Planning the Future of Particle Physics

Asia-Europe-Pacific School of HEP
October 17, 2022
South Korea

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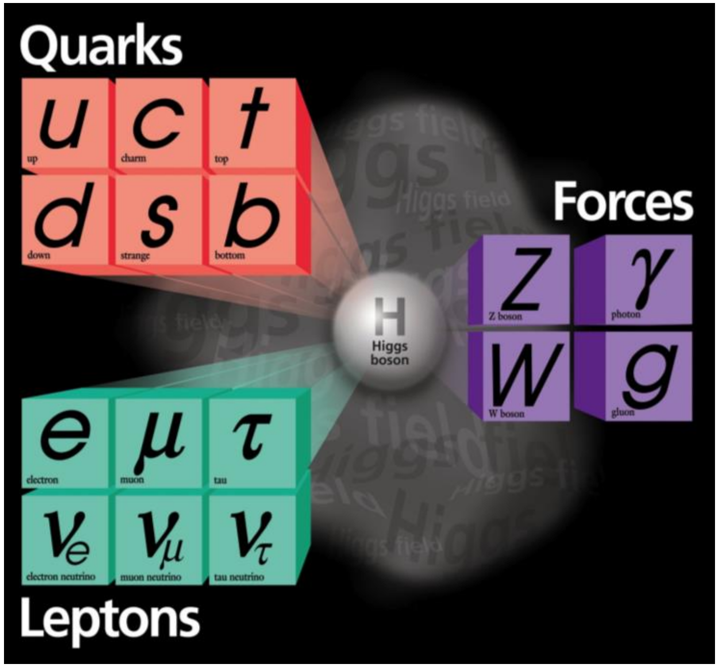
University of Chicago

Particle Physics: Standard Model & Mysteries

The Standard Model is Complete!



Phenomena in nature
that the Standard Model cannot explain.

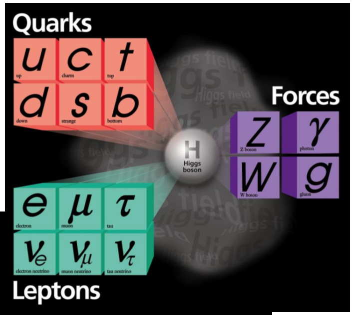
WHY ?

- mass
- 6 quarks
- 3 families
- forces
- anti-matter
- Neutrinos
- …..

WHAT ?

- dark matter
- dark energy

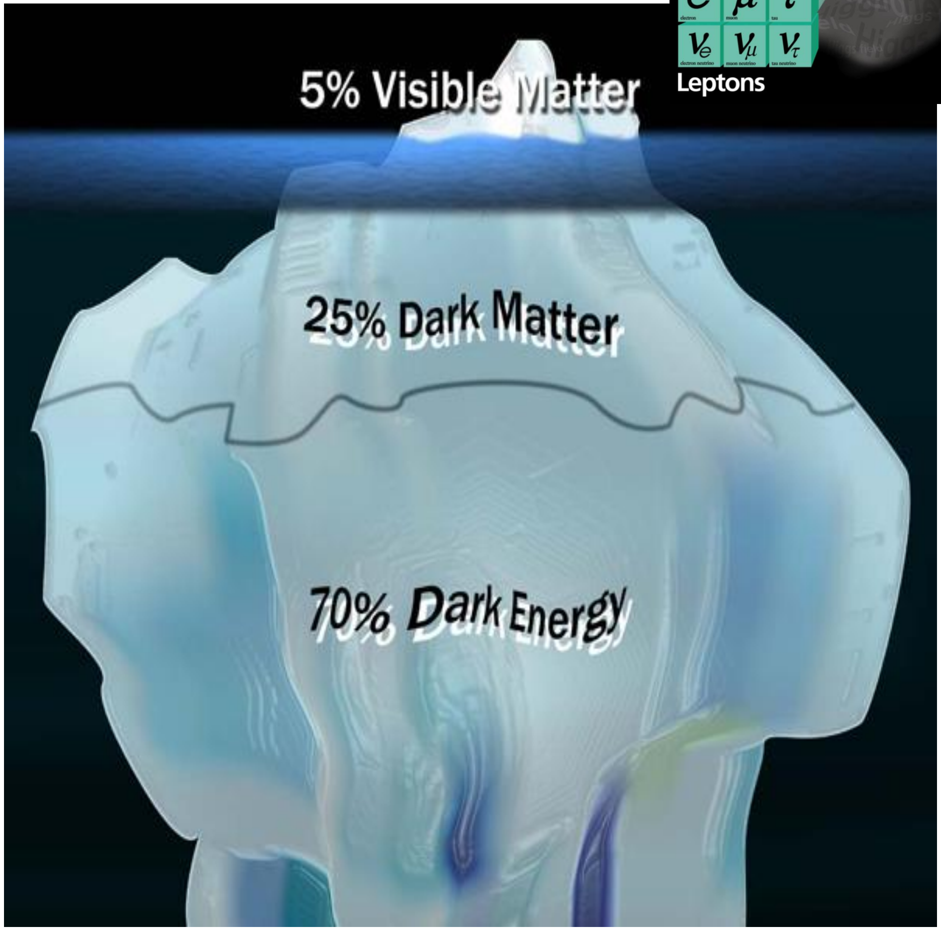
Particle Physics: Standard Model & Mysteries



Why ?

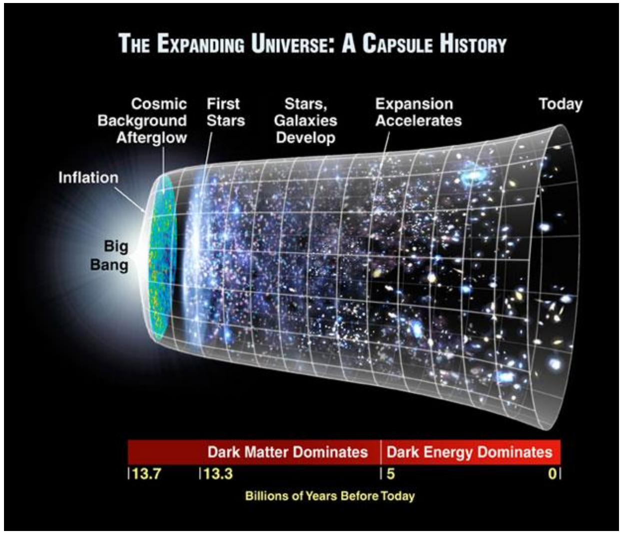
What ?

What ?



Visible Universe

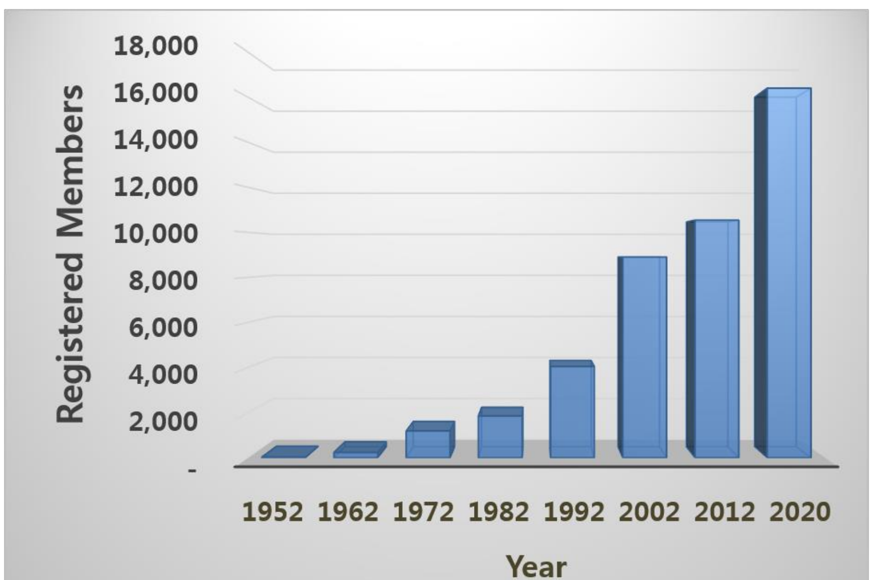
Invisible Universe
(Dark Universe)

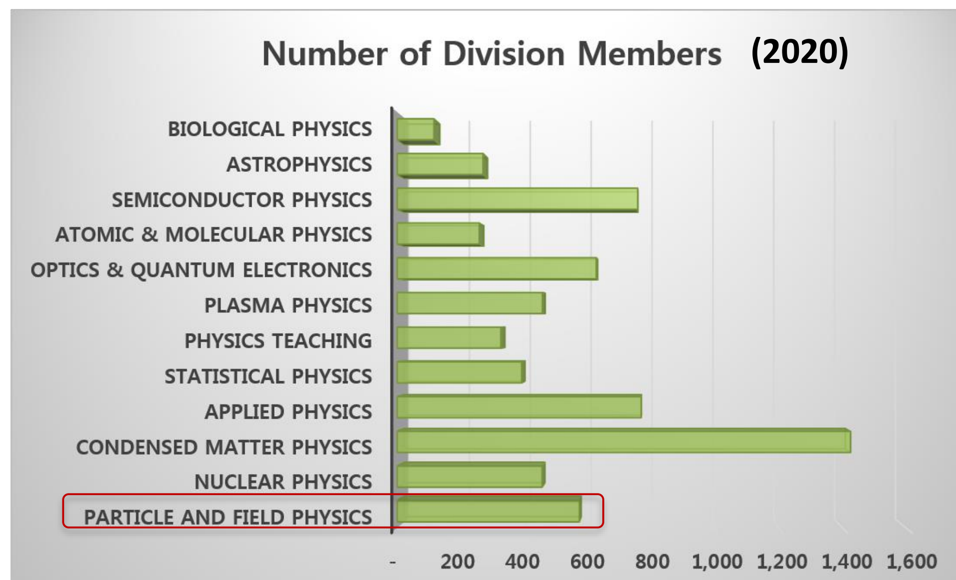


Congratulations!

70th Anniversary of Korean Physical Society

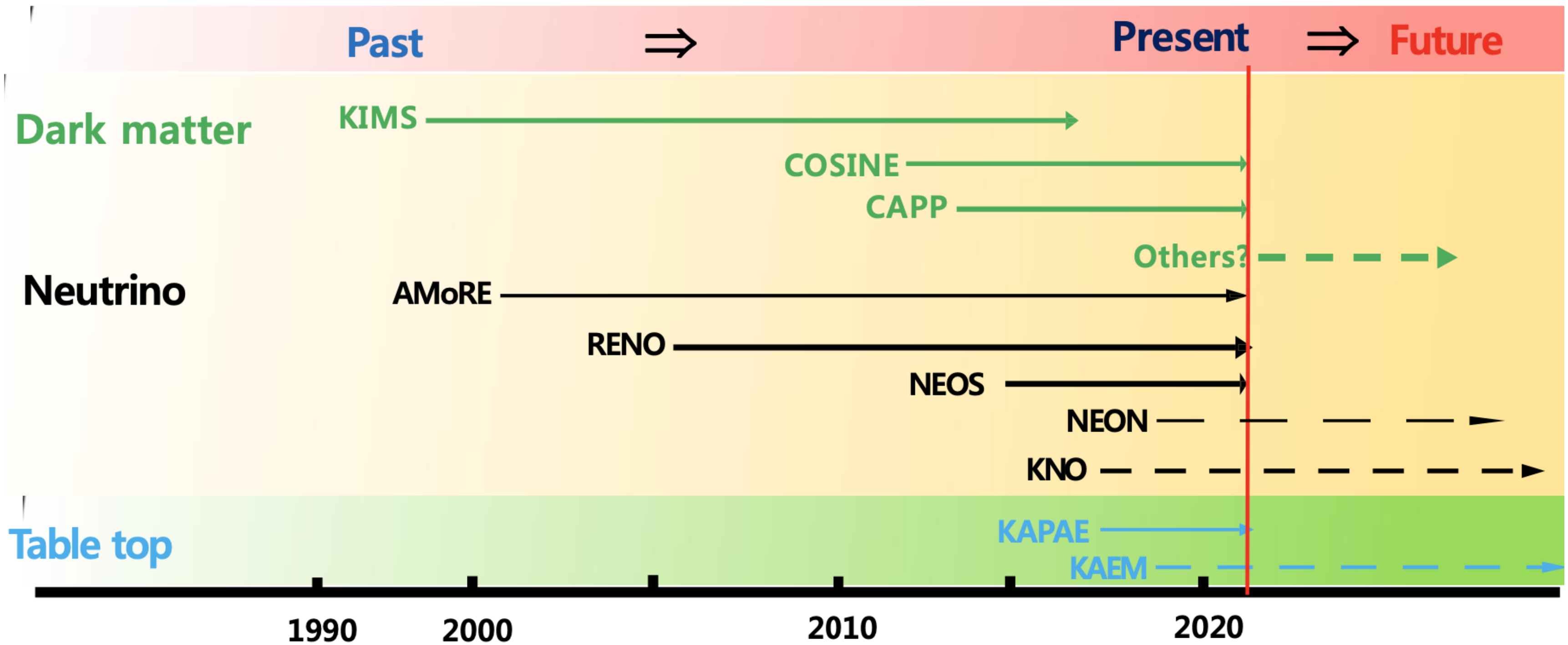
Korean Physical Society (KPS)
Inauguration meeting
in Pusan (1952)





Facilities in Korea for Particle Physics

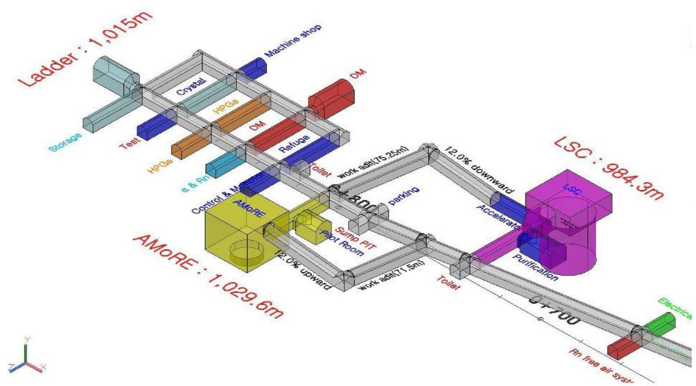
HongJoo Kim

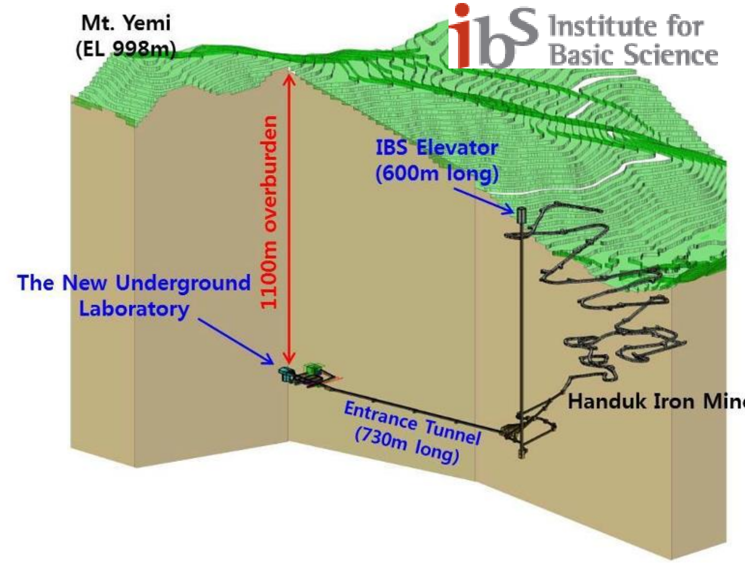


Large Facilities in Korea for Particle and Nuclear Physics

Yemi Lab in Jeongseon

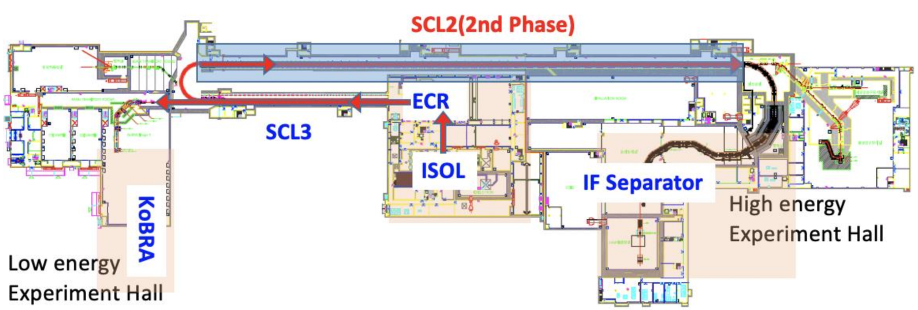
- Dark Matter, Neutrino, ….





RAON in Sejong

- Rare Isotope Science, ….



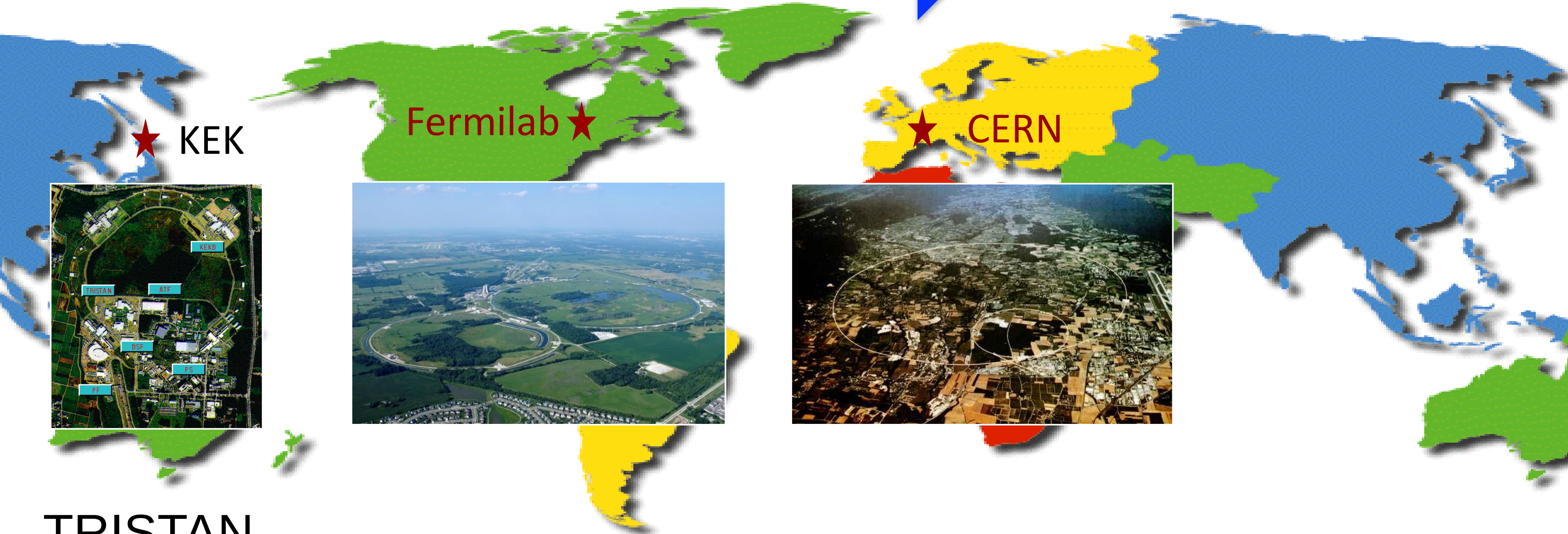
KoBRA Data taking: ~March 2023

Rare isotope Accelerator for ON-line experiments

Particle Physics

Long-Term Planning

My journey so far



TRISTAN

e^+e^-: 60 GeV

Tevatron

$p\bar{p}$: 2 TeV

LHC

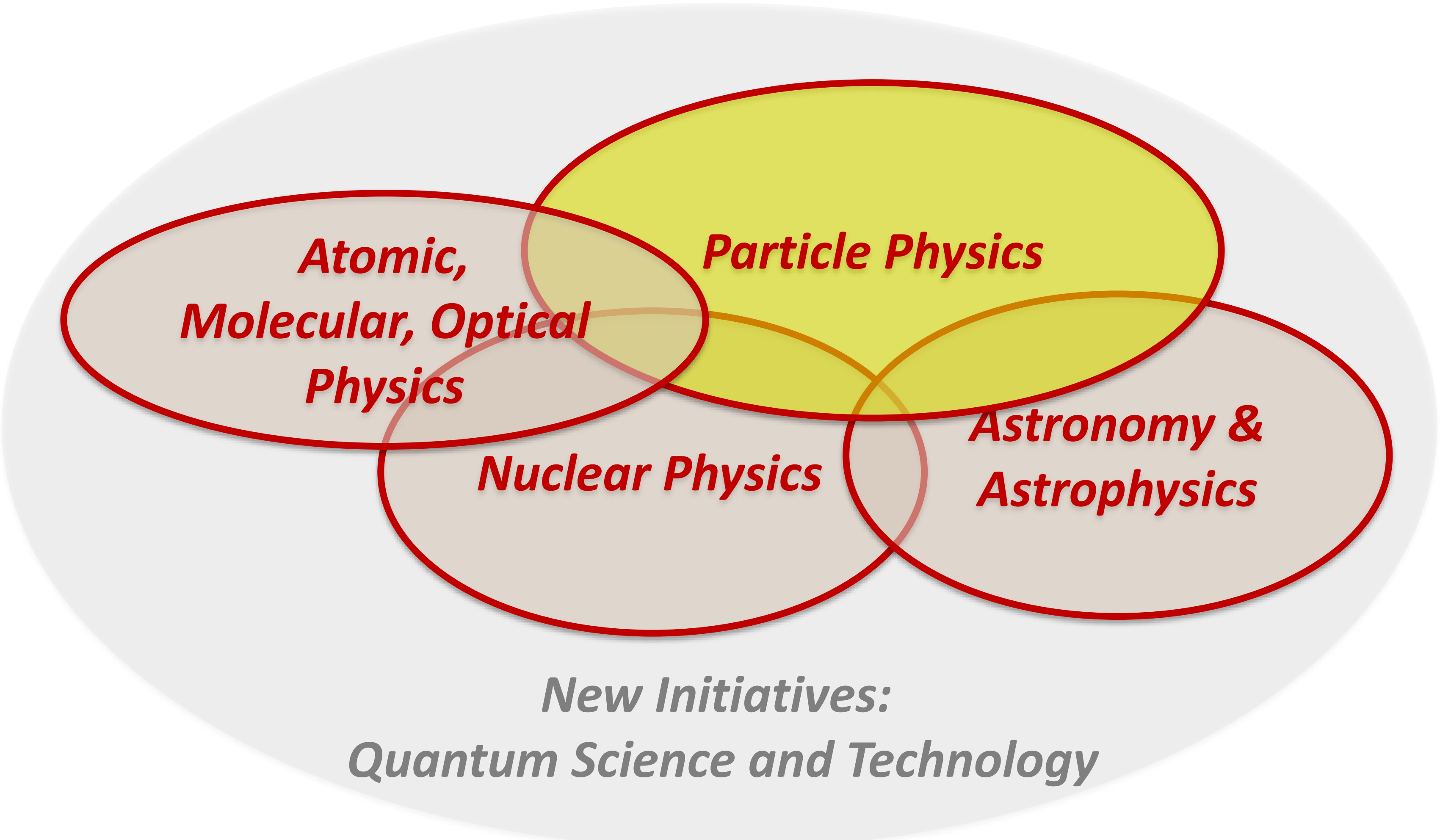
pp: 7,8 TeV → 13 TeV

Decades of
planning + technology
development + construction

Future
Collider

Particle Physics is not Isolated

Intersections among various fields

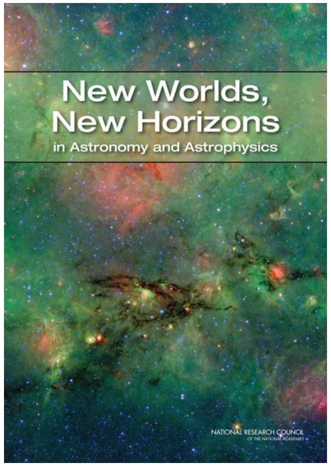


Astronomy & Astrophysics

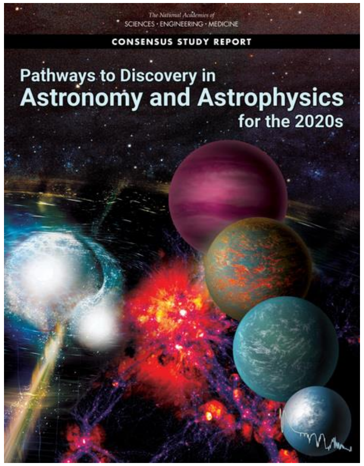
Decadal Surveys: U.S. Long Range Planning Process

Once every ten years, the astronomical communities gather panels of experts to set community-wide priorities for the coming decade. These surveys are facilitated by the National Academies and commissioned by the Federal agencies.

Astro 2010



Astro 2020



Ground-Based Astronomy: A Ten-Year Program (1964)

Astronomy and Astrophysics for the 1970s (1972)

Astronomy and Astrophysics for the 1980s (1982)

The Decade of Discovery in Astronomy and Astrophysics (1991)

Astronomy and Astrophysics in the New Millennium (2001)

New Worlds, New Horizons in Astronomy and Astrophysics (2010)

Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021)

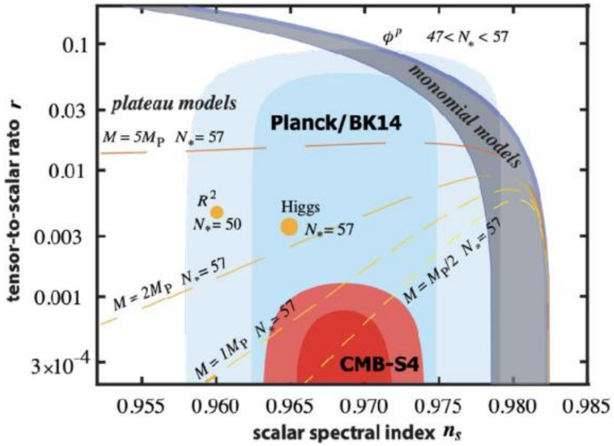
Astronomy & Astrophysics: Astro 2010

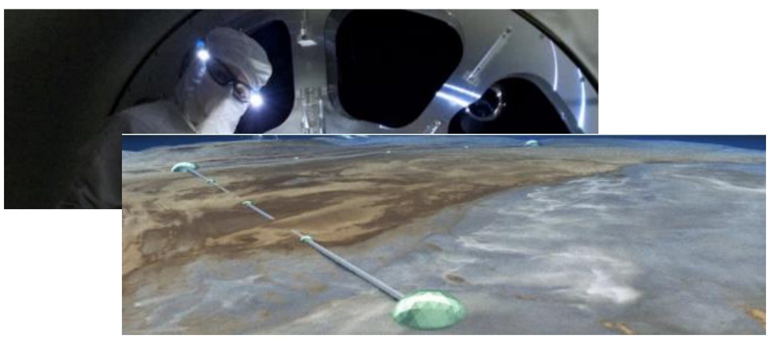
- Scientific questions to be answered include:
  - Nature of dark energy
  - Structure, distribution, and evolution of exoplanetary systems
  - Detailed examination of extreme processes including supervovae and the merger of superdense objects
  - How galaxies and galaxy clusters formed from the early hot universe
- The top priorities identified include:
  - WFIRST (Wide-Field Infrared Survey Telescope), …. the nature of dark energy
  - LSST (Large Synoptic Survey Telescope)
  - CCAT (Cerro Chajnantor Atacama Telescope)
  - LISA (Laser Interferometer Space Antenna)
  - International X-ray Observatory
  - Explorer program for small and medium-sized missions

Astronomy & Astrophysics: Astro 2020

- The Scientific Opportunities
  - ***Worlds and Suns in Context*** builds on revolutionary advances in our observations of exoplanets and stars and aims to understand their formation, evolution, and interconnected nature, and to characterize other solar systems.
  - ***New Messengers and New Physics*** will exploit the new observational tools of gravitational waves and particles, along with temporal monitoring of the sky across the electromagnetic spectrum and wide-area surveys from the ultraviolet and visible to microwave and radio to probe some of the most energetic processes in the universe and also address the nature of dark matter, dark energy, and cosmological inflation.
  - ***Cosmic Ecosystems*** will link observations and modeling of the stars, galaxies, and the gas and energetic processes that couple their formation, evolution, and destinies.

Astronomy & Astrophysics: Astro 2020





- Cosmic Microwave Background Stage 4 Observatory
  - The NSF and DOE should jointly pursue the design and implementation of the next generation ground-based CMB-S4
- IceCube-Generation 2 Neutrino Observatory
  - The IceCube-Generation 2 neutrino observatory would provide significantly enhanced capabilities for detecting high-energy neutrinos, including the ability to resolve the bright, hard-spectrum TeV-PeV neutrino background into discrete sources.
- Technology Development for Future Ground-based Gravitational Wave Observatories
  - Continuous technology development will be needed this decade for next generation detectors like Cosmic Explorer.

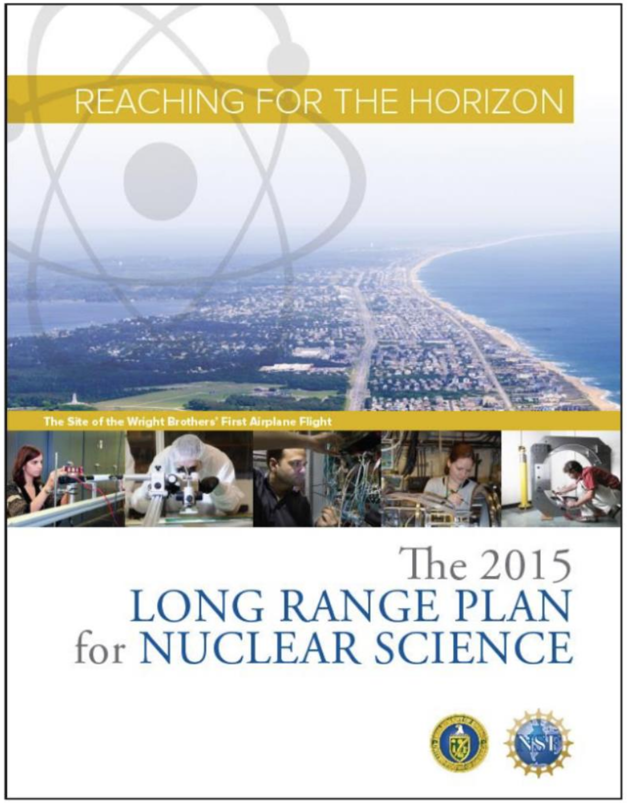
Nuclear Physics

The U.S. Nuclear Science Advisory Committee (NSAC) provides advice to the Department of Energy (DOE) and the National Science Foundation (NSF) on the US program for basic nuclear science research.

Every 4~7 years NSAC is charged by DOE and NSF to make a long-range plan

Nuclear Physics: LRP 2015

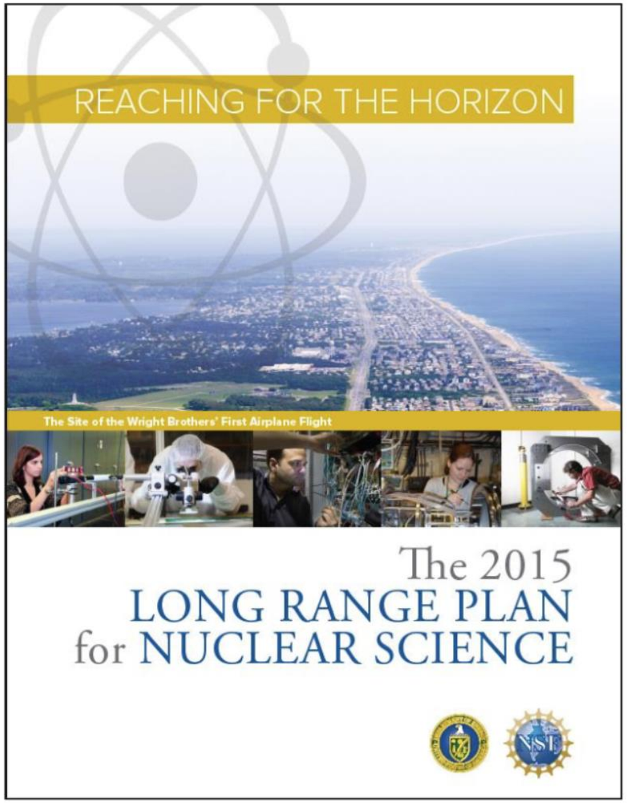
Most recent instance:



- Long Range Plan (LRP) working group
  - ~60 members from different sectors of the community + international observers from Europe and Asia
- Few months of community activities: DNP "Town Meetings" (summer 2014)
  - Education and Innovation
  - Nuclear Structure and Nuclear Astrophysics
  - Hadron and Heavy Ion QCD
  - Fundamental Symmetries, Neutrinos, Neutrons and Relevant Nuclear Astrophysics
- White papers submitted by community. (Jan 2015)
- Resolution meeting of entire working group, to finalize recommendations (April 2015)
- Report finalized October 2015

Nuclear Physics: LRP 2015

Most recent instance:

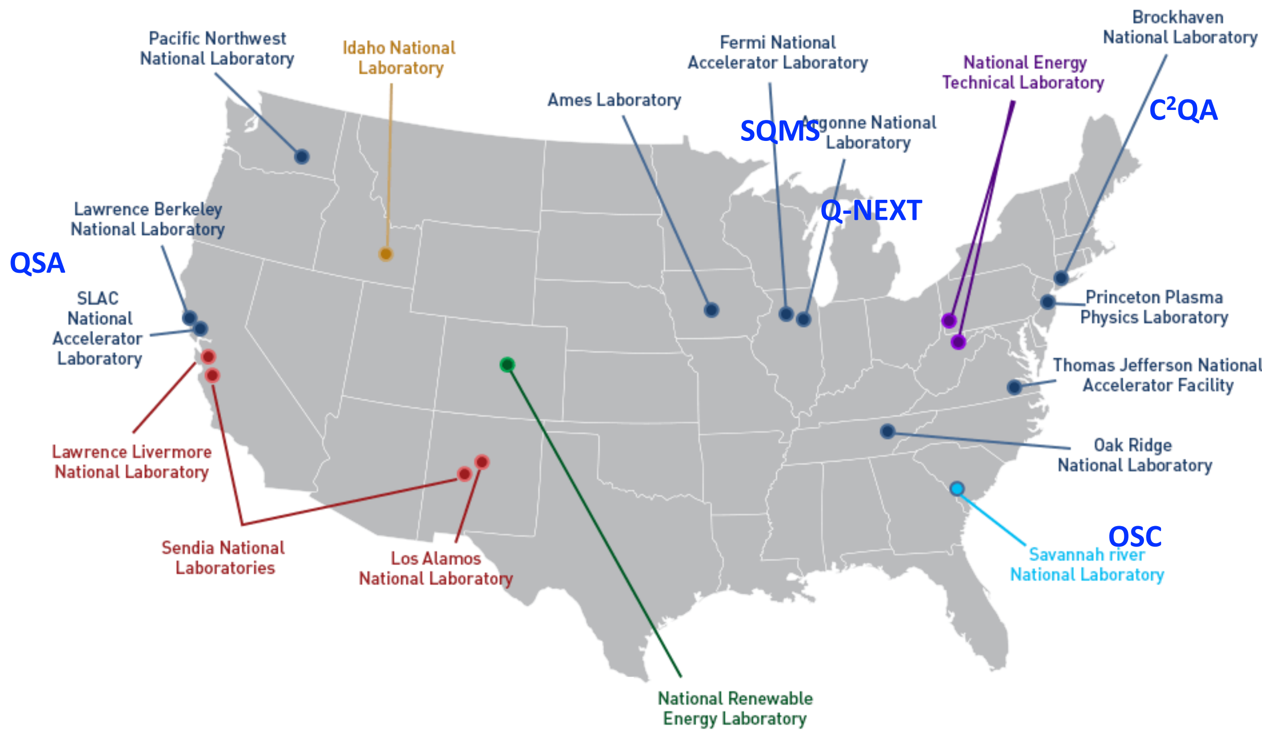


- Recommendations (LRP 2015)
  - Capitalize on investments made to maintain U.S. leadership in nuclear science.
  - Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
  - Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB (Facility for Rare Isotope Beams)
  - Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

National Quantum Initiatives

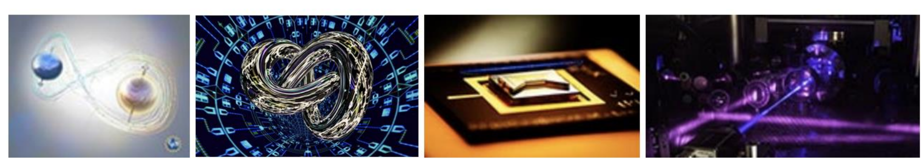
U.S. DEPARTMENT OF ENERGY

Department of Energy National Laboratories



National Science Foundation

Quantum Information Science and Engineering Research at NSF

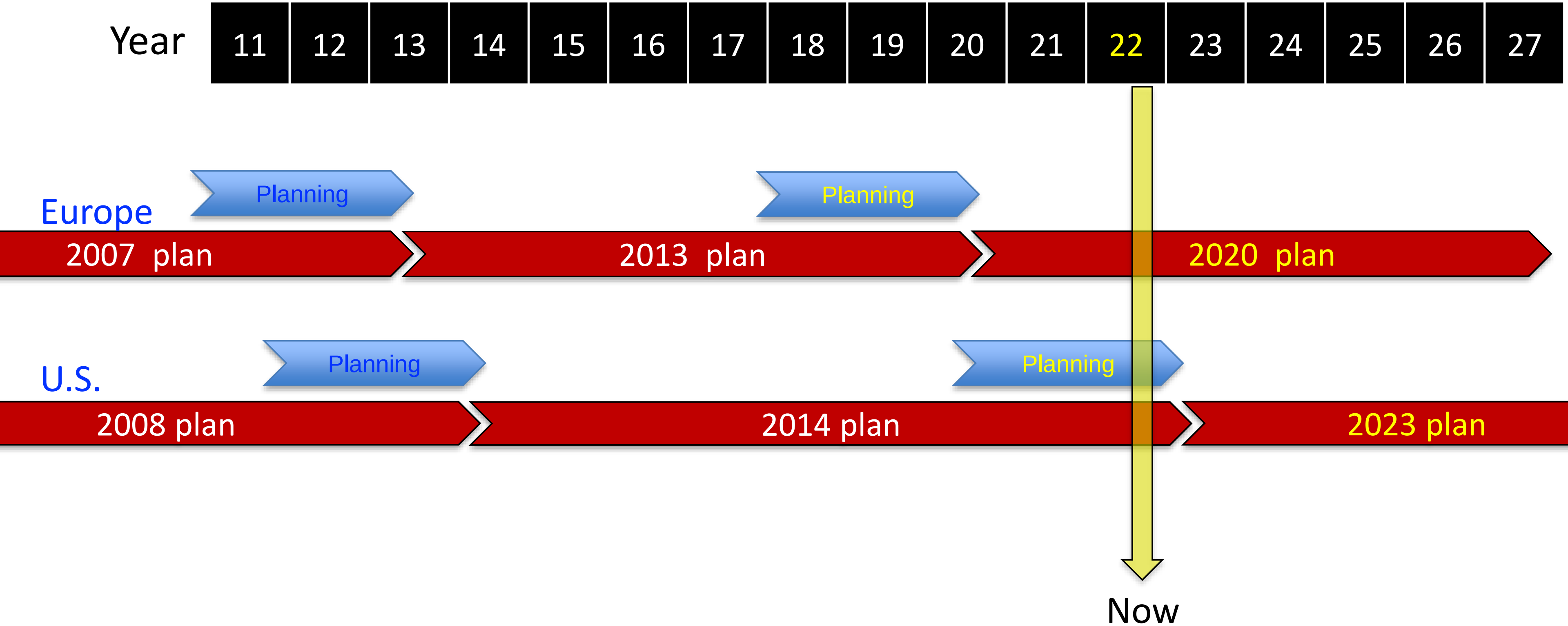


Particle Physics is Global

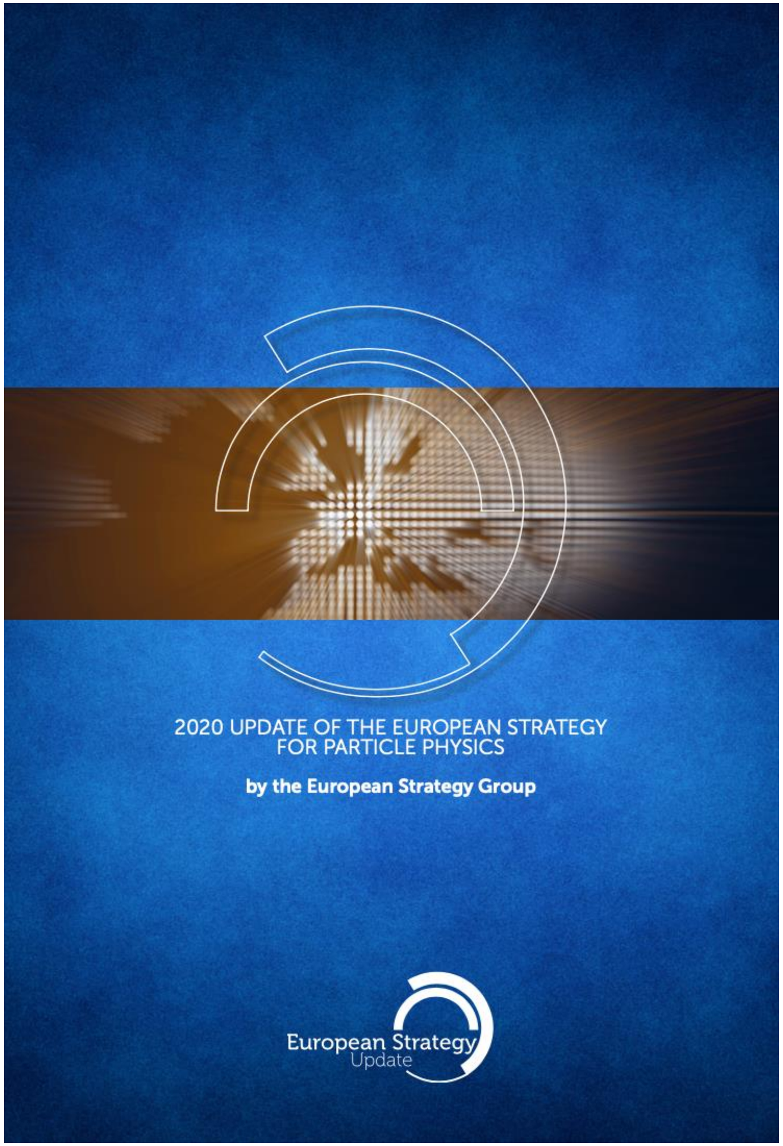
Particle Physics is Global

Regional processes in the global context

- Europe: 7 years, particle physics (primarily accelerator based)
- U.S.: ~8 years, particle physics (accelerator based and non-accelerator based)
- Canada: 5 years, particle and nuclear physics
- Korea, Japan, China, Latin America, ….



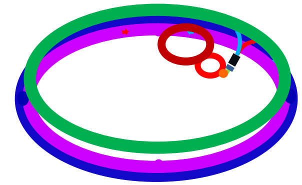
European Strategy for Particle Physics



European Strategy for Particle Physics (2020)

- Energy Frontier
  - The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
  - An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology.

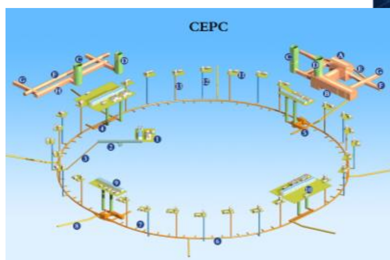
Exploring Future Colliders



Super pp Collider (SppC)
E_{cm} ~ 100 TeV

Muon collider
~10 TeV

Compact Linear Collider (CLIC)
e^+e^- E_{cm} < 3 TeV



Circular Electron Positron Collider (CEPC) E_{cm} ~ 250 GeV

LHC

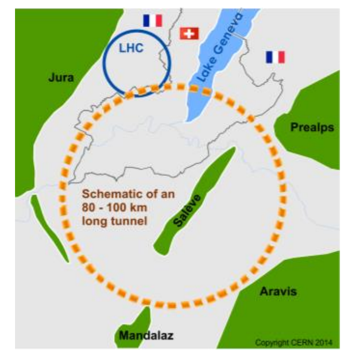
2025

2030

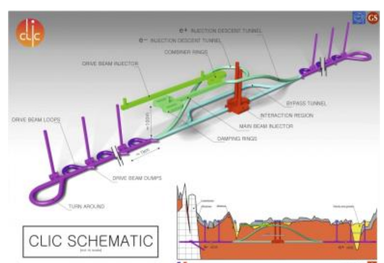
2035

2040

2045



Future Circular Collider (FCC)
e^+e^- E_{cm} < 350 GeV
pp E_{cm} ~ 100 TeV
AA E_{cm} ~ 40TeV



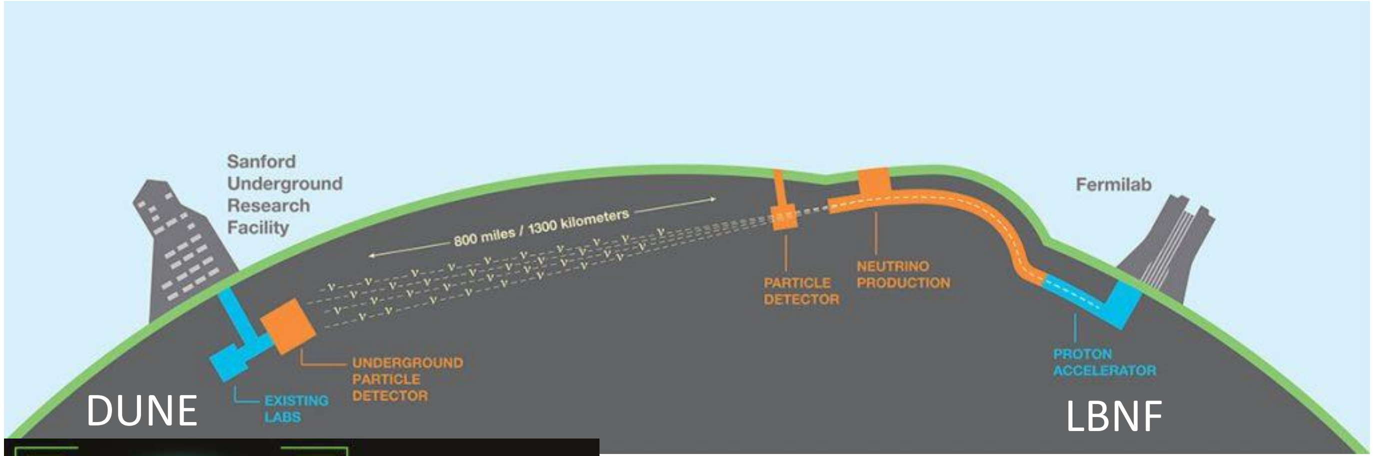
International Linear Collider (ILC)
e^+e^- E_{cm} < 1 TeV

European Strategy for Particle Physics (2020)

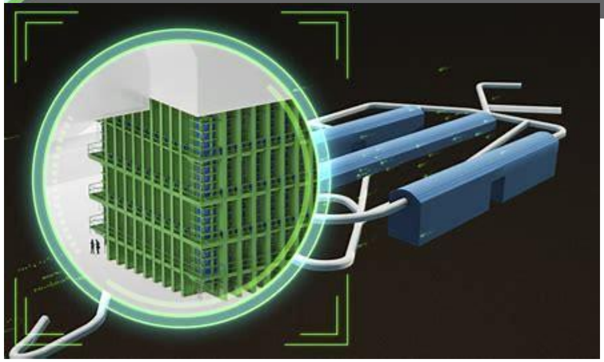
- Energy Frontier
  - The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
  - An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology.

- Neutrino Frontier
  - Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the U.S. and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

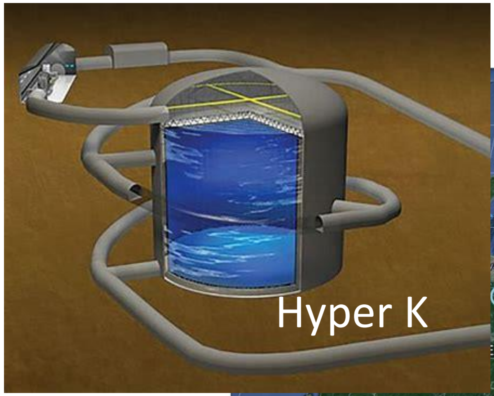
New Neutrino Facilities: Operational late 2020s

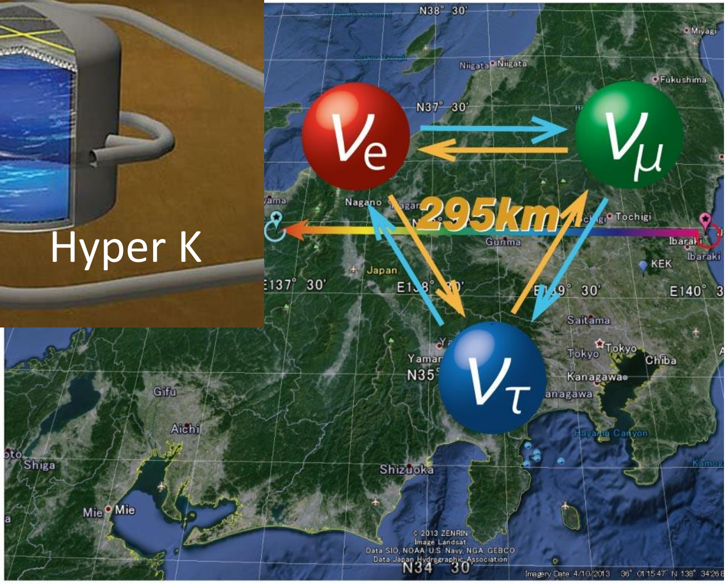


Science
- ν oscillation
- Proton decay
- Supernova relic ν
- Solar ν



- 1,300 km
- Liquid Ar





- 295 km
- Water

European Strategy for Particle Physics (2020)

- Cosmic Frontier; Rare Processes & Precision Measurements Frontier
  - The quest for dark matter and the exploration of flavor and fundamental symmetries are crucial components of the search for new physics: precision measurements of flavor physics and electric/magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particle (energy-frontier colliders, accelerator and non-accelerator experiments).

- Theory Frontier
  - Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results.

- Accelerator Frontier; Instrumentation Frontier; Computational Frontier
  - Innovative accelerator technology underpins the physics reach, and is a powerful driver for many accelerator-based science and industry.
  - The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.
  - Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programs

European Strategy for Particle Physics (2020)

- Synergies with neighboring fields
  - Nuclear physics including EIC (electron-ion collider in U.S.)
  - Astro-particle physics

- Organizational issues
  - Global collaboration and a long-term commitment (e.g., next-generation collider project)
  - Open Science

- Environmental and societal impact
  - Energy efficiency of present and future accelerations & computing facilities, Travel, …
  - Education and training for the next generation
  - Knowledge and technology transfer to the society
  - Public engagement, education, communication to the public

U.S. Strategic Planning Process for Particle Physics

~year-long process
Snowmass Community-Wide "Science" Study
Organized by Division of Particles and Fields (DPF) of APS

Input to P5

~year-long process
P5, Particle Physics Project Prioritization Panel
(subpanel of HEPAP, High Energy Physics Advisory Panel for DOE/NSF funding agencies)
formulate a 10-year execution plan (20 year vision) within funding constraints

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Particle Physics is not isolated: include plans of related fields
Particle Physics is Global: include plans of other regions

Snowmass

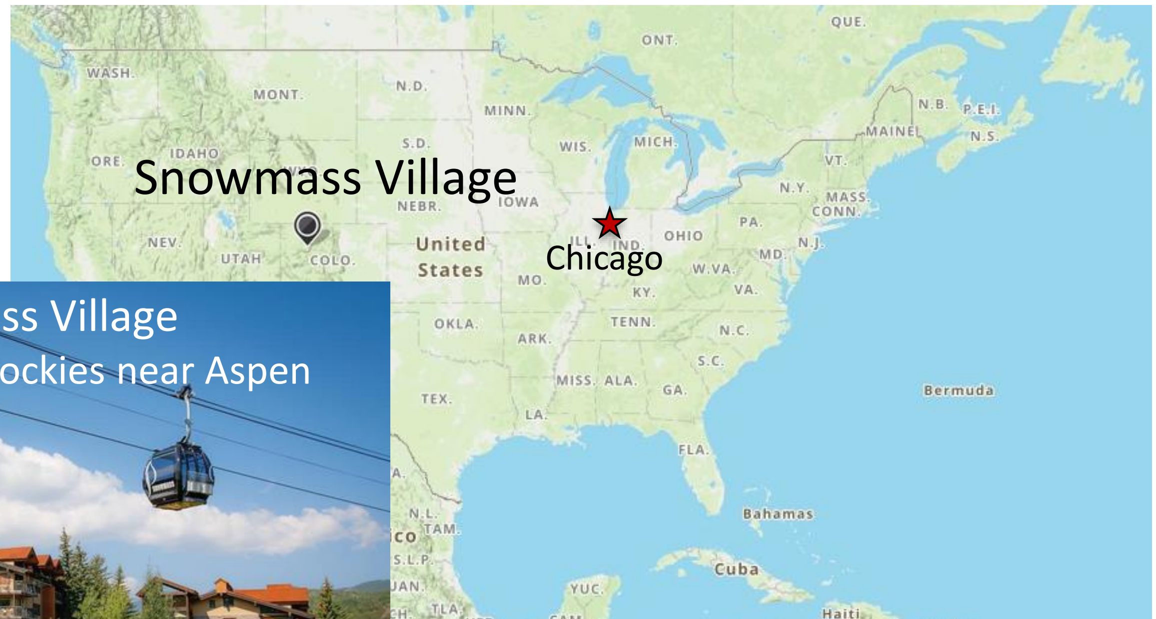
Long-term planning exercise for the particle physics community

Its goal is to develop the community's long-term physics aspirations.

to define the most important questions for the field of particle physics
to identify promising opportunities to address them

Snowmass: Historical Context

Snowmass Summer Studies: 3 weeks in Summer in Snowmass, Colorado

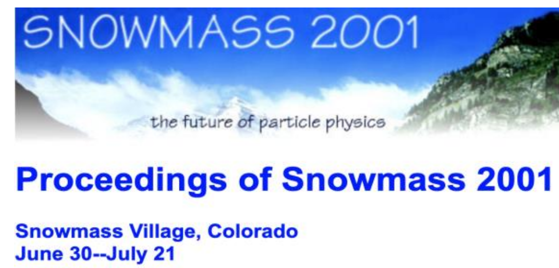


"~a thousand physicists gathered for three weeks to talk about the future of particle physics in the U.S. — and the rest of the world"

Snowmass: Historical Context

3 weeks in Summer in Snowmass

Snowmass 82 DPF Summer Study on Elementary Particle Physics and Future Facilities, June 28 – July 16
Snowmass 84 DPF Summer Study on the Design and Utilization of Superconducting Super Collider, SSC, June 23 – July 13
Snowmass 86 DPF Summer Study on the Physics of the SSC, June 23 – July 11
Snowmass 88 DPF Summer Study on High-Energy Physics in the 1990s, June 27 – July 15
Snowmass 90 DPF Summer Study on High-Energy Physics: Research Directions for the Decade, June 25 – July 13
Snowmass 94 DPF Summer Study on High-Energy Physics: Particle and Nuclear Astrophysics and Cosmology in the Next Millennium, June 29 – July 14
Snowmass 96 DPF/DPB Summer Study on New Directions for High-Energy Physics, June 25 – July 12
Snowmass 2001 DPF/DPB Summer Study on the Future of Particle Physics, June 30 – July 21



> 1 year long; not in Snowmass

Snowmass 2013

- Organized by DPF
- Summer 2012 – December 2013 (similar in its scope to 2001 but spread out through ~1 year)

Snowmass 2021

- Organized by DPF with strong participation from related fields (DPB, DAP, DGRAV, DNP)
- April 2020 – October 2022

Snowmass (2013 Report)

Frontiers

- Energy Frontier
- Intensity Frontier
- Cosmic Frontier

Cross-Cutting

- Facilities (Underground and Accelerator)
- Instrumentation
- Computing
- Theory
- Communication

Key Questions

1. Probe the highest possible energies and distance scales with the existing and upgraded LHC and reach for even higher precision with a lepton collider; study the properties of the Higgs boson in full detail
2. Develop technologies for the long-term future to build multi-TeV lepton colliders & 100 TeV hadron colliders
3. Execute a program with US as host that provides precision tests of the ν sector with an underground detector; search for new physics in quark and lepton decays in conjunction w/ precision meas.s of electric dipole and anomalous magnetic moments
4. Identify the particles that make up dark matter through complementary experiments deep underground, on the Earth's surface, and in space, and determine the properties of the dark sector.
5. Map the evolution of the universe to reveal the origin of cosmic inflation, unravel the mystery of dark energy, and determine the ultimate fate of the cosmos.

6. Invest in the development of new, enabling instrumentation &accelerator technology
7. Invest in advanced computing technology and programming expertise essential to experiment and theory.
8. Carry on theoretical work in support of experimental projects and to explore new unifying frameworks.

9. Invest in the training of physicists to develop the most creative minds to generate new ideas in theory & expt that advance science and benefit the broader society.
10. Establish a nationally coordinated communication, education and outreach effort to convey the excitement and value of our field to others.

Snowmass → P5: Science Drivers & Recommendations

P5 2014 Report

- **Five intertwined scientific Drivers** were distilled from the results of a yearlong community-wide study:
  - Use the Higgs as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

29 recommendations !!

Particle Physics: Snowmass (2013) + P5 (2014)

P5 2014 Report

- Support a program of projects of all scales (large, medium, small), new ideas & developments
- Accelerator science / R&D, instrumentation R&D, computing / software; next gen. education and training

(large projects)

FIGURE 1 Approximate construction (blue; above line) and expected physics (green; below line) profiles for the recommended major projects, grouped by size (Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

Snowmass 2021

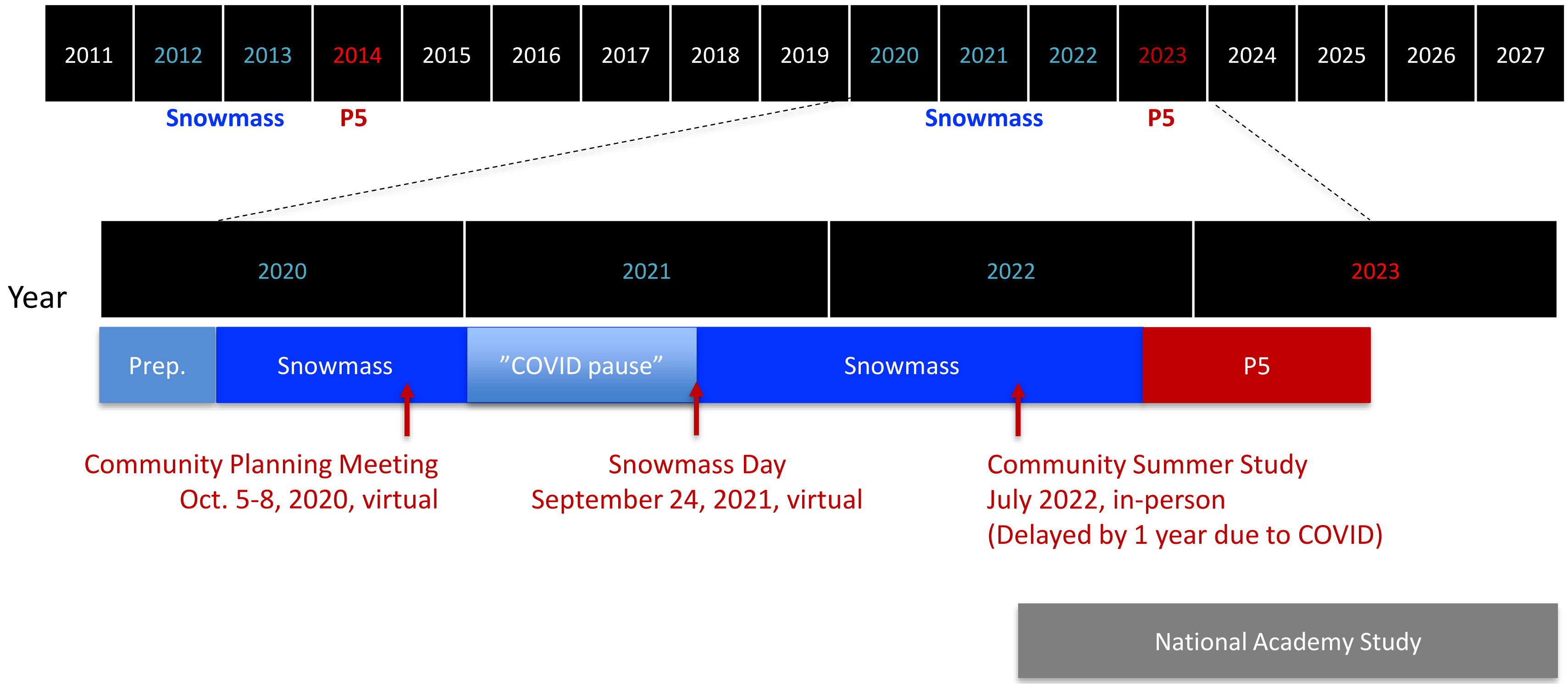
- Successful Snowmass 2013 is our guide!
  - Implement lessons learned from Snowmass 2013
- Snowmass 2021: Ten Frontiers
  - Energy Frontier
  - Frontiers in Neutrino Physics
  - Frontiers in Rare Processes & Precision Measurements
  - Cosmic Frontier
  - Theory Frontier

  - Accelerator Frontier
  - Underground Facilities and Infrastructure Frontier
  - Instrumentation Frontier
  - Computational Frontier

  - Community Engagement Frontier

Particle Physics:
Snowmass (2020-2022) + P5 (2022-2023) + NAS (2022-2024)

Snowmass: 2020 - 2022



Frontiers and Topical Groups

10 Frontiers	80 Topical Groups
Energy Frontier	Higgs Boson properties and couplings, Higgs Boson as a portal to new physics, Heavy flavor and top quark physics, EW Precision Phys. & constraining new phys., Precision QCD, Hadronic structure and forward QCD, Heavy Ions, Model specific explorations, More general explorations, Dark Matter at colliders
Frontiers in Neutrino Physics	Neutrino Oscillations, Sterile Neutrinos, Beyond the SM, Neutrinos from Natural Sources, N[illegible]trino Properties, Neutrino Cross Sections, Nuclear Safeguards and Other Applications, Theory of Neutrino Phys[illegible]al Neutrino Sources, Neutrino Detectors
Frontiers in Rare Processes & Precision Measurements	Weak Decays of b and c, Strange and Light Quarks, Fundamental [illegible]aryon and Lepton Number Violation, Charged Lepton Flavor Violation, Dark S[illegible]scopy
Cosmic Frontier	Dark Matter: Particle-like, Dark Matter: Wave-[illegible] Energy & Cosmic Acceleration: The Modern Universe, Dark Energy & Cosmi[illegible], Dark Energy & Cosmic Acceleration: Complementarity of Probes and N[illegible]
Theory Frontier	String theory, quantum [illegible]ory techniques, CFT and formal QFT, Scattering amplitudes, Lattice gauge th[illegible] physics, Collider phenomenology, BSM model building, Astro-particle p[illegible]ation science, Theory of Neutrino Physics
Accelerator Frontier	[illegible]tion, Accelerators for Neutrinos, Accelerators for Electroweak and Higgs Physics, [illegible]ors for Physics Beyond Colliders & Rare Processes, Advanced Accelerator Concepts, [illegible] R&D: RF, Magnets, Targets/Sources
Instrumentat[illegible]	[illegible]ensors, Photon Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas Detectors, [illegible]imetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio Detection
Computational [illegible]	Experimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and processing resource access (Facility and Infrastructure R&D), End user analysis
Underground Facilities and Infrastructure Frontier	Underground Facilities for Neutrinos, Underground Facilities for Cosmic Frontier, Underground Detectors
Community Engagement Frontier	Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement

30 Frontier conveners, ~250 Topical Group conveners,
>40 Inter-Frontier Liaisons, ~25 Early Career Liaisons

Snowmass Early Careers; Snowmass Ethics

- Snowmass Early Careers
  - Snowmass is towards a long-term strategic plan (20 years)
    - Voices of early career members are critically important
    - Forming representatives for Snowmass Early Careers
      - Solicited nominations: > 250 nominated!! (Spring 2020)
    - Key initiatives
      - Snowmass Coordination: Snowmass involvement
      - Diversity, Equity, and Inclusion
      - Survey of the early career membership
      - In-reach: Professional development and building cohesion
      - Long-Term Organization

- Snowmass Ethics
  - Snowmass: dynamic exchange of ideas across a large swath of the community in a variety of formats (slack channels, meetings, workshops)
  - All community should feel safe and supported in engaging in all exchanges.

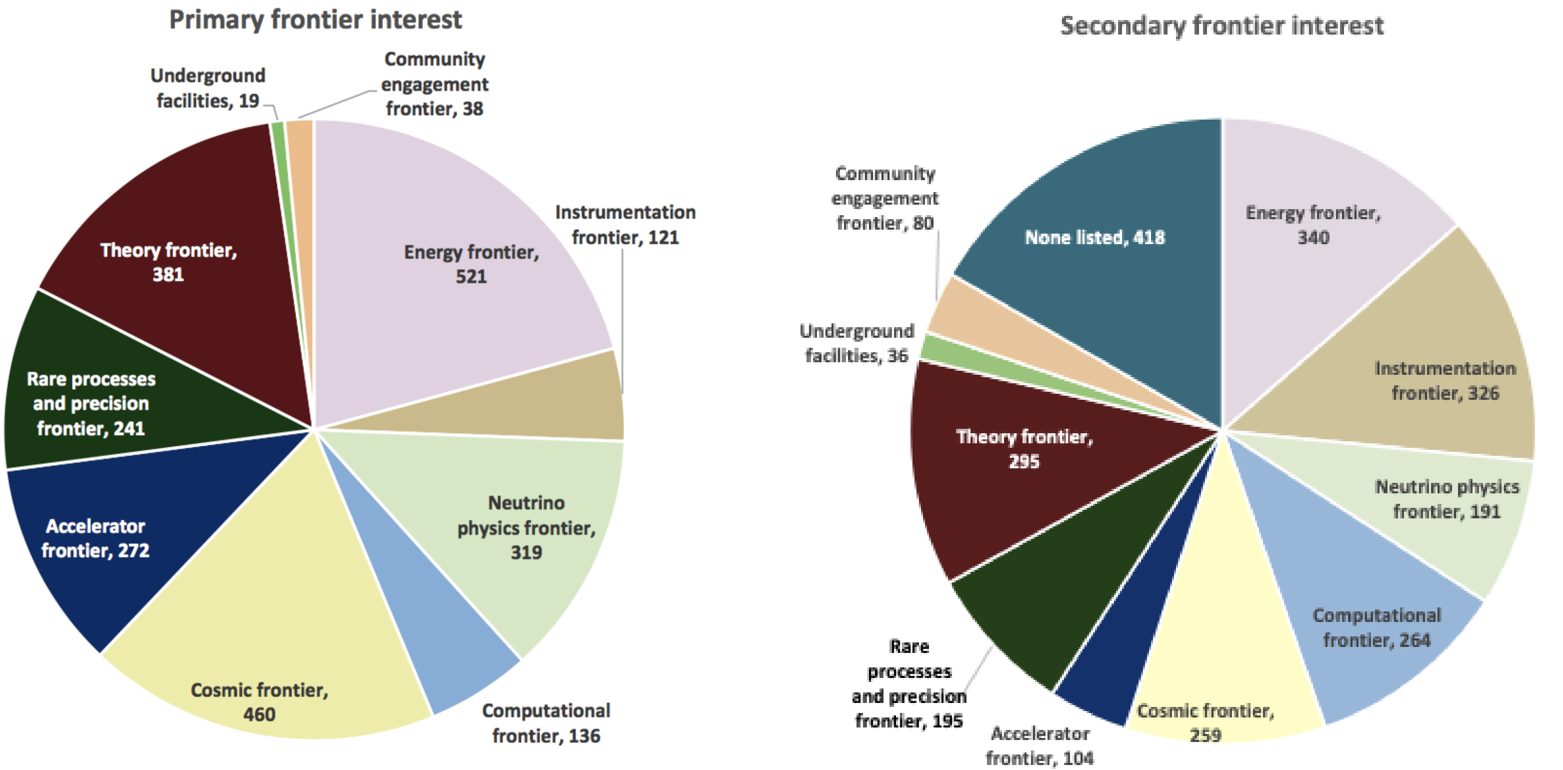
Snowmass Community Planning Meeting (Oct. 2020)

~3,000 participants (virtual)

~650 outside the North America Time Zone

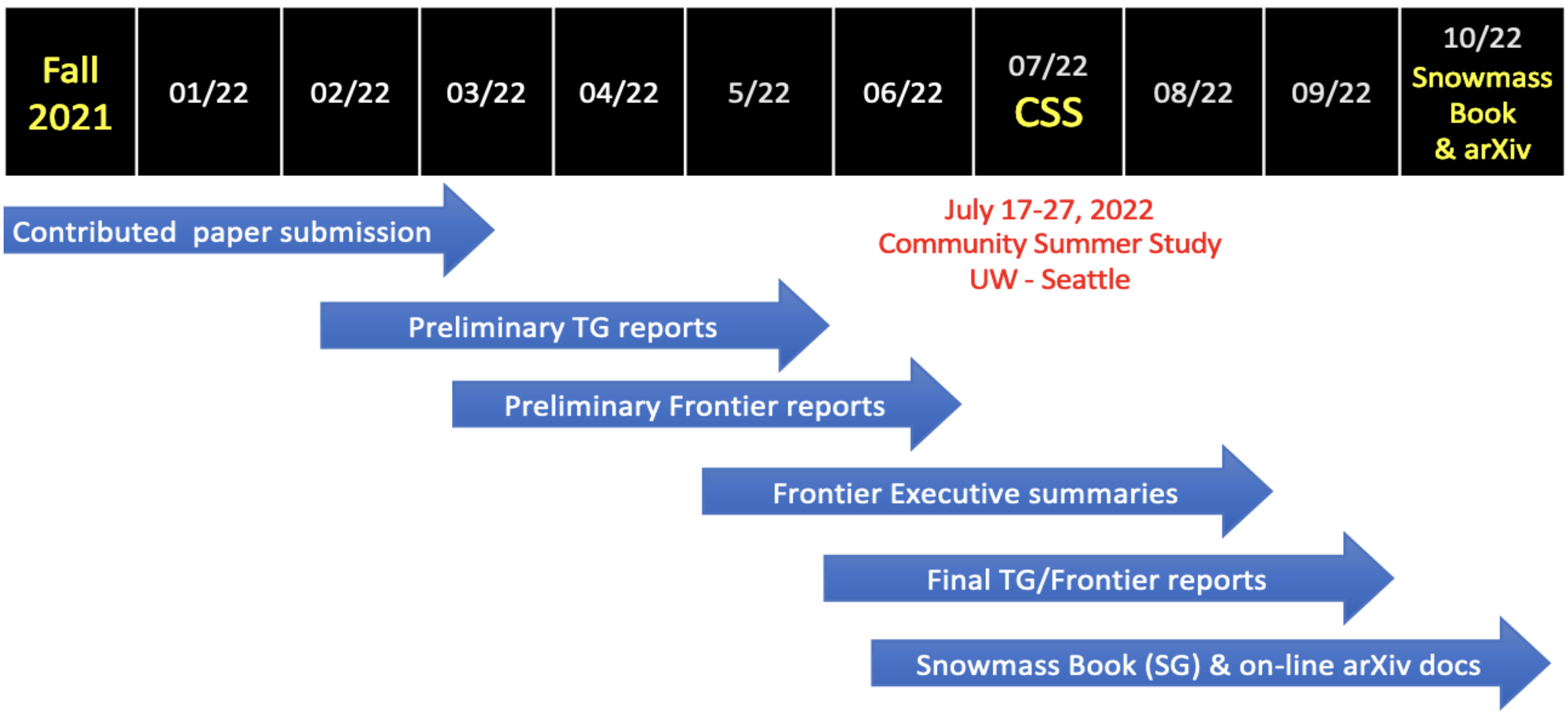
(Note that 11am-4pm U.S. Central time was inconvenient – very inconvenient for many countries)

1,574 in total: submitted before August 31, 2020 (many LOIs – multiple frontiers)



“Snowmass Day” (September 2021)

- Snowmass paused due to the COVID-19 (Jan. – Aug. 2021)
- Resumed the full activity from September 2021
- “Snowmass Day” (~1,000 virtual participants) to get back together and refocus attention to the Snowmass activities



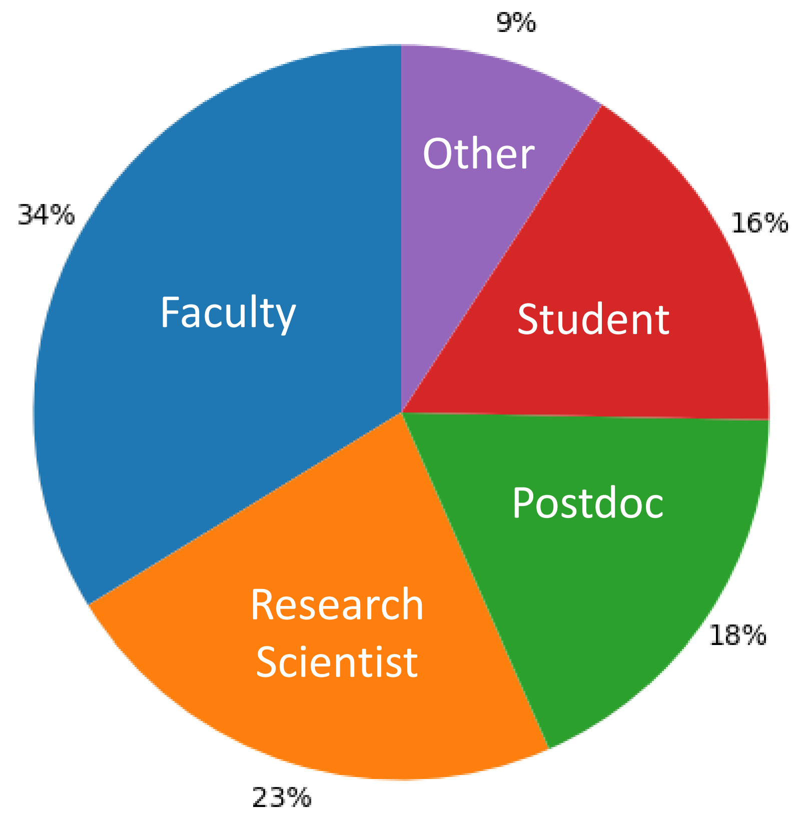
Snowmass Community Summer Study (July 2022)

July 17 – 27, 2022 at University of Washington, Seattle

Snowmass CSS

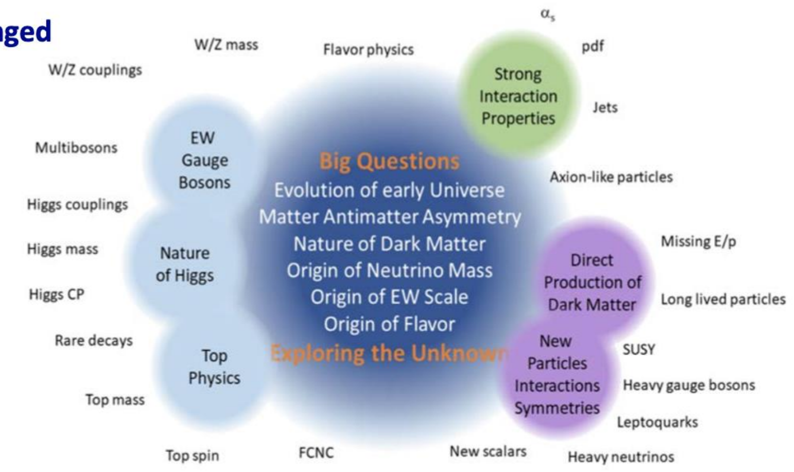
July 17 – 27, 2022

# of total participants = 1135
# of in-person participants = 725
# of virtual participants = 409



Energy Frontier (Message)

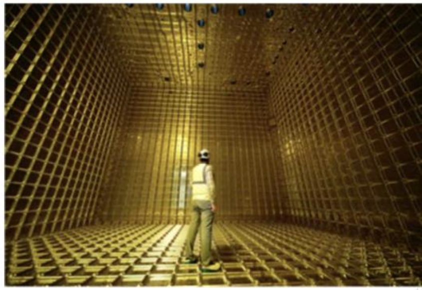
- **Compared to Snowmass 2013 the physics landscape has significantly changed**
  - The program of measuring the Higgs boson properties is well underway at the LHC with growing precision
  - A broad range of searches have explored multiple BSM scenarios without convincing evidence of new physics
  - The HL-LHC is an approved project
- **Without a robust support for the HL-LHC and a clearly defined path towards a Higgs factory we leave critically important physics unchecked and crucial questions unanswered**
- **The EF community should be prepared to explore a broad range of BSM phenomena at the 10 TeV mass scale**



The Energy Frontier community voices a strong support for

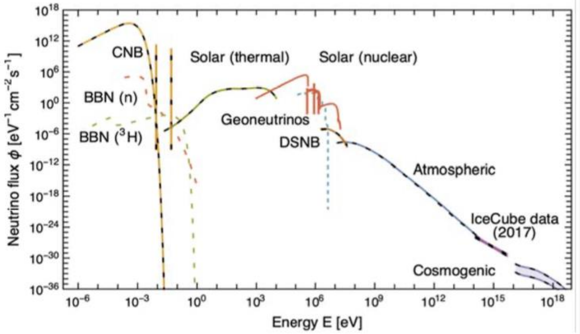
1. **HL-LHC operations and 3 ab^{-1} physics program, including auxiliary experiments**
2. **The fastest path towards an e^+e^- Higgs factory (linear or circular) in a global partnership**
3. **A vigorous R&D program for a multi-TeV collider (hadron or muon collider)**

Neutrino Frontier



* We need to **finish DUNE**, and its broad physics program.
  Both Phase I and Phase II are required to complete the original DUNE design.
* We are excited about long-term, broader possibilities that make use of our investment in the facility and could expand the DUNE scope beyond that originally envisioned.
* A healthy program of projects of different sizes and time scales, with wide-ranging connections is highly desired and very much needed.

Impacts everywhere! But if we have to choose it's the Cosmic Frontier, due to deep connections and intertwined BSM searches in multiple areas.



Neutrinos are tools for astrophysics and cosmology. Astrophysics and cosmology provide insight into NF physics.

What surprised us? Great technical progress on the detectors!
Well, that was not totally a surprise– but it was even more impressive than expected!

Rare And Precision Frontier

Message

The physics of flavor must have greater emphasis in the US program
with a **new science driver** to uncover the mystery of generations and probe new physics

Flavor Physics, Dark Sector searches, studies of exotic hadrons, and fundamental symmetry tests make unique contributions to the science driver ”explore the unknown: new particles, interactions and physical principles”

Intersections Outward

- Neutrino and Energy Frontier physics will be profoundly affected by what we learn
- Experimental synergies with nuclear and AMO will enrich our program
- Phenomenology and lattice QCD calculations are key to achieving our goals
- Synergies with instrumental & computing efforts will improve sensitivities and cost

Most Surprising

- How unified we really are – even without the focus of a machine or particle, we found we have a shared sense of purpose and intellectual questions
- How well we did despite COVID. You’re all amazing! (especially UW!! 👏)

Cosmic Frontier

The Cosmic Frontier is the bedrock of the field in the 21st century. CF realizes the HEP vision in all its scales and provides a compelling science case on which much of the current HEP program is based. In the next decade, CF will address the most pressing questions facing fundamental physics today, aiming to discover the identity of dark matter, understand the physics of cosmic acceleration, and search for new particles, new forces, and new principles of Nature.

CF seeks increased research support to execute the science goals of all projects in its portfolio, including new funding for cross-survey science leveraging the recently-completed projects DESI and LSST.

Our top project priority is to complete construction CMB-S4, while launching new projects to delve deep and search wide for dark matter, as well as to make the next leap in dark energy and cosmic acceleration research.

Theory Frontier

- Theory is essential to the field of particle physics, unifying the frontiers and producing transformative science both in connection to projects and in its own right.

- It is central to the motivation, analysis, and interpretation of experiments; lays the foundations for future experiments; and advances our understanding of Nature in regimes that experiments cannot (yet) reach.

Intersections Outward					
AF	CompF	CF	EF	NF	RPF
Motivation	Motivation, algorithms, tools	Motivation, analysis, interpretation			

Biggest surprise: how deeply interconnected the many facets of theory truly are, from fundamental to phenomenological to computational theory, and how completely interwoven they are with the other frontiers.

Image Credits: Flip Tanedo (L) and Jesse Thaler (R)

Accelerator Frontier

Message

- The accelerator community has technology and expertise to address the next generation accelerator.

- By the time of next Snowmass/P5 a National Future Colliders R&D program (new initiative!) should consider international and US based options and carry out technical and design studies sufficient to make informed decision on future directions toward
    - Higgs/EW factories
    - 10 TeV/parton colliders.

Intersections: Progress in accelerators will critically impact all future particle physics endeavors (neutrinos, colliders, DM) and therefore R&D should be prioritized by P5 inclusively

accelerators need to be part of the P5 charge.

Full utilization of the unique proton power capability of the upcoming PIP-II accelerator should be developed by the HEP community (use remaining 98% of full beam power).

Surprising Thing this week at Snowmass:

We seem to be clever enough to be seriously taken by the Theory Frontier (they even did argue with us)…

Instrumentation Frontier

- We need to *double* the US Detector R&D budget over the *next five years* and modify existing funding models to enable R&D Consortia along critical key technologies for the planned long term science projects, and sustain the support for such collaborations for the needed duration and scale.

- Develop and maintain the critical and diverse technical workforce and enable careers for technicians, engineers and scientists across disciplines working in HEP detector instrumentation, at laboratories and universities.

Intersections: *CF, EF, NF and RPF are most affected by progress in IF, since advances in detector instrumentation enable scientific advances in ALL science frontiers.*

Comparing to 2013 Snowmass, we independently came to the same five key messages. Nothing has changed and significant investment is still needed for instrumentation.

➔ Strong turnout for IF at Snowmass. Now we need equally strong support from the community!

Computation Frontier

Message: The size and complexity of the Software and Computing (S&C) is commensurate with that of the experimental instruments, but S&C changes on a faster timescale than facilities, experiments, and surveys. We need an entity that can continuously promote, coordinate, and assist on S&C needs. We propose a new DPF panel that can inform HEPAP.

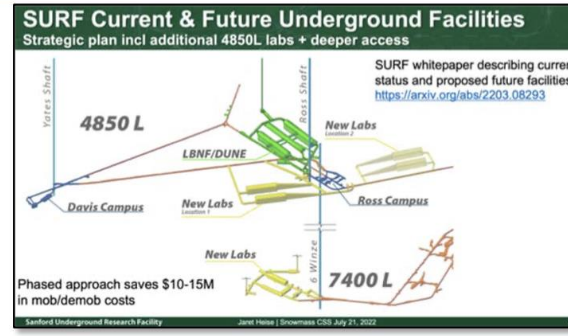
Intersection outward: Everyone needs software and computing, even instrumentation and theory. Without computing, there will be a higher cost or lost science.

- TF report states they would like computers at the 10 exaflop speed, just as we get the first exaflop computing
- Both CMS and ATLAS see a large gap between how much storage (disk) they can afford and what will be required, unless they engage in R&D to improve storage efficiency.
- Tools like Geant4 that are critical for the work of the four physics frontiers, instrumentation, and underground facilities are largely unfunded. This is one example of a tool that is really critical to HEP (in fact, it is one of the most cited HEP papers of all time!) and yet does not squarely fit into an existing funding structure.

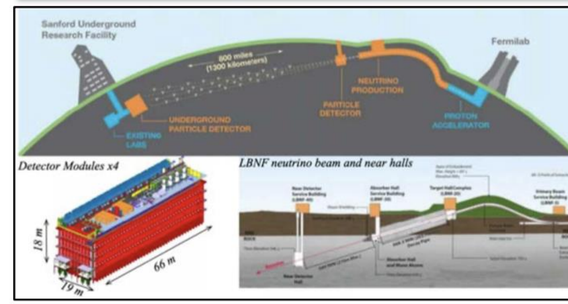
Surprisingly, some colleagues seem to fail to recognize the enormous physics content of the software and computing endeavor within HEP, unlike the case of instrumentation, where the physics content is recognized.

Underground Facilities & Infrastructure Frontier

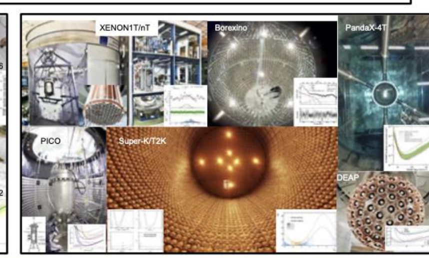
1. **Key message:**
   - Establish *SURF as an underground User Facility*.
   - Ensure support to *complete and operate LBNF and DUNE*.
   - Immediately pursue opportunities to create *underground facility space for G3 dark matter* as recommended in 2014 P5 report.



2. **Intersections outward:**
   - **Neutrino Frontier:** LBNF and DUNE, *long-baseline neutrino science*, are key U.S. high energy physics programs relying on underground facilities.
   - **Cosmic Frontier:** Establishing a commitment to underground facilities for a large-scale *third generation direct detection dark matter* program is a major impact of planning efforts.

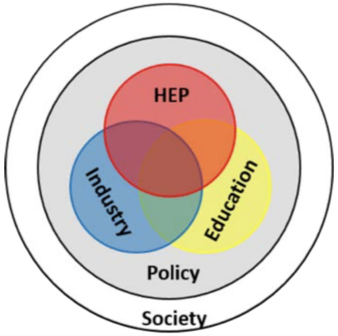


3. **Most surprising ("Most exciting" is more apt):**
   - Incredible *progress* in performing research science in underground facilities since Snowmass 2013.
   - Incredible *opportunity* on horizon for high energy physics and other research using underground facilities.
   - Physics *karaoke* is a thing and it happened at Snowmass.



Community Engagement Frontier

1. Our goal and hope is that by the end of Snowmass 2021, all of us will be convinced of and committed to the following propositions:
    1. It is critical that we all agree on the importance of *everyone* working together in *CEF* to organize and develop our ongoing *CE* efforts in a *coherent* manner focused on improving our HEP community and achieving the vision we are defining for our field.
    2. A *structure* must be established within HEP for taking ownership and responsibility for *implementing* CEF recommendations and *monitoring* their progress across the entire field.
2. CEF is a Frontier that cuts across all other Frontiers, and *everyone* in HEP works within and is a part of CEF. Furthermore, there is no activity within our field that lies outside CEF. For these reasons, every activity in every Frontier is dependent on progress in the work of CEF.



Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement

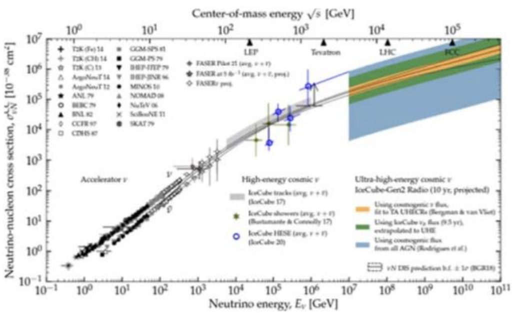
The Science Message

The landscape has changed,
but the fundamental physics drivers have not

Paradigms have shifted, requiring new search strategies

Changed Landscape in science

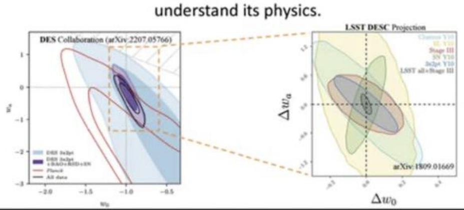
Concentrate on measurements, not limits



Our knowledge of the cosmos
and its connection to particle physics
has increased tremendously.

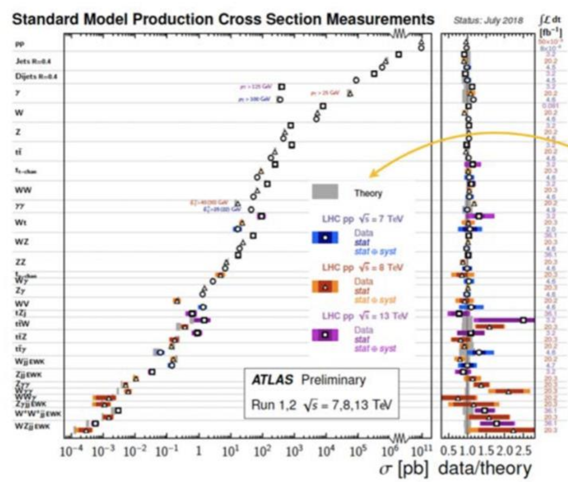
Precision cosmology

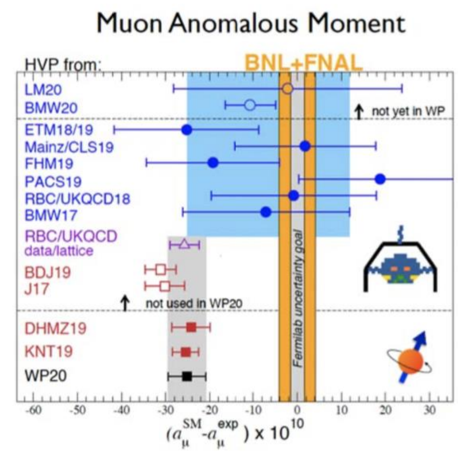
The discovery of **dark energy** led to a **precision measurement program** to understand its physics.



We continued to improve our knowledge of the Standard Model
We've measured couplings, particle masses and the structure of interactions
New quark and gluon combinations, magnetic and electric dipole moments

Glory in our successes – and shamelessly promote them





LHC Run 1 & 2: **Experimental** and **Theoretical** triumph (see J. Thaler talk)

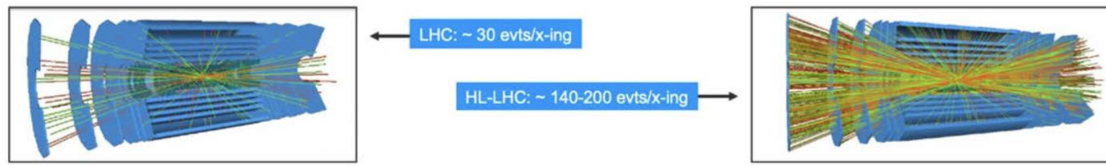
And in what we can build

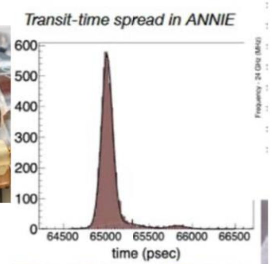
New capabilities

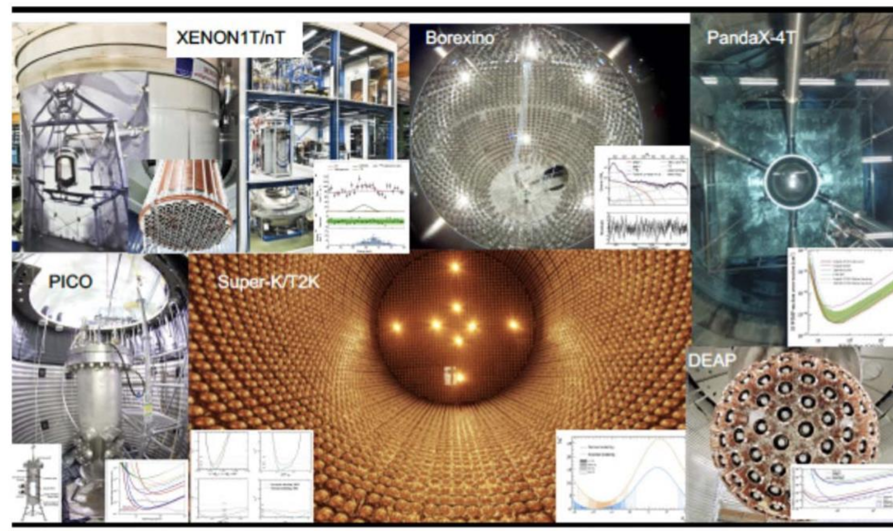
New accelerators and detectors

R&D in AF, IF, CF

Face of computing has changed







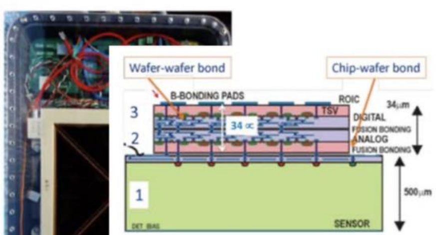
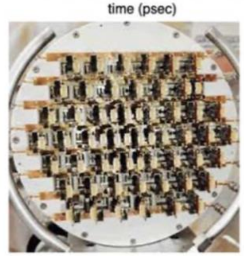


Figure 1: Example of 3D integration of sensor and readout chip.



P5 will define the 2023 Physics Drivers

But a clear take-away from Snowmass is that the 2014 Physics Drivers still guide our future

Great Message: We are making steady progress on a path which is **still** a community priority

There may be some room for tweaking

suggestions I have heard: “explore the unknown” could be sharpened

“Understand the physics of flavor”

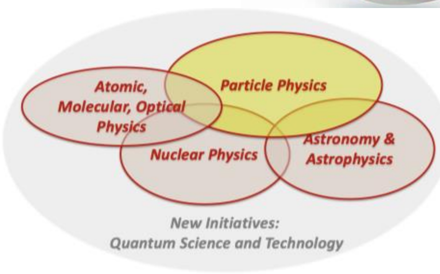
Include Theory and Community Engagement in our Big Picture

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

- Develop transformative concepts and technologies to enable future discoveries
- Cultivate a vibrant, inclusive, and supportive scientific community

Closing Remarks

- Particle Physics is Global
  - International collaboration
  - Open science



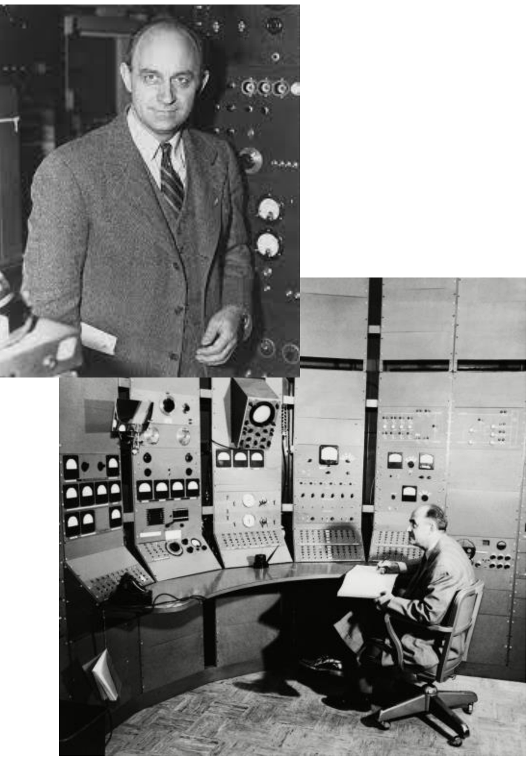
- Particle Physics is Not Isolated
  - Connections to related fields

- Environmental and Societal Impact
  - Training for the next generation
  - Diversity and inclusion
  - Knowledge / technology transfer
  - Public engagement, communication to the public, …
  - Energy efficiency (accelerations & computers), Travel, …

- Long-Range Planning for Particle Physics
  - Engagement of early careers in the process

Fermi's Vision

Highest energies possible



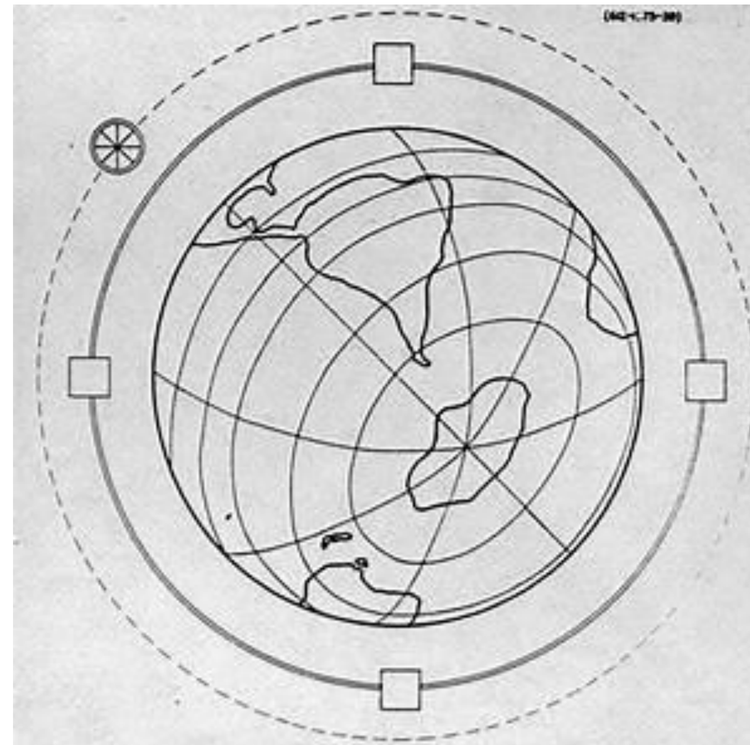
Enrico Fermi (1901 – 1954)

1953

"What Can We Learn with High Energy Accelerators?"

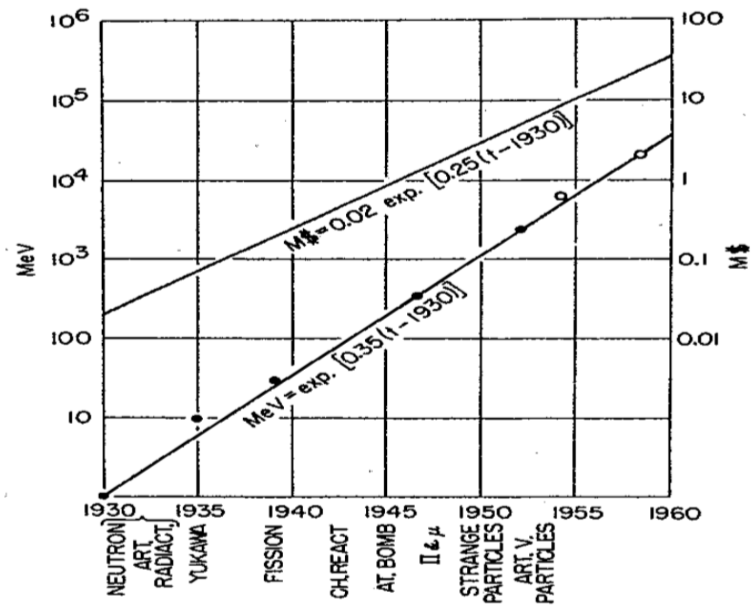
The way to access new physics is through the development of higher- and higher-energy accelerators

Fermi's Globatron

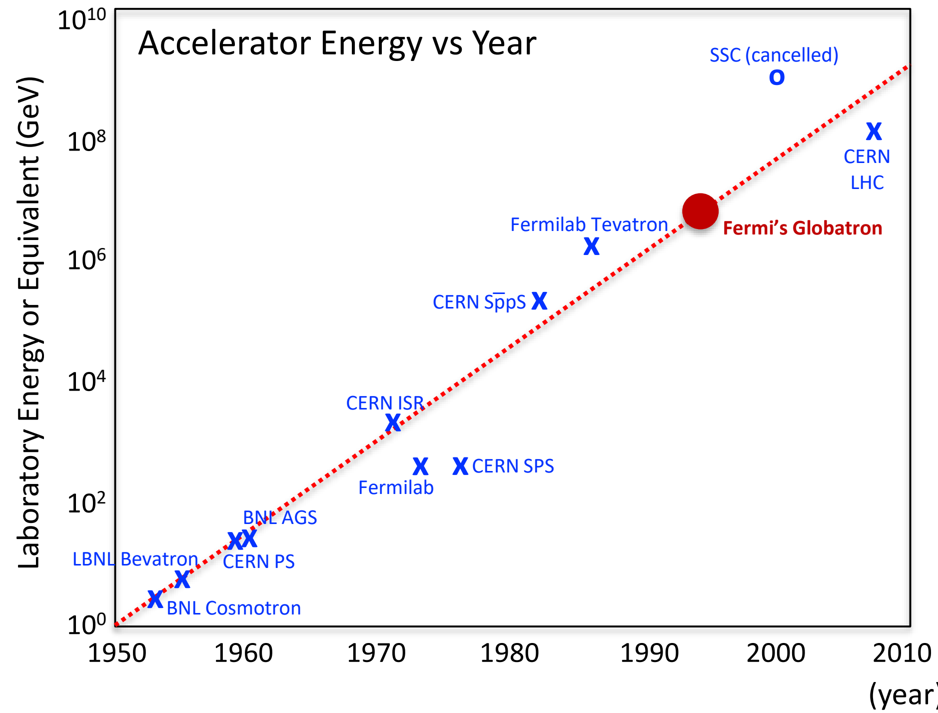


You cannot get more global than this!!

Fermi's Globatron



Fermi's slide 1, cost and energy of accelerators vs. year
(Special Collections, University of Chicago)



Fermi's Globatron (Projection):

- ~40,000 km
- ~1994
- ~170B 1954 $ (~1,000B 2021 $)

Actual Accelerators:

- Energy achieved in ~1990
- Dramatically smaller (~10 km)
- Dramatically cheaper (~a few B 2021 $)

Thanks to: Science & Technology Breakthroughs
Open Science & Open Technology
Collaboration & Competition