HIGH-QUALITY POLARISED ELECTRON BUNCHES FROM COLLIDING PULSE INJECTION

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Spin-polarised electron beams find widespread use

Compact source of polarised electrons could spark innovation and progress in many fields

- Polarised electron beams extensively used for
  - Material science
  - Atomic, molecular physics
  - Nuclear physics
  - Particle physics
- Polarised electron beams can generate polarised photon and positron beams
- Longitudinal spin of main interest in high energy physics
- Also: polarisation important for fusion!

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$P_\kappa = \frac{1}{N} \sum_i^N \vec{s}_{\kappa,i}$$

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Electrons align spin opposite to B-field

$$U_{mag} = -\vec{\mu} \cdot \vec{B}$$

Used at storage rings

Relaxation time ~hours

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Polarised atoms of the photocathode material

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Spin rotators (3)

Rotate spin from longitudinal to transverse

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(3) Moffeit et al, SLAC-TN-05-045

Advanced sources of spin polarised electron beams

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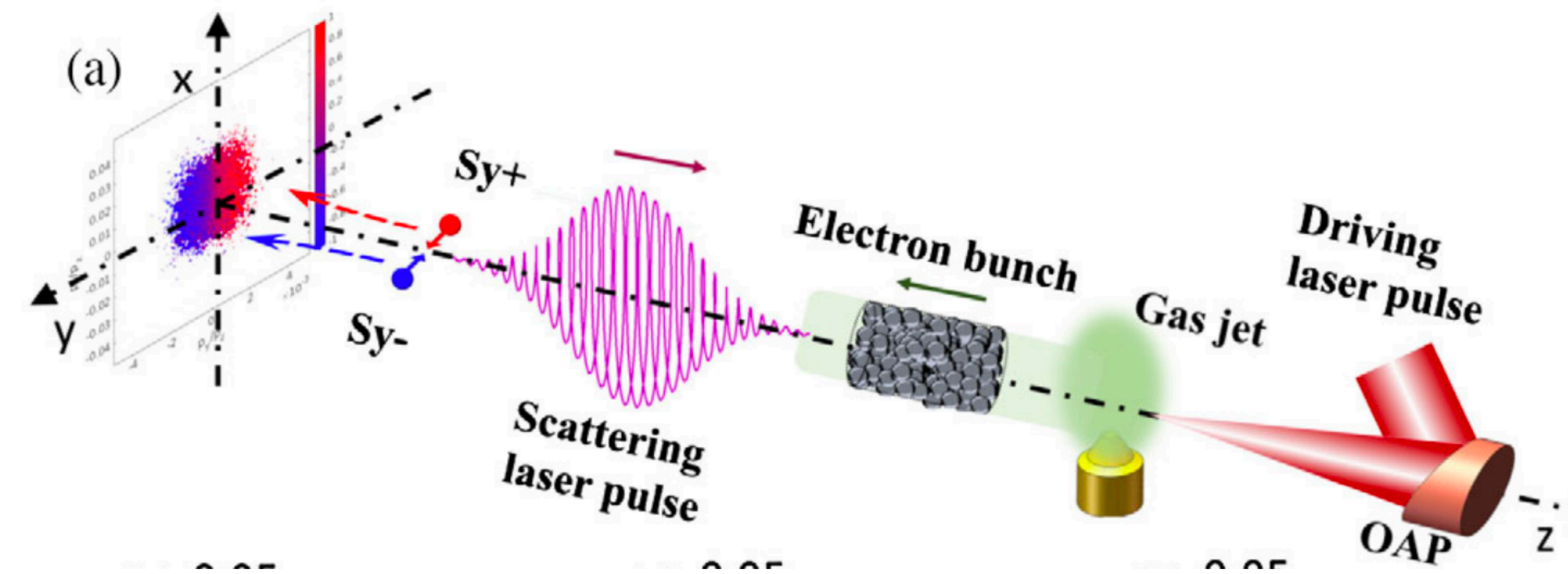

- Spin-filter (1)
- “Stern-Gerlach” beam splitter (2)
- Intense lasers interactions
  - Spin-dependent radiation reaction of relativistic electron beams (3)
  - Sokolov-Ternov in colliding laser fields (4)

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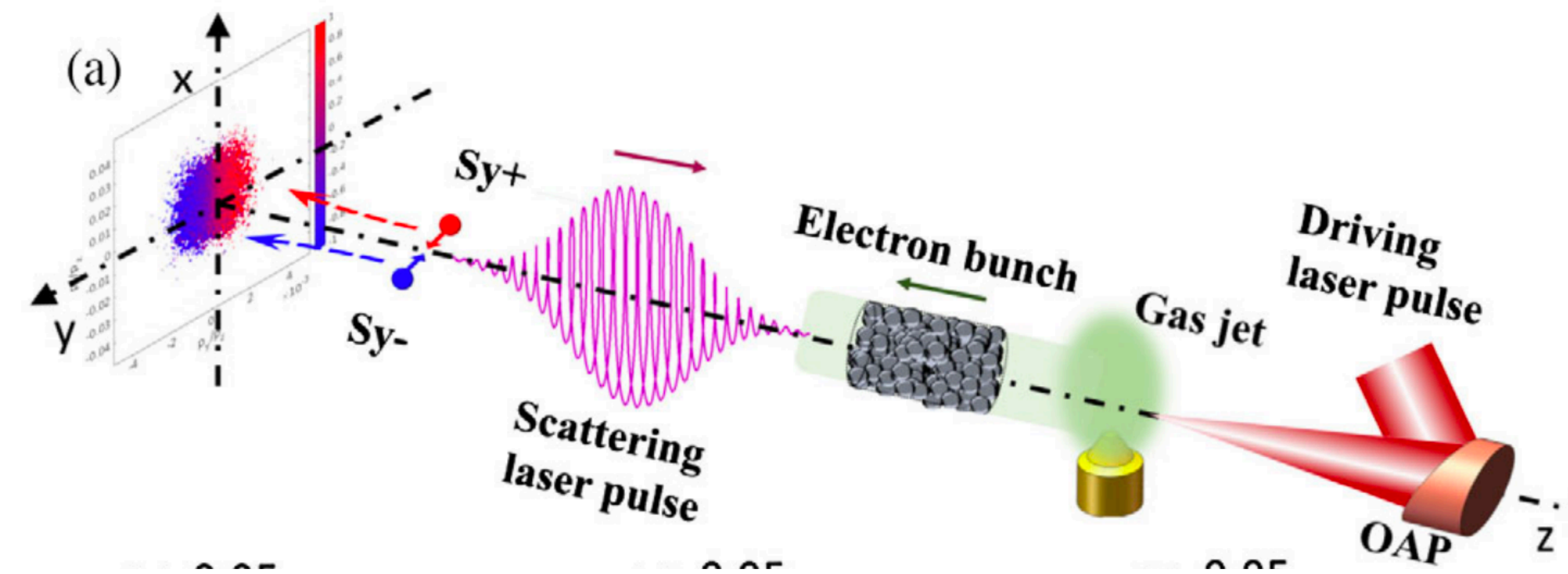
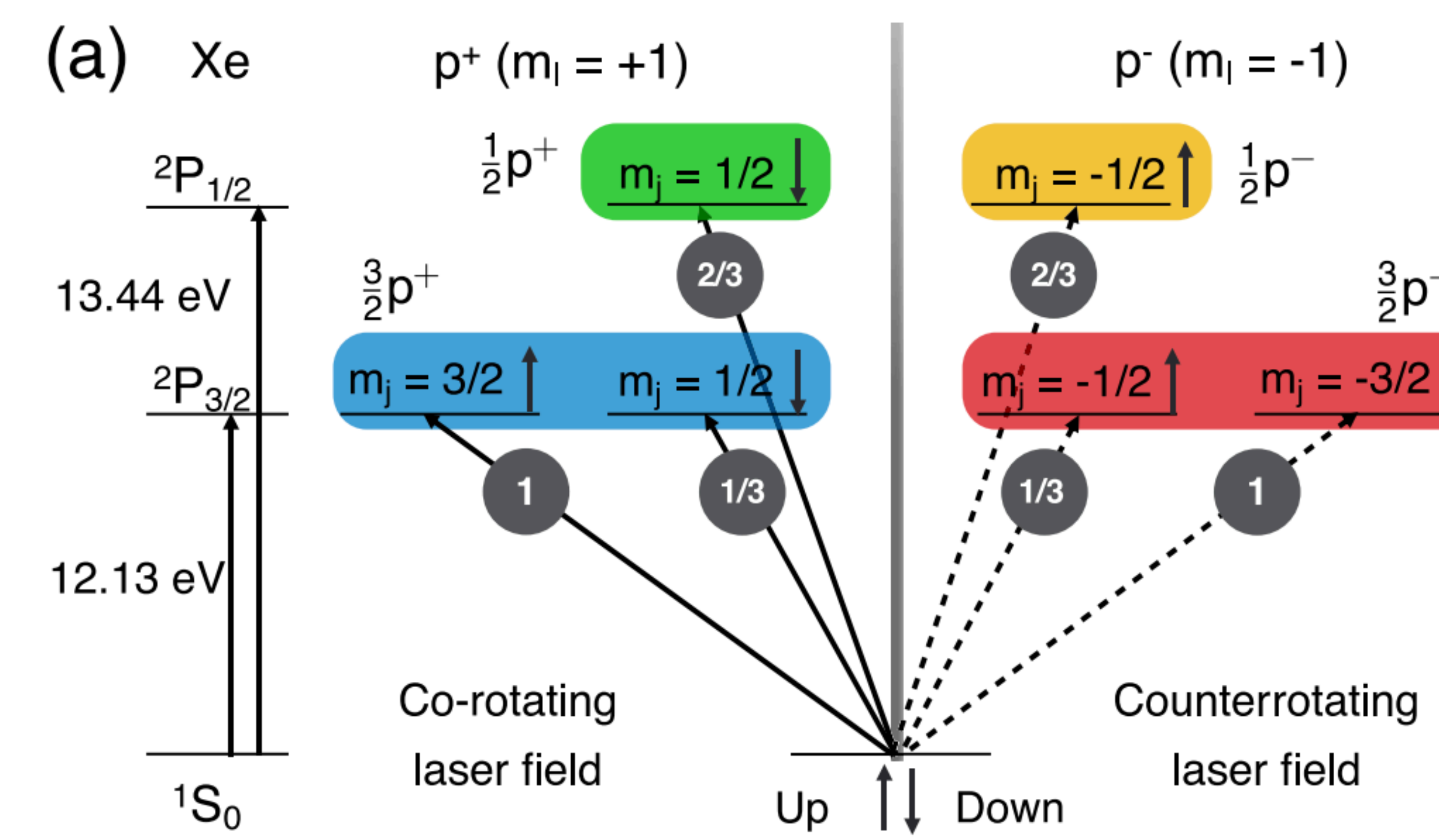
- **Plasma-based methods**
  - Selective multi-photon ionisation [5]
  - Pre-polarised plasma sources [6-9]





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(5) Nie et al, PRL **126** 054801 (2021)
(6) Rakitzis et al, Science **300** 1936 (2003)
(7) Wen et al, PRL **122** 214801 (2019)
(8) Wu et al, PRE **100** 043202, (2019)
(9) Wu et al, New J. Phys. **21** 073052 (2019)

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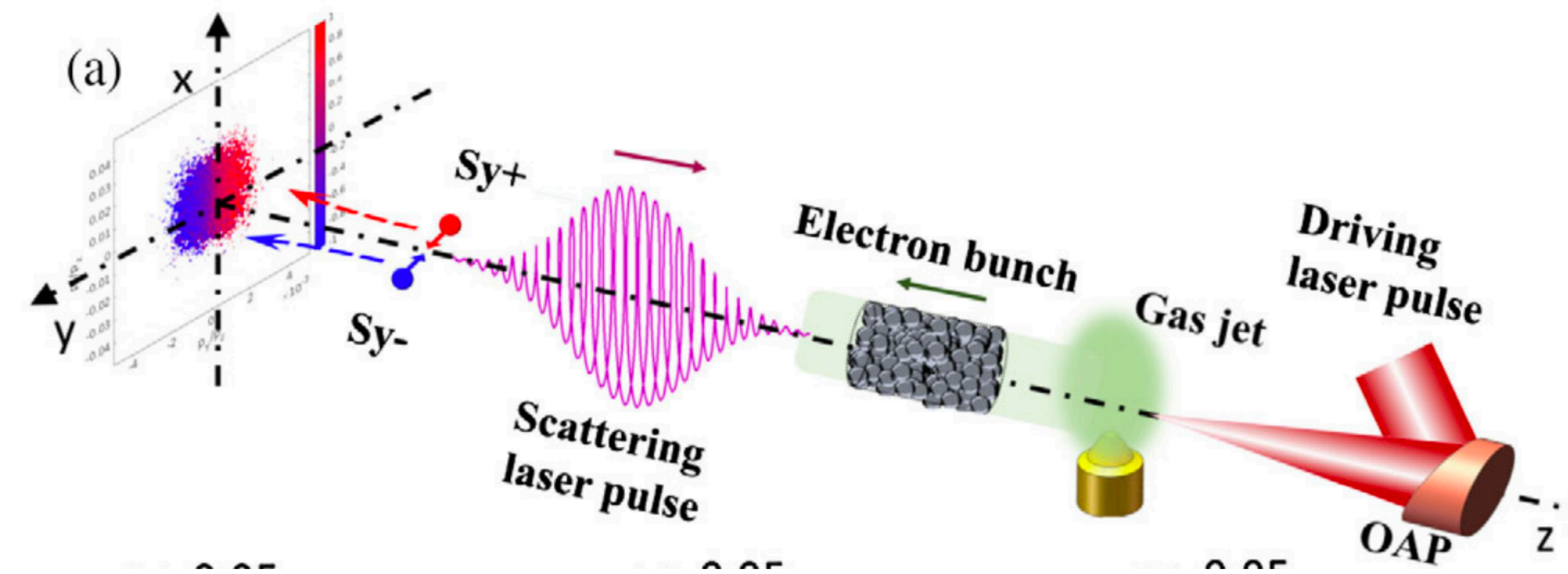

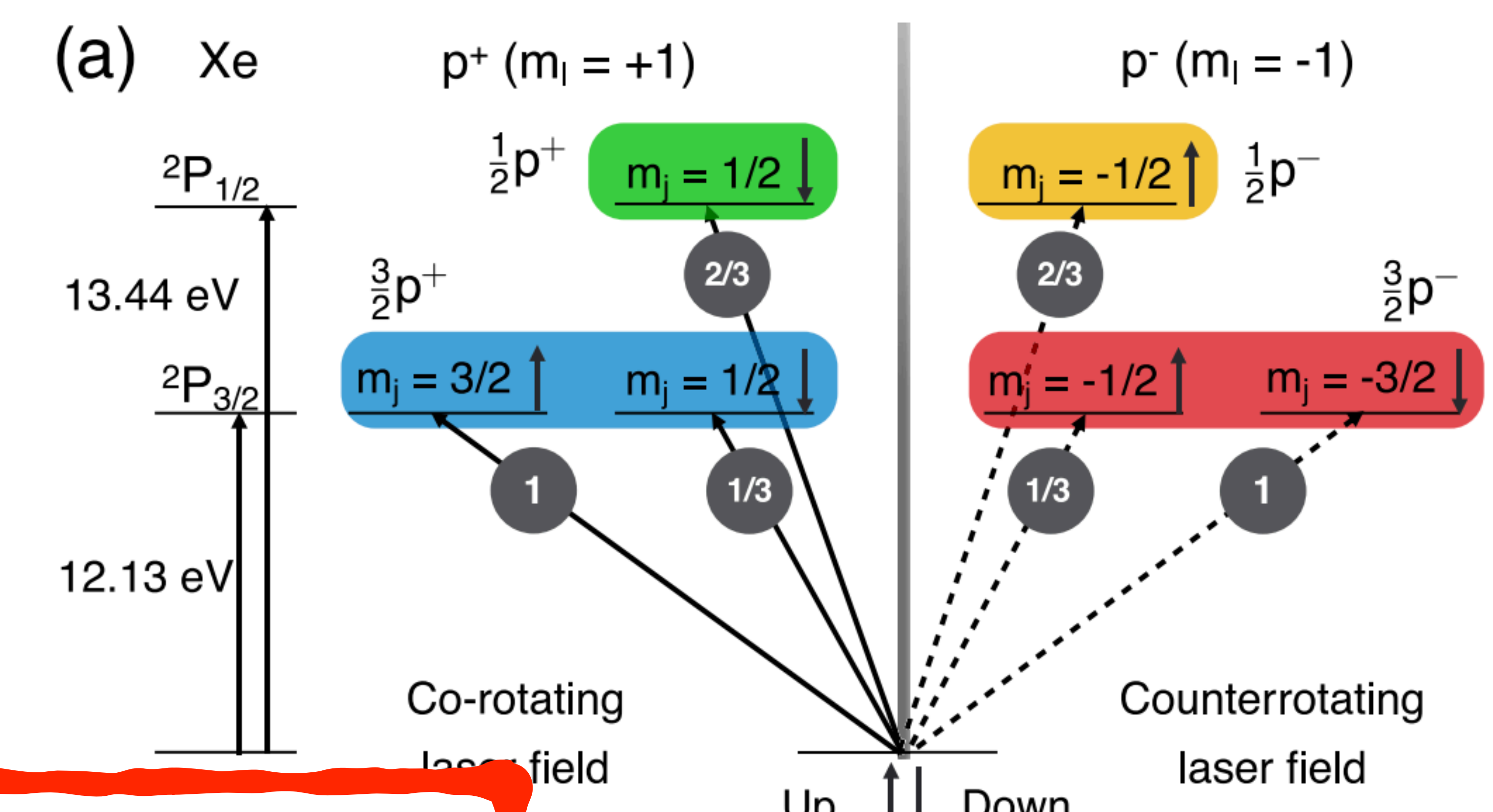

No experimental demonstrations yet!

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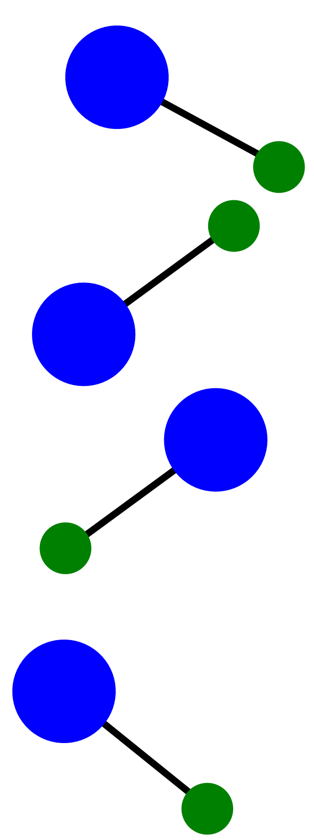
Concepts for pre-polarised plasma sources are available

Laser-based generation of spin-aligned atoms through dissociation of halide molecules



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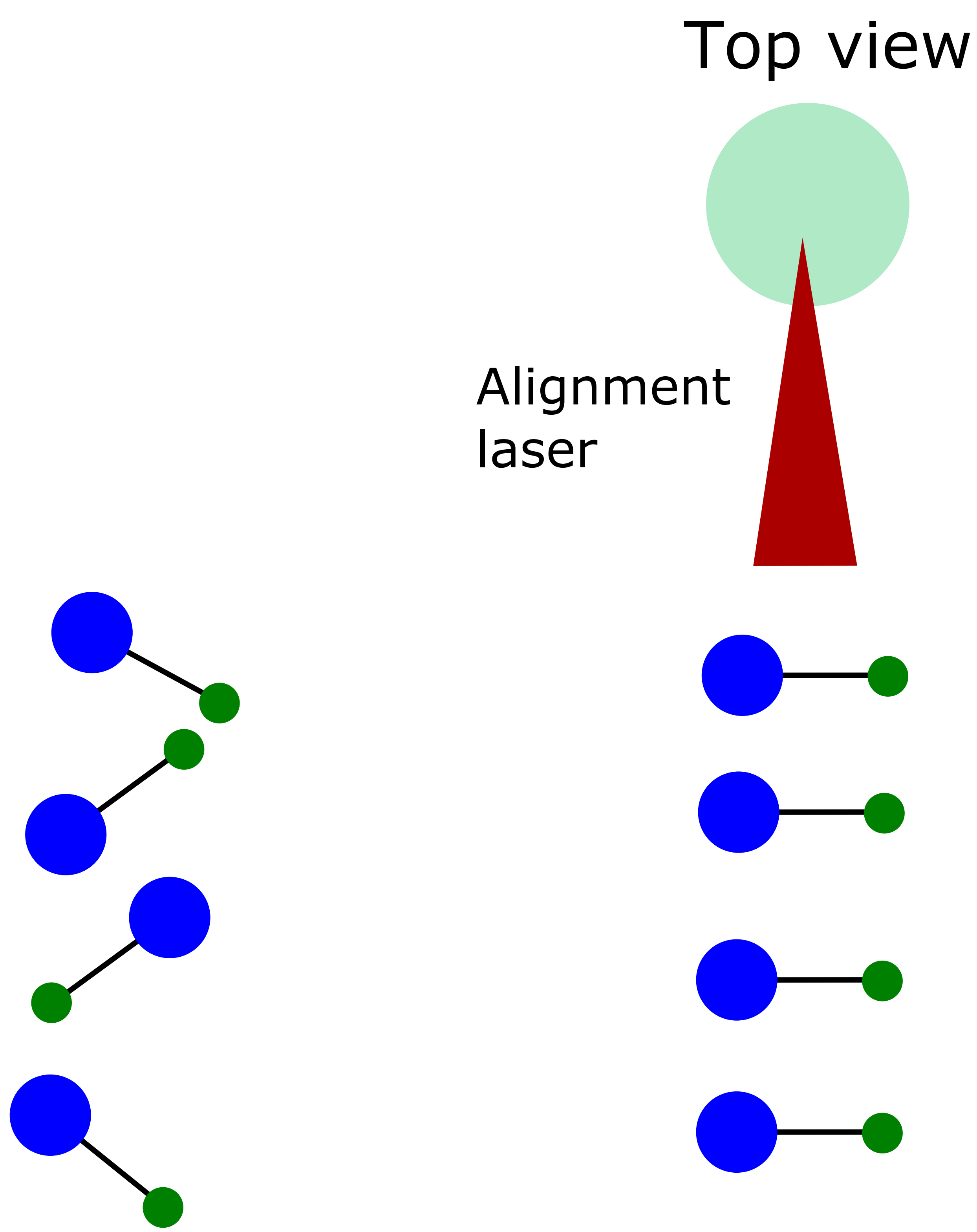

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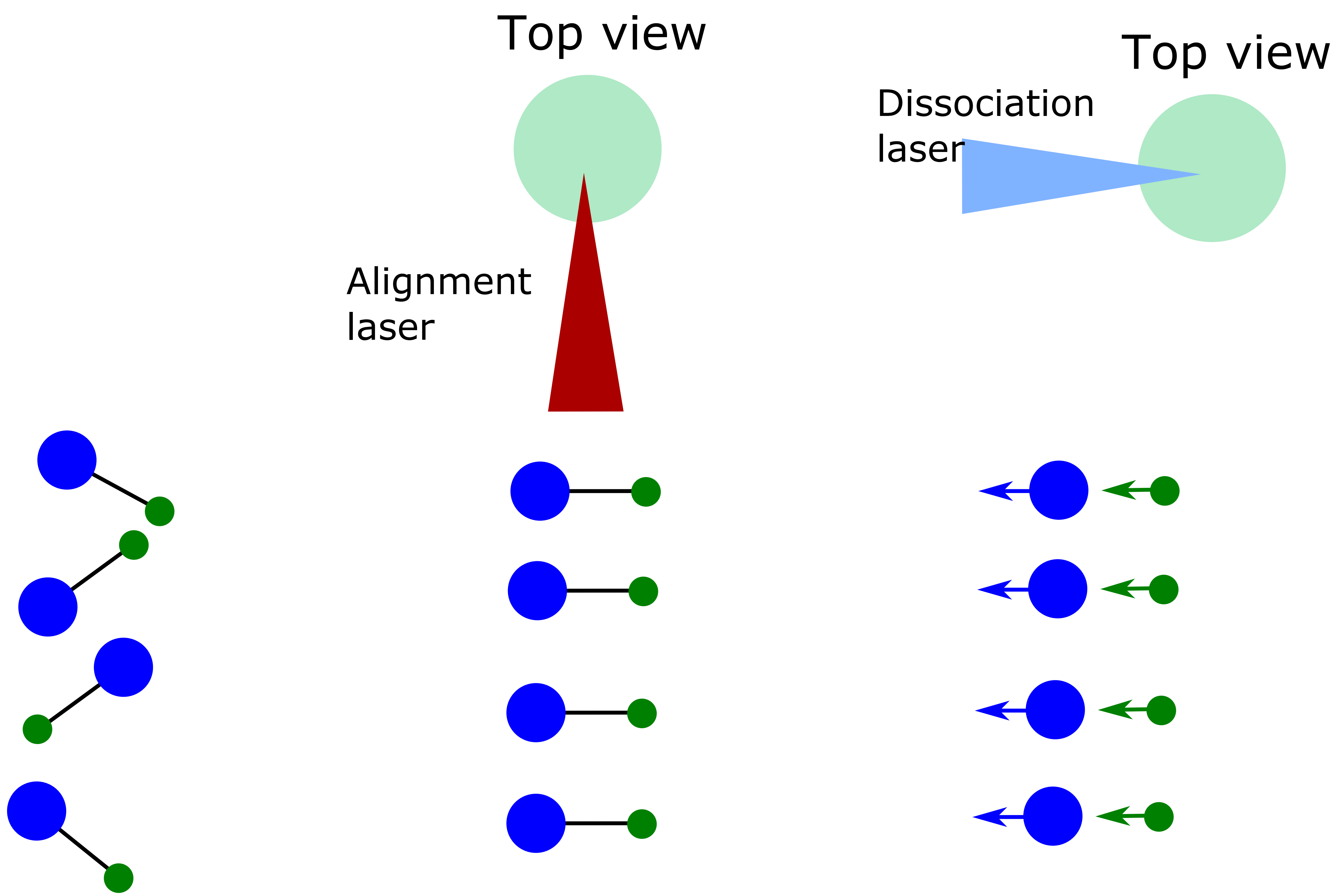

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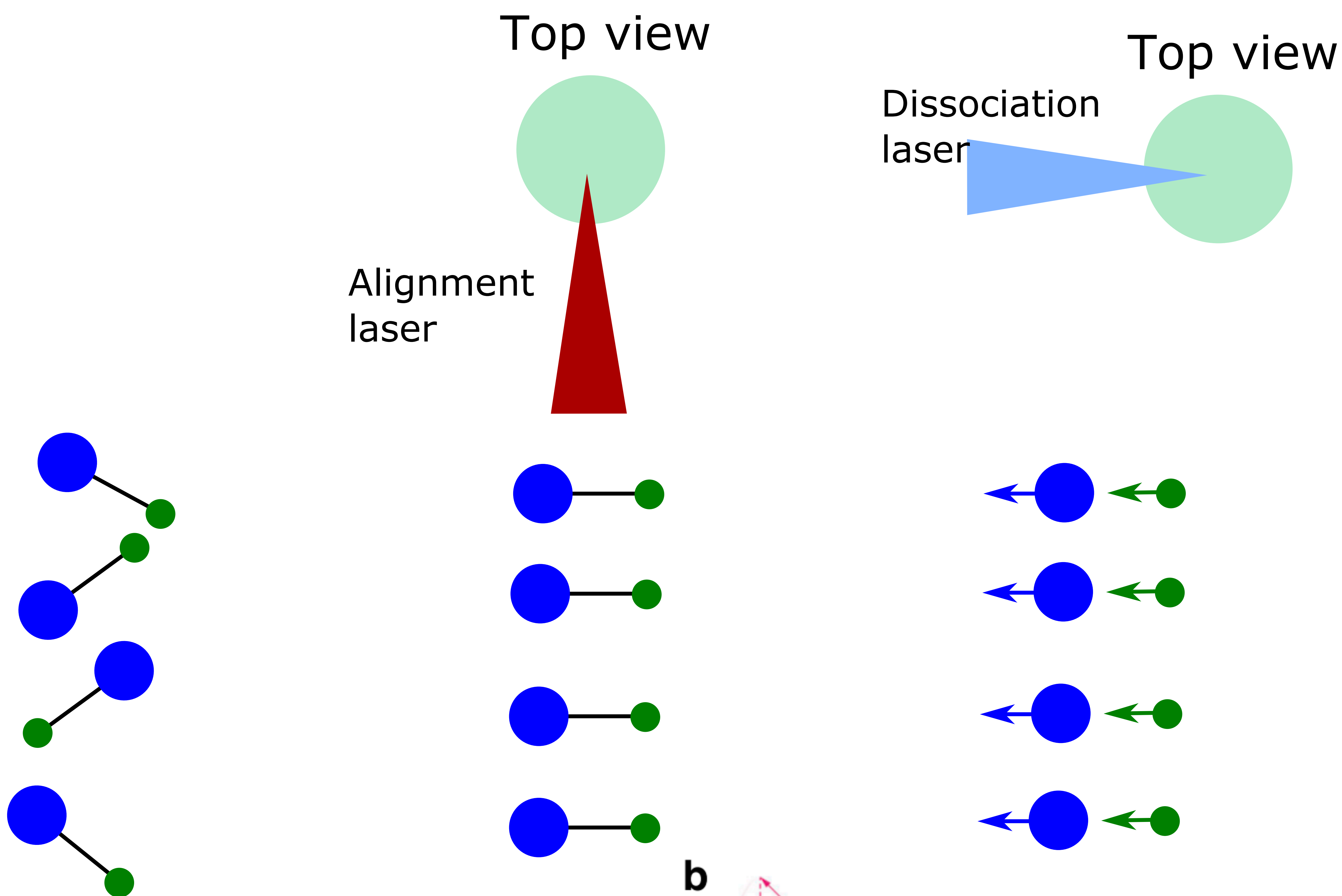

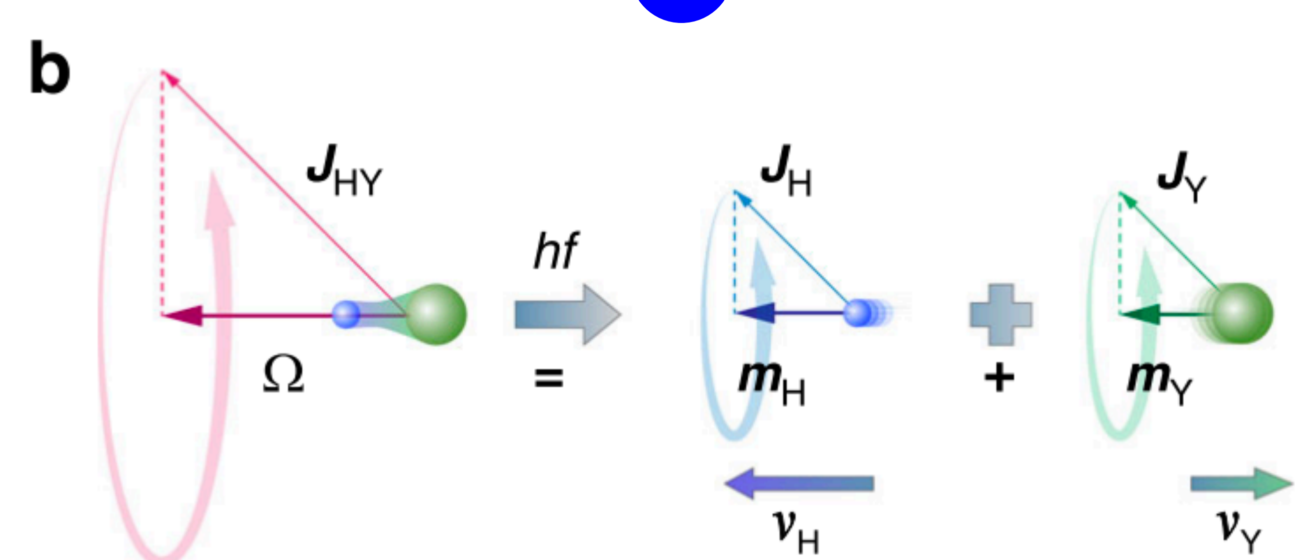

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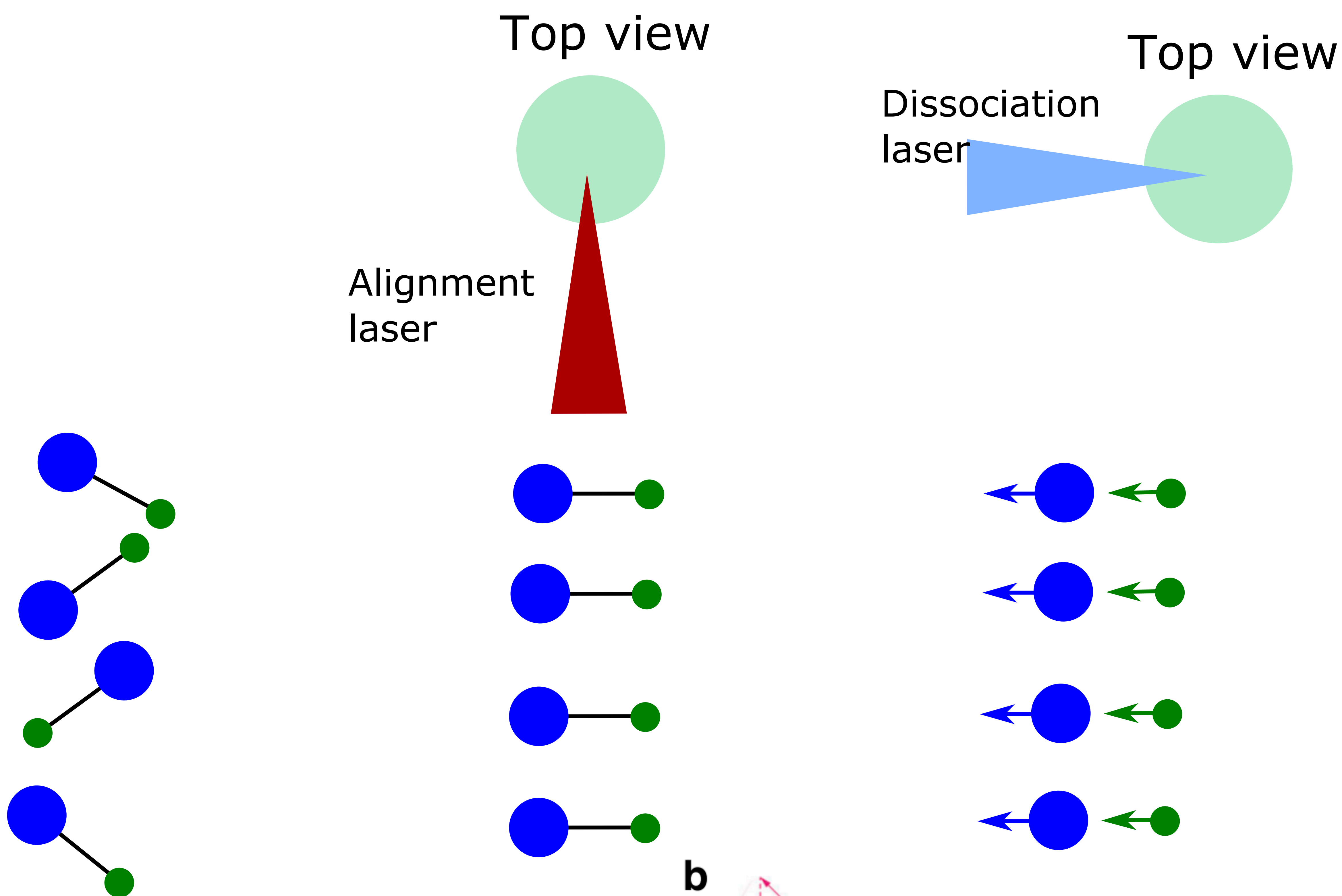

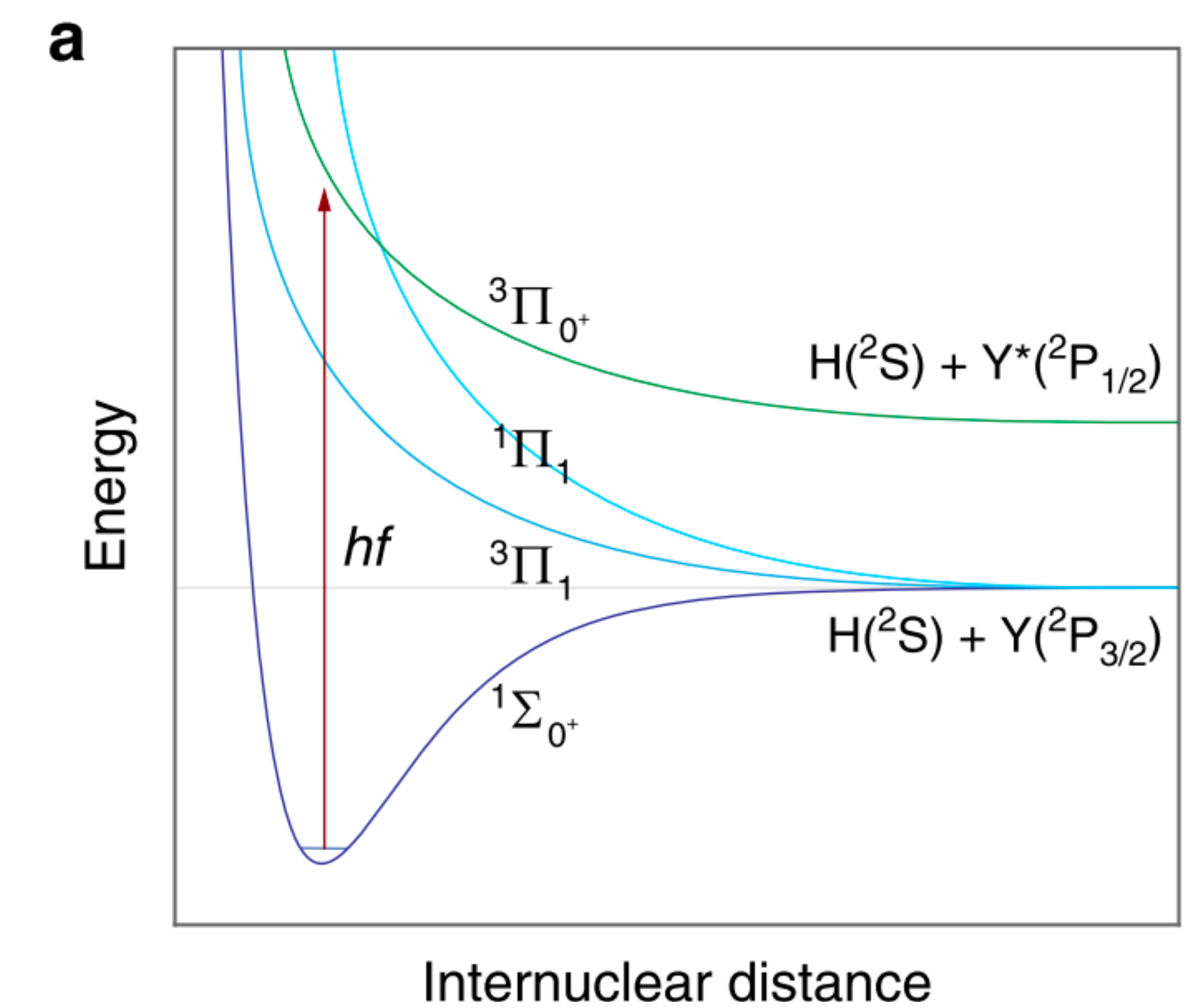

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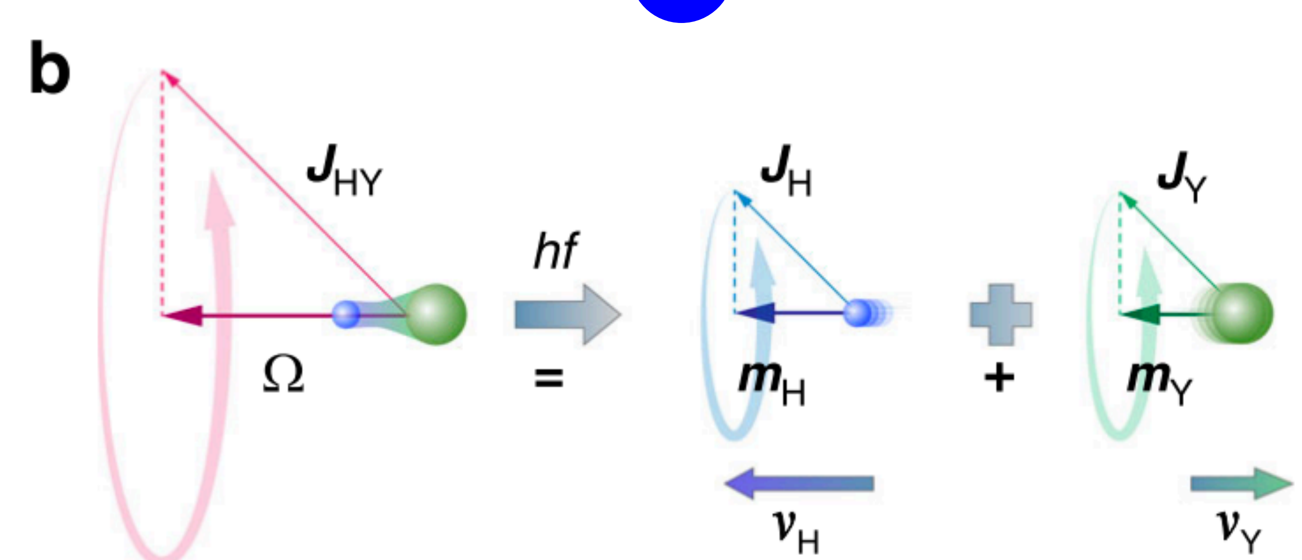

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Spin dynamics in (L)PAs

Very strong fields in laser-drivers and inside the bubble can lead to depolarisation

Spin precession

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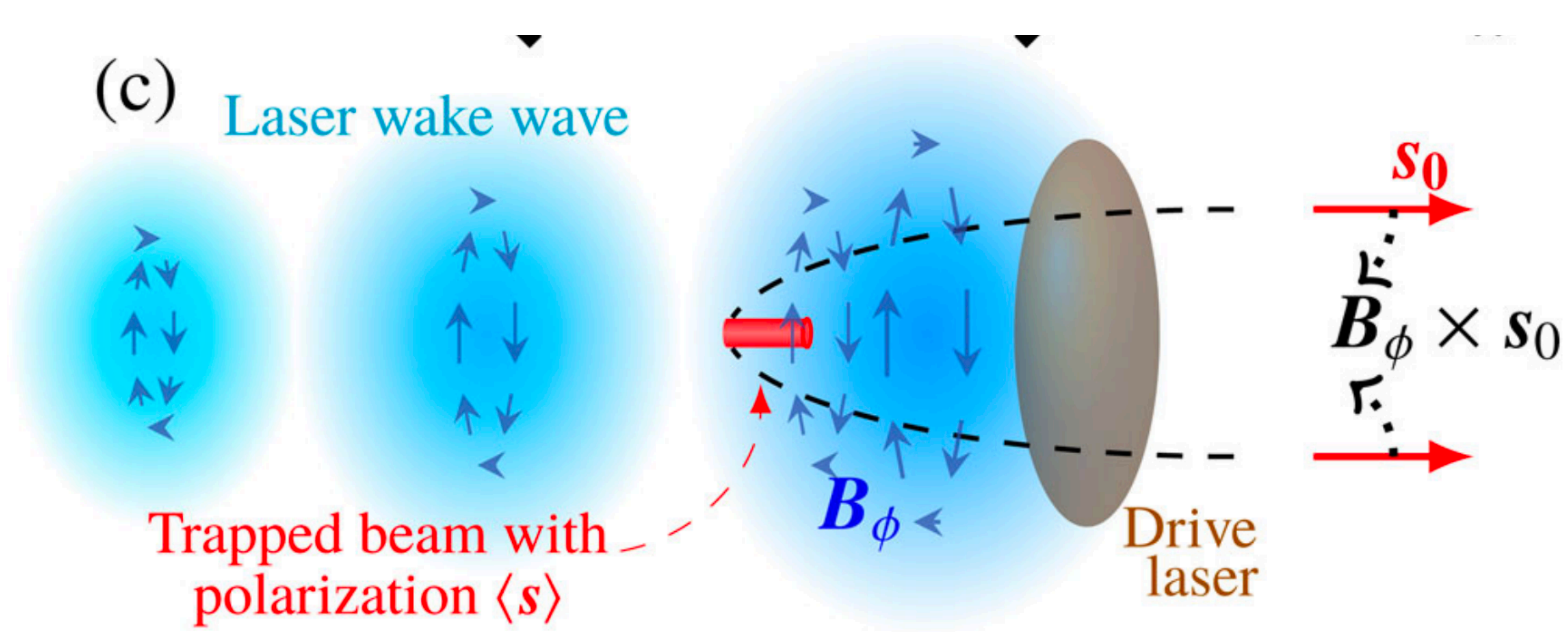

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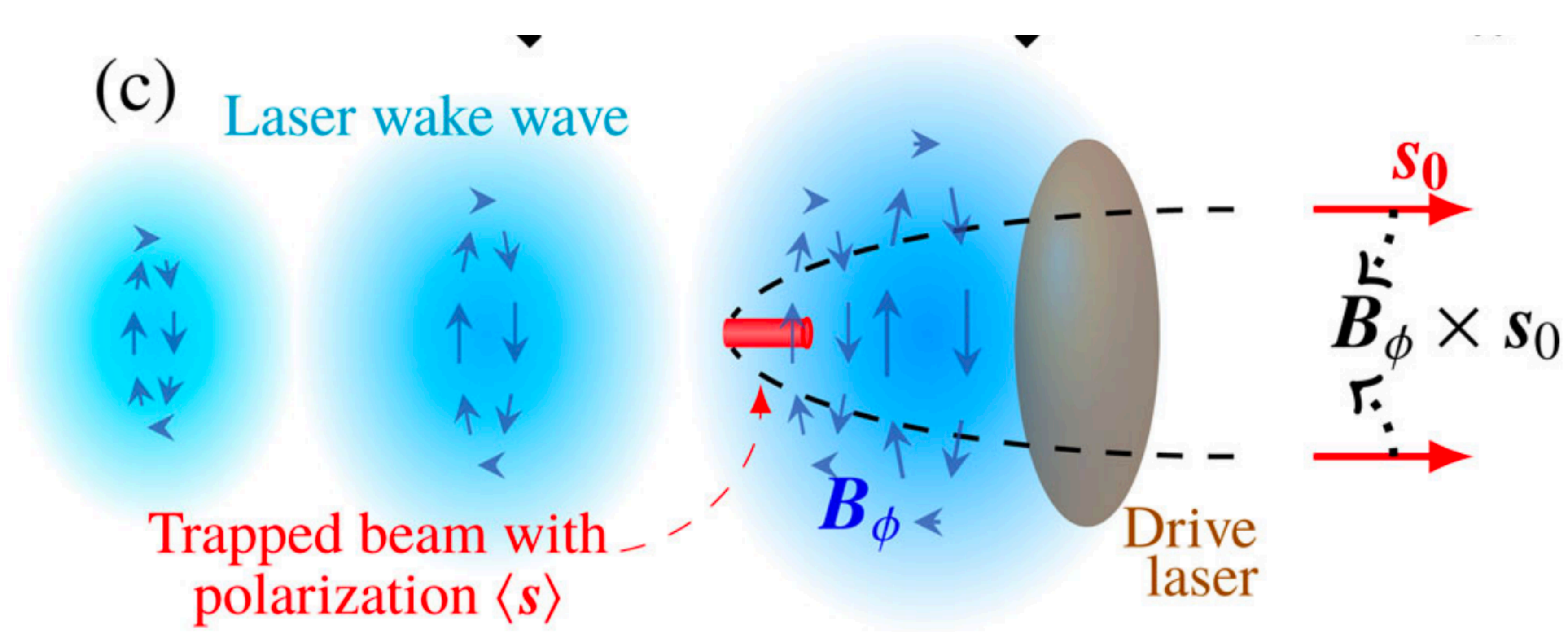

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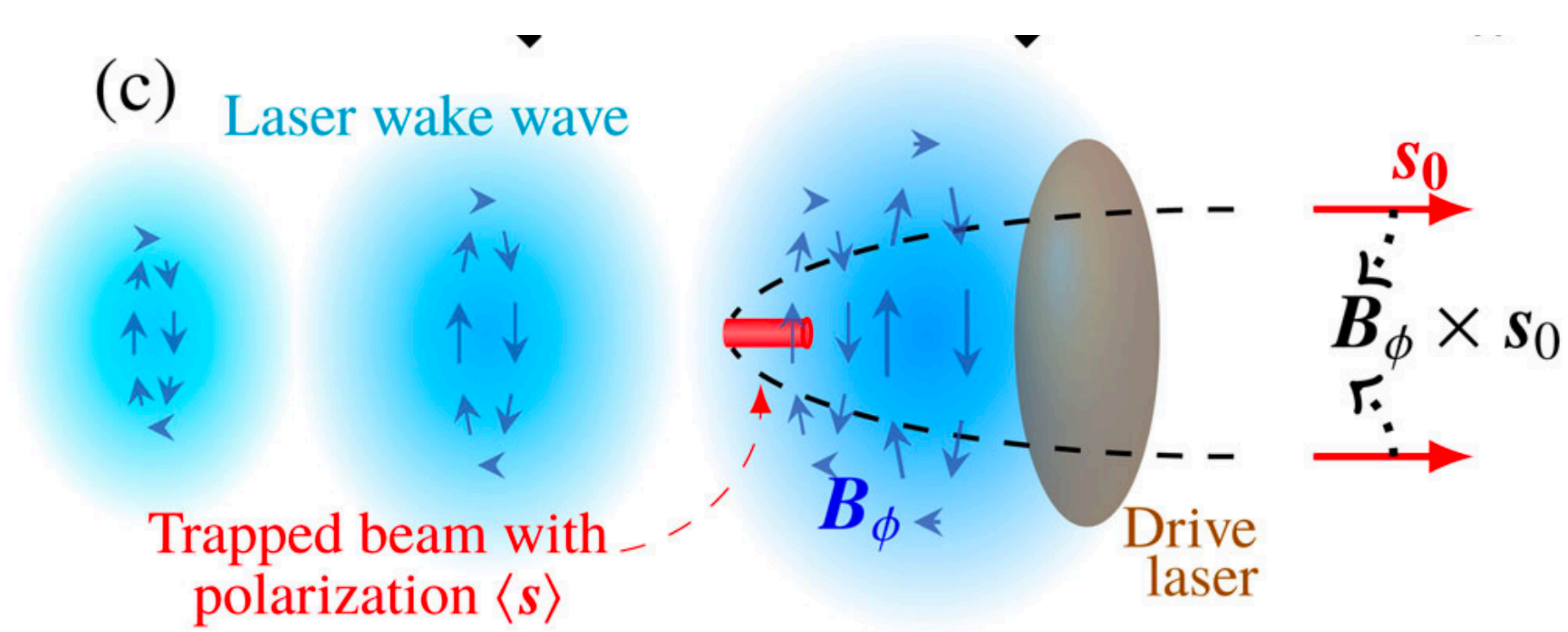
- Strong **E** fields lead to precession
  - But all electrons together, so P stays high



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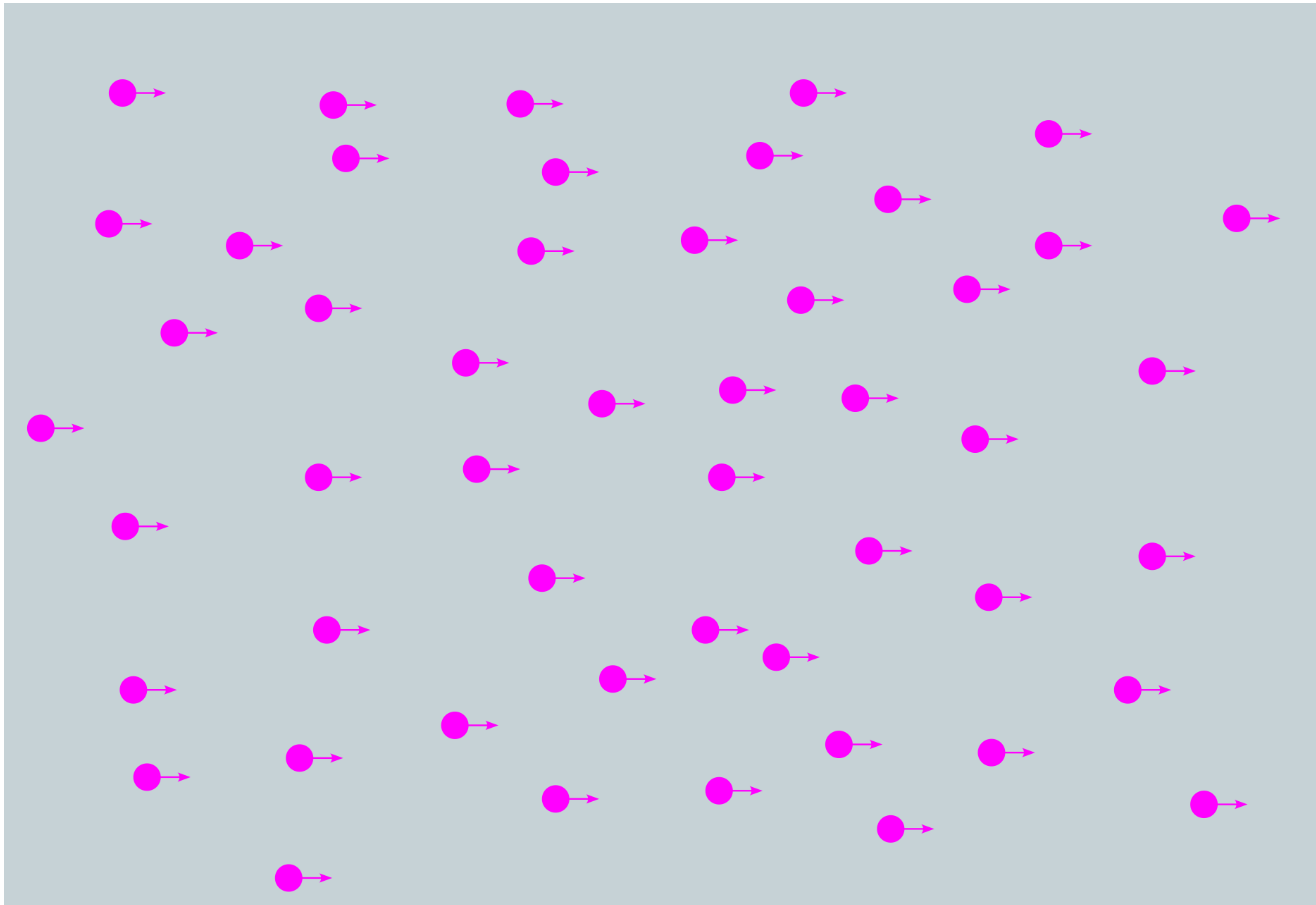

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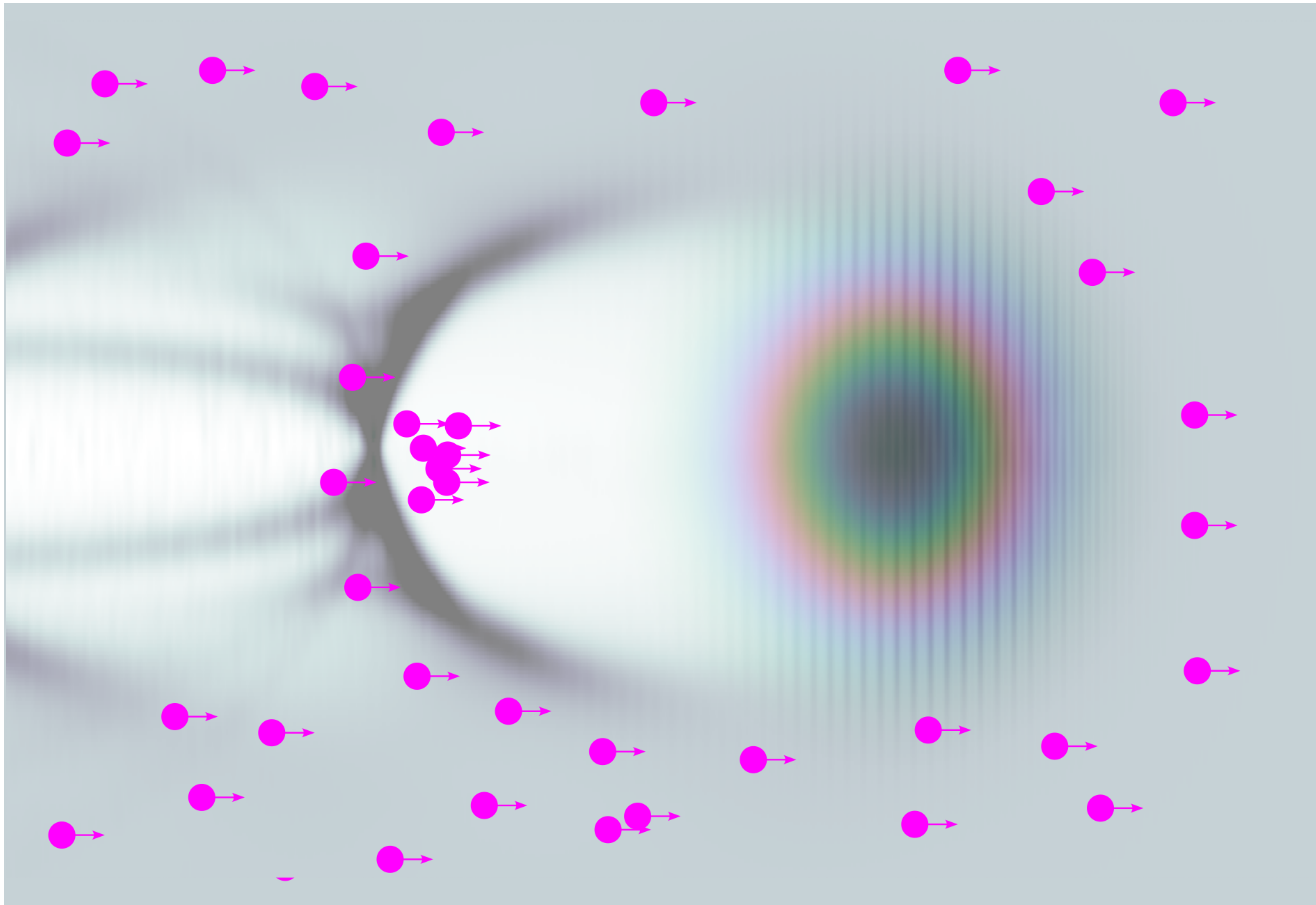

Injection requires sufficient longitudinal momentum

$$\mathcal{H}(\xi, p_z) = -|e|\varphi(\xi) + c\sqrt{m_e^2 c^2 + p_z^2} - v_d p_z$$

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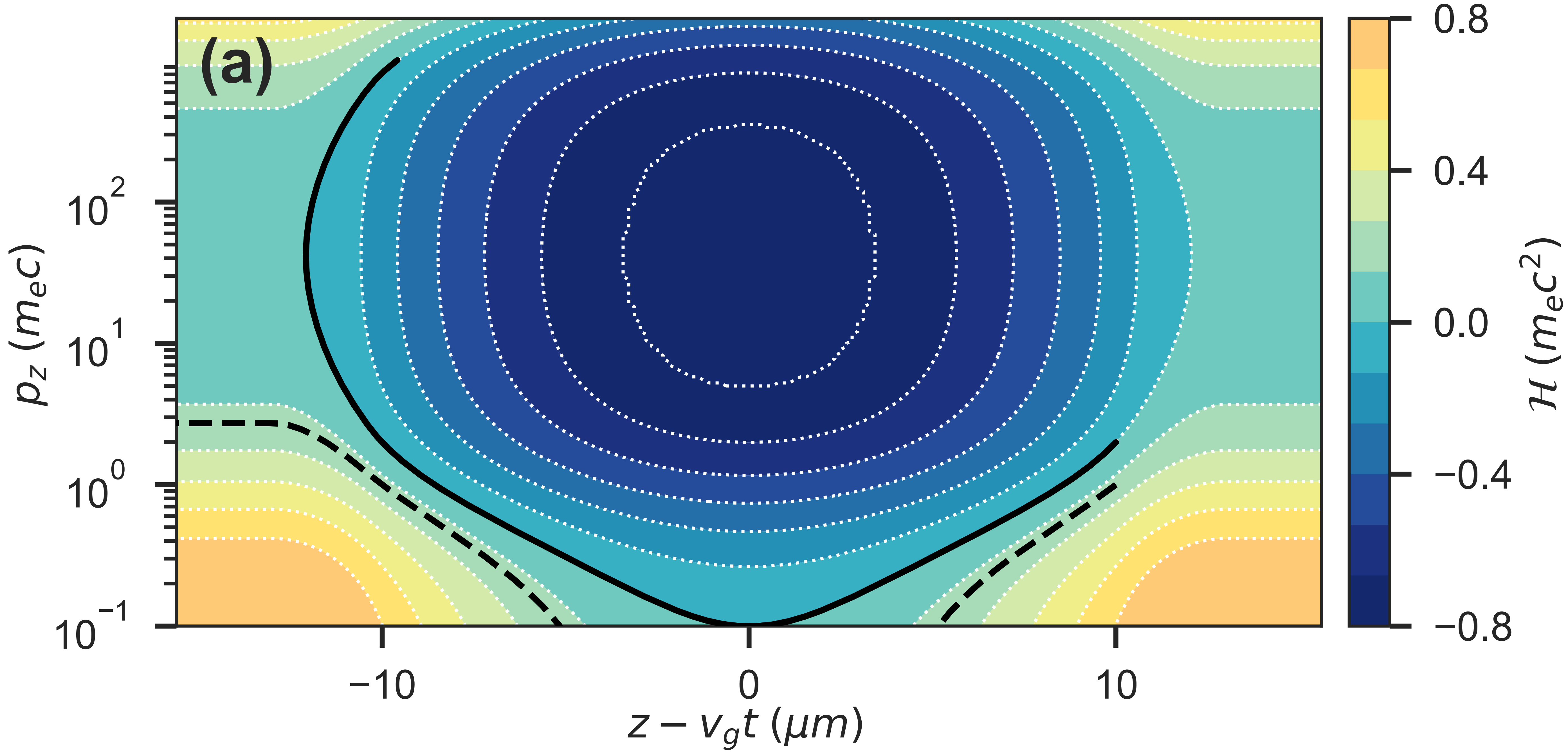

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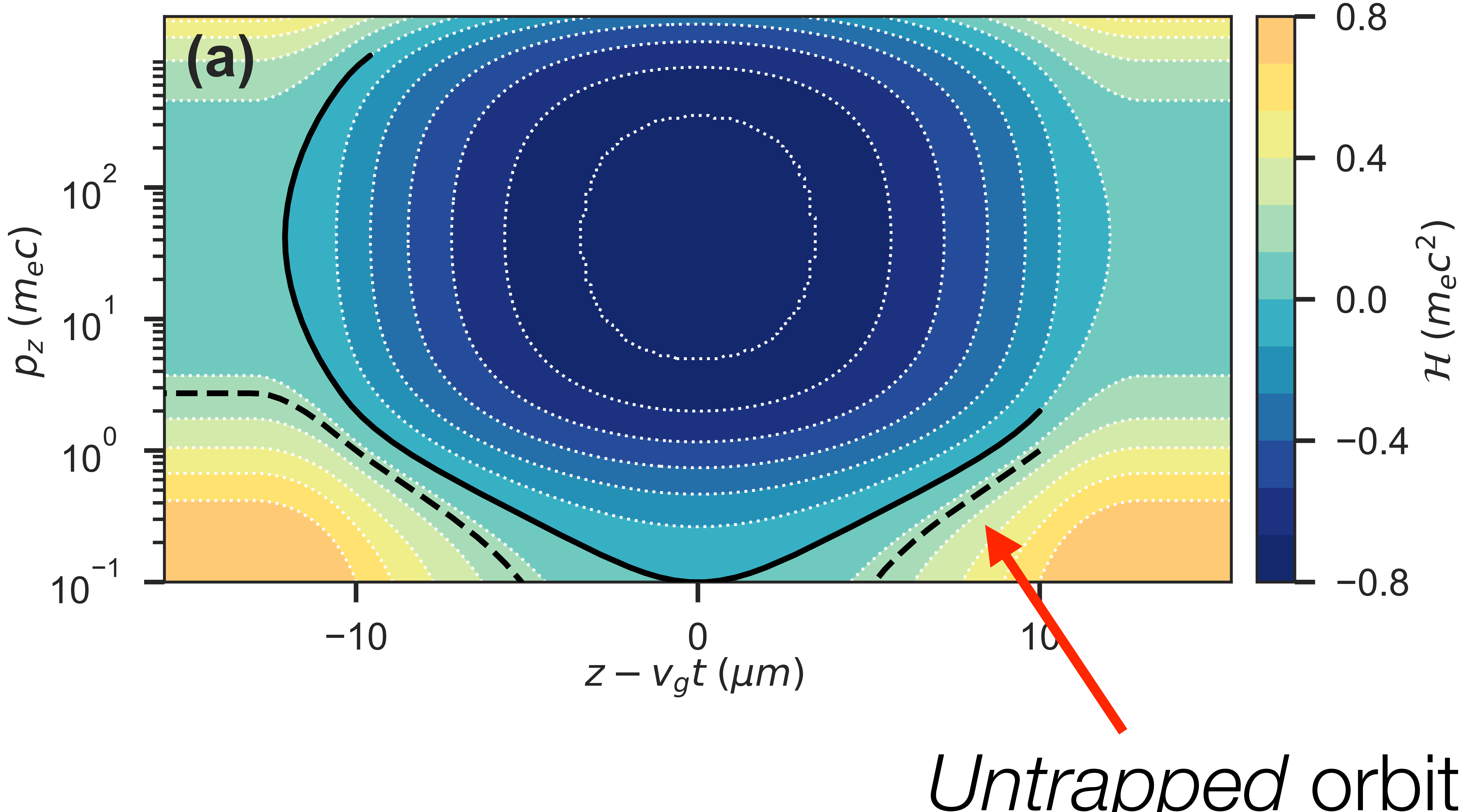

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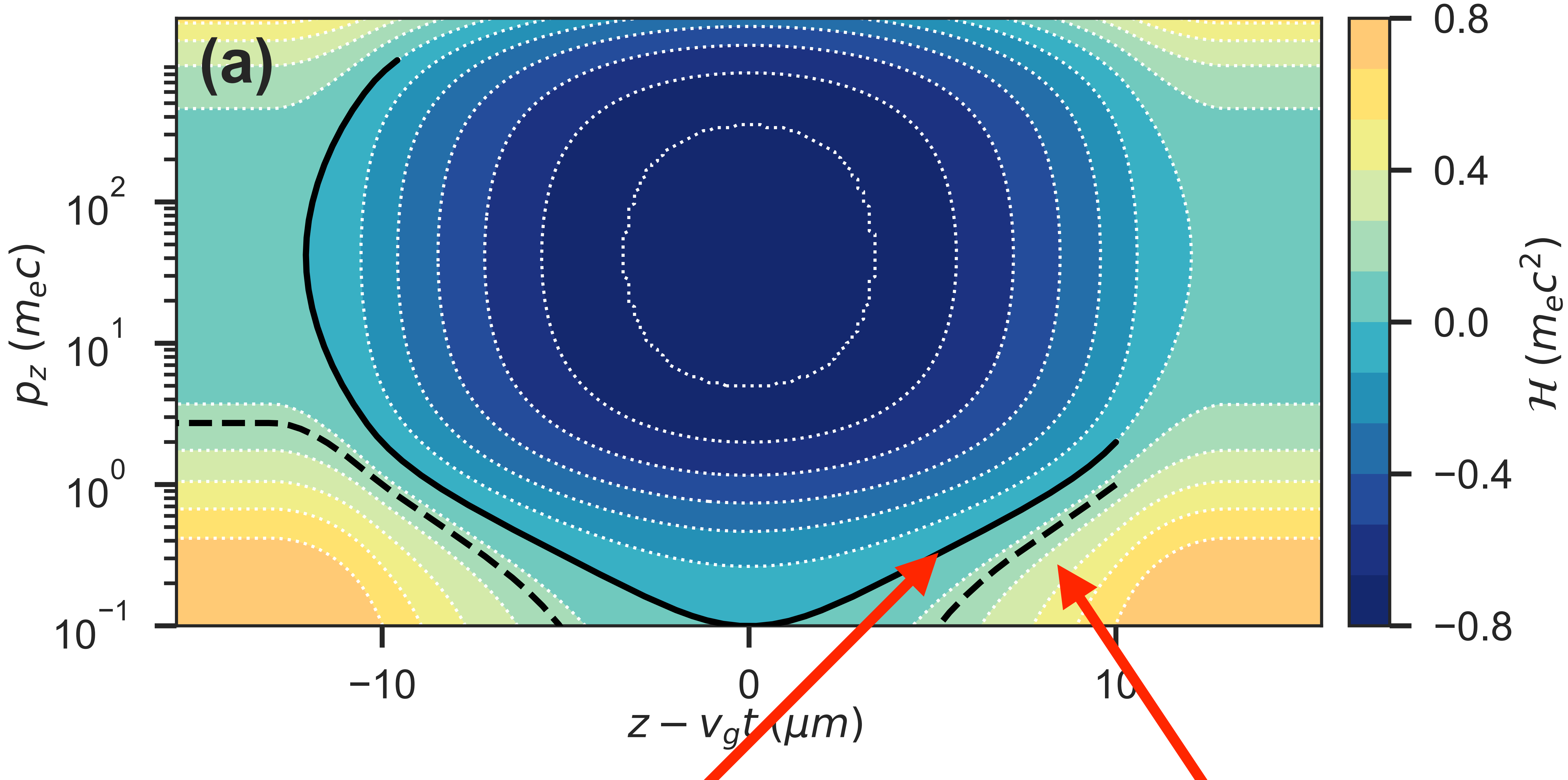
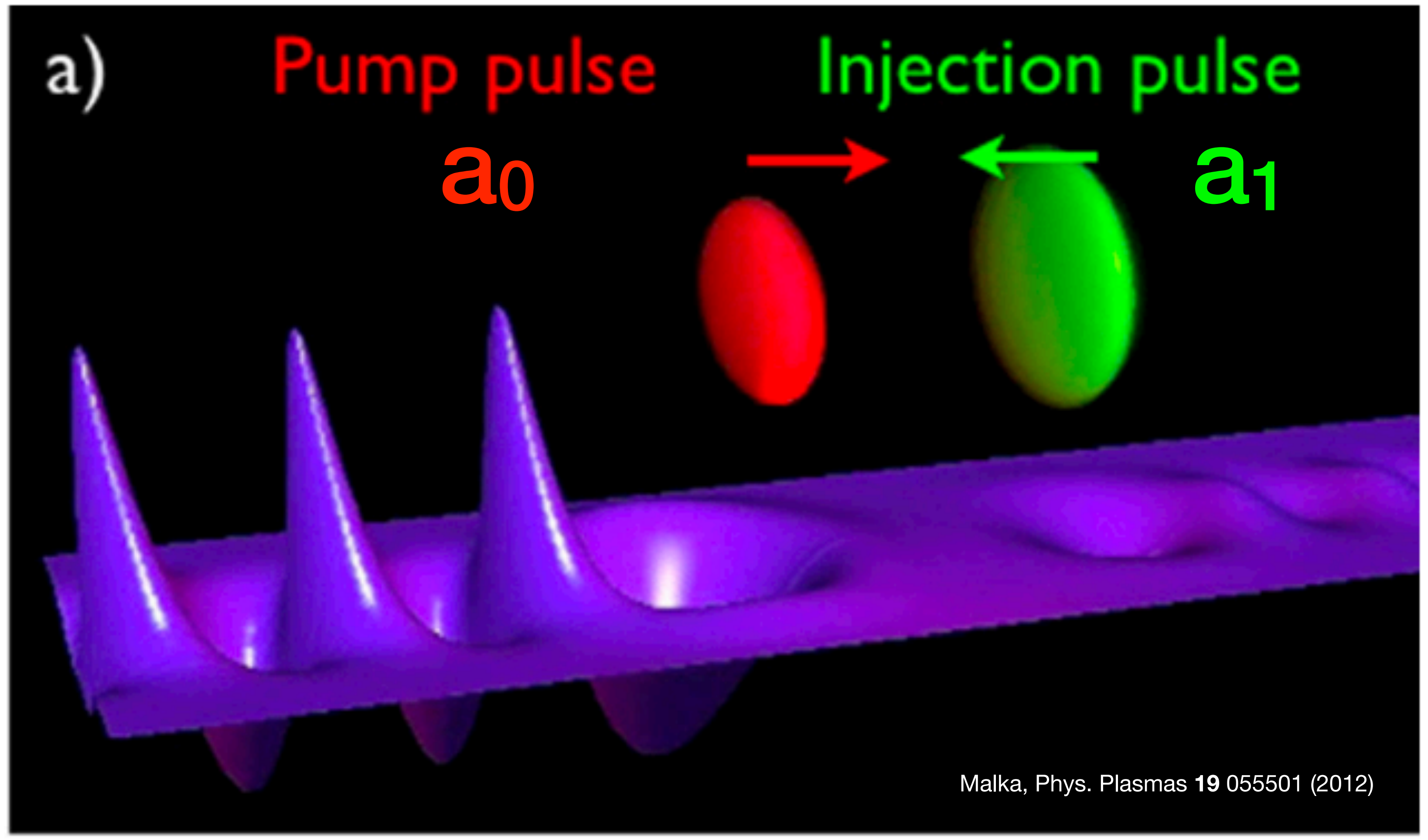


Trapped orbit *Untrapped* orbit

Colliding two laser pulses can lead to trapping

Stochastic heating in the lasers' interaction region gives electrons residual longitudinal momentum



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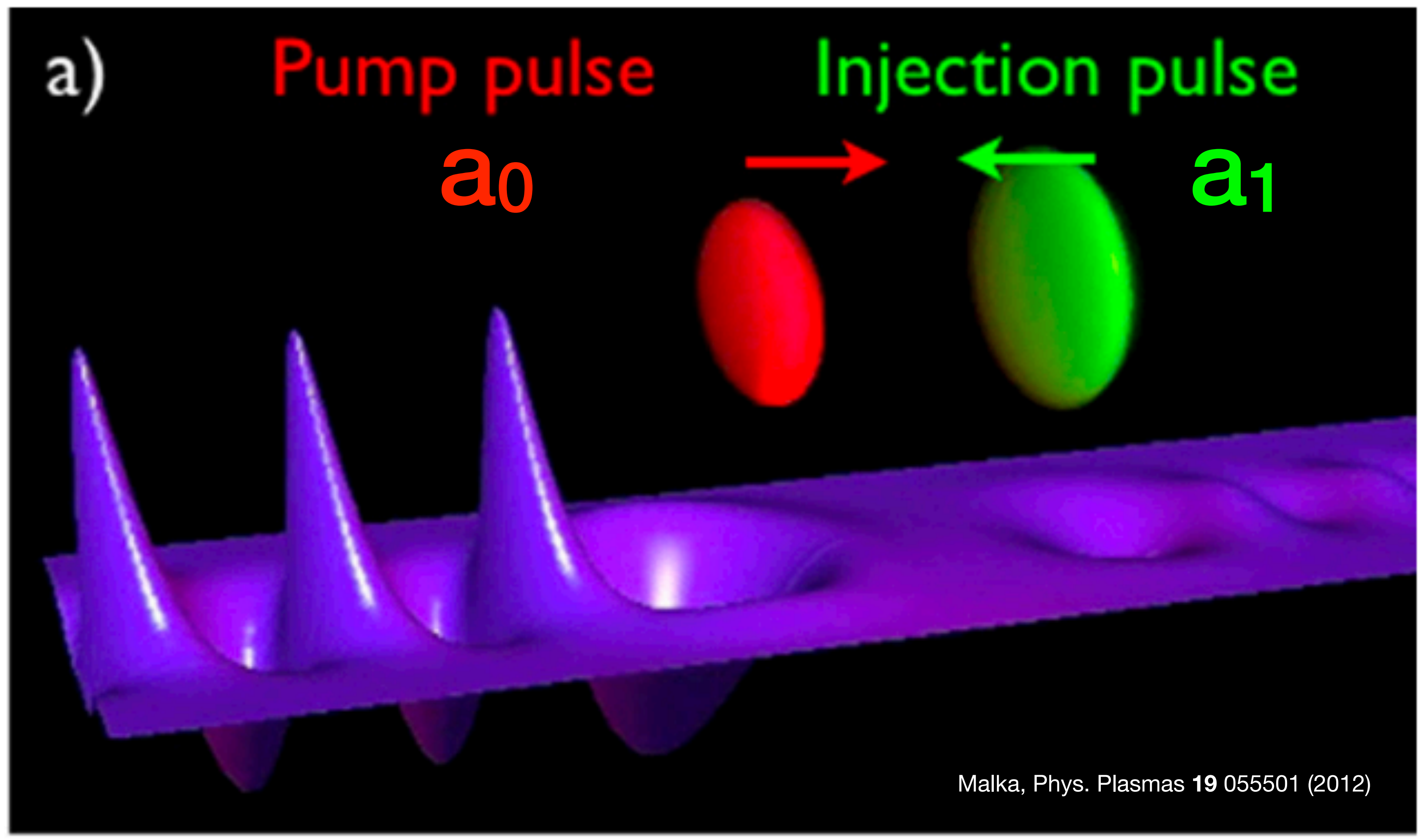

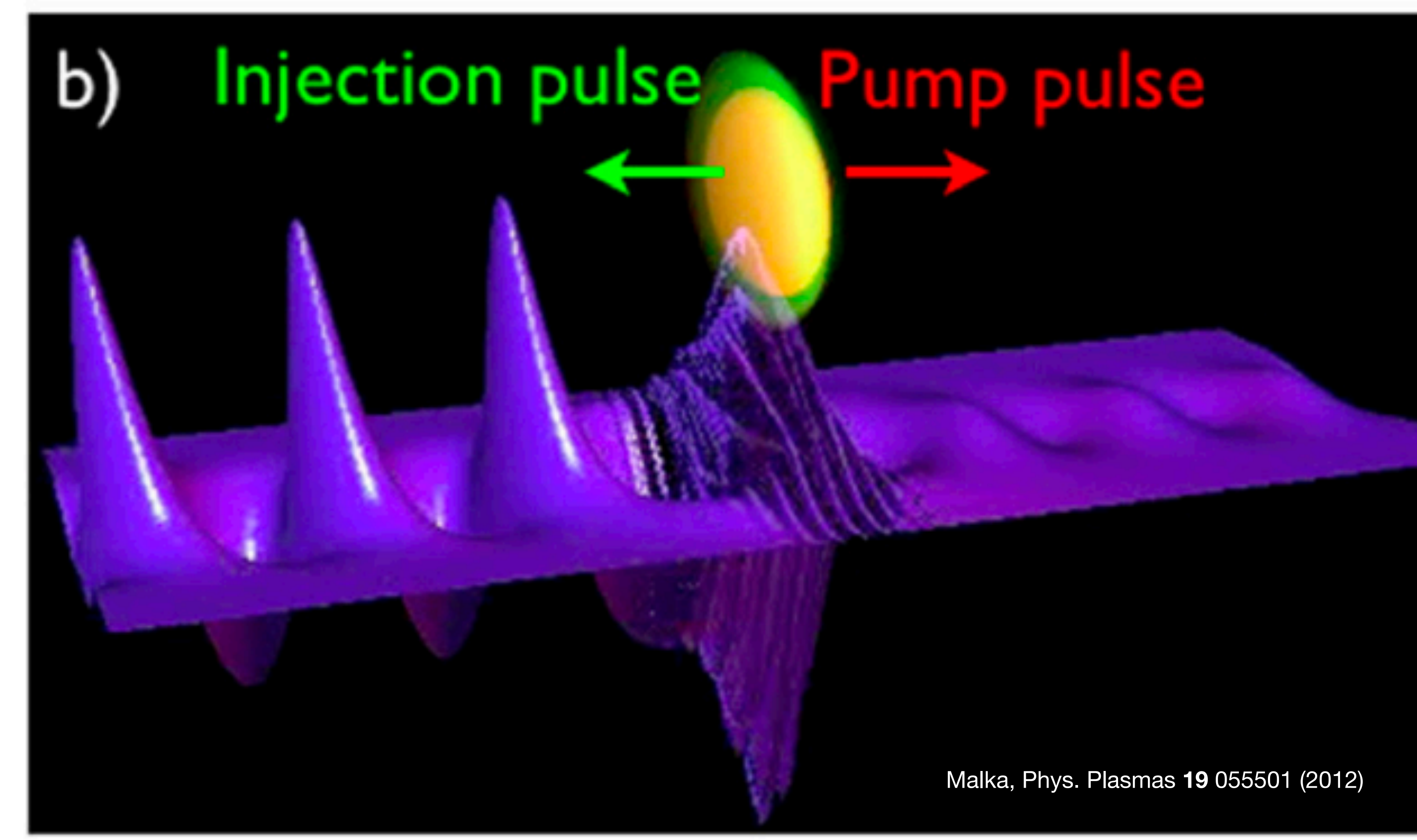

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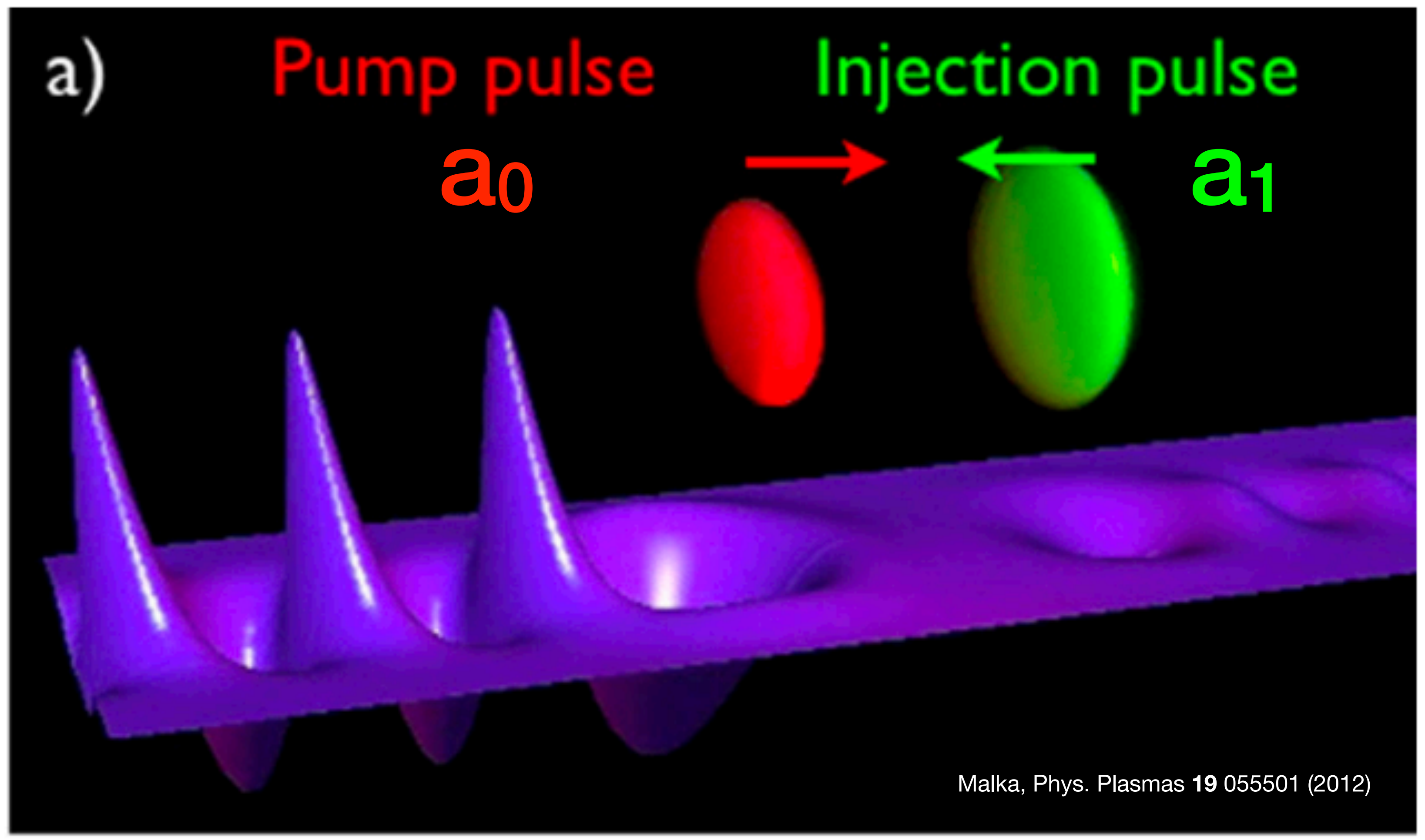

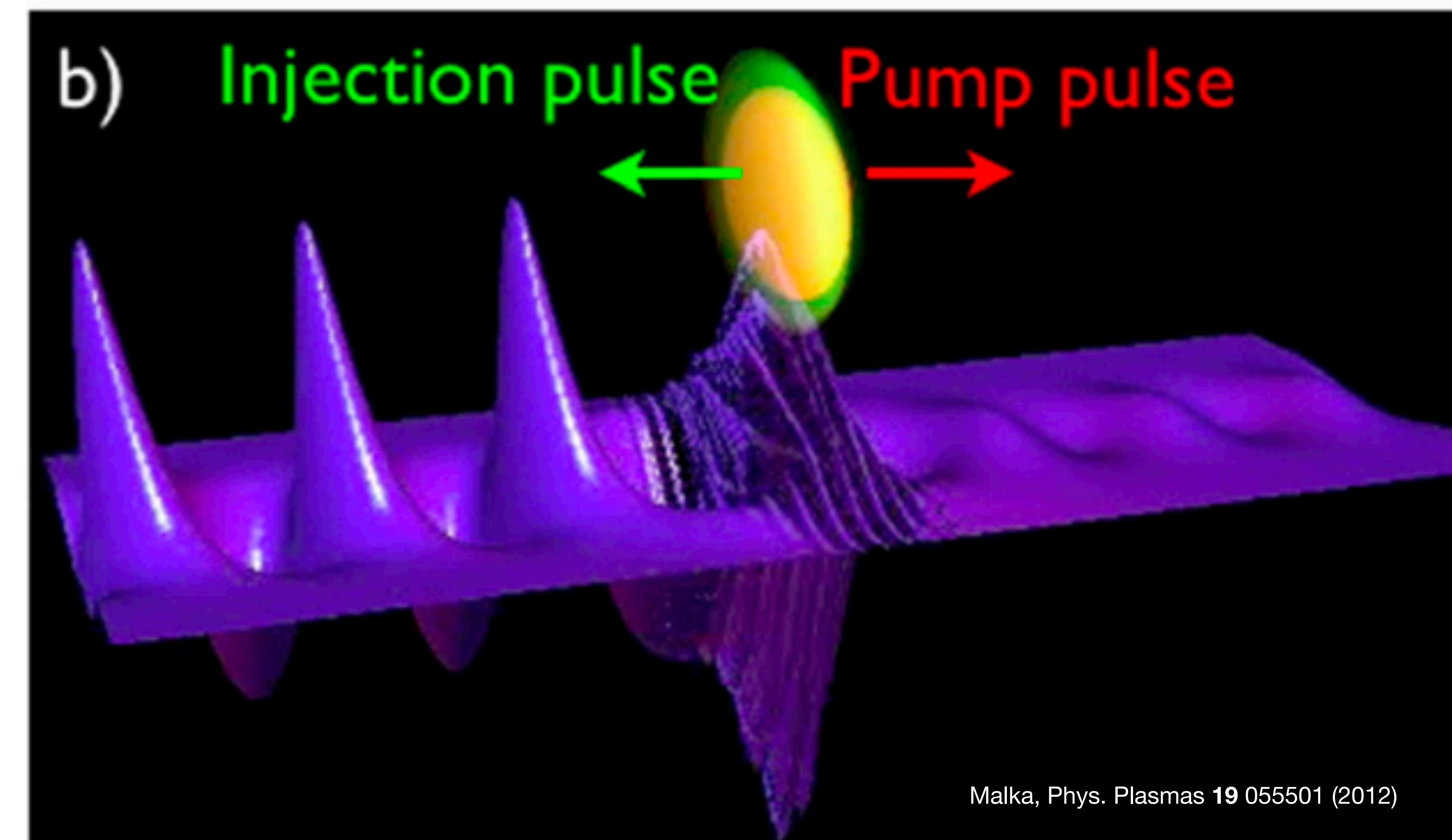

$$\frac{dp_x}{d\phi} = \frac{m_e^2 c^2}{p_-}[a_0^2 \cos\phi \sin\phi + a_0 a_1 \sin(2k_0 x + \phi_1) - a_1^2 \cos(\phi + 2k_0 x + \phi_1)\sin(\phi + 2k_0 x + \phi_1)]$$

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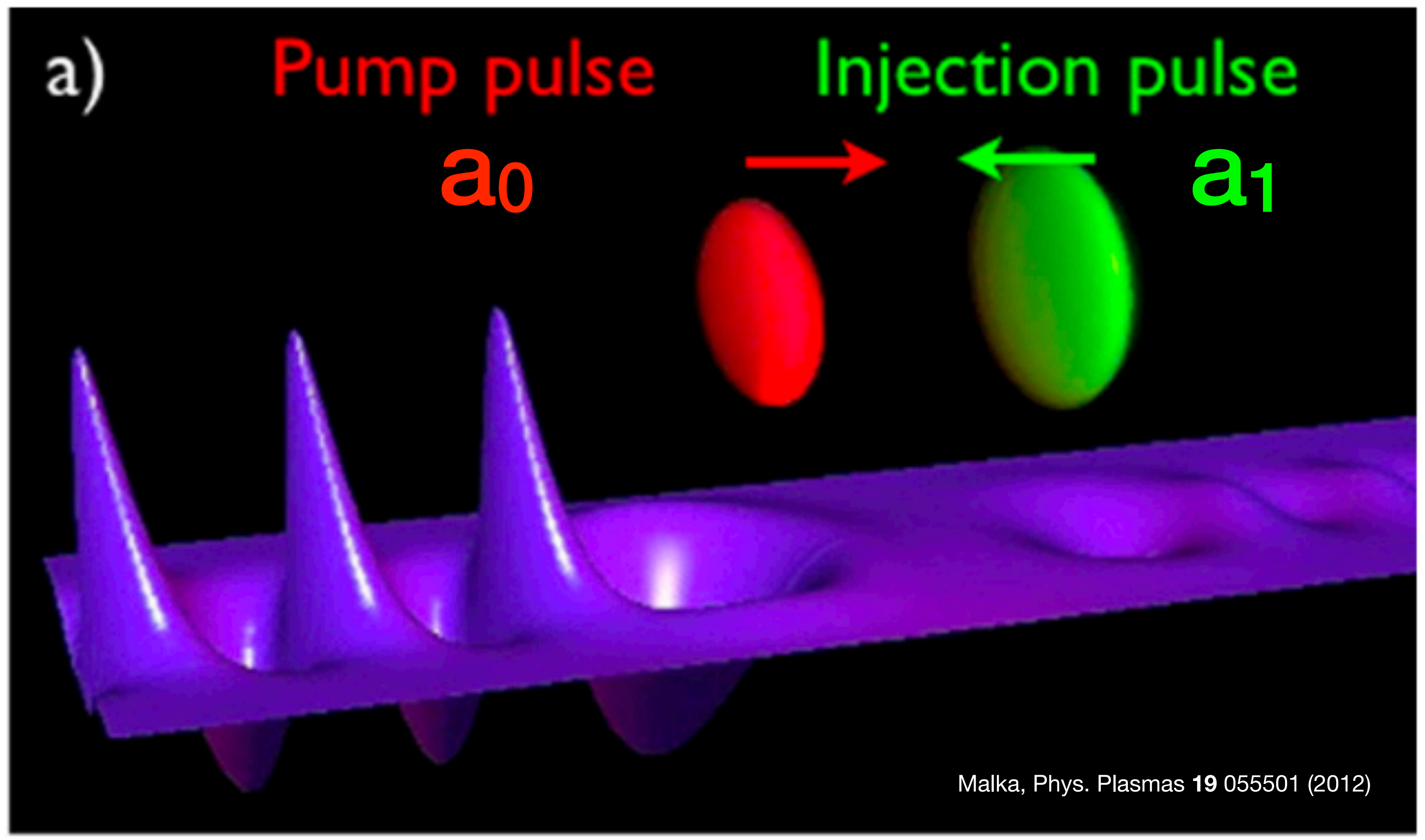

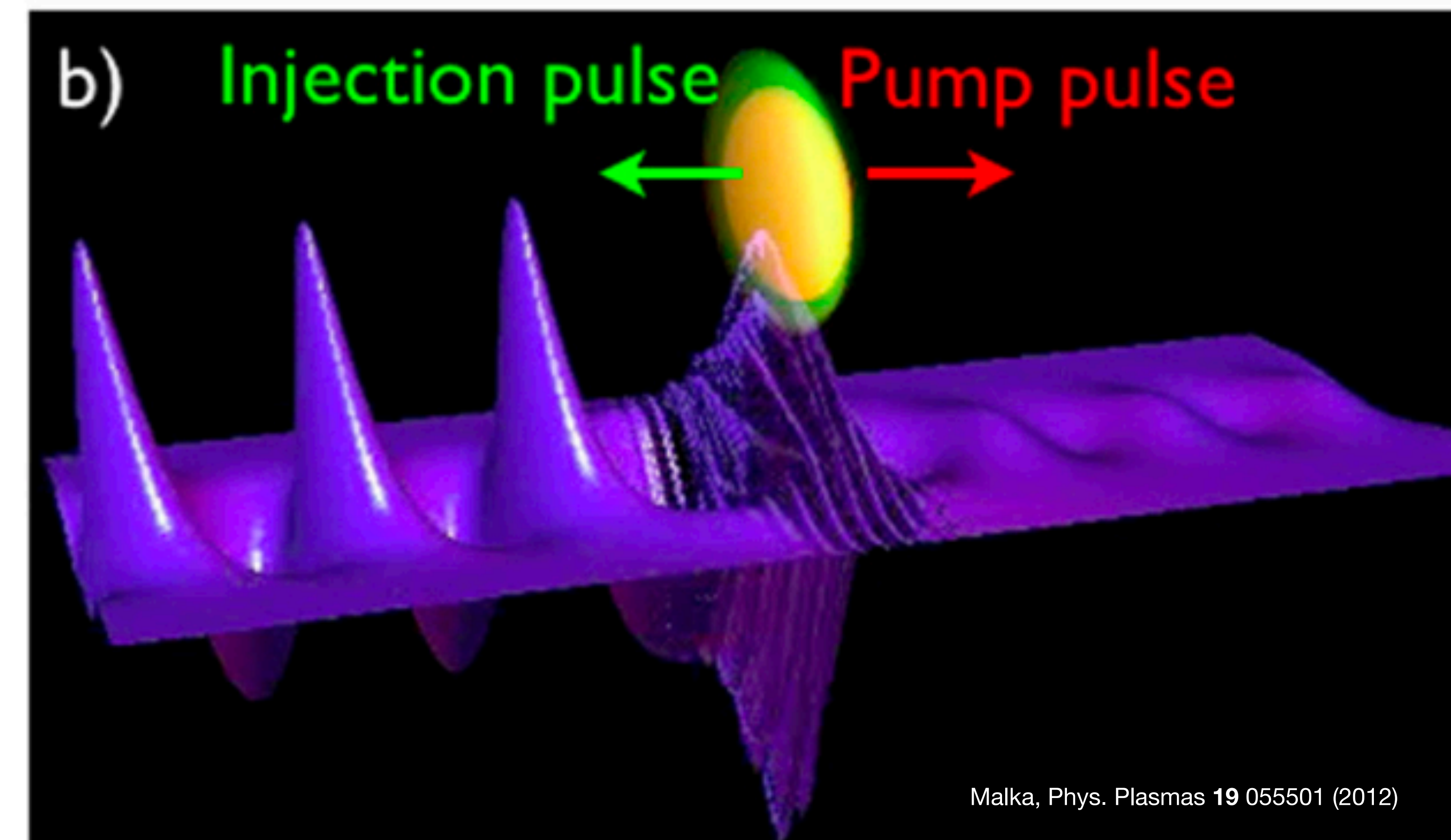

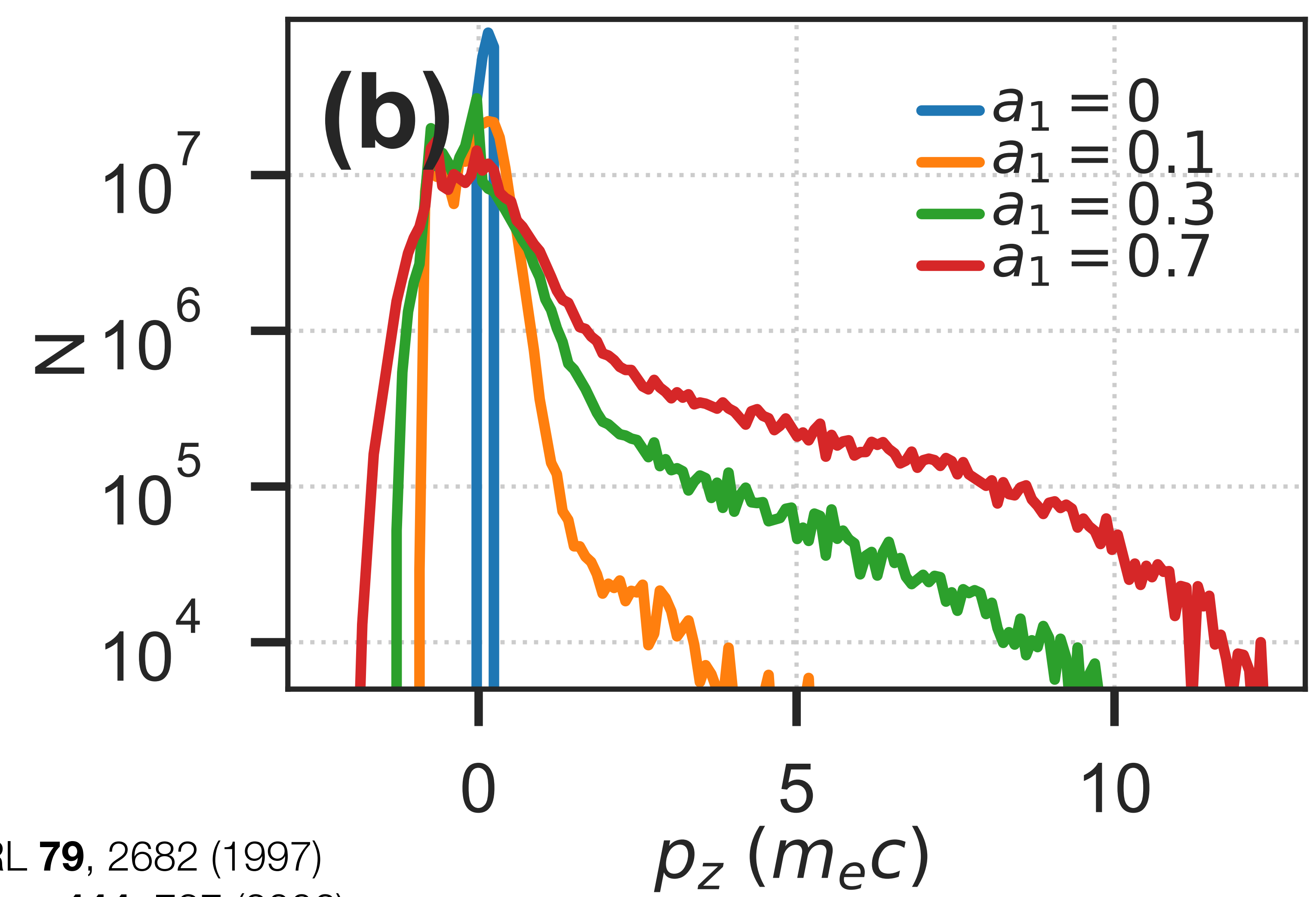

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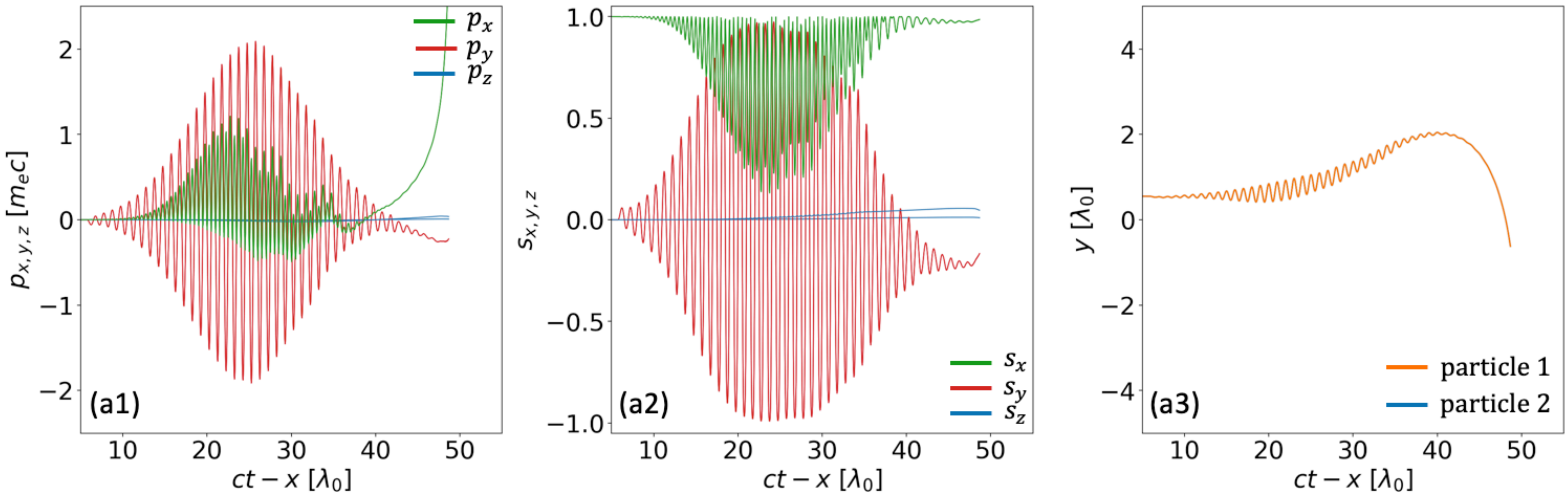
Spin evolution in colliding pulse injection



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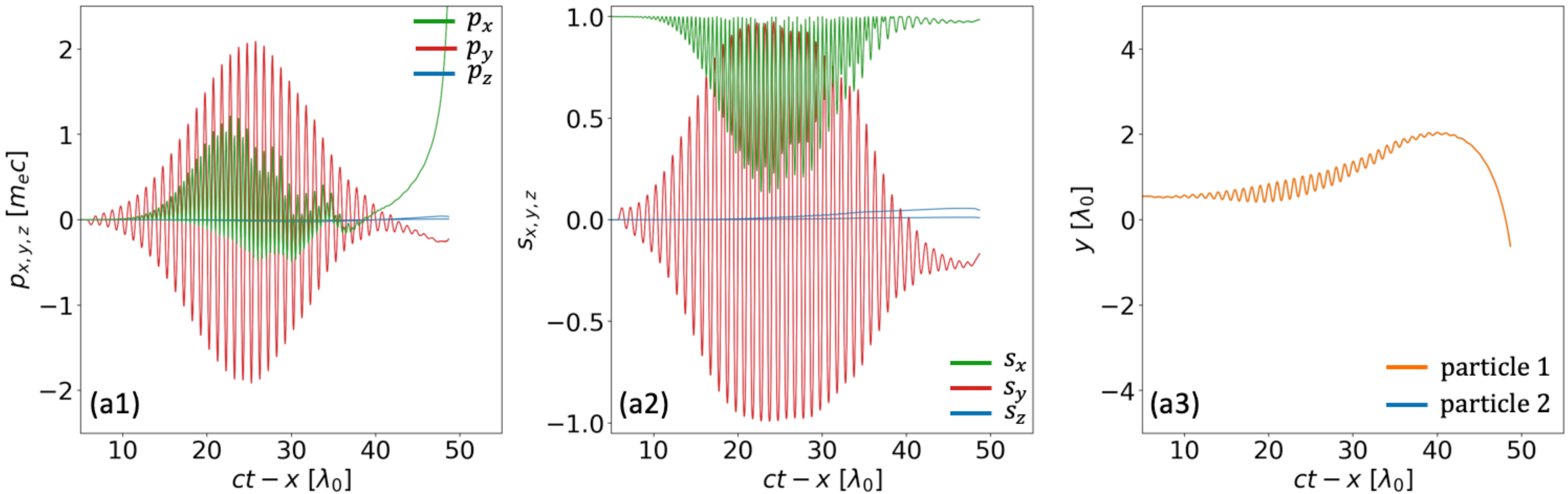
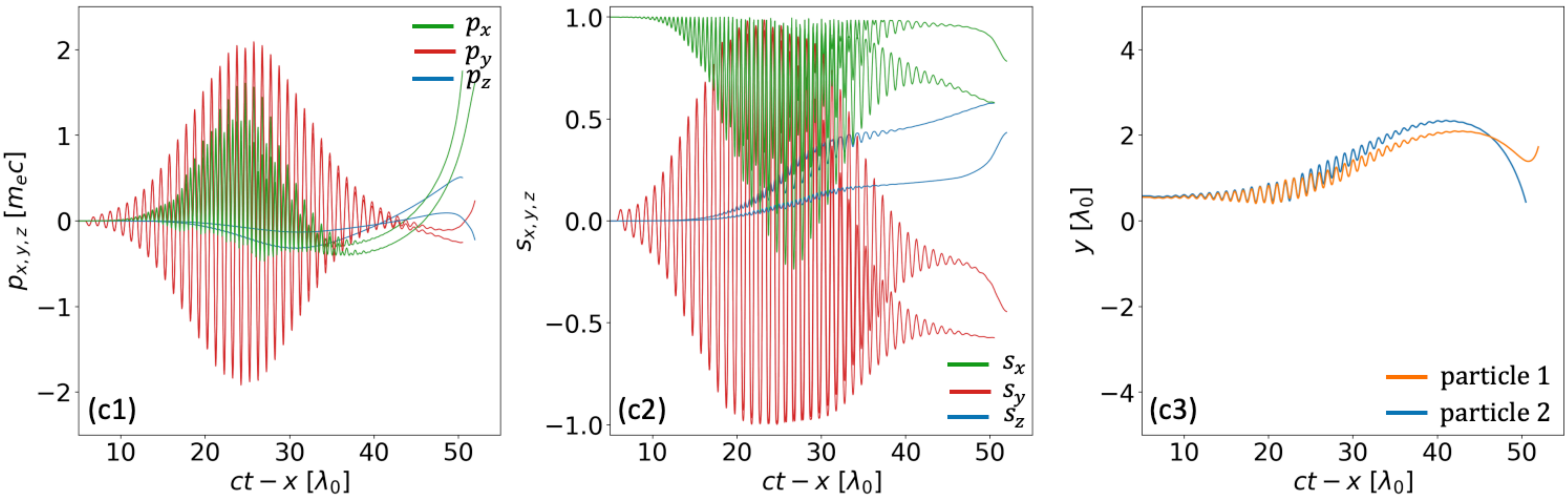
Precession 🙂

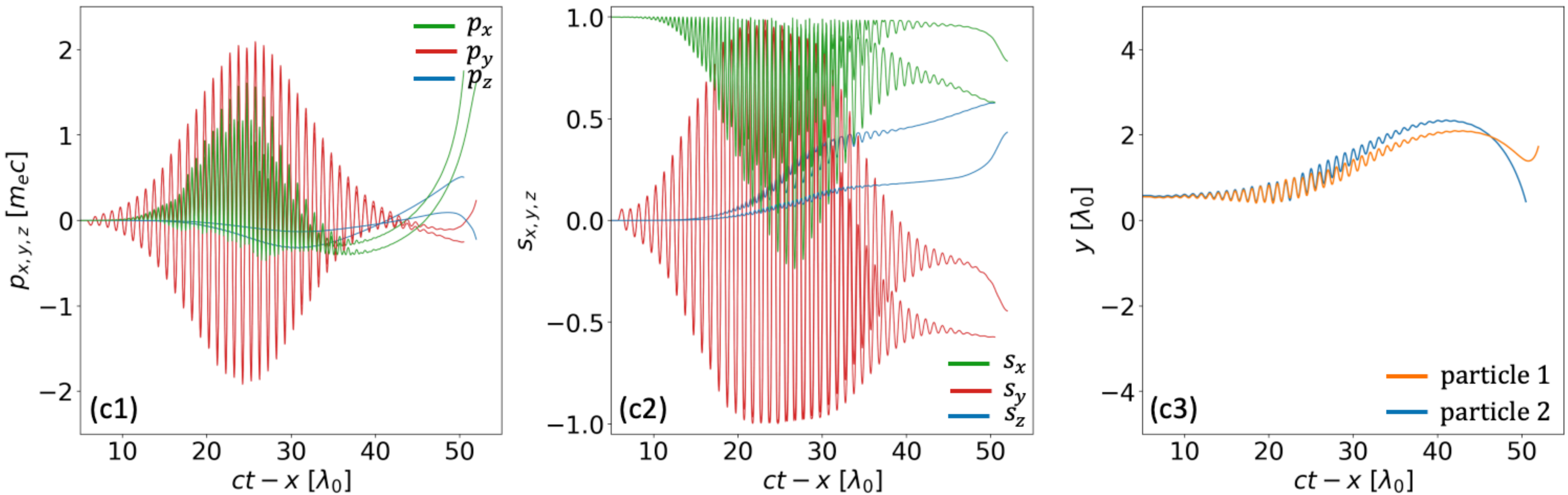


Spin evolution in colliding pulse injection



Spin evolution in colliding pulse injection

Stochastic motion ☹️



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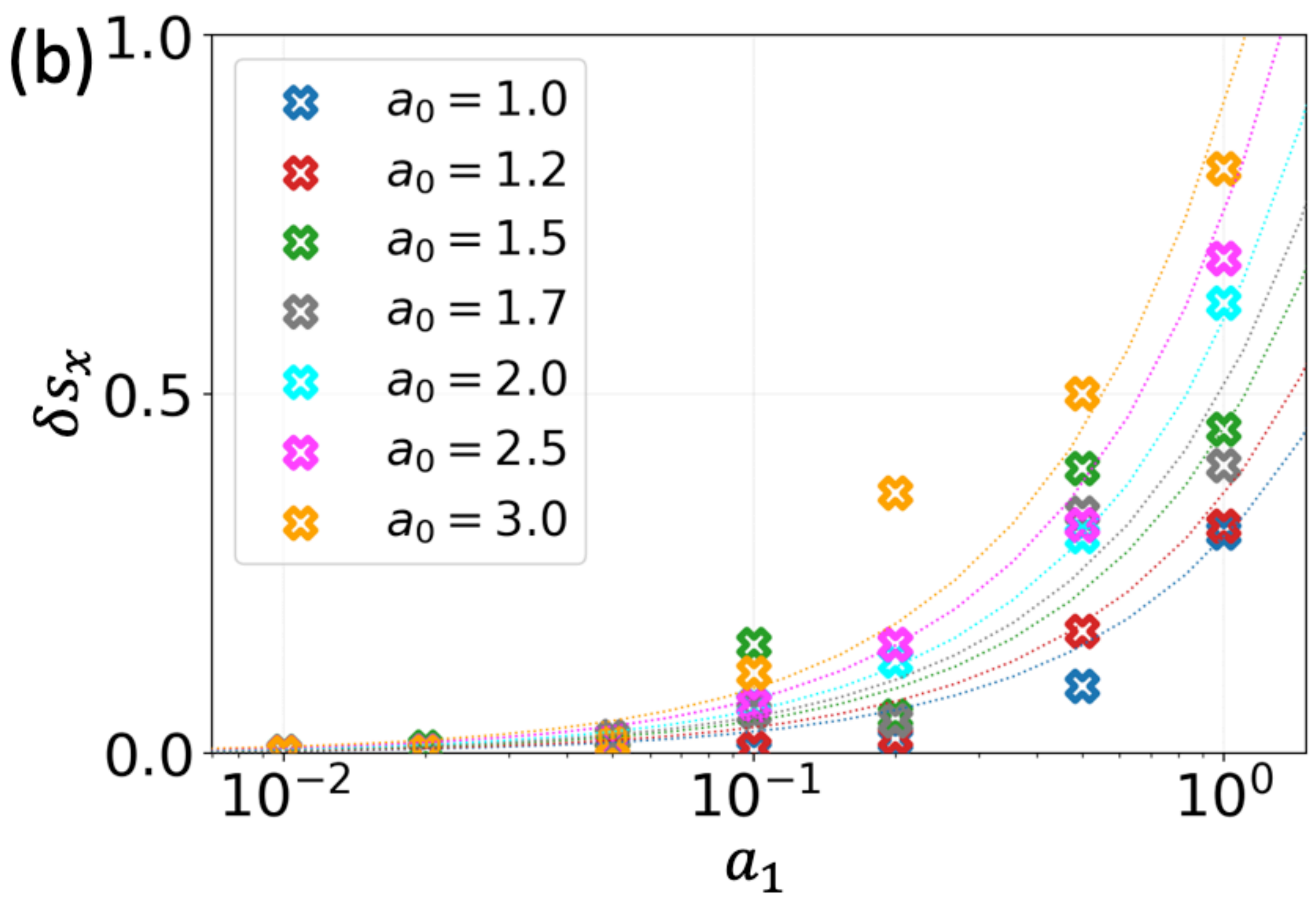
Stochastic motion in beatwave leads to stochastic spin evolution for some electrons

Test particles in 25 fs plane waves



$$\delta s_z \equiv 1 - s_z = 0.25 a_0 a_1$$

Lehe et al, CPC **203**, 66 (2016)
Gong *et al*, Matter Radiat at Extremes *in press*

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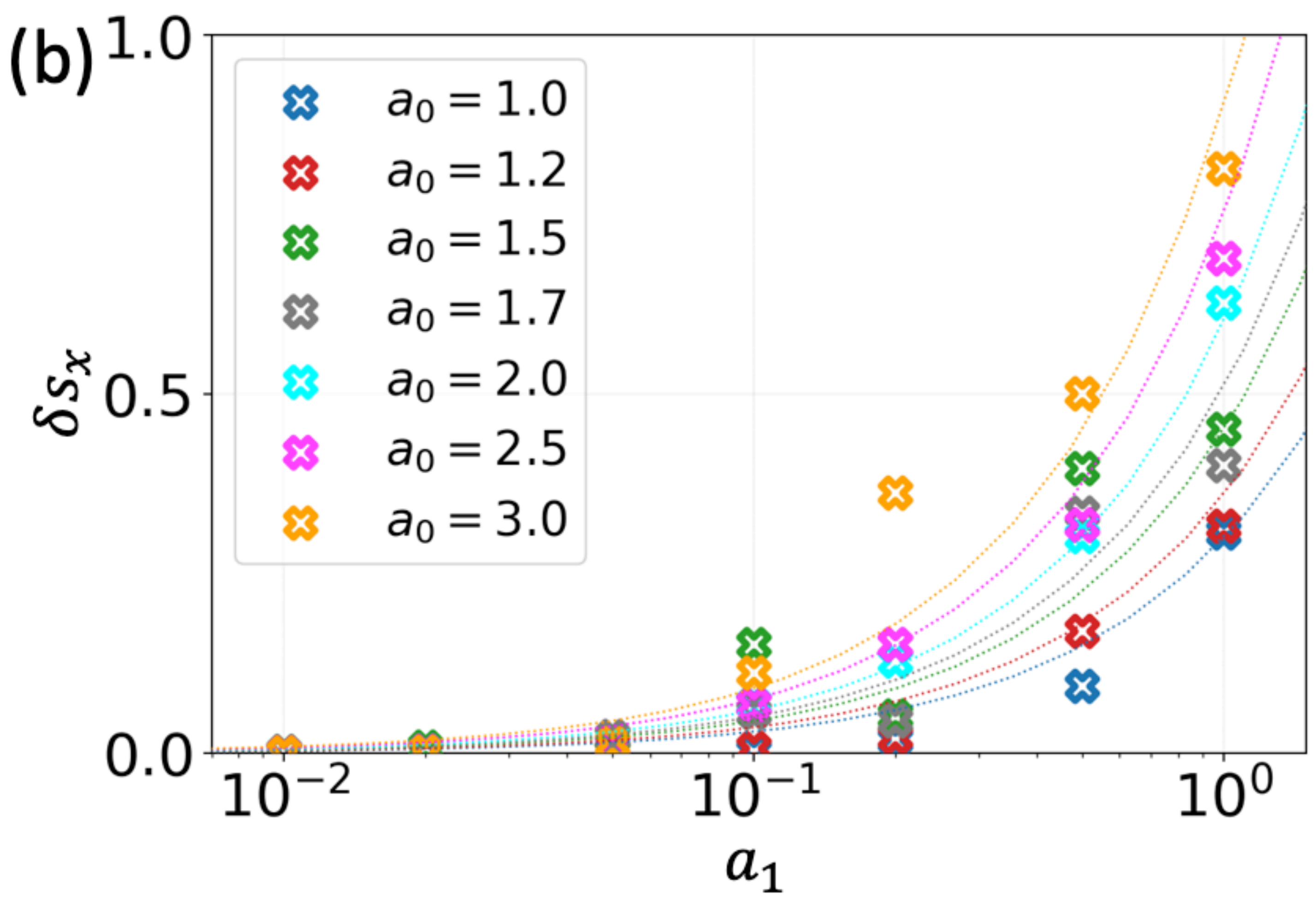

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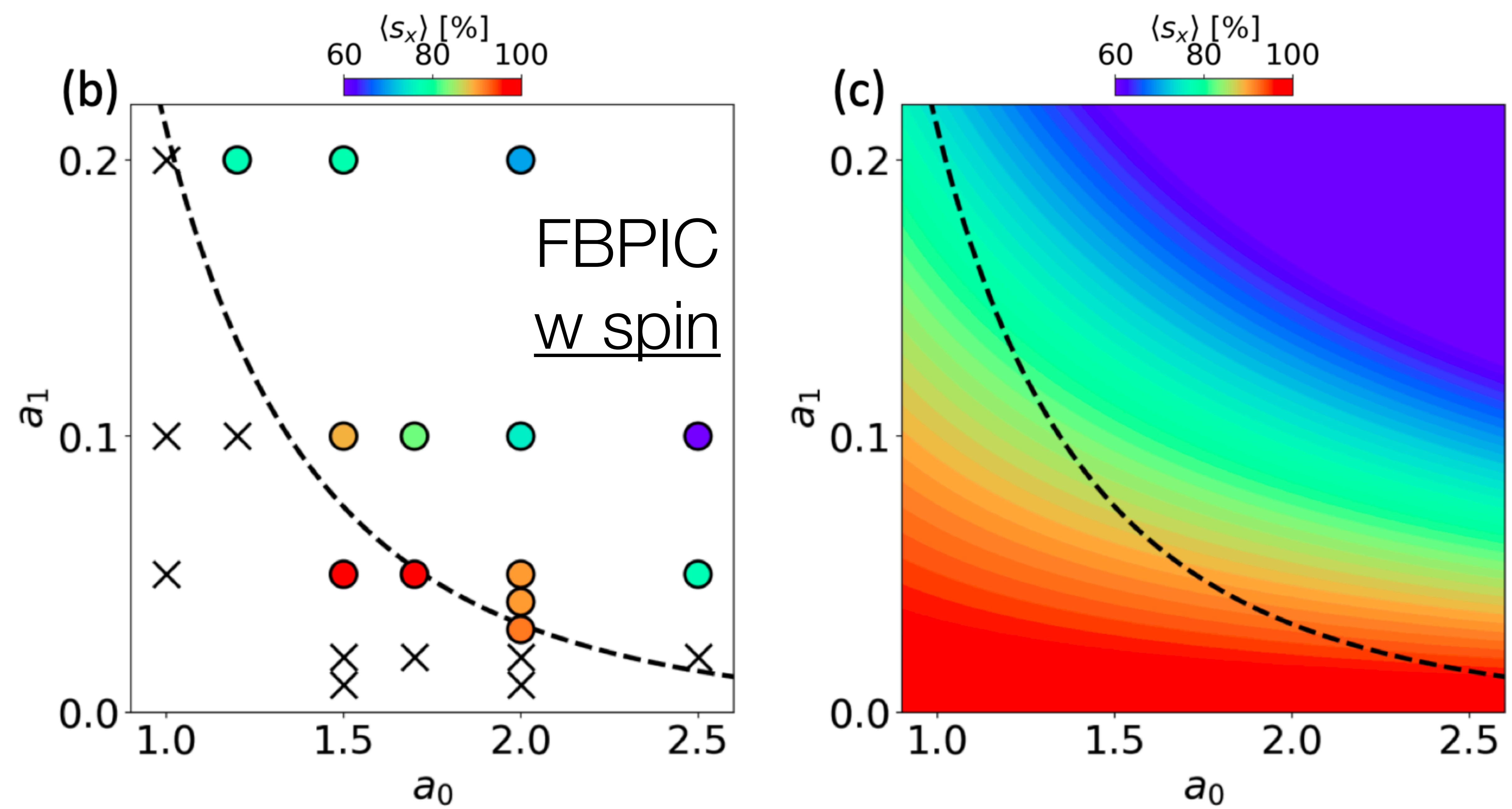

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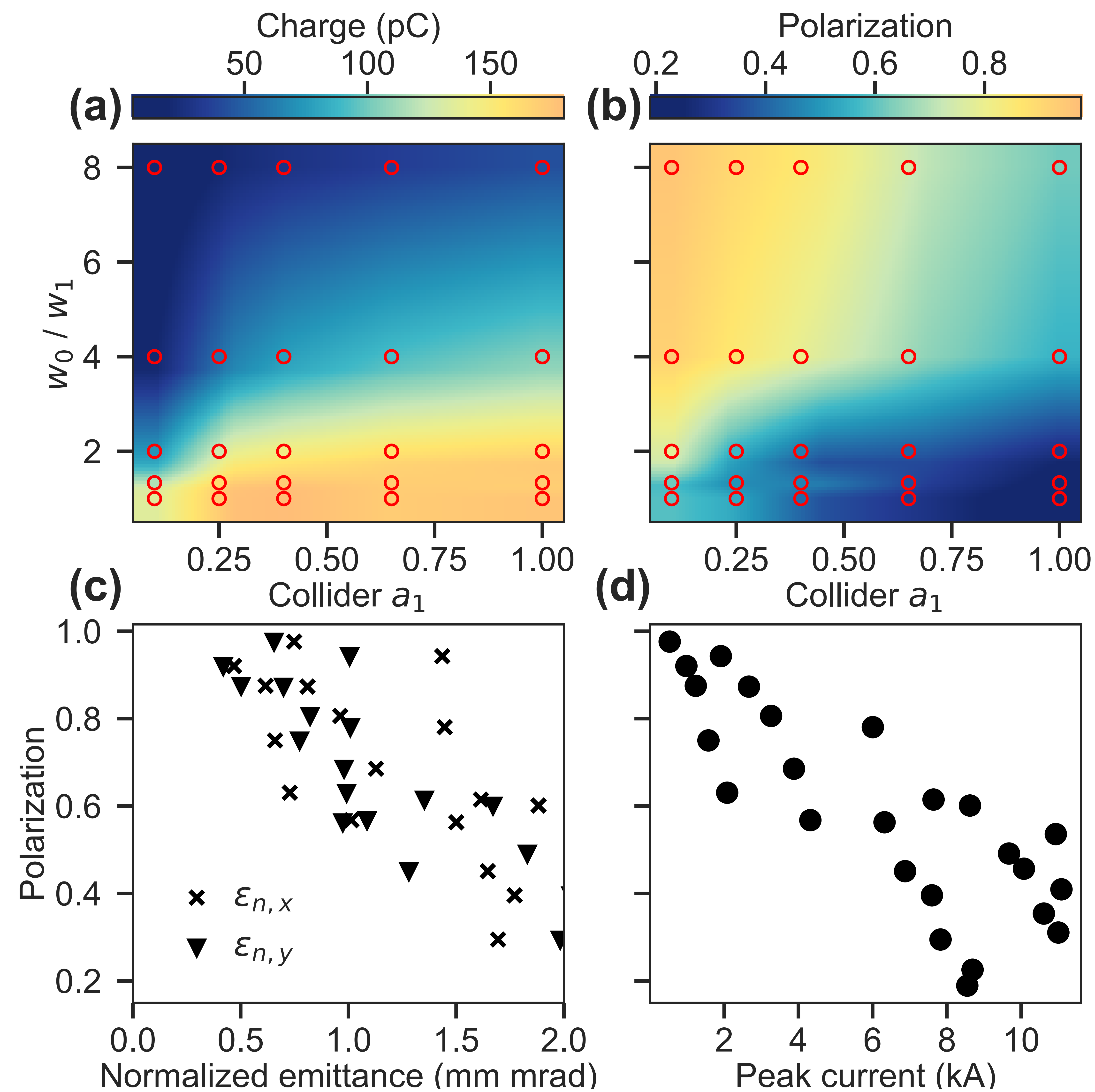
Colliding pulse injection creates high-current polarised beams

Control over the driver and collider laser enables balancing charge and polarisation degree



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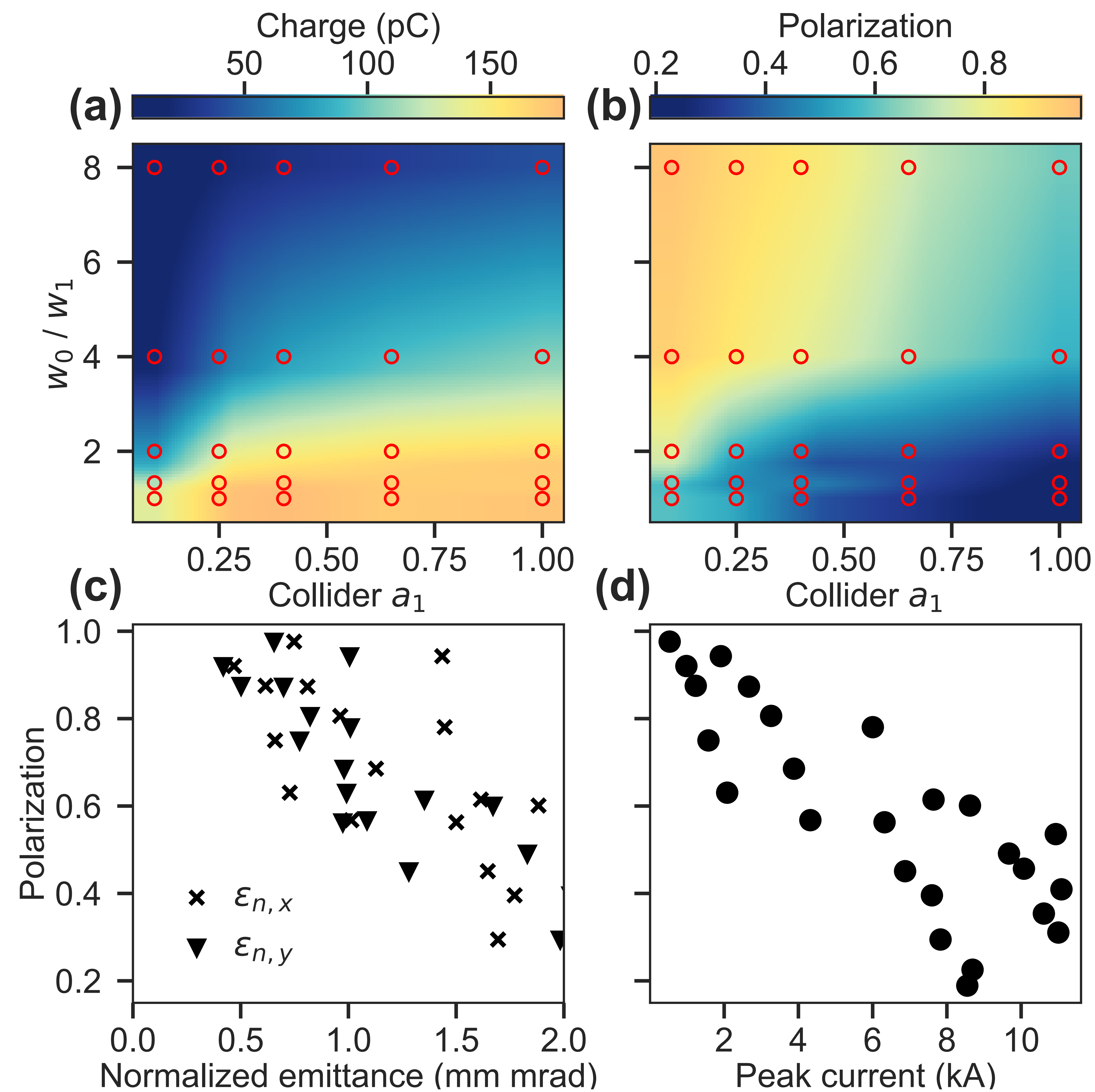

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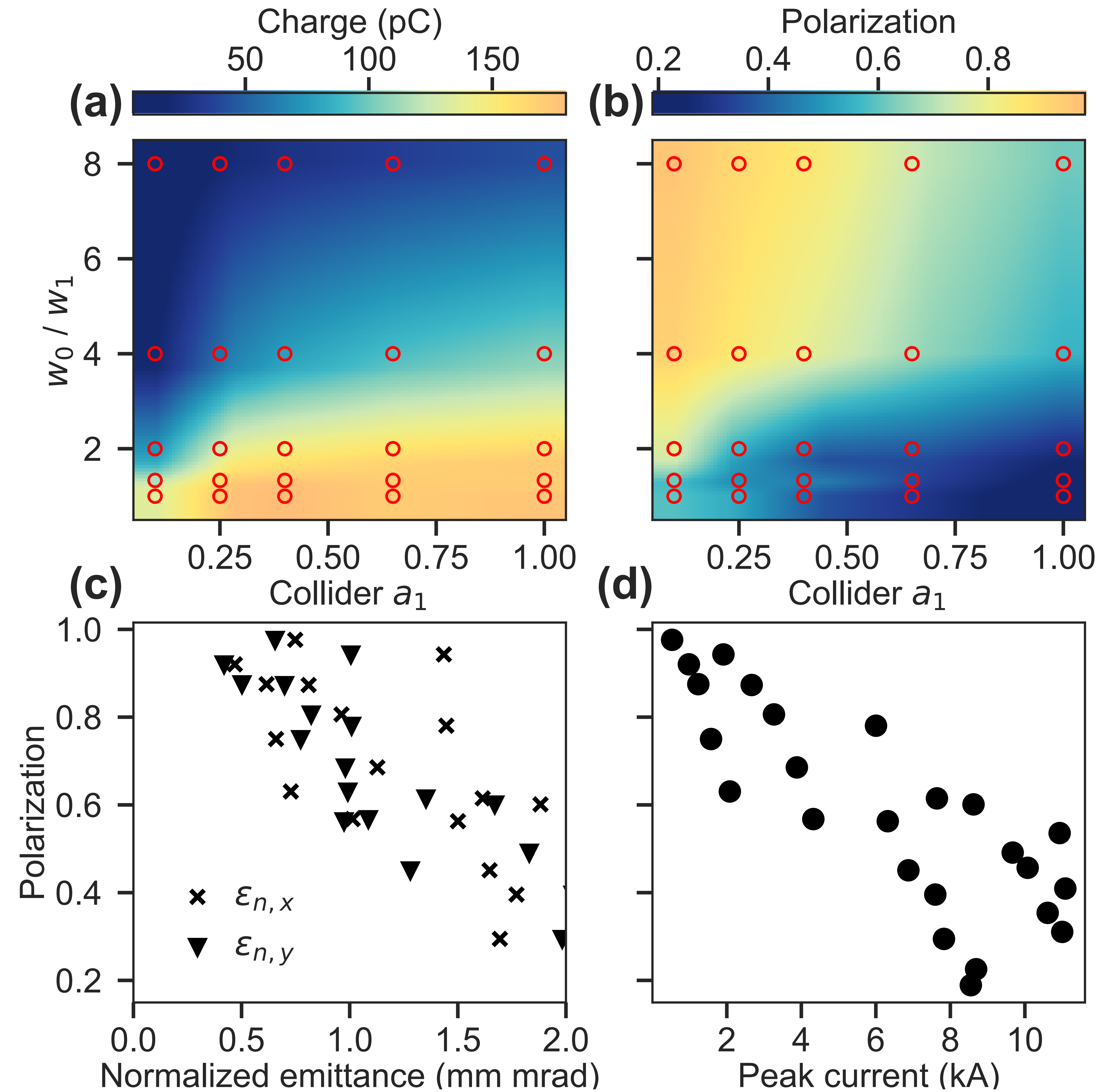

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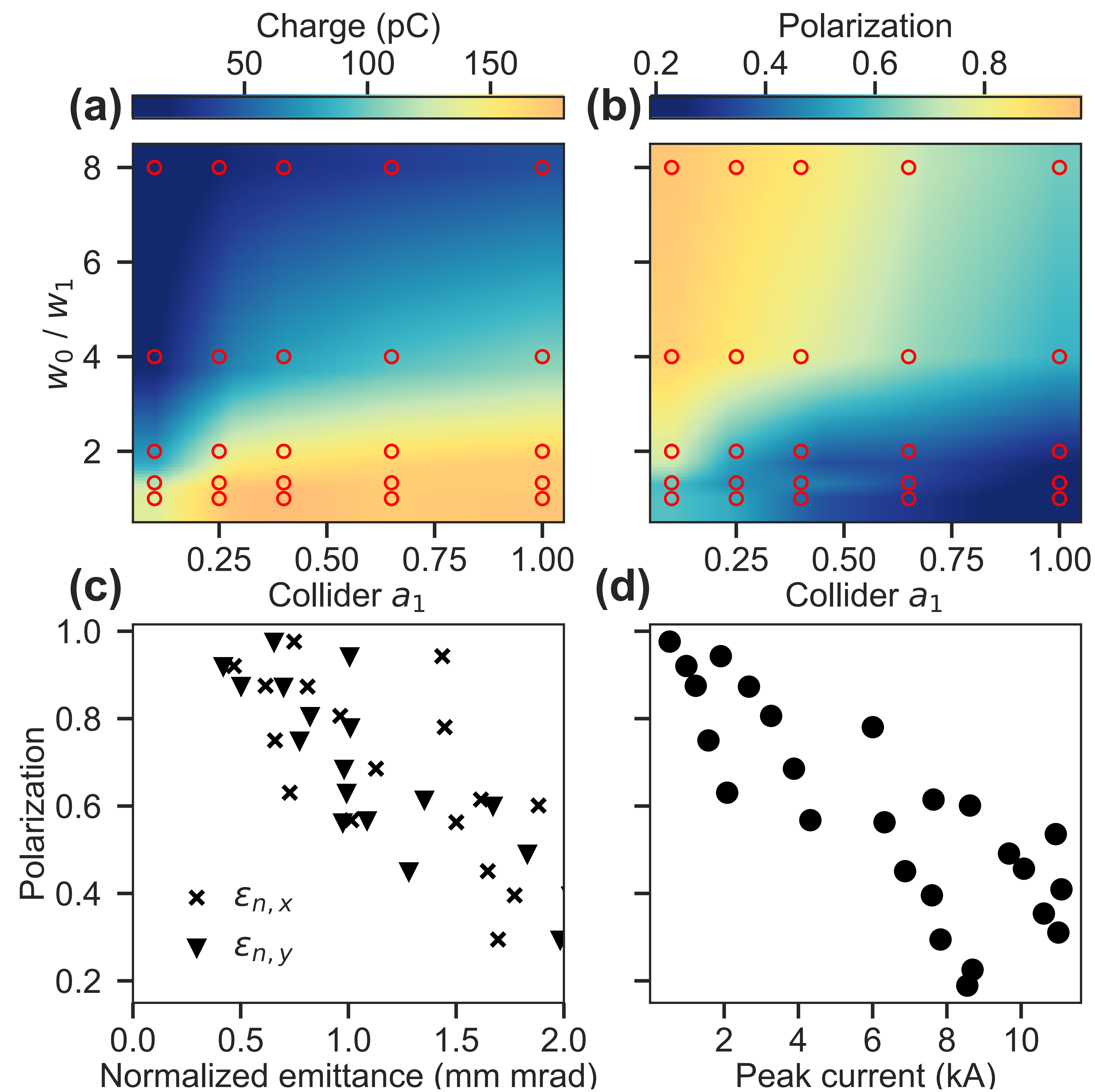

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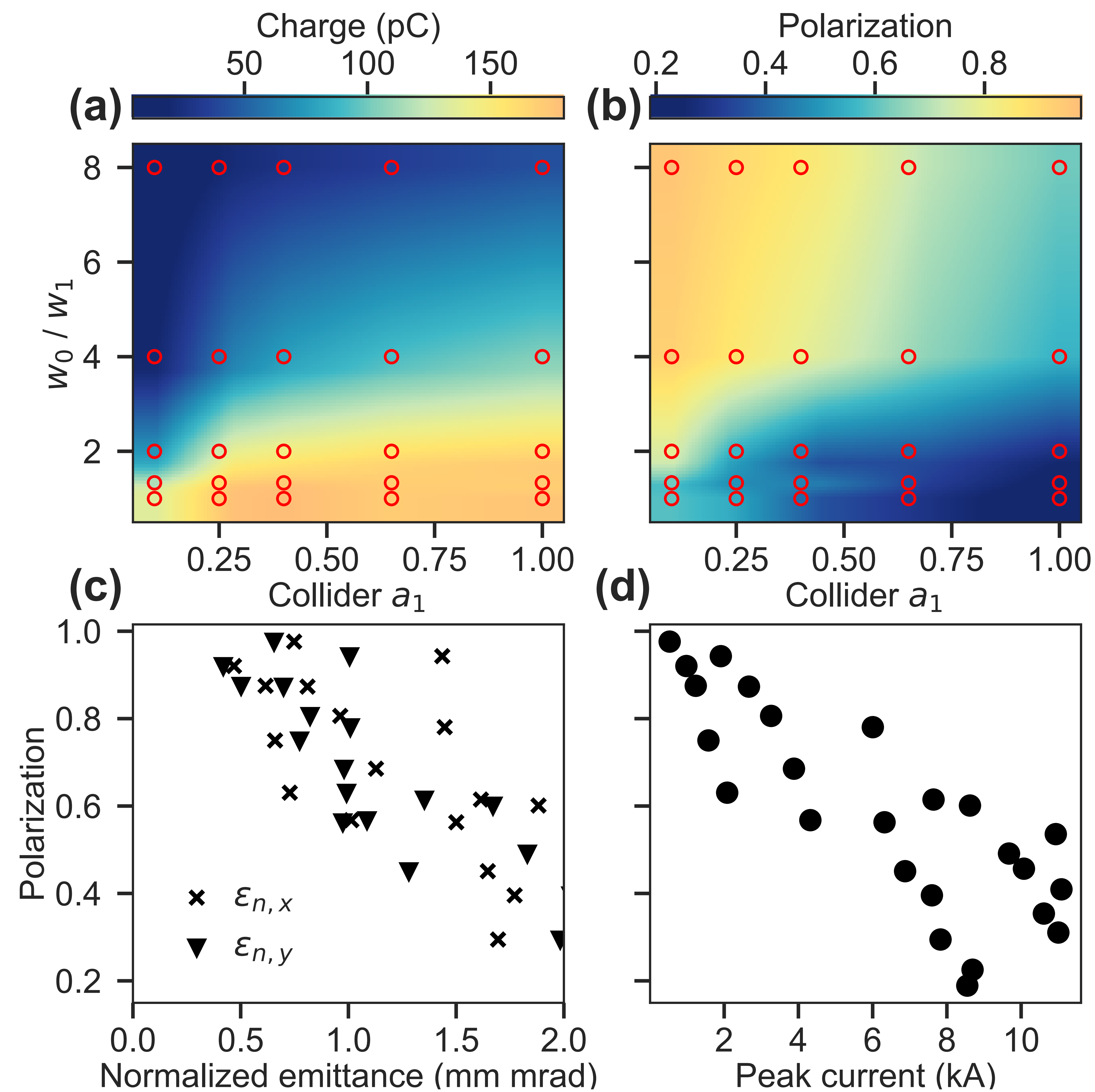

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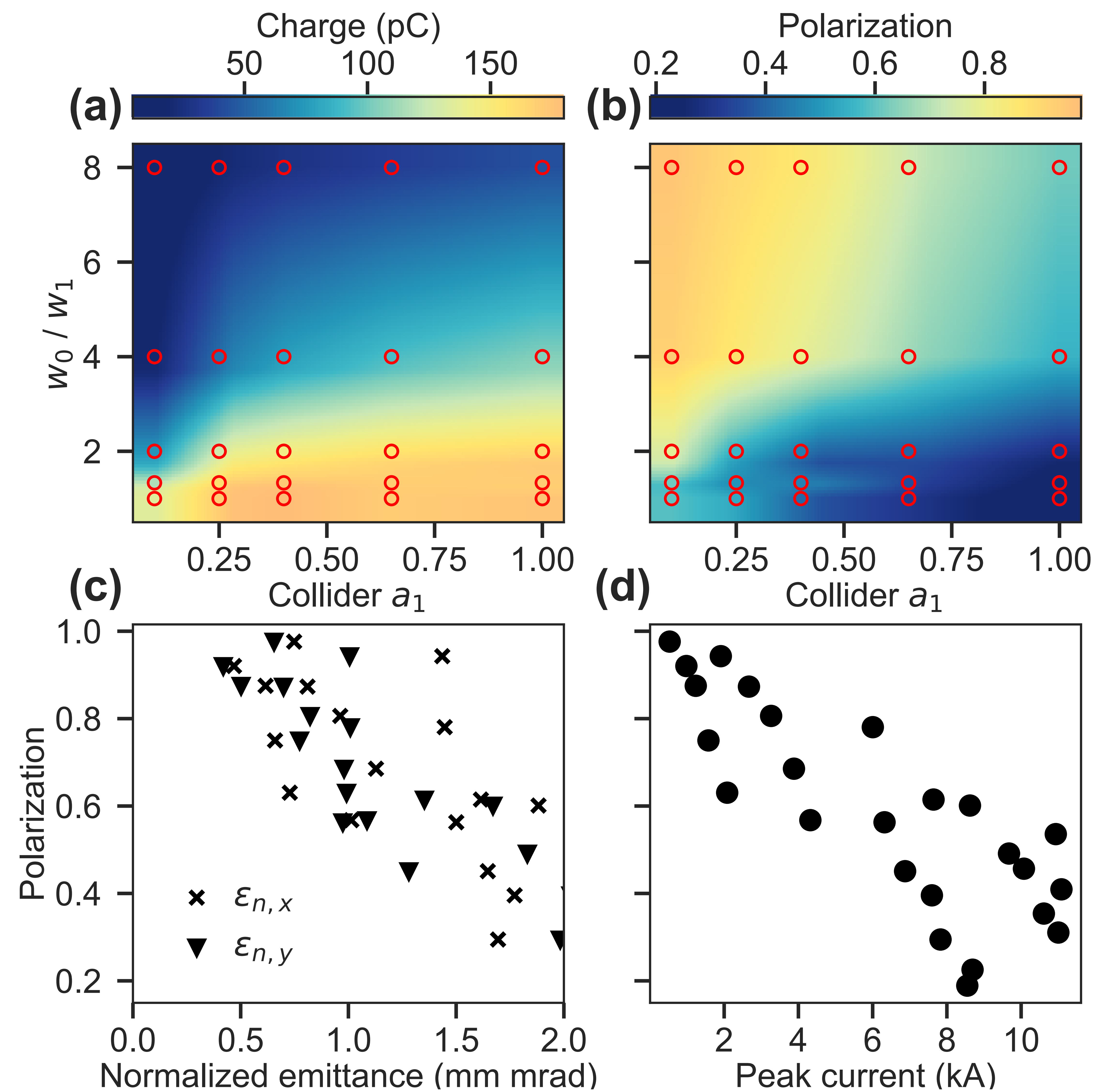
  - 6kA with 80% polarisation
- Charge and polarisation interdependent
  - Extra charge injected with lowered polarisation



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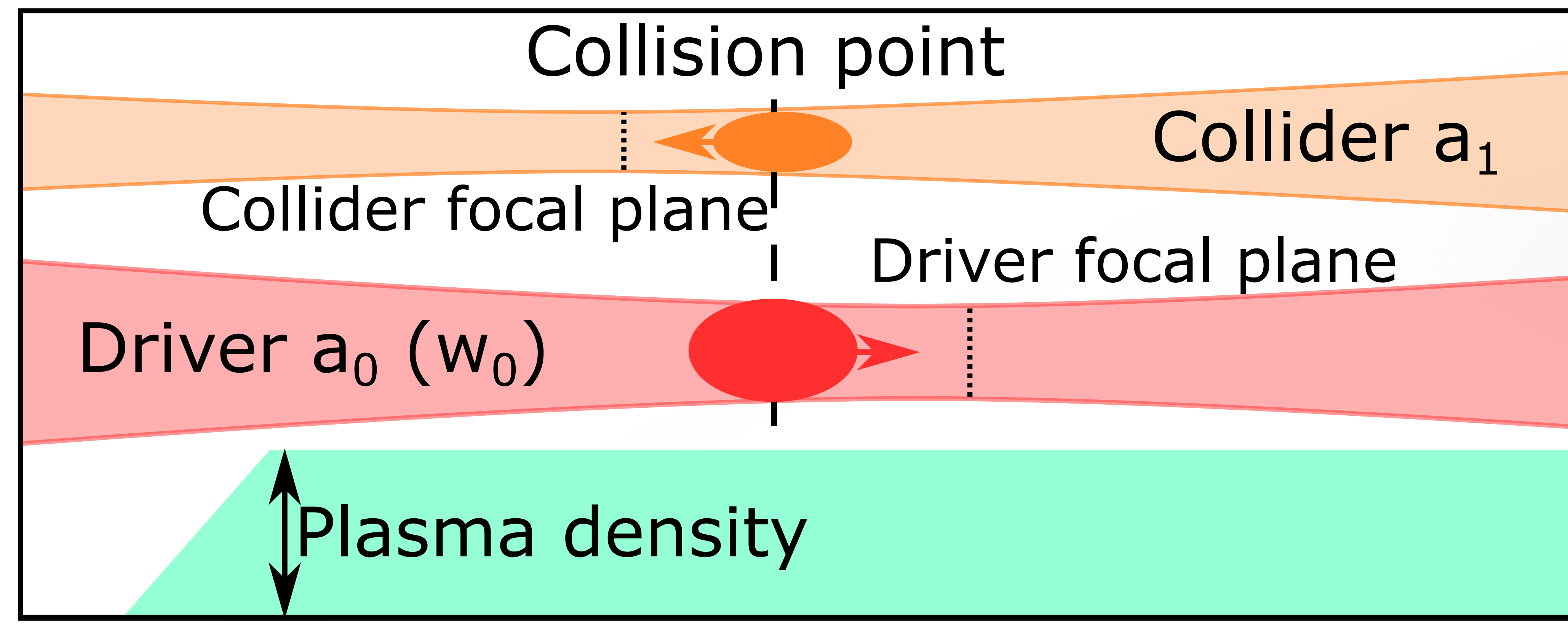
Colliding pulse scheme is highly optimisable

High amount of easily controllable degrees of freedom enable precision tuning and optimisation

- Using OPTIMAS[1] library for Bayesian Optimisation, varying
  - Collider a_1
  - Driver a_0/w_0 with fixed P=100 TW
  - Focal plane of the lasers
  - Collision point in plasma
  - Plasma density



[1] A. F. Pousa et al, PRAB **26**, 084601 (2023)

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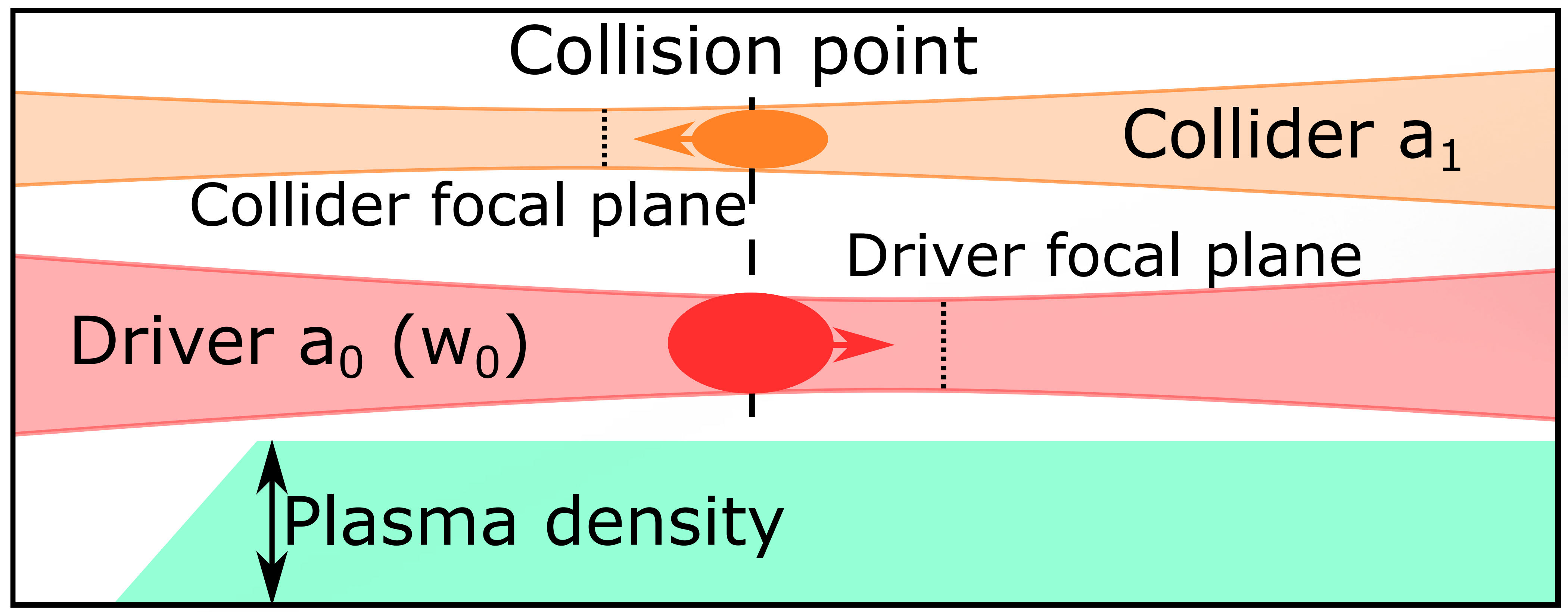

$$f = -\frac{\sqrt{QE_m}}{\Delta E(1-P)}$$

(1) A. F. Pousa et al, PRAB **26**, 084601 (2023)

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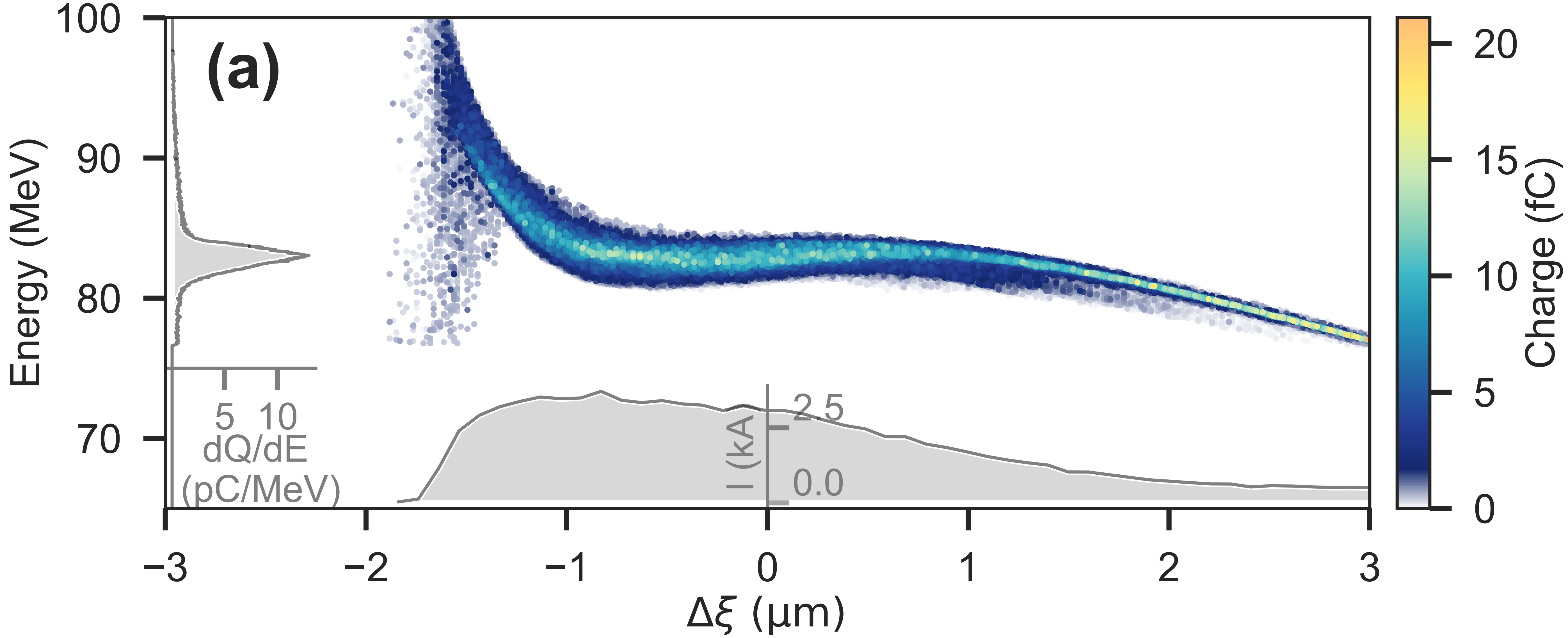

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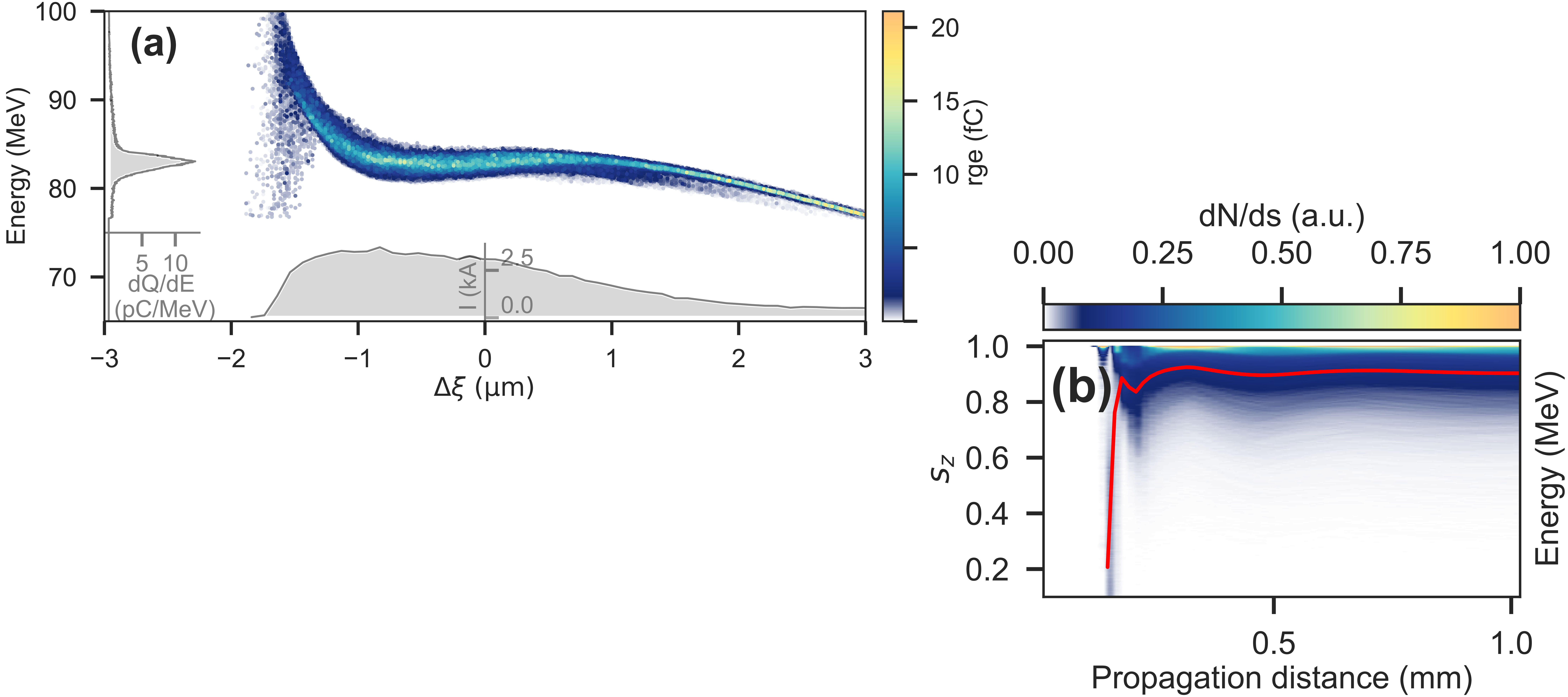

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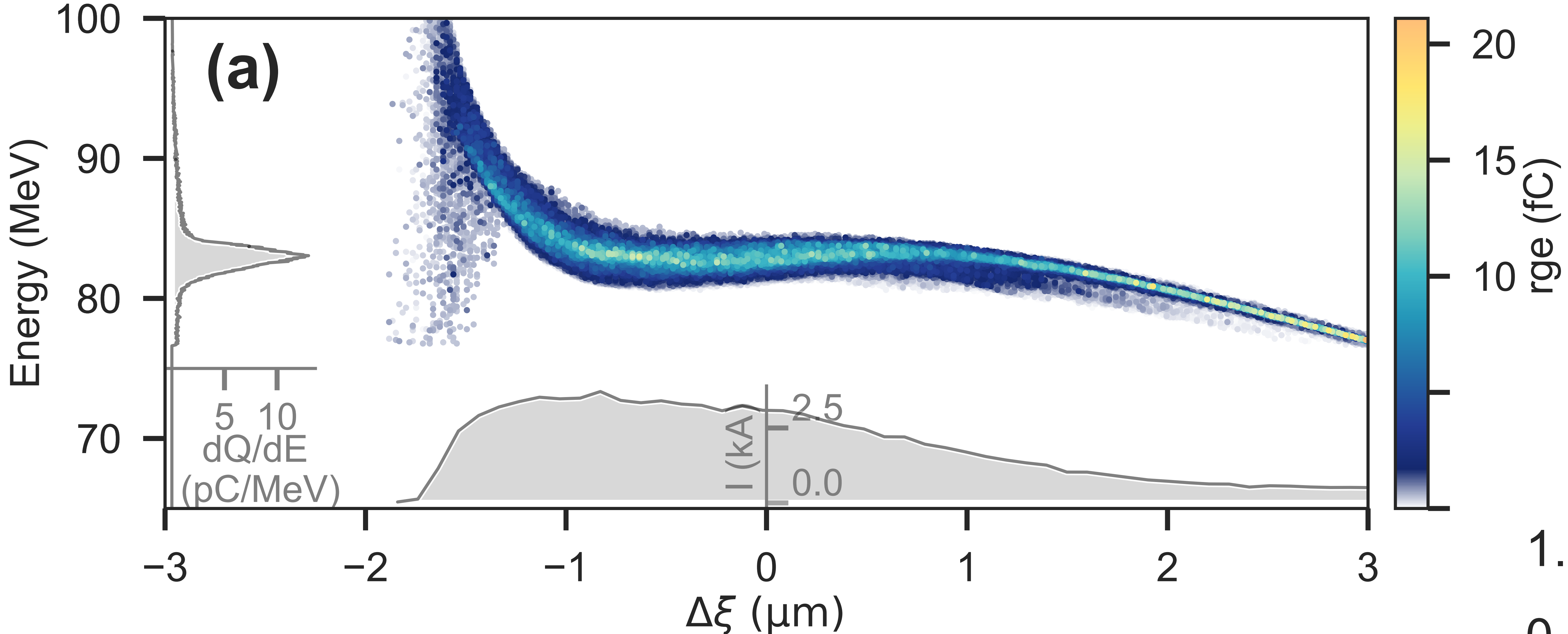
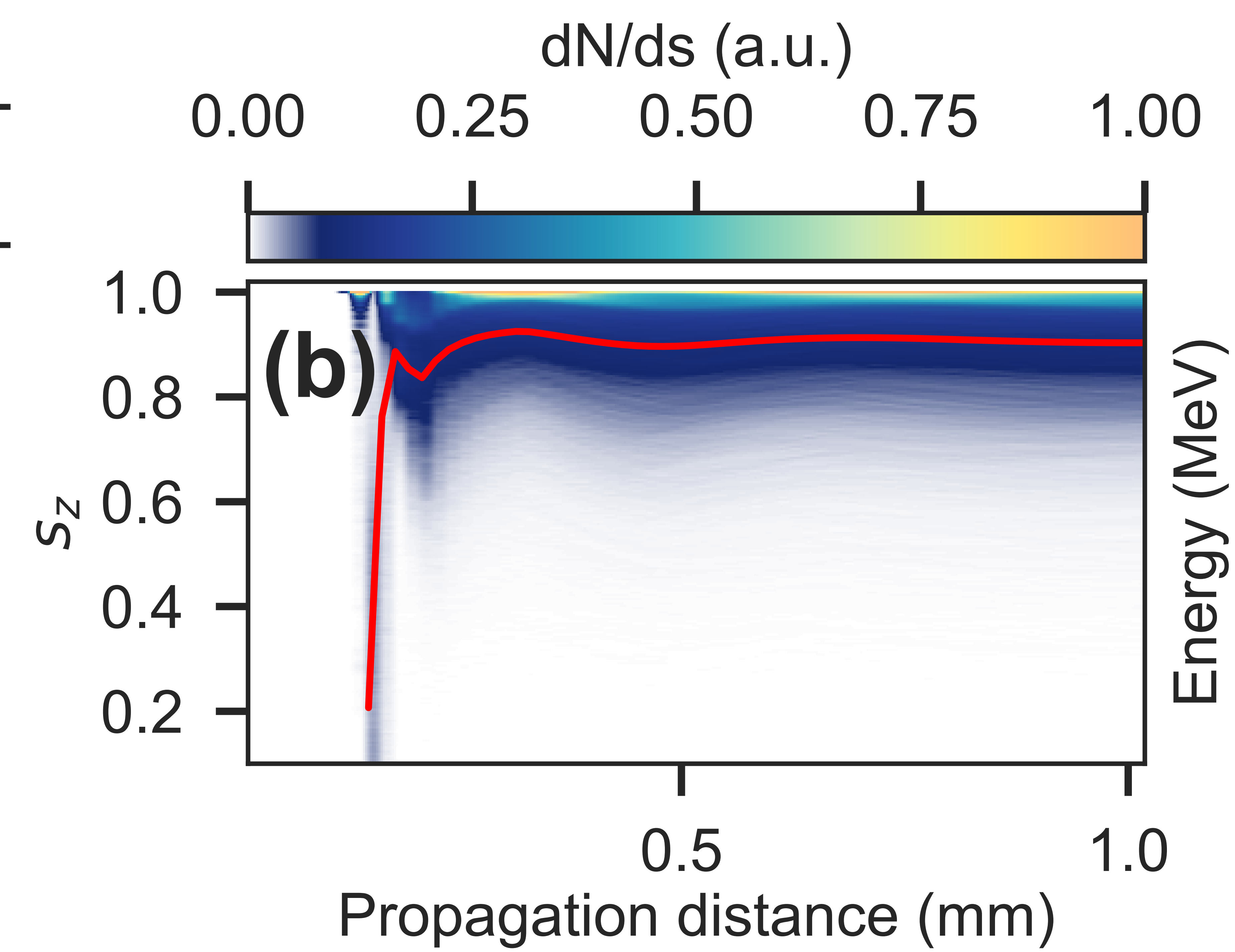




Beam parameter	Value	Unit
Mean energy	85.2	MeV
Energy spread (rms)	4.4	%
Peak current	3.6	kA
Bunch duration (rms)	3.8	fs
Charge	31.8	pC
Normalized emittance, *x* plane	0.90	mm mrad
Normalized emittance, *y* plane	0.84	mm mrad
Spin polarization	0.90	

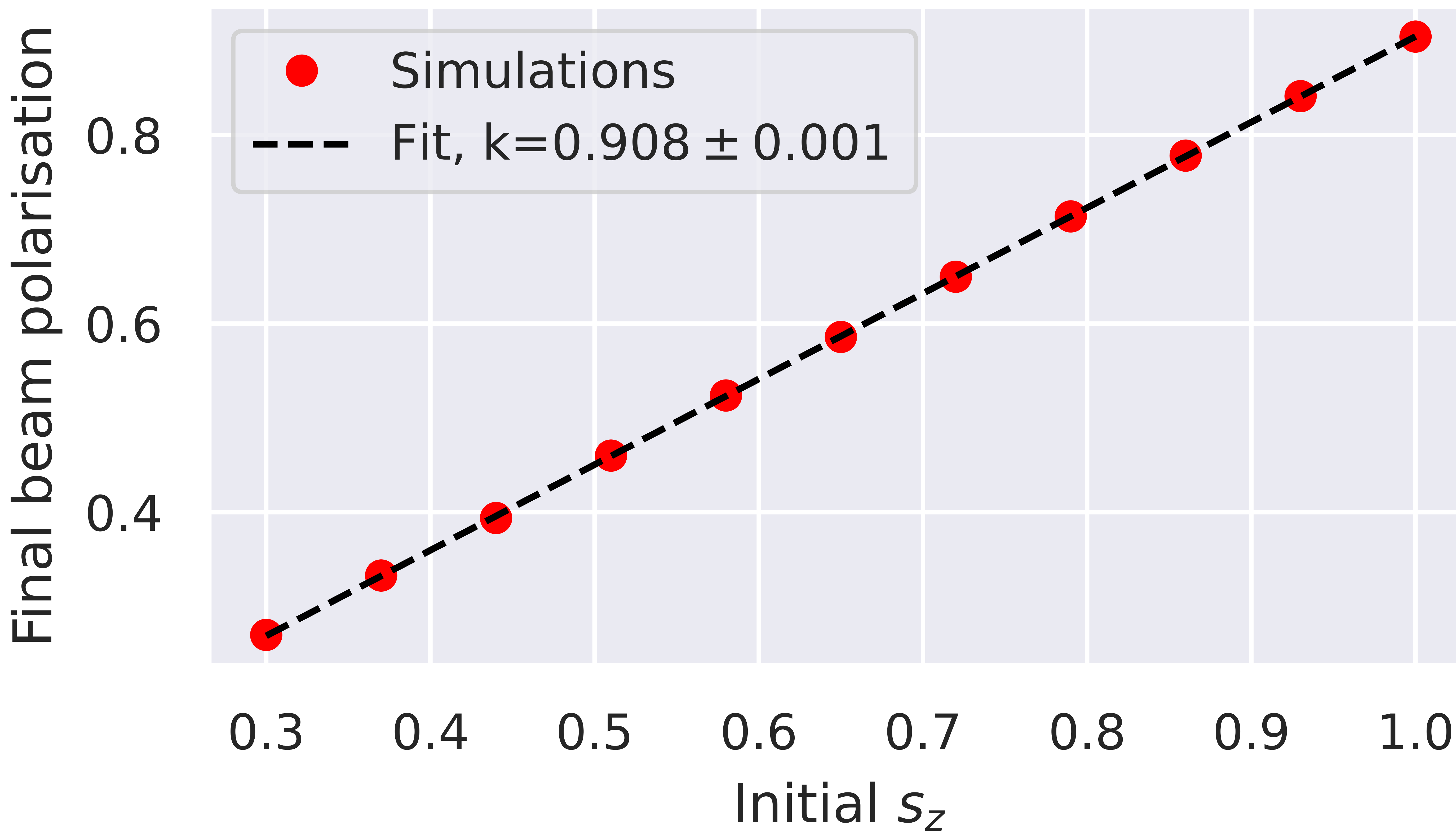
Bohlen *et al*, Phys Rev Research *in press*

Optimised depolarisation enables first demonstrations

Isn’t 100% pre-polarisation a little too optimistic?

Optimised depolarisation enables first demonstrations

Lowered pre-polarisation simply leads to lower final polarisation



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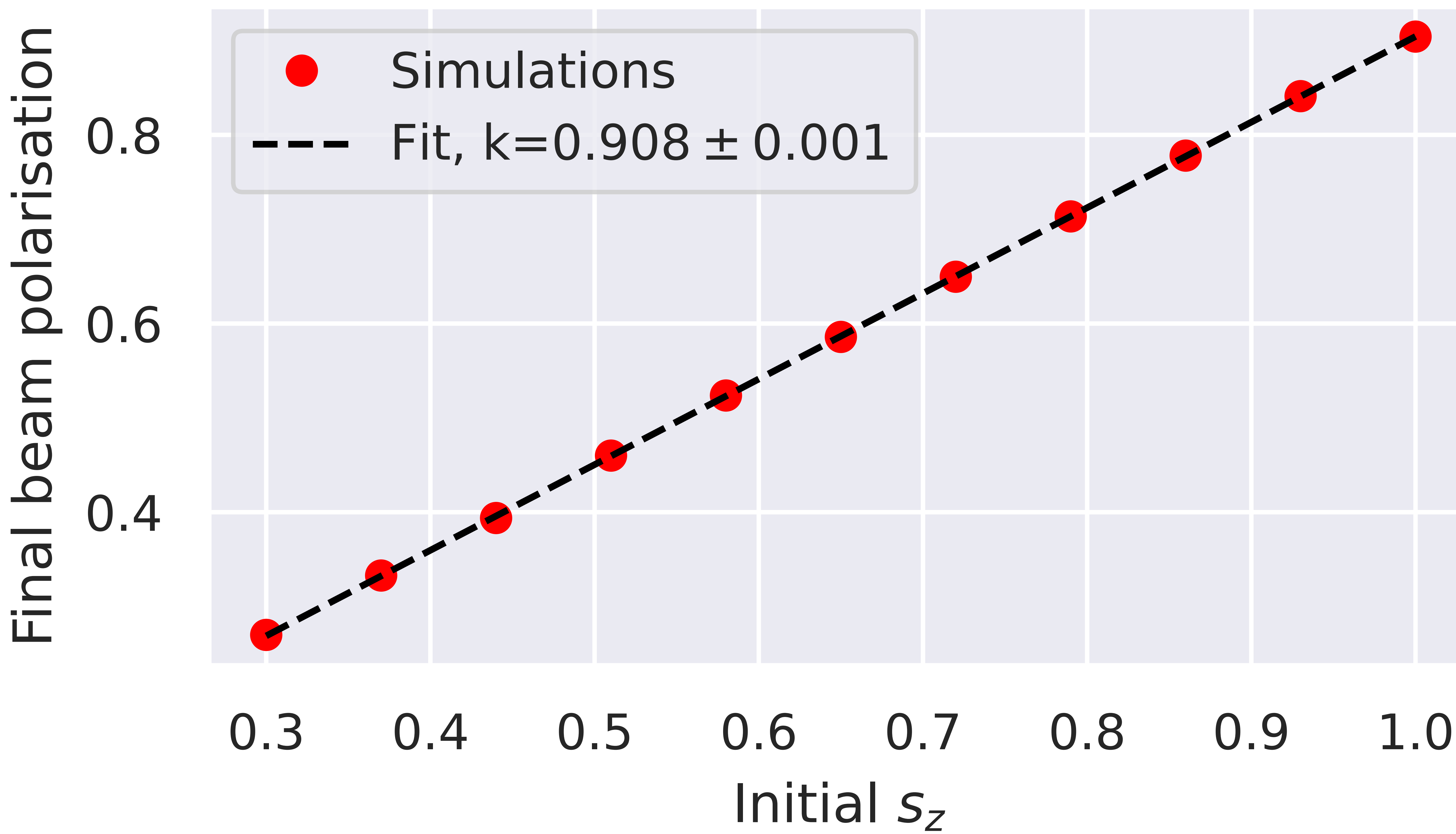

Enables first demo experiments with lower initial pre-polarisation giving detectable polarisation!

Colliding pulse injection for high-quality polarised beams

Realistic pathway to polarised laser-plasma accelerators

- LPA-based polarised electron sources possible based on pre-polarisation technique
- Colliding pulse injection enables
  - High overall polarisation
  - High-quality beam generation
  - Wide tunability and many tuning knobs for optimisation
- The polarised colliding pulse scheme highly advantageous for near-term experiments!