MARVELOUS MACHINES

Laser-Plasma Accelerators:

Riding the Wave to the Next Generation X-Ray Light Sources

Félicie Albert, LLNL

with Dan Burns, Los Gatos HS

Science on Saturday

Presented by

Lawrence Livermore National Laboratory

LLNL-PRES-746399

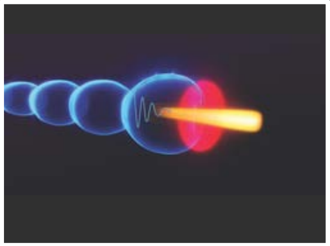
Outline of today's talk

Photo: SLAC National Laboratory

- What are particle accelerators and how do they work?
- Making X-rays with particle accelerators

- Miniature particle accelerators using lasers and plasmas: laser wakefield accelerators

- Making x-rays with laser wakefield accelerators

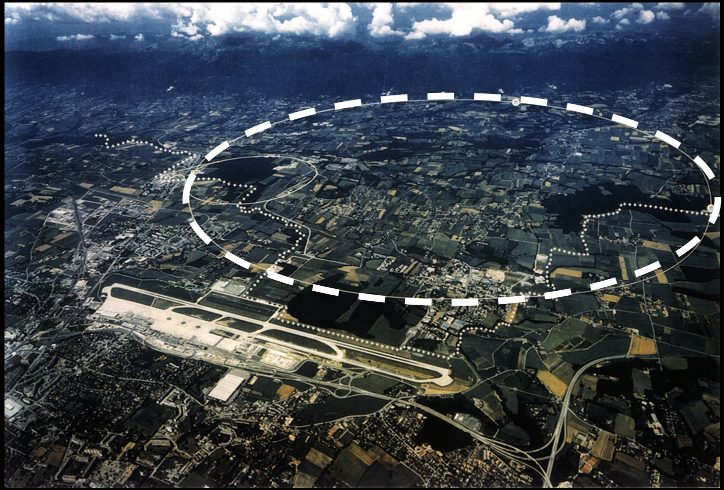


- Some applications

What are particle accelerators?

Particle accelerators are big machines

CERN (Geneva)
Large Hadron Collider



27 km circumference

Paris

31 km circumference

What are particle accelerators used for?

Fundamental Discoveries

Medical Applications

Industry

National Security

Particle accelerators use charged particles

Elements: what constitutes ordinary matter around us

Hydrogen, Oxygen (H_2O)

Oxygen (O_2)
Nitrogen (N_2)

Carbon (C)

Copper (Cu)

Particle accelerators use charged particles

Elements: what constitutes ordinary matter around us

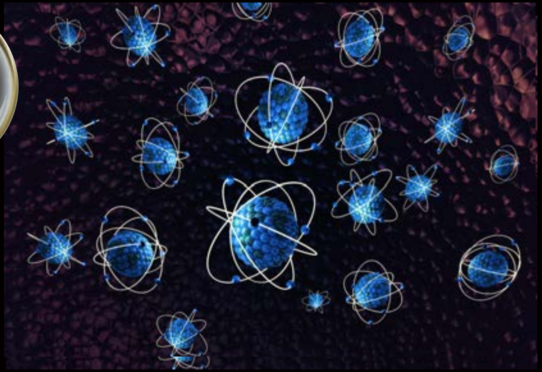
Hydrogen, Oxygen (H_2O)

Oxygen (O_2)
Nitrogen (N_2)

Carbon (C)

Copper (Cu)

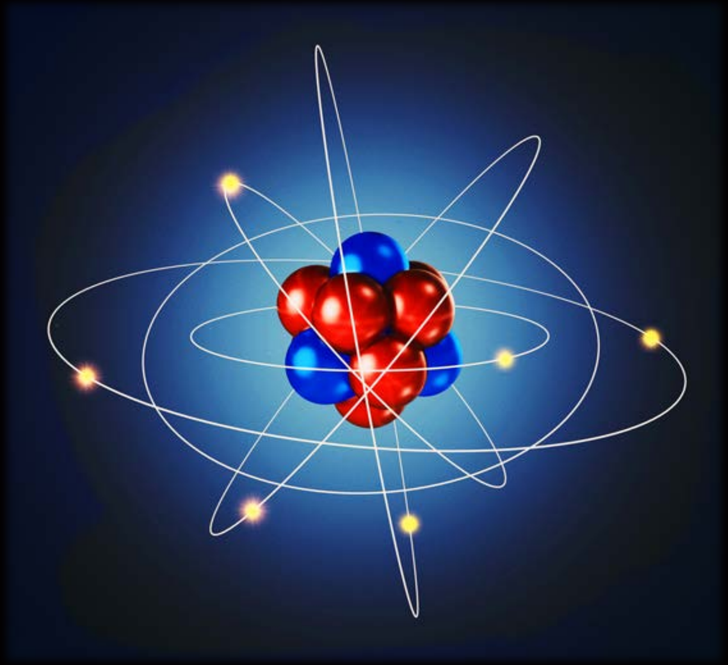
Atom: smallest form of matter that retains the properties of an element



A one carat diamond has 10^{22} carbon atoms!

Particle accelerators use charged particles

This is an atom



Proton: subatomic particle with positive charge

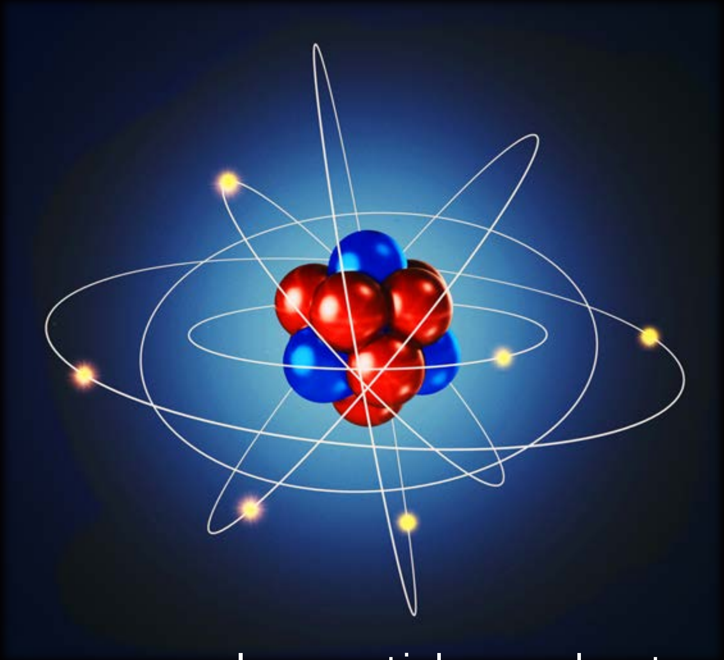
Neutron: subatomic particle with no charge

Nucleus

Electron: subatomic particle with negative charge

Particle accelerators use charged particles

This is an atom



- Proton: subatomic particle with positive charge
- Neutron: subatomic particle with no charge

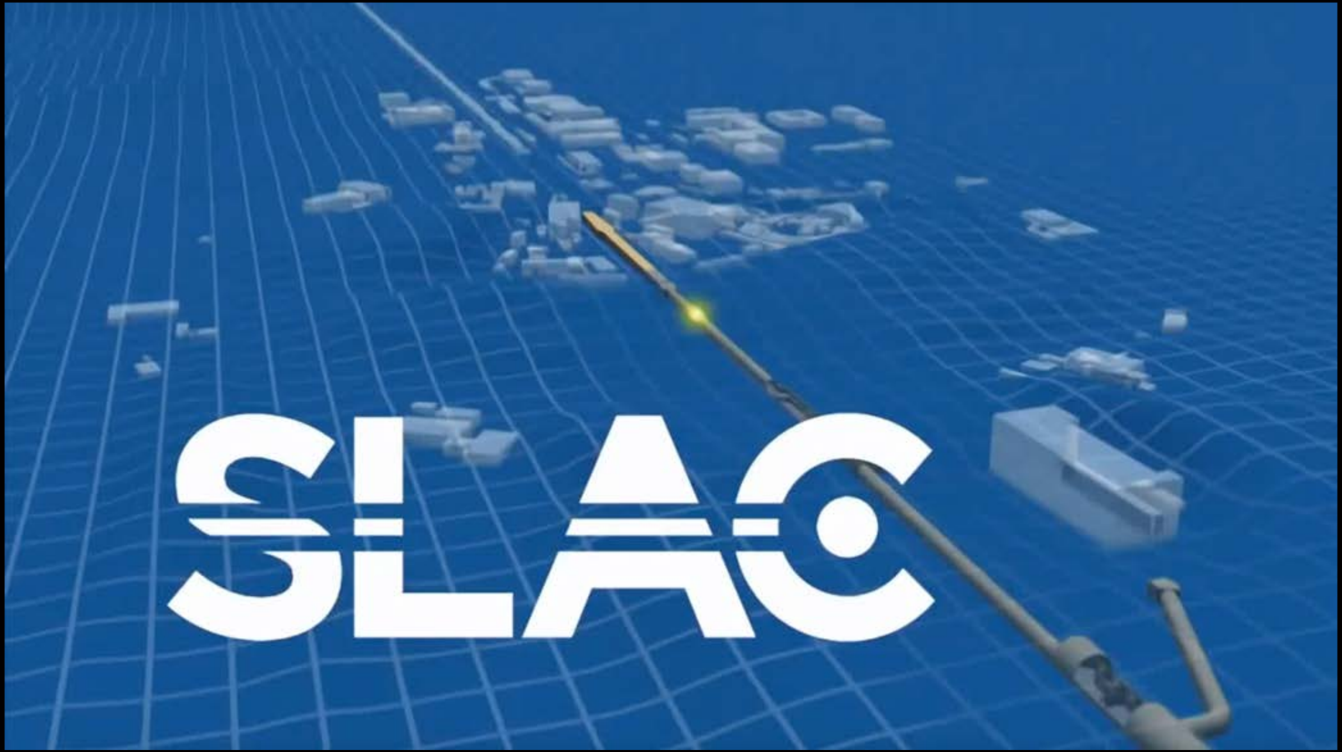
Nucleus

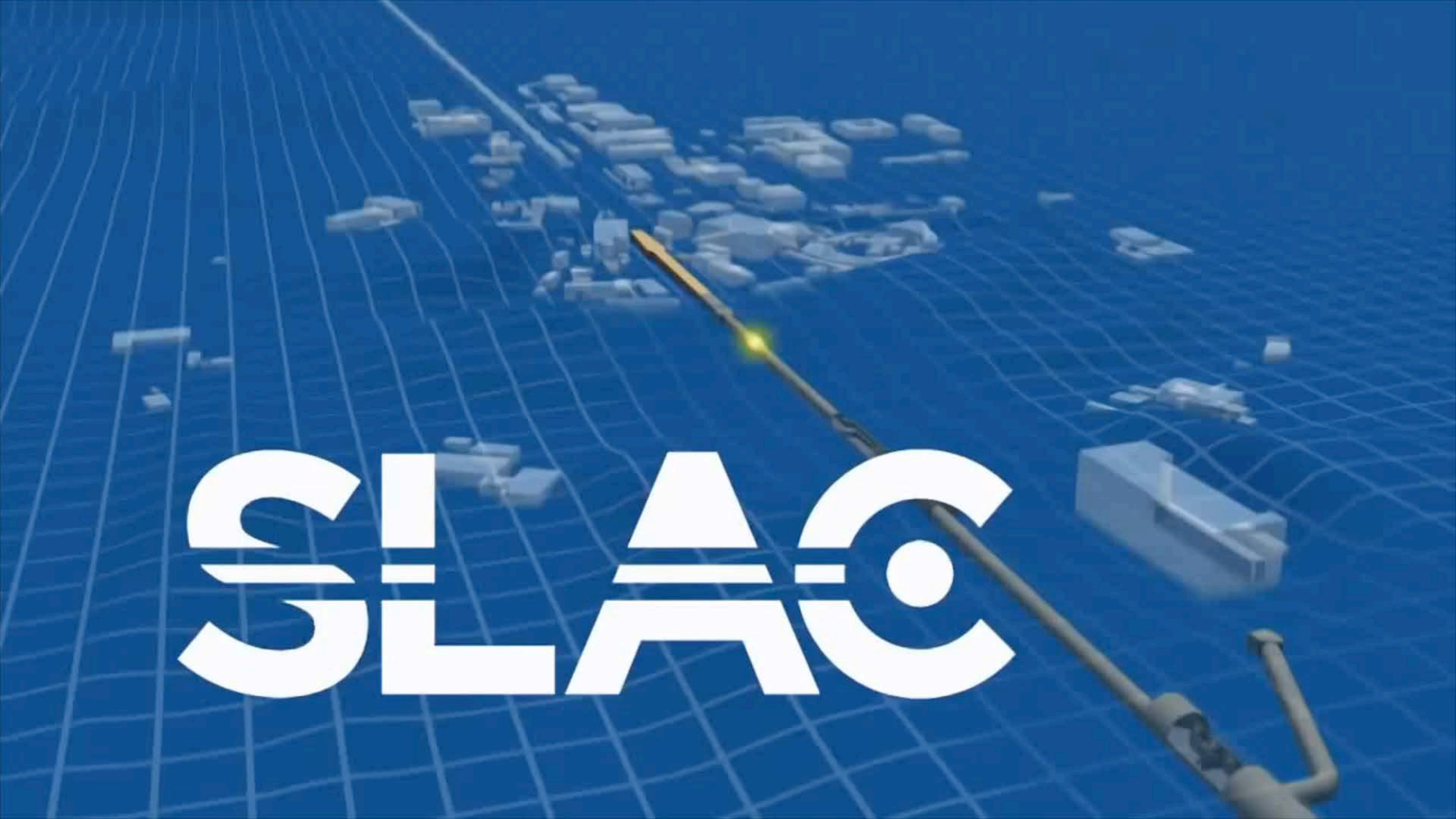
- Electron: subatomic particle with negative charge

In a particle accelerator, particles will go up to the speed of light

That’s 300,000 km per second – about 10 million times the speed of a car on the freeway!

How do they work?




SLAC

One use of particle accelerators is to make X-rays

X-rays are like visible light

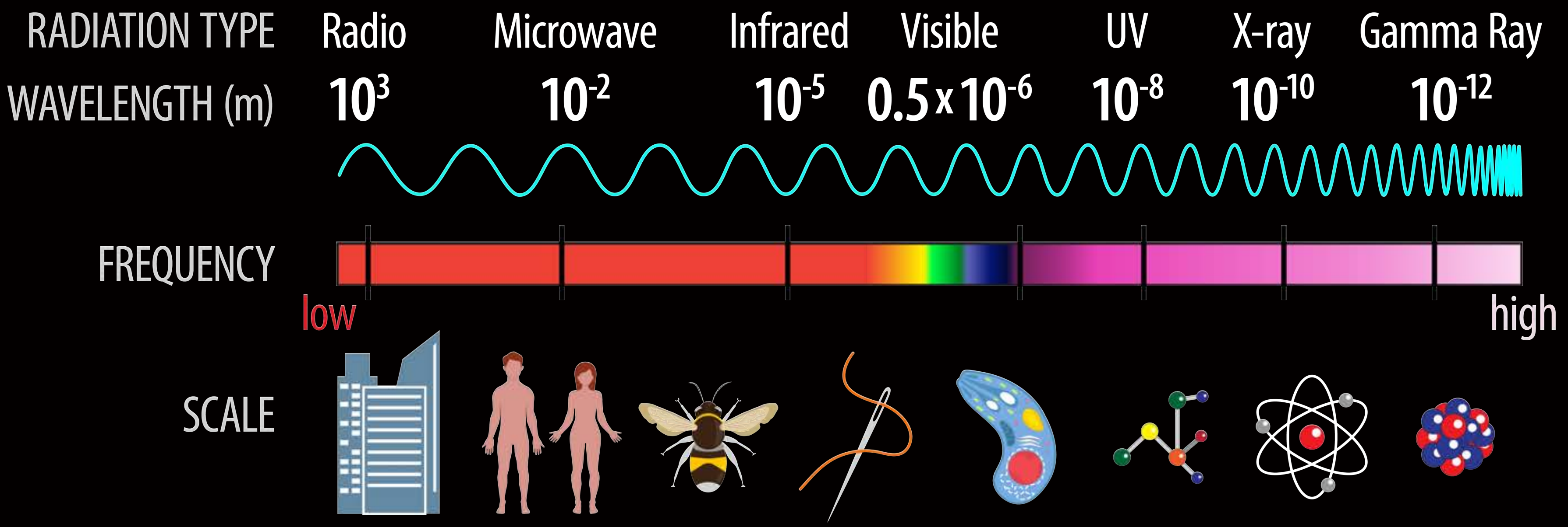
….. But you cannot see them

Light is made of electromagnetic waves

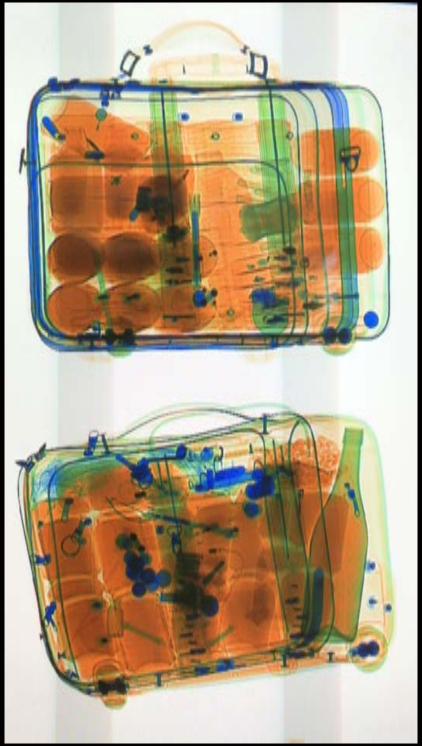
Electromagnetic waves are waves that

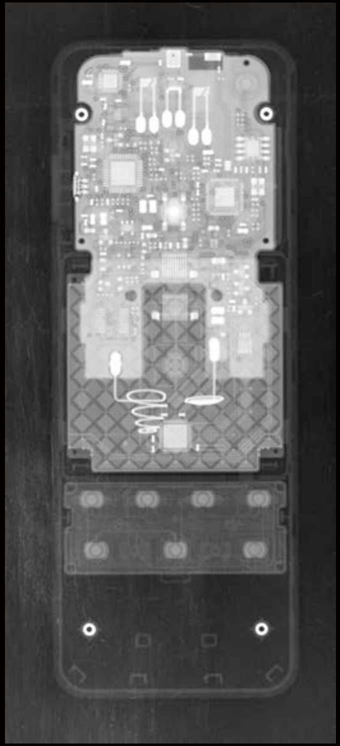
- Carry energy
- Travel through empty space or air at the speed of light
- We characterize them by their wavelength

The electromagnetic spectrum

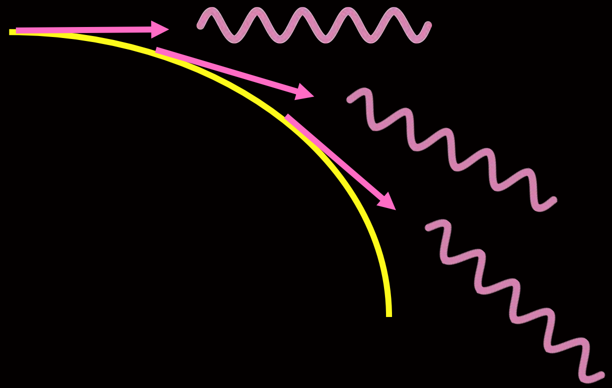


Examples of X-ray images



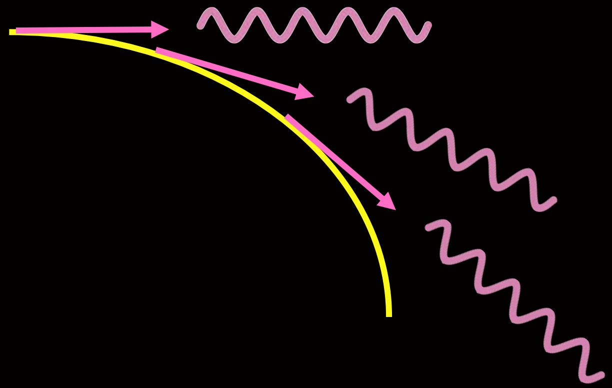


How to make X-rays with a particle accelerator



A particle changing direction
emits radiation along its path

How to make X-rays with a particle accelerator



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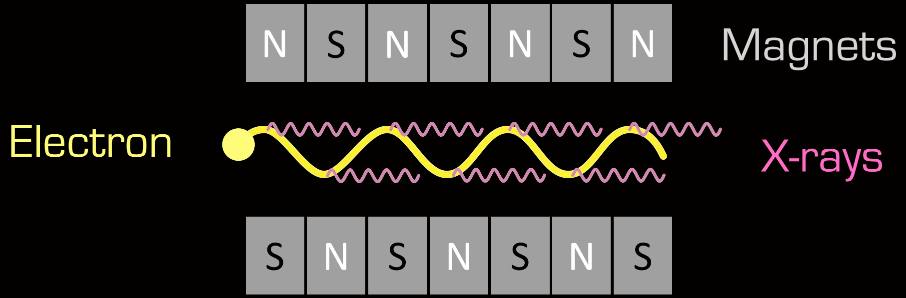
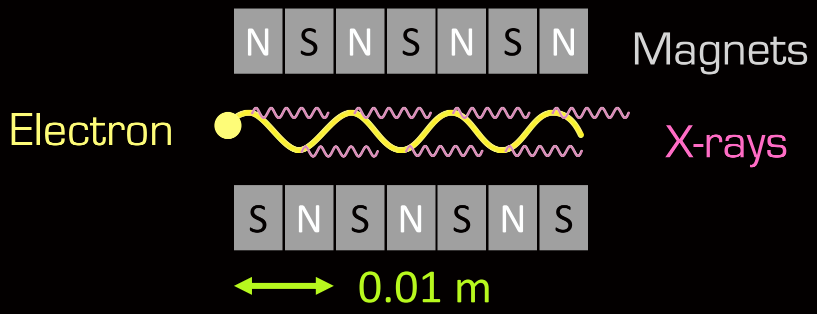
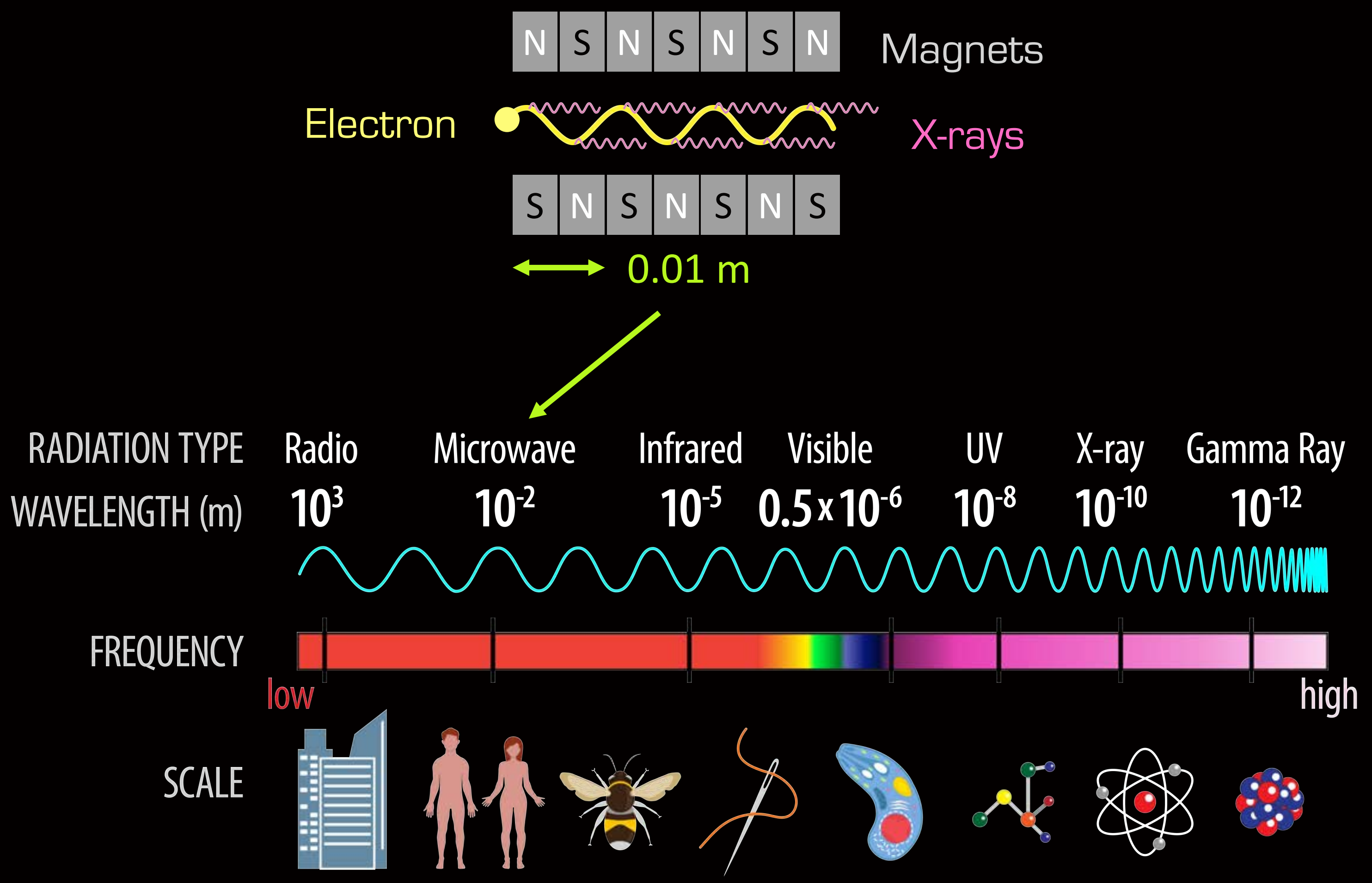
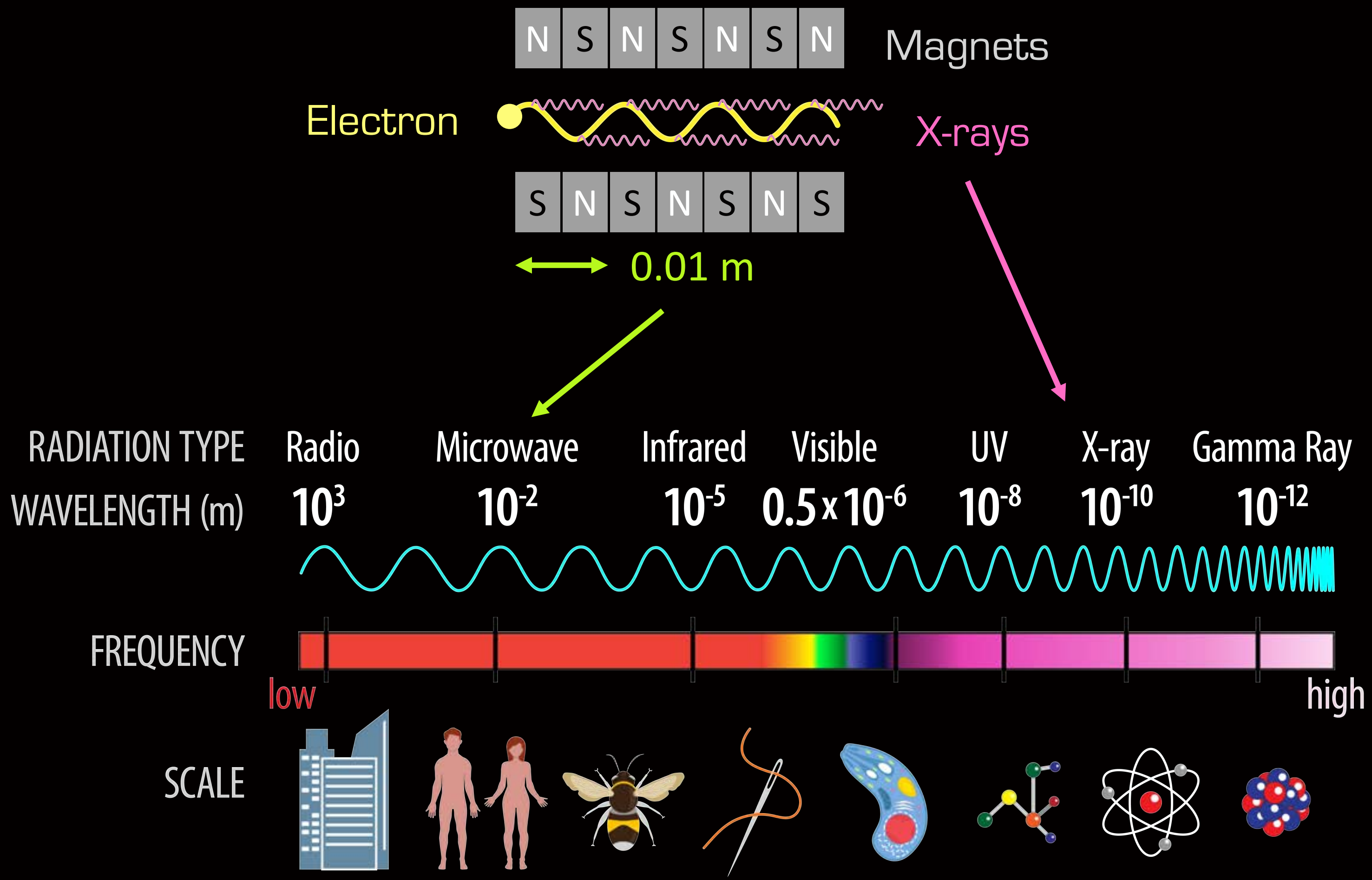


Magnets are used to change the particle's path


N S N S N S N
Magnets
Electron
X-rays
S N S N S N S
0.01 m


N S N S N S N
Magnets
Electron
X-rays
S N S N S N S
0.01 m
RADIATION TYPE
Radio
Microwave
Infrared
Visible
UV
X-ray
Gamma Ray
WAVELENGTH (m)
10^3
10^{-2}
10^{-5}
0.5×10^{-6}
10^{-8}
10^{-10}
10^{-12}
FREQUENCY
low
high
SCALE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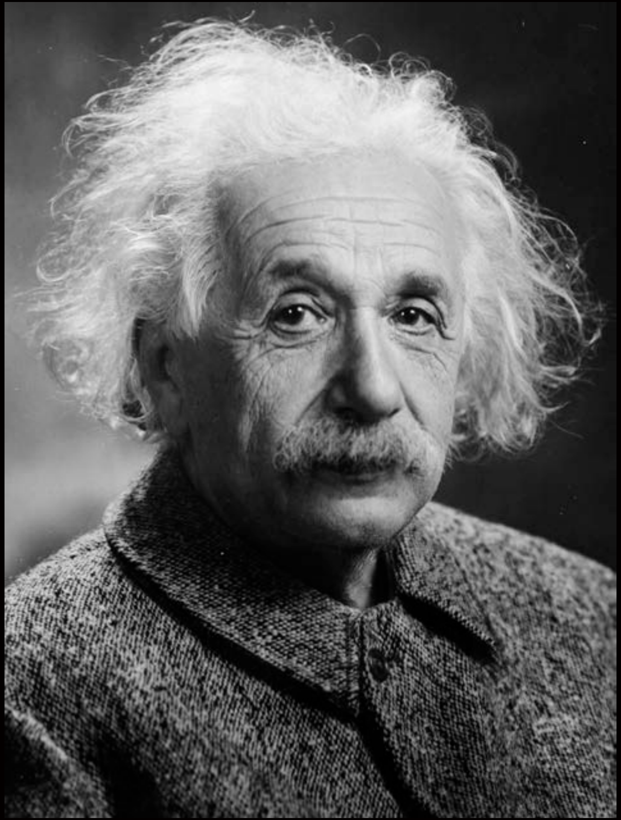
FREQUENCY
low
high
SCALE

To understand how particle accelerators make X-rays...

Let’s get some help from Albert Einstein



Einstein’s Special Theory of Relativity

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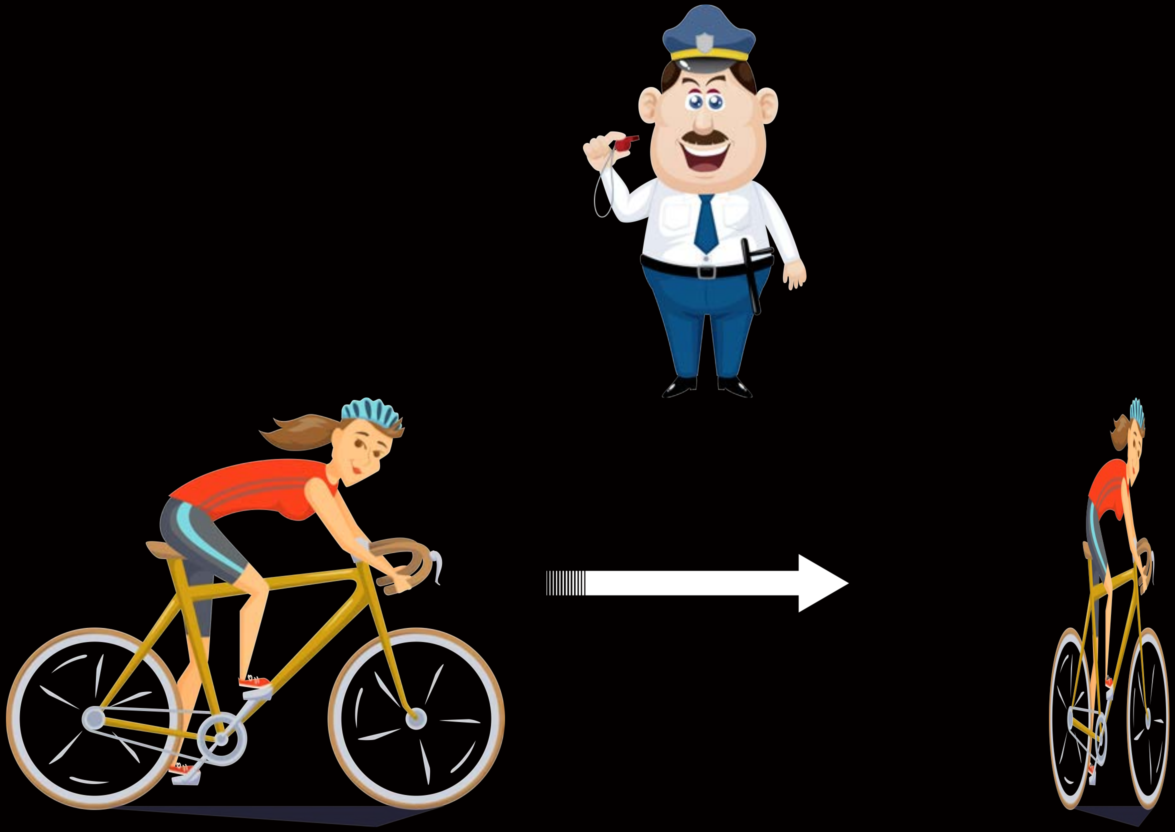
Einstein's Special Theory of Relativity



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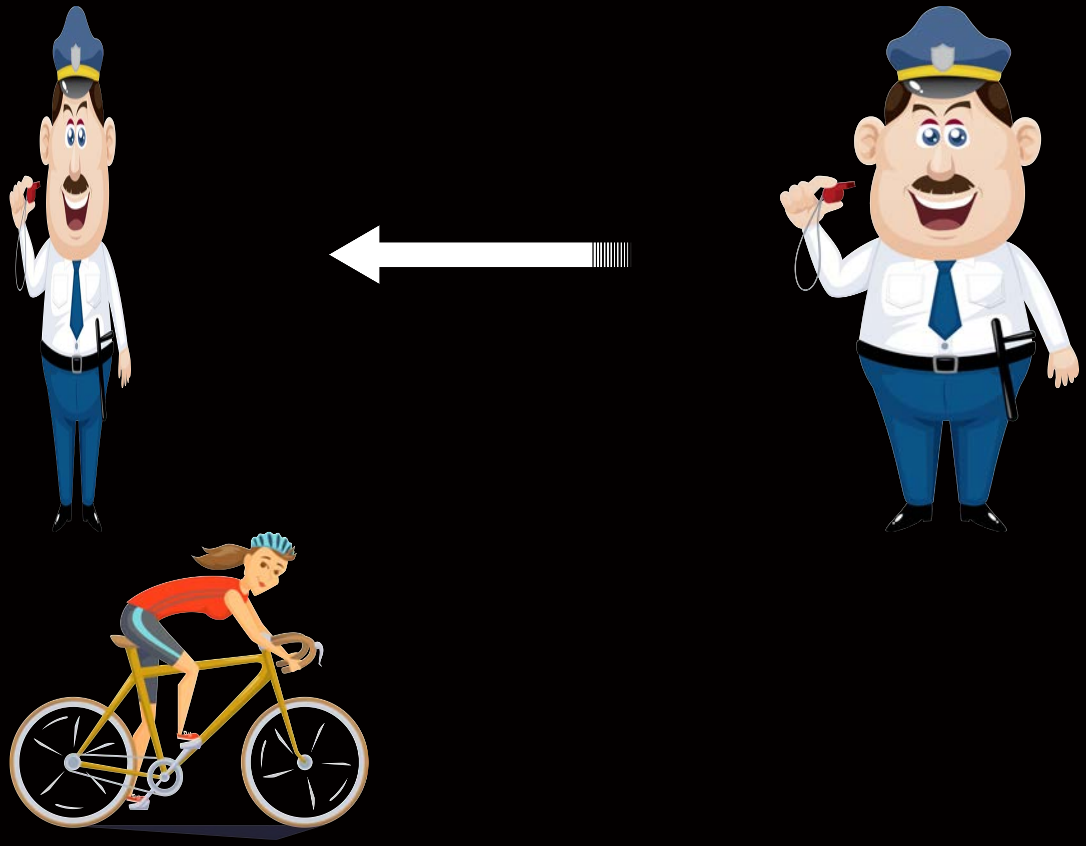
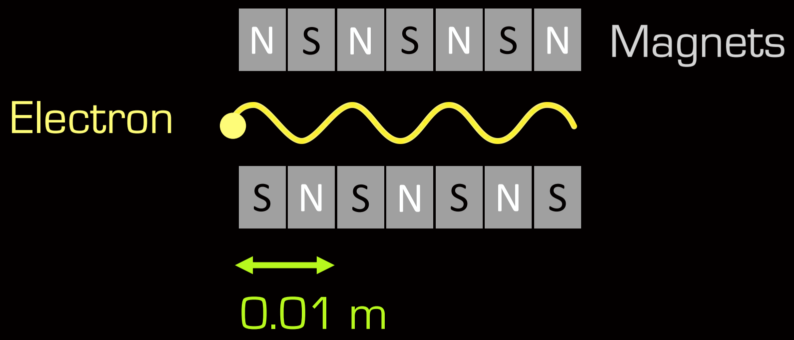
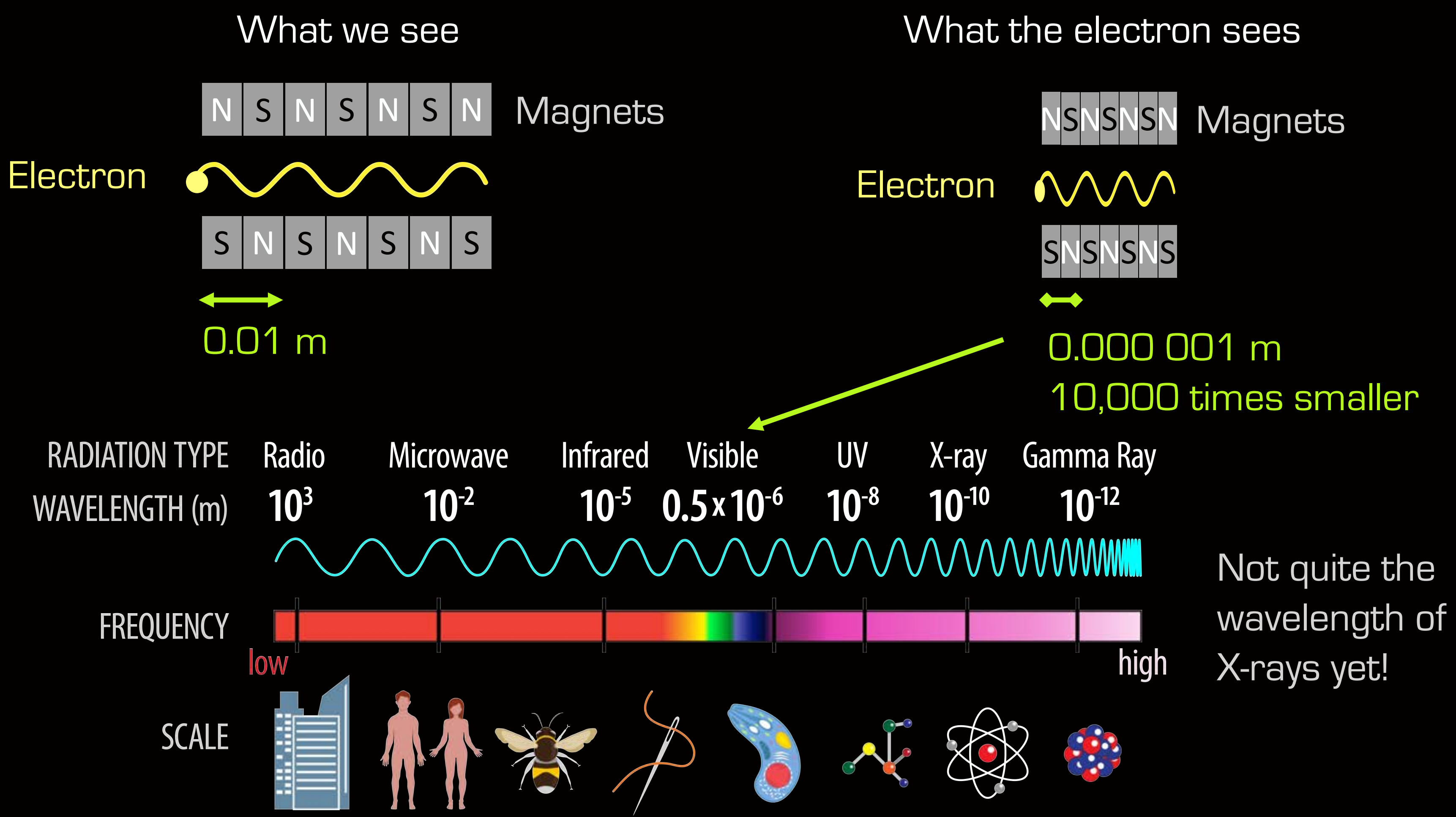


What we see




What we see
N S N S N S N
Magnets
Electron
S N S N S N S
0.01 m
What the electron sees
NSNSNSN
Magnets
Electron
SNSNSNS
0.000 001 m
10,000 times smaller


What we see
N S N S N S N
Magnets
Electron
S N S N S N S
0.01 m
What the electron sees
NSNSNSN
Magnets
Electron
SNSNSNS
0.000 001 m
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RADIATION TYPE
Radio
Microwave
Infrared
Visible
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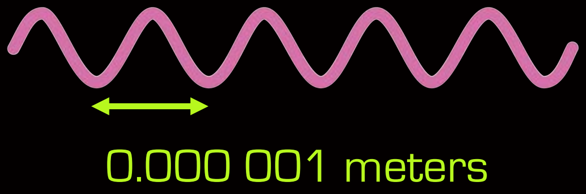
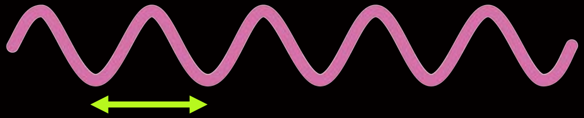
X-ray
Gamma Ray
WAVELENGTH (m)
10^3
10^{-2}
10^{-5}
0.5×10^{-6}
10^{-8}
10^{-10}
10^{-12}
FREQUENCY
low
high
SCALE
Not quite the wavelength of X-rays yet!

What the electron sees and emits

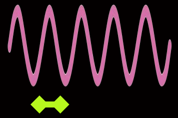


What the electron sees and emits

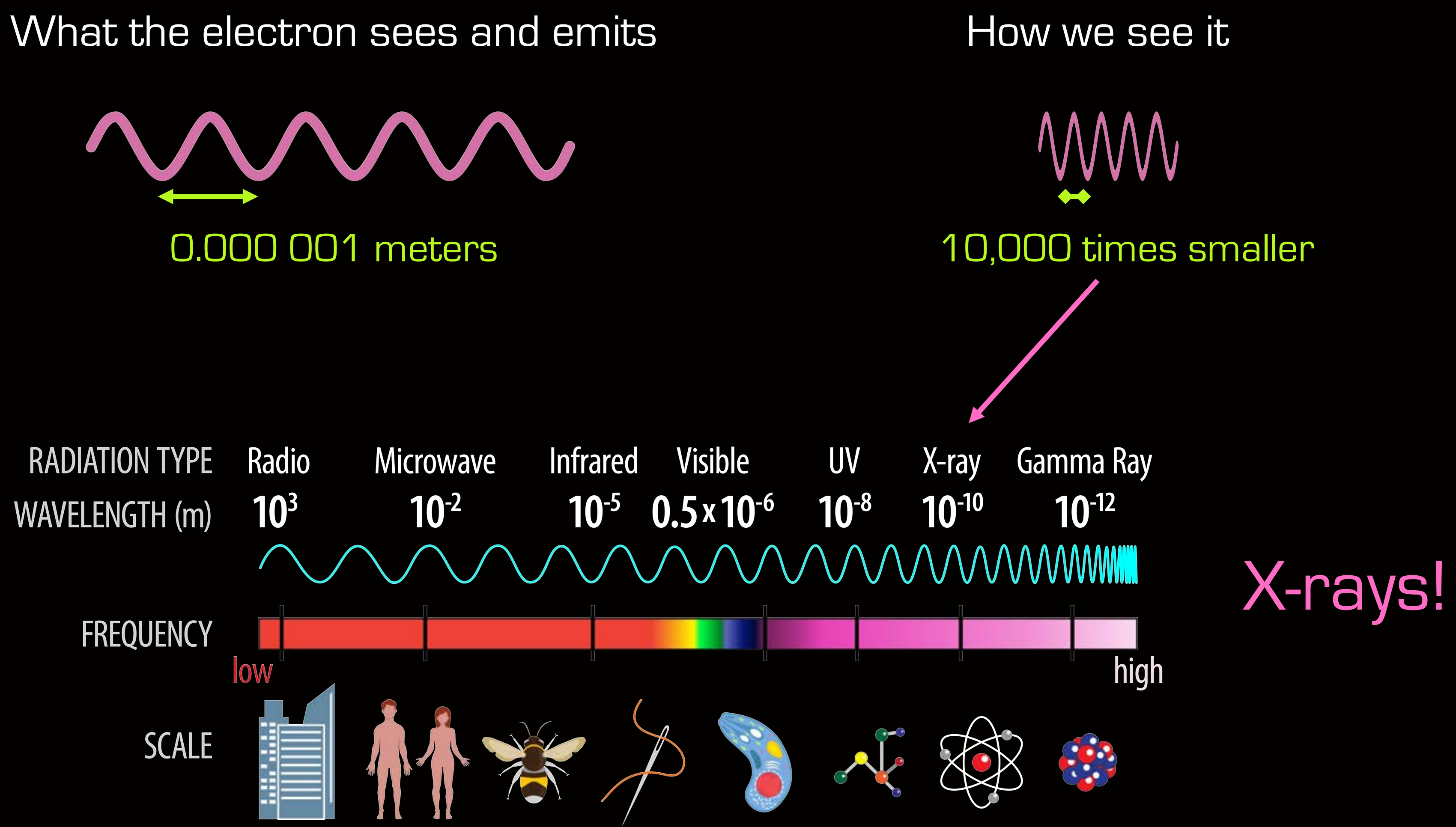


0.000 001 meters

How we see it



10,000 times smaller


What the electron sees and emits
How we see it
0.000 001 meters
10,000 times smaller
RADIATION TYPE
Radio
Microwave
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Visible
UV
X-ray
Gamma Ray
WAVELENGTH (m)
10^3
10^{-2}
10^{-5}
0.5×10^{-6}
10^{-8}
10^{-10}
10^{-12}
X-rays!
FREQUENCY
low
high
SCALE

Synchrotrons and X-ray free electron lasers

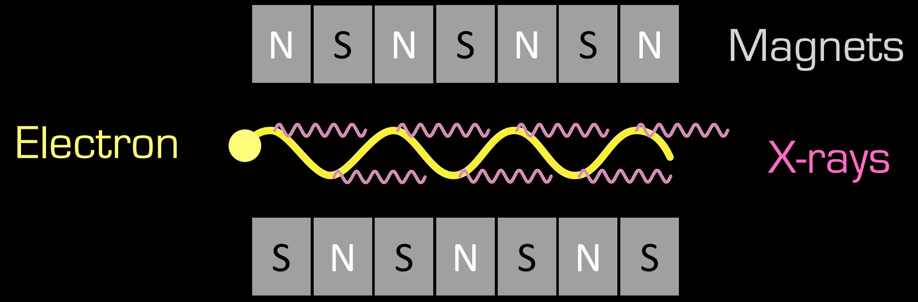


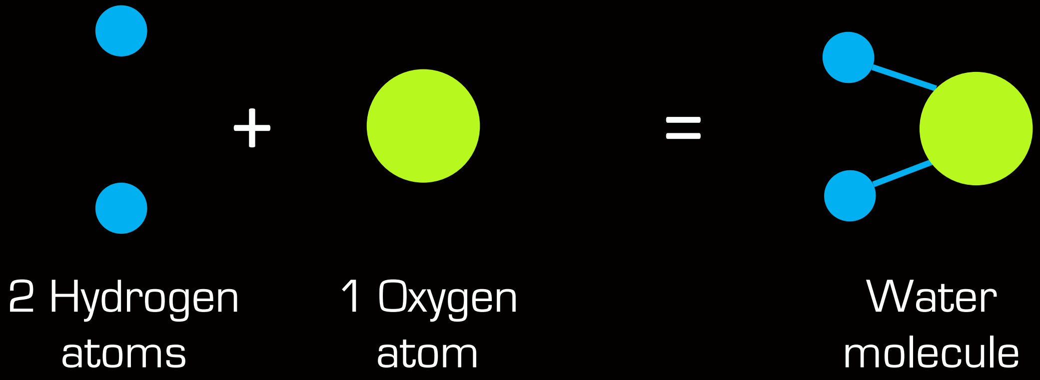

Photo: Argonne National Laboratory

Synchrotron


Photo: SLAC National Laboratory

X-ray Free Electron Laser

X-rays wavelengths are small enough to “look” at molecules and atoms



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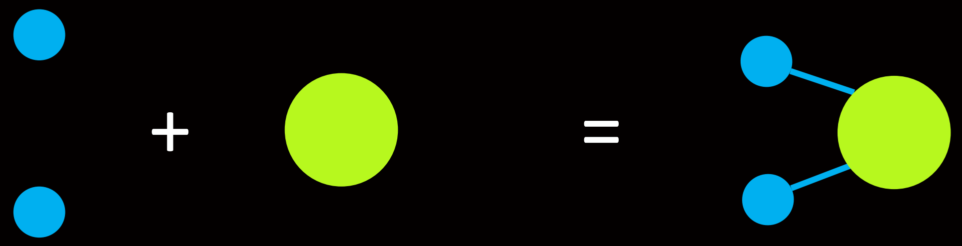


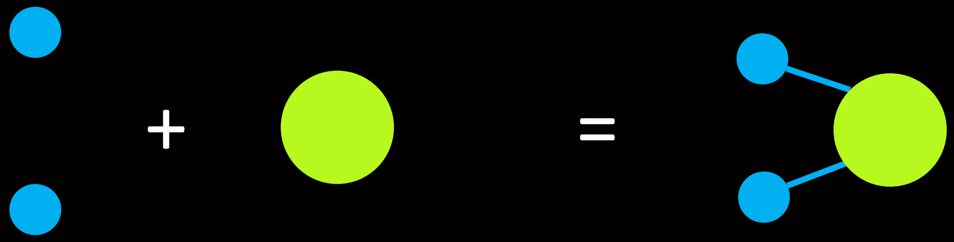
2 Hydrogen atoms

1 Oxygen atom

Water molecule

But this happens very quickly! About 10 femtoseconds

X-rays wavelengths are small enough to “look” at molecules and atoms



2 Hydrogen atoms

1 Oxygen atom

Water molecule

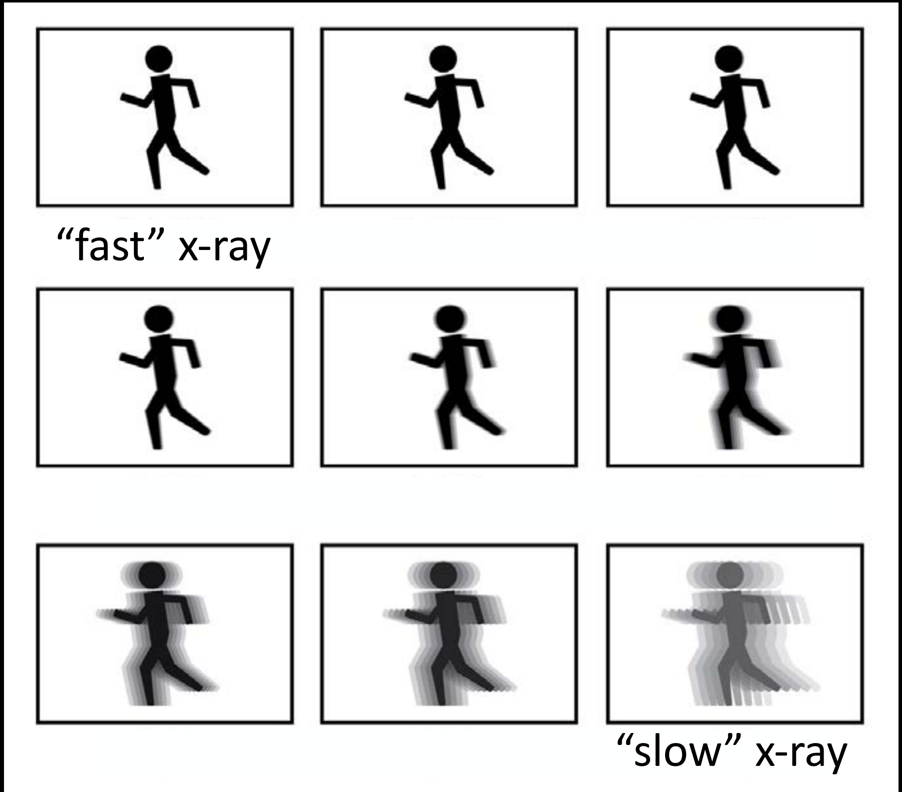
One femtosecond is 0.000 000 000 000 001 seconds (one quadrillionth)

A femtosecond is to a minute what a minute is to the age of the universe (14 billion years)

In one second, light almost has time to go to the moon

In one femtosecond, light barely has time to cross the width of human hair

To make movies of these molecules we need ”fast” x-rays



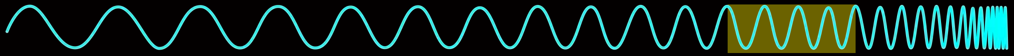
What are big X-ray machines missing?

Photo: Argonne National Laboratory

Synchrotron

Several X-ray
wavelengths
Slow

Radio	Microwave	Infrared	Visible	UV	X-ray	Gamma Ray
10^{3}	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}



What are big X-ray machines missing?

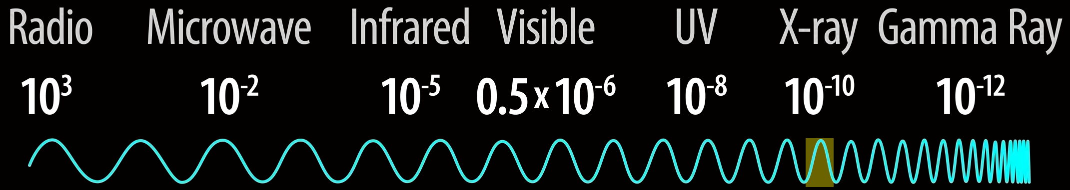
Photo: SLAC National Laboratory

X-ray Free Electron Laser

One X-ray

wavelength

Fast



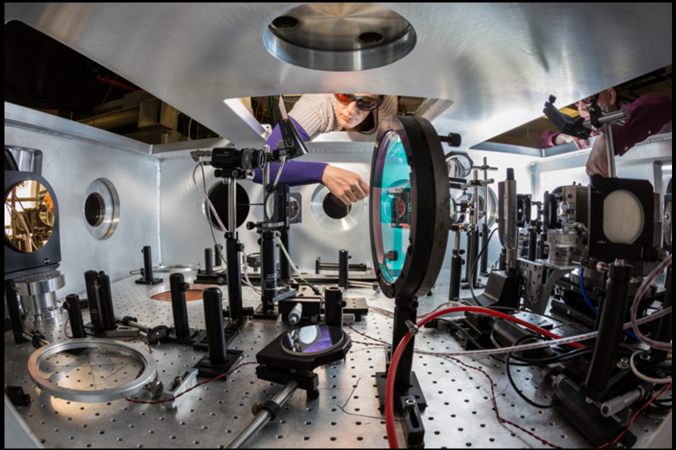
How to accelerate particles on a smaller scale?

By using lasers and plasmas to do laser wakefield acceleration

A regular particle accelerator

Photo: SLAC

A laser plasma accelerator

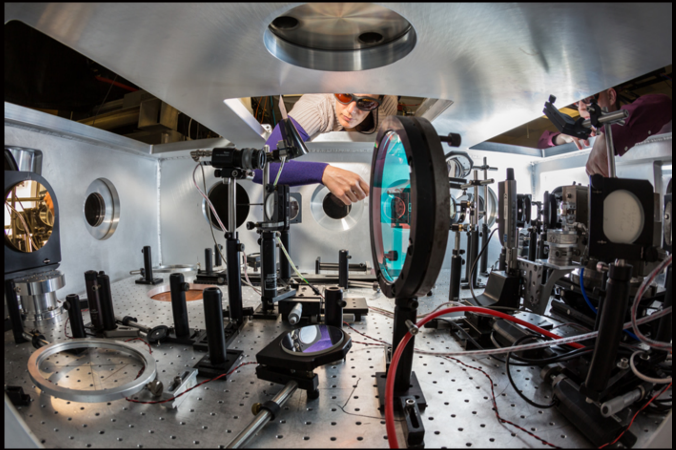


1 meter

By using lasers and plasmas to do laser wakefield acceleration

A regular particle accelerator

A laser plasma accelerator



1 meter

Accelerating electrical field is 1000 times stronger

What is a laser?

Light

Amplification by

Stimulated

Emission of

Radiation

Light bulb

Many colors in all directions

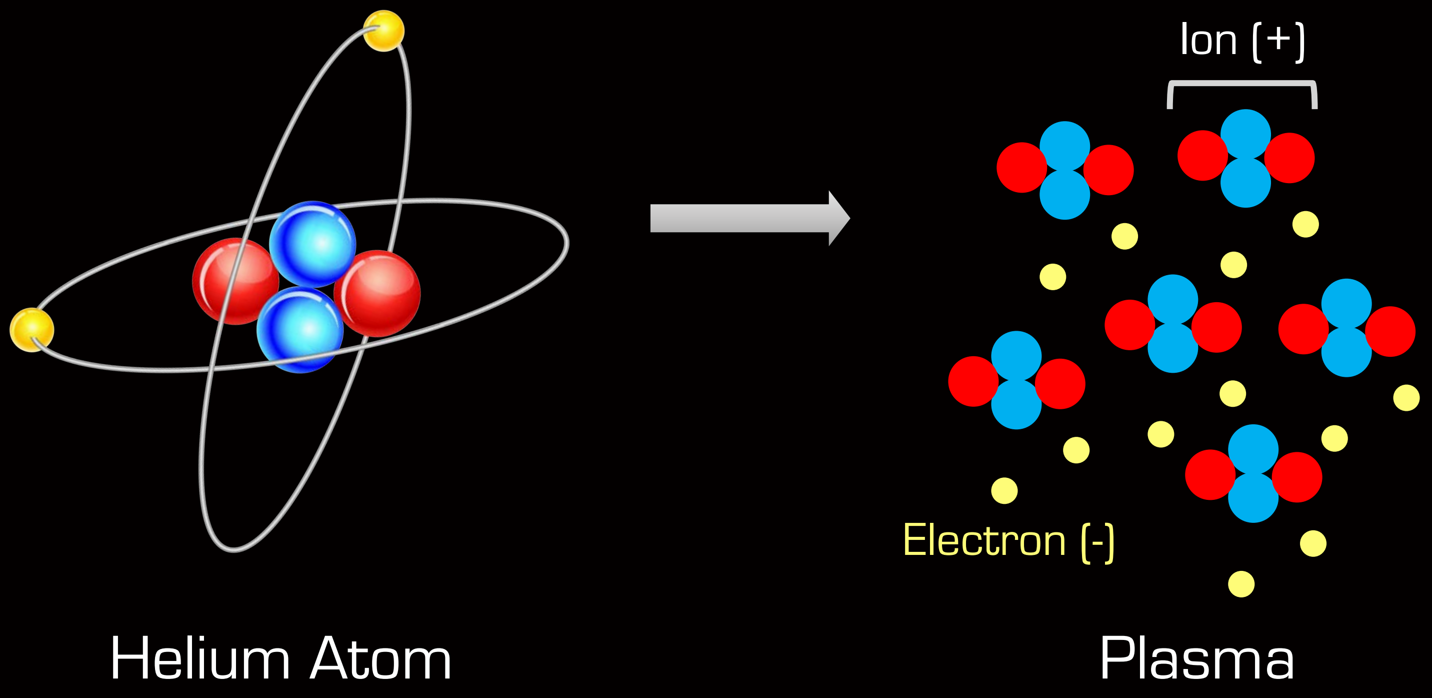
Laser

One color in one direction

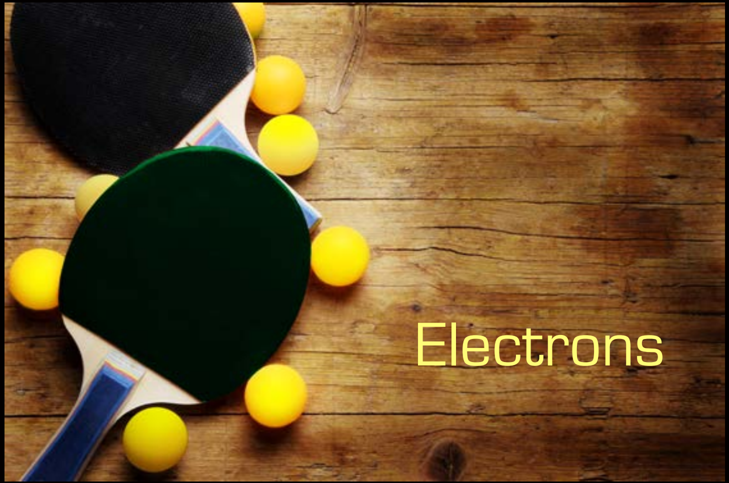
Laser

DEMO

A laser can separate electrons from ions in an atom to form a plasma



In a plasma, ions are much heavier than electrons and move around faster



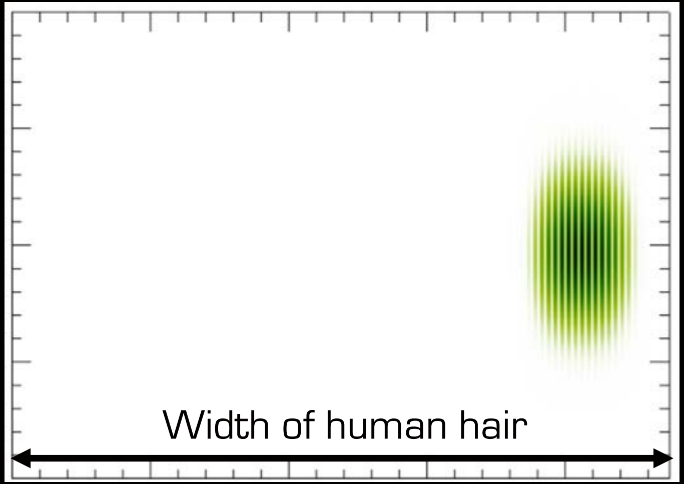
Electron plasma wave

Wake behind a boat

Electron plasma wave

Wake behind a boat

Plasma wave behind a laser

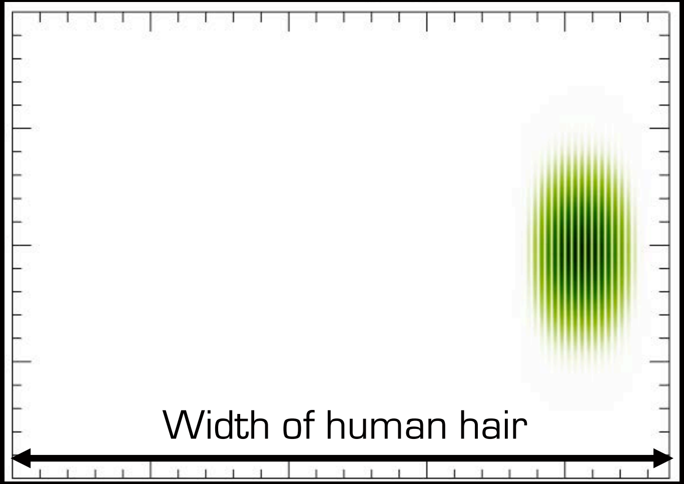


Nuno Lemos, LLNL

Electron plasma wave

Wake behind a boat

Plasma wave behind a laser



Nuno Lemos, LLNL

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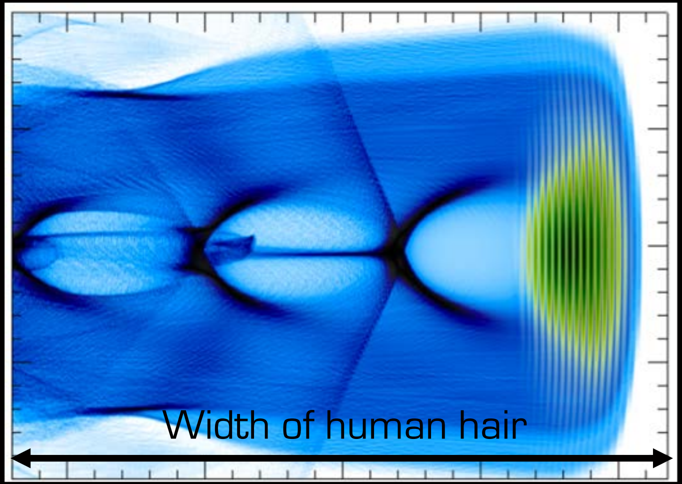
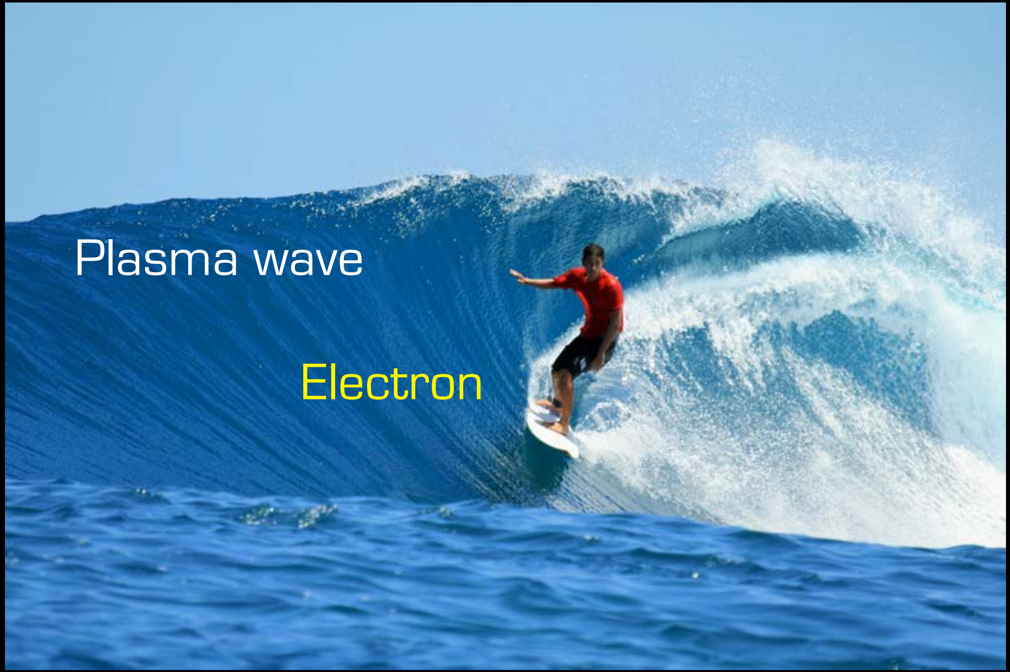


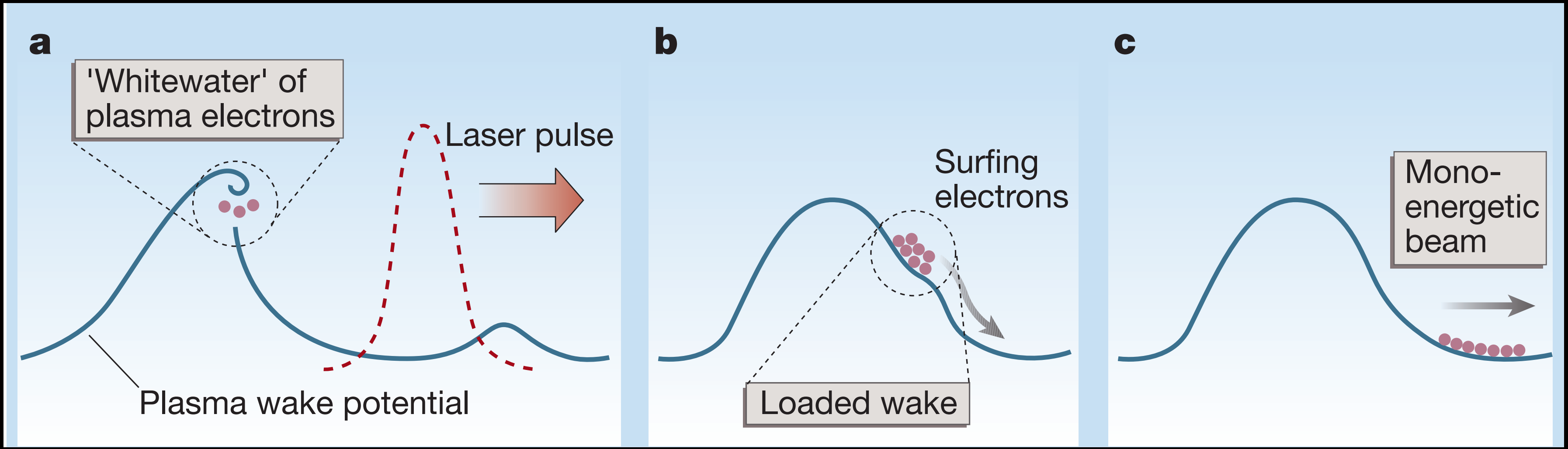
Nuno Lemos, LLNL

What can electrons do in a plasma wave?



Surf’s up! Electrons will ride the plasma wave to gain speed:
we just created a particle accelerator

Trapped electrons surf on the plasma wave to gain energy

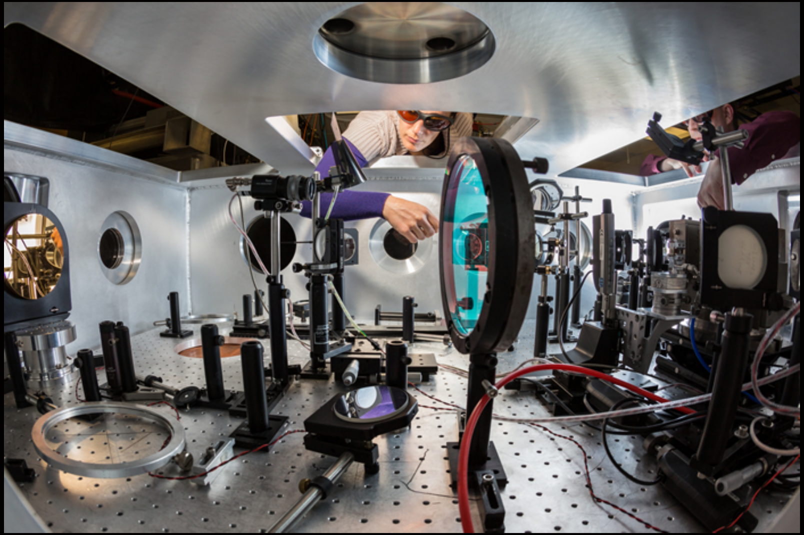


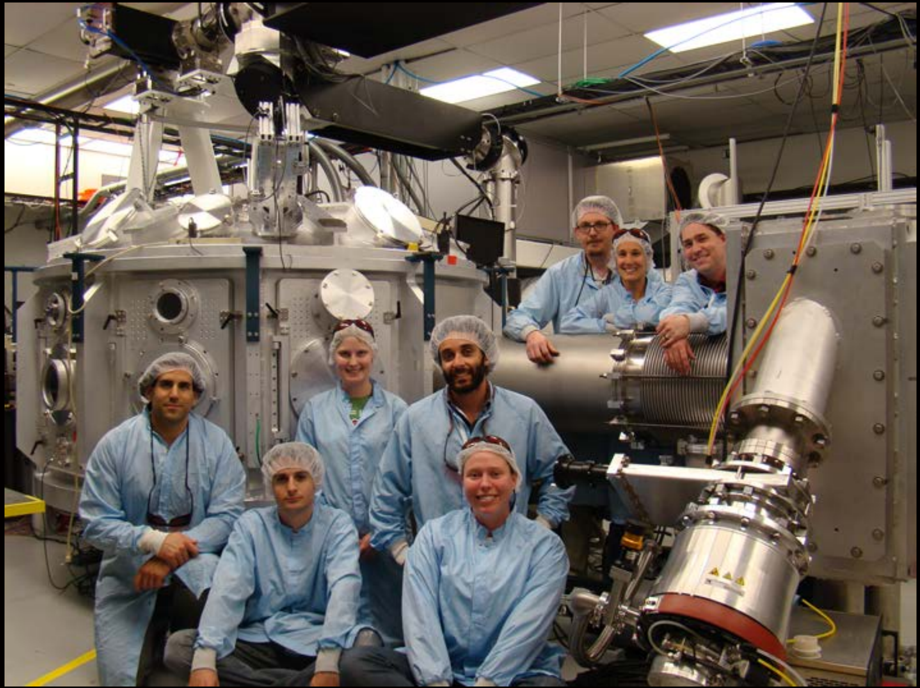
T. Katsouleas, "electrons hang ten on laser wake", *Nature* (2004)

Just like surfing, laser wakefield acceleration requires good synchronization

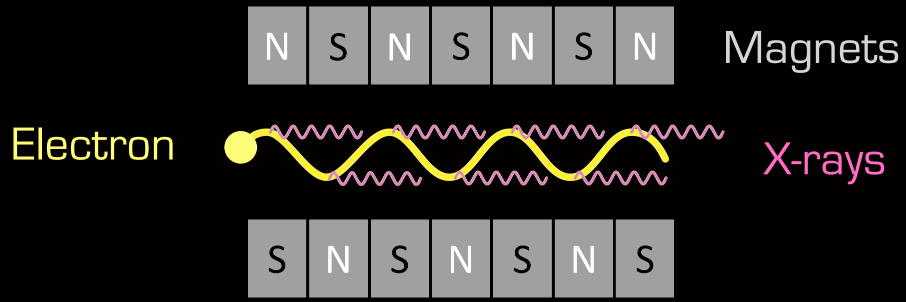
It is not always easy ....

Lasers we use at LLNL for laser wakefield acceleration

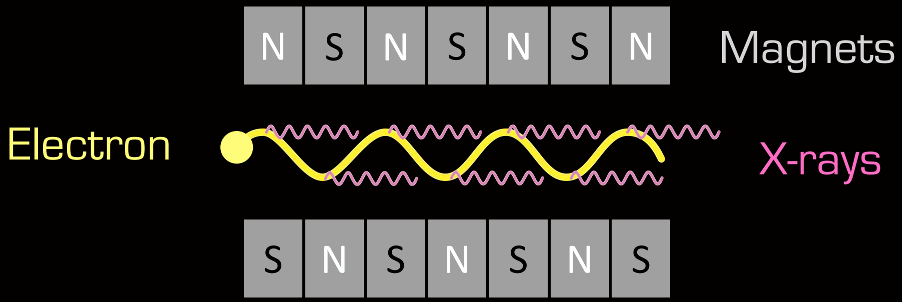




How to make X-rays with a laser wakefield accelerator

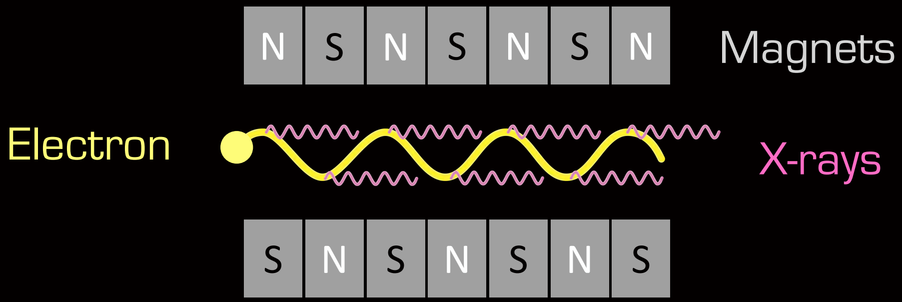


Remember how X-rays are made with a particle accelerator...



Remember how X-rays are made with a particle accelerator...

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



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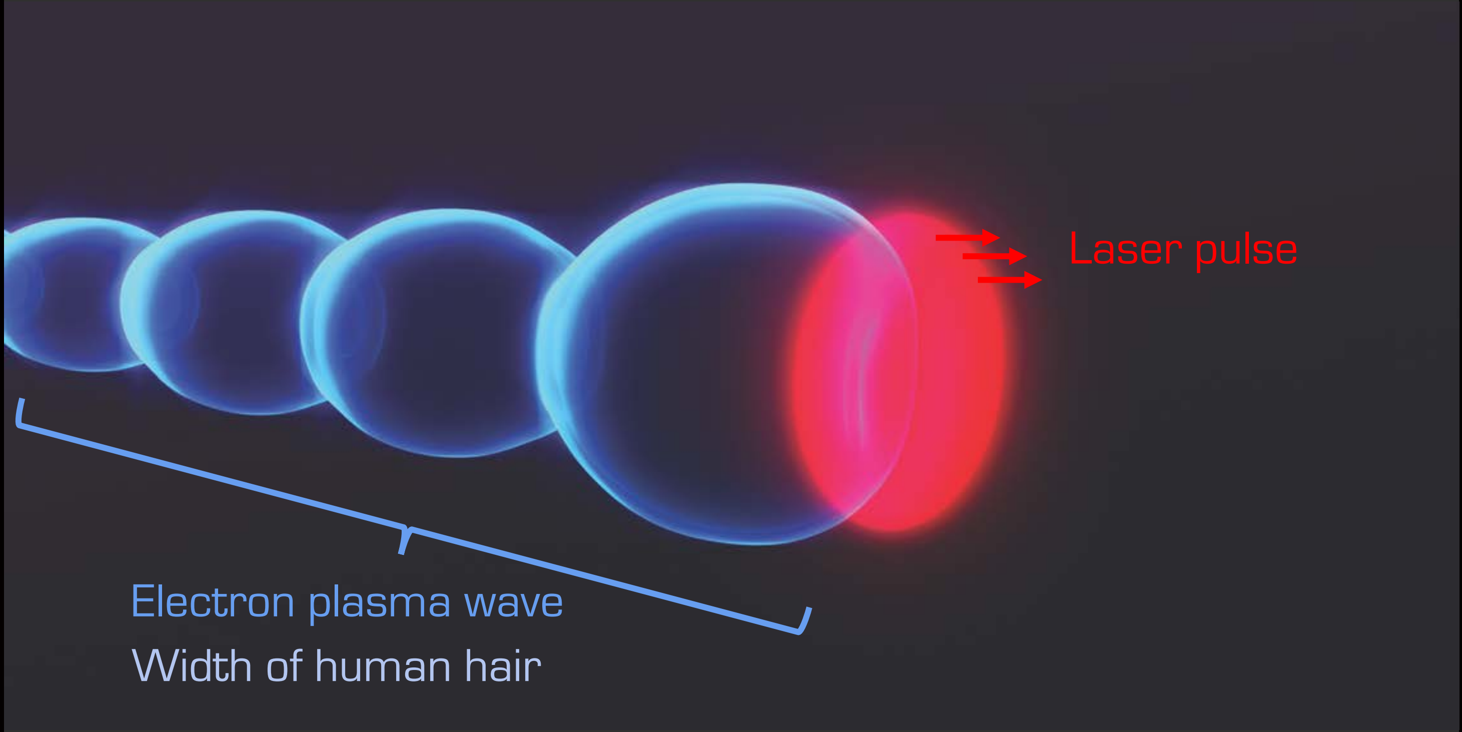
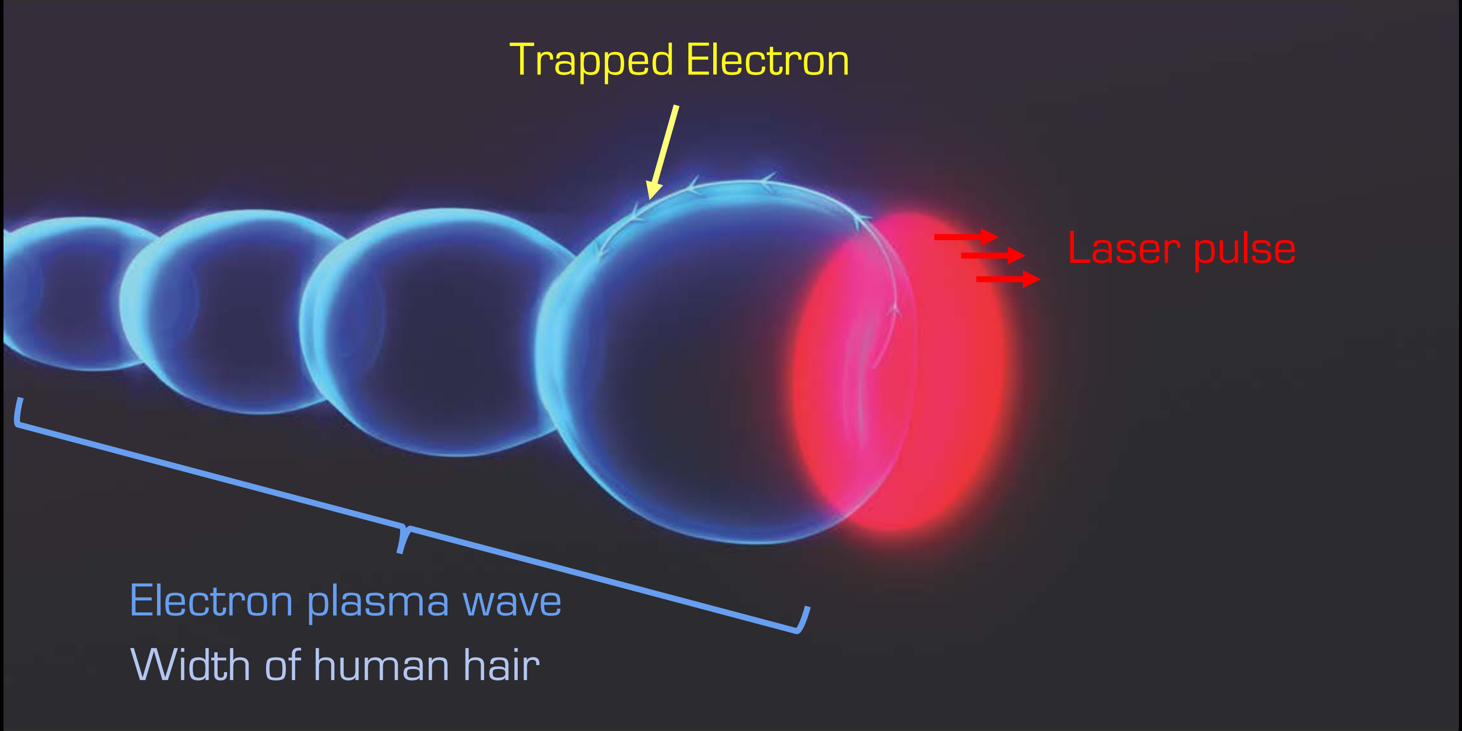
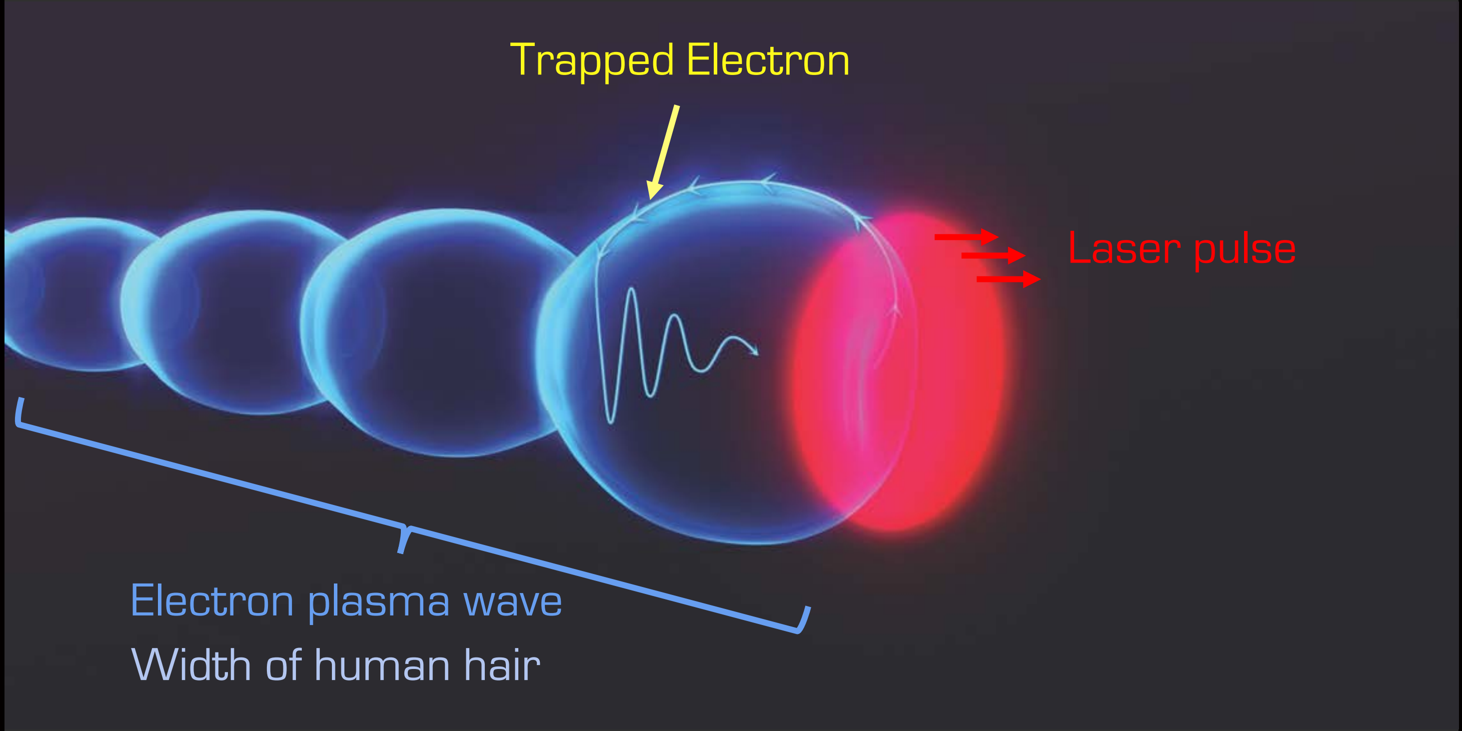

Laser pulse
Electron plasma wave
Width of human hair


Trapped Electron
Laser pulse
Electron plasma wave
Width of human hair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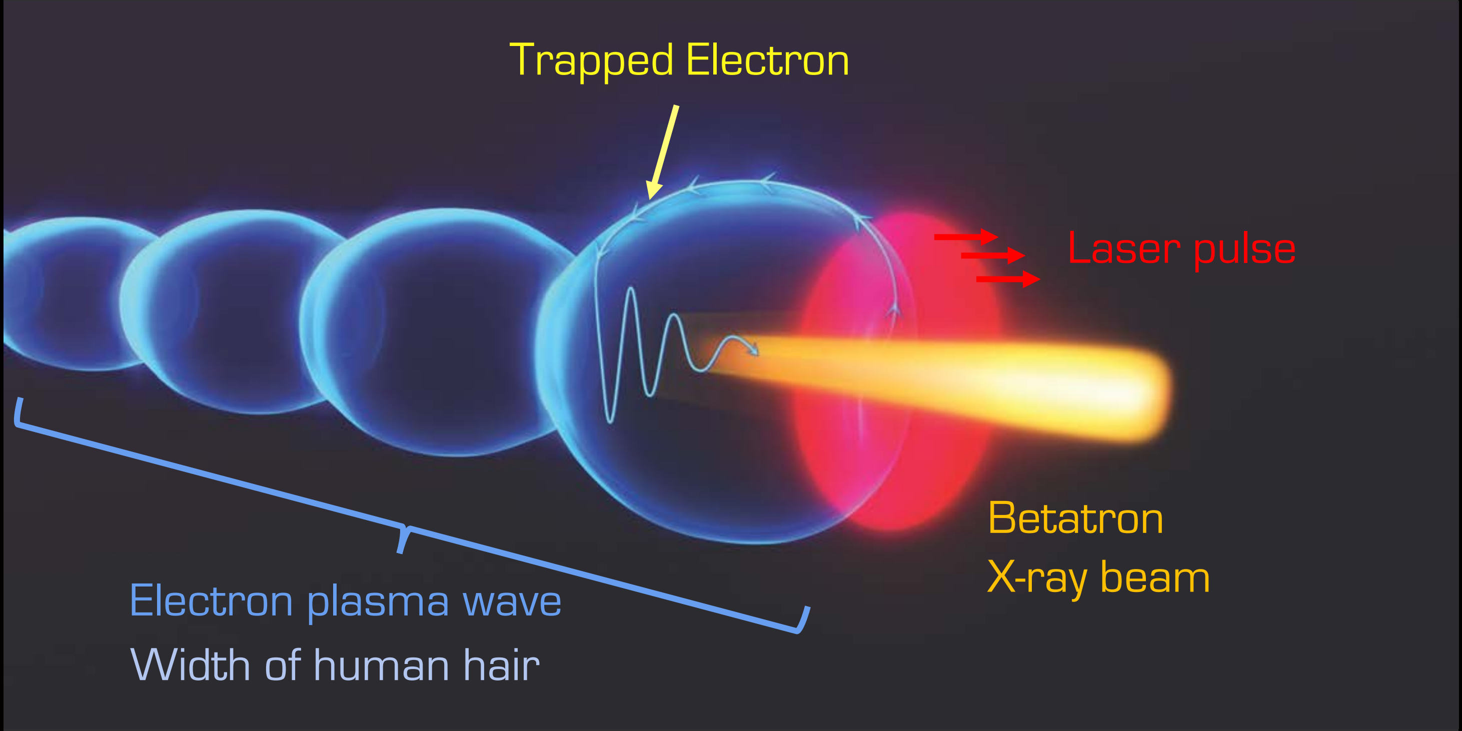
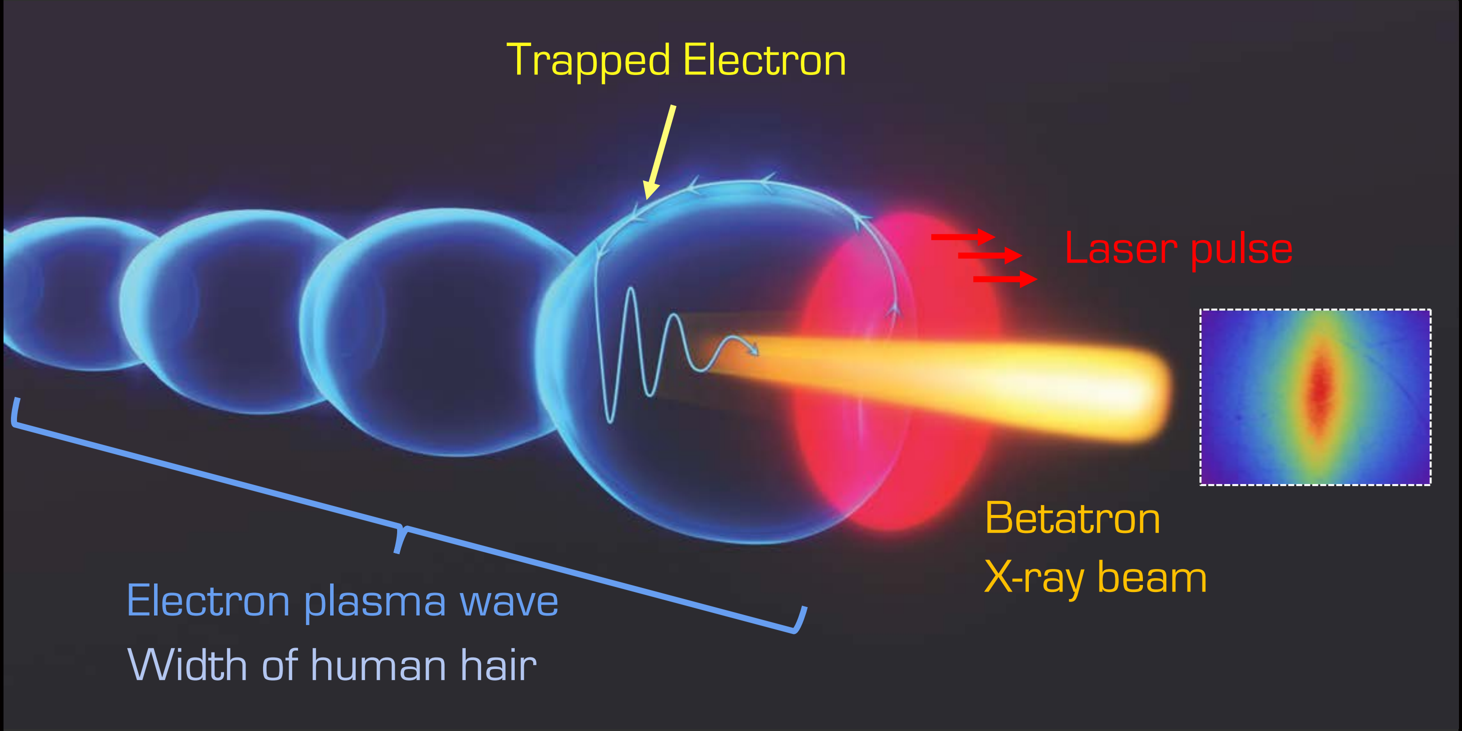

Trapped Electron
Laser pulse
Betatron
X-ray beam
Electron plasma wave
Width of human hair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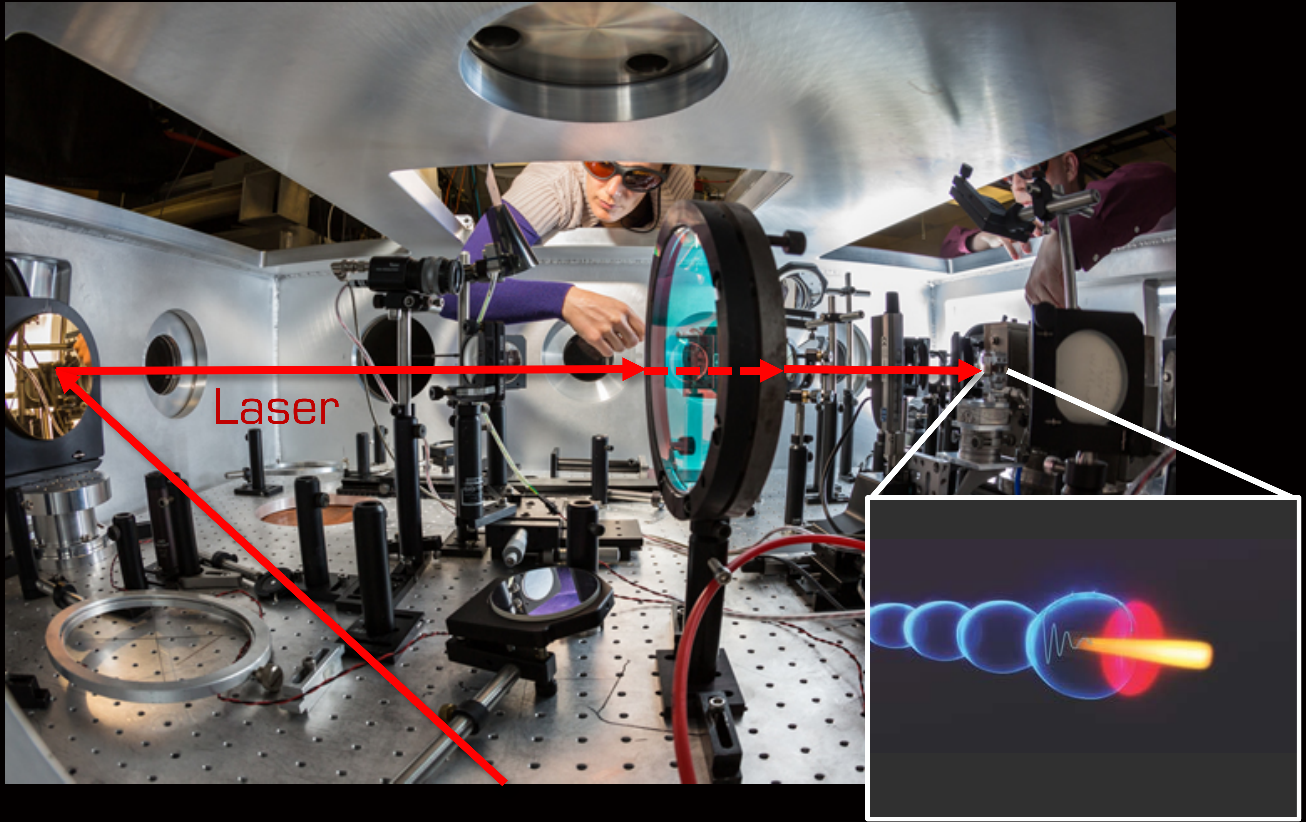

Laser

Laser wakefield acceleration can produce X-rays just like the big machines but on a much smaller scale

Synchrotron

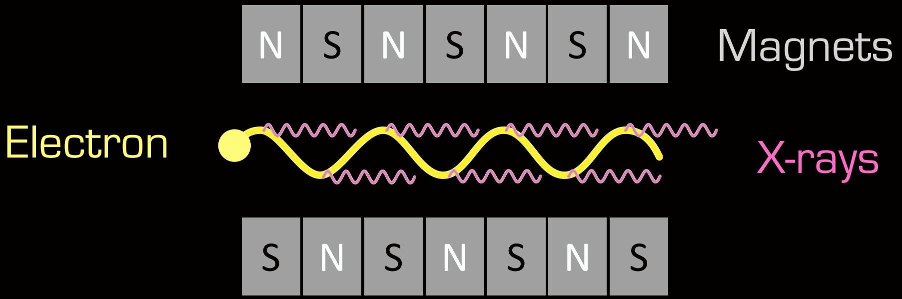
Photo: Argonne Nat. Lab

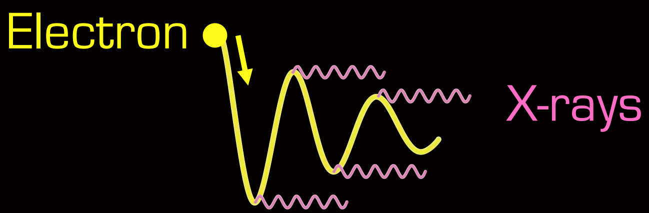
X-ray Free Electron Laser

Photo: SLAC

Laser wakefield

Photo: LLNL





Laser wakefield acceleration can produce X-rays just like the big machines but on a much smaller scale

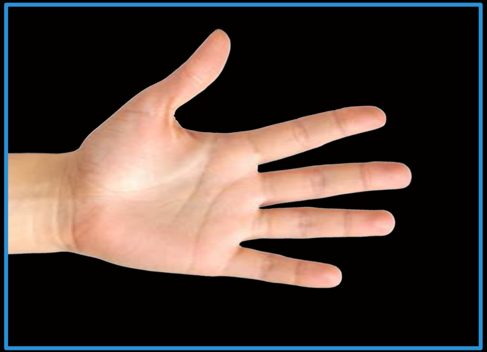
Synchrotron	X-ray Free Electron Laser	Laser wakefield
		
Photo: Argonne Nat. Lab	Photo: SLAC	Photo: LLNL
Several X-ray wavelengths	One X-ray wavelength	Several X-ray wavelengths
Slow	Fast	Fast

Some applications of X-ray light sources from laser wakefield acceleration

X-rays for radiography

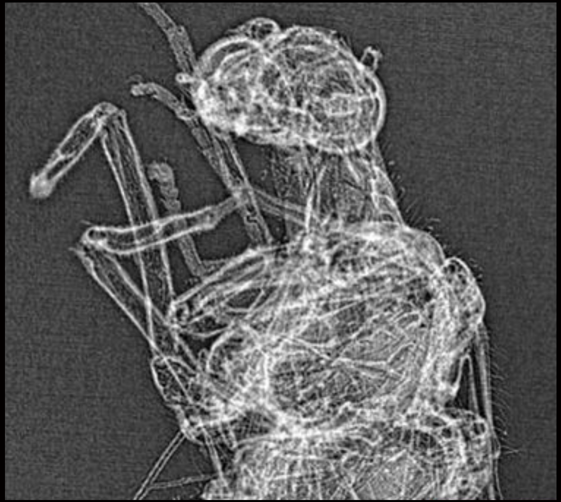
Radiography

X-rays in

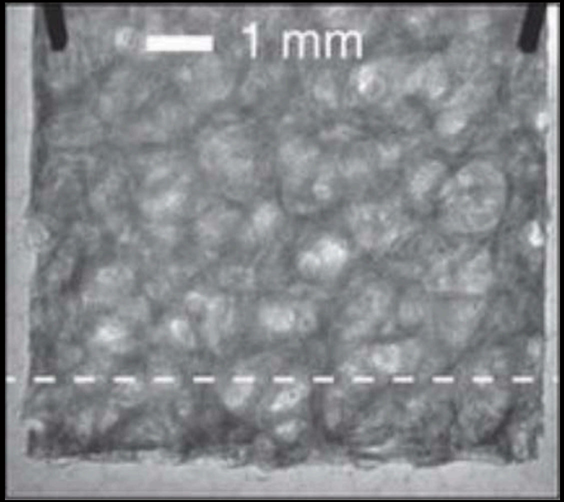


X-rays out

Radiography of biological objects with X-rays from laser wakefield accelerators



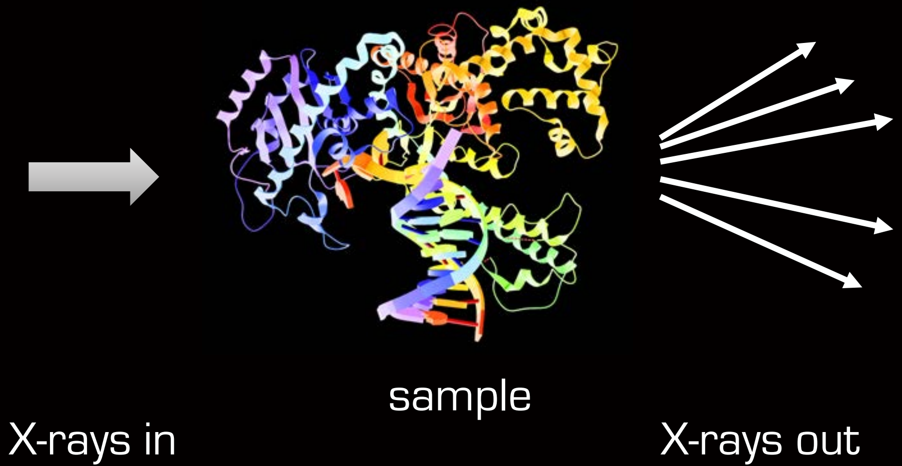
Chrysoperia carnea
Wenz et al, *Nat. Comm* (2015)



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

X-rays for absorption spectroscopy

X-rays for diffraction



Pump-probe experiments

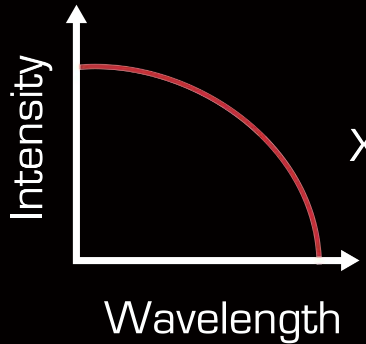
Pump-probe experiments

Laser in at Time 0 (T_0)

sample

Pump-probe experiments

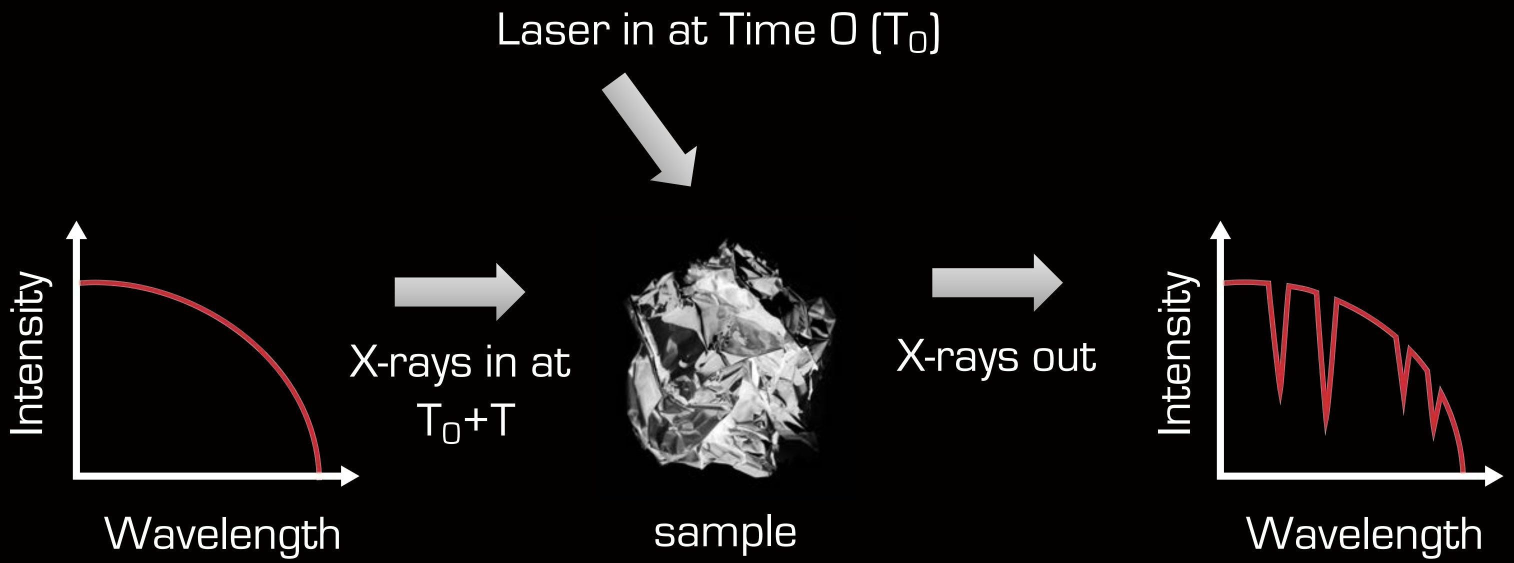
Laser in at Time 0 (T_0)



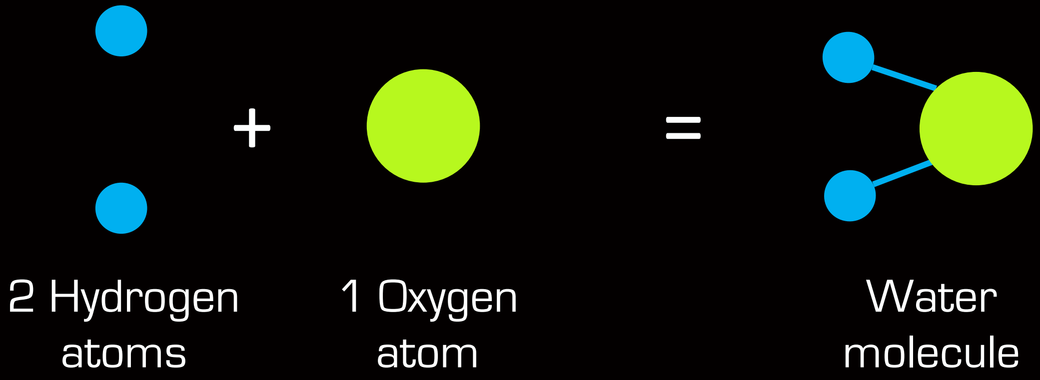
X-rays in at T_0+T

sample

Pump-probe experiments



X-rays have small wavelengths to “look” at molecules and atoms



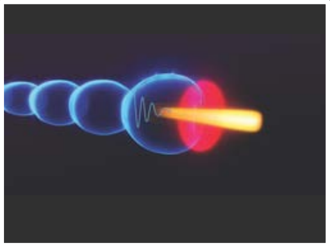
What we've learned today

Photo: SLAC National Laboratory

- What are particle accelerators and how do they work?
- Making X-rays with particle accelerators

- Miniature particle accelerators using lasers and plasmas: laser wakefield accelerators

- Making x-rays with laser wakefield accelerators



- Some applications

Laser plasma accelerators will revolutionize these fields

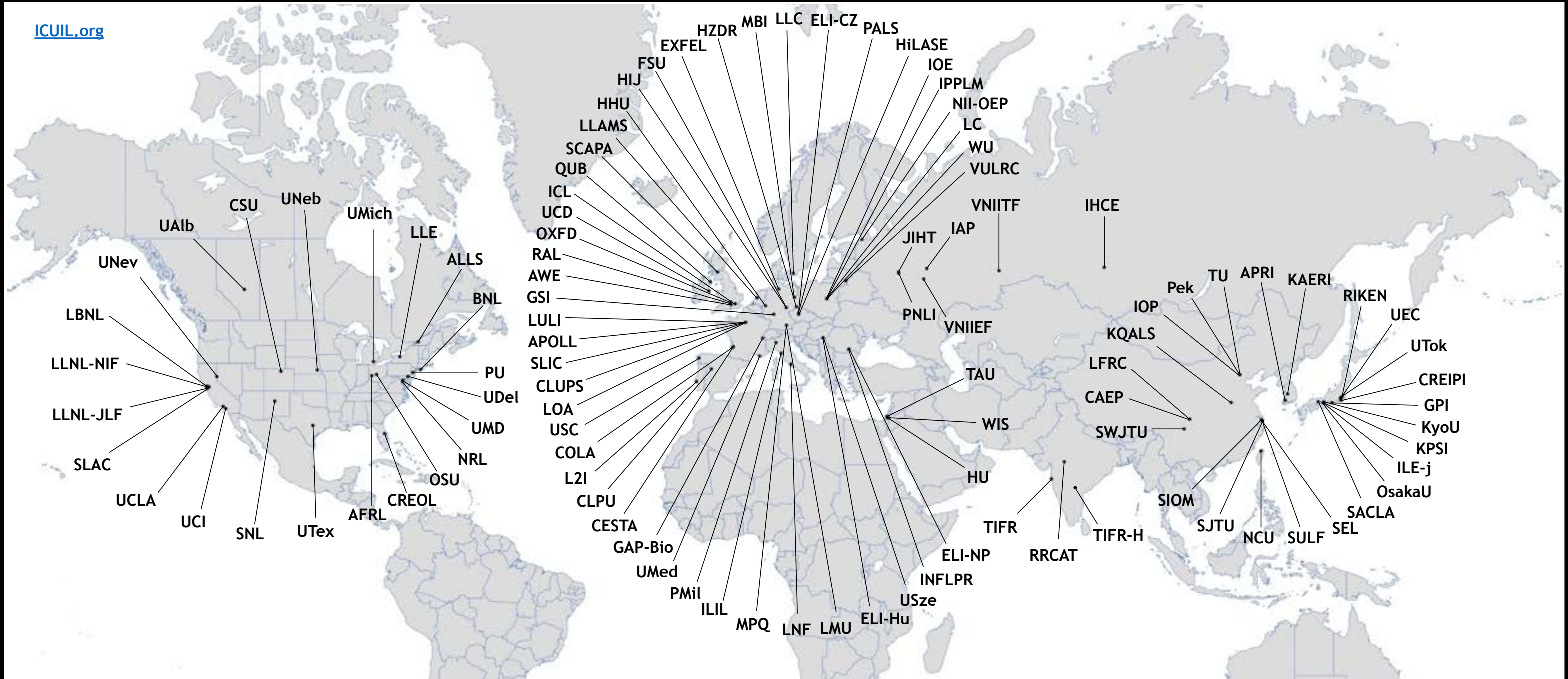
Fundamental Discoveries

Medical Applications

Industry

National Security

The ultra high intensity lasers world map



AFRL	Air Force Research Laboratory	Dayton
ALLS	Advanced Laser Light Source	Varennes
APOLL	APOLLON at Université Paris Saclay	Saclay
APRI	Advanced Photon Research Institute	Gwangju
AWE	Atomic Weapons Establishment	Aldermaston
BNL	Brookhaven National Lab, ATF	Upton
CAEP	Chinese Academy of Engineering Physics- PW Laser	Mianyang
COLA	Centre Optique et Laser en Aquitaine	Bordeaux
CESTA	Centre d'Etudes Scientifiques et Techniques d'Aquitaine	Le Barp
CLPU	Centro de Laseres Pulsados	Salamanca
CLUPS	Laser Center of the University of Paris - Sud	Sud
CRIEPI	Central Research Institute of Electric Power Industry	Yokosuka
CREOL	College of Optics & Photonics, UCF	Orlando
CSU	Colorado State University	Fort Collins
ELI-Hu	Extreme Light Infrastructure Attosecond Light Pulse Source	Szeged
ELI-Cz	Extreme Light Infrastructure Czech Republic	Dolní Břežany
ELI-NP	Extreme Light Infrastructure Nuclear Physics	Bucharest
EXFEL	European XFEL, High Energy Density Group	Schenefeld
FSU	IOQ/Friedrich Schiller University of Jena	Jena
GAP-Bio	Université de Genève, GAP-Biophotonics	Carouge
GPI	Graduate School for the Creation of New Photonics Ind.	Hamamatsu
GSI	GSI-Helmholtzzentrum fuer Schwerionenforschung GmbH	Darmstadt
HHU	Heinrich Heine Universität, Düsseldorf	Düsseldorf
HIJ	Helmholtz Institute Jena	Jena
HiLASE	HiLASE	Dolní Břežany
HU	Hebrew University, Arie Zigler Group	Jerusalem
HZDR	Helmholtz Zentrum Dresden- Rossendorf	Dresden
IAP	Institute of Applied Physics, Russian Academy of Sciences	Nizhny Novgorod
ICL	Imperial College London	London
IHCE	Institute of High Current Electronics	Tomsk
ILE-j	Institute for Laser Engineering, Osaka University	Osaka
ILIL	Intense Laser Radiation Laboratory	Pisa
INFLPR	National Institute for Laser, Plasma, and Radiation Phys.	Bucharest
IOE	Instytut Optoelektroniki, Wojskowa Akademia Tech.	Warsaw
IOP	Institute of Physics, Chinese Academy of Sciences	Beijing
IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw
JIHT	Joint Institute for High Temperatures	Moscow
KAERI	Korean Atomic Energy Research Institute	Daejoen
KPSI	Kansai Photon Science Institute	Kizugawa
KQALS	Kaifeng Qiyuan Advanced Light Source Research Institute	Kaifeng
KyoU	Kyoto University, Institute for Chemical Research	Kyoto
L2I	Laboratory for Intense Lasers (L2I)	Lisbon
LBNL	Lawrence Berkeley National Laboratory	Berkeley
LC	Centrum Laserowe, Instytutu Chemii Fizycznej	Warsaw
LFRC	Laser Fusion Research Center at the CAEP	Mianyang
LLAMS	LaserLab Amsterdam	Amsterdam
LLC	Lund Laser Center	Lund
LLE	Laboratory for Laser Energetics	Rochester
LLNL-NIF	Lawrence Livermore NL - National Ignition Facility	Livermore
LLNL-JLF	Lawrence Livermore NL - Jupiter Laser Facility	Livermore
LMU	Ludwig Maximilians- Universität München, LEX Photonics	Munich
LNF	Laboratori Nazionali di Frascati, SPARC Lab	Frascati
LOA	Laboratoire d'Optique Appliquée-ENSTA-Ecole Polytech.	Palaiseau
LULI	Laboratoire pour l'Utilisation des Lasers Intenses	Palaiseau
MBI	MAX-BORN-INSTITUT für Nichtlineare Optik und...	Berlin
MPQ	Max Planck Institute for Quantum Optics	Garching
NCU	National Central University	Taoyuan City
NII-OEP	Scientific Research Inst. for Optoelectronic Instrum. Engin.	Сосновый Бор
NRL	Naval Research Laboratory	Washington DC
OsaU	Osaka University	Osaka
OSU	Ohio State University, Scarlet Laser Facility	Columbus
OXFD	University of Oxford	Oxford
PALS	Prague Asterix Laser System Research Centre	Prague
Pek	Peking University	Peking
PMil	Politecnico Milano	Milan
PNLI	PN Lebedev Institute of Russian Academy of Science	Moscow
PU	Princeton University, Extreme Light-Matter Interactions Lab	Princeton
QUB	Queen’s University Belfast, Centre for Plasma Physics	Belfast
RAL	STFC Rutherford Appleton Laboratory, Central Laser Facility	Didcot
RIKEN	RIKEN (from concatenation of Rikagaku Kenkyusho	Tokyo
RRCAT	Raja Ramanna Centre for Advanced Technology	Indore
SACLA	Spring-8 Angstrom Compact Free Electron Laser	Sayo
SCAPA	Scottish Centre for the Appl. of Plasma-based Accelerators	Glasgow
SEL	Station for Extreme Light	Shanghai
SIOM	Shanghai Institute of Optics and Fine Mechanics	Shanghai
SJTU	Shanghai Jiao Tong University	Shanghai
SLAC	Stanford Linear Accelerator Center	Stanford
SLIC	Saclay Laser-matter Interaction Center	Saclay
SNL	Sandia National Laboratory	Albuquerque
SULF	Shanghai Superintense Ultrafast Laser Facility	Shanghai
SWJTU	Southwest Jiaotong University	Emeishan
TAU	Tel Aviv Univ., Intense Lasers and Ultrafast Science Group	Tel Aviv
TIFR	Tata Institute of Fundamental Research	Mumbai
TU	Tsinghua University	Beijing
TIFR-H	Tata Institute of Fundamental Research, Hyderabad	Hyderabad
UAlb	University of Alberta	Edmonton
UCD	University College Dublin	Dublin
UCI	University of California, Irvine	Irvine
UCLA	University of California, Los Angeles	Los Angeles
UDel	University of Deleware	Newark
UEC	University of Electro-Communications Inst. for Laser Science	Tokyo
UMD	University of Maryland	College Park
UMed	Université de la Méditerranée, Laboratoire LP3	Marseilles
UMich	University of Michigan, Center for Ultrafast Optical Science	Ann Arbor
UNeb	University of Nebraska- Lincoln, Extreme Light Laboratory	Lincoln
UNev	University of Nevada at Reno, Nevada Terawatt Facility	Reno
USC	University of Santiago de Compostela, L2A2	Santiago
USze	University of Szeged	Szeged
UTex	University of Texas at Austin	Austin
UTok	University of Tokyo, Institute for Solid State Physics	Tokyo
VNIIEF	RFNC- All-Russian Research Institute of Experimental Phys.	Sarov
VNIITF	RFNC- Russian Research Institute of Technical Physics	Снежинск
VULRC	Vilnius University Laser Research Center	Lithuania
WIS	Weizman Institute of Science	Rehovot
WU	Warsaw University, Ultrafast Phenomena Lab	Warsaw

Q&A

Lawrence Livermore
National Laboratory

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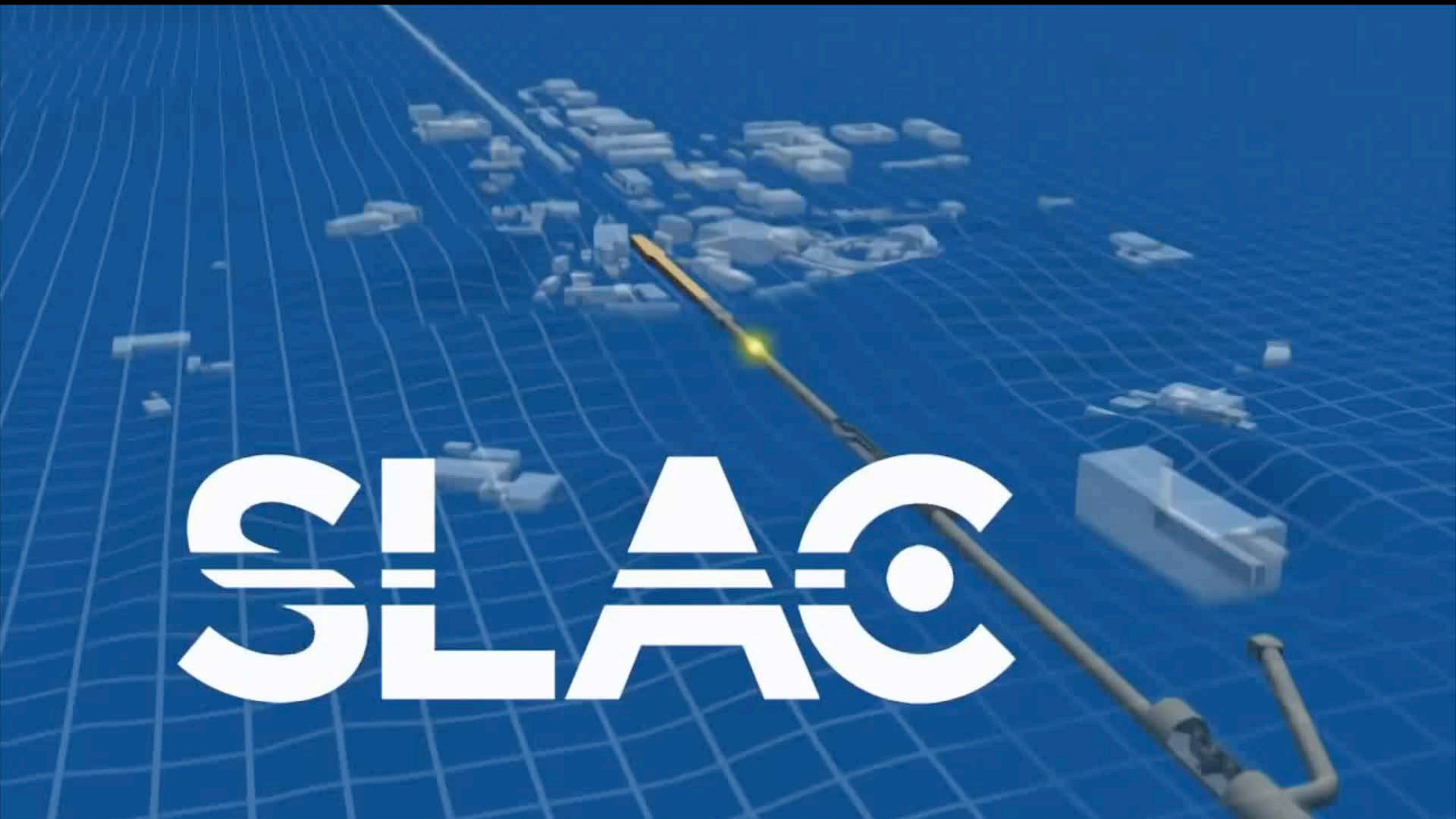
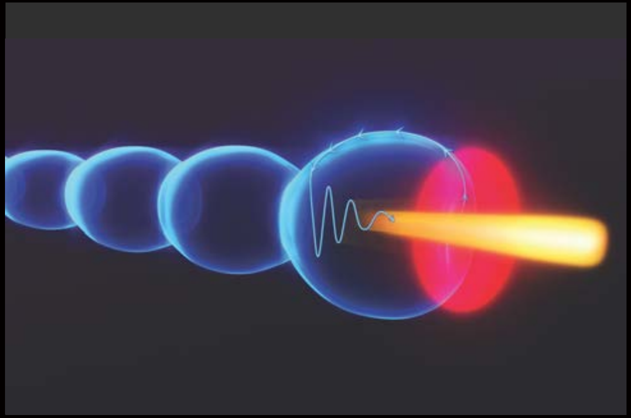

SLAC

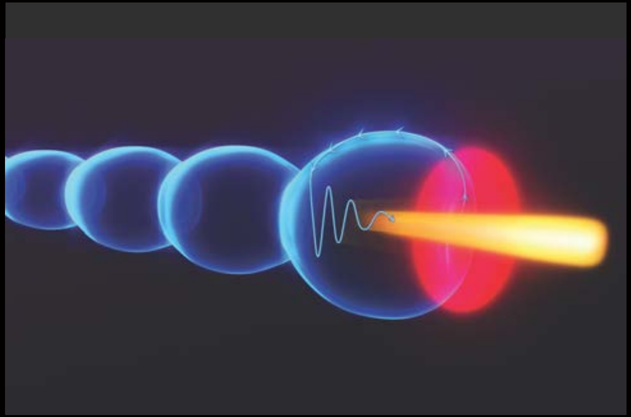
What we've learned today

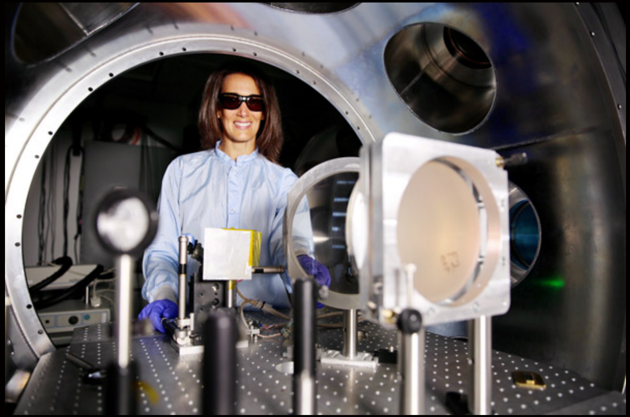
What we've learned today

What we've learned today



What we've learned today





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