Positron Acceleration in Plasma Wakefields

Current efforts, the root challenge, and future directions

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Outline

- A brief history
- Collider requirements
- What is missing?
- Scheme comparison
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- Going beyond the limit

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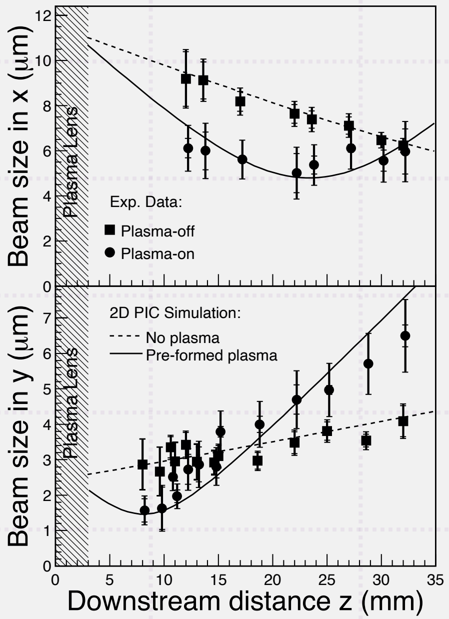
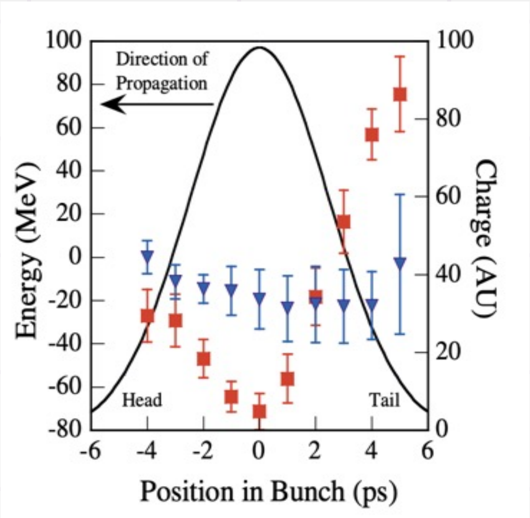
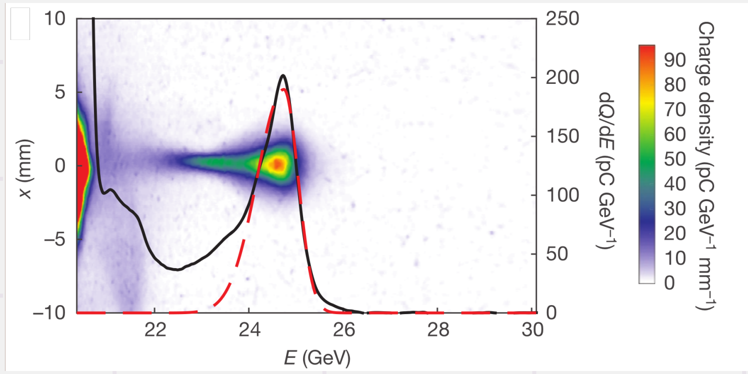
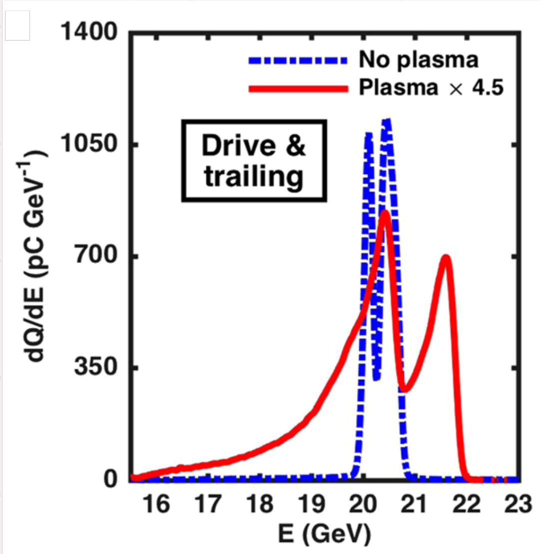
Positron PWFA in Homogenous Plasma





*The years refer to year of publication





2001

First evidence for positron focusing

2003

First broadband ac(de-)celeration

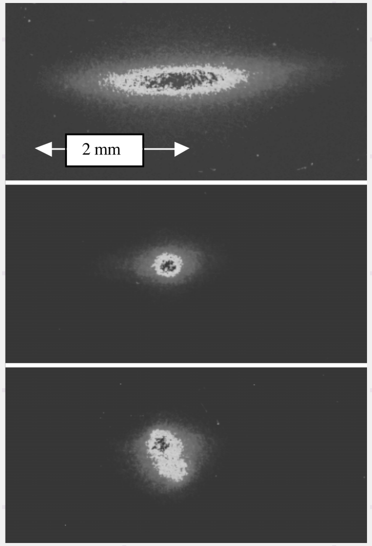
2015

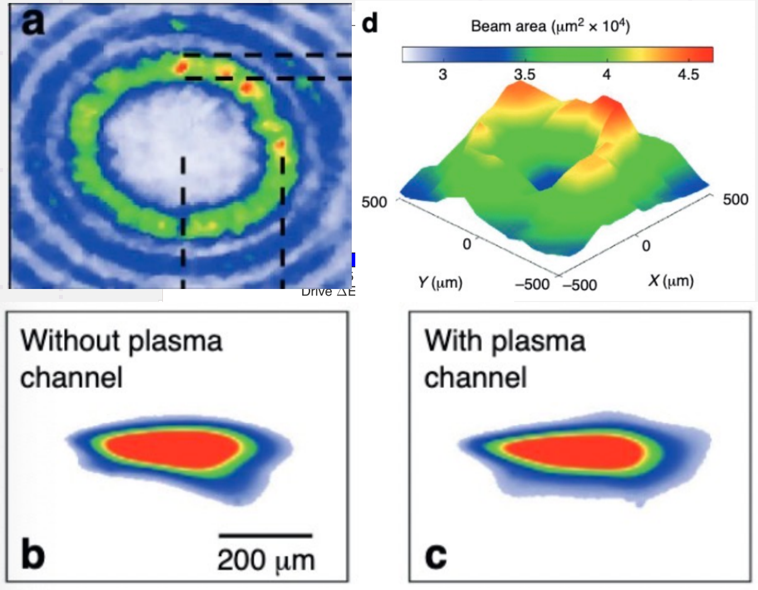
First multi-GeV energy gain

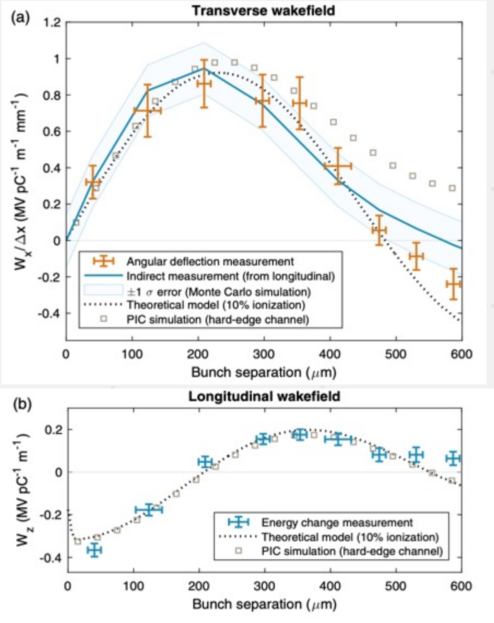
2017

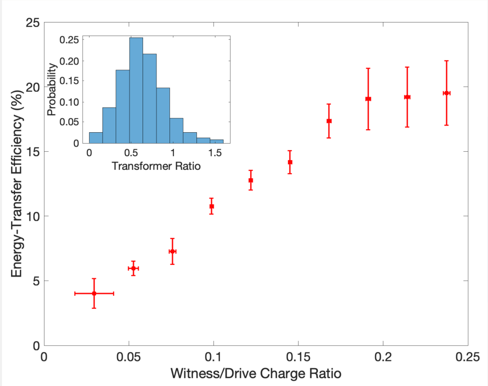
First acceleration of a distinct bunch

Positron PWFA in a Hollow Channel









2003

First positron guiding in a near-hollow channel

2016

First acceleration in a true hollow channel

2018

First wakefield measurements

2023

First demo of efficient energy transfer

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Collider Requirements

Ultimate objective: plasma-based e-e+ linear collider

Two figure-of-merit parameters for linear colliders:

- ➢ Acceleration gradient
- ➢ Luminosity per wall-plug power
  - o Small beam size (low emittance and small energy spread)
  - o High charge
  - o High efficiency

$$\frac{\mathcal{L}}{P_{wall}} \equiv \mathcal{L}_p \approx \frac{\eta_{wall-main} N}{\sqrt{\beta_x \beta_y}\,\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

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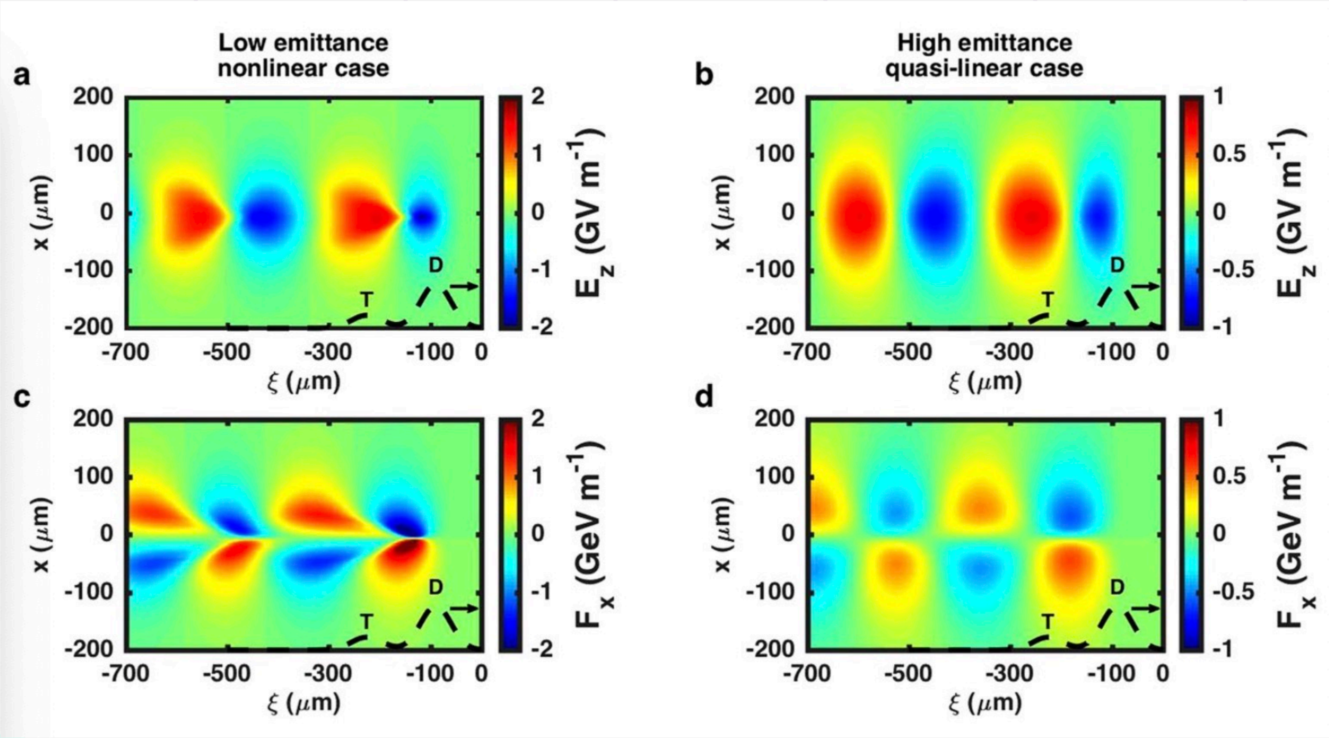
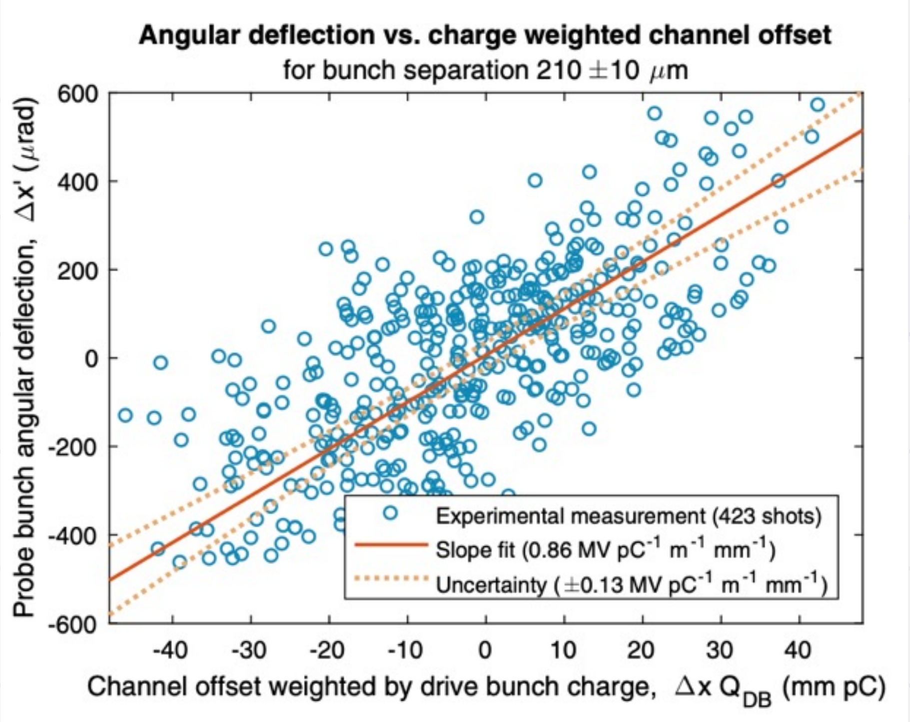
What’s missing: beam quality



In homogeneous plasma: emittance $O(100\mu m)$ and likely not preserved.



In hollow channel: beam break-up instability.

New proposals try to address these issues.

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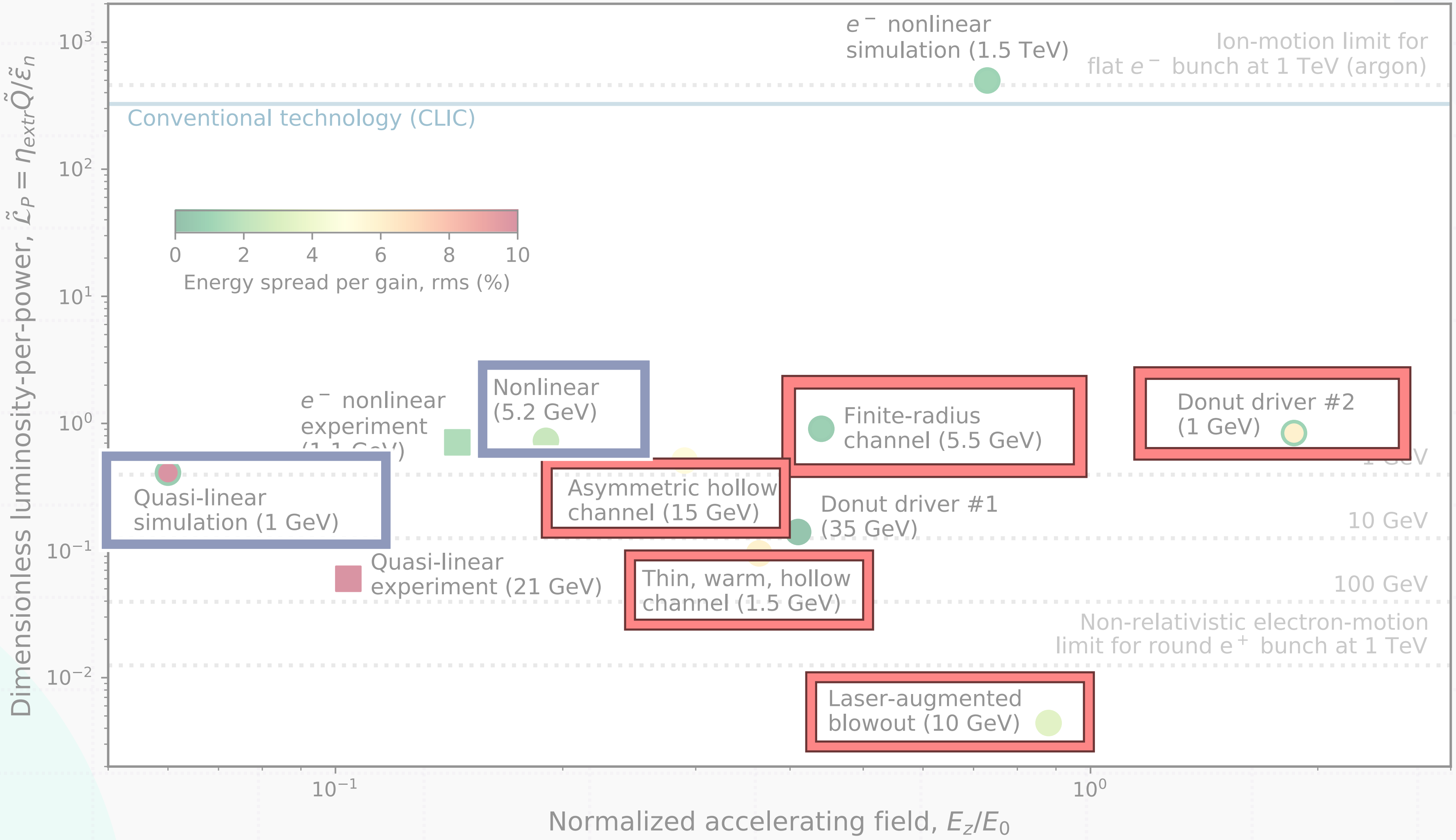
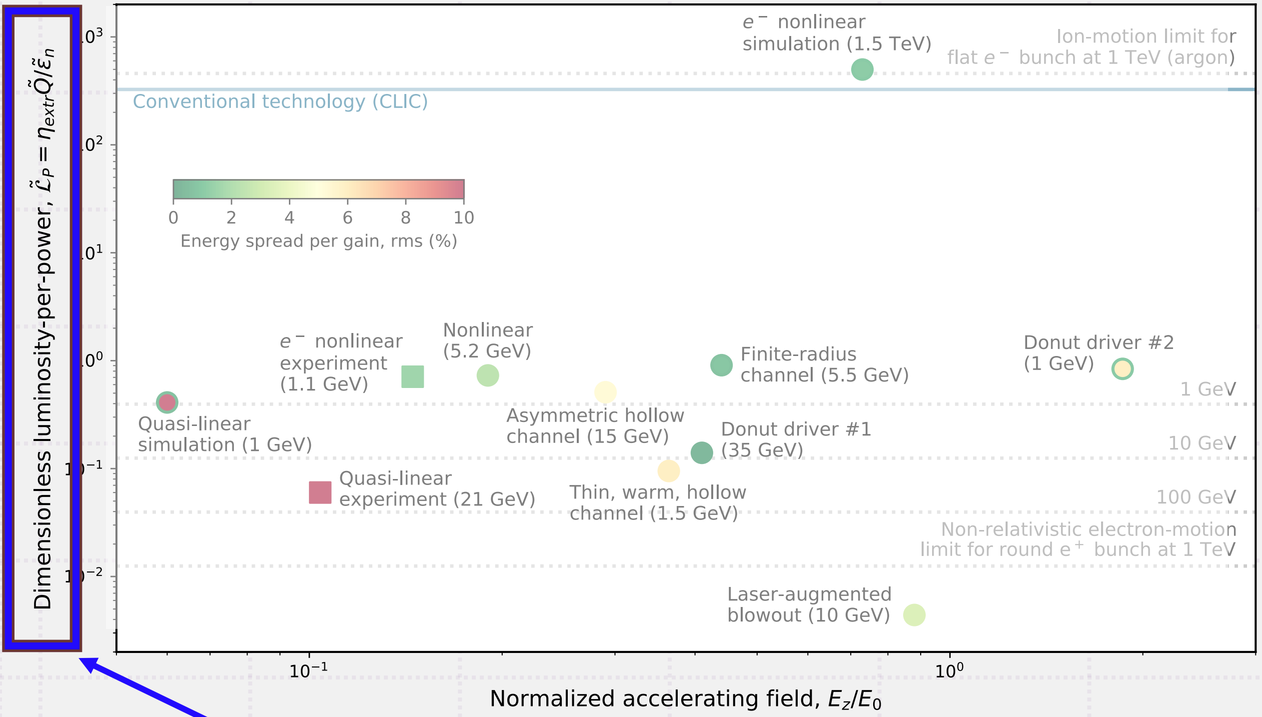
Proposed Schemes Comparison



From luminosity per power to dimensionless luminosity per power



Assumed to be the same for all schemes

$$= \eta_{prod}\eta_{depl}\eta_{extr}$$

$$\mathcal{L}_p \approx \frac{1}{8\pi m_e c^2}\frac{1}{\sqrt{\beta_x\beta_y}}\frac{\eta_{wall-main}N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

FF system, assumed to be the same for all schemes

$$\mathcal{L}_p \propto \frac{\eta_{extr}N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

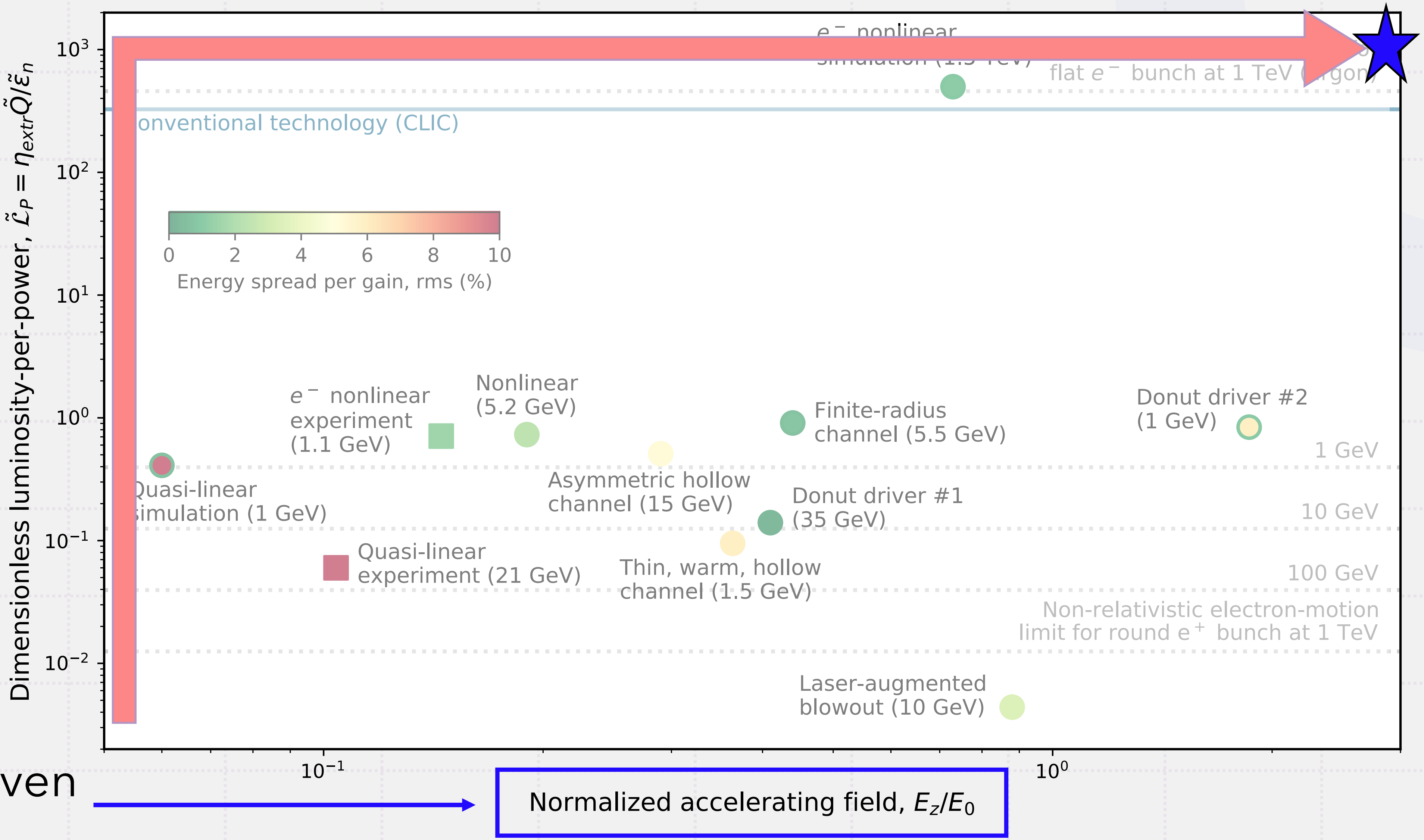
Normalize to plasma parameters

$$\tilde{Q} = \frac{k_p^3 N}{n_0} \qquad \tilde{\epsilon}_n = k_p\sqrt{\epsilon_{nx}\epsilon_{ny}}$$

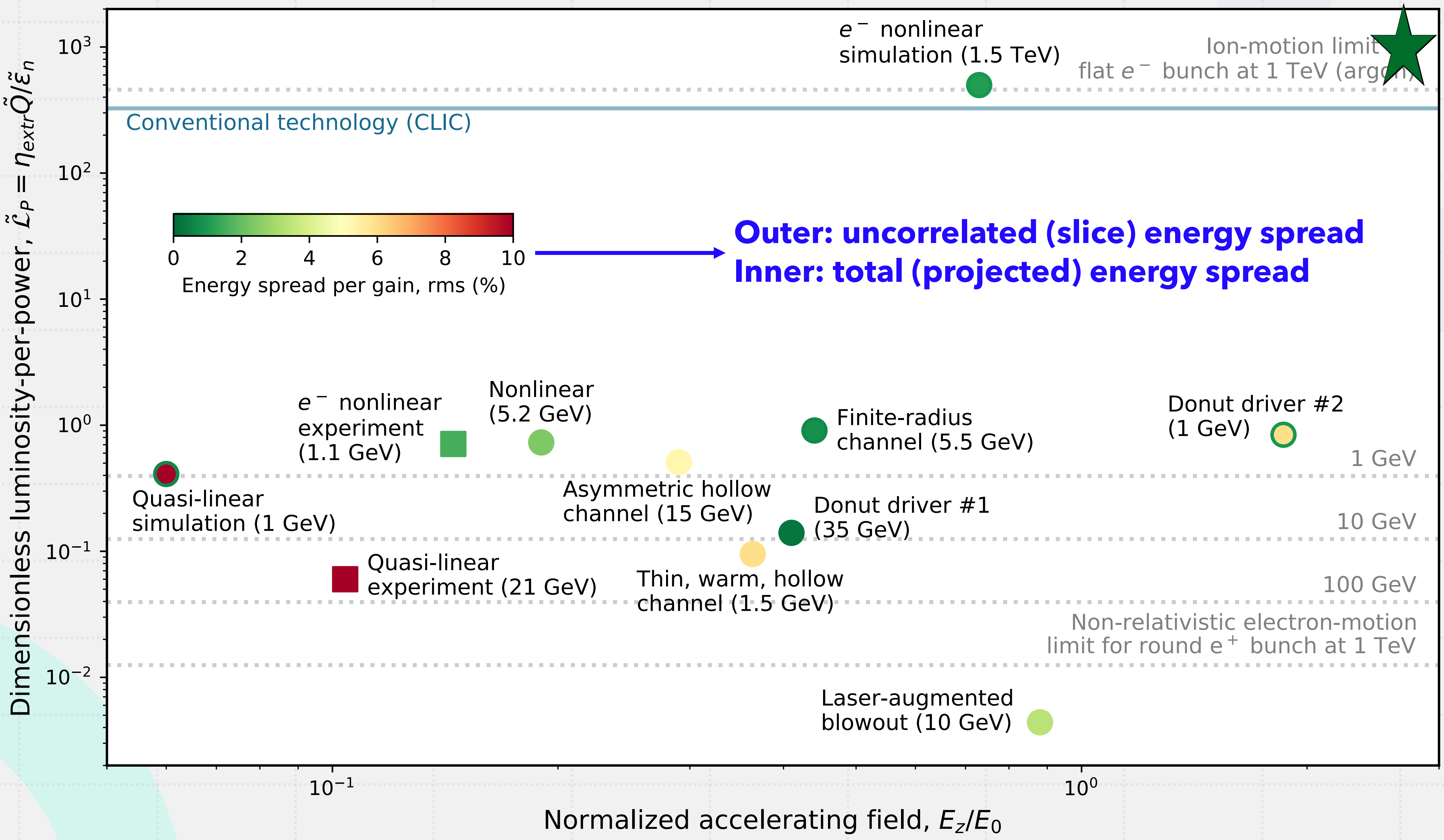
$$\boxed{\tilde{\mathcal{L}}_p \propto \frac{\eta_{extr}\tilde{Q}}{\tilde{\epsilon}_n}}$$

$\tilde{\mathcal{L}}_p$ is independent of plasma density

Ideal working point



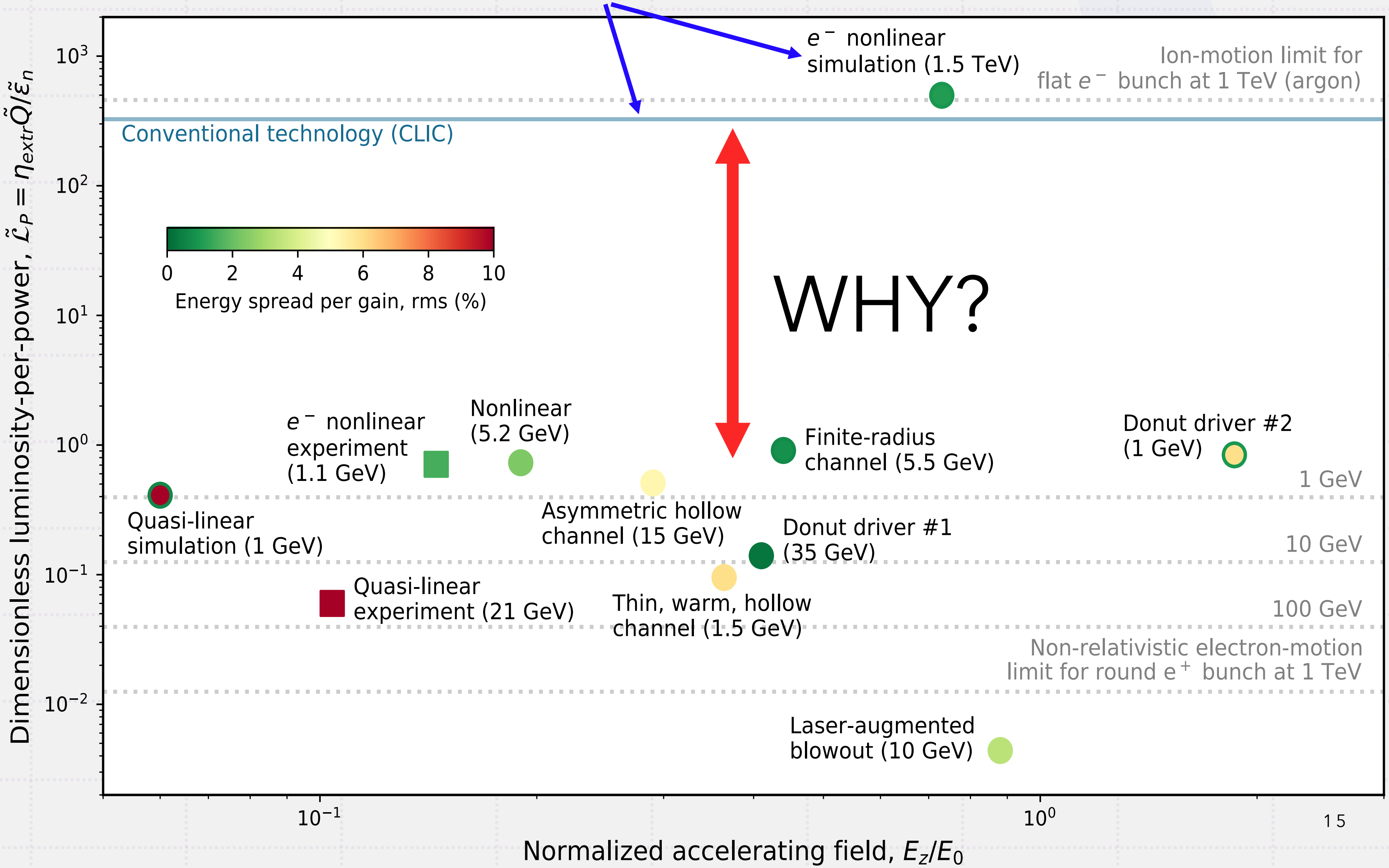
Gradient at a given plasma density

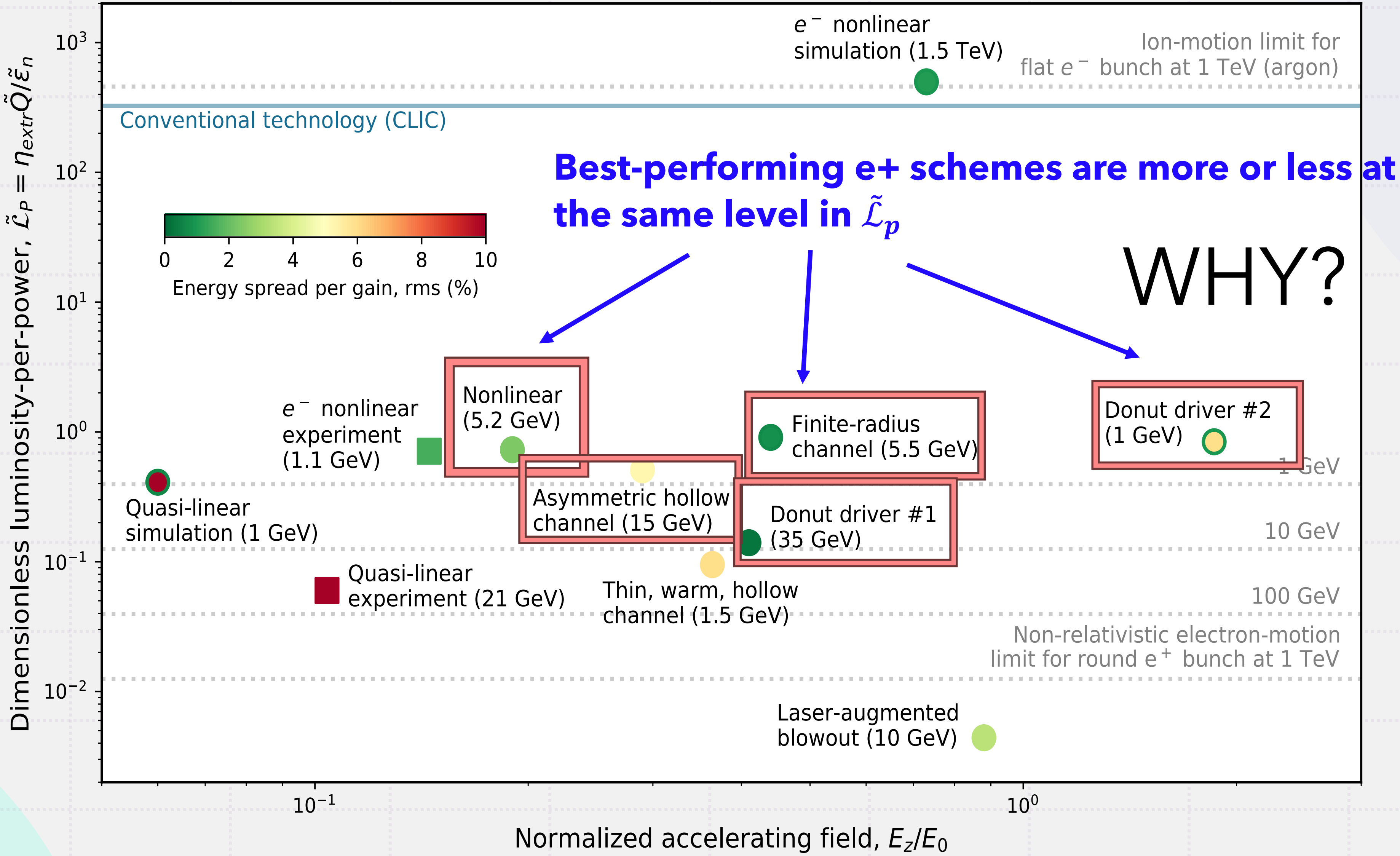


Ideal working point

Outer: uncorrelated (slice) energy spread
Inner: total (projected) energy spread

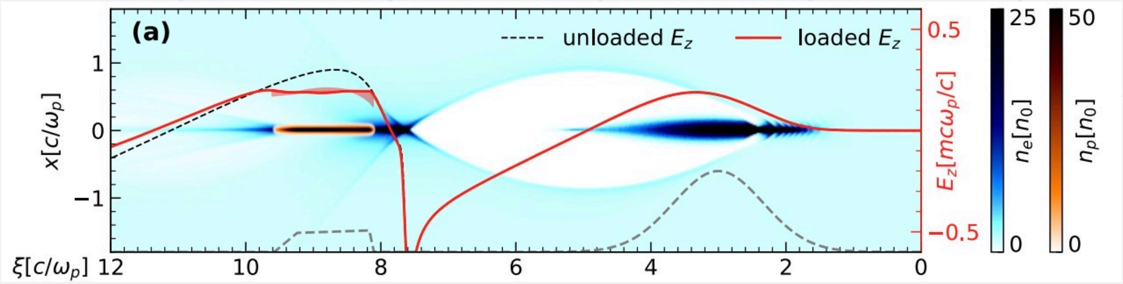
e- PWFA and CLIC are at least 2.5 orders of magnitude higher in $\tilde{\mathcal{L}}_p$ than all e+ schemes



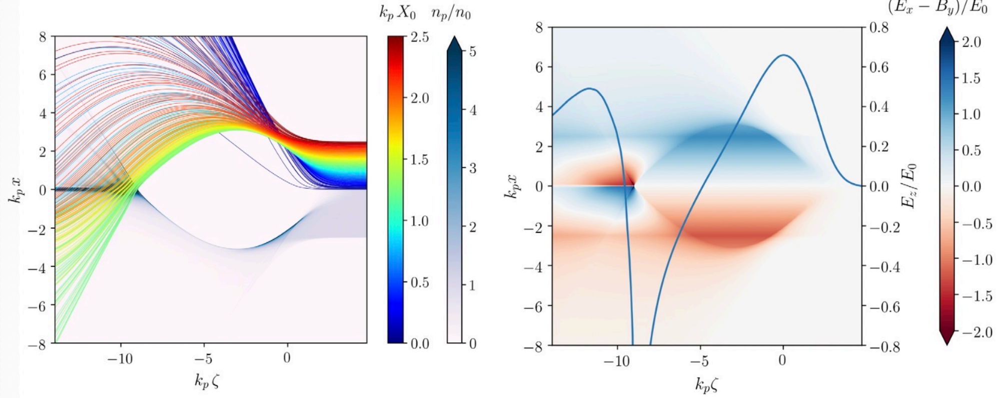


Best-performing e+ schemes are more or less at the same level in $\tilde{\mathcal{L}}_p$

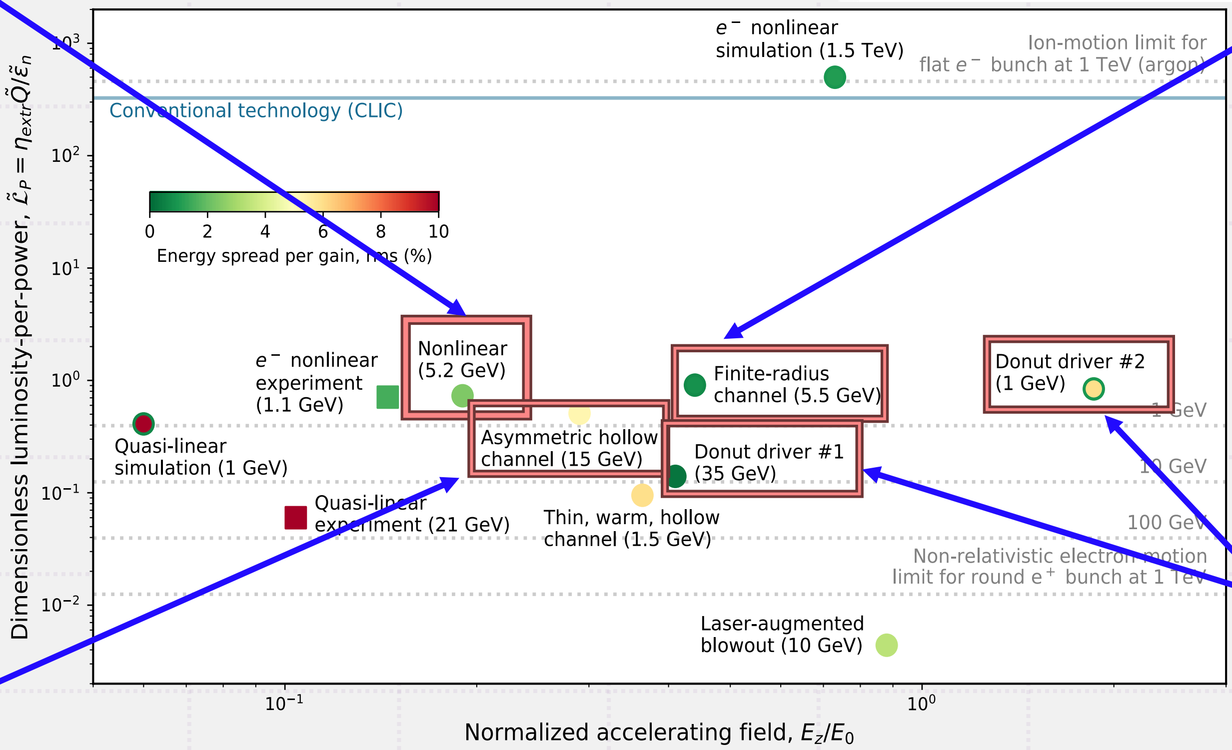
WHY?

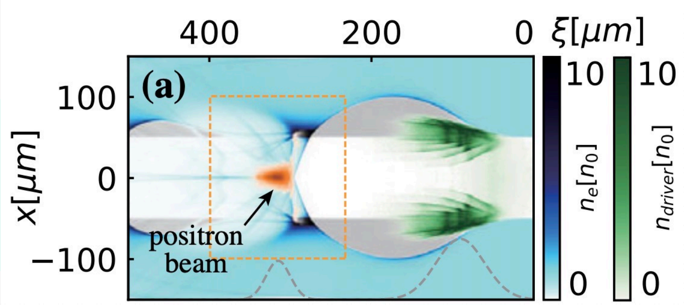


e- driven nonlinear blowout, optimally loaded

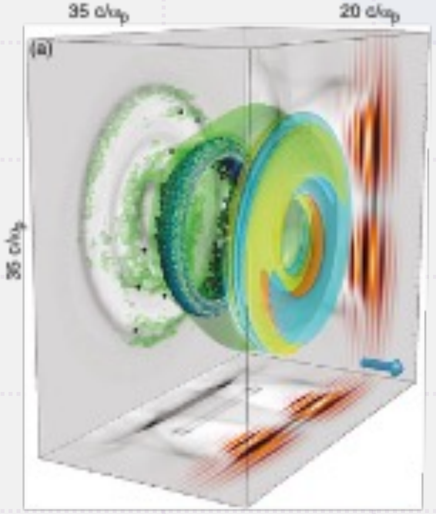


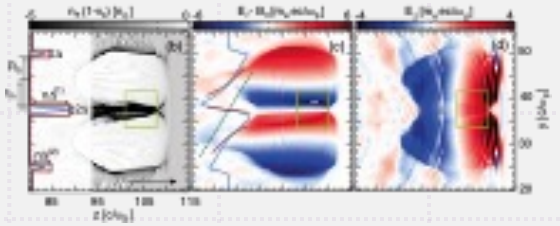
Finite-radius plasma channel





Asymmetric hollow channel





Donut-shaped e- or laser driver

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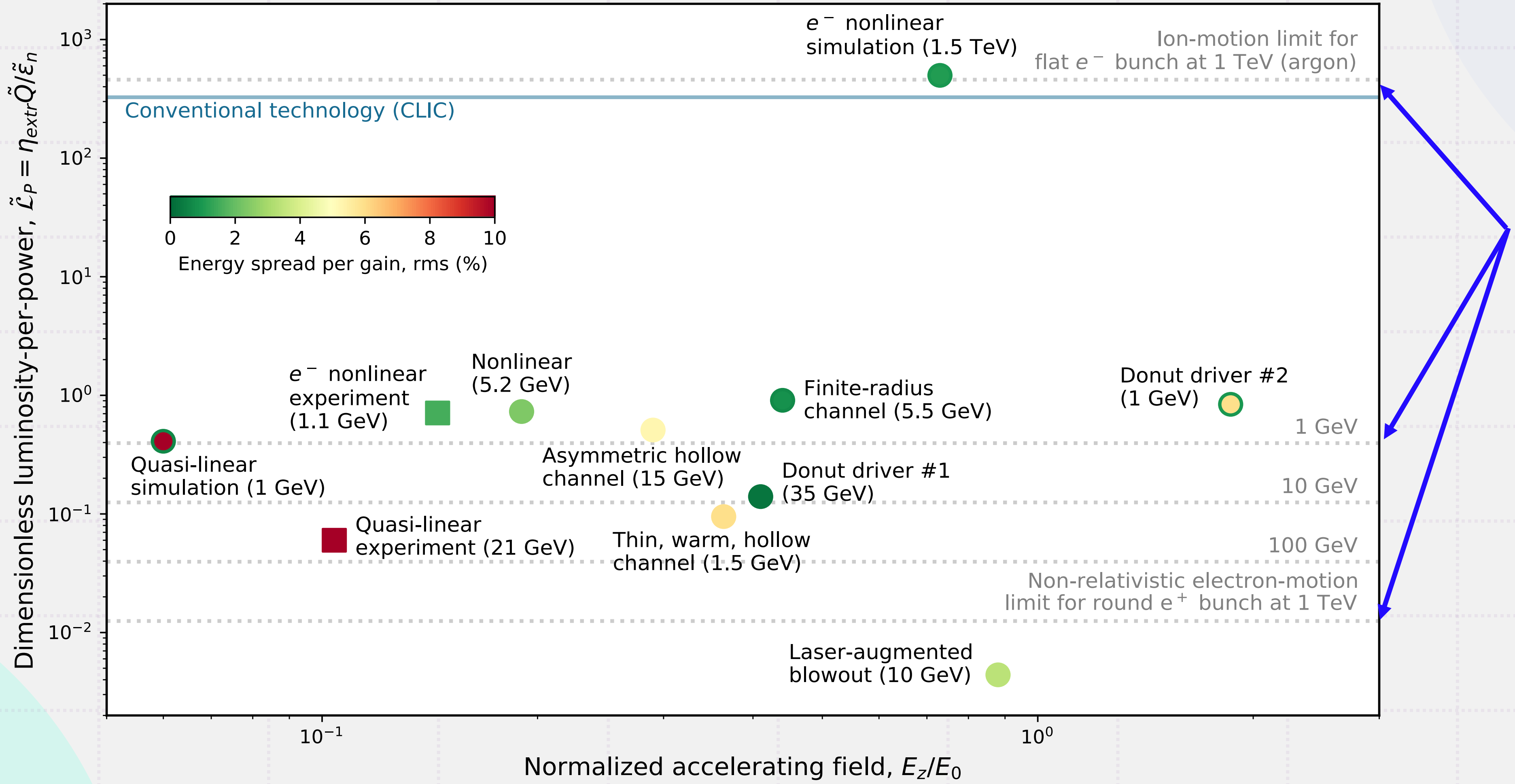
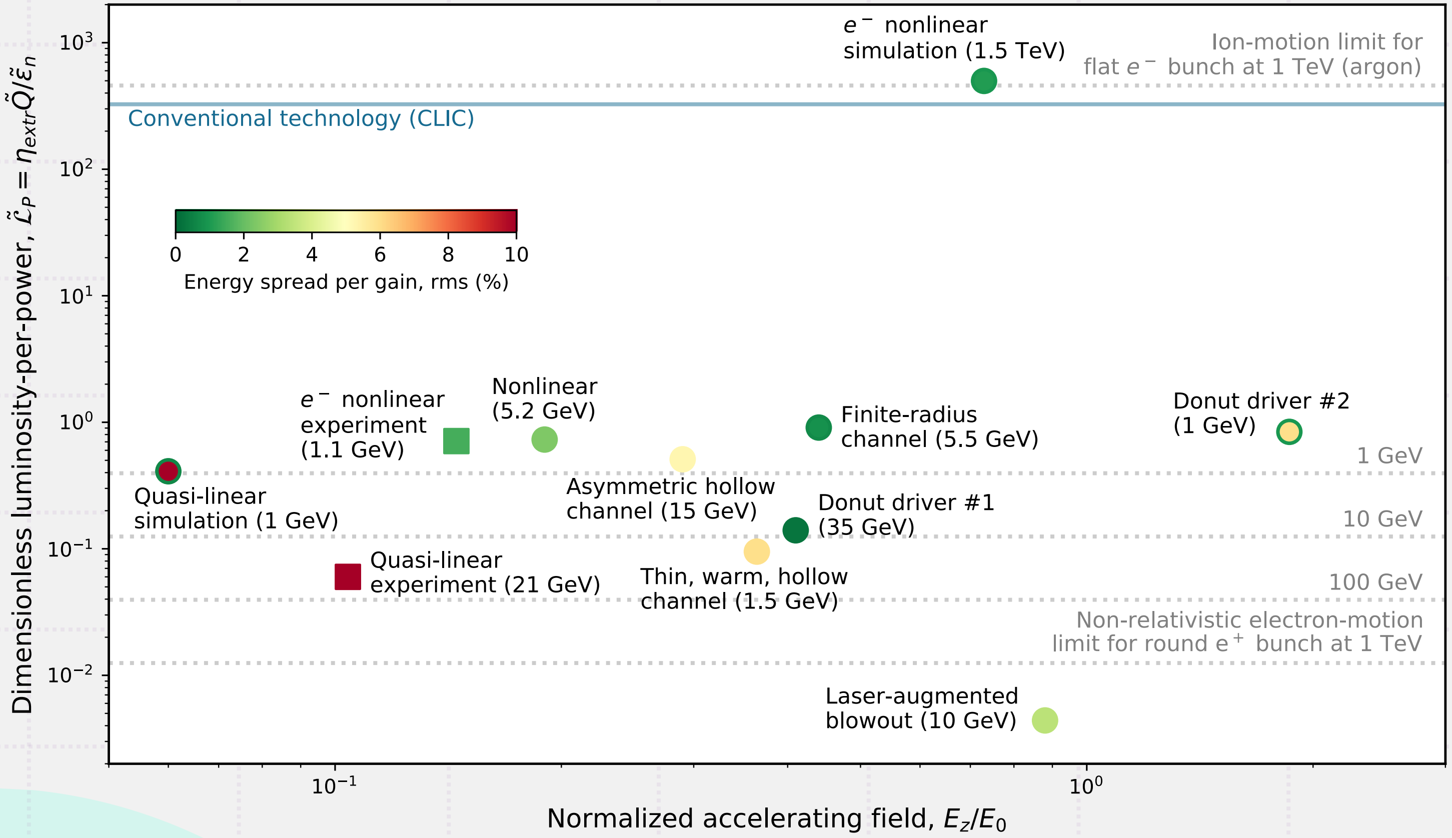
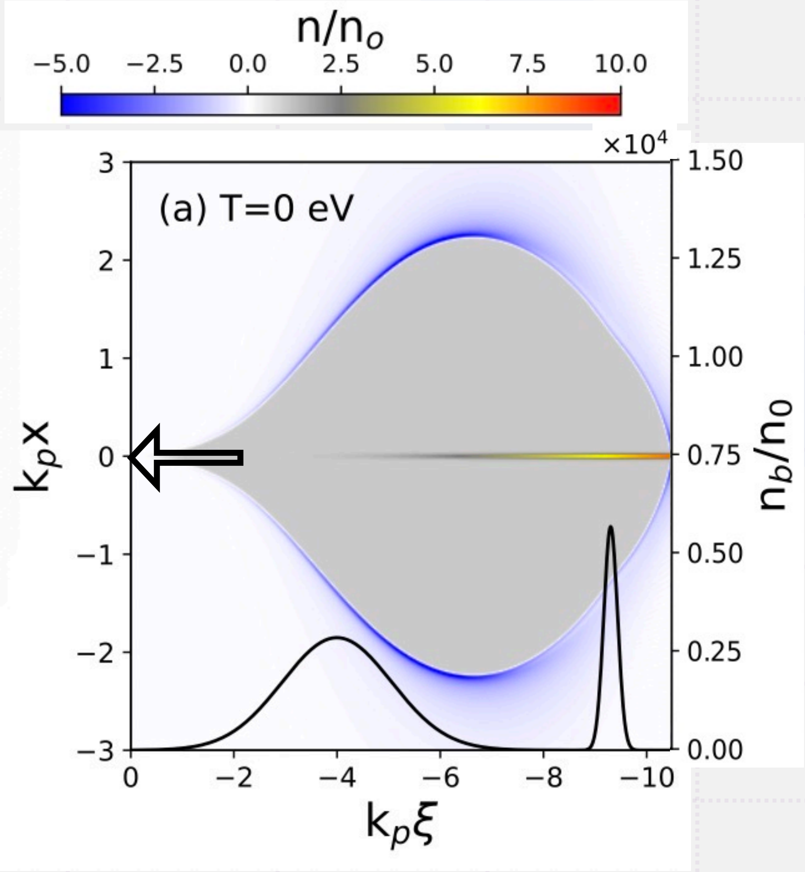
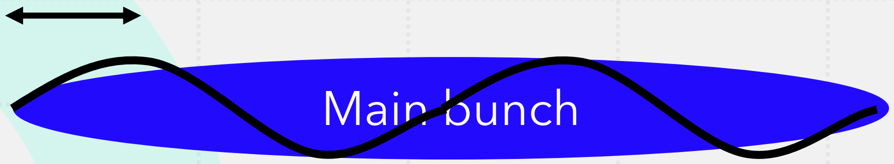
Why is there an ion/electron motion limit and what do they mean?



High ion phase advance degrades beam quality



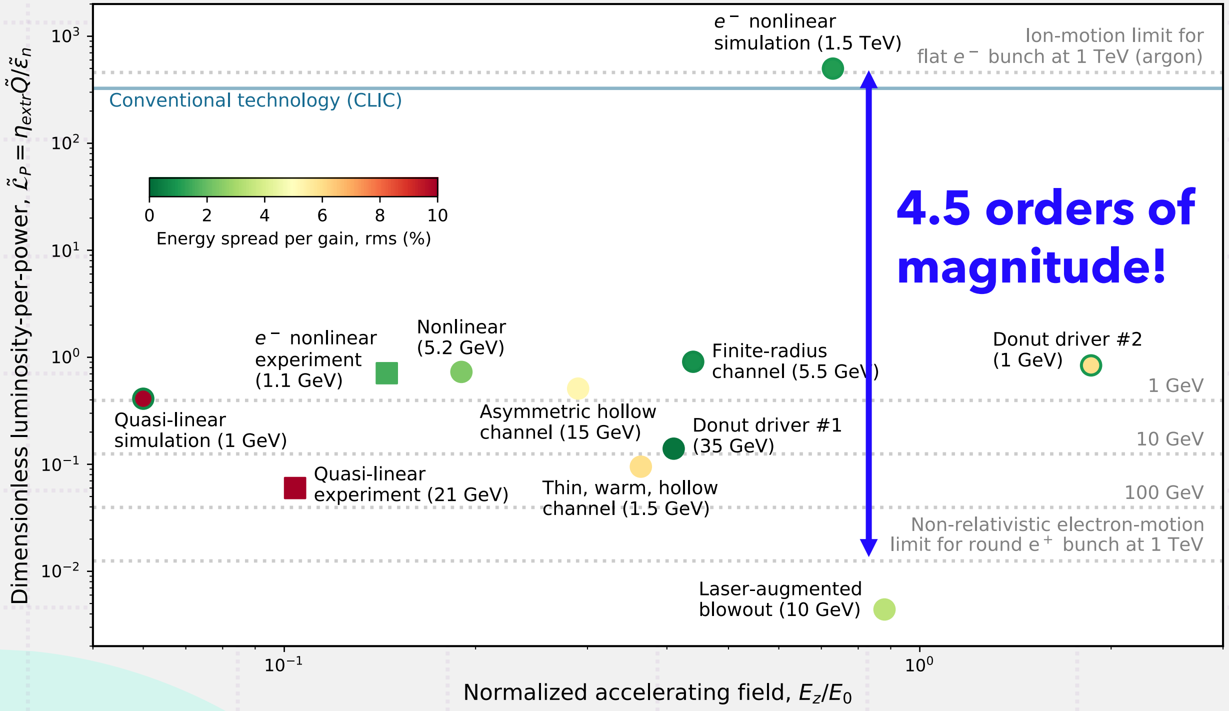




Ion phase advance by Rosenzweig:

$$\Delta\phi_i \approx k_i \Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2}\frac{Z\sigma_z N}{m_i}\sqrt{\frac{r_e\gamma n_0}{\epsilon_{nx}\epsilon_{ny}}}} \lesssim \frac{\pi}{2}$$

From ion motion to electron motion: it’s the same challenge!



4.5 orders of magnitude!

$$\Delta\phi_i \approx k_i\Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2}\frac{Z\sigma_z N}{m_i}\sqrt{\frac{r_e\gamma n_i}{\epsilon_{nx}\epsilon_{ny}}}}$$

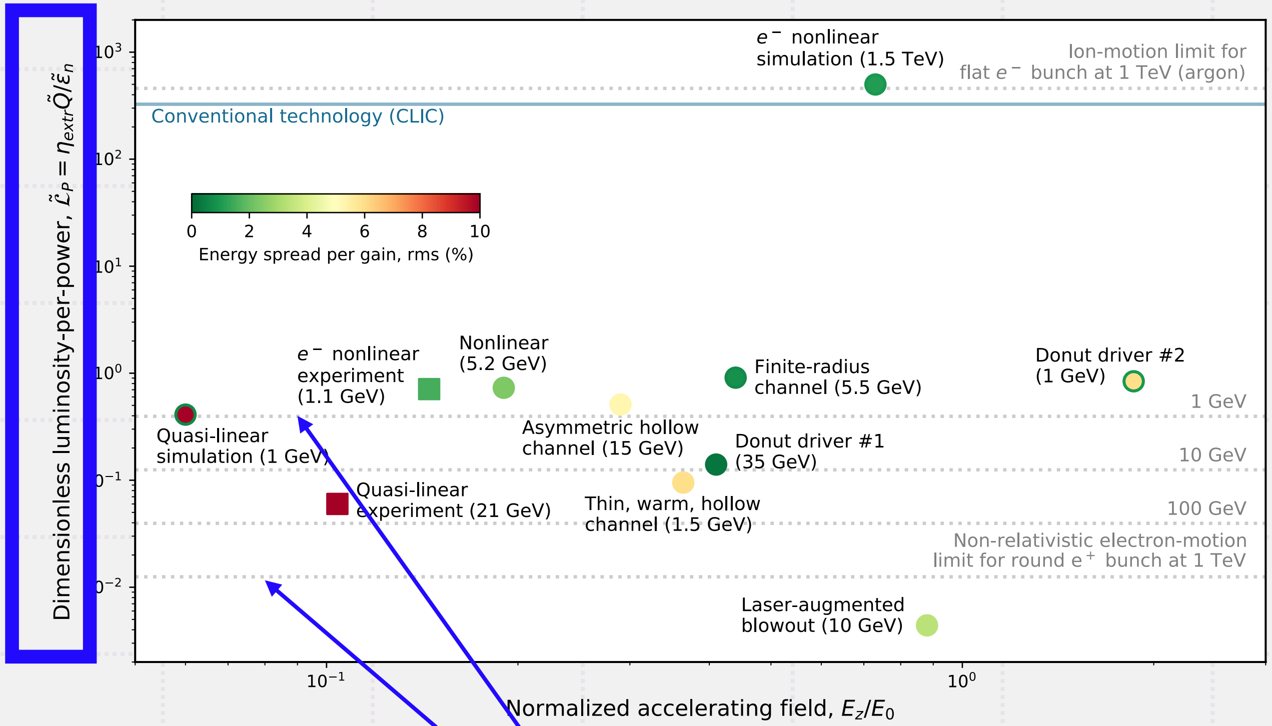
$$\Downarrow$$

$$\Delta\phi_e \approx k_e\Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2}\frac{1\sigma_z N}{\gamma_{pe} m_e}\sqrt{\frac{r_e\gamma\Delta n}{\epsilon_{nx}\epsilon_{ny}}}}$$

Note: $m_{ar} \sim 70000 m_e$

There’s a relation between $\Delta\phi$ and $\tilde{\mathcal{L}}_p$!

From phase advance to dimensionless luminosity per power



$$\Delta\phi_e \approx k_e\Delta\zeta = \sqrt{\frac{\mu_0 e^2}{2}\frac{\sigma_z N}{\gamma_{pe} m_e}\sqrt{\frac{r_e\gamma\Delta n}{\epsilon_{nx}\epsilon_{ny}}}}$$

$$\Updownarrow$$

$$\tilde{\mathcal{L}}_p \equiv 4\pi r_e \frac{\eta_{extr}N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

$$\tilde{\mathcal{L}}_p^{e^+} = (\Delta\phi_e)^2\sqrt{\frac{16\pi}{\gamma}}\left(\frac{\eta_{extr}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$

$$\lesssim \frac{\pi}{2}$$

$$\approx 1$$

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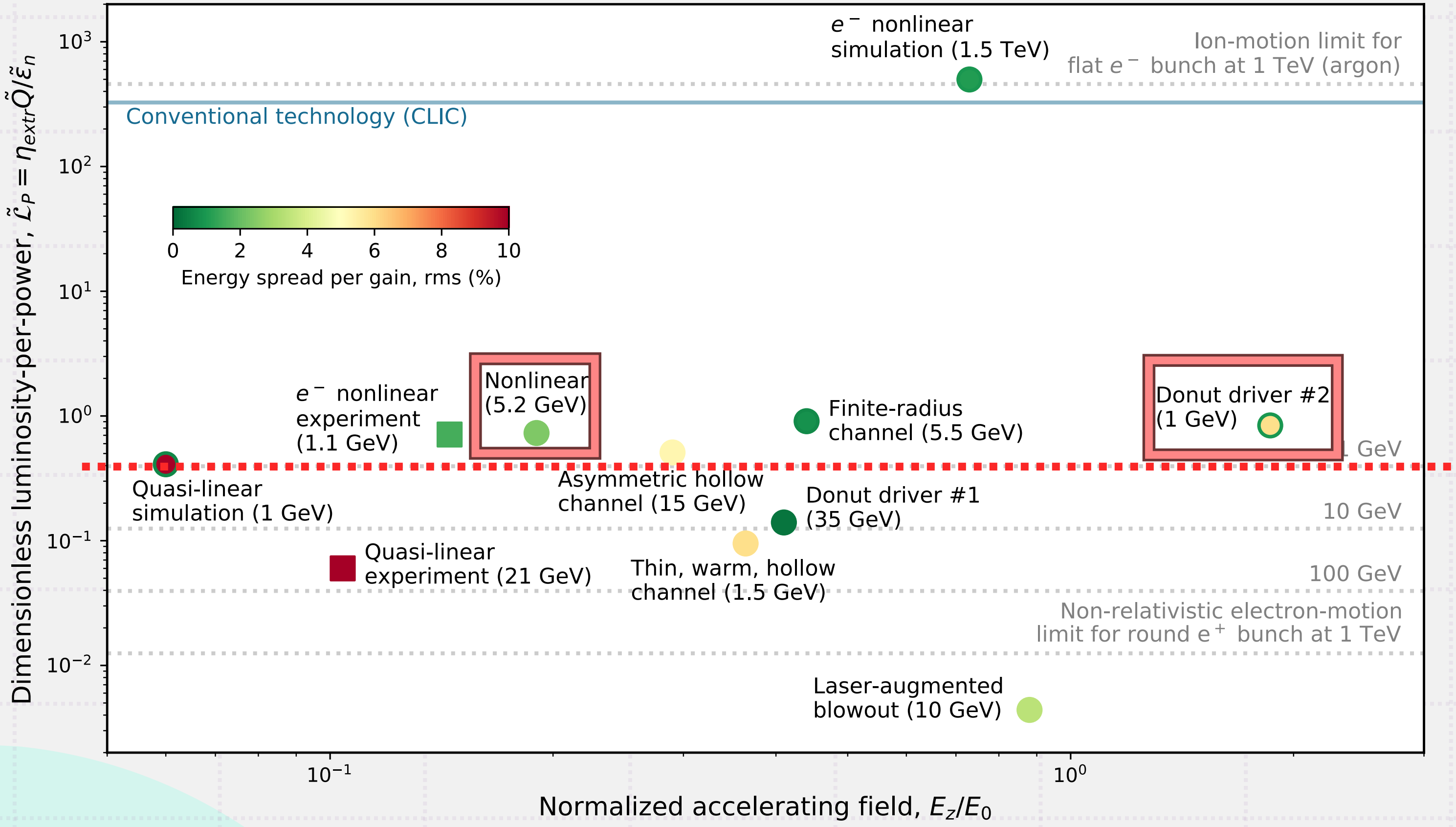
Some schemes go beyond the limit



$$\tilde{\mathcal{L}}_p^{e^+} = (\Delta\phi_e)^2 \sqrt{\frac{16\pi}{\gamma}} \left(\frac{\eta_{extr}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$

7.6
Nonlinear

$5 \times \frac{\pi}{2}$ limit

~4
Donut Driver #2

4 ×1 assumption

*overloaded, 6% energy spread

We can go beyond the limit in several ways

Extract more energy with shorter bunch lengths

$$\tilde{\mathcal{L}}_p^{e^+} = \sqrt{\frac{16\pi}{\gamma}}(\Delta\phi_e)^2\left(\frac{\eta_{extr}}{k_p\sigma_z}\right)$$

Use and maintain weak focusing:

Plasma temperature

Tolerate higher phase advance:

Maintain a uniform plasma e- distribution/slice by slice matching

Use relativistic plasma e-

Some parameters may work against each other

Plasma e- oscillate less in shorter bunches

$$\tilde{\mathcal{L}}_p^{e^+} = \sqrt{\frac{16\pi}{\gamma}}\,(\Delta\phi_e)^2\left(\frac{\eta_{extr}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$

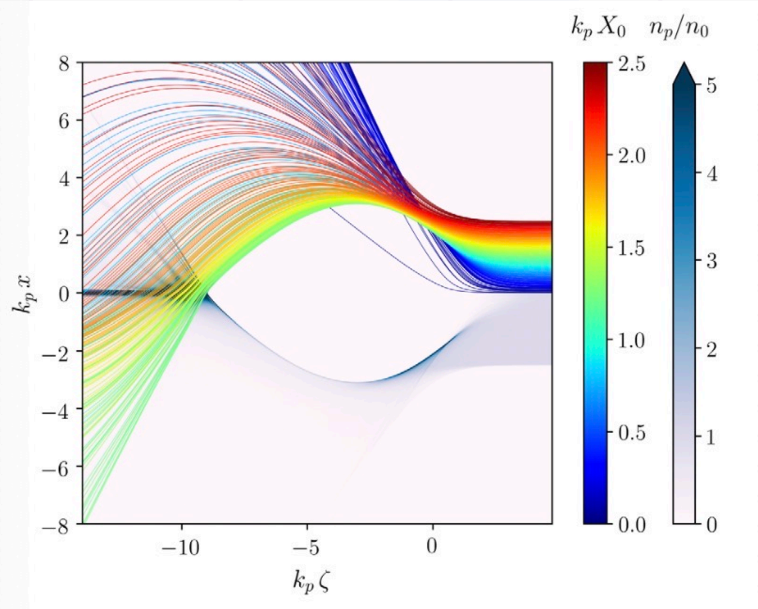
Using relativistic plasma e- makes it more difficult to capture them for focusing

The finite-radius plasma channel is not limited by electron motion

Essentially no oscillations, but effectively tolerating very high phase advance: ~34

$$\tilde{\mathcal{L}}_p^{e^+} = \sqrt{\frac{16\pi}{\gamma}}(\Delta\phi_e)^2\left(\frac{\eta_{extr}}{k_p\sigma_z}\right)\gamma_{pe}\sqrt{\frac{n_0}{\Delta n}}$$

Weakness of the scheme, <0.1



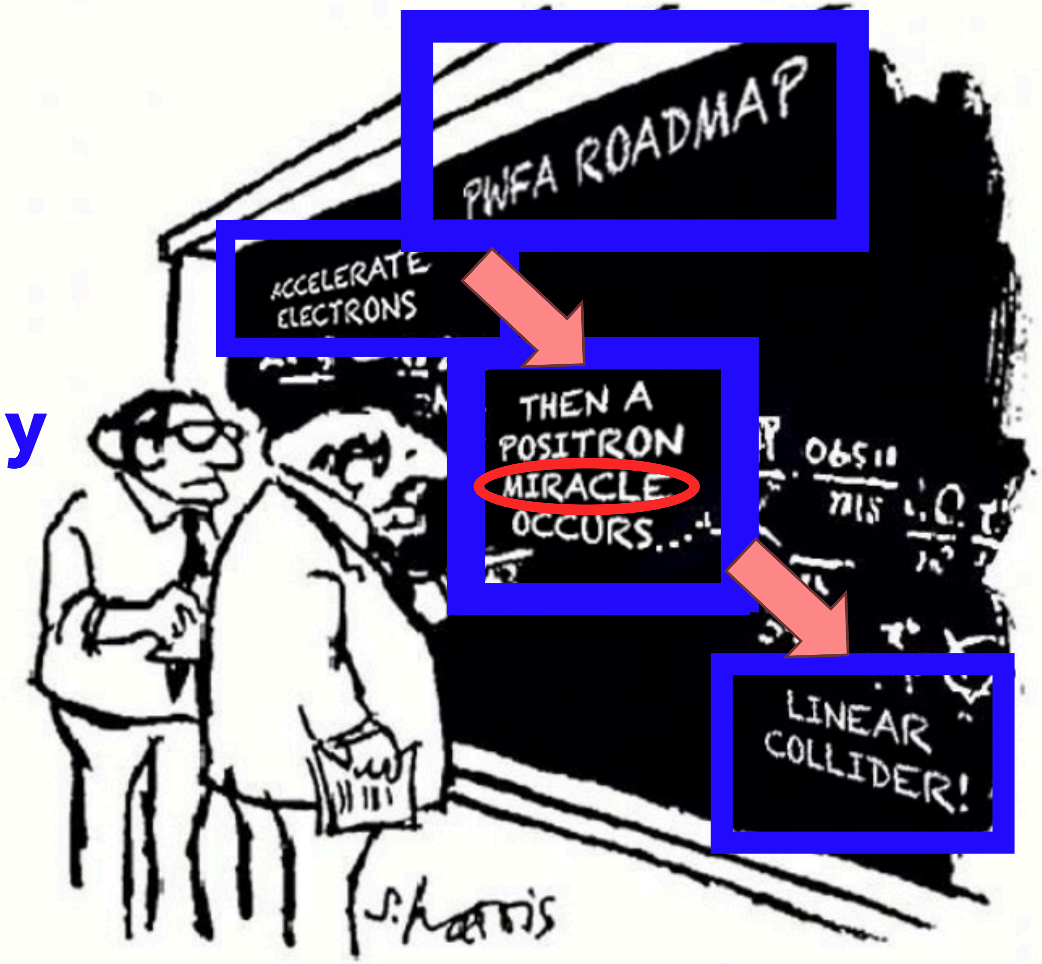
Unique features of the scheme:

1. Use of initial plasma e- transverse momentum and small beams (small emittance)—making capture harder, no oscillations
   - ➢ Good for quality preservation
2. Does not rely on plasma e- oscillations for focusing

Conclusion

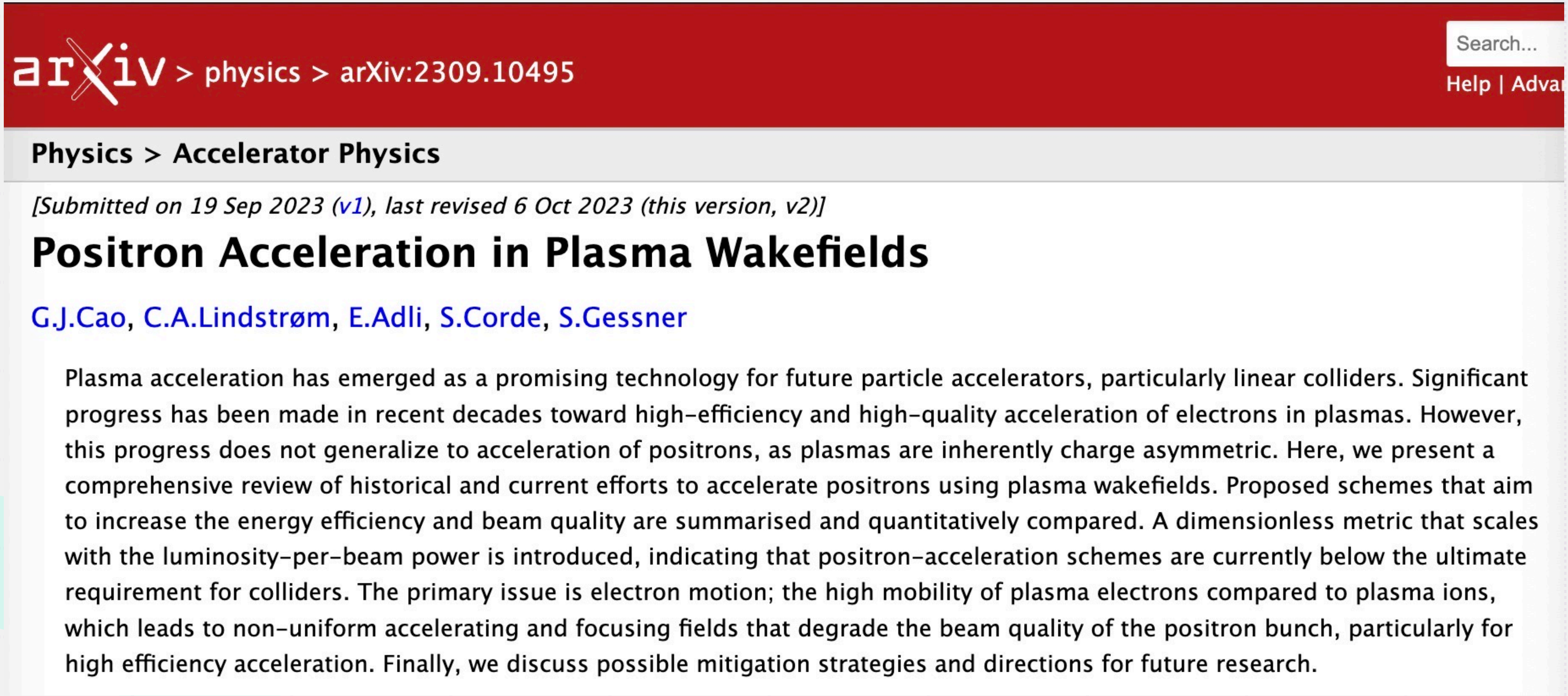
- Two sets of e+ PWFA experiment were performed at SLAC over the past 2 decades: in homogeneous plasma and hollow channels.
- Proposed schemes aim to address the beam quality issues observed in these experiments.
- Scheme comparison show similar performance for many schemes and ~3 orders of magnitude lower in luminosity per power for plasma-accelerated e+ compared to e-.
- The ultimate challenge is electron motion within the e+ bunch—the same principle as ion motion!
- Several strategies exist to go beyond the electron-motion limit or even get around the problem!

~~Miracle~~ → Strategy



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

More details in the review paper (submitted to PRAB)



Physics > Accelerator Physics

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Positron Acceleration in Plasma Wakefields

G.J.Cao, C.A.Lindstrøm, E.Adli, S.Corde, S.Gessner

Plasma acceleration has emerged as a promising technology for future particle accelerators, particularly linear colliders. Significant progress has been made in recent decades toward high-efficiency and high-quality acceleration of electrons in plasmas. However, this progress does not generalize to acceleration of positrons, as plasmas are inherently charge asymmetric. Here, we present a comprehensive review of historical and current efforts to accelerate positrons using plasma wakefields. Proposed schemes that aim to increase the energy efficiency and beam quality are summarised and quantitatively compared. A dimensionless metric that scales with the luminosity-per-beam power is introduced, indicating that positron-acceleration schemes are currently below the ultimate requirement for colliders. The primary issue is electron motion; the high mobility of plasma electrons compared to plasma ions, which leads to non-uniform accelerating and focusing fields that degrade the beam quality of the positron bunch, particularly for high efficiency acceleration. Finally, we discuss possible mitigation strategies and directions for future research.

Questions?