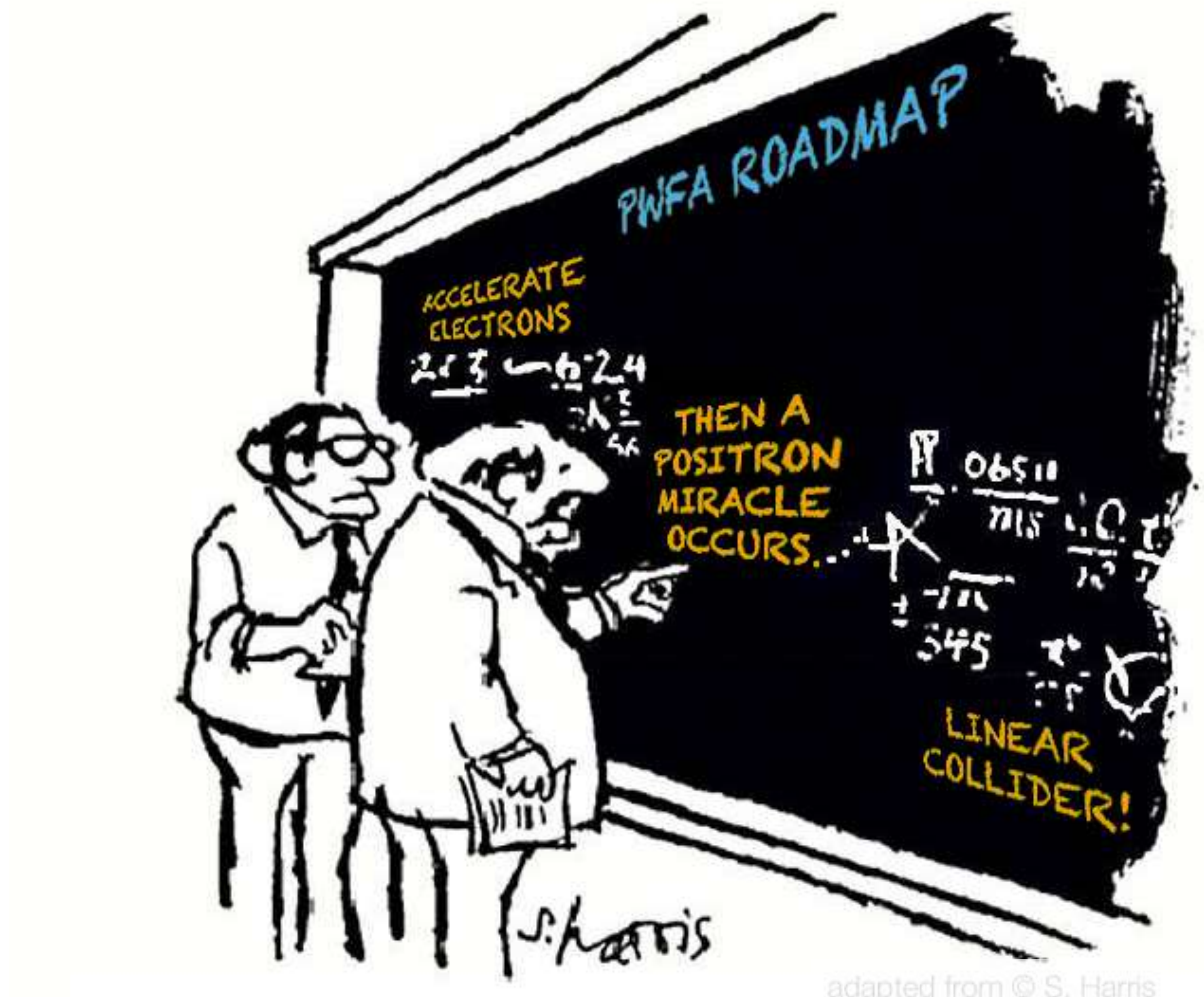


"I think you should be more explicit here in step two."

OVERVIEW OF

POSITRON ACCELERATION IN PLASMA-BASED ACCELERATORS

Dr. Carl A. Lindstrøm
Research Fellow at FLASHFORWARD
DESY.

OVERVIEW OF

POSITRON ACCELERATION IN PLASMA-BASED ACCELERATORS

Dr. **Carl A. Lindstrøm**

FLASHFORWARD▸▸ Research Fellow | Research Group for Plasma Wakefield Accelerators
Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany

PART 1:
THE POSITRON PROBLEM

COLLIDERS FOR HIGH ENERGY PHYSICS

- Particle colliders are the work horses of high energy physics.
  - Discovery machines — *proton–proton colliders*
  - Precision machines — *electron–positron colliders (next up)*
    - Model independent measurements of couplings etc.

- Proposed machines are extremely large
  - ILC: 31 km (0.5 TeV)
  - CLIC: 13–50 km (0.5–3 TeV)

- Energy limited by <u>cost</u> and <u>accelerating gradient.</u>
  - ~$10 billion is at the cost limit of science
  - Gradient of RF cavities limited to ~100 MV/m

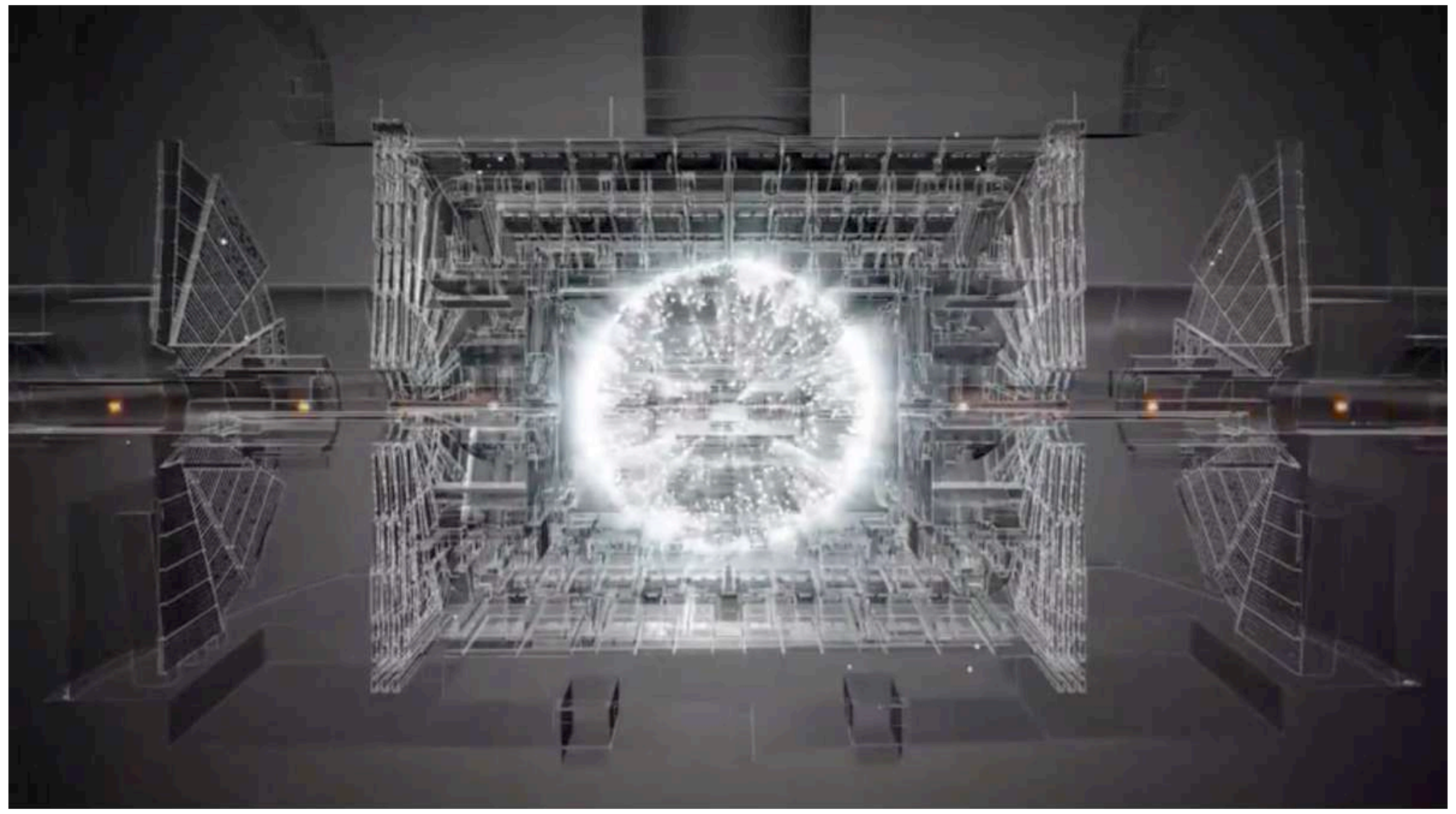


Image credit: CERN

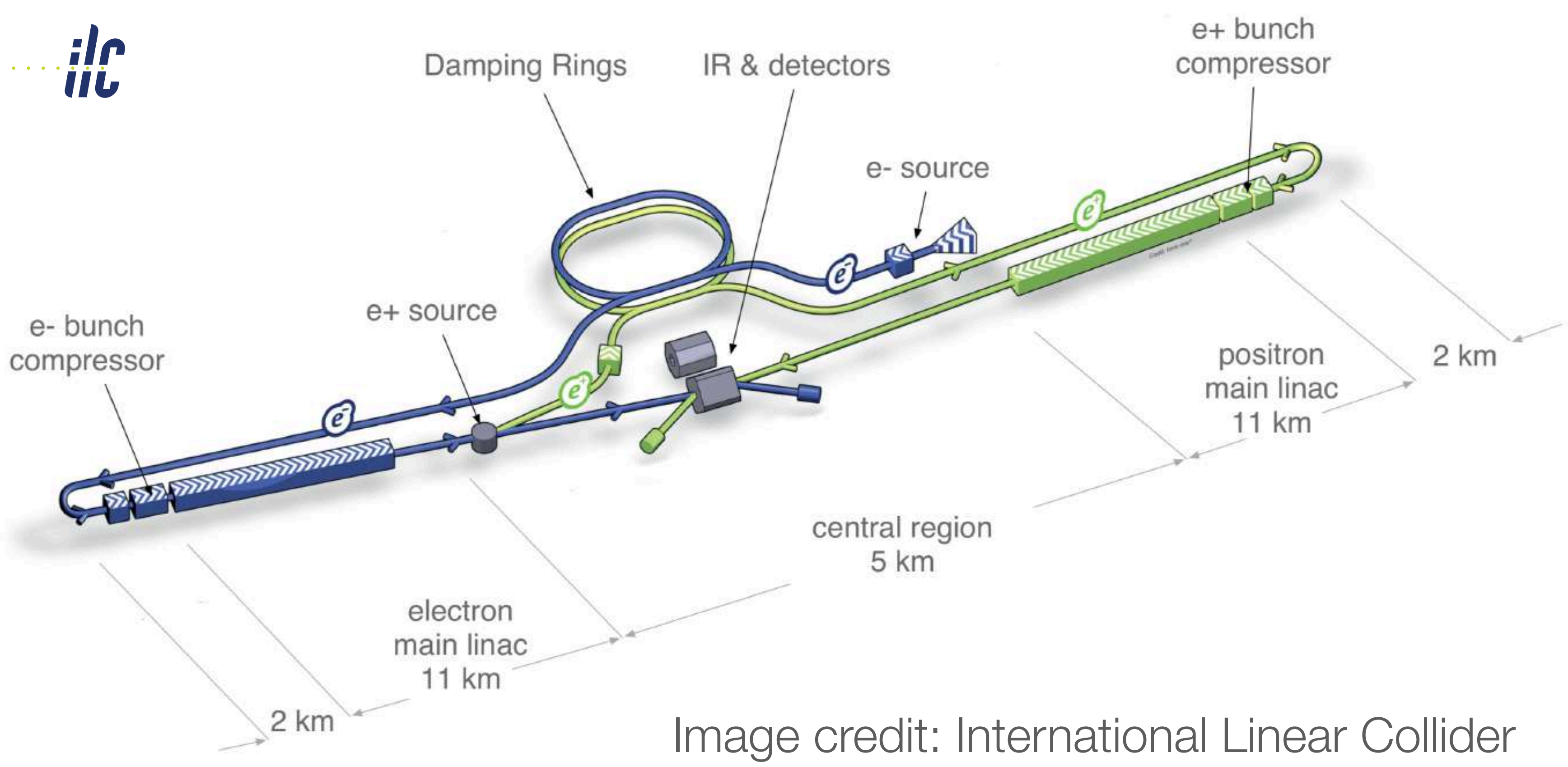
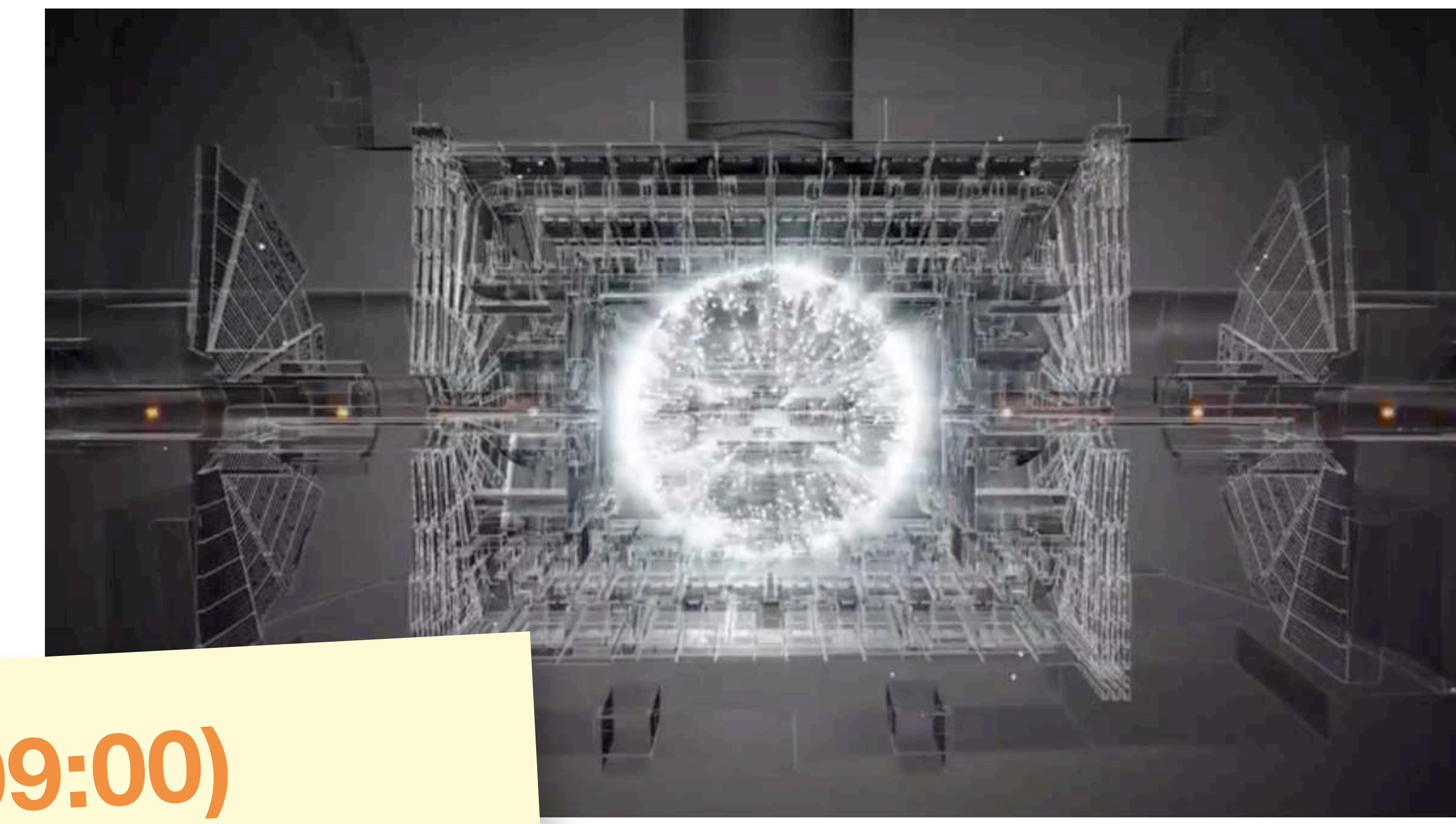


Image credit: International Linear Collider

Colliders for high energy physics



- Particle colliders are the work horses of high energy physics.
  - Discovery machines — *proton–proton colliders*
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    - Model independent measurements of couplings etc.

- Proposed machines are extremely
    - ILC: 31 km (0.5 TeV)
    - CLIC: 13–50 km (0.5–3 Te

Plenary talk **(Thursday 09:00)**

The road to very high energies

— Steinar Stapnes (CERN)

- Energy limited by <u>cost</u> and <u>accelerating gradient.</u>
    - ~$10 billion is at the cost limit of science
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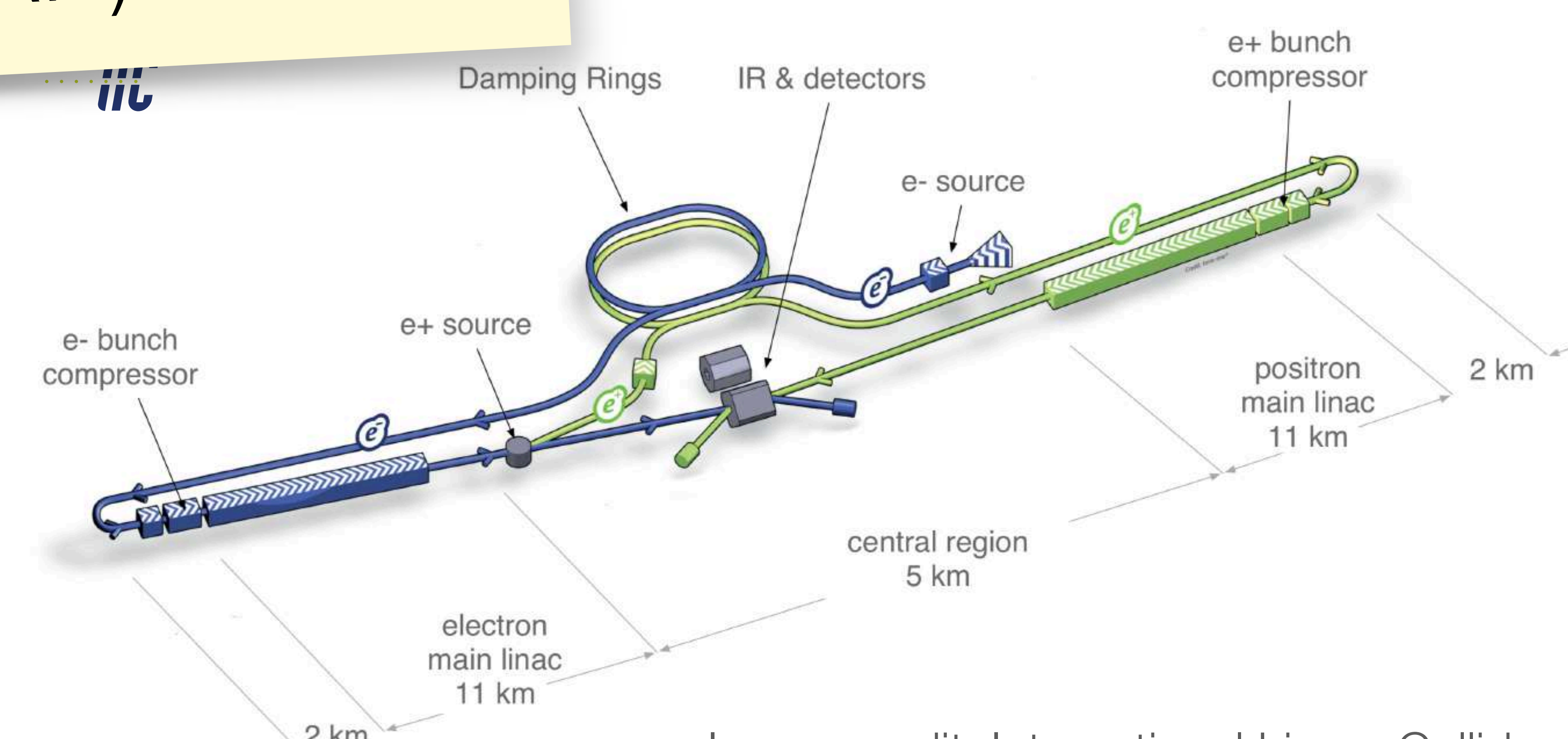

Image credit: International Linear Collider

REQUIREMENTS FOR A LINEAR COLLIDER

- **Fundamental physics requirements:**
  - High energy (TeV-scale) — *for the physics*
  - High luminosity (10^{34} cm^{-2} s^{-1} = 600 million events s^{-1}) — *for the statistics*
- **Practical funding requirements:**
  - High power efficiency (~10%) — *for the running costs*
  - High gradient (GV/m-scale) — *for the construction costs*

Nonlinear plasma wakefields — ideal for electron acceleration

> In theory a good match for colliders:

> **High gradients:** multi-GV/m

> **Beam loading:** high charge, high efficiency, low energy spread

> **Linear focusing fields:** emittance preservation

> **Beam-driven**: high wall-to-driver efficiency (~10%).

> PWFA experiments are catching up to theory:

> FFTB — High gradient (52 GV/m), high gain (42 GeV)

> FACET — Two bunches, high efficiency (~30% driver–witness)

> **FLASHForward, FACET-II — Emittance preservation,**
(in progress) **Total efficiency,**
Low energy spread

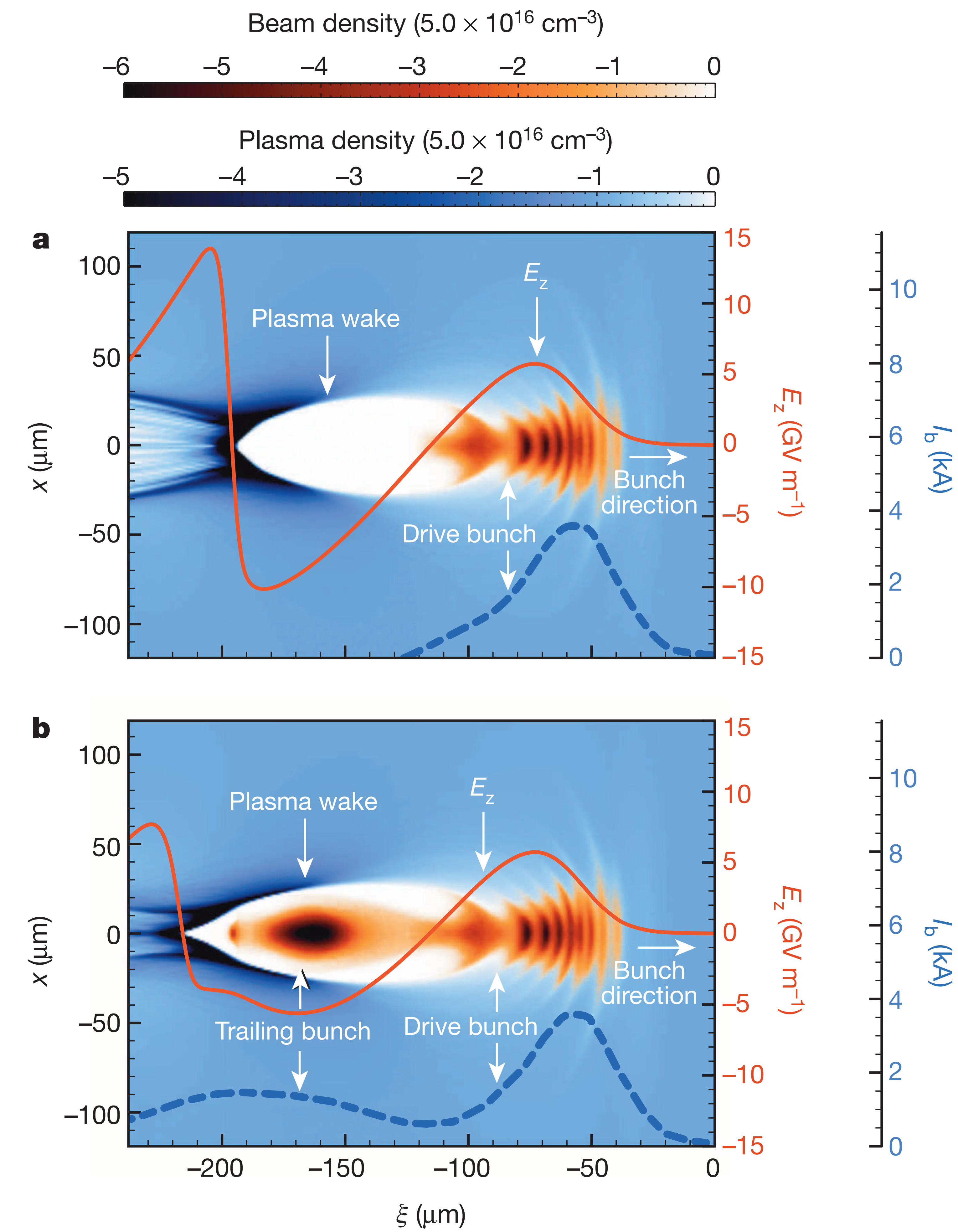

Image credit: M. Litos *et al.*, Nature 515, 92 (2014)

PLASMAS ARE ASYMMETRIC — POSITRONS NOT INVITED

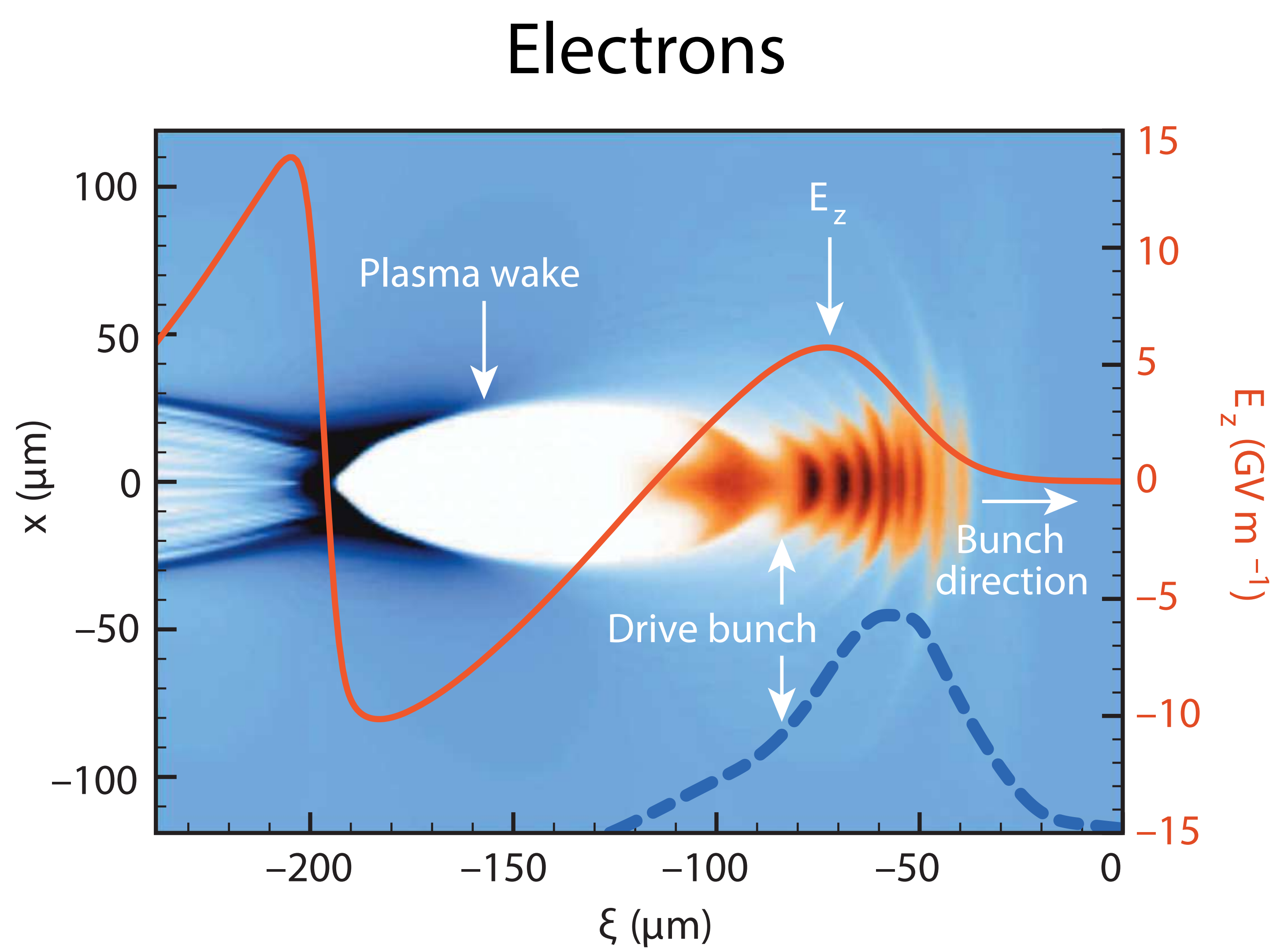

Image credit: M. Litos *et al.*, Nature 515, 92 (2014)

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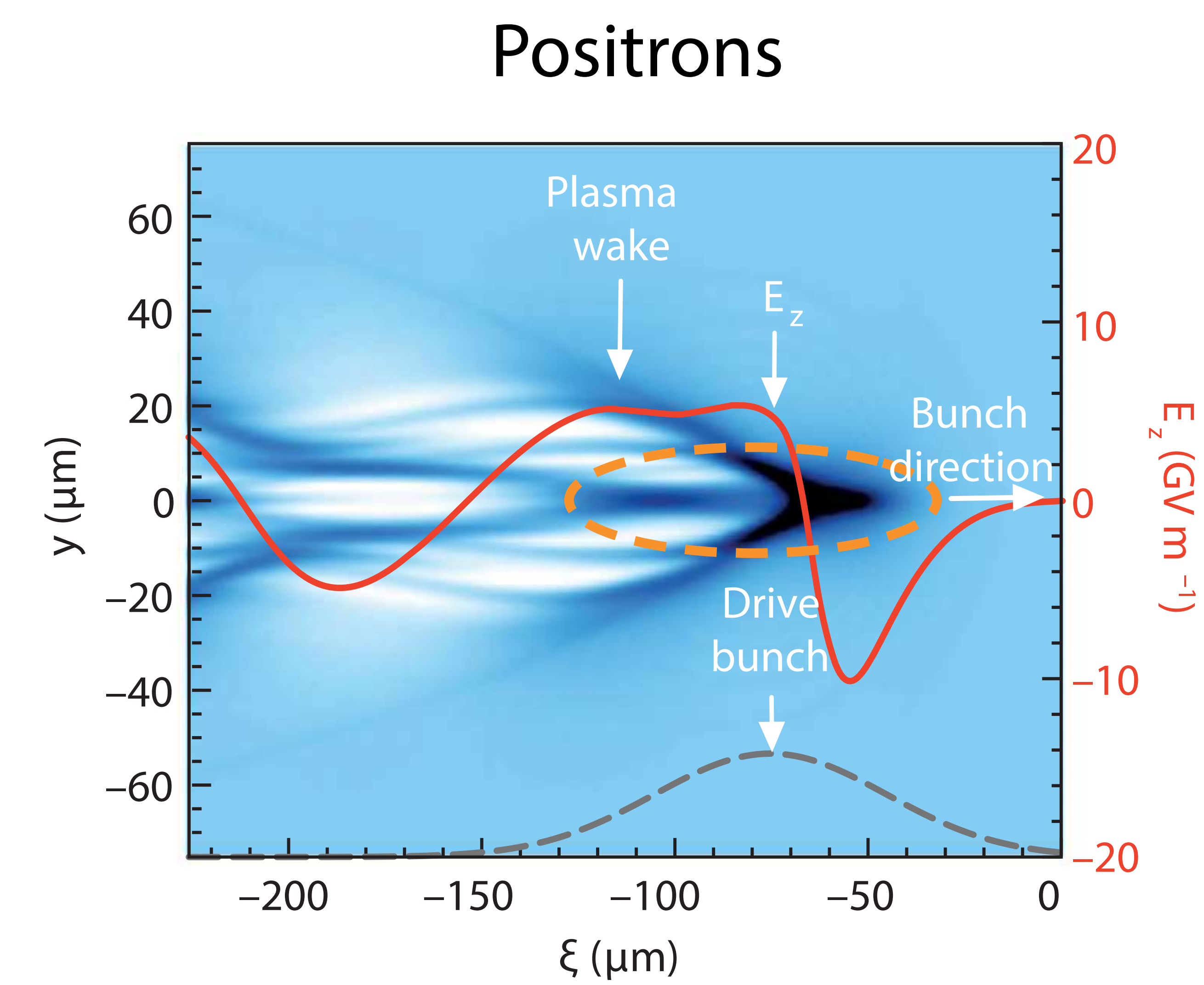


Image credit: S. Corde *et al.*, Nature 524, 442 (2015)

> Blowout regime — *defocusing for positrons*.

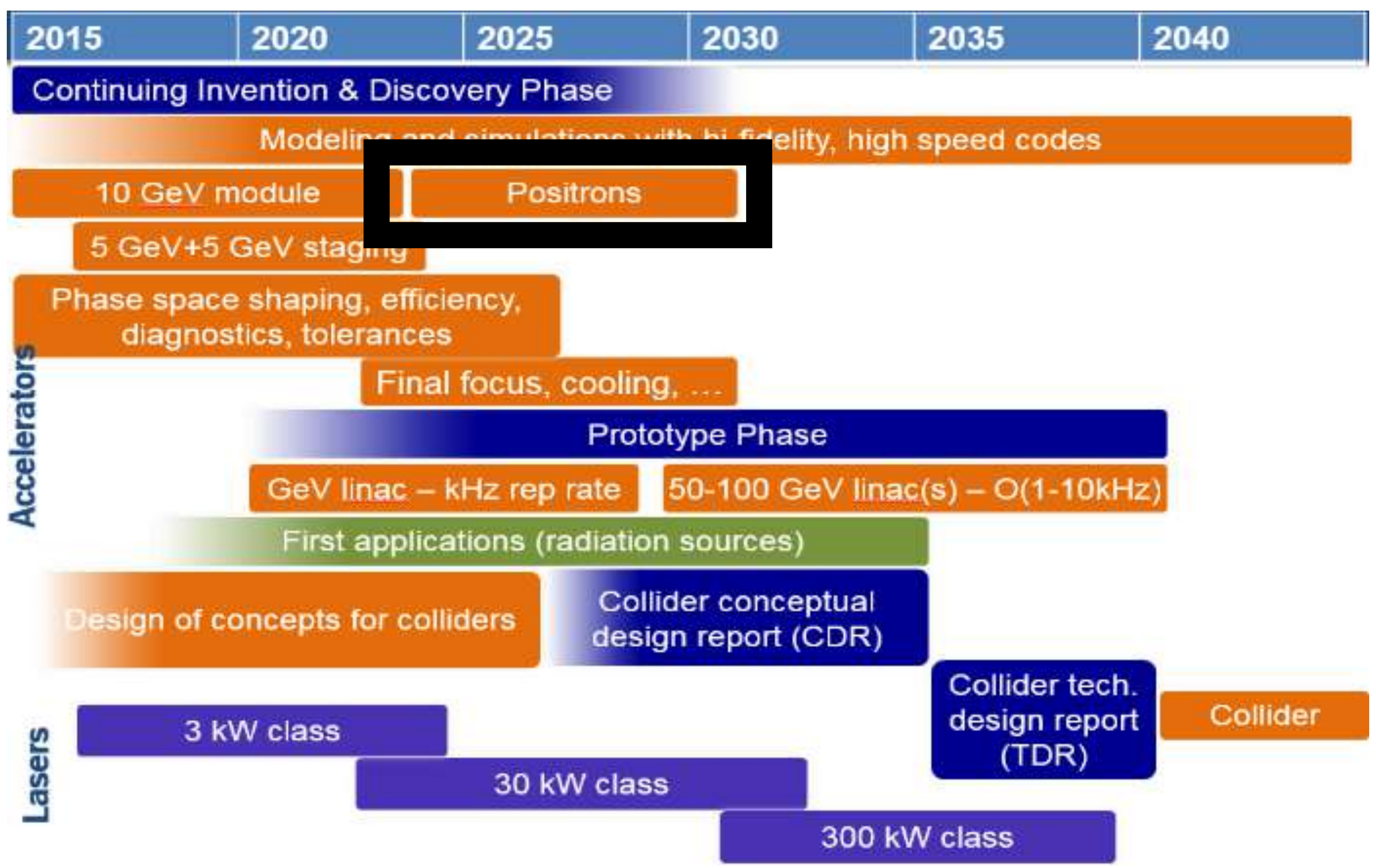
> The success for electrons does not translate to positrons — *need a new concept*.

> **The Positron Problem — Can positrons be efficiently accelerated at high gradient while preserving emittance?**

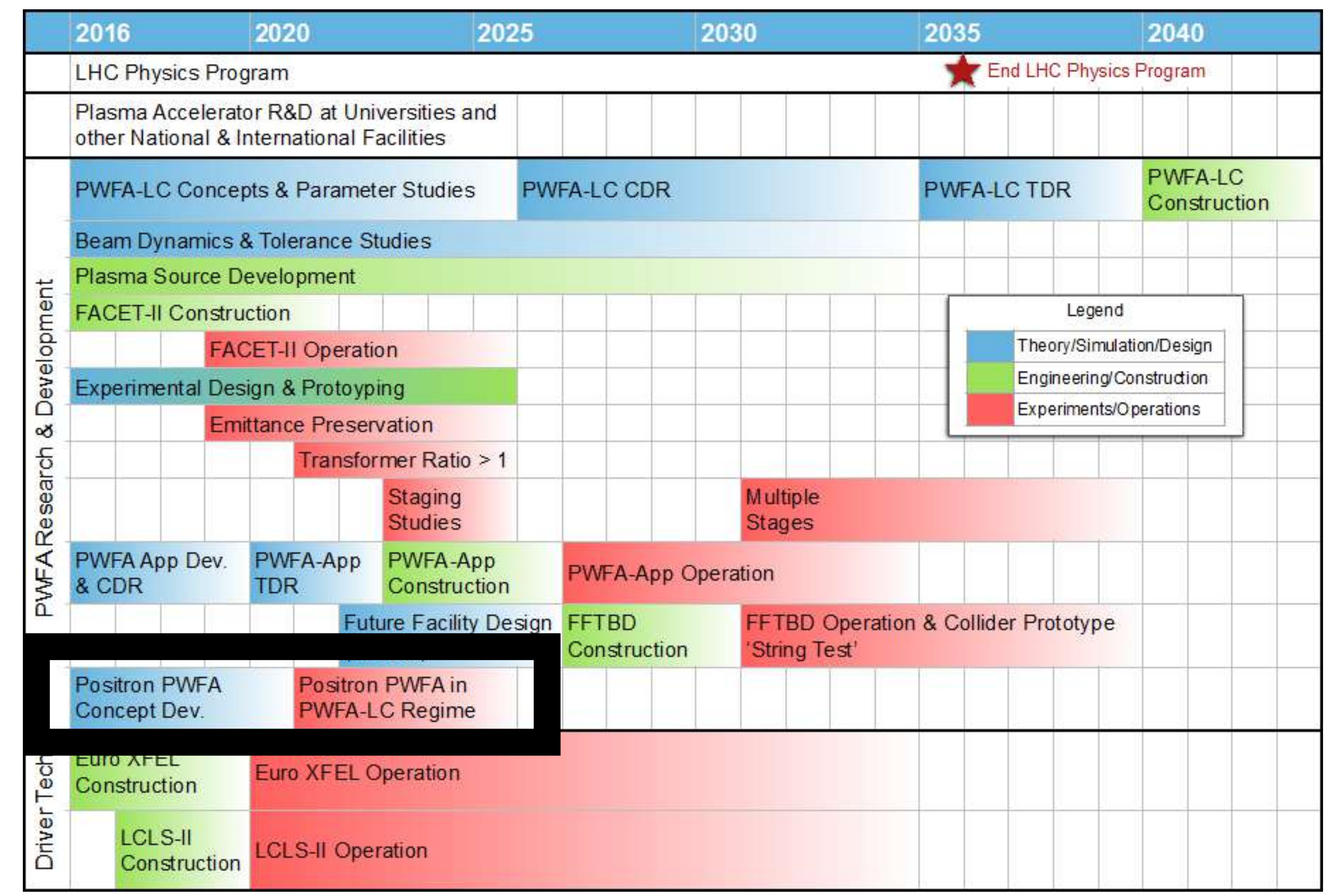
But promises were made…

E. R. Colby and L. K. Len, Rev. Accel. Sci. Technol. 9, 1 (2016).

> Plasma colliders road maps **assume positrons acceleration** will be developed soon.



Laser-driven plasma collider road map (LBNL)



Beam-driven plasma collider road map (SLAC)

> Increasing tension between promises and progress…

PART 2:
PROPOSED SOLUTIONS

CHOOSE YOUR POSITRON ADVENTURE!

LINEAR WAKEFIELDS

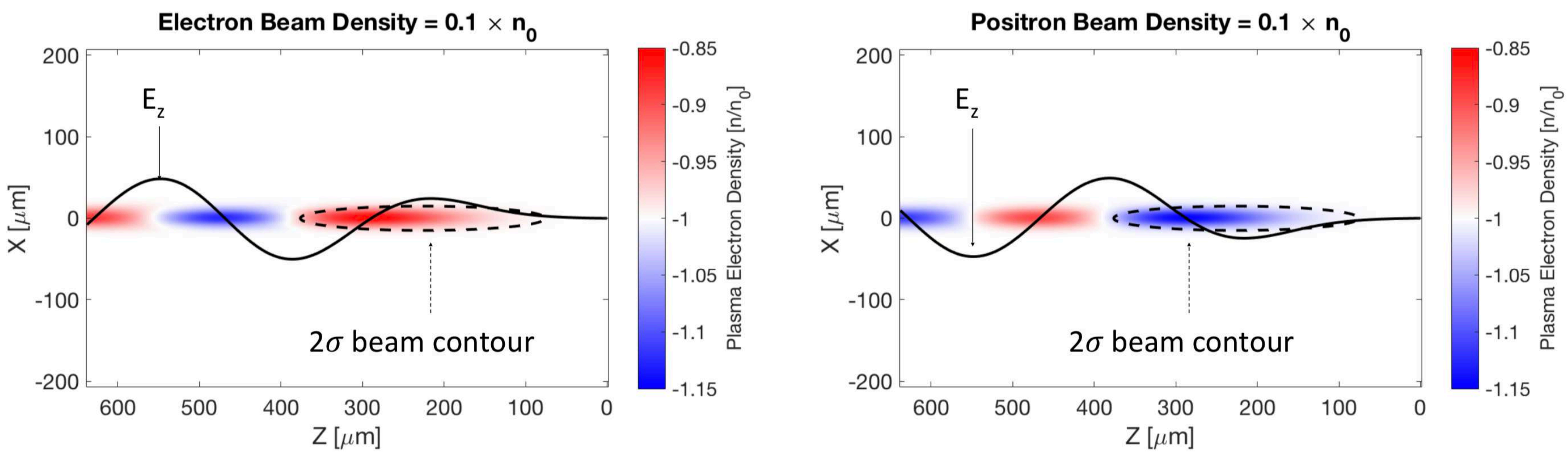


Image credit: S. Corde (QuickPIC)

> Symmetrizes the electron–positron plasma response

> **Acceleration and focusing of positrons is possible!**

LINEAR WAKEFIELDS — FFTB EXPERIMENTS (ACCELERATION)

B. Blue *et al.*, Phys. Rev. Lett. 90, 214801 (2003)

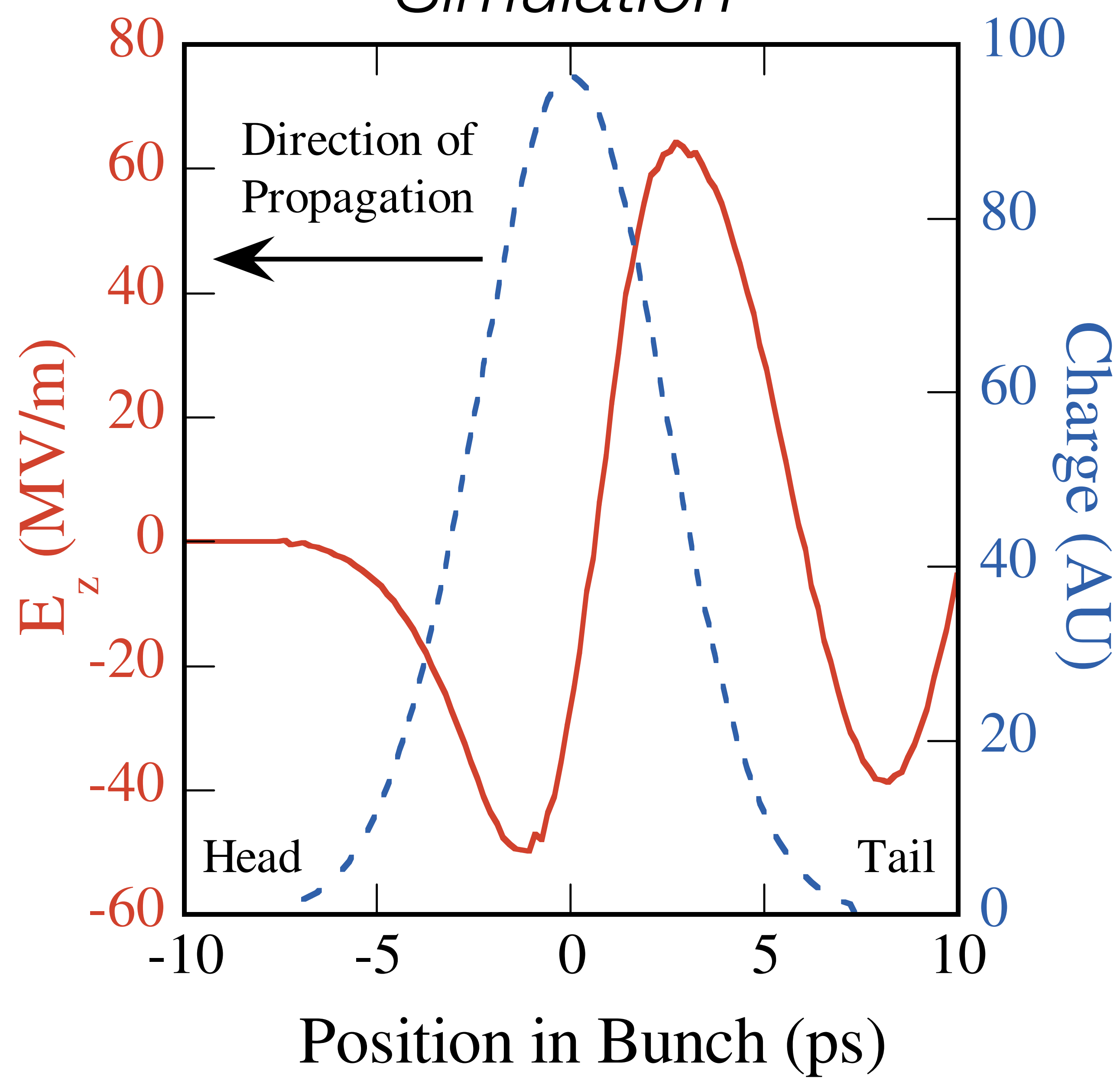
> Positron experiments performed at FFTB (SLAC):

> > High-energy (28.5 GeV), high-charge (3 nC), long bunches (700 μm rms).

> > Long plasma (1.4 m), medium density (1.8×10^{14} cm^{-3} => λ_p = 2.5 mm).

> **Observed linear plasma wakefields (E_z/E_{wb} ~ 0.05)** — *first positrons accelerated in a plasma!*

Simulation



Experiment

(dipole + streak camera)

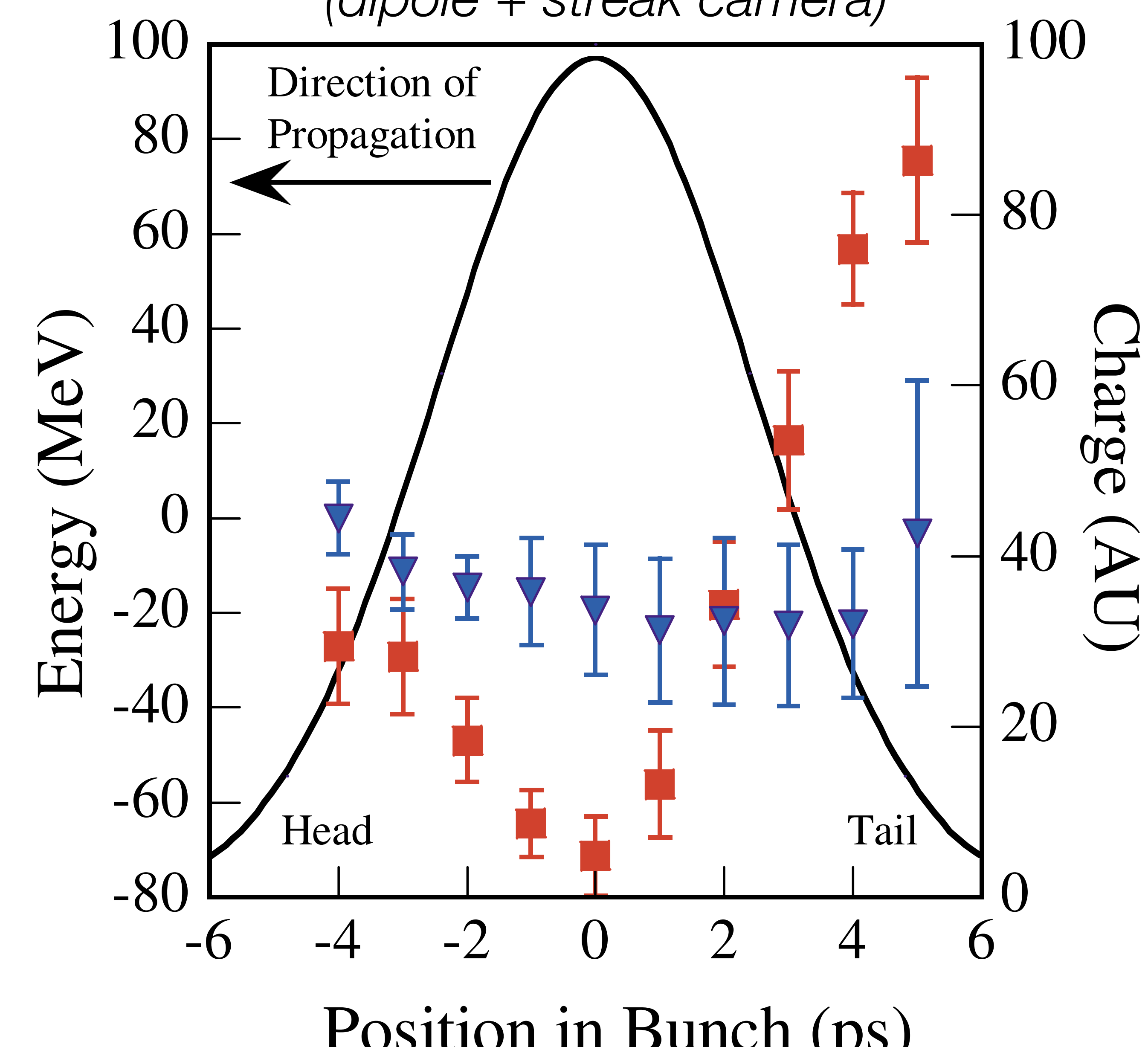


Image credit: B. Blue *et al.*, Phys. Rev. Lett. 90, 214801 (2003)

LINEAR WAKEFIELDS — AVOIDING COLLAPSE *REQUIRES* LARGE EMITTANCE

> High efficiency => high trailing beam current

> The trailing bunch is strongly focusing

> To avoid subsequent collapse
=> beta function must be matched

> Avoiding initial high beam density
=> large beam sizes must be used.

> **Resulting emittance is very large**

> *Example (simulation by W. An, 2018)*

> Plasma density 10^{16} cm^{-3}

Bunch	Charge	Bunch length	Peak current
Driver	2 nC	16 µm (rms)	15 kA
Trailing	1 nC	20 µm (rms)	6 kA

> Gradient: ~200 MV/m

> Normalized emittance: **4000 mm mrad**

> Can be avoided by using very small (low charge) bunches.

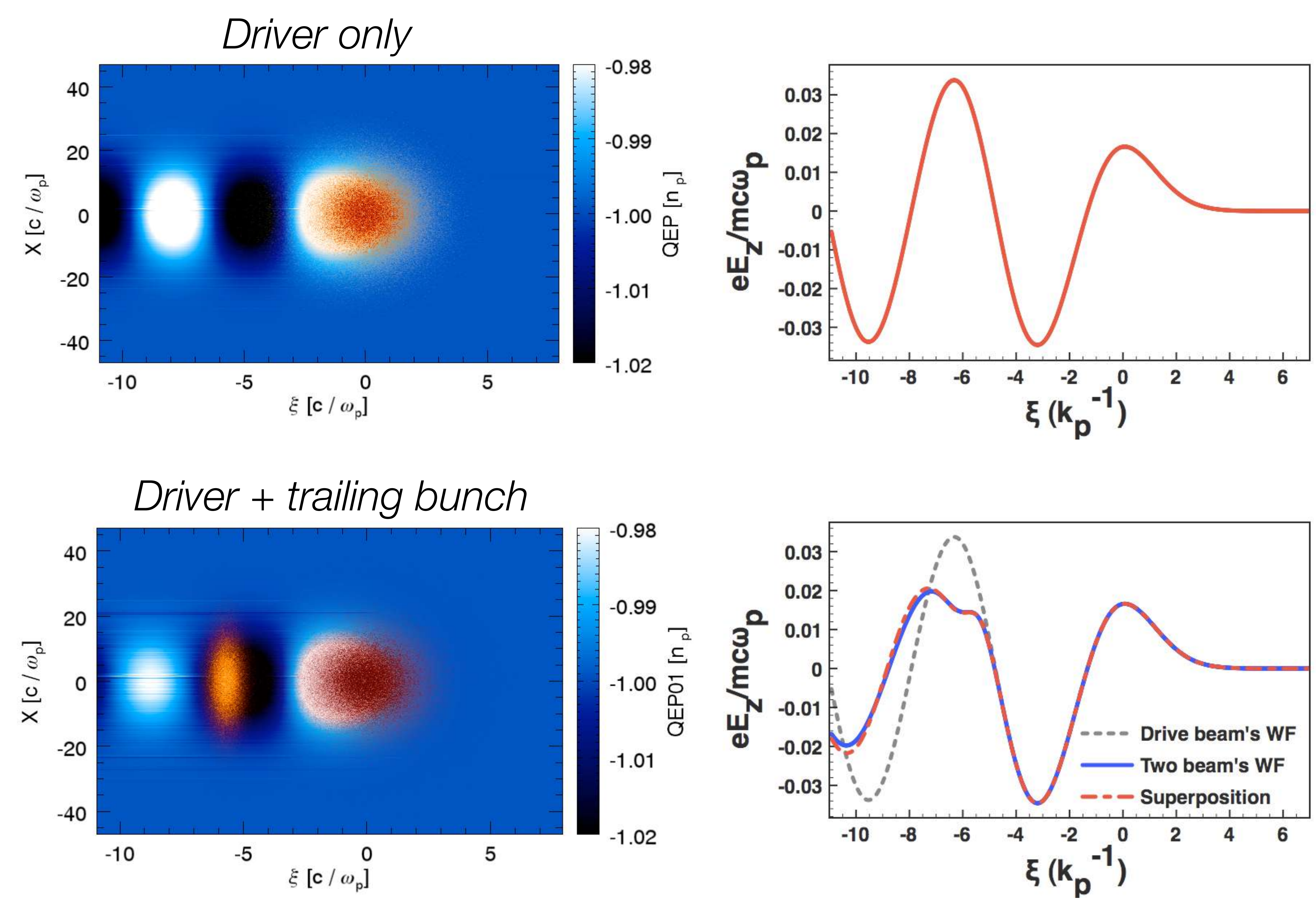


Image credit: QuickPIC simulations by W. An (2018)

> Linear regime <u>not suitable</u> for positron acceleration with high-efficiency, low emittance and high gradient

Linear (?) wakefields — FFTB experiments (Transport)

M. Hogan *et al.*, Phys. Rev. Lett. 90, 205002 (2003)
P. Muggli *et al.*, Phys. Rev. Lett. 101, 055001 (2008)

> Similar beam parameters as for acceleration experiments.

> *Low density experiments (< 7×10¹² cm⁻³)*

> **Slice dependent / nonlinear focusing** observed

> Tail focused with 7×n_e (background electron density)

> **Evidence of an axial density spike.**

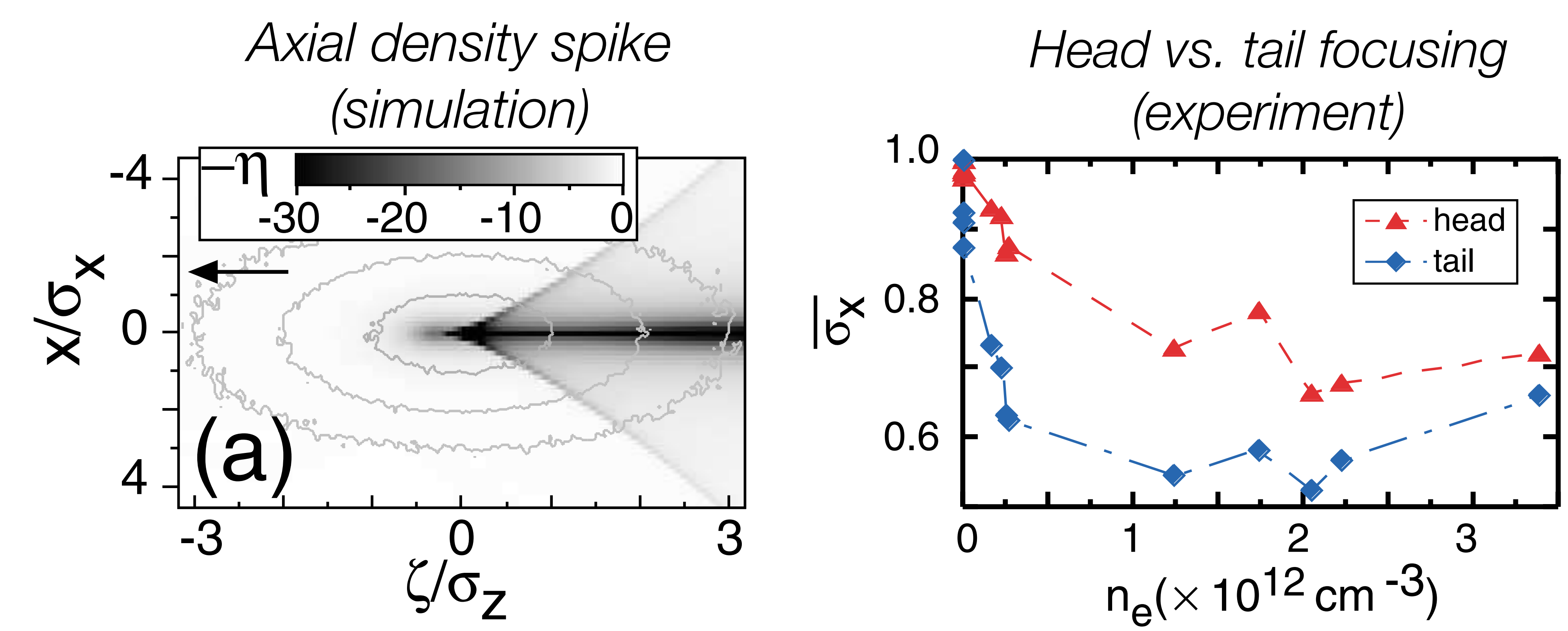


Image credit: M. Hogan *et al.*, Phys. Rev. Lett. 90, 205002 (2003)

> *Higher density experiments (7×10¹³ cm⁻³)*

> Non-Gaussian beam halo forms, containing ~40% of the charge.

> **Results in large emittance growth.**

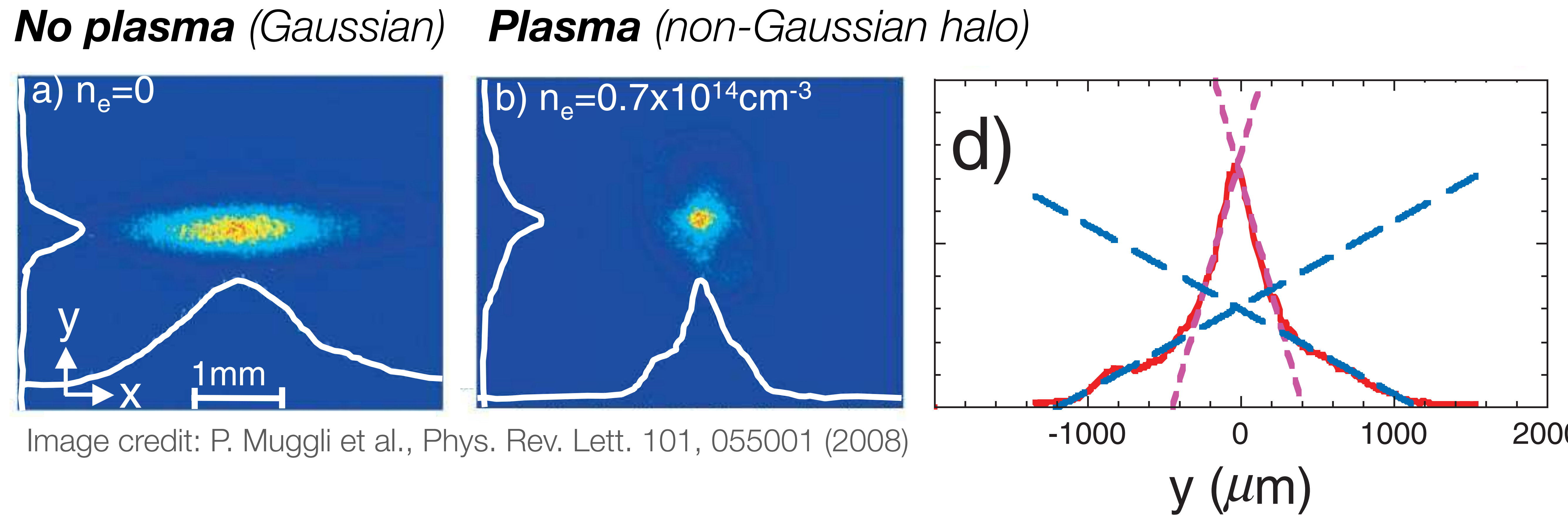


Image credit: P. Muggli et al., Phys. Rev. Lett. 101, 055001 (2008)

STRONGLY NONLINEAR WAKEFIELDS (POSITRON-DRIVEN)

- *Tactic: Embrace the nonlinearity!*
- Intense positron bunches => **blowout-like structure forms** after plasma electrons cross the axis.
- Large accelerating gradients, but the accelerating phase is **defocusing**.
- Strong beam loading: **The accelerating beam self-focuses by "trapping" electrons on axis —** *"self-loaded regime"*

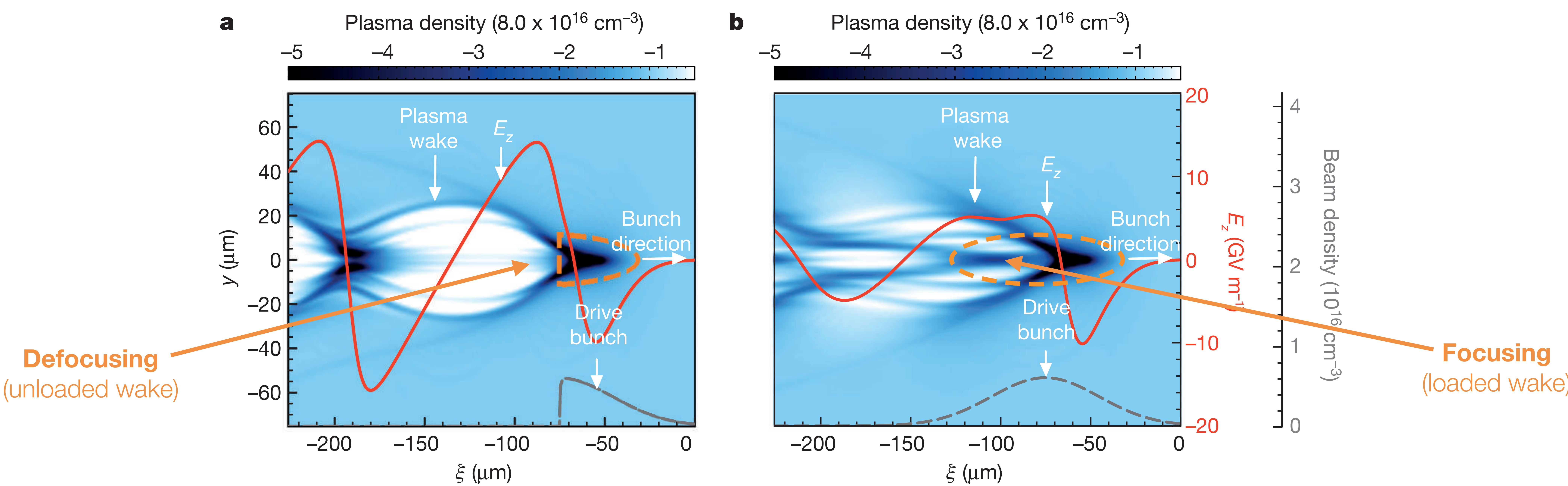


Image credit: S. Corde *et al.*, Nature 524, 442 (2015)

SELF-LOADED REGIME — FACET EXPERIMENTS

S. Corde *et al.*, Nature 524, 442 (2015)
A. Doche *et al.*, Sci. Rep. 7, 14180 (2017)

- High-energy (20 GeV), high charge (2.2 nC), **compressed bunches** (30–50 µm rms)
- Long (1.15 m), **high-density** (8×10^{16} cm^{-3}) plasma channel.
- Single bunch experiment:
  - **Large energy gain observed: ~5 GeV (3.8 GV/m)**
  - **Low energy spread** (~2% spectral peak)
  - **High energy efficiency** (~30%)
- Also successfully performed a two-bunch experiment

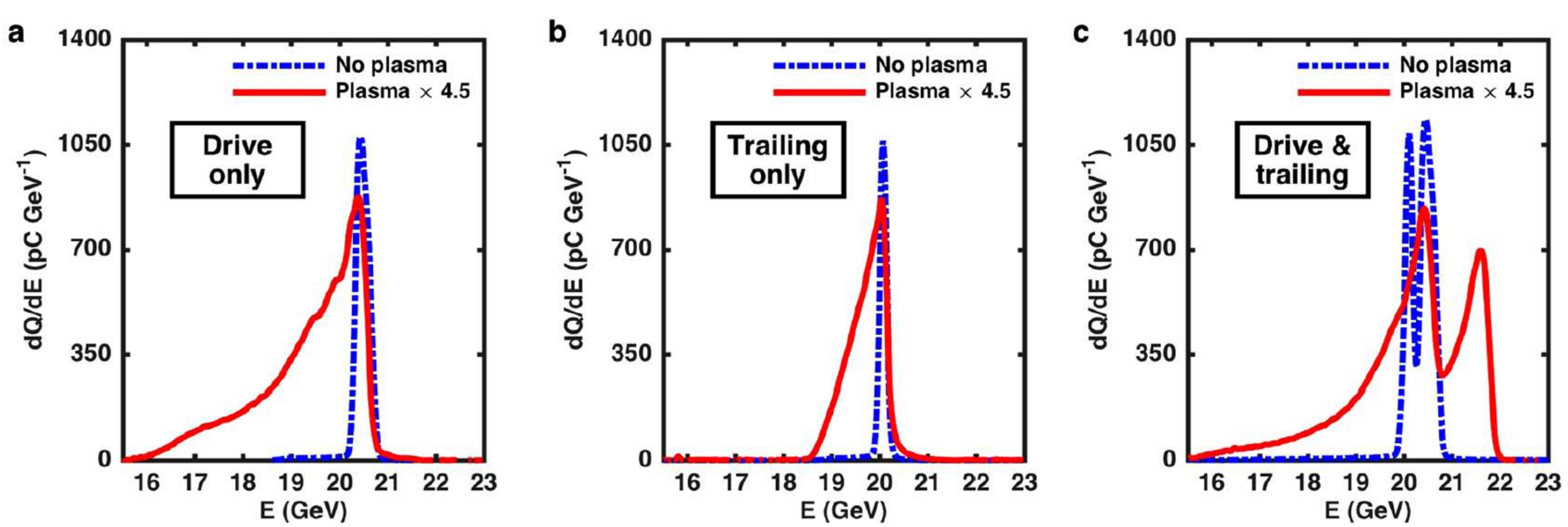


Image credit: A. Doche *et al.*, Sci. Rep. 7, 14180 (2017)

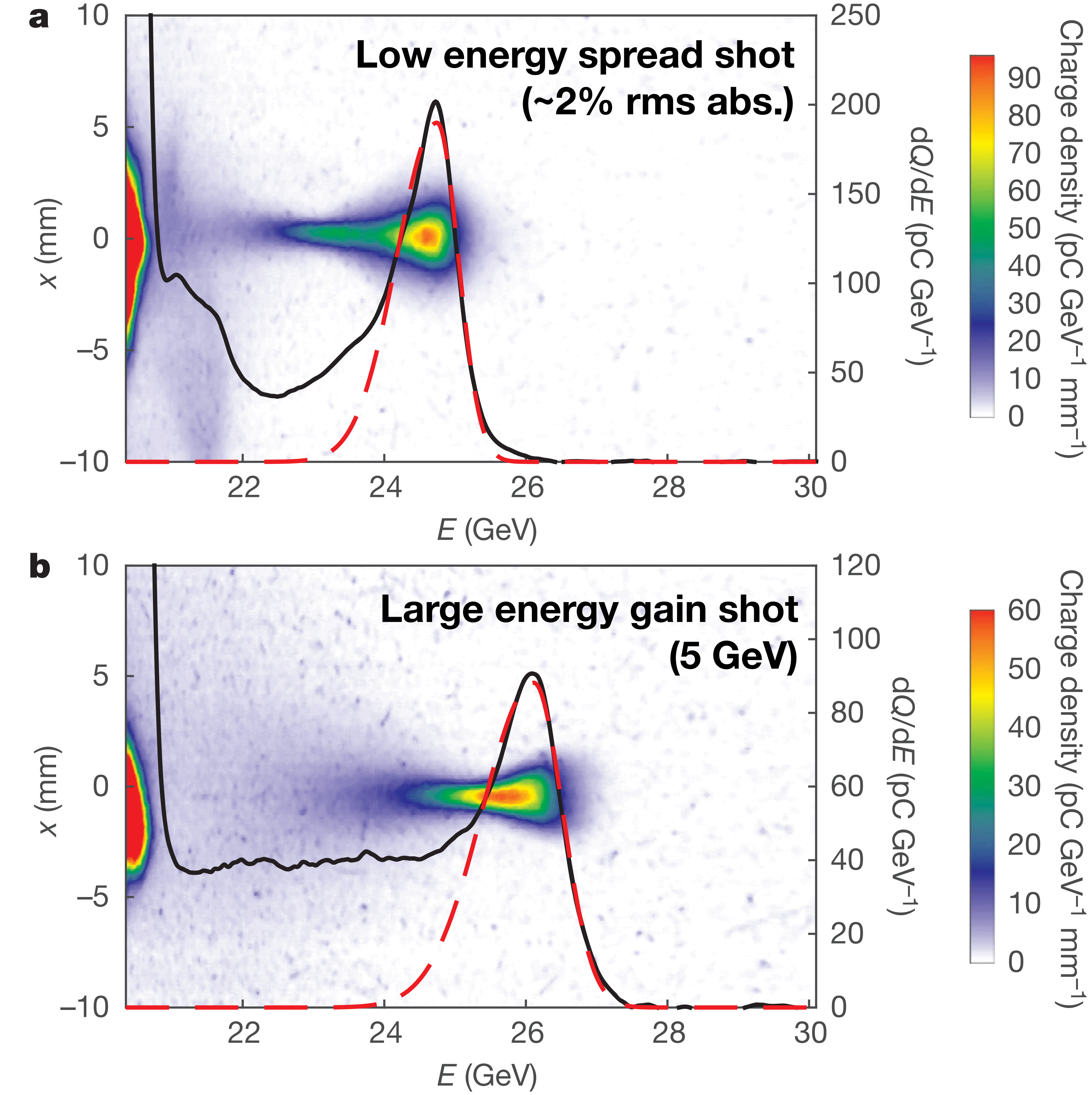


Image credit: S. Corde *et al.*, Nature 524, 442 (2015)

Self-loaded regime — Emittance growth and equilibrium shapes

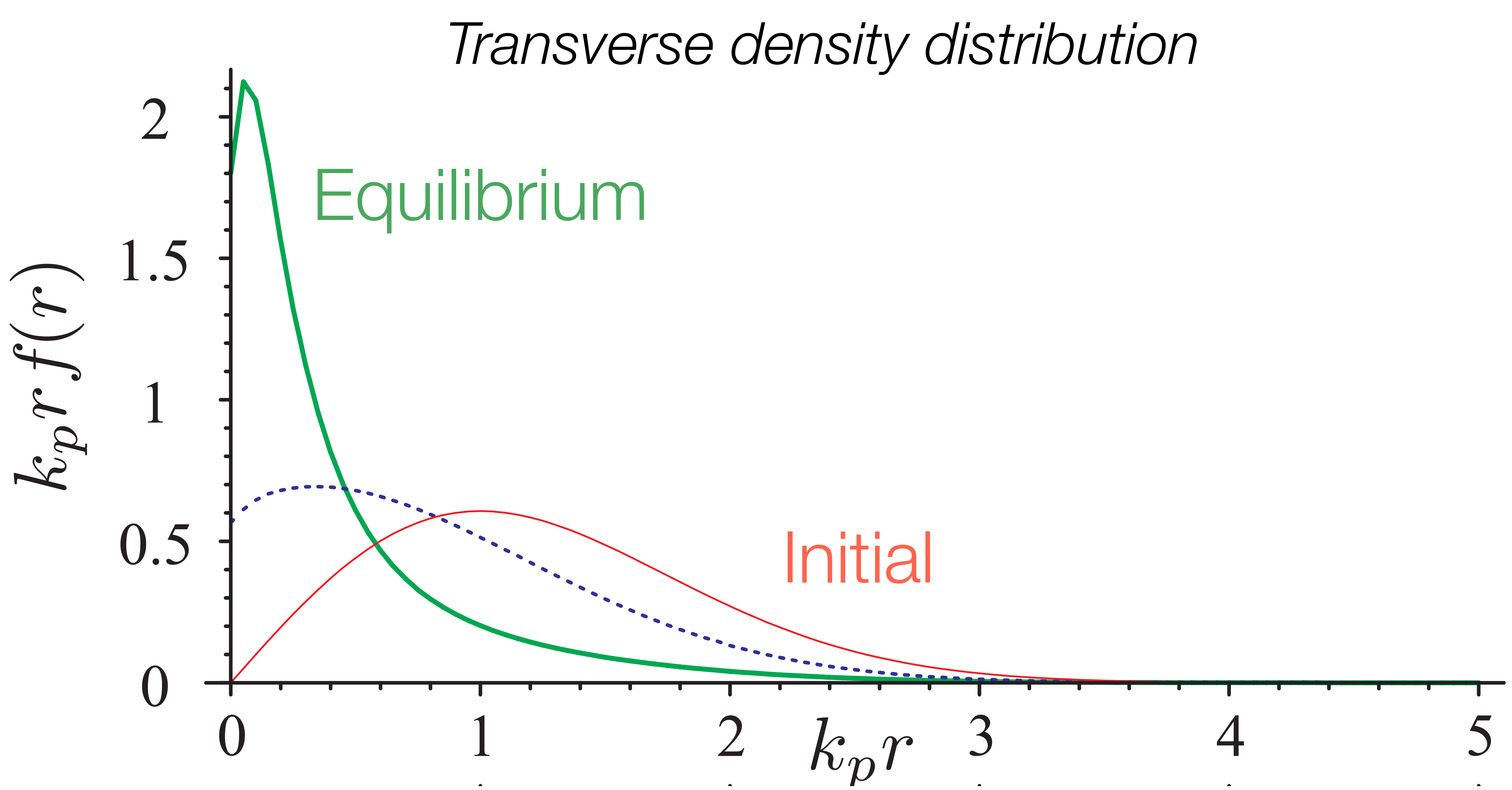
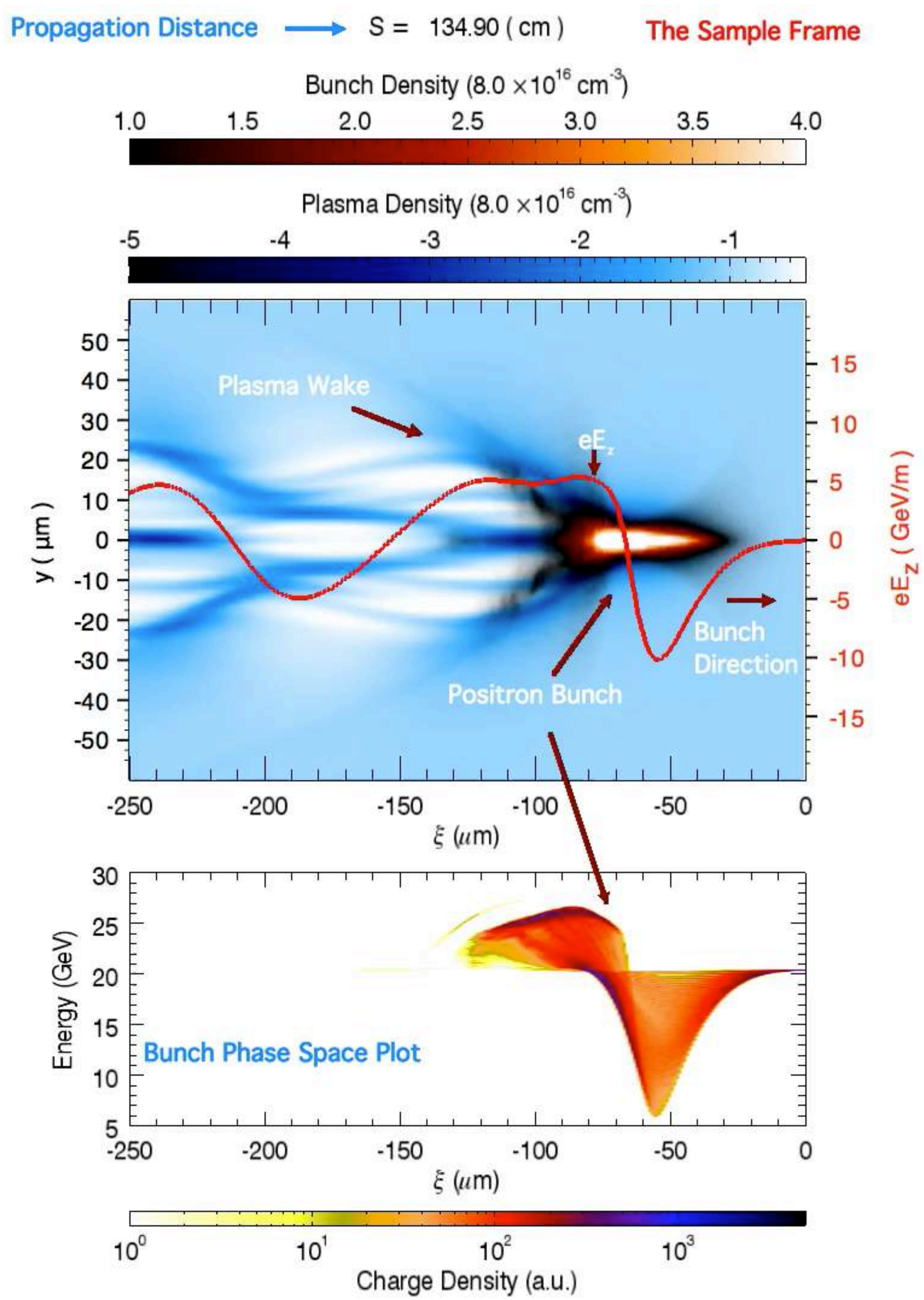


Image credit: K. Lotov, Phys. Plasmas 24, 023119 (2017)



> Eventually reaches a **non-Gaussian equilibrium shape** — large emittance growth expected.

> > *In FACET experiments, equilibrium was reached after ~30 cm of plasma.*

> Important question: **Is it possible to match directly to the equilibrium shape with a low-emittance beam?**

Nonlinear wakefields — electron-driven, finite channel radius

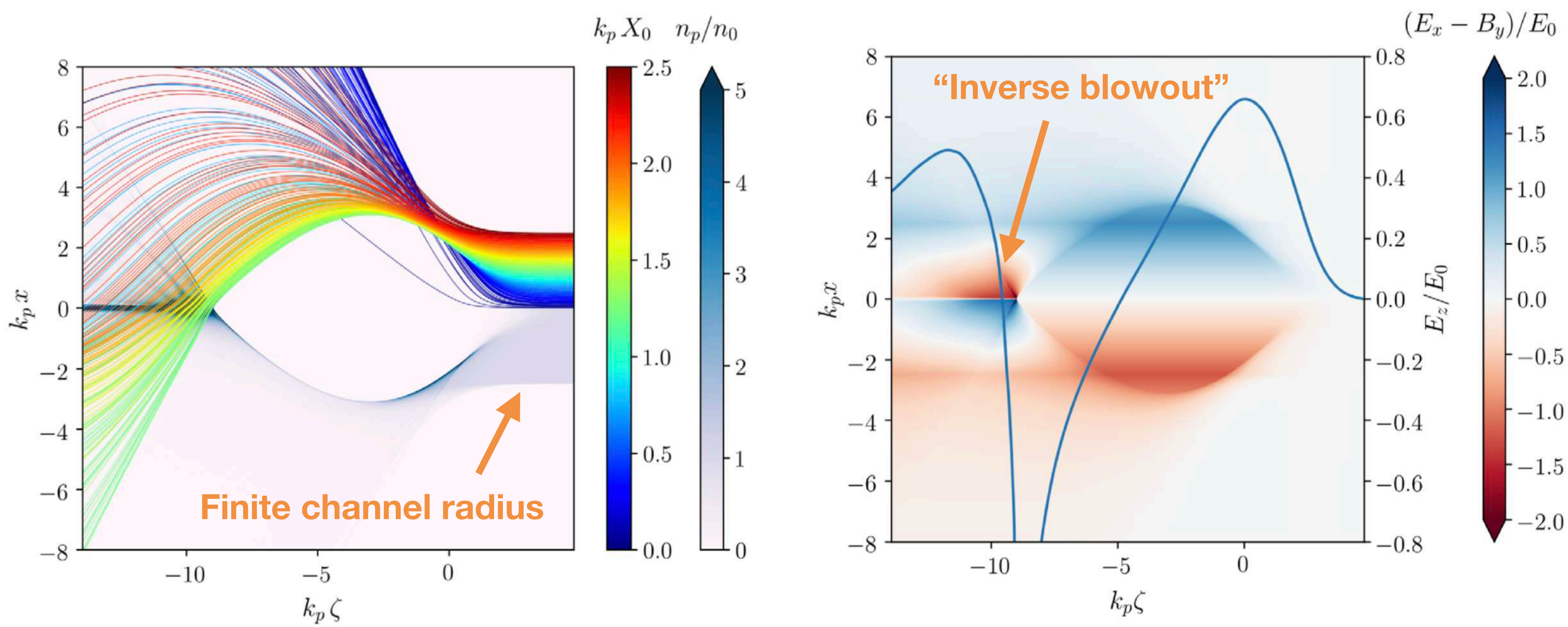
S. Diederichs *et al.*, PRAB 22, 081301 (2019)

> **What happens to a blowout if we restrict the plasma column radius?**

> Blown-out electrons from different radii have different trajectories — *do not form a single sheath!*

> The plasma electron axis-crossing is stretched out — an "inverse blowout" forms behind the blowout!

> Positrons can be accelerated and focused simultaneously!



> **Recent theoretical development (2019)— no experiments yet.**

Strongly nonlinear wakefields (electron-driven) — finite channels

S. Diederichs *et al.*, PRAB 22, 081301 (2019)

- Positrons are attracted by on-axis electron density spike
  - Non-linear focusing (step-function), but emittance can be preserved.
- Difference to other schemes: on-axis electrons are ~relativistic
- Current research questions:
  - Emittance preservation for high beam loading (high efficiency)?
  - Stability to misalignments?

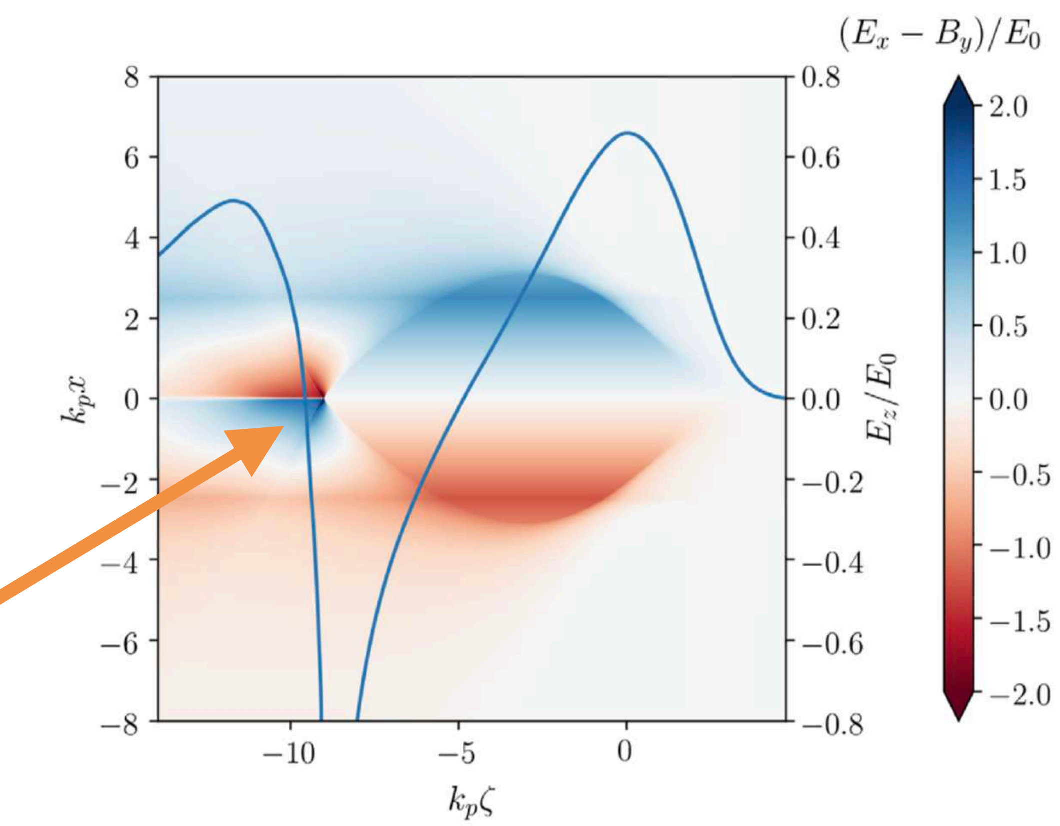
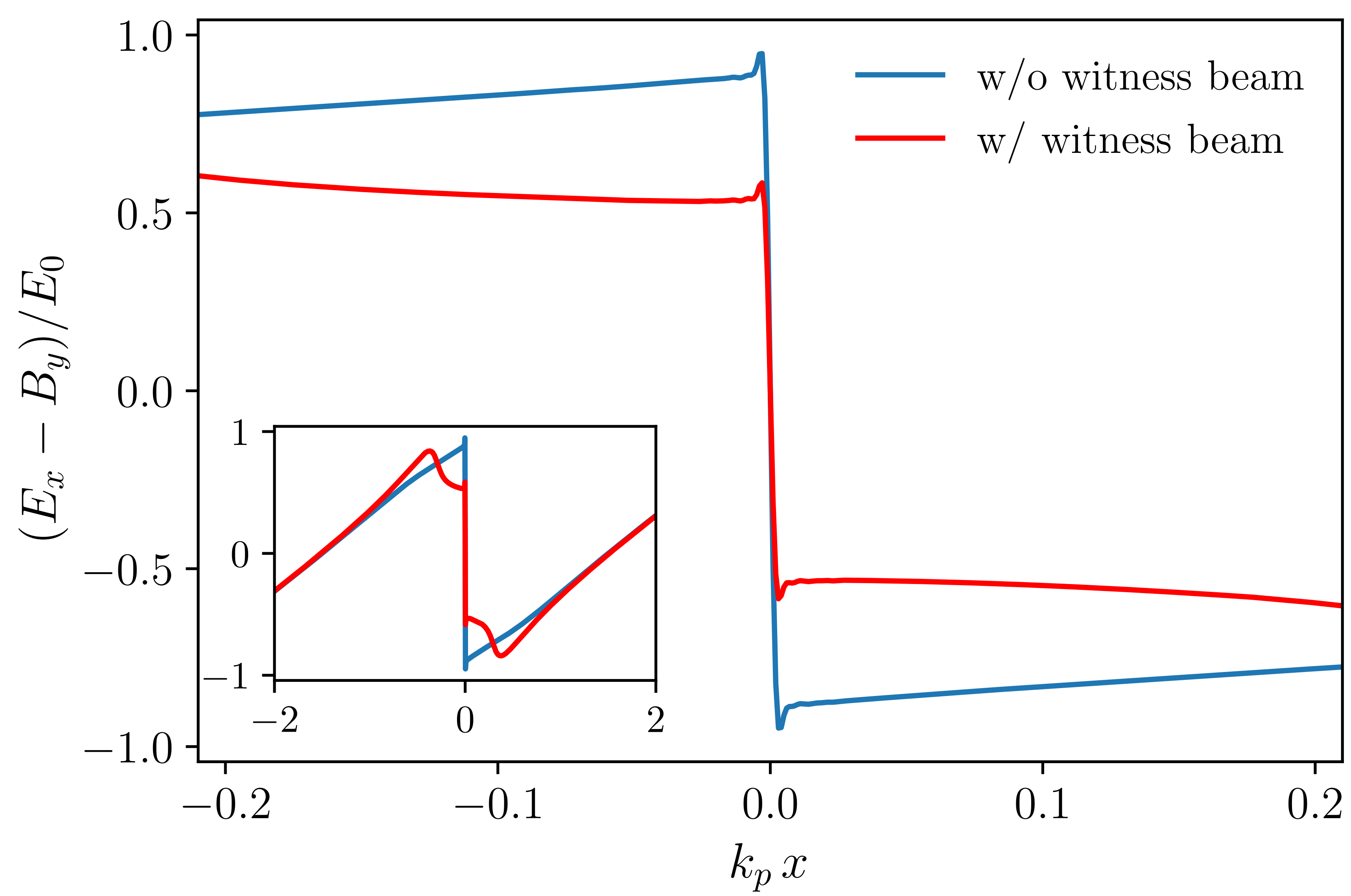
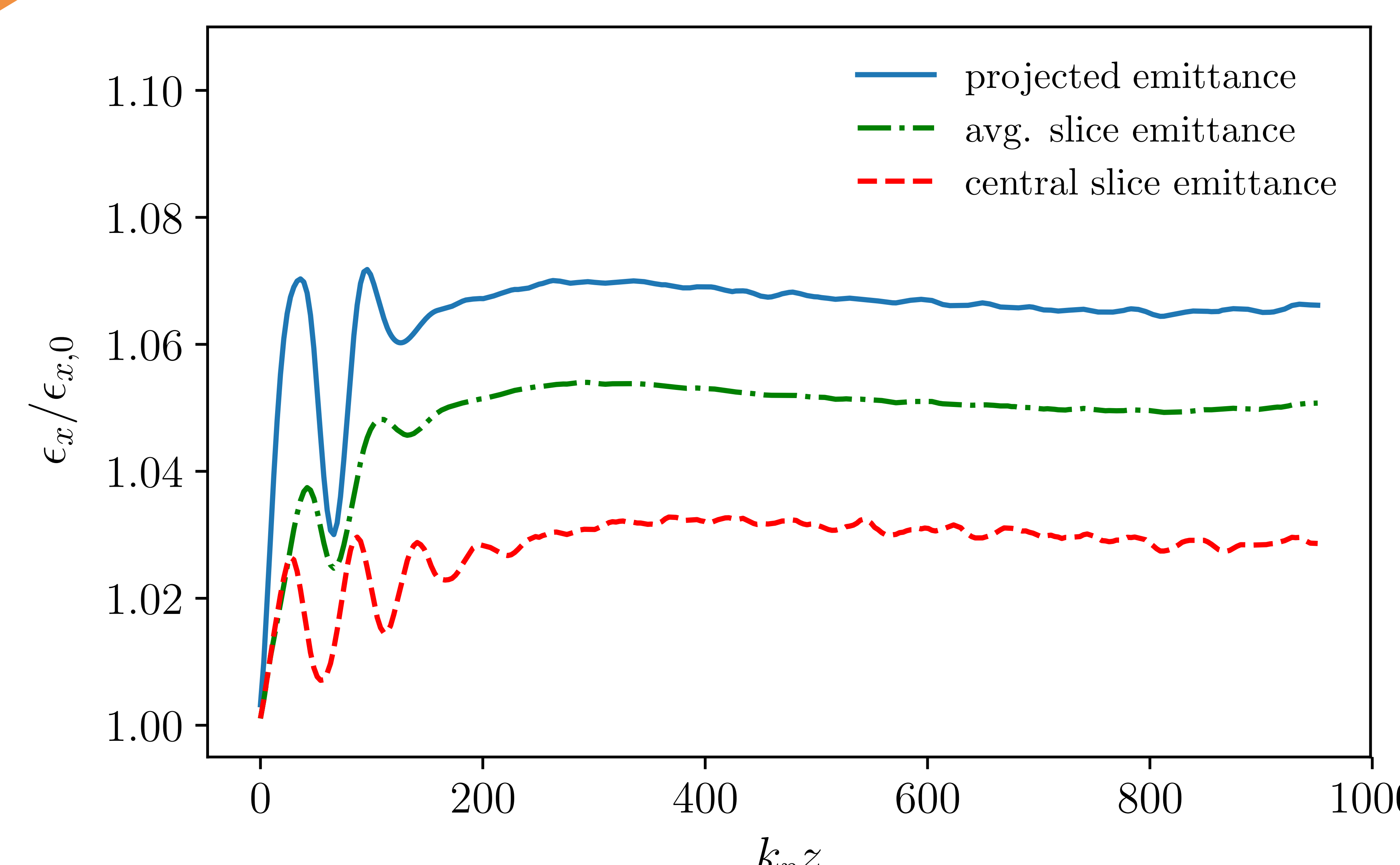


Image credit: S. Diederichs et al., PRAB 22, 081301 (2019)

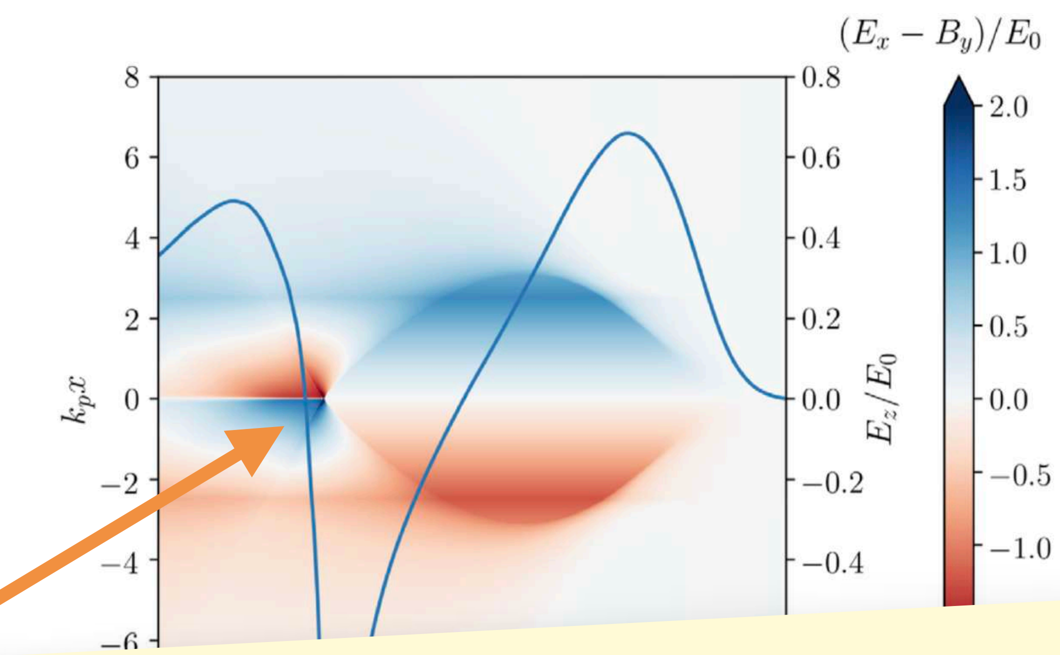




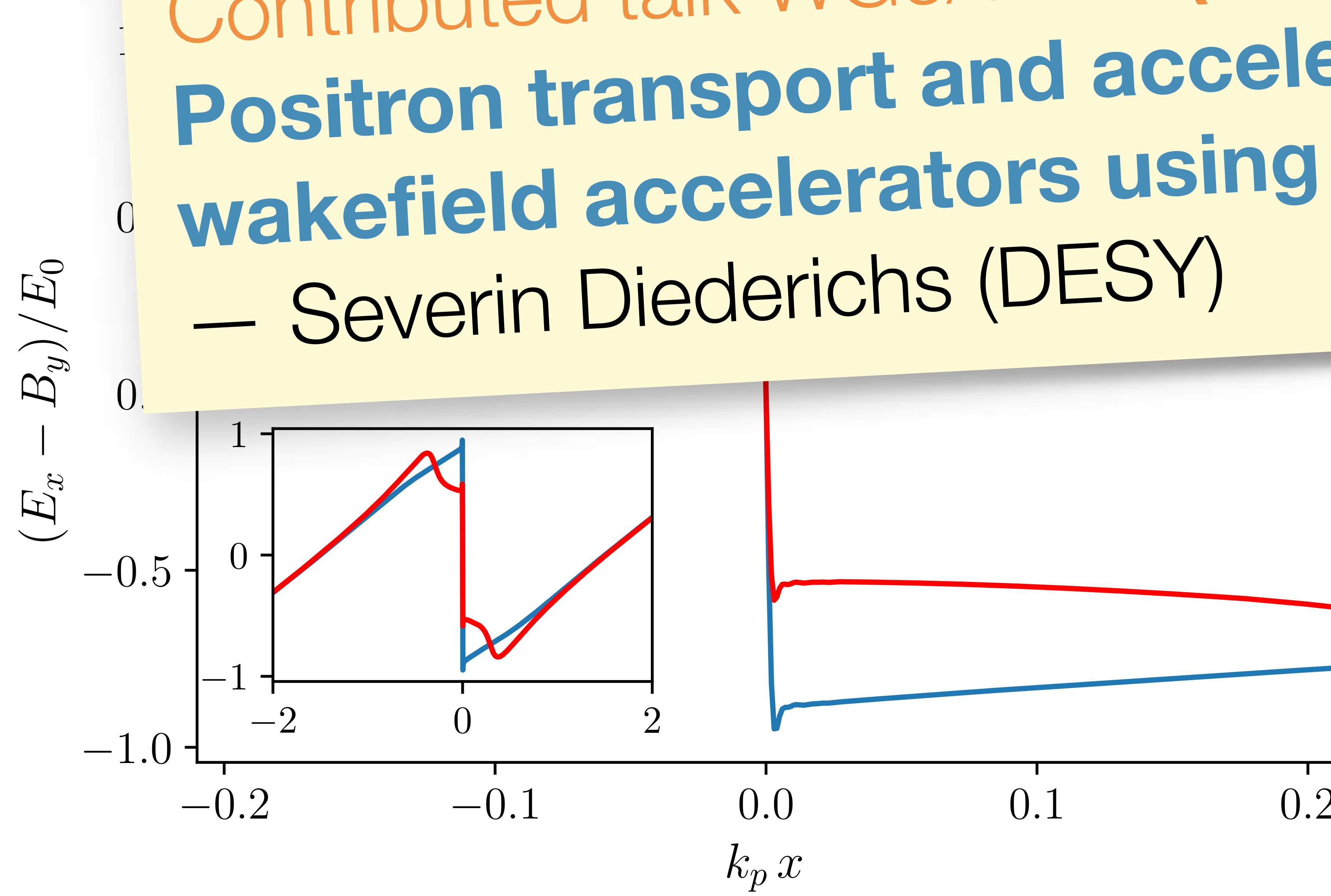
STRONGLY NONLINEAR WAKEFIELDS (ELECTRON-DRIVEN) — FINITE CHANNELS

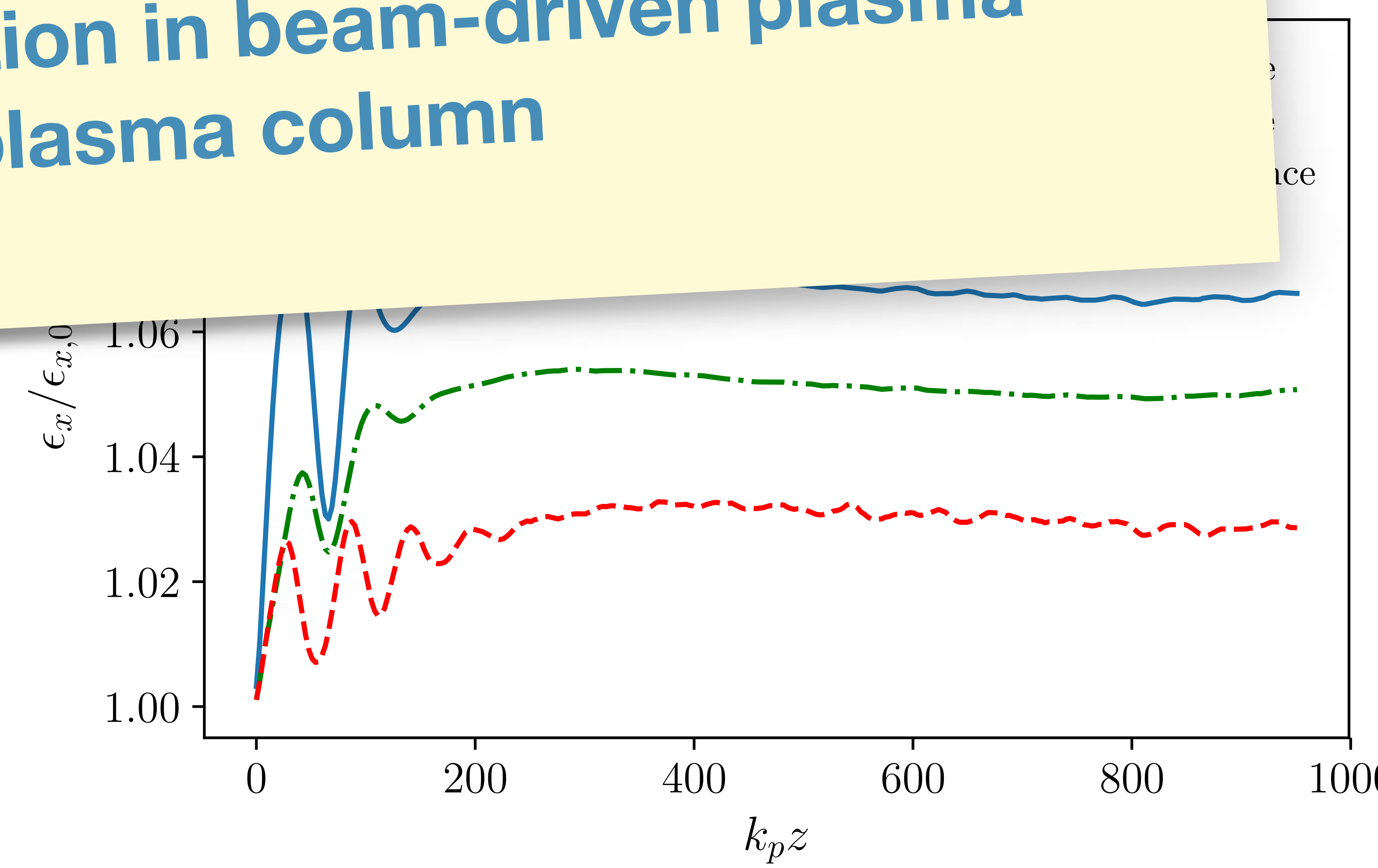
S. Diederichs *et al.*, PRAB 22, 081301 (2019)

> Positrons are attracted by on-axis electron density spike
  > Non-linear focusing (step-function), but emittance can be preserved.
> Difference to other schemes: on-axis electrons are ~relativistic
> Current research questions:
  > Emittance preservation for high beam loading (high efficiency)?
  > Stability to misalignments?



Contributed talk WG6/WG8 **(Wednesday 17:00)**
Positron transport and acceleration in beam-driven plasma wakefield accelerators using a plasma column
— Severin Diederichs (DESY)





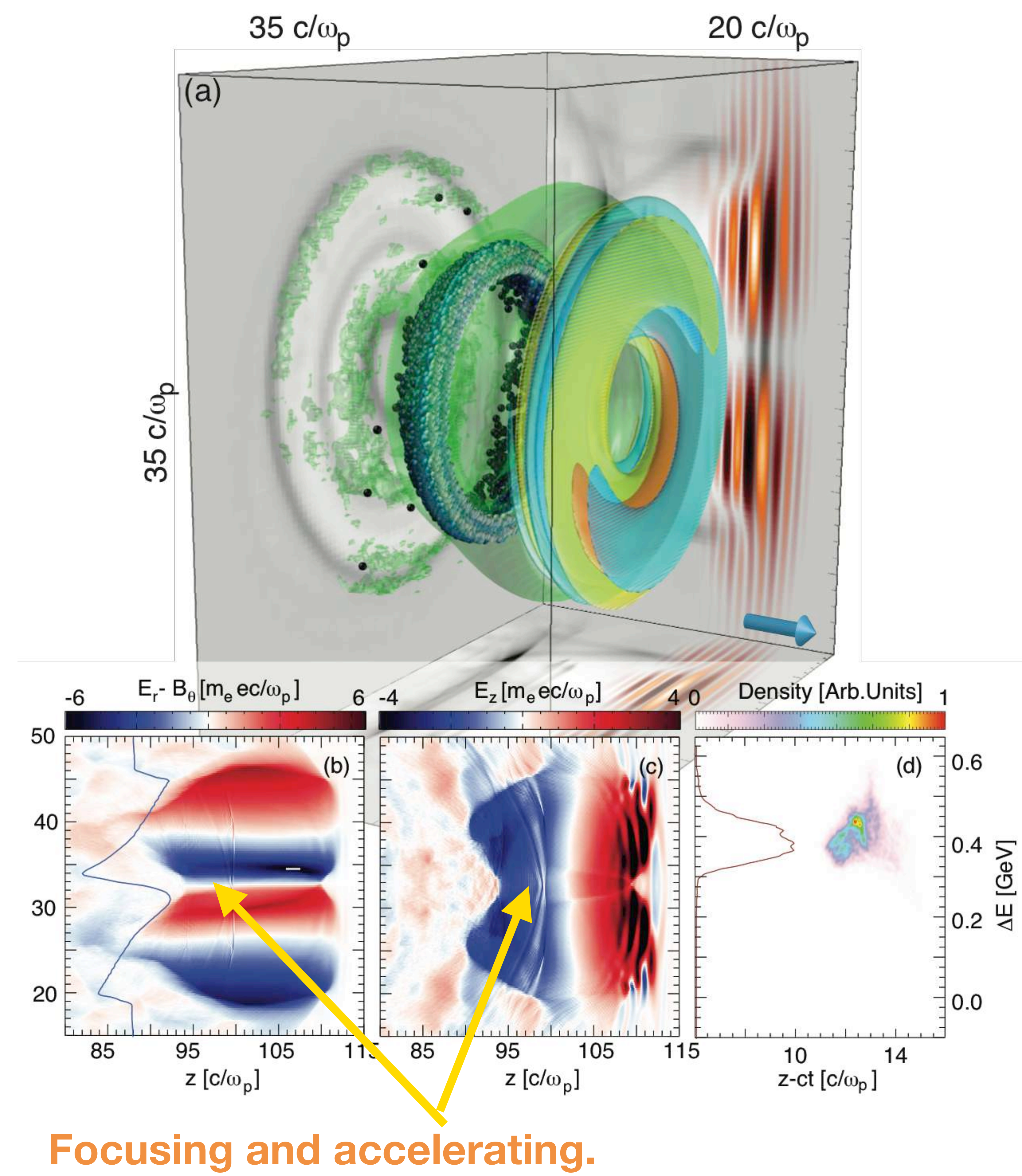
STRONGLY NONLINEAR WAKEFIELDS (ELECTRON-DRIVEN) — WAKE INVERSION

J. Vieira & J. T. Mendonça, Phys. Rev. Lett. 112, 215001 (2014)
J. Vieira *et al.*, AIP Conf. Proc. 1777, 070012 (2016)

> *Tactic: Engineer the driver such that an inverse wake forms.*
  > Use a **ring-shaped beam** to wrap a blowout around the axis!
  > Electrons are “blown in” towards the axis.
  > The wakefield is accelerating and linearly focusing!

> Example (simulation by Vieira et al.)
  > Low emittance (5 μm), low charge witness bunch (~26 pC)
  > Accelerating gradient: ~8.5 GV/m
  > Driver-to-witness efficiency ~1%

> **However, beam loading with a positron bunch changes the wakefield — non-linear focusing occurs.**



CORE PROBLEM: LONGITUDINAL VS. TRANSVERSE BEAM LOADING

> Longitudinal beam loading — *Required for efficiency*

> **The beam alters the longitudinal wakefield by extracting energy from high-momentum plasma electrons**

> Transverse beam loading — *Leads to nonlinear focusing (and emittance growth)*

> The beam alters the (on-axis) transverse wakefield by attracting/repelling charge.

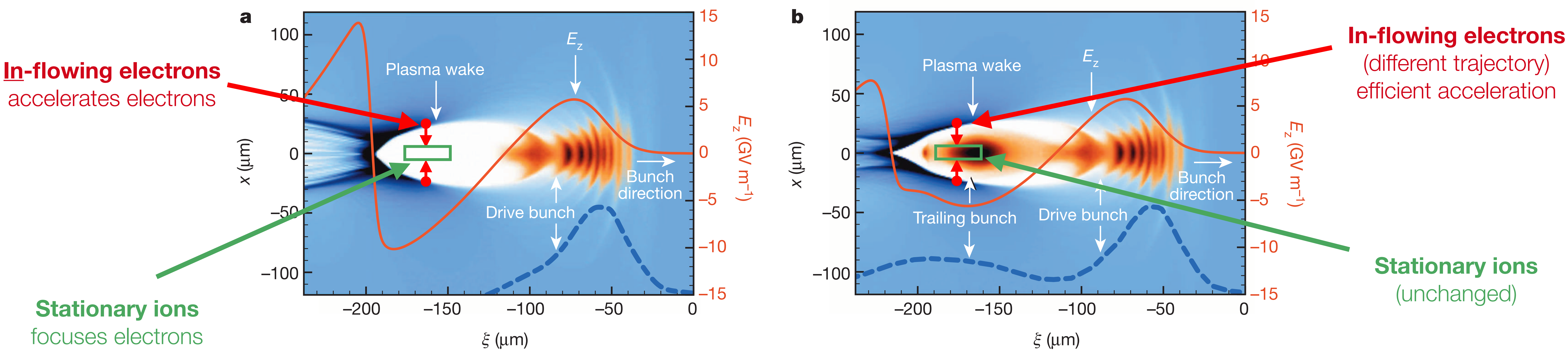


Image credit: M. Litos *et al.*, Nature 515, 92 (2014)

> **The *Blowout Miracle*: Longitudinal beam loading without transverse beam loading**

> Electrons responsible for *acceleration only* (ions responsible for focusing).

Core problem: Longitudinal vs. transverse beam loading

> Longitudinal beam loading — *Required for efficiency*

  > The beam alters the longitudinal wakefield by extracting energy from high-momentum plasma electrons

> Transverse beam loading — *Leads to nonlinear focusing (and emittance growth)*

  > **The beam alters the (on-axis) transverse wakefield by attracting/repelling charge.**

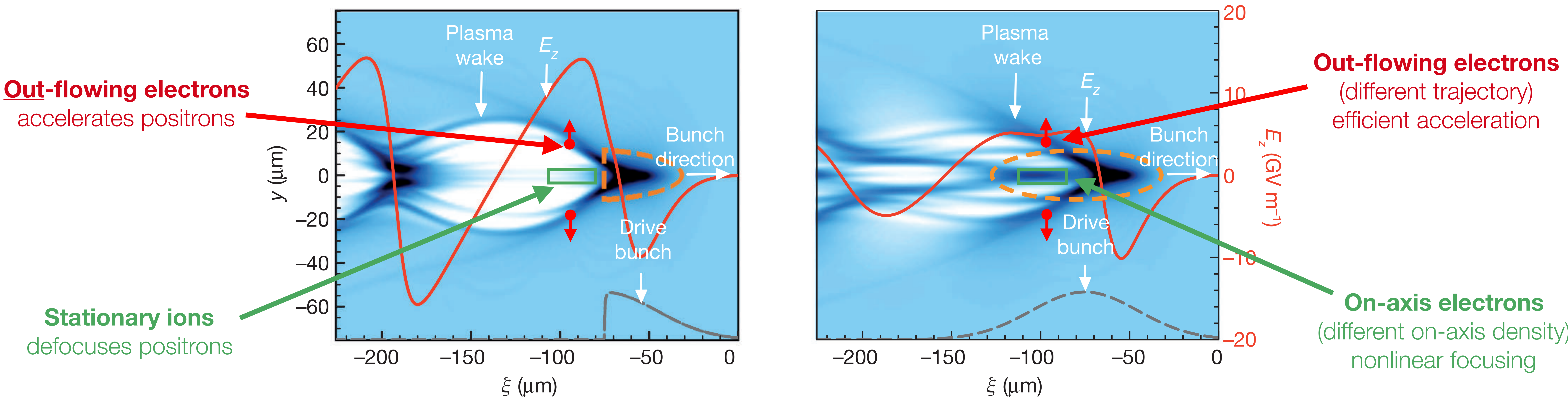


Image credit: S. Corde *et al.*, Nature 524, 442 (2015)

> **The Positron Problem: Can positrons be longitudinally beam loaded without transverse beam loading?**

> Electrons responsible for *both acceleration and focusing*.

Hollow plasma channels

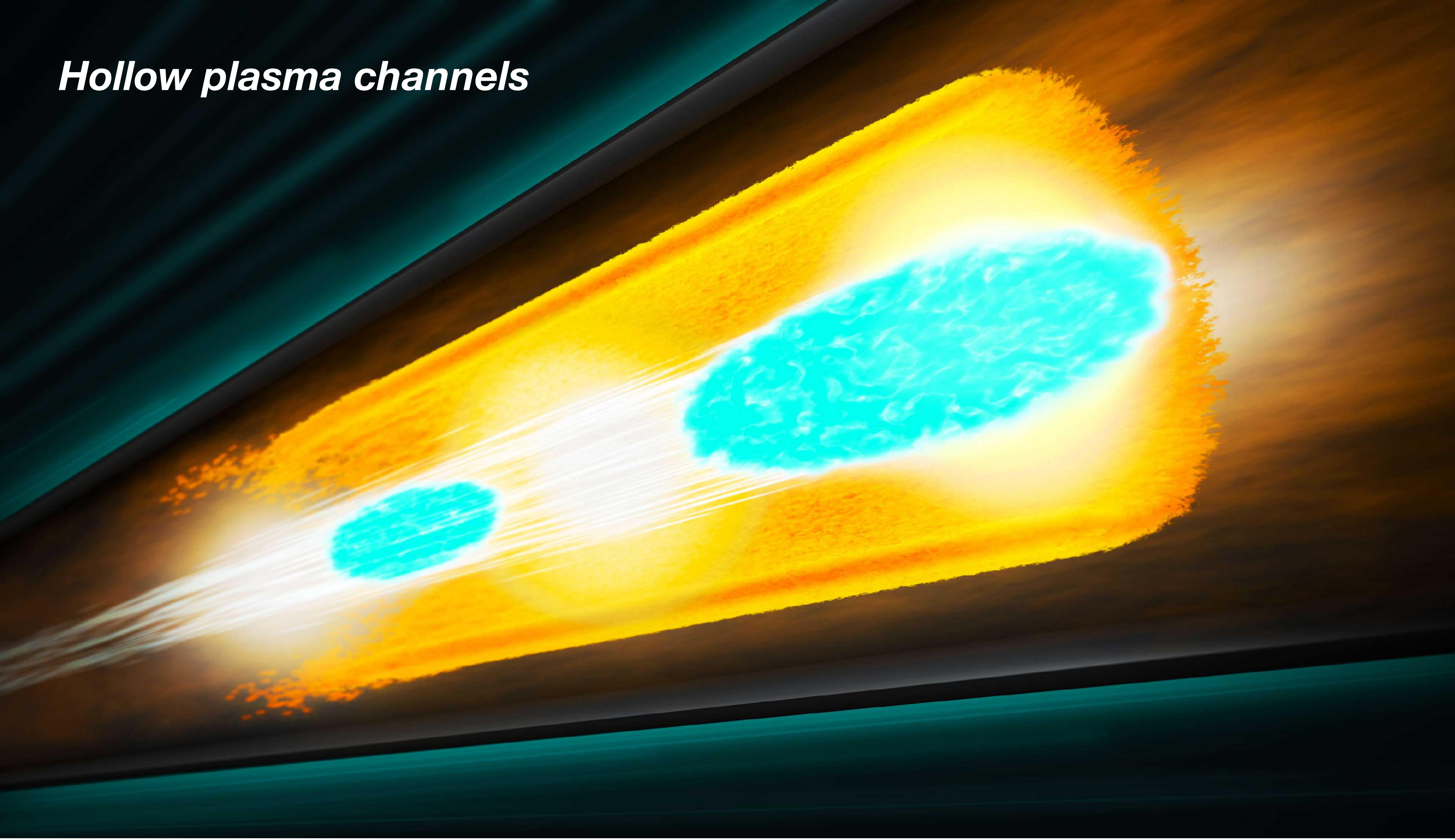


Image credit: SLAC National Accelerator Laboratory

Hollow channels

T. Tajima, Proc. of HEACC1983, p. 470 (1983)
S. Lee *et al.*, Phys. Rev. E 64, 045501 (2001)

> **No plasma on axis — no focusing on axis**

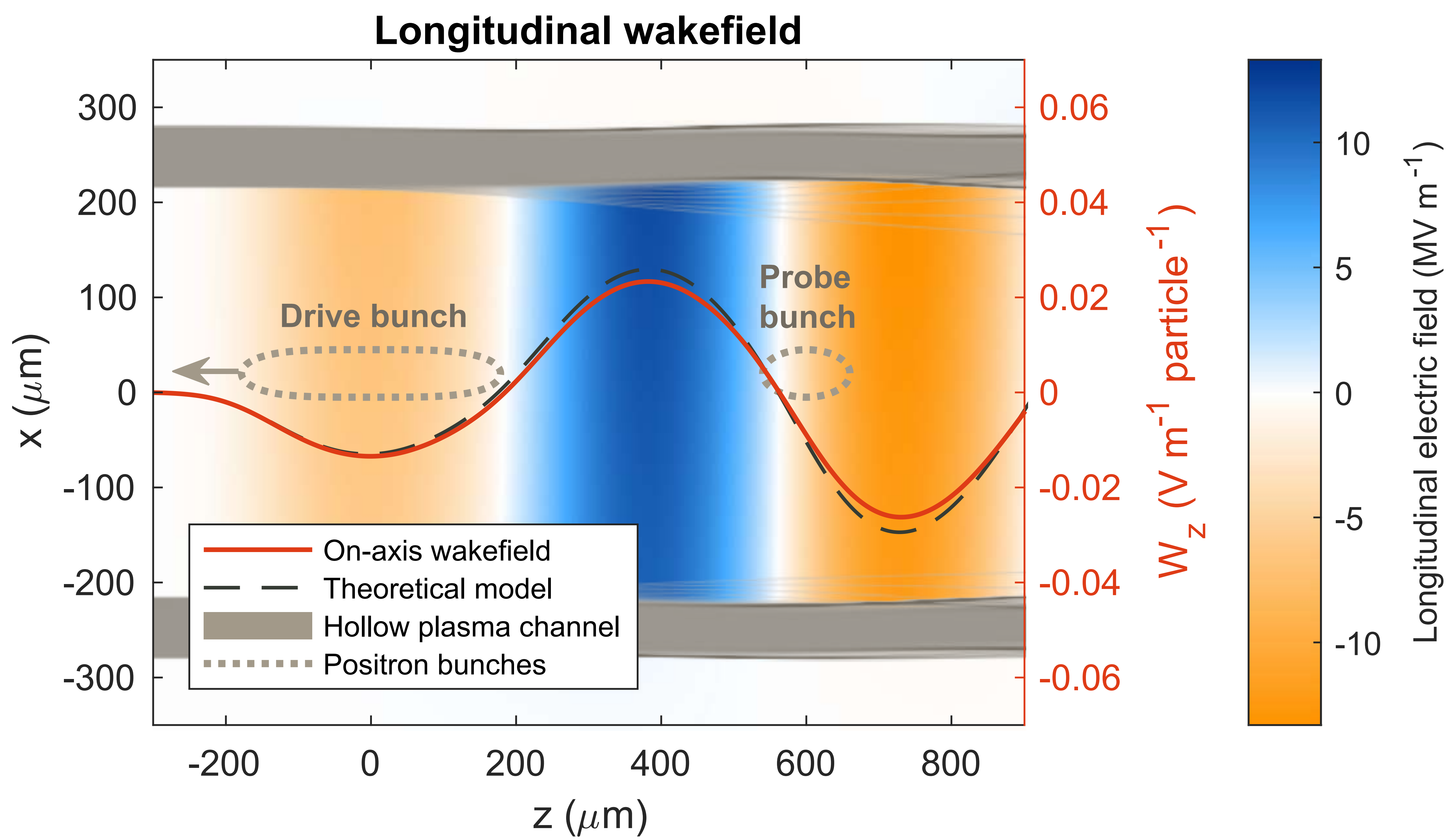


Image credit: C. A. Lindstrøm et al., Phys. Rev. Lett. 120, 124802 (2018)

> A (electron / positron / proton / laser) beam drives a **similar longitudinal wakefield**.

> On-axis beam => **no focusing fields inside** — *emittance is preserved*

Hollow channels — FACET experiments: Longitudinal wakefields

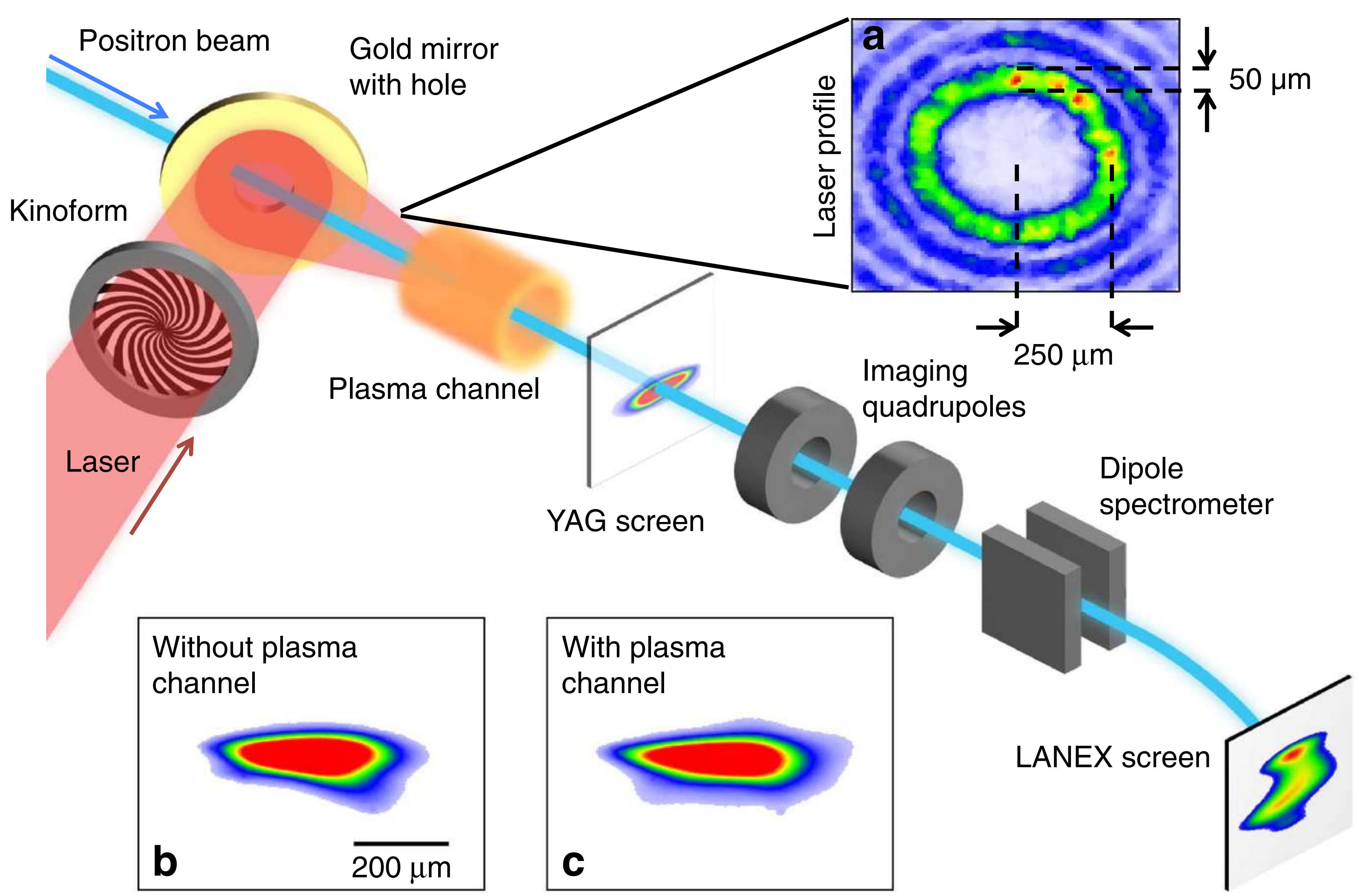
S. Gessner *et al.*, Nat. Comms 7, 11785 (2016)

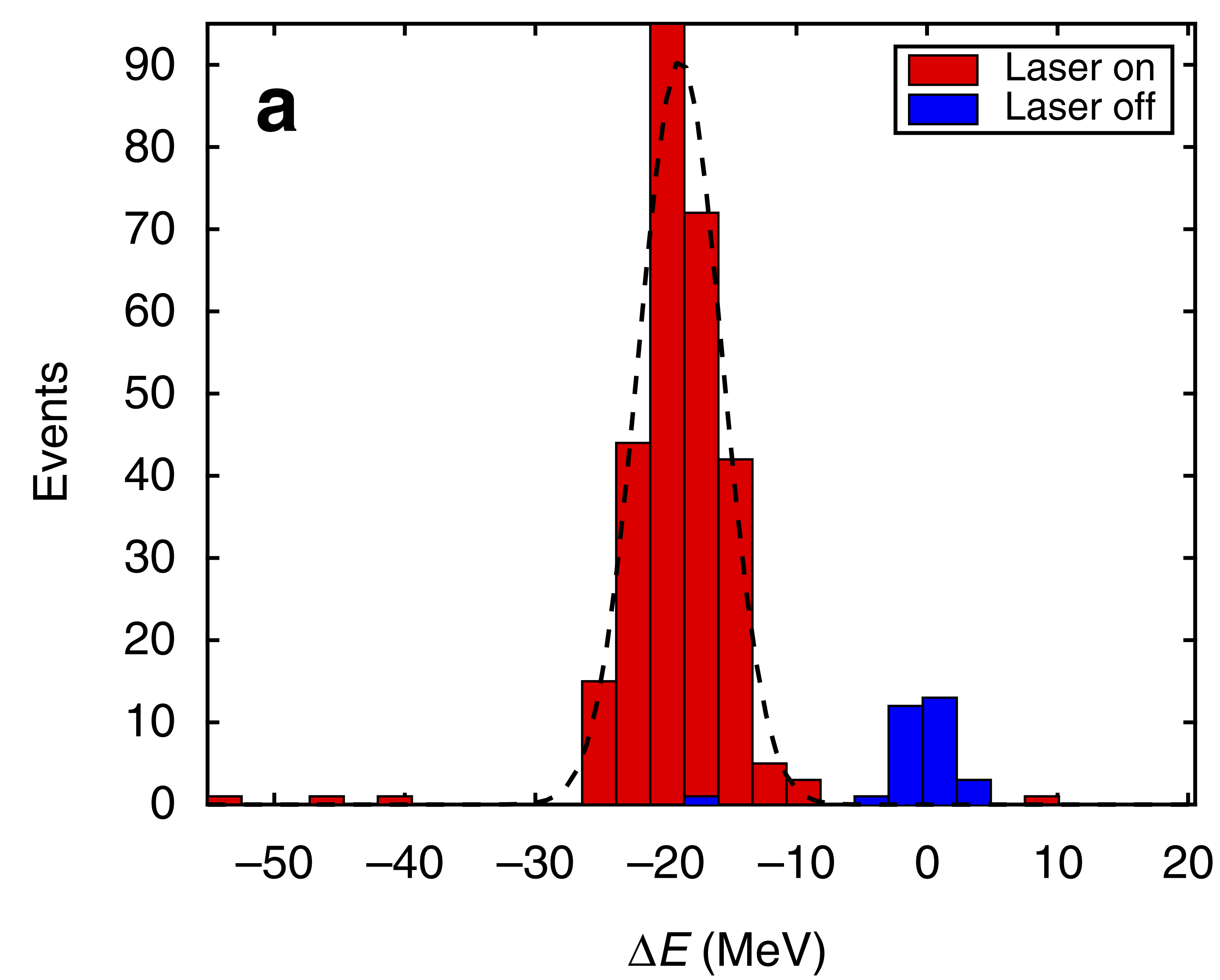
> FACET E225 experiment at SLAC

  > 10 TW laser + kinoform optic = 12 cm long, 500 μm diameter channel

  > 20 GeV positron beams, 850 pC, 35 μm (rms) long, single bunch

> **230 MV/m decelerating fields measured!** Acceleration observed in later experiments.





Hollow channels — Transverse wakefields

C. B. Schroeder *et al.*, Phys. Rev. Lett. 82, 1177 (1999)

> Misaligned bunches induce a (dipole) transverse wakefield — *deflecting away from the axis!*

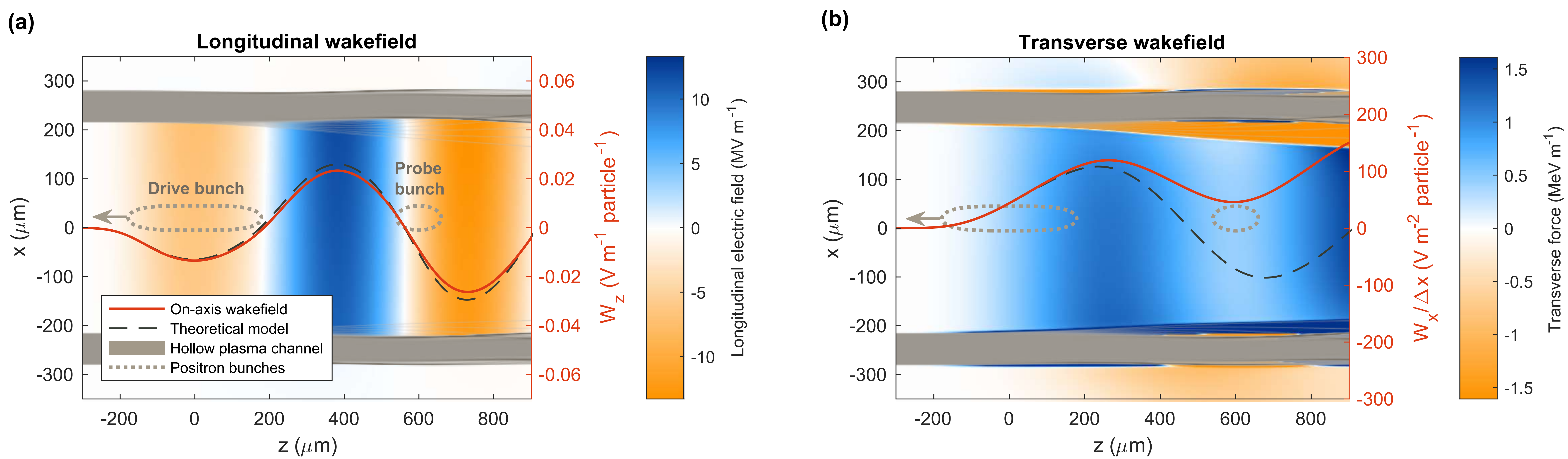


Image credit: C. A. Lindstrøm et al., Phys. Rev. Lett. 120, 124802 (2018)

> **Panofsky–Wenzel theorem links longitudinal and transverse wakefields** — *the short-range wake theorem*

> Transverse wakefield scales more strongly with decreasing aperture.

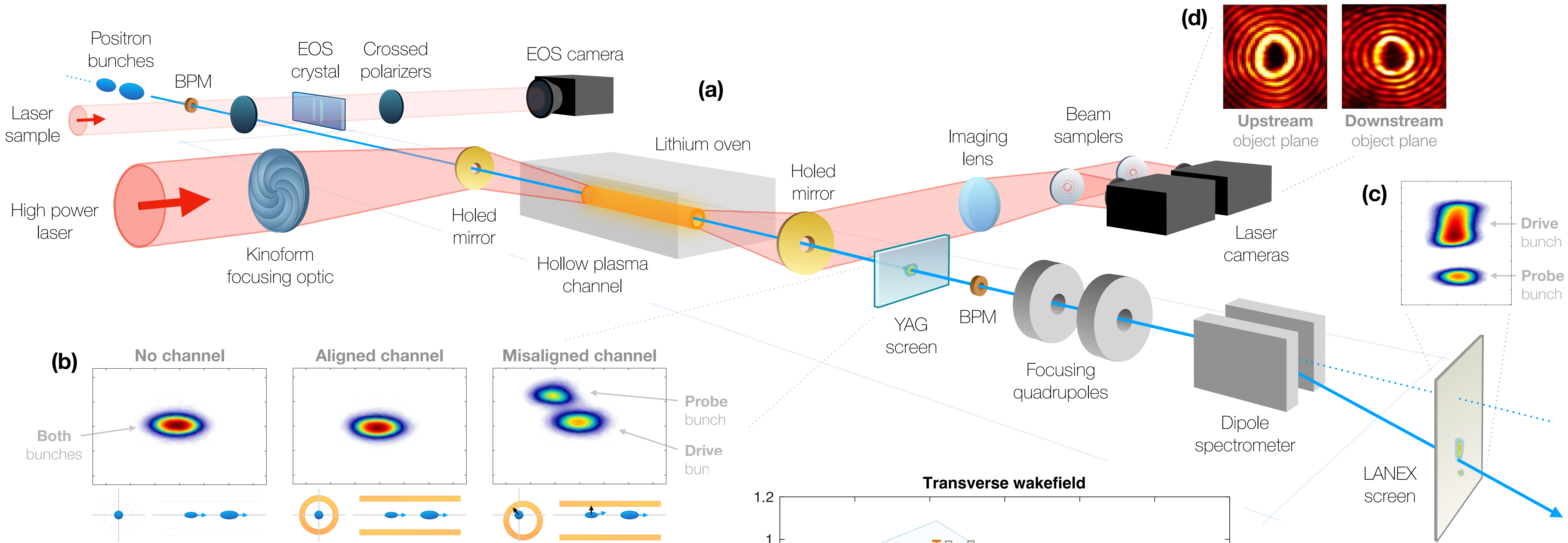
> CLIC cavity (*a* = 3 mm) — $W_x/\Delta x$ = 100 V/pC/m/mm

> E225 hollow channel (*a* = 215 μm) — $W_x/\Delta x$ = 1,000,000 V/pC/m/mm

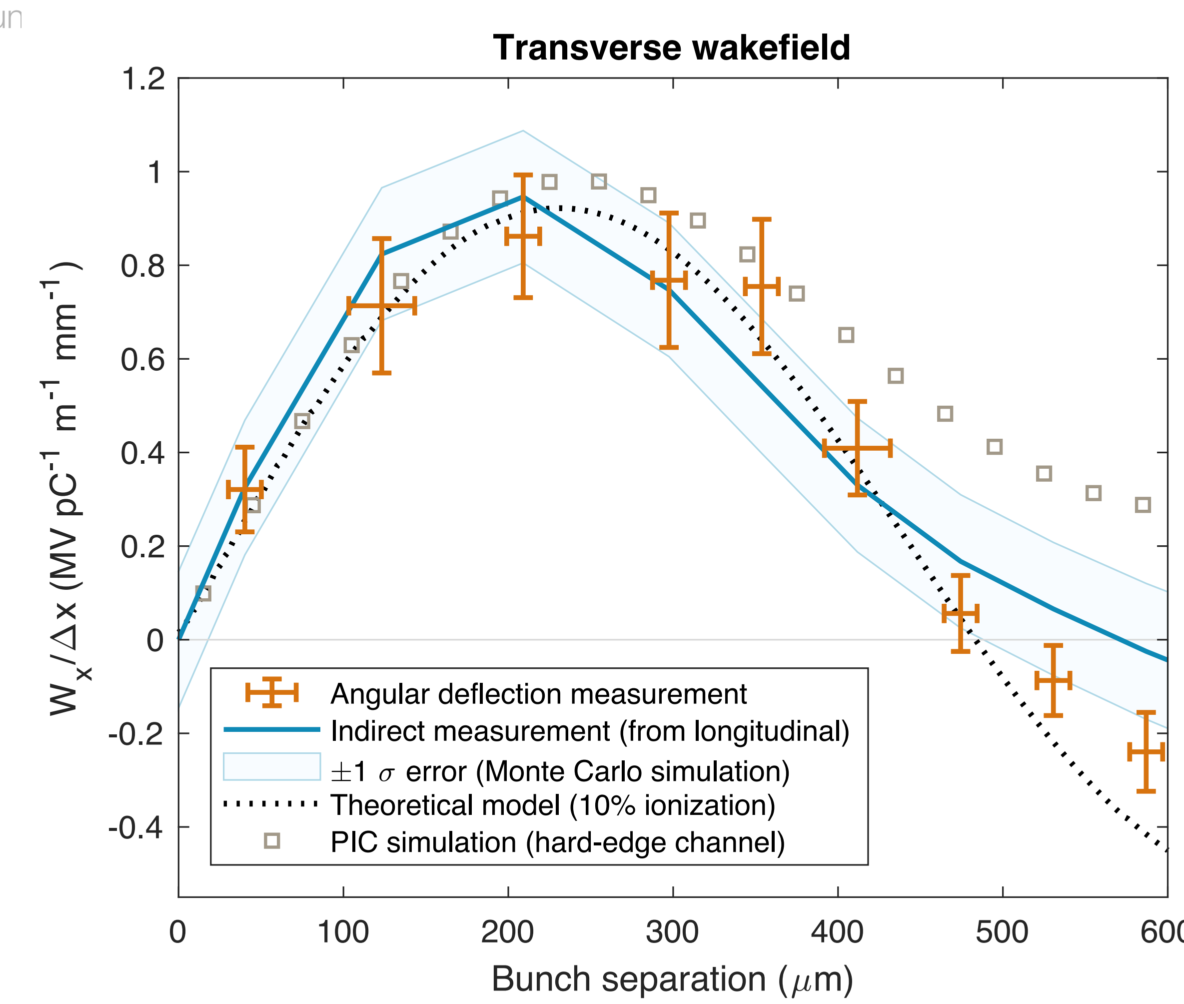
$$\frac{W_x(z)}{\Delta x} = -\frac{\kappa(a,b)}{a^2}\int_0^z W_z(z')dz'$$

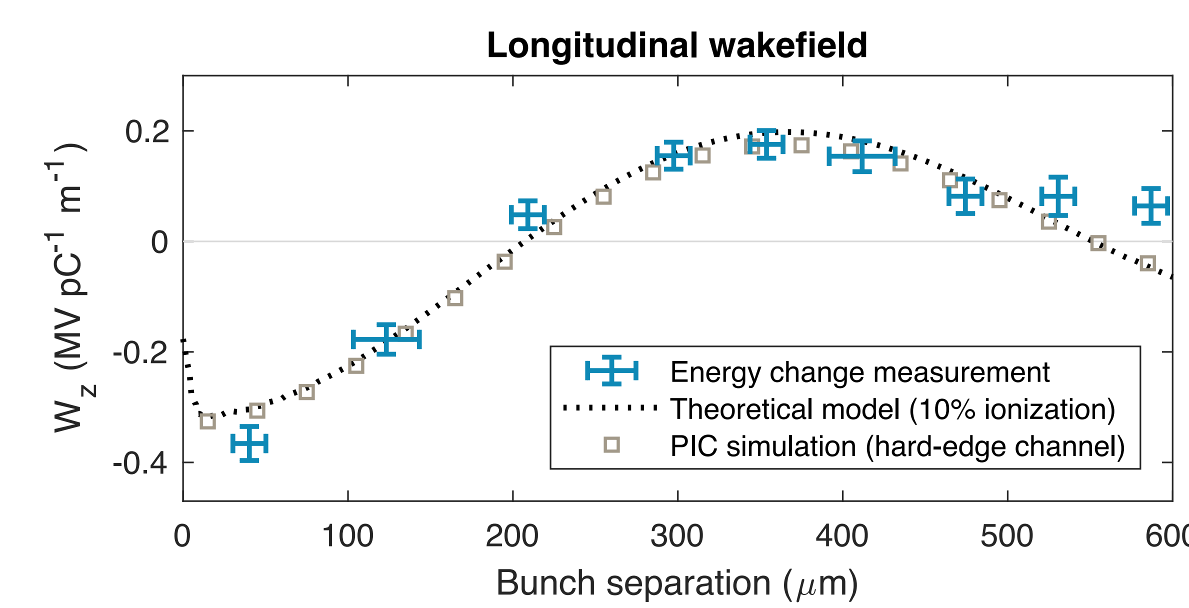
HOLLOW CHANNELS — FACET EXPERIMENTS: TRANSVERSE WAKEFIELDS

C. A. Lindstrøm *et al.*, Phys. Rev. Lett. 120, 124802 (2018)



- E225 experiment at FACET, SLAC.
  - 20 GeV positrons, **two bunches**
  - 25 cm long hollow channel, 500 μm diameter
- **Correlation between channel offset and probe bunch deflection angle**
  => Transverse wakefield could be extracted
- Repeated for several bunch separations (50–600 μm).
- Experiment agrees well with theory.





Hollow channels — Mitigating transverse wakefields

> Ideally: perfect alignment, no instability seed.

> **Focusing is required to avoid instability!**

> External focusing? (i.e., quadrupoles)

  > Studied for dielectric channels (same physics)

  > Practically limited to ~150 MV/m only.

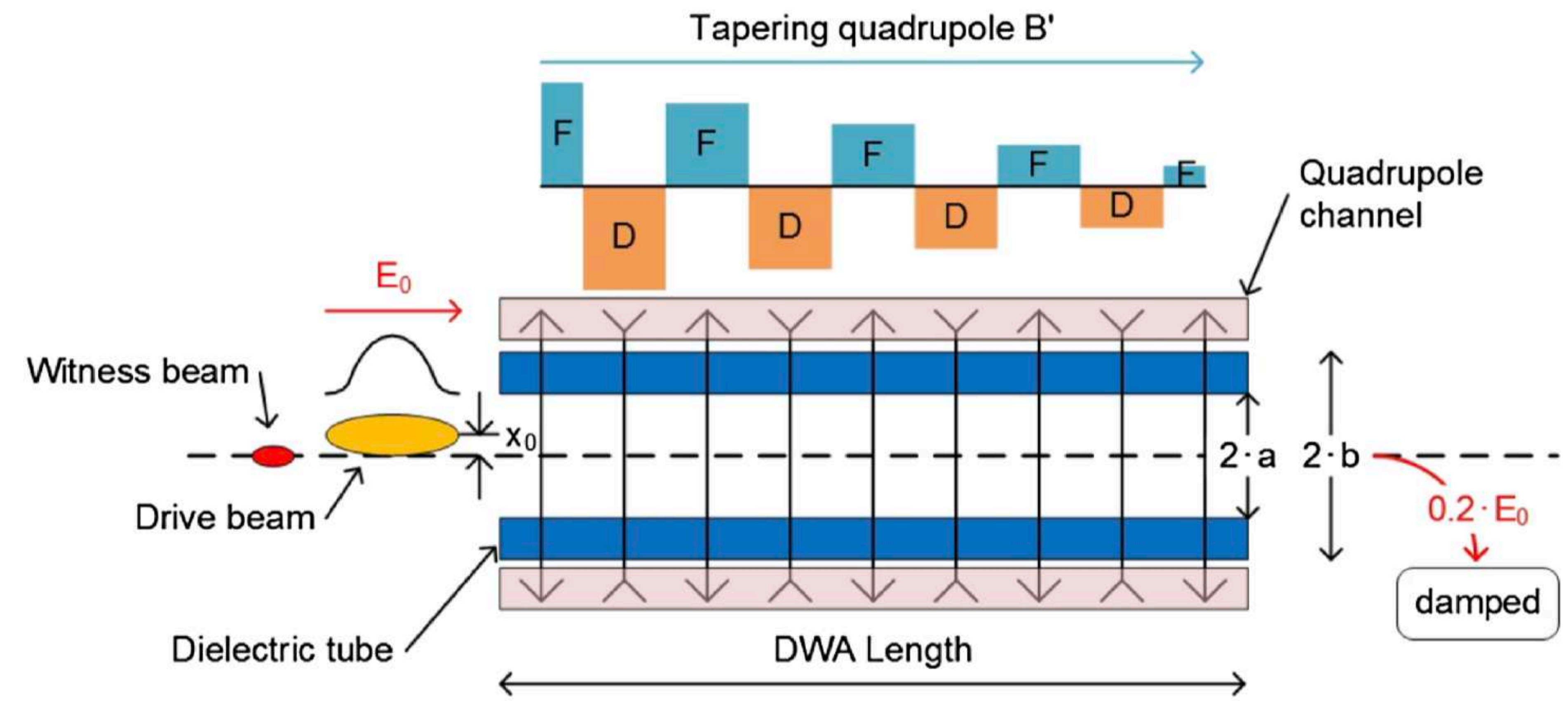


Image credit: C. Li *et al.*, Phys. Rev. ST Accel. Beams 17, 091302 (2014)

> Need on-axis electrons without transverse beam loading.

> **Idea: Use *relativistic (GeV), counter-propagating* electrons**

  > Makes on-axis electrons immobile like ions (large relativistic mass)

  > "Electron lensing" demonstrated for low energy (10 keV) at the Tevatron, Fermilab in 1999.

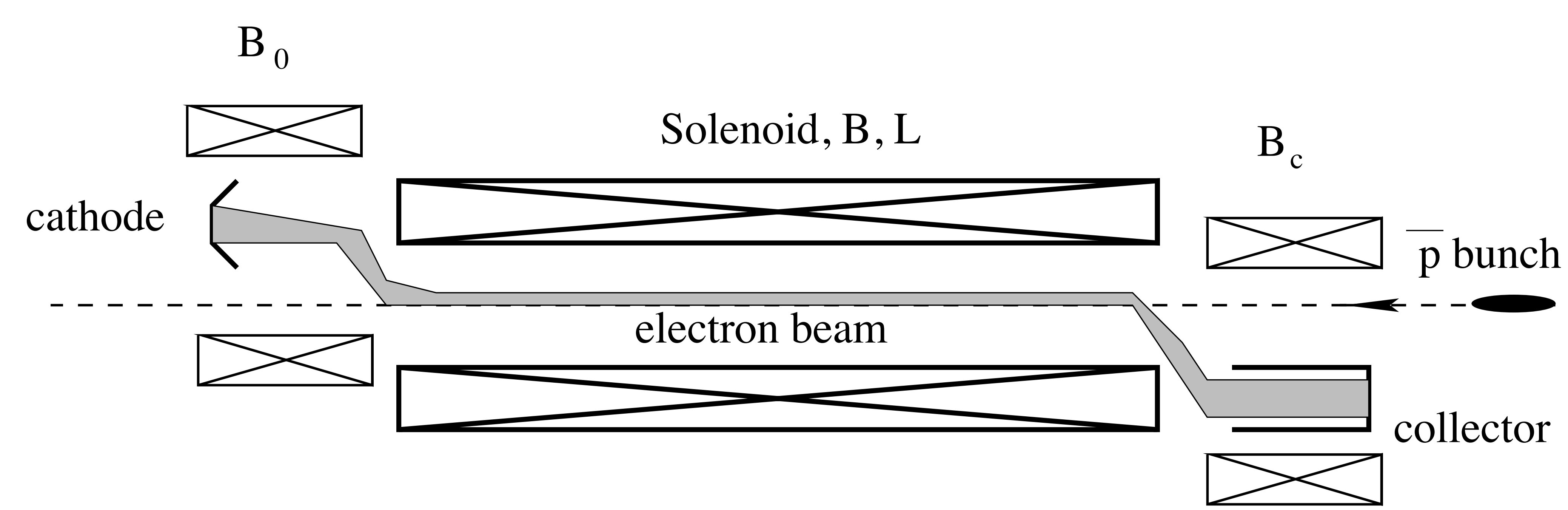
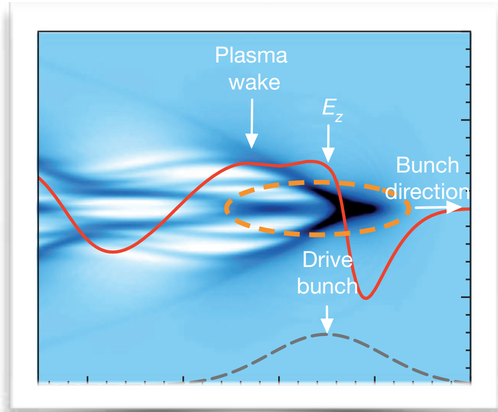
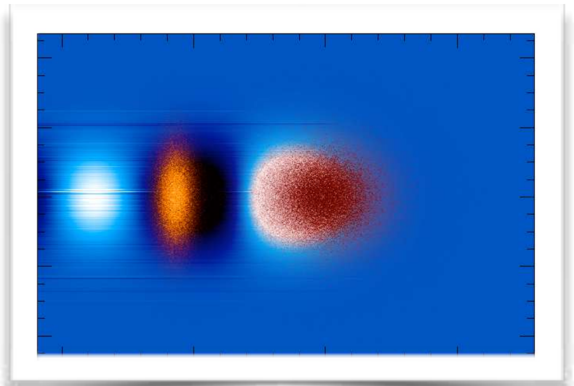
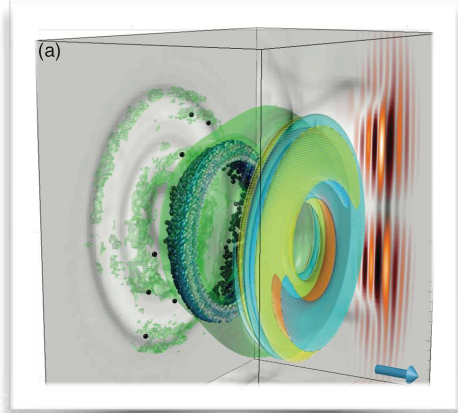
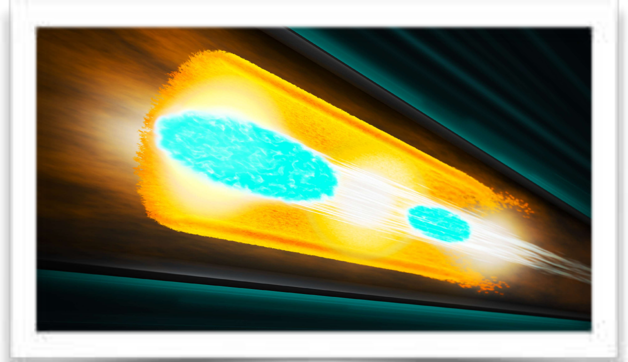


Image credit: Shiltsev et al., Phys. Rev. ST Accel. Beams 2, 071001 (1999)

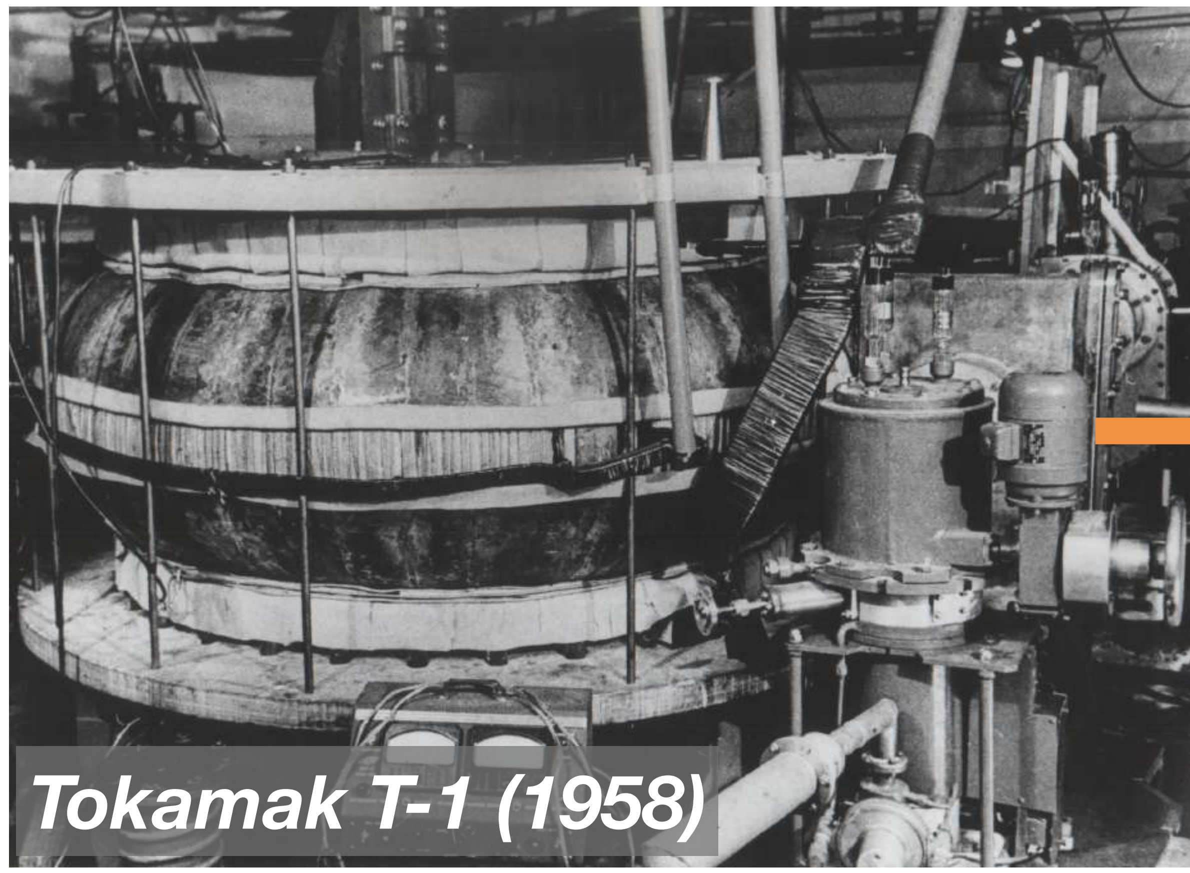
PART 3:
COMPARING CONCEPTS

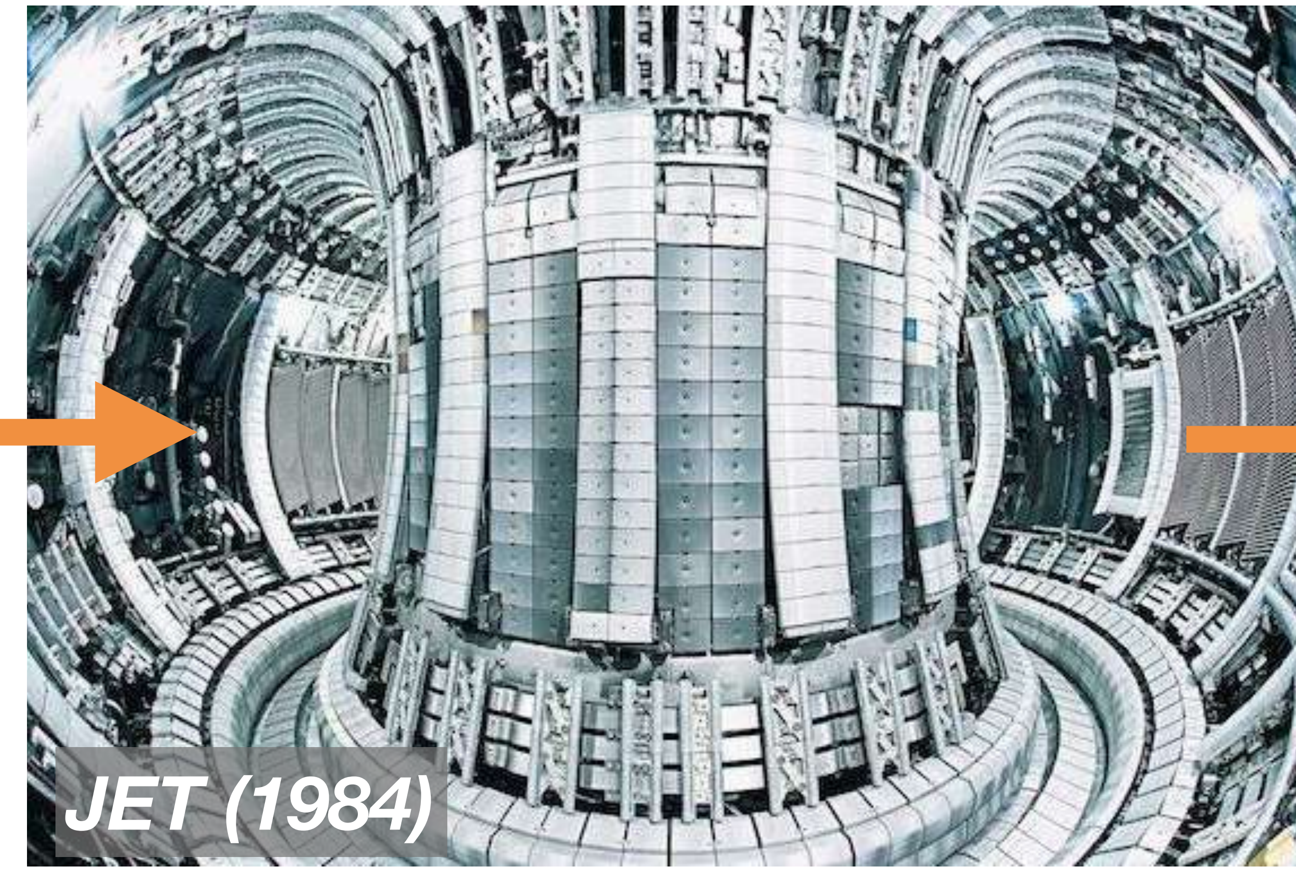


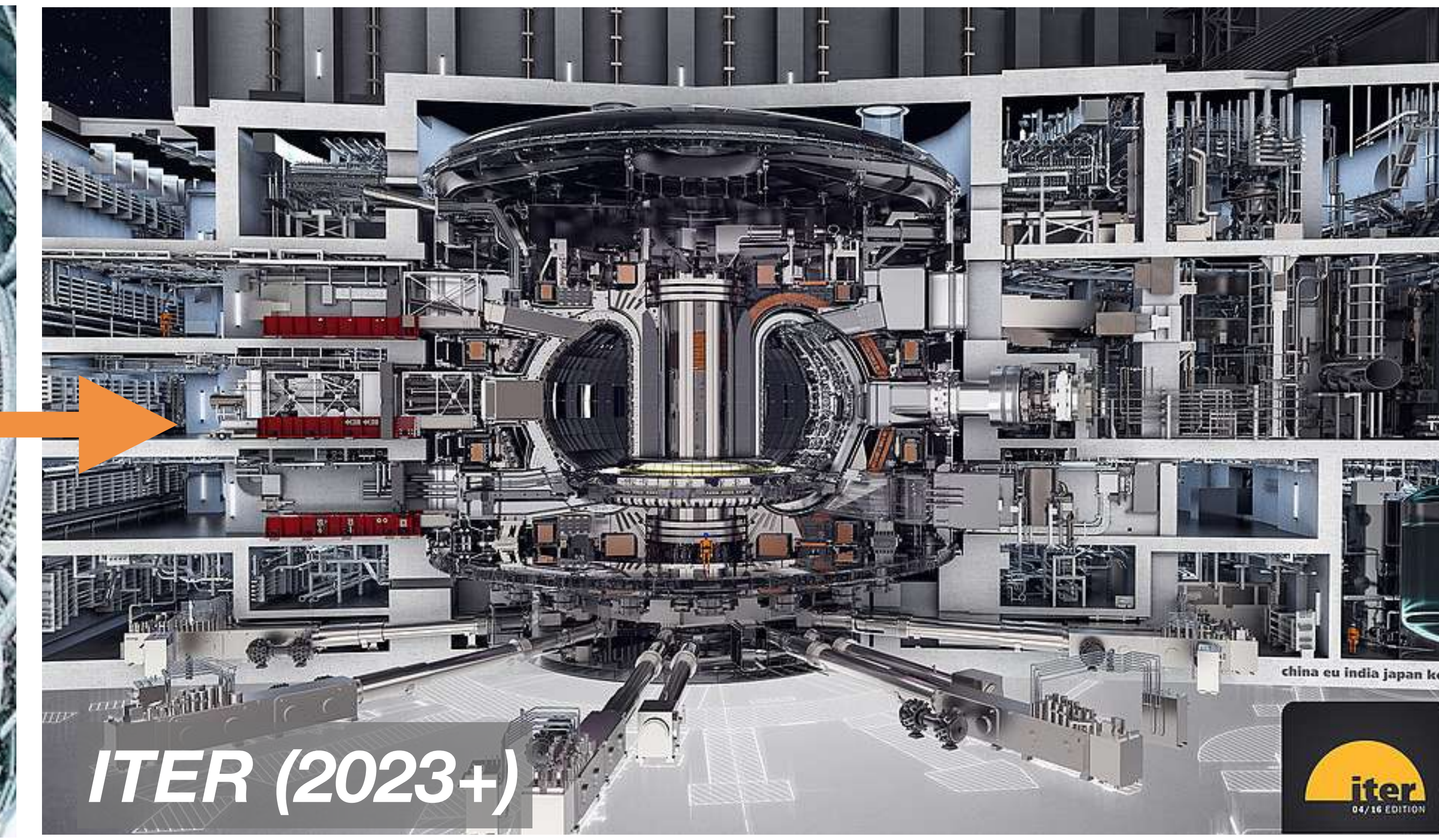





TAKING INSPIRATION FROM FUSION RESEARCH



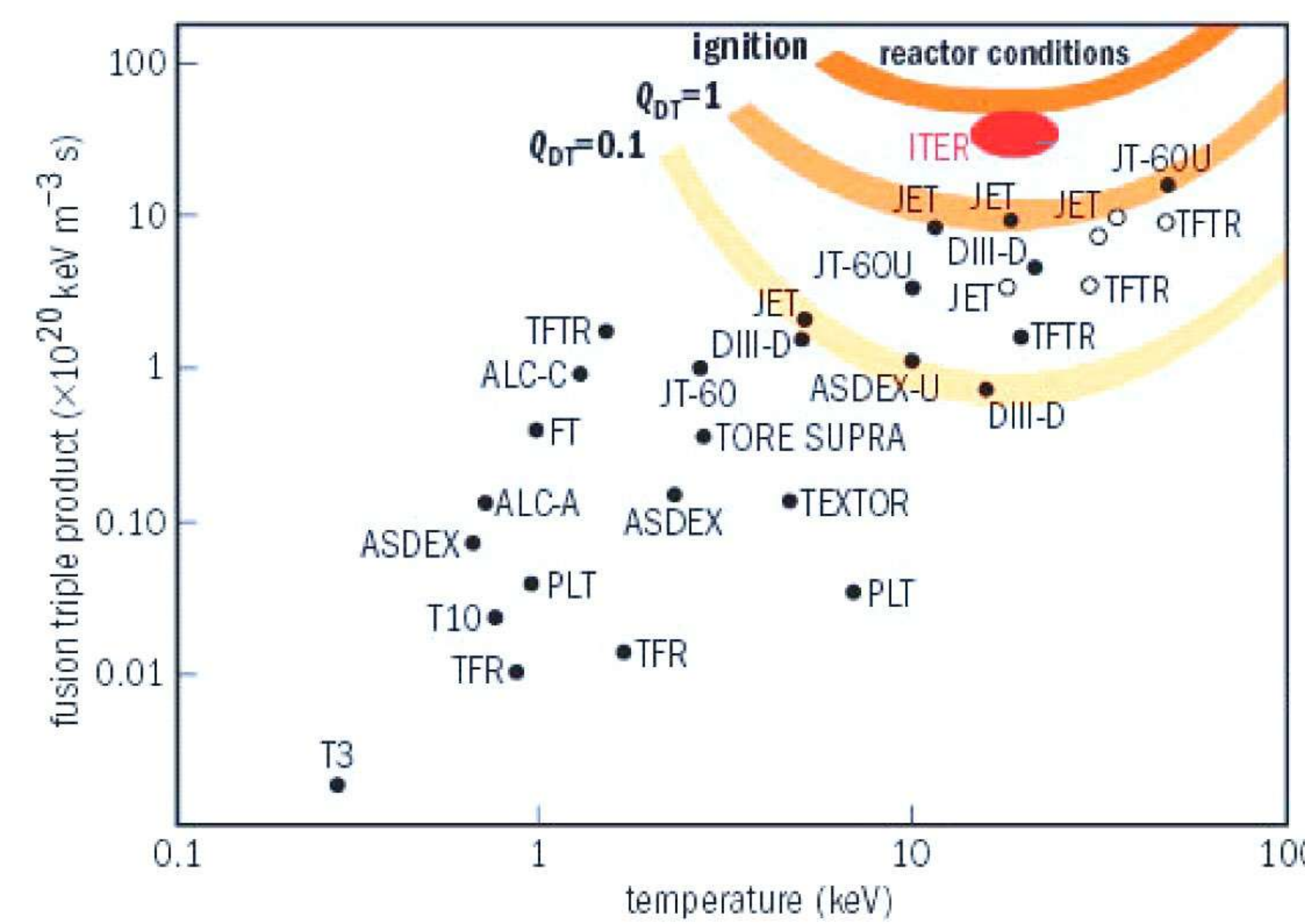




- John Lawson proposed a figure of merit for fusion research.
- The *triple product:*

  Density x **Confinement time** x **Temperature**

- Allows comparison between different technologies and machines.
- Has guided the research towards large tokamaks (e.g., JET and ITER)
- **Need a similar guide for plasma collider concepts!**



LUMINOSITY PER POWER — OUR "TRIPLE PRODUCT"

> Main figure of merit — **Luminosity per wall-plug-power**

> Many assumptions:

> > Factors out rep. rate

> > Concept can be scaled to high energy (TeV) — *staging*

> > Sub-% energy spread required

> > Beam stability (~10 nm misalignment tolerance)

> **Provides a way of comparing concepts based on instantaneous physics (fast) instead of full-scale collider design (slow).**

> (Applies equally to electron and positron arm)

Luminosity | Geometric factor | Wall-plug power | Wall-plug-to-beam efficiency | Bunch charge

$$\mathscr{L} = \frac{H}{8\pi m_e c^2} \frac{P_{wall}}{\sigma_x} \frac{\eta N}{\sqrt{\beta_y \epsilon_{Ny}}}$$

Hor. beam size | Beta function (final focus) | Emittance (one plane)

Low energy regime

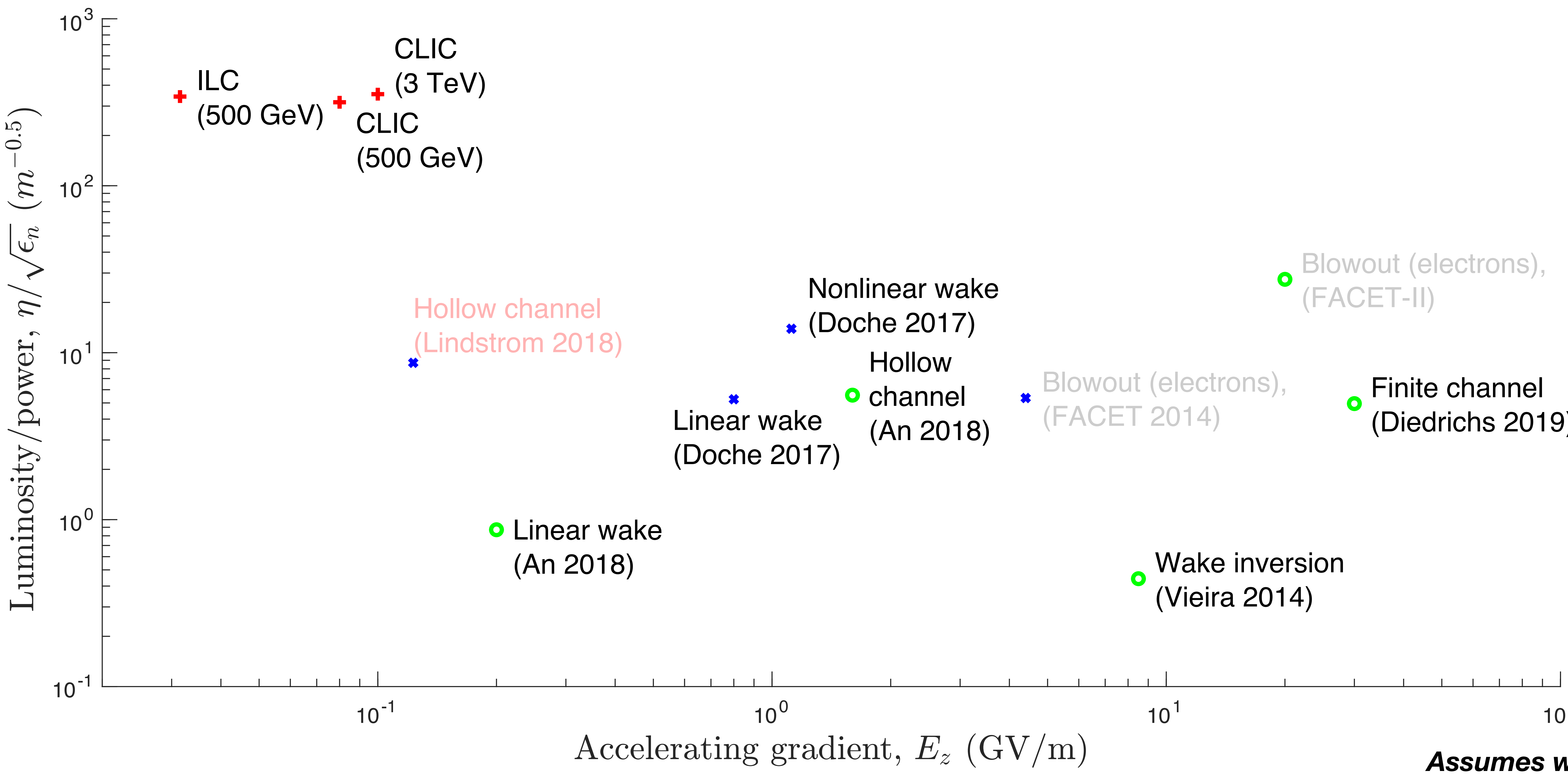
$$\frac{\mathscr{L}}{P_{wall}} \sim \frac{\eta}{\sqrt{\epsilon_{Ny}}}$$

High-energy regime

$$\frac{\mathscr{L}}{P_{wall}} \sim \frac{\eta}{\sqrt{\sigma_z \epsilon_{Ny}}}$$

(beamstrahlung limited)

COMPARISON VIA LUMINOSITY PER POWER (LOW ENERGY REGIME) — EXAMPLE



Assumes wall plug–driver efficiency of 11% (CLIC-like)

> Showing only published parameter sets (experiment, simulation)

> **Too early to conclude which concept is better** — *concepts need to be optimized for luminosity/power.*

POSITRON EXPERIMENTS AT FACET-II

> Only one way to find out — **positron experiments!**

FACET-II

Facility for Advanced Accelerator Experimental Tests

> Positrons acceleration is foreseen for later phases of FACET-II operation (2022+).

> **Important for the community to express support for <u>positron experiments at FACET-II</u>.**

> Keeping the momentum: Theoretical advances often made in the vicinity of experimental research.

Positron experiments at FACET-II

> Only one way to find out — **positron experiments!**

Plenary talk **(Thursday 10:10)**
Plasma Wakefield Acceleration Science at FACET-II
— Mark Hogan (SLAC)

> Positrons ... phases of FACET-II operation (2022+).

> **Important for the community to express support for <u>positron experiments at FACET-II</u>.**

> Keeping the momentum: Theoretical advances often made in the vicinity of experimental research.

TAKE-AWAY MESSAGES

> TeV-scale electron–positron colliders — *important for future high-energy physics.*

> Plasma wakefields are promising for electrons — *does not translate to positrons*

> Several proposed methods:

> > Quasi-linear wakefields — *must beam loading imply large emittance?*
> >
> > Nonlinear wakefields (self-loaded) — *Is there a low-emittance equilibrium distribution?*
> >
> > Nonlinear wakefields (finite channel) — *Is it stable? Can it be efficient?*
> >
> > Wake inversion — *Can nonlinear fields be avoided when loading?*
> >
> > Hollow channels — *Can we suppress instability by strong focusing?*

> **Core issue: Longitudinal beam loading without transverse beam loading for positrons?**

> > *Can plasma electrons simultaneously focus uniformly and accelerate efficiently?*

> Urgently need optimization and comparison — *figure of merit = luminosity/power*

> Positron experiments planned for FACET-II — *very important for the advancement of the field*

WORDS TO LEAVE ELBA WITH…

"Napoleon Bonaparte on Elba" by Horace Vernet

Impossible n'est pas français.

…alternatively…

Impossible is a word to be found only in the dictionary of fools.

– Napoleon Bonaparte