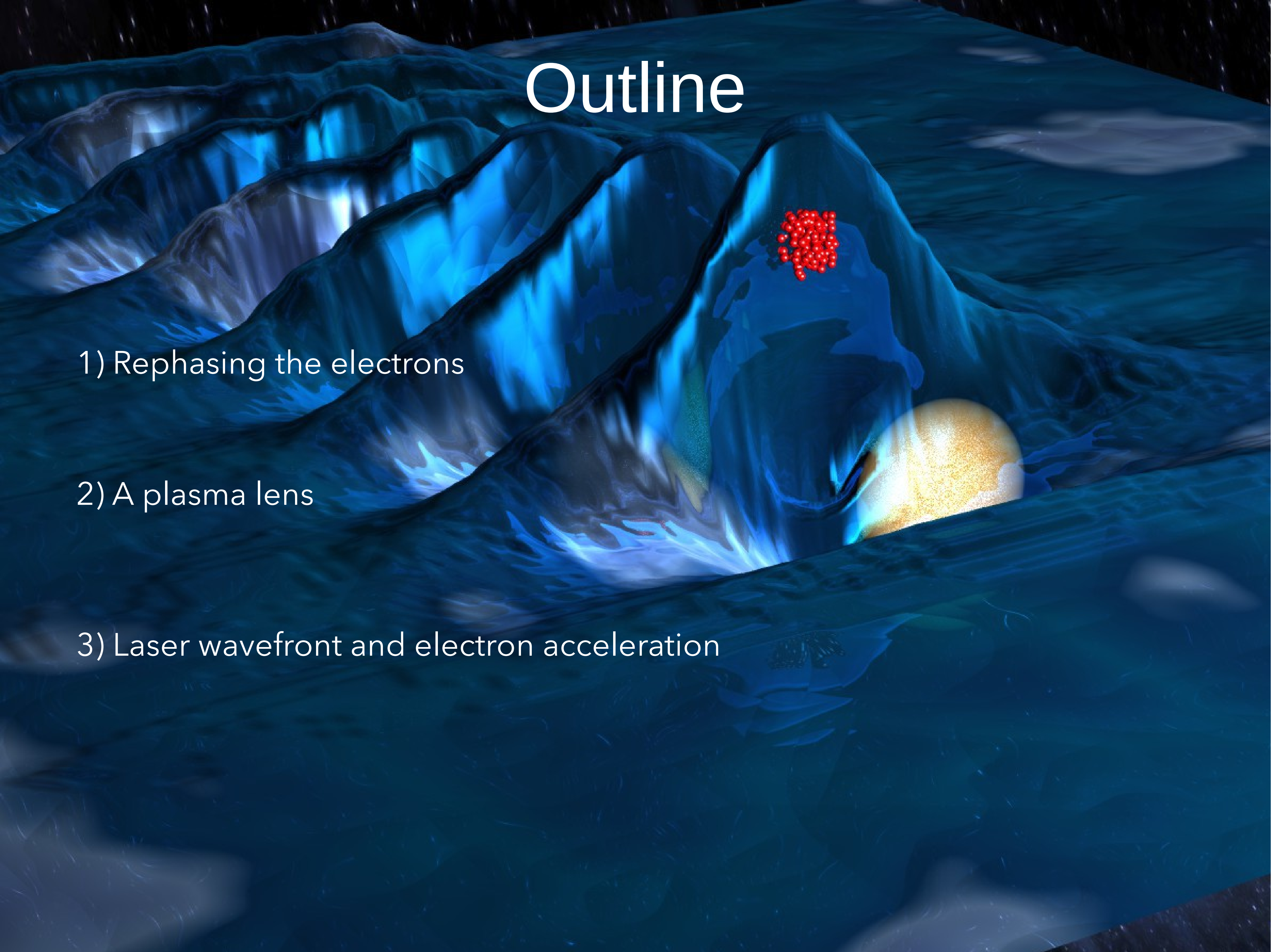
Recent advances
in laser wakefield accelerators

A. Lifschitz, E. Guillaume, A. Doepp, C. Thaury, K. Ta Phuoc,V. Malka,
B. Beaurepaire, A. Vernier, R. Lopez Martens and J. Faure

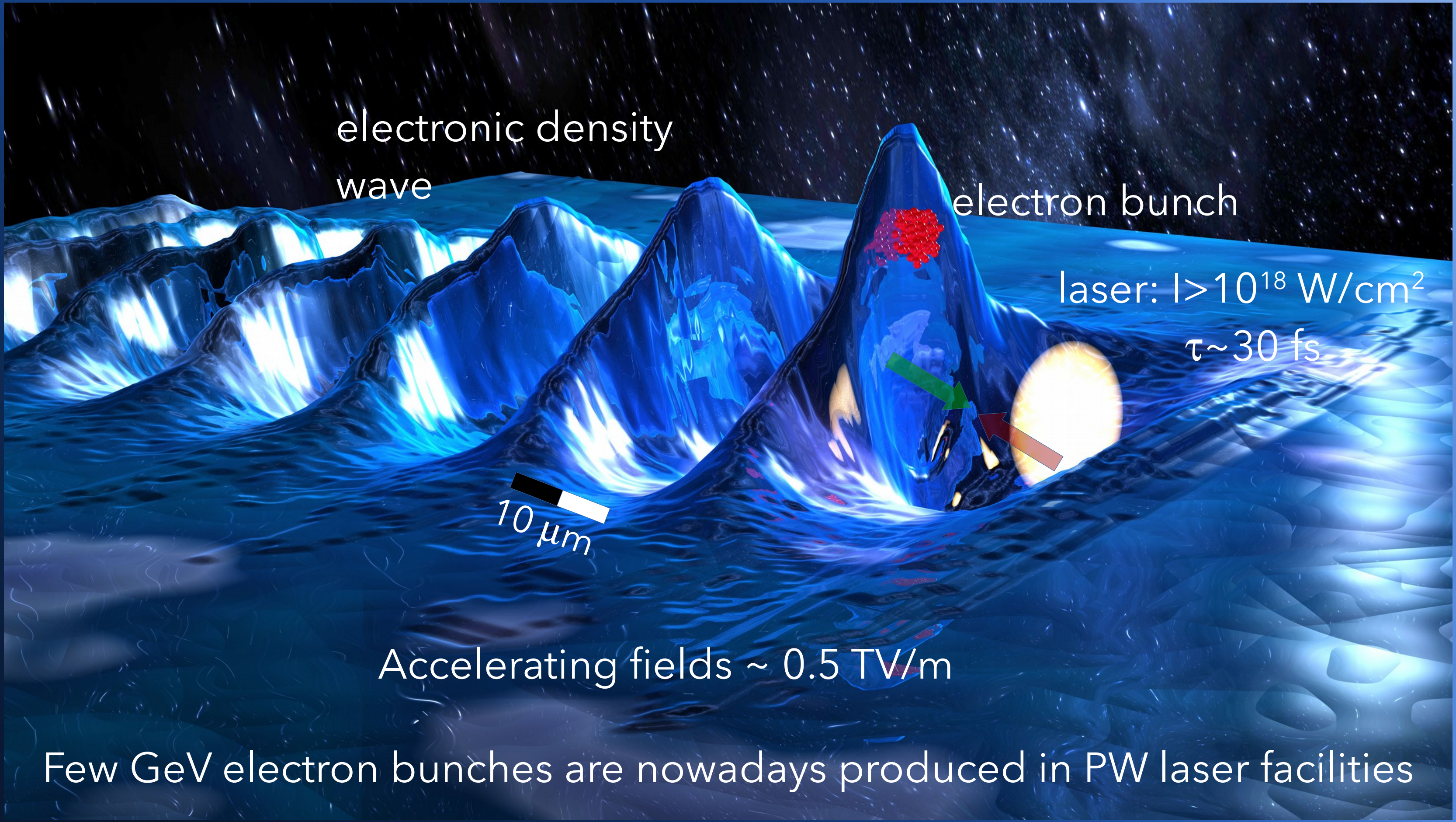
Laboratoire d'Optique Apliquee, ENSTA-CNRS-Polytechnique, UMR 7639, Palaiseau, France

Physics and Applications of High Brightness Beam
March 29th – April 1st , La Habana, Cuba


Outline
1) Rephasing the electrons
2) A plasma lens
3) Laser wavefront and electron acceleration

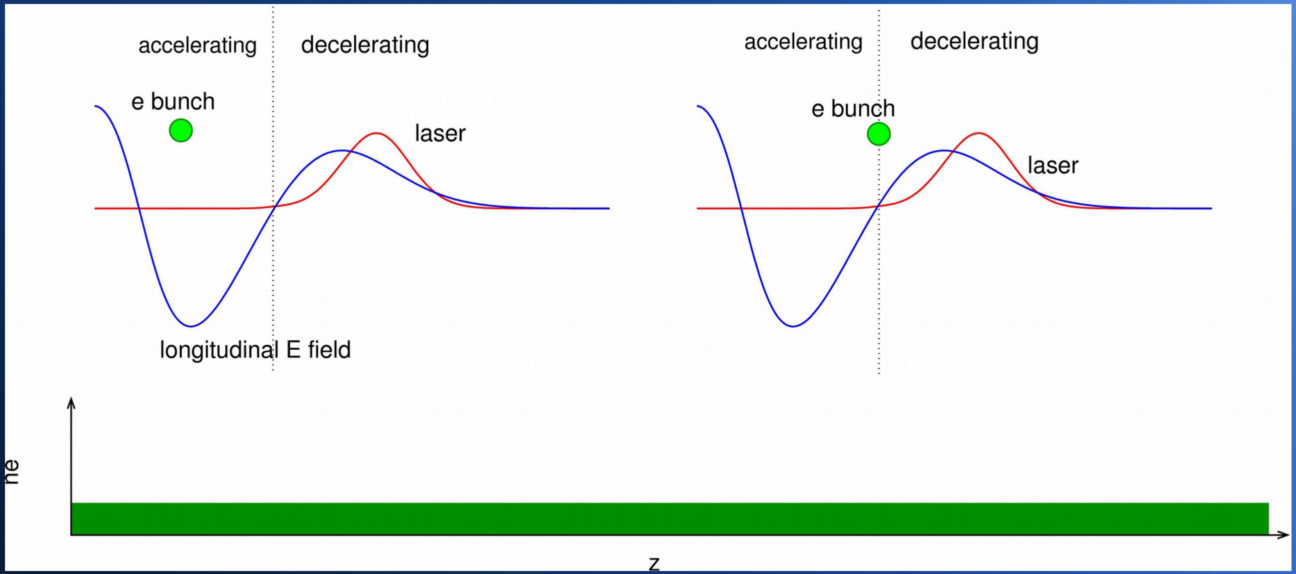
Rephasing the electron bunch

Laser wakefield electron acceleration



Rephasing the electron bunch

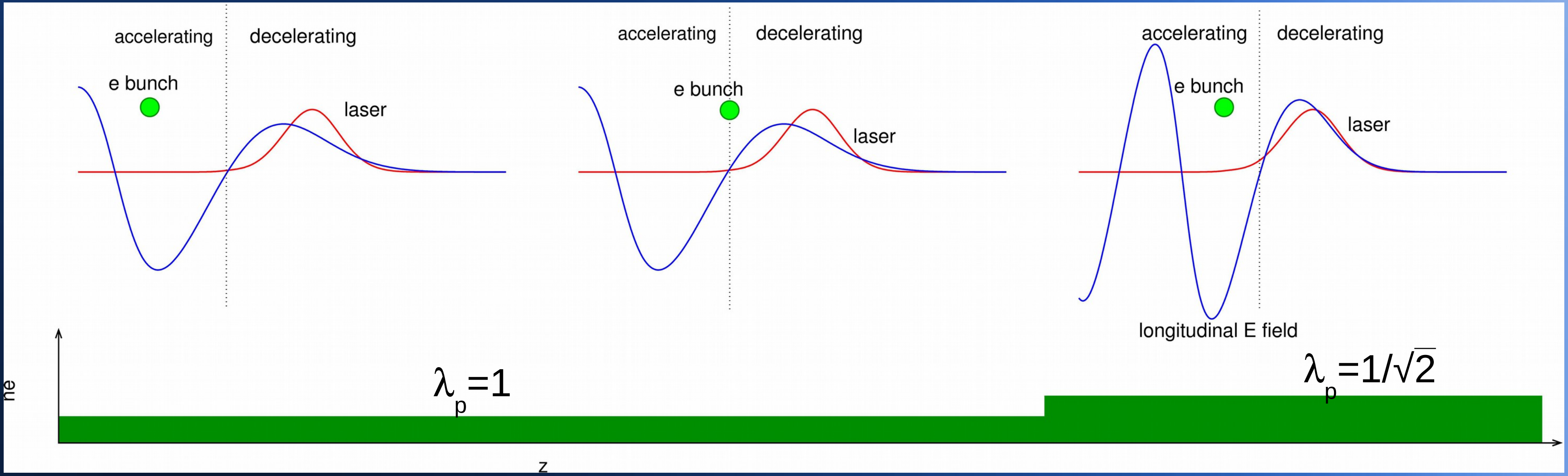
Acceleration ends when electrons slippage into the decelerating region



Dephasing limits the maximum attainable energy of a laser-plasma accelerator

Rephasing the electron bunch

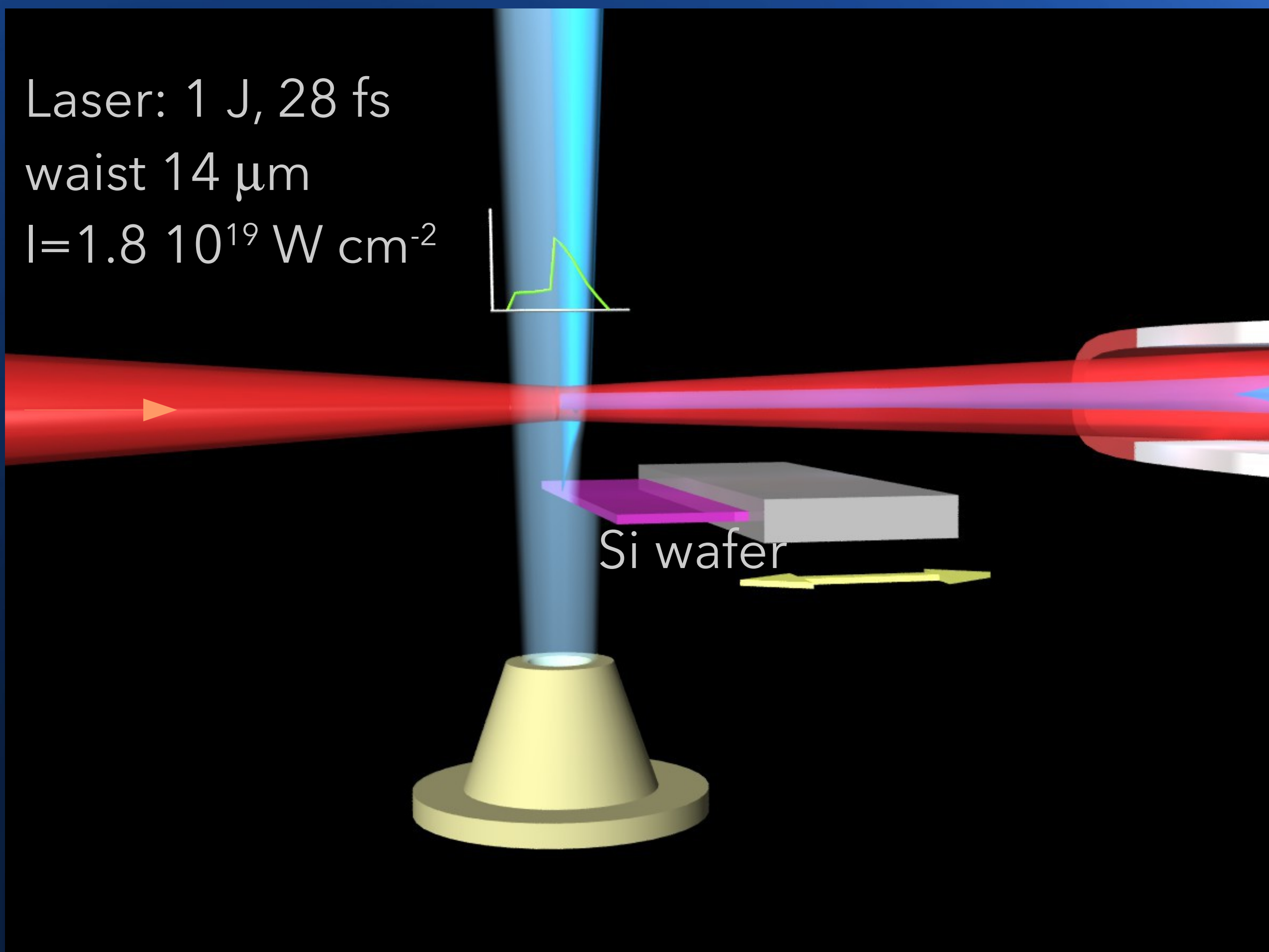
Electrons retrieve an accelerating field by raising the density

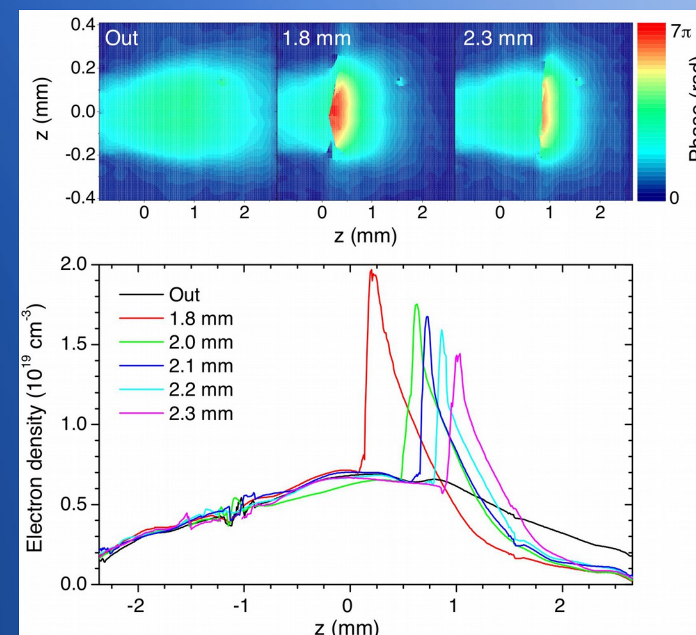


The electron bunch is rephased

Rephasing the electron bunch

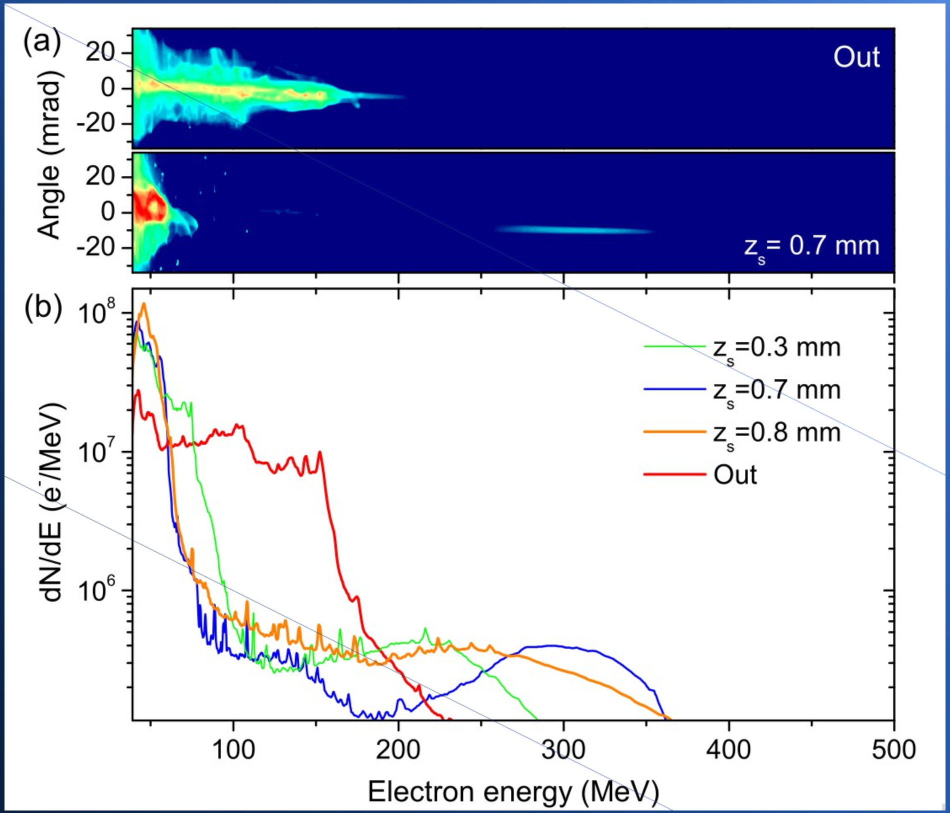
Machining a gas jet to get a two-densities plasma





E. Guillaume *et al,* PRL **115** 155002 (2015)

Rephasing the electron bunch



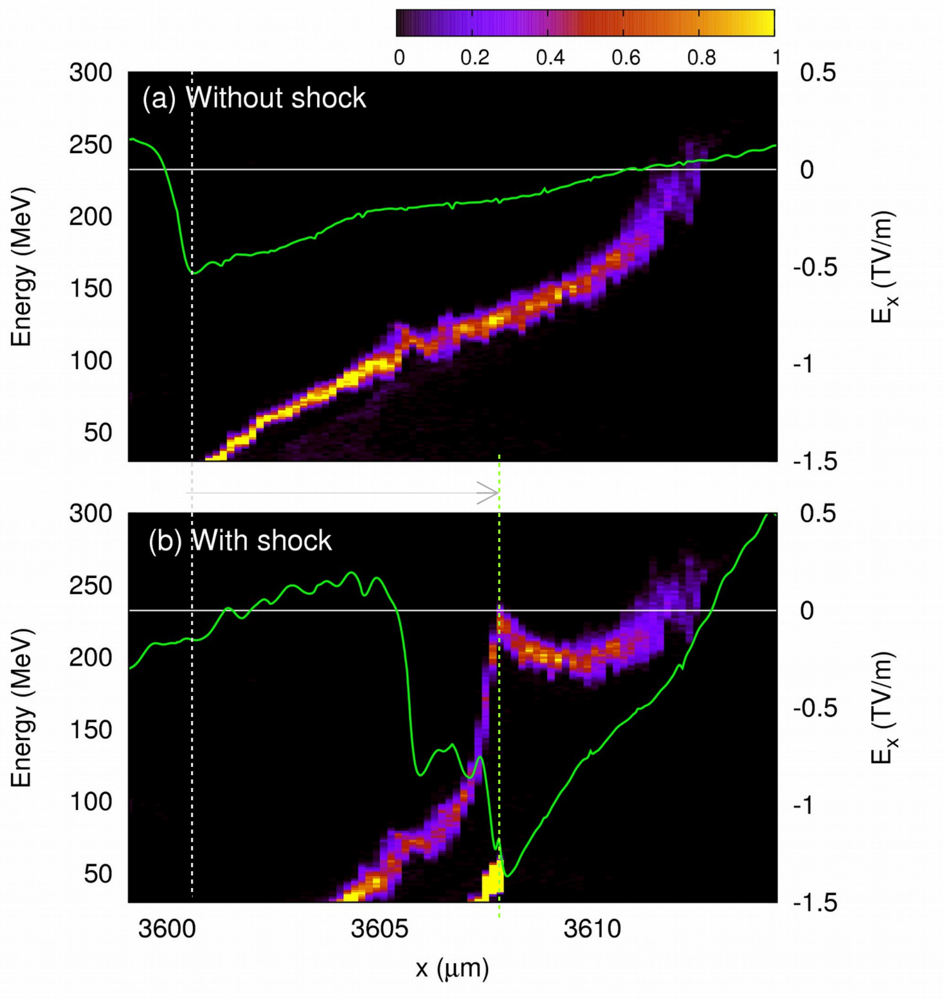
Up to 150 MeV of energy gain!

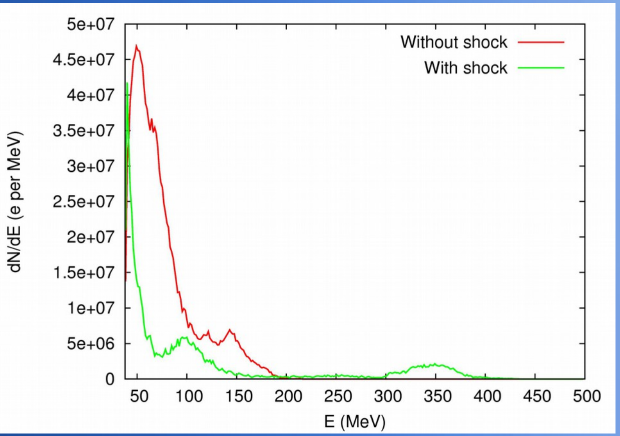
- A high energy peak appears in the spectrum
- A gap between 100 MeV and 200 MeV appears

E. Guillaume *et al*, PRL **115** 155002 (2015)

Rephasing the electron bunch

3D Particle-in-Cell simulations using CalderCirc

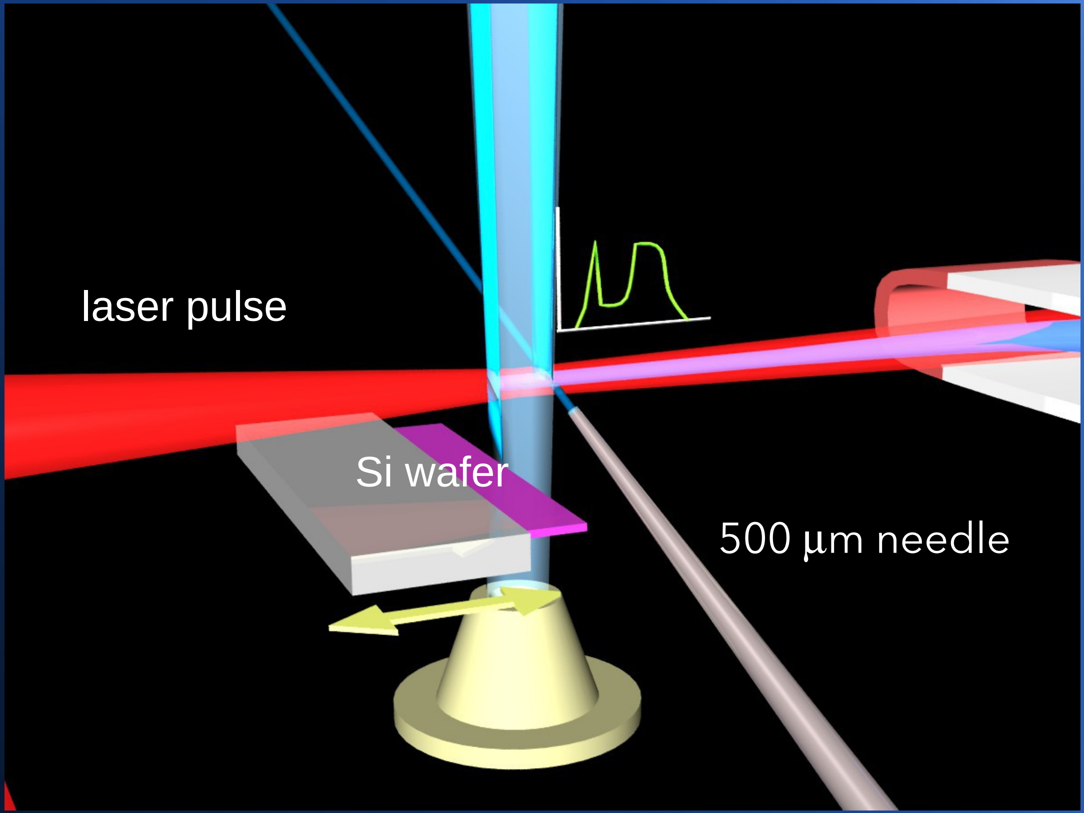




E. Guillaume *et al*, PRL **115** 155002 (2015)

Rephasing the electron bunch

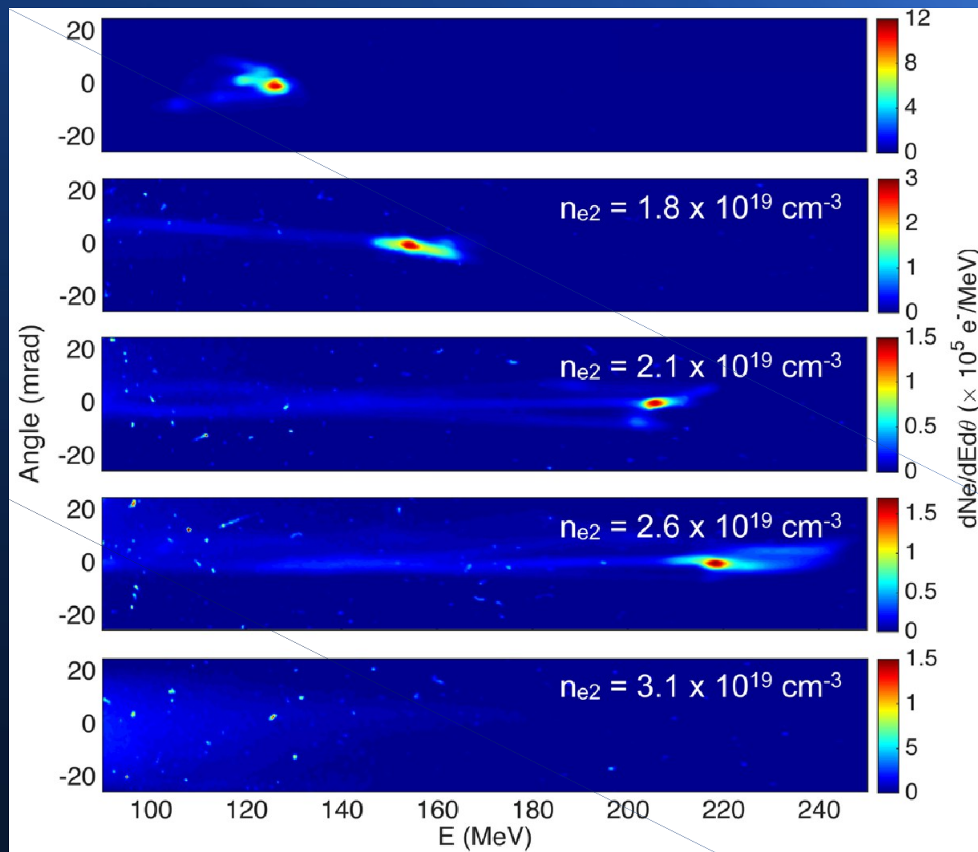
Using shock injection (quasi-monochromatic beam)



E. Guillaume *et al*, PRL **115** 155002 (2015)

Rephasing the electron bunch

Using shock injection (quasi-monochromatic beam)



Without needle

Bunch rephased

Jump too high → bunch out of the bubble

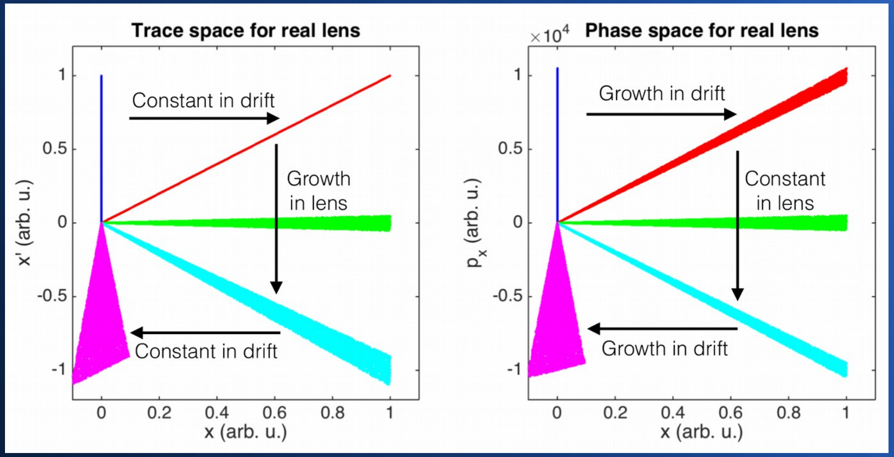
E. Guillaume *et al,* PRL **115** 155002 (2015)

Rephasing the electron bunch: Remarks

- A very simple machining of the gas jet produces a drastic effect over the spectrum
- It is possible to accelerate a fraction of the bunch already in the decelerating region : **rephasing**
- An energy gain up to 150 MeV achieved

Plasma lens

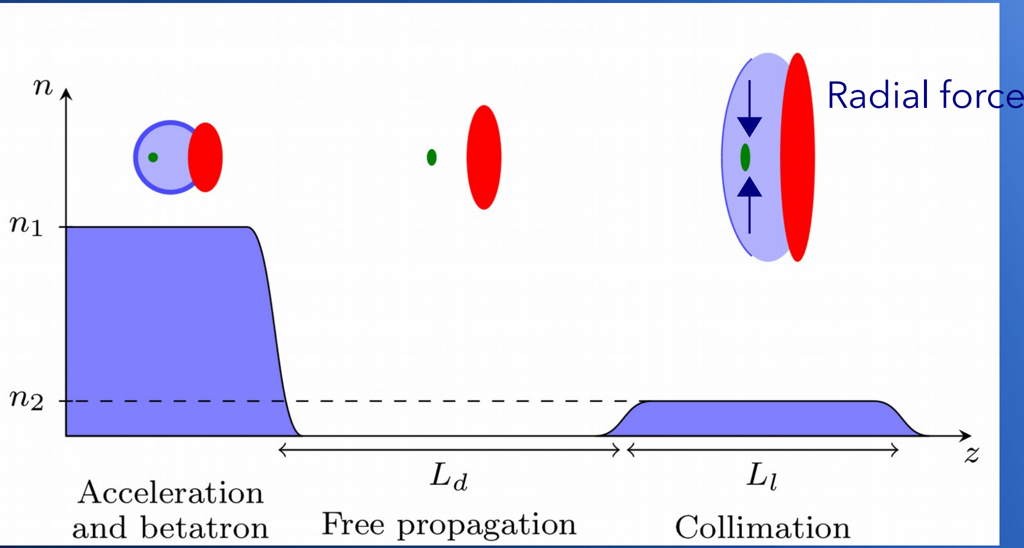
- LPA electron beams: very small (r~1 μm), divergent (>1 mrad) and not very monochromatic (ΔE>1%)
- Focusing these beams requires very strong fields
- To limit chromatic emittance grows, first magnet must be as close as possible to the accelerator (minimum for state-of-the-art quads ~2 cm)

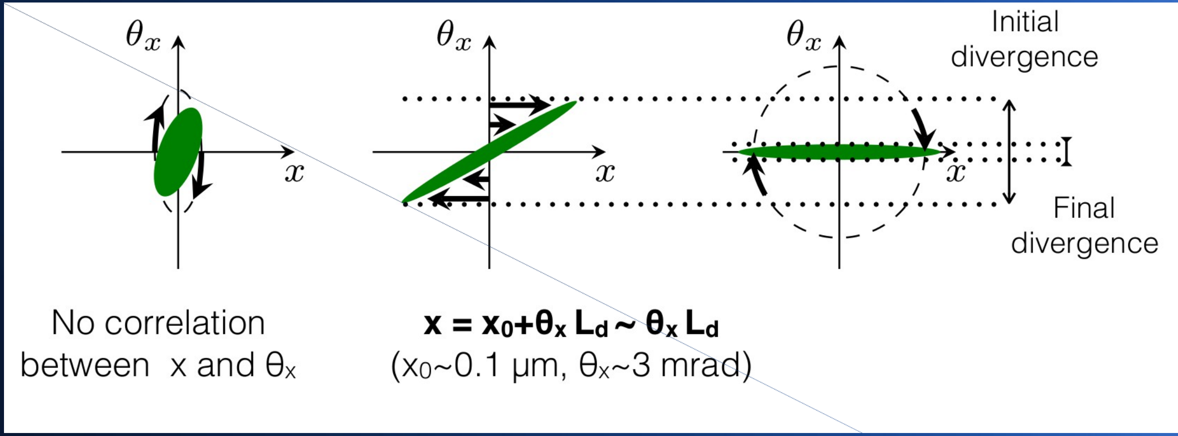


We propose a way to reduce the divergence of the beams ~1 mm away from the accelerator: **the plasma lens**

Plasma lens

Goal: to use the transverse force in the wakefield to focus the electrons

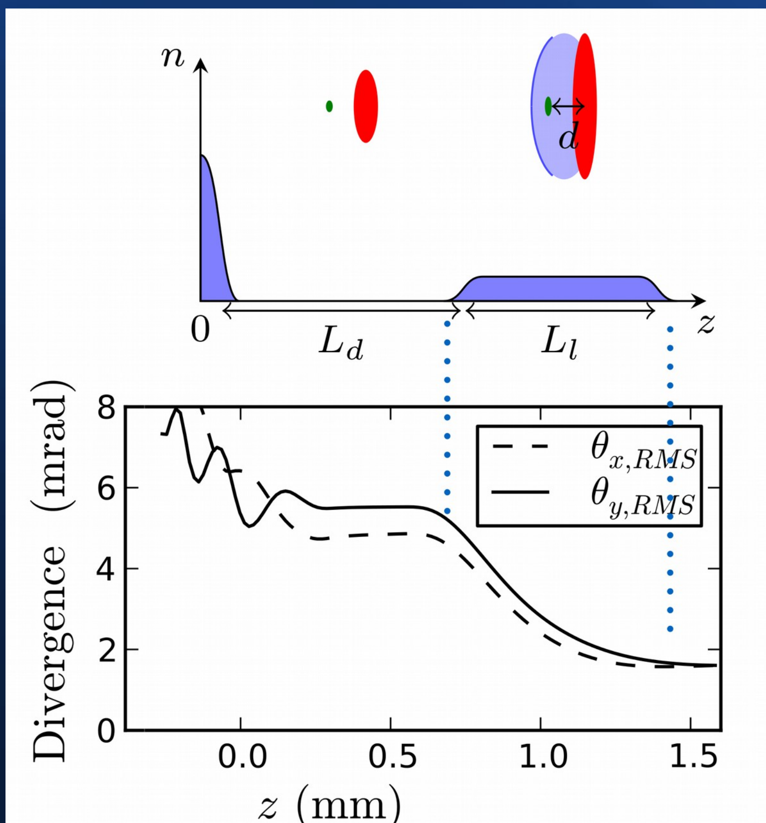




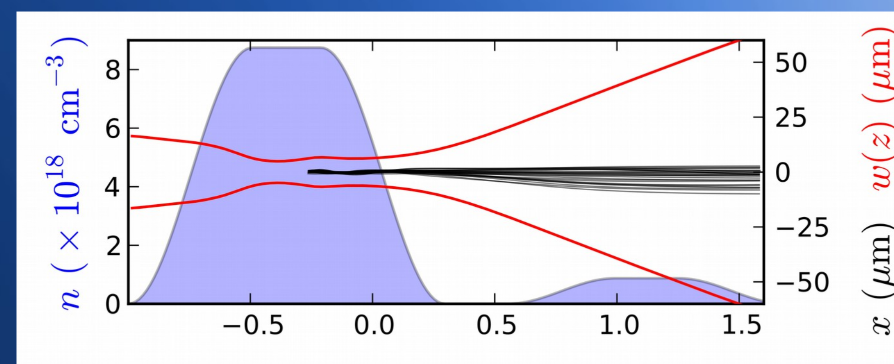
R. Lehe *et al*, PRSTAB **17** 121301 (2014)

Plasma lens

- 3D PIC simulations



Small laser amplitude → quasi-linear regime

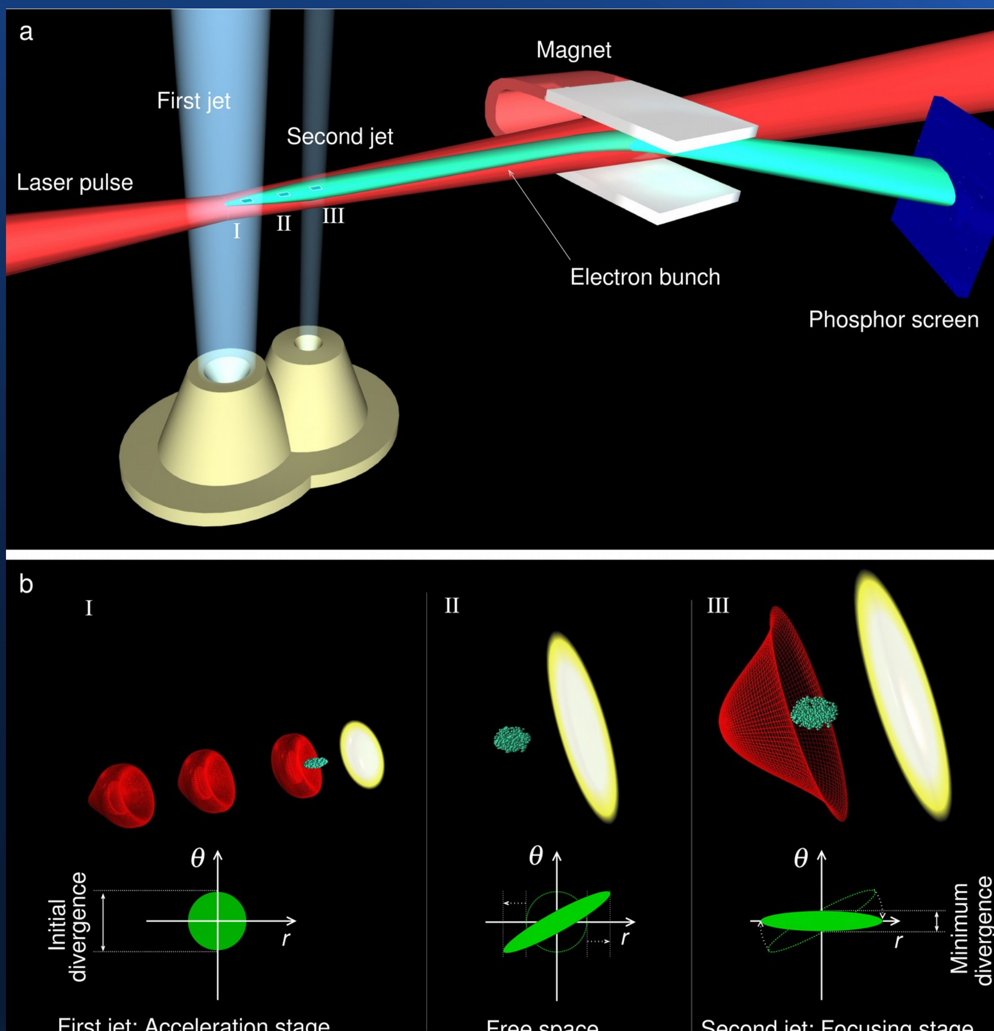


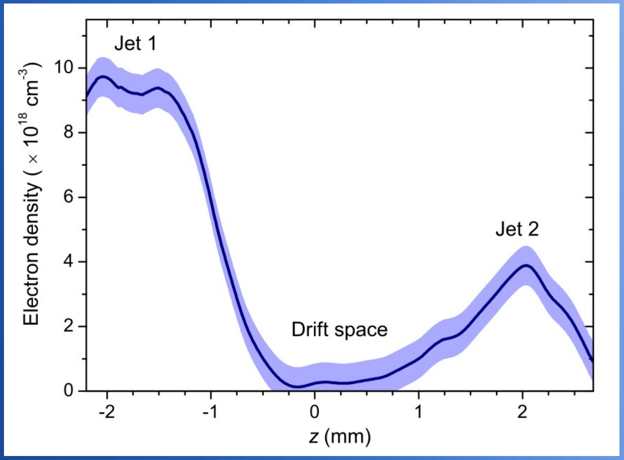
Divergence is divided by 3

R. Lehe *et al*, PRSTAB **17** 121301 (2014)

Plasma lens

- Laser pulse 1 J, 28 fs, waist 12 μm, I=1.8 10^{19} W cm^{-2}





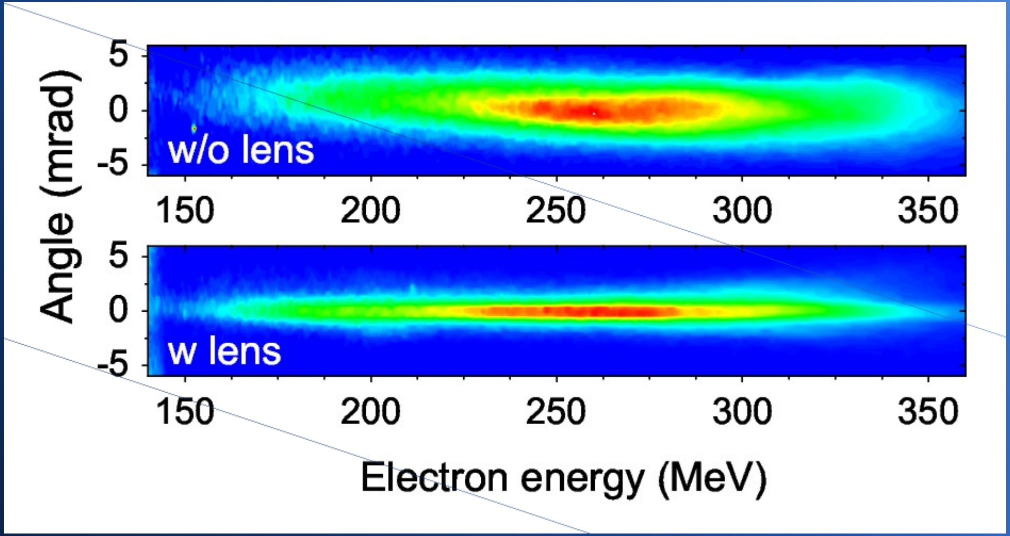
C. Thaury *et al,* Nat. Comm. **6** 6860 (2015)

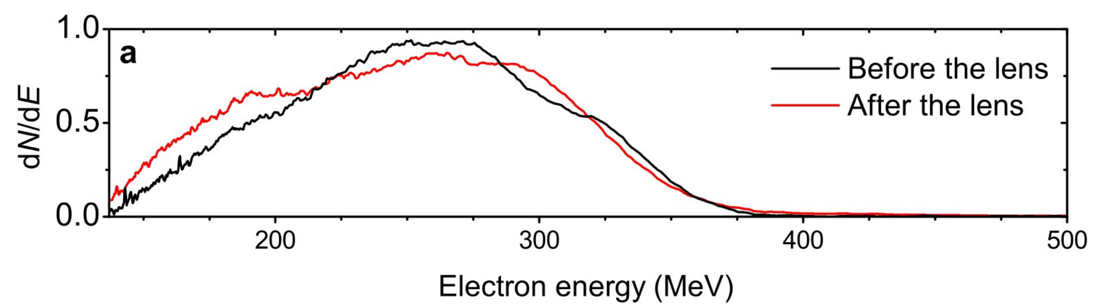
Plasma lens

Lens parameters: L_d=1.8 mm n_2=3.9 10^{18} cm^{-3}

σ_x=4.1 ± 0.6 mrad
(avg. over 10 shots)

σ_x=1.6 ± 0.2 mrad
(avg. over 10 shots)



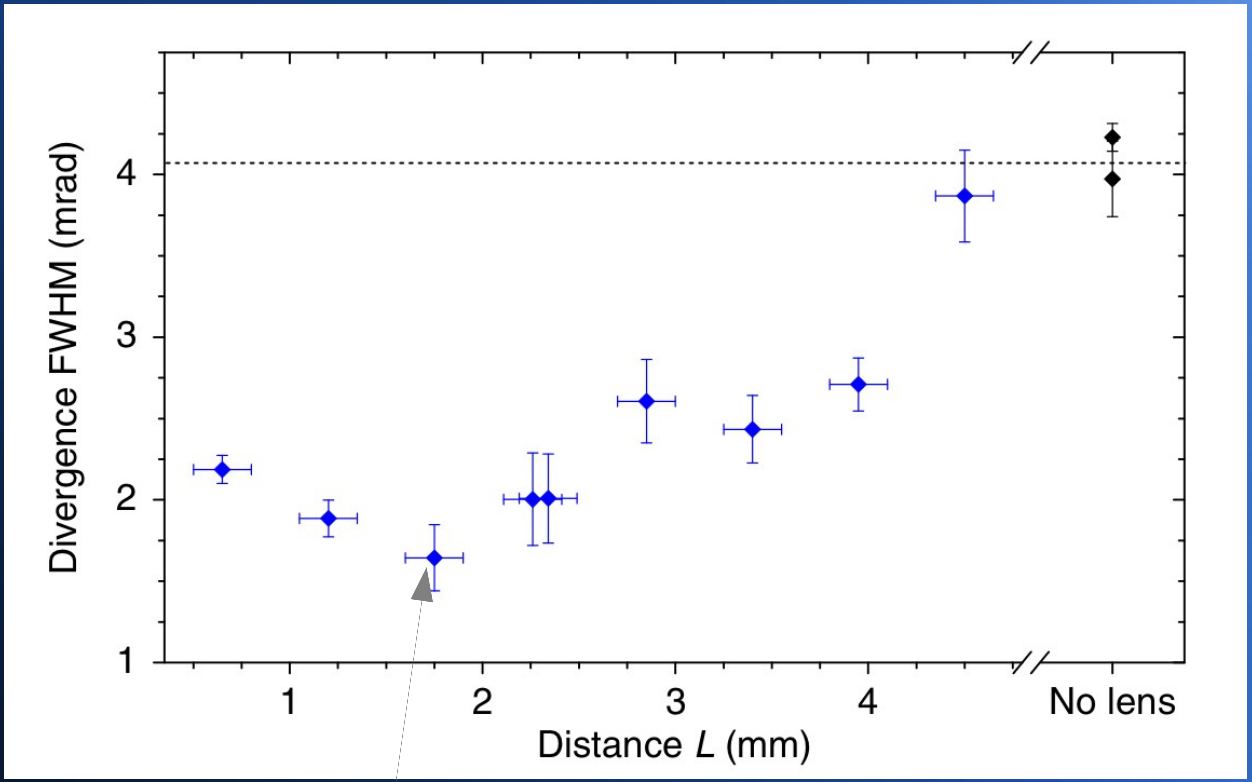


Divergence reduced by a factor 2.6

C. Thaury *et al*, Nat. Comm. **6** 6860 (2015)

Plasma lens

Final divergence vs drift distance for n_2=3.9 10^{18} cm^{-3}



Optimum **Plasma Lens**

C. Thaury *et al*, Nat. Comm. **6** 6860 (2015)

Laser wavefront & electron acceleration

Experiments shows than a nice laser spot → nice electron beam

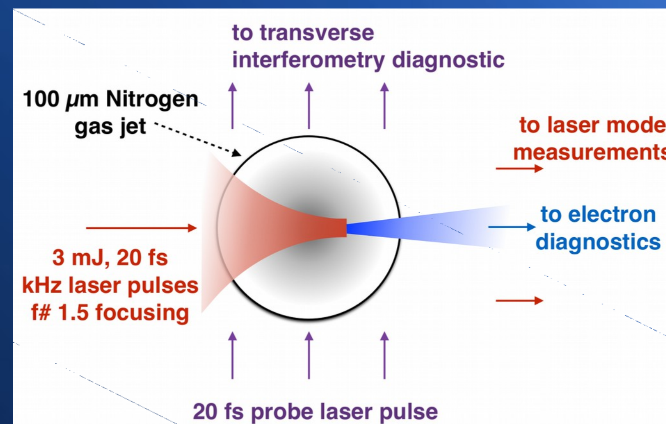
But sometimes the laser spot is nice but they are not even electrons

What are the hidden parameters?

The role of the **wavefront** was unlighted in an recent work

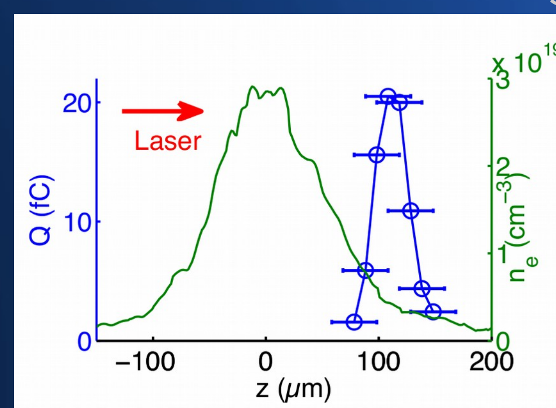
Laser wavefront & electron acceleration

High repetition rate laser focused in a tiny gas jet



waist 2 μm FWHM → $L_{Rayleigh}$ ~ 15 μm

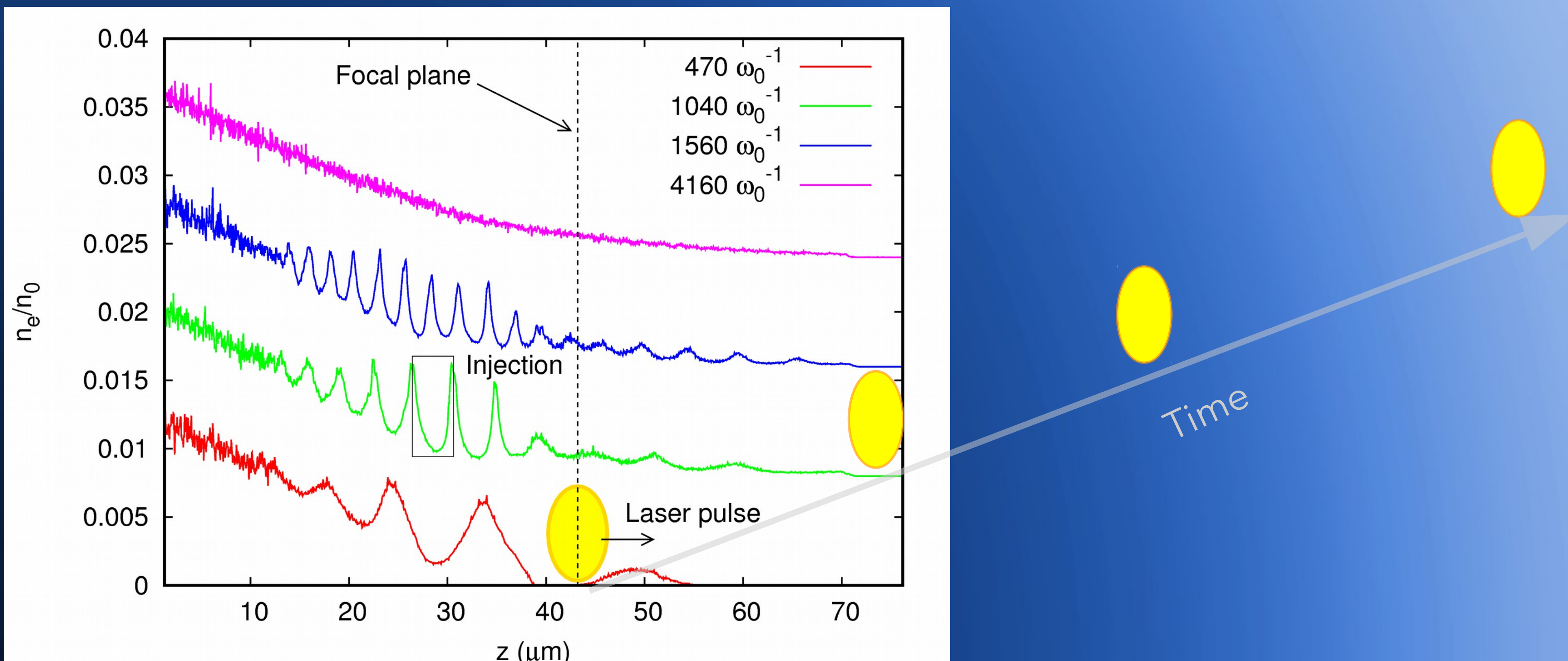
Electron beam with few hundreds keV when focusing the laser at the gas jet end



B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

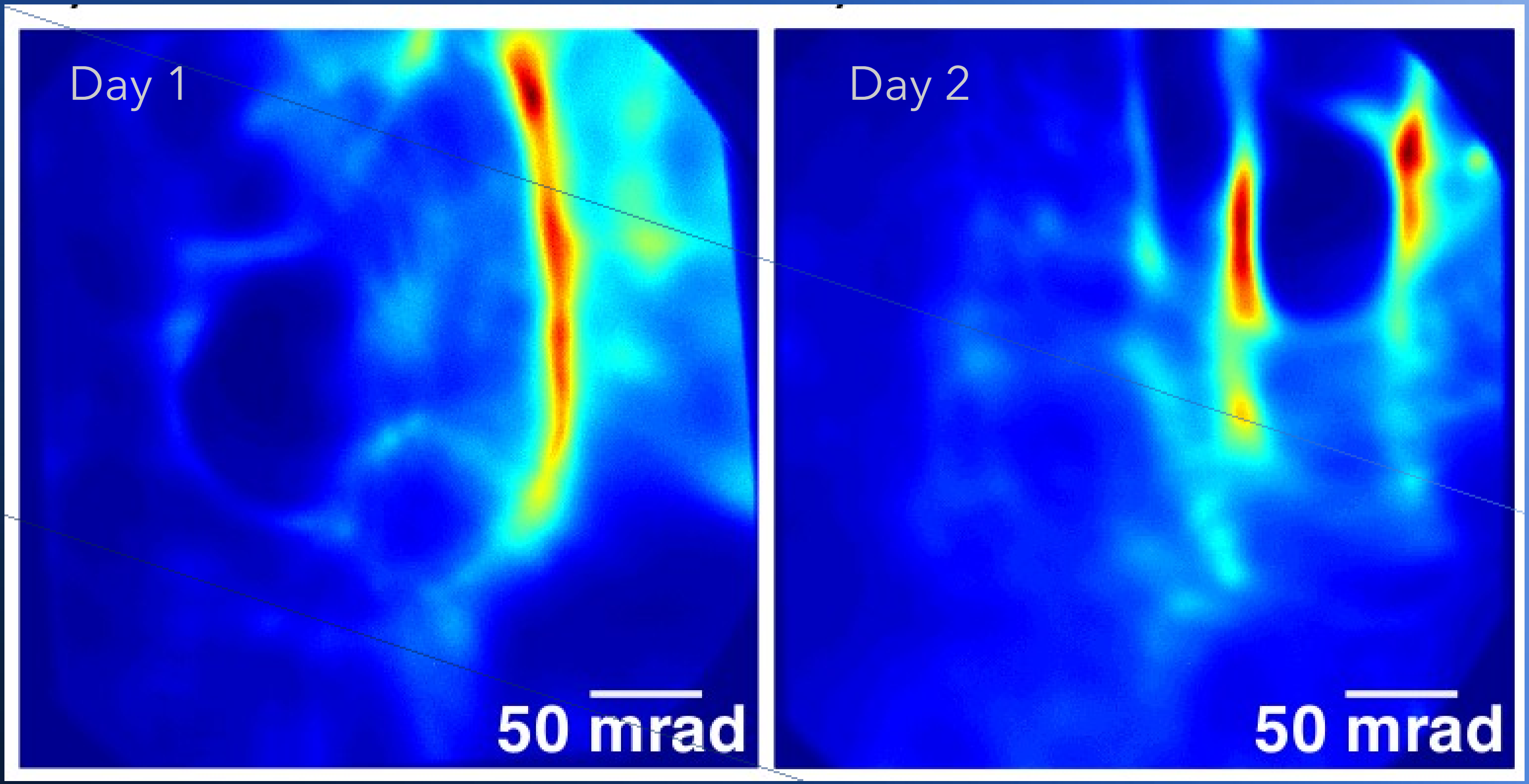
- Gradient injection: the farther from the laser, the slower wakefield



PIC simulation results

B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

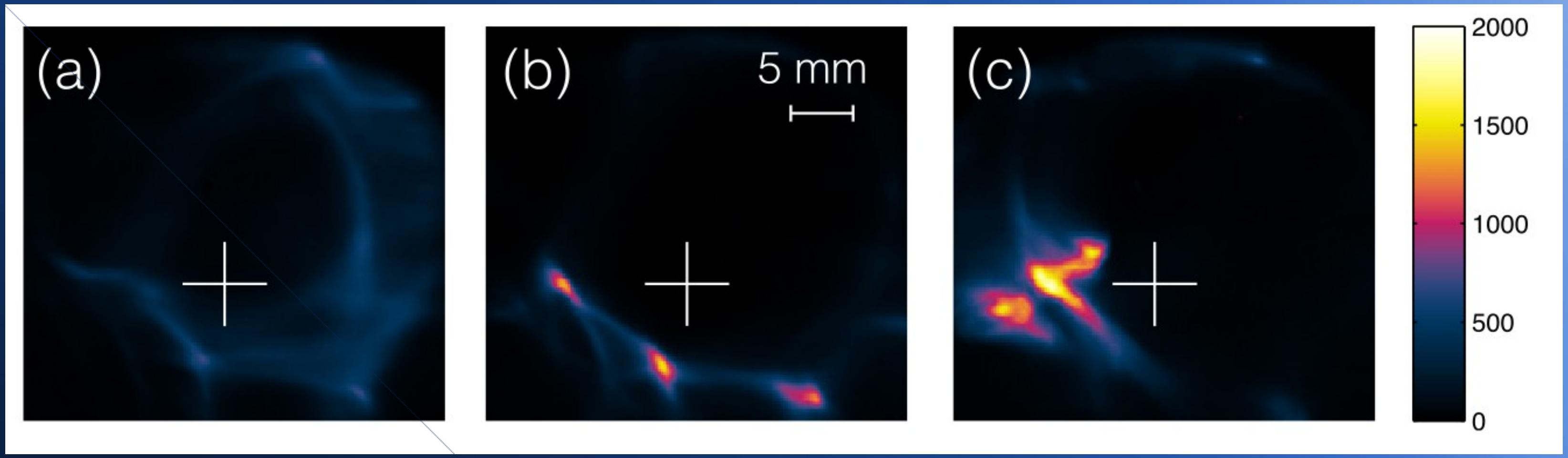


- Complex patterns stable over hours (millions of shots)

B. Beaurepaire *et al,* PRX **5** 031012 (2015)

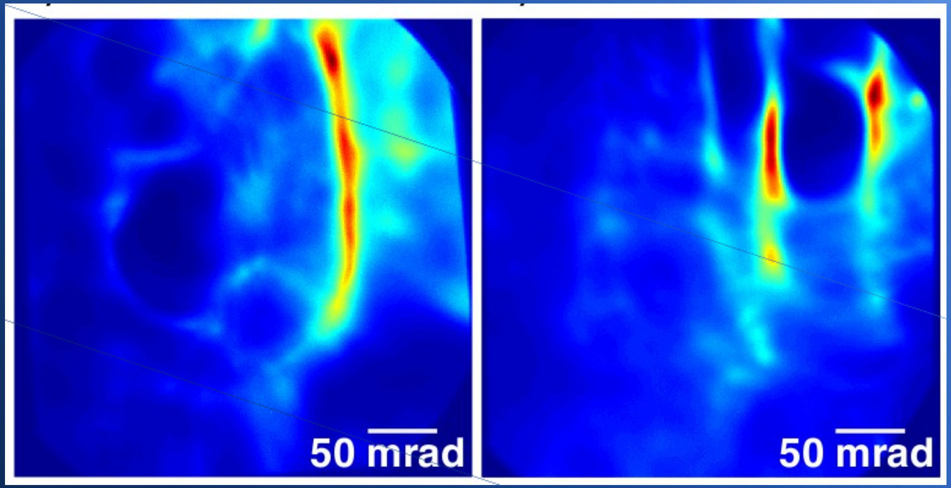
Laser wavefront & electron acceleration

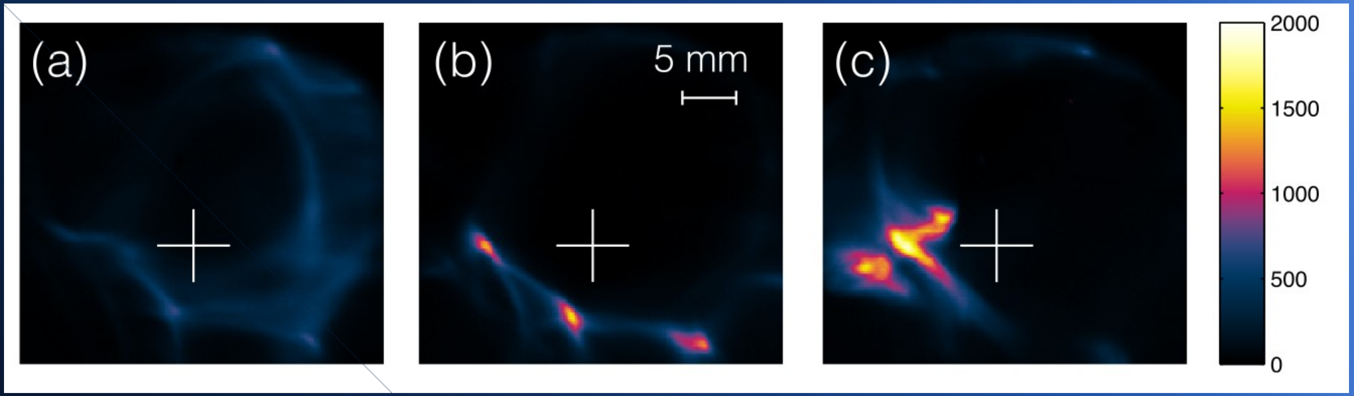
- Similar complex patterns had been found at CUOS (Ann Arbor, USA)



Taken from Z.-H. He *et al,* NJP **15** 053016 (2013)

Laser wavefront & electron acceleration





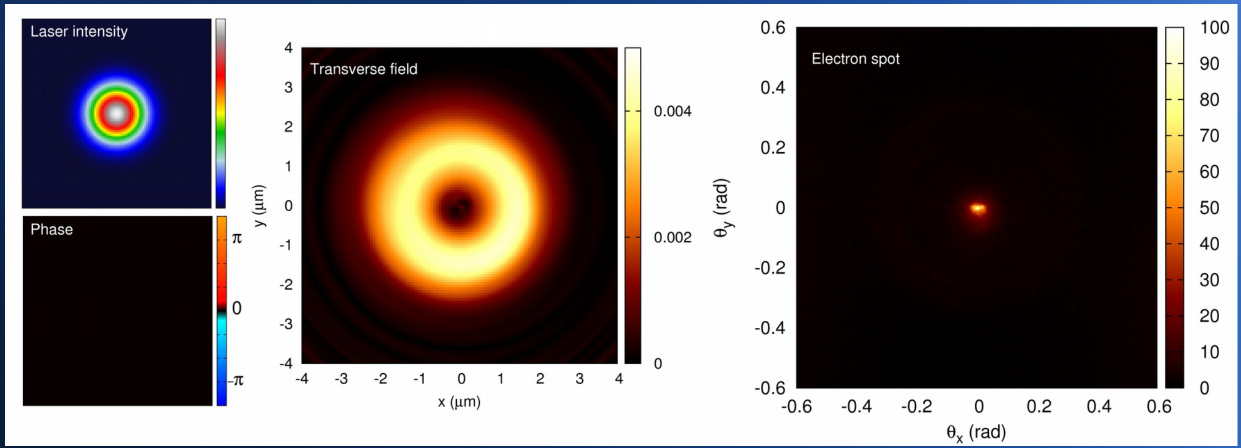
Taken from Z.-H. He *et al*, NJP **15** 053016 (2013)

Where these structures come from?

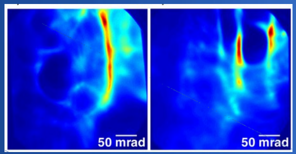
Laser wavefront & electron acceleration

- We performed 3D Particle-in-Cell simulations using CalderCirc

For a Gaussian radial profile laser pulse



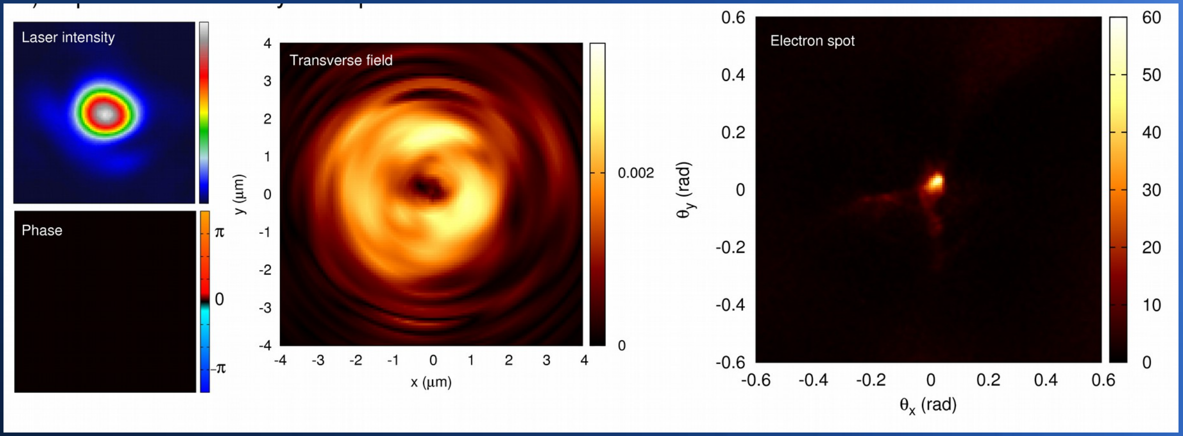
Nice and collimated electron beam



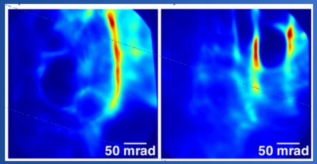
B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

Using the laser spot from the experiment

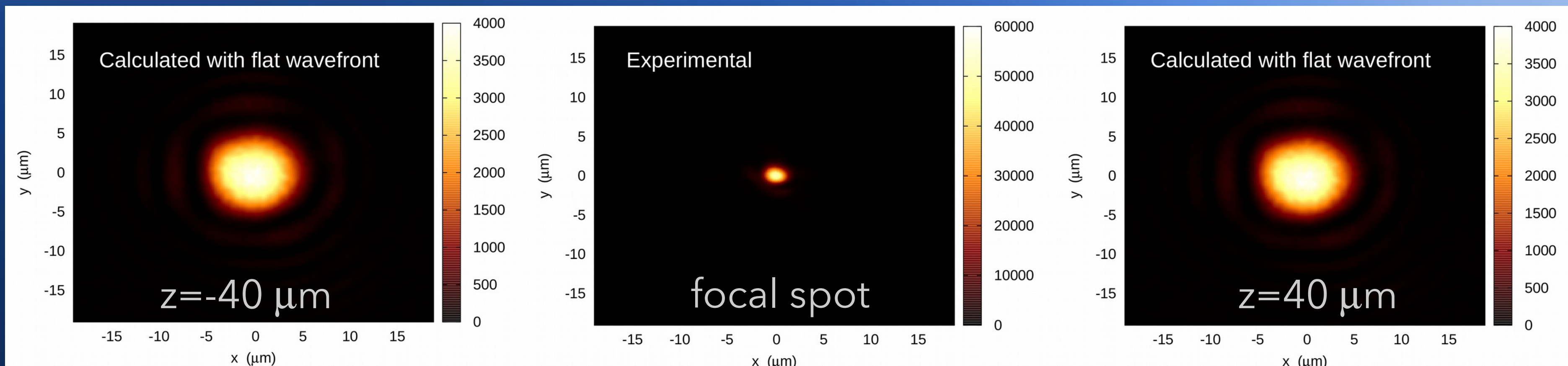


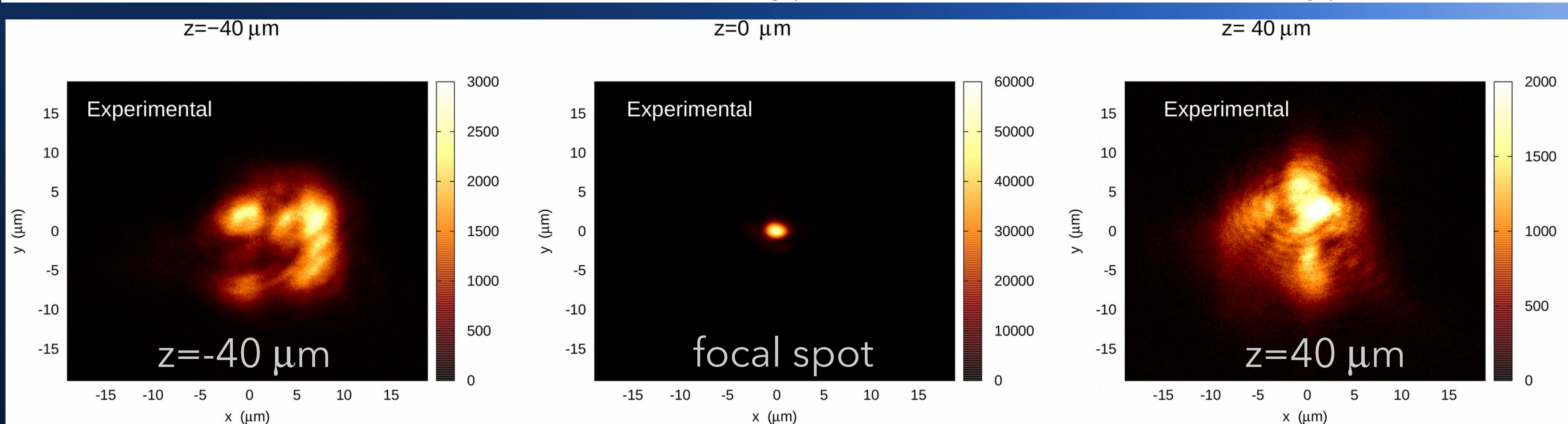
Still a nice and collimated electron beam



B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

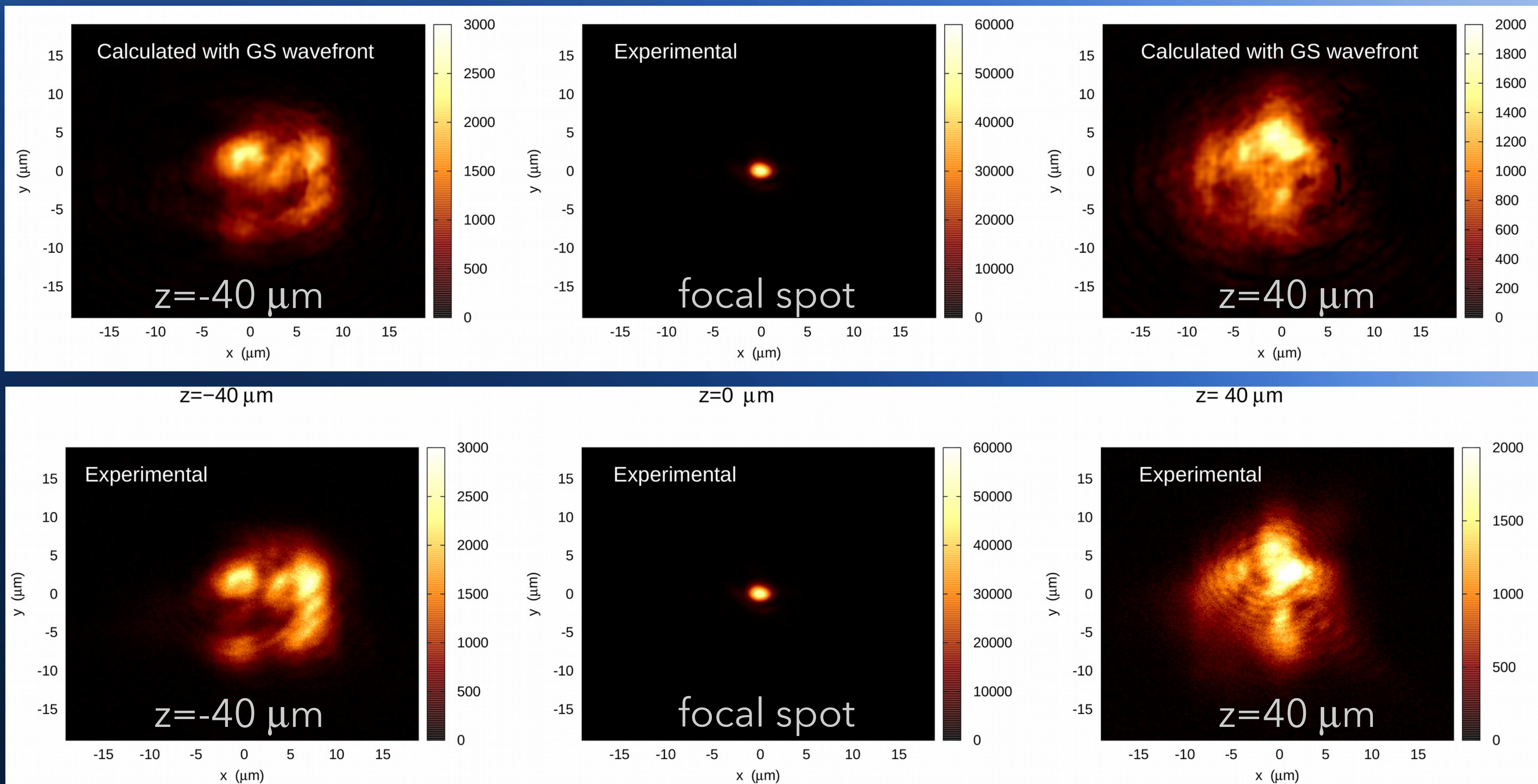




Gerberch-Saxton algorithm to retrieve the wavefront from the intensity at three planes

B. Beaurepaire *et al*, PRX **5** 031012 (2015)

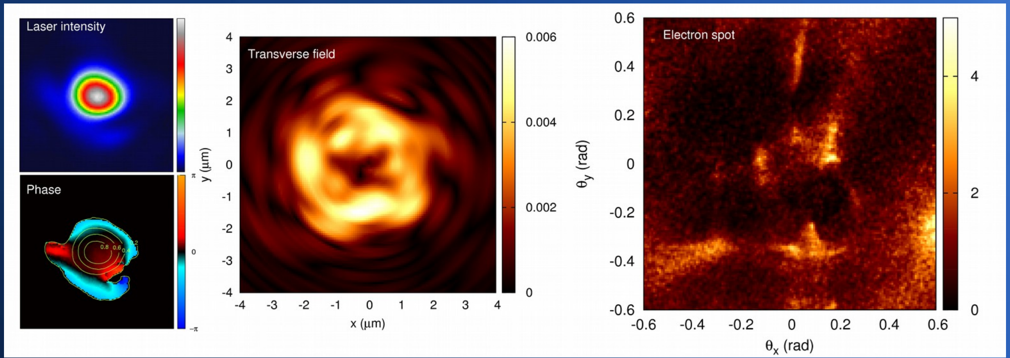
Laser wavefront & electron acceleration



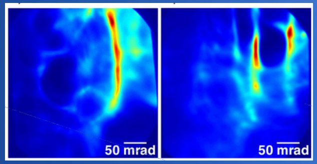
B. Beaurepaire *et al,* PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

Using the laser spot and the wavefront from the experiment



Complex and divergent electron beam →

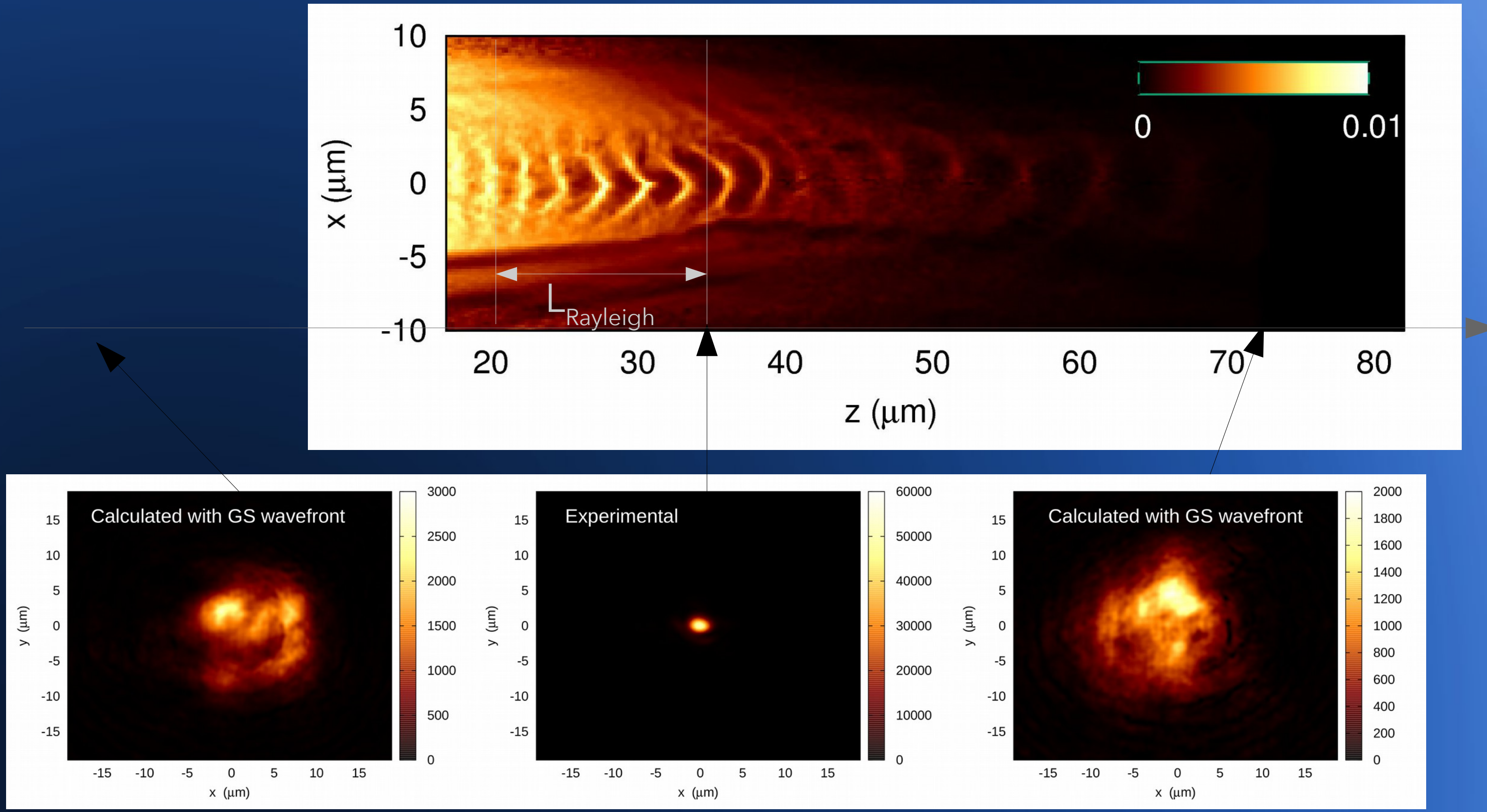


B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration

$L_{Rayleigh} \sim \lambda_p$ → out of focus features are critical

focal plan



B. Beaurepaire *et al*, PRX **5** 031012 (2015)

Laser wavefront & electron acceleration: Remarks

- Simulations performed with 100 TW laser shows also a strong effect of laser wavefront

- Laser wavefront aberrations affect the laser propagation, the injection and acceleration

- Optimization of the focal spot can results in a "degradation" of the wavefront (the laser intensity close to the focus)
→ degradation of the electron beam

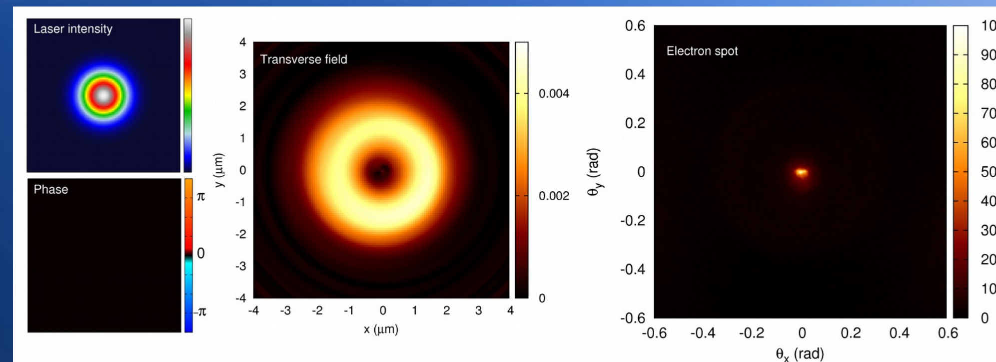
The laser wavefront matters!

Thank you!

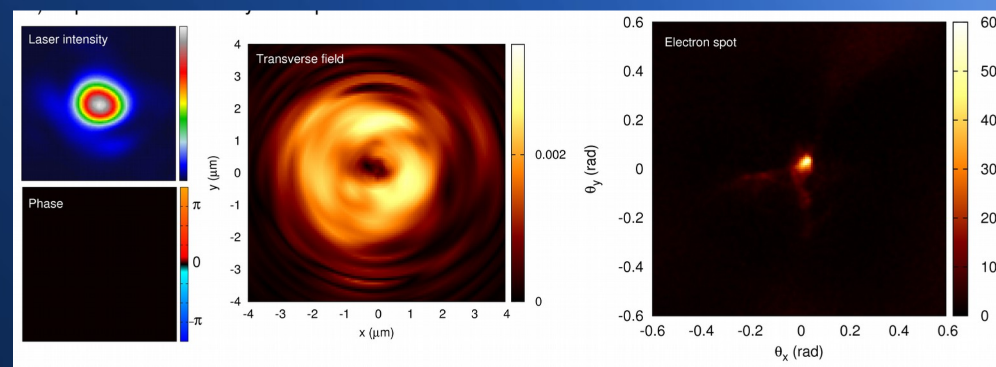
Work partially funded by ERC Grant X-FIVE and ERC Grant FEMTOELEC

Laser wavefront & electron acceleration

- Gaussian intensity profile & flat wavefront

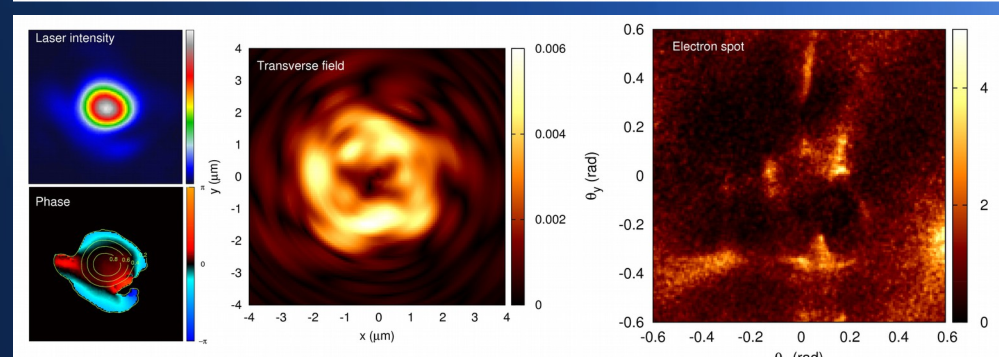


- **Experimental** intensity profile & flat wavefront

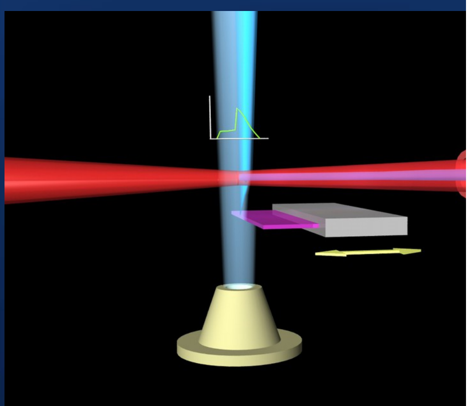


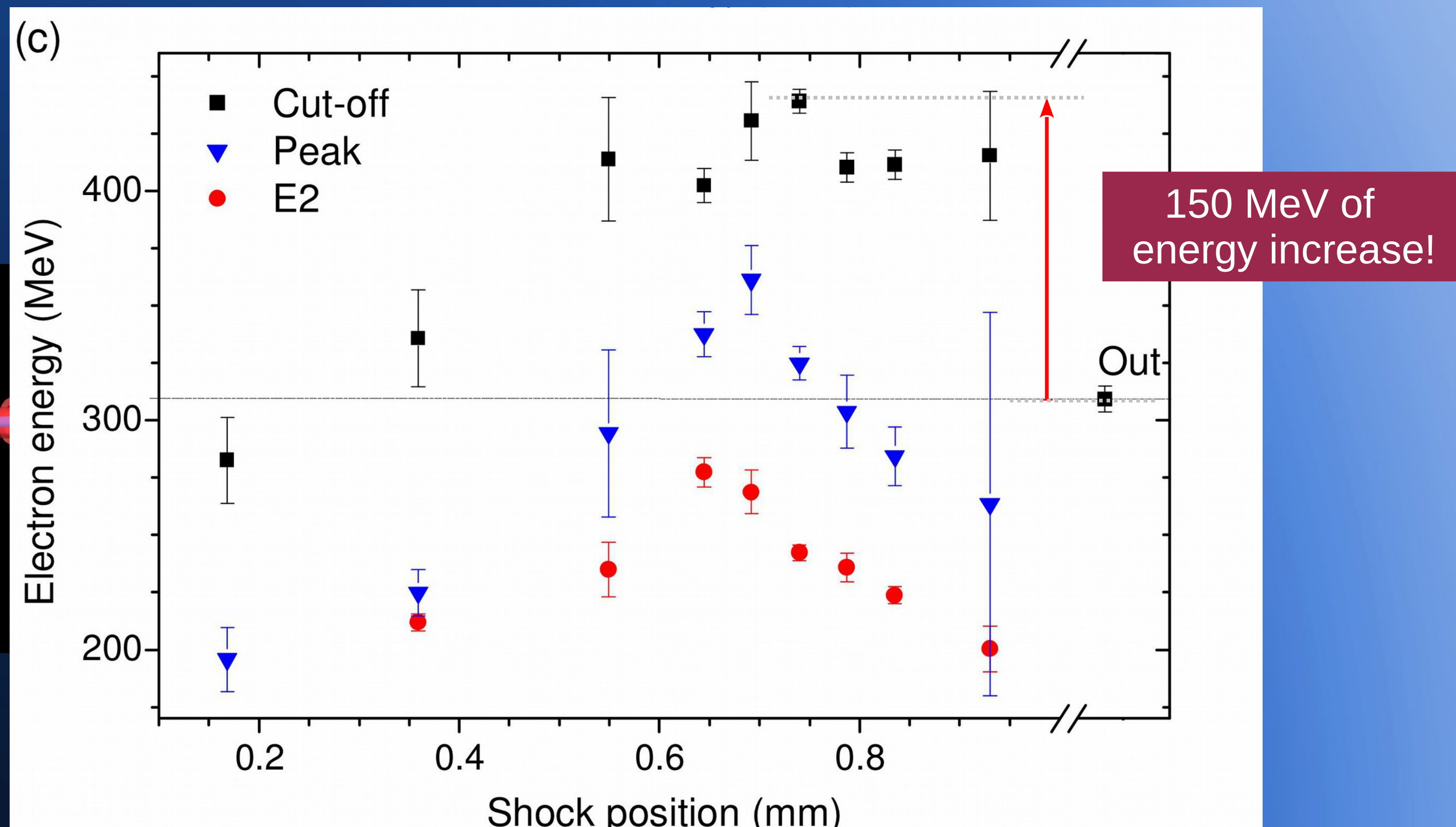
- **Experimental** intensity profile & **experimental** wavefront

Note that $L_{Rayleigh} \sim \lambda_p$



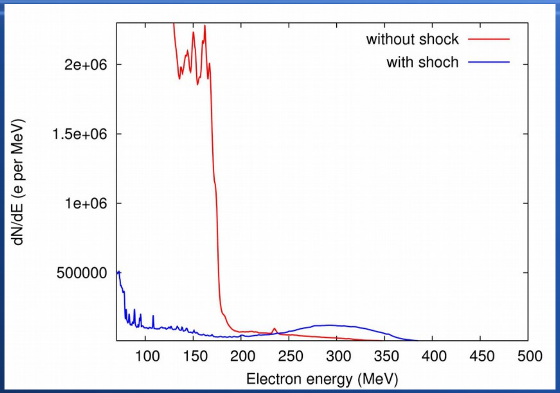
Changing the position of the shock



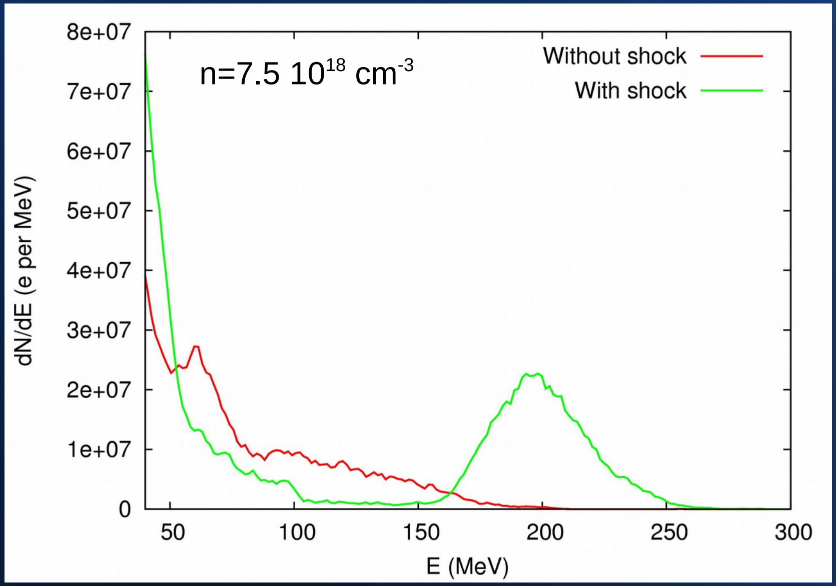


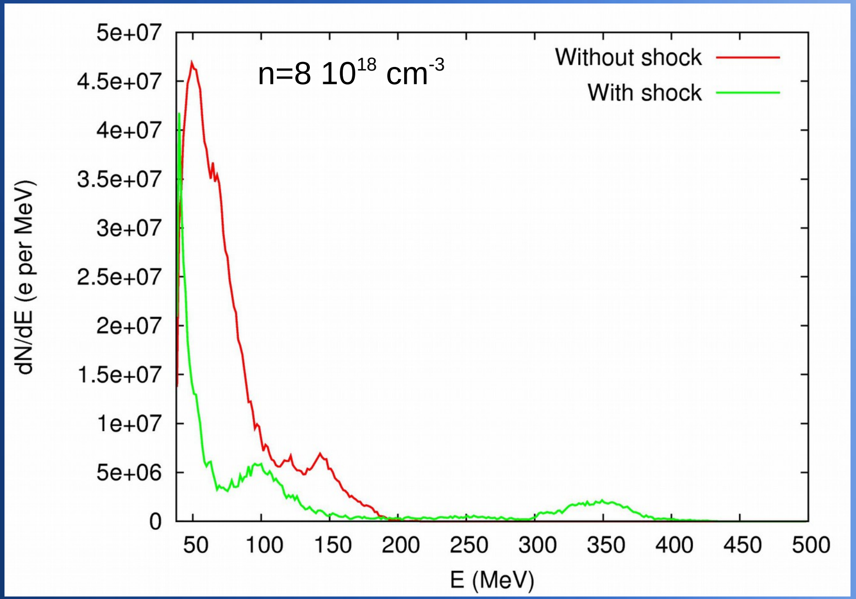
- It is possible to change the peak energy by changing the position of the shock
- 150 MeV of energy increase in optimum case

Spectra comparison



experimental





E. Guillaume *et al*, PRL **115** 155002 (2015)