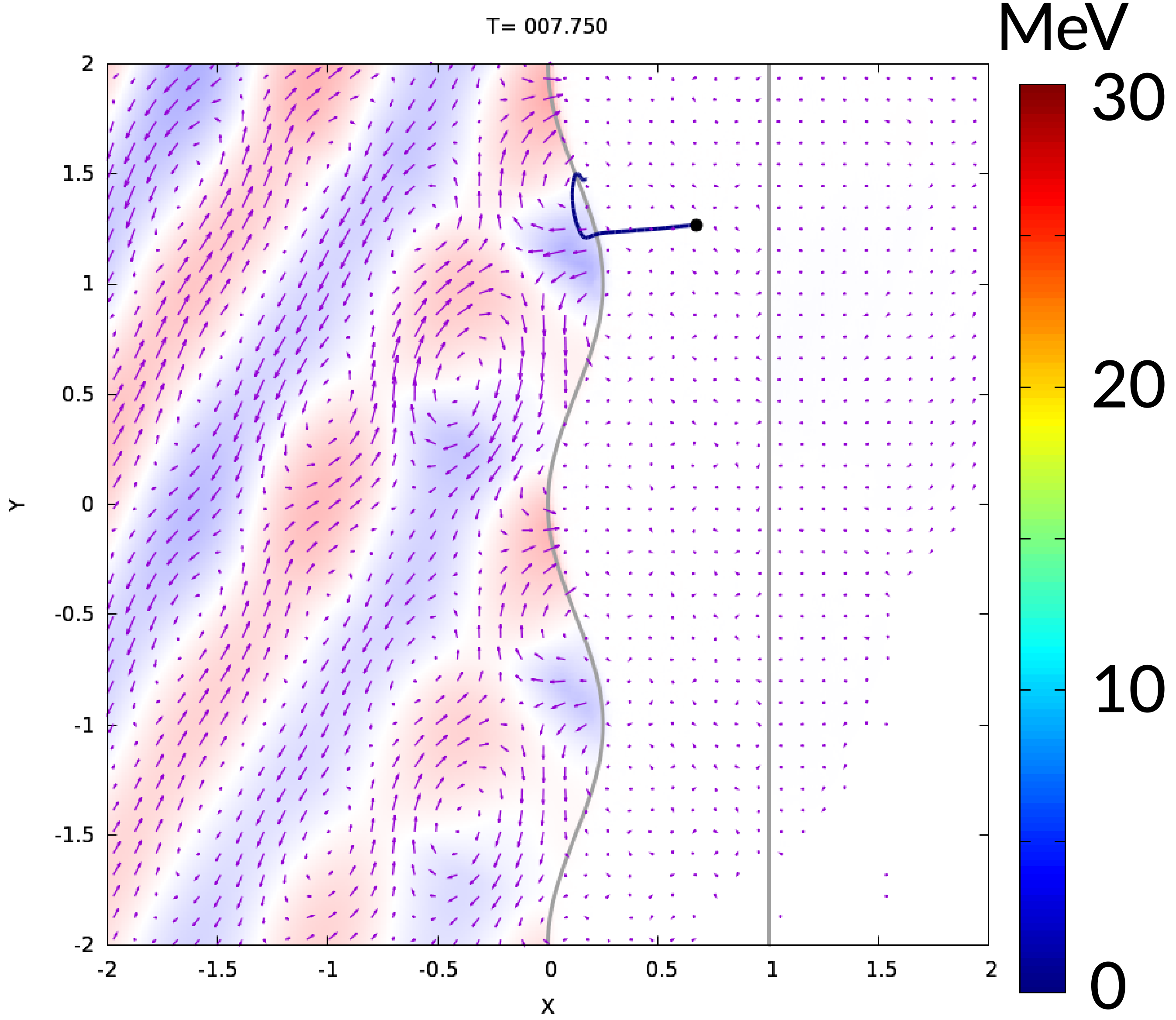

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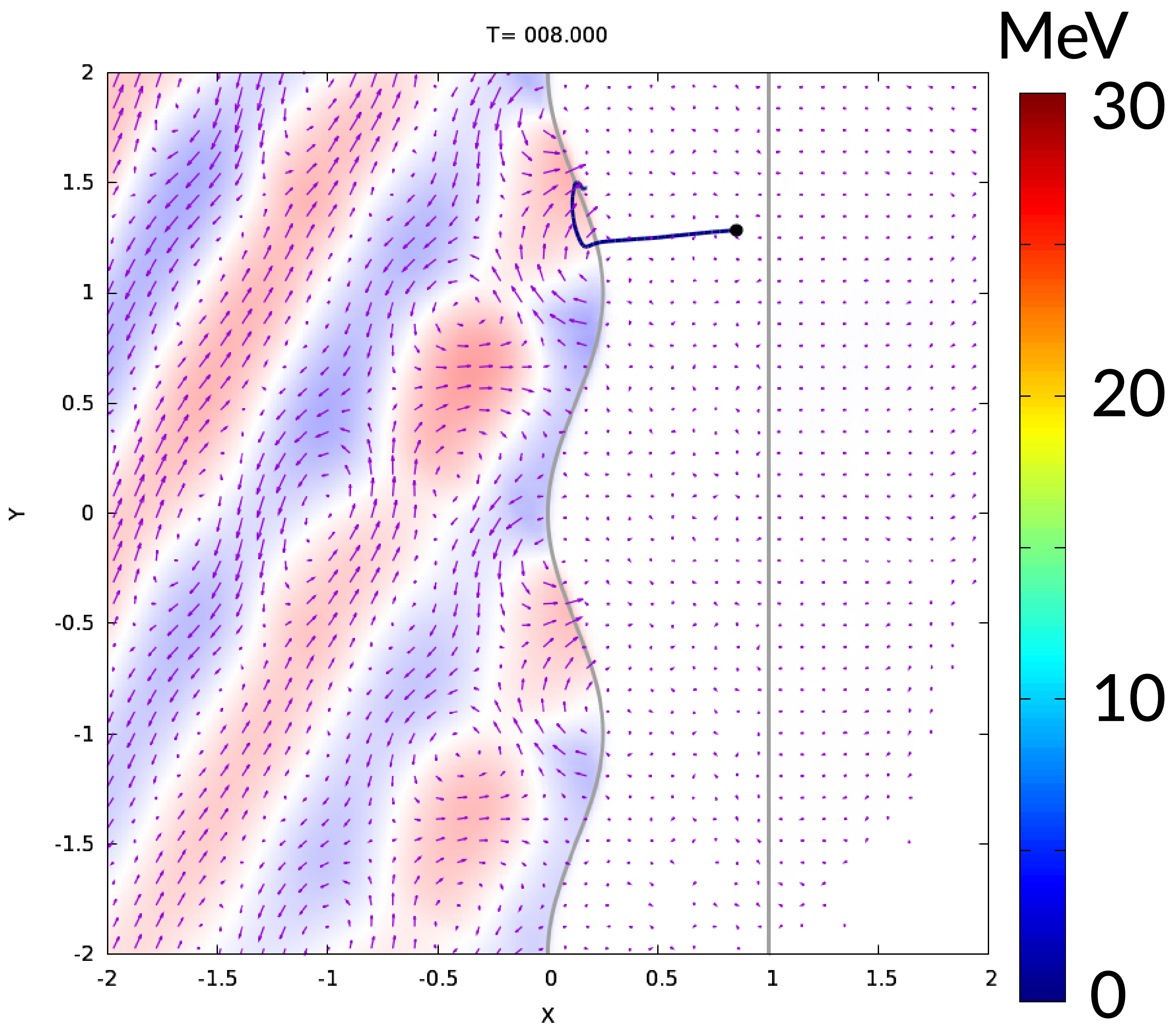

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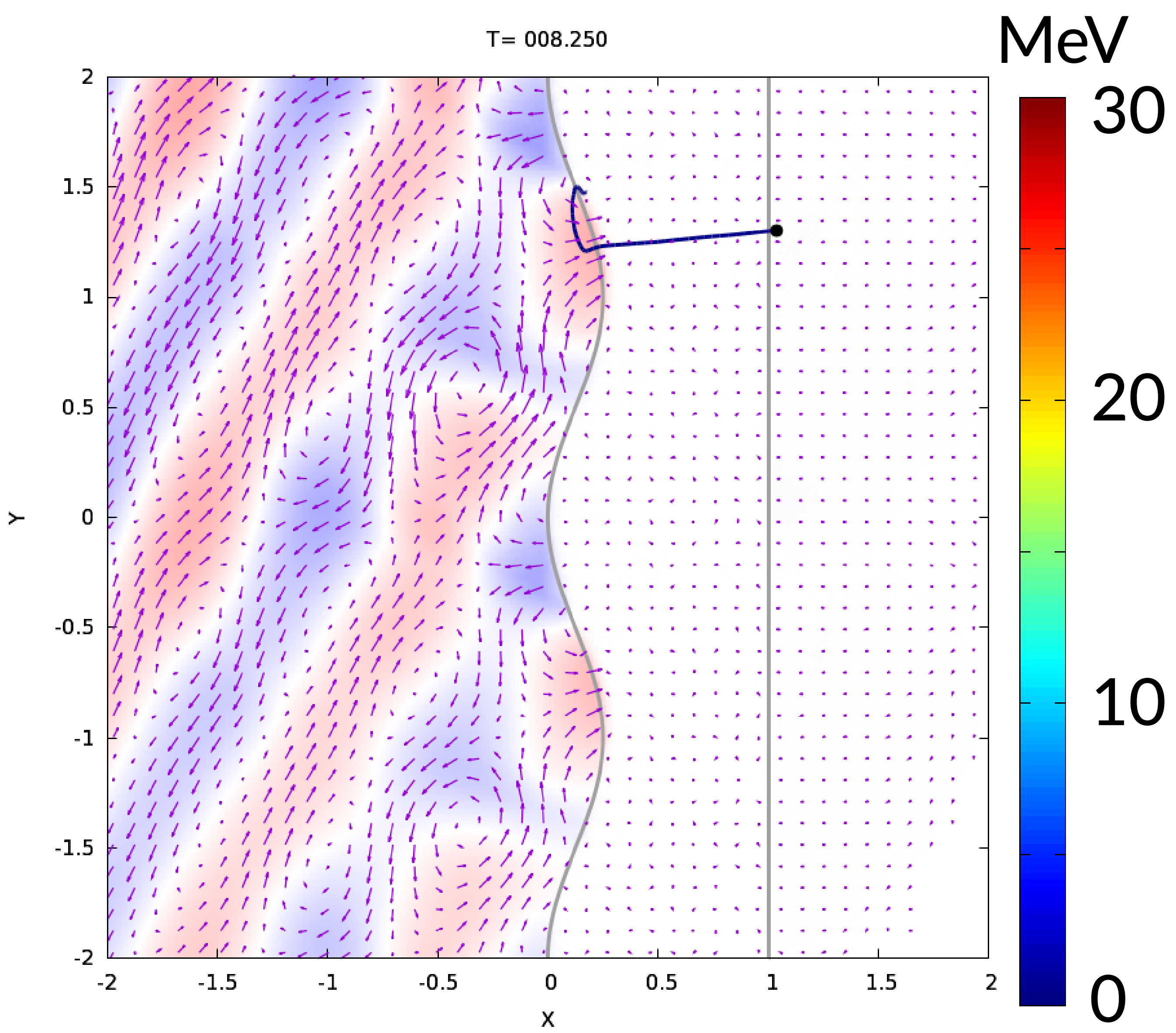

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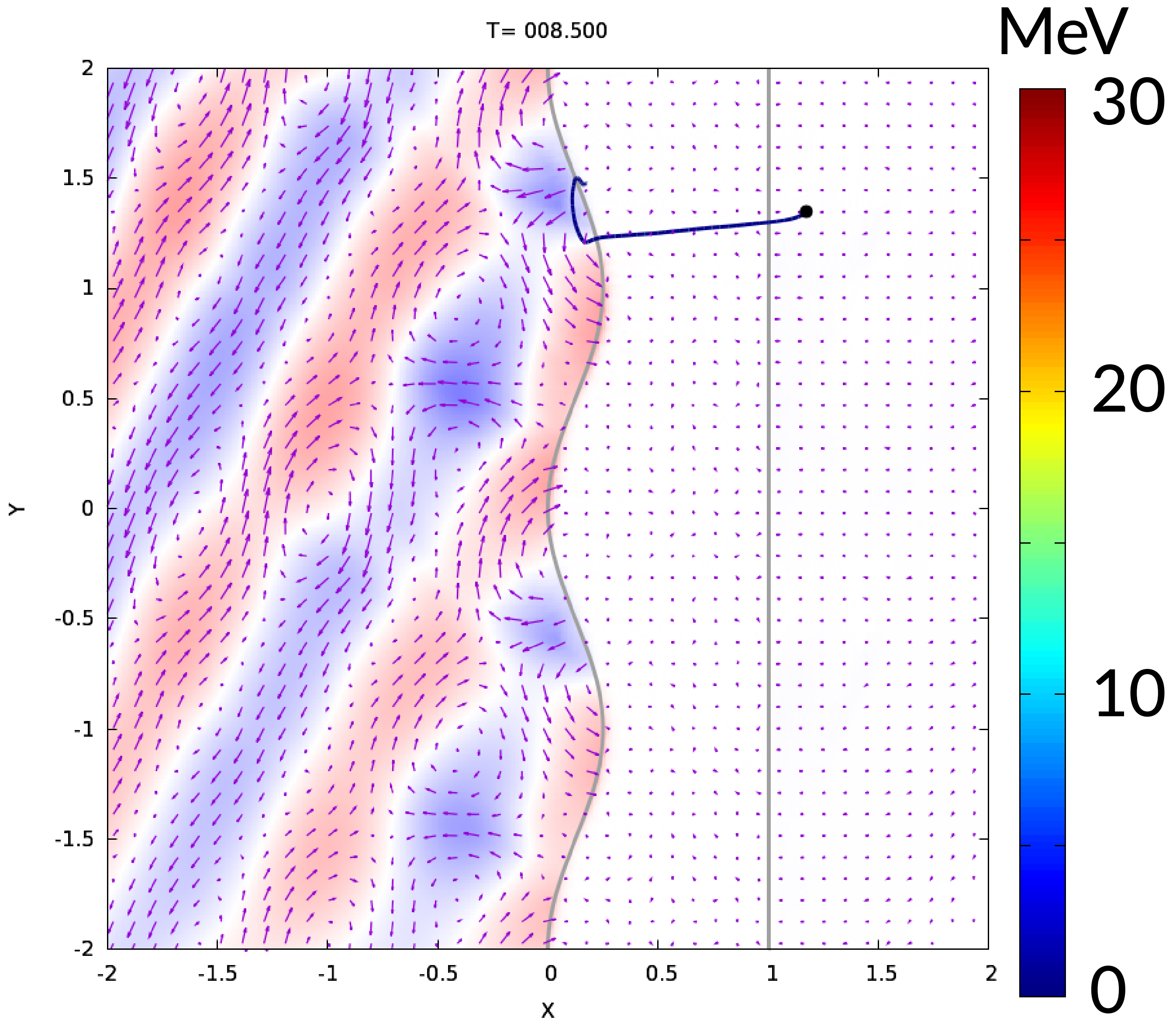

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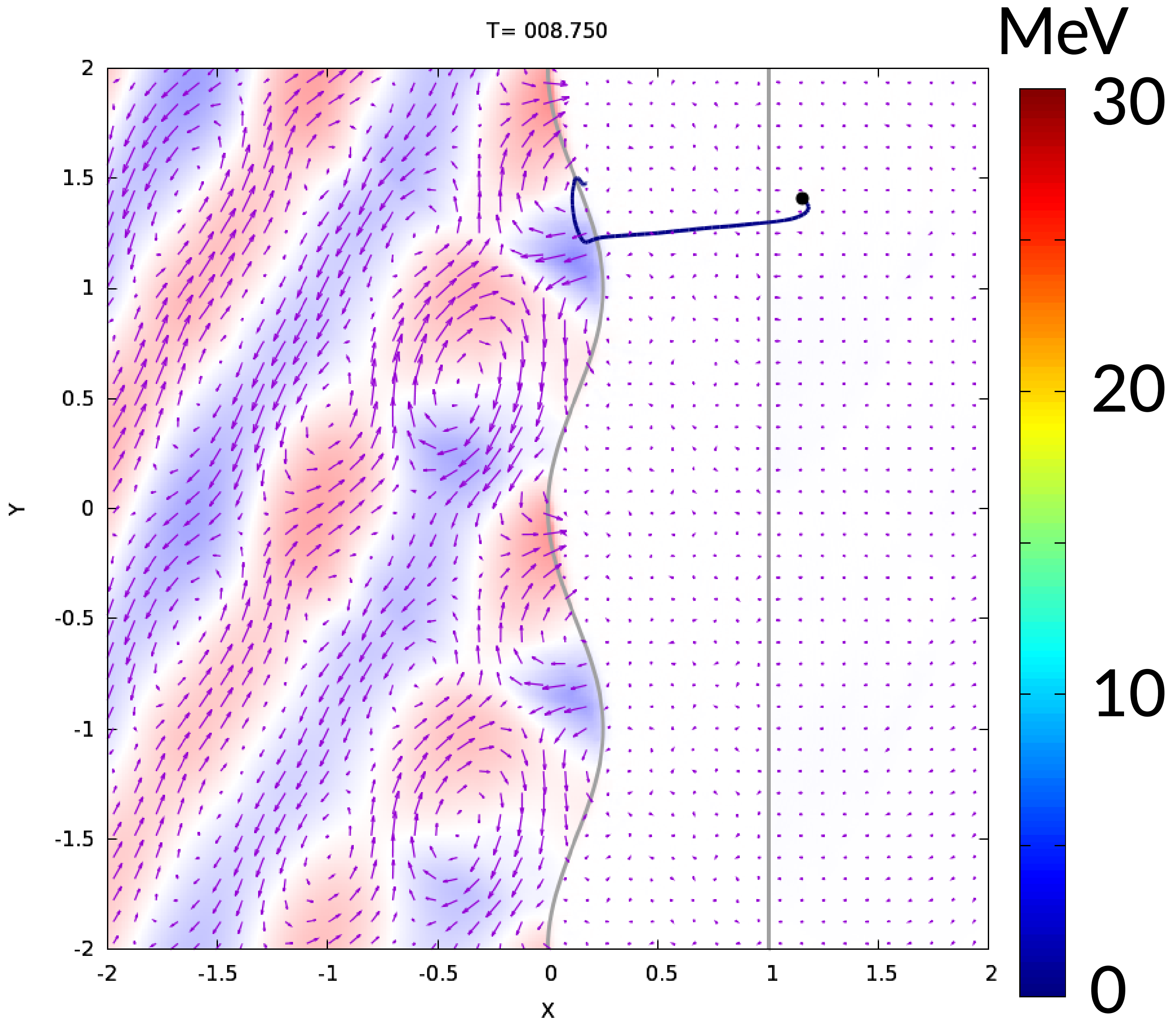

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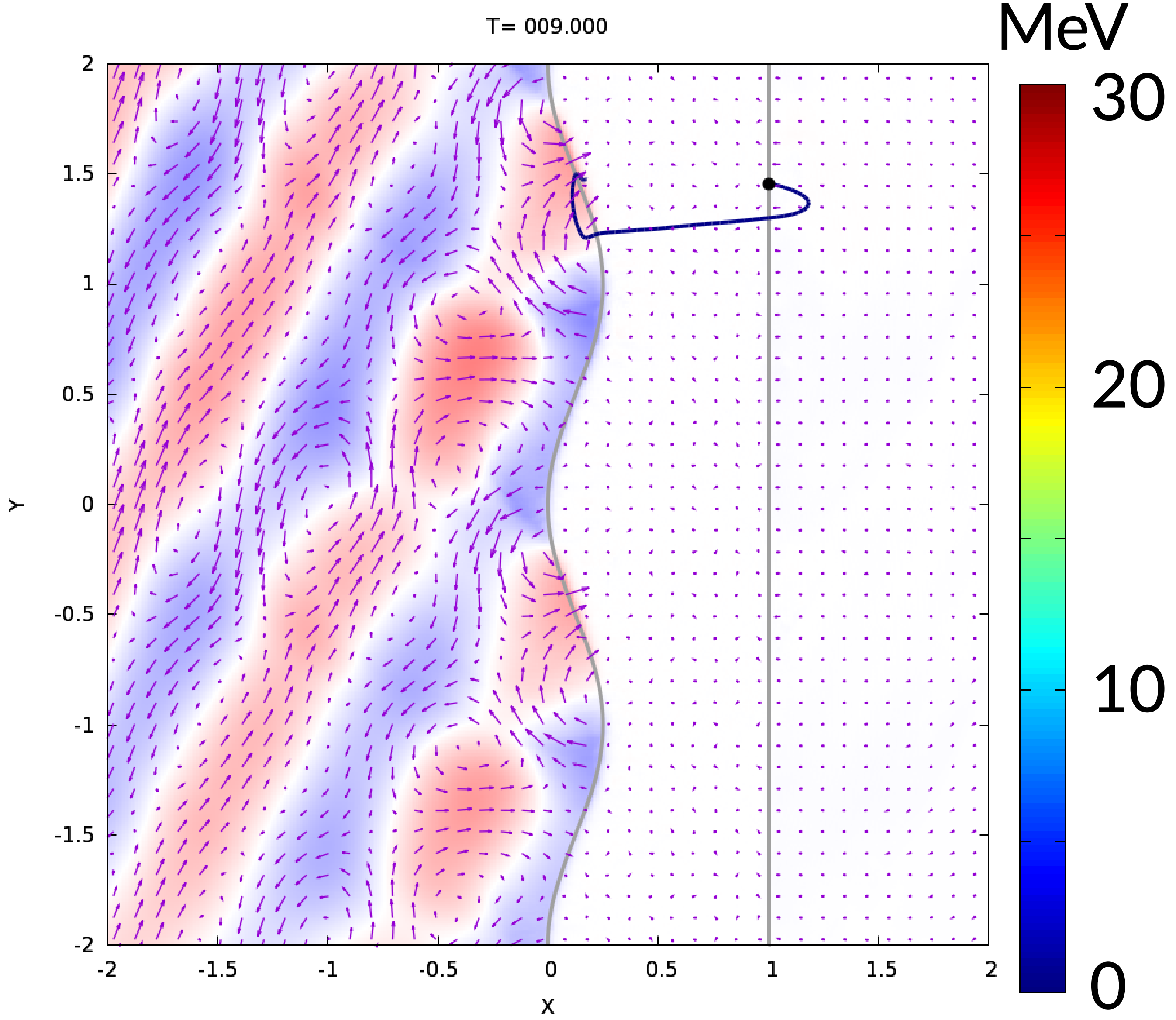

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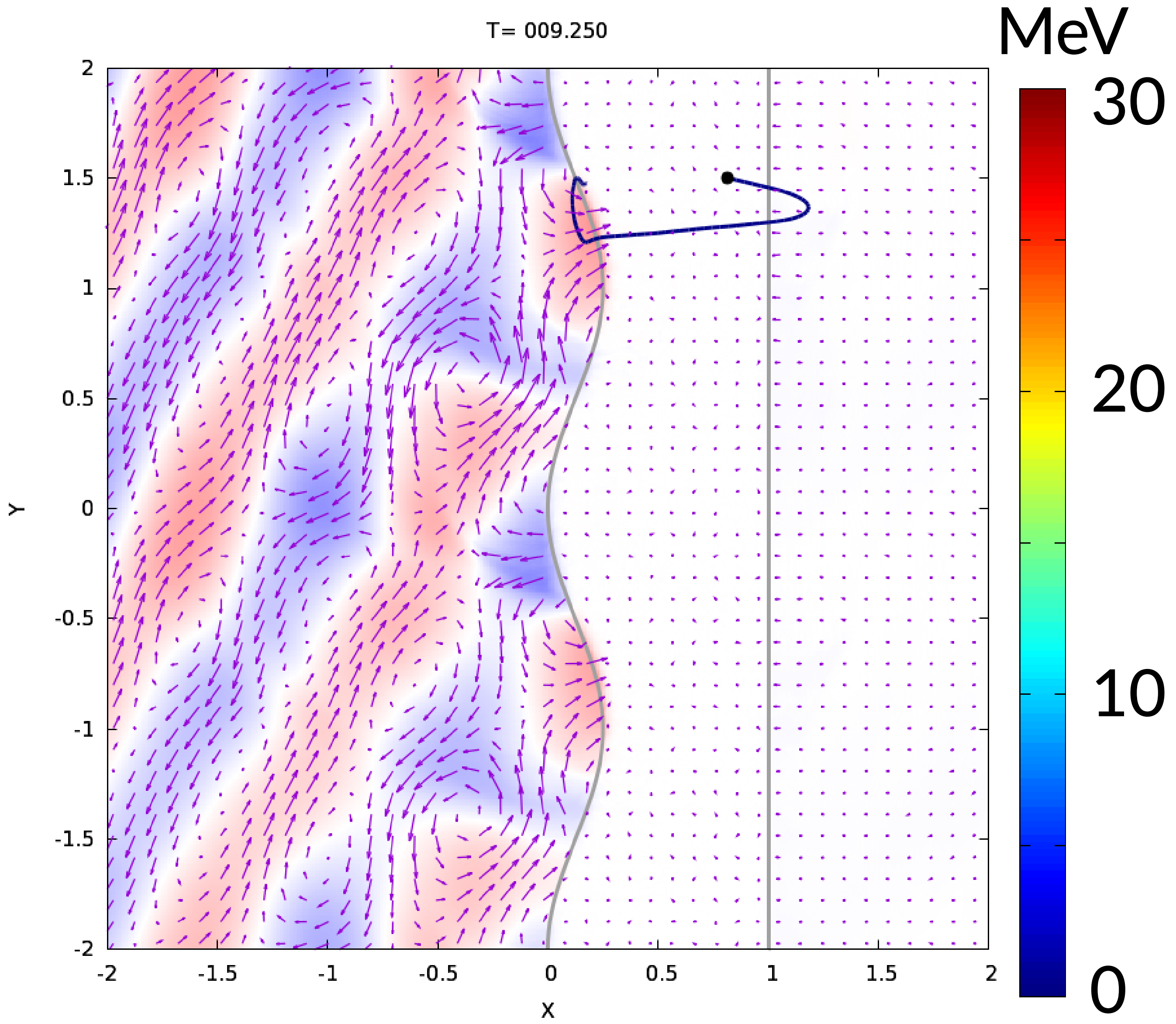

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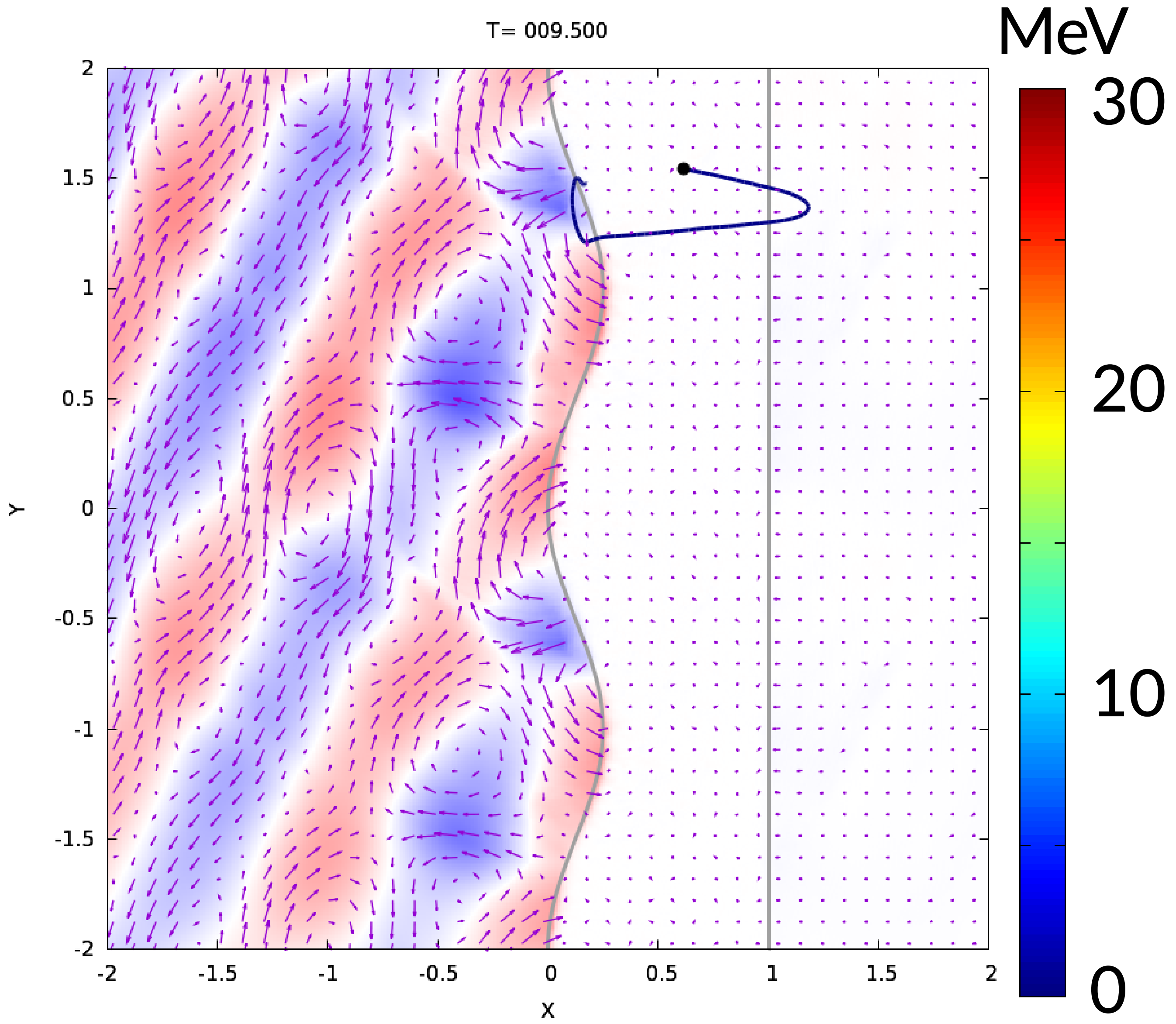

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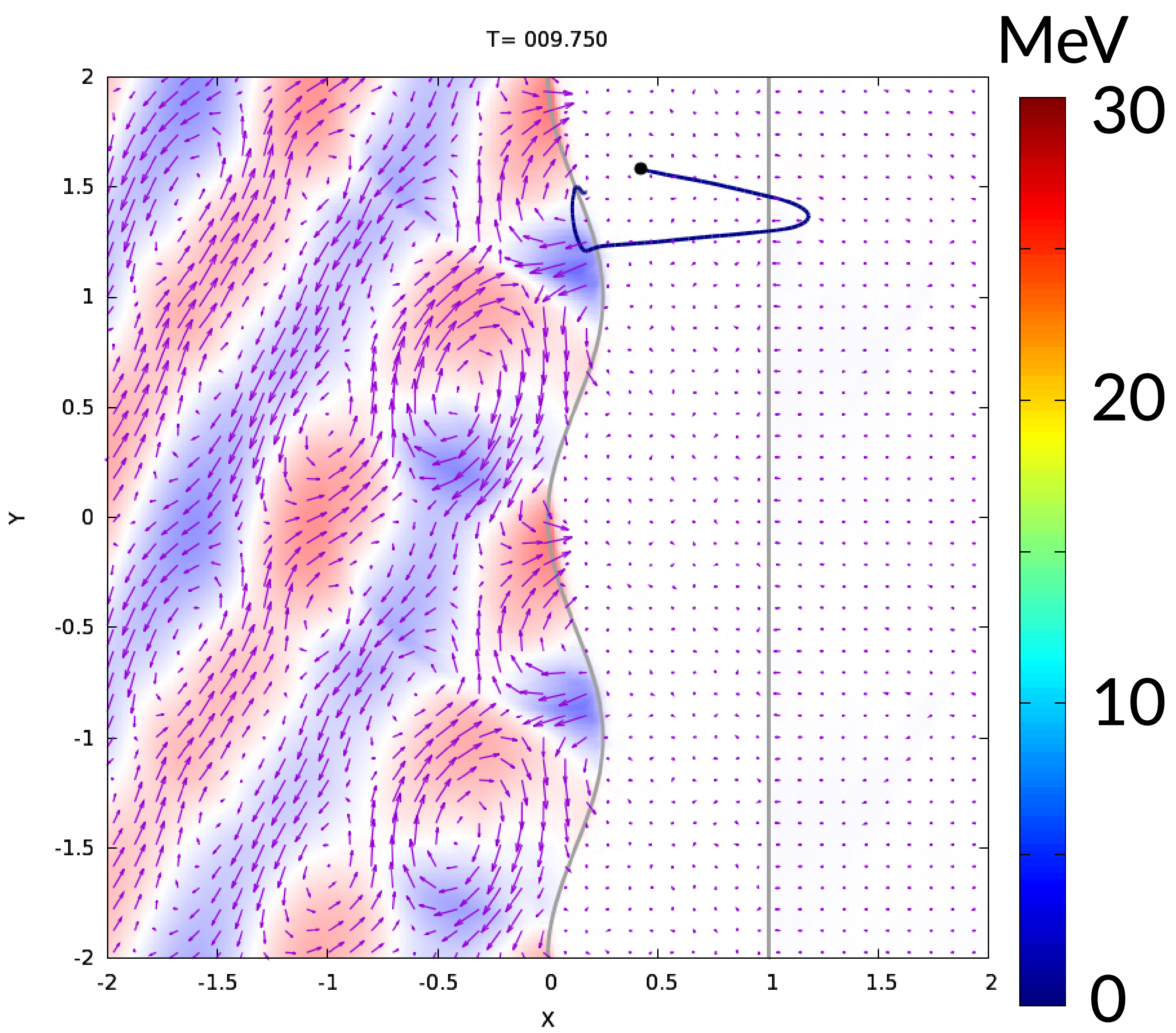

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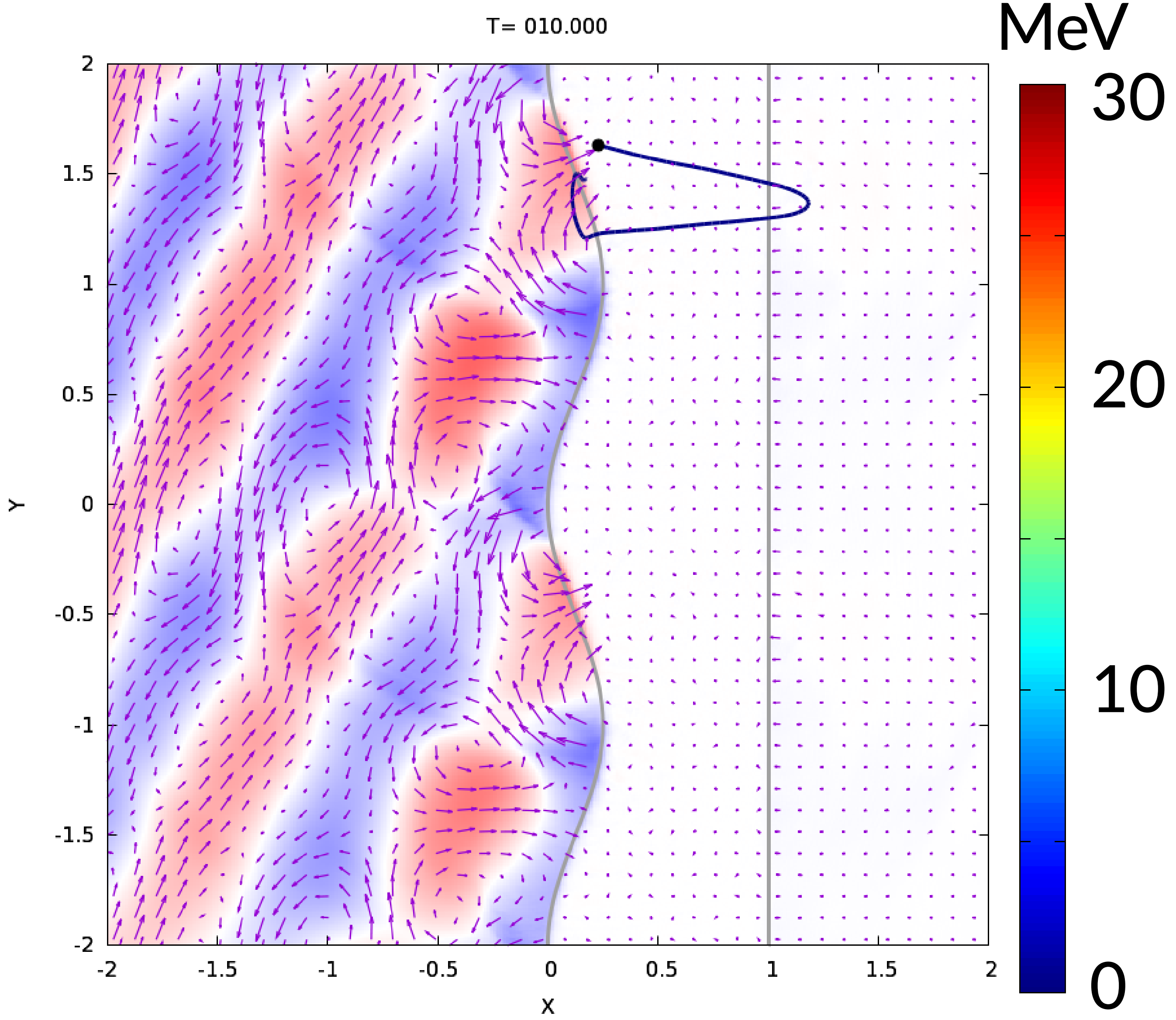

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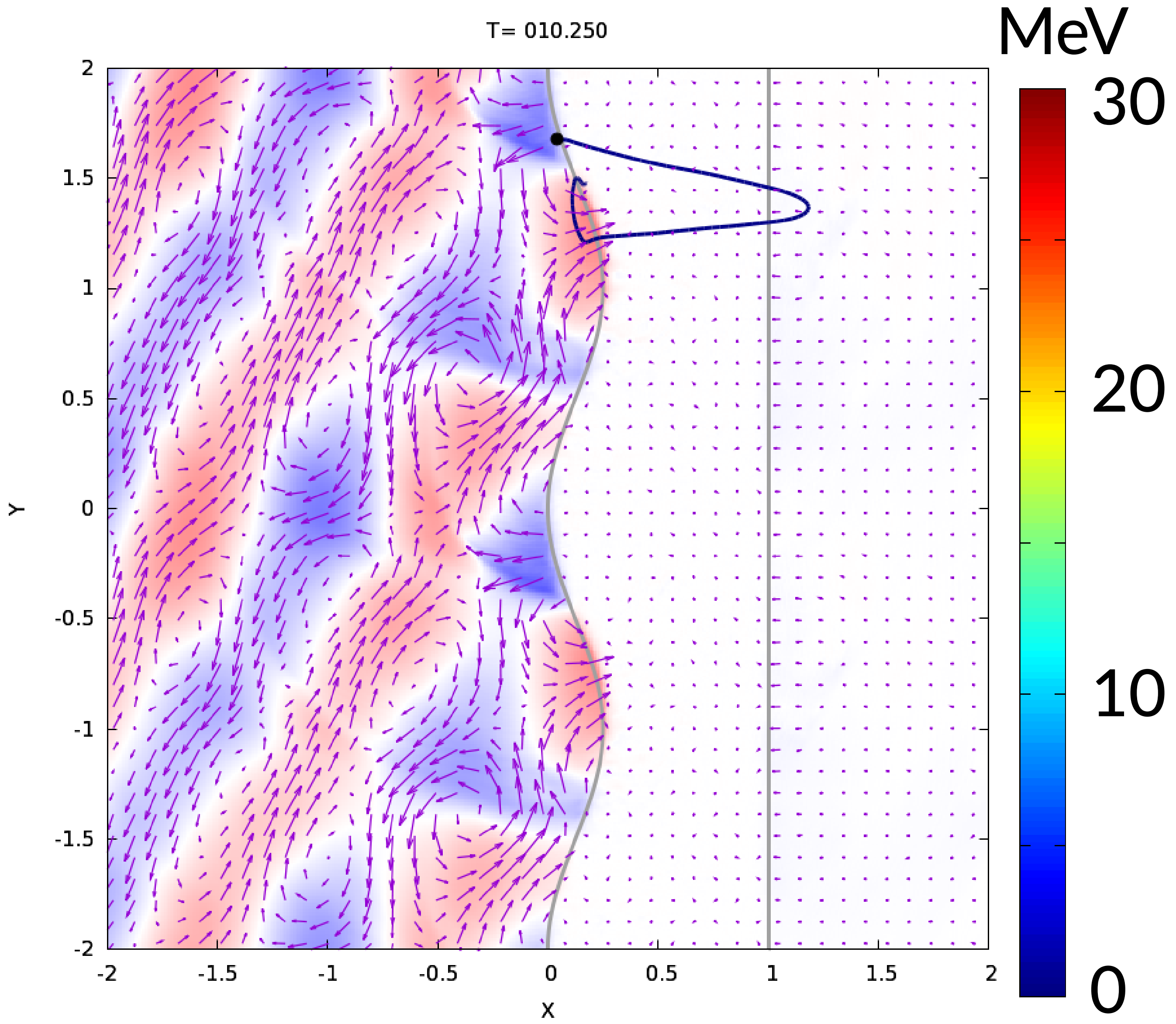

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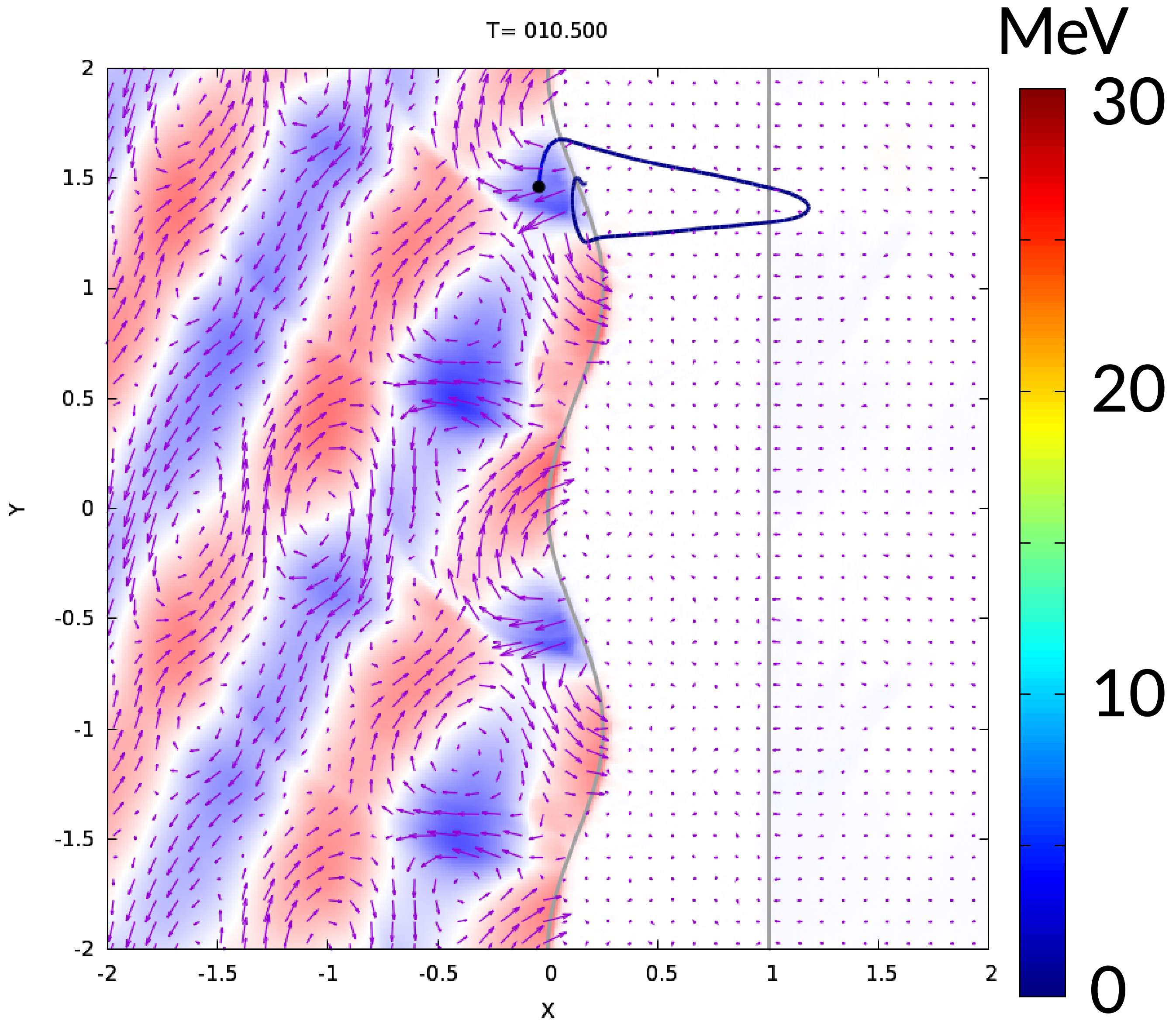

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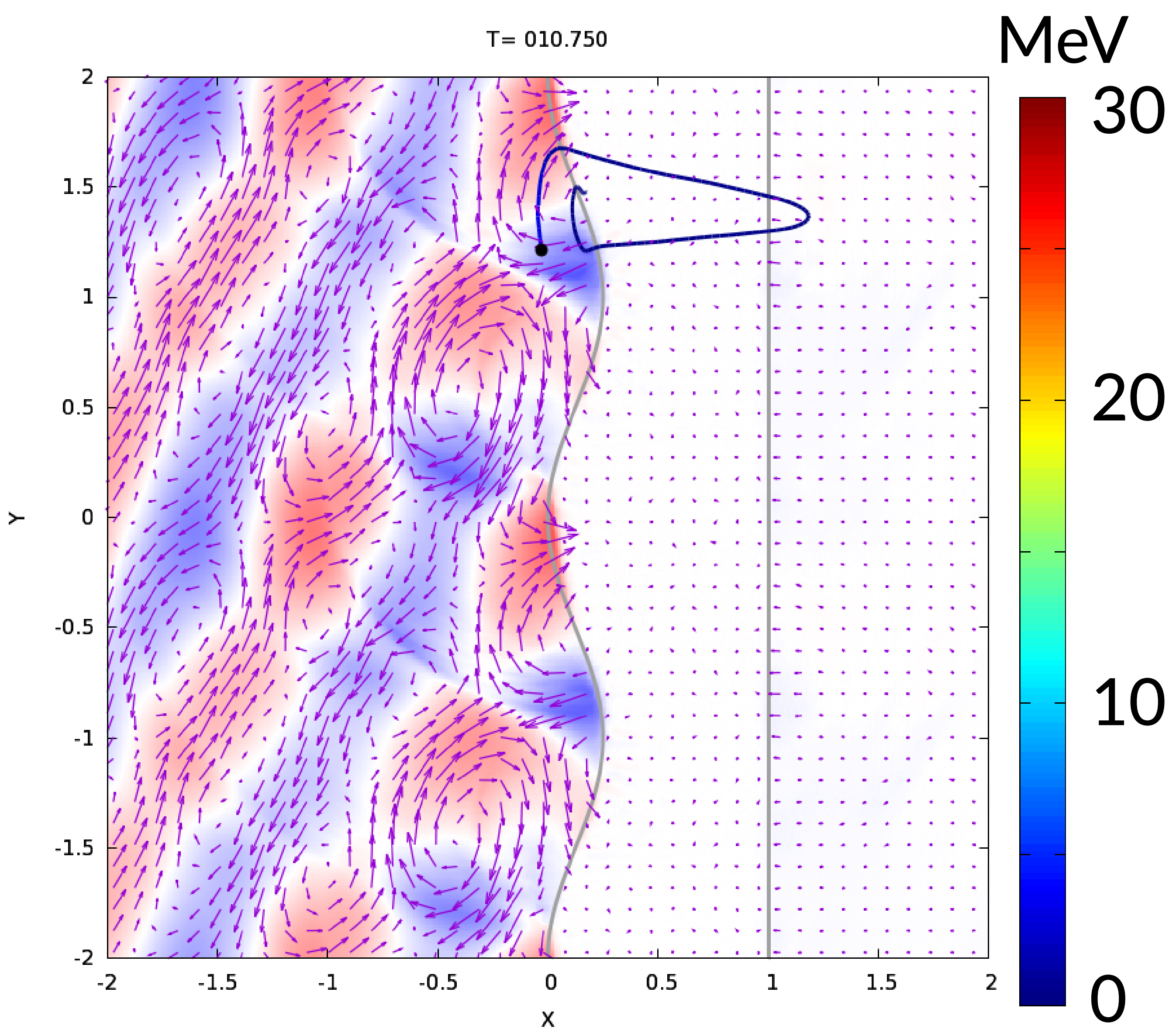

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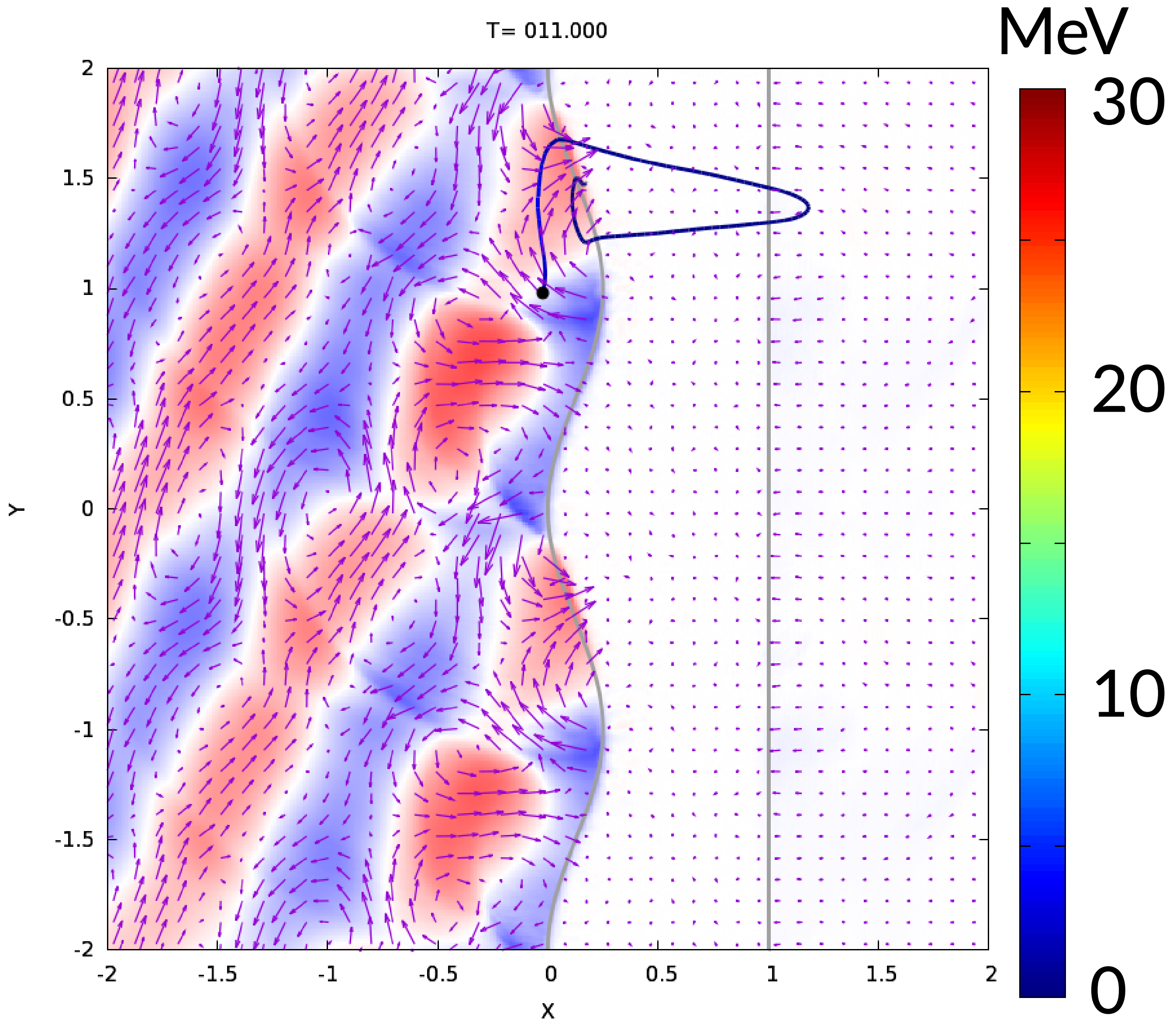

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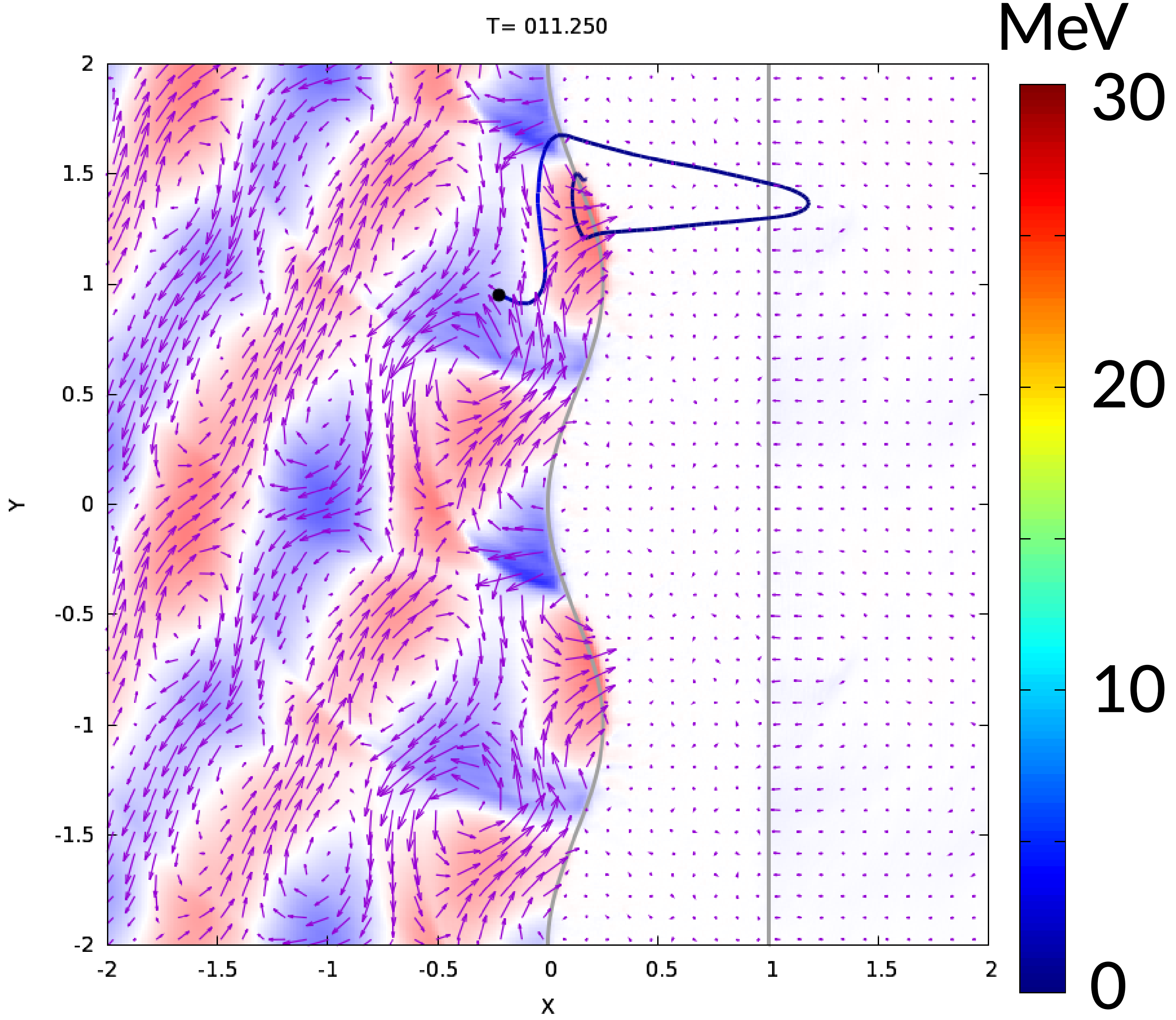

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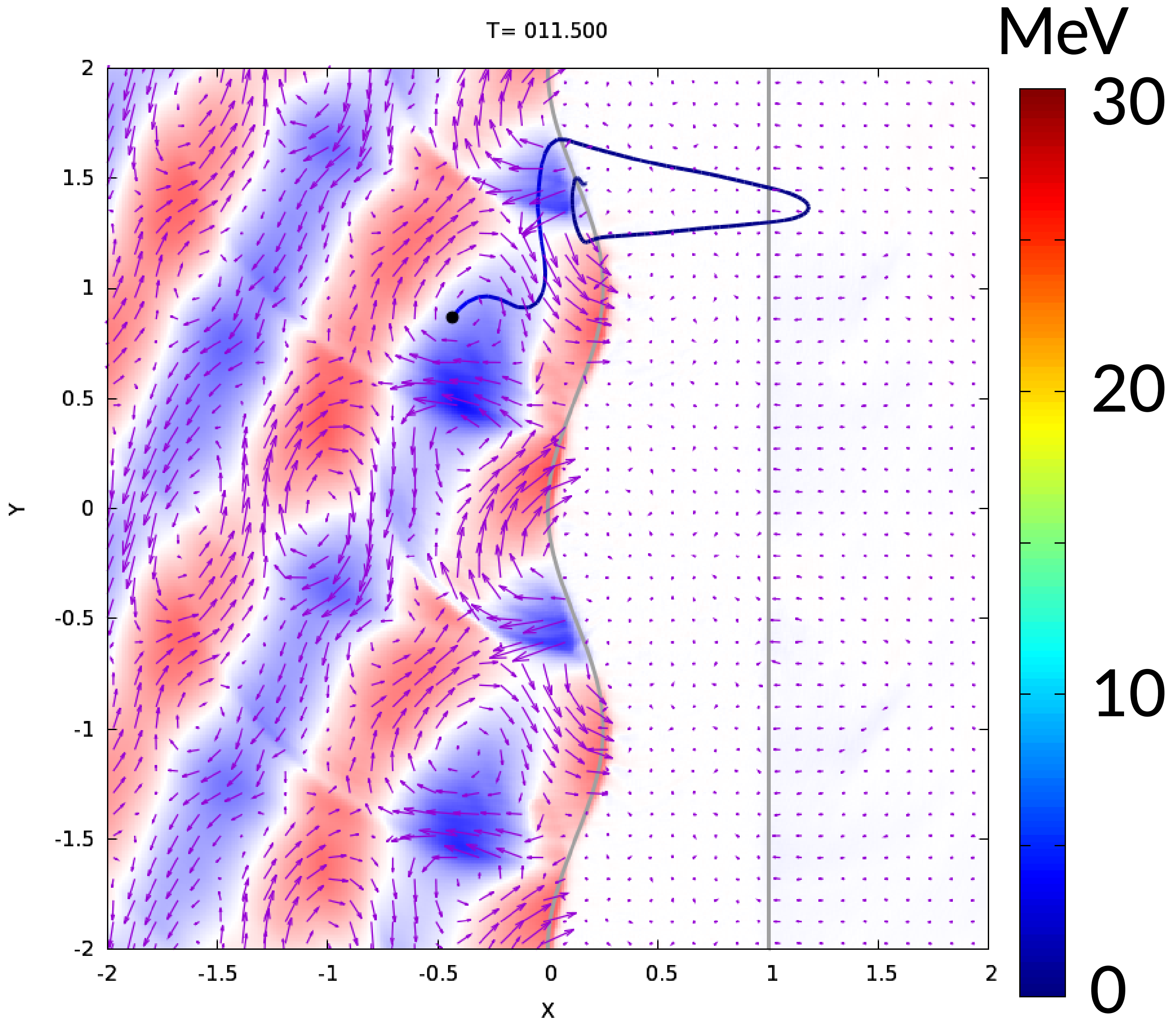

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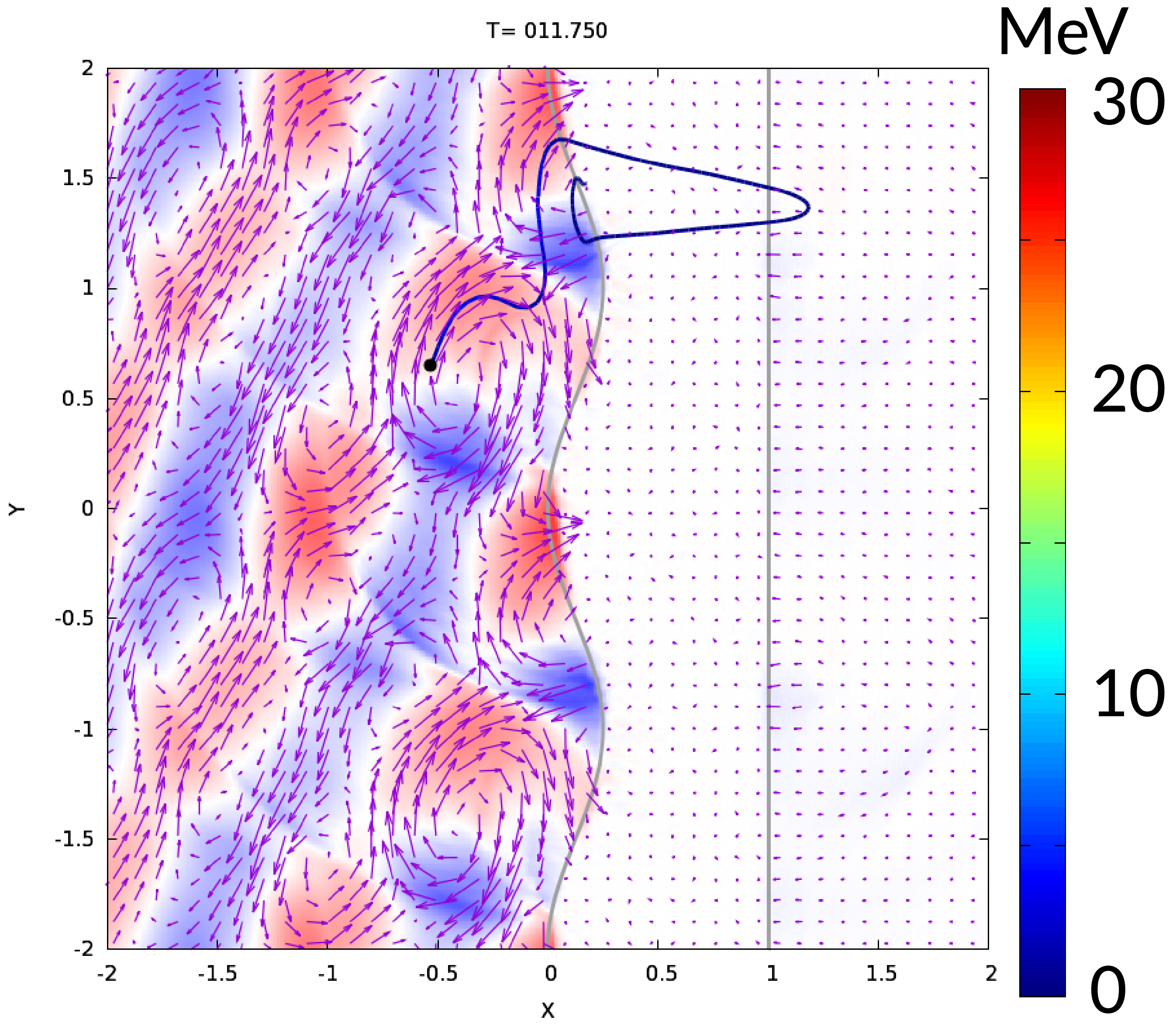

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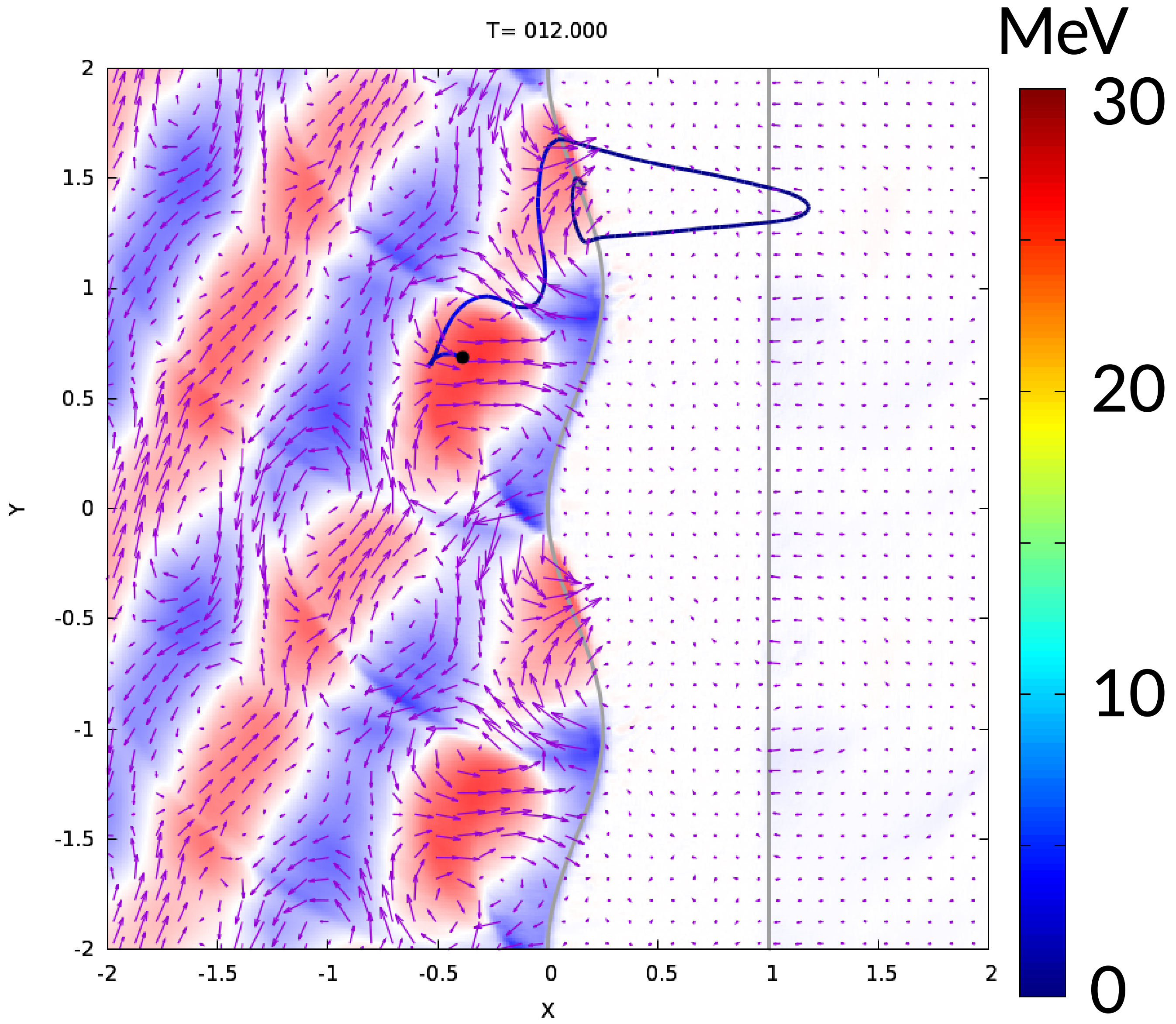

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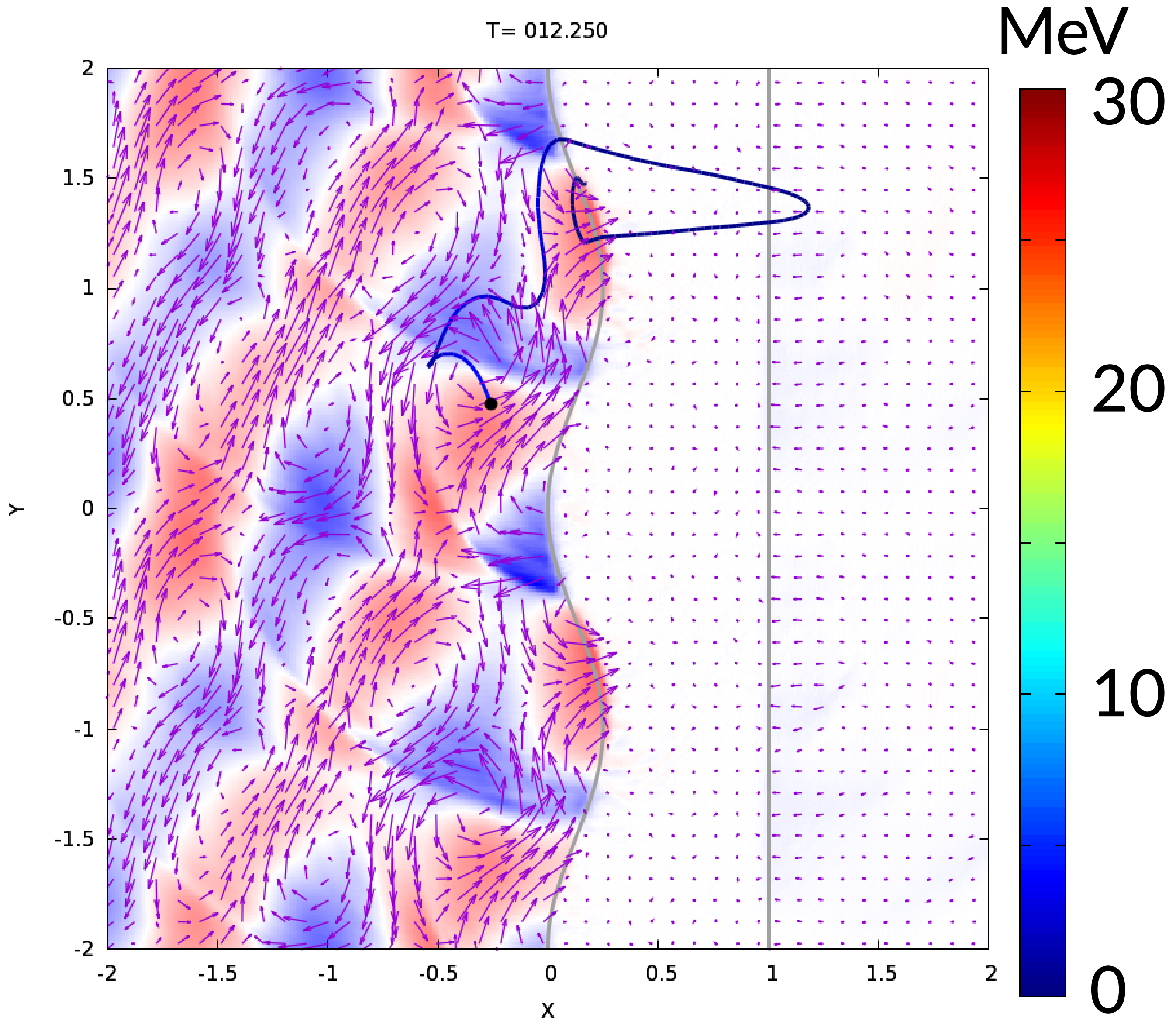

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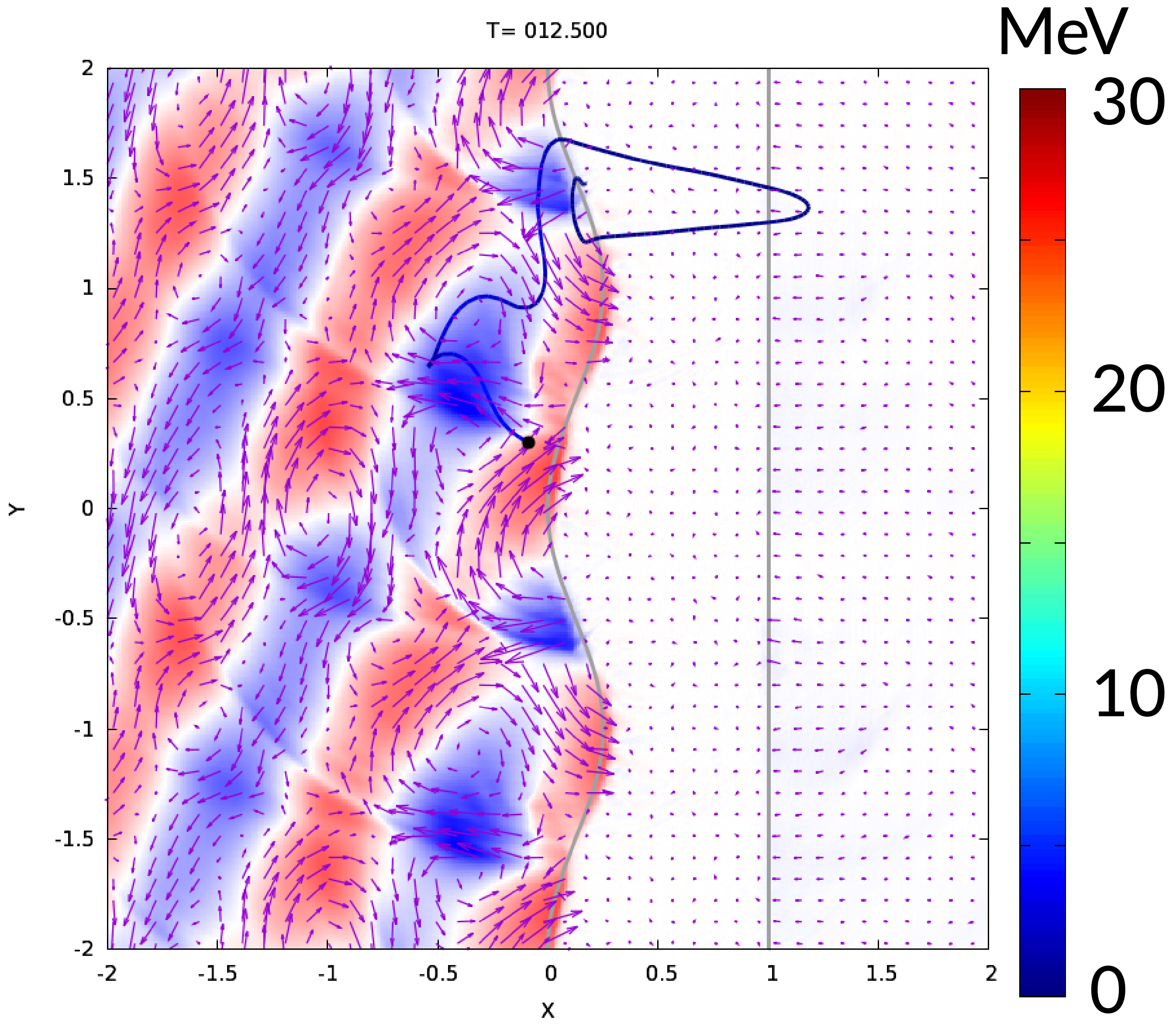

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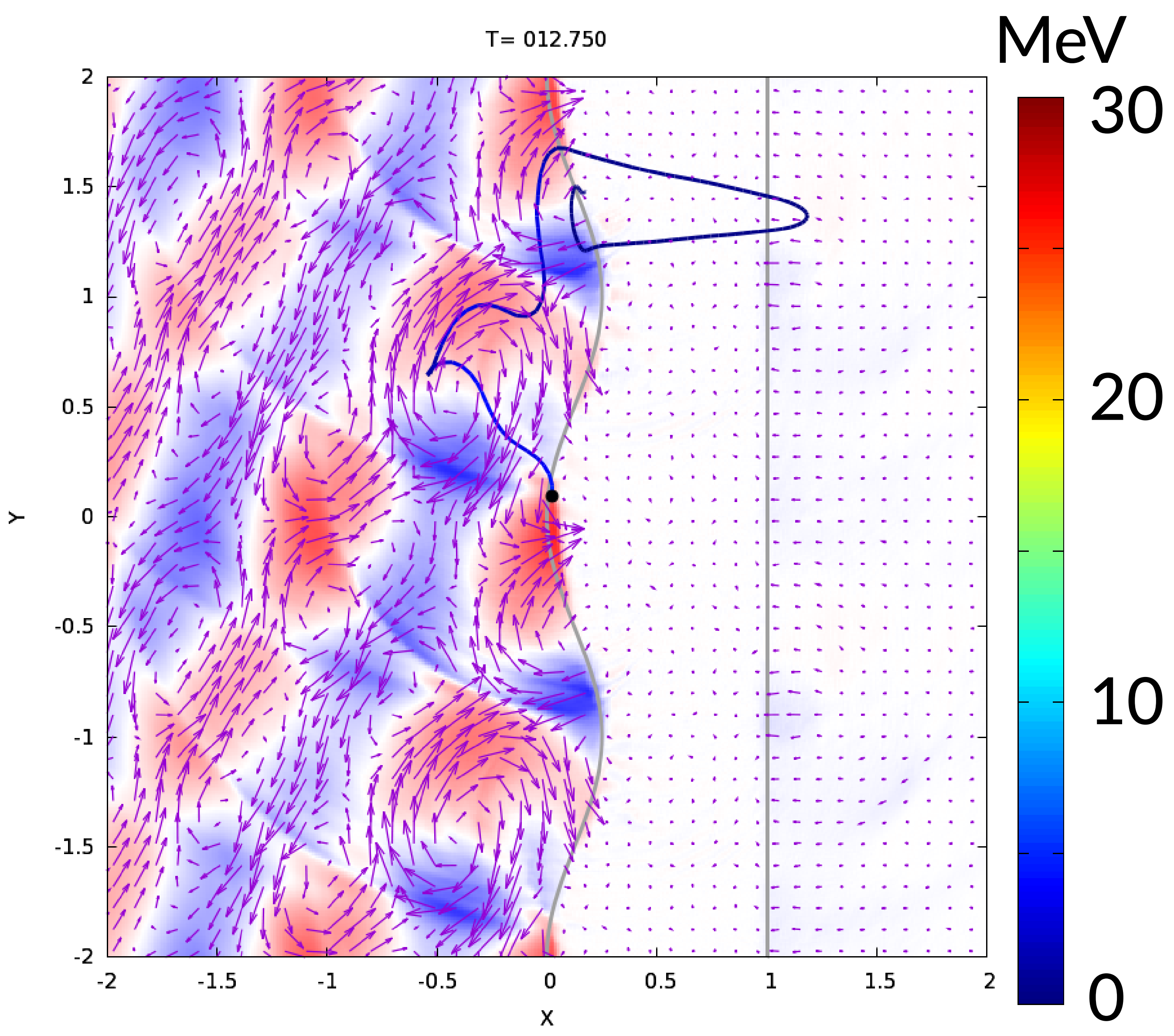

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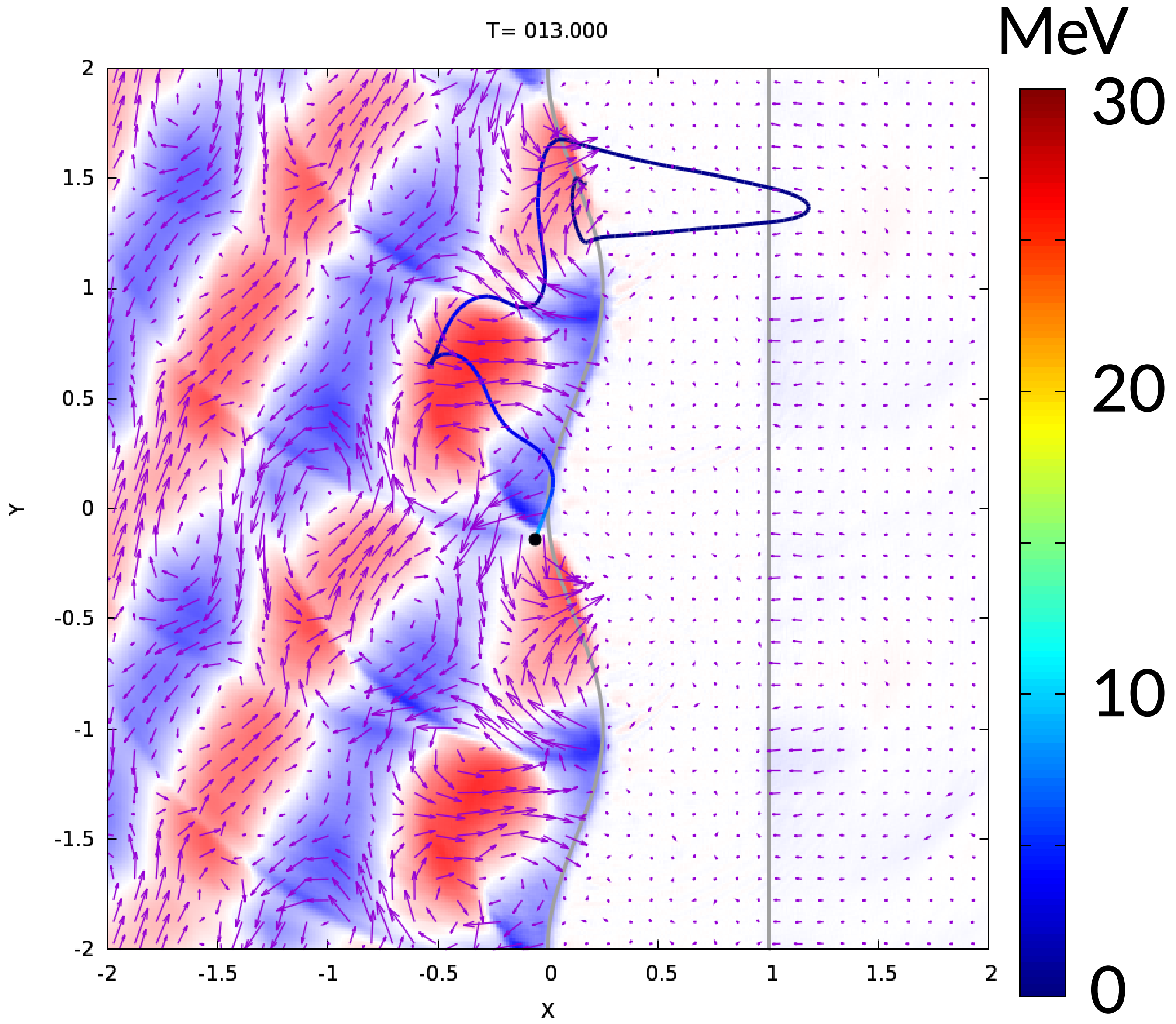

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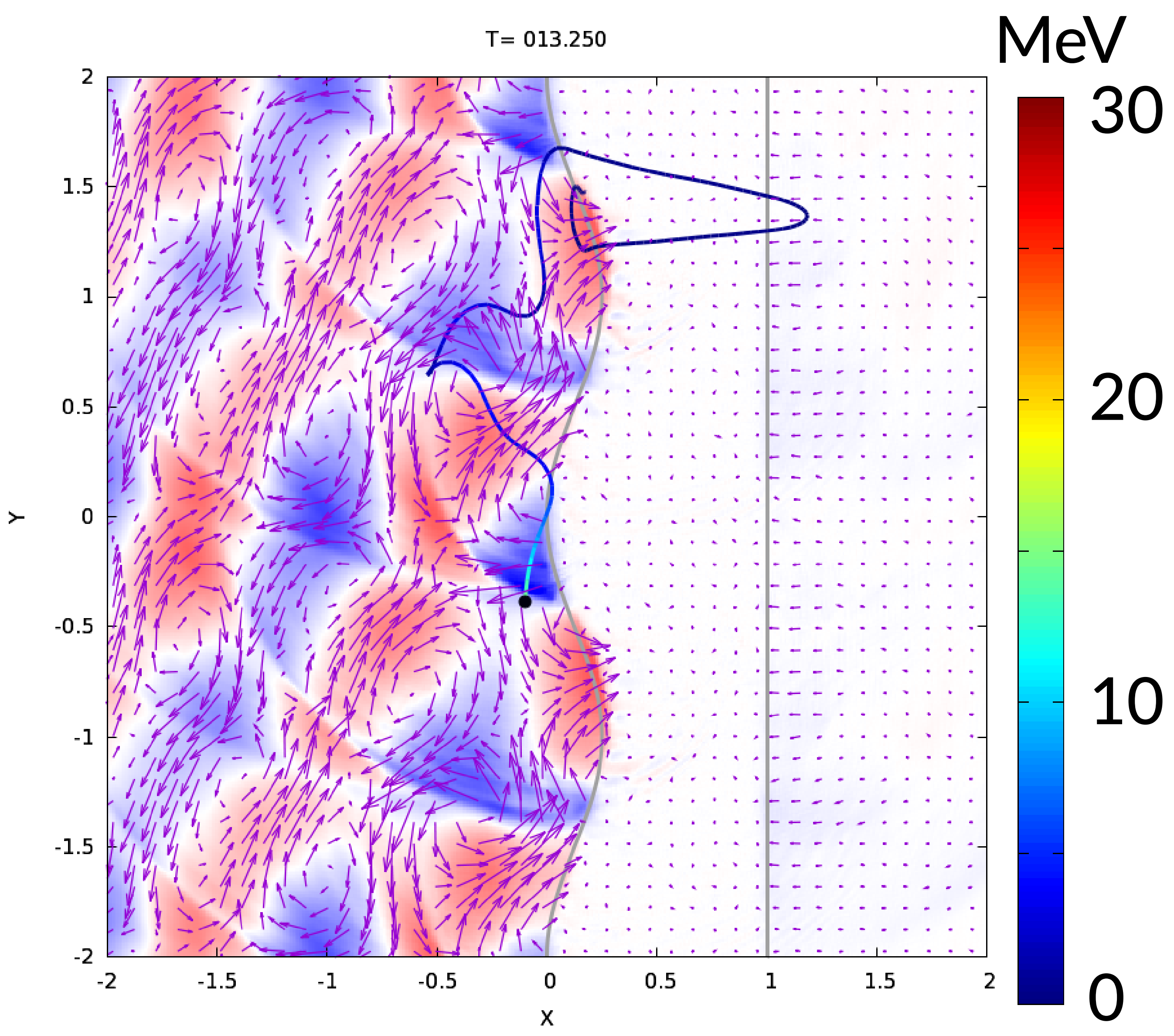

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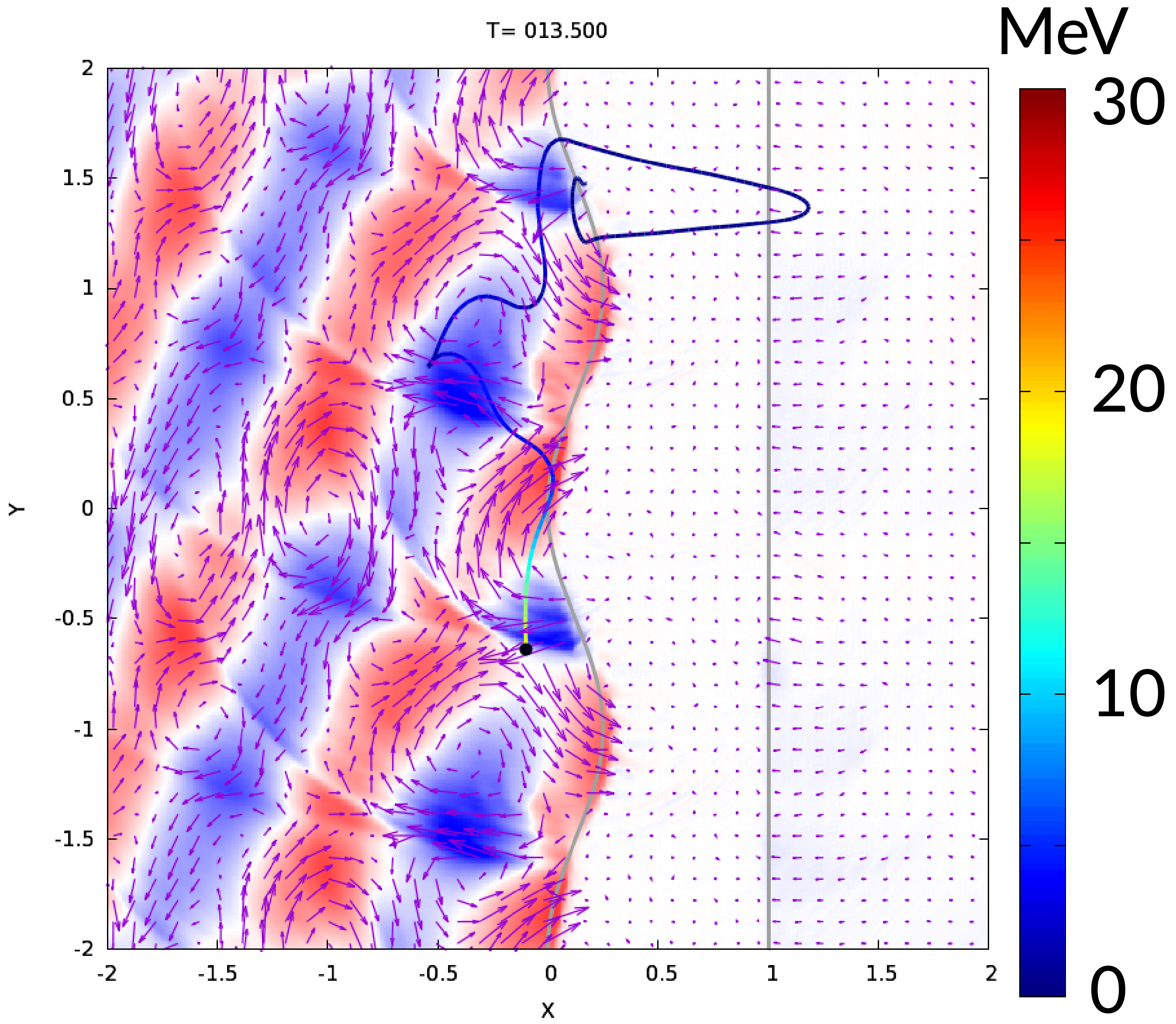

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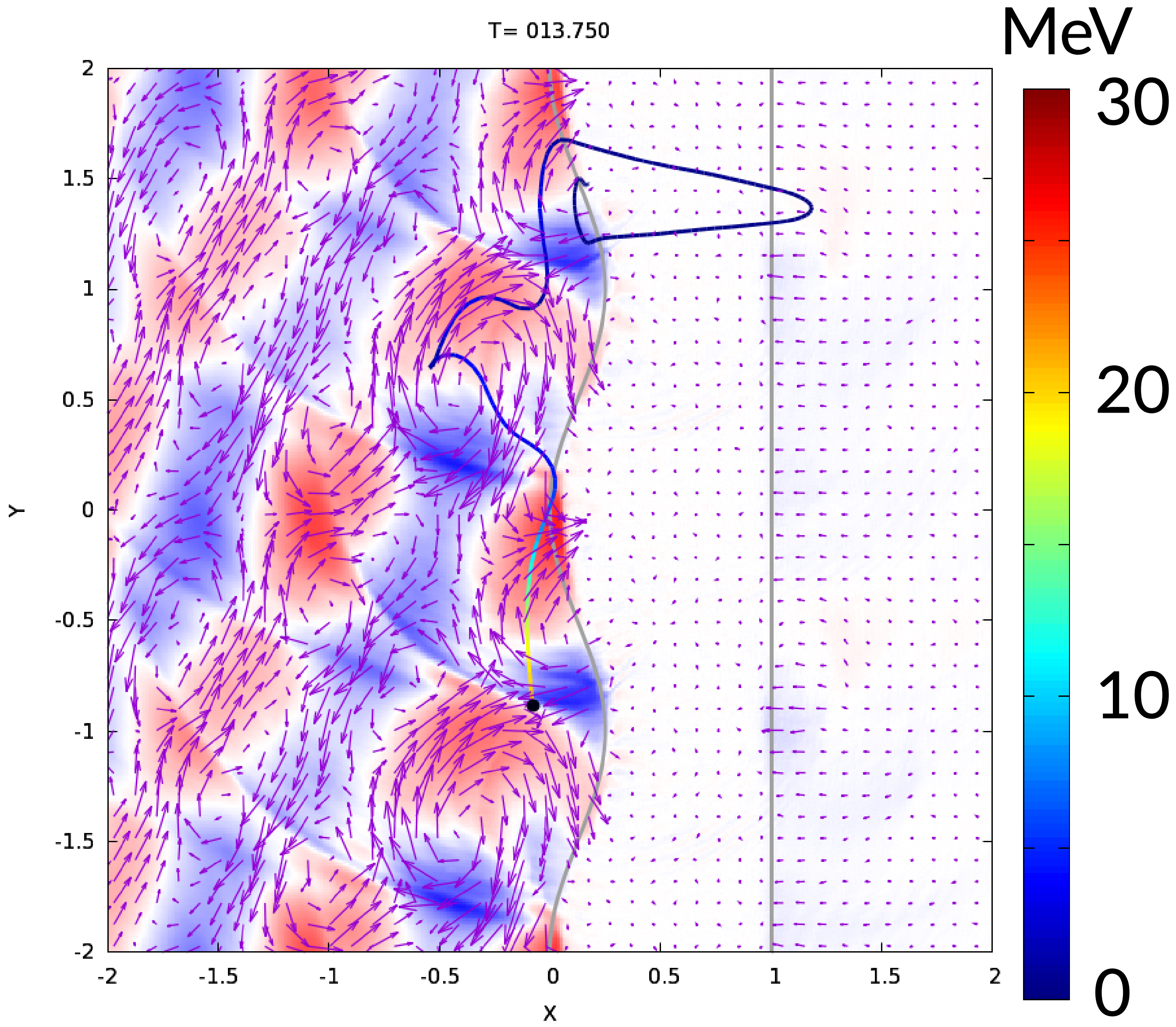

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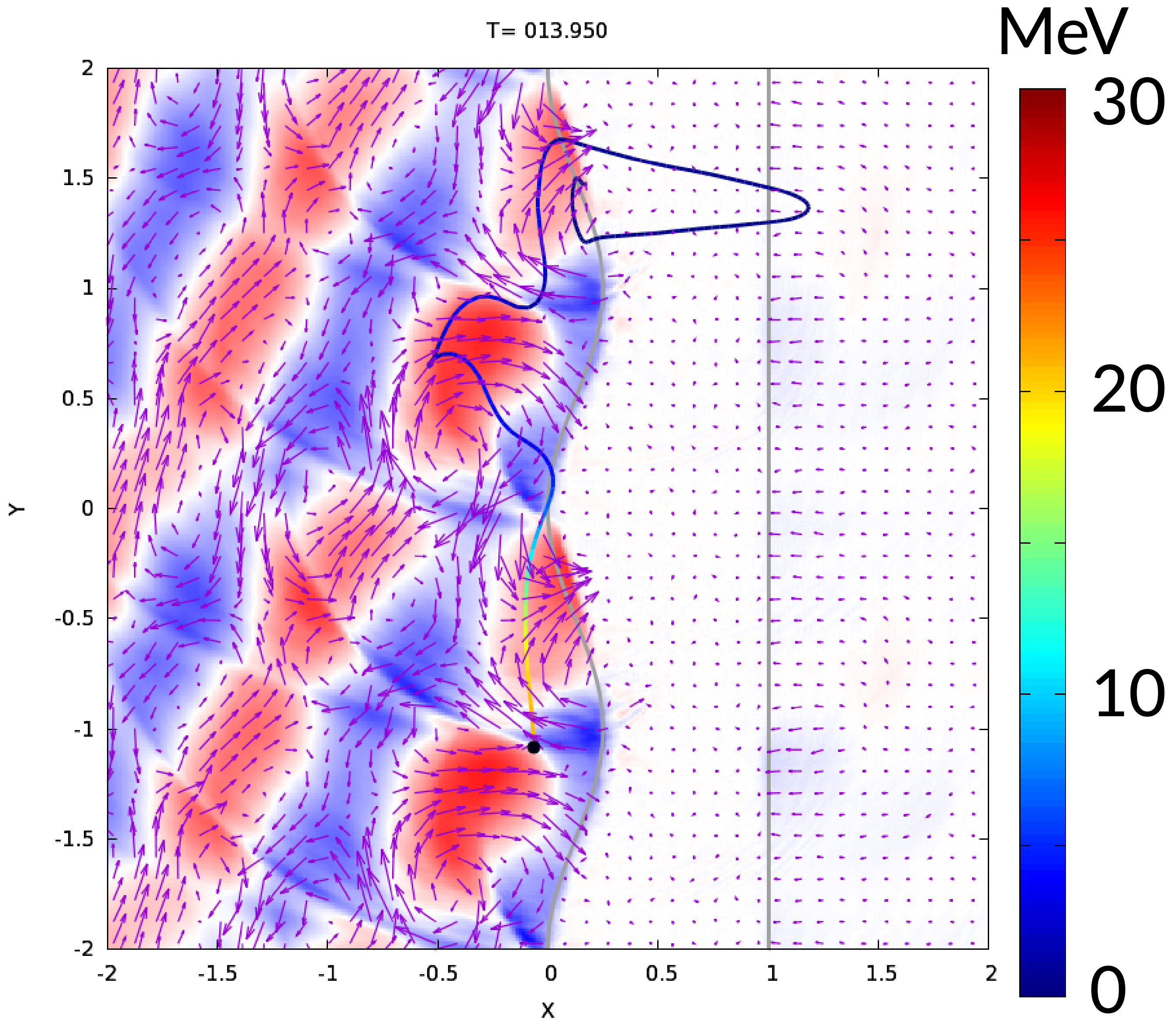
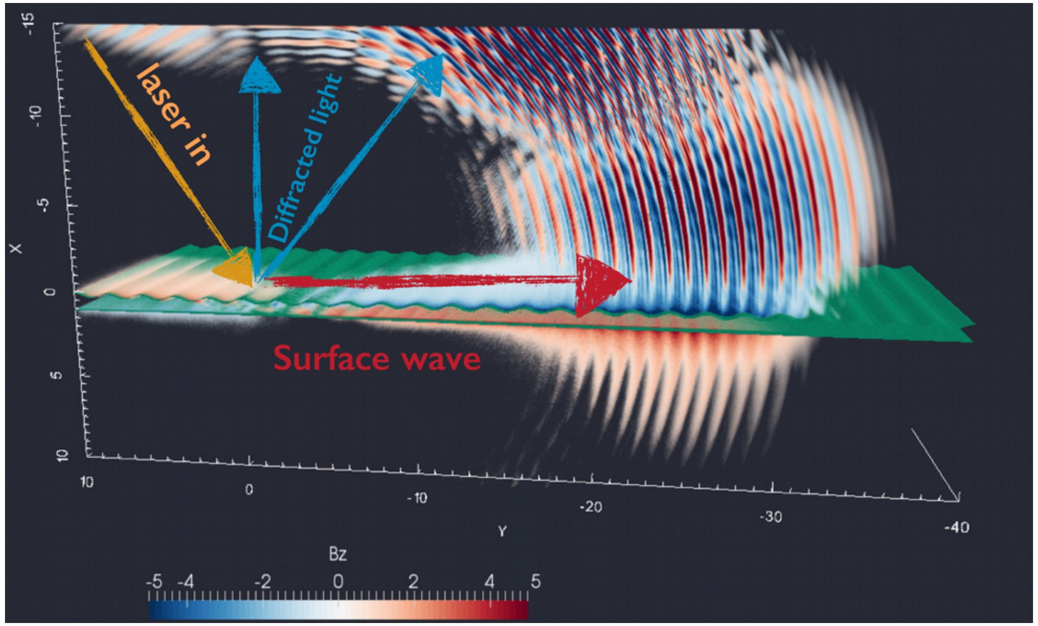
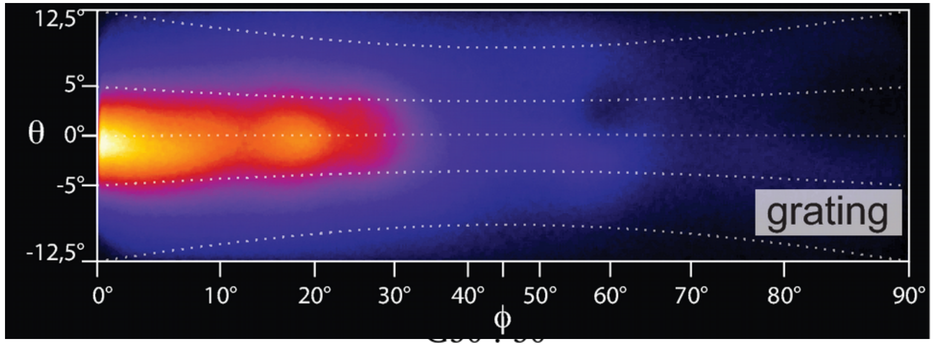


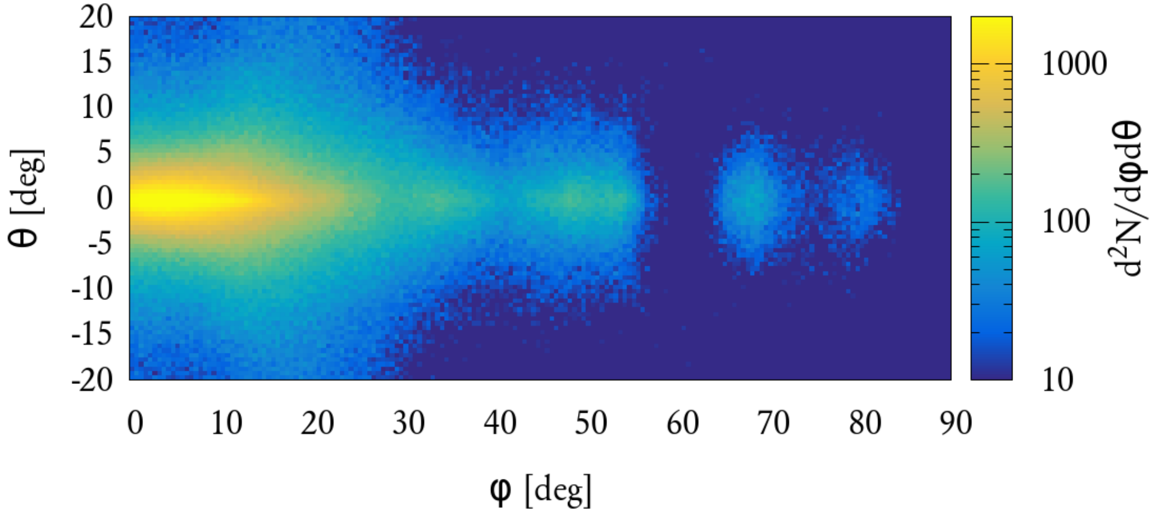
3D simulations allow to reproduce essential experimental features



3D simulation

Lanex from experiments

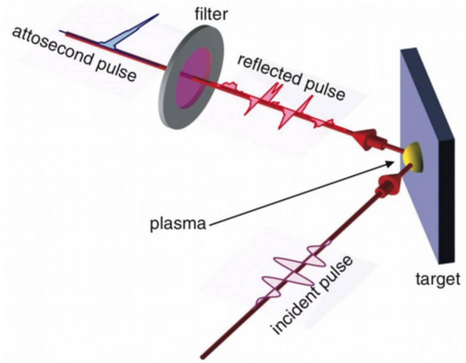


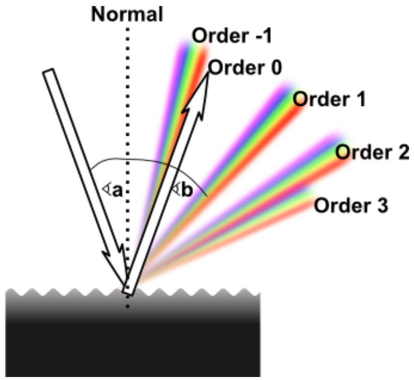


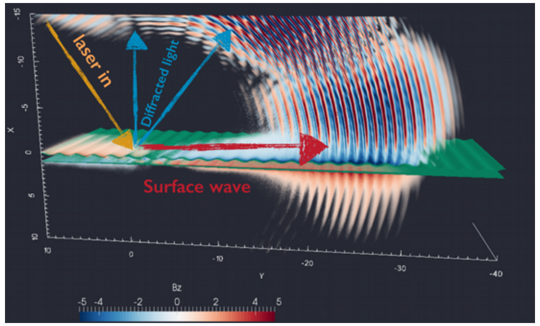
Lanex from simulations

High-order Harmonics

Three "ingredients"





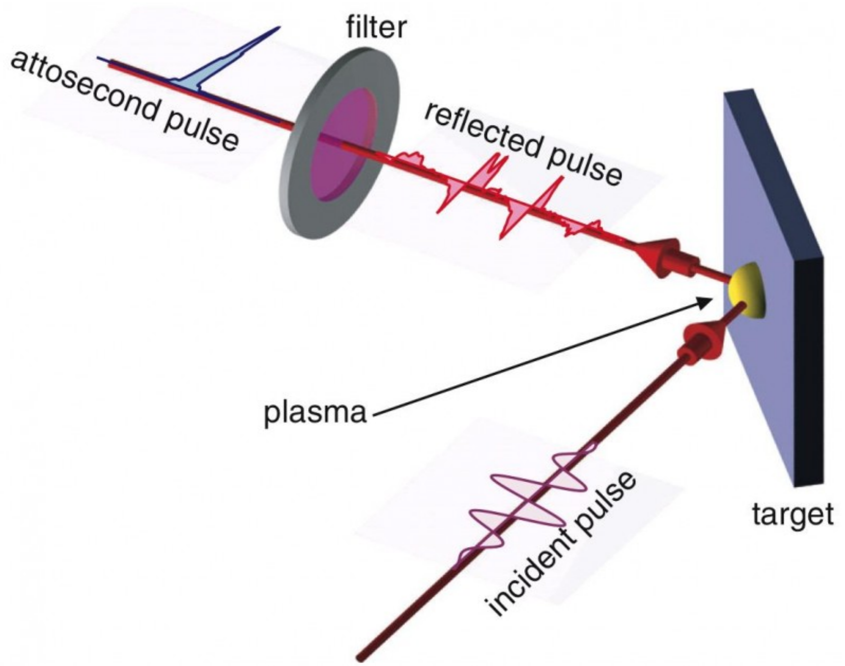


HHG with irradiated solid targets

HHG with gratings

Grating targets irradiated at resonance angle for surface plasmon excitation

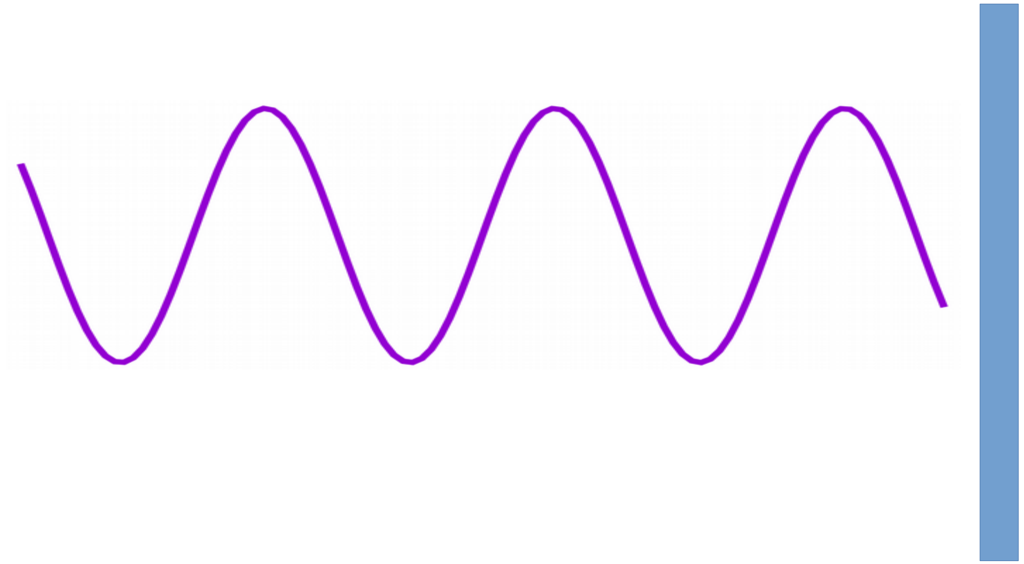
We can generate harmonics with intense lasers



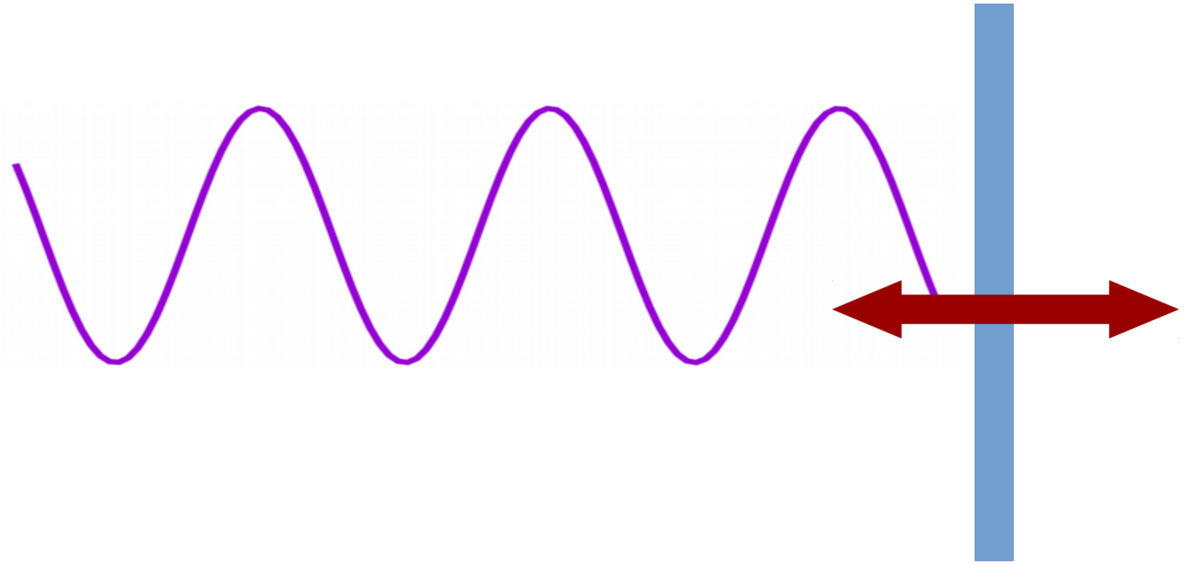
No a priori limits for the maximum **intensity** (relativistic oscillating mirror)

Teubner et al. 2009. RevModPhys,81
Vincenti et al. 2012. PRL, 108

Oversimplified model: Relativistic Oscillating Mirror



Oversimplified model:
Relativistic Oscillating Mirror



Oversimplified model:
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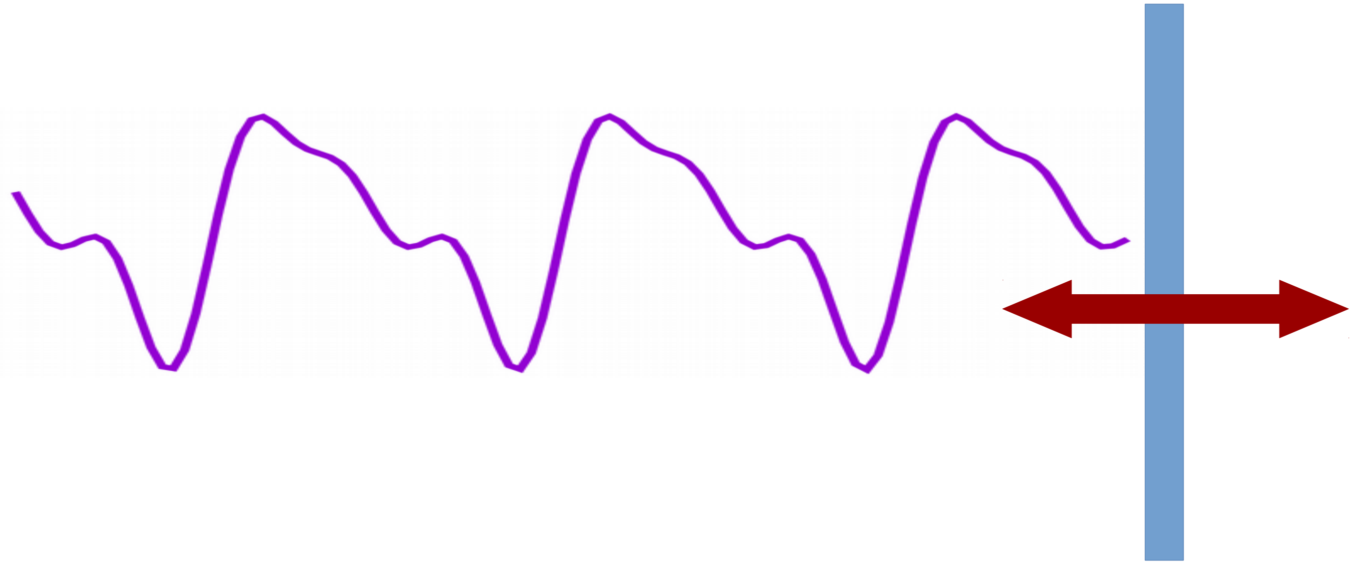
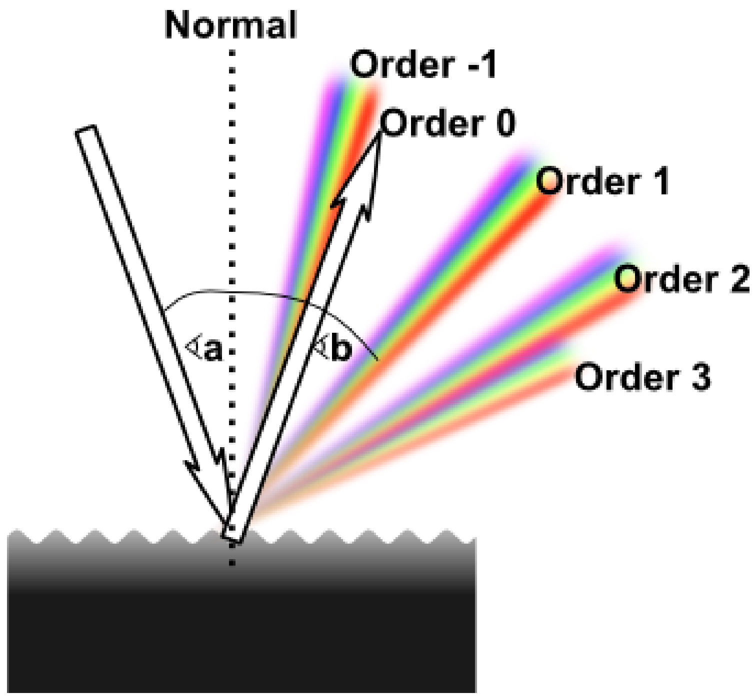


What if we irradiate a grating?

We should obviously expect diffraction of harmonics (well known)

$$\frac{n\lambda}{md} = \sin(\theta_i) + \sin(\theta_{mn})$$



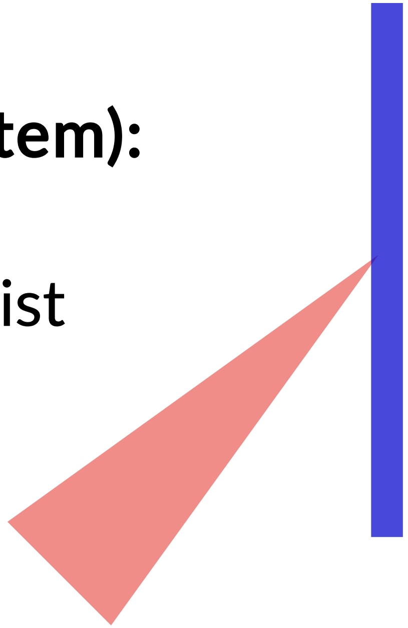
X. Lavocat-Dubuis & J.P. Matte PoP 17 2010

M.Yeung et al. New Journal of Physics 15 2013

But what if we irradiate a grating at resonance?

2D numerical simulation campaign

Laser (~100s TW system):
P-pol, a_0 = 15,
32 fs FWHM, 4 μm waist

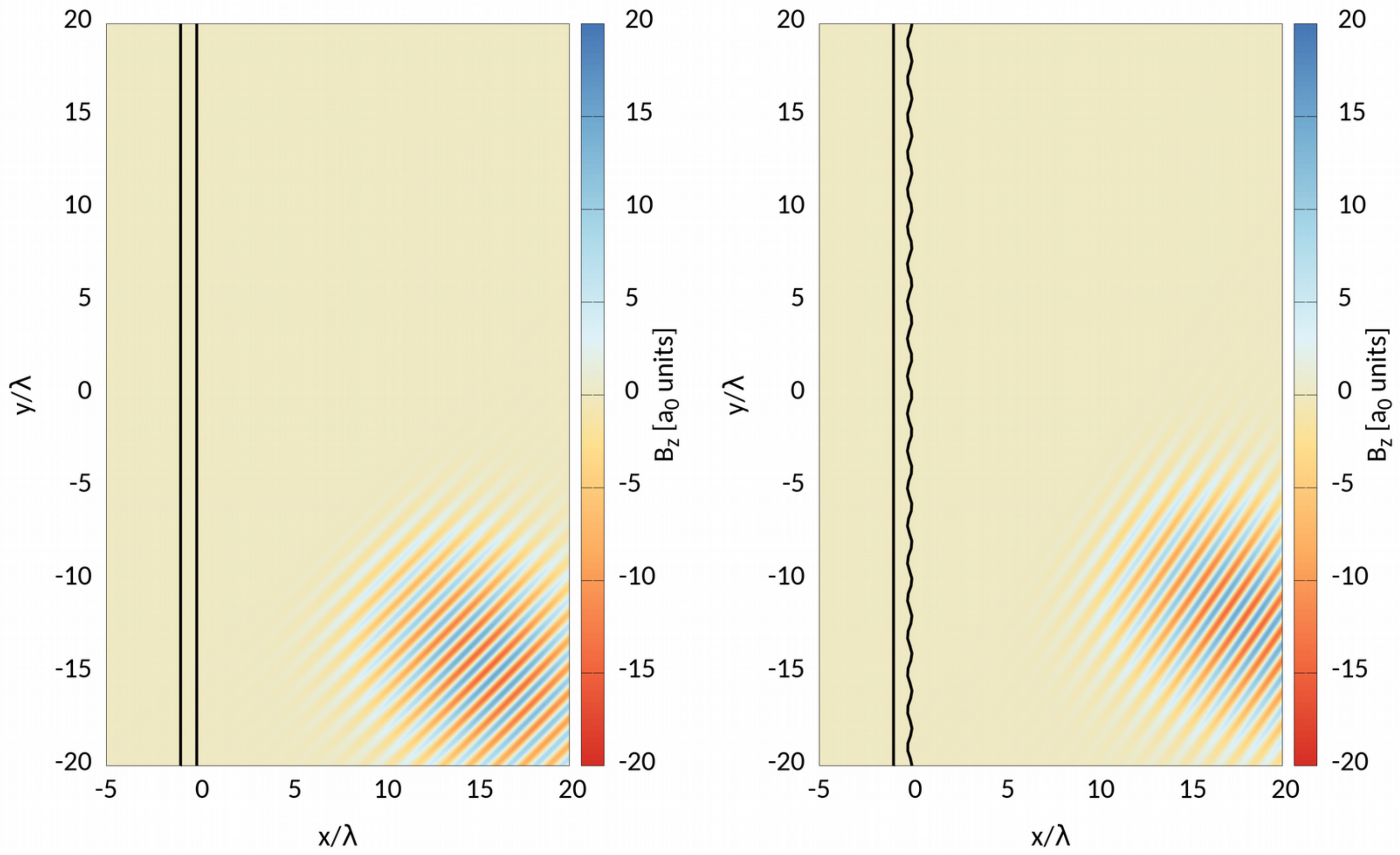


Target:
Either a **flat target** or a **grating target** with d=2.0λ (resonance at 30°) and peak-to-valley depth of 0.25λ

Few snapshots of the EM fields

Flat target @ 45°

Grating target @ 35°



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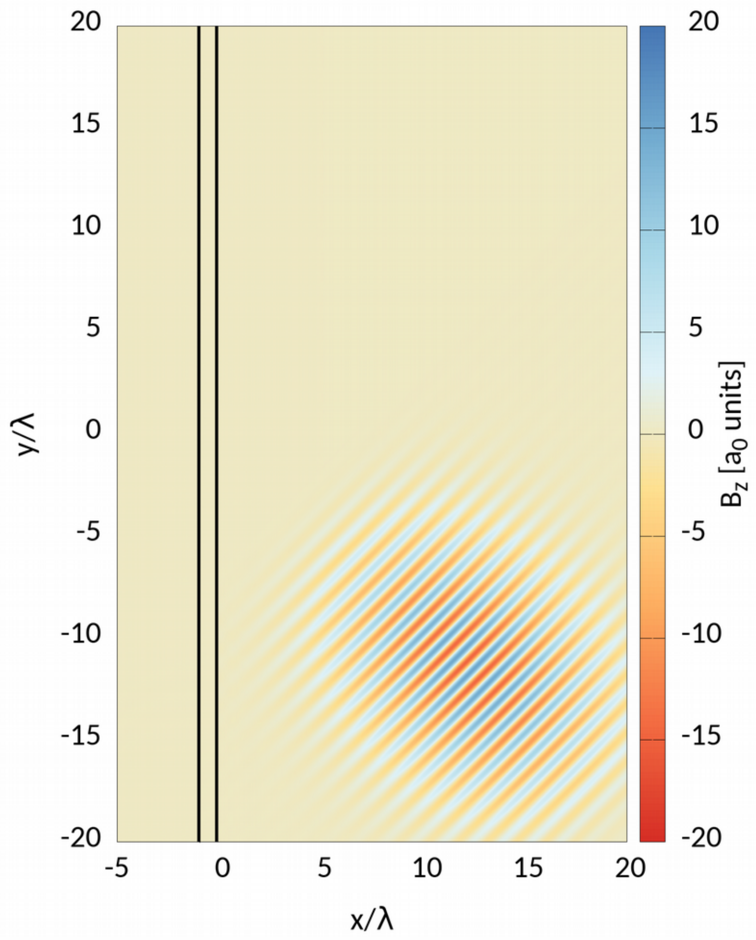
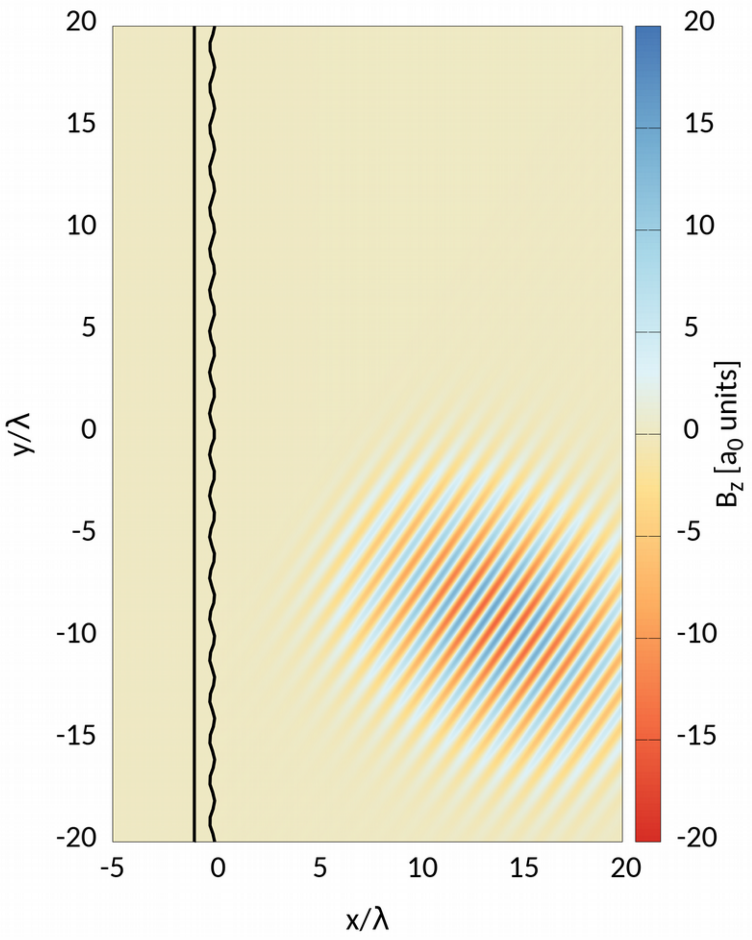


Grating target @ 35°



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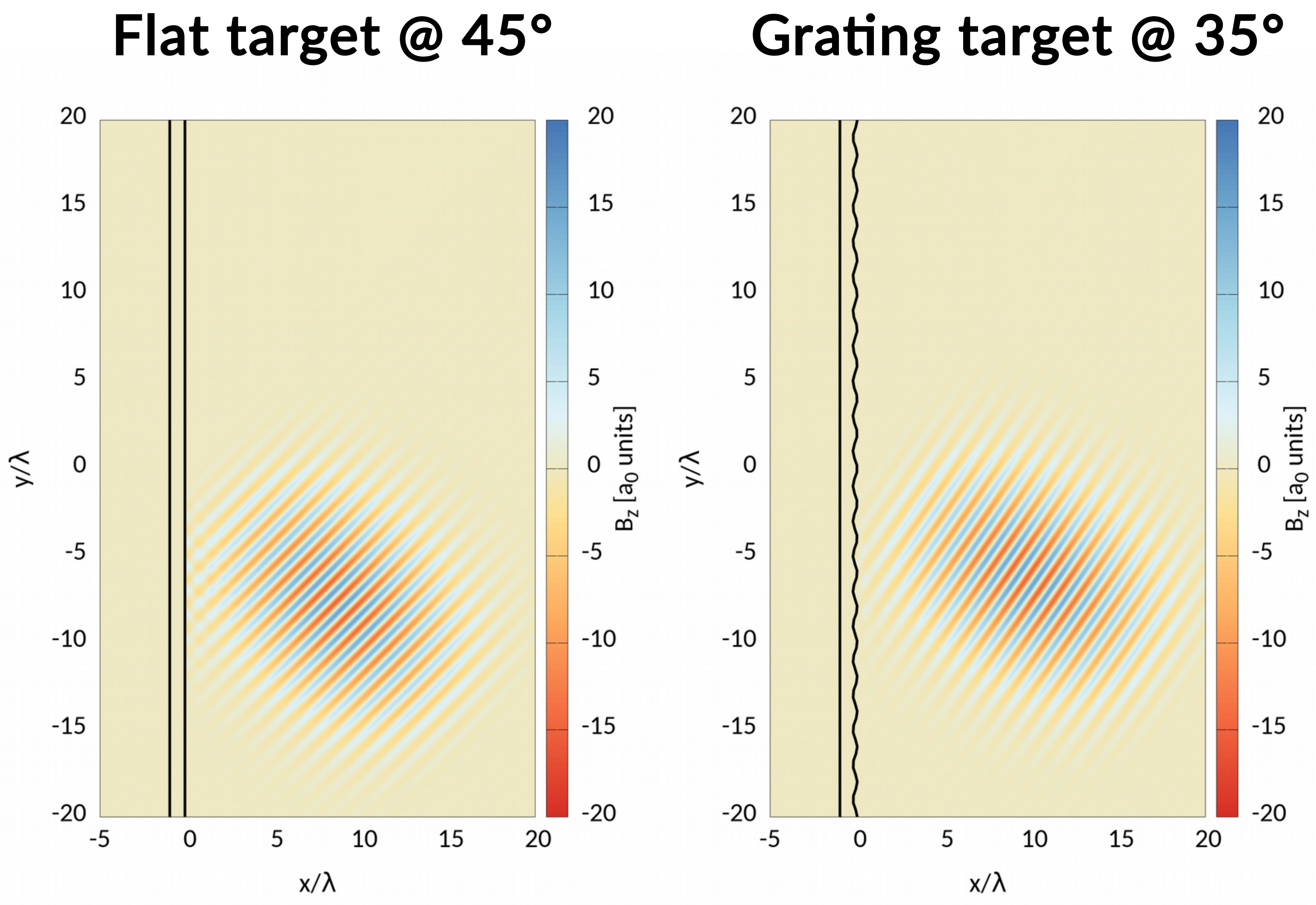

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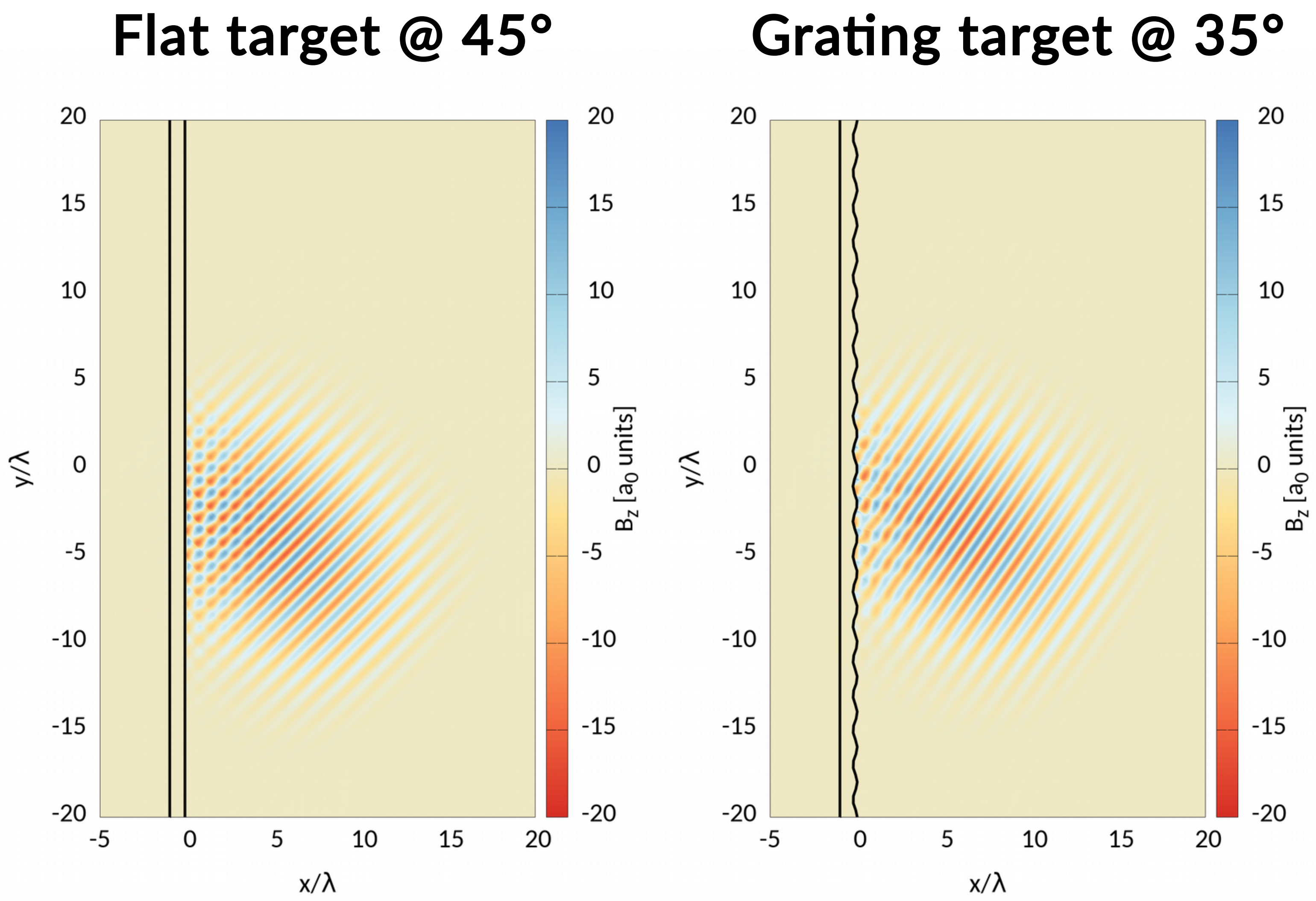

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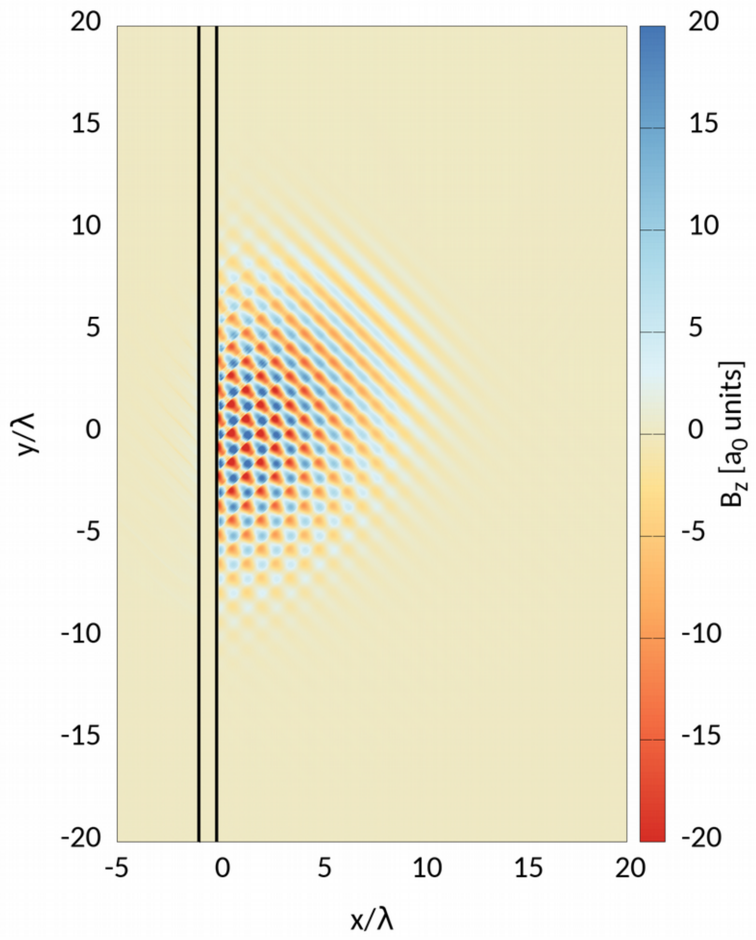

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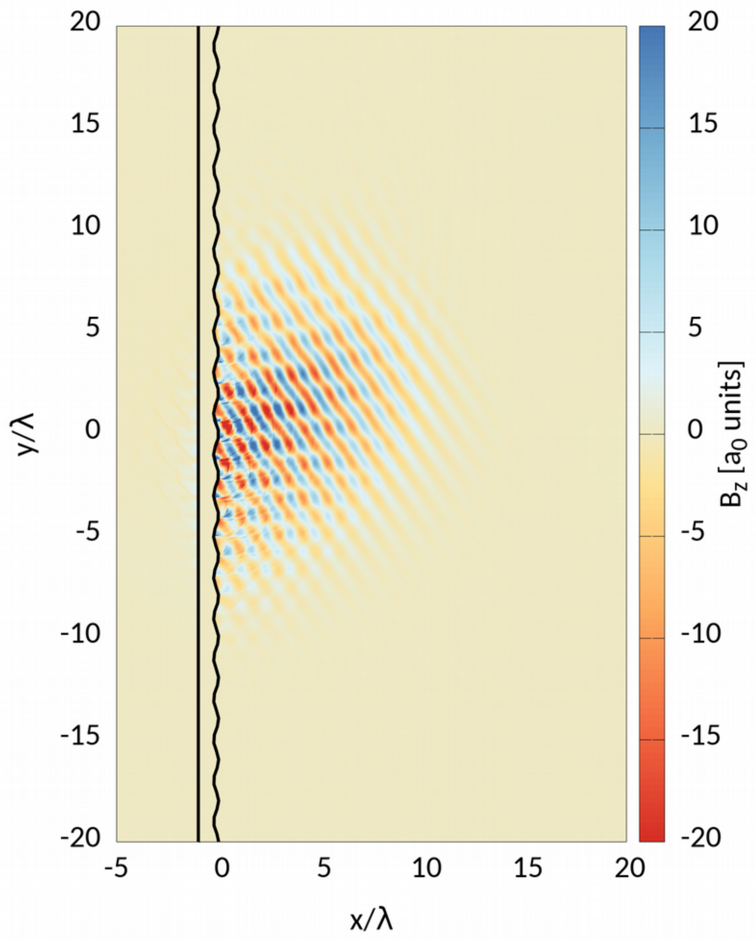

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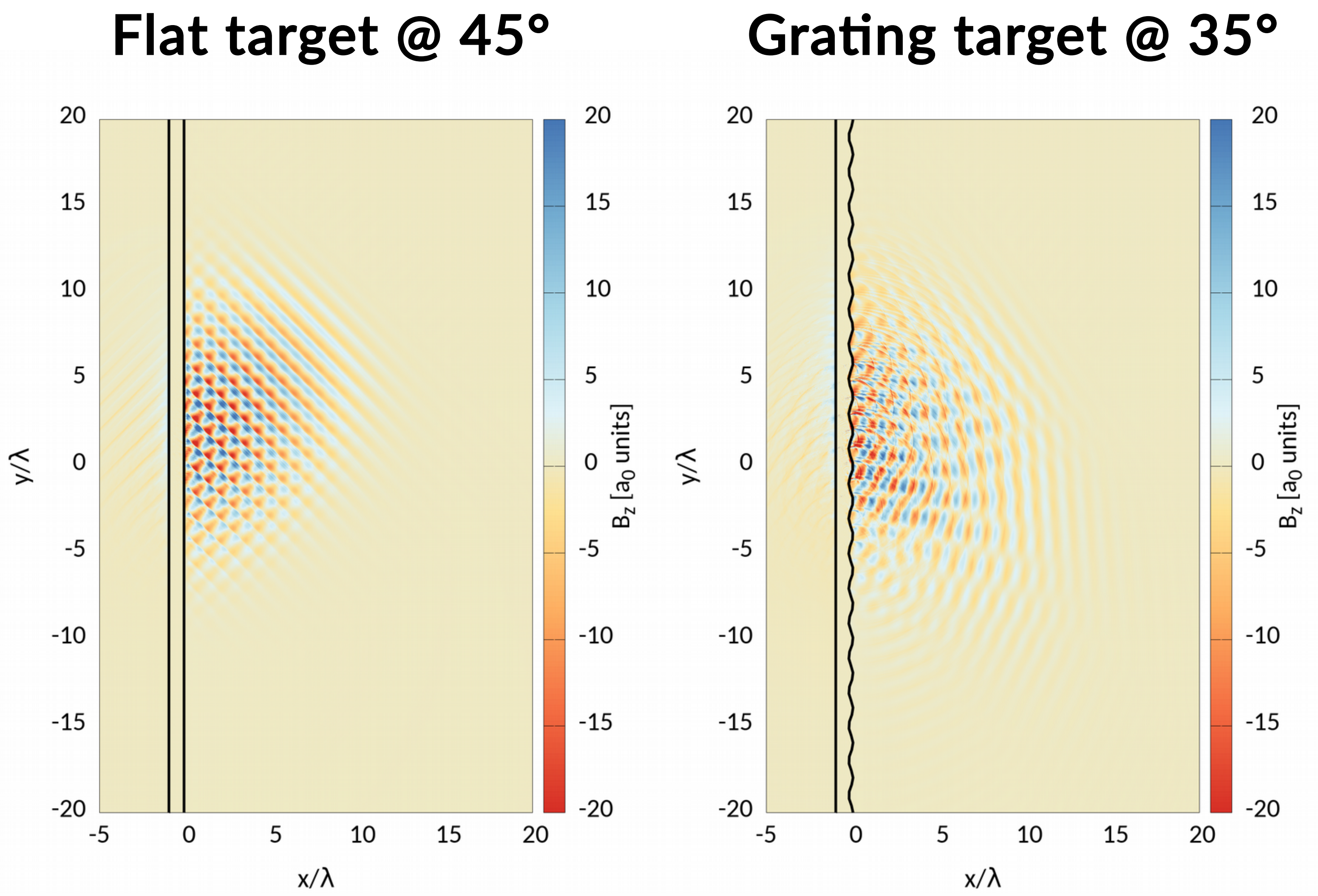

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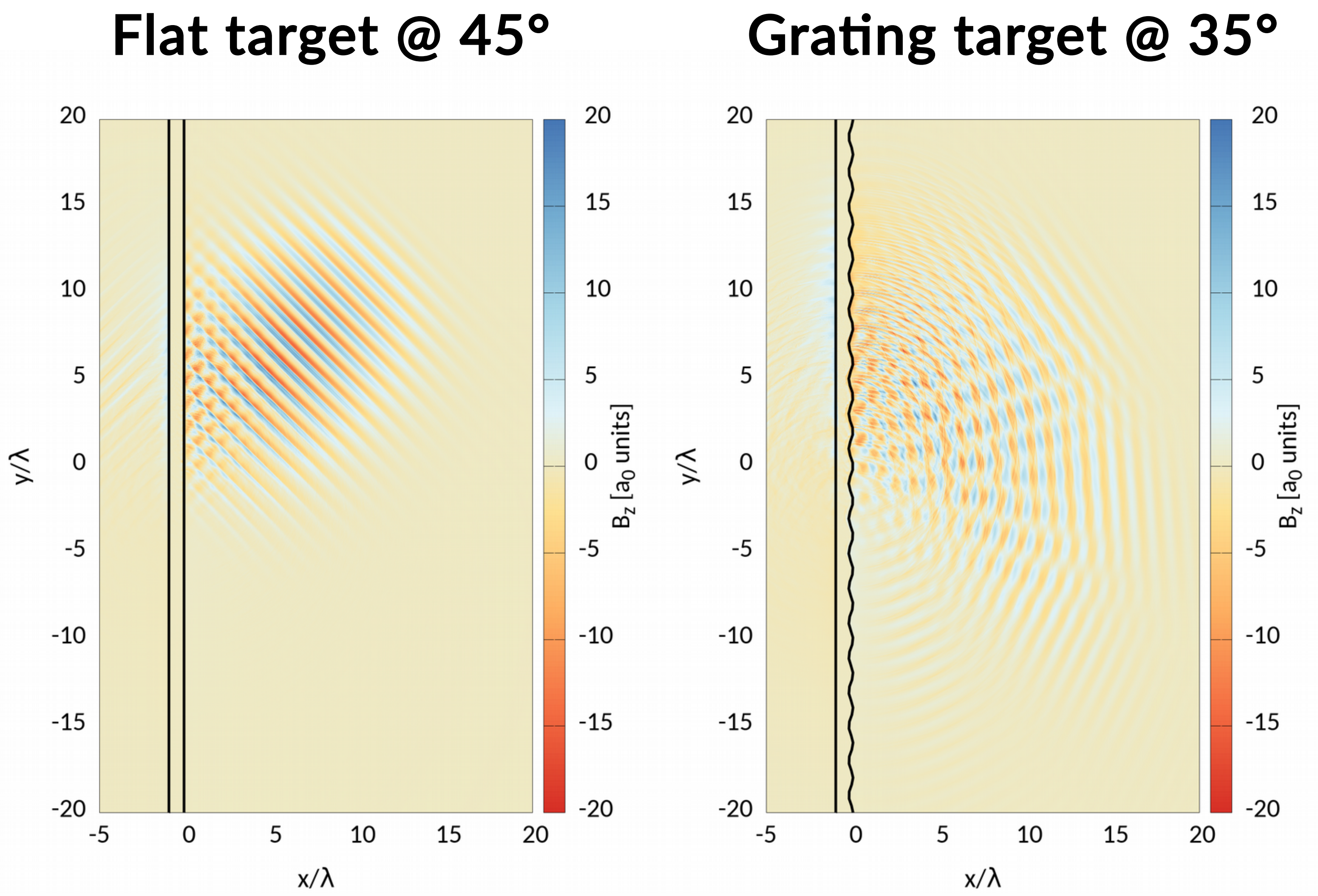
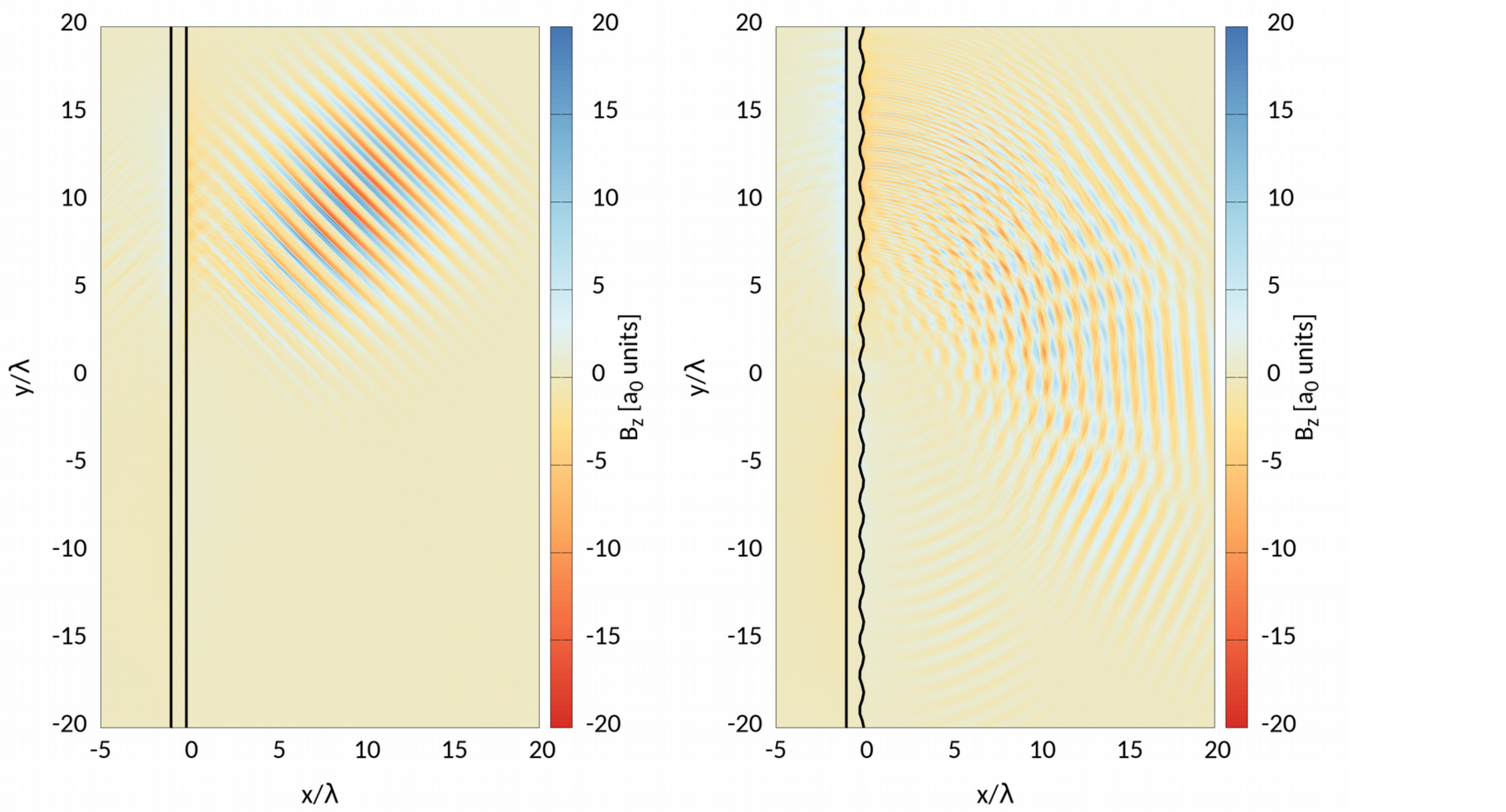
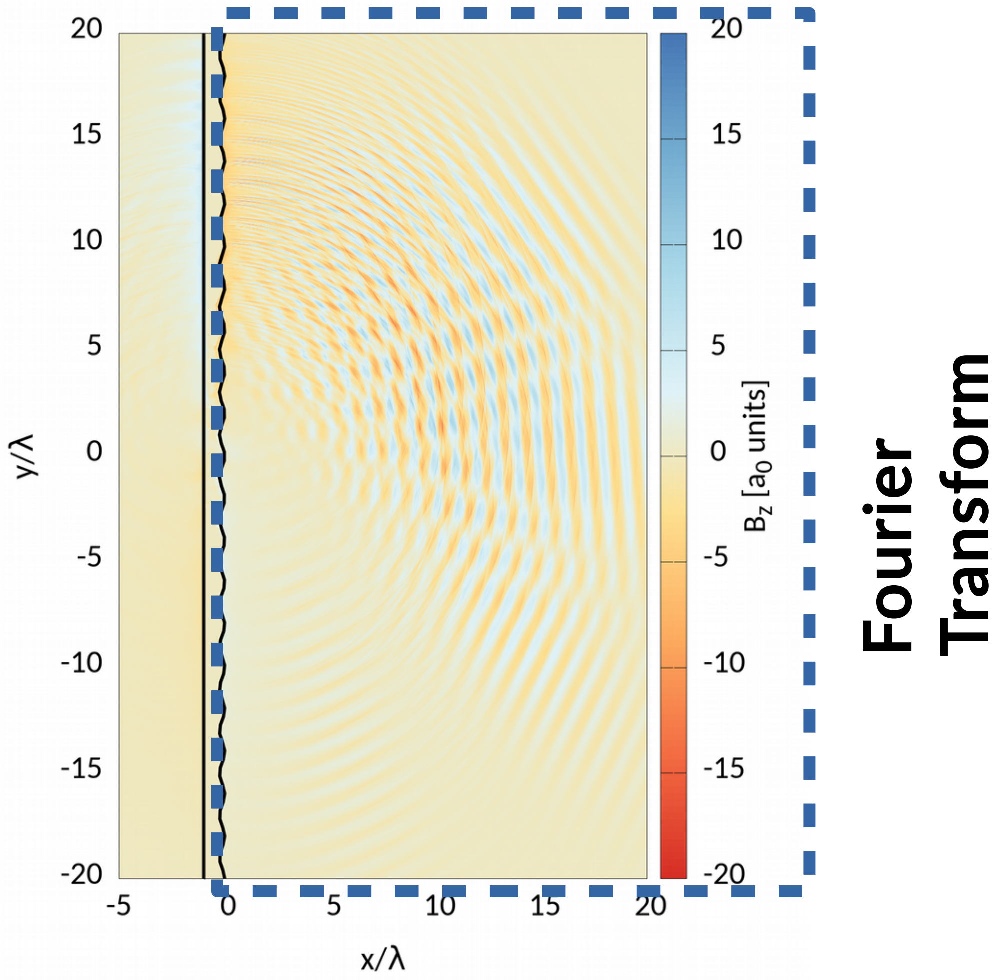


Few snapshots of the EM fields

Flat target @ 45° **Grating target @ 35°**



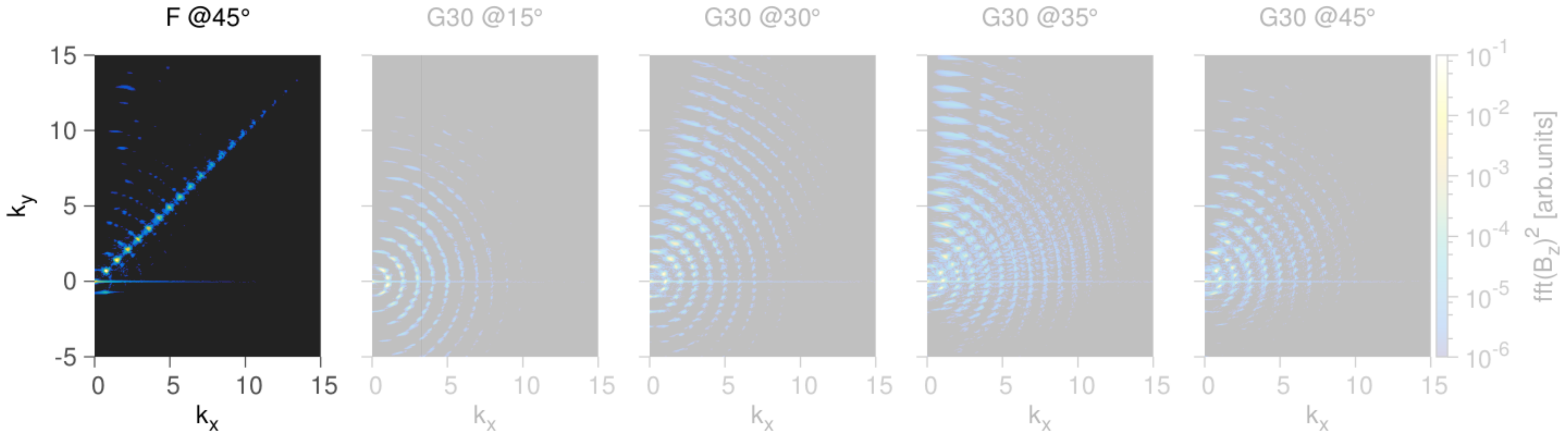
Fields are analyzed via Fourier Transform



We observe an enhancement of HHG near resonance

FLAT TARGET

GRATING



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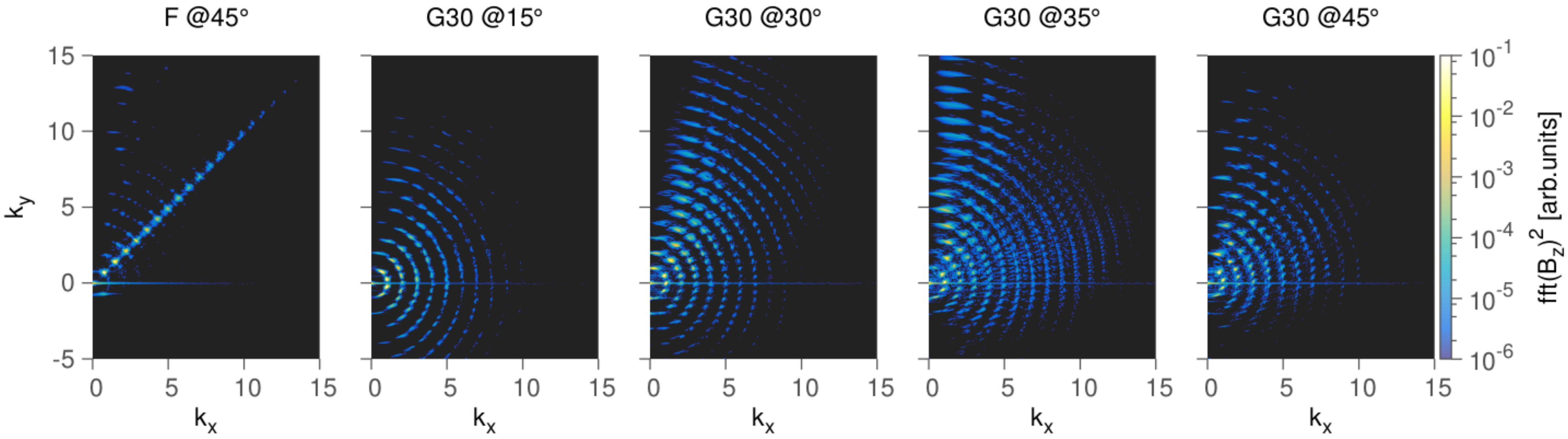
FLAT TARGET **GRATING**



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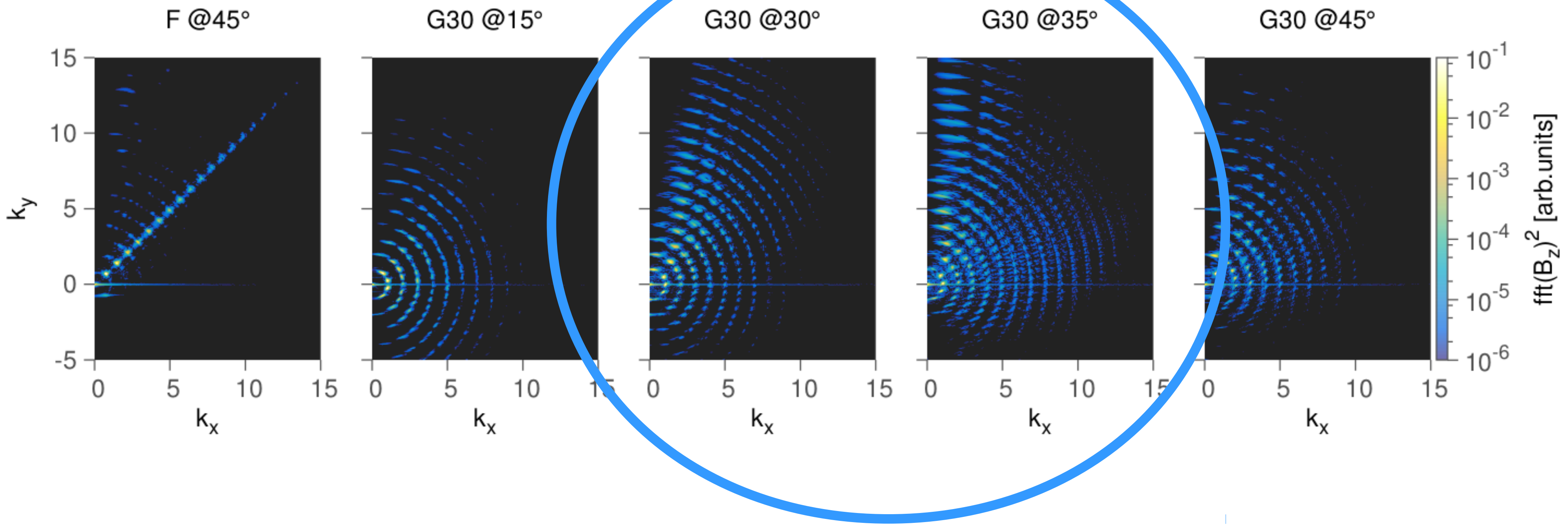
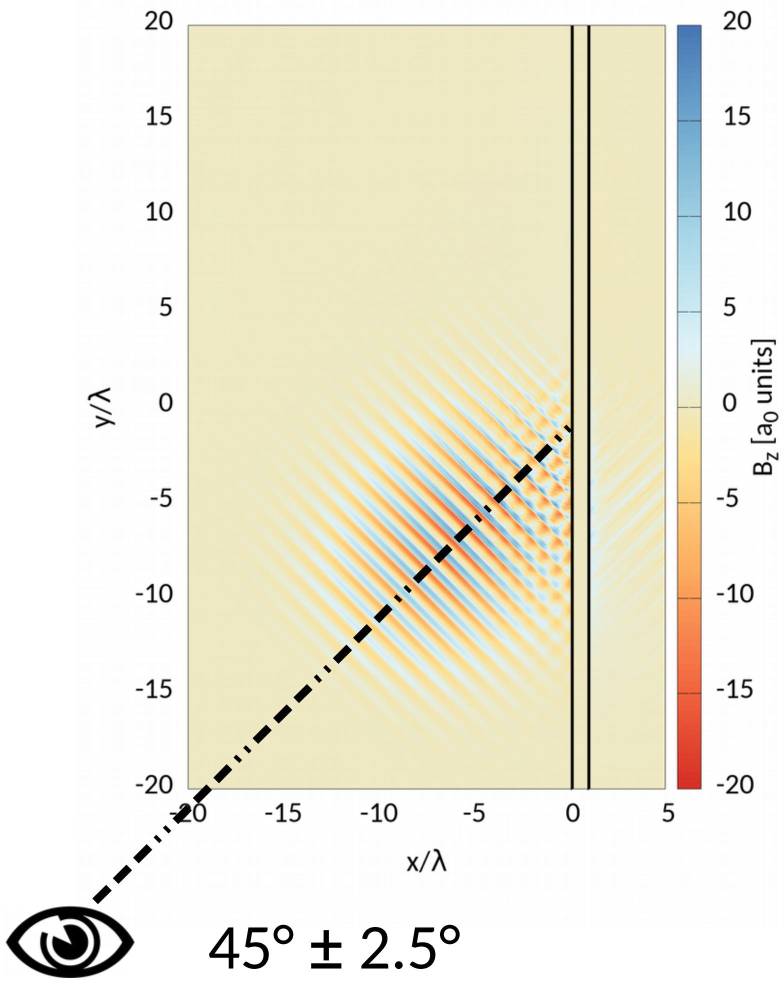
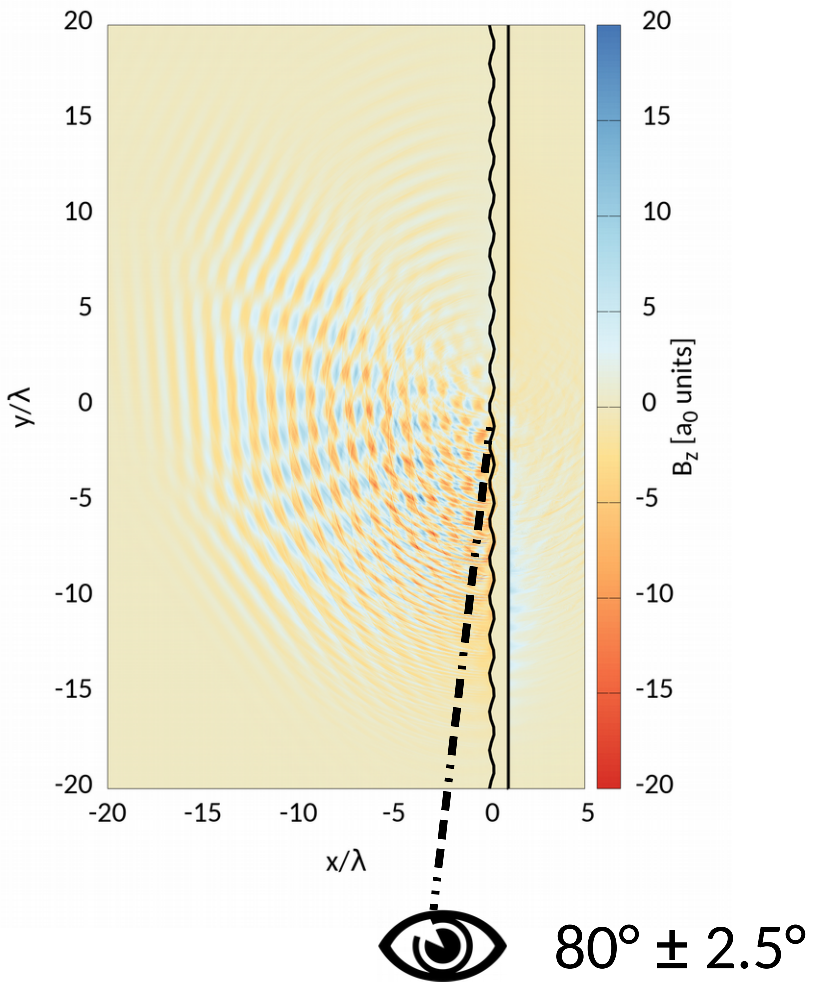
FLAT TARGET **GRATING**



What would a real, finite-size detector see?





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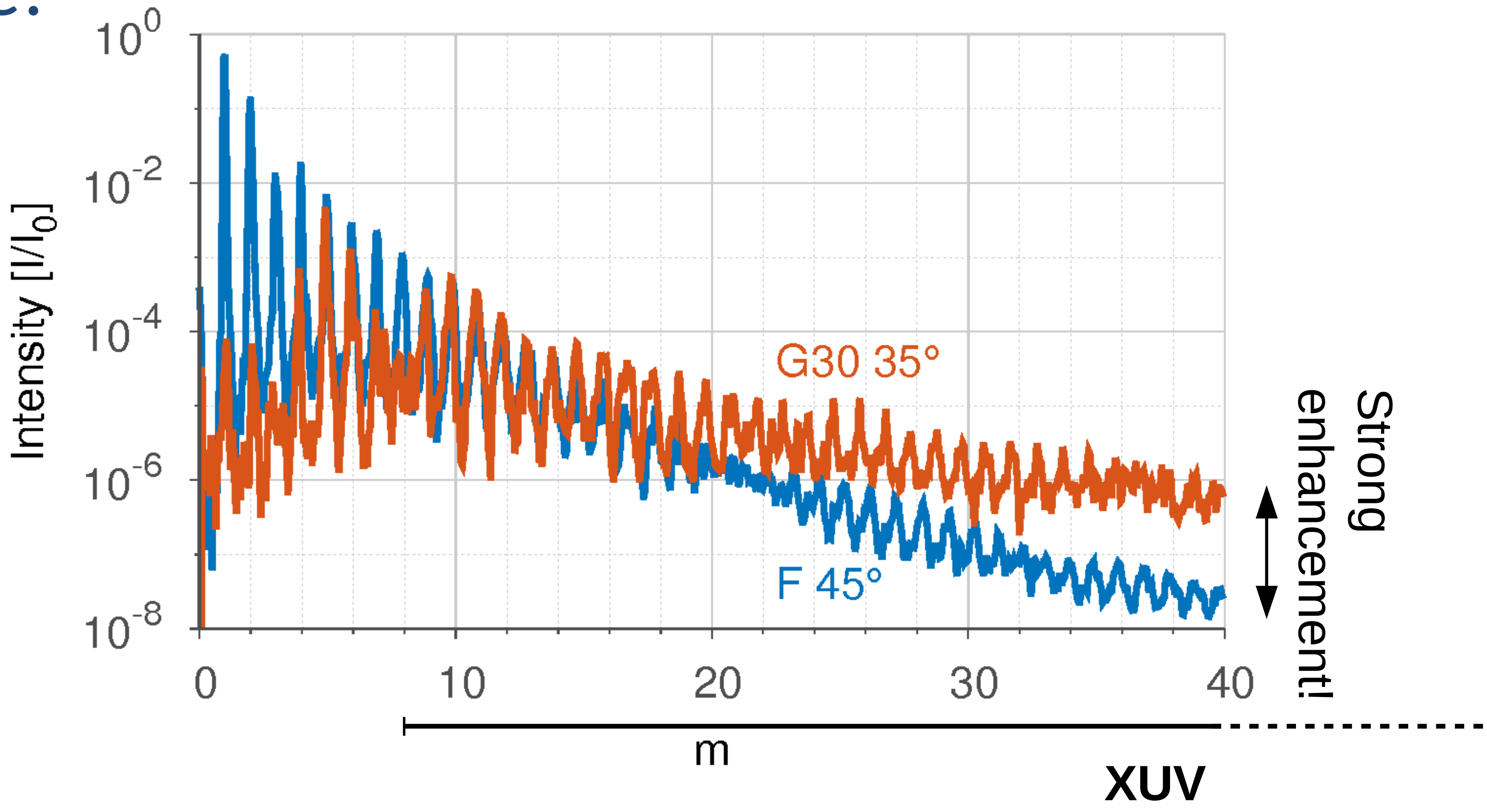

Conclusions

Grating targets as a possible path to observe plasmon-related effects at high field intensities

Resonant enhancement of laser-driven ion acceleration

Resonant enhancement electron emission from irradiated gratings

Resonant enhancement of HHG from irradiated gratings

POLITECNICO
MILANO 1863

Thank you for your attention

POLITECNICO
MILANO 1863

Some encouraging results from holes in the targets

Simple flat foil

Grating at resonance

At least the gratings work at ultrahigh intensities

Electron acceleration works also at **higher intensities:** successful preliminary tests at **PW laser at GIST**, Gwangju, South Korea