Nonlinear Laser Wakefield Accelerators for collider applications
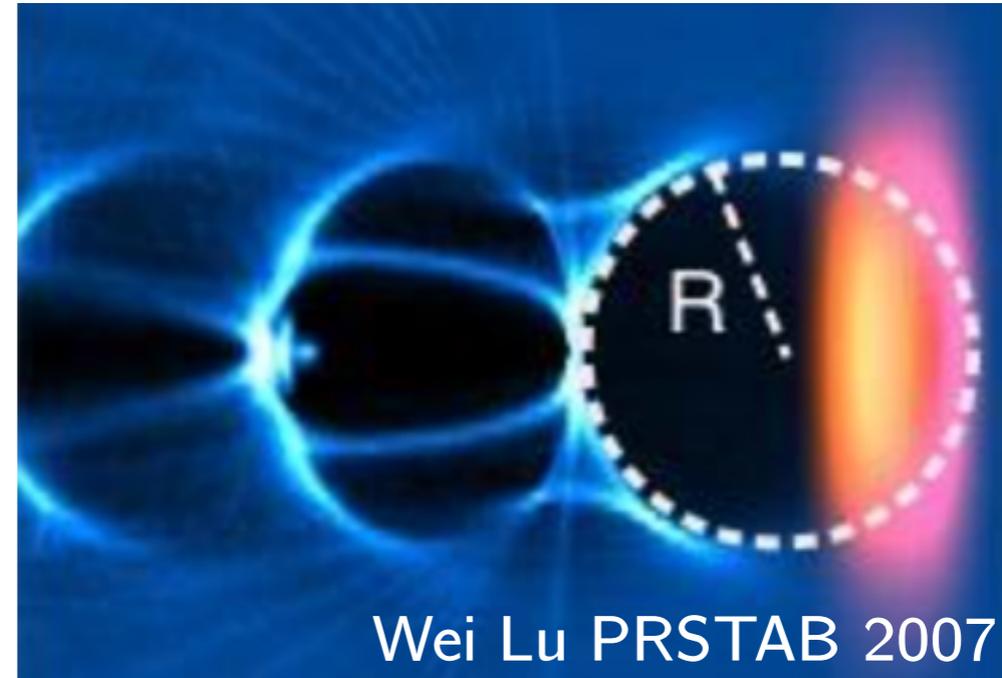
Stuart Mangles

Talk Outline

- What is the nonlinear regime?

- Are experiments in nonlinear regime?

- Can we predict properties of beams in nonlinear wakes?

- What are challenges that must be addressed if we want to make a collider based on nonlinear wakes?
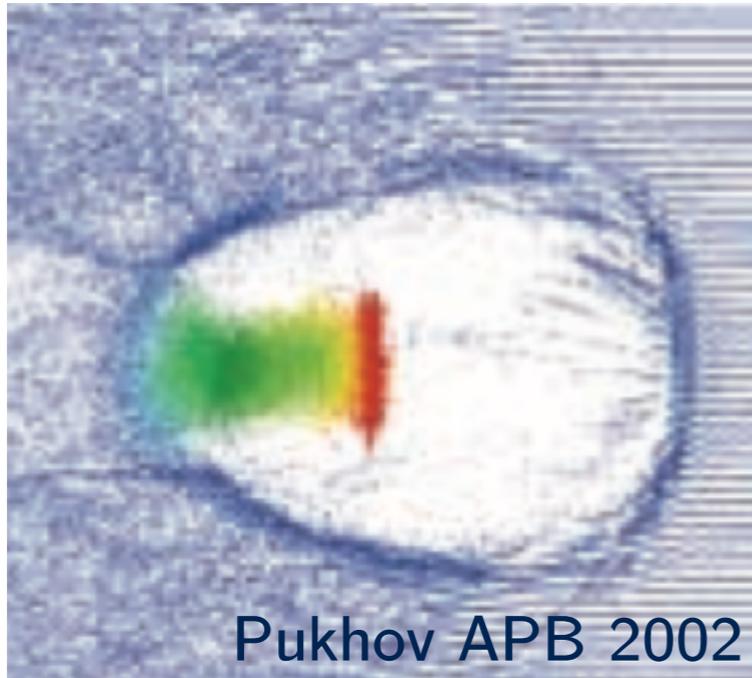
Talk Outline

- **What is the nonlinear regime?**

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Nonlinear regime of laser wakefield acceleration

Pukhov APB 2002

Wei Lu PRSTAB 2007

- Nonlinear regime
  - "*blow-out*" of electrons from first plasma wave period: the "*bubble*"
  - produces narrow energy spread beams (compared to earlier LWFAs)

- Needs a high intensity laser:
  - $a_0 > 2$
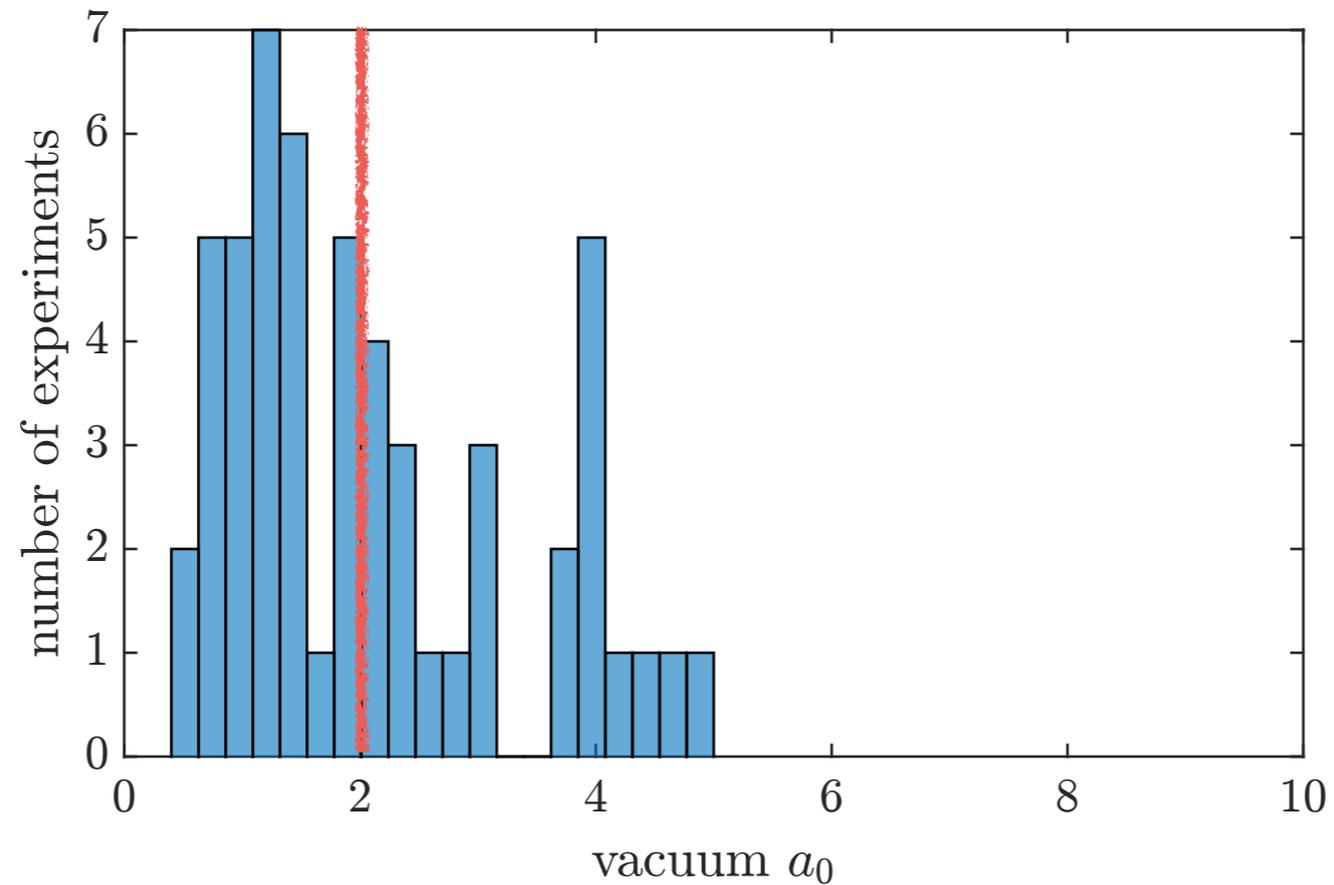 - $I > 0.8 \times 10^{19}$ W cm^{-2}

Talk Outline

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We now have a body of experimental evidence to examine scalings etc.
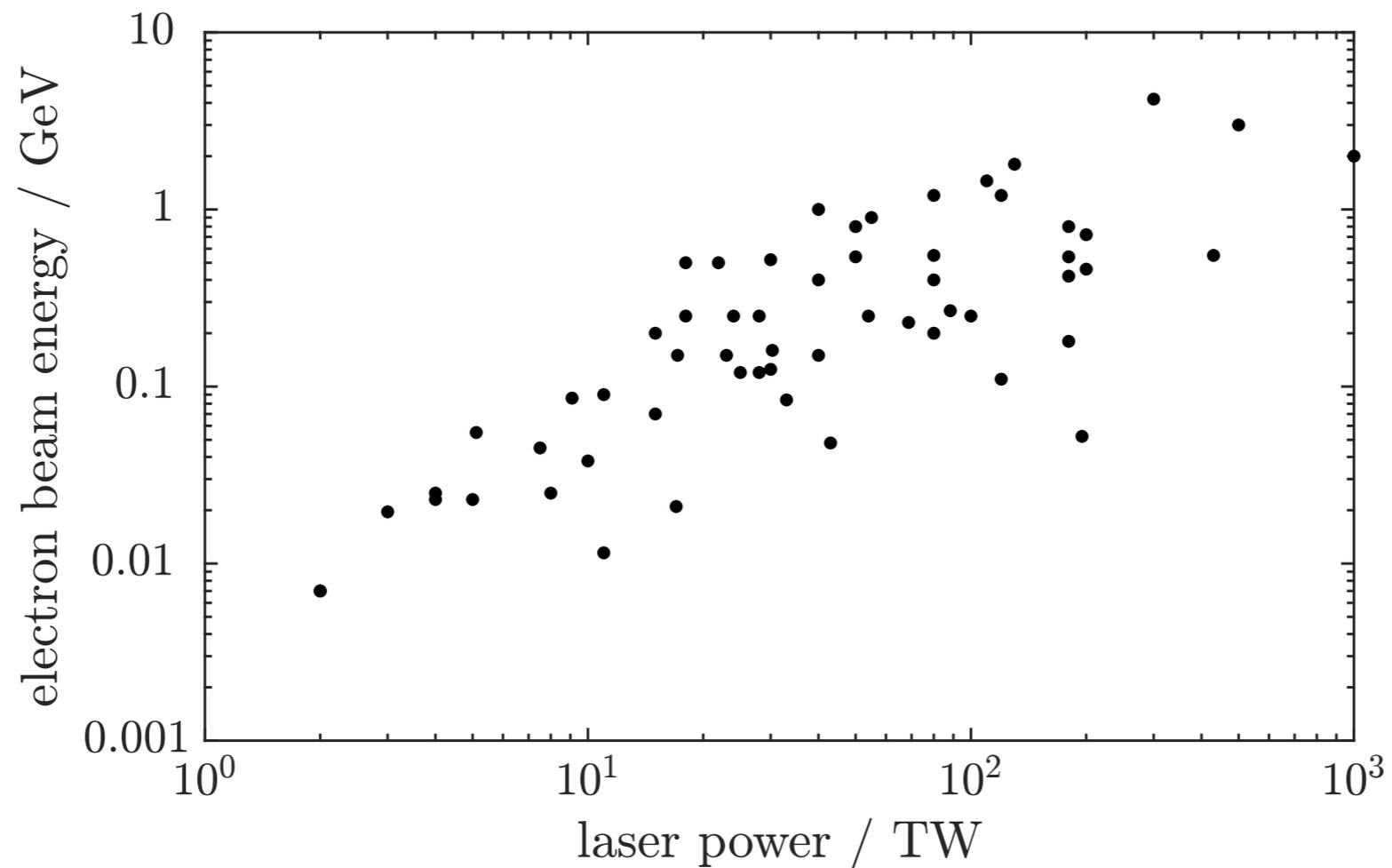
Are experiments in the nonlinear regime?

- We could use the vacuum laser strength, a_0, to classify the regime

Nonlinear pulse evolution affects a_0 inside the plasma

- Laser pulse undergoes nonlinear evolution in the wake:
  - self-focusing (e.g. Thomas PRL 2007)
  - pulse compression (e.g. Faure PRL 2005)
- vacuum a_0 is not the correct parameter
  - simple estimate of a0 after evolution is

$$a_{\mathrm{max}} \simeq 2 \left(\frac{\alpha E}{\tau_f P_c} \right)^{\frac{1}{3}}$$

  - α is fraction of energy contained in spot (usually 30 - 50%)
  - τ_f is pulse duration after compression. (a good estimate for this is $\tau_f = \tau_0/2$, Schreiber PRL 2010)

Are experiments in the nonlinear regime?
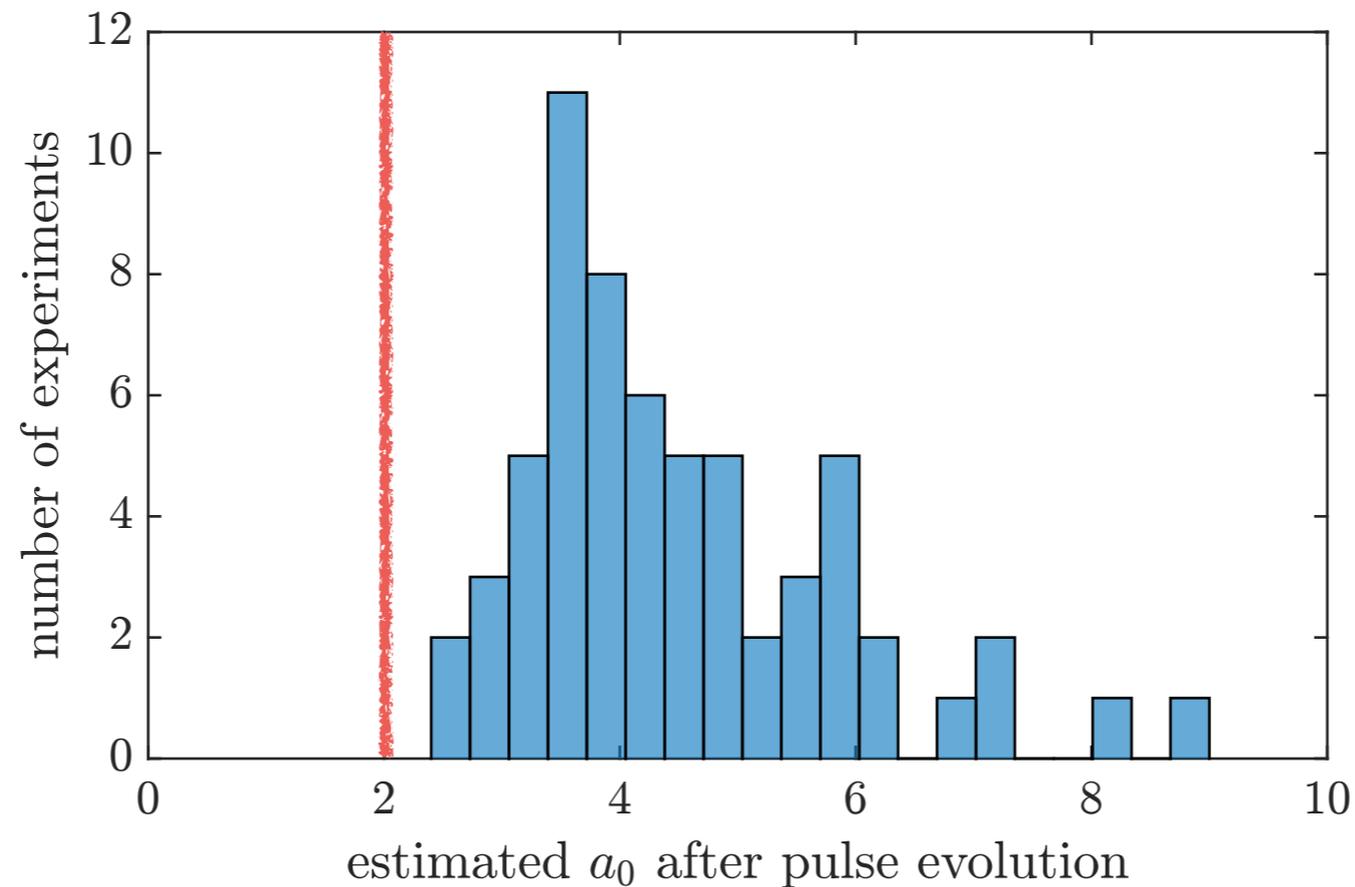
- Instead laser strength after evolution to classify which regime.
  - This puts virtually all experiments to-date into nonlinear regime

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Scaling laws for nonlinear LWFA

- Energy gain in nonlinear wake depends on a_0 and density

$$\frac{W_{\max}}{m_e c^2} = \frac{2}{3}\frac{n_c}{n_e}a_0 \qquad (1)$$

- Nonlinear pulse evolution means a_0 is a property of laser power and density

$$\frac{W'_{\max}}{m_e c^2} \approx \frac{4}{3}\frac{n_c}{n_e}\left[\frac{\alpha\beta P}{P_c}\right]^{\frac{1}{3}} \approx \frac{4}{3}\frac{n_c}{n_e}\left[\frac{P}{P_c}\right]^{\frac{1}{3}} \qquad (2)$$

  − α is the fraction of energy in the focal spot and β is the pulse compression factor (αβ is approximately 1)

erc

John Adams Institute for Accelerator Science

# What is the relationship between plasma density and power?
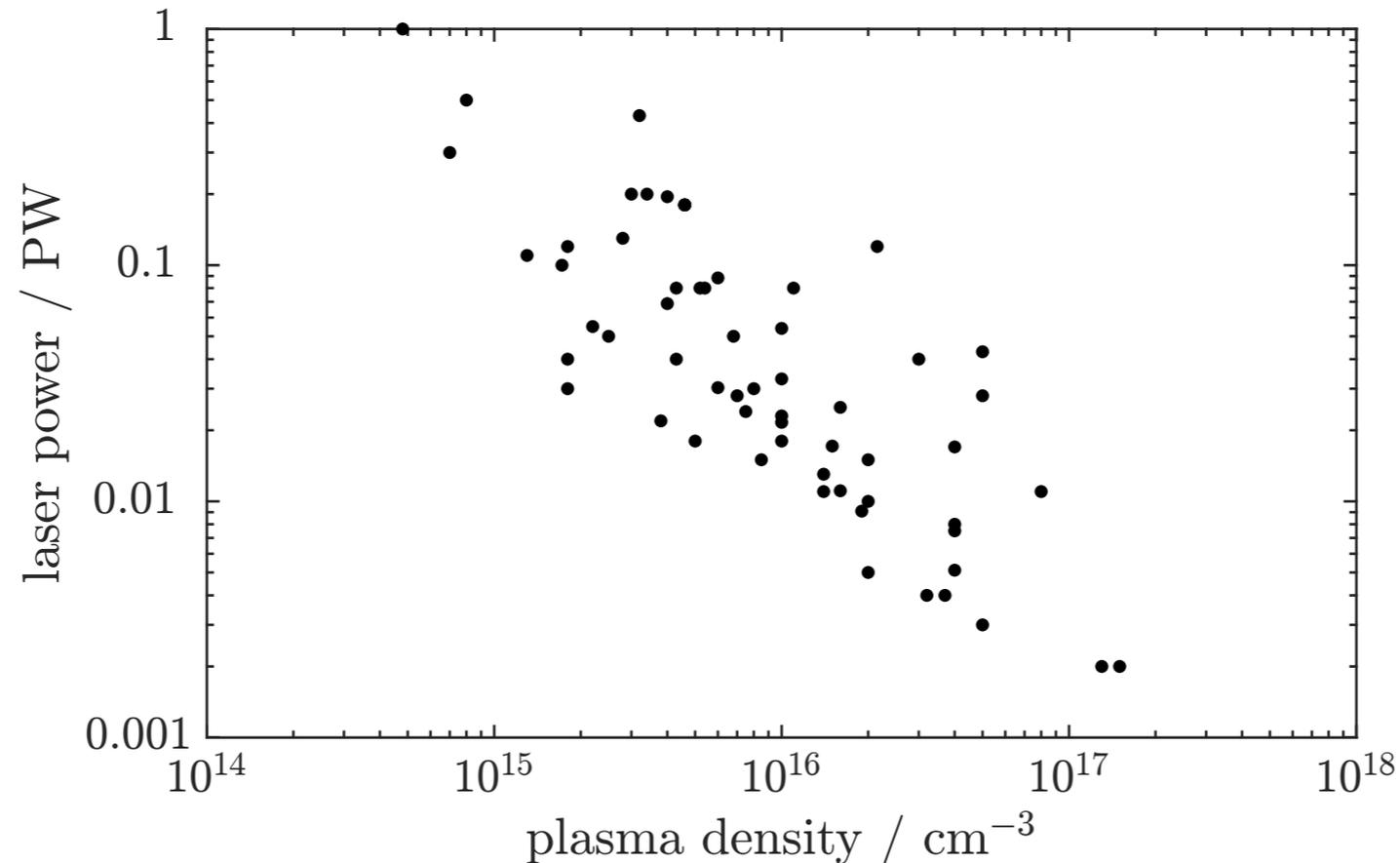
- Experiments show higher power lasers operate at lower density
  - produces higher energy beams (dephasing)
- But if you operate at a density which is too low, no electrons are injected
  - there is an injection threshold

A self-injection threshold model

- Self-injection threshold, taking into account pre-injection evolution phase:

$$\frac{\alpha P}{P_{\mathrm{c}}} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3 \qquad (3)$$

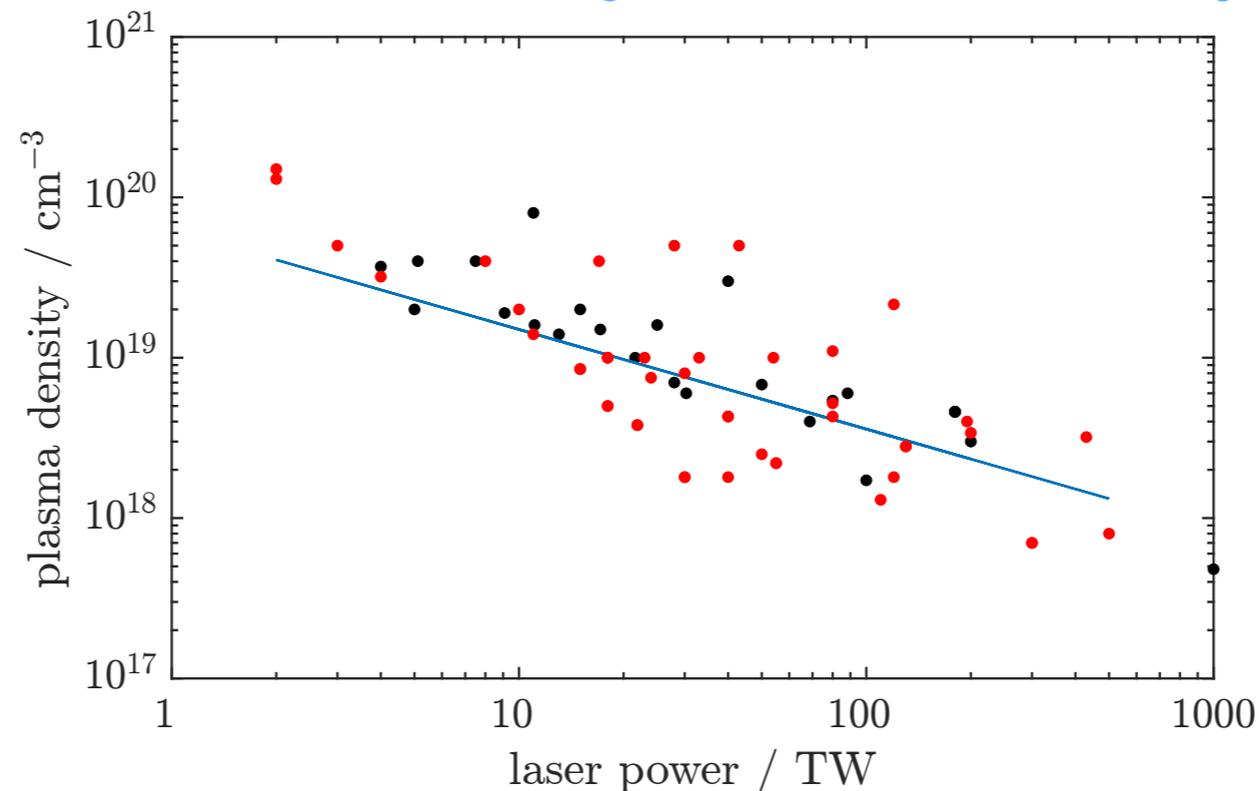- Self-injection experiments lie above this threshold
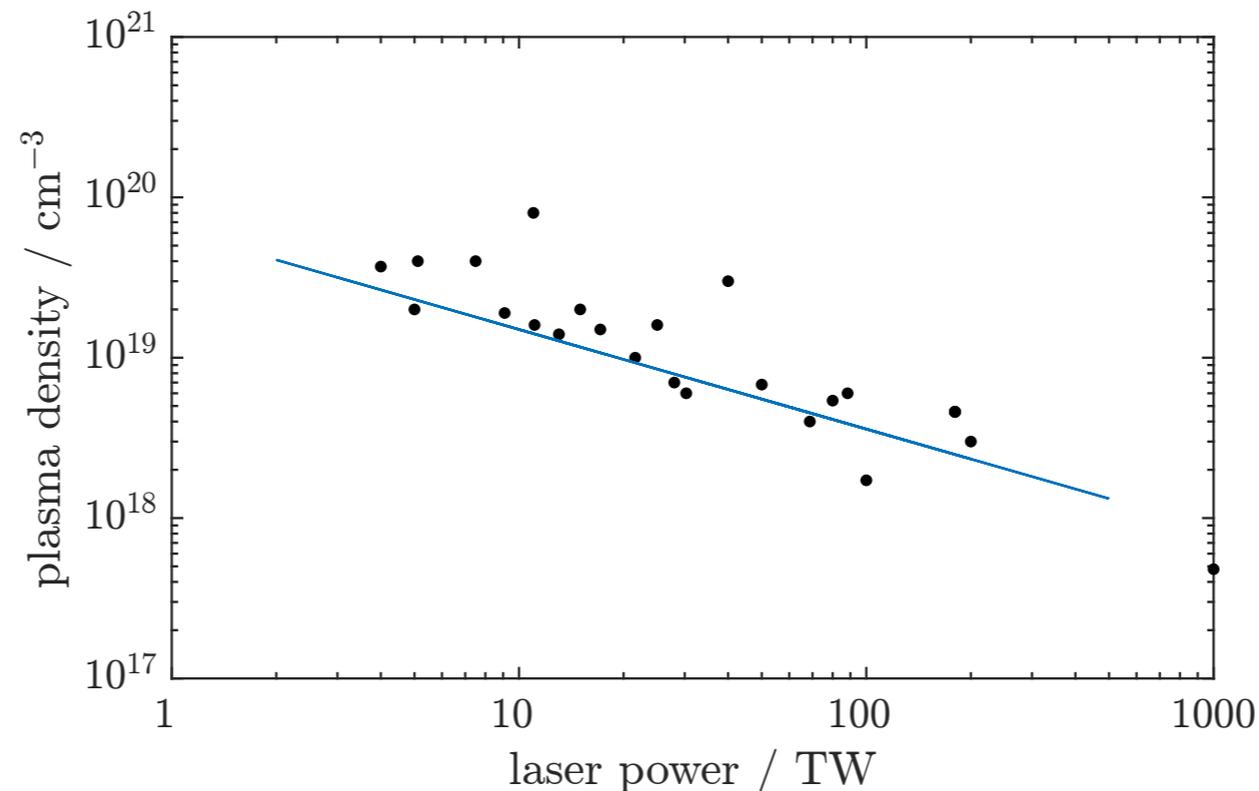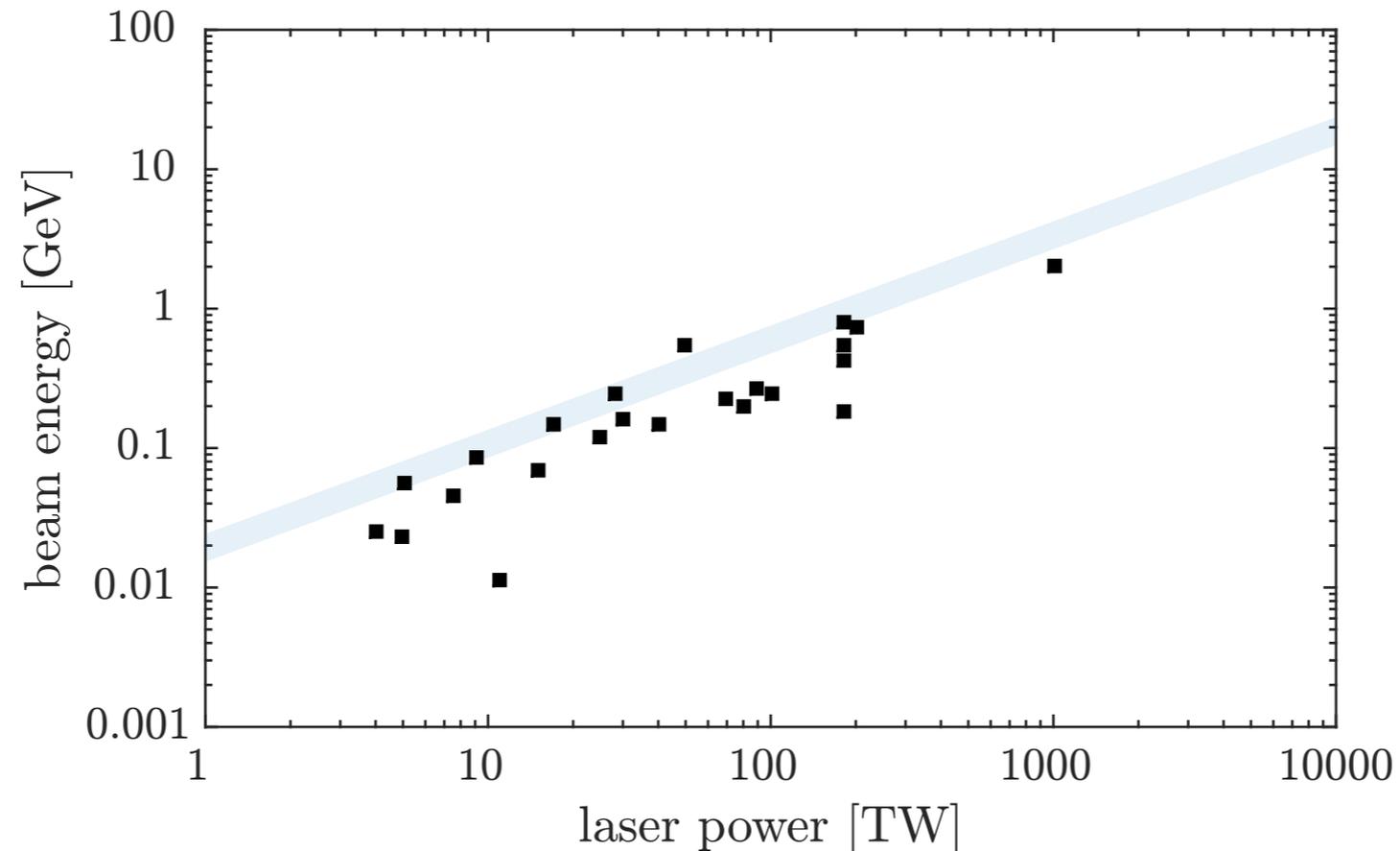
The injection threshold links density and laser power

- Self-injection threshold, taking into account pre-injection evolution phase:

$$\frac{\alpha P}{P_{\rm c}} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3 \qquad (3)$$

- Self-injection experiments lie above this threshold
  - But other injection methods can inject at lower density

Mangles PRSTAB 2012

A model to predict beam energies in nonlinear LWFA?

- Model that combines Wei Lu scaling with pulse evolution (2) and self-injection threshold (3) in good agreement with experimental data for nonlinear LWFA experiments
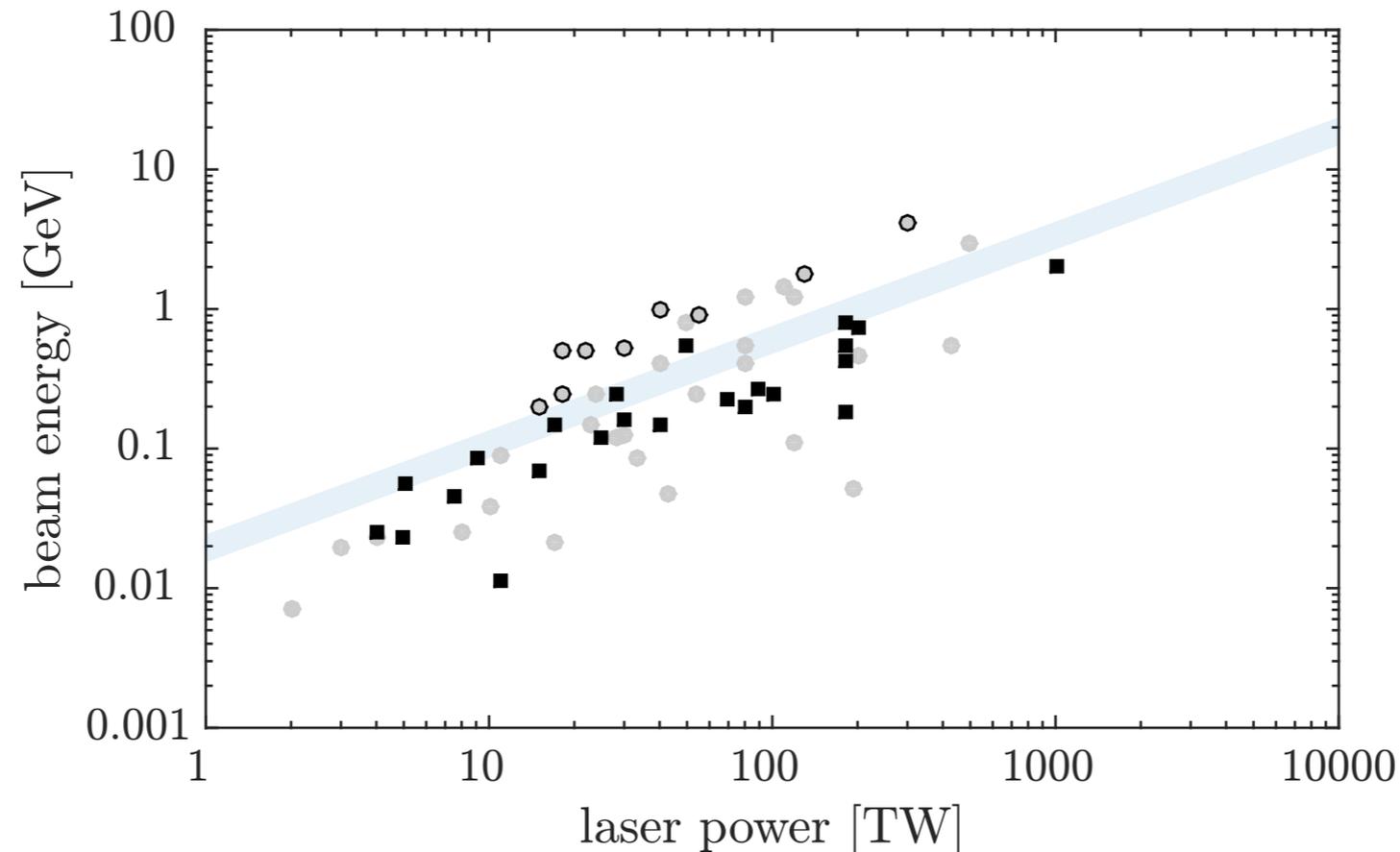 - self-guided
  - self-injection

# A model to predict beam energies in nonlinear LWFA?

- Model that combines Wei Lu scaling with pulse evolution (2) and self-injection threshold (3) in good agreement with experimental data for nonlinear LWFA experiments
  - other injection methods (ionization, colliding pulse, shock)
  - experiments in plasma waveguides

Pre-injection pulse evolution length

- Self-injection doesn't occur immediately

  – pulse evolution usually occurs before injection

- Over what length does this occur

  – Pre-injection Pulse evolution length L_{PIPE}

- How does this modify the scaling laws?

  – does it explain why most SI experiments don't hit the scaling law?

Pre-injection pulse evolution length

Mangles PhD Thesis

Thomas PRL 2007
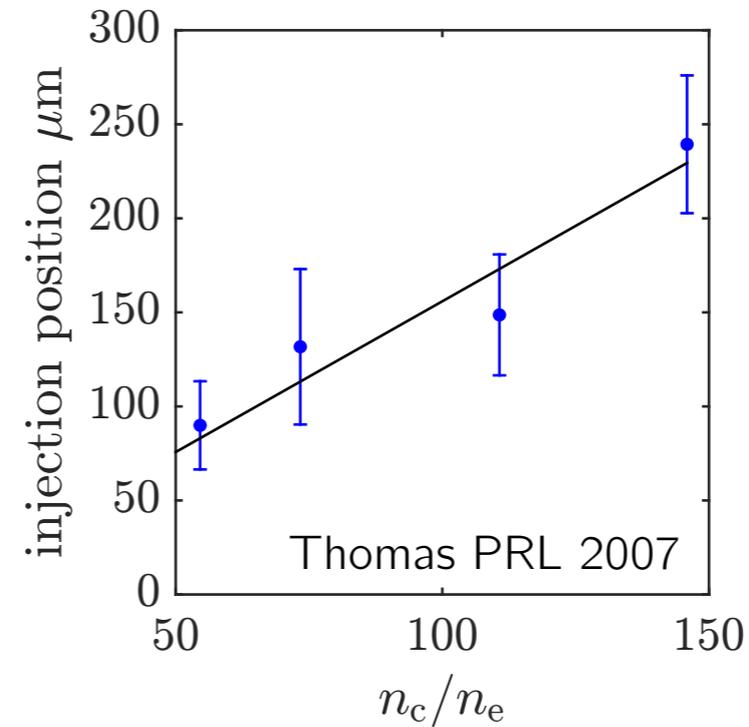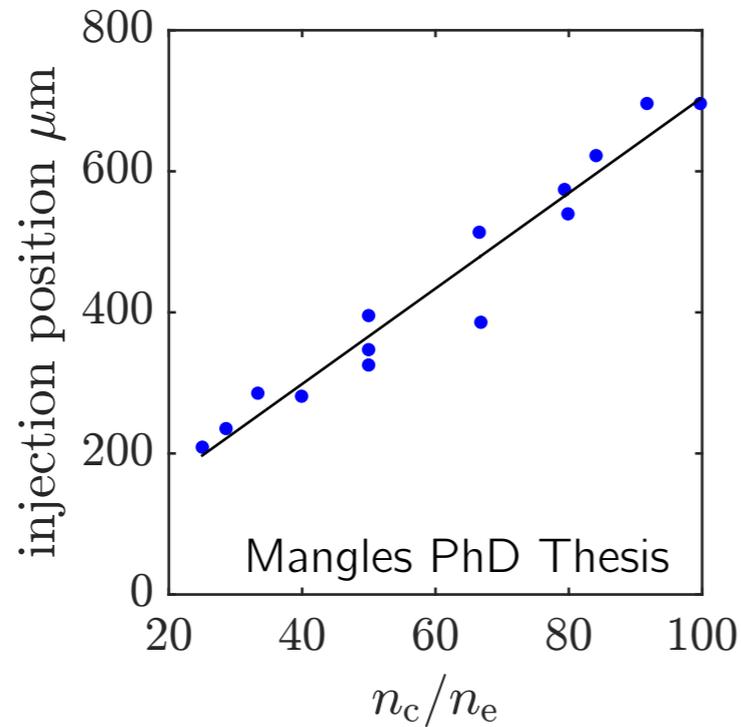
- L_{PIPE} scales inversely with plasma density
  - simulations of 2004 Nature paper
  - wave breaking radiation

$$L_{\mathrm{PIPE}} = S\frac{n_{\mathrm{c}}}{n_{\mathrm{e}}}$$
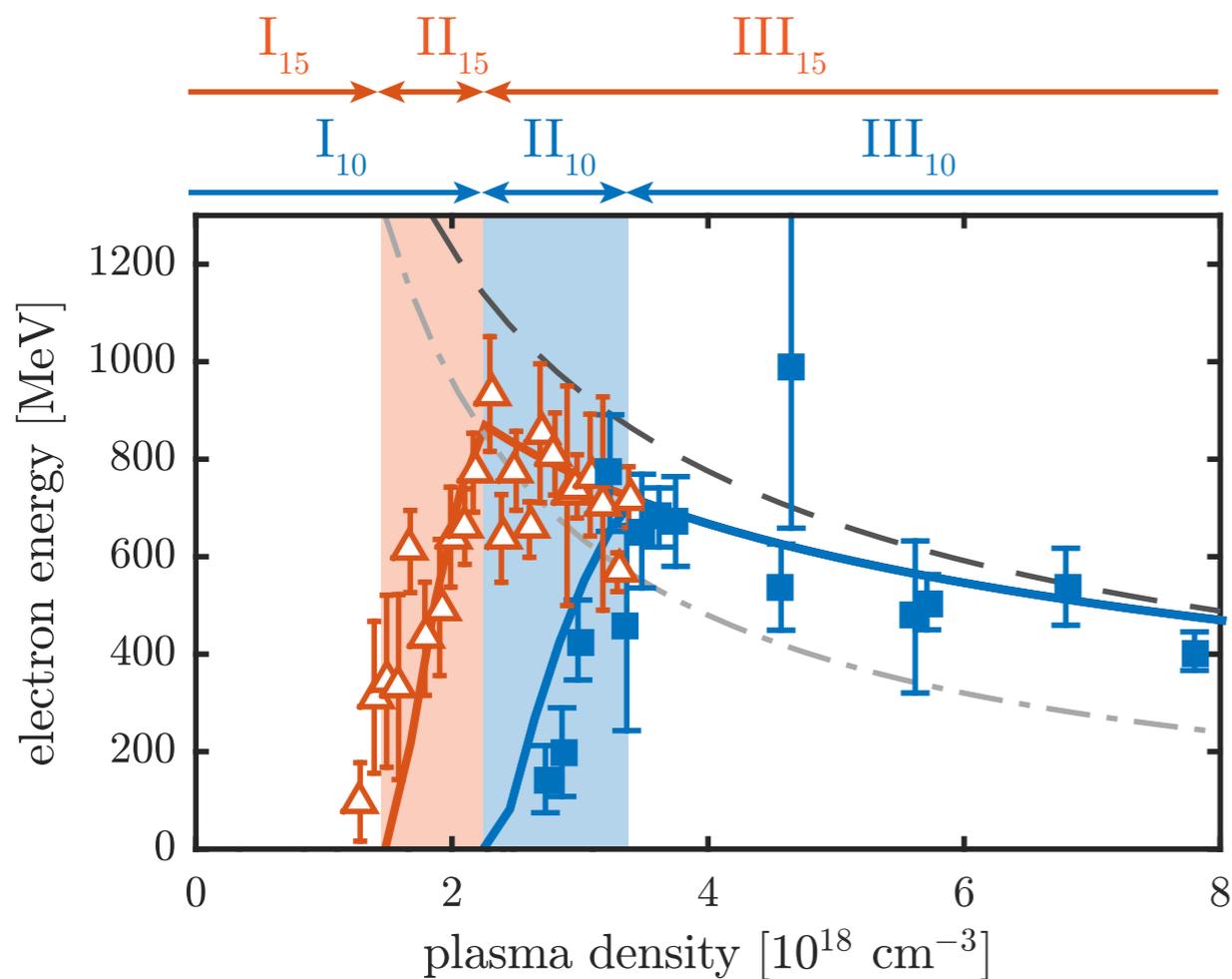
Pre injection pulse evolution length

- Maximum energy reached determined by length of accelerator after injection

- Total accelerator length L_{max} limited by:
  - distance over which pulse loses energy (depletion)
  - end of plasma target (which ever comes first)

$$\Delta_{\mathrm{acc}} = (L_{\mathrm{max}} - L_{\mathrm{PIPE}})/L_\phi$$

- Assuming acceleration in linear electric field inside bubble:

$$W''_{\mathrm{max}} = W'_{\mathrm{max}}\left(2\Delta_{\mathrm{acc}} - \Delta^2_{\mathrm{acc}}\right)$$

PIPE model predicts electron beam energies


Bloom, submitted, http://arxiv.org/abs/1710.05740

- Data from density scan on 200TW Gemini laser
  - Two different target lengths
    - 10 mm, 15 mm
- Three phases of accelerator

  I. PIPE is longer than accelerator: no injection

  II. Target is shorter than depletion length (target limited)

  III. Depletion length is shorter than target (depletion limited)

- Optimum is when $L_{target} = L_{depletion}$
  - not when $L_{PIPE} + L_{dephase} = L_{target}$

PIPE model also predicts betatron X-ray properties
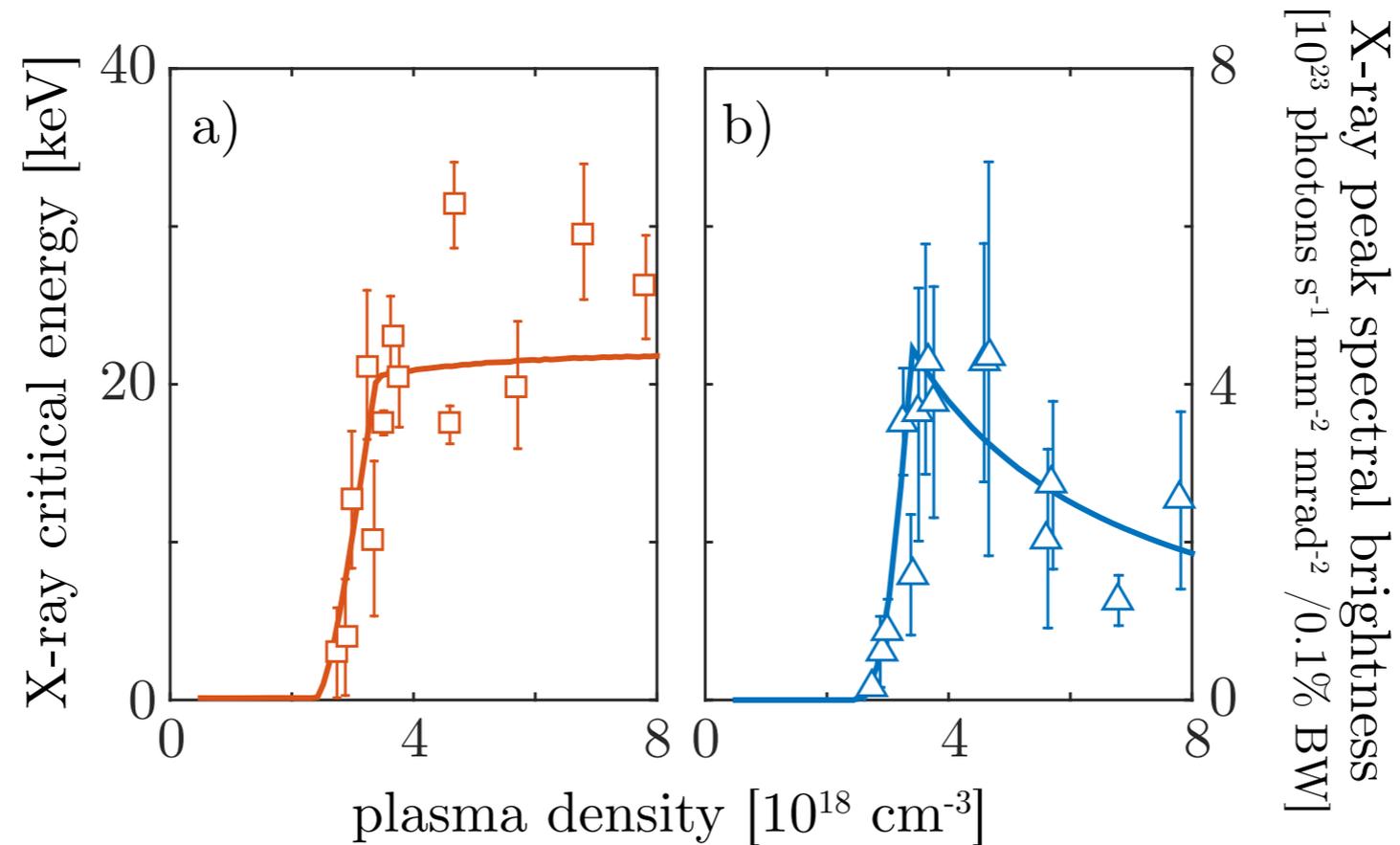
- PIPE model also allows betatron X-ray properties to be predicted

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A nonlinear LWFA collider?

- Pulse evolution is inextricably linked to nonlinear wakefields
  - is this evolution intrinsically unstable?
    - i.e. do small changes to input laser and plasma parameters make large changes to beam output?

A nonlinear LWFA collider?
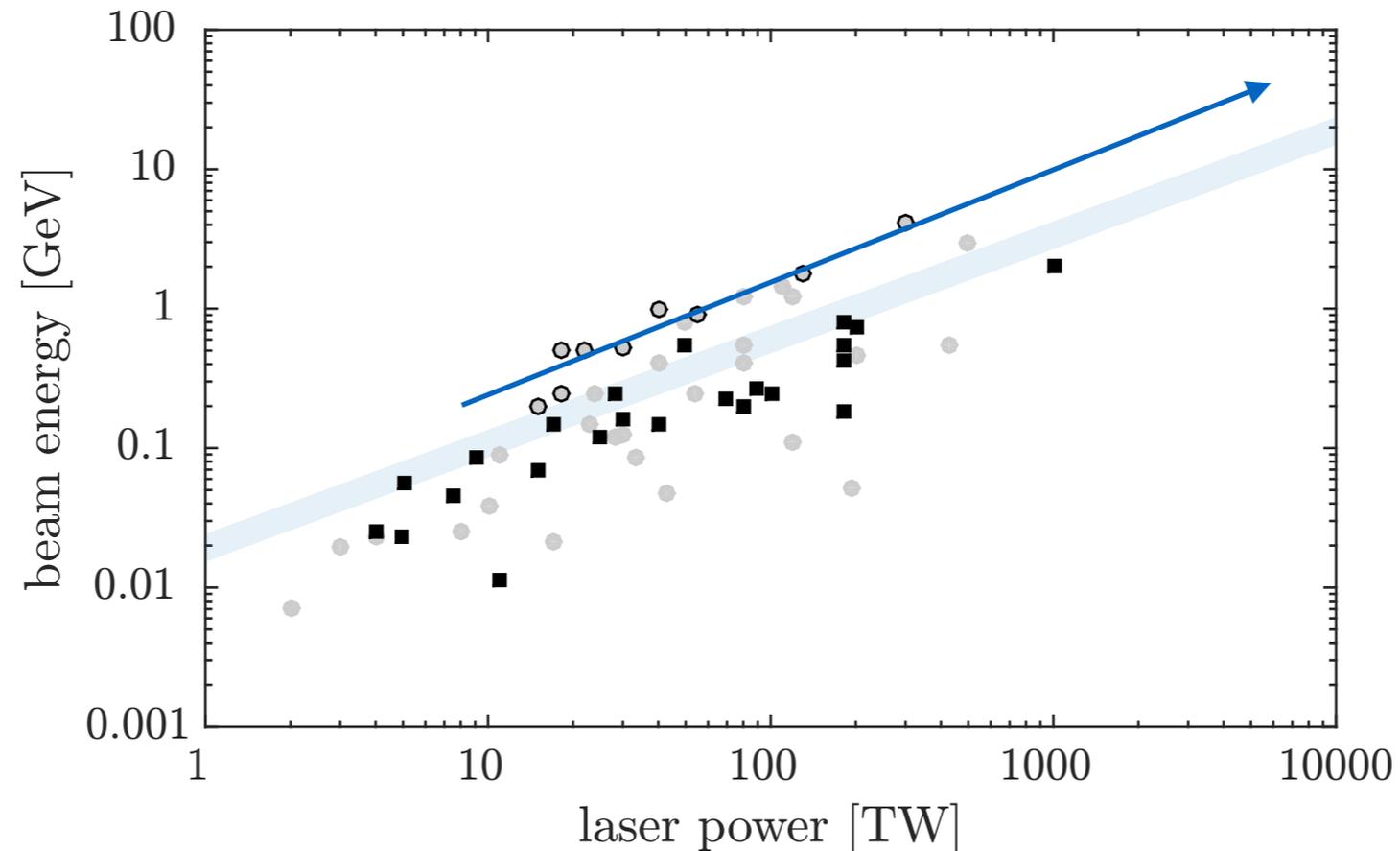
- Model predicts we need multi-petawatt laser for a 10 GeV stage
  - efficiency, cost, repetition rate
  - target survival

A nonlinear LWFA collider?

- Staging:

  – major challenges for efficient coupling of electron beam
    into a second nonlinear stage

A nonlinear LWFA collider?

- Nonlinear wake is not symmetric for positrons
  - half the bubble is accelerating *and* focusing for electrons
  - only small fraction is accelerating *and* focusing for positrons
    - positron injection is a major challenge
    - significantly reduced dephasing length for positrons.

Summary

- Are experiments in nonlinear regime?

  – yes, when we include pulse evolution

- Can we predict properties of beams in nonlinear wakes?

  – yes, when we include pulse evolution

- What are challenges that must be addressed if we want to make a collider based on nonlinear wakes?