Generation and acceleration of polarised electron bunches in plasma accelerators

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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!

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

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

Conventional spin polarised electron sources

Current work-horse methods in the field are limiting access to polarised beams

Sokolov-Ternov effect (1)

Electrons align spin opposite to B-field

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

Used at storage rings

Relaxation time ~hours

Polarised photocathodes (2)

Polarised atoms of the photocathode material

Guns used at many facilities

Limited peak current

Spin rotators (3)

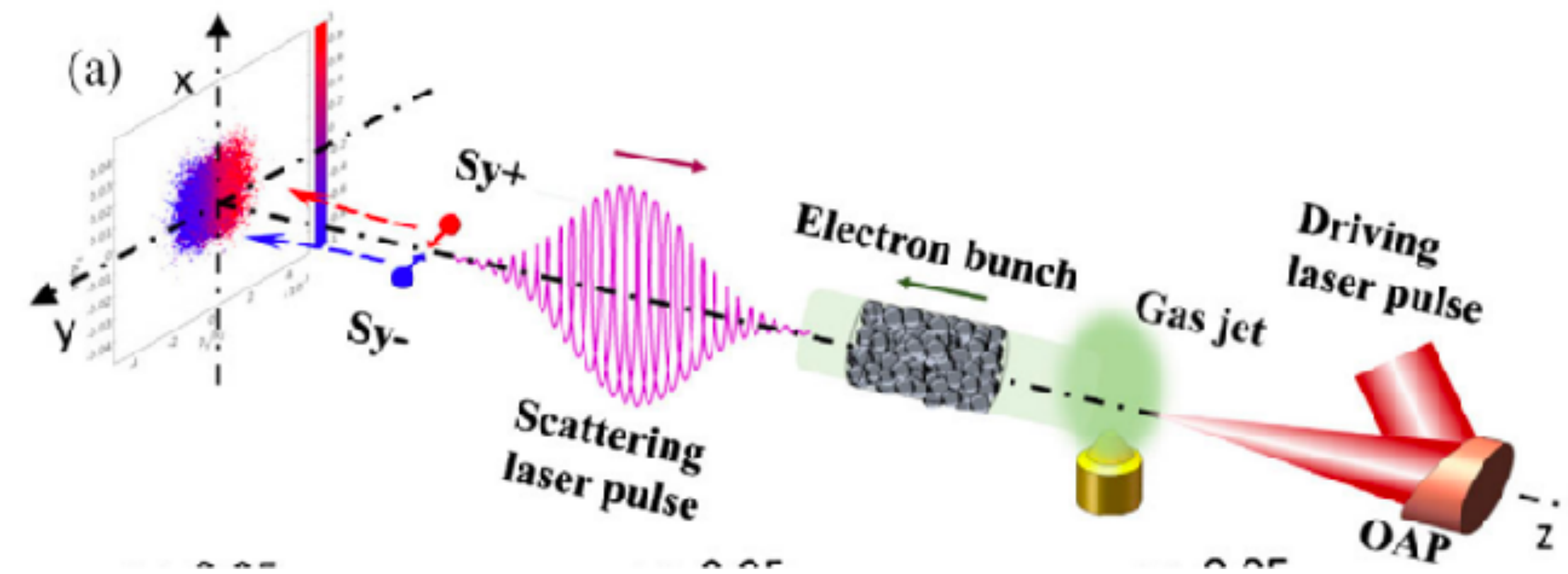
Rotate spin from longitudinal to transverse

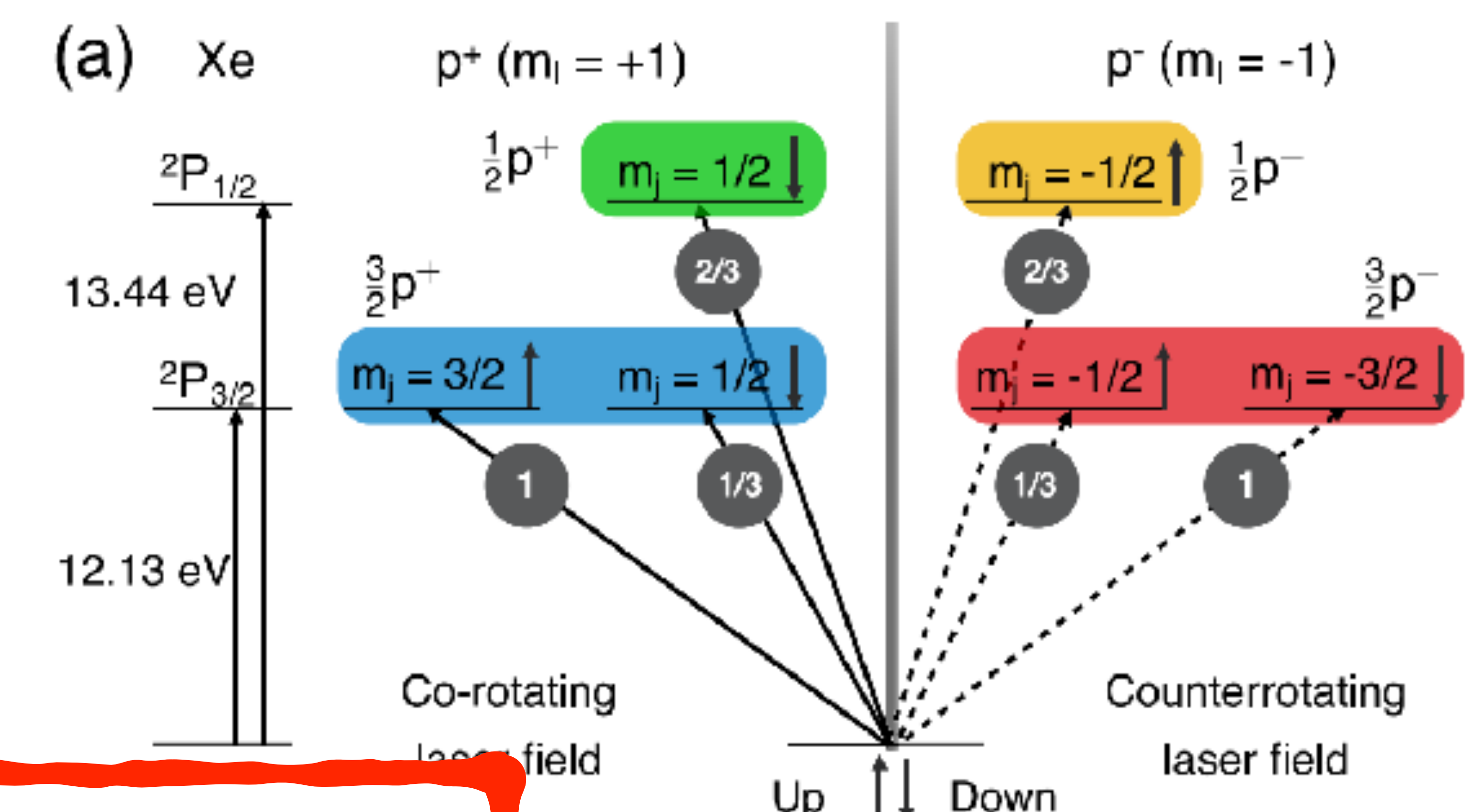
(1) Sokolov and I.M. Ternov, Sov. Phys. J. **10**, 39 (1967).
(2) Pierce et al, APL **26** 670 (1975)
(3) Moffeit et al, SLAC-TN-05-045

Alternative sources of spin polarised electron beams

Many novel ideas developed over the last years

- 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)
- **Plasma-based methods**
  - Selective multi-photon ionisation (5)
  - Pre-polarised plasma sources (6-11)





No experimental demonstrations yet!

(1) Dellweg & Müller, PRL **118** 070403 (2017)
(2) Batelaan et al, PRL **82** pp4216 (1999)
(3) Li et al, PRL **122** 154801 (2019)
(4) Del Srobo et al, PRA **96** 043407 (2017)
(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)
(10) Fan et al, New J Phys. **22** 083047 (2022)
(11) Sun et al, PRL **132** 045001 (2024)

Spin dynamics in (L)PAs

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

Spin precession

Sokolov-Ternov Effect

Stern-Gerlach force

Spin dynamics in (L)PAs

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

Spin precession

Thomas-Bargmann-Michel-Telegdi equation

$$\frac{\mathrm{d}\mathbf{s}}{\mathrm{d}t} = (\boldsymbol{\Omega}_\mathbf{T} + \boldsymbol{\Omega}_\mathbf{a}) \times \mathbf{s}$$

$$\boldsymbol{\Omega}_\mathbf{T} = \frac{e}{m}\left(\frac{1}{\gamma}\mathbf{B} - \frac{1}{1+\gamma}\frac{\mathbf{v}}{c^2} \times \mathbf{E}\right)$$

$$\boldsymbol{\Omega}_\mathbf{a} = a_e\frac{e}{m}\left(\mathbf{B} - \frac{1}{1+\gamma}\frac{\mathbf{v}}{c^2}\mathbf{v}\cdot\mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E}\right)$$

Sokolov-Ternov: timescale ~us

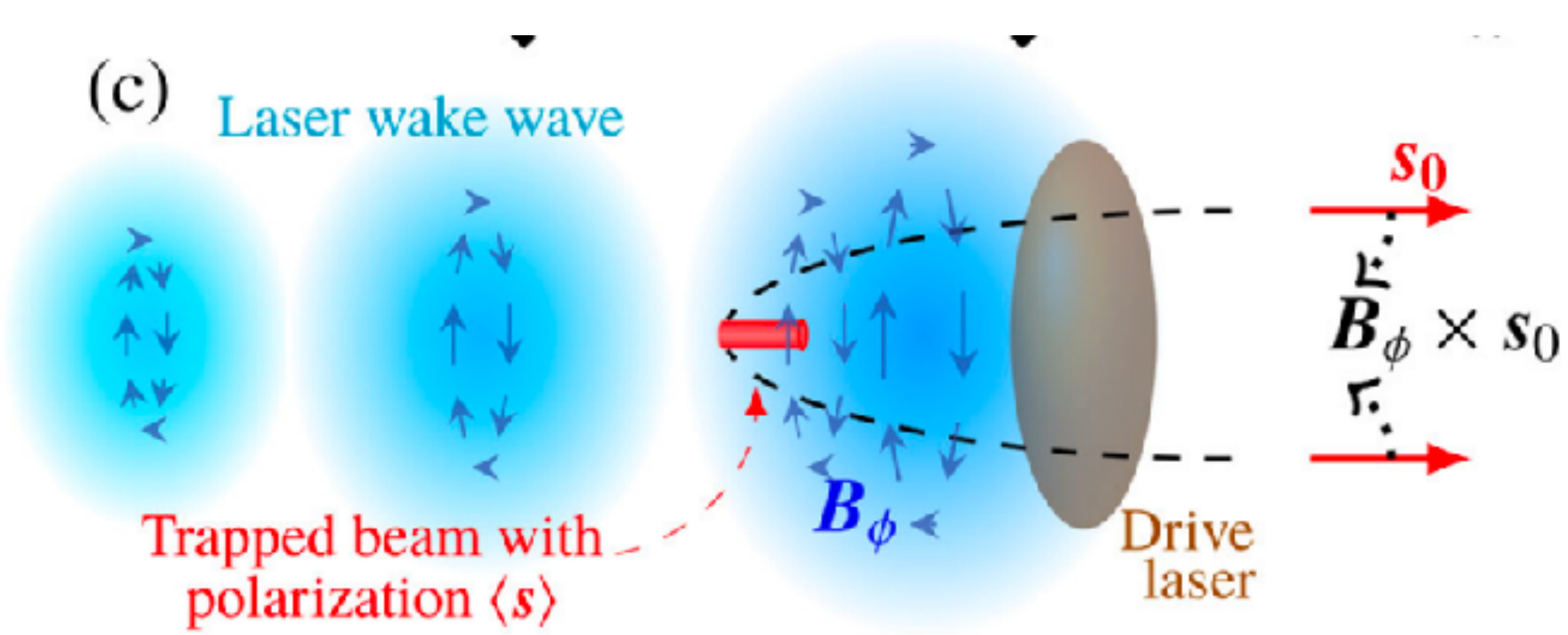
Stern-Gerlach << Lorentz

Wen *et al*, Phys Rev Lett **122**, 214801 (2019)

Spin dynamics in (L)PAs

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

- High gamma -> little precession!
  - Delicate during injection
- **B** x **s** term: azimuthal B-fields problematic
  - Stay close to axis
- Strong **E** fields lead to precession
  - But all electrons together, so P stays high



Wen *et al*, Phys Rev Lett **122**, 214801 (2019)

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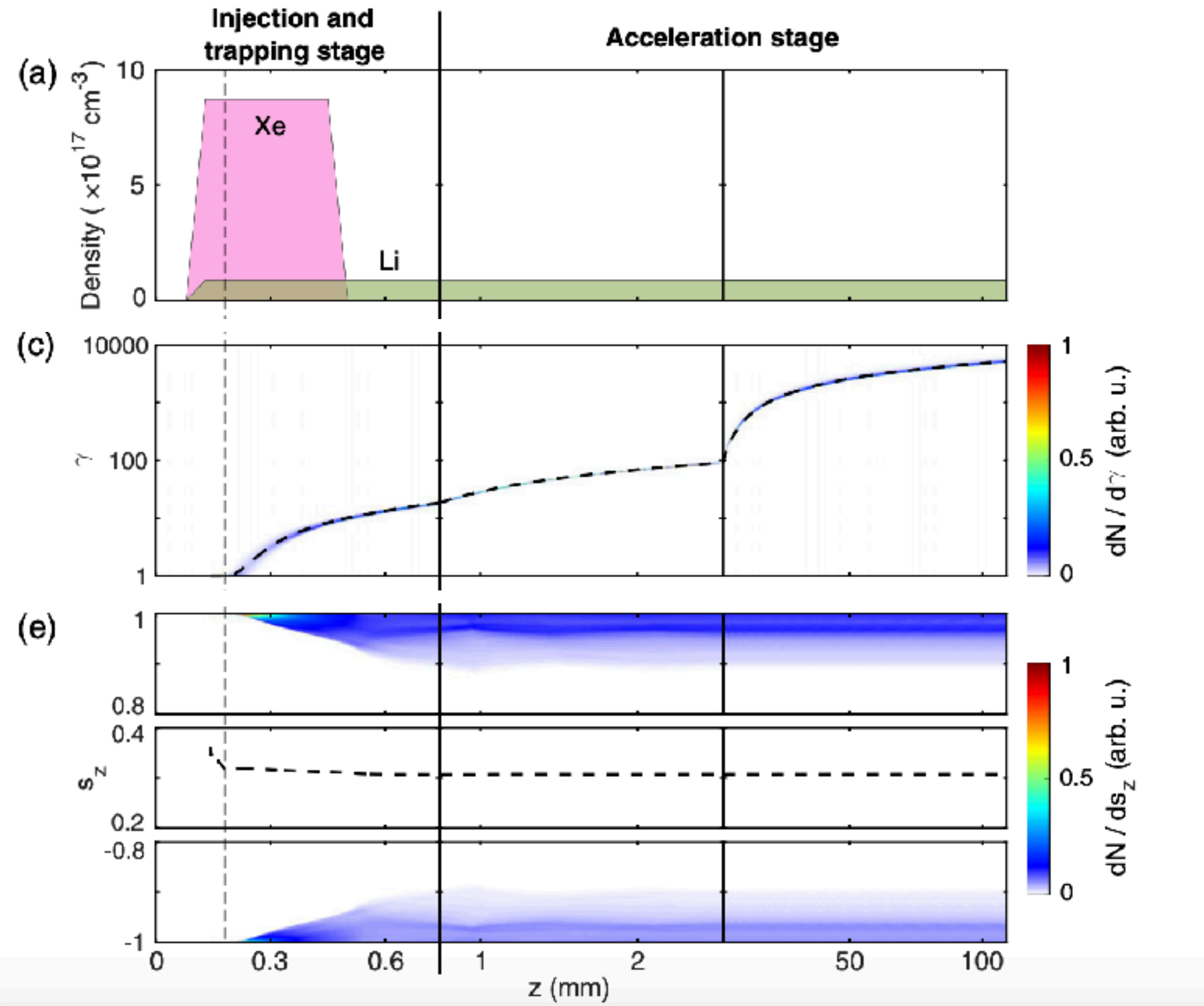
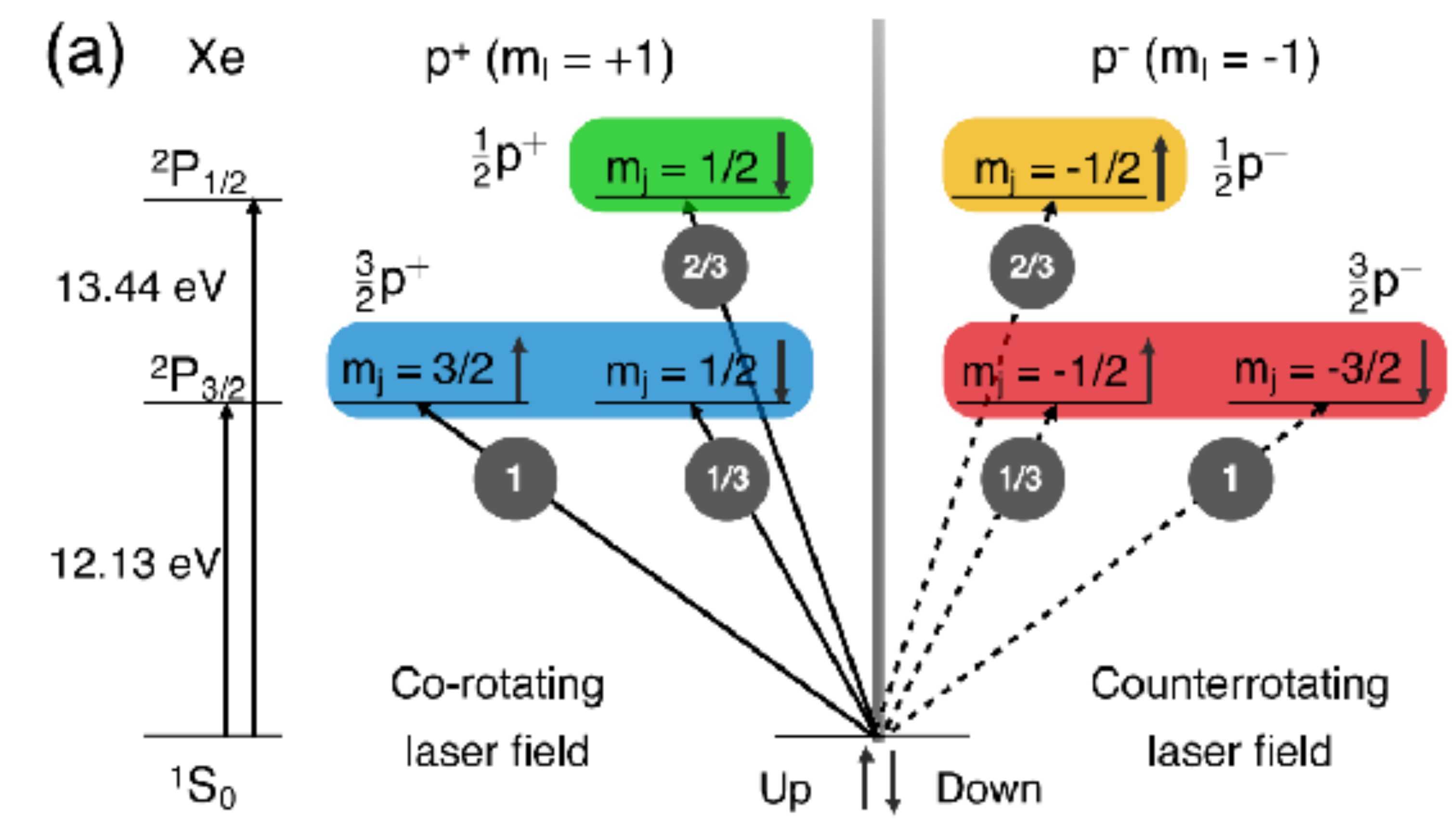
Sokolov-Ternov: timescale ~us
Stern-Gerlach << Lorentz

Selective ionisation with beam driver

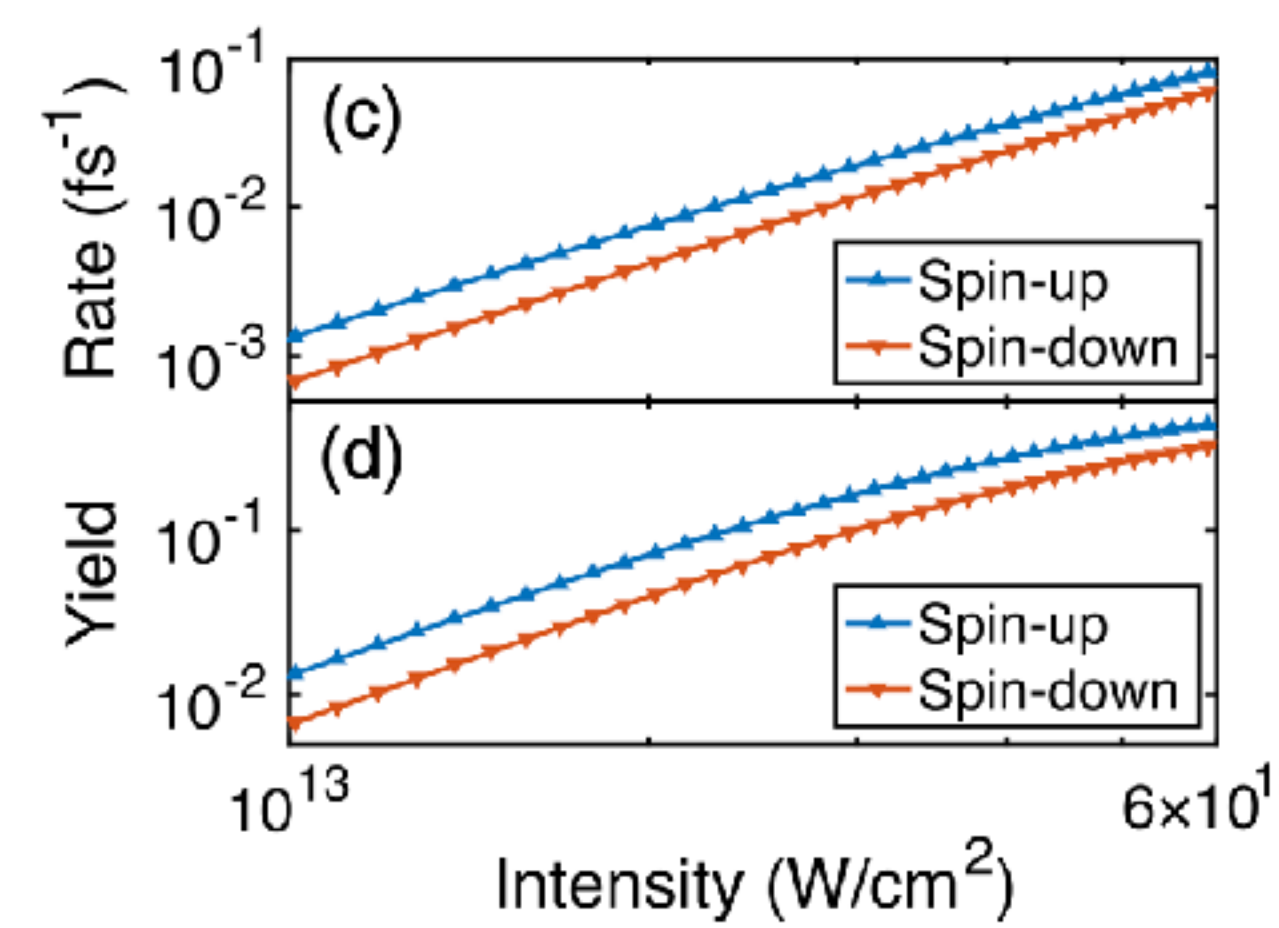
Multi-photon ionisation allows extracting spin-polarised electrons from a gas



2.7 GeV, 3pC, 37nm in 11cm
P=30.7%



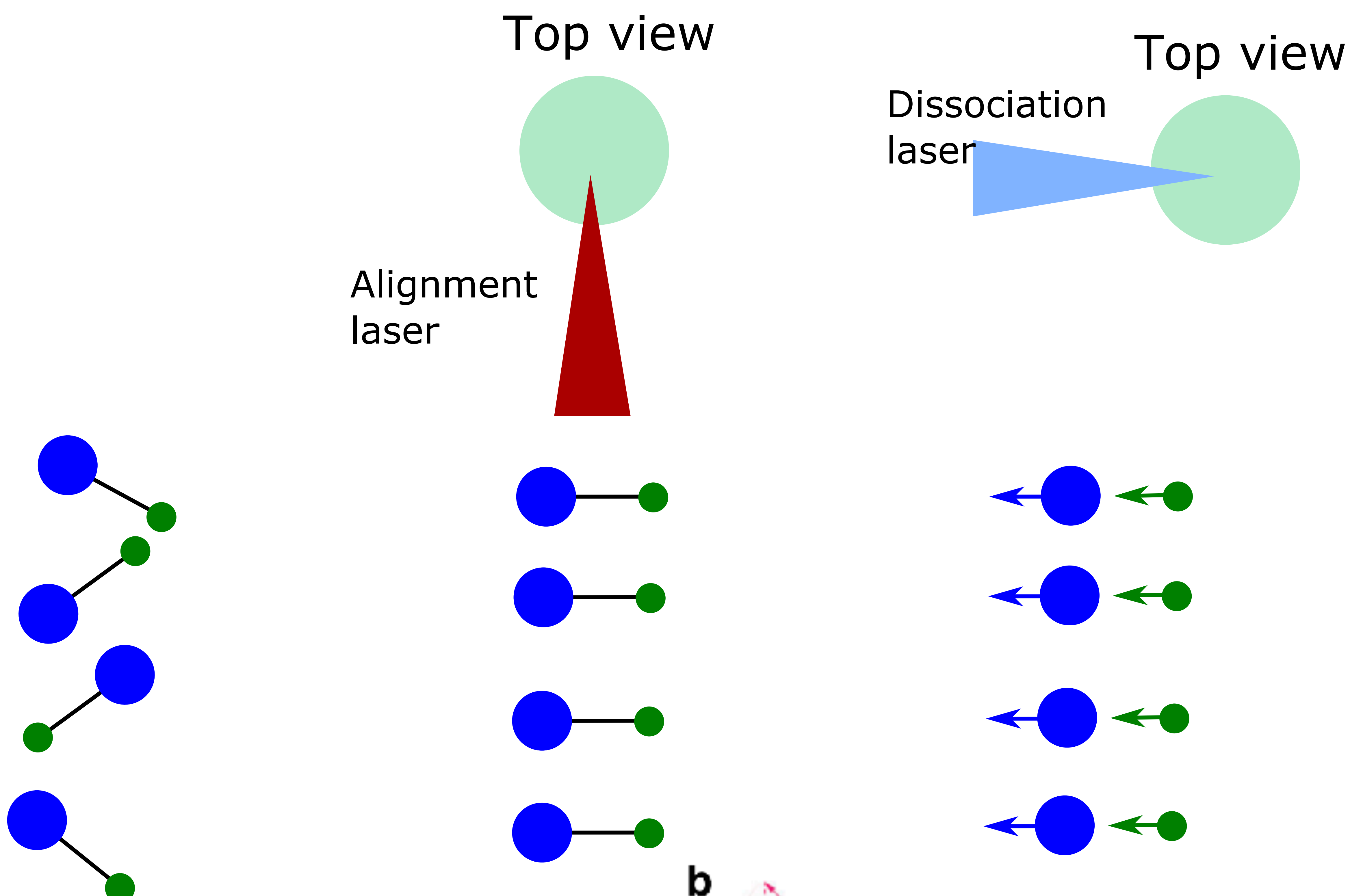
260 nm, 30 fs, CP, I=2.5e13 W/cm², w_0=1.5 um

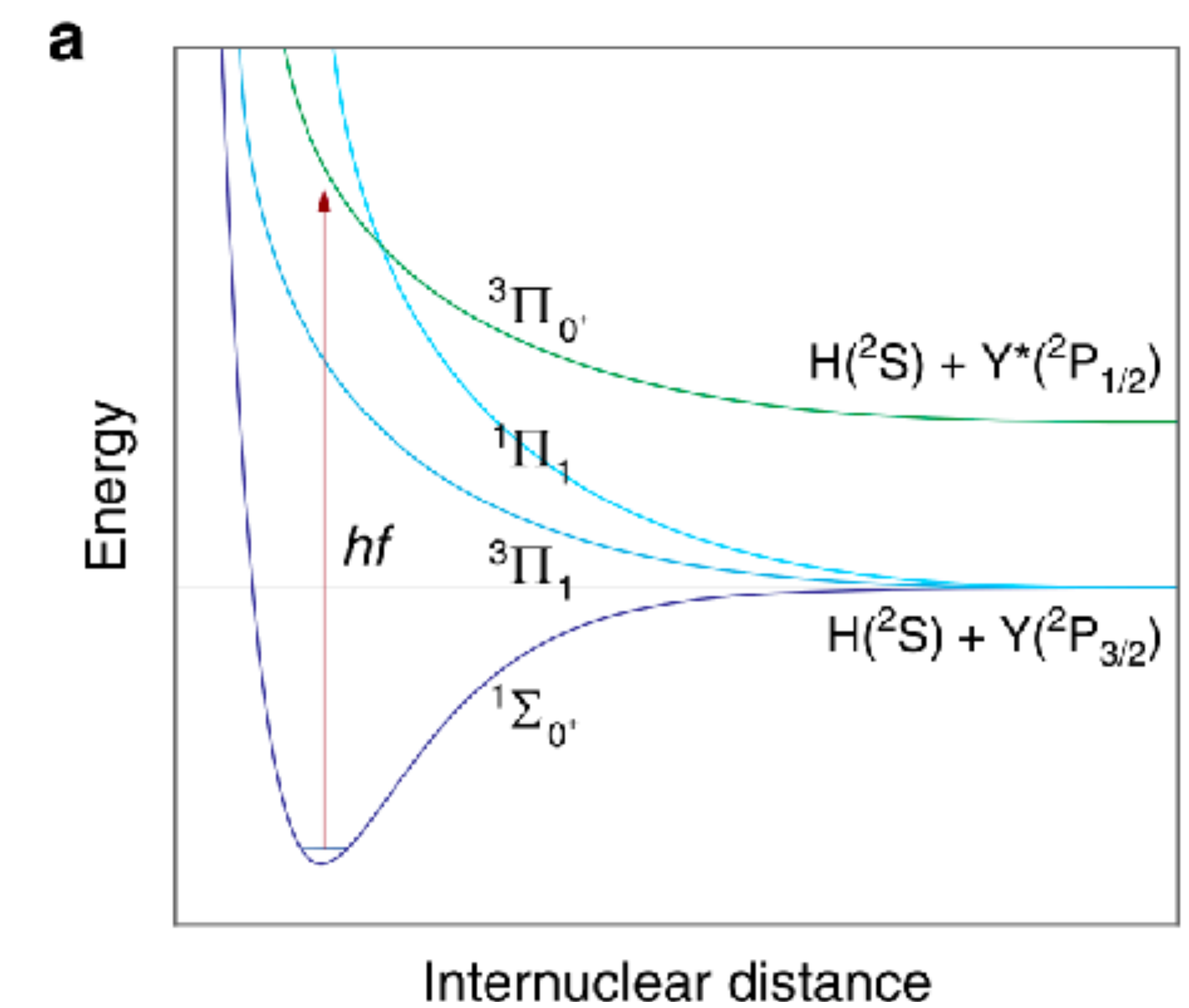


(5) Nie et al, PRL **126** 054801 (2021)

Pre-polarised plasma sources enable polarised beams

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

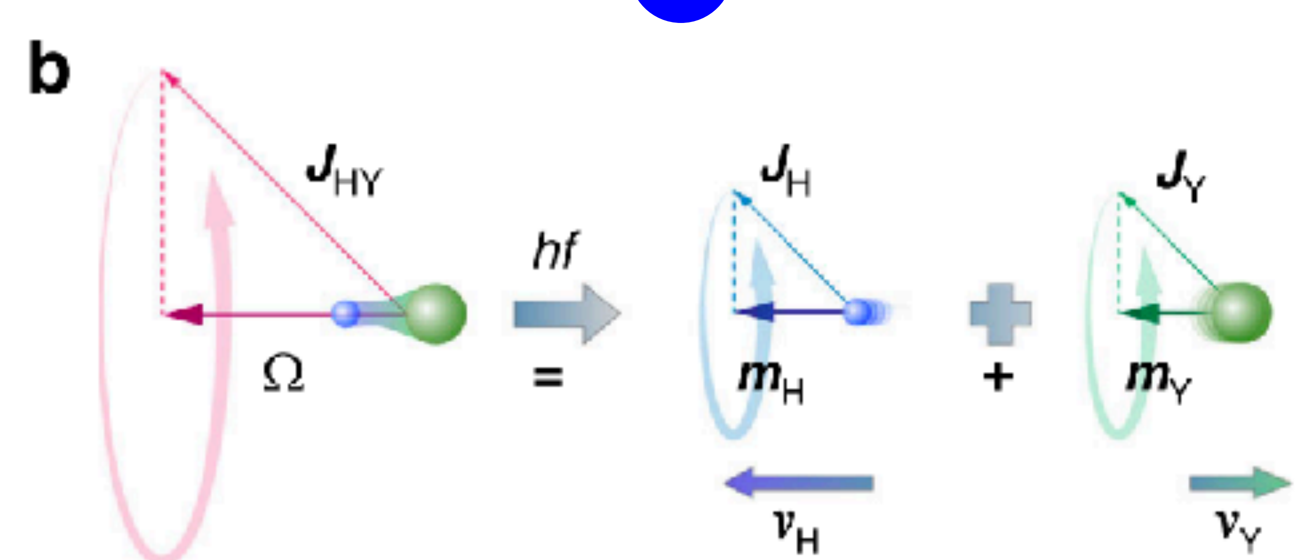




$$\mathrm{HY}(A^1\textstyle\prod_1;\ \Omega=\pm 1)\rightarrow \mathrm{H}(\mathrm{m_H}=\mp 1/2) + \mathrm{Y}(\mathrm{m_Y}=\pm 3/2) \quad (2)$$

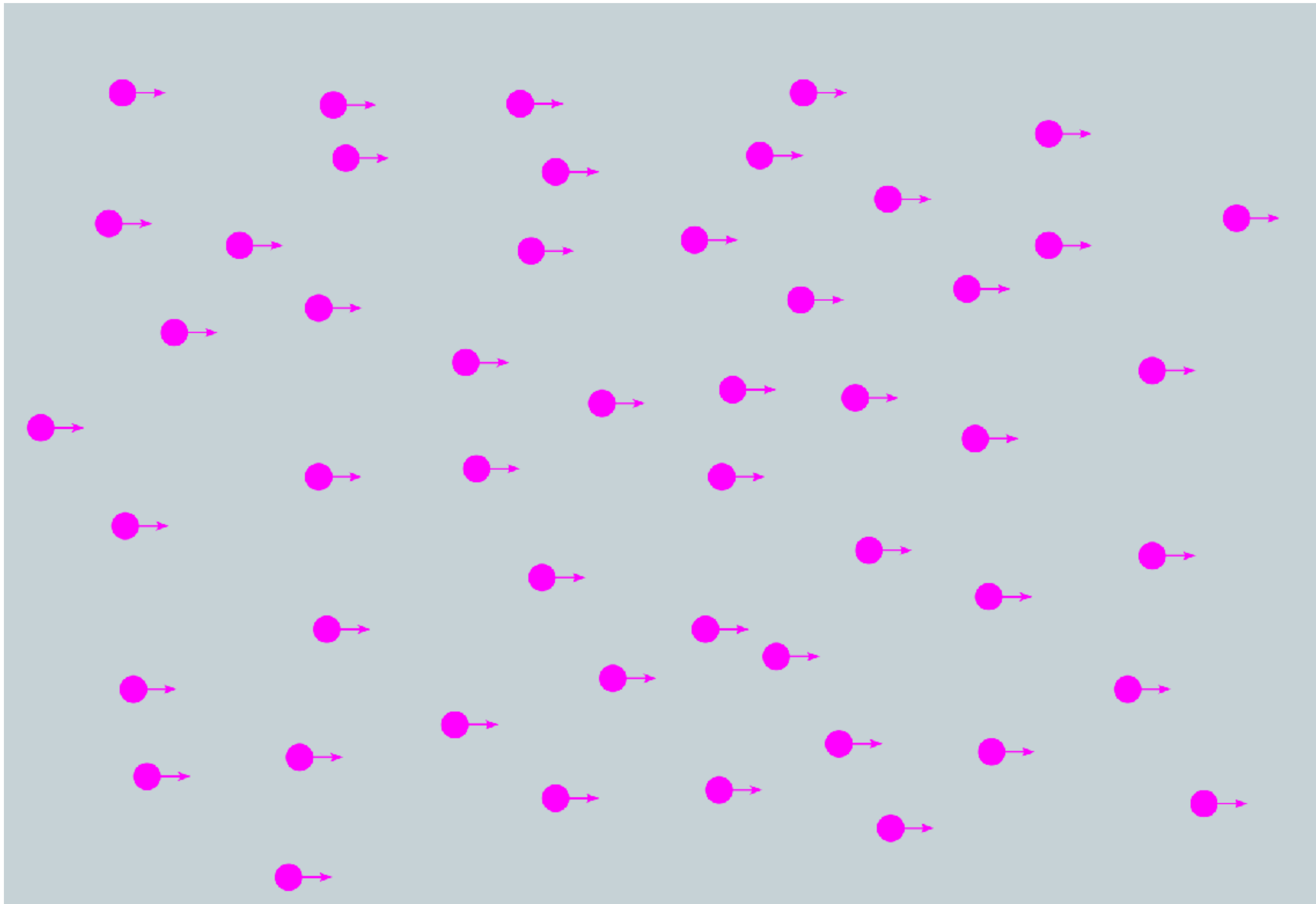
$$\mathrm{HY}(a^3\textstyle\prod_1;\ \Omega=\pm 1)\rightarrow \mathrm{H}(\mathrm{m_H}=\pm 1/2) + \mathrm{Y}(\mathrm{m_Y}=\pm 1/2) \quad (3)$$

$$\mathrm{HY}(a^3\textstyle\prod_{0+};\ \Omega=0)\rightarrow \mathrm{H}(\mathrm{m_H}=\pm 1/2) + Y^*(\mathrm{m_{Y^*}}=\mp 1/2) \quad (4)$$



Spiliotis et al, Light Sci. Appl. **10**:35 (2021)

Injection of pre-polarised electrons is key



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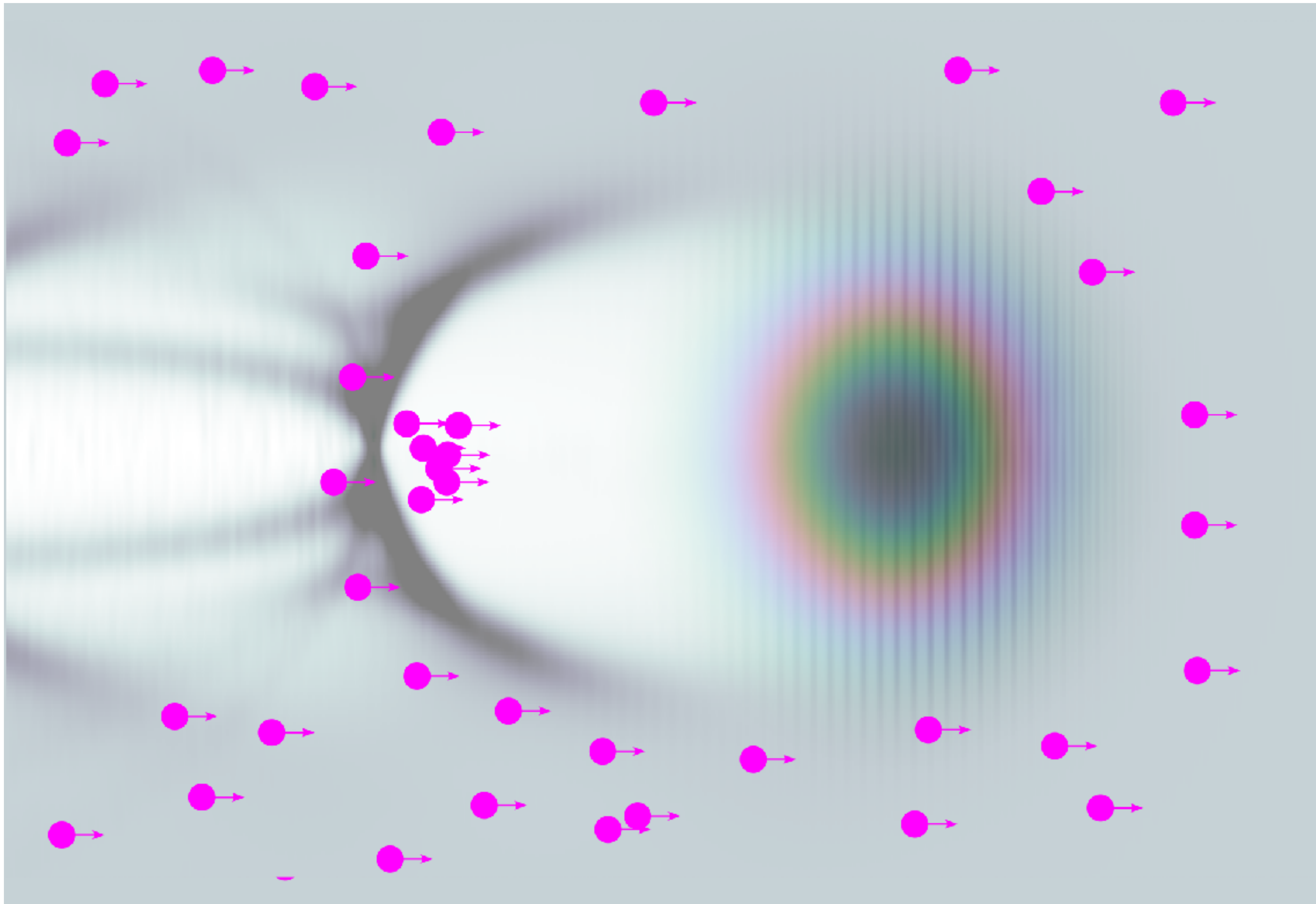
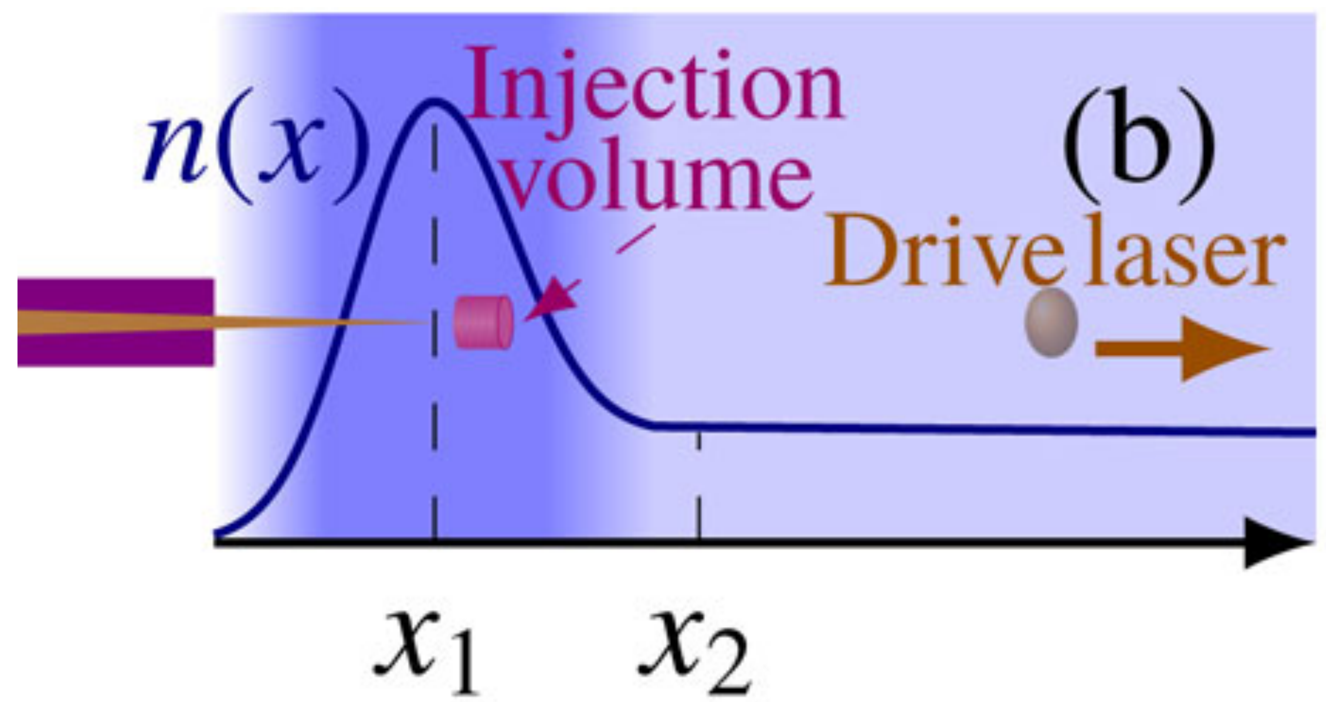


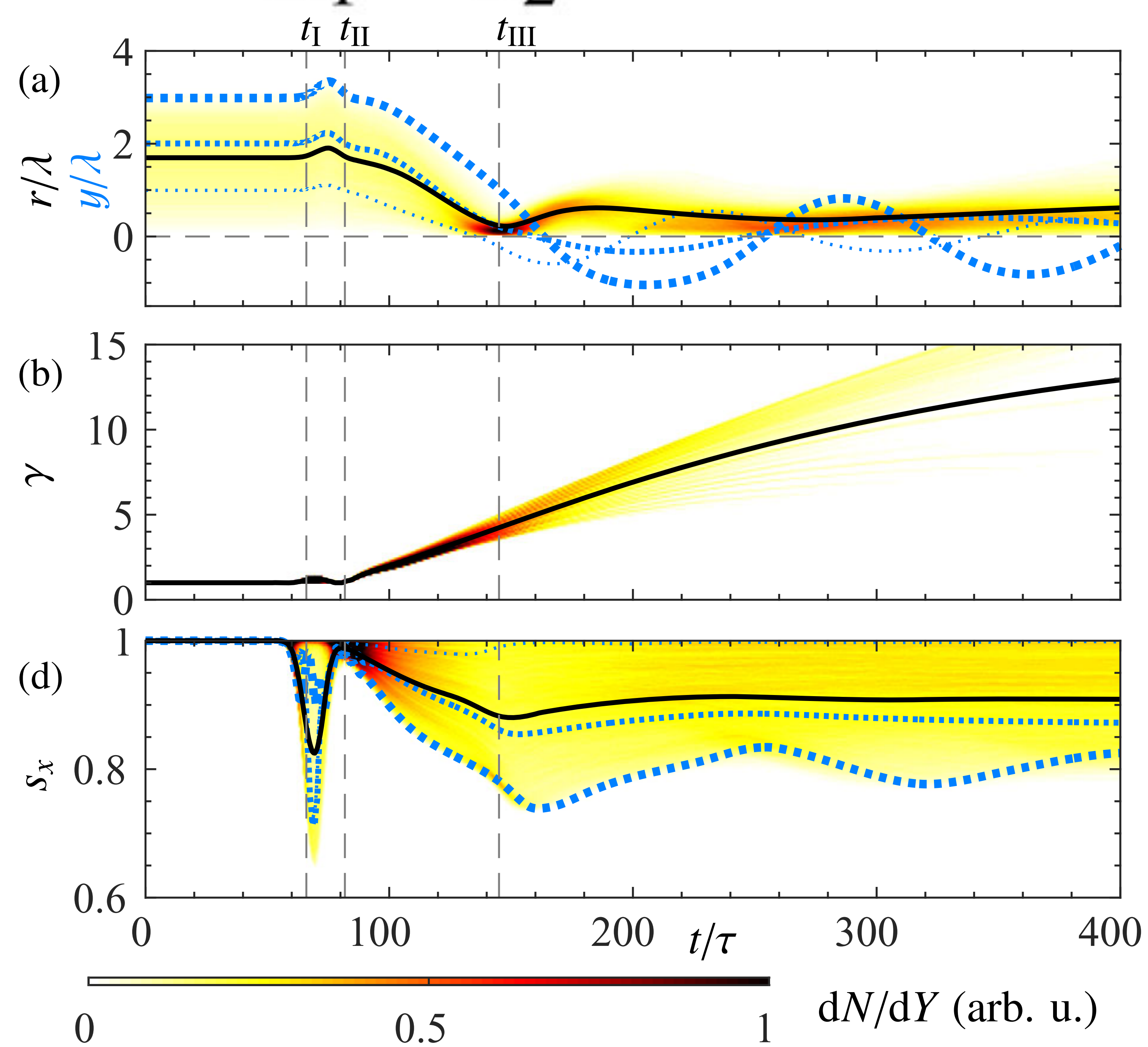
Density downramp injection

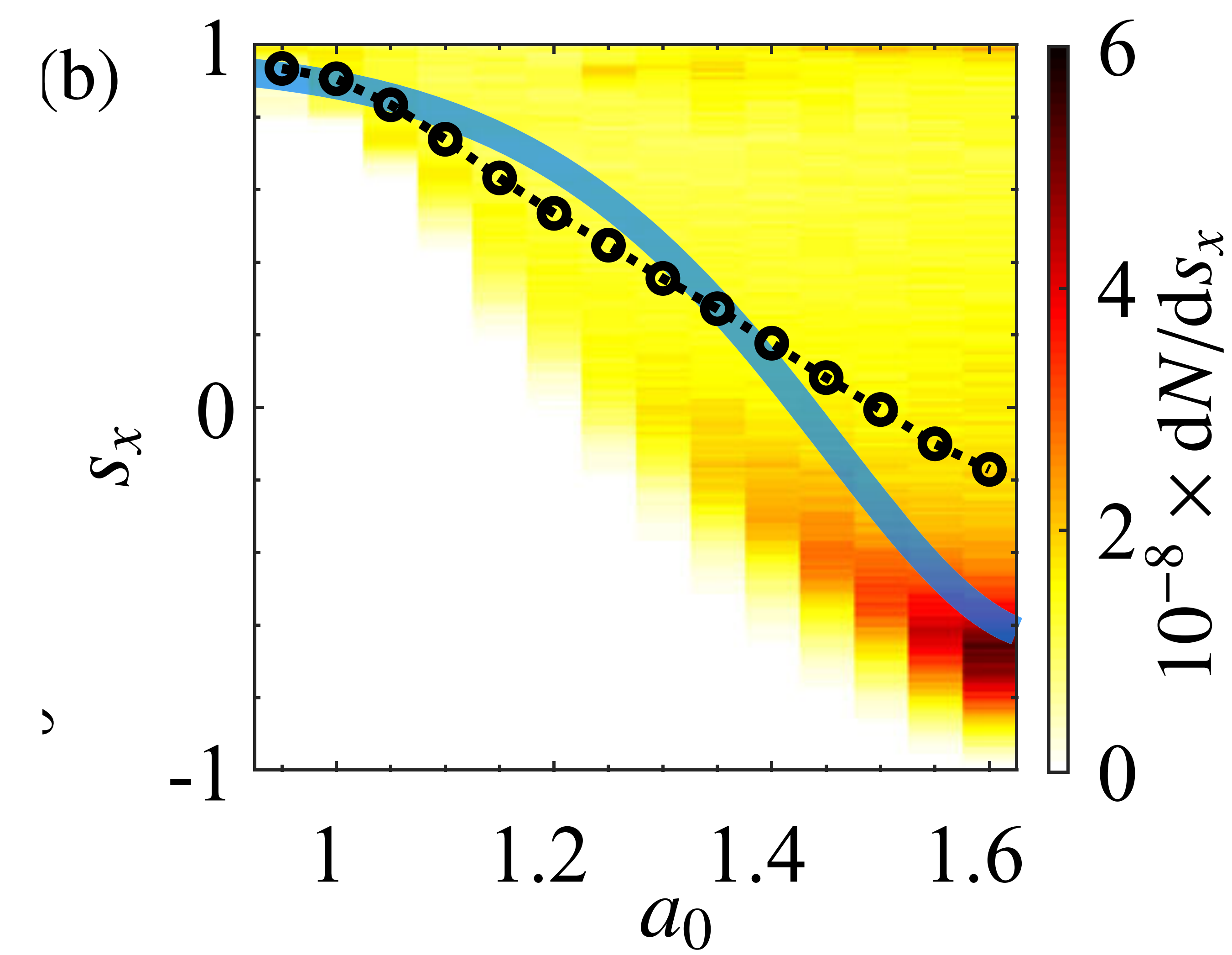
Ramp lengths limit practicality, while injection physics limits maximum current

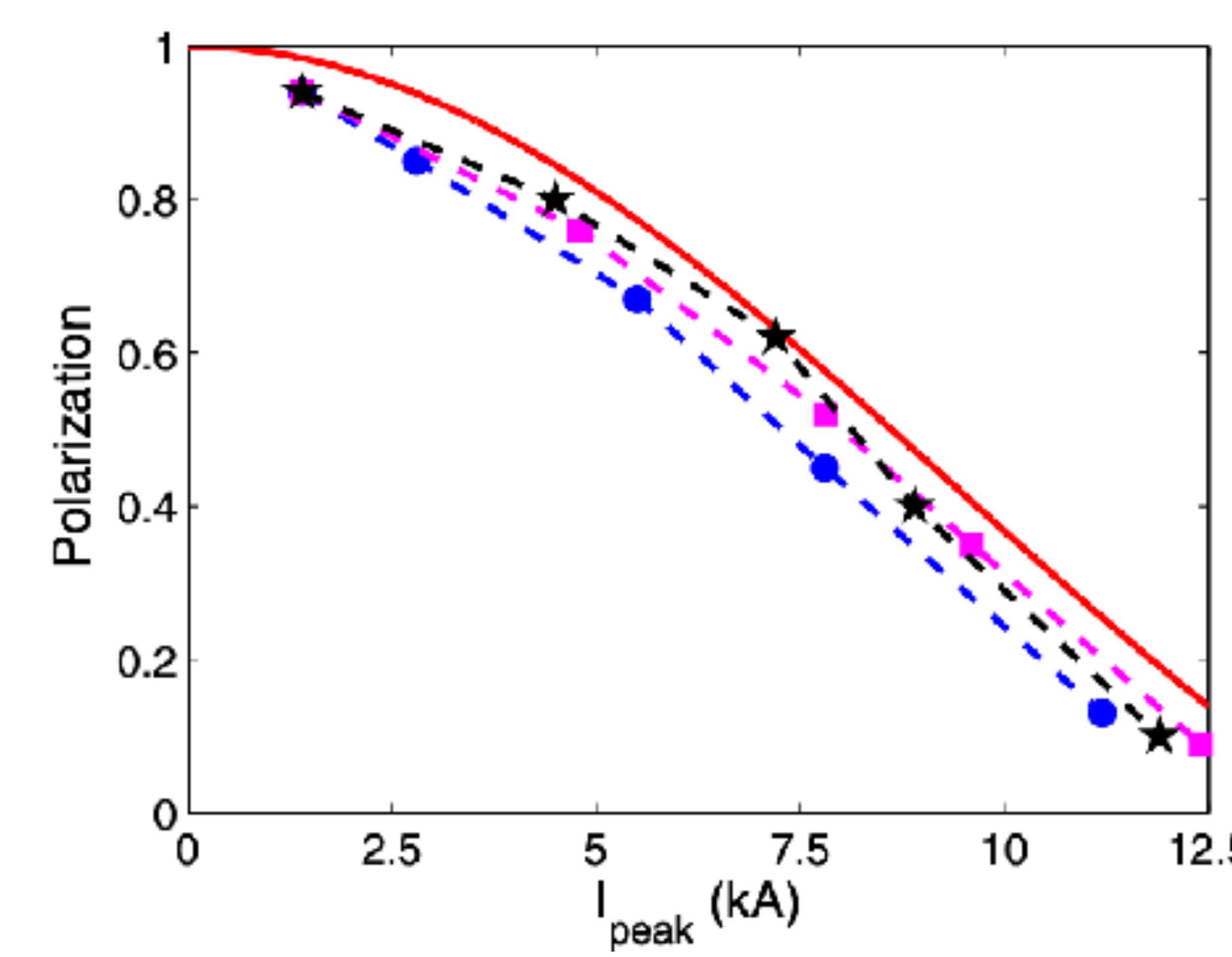
l_R~10um

n/n_0=4





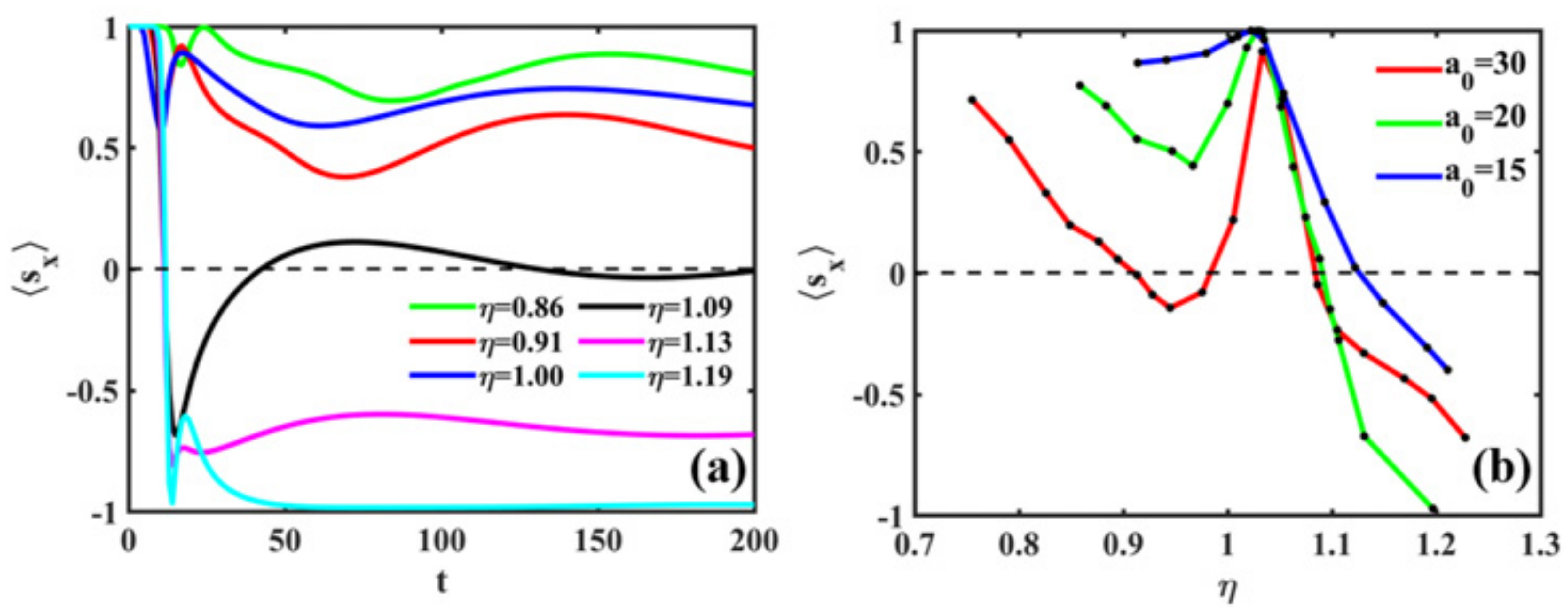


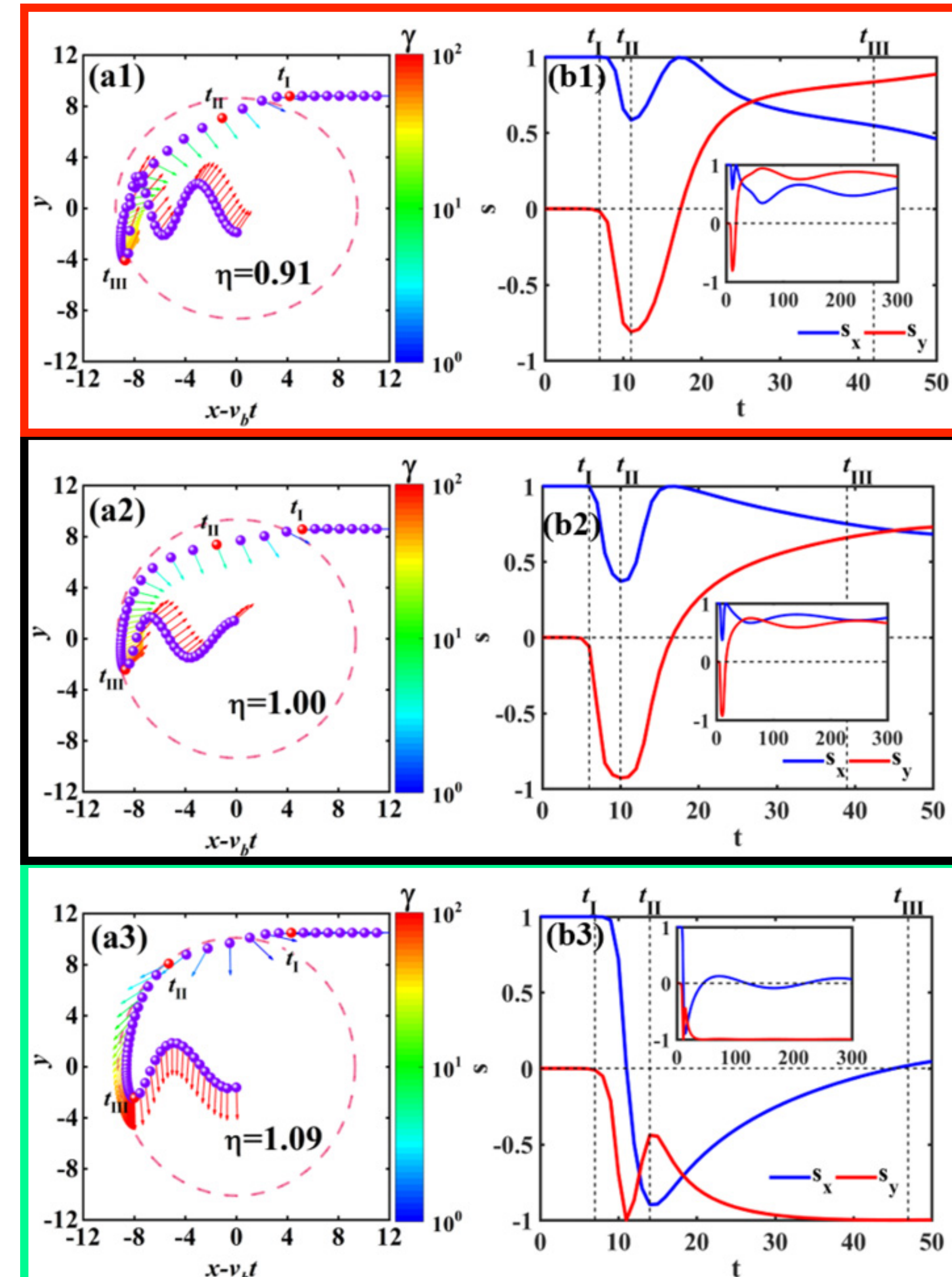


(7) Wen et al, PRL **122** 214801 (2019)
(8) Wu et al, PRE **100** 043202, (2019)

Self-injection: yes, but definitely no

Extreme sensitivity to bubble symmetry can lead to unpracticalities





A lot of spin rotation during injection!

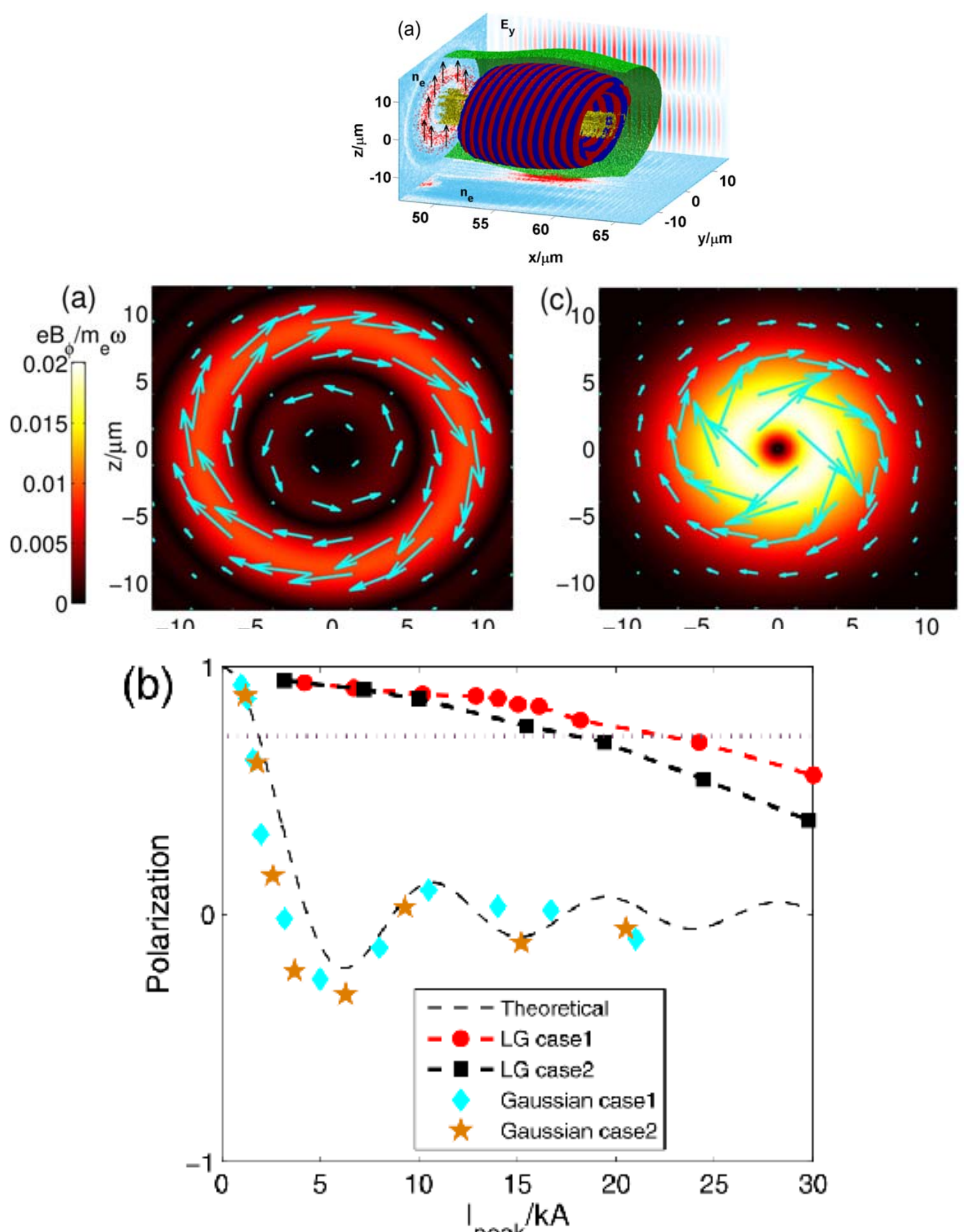
Very sensitive to bubble shape

(10) Fan et al, New J Phys. **22** 0 83047 (2022)

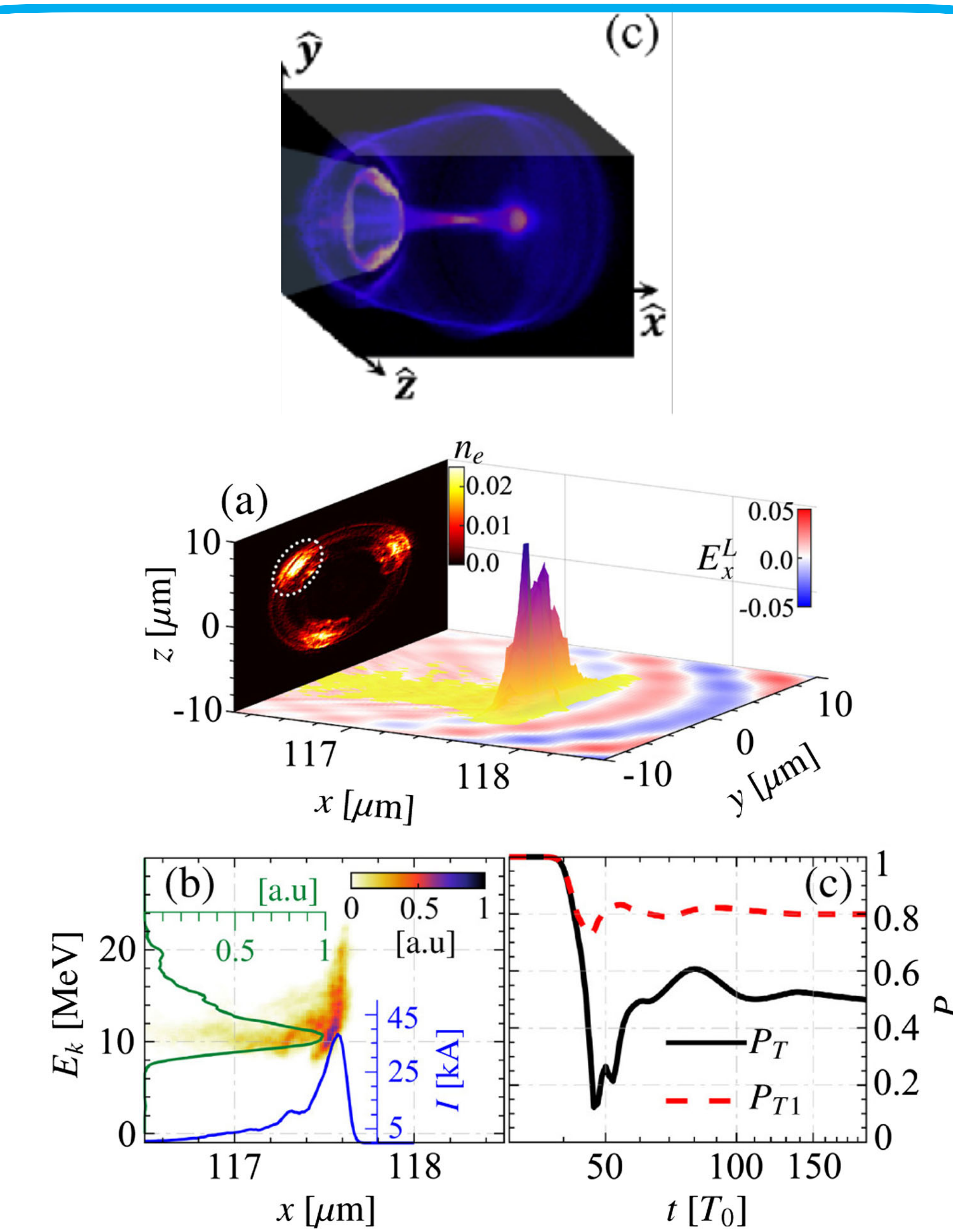
Exotic laser pulses

Short density ramps still needed, generating exotically-shaped electron beams

LG-beam



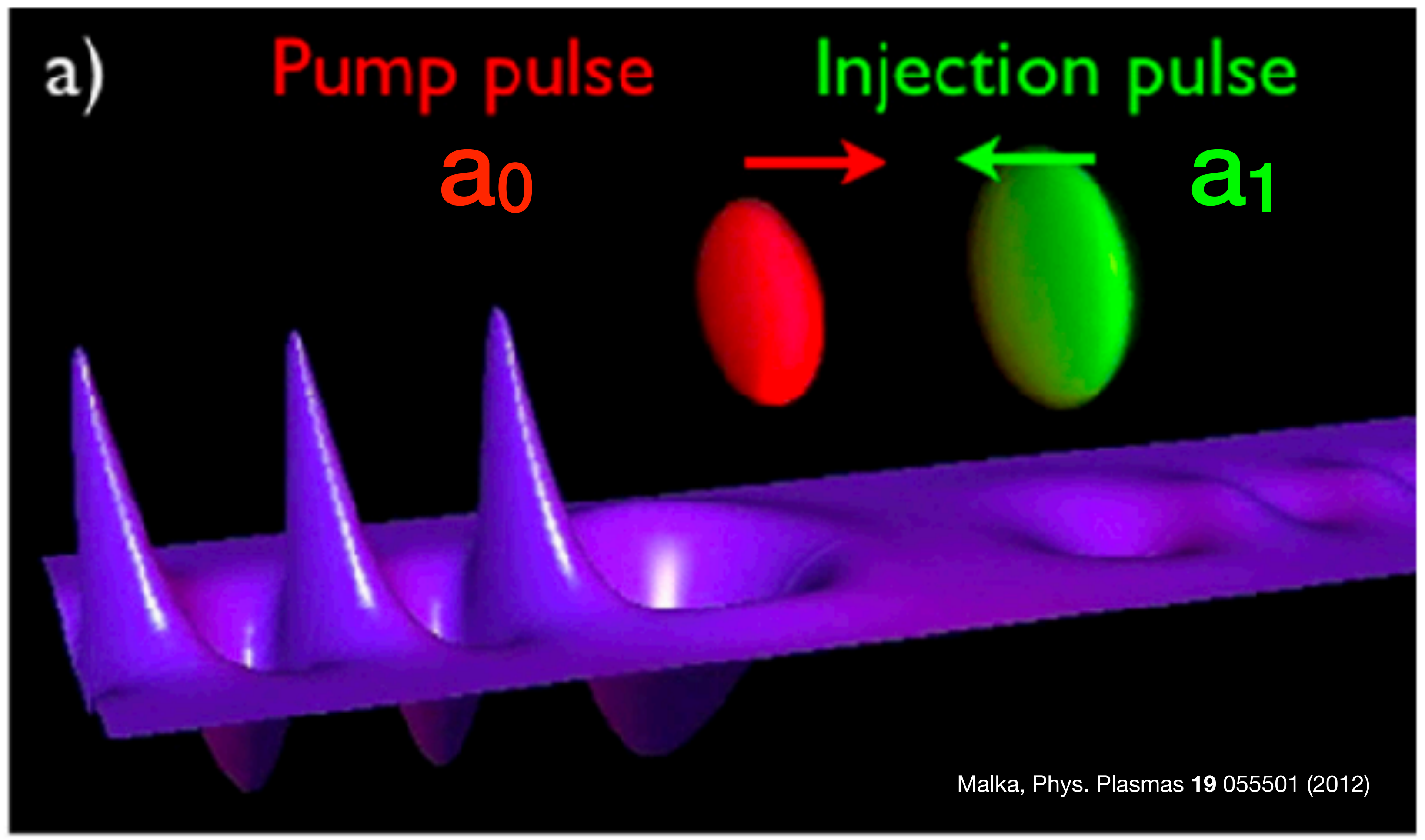
Vortex beam

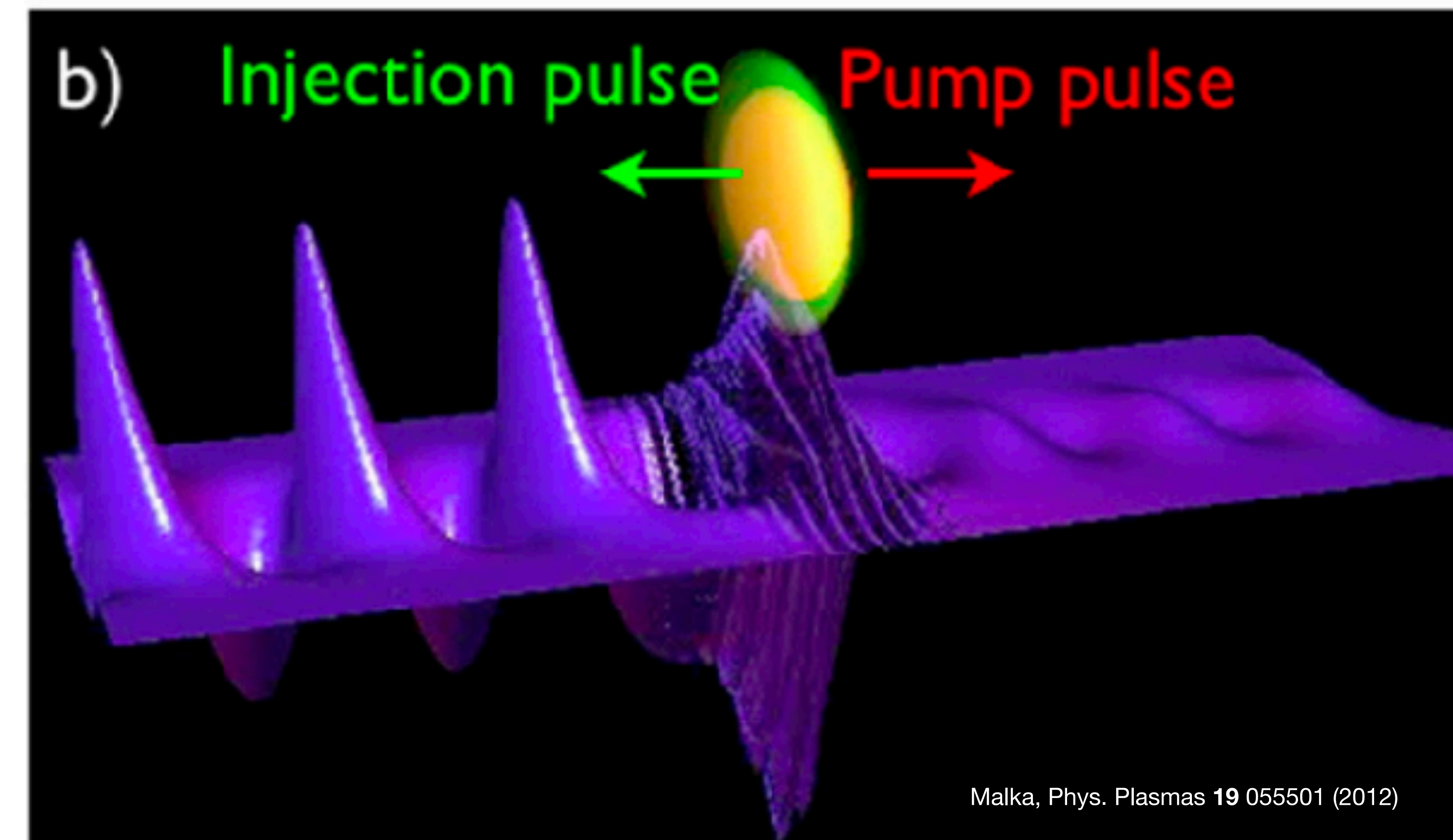


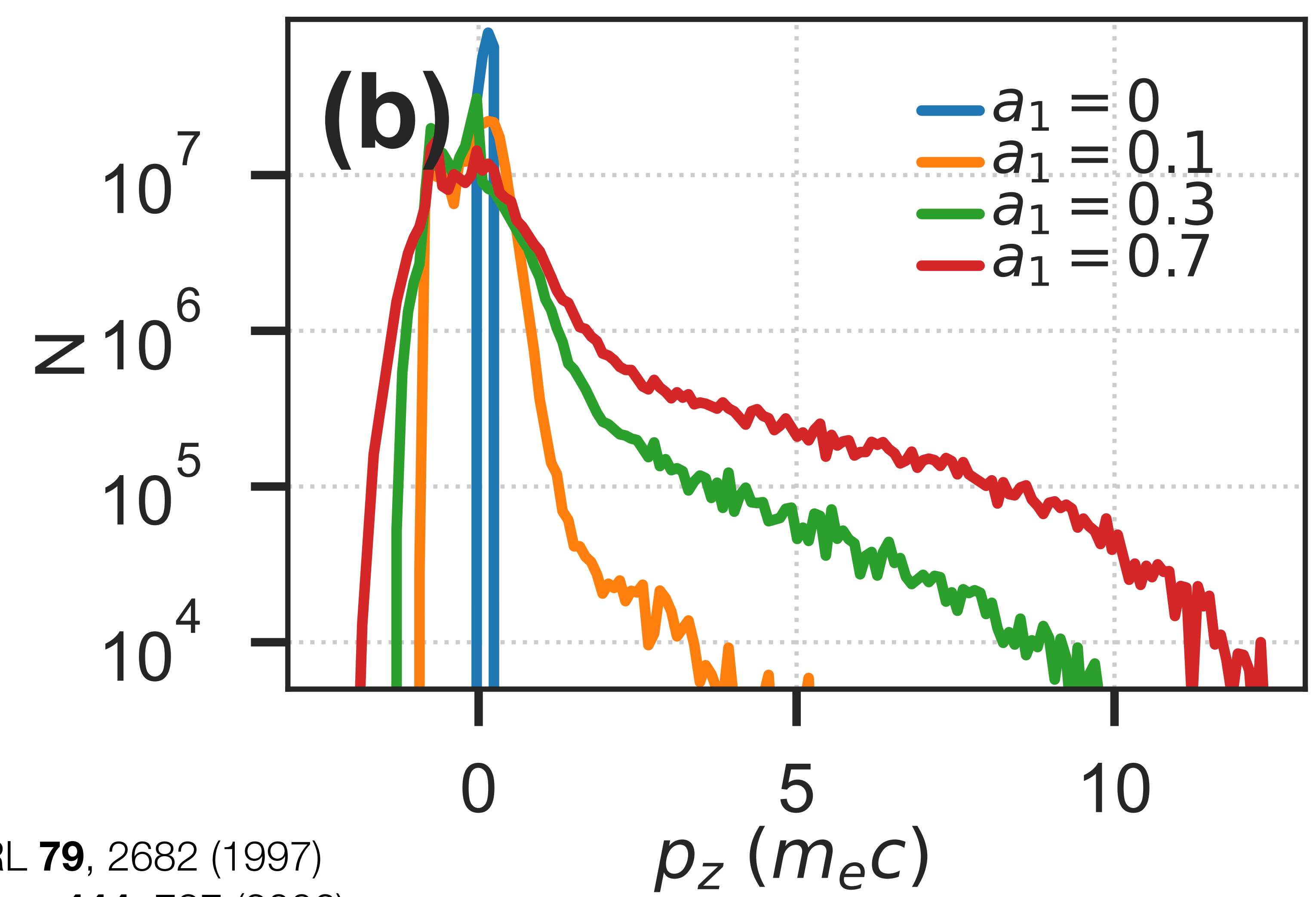
(9) Wu et al, New J. Phys. **21** 073052 (2019)
(11) Sun et al, PRL **132** 045001 (2024)

Colliding pulse injection

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







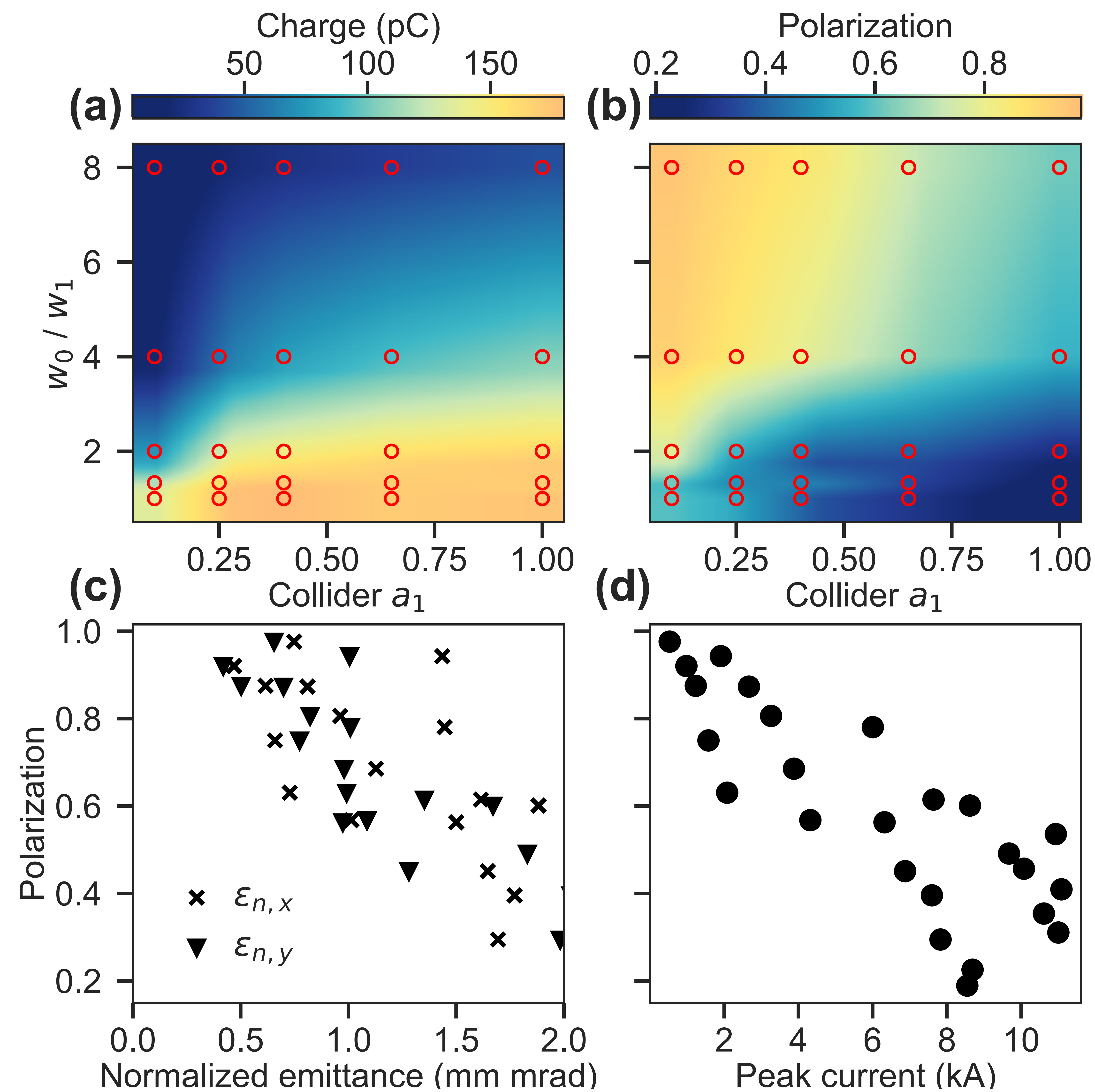
$$\frac{dp_x}{d\phi} = \frac{m_e^2 c^2}{p_-}[a_0^2 \cos\phi \sin\phi + a_0 a_1 \sin(2k_0 x + \phi_1) - a_1^2 \cos(\phi + 2k_0 x + \phi_1) \sin(\phi + 2k_0 x + \phi_1)]$$

Esarey et al, PRL **79**, 2682 (1997)
Faure et al, Nature **444**, 737 (2006)
Malka et al, Phys Plasmas **16**, 056703 (2009)

Colliding pulse injection creates high-current polarised beams

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

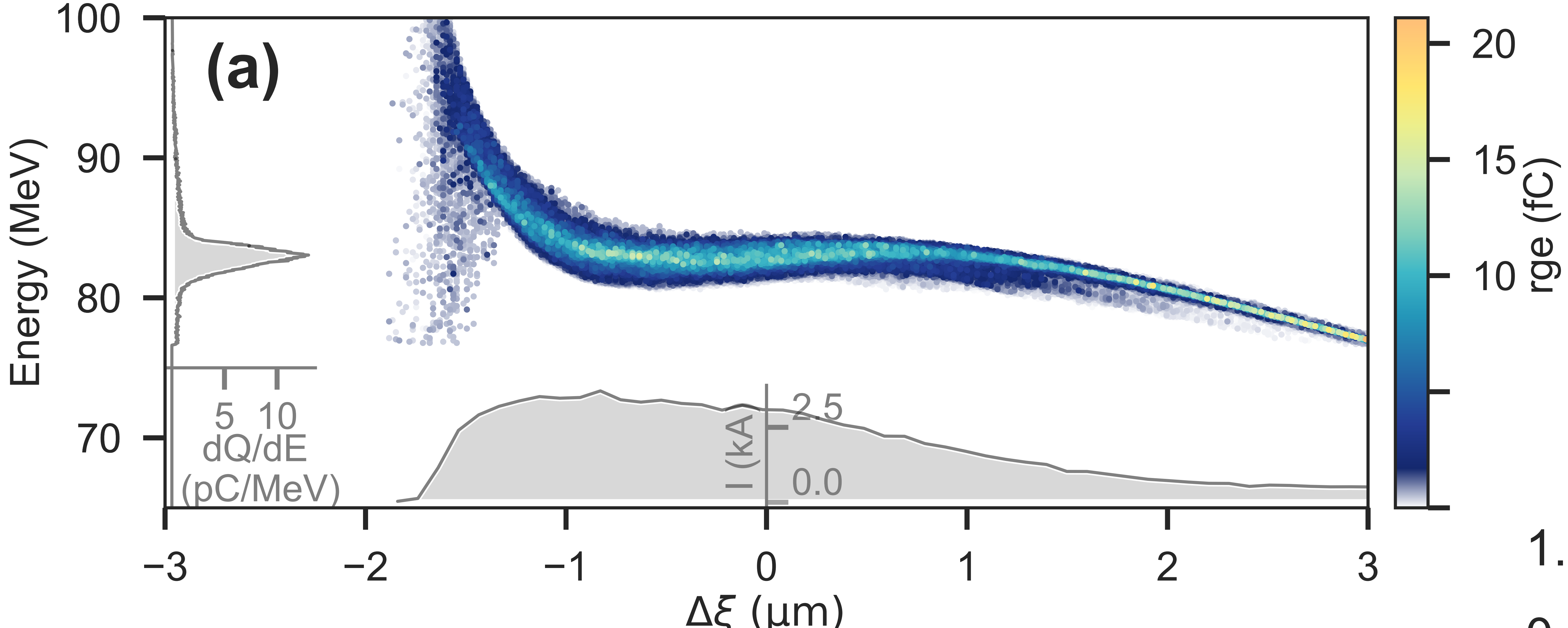
- Without any optimisation, can get
  - Highly polarised (>90%) beams
  - Sub-micron emittance
  - 6kA with 80% polarisation
- Charge and polarisation interdependent
  - Extra charge injected with lowered polarisation



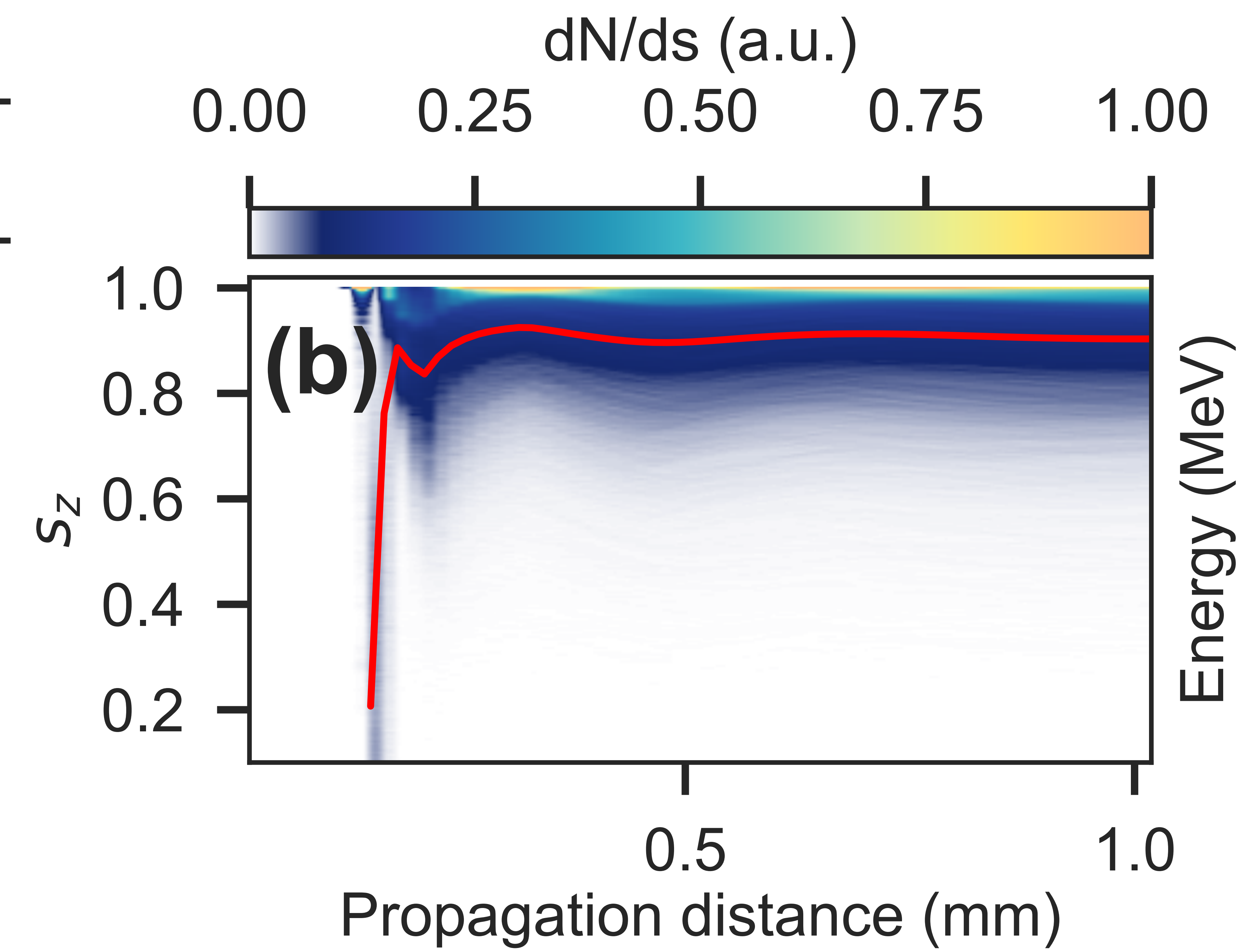
Gong *et al*, MRE **8**, 064005 (2023)
Bohlen *et al*, PRR **5**, 033205 (2023)

Colliding pulse scheme is highly optimisable

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



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,* PRR **5**, 033205 (2023)

Acceleration of polarised electron beams

Plasma can in principle preserve spin-polarisation at high energies

- Early work shows low depolarisation in a long plasma stage
  - Reduced analytic model
- Overall, small beam at e.g. HALHF is good!
- But many effects must be examined
  - Ion motion!
  - Self-fields!
  - Asymmetric emittance!
  - Jitters!
- TBMT now in FBPIC and HiPACE++
  - HALHF-relevant simulations running…

Tracking sims of 1 LPA stage(1)

n_e = 2.4 x 10^{15} cm^{-3}

$E_{initial}$ = 4.7 GeV/m

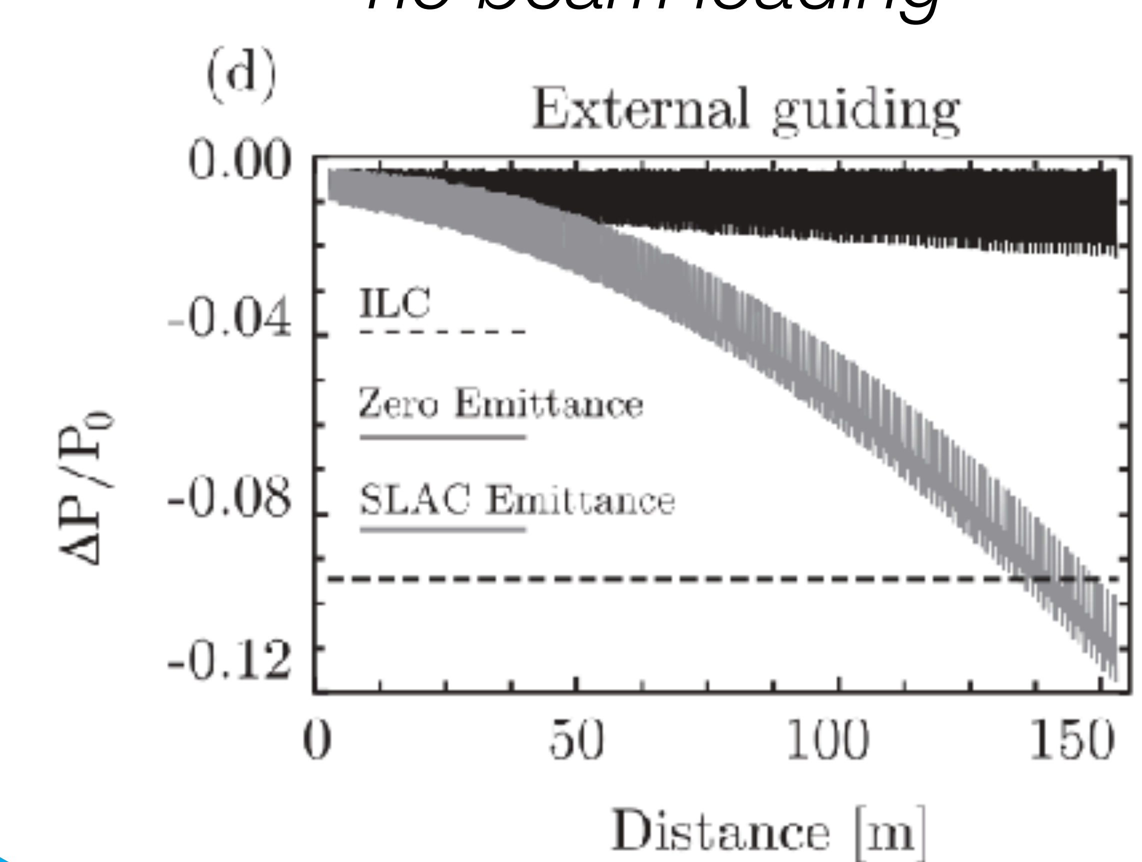
ϵ_x = 50 um

ϵ_y = 20 um

σ_r = 10 um

$\gamma_0 m_e c^2$ = 30 GeV

no beam loading



Vieira *et al*, Phys Rev STAB **14**, 071303 (2011)

Plasma-based polarised electrons beams are possible

Colliding pulse injection is a realistic pathway to polarised laser-plasma accelerators

- Plasma-based polarised electron sources possible based on pre-polarisation technique
- Colliding pulse injection enables
  - High polarisation & beam quality
  - Wide tunability and many tuning knobs for optimisation
- Preliminary simulation studies of O(100m) plasmas ongoing