Laser-wakefield experiments to probe high-field QED

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Introduction

Radiation Reaction

⇒ Radiation Reaction is one of the oldest and most fundamental problems in electromagnetism: How do we correctly model the electron dynamics if we include radiative losses?

0. Classical Lorentz force

$$m\frac{du^{\mu}}{ds} = eF^{\mu\nu}u_{\nu}$$

X No energy loss

1. LAD Equation

Schott's term

$$m\frac{du^{\mu}}{ds} = eF^{\mu\nu}u_{\nu} + \frac{2}{3}e^2\left(\frac{d^2u^{\mu}}{ds^2} + \frac{du^{\nu}}{ds}\frac{du^{\nu}}{ds}u^{\mu}\right)$$

✓ Damping force (radiation reaction term)

X Classical renormalisation (point-like electron)

X Runaway solutions! (diverging acceleration even without external field)

2. LL Equation

$$m\frac{du^{\mu}}{ds} = eF^{\mu\nu}u_{\nu} + \frac{2}{3}e^2\left(\frac{e}{m}(\partial_{\alpha}F^{\mu\nu})u^{\alpha}u_{\nu} - \frac{e^2}{m^2}F^{\mu\nu}F_{\alpha\nu}u^{\alpha} + \frac{e^2}{m^2}(F^{\alpha\nu}u_{\nu})(F_{\alpha\lambda}u^{\lambda})u^{\mu}\right)$$

✓ No runaway solutions

✓ Valid in classical relativity

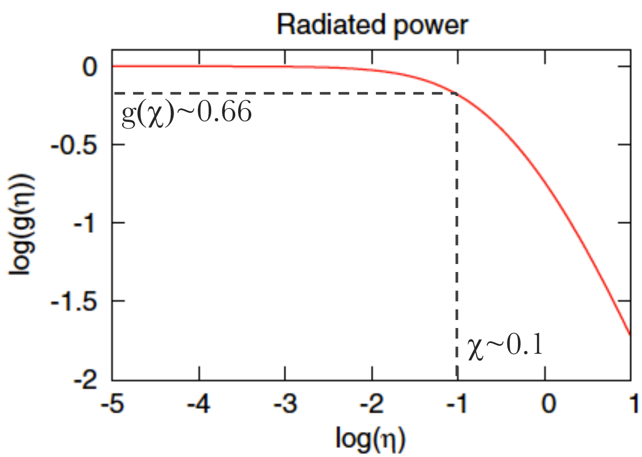
$\lambda >> \alpha\lambda_C$ (localised wavefunction)

$F << F_{cr}/\alpha$ (classical critical field)

Quantum Radiation Reaction

⇒ The classical treatment of radiation reaction neglects three main additional phenomena:

1. The energy of a single emitted photon can not exceed that of the electron



Generally speaking, this leads to a classical overestimate of the total energy loss experienced by the electron $(\chi = \gamma F_L / F_S)$

$$g(\chi) \sim \left(3.7\chi^3 + 31\chi^2 + 12\chi + 1\right)^{-4/9}$$

J. G. Kirk et al., PPCF 2013

A. G. R. Thomas et al., PRX 2012

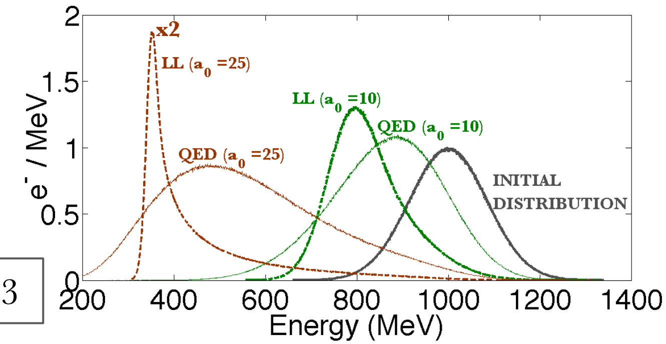
2. Photon emission is probabilistic

2.a $a_0 >> 1$

2.b constant cross-field approximation (instantaneous photon emission))

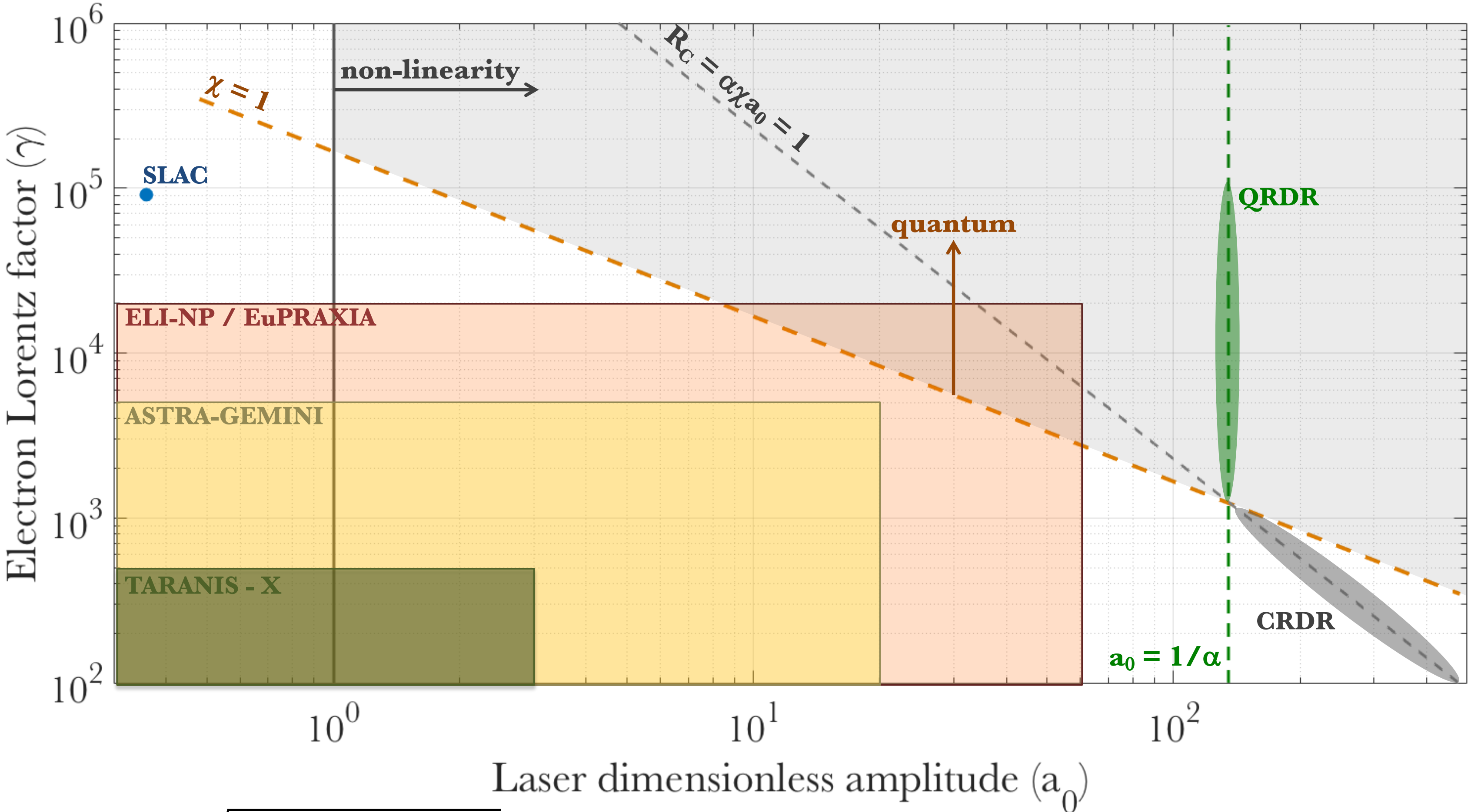
V. I. Ritus, J. Sov. Laser Res. 1985

N. Neitz and A. Di Piazza, PRL 2013



3. Production of electron-positron pairs (important only for $\chi \geq 1$)

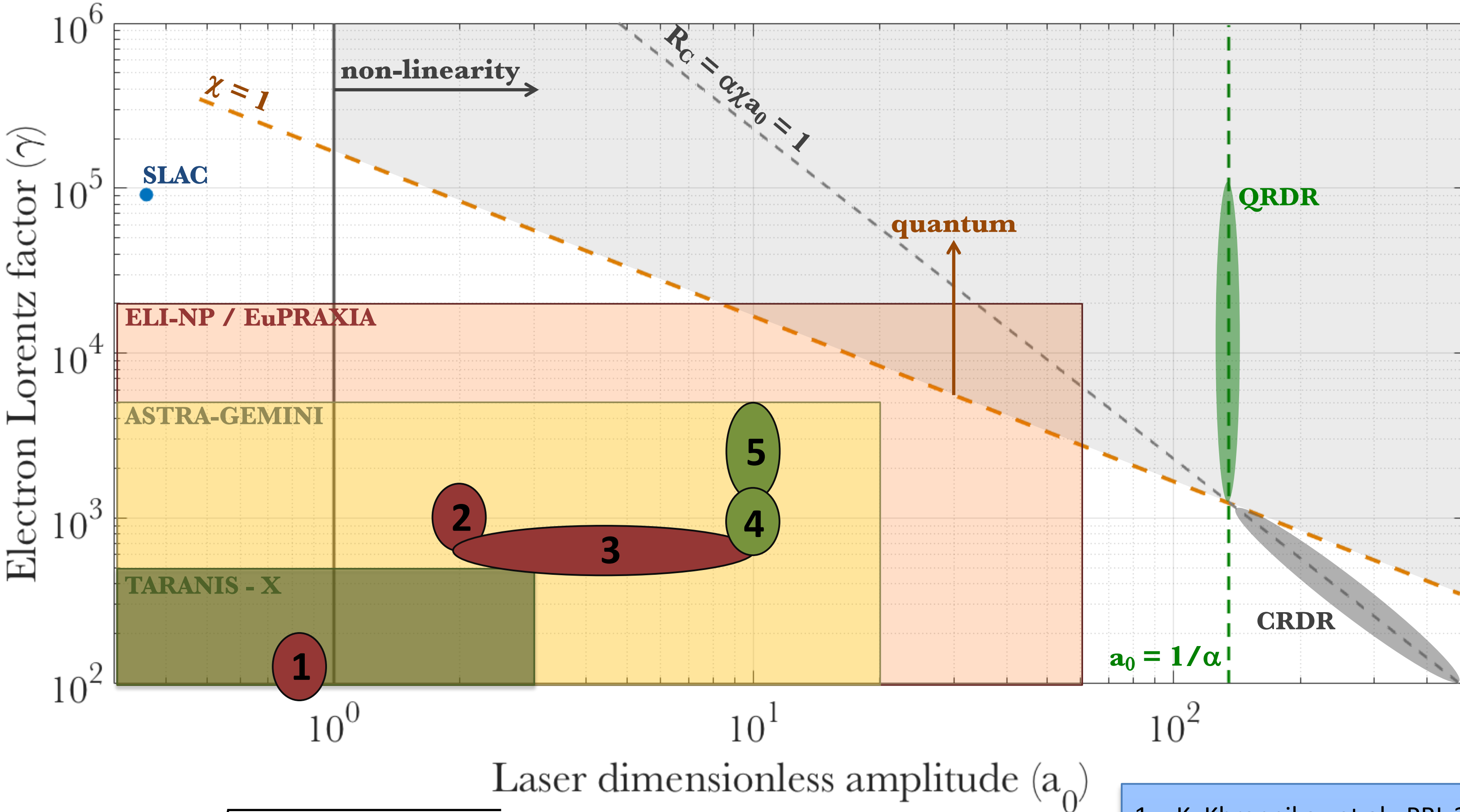
Current status



$$a_0 \sim 6\lambda_L[\mu m]\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$

$$\chi \sim 6.1\times10^{-6}\gamma_e a_0$$

Current status



$$a_0 \sim 6\lambda_L[\mu m]\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$

$$\chi \sim 6.1\times10^{-6}\gamma_e a_0$$

1. K. Khrennikov et al., PRL 2015
2. G. Sarri et al., PRL 2014
3. W. Yan et al., Nat. Phot. 2017
4. J. Cole et al., PRX 2018
5. K. Poder et al, PRX 2018

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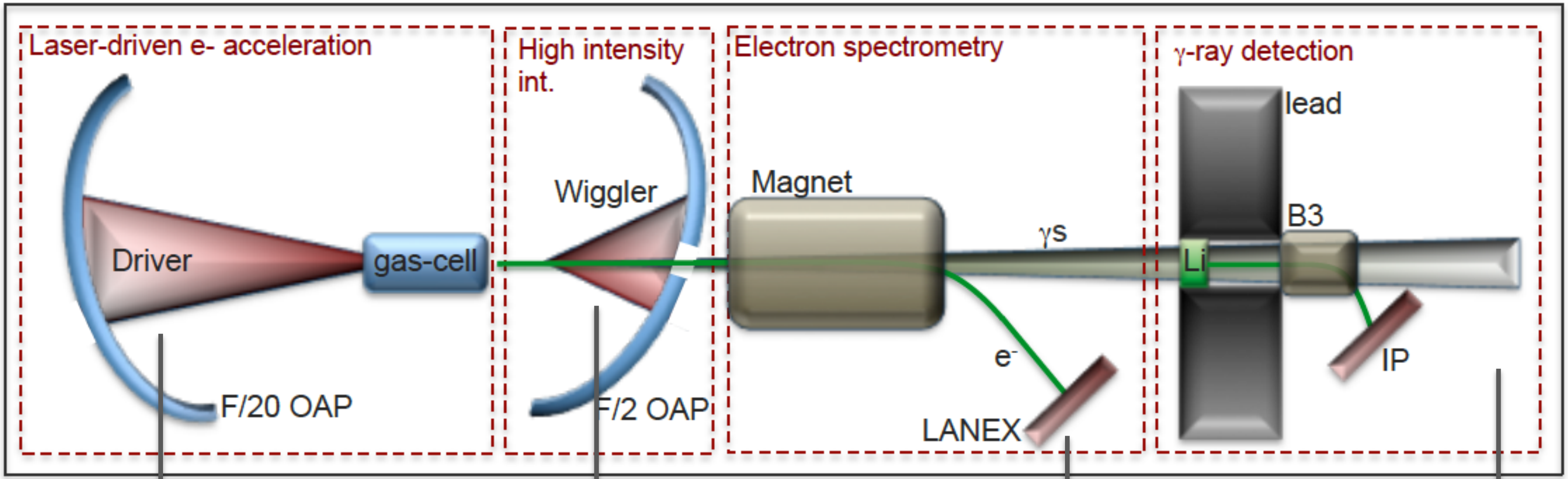
The general setup

Electron-laser collisions



DRIVER LASER:

- $t_L \sim$ 30-40 fs
- E ~ 1 – 10 J
- Long focal length
- $a_0 \sim 1$

SCATTERING LASER:

- $t_L \sim$ 30-40 fs
- E ~ 1 – 10 J
- Short focal length (holed)
- $a_0 >> 1$

e^- SPECTROMETER

γ-ray SPECTROMETER

✗ Unstable electron beam spectrum — G. Samarin et al., J. Mod. Opt. 65, 1362 (2017)

✗ Pointing fluctuations

✗ fs-scale synchronisation — D. Corvan *et al.*, Opt. Express **24**, 3127 (2016).

A low-intensity experiment

$(a_0 \sim 2, \gamma_e \sim 1000, \chi \sim 0.01)$

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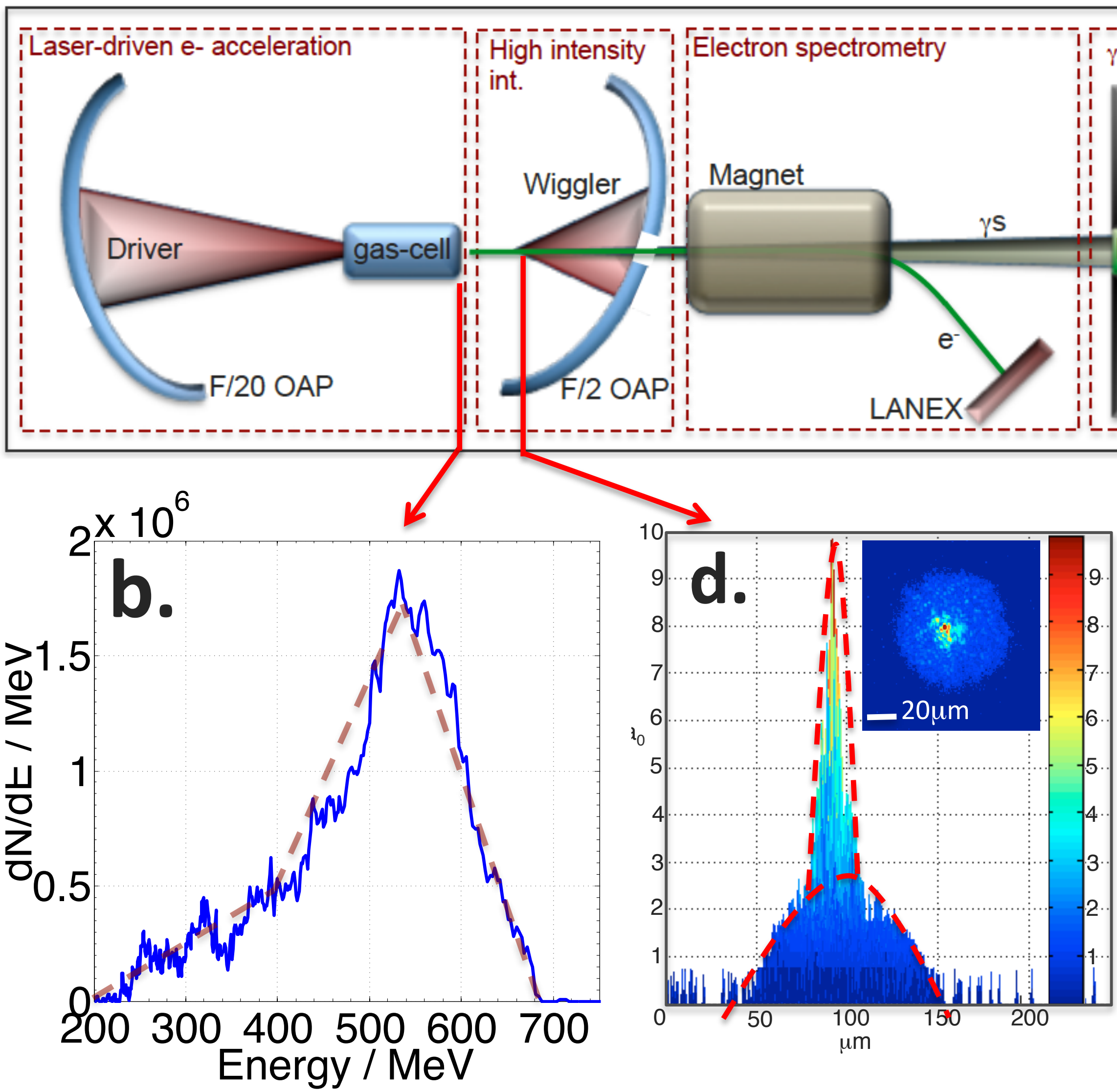
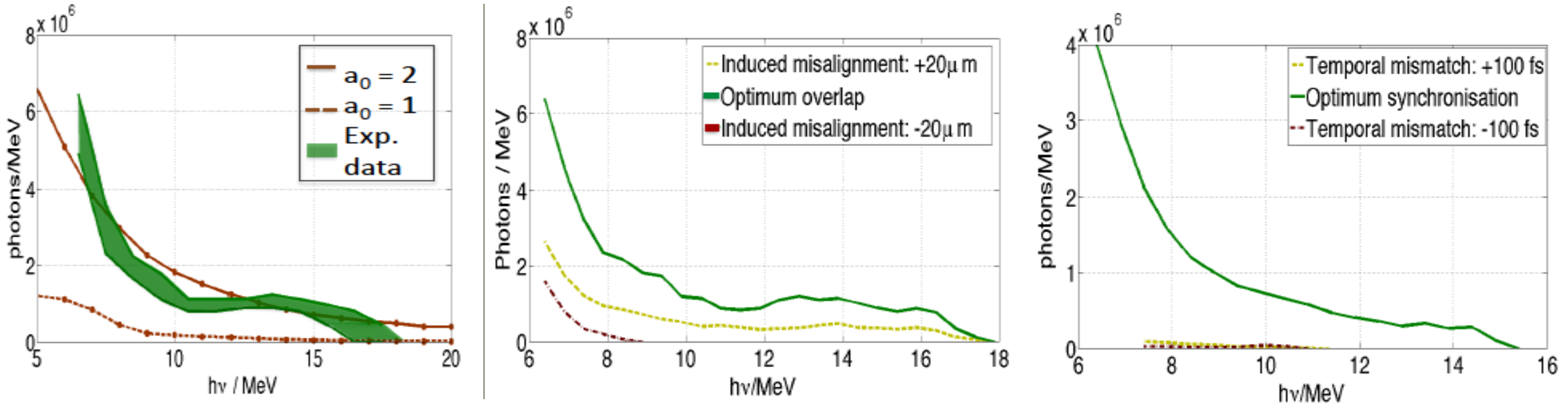
Experimental setup



- Spatial diffuser for a broad intensity envelope ($a_0 \sim 2$)
- Only 1/100 of the electrons interact with $a_0 \sim 10$ (negligible)
- Negligible radiation friction ($\chi \sim 1\%$)
- Simultaneous measurement of electrons and γ-rays

γ-ray spectra



- Gamma-rays with energy per photon reaching **15 – 18 MeV.**
- Signal drops to zero if artificial temporal delay is introduced and it significantly decreases if the beams are spatially misaglined.
- Measured yield and energy agrees with analytical calculations for $a_0 = 2$ indicating onset of **non-linear Thomson scattering.**
- Measured maximum divergence of **2.5 mrad.**
- Source size of **~30 microns**
- Calculated brightness of **$\sim 10^{20}$ photons/s/mm^2/mrad^2 x 0.1% BW**

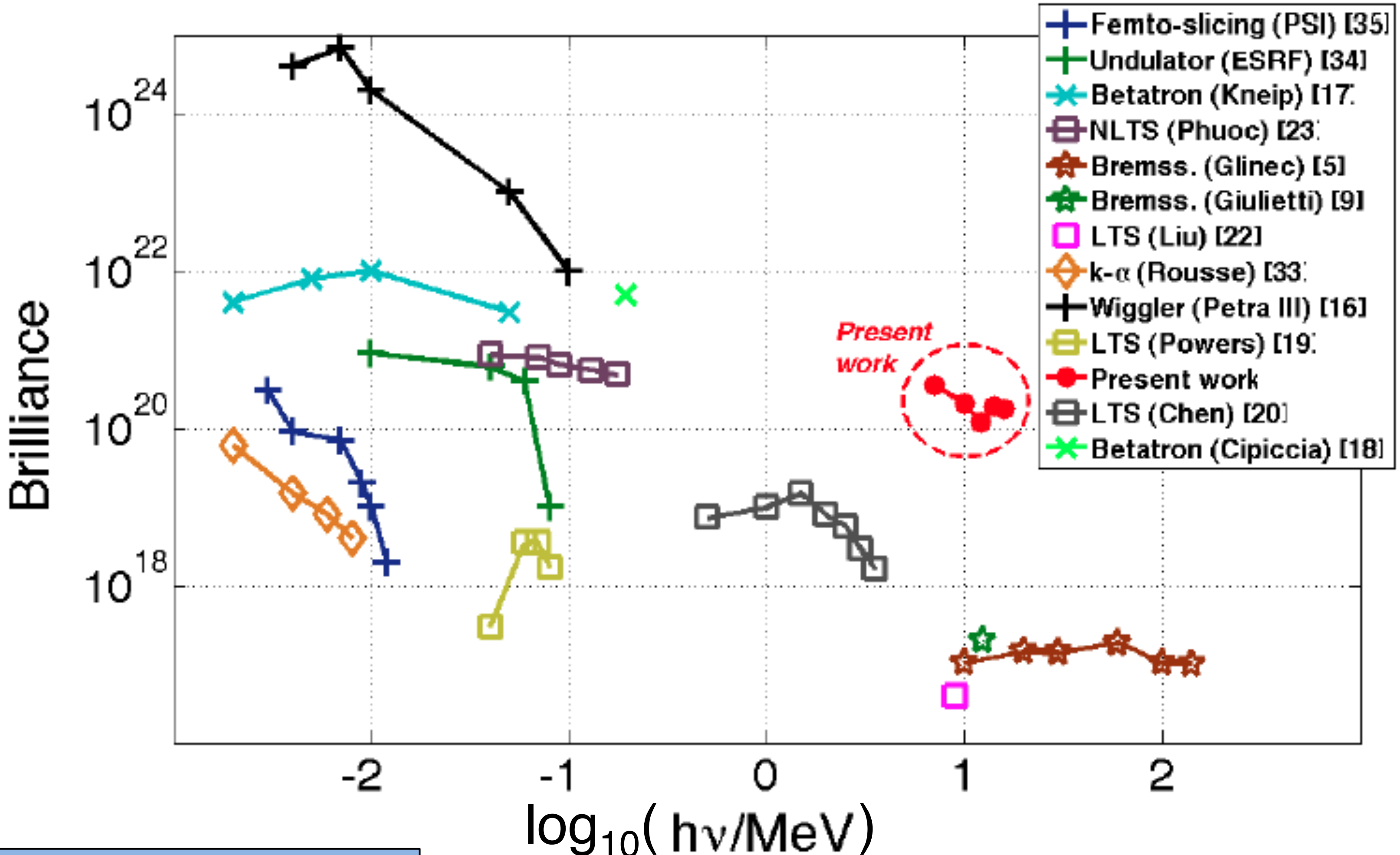
G. Sarri *et al.*, Phys. Rev. Lett. **113, 224801** (2014).

D. Corvan *et al.*, Rev. Sci. Instrum. **85, 065119** (2014).

D. Corvan *et al.*, Opt. Express **24**, 3127 (2016).

Brilliance

- **NEXT GENERATION OF MULTI-MEV γ-RAYS**



G. Sarri *et al.*, Phys. Rev. Lett. **113, 224801** (2014).

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A high-intensity experiment

$(a_0 \sim 10, \gamma_e \sim 4000, \chi \sim 0.2)$

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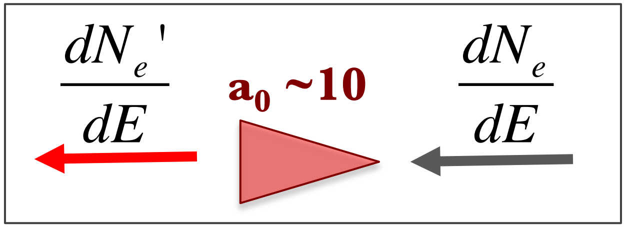
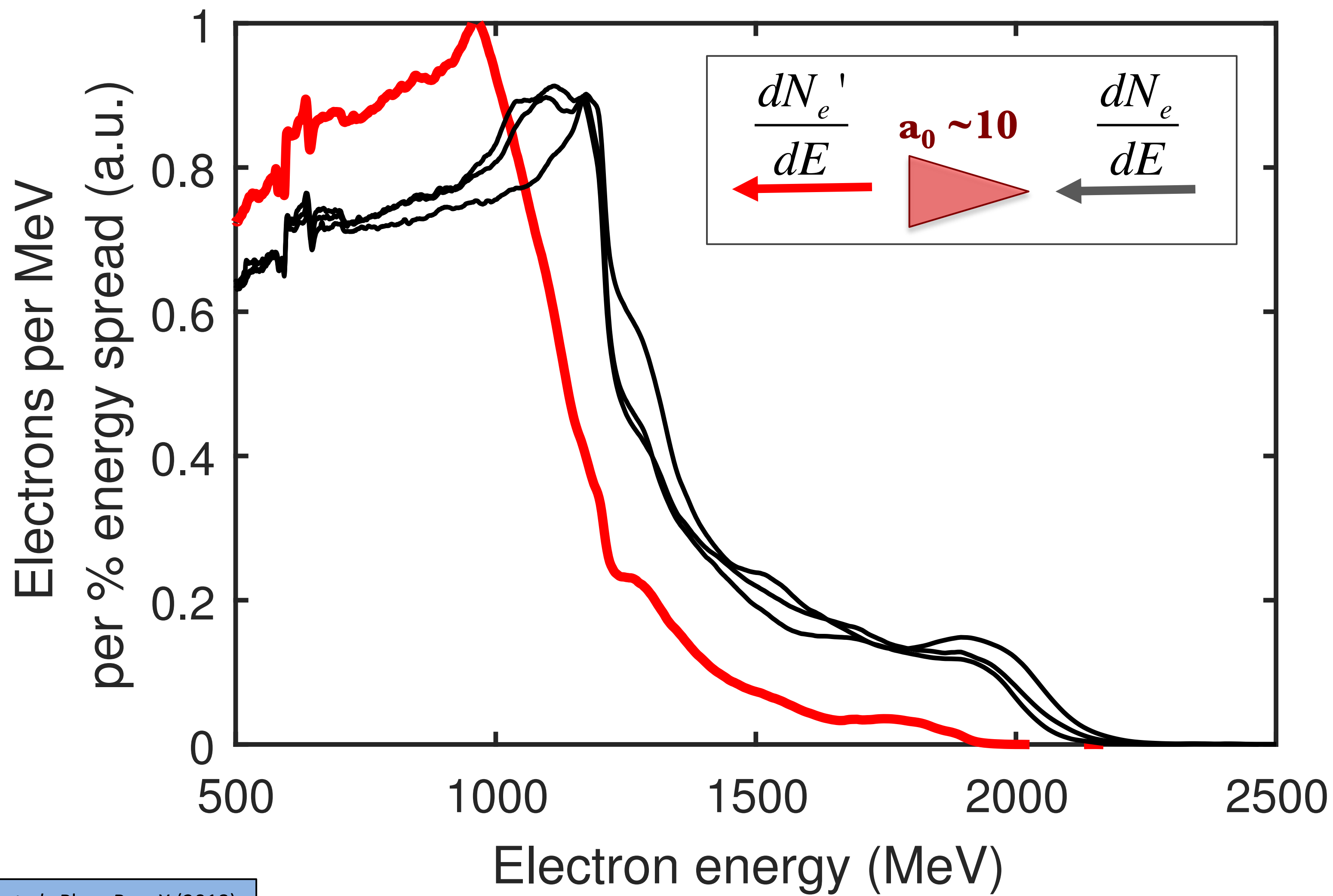
What do we see?

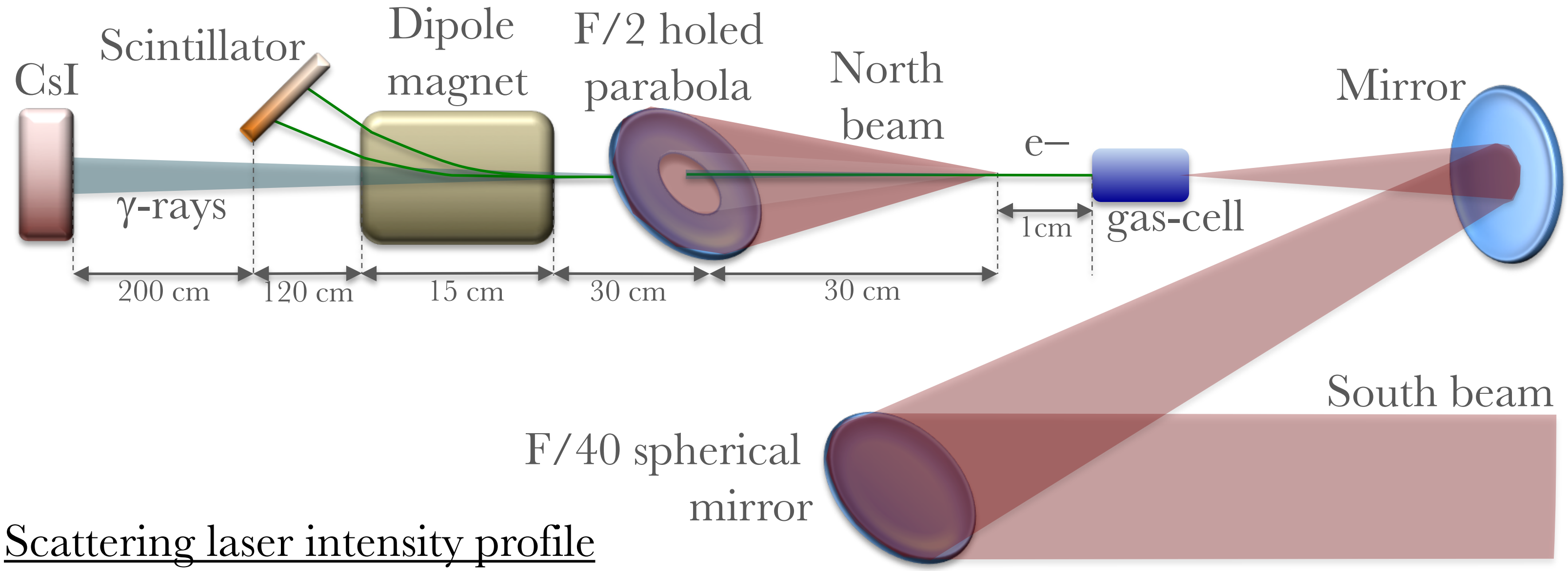


What do we see?

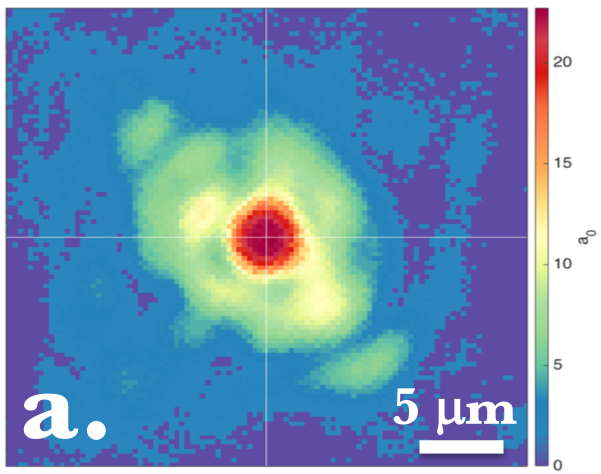


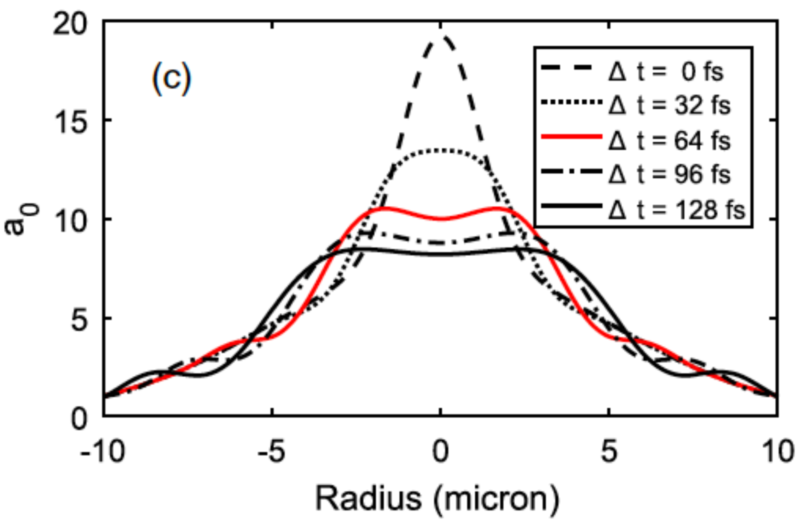
K. Poder *et al.*, Phys. Rev. X (2018)

Experimental setup

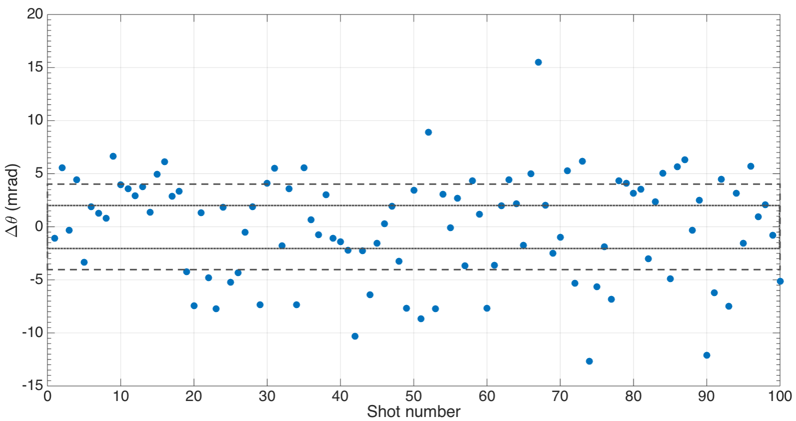


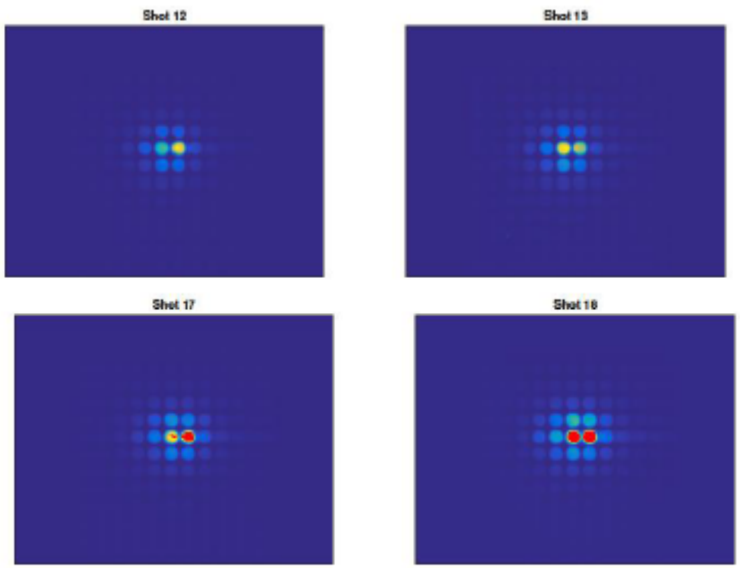
Scattering laser intensity profile

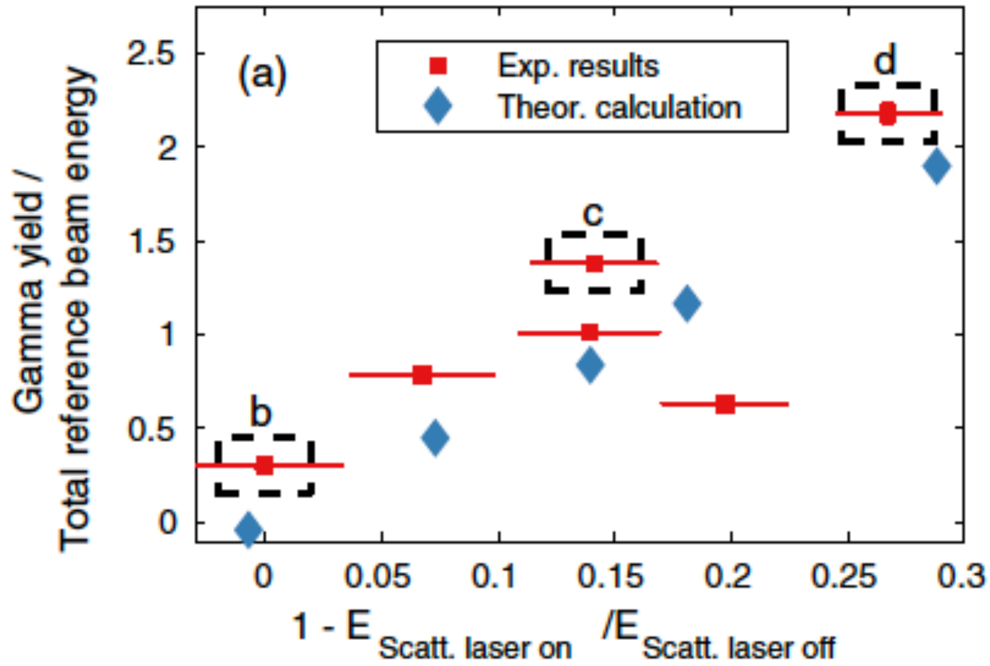




Collision diagnostic



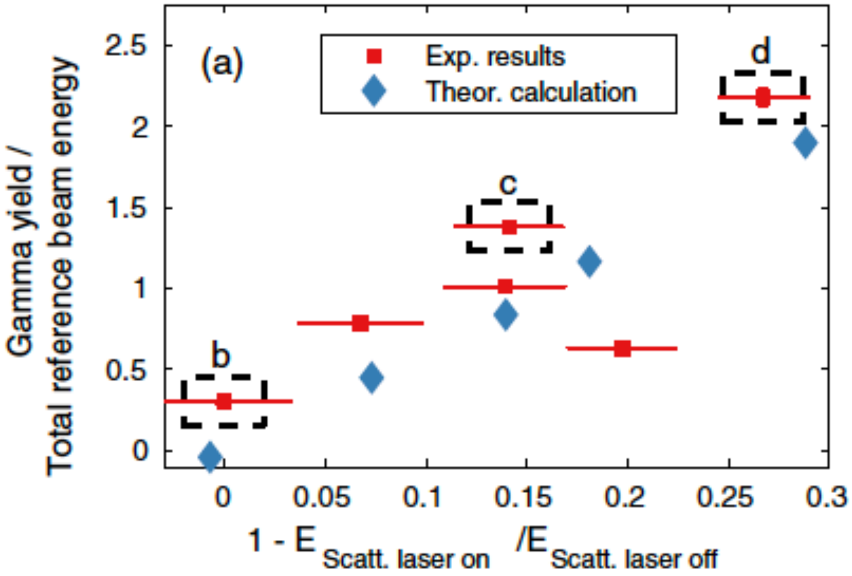




good electron-laser overlap → high photon yield, high energy loss

K. Poder *et al.*, Phys. Rev. X (2018)

Collision diagnostic



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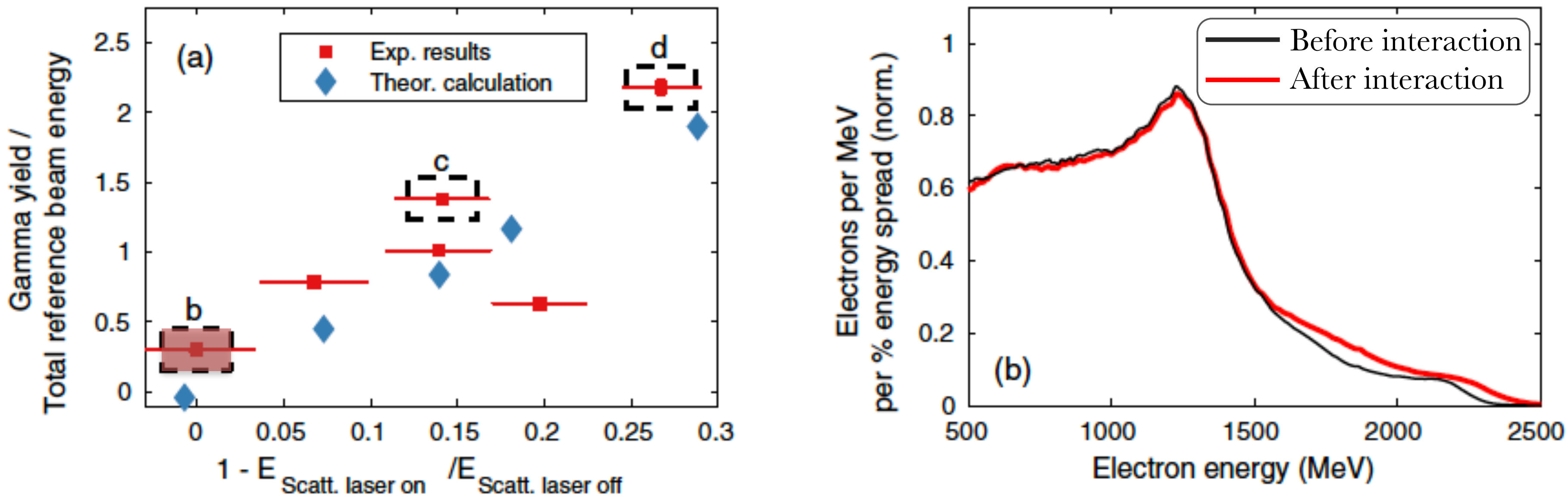

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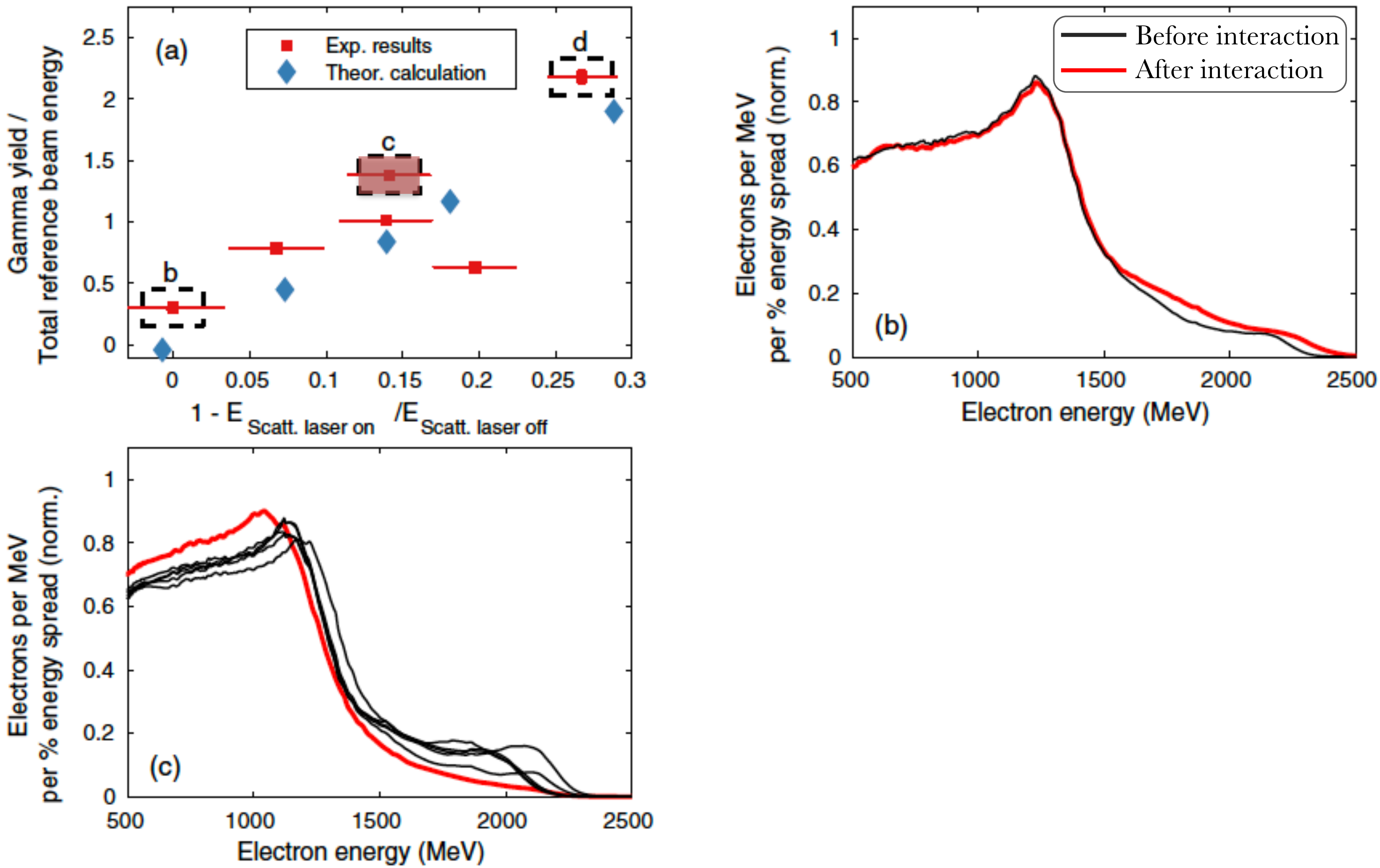

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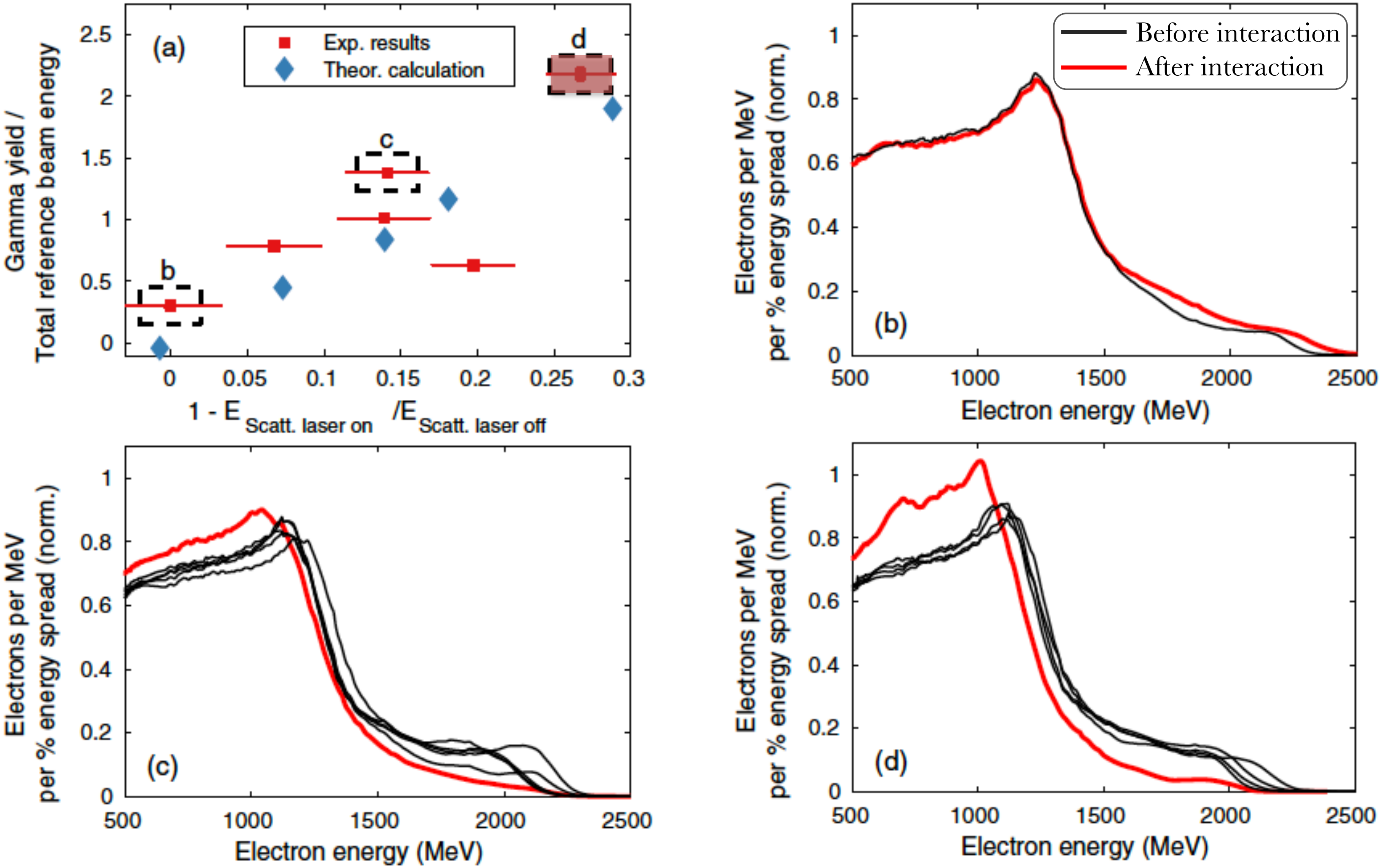

Comparison with theoretical models

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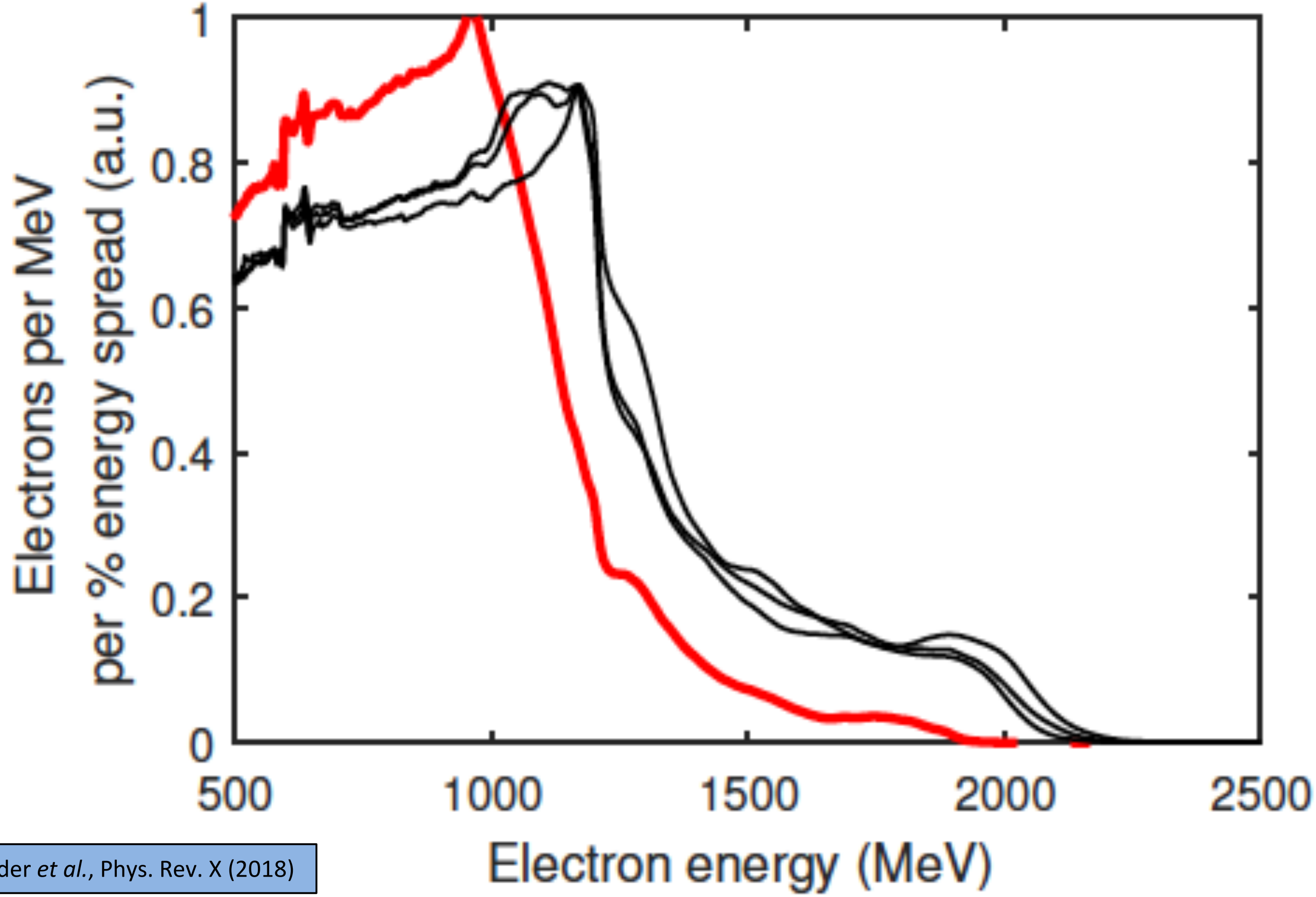
Comparison with theory



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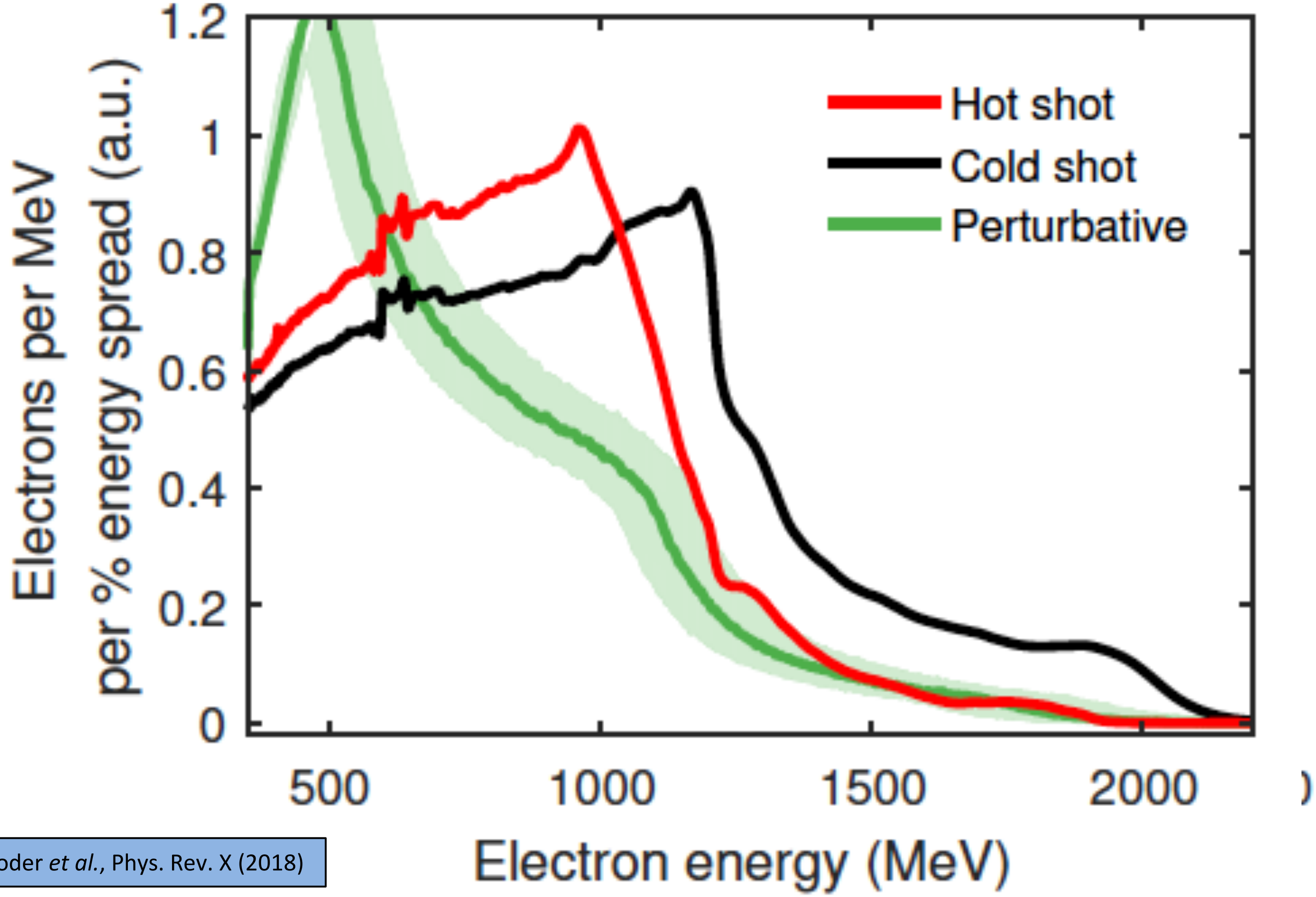

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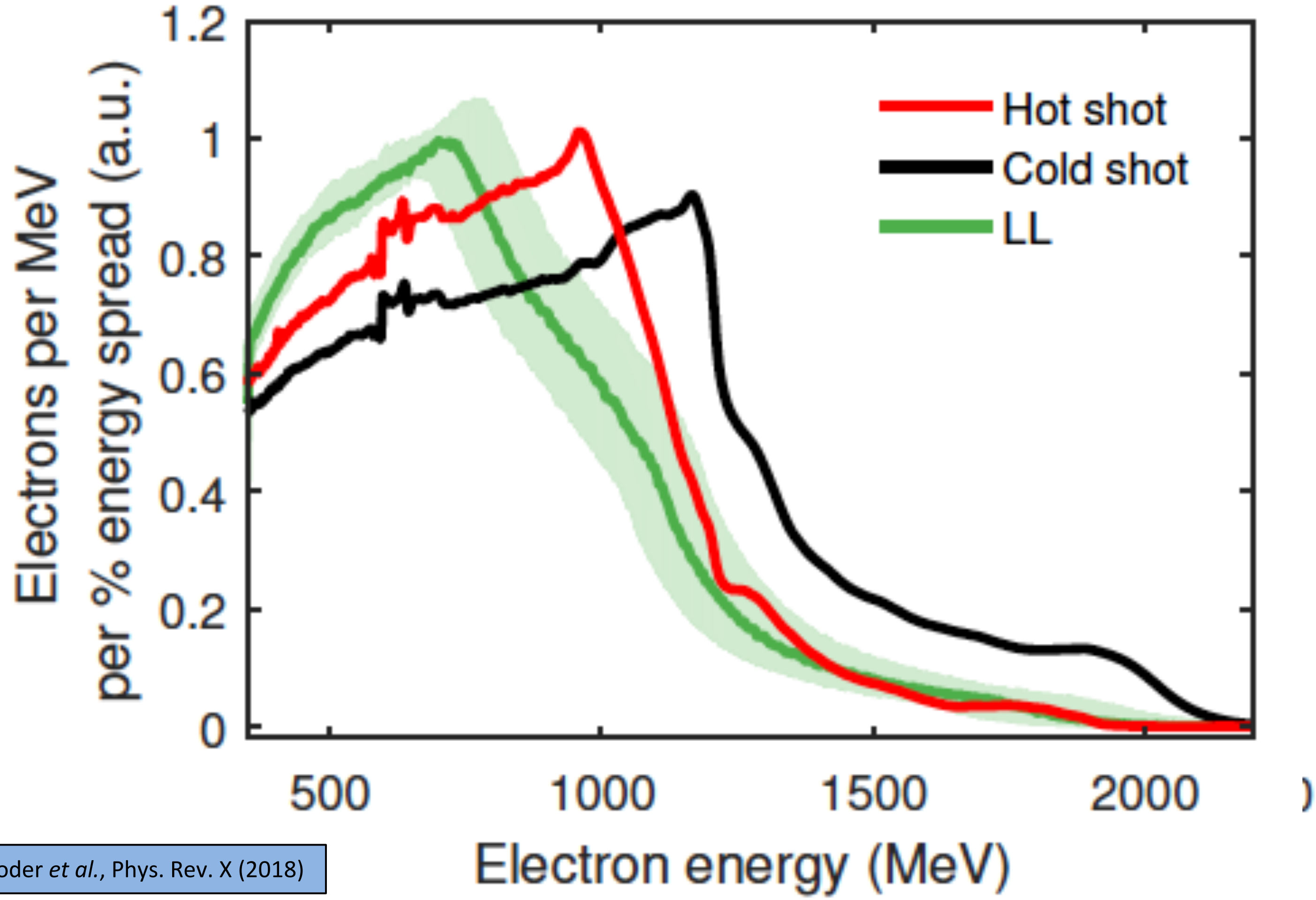

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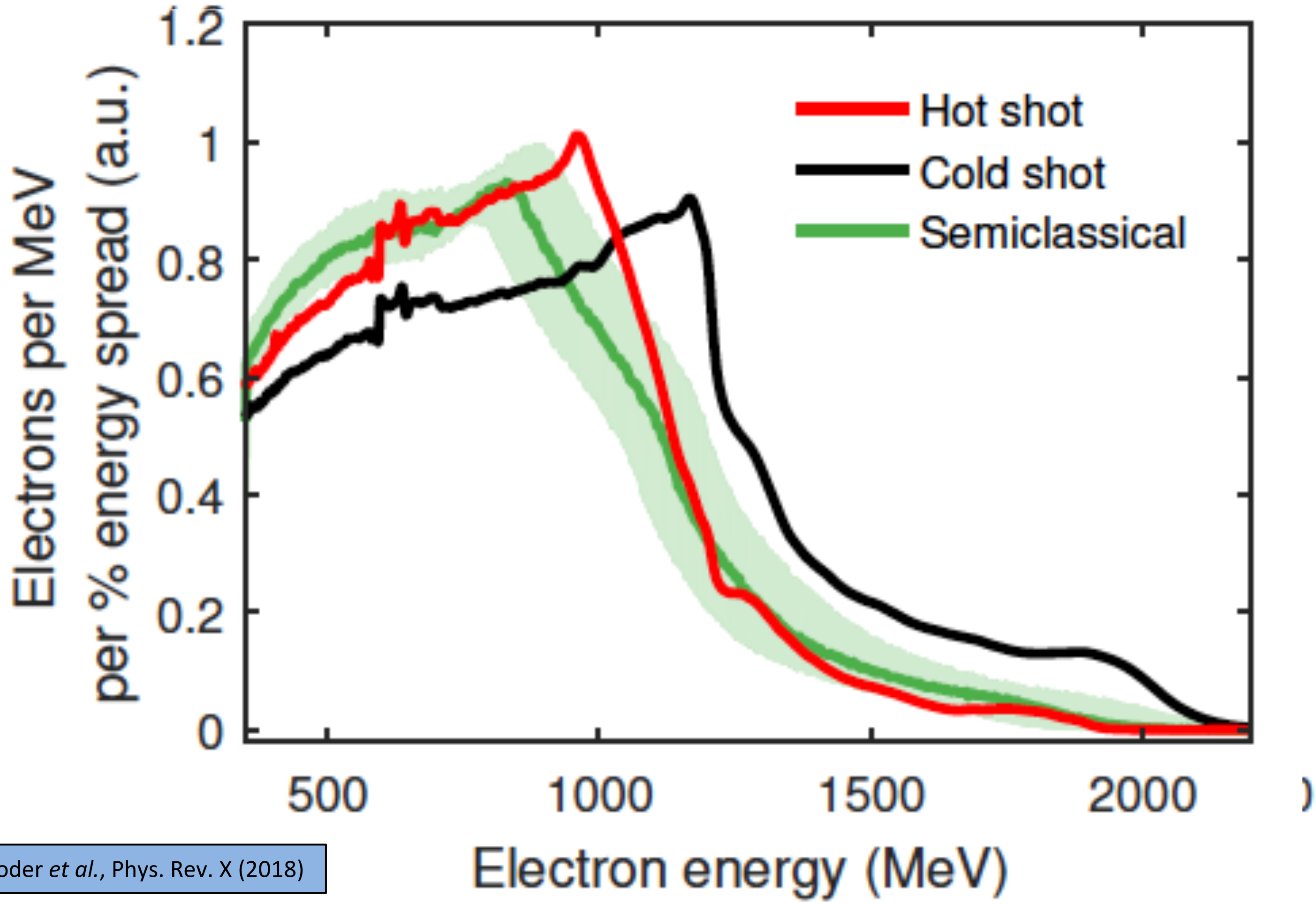

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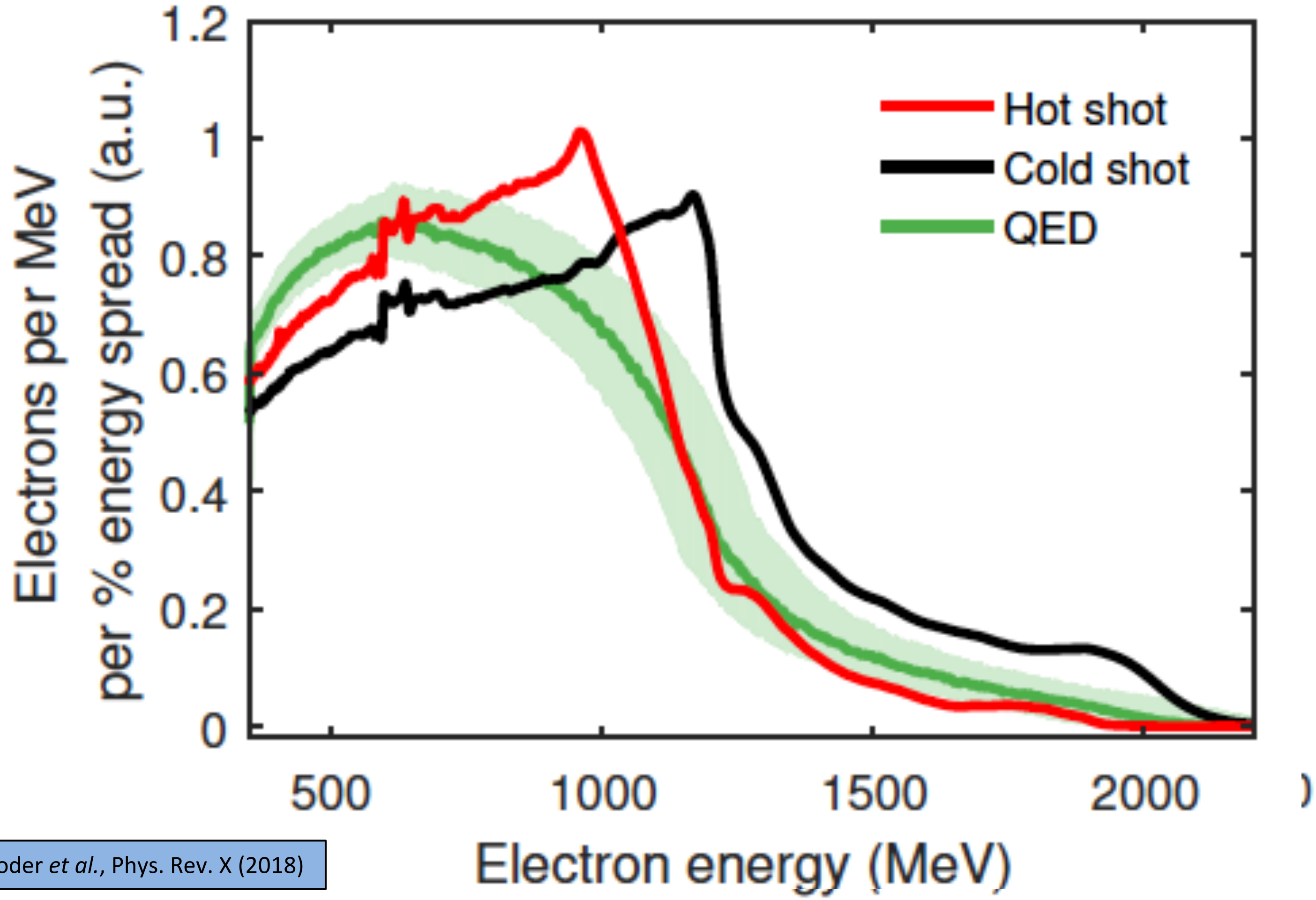

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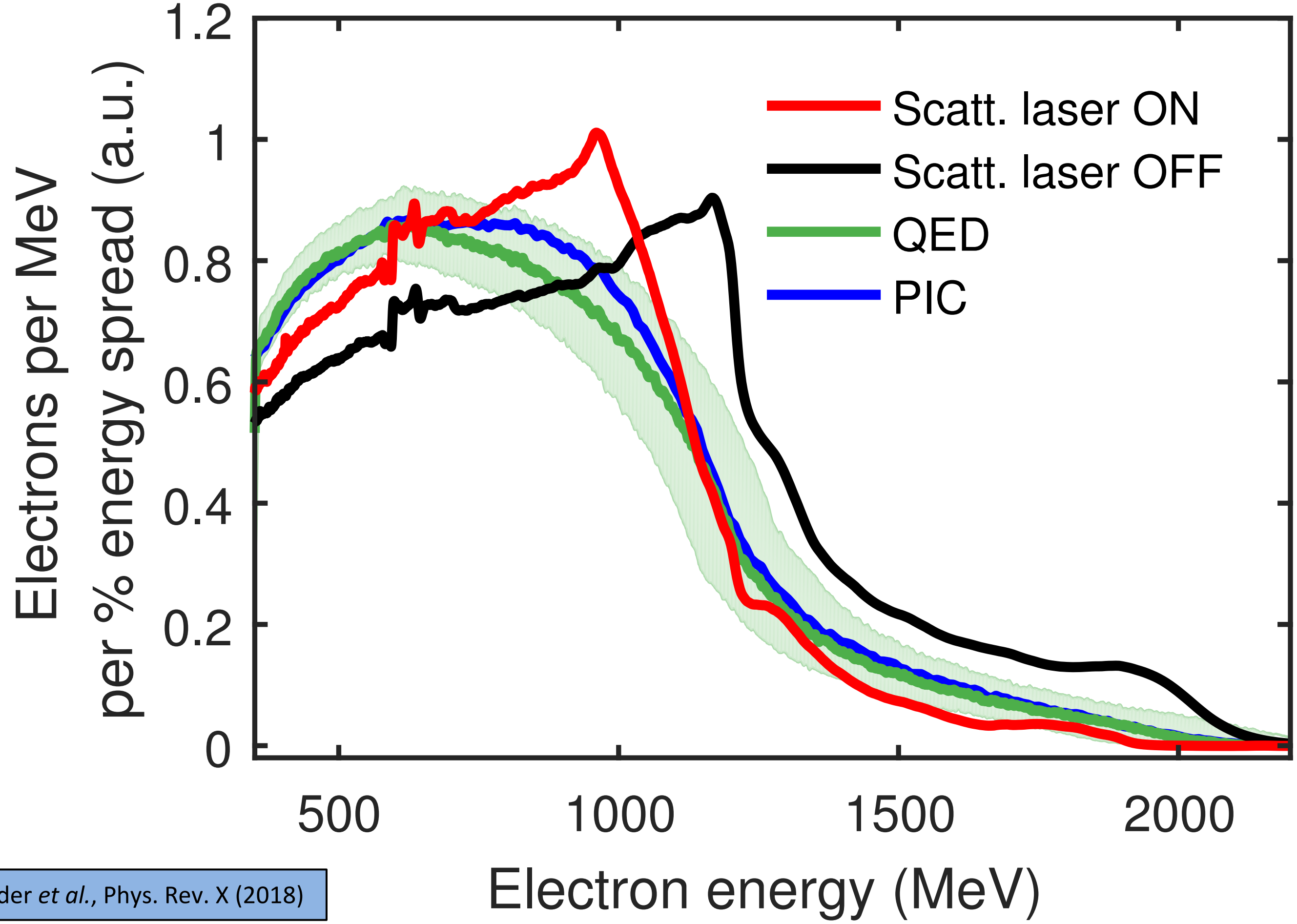

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CCF approximation

Why are the semiclassical and QED model not reproducing the data exactly?

Several possibilities:

- **Incomplete knowledge of laser spectral phase**
- **Incomplete knowledge of longitudinal laser distribution**
- **…**

CCF approximation

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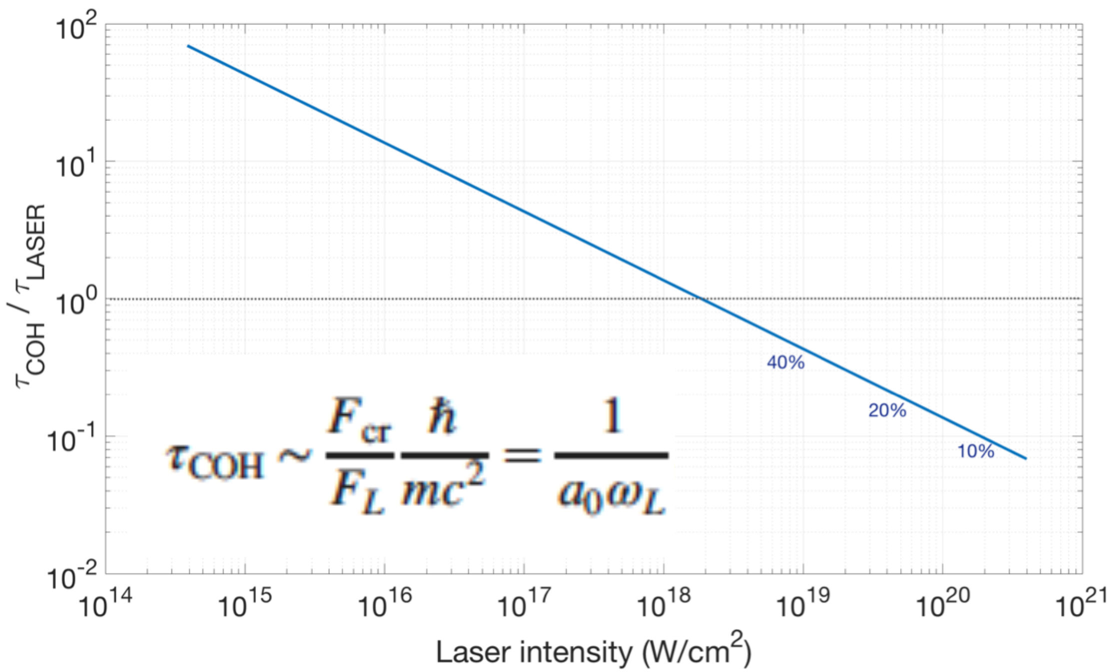
OR, we could be in a situation where the **constant cross-field approximation** is not strictly valid



$$\tau_{COH} \sim \frac{F_{cr}}{F_L}\frac{\hbar}{mc^2} = \frac{1}{a_0\omega_L}$$

This approximation is used to calculate

$g(\chi)$ in the semiclassical model

Photon emission probability in the QED model

Conclusions and Outlook

Conclusions and Outlook

- First experimental observation of high-field QED phenomena in a fully optical setup **obtained at the Central Laser Facility**

- For the next steps we need: A. Higher laser intensities
  B. Improved pointing and spectral stability of electron beams
  C. Higher electron energy

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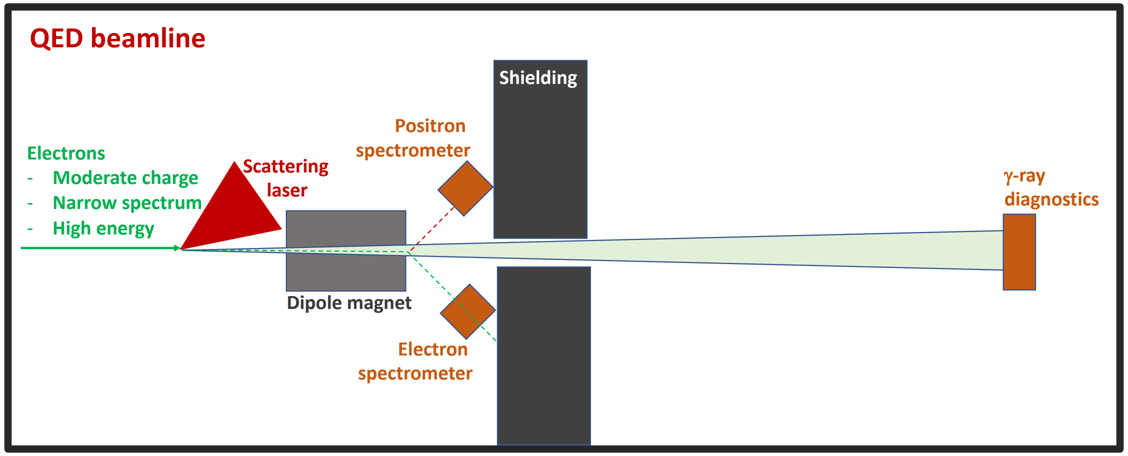
- European consortium for a plasma-based accelerator of 5 GeV electron beams of industrial quality

- High-field QED studies proposed as a pilot application



5 GeV, 5% ($\gamma_e \sim 10^4$)
I ~ 10^{21} Wcm^{-2} → **$a_0 \sim 20$, $\chi \sim 1.3$**

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EuPRAXIA

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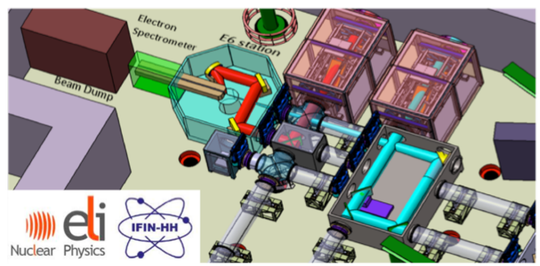

- Extreme-Light Infrastructure Nuclear Pillar

- 2 x 10 PW laser beams

- First commissioning experiments early 2019

- PWASC

- New roadmap for research in wakefield acceleration in the UK

Thanks for your attention!

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References:

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