Introduction to plasma wakefield acceleration

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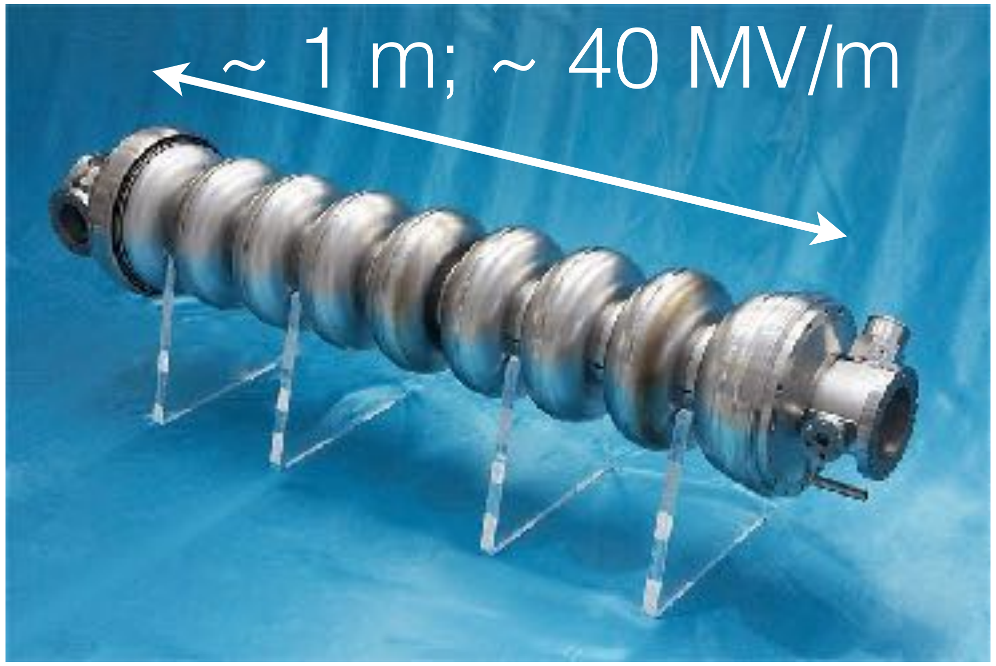
plasma as an accelerator

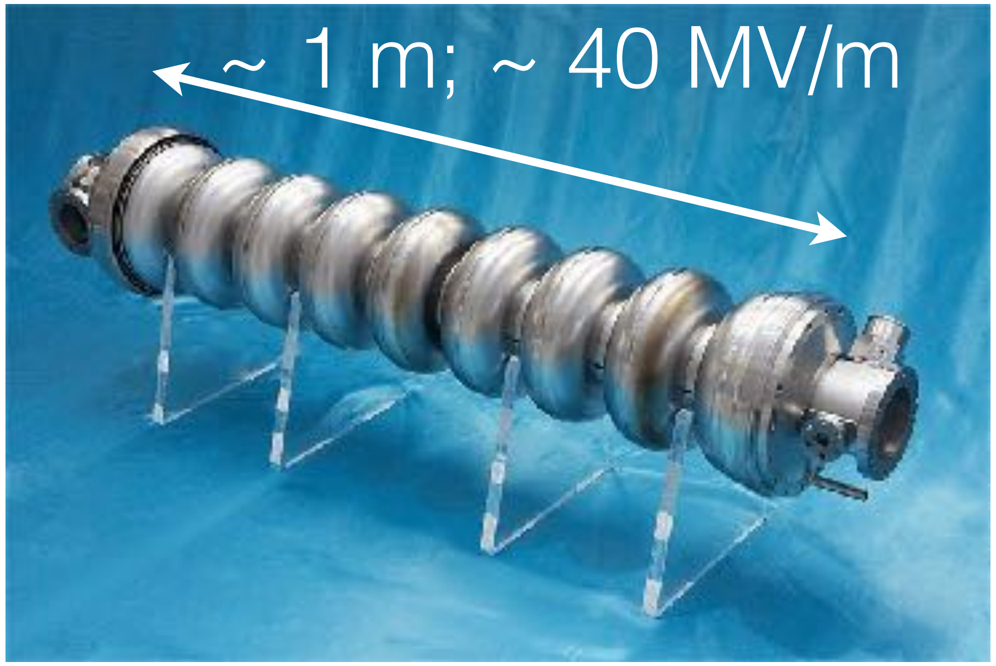


a section of RF cavity

a plasma wave

- Conventional Accelerators are large (100 metres) and expensive 10-100M$
- Conventional accelerators cannot achieve better than a few 10 MV/m or you get breakdown
- Plasma waves are a possible alternative - providing a route to university scale accelerators and radiation sources

plasma as an accelerator



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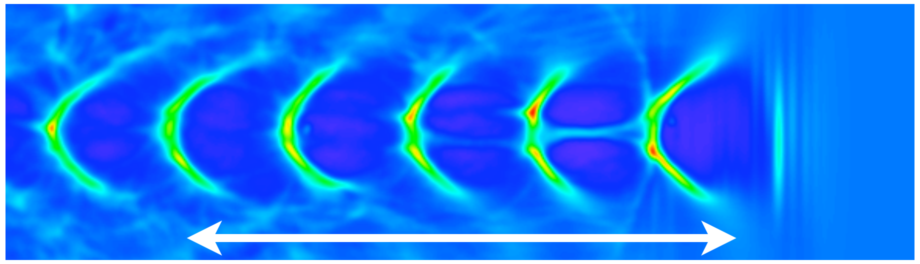

~ 50 μm; ~ 100 GV/m

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- Plasma based accelerators are a possible compact alternative
- in particular we are now quite good at accelerating electrons to ~ 1 GeV with ~ 100 TW lasers

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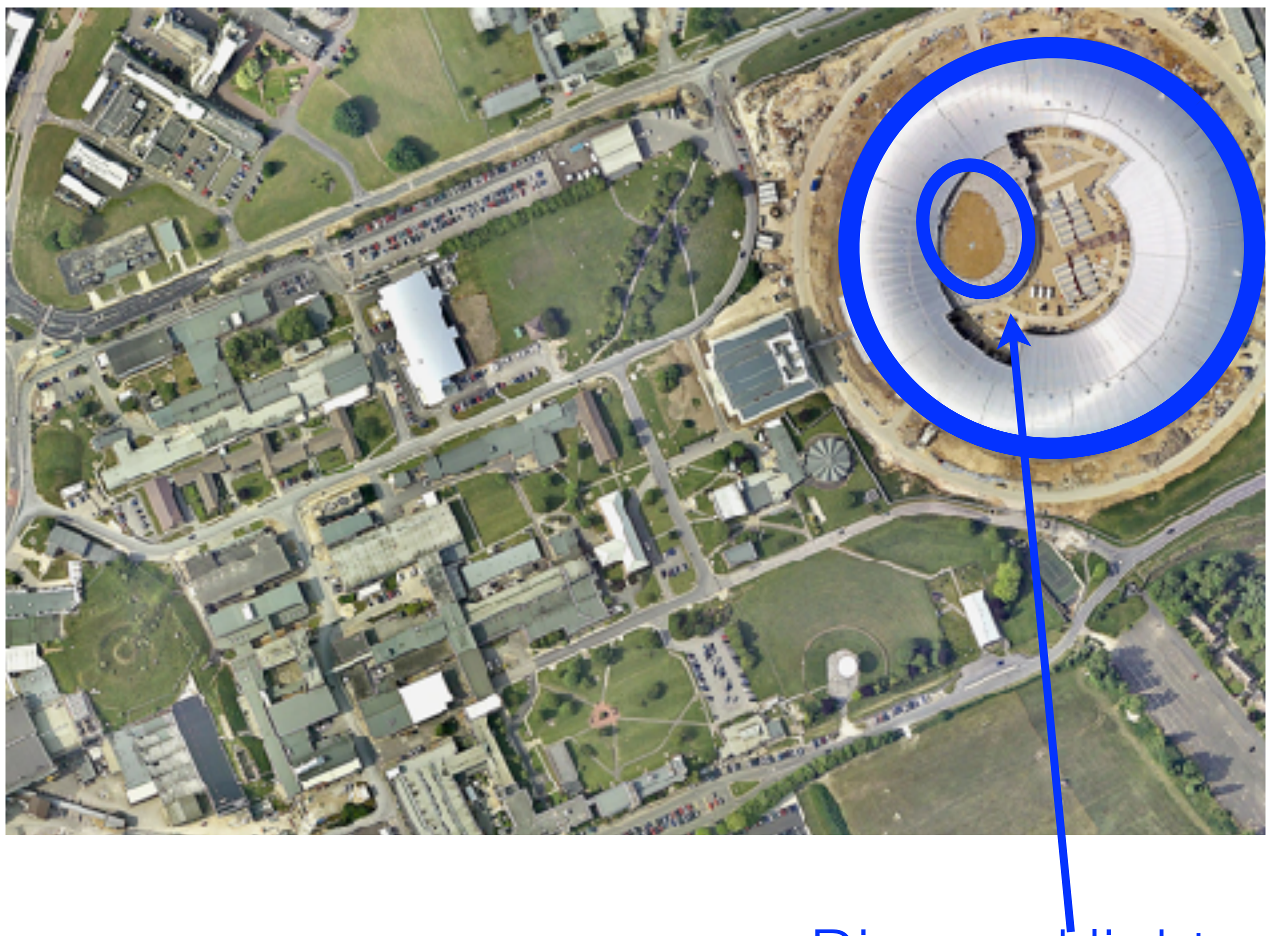

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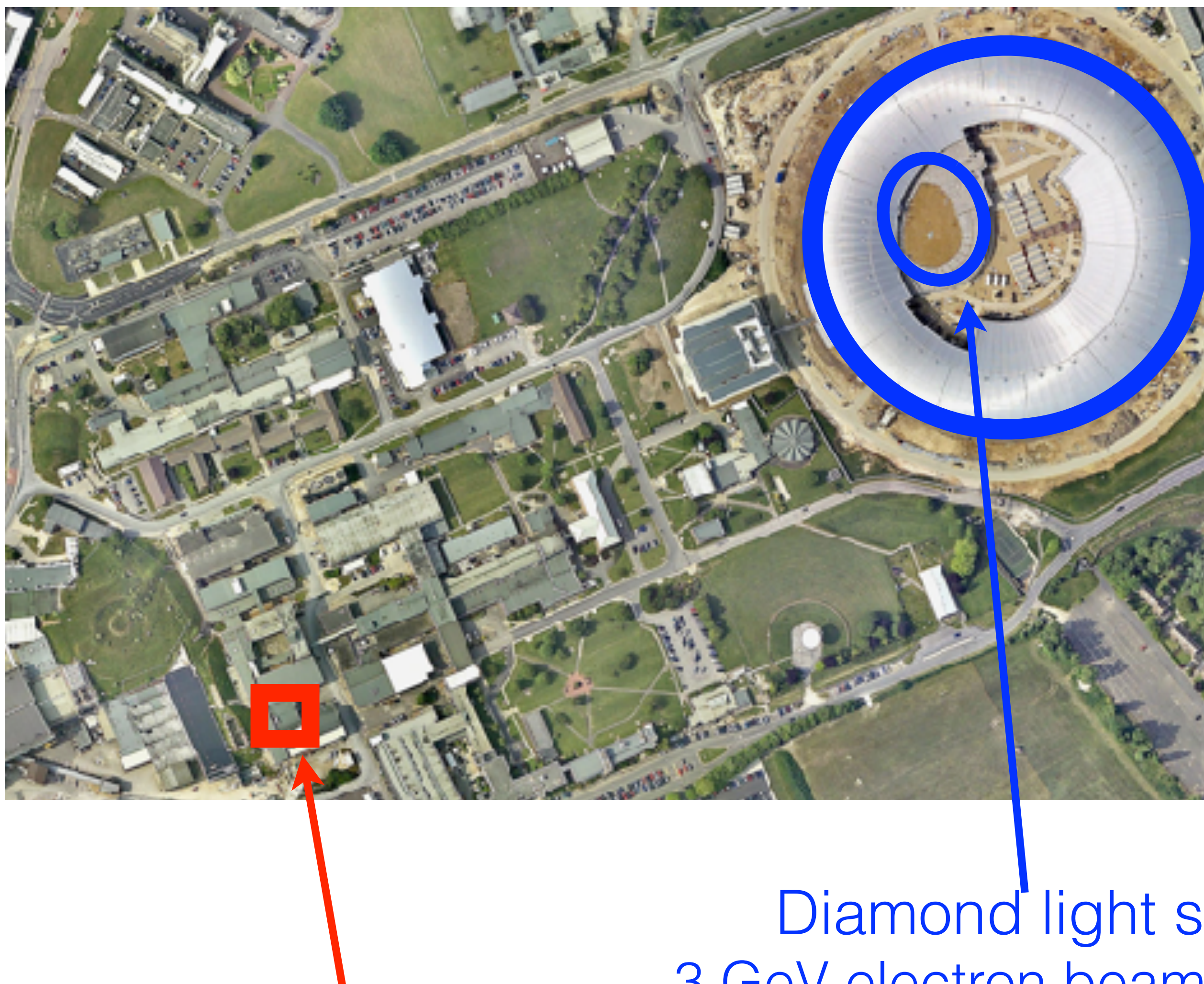

Diamond light source
3 GeV electron beam ~ £300 M

Astra Gemini Laser
1 GeV electron beam ~ £3 M

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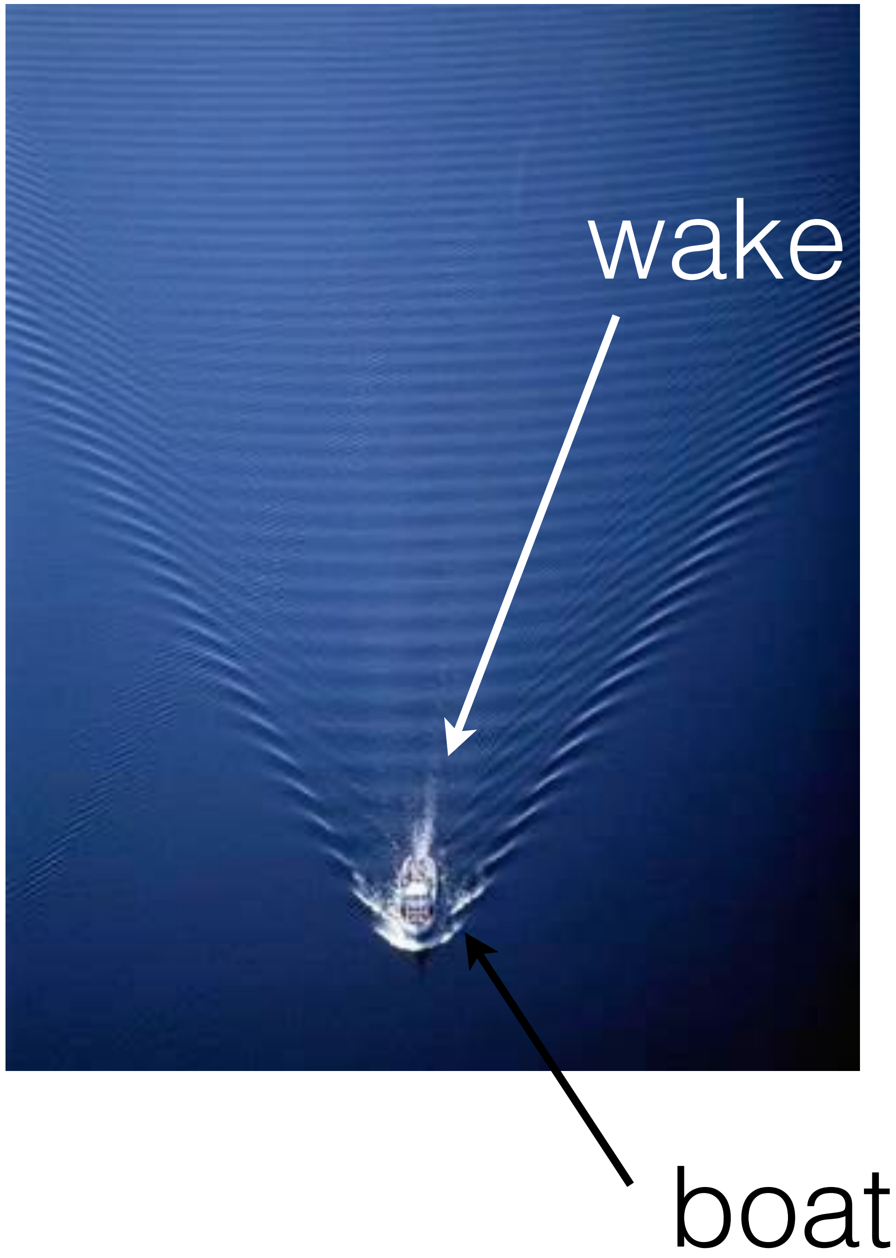
Wakefield acceleration



- when a boat travels through water it produces a wave behind it - a 'wake'
- the phase velocity of the wave is just the speed of the boat
- so we can use a laser pulse travelling at close to c in a plasma to drive a strong wave behind it.
- The wave in this case is an electron plasma oscillation

$$\omega_p = \left(\frac{n_0 e^2}{m_e \epsilon_0}\right)^{\frac{1}{2}}$$

- Because these are high frequency oscillations the ions do not move and we can have very strong electric fields

Driving Force

- For laser wakefield accelerators wake driven by ponderomotive force

$$\frac{d\mathbf{p}}{dt} = -\frac{e^2}{2m_e\omega_0^2}\nabla\langle E^2\rangle = -\frac{e^2}{2m_e}\nabla\langle A^2\rangle = -\frac{1}{2}m_e c^2\nabla\langle a^2\rangle$$

- For particle beam drivers wake driven by space charge field of drive bunch

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = -e\mathbf{E}$$

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n_1}{n_0} = -\frac{c^2}{2}\frac{\partial^2 a^2_{\mathrm{laser}}}{\partial x^2} - \omega_p^2\frac{n_{\mathrm{beam}}}{n_0}$$

Ponderomotive Force

- This simple derivation was for low intensity ($a_0 < 1$) also called non-relativistic intensities ($I < 10^{18}$ Wcm^{-2}).
- How do we extend to high intensities?
- method 1) just replace $m_e c^2$ with $\gamma m_e c^2$- but do it at the right stage

$$\mathbf{F}_p = -\frac{e^2}{2\langle\gamma\rangle m_e \omega_0^2}\nabla\langle E^2\rangle = -\frac{1}{2} m_e c^2 \frac{1}{\langle\gamma\rangle}\nabla\langle a^2\rangle$$

- method 2) do it properly solving the equation of motion relativistically (see Quesnel + Mora Phys Rev E 1998)

$$\mathbf{F}_p = -\frac{1}{2} m_e c^2 \frac{1}{\langle\gamma\rangle}\nabla\langle a^2\rangle$$

Driving relativistic plasma waves

- The drive pulse of an intense laser pulse pushes away electrons just like a boat pushes away the water
- The much heavier ions are left behind - this charge separation makes a very large electric field
- As the electrons rush back to their original position they overshoot forming a plasma wave
- Plasma wave amplitude is largest if the drive duration is less than the plasma wavelength $c\tau_L < \lambda_p$

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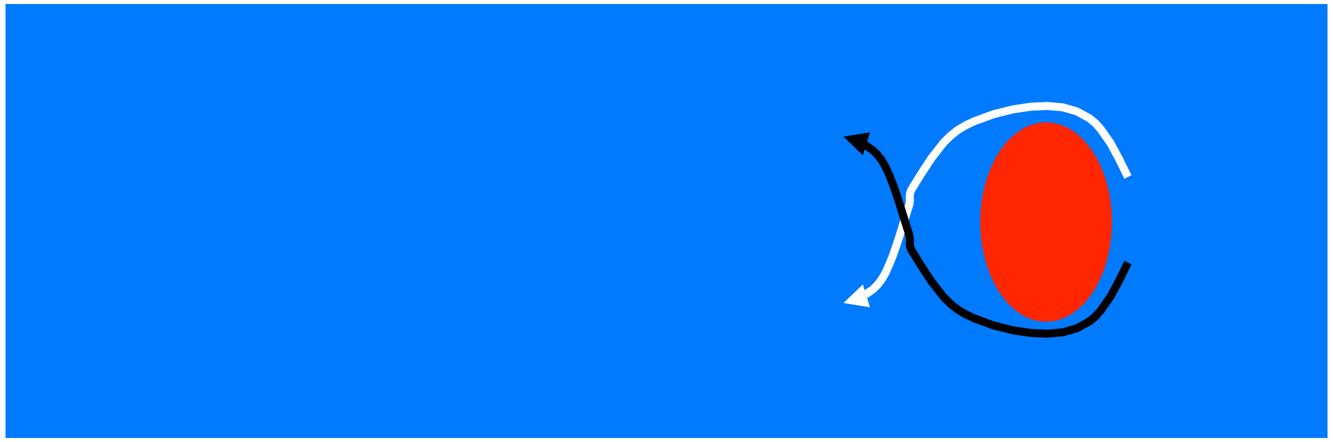

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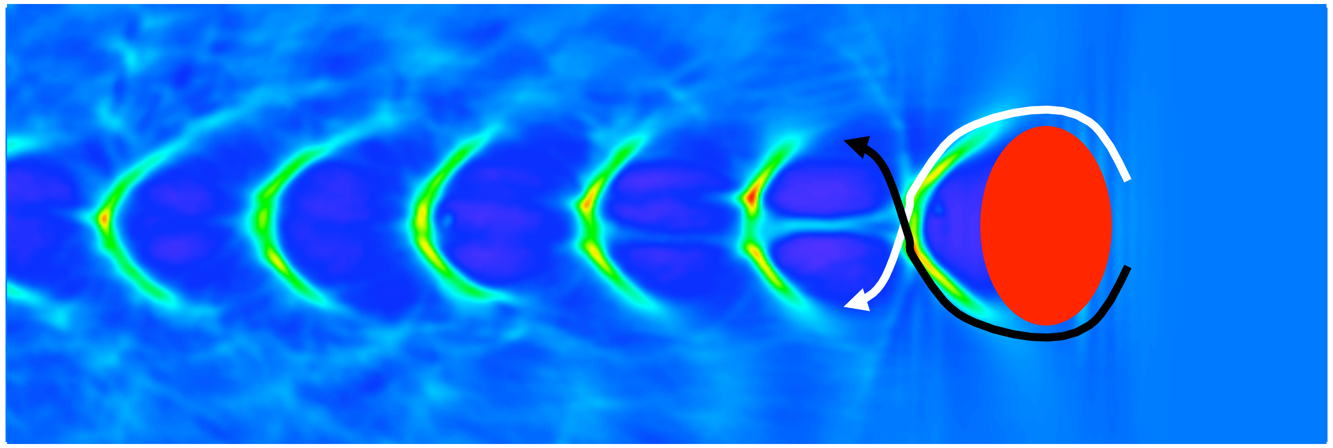

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- The picture of wakefield I have shown so far is from a particle-in-cell numerical simulation
- But is it possible to "see" the plasma wave directly in experiments?

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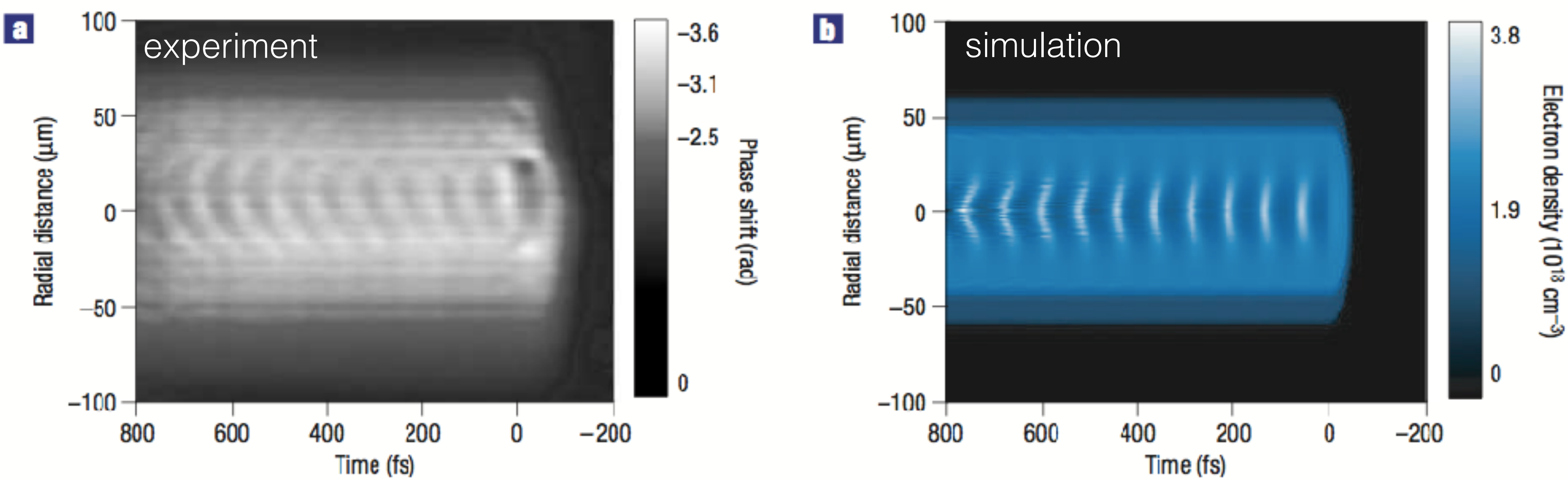
- But is it possible to “see” the plasma wave directly in experiments?
  - Yes! This is using a technique called Fourier domain holography (Matlis Nature Physics 2006)



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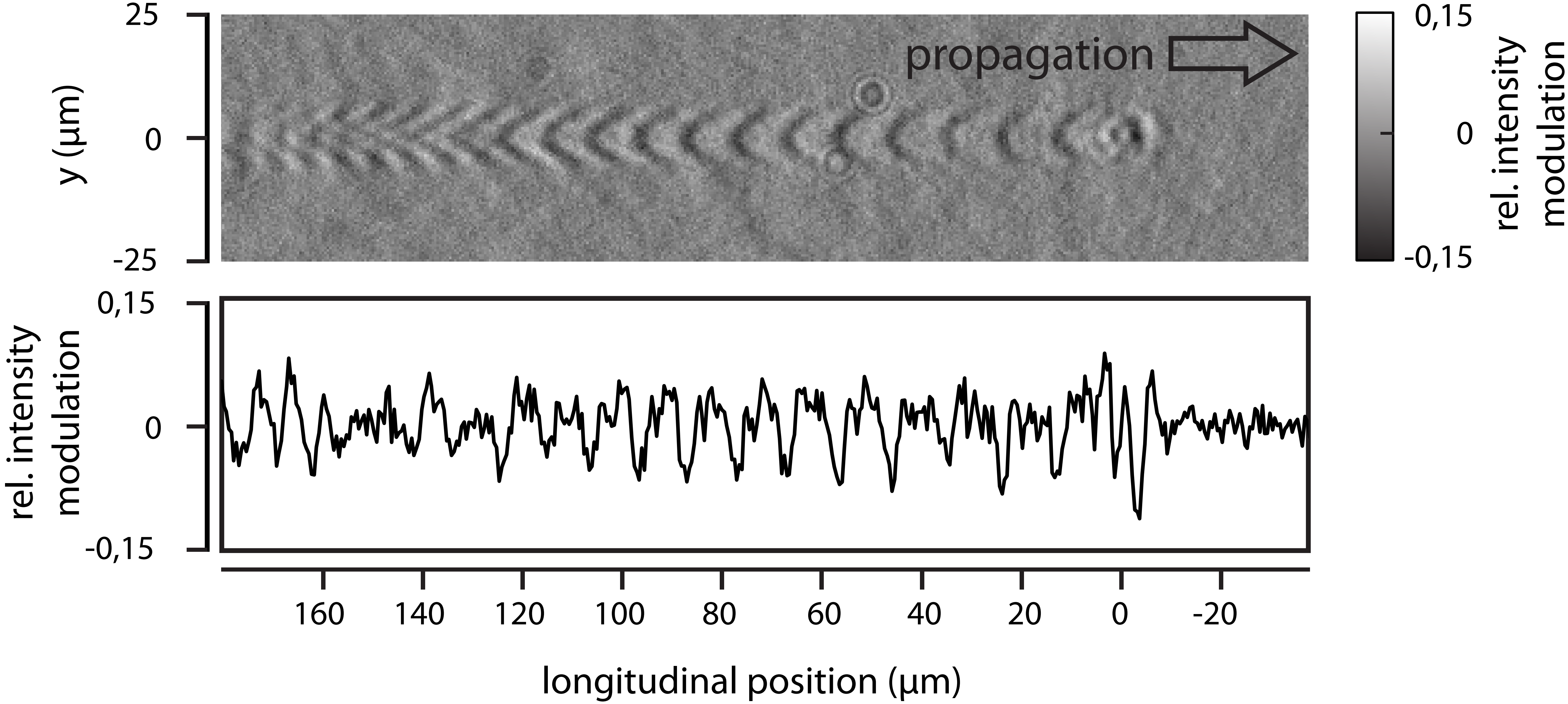

A Sävert Phys. Rev. Lett. 115, 055002 (2015)

Phase velocity and wavelength of plasma waves

- The laser pulse speed determines the wavelength and phase velocity.
- Think of each electron as a separate oscillator, that is set in motion by the laser when the laser gets to it.
- If the first electron (at $z = 0$) is set in motion at $t = 0$, the next electron (at $z = \Delta z$) will start oscillating at $t = \Delta t = \Delta z / v_g$ where is the velocity of the laser pulse in the plasma (group velocity)
- there will be a wave with a phase velocity of $v_p = \Delta z / \Delta t = v_g$
- The wavelength will therefore be

$$\lambda_p = \frac{2\pi v_g}{\omega_p} \simeq \frac{2\pi c}{\omega_p}$$

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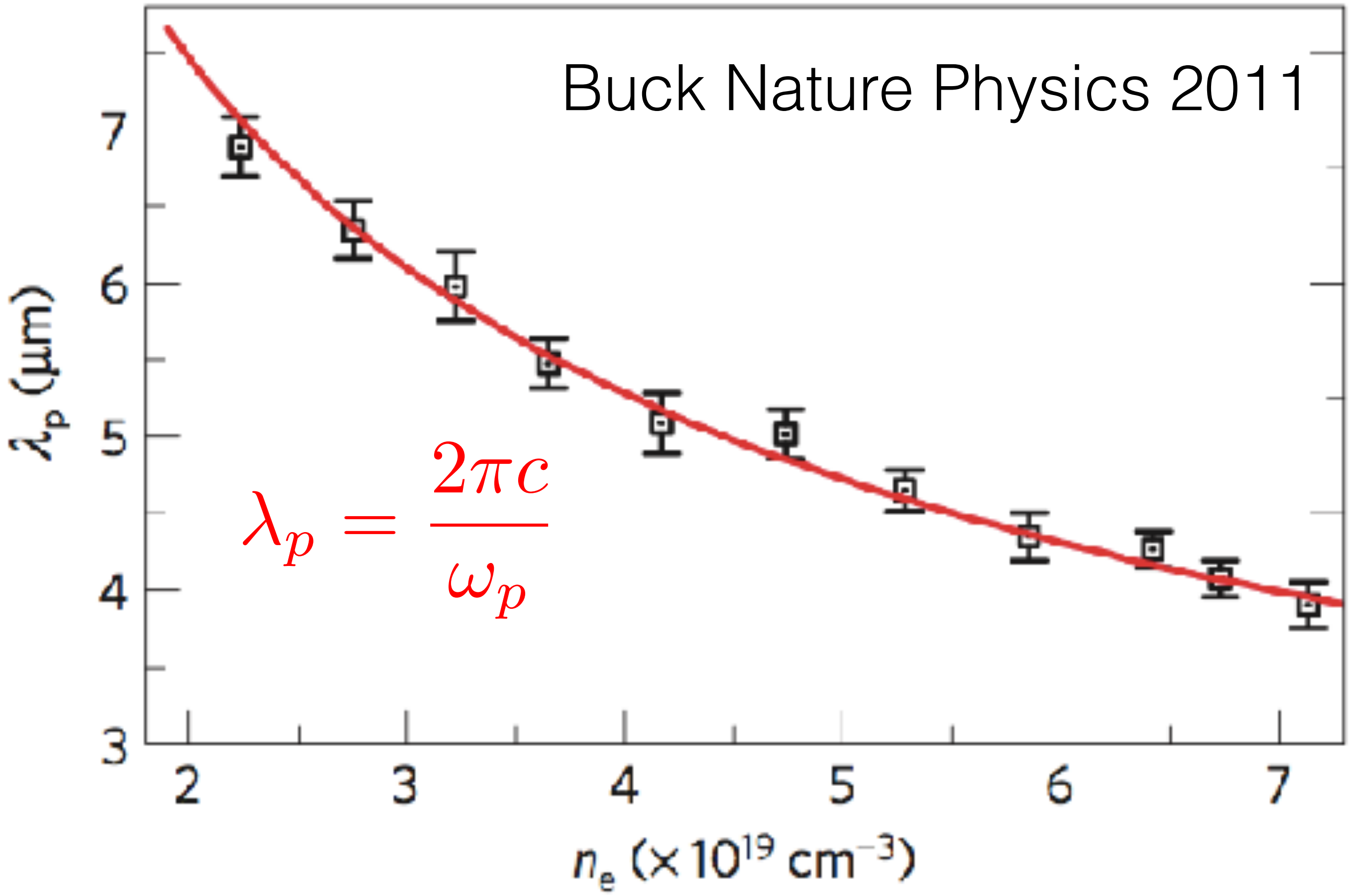

- The wavelength of plasma waves is also experimentally verifiable

$\lambda_p \simeq 10\ \mu\text{m}$ at $n_e \approx 10^{19}$ cm^{-3}

(for λ = 800 nm laser)

Dephasing

- electrons travel slightly faster than the wave - eventually they stop being accelerated, this is called "dephasing"

Limits to Acceleration: 1) Dephasing

- Relativistic electrons ($v_e/c = \beta_e \rightarrow 1$) accelerating in the wave will move ahead of the wave which is moving at

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$$t_d = \frac{\lambda_p}{2c\left(\beta_e - \beta_p\right)} \approx \frac{\lambda_p}{c}\frac{n_c}{n_e} \qquad L_{dp} = \lambda_p \frac{n_c}{n_e}$$

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- Dephasing length < 8 mm at $n_e = 4 \times 10^{18}$ cm^{-3}
- Dephasing is the fundamental limit to energy gain in LWFA

Limits to Acceleration: 2) pump depletion

- Creating the plasma wave takes energy - this must come from the drive pulse.

$$U_{\rm plasma} = \frac{1}{4}\epsilon_0 E_{z0}^2$$ plasma wave electric field energy density $$E_{z0} = \delta\ \frac{m_e c\omega_p}{e}$$

$$W_{\rm plasma} = U_{\rm plasma} AL$$ energy in plasma wave cross section *A*, length *L*

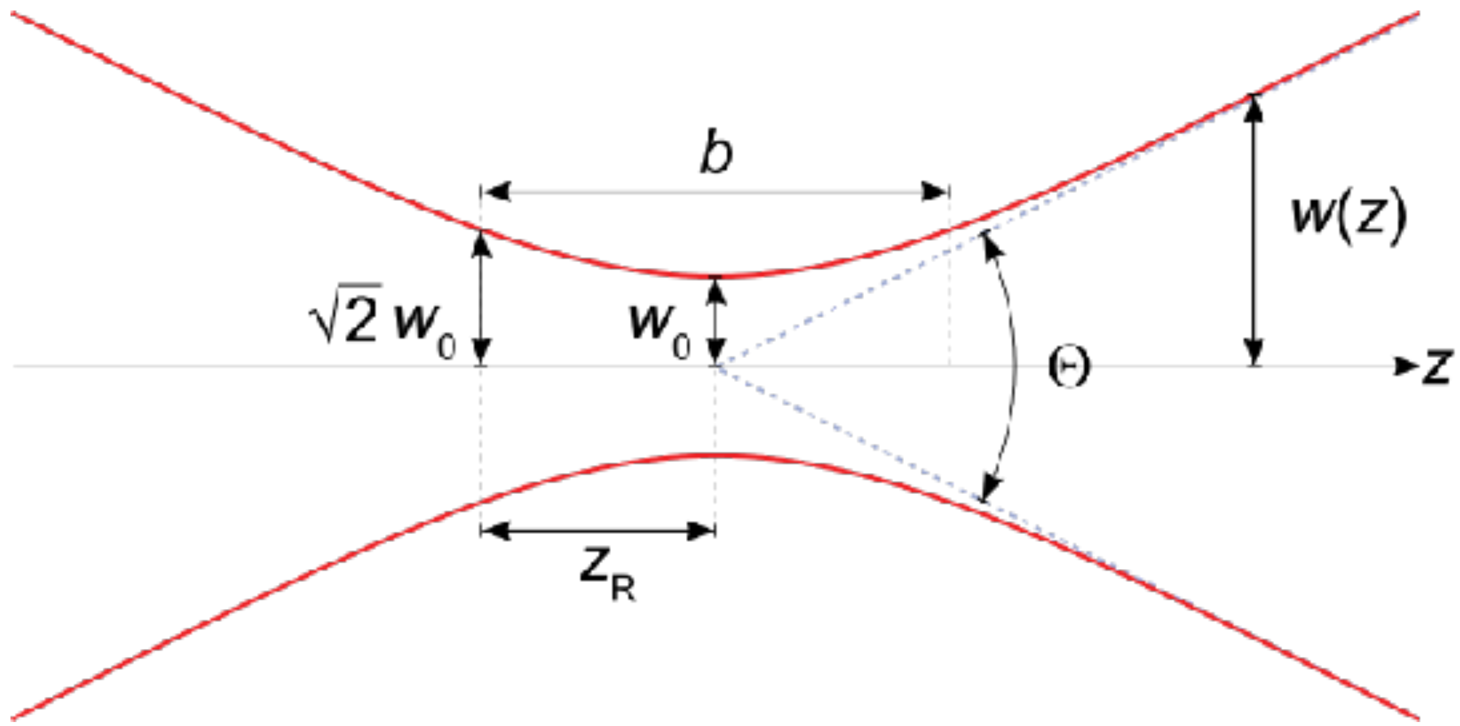
$$U_{\rm laser} = \frac{1}{2}\epsilon_0 E_{L0}^2$$ laser electric and magnetic field energy density $$E_{L0} = a_0\ \frac{m_e c\omega_0}{e}$$

$$W_{\rm laser} = U_{\rm laser} Ac\tau_L$$ energy in laser pulse wave cross section *A*, duration *τ* $$c\tau = \epsilon\ \lambda_p$$

$$L_{pd} = 2\epsilon\left(\frac{a_0}{\delta}\right)^2 \frac{n_c}{n_e}\lambda_p$$

we can tailor parameters so pump depletion > dephasing

Limits to acceleration: 3) diffraction



- We need to keep the laser intense over the entire interaction
- Distance over which a laser diffracts in vacuum is the Rayleigh Range

$$z_R = \frac{\pi w_0^2}{\lambda_0}$$

- For z_R = 1 cm we need focal spots ~ 50 µm - difficult to make very intense focal spot this large
  - (e.g. you need P > 90 TW for a_0 = 1)

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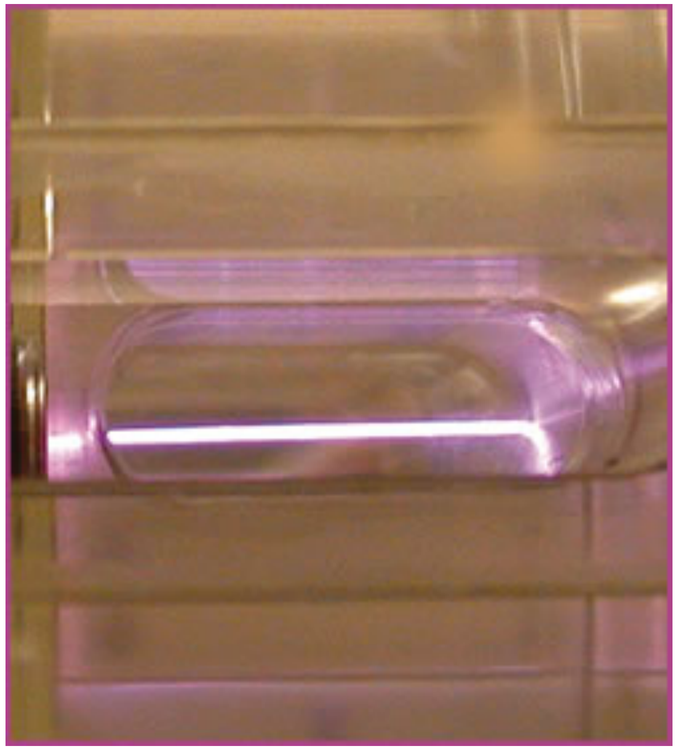
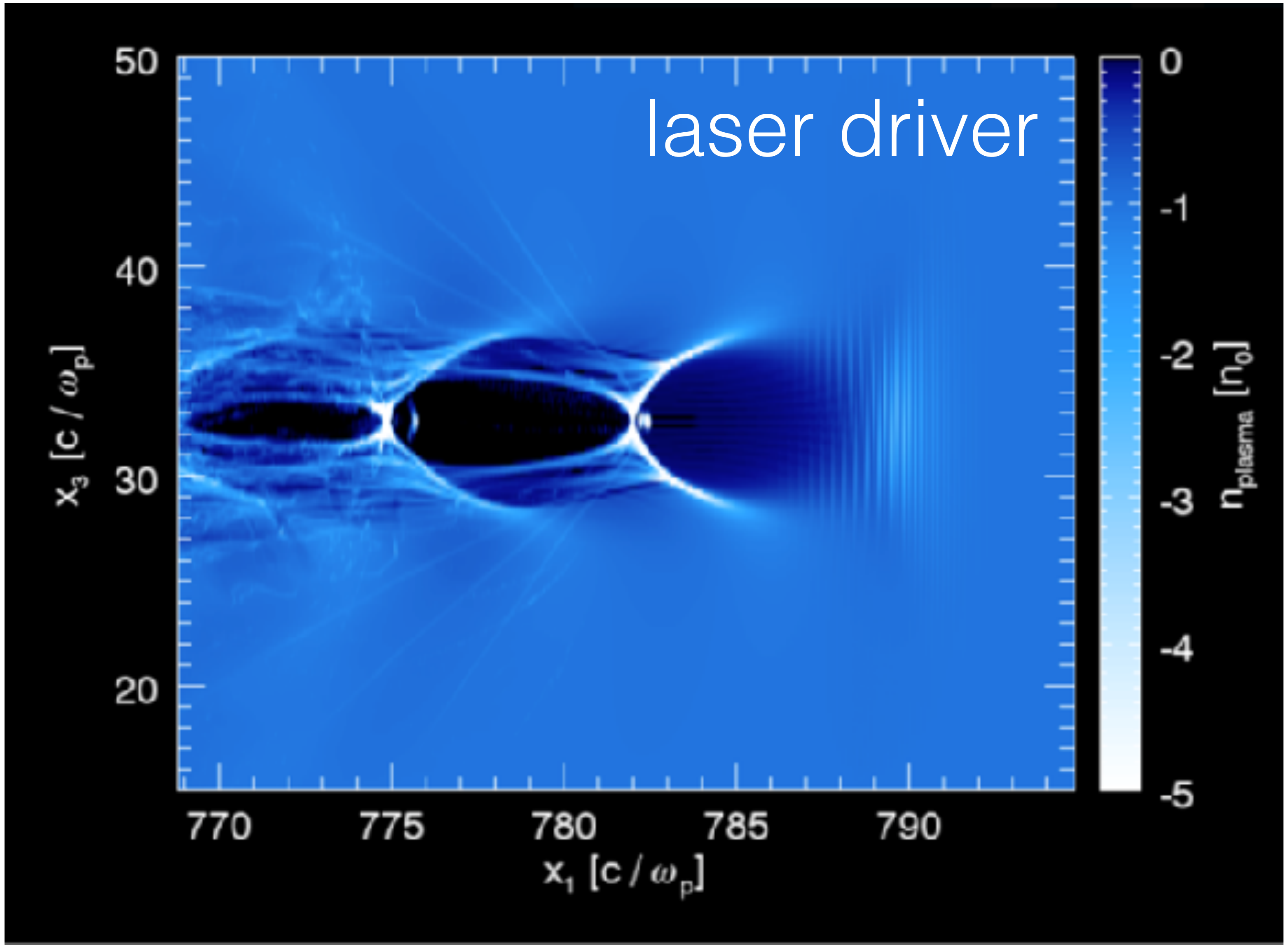


- To overcome diffraction we need to guide the laser - an optical fibre
- Can’t use a normal optical fibre - it will damage!
  - plasma waveguide - plasma density minimum on axis
- Pre-formed plasma waveguides (Hooker group)
- Self-guiding - pulse forms its own waveguide

The blow-out regime



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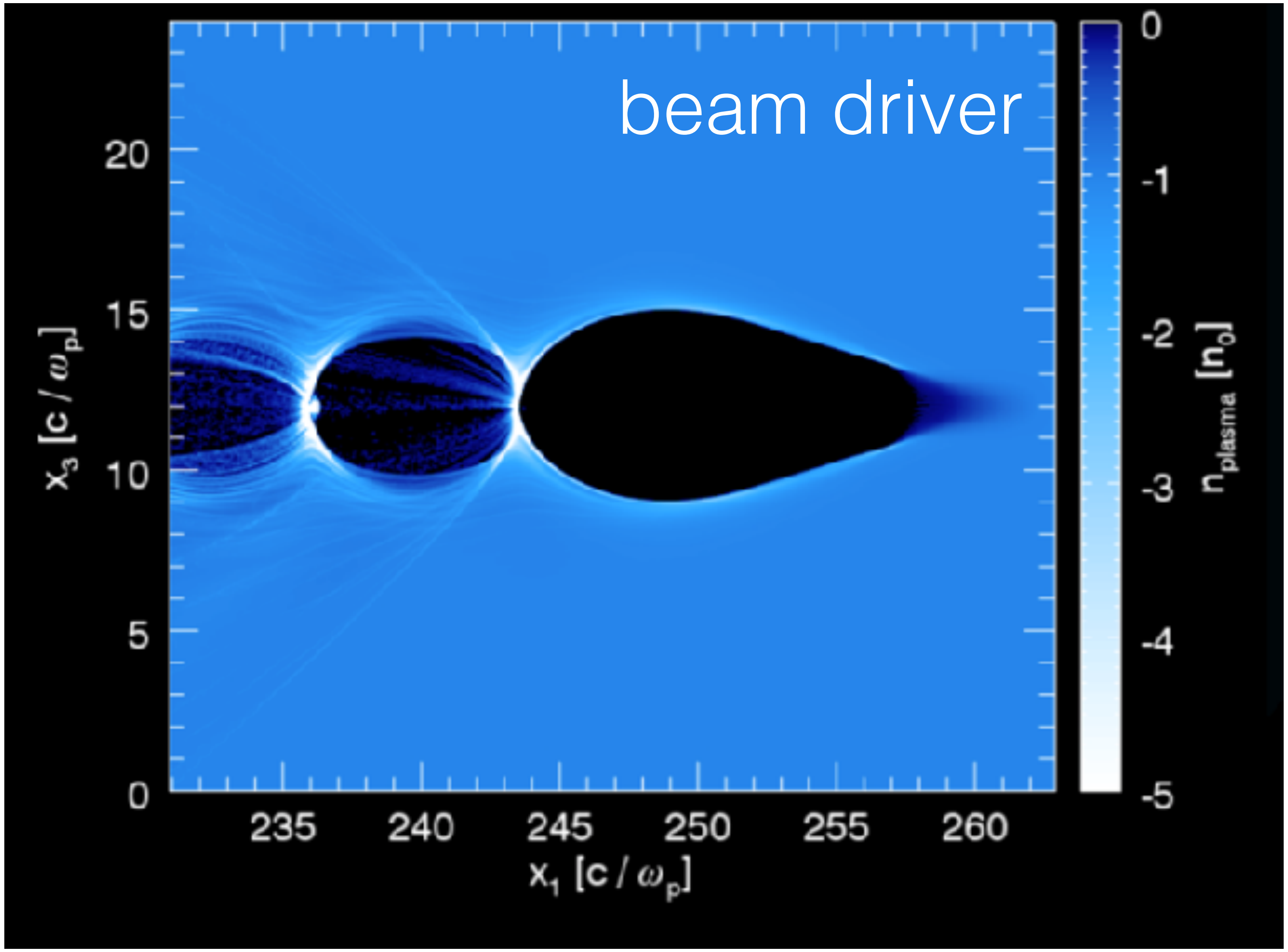

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it turns out that the situation is best if the laser spot size is matched to the bubble so we have:

$$r_b \approx 2\sqrt{a_0} \frac{c}{\omega_p}$$

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- For $a_0 \approx 3$ and a plasma density of $n_0 = 4 \times 10^{18}$ cm^{-3} we get a maximum field of 330 GV/m !
- Combining this with the dephasing length we would get a maximum electron energy of 2.4 GeV
  - this is an overestimate as non-linear effects make the group velocity a bit slower

Injecting electrons into the wave

- For a surfer to "catch a wave" he must swim to get up to speed before the wave arrives
- if he is too slow the wave will just pass over him
- we must find a way of accelerating electrons up to the correct speed for them to be trapped by the wave and accelerated

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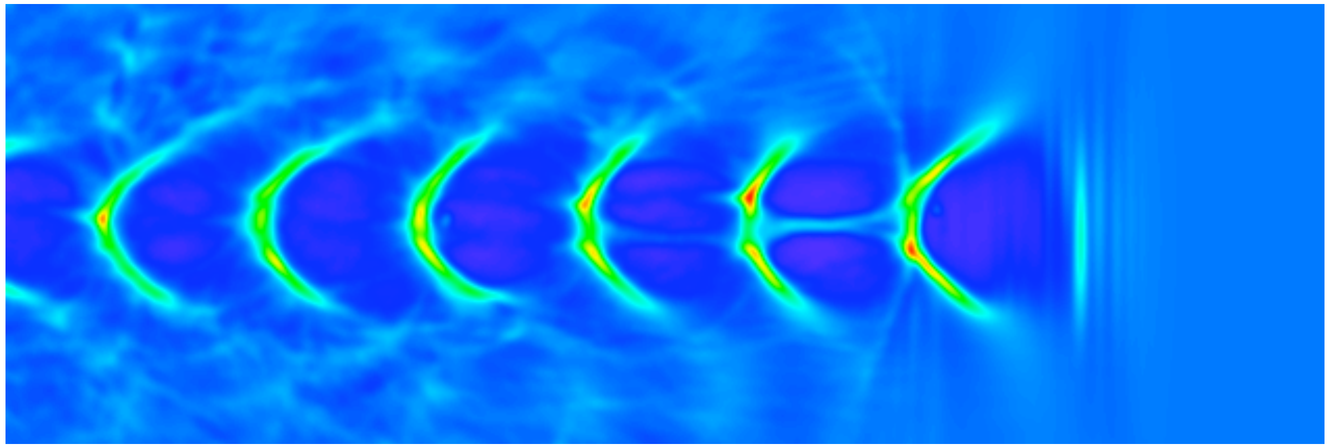

- Nature is kind to us - when the wakefield has a large enough amplitude some electrons can be trapped
- They are all injected at the back of the bubble so can be accelerated to the same energy - quasi-monoenergetic electron beams

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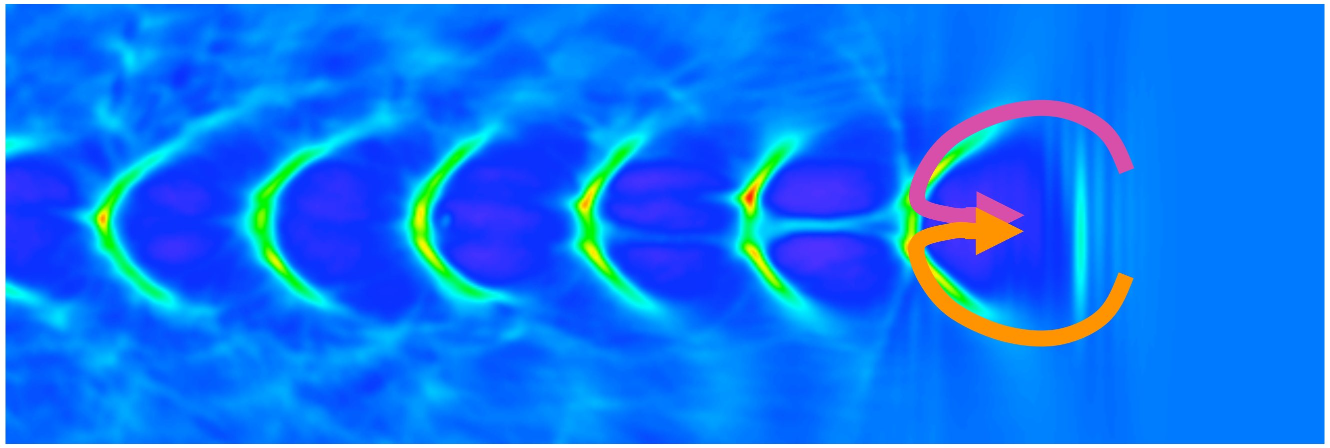

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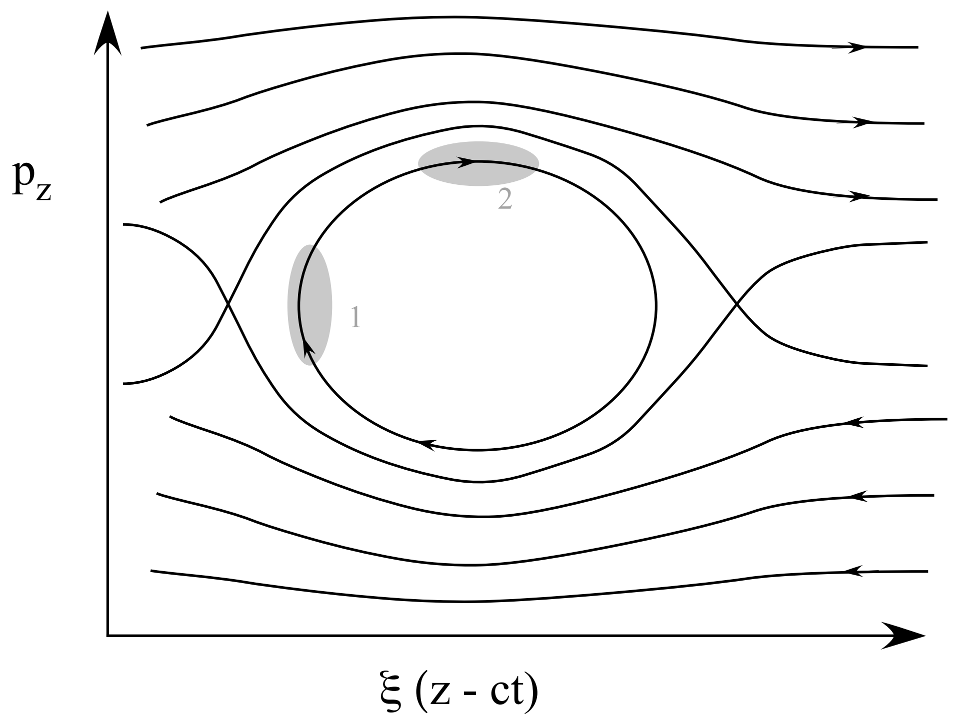

- this a plot of the longitudinal position ($\xi = z\text{-}ct$) in the wave against the longitudinal momentum p_z (called the p_z–ξ phase space)
    - The black arrows show electron trajectories
    - Trapped electrons follow closed orbits
- self-injection in the bubble only happens over a small range of ξ at the back of the bubble
- phase space rotation exchanges initial spread in p_z for spread in ξ

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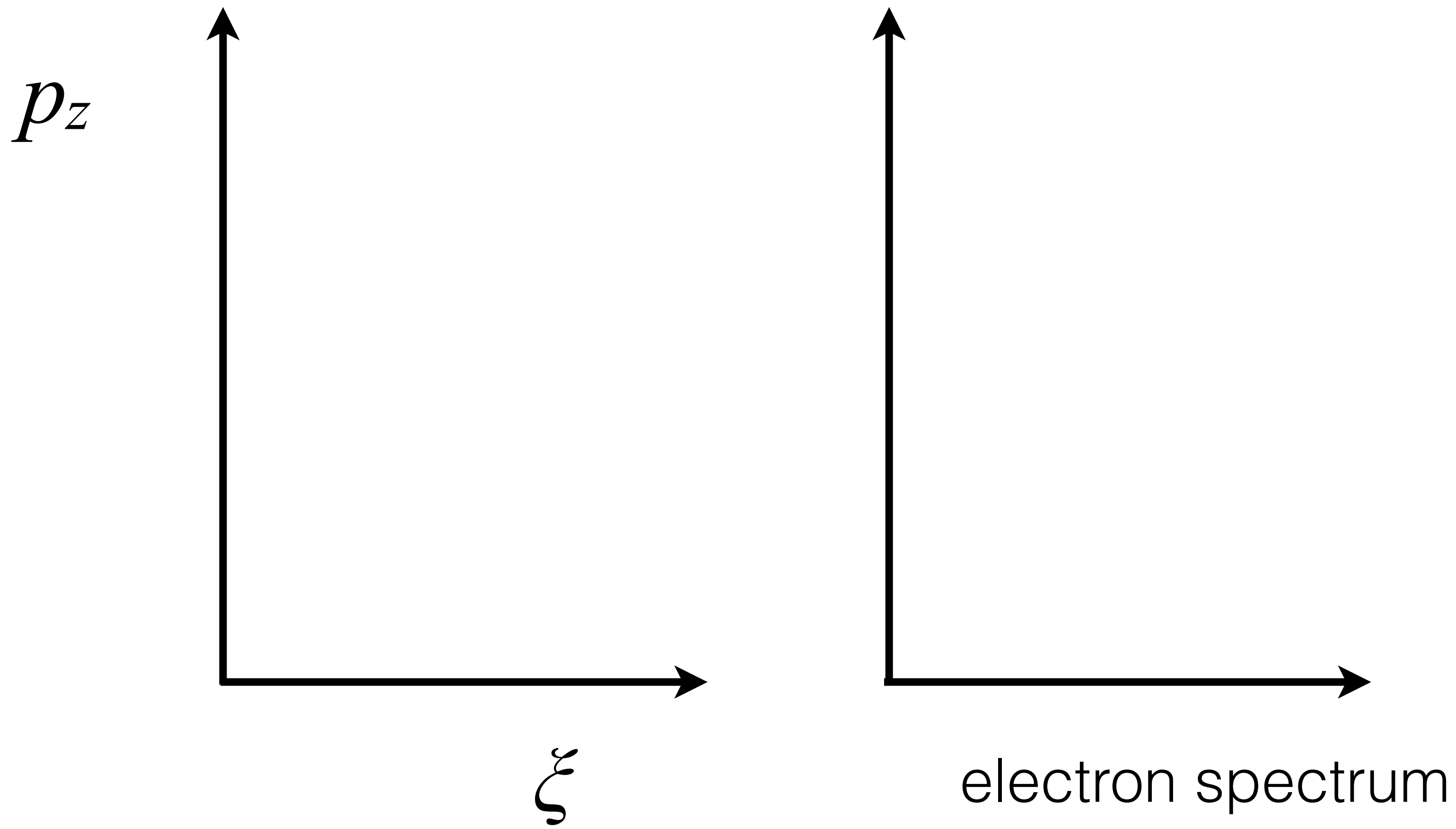

- This animation demonstrates how phase space rotation changes the electron spectrum

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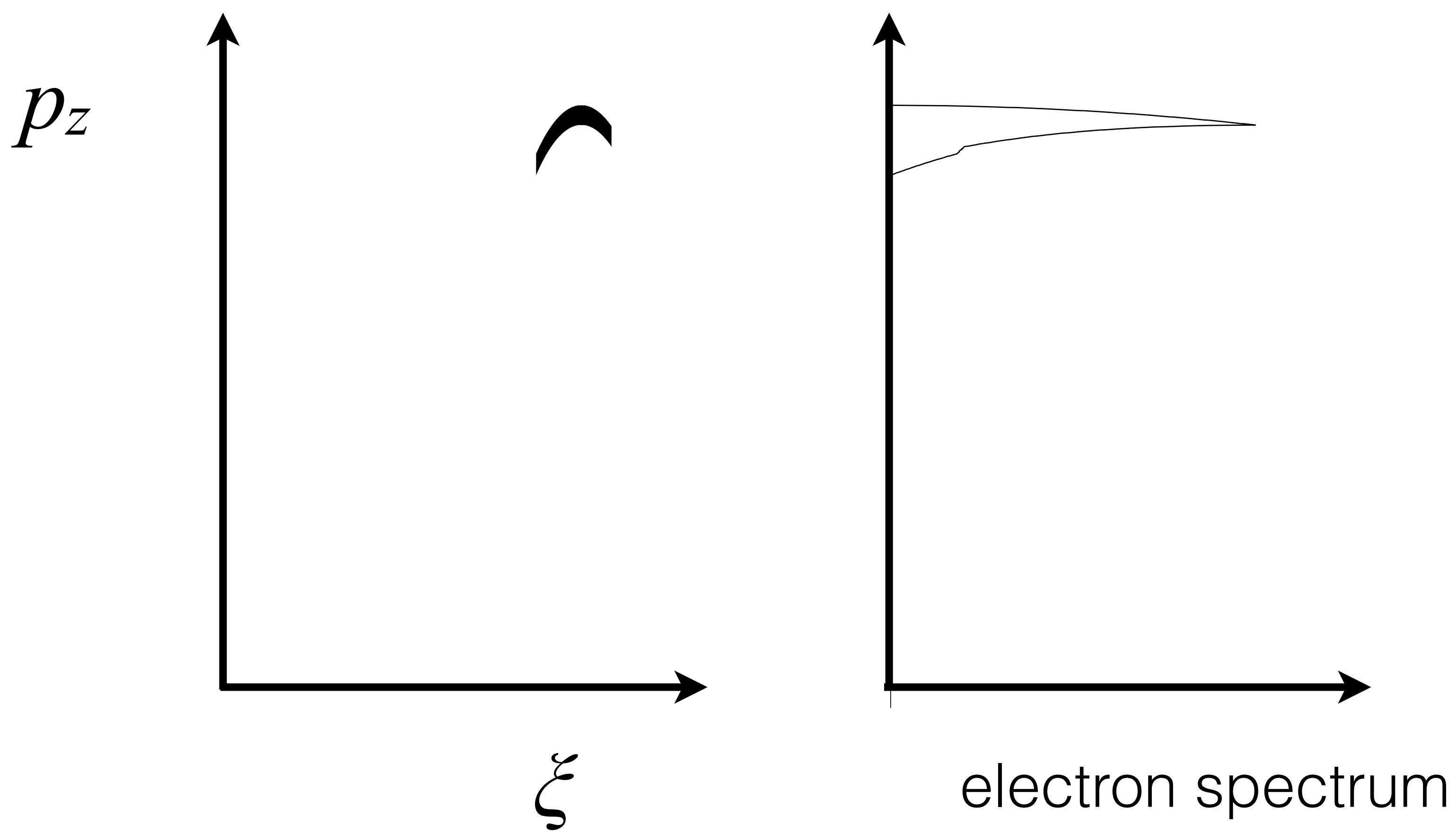

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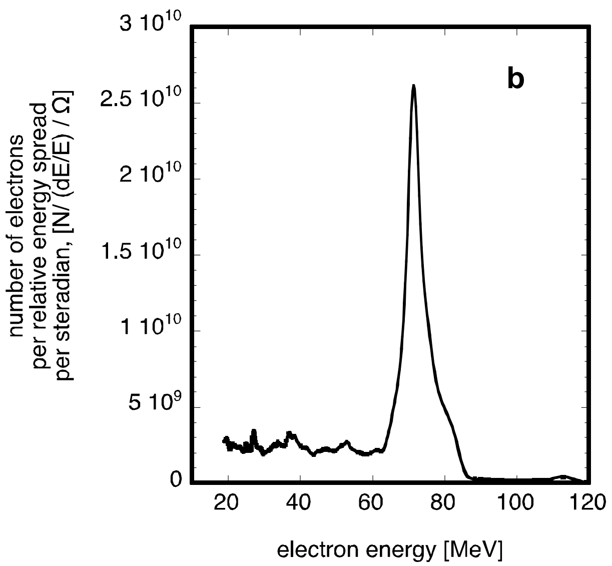
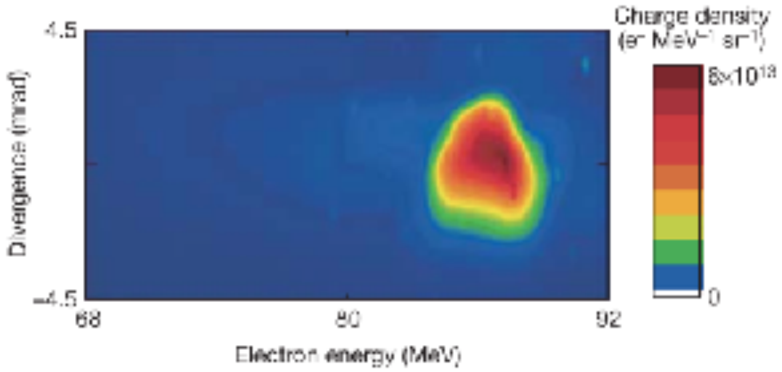
what sort of electron beams can we get?

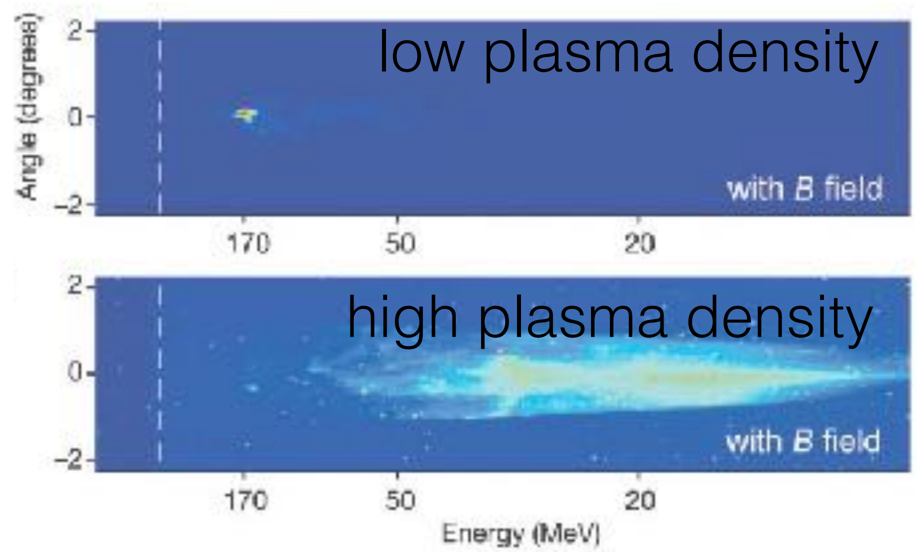
- Back in 2004 the Imperial College group, a group in the US (LBNL) and a group in France (LOA) were the first to report narrow energy spread beams from a laser wakefield accelerator



Mangles et al Nature 2004

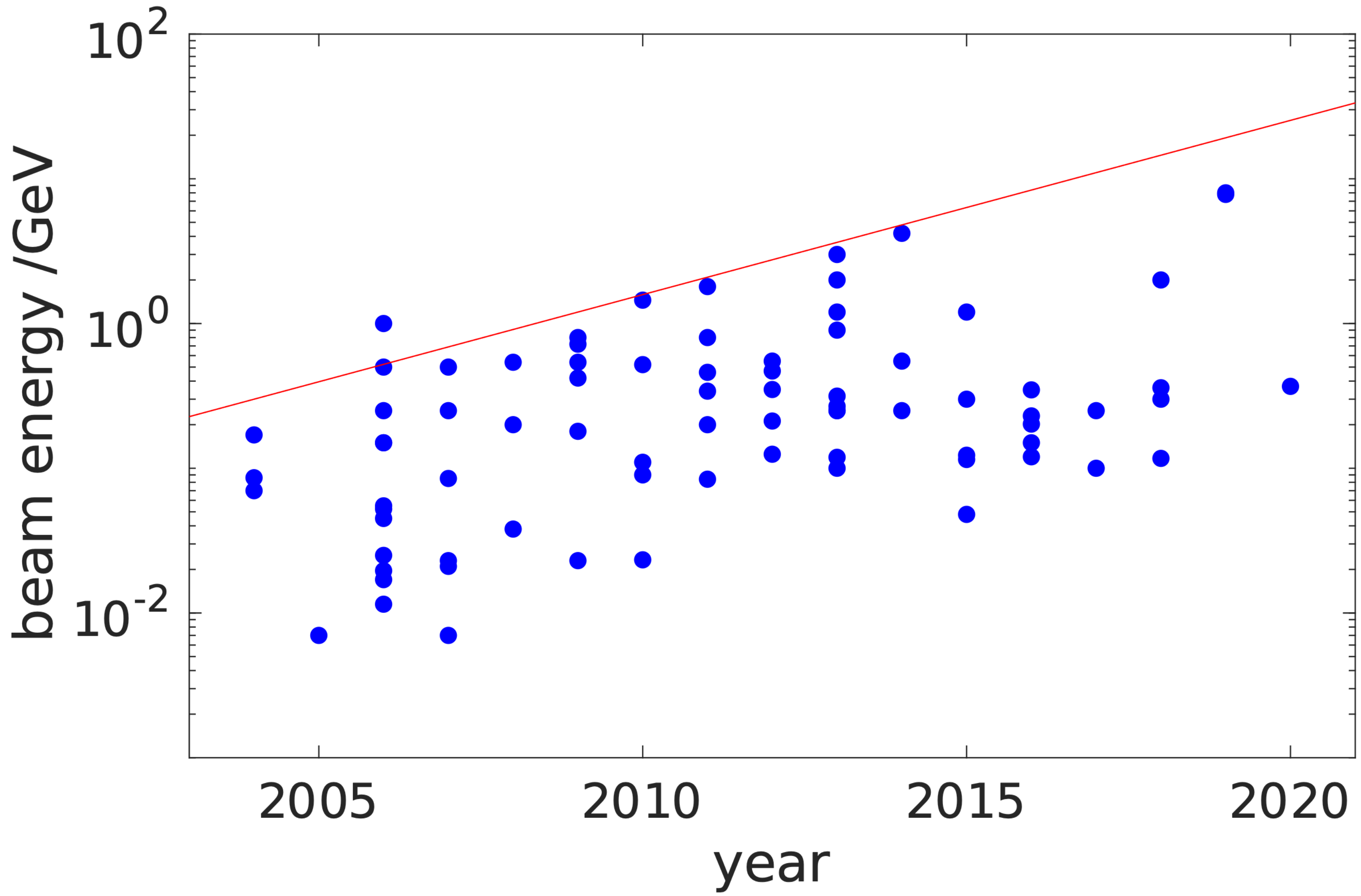


Geddes Nature 2004



Faure et al Nature 2004

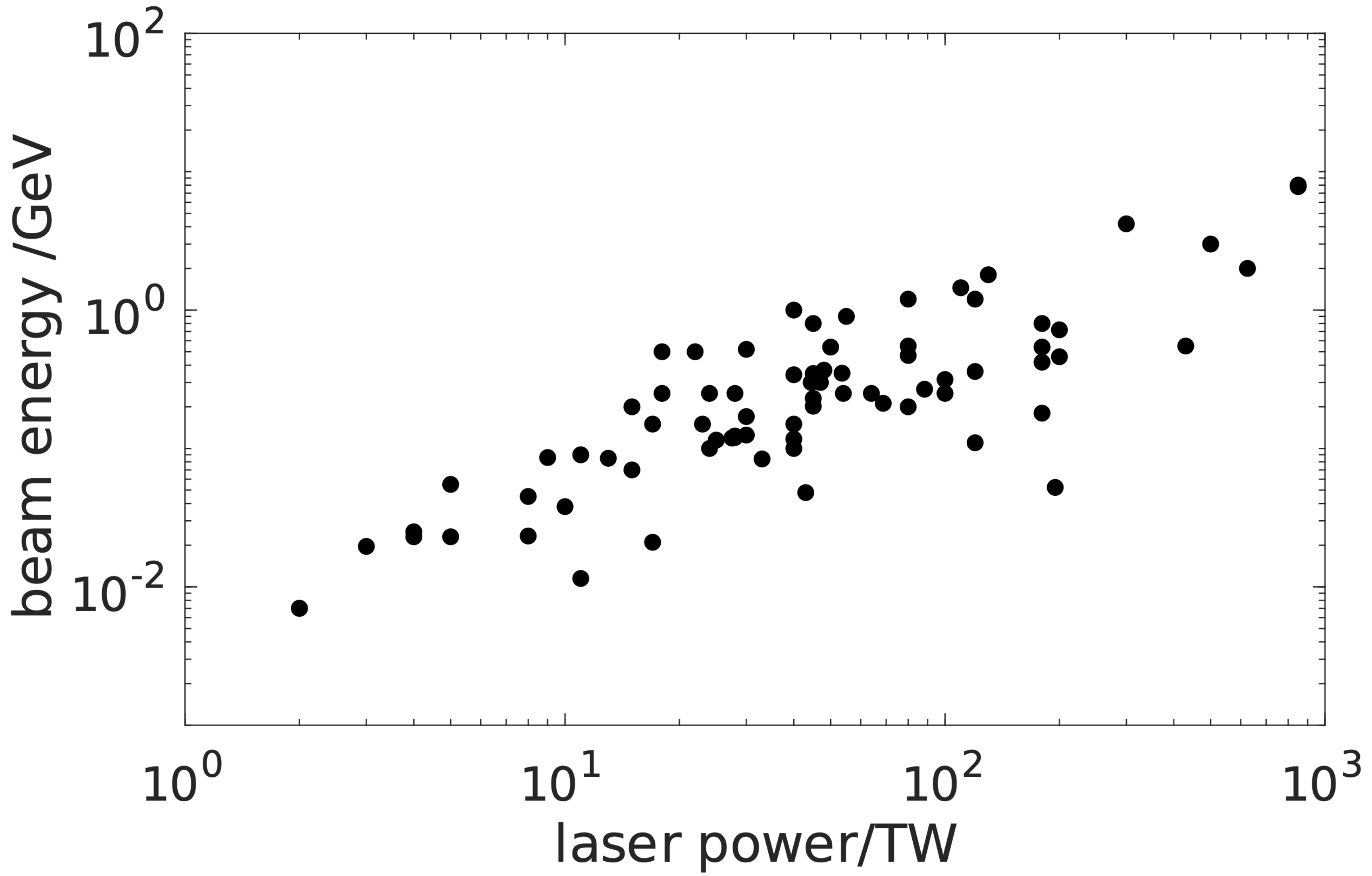
What sort of electron beams can we get?



- There has been steady progress in LWFAs
  - » e.g. beam energy doubles every 2.5 years (roughly!)

*to add data to this database please go to: https://forms.gle/D3zR2uHpjos9RQXt6

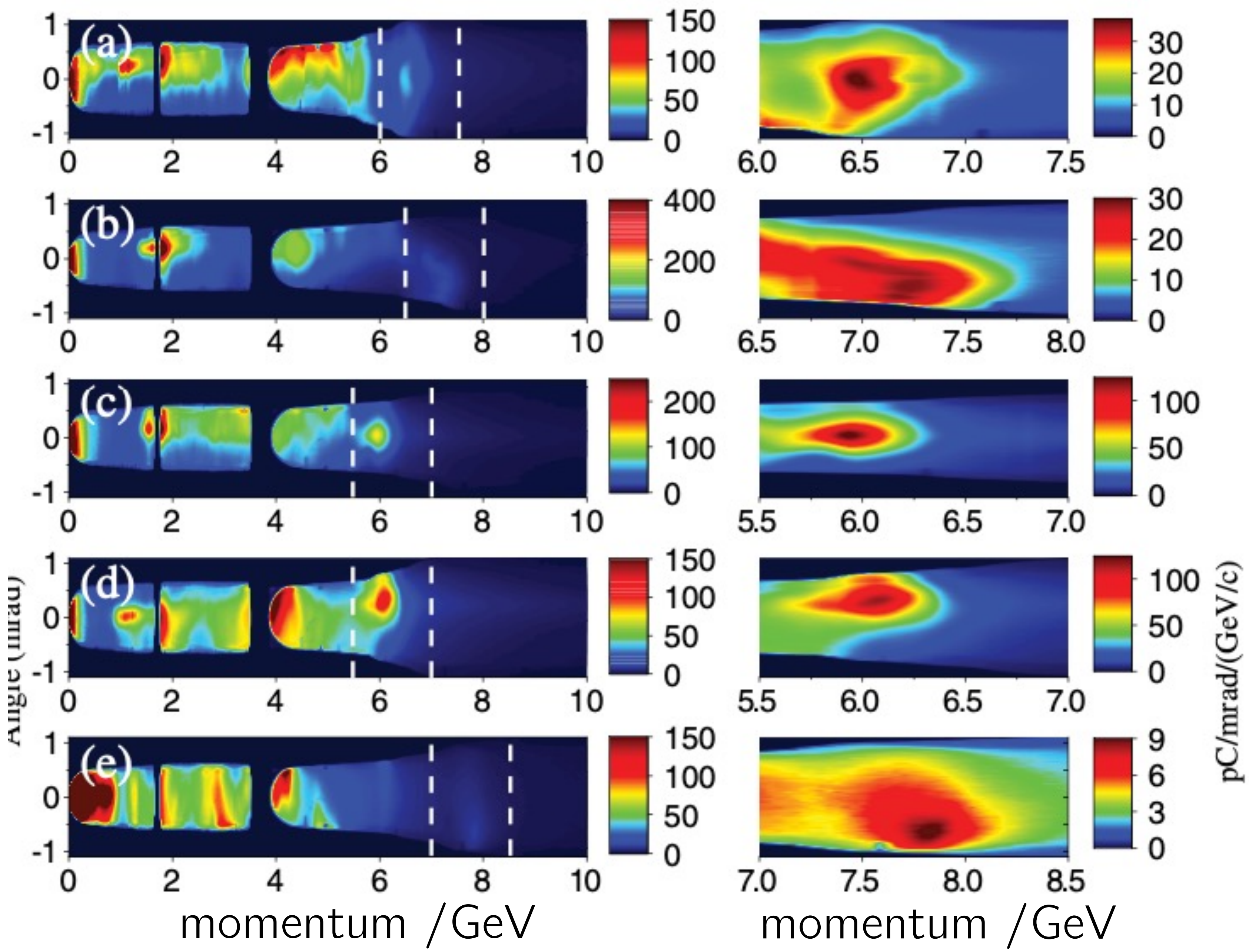
What sort of electron beams can we get?



- Increase in Beam energy has has been achieved by using higher power lasers.
    - *why do we need higher power lasers to get higher energy electrons?*

*to add data to this database please go to: https://forms.gle/D3zR2uHpjos9RQXt6

What sort of electron beams can we get?



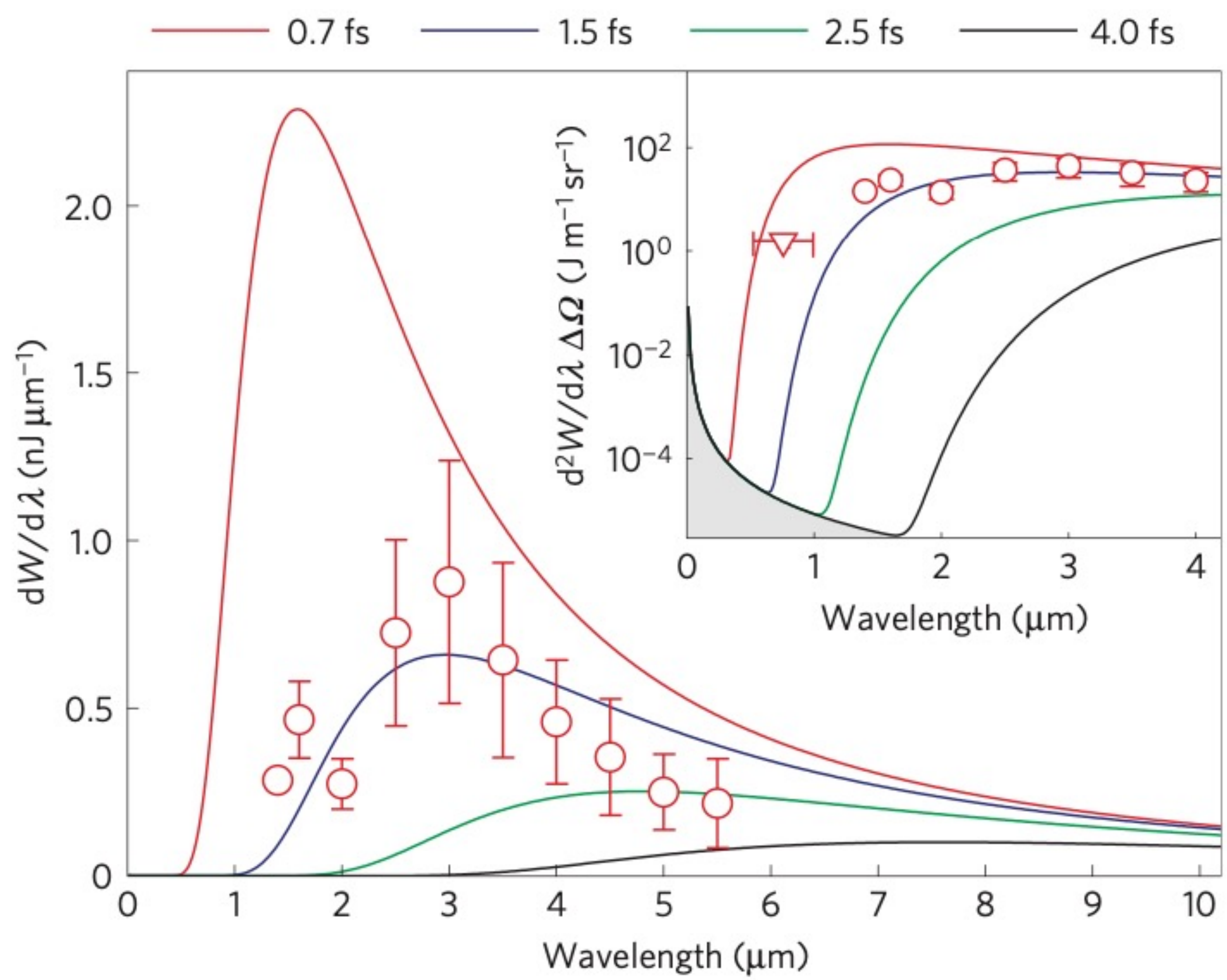
Gonsalves, PRL, **122**, 084801 (2019)

- Current record is 8 GeV in 20 cm with a 0.85 PW laser

Beam energy is not the only important parameter!

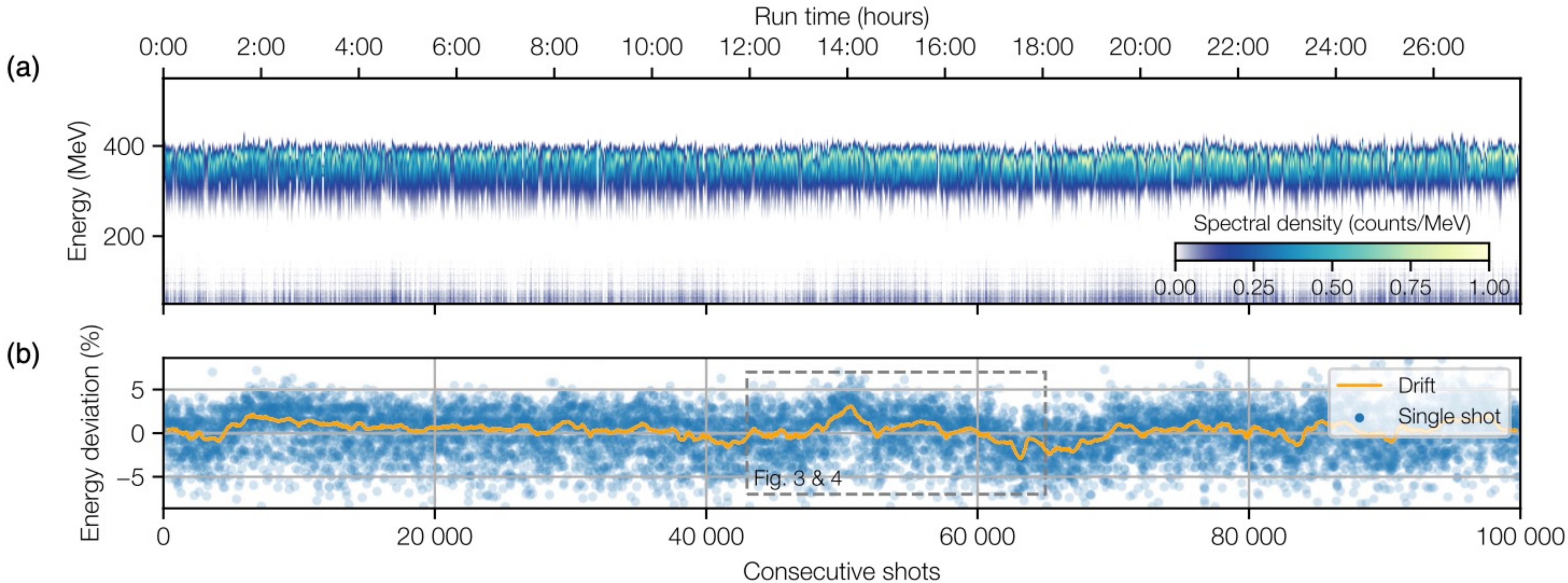
Laser wakefield accelerators can produce ultra short duration electron beams

- LWFA bunches measured to be less than 2 fs



Lundh et al Nat. Phys. **7**, 219–222 (2011)

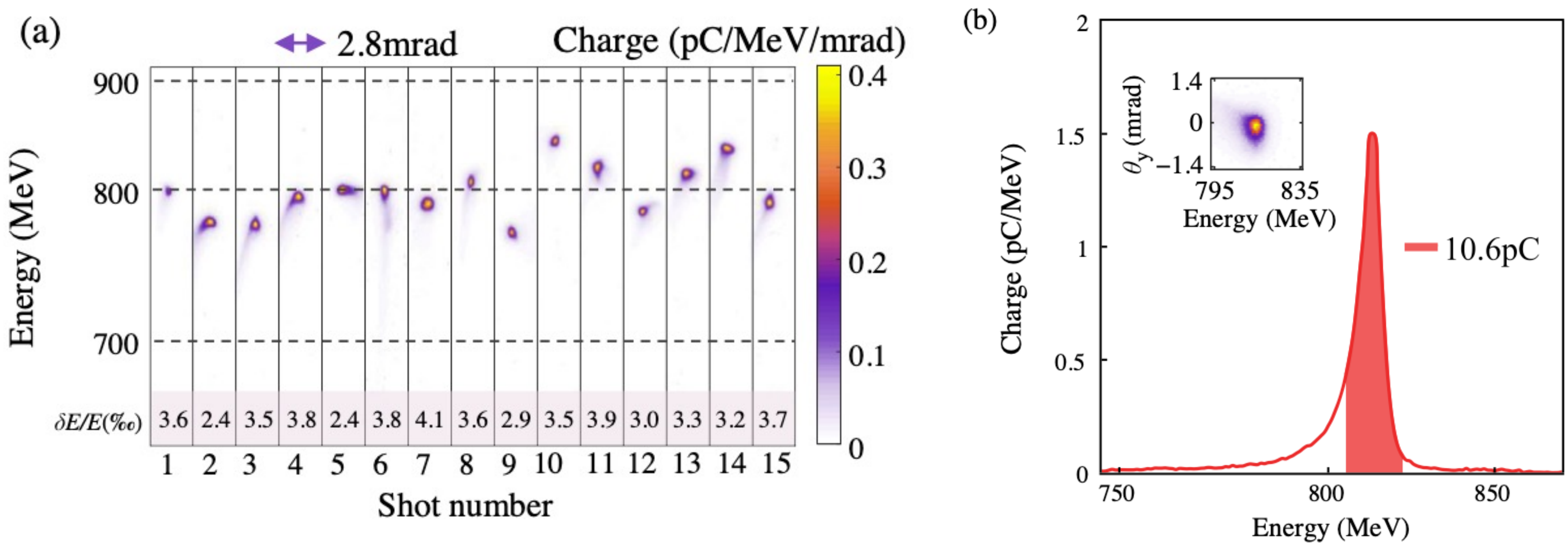
Laser wakefield accelerators can operate consistently



Maier et al PRX **10**, 031039 (2020)

- Dedicated LWFA facility running at 10 Hz for more than 24 hours
  - Stable, consistent operation

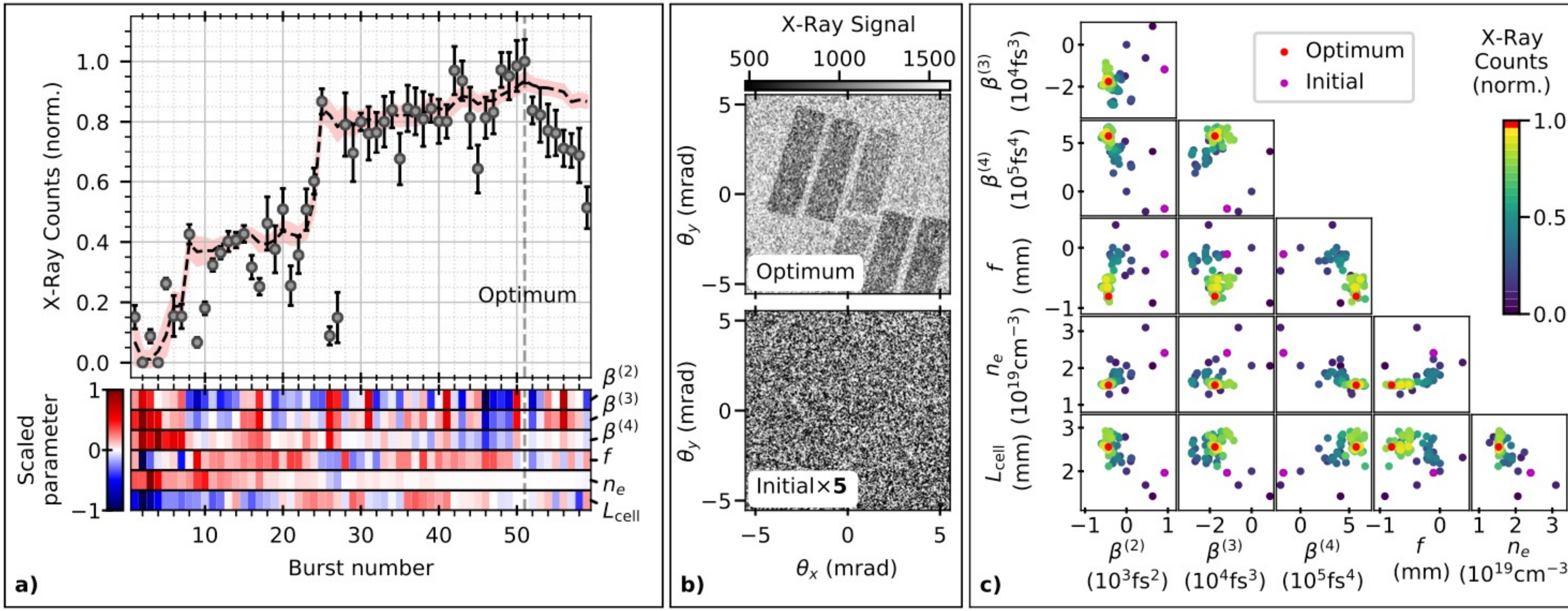
Laser wakefield accelerators can produce narrow energy spread beams



LT Ke et al PRL **126**, 214801 (2021)

- New injection methods can produce very narrow energy spread beams at the per mille level

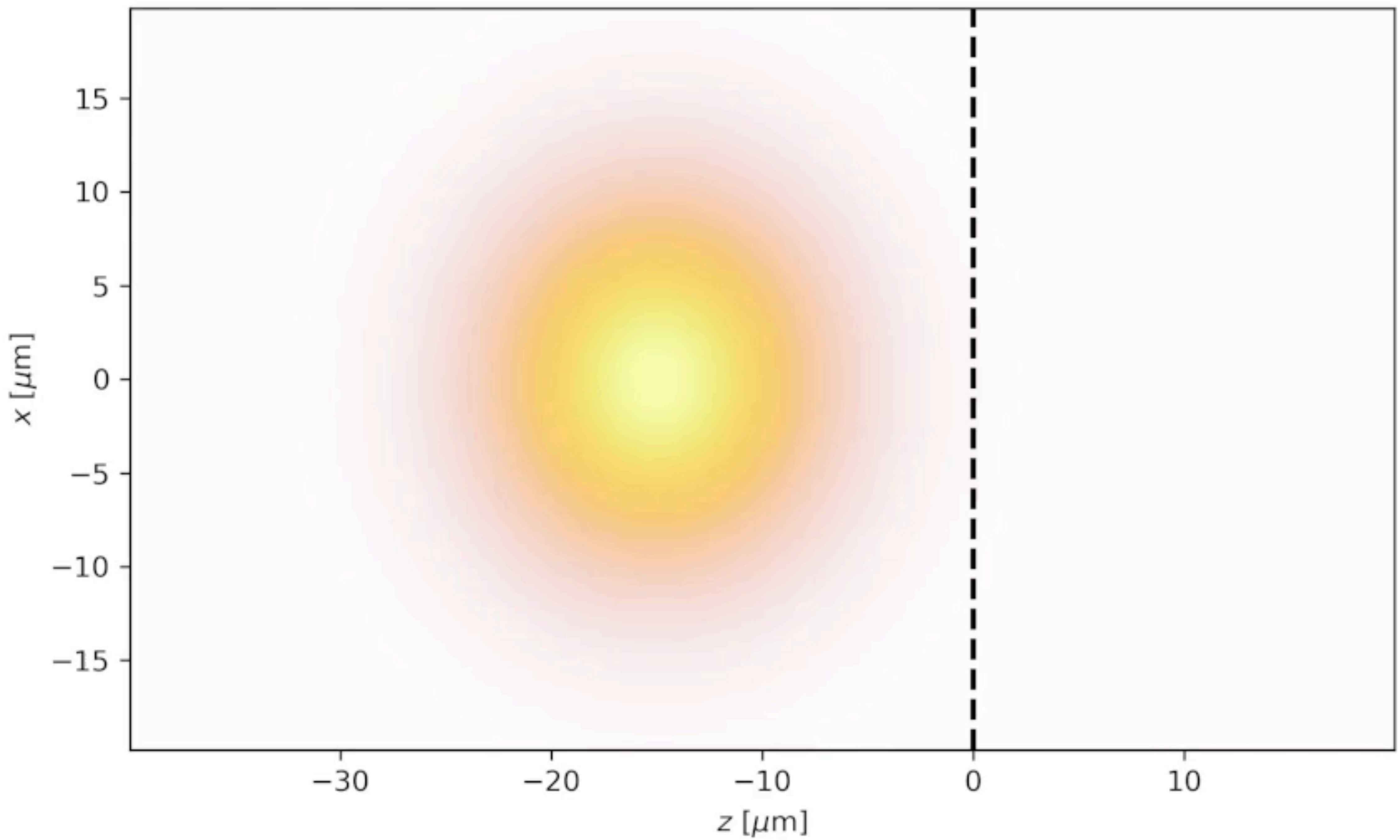
Laser wakefield accelerators can be controlled and optimised



Shalloo et al, Nat Comms, **11**, 6355 (2020)

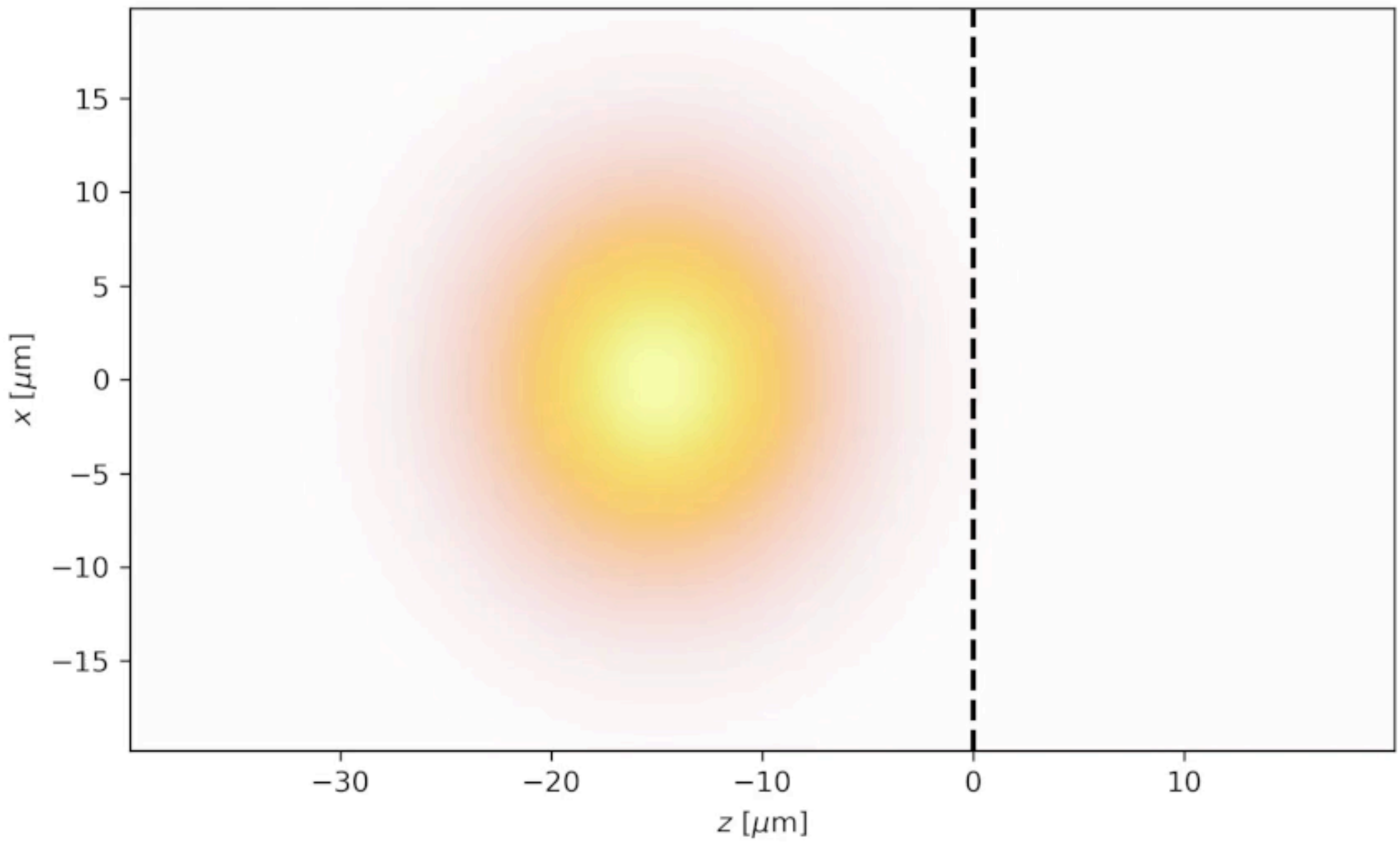
- Machine learning methods can be used to optimize and control laser wakefield accelerators
  - »6D optimization of LWFA using Bayesian Optimization

When a high power laser enters a plasma, something amazing happens...



movie by M Streeter

When a high power laser enters a plasma, something amazing happens...



movie by M Streeter

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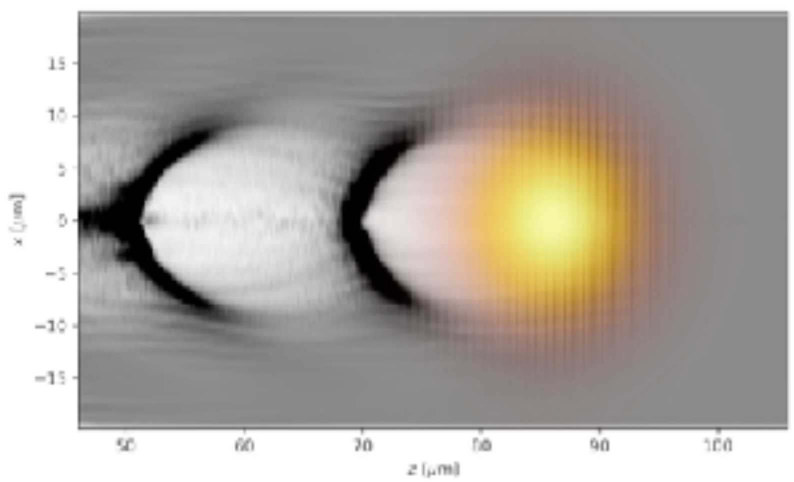
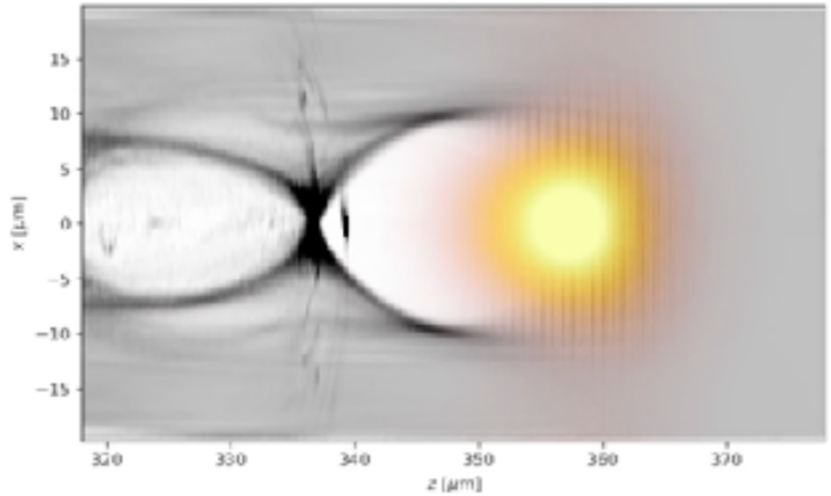
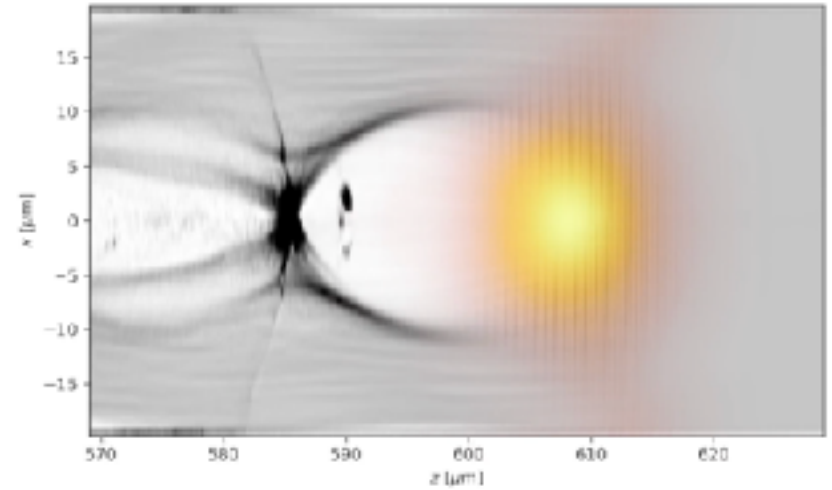


- Laser enters plasma, driving a plasma wave in its wake

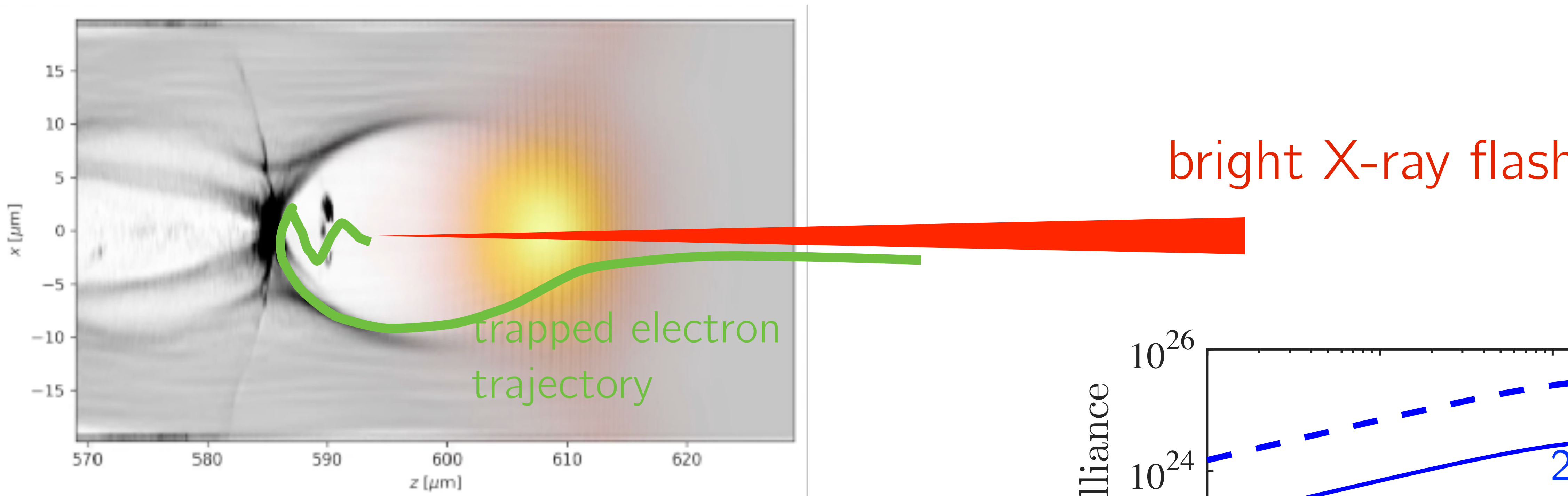


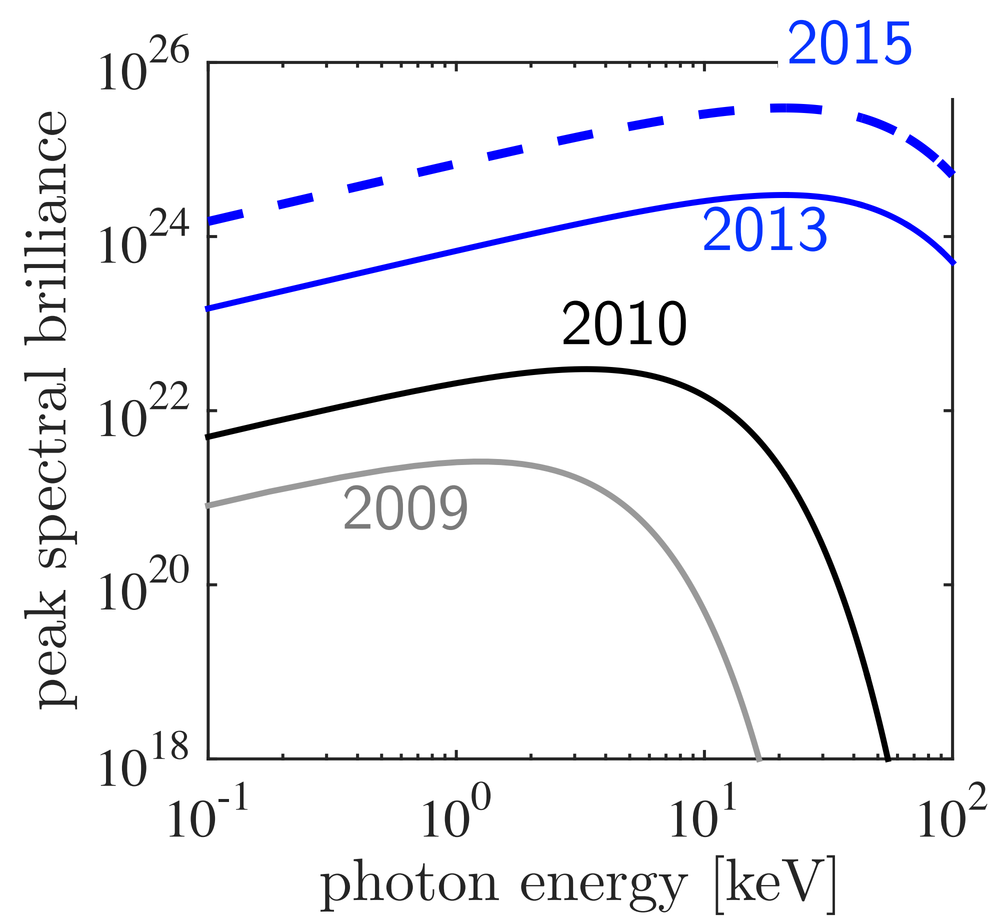
- Wake amplitude grows and electrons from background plasma are swept up and accelerated by the wake



- Electrons undergo betatron oscillations in the wake, generating X-rays

Laser wakefield accelerators are a source of interesting X-ray beams

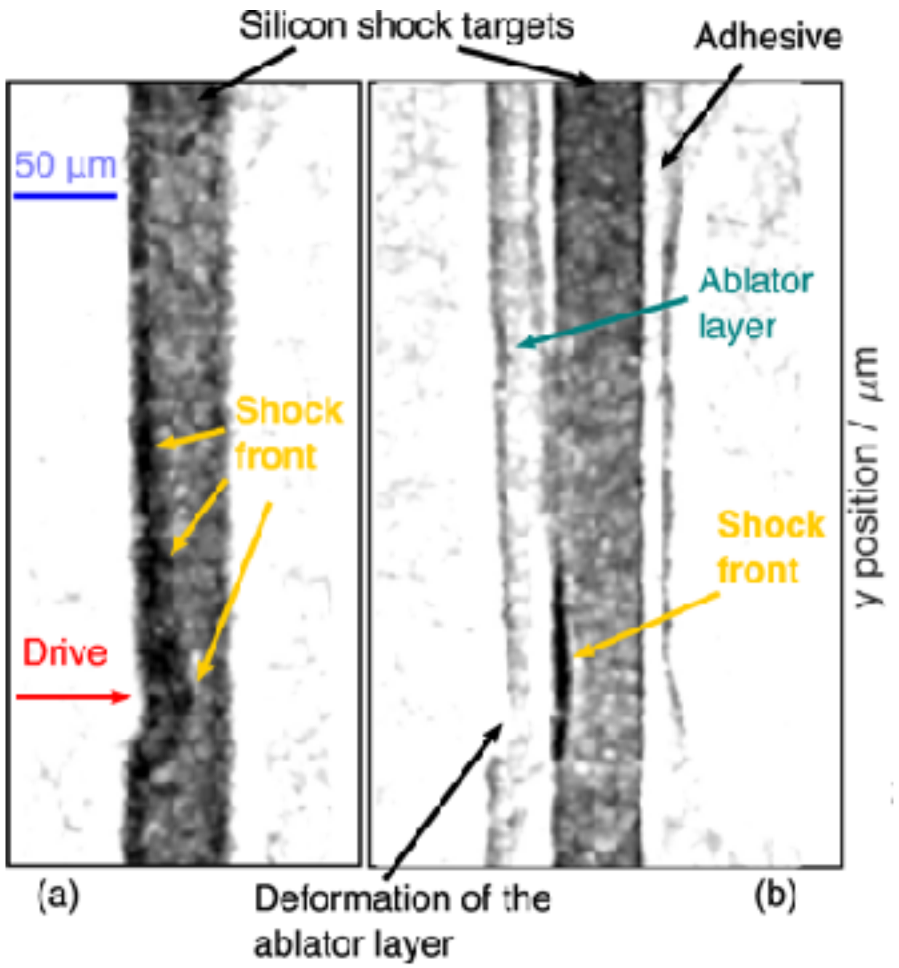




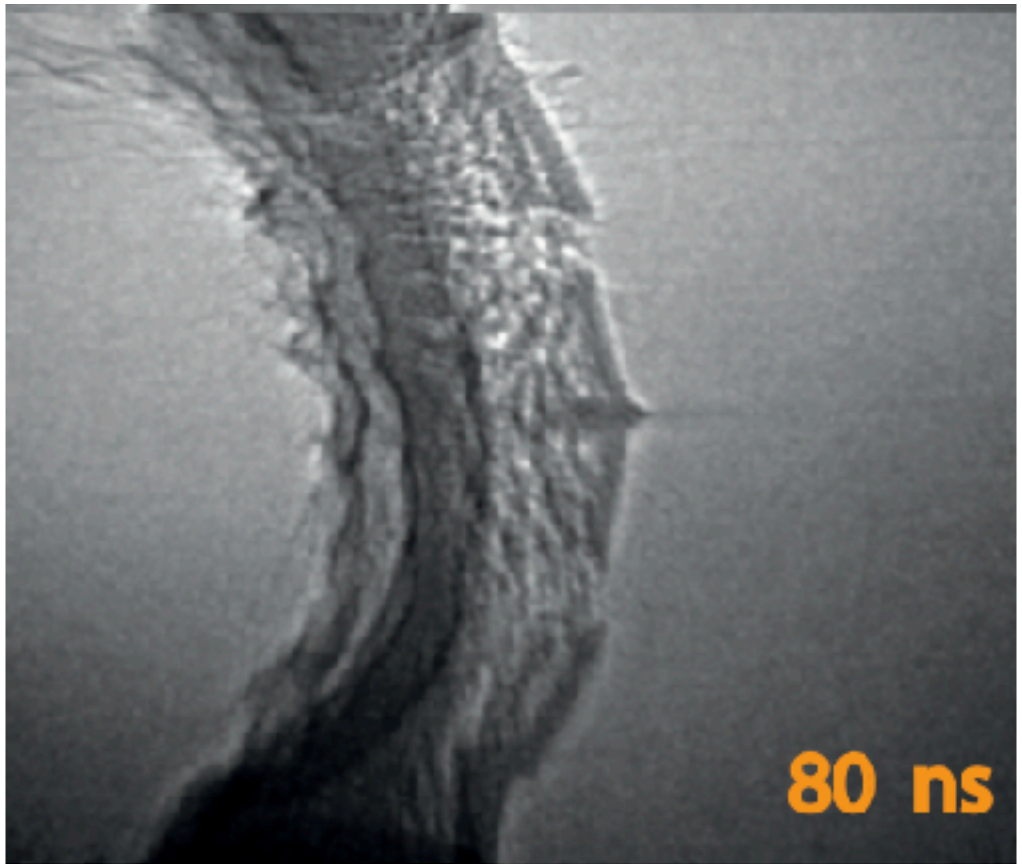
- LWFA produce X-rays "betatron radiation"
  - high-energy (10s keV);
  - broadband (synchrotron spectrum)
  - ultra-fast (femtosecond duration);
  - bright (> 10^9 photons per shot)

Co-location with other laser pulses makes laser wakefield accelerators tools for diverse experiments

Laser Wakefield Accelerators for Dynamic Imaging



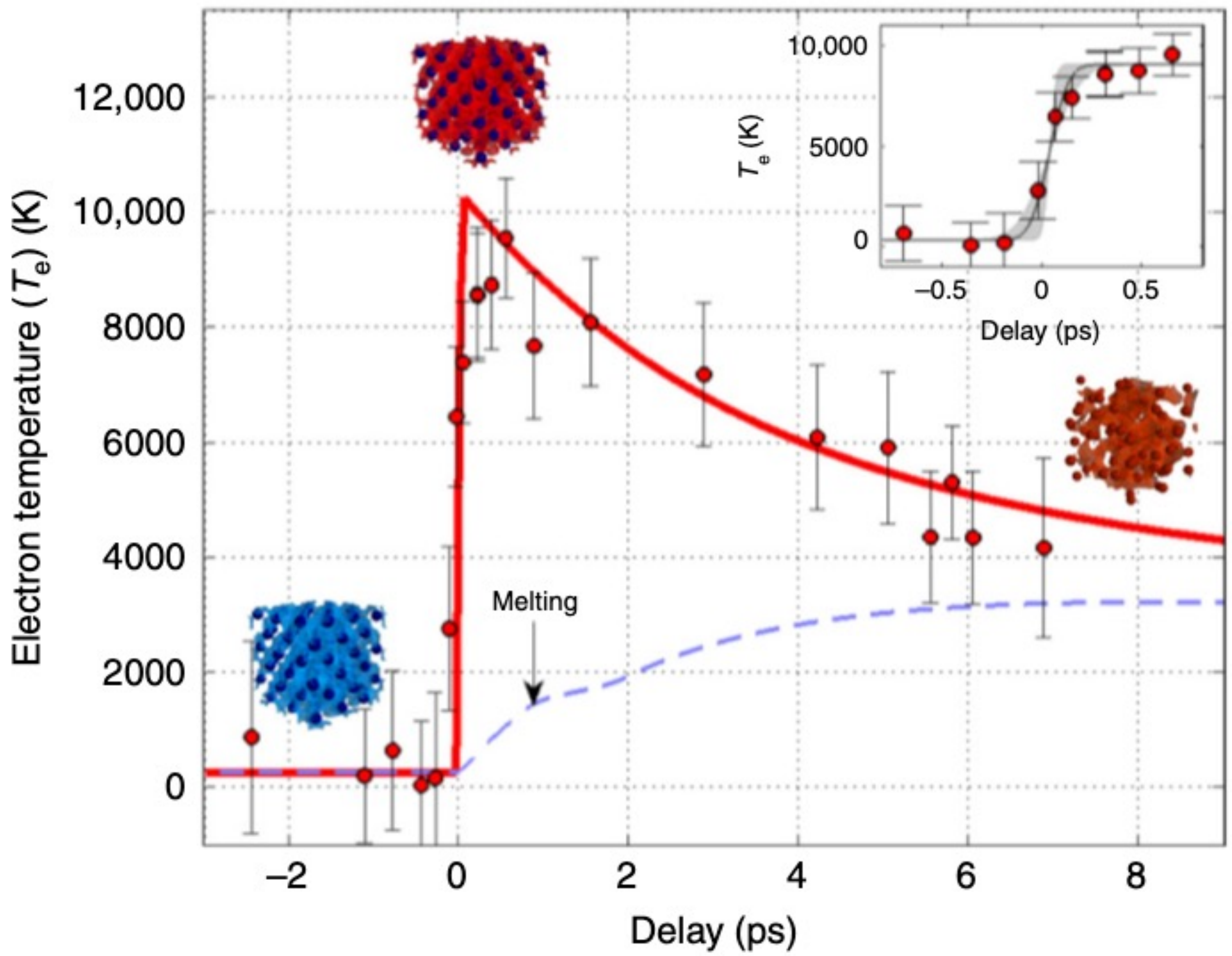
J Wood et al Sci Rep 8, 11010 (2018)



J Wood PhD Thesis, Imperial 2017

- Small (1 µm) source size enables use to make high resolution imaging of laser driven shocks

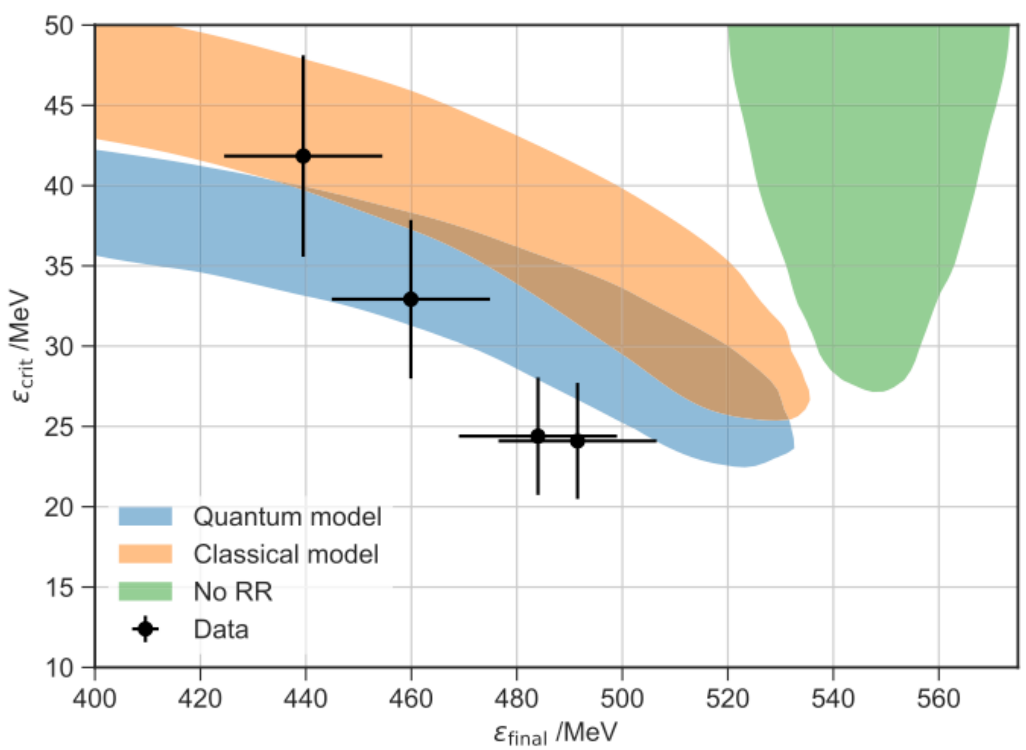
Co-location with other laser pulses makes laser wakefield accelerator tools for diverse experiments



Mahieu et al, Nat Comms **9**, 3276 (2018)

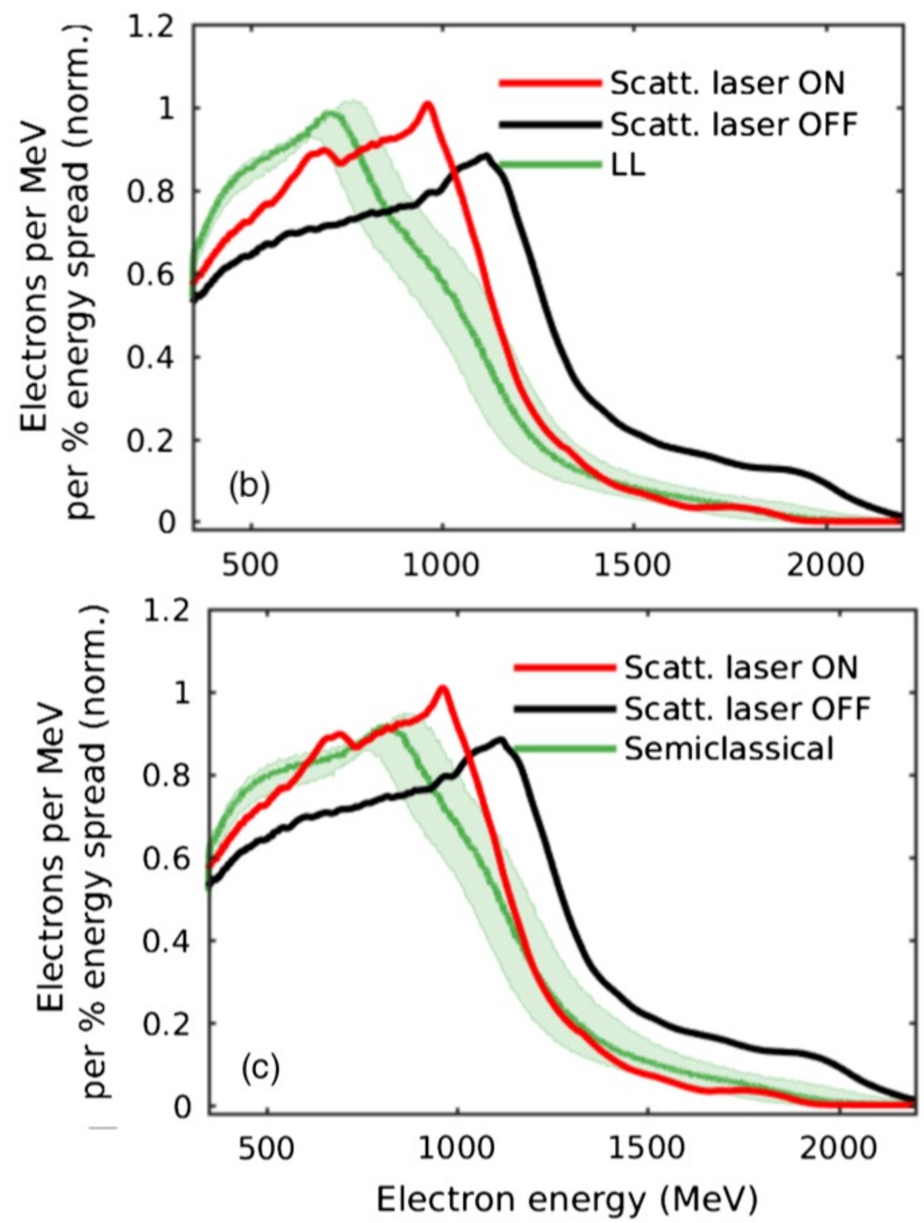
- X-rays generated by laser wakefield beams as ultrafast probe of dense matter
  - Non-equilibrium dynamics of matter in extreme conditions

Co-location with other laser pulses makes laser wakefield accelerator tools for diverse experiments



Cole et al, PRX **8**, 011020 (2018)

- Collisions between high intensity lasers and electrons can probe electrodynamics in extreme fields
  - experimental evidence for "radiation reaction"
  - Signatures of quantum nature of this in strong fields



Poder et al,
PRX **8**, 031004 (2018)

Summary

- This lecture has covered:
  - introduction to laser wakefield acceleration
    - driving plasma waves with lasers
    - Limits to acceleration with LWFA
    - Trends and status of L
- Any questions?

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