# Laser wakefield acceleration and applications to light sources

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2022 Introduction to Fusion Energy and Plasma Physics Course

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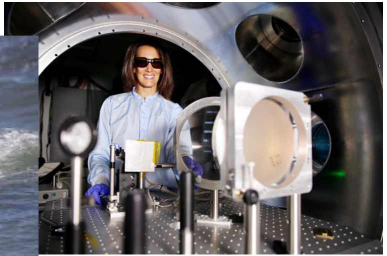
Lawrence Livermore National Laboratory

# How did I get here?

Then


- As a kid, I loved astronomy and skiing, and wanted to be astronaut or orthopedic surgeon
- Chose physics in undergraduate
- 2002: Exchange program with University of Central Florida
- 2004 – 2007: PhD in France
- 2008: My UCF professor offered me a postdoc position at LLNL!
- 2008 – Now: I was supposed to stay at LLNL 2 years and then go back, I am still here, so you guessed I kind of like working with lasers and plasmas (and surfing!)


Now



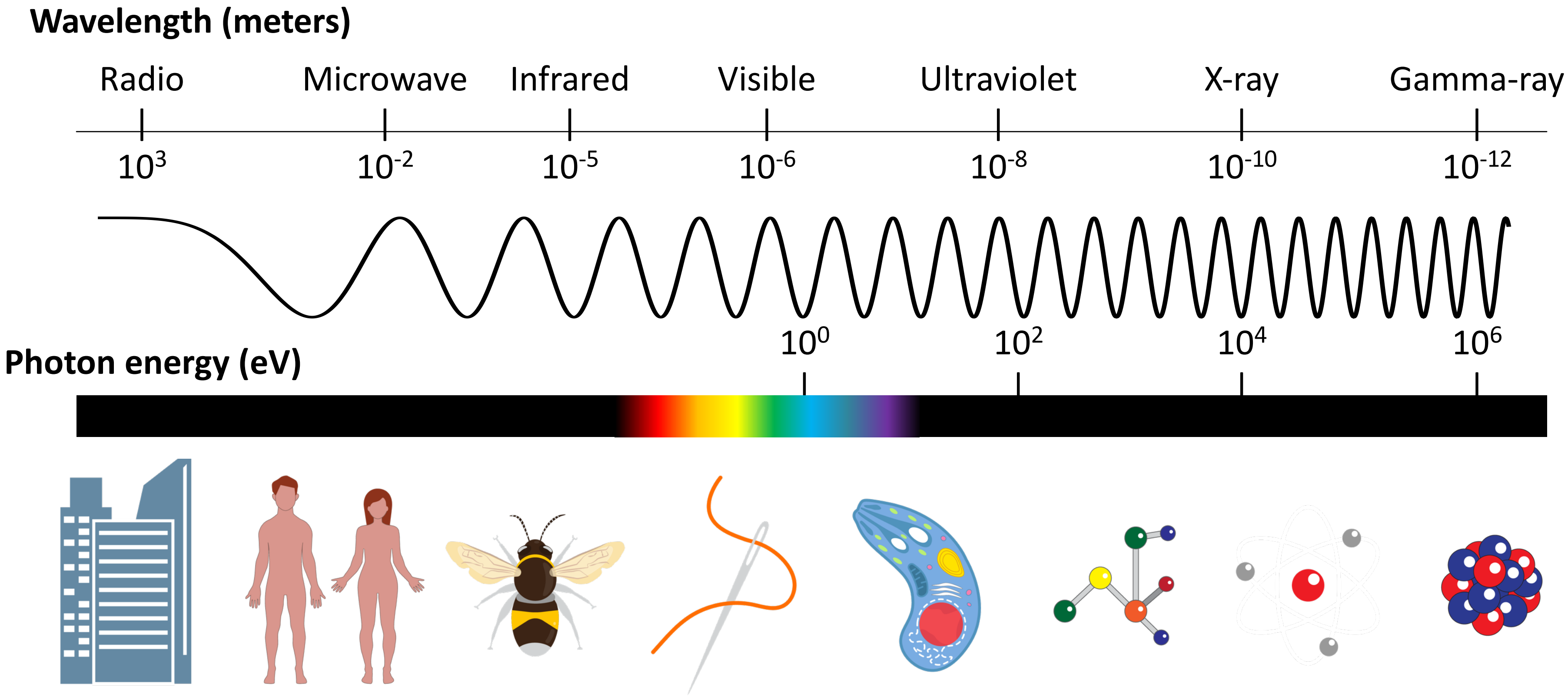
# Outline

- Conventional light sources: Synchrotrons and X-ray Free Electron Lasers
- Laser Plasma Acceleration
- High Intensity Lasers
- Light sources driven by laser plasma acceleration
  - Betatron
  - Compton scattering
  - Bremsstrahlung
  - X-ray free electron laser
  - Terahertz
- How wan we use these sources?

# Preliminary definitions and notations

- Electron volt: energy gained by one electron in a 1 Volt potential
  - 1 eV = 1.6 x $10^{-19}$ J
- Electron relativistic factor and normalized velocity
  - $\gamma = \sqrt{\frac{1}{1-\frac{v^2}{c^2}}}$ and $\beta = \frac{v}{c}$
  - $\gamma = 1$ electron at rest, 0.511 MeV
  - $\gamma = 1000$ electron at ~ 500 MeV and $\beta = 0.9999995$
- Unless otherwise specified, using MKS units
  - Speed of light $c$=299792458 m.s$^{-1}$
  - Free space permittivity $\epsilon_0$ =8.85418782 × $10^{-12}$ F.m$^{-1}$
  - Free space permeability $\mu_0 = 4\pi 10^{-7}$ H.m$^{-1}$

# The electromagnetic spectrum

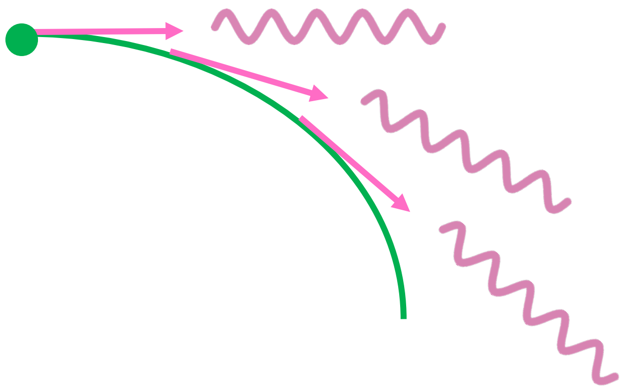


# Conventional x-ray light sources are large scale national facilities

## X-ray free electron laser: LCLS

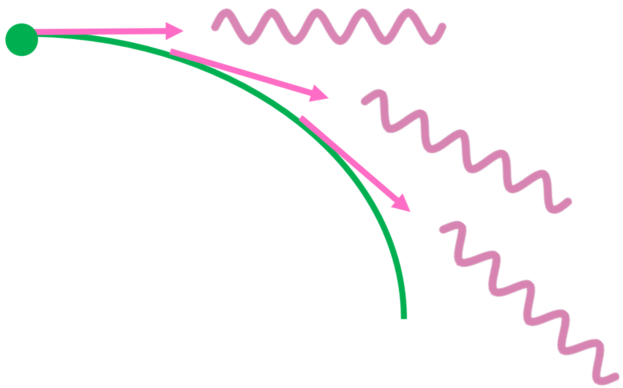

## Synchrotron: APS

# How do we produce x-rays with large particle accelerators?

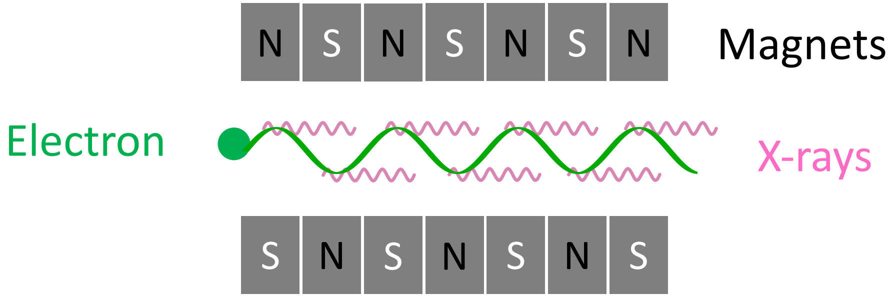


A particle changing direction
emits radiation along its path

# How do we produce x-rays with large particle accelerators?

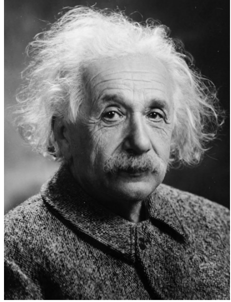


A particle changing direction emits radiation along its path



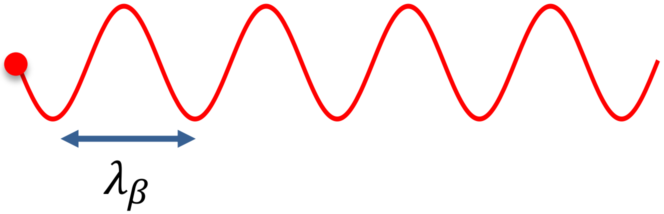

In synchrotrons and XFELs Magnets are used to change the particle's path

# Relativity detour



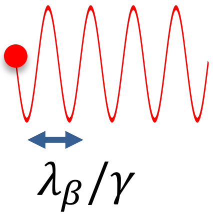
- An electron oscillating with period $\lambda_\beta$ emits at a wavelength $\lambda_\beta/2\gamma^2$

**Electron trajectory in Lab frame**

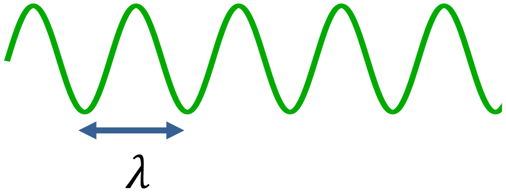



**→ Lorentz transform →**

**Electron trajectory in electron frame**

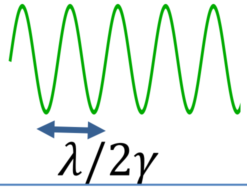



**Emission wavelength in electron frame**




**→ Doppler effect →**

**Emission wavelength in Lab frame**

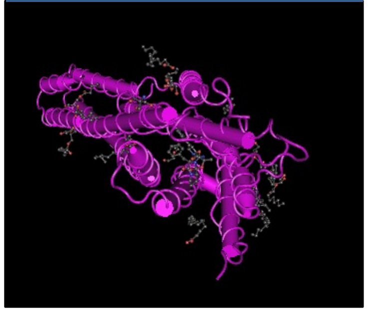



<u>Example:</u> $\lambda_\beta = 1\ cm$ and $\gamma = 10\ 000 \rightarrow 0.1\ nm$ wavelength

If you can reduce $\lambda_\beta$ you can use a lower energy electron beam to make a light source!

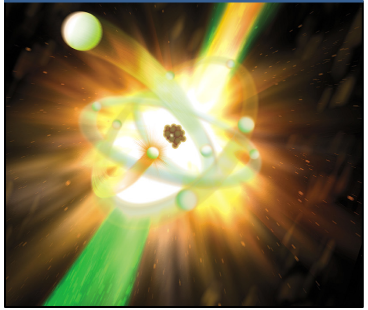
# These light sources have enabled seminal discoveries

Structure of proteins



Liu Science 2013

Atomic x-ray laser

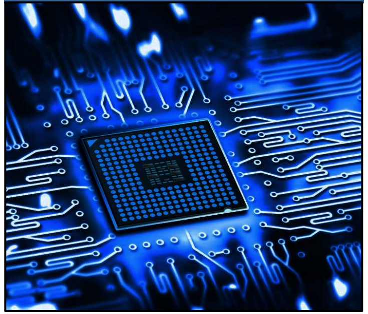


Rohringer Nature 2012

Material strain studies

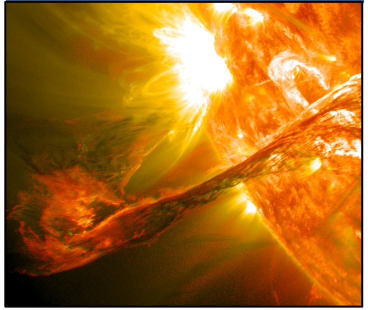
http://www.diamond.ac.uk/industry/

Semiconductor research



Margaritondo, J. Phys. IV 2006

Solar plasmas



Vinko Nature 2012

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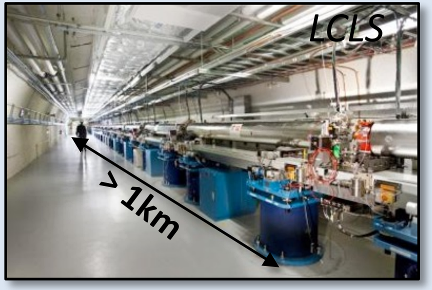
# Sources driven by laser-plasma accelerators offer an alternative

## Synchrotron

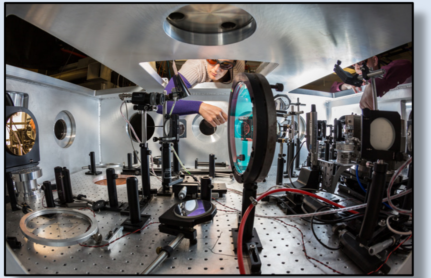

Electrons from storage ring wiggled by undulators

## Free Electron Laser



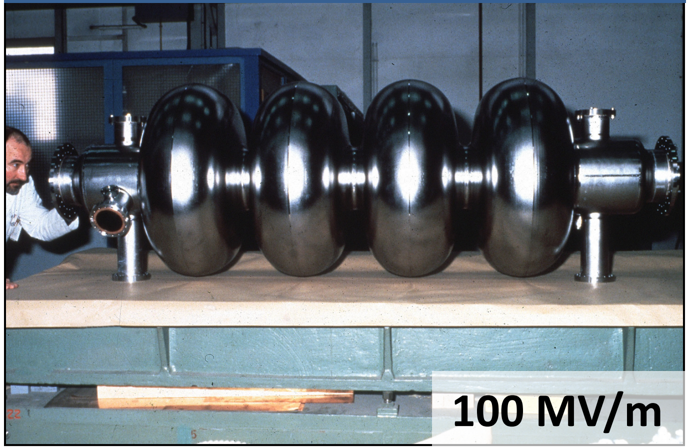
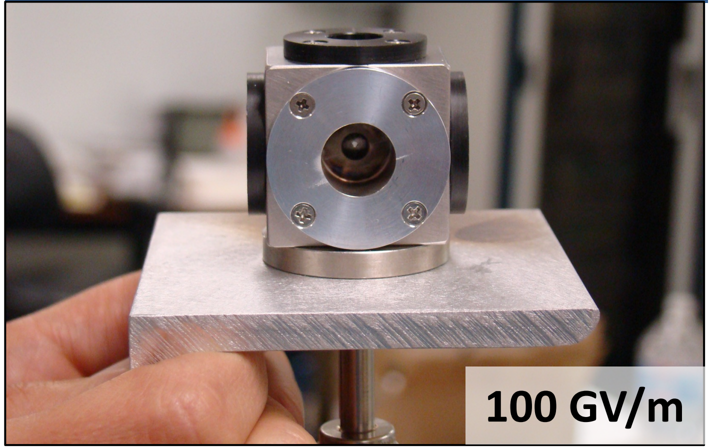

Electrons from linac wiggled by undulators

## Laser-plasma



Electrons from laser-produced plasma wiggled by plasma

# Plasmas can naturally sustain large acceleration gradients

| (S)RF Cavity | Gas cell – laser plasma |
|---|---|
|  |  |
| 100 MV/m | 100 GV/m |

# Plasma definitions

- Intense laser beams have sufficient intensity to form fully ionized plasmas of helium or hydrogen
- An electromagnetic wave with frequency $\omega_0$ and wavenumber $k$ will propagate in a plasma if the electron density $n_e$ of the plasma is less than the critical density $n_c$ such that $\omega_0 = \sqrt{\frac{n_c e^2}{m\varepsilon_0}}$
- Then the pulse propagates and obeys the dispersion relation $\omega_0^2 = \omega_p^2 + k^2c^2$
- $\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$ is the electron plasma frequency (ie natural oscillations of electrons in plasma)
  - $\lambda_p = 2\pi c/\omega_p$ is the plasma period
- $\omega_{pi} = \sqrt{Z\frac{m}{m_i}}\omega_p$ is the ion plasma frequency (ie natural oscillations of ions in plasma)

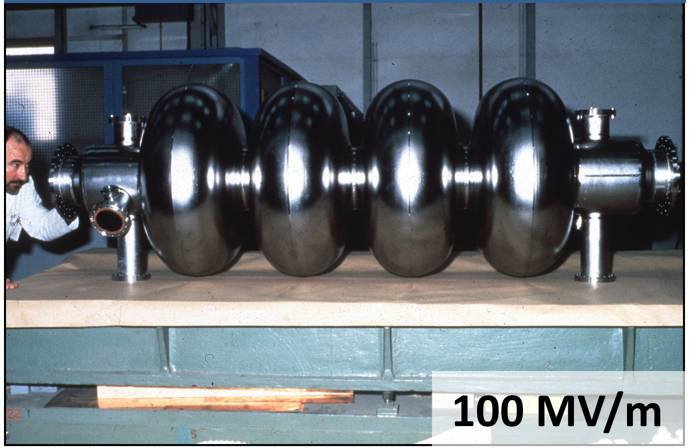
<u>Example:</u>

For $n_e = 10^{19}$ cm$^{-3}$ , $\omega_p = 1.78\times10^{14}$ s$^{-1}$ and $\lambda_p = 10.5$ µm

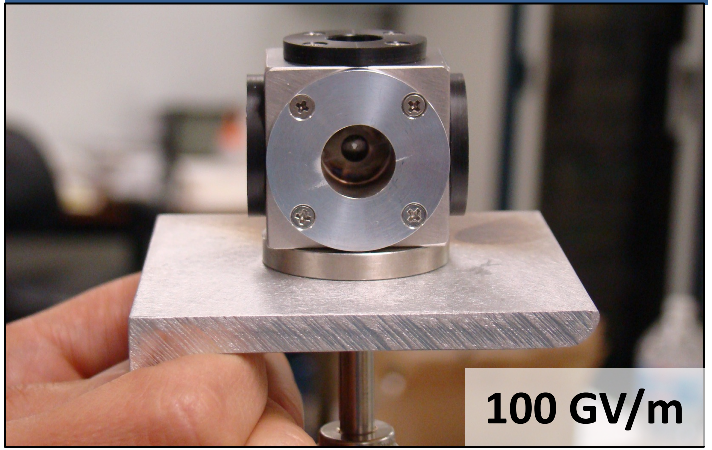
For a fully ionized helium plasma $\omega_{pi}{\sim}0.03\ \omega_p$

# Plasmas can naturally sustain large acceleration gradients

**(S)RF Cavity**




**Gas cell – laser plasma**




Acceleration gradient

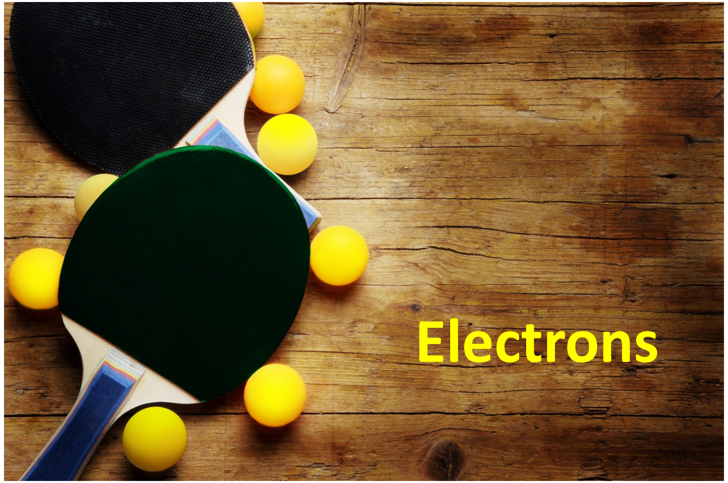
$$E_0 = \frac{mc\omega_p}{e}$$

Plasma frequency

$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

$$n_e = 10^{18}\ \text{cm}^{-3} \rightarrow E_0 = 96\ \text{GV/m}$$

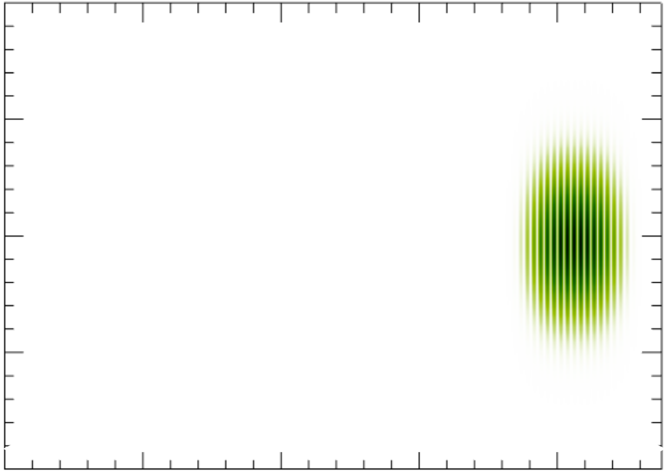
# Most of the time we will consider the ions to be immobile

# Electron plasma wave

Wake behind a boat

Plasma wave behind a laser



OSIRIS PIC simulation
Nuno Lemos, LLNL

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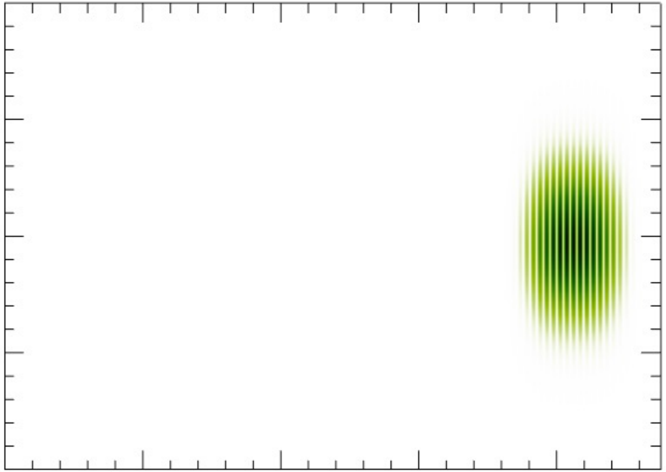

OSIRIS PIC simulation
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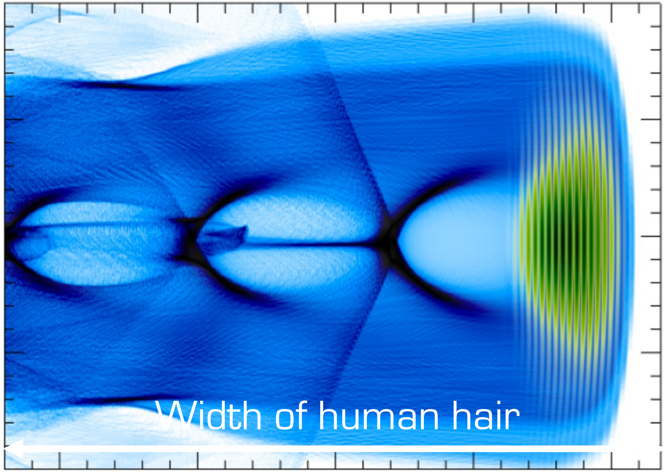
# Electron plasma wave

Wake behind a boat

Plasma wave behind a laser




OSIRIS PIC simulation
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# A brief history of laser wakefield acceleration

**1979:** Tajima and Dawson propose using laser-driven plasma waves to accelerate electrons

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

## Laser Electron Accelerator

T. Tajima and J. M. Dawson
*Department of Physics, University of California, Los Angeles, California 90024*
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

# A brief history of laser wakefield acceleration

**1979:** Tajima and Dawson propose using laser-driven plasma waves to accelerate electrons
**1980's:** Experimental production and measurement of relativistic plasma waves (UCLA)
**1985:** Invention of chirped pulse amplification (CPA) enabling ultrashort high peak power laser pulses (LLE)
**1995:** Acceleration of electrons in the self-modulated regime out to 40 MeV (UCLA/RAL)
**2002:** Acceleration of electrons in the nonlinear regime with ultrashort pulses out to 200 MeV (LOA)
**2004:** Three groups independently demonstrate the acceleration of monoenergetic electron beams (~100 MeV) with ultrashort pulses. Nature cover, the "dream beam" (LBNL, Imperial College, LOA)
**2006:** 1 GeV barrier is broken (LBNL), controlled injection demonstrated (LOA, France)
**2007:** Theory of blowout regime of laser wakefield acceleration (UCLA)
**2014:** Acceleration of electrons with PW laser pulses, 4.2 GeV (LBNL)
**2018:** More than 20 groups worldwide are working on LWFA and applications with dedicated facilities and user facilities (eg. ELI)
**2022**: Several groups now working on using these sources for applications

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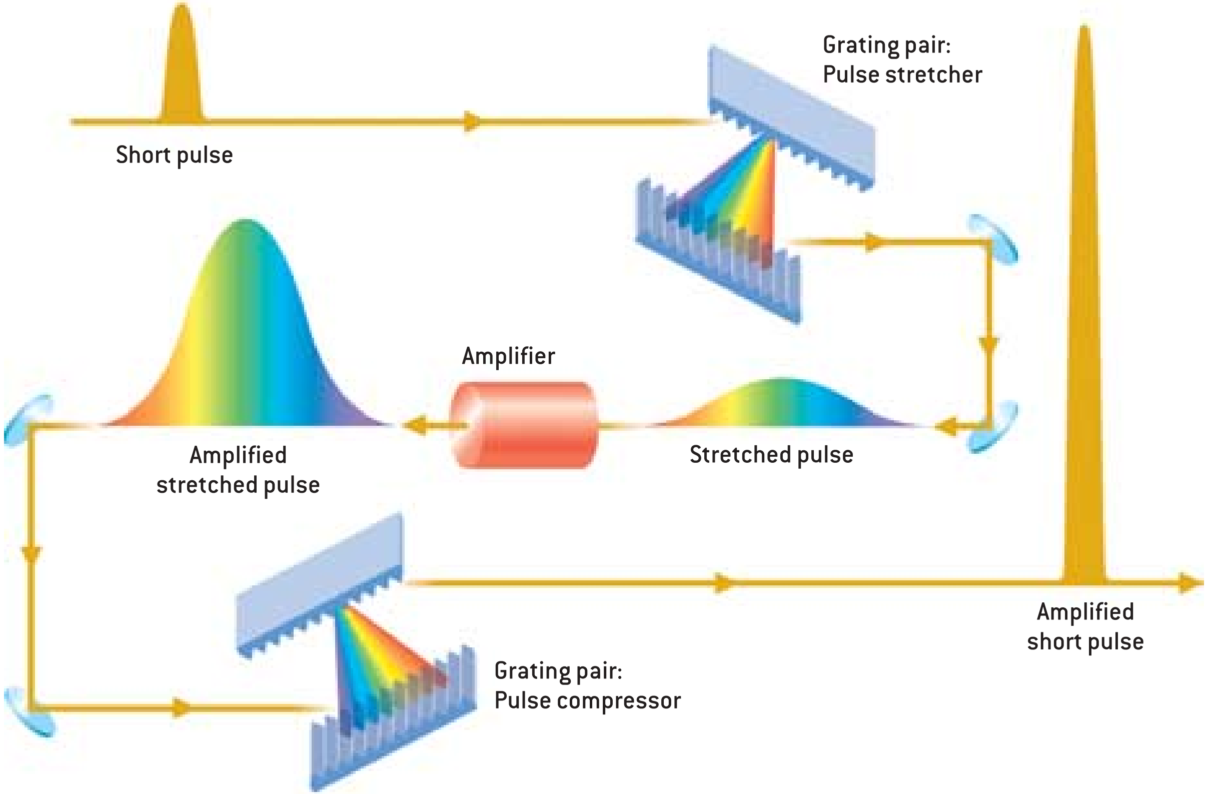
# Intense laser pulses were made possible by Chirped Pulse Amplification (CPA) in 1985




"Extreme light", G. A. Mourou and D. Umstadter, Scientific American (2002)

# Donna Strickland is the first woman to have been awarded the Nobel Prize in Physics for CPA in 55 years

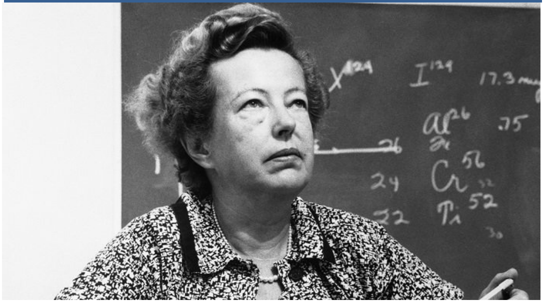
Donna Strickland 2018

"For methods of generating high intensity ultrashort laser pulses"

Marie Curie 1903

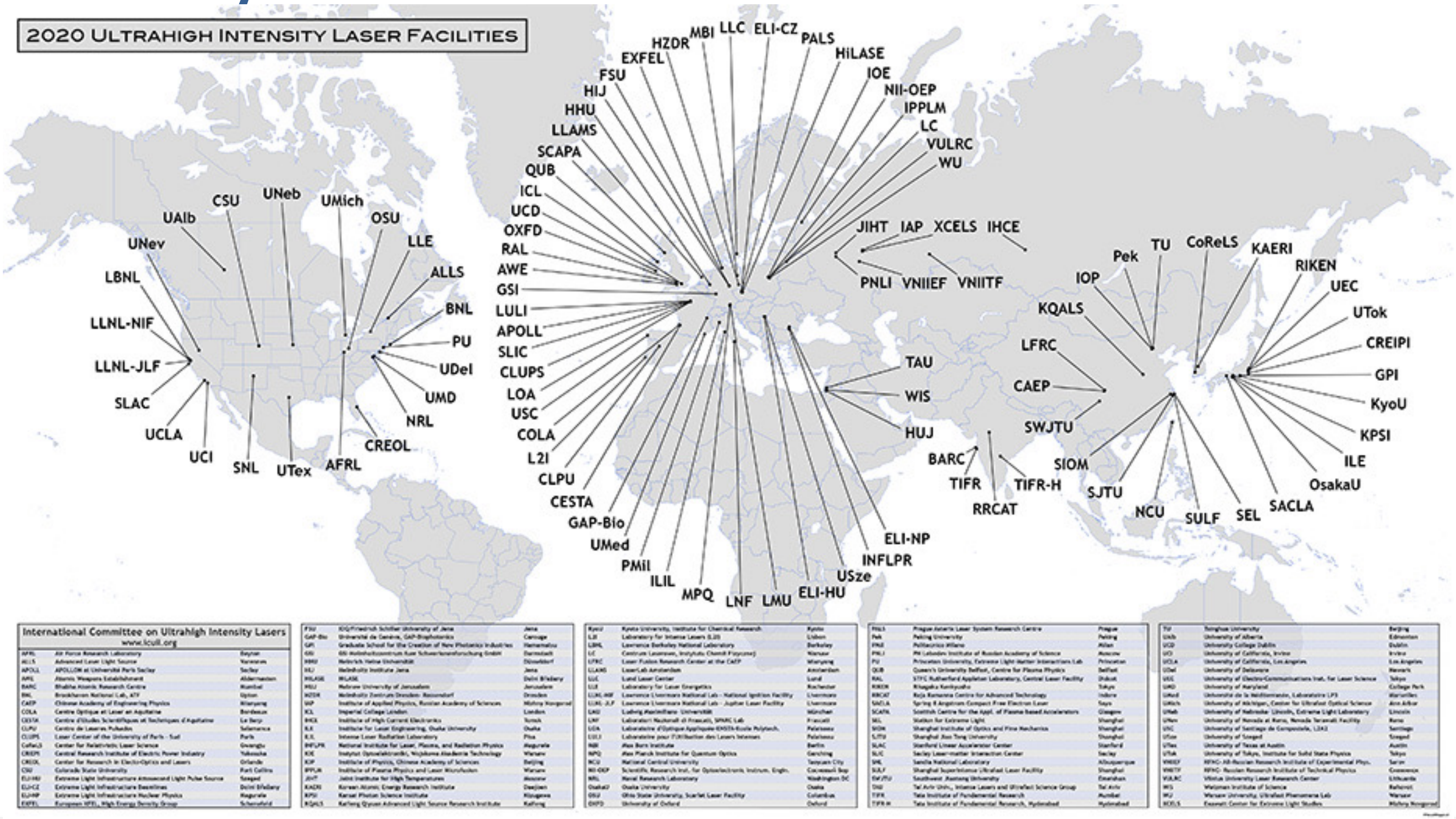
"for joint researches on the radiation phenomena discovered by Professor Henri Becquerel"

Maria Goeppert Mayer 1963

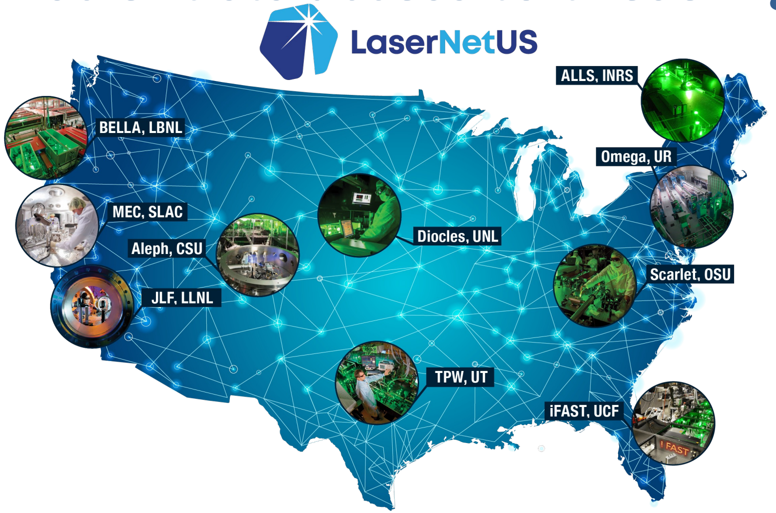


"for discoveries concerning nuclear shell structure"

# High Intensity lasers around the world

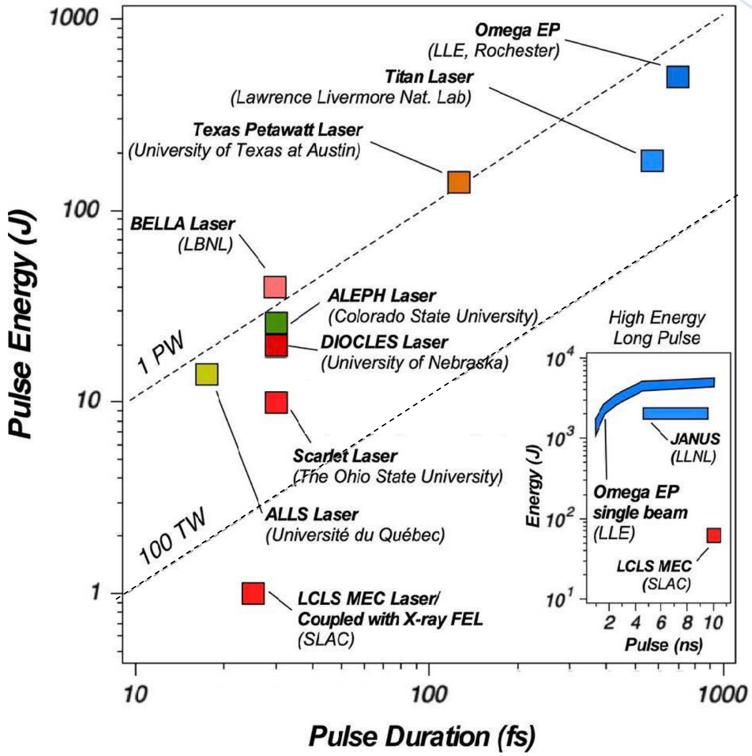


# In 2018 the DOE – FES established LaserNetUS to allow scientists access to these high intensity lasers




- **10** high power laser facilities*
- Includes the **6** most powerful lasers housed at Universities
- Highest powers exceed **1 petawatt**
- Dedicated to the proposition that **ALL** research groups should have access to the brightest light

*UCF not yet offering beam time



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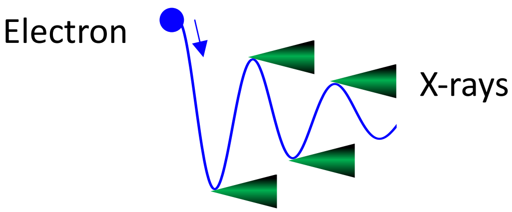
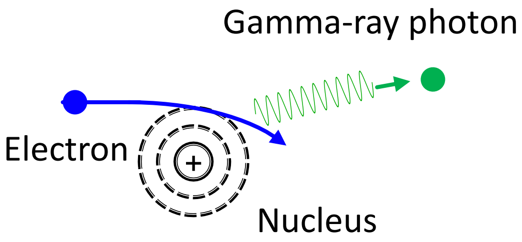
# Electrons from laser plasma accelerators can emit radiation

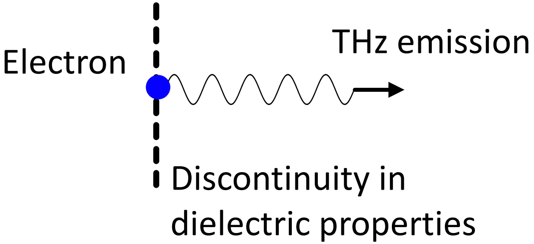
**Betatron x-ray radiation**



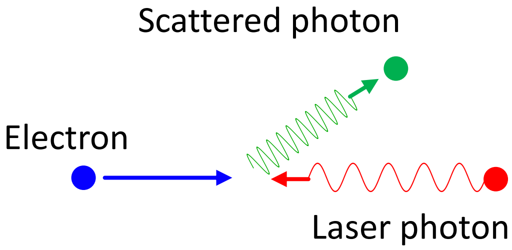

**Bremsstrahlung**



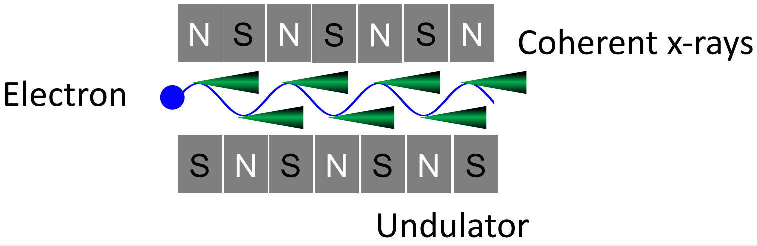

**THz/transition radiation**



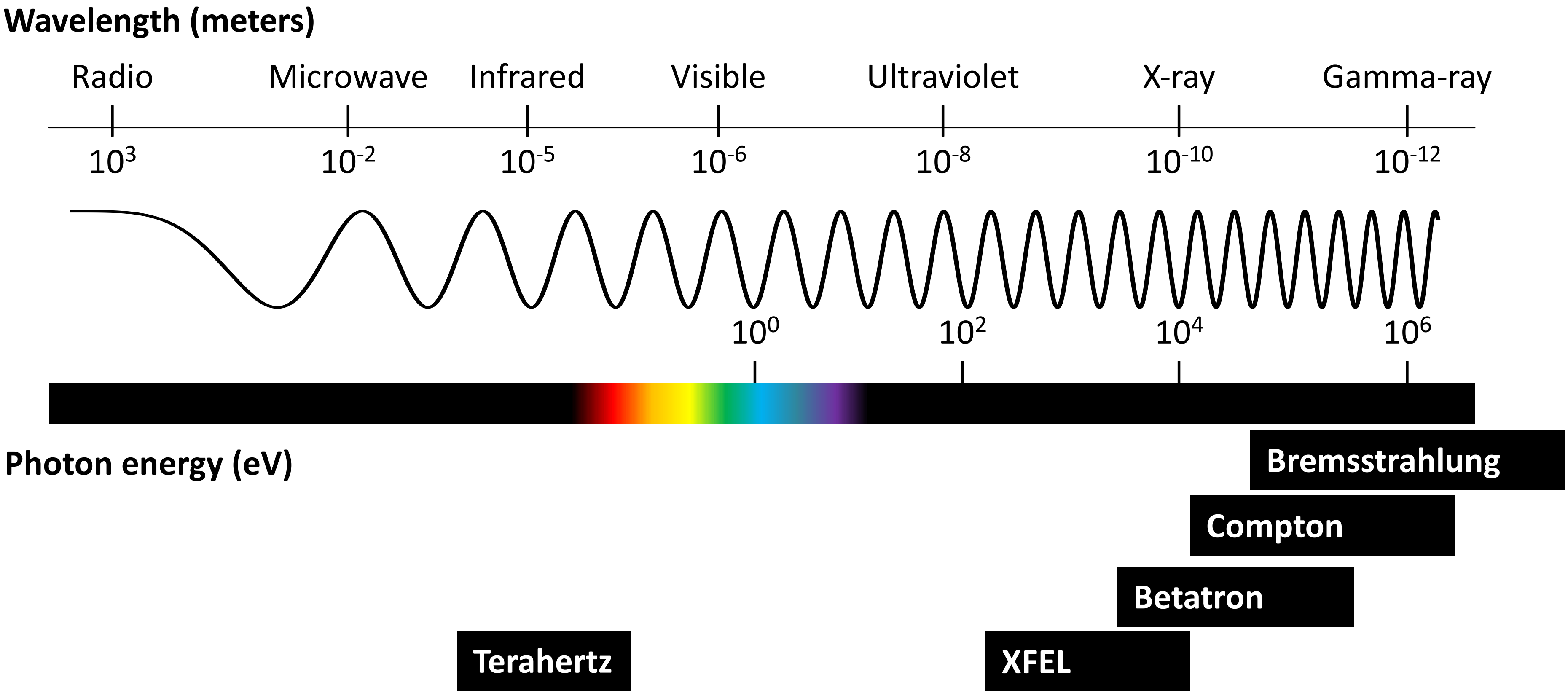

**Compton scattering**




**Undulator/X-FEL radiation**

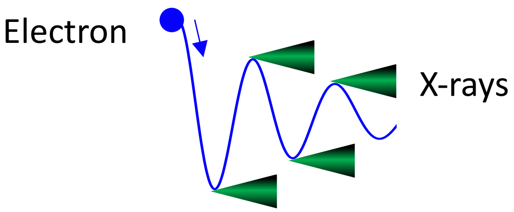


# Sources driven by LPA span the entire spectrum of radiation



# Electrons from laser plasma accelerators can emit radiation

## Betatron x-ray radiation




## Bremsstrahlung



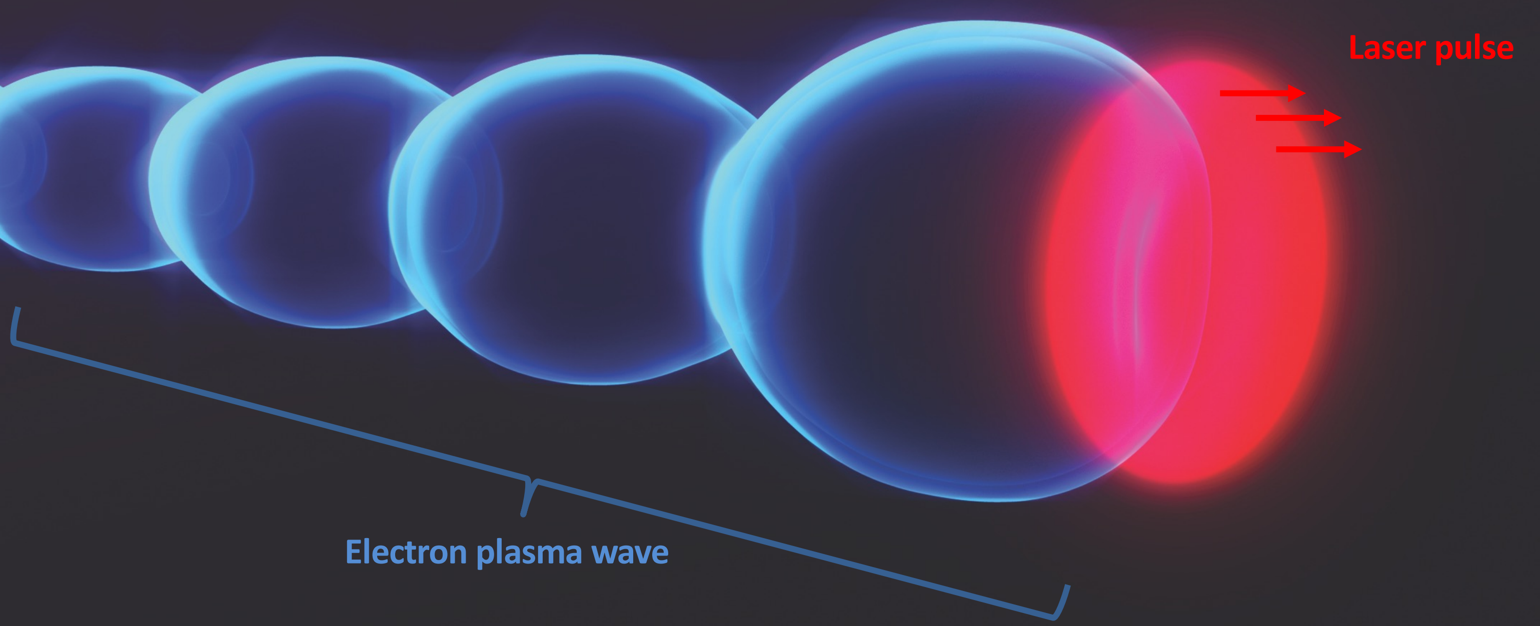

## THz/transition radiation



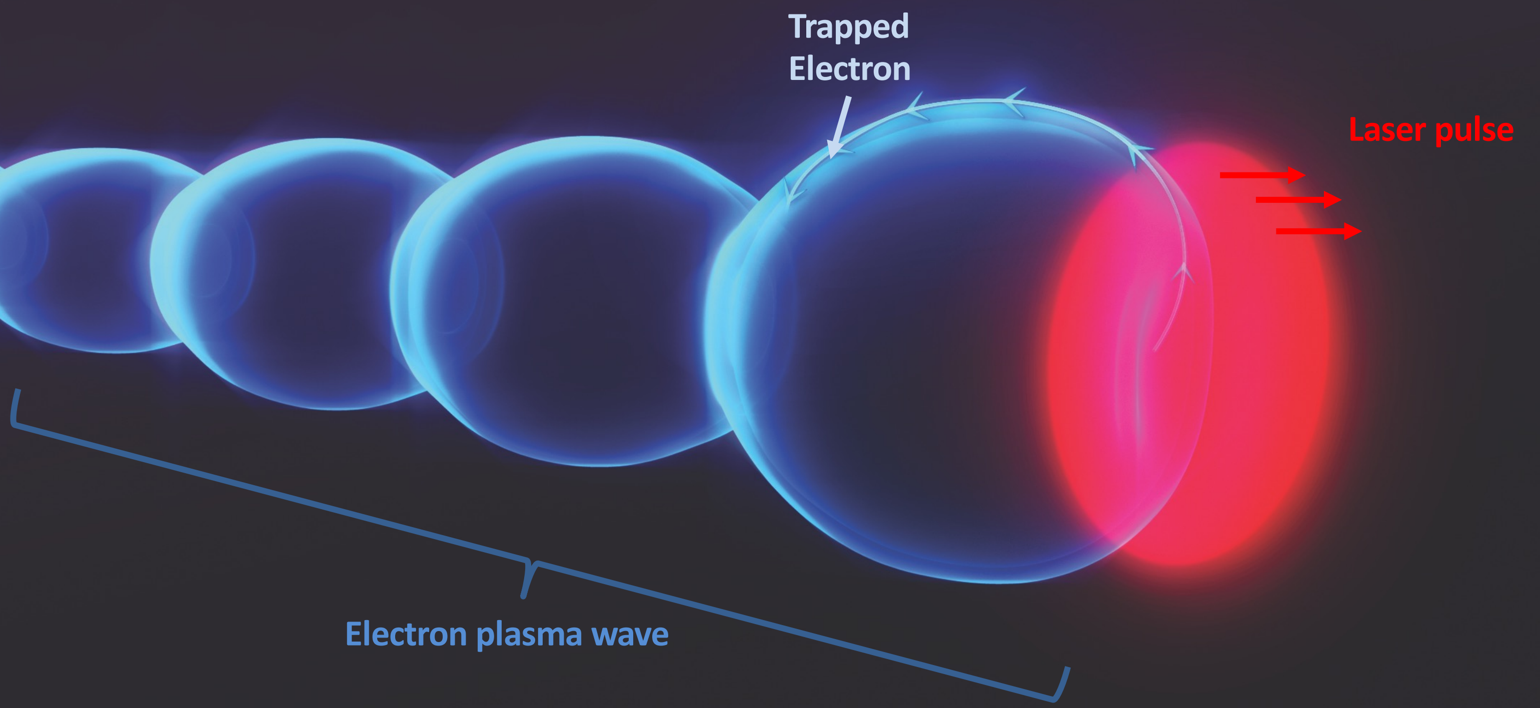

## Compton scattering




## Undulator/X-FEL radiation




F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)

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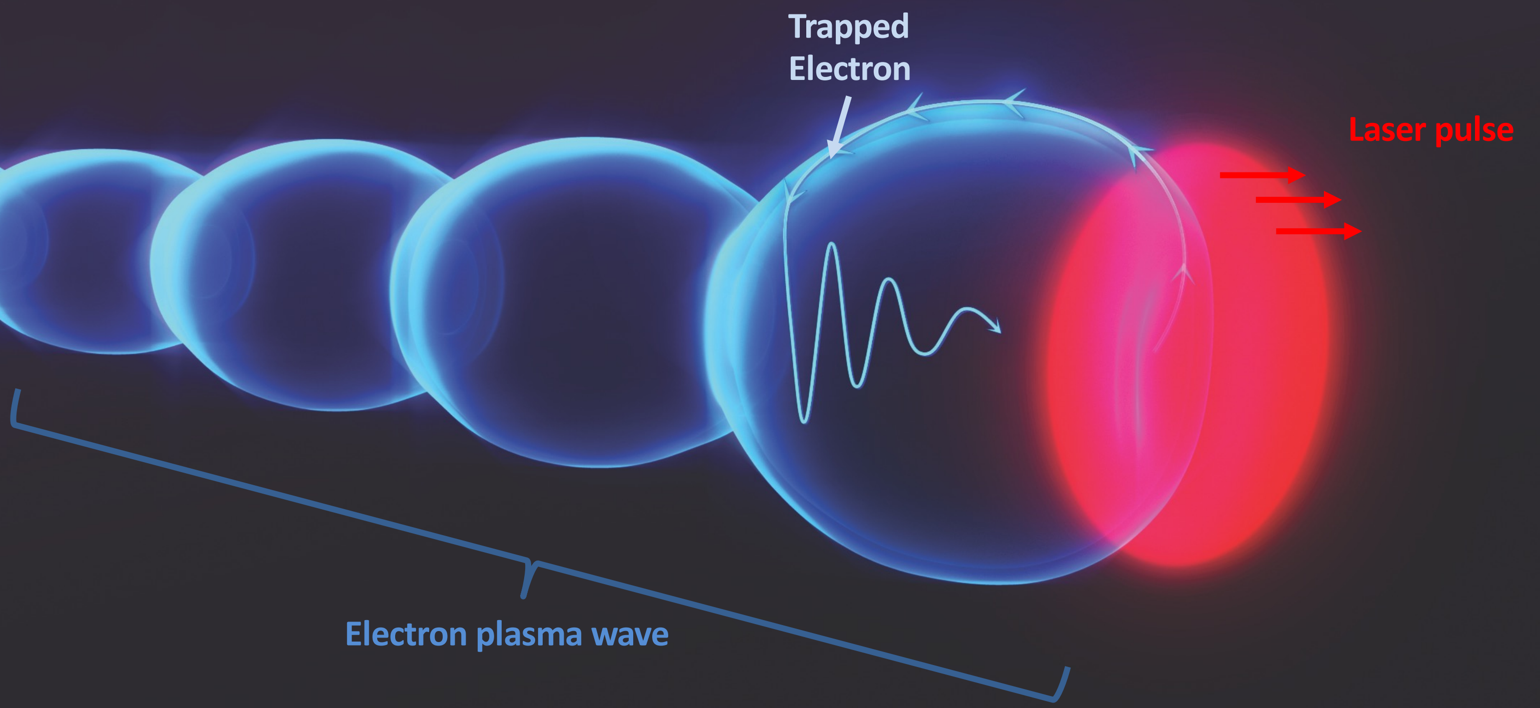


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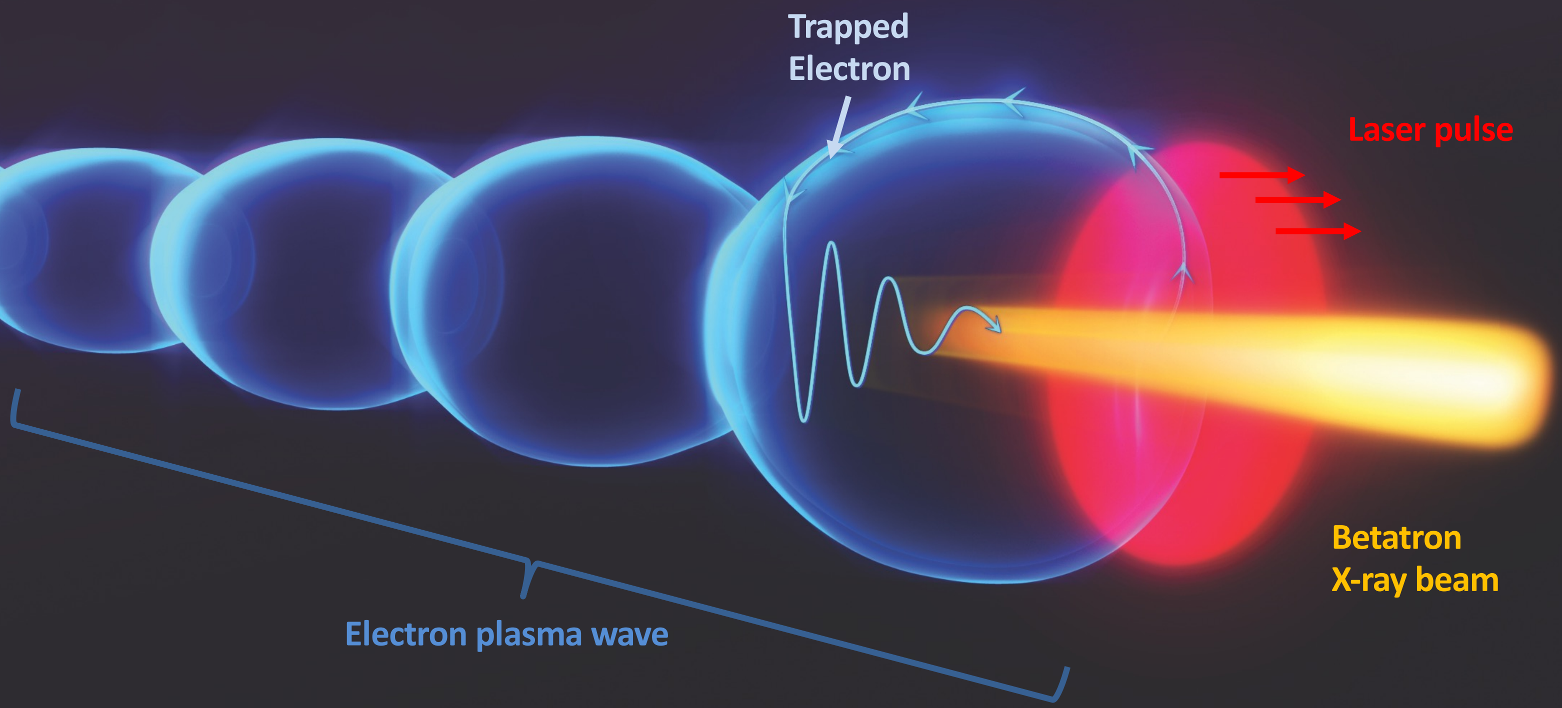


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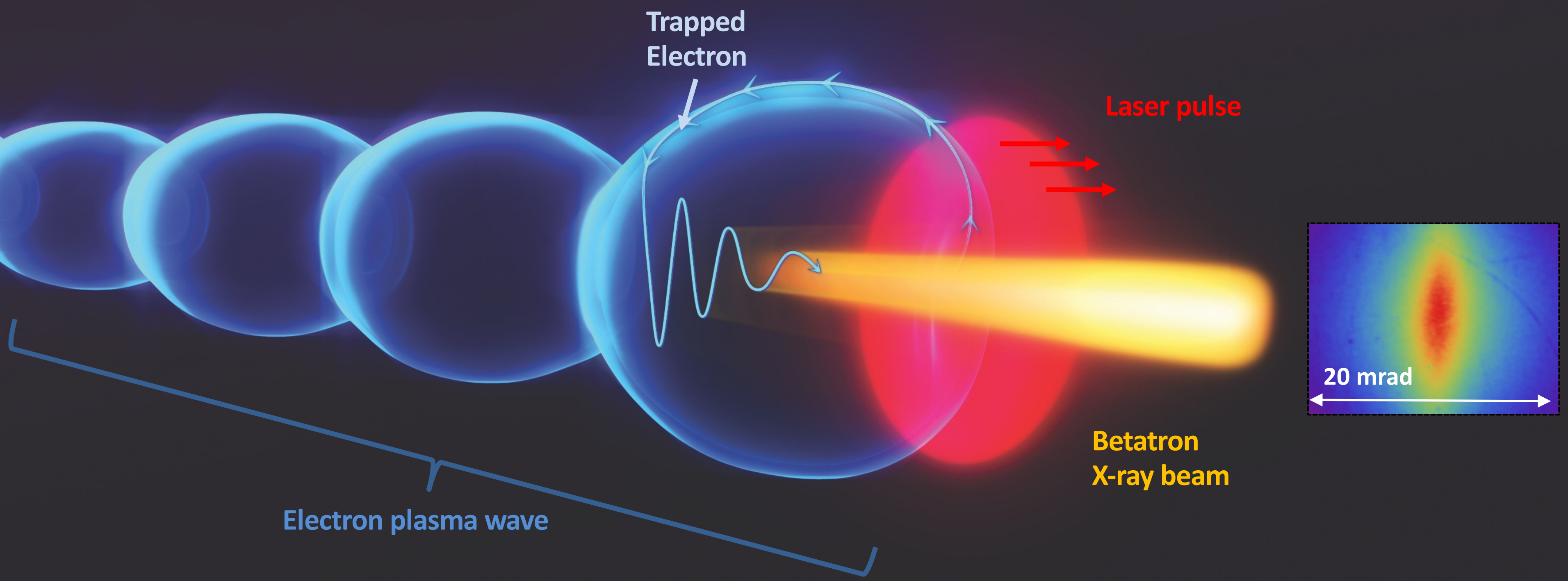


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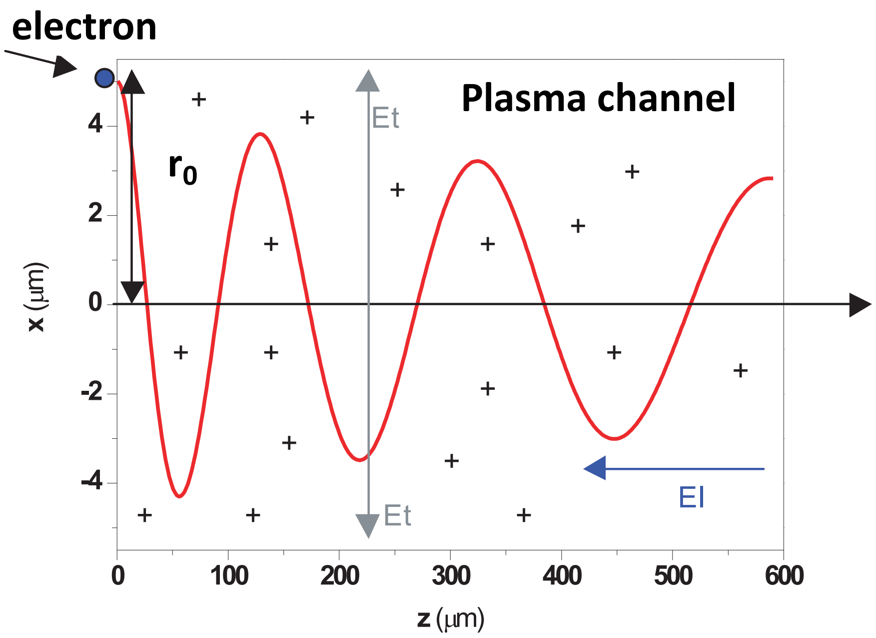
# Single electron model of betatron oscillations

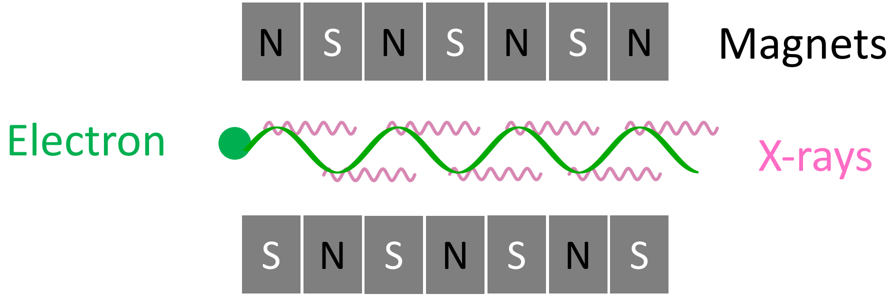
- If the electron is injected off axis, the transverse restoring force can be calculated with Gauss Law $\boldsymbol{F} = -m_e \omega_p \frac{\boldsymbol{r}}{2}$
- The equation of motion for the electron is $\frac{d\boldsymbol{p}}{dt} = -m_e \omega_p \frac{\boldsymbol{r}}{2} - \mathrm{e}\boldsymbol{E_z}$
- Neglecting acceleration, the equation is that of an harmonic oscillator: $\frac{d^2x}{d^2t} = -\frac{\omega_p^2}{2\gamma} x$
- $x = r_0 \sin(\omega_\beta t)$ and $\beta_x = \frac{v_x}{c} = k_\beta r_0 \cos(\omega_\beta t)$
- Betatron freq. $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} = k_\beta \mathrm{c} = 2\pi c/\lambda_\beta$




Example: $n_e$ = 1 x $10^{19}$ $cm^{-3}$ and $\gamma = 200$ means $\lambda_\beta = 212\ \mu m$

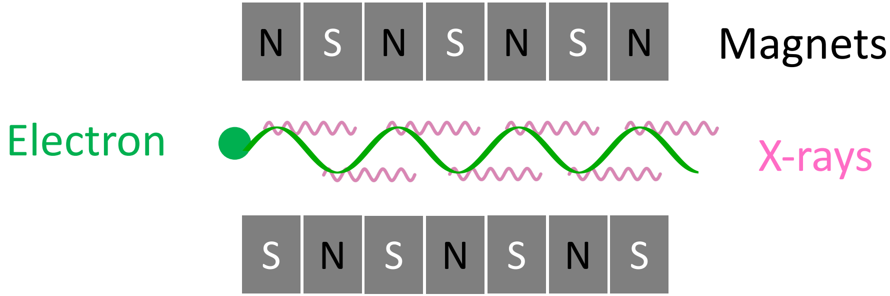
# How does the betatron source compare to a synchrotron?

# How does the betatron source compare to a synchrotron?




In synchrotrons
Magnets are used to change the particle's path

# How does the betatron source compare to a synchrotron?

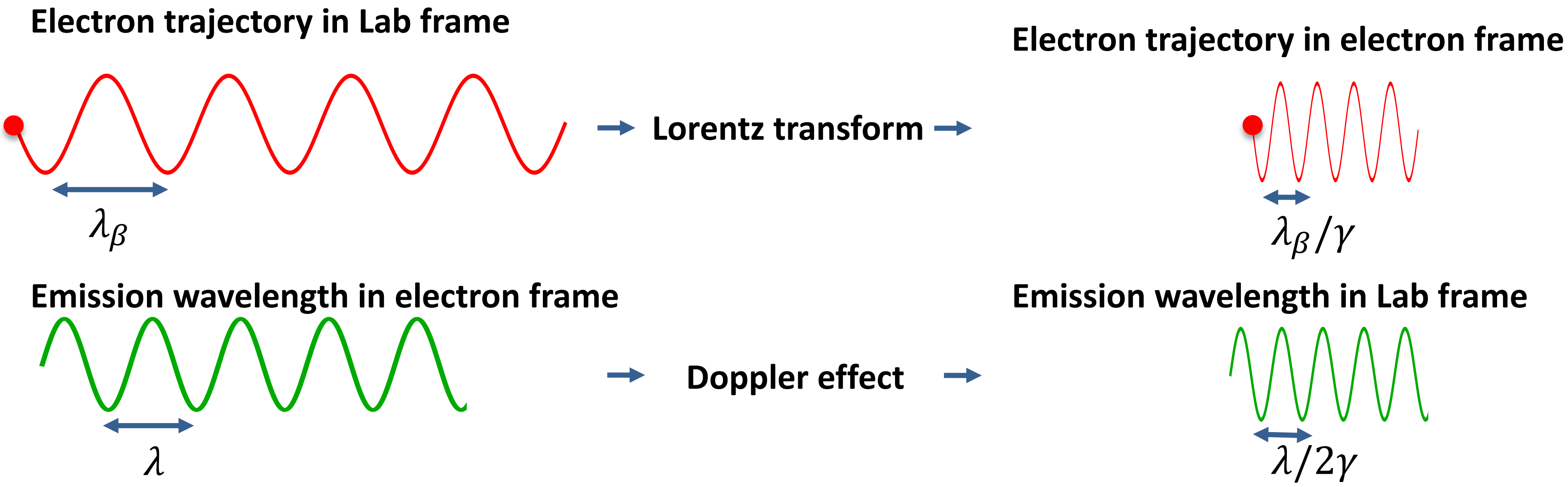



In synchrotrons
Magnets are used to change the particle's path

There are no magnets in a plasma but the electron will use the wave to wiggle

# Another Relativity detour

- An electron oscillating with period $\lambda_\beta$ emits at a wavelength $\lambda_\beta/2\gamma^2$



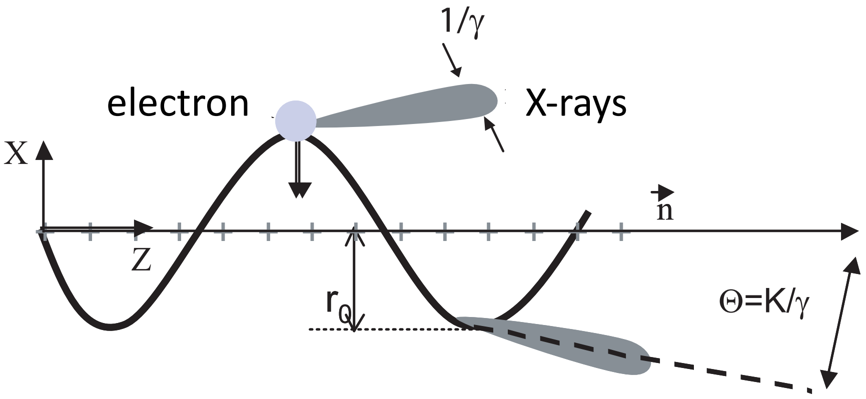

<u>Example:</u> $n_e$ = 1 x $10^{19}$ $cm^{-3}$ and $\gamma = 200$ means $\lambda_\beta = 212\ \mu m \rightarrow 2.64\ nm$ emission (470 eV)

# Betatron wiggler strength K

- If we approximate $z \sim ct$ (electrons near speed of light) then $x = r_0 \sin(k_\beta z)$
- The angular excursion of the particle with respect to the propagation axis is $\theta = \left(\frac{dx}{dz}\right)_{z=0} = k_\beta r_0$
- We define the wiggler strength $K = \gamma\theta = \gamma k_\beta r_0$
- Practical units

$$K = 1.33\times10^{-10}\sqrt{\gamma n_e[cm^{-3}]}r_0[\mu m]$$

- Undulator regime $K < 1$
- Wiggler regime $K >> 1$




Example: $n_e$ = 1 x 10$^{19}$ cm$^{-3}$, $\gamma = 200$ and $r_0 = 3\ \mu m$ means $K = 18$
Most of the time we are in the wiggler regime

# Wiggler regime K>>1

- $z \sim ct$ is only an approximation
- We need to take into account the longitudinal and transverse components of the electron velocity such that

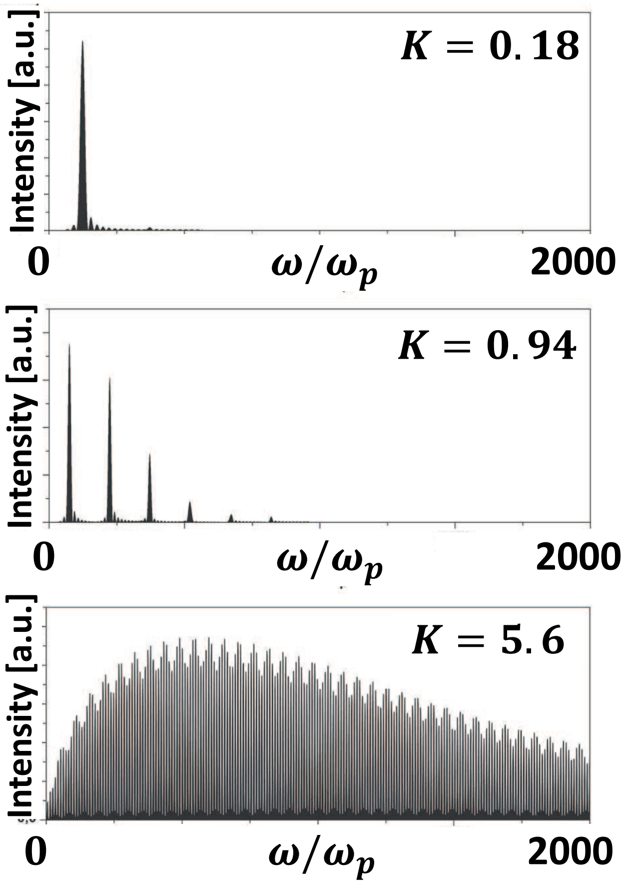
$$\gamma = \sqrt{\frac{1}{1-\beta^2}} = \sqrt{\frac{1}{1-\beta_z^2-\beta_x^2}}$$

- Coupling between transverse and longitudinal components -> position and velocity have harmonics

$$\beta_z \simeq 1 - \frac{1}{2\gamma^2} - \frac{k_\beta^2 r_0^2}{4} - \frac{k_\beta^2 r_0^2}{4}\cos(2k_\beta ct),$$

$$z \simeq (1 - \frac{1}{2\gamma^2} - \frac{k_\beta^2 r_0^2}{4})ct - \frac{k_\beta^2 r_0^2}{8}\sin(2k_\beta ct).$$

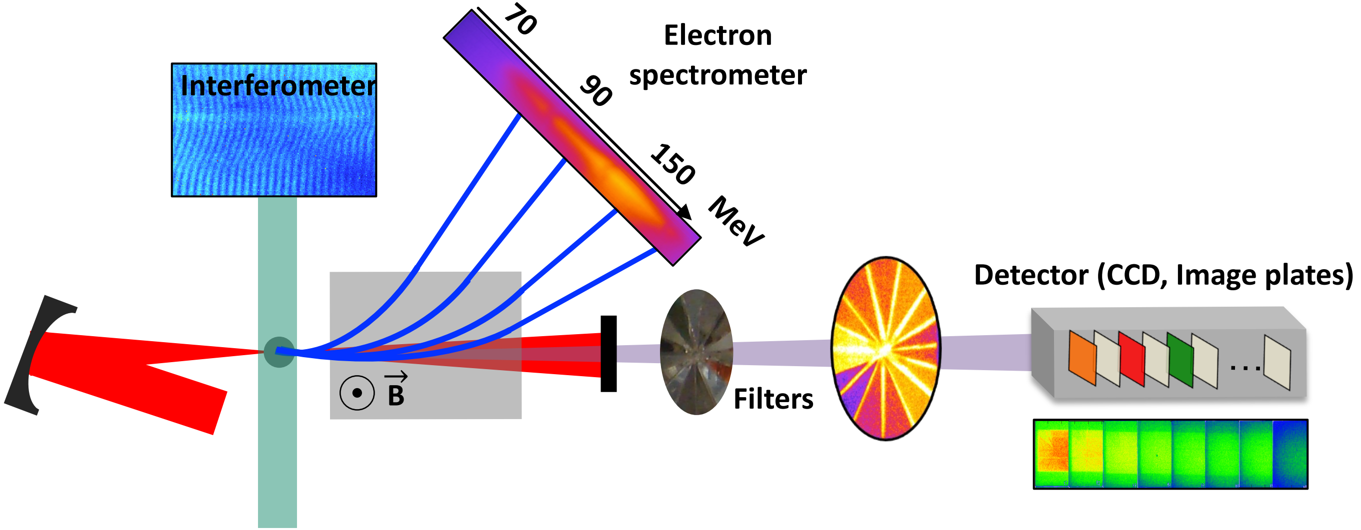
- Emission will contain harmonics of fundamental radiation and $\omega_n = \frac{2\gamma^2 n\omega_\beta}{1+K^2/2}$






E Esarey, Phys. Rev. E (2002); K. Ta Phuoc, Physics of Plasmas (2005)

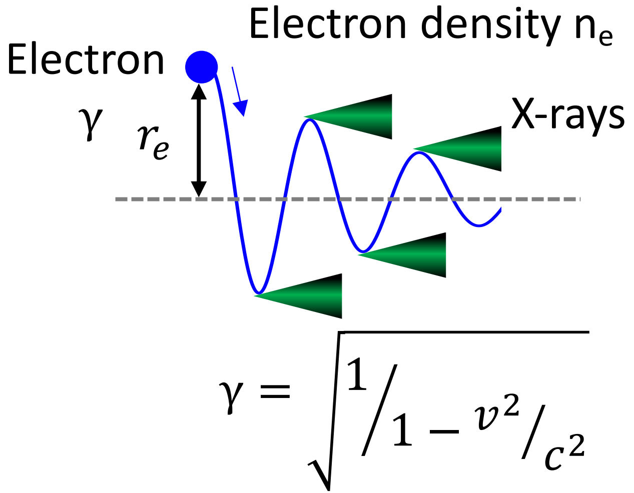
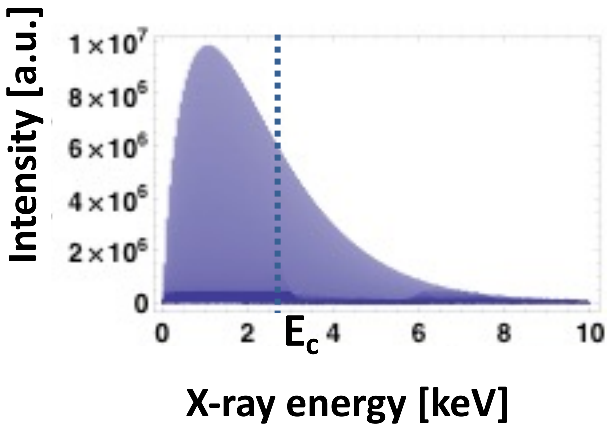
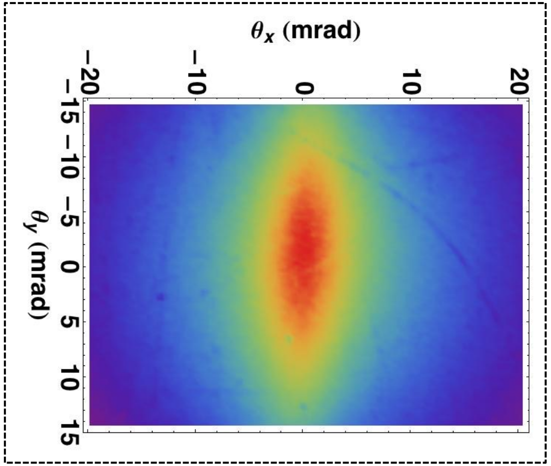
# A typical betatron radiation experiment






F. Albert et. al, *Phys. Rev. Lett*. 111, 235004 (2013), *Phys. Rev. Lett*. 118, 134801 (2017)

# Betatron x-ray source properties

| Electron trajectory | Spectrum | Beam profile |
| --- | --- | --- |
|  |  |  |







**Critical energy $E_c$ ~** $\gamma^2 n_e r_0$

**Beam divergence $\theta$ ~** $r_0 \sqrt{\frac{n_e}{\gamma}}$

# Electrons from laser plasma accelerators can emit radiation

## Betatron x-ray radiation



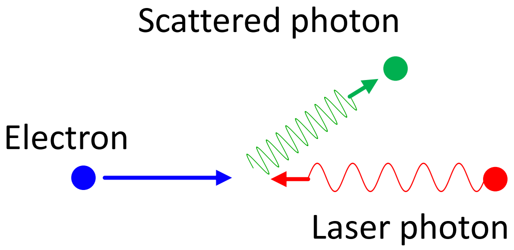

## Bremsstrahlung




## THz/transition radiation

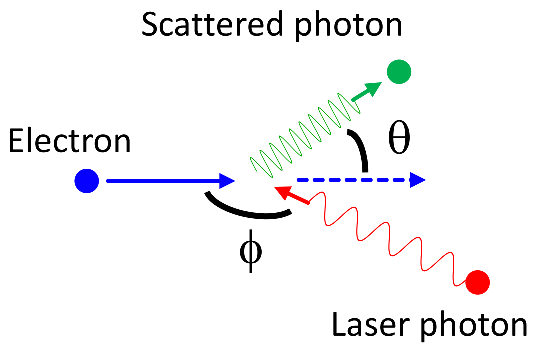



## **Compton scattering**




## Undulator/X-FEL radiation

# Compton scattering relies on energy-momentum conservation




Electron energy

Laser photon energy

$$E_x = \frac{2\gamma^2(1 - \cos\phi)}{1 + \gamma^2\theta^2 + a_0^2/2 + 2\gamma k_0 \lambda_c} E_{\rm ph}$$

Nonlinear effects

Recoil "radiation reaction"

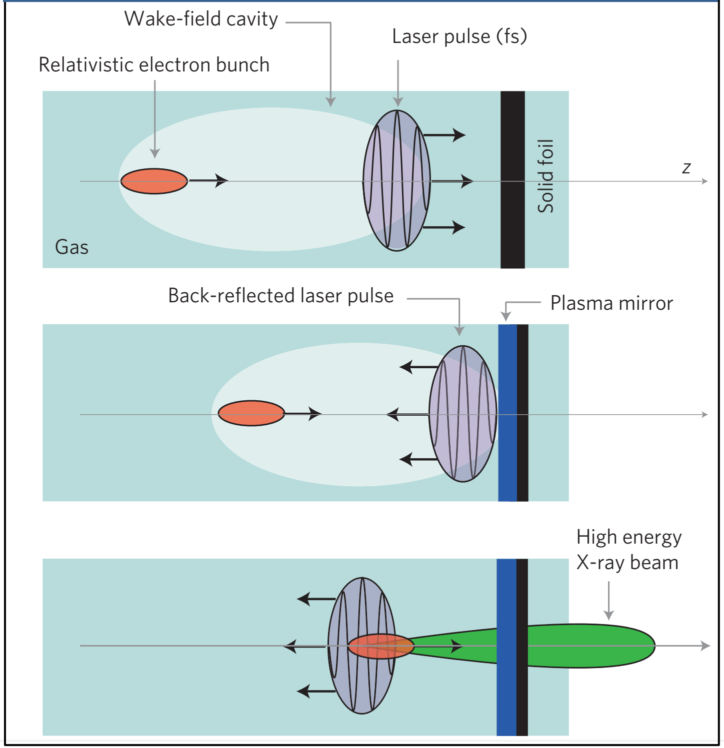
For head on collision (ϕ=180 degrees) and on axis (θ=0 degrees)

**Photon energy E$_x$** $\sim 4\gamma^2 E_L$

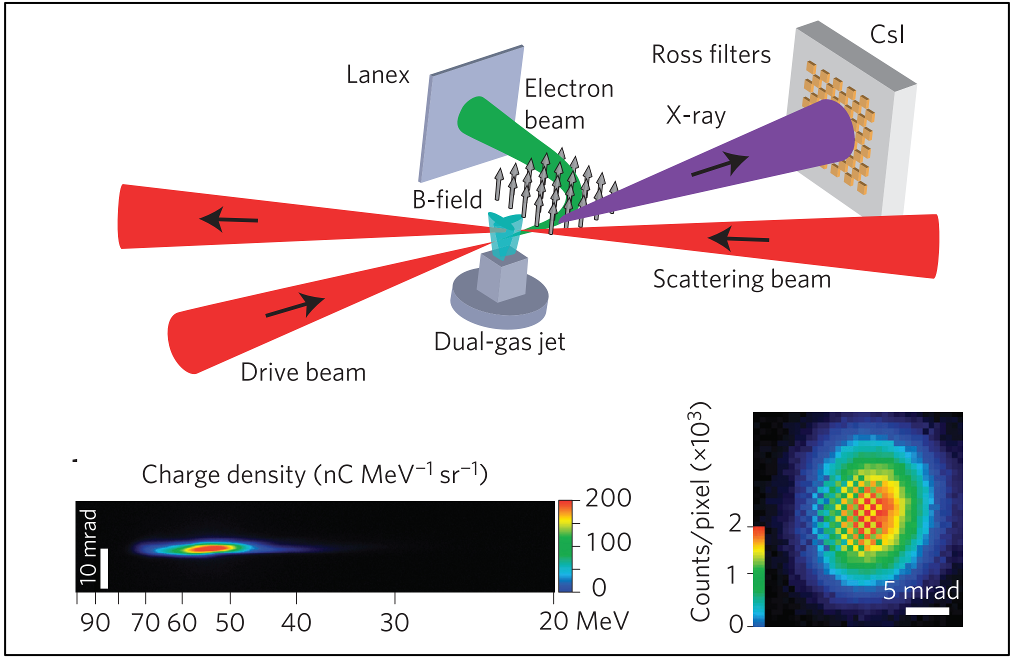
Example: $\gamma = 200$ and $E_L = 1\ eV$ means $E_X = 160\ keV$
You get higher energies than with betatron radiation!

# The colliding laser is provided by a plasma mirror or a second beam

## Plasma mirror[1]




## Two beams[2]





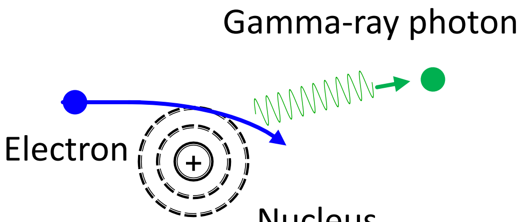

[1] **K. Ta Phuoc et al, Nature Photonics (2012),** H.E. Tsai et al, Phys. Plasmas (2015). [2]H. Schwoerer et al, Phys. Rev. Lett (2006), **N.D. Powers et al, Nature Photonics (2014),** K. Khrenikov et al, Phys. Rev. Lett (2015)

# Electrons from laser plasma accelerators can emit radiation

## Betatron x-ray radiation




## Bremsstrahlung




## THz/transition radiation

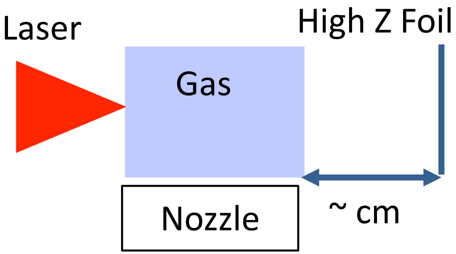



## Compton scattering

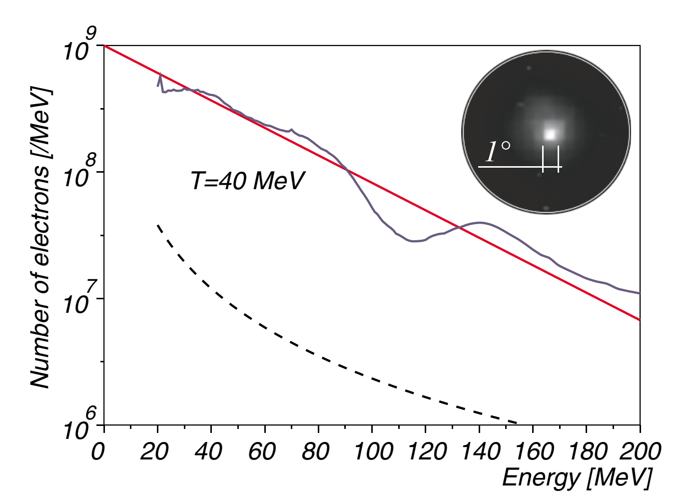



## Undulator/X-FEL radiation

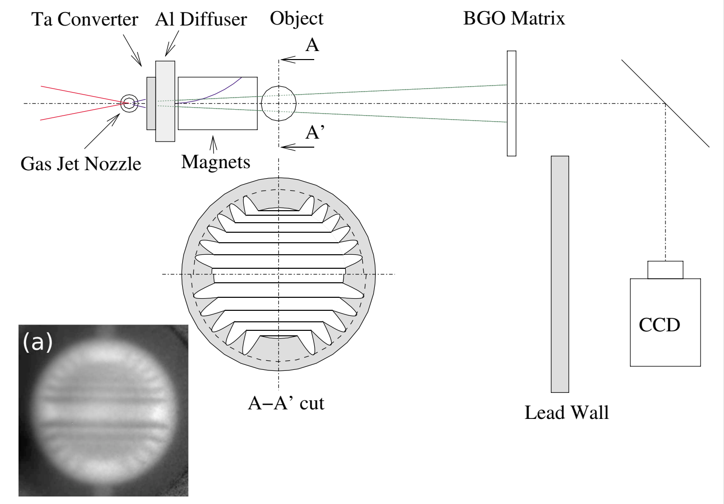
# Bremsstrahlung is produced when electrons from the LPA are bombarded into a high Z solid foil




## Higher energy spectrum than Compton




## Gamma-ray radiography

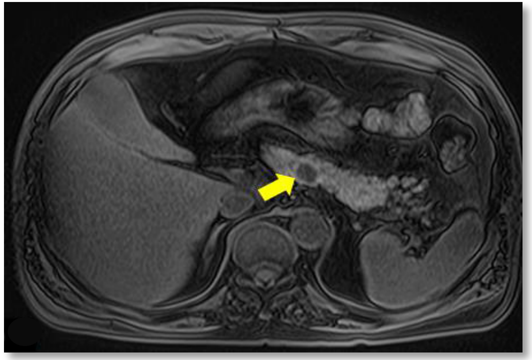


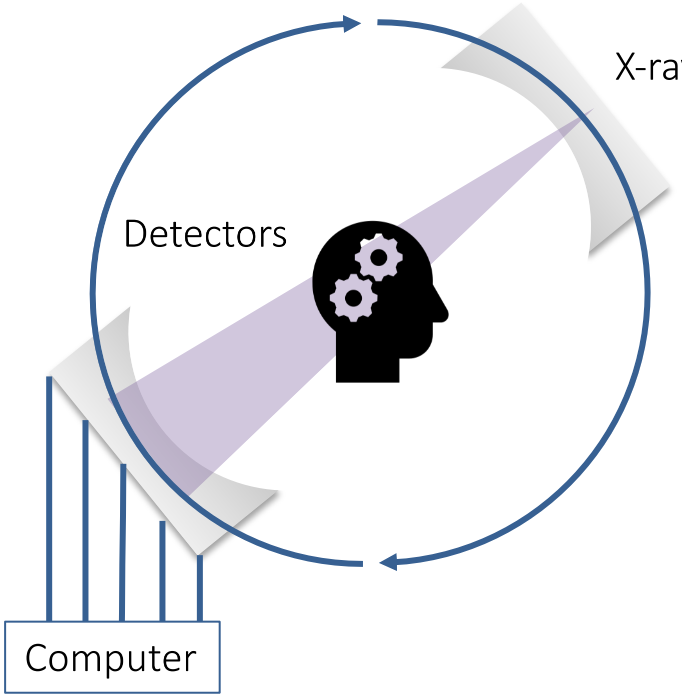

Y. Glinec et al, Phys. Rev. Lett (2005)

# Outline

- Conventional light sources: Synchrotrons and X-ray Free Electron Lasers
- Laser Plasma Acceleration
- High Intensity Lasers
- Light sources driven by laser plasma acceleration
  - Betatron
  - Compton scattering
  - Bremsstrahlung
  - X-ray free electron laser
  - Terahertz
- How wan we use these sources?

# Medical x-ray imaging requires excellent spatial resolution, fast acquisition and low dose delivered to the patient



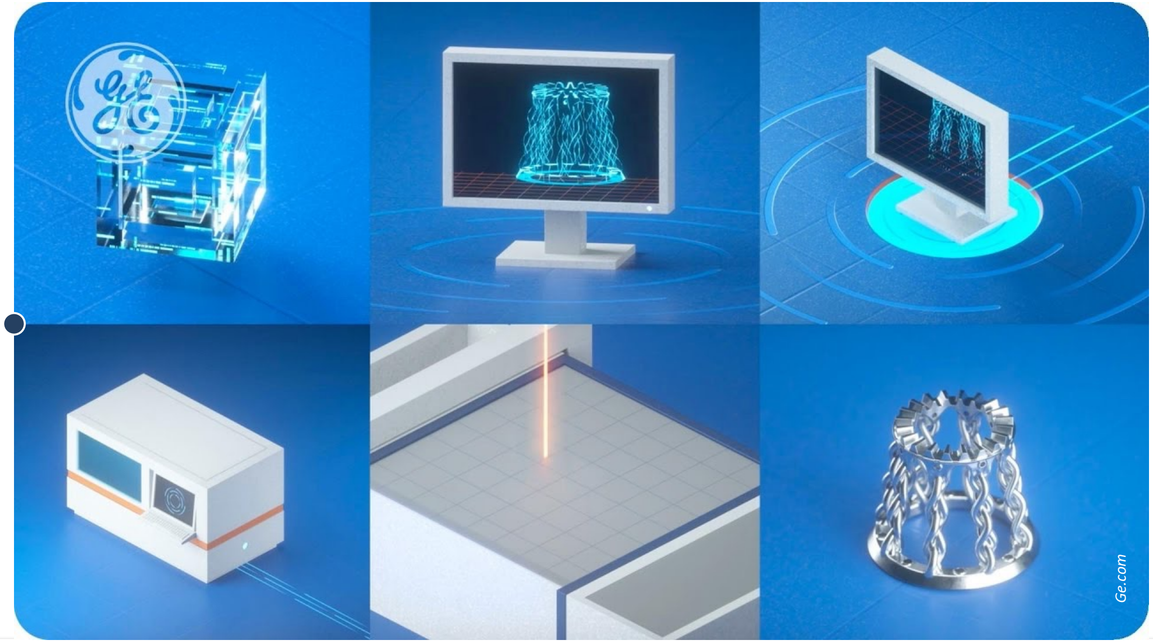

## Typical x-ray CT scan specs

- **Resolution:** ~ mm (100 µm possible with longer exposure time)
- **Cost:** ~ $1200/scan (machine ~ $1 Million)
- **Dose:** *1000x* regular x-ray (CT is 15 % of all exams but 70 % of the dose)

*D. W. Lee et al, Clin Endosc (2017)*

# Additive manufacturing (AM) requires non-invasive, in-situ diagnostic methods with extreme precision that x-ray imaging can offer

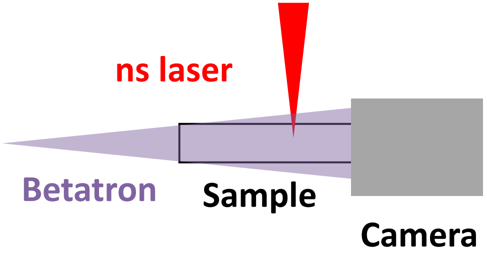
AM builds parts by adding material as opposed to standard machining techniques

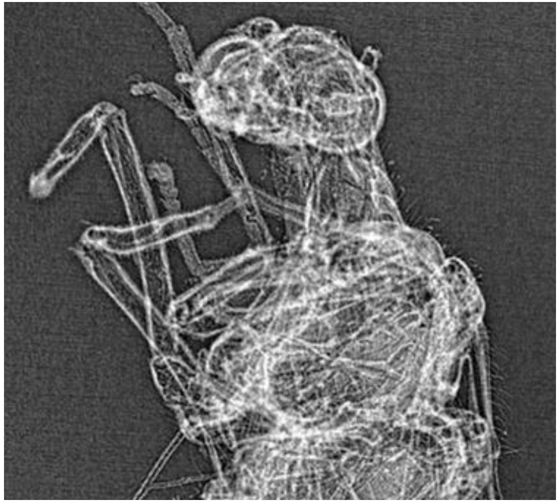



**Production issues can occur**

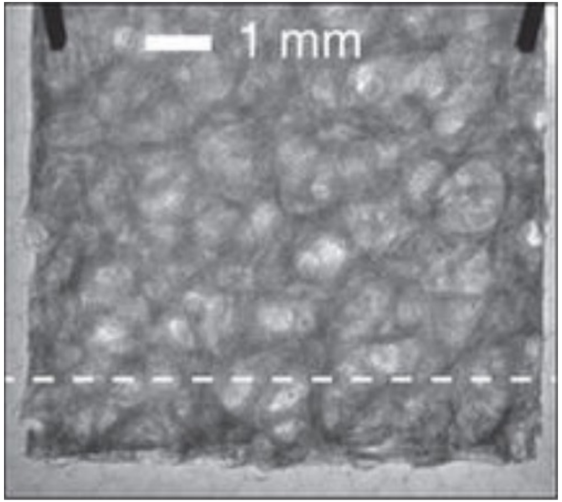
- Incorrect processing parameters or build conditions
- Surface roughness or imperfections
- Deformation caused by stress
- Anisotropic mechanical properties

# Small source size enables x-ray phase contrast imaging

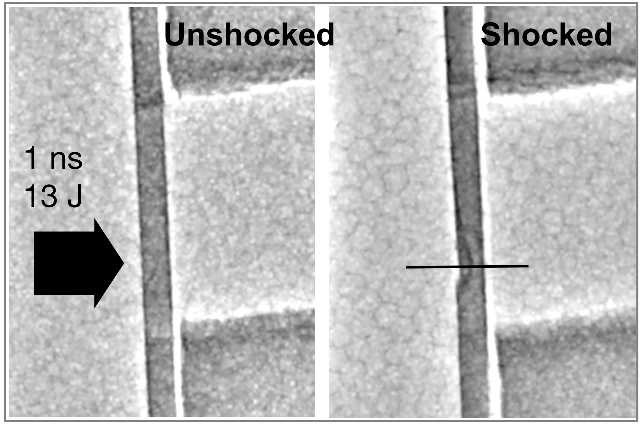


Chrysoperia carnea
Wenz et al, *Nat. Comm* (2015)



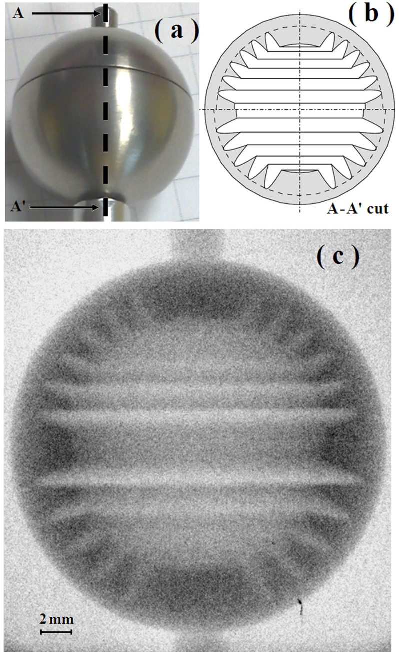

Trabecular hip bone sample
Cole et al, *Sc. Rep* (2015)



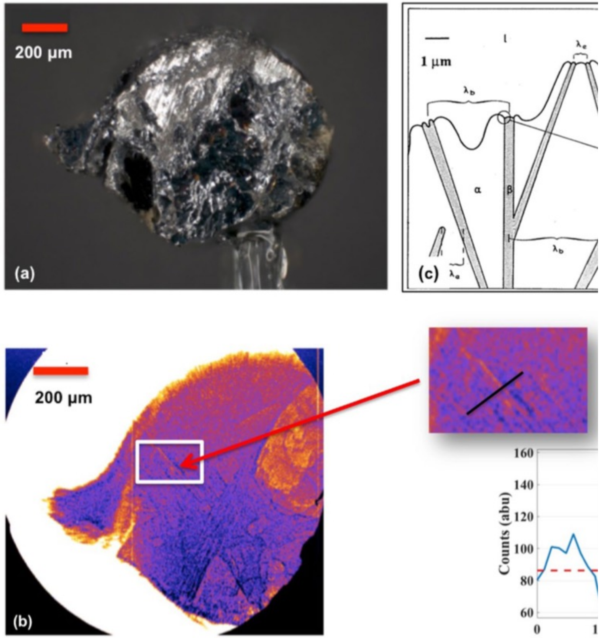

Laser-driven shock
J. Wood et al, *Sc. Rep* (2018)

# Radiography of materials and compounds for industrial and national security applications

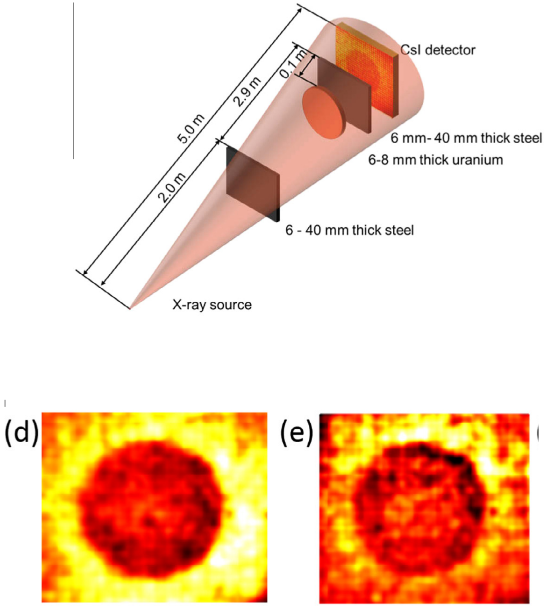
Complex objects (Bremsstrahlung)




Surface defects in alloys (Betatron)



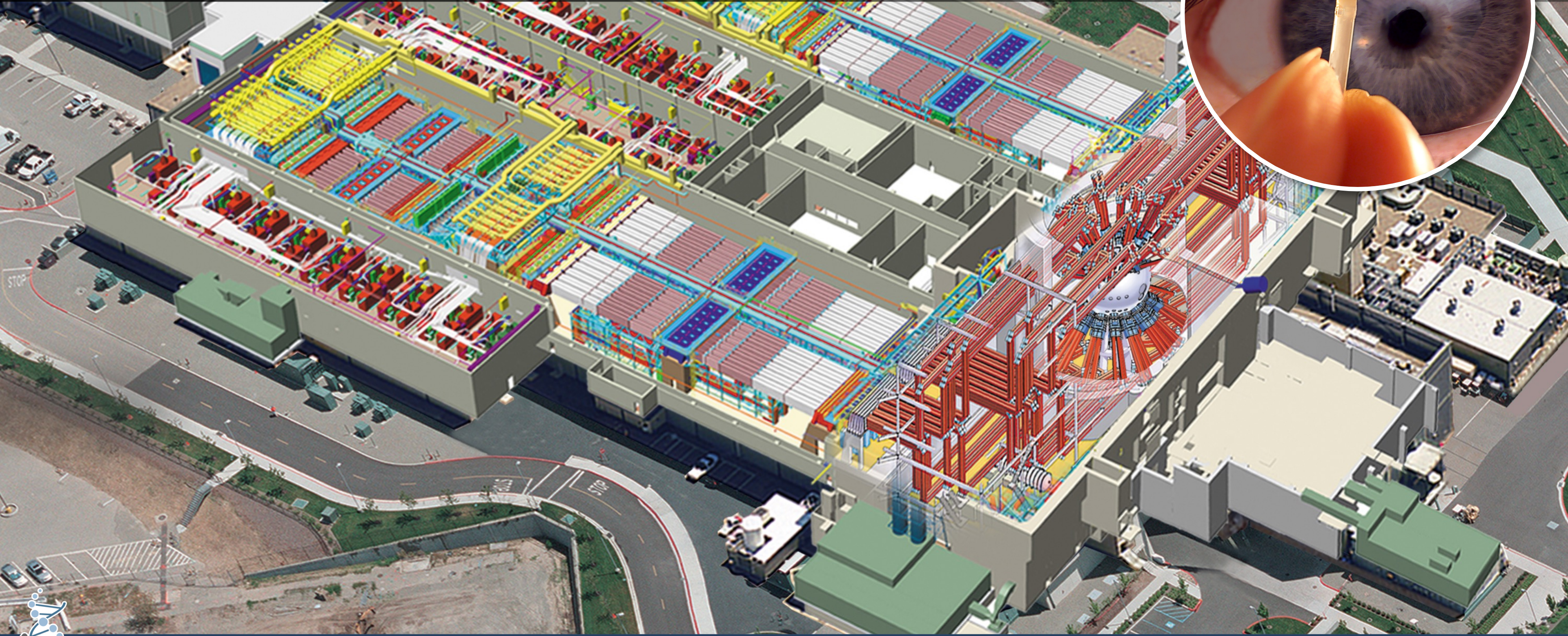

Concealed threats (Compton scattering)



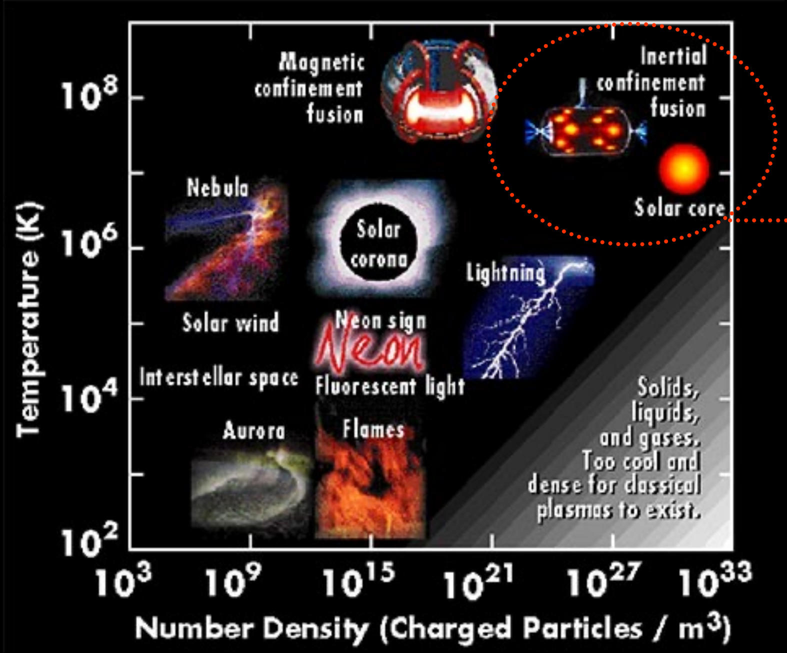


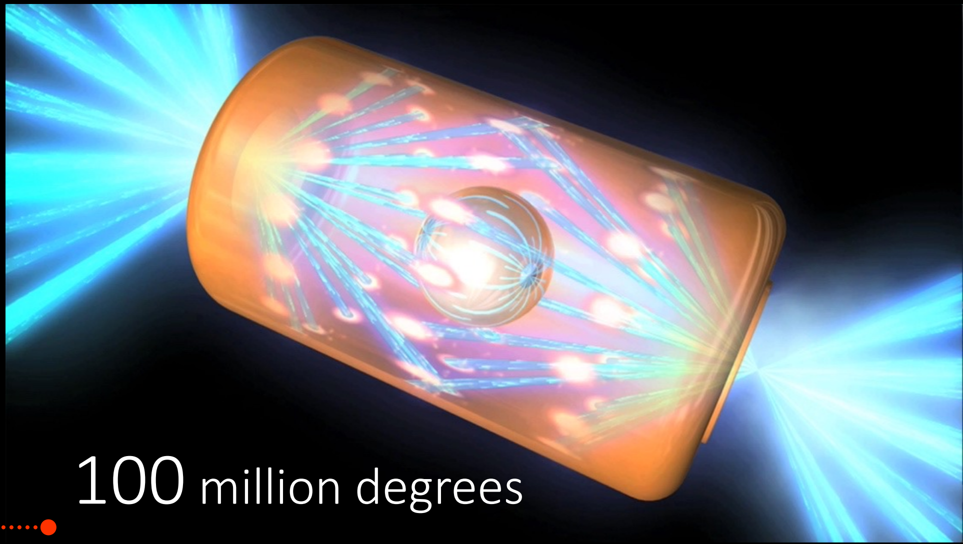

A. Ben-Ismail et al., *Appl.Phys.Lett.* (2011); A. E. Hussein et al., *Sc Rep.* (2019); S. Chen et al., *Nuc. Inst. Meth. Phys. Res. B* (2016)

# At LLNL we use the largest, most energetic laser on earth to concentrate its 192 beams into a mm3



# Such experiments create extreme, transient conditions of temperature and pressure that are hard to diagnose

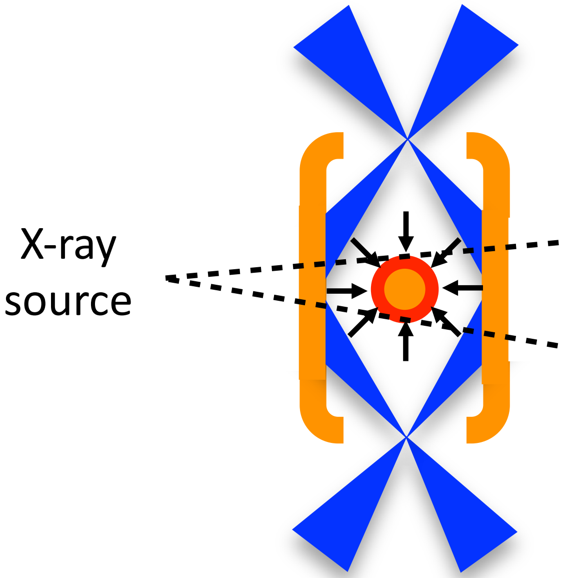


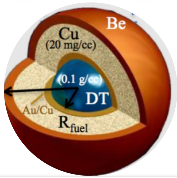



100 million degrees

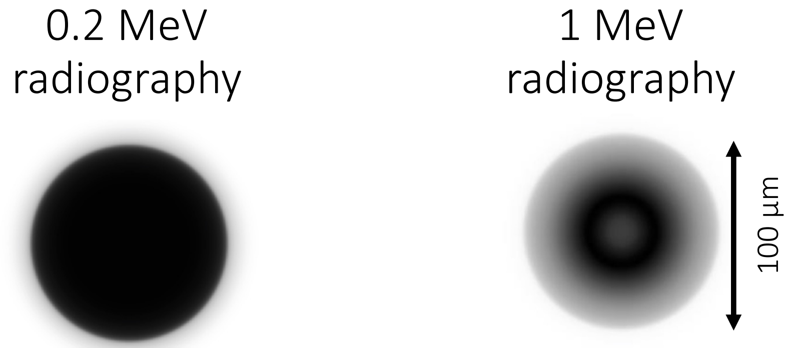
20x the density of lead

# X-ray sources with MeV photons and <10 µm resolution are required to understand some of the experiments done at the NIF



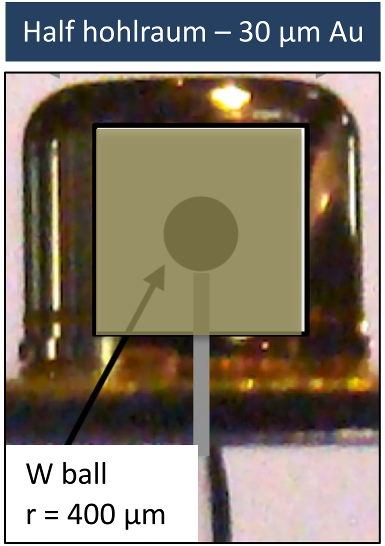




Double shell
implosion, 1800 g/cc

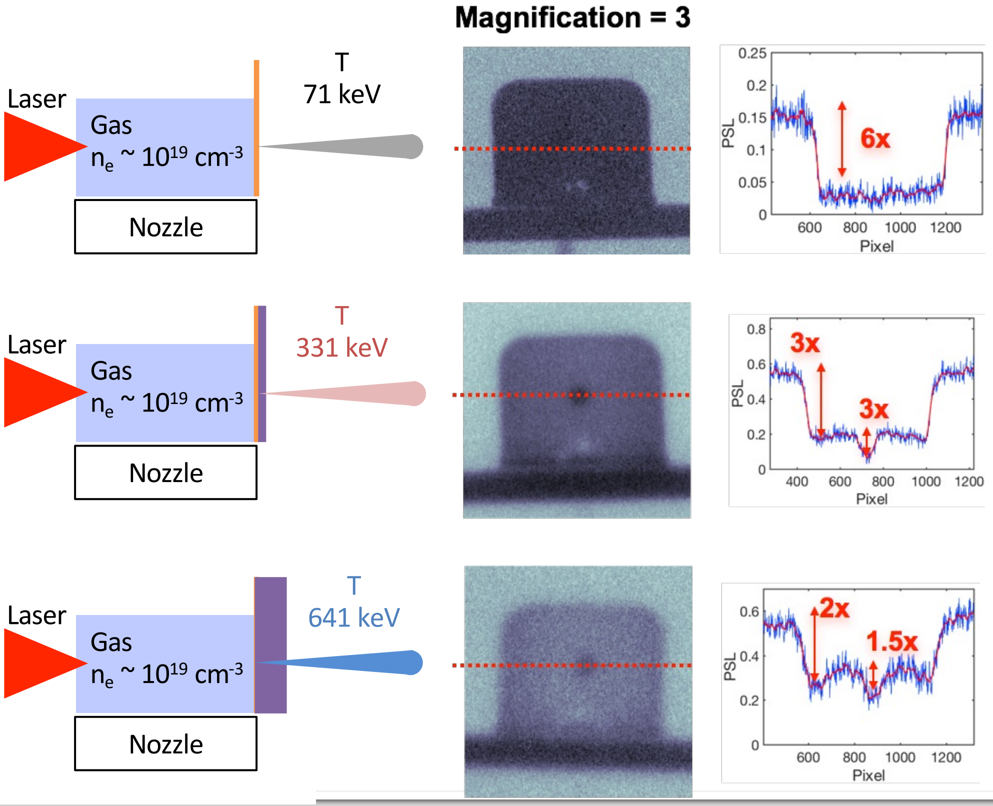



**Fully imploded capsule**

# Spectral and flux tuning allows for optimized radiography applications



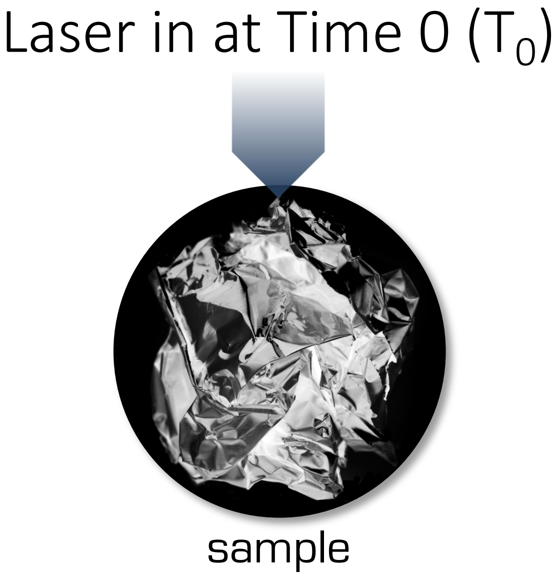

W ball areal density
~ 0.7 g/cm$^2$



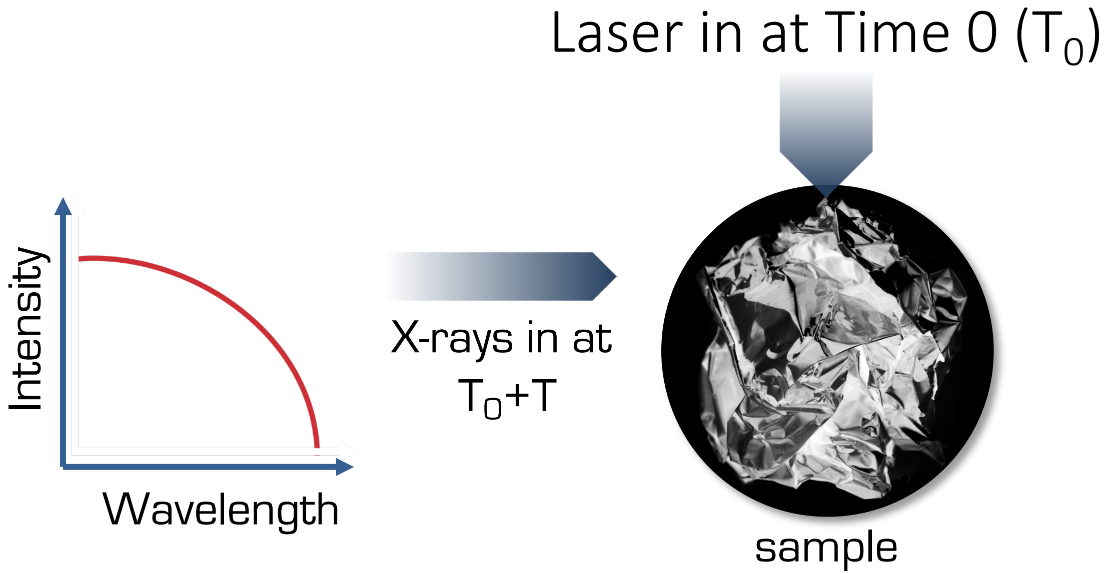
# We use ”pump-probe” experiments and x-ray measurement techniques to understand these conditions

## X-ray absorption spectroscopy

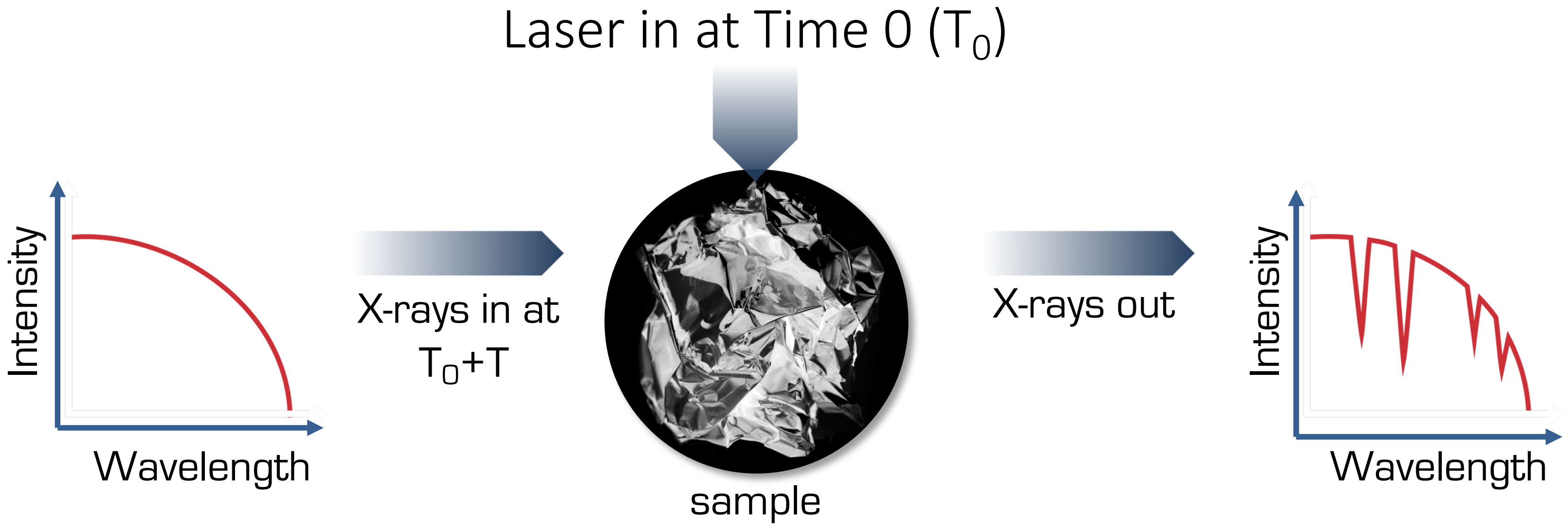
# We use ”pump-probe” experiments and x-ray measurement techniques to understand these conditions



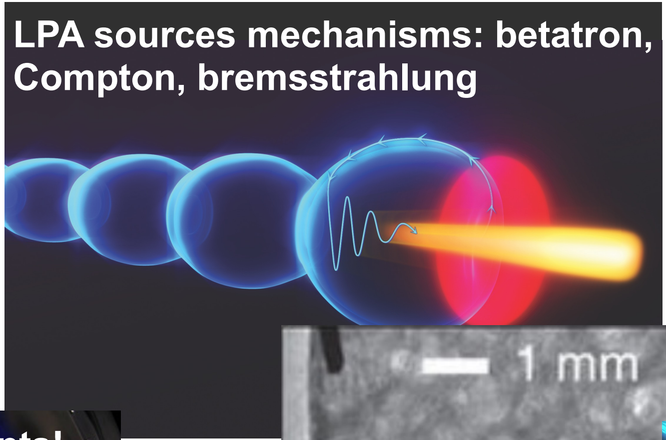
# We use ”pump-probe” experiments and x-ray measurement techniques to understand these conditions



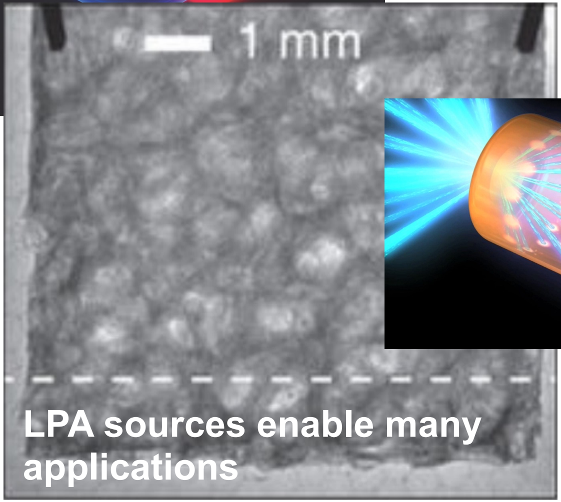
# We use ”pump-probe” experiments and x-ray measurement techniques to understand these conditions

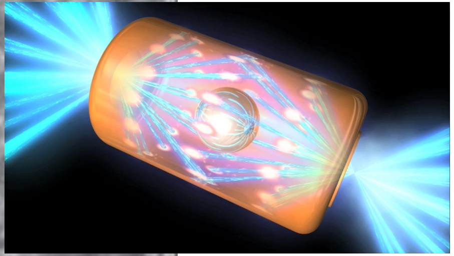


# What we’ve learned today





Lawrence Livermore
National Laboratory