Extreme plasma physics in the laboratory and in astrophysics

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golp ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR TÉCNICO LISBOA erc

Acknowledgements

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W.B.Mori, R. Bingham, D. Uzdensky, A. Spitkovsky, G. Gregori

Simulations performed at **Accelerates (IST), Dawson2 (UCLA), Jugene/Juqueen (FZ Jülich), SuperMUC (Münich), MareNostrum (BSC), Sequoia (LLNL)**

ACCELERATES erc PRACE INPAIRS

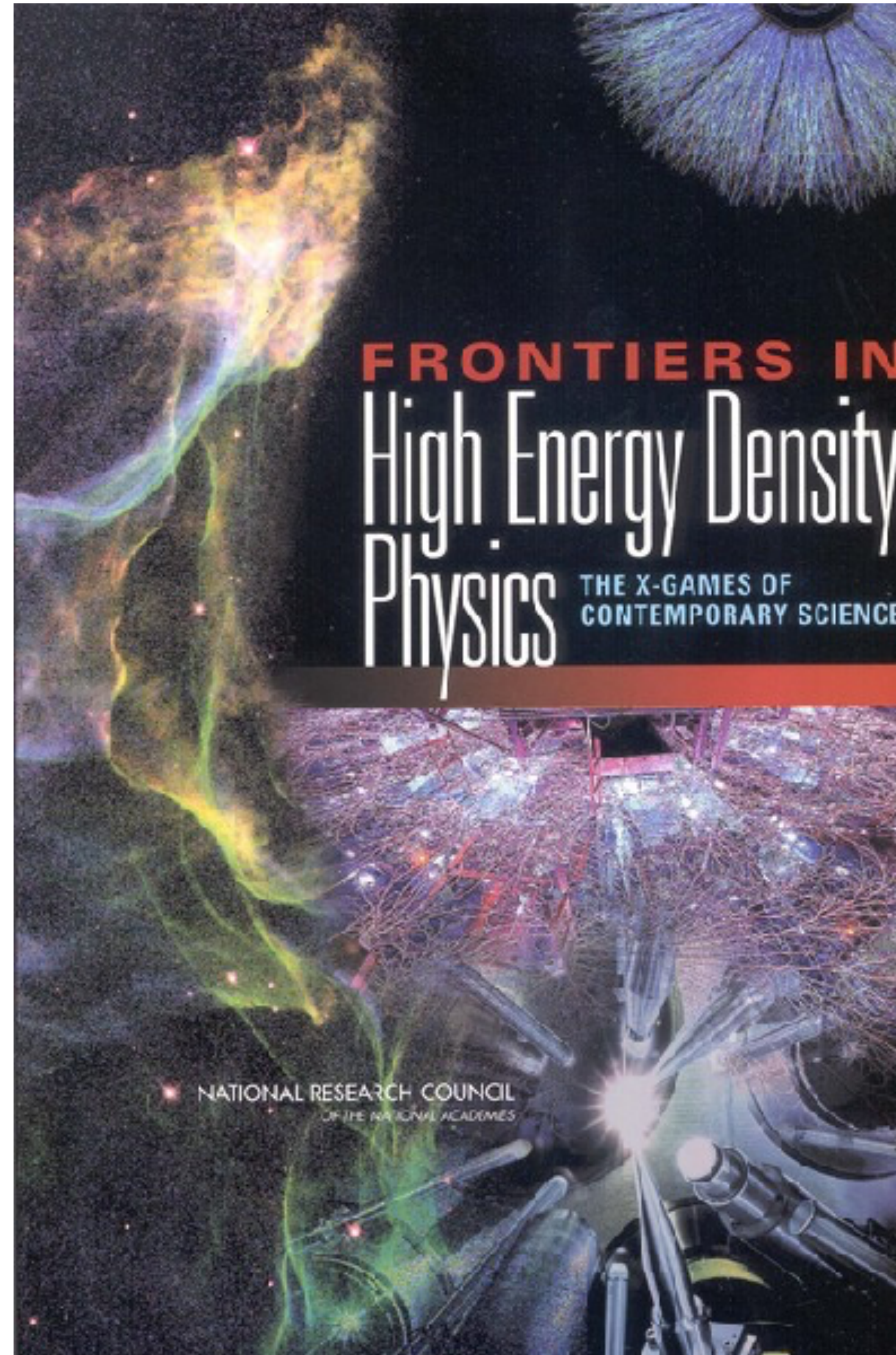
GoLP | golp.tecnico.ulisboa.pt

Committed to continuously raising the bar

A bit of history

Focusing light with the power of
1,000 HOOVER DAMS onto a point the size of
A CELL NUCLEUS accelerates electrons to the speed
of light in a femtosecond

By Gérard A. Mourou and Donald Umstadter



Extreme Plasma Physics

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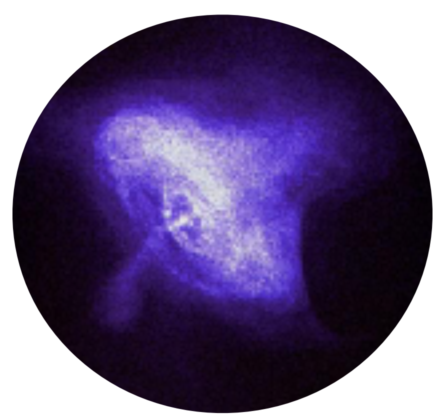
Plasma physics supplemented by several additional physical effects that

"…would be considered "exotic" in traditional plasma physics e.g.

- special-relativistic effects relativistically hot plasmas and relativistic bulk motions
- radiation-reaction effects e.g., synchrotron or inverse-Compton radiative cooling
- electron-positron pair creation
- ultra-strong magnetic fields QED effects such as 1-photon pair creation
- general-relativistic effects."

D. Uzdensky *et al.*, Extreme Plasma Astrophysics, arXiv:1903.05328

Ultra intense laser and particle beams



Relativistic Astrophysics

Sci-fi

Overarching questions

What is the behavior of matter (and vacuum) at the intensity frontier ($> 10^{23}$ W/cm^2) in lab and in astro?

How can we understand and explore the complex and nonlinear behavior with a combination of simulations + theory + experiments with lasers and beams?

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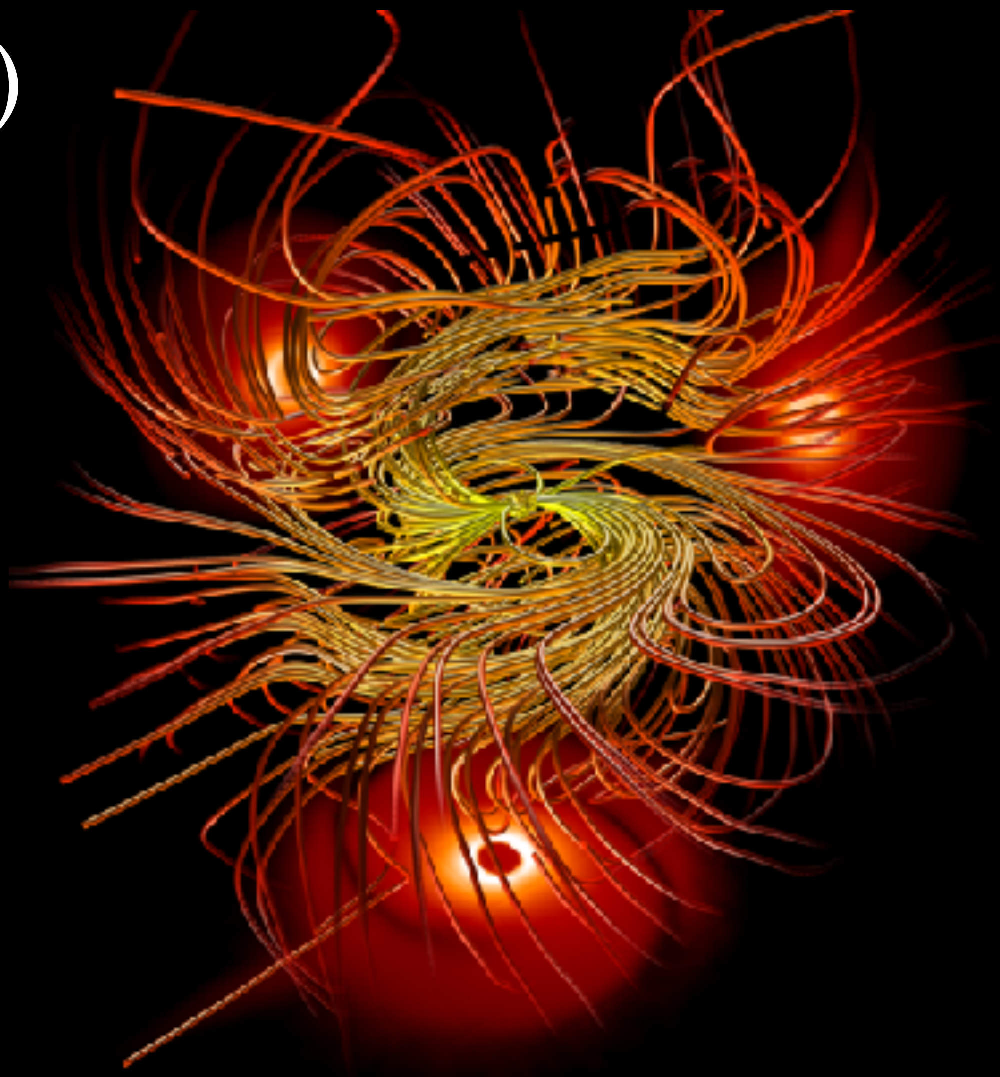
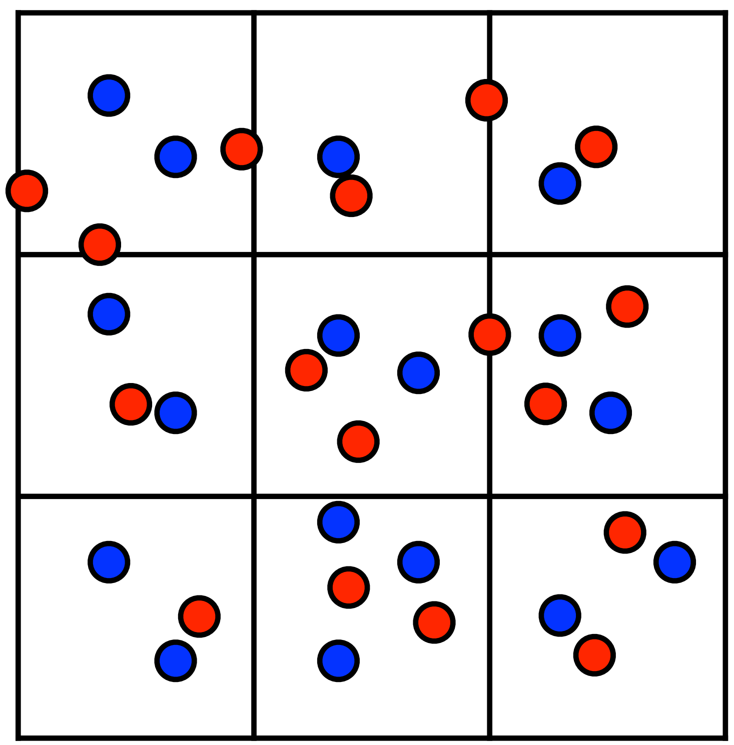


Particle-in-cell simulations

Solving Maxwell's equations on a grid with self-consistent charges and currents due to charged particle dynamics



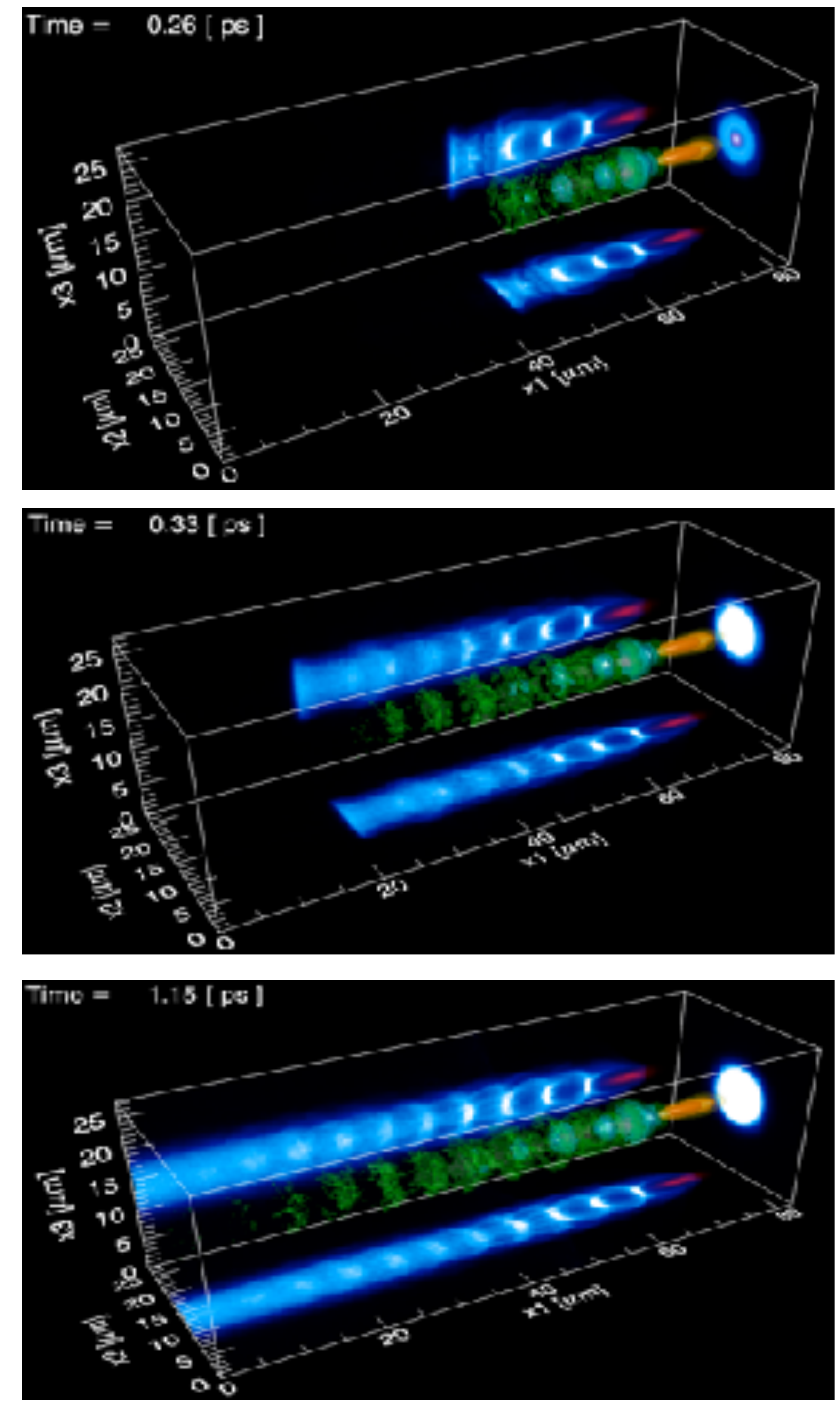
State-of-the-art

~ 10^{12} particles

~ $(12000)^3$ cells

RAM ~ 1 Gbyte - 100 TByte
Run time: hours to months
Data/run ~ few MB - 100s TByte

One-to-one simulations of plasma based accelerators & cluster dynamics
Weibel/two stream instability in astrophysics, relativistic shocks, fast igniton/inertial fusion energy, low temperature plasmas

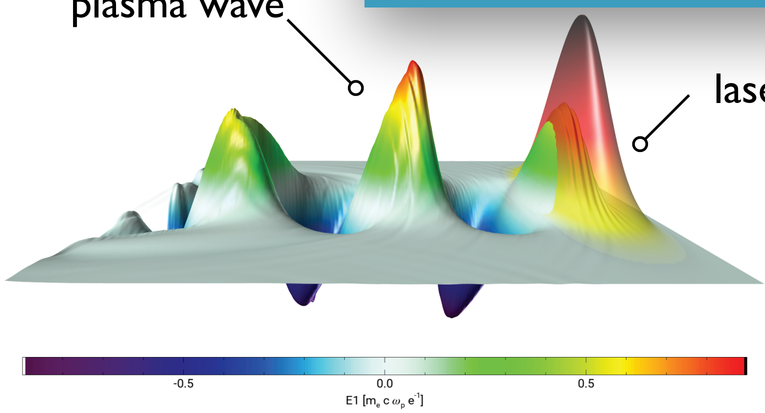


Particle-in-cell (PIC) - (Dawson, Buneman, 1960's)
Maxwell's equation solved on simulation grid
Particles pushed with Lorentz force

ZPIC educational code suite

Come find us on GitHub
github.com/zambzamb/zpic

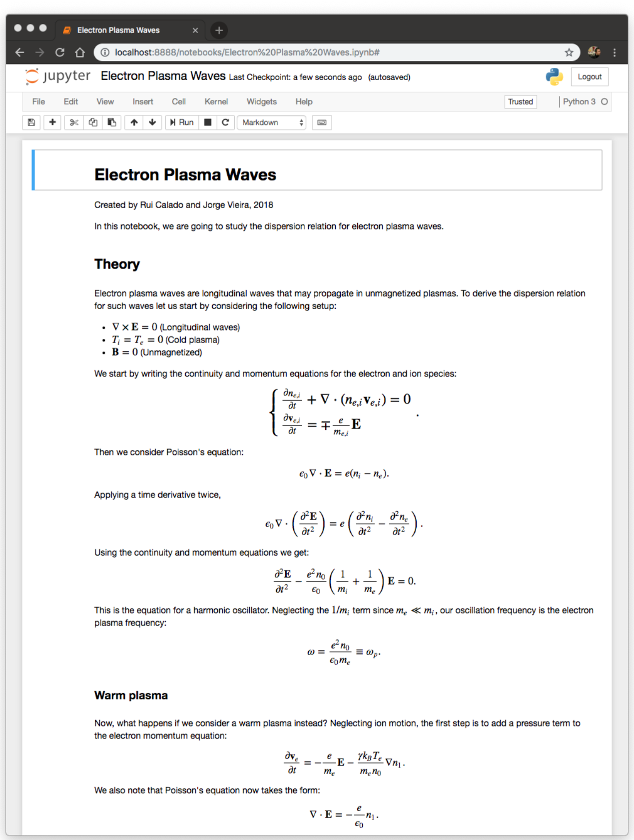
- **Particle-in-cell Code suite.** Fully relativistic electro-magnetic 1D and 2D (FDTD/spectral) and 1D Electrostatic.
- **Python interface.** All simulation codes/parameters can be controlled via Python interface.
- **Educational examples.** Set of Python Jupyter notebooks with detailed physics problem description and simulation setup.



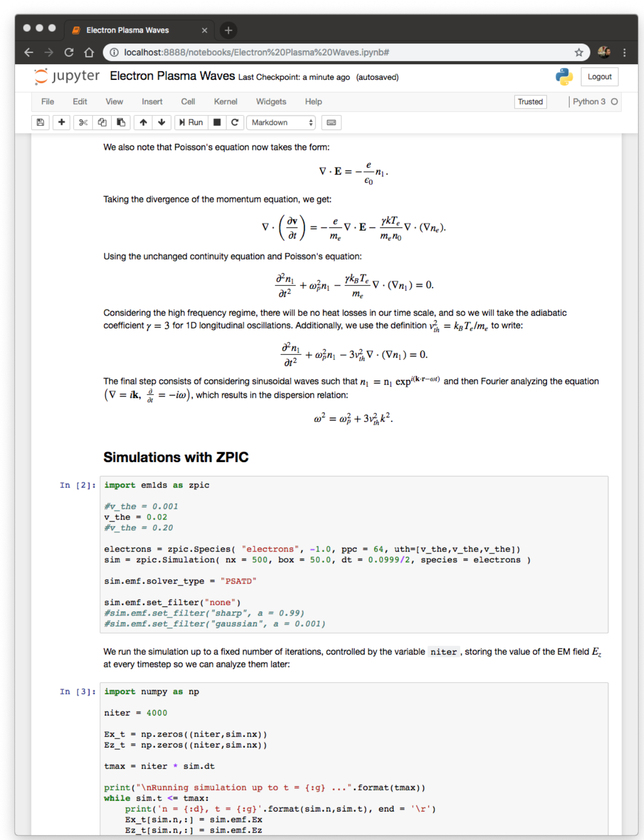
compact plasma accelerator

Example notebook

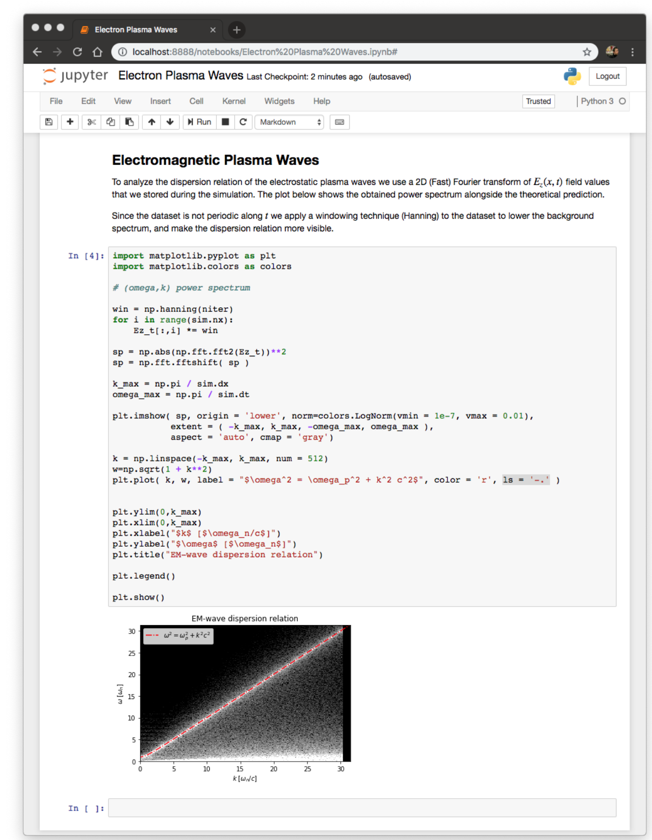
Theoretical introduction



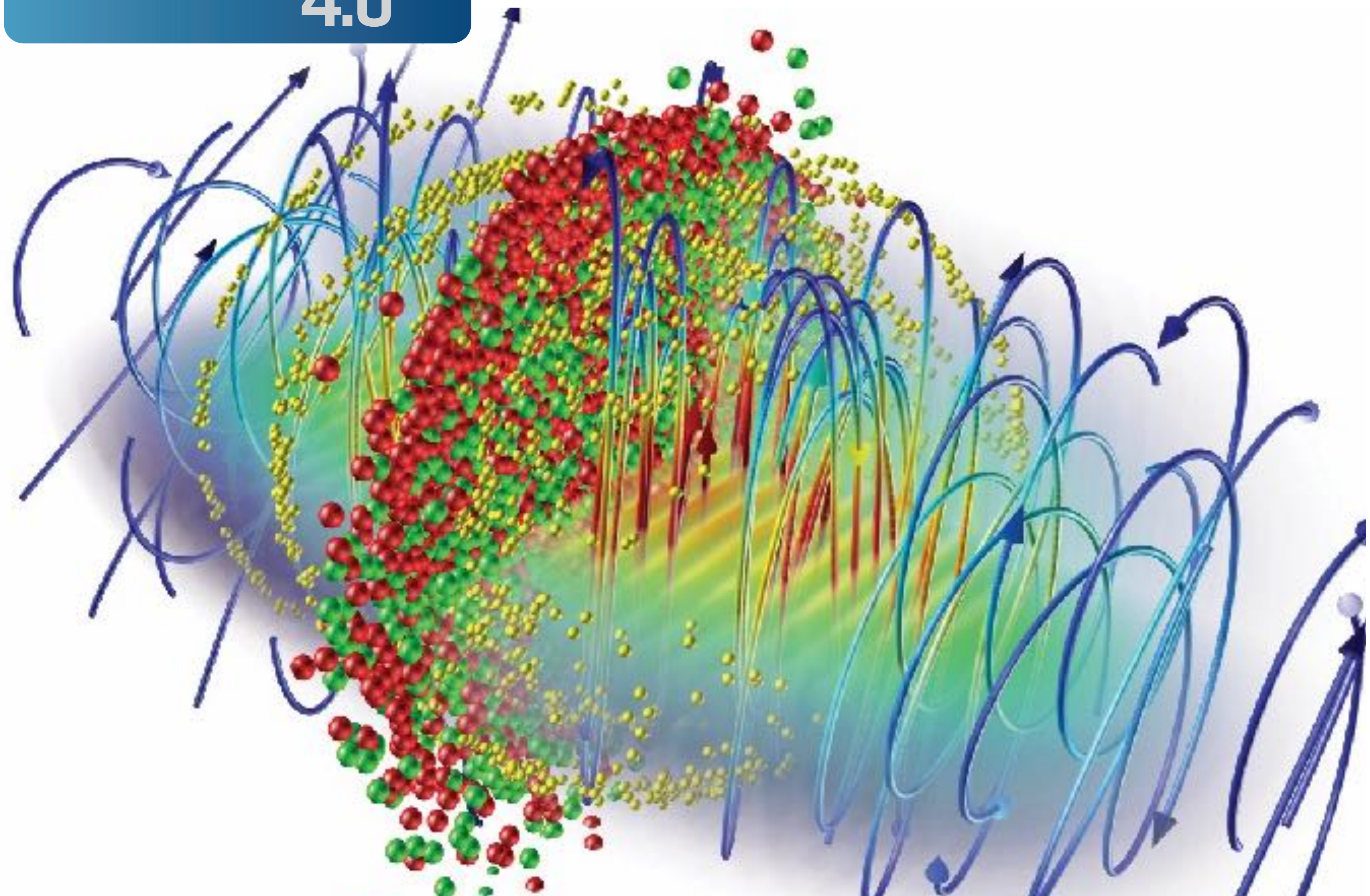
simulation initialisation



analysis and questions for discussion



Committed to open science



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended simulation/physics models

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 250+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/osiris

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

QED plasmas and PIC codes

Monte Carlo simulations demonstrating pair production *via* real photons per electron

J. G. Kirk, A. R. Bell, and I. Arka, PPCF (2009)

R. Duclous, J.G. Kirk & A.R. Bell, PPCF (2010)

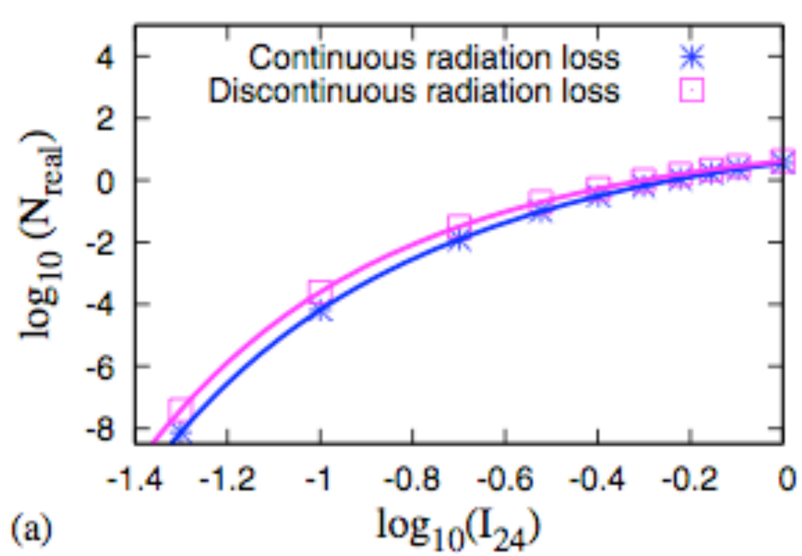
PIC simulations of QED cascade in various configuration (counter propagating laser, rotating field)

N.V. Elkina et al, Phys. Rev. ST. AB (2011)

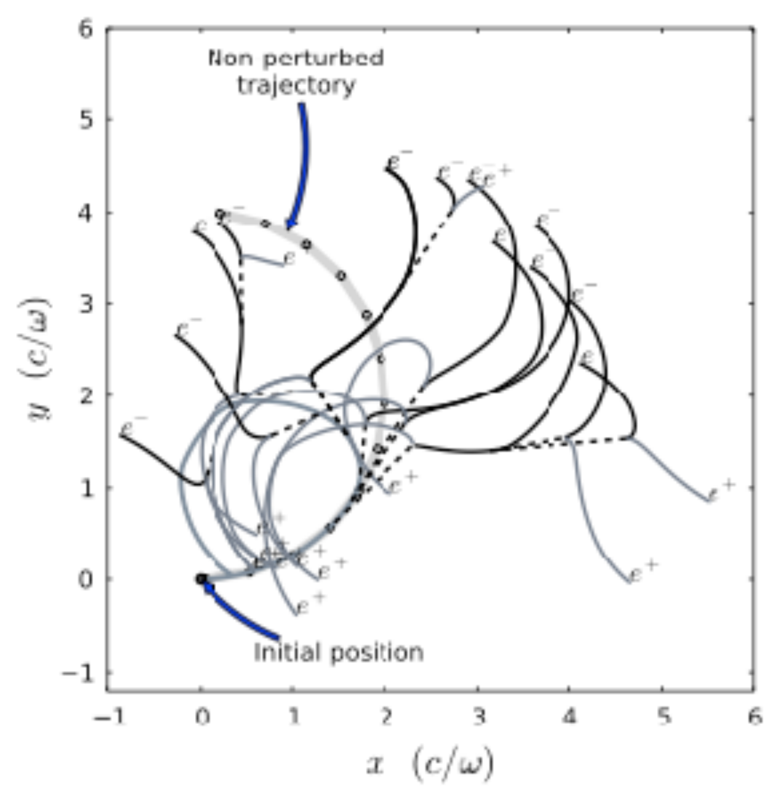
E.N. Nerush, et al, Phys. Rev. Lett. (2011)

Dense pair Plasmas and Ultra-Intense Bursts of Gamma-Rays from Laser-Irradiated Solids

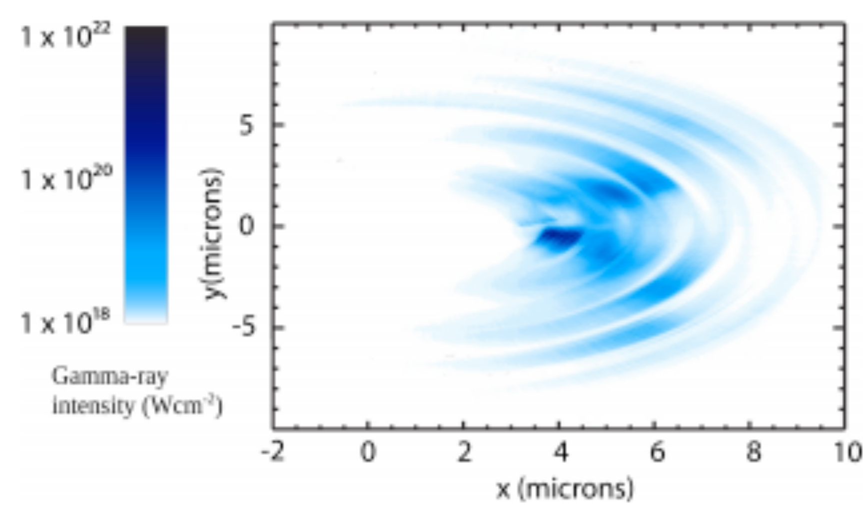
C.P. Ridgers, et al Phys. Rev. Lett., (2012)



Number of pairs produced



Cascade in rotating field



Gamma rays from laser-irradiated solid

QED-PIC loop + Particle Merging

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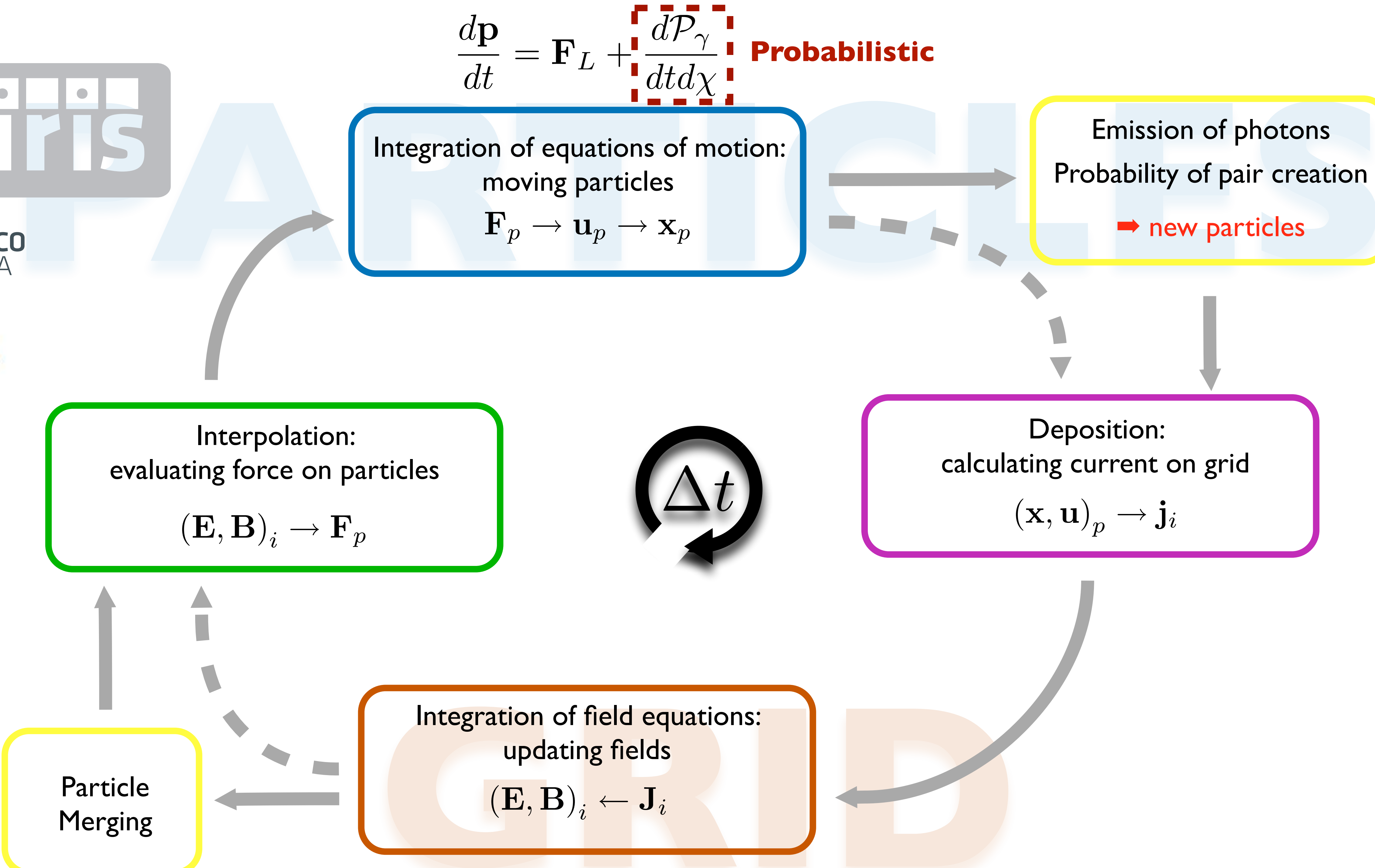
UCLA



$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

M.Vranic, *et al.*,
Comput. Phys. Commun. (2015)

For a review
A. Gonoskov *et al.*, PRE (2015)

The emergence of (relativistic) quantum behaviour with intense fields

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Schwinger field

$$E_s = \frac{m^2 c^3}{e\hbar}$$

$$E_s \simeq 1.32 \times 10^{18}\ \mathrm{V/cm}$$

Julian Schwinger, 1918-1994

Pair creation probability

$$W \propto \exp(-\pi E_s/E)$$

Normalized electric field

$$\chi = \frac{E}{E_s}$$

Generalization for any Lorentz frame

$$\chi = \frac{1}{E_s}\sqrt{(\gamma \mathbf{E} + \frac{\mathbf{p}}{mc} \times \mathbf{B})^2 - (\frac{\mathbf{p}}{mc} \cdot \mathbf{E})^2}$$

Lower E still leads to pair creation due to Lorentz boost

$$\chi \simeq \frac{\gamma E_\perp}{E_s}$$

For reviews:

GA Mourou, T Tajima, SV Bulanov, RMP (2002); M. Marklund and P. K. Shukla, RMP (2006); A Di Piazza, C Müller, KZ Hatsagortsyan, CH Keitel RMP (2012)

Plethora of QED processes

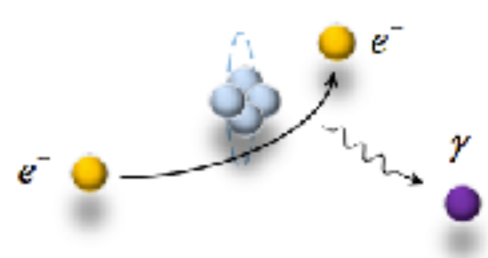
Incoherent processes

- Pair production
- Photon production
- Photon annihilation
- “Comptonisation”

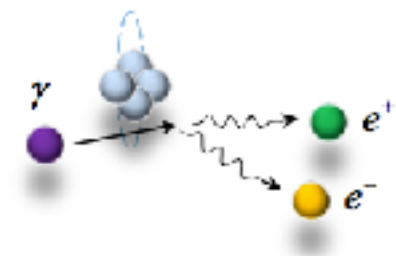
$$\sigma \sim \alpha^n \sigma_T \times f(\mathcal{E})$$

Cross section

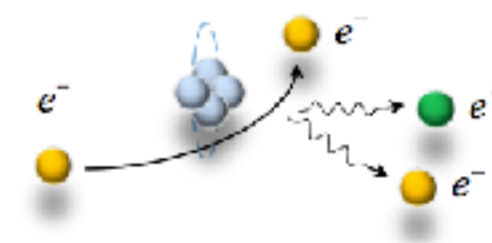
Bremstralhung



Bethe-Heitler



Trident Coulomb



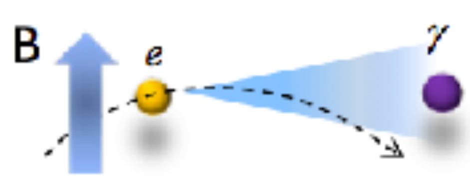
Coherent processes

- Nonlinear Breit-Wheeler
- Nonlinear Compton
- Schwinger mechanism
- Photon splitting

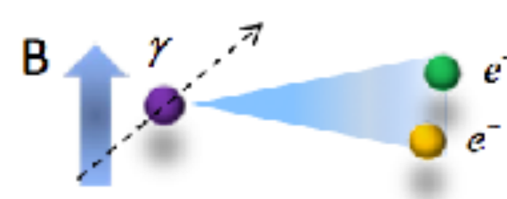
$$d\mathcal{P}/dt \sim (\alpha c/\lambda_C) f(E/E_S, \mathcal{E})$$

Probability of the process

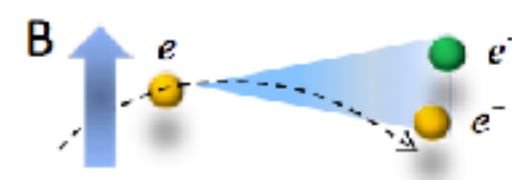
Nonlinear Compton



Nonlinear Breit-Wheeler



Tridente EM

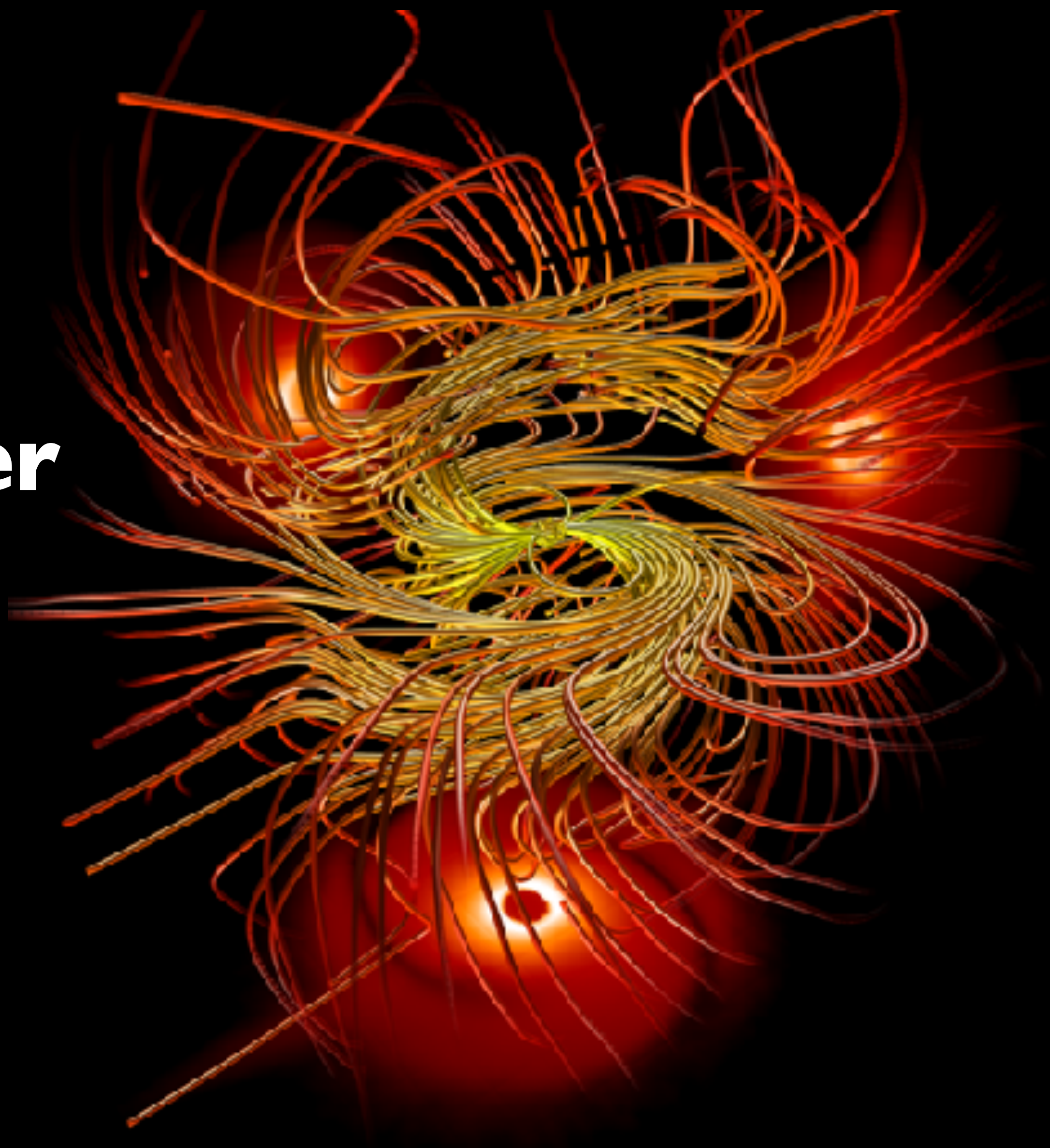


Courtesy: T. Grismayer and B. Martinez

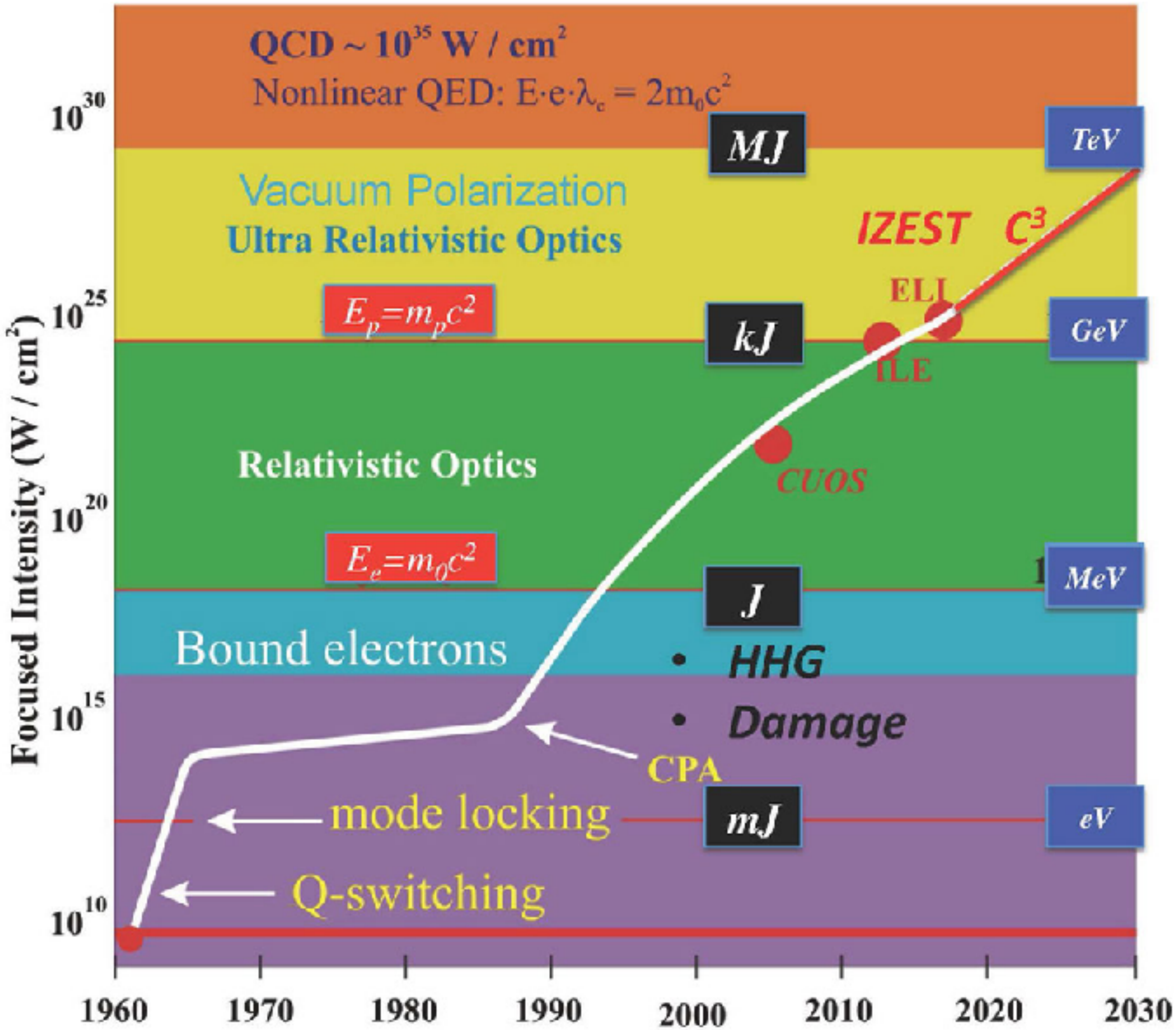
Extreme Plasma Physics

Ultra intense lasers & particle beams and the intensity frontier

QED plasma processes in relativistic astrophysics (pulsars)



At the focus of intense lasers



Adapted from Mourou, Tajima, Bulanov, Rev. Mod. Phys. (2006)

Similar intensities are present in particle beams

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Existing or planned particle beams

LHC @ CERN I ~ 2.5×10^{19} W/cm^2
100 kJ, 7 TeV per proton, 10^{11} protons per beam; 10 cm long bunch; 200 microns spot

SPS @ CERN I ~ 1.5×10^{18} W/cm^2
~7 kJ, 0.5 TeV per proton, 10^11 protons per beam; 10 cm long bunch; 200 microns spot

ILC I ~ 1.5×10^{24} W/cm^2
1.6 kJ, 0.5 TeV per electron/positron, 2×10^{10} electrons/positrons; < 10 nm width in x; < ~100 nm width in y; 6 mm long

SLAC I ~ 1.2×10^{19} W/cm^2
160 J, 50 GeV per electron/positron, 2×10^{10} electrons/positrons; ~50 microns long; ~50 microns spot

Plasma accelerators are an example of extreme plasma physics at the forefront of Science

Simulations + lasers + sources directly impacted this progress

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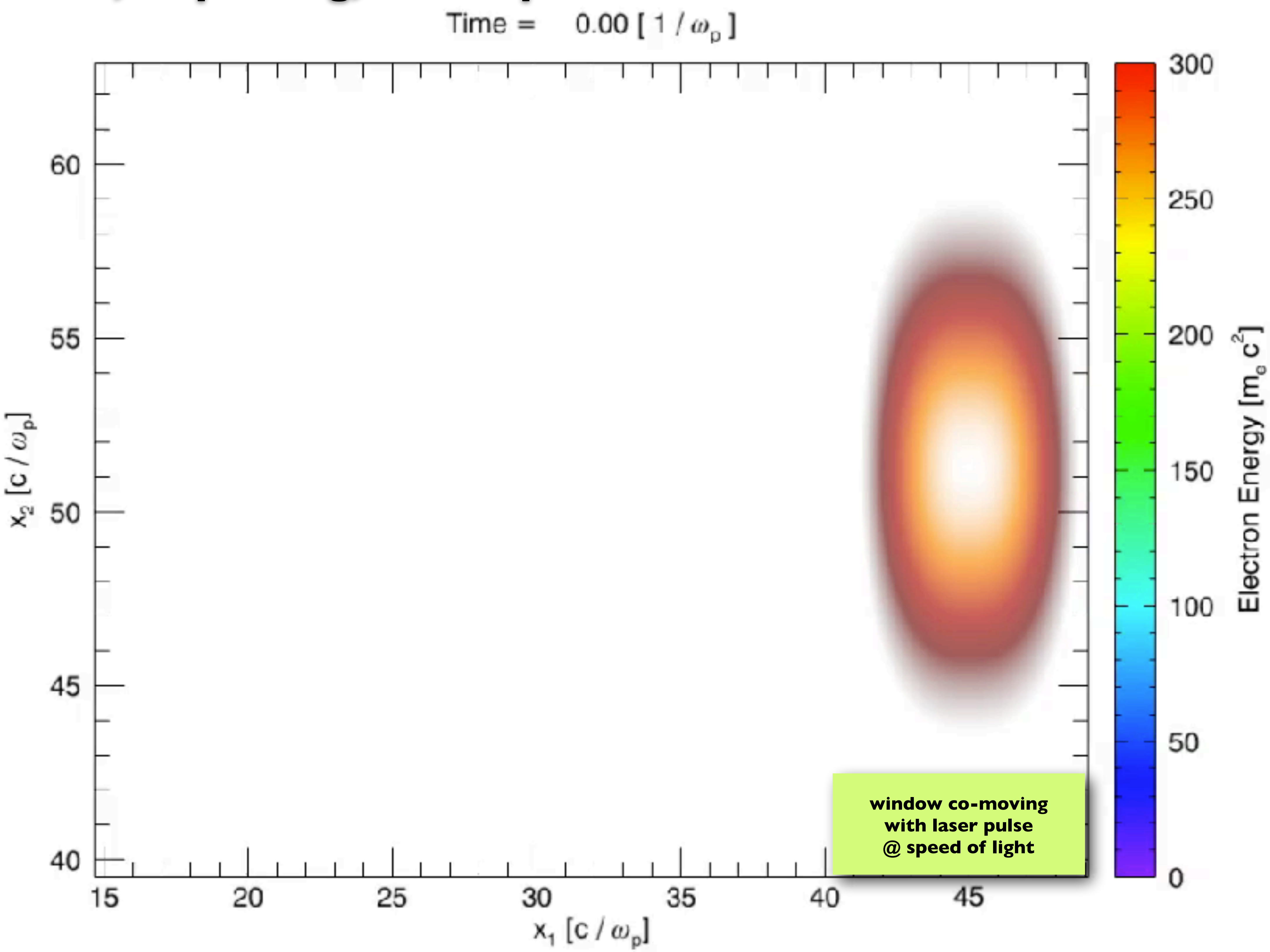
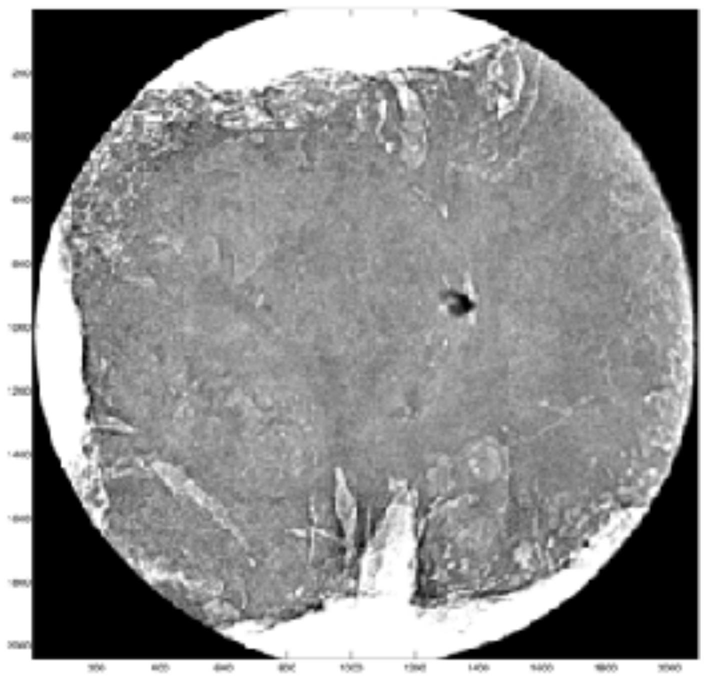
Self-injection, Dephasing, and Depletion



S.F. Martins *et al.*, Nature Physics (2010)

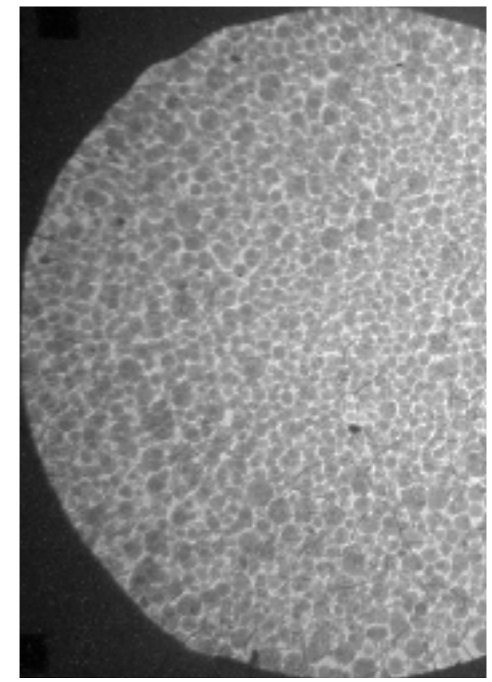
Betratron x-ray imaging

Application to bone micro-structure* imaging (above)
biological, medical, material and shock imaging (below)

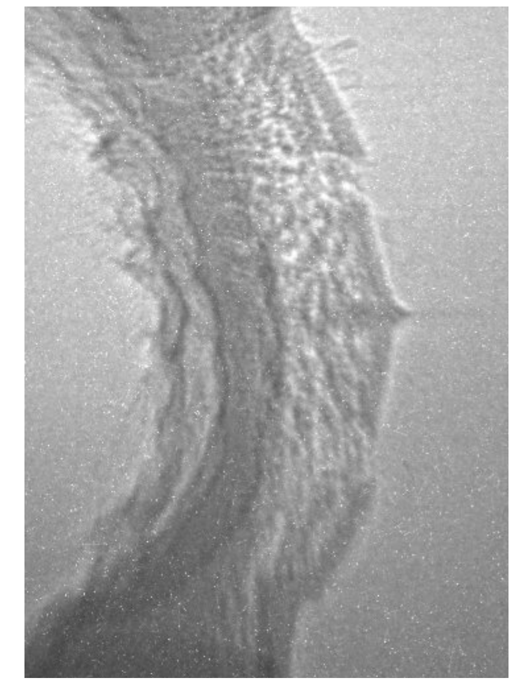


5 mm thick breast sample

mouse embryo raw image and HQ tomographic reconstruction



imaging of sintering powders



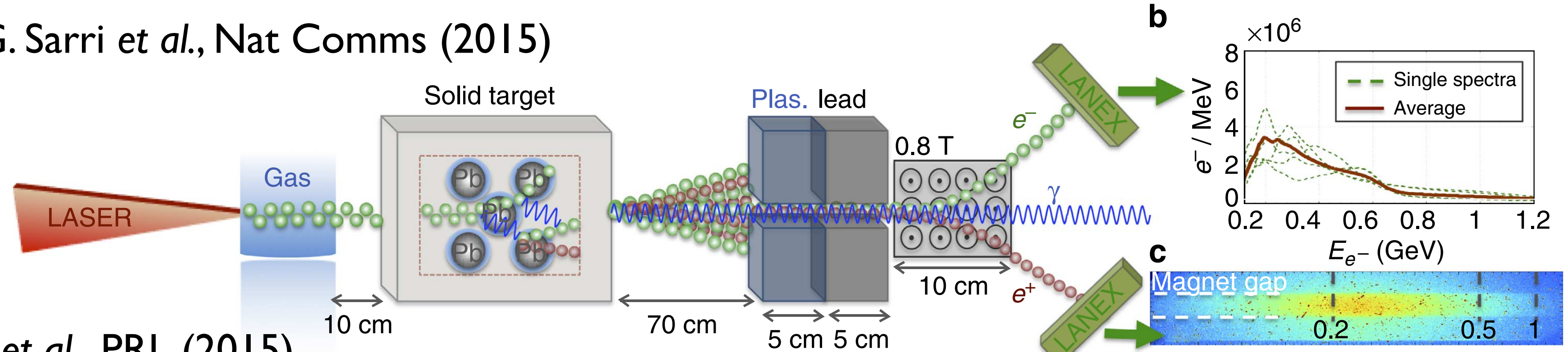
imaging of laser induced shocks

J. M. Cole, J. C. Wood, N. C. Lopes *et al.*, Sci. Rep. 5, 13244(2015)

e-e+ fireballs from lasers and beams

Experiment with LWFA beams demonstrated formation of e-e+ fireball

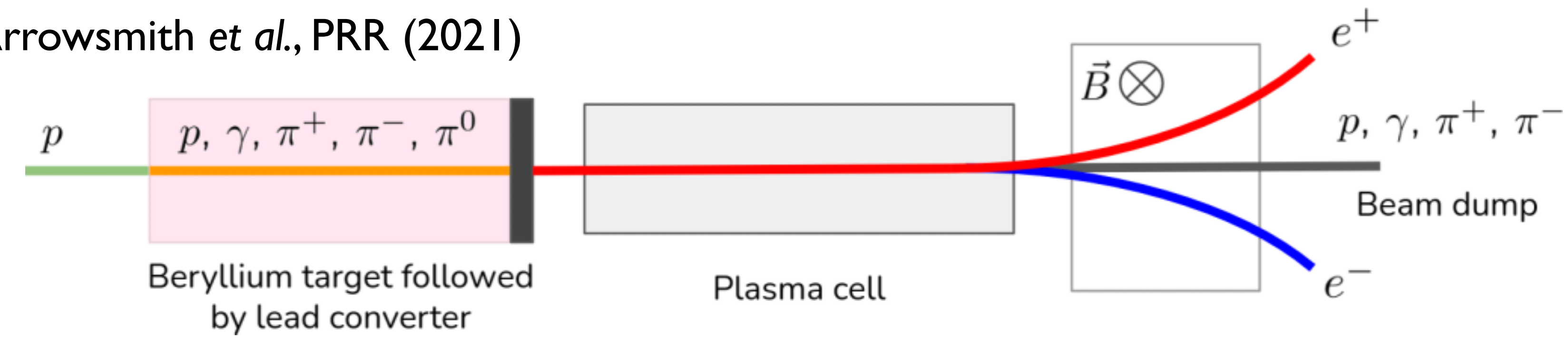
G. Sarri *et al.*, Nat Comms (2015)



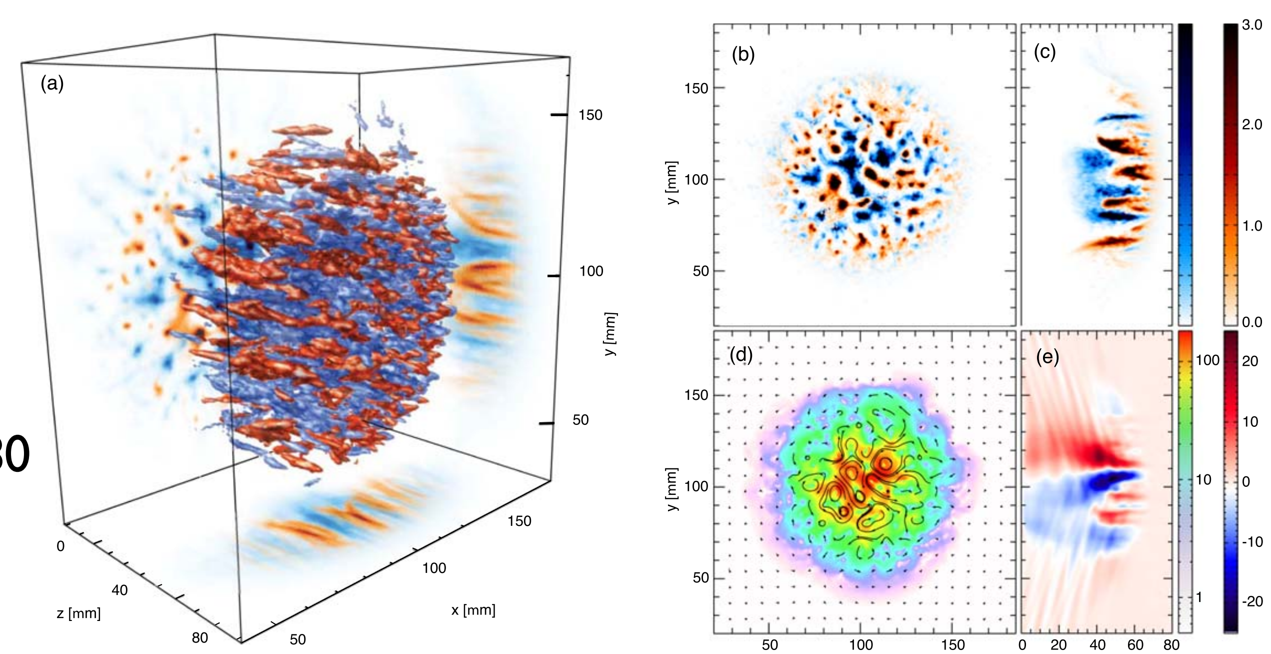
See also
H. Chen *et al.*, PRL (2015)

Generating ultradense pair beams using 400 GeV/c protons

C. D. Arrowsmith *et al.*, PRR (2021)

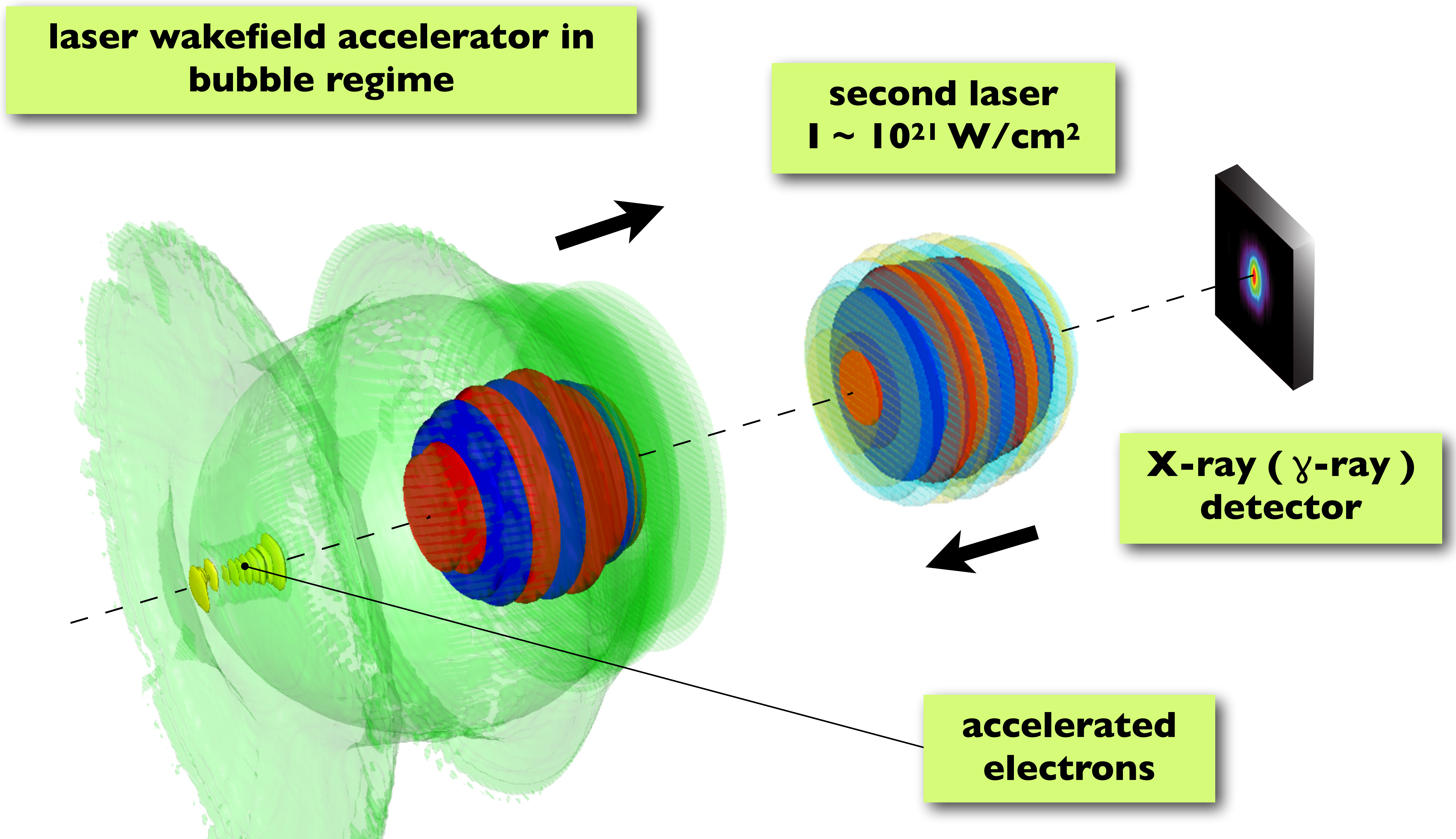


P. Muggli *et al.*, arXiv:1306.4380
N. Shukla et al., JPP (2018)
N. Shukla *et al.*, NJP (2020)



All-optical radiation reaction configuration

Identifying radiation reaction signatures and the emergence of quantum behaviour



S.V. Bulanov *et al.*, NIM A (2011)
A. G. R. Thomas *et al.*, PRX (2012)
M. Vranic *et al.*, PRL (2014)

[also connection with S. Cippicia *et al.*, Nature Physics (2011)]

The emergence of QED behaviour:
classical to quantum transition in the relativistic regime

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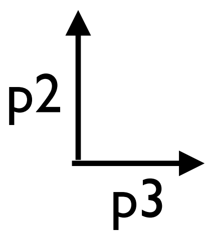
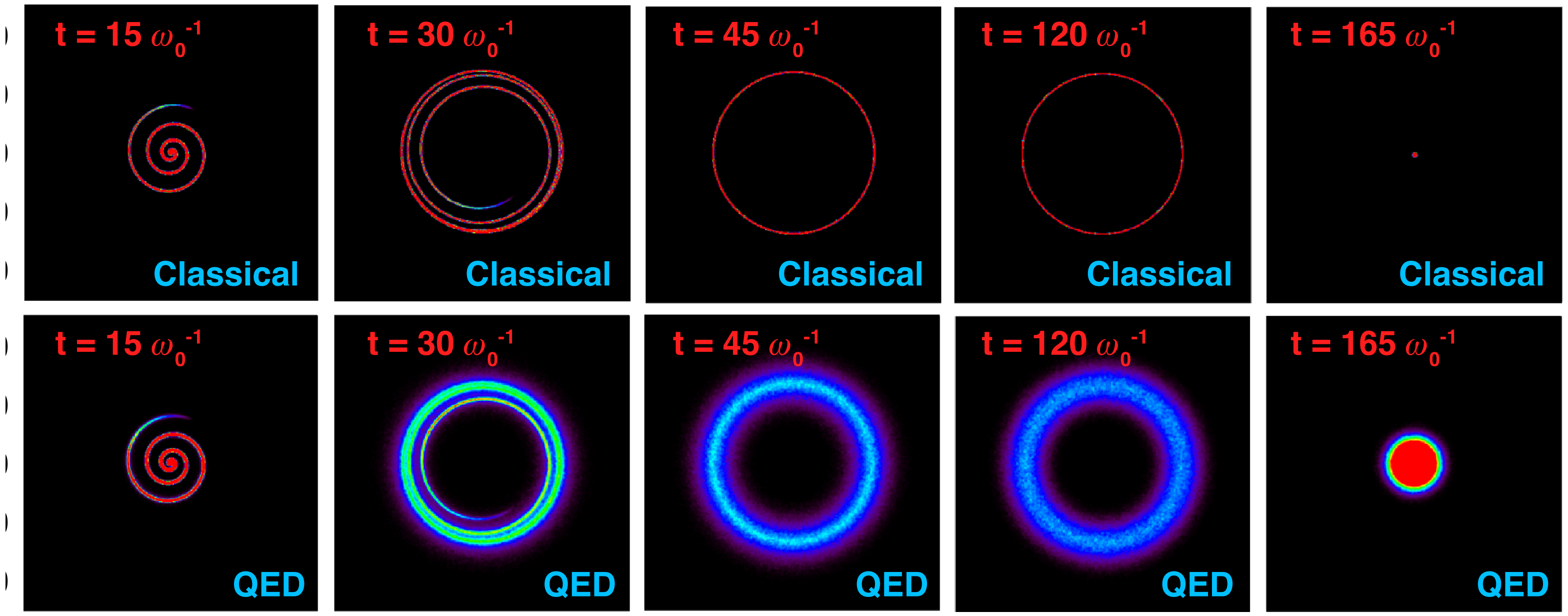
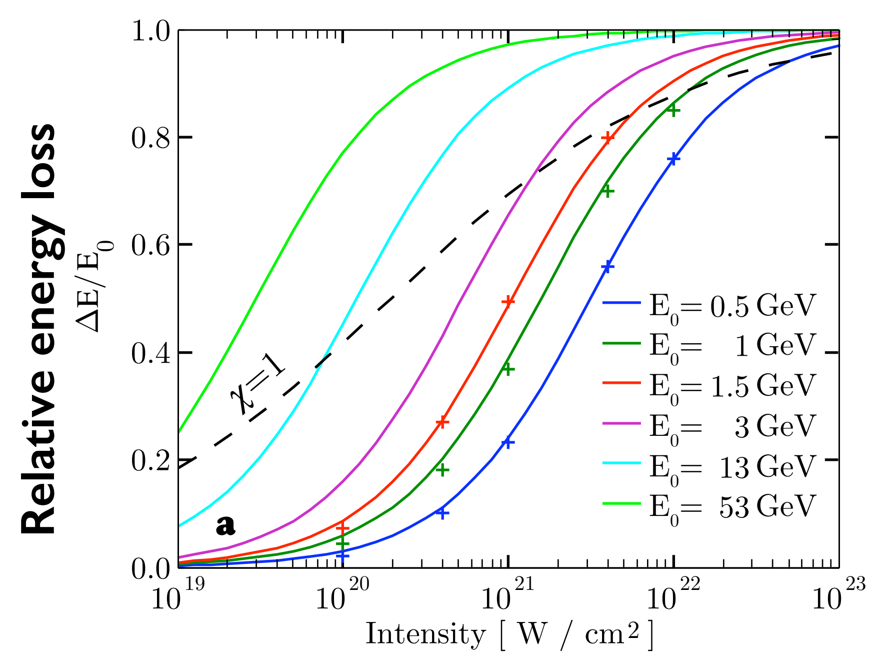
Transverse momentum space



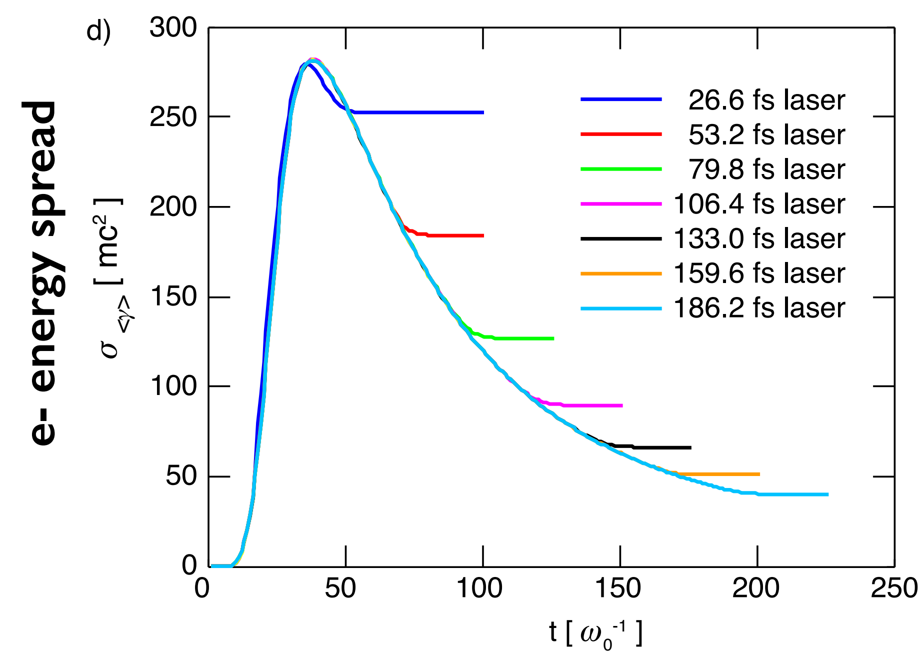


Energy loss for electron beams (classical)



M. Vranic *et al.*, PRL (2014)
M. Vranic *et al.*, Comput. Phys. Comm. (2016)

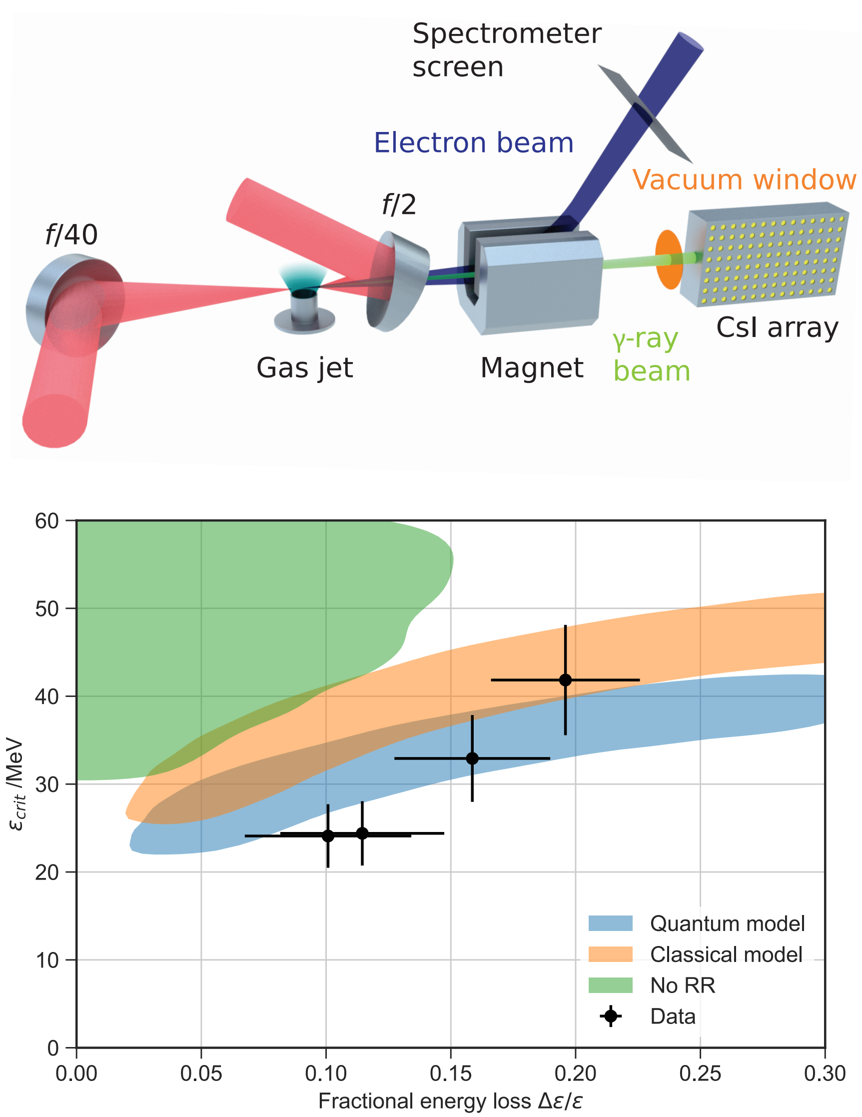
Competition: drift (classical) *vs* diffusion (quantum)



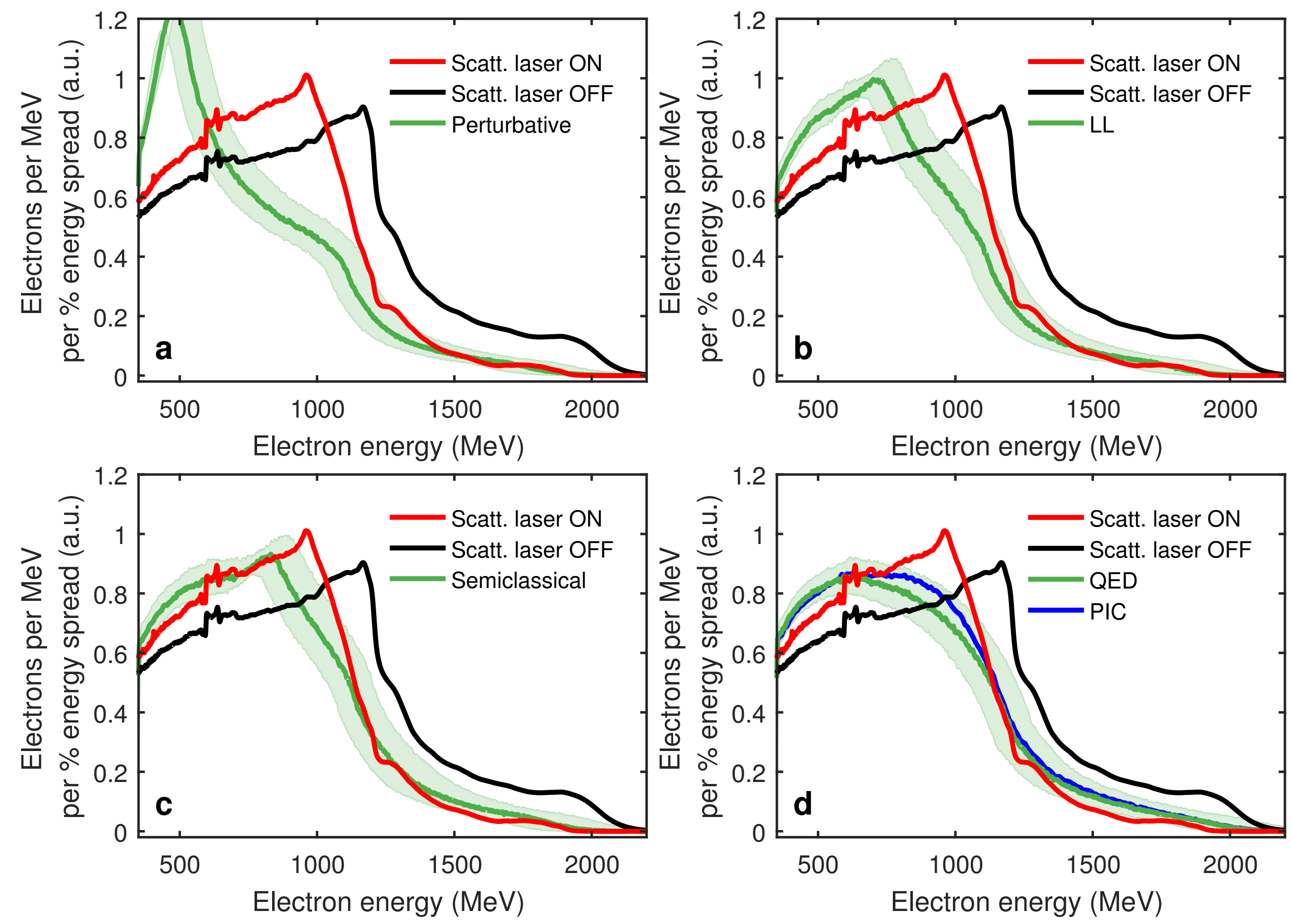
M. Vranic *et al.*, New J. Phys. (2016)
Also N. Neitz and A. Di Piazza, PRL (2013), S. Yoffe *et al.*, NJP (2015)

Recent experimental results provide evidence and open new questions

J. M. Cole *et al.*, PRX (2018)

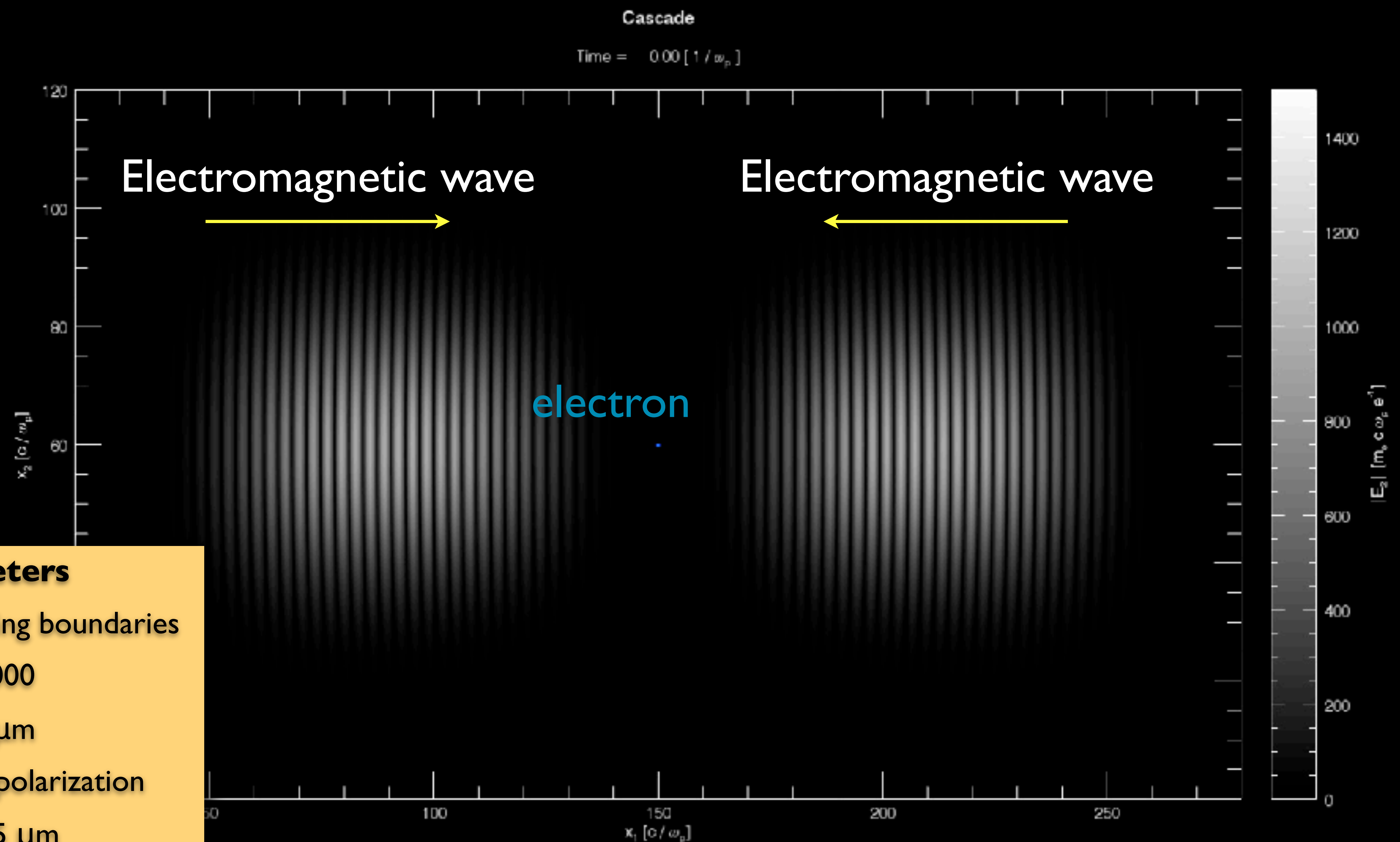


K. Poder *et al.*, PRX (2018)



QED cascades (& radiation cooling)

T. Grismayer *et al.*

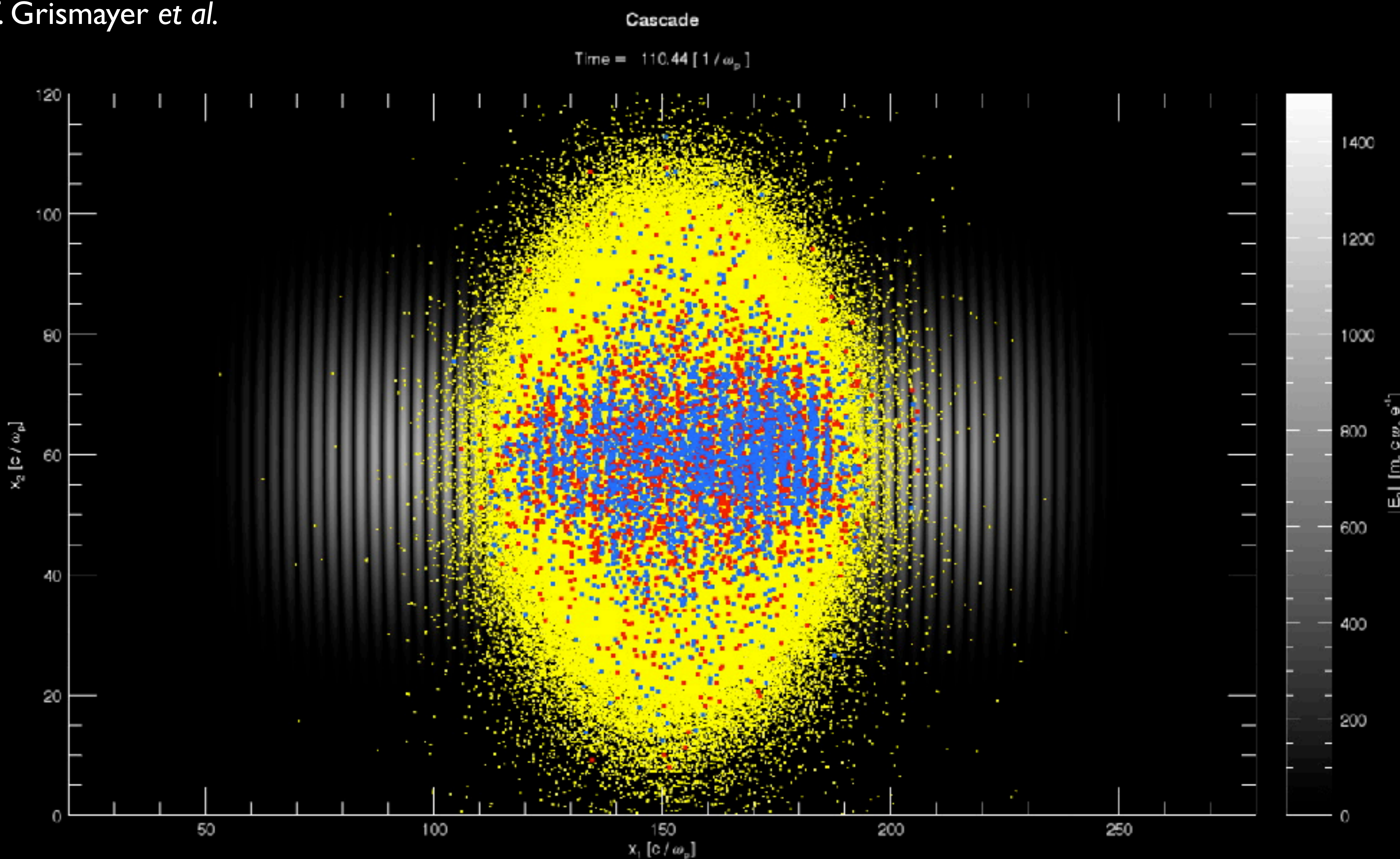


Parameters

- absorbing boundaries
- a0 = 1000
- λ0 = 1µm
- Linear polarization
- W0 = 5 µm
- τ = 30 fs

QED cascades in counter propagating electromagnetic fields

T. Grisмayer *et al.*



photons positron electron

Optimal QED configurations with standing waves

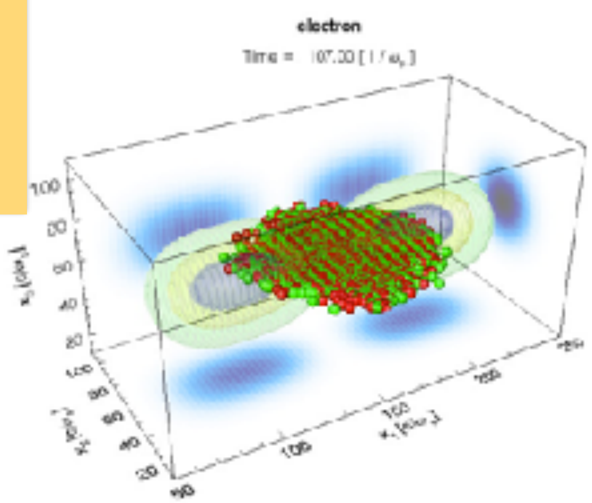
This requires finding where the parameter $\frac{1}{E_S}\sqrt{\left(\gamma \mathbf{E} + \frac{\mathbf{p}}{mc} \times \mathbf{B}\right)^2 - \left(\frac{\mathbf{p}}{mc} \cdot \mathbf{E}\right)^2}$ **reaches high values**

Parameters

- absorbing boundaries
- a0 = 1000
- λ0 = 1μm
- W0 = 5 μm
- τ = 30 fs

Linear

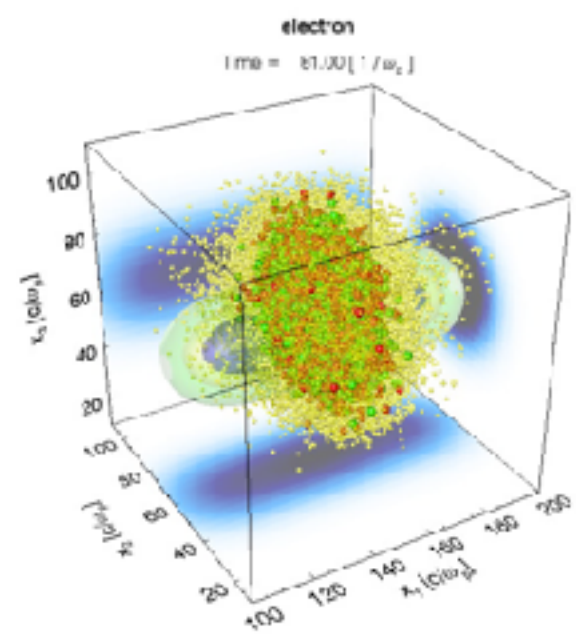
- **electron**
- **positron**



Particles remain in the x_1-x_2 plane

Double clockwise

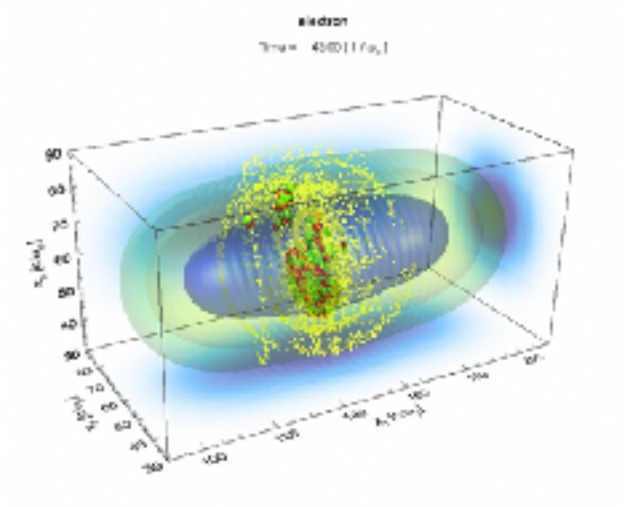
- **electron**
- **positron**
- **photon**



Particles explore the whole space

Clockwise-anti clockwise

- **electron**
- **positron**
- **photon**



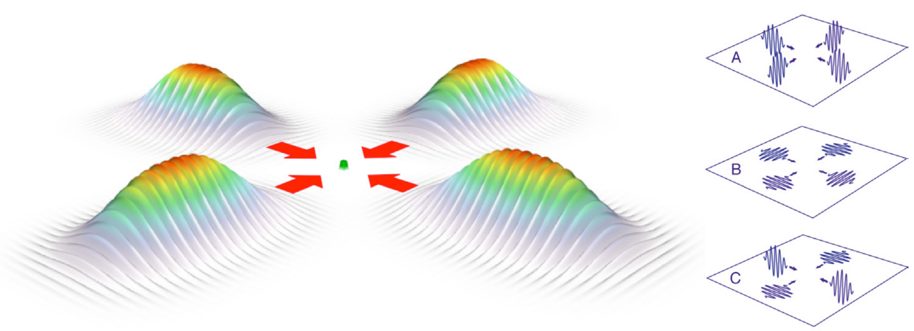
Particles rotate mainly in the x_2-x_3 plane

T. Grismayer et al., *PRE* 95, 023210 (**2017**)
T. Grismayer et al., *APS* DPP (**2012**)

Optimizing χ with multiple laser pulses

$$\chi = \frac{1}{E_S}\sqrt{\left(\gamma\mathbf{E} + \frac{\mathbf{p}}{mc}\times\mathbf{B}\right)^2 - \left(\frac{\mathbf{p}}{mc}\cdot\mathbf{E}\right)^2}$$

4 pulse configuration



$$\Gamma \sim \frac{8}{15\pi}\left(\frac{2\pi}{3}\right)^{\frac{1}{4}}\frac{\alpha}{\tau_c\bar{\gamma}}K_{1/3}^2\left(\frac{4}{3\bar{\chi}_e}\right)$$

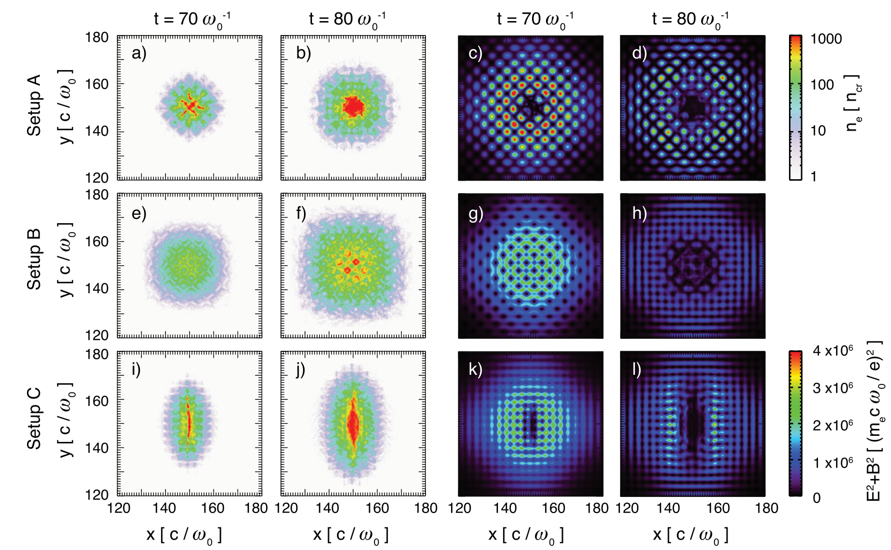
$$\chi_e \approx \frac{1}{E_S}\left\|\frac{\vec{p}}{mc}\times\vec{B}\right\|$$

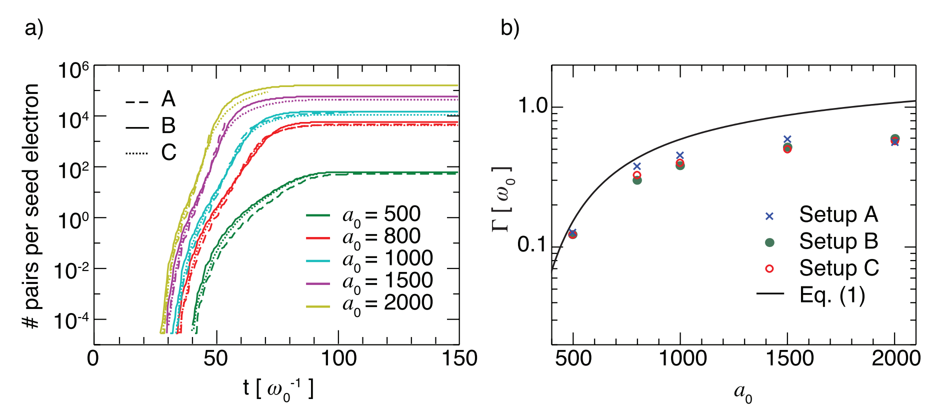
$\bar{\gamma} \approx 6a_0$ $\qquad$ $\bar{\chi}_e \approx 12a_0^2/(\pi a_S)$

$a_S = mc^2/(\hbar\omega_0)$

M.Vranic *et al.*, PPCF (2017), arXiv:1609.08081
Z. Gong *et al.*, PRE (2017), arXiv:1609.09567

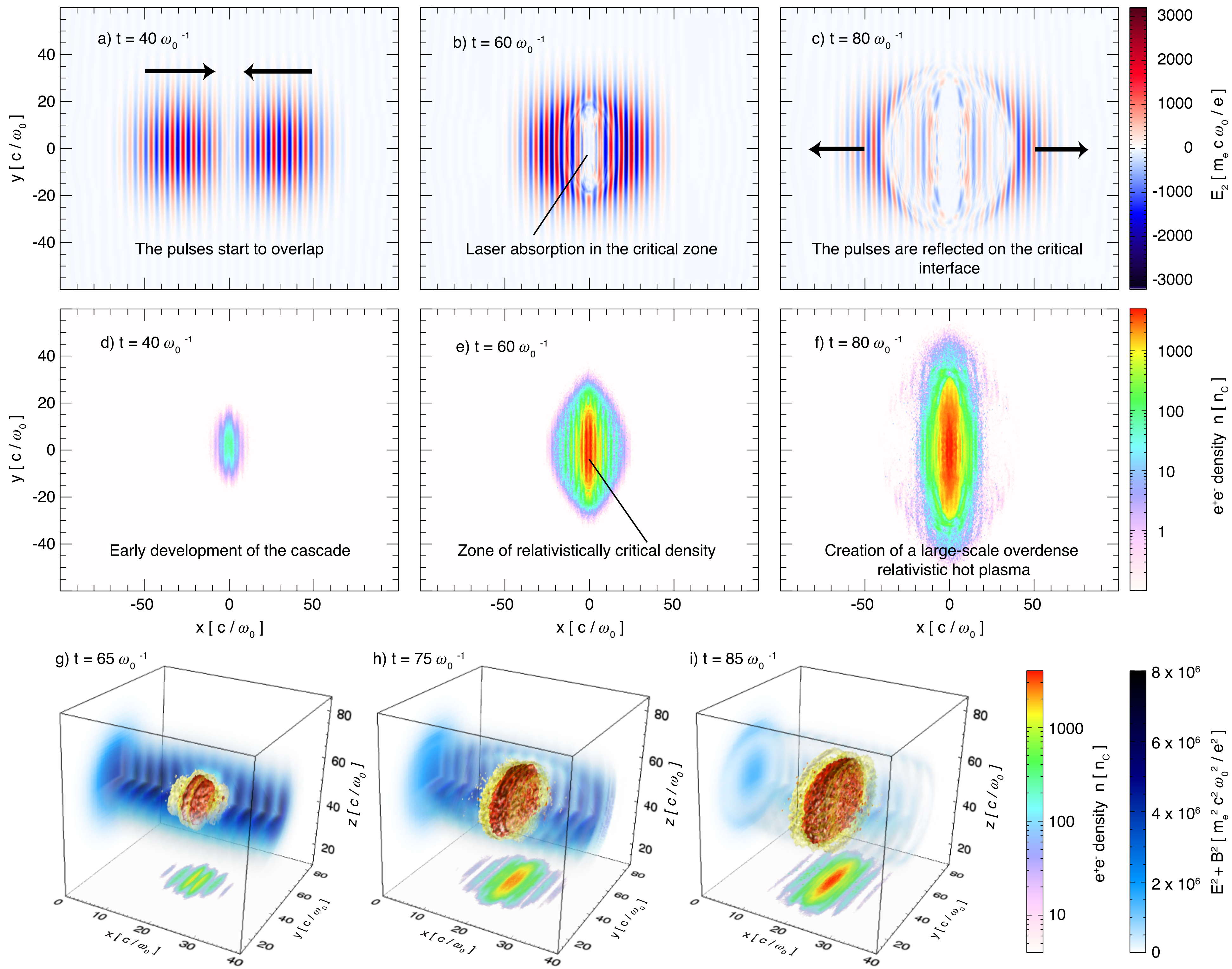
Standing wave pattern enhances e-e+ plasma





Ideal configuration has been first explored in I. Gonoskov et al., Phys Rev A (2012)

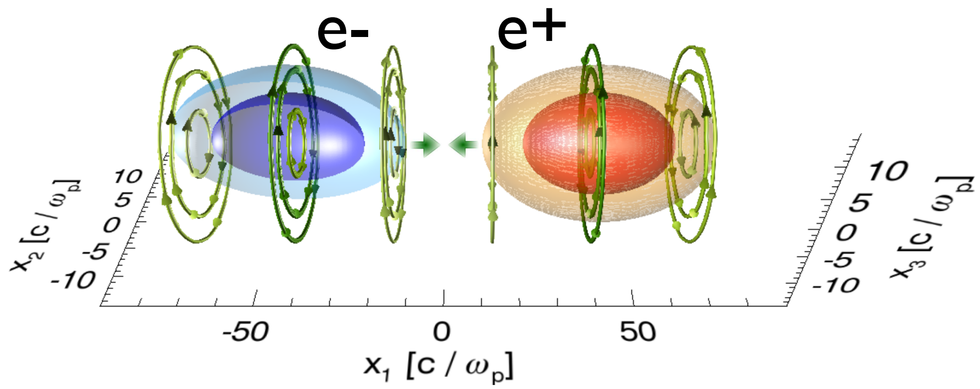
Self-consistent dynamics of e-e+ plasma impacts field dynamics



T. Grismayer *et al.*, PRE (2017)
T. Grismayer *et al.*, PoP (2016)
See also A. Fedotov *et al.*, PRL (2010); E. Nerush *et al.*, PRL (2011); V. Bashmakov *et al.*, PoP (2014)

Beam-driven scenarios are also of relevance

Beam-beam collider



At the interaction point, the particles in one beam will feel:

$$E_\perp \simeq B_\perp \sim e n_0 \sigma_0$$

$$E_\| \sim E_\perp / \gamma$$

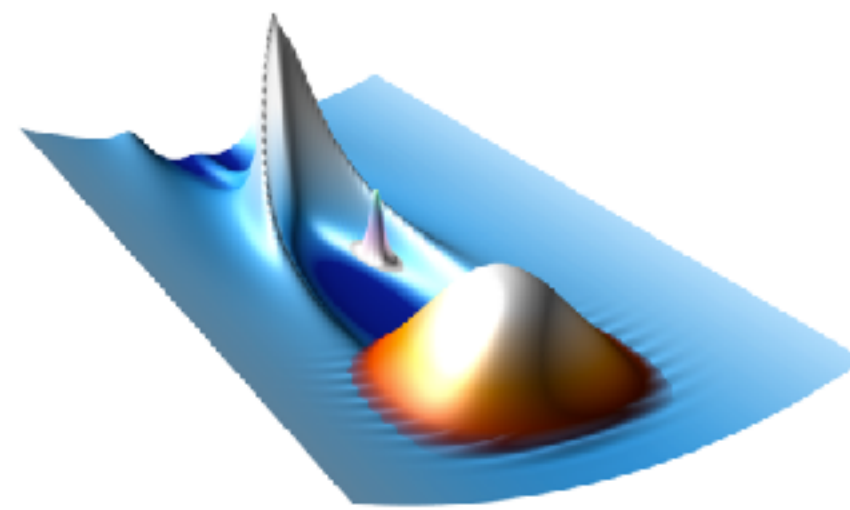
$$\chi(r,z) = 2\gamma B_\perp(r,z)/E_s$$

Beams will then pinch (in e- e- collider will diverge). Number of pinching points during crossing time is

$$D = \frac{r_e N \sigma_z}{\gamma \sigma_0^2}$$ Disruption parameter

P. Chen, S. Rajagopalan and J. Rosenzweig, PRE (1989)
P. Chen and K. Yokoya *et al.*, PRD (1988)
T. Katsouleas *et al.*, PoP (1990)

Betatron in ion channels



$$E_\perp = 4\pi e n_{e0} \frac{r}{2} \qquad \chi(r) = \gamma \frac{E_\perp}{E_s}$$

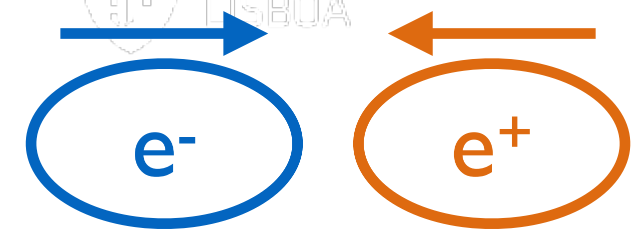
In the blowout regime $n_{\rm beam} > n_{e0}$

Beam can drive ion channel

For small emittance, long propagation in ion channel @ 30 GeV

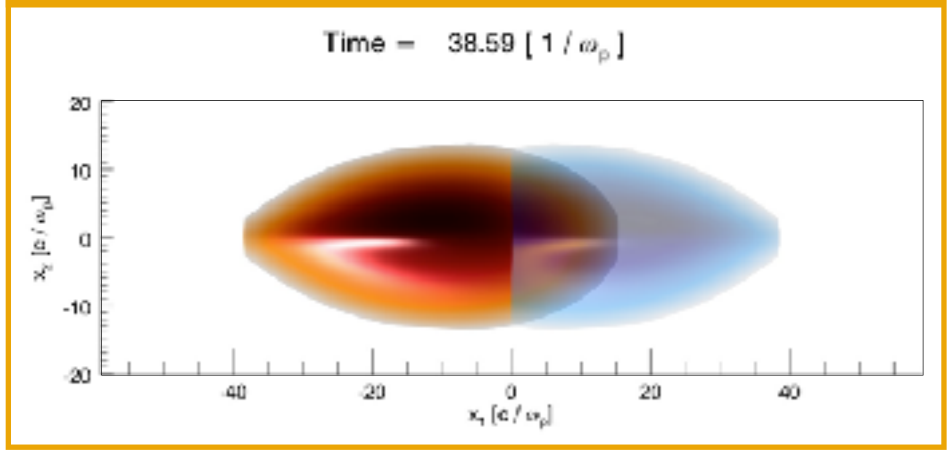
$$\sigma_0 \approx \mu{\rm m} \qquad \chi \approx 0.1 - 1$$

High disruption e⁻e⁺ colliding beams prone to QED effects

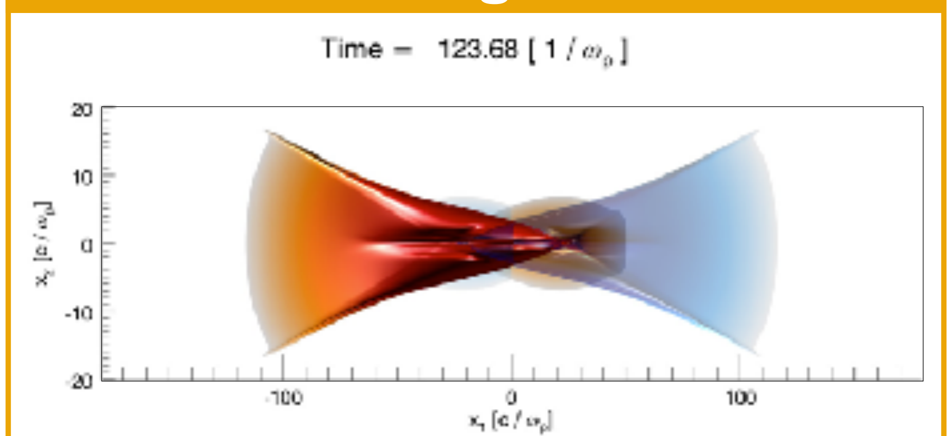


$$D = \frac{r_e N \sigma_z}{\gamma \sigma_0^2}$$

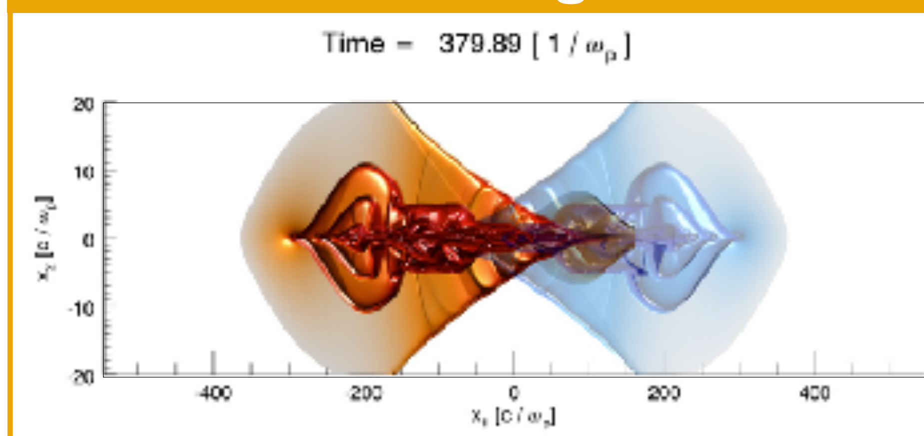
Low disruption regime D<1



Transition regime 1<D<10



Confinement regime D>10

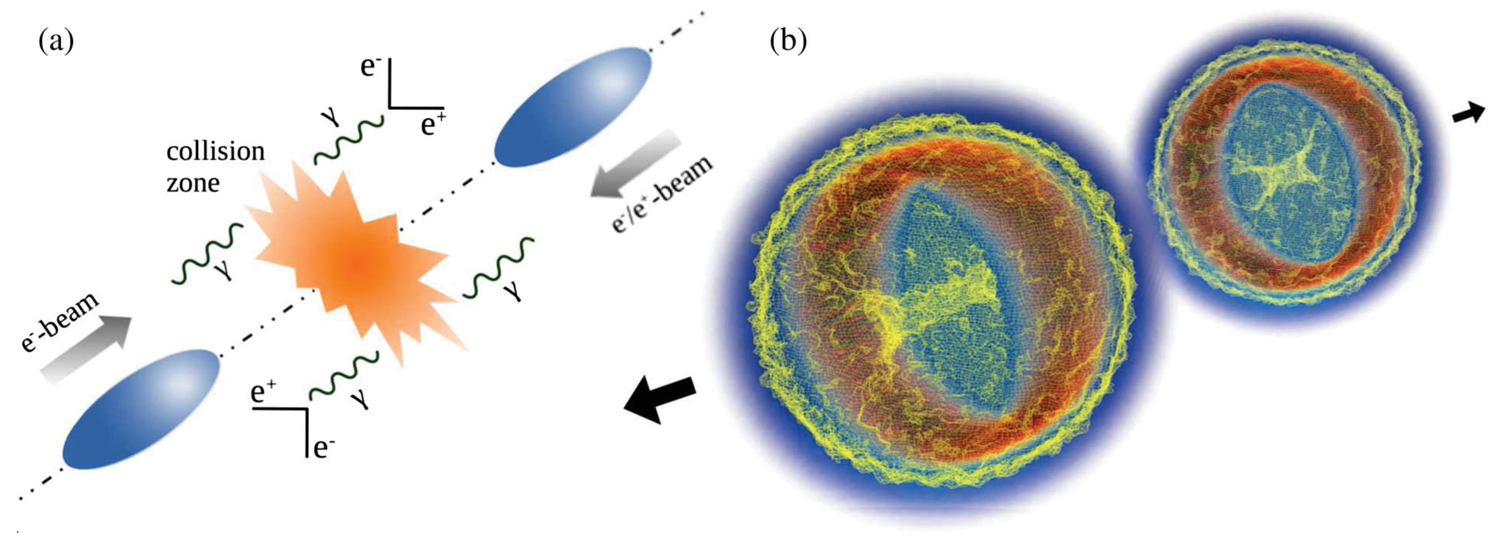


Electron beam density
Positron beam density

Exploring LWFA like beams for radiation in the low D regime
F. Del Gaudio, *et al.*, PRAB 2019

Medium to high D regime - W. L. Zhang *et al.*, in preparation

SLAC PWFA @ 500 GeV can reach the QED regime (and beyond)



Energy : 500 GeV
N : 10^{10}
Length : 15 μm
Spot size : 15.7 nm

@ Interaction Point D > 1 χ >30

Abundant secondary pairs are created in a stochastic manner, leading to the kink instability

Additional note: also possible to reach conditions where QED might "breakdown"

Ritus-Narozhny conjecture: the expansion parameter of QED in the strong field sector is

V. Ritus, AP (1972); N. Narozhny, PRD (1980)
A. Fedotov, JP Conf Series (2017)

$$\alpha \chi^{2/3}$$

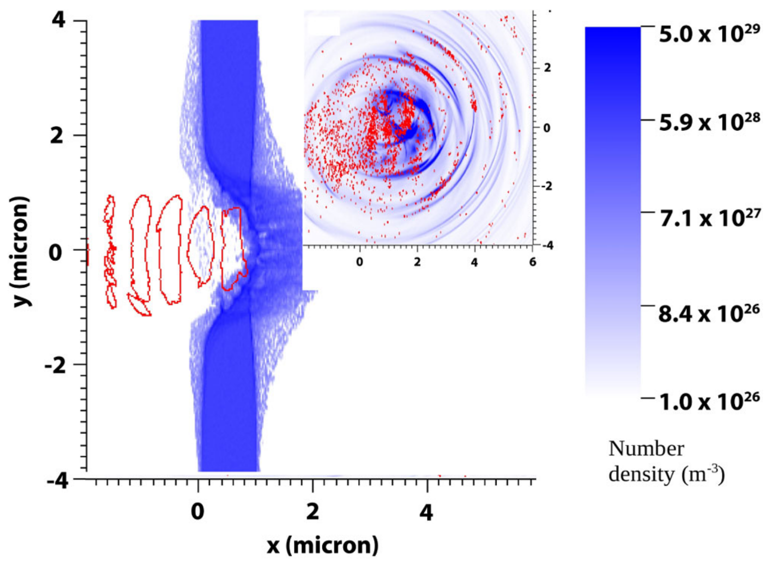
i.e. QED becomes a strongly coupled theory if $\alpha \chi^{2/3} \gtrsim 1$

V. Yakimenko *et al.*, PRL (2019)
also C. Baumann *et al.*, Sci Reports (2019), T. Blackburn *et al.*, NJP (2019)
for electron beam - laser configuration

System (plasma) size $W_0^3 \sim \left(\text{few}\,\mu m\right)^3 \gtrsim \left(\text{few}\,\lambda_D\right)^3$

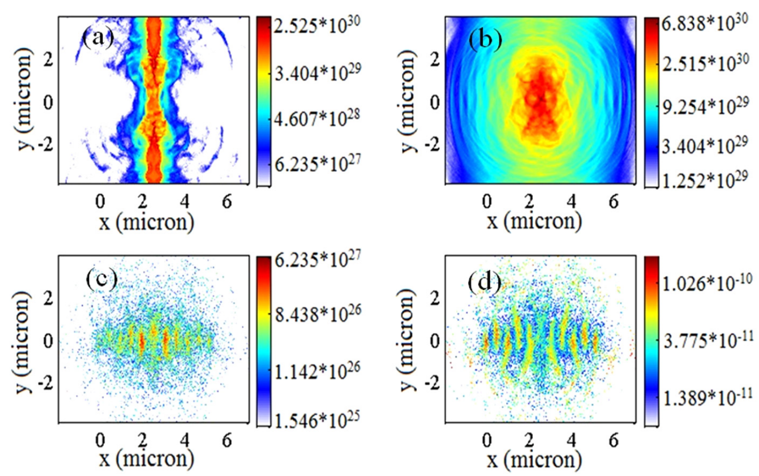
$n_{e^-e^+} \gtrsim 10^{20}\text{cm}^{-3}$ LOS *et al.*, in preparation

QED in hole boring



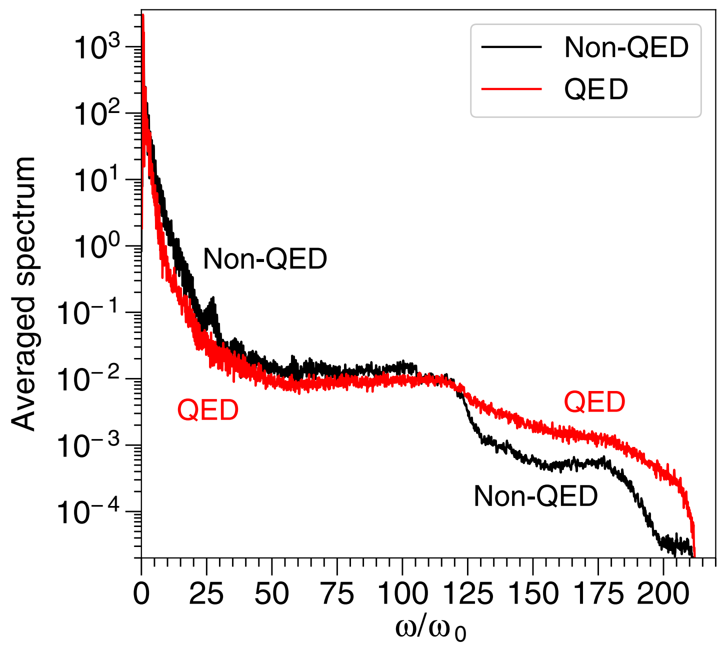
C. Ridgers *et al.*, PRL (2012)

QED in ~n_c targets with 2 lasers



W. Luo *et al.*, PoP (2015)
T. Grismayer *et al.*, PoP (2016)

QED in HHG



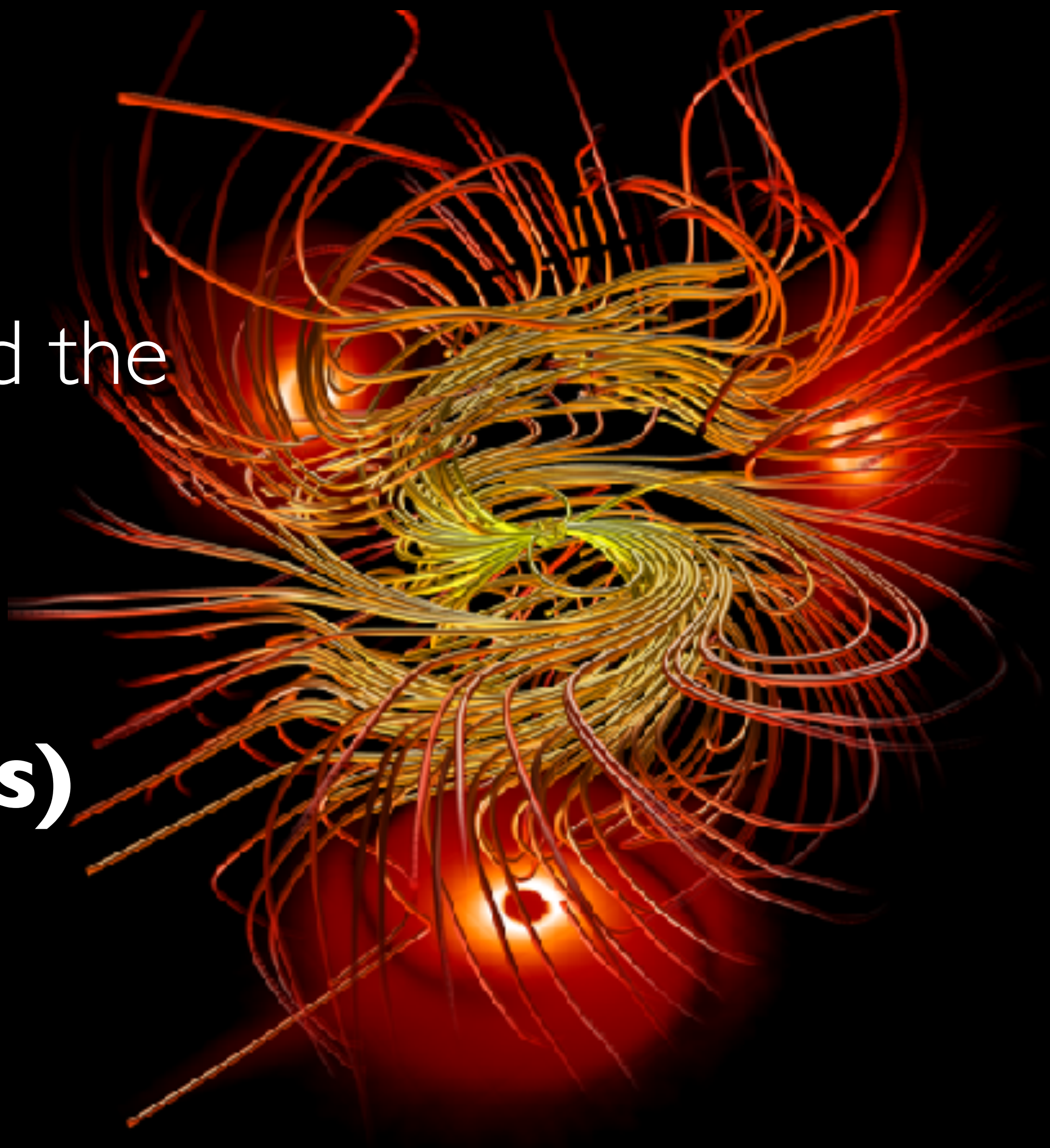
W. L. Zhang *et al.*, PRE (2021)

For beam-beam collisions, collective effects when $D \gtrsim 1$

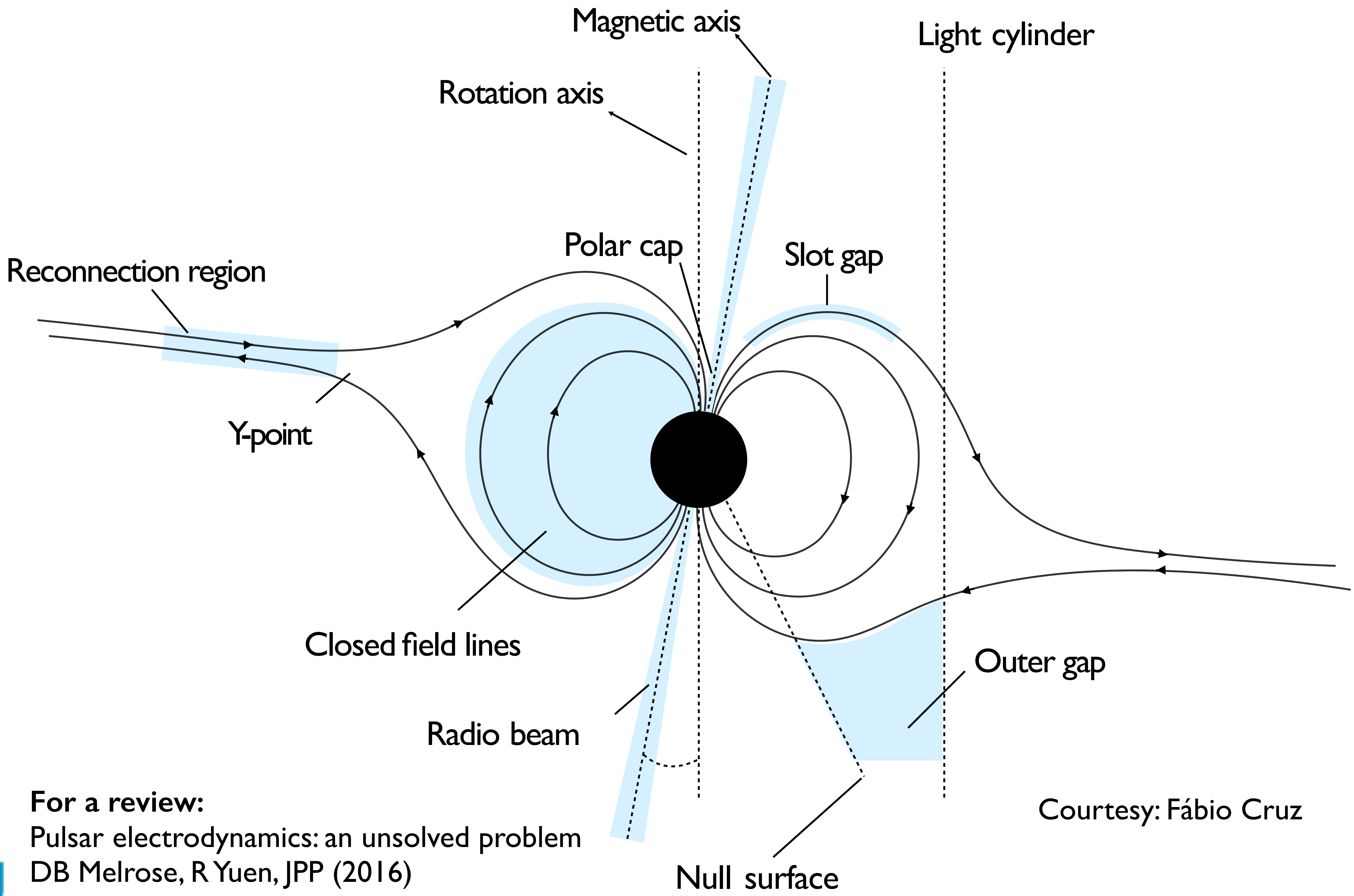
Extreme Plasma Physics

Ultra intense lasers & particle beams and the intensity frontier

QED plasma processes in relativistic astrophysics (pulsars)



Understanding the properties of the magnetospheres of neutron stars/pulsars from first principles



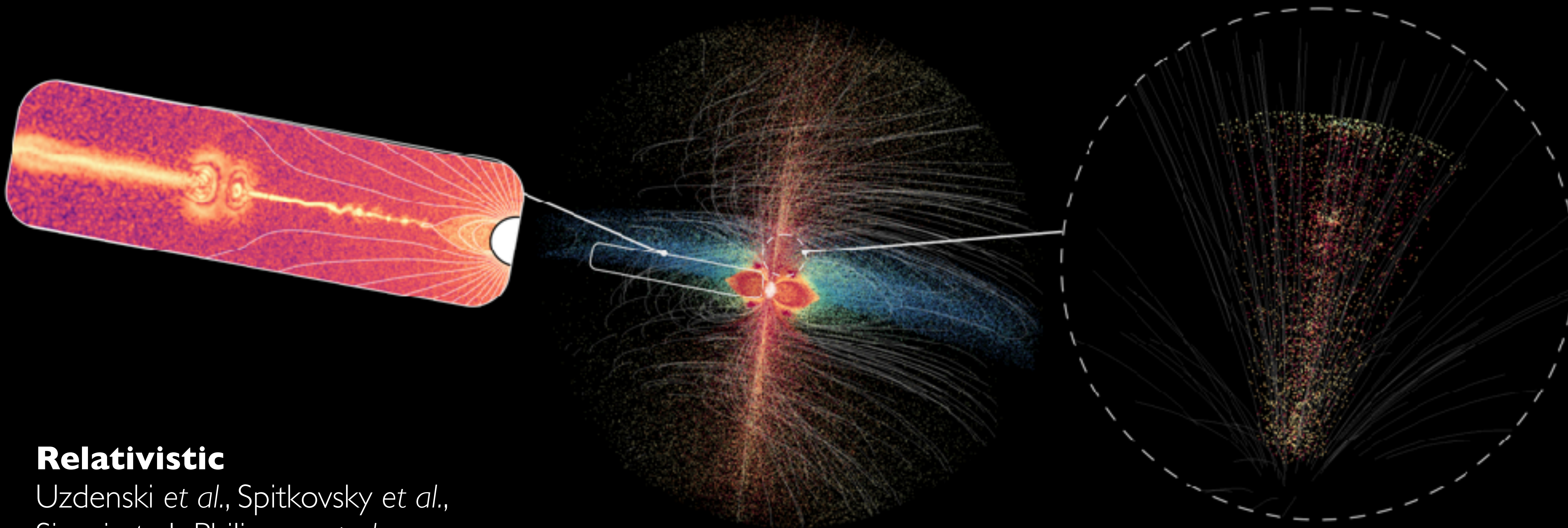
For a review:
Pulsar electrodynamics: an unsolved problem
DB Melrose, R Yuen, JPP (2016)

Courtesy: Fábio Cruz

Global

Reconnection

Polar Cap

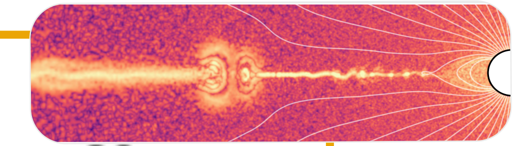


Relativistic
Uzdenski *et al.*, Spitkovsky *et al.*, Sironi et al., Philippov *et al.*
QED
Schoeffler *et al.*

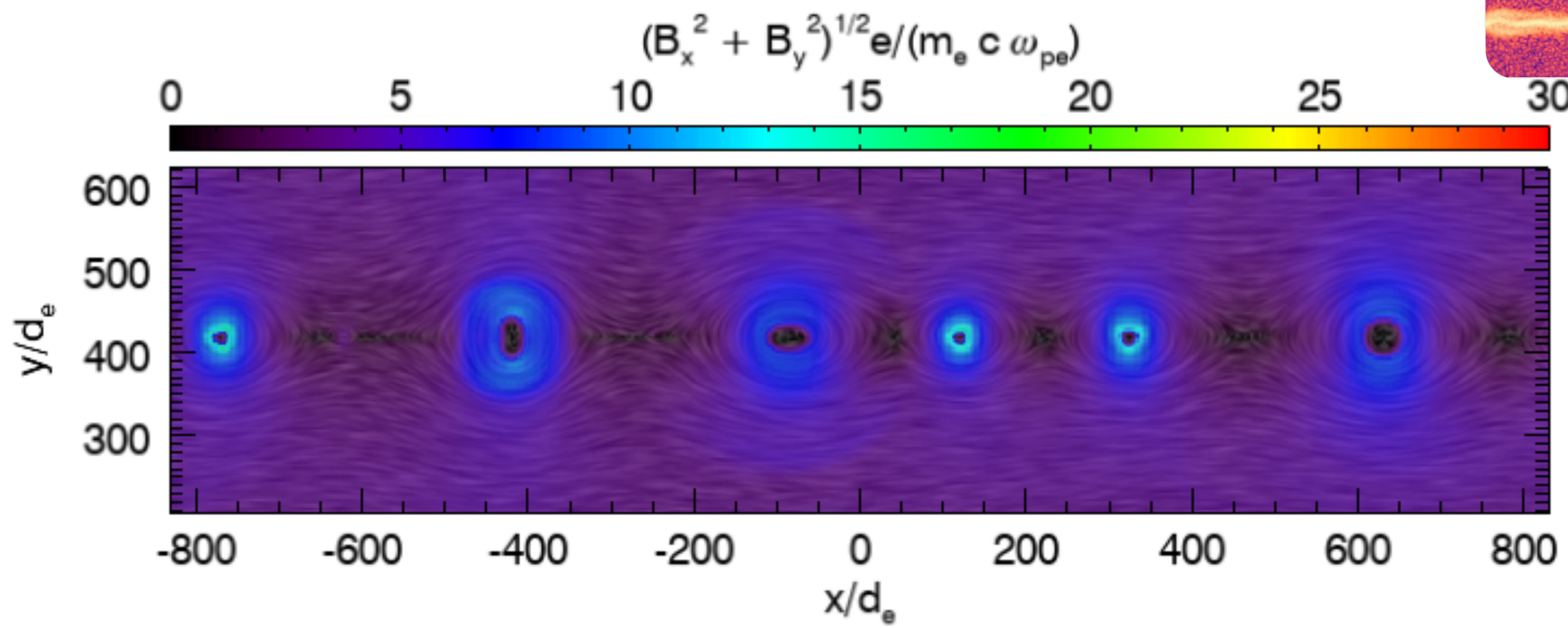
Spitkovsky *et al.*, Cerruti *et al.*, Philippov *et al.*
GR
Spitkovsky *et al.*
(BH) Parfrey *et al.*, Torres *et al.*

Timokhin & Arons, Philippov *et al.*, Cruz *et al.*

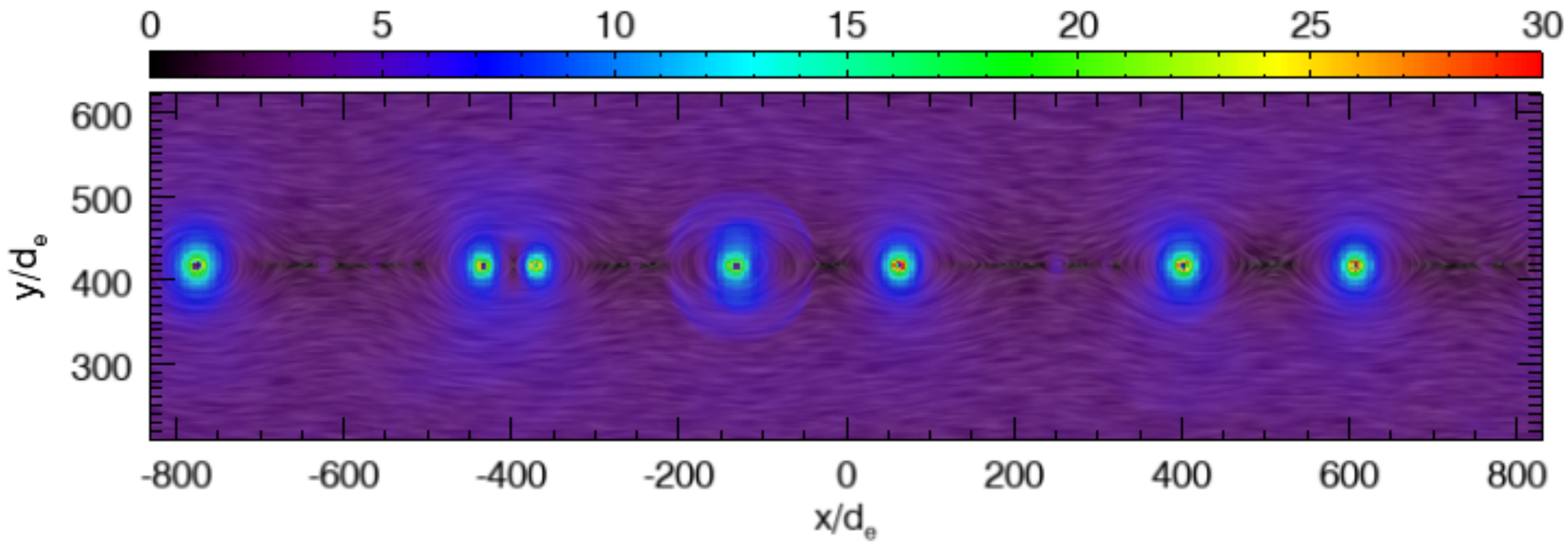
In-plane B field (compression) shows clear differences



Classical relativistic reconnection



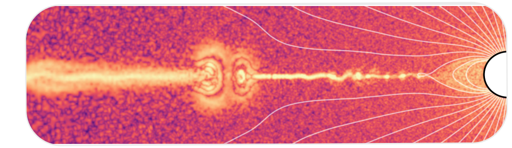
QED reconnection with pairs



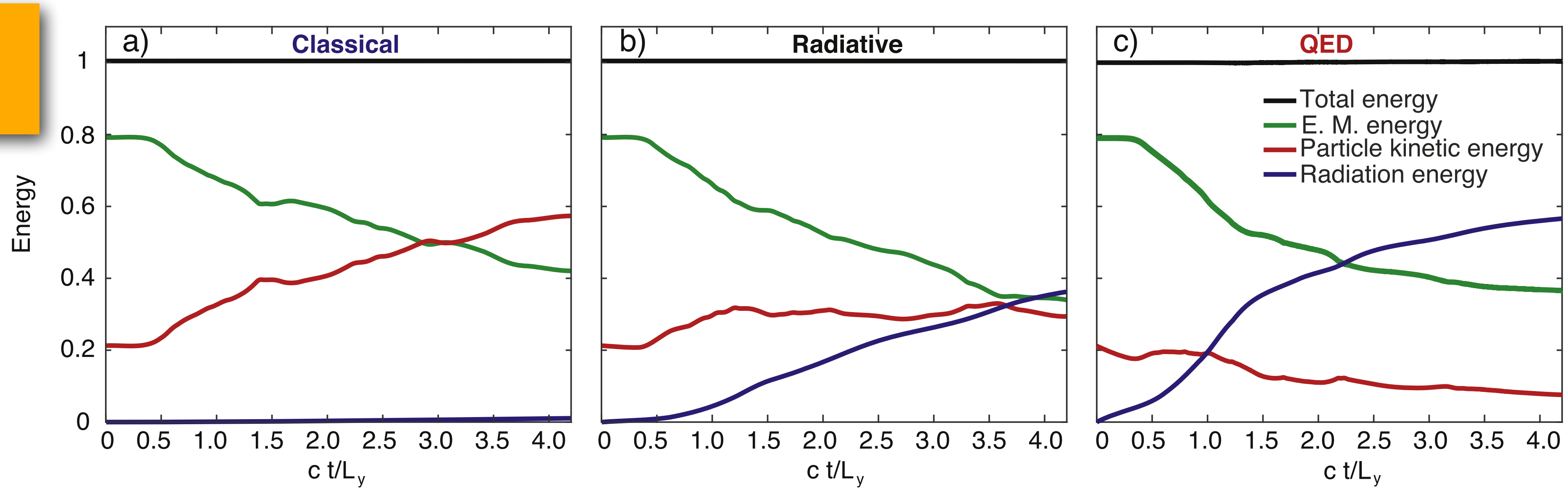
K. Schoeffler *et al.*, ApJ (2019)

Significant differences depending on regime

TÉCNICO LISBOA

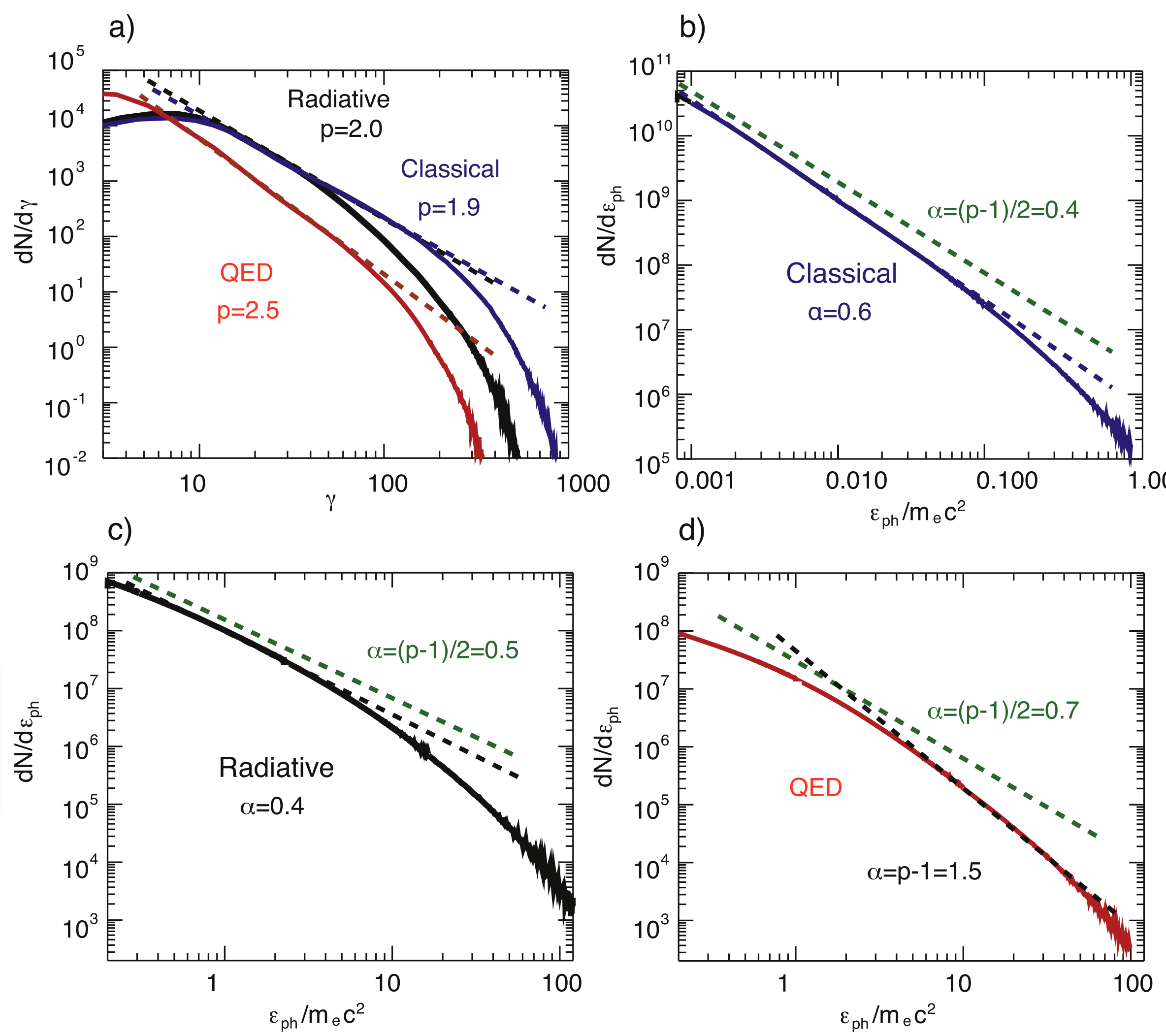


Energy



e- spectrum

photon spectrum



K. Schoeffler *et al.*, ApJ (2019)

Cyclic outflow of e-e+ bursts accompanied by kinetic instabilities

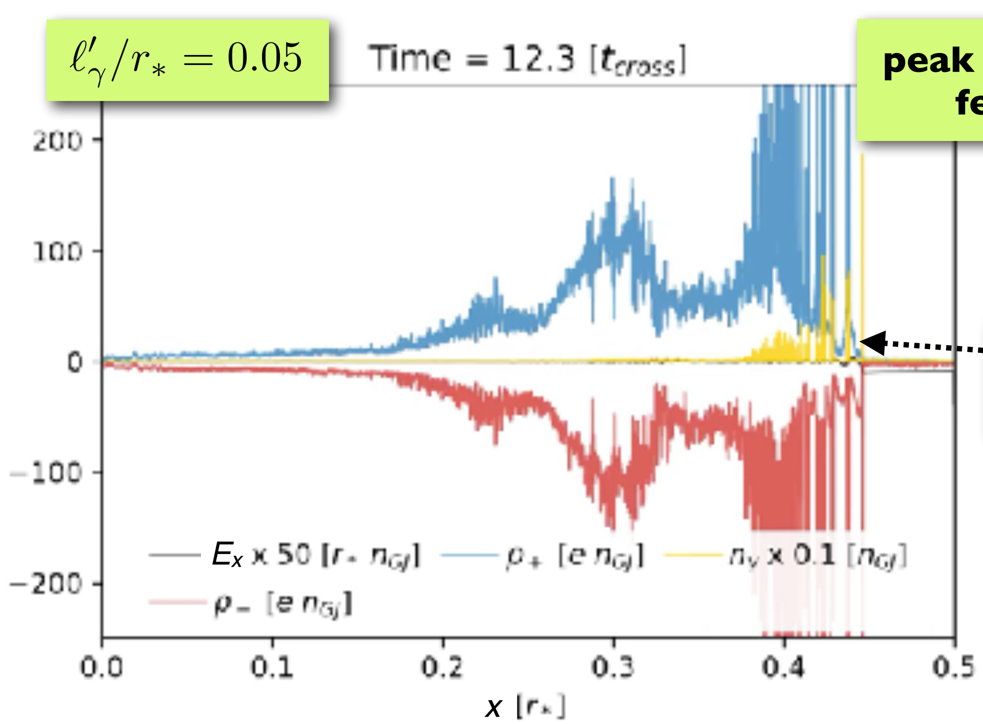
Modelling pulsar polar vacuum gaps

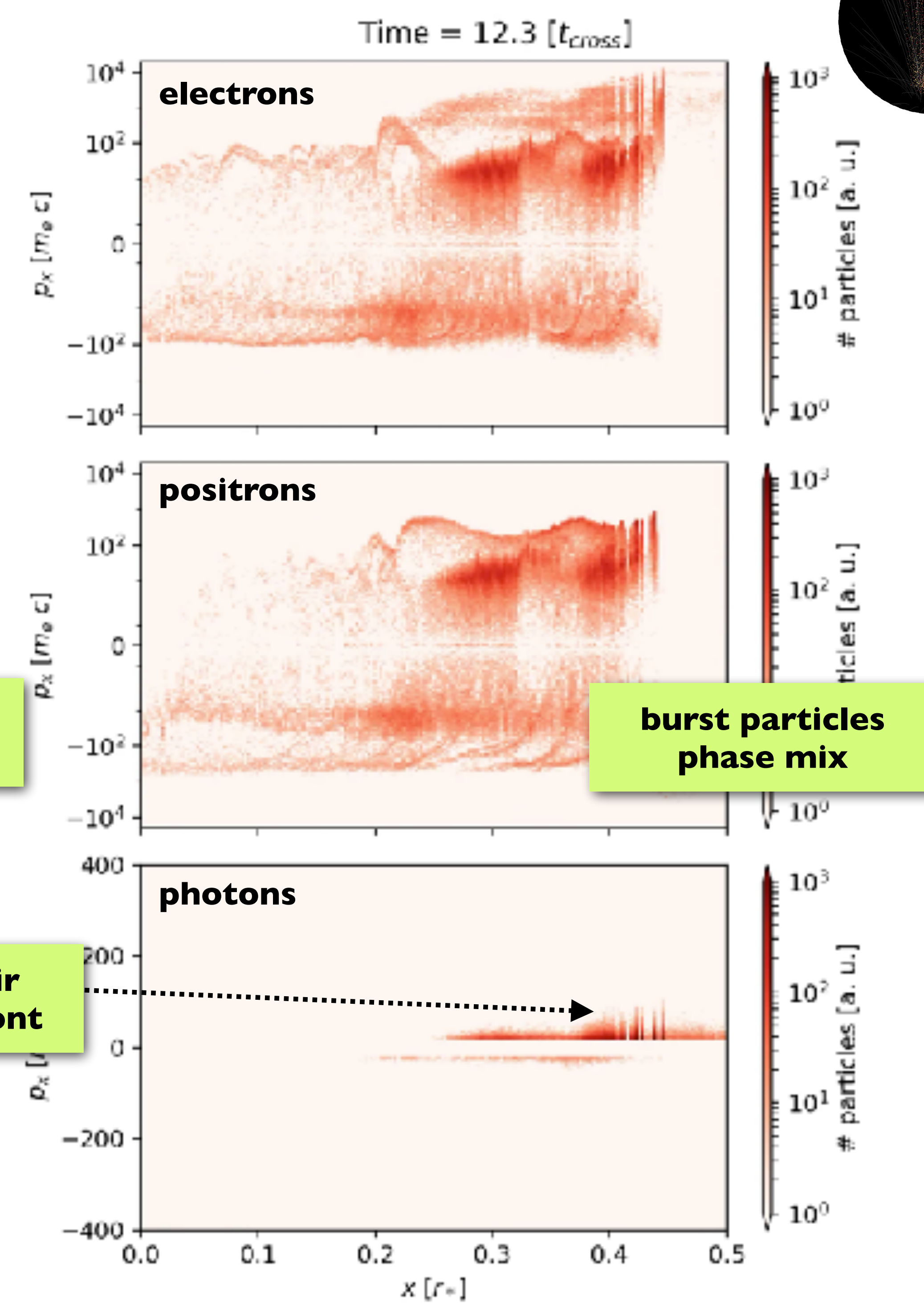
1D cascades with constant curvature **B** show cascade-shielding cycles with:

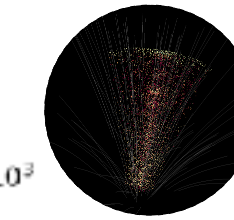
Co-rotation frame $\nabla \cdot \mathbf{E} = 4\pi(\rho - \rho_{\mathrm{GJ}})$

An imposed current component $\mathbf{J_m}$ required by the magnetosphere

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi(\mathbf{J} - \mathbf{J}_{\mathrm{m}}) \qquad \mathbf{J_m} = 1.5\ \rho_{\mathrm{GJ}} c\ \hat{\mathbf{x}}$$







F. Cruz *et al.*, ApJ (2021); *idem*, PRE (2021)

Set-up similar to A. Timokhin & Arons, see also A. Philipov *et al.*, PRL (2020)

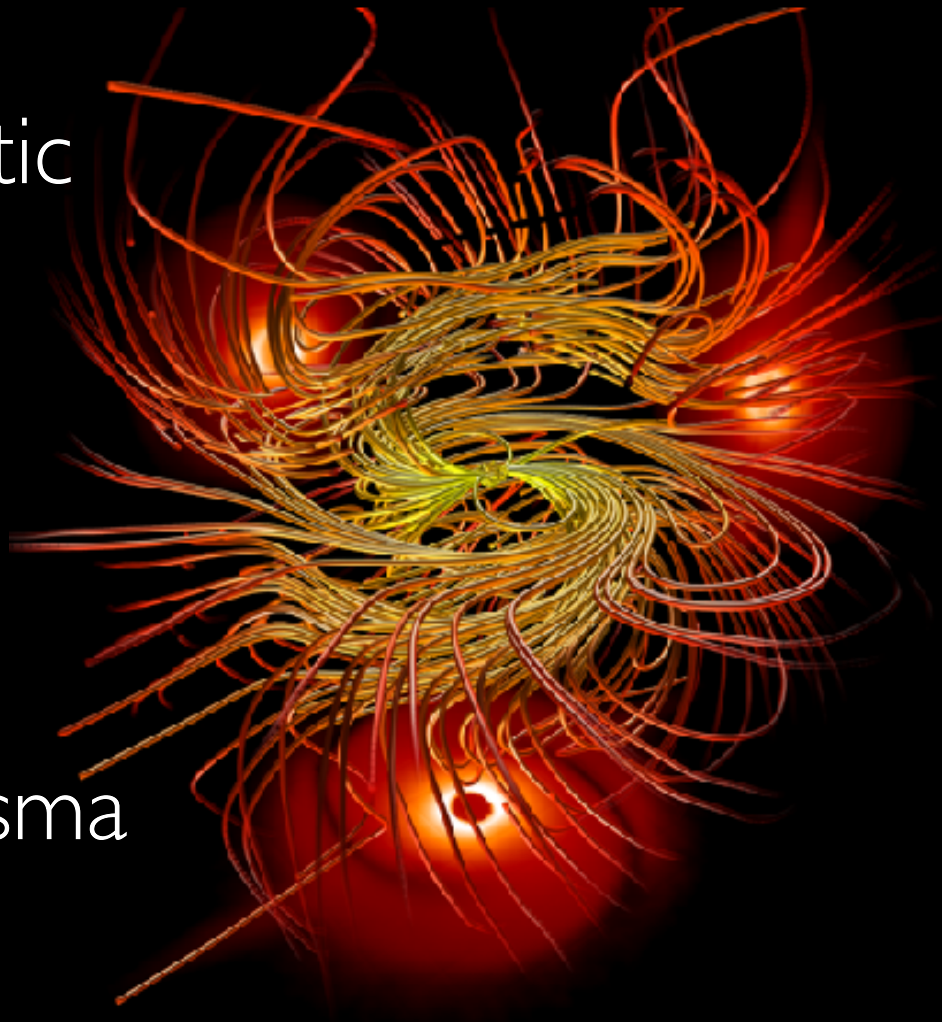
Exciting frontiers in extreme plasma physics

Several open questions in fundamental QED processes in intense fields + *expressing/* benchmarking those processes in plasma kinetic codes

Optimization/configurations for secondary sources of gamma rays and e+

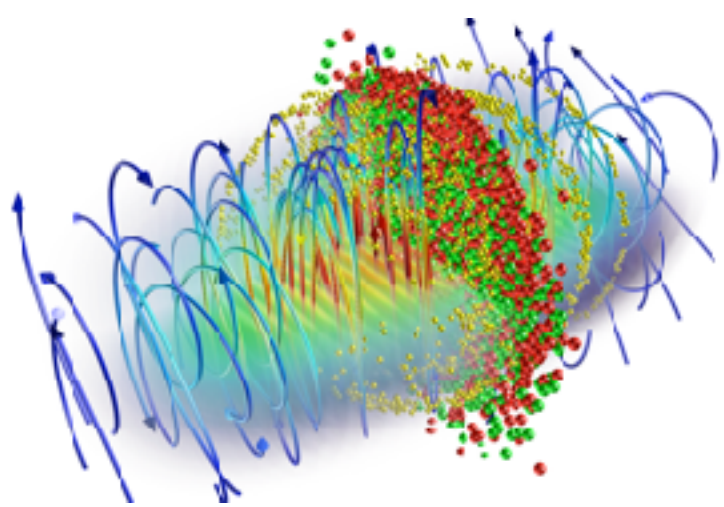
Radiation signatures of collective extreme plasma processes in laboratory and in astrophysics

Coupling with GR



Revolutionary computational power is reshaping our understanding of plasmas in extreme conditions

We now have the ability to explore multi-scale processes from first principles with unprecedented detail and explore unique highly nonlinear scenarios - some of these to be explored soon in the laboratory, others with astrophysical consequences



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Advanced Program in Plasma Science and Engineering

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It awards a PhD degree in Physics or Engineering Physics.

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Application deadline: 28 January 2022

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