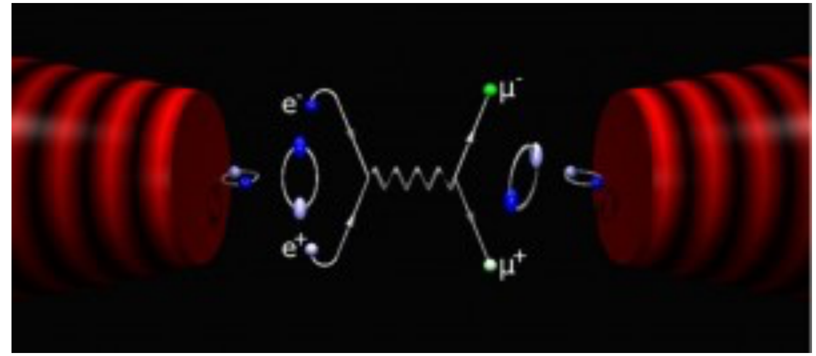


ExHILP 2015 conference, July 21-24 2015

Possibility of pair creation in the collision of gamma-ray beams produced by high intensity laser plasma interaction

E. d'Humières[1], X. Ribeyre[1], M. Lobet[1,2], S. Jequier[1], O. Jansen[1] and V. T. Tikhonchuk[1]

[1]Univ. Bordeaux-CNRS-CEA
33405 Talence, France

[2]CEA, DAM, DIF, F-91297,
Arpajon, France

Outline

➔Context: importance of the Breit-Wheeler process and previous work

➔Configurations allowing to produce 2 photons Breit-Wheeler pairs using nowadays installations

➔Focus on the collision of MeV photon beams

➔Simulation results and estimations of parasite pairs numbers

➔Conclusions and perspectives

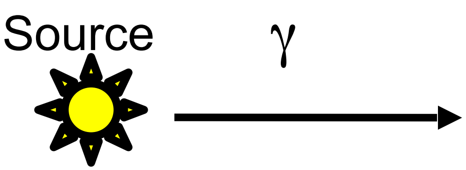
Photon-Photon collision and pair production in astrophysics[1]

Breit-Wheeler process[2]
Collision of two light quanta

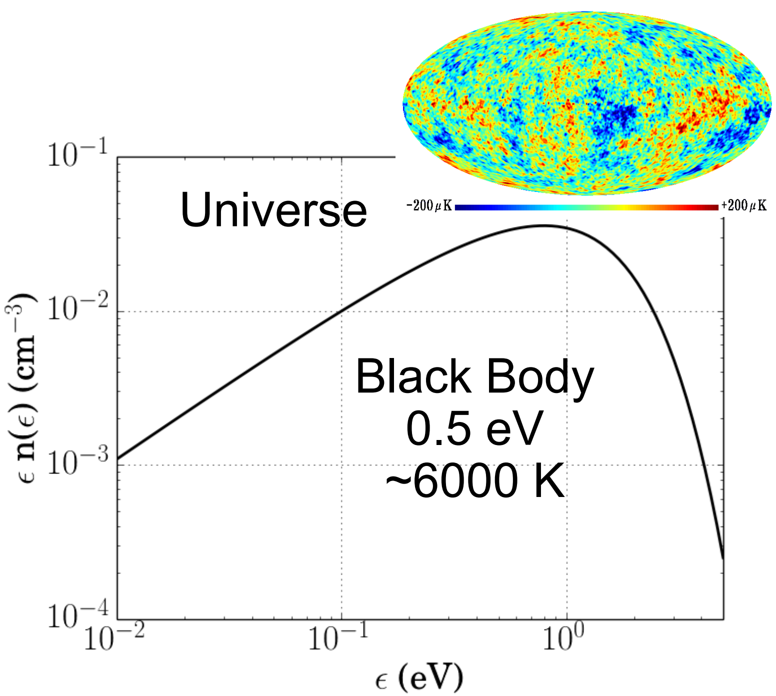
$$\gamma + \gamma \longrightarrow e^+ + e^-$$

- Absorption of high-energy photons in the Universe[3], **cut-off in high energy gamma rays**

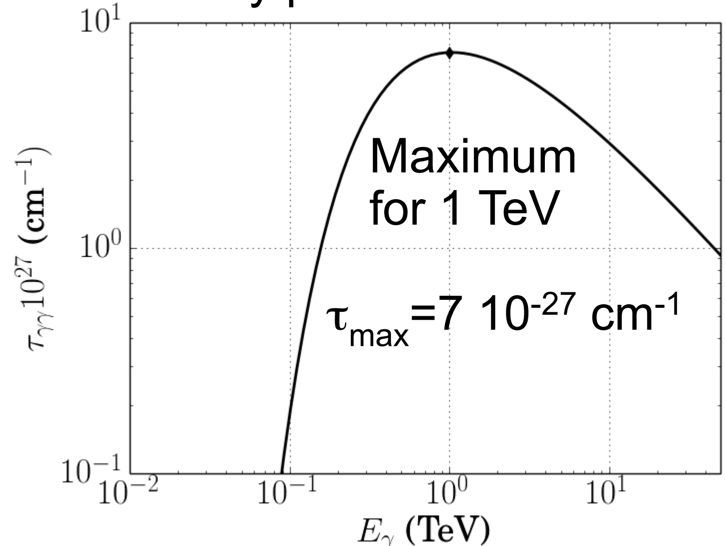
Nikishov[3] (1962) first showed that the maximum of absorption in universe is around 1 TeV



R_c= distance
Source-Observation
(Cygnus A)



Absorption (opacity)
by pair creation



Attenuation: $\eta=\exp(\tau R_c)$

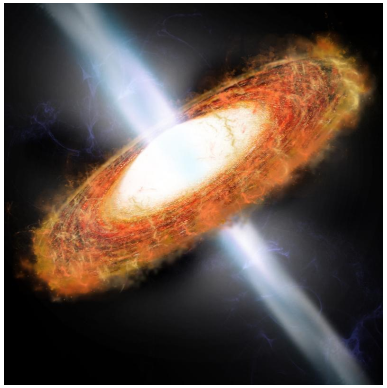
R_c=6.6 10^{26} cm = 213 Mpc $\eta=\exp(4.6)$

[1]Ruffini, R. et al. Physics Reports, 487, 1-140 (2010)
[2]Breit, G. and Wheeler J. A. PRL **15** (1934)
[3]Nikishov A. I., JETP **14** (1962), Gould, R. J. PRL **155**, 5 part 1, part2 (1967), Kneitske, T.M. et al. A&A 413, 807 (2004)

Photon-Photon collision and pair production in astrophysics

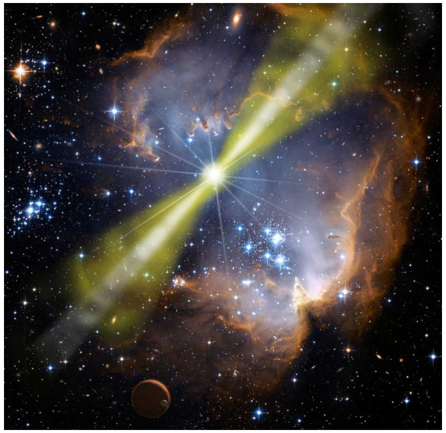
Breit-Wheeler process
Collision of two light quanta

$$\gamma + \gamma \longrightarrow e^+ + e^-$$



Artiste composition

- e^+/e^- pair production in AGN (Active Galaxy nuclei), Blazar, Quasar[1]



Artiste composition

- e^+/e^- pair production in
  - GRB[2] (Gamma ray burst), Supernovae, Hypernovae…
  - In pulsar – electron-positron pair plasma
  - Merging neutron start, black hole
  - Accretion disk

→ Controls energy release in astrophysical processes

[1]Bonometto, S. and Ress, M. J. MNRAS, **152** 21-25 (1971)

[2]Piran, S. Rev. Mod. Phys. 76 (2004)

Pair creation with two real photons has not been observed in laboratory

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

S. C. Berridge, W. M. Bugg, K. Shmakov, and A. W. Weidemann
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996

C. Bula, K. T. McDonald, and E. J. Prebys
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

C. Bamber,* S. J. Boege,† T. Koffas, T. Kotseroglou,‡ A. C. Melissinos, D. D. Meyerhofer,§ D. A. Reis, and W. Ragg‖
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 2 June 1997)

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

PACS numbers: 13.40.–f, 12.20.Fv, 14.70.Bh

See also Pike, O. J. et al. Nature Photonics, 8, 434, (2014)

The production of an electron-positron pair in the collision of two real photons was first considered by Breit and Wheeler [1] who calculated the cross section for the reaction

$$\omega_1 + \omega_2 \rightarrow e^+e^- \quad (1)$$

to be of order r_e^2, where r_e is the classical electron radius. While pair creation by real photons is believed to occur in astrophysical processes [2], it has not been observed in the laboratory up to the present.

approaches or exceeds unity. Here the laser beam has laboratory frequency ω_0, reduced wavelength λ_0, root-mean-square electric field $\mathcal{E}_{\rm rms}$, and four-vector potential A_μ; e and m are the charge and mass of the electron, respectively, and c is the speed of light.

For photons of wavelength 527 nm a value of $\eta = 1$ corresponds to laboratory field strength of $\mathcal{E}_{\rm lab} = 6 \times 10^{10}$ V/cm and intensity $I = 10^{19}$ W/cm^2. Such intensities are now practical in tabletop laser systems based on chirped-pulse amplification [6].

Photon-Photon collision and pair production in laboratory (SLAC)

Non-linear Breit-Wheeler process[1]

$\gamma + n\omega \longrightarrow e^+ + e^-$

Two steps process

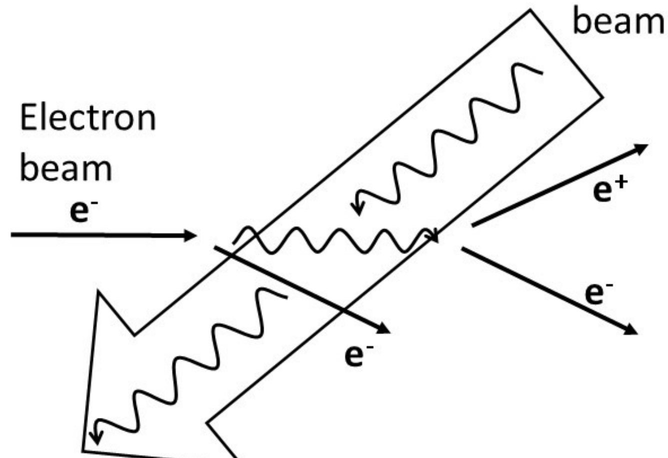
Laser ω
2.35 eV

E144 experiment

1- Non-linear Compton scattering

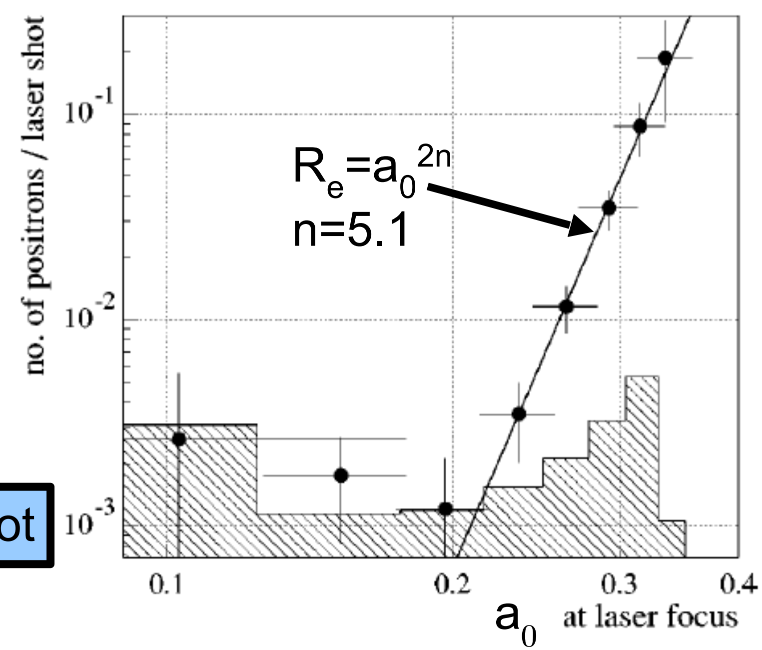
e^- (46 GeV)+ $n\omega \longrightarrow e' + \gamma$ (29 GeV)

SLAC electrons
46.6 GeV



2- Non-linear Breit-Wheeler pair

γ (29 GeV) + $n\omega$ (eV) $\longrightarrow e^+ + e^-$



First observation of non-linear Breit-Wheeler pair production with real photons[2] (with n>4)

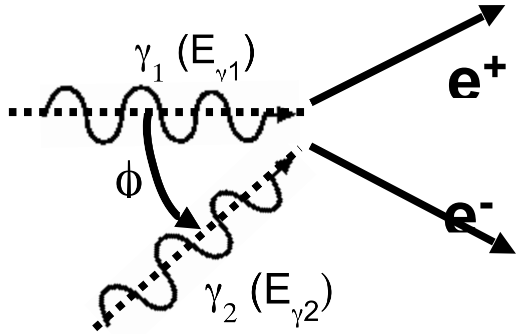
Nb of interacting photon becomes large if a_0>1

0.01 - 0.2 pair per laser shot

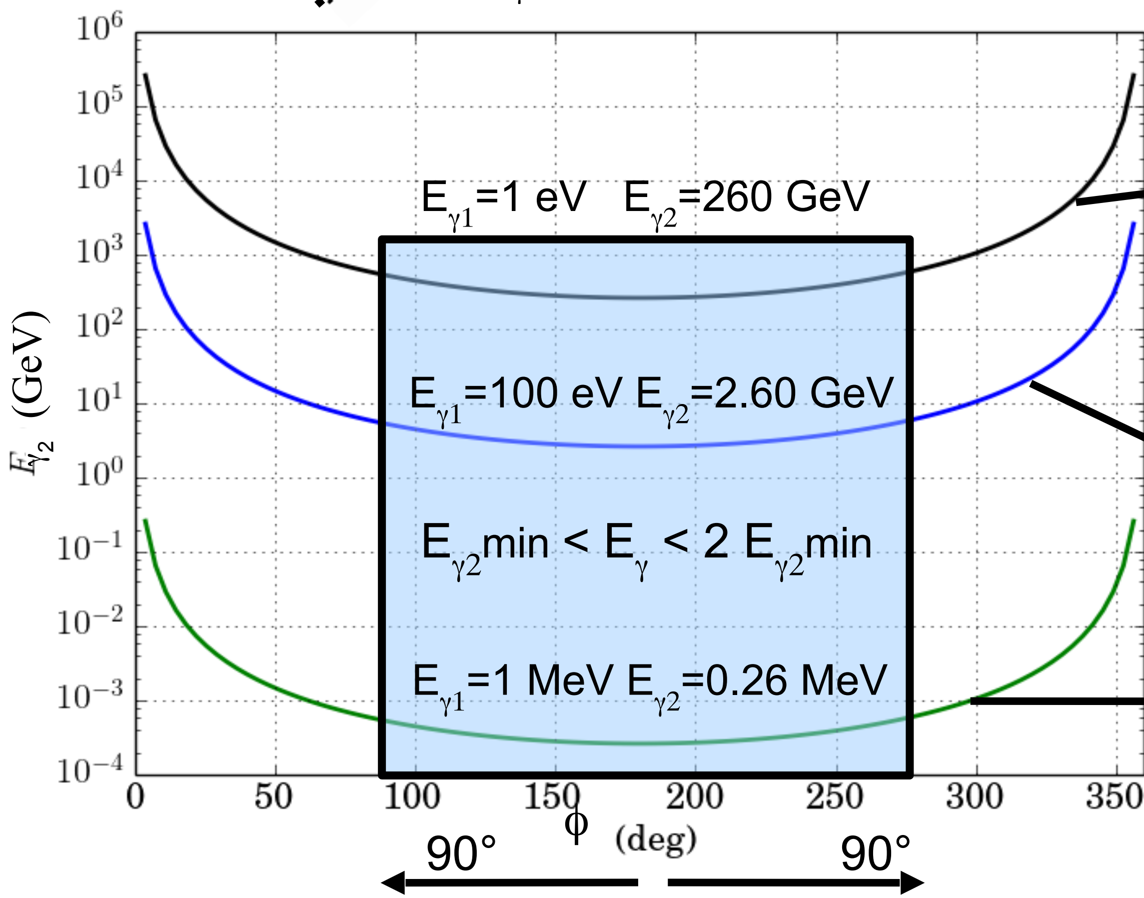
[1]Bamber, C. et al. PRD, 60 092004 (1999)

[2]Burke, D. L. et al. PRL 79, 9 (1997)

Search for other experimental configurations



$$E_{\gamma_2} = \frac{2m_e^2c^4}{E_{\gamma_1}(1-\cos(\phi))}$$



Perturbative regime, i.e.
Non-linear Breit-Wheeler

SLAC E-144 exp.

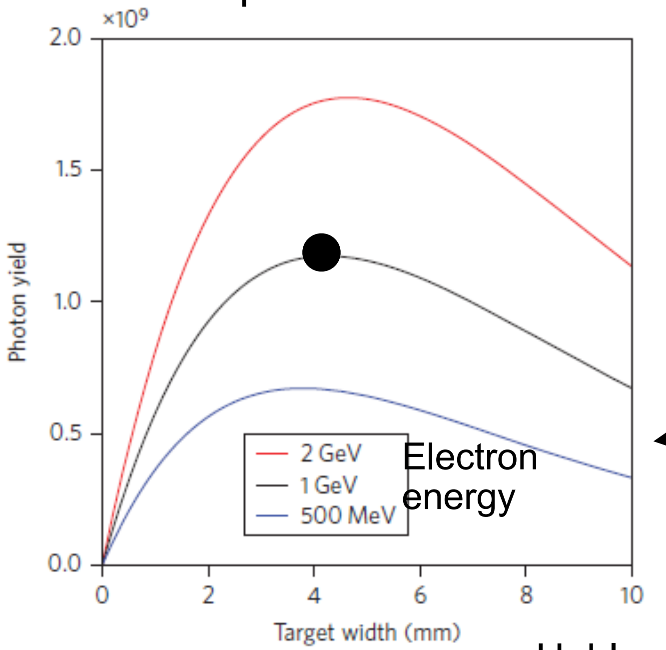
Non-perturbative regime, i.e.
linear Breit-Wheeler
Real photon-photon collision

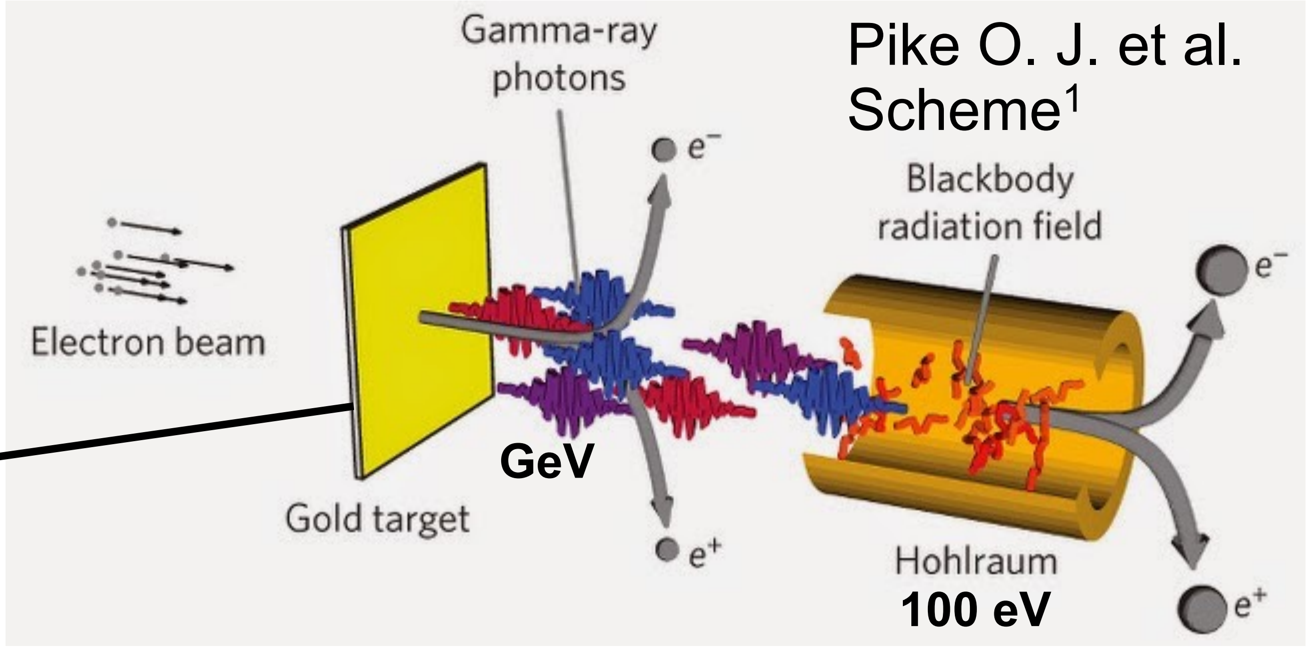
(1) γ **photon- photon bath collision**

(2) MeV-MeV photon collision

(1) New experimental concept for pair creation

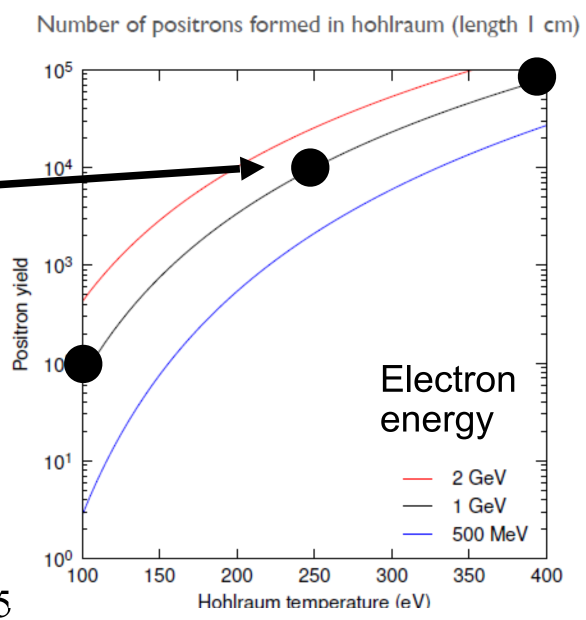
Number of photons above 100 MeV





Hohlraum Temperature	Nb of positrons
100 eV	10^2
250 eV	$\mathbf{10^4}$
400 eV	10^5

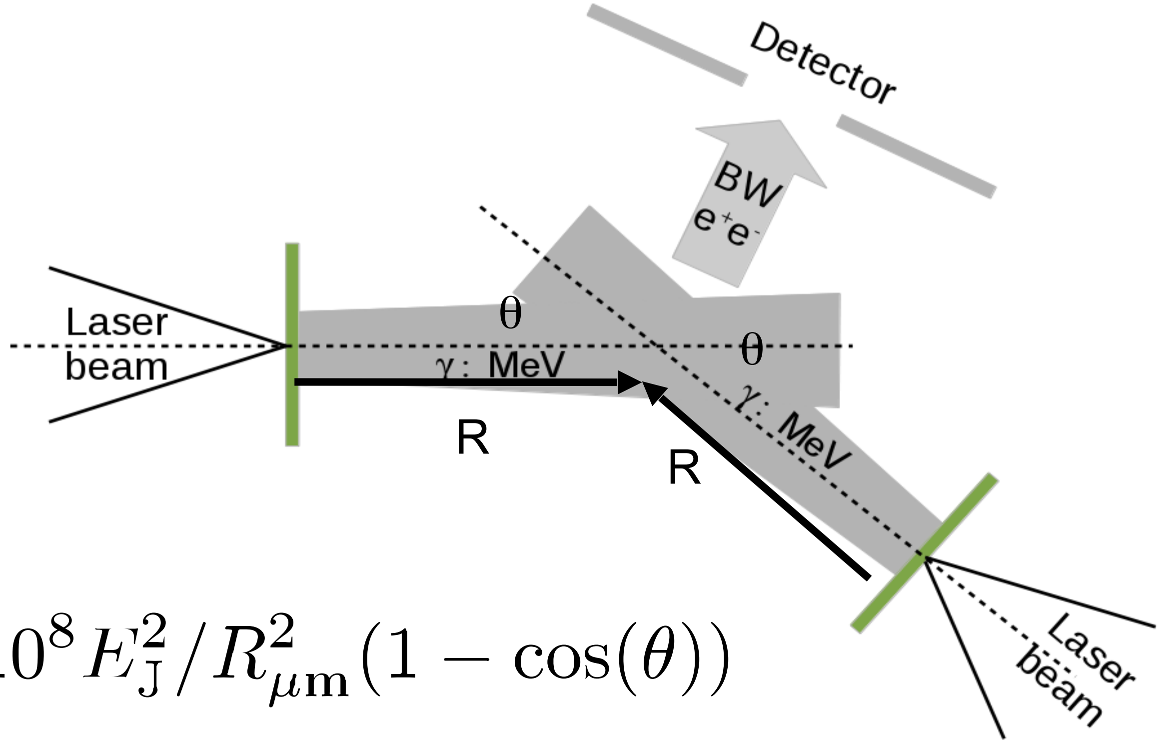
Possible experimentation on LMJ-PETAL facility



[1]Pike, O. J. et al. Nature Photonics, **8**, 434, (2014)

Caveats: Noise due to the positrons created with Bethe-Heitler and Trident processes, production pair Inside the gold cavity (Hohlraum)

(2) Collision of MeV-MeV photons in vacuum



θ : γ–beam divergence

R : distance between γ source and photons collision zone

$$N_p = 10^8 E_J^2 / R_{\mu m}^2 (1 - \cos(\theta))$$

MeV-MeV photons collision

$$\mathrm{E_J} = 1 - 10\,\mathrm{J} \text{ and } \mathrm{R} = 500\,\mu\mathrm{m} \quad \theta = 30^\circ$$

Pair production per shot : $\mathrm{N}_p = 3 \times 10^3 - 3 \times 10^5$

Need for high-intensity collimated MeV photon beams

γ–ray sources in MeV range

Performances comparison between different γ–ray sources

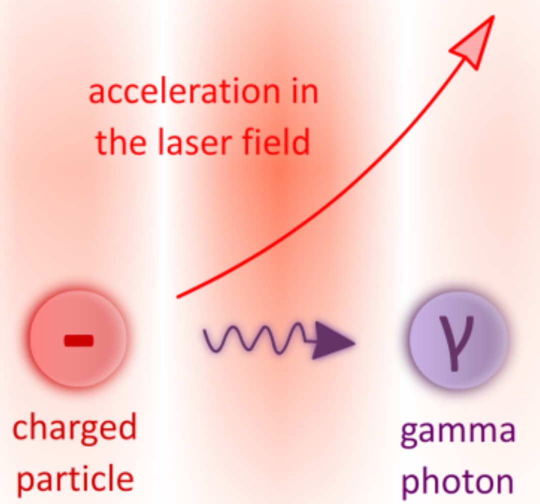
Sources	Bremss.	Betatron	Compton	Synch.
γ energy	3–50 MeV	1-7 MeV	1–10 MeV	1–10 MeV
Beam energy	1–2 J	1 μJ	10 μJ	1–10 J
Efficiency	2×10^{-2}	10^{-6}	10^{-5}	10^{-2}
Divergence (θ)	$\sim 15°$	$\sim 1°$	$\sim 1°$	$\sim 30°$
Reference	[23]	[29]	[32]	[30],
N_p from Eq.(3) at $R = 500\ \mu$m	$\sim 10^4$	10^{-5}	$\sim 10^{-5}$	$\sim 10^4$

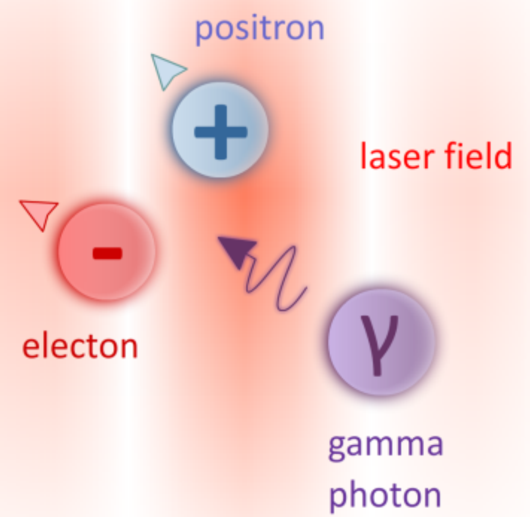
Synchrotron radiation sources seem to be a good choice for pair production
Possibility to use gas targets (low noise sources)

[23] Henderson A. et al. High Energy Density Physics **12**, 46 (2014)
[29] Cipiccia S. et al. Nature Physics **7**, 867 (2011)
[32] Sarri G. et al. PRL **113,** 224801 (2014)
[30] Capdessus, R. et al. PRL **110** (2013), Capdessus, R. PoP **21** (2014)

Radiative and QED effects[1] in ultra-intense laser plasma interaction[2,3]

Apollon (10 PW, 100J, 15 fs) → **ELI** (100 PW) → **IZEST** (> 1EW)





Non-linear Compton scattering: high-frequency photon emission in the laser field

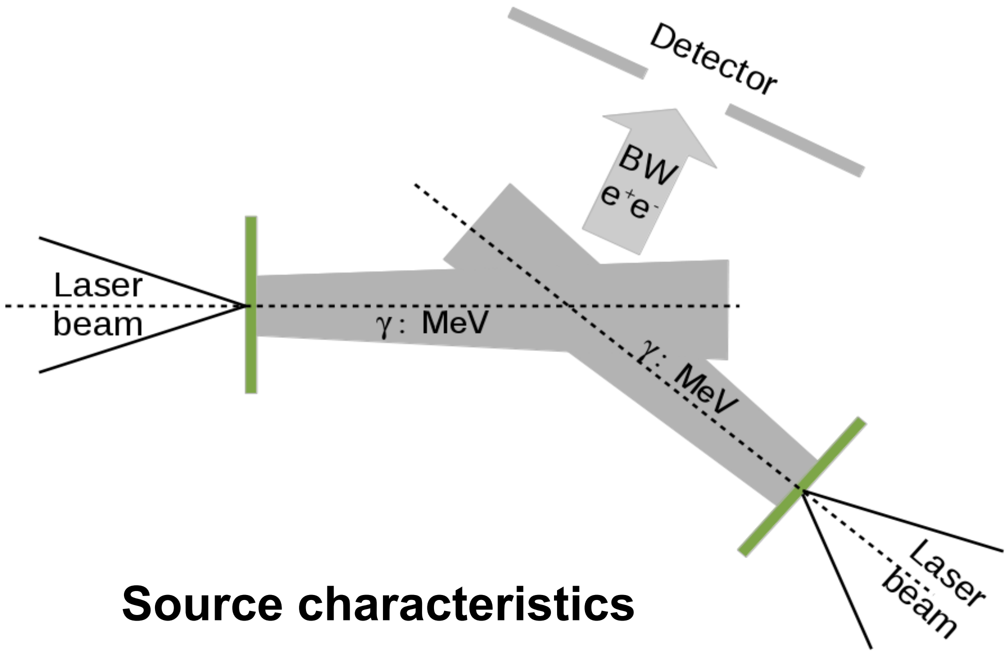
Multiphoton Breit-Wheeler: e^-e^+ pair generation in the laser field ($I > 10^{23}$ Wcm^{-2})

- Implementation of these mechanisms in the PIC code CALDER

And competition with Bethe-Heitler and Trident processes when using solid foils

[1] – A. Di Piazza *et al.*, Rev. Mod. Phys. **84**, 1177 (2012) – A. Bell *et al.*, Phys. Rev. Lett. **101**, 200403 (2008).
[2] – A. Zhidkov *et al*, PRL **88**, 185002 (2002) – M. Tamburini *et al*, NJP **12**, 123005 (2010) – R. Capdessus *et al*, PRL **110**, 215003 (2013)
[3] – C. P. Ridgers *et al*, PoP **20**, 056701 (2013) – C. S. Brady *et al*, arXiv preprint 1311.5313 (2013) – L. L. Ji *et al*, PoP **21**, 023109 (2014)

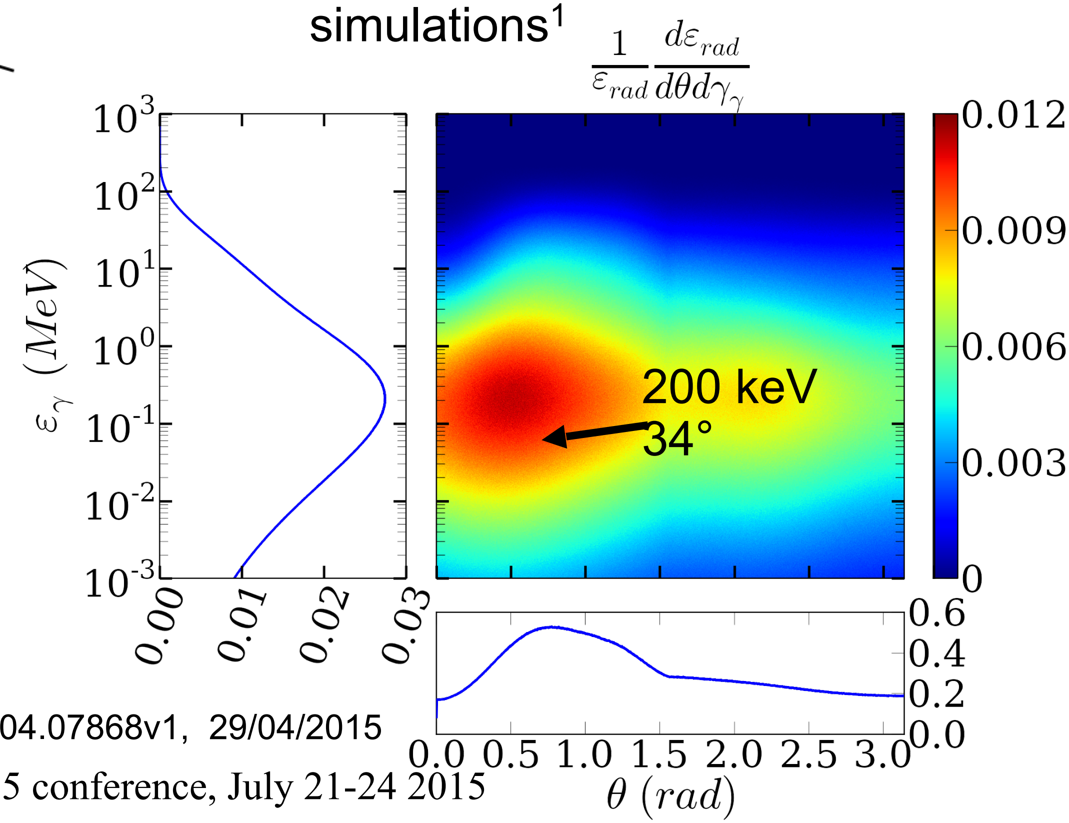
Collision of MeV-MeV photons from PIC simulations



-**Laser parameters (ELI Facility)**
λ_L=0.8 μm, τ_L=15 fs,
150 J, 10 PW
Φ_L=3 μm, 0.05 Hz
I =10^{23} W/cm^2

-**Target properties Aluminium**
(1.7 g/cc, n_{Al}=60 n_c)

Normalized spectrum of photon source from PIC simulations[1]



Source characteristics

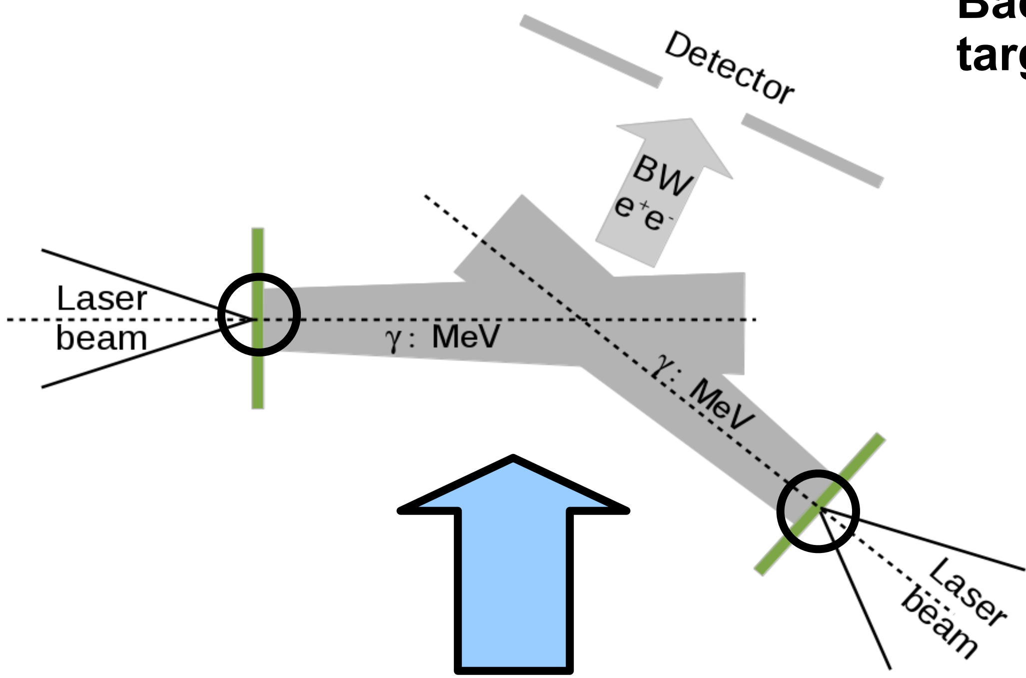
- Conversion: 10-20 % of laser energy
- 10^{13} photons up to 1 MeV
- 10^{12} photons in 1-3 Mev range
  Forward emitted [0, π]

Pair production with pure BW process

- Head on collision : **10^8 pairs**
- At R=500 μm distance : **10^4 pairs**

[1]Lobet, M. et al. ArXiV:1311.1107 (2013), Ribeyre X. et al. arXiv:1504.07868v1, 29/04/2015

Other e+e- pair production can perturb the detection of BW pairs



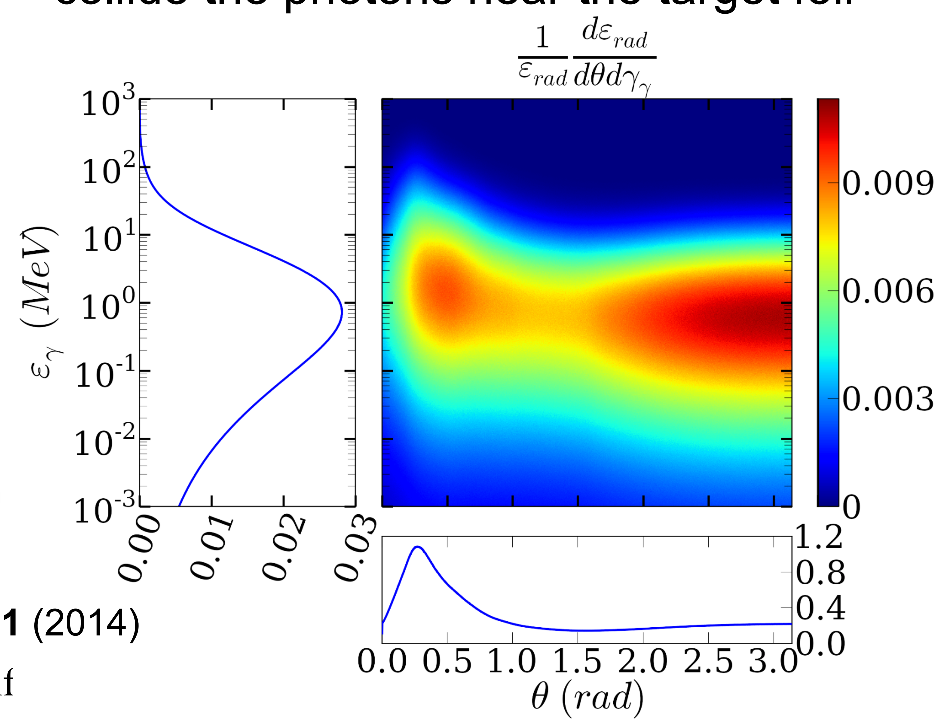
Background pairs production during laser target interaction from PIC simulations

- Non-linear BW pairs : **10^5**
- Trident pairs : **10^7**
- Bethe-Heitler pairs : **10^9**

Number of Bethe-Heitler pairs ten times higher than Breit-Wheeler pairs if we collide the photons near the target foil

For the pure BW pair production in vacuum we need to separate the source from the collision zone.

Use low density target and high repetition rate laser to improve S/N ratio.

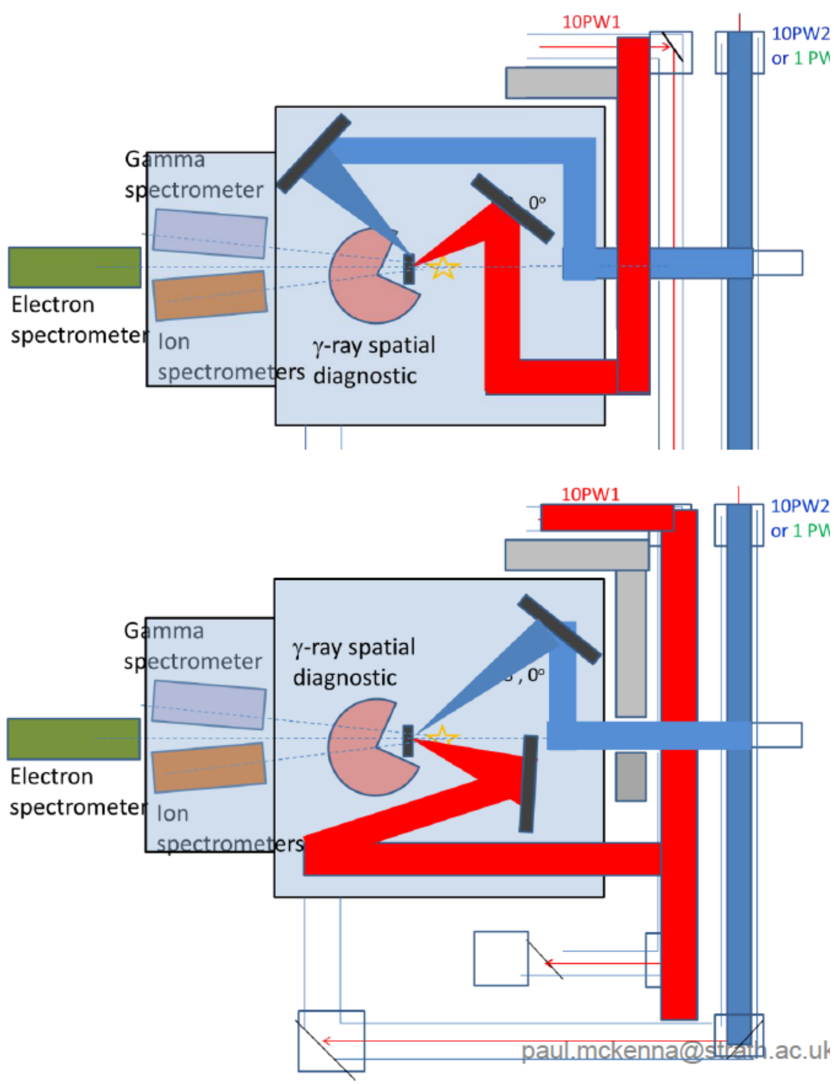


[1]Capdessus, R. et al. PRL **110** (2013), Capdessus, R. et al. PoP **21** (2014)

Beam geometry on ELI -NP laser facility

Laser-based Nuclear Physics pillar of ELI

that will focus on high-intensity laser-based nuclear physics (Bucharest-Magurele Romania).



Two 10 PW beams (100 J, 15 fs). Intensity on target $10^{23}-10^{24}$ W/cm², 0.05 Hz

With different beams interaction angles (operational 2018)

Conclusions

Pure Breit-Wheeler pairs creation :
- Never observed experimentally
- Great interest for fundamental physics and astrophysics

Three experimental schemes

- **250 GeV - eV Photons** collider : SLAC experiment:
  0.01-0.2 pair per shot : Non-linear process

[1] Ribeyre X. et al. arXiv: 1504.07868v1, 29 Apr 2015

- **GeV - 100 eV Photons** collider
  Until **10^4** pair per shot (1 shot per day)
  Possible experiment on LMJ-PETAL facility
  But important perturbations due to other pair creation processes

- **MeV - MeV Photons** collider **10^4** pair per shot[1]
  (laser repetition rate > **1 shot per min**)
  Possible experiment on ELI or Apollon facilities
  Need a separation between photon sources and photons collision zone
  Shielding and localized B fields (J. Santos et al. accepted by NJP) to filter other pairs

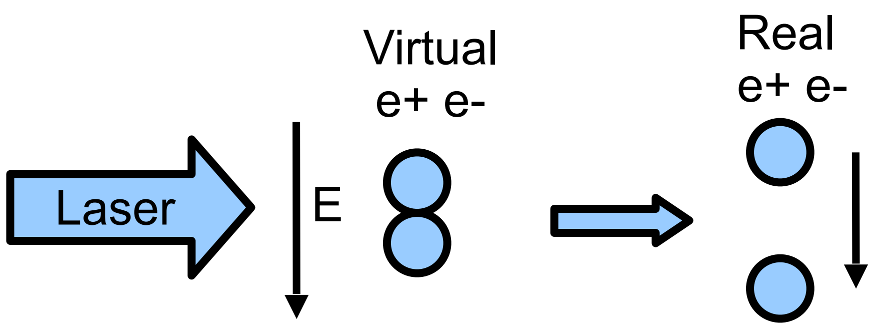
Further Studies:
- Source optimisation : PIC simulations of MeV synchrotron photon source
- Monte Carlo simulations of pairs production during Photon-Photon collision[2]
- Toward experimental proposal

[2] Oliver Jansen et al. P.12 ExHILP Poster session

e^+e^- pairs creation and the Schwinger Limit

It would occur in a strong electric field in vacuum: Quantum ElectroDynamic (QED) theory

The electric field separates virtual (e^+, e^-) by a distance of compton length and provided 2 $m_e c^2$ of energy



$$\lambda_c = \frac{h}{m_e c}$$

$$\text{Energy} = 2eE\lambda_c = 2m_e c^2$$

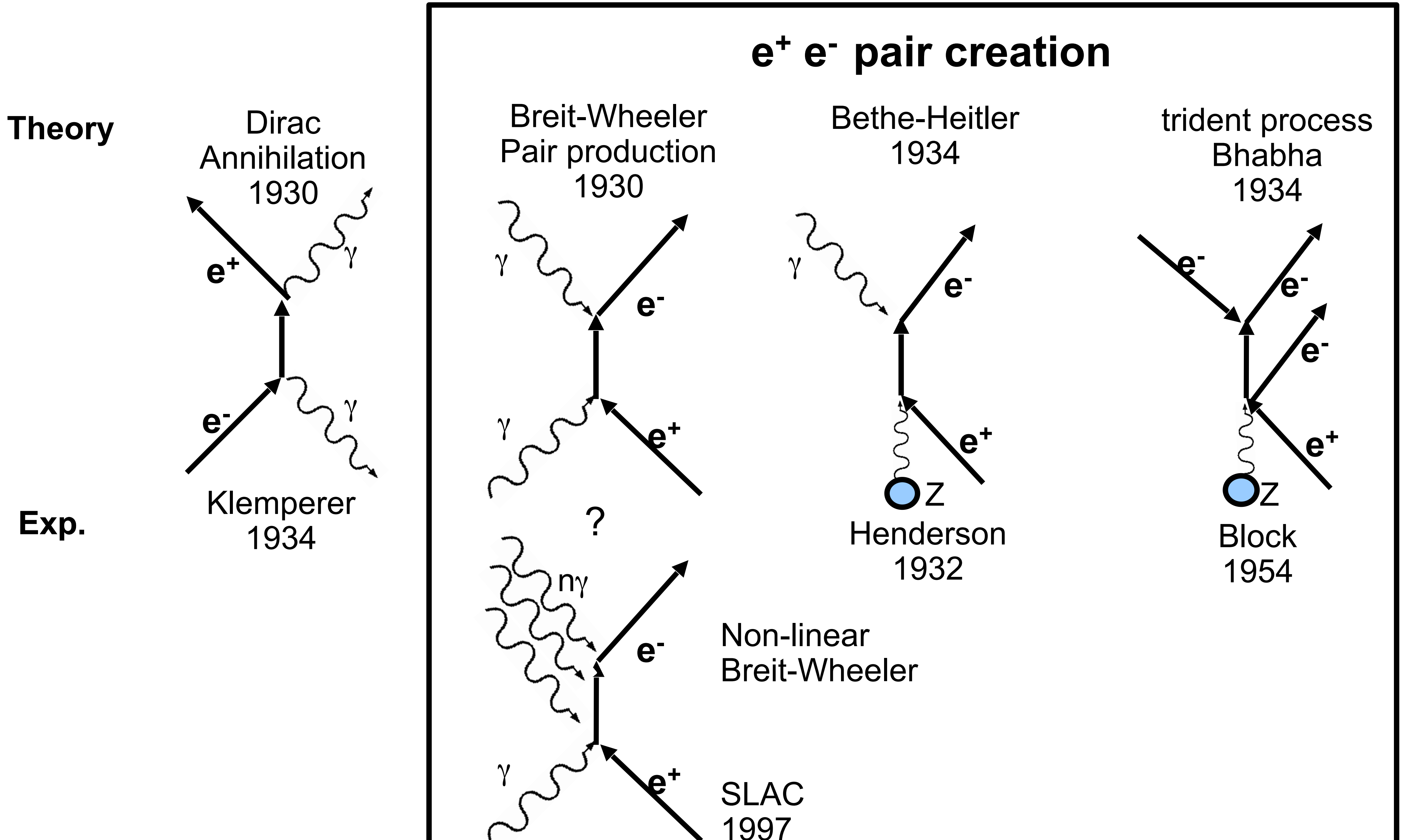
Electric field :

$$E \simeq E_c \equiv \frac{m_e^2 c^3}{e\hbar}$$

Schwinger limit[1] $I_c \simeq 2.3 \times 10^{29} \mathrm{W/cm^2}$

[1]Schwinger J., Phys. Rev, **82**, 664 (1951)

e^+e^- pairs creation in Quantum ElectroDynamics (QED)



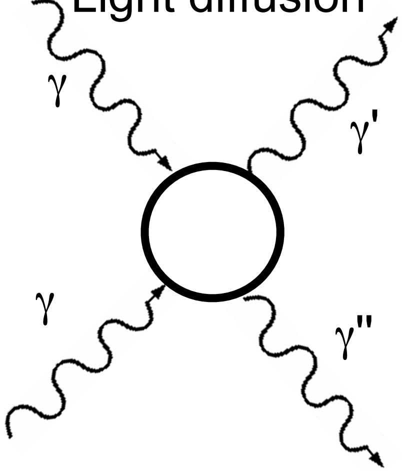
Pure photon-photon collision

Light-light scattering in vacuum does not occur in classical electrodynamic (Maxwell equations are linear)

In QED theory

$$\hbar\omega \leq m_e c^2$$

Light diffusion



$$\sigma_{\gamma\gamma} \sim 3 \times 10^{-2} \alpha^2 r_e^2 \left(\frac{\hbar\omega}{m_e c^2}\right)^6$$

$$\hbar\omega = 400\,\mathrm{keV}$$

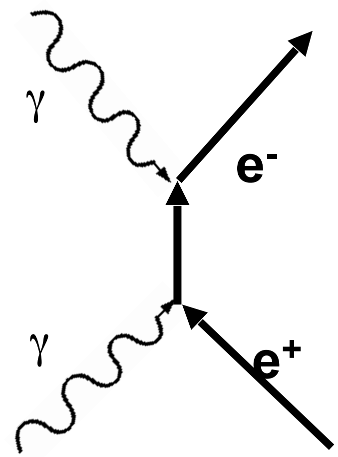
$$\sigma_{\gamma\gamma} \simeq 3.7 \times 10^{-7} r_e^2$$

$$\sigma_{\gamma\gamma} = 3 \times 10^{-32}\mathrm{cm}^2$$

$$\ll$$

$$\hbar\omega \geq m_e c^2 = 511\,\mathrm{keV}$$

Breit-Wheeler process



$$\sigma_{\gamma\gamma} \simeq r_e^2$$

$$\sigma_{\gamma\gamma} \simeq 8 \times 10^{-26}\mathrm{cm}^2$$

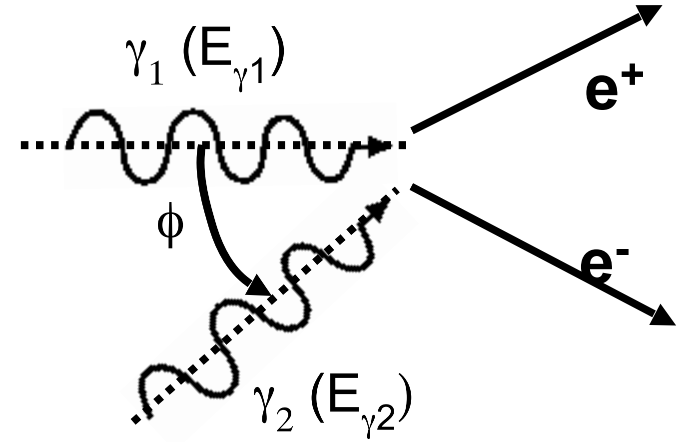
Minimum photon energy for pair creation

$$\gamma_1 + \gamma_2 \longrightarrow e^+ + e^-$$

Energy conservation in the center of mass frame (CM) :

$$E^2-(pc)^2=m_e^2c^4$$

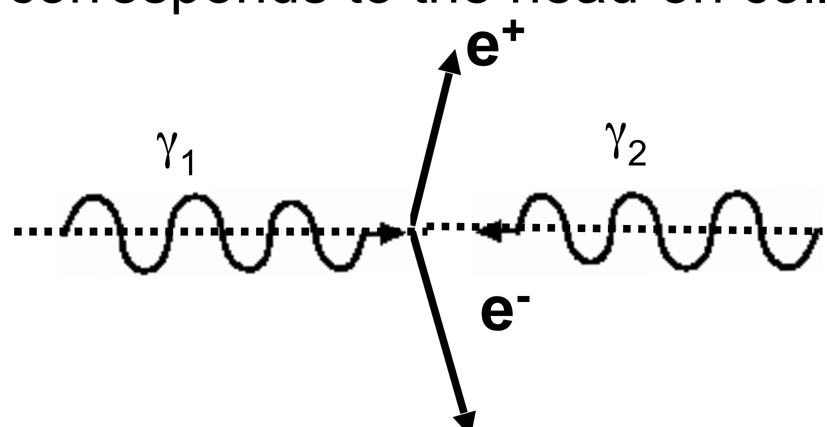
$$E_{\gamma_2} = \frac{2m_e^2c^4}{E_{\gamma_1}(1-\cos(\phi))}$$



Minimum for the gamma ray energy corresponds to the head-on collision

ϕ=180°

$$E_{\gamma_2} = \frac{m_e^2c^4}{E_{\gamma_1}}$$



e^+e^- pair production cross sections

Signal : Pure BW

-**Linear BW pairs:** $\gamma + \gamma \longrightarrow e^+ + e^-$ $\sigma \propto r_e^2$

Noise : Main pairs production process during laser target interaction[1]

- **Non-linear BW pairs:** $\gamma + n\omega \longrightarrow e^+ + e^-$
less probable than pure BW

- **Trident pairs** : $e^- + Z \longrightarrow Z + e^- + e^+ + e^-$ $\sigma \propto Z^2 \alpha^2 r_e^2$

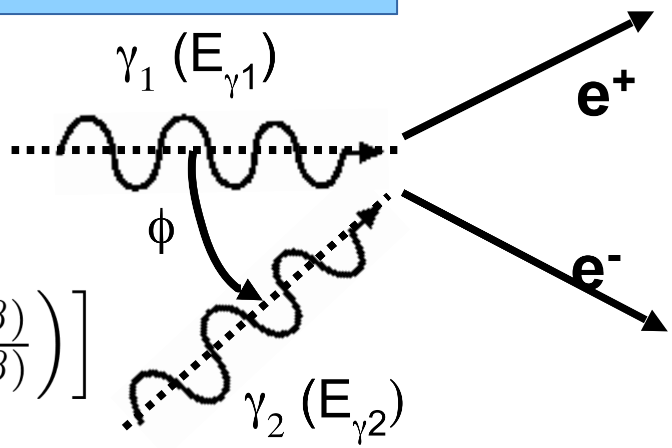
- **Bethe-Heitler pairs** : $\gamma + Z \longrightarrow Z + e^+ + e^-$ $\sigma \propto Z^2 \alpha r_e^2$

$$r_e = 2.8 \times 10^{-13}\mathrm{cm}$$
$$\alpha = 1/137$$

[1]Landau and Lifshitz, Quantum electrodynamics

Photon-Photon collision and pair production cross section

$$\gamma_1 + \gamma_2 \longrightarrow e^+ + e^-$$



Breit-Wheeler cross section[1] in CM

$$\sigma_{\gamma\gamma}(s) = \frac{\pi r_e^2}{2}(1-\beta^2)\left[2\beta\left(\beta^2-2\right)+(3-\beta^4)\log\left(\frac{(1+\beta)}{(1-\beta)}\right)\right]$$

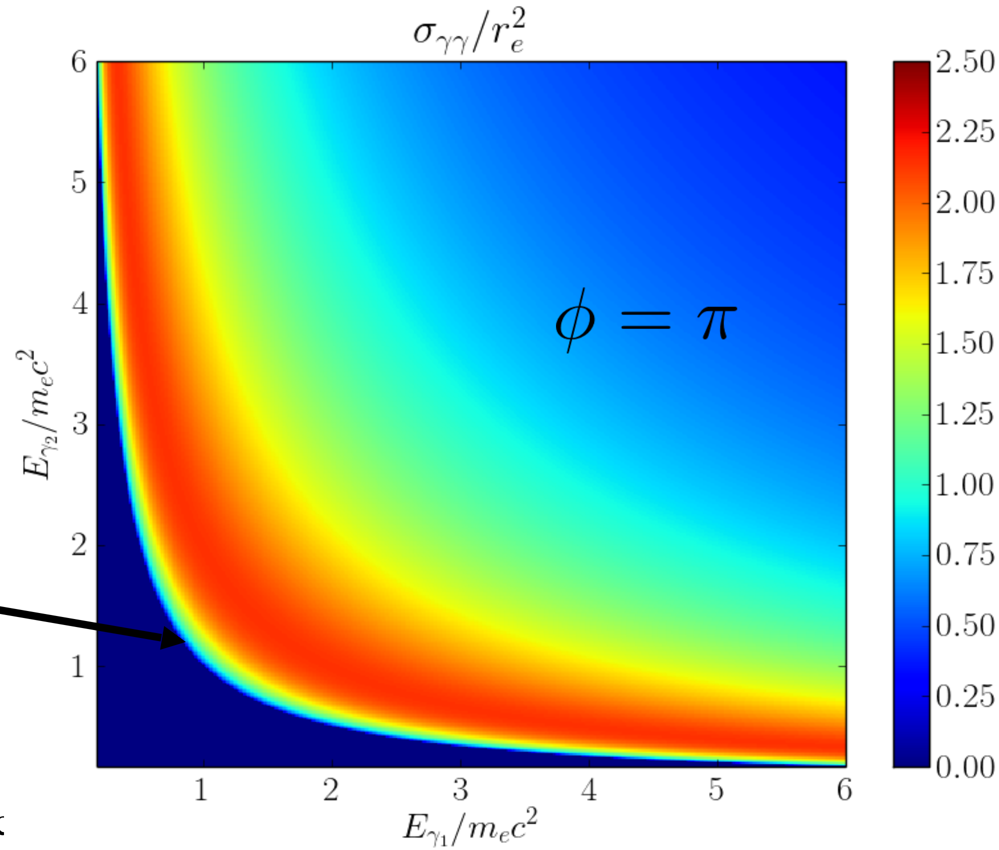
$$\beta = \sqrt{1-\frac{1}{s}} \qquad s = \frac{E_{\gamma_1}E_{\gamma_2}}{2m_e^2c^4}(1-\cos\phi)$$

$$\sigma_{\gamma\gamma} \propto r_e^2$$

Threshold pair
Production : s=1

$$\mathrm{E}_{\gamma_1}\mathrm{E}_{\gamma_2} = \mathrm{m_e^2c^4}$$

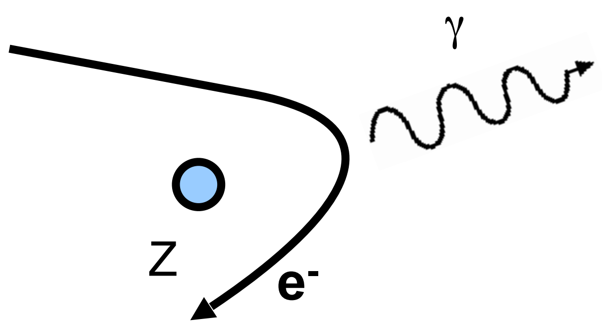
Maximum production
for s=2

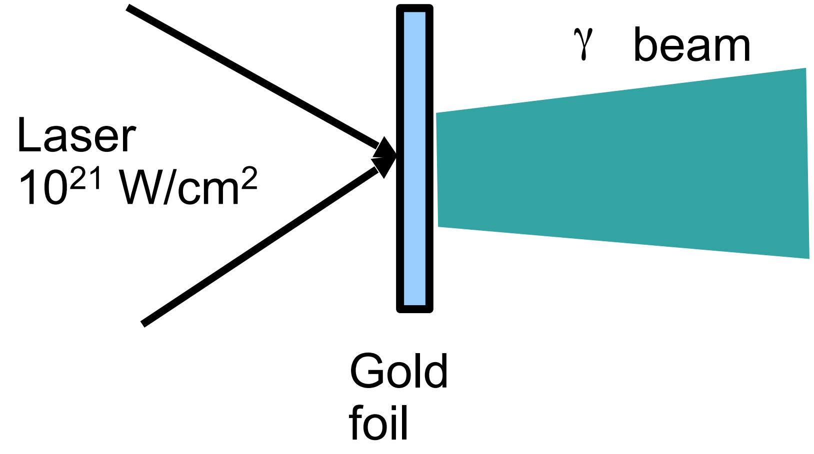


[1]Breit, G. and Wheeler J. A. PRL **15** (1934)

γ–ray sources in MeV range (1)

Bremsstrahlung source *





Gamma beam characteristics

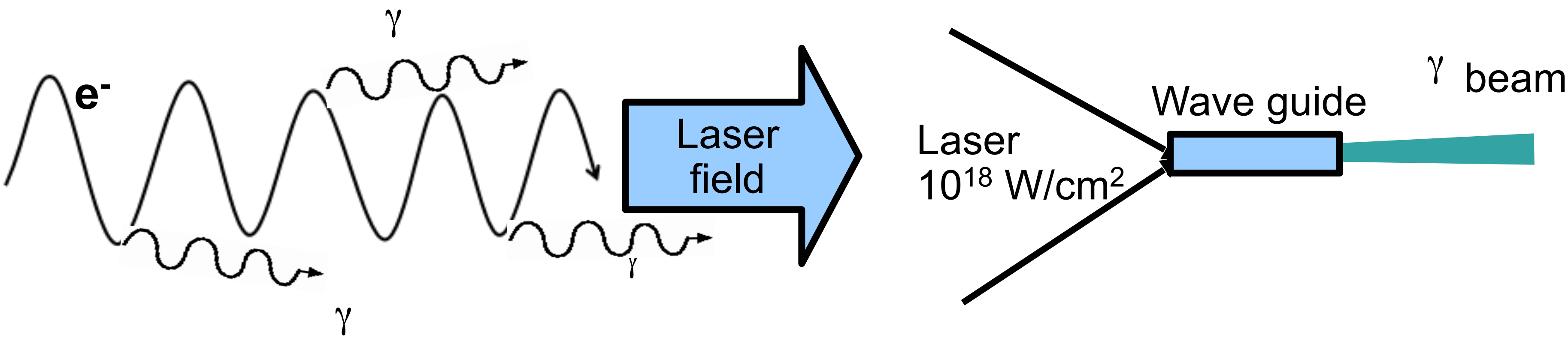
Beam Energy : 1-2 J γ Energy : 3-50 MeV Divergence : θ=15°

The beam characteristic are interesting
But because of high-Z target there is lot of pairs creation due to BH and Trident process inside the target

*Henderson A. et al. High Energy Density Physics **12**, 46 (2014)

γ–ray sources in MeV range (2)

Betatron source *



Incoherent photon source

Gamma beam characteristics

Beam Energy : 1 μJ

γ Energy : 1-7 MeV

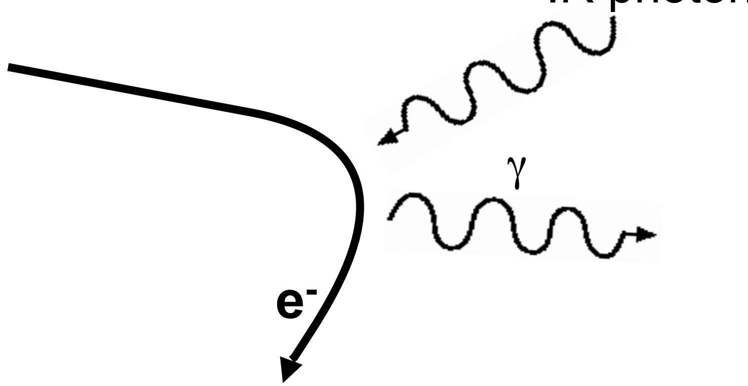
Divergence : $\theta = 1°$

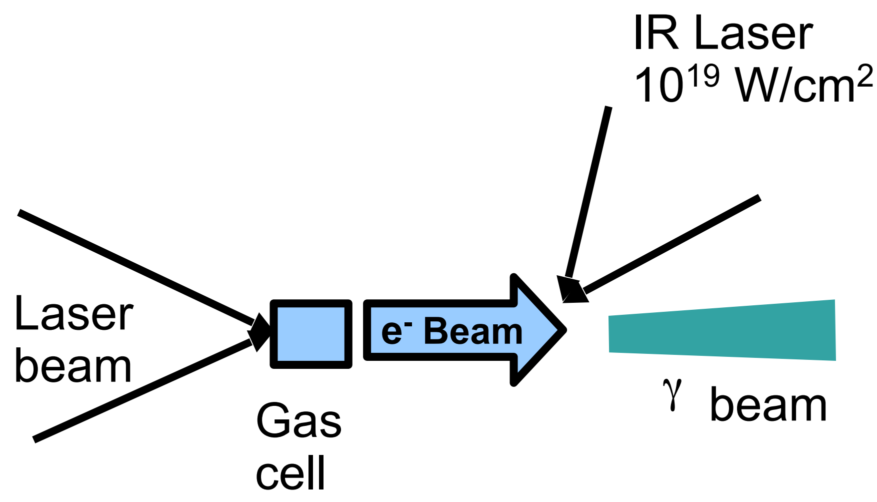
Too low energy beam for efficient pairs production

* Cipiccia S. et al. Nature Physics 7, 867 (2011)

γ–ray sources in MeV range (3)

Compton source *





Gamma beam characteristics

Beam Energy : 10 μJ

γ Energy : 1-10 MeV

Divergence : θ = 1°

The beam characteristics are interesting
Too low energy for efficient pair production

*Henderson A. et al. High Energy Density Physics **12**, 46 (2014)

γ–ray sources in MeV range (4)

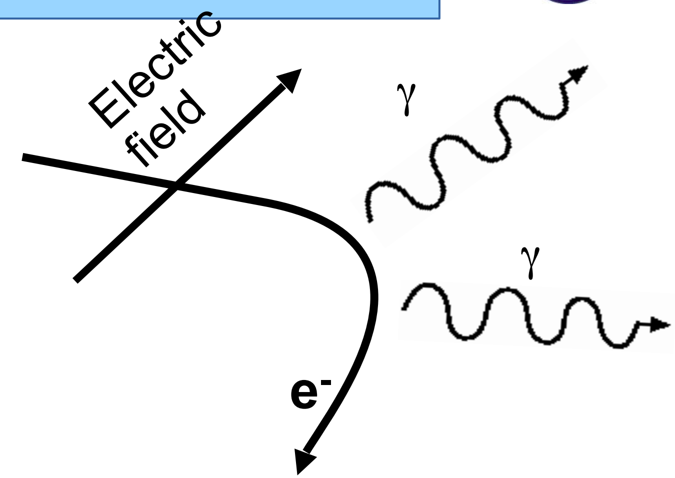
Synchrotron emission[1,2]

Reaction force[1]

$$\frac{d\vec{P}}{dt} = -e(\vec{E} - \frac{\vec{v}}{c} \times \vec{B}) - \vec{R}$$

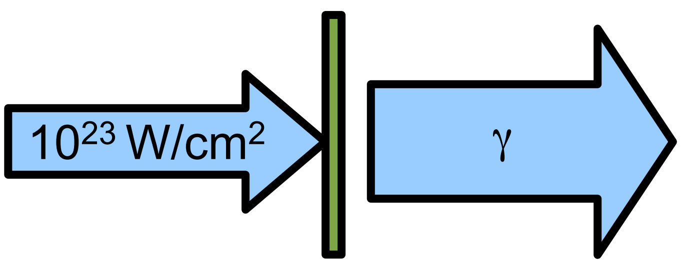
Lorentz force

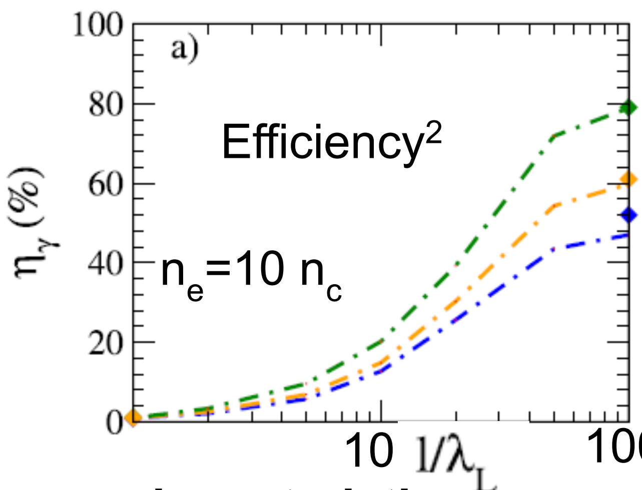
Radiation reaction force (self force)

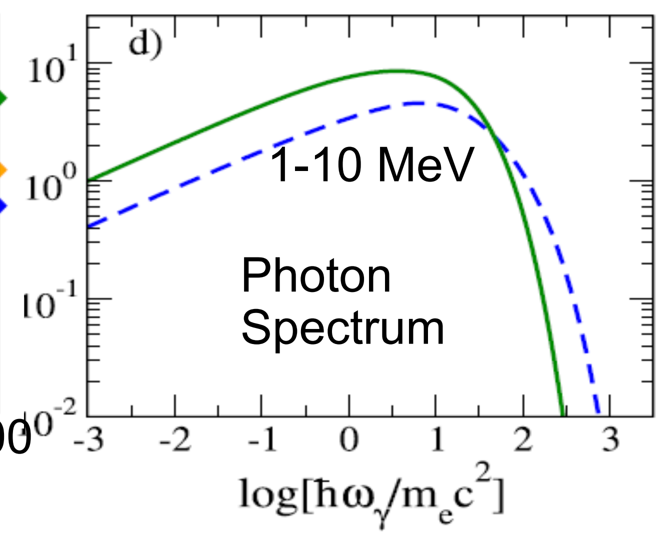


$$I > 10^{23}\mathrm{W/cm^2}$$

Radiated energy during acceleration is close to its kinetic energy, it yields, radiation reaction is important







Gamma beam characteristics

Beam Energy : 1-10 J γ Energy : 1-10 MeV Divergence : θ=30°

[1] Landau and E. Lifschitz, The Classical Theory of Fields (1994); Sokolov I. V., J. Exp. Theor. Phys. 109 207 (2009)
[2] Capdessus, R. et al. PRL **110** (2013), Capdessus, R. et al. PoP **21** (2014)