Imperial College London

Observing the two-photon Breit-Wheeler process for the first time

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23 October 2014

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- Hui Chen, Brad Pollock and Bruce Remington

  Lawrence Livermore National Laboratory, Livermore, California, USA

- Louise Willingale and Alexander Thomas

  Center for Ultrafast Optical Science, University of Michigan, Michigan, USA

Outline of talk

1. Introduction
2. A photon-photon collider in a vacuum hohlraum
3. Implementing experiment on current-generation facilities
4. Summary

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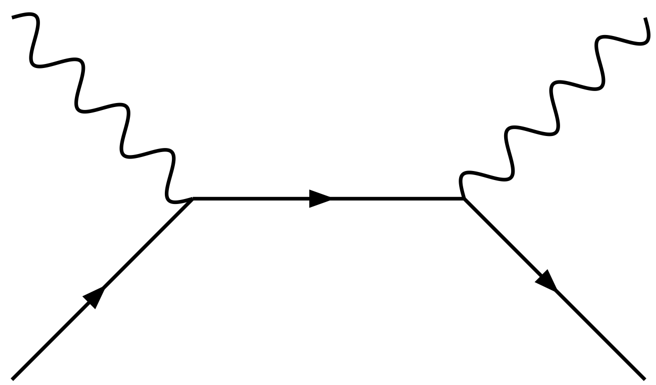
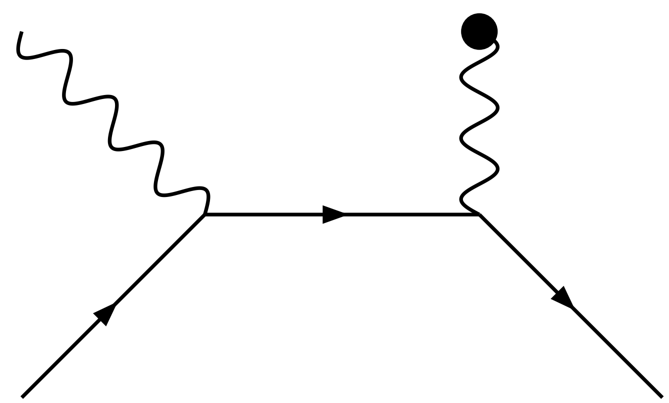
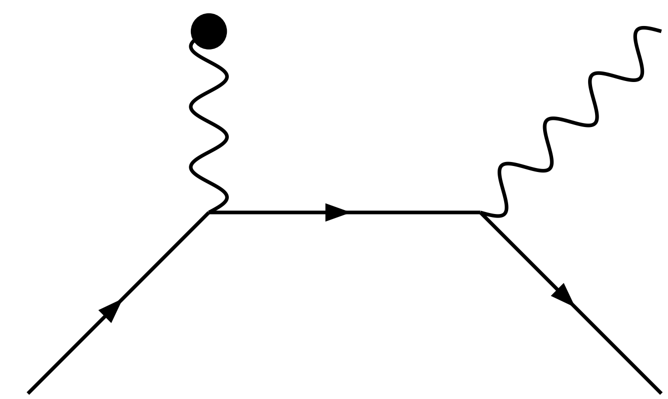
The simplest interactions between light and matter: the basics of QED



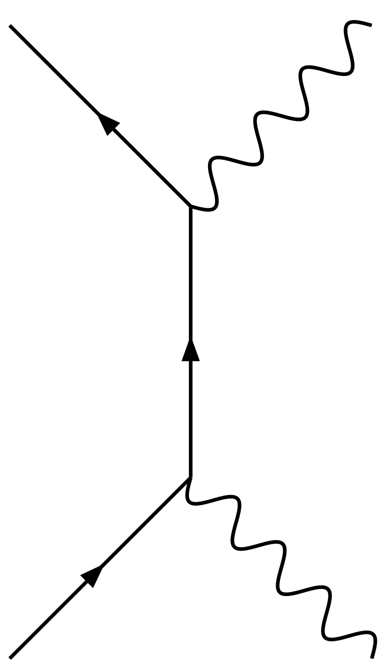
Compton scattering



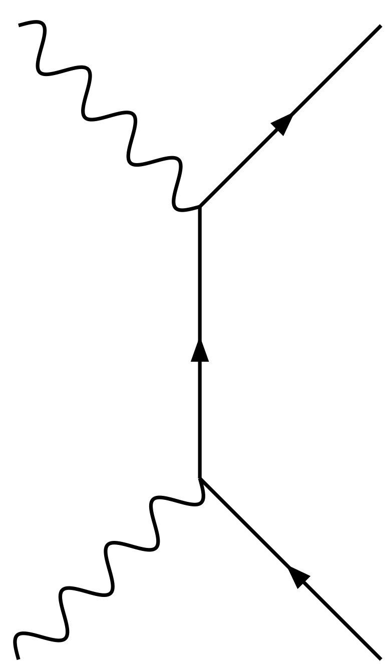
Photoelectric effect



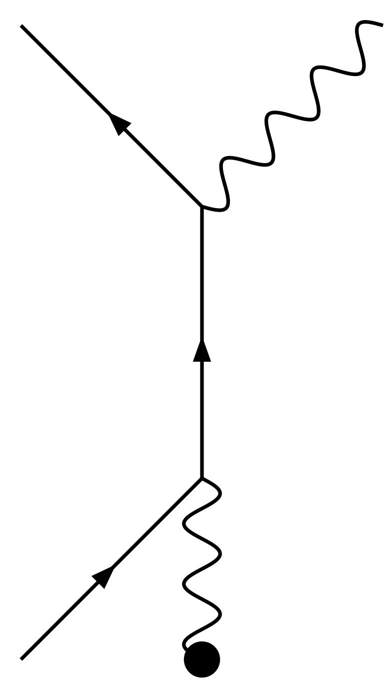
Bremsstrahlung



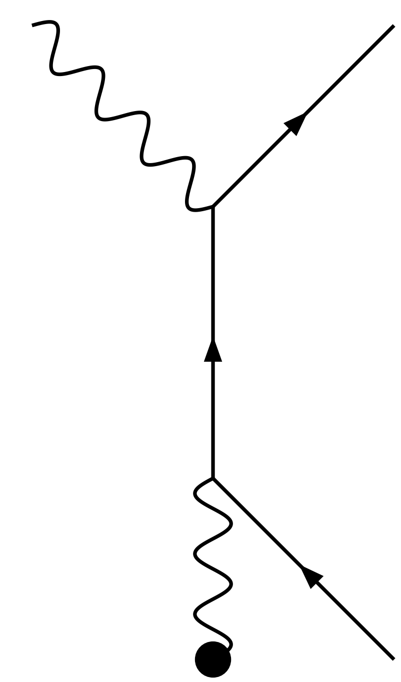
Dirac
annihilation



Breit-Wheeler
pair production



Single photon
annihilation

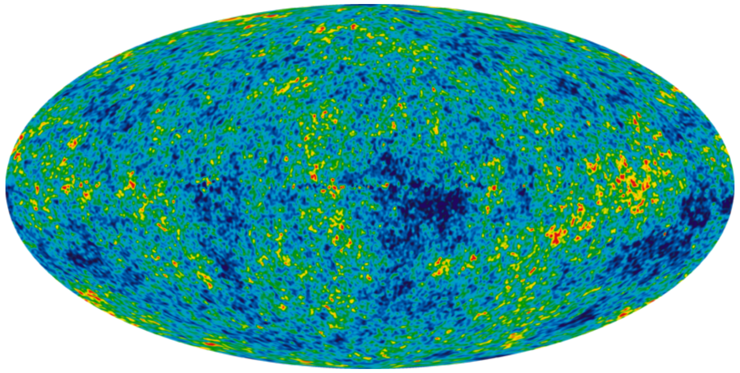


Bethe-Heitler
pair production

Breit-Wheeler pair production as a fundamental process in high-energy astrophysics

Cut-off in high-energy gamma-rays

- Cut-off of high-energy gamma-rays above 10^{13} eV due to pair production with the cosmic microwave background.



NASA

Gould and Schréder, *PRL* **16,** 252 (1966)

Radiation fields of compact objects

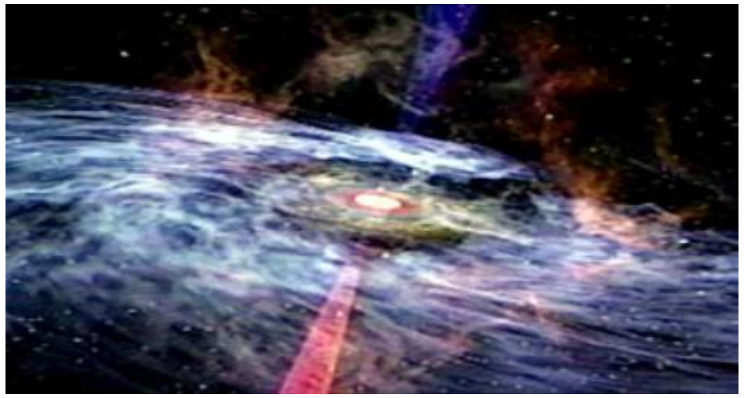
- Breit-Wheeler pair production important for determining electron and photon spectra around compact objects.

ESO/M. Kornmesser

Bonometto and Rees, *MNRAS* **152,** 21 (1971)

'Compactness problem' of gamma-ray bursts

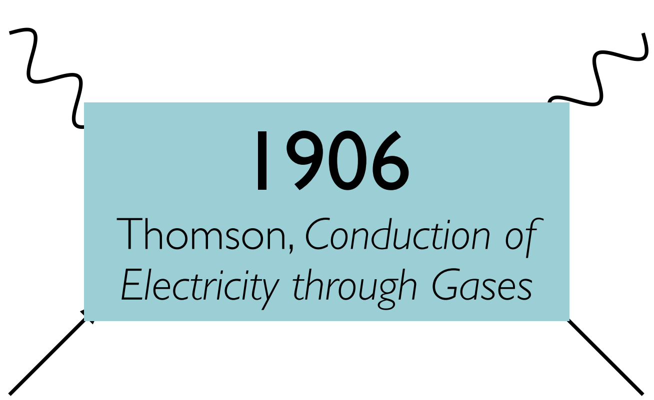
- Opacity due to pair production important consideration in models for gamma-ray burst emission.



NASA

Piran, *Rev Mod Phys* **76,** 1194 (2004)

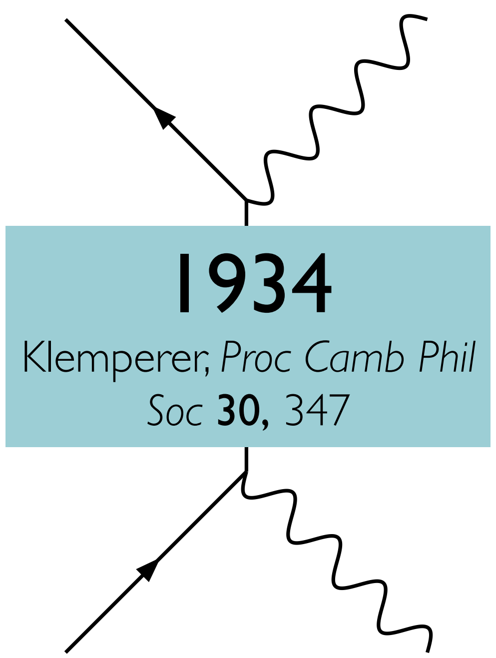
The simplest interactions between light and matter: earliest results of QED



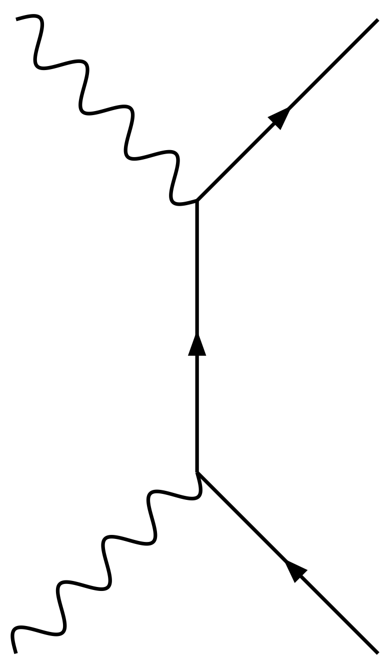
Compton scattering

Photoelectric effect

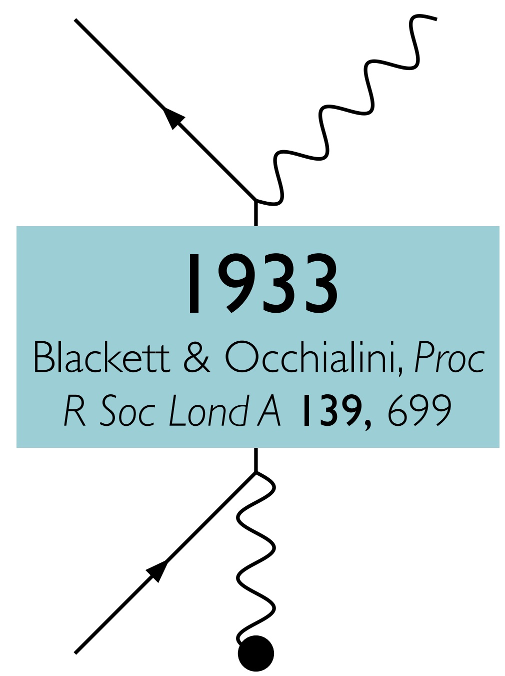
Bremsstrahlung



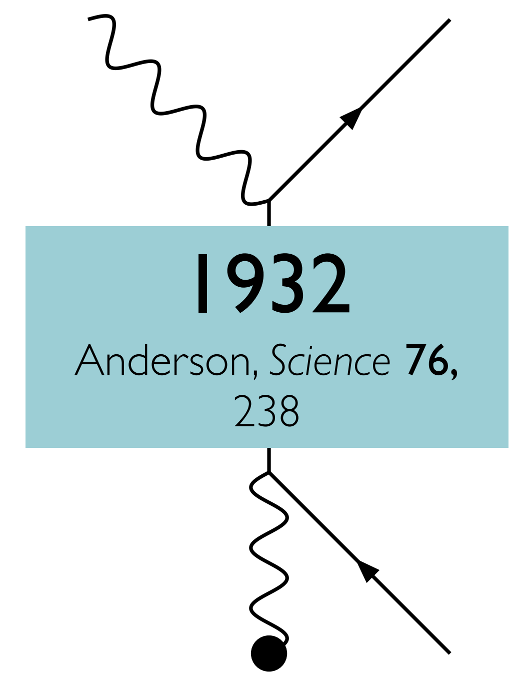
Dirac annihilation



Breit-Wheeler pair production



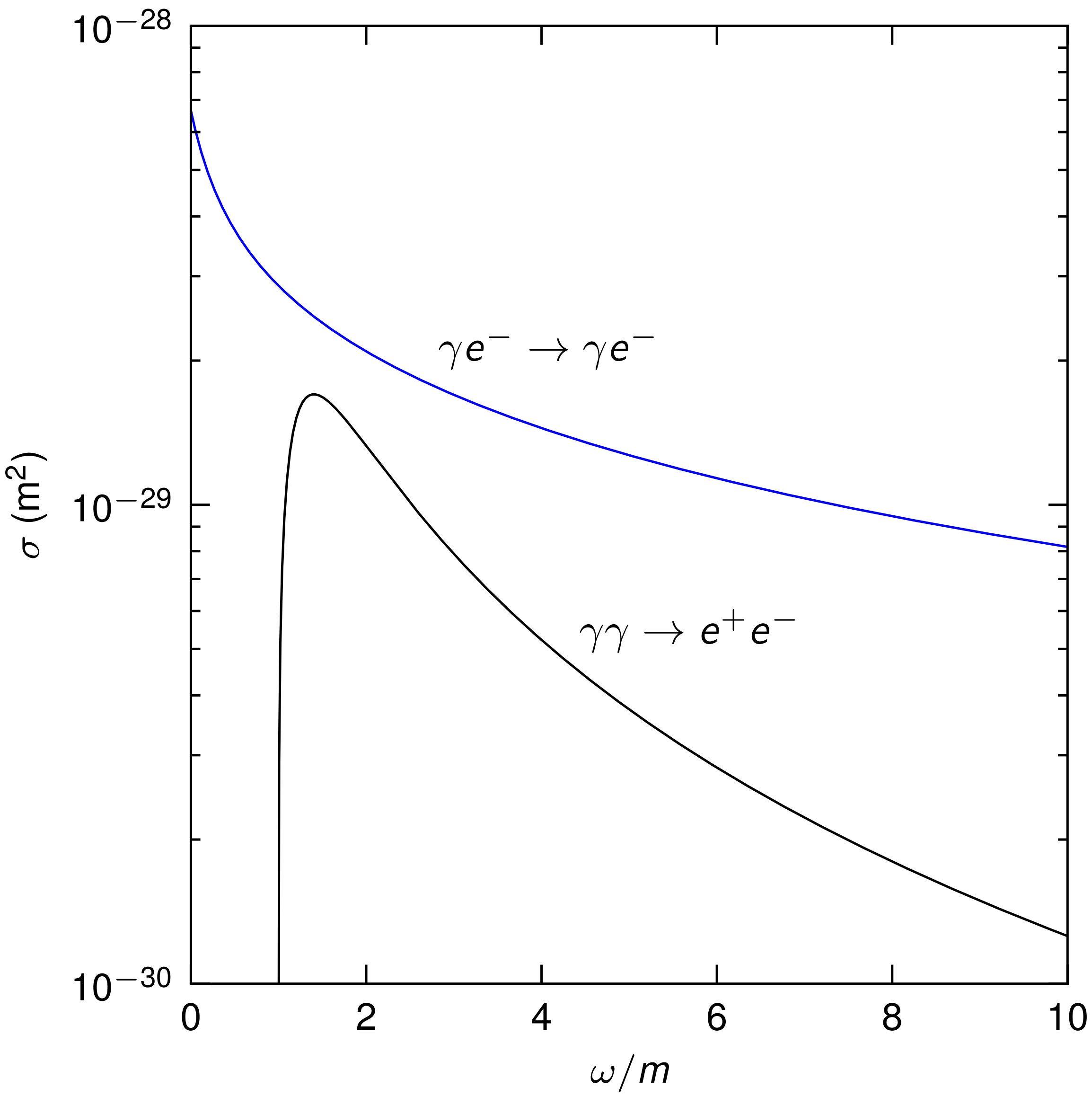
Single photon annihilation



Bethe-Heitler pair production

Why is the Breit-Wheeler process so elusive?

Breit-Wheeler and Klein-Nishina cross-sections



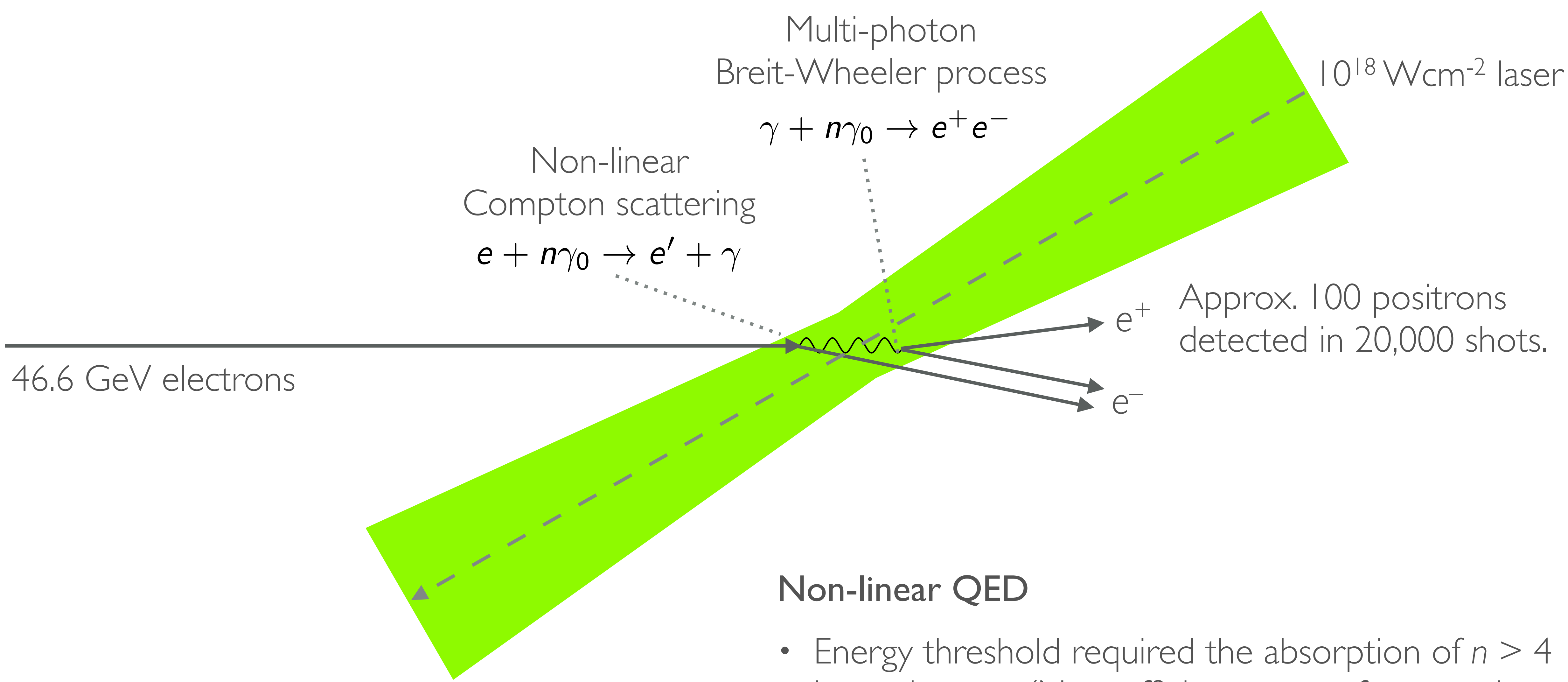
Breit and Wheeler, *Phys Rev* **46,** 1087 (1934)
Jauch and Rohrlich, *The Theory of Photons and Electrons* (1959)

- The Breit-Wheeler cross-section

$$\sigma_{\gamma\gamma} = \pi r_0^2 \left(\frac{m}{\omega}\right)^2 \left\{ \left[2\left(1 + \left(\frac{m}{\omega}\right)^2\right) - \left(\frac{m}{\omega}\right)^4 \right] \cosh^{-1}\frac{\omega}{m} - \left(1 + \left(\frac{m}{\omega}\right)^2\right)\sqrt{1 - \left(\frac{m}{\omega}\right)^2} \right\}$$

  is, at its peak, of the same order as that of Compton scattering and Dirac annihilation.
- However, to create matter from a massless state, the centre-of-mass energy must be at least $2m$.
- It has previously not been possible to promote enough photons above threshold for the process to be observable and Breit-Wheeler pair production has eluded any direct detection.

SLAC E-144 experiment: first sign of positron production in light-by-light scattering



Non-linear QED

- Energy threshold required the absorption of $n > 4$ laser photons. (Not sufficient energy for two-photon interaction.)
- Recently shown that, on average, $n = 6.44$ laser photons were absorbed.

Burke et al., *PRL* **79,** 1626 (1997)
Hu & Müller, *PRL* **107,** 090402 (2010)

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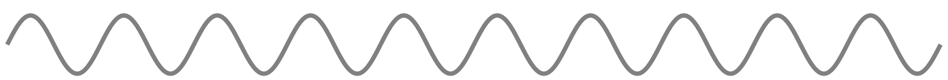
On searching for Breit-Wheeler pair production: three different approaches

Threshold for Breit-Wheeler: product of two photon energies > 511^2 keV^2

Beam + Laser



Gamma-ray (100 GeV)

Optical laser photon (eV)

On searching for Breit-Wheeler pair production: three different approaches

Threshold for Breit-Wheeler: product of two photon energies > 511^2 keV^2

Beam + Laser	Gamma-ray (100 GeV)	Optical laser photon (eV)
Beam + Beam	Gamma-ray (MeV)	Gamma-ray (MeV)

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Threshold for Breit-Wheeler: product of two photon energies > 511^2 keV^2

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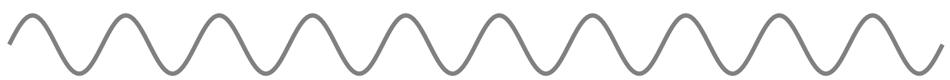


Gamma-ray (100 GeV)

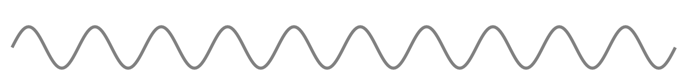
Optical laser photon (eV)

Beam + Beam

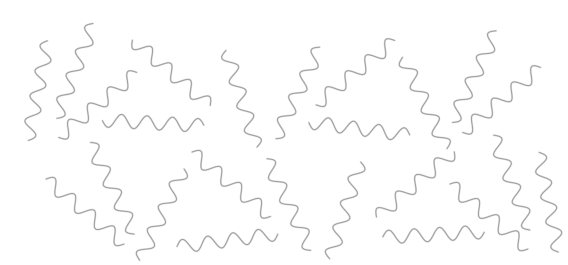
Gamma-ray (MeV)

Gamma-ray (MeV)

Beam + Target



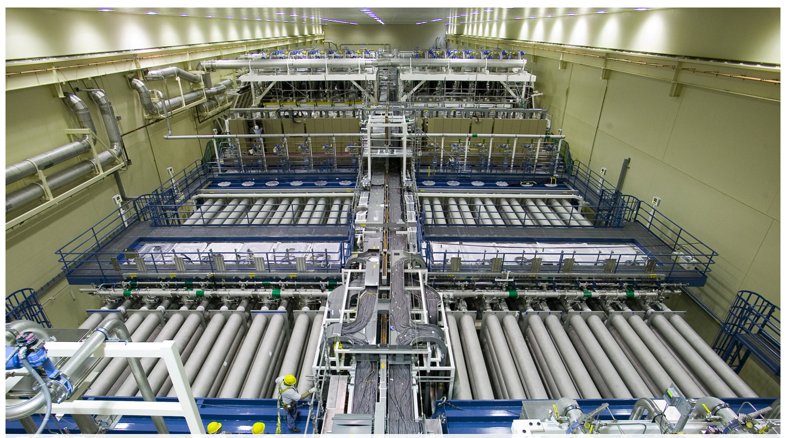
Gamma-ray (GeV)



Thermal x-ray field (100 eV)

High temperature radiation fields are produceable at large optical laser facilities

National Ignition Facility (USA)



Long-pulse: 2 MJ in 192 beams

LLNL

Laser Megajoule (France)

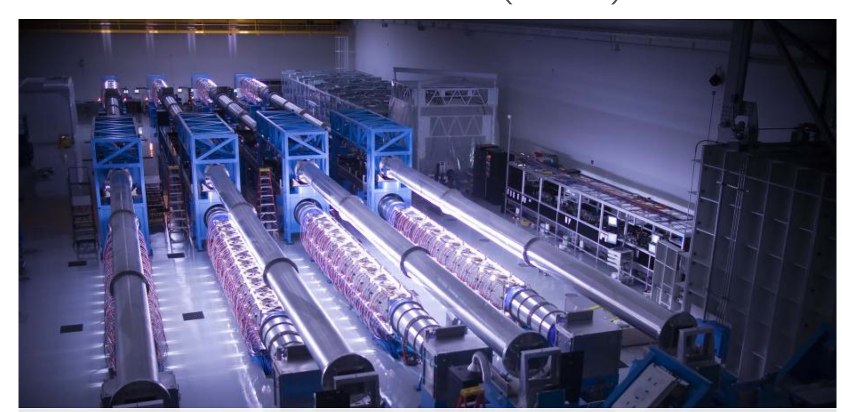
Long-pulse: 1.4 MJ in 176 beams

P. Labeguerie / CEA

Orion Laser (UK)

Long-pulse: 5 kJ in 10 beams

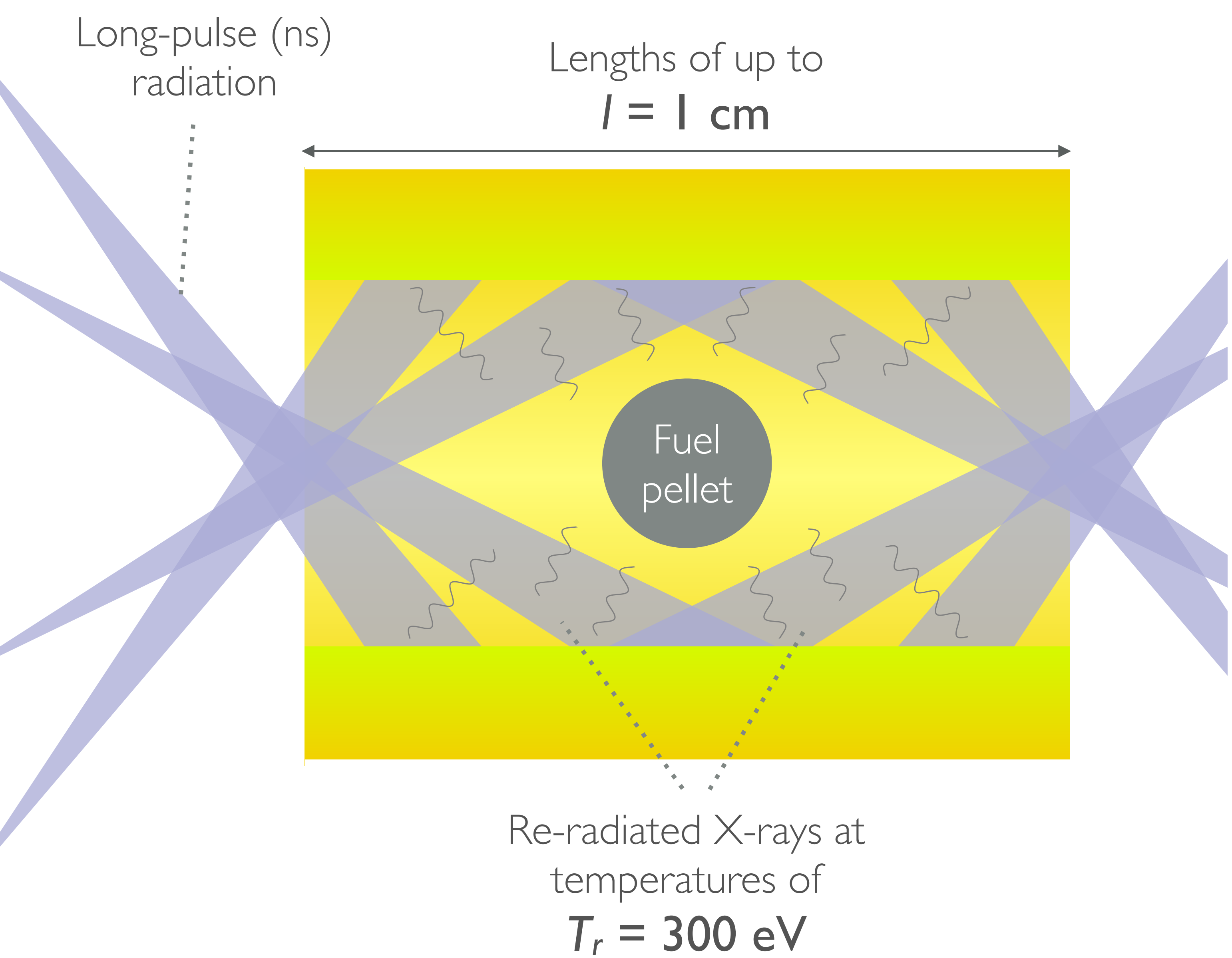
OMEGA EP (USA)

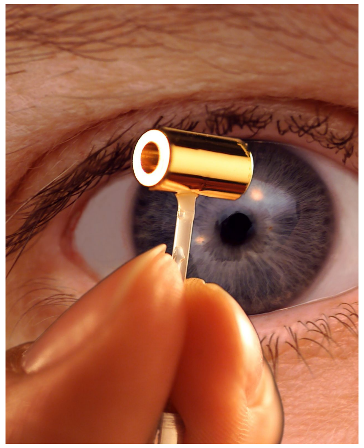


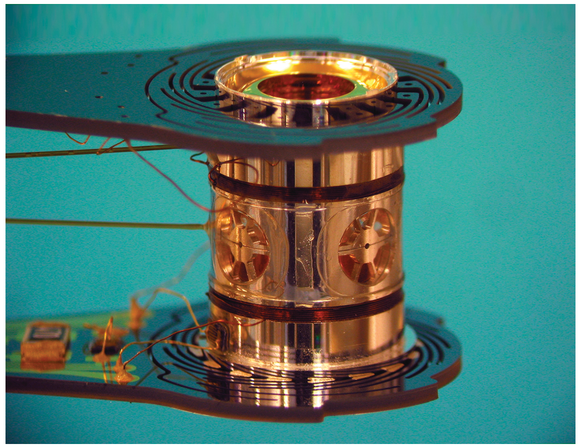
Long-pulse: 40 kJ in 60 beams

University of Rochester

In inertial fusion, X-ray radiation produced inside a laser-heated hohlraum is used to heat and compress the target



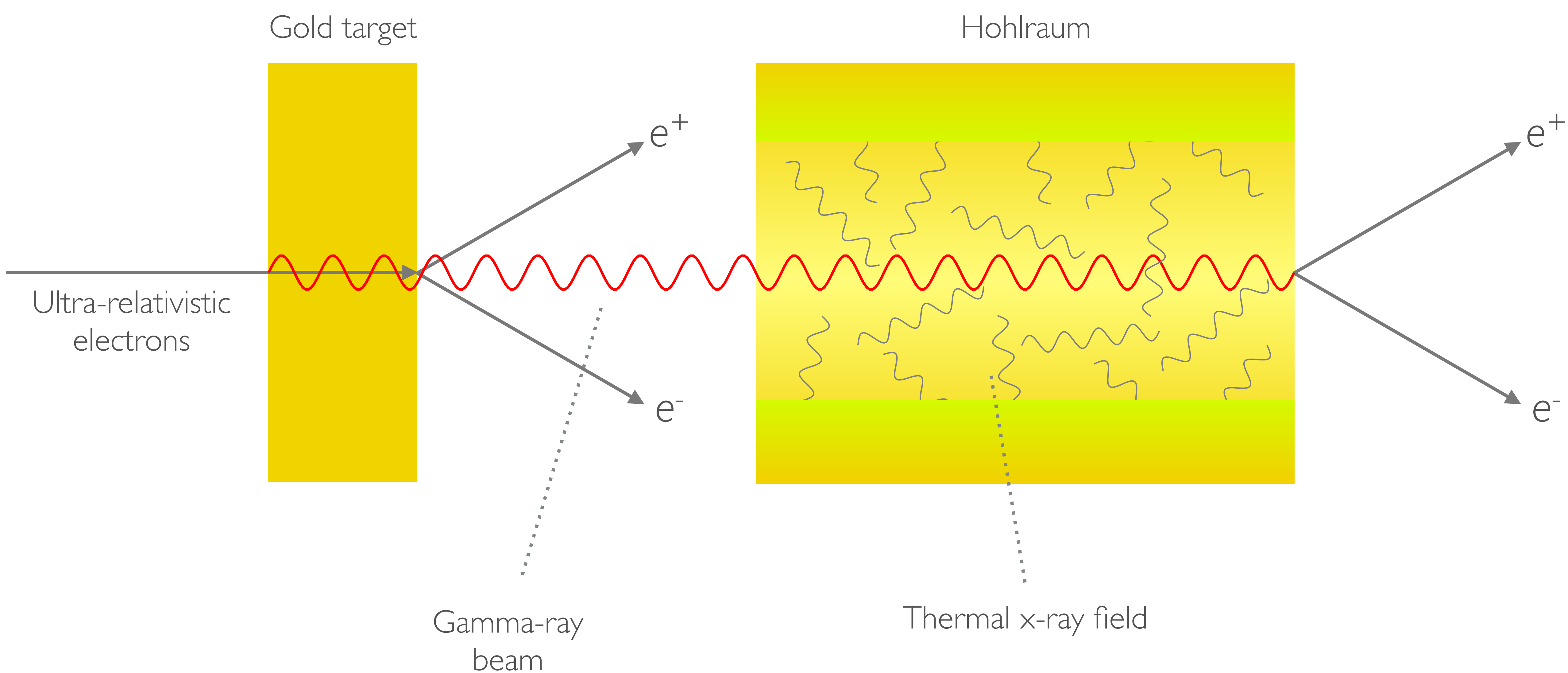

LLNL


LLNL

- Hohlraum — gold cylinder used to house fuel pellet in indirect-drive ICF. Laser beams strike hohlraum's inner surface, which re-radiates X-rays that irradiate the target.
- Provides more uniform drive than direct laser irradiance of capsule. (Asymmetries remain one of the primary barriers to ignition in ICF.)

Lindl et al., PoP **11,** 339 (2004)
Glenzer et al., PRL **106,** 085004 (2011)

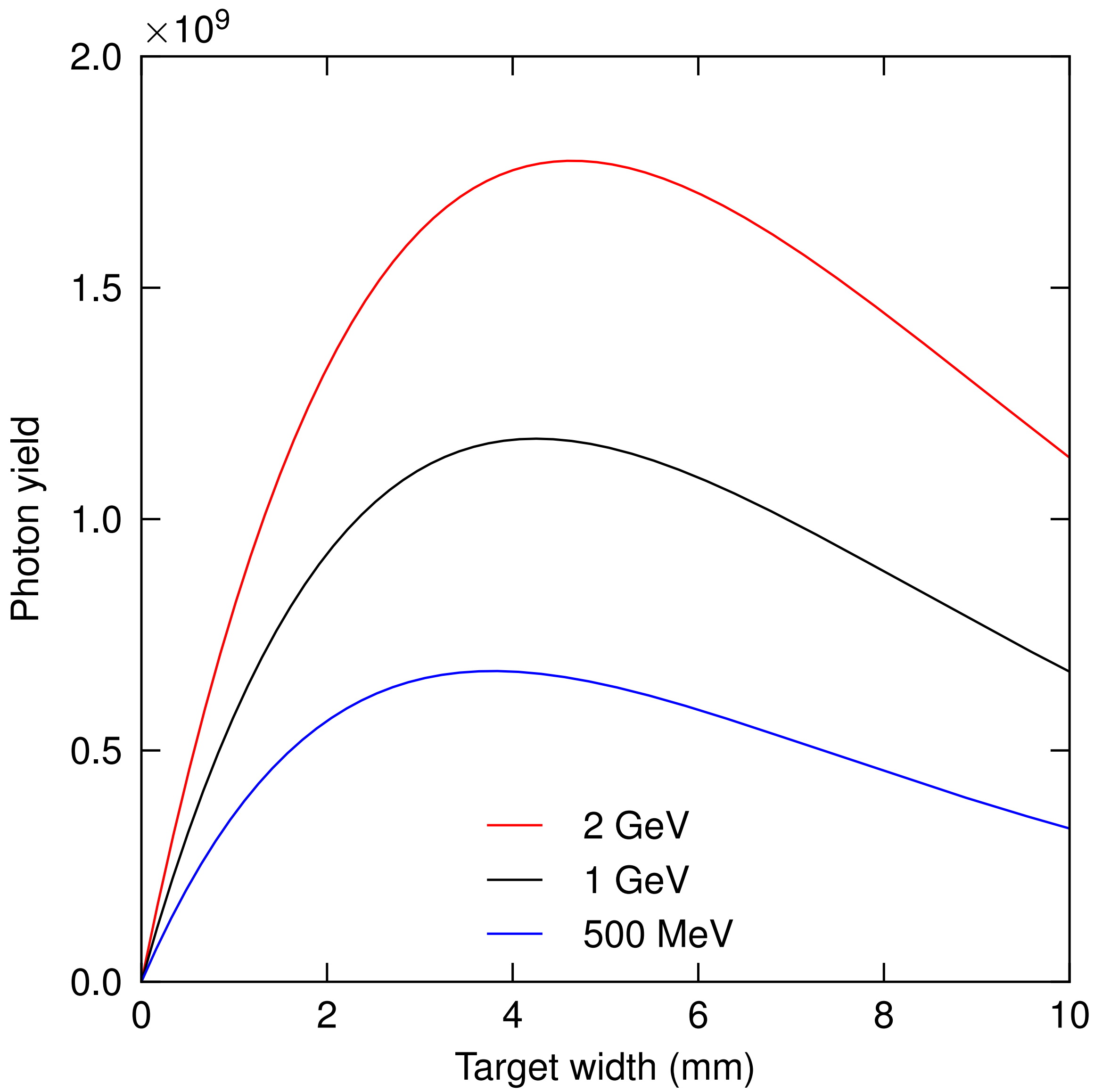
A photon-photon collider in a vacuum hohlraum: a new HEP experiment using HEDP facilities



Pike et al., *Nature Photonics* **8,** 434 (2014)

High conversion of electrons into gamma-rays can be achieved using bremsstrahlung in a gold target

Number of photons emitted over 100 MeV



- Ultra-relativistic electrons lose energy in gold almost solely by bremsstrahlung. (Other loss mechanisms such as ionisation and Compton scattering are suppressed at GeV energies.)
- Cross-section well known:

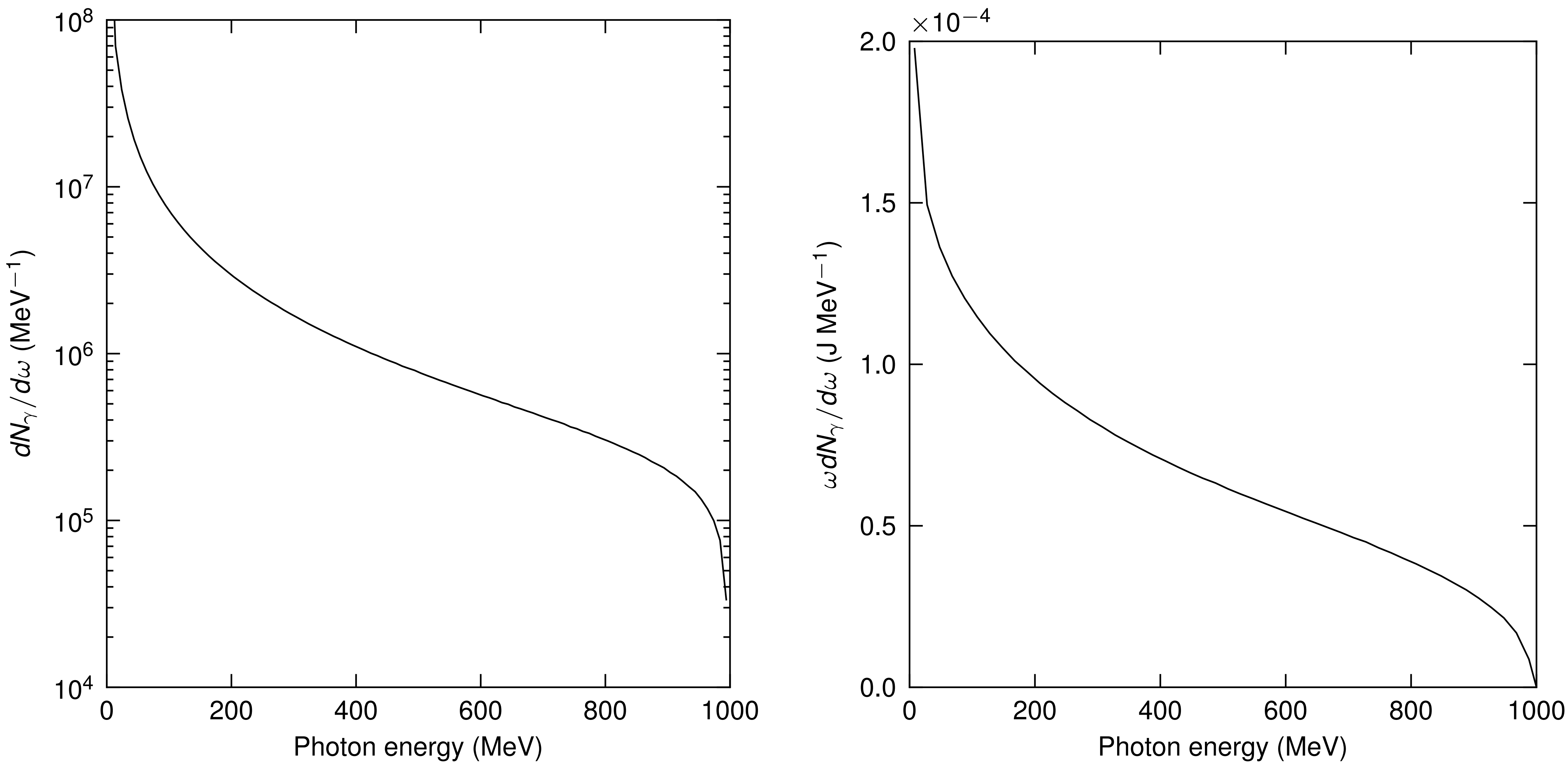
$$\frac{d\sigma_{eZ}}{d\omega}(\omega, y) = \frac{\alpha r_0^2}{\omega}\Big\{ \left(\tfrac{4}{3} - \tfrac{4}{3}y + y^2\right) \times \left[Z^2\left(\varphi_1 - \tfrac{4}{3}\ln Z - 4f\right) + Z(\psi_1 - \tfrac{8}{3}\ln Z)\right] + \tfrac{2}{3}(1-y)[Z^2(\varphi_1 - \varphi_2) + Z(\psi_1 - \psi_2)]\Big\}$$

- Emitted photons pair produce, resulting in cascades of low energy particles
- For maximum conversion to ultra high-energy photons, optimal target width a few mm

Pike et al., *Nature Photonics* **8**, 434 (2014)

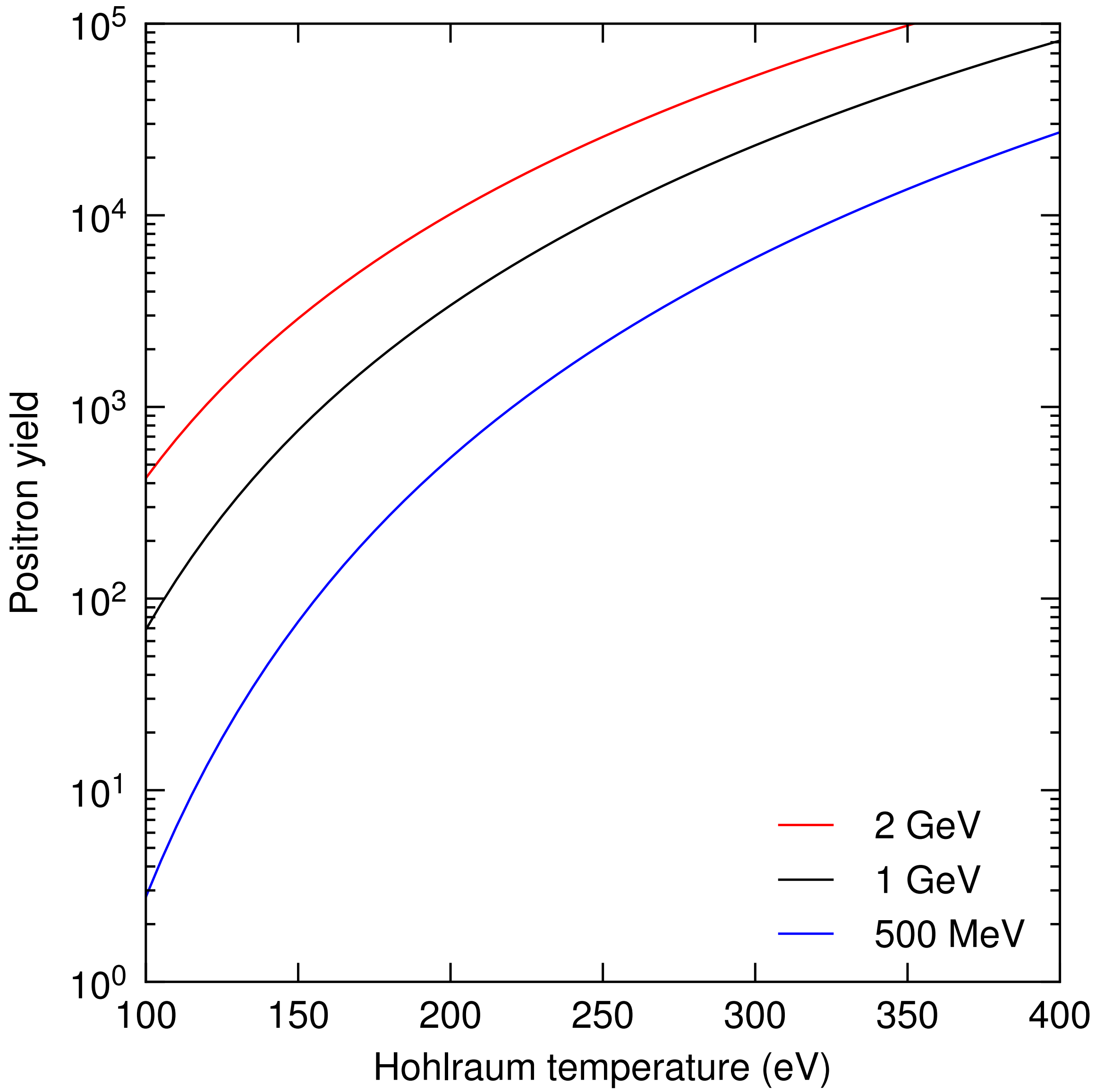
The distribution of gamma-rays leaving target is broad, but a significant number of them have very high energies

Distribution of photons leaving back surface of gold converter (3 mm thick)



Significant Breit-Wheeler pair production expected over wide range of beam energies and hohlraum temperatures

Number of positrons formed in hohlraum (length 1 cm)



- Number of Breit-Wheeler positrons formed in hohlraum given by

$$N_{e^+} \sim N_{\gamma_1} n_{\gamma_2} \delta x \cdot \sigma$$

where

N_{γ_1}	$\sim 10^9$	Gamma-ray number
n_{γ_2}	$\sim 10^{27}\ \mathrm{m}^{-3}$	X-ray number density
δx	$\sim 10^{-2}\ \mathrm{m}$	Length of hohlraum
σ	$\sim 10^{-29}\ \mathrm{m}^2$	Breit-Wheeler cross-section

for a hohlraum of temperature 400 eV, leading to up to

$$N_{e^+} \sim 10^5$$

events per shot

Pike et al., *Nature Photonics* **8**, 434 (2014)

LETTERS
PUBLISHED ONLINE: 18 MAY 2014 | DOI: 10.1038/NPHOTON.2014.95

nature photonics

A photon–photon collider in a vacuum hohlraum

O. J. Pike[1]*, F. Mackenroth[1,2], E. G. Hill[1] and S. J. Rose[1]

The ability to create matter from light is amongst the most striking predictions of quantum electrodynamics. Experimental signatures of this have been reported in the scattering of ultra-relativistic electron beams with laser beams[1,2], intense laser–plasma interactions[3] and laser-driven solid target scattering[4]. However, all such routes involve massive particles. The simplest mechanism by which pure light can be transformed into matter, Breit–Wheeler pair production ($\gamma\gamma' \rightarrow e^+e^-$)[5], has never been observed in the laboratory. Here, we present the design of a new class of photon–photon collider in which a gamma-ray beam is fired into the high-temperature radiation field of a laser-heated hohlraum. Matching experimental parameters to current-generation facilities, Monte Carlo simulations suggest that this scheme is capable of producing of the order of 10^5 Breit–Wheeler pairs in a single shot. This would provide the first realization of a pure photon–photon collider, representing the advent of a new type of high-energy physics experiment.

For more info see:

O. J. Pike, F. Mackenroth, E. G. Hill and S. J Rose,
A photon-photon collider in a vacuum hohlraum.
Nature Photonics **8**, 434-436 (2014).

doi:10.1038/nphoton.2014.95

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The scheme can be applied to a range of current-generation optical laser facilities

	Coupled short- and long-pulse facilities	Ultra-short pulse laser facilities
Examples of facilities	• National Ignition Facility (USA) • Orion laser (UK) • Laser Megajoule (France) • OMEGA EP (USA)	• Astra Gemini (UK) • Texas Petawatt (USA) • Berkeley Lab Laser Accelerator (USA) • FLAME (Italy)
Gamma-ray beam	• Direct laser acceleration / self-modulated laser wakefield	• Laser wakefield acceleration
X-ray field	• Hohlraum	• Burn-through foil
Rep rate	~ /hour	~ /min or /sec
Yield (per shot)	**10^3-10^4**	**0.1-1**

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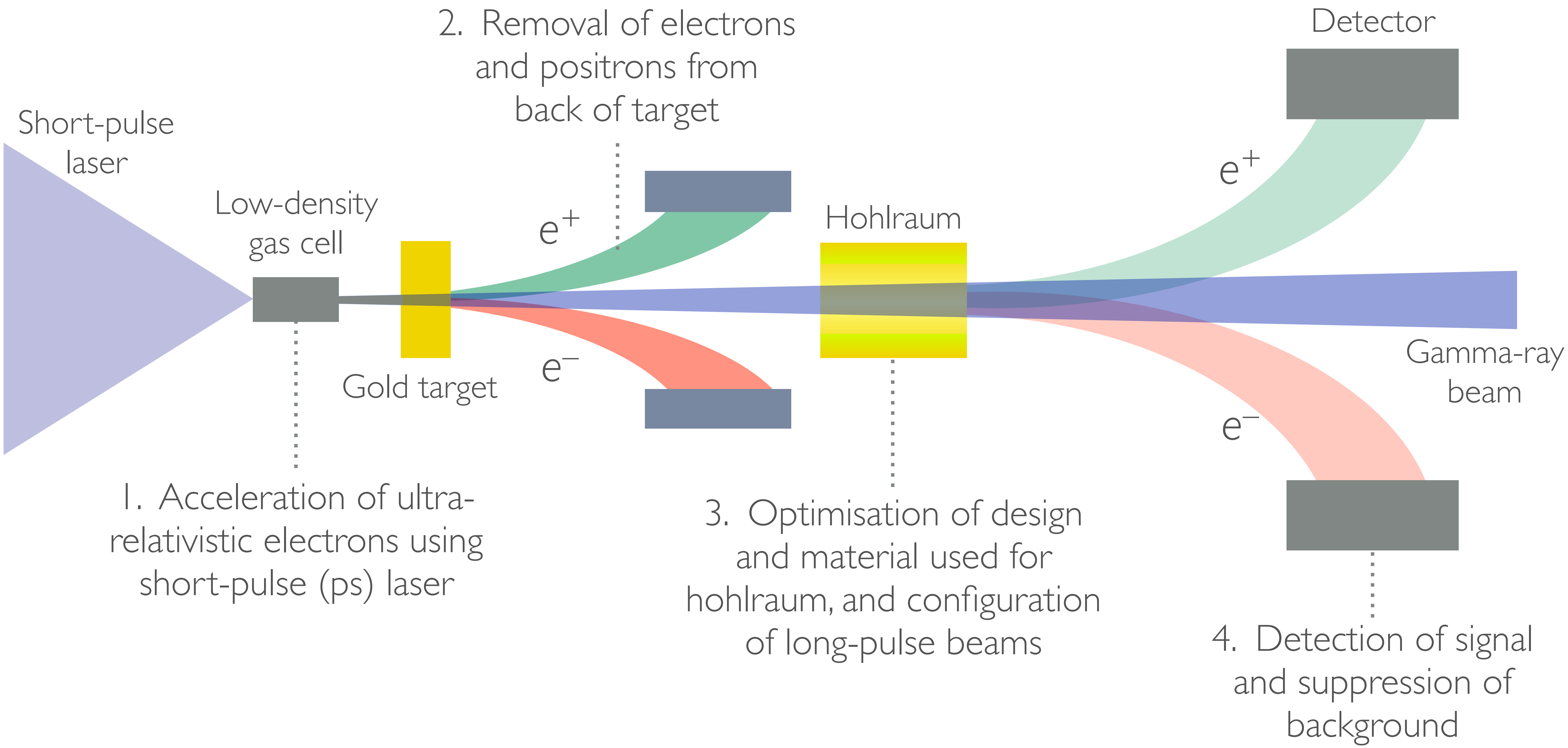
There are various considerations when implementing this experimental scheme in the laboratory



Picosecond pulses have previously accelerated electrons in a thermal distribution extending to 100s of MeV

	Short-pulse lasers	Ultra-short pulse lasers
Pulse length	• Of order ps • Longer than plasma wavelength	• Of order 10 fs • Matched to plasma wavelength
Focusing	• Fast (e.g., f/3)	• Slow (e.g., f/20)
Acceleration mechanism	• Direct laser acceleration • Self-modulated laser wakefield	• Laser wakefield acceleration
Energies	• Up to a few 100 MeV • Thermal distribution	• Up to 1 GeV • Quasi-monoenergetic
Divergence	• Few degrees	• Few mrad

Mangles et al., *PRL* **94**, 245001 (2005)
Kneip et al., *PRL* **103**, 035002 (2009)

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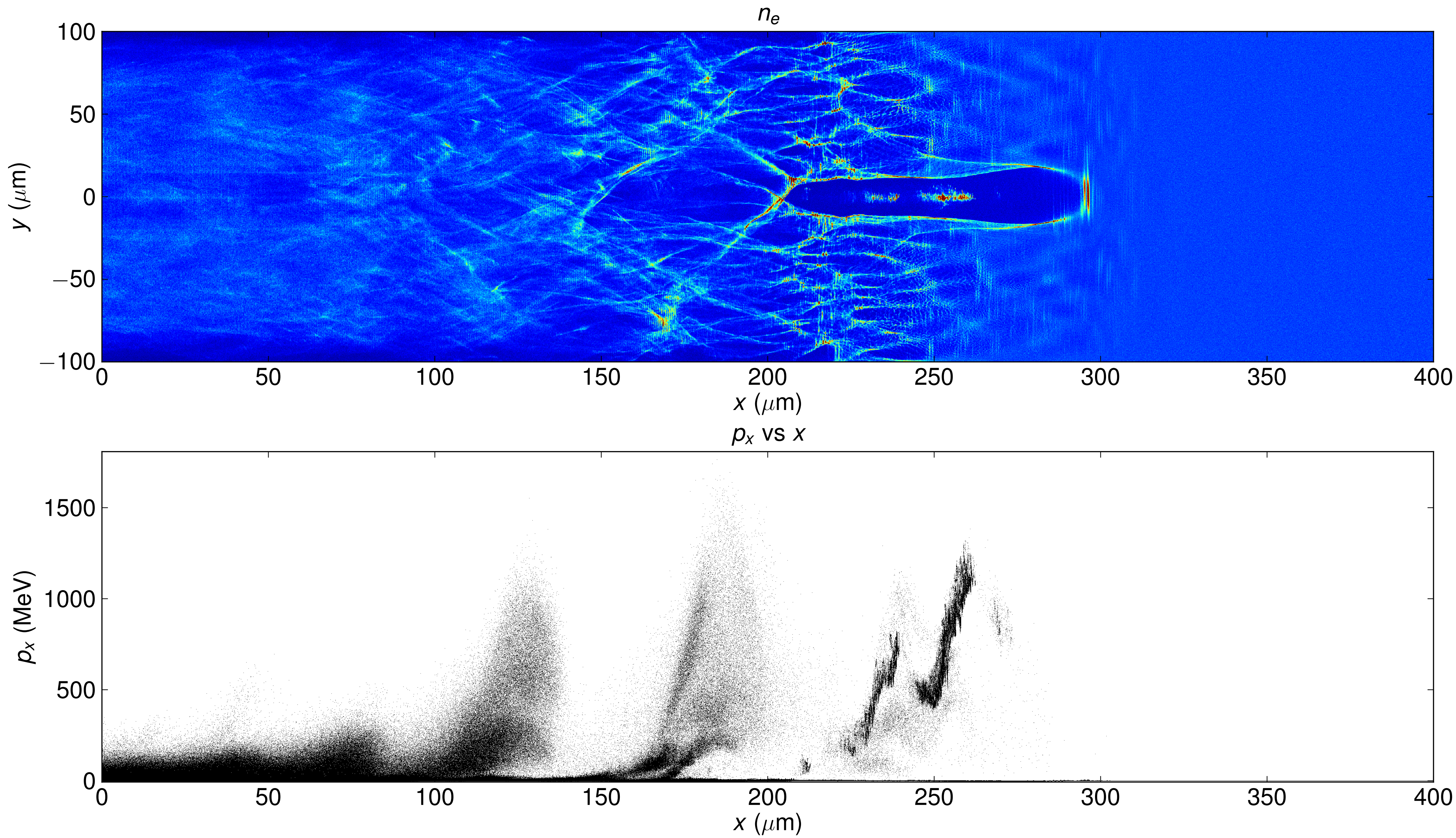
Mangles et al., *PRL* **94**, 245001 (2005)
Kneip et al., *PRL* **103**, 035002 (2009)

Preliminary 2D PIC results suggest that acceleration to GeV energies may be possible with longer pulses

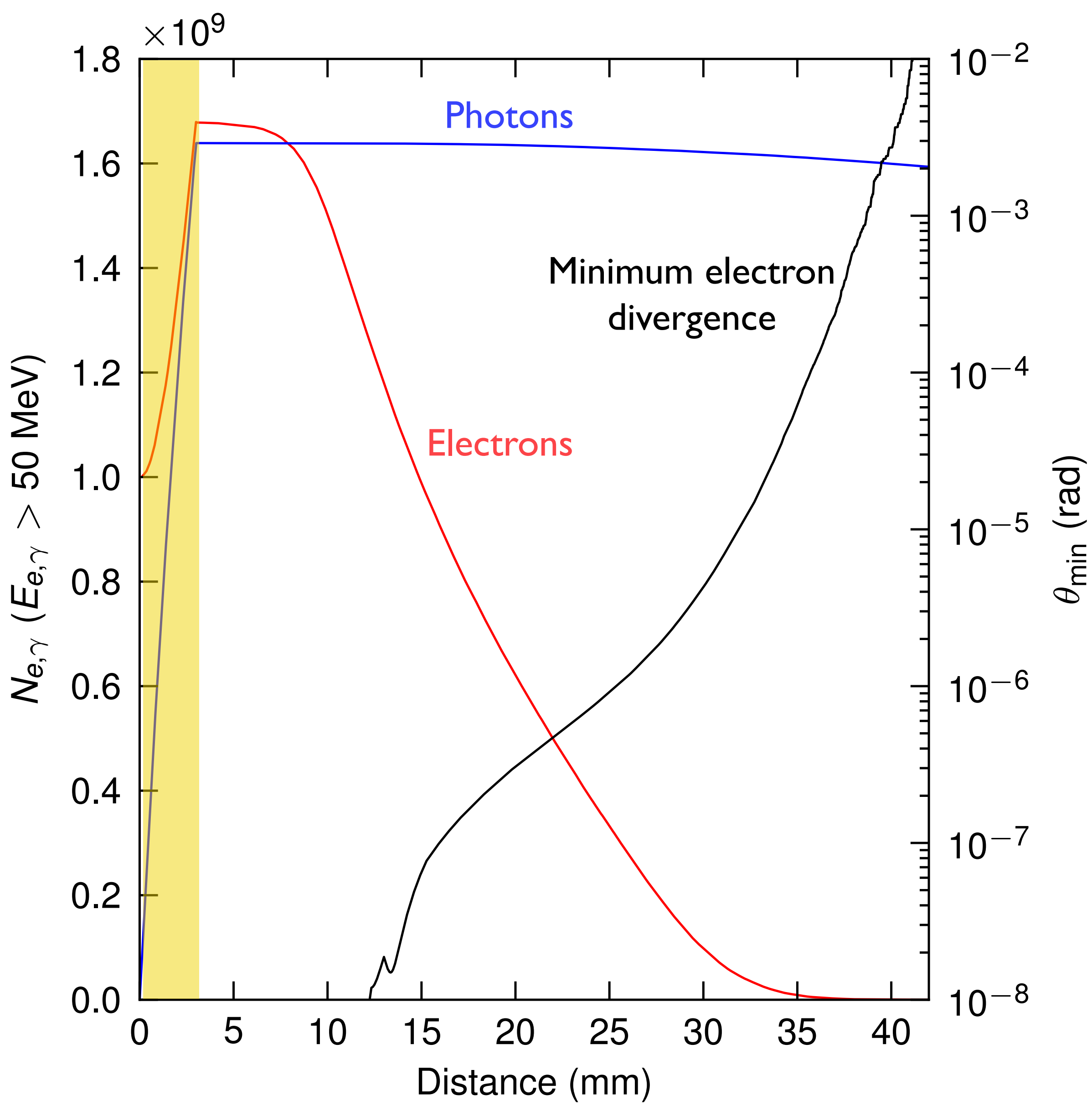
Electron acceleration with short-pulse laser



Pike et al., in preparation (2014)

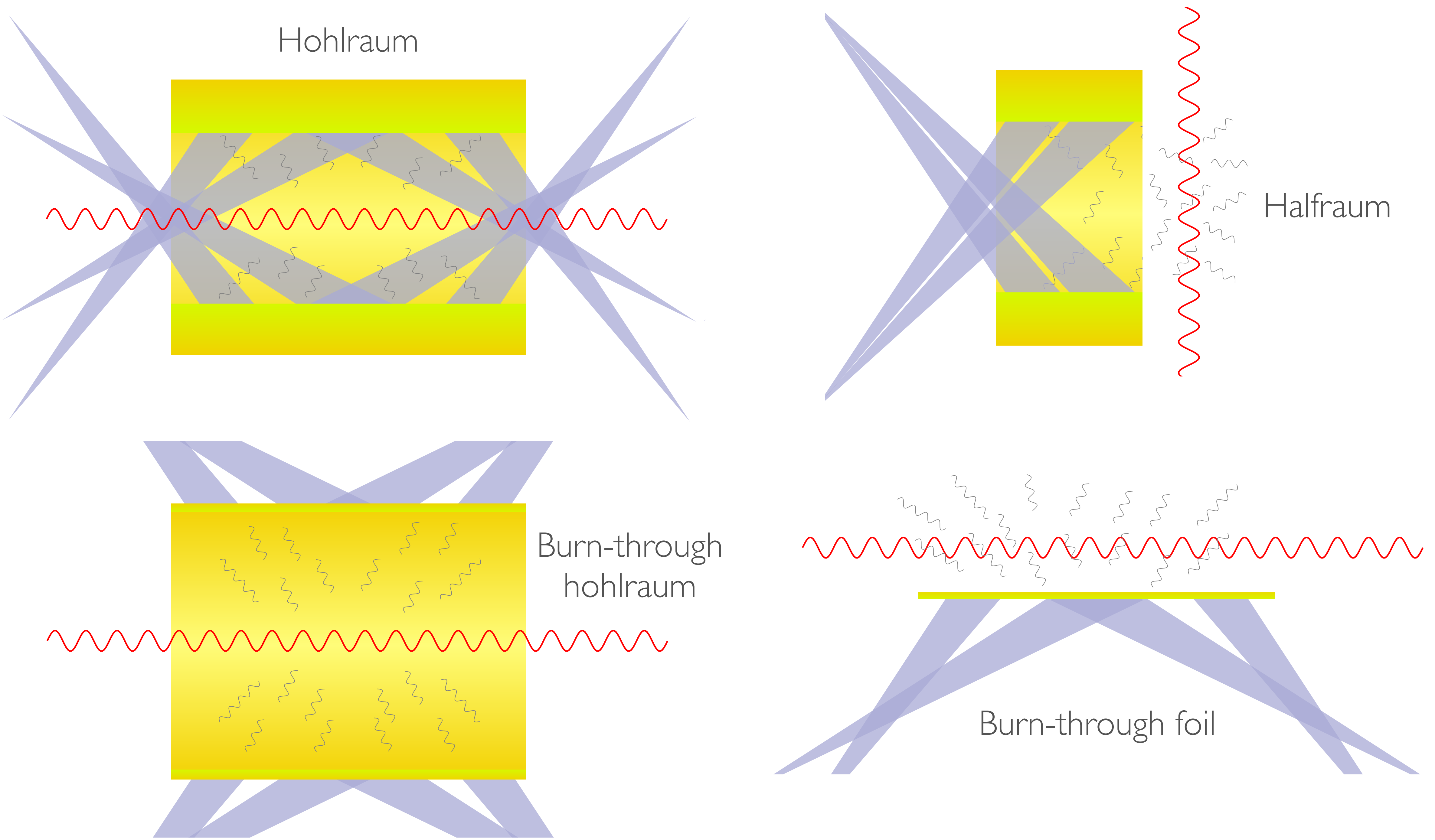
Electrons and positrons can be effectively removed from the beam line using an 8 T electromagnet

Number of particles within 1 mm of beam axis



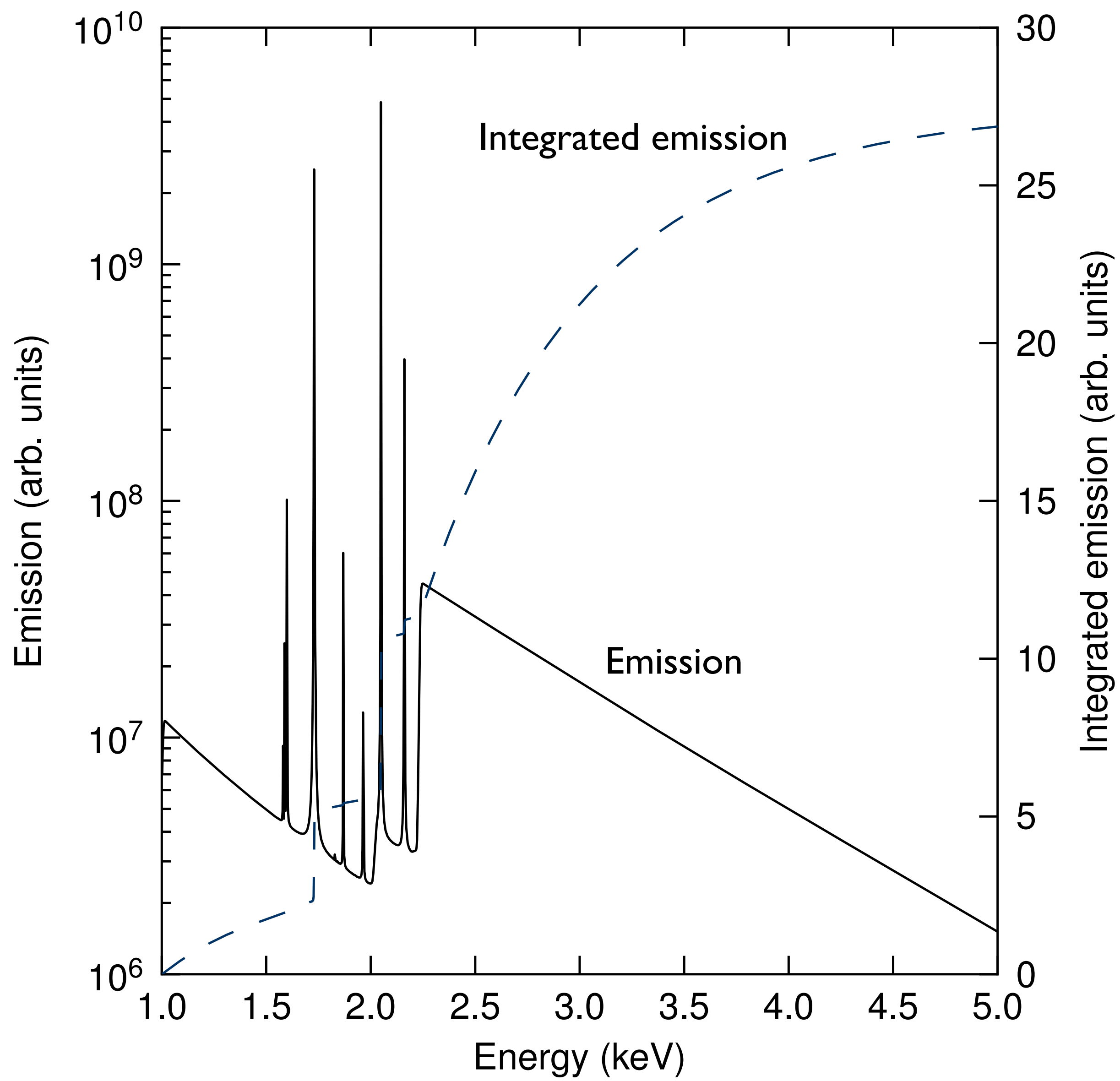
- Electrons and positrons emerging from the back of the gold converter must be removed from the beam line to prevent them from entering the hohlraum.
- This can be effectively achieved using an 8 T electromagnet, with minimal divergence of the gamma-ray beam.
- Permanent magnets (approx. 1 T) unlikely to be sufficient.

Optimising hohlraum for maximum radiation temperature with minimum blow-off and self-generated E/M fields



Material of X-ray generator is also an important consideration for maximum yield

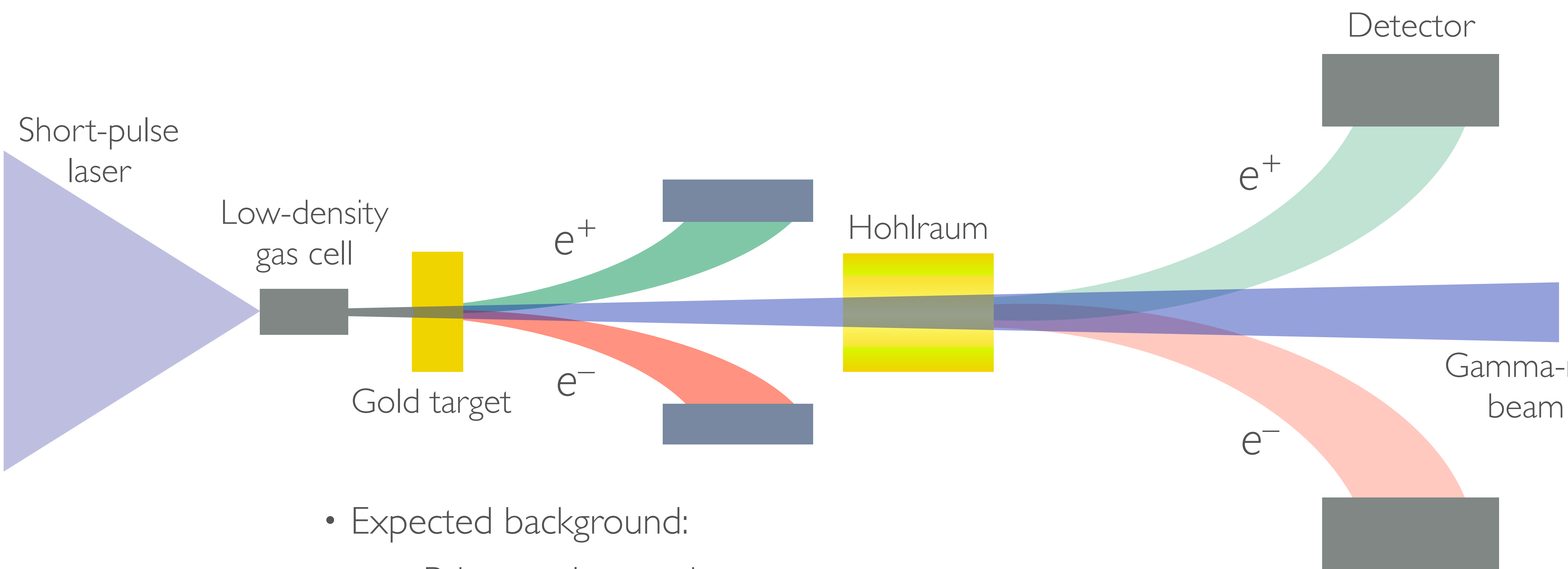
X-ray spectrum for Al at 100 eV and a tenth solid density



Hill, private communication (2014)

- Radiation produced inside gold hohlraum / using gold burn-through foil is well described as a thermal distribution with temperature ~100 eV.
- Non-thermal radiation — produced from emission in the *l*-shell and *M*-band, for example — can have higher energies (~ 1-10 keV).
- This can relax the constraints on the gamma-ray energies, if required.

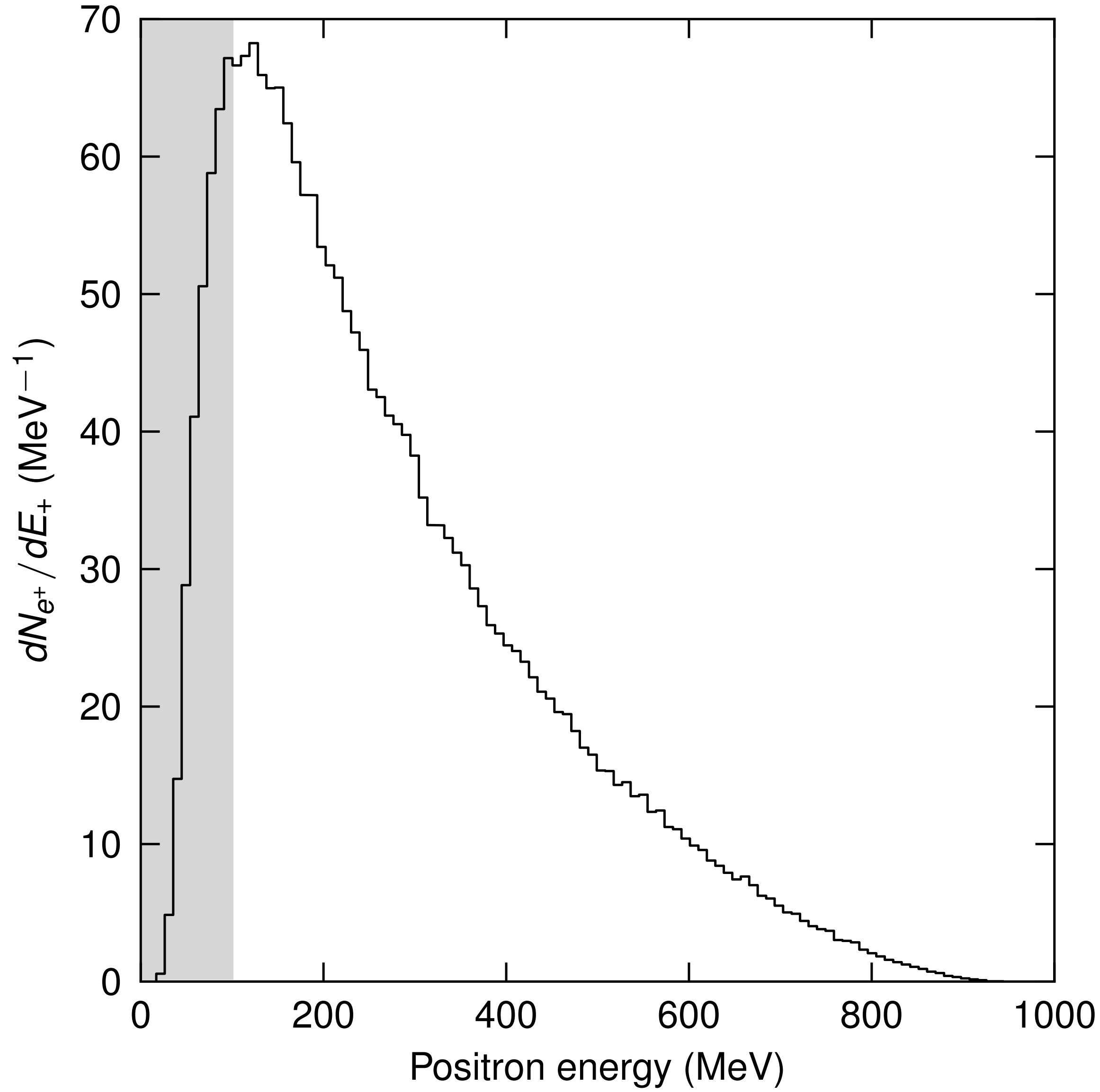
There are various sources of background that need to be considered in this experiment



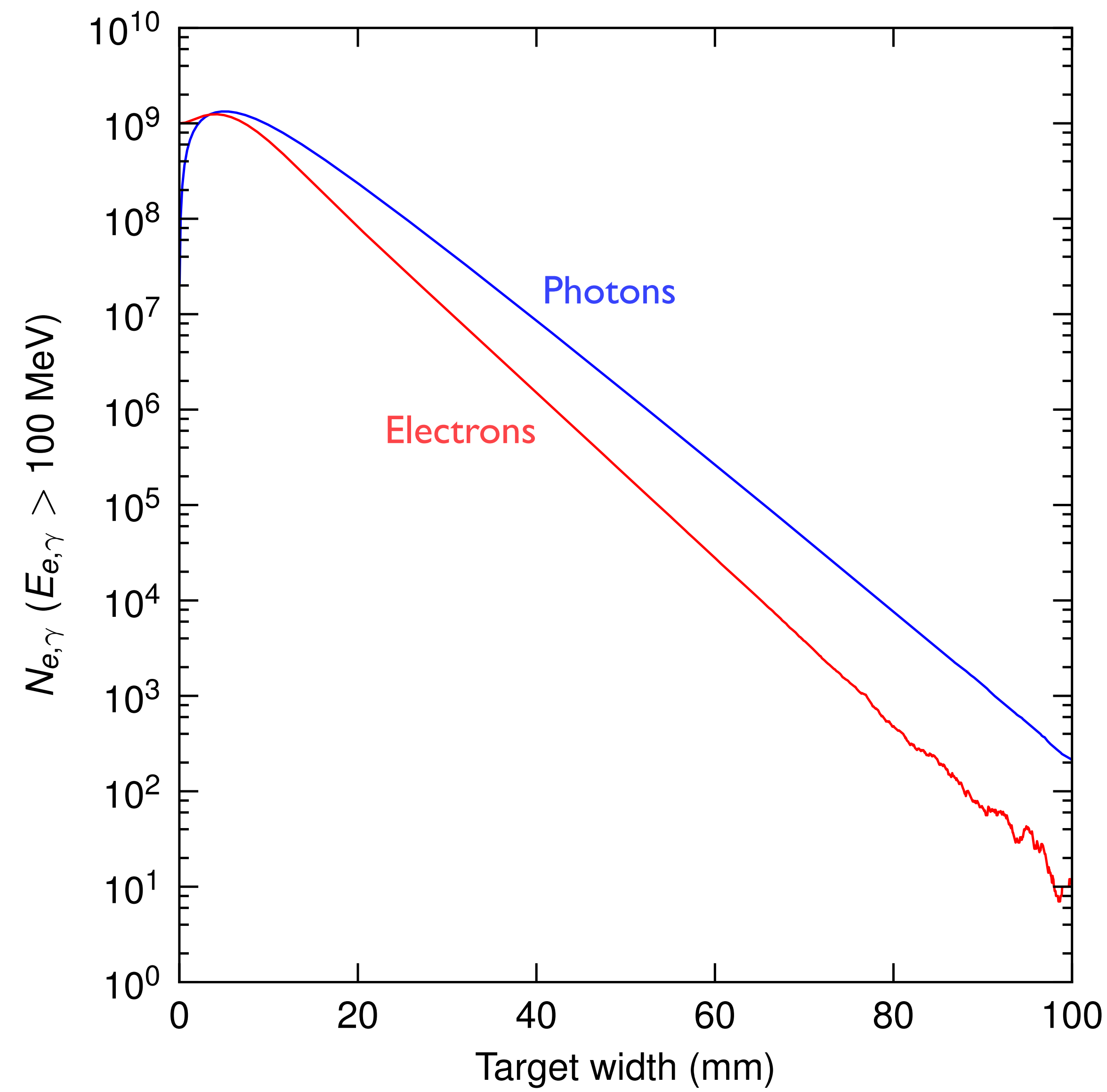
- Expected background:
  - Primary electron beam
  - Pairs produced in gold converter
  - Pairs produced as gamma-ray interacts with plasma blow-off in hohlraum
  - Compton up-scattered electrons
  - etc.

Given significant background expected below 100 MeV, detector needs to effectively screen low-energy particles

Predicted Breit-Wheeler positron spectrum



Removal of high-energy background using high-Z shielding



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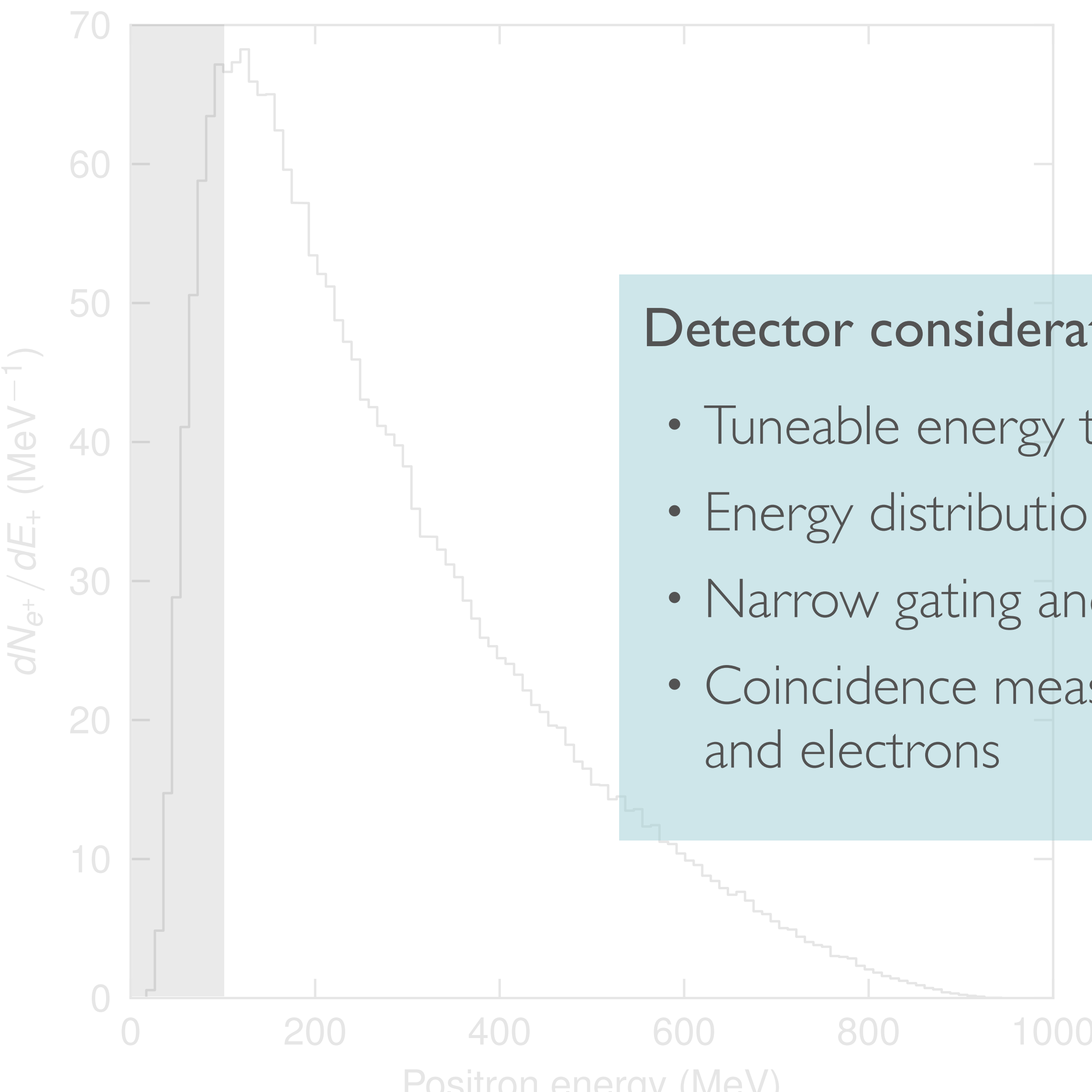

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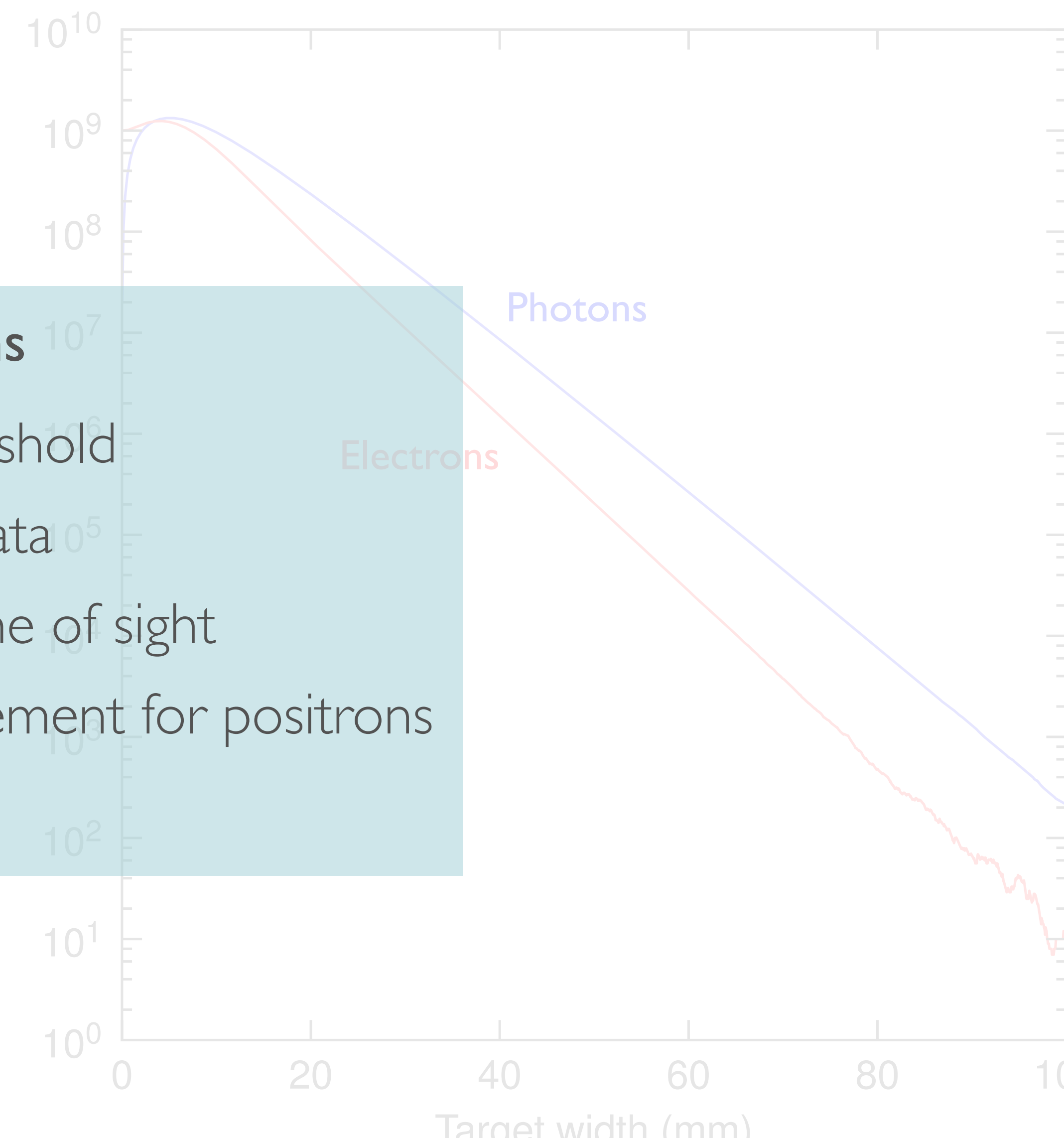

Detector considerations

- Tuneable energy threshold
- Energy distribution data
- Narrow gating and line of sight
- Coincidence measurement for positrons and electrons

Outline of talk

1. Introduction
2. A photon-photon collider in a vacuum hohlraum
3. Implementing experiment on current-generation facilities
4. Summary

Summary

- Demonstrated the feasibility of performing a new HEP experiment using HEDP facilities.
  - Experiment would provide first direct observation of the Breit-Wheeler process.
  - Would also demonstrate interaction of light in vacuum for the first time.
- For more info see:

  O. J. Pike et al., A photon-photon collider in a vacuum hohlraum. *Nature Photonics* **8,** 434-436 (2014). doi:10.1038/nphoton.2014.95
- Currently developing experimental design for specific facilities, including detailed study of electron acceleration, X-ray field generation, shielding of background and detection.
- We hope to perform this experiment in the near future.