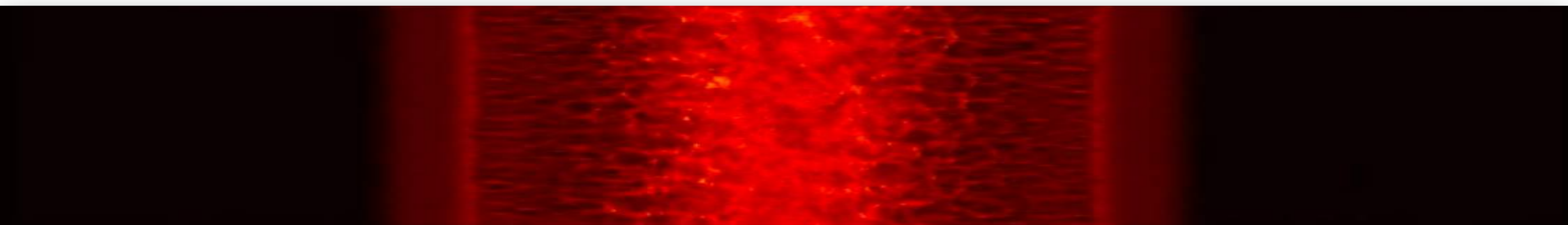
Strong-Field QED effects in PIC codes
Application to Collision-less Shocks in Electron-Positron Plasmas

Mickael Grech, CNRS
Laboratoire pour l’Utilisation des Lasers Intenses (LULI)



Mathieu Lobet, Charles Ruyer, Arnaud Debayle,
Xavier Davoine and Laurent Gremillet
CEA/DAM Ile-de-France

Emmanuel d’Humières
Centre Lasers Intenses et Applications (CELIA)

Martin Lemoine
Institut d’Astrophysique de Paris (IAP)

mickael.grech@gmail.com - ExHILP Conference, Heidelberg, July 2015

Creation of electron-positron plasmas in the lab

state-of-the-art: from conventional to laser-based e^+ sources

- Conventional sources:

  β^+decay of radioactive isotopes (^{22}Na, ^{58}Co, ^{64}Cu)

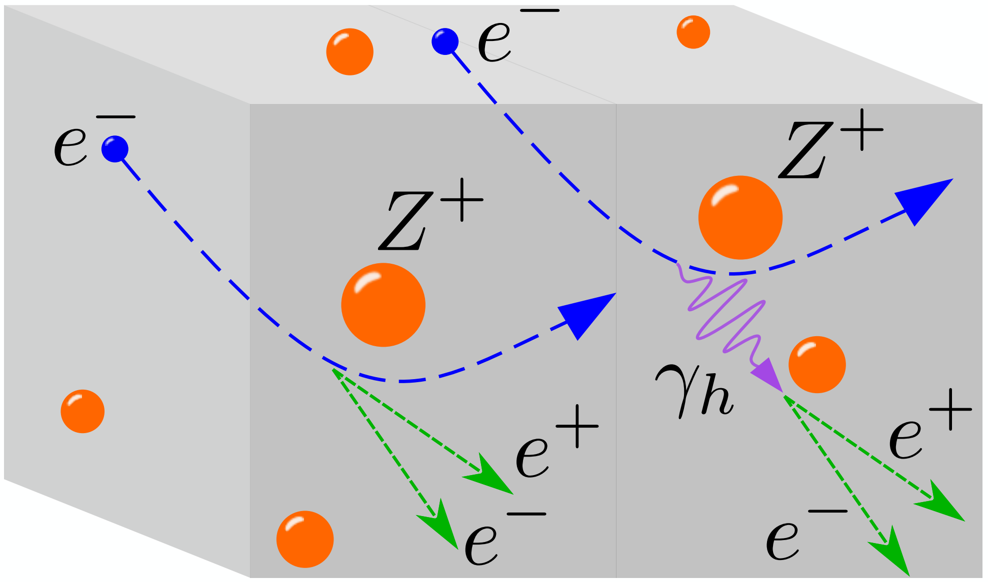
  e- beam stopped in a high-Z absorber

  undulator-based high-energy γ photons in a high-Z absorber

- Laser-based sources:

  UHI lasers can be used to generate a large number of positrons:

  - Cowan et al., Laser Part. Beams **17**, 773 (1999)
  - Ghan et al., Appl. Phys. Lett. **77**, 2662 (2000)
  - Chen et al., Phys. Rev. Lett. **102**, 105001 (2009)



Creation of electron-positron plasmas in the lab

state-of-the-art: from conventional to laser-based e^+ sources

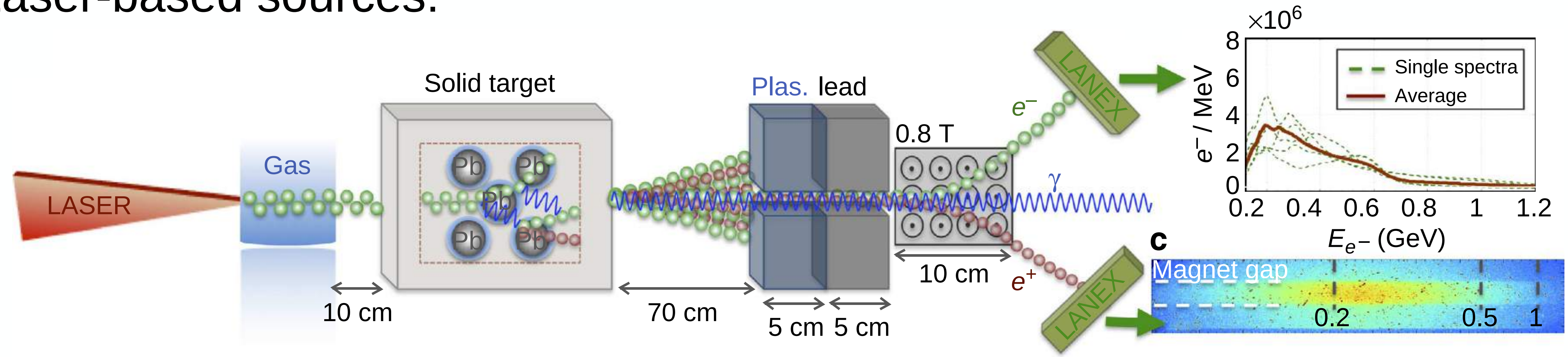
- Conventional sources:

  β^+decay of radioactive isotopes (^{22}Na, ^{58}Co, ^{64}Cu)

  e- beam stopped in a high-Z absorber

  undulator-based high-energy γ photons in a high-Z absorber

- Laser-based sources:



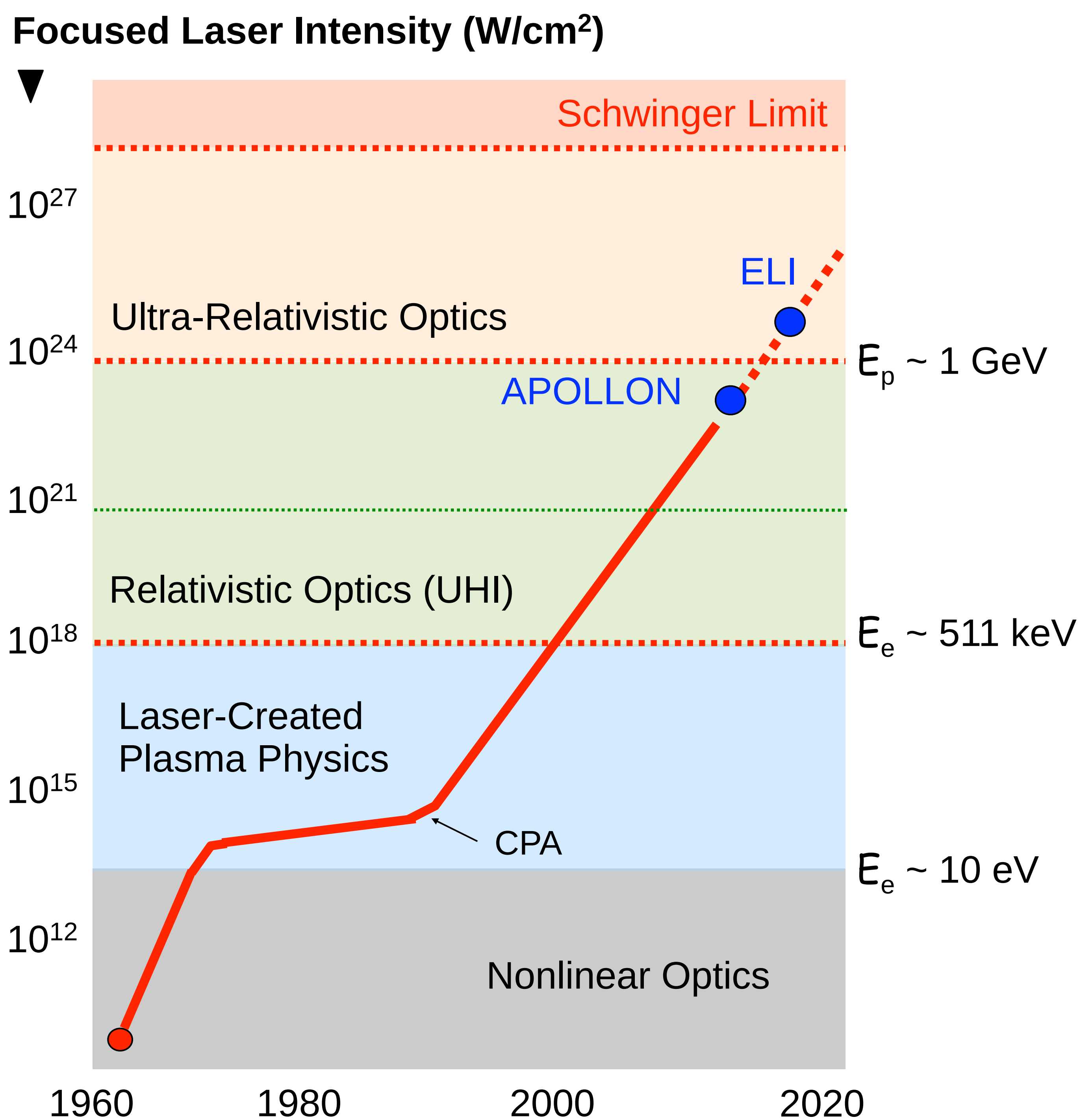
$$n_- \sim n_+ \sim 10^{16}\ \mathrm{cm}^{-3}$$

$$\theta_- \sim \theta_+ \sim 10 - 20\ \mathrm{mrad}$$

$$\langle\gamma_-\rangle \sim \langle\gamma_+\rangle \sim 15$$

G. Sarri et al., Nature Comm. 6, 6747 (2015)

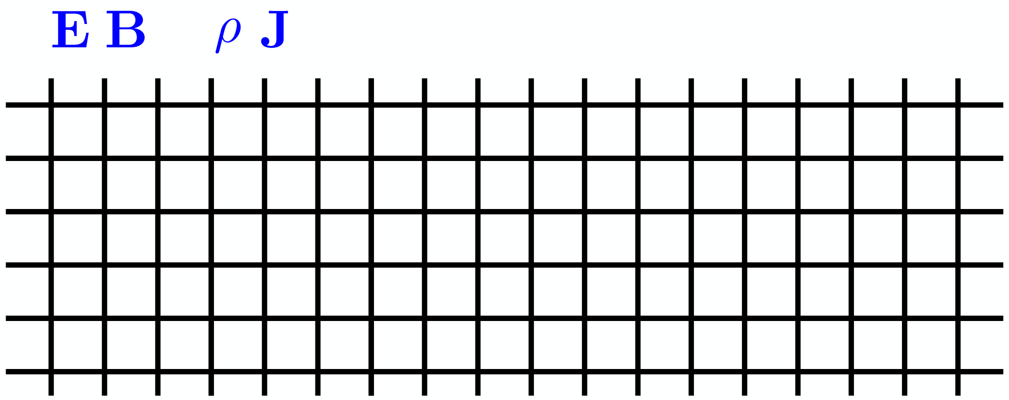
Context & Motivations



Power	Project	Properties
10 PW	Apollon (Fr)	150 J, 15 fs, 10 PW at 0.1 Hz
	Vulcan (UK)	300 J, 30 fs, 10 PW + 1PW laser
	ELI (Eu)	2 x (100 J, 15 fs) at 0.1 Hz
100 PW	ELI upgrade	10 x 10 PW lasers
	XCELS (Ru)	12 x 15 PW lasers
exaW	IZEST	Compressed NIF/ LMJ-class lasers?

The Particle-In-Cell (PIC) Method

capture collective effects by solving the Vlasov-Maxwell Eqs.



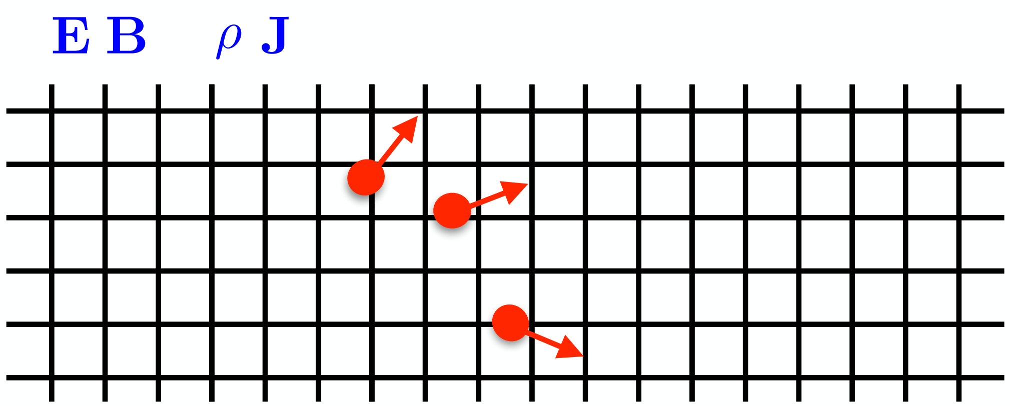
- Maxwell's Eqs. are solved on the grid:

$$\nabla \cdot \mathbf{E} = \rho \qquad \partial_t \mathbf{E} = -\mathbf{J} + \nabla \times \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

The Particle-In-Cell (PIC) Method

capture collective effects by solving the Vlasov-Maxwell Eqs.



- Vlasov Eq. is solved using so-called macro-particles

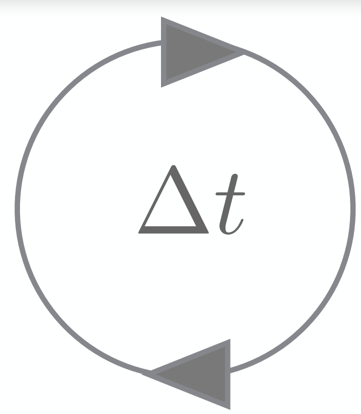
$$f_s(t, \mathbf{x}, \mathbf{p}) = \sum_N w^N \, S(\mathbf{x} - \mathbf{x}^N(t)) \, \delta(\mathbf{p} - \mathbf{p}^N(t))$$

Interpolation

$$\forall N \ [\mathbf{E}, \mathbf{B}] \rightarrow [\mathbf{E}^N, \mathbf{B}^N]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla \times \mathbf{B}$$
$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$



Pusher

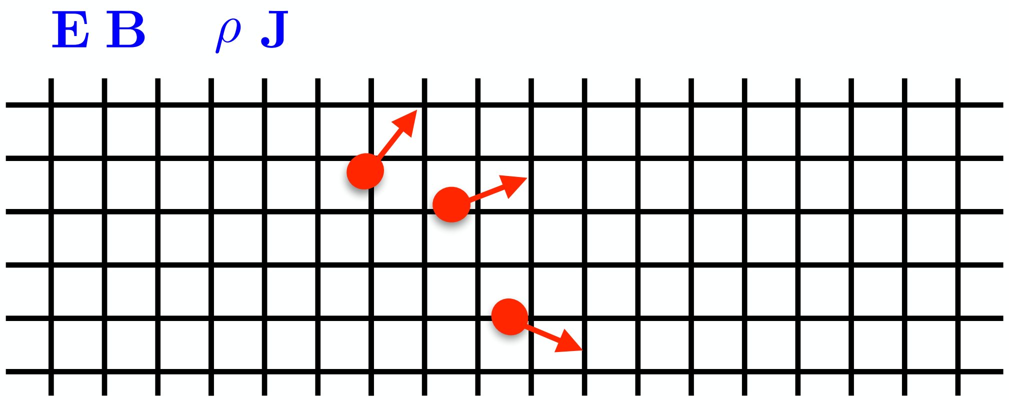
$$\forall N \quad \begin{aligned} d_t \mathbf{p}^N &= \mathbf{F}_L^N \\ d_t \mathbf{x}^N &= \mathbf{p}^N / (m\,\gamma) \end{aligned}$$

Projection

$$\forall N \ [\mathbf{x}^N, \mathbf{p}^N] \rightarrow [\rho, \mathbf{J}]$$

The Particle-In-Cell (PIC) Method

capture collective effects by solving the Vlasov-Maxwell Eqs.

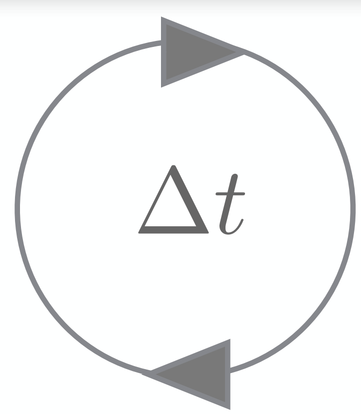


- Vlasov Eq. is solved using so-called macro-particles

$$f_s(t,\mathbf{x},\mathbf{p}) = \sum_N w^N\, S(\mathbf{x}-\mathbf{x}^N(t))\,\delta(\mathbf{p}-\mathbf{p}^N(t))$$

Interpolation

$$\forall N\ [\mathbf{E},\mathbf{B}] \rightarrow [\mathbf{E}^N,\mathbf{B}^N]$$



Projection

$$\forall N\ [\mathbf{x}^N,\mathbf{p}^N] \rightarrow [\rho,\mathbf{J}]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla\times\mathbf{B}$$
$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$

Modified Electron Pusher

$$\chi_e = \left|\frac{F^{\mu\nu}}{E_S}\frac{p^\nu}{m_e c}\right|$$

$\chi_e < 10^{-5}$ classical relativistic push.

$\chi_e < \chi_e^{th}$ radiation reaction force

$\chi_e > \chi_e^{th}$ Monte-Carlo method

Photon Pusher

for > 1.022 MeV photons:

$$\epsilon_\gamma > 2\,m_e c^2$$

$$\chi_\gamma = \left|\frac{F^{\mu\nu}}{E_S}\frac{\hbar k^\nu}{m_e c}\right|$$

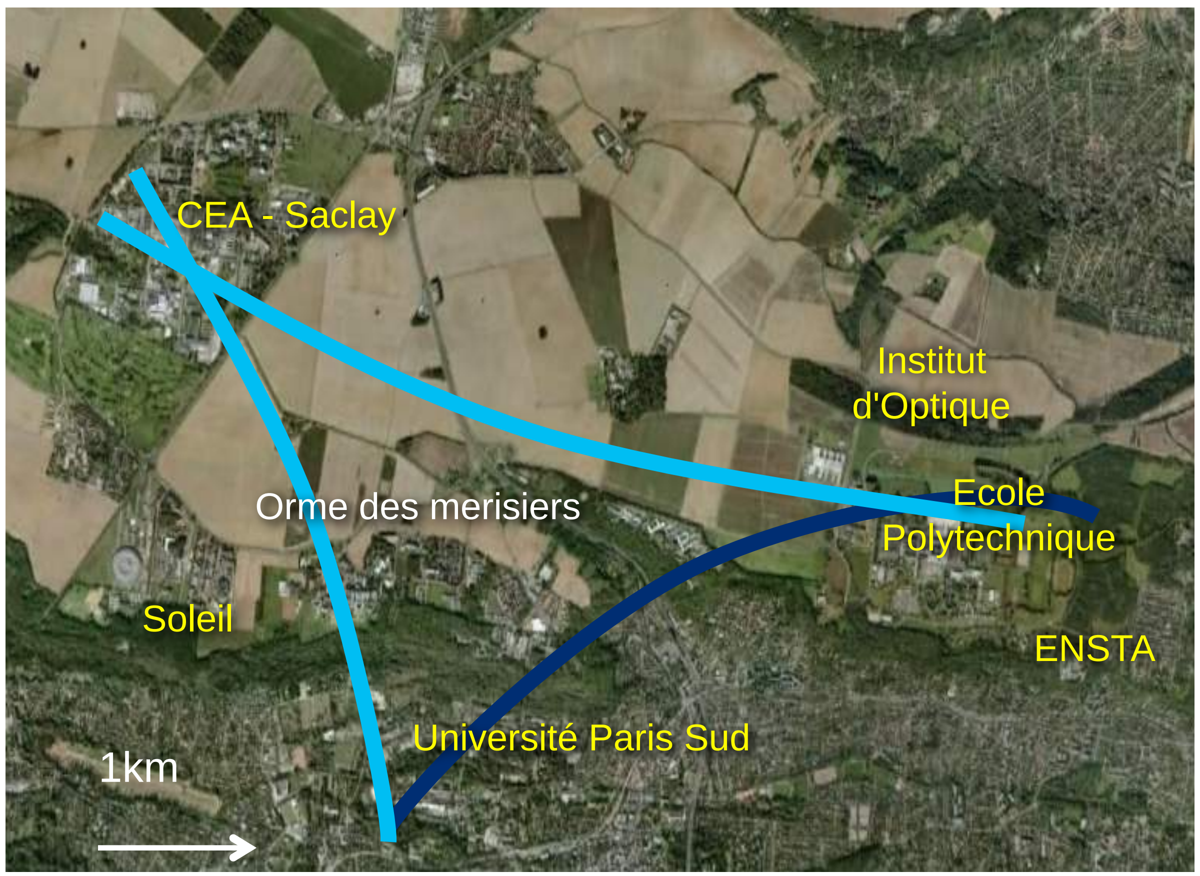
multiphoton Breit-Wheeler process

Implemented in the PIC code CALDER

Lobet et al., arXiv:1311.1107 (2013)

The QED-PIC code: a central tool for the CILEX/ Apollon 10PW laser project

Ph. Martin's talk on Tuesday



Power	Project	Properties
10 PW	Apollon (Fr)	150 J, 15 fs, 10 PW at 0.1 Hz
	Vulcan (UK)	300 J, 30 fs, 10 PW + 1PW laser
	ELI (Eu)	2 x (100 J, 15 fs) at 0.1 Hz
100 PW	ELI upgrade	10 x 10 PW lasers
	XCELS (Ru)	12 x 15 PW lasers
exaW	IZEST	Compressed NIF/ LMJ-class lasers?

Pair plasma production at CILEX/Apollon

head-on GeV-electron - PW laser collision

Generation of high-energy electron-positron beams in the collision of a laser-accelerated electron beam and a counter-propagating multi-PW laser

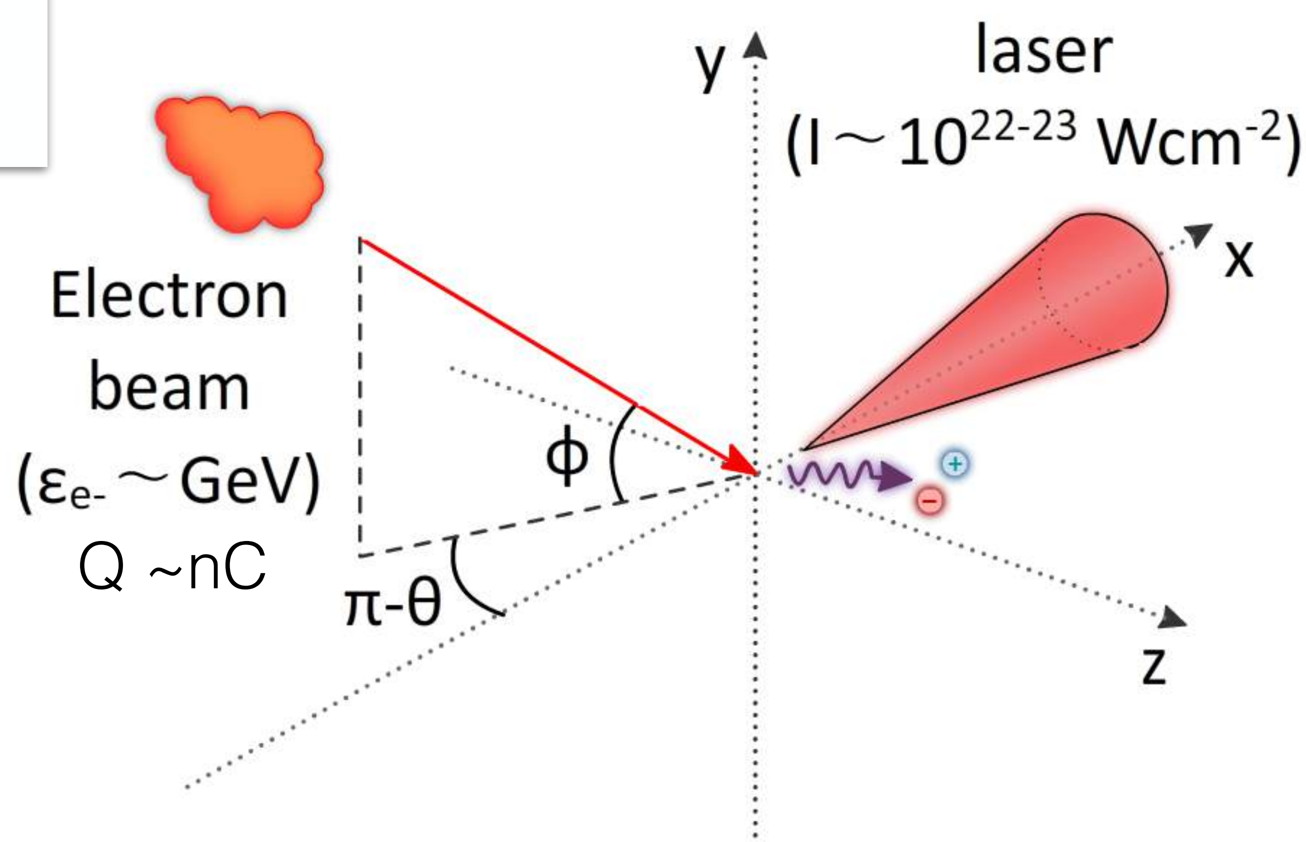
M. Lobet,[1,2,*] X. Davoine,[1,†] E. d'Humières,[1] and L. Gremillet[1,‡]

[1] *CEA, DAM, DIF, F-91297, Arpajon, France*

[2] *CELIA, UMR 5107, Université de Bordeaux-CNRS-CEA, 33405, Talence*

TEASER

Acceleration laser
15 J - 30 fs
FWHM 23 μm



Cilex Apollon

Pair plasma production at CILEX/Apollon

head-on GeV-electron - PW laser collision

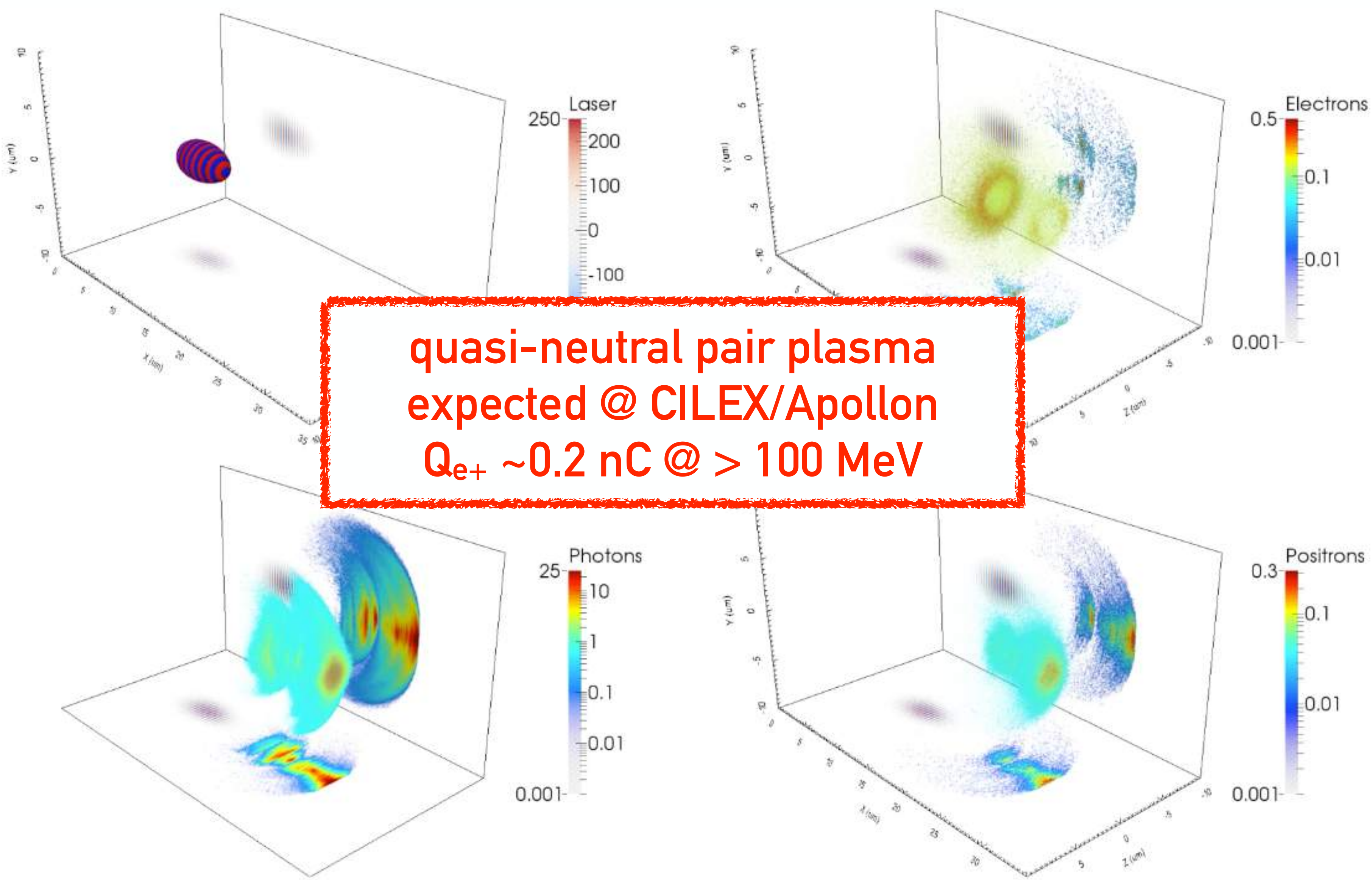
TEASER

Generation of high-energy electron-positron beams in the collision of a laser-accelerated electron beam and a counter-propagating multi-PW laser

M. Lobet,[1,2,*] X. Davoine,[1,†] E. d'Humières,[1] and L. Gremillet[1,‡]

[1] *CEA, DAM, DIF, F-91297, Arpajon, France*

[2] *CELIA, UMR 5107, Université de Bordeaux-CNRS-CEA, 33405, Talence*



quasi-neutral pair plasma expected @ CILEX/Apollon

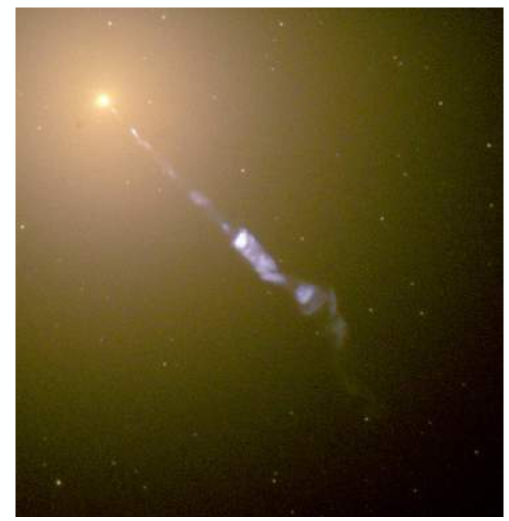
Q_{e+} ~0.2 nC @ > 100 MeV

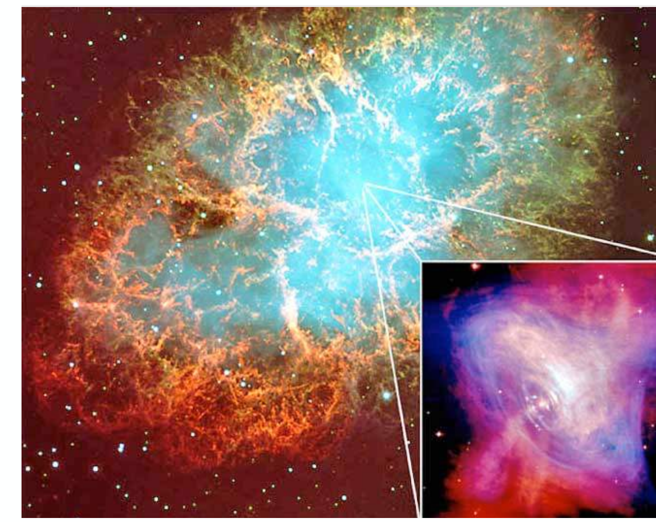
Collisionless shocks in electron-positron plasmas

an ubiquitous process in astrophysics

Various astrophysical environments:
- active galactic nuclei
- pulsar wind nebulae
- supernovae remnants

Generation of non-thermal particles and radiations:
- cosmic rays
- gamma-ray bursts

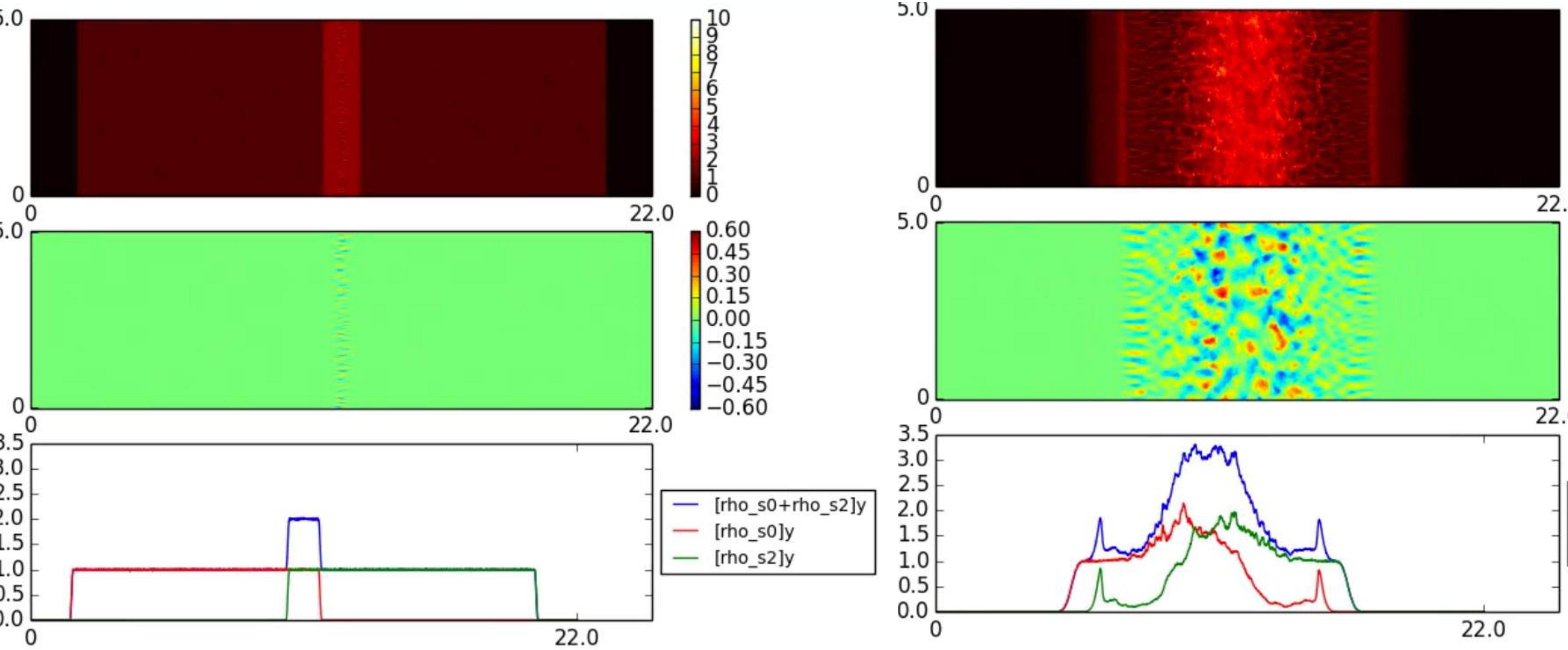

M87 (Hubble)


Crab nebulae

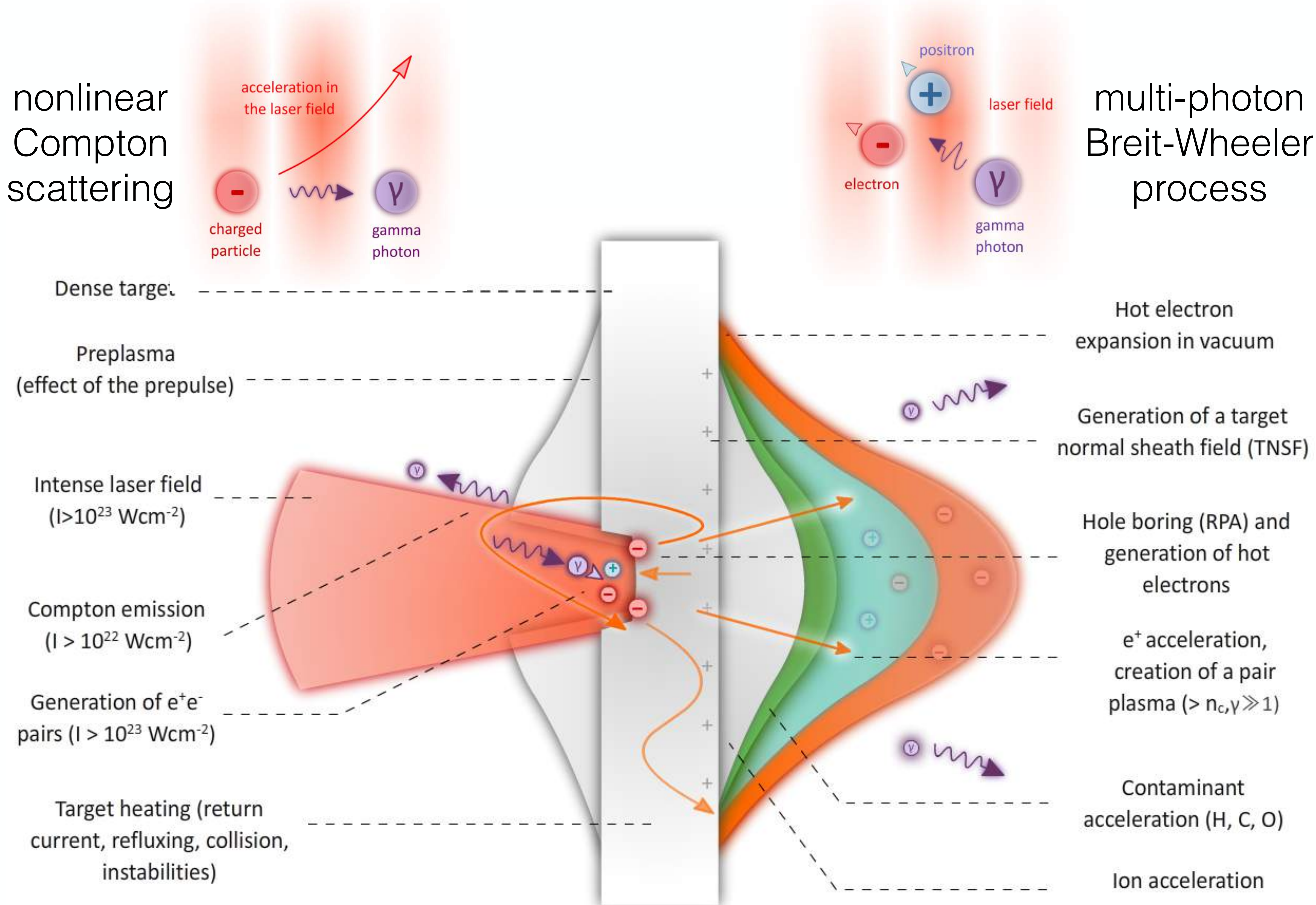
How to create a shock without collision?

Collisionless shocks in electron-positron plasmas

an ubiquitous process in astrophysics



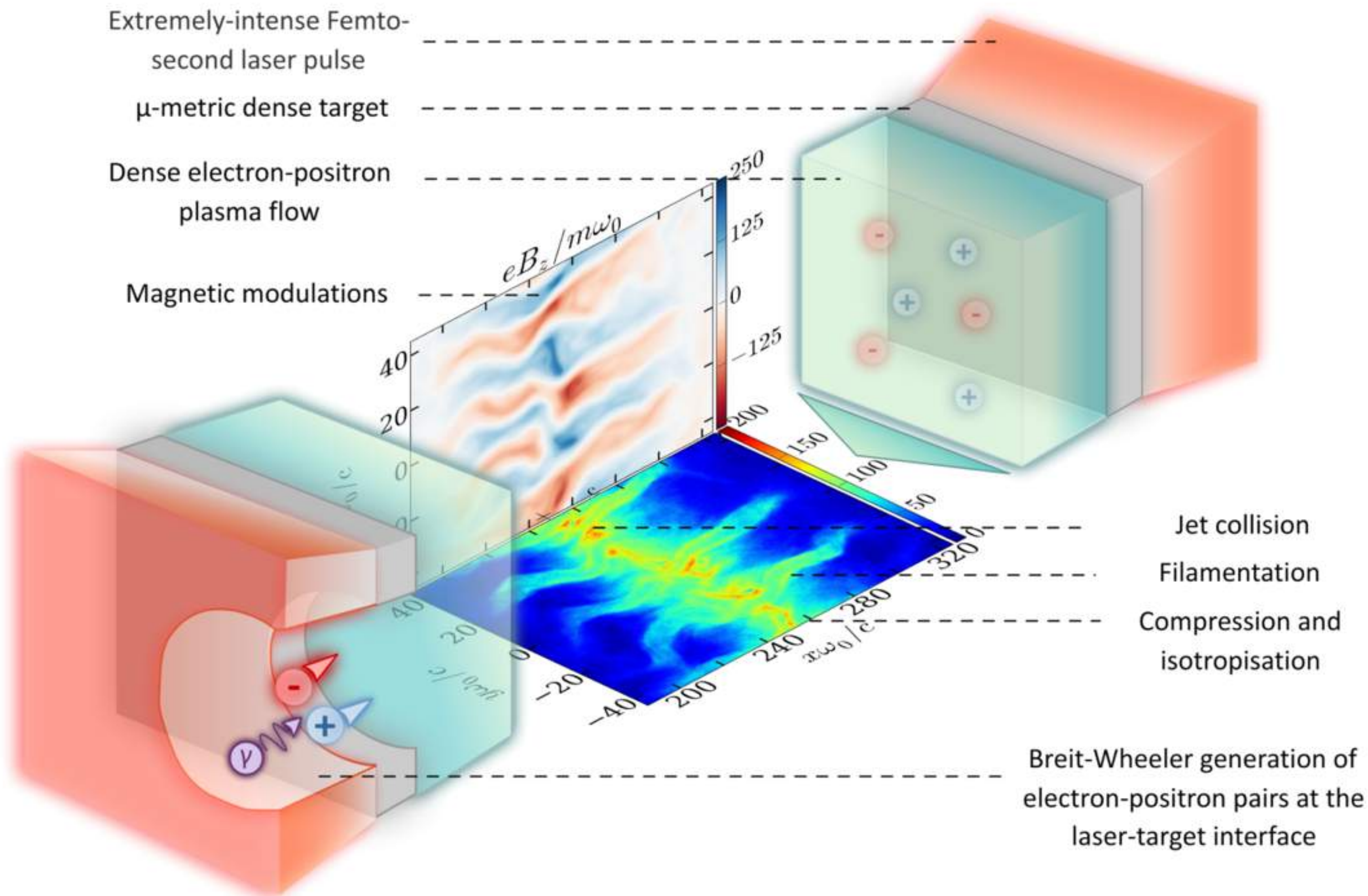
How to create a dense electron-positron plasma in the lab: pair creation from electron-photon scattering



Ridgers et al., Phys. Rev. Lett. **108**, 165006 (2012)

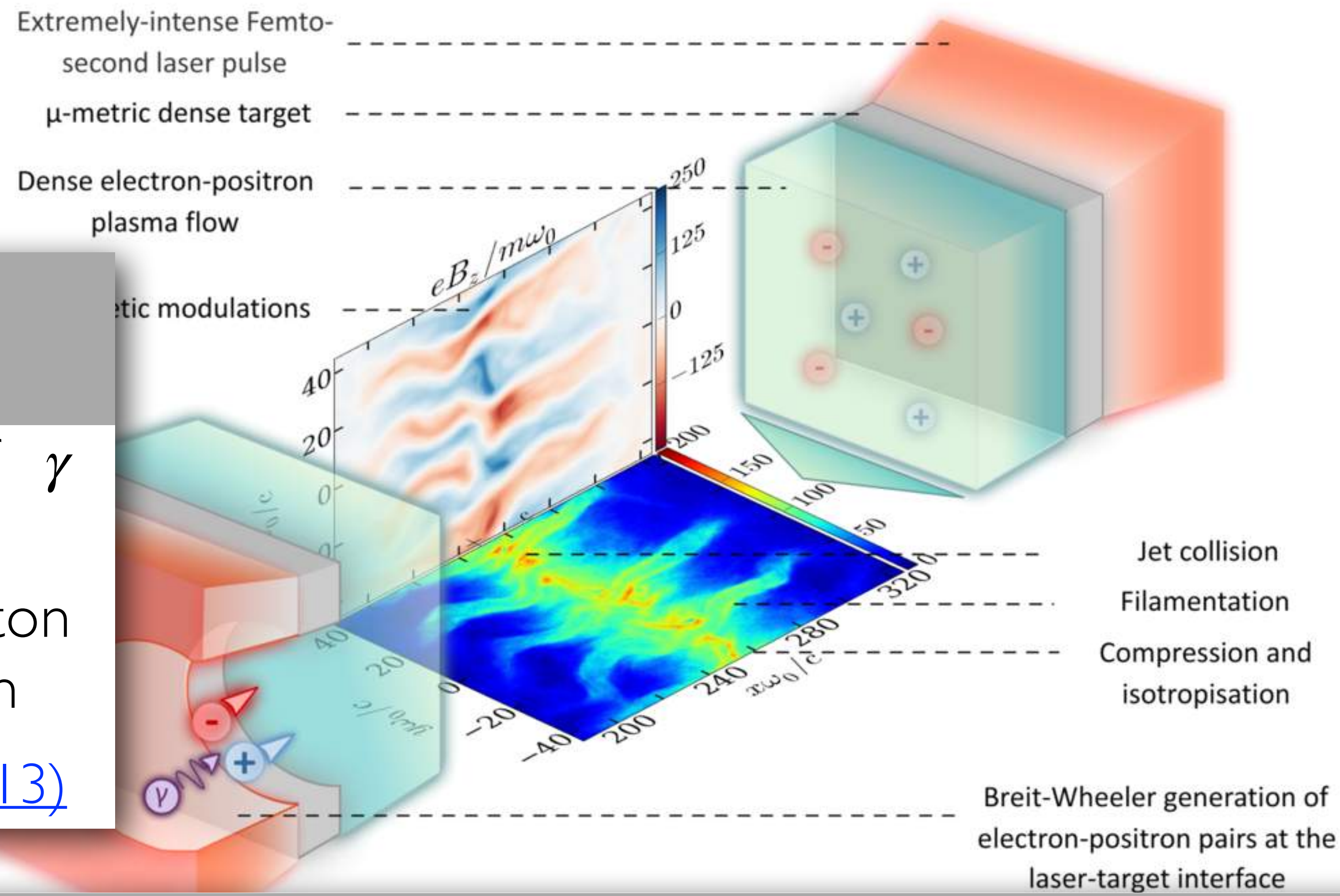
Collisionless shocks in electron-positron plasmas

using extreme-light laser pulses



Collisionless shocks in electron-positron plasmas

using extreme-light laser pulses



Upgraded QED-PIC code CALDER

- **synchrotron** emission of γ photons & back-reaction
- **Breit-Wheeler** multi-photon process for positron generation

Lobet et al., arXiv:1311.1107 (2013)

Physical & Numerical Parameters

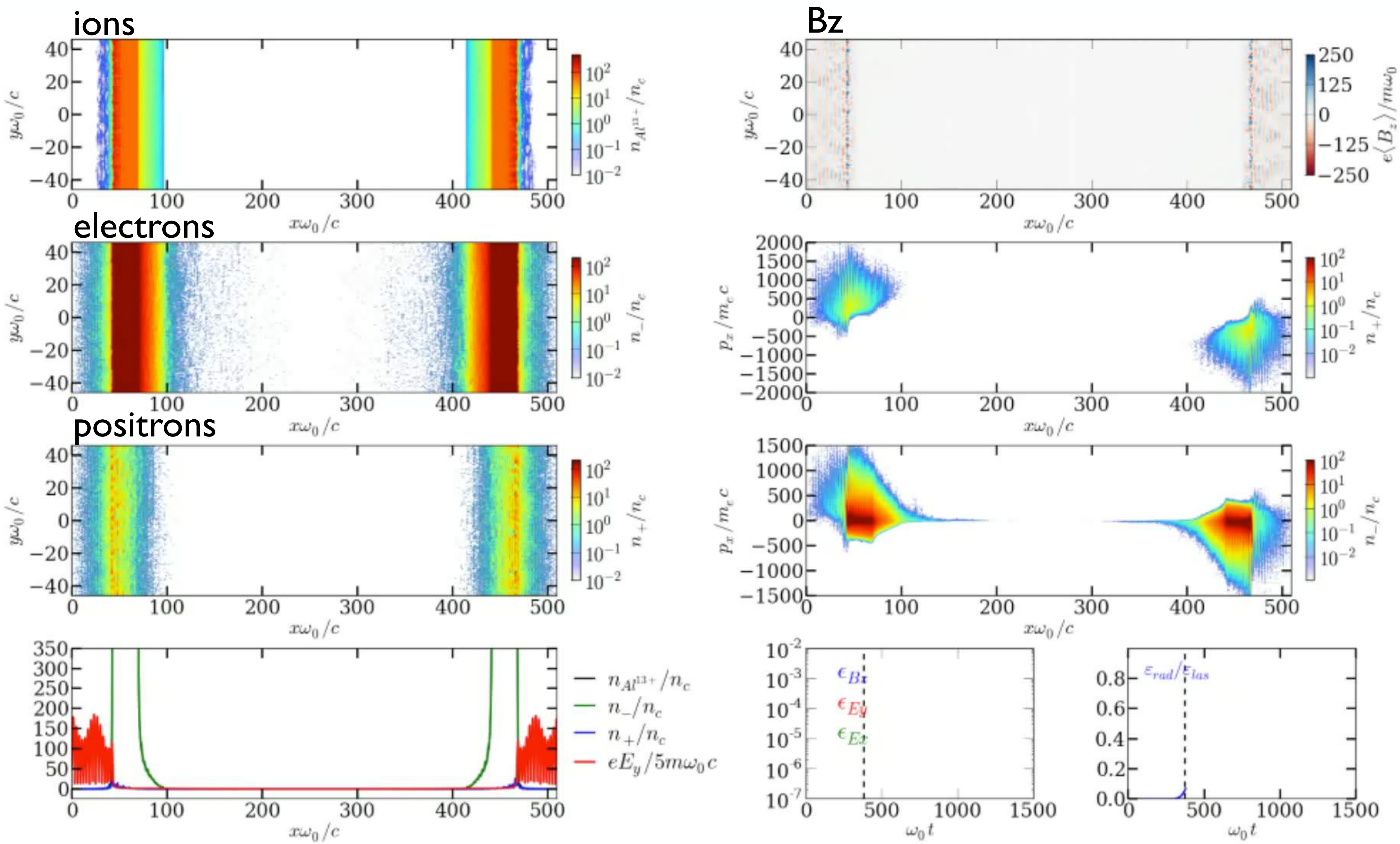
Laser: amplitude a_0=800 (8.9×10^{23} W/cm^2), plane wave (1m), Gaussian time profile with 125/ω_0 (65 fs) FWHM, linear polarization

Target: 5 μm thick (with 2 μm preplasma) fully ionized Al^{13+}

Domain: 81x15 μm^2 = 3000x500 cells with periodic transverse boundary cond.

Comp. time: 72 hours over 2000 proc., using MPI domain decomposition

Collisionless shocks in electron-positron plasmas

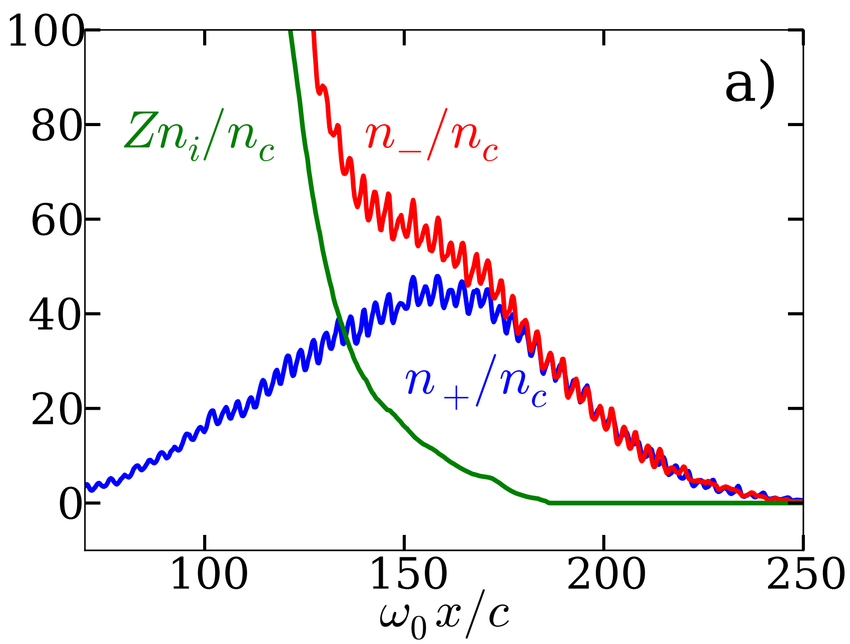


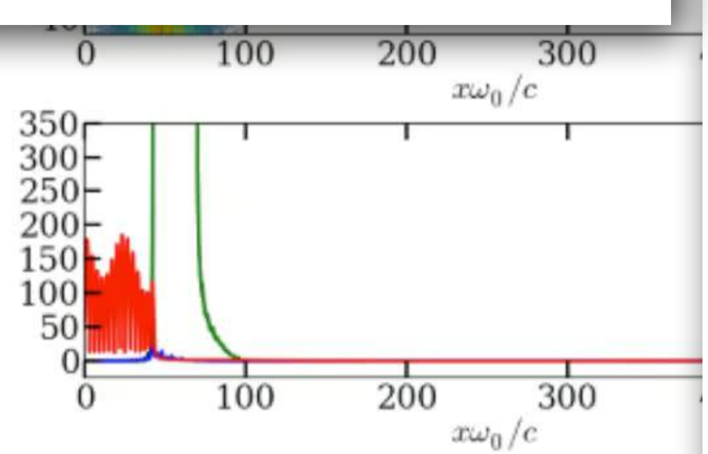
Collisionless shocks in electron-positron plasmas

pair plasma creation → Weibel instability growth → isotropization & thermalisation → ion plasma collision

Neutral pair plasma

$$n_+ \sim n_- \sim 45$$





Ultra-relativistic flow

Average Lorentz factors:

$$\langle \gamma_- \rangle \sim 550 \sim \sqrt{1 + a_0^2/\sqrt{2}}$$

$$\langle \gamma_+ \rangle \sim 1100 \sim \langle \gamma_- \rangle + \phi_{TNSA}$$

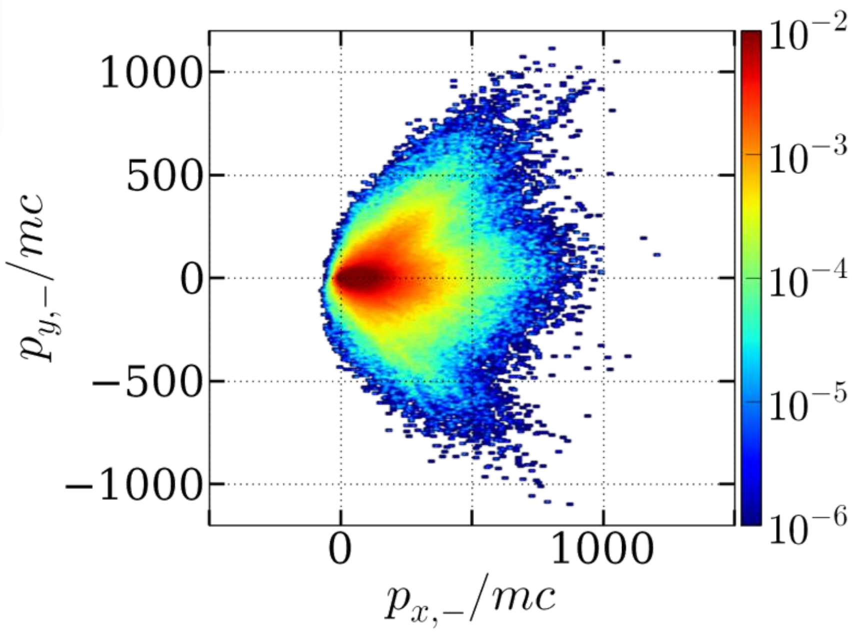
Average emission angles:

$$\langle \theta_- \rangle \sim 0.6$$

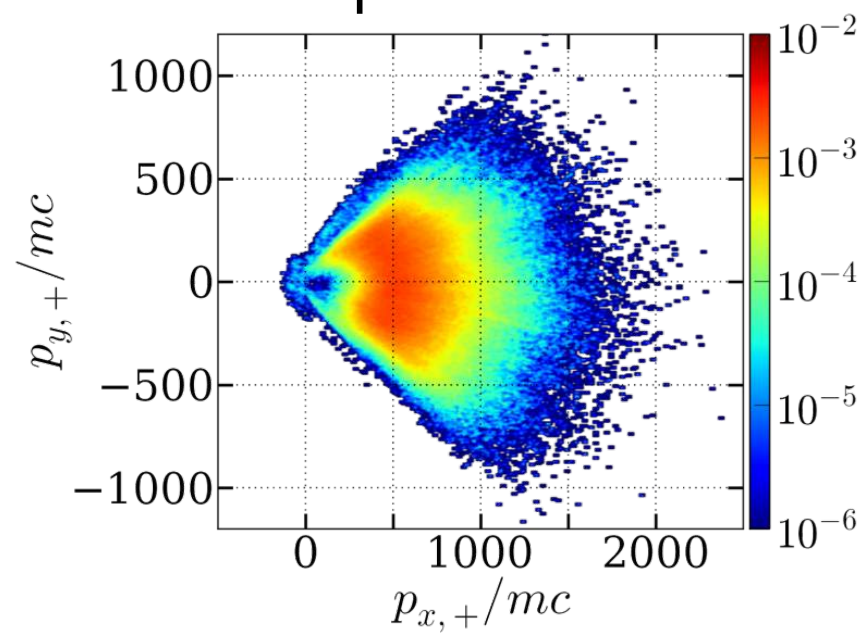
$$\langle \theta_+ \rangle \sim 0.13$$

(p_x,p_y) phase-space:

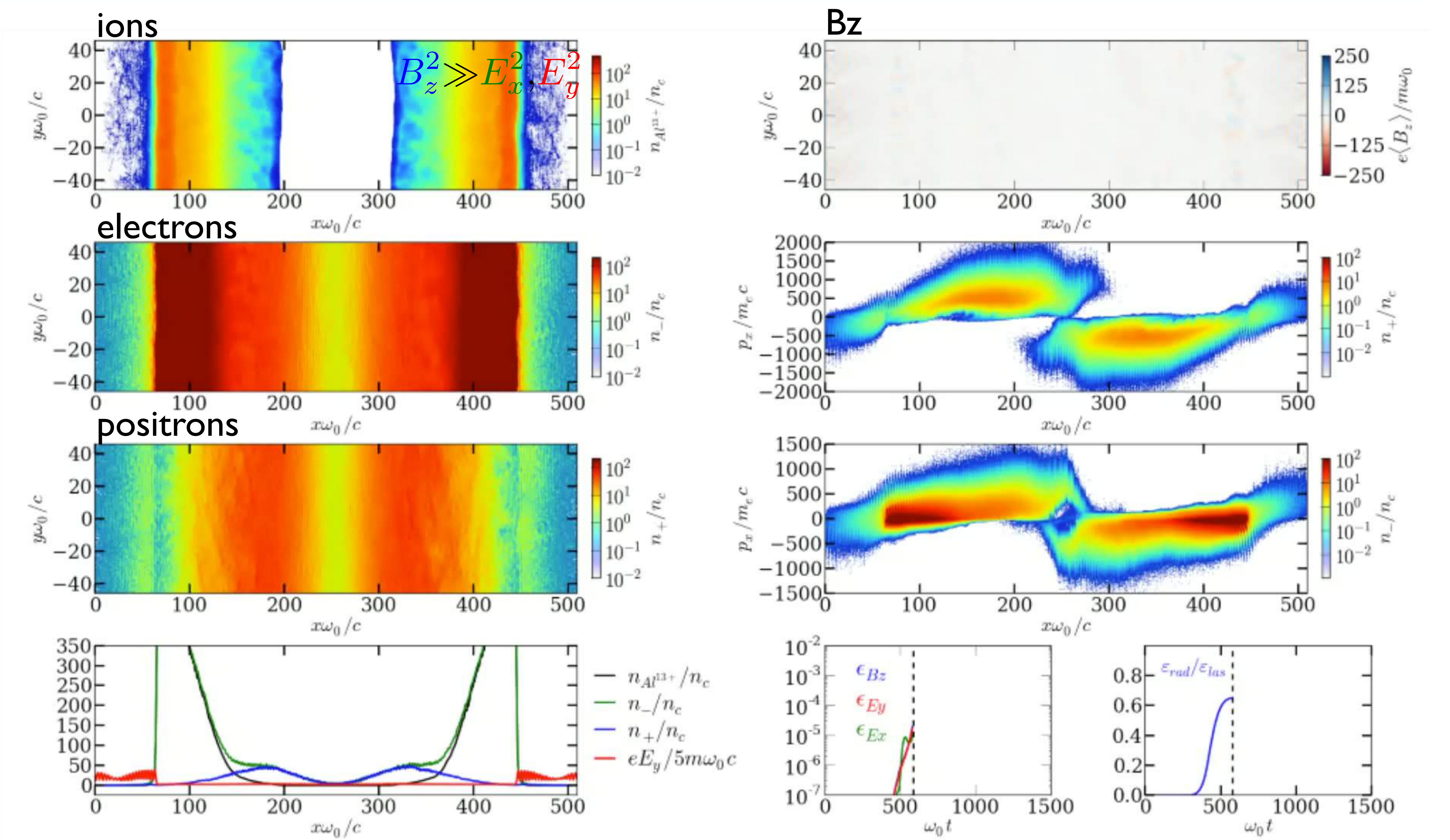
electrons



positrons



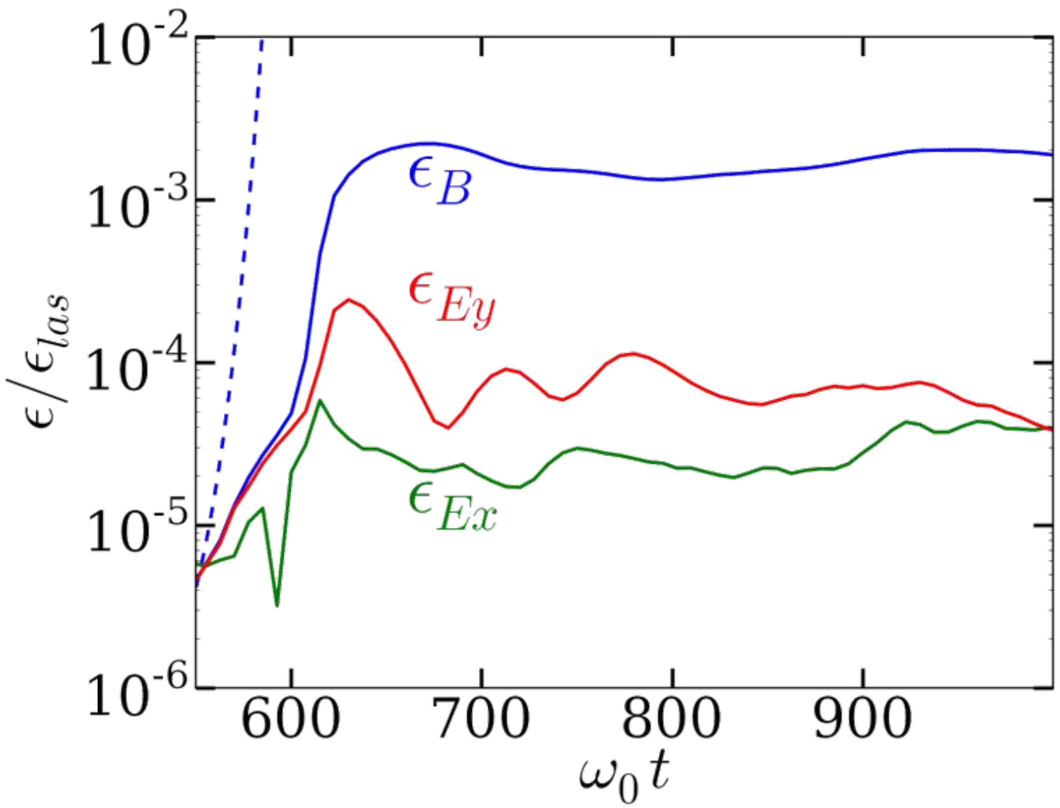
Collisionless shocks in electron-positron plasmas



Collisionless shocks in electron-positron plasmas

Magnetic instability growth rates

Magnetic nature of the instability:



Simulation & theoretical growth rates:

$\Gamma_{\rm sim} \sim 0.24\ \omega_0^{-1}$

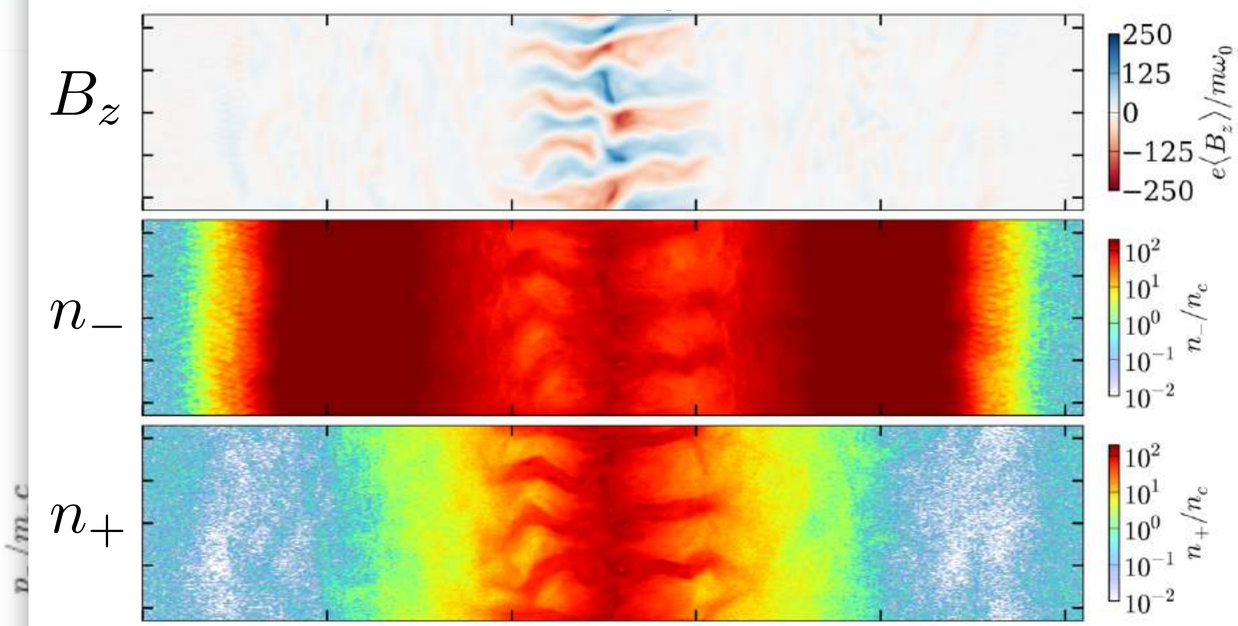
Cold fluid theory (ultra-relativistic limit):

$\Gamma_{\rm cf} \sim 0.5\ \omega_0^{-1}$

Multi-waterbag approach:

$\Gamma_{\rm wb} \sim 0.2\ \omega_0^{-1}$

Filament properties & Magnetic field at saturation



Saturated B-field & filament width in the simulation:

$B_{z,\rm sat} \sim 150\ m_e\,\omega_0/e \sim 1.5\ \rm MT$

$\lambda_{\rm sat} \sim 20\ c/\omega_0$

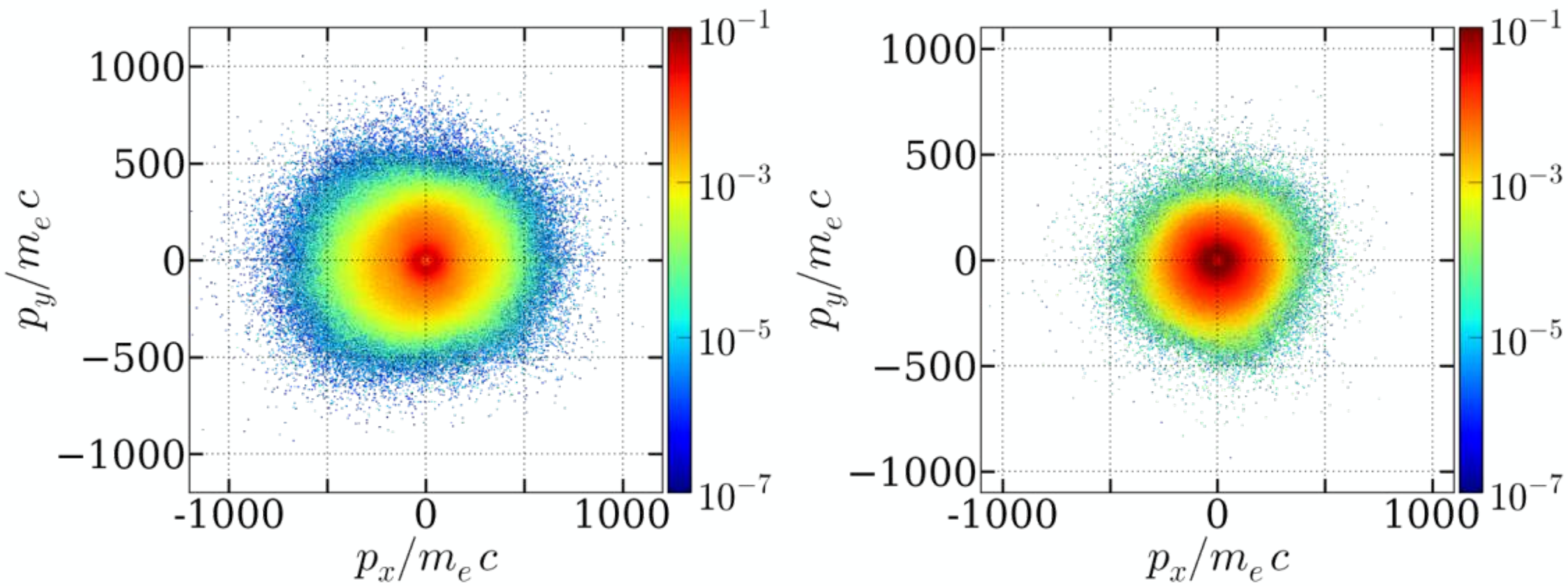
Simple estimates (in the Alfen limit):

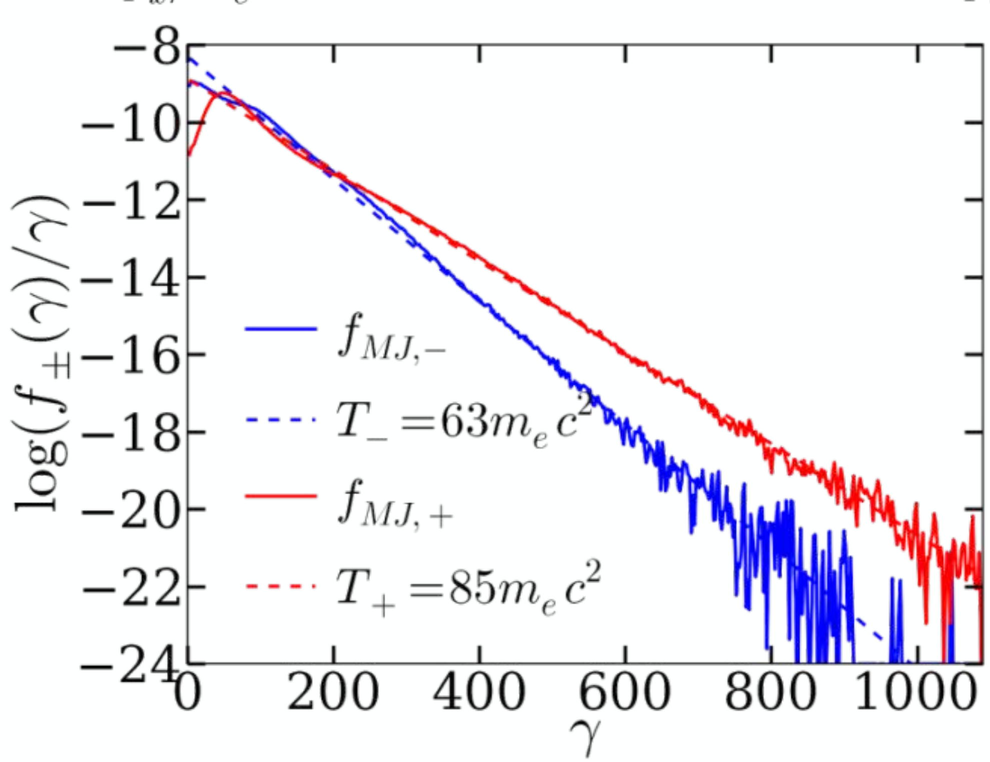
$B_{z,\rm th} \simeq \sqrt{2\langle\gamma_-\rangle\, n_-} \sim 105$

$\lambda_{\rm th} \simeq 2\pi\sqrt{\langle\gamma_-\rangle/n_-} \sim 14\ c/\omega_0$

Collisionless shocks in electron-positron plasmas

Phase-space (p_x,p_y) & distribution functions at the end of the collision



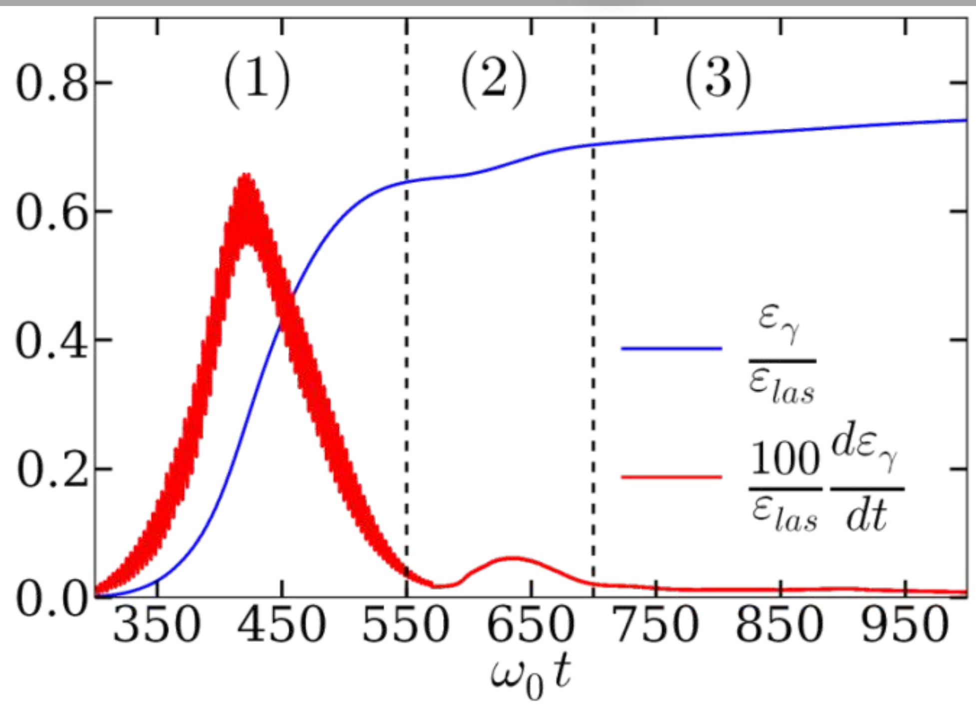


- **isotropic** (electron & positron) distribution
- **significant thermalization**: the distribution functions approach Maxwell-Jüttner distr.
- lowest energy electrons (γ<50) are not thermalized
- equilibrium between the temperatures not yet achieved:

$$T_+ \sim 85 \text{ MeV} > T_- \sim 63 \text{ MeV}$$

Collisionless shocks in electron-positron plasmas

Radiated energy vs. time



(1) Radiation emission during LPI

(2) Synchrotron radiation during collision:

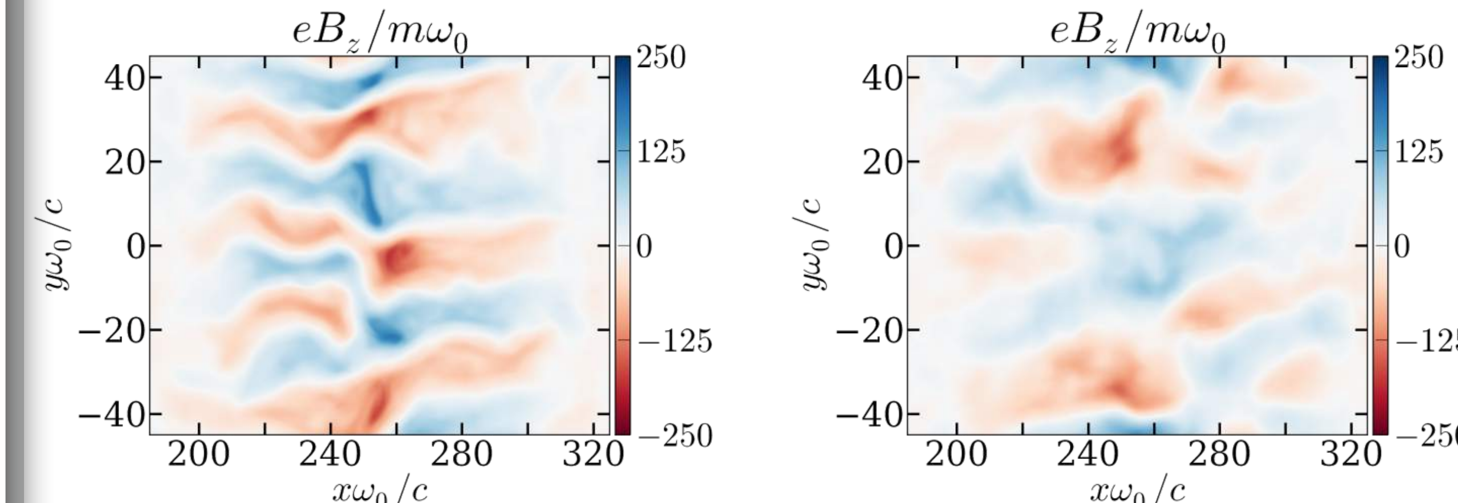
$$\chi_- \sim 0.06\,, \quad \chi_+ \sim 0.1$$

- **synch. emission corresponds to 60% of the incoming e^- & e^+ incoming energy**
- ultra-relativistic e^- & e^+ (γ>200) lose 50% of their energy in less than 25 fs (~100 B-field)

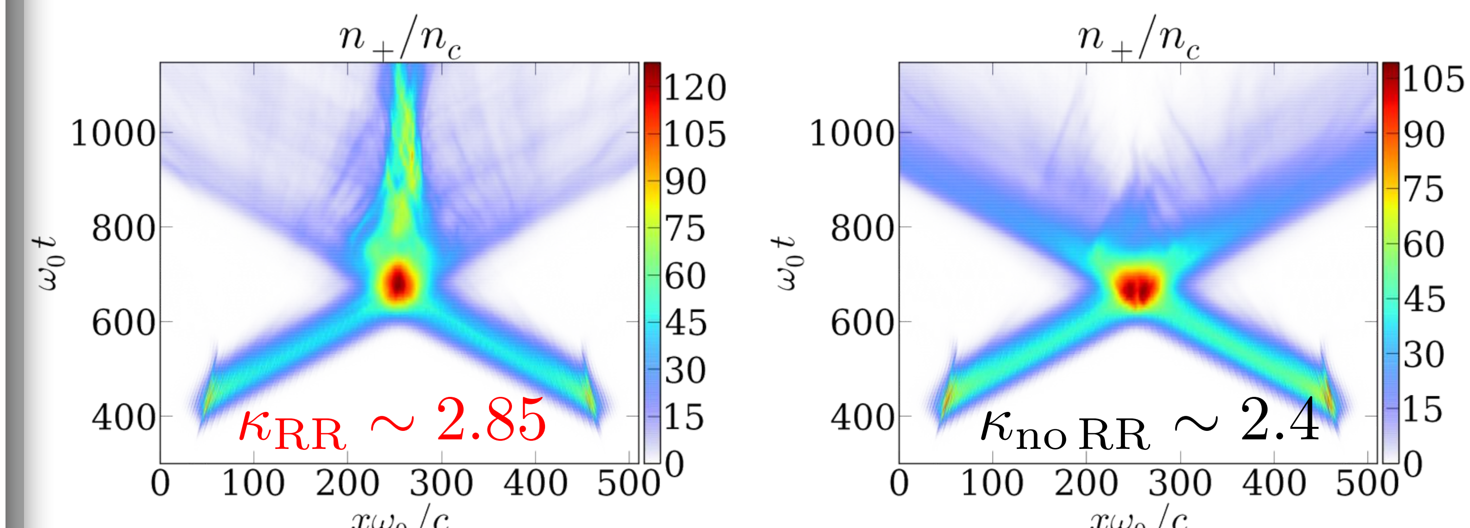
(3) latest time: ion-ion collision with weak rad.

Radiation enhanced compression

with radiation **without radiation**

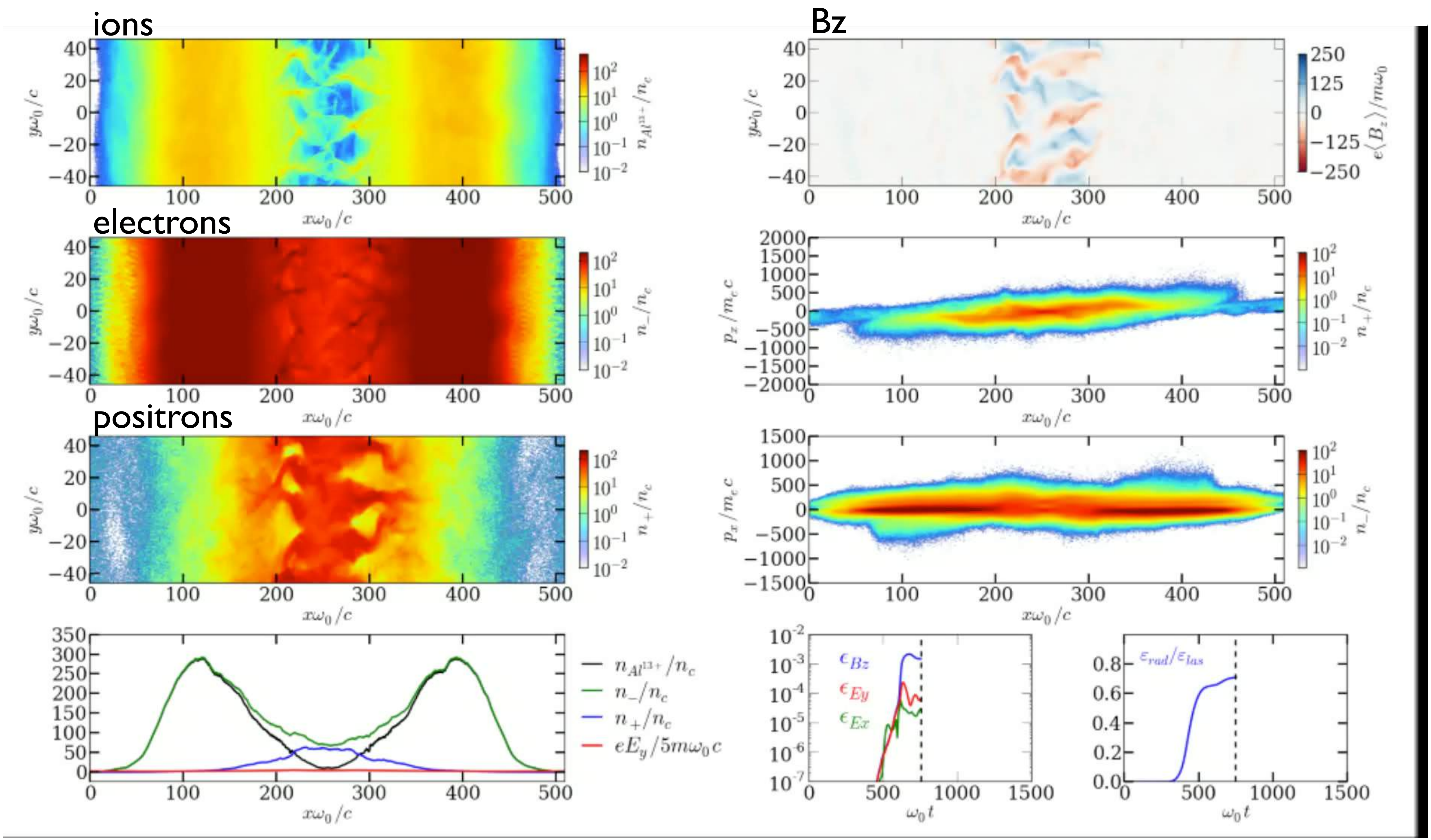


w/out radiation, filament are wider and more diffuse



- radiation enhances compression: $\kappa_{\rm RR} > \kappa_{\rm noRR}$
- but still the shock is not formed: $\kappa_{\rm RR} < 3$

Collisionless shocks in electron-positron plasmas

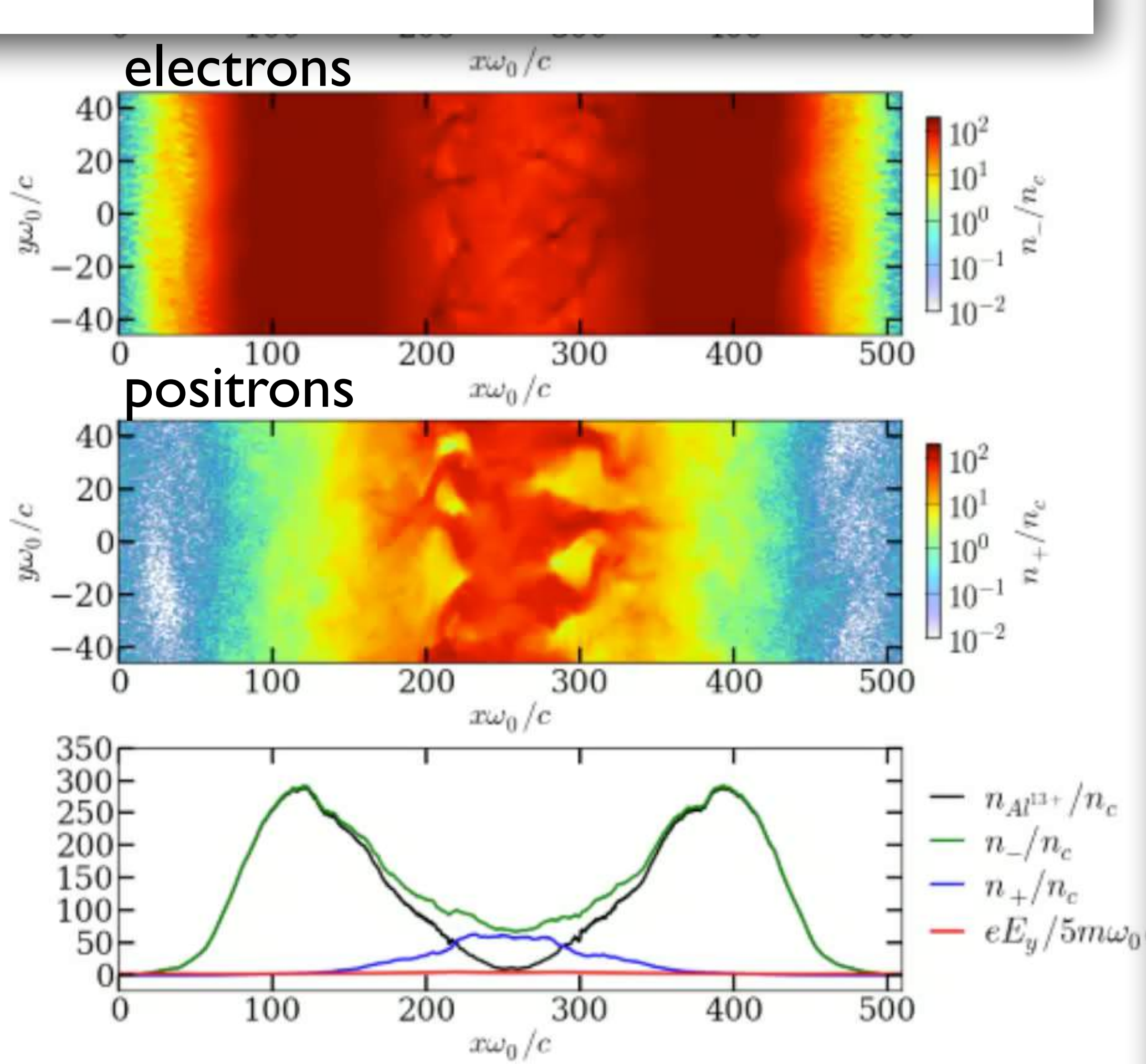


Collisionless shocks in electron-positron plasmas

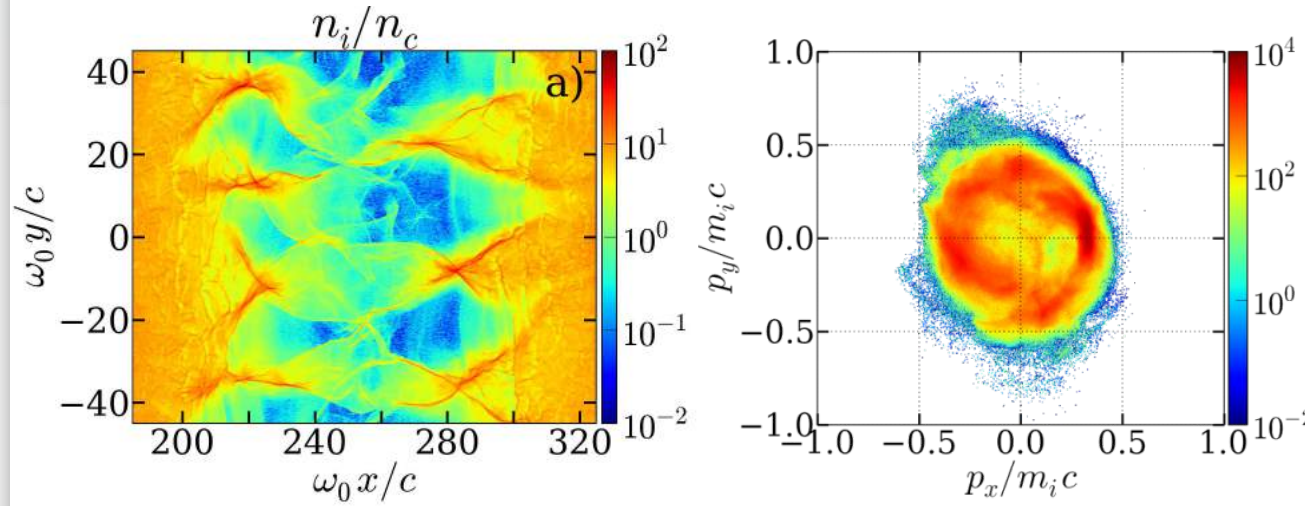
pair plasma creation — Weibel instability growth

Magnetic field compression

$B_z \sim 300\ m_e\omega_0/e \sim 3.3\ \mathrm{MT}$



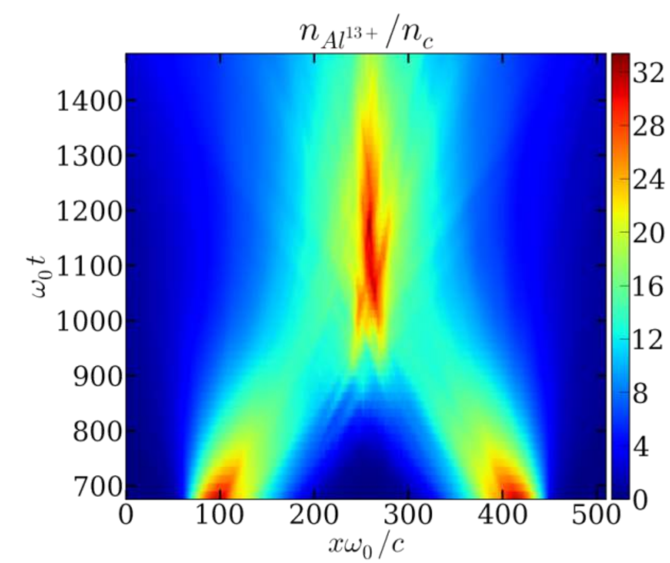
Ion isotropization



Strong deflection of ions in the B-field:

$$r_L \sim 34\ c/\omega_0 \sim \lambda_i$$

Isotropization nearly achieved, yet no thermalization.



No compression observed: $\kappa_{\mathrm{ion}} \sim 2.0$

Conclusions

- First **fully-integrated simulation** of neutral pair plasma laser-induced generation and collision
- This scheme requires **200 kJ - 60 fs** laser pulse such as might be available on future **compressed NIF/LMJ-class** laser systems

- **strong MT magnetic fields** develop in the overlapping region
- **ultra-fast isotropization & thermalization** (if not complete) of electron & positron is demonstrated
- **compression up to 2.85** is obtained, which is not yet enough for a shock to develop
- **radiation in the strong MT B-field enhances compression**

Thank you for your attention!

Financial support from the french Agence National pour la Recherche
(LABEX PALM-ANR-10-LABX-39 Project SimPLE & ANR Project SILAMPA)
is acknowledged