Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Introduction to Nuclear and Particle Physics Directorate

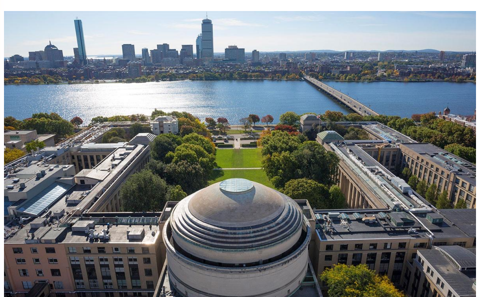
Haiyan Gao

October 2022

Brief Introduction of myself




Tsinghua University (84-88) (BS)
California Institute of Technology (89-94) (Ph.D.)
Univ. of Illinois, Urbana-Champaign (94-96) (postdoc)
Argonne National Lab (96-97) (staff)
Massachusetts Institute of Technology (97-04)
Duke Univ. (02-present)
Duke Kunshan University (Jan 2015 – June 2019)
Brookhaven National Laboratory (June 2021 –)




Brookhaven National Laboratory

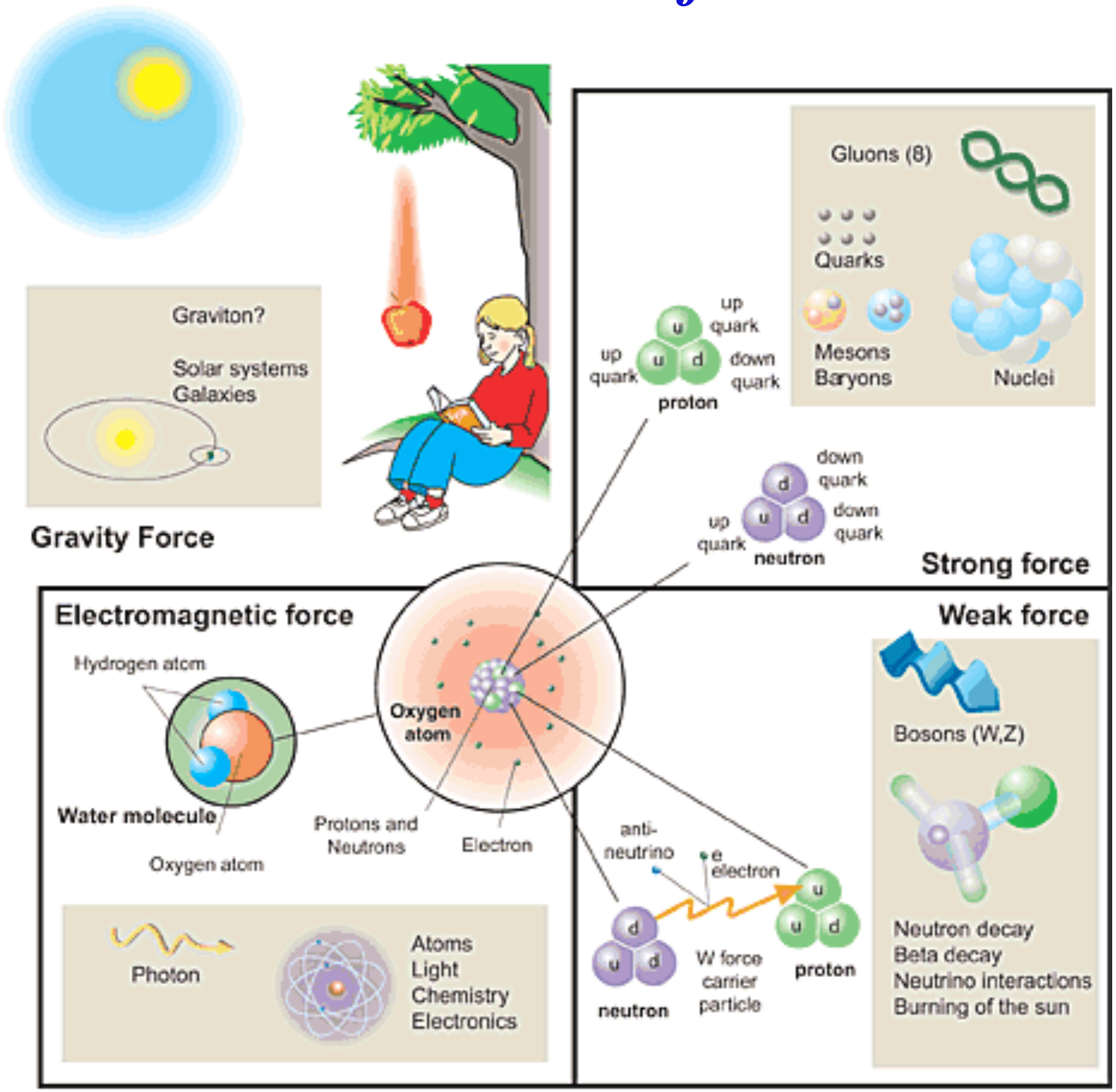
Nuclear and Particle Physics

Our mission is to lead and support discovery-based, innovation-driven research at the frontiers of the subatomic world. We are world-leading in nuclear physics research, building and operating accelerator-based user facilities that serve international scientific communities. We also play a leading role in global particle physics programs that push the limits of precision and expand our understanding of the cosmos. Our pursuit of this fundamental and discovery research yields scientific and technological breakthroughs, and applications that benefit society—such as radioisotopes used to support industrial, medical and national security needs.

Our work draws on an international community filled with unique voices and perspectives, all contributing their ideas and experiences. We are passionate about welcoming people from all backgrounds and helping them succeed. Collectively, we will expand the boundaries of science and technology, advance the knowledge of humankind, bring new applications to society, and further our understanding of the natural world.

New NPP web page https://www.bnl.gov/npp

Fundamental forces in nature



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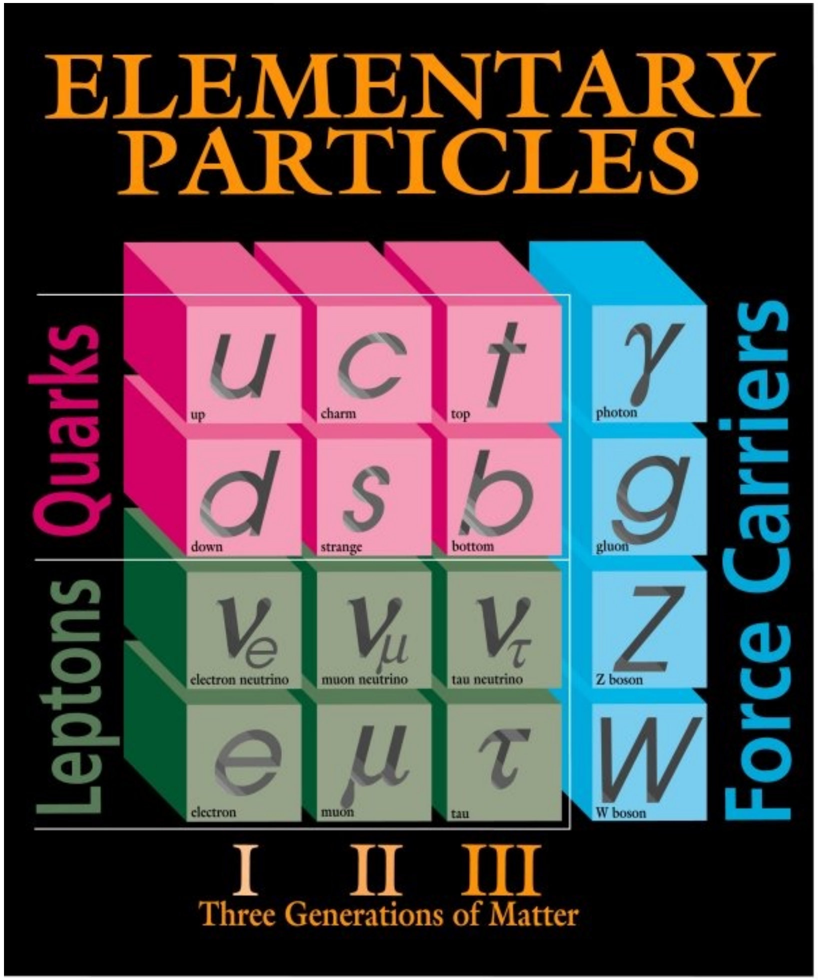
http://www.kva.se/KVA_Root/pictures/prizes/nobel04/phypub1lowen.gif

The standard model of Particle Physics



Fermilab 95-759

Interaction	Mediators	Relative Strength	Range (m)
Strong	**g**	**10^{38}**	**10^{-15}**
E&M	**γ**	**10^{36}**	**∞**
Weak	**W, Z**	**10^{25}**	**10^{-18}**
Gravitation	gravitons	1	∞

SM very successful (no gravity)
New physics exists (neutrino mass, dark matter, baryon number asymmetry of the universe,….)
HEP: Energy, intensity, cosmic frontiers
NP: Fundamental symmetries and neutrinos, precision measurements

HEP: high-energy physics
NP: nuclear physics

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High Energy Physics: Understanding the Origin of Space and Time

ATLAS experiment (energy frontier)

- Lead Lab for U.S. ATLAS collaboration of 800 U.S. scientists
- Leading US ATLAS Operations program and hosting ATLAS computing center

Neutrino Program (intensity frontier)

- Studying properties of neutrinos with MicroBooNE experiment
- Operating Proto-DUNE detector with BNL-developed cold electronics

Belle II experiment (intensity frontier)

- Lead Lab for U.S. Belle II experiment in Japan

Rubin Observatory (cosmic frontier)

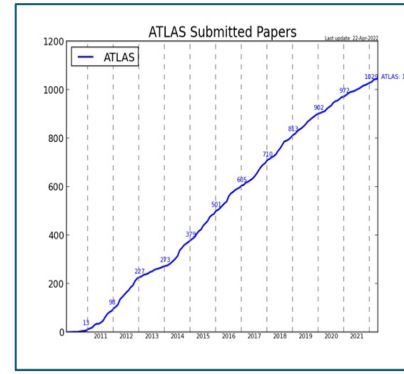
- Commissioning the experiment in Chile
- Developing computing and software for data analysis

Theory (all)

- Developing new ideas and models in neutrino, collider, and precision particle physics

Assembly of muon system at CERN

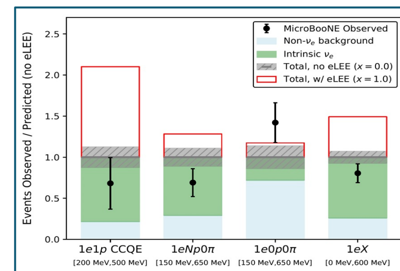
ATLAS published over 1000 papers



2010 2022

New ATLAS/Belle II computing center

Exclusion of sterile neutrinos



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High Energy Physics: Driving and Enabling the Future of the Field

Energy Frontier
- Hosting project office for $250M ATLAS upgrade
- Building magnets for the HL-LHC upgrade
- Developing computing and software for effective ATLAS data management

Intensity Frontier
- Key contributions to DUNE experiment
  - Leading DUNE Module 2 activities
- Planning studies of charge-parity violation with Belle II experiment

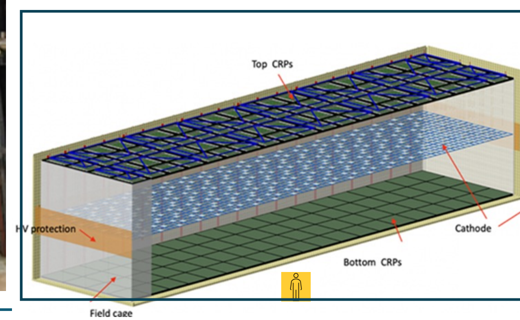
Cosmic Frontier
- Soon to analyze unique Rubin Observatory camera data
- Lead lab for LuSEE-Night mission to the far side of the moon
  - Detect "Dark Ages" signal from early Universe

Leading Technology Developments for Particle Physics
- Computing, software, detectors, and electronics
- Accelerator R&D, including superconducting magnets

LHC magnet testing at BNL

ATLAS silicon assembly at BNL

DUNE Module #2 design



Participating in long term planning at Snowmass
- Over 130 white papers with proposals submitted by BNL scientists

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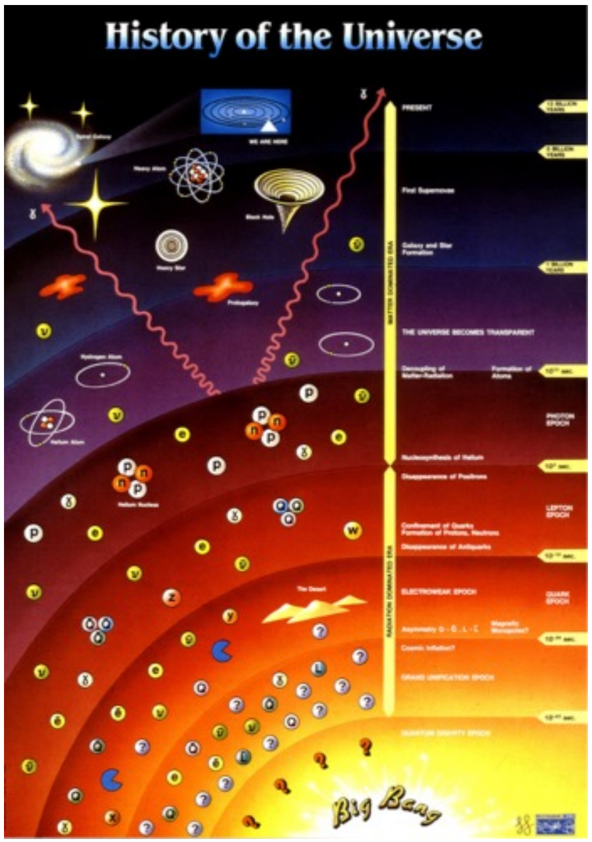
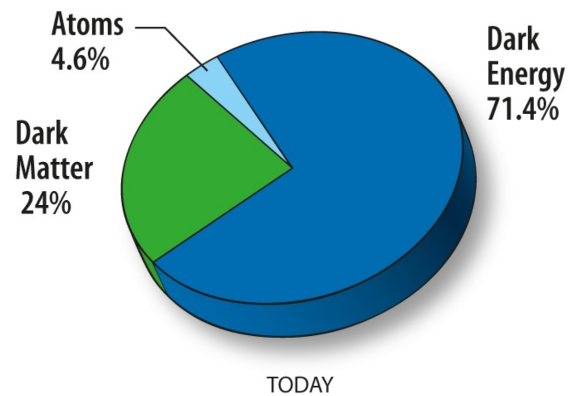
Nuclear physics – study of structure of matter in all its forms

– **Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.**

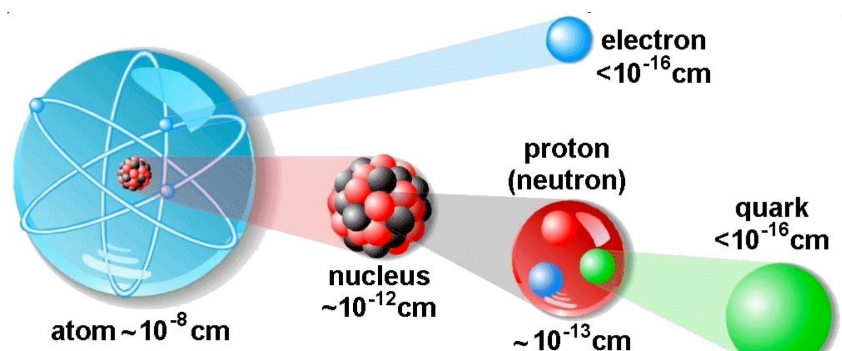
– **The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak).**



About 1 second after the Big Bang, protons and neutrons are formed



In today's universe, 99% visible matter are atomic nuclei (protons and neutrons).



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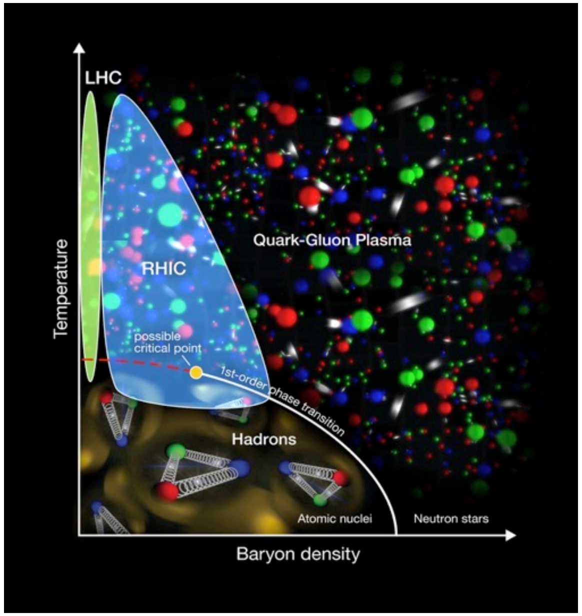
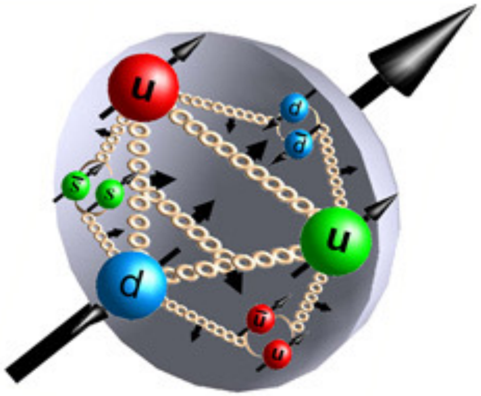
RHIC – a Unique Research Tool

- Heavy ion collisions
  - Explore new state of matter: Quark Gluon Plasma
  - Collide many different ion species
- Polarized proton collisions
  - Only collider of spin polarized protons to explore the internal spin structure of protons.
  - Gluons carry part of proton spin





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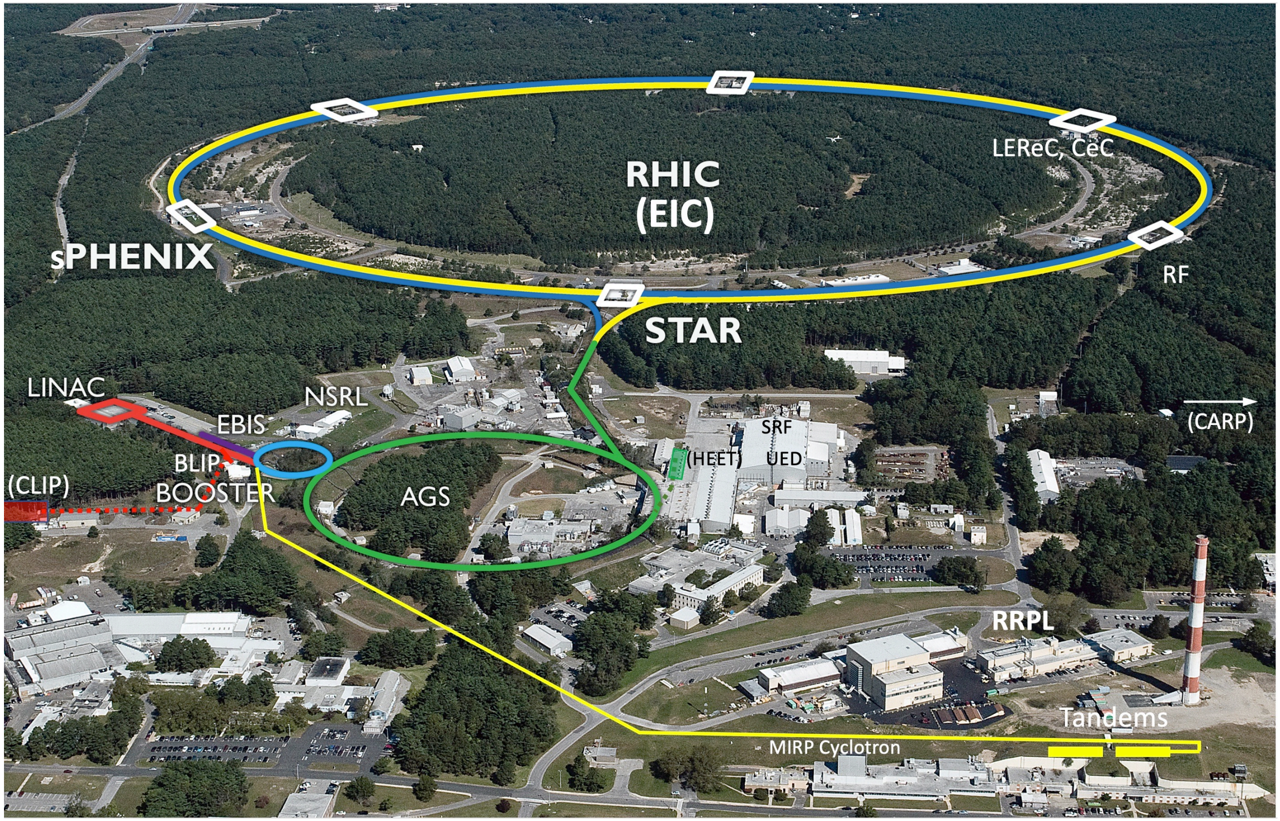
Relativistic Heavy Ion Collider (RHIC) Complex



- ➢ Uniquely flexible and only hadron collider in the United States for exploration of QCD phase diagram and proton spin
- ➢ Injectors also used for application programs
  - Linac/BLIP for isotope production
  - Booster/NSRL for space radiation studies
  - Tandem for industrial/academic users
- ➢ R&D for future facilities and application (sources, cooling, pol. beams, …)

NASA Space Radiation Laboratory (NSRL)

- Started in 2003, simulates galactic radiation for human space flight
  - Heavy ion beams from AGS Booster
  - Electron Beam Ion Source (EBIS) provides all necessary ion beams
  - New laser ion source for EBIS allows for rapid species switching to simulate energy and species spectrum of deep space radiation field

- Additional uses of NSRL
  - **Radiation effects studies (rapidly growing demand for satellite electronics testing)**
  - R&D of ion beam cancer treatment
  - Agreement with NASA in place for non-NASA users ("non-designated user facility")

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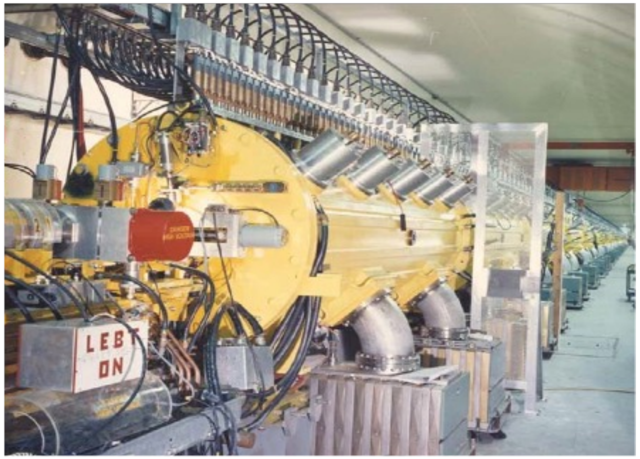
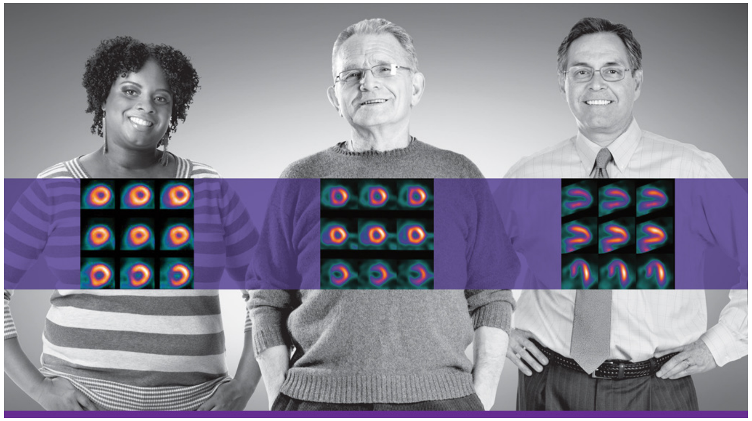
Brookhaven Linac Isotope Producer (BLIP)

50th anniversary

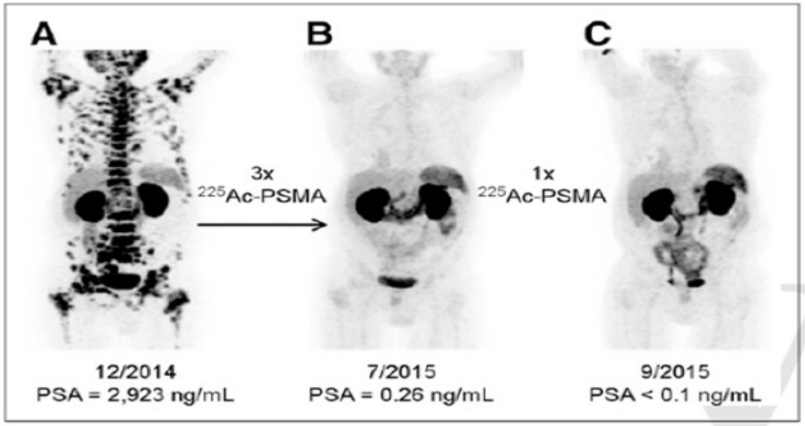
Official Use Only

- Target irradiation with 116 – 200 MeV, 160 mA proton beam
- Production of medical radio-isotopes for U.S.:
  - Mainly Sr-82, shared between LANL and BNL
  - R&D of new radio-isotopes for diagnosis and therapy (Ac-225, needs ~ 200 MeV protons)
- Significant expansion is underway:
  - BLIP target and proton beam intensity upgrades
  - Refurbishment of additional hot cells for Ac-225 processing
  - Bringing up a low-energy Cyclotron for supplying radionuclides currently available only from foreign suppliers, and an alternative Ac-225 production route with radium targets (Ac-225 without Ac-227 contamination)





Sr-82: coronary artery disease diagnosis, used under rest and stress conditions



Ac-225: Alpha emitter for treatment of metastatic prostate cancer

Quark-gluon plasma as "perfect liquid" discovered at RHIC

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The News of the QGP Hit the Streets

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

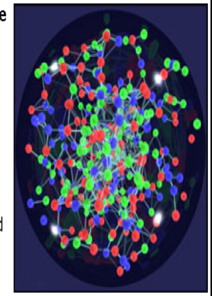
The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

BBC NEWS



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

An atom smasher on Long Island re-creates the particle soup that gave rise to the universe

"Here is where the action takes place. This is where we effectively try to turn the clock back 14 billion years. Right above your head, about 13½ feet in the air."

Looking up, I try to imagine the events Tim Hallman is describing—atoms of gold colliding at 99.99 percent the speed of light; temperatures instantly soaring to 1 trillion degrees, 150,000 times hotter than the core of the sun. Then I try to picture a minuscule five-dimensional black hole, which, depending on your point of view, may or may not have formed at that same spot over my head. It's all a little much for an imagination that sometimes struggles with the plot of *Battlestar Galactica*.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

John Harris (Yale) 20th Anniversary of RHIC BNL-Online, June 12, 2020

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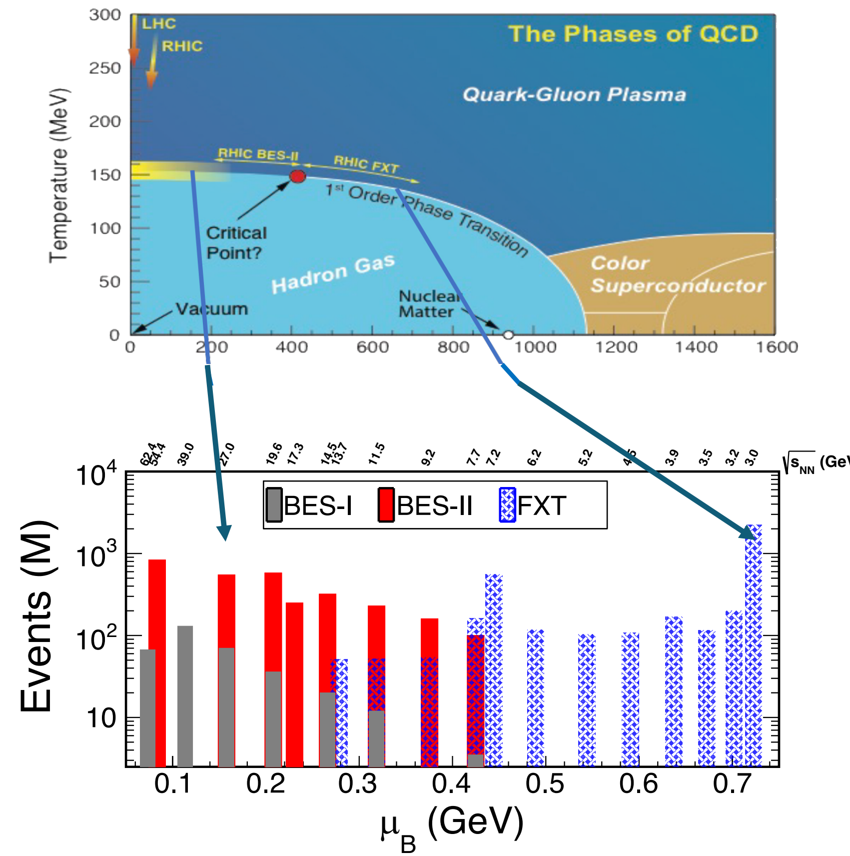
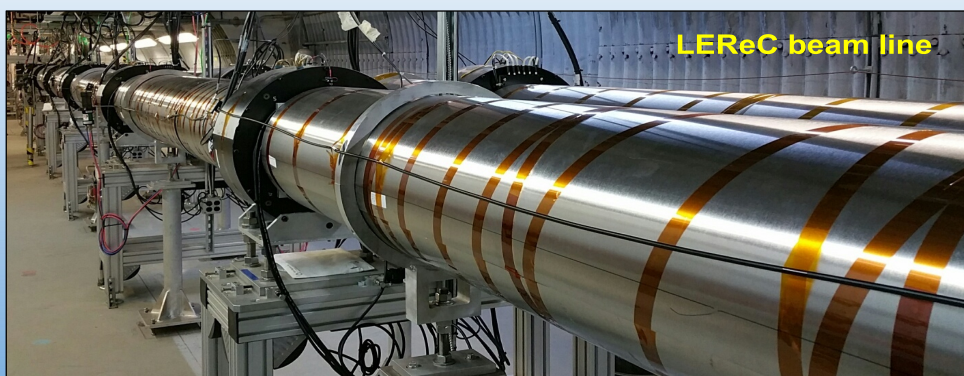
RHIC in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP)

"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC."**



LEReC = Low Energy RHIC electron Cooling
First-ever electron cooling with bunched beams
Test case for electron cooling at EIC



Beam Energy Scan

- What is the phase boundary of ordinary nuclear matter?
- Is there a critical point (e.g., liquid/vapor phases coexist for water) in the QCD phase diagram? If so, where?

BES-2 Completed as of June 7, 2021!

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Completing the RHIC Mission with sPHENIX and STAR

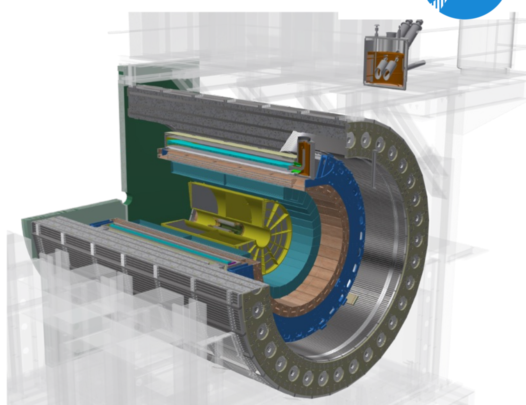
- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- State-of-the-art collider detector using technology developed for LHC by ONP and OHEP
- sPHENIX magnet and its hadron calorimeter could be part of the EIC project detector

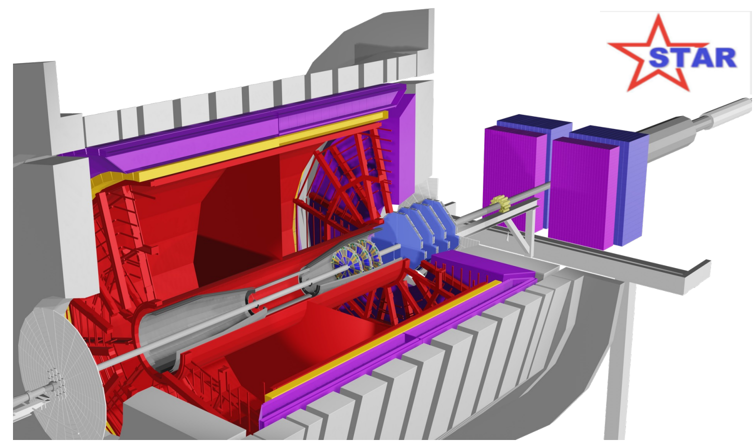
- STAR with forward upgraded detectors ran successfully in Run 2022
  - 3-D tomography (like Magnetic Resonance Imaging) of the nucleon uncovers new information
  - STAR exploits such 3-D parton dynamics in ways complementary to the EIC, where precision tomography of the nucleon and nuclei will be carried out

Forward Upgrade

Magnet & Calorimeter

sPHENIX



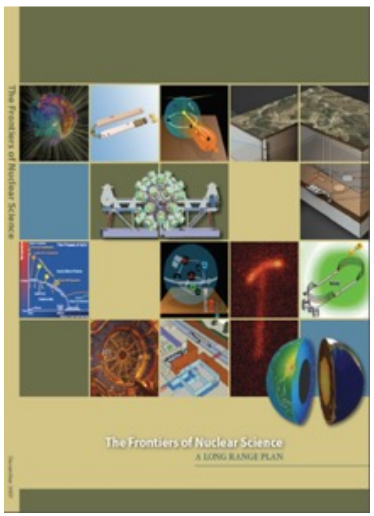


RHIC data taking scheduled for 2023–2025
sPHENIX upgrade and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC

The Electron-Ion Collider – The Next QCD Frontier

2018 NAS Report : An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of dense systems of gluons?




The EIC Science case: a report on the joint BNL/INT/JLab program

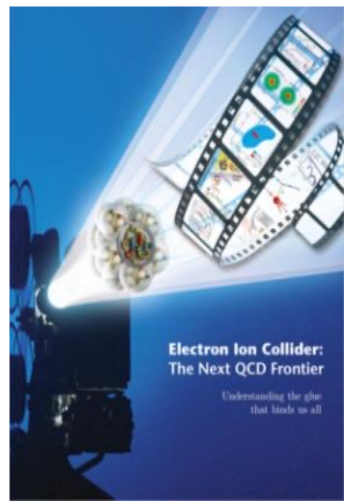
Gluons and the quark sea at high energies:
distributions, polarization, tomography

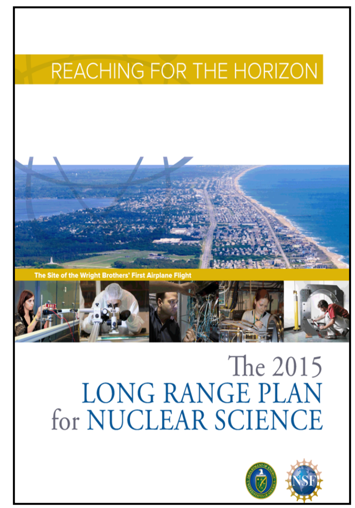
Institute for Nuclear Theory, University of Washington, USA
September 13 to November 19, 2010

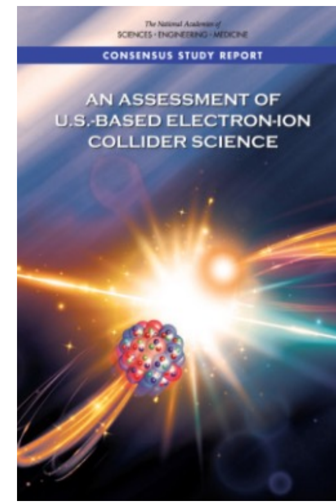
Editors:
D. Boer, Universiteit Groningen, The Netherlands
M. Diehl, Deutsches Elektronen-Synchroton DESY, Germany
R. Milner, Massachusetts Institute of Technology, USA
R. Venugopalan, Brookhaven National Laboratory, USA
W. Vogelsang, Universität Tübingen, Germany

Brookhaven National Laboratory, Upton, NY
Institute for Nuclear Theory, Seattle, WA
Thomas Jefferson National Accelerator Facility, Newport News, VA

arXiv:1108.1713v2 [nucl-th] 28 Nov 2011







NSAC LRP 2007

EIC INT Report 2011

EIC White Paper 2015

NSAC LRP 2015

NAS Report 2018

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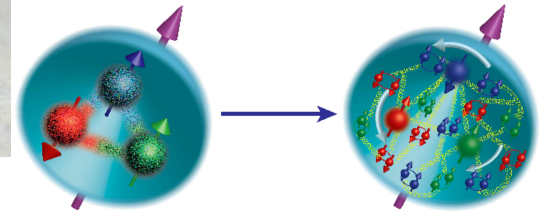
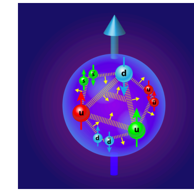
Proton Spin Puzzle

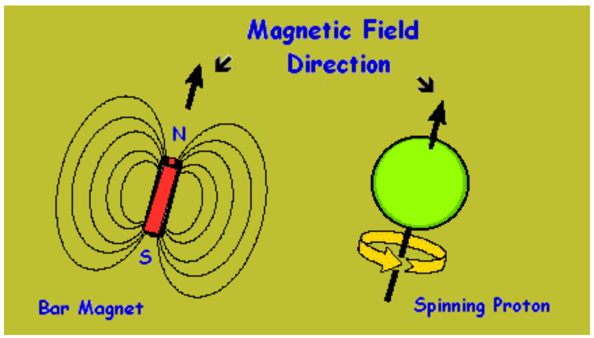


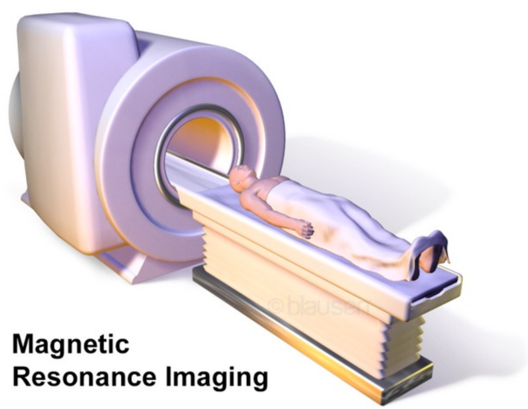


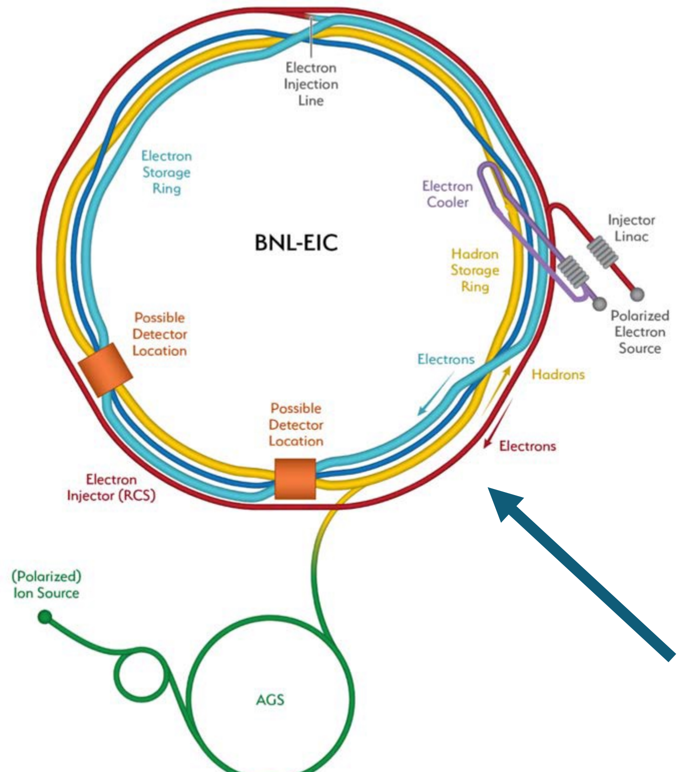
Fermions: half-integer spins
Bosons: integer spins

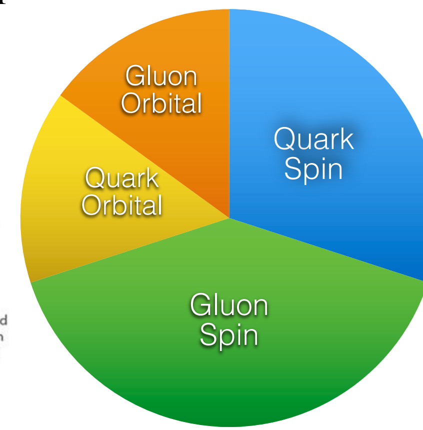
Proton spin (1/2) decomposition:

Quark spin only contributes a small fraction to the proton spin ~ 30%









Electron-Ion Collider
To be built at BNL

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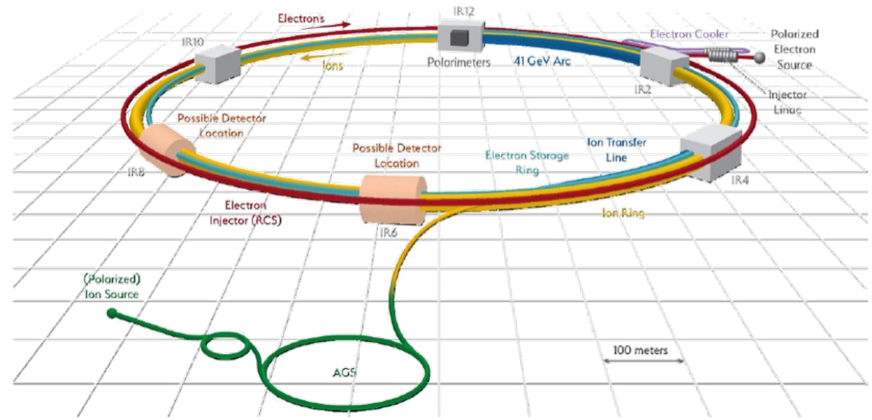
The Electron-Ion Collider

Recent IRA funding is a game changer!

Project Design Goals

- High Luminosity: L= 10^{33}–10^{34} cm^{-2}sec^{-1}, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 20–140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)



Double Ring Design Based on Existing RHIC Facility

1362 collaborators, 36 countries, 267 institutions

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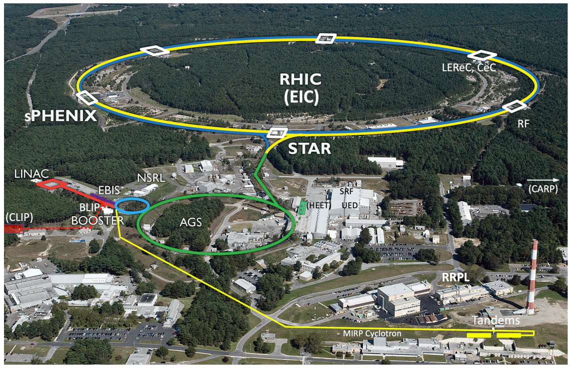
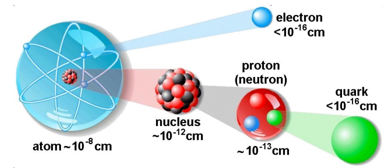
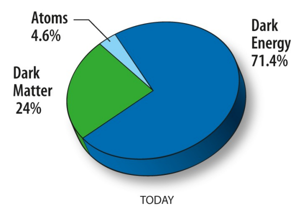
Major milestones: CD-0 December 2019; DOE EIC site (BNL) selection on Jan 9, 2020; CD-1 June 2021; EIC project detector reference design selected in March 2022; ePIC collaboration formed in July 2022

Nuclear & Particle Physics at BNL

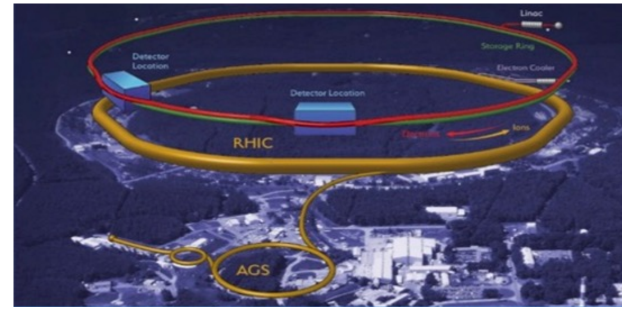


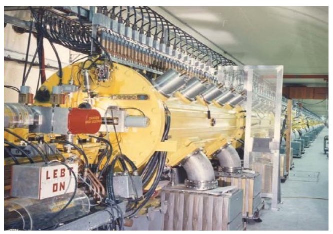
To understand sub-atomic world deeper and deeper





Electron-Ion Collider

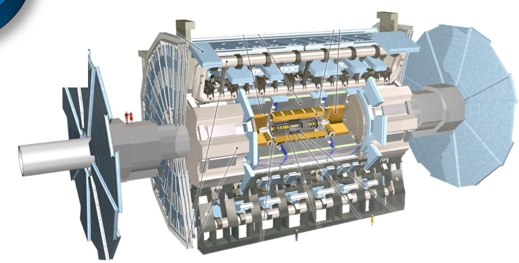




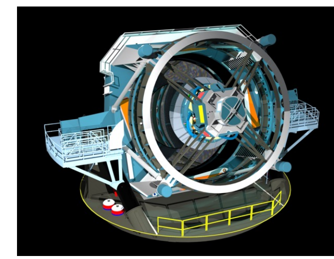
BLIP: Medical Isotopes

NASA Space Radiation Lab

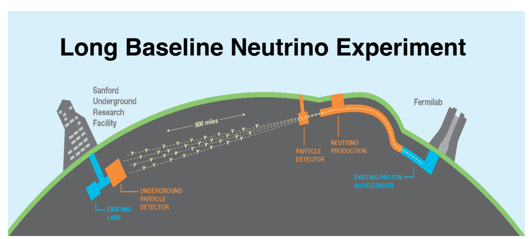
Develop unique technologies to answer fundamental questions in nature and applications of societal benefits

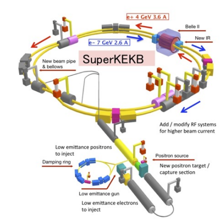


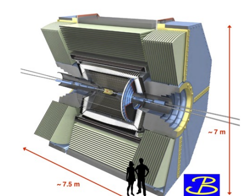
ATLAS @ LHC



Rubin Observatory







Belle II at SuperKEKB

High-Energy Theory, Nuclear Physics Theory
Center for Fundamental Nuclear Science
RIKEN-BNL Research Center

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