The Schwinger plasma: An experimental program to study the plasmas that exist inside the vacuum

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Work supported by the DOE Office of Science, Fusion Energy Sciences Division

The Bucksbaum Group studies motion on the quantum-scale induced and controlled by strong fields

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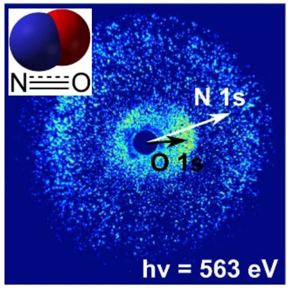
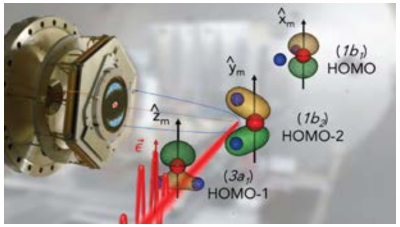
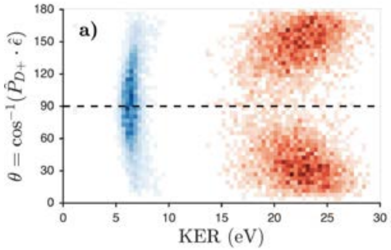
- **Attosecond electron motion across molecules induced by x rays or strong fields**
  - James Cryan, Ruaridh Forbes, Andrei Kamalov, Jordan O'Neal,Nick Werby, Anna Wang: **Supported by DOE-BES-CSGB**



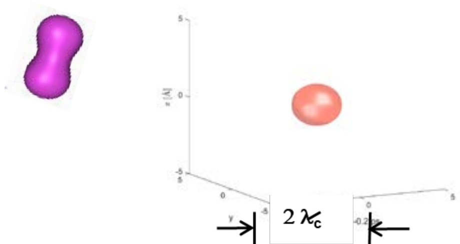
Work supported by DOE Office of Basic Energy Science, Chemical Sciences, Geosciences, and Biosciences Division

- **Strong-field femtosecond laser-molecule quantum control**
  - Ruaridh Forbes, Andy Howard, Greg McCracken, Chelsea Liekhus-Schmaltz; **Supported by NSF**



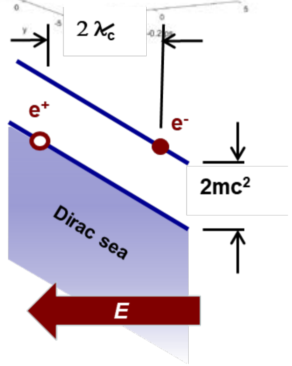


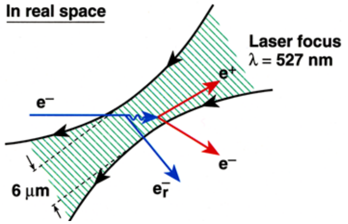
- **Ultrafast X-ray diffraction for molecular movies**
  - Adi Natan, Matt Ware, Mike Glownia, James Cryan, Ian Gabalski; **Supported by DOE-BES-CSGB**



Come to the Ford Distinguished Lecture in UM Physics on February 12, 2020 to hear about this.

- **Strong-fields beyond the Schwinger limit**
  - Sebastian Meuren, David Reis; **Supported by DOE-FES**





What is the vacuum? Not exactly nothing…

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- **Occupies all space**
- **Has no charge**
- **Has no angular momentum (isotropic)**
- **Has no preferred origin (homogeneous)**
- **Non-dispersive (c(λ)=constant)**
- **Maxwell's Equations for fields in the vacuum:**

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

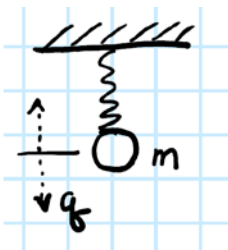
Both Lorentz and gauge invariant

$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

- **Energy density = ?Zero?? Maybe not…**

All particles and fields in quantum mechanics have "Zero Point Energy"

Example: Harmonic Oscillator



$$H = \frac{p^2}{2m} + \frac{1}{2} m \omega^2 q^2$$

$$\dot{q} = [q, H] = i\hbar \, p/m$$

$$\dot{p} = [p, H] = -i\hbar \, m\omega q$$

$$H = \hbar\omega\left(N + \tfrac{1}{2}\right)$$

ZPE → $\tfrac{1}{2}$

Light has it, too

$$H = \hbar\omega\left(N_{k,\lambda} + \tfrac{1}{2}\right)$$

Each mode has $ZPE = \frac{1}{2}\hbar\omega$

Number of modes: $\frac{V}{8\pi^3} \sum_\lambda \int d^3k$

ZPE density is $\frac{2}{8\pi^3} \int d^3k \left(\frac{1}{2}\hbar\omega\right)$

Over a finite frequency range

$$\rho_0(\omega_1, \omega_2) = \frac{\hbar}{8\pi^2 c^3}\left(\omega_2^4 - \omega_1^4\right)$$

How much? I did the math: 50 visible-wavelength photons / μ^3;

Or about 100 kW of visible ZPE entering and leaving your eyes -- <u>in the dark.</u>

If the vacuum contains radiation, then it also contains matter from pair-production by vacuum modes with $\hbar\omega \geq 2mc^2$:

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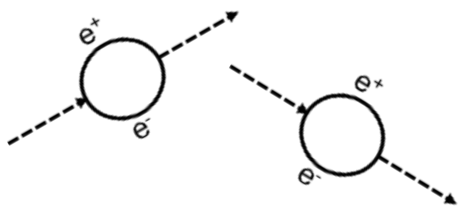
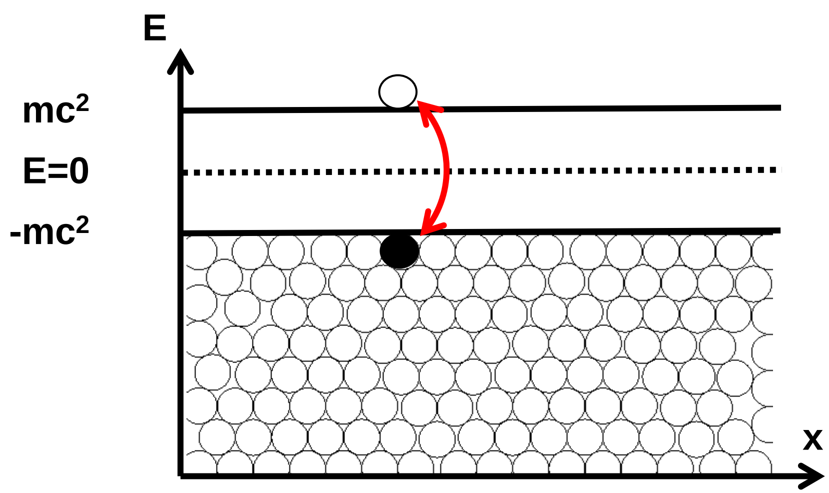


Heisenberg Uncertainty relation sets the scale:
$\Delta E \Delta t \geq \hbar$, with $\Delta E = 2mc^2$

Virtual pair "lifetime" $\Delta t = \hbar/2mc^2$
$= 0.6$ billionths of a femtosecond (0.6 yoctoseconds)

Virtual pair "size" = $2\hbar/mc$ = $2\lambda_c$
$= 0.39$ femtometers

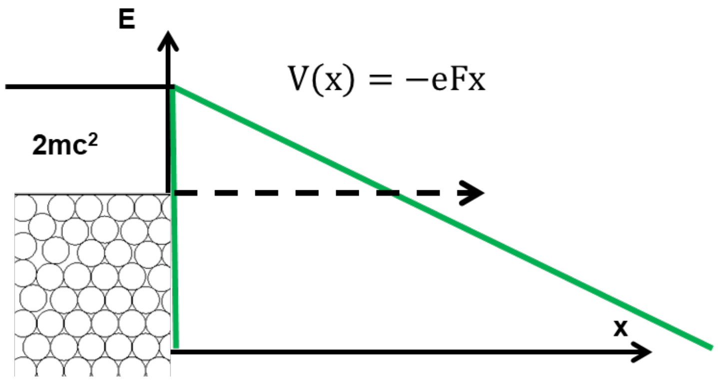


Dirac's View: Vacuum is like an insulator with a negative energy "sea" filled with electrons.

Quantum fluctuations create virtual electron-"hole" pairs --

A PLASMA
IN THE QUANTUM VACUUM

Interrogating the quantum vacuum plasma with an external field **F**

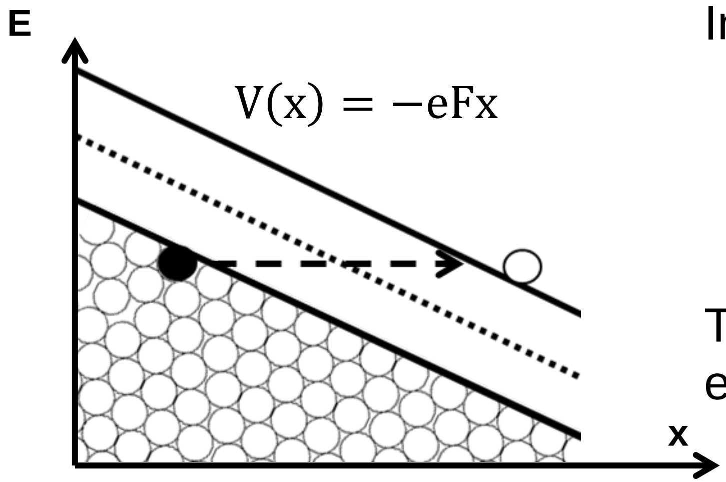


Fowler-Nordheim tunneling

$$\sim e^{-\frac{4}{3}\frac{4m^2c^3}{e\hbar F}} = e^{-\frac{16}{3}\frac{F_{cr}}{F_L}}$$

$$F_{cr} = \frac{mc^2}{e\lambda_C}$$

Interrogating the quantum vacuum plasma with an external field **F**



Incorporate relativity (Dirac Equation)

$$\frac{j_{trans}}{j_{incident}} = \frac{e^{-\pi F_{cr}/F_L}}{1 - e^{-\pi F_{cr}/F_L}}$$

This is a Fermi-Dirac distribution where each mode tunnels with probability

$$P_n = e^{-\pi F_{cr}/F_L}$$

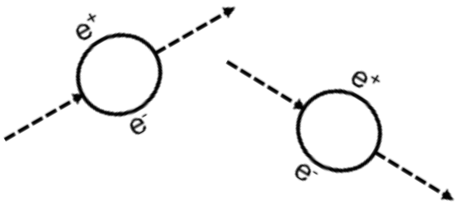
J. Schwinger, Physical Review 82, 664 (1951).

$$\frac{F_L}{F_{cr}} = \frac{eF_L\lambda_C}{mc^2} = \frac{work\ done\ over \lambda_C}{mc^2}$$

$F_{cr} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16}\, V/cm$, the Schwinger critical field

$I_{cr} = \frac{F_{cr}^2}{4\pi} = 2.2 \times 10^{29} W/cm^2$. So how big is that?

Big enough to pull electrons out of the vacuum during quantum fluctuations:



Virtual pair "lifetime" = $\hbar/2mc^2$
Virtual pair "size" = $2\hbar/mc$ = $2\lambda_c$
Work done on a virtual pair over its lifetime

$$|e|F_{cr}2\lambda_c = 2mc^2$$

Or, in relativistic units:

$$F_{cr} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16}\,V/cm$$

$$I_{cr} = \frac{F_{cr}^2}{4\pi} = 2.2 \times 10^{29} W/cm^2$$

A uniform (or low frequency laser) field of F_{cr} does work $2mc^2$ on a virtual e^+e^- pair in a distance on the order of the Compton wavelength $\lambda_c = \hbar/mc$, implying the instability of the vacuum under $e^+ - e^-$ pair creation.

A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, Rev. Mod. Phys. 84, 1177 (2012).

What laser properties really matter for this application? Laser field amplitude F_L

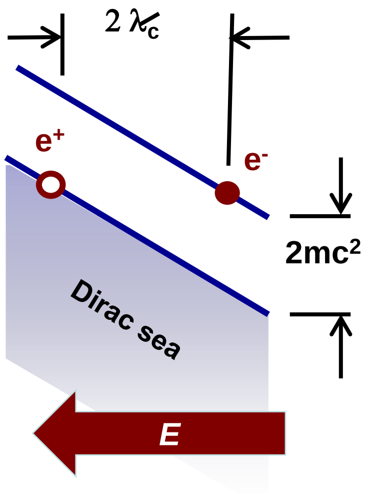
Lorentz-invariant dimensionless quantities related to F_L:

$$\eta = \frac{eF_L\lambda_L}{2\pi mc^2} = \frac{work\ done\ in\ 1\ radian\ of\ laser\ wavelength}{mc^2} =$$

$$a_0 = \frac{eF_L}{\omega_L mc} = \frac{momentum\ transferred\ in\ 1\ radian\ of\ laser\ period}{mc}$$

Dimensionless figure of merit for breaking the vacuum:

$$\Upsilon = \frac{eF_L^*\lambda_C}{mc^2} = \frac{work\ done\ over \lambda_C}{mc^2} = \frac{F_L^*}{F_{cr}}$$

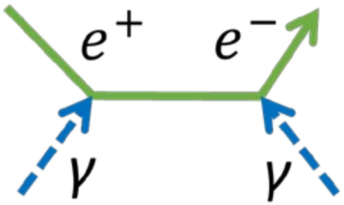


(F_L^* is in the CM frame for the pair)

When $\Upsilon = 1$, the quantum vacuum breaks down into e^+e^- pairs.

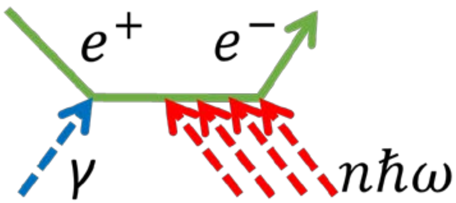
Paradigm shift from QED to SFQED

$\gamma + \gamma' \rightarrow e^{+} + e^{-}$



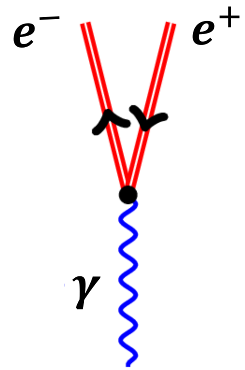
Breit-Wheeler

$\gamma + n\hbar\omega \rightarrow e^{+} + e^{-}$



Multiphoton Breit-Wheeler

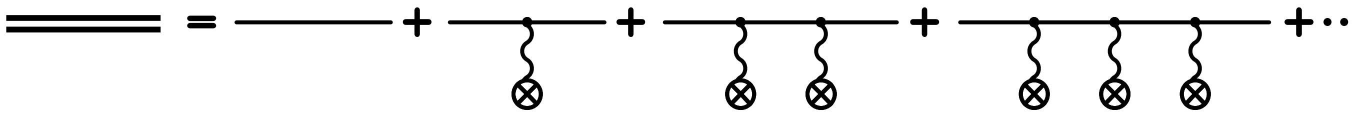
$\gamma + \vec{A}_L(\vec{x}, t) \rightarrow e^{+} + e^{-} + \vec{A}_L(\vec{x}, t)$



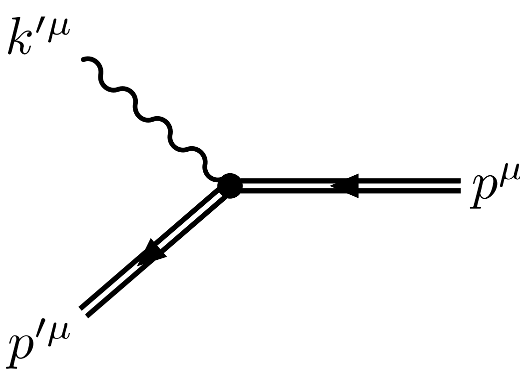
Dressed state Breit-Wheeler

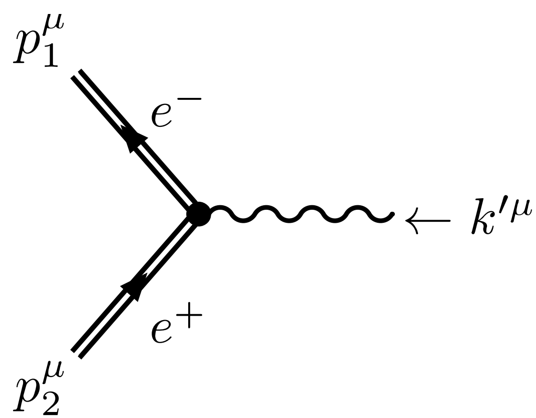
Non-linear/non-perturbative QED

$$\eta = \frac{e}{mc^2}\sqrt{-\langle A_\mu A^\mu \rangle} = \frac{eE\lambda}{2\pi mc^2} \qquad \Upsilon = \frac{e\hbar}{m^3c^5}\sqrt{\langle (F_{\mu\nu}p^\nu)^2 \rangle} = \frac{eE^*\lambda_c}{2\pi mc^2} = \eta\frac{\lambda_c}{\lambda^*}$$



Dressed state (Furry, Volkov, …)





Photon emission

Multi-photon Compton
Quantum radiation reaction
…

Photon decay

Multi-photon Breit-Wheeler Pair production
"Schwinger Assisted" pair production
…

Magnetars are spinning neutron stars that contain B fields above the Schwinger critical value

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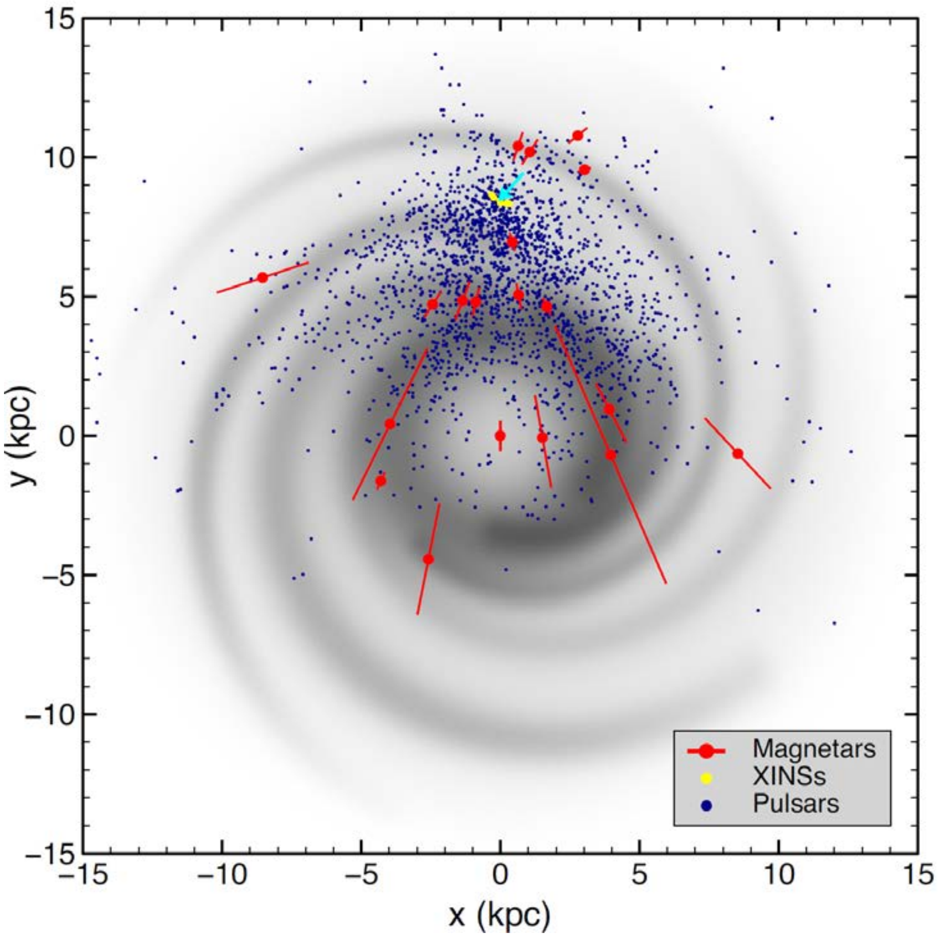
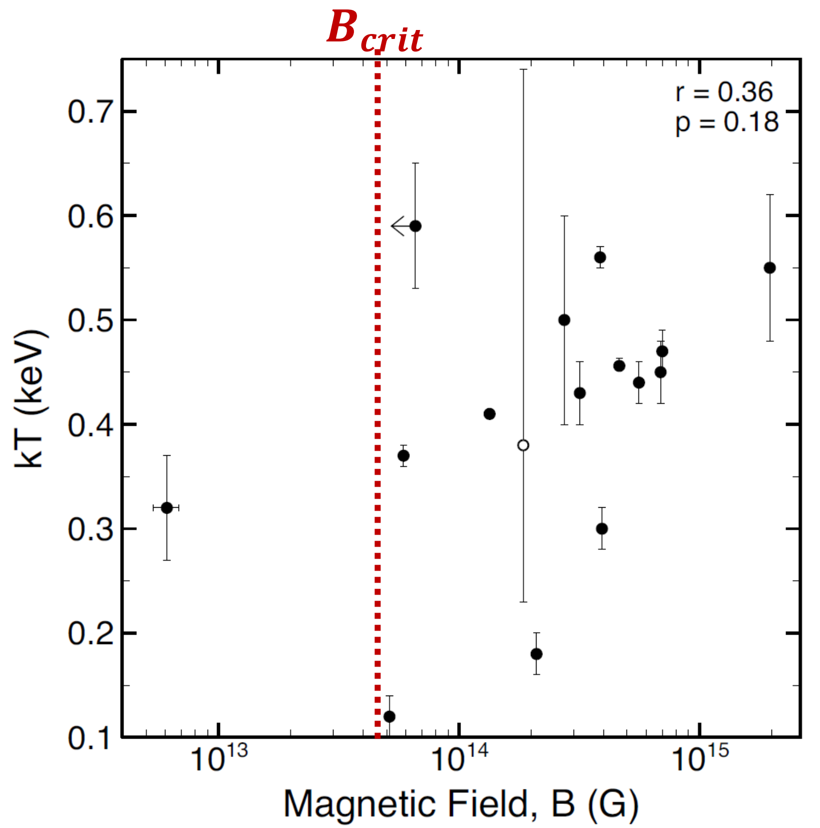


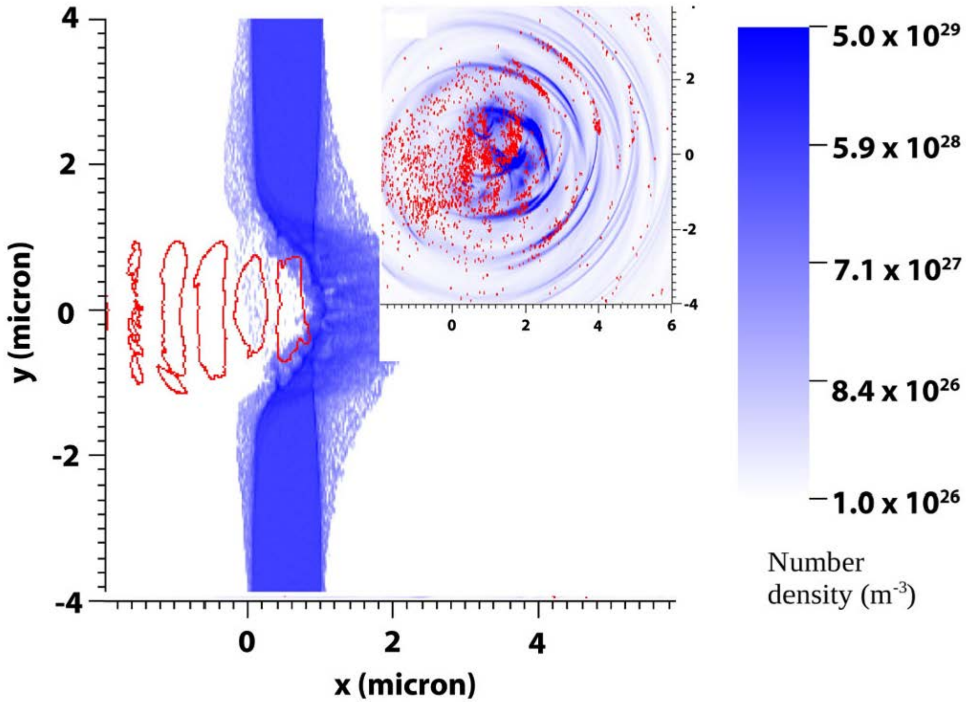
Map of magnetars detected in our galaxy



Surface magnetic fields (inferred from P and $\dot{P}$)

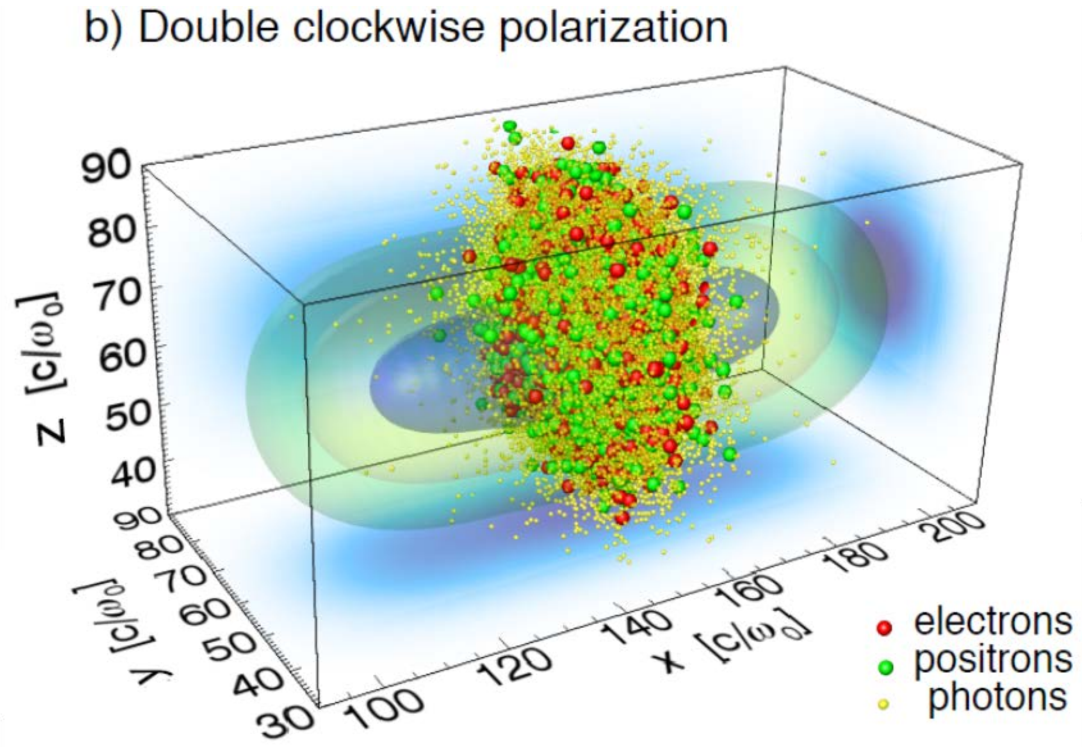
S. A. Olausen and V. M. Kaspi, ApJS 212, 6 (2014).

Dense e+e- plasmas produced by Breit-Wheeler pair production at a surface create a dense beam of gamma rays



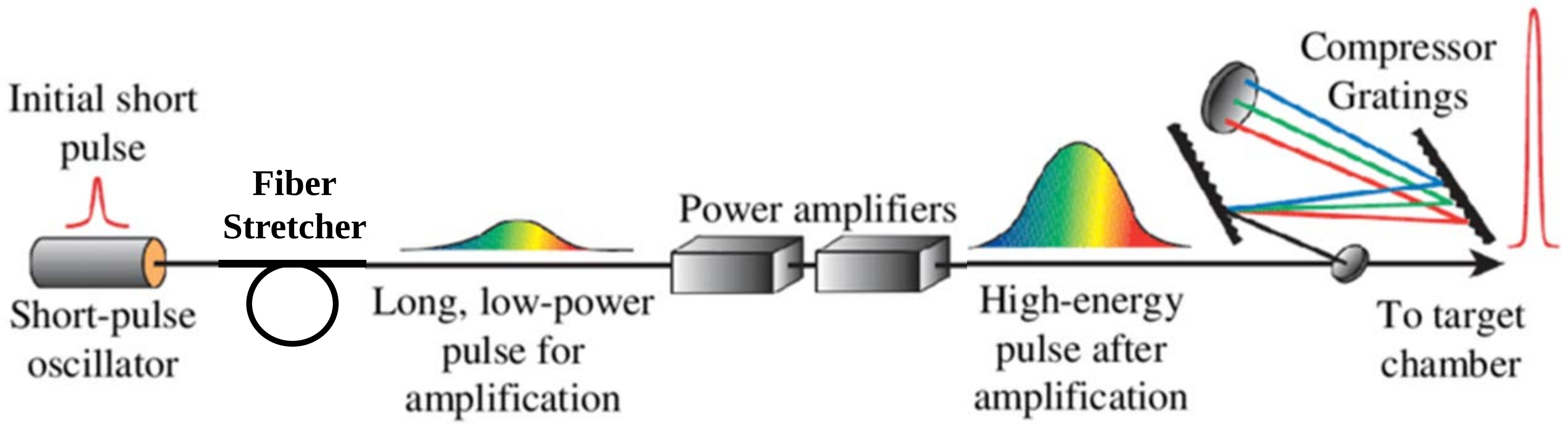
C. P. Ridgers, C. S. Brady, R. Duclous, J. G. Kirk, K. Bennett, T. D. Arber, A. P. L. Robinson, and A. R. Bell, Phys. Rev. Lett. 108, 165006 (2012).

Above the Schwinger threshold colliding laser beams decay into a cloud of e+e- plasma, a "QED Cascade."

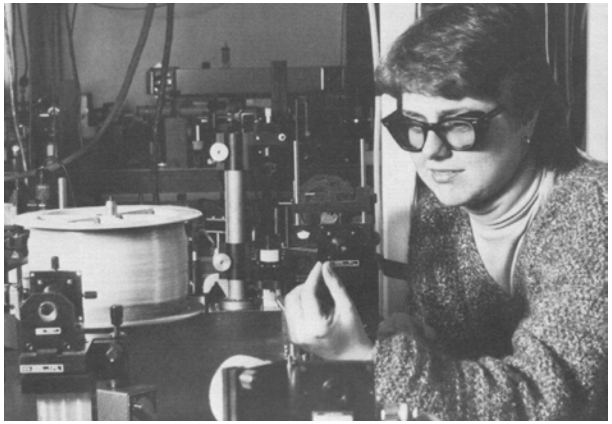


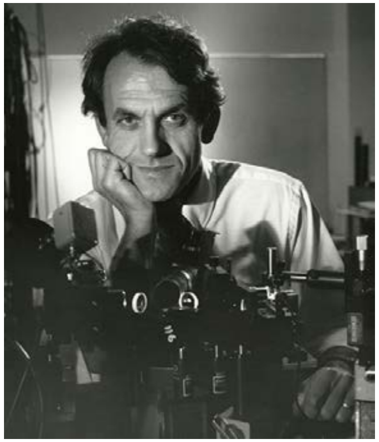
T. Grismayer, M. Vranic, J. L. Martins, R. A. Fonseca, and L. O. Silva, Physical Review E 95, (2017).

Breaking the vacuum in the lab: First breakthrough: CPA, circa 1985, started with the "Table-top Terawatt" laser

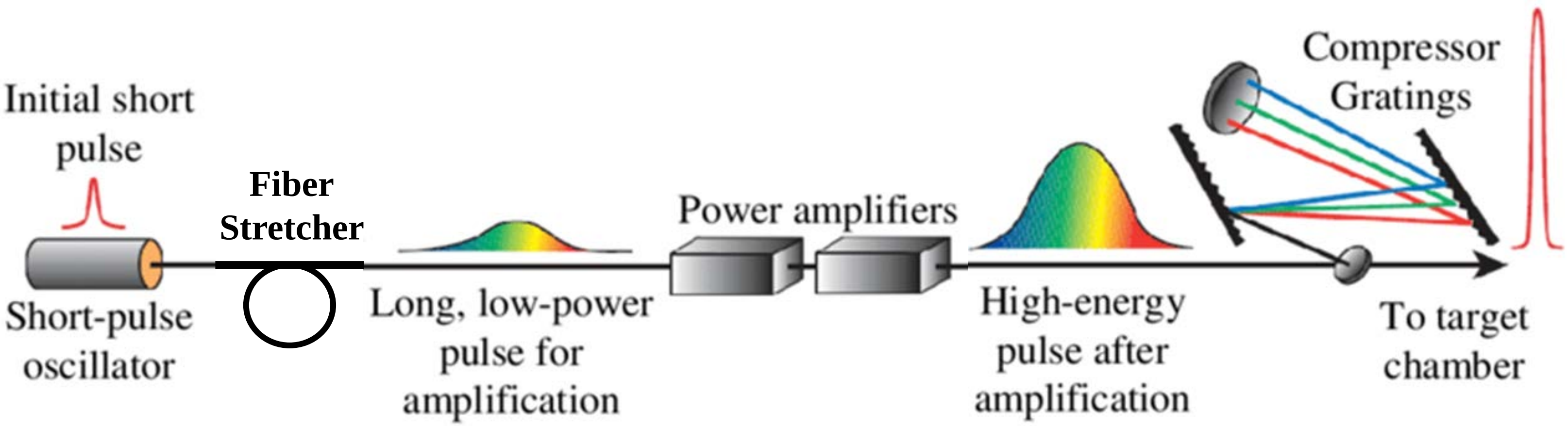


D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", Opt. Commun. 56, 219 (1985)





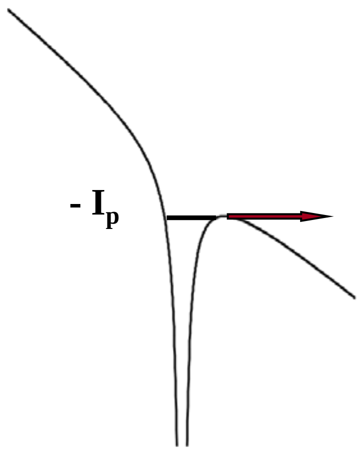
First breakthrough: CPA, circa 1985, started with the "Table-top Terawatt" laser



Two happy people in Stockholm last year:

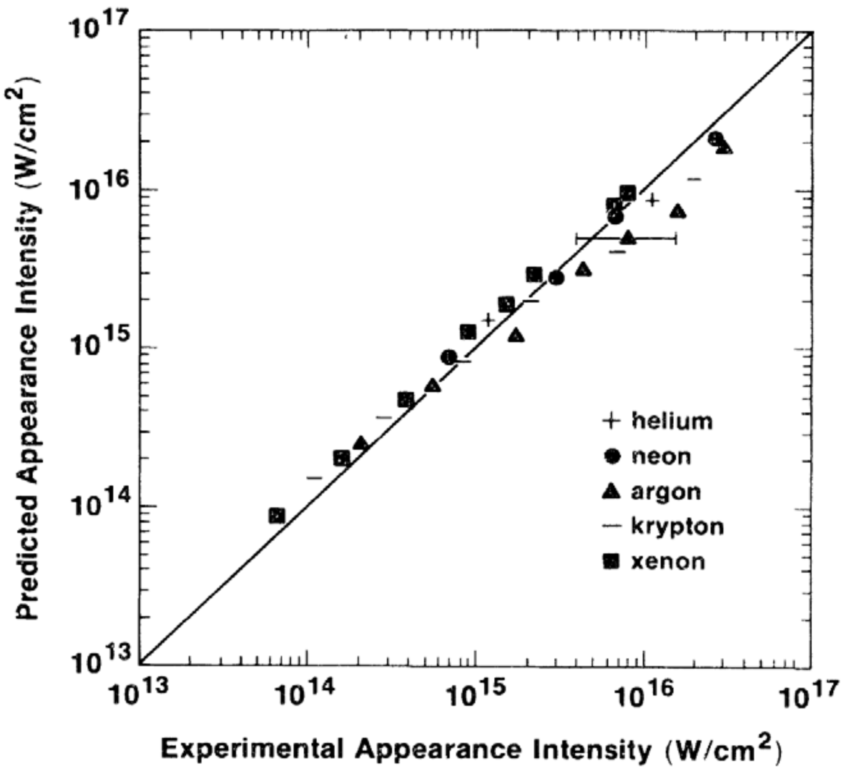
D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", Opt. Commun. 56, 219 (1985)

That T[3] laser (in Rochester, not Michigan) was used to pull electrons out of atoms. It was a start…



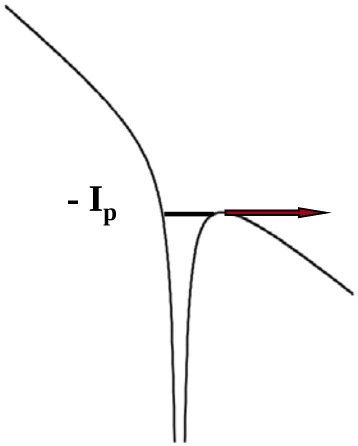
atomic

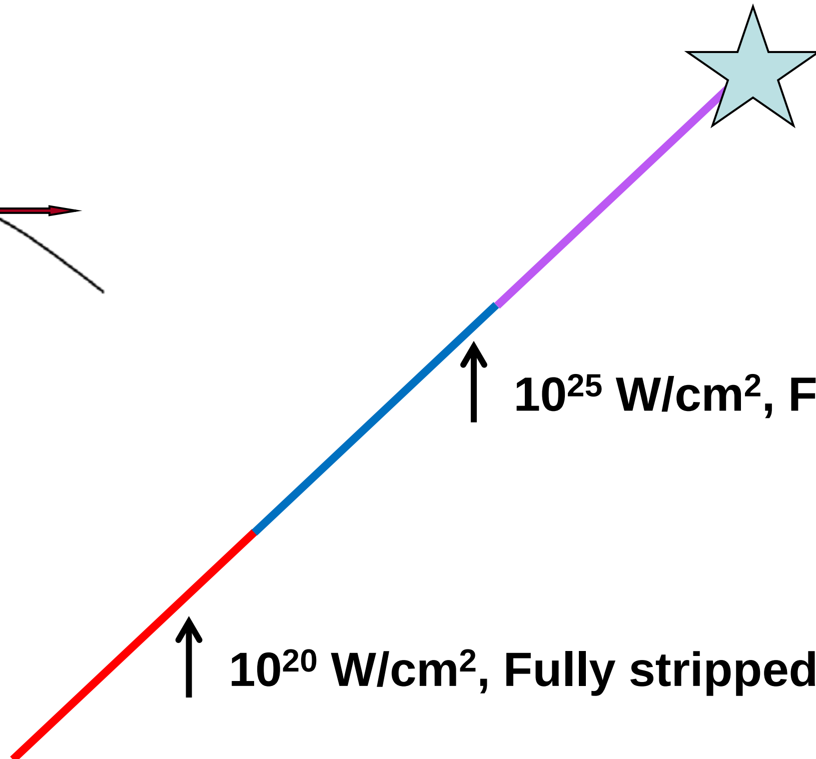
$$E_c = \alpha^4 mc^2/r_e = 2I_P/a_0 = 5 \times 10^9 \mathrm{V/cm}$$



S. Augst, D. Strickland, D. D. Meyerhofer, S. L. Chin, and J. H. Eberly, Phys. Rev. Lett. 63, 2212 (1989).

Where is high intensity physics going?

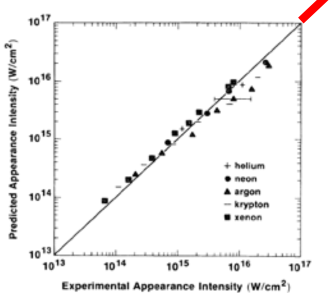




Schwinger limit

10^{25} W/cm^2, Fully stripped U

10^{20} W/cm^2, Fully stripped Ar



atomic

$$E_c = \alpha^4 mc^2/r_e = 2I_P/a_0 = 5\times10^9 \mathrm{V/cm}$$

vacuum

$$E_c = \alpha mc^2/r_e = I_P/\lambda_c = 1.3\times10^{16} \mathrm{V/cm}$$

Later refinements have brought us to the petawatt frontier illustrated by the Mourou plot

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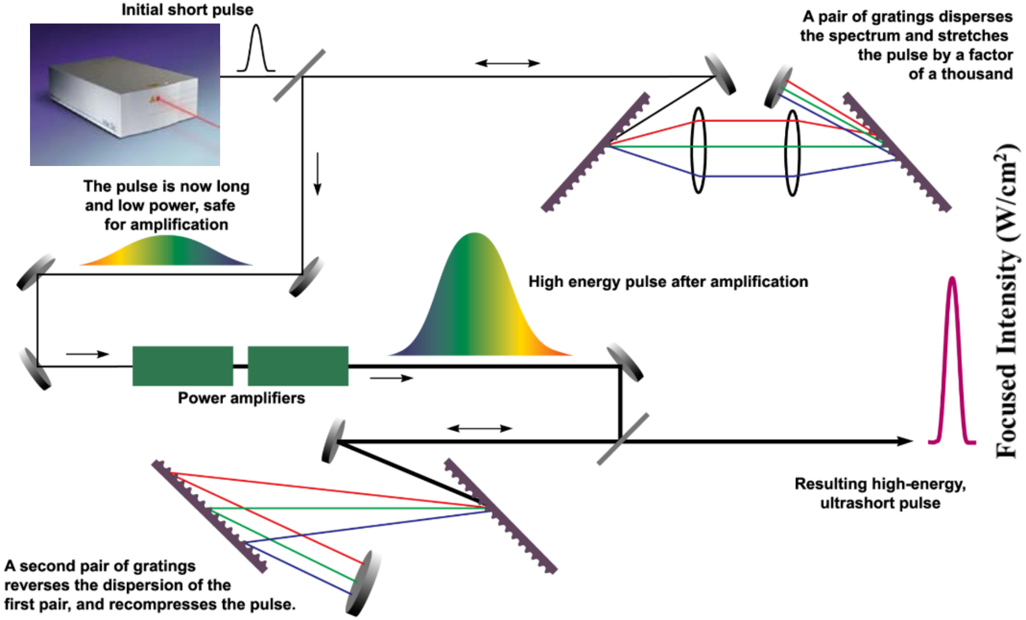
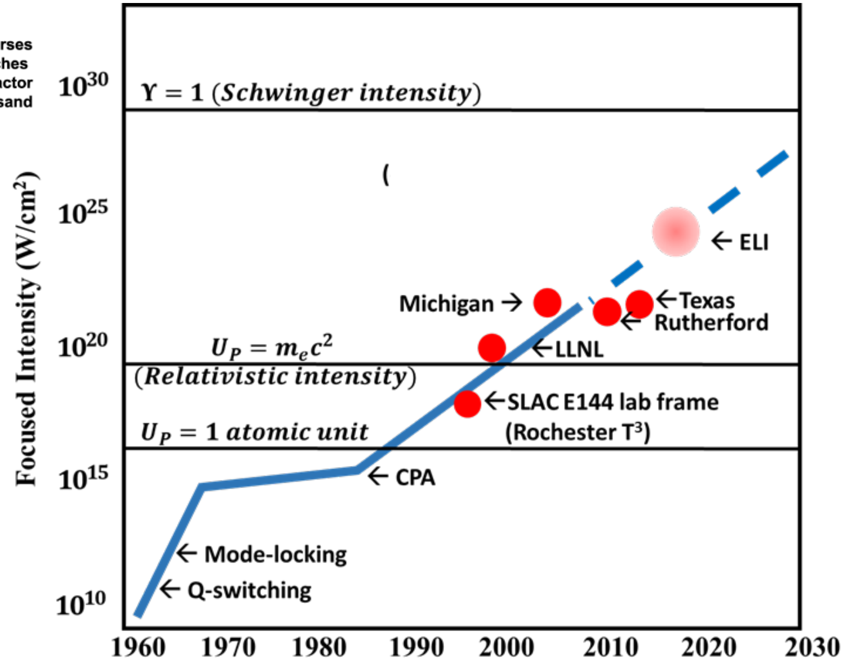
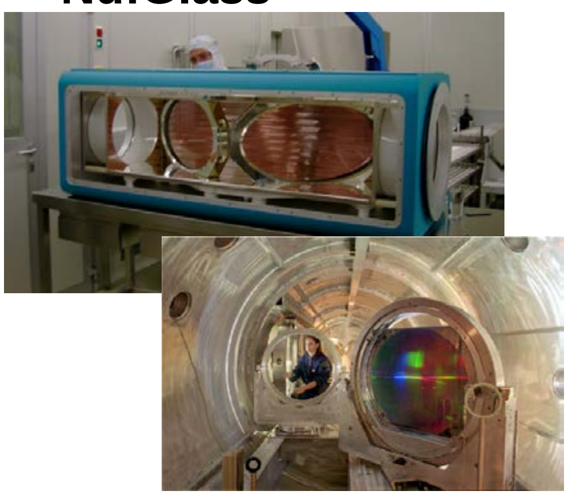
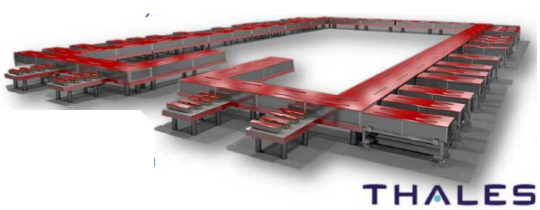




Nd:Glass



Ti:sapphire



OPCPA

Most of these lasers are being built for high field discovery science

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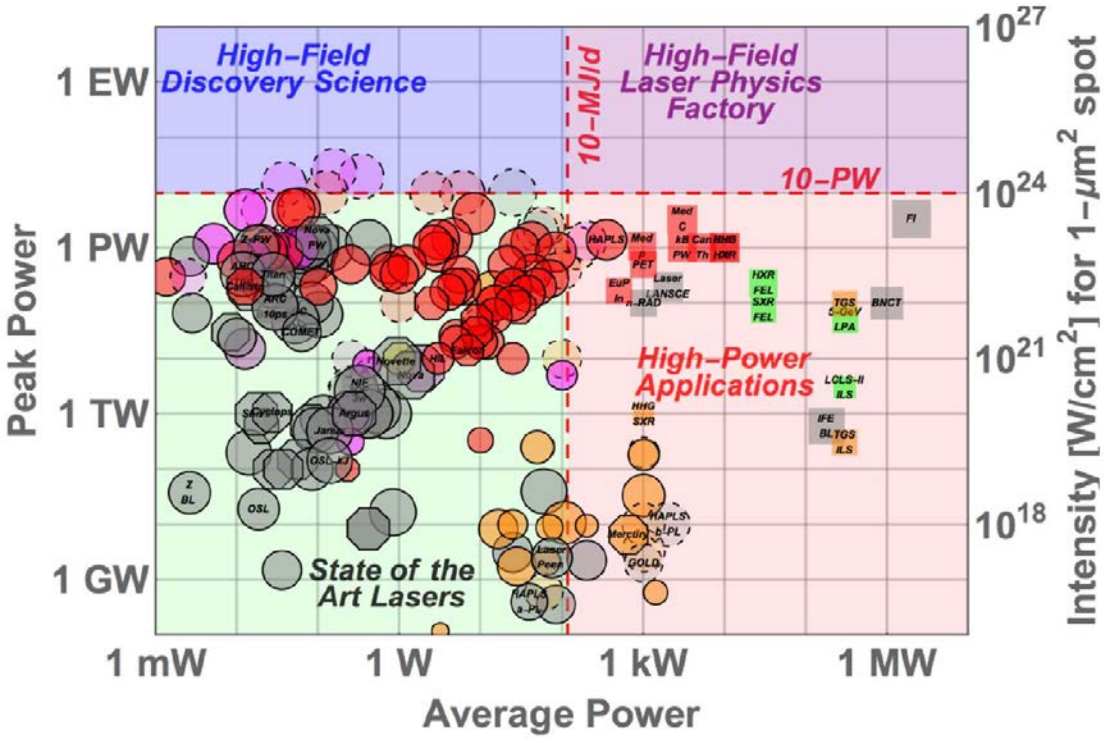
C. N. Danson, et al., High Pow Laser Sci Eng 7, e54 (2019).



Ti:Sapphire

Nd:X

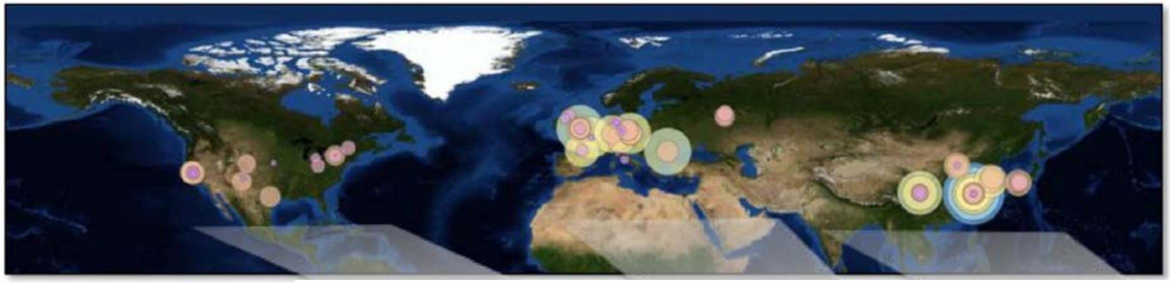
OPCPA

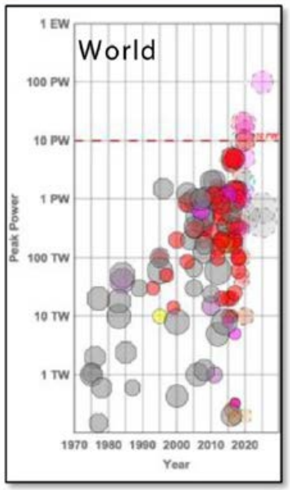
In operation (solid line)

Planned (dashed line)

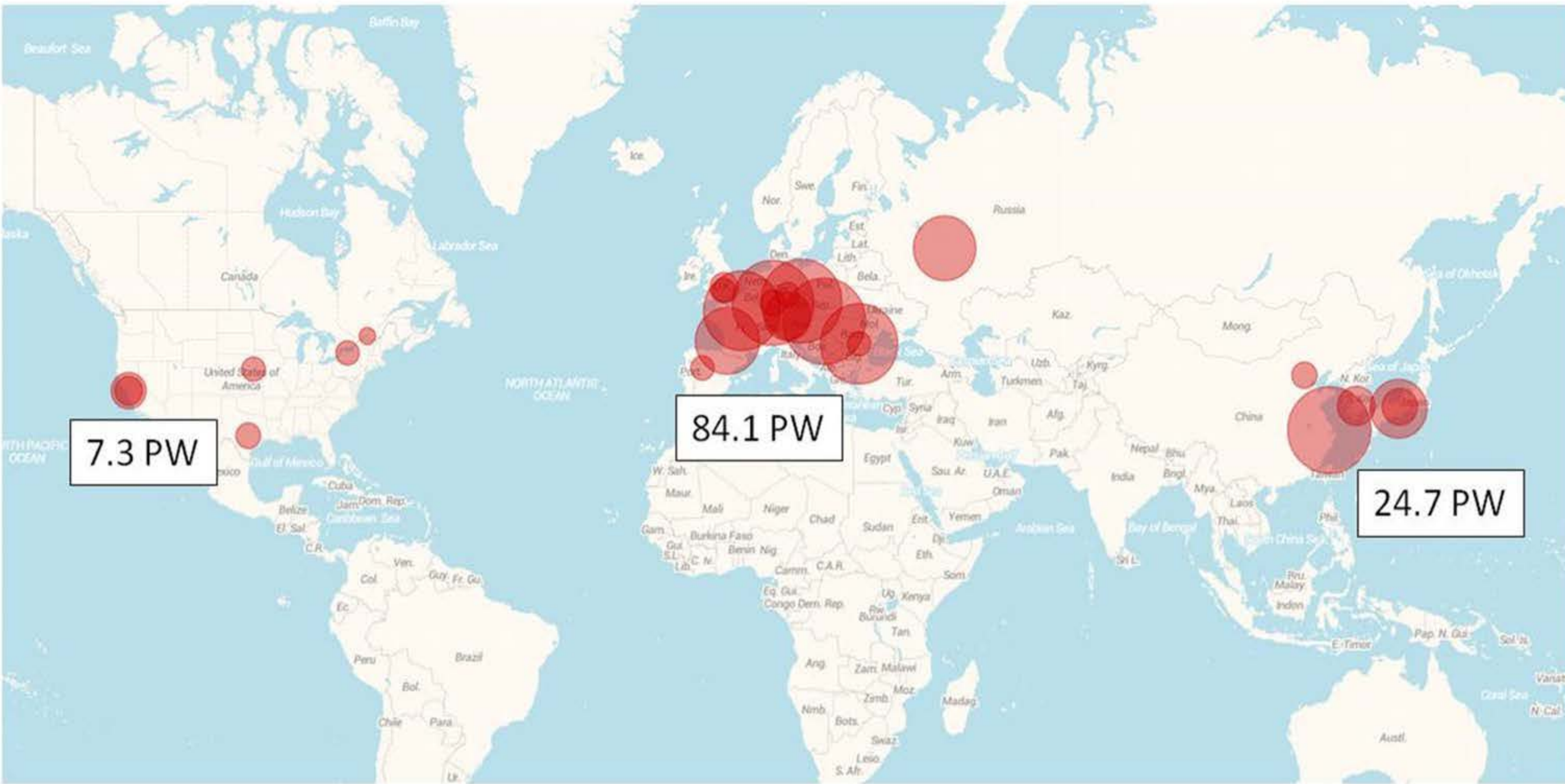
The comprehensive Mourou plot:

C. N. Danson, et al., High Pow Laser Sci Eng 7, e54 (2019).

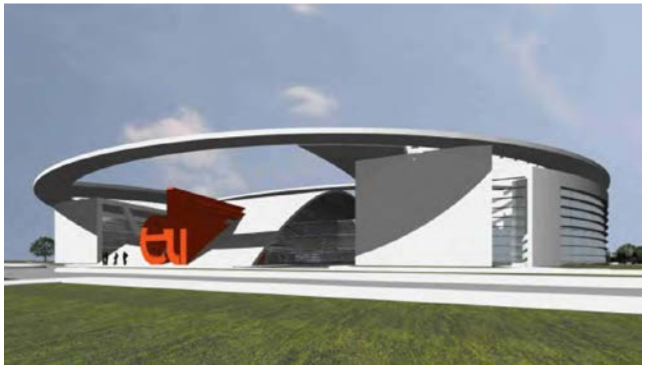




PW-class lasers: concentrated in Europe



European ELI project (~$1B)



Attosecond Light Pulse Source (Szeged, Hungary)

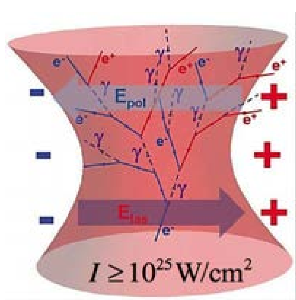
-Ultrafast light sources, and coherent x-ray sources
-PW drive laser
-Several beam lines, from 10KHz 100 mJ to 0.1 Hz 300J

High Energy Beam-Line Facilitiy (Prague, Czech Republic)

Beam lines from -200mJ to 1.3kJ lasers, including 2 10PW lasers;
Six experimental areas, including exotic physics, acceleration, x-rays, materials science.

Nuclear Physics Facility (Magurele, Romania)

2 multi-petawatt, 200J, 0.1Hz, <30fs lasers
Compton backscatter gamma ray source
Experiments aimed at nuclear physics.



10^{23-24} W/cm^2 @Beamlines and NP

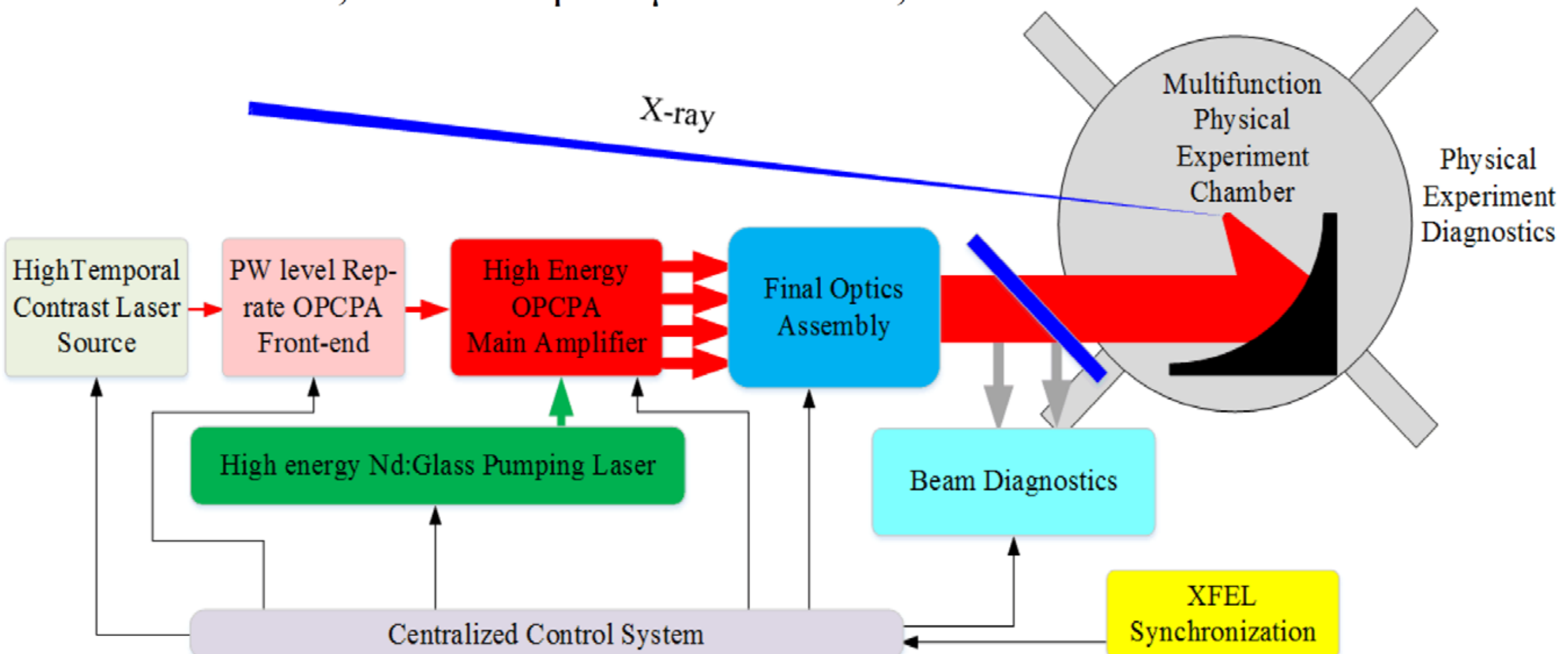
eXtreme light infrastructure

China plans to dominate this technology, and probably will, with plans for a 100 PW system based on Optical Parametric CPA:

- Main specifications:

Focused intensity 1×10^{23} W/cm^2; Peak power 100 PW;

Pulse duration 15fs; Focused spot 5μm diameter;



What's one Petawatt after all? Not enough for our needs.

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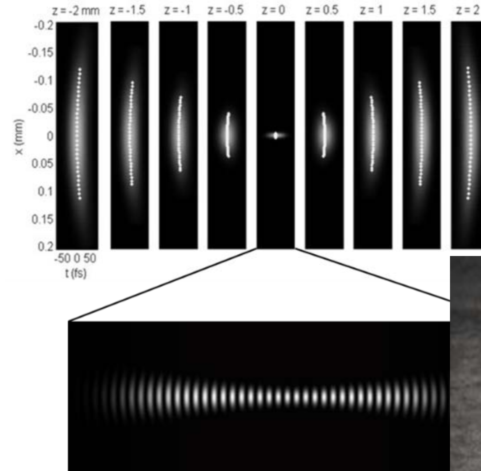
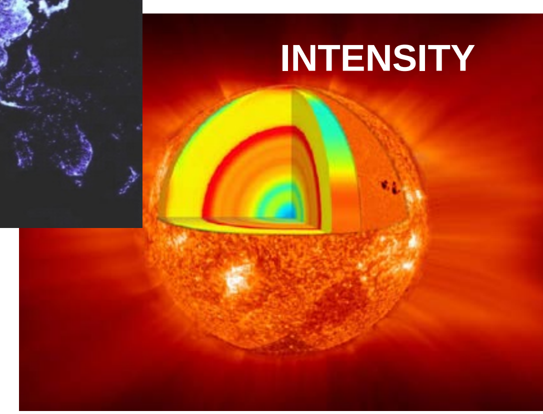
- 100 J in 100 fs, at λ=800 nm, focused to 10µm $\Longrightarrow 10^{21}\, W/cm^2$.
- The total energy, 100 Joules, is about the the kinetic energy of a pitched baseball, calories in a potato, 10x the energy in a SLAC electron bunch.
- The peak power, 1 PW, is nearly 100x the world's power comsumption rate.
- The focused intensity is greater than the center of the sun. The rms electric field is 100 trillion V/m.
- $\boldsymbol{F_L = 10^{12}\, V/cm,\ only\ 10^{-4} F_{cr}}$

What is a petawatt laser pulse?





Report Box 1.1

SFQED is featured prominently in the recent NAS "Reaching for the Brightest Light" PW laser report.

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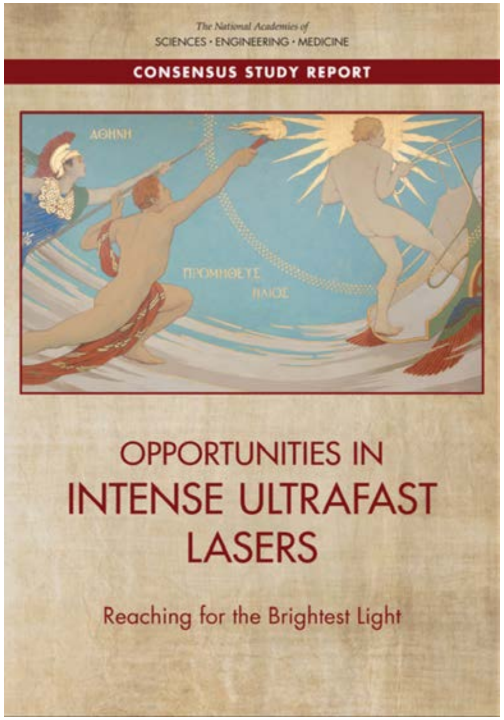

5.7 EXTREME INTENSITY: TOWARD AND BEYOND THE SCHWINGER LIMIT OF 10^{14} PW/CM^2 ...
5.7.1 Introduction ....
5.7.2 The Schwinger Limit ....
5.7.3 Vacuum Polarization: Matter from Light ....
5.7.4 Nonlinear Thomson and Compton Scattering ....
5.7.5 Radiation Reaction ....
5.7.6 Vacuum Polarization: Elastic Light Scattering ....
5.7.7 Beyond the Standard Model ....

Full report
http://nap.edu/24939

Study conclusions

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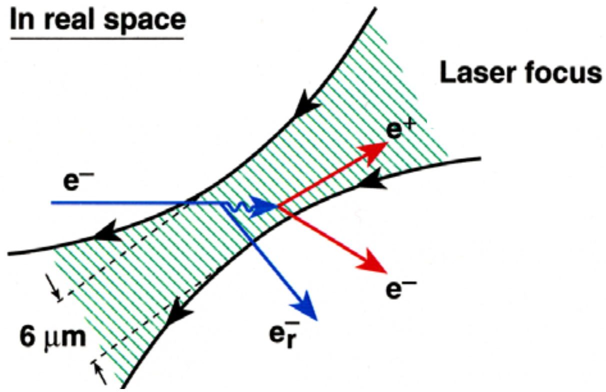
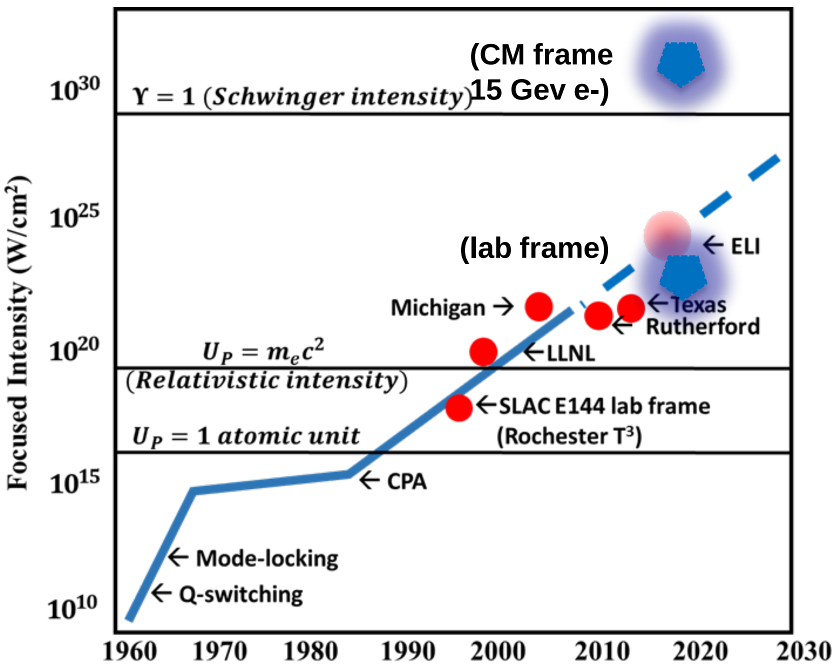
1) **The science is important.**
2) **Applications exist in several areas.**
3) **The community is large but fragmented.**
4) **No cross-agency stewardship exists.**
5) **The US has lost its previous dominance.**
6) **Co-location of intense lasers with existing infrastructure is essential; key US advantage over ELI**
7) **University/Laboratory/Industry cooperation is necessary to retain and renew the talent base.**

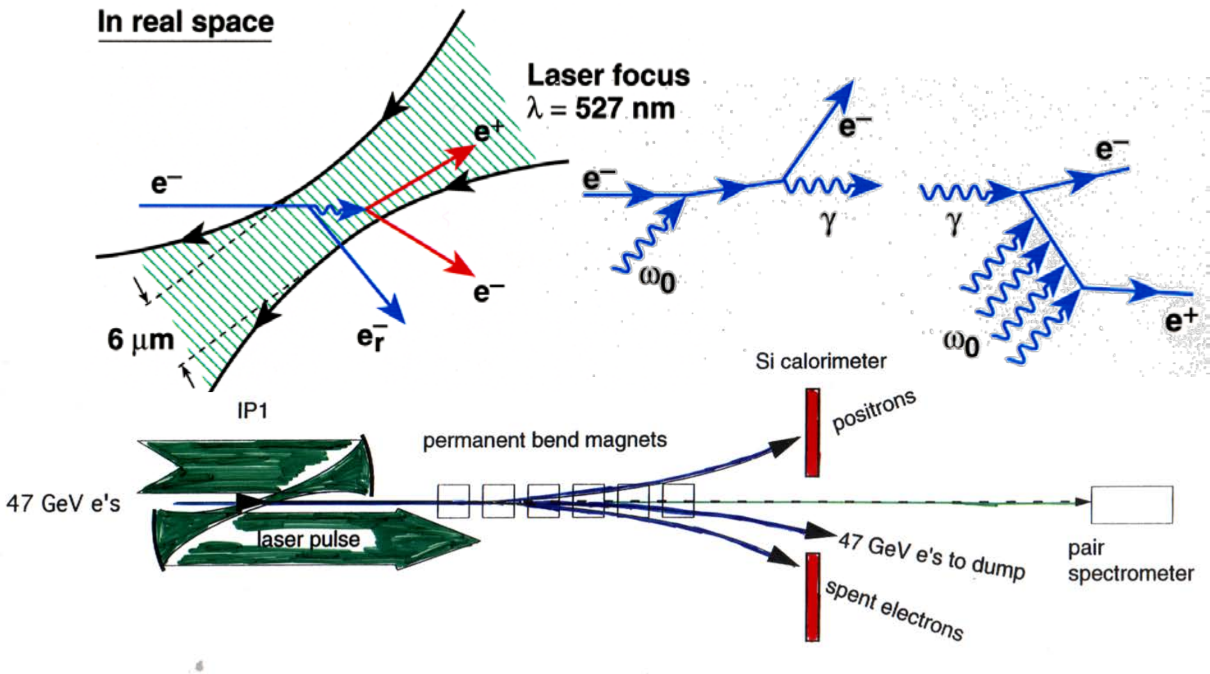
Here's what makes collocation essential:

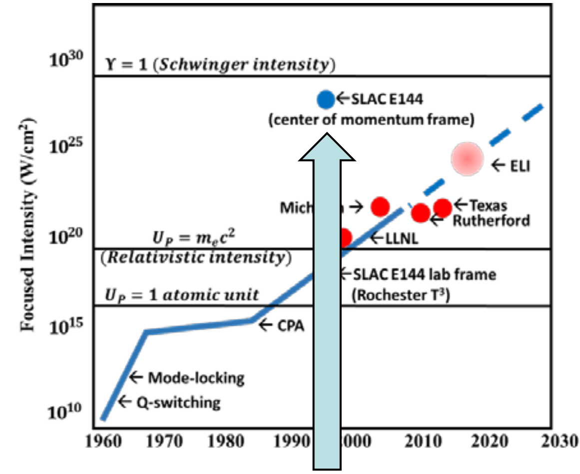




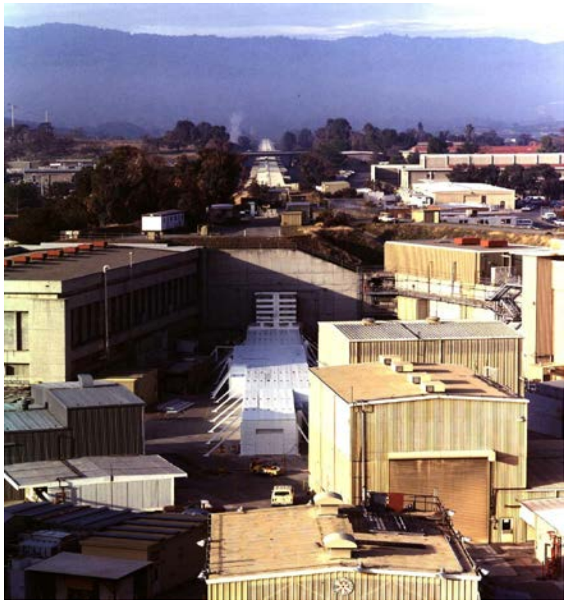
- **Intensity of the laser in the CM frame of a relativistic electron scales as $4\gamma^2$**
- **Fundamental physics in a new nonperturbative regime**
  - **Transition from multiphoton to tunneling.**

The highest intensity experiment to date is SLAC E144, which pushed lasers off the Mourou plot trend line:





FFTB (now LCLS transport)



- **Near head-on collisions of TW laser (ħω = 2.34 eV) with backscattered photons, ħω ~ 28 GeV, from 46.6 GeV SLAC beam.**
- **Need ≥ 4 photons to produce a pair (1.02 MeV in COM)**
- **Intensity in COM frame approaching Schwinger limit (~10^{29} W/cm^2) and QED critical field.**

The laser: T³:table-top-TW, Chirped Pulse Amplification Nd: glass laser

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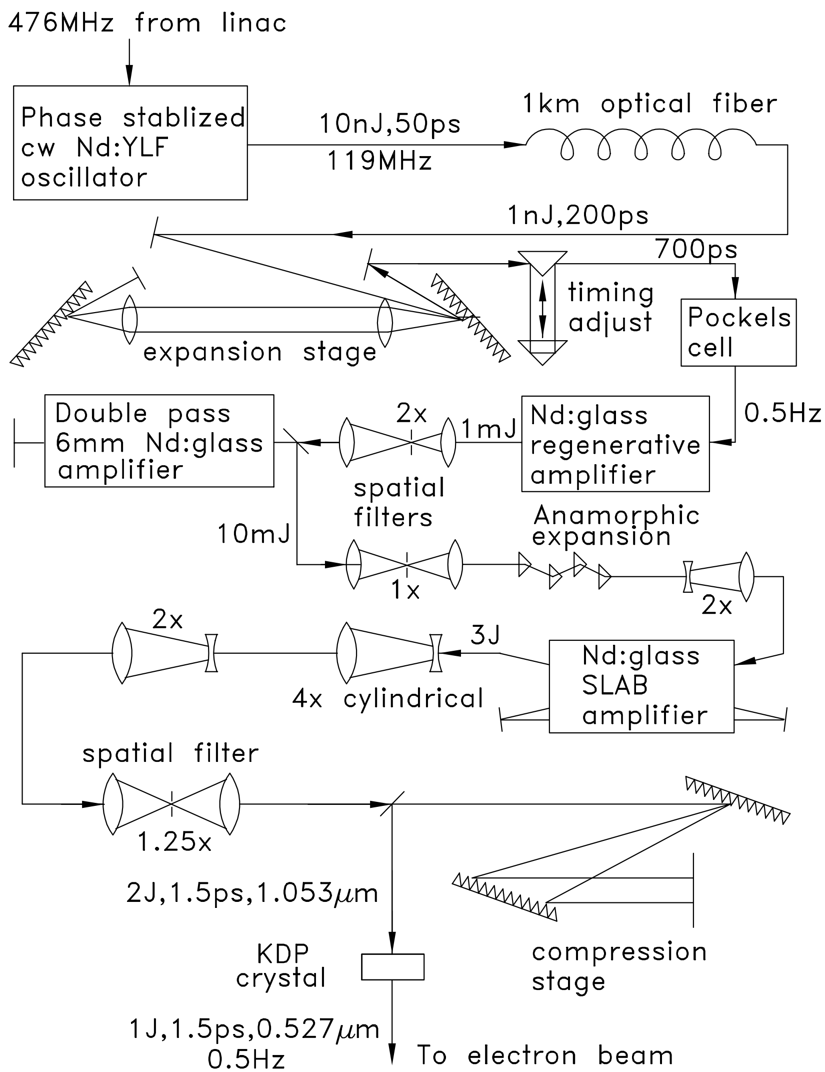


- Mode-locked Nd:YLF synchronized
- to rf cavities to few ps

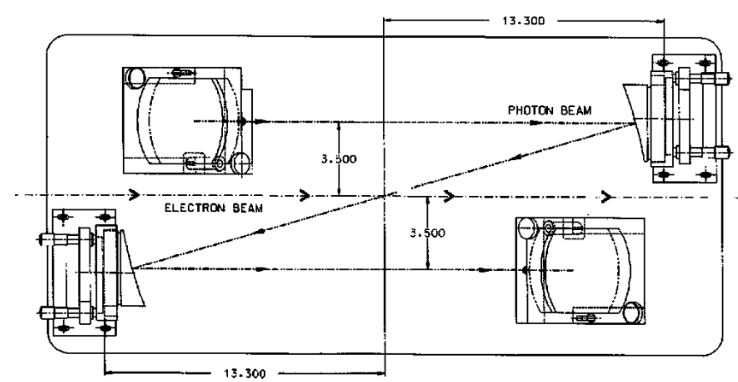
- Fiber and grating stretcher
- Multi-stage amplification

- Zig-zag SLAB amplifier
- ~1J, 1.5ps, 0.5 Hz

- 1054 nm fundamental
- 527 nm (KDP)

- f/# 6 focusing 2X diffraction limit

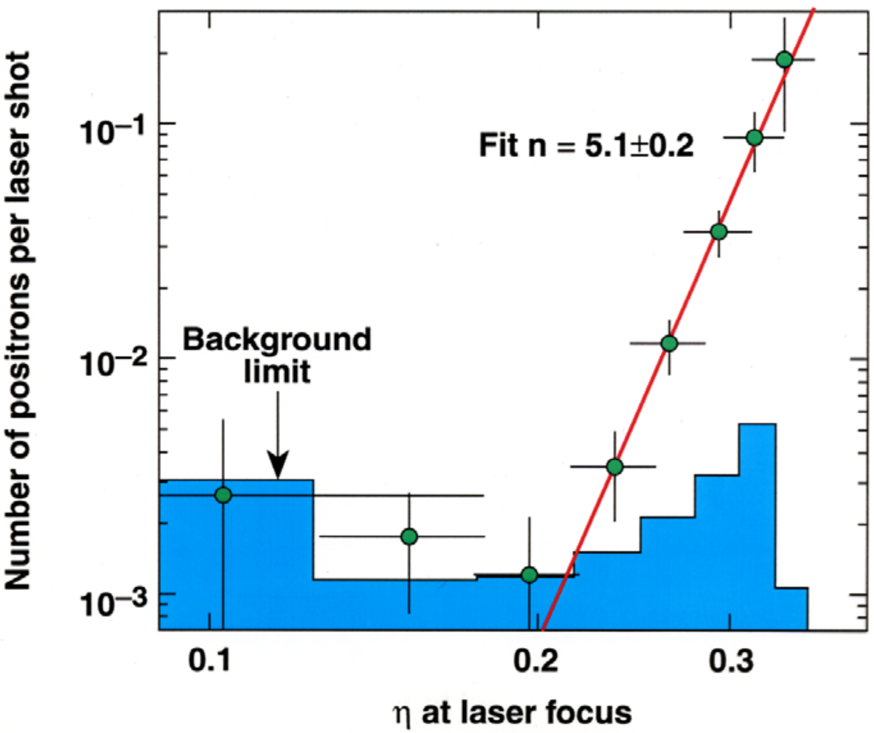
- ~10^{18} W/cm^2



E144 Measured in transition regime

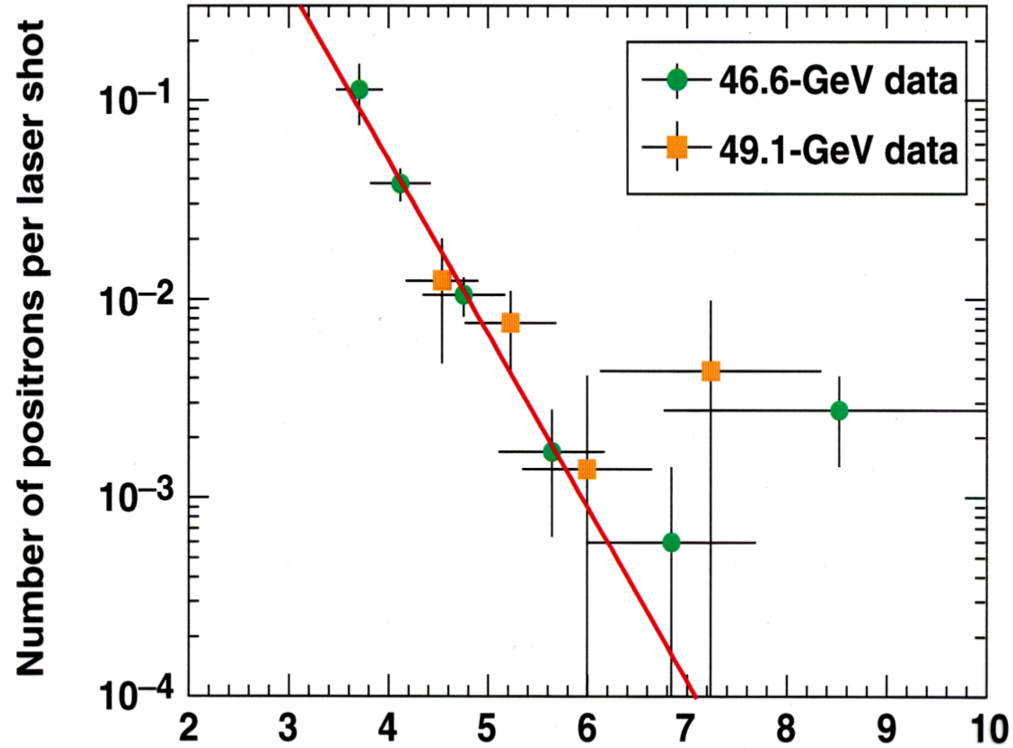
Process involving *n* laser photons has probability

$$P \sim \eta^{2n} \quad \text{where} \quad \eta^2 = \left[\frac{eE}{\omega mc}\right]^2 = \left[\frac{e}{\omega mc}\right]^2 Z_0 I$$



Multi-photon picture

Tunneling Picture (Schwinger)

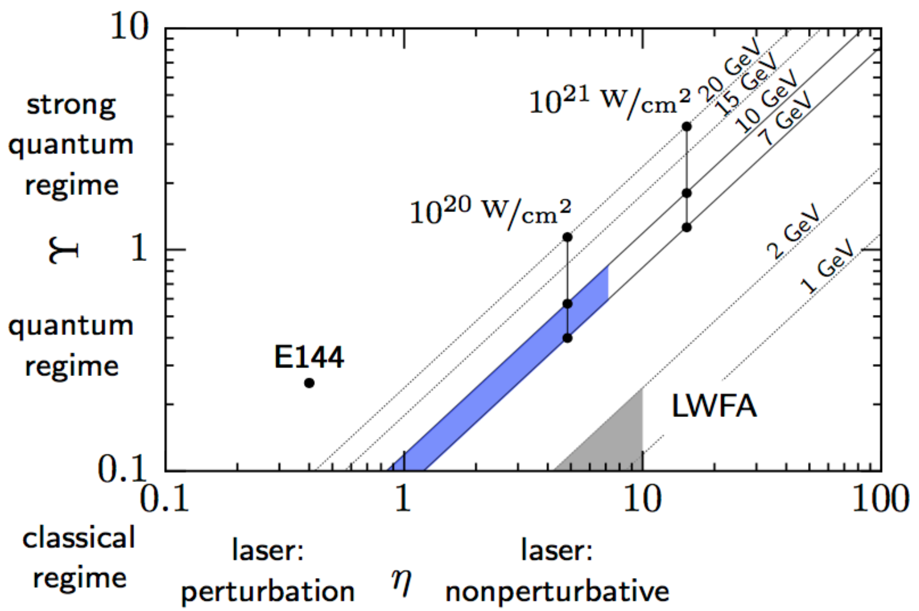


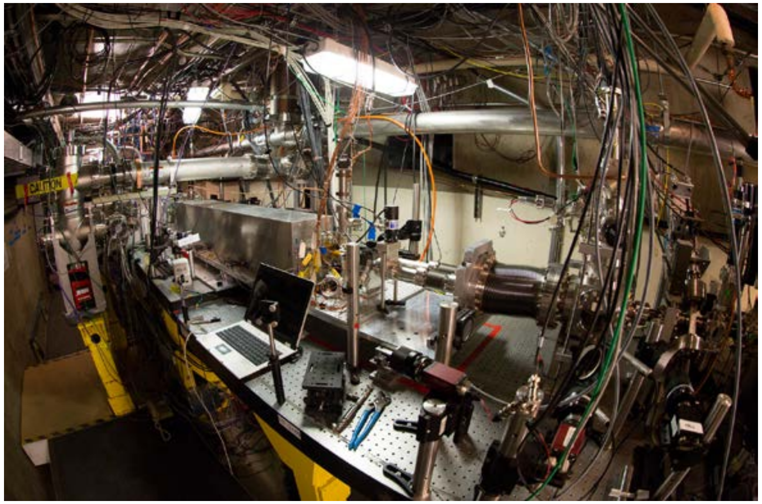
$\prod$= E/E$_c$ 1/Υ

Fit to $e^{-\alpha/\Upsilon} \rightarrow \alpha = 2.02 \pm 0.12$

Reaching strong-field regime @FACET-II

Baseline: 20 TW, 13 GeV





Focused Intensity Frontier

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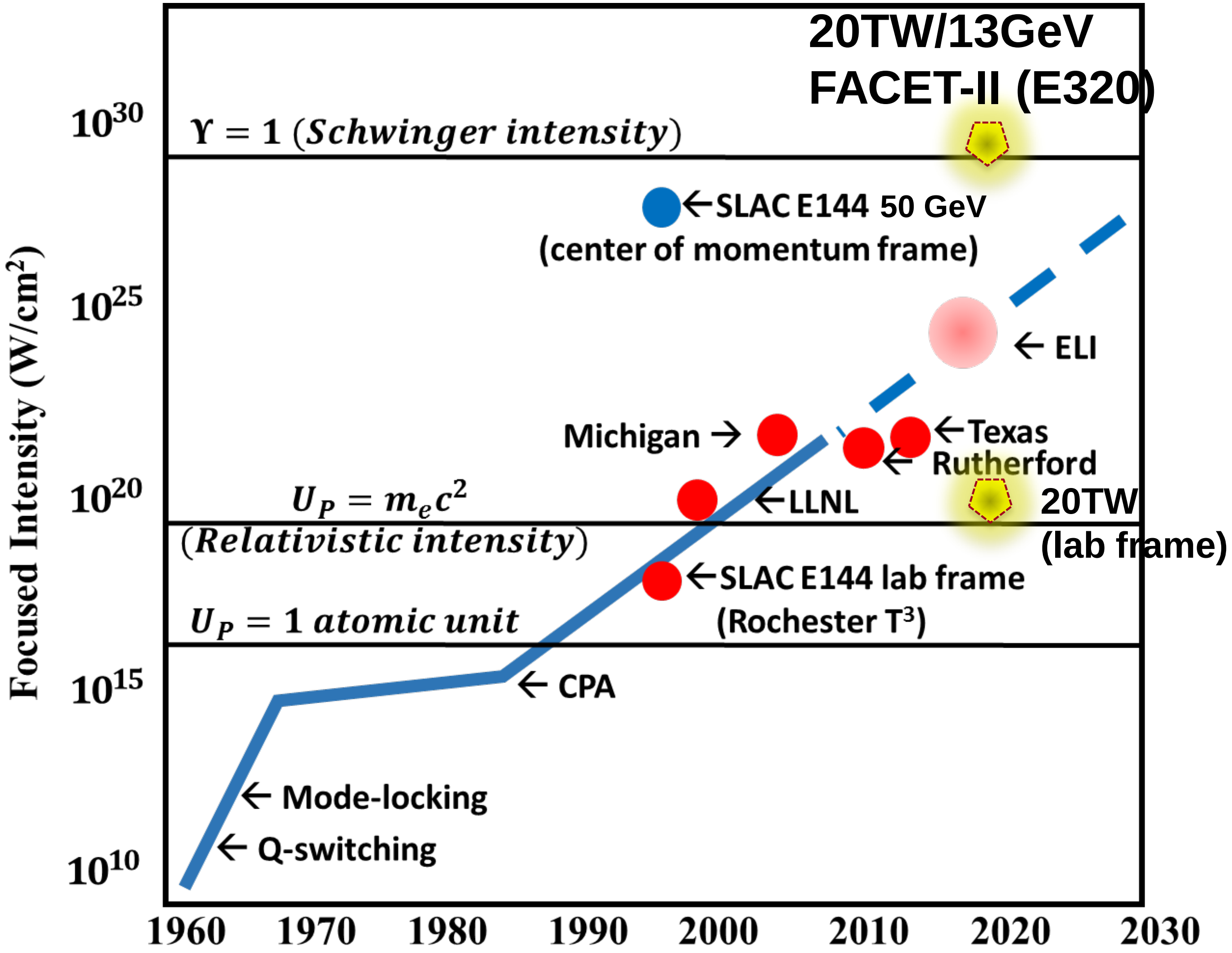


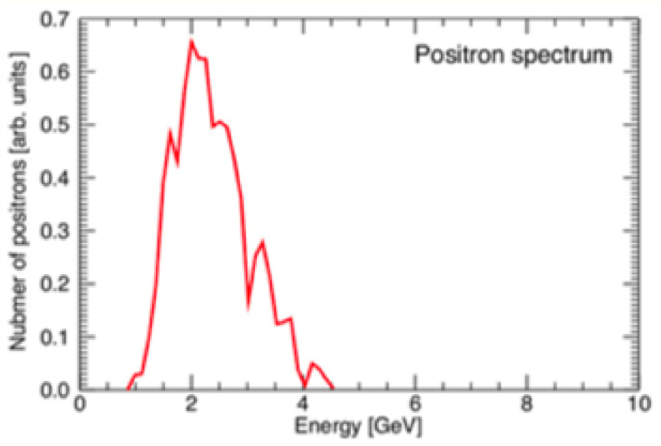
Y >1 possible now with current facilities (SLAC/DESY…) …and modest laser

FACET-II E-320 collaboration

SFQED theory & simulation	A. DiPiazza, F. Fiuza, T. Grismayer, C.H. Keitel, **S. Meuren**, L.O. Silva, D. Del Sorbo, M. Tamburini, M. Vranic
SLAC E144	**D.A. Reis** (SF AMO/xray), T. Koffas (HEP)
LWFA SFQED experiments	G. Sarri, M. Zepf
Crystal SFQED experiments	R. Holtzapple, U. I. Uggerhoj
Strong-field AMO/x-ray science	**P.H. Bucksbaum**, M. Fuchs, C. Rödel
Laser-plasma interaction, HEDP	F. Albert, S. Corde, S. Glenzer, C. Joshi, M. Litos, W. Mori
Accelerator physics	G. White
Detectors	A. Dragone, C. J. Kenney
High intensity lasers	A. Fry

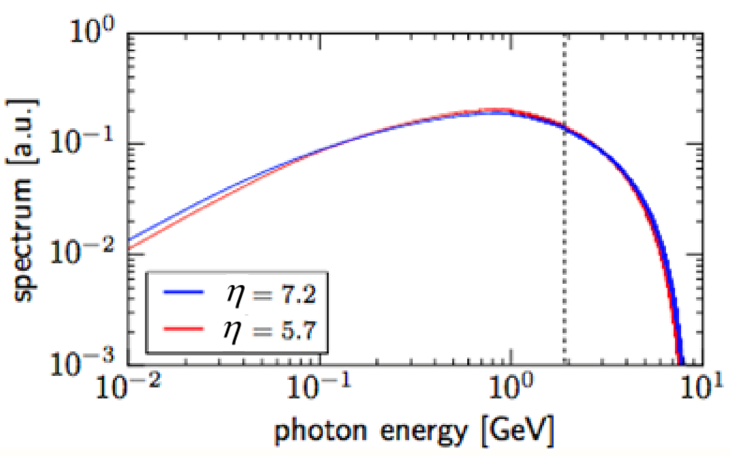
Collaborating Institutions: Carleton University (Canada), Aarhus University (Denmark). Ecole Polytechnique (France) Max-Planck-Institut für Kernphysik (Germany), Helmholtz-Institut Jena (Germany), Friedrich-Schiller-Universität Jena (Germany), Universidade de Lisboa (Portugal), Queen's University Belfast (UK), California Polytechnic State University (CA USA), Lawrence Livermore National Laboratory (CA USA), Princeton University (NJ USA), SLAC National Accelerator Laboratory (CA USA), University of California Los Angeles (CA USA), University of Colorado Boulder (CO USA), University of Nebraska - Lincoln (NE USA)

E-320 can test various aspects of SFQED



Tunneling pair production/vacuum breakdown

- Pair production inside quasi-static field
- Nonperturbative tunneling exponent
- Much higher statistics: >10^3 positrons/shot



Strong-field synchrotron radiation

- Reduced radiation probability, spectrum: redshift
- Coherent interaction with ~10^2 laser photons
- Emission of high harmonics (up to 8Gev photons

Simulations: Tamburini, Vranic, E-320 collaboration

E-320 can test various aspects of SFQED

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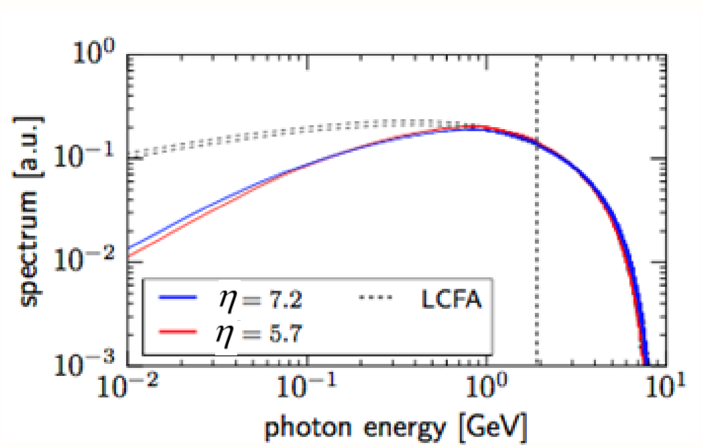
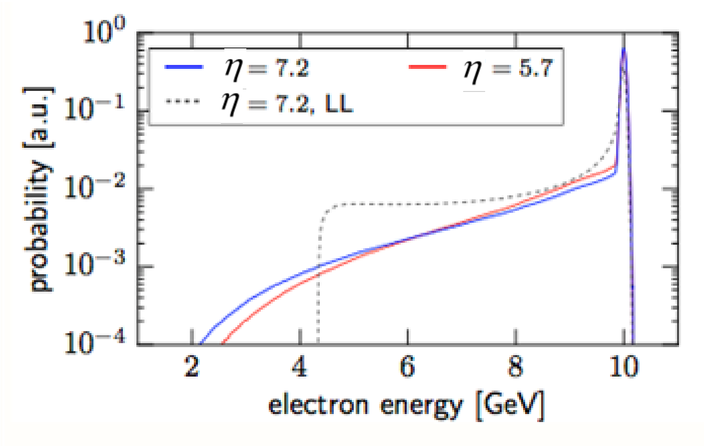


Breakdown of the Local Constant Field Approximation (LCFA)

- Applicability of the LCFA: vital for numerical codes
- Formation region depends on photon frequency
- LCFA faild: suppression of low-frequency radiation



Quantum radiation reaction (QRR) -energy

- Stochasticity: broadening of the energy distribution
- Quenching: some electrons don't radiate at all
- Quantum corrections to Landau-Lifshitz

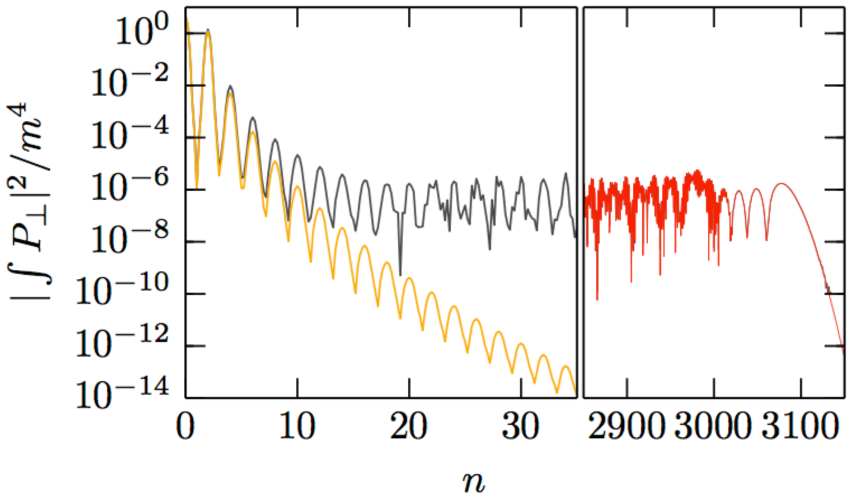
Simulations: Tamburini, Vranic, E-320 collaboration

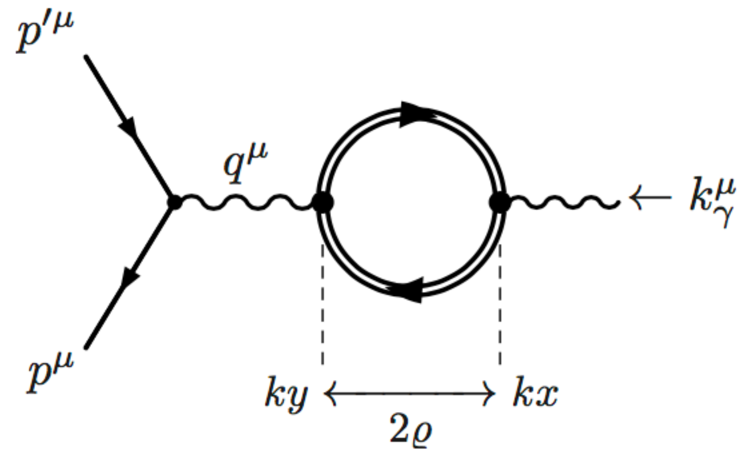
"New" physics: re-collisions.

$\eta \gg 1, \Upsilon \sim 1,$

Stationary phase approximation,
Tunneling, classical trajectories, re-collisions similar to SF-AMO

Possiblity for $\mu^+ + \mu^-$, $\pi^+ + \pi^-$; π^0… productions well below threshold



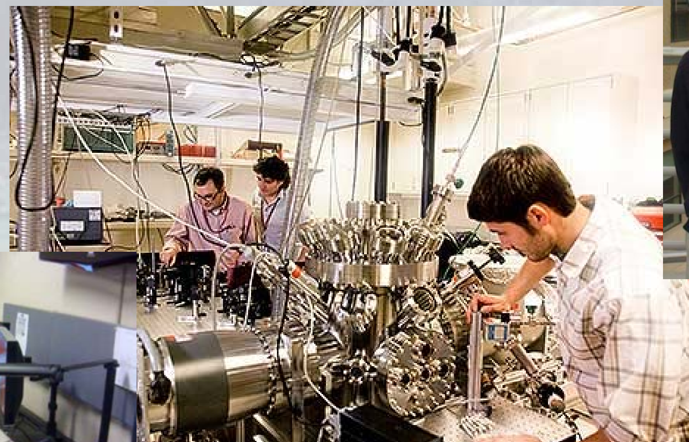


S. Meuren, 2015

Summary: Plasmas inside the vacuum

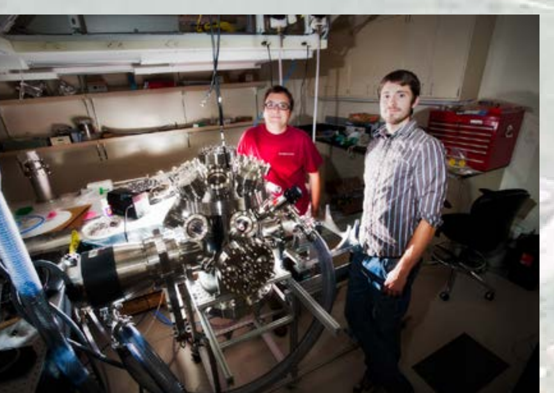
- **The vacuum is filled with quantum fluctuations of radiation and particles**
- **The quantum vacuum is a fundamental plasma frontier**
- **The entry point for study is fields that exceed the Schwinger threshold of $mc^2/e\lambda_c$**
- **Experimental studies are enabled by locating petawatt-class lasers together with relativistic particle accelerators**

Above the Schwinger threshold, CPA lasers can generate copious quantities of electron-positron pairs emulating conditions in the most energetic parts of the universe.



Thanks!

Parts of this work were supported by the U.S. Department of Energy, Office of Science, Chemical Sciences, Geosciences, and Biosciences Division



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