PERFORMANCE ENVELOPE OF LASER WAKEFIELD ACCELERATORS

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AGENDA

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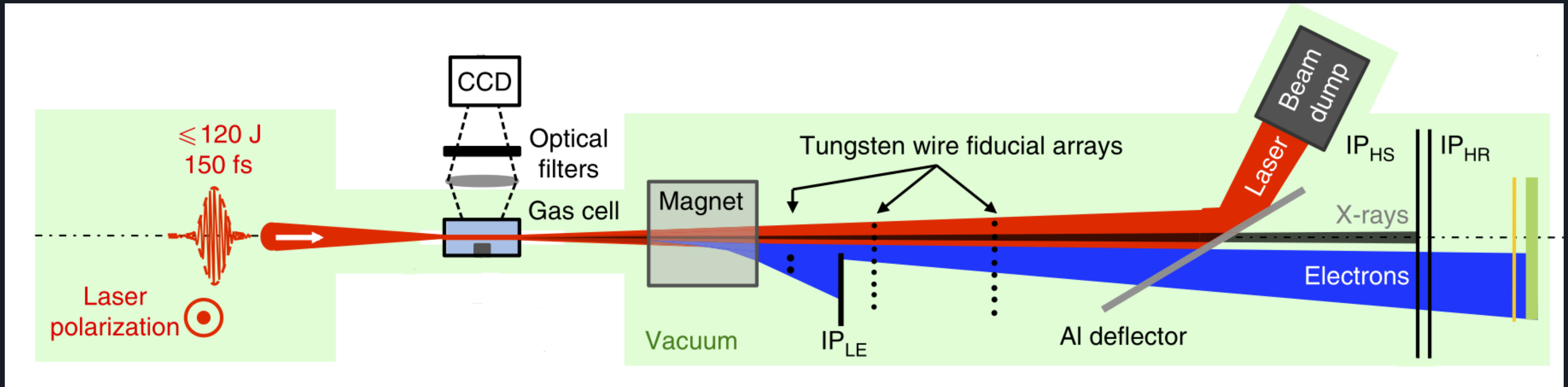
MOTIVATIONS

1. Improve understanding of LWFA capabilities
   - Example: what is the trade-off between beam energy and charge?
2. Check model predictions against reality
   - Analysis and simulations give estimates for beam energy but models' recommendations are also frequently ignored in practice
3. Begin study of efficiency
   - Tau Systems is in the business of **applying** LWFA: we want to know the minimal (cheapest) system capable of achieving a particular performance

The Idea: Literature now contains a fair amount of data on laser wakefield accelerators: can we leverage the ensemble of experiments?

LWFA INPUTS AND METRICS

System components:
- Laser
- Gas jet/cell
- Diagnostics



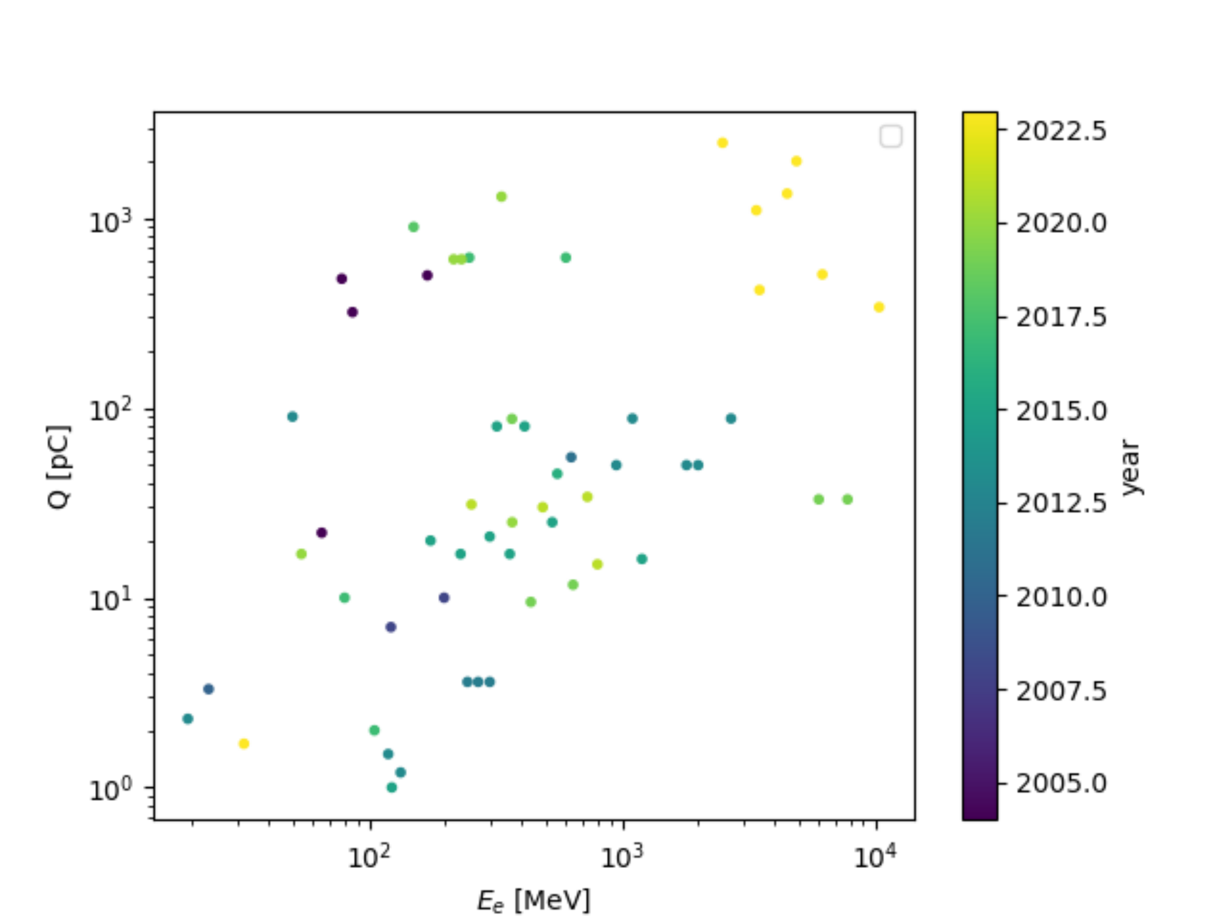
[Wang et al, Nat. Comm., 2013]

Inputs
1. Laser energy
2. Laser pulse duration
3. Laser (vacuum) spot size
4. Gas density
5. Gas profile
6. Injection method

Metrics
1. Electron energy distribution (energy spread)
2. Beam charge
3. Emittance (beam size and divergence)
4. Bunch duration

METHOD

- Collate dataset of >40 distinct experiments
- Extract summaries of laser inputs and beam metrics
- Fit trends with two-parameter power law
  - Basic least-squares metric (simple but largely effective) $y = Cx^{\alpha}$



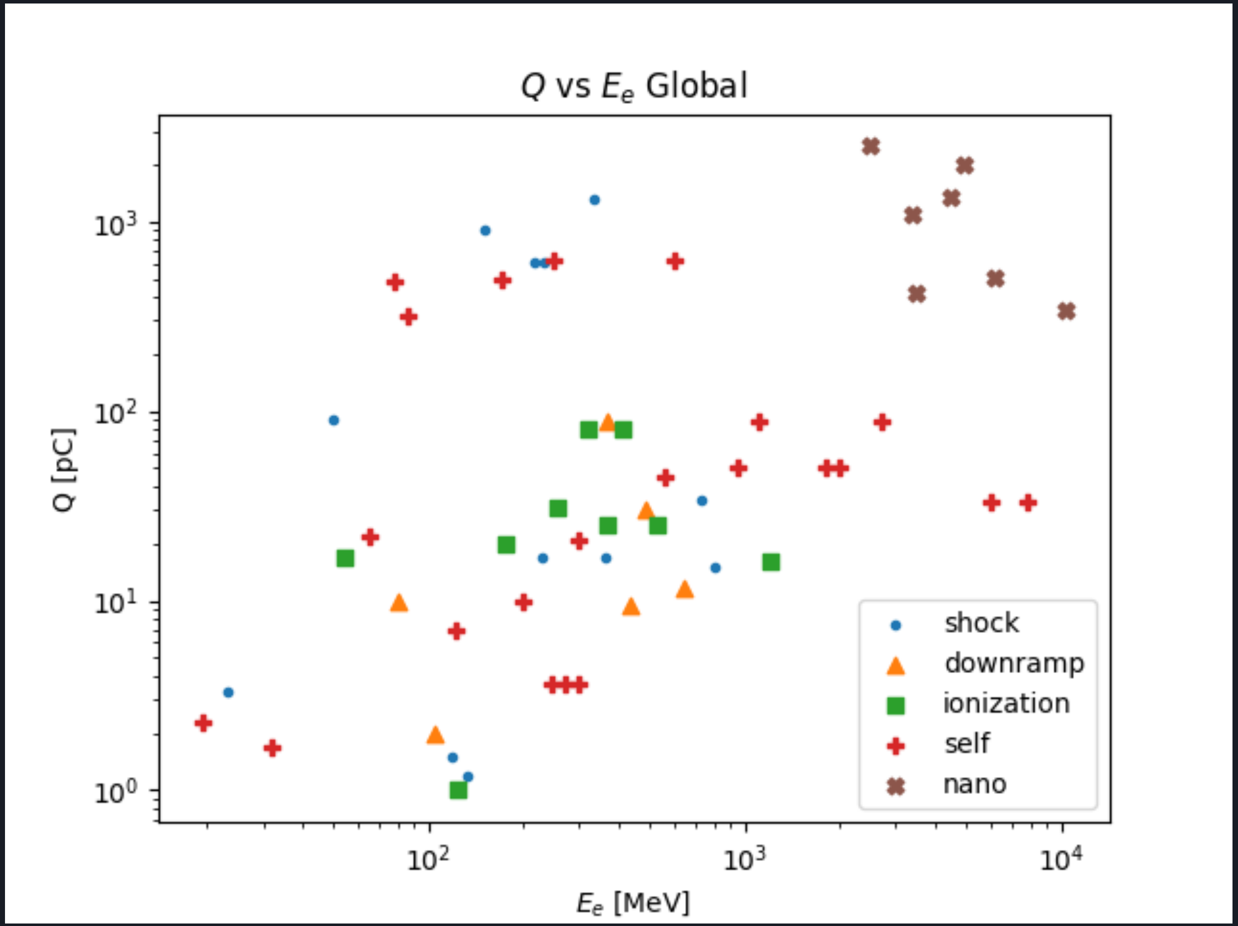
Issues with the data

- Early papers publish single shots – presumably best only without context
- Inconsistent definitions
  - Eg "beam energy" frequently means centroid on spectrometer screen
  - "Downramp" vs "shock" injection
- Incomplete diagnostics/reporting
- Not all experiments were optimized

OVERVIEW OF DATA

My definition:

- Downramp = density contrast from variable backing pressure
- Shock = blade or optical induced



MODELS FOR LWFA PERFORMANCE

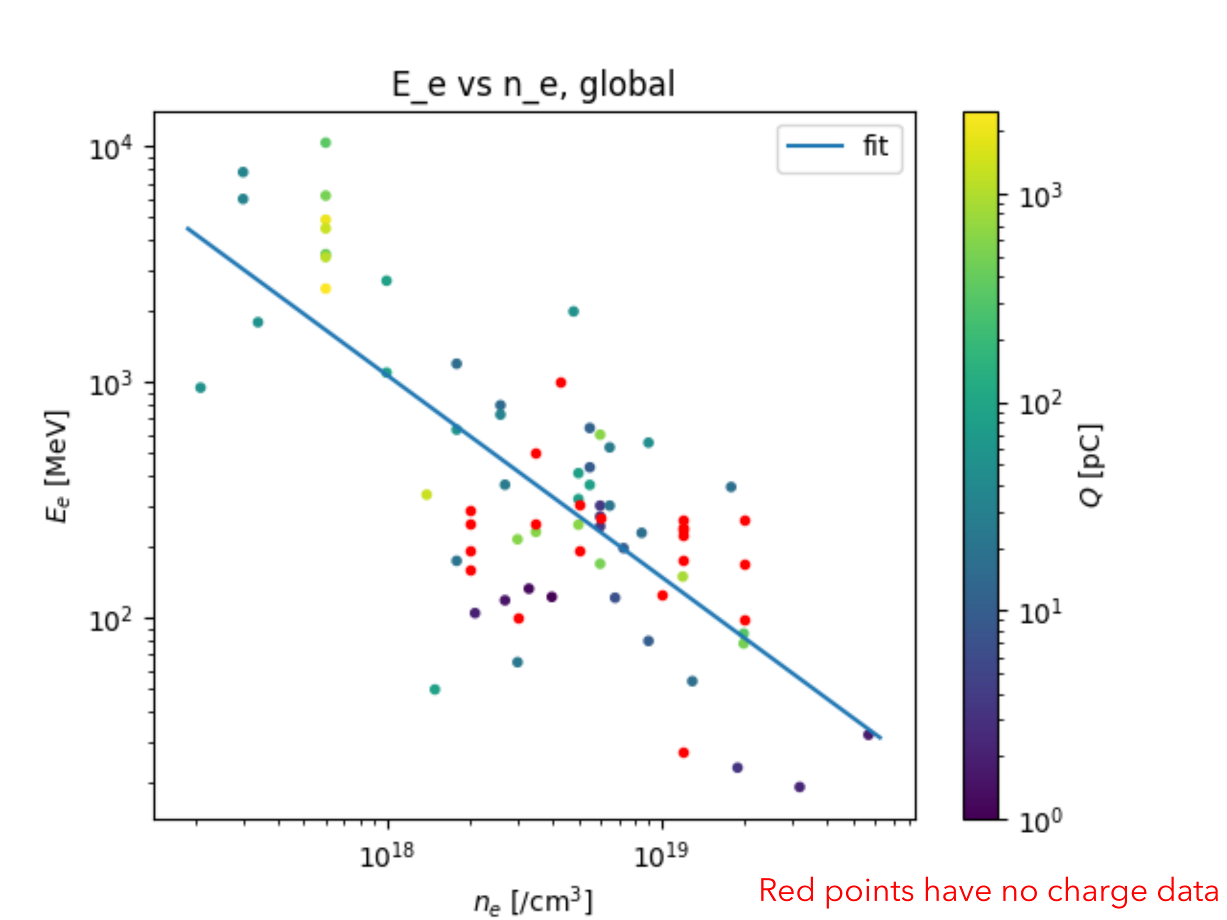
"Matched": $w_0 \simeq R_b$ $$\Delta E[GeV] \simeq 1.7 \left(\frac{P}{100TW}\right)^{\frac{1}{3}} \left(\frac{n_e}{10^{18}/cm^3}\right)^{-\frac{2}{3}}$$ [Lu et al, 2007]

"Naïve" $$\Delta E[MeV] \simeq \frac{1}{2} eE_{z,max} L_{acc} \simeq \frac{2}{9}\pi^2 m_e c^2 \frac{n_{cr}}{n_e}$$ [unpublished]

$$Q[pC] \simeq 400 \left(\frac{P}{100TW}\right)^{\frac{1}{2}}$$ [Lu et al, 2007]

- Lu, 2007 model for beam charge assumes a majority of longitudinal electrostatic energy in bubble is converted to particle kinetic energy
- Many experiments explicitly do not use "matched" regime

TREND: ELECTRON ENERGY VS DENSITY



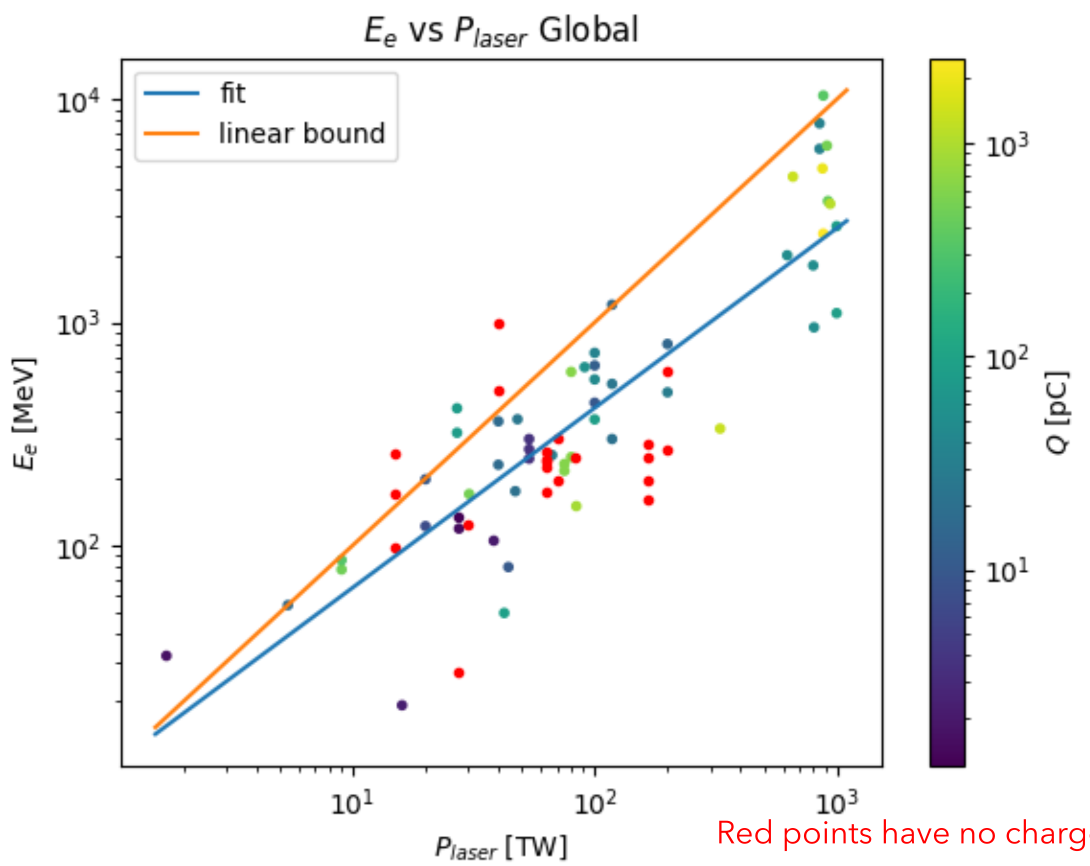
Red points have no charge data

Power-law model: $E_e = C\, n_e^{\beta}$

	β	log₁₀C	Δβ	ΔlogC
Fit	-0.86	18.4	0.089	1.7
Matched	-2/3			
Naive	-1			

- Includes experiments creating a low-density guiding channel
- Throwing away bottom 90% in each density bin (as not optimized) looks to produce stronger power $\sim n_e^{-1}$
- Suggests $\Delta E > 100\ GeV$ requires $n_e < 10^{17}/cm^3$

TREND: ELECTRON ENERGY VS LASER POWER



Red points have no charge data

Power-law model: $E_e = C\, P_\ell^{\beta}$

	β	$\log_{10}C$	Δβ	ΔlogC
Fit	0.81	1.0	0.059	0.12
Matched	1/3			
Naive	1/2			

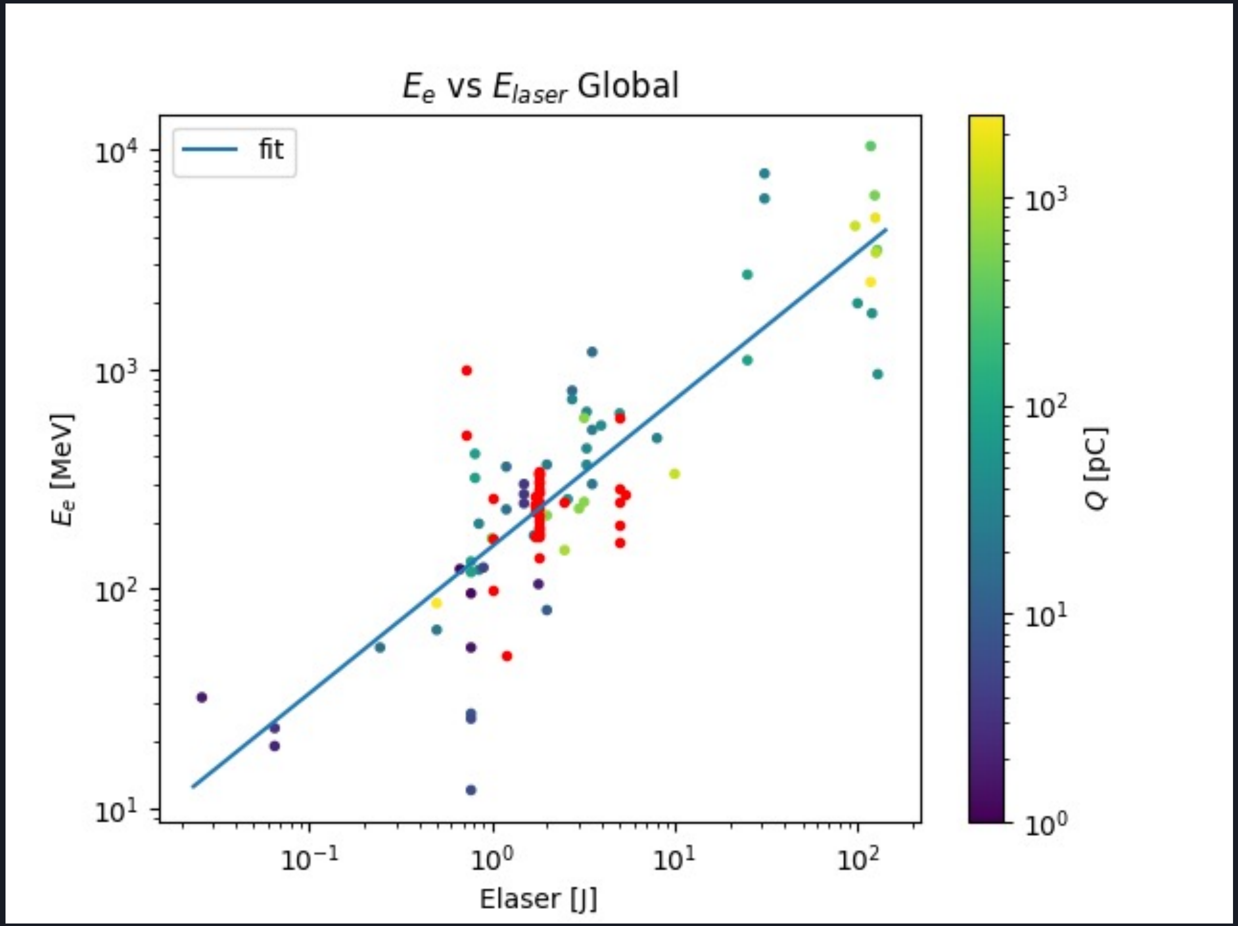
Differs significantly from both matched regime and linear estimated limit

$$E_e[MeV] < 10P_\ell[TW]$$

(Wenz + Karsch, 2020)

Compare performance of initial RF stage: $P_{in} = \frac{V_{cavity}^2}{R} \Rightarrow \Delta E \propto \sqrt{P_{in}}$

TREND: ELECTRON ENERGY VS LASER ENERGY

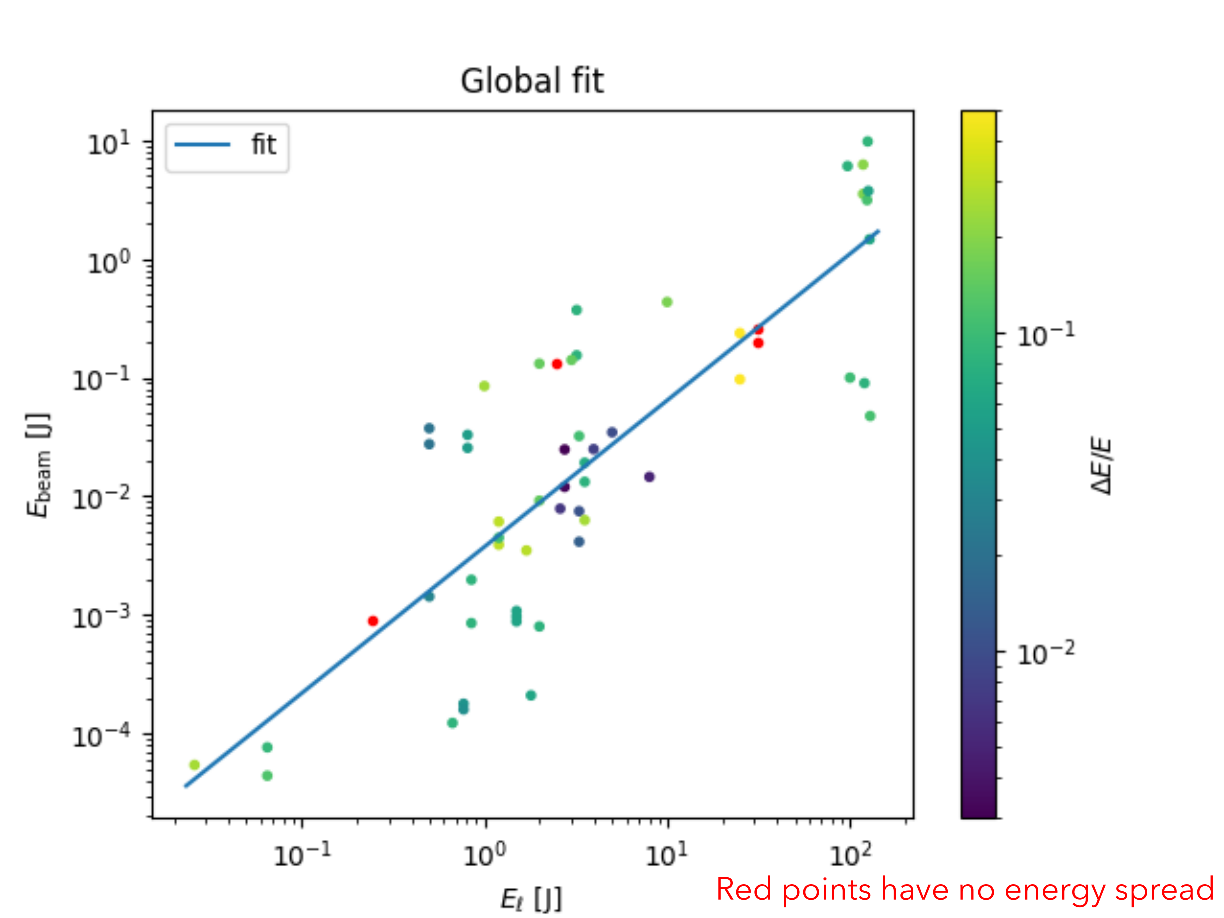


Power-law model: $E_e = C\, E_\ell{}^{\beta}$

	β	$log_{10}C$	Δβ	ΔlogC
Fit	0.65	2.23	0.042	0.039

- Linear bound (from Wenz+Karsch) works less well here

ENERGY EFFICIENCY



Red points have no energy spread

Define beam energy:

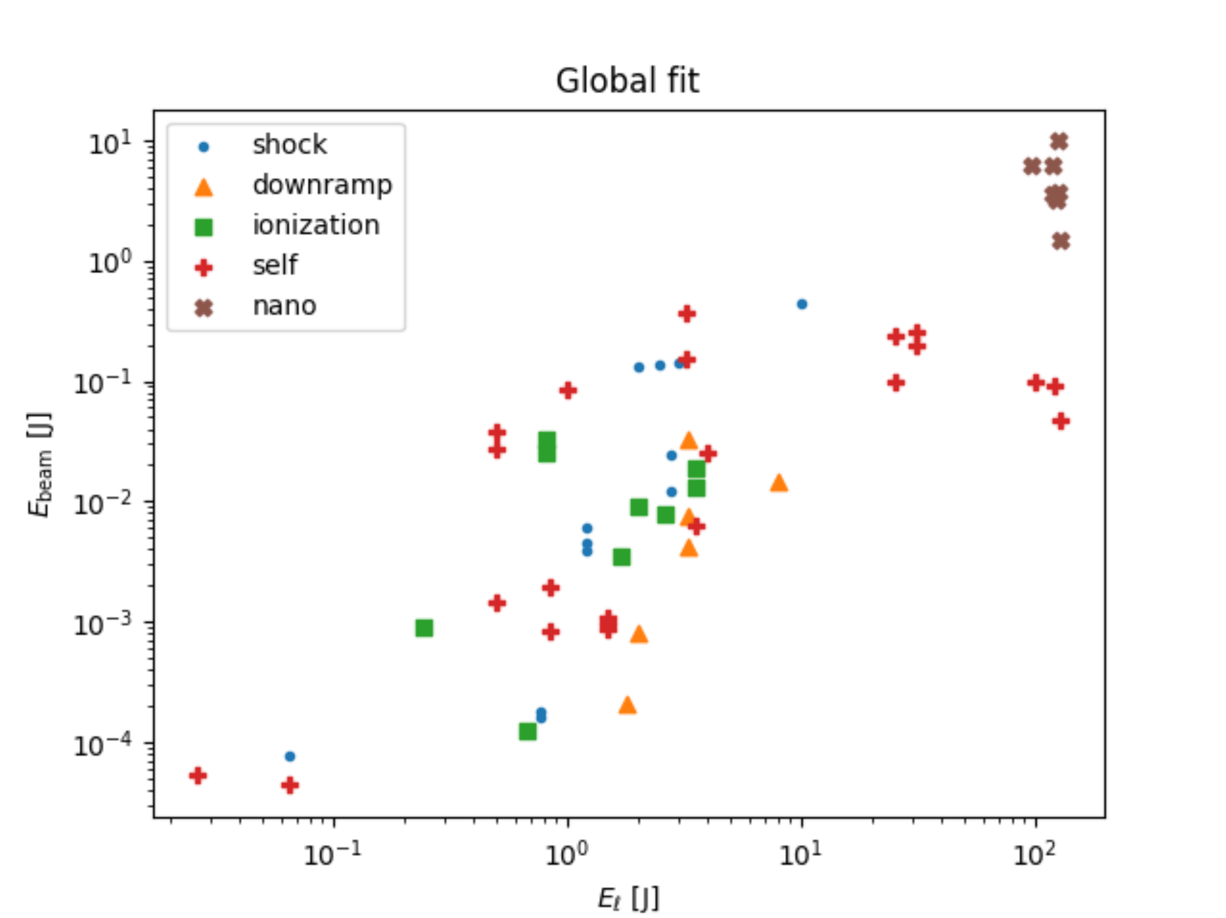
$$E_b[mJ] = Q[nC]\, E_{peak}[MeV]\left(1 + O\left(\frac{\Delta E}{E}\right)\right)$$

Then fit same power law: $E_b = C\, E_\ell{}^\beta$

	β	$\log_{10}$C	Δβ	ΔlogC
Fit	1.23	-2.43	0.12	0.12

- Percent-level efficiencies typical
- If optimized, should push up whole curve, potentially to ~5% level
- Strong scaling may arise from constant intensity $a_0 \sim 2$

ENERGY EFFICIENCY



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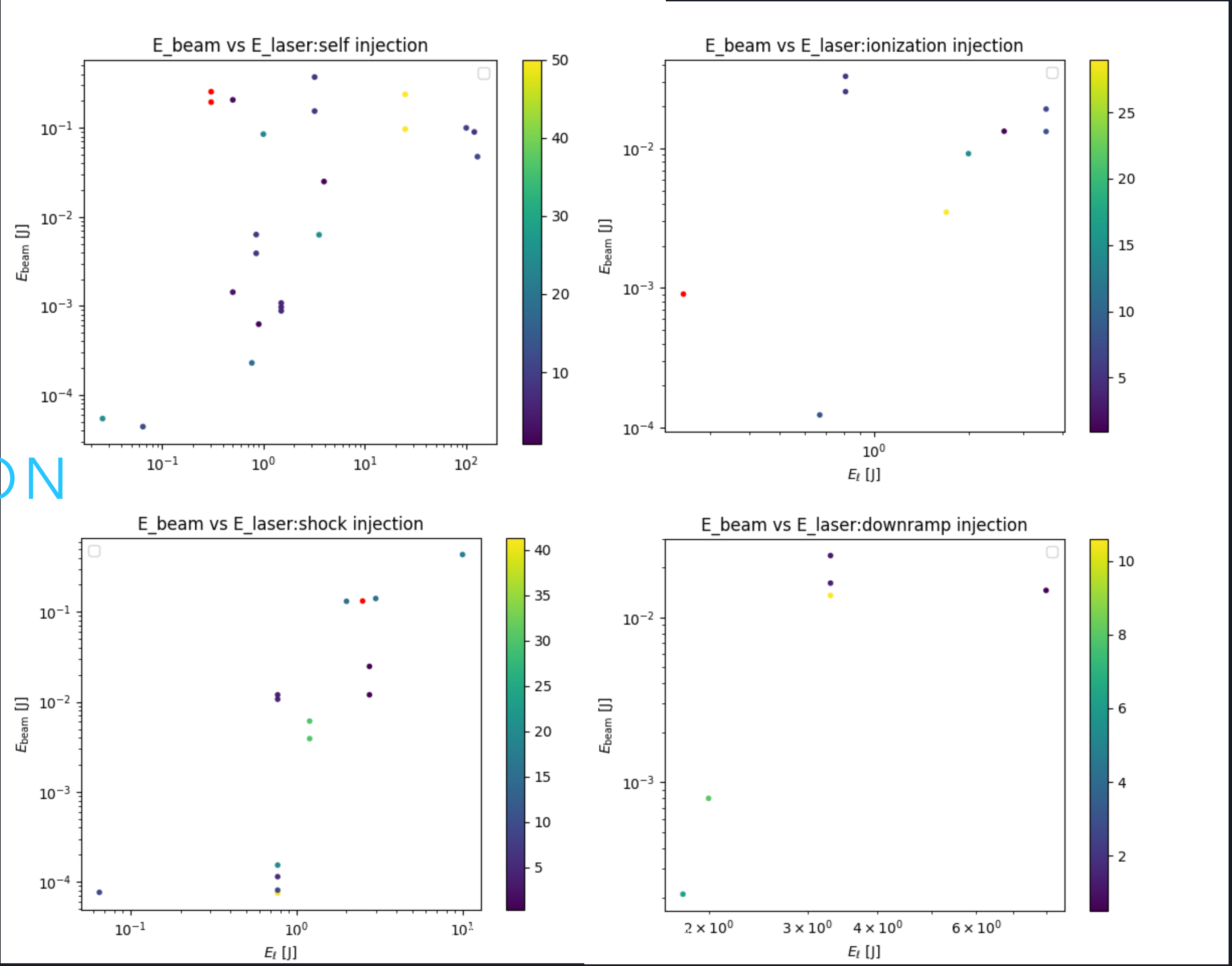
- Percent-level efficiencies typical
- If optimized, should push up whole curve, potentially to ~5% level
- Highest efficiency is
- 2 published experiments with nanoparticle injection–1 did not have charge calibration

ENERGY EFFICIENCY BY INJECTION



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CONCLUSION

- Need more consistent data reporting and analysis
- Peak/centroid energy scales inversely with density roughly as expected
- Peak/centroid energy scales strongly with laser power $\propto P^{0.8}$
- Total beam energy (charge x peak energy) scales very favorably with laser energy $\propto E^{1.2}$
- Upshot for future: require $n_e < 10^{17}/cm^3$ and ~100 J laser for 10pC, 100 GeV stages
- After this conference, I have more data points to add!