Generation of positrons with intense lasers

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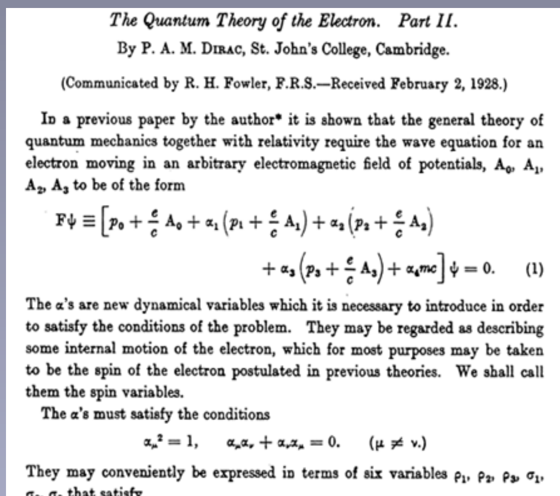
Positrons (antielectrons) are the antimatter counterpart of electrons

Theorized by Dirac in 1928



The Quantum Theory of the Electron. Part II.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received February 2, 1928.)

In a previous paper by the author* it is shown that the general theory of quantum mechanics together with relativity require the wave equation for an electron moving in an arbitrary electromagnetic field of potentials, A_0, A_1, A_2, A_3 to be of the form

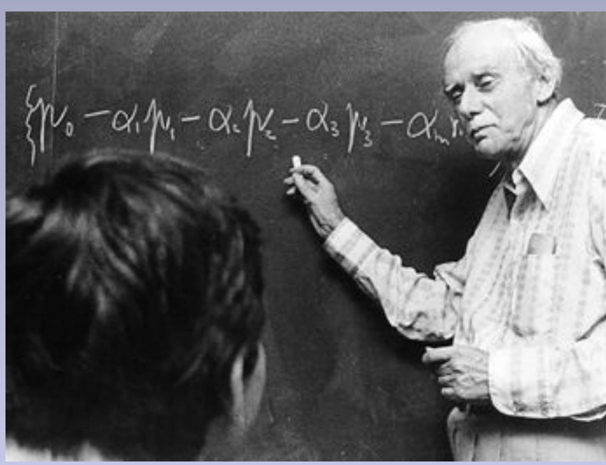
$$F\psi \equiv \left[p_0 + \frac{e}{c}A_0 + \alpha_1\left(p_1 + \frac{e}{c}A_1\right) + \alpha_2\left(p_2 + \frac{e}{c}A_2\right) + \alpha_3\left(p_3 + \frac{e}{c}A_3\right) + \alpha_4 mc\right]\psi = 0. \qquad (1)$$

The α's are new dynamical variables which it is necessary to introduce in order to satisfy the conditions of the problem. They may be regarded as describing some internal motion of the electron, which for most purposes may be taken to be the spin of the electron postulated in previous theories. We shall call them the spin variables.

The α's must satisfy the conditions

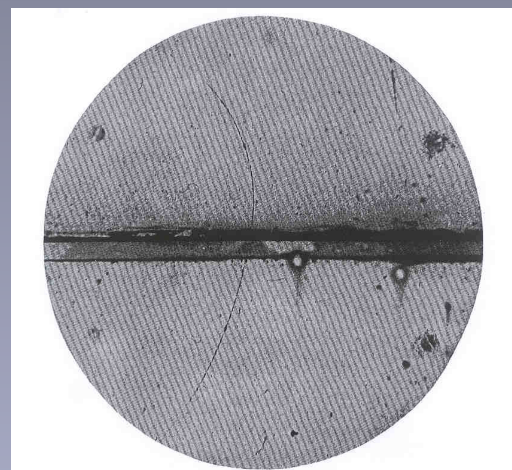
$$\alpha_\mu^2 = 1, \qquad \alpha_\mu\alpha_\nu + \alpha_\nu\alpha_\mu = 0. \qquad (\mu \neq \nu.)$$

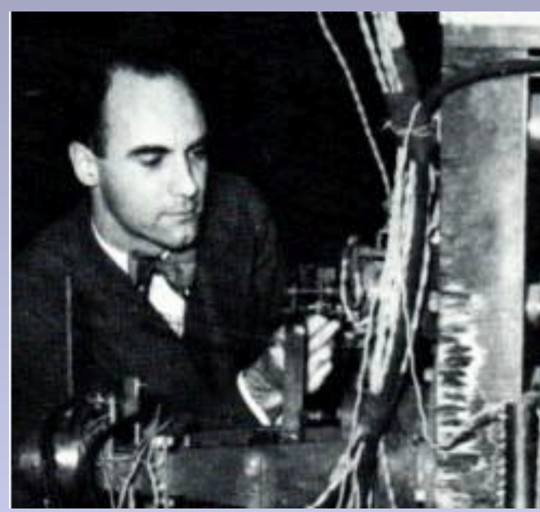
They may conveniently be expressed in terms of six variables ρ_1, ρ_2, ρ_3, σ_1, σ_2, σ_3 that satisfy



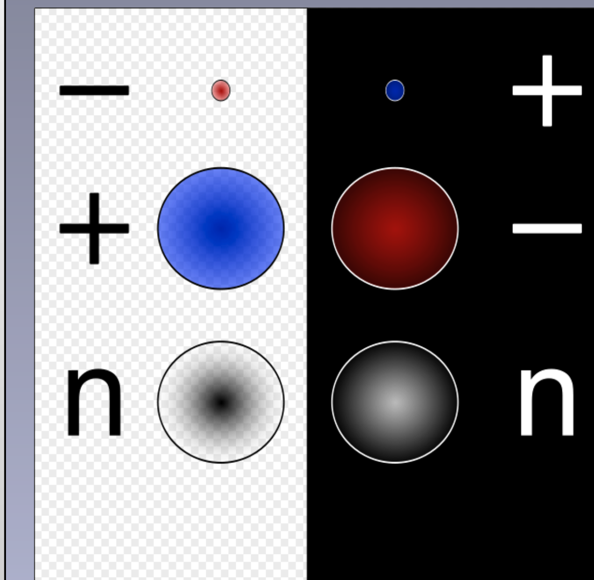
Dirac lecturing at FSU, Tallahasse

Verified by Anderson in 1932





Other Antiparticles



Positrons - 0.511 MeV

Antimuon - 212 MeV
Antiproton - 938 MeV
Antineutron - 940 MeV

Positrons can be produced through two processes: (1) e^+e^- pair production; (2) radioactive β^+ decay

1932 (Anderson experiment):
Pair production from Cosmic ray

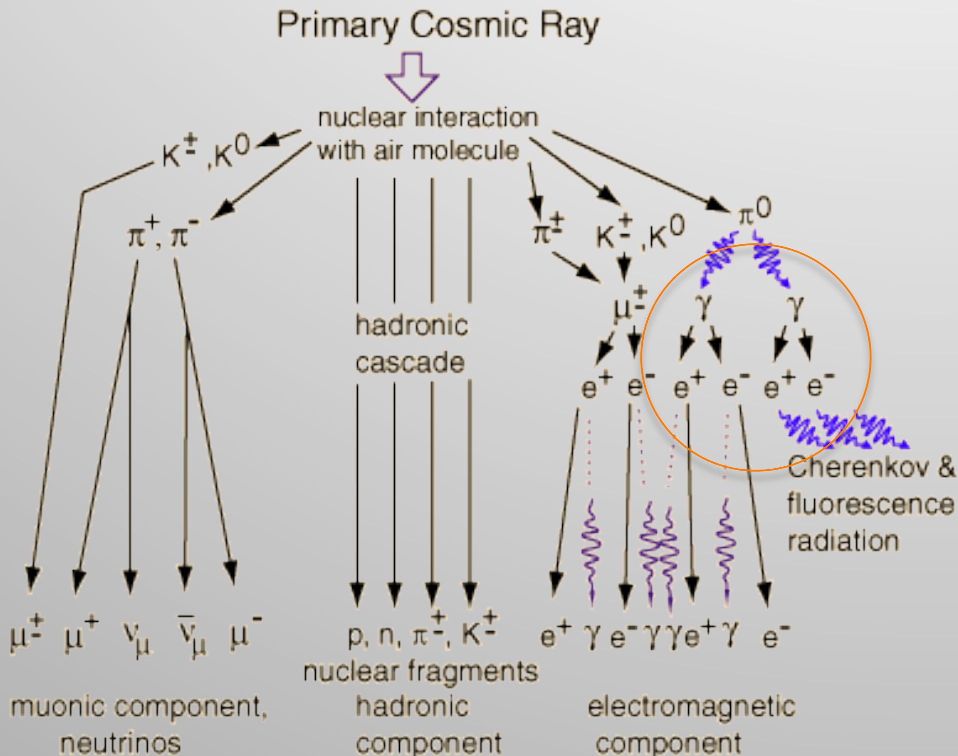
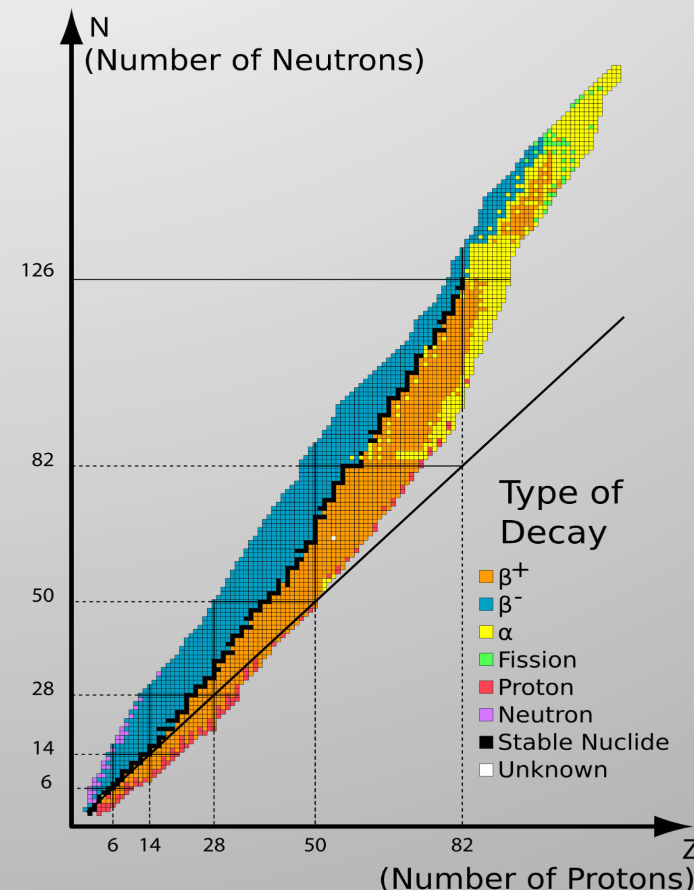


Diagram credit: GSU

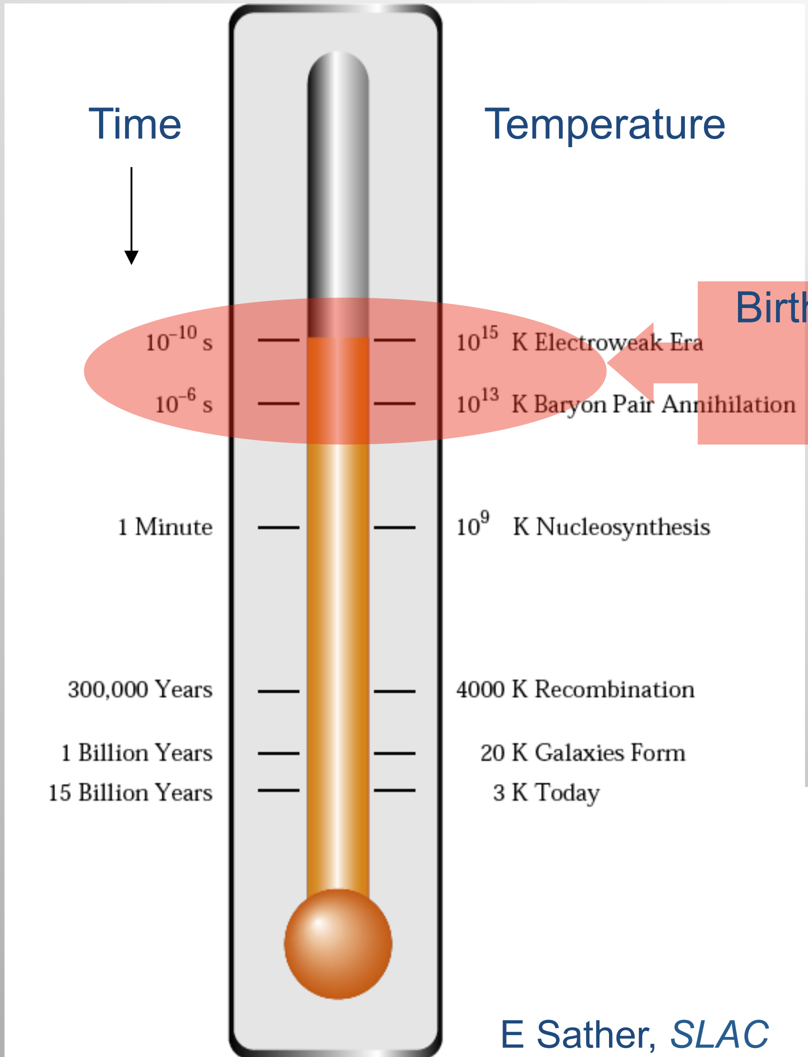
1934 (Curie):

$^{27}Al + \alpha \rightarrow {}^{30}P + n$;

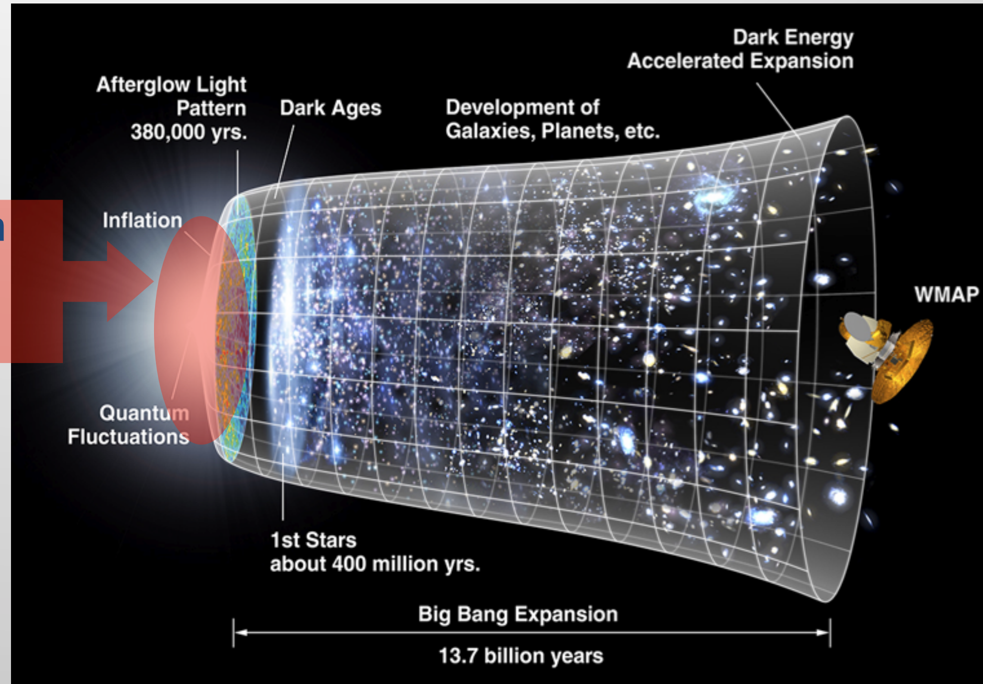
$^{30}P \rightarrow {}^{30}Si + e+ + \nu_e$



Positrons and other antimatter were first created, like matter, at the beginning of universe



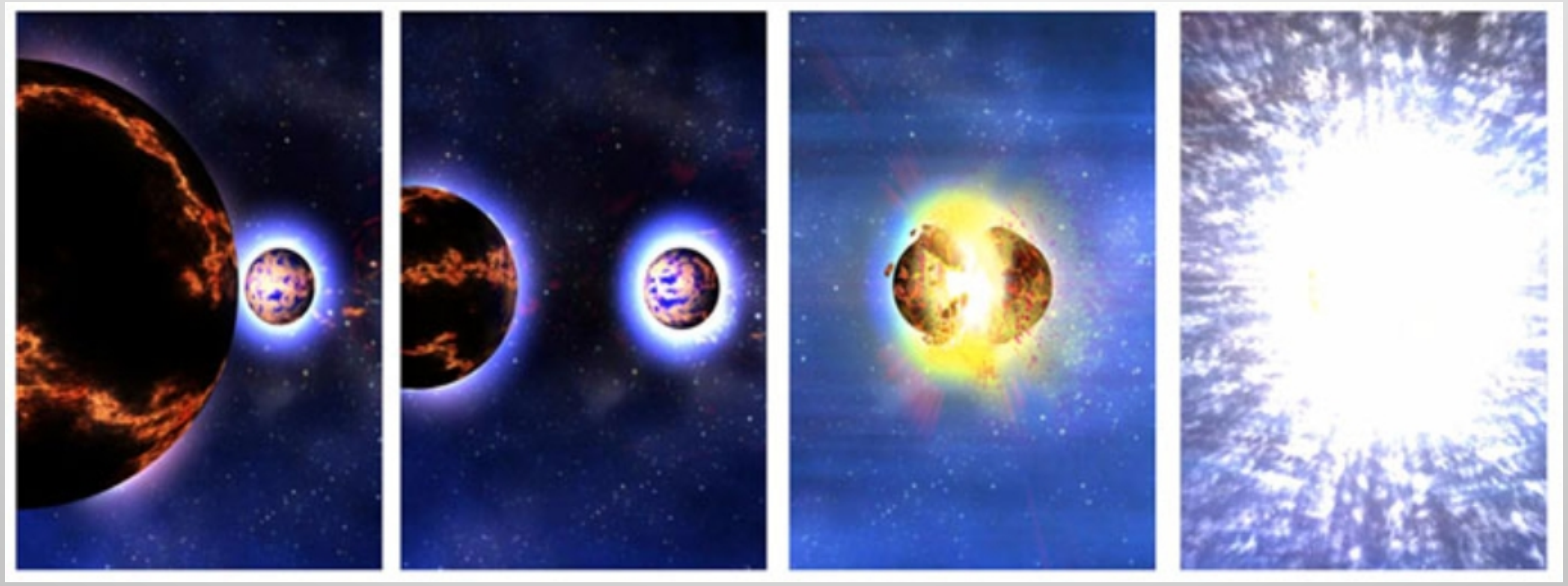
E Sather, *SLAC*



WMAP, *NASA*

The matter-antimatter asymmetry at the present time is an unsolved mystery in physics

Positron-electron pairs are believed to be produced in natural cosmic events (ex. Gamma Ray Bursts)



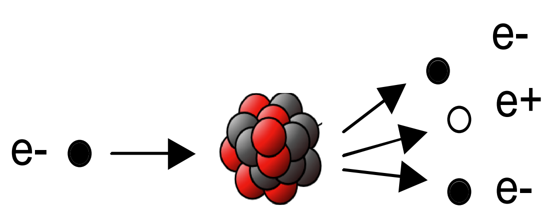
Credit: NASA/Dana Berry

Astronomers believe this burst, and probably other short bursts, are produced by a rapid explosion which occurs when one neutron star merges with another neutron star.

How about positrons on earth?

Examples of positrons from (1) accelerators and (2) nuclear isotopes

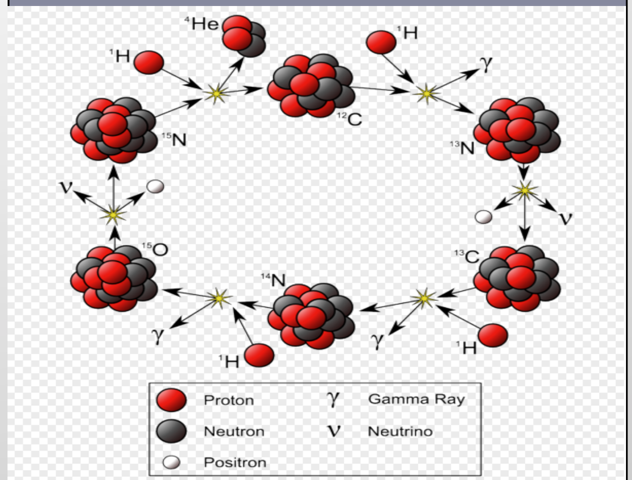
Accelerator Electron Beam



SLAC

- ~ 10^{10} positrons/bunch
- Energies > ~100 MeV

Beta-decay Isotopes



- Medical-PET
- Material study
- Researches

- ~ $10^{6\text{-}12}$ positrons/s
- Energies < ~1 MeV

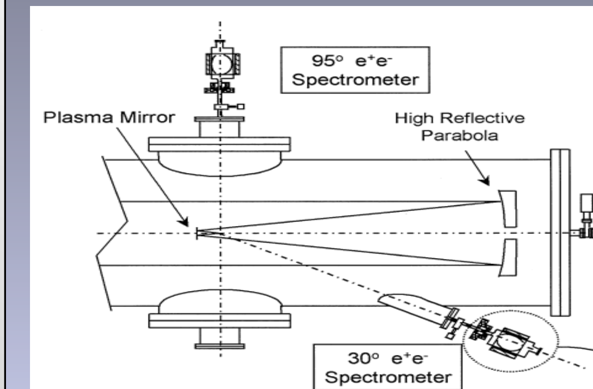
Substantial theoretical work performed on laser-pair subject, but little exp. data existed before this work

Theoretical/Modeling

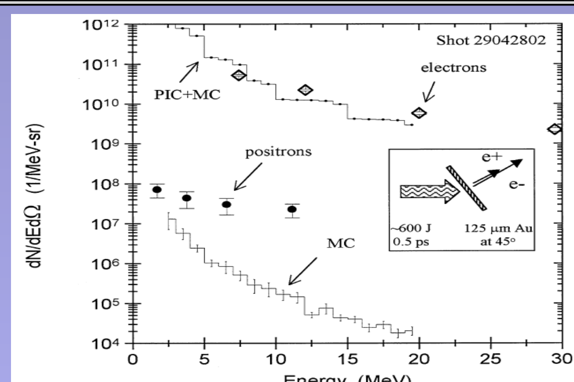
Shearer et al. 1973
Liang et al. 1995, 1998
Shkolnikov et al. 1997
Gryaznykh et al. 1998
Shen & Meyer-ter-Vehn, 2001
Nahashima & Takabe, 2002
Berezhiani et al., 2007
Myatt et al., 2008
……

Assume a T_{hot}, it was predicted for 100 J laser 10^7 - 10^9 positrons would be produced (depending on mechanisms target Z, thickness, Laser parameter etc.)

LLNL NOVA PetaWatt Exp.

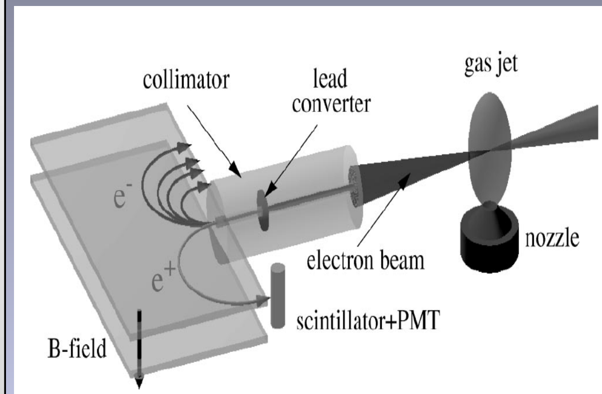


Cowan et al. (1999)

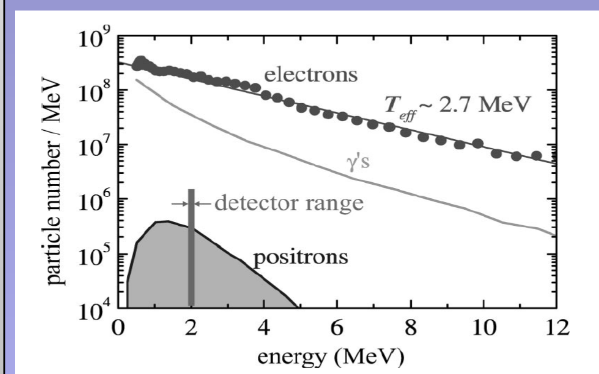


- <100 were detected
- e+/e- ~ 10^{-4}

Accelerator Electron Beam



Gahn et al. (2002)



- ~30/shot at 2 MeV
- e+/e- <10^{-3}

Other recent works related to laser produced positrons using B-H process

Theory and modeling:

“Monte Carlo simulation study of positron generation in ultra-intense laser-solid interactions”
Yan, Yonghong; Wu, Yuchi; Zhao, Zongqing; Teng, Jian; Yu, Jinqing; Liu, Dongxiao; Dong, Kegong; Wei, Lai; Fan, Wei; Cao, Leifeng; Yao, Zeen; Gu, Yuqiu
Physics of Plasmas, Volume 19, Issue 2, pp. 023114-023114-6 (2012)

Experiments:

“Table-Top Laser-Based Source of Femtosecond, Collimated, Ultrarelativistic Positron Beams”
Sarri, G.; Schumaker, W.; Di Piazza, A.; Vargas, M.; Dromey, B.; Dieckmann, M. E.; Chvykov, V.; Maksimchuk, A.; Yanovsky, V.; He, Z. H.; Hou, B. X.; Nees, J. A.; Thomas, A. G. R.; Keitel, C. H.; Zepf, M.; Krushelnick, K.
Physical Review Letters, vol. 110, Issue 25, id. 255002

“Positron and Gamma-Ray Creation using the Texas Petawatt Laser Irradiating Gold Targets”
Liang, Edison; Taylor, Devin; Clarke, Taylor; Henderson, Alexander; Chaguine, Petr; Wang, Xin; Dyer, Gilliss; Serratto, Kristina; Riley, Nathan; Donovan, Michael; Ditmire, Todd
American Physical Society, 54th Annual Meeting of the APS Division of Plasma Physics, October 29-November 2, 2012, abstract #NO7.015

Using intense lasers to create relativistic, electron-positron pair jets and pair plasmas

What were the experimental components?

- Laser parameters
- Basic pair production process
- Experimental layout
- Role of Diagnostics

What are the unique features?

1. Positron acceleration
2. Quasi mono-energy
3. Relativistic electron-positron jet
4. Beam emittance
5. Scaling against laser energy
6. Collimation

What we plan to do next?

NASA/ CXC/ CfA/ R.Kraft et al.

At high laser intensities photon-particle and particle-particle interactions become relativistic

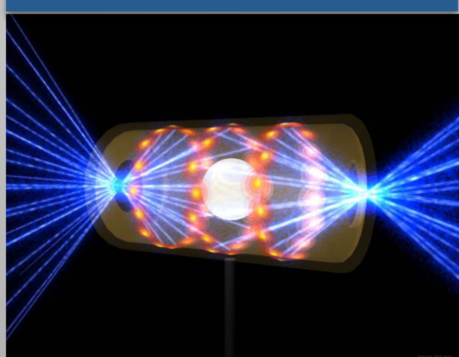
10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22} 10^{24} 10^{26} 10^{28} W/cm^2

- atomic processes
- collisional absorption
- non-linear optics

- relativistic electrons
- nuclear processes
- γ-production
- e^+e^- plasmas

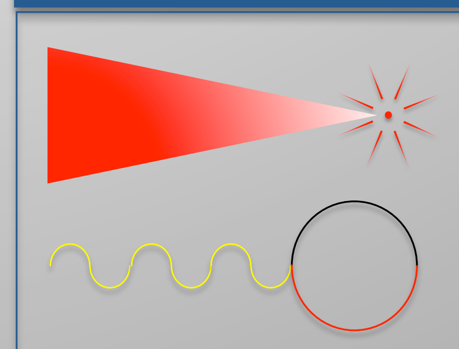
- pion production
- relativistic protons
- QED

ICF experiments

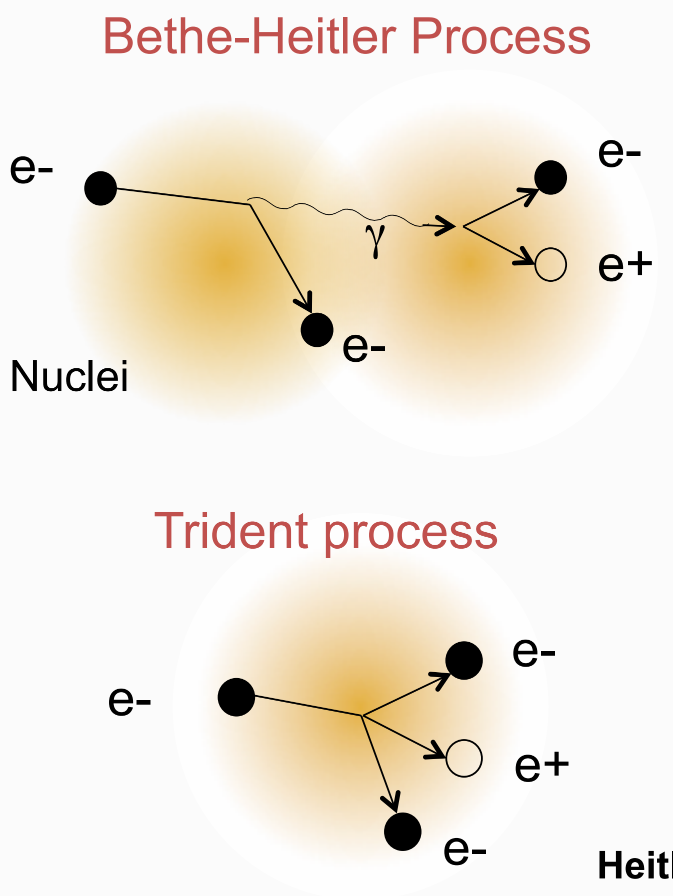


Typical parameters	> 10^{20} W/cm^2
Electric fields	10^{12} V/m
Magnetic fields	100's MG
Pressure	Gbar
Temperature	keV or 10^7 K
Acceleration	10^{21} g
Density	Nc or solid

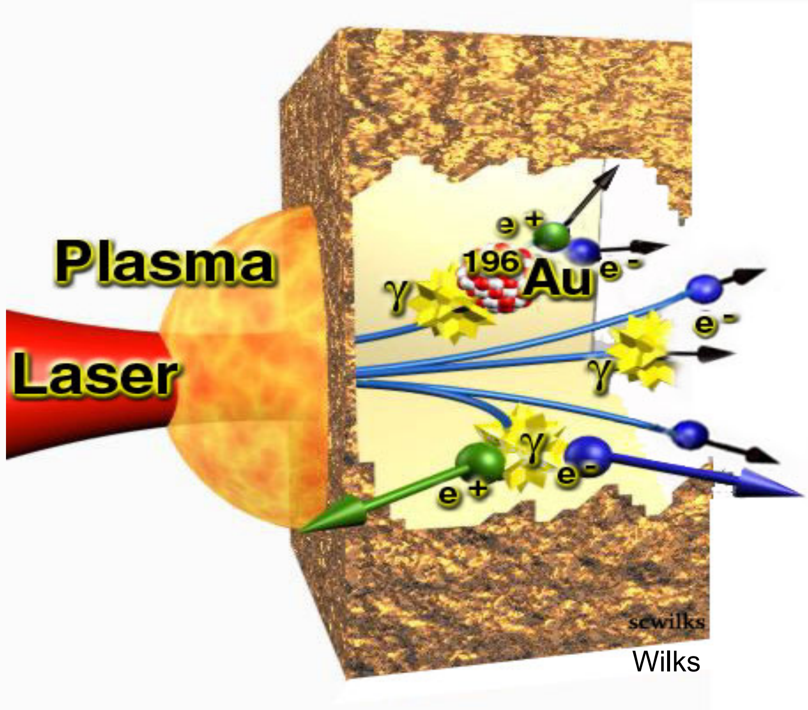
Vacuum Pairs



Lasers can create positrons indirectly via two processes using targets with high atomic numbers



Heitler, 1954



Pair producing probability is much enhanced in the nuclear field as the momentum conservation is more easily preserved.

Laser produced MeV hot electrons are the key to the positron-electron pair creation

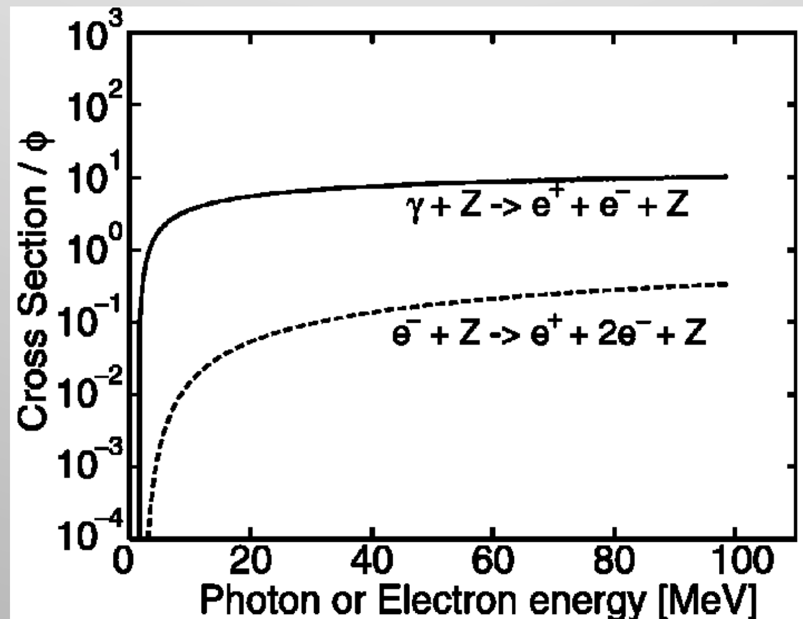
$$N_{e+} \propto \int N_{\mathrm{Au}} N_e(E) \sigma_{eZ}(E) dE$$

N_{au}: Target density

σ_{eZ}: cross-section for pair production

$$\begin{cases} \sigma_{eZ} \propto Z^2 \text{ for Trident} \\ \sigma_{eZ} \propto Z^4 \text{ for Bethe-Heilter} \end{cases}$$

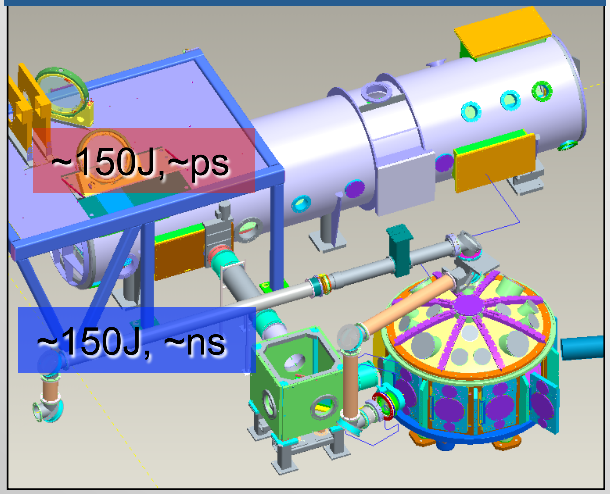
N_e: High energy (> 1MeV) electron number



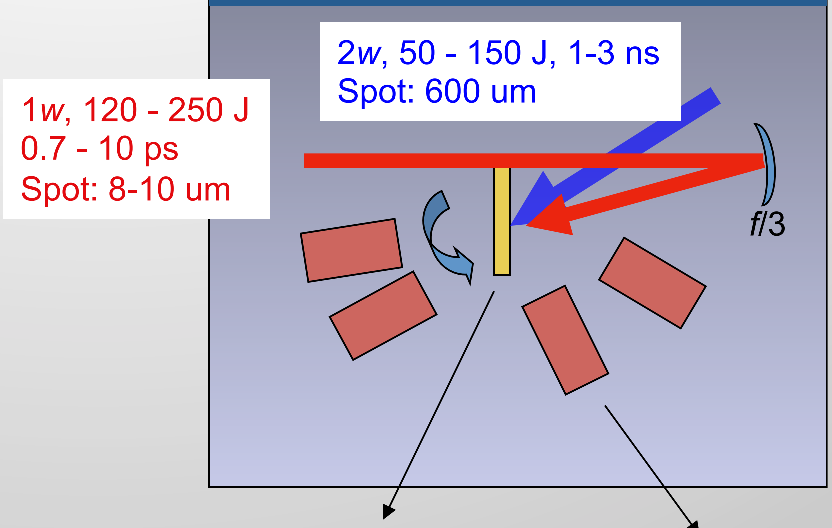
Nakashima & Takabe, PoP 2002

ps-lasers combined with *ns*-lasers provide the core experimental arrangement

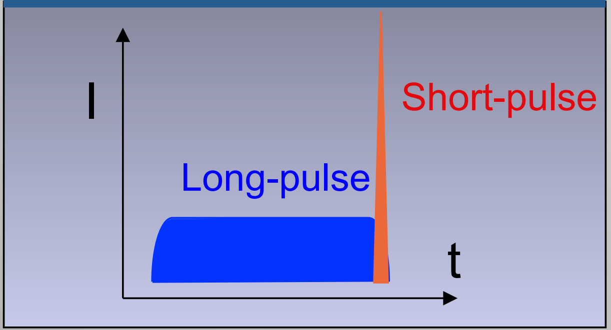
LLNL Titan two-beam laser



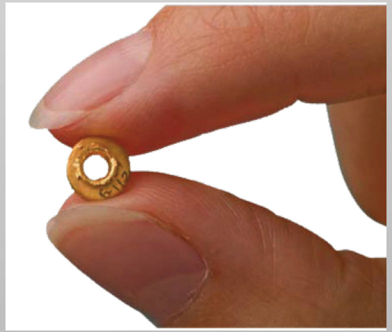
Experimental setup



Timing for the two beams

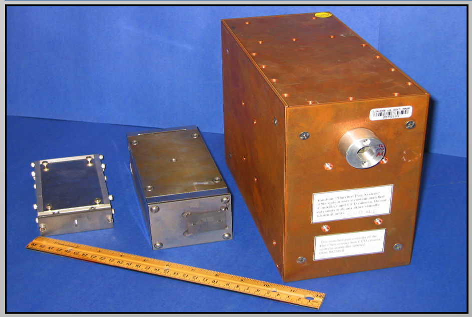


Target post-shot



Al, Cu, Sn, Ta, Au
Thickness: 0.1 - 3.1 mm

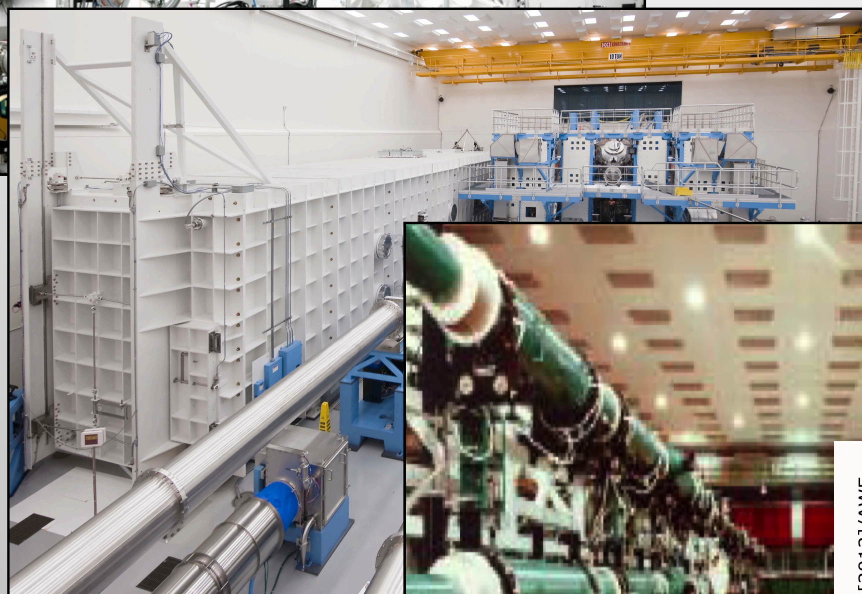
Spectrometers



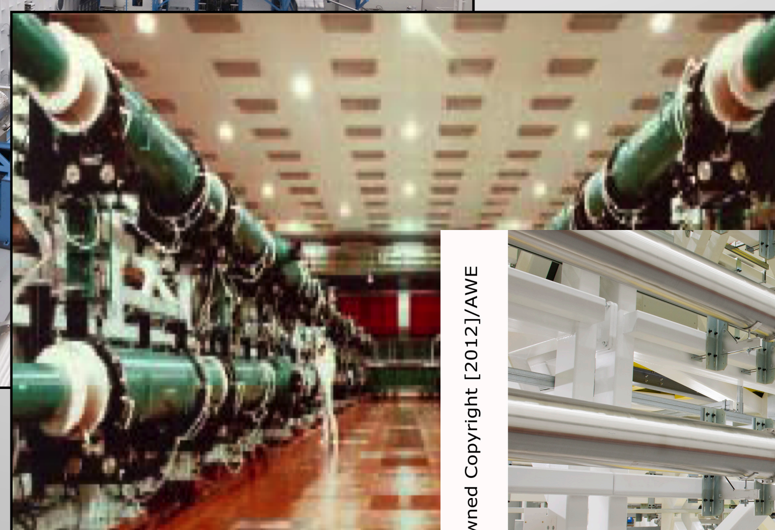
Chen et al. RSI 2008

Our experiments were performed on four facilities

Titan laser (LLNL)
1-10 ps, 100-350 J
5-10 shots/day



Omega EP (LLE)
1-10 ps, up to 1.3 kJ
5 shots/day



LFEX (ILE)
2-4 beams, 1 ps,
~1 kJ each beam

ORION (AWE)
2 SP beams
0.5-1 ps, up to 500 J

Advancement in diagnostics have led to “better understanding of complex physics”

Physical Review Focus

Focus Archive | Image Index | Focus Search

Previous Story / Next Story / Volume 23 archive

Phys. Rev. Lett. **102**, 105001
(issue of 13 March 2009)
Title and Authors

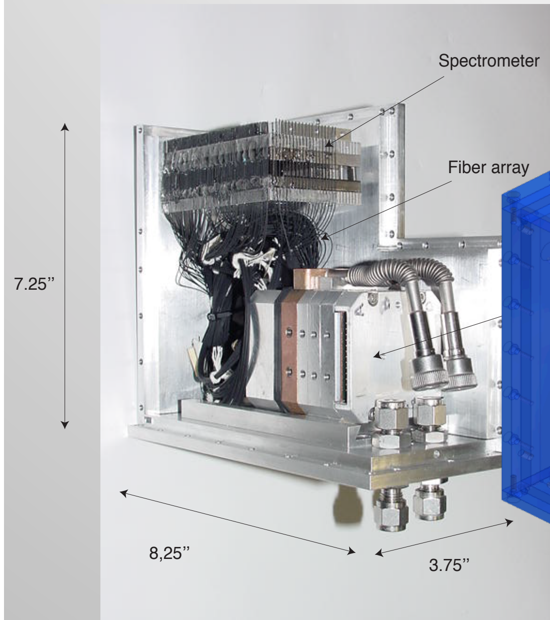
13 March 2009

Lasers Provide Antimatter Bonanza

Prof. Donald Umstadter of the University of Nebraska in Lincoln says **the specialized positron spectrometers allowed the team to demonstrate the importance of the Bethe-Heitler process** and shows "how a simple improvement in instrumentation can often lead to better understanding of complex physics.”

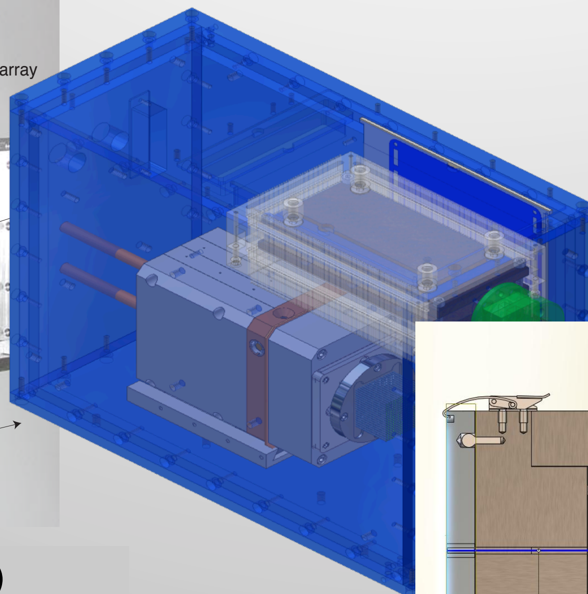
Generations of spectrometers improved energy coverage, S/N ratio and E/dE

Fiber-CCD for electrons



RSI, 74, 1551 (2003)

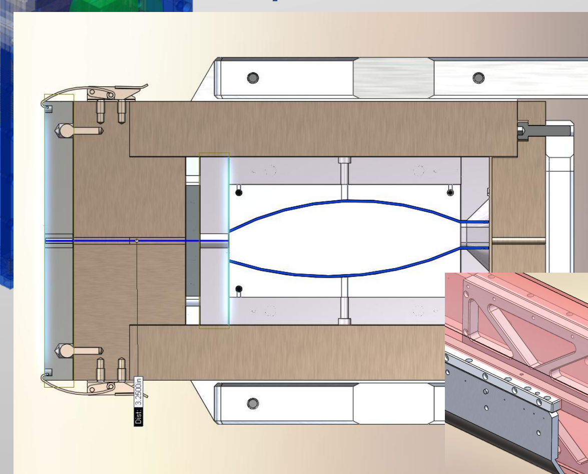
Fiber-CCD/image plate for electrons & positrons



(2005)

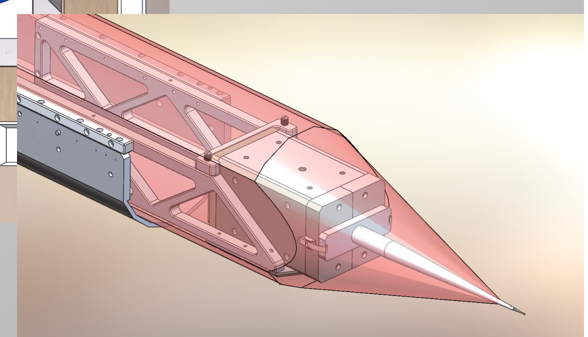
EPPS (Electron-Positron-Proton Spectrometer)

Compact EPPS



RSI (2008)

Adapted to TIM

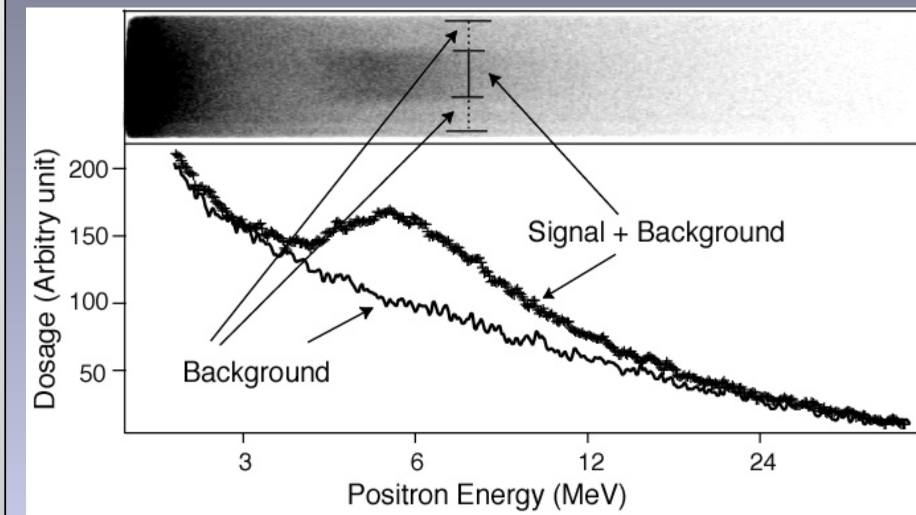


(2009)

- **Absolute calibration**
- **Cross-comparison with other detectors/simulations**

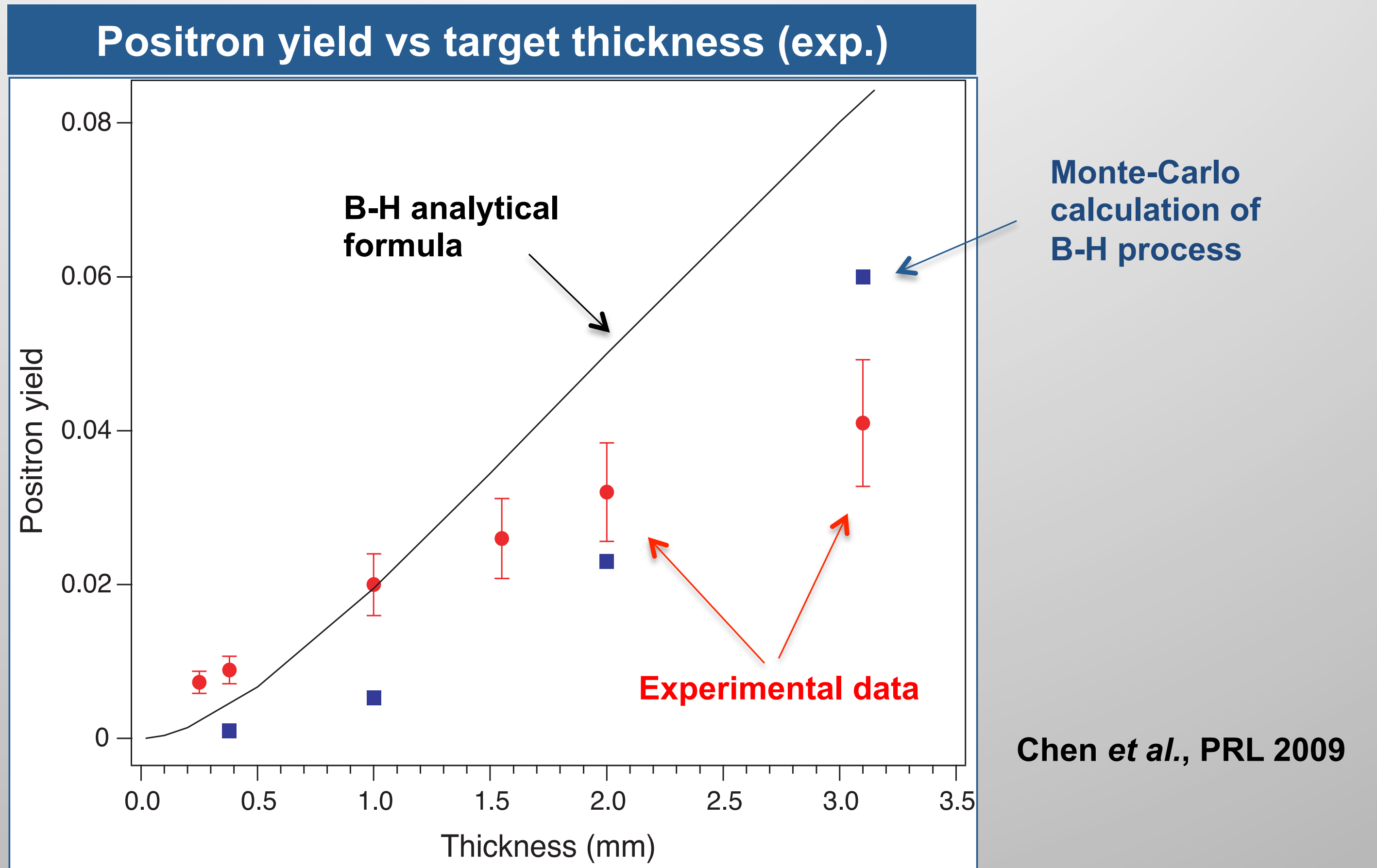
Electron-positron-proton-spectrometer measures the numbers of positrons vs energy from each shot

Raw positron data image (Au, 1mm)



- **Positron signal was verified using filtration methods and various Z targets**
- **Positron energy: ~3 to 20 MeV (relativistic)**
- **Equivalent of about 10^6 positrons on the detector**

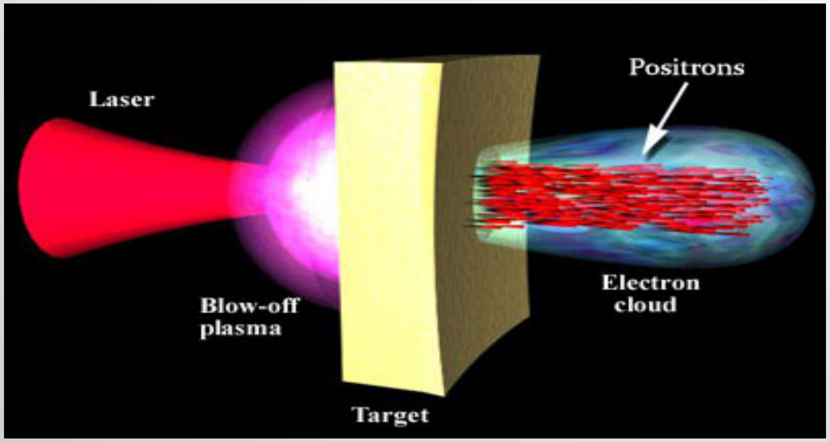
Pair production was shown to be primarily made through the Bethe-Heitler process



Chen *et al.*, PRL 2009

Accelerators also use the Bethe-Heitler process to produce positrons.

Laser produced positrons have 6 unique features



S. Wilks

1. Positron acceleration
2. Quasi mono-energy
3. Relativistic electron-positron jet
4. Beam emittance
5. Scaling against laser energy
6. Collimation

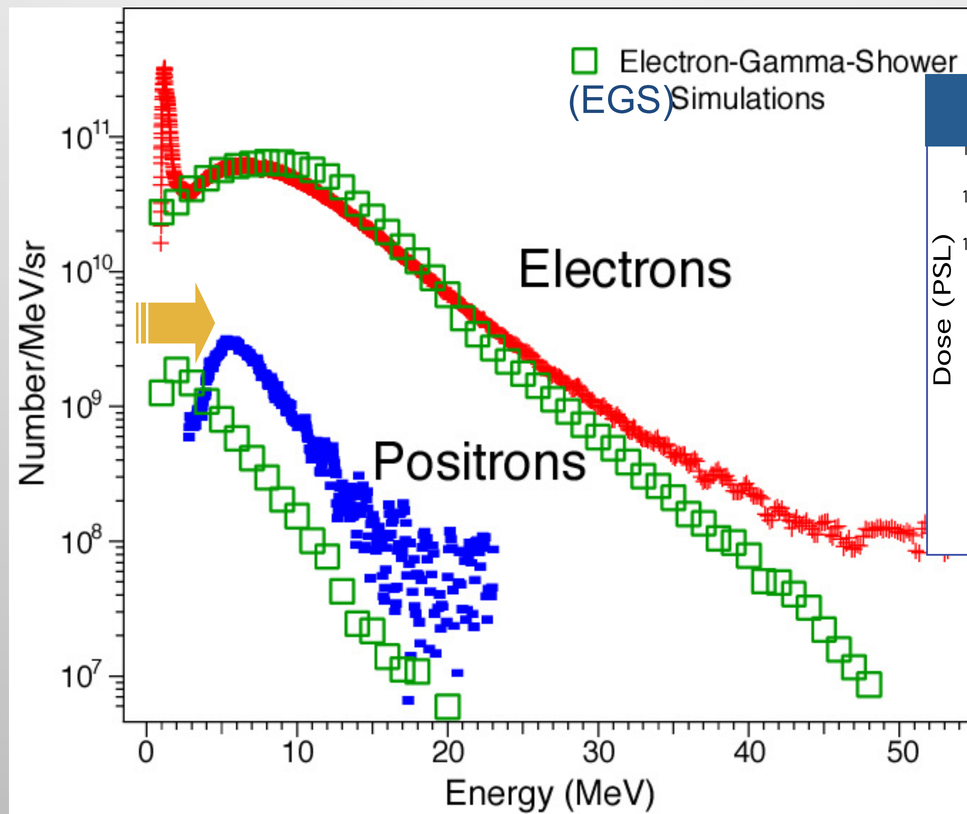
Chandra X-ray image of relativistically moving jets of electron-positron pair plasma powered by a supermassive black hole in a nearby galaxy Centaurus A.

NASA/CXC/CfA/ R.Kraft et al.

Lasers produce burst of relativistic jets. Is this miniature jets useful to understand cosmic jets?

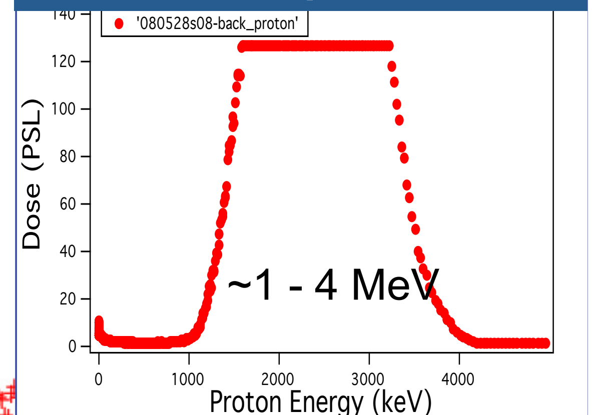
Measured positron and electron energy spectra reveal the positron acceleration mechanism

Measurement vs Monte-Carlo simulation

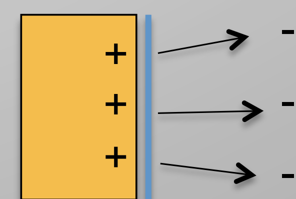


Is the energy shift of positron peak from the same acceleration field for protons?

Proton spectrum



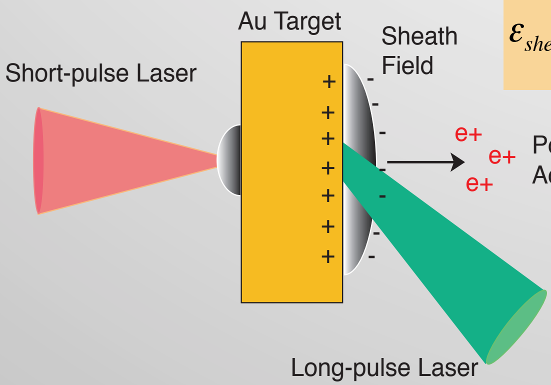
Sheath E field



E ~ MeV/μm

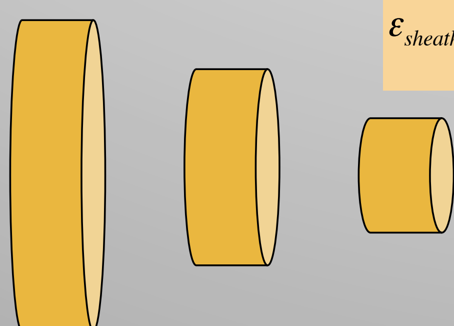
Sheath acceleration of positrons is verified experimentally

Varying plasma scale-lengths



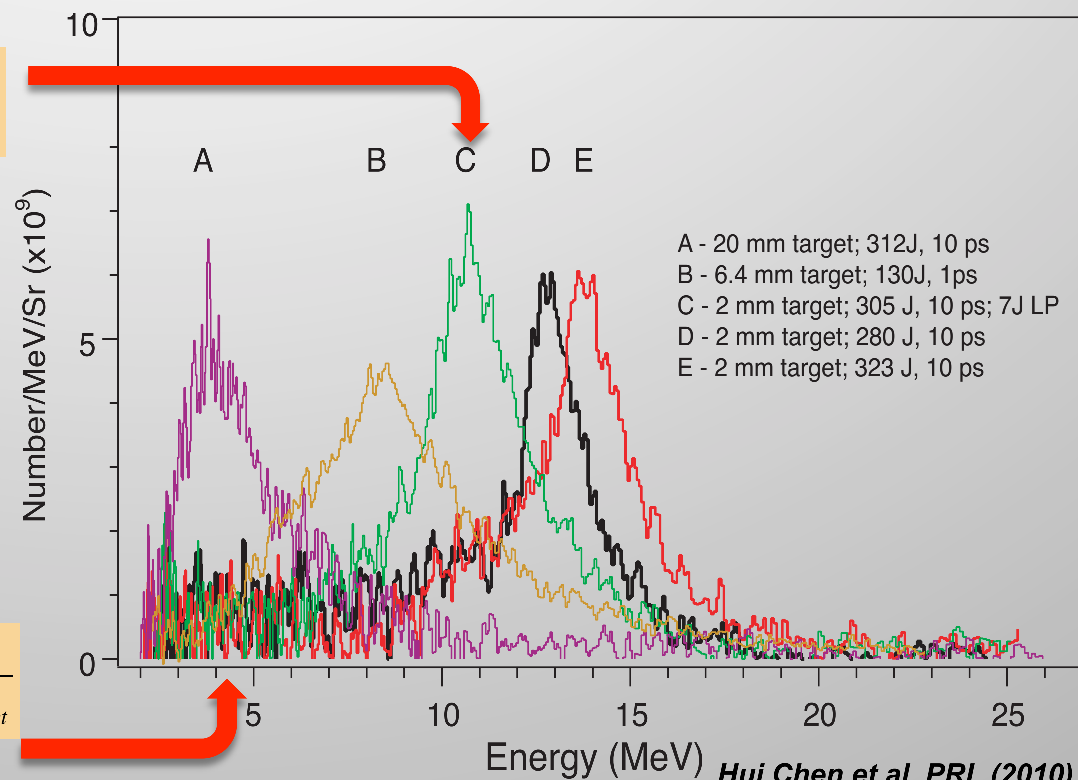
$$\varepsilon_{sheath} \propto \frac{T_e}{L_{ion}}$$

Varying target sizes



$$\varepsilon_{sheath} \propto \frac{Q_e}{C_{target}}$$

Positron spectra vs target/laser setup

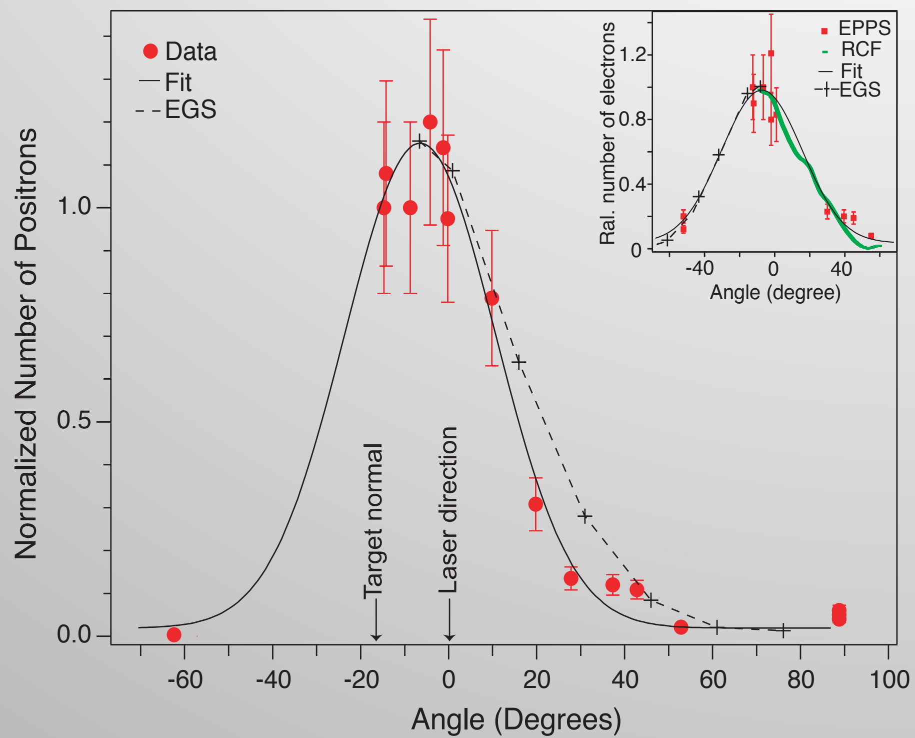


Hui Chen et al. PRL (2010)

Positron distributions are quasi mono-energetic (E/dE~ 2-5), and can be controlled.

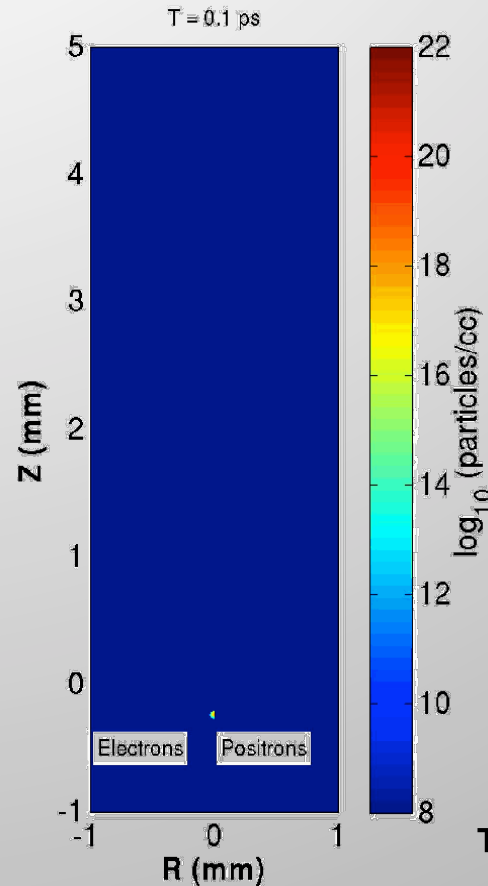
Laser produced relativistic pairs form jets at the back of the target

Laser pair angular distribution



Chen *et al.*, PRL 2010

LSP simulations of the jets



Tony Link

Jet angular spread: 20-30 degrees. The jets are shaped by the E and B fields of the target. Its direction is controlled by the lasers and target.

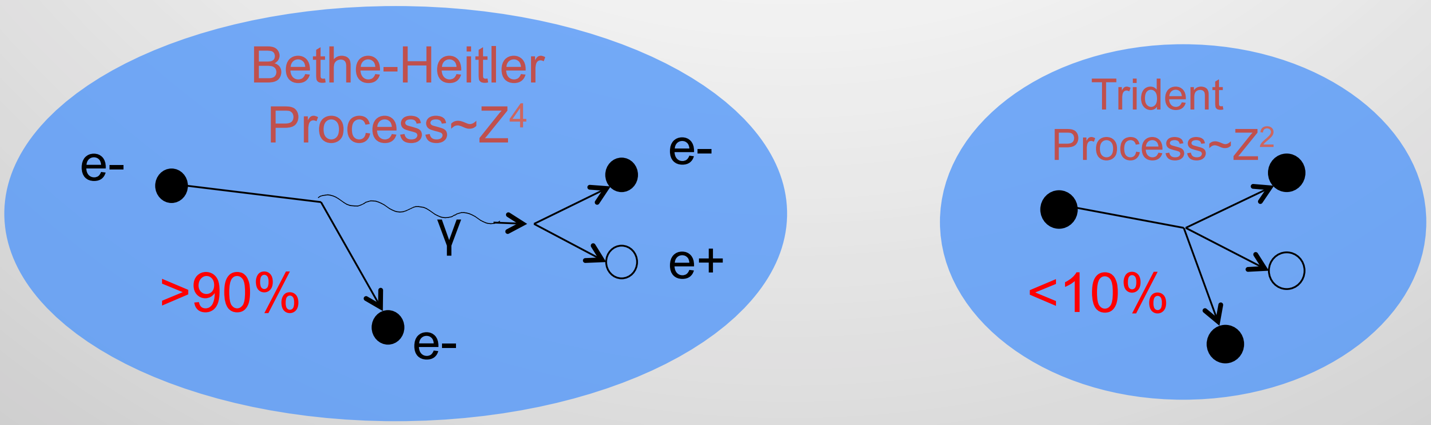
Intense lasers produce very high flux, relativistic pairs in 10s *ps* time scale

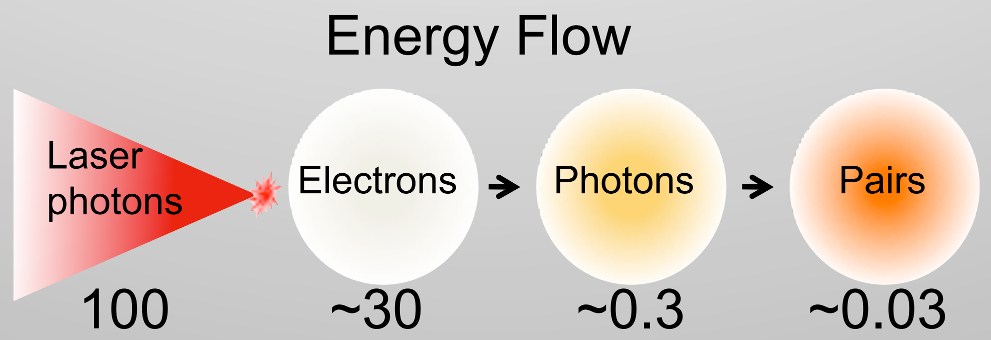
Parameter	Value
Pair number	10^{10}-10^{12}
Pair flux duration	~10-100 ps
Pair rate	~10^{22} /s
Peak energy	4 - 30 MeV
Peak flux	>10^{25} $cm^{-2}s^{-1}$

In comparison, pair rate of the intense positron source* is about 10^6-10^9 /s.

* C. Hugenschmidt, "Positron sources and positron beams", Proc. Inter. School of phys. "Enrico Fermi" Course CLXXIV

About 0.03% of laser energy converted to positrons mostly through the Bethe-Heitler process

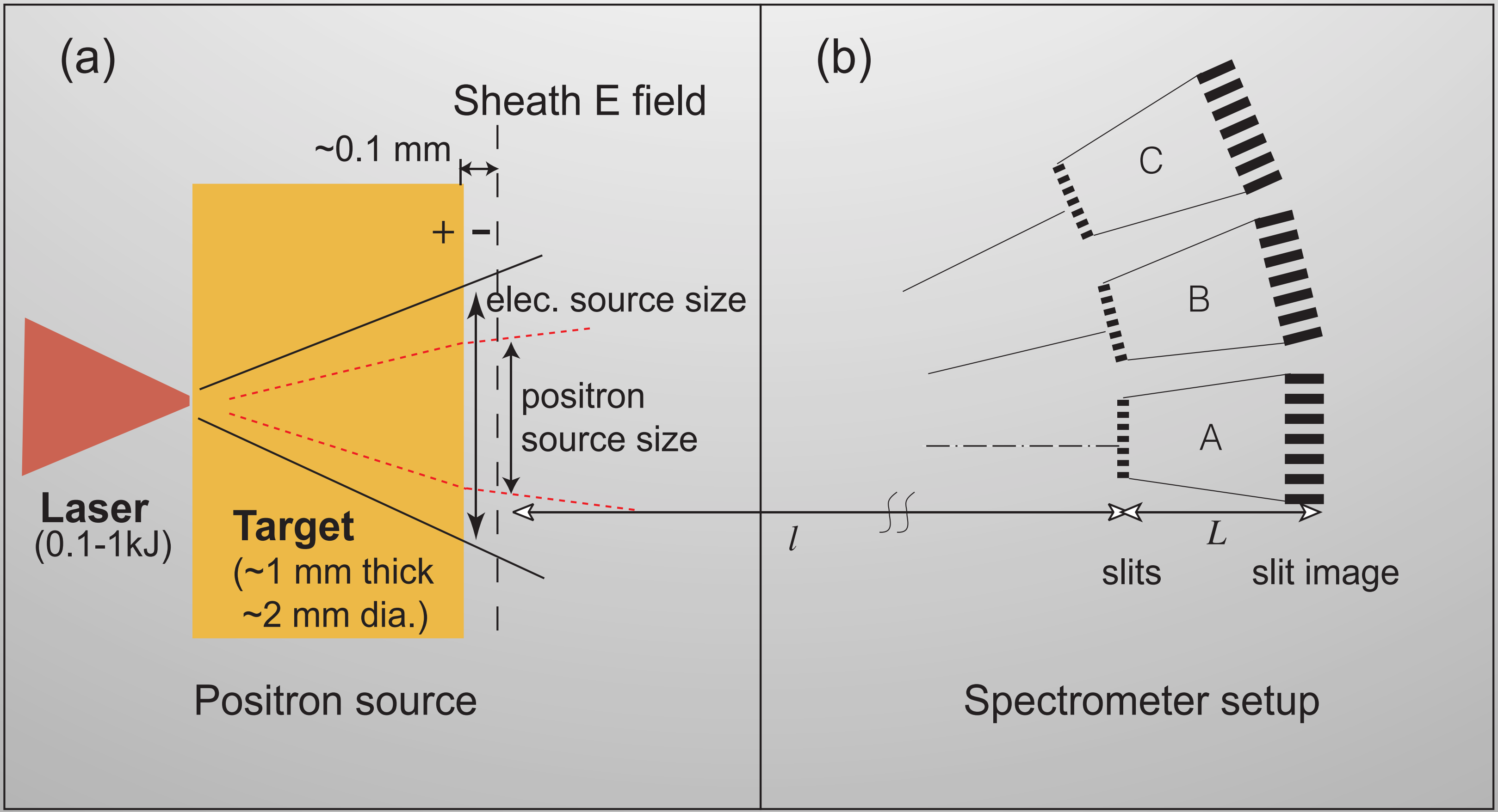




The positron yield is comparable to that of characteristic x-rays (10^{-4}), indicating an efficient energy transfer from laser to positrons.

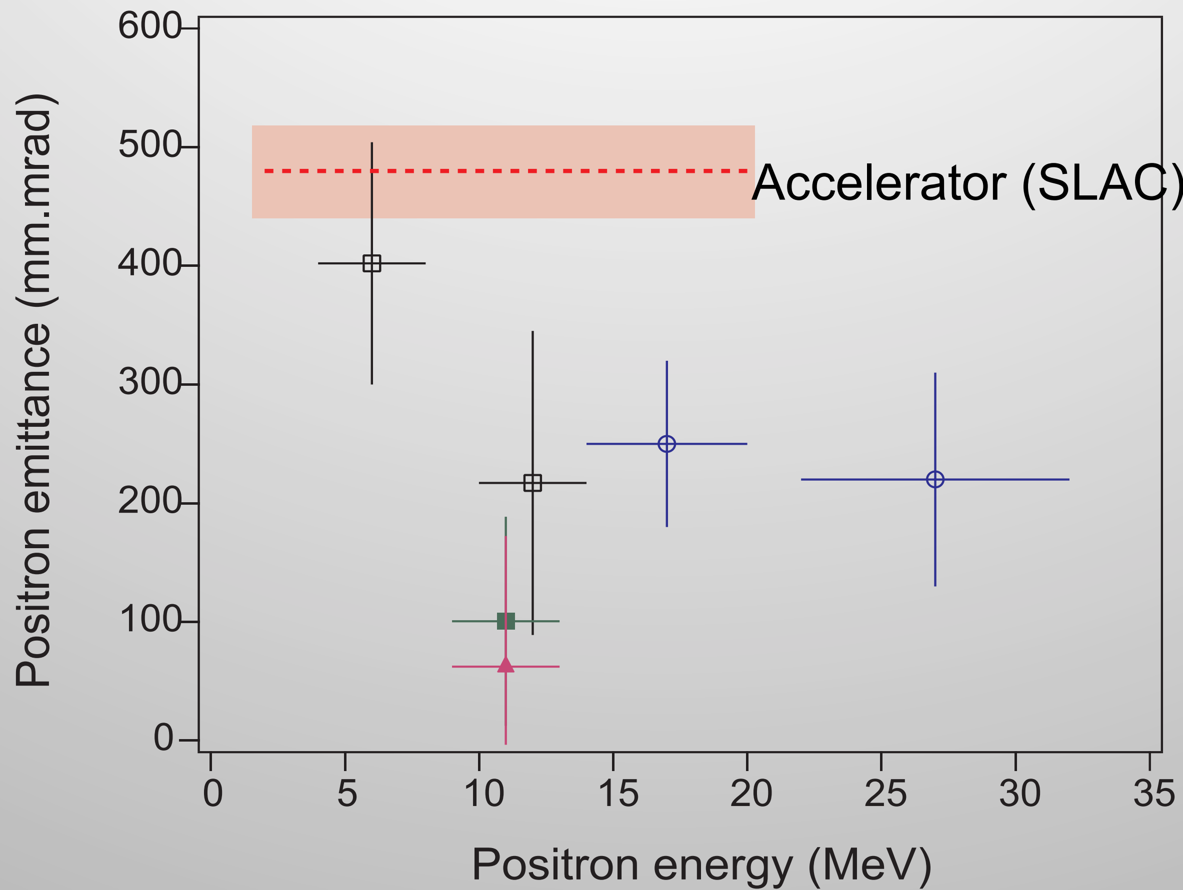
Positron beam emittance is determined by its angular divergence and source size

$$\varepsilon_{RMS} \sim a\sigma, a \text{ is the source size, } \sigma \text{ the angular divergence}$$



Chen, et al. Phys. Plasmas 20, 012507 (2013)

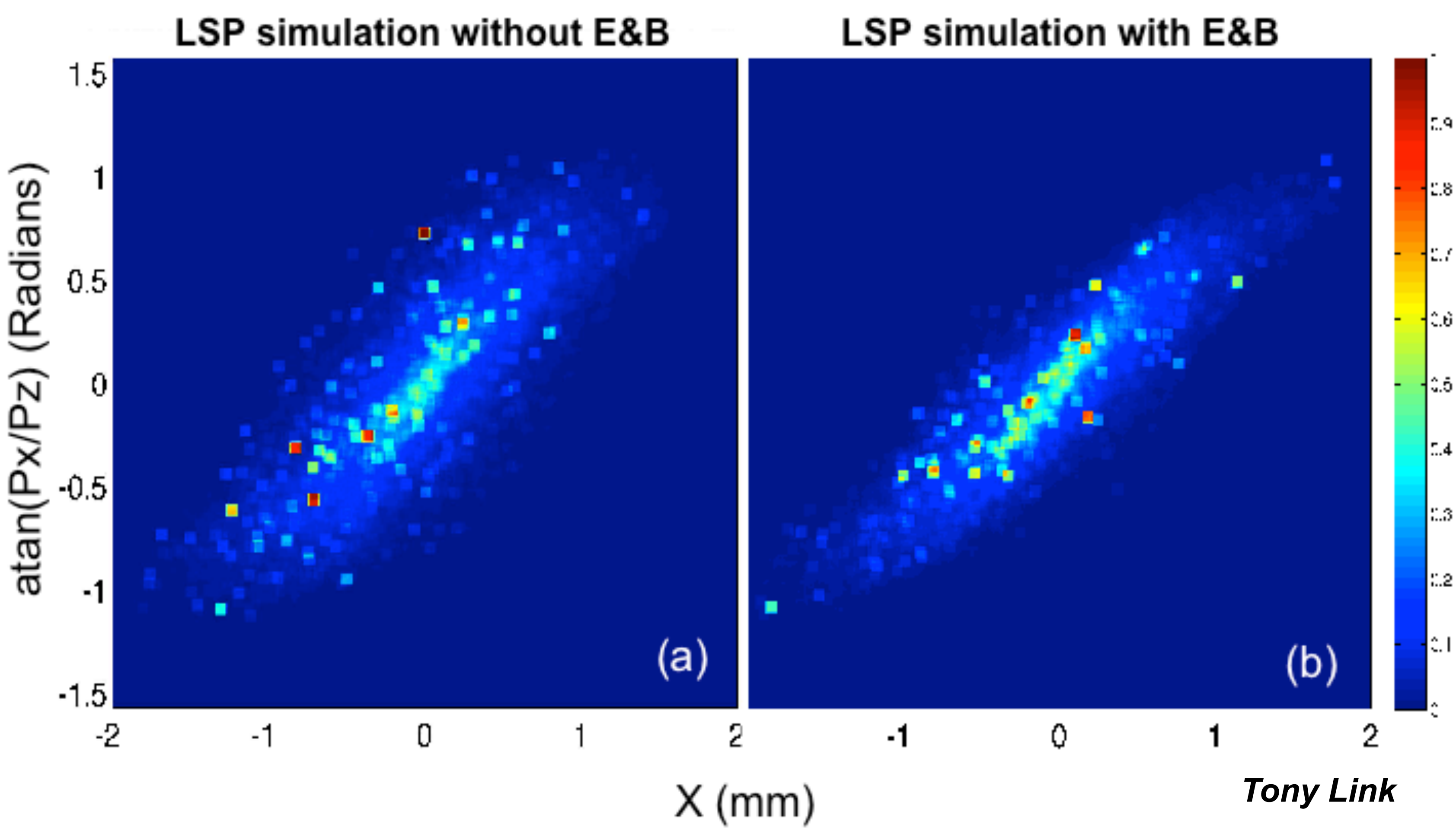
The emittance of laser positrons is comparable/ smaller to/than large accelerator sources



In collaboration with SLAC

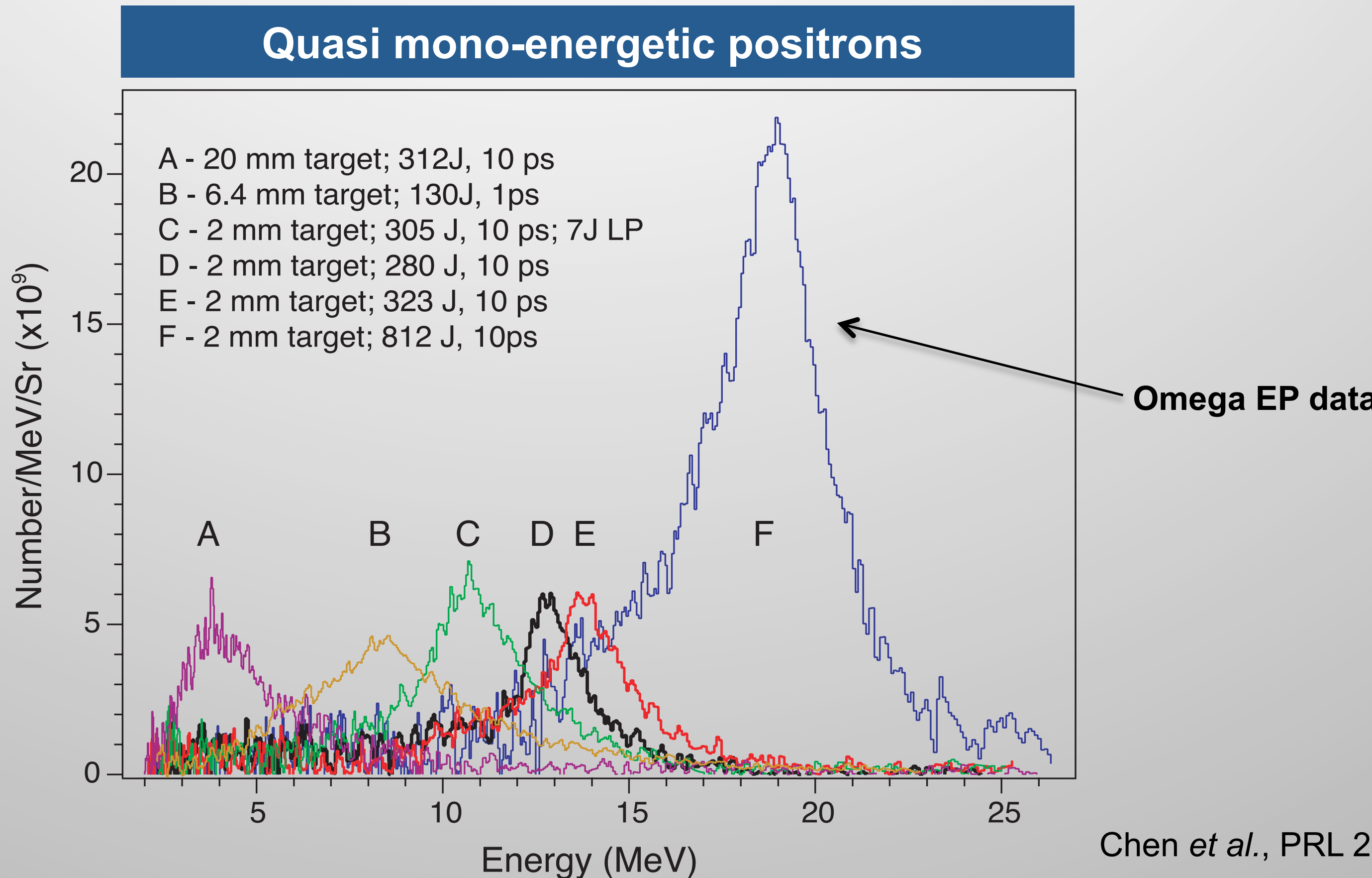
Positrons from a laser source could be a cheaper source for future positron accelerators

Electromagnetic fields from laser-matter interactions reduce the positron beam emittance



This property is unique to the laser positron source

Laser produced relativistic, quasi mono-energetic positrons scales with laser energy

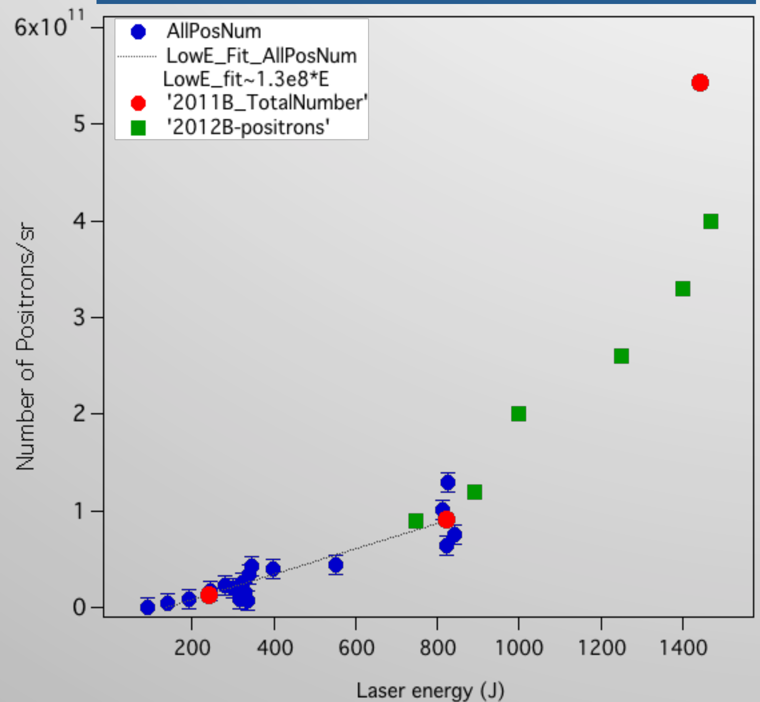


Chen *et al.*, PRL 2010

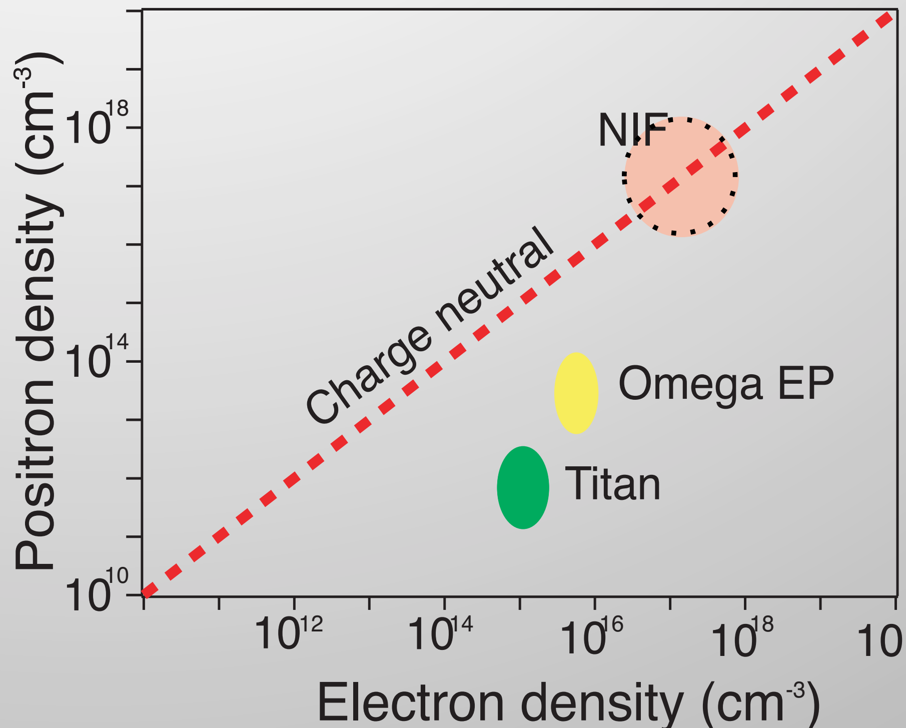
- Omega EP shots produced ~2×10^{11} positrons
- Positron peak energy shift to ~18 MeV

Laser produced relativistic, quasi mono-energetic positrons scales with laser energy, non-linearly

Pair number vs laser energy



Positron jet vs electron jet density

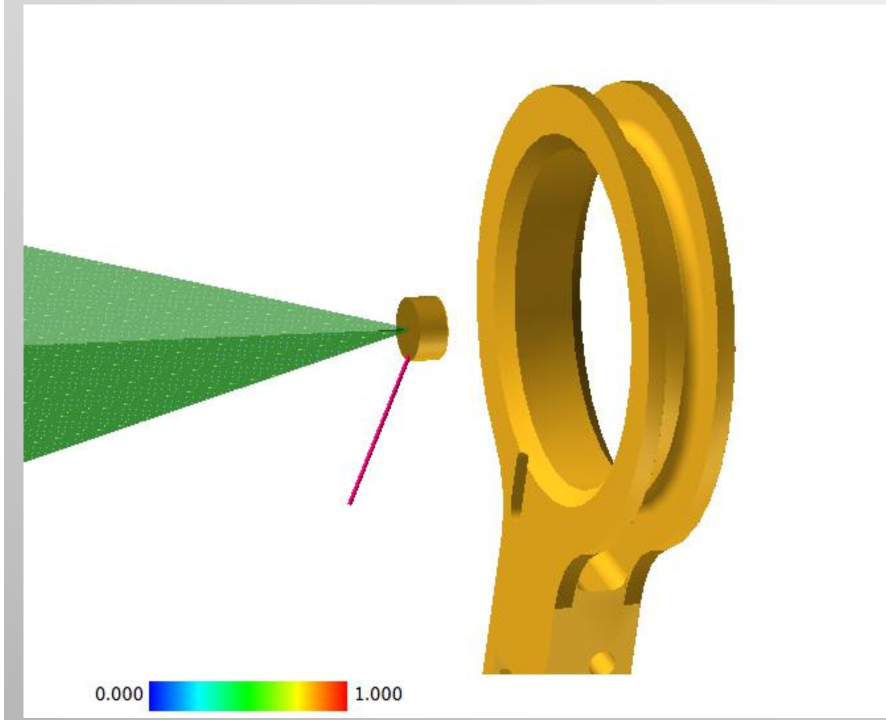


Myatt et al, 2009; Chen, Meyerhofer, Sentoku et al, to be published

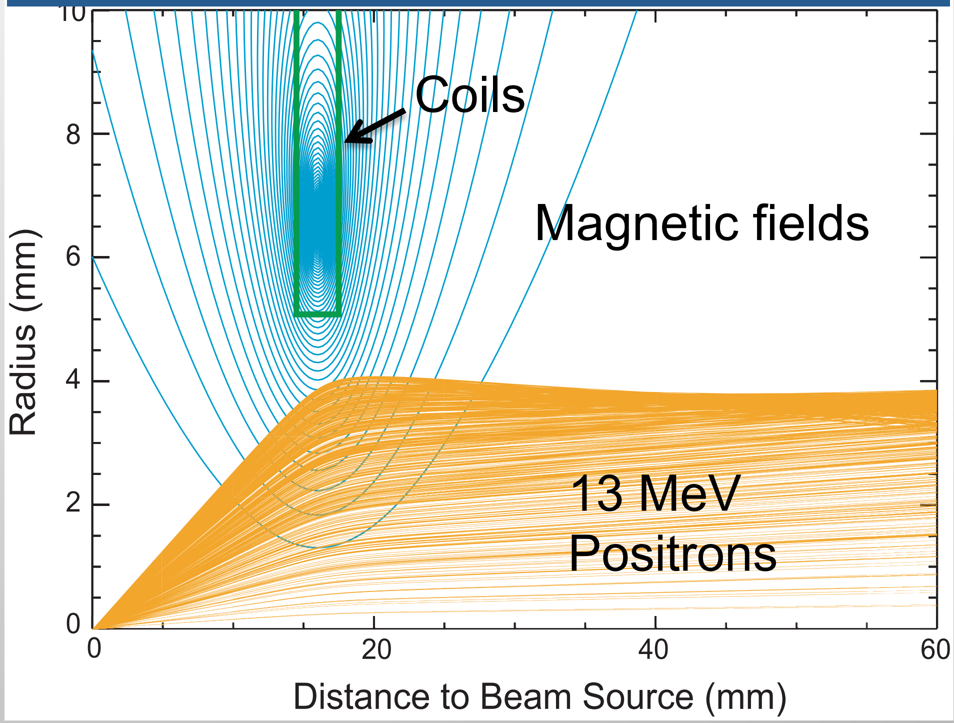
This feature is critical to future laboratory experiments using relativistic pair plasmas

Pair plasma can be collimated using externally applied axial magnetic fields

Positron exp setup using MIFEDS*



Simulation of positrons in MIFEDS B-fields

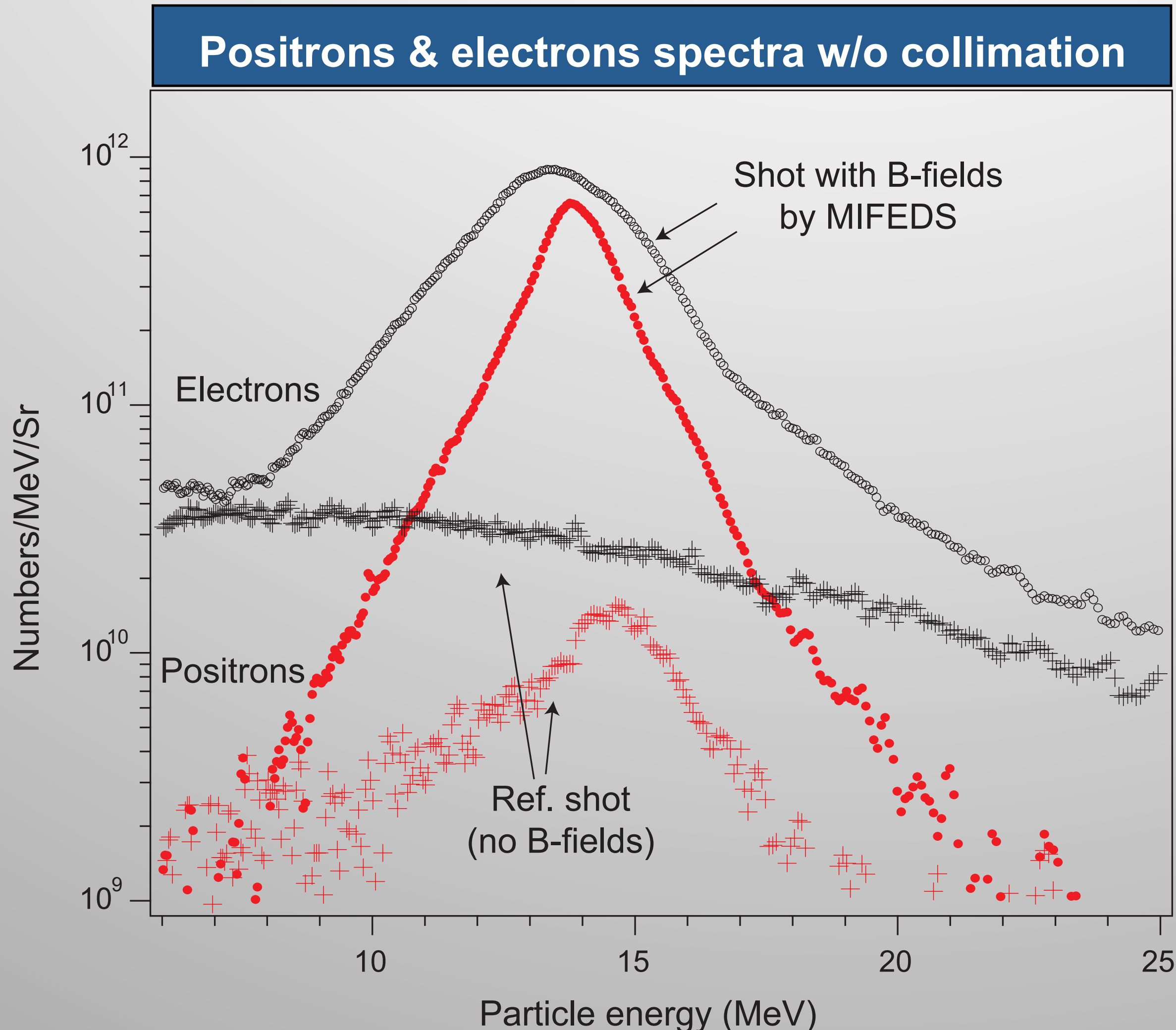


* O. Gotchev, et al., Rev. Sci. Instrum. 80, 043504 (2009)

Simulation by G. Fiksel

The pulsed B-field is sustained for μs, relative to the ps time scale of the electron-positron beam, therefore allows precisely controlled experiments.

Excellent results were obtained in 2013 from EP collimation experiments using MIFEDS



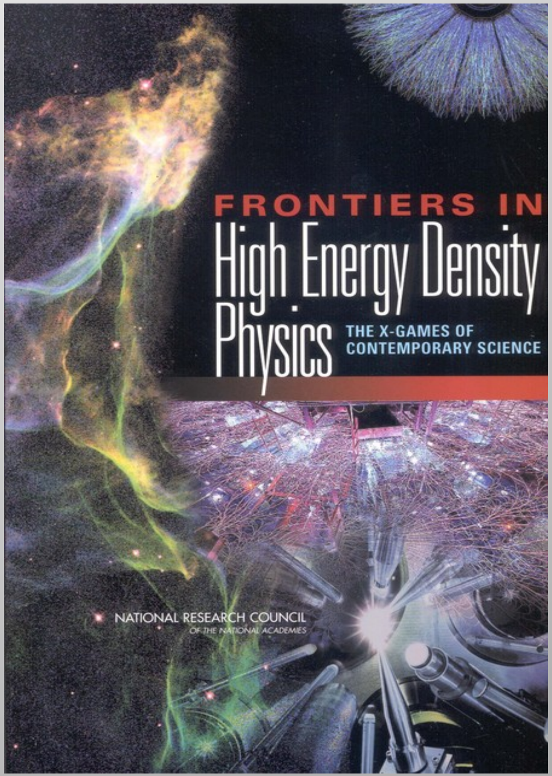
- **The effective divergence of the beam reduced from 30 deg FWHM to 5 deg;**
- **The charge (e-/e+) ratio in the beam reduced from ~100 to 5.**

Chen and Fiksel, et al. to be published, 2013

Laser generated positrons have many exciting potential applications

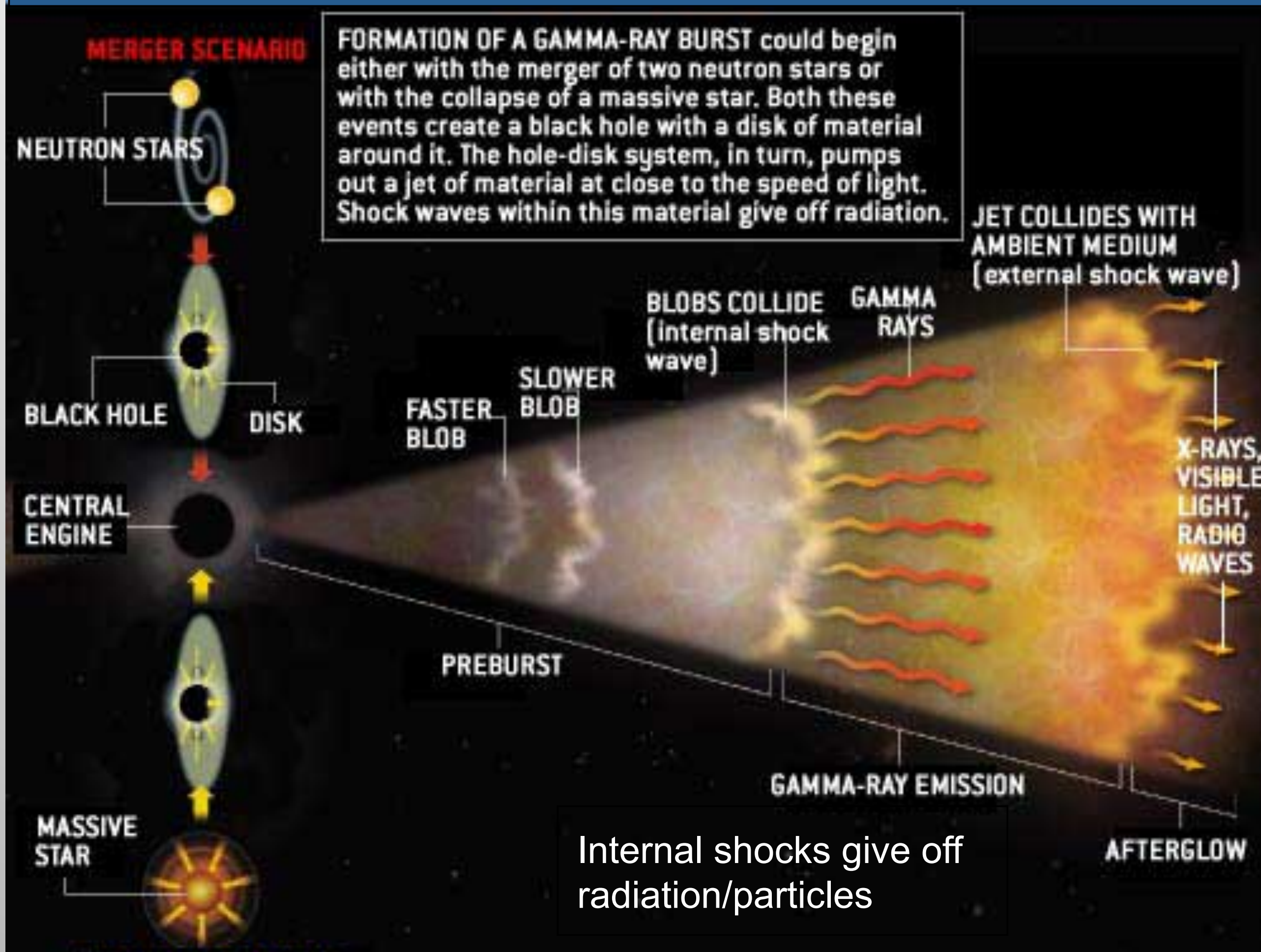
- **Fundamental pair plasma science at the relativistic regime**
- **Positron tomography for diagnosing high-energy-density plasma dynamics**
- **Pico-second gamma ray source at 511 keV**
- **New source for accelerators and positron science & applications**
- **Relativistic pair plasma jets for lab astrophysical studies**

  This is one of the five fundamental questions for High Energy Density Physics (HEDP) identified by *the National Research Council*: **"Are relativistic shocks the source of the gamma rays in Gamma Ray Bursts? Are they the source of ultrahigh energy cosmic rays?"**



Shocks set up by pair plasma jets may be the underlying physics for Gamma-ray-bursts

A Gamma-ray-burst (GRB) physics model

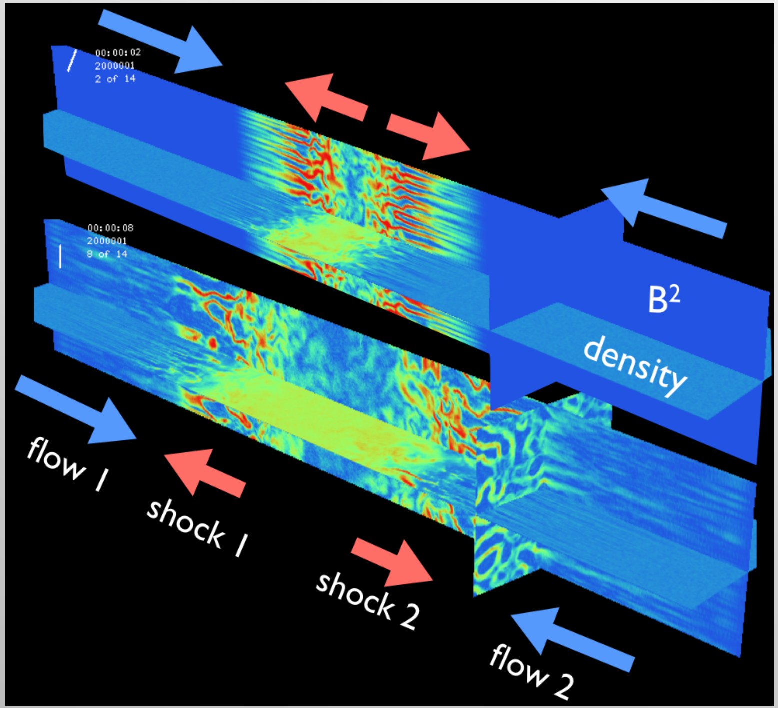


Art credit: Juan Velasco

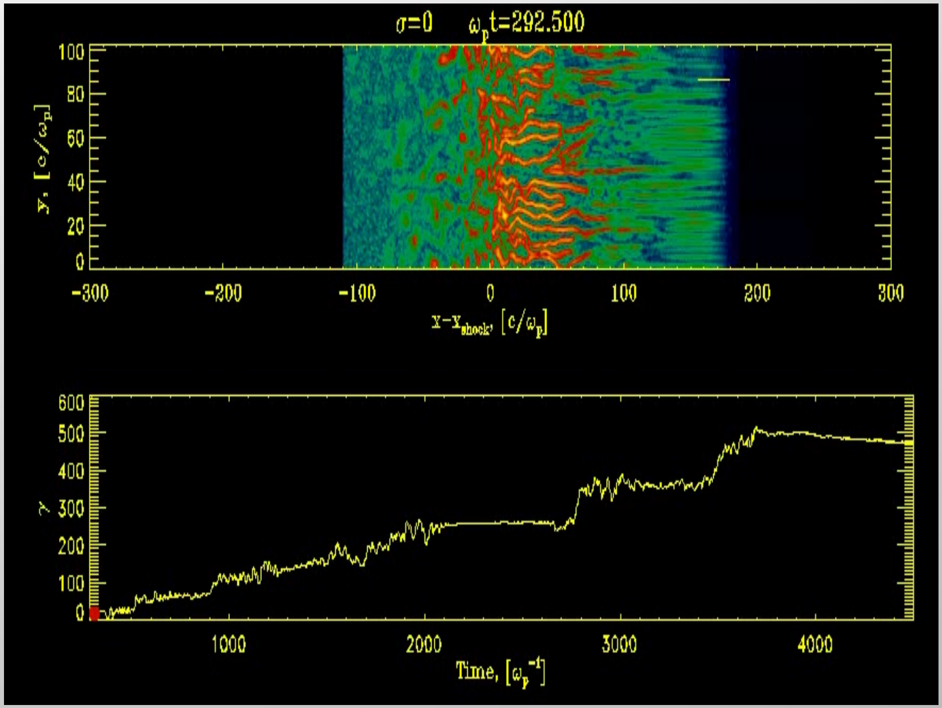
Colliding jets can mimic the internal shock of GRBs, allowing study of how energy is transferred to particles

Computer simulations indicate that shock from colliding jets can accelerate particles

Jet collision creates shock

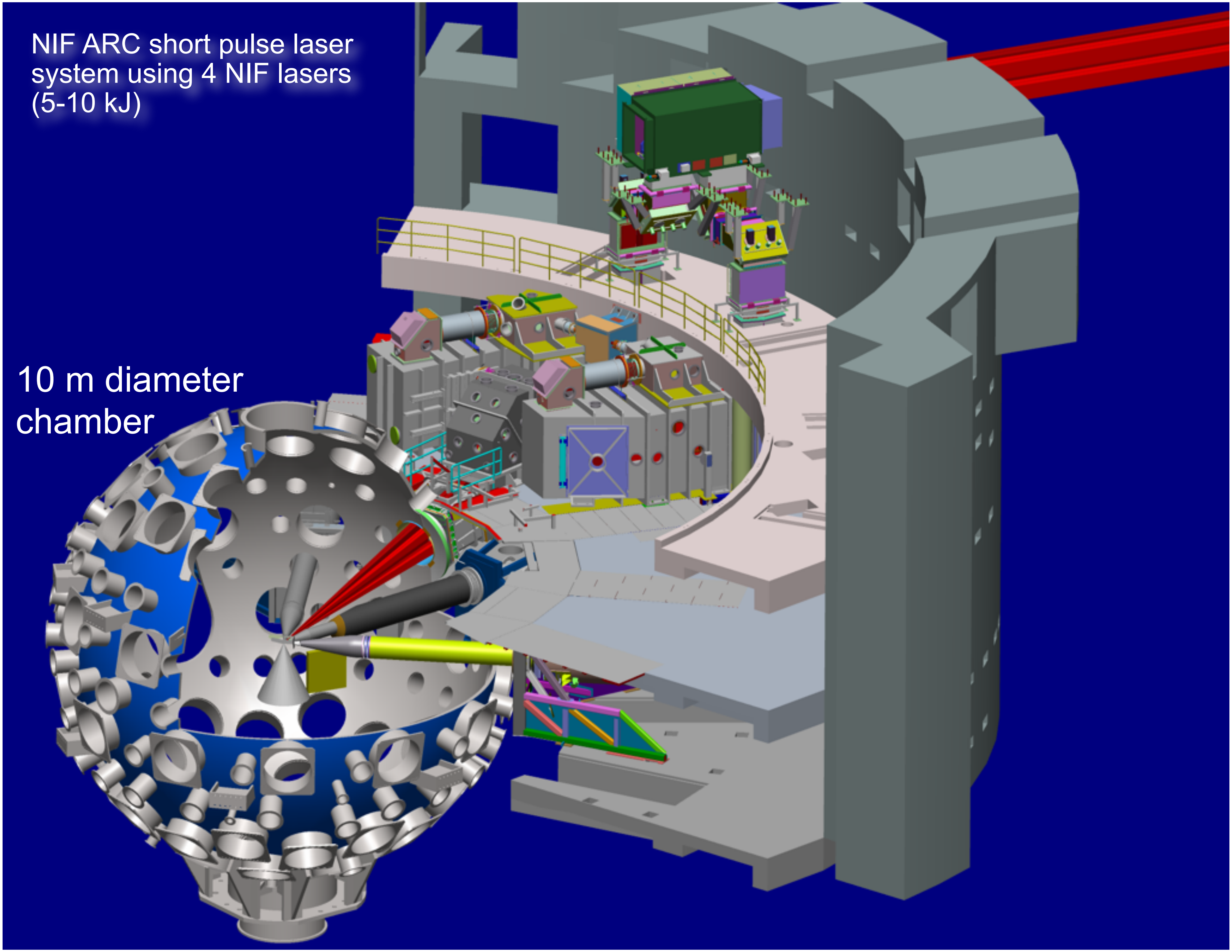


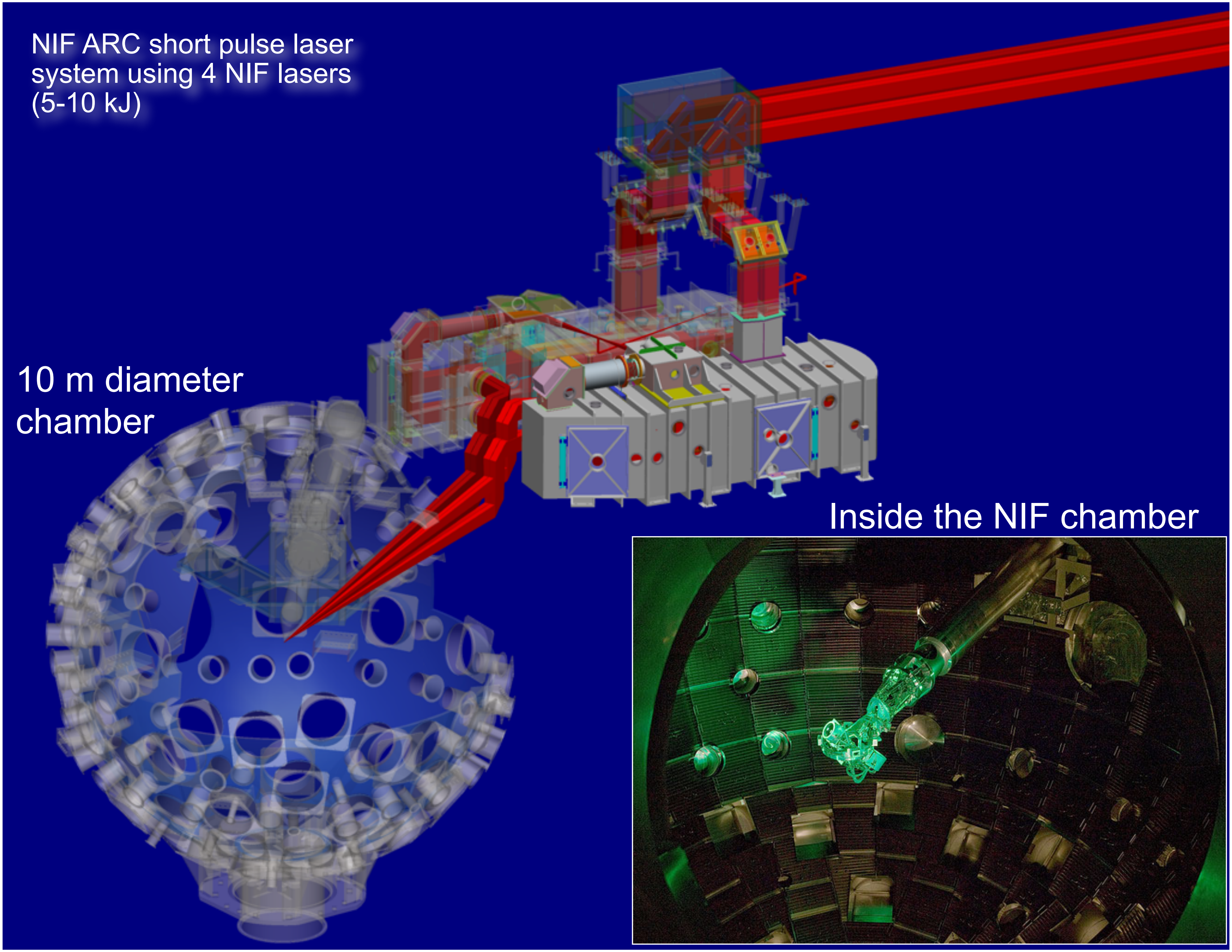
Particles are accelerated in the shock



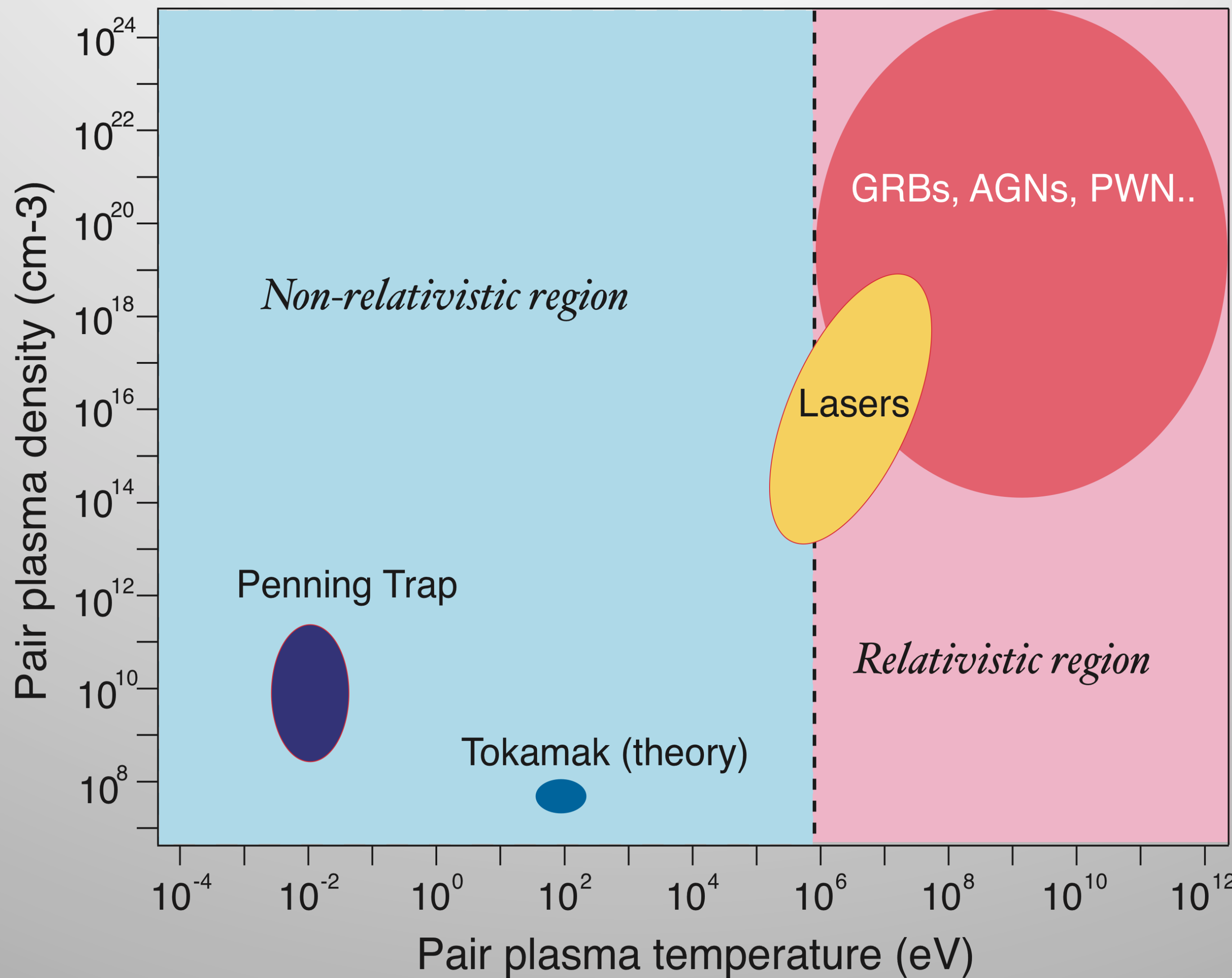
Anatoly Spitkovsky

Laser produced relativistic pair plasma jets will provide the first opportunity to test such theory and modeling


NIF ARC short pulse laser system using 4 NIF lasers (5-10 kJ)
10 m diameter chamber


NIF ARC short pulse laser system using 4 NIF lasers (5-10 kJ)
10 m diameter chamber
Inside the NIF chamber

Soon we will access in the lab the conditions of some of the most energetic events in the universe



Summary: Intense lasers produce relativistic pair plasma jets with very useful features …

What does it take for lasers to make pairs?

- High intensity (>10^{18} W/cm^2)
- Lot of >MeV electrons
- High-Z targets
- Laser beam setup

What are their unique features?

- Relativistic, short burst
- Jet-like
- Quasi mono-energetic
- Small emittance
- Magnetic collimation
- Scale up with laser E

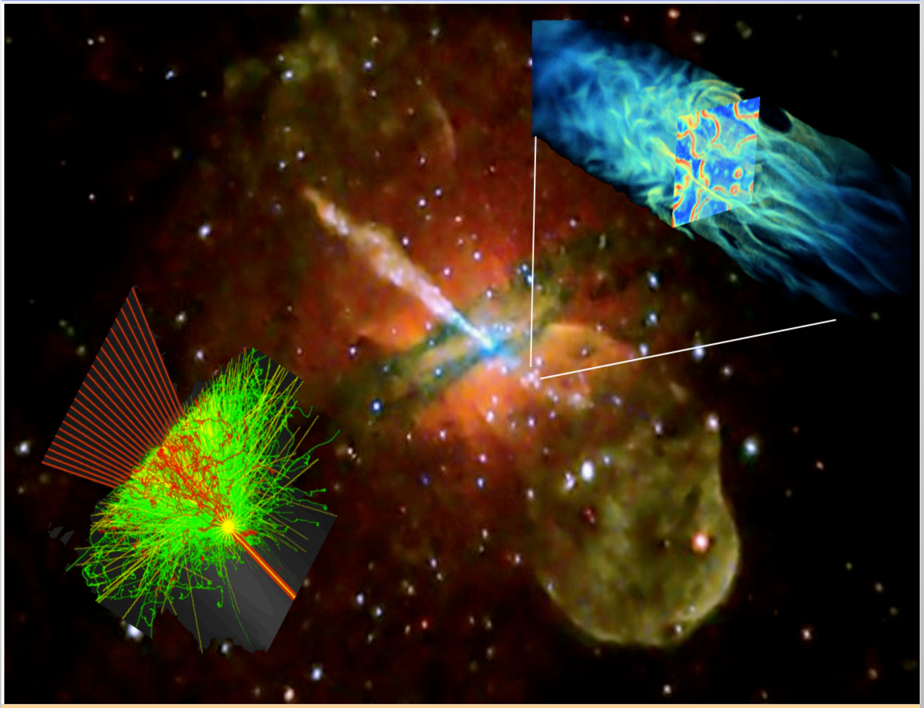
…. their important applications include the laboratory study of otherwise inaccessible natural phenomena

What does it take for lasers to make pairs?

What are their unique features?

What are their possible applications?

Laser pair plasmas can simulate real events



X-ray image of relativistically moving jets of electron-positron pair plasma powered by a supermassive black hole in a nearby galaxy Centaurus A. We may study this using the laser created relativistic pair jets to recreate relativistic collisionless shock waves that are thought to energize particles in astrophysical jets. (Chandra image credit: NASA/CXC/CfA/R.Kraft et al.

Acknowledgments

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- *University of California, San Diego*
- *University of Michigan*
- *AWE, UK*

Full name list can be found from our publications.