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

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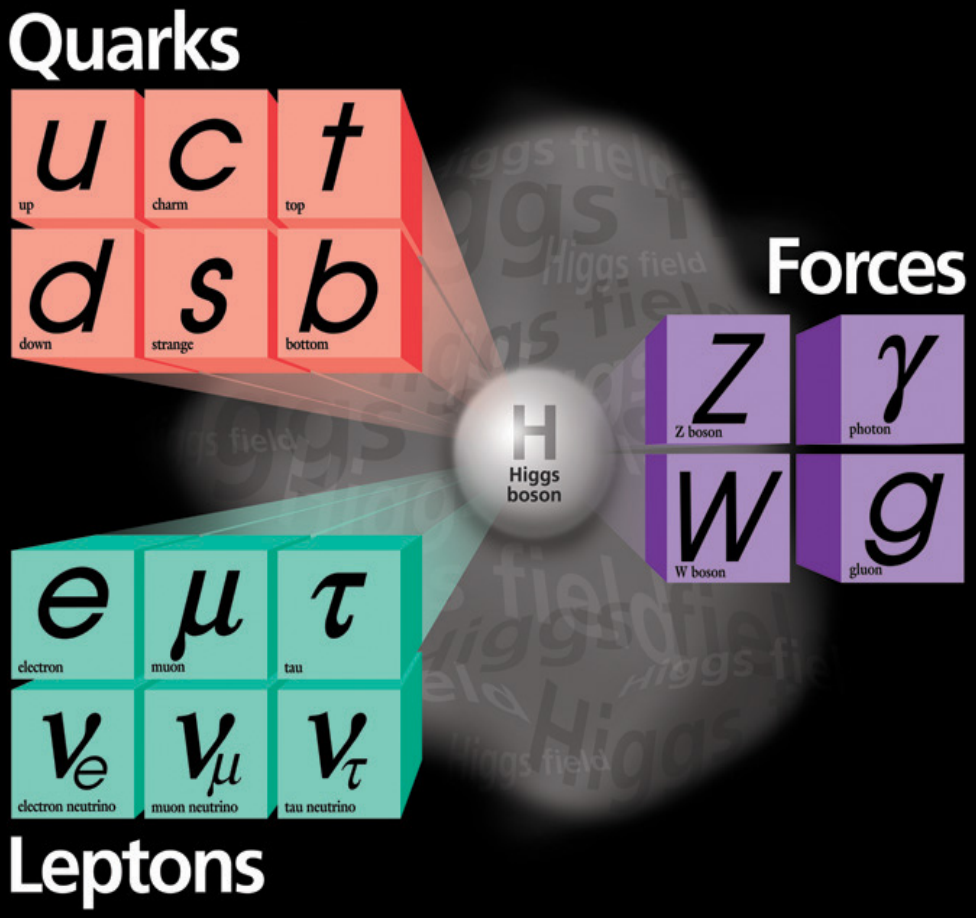
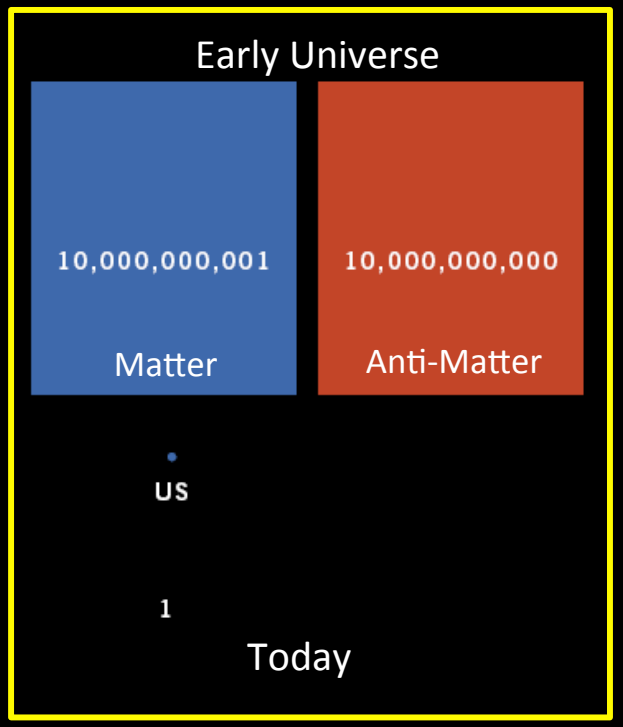
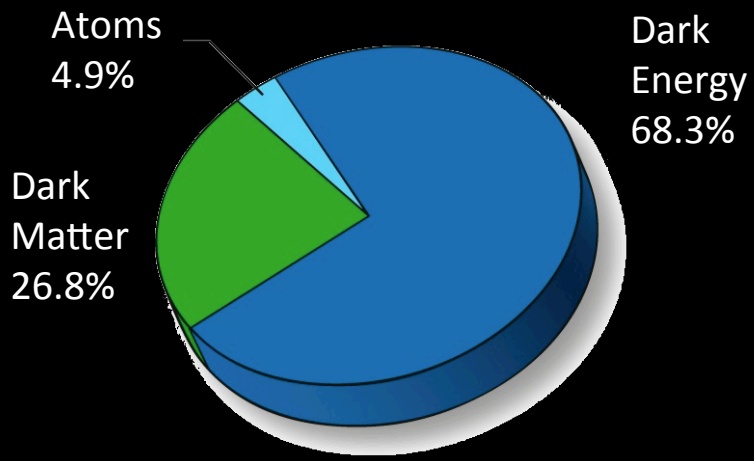
Fermilab Colloquium

August 31, 2016

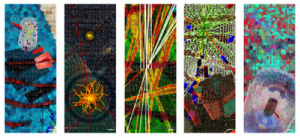
The Field of Particle Physics

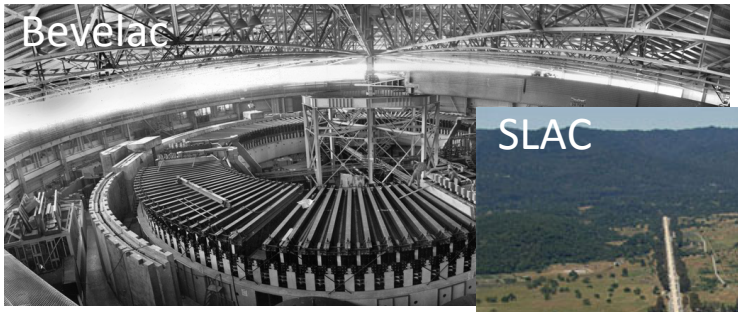






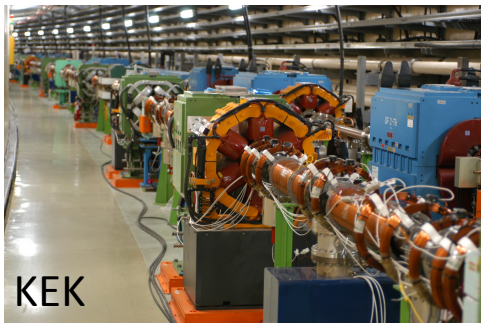
The Tools of Particle Physics





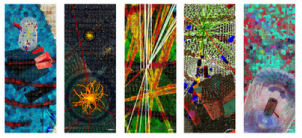
There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out.'

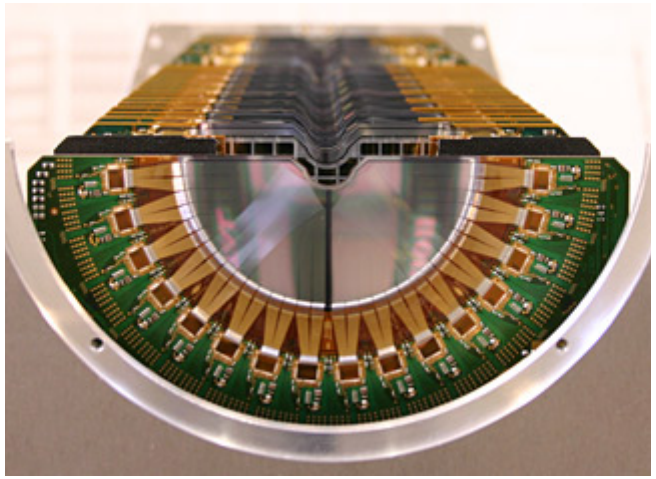
--Isaac Newton, Opticks (1704)



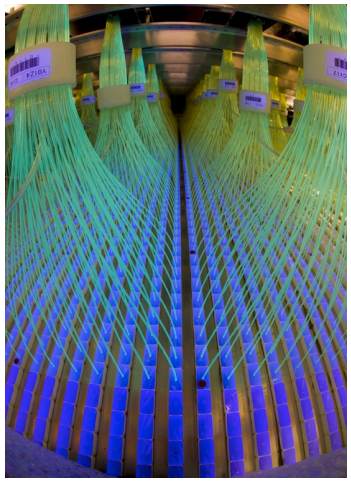
… to show a few

The Tools of Particle Physics

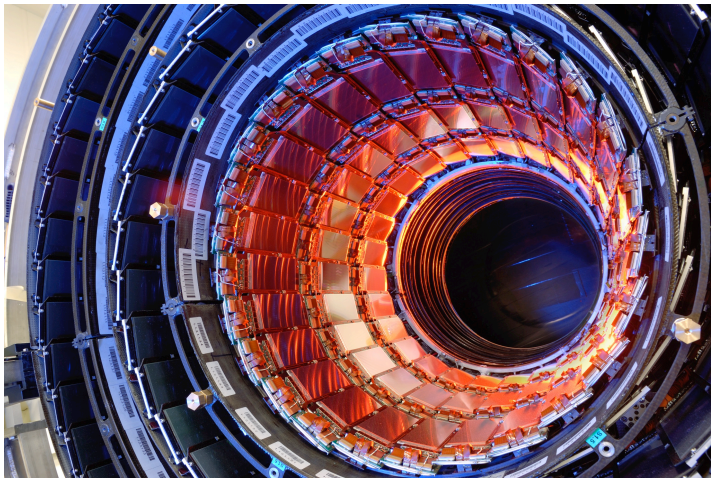




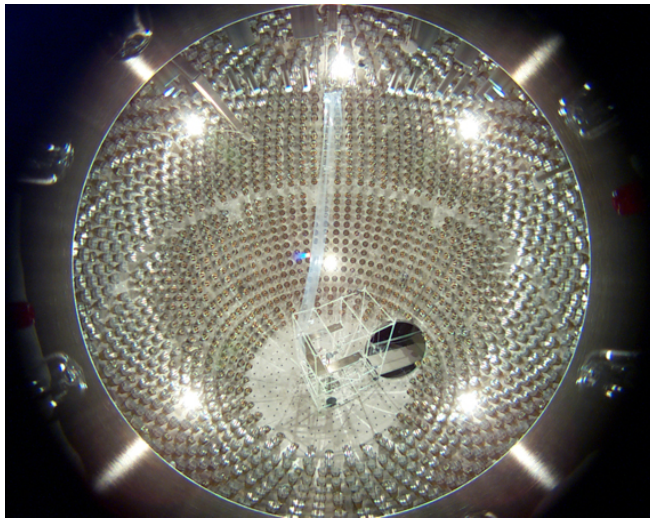
LHCb VELO



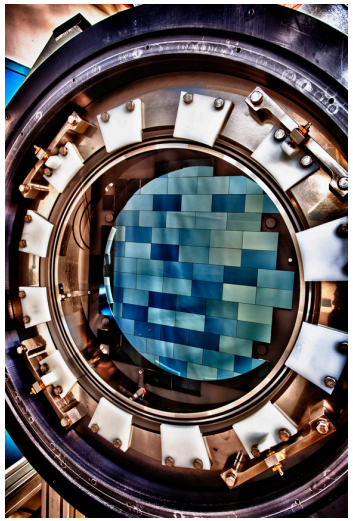
SciBoone SciBar



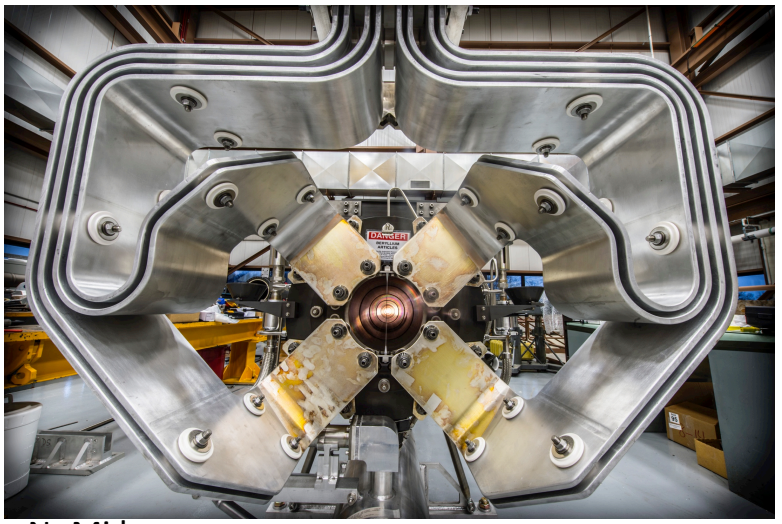
CMS TOB



Borexino

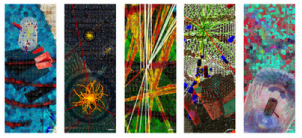


DES Decam

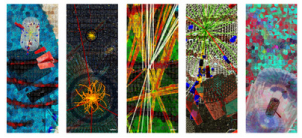


NuMi horn

The Tools of Particle Physics



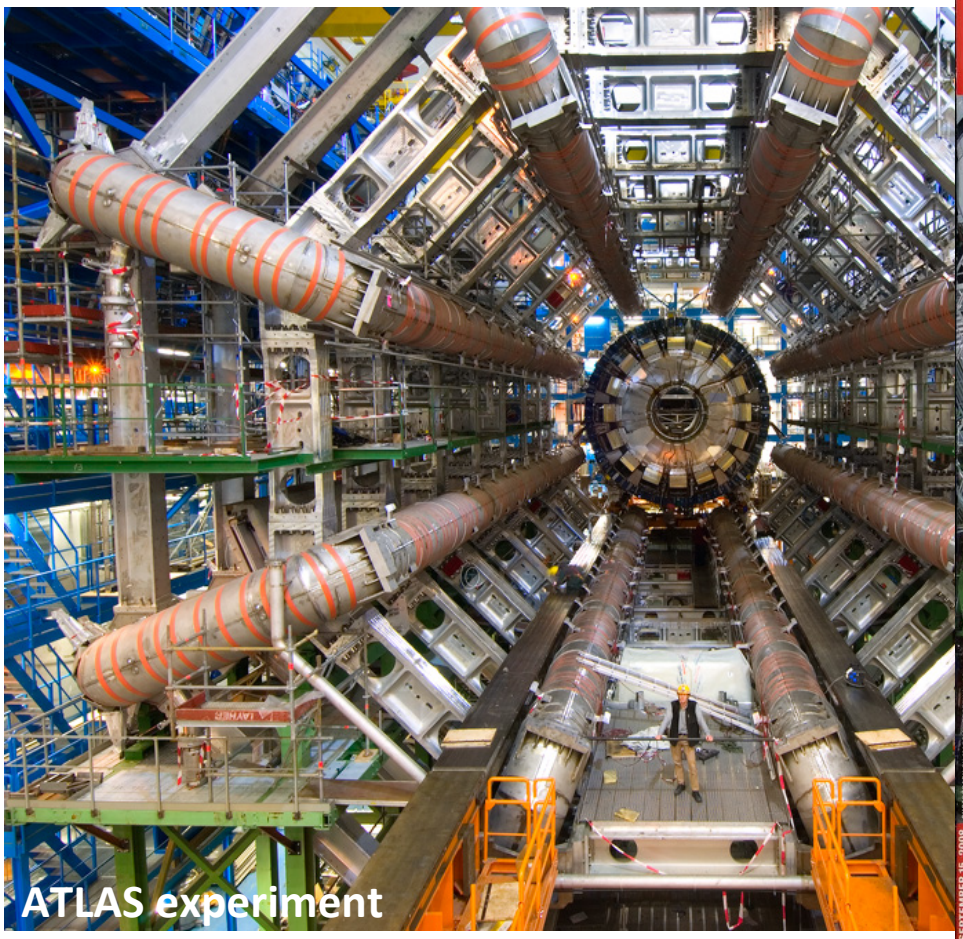
Particle Physics Culture



- **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 exists, 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 others research disciplines and ultimately society

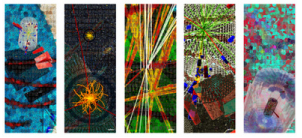
- **Particle physics has been a key driver for innovation !**

Particle Physics Experiments



Digital Cameras the Size of Cathedrals

Elements of Particle Physics Detectors



Radiation Damage

Very precise low-mass tracking

High Rate

Photon Measurement

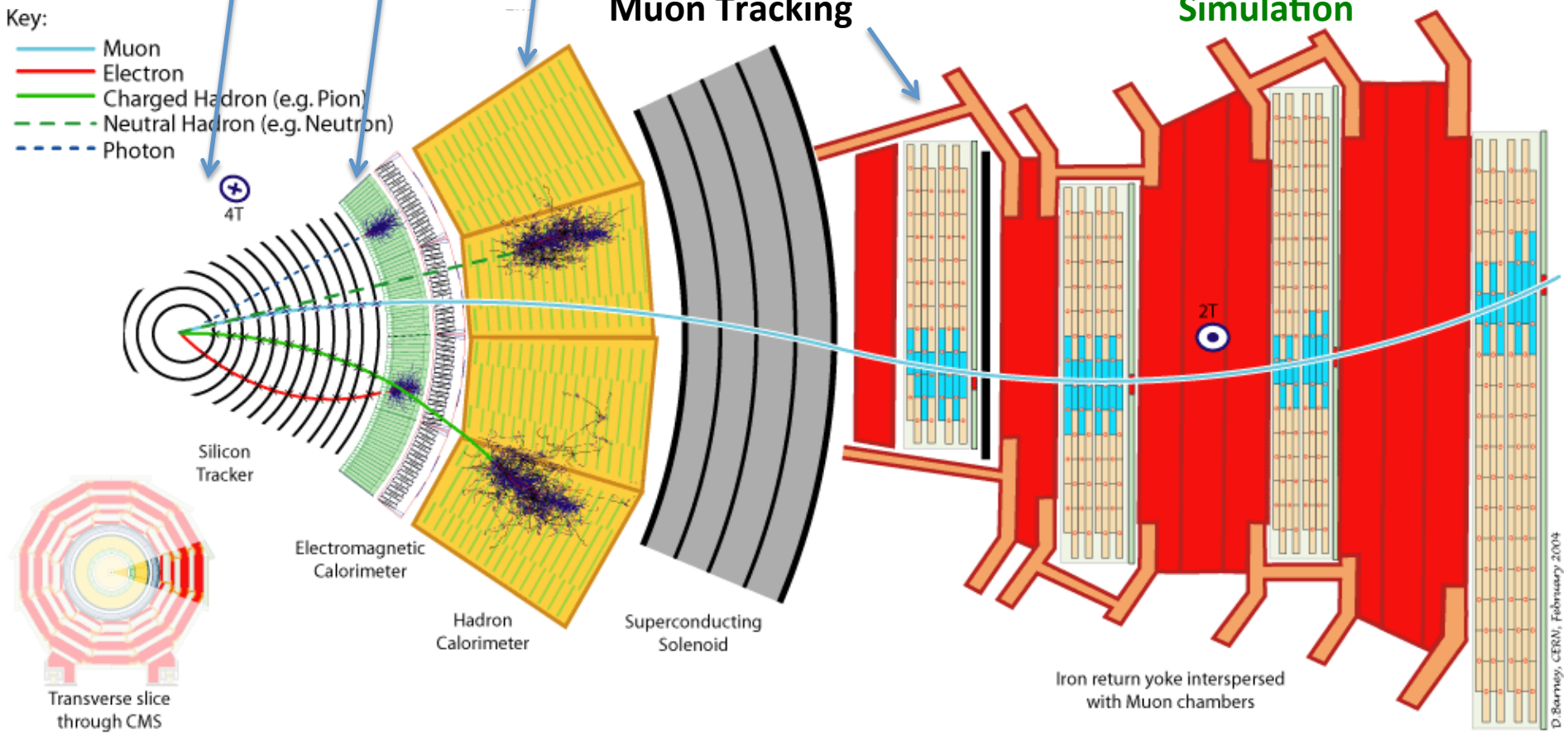
Big Data

Calorimetry

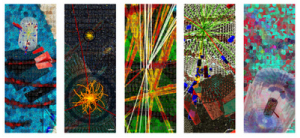
Compute Intensive

Muon Tracking

Simulation

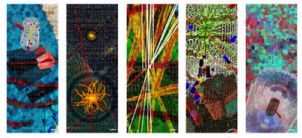


Web of Connections



- 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

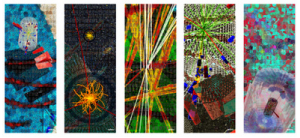


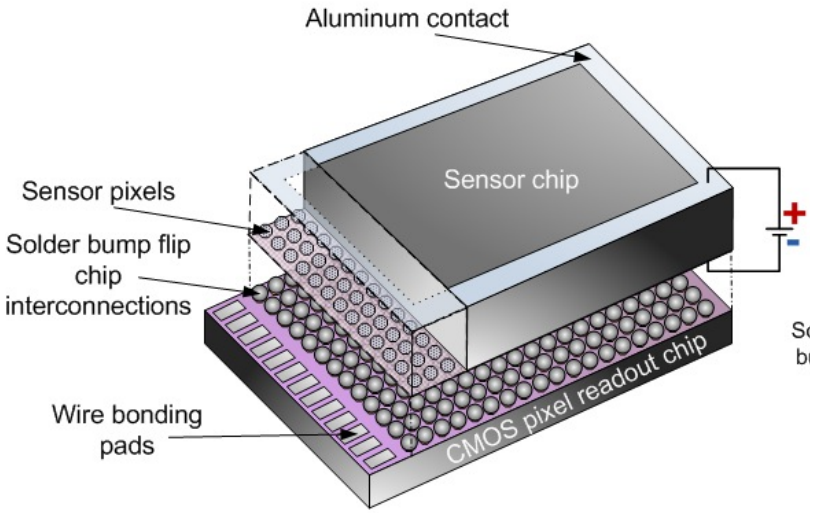
- Detector Technology
- Computing, Software and Data Management
- Accelerators and Particle Physics Facilities
- Cost Benefit Analysis
- Accelerating Technology Transfer
- Conclusions

Detector Technology

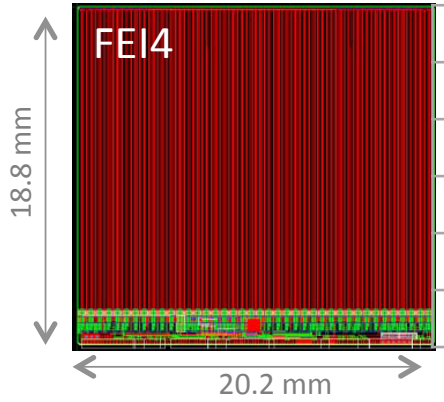
A major area of connections
of particle physics

Silicon Technology



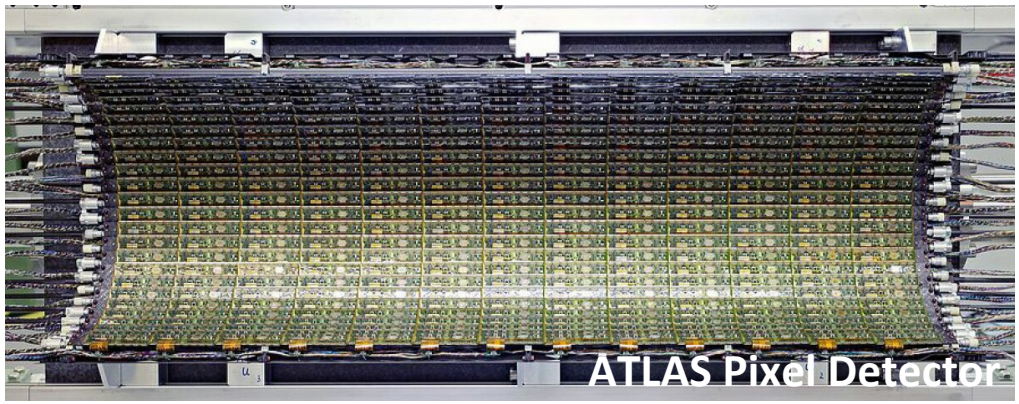


Application Specific Integrated Circuit

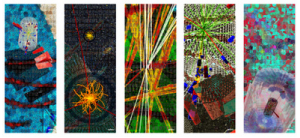


Pixel size	50x50 μm^2
Chip size	> 20x20 mm^2
Transistor count	500M – 1G
Technology	65 nm
Readout Rate	1 – 4 Gb/s
Trigger Rate	~ 1MHz

- The silicon detector and readout technology for particle detectors was enabled by the semi-conductor industry
- Particle Physics customized the technology and has taken it to unprecedented scale
- Realized through diagnostics measurements its applicability for x-ray detection

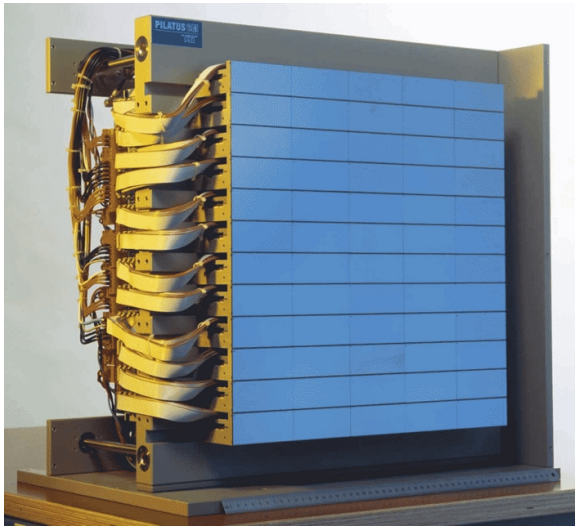


X-Ray Detectors



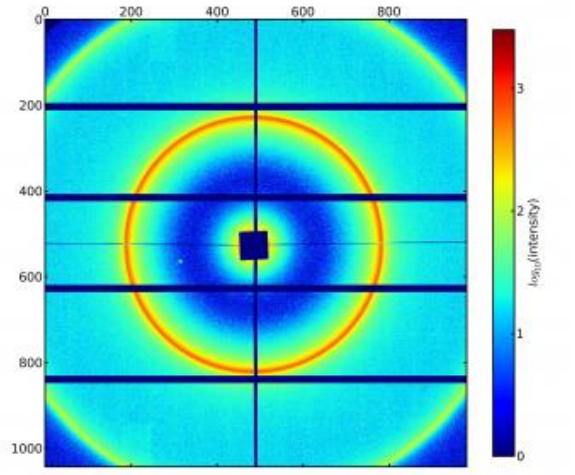
CMS Pixel detector

- 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



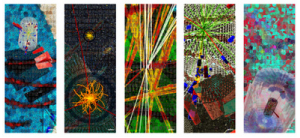
Photon Science Enabler

Greenland
Iceland
Finland
Sweden
Norway
Russia
United Kingdom
Poland
Canada
Ukraine
Kazakhstan
Mongolia
France
Italy
Spain
Turkey
China
South Korea
United States
North Atlantic Ocean
Afghanistan
Iraq
Iran
Pakistan
Algeria
Libya
Egypt
Saudi Arabia
India
Thailand
Mexico
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DR Congo
Tanzania
Indonesia
Papua New Guinea
Brazil
Peru
Angola
Bolivia
Namibia
Botswana
Madagascar
Indian Ocean
Australia
Chile
South Pacific Ocean
South Atlantic Ocean
South Africa
Argentina
New Zealand

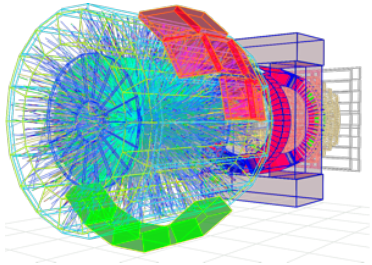
User
OEM Partner

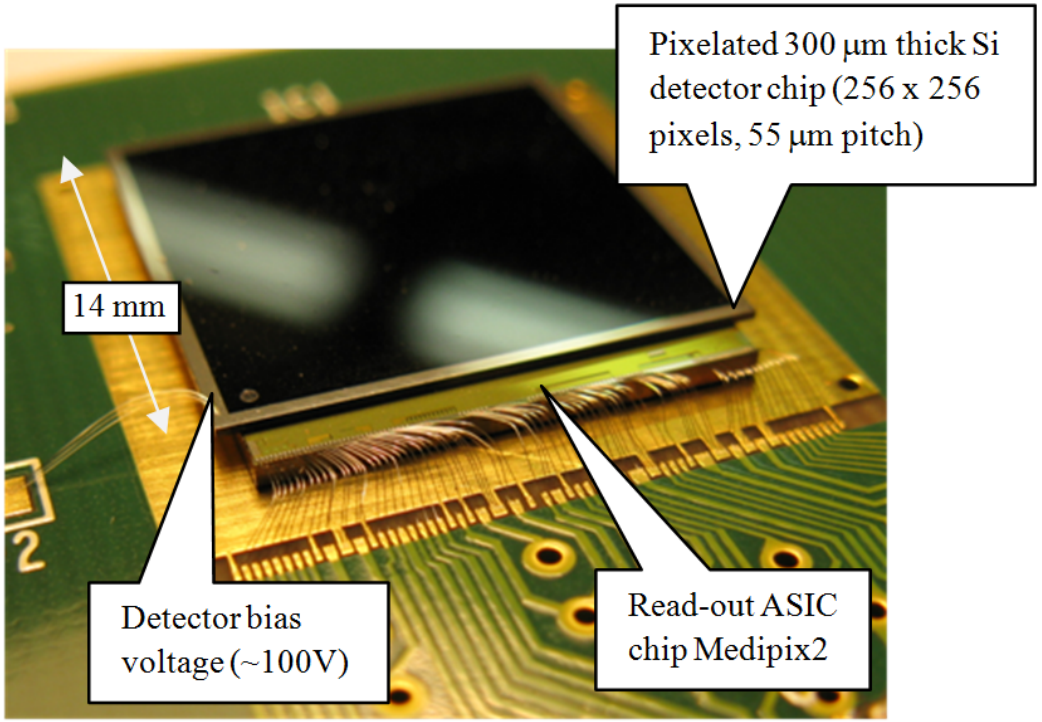
Nearly all Light Sources use DECTRIS devices

MediPix and TimePix

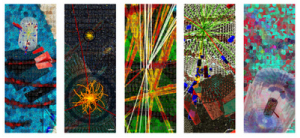


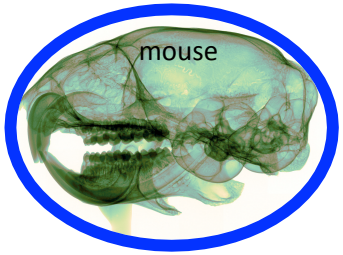
- Development of an ASIC for the ALICE experiment at the LHC at CERN led to the development of an imaging application:
  - Medipix: single photon counting ASIC
  - Timepix: added time measurement
  - Medipix3: counts photons with energy thresholds and timing



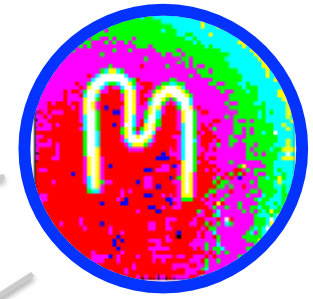


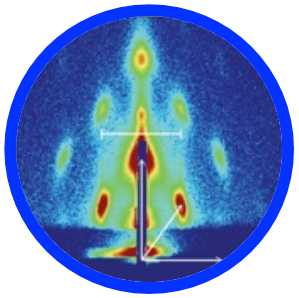
MediPix and TimePix



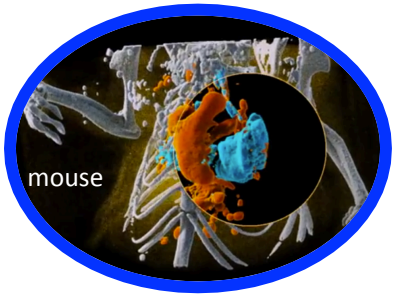


X-ray Imaging





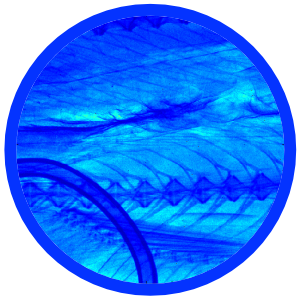
Grazing Incidence SAXS



In vivo 3D tomography

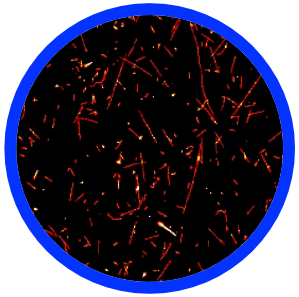
Dosimetry on International Space Station

X-ray Fluorescence

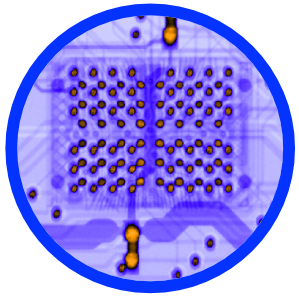


Small-angle X-ray Scattering (SAXS)

X-ray diffraction
2011 R&D 100 award

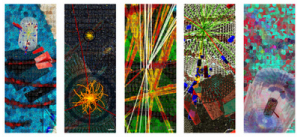


Particle monitoring



Non-destructive materials testing

Companies Using MediPix / TimePix



ADVACAM Imaging the Unseen www.advacam.com/

mars Medipix All Resolution System http://www.marsbioimaging.com/

AMSTERDAM SCIENTIFIC INSTRUMENTS http://www.amscins.com/

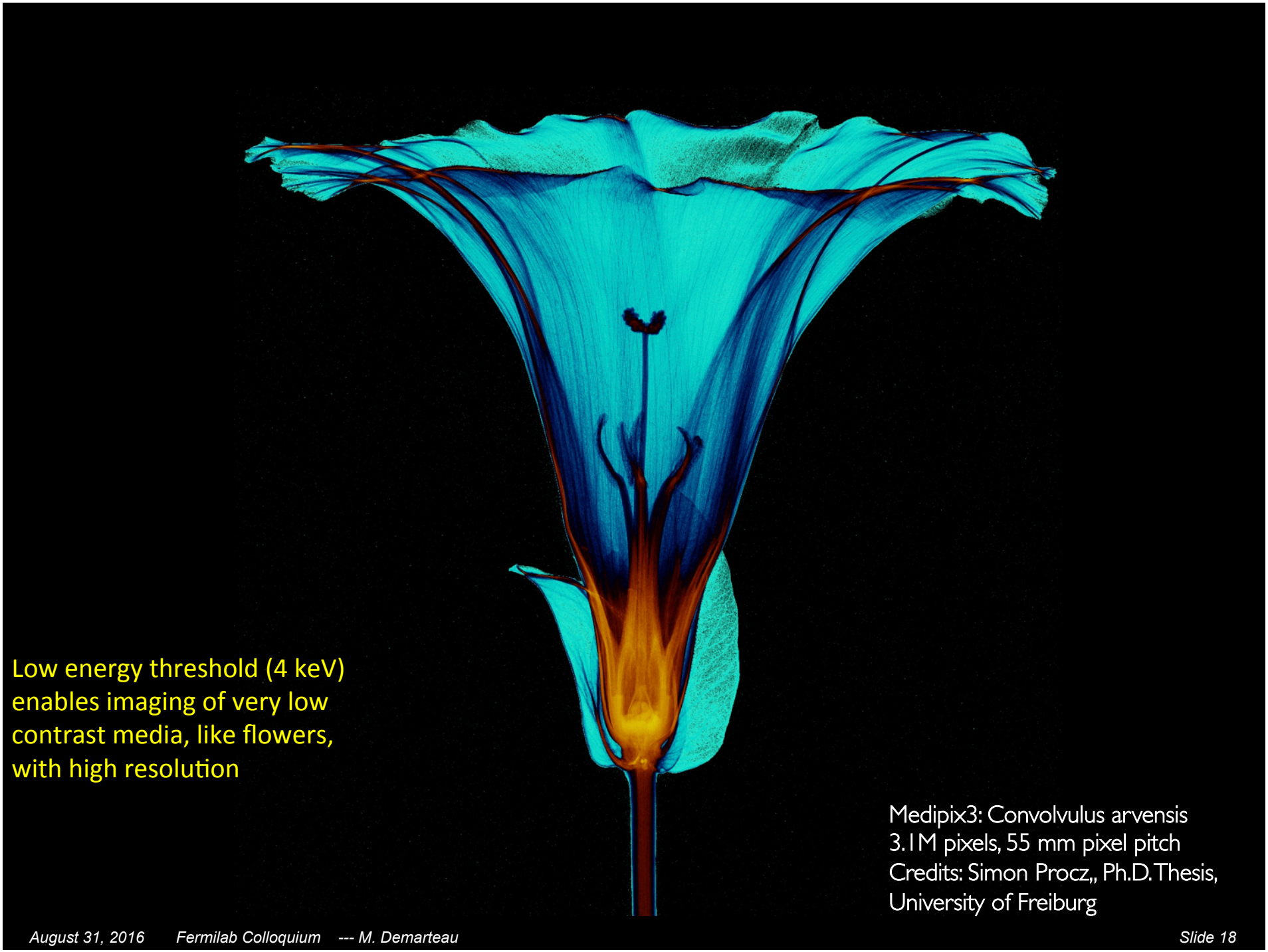
X-RAY IMAGING EUROPE http://www.xi-europe.com/

Plus Light and Neutron Sources

JABLOTRON CREATING ALARMS http://www.jablotron.com/

XRAY IMATEK PHOTON COUNTING DETECTORS http://xray-imatek.com/

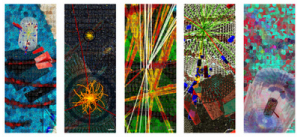
Quantum DETECTORS http://quantumdetectors.com/



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

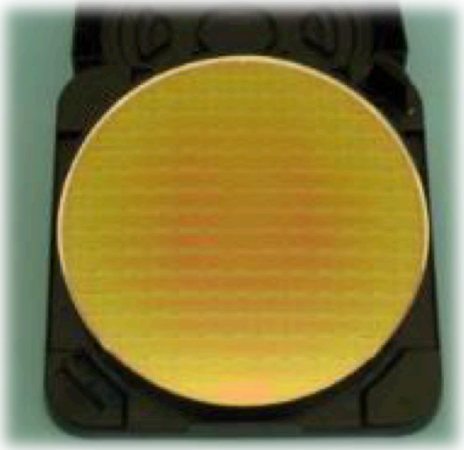
Medipix3: Convolvulus arvensis
3.1M pixels, 55 mm pixel pitch
Credits: Simon Procz,, Ph.D. Thesis, University of Freiburg

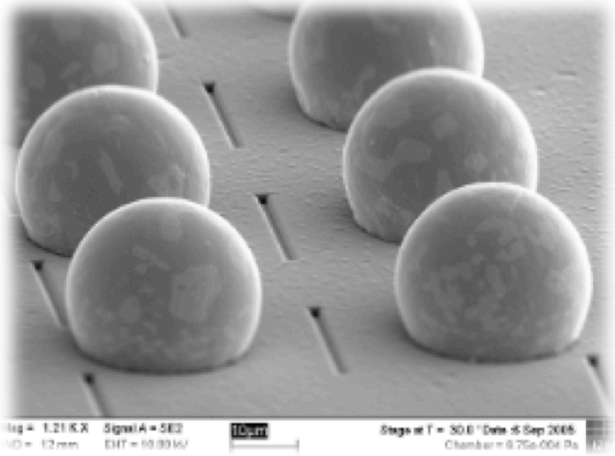
Ultra-Fine Pitch Bonding

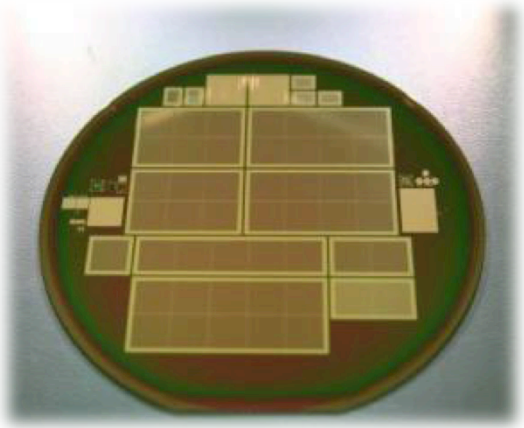


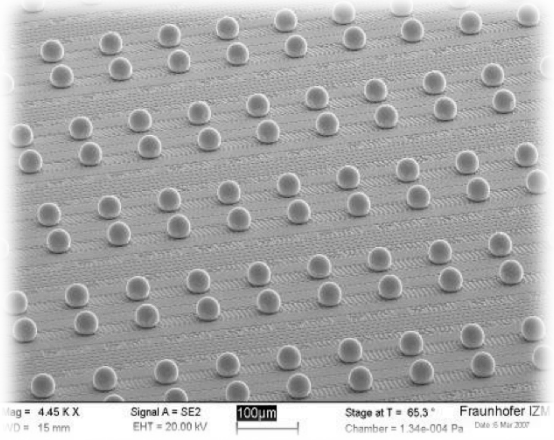
- Electrically connecting the sensor to the readout at ultra-fine pitch, high density; particle physics drives technology to scale and technical limits

- 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

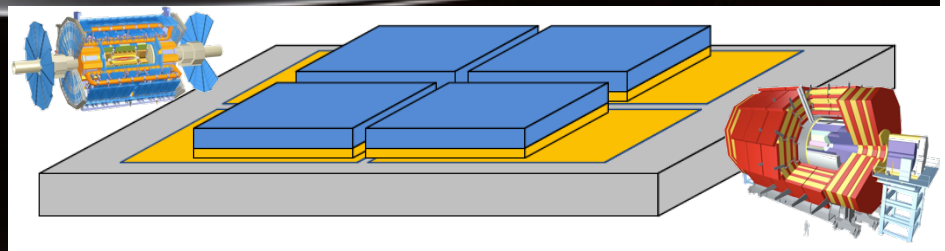
Fraunhofer

DAIMLER

OSRAM

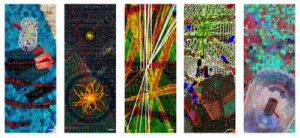
Infineon

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

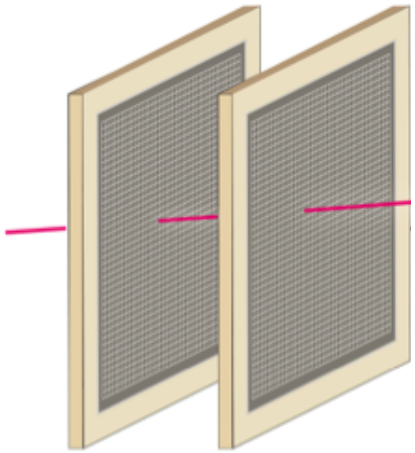


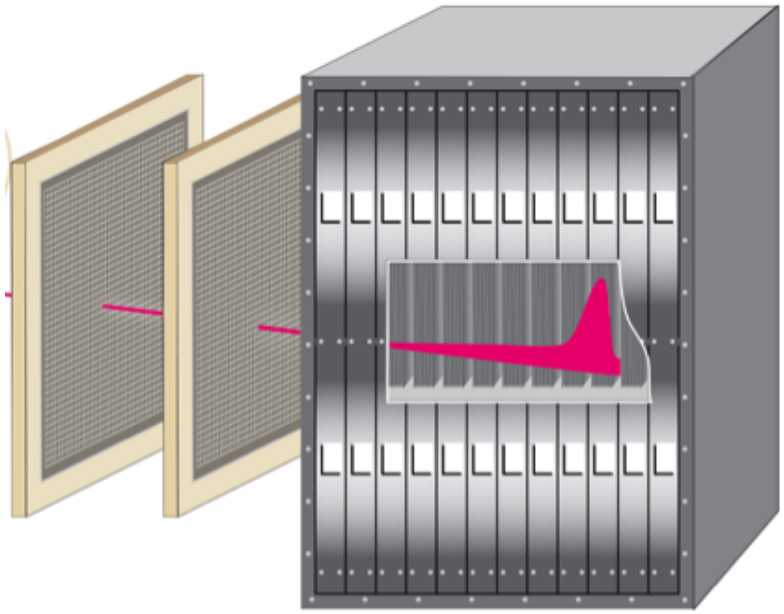

Adaptive LED Headlights
Fraunhofer
DAIMLER
OSRAM
Infineon
Sorry, only available on
high-end luxury cars
(comfort: not allowed in the US)

Tracking and Calorimetry



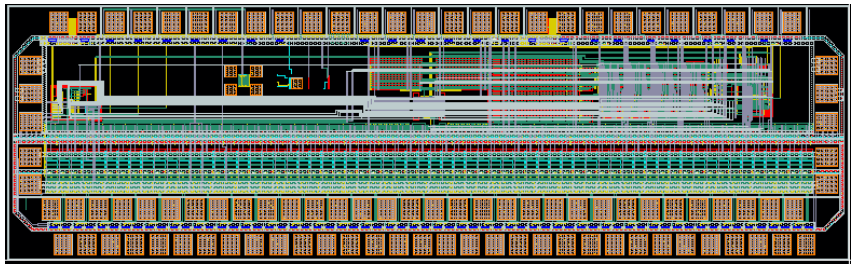
- Proton Computed Tomography (Proton Therapy): correlate the measured E-loss with the path of the proton through the patient





Tracking Detectors
Silicon Strips / Scintillating Fibers

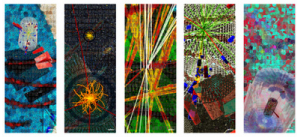
High-grained Imaging Ranging Calorimeter
Scintillator, RPC, GEM



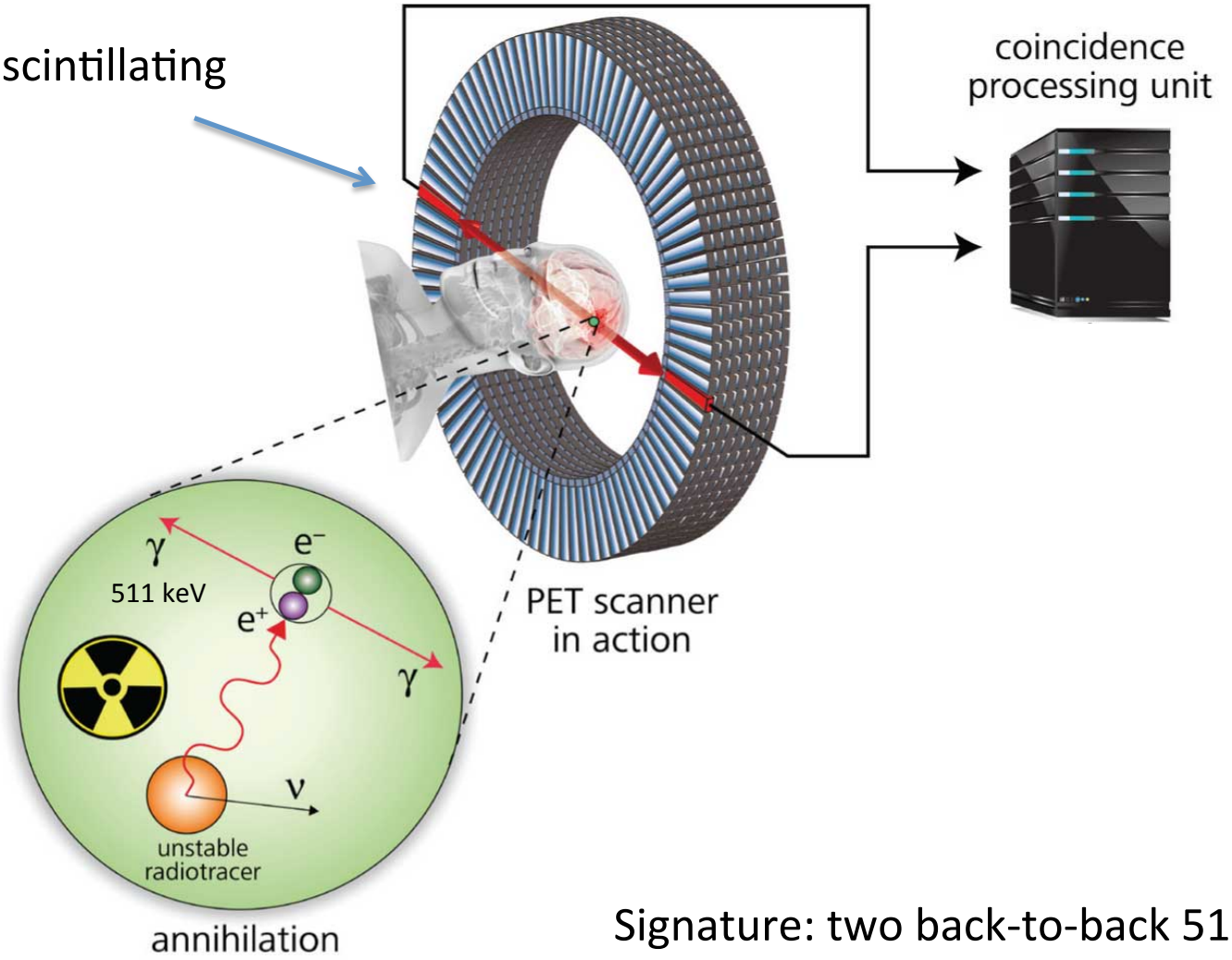
Readout adapted after Si strip readout for FERMI/GLAST experiment

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

Positron Emission Tomography

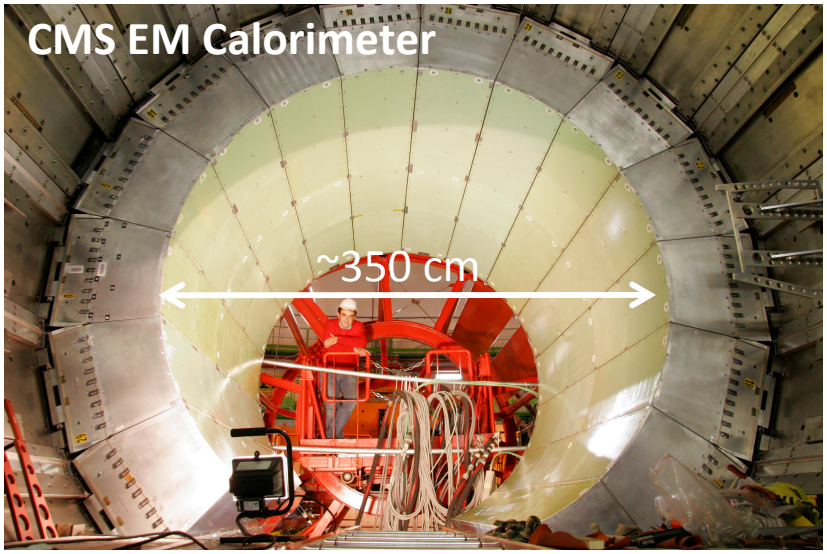


Array of scintillating crystals



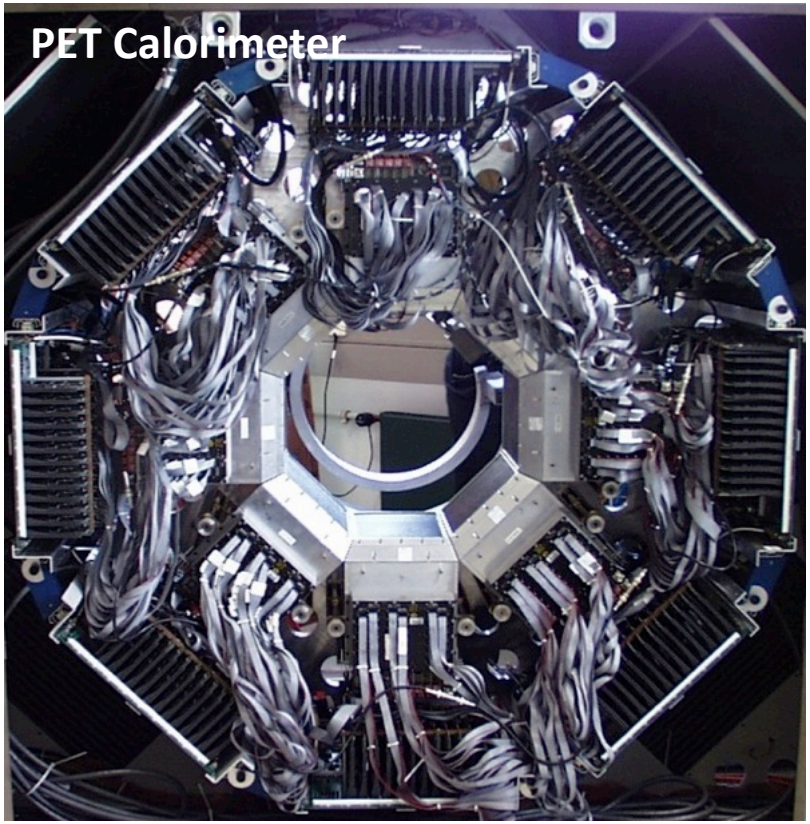
Signature: two back-to-back 511 keV γ's

Calorimetry



$H \rightarrow \gamma\gamma$

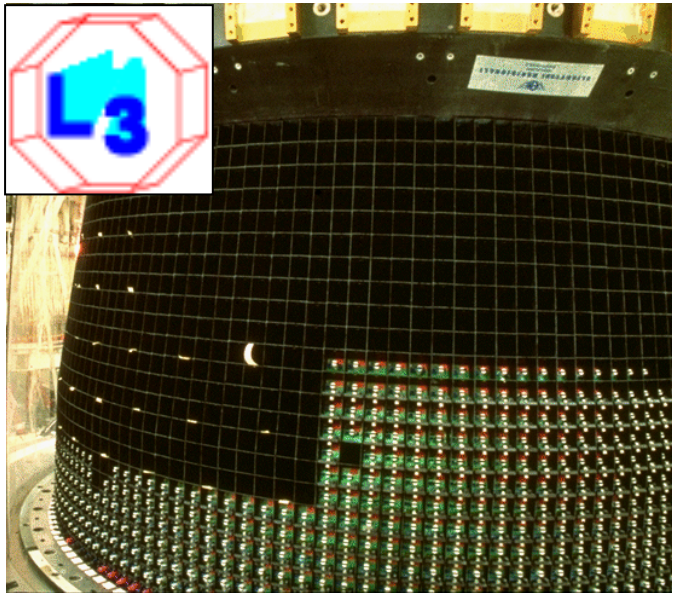
~80,000 $PbWO_4$ crystals



< 1,000 BGO, LSO, LYSO crystals

First PET scanners used BGO

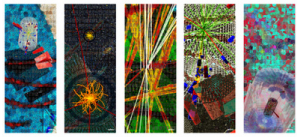
BGO Crystal Development

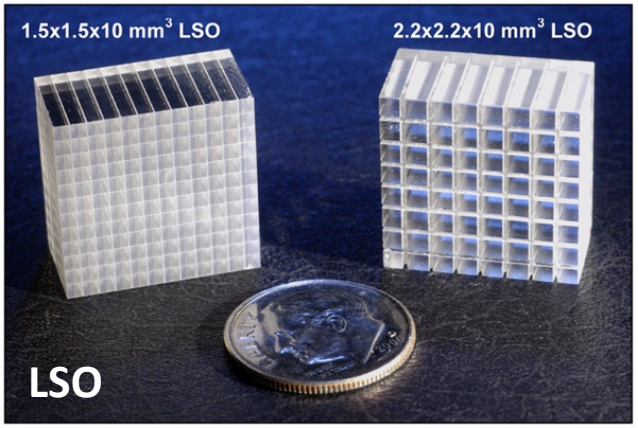


- The L3 experiment at LEP built the 1st BGO crystal calorimeter consisting of 11,400 BGO crystals with total volume of 1.5 m^3
- Led Shanghai Institute for Ceramics (SIC) to the multi-crucible growth technology allowing growth of up to 36 crystal ingots per oven

- 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

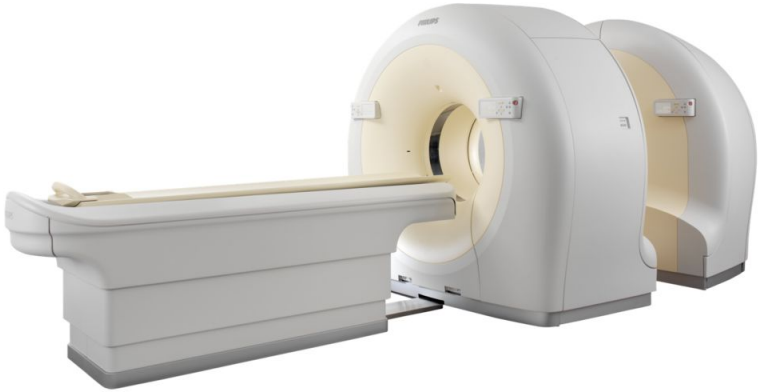




- LSO (Lutetium Orthosilicate) crystals invented and developed at Schlumberger (Charles Melcher)

- Radiation damage studies of Lead Tungstate (PWO) crystals for CMS at the LHC showed that yttrium doping was effective to improve crystal radiation hardness.

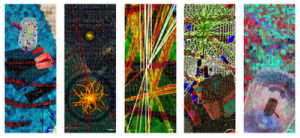
Philips GEMINI TF PET/CT



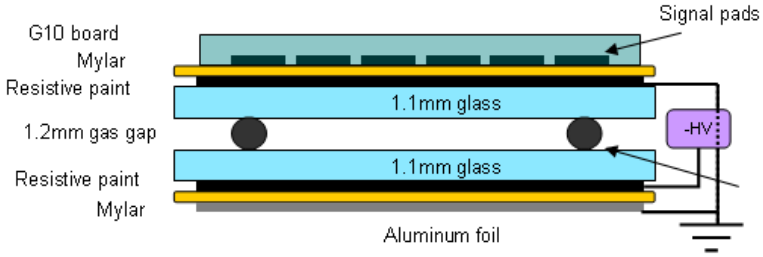
LYSO crystals: 4x4x22mm

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

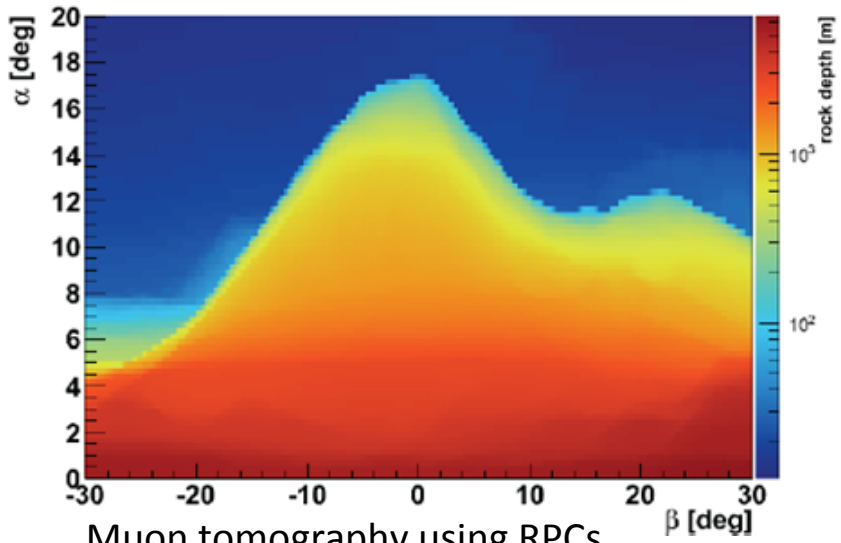
Environment



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



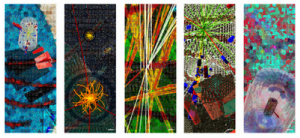
The Puy de Dome (Massive central)



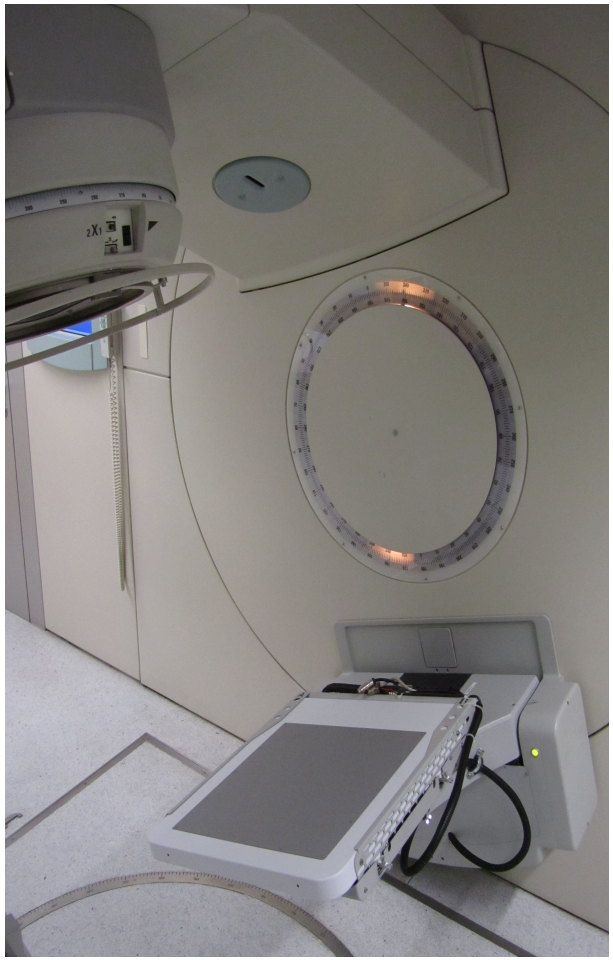
Muon tomography using RPCs (Tomuvol experiment)

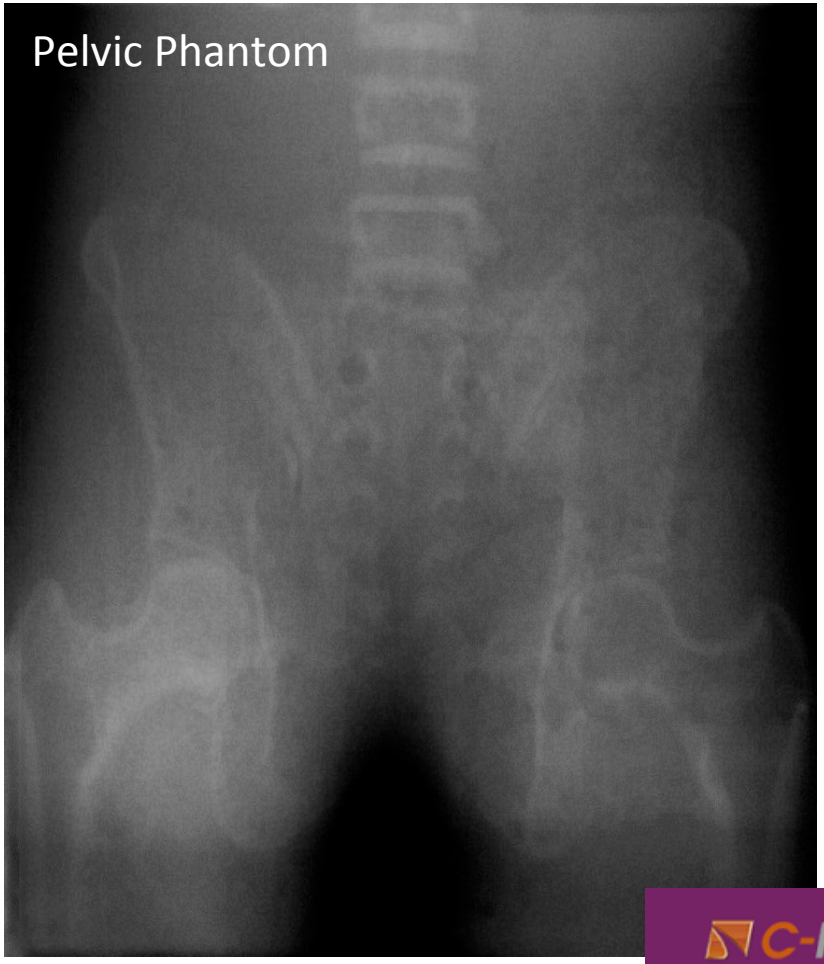
- Similar measurements planned at Stromboli and Vesuvius (Mu-Ray Project) using scintillator tiles and Silicon Geiger-mode Photo-Multipliers
- Scintillator strips and Cherenkov counters used for imaging Maya ruins

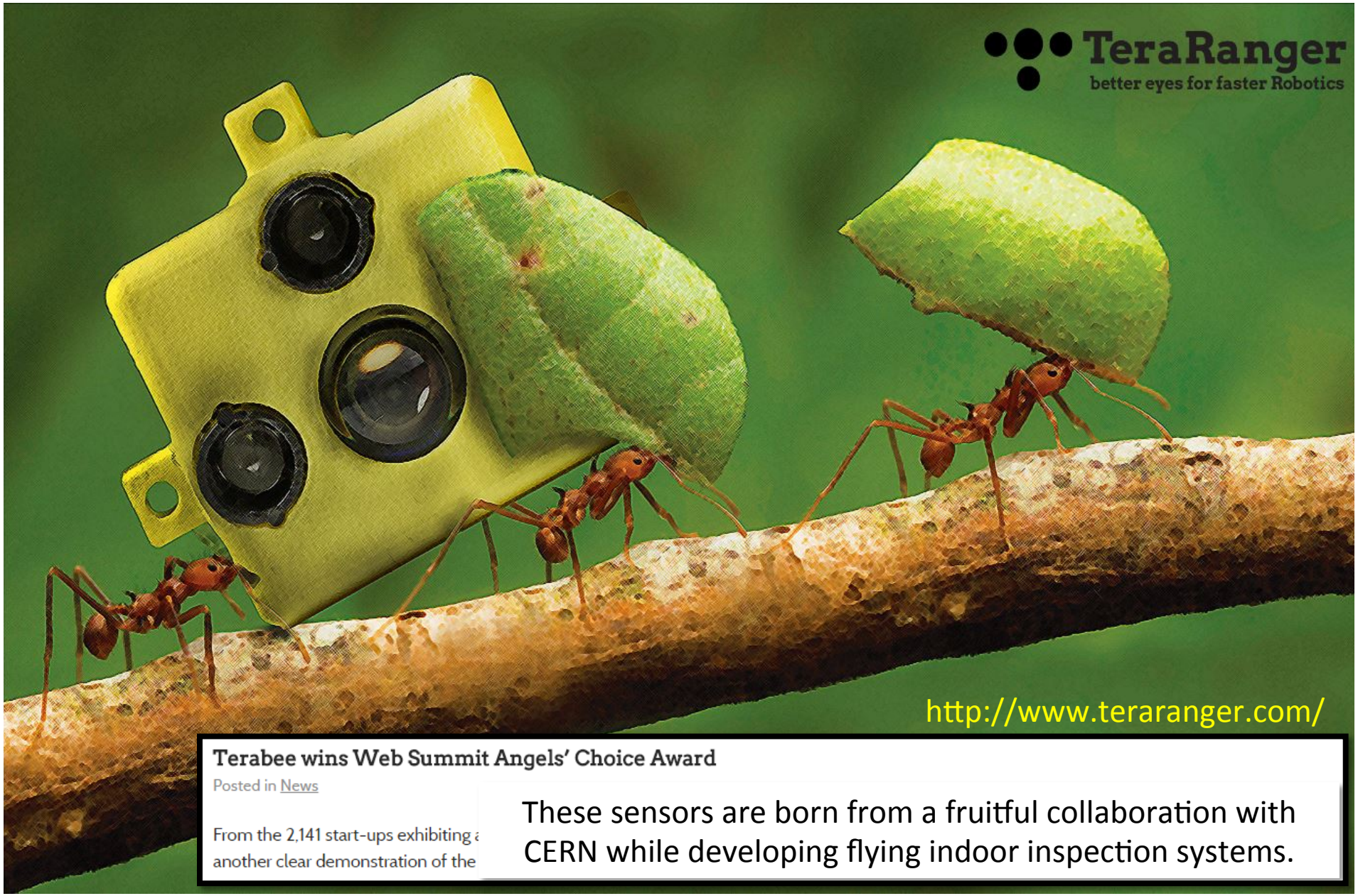
X-Ray Imaging



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

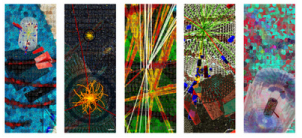


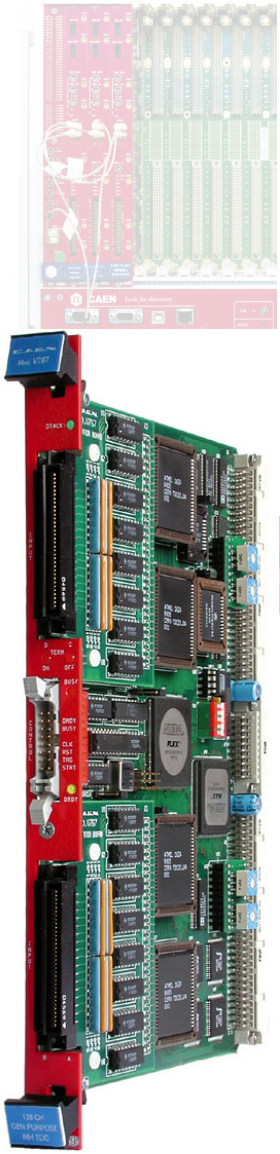


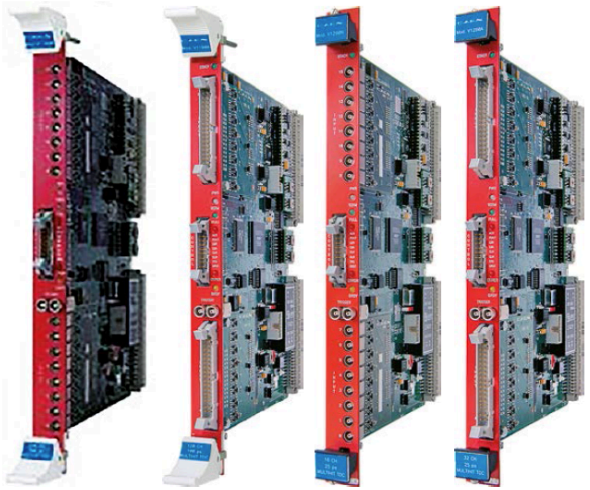


How to locate equipment in the LHC tunnel where there is no GPS signal

Industry Collaboration



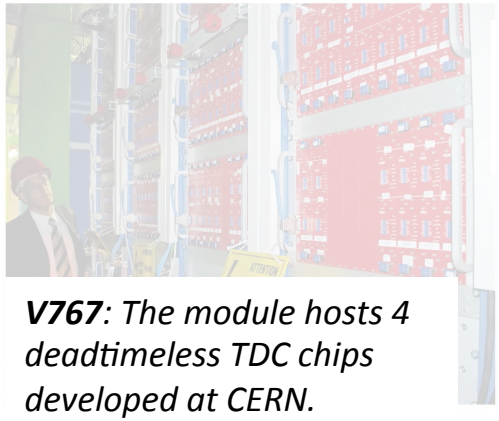




V1290-2eSST Family

" The units features High Performance Time to Digital Converter chips developed by CERN."

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

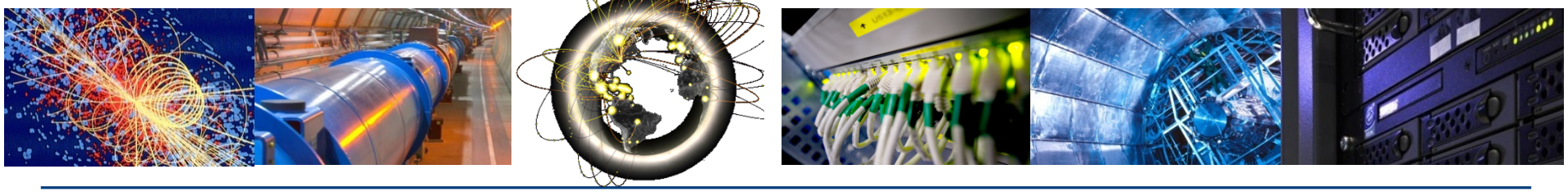


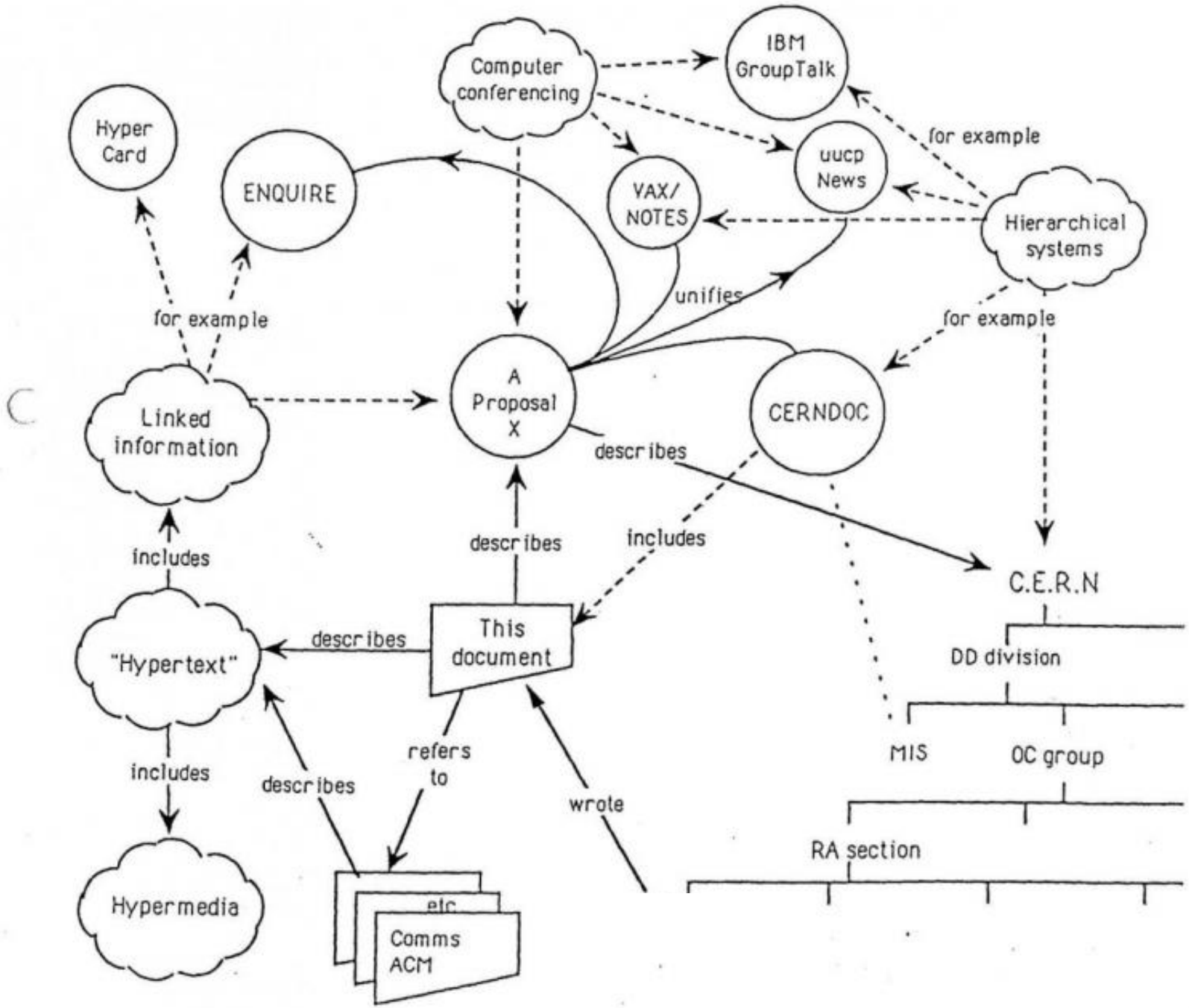
***V767**: The module hosts 4 deadtimeless TDC chips developed at CERN.*

CAEN
Tools for Discovery

Computing, Software, Data Management

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



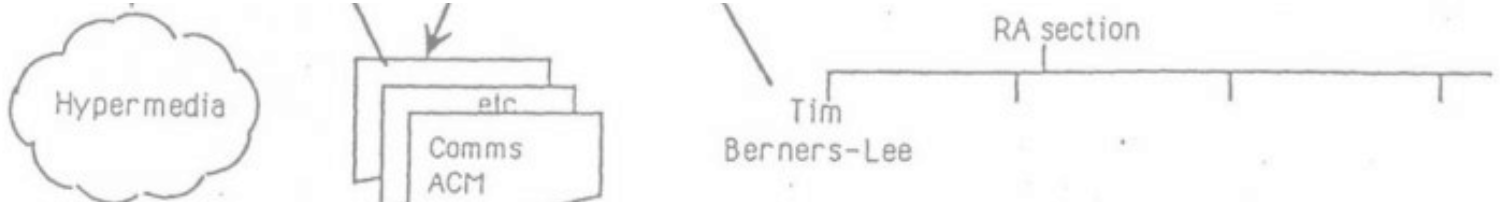

Computer conferencing
IBM GroupTalk
Hyper Card
ENQUIRE
uucp News
VAX/ NOTES
for example
Hierarchical systems
unifies
for example
for example
A Proposal X
CERNDOC
Linked information
describes
includes
describes
includes
C.E.R.N
"Hypertext"
describes
This document
DD division
MIS
OC group
includes
refers to
describes
wrote
RA section
Hypermedia
etc
Comms ACM

Cover Page of a 10-page proposal titled:

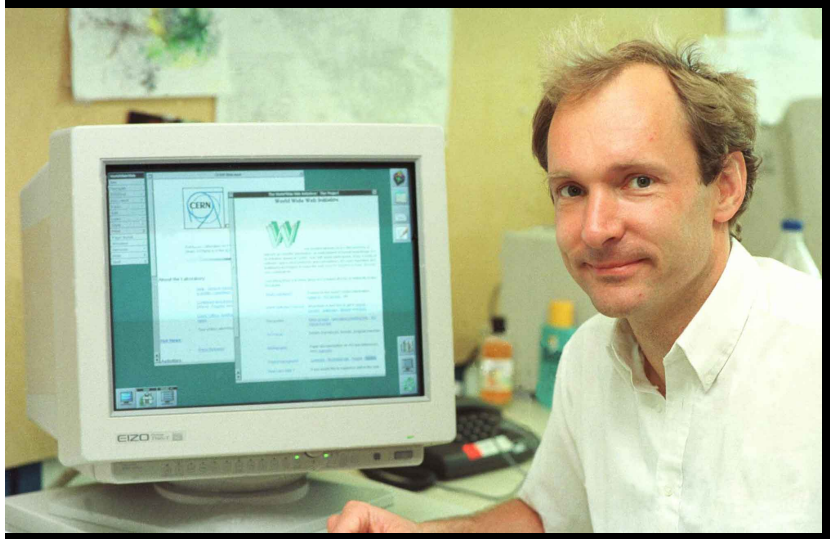
Information Management: A Proposal

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.

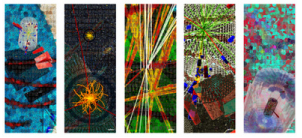


http://home.cern/about/updates/2014/03/world-wide-web-born-cern-25-years-ago



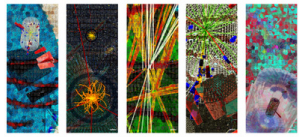
On 30 April 1993 CERN put the World Wide Web software in the public domain and made the release available with an open license, as a more sure way to maximise its dissemination, enabling the web to flourish.

Petabytes and Petaflops

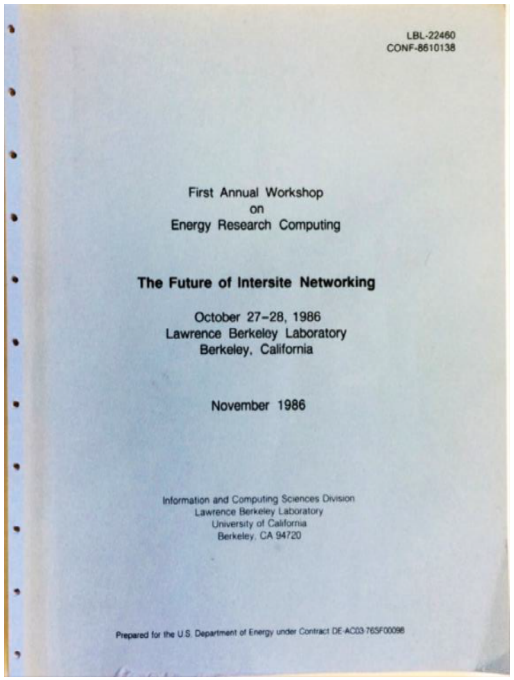


The LHC Data Challenge was recognized very early

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."



LBL-22460
CONF-8610138

First Annual Workshop
on
Energy Research Computing

The Future of Intersite Networking

October 27–28, 1986
Lawrence Berkeley Laboratory
Berkeley, California

November 1986

Information and Computing Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

1986 workshop on:
"The Future of Intersite Networking"

1st ANNUAL WORKSHOP ON ENERGY RESEARCH COMPUTING

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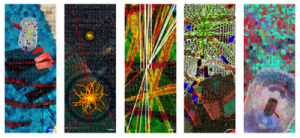
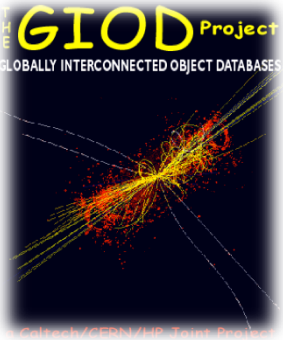
STEVE@BRL.ARPA,

From Barb Helland, HEPAP Meeting, April 1, 2016

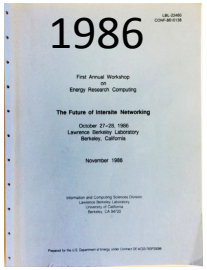
Evolution of Grids





Globally Interconnected Object Databases (GIOD, ~1997)

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


1986

First Annual Workshop on Energy Research Computing

The Future of Interste Networking

October 27-28, 1986
Lawrence Berkeley Laboratory
Berkeley, California

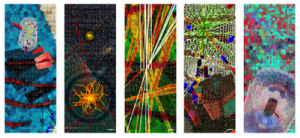
November 1986

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

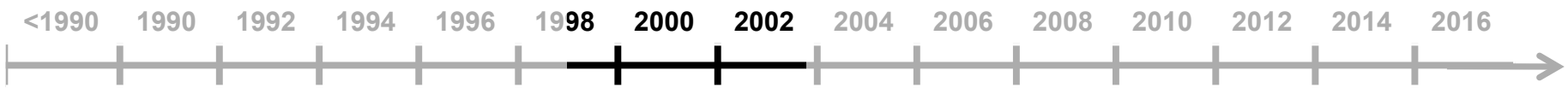


Particle Physics Data Grid (PPDG, 1999)

Grid Physics Network (GriPhyN, 2000)

International Virtual Data Grid Laboratory (iVDGL, 2002)

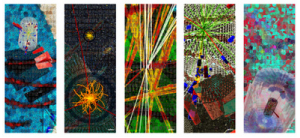
Trillium: GriPhyN + iVDGL + PPDG



"Embryonic Grid" **"Grid Era Begins"**

Strong collaboration with European efforts

Science Grids



DataTAG

Data GRID

eGee Enabling Grids for E-sciencE

the globus project™ www.globus.org

CROSSGRID

GRIP UK Particle Physics

.....

WLCG Worldwide LHC Computing Grid

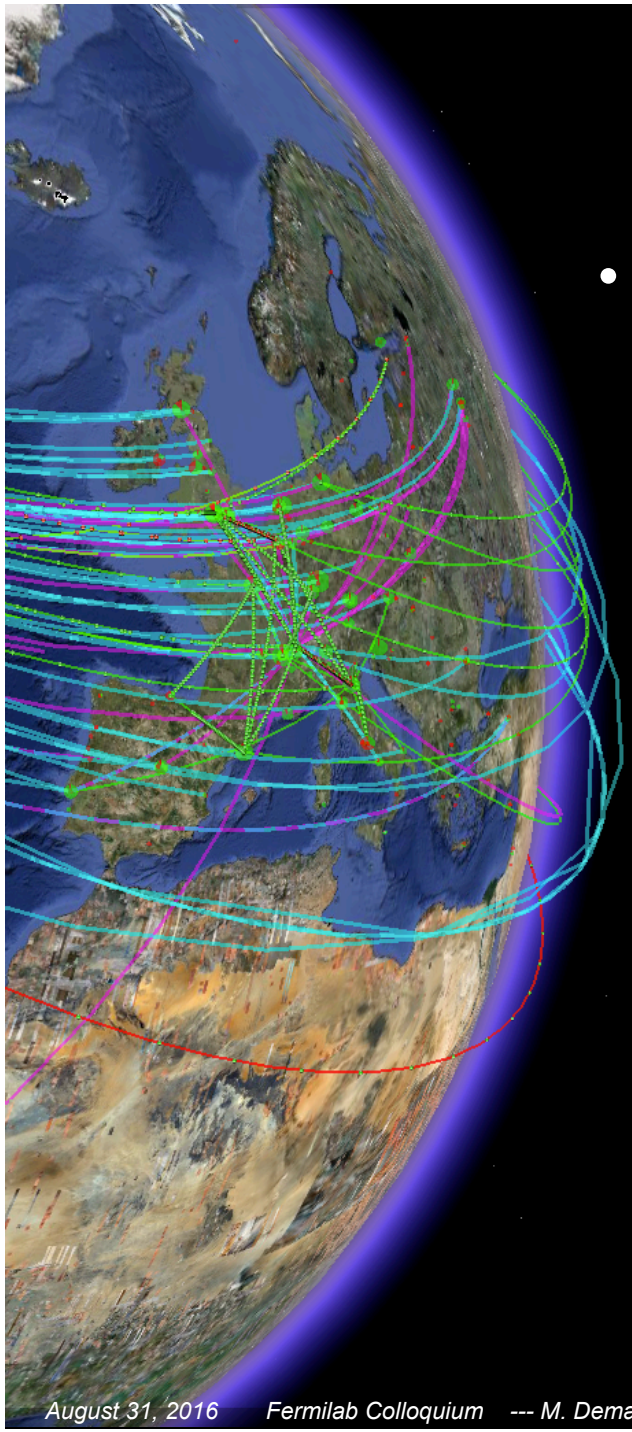
Open Science Grid

ESnet ENERGY SCIENCES NETWORK

<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

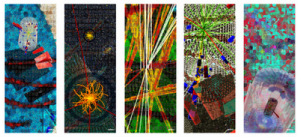
- Worldwide LHC Computing Grid has been leveraged on both sides of the Atlantic, to the benefit of the wider scientific community and particle physics

  - Europe:
    - Grids for E-sciencE
      European Grid Infrastructure

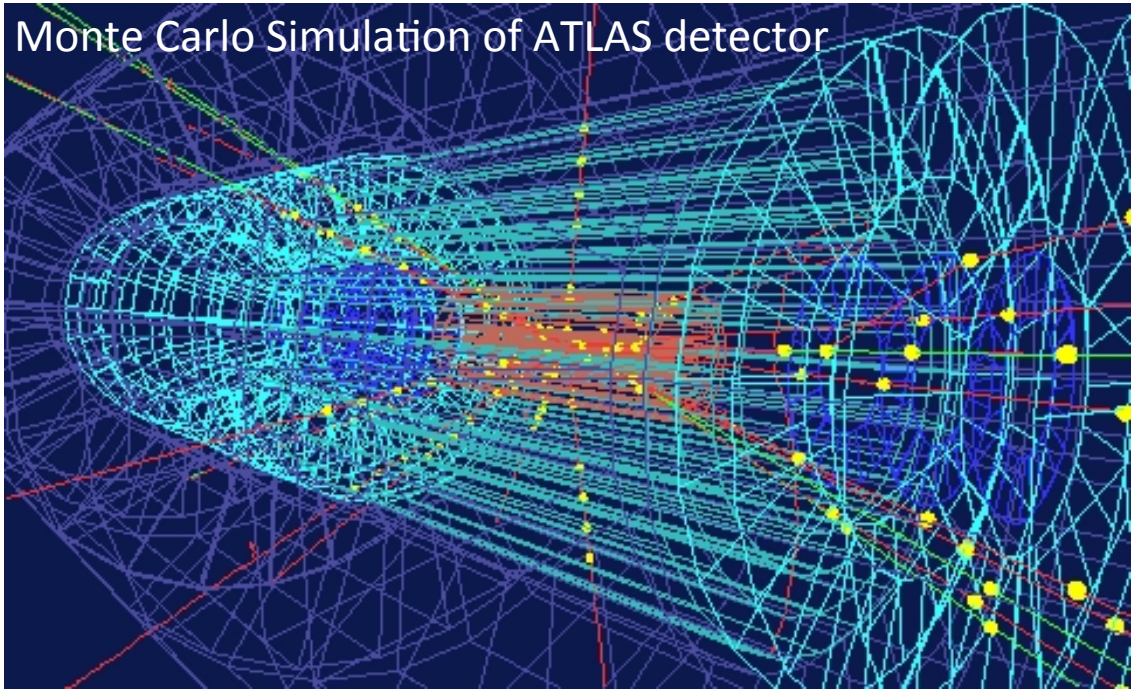
  - USA:
    - Open Science Grid (OSG)
    - ESnet:
      > 400 Gb/s cross Atlantic
      > 100 PB/months

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



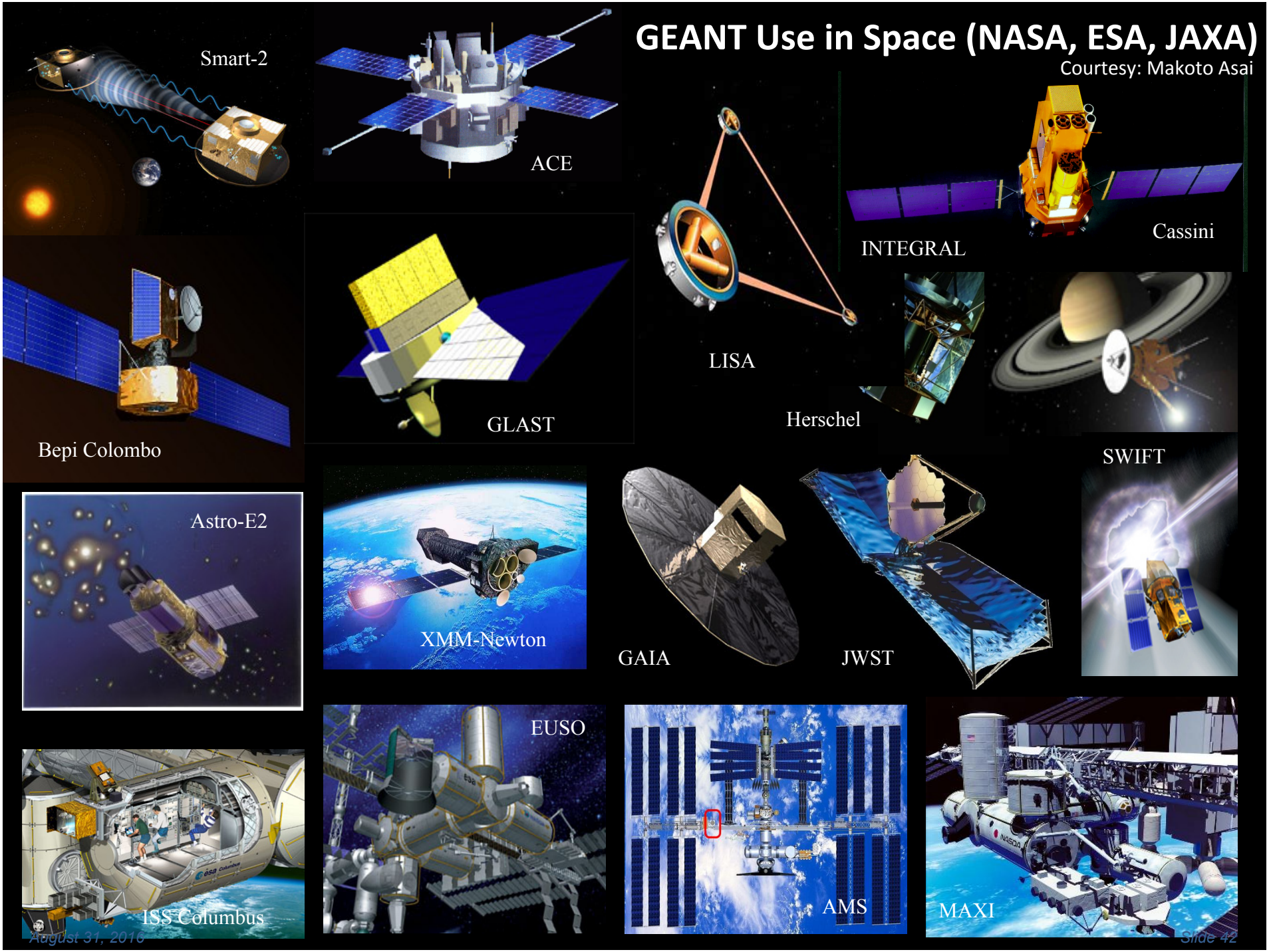
Definition at will of:

- Geometry
- Materials
- Segmentation
- Tracking through media

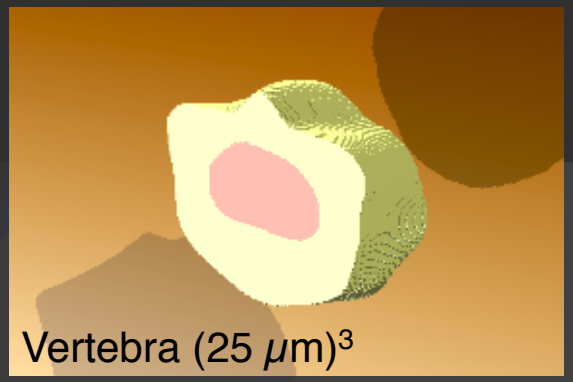
- **GEometry ANd Tracking Toolkit for detector simulations developed: GEANT**
- **Seen very broad use**

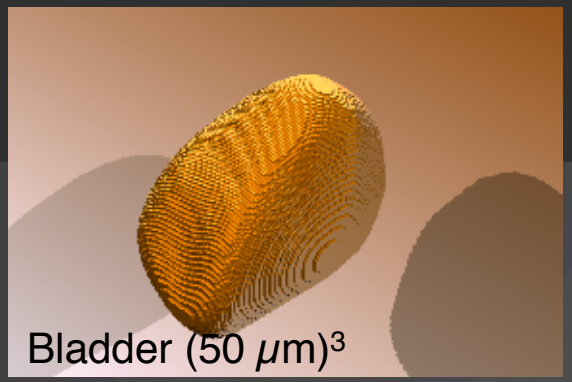
GEANT Use in Space (NASA, ESA, JAXA)

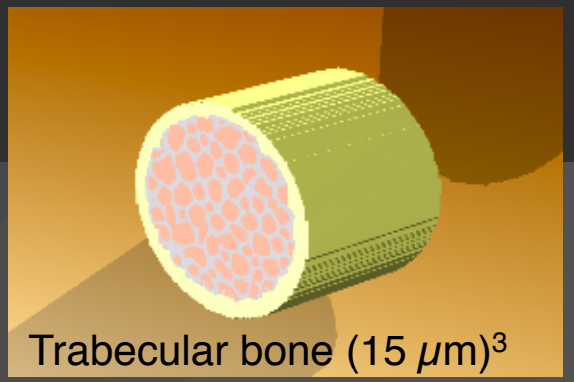
Courtesy: Makoto Asai



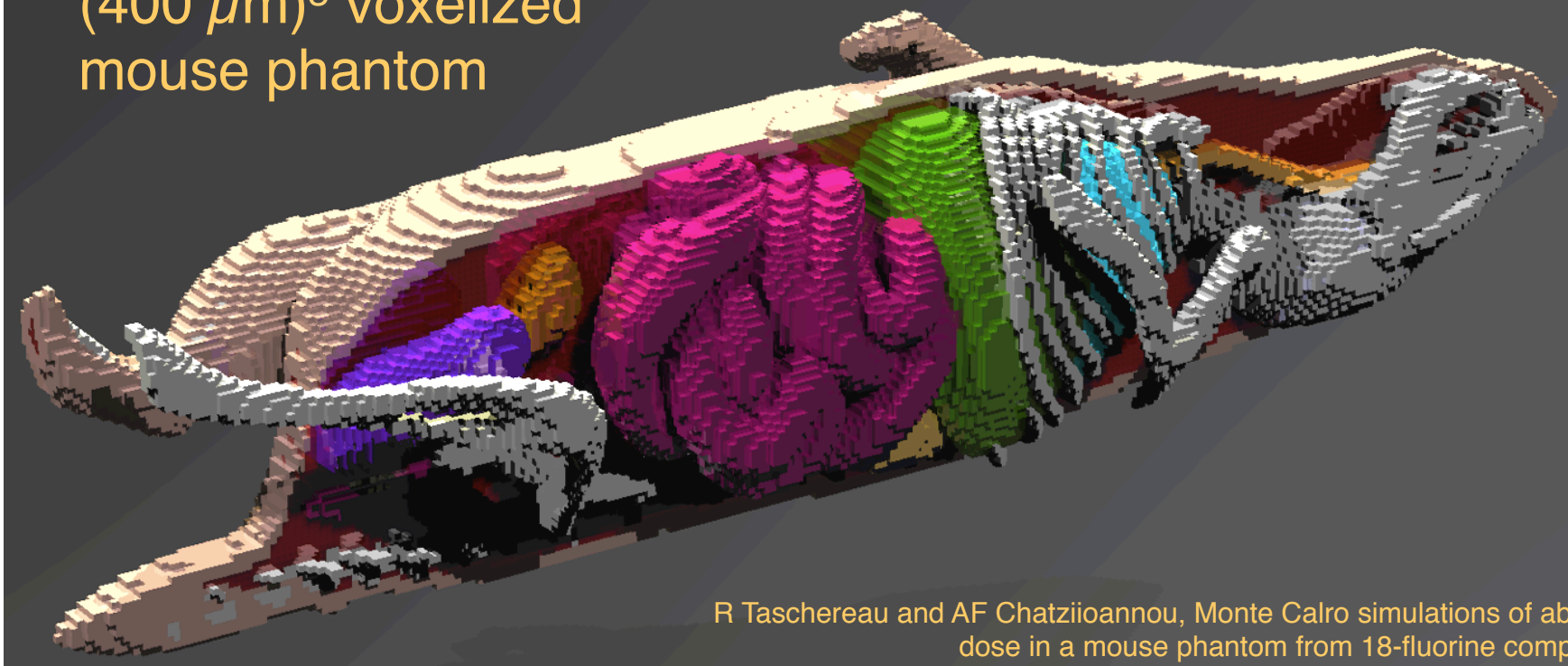
High resolution phantoms


Vertebra (25 μm)^3


Bladder (50 μm)^3

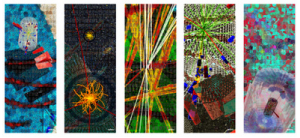

Trabecular bone (15 μm)^3

(400 μm)^3 voxelized mouse phantom



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

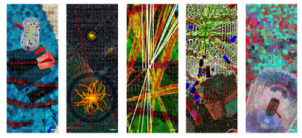
GEANT and Air Travel



- HEP Monte Carlo simulations are used for modeling of radiation exposure in (ultra-) long-haul flights

- The dose received during a flight is about ~5 – 10 μSv/hr
  - X-ray: ~ 6μSv
  - Mammogram: ~3,000 μSv.
- 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

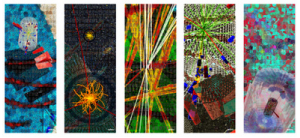
INVENIO

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

CERN spin-off

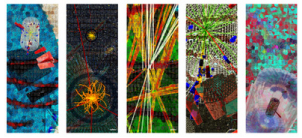
CERN technology

TIND



http://tind.io

TIND



Canton de Fribourg

fri-tic

Techno. de l'Inform. la Com.

University of Minnesota

UM library management

The Graduate Institute Geneva

Graduate Institute Geneva

TIND

www.tind.io

NTNU
Norwegian University of Science and Technology

United Nations

UN Dag Hammarskjöld Library

Union of Concerned Scientists
Science for a healthy planet and safer world

ITU

UN Int. Telecom. Union

The Academy of Sciences of the Czech Republic

KAY

UNITED NATIONS HUMAN RIGHTS
OFFICE OF THE HIGH COMMISSIONER

UNOV
United Nations Office at Vienna

UNESCO

Intl. Bureau of Education

Universidad Zaragoza

Caltech

Caltech library management

Hes·so
University of Applied Sciences and Arts Western Switzerland

Max Planck institute

Max-Planck-Institut für extraterrestrische Physik

For Extraterrestrial Physics

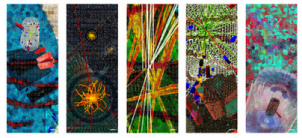
CERN

EU Found. for the Improvement

Eurofound

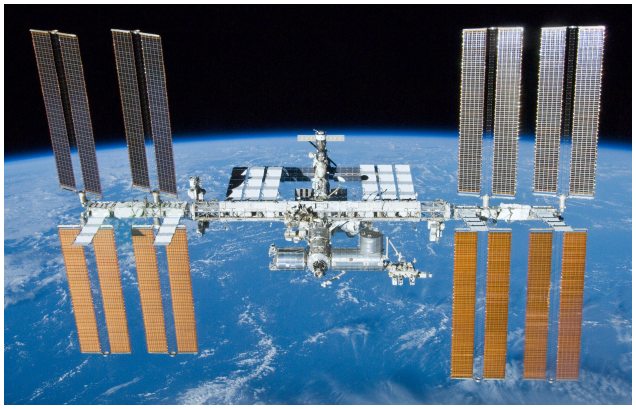
of Living and Working Conditions

Scientific Linux



- One of the "Top 20 Innovations in Chicago" that changed the world
  - 1998: Fermilab created "FermiLinux" for its experiments
  - 2004: Fermilab and CERN improved it and renamed it Scientific Linux

- More than 140,000 users run Scientific Linux
- Runs on the International Space Station
- Runs on majority of campus grid at UW-Madison, powering student research from economics to engineering



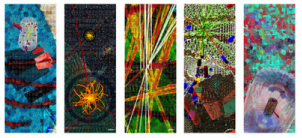
- Other notable innovations on the list: zipper, dishwasher, vacuum cleaner, open-heart surgery, sustained nuclear reaction...

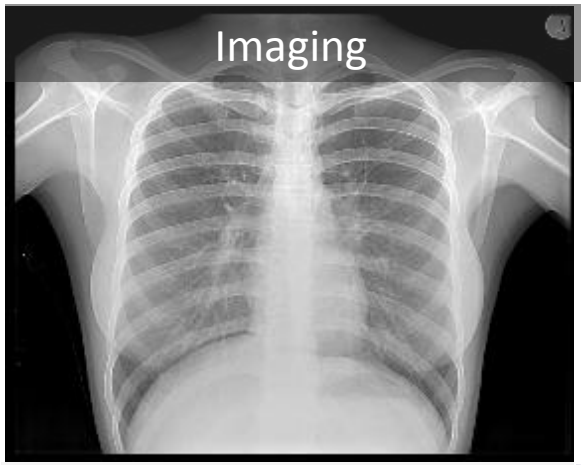
http://bluesky.chicagotribune.com/originals/chi-countdown-to-20-top-chicago-innovations-bsi-20131015,0,0.html

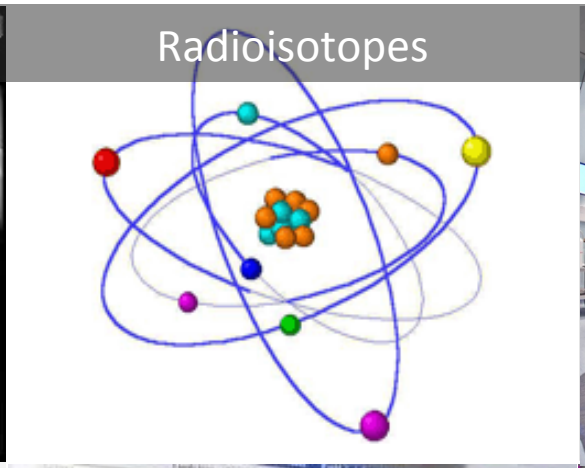
Accelerators

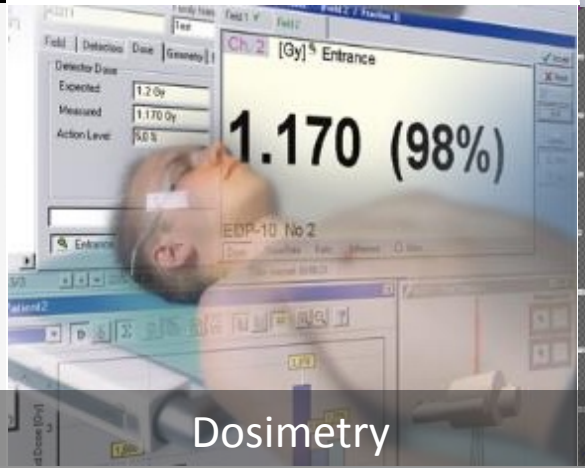
The workhorse of HEP has established major connections to the medical industry and industry in general

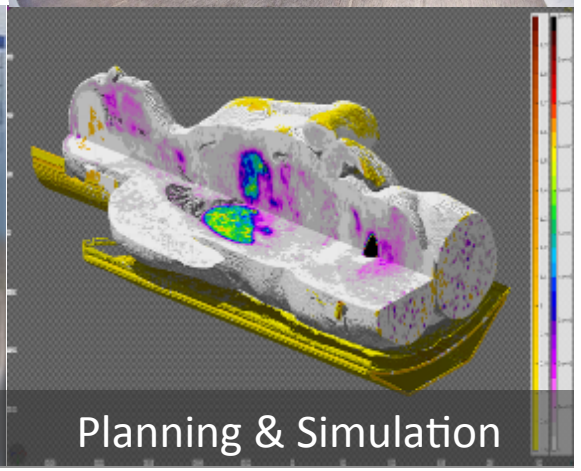
Medical Applications



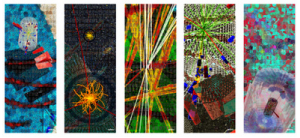








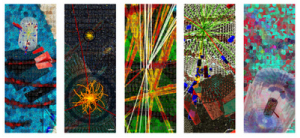
Material Hardening



- 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.

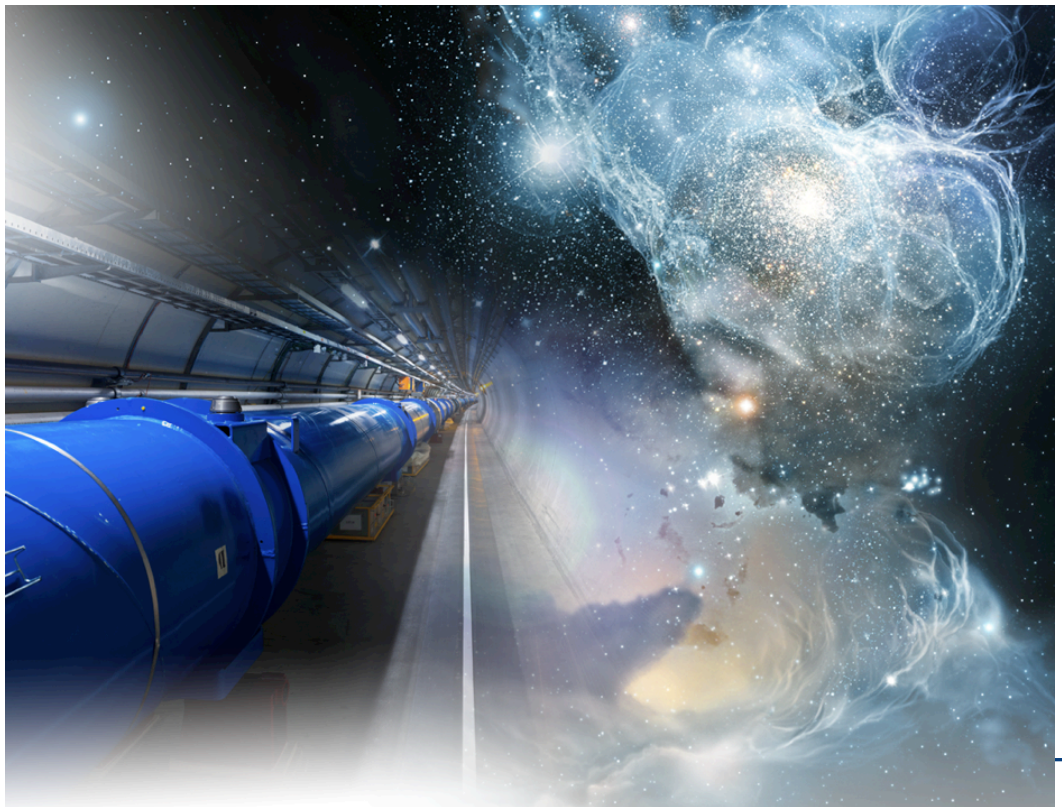
More than **24 000** patients have been treated by hadron therapy in Europe.

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€**.

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

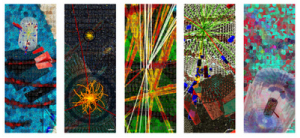
Big Business



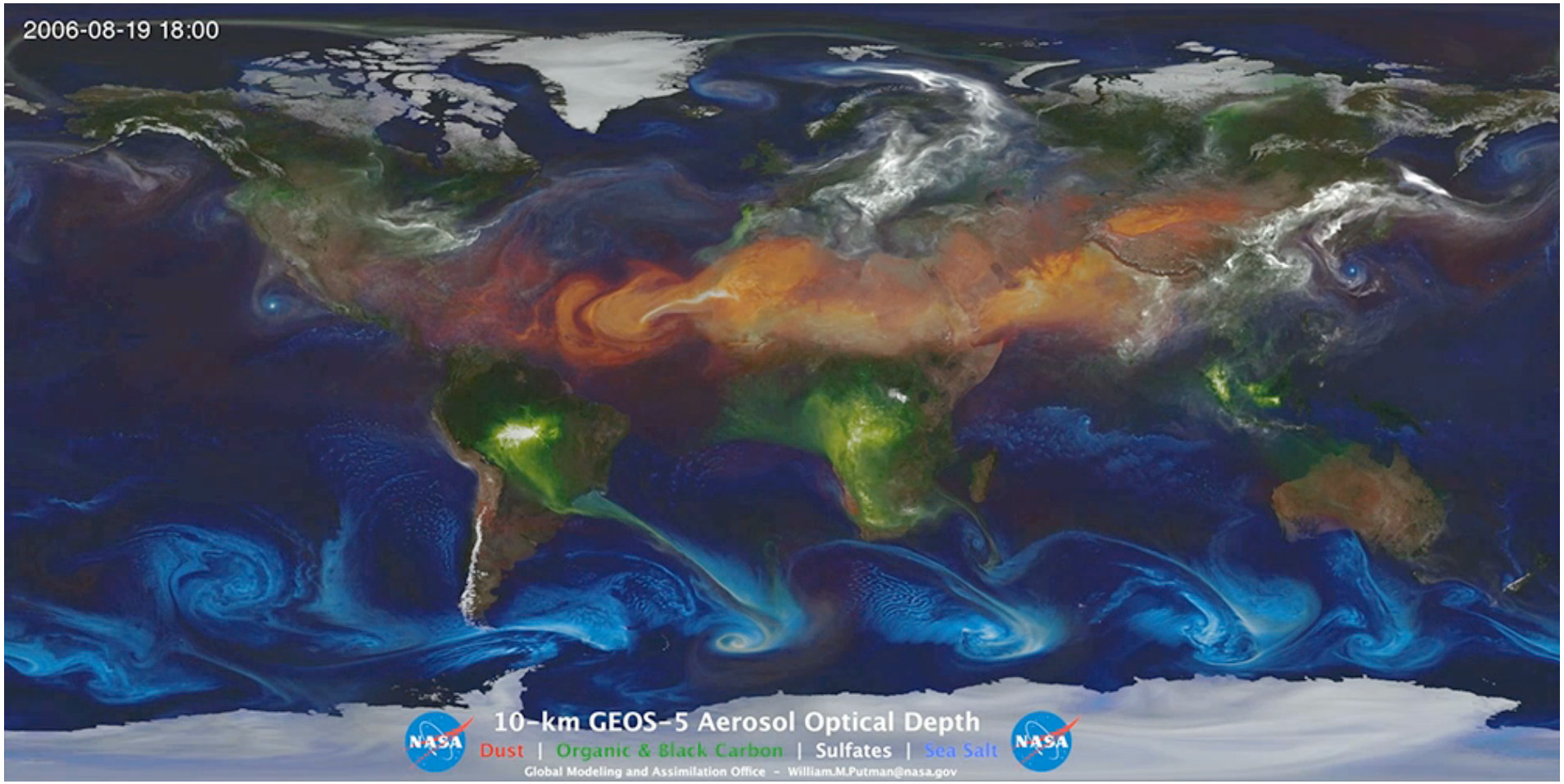
Facilities

Particle Physics facilities for the world

Atmospheric Aerosols

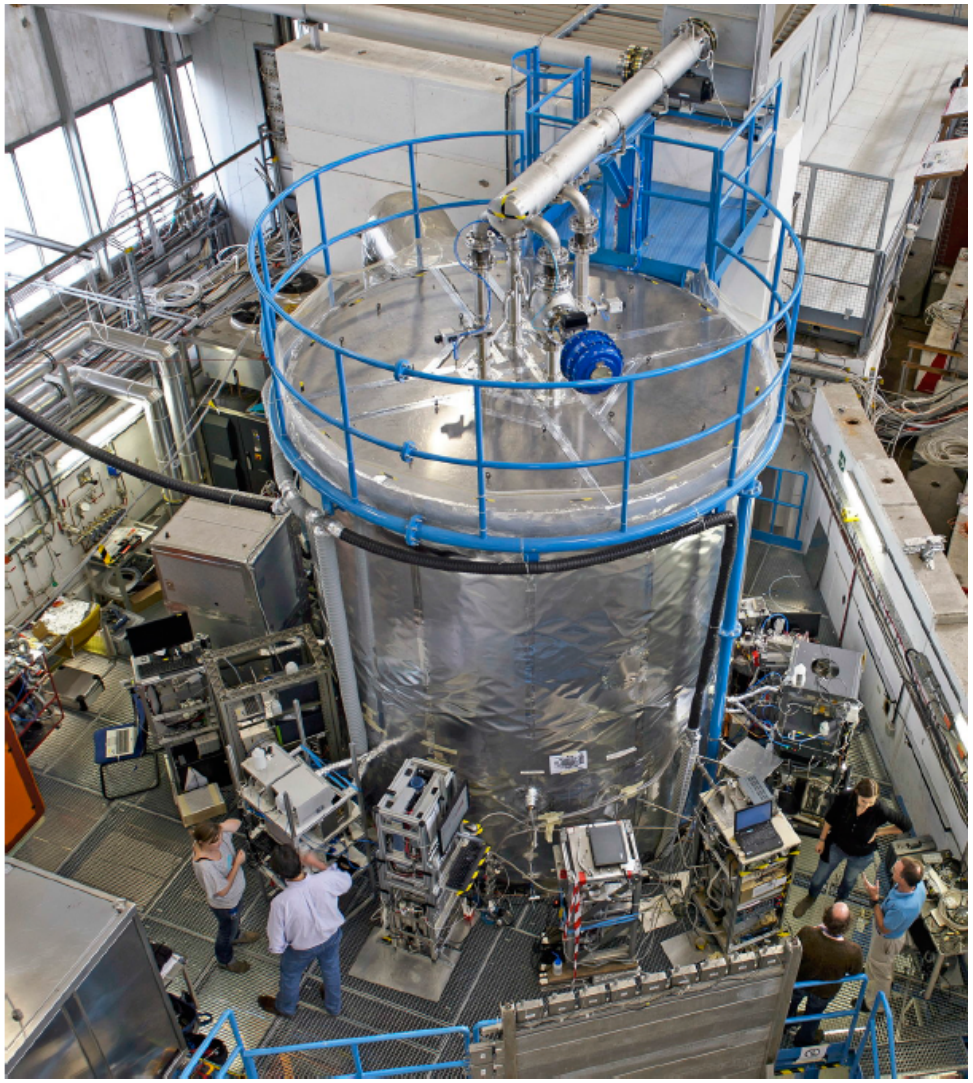


- Aerosols recognized as the 4th leading cause of premature death as well as a key agent in climate system (e.g. Lelieveld et al., Nature 525 367 (2015)).



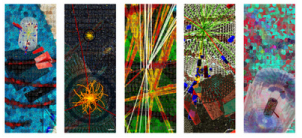
From: H. Gordon (CERN 01.04.16)

CLOUD Experiment

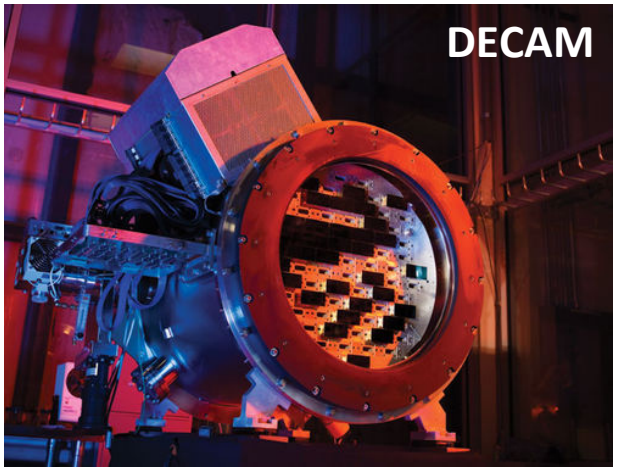


- Cosmics Leaving Outdoor Droplets (CLOUD) experiment at CERN
  - Understand aerosol formation with ions (from CERN test beams)
  - Study correlation between cosmic rays and global temperatures via aerosols
  - Study galactic cosmic rays and cloud formation (Nature 502, 359–363 (17 October 2013))

HEP-Built Facilities

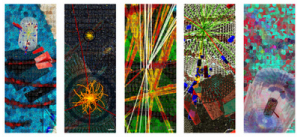


- Sky surveys
  - Cameras built by HEP in partnership with and for the benefit of particle astrophysics and the wider astronomy community: SDSS, DES, LSST



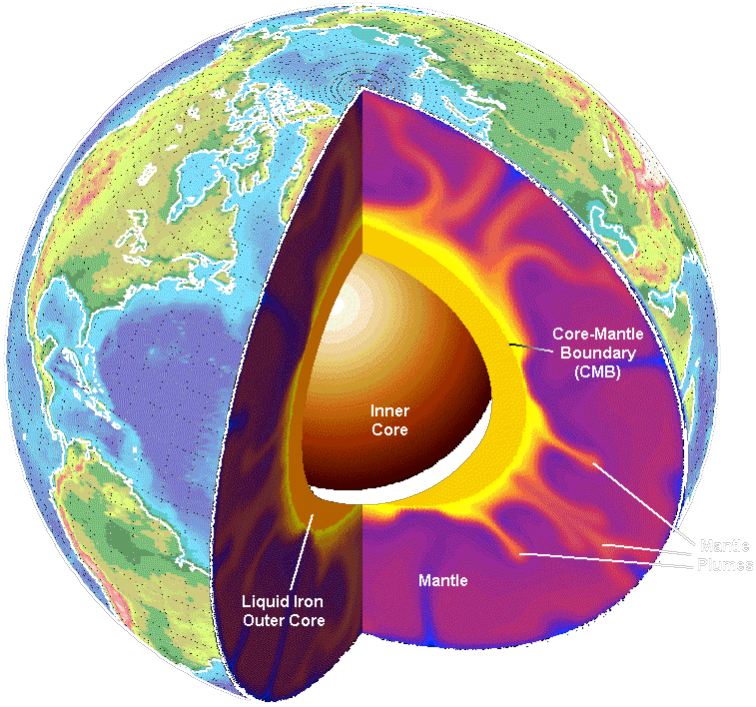
- Light sources: new lives for particle physics machines:
  - SLAC linac now drives the Linac Coherent Light Source (LCLS)
  - PETRA, where the gluon was discovered, now the PETRA III x-ray facility

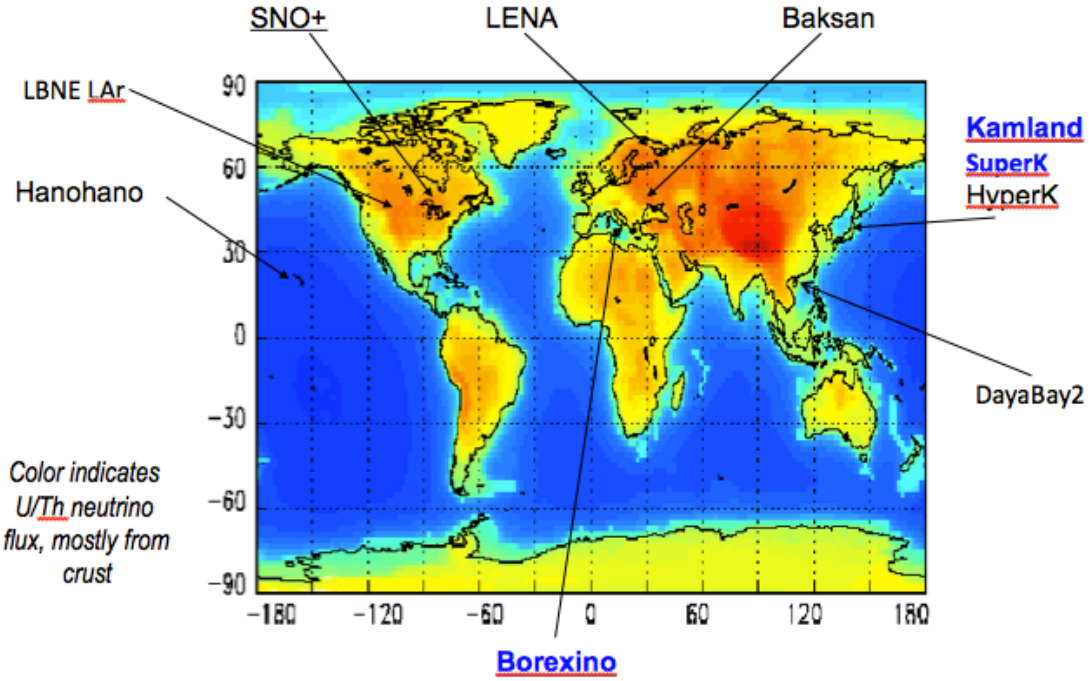
Detectors for Geo-Neutrinos

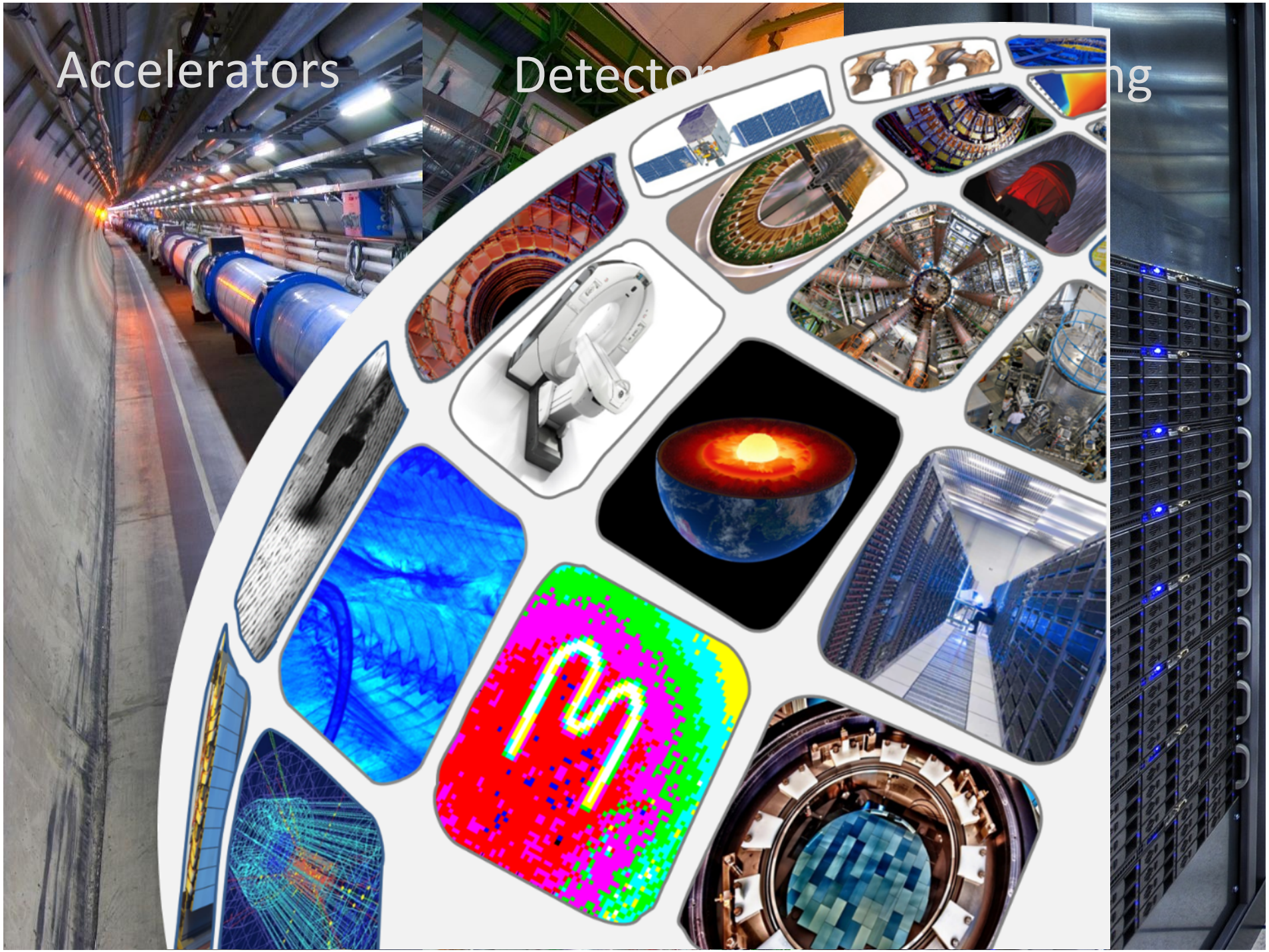


- Understanding the center of the earth
- Total Heat Flow at surface 47 ± 2 TW
  - Geology predicts 16-42 TW of radioactive power
    - ~20 % escapes to space as geoneutrinos
    - ~80 % heats planet

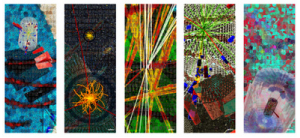
Present and possible experiments for geoneutrinos






Accelerators

Cost Benefit Analysis



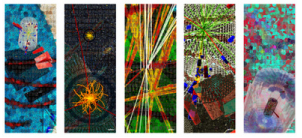
- Analysis of cost-benefit of LHC (1993 – 2025):
- Cost assumed to be 13.5 G€; benefits metric:
  - Impact of publications (low)
  - Human capital formation (highest)
  - Procurement technology transfer and software (high)
  - Benefit to general public (high)
- Study yields Benefit / Cost ratio of 1.2
- Study excludes (most important) direct impact of key elements:
  - Superconducting magnet development
  - Grid computing
  - Medical applications (>400 G€)
  - Imaging applications (>5 G€)

  And indirect benefits:
  - Technology advancement

arXiv:1603.00886
arXiv:1507.05638
arXiv:1511.05477

Impact of Particle Physics is huge and easily exceeds cost by factor of 5

Technology Transfer Networks (EU)



EIROforum

ENLIGHT

enterprise europe network

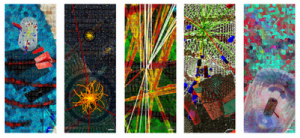
T0 circle

AUTM

ASTPPROTON
KNOWLEDGE TRANSFER EUROPE

HEPTech

Technology Transfer



- Have a great idea?

CHAIN REACTION INNOVATIONS

- Apply for the Argonne:
  Lab-Embedded Entrepreneurship Program (LEEP)

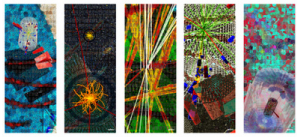
- Requirements:
  - minimum of five years of technology R&D experience
  - first-time technical founder
  - Not have raised more than $1 million in private sector funding

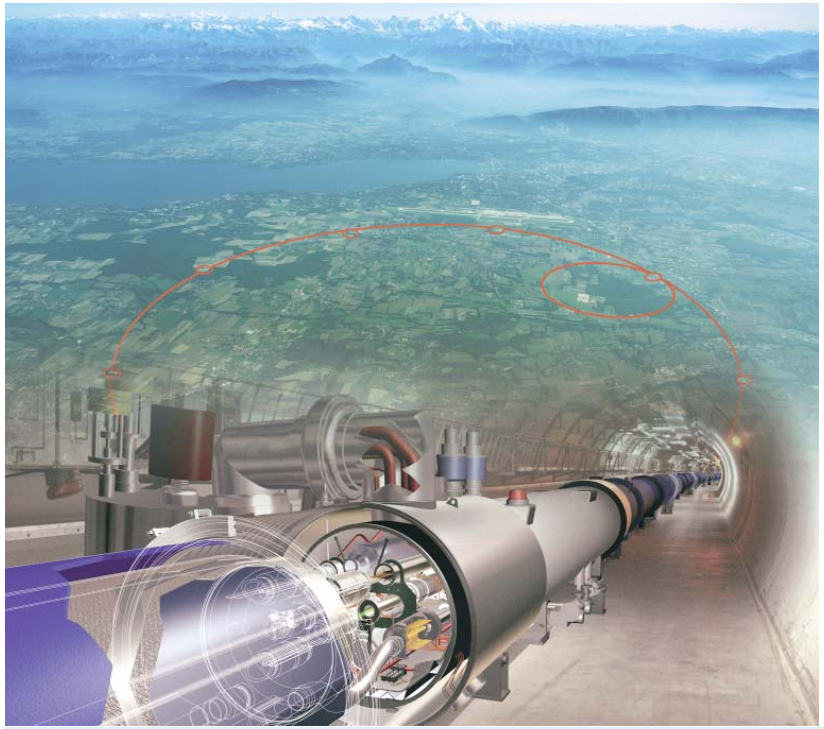
- Benefits:
  - Personal stipend of $89,000 per year (80% appointment)
  - $350k in development funds
  - Access to all resources at the laboratory

http://chainreaction.anl.gov/

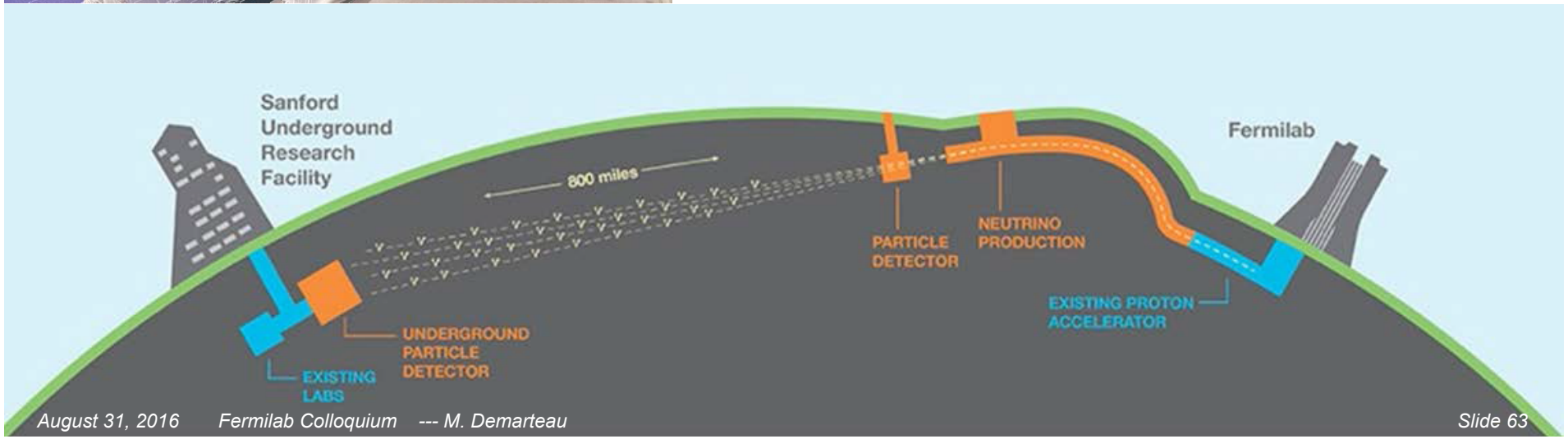
Conclusion

Particle Physics Projects



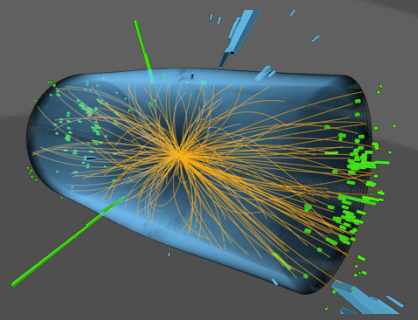


- The Power of Collective Ownership.
- Sense of Trust, with mutual code of ethics
- Shared Vision
- Equal Learning Opportunity



Particle Physics And Its Impact

- **Curiosity driven science research**
  - Energy, mass composition of the universe



- **Advancing frontiers of technology, diffusing innovations to society and improving our standard of living**

- **Training current and next generation scientists**
  - Champion Science, Technology, Engineering, Mathematics

- **Uniting the world through science for peace**
  - CERN granted observer status to the United Nations General Assembly, 14 Dec 2012

See also: “Particle and Nuclear Physics Instrumentation and Its Broad Connections”
M. Demarteau, H. Nicholson, R. Lipton, I. Shipsey
Reviews of Modern Physics

With many thanks to: Daniela Bortoletto, Oswin Ehrmann, Paul Grannis,
David Mazur, Filippo Resnati, Petra Riedler, …