

# The Tools and Techniques of Particle Physics and Their Impact on Society

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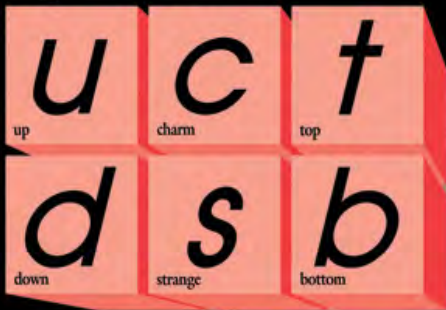
*Argonne National Laboratory*

*July 28, 2017*

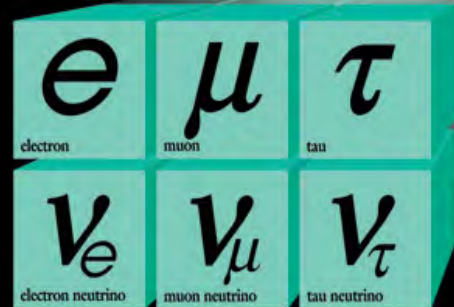
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# The Field of Particle Physics

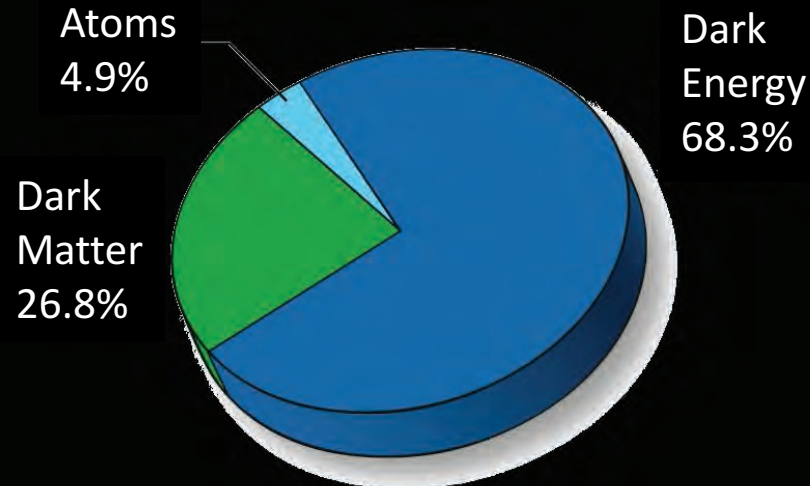
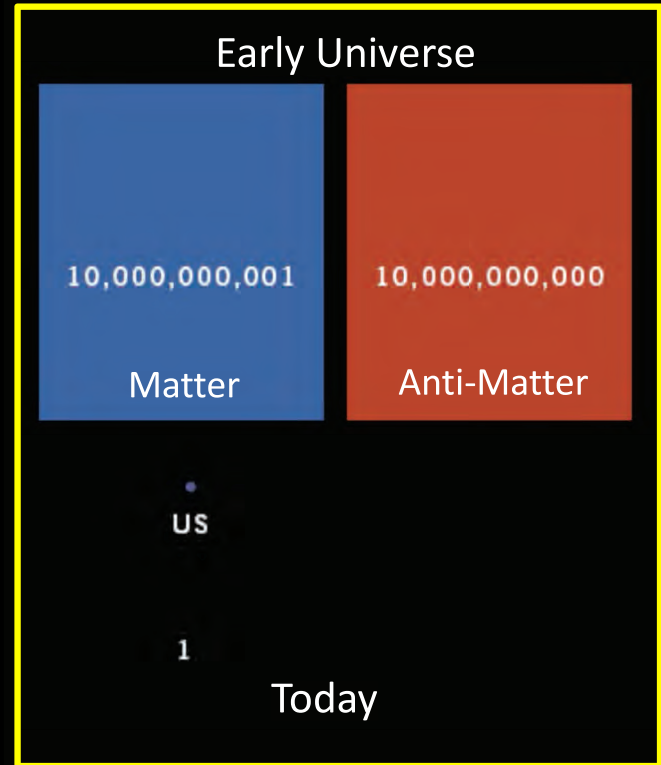
## Quarks



## Forces

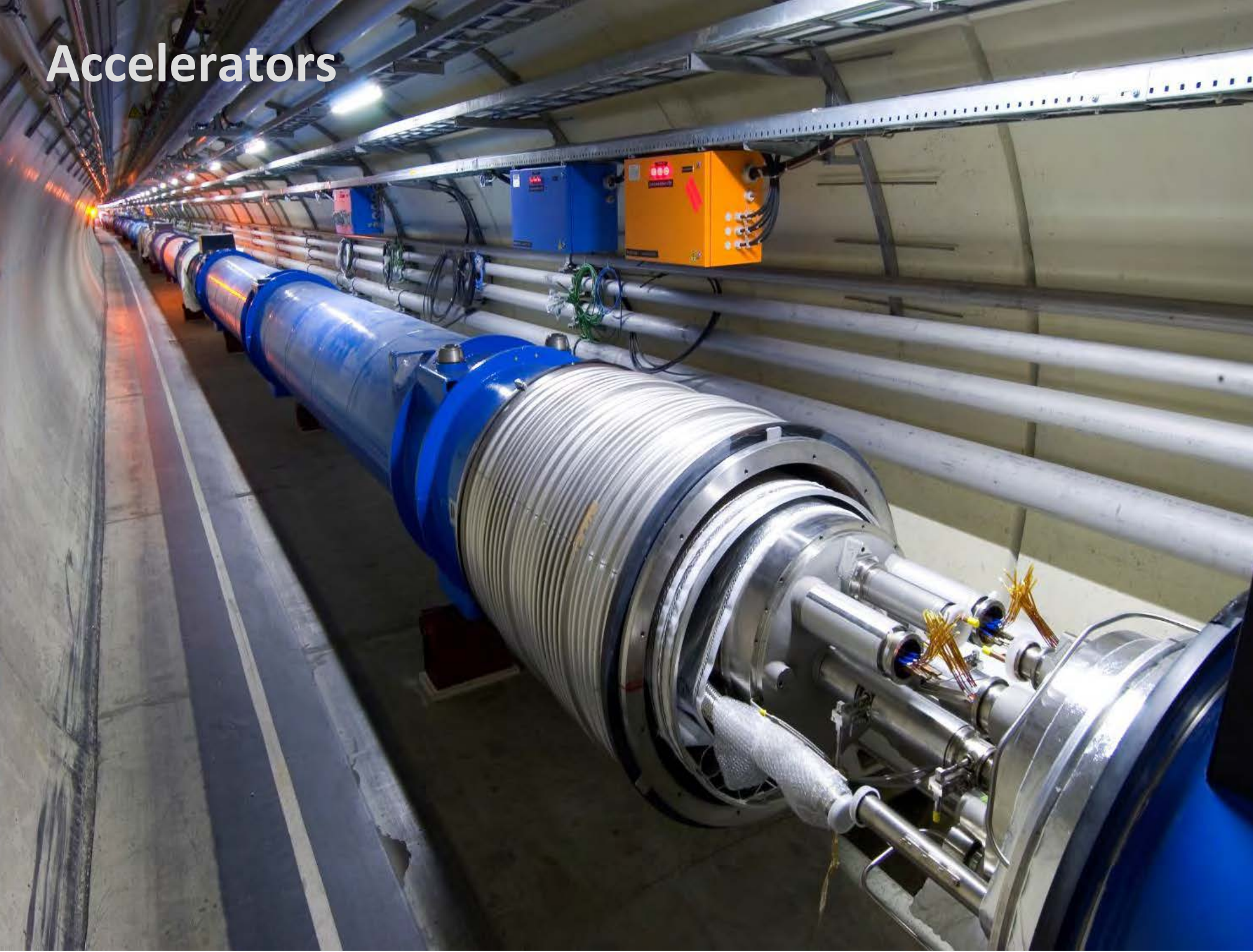


## Leptons



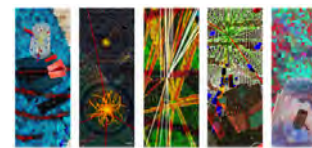


# Accelerators





# The Tools of Particle Physics



E. Lawrence

80 keV



Bevatron



SLAC

There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out.'

--Isaac Newton, Opticks (1704)



HERA



Tevatron



KEK

... to show a few



Accelerators

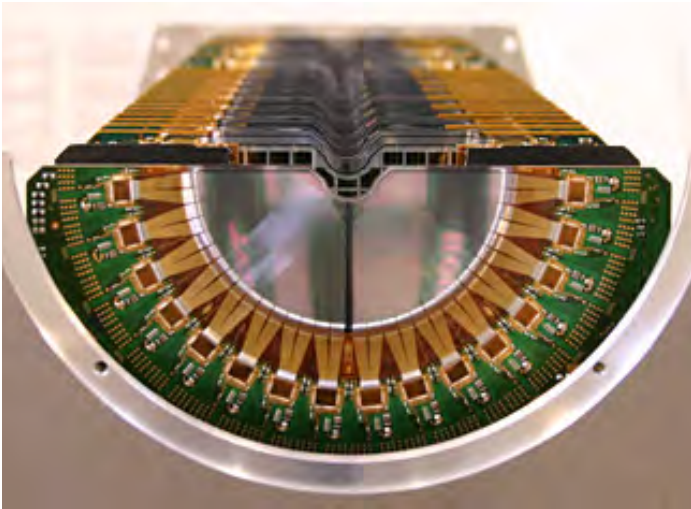
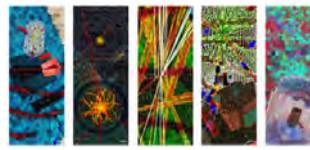


Detectors

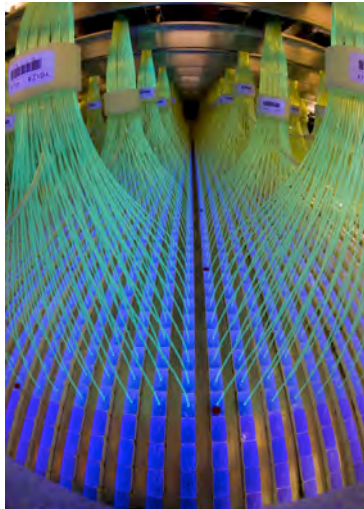




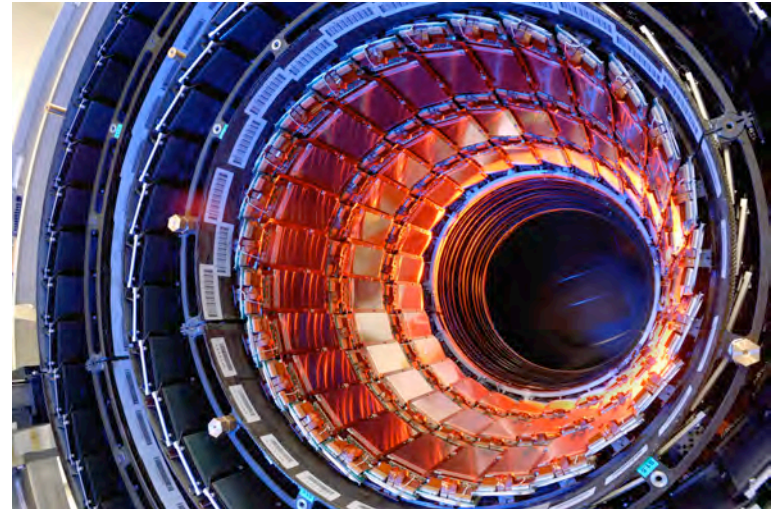
# The Tools of Particle Physics



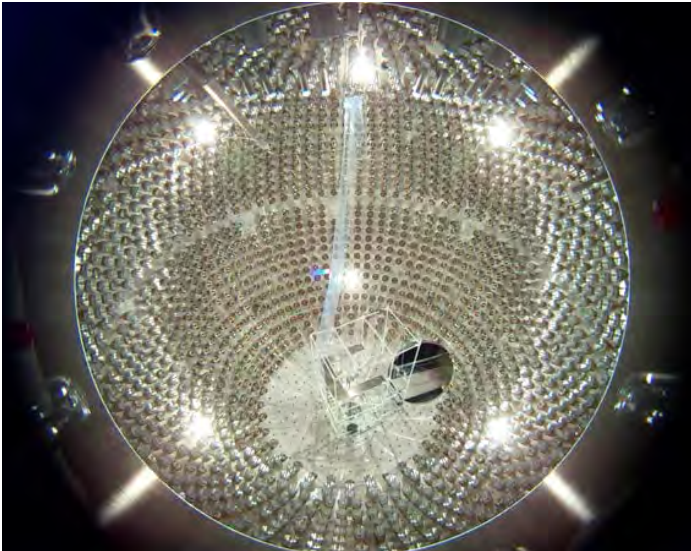
LHCb VELO



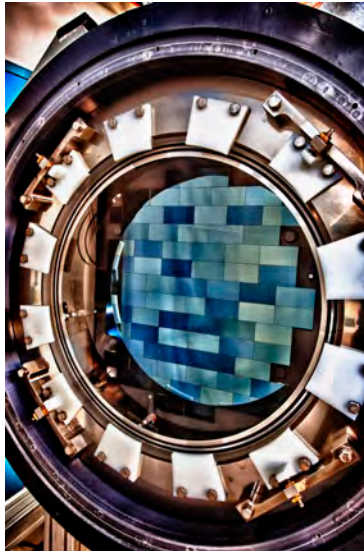
SciBoone SciBar



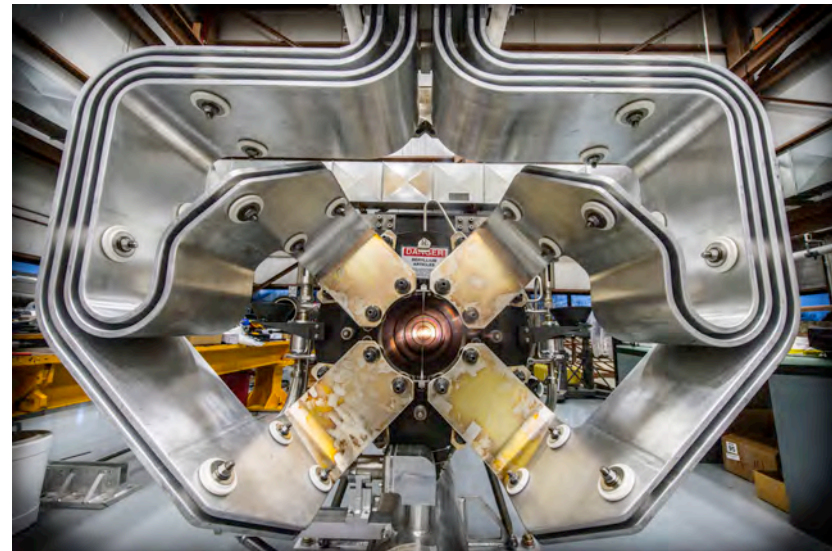
CMS TOB



Borexino



DES Decam



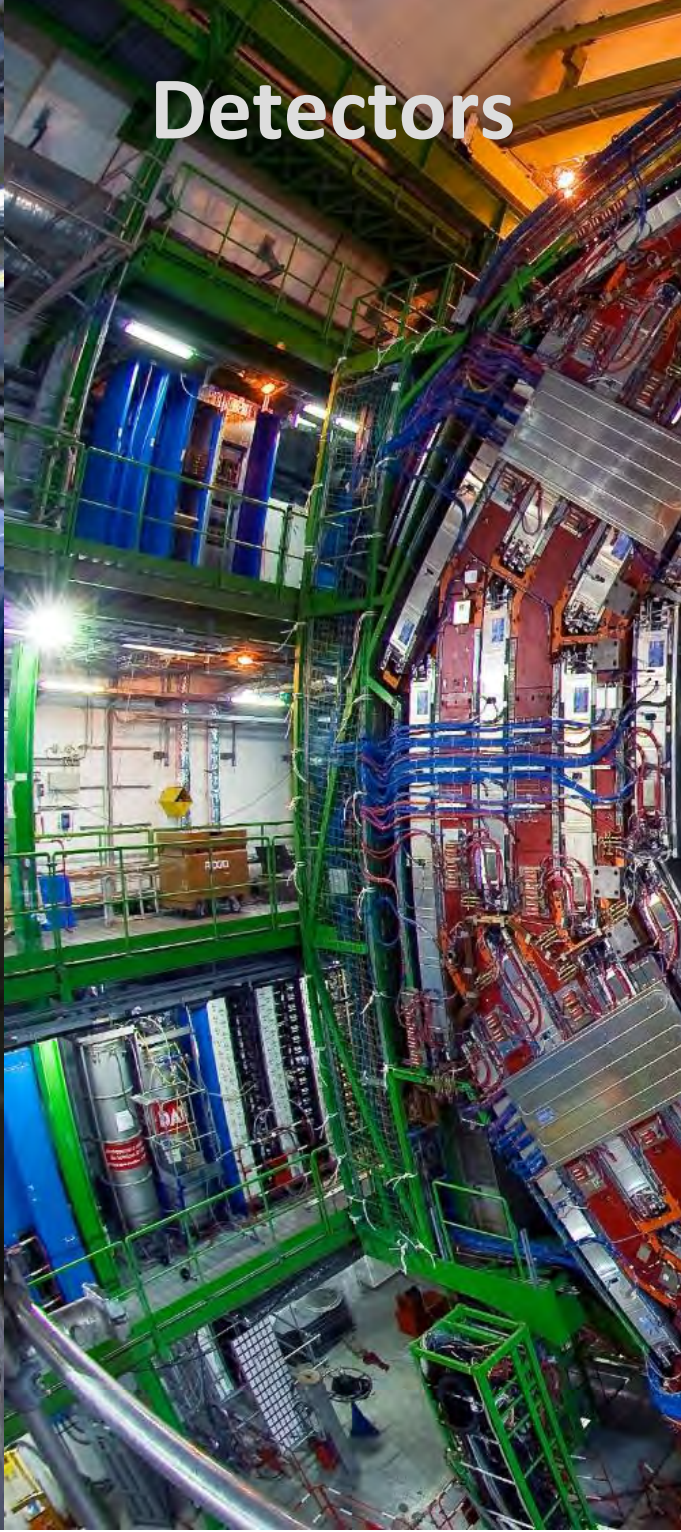
NuMi horn



**Accelerators**



**Detectors**

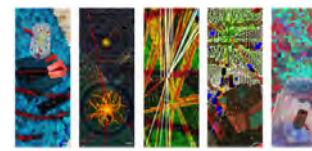


**Computing**





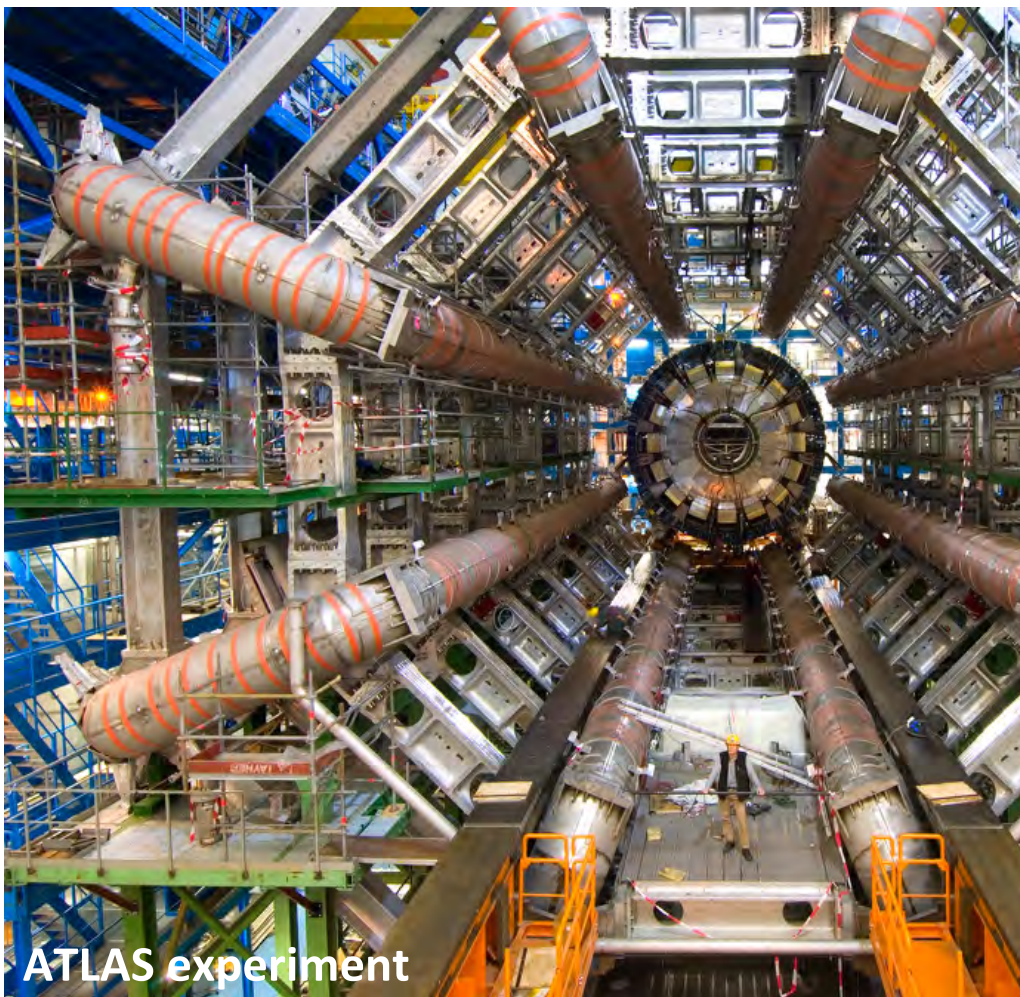
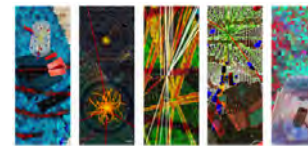
# Particle Physics Culture



- ❑ **Particle Physics is a highly collaborative open science environment**
  - Requires teams of hundreds of scientists to design and build the (often large) experiment
  - Requires expertise in many technology domains
  - Requires long-term and tight collaboration with high-tech industry
  - If the technology does not exist, the community develops it in collaboration with industry
  - Long timescale to build the detector; experiment takes years
  - Instruments are built to scale
- ❑ **For a particle physicist, the detector is the experiment**
  - Experiments are extremely demanding in terms of design
  - Often generates novel technical approach which benefits other research disciplines and ultimately society
- ❑ **Particle physics has been a key driver for innovation !**



# Particle Physics Experiments



ATLAS experiment

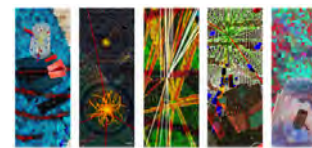


CMS experiment

## Digital Cameras the Size of Cathedrals



# Elements of Particle Physics Detectors



Radiation Damage

High Rate

Big Data

Compute Intensive

Simulation

Very precise low-mass tracking

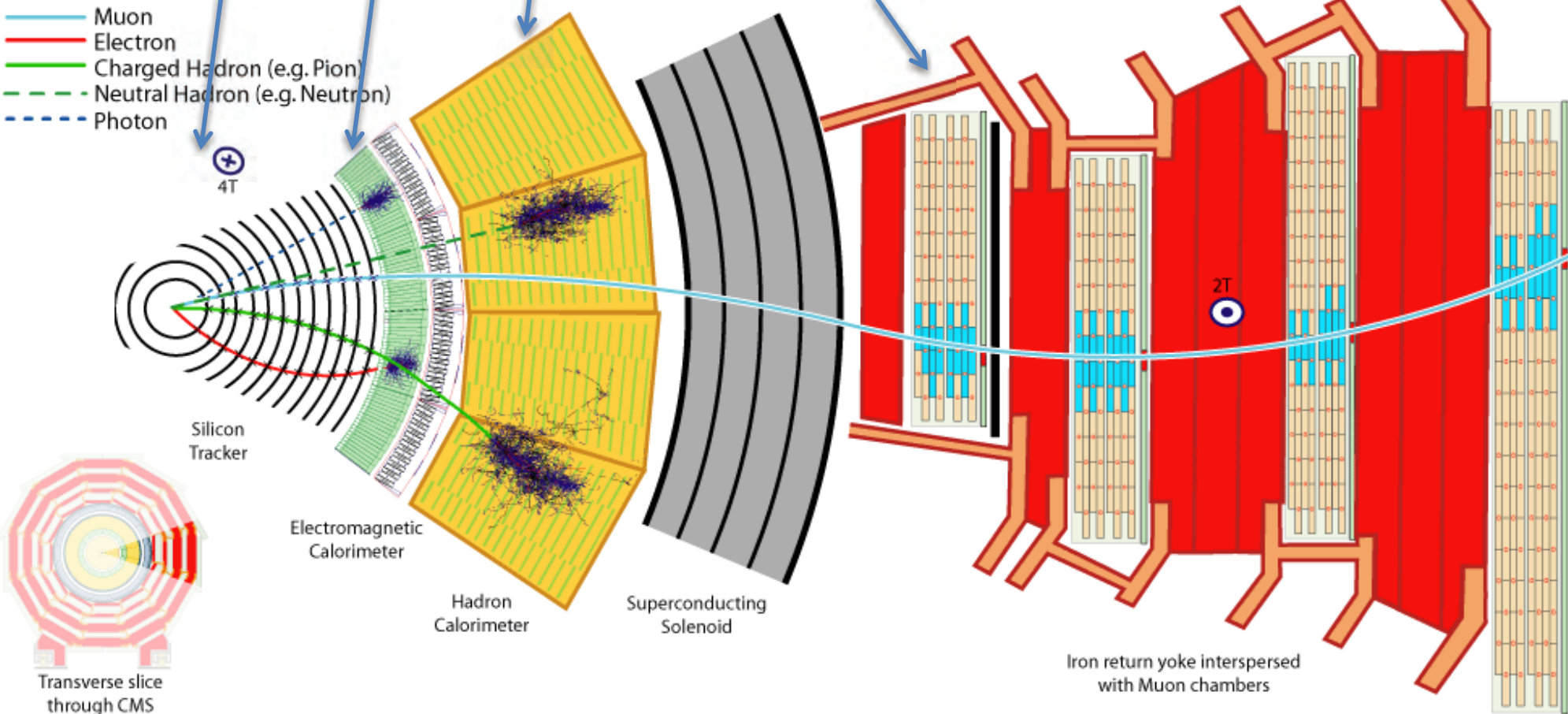
Photon Measurement

Calorimetry

Muon Tracking

Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
- - - Photon



4T

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

2T

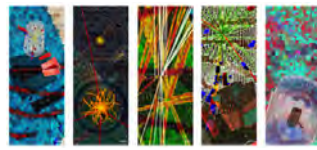
Iron return yoke interspersed with Muon chambers

Transverse slice through CMS



# Web of Connections

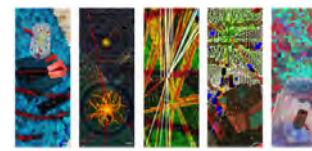
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- ❑ Particle physics has benefited tremendously from the developments in and support of other science disciplines
- ❑ At the same time, particle physics has had profound impact in broad areas of science and society



# Outline



- ❑ **Detector Technology**
- ❑ **Computing, Software and Data Management**
- ❑ **Accelerators and Particle Physics Facilities**
- ❑ **Accelerating Technology Transfer**
- ❑ **Conclusions**





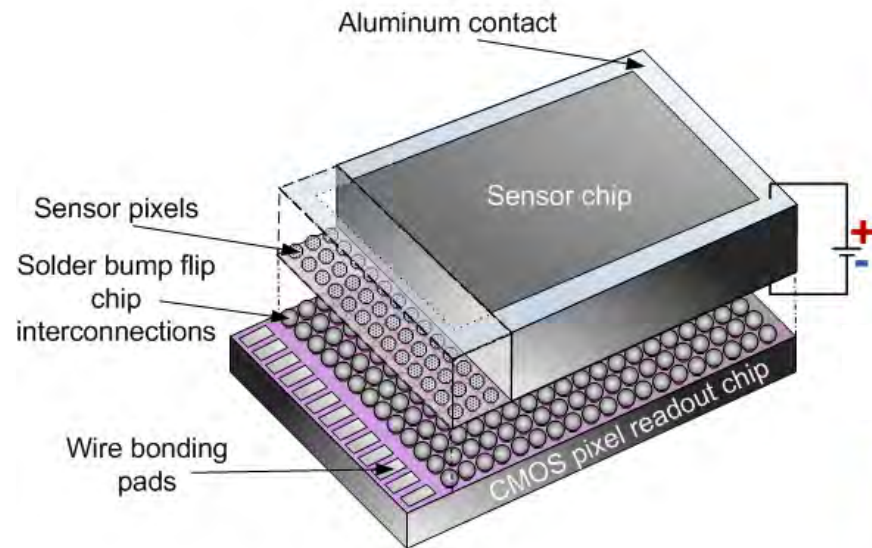
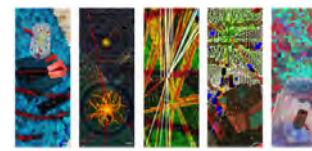
# Detector Technology

A major area of connections  
of particle physics





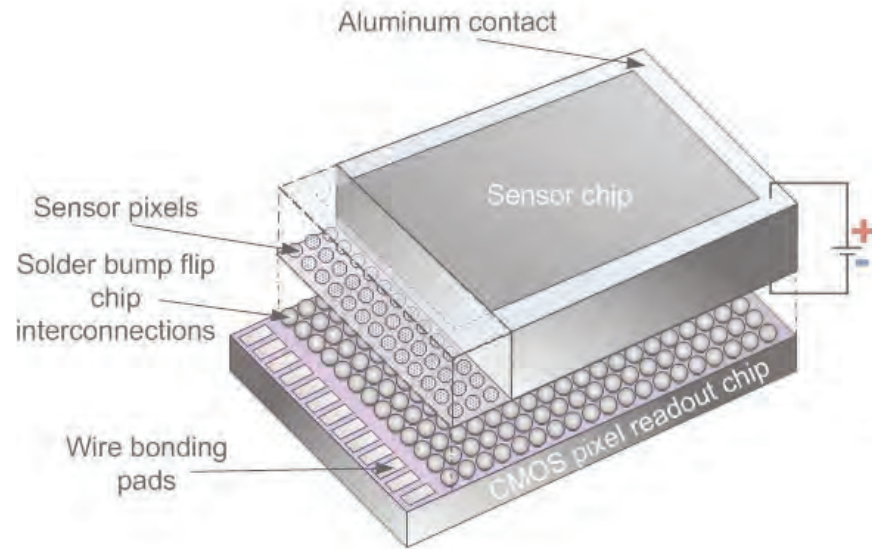
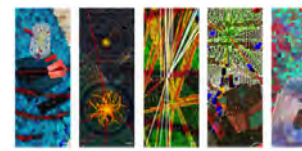
# Silicon Technology



- ❑ The silicon detector and readout technology for particle detectors was enabled by the semi-conductor industry

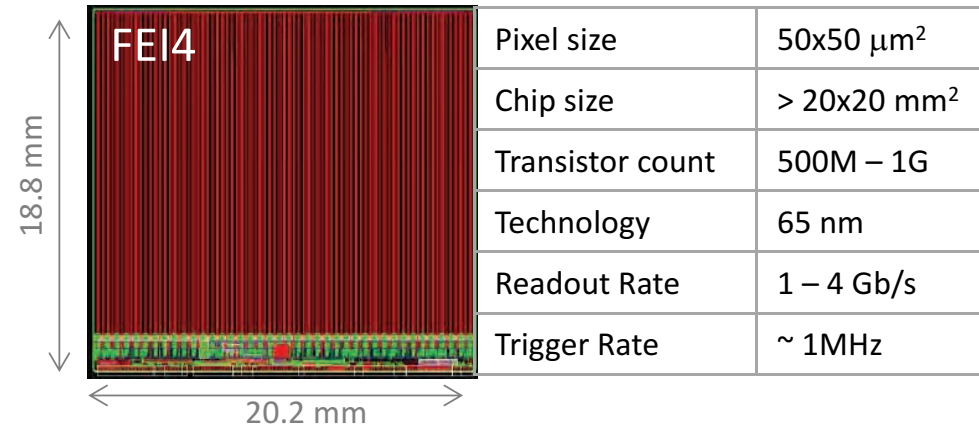


# Silicon Technology



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## Application Specific Integrated Circuit



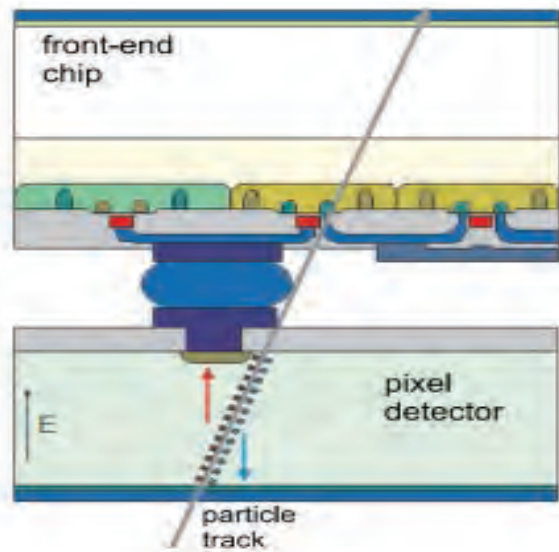
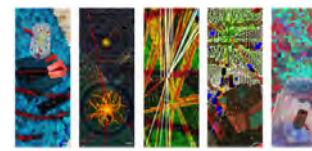
- ❑ Particle Physics customized the technology and has taken it to unprecedented scale



**ATLAS Pixel Detector**

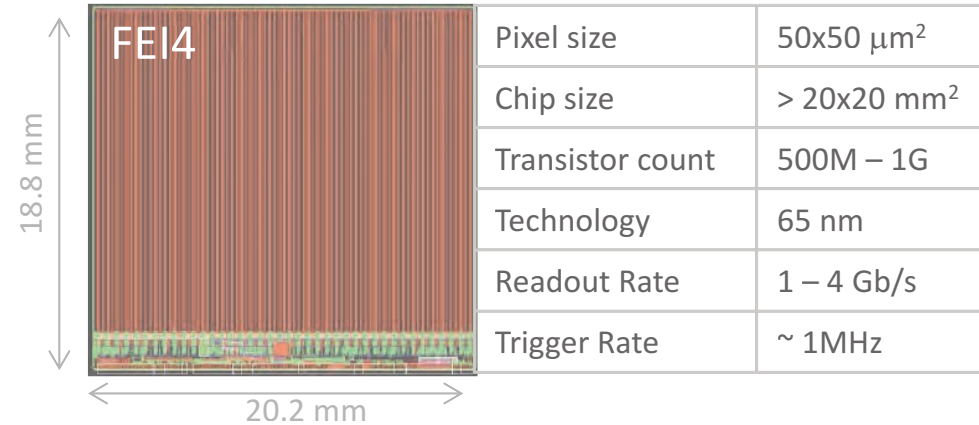


# Silicon Technology

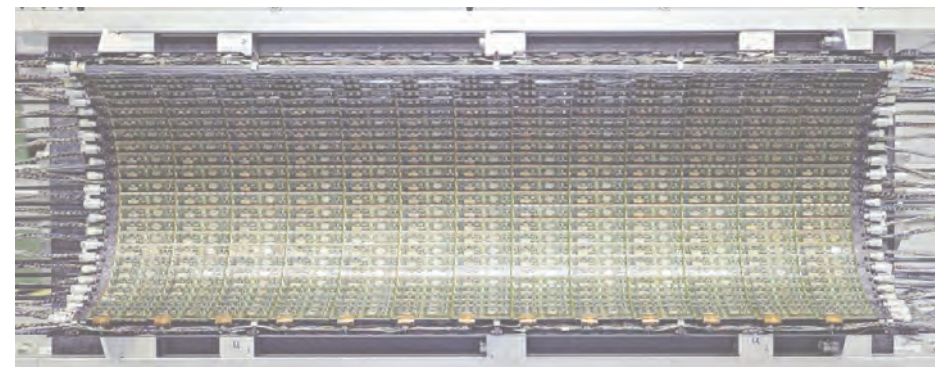


- ❑ **Diagnostics measurements to ensure electrical connectivity quickly showed its applicability for x ray detection**

## Application Specific Integrated Circuit

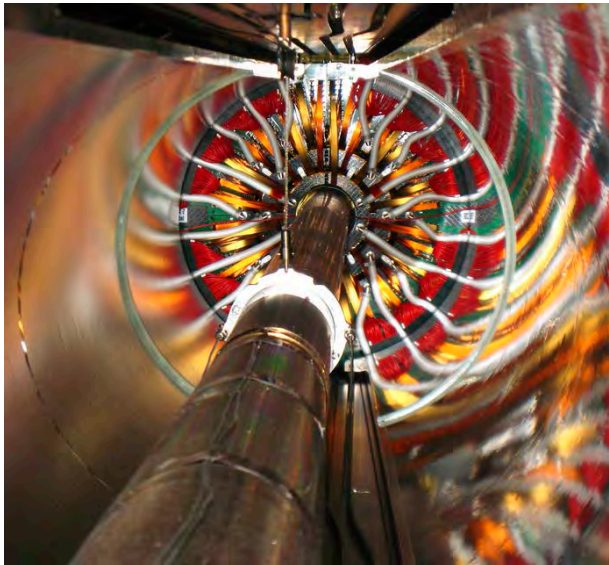
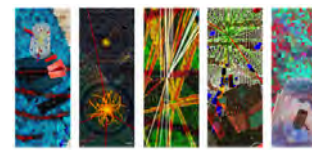


- ❑ Particle Physics customized the technology and has taken it to unprecedented scale



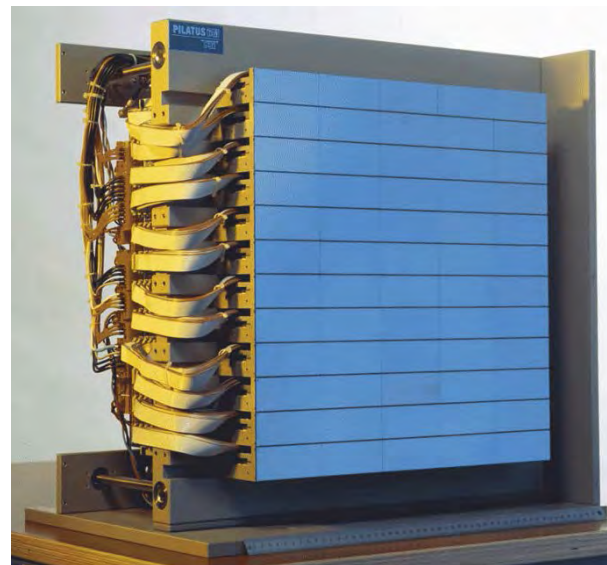
**ATLAS Pixel Detector**

# X-Ray Detectors



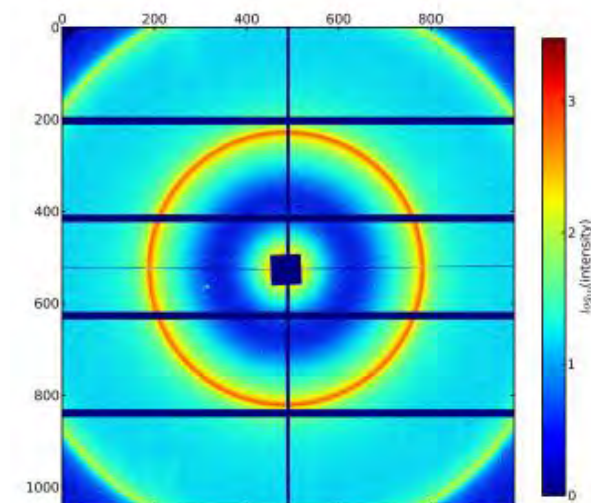
CMS Pixel detector

- ❑ Development of CMS pixel detector led directly to development of X-ray detectors
- ❑ Spin-off company from CMS development at the Paul Scherrer Institute: DECTRIS.



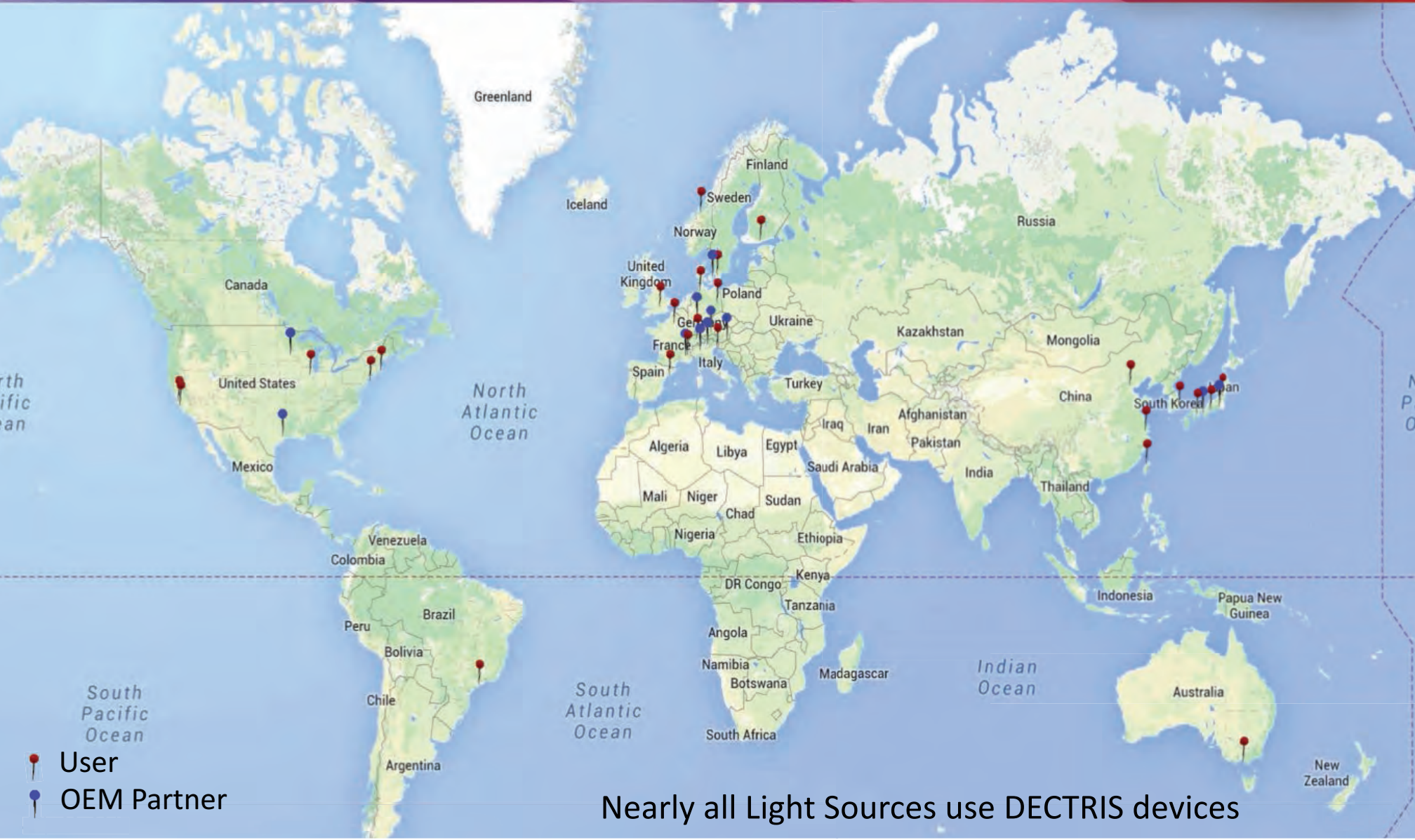
Pilatus X-ray detector

Pilatus Diffraction Pattern

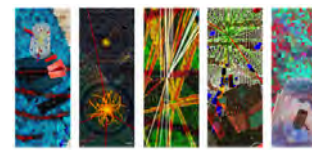




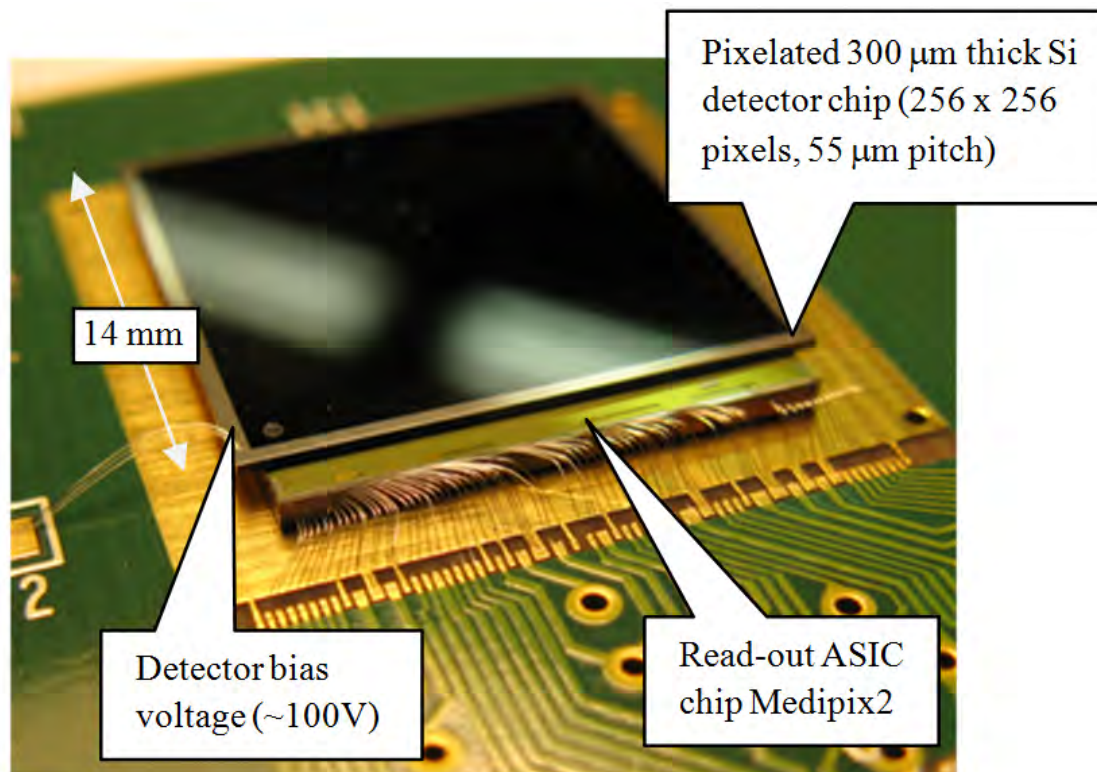
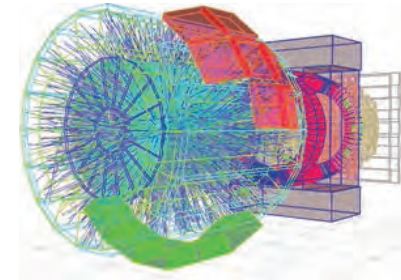
# Photon Science Enabler



# MediPix and TimePix

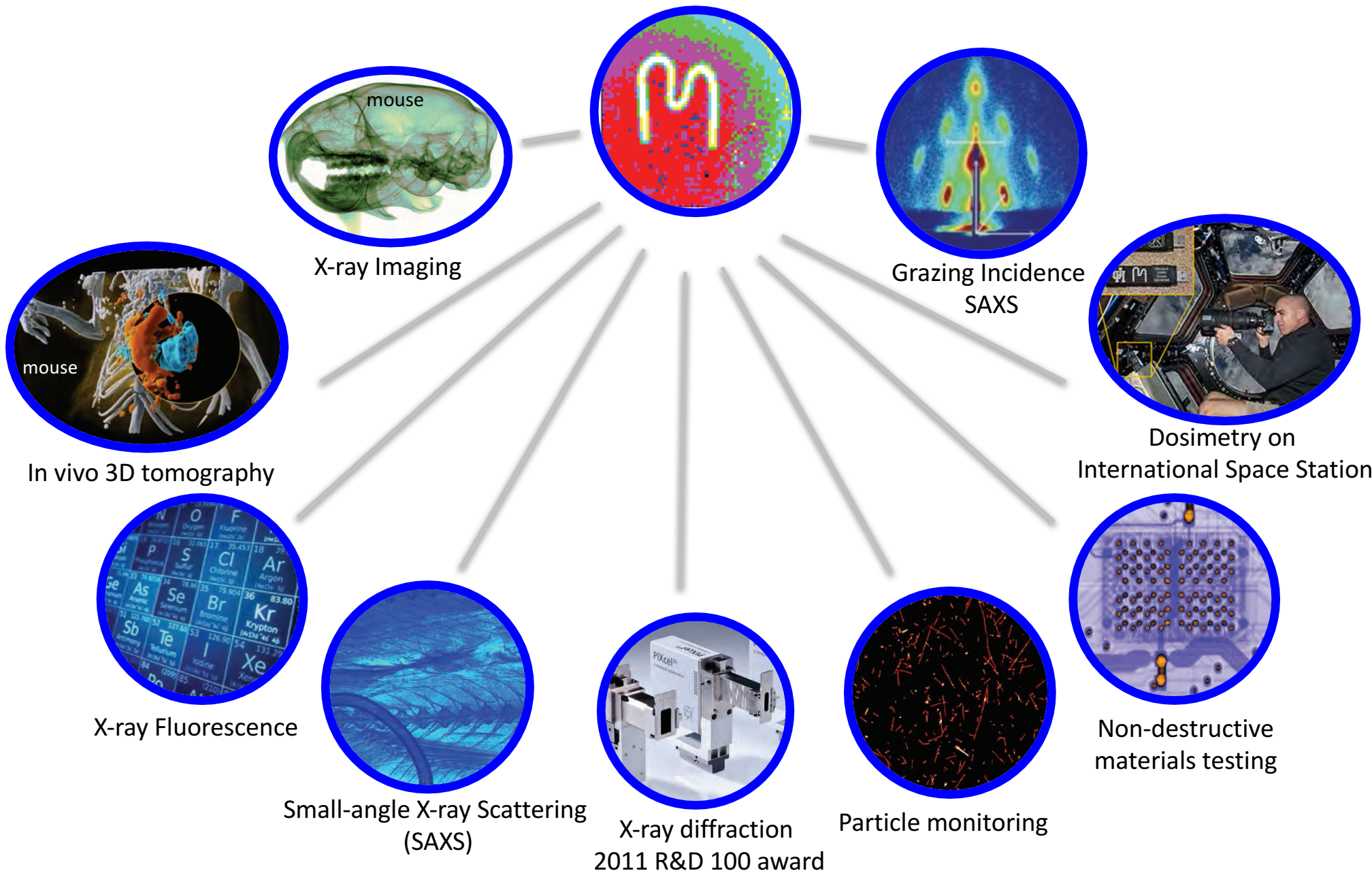
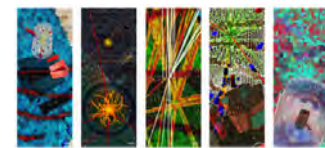


- Development of an ASIC for the ALICE experiment at the LHC at CERN led to the development of an imaging application:
  - MediPix: single photon counting ASIC
  - Timepix: added time measurement
  - MediPix3: counts photons with energy thresholds and timing

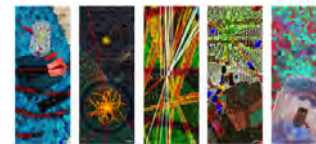




# MediPix and TimePix



# Companies Using MediPix / TimePix



**ADVACAM**  
Imaging the Unseen

[www.advacam.com/](http://www.advacam.com/)



<http://www.marsbioimaging.com/>



AMSTERDAM  
SCIENTIFIC  
INSTRUMENTS

<http://www.amscins.com/>



X-RAY  
IMAGING  
EUROPE

<http://www.xi-europe.com/>

**Plus Light and Neutron  
Sources**

**JABLOTRON**  
CREATING ALARMS

<http://www.jablotron.com/>

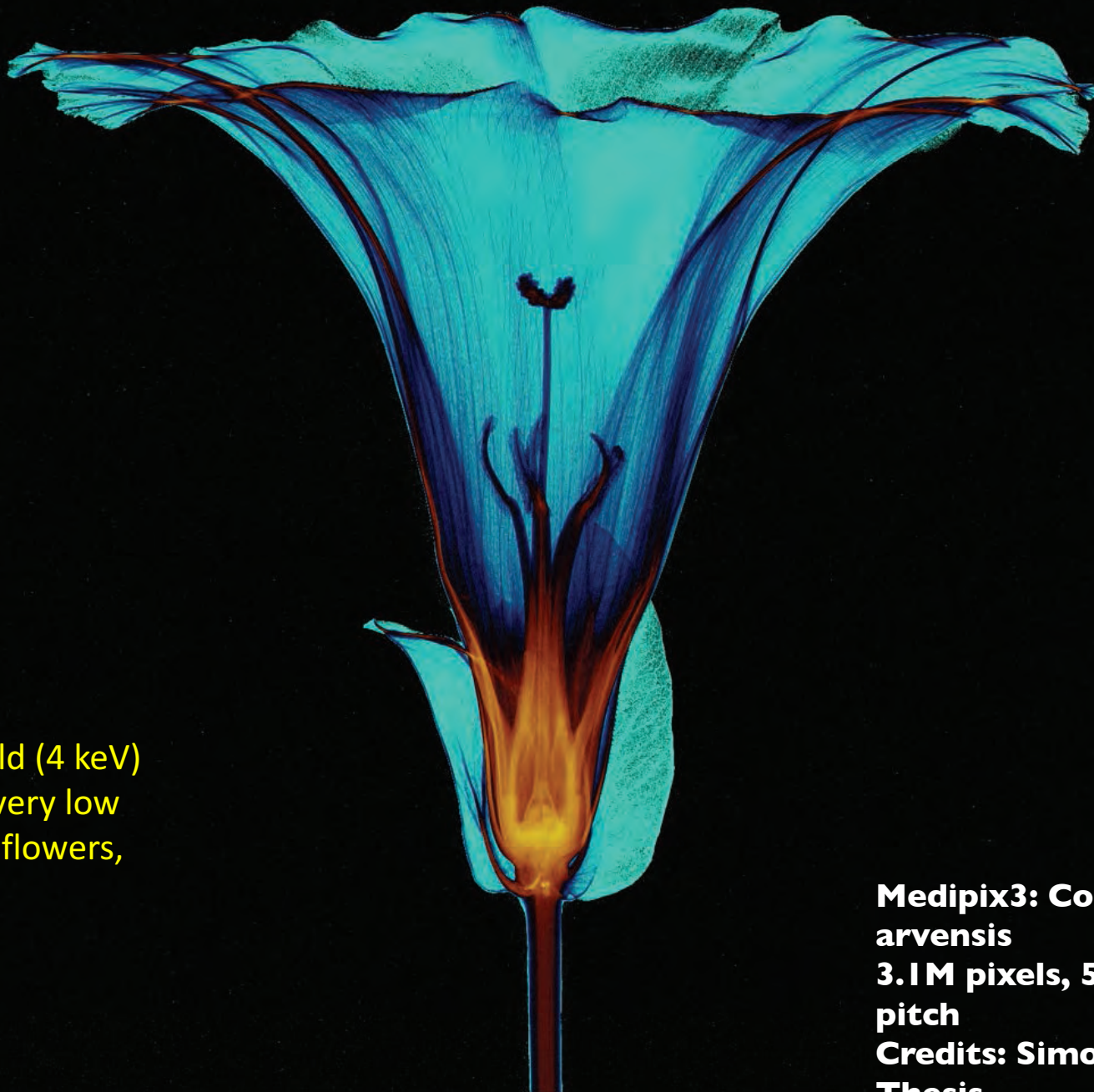
X R A Y  
**IMATEK**  
PHOTON COUNTING DETECTORS

<http://xray-imatek.com/>



<http://quantumdetectors.com/>

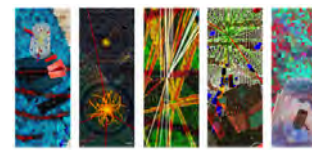




Low energy threshold (4 keV)  
enables imaging of very low  
contrast media, like flowers,  
with high resolution

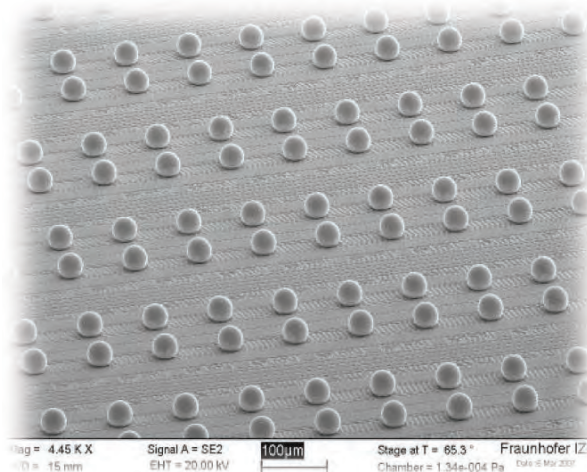
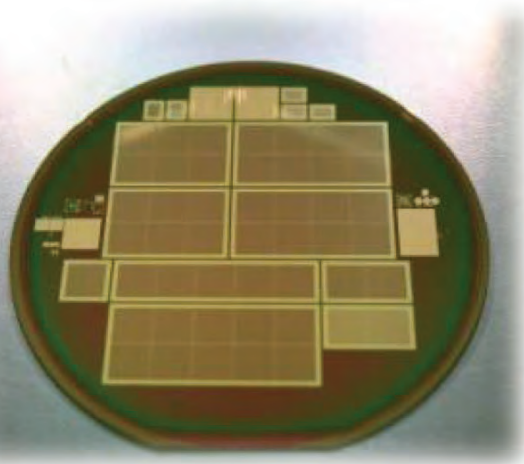
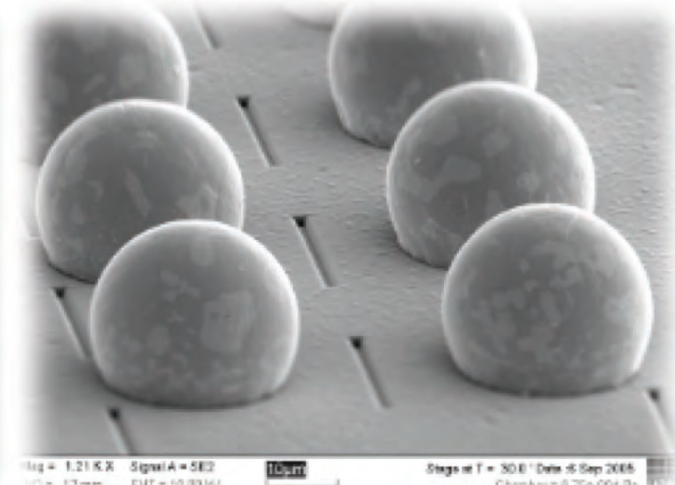
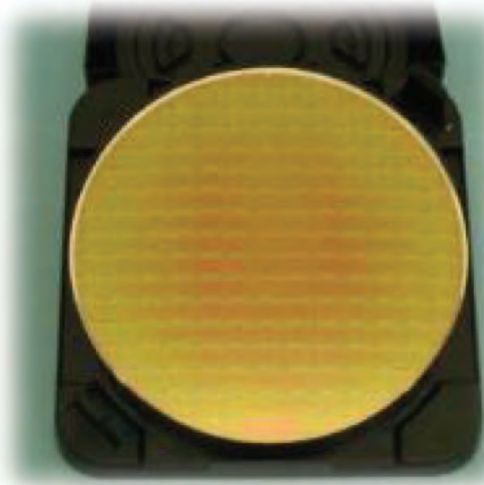
**Medipix3: Convolvulus  
arvensis  
3.1 M pixels, 55 mm pixel  
pitch  
Credits: Simon Procz,, Ph.D.  
Thesis,  
University of Freiburg**

# Ultra-Fine Pitch Bonding



- Electrically connecting the sensor to the readout at ultra-fine pitch, high density; particle physics drives technology to scale and technical limits

- **ATLAS pixel detector**
  - SnPb bumps
  - ~1150 modules
  - >18,600 readout chips



- **CMS pixel detector upgrade**
  - SnAg bumps
  - ~300 modules
  - ~7000 readout chips



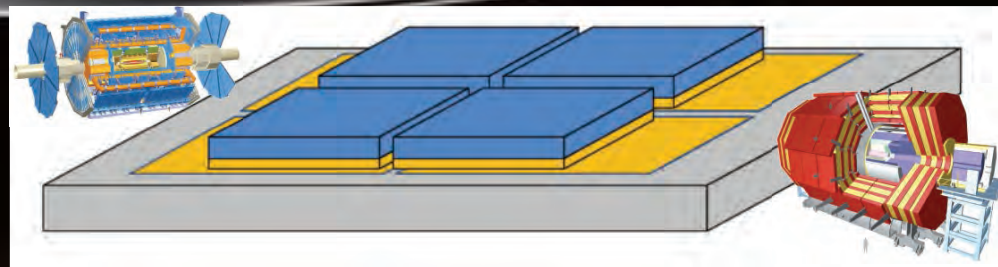
# Adaptive LED Headlights



OSRAM



Four LED chips, each 256 pixels,  
125 $\mu$ m size, connected to driver  
electronics chip through gold-tin  
porous sponge bond



# Adaptive LED Headlights



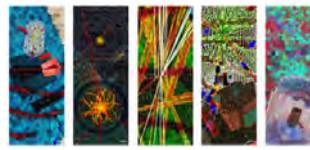
**OSRAM**



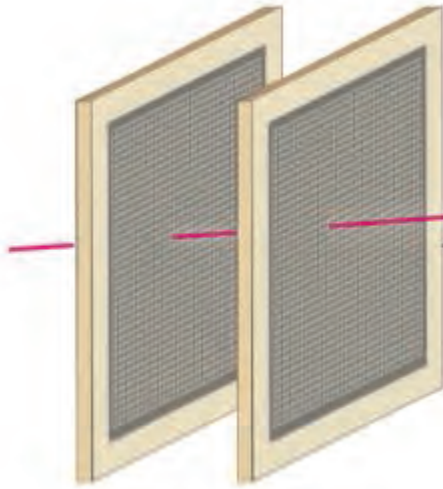
**Sorry, only available on  
high-end luxury cars  
(comfort: not allowed in the US)**



# Tracking and Calorimetry

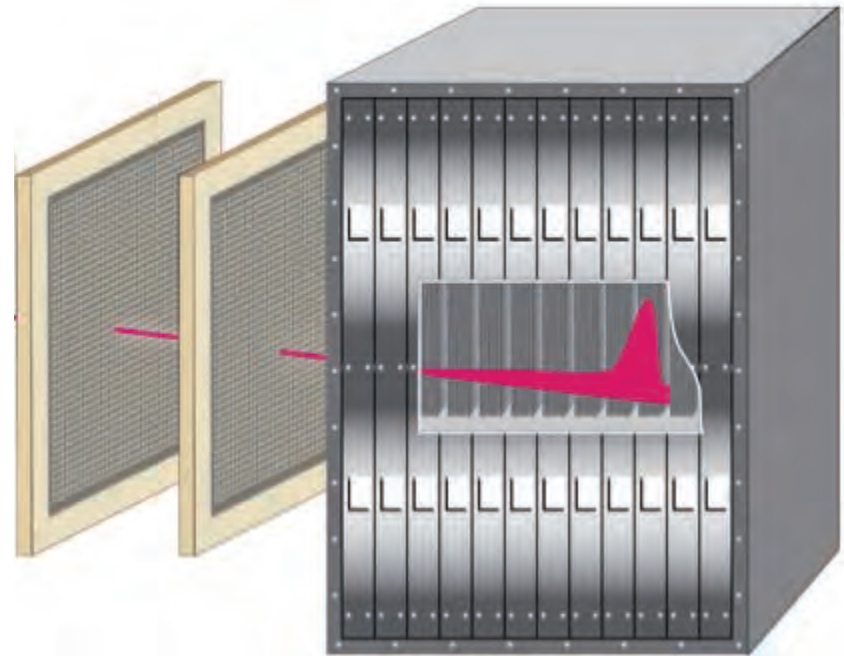


- Tracking detectors + high grained ranging calorimeter



Tracking Detectors

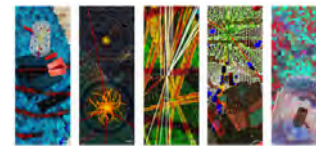
Silicon Strips / Scintillating Fibers



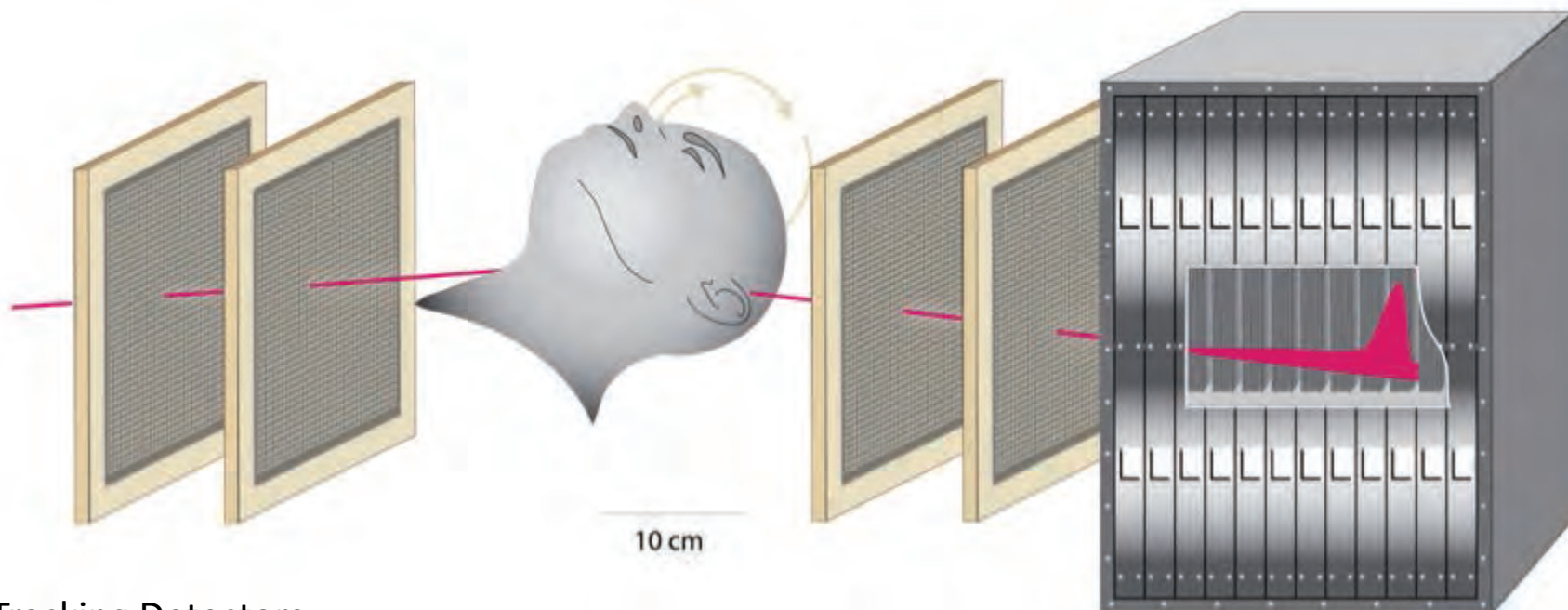
High-grained Imaging Ranging Calorimeter

Scintillator, RPC, GEM

# Proton Computed Tomography



- ❑ Correlate the measured E-loss with the path of the proton through the patient

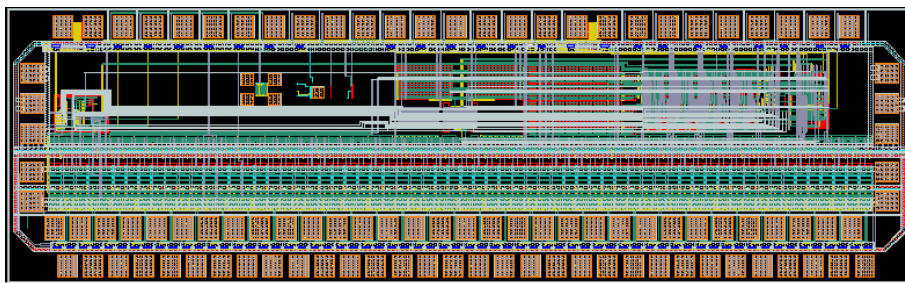


Tracking Detectors

Silicon Strips / Scintillating Fibers

High-grained Imaging Ranging Calorimeter

Scintillator, RPC, GEM

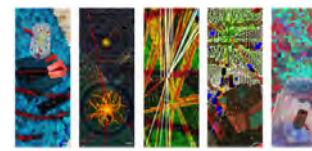


Readout adapted after Si strip readout for FERMI/GLAST experiment

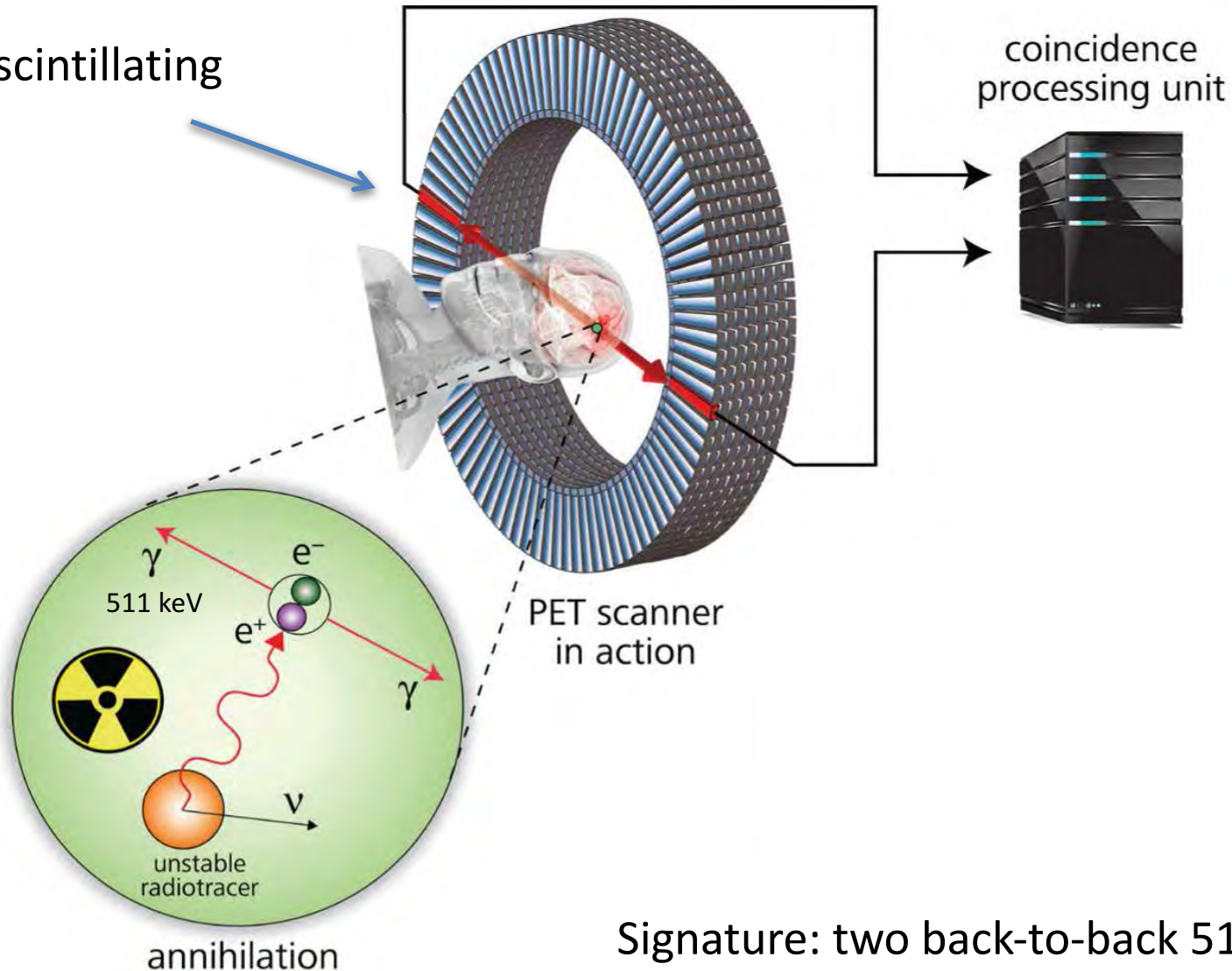
Data rate of 1 million protons per second for an image to be acquired



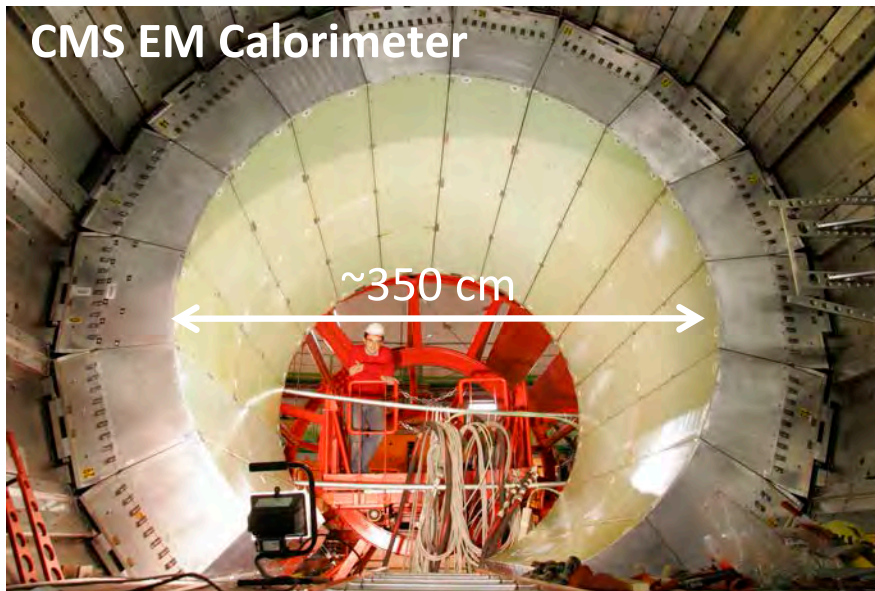
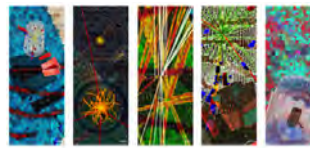
# Positron Emission Tomography



Array of scintillating crystals

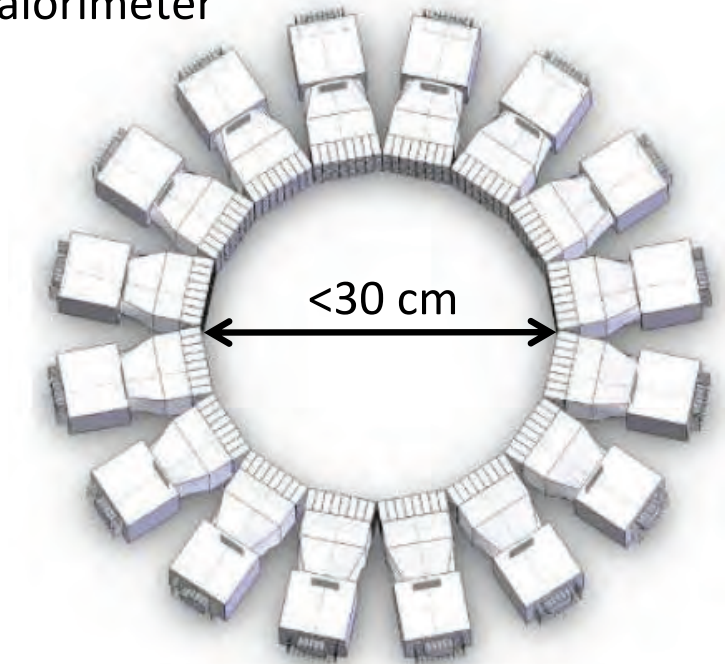


# Calorimetry



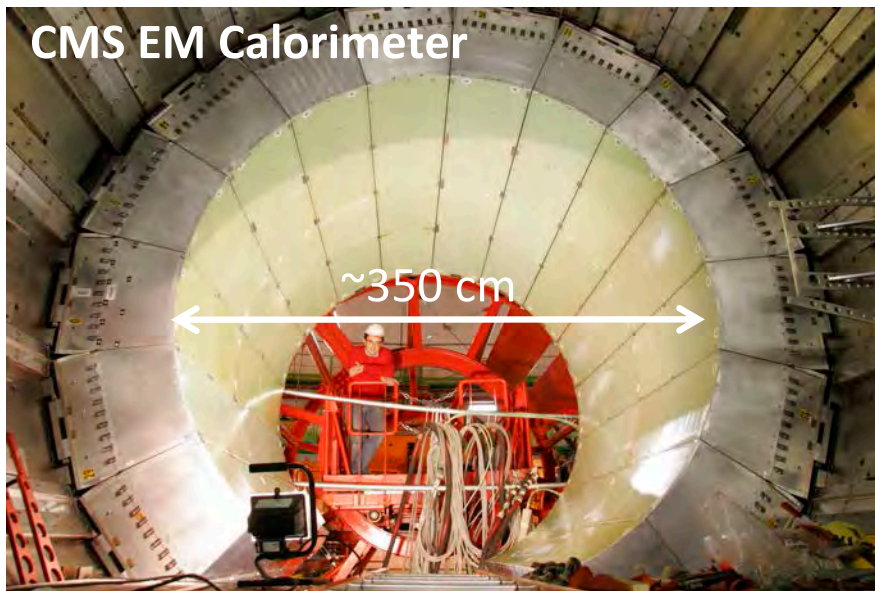
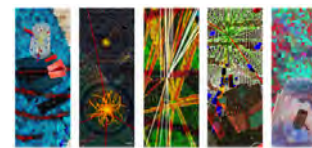
$$H \rightarrow \gamma \gamma$$

PET Calorimeter





# Calorimetry



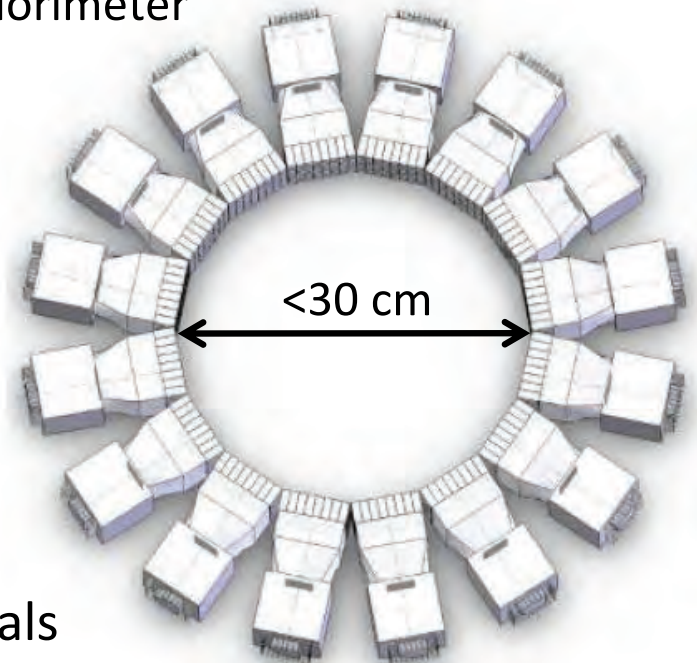
$$H \rightarrow \gamma \gamma$$

~80,000 crystals

First PET scanners used BGO

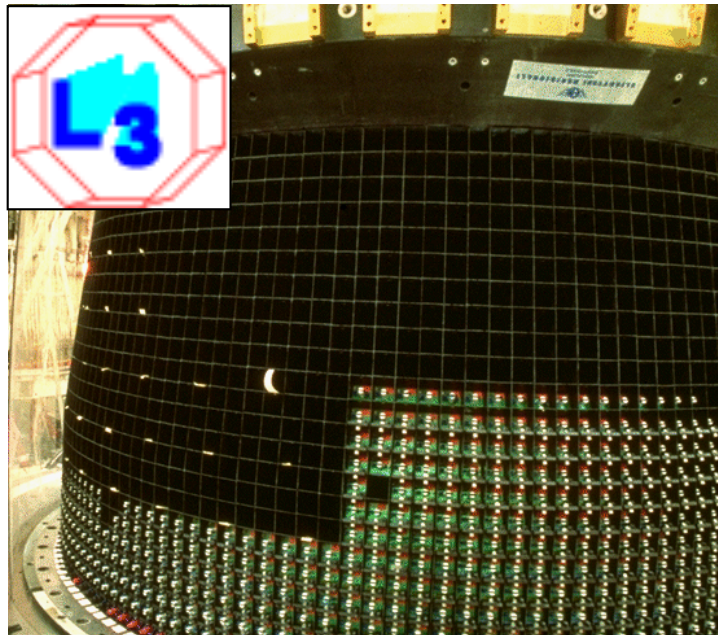
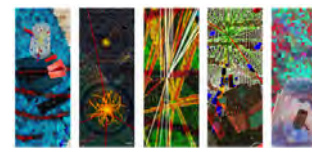
Crystal development driven by  
Particle Physics !

PET Calorimeter



< 1,000 crystals

# BGO Crystal Development



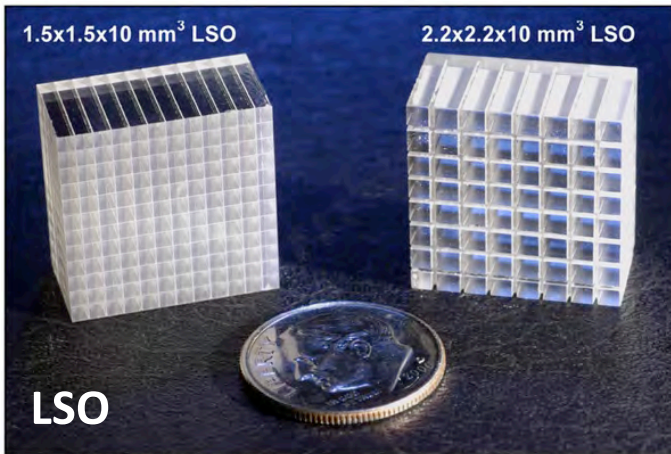
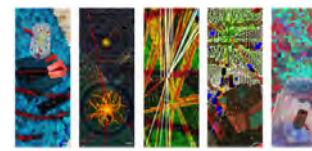
- ❑ The L3 experiment at LEP built the 1<sup>st</sup> BGO crystal calorimeter consisting of 11,400 BGO crystals with total volume of 1.5 m<sup>3</sup>
- ❑ Led Shanghai Institute for Ceramics (SIC) to the multi-crucible growth technology allowing growth of up to 36 crystal ingots per oven

- ❑ Particle physics opened PET market. More than 1,500 PET scanners have been built with SIC BGO by GE Healthcare
  - PET scanner cost: \$250k – \$600k
  - ~1.5 million PET scans/year in the US



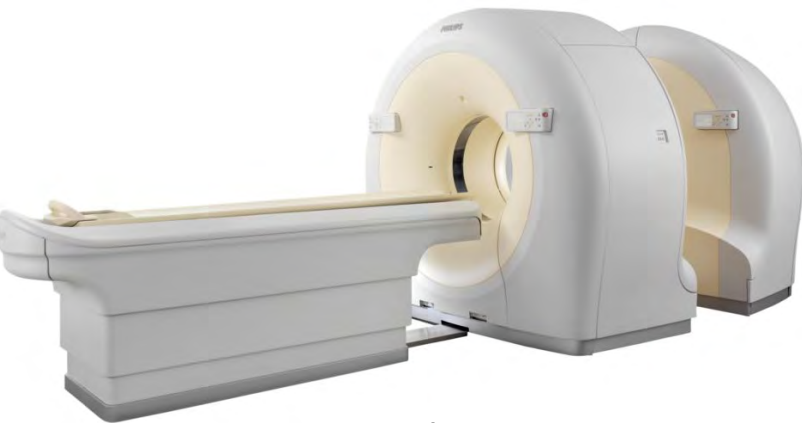


# LYSO Crystal Development



- ❑ LSO (Lutetium Orthosilicate) crystals invented and developed at Schlumberger (Charles Melcher)
- ❑ Radiation damage studies of Lead Tungstate (PWO) crystals for CMS at the LHC showed that yttrium doping was effective to improve crystal radiation hardness.

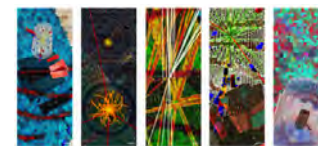
## Philips GEMINI TF PET/CT



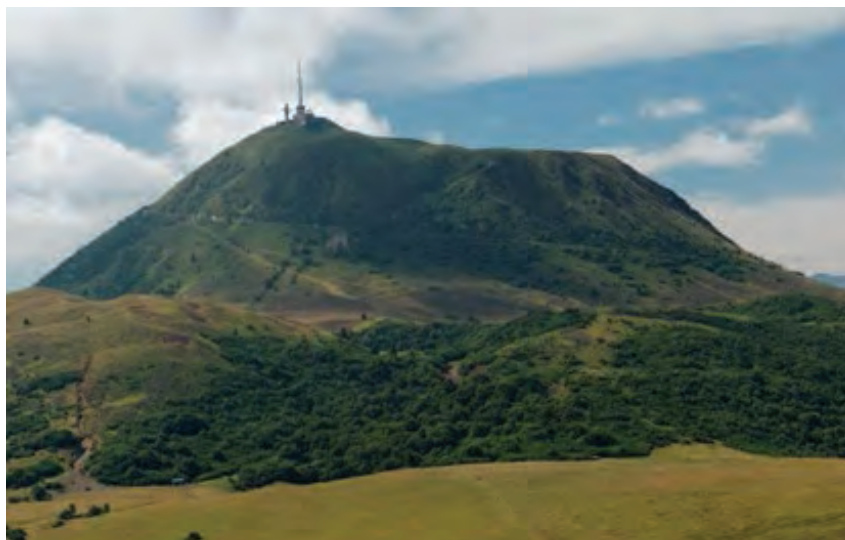
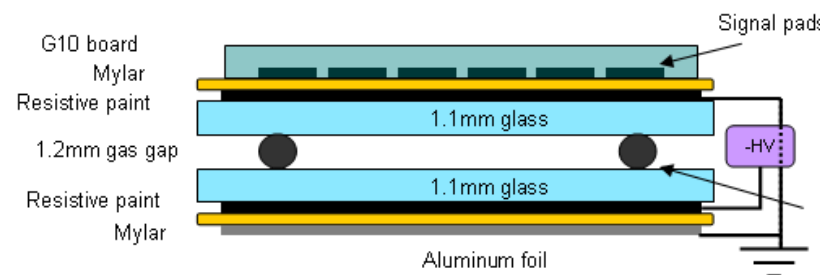
LYSO crystals: 4x4x22mm

- ❑ Led to the development of cerium doped Lutetium Yttrium Orthosilicate (LYSO) crystals which currently dominates the PET market

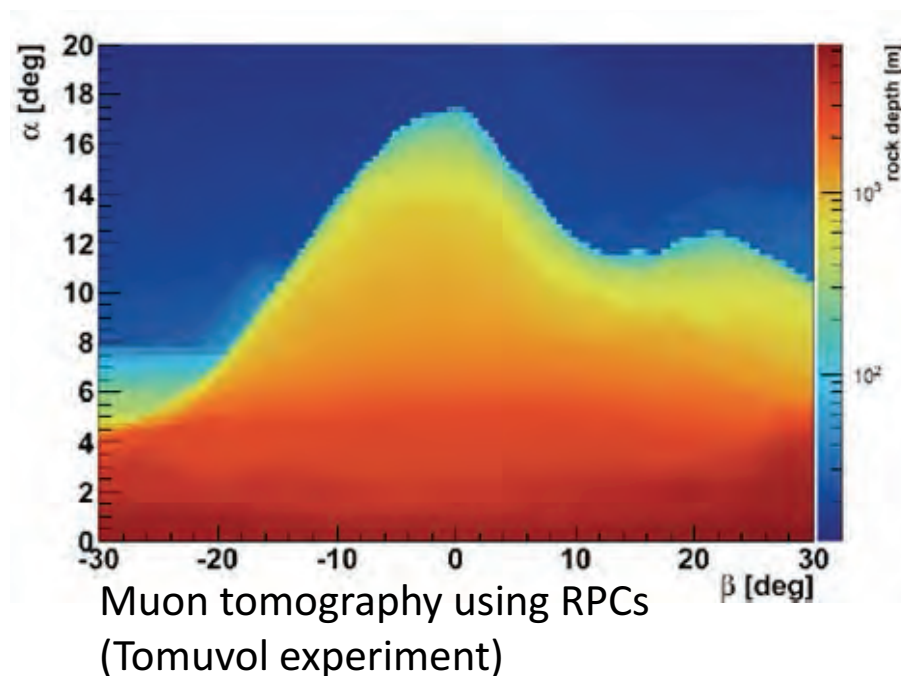
# Environment



- ❑ Resistive Plate Chamber Technology used for volcano tomography using atmospheric muons



The Puy de Dôme (Massive central)

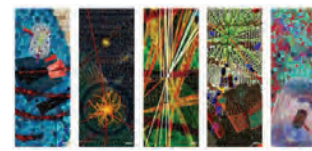


Muon tomography using RPCs (Tomuvol experiment)

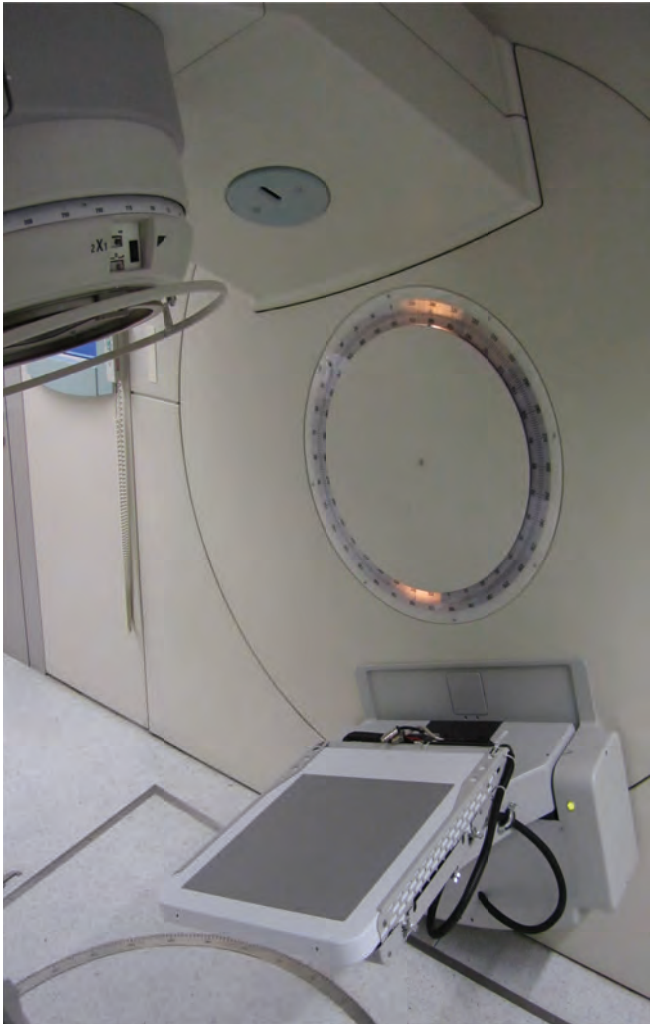
- ❑ Similar measurements planned at Stromboli and Vesuvius (Mu-Ray Project) using scintillator tiles and Silicon Geiger-mode Photo-Multipliers
- ❑ Scintillator strips and Cherenkov counters used for imaging Maya ruins



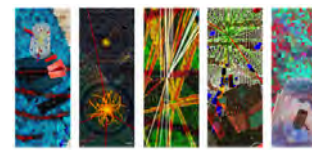
# X-Ray Imaging



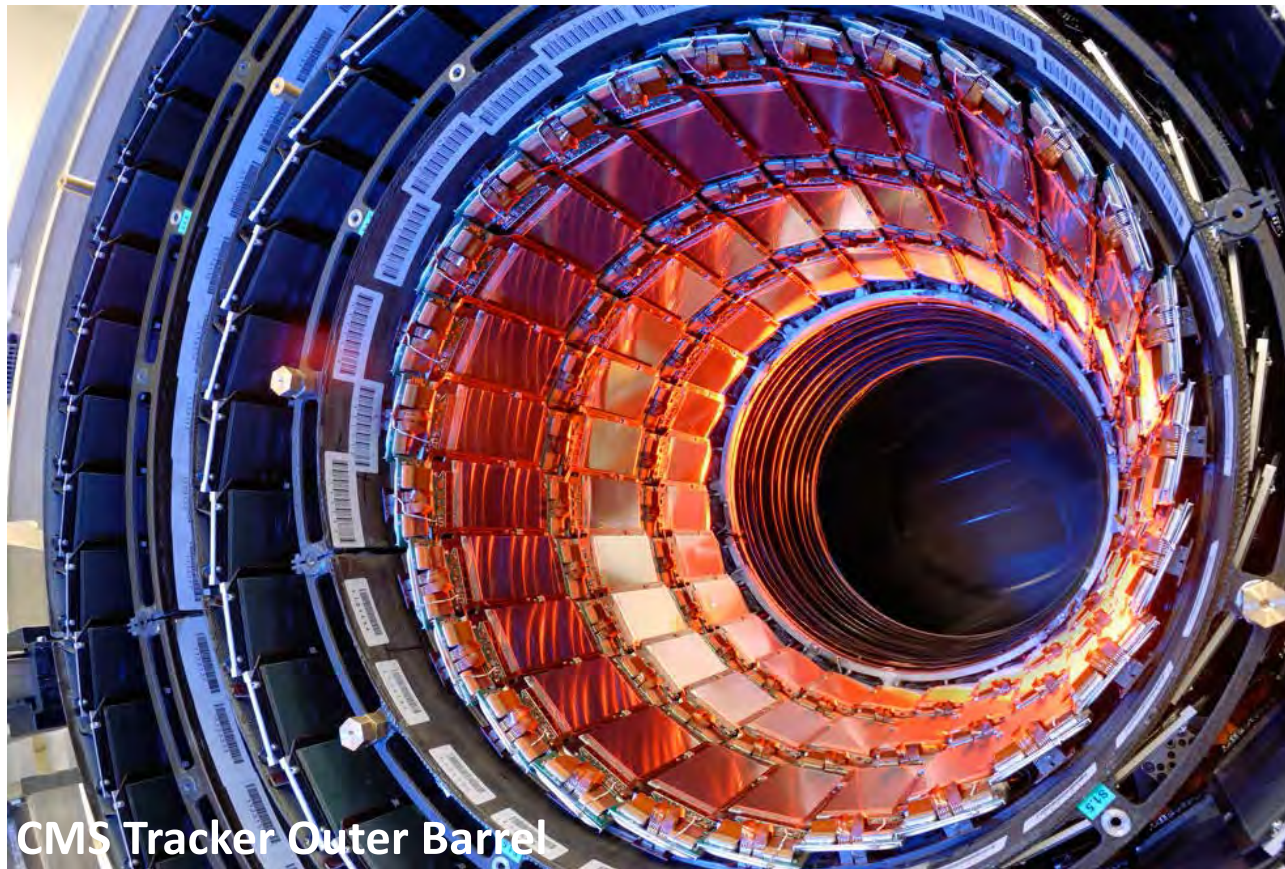
- ❑ X-ray imaging based on Gas Electron Multiplier (GEM) detectors
- ❑ C-RAD: Swedish company developing and commercializing the detector



# Cultural Heritage



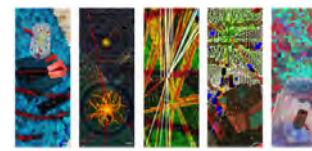
- ❑ To measure the decay of long-lived particles and the trajectory of their decay products, silicon detectors are built with utmost precision using optical metrology



CMS Tracker Outer Barrel



# Cultural Heritage

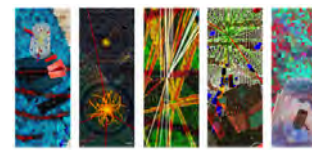


- ❑ To measure the decay of long-lived particles and the trajectory of their decay products, silicon detectors are built with utmost precision using optical metrology

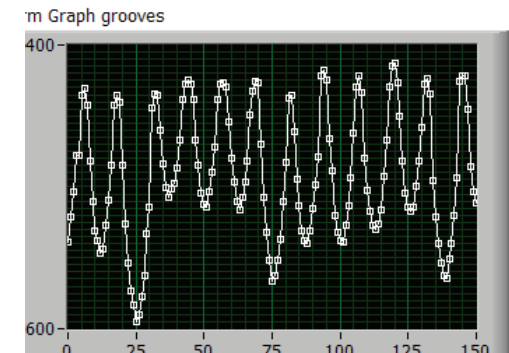
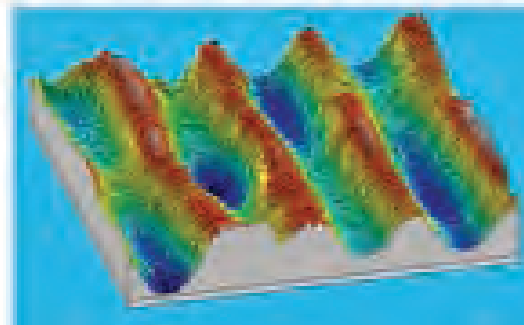
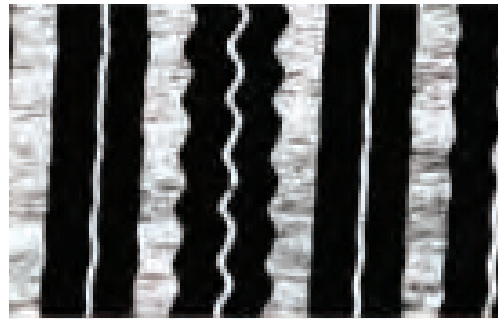
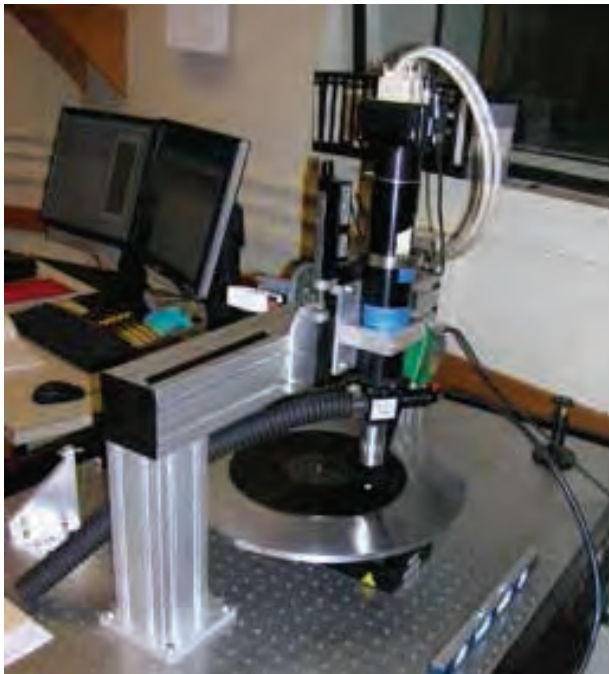


- ❑ Traffic jam + NPR .....

# Cultural Heritage



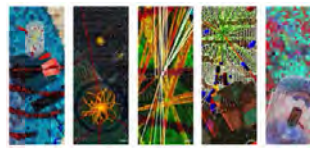
- ❑ Old recordings are grooves made on wax cylinders or vinyl disks
- ❑ Use the same **non-contact** optical metrology to scan the grooves and reconstruct the mechanically recorded sound by image processing:  
A “smart” copying machine for records



Surface profile of a wax cylinder: A 3-dimensional image is required for vertical cut grooves



# LHC Physicists Preserve Native American Voices



- The Physicist Who's Saving the Music (Wall Street Journal, August 21, 2015)



<http://irene.lbl.gov/>

<http://www.newyorker.com/magazine/2014/05/19/a-voice-from-the-past>

<http://www.symmetrymagazine.org/article/june-2015/lhc-physicists-preserve-native-american-voices>





<http://www.teraranger.com/>

**Terabee wins Web Summit Angels' Choice Award**

Posted in [News](#)

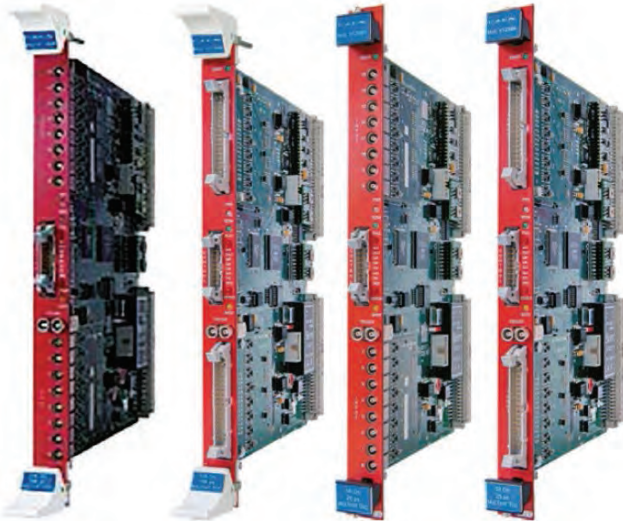
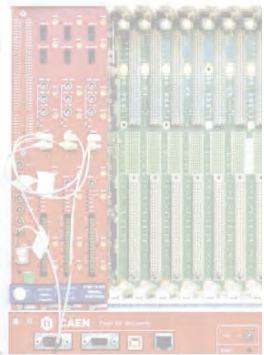
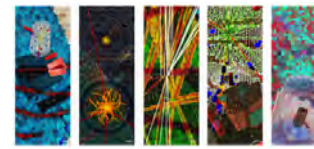
From the 2,141 start-ups exhibiting at the event, Terabee was another clear demonstration of the

These sensors are born from a fruitful collaboration with CERN while developing flying indoor inspection systems.

How to locate equipment in the LHC tunnel where there is no GPS signal

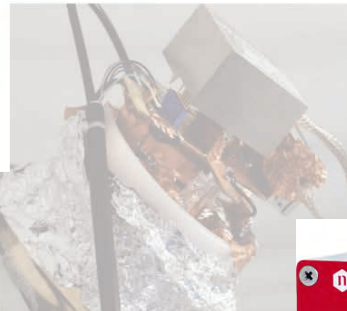


# Industry Collaboration



## V1290-2eSST Family

*“The units features High Performance Time to Digital Converter chips developed by CERN.”*



*DT5742: Based on DRS4 chip (Paul Scherrer Institute design)*

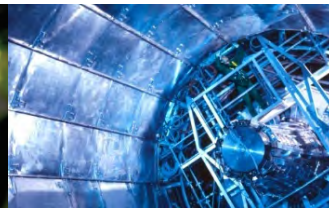
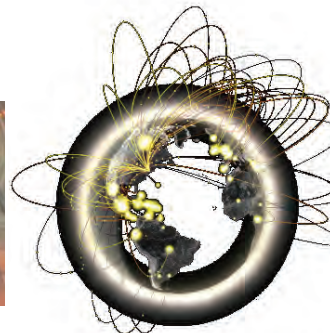
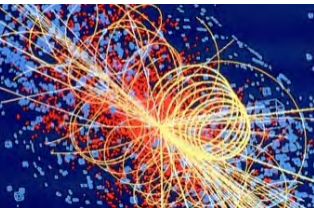


*V767: The module hosts 4 deadtimeless TDC chips developed at CERN.*

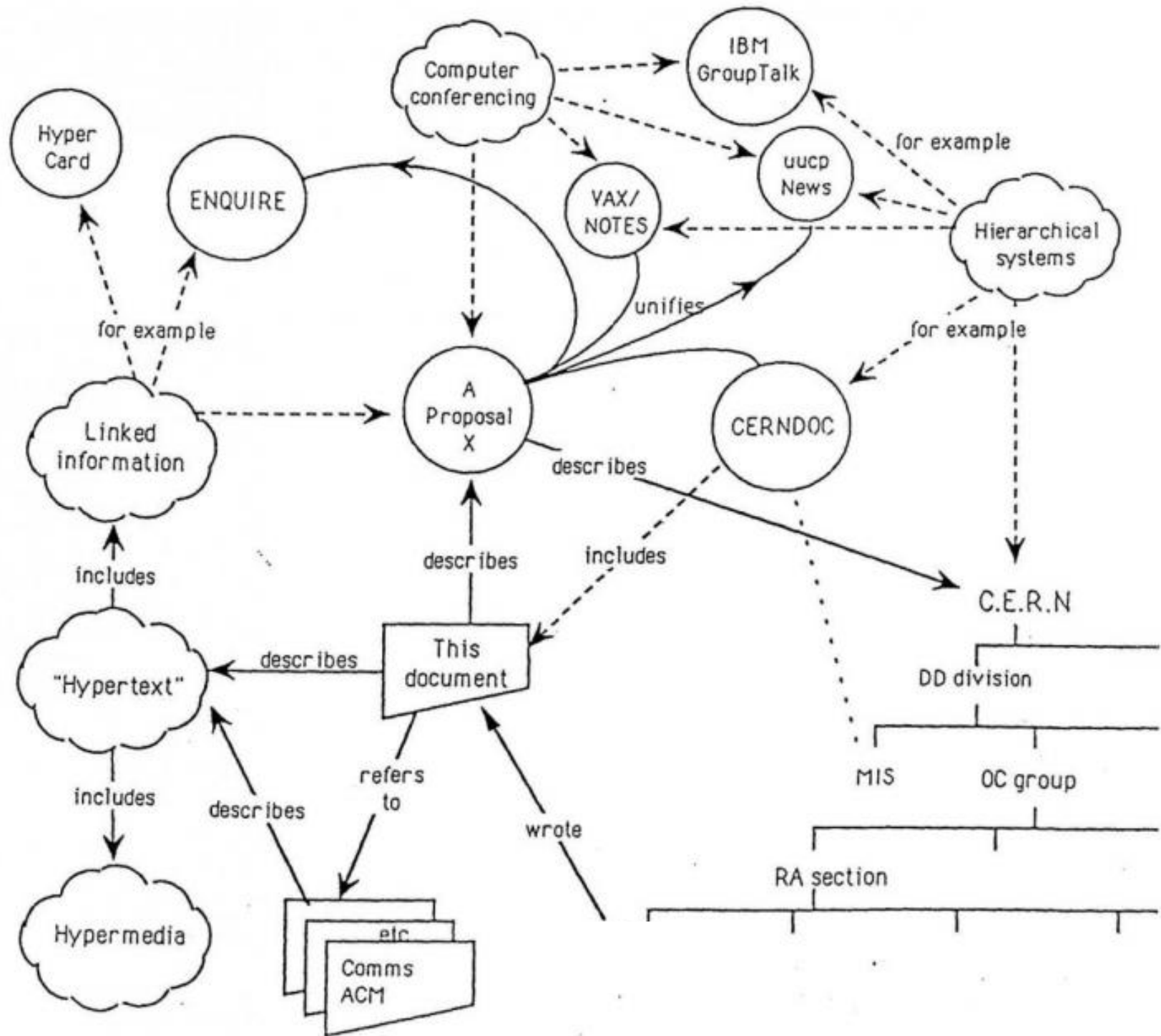


# Computing, Software, Data Management

HEP has been at the forefront  
of big data and the need for  
advanced networking







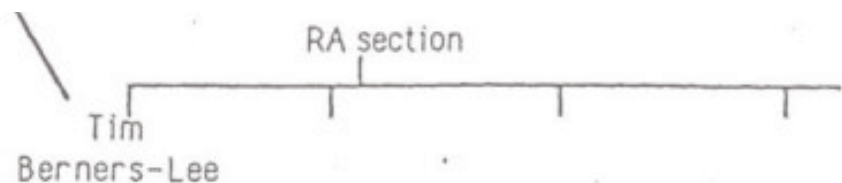
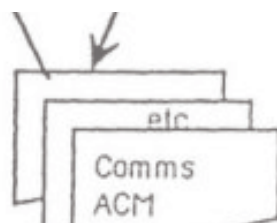


**Cover Page of a 10-page proposal titled:**

# Information Management: A Proposal

**Tim Berners-Lee, CERN  
March 1989**

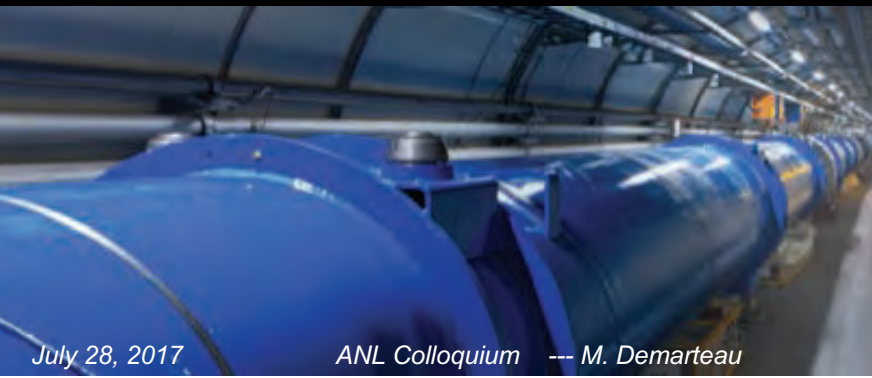
This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.



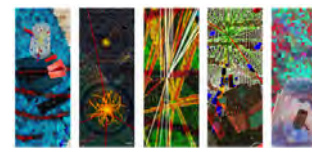




On 30 April 1993 CERN put the **World Wide Web** software in the public domain and made the release available with an open license, as a more sure way to maximise its dissemination, enabling the web to flourish.



# Petabytes and Petaflops

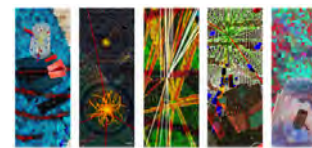


The LHC Data Challenge was recognized very early





# Particle Physics and Data Networks



“Just as we expect a computer to perform as if we are the only user, we expect the network to give that same appearance.”

1986 workshop on:  
“The Future of Intersite Networking”



## 1st ANNUAL WORKSHOP ON ENERGY RESEARCH COMPUTING

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Physics Dept.  
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HELLAND@ALISUVAX.BITNET,  
HELLAND@ISUL.MFENET,

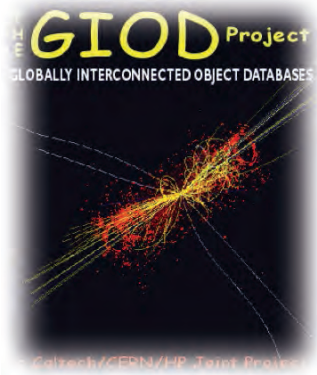
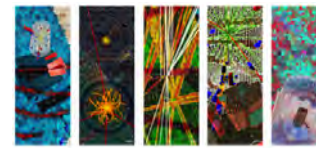
William Johnston  
Bldg 50B-3238  
Lawrence Berkeley Laboratory  
1 Cyclotron Road  
Berkeley, CA 94720  
WEJOHNSTON@LBL.ARPA,

Stephen Wolf  
Room 533  
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1800 G Street, N.W.  
Washington, D.C. 20550

(202) 357-9717  
STEVE@BRL.ARPA,

From Barb Helland, HEPAP Meeting, April 1, 2016

# Evolution of Grids



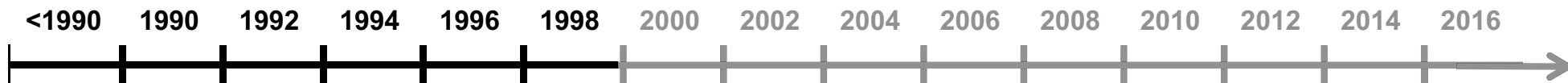
Globally Interconnected Object Databases (GIOD, ~1997)



Models of Networked Analysis at Regional Centers (MONARC, ~1998)



Accessing Large Data archives in Astronomy and Particle Physics (ALDAP, 1999)

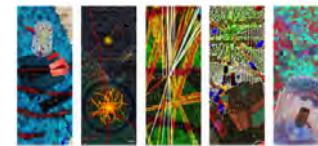


**“Embryonic Grid”**

World-wide university and National Lab effort with collaboration from LIGO, Astrophysics community, Microsoft, Hewlett Packard, L3 communications, ...



# Evolution of Grids: Grid Era Begins



Particle Physics Data Grid (PPDG, 1999)



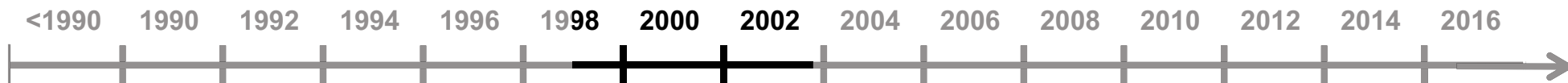
Grid Physics Network (GriPhyN, 2000)



International Virtual Data Grid Laboratory (iVDGL, 2002)



Trillium: GriPhyN + iVDGL + PPDG

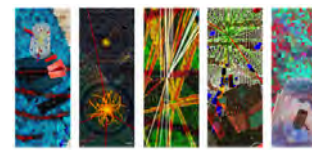


“Embryonic Grid”

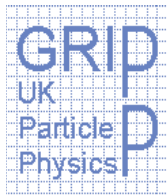
“Grid Era Begins”

Strong collaboration with European efforts

# Science Grids



Open Science Grid



.....

<1990 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016



“Embryonic Grid”

“Grid Era Begins”

“Grid Projects”

“Science Grid”

Particle Physics has been in the vanguard of the development of monitored advanced networks and computing infrastructure, including HPC, building on the needs of the experiments, notably the LHC



# Global Grid

- Worldwide LHC Computing Grid has been leveraged on both sides of the Atlantic, to the benefit of the wider scientific community and particle physics

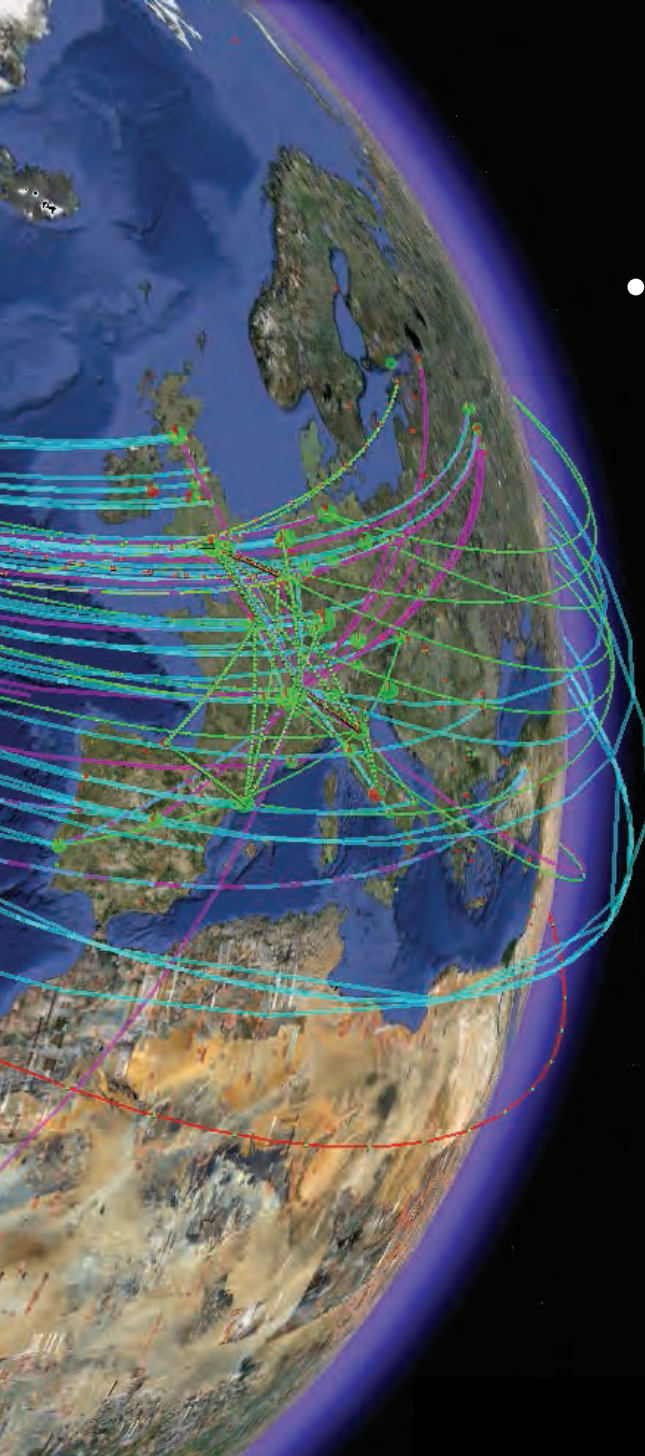
- Europe:

- Grids for E-science  
European Grid Infrastructure

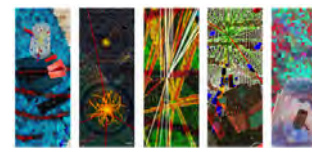
- USA:

- Open Science Grid (OSG)
- ESnet:
  - > 400 Gb/s cross Atlantic
  - > 100 PB/months

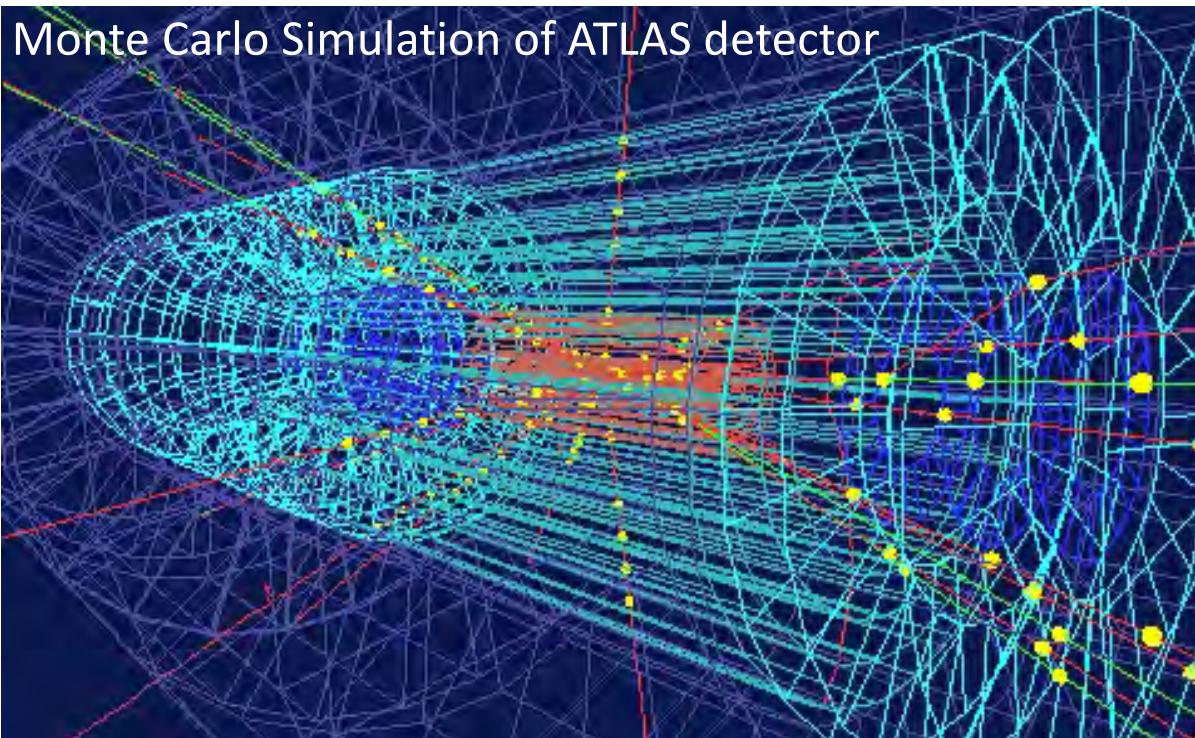
**Archeology**  
**Astronomy**  
**Astrophysics**  
**Civil Protection**  
**Comp. Chemistry**  
**Earth Sciences**  
**Finance**  
**Fusion**  
**Geophysics**  
**High-Energy Physics**  
**Life Sciences**  
**Multimedia**  
**Material Sciences**  
...



# Modeling and Simulation



- ❑ Experiments big, difficult and expensive: need for detailed simulations



Definition at will of:

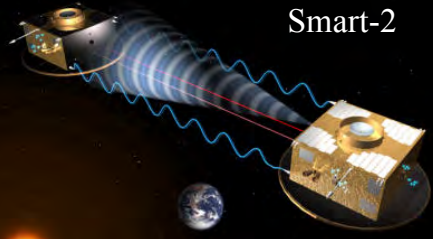
- ❑ Geometry
- ❑ Materials
- ❑ Segmentation
- ❑ Tracking through media

- ❑ **GEometry ANd Tracking Toolkit for detector simulations developed: GEANT**
- ❑ **Seen very broad use**

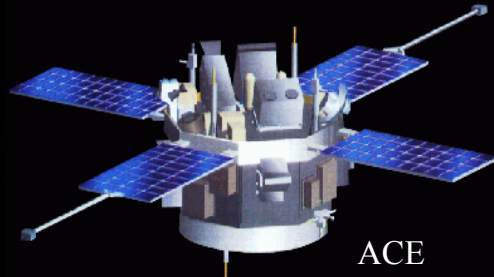


# GEANT Use in Space (NASA, ESA, JAXA)

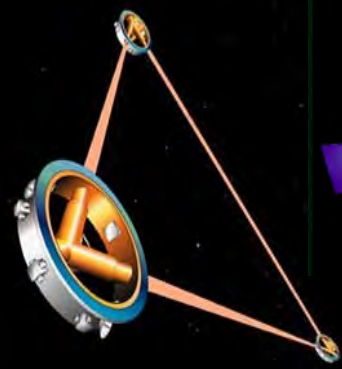
Courtesy: Makoto Asai



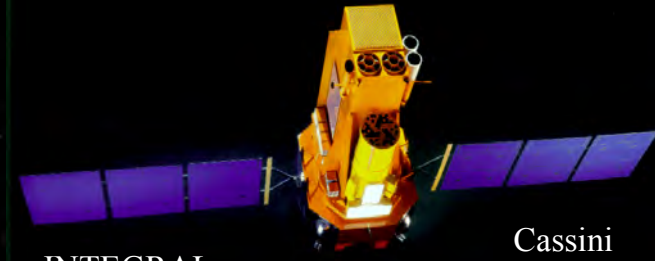
Smart-2



ACE



LISA

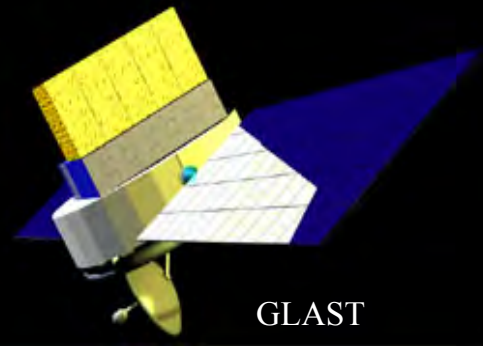


Cassini

INTEGRAL



Bepi Colombo



GLAST



Herschel



SWIFT



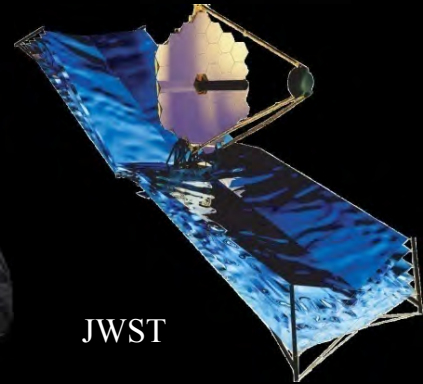
Astro-E2



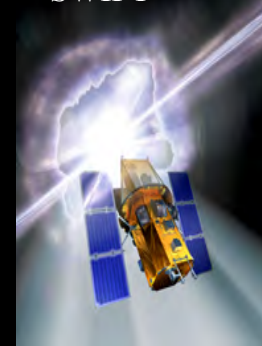
XMM-Newton



GAIA

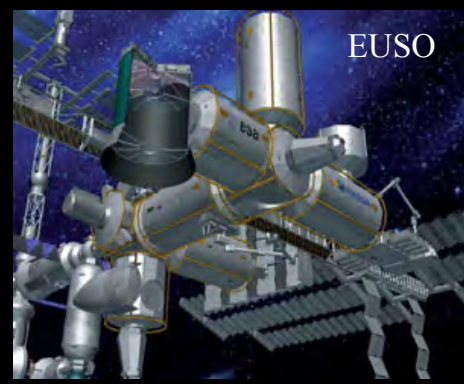


JWST

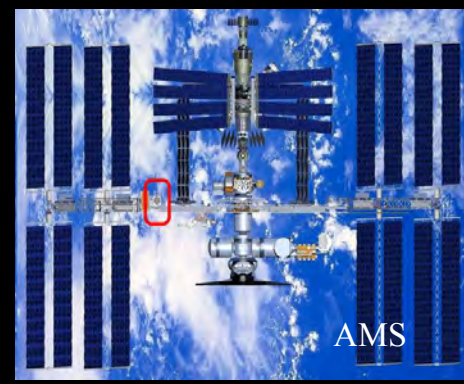


ISS Columbus

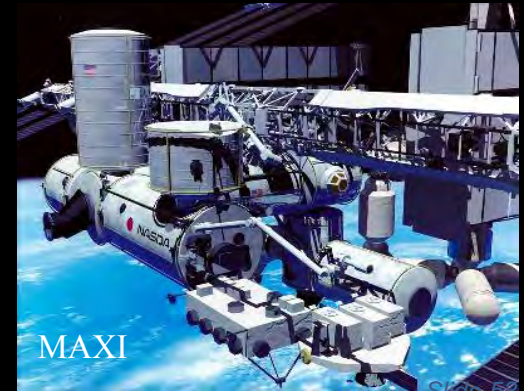
July 28, 2017



EUSO



AMS



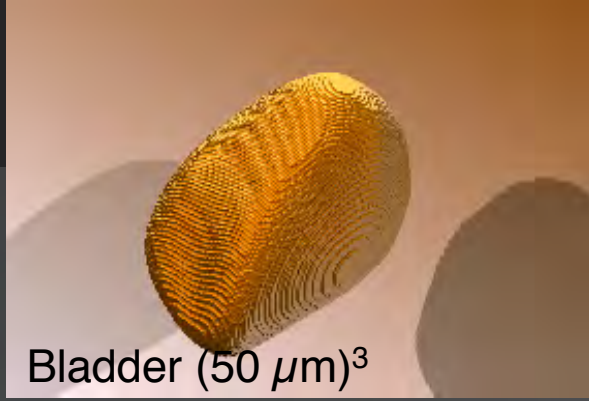
MAXI



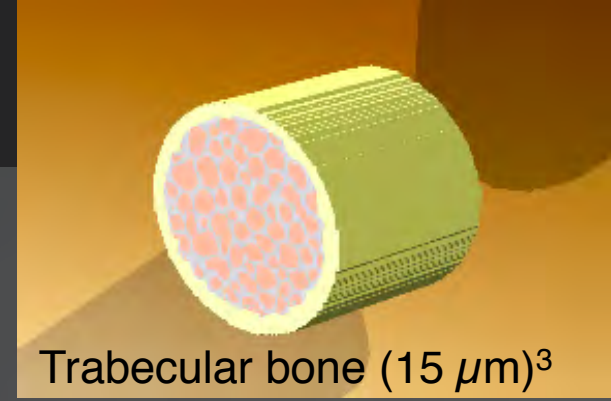
# High resolution phantoms



Vertebra ( $25 \mu\text{m}$ )<sup>3</sup>

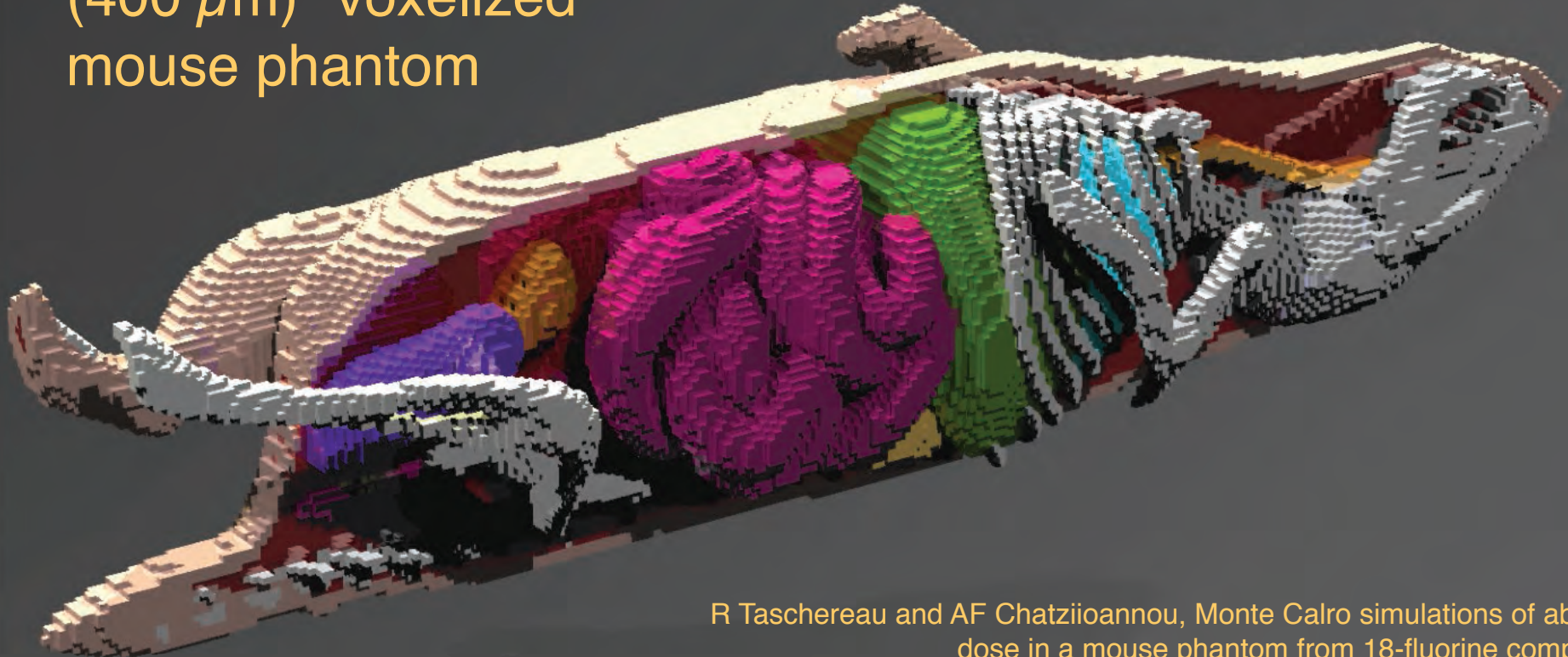


Bladder ( $50 \mu\text{m}$ )<sup>3</sup>



Trabecular bone ( $15 \mu\text{m}$ )<sup>3</sup>

( $400 \mu\text{m}$ )<sup>3</sup> voxelized  
mouse phantom



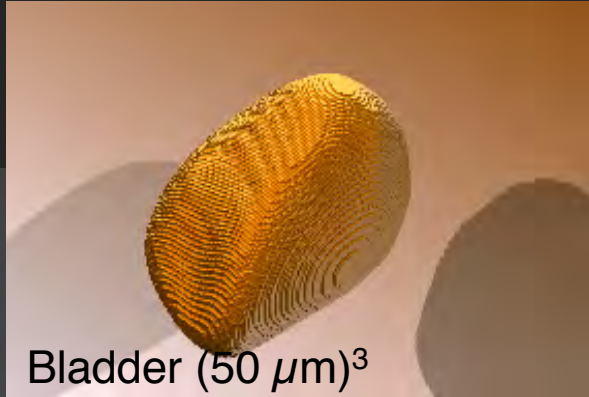
R Taschereau and AF Chatziioannou, Monte Carlo simulations of absorbed dose in a mouse phantom from 18-fluorine compounds, *Medical Physics*, 34(3), 1026-36 (2007)



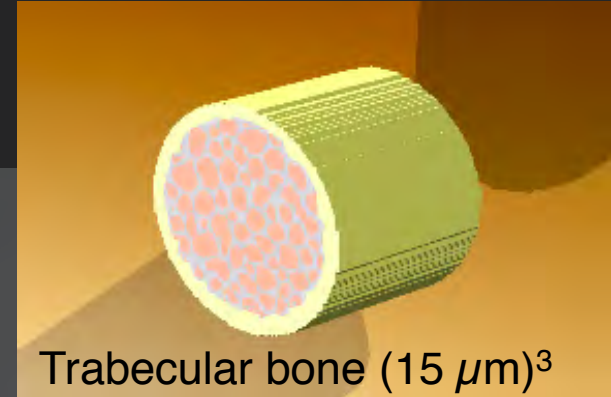
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Bladder ( $50 \mu\text{m}$ )<sup>3</sup>



Trabecular bone ( $15 \mu\text{m}$ )<sup>3</sup>

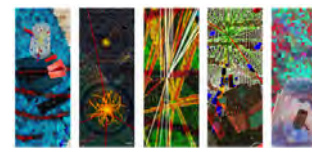
$(400 \mu\text{m})^3$  voxelized mouse phantom



R Tasch

The Medical Community is currently a larger user of GEANT than the Particle Physics Community

# GEANT and Air Travel

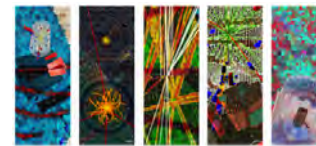


- ❑ HEP Monte Carlo simulations are used for modeling of radiation exposure in (ultra-) long-haul flights
- ❑ The dose received during a flight is about  $\sim 5 - 10 \mu\text{Sv/hr}$ 
  - X-ray:  $\sim 6 \mu\text{Sv}$
  - Mammogram:  $\sim 3,000 \mu\text{Sv}$ .
- ❑ Second highest exposure level for crews after radon environmental exposure
  - Aircraft crew radiation exposure is close to a few mSv/year
- ❑ Simulation: a mathematical model of Airbus A340, A. Ferrari et al., Radiation Protection Dosimetry (2004), Vol. 108, No. 2, pp. 91-105
  - The shielding influence of aircraft structures and contents has proven to be significant on radiation levels onboard
- ❑ Boeing Company hosted the GEANT4 Space User's workshop in 2006, Seattle





# INVENIO



- ❑ Invenio is a free software suite enabling you to run your own integrated digital library or document repository on the web
- ❑ It is a suite of applications, which provides the framework and tools for building and managing an autonomous digital library server.
- ❑ Invenio is developed since 2002 by CERN and at CERN runs:
  - CERN Document Server (1 million records)
  - INSPIRE (1 million records)
  - ILC Document Server
  - CERN Indico search engine
  - CERN Bulletin web site
  - CERN Multimedia Gallery web site



- ❑ **TIND, a spin-off company based in Trondheim, Norway, provides professional cloud-based services to customize and maintain INVENIO**

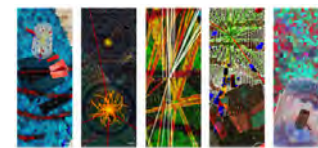


*spin-off*



*technology*

# Agenda Server



## International Workshop on Future Linear Colliders (LCWS2016)

4-9 December 2016  
Aiina Center & MALIOS in Morioka  
Asia/Tokyo timezone

- Overview
- Timetable**
- LCWS2016 (Home)

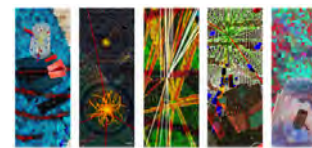
### Timetable

Sun 04/12 **Mon 05/12** Tue 06/12 Wed 07/12 Thu 08/12 Fri 09/12 All days

- Print
  - PDF
  - Full screen
  - Detailed view**
  - Filter
- Session legend

09:00	<b>Welcome from LOC</b> <i>Odashimagumi Hall (Aiina Hall), Aiina</i>	<i>LOC Chair: Shinya Narita</i> 09:00 - 09:05
	<b>Greetings from Iwate prefecture</b> <i>Odashimagumi Hall (Aiina Hall), Aiina</i>	<i>Governor: Takuya Tasso</i> 09:05 - 09:15
	<b>Japanese status</b> <i>Odashimagumi Hall (Aiina Hall), Aiina</i>	<i>KEK DG: Masanori Yamauchi</i> 
	<b>LC status</b> <i>Odashimagumi Hall (Aiina Hall), Aiina</i>	<i>LCC Director: Lyn Evans</i> 
10:00	<b>LC physics overview for non-specialists</b>	<i>Nathaniel Craig</i> 





## MANAGE, SHOWCASE AND PRESERVE ALL DIGITAL ASSETS.



### RESEARCH OUTPUT

Publications, Presentations,  
Reports and more.



### RESEARCH DATA

Data sets of any size  
and format.



### MULTIMEDIA

Videos, Pictures  
and Audio.

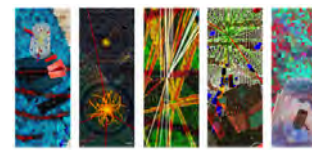


### LIBRARY MANAGEMENT

Electronic and Print  
Resources.

CERN open source software provided as a  
professional cloud service.

<http://tind.io>



Canton de Fribourg



Techno. de l'Inform. la Com.



UM library management



Graduate Institute Geneva

# TIND



[www.tind.io](http://www.tind.io)



UN Int. Telecom. Union



UNESCO



Intl. Bureau of Education



Max Planck institute

EU Found. for the Improvement



For Extraterrestrial Physics



of Living and Working Conditions

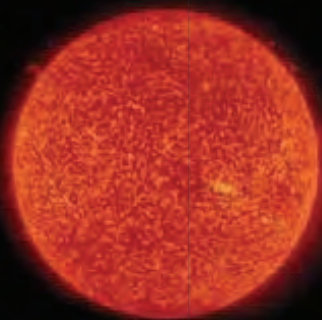
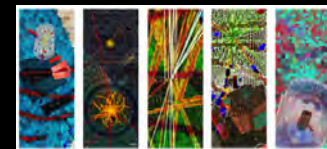


# Accelerators

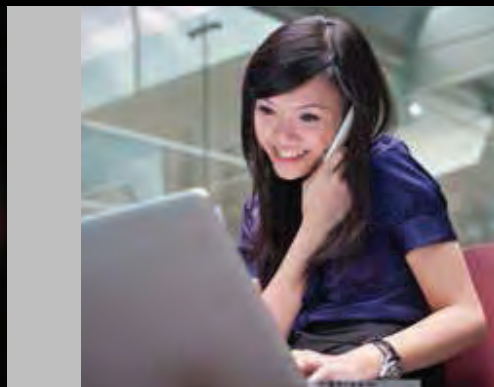
The workhorse of HEP has established major connections to the medical industry and industry in general



# Accelerators for Society



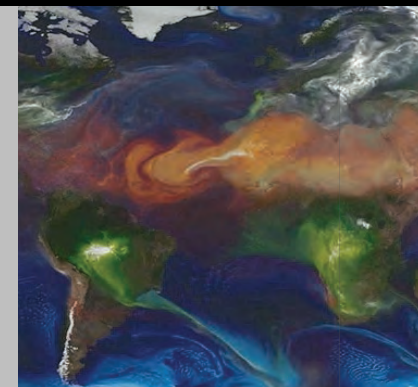
Energy



Ion Implantation



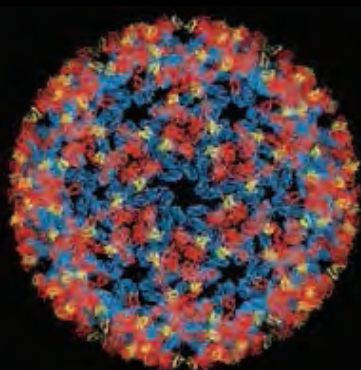
Hardening Materials



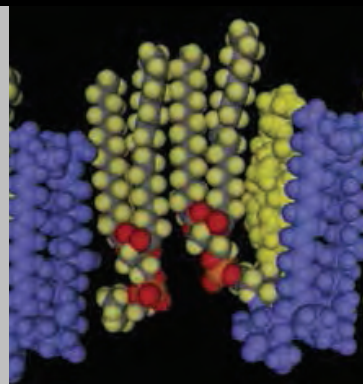
Climate Change



Controlling Emissions



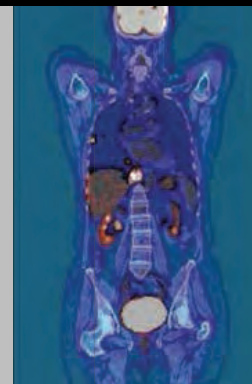
Protein Modeling



Materials Research



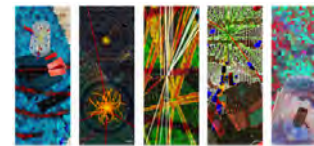
Hadron Therapy



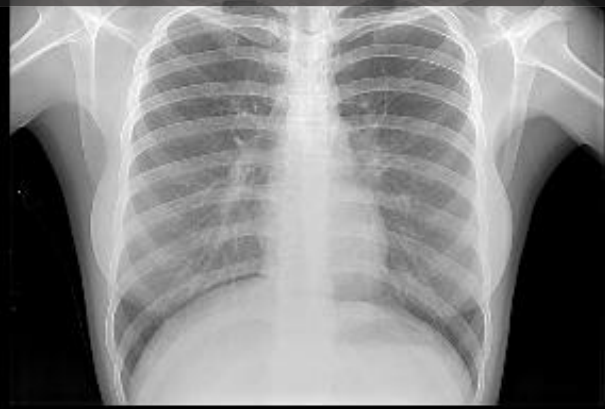
Radioisotope Production



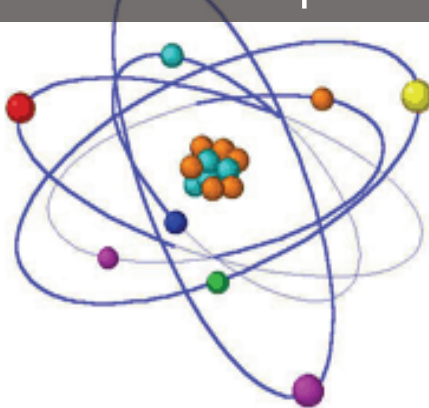
# Medical Applications



Imaging



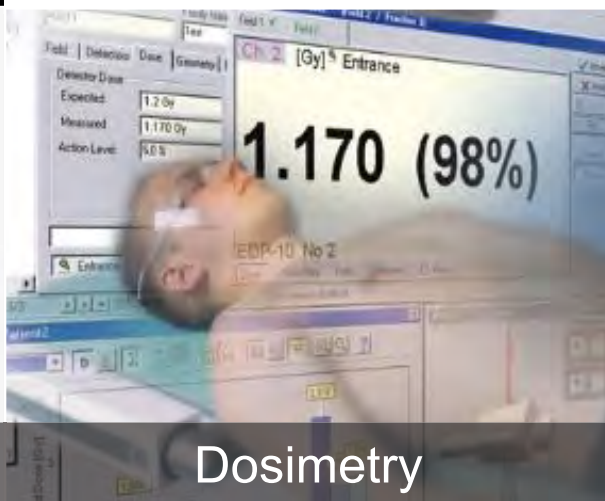
Radioisotopes



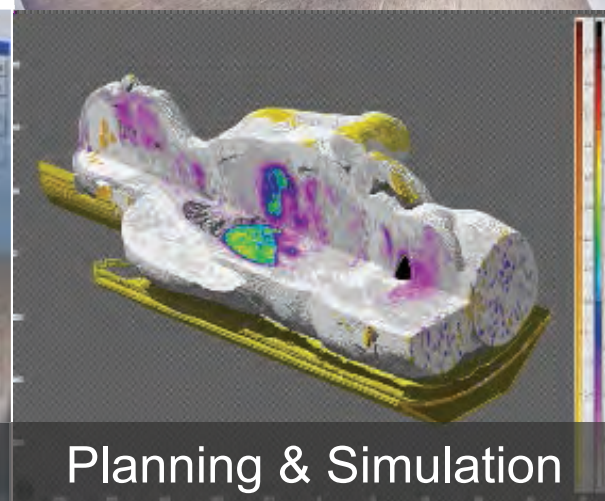
Hadron Therapy



MRI Systems

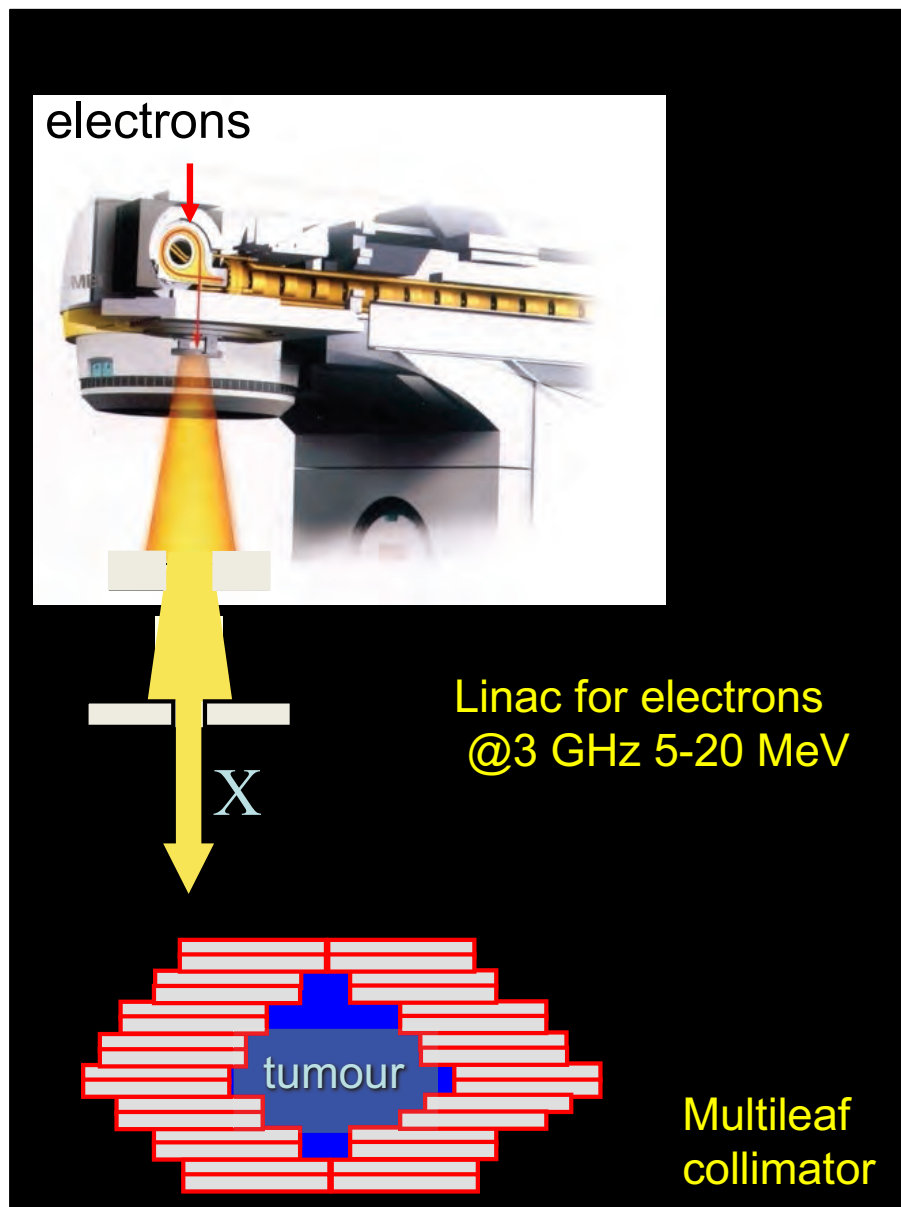
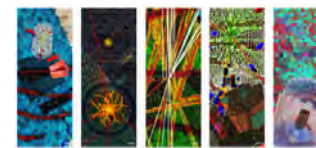


Dosimetry



Planning & Simulation

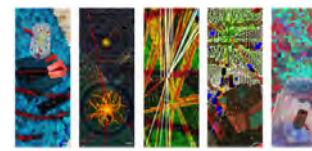
# Conventional Radiotherapy



- ❑ Dominated by linear accelerators
- ❑ 20,000 patients per year treated
- ❑ One Linac every ~ 250,000 inhabitants



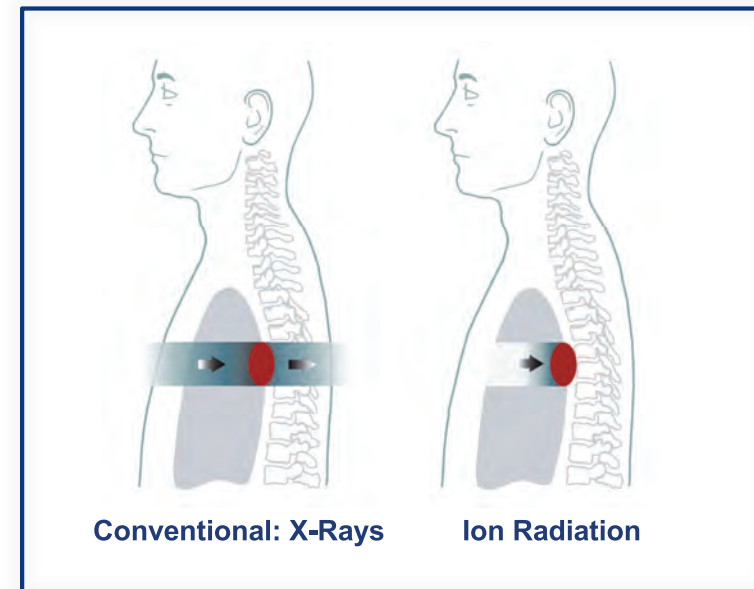
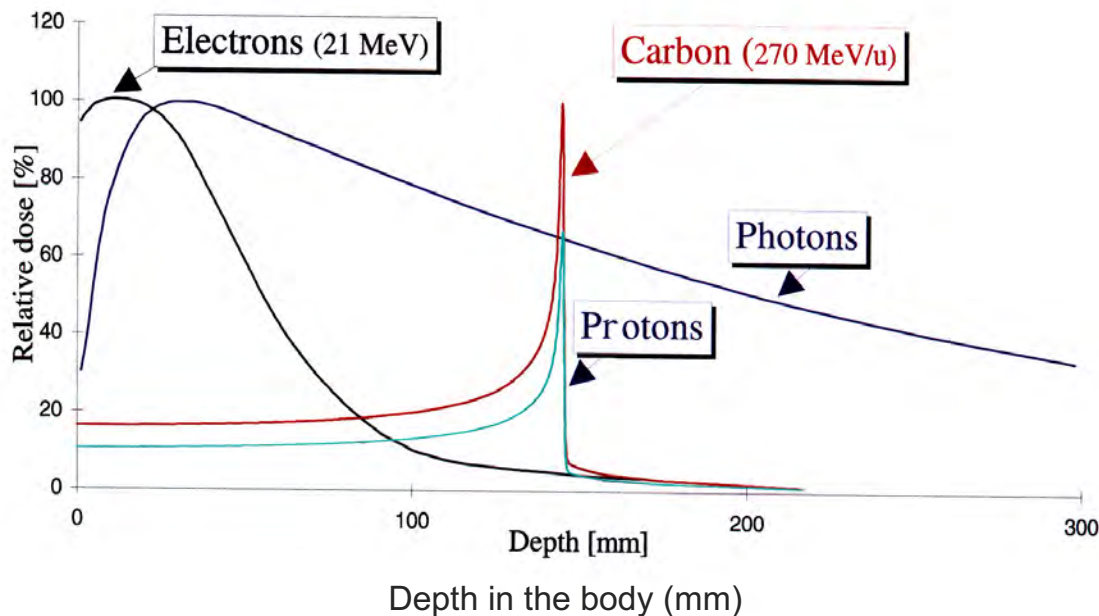
# Hadron Therapy



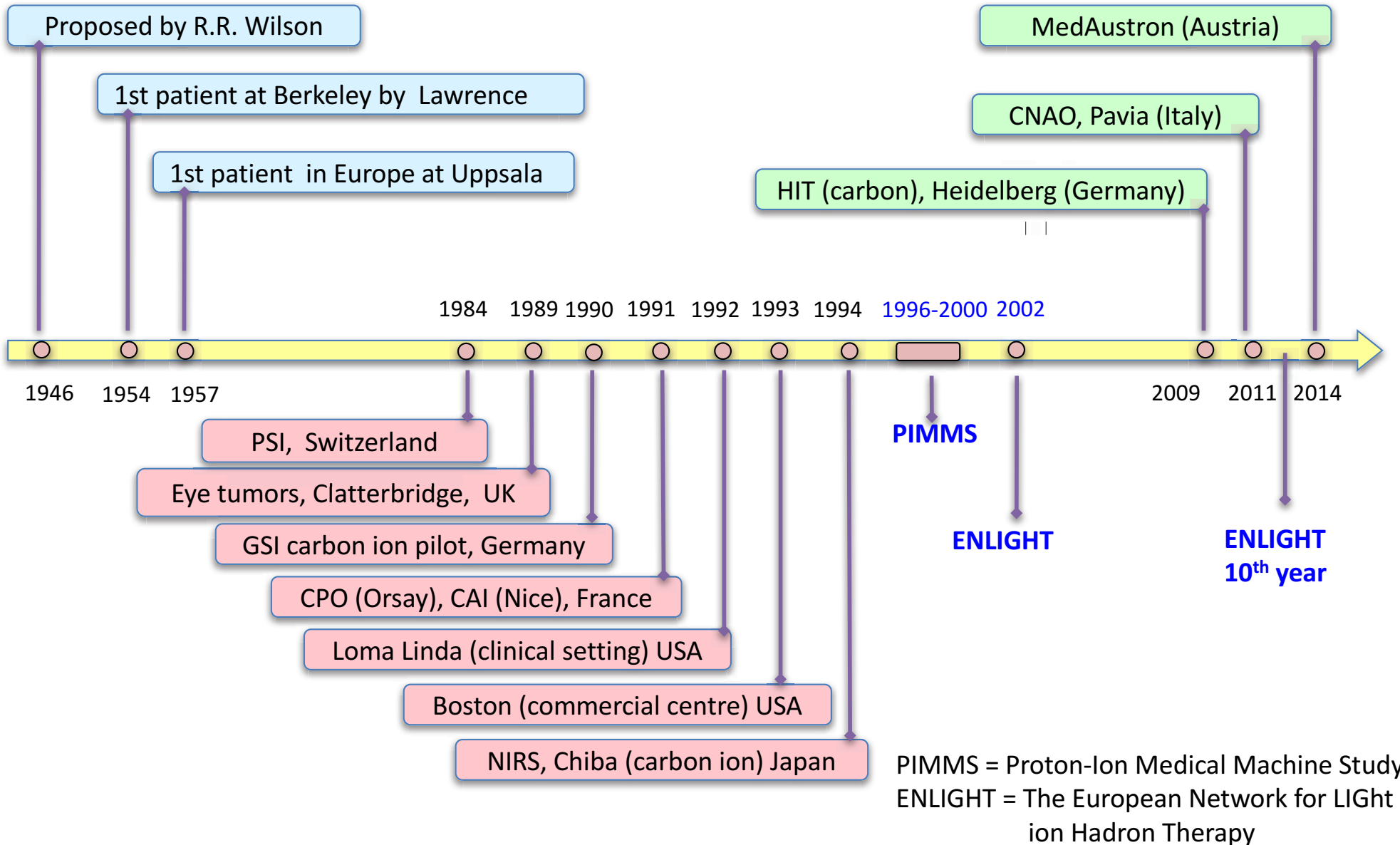
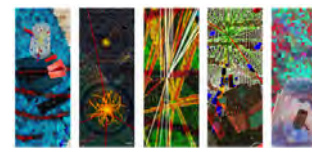
Robert Wilson

In 1946 Robert Wilson (first director of Fermilab):

- Protons can be used clinically
- Accelerators are available
- Maximum radiation dose can be placed into the tumor
- Proton therapy provides sparing of normal tissues

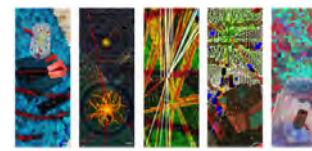


# Proton and Ion Beam Therapy History

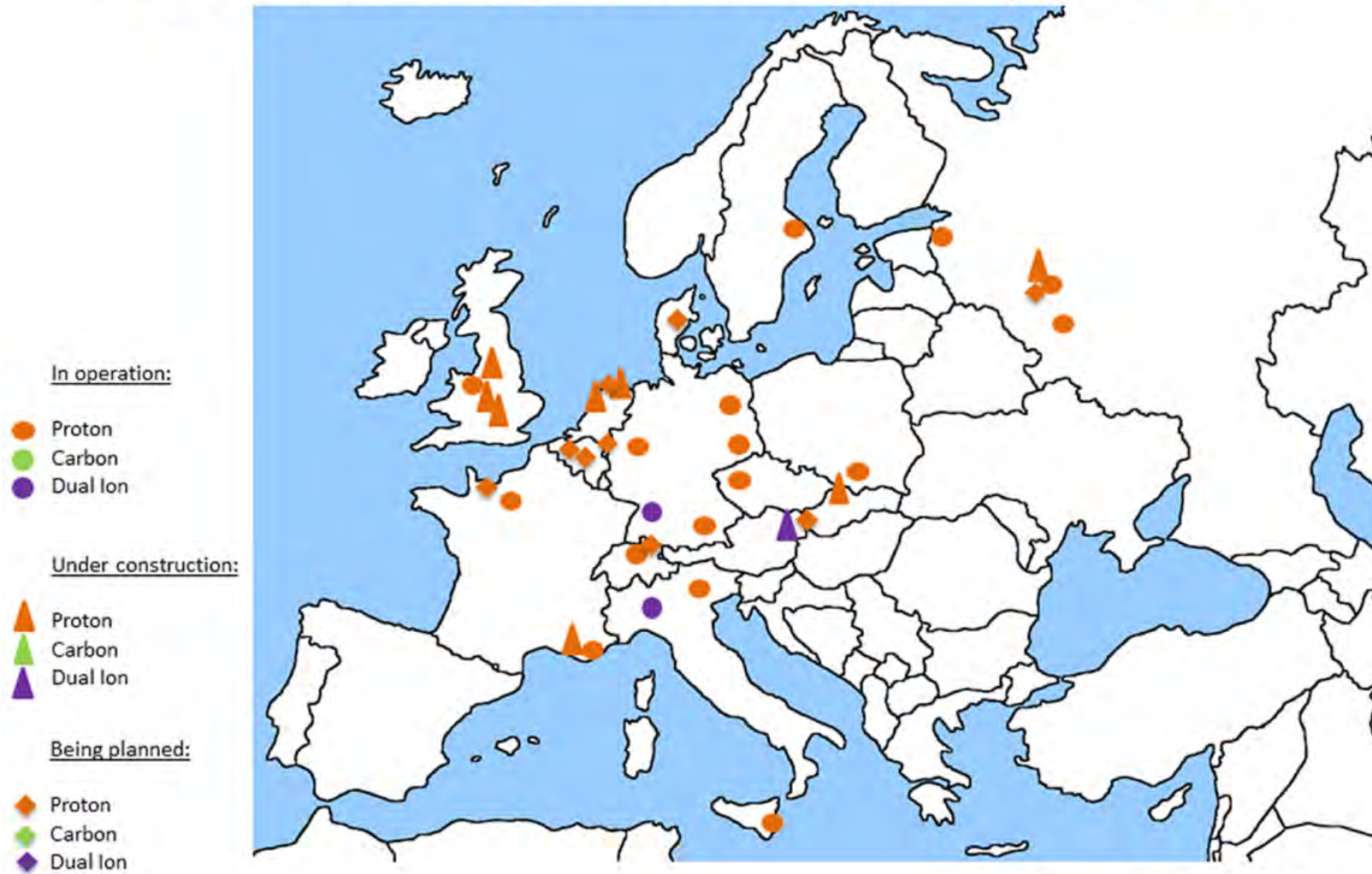




# Proton and Ion Beam Therapy Centers

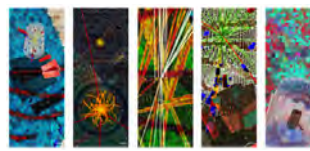


## Particle therapy centres in Europe - 2015

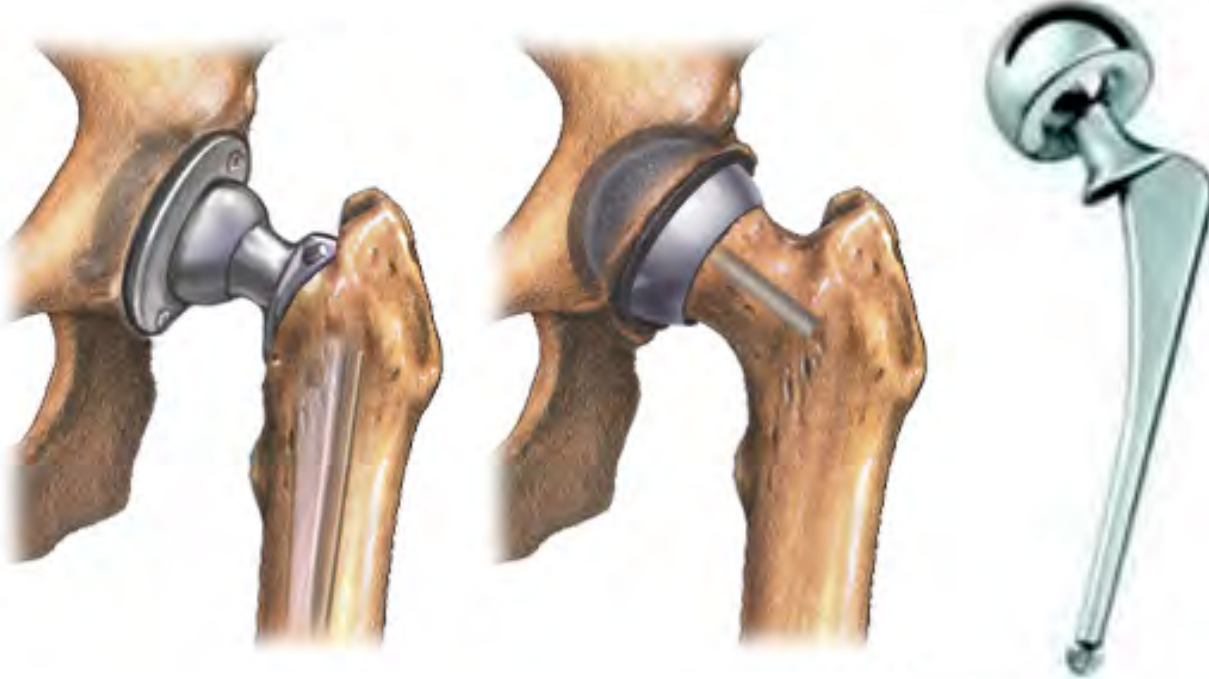


Source: PTCOG, October 2015

# Material Hardening



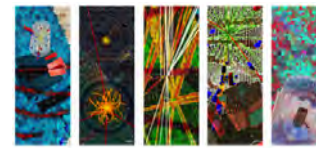
- Almost all prosthetic implants are hardened by ion implantation using particle accelerators



- Nitrogen ion implantation of titanium and cobalt-chrome alloys improve surgically implantable artificial joints by converting chromium in the surface layers to chromium nitride.



# Accelerators for Society



More than

**400 B€**

of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

More than **24 000** particle accelerators have been built globally over the past **60 years** to produce charged particle beams for use in industrial processes.

This number does not include the more than **11 000** particle accelerators that have been produced exclusively for medical therapy with electrons, ions, neutrons, or X-rays.

More than **24 000**

patients have been treated by hadron therapy in Europe.

More than **75 000**

patients have been treated by hadron therapy in the world.

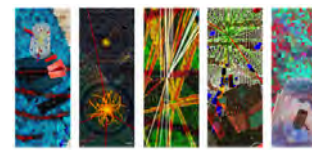
Around **200** accelerators are used for research worldwide, with an estimated

yearly consolidated cost of **1 B€**.

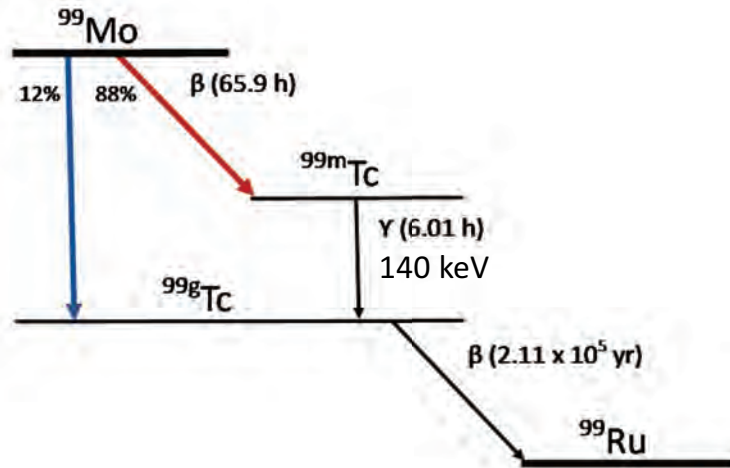
**Big Business**

<http://www.accelerators-for-society.org/>

# Medical Imaging



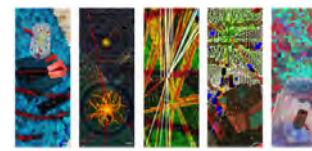
- Technetium-99m, the decay product of molybdenum-99, is the most widely used radionuclide for medical imaging.



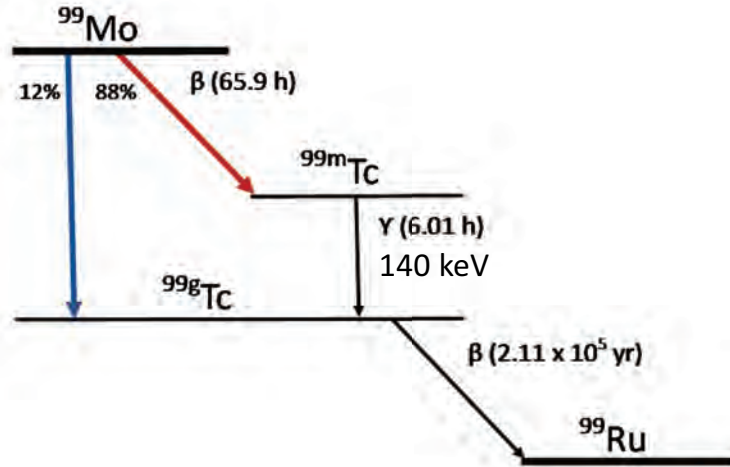
- The United States consumes about half of the world's supply of Mo-99, but there has been no domestic production of this isotope since the late 1980s.



# Medical Imaging



- Technetium-99m, the decay product of molybdenum-99, is the most widely used radionuclide for medical imaging.



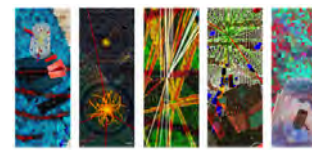
- The United States consumes about half of the world's supply of Mo-99, but there has been no domestic production of this isotope since the late 1980s.

- About 95 percent of the global supply of Mo-99 for medical purposes is produced in seven research reactors.

HEU = highly enriched uranium  
LEU = low enriched uranium

Reactor	Country	Fuel Type	Target Type	Start Year	Global Available Production Capacity (%)
HFR	Netherlands	LEU	HEU	1961	23*
BR-2	Belgium	HEU	HEU	1961	21
NRU	Canada	LEU	HEU	1957	19
SAFARI-1	South Africa	LEU	HEU/LEU	1965	13
MARIA	Poland	LEU	HEU	1974	9
OPAL	Australia	LEU	LEU	2006	8
LVR-15	Czech Republic	LEU	HEU	1957	7

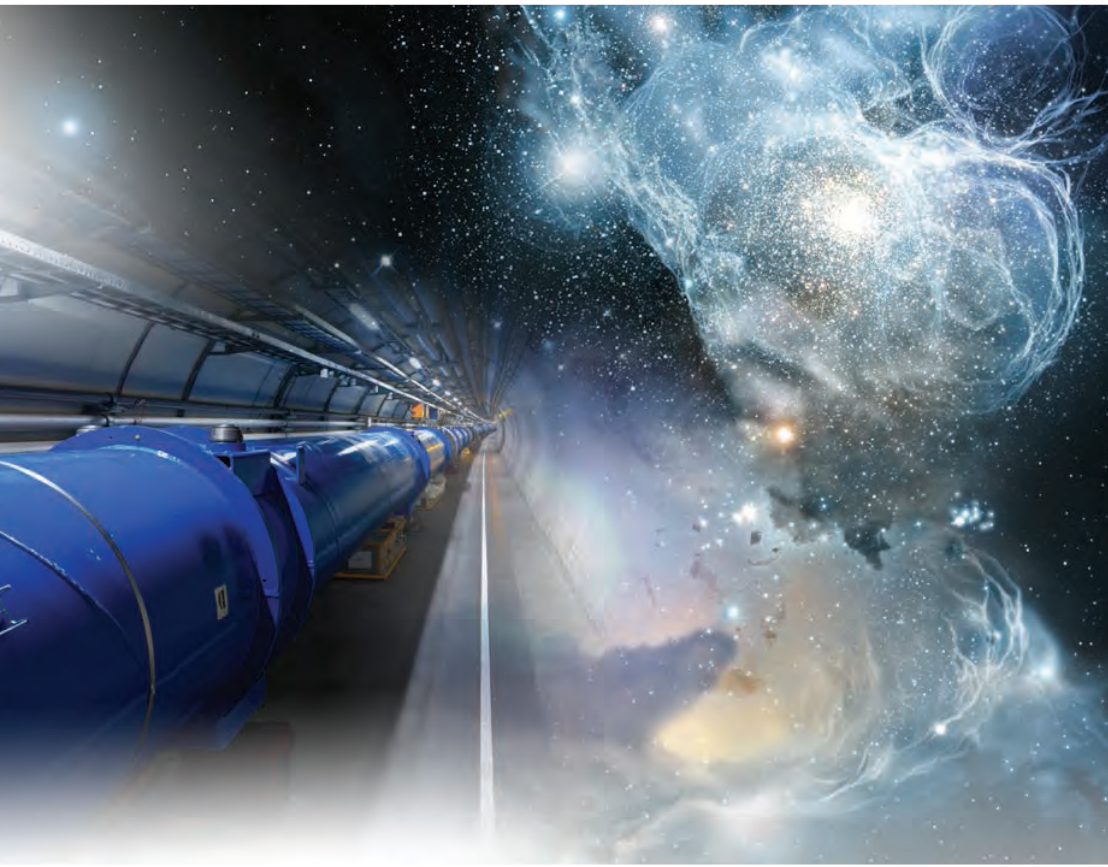
# Accelerator-Based Isotope Production



- ❑ Argonne is developing the 'Compact Accelerator-Driven Multiplier for Isotopes: CAMI' for production of  $^{99}\text{Mo}$ 
  - Using an electron beam, radiating photons:  
Photon-induced transmutation:  $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$
  - Using a 100 MeV proton beam:  
Direct production  $^{100}\text{Mo}(p, 2n)^{99\text{m}}\text{Tc}$





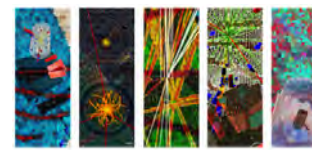


# Facilities

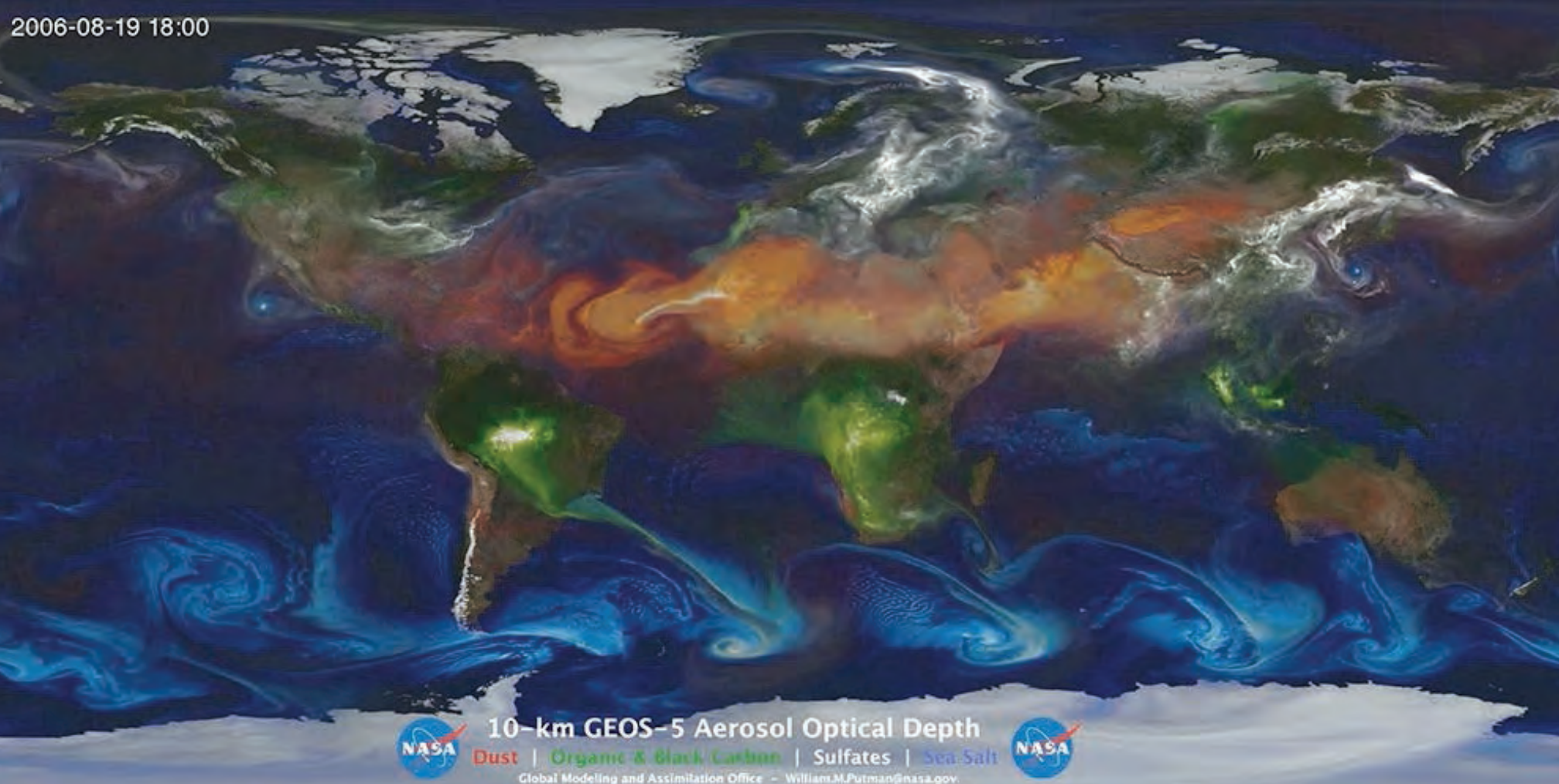
Particle Physics  
facilities for the  
world

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# Atmospheric Aerosols



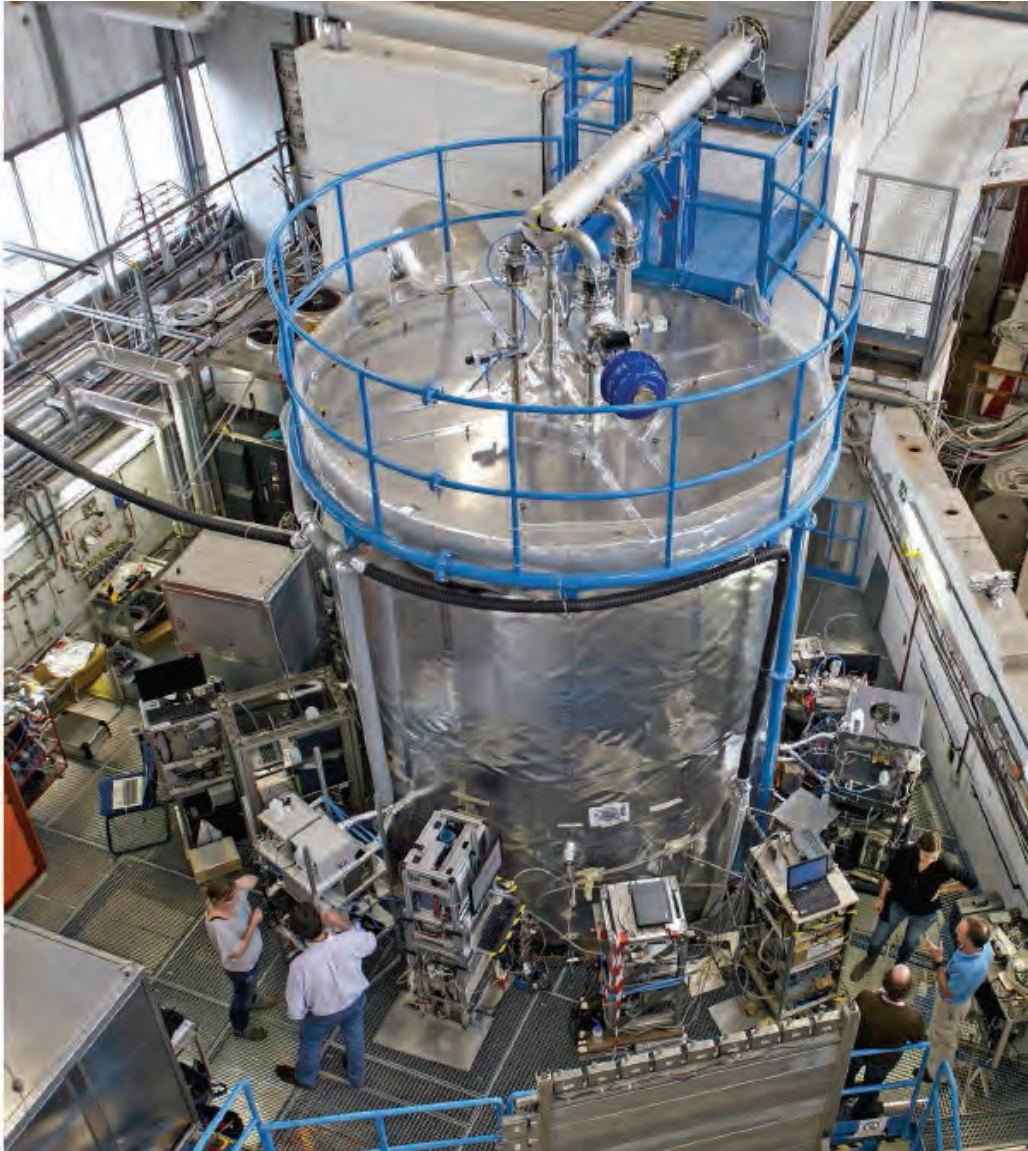
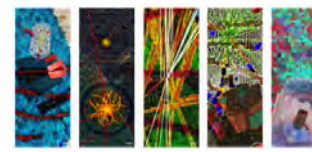
- Aerosols recognized as the 4<sup>th</sup> leading cause of premature death as well as a key agent in climate system (e.g. Lelieveld et al., Nature 525 367 (2015)).



From: H. Gordon (CERN 01.04.16)



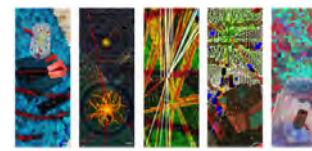
# CLOUD Experiment



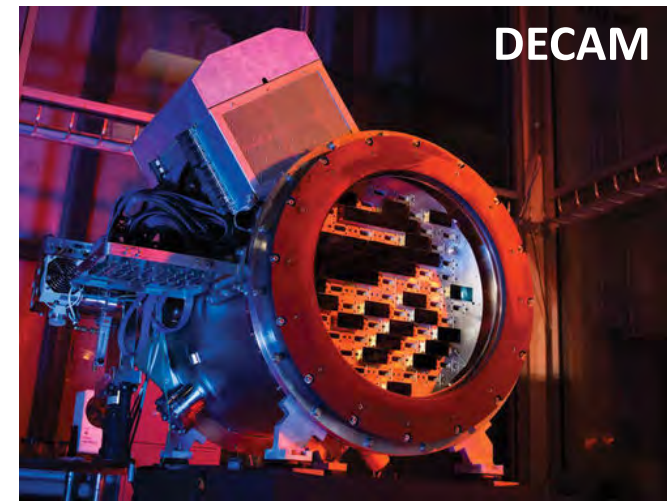
- Cosmics Leaving Outdoor Droplets (CLOUD) experiment at CERN
  - Understand aerosol formation with ions (from CERN test beams)
  - Study correlation between cosmic rays and global temperatures via aerosols
  - Study galactic cosmic rays and cloud formation (Nature 502, 359–363 (17 October 2013))



# HEP-Built Facilities

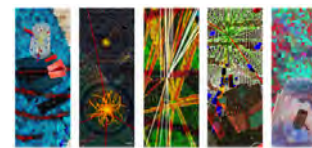


- Sky surveys
  - Cameras built by HEP in partnership with and for the benefit of particle astrophysics and the wider astronomy community: SDSS, DES, LSST
  
- Light sources: new lives for particle physics machines:
  - SLAC linac now drives the Linac Coherent Light Source (LCLS)
  - PETRA, where the gluon was discovered, now the PETRA III x-ray facility



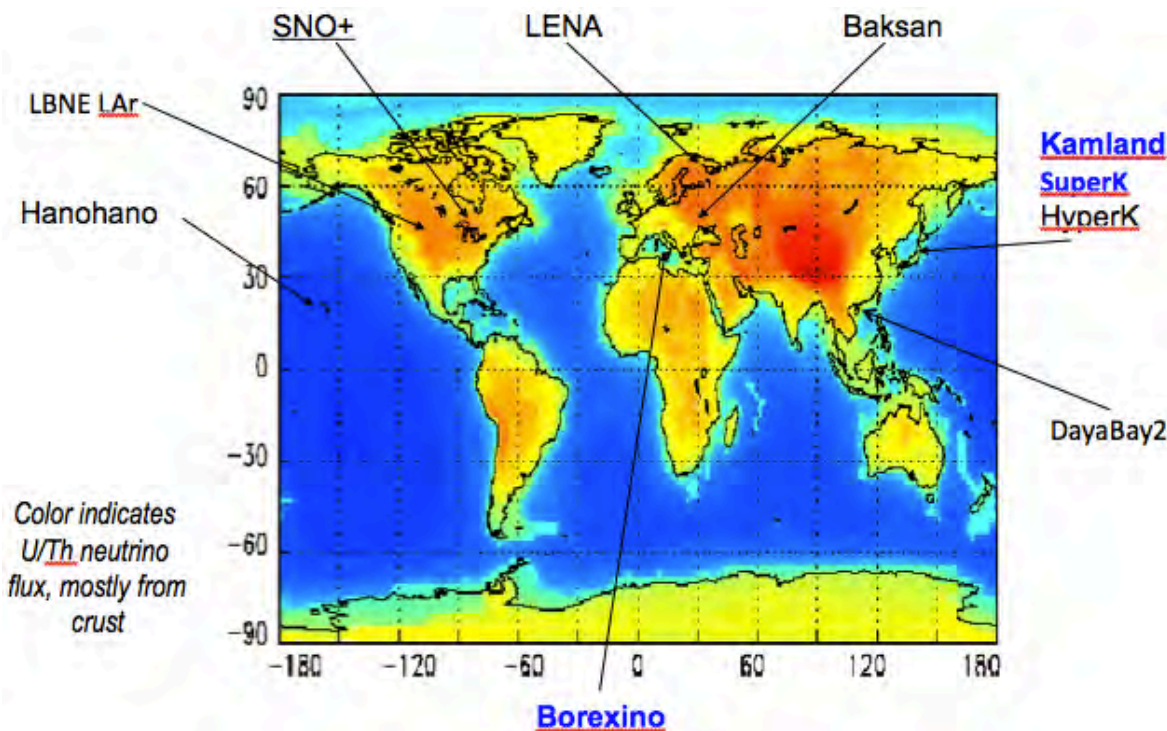
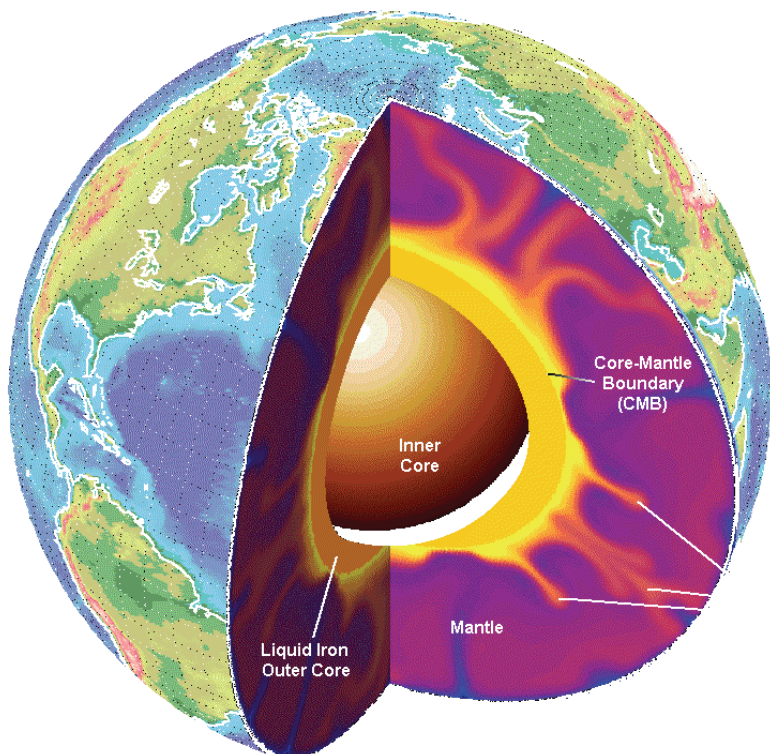


# Detectors for Geo-Neutrinos



- ❑ Understanding the center of the earth
- ❑ Total Heat Flow at surface  $47 \pm 2$  TW
  - Geology predicts 16-42 TW of radioactive power
    - ~20 % escapes to space as geoneutrinos
    - ~80 % heats planet

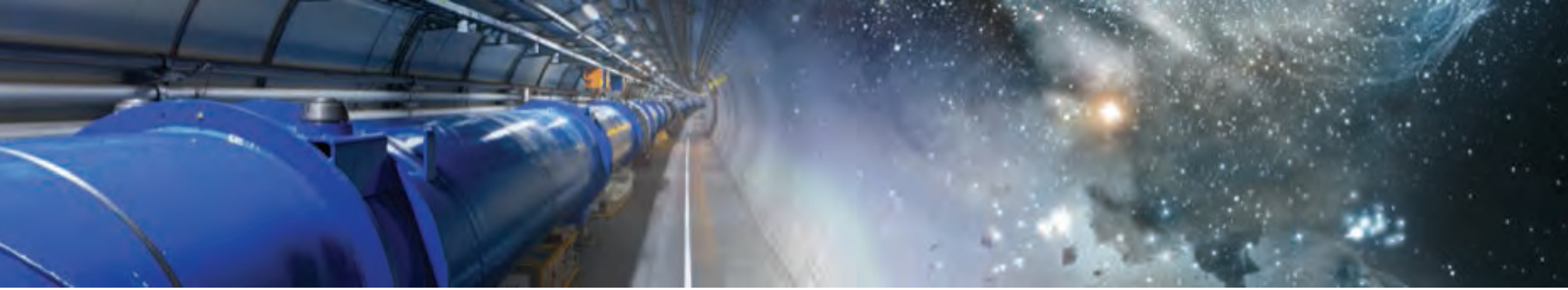
Present and possible experiments for geoneutrinos





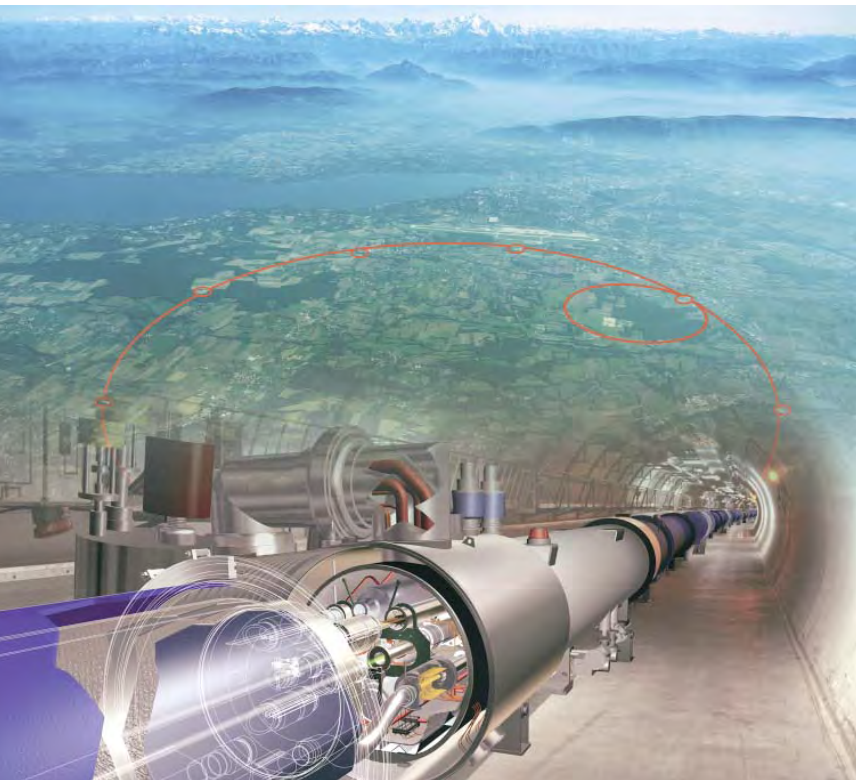
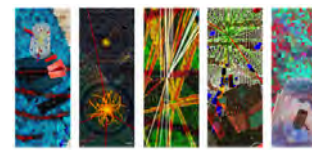




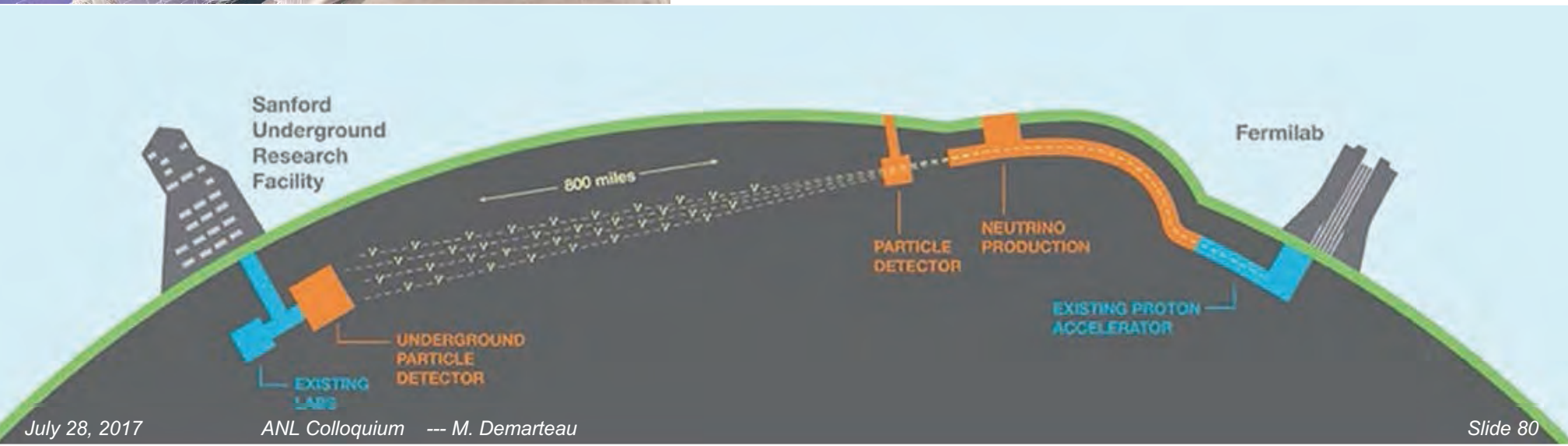


**Conclusion**

# Particle Physics Projects



- ❑ The Power of Collective Ownership.
- ❑ Sense of Trust, with mutual code of ethics
- ❑ Shared Vision
- ❑ Equal Learning Opportunity





# Particle Physics And Its Impact

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- ❑ ***Curiosity driven science research***
- ❑ ***Advances frontiers of technology, diffusing innovations to society in unexpected ways and improving our standard of living***
- ❑ ***Trains current and next generation scientists***
  - Champion of Science, Technology, Engineering, Mathematics
- ❑ ***Unites the world through science for peace***
  - CERN granted observer status to the United Nations General Assembly, 14 Dec 2012

