Laser-driven magnetic filament
as a platform for high-field scien

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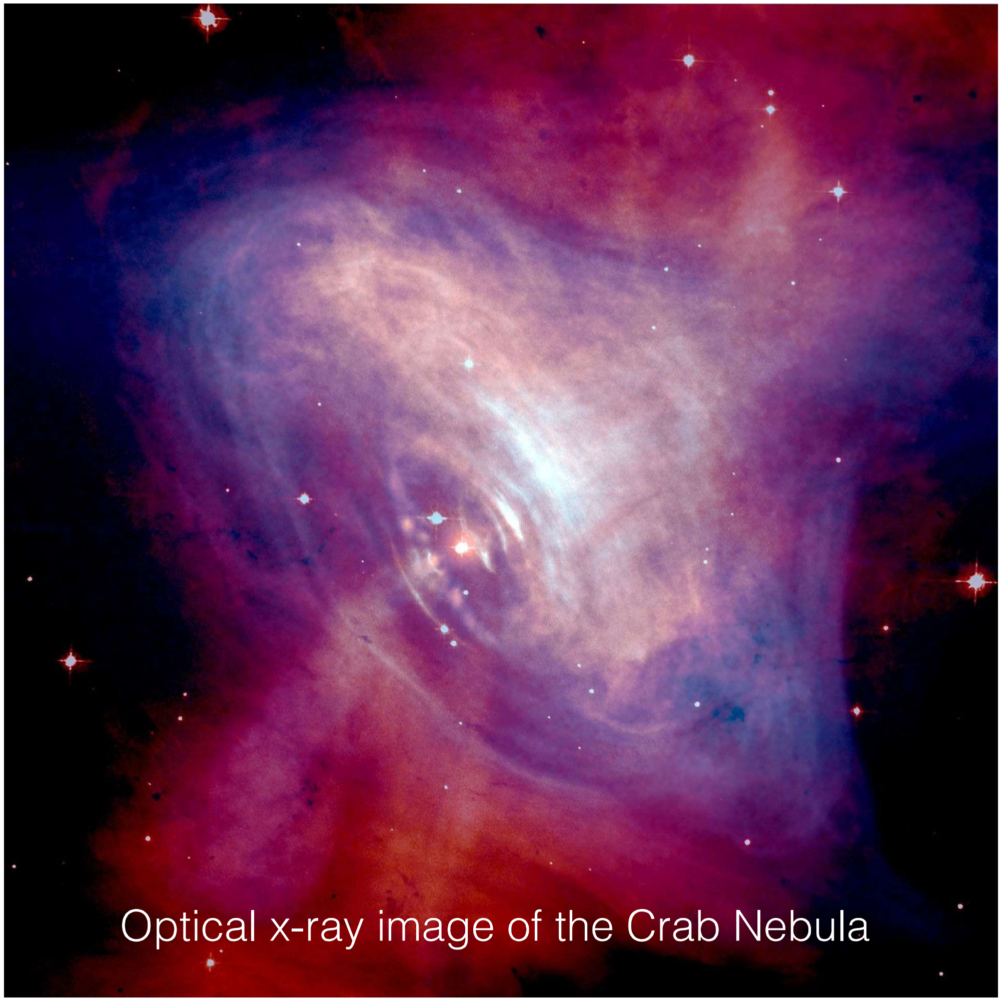
XSEDE
Extreme Science and Engineering
Discovery Environment

EPO

Extreme astrophysical regimes as moti


Optical x-ray image of the Crab Nebula

Interest in high-field physi
motivated by extreme astr
environments:

- **Example 1:** Neutron sta
  Megatesla magnetic fie

- **Example 2:** Pulsar mag
  filled with an electron-p
  produced by colliding p

Can we probe relevant
physics in laboratory

Current status for laborato

- ITER's field is 10 T

What are the obstacles?

- <u>The B-field is too strong</u>: the force of the B-field causes metal coils to blow up at about 50 T.

- <u>The cross-section for the pair production is too small</u> $(10^{10}$ smaller than that for electron impact ionization):

$$\sigma_{\gamma\gamma} \sim 10^{-29}\ \mathrm{m}^2$$

- The photon density must be high to overcome the smalln

At $n_\gamma \approx 10^{27}$ m^{-3}, $\Sigma_{\gamma\gamma} = n_\gamma \sigma_{\gamma\gamma} \approx 10^{-2}$ 1/m ➡ $l_{\mathrm{mfp}} =$

- <u>The process requires very energetic photons:</u>

Multi-PW laser facilities as a novel too

- ELI laser facilities (ELI-NP and ELI Beamlines) will have m groundbreaking features:

  - laser power up to 10 PW
  - on-target peak laser intensity of $5{\times}10^{22}$ W/cm^2 and above
  - multiple multi-PW laser beams

- These features make it possible to probe high-field physics regimes by overcoming several

The ELI vision

Though each of the three Extreme Light Infrastructure (ELI) sites in Europe remain under development, all plan to ramp up operations for scientific users this year. Here's a look what the sites hope to offer when fully equipped.

ELI–ALPS

Outline

This talk is an upper-level overview of several interconnect
phenomena that can be unlocked by high-power high-inte

- Generation of extremely strong magnetic fields
- Production of dense gamma-ray beams
- Production of matter and antimatter from light alone

Generation of strong plasma magnetic fields

Why do we need high intensity?

- Strong B-field requires a high current density, but it is limited

$$|j| \approx |e| n_e v_e < |e| n_e c$$

- For nonrelativistic electrons, the density cutoff is set only by th
  wavelength λ_0:

$$n_e \ll n_{cr} \equiv m_e \pi c^2 / \lambda_0^2 e^2$$

- At high laser intensity, electrons become relativistic and a de
  becomes transparent:

$$n_e \ll a_0 n_{cr}$$

The laser can g
that is 100 time

$$a_0 \equiv \frac{|e| E_0}{m_e \omega c} \gg 1$$

$a_0 = 150$ for $I = 5{\times}10^{22}$ W

Can we generate a “static” B-field?

- A plasma can potentially sustain a very strong B-field.

- A quasi-static magnetic field arises naturally if

$$\tau_e \ll \tau_L$$

- The characteristic electron response is

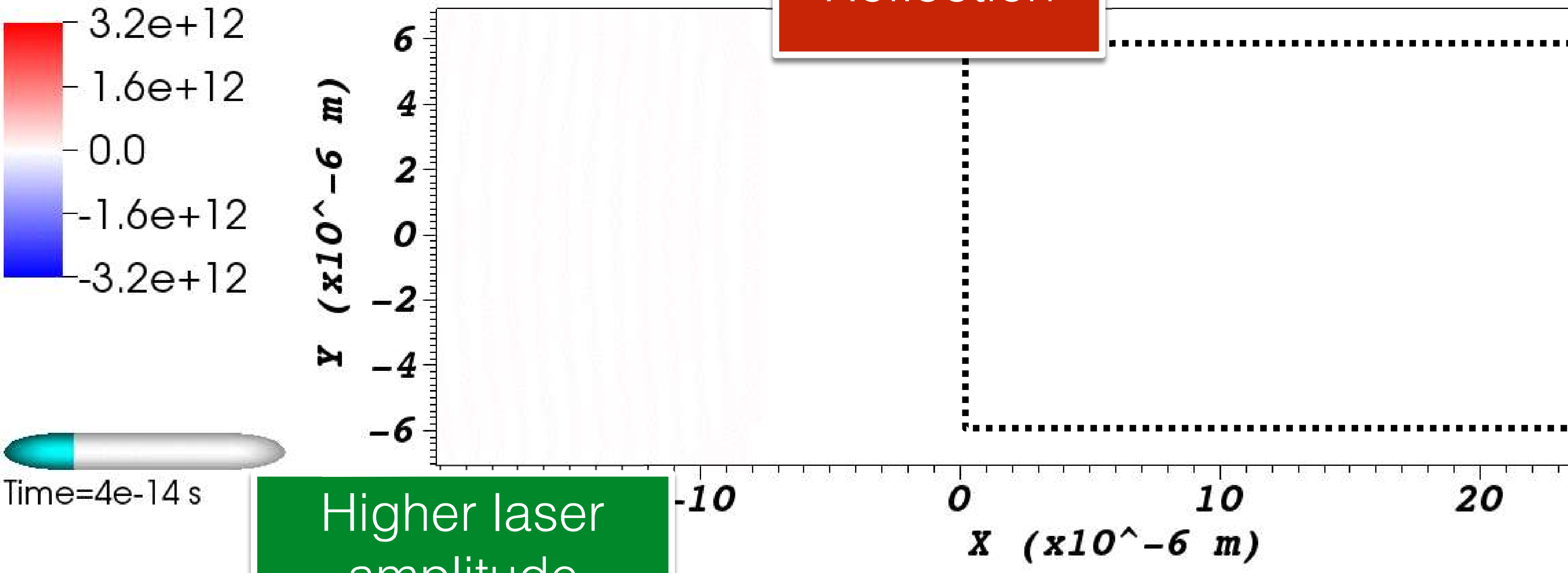
$$\tau_e \approx 1/\omega_{pe} = \sqrt{m_e/4\pi n_e e^2}$$

- The laser pulse duration and density must satisfy the conditio

$$\boxed{n_e/n_{cr} \gg T^2/\tau_L^2}$$

$$n_{cr} \equiv m_e \pi c^2/\lambda_0^2 e^2,$$

Example of relativistic transparency

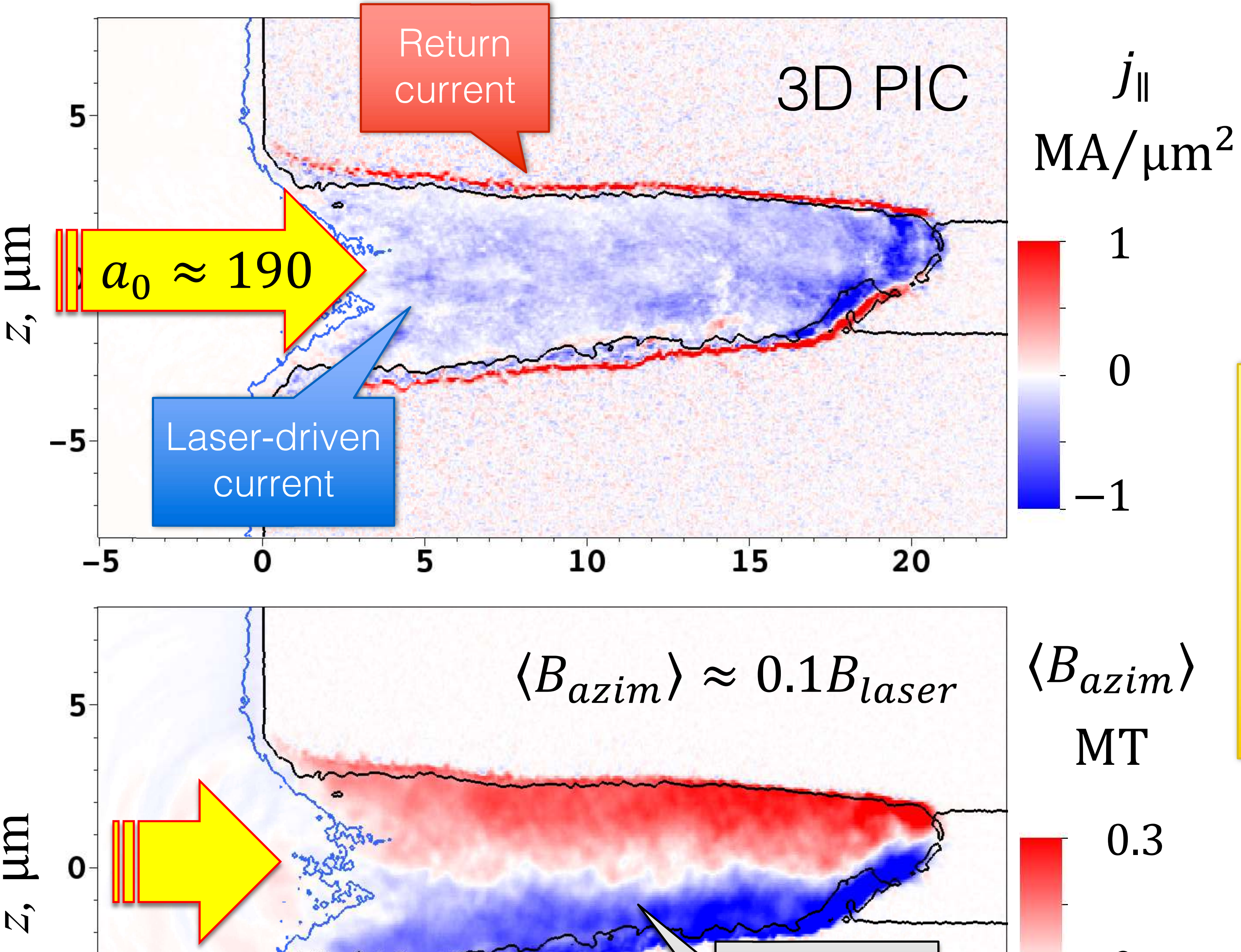


Reflection

Higher laser amplitude

Propagation

Generation of a strong static B-field



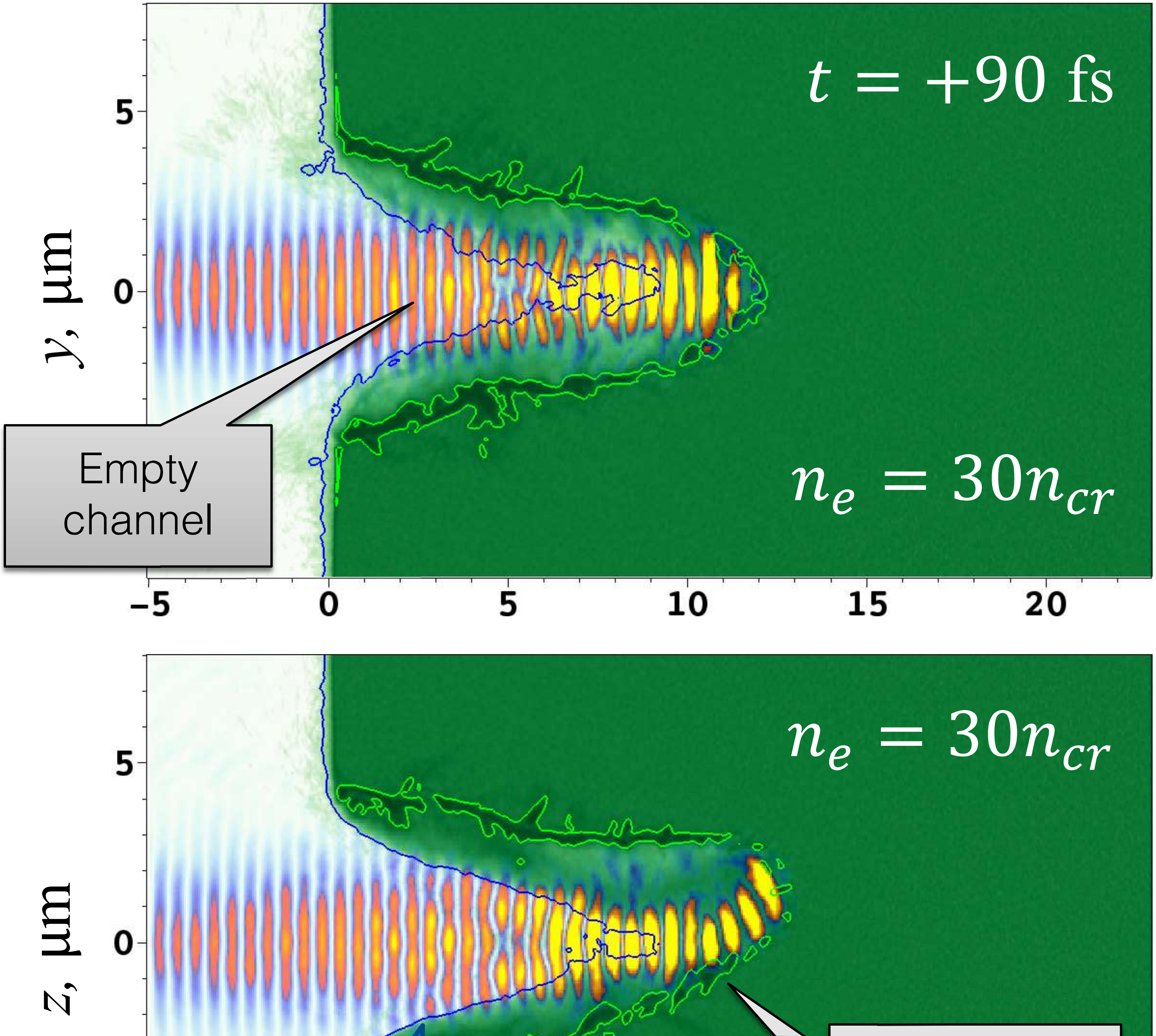
- The pul
strong c
dense p

$J_\parallel \approx$

- The cur
extreme
magnet
compar
field (10

Open que
approach

Ineffective long-term interaction



$t = +90$ fs

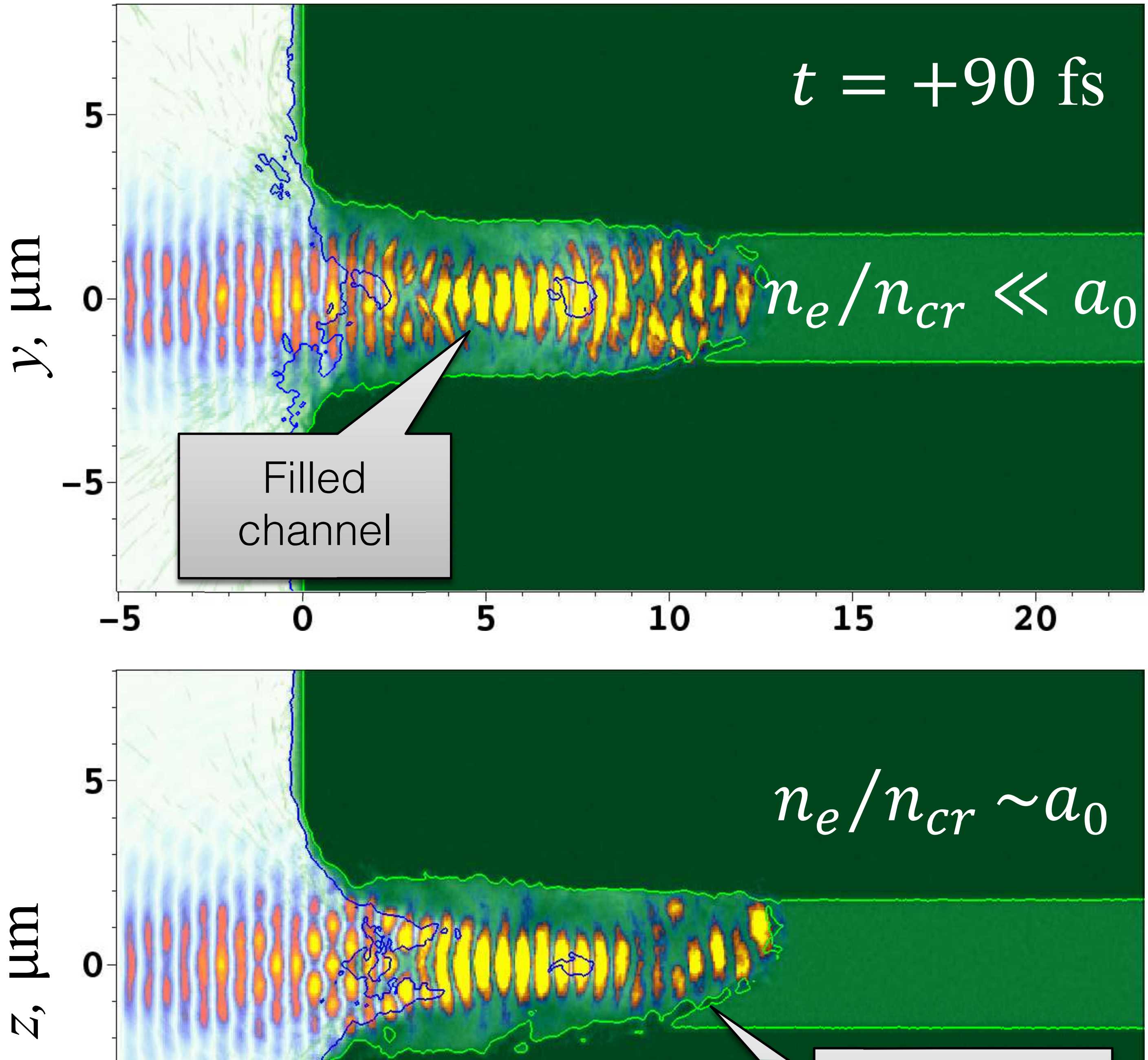
$n_e = 30 n_{cr}$

Empty channel

$n_e = 30 n_{cr}$

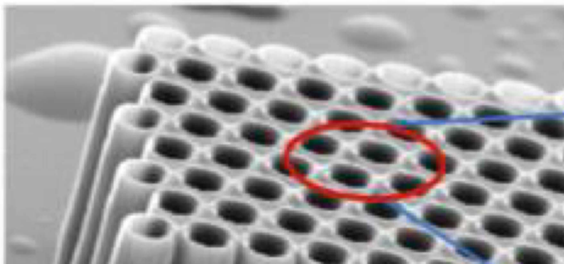
- A tightly focu
beam expels
laterally.
- As the ions fo
channel beco
- Laser pulse p
becomes uns
- Long-term in
ineffective in
uniform plas

Benefits of structured targets



- Structured targe
  propagation of
- The channel re
  dense plasma e
  extended intera
- These targets h
  manufactured a
  experiment has

Rinderknecht



Generation
of dense gamma-ray bea
and energetic electrons

How impactful is the strong B-field?

- Electron deflections cause photon emission determined b

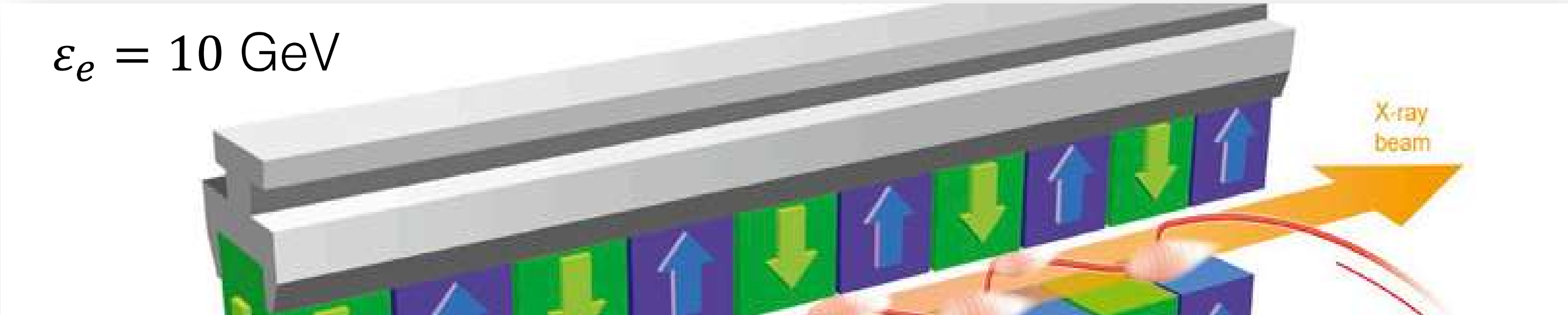
Power $P \propto \eta^2$

Photon energy $\varepsilon_\gamma / \varepsilon_e \approx 0.4\eta$

$B = 0.5$ MT

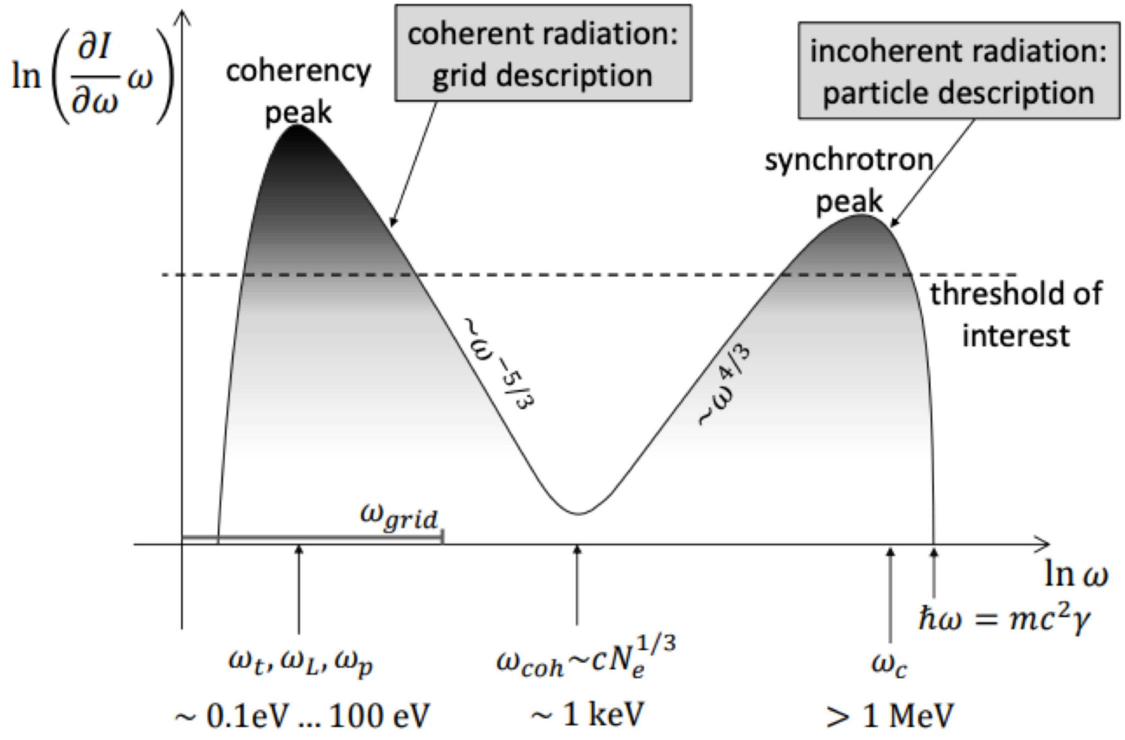
$\varepsilon_e = 100$ MeV

$B_c \approx 4.4\times10^9$ T



$\varepsilon_e = 10$ GeV

The need for QED-PIC



- Photon wavelength: $\lambda(1\,\mathrm{MeV}) \approx 10^{-3}$ nm
- High res. simulation: $\Delta x \approx \lambda_0/100 \approx 10$ nm
- Distance between the electrons at

- Spatial scale ordering

  $\Delta x \gg l \gg \lambda(1$

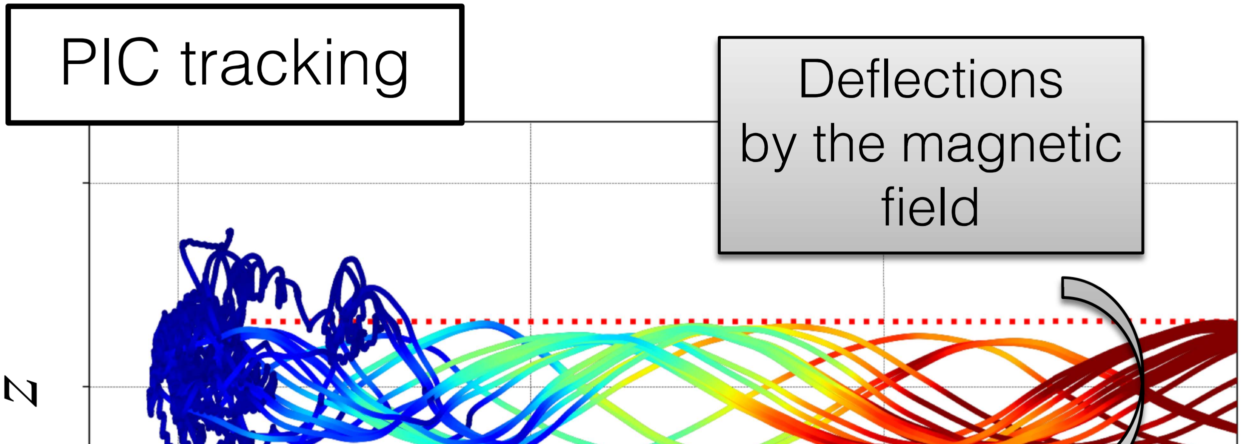
- The photon waveleng resolved using a PIC c
- The emission can be t incoherent, because λ
- QED-PIC emits high e individual particles in
- The electrons experie

Energy enhancement by the B-field (1/

Energy gain requirement

$$\dot{\varepsilon}_e \propto -E_{\perp}^{laser} v_{\perp}$$

The electron gains energy only when v is antiparallel to E



- Electrons move fo
  the forward push

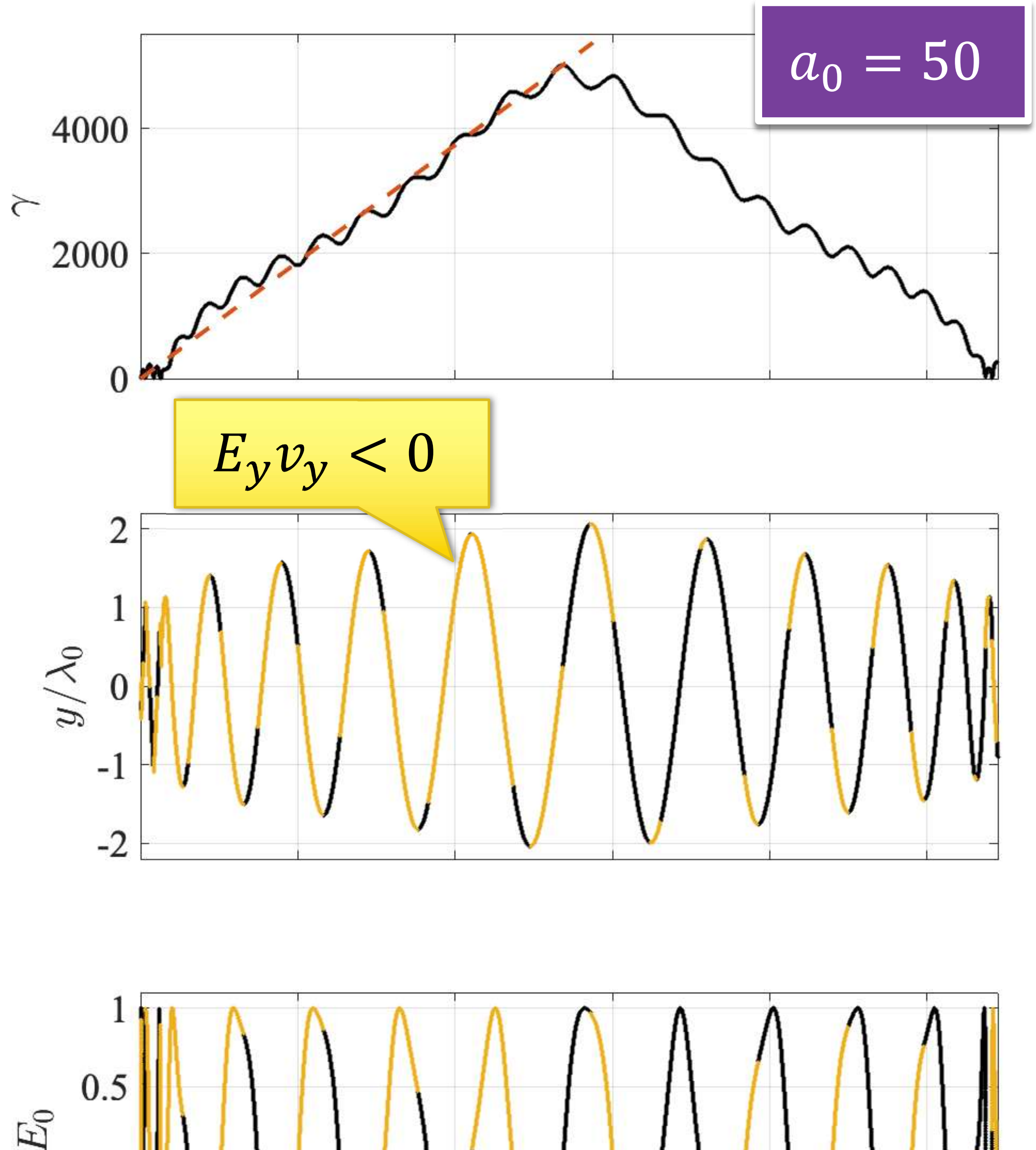
- The electrons are
  respect to E_{laser},

  $$v_{ph} \geq c >$$

- W/o the B-field, th
  terminates the en

- The plasma B-fiel
  mitigate the deph

Energy enhancement by the B-field (2/


$a_0 = 50$

$E_y v_y < 0$

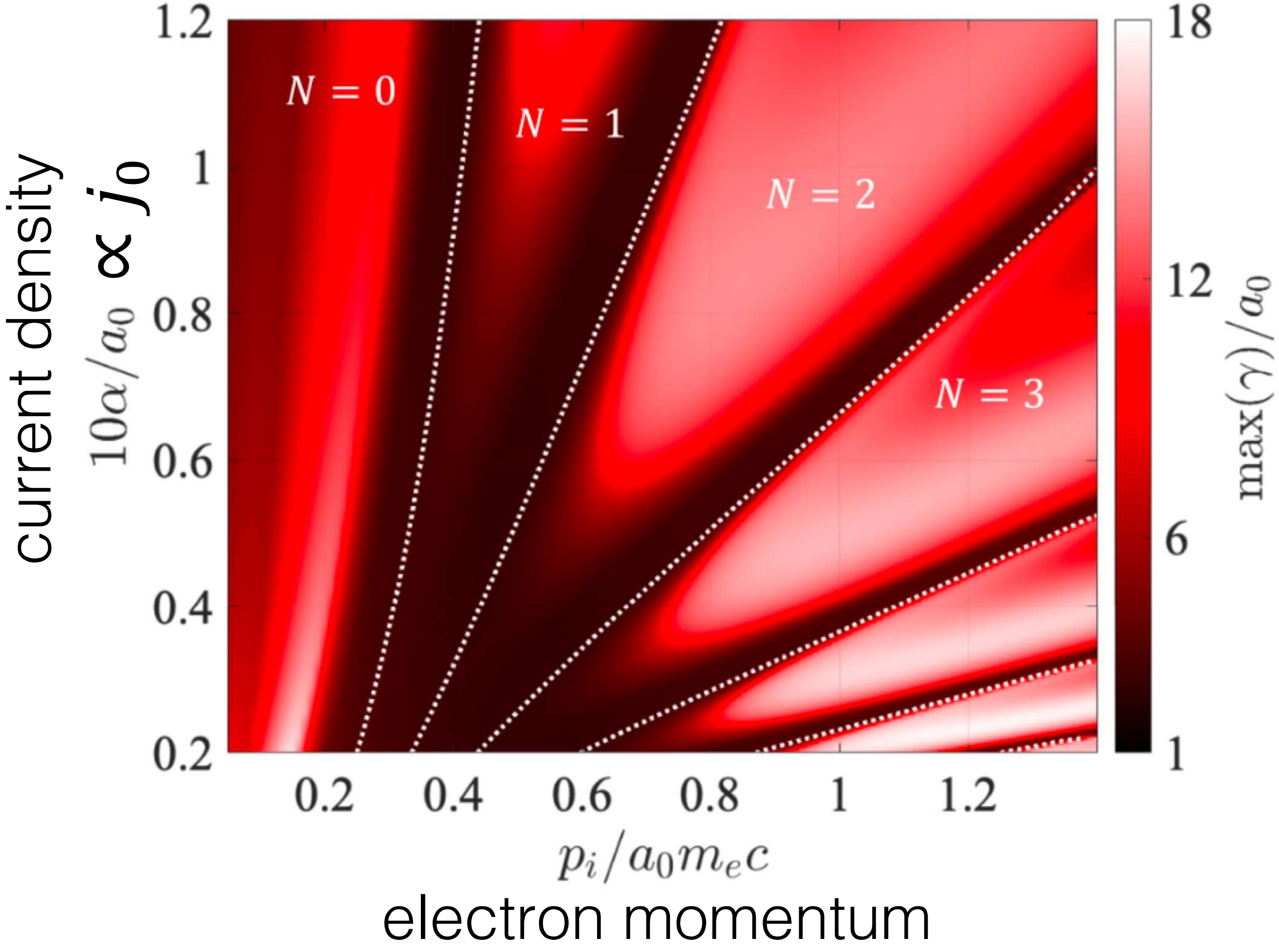
- Transverse deflect
magnetic field kee

- The energy gain c
the electron is slip
respect to the lase

- The prolonged ene
to an energy enha
for electrons with a
transverse momen

Plasma current/density requirement

Single half-bounce



$$\alpha = \pi\lambda_0^2 j_0/I_A$$

- Our test particle a universal depe energy gain on th momentum $p_\perp =$ current j_0.

- Preferred regime on p_i “disappear

$$\alpha > a_0/$$

$n_e > 10^{-}$

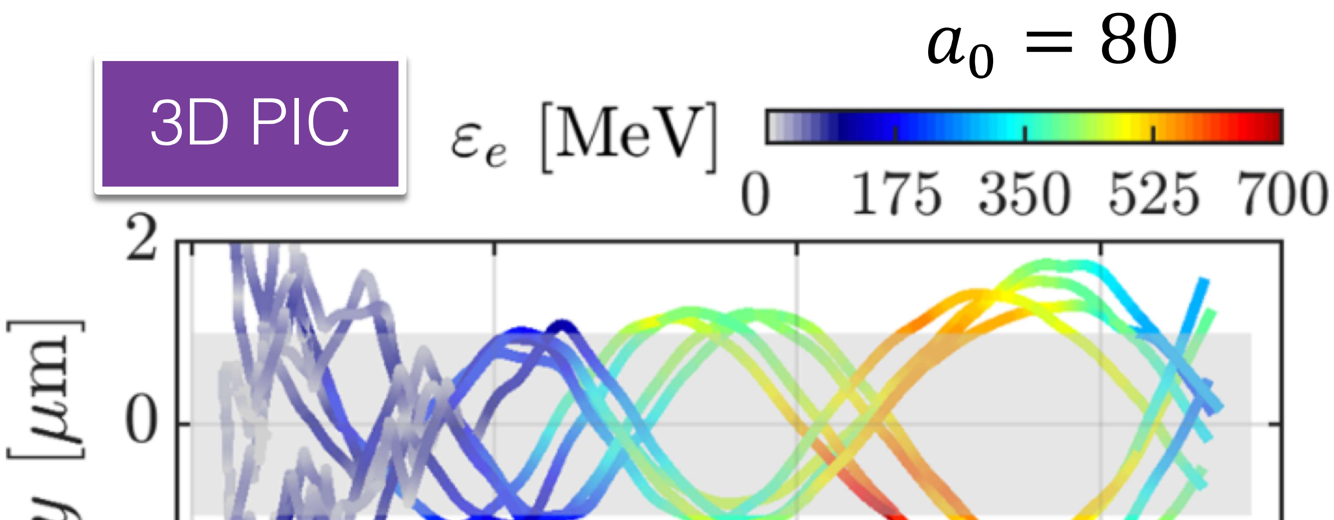
Impact of superluminosity

T. Wang

- The B-field confines electrons within a magnetic bounda

$$r \le r_{\mathrm{MB}} \propto j_0^{-1/2}\sqrt{\gamma_i + \gamma\left(v_{ph} - c\right)/c}$$

- The plasma makes the wave fronts superluminal, $v_{ph} > c$
- Noticeable expansion occurs at $\gamma > 10a_0$ for $\gamma_i \approx 0.1a_0$.



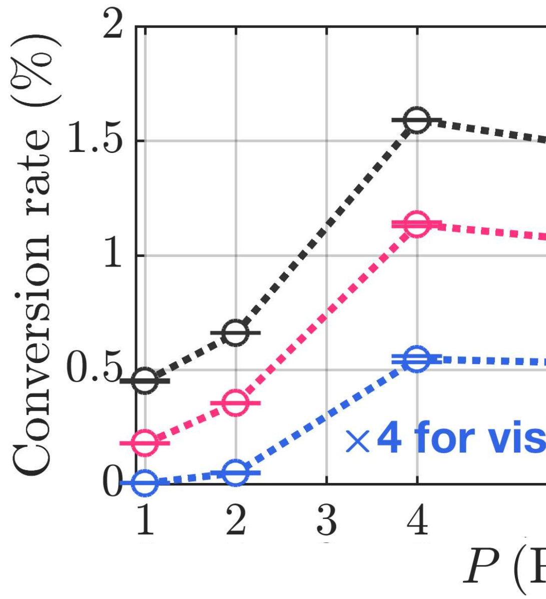
- The superlumin magnetic boun during the ener to electron loss

Emission of dense γ-ray beams in 3D P

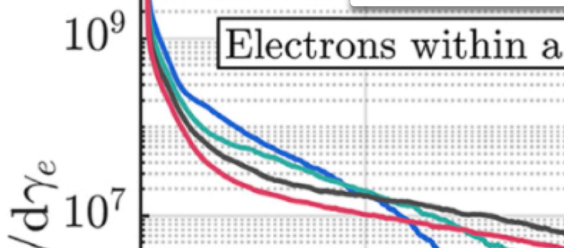
T. Wang et al, Phys. Re

- The scan is performed for $a_0 \approx 190$, by increasing the beam width (or power P) and the channel radius.
- The electron energy spectrum becomes more energetic ($\gamma_e \sim 2000$) due to the improved electron confinement.
- The energy conversion rate into gamma-rays increases with P.
- Laser beam filamentation sets an upper limit on P (like reverting to smaller beams)

Power
at fixed i

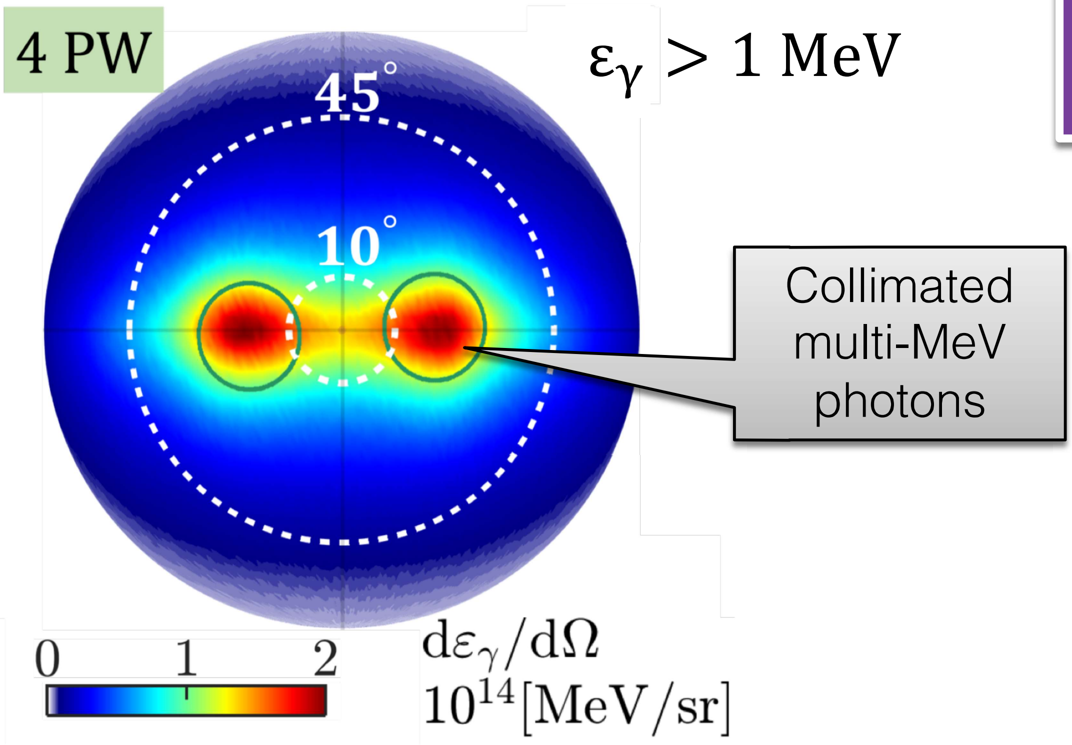


$a_0 \approx 1$



Emission of dense γ-ray beams in 3D P

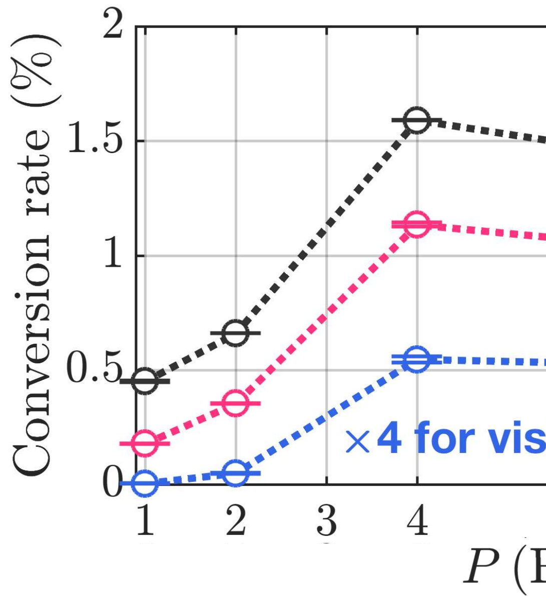
T. Wang et al, Phys. Re



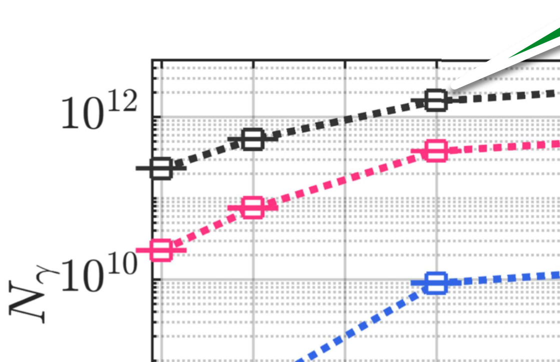
Collimated multi-MeV photons

$a_0 \approx 190$

Power
at fixed i



- The optimal power is in the range of 4 PW.



- 1.5% of the laser energy is converted into 10^{12} multi-MeV photons within a 10° cone.

Production of matter and antimatter from light alon through photon-photon collis

Two-photon pair production conce

O. Pike et al, Nat. Photonics **8**, 434 (2014)

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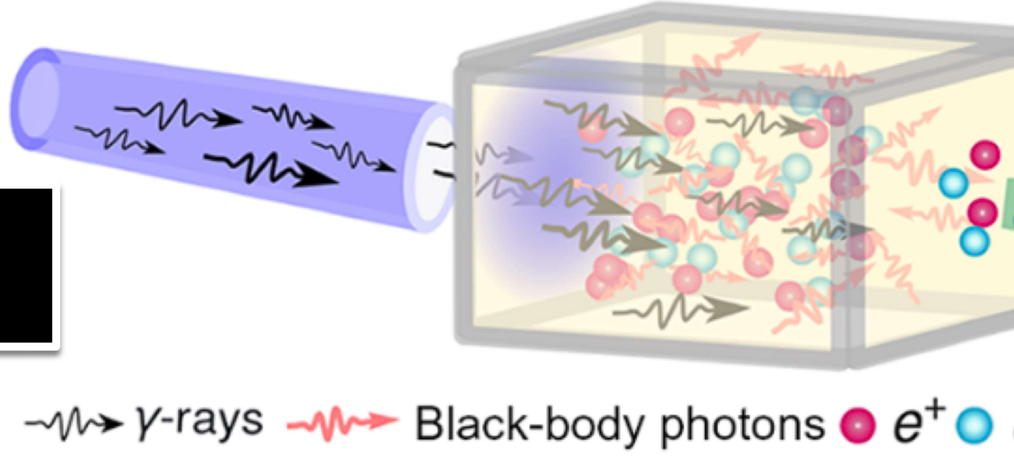
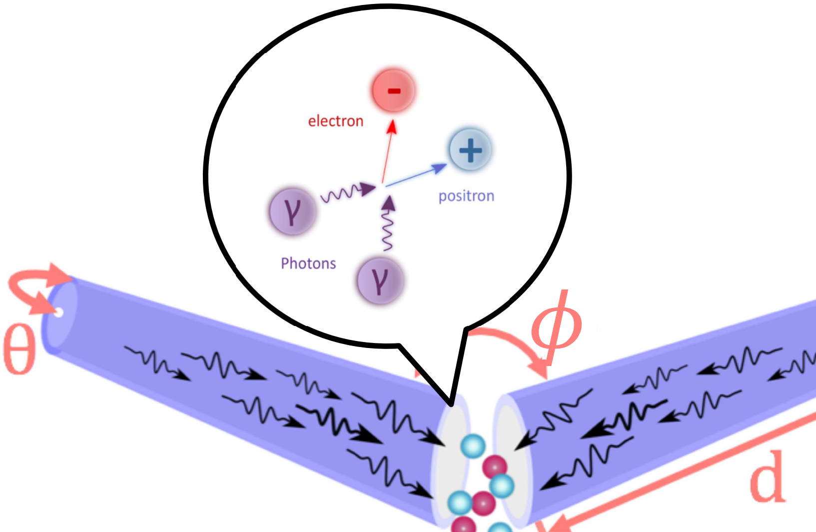


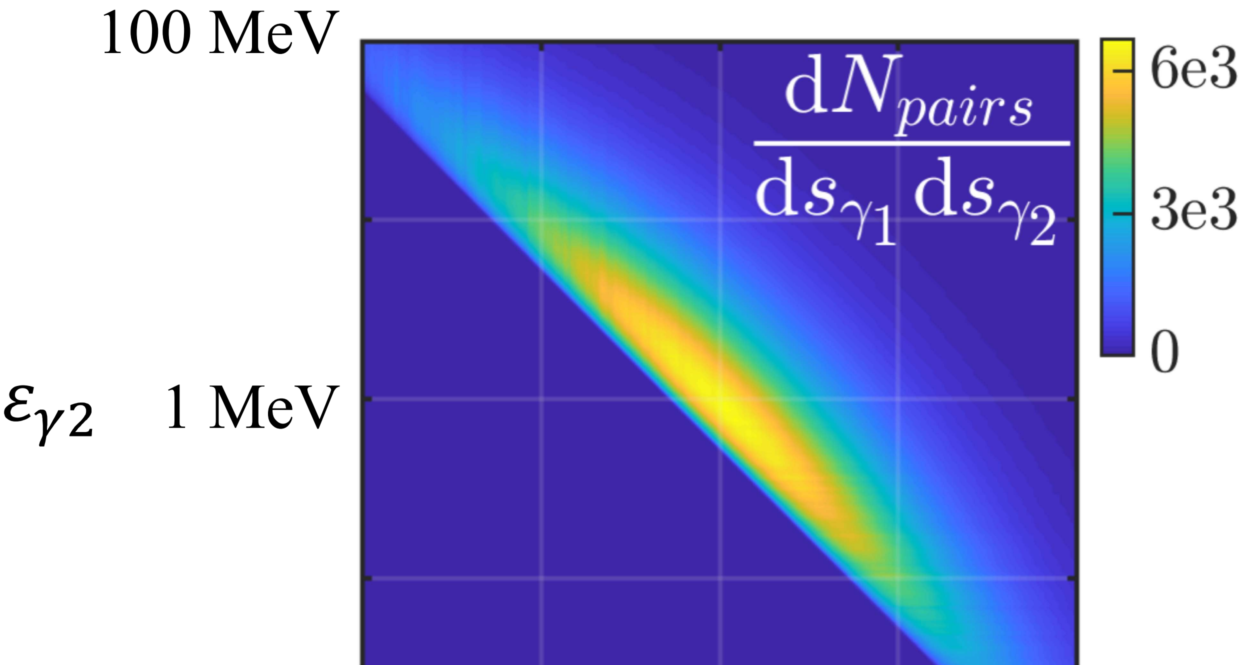
Two concepts have been suggested for generating pairs in vacuum:

B



Pair production with two gamma-ray b

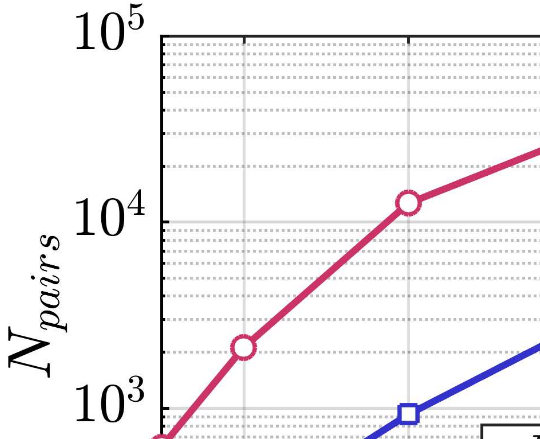
- Two multi-PW lasers can create colliding gamma-ray beams.
- Photons with $\varepsilon_{\gamma}\sim 100$ keV play an important role.



- The “low” energy pho due to the broad pho

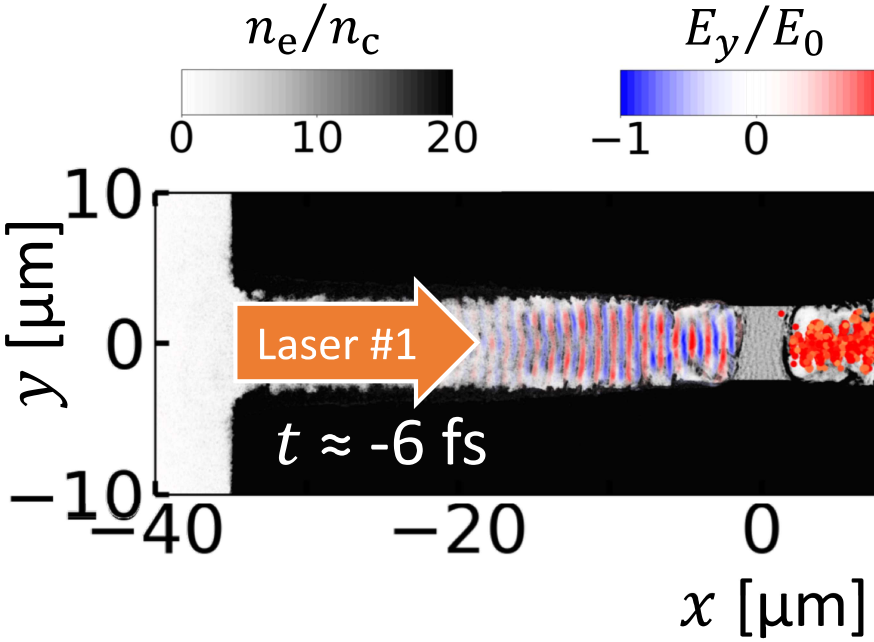
$$\varepsilon_{\gamma 1}\varepsilon_{\gamma 2} > [m_e$$

- Over 10^4 pairs can b the distance ($d = 25$ significant limiting fac

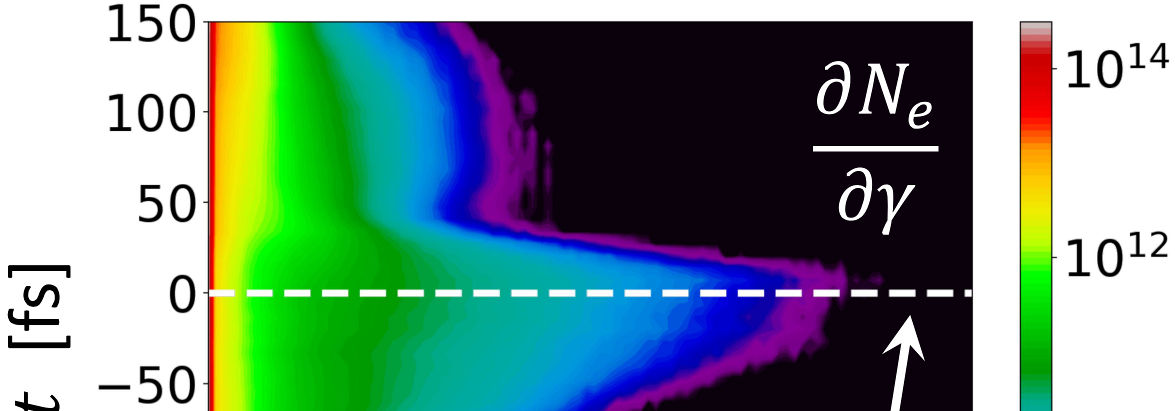


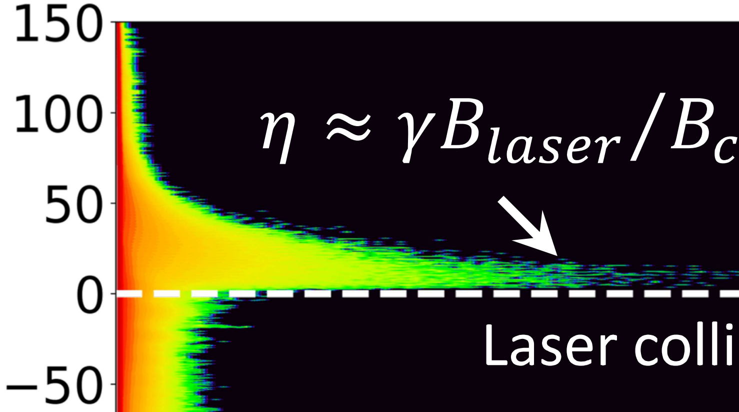
Laser collision inside a plasma

- The target provides alignment.
- More emissions occur when energetic electrons collide with a laser beam (higher η).
- The emission is highly localized.

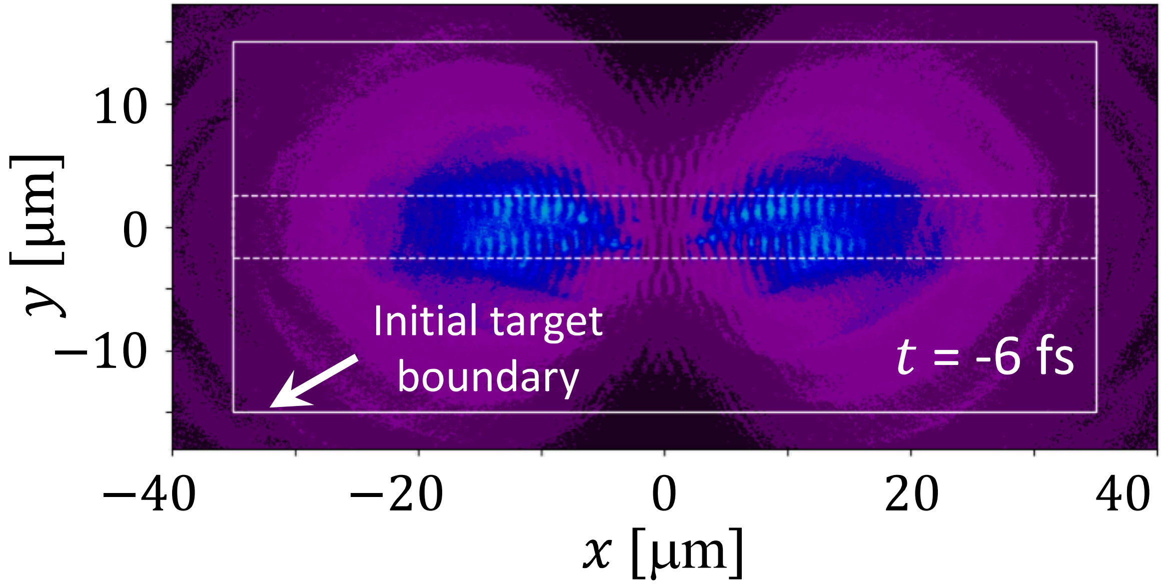


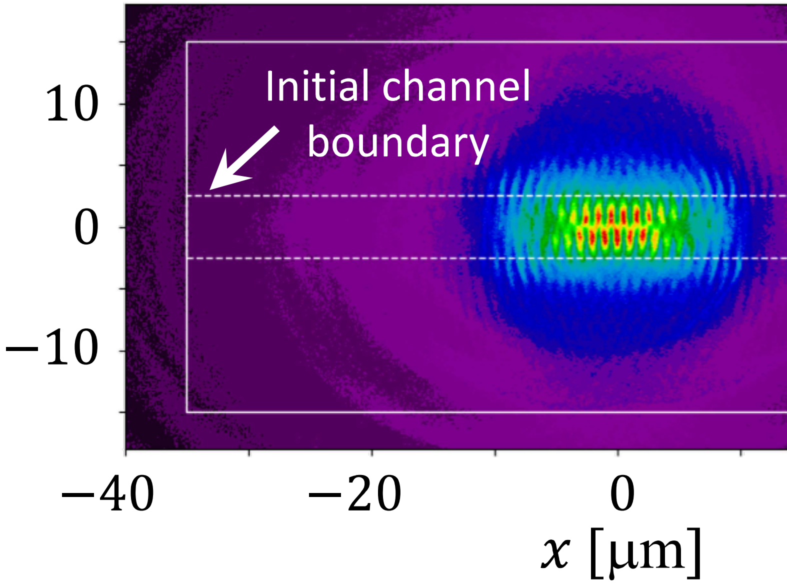
$$\varepsilon_\gamma \approx 0.4\eta\varepsilon_e$$



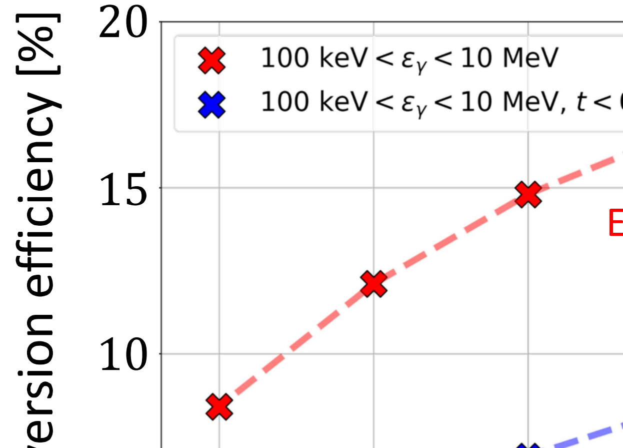


Increase in photon density


Before the collision

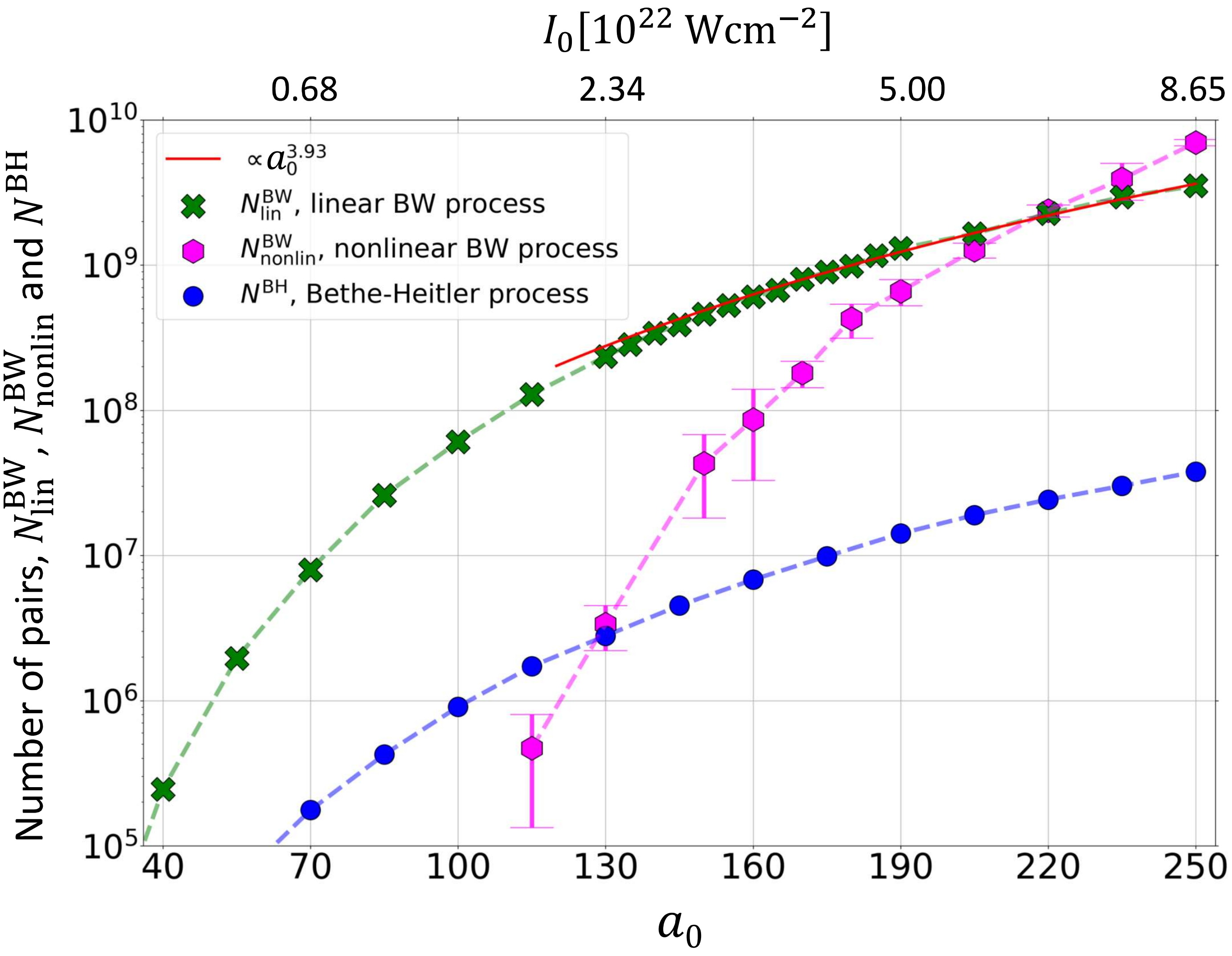

After the collisio

- The collision increases the conversion efficiency as well.
- The density of x-rays with energy $\varepsilon_\gamma > 1$ keV exceeds $600n_c$.



Two-photon pair production as domina

He et al, (



- PIC codes ar
  compute the
  (binary photo

- We compute
  grouping pho
  beamlets co
  photons with

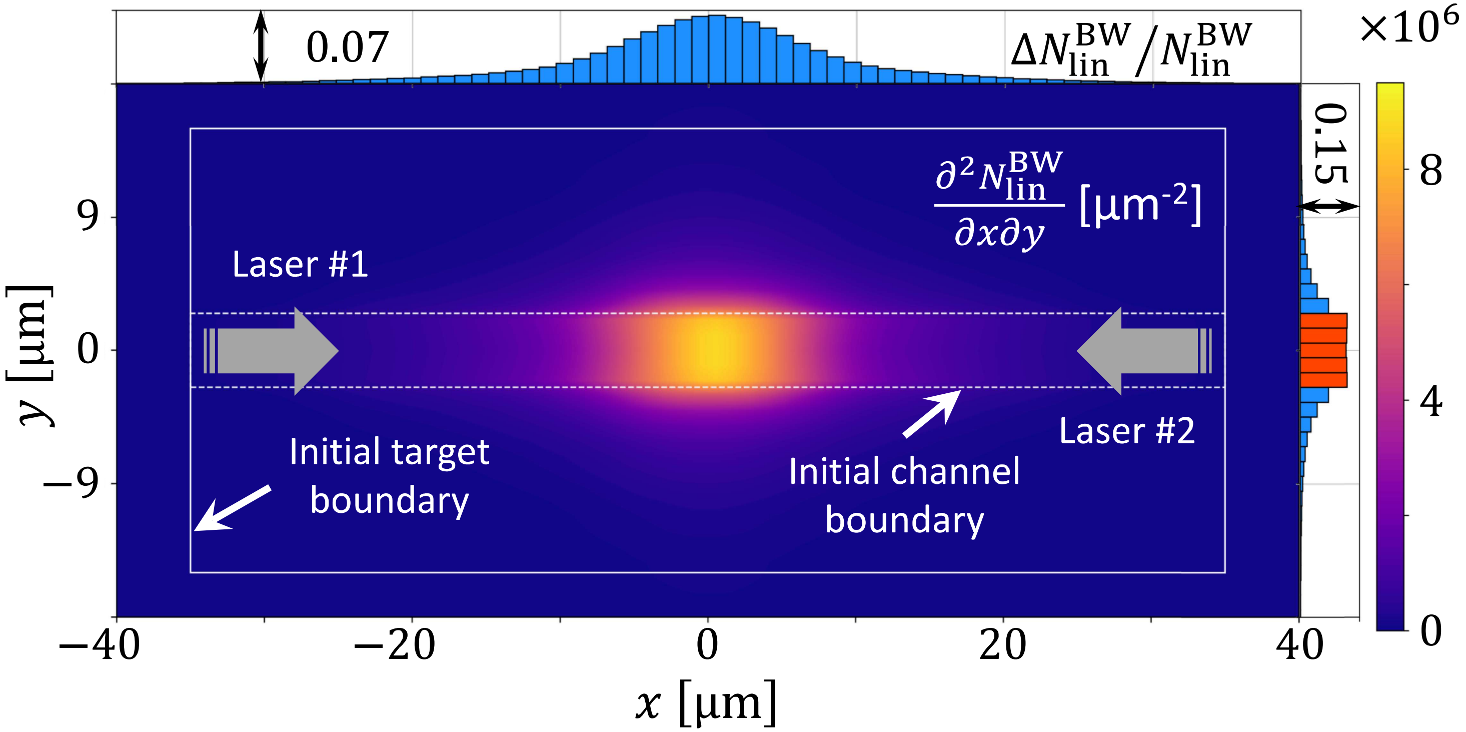
- Over 10^8 pai
  via linear BW
  experimental
  intensity of 4

There are 3 relevant processes:

- Linear Breit Wheeler (gamma+gamma)

Generation of positron jets

He et al,



- We found that
pairs are loca
filament.

- As the magne
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- After the collis
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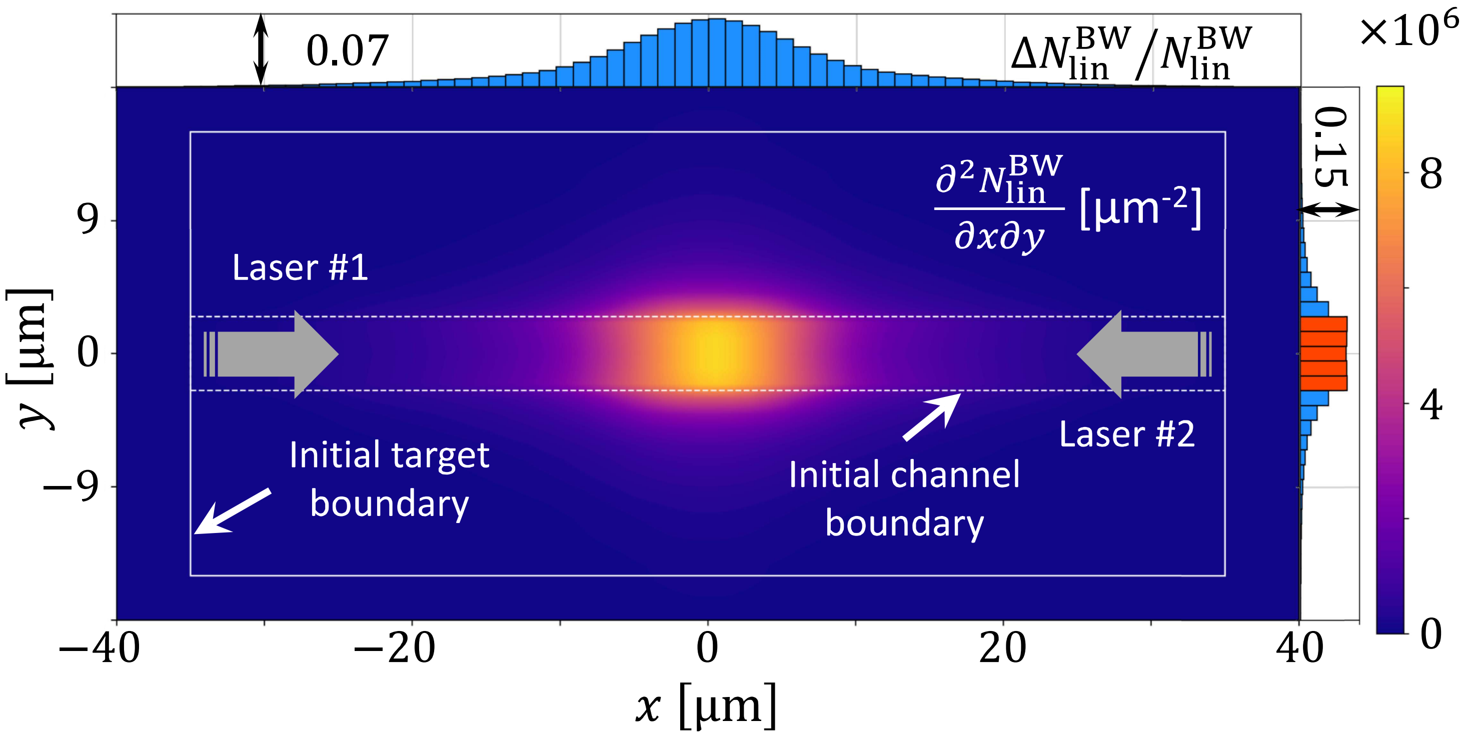
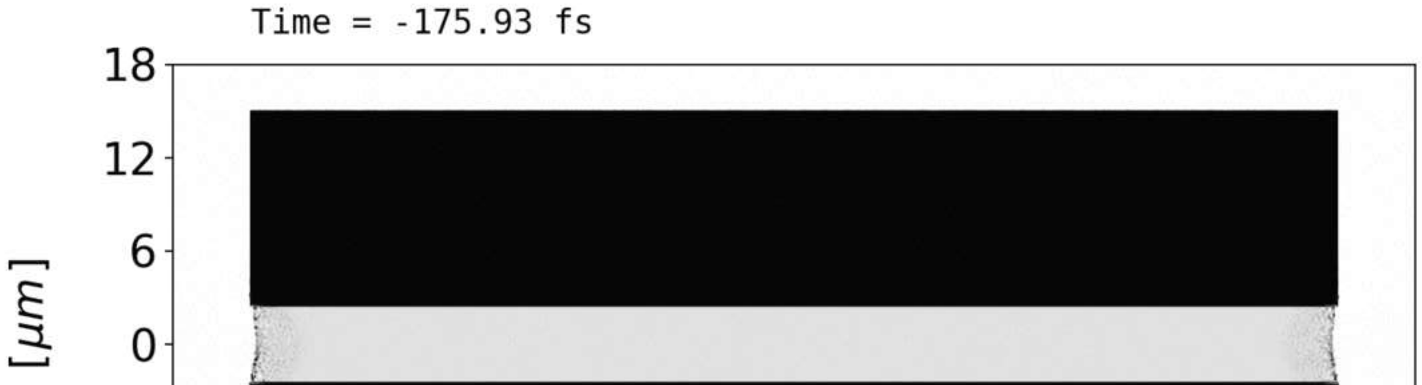
moving with e
rather than the

Generation of positron jets

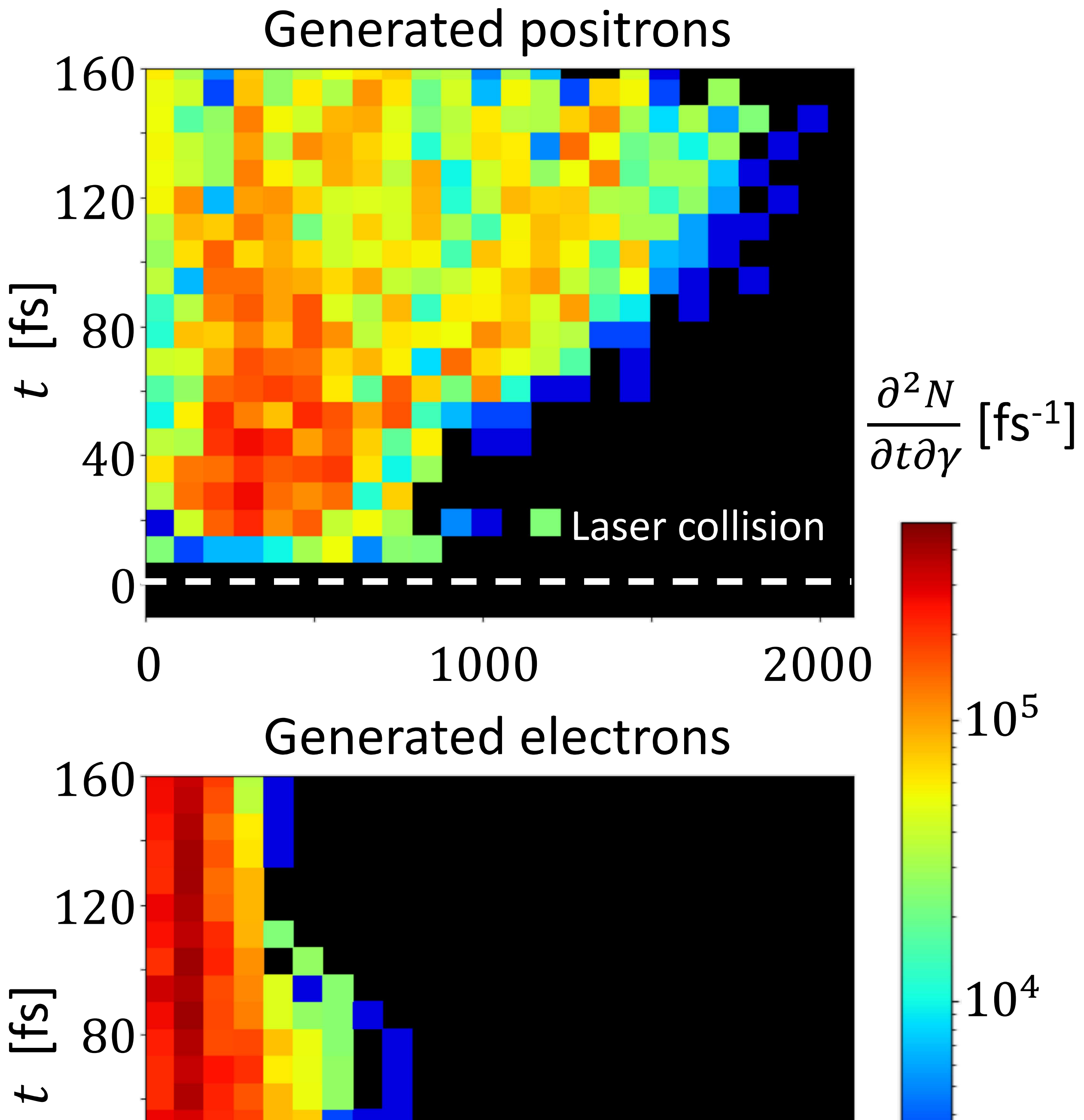
He et al,





- We found that pairs are loca filament.
- As the magne polarity after t polarity with re beam is now r
- After the collis confines gene moving with e rather than the

Acceleration of positron jets


Generated positrons

Generated electrons

- The mechanism for acceleration after th the same as that fo before the collision
- The energy reache
- Nonlinear BW posit ultra-relativistic jets energy from one of
- Linear BW positron expected to behav

Summary

- Laser-matter interactions at multi-beam multi-PW las
have the potential to enable qualitatively novel regi
characterized by
  - MT magnetic fields
  - dense multi-MeV photon populations
  - matter and antimatter creation from light alone