Accelerators for Society

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PAUL SCHERRER INSTITUT

I.FAST Challenge Based Innovation Seminar, July 6, 2023

Accelerator driven applications to meet the needs of society

- Advanced instruments for basic and applied science
- Analysis of physical, chemical and biological materials
- Modification of physical, chemical and biological properties of matter
- Medical: diagnostics, treatment and targeted drug design
- Security: cargo scanning, IT hardware
- Environment
- Energy

A beam of particles is a very useful tool.
A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey
or
discover the secrets of the universe

From the [Report "Accelerators for America's Future", US Department of Energy, 2010]

Instruments development:

400 years of discoveries with “telescopes” and “microscopes”

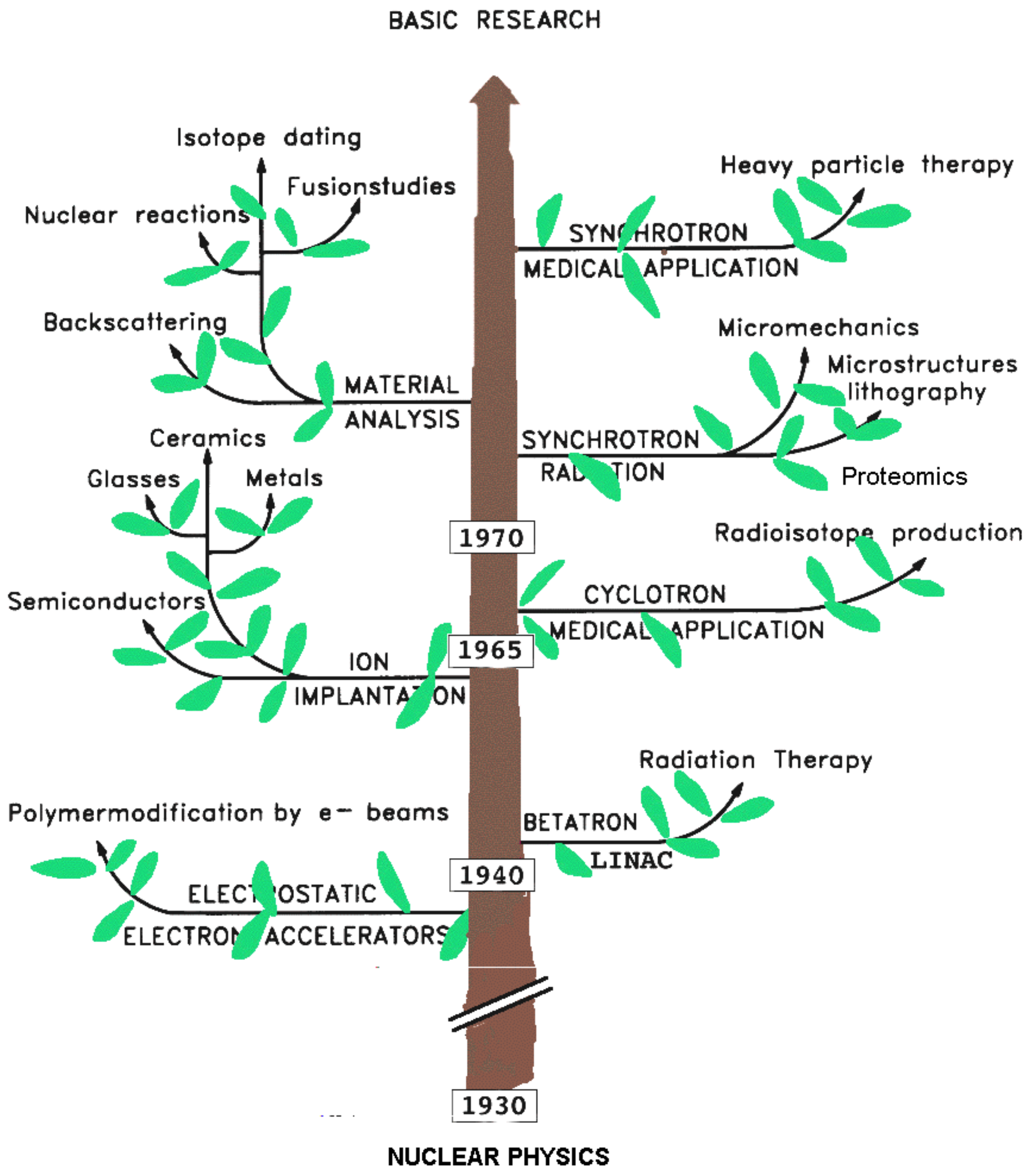
Galileo Galilei

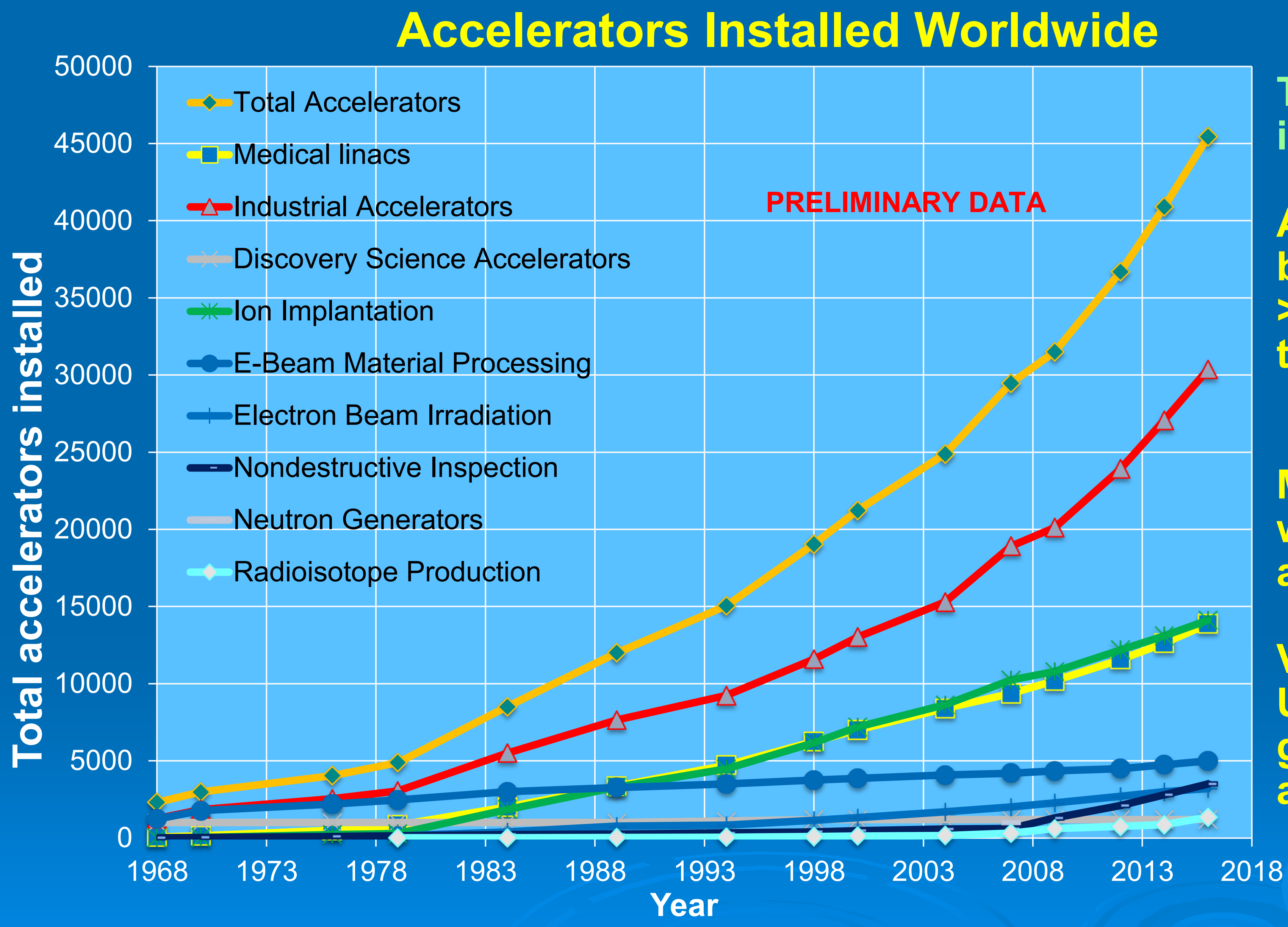
Zacharias Janssen

The role of accelerators in Physical and Life Sciences

“Instruments have a life of their own.
They do not merely follow theory; often they determine theory, because instruments determine
what is possible, and what is possible determines to a large extent what can be thought. The telescope, the microscope, the chronograph, the photograph: all gave rise to a blossoming of theoretical understanding
not possible before their invention”

Hankins & Silverman,
Instruments and the Imagination





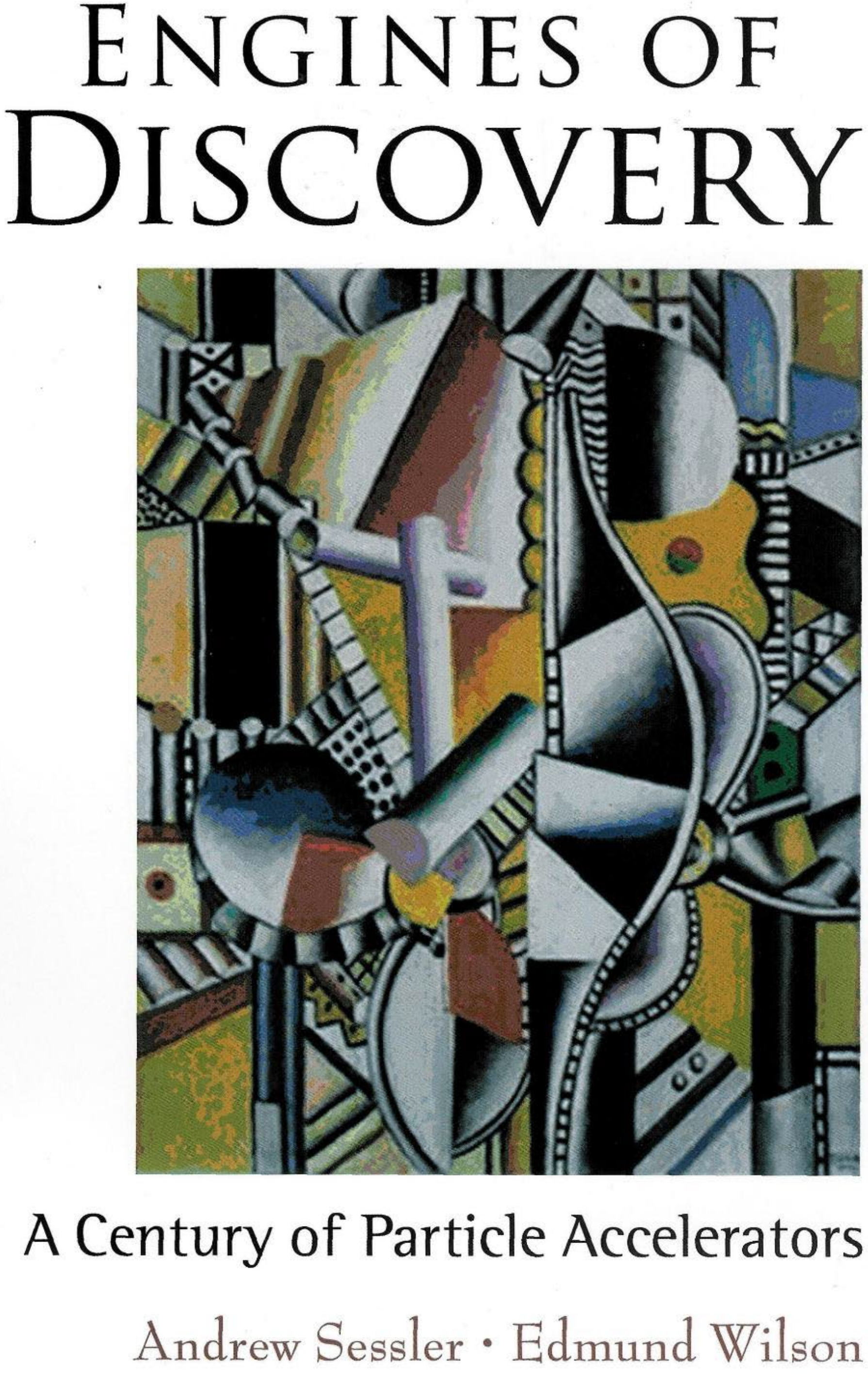
Total sales of accelerators is ~US$5B annually

About 47,000 systems have been sold,
> 40,000 still in operation today

More than 100 vendors worldwide are in the accelerator business.

Vendors are primarily in US, Europe and Japan, but growing in China, Russia and India

R. Hamm, Accelerator-Industry Co-Innovation Workshop, Feb 6, 2018, Brussels, Belgium



« Le seul véritable voyage … ce ne serait pas d'aller vers de nouveaux paysages, mais d'avoir d'autres yeux, de voir l'univers avec les yeux d'un autre, de cent autres, de voir les cent univers que chacun d'eux voit, que chacun d'eux est. »

(Marcel Proust, La Prisonnière, 1923)

"The real voyage of discovery consists not in seeking new landscapes but in having new eyes"

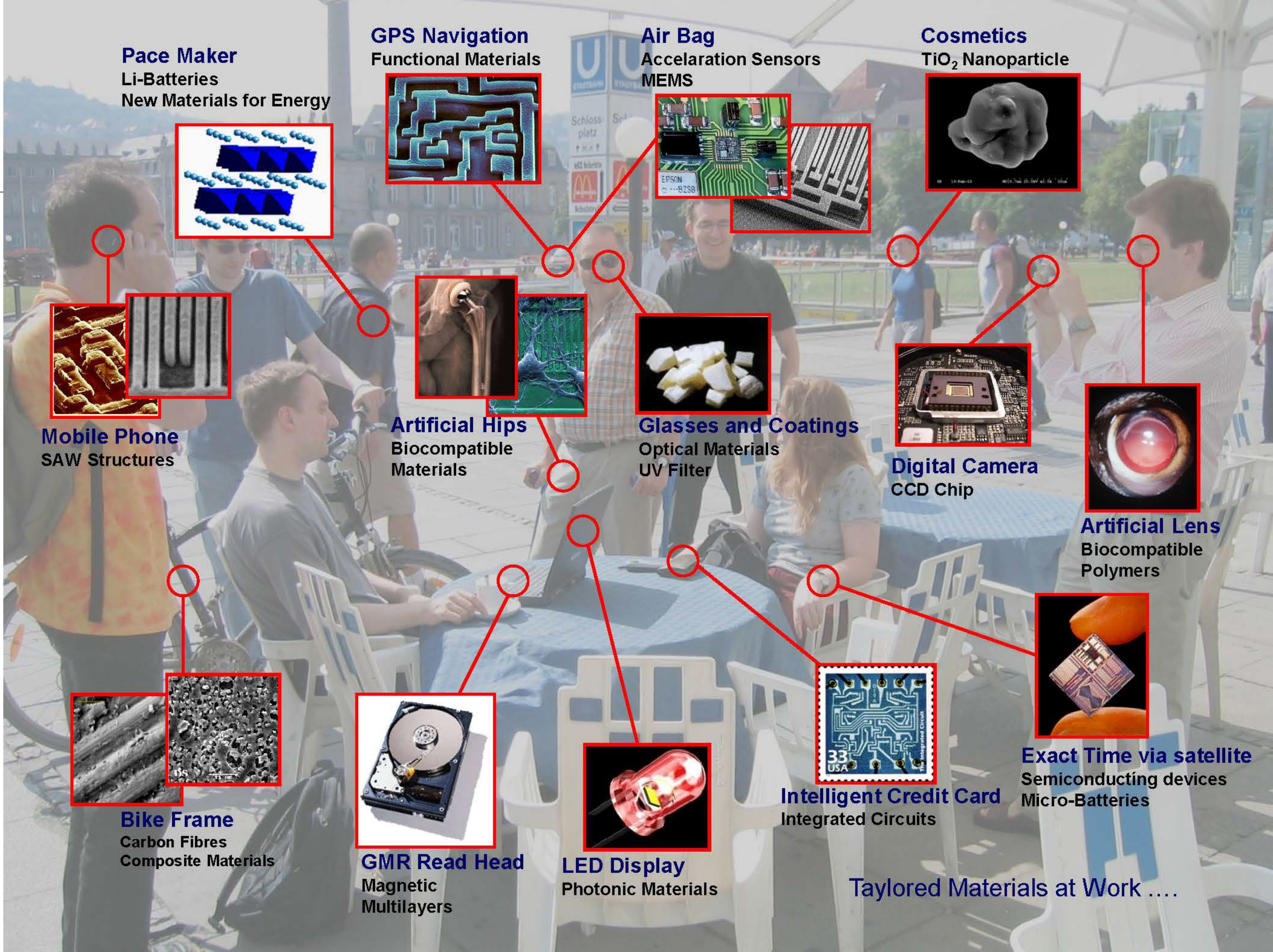
Marcel Proust

Materials

Modern day materials

Accelerators had an impact on a wide range of materials

Modern day materials



Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties (boron, phosphorus)

Semi Conductors

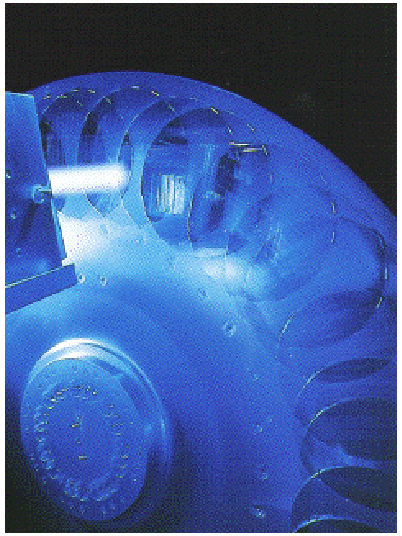
- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!



N2 ions reduce wear and corrosion in this artificial femur

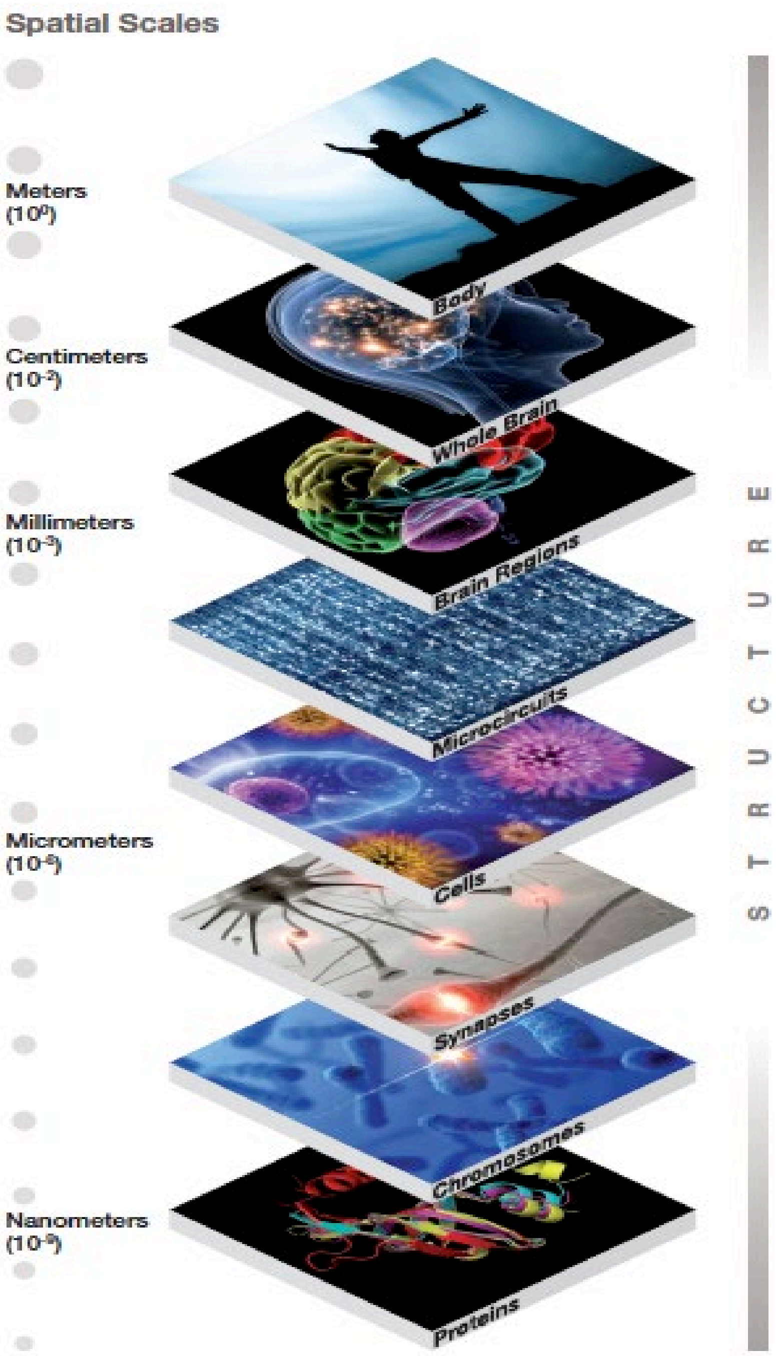
Easter morning 1900: 5th
the automobile.

Easter morning 1913: 5th Ave, New York City.
Spot the horse.

Light sources

Imaging things
on all length and time scales
using accelerators,

e.g. latest X-Ray and
computational technologies
(developed at accelerators)



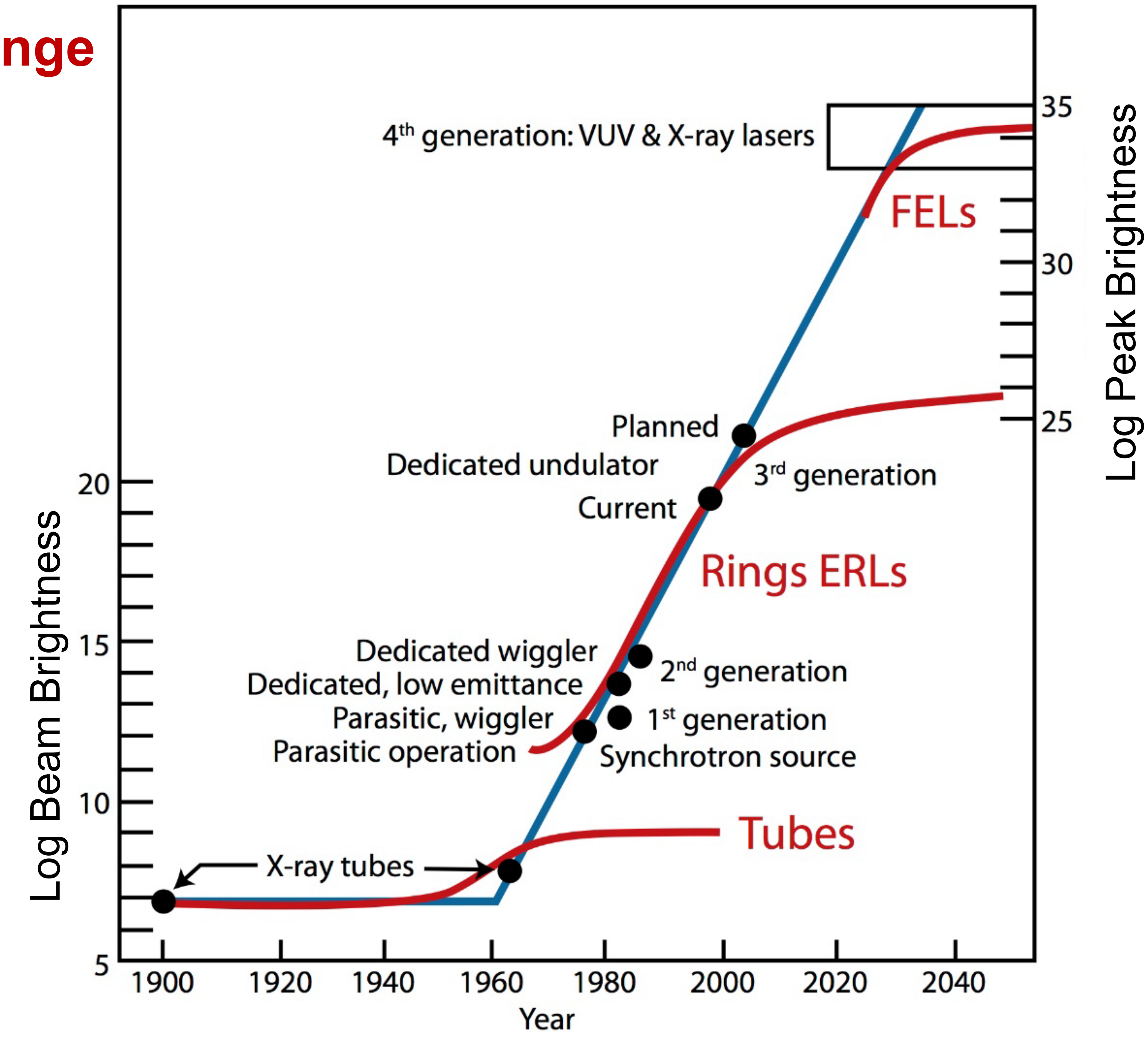
Synchrotron Light Sources: about 50 storage ring based

60‘000 users world-wide

Established, mature technology

Brightness: disruptive change

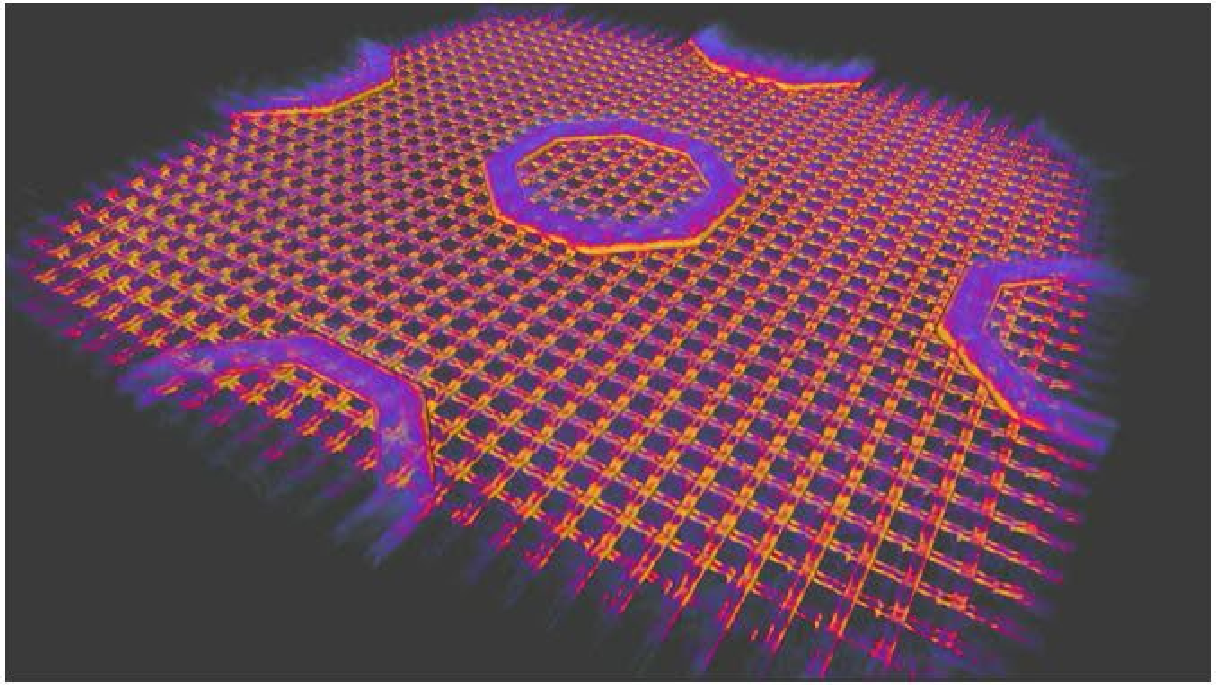
- X-ray Tubes
- Storage Rings
- FELs
- ? Compact sources ?



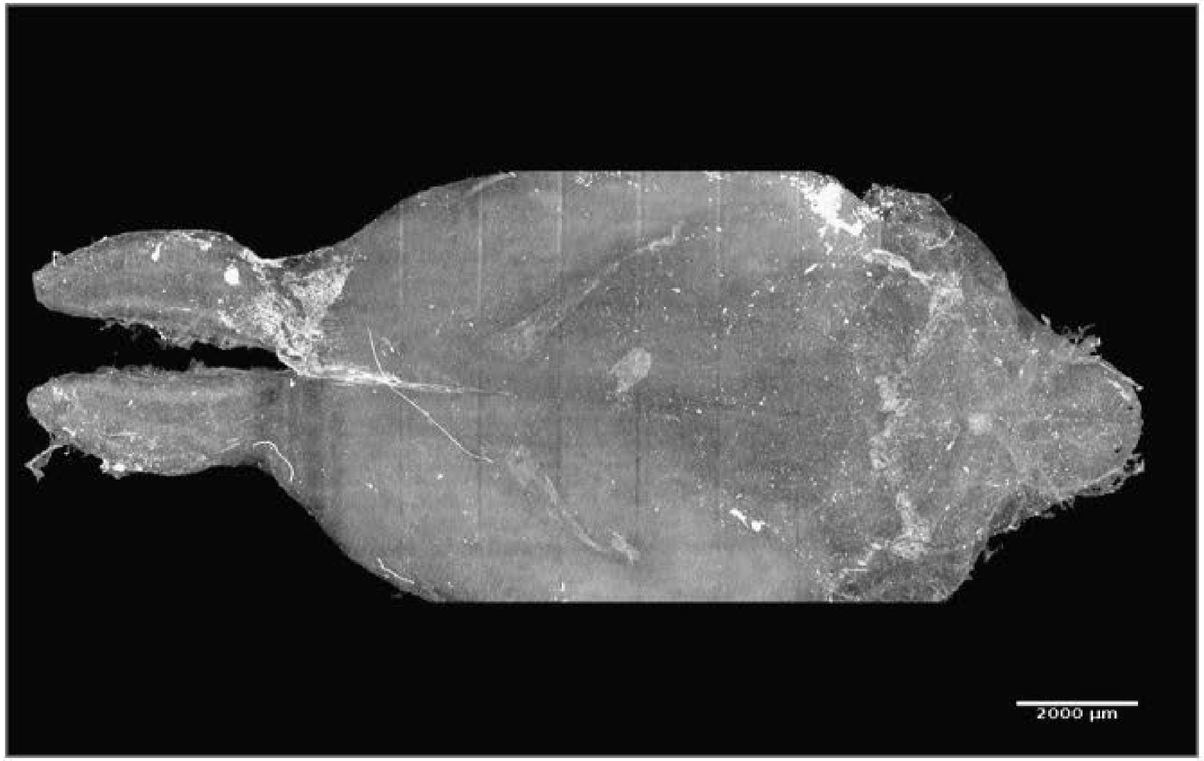
X-Ray tomography

Architecture of artificial and natural intelligence on all scales

Nature Electronics 2, 464-470 (2019)

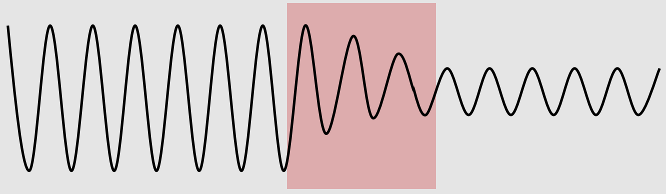


Brain of a mouse in 3-D
Miettinen *et al.*

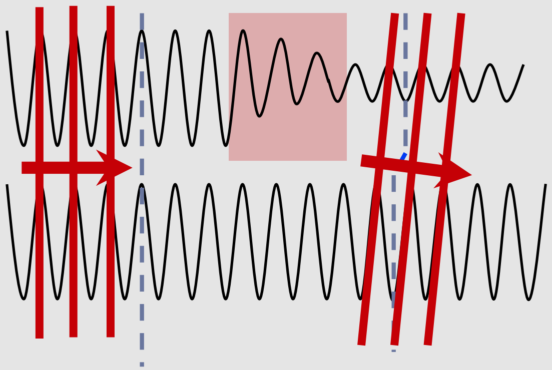


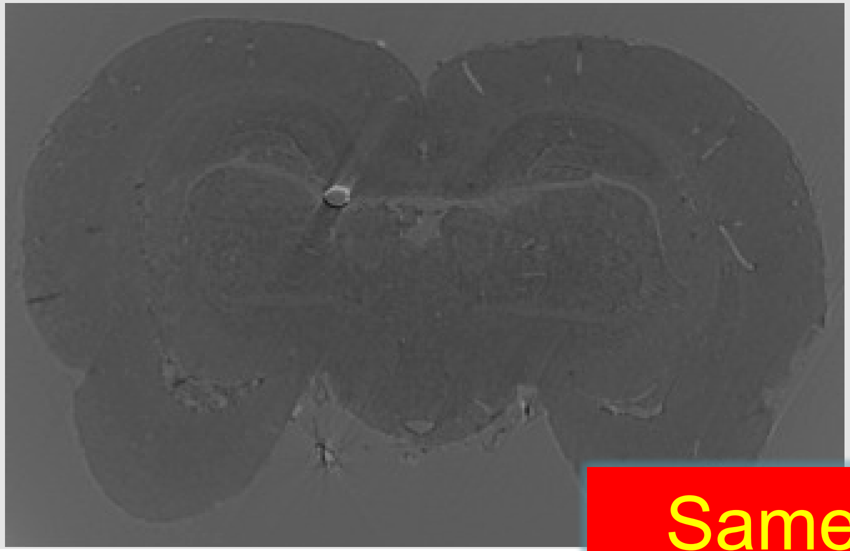
Phase contrast X-Ray imaging: improved soft tissue contrast

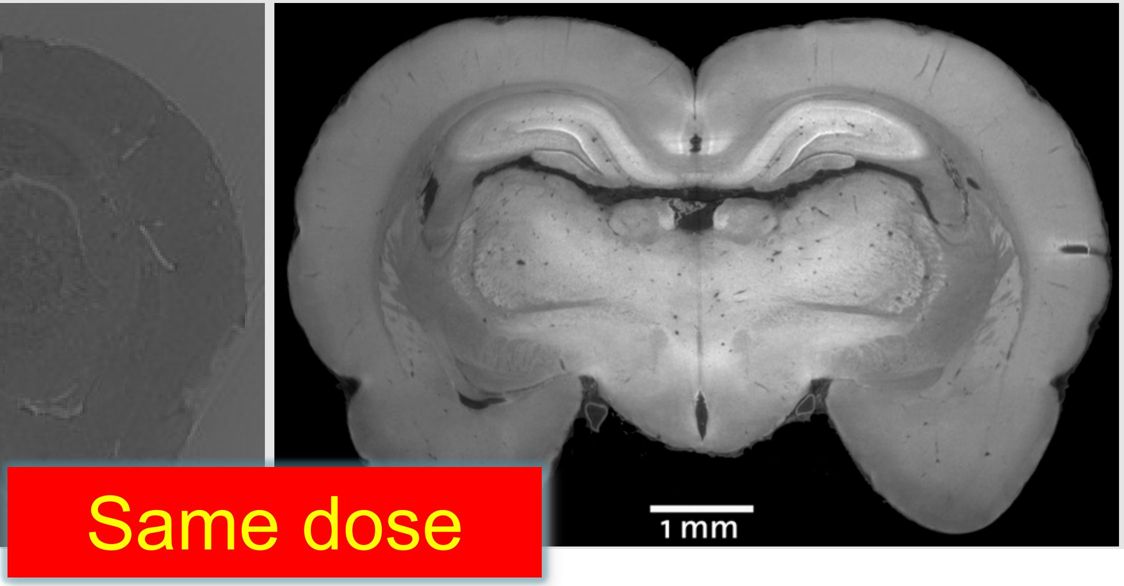
Absorption



Phase contrast







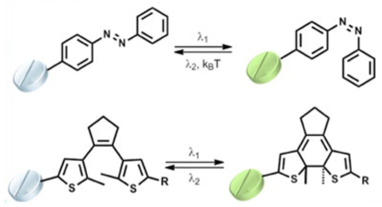
Time-resolved Structural Biology

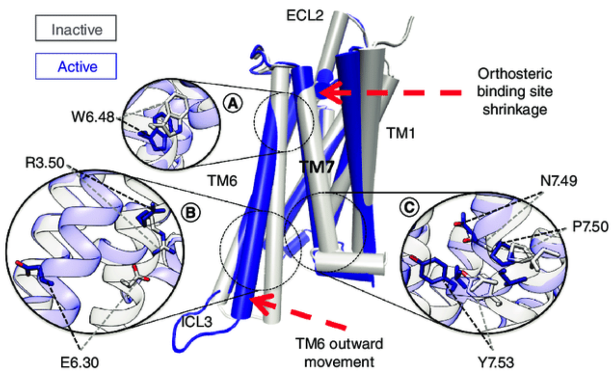
Driving Structural biology from molecular snapshots towards molecular movies

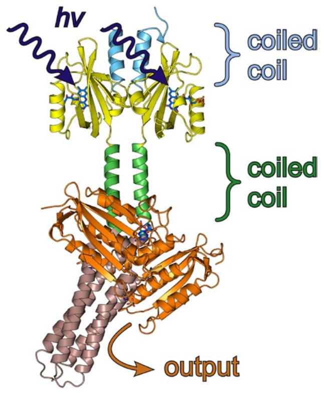
Femtochemistry | Protein Dynamics | Multi-domain Protein

Structural element

Activation with light
High spatiotemporal precision
Regulated dosage
Molecular approach
Examples:







Time: fs — ps — ns — µs — ms — s

Process: bond formation and breakage | concerted atom motions | small to medium scale conformational changes | large scale changes / complex formation

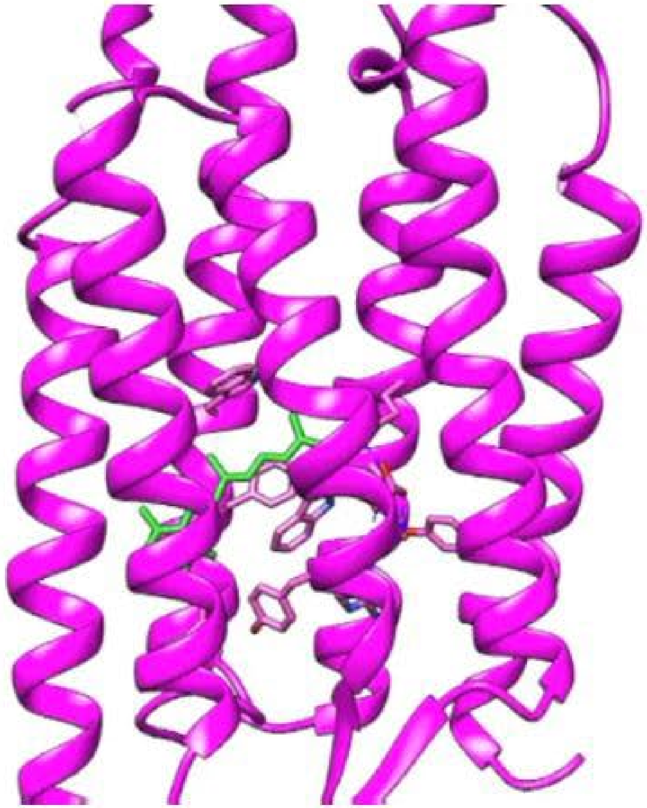
Structure: X-ray laser | Synchrotron | cryo-EM

Spectroscopy: Time-resolved spectroscopy

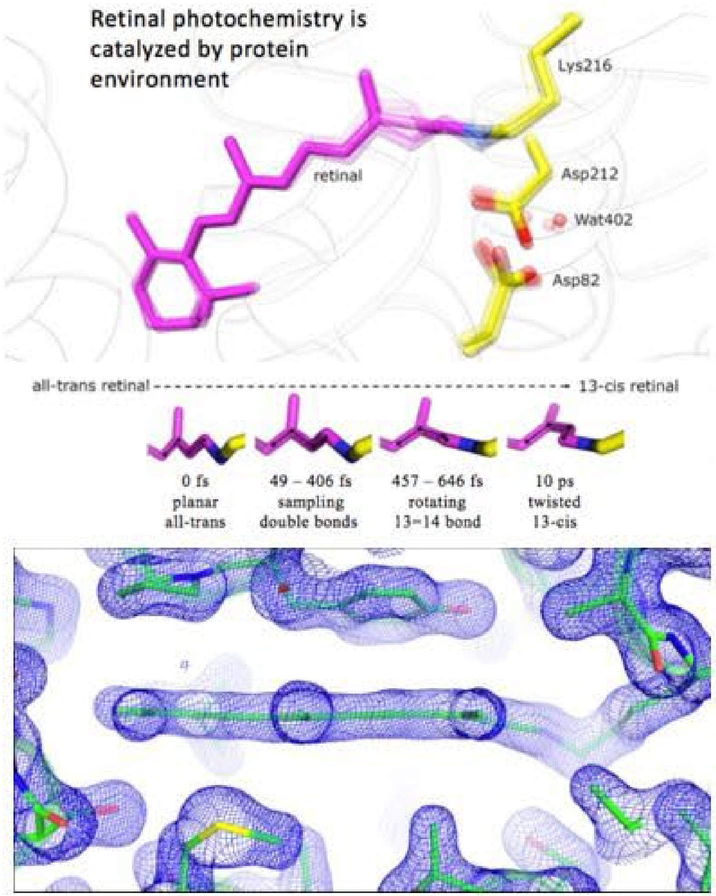
Simulation: Quantum Mechanics to Steered Molecular Dynamics

Light harvesting in marine life: major contributors to solar energy captured in the sea
Scientists "film" one of the fastest reactions in biology

Time resolved structural analysis of bacteriorhodopsin: Structural basis of photocatalysis



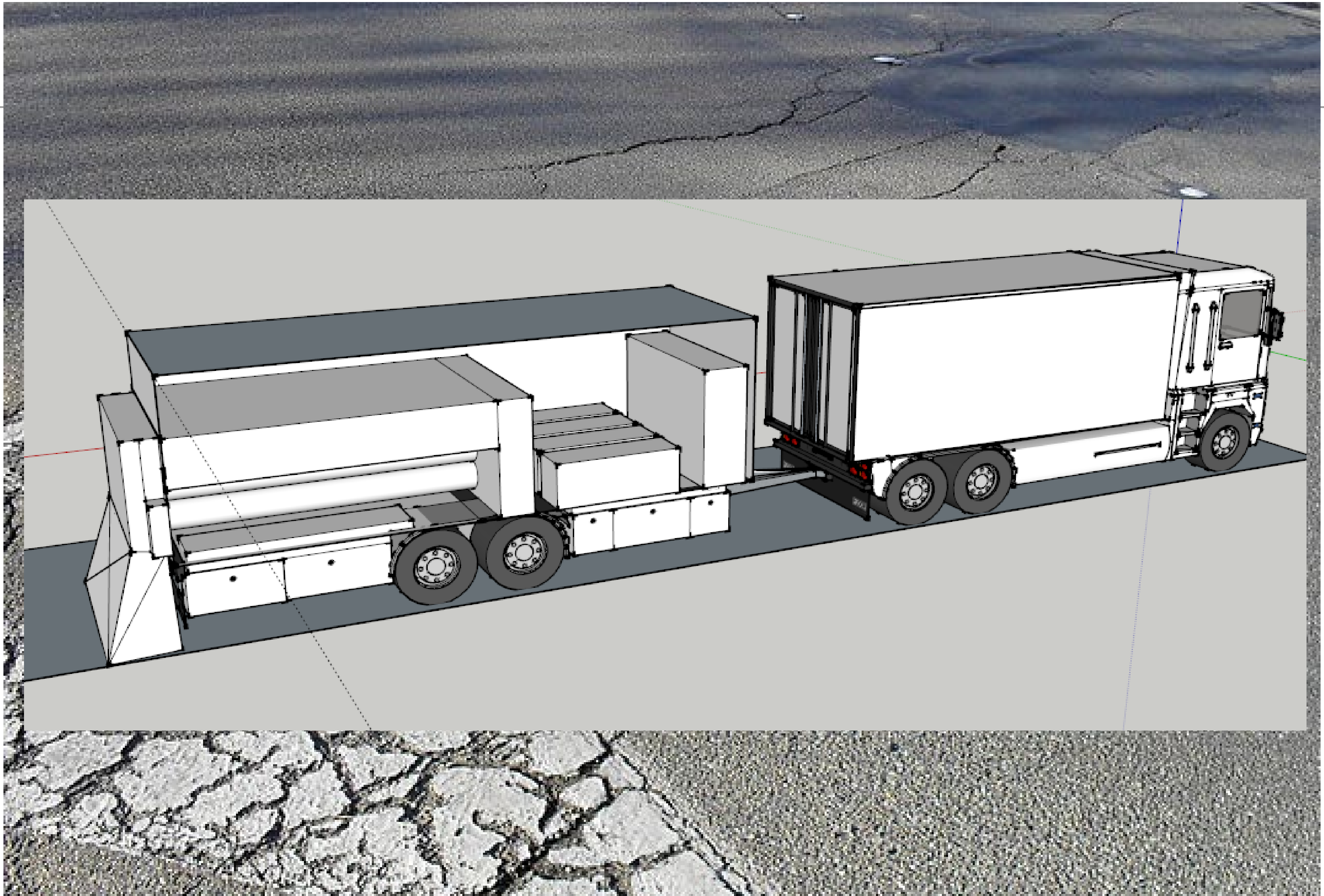
The chemical basis of optogenetics



Nogly et al. Science 2018; DOI: 10.1126/science.aat0094

Compact accelerators:
sources of photons, neutrons, electrons etc.

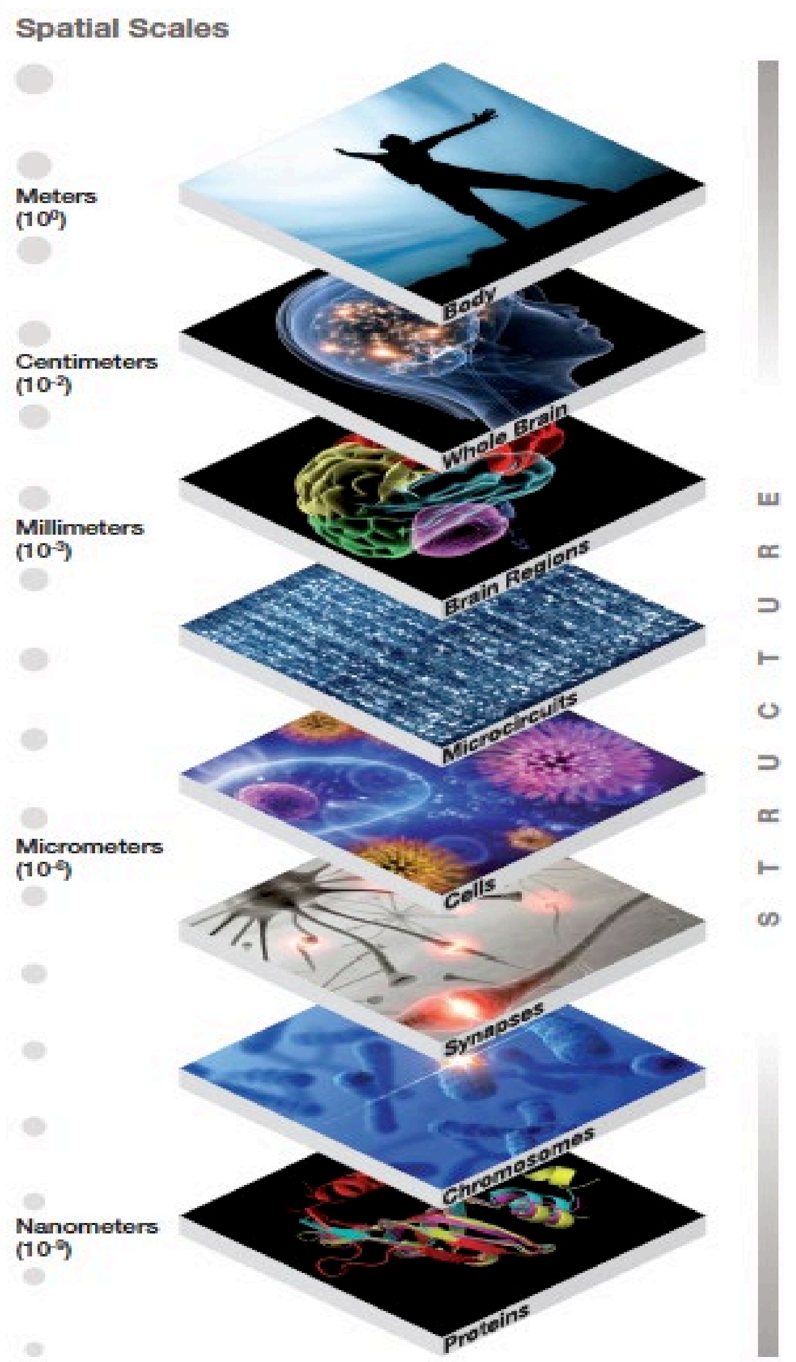
Road pavement durability: mobile electron accelerators?



Imaging things

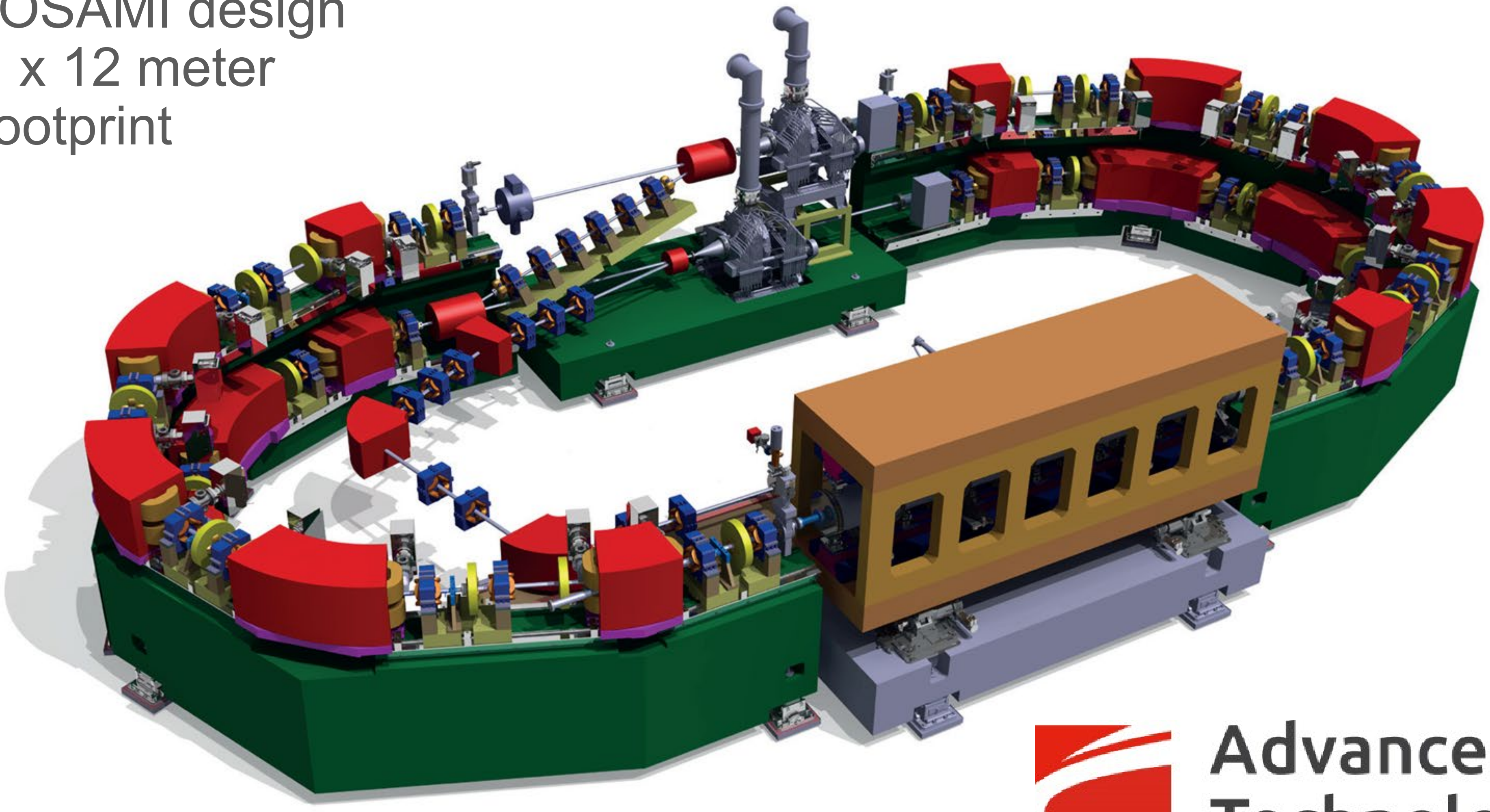
on all length and time scales
using accelerators,

e.g. latest X-Ray and
computational technologies
(developed at accelerators)



Disruptive storage rings technology change: a much brighter compact sources e.g. for shorter wavelength lithography

COSAMI design
5 x 12 meter
Footprint

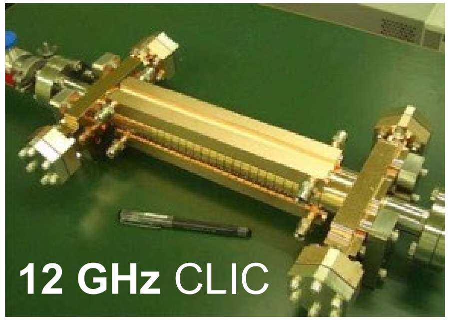


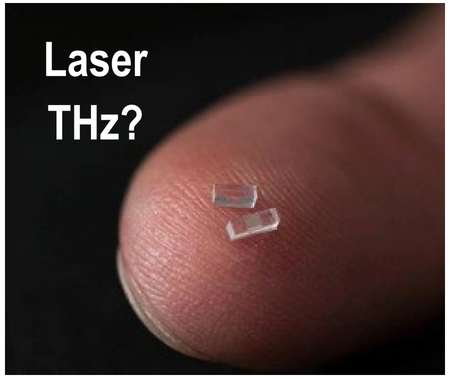
Advanced Accelerator Technologies

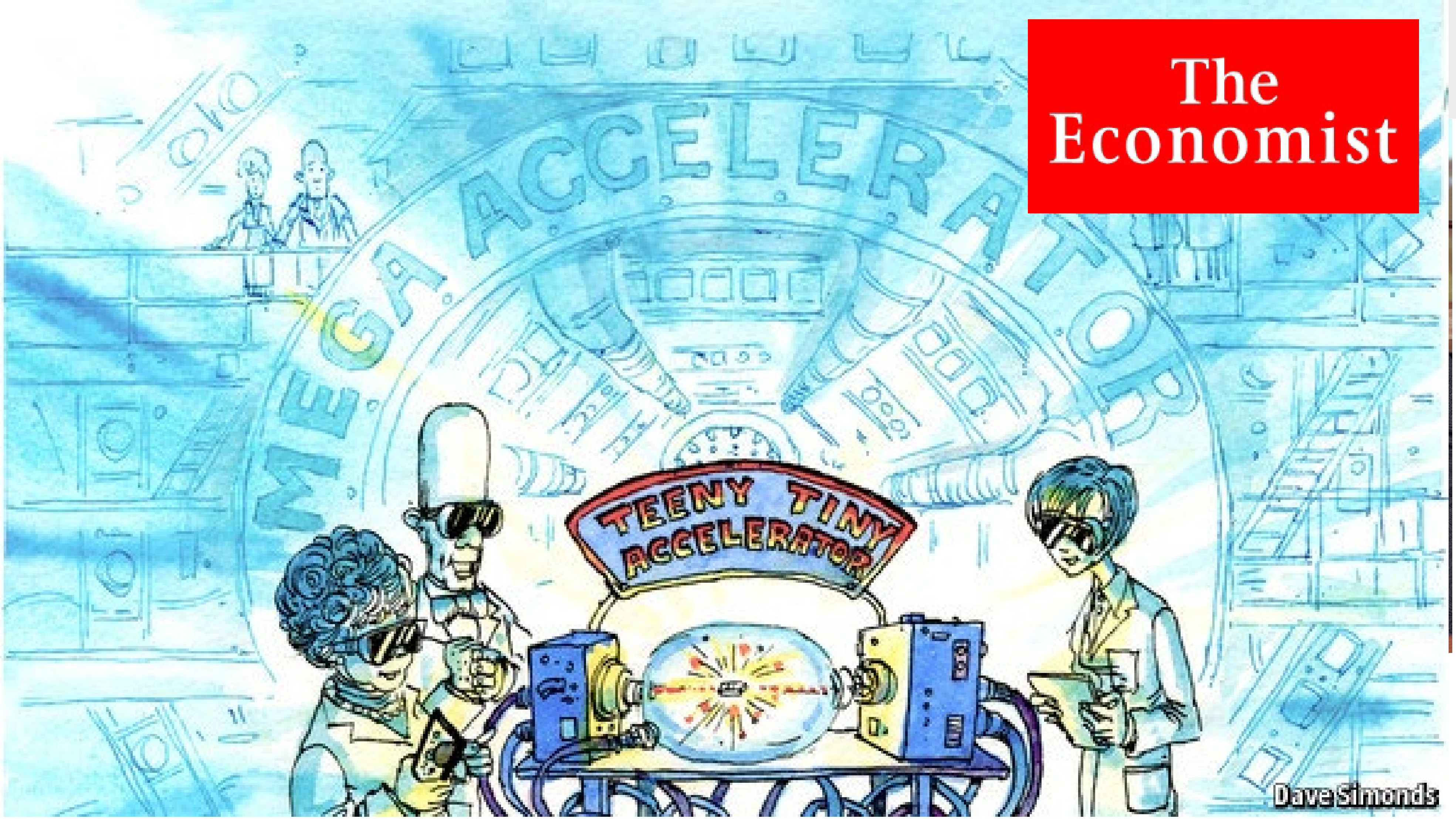
Compact accelerators

GORDON AND BETTY MOORE FOUNDATION

DESY | EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG | PAUL SCHERRER INSTITUT PSI | SLAC NATIONAL ACCELERATOR LABORATORY







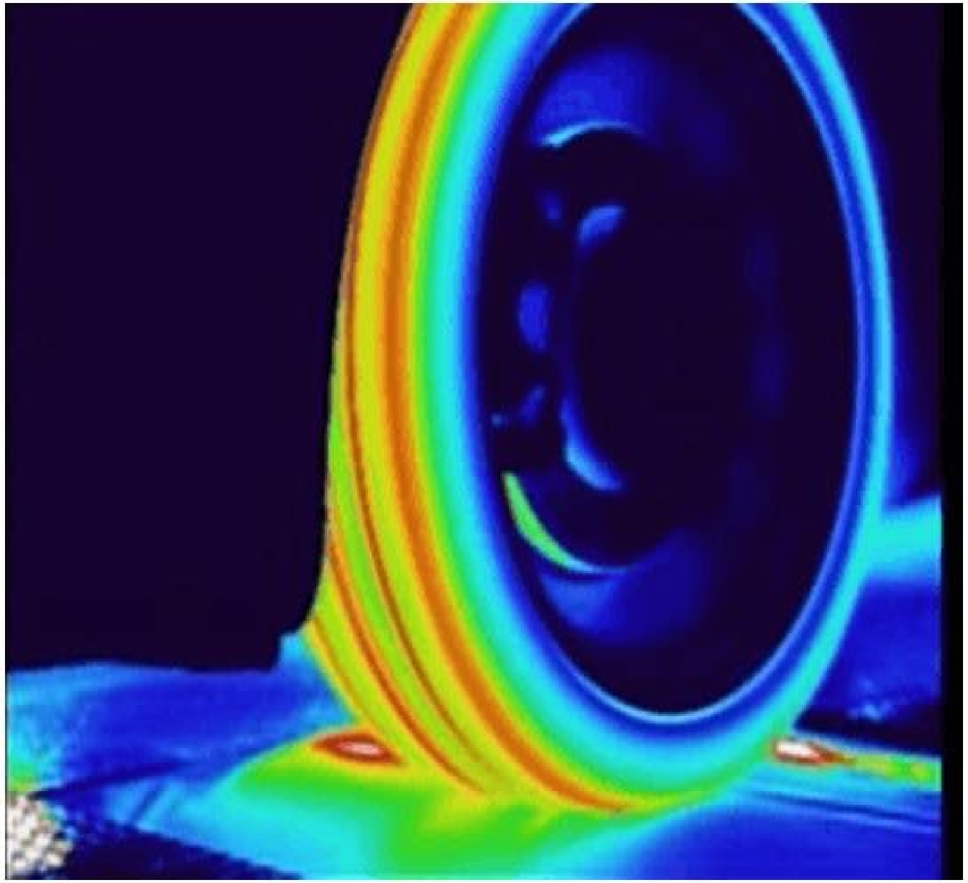
Environmental Protection examples:

- sewage treatment
- medical waste treatment
- radioactive waste transmutation
- power plant gas emission
- oil sludge treatment

Improving energy efficiency: energy-saving tire

Conventional Tire

エナセーブ
PREMIUM



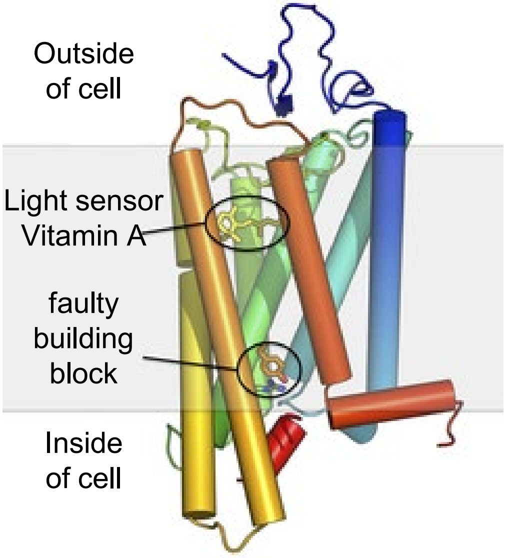
Low Energy Loss

6% Saving of Gas Consumption

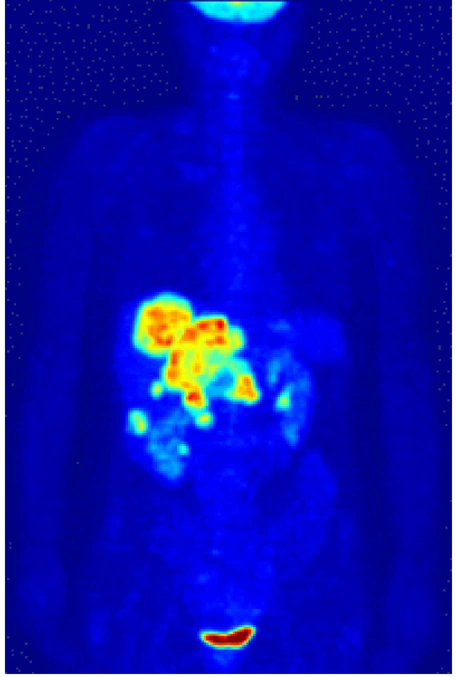
39% Reduction of Friction Resistance

Medical applications

Accelerators for medicine

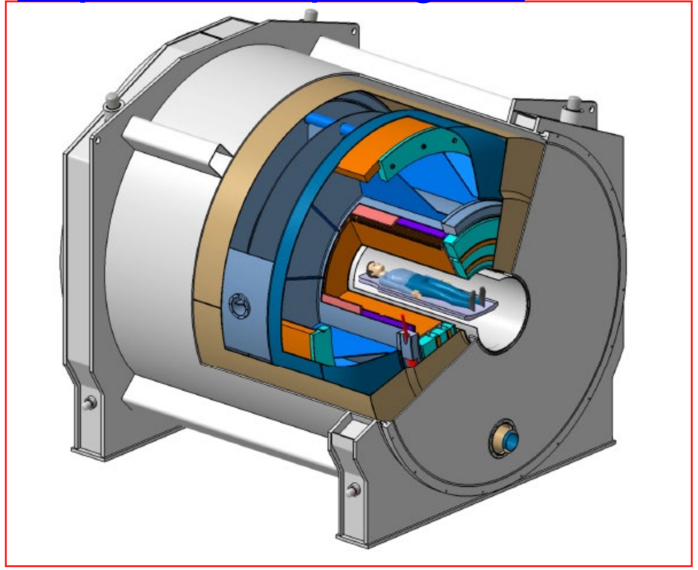


Structure of proteins:
targeted drug design



Radio pharmaceuticals:
diagnostics and therapy

Particle therapy: https://www.ptcog.ch/



ISEULT
Whole body MRI 11.75 T

X-Ray radiotherapy: using electron beams to produce X-Rays

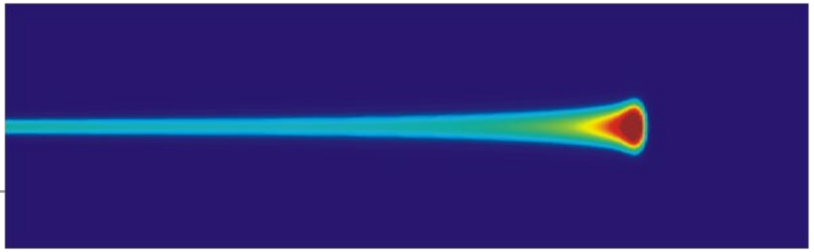
Varian brothers started at Stanford

1947, 2 MeV/m
One meter long

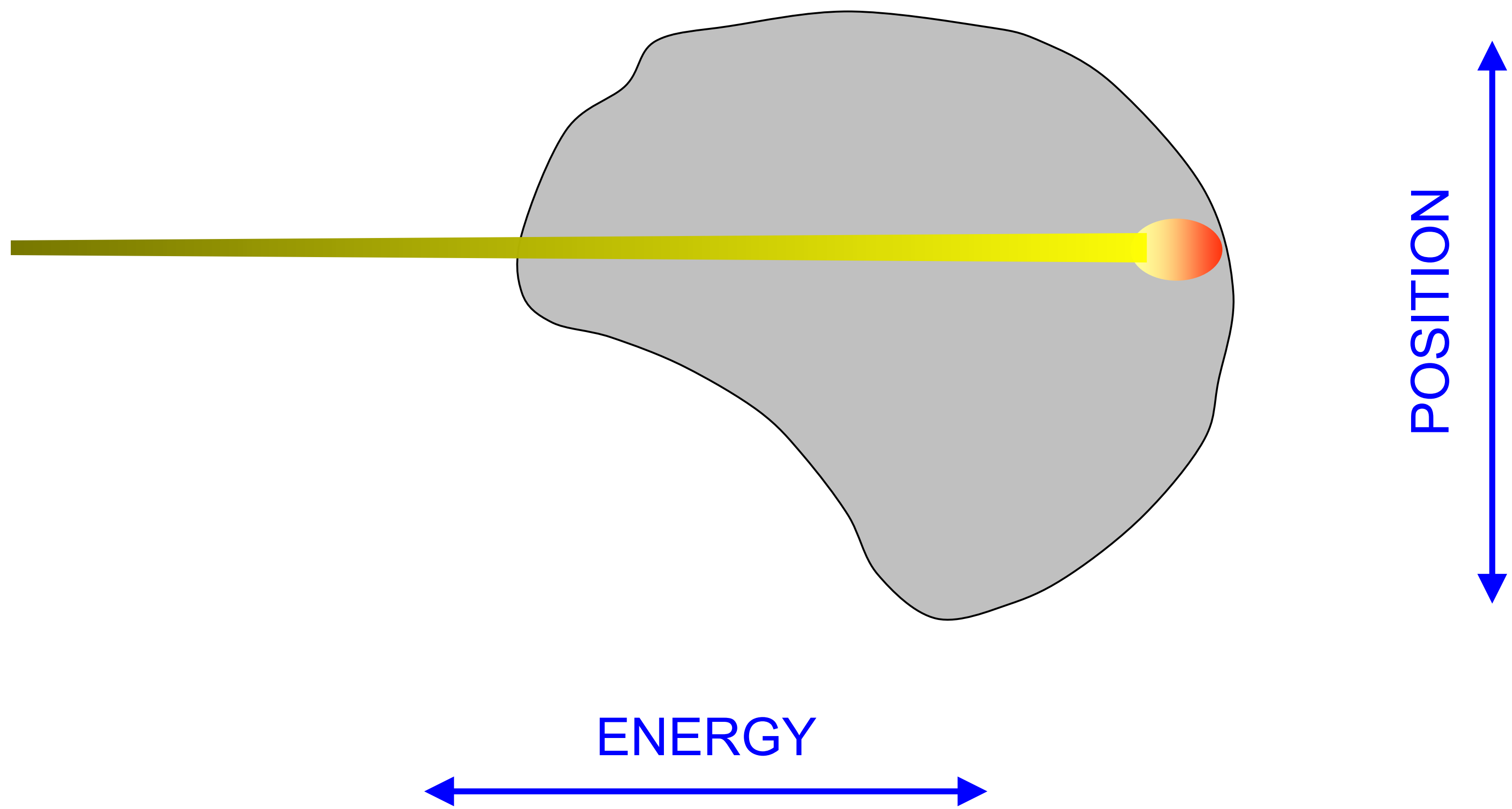
50,000,000

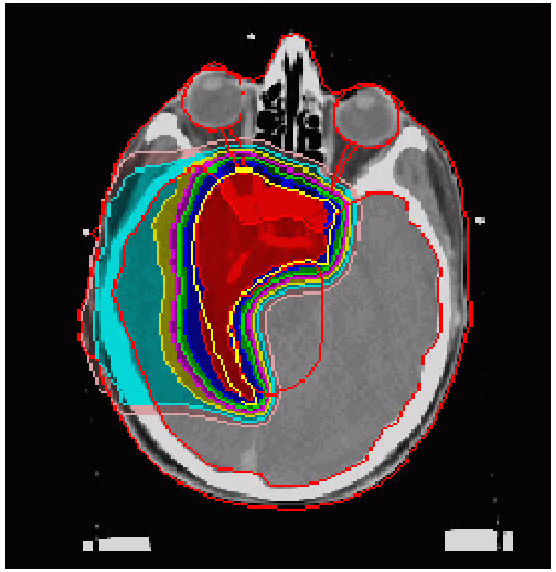
patients treated with photons

BRAGG PEAK: SPOT SCANNING

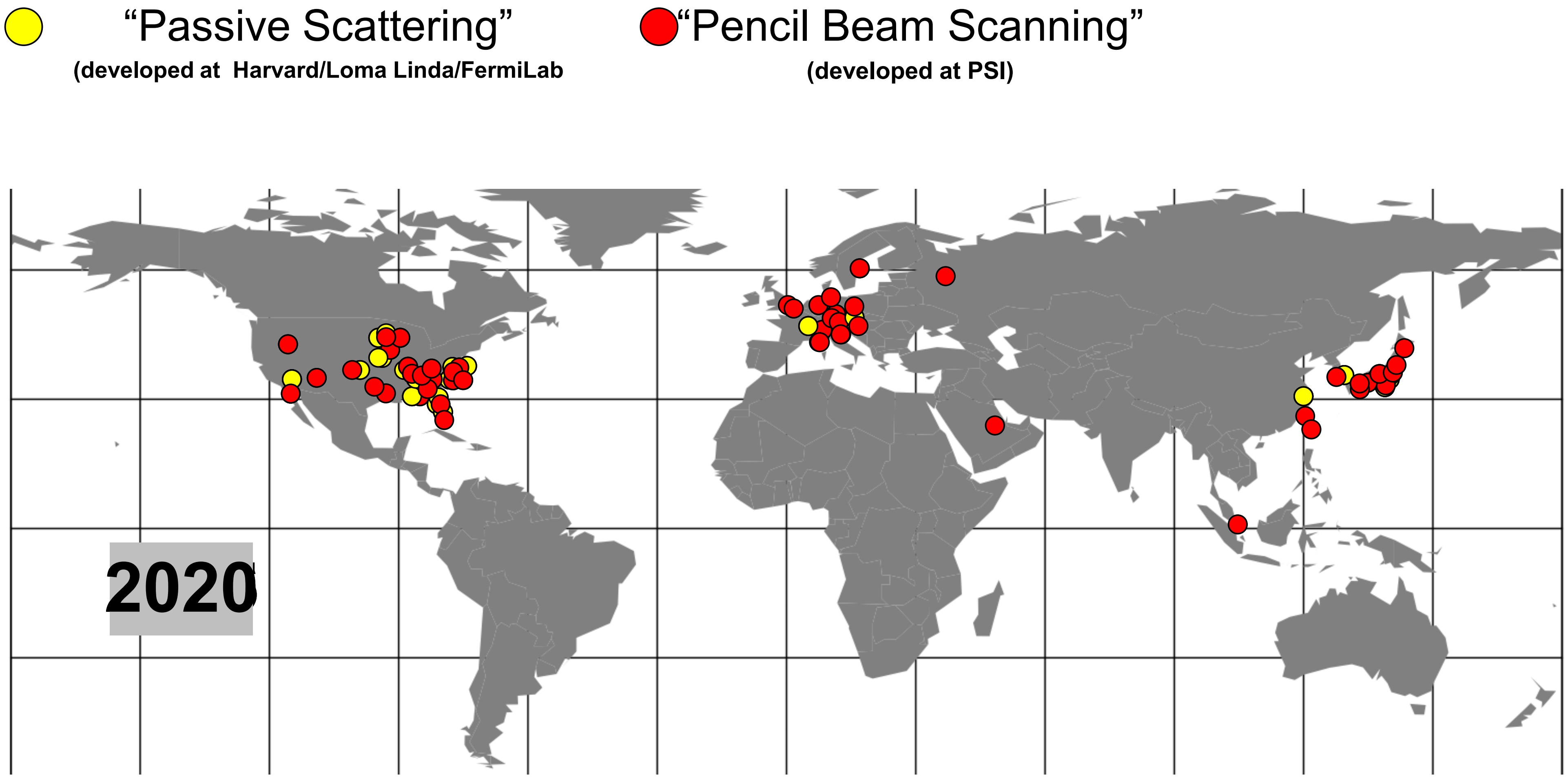


TREATMENT OF DEEP LYING TUMORS WITH BEST PROTECTION OF THE SURROUNDING

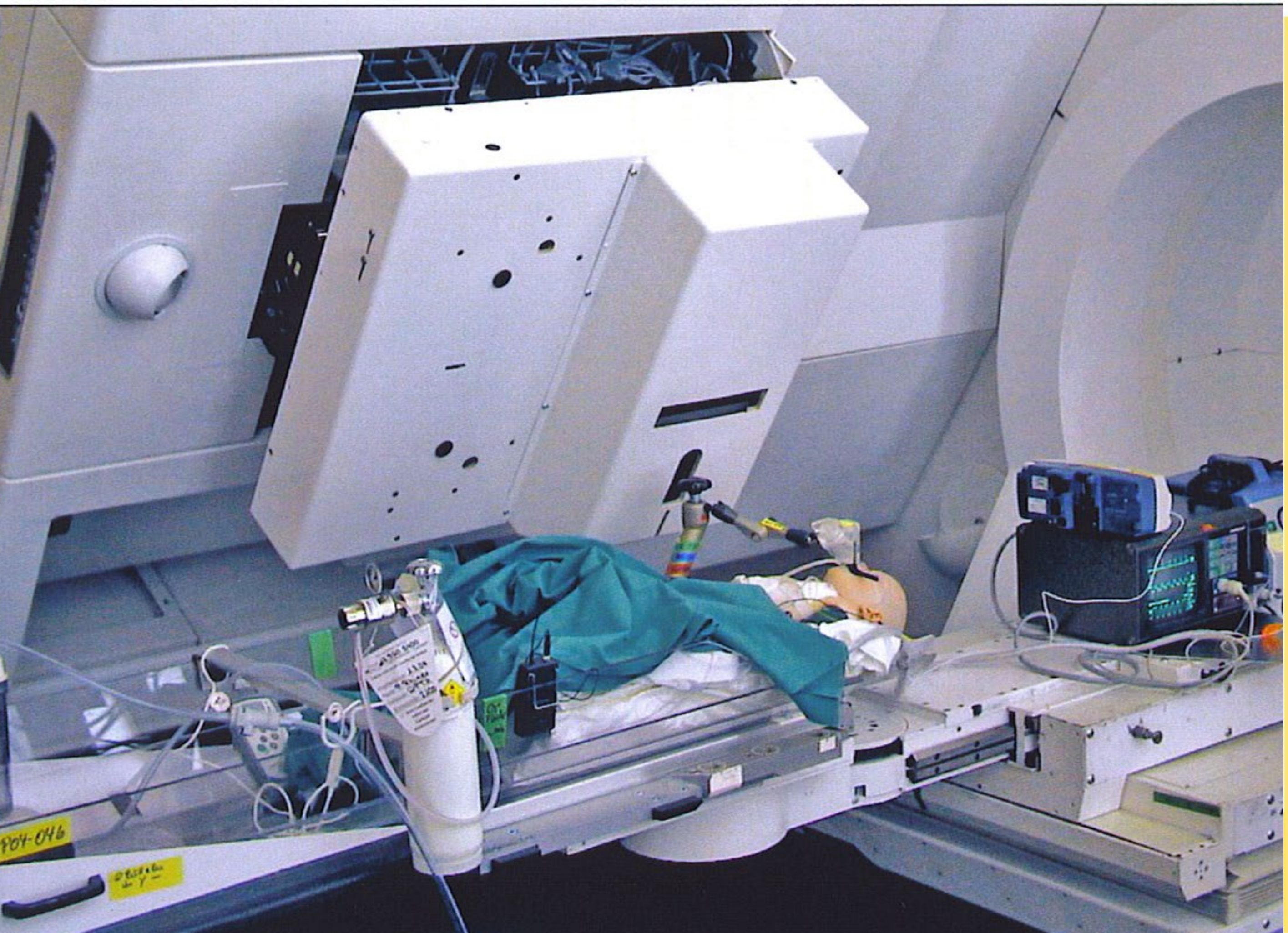


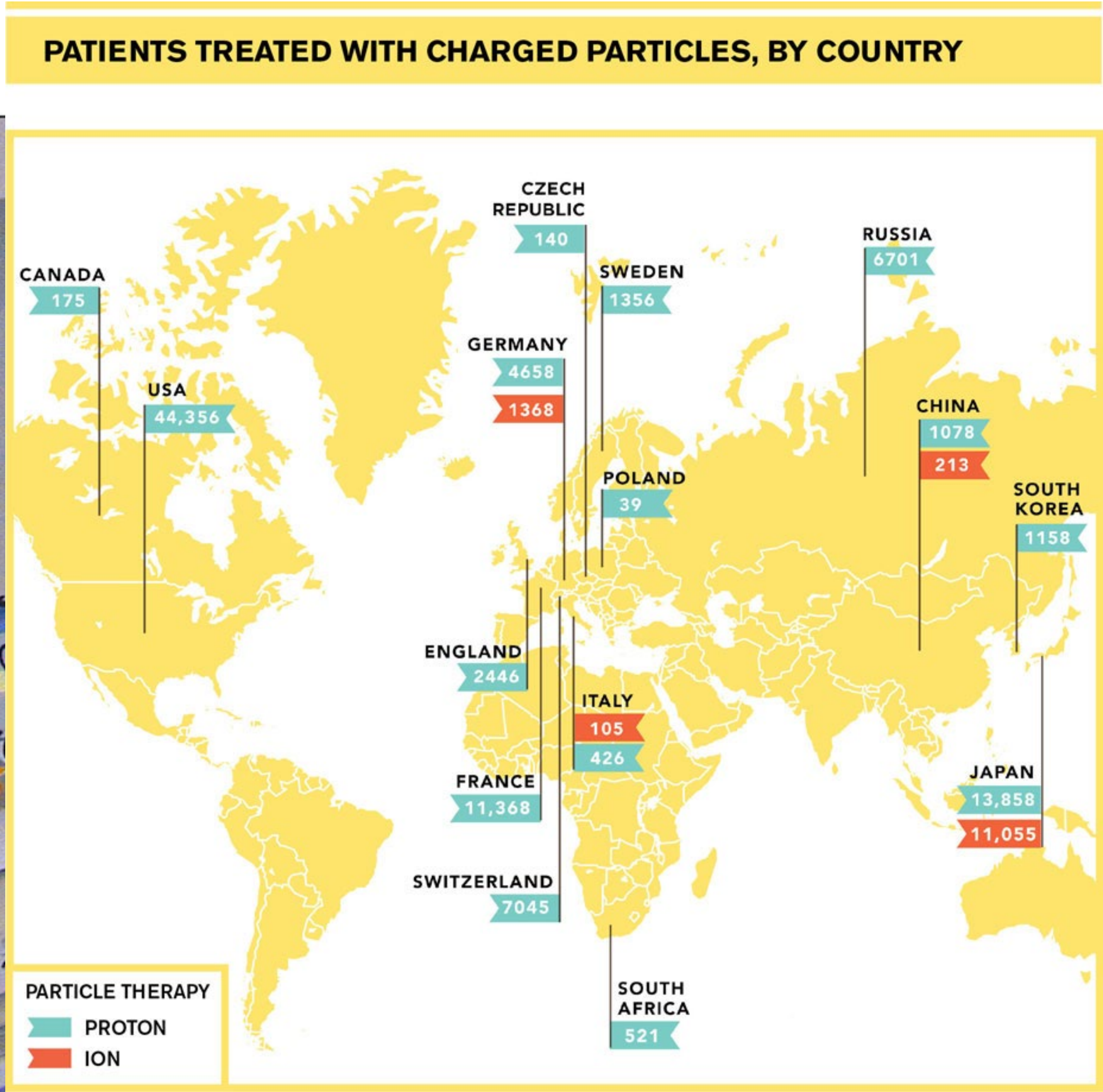


Spread of proton therapy technologies (Gantries)



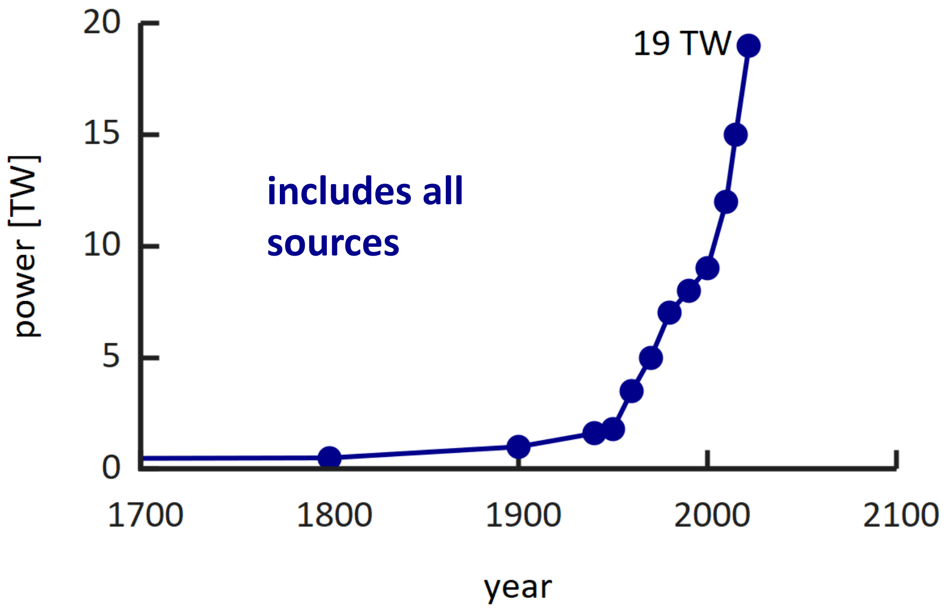
Hadron therapy: method of choice for pediatric cancers





Energy

Energy Consumption - Motivation

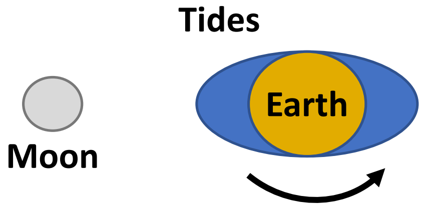


The world energy consumption has been continuously rising, reaching **19 TW** today, 2022.

As a science community we rather want to contribute to solutions and not be part of the problem.

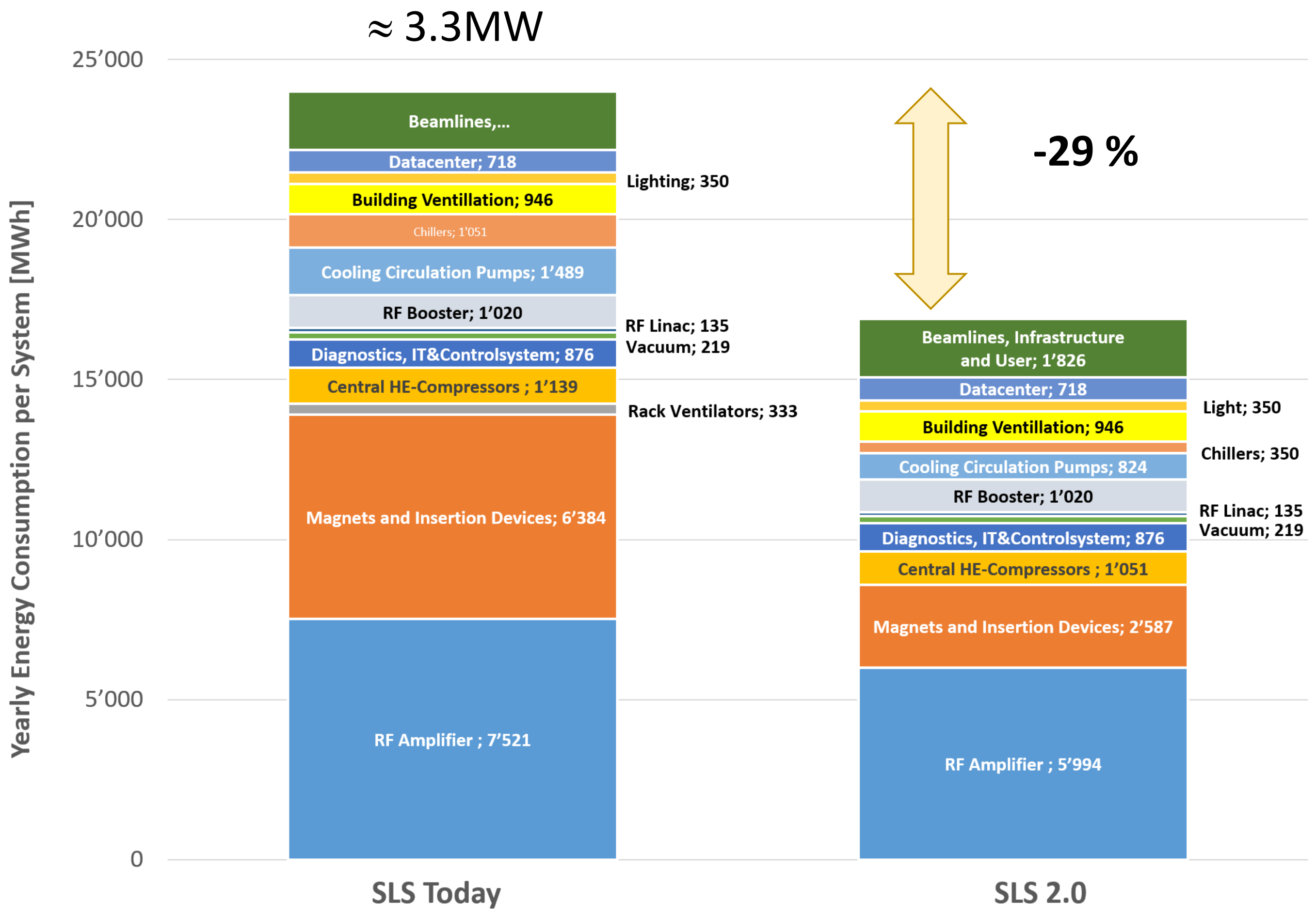
<u>example from nature</u>:
the Earth-Moon system dissipates **3.8 TW** power from the rotation energy of earth

[Williams, Boggs, 2016]



School Strike for Climate Wikipedia

Example Swiss Light Source SLS and its Upgrade



X-ray brightness increase 35-fold for users
Less electricity consumption

Key savings:

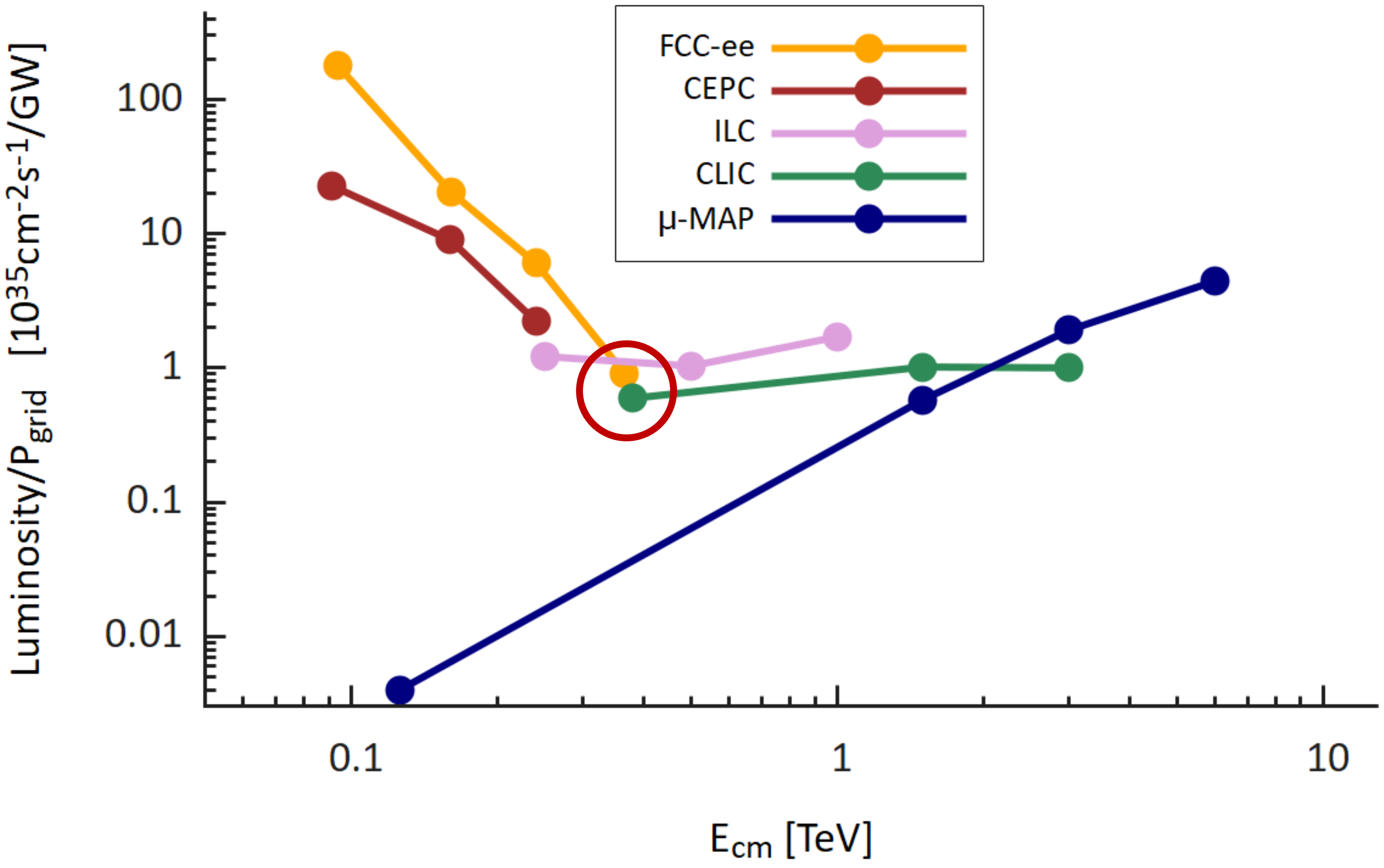
Electromagnets → Permanent magnets
Klystrons → Solid state amplifiers (63%)
standard pumps → modern pumps for cooling

SLS2.0

P_{tot} = 2.4MW
P_{RF} = 0.82MW
P_{γ} (undulators) = 91kW

Overview Lepton Proposals

energy specific
luminosity production:



Efficient Technologies

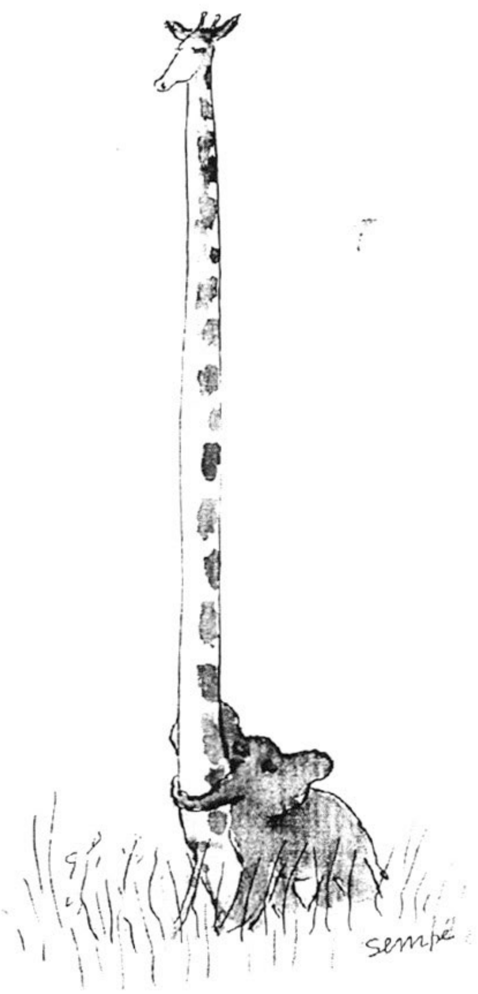
- **s.c. magnets & high Q cavities** provide efficient solutions, **higher temperature operation (HTS)**; perhaps the most important development
- **efficient RF sources**: klystrons, solid state amps, magnetrons
- **permanent magnets**
- heat recovery & photovoltaics
- other sustainability: water & He consumption, critical materials, lifecycle management, carbon footprint, energy procurement

Energy Amplifier (C. Rubbia, CERN/AT/95-44)

- **Subcritical system** driven by a proton accelerator
- **Fast neutrons** and fuel cycle based on natural **Thorium**
- **Closed cycle**: all actinides are recycled indefinitely.
  The "waste" are fission fragments and structural materials which are relatively short-lived
- **Lead** as target both as neutron moderator and as heat carrier
- **Deterministic safety** with passive elements to eliminate
  - Criticality
  - Meltdown
  - Decay heat
  - Seismic protection

Accelerator Driven Systems (ADS)

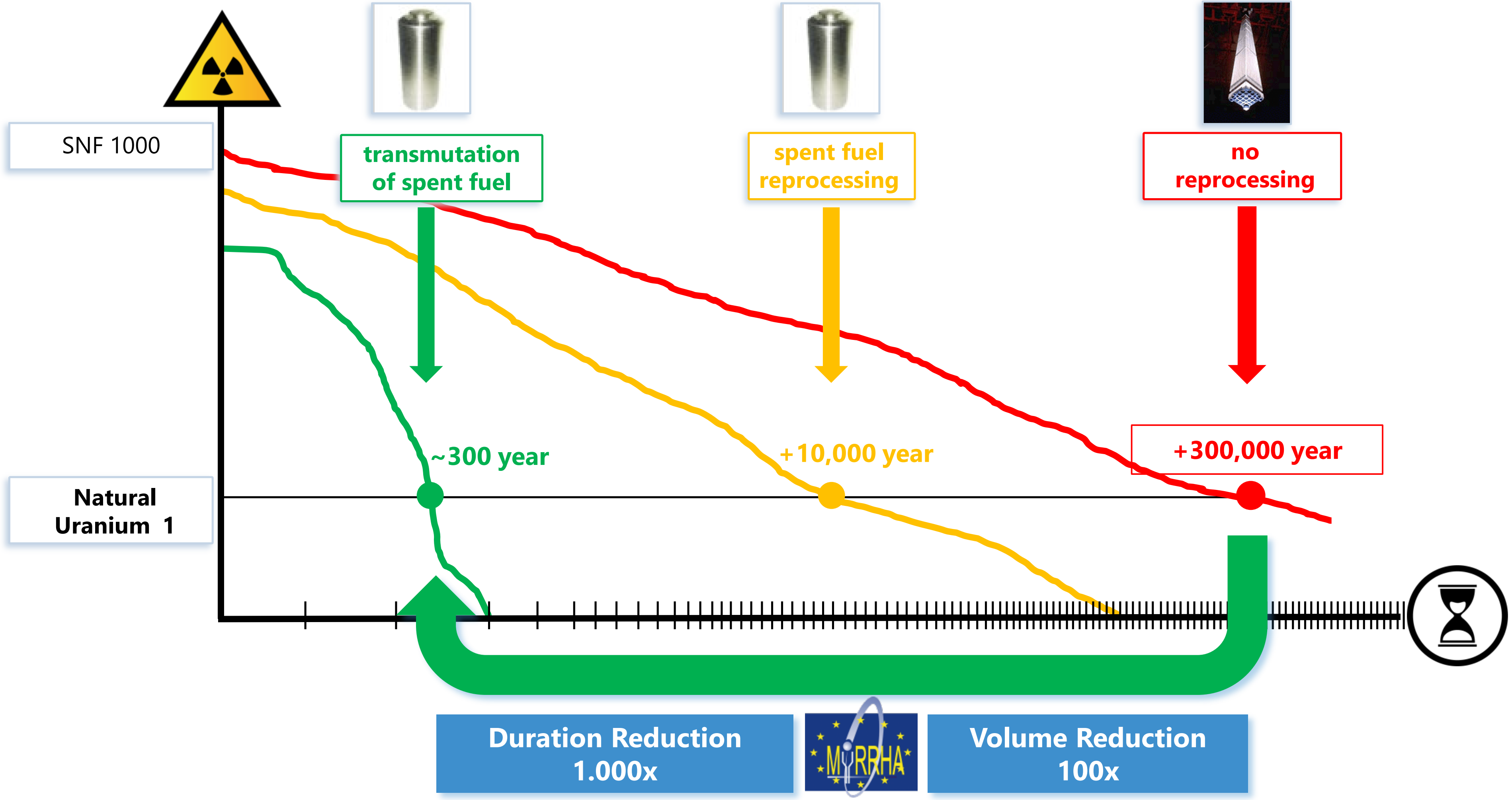
The coupling of an accelerator and of a nuclear reactor:
a mating against nature or the future of the nuclear energy ?



Le couplage d'un accélérateur et d'un réacteur nucléaire : un accouplement contre nature ou l'avenir de l'énergie nucléaire ?

Carlo Rubbia

Transmutation: better solution for Spent Nuclear Fuel

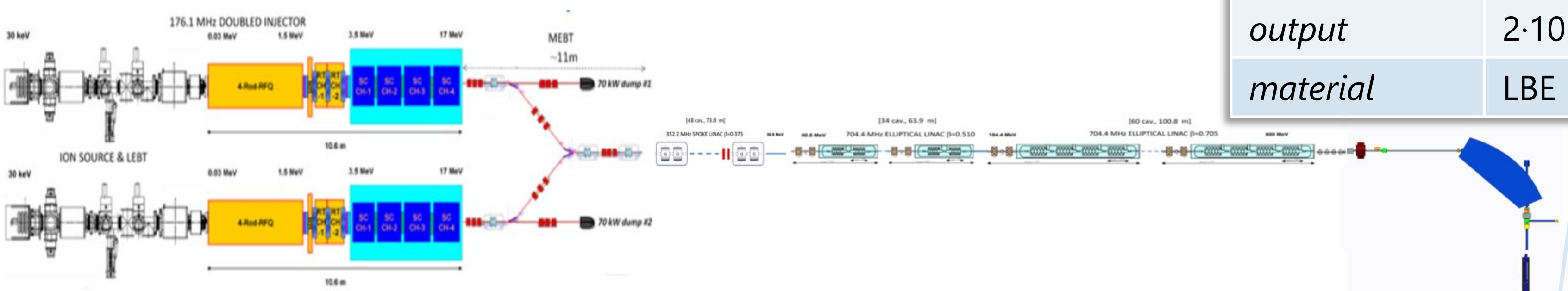


Source: European Commission Strategy Paper on Partitioning & Transmutation (2005), SCK•CEN MYRRHA Project Team

MYRRHA = Accelerator Driven System
Key Objectives

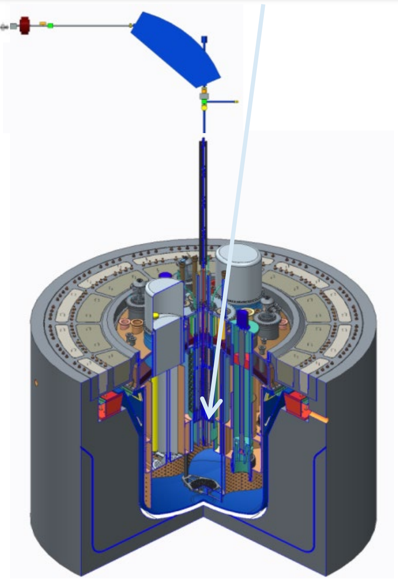
1. **Demonstrate the ADS concept at pre-industrial scale**
2. **Demonstrate transmutation**
3. **Multipurpose and flexible irradiation facility** (with fast neutron source)

Target	
main reaction	spallation
output	$2{\cdot}10^{17}$ n/s
material	LBE (coolant)



Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Reactor	
power	65 to 100 MW_{th}
k_{eff}	**0,95**
spectrum	fast
coolant	LBE



MYRRHA (under construction in Belgium)

Summary

In the past 90 years accelerators have become an essential tool for research and numerous applications (proton therapy, synchrotron light sources, industrial use, etc.), able to address society's essential needs

Accelerator development ushers in new, powerful applications in many fields

Future poses formidable challenges for the accelerator R&D, not the least of them is educating the new generation of specialists