Positron-Electron Pair Creation with Intense Lasers and Applications

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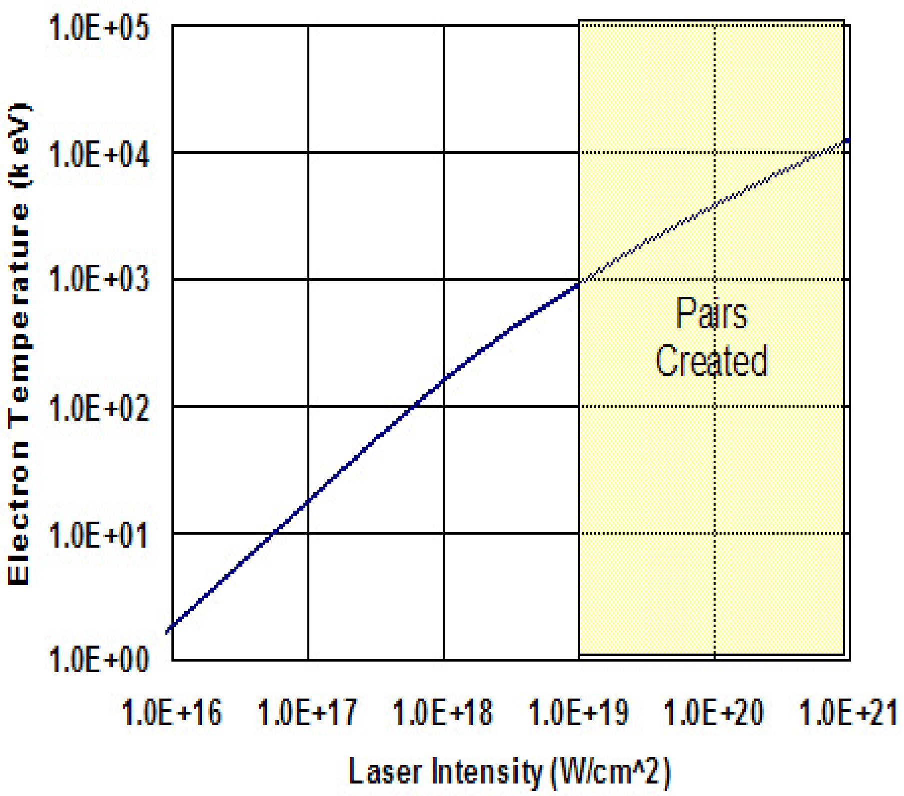
Antimatter has many potentially revolutionary applications. But current technique of creating positrons with accelerators and trapping them with electrostatic traps is very inefficient and can only produce low density e+ (Surko and Greaves 2004):

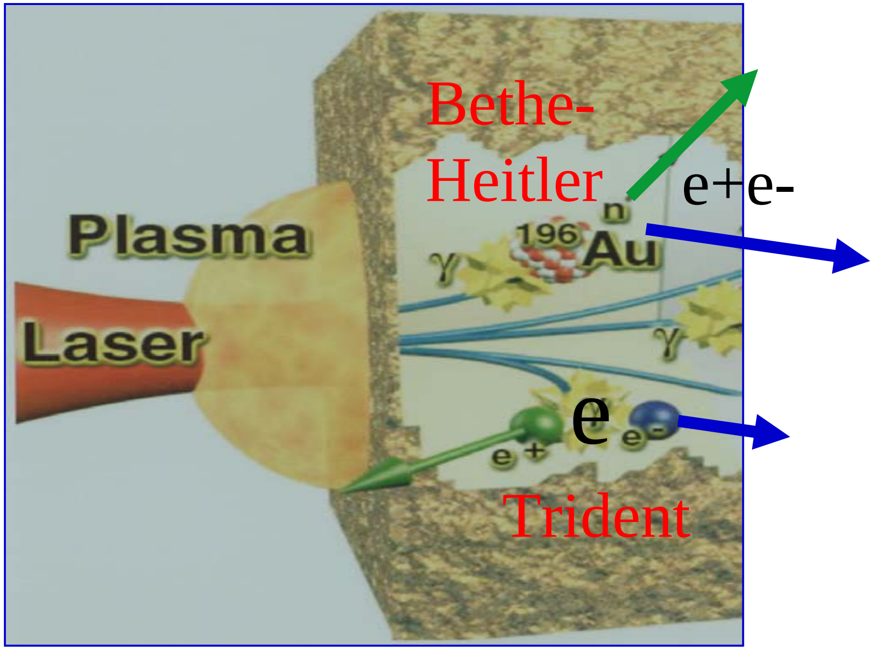
Maximum Beam Intensity $< 10^{10}$ e+/s

Maximum Density $< 10^{14}$ e+/cm^3

Ultra-intense lasers opens up exciting new approach to produce high intensity, high density e+e- pairs with high efficiency

It is very desirable to reach pair density $> 10^{18}$/cm^3 for applications


1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Electron Temperature (keV)
Pairs
Created
1.0E+16
1.0E+17
1.0E+18
1.0E+19
1.0E+20
1.0E+21
Laser Intensity (W/cm^2)


Bethe-
Heitler
e+e-
Plasma
Laser
196 Au
n
γ
γ
e
e+
e-
Trident

Sample Laser Numbers

$1\ \mathrm{PW} = 1\ \mathrm{kJ} / 1\ \mathrm{ps}$

$1\ \mathrm{PW} / (30\ \mu\mathrm{m})^2 = 10^{20}\ \mathrm{W/cm^2}$

$10^{20}\ \mathrm{W/cm^2/c} \sim 3.10^{16}\ \mathrm{erg/cm^3} \sim 2.10^{22}\ \mathrm{e{+}e{-}\ /cm^3}$

Solid Au ion density ~ $6.10^{22}\ /\mathrm{cm}^3$

$n_+/n_e \sim 4.10^{-3}$

In reality, the max. achievable pair density is

probably around $10^{19} - 10^{20}\ \mathrm{cm}^{-3}$

PAIR PRODUCTION BY SUPERTHERMALS ON HIGH-Z TARGET:

$$dN+/dt \;=\; (dN+/dt)_{eion} + (dN+/dt)_{\gamma ion} + (dN+/dt)_{\gamma\gamma}$$

trident 1 > 2 Bethe-Heitler 3

for thin (<< 20 µm) laser targets. Hence

$$dN+/dt \;=\; (N+ + N-) < N_{ion}\, (f(\gamma)\, v\, \sigma_{eion})>$$

f(γ) is normalized superthermal distribution function and

$$\sigma_{eion} \sim 1.4 \times 10^{?0}\ \mathrm{cm}^2\, Z^2\, (\ln \gamma)^3 \qquad \text{for } \gamma >> 1$$

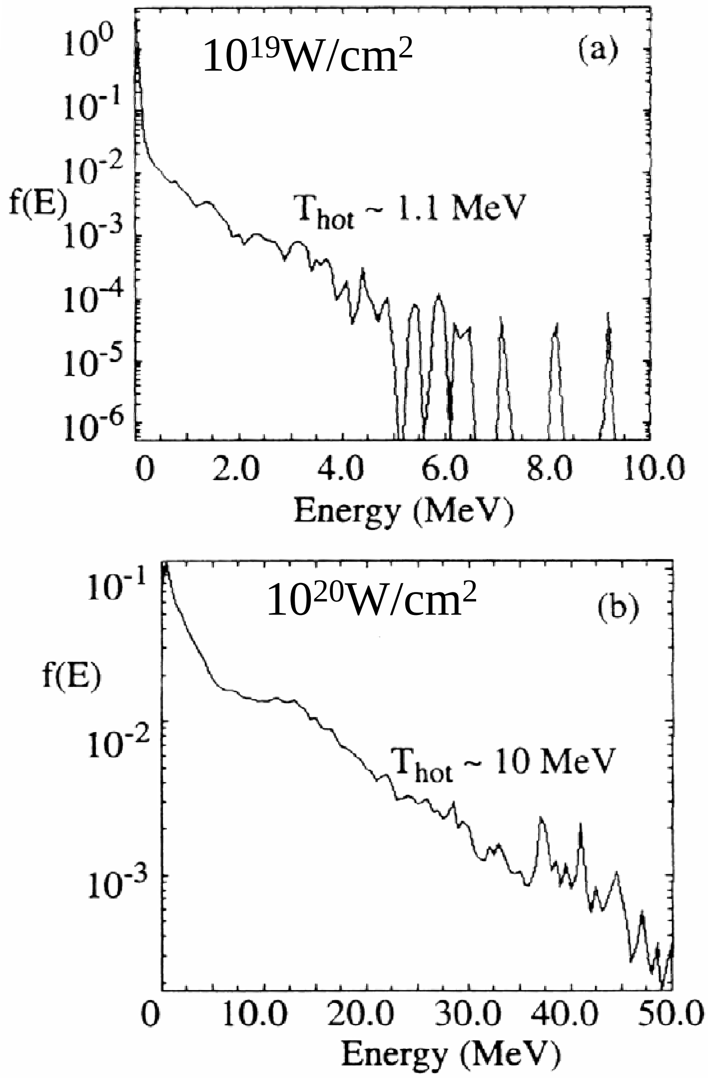
is trident pair production cross section (e+ion➔e+ion+γγ):

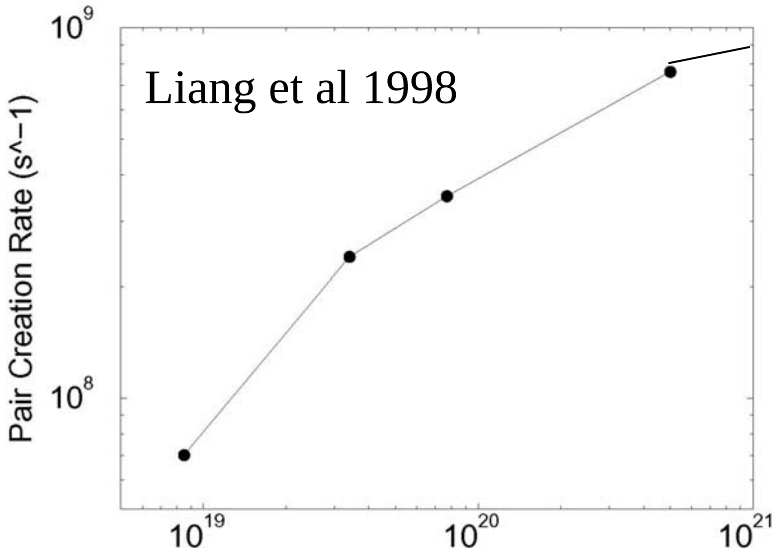
Solving above equation:

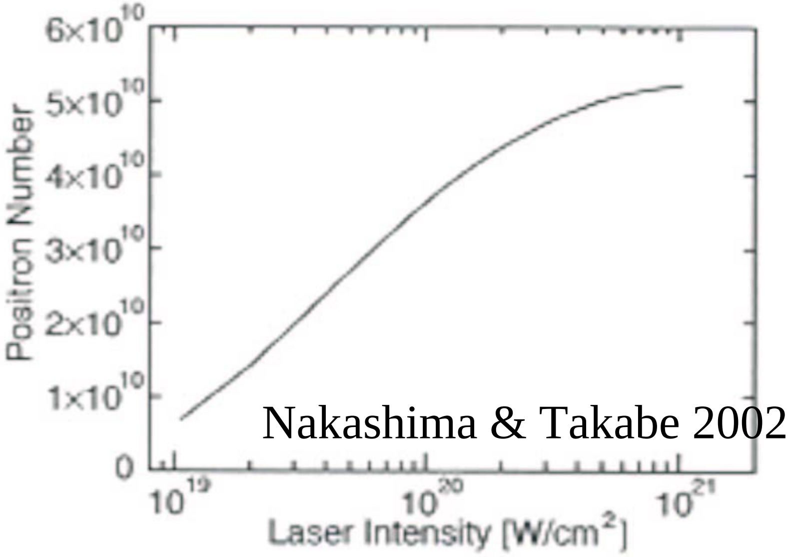
$$N+ = Z\, N_{ion}\, \{\exp(\Gamma t)\ ?1\}/2 \sim Z N_{ion} \Gamma t/2 \qquad \text{for } \Gamma t << 1$$

➔ $N+/N_e \sim \Gamma t/2 \sim 2 \times 10^{-5}$ for t ~ 1 ps, I = 10^{20} Wcm^{-2}

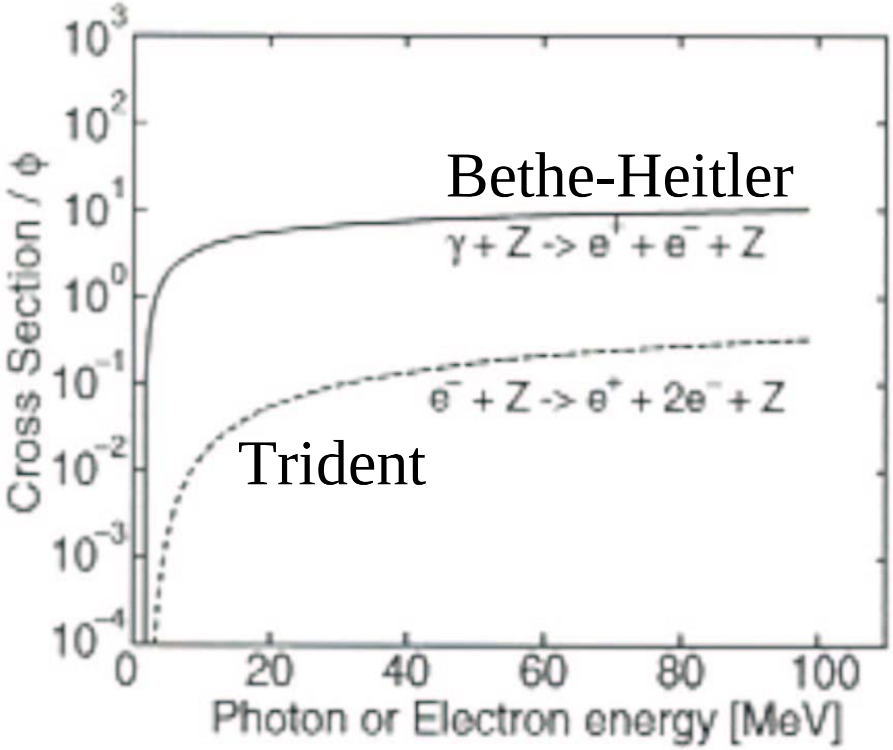
For Au: $N+ \sim 10^{20}\ \mathrm{cm}^{-3}$

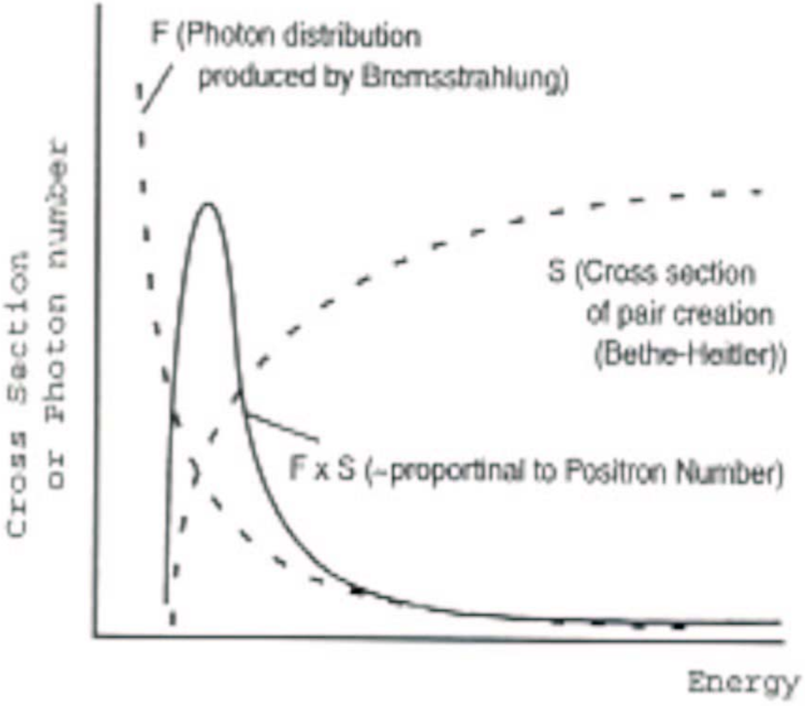



Liang et al 1998


Nakashima & Takabe 2002

Pair Creation Rate Rises Rapidly with Laser Intensity to ~10^{20}Wcm^{-2}, but levels off after 10^{21}Wcm-^{2}.

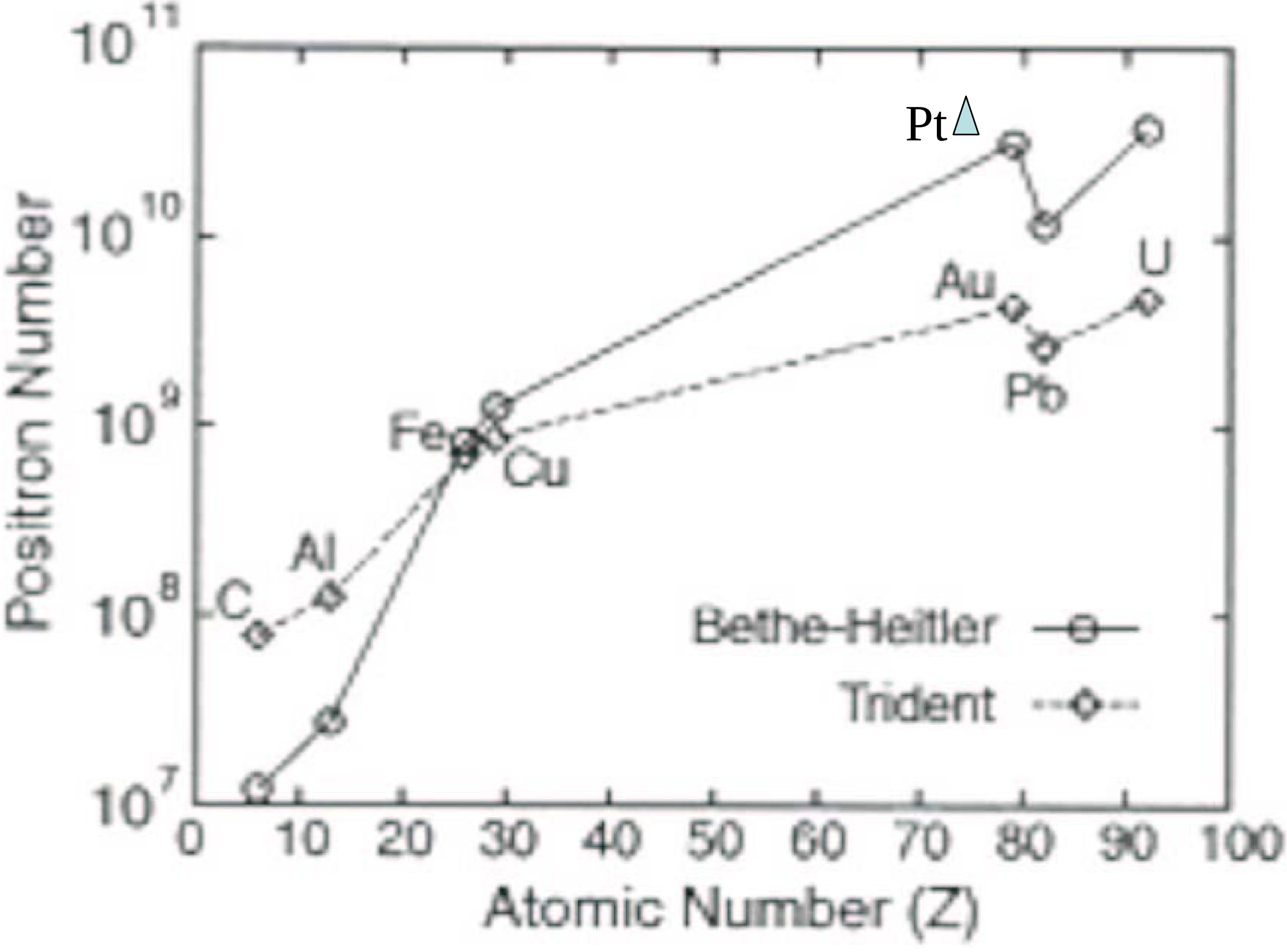




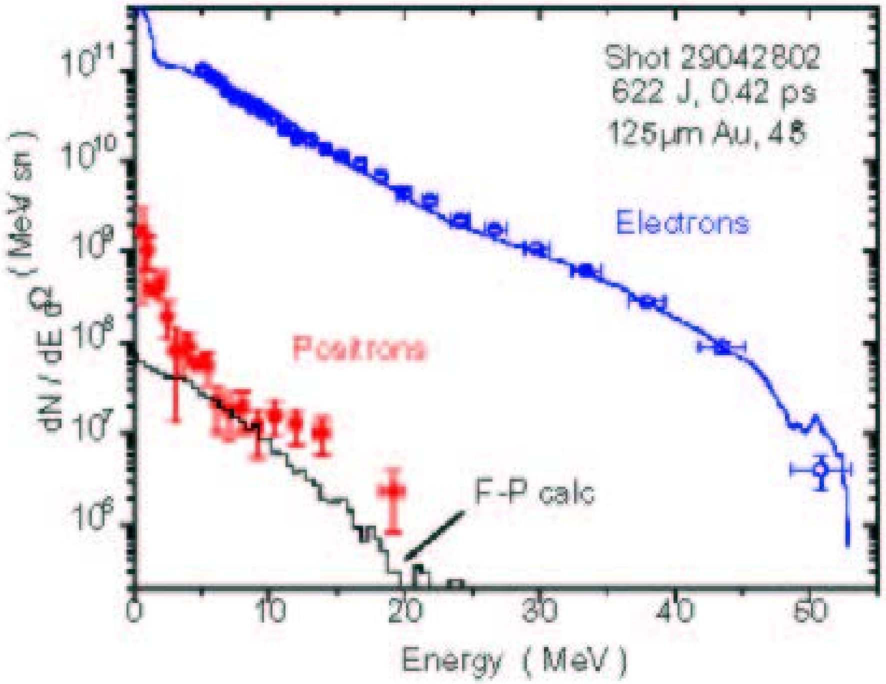
Nakashima & Takabe 2002

Bethe-Heitler pair-production has larger cross-section than Trident, but it depends on photon density, Z and optical depth of the high-Z target

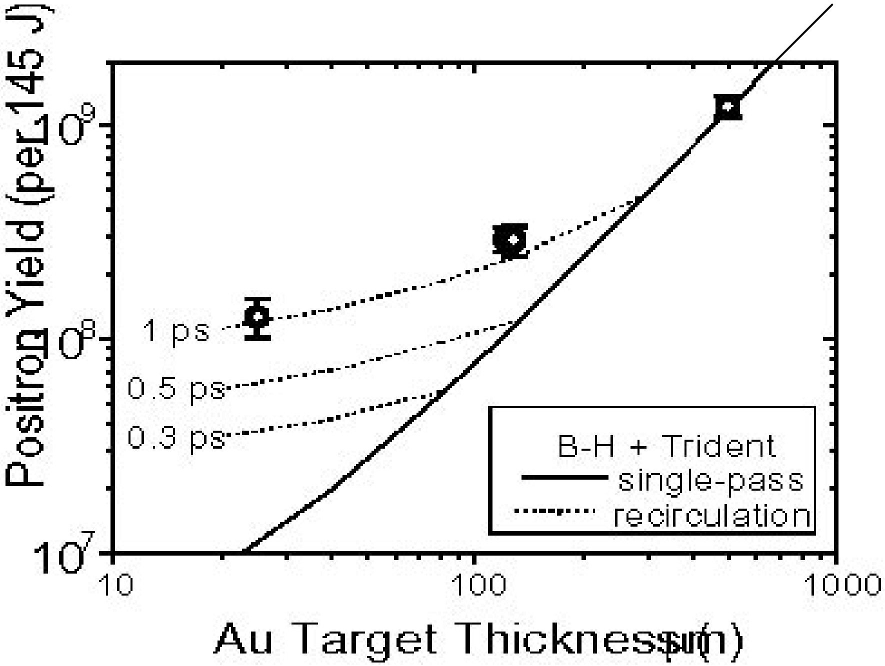
Nakashima & Takabe 2002

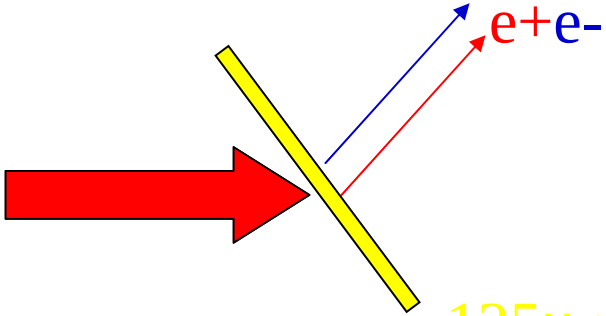


LLNL PW laser experiments first demonstrated e+e- production with Au foils. But the flux was low due to off-axis measurements



Cowan et al 2002



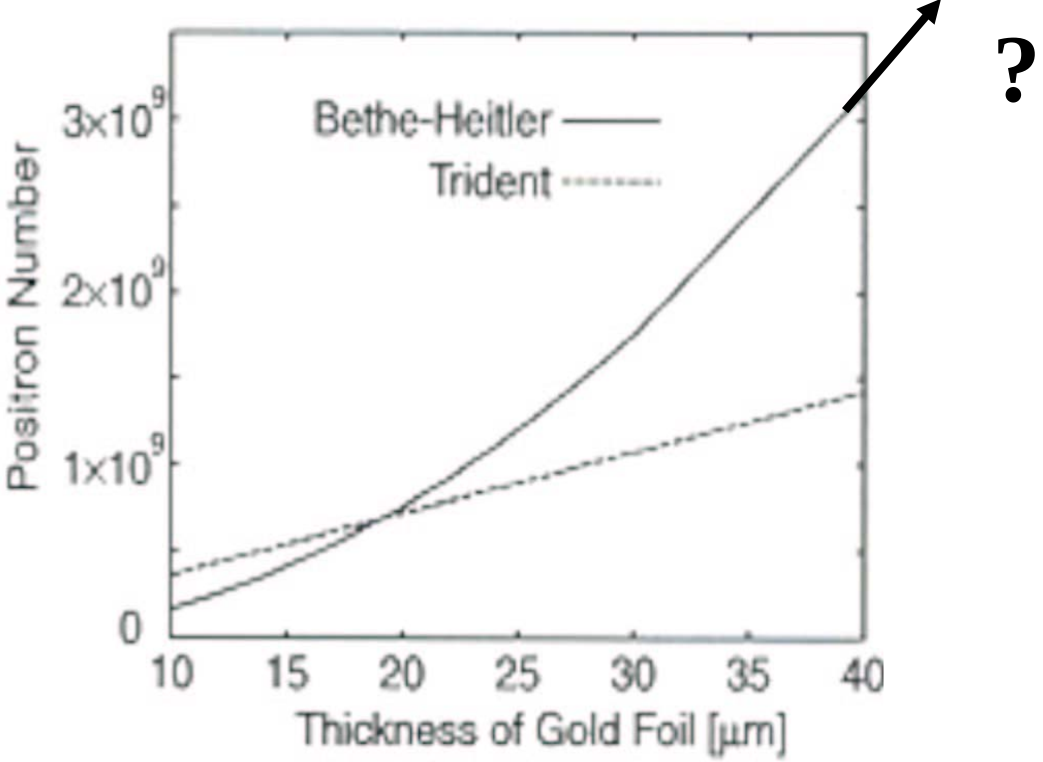


e+e-

2.10^{20}W.cm^{-2}

0.42 p s

125µm Au



$I=10^{20}Wcm^{-2}$

Nakashima & Takabe 2002

Trident process dominates for thin targets.
But Bethe-Heitler dominates for thick targets.
How high can the e+ yield go if we use very thick targets?

Positron yield per incident hot electron increases with Au thickness: transition from quadratic to linear occurs around 2-3 mm.

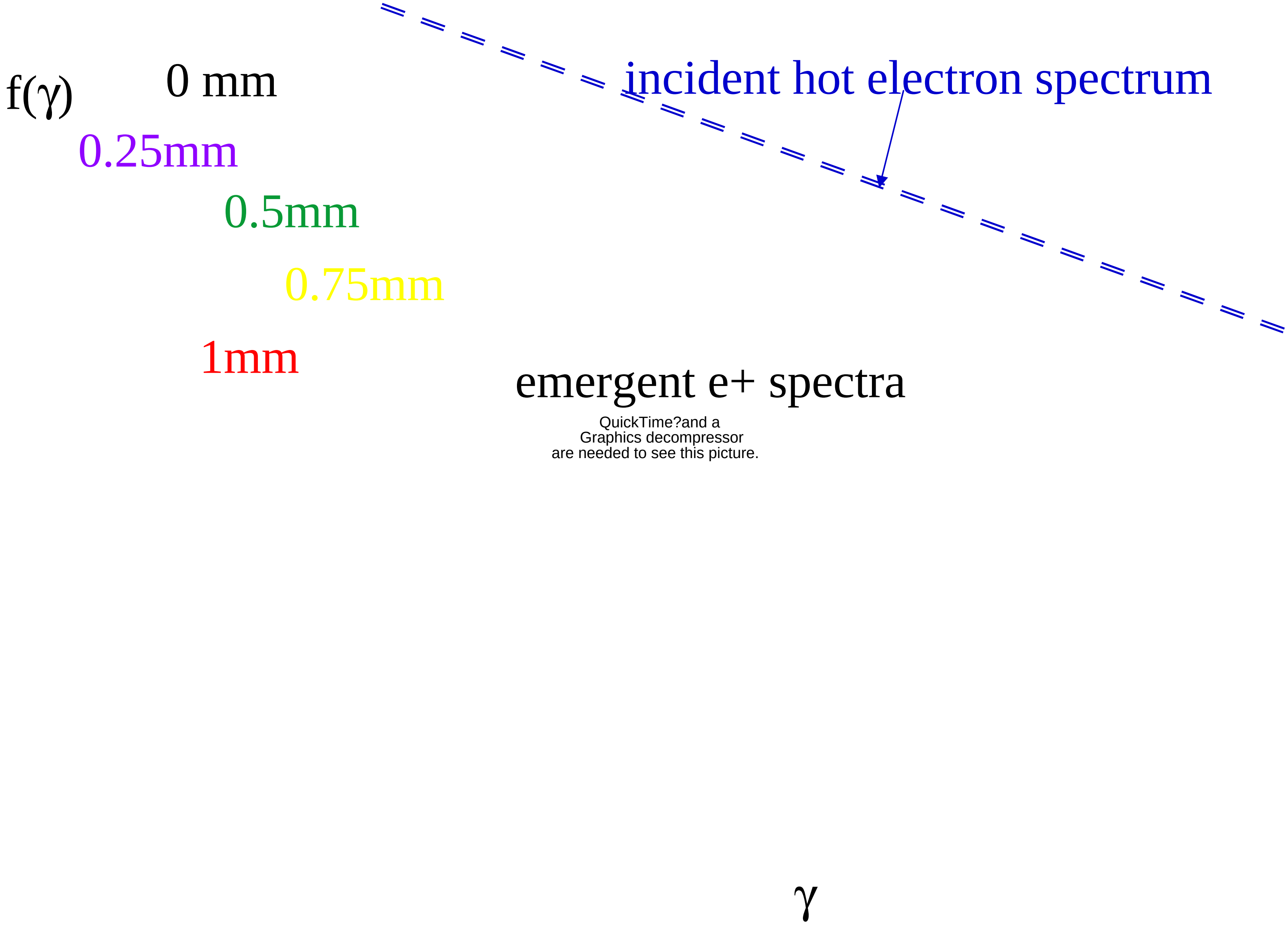
bremss-γ opt.thick

QuickTime?and a
Graphics decompressor
are needed to see this picture.

bremss-γ
opt. thin

thickness (mm)

But emergent positrons are attenuated by cold absorption inside target : low energy e+ are absorbed by thick target due to ionization losses



Allowing for cold attenuation , emergent e+ yield per incident hot electron peaks at ~ 2.6 % where Au thickness ~ 5 - 6 mm

QuickTime?and a
Graphics decompressor
are needed to see this picture.

thickness (mm)

Assuming that the conversion of laser energy to hot electrons is ~ 30 % and the hot electron temperature is ~ 5 -10 MeV, the above analysis suggests that the optimal positron yield is

~ few x 10^{12} e+ per kJ of laser energy
when the Au target ~ 5 - 6 mm

The in-situ e+ density should reach > $10^{17}/cm^3$

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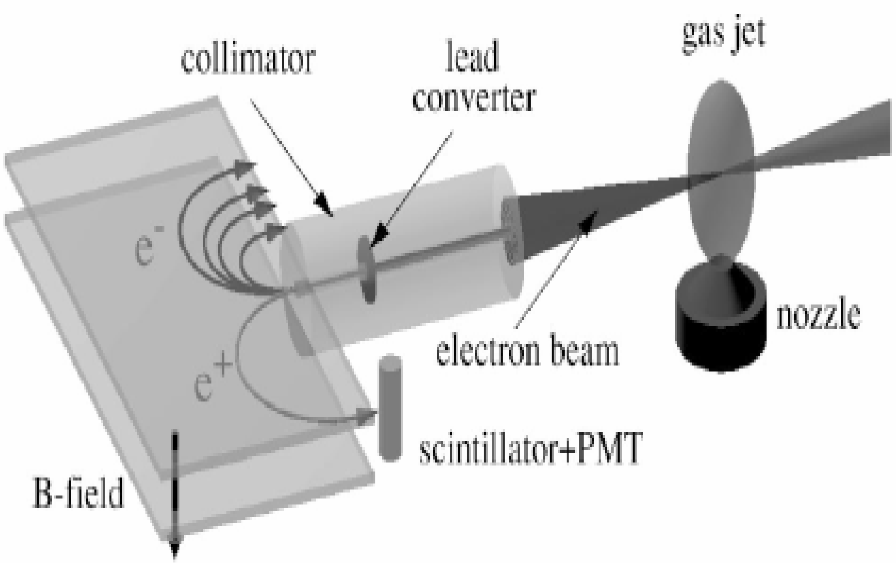
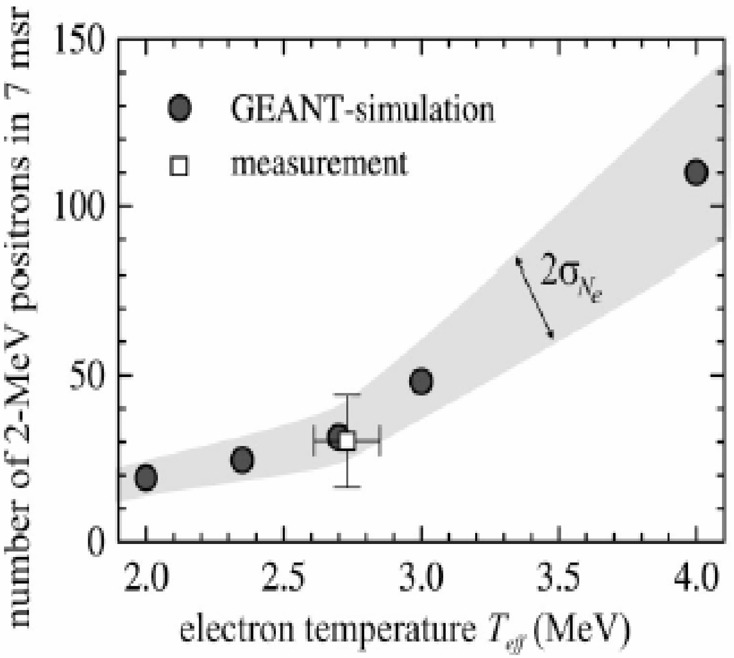
For a 1 mm target, the e+ yield is ~ 10^{12} per kJ of laser energy.

These results are roughly consistent with the latest Titan experiments (*Chen et al* PRL 2008 submitted and talk at the upcoming DPP November 2008 meeting in Dallas)

Above direct irradiation of solid high-Z solid target requires PW-class lasers (“1-step” process). Alternative approach demonstrated by Gahn et al (2000, 2002) uses smaller lasers to first accelerate an MeV e-beam in a gas target (LWFA or bubble accelerator). The MeV electrons then create pairs by hitting a second high-Z converter. This “2-step” process produces lower e+ yield per J of laser energy, and lower e+ density, but it has higher rep rate so it can produce a semi-continuous e+ beam.





What are the most exciting applications of a dense e+ source?

High density e+ source makes it feasible to create a BEC of Ps at cryogenic temperature

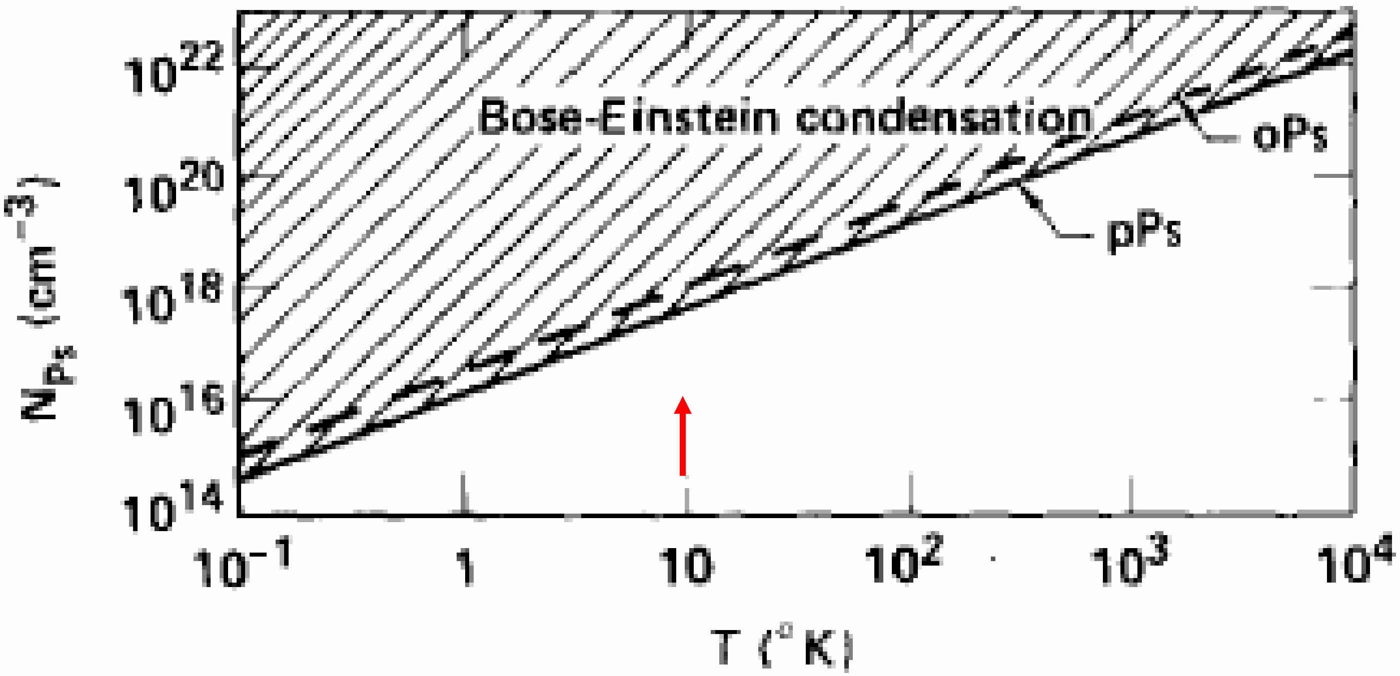
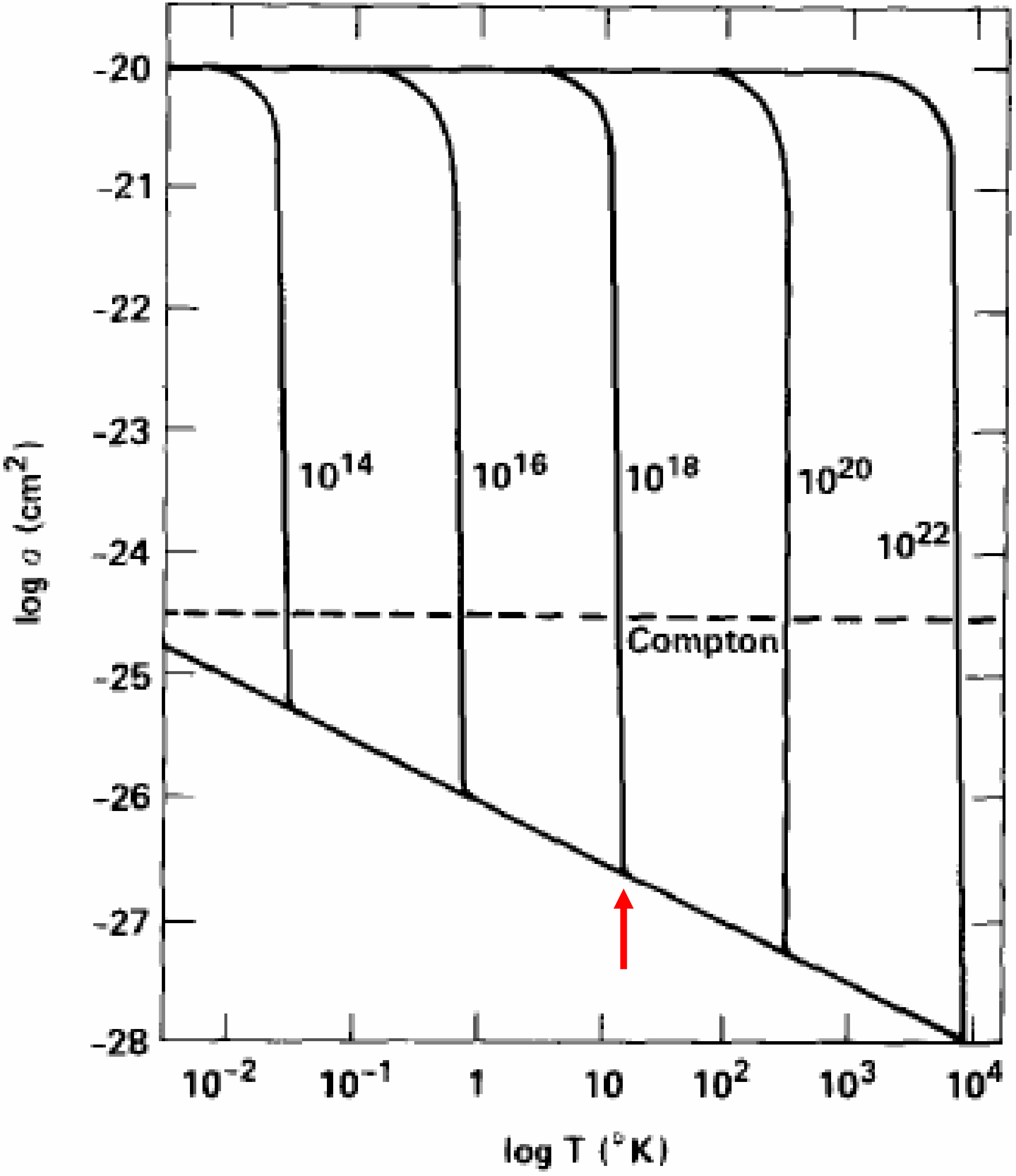


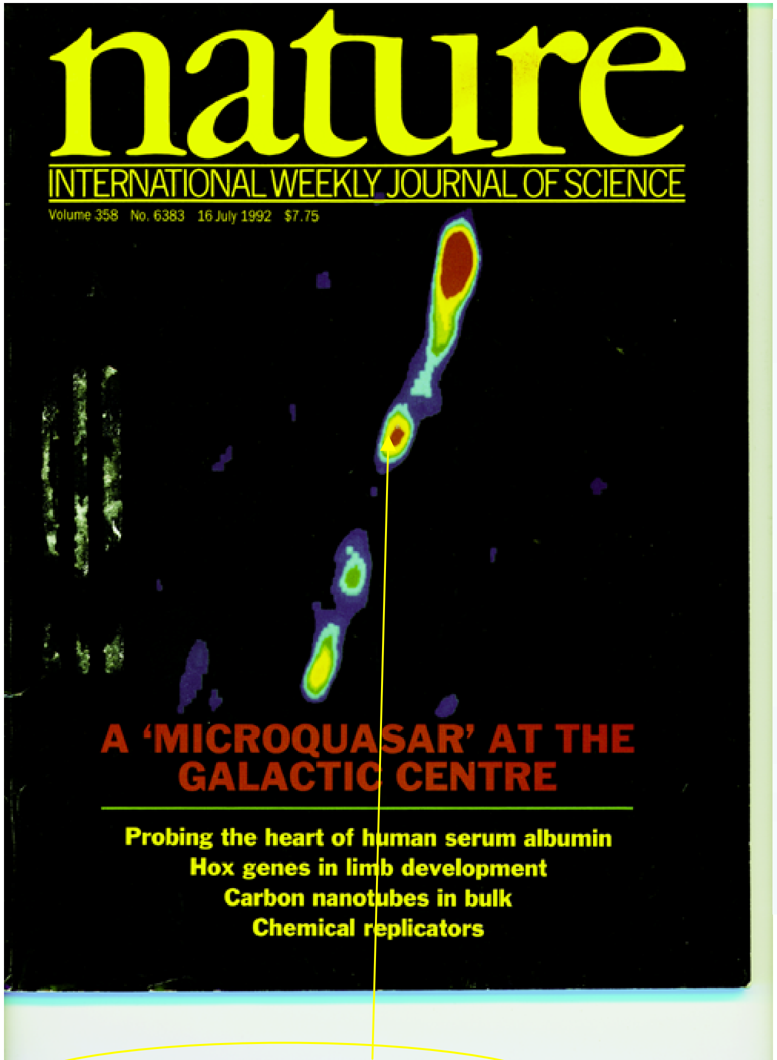
Fig. 4. Solid curve denotes the Bose–Einstein critical density as a function of temperature for pPs. Dashed curve denotes that of oPs. (See also ref. [7]). *(from Liang and Dermer 1988).*

A Ps column density of 10^{21} cm^{-2} could in principle achieve a gain-length of 10 for gamma-ray amplification via stimulated annihilation radiation (GRASAR).

(from Liang and Dermer 1988)



relativistic e+e- plasmas are ubiquitous in the universe



nature

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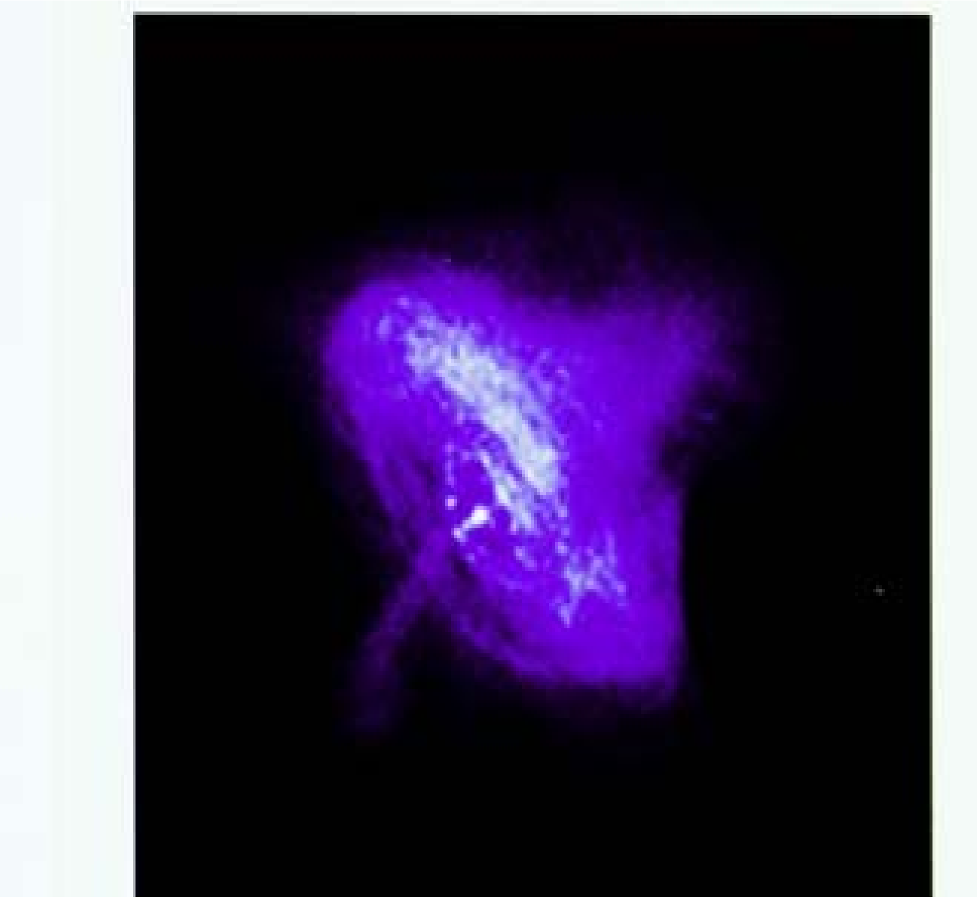
A 'MICROQUASAR' AT THE GALACTIC CENTRE

Probing the heart of human serum albumin
Hox genes in limb development
Carbon nanotubes in bulk
Chemical replicators

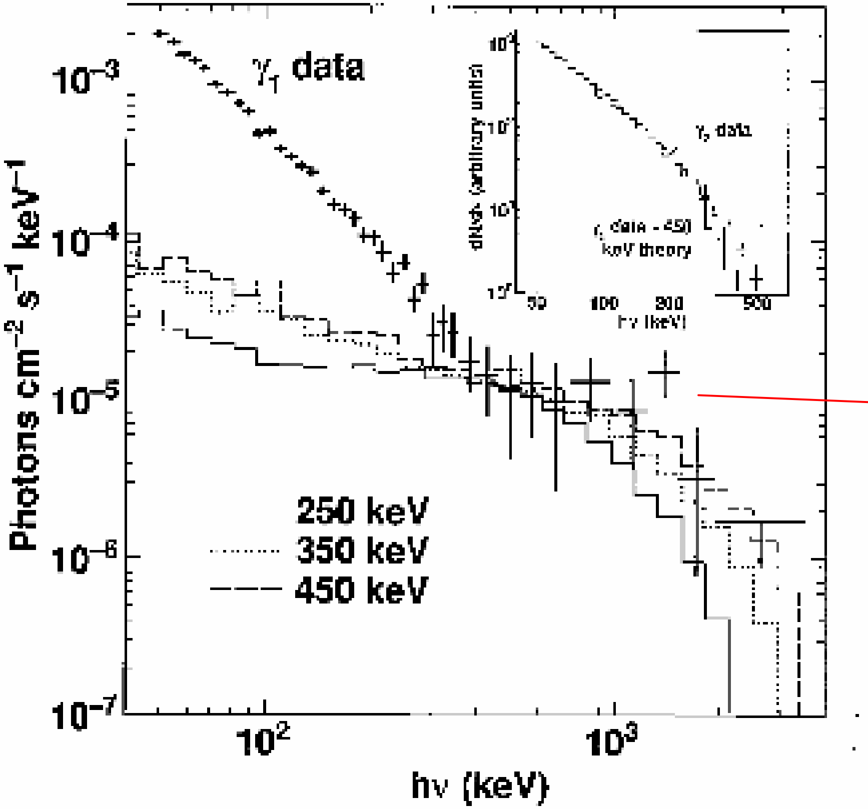
Thermal MeV pairs

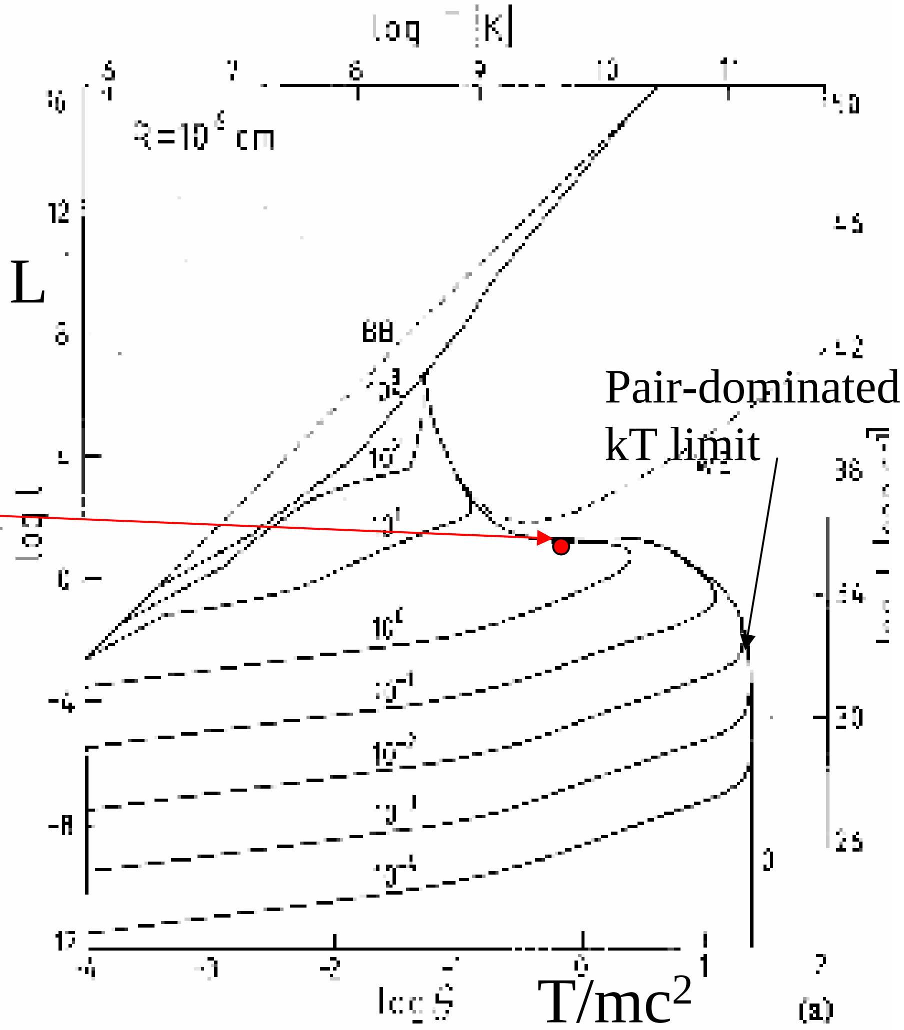


Nonthermal TeV pairs

Laser-produced pair plasmas can be used to study lab astrophysics

The Black Hole gamma-ray-bump can be interpreted as emissions from a pair-dominated MeV plasma with $n_+ \sim 10^{17}$cm^{-3}





L

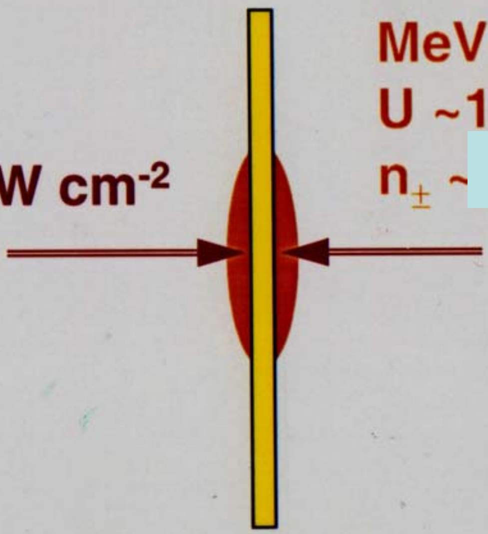
Pair-dominated kT limit

T/mc^2

Can laser-produced pair plasmas probe the pair-dominated temperature limit?

Another concept:two-sided irradiation may create more pairs, due to hotter electrons and longer confinement time

Creating a Pair Fireball



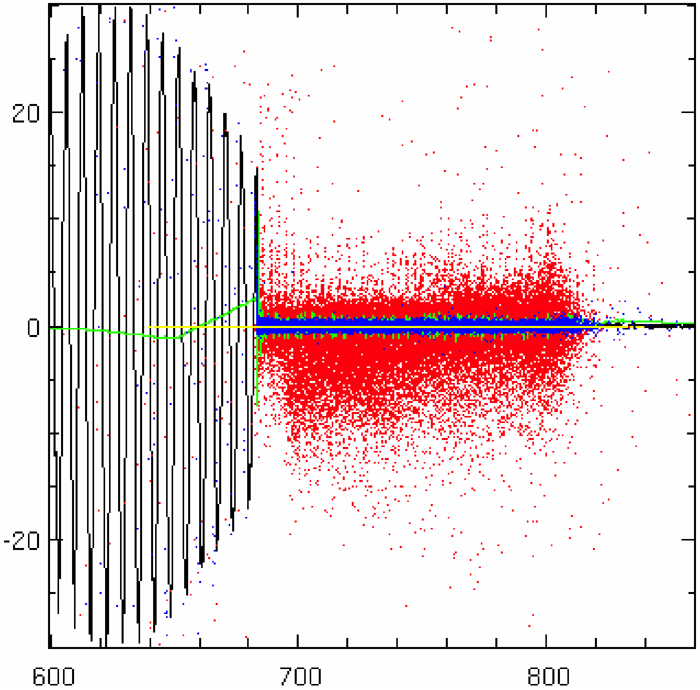
MeV pair plasma
U ~10^{16} erg cm^{-3}
$n_{\pm}$ ~ 10^{21} cm^{-3}

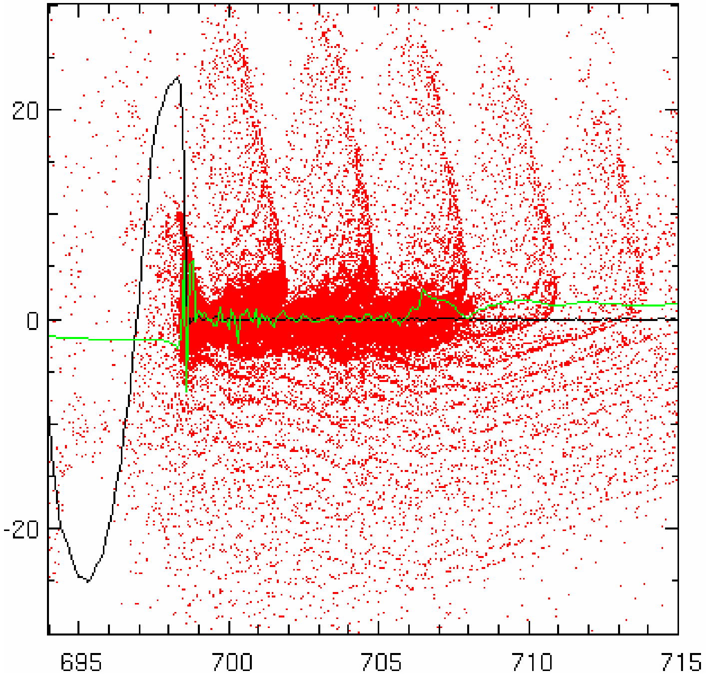
laser 10^{21} W cm^{-2}
for 1 ps

<10 μm thick
Au (Z=79) foil

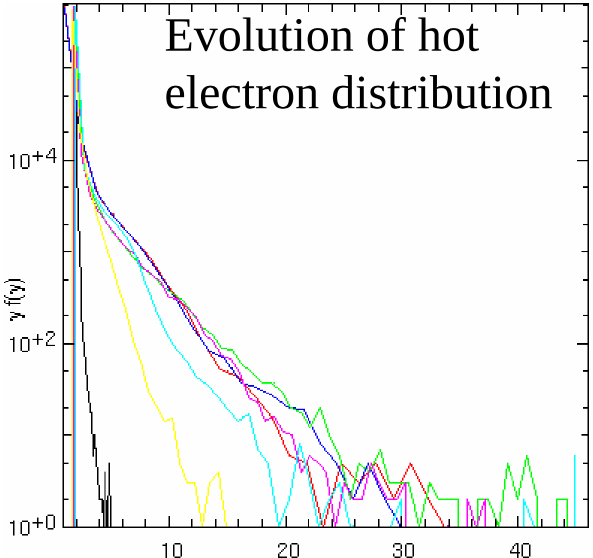
Ponderomotive forces can lead to a pair cascade by reaccelerating the primary pairs in the foil

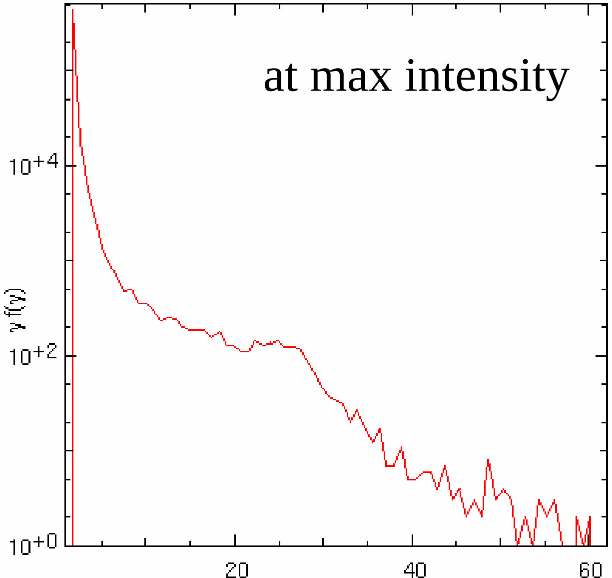
Future Work: Needs to study the detailed interactions of laser induced EM fields with hot electrons and pairs inside target



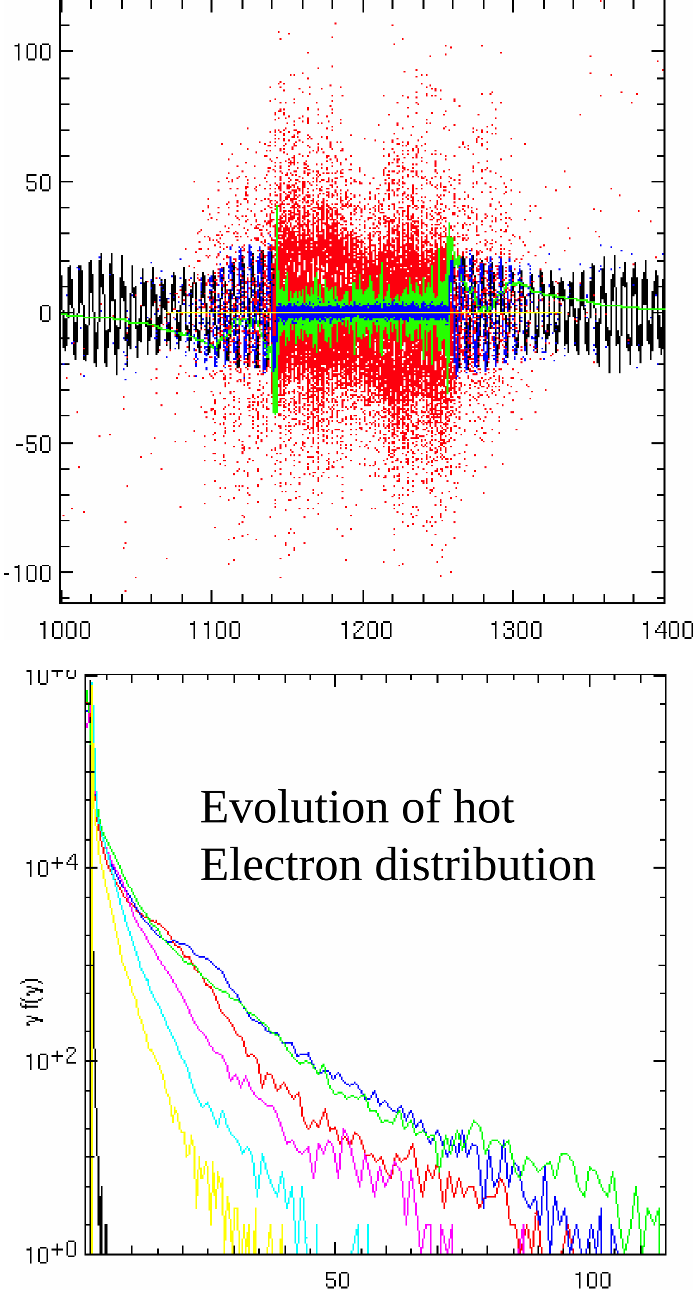


20 µm
Au foil
10^{21} Wcm^2
150 fs
laser


Evolution of hot electron distribution

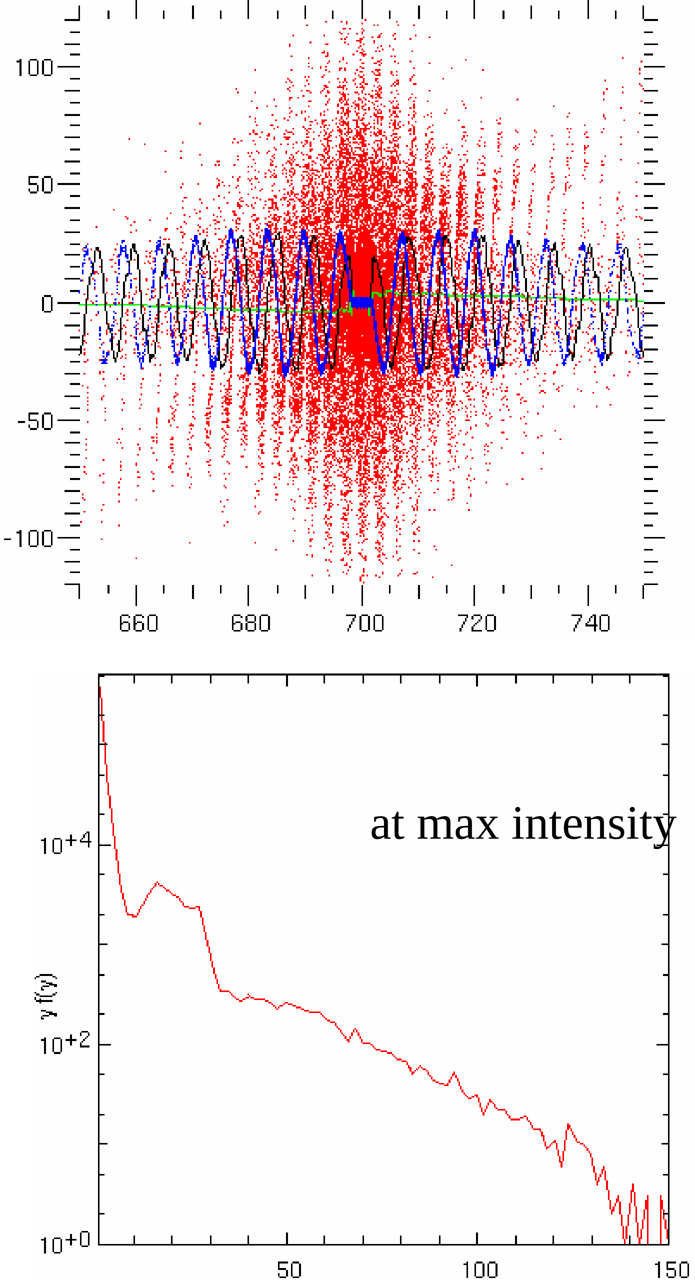

at max intensity

2 µm
foil



Evolution of hot
Electron distribution

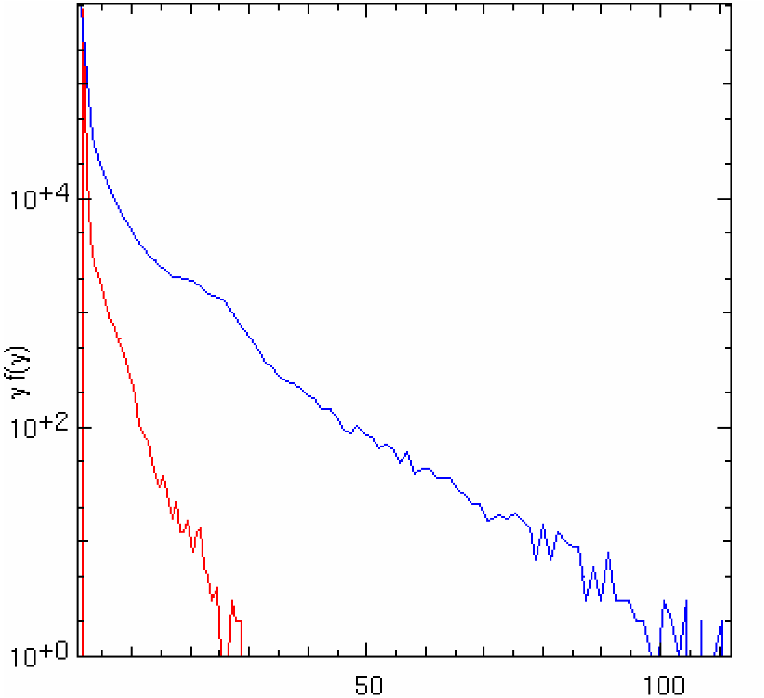
20 µm foil



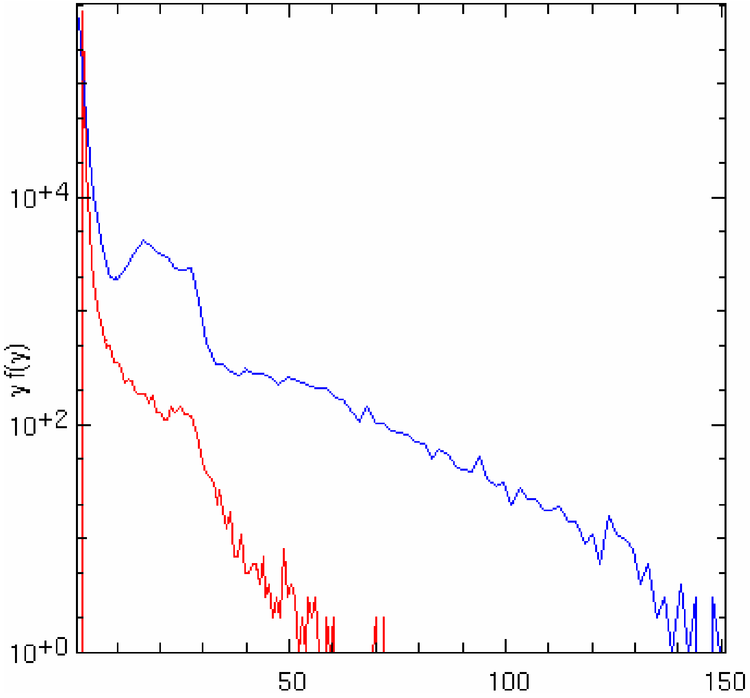
at max intensity

2 µm foil

blue=2-sided irradiation, red=1-sided irradiation



20 μm foil



2 μm foil

2-sided irradiation of a thin foil seems to produce much hotter electrons for pair production

Summary

1. Both experiments and numerical simulations point towards copious production of e+e- pairs using lasers with I > 10^{20} Wcm^{-2}.
2. We estimate max. e+ yield > 10^{12} per kJ of laser energy (conversion efficiency ~ few %).
3. The in-situ e+ density can exceed 10^{17} cm^{-3}.
4. Such a dense and intense e+ source makes it feasible to think about creating a BEC of Ps at cryogenic temperatures.
5. Such a Ps BEC would be a strong candidate for a GRASAR