High Energy Physics Experimental Connections

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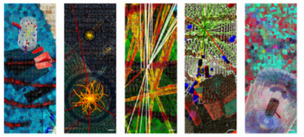
With thanks to
L. Chatterjee, M. Cooke

December 17, 2013
P5 Meeting
Brookhaven National Laboratory

* = co-chair

Charge



- Articulate key connections and synergies between the tools, techniques and technologies developed for particle physics and other disciplines, in particular identify:
  - Current and potential impacts on other scientific fields and society at large.
  - Benefits and potential opportunities to particle physics from exchanges with other sciences and industry.
  - Potential opportunities by other disciplines to enhance the effective scope of particle physics experiments.
  - Potential for HEP facilities to serve communities outside particle physics.
  - Contributions of HEP to workforce and general training.
- We accepted the charge because we believe such an exercise is timely (overdue), and ultimately will benefit HEP, other sciences and society as a whole.
- Note: this is a fascinating topic and our study is just a start and we hope it will be continued

Process

- Reviewed existing documentation on impacts of tools, techniques, technologies and skills
- Contacted many experts, both within and outside particle physics to discuss current and potential bi-directional impacts
  - All supported us enthusiastically (thank you!)
- Noted existing “hard data” and places where additional statistics would be particularly useful
- Compiling table of HEP-trained people in other sciences and industry for later follow up

- This presentation represents preliminary comments and observations – full submissions from contributors arriving now

- Area is very large; were able to only cover a fraction

Contributing Experts

Laci Andricek (MPG, HLL)
Tim Antaya (MIT)
David Asner (PNNL)
Vineer Bhansali (PIMCO)
Ian Bird (CERN)
Glenn Boyd (PANNIA)
Michael Campbell (CERN)
Manuela Cirilli (CERN)
Bruce Chai (Crystal Photonics)
Dhiman Chakraborty (NIU)
George Coutrakon (Loma Linda/NIU)
Peter Denes (LBNL)
Manjit Dosanjh (CERN)
Daniel Elvira (Fermilab)
Michael Ernst (BNL)
Jeff Fang (Shanghai Institute of Ceramics)
Paulo Fonte (LIP, Coimbra)
Alex Guenther (PNNL)
Steve Ghan (PNNL)
Salman Habib (Argonne)

Steve Holland (LBNL)
Robert Johnson (UCSC)
Carol Johnstone (Fermilab)
John Krane (Financial Services)
Thomas Kroc (Fermilab)
John Learned (Univ. of Hawaii)
Wim Leemans (LBNL)
Alan Litke (UCSC)
Thomas Ludlum (BNL)
Paul Mackenzie (Fermilab)
Peter McMurry (Univ. Minnesota)
Markus Nordberg (CERN)
Ken Olson (SPAFOA)
Joseph Perl (SLAC)
Klaus Peters (Uni. Frankfurt)
Ruth Pordes (Fermilab)
Erik Ramberg (Fermilab)
Paul Rubinov (Fermilab)
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Zhehui Wang (Los Alamos)
Mark Wise (Caltech)
Doug Worsnop (Aerodyne)
Dennis Wright (SLAC)
Ren-yuan Zhu (Caltech)

~40% of contributors outside of HEP

Focus areas for this report

- Medical Sciences
- Computing and Software
- Accelerators
- Detectors
- Facilities
- Finance

Medicine

A major area of impact of HEP, from therapy accelerators to imaging detectors to a well-trained workforce

BGO Crystal Development

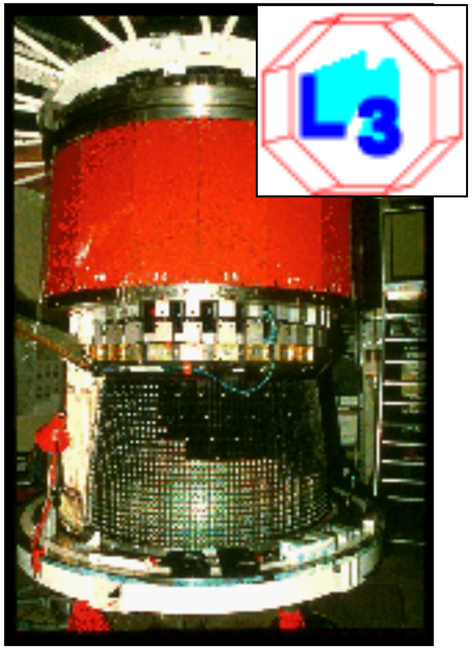
- BGO crystal scintillator was discovered in seventies and quickly adopted by HEP for precision EM calorimetry

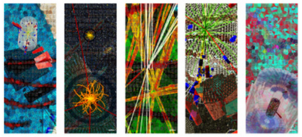
- The L3 experiment at LEP built the 1st BGO crystal calorimeter consisting of 11,400 BGO crystals of 1.5 m^3, which were grown at Shanghai Institute of Ceramics (SIC)

- Although a one shot HEP market for SIC in early eighties, it led to the multi-crucible growth technology allowing growth of up to 36 crystal ingots per oven

- Opened medical 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

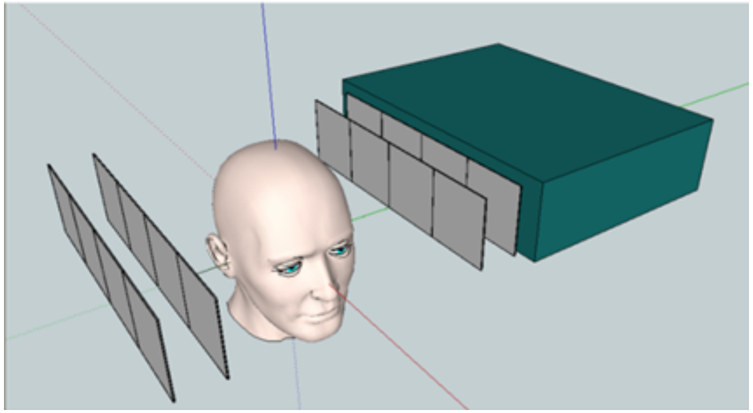
- The cost-effective modified Bridgman growth technology developed at SIC for BGO crystals has also been utilized in developing new crystal scintillators for HEP experiments and industry.

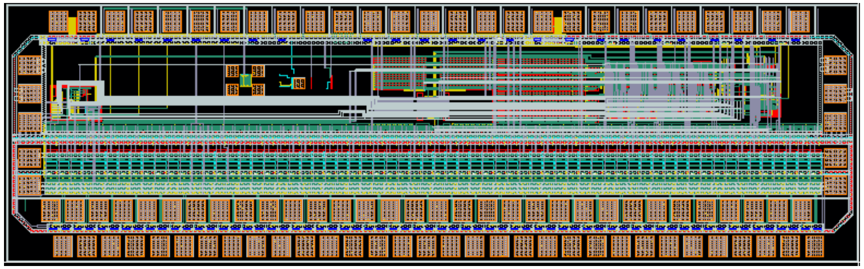




Proton Computed Tomography (pCT)

- In a pCT head scanner, planes of Silicon Strip Detectors track the proton entering and leaving the patient, before the energy loss is measured in the energy detector. Correlate the measured E-loss with the path of the proton through the patient.



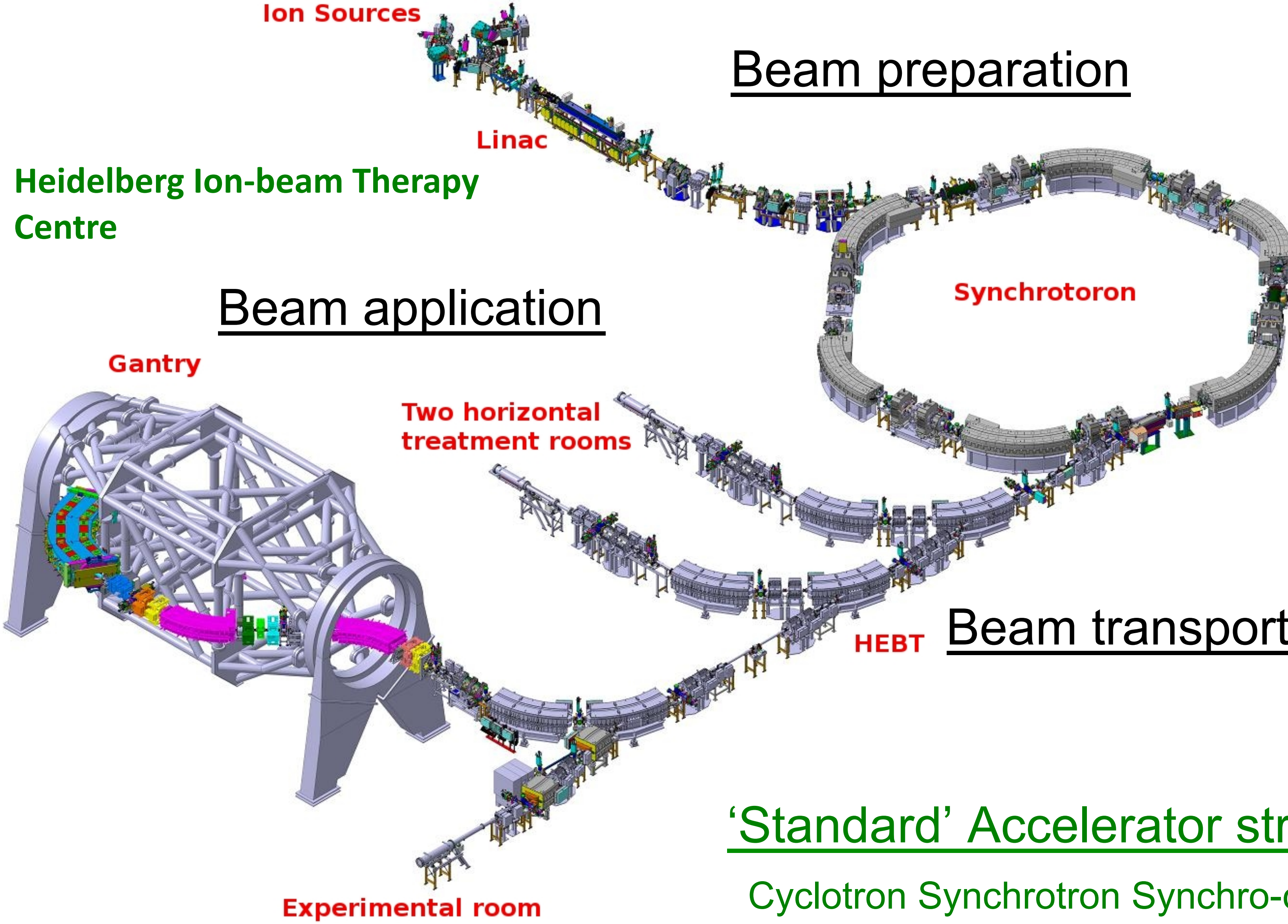


ASIC modeled after GLAST/FERMI

- Development based on silicon strip technology developed for ATLAS and GLAST/Fermi
  - A crucial parameter is the sustained data rate needed for an image to be acquired in an acceptable time frame of a few minutes. Target data rate of 1 million protons measured per second.
    - The ASIC and the DAQ are patterned after that of GLAST/Fermi, but with a 100-fold increase in speed.
- The design of the head scanner and the ability to reconstruct a billion events per image have been made possible by software developed within HEP.

Ion Therapy

Heidelberg Ion-beam Therapy Centre



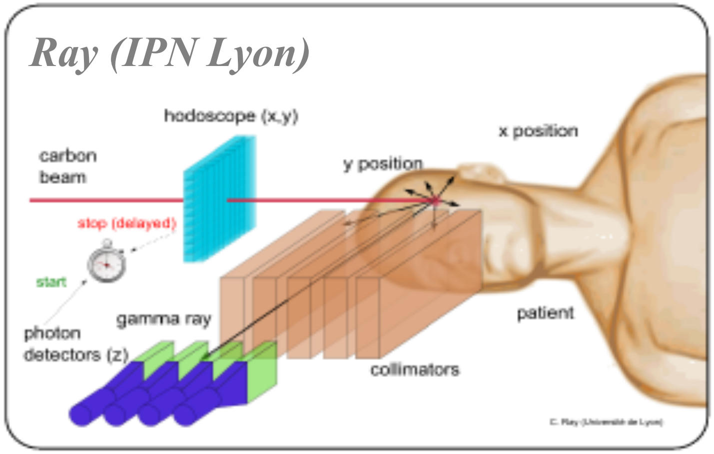
'Standard' Accelerator structures

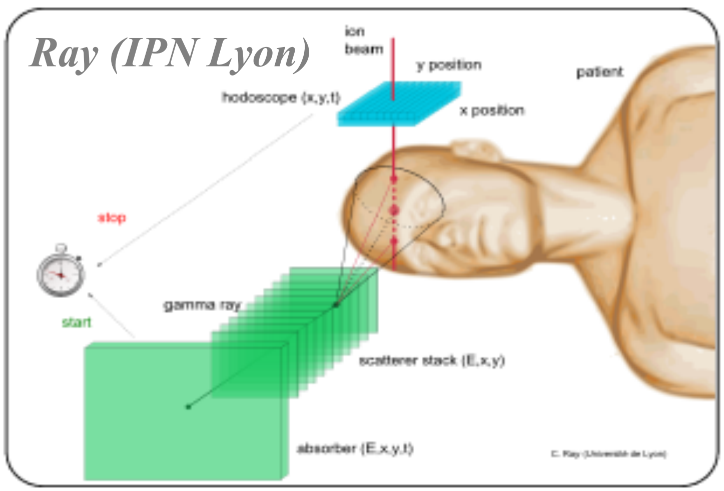
Cyclotron Synchrotron Synchro-cyclotron

Prompt γ-ray imaging

Single Particle Tomography

on-line / in-beam





SPECT
Prompt γ-rays

- Passive collimation – Slit camera
  - Single slit
  - Multi slit
- Electronic collimation – Compton camera
  - Silicon Scintillator
  - Scintillator Scintillator
  - CZT SCI,CZT

Required devices:

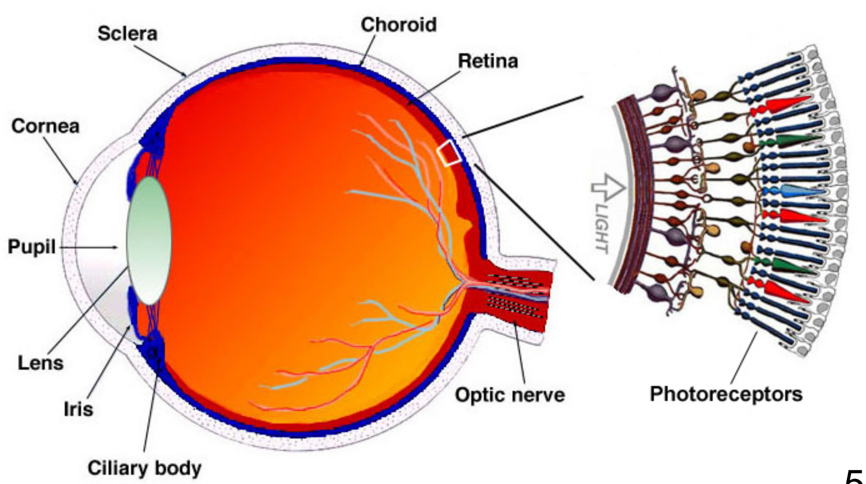
Hodoscope (x,y,t)

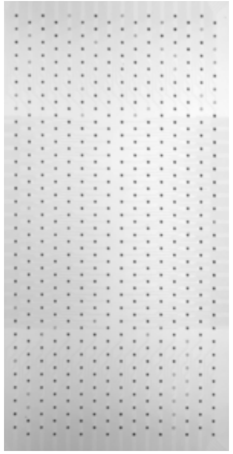
Scatterer (x,y,E)

Absorber (x,y,z,E,t)

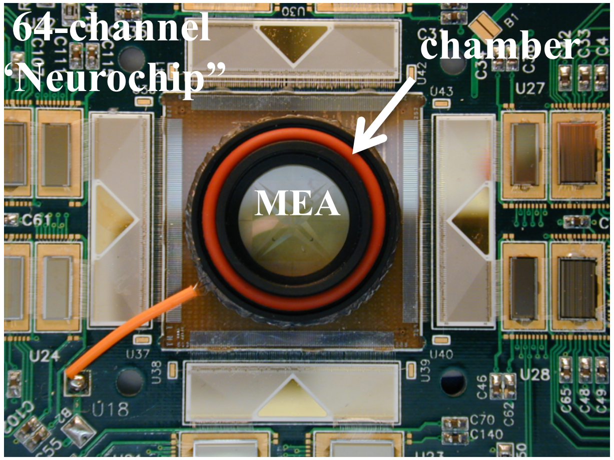
Neurobiology and Medical Applications

- Development of a "Pixel Detector" – based on experience with Mark II and LHC – for study of retinal output



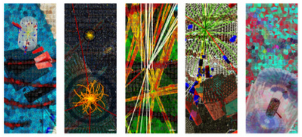


512-electrode MEA



512-electrode "Neuroboard" (2003)

- Custom-designed multichannel readout ICs
- High-density wire-bonding for interconnect
- The Neuroboard has a multi-electrode array (MEA) with 512 electrodes – 60 µm interelectrode spacing; 5 µm electrode diameter – to detect the electrical signals ("spikes") generated by hundreds of neurons.



Neurobiology and Medical Applications

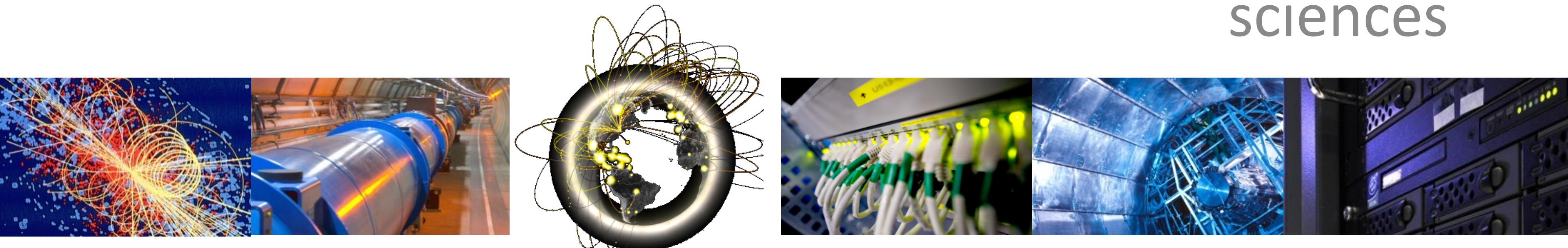
- Technology Development:
  - 512-electrode MEA neural recording system
  - 512-electrode system with both electrical stimulation and recording
  - Wireless brain activity recording system; for studies of awake, naturally behaving animals

- Neurobiology
  - **Discovery of a new functional type of primate retinal output (ganglion) cell (may be involved in motion perception)**
  - Functional connectivity map of the primate retina at the resolution of individual cones and individual retinal output cells

- Biomedical Applications
  - Retinal prosthesis studies for diseases that cause blindness due to photoreceptor degeneration (e.g. retinitis pigmentosa)
  - Restoration of retinal function after selective photocoagulation

Computing and Software

HEP has been at the forefront of big data and advanced networking, pushing the envelope for the benefit of other sciences



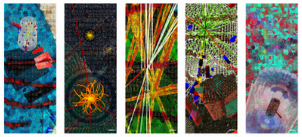
Impact of HEP Computing

- HEP as driver of "Big Data" for science
  - Infrastructure and tools developed and demonstrated to manage and distribute ~100 PB data sets
  - Network infrastructure – HEP demonstrates capability and operability
- HEP development of World-Wide-Web
  - Fundamentally changed all aspects of business and social interactions
- Supercomputing
  - Lattice gauge theorists involved with the development of supercomputing from the start
- Large scale distributed computing
  - World LHC Computing Grid (WLCG) as exemplar; leads to acceptance of such infrastructures for science
  - Ensures/enables inclusion of world wide collaborators – community building

Impact of HEP Computing

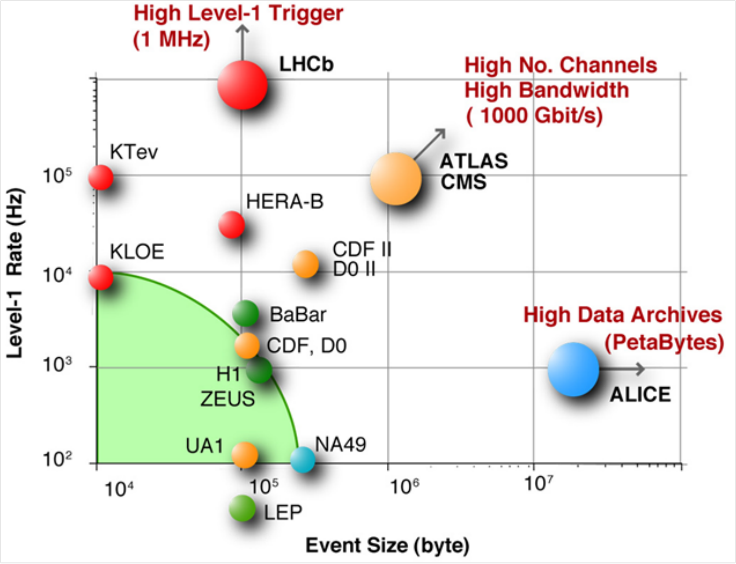
- Global federations of trust
  - Developed to enable WLCG to allow researchers to access world-wide resources
  - Now a recognised need for all academics and researchers: a unique identifier to enable access to (global) IT resources
- Software:
  - GEANT4 – simulation code used worldwide in many areas needing particle transport: medical diagnosis, radiation protection, etc
  - Scientific Linux – OS for scientific computing used worldwide
  - Libraries of mathematics and scientific algorithms available as open source (cernlib, ROOT, etc.)

- The Web, grid computing, ESnet: HEP ability to take Computer Science ideas and turn them into a practical reality



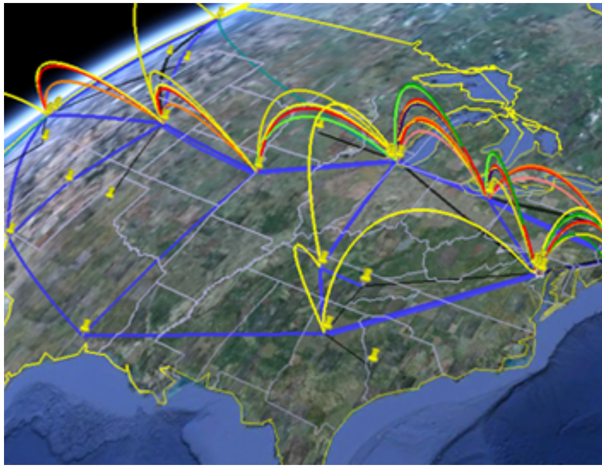
Energy Sciences Network (ESnet)

- Energy Sciences Network (ESnet) is a high-performance, unclassified US network to support scientific research.
- For decades, HEP network traffic has been primary driver of National Research and Education Network (NREN) growth
  - Large-scale HEP data flows recognized by ESnet as primary driver for strategy for evolving architecture and implementation of ESnet across SC labs and worldwide
  - HEP provided specific requirements leading to detailed design of ESnet4 in 2007-9, leading to the first generation network designed specifically for data-intensive science



ESnet

- Spurred by HEP needs, ESnet developed virtual circuit service: OSCARS
  - The On-demand Secure Circuits and Reservation System
  - A software service that creates dedicated bandwidth channels for scientists who need to move massive, time-critical data sets around the world.
    - The service is now used by other data-intensive science communities
    - Received 2013 R&D 100 award
- Due to global nature of HEP community ESnet got very actively engaged in collaborations with Research Network providers around the globe
    - Major international traffic exchange locations associated with SC programs are driven by HEP requirements



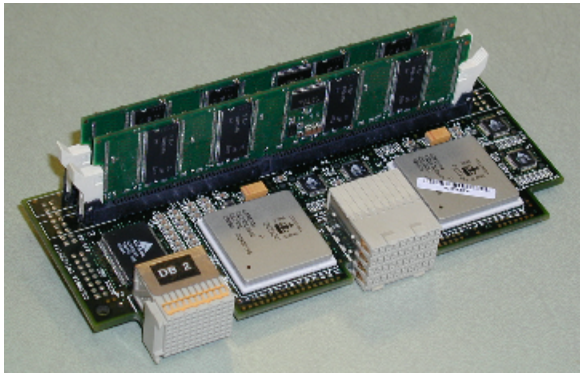
OSCARS 0.6 was recognized as one of R&D Magazine's top 100 technologies.

Lattice QCD and Supercomputing

- Lattice gauge theorists have been involved with the development of supercomputing from the beginning.
  - Ken Wilson, inventor of lattice gauge theory, was an early proponent of supercomputing.
    - In the 70s, he was programming array processors in assembly language to attack critical phenomena problems for which he won the Nobel Prize; wrote Fortran compiler for the FPS array processor.
    - In the 1982, he contributed ~1/7 of the Lax Report which led to the establishment of the NSF supercomputing centers in 1985 and NSFNET (forerunner of the internet) in 1986.
  - In the 80s, lattice gauge theorists worked to design highly parallel machines aimed at lattice QCD
    - In academic efforts at Caltech (Cosmic Cube), Columbia, IBM (GF11, not a commercial project), Fermilab, ..., and as part of the Thinking Machines project.
    - These helped established the massively parallel paradigm for large-scale supercomputing that has been the industry model for the last twenty years.

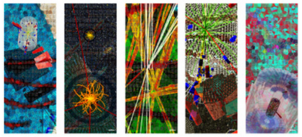
Example: IBM's Blue Gene Supercomputers

- The IBM Blue Gene Supercomputers grew out of the Columbia QCD machines
- The Columbia group, led by Norman Christ, won the Gordon Bell prize for price/performance in 1998 for the QCDSP, a machine purpose-built for lattice QCD.
- It was succeeded by the QCDOC.
- A team led by Alan Gara that had been part of these projects went to IBM and designed the closely related BG/L (commercial), which won the Gordon Bell prize for performance in 2005 (Alan Gara now at Intel)
  - The system-on-a-chip design, tightly coupled standard processor and FP unit, torus network, and style of mechanical design (small easily replaced node cards) were modeled on the Columbia machines.



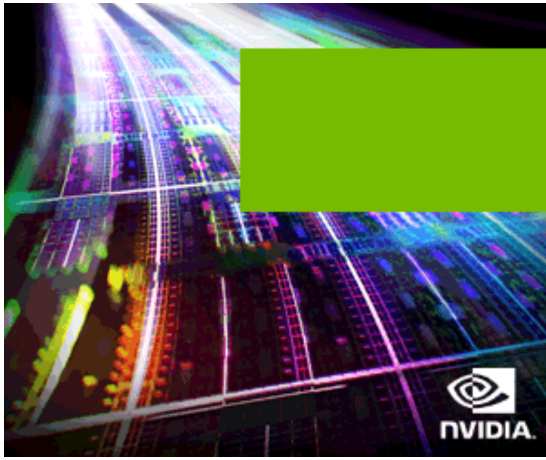
QCDOC compute card.

BG/L compute card.



HPC Next: Graphic Processor Units

- Very promising multi-grid methods have emerged to solve the highest priority problems in QCD today.
  - Lattice QCD community is working with collaborators in the FASTMath SciDAC Institute and the NVIDIA emerging applications group.
  - FASTMath colleagues provide a framework for fast turn-around exploration and testing of novel algorithmic ideas; interface lattice QCD kernels with the FASTMath HYPRE applied mathematics effort.
  - Collaboration with NVIDIA to adapt these methods for many-core architectures.



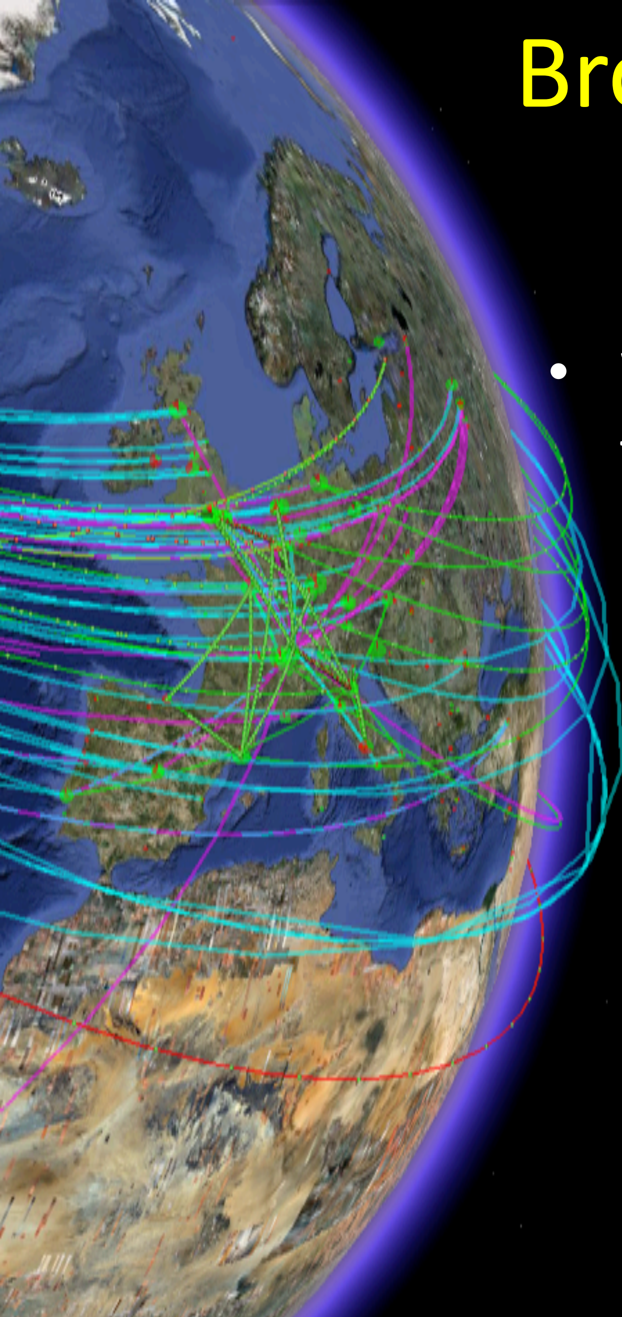
- Computing industry, e.g. NVIDIA, has hired USQCD's top GPU experts.
  - They work with academic collaborators to attain best performance,
  - Mike Clark, former BU postdoc, evaluates potential future architectures in terms of QCD (cache sizes, memory bandwidths, network bandwidth, latency sensitivity).

Worldwide LHC Computing Grid

- Powers LHC computing and data analysis
- Development began in 2002, initial deployment in 2008
- Depends on two major science grid infrastructures:
  - European Grid Infrastructure
  - Open Science Grid (OSG) in United States

A map of the worldwide LCG infrastructure operated by EGEE and OSG.

Broader Impact of the LHC Computing Grid



- WLCG has been leveraged on both sides of the Atlantic, to benefit the wider scientific community
  - Europe:
    - Enabling Grids for E-sciencE (EGEE) 2004-2010
      110 M€ EC Funding
    - European Grid Infrastructure (EGI) 2010-2014
      25 M€ EC Funding
  - USA:
    - Open Science Grid (OSG) 2006 onwards
- Many scientific applications ➔

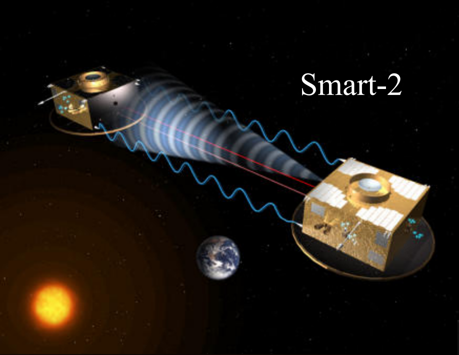
Archeology
Astronomy
Astrophysics
Civil Protection
Comp. Chemistry
Earth Sciences
Finance
Fusion
Geophysics
High Energy Physics
Life Sciences
Multimedia
Material Sciences
…

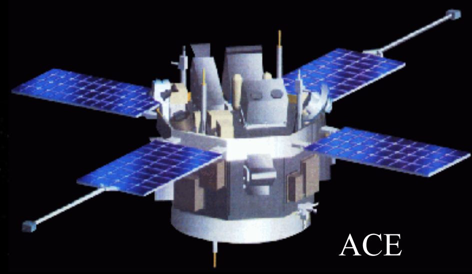
WLCG
Worldwide LHC Computing Grid

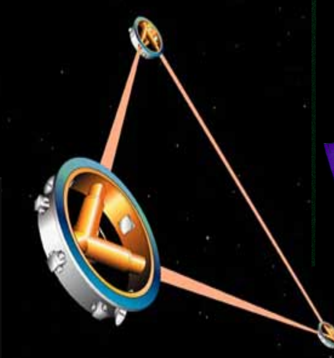
GEANT4

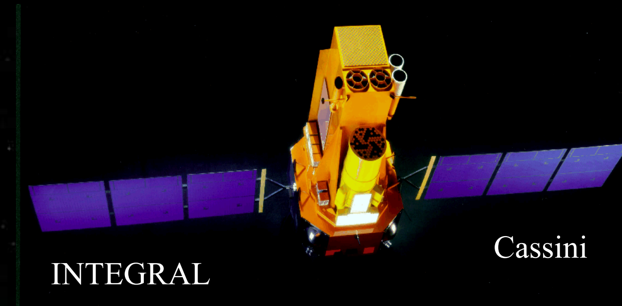
- The GEometry ANd Tracking Toolkit for HEP detector simulation
- Geant4, object oriented successor of Geant3, started at CHEP 1994 in San Francisco
  - December ’94: CERN RD44 project start
  - Apr ’97: First alpha release
  - Dec ’98: First Geant4 public release - version 1.0
- Its use goes currently well beyond particle physics:
  - G4NAMU: Geant4 North Americas Medical Users
    http://geant4.slac.stanford.edu/g4namu/
  - Geant4EMU: European Medical User Organization
    http://g4emu.wikispaces.com/
  - Geant4MED: Medical Physics in Japan
    http://g4med.kek.jp/
  - GAMOS: Geant Architecture for Medicine-Oriented Simulations
    http://fismed.ciemat.es/GAMOS/
  - GATE: Geant4 Application for Tomographic Emission
    http://www.opengatecollaboration.org/
  - GEANT for Space Applications initiated by the European Space Agency
    http://geant4.esa.int/
  - GEANT4-DNA: Biological damage to DNA by ionizing radiation
    http://geant4-dna.org/
  - G4Beamline: Simulation of beamlines with emphasis on muon facilities
    http://www.muonsinternal.com/muons3/G4beamline

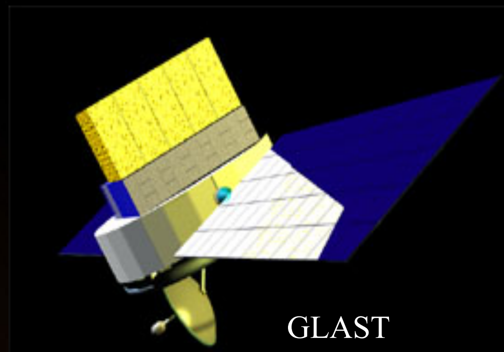
GEANT use in SPACE (NASA, ESA, JAXA)

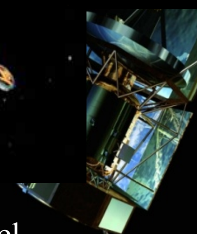


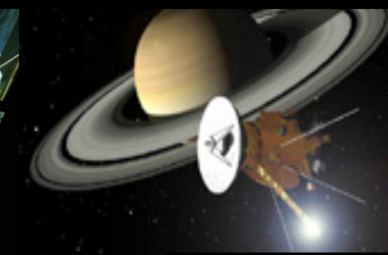


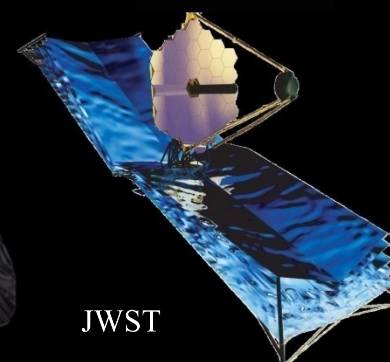


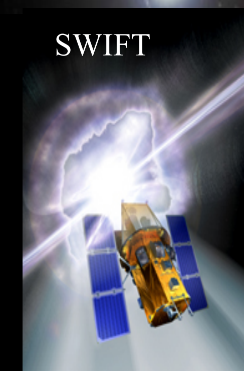


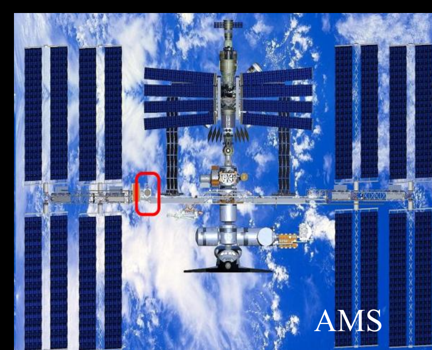


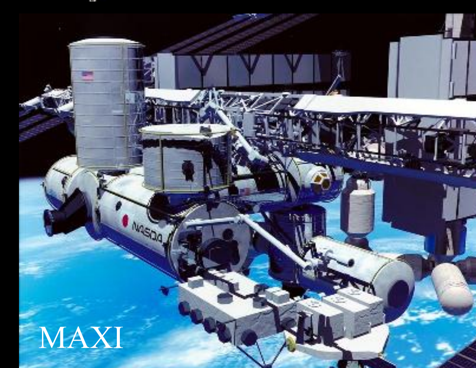






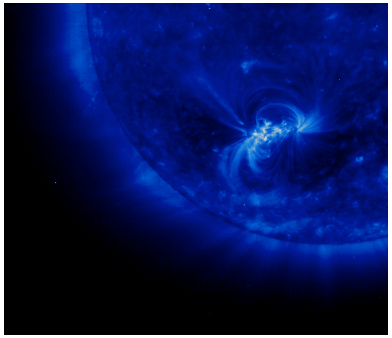


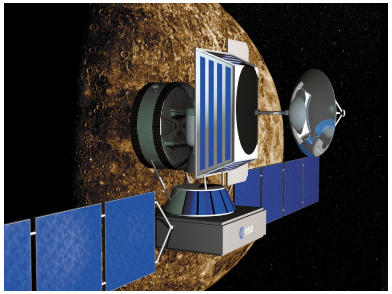


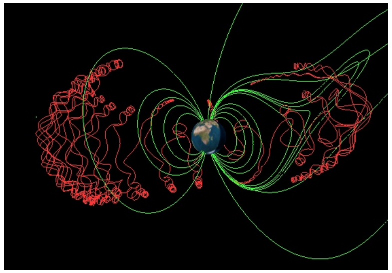


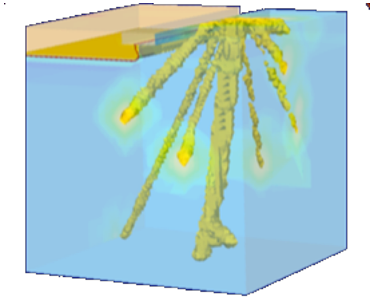
Applications of GEANT

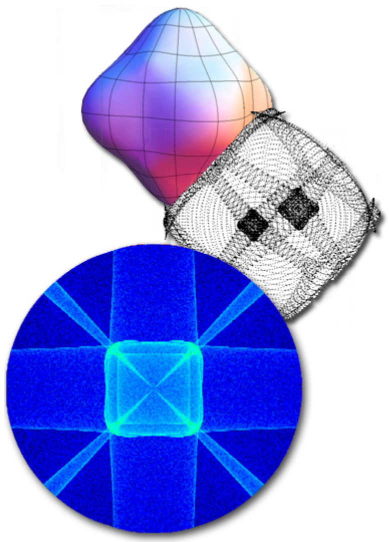
- Effect of Compton scattering on Gamma-ray spectrum in solar flares
- X-Ray mineralogical survey of mercury by Beppi-Colombo
- Cosmic Rays in planetary atmo-magnetospheres
- Single Event Upset (SEE) in SRAM
- Condensed Matter Physics
  - Phonon propagation
  - e-/h+ transport
- DNA modeling and effects of ionizing radiation



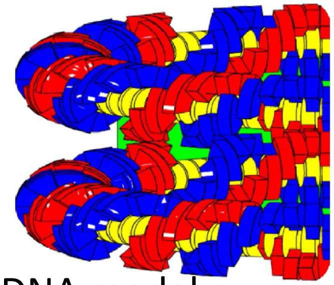




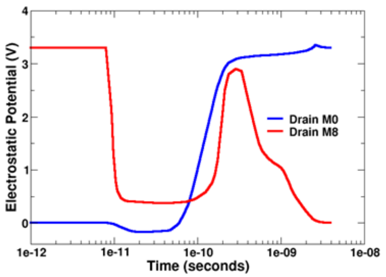




Phonon propagation



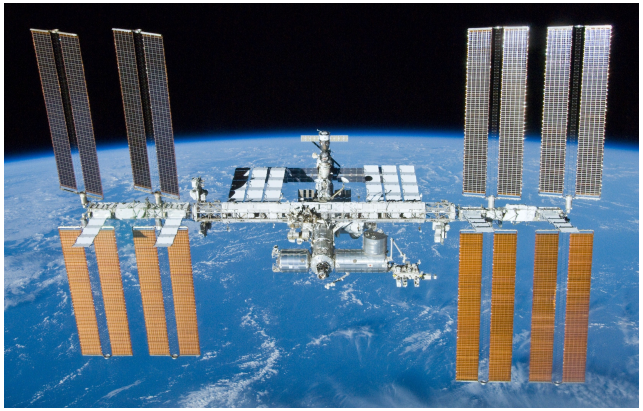
DNA model



Scientific Linux

- One of the Chicago Tribune's 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



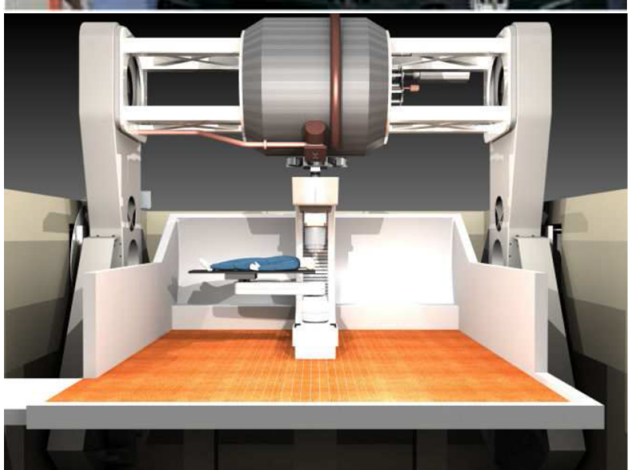
- Other notable innovations on the list: zipper, dishwasher, vacuum cleaner, open-heart surgery, sustained nuclear reaction...

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

Accelerators

Mainly covered in 'Accelerators for America's future'; few more recent developments covered here

Compact Cyclotrons



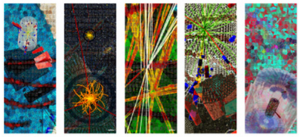
- Compact superconducting proton cyclotron for proton therapy developed by MeVion:
  - Nb_3Sn Coils
  - High J_c strand- ~3000 A/mm^2

LARP

- Conductor comes straight out of the DOE HEP Conductor Development Program and extensively vetted by US LARP

- MEVION S250 at the Siteman Cancer Center at Barnes-Jewish Hospital and Washington University School of Medicine now in clinical commissioning.

Support from Other Sciences



- Bringing the energy frontier back to the U.S. will require major innovations in compactness and cost of accelerator technology
  - Laser-driven acceleration has demonstrated >100 GeV/m gradient
- R&D needs for laser driven systems that will come from other sciences:
  - Infrared, ultrafast (<1 ps)
  - Joule-class energy
  - Lasing materials
  - TW/PW peak power
  - kW average power
  - Efficient (>15%)
  - kHz rep rate
  - High quality
    - Stable
    - Beam quality
    - Low phase noise
    - high pulse contrast

U.S. DEPARTMENT OF ENERGY

Workshop on Laser Technology for Accelerators

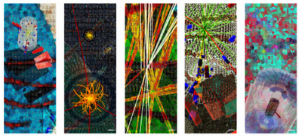
Summary Report

January 23–25, 2013

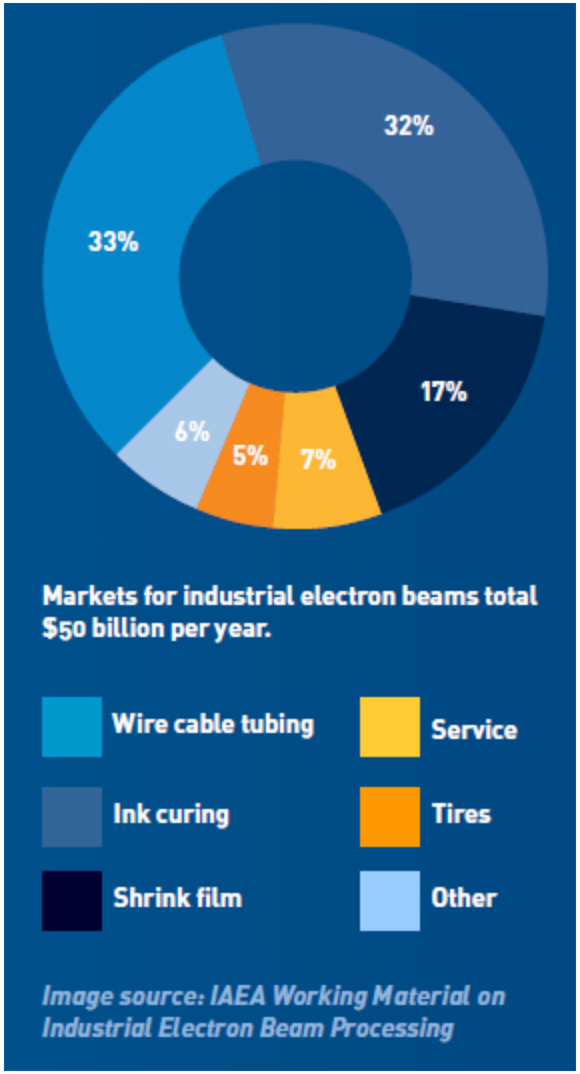
- Serves electron-positron accelerators, light sources and medical accelerators

Report: http://science.energy.gov/hep/research/accelerator-rd-stewardship/workshop-reports/

Highlights from ACCELERATORS FOR AMERICA'S FUTURE



- Many applications in industry include:
  - Electron beam used for cross-linking polymers displaces the use of volatile chemicals in many manufacturing processes:
    - Wire insulation, heat-shrinkable films & tubing, foam, tires
  - Electron beam curing of inks, coatings & adhesives to eliminate chemical waste and reduce power consumption vs. thermal curing
  - Sterilization of medical equipment
  - Disinfection and removal of pathogens from food, water & waste water
  - Ion implantation to dope silicon and germanium in semiconductors
  - Ion beam treatment of high-speed cutting tools and artificial joints
  - Superconducting RF accelerators to provide compact light sources
  - Irradiation of mail for security
- Industry applications tend to demand improved beam power, but rarely higher energy or beam brightness…

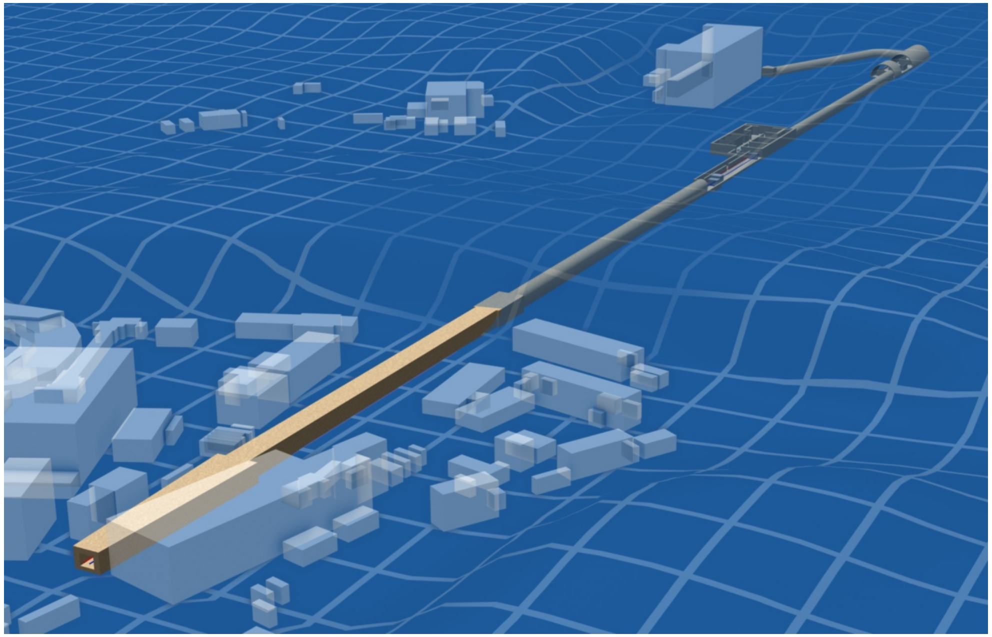


Markets for industrial electron beams total $50 billion per year.

Image source: IAEA Working Material on Industrial Electron Beam Processing

LCLS-II

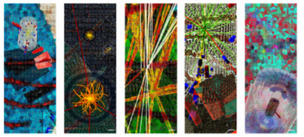
- A major project in Basic Energy Sciences is being modified to take advantage of the R&D efforts in SRF technology made by HEP and NP
  - The modified plans for the update to the Linac Coherent Light Source at SLAC call for a superconducting RF linear accelerator in the first third of the existing linac tunnel
  - In the updated plan, Fermilab and Jefferson Lab would provide SRF components for this critical initial portion of LCLS-II
  - LCLS-II "will enable world-leading experiments in chemistry, physics, biology, and materials science – experiments that will expand the science frontiers and advance energy science resulting in broad economic and societal benefits."



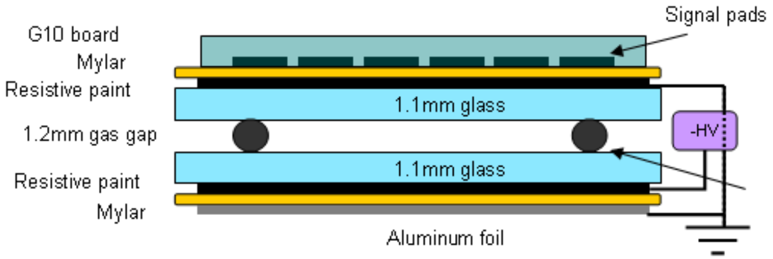
Detectors

Not just for particle physics …

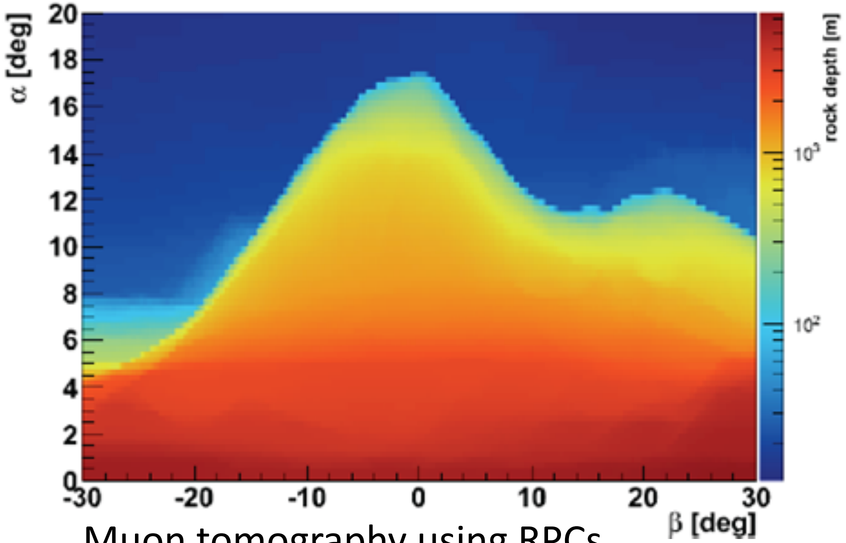
Environment



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



The Puy de Dome (Massive central)

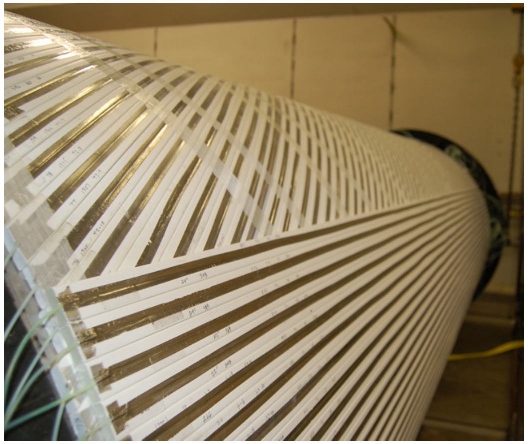


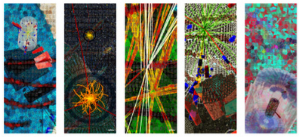
Muon tomography using RPCs (Tomuvol experiment)

- 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

Archeology

- Scintillating strips and Cherenkov counter used for imaging inside of Maya ruins





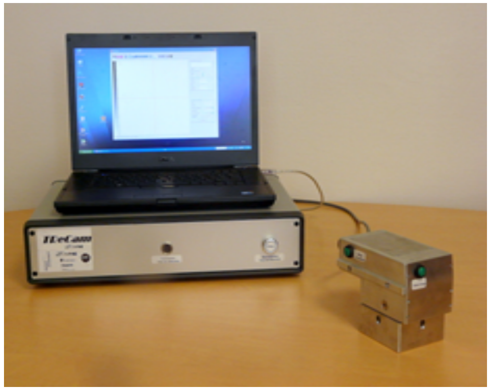
HEP ASIC for Medical Imaging

- ASIC developed for readout of Silicon PMs being used in a handheld peri-operative gamma camera called TReCam (Tumor Resection Camera) for lymphoscintigraphy
- Cancer detection through injection of a radioactive solution around the tumor; Lympho-scintigraphy then counts the lymph nodes and situate them precisely.

TReCam camera

49 x 49 mm^2 field of view
$LaBr_3$:Ce crystal optically coupled to a multi-anode photomultiplier tube

Peri-operative compact imager to aid breast cancer surgery

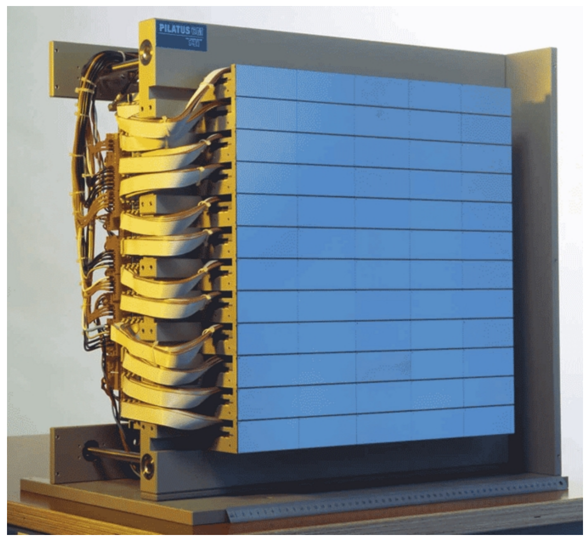


Data acquisition based on the SPIROC ASIC developed for CALICE

X-Ray Detectors

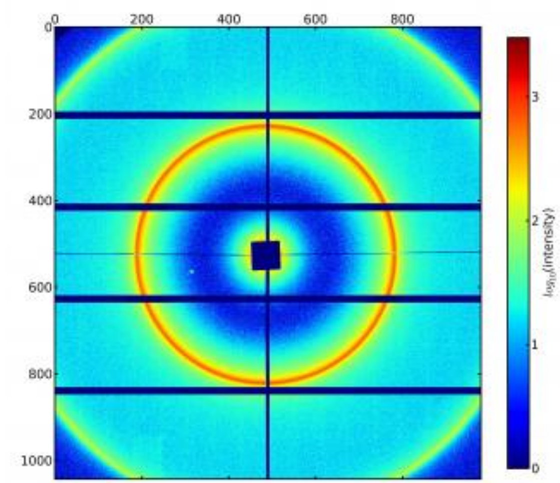
- The Pilatus detector is currently a workhorse at synchrotron facilities
- Developed at PSI, it is a direct descendant of the CMS pixel detector

CMS Pixel detector



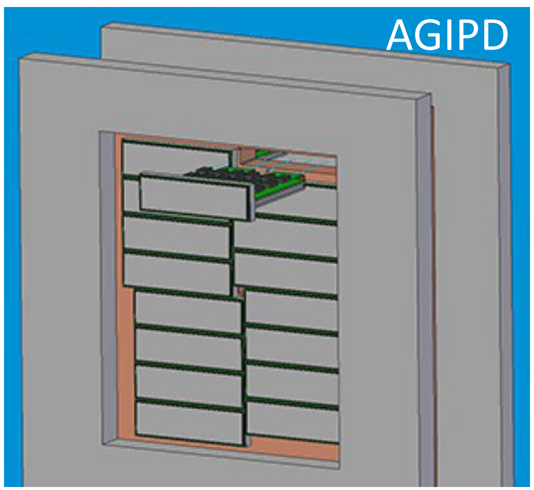
Pilatus X-ray detector

Pilatus Diffraction Pattern

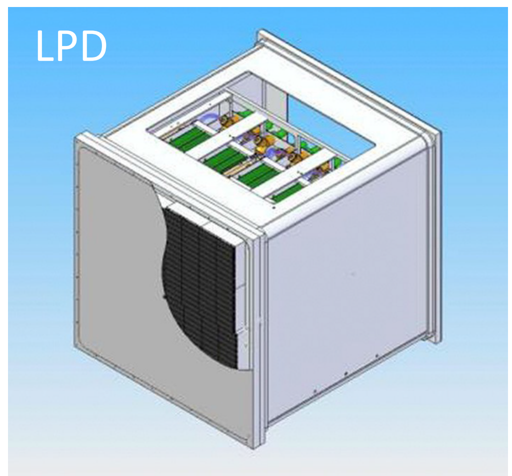


X-Ray Detectors

- Three major 2D Imaging x-ray detector developments in Europe for XFEL, with corresponding DAQ systems; expertise straight out of HEP
  - Adaptive Gain Integrating Pixel Detector – AGIPD
  - Large Pixel Detector – LPD
  - DEPFET Sensor with Signal compression – DSSC

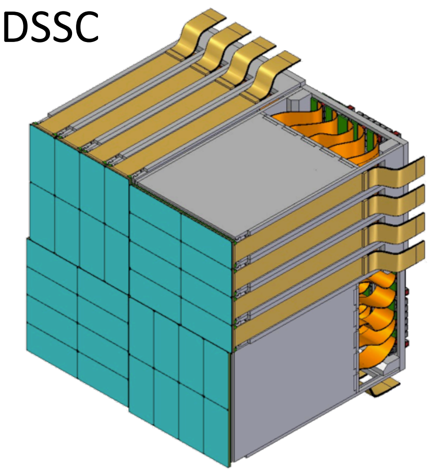


AGIPD: Hybrid pixel detector
Dynamic range/pixel/pulse
10^4 @12 keV
# of Storage cells 250 – 300
Pixel size: 200 x 200 μm^2



LPD: Hybrid pixels
Dynamic range
10^5@12 keV
Storage Cells ≈ 512
Pixel Size 500 x 500 μm^2

DSSC

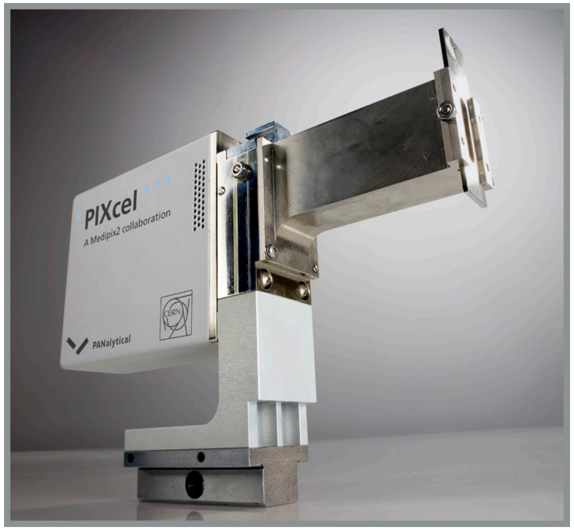


DSSC: DEPFET-based
Dynamic range/pixel/pulse
6000 @1 keV
Storage Cells ≈ 640
Pixel Size ≈ 236 x 236 μm^2

MediPix and TimePix

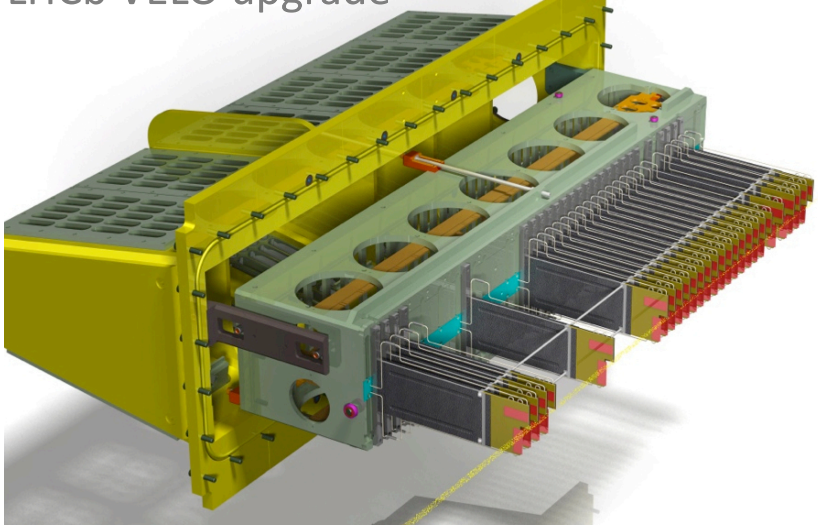
- Grew out of the development of the silicon hybrid pixel detectors for LHC
- The single photon counting provides excellent noise free images, Ideal in photon starved situations
- Many different application both foreseen and otherwise!
  - Electron microscopy
  - Neutron imaging
  - Nuclear power plant decommissioning
  - Adaptive optics
  - Dosimetry in space
  - Gas detectors
  - Beam collimation studies for sLHC

- All development nearly ideally suited for upgrade plans for LHCb VELO detector

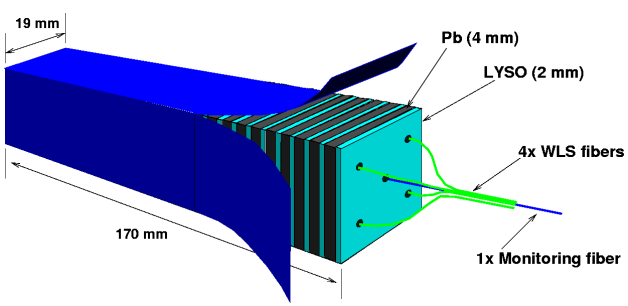


Licensed to PanAnalytical
>500 systems in use

LHCb VELO upgrade



LYSO Crystal Development



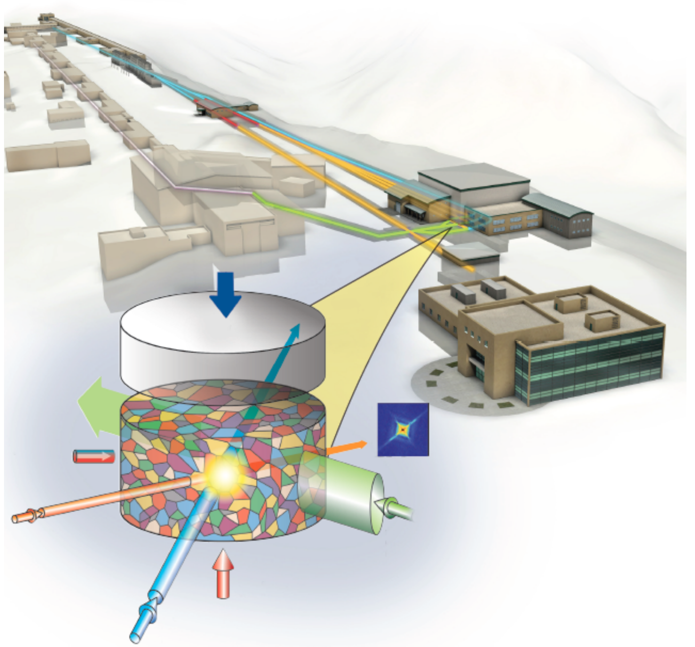
LYSO for CMS FCAL Upgrade

- Radiation damage studies of PWO crystals showed that thermal annealing of PWO crystals in oxygen atmosphere and yttrium doping were effective to improve crystal radiation hardness.
- Idea adopted and Ce:LYSO crystals and thermal annealing for Ce:LYSO were patented by B. Chai in 2005 and 2006 respectively.
- With its brighter and faster scintillation than BGO Ce:LYSO dominates TOF PET market. Thousands LYSO based PET scanners have been marketed by GE and Phillips.
- HEP now interested in Ce:LYSO crystals for the CMS forward calorimeter upgrade and (was for) Mu2e

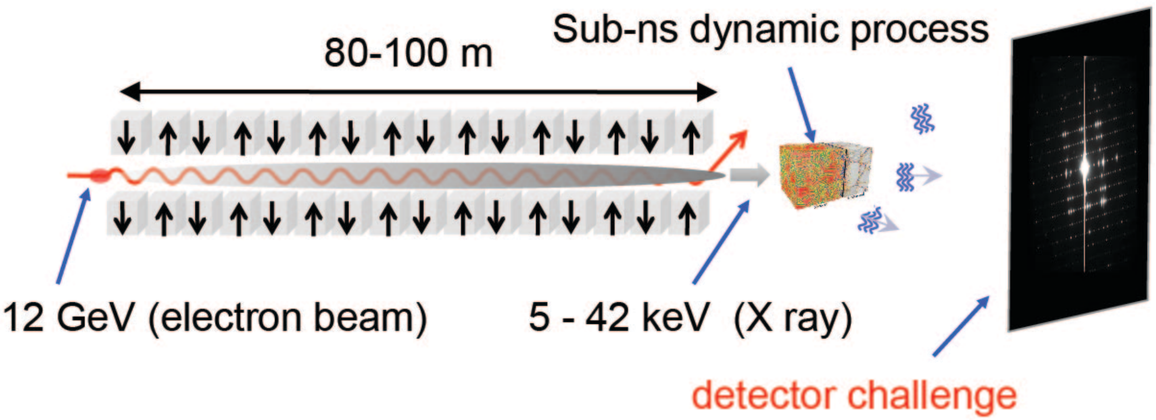
Crystals and Radiation Interaction

- MaRIE experimental facility (LANL): Matter-Radiation Interactions in Extremes

- For the study of processes under extreme conditions, need
  - Picosecond time-response
  - Gigahertz frame-rate
  - Large data handling;



MaRIE: Matter-Radiation Interactions in Extremes

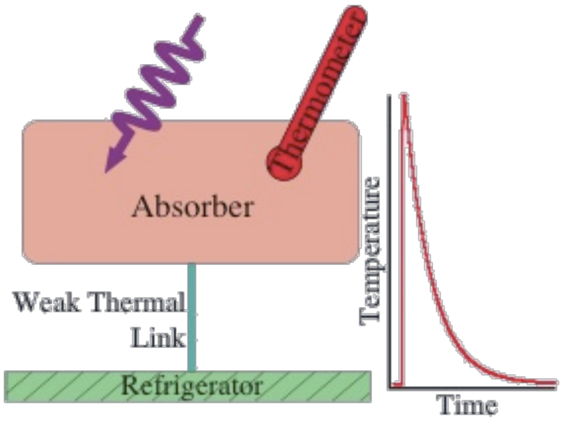


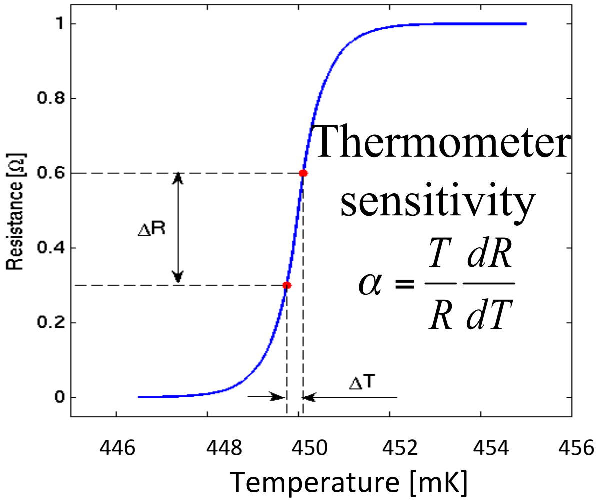
- Synergy with HEP
  - Fast crystals: BaF_2, LYSO, ...
  - ASICs

Transition Edge Sensors

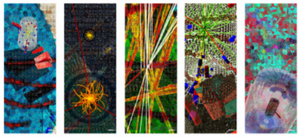
- Developed by Particle Physics for the study of neutrinos and dark matter (and SQUID development at NIST)

- After invention, rapidly implemented in other areas:
  - Astrophysics and astronomy (mm, sub-mm, optical, x-ray)
  - National Security (video thermal imaging, nuclear non-proliferation)
  - Materials (elemental, molecular, biology)
  - Quantum Mechanics (quantum cryptography, Einstein-Podolsky-Rosen tests)
  - Non-accelerator neutrino physics (beta decay, coherent neutrino scattering, cosmic neutrino background)

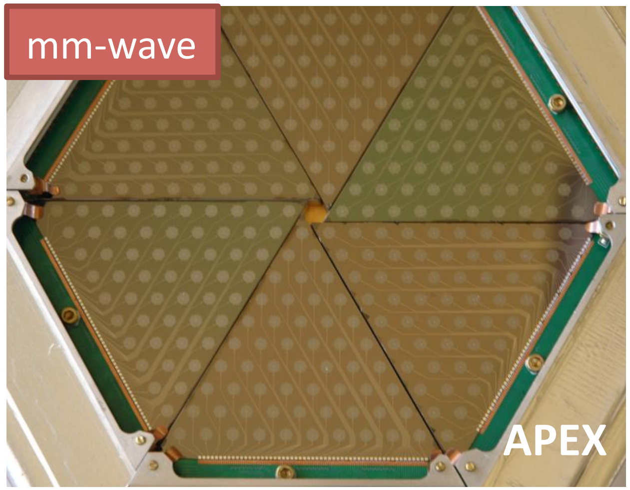


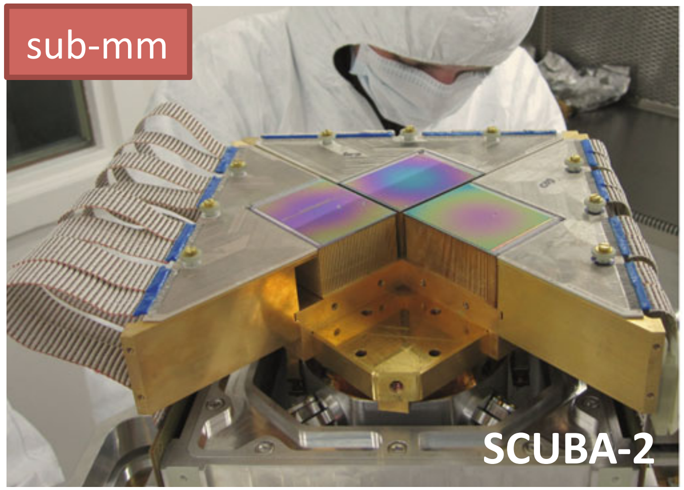


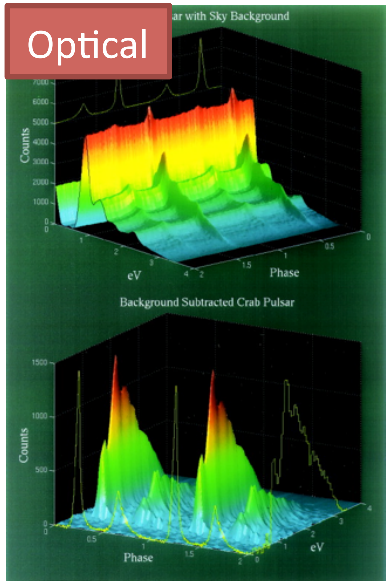
Astrophysics and Astronomy

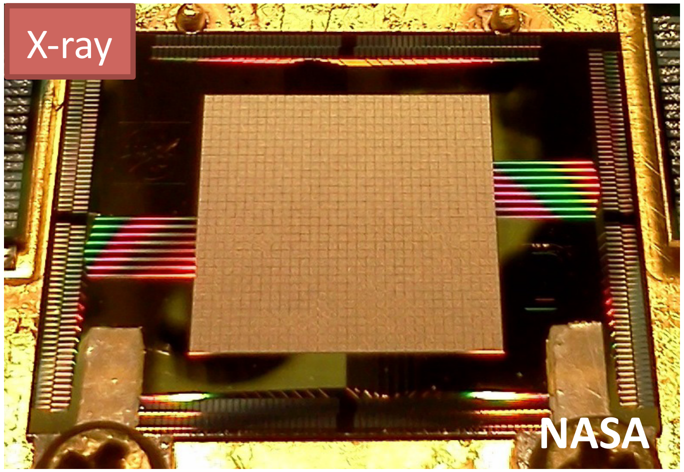


- Transition Edge Sensors tuned for various frequency ranges



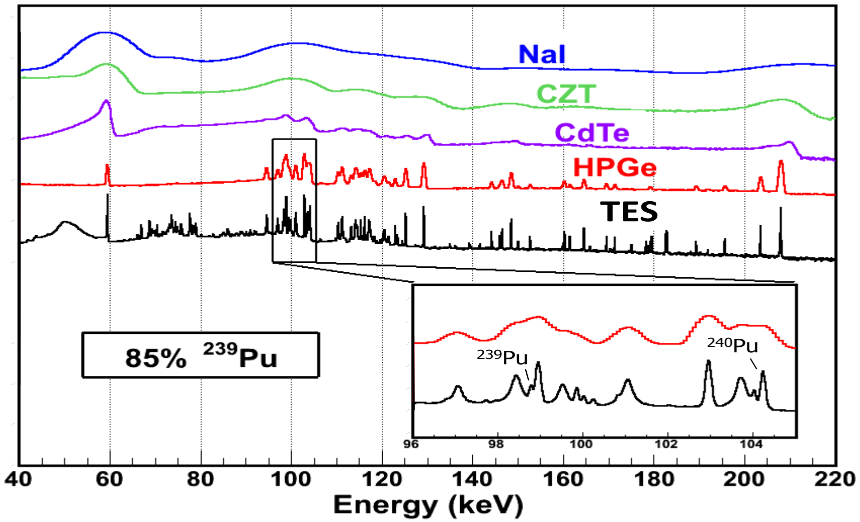


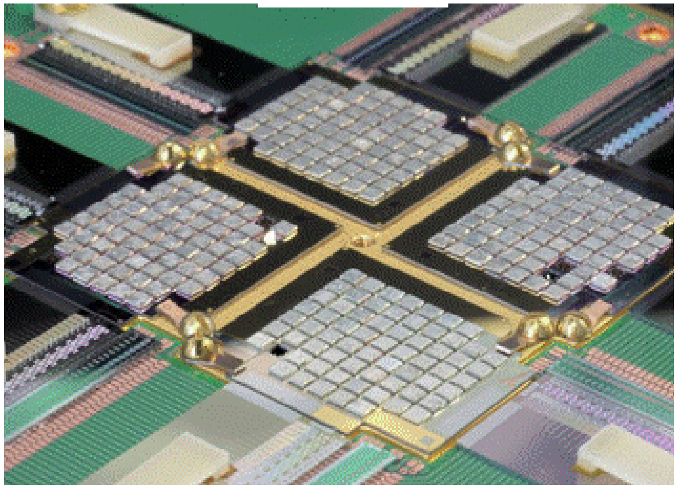




TES in National Security and Biology

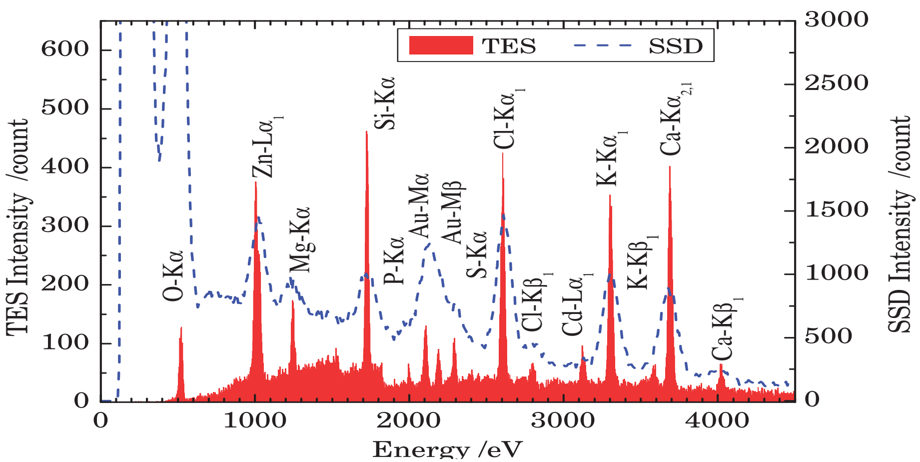
- Use as calorimeters with very good energy resolution in non-proliferation

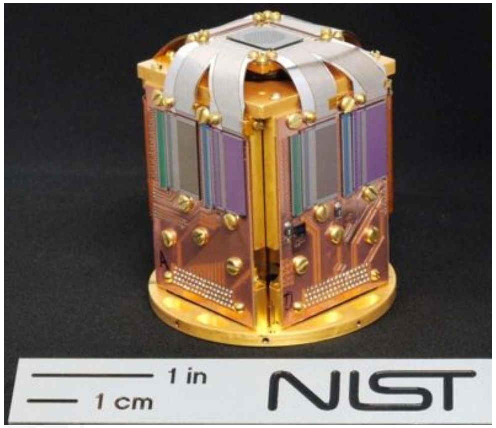




Hoover, A.S. et al., Nuclear Science, IEEE Trans., Vol.60, no.2, pp.681-688, April 2013

- Calorimeter application in biology





TES in Quantum Mechanics

- Test of Bell's theorem

LETTER

Nature 497, 227–230 (09 May 2013)

Bell violation using entangled photons without the fair-sampling assumption

Marissa Giustina[1,2]*, Alexandra Mech[1,2]*, Sven Ramelow[1,2]*, Bernhard Wittmann[1,2]*, Johannes Kofler[1,3], Jörn Beyer[4], Adriana Lita[5], Brice Calkins[5], Thomas Gerrits[5], Sae Woo Nam[5], Rupert Ursin[1] & Anton Zeilinger[1,2]

- Quantum communication

nature COMMUNICATIONS OPEN

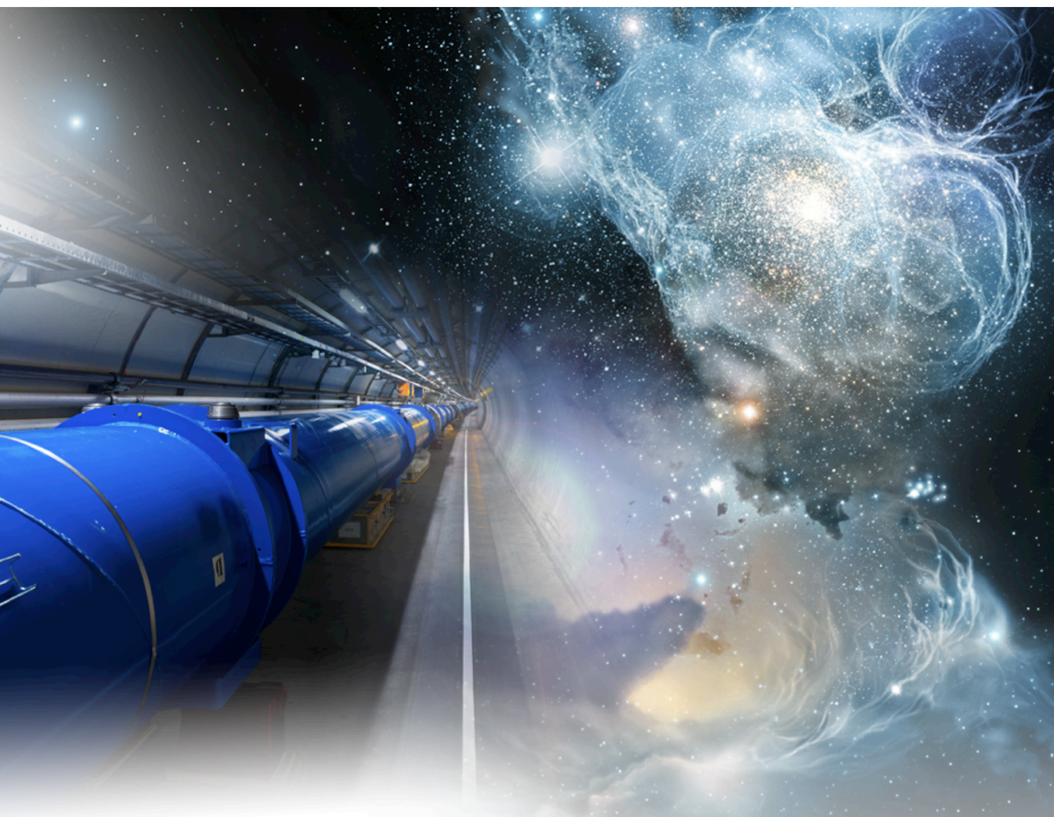
ARTICLE

Received 3 Aug 2011 | Accepted 30 Nov 2011 | Published 10 Jan 2012 DOI: 10.1038/ncomms1628

Conclusive quantum steering with superconducting transition-edge sensors

Devin H. Smith[1,2], Geoff Gillett[1,2], Marcelo P. de Almeida[1,2], Cyril Branciard[2], Alessandro Fedrizzi[1,2], Till J. Weinhold[1,2], Adriana Lita[3], Brice Calkins[3], Thomas Gerrits[3], Howard M. Wiseman[4], Sae Woo Nam[3] & Andrew G. White[1,2]

Facilities

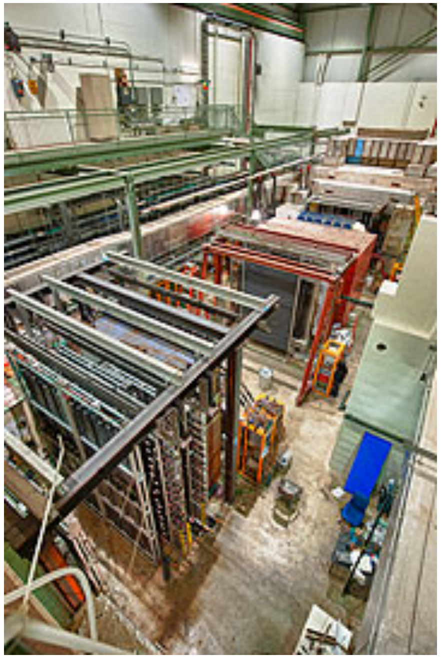


From materials science to astronomy, many sciences benefit from HEP facilities and vice-versa

HEP Operated Facilities

- Accelerator Based particle physics sites have particle beams – protons, pions, electrons, muons, ...
- Study of nucleation of aerosol particles and their effects on the atmosphere; effects of cosmic rays in the context of seeding clouds
- Cosmics Leaving Outdoor Droplets (CLOUD) experiment at CERN
  - Based at CERN's Proton Synchrotron
  - Uses a cloud chamber to study the possible link between galactic cosmic rays and cloud formation
    (Nature 502, 359–363 (17 October 2013))
- SeaQuest nuclear physics experiment at Fermilab
  - Measuring contributions of antiquarks to nucleon structure using protons from the Fermilab Main Injector accelerator

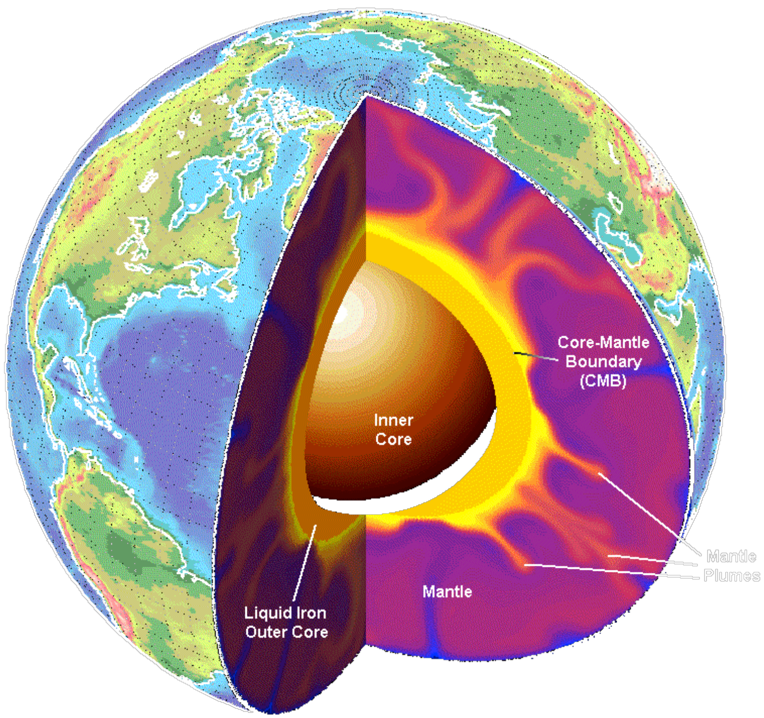
CLOUD experiment



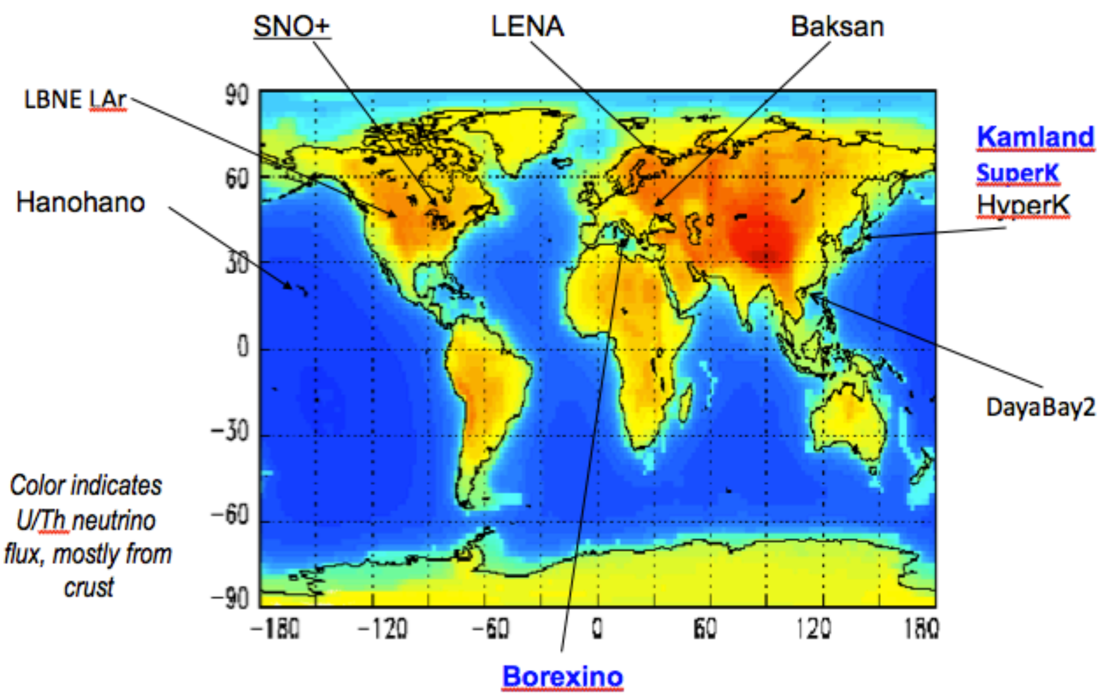
SeaQuest

Detectors for GeoNeutrinos

- How to 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

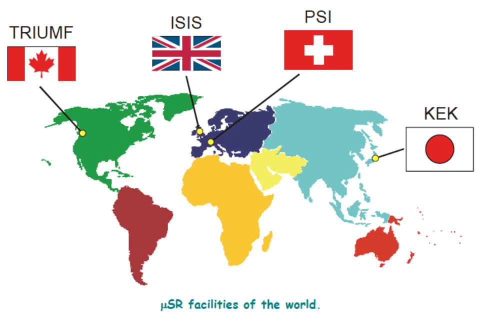


Present and possible experiments for Geoneutrinos



Stopped Muon Beams

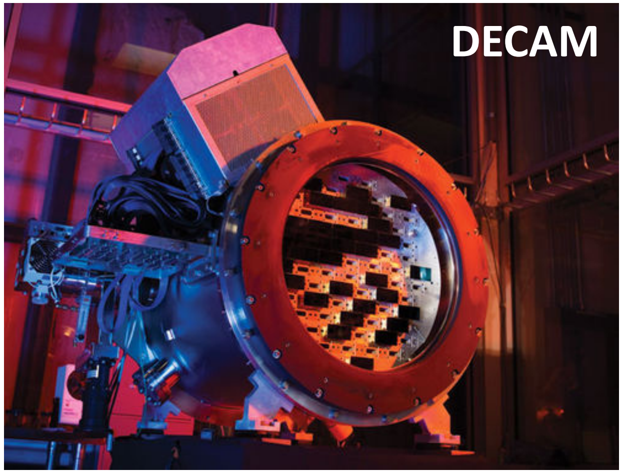
- Muons provide a complementary probe to neutrons, particularly in the areas of magnetism, superconductivity and charge transport
- Requires stopped muon beams, with fluxes of the order of 10^4-10^7/s/cm^2
  - Muon Spin Resonance (μSR) & Spectroscopy (μ^+)
    - Magnetic systems: spinglasses, colossal magnetoresistance, quasi-crystals
    - Superconductors: magnetic phase diagrams, vortex phases
    - Transport: quantum diffusion, conducting polymers
    - Semiconductors
  - Muonic Chemistry (μ^-): free radical systems
  - Muon Catalyzed Fusion (μ^-)
  - Potential (currently mostly theoretical) interest: Parity Violation experiments, Vacuum Polarization, muon induced fission
- Since the Los Alamos Muon Facility shut down, experiments are conducted at muon facilities at international particle physics labs



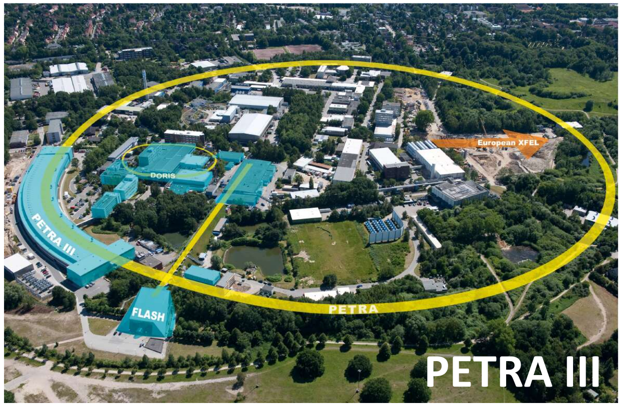
- μSR2014, held every three years: http://indico.psi.ch/internalPage.py?pageId=0&confId=2039
  Muon Spectrocopy: http://www.isis.stfc.ac.uk/instruments/muon-spectroscopy4762.html

HEP-Built Facilities

- Sky surveys
  - Cameras built (or being built) by HEP for the benefit of particle astrophysics and the wider astronomy community: SDSS, DES, LSST



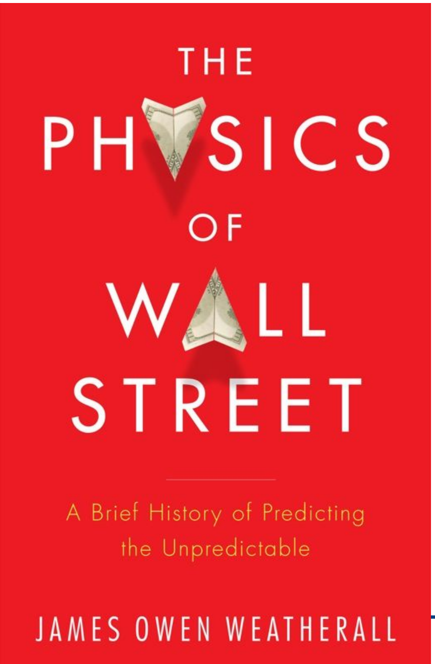
- Light sources: second lives for particle physics machines:
  - SLAC linac now drives the Linac Coherent Light Source (LCLS), creating x-ray pulses of unprecedented brilliance
  - PETRA, where the gluon was discovered, now forms the heart of the PETRA III x-ray radiation source



Finance and (High Energy) Physics

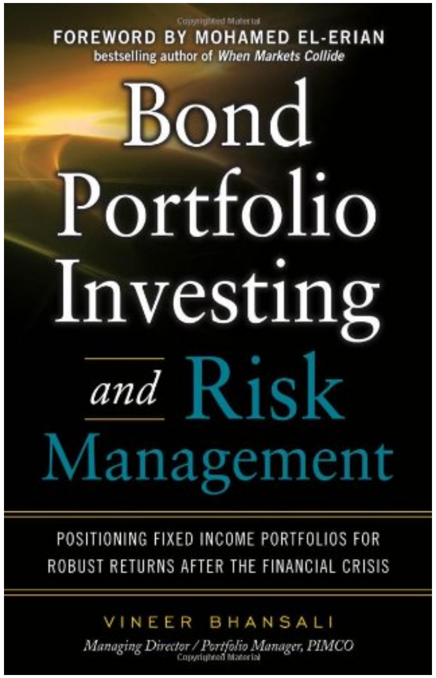
Tremendous impact

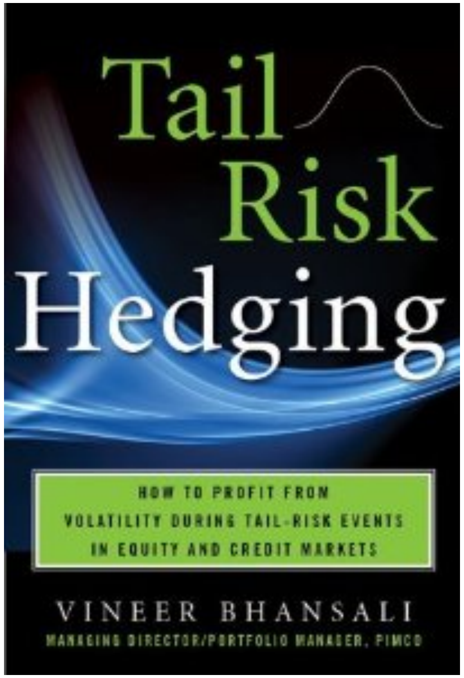
Hard to quantify

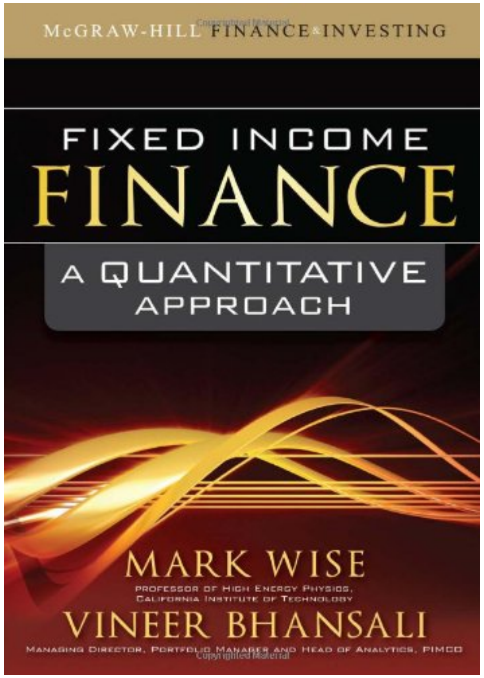


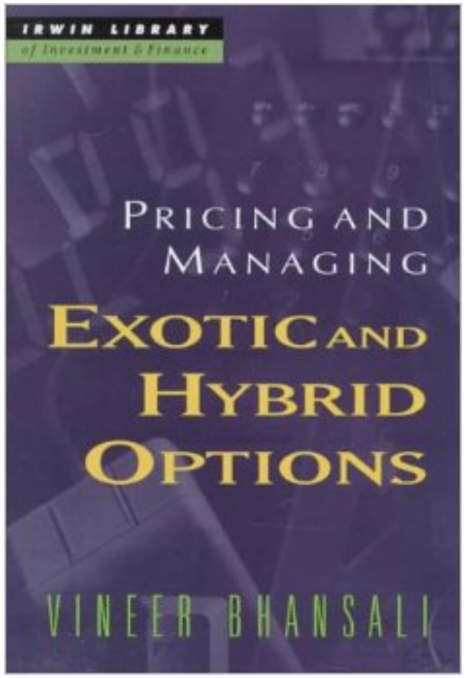
Example

- PhD Thesis “Symmetries, Anomalies and Effective Field Theory”, Harvard, advisor Howard Georgi (1992)
- Undergraduate at Caltech with P5 panel member
- Currently managing director and portfolio manager with Pacific Investment Managing Company (PIMCO)







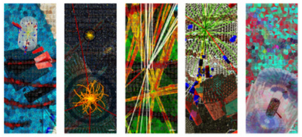


Why Physicists Succeed in Finance

- Good mix of “hard” and “soft” skills often lacking in people trained by other fields
- “Hard” skills:
  - Higher Mathematics, Probability, (informal) Statistical Inference
  - Scientific Methodology
  - Can extract info from dense text (physics articles, but also legislation, etc.)
  - Skillful document writing
  - C++, Python, other computer programming
  - "Big Data" Analysis Techniques
- “Soft” skills:
  - Collaborative Teamwork with hundreds or thousands of peers
  - Public speaking (technical or general audiences)
  - Critical thinking, creatively solving previously unsolved problems, often complex problems with many steps
  - Scheduling (and sometimes construction of) large projects
  - Mental focus
  - Strong Self-Motivation

Context and Conclusion

Horizon 2020 and ATTRACT



- Horizon 2020 is a EU Research and Innovation program with ~€80 billion of funding available over 7 years (2014 to 2020), implementing the "Innovation Union", a flagship initiative aimed at securing Europe's global competitiveness.

- ATTRACT (breAkThrough innovaTion pRogrAmme for deteCtor / infrAstructure eCosysTem) is a proposal from CERN to the European Commission (EC) for a dedicated EC-funded program to develop new (ionizing) radiation sensor and imaging technologies for scientific purposes, while addressing also societal challenges in the domains of health, sustainable materials and information and communication technologies (ICT)

- Goal of ATTRACT is ~1% of H2020, with a HEP "share" of ~20%, i.e. ~200 M€

Observations

- This presentation could only give a taste of the connections of the tools, techniques and technology of HEP to other sciences and society as a whole; apologies to those topics not covered.
- The connections of HEP reach far and wide and sometimes in unexpected places.
- Some developments have made a huge impact.
  - World-wide web, hadron therapy, PET scan, ...
- Potential for much more in the future. Particle physics community should not only continue its efforts to reach out to other communities, but up its game.
- These connections help make the case for particle physics and discovery science. Other fields are extremely attractive and challenging for new generations of scientists; HEP has a lot to gain by establishing connections with other fields (and a lot to lose by not doing so).

Recommendations

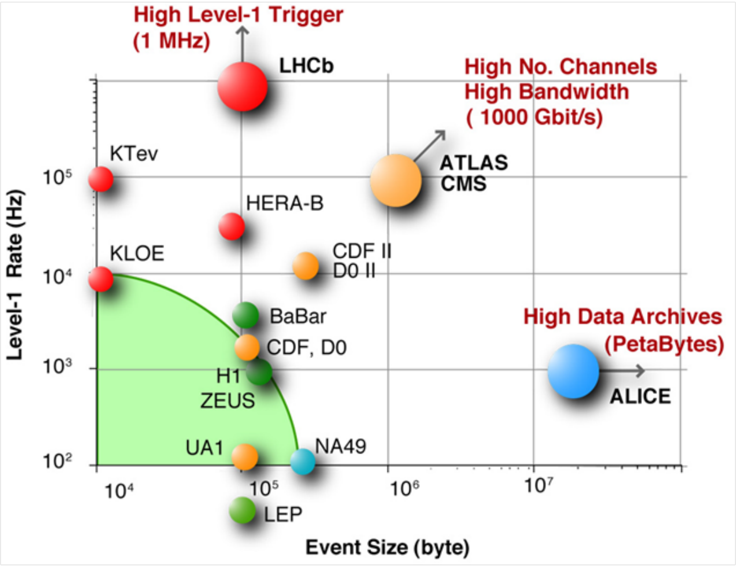
- More complete case studies – possibly quantitative – should be undertaken to evaluate the impact of HEP, e.g.
  - BGO crystals and PET Imaging
  - Supercomputers (HEP + NP)
  - Proton Therapy
  - Scientific Linux

- A series of joint workshops should be held to explore the connections of HEP with other sciences and to initiate the process of breaking down the stove-piping for detector development among the sciences
  - Joint workshops with materials science and condensed matter physics
  - Joint workshop on imaging and X-ray detectors
  - Joint workshop on hadron therapy
    - Note: there was a DOE – National Cancer Institute (NCI) joint workshop, Jan 9 – 11, 2013 http://science.energy.gov/hep/research/accelerator-rd-stewardship/workshop-reports/
  - Joint workshop on atmospheric sciences

Backup: further material

Energy Sciences Network (ESnet)

- Energy Sciences Network (ESnet) is a high-performance, unclassified US network to support scientific research. Links the entire National Laboratory system, its supercomputing facilities, and its major scientific instruments.



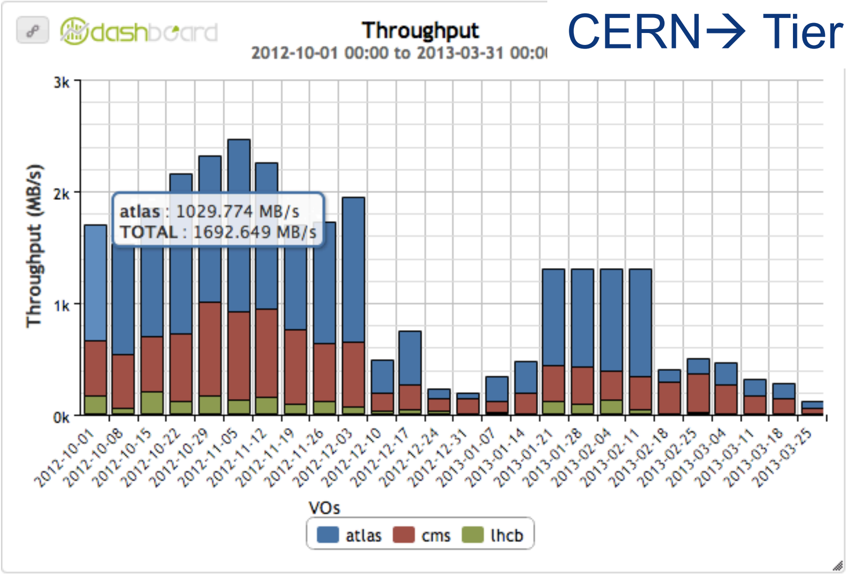
- Research in HEP depends on availability of reliable high-bandwidth, feature-rich Computer Networks for interconnecting instruments and computer centers globally
  - Research Networks becoming extensions of HEP discovery instruments

- For decades, HEP network traffic has been primary driver of National Research and Education Network (NREN) growth
  - Partnerships between HEP and NRENs have broken new ground
  - HEP requirements motivate NREN research activities
    - Needs process of translating results into architectures NRENs can deploy
  - Productivity of HEP dependent on ecosystem of innovative global NRENs
    - Collaborative research by HEP, network researchers and NREN staff

Data Transfers

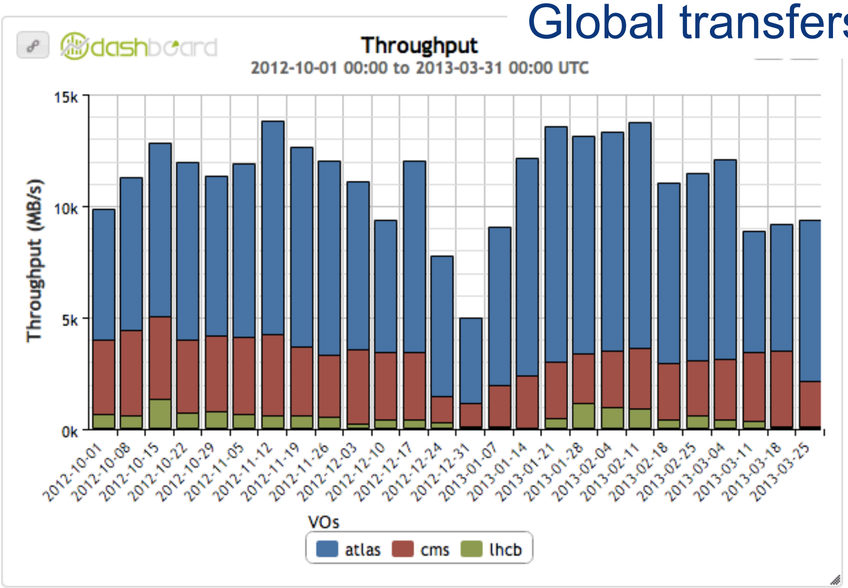
- ❑ CERN export rates driven (mostly) by LHC data export

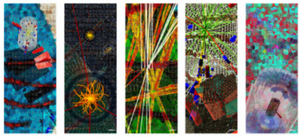
CERN→ Tier 1s



- ❑ Global transfer rates are always significant (12-15 GB/s) – permanent on-going workloads

Global transfers





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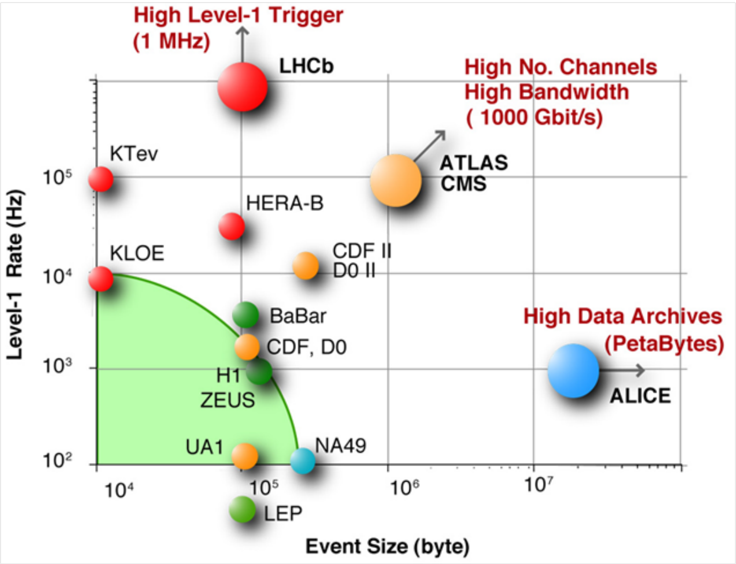

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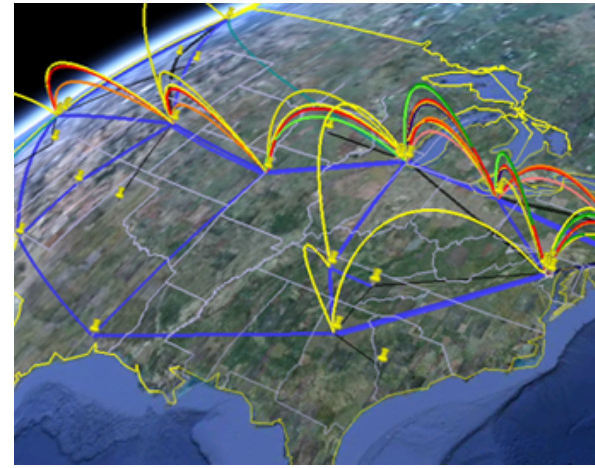
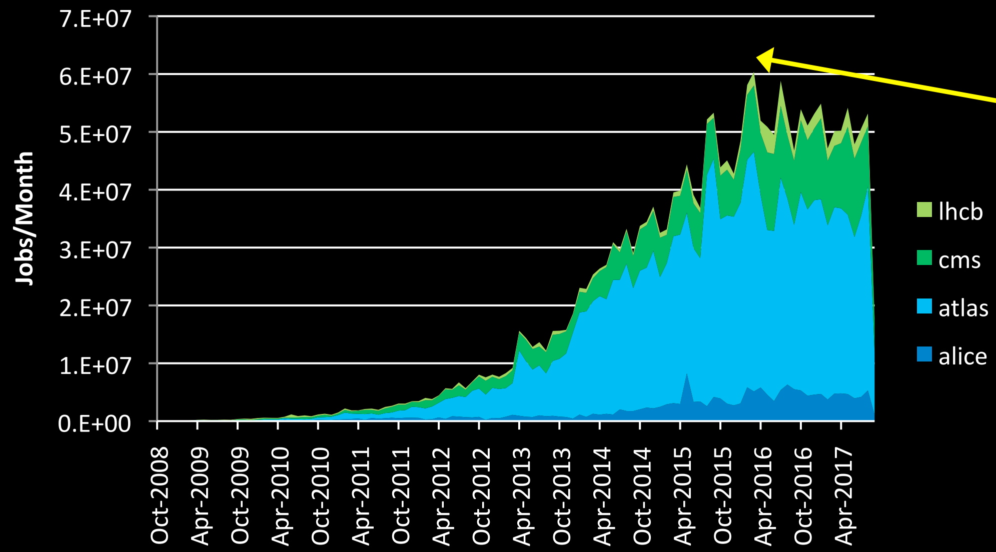
ESnet



- Large-scale HEP data flows recognized by ESnet as primary driver for strategy for evolving architecture and implementation of ESnet across SC labs and worldwide
- HEP in particular provided specific requirements leading to detailed design of ESnet4 in 2007-9, leading to the first generation network designed specifically for data-intensive science
- Spurred by HEP needs, ESnet developed virtual circuit service: OSCARS
  - The On-demand Secure Circuits and Reservation System
  - OSCARS is a software service that creates dedicated bandwidth channels for scientists who need to move massive, time-critical data sets around the world.
    - The service is now used by other data-intensive science communities; received 2013 R&D 100 award
- Due to global nature of HEP community ESnet got very actively engaged in collaborations with Research Network providers around the globe
    - Major international traffic exchange locations associated with SC programs are driven by HEP requirements

OSCARS 0.6 was recognized as one of R&D Magazine's top 100 technologies.

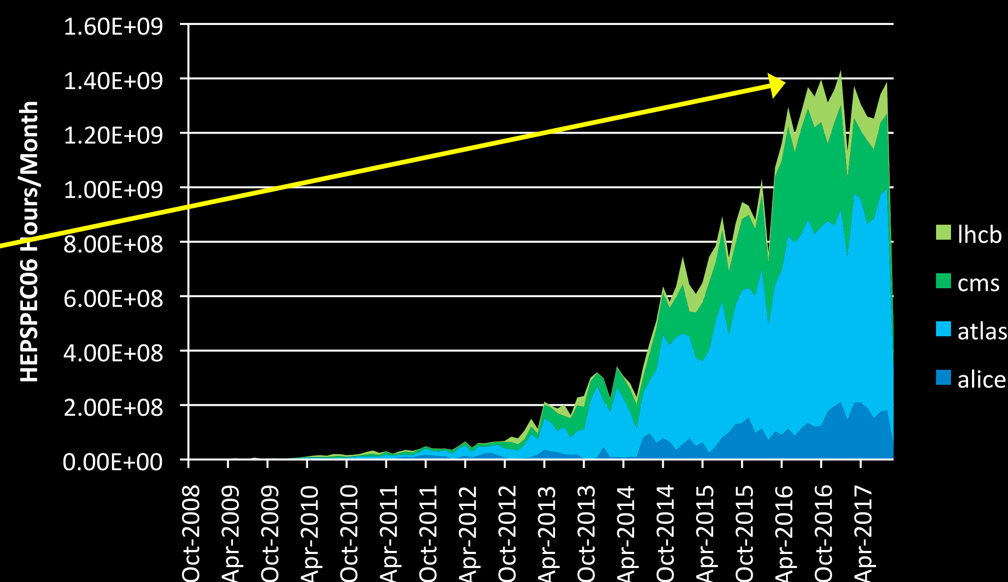
Processing on the Grid



2M Jobs/day

1.4 10^9 HEPSPEC06/Month
(210 K CPU continuous use)

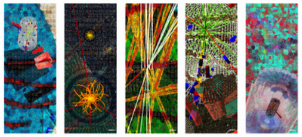
Close to full capacity



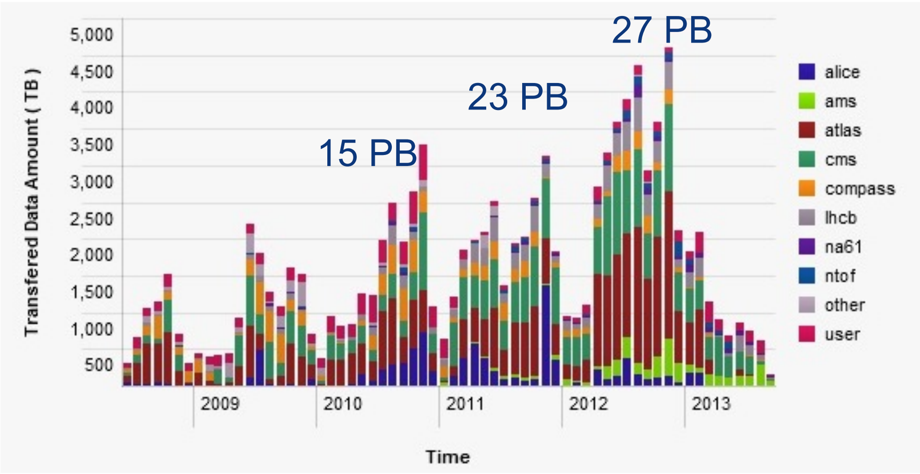
(W)LCG – Project and Collaboration

- LCG was set up as a project in 2 phases:
  - Phase I – 2002-2005: Development & planning; prototypes
    - End of this phase the computing Technical Design Reports were delivered (1 for LCG and 1 per experiment)
  - Phase II – 2006-2008: Deployment & commissioning of the initial services
    - Program of data and service challenges
- During Phase II, the WLCG Collaboration was set up as the mechanism for the longer term:
  - Via an MoU – signatories are CERN and the funding agencies
  - Sets out conditions and requirements for Tier 0, Tier 1, Tier 2 services, reliabilities, etc.
  - Specifies resource contributions – 3 year outlook

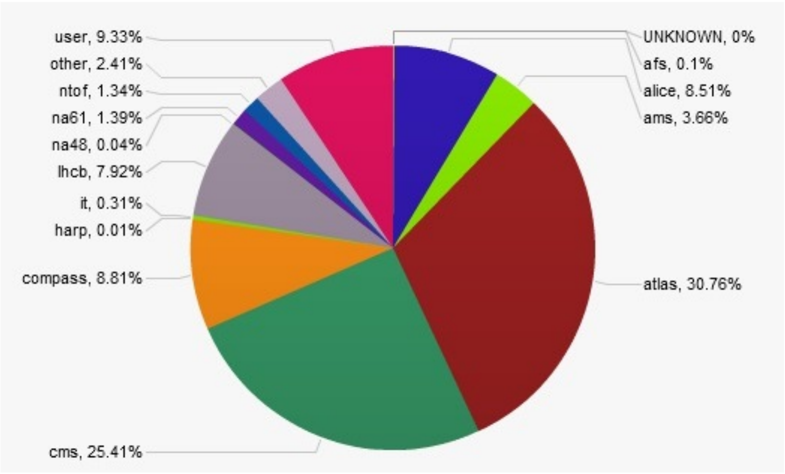
LHC Data: 2008 – 2013



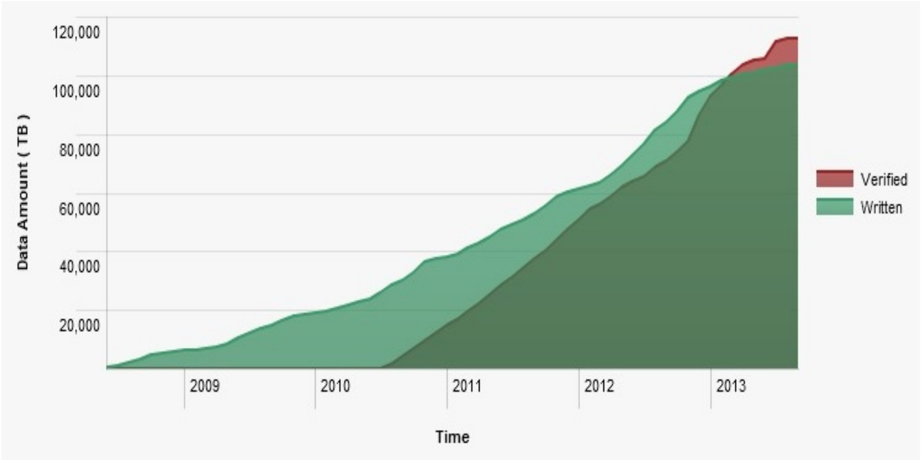
CERN Tape Writes



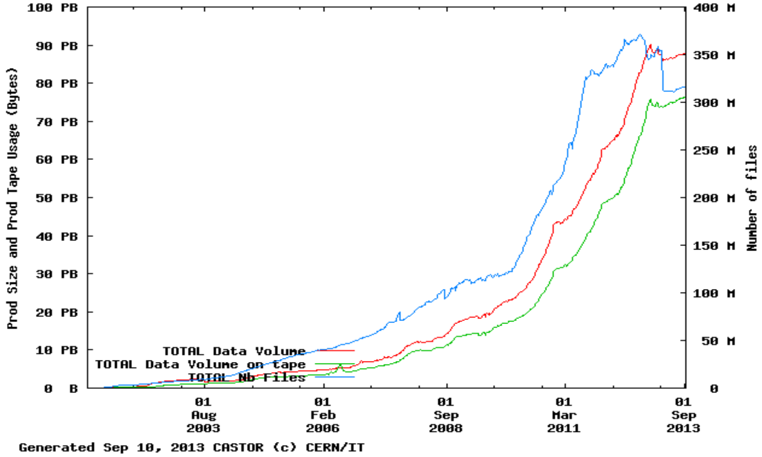
Tape Usage Breakdown



CERN Tape Verification



CERN Tape Archive



Data Loss: ~65 GB over 69 tapes
Duration: ~2.5 years

GEANT Growing Communities

- Geant4 2013 International User Conference and tutorial: At the frontier between Physics, Medicine and Biology

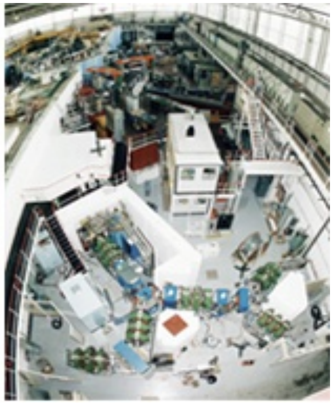
- 62 Talks from around the globe; 104 participants
- http://geant4.in2p3.fr/2013

Software

Tools Beyond HEP

International μSR Research

Paul Scherrer Institute



Rutherford Lab RAL, UK and RIKEN RAL Facility for Muons

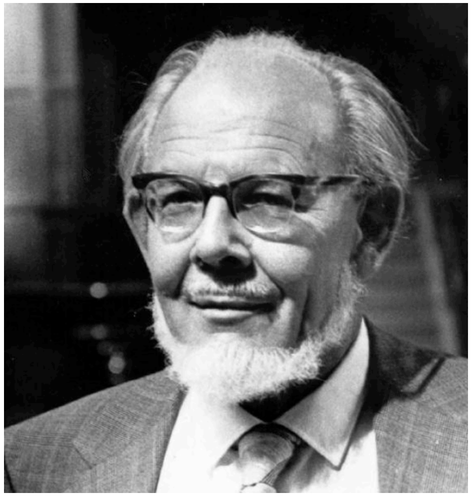
DUBNA,
Russia

High Energy Accelerator Research Organization (KEK)

TRI-University Meson Facility (TRIUMF)

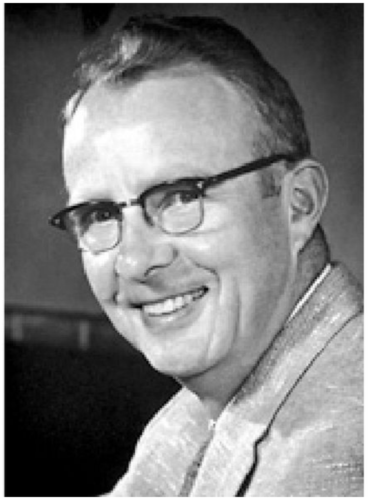
μSR Theorized and Discovered in the 50's

Andrei Sakharov



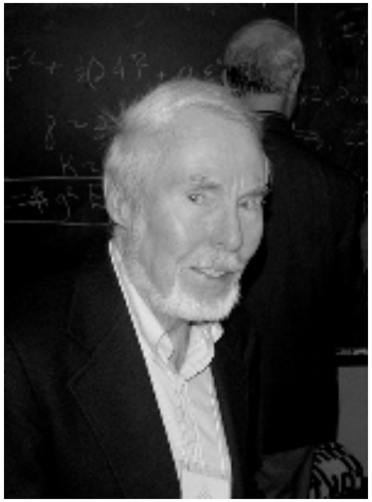
Sir Frederick Charles Frank

Yakov B. Zel'dovich



Luis W. Alvarez

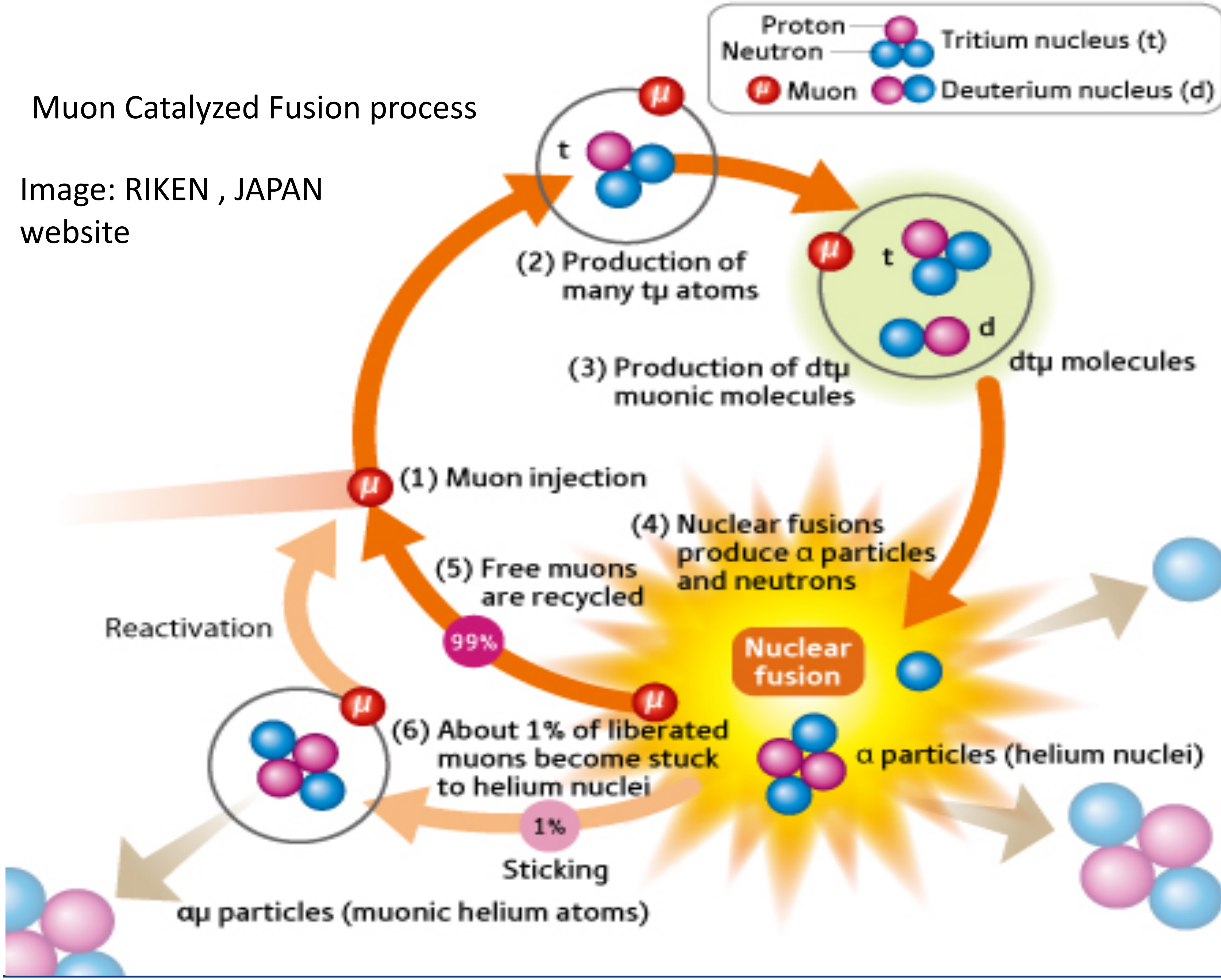
Edward Teller



JD Jackson

Muon Catalyzed Fusion process

Image: RIKEN , JAPAN website



Stopped Muon Beam μ^-

Rapidly form bound states with nuclei – Muonic atoms & molecules

being 206 times smaller than normal electronic atoms (Mμ/ Me ~ 206)

Non Particle Physics opportunities: Muonic chemistry and

Muon catalyzed fusion in the hydrogen systems – the latter (for pdμ)

was discovered by Alvarez (by accident) – at LBNL; explained by E Teller

and calculated exhaustively one weekend by JD Jackson – in the sixties.

Postulated theoretically earlier.

Muon Catalyzed Fusion (μcf) research was funded for a brief period of

time by the DOE Advanced Energy Program and the status analyzed in a

JASON report JSR-88-300 in 1990 by F. Dyson, D. Eardley, S. Koonin,

C. Max, R. Muller, M. Rosenbluth, and S. Trieman.

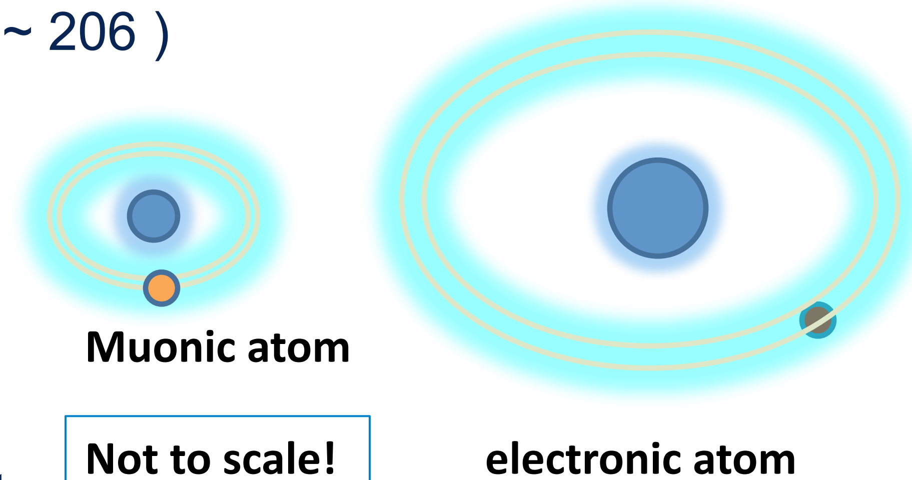
Like any other paths to nuclear fusion – the reactions generate energy

and in the case of ddμ - Helium -3

Research continues internationally – KEK, ISIS, PSI, DUBNA…

Negative Muons

- Rapidly form bound states with nuclei – the resulting Muonic atoms being 206 times smaller than normal electronic atoms (Mμ/ Me ~ 206)
  Muonic atoms rapidly form Muonic Molecules
- Muonic Chemistry
  These ‘exotic’ atoms and molecules also host muon catalyzed fusion in the hydrogen systems.

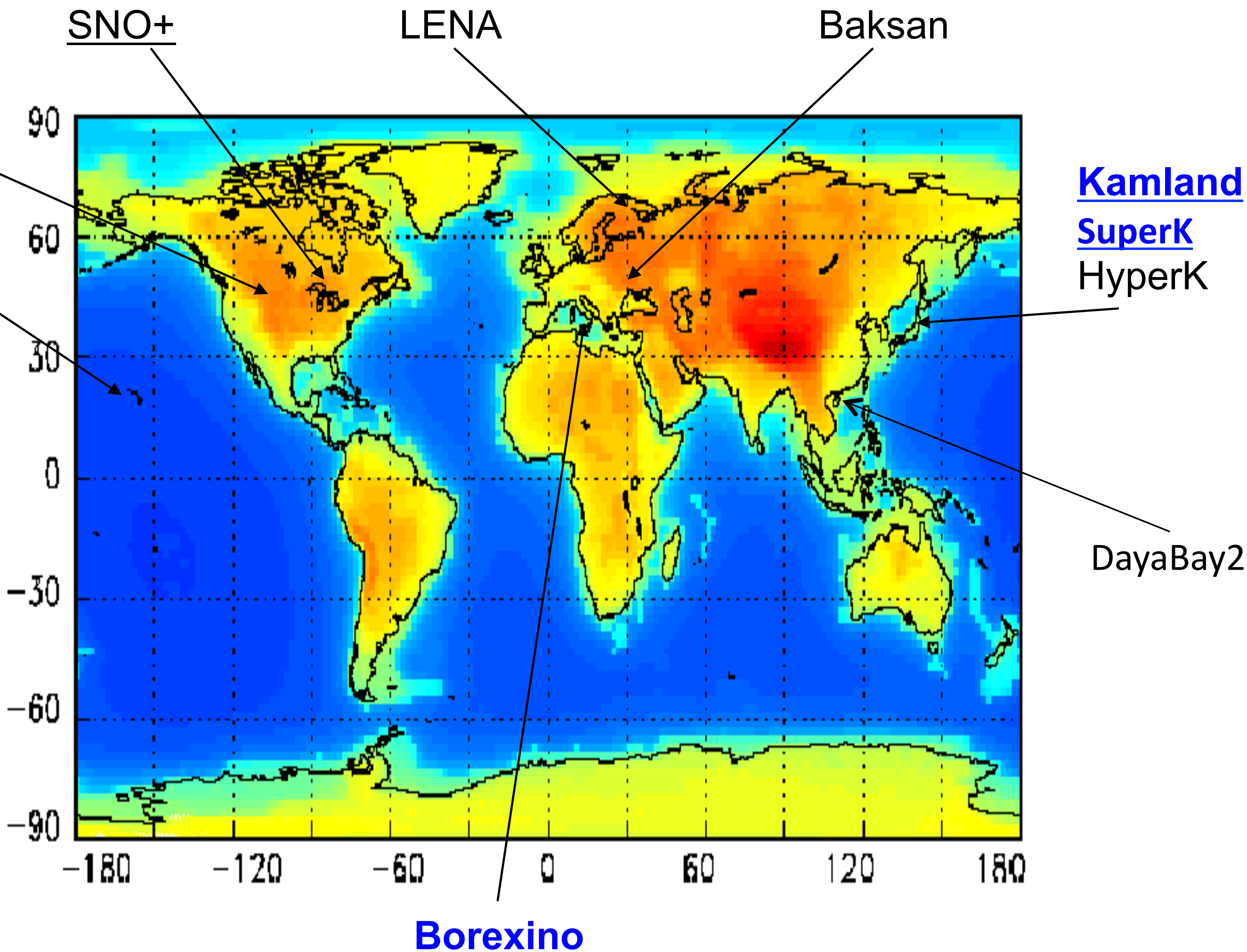


- The process (for pdμ) was discovered by Alvarez (by accident) – at LBNL; explained by E Teller and calculated exhaustively one weekend by JD Jackson.

US Research and Jason Report

- Muon Catalyzed Fusion (μcf) research was funded for a brief period of time by the DOE Advanced Energy Program and the status analyzed in a JASON report JSR-88-300 in 1990 by F. Dyson, D. Eardley, S. Koonin, C. Max, R. Muller, M. Rosenbluth, and S. Trieman.

- Research continues at the international muon facilities
- And the potential promise of energy and helium 3 (as with other fusion channels remains a (distant?) possibility



Color indicates U/Th neutrino flux, mostly from crust

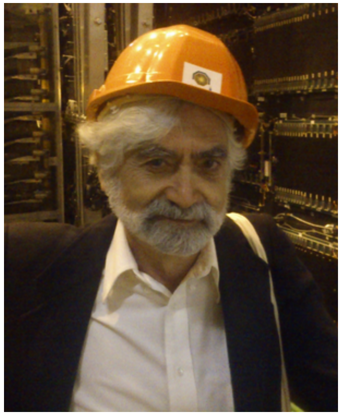
A Few Historical Highlights

- Early 1900s: J.W. Gibbs
  - Arguably the first American mathematical physicist
  - Helped lay the foundation of thermodynamics and statistical mechanics
- Early 1900s: Gibbs' student E.B. Wilson studied "vital statistics" at Harvard school of public health; became mentor of Paul Samuelson
- Mid-1900s: Paul Samuelson became a disciple of the Gibbsian tradition and rewrote economics in the language of mathematics, borrowing extensively from Gibbs' statistical mechanics
  - Awarded the second Nobel prize in economics
- 1959: Maury Osborne, trained as an astronomer, wrote the seminal paper "Brownian Motion in the Stock Market" at Naval Research Laboratory
- 1970s and 1980s: Physicists and mathematicians begin to enter finance en masse

Examples

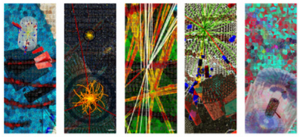
- James Simon: PhD in mathematics from Berkeley (1961)
  1964-1968 at MIT and Harvard;
  1968: chairman math department Stony Brook
- Developed, with Chern, topological quantum field theory; "Chern–Simons forms", especially the 3-form, play an important role in gauge and string theory.

- 1982 founded the Renaissance hedge fund, in East Setauket. Best hedge fund ever (arguably the best mathematical physics department in the US)
  - #82 on Forbes' World Richest People list

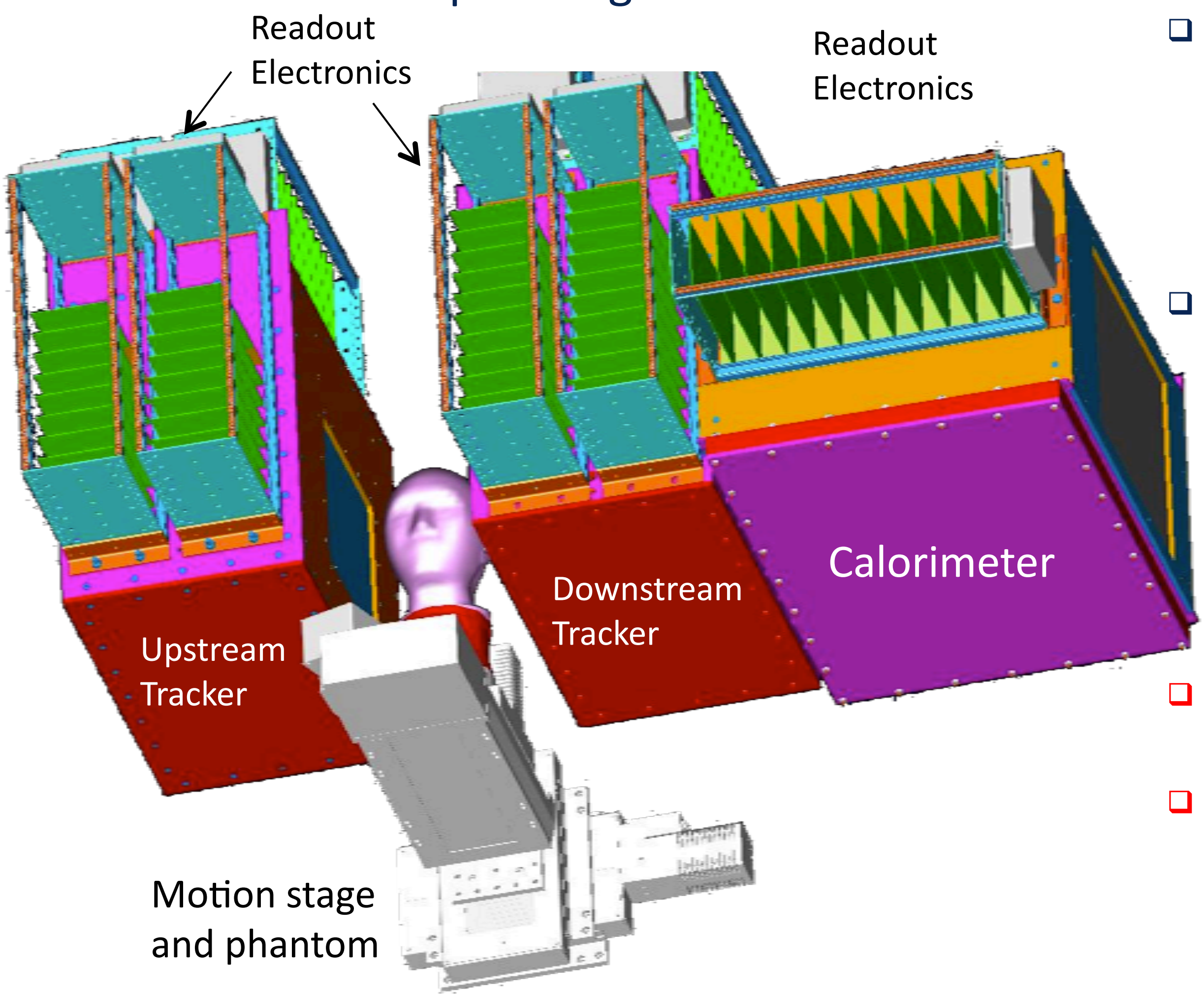


- Quark model invented by: Gell-Mann and Zweig (1964)
- George Zweig works since 2004 for Renaissance

Proton Computed Tomography (pCT)



- Proton computed tomography (pCT) is a low-dose imaging modality to generate a map of the proton stopping power in the patient's tissue, to be used in treatment planning.

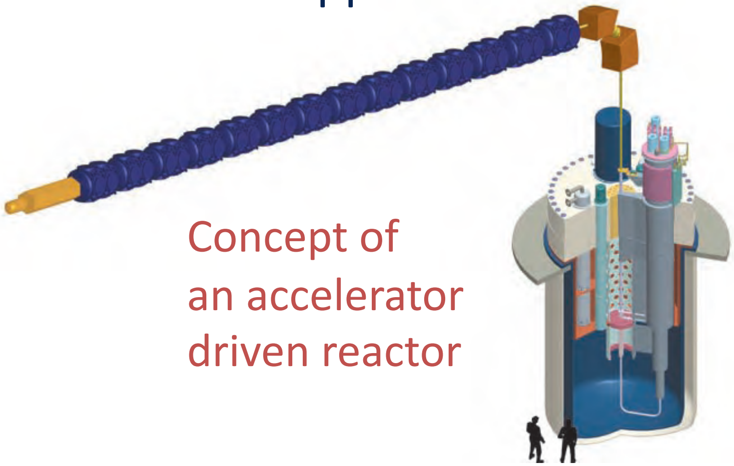


- Tracker
  - Scintillating fiber tracker
  - High efficiency, low mass
- Calorimeter
  - Scintillating tile imager (think ILC imaging calorimeters)

- HEP investments in R&D: Dzero, MICE, ILC, MINOS, ...
- Transferred to medical applications

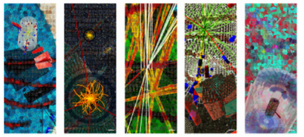
Highlights from ACCELERATORS FOR AMERICA'S FUTURE

- This 2010 report highlights a suite of potential accelerator applications
- Energy and the Environment
  - Accelerator-driven subcritcal reactors & transmutation of nuclear waste
  - Electron beams to turn pollutants from fossil fuel flue gas into fertilizer



Concept of an accelerator driven reactor

- Medicine
  - Proton and ion beam radiation therapy
  - Generation of medical isotope for diagnosis and treatment of patients
- Security and Defense
  - Stockpile stewardship & non-proliferation
  - Cargo inspection and interrogation requires a well-characterized beam and reliable & sensitive detectors
  - Compact, fieldable accelerators (SRF, plasma wake field, solid state RF?)
  - Use of GEANT to inform requirements for security & defense applications



Accelerator Task Force Report (2012)

- "This report and much of its content addresses the broad question of how accelerator R&D benefits the nation and how it can further benefit the nation's needs in the future."

Science Goal "Push"								Application "Pull"				
High Energy	Beam Power	Beam Emittance	High Gradient	New Methods	Brightness & Coherence	Compact Accelerators	DOE R&D Program Thrust	Industry	Medicine	Energy and Environment	Defense and Security	Discovery Science
●	●		●			●	Superconducting RF	●		●	●	●
●	●	●		●	●		Accelerator, Beam, Computation			●	●	●
	●	●			●		Particle Sources	●		●	●	●
●	●		●				RF Sources	●		●	●	●
	●	●			●		Beam Inst. & Controls		●		●	●
			●			●	NC High-gradient Acc. Structures	●			●	●
●				●		●	New Accelerator		●		●	●
●		●				●	Superconducting Magnets	●	●			●

Lattice QCD and Scales

- Two main components of a lattice calculation:

100s of GB file sizes

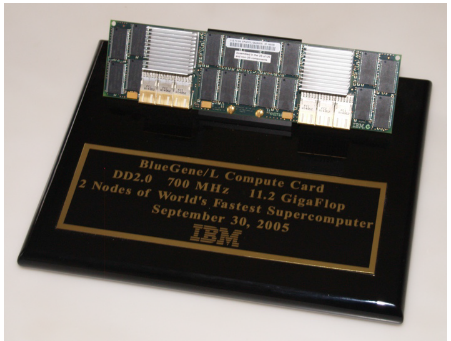
Generate *O*(1,000) gauge configurations serially at a leadership-class facility. Hundreds of millions of core-hours for a single job. Can only be done at an LCF. ("Capability computing.")

Transfer to labs to analyze each configuration in parallel on clusters. More total flops, but each job 1,000 times smaller. More flops/$ than on LCFs. ("Capacity computing.")

Computing needs of experimental high energy physics are almost entirely capacity computing: large farms of single-node machines do event reconstruction and simulation for the LHC one event at a time.

Lattice Gauge Theory and Supercomputing

- Nobel Prize winner Ken Wilson, inventor of lattice gauge theory, was an early proponent of supercomputing
- Lattice gauge theorists worked to design machines aimed at lattice QCD in the early 80s in academic efforts at Caltech, Columbia, IBM, Fermilab, and as part of the Thinking Machines project.
- The Columbia group won the Gordon Bell prize for price/performance in 1998 for the QCD-SP, a machine purpose-built for lattice QCD.
- A team led by Al Gara, that had been part of these projects went to IBM and designed the closely related (commercial!) Blue Gene/L, which won the Gordon Bell prize for performance in 2005.
- The Columbia group also participated in the design of the Blue Gene/Q; Lattice QCD used as benchmark for Blue Gene HPCs



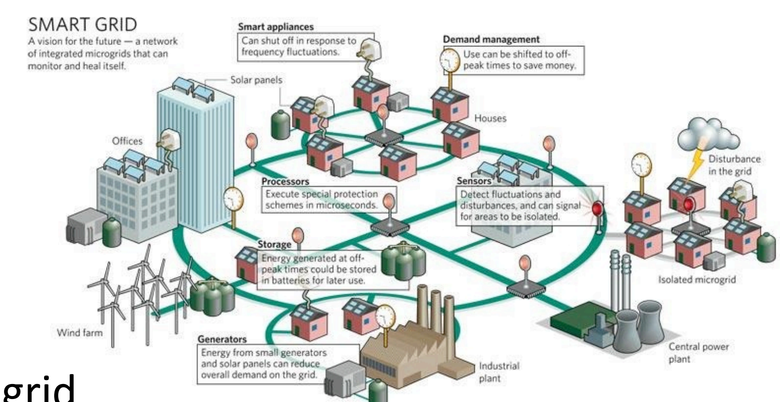
BG/L compute card

The Blue Gene/Q

The Grid for the Electrical Grid

Particle Physics computing needs

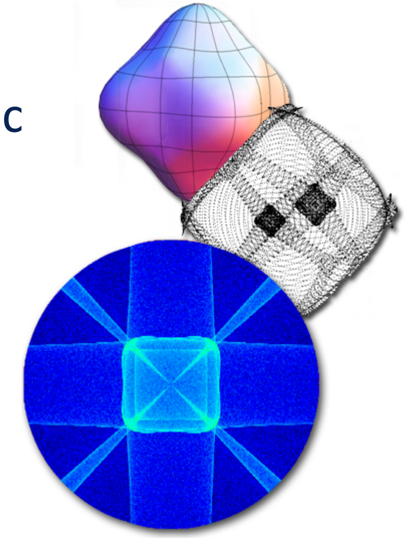
Industry developed Connectivity



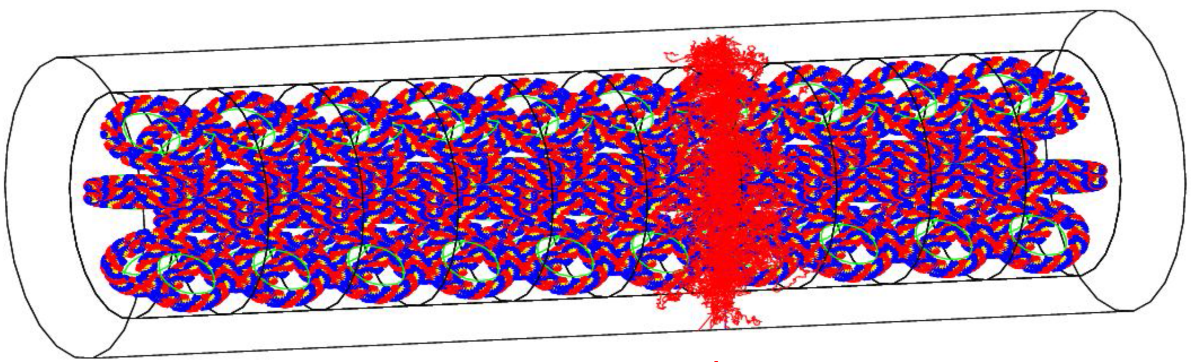
Optimize energy flow
Renewable energy in the grid

Applications of GEANT

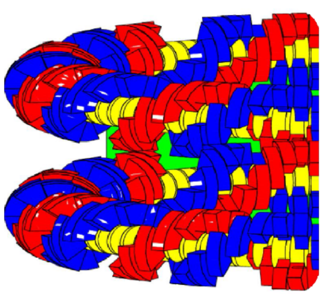
- Condensed Matter Physics
  - Phonon propagation, including focusing based on elastic (right)
  - e-/h+ transport, including conduction band anisotropy



- DNA modeling and effects of ionizing radiation
  - DNA model: M. A. Bernal and J. A. Liendo, Med. Phys. , vol. 36, pp. 620-625, 2009

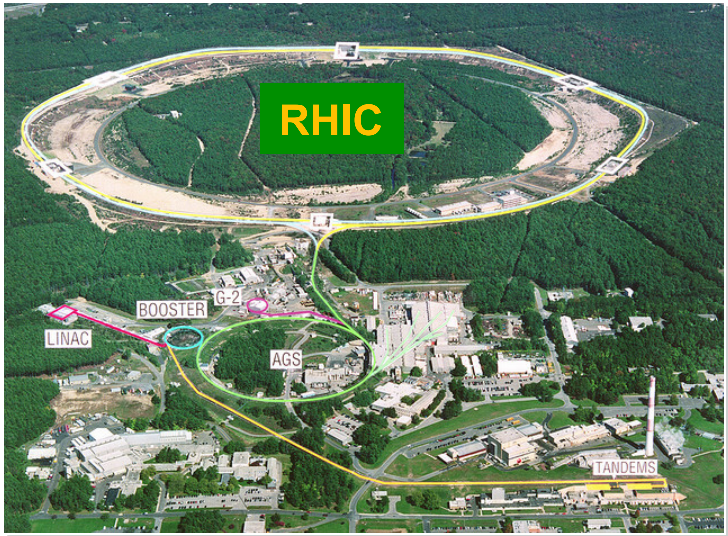


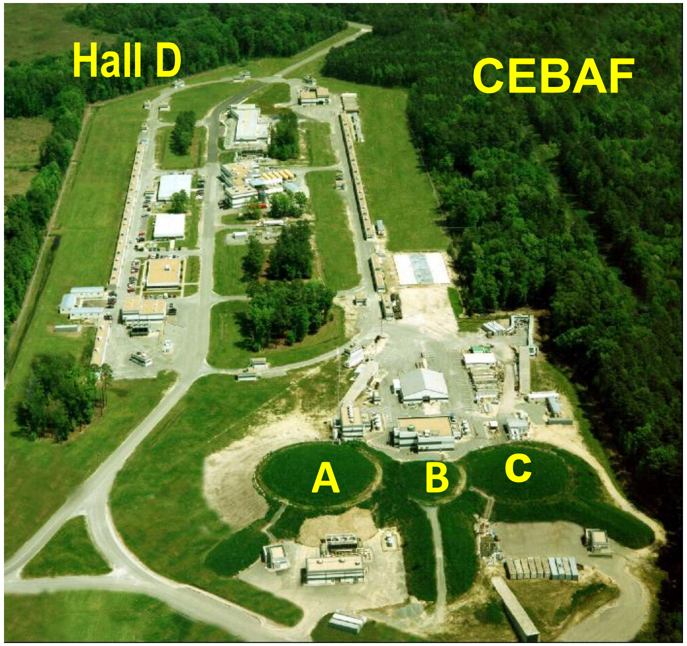
500 keV He^{+}

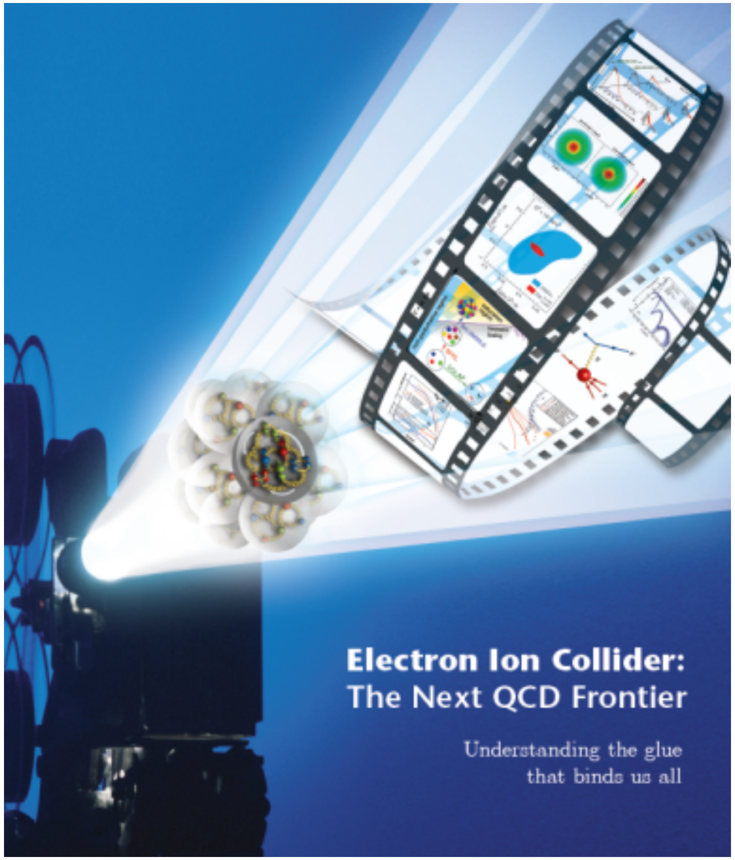


DNA model

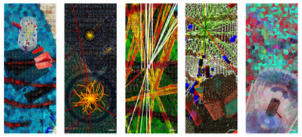
HEP Impact on NP and Mutual Synergies







Areas of Mutual Interest and Activity



<u>Design and analysis tools</u>

- **Detector simulation (GEANT)**
- **Monte Carlo event generators**
- **Algorithms for jet ID and reconstruction**
- **Large-scale processing and archiving of data**

<u>Electronics:</u> **ASIC development**

<u>Silicon Micro Vertex detectors</u>

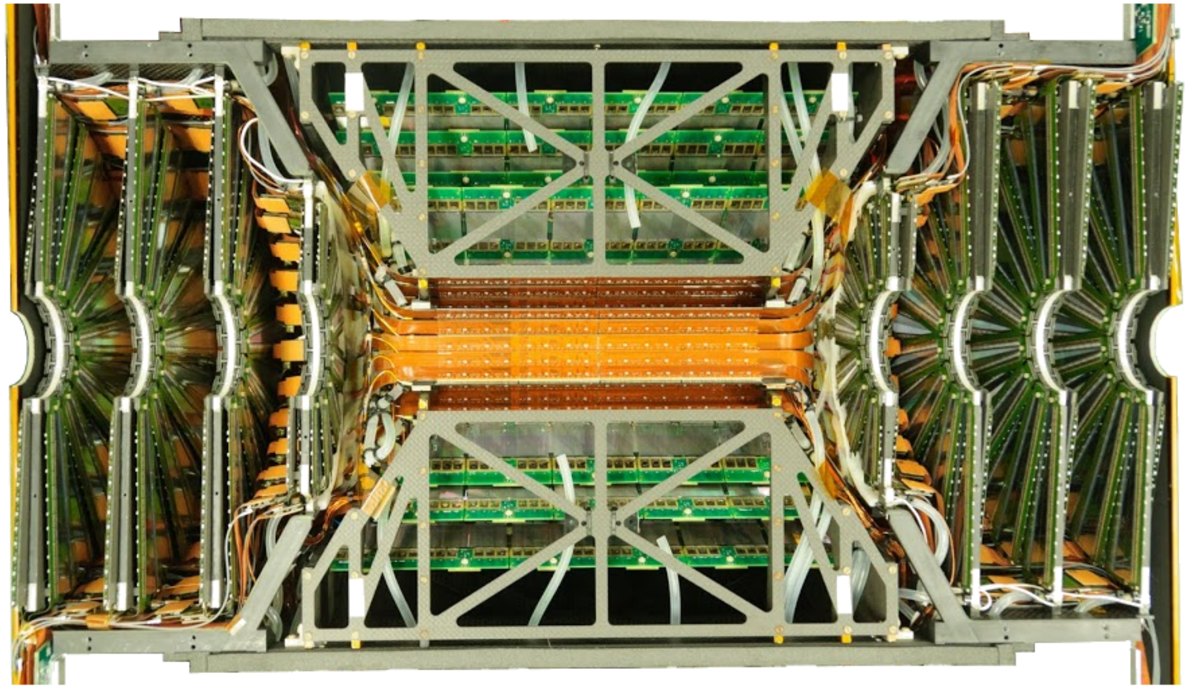
<u>Micropattern tracking detectors and compact calorimetry</u>

<u>Repurposed use of existing instrumentation</u>

- **Current example: BaBar magnet and DIRC**

PHENIX precision Si Vertex Tracking

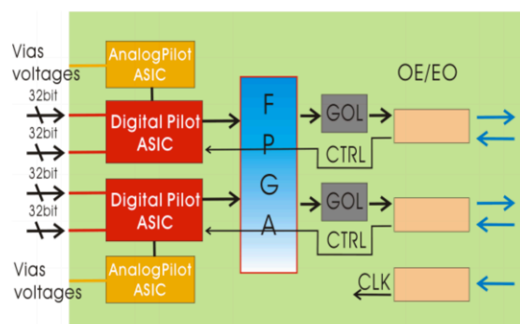
Two major new silicon vertex trackers

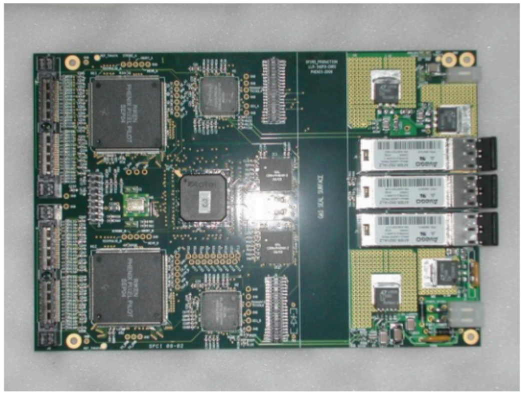


<u>Barrel detector:</u>
- 2 inner layers of Si pixels
- 2 layers of strip-pixel detectors read out with Fermilab's SVX4 ASIC

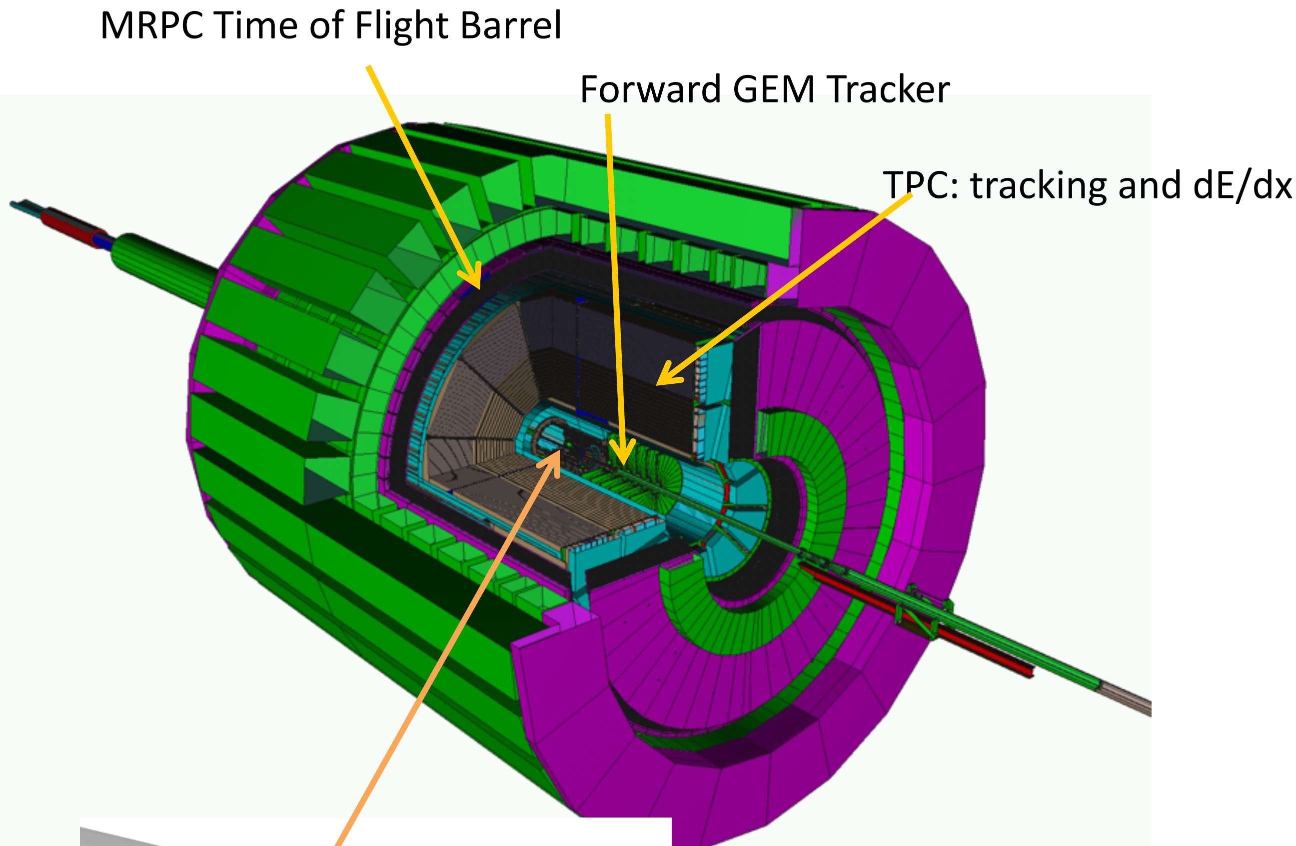
<u>Four-plane endcaps:</u>
Read out with Fermilab FPHX ASIC (modified)

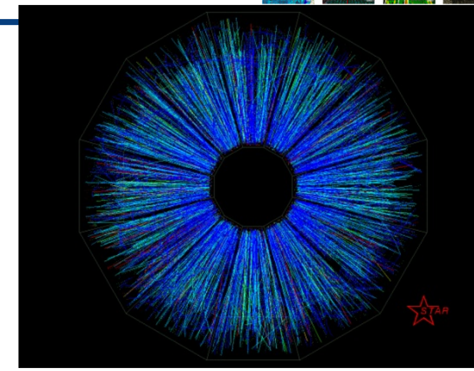
<u>Barrel pixel readout:</u>
- Based on ALICE ITS design
- 50x425 μm pixels
- CERN ASIC designs

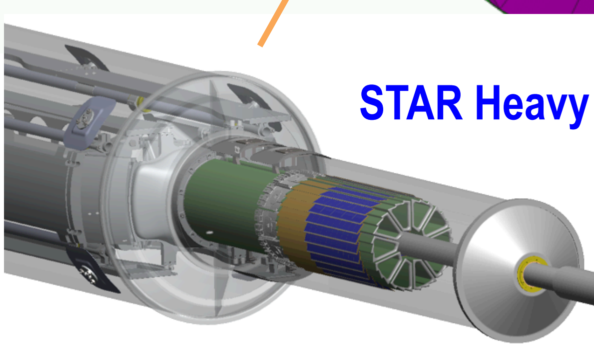




Tracking and PID in STAR detector



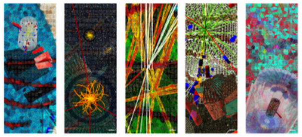


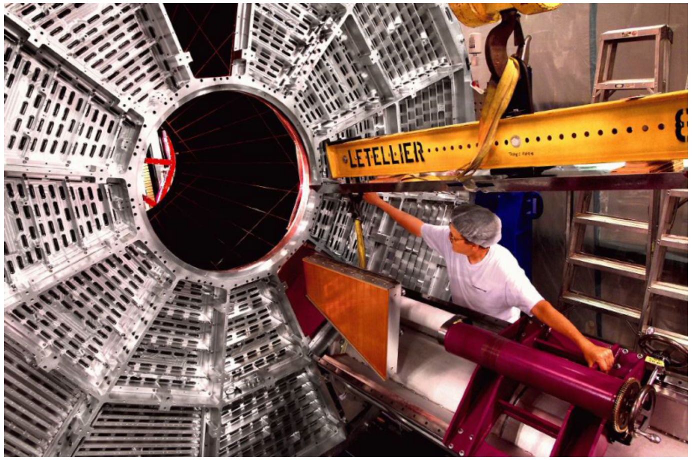


Innermost Pixel Layers use 400 Monolithic Active Pixel Sensors (MAPS): 3.6×10^{8} pixels, 20.7 μm/pixel

First large-scale use of MAPS technology

ASICs in STAR Upgrades



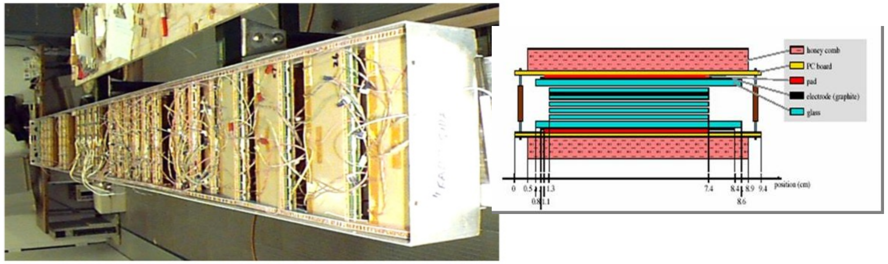


DAQ1000 Upgraded STAR TPC electronics (135,000 channels) and DAQ chain to increase event rate limit from ~100Hz (100% dead time) to 1KHz with 1% dead time.

Utilized CERN ASIC chips developed for ALICE:

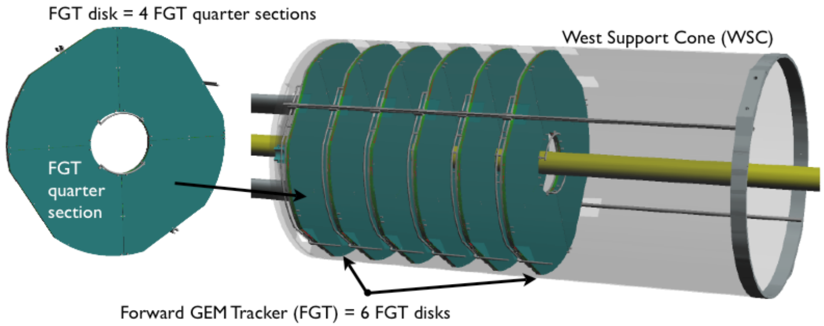
"PASA" pre-amp/shaper

"ALTRO" signal processing, digitizing, event buffering



MRPC Time-of-Flight readout

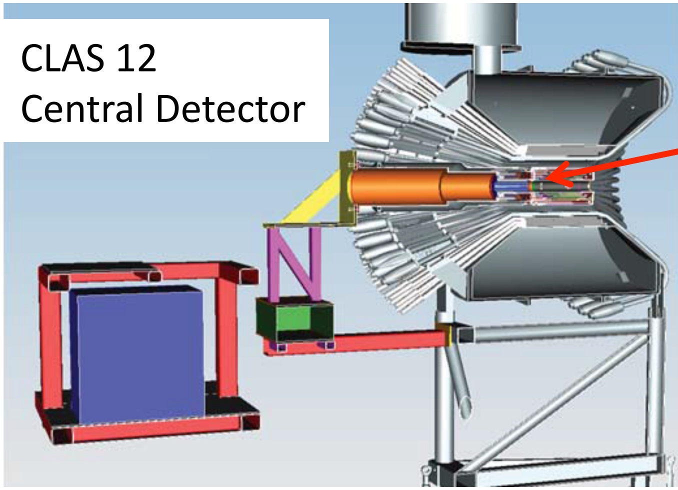
Utilized CERN/ALICE "NINO" chip for analog readout of MRPC modules to digitizer.

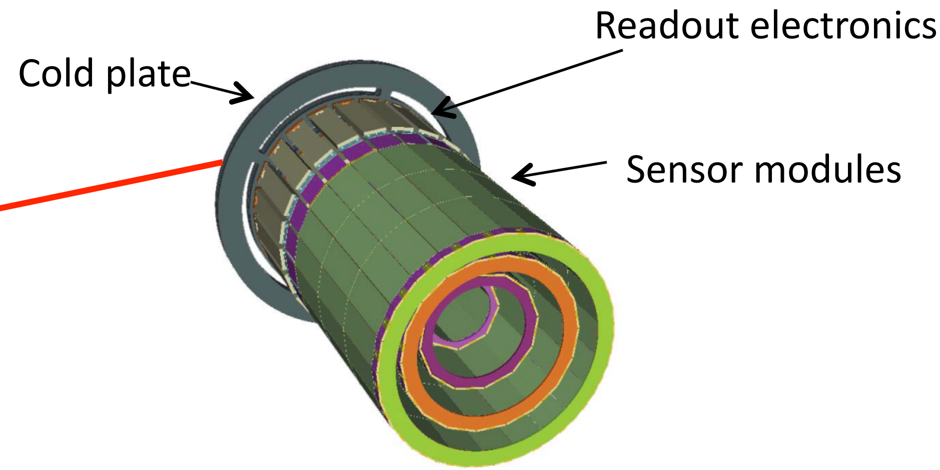


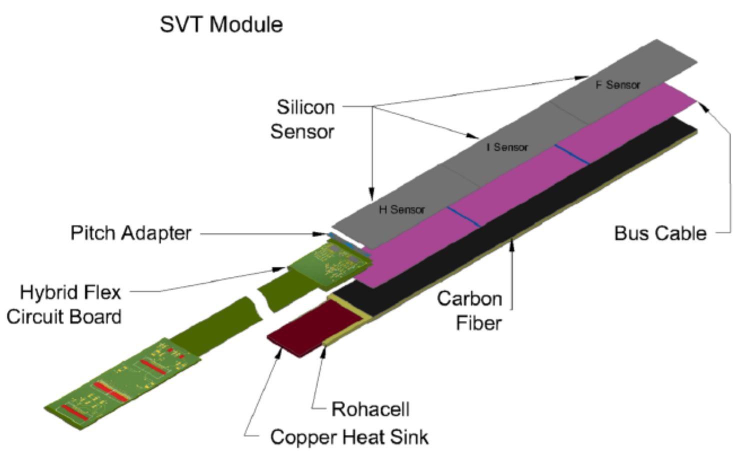
Forward GEM Tracker

Six disks of triple-GEM detectors with pad readout.
Uses APV25 chips developed for CMS.
37,000 channels

JLab Hall B CLAS12 Si Vertex Tracker (SVT)





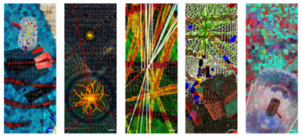


SVT operates in 5T field, L = 10^{35} $cm^{-2}sec^{-1}$
500 fb^{-1} per year.
Radiation dose (Carbon target) = 2.5 Mrad

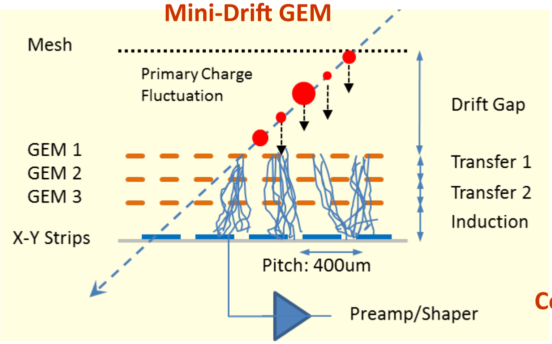
Readout uses FSSR2 ASIC, developed at Fermilab for BTeV.

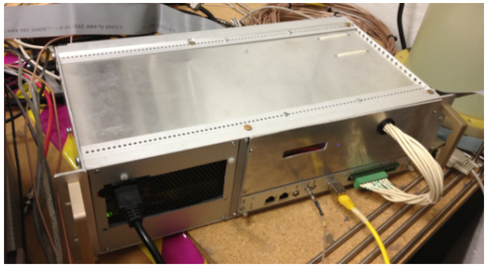
Sensor modules read out by 4 ASICs of 128 channels each.

Micropattern Gas Detectors



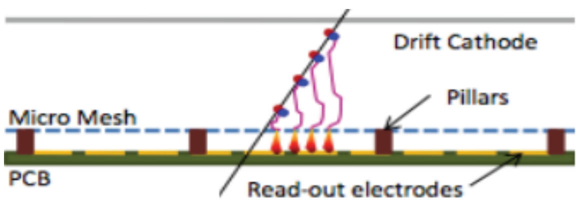
PHENIX Minidrift GEM Detector and MicroMegas Detectors for the ATLAS Muon Trigger Upgrade being tested together at CERN last year



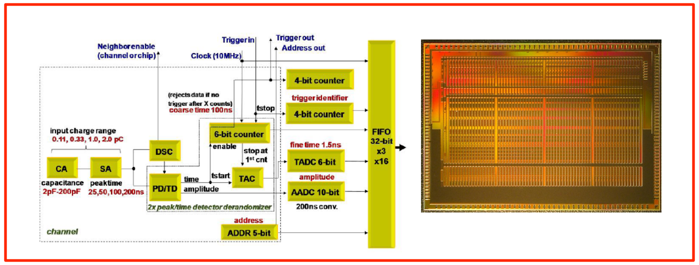


Common Scalable Readout System (SRS) developed at CERN used for beam test

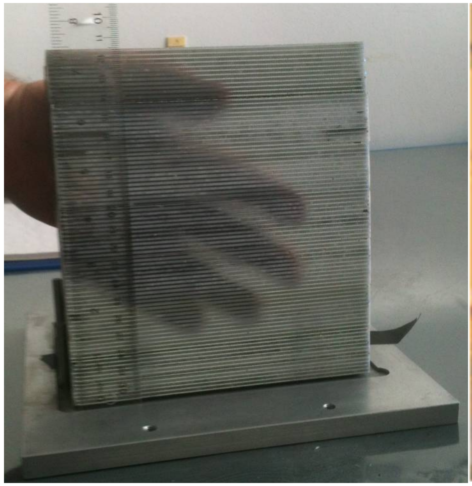
Micro TPC MicroMegas



VMM1 readout chip being developed at BNL for ATLAS could be used by both ATLAS and PHENIX

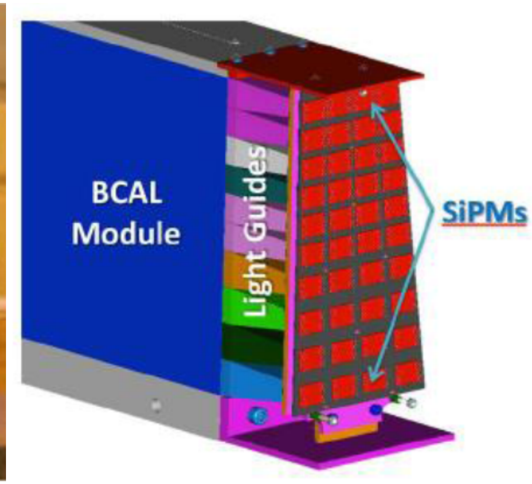


Calorimetry in HEP and NP

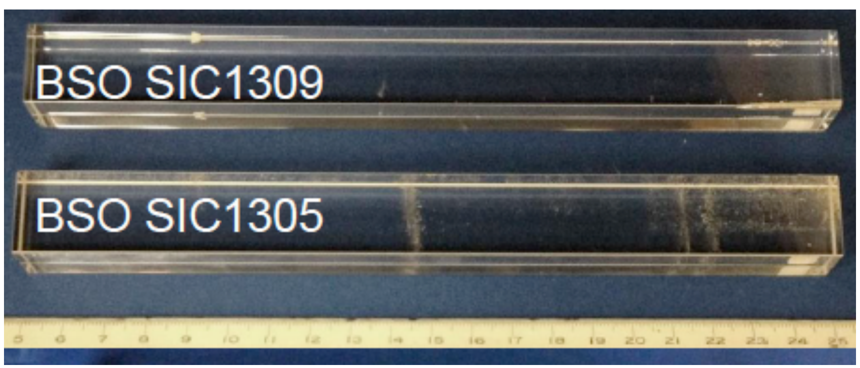


PHENIX W-SciFi EMCAL Prototype

STAR W Powder-Epoxy-SciFi EMCAL Prototype

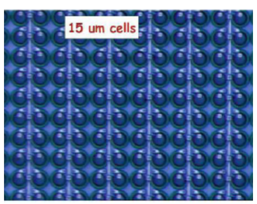


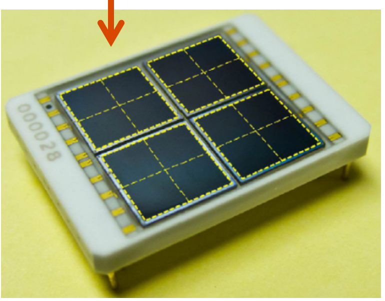
GlueX Pb-SciFi EMCAL

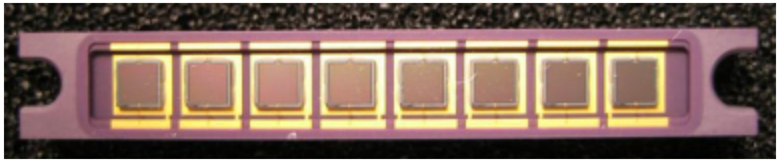


New crystals (e.g, BSO) being developed for HE & NP

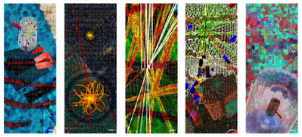
All using SiPM readout







SiPMs for the CMS HB-HE Upgrade

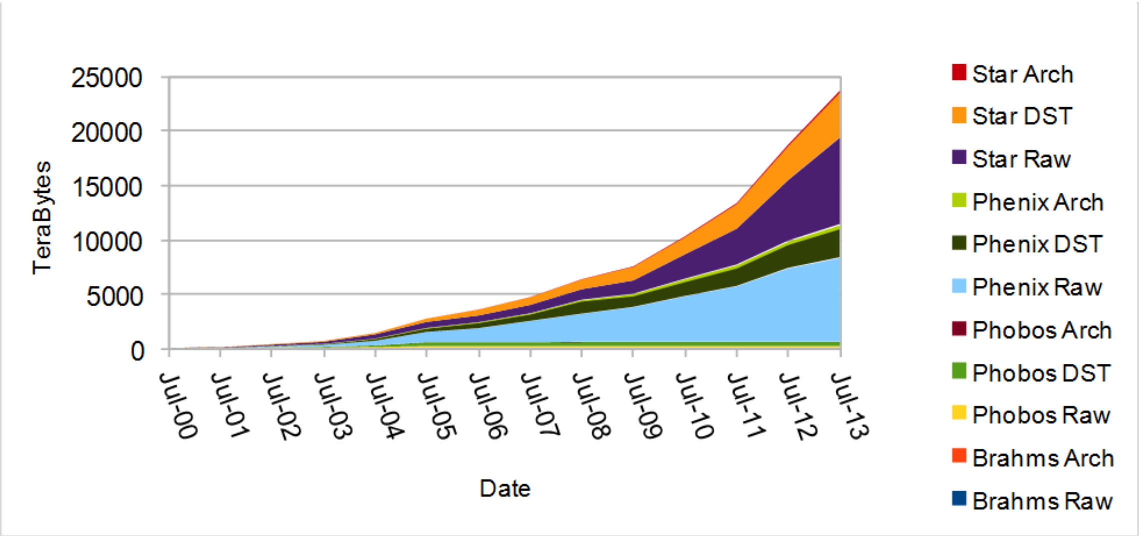


RHIC Computing Facility…

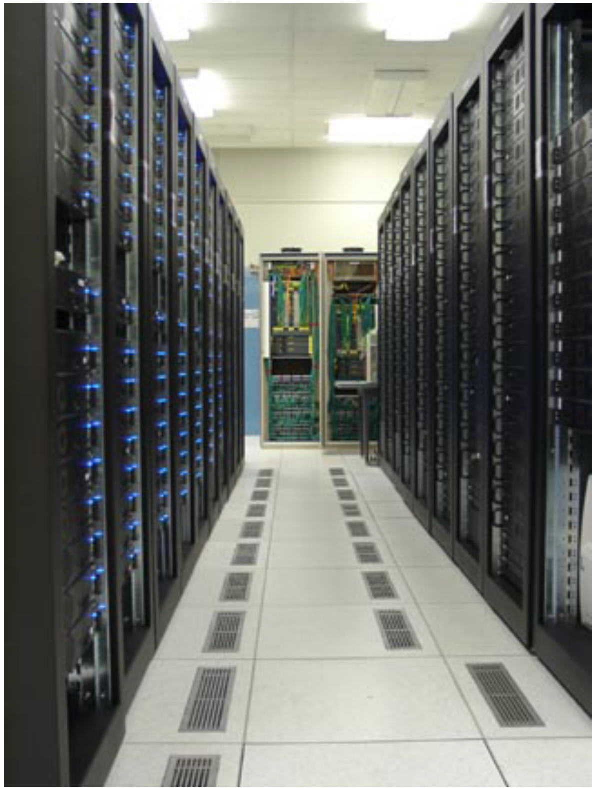
A shared facility with ATLAS Tier-1 Center:

Comparable staffs for both NP and HEP

Archived data from RHIC runs



Michael Ernst, Director

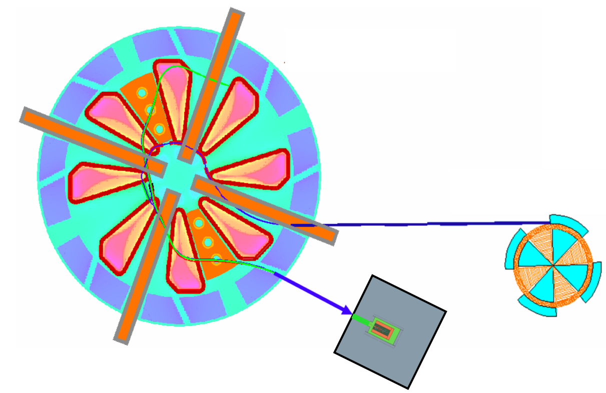


- Online recording of raw data
- Primary facility for data reconstruction and analysis
- Long-term archiving and serving of all RHIC data

Scalable architecture based on arrays of commodity components keeps pace with Moore's law through annual "refresh" of equipment at modest cost.

Technology Connections: DAEδALUS/IsoDAR

This collaboration is developing high power cyclotrons
as decay-at-rest neutrino sources



Those involved:

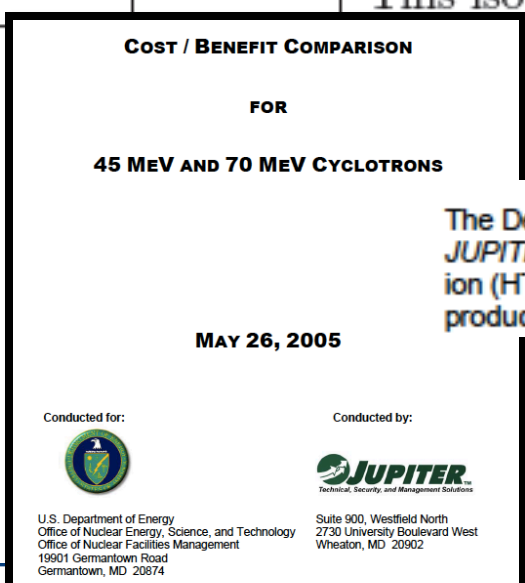
16 Universities (mostly US)
4 Laboratories (international)
and…AIMA, Best Cyclotron Systems, IBA, Sumitomo

Major Cyclotron Companies

The scientists at the companies are collaborators,
not contractors!

Isotope production by 60 MeV p

Isotope	Half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium.
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb, a potassium analogue. This isotope is also directly used as a PET isotope for heart imaging.


COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

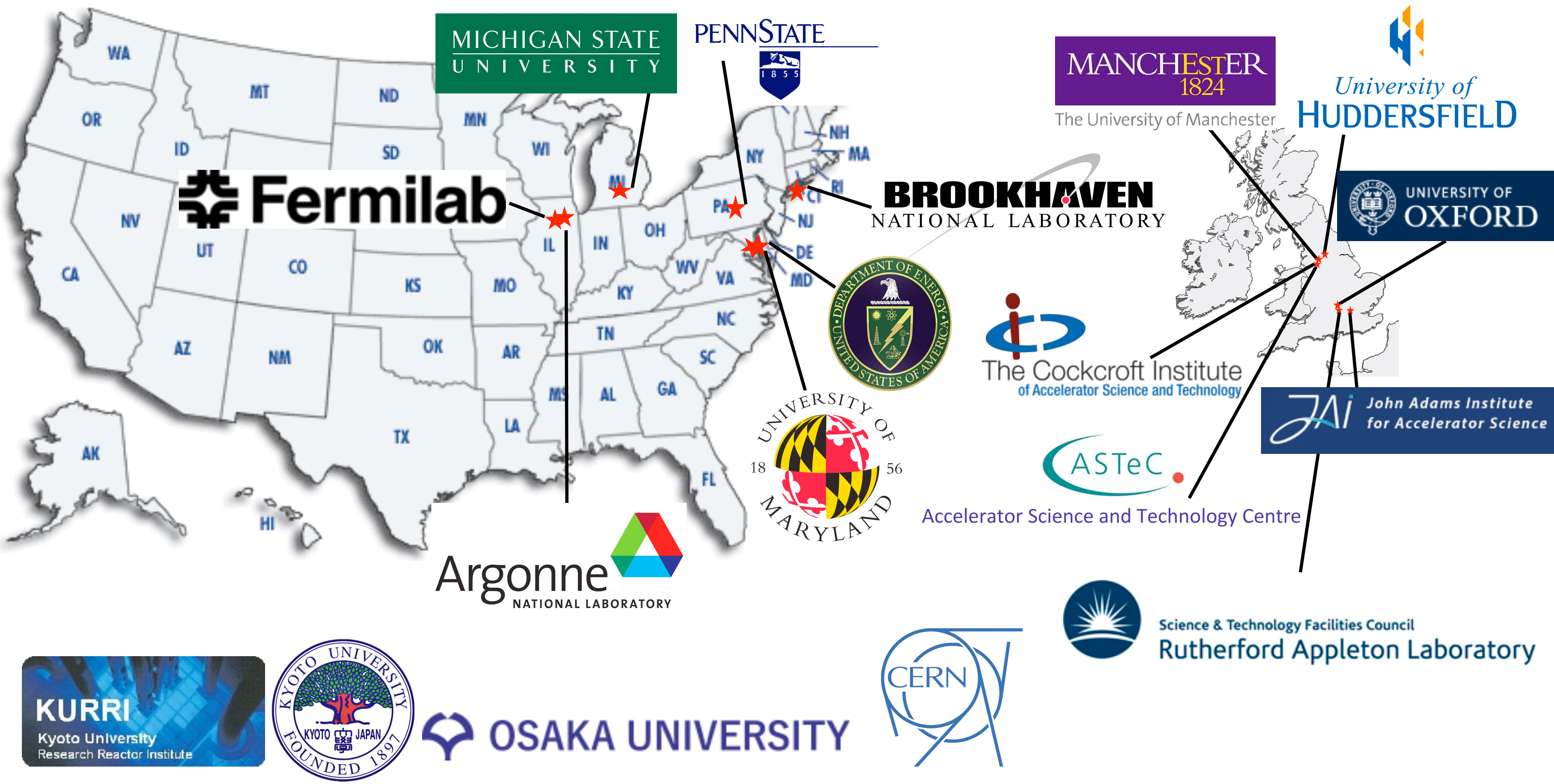
Conducted by:

JUPITER
Technical, Security, and Management Solutions

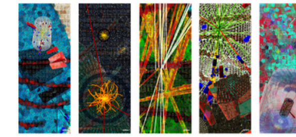
Suite 900, Westfield North
2730 University Boulevard West
Wheaton, MD 20902

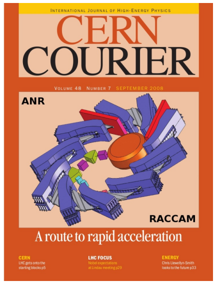
The Department of Energy's (DOE) Office of Nuclear Energy, Science, and Technology (NE) asked *JUPITER* Corporation (*JUPITER*) to conduct a cost comparison between 45 MeV and 70 MeV negative ion (H⁻) cyclotrons to help support an NE decision on the potential purchase of an accelerator for the production of medical radioisotopes. We have conducted a survey of accelerator manufacturers and

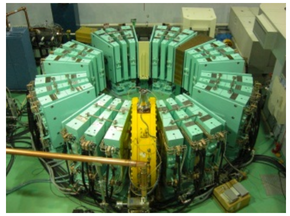
The international FFAG collaboratio



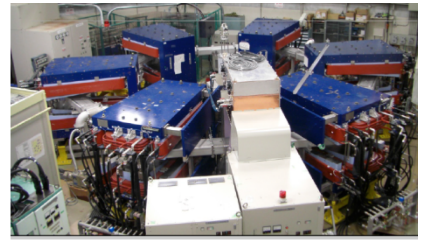
International Development of FFAG



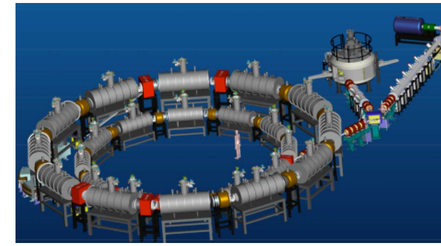




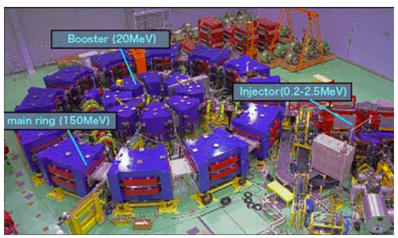
ERIT: neutron source
KURRI, Japan



PRISM: intense muon beam
Lepton flavor violation exp.
Osaka, Japan



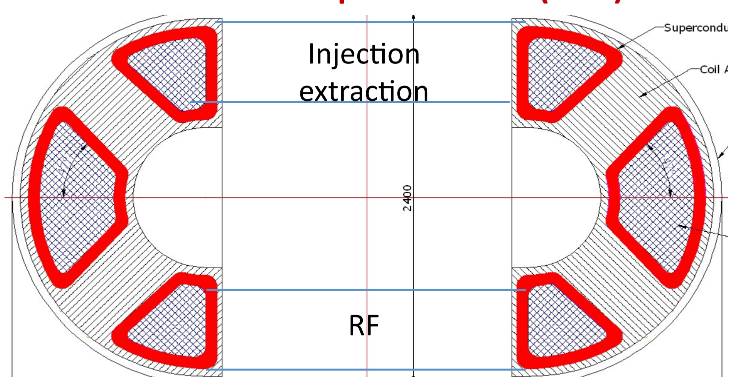
PAMELA: hadrontherapy design
Oxford, U.K.



70 - 430 MeV/nucleon Ion FFAG
330 MeV pCT
1 GeV intense proton FFAG (ADS)

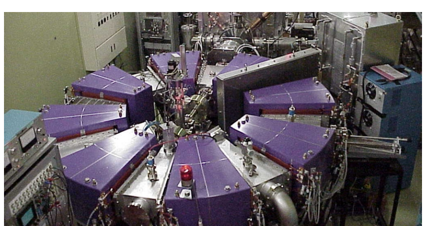
EMMA: POP muon acc demo
Daresbury Laboratory, U.K.

~ 4 m



~6 m

Compact CW ns-FFAG racetrack design capable of variable energy and various applications



POP, 1st p FFAG, KEK, Japan