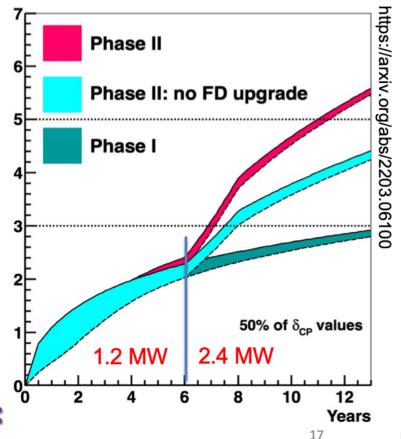


Multi-MW v Beams for DUNE

LBNF/DUNE Project – Phase I:

- By 2032: 1.2 MW proton beam (120 GeV, MI) on target + near ν-detector + 20 kton LAr ν-detector in Lead, SD
- Expected rate of "physics" outcome $\[\]$ up to ~3 σ in δ_{CP} , in the first 6 years (also Δm^2_{32} , $\sin^2\theta_{23}$, $\sin^22\theta_{13}$)
- To get to ~5_o will take too long, plus competitor experiment *Hyper-K* in Japan (30 GeV J-PARC p beam)



Proposed LBNF/DUNE Phase II:

- By 2038: ~2.4 MW proton beam + new near ν-detector + extra 20 kton Lar ν-detector
- Expected to get to $\sim 5\sigma$ in δ_{CP} in the following 6 years

07/22/2022

Shiltsev | Accelerator Frontier

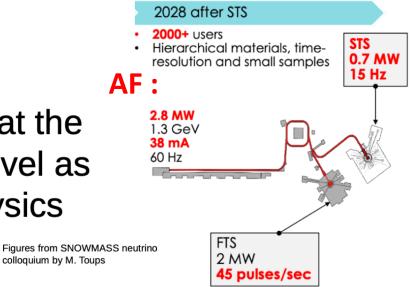
Accelerator-v synergistic aspects:

RPF & IF:

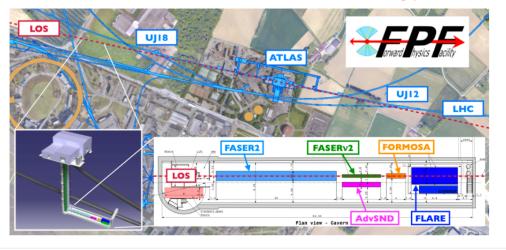


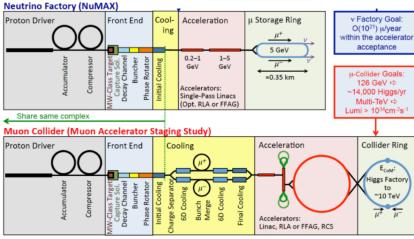
Booster replacement (beam upgrade)

Synergies at the machine level as well as physics



EF & AF:





Rare Processes & Precision Measurement Frontier

This Frontier explores fundamental physics with intense sources and ultra-sensitive detectors. It encompasses seeking tiny deviations from Standard Model expectations in properties and transitions of elementary particle and searches for extremely rare processes.



Marina Artuso (Syracuse U.)

Co-Conveners



Alexey Petrov (Wayne State U.)



Bob Bernstein (FNAL)

Topical Group		Topical Group co-Conveners	
RF01	Weak Decays of b and c	Angelo di Canto	Stefan Meinel
RF02	Strange and Light Quarks	Emilie Passemar	Evgueni Goudovski
RF03	Fundamental Physics and Small Experiments	Tom Blum	Peter Winter
RF04	Baryon and Lepton Number Violation	Pavel Filievez Perez	Andrea Pocar
RF05	Charged Lepton Flavor Violation	Sacha Davidson	Bertrand Echenard
RF06	Dark Sector at Low Energies	Stefania Gori	Mike Williams
RF07	Hadron Spectroscopy	Tomasz Skwarnicki	Richard Lebed

II: >20 Proposed Experiments For Rare Processes

(most via Snowmass Whitepapers)

Searches for DM, axions, EDMs, CLFV experiments, muons, light mesons, beam dump

experiments...calls for corresponding beam facilities @FNAL,SLAC,Jlab,SNS

Experiment	Experiment type	Primary beam particle	Beam Energy [GeV]	Beam power [kW]	Beam time structure
Proton Storage Ring: EDM and Axion Searches	Precision tests, Dark Matter	proton	0.7 GeV/c beam momentum	1e11 polarized protons per fill	Fill the ring every 1000s
Physics with Muonium	Precision tests	proton (producing surface muons)	0.8 GeV	1e13pm1 POT per second	cw
Nucleon Electromagnetic Form Factors from Lepton Scattering	Neutrino	electron or proton (producing muons)	0.85 GeV to 2 GeV	1 nA to 10 microA for electrons, 10/7 to 10/8 per second for muons	A confinuous or pulsed structure (ideally with a duty factor of 1% or larger) should be sufficient
Rare Decays of Light Mesons (REDTOP)	Precision tests	proton	1.8-2.2 GeV (Run I), 0.8- 0.92 (Run II), 1.7 (Run III)	0.03-0.05 (Run I), 200 (Runs II and III)	CW, slow extraction for Run I
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	proton	0.8-2	1,000	quasi-continuous
CLFV with Muon Decays	CLFV	proton	Not critical 0.8 to a few GeV	100 or more	continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better
Mu2e II	CLFV	proton	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	0.8 to 1.5 GeV	100 or more	<o(1 <o(30="" for="" measurements,="" micro="" neutrino="" ns)="" pulse="" pulse<br="" s)="" width="">width for dark matter searches, 10/(-5) or better duty factor</o(1>
FRISM-like Charged Lepton Flavor Violation	CLFV	proton	1-3 GeV	up to 2 MW	15ns pulses at a rep rate of about 1 kHz
Electron Missing Momentum (LDMX)	Dark Sector	electron	~3 GeV to ~20 GeV	O(1 electron per RF bucket at 53 MHz)	CWish
Electron Beam Dumps	Dark Sector	electron	few GeV	10 ¹ (20) electrons on target over the experiment all runtime	Pulsed beam (duty factor not specified)
Proton Irradiation Facility	R&D	proton	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)
SBN	Neutrino	proton	8	32	20Hz
Mu2e	CLFV	proton	8	8	<10Y-10} extinction
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec
Muon beam dump	Dark Sector	proton (producing muons)	3 GeV muons	3e14 muons in total on target for the whole run	cw
Muon Collider R&D and Neutrino Factory	R&D	proton	5 - 30GeV	1e12 to 1e13 protons per bunch	10 - 50 Hz rep rate and bunch length 1-3 ns
Muon Missing Momentum	Dark Sector	proton (producing muons)	few 10s of GeV	10/(10) muons per experimental runtime	Pulsed beam (duty factor not specified)
High Energy Proton Fixed Target	Dark Sector, Neutrino	proton	O(100 GeV)	1e12 POT/s therefore ~20 kW	OW via resonant extraction. "IF we could up the duty factor that woull dibe even better"(?)
Test-Beam Facility	R&D	proton	120, lower energies would also be beneficial	10 to 100 KHz on the testing apparatus	Pulsed beam (duty factor not specified)
Tau Neutrinos	Neutrino	proton	120	1200 or higher	MI time structure

Electron beams:

~ GeV to multi-GeV

Proton beams:

~2 GeV CW-capable beam

~2 GeV pulsed beam from storage ring ~1MW

~8 GeV pulsed beam ~1MW

120 GeV Slow extraction or LBNF beam

In many cases, existing or planned facilities can be and should be fully utilized!

Cosmic Frontier

The Cosmic frontier includes probes of the fundamental nature of dark matter and dark energy, and opportunities using astrophysical and cosmological data to learn about fundamental physics.



Aaron Chou (Fermilab)

Co-Conveners



Marcelle Soares-Santos (U.Michigan)



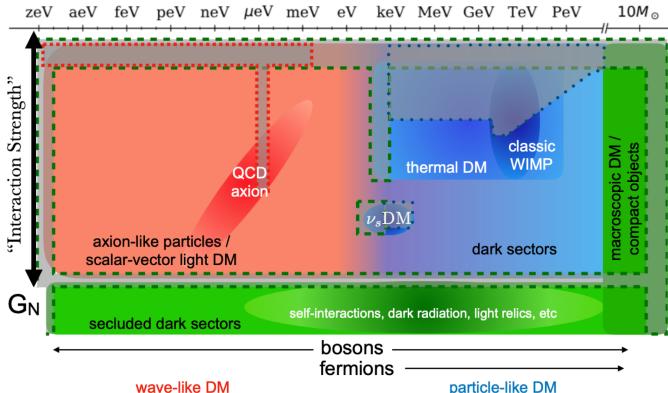
Tim Tait (UC Irvine)

Topical Group		Topical Group co-Conveners					
CF01	Particle DM	Jodi Cooley (SMU)	Tongyan Lin (UCSD)	Hugh Lippincott (UCSB)	Tracy Slatyer (MIT)		
CF02	Wavelike DM	Joerg Jaeckel (Heidelberg)	Gray Rybka (UW)	Lindley Winslow (MIT)			
CF03	DM Astro Probes	Alex Drlica-Wagner (FNAL)	Chanda Prescod- Weinstein (NH)	Haibo Yu (Riverside)			
CF04	DE & CA The Modern Universe	Jeff Newman (Pittsburgh)	Jim Annis (FNAL)	Anze Slosar (BNL)			
CF05	DE & CA Cosmic Dawn & Before	Clarence Chang (ANL)	Deirdre Shoemaker (Georgia Tech.)	Laura Newburgh (Yale)			
CF06	Dark Energy complementarity	David Schlegel (LBNL)	Brenna Flaugher (FN	AL) Vivian Miranda (Ston	y Brook)		
CF07	Cosmic Probes	Luis Anchordoqui (CUNY)	B.S. Sathyaprakash (Penn State)	Rana Adhikari Ke Fang (CalTech) (Wiscons			

Big Questions

- What is the fundamental nature of the dark matter? How does it fit in with the Standard Model and what would we learn by detecting it?
 - Does it manifest as individual quanta (CFI)...or as collective waves (CF2)?
 - Can we further refine our understand of its properties based on cosmic observations (CF3) ?
- What is the nature of dark energy and cosmic acceleration (CF4 & CF5)?
 - Is the dark energy dynamical? What is the physics of cosmic inflation? Are there other cosmological transitions whose existence we can infer?
 - Can we constrain or discover ultra-weakly interacting or super-heavy components of the Universe?
 - How can we use our existing and planned facilities to extract information that is more than the sum of the individual parts (CF6)?
- How can we use cosmic probes to learn about fundamental physics (CF7)?

Dark Matter Mass



wave-like DM

'Delve Deep, Search Wide' employs a range of direct searches for WIMPs interacting with targets on Earth, indirect searches for annihilation products, and cosmic probes based on structure, to scrutinize priority targets such as WIMPs and QCD axions, while broadly scanning parameter space, leaving no stone unturned.

The next 10 years, including future Generation 3 direct searches for WIMPs and axions, combined with future indirect observatories, a program of smaller scale searches, and key inputs from cosmic probes, results in **broad** coverage.

Theory Frontier

The goal of the Theory Frontier is to articulate the recent advances and future opportunities in all aspects of theory relevant to HEP, including particle theory, formal/string theory, cosmological and astro-particle theory, and quantum information science.



Nathaniel Craig (UCSB)

Co-Conveners



Csaba Csaki (Cornell)



Aida El-Khadra (UIUC)

Topica	l Group	Topical Group co-Conveners			
TF01	String theory, quantum gravity, black holes	Daniel Harlow	Shamit Kachru	Juan Maldacena	
TF02	Effective field theory techniques	Patrick Draper	Ira Rothstein		
TF03	CFT and formal QFT	David Poland	Leonardo Rastelli		
TF04	Scattering amplitudes	Zvi Bern	Jaroslav Trnka		
TF05	Lattice gauge theory	Zohreh Davoudi	Taku Izubuchi	Ethan Neil	
TF06	Theory techniques for precision physics	Radja Boughezal	Zoltan Ligeti		
TF07	Collider phenomenology	Fabio Maltoni	Shufang Su	Jesse Thaler	
TF08	BSM model building	Patrick Fox	Hitoshi Murayama	Graham Kribs	
TF09	Astro-particle physics and cosmology	Dan Green	Joshua Ruderman	Ben Safdi	Jessie Shelton
TF10	Quantum information science	Simon Catterall	Roni Harnik	Veronika Hubeny	
TF 11	Theory of neutrino physics	André de Gouvêa	Irina Mocioiu	Saori Pastore	Louis Strigari



HEP Theory



138 white papers submitted

unifies the frontiers of particle physics

lays the foundations for future experiments

connects to gravity, cosmology, astrophysics nuclear physics, condensed matter, AMO, mathematics

advances our understanding of Nature in regimes that experiment cannot (yet) reach

Fundamental Theory

Phenomenology

interconnected scientific eco system closely aligned with experiment

Computational Theory

central to the motivation, analysis, and interpretation of experiments

responsive:

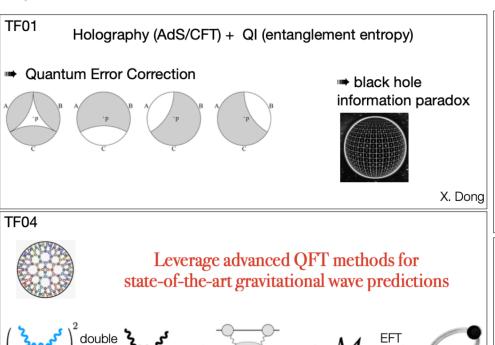
propose new directions based on data propose/guide new experiments develop new analysis tools

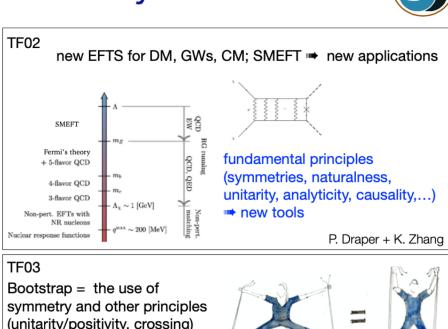
incorporates new perspectives (QI, ML) and technologies to extend the boundaries of our knowledge



Fundamental Theory





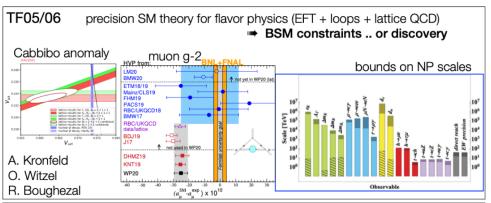


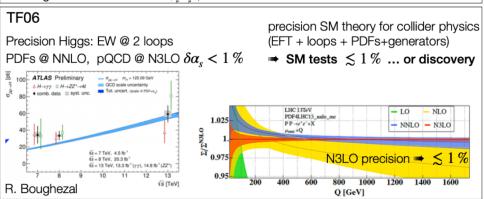
Z. Bern + E. Herrman + M. Solon

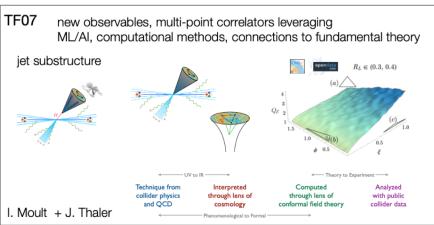


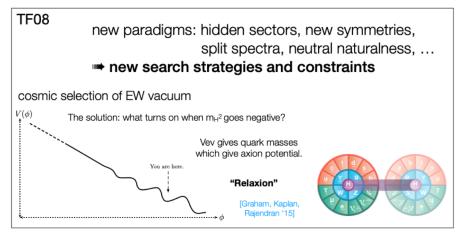
Phenomenology







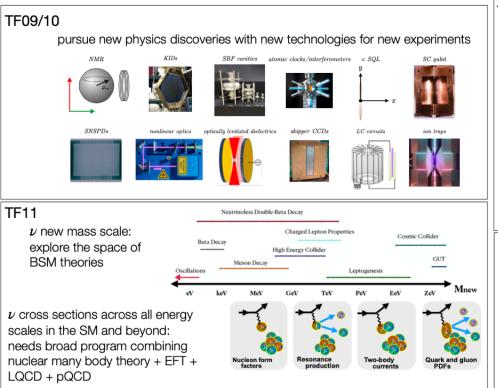


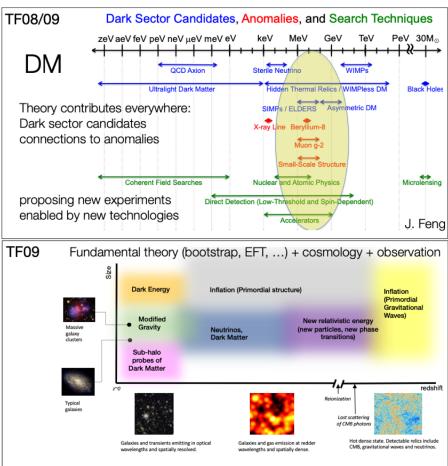




Phenomenology



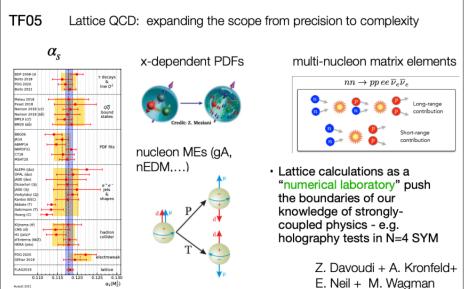


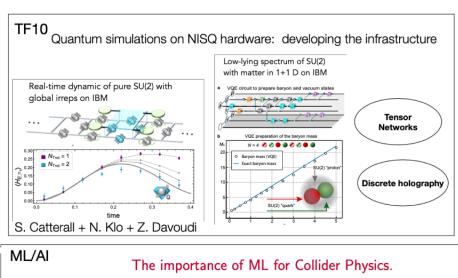


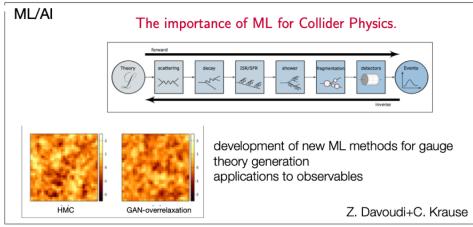


Computational Theory









August 2021

Instrumentation Frontier

IF is geared to discussing detector technologies and R&D needed for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier.



Phil Barbeau (Duke)

Co-Conveners



Petra Merkel (FNAL)



Jinlong Zhang (ANL)

		(Duke)	(IIVAL)	(AIVL)			
Topical Group		Topical Group co-Conveners					
IF01	Quantum Sensors	Thomas Cecil (ANL), Kent Irwi	Thomas Cecil (ANL), Kent Irwin (SLAC), Reina Maruyama (Yale), Matt Pyle (Berkeley)				
IF02	Photon Detectors	Juan Estrada (FNAL)	Mayly Sanchez (ISU)	Abigail Vieregg (Chicago)			
IF03	Solid State Detectors&Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Lucie Linssen (CERN)			
IF04	Trigger and DAQ	Darin Acosta (Florida)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)			
IF05	Micro Pattern Gas Detectors	Thomas Schwarz (Michigan)	Maxim Titov (SACLAY)	Sven Vahsen (Hawaii)			
IF06	Calorimetry	Andy White (UTA)	Minfang Yeh (BNL)	Rachel Yohay (FSU)			
IF07	Electronics/ASICS	Gabriella Carini (BNL)	Mitch Newcomer (UPenn)	John Parsons (Columbia)			
IF08	Noble Elements	Eric Dahl (Northwestern)	Roxanne Guenette (Harvard)	Jen Raaf (FNAL)			
IF09	Cross Cutting and System Integration	Jim Fast (PNNL)	Maurice Garcia-Sciveres (LBL)	Ian Shipsey (Oxford)			
IF10	Radio Detection	Amy Connolly (Ohio State)	Albrecht Karle (Wisconsin)				

Instrumentation Frontier

Wiki: https://snowmass21.org/instrumentation/start

The Instrumentation Frontier is geared to discuss detector technologies and R&D needs for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier. It is divided into diagonal topical groups with some overlap among a few of them. Synergies between the different topical groups, as well as with other Frontier groups and research areas outside of HEP will be paid close attention to.

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson

Computational Frontier

The Computational Frontier will assess the software and computing needs of the High Energy Physics community emphasizing common needs and common solutions across the frontiers.



Steven Gottlieb (Indiana U.)

Co-Conveners



Ben Nachman (LBNL)



Daniel Elvira (FNAL)

Topical Group		Topical Group co-Conveners			
CompF01	Experimental Algorithm Parallelization	Guiseppi Cerati (FNAL)	Katrin Heitmann (ANL)	Walter Hopkins (ANL)	
CompF02	Theoretical Calculations and Simulation	Peter Boyle (BNL)	Daniel Elvira (FNAL)	Ji Qiang (LBNL)	
CompF03	Machine Learning	Phiala Shanahan (MIT)	Kazu Terao (SLAC)	Daniel Whiteson (Irvine)	
CompF04	Storage and processing resource access (Facility and Infrastructure R&D)	Wahid Bhimji (NERSC)	Meifeng Lin (BNL)	Frank Würthwein (UCSD)	
CompF05	End user analysis	Gavin Davies (U.Mississippi)	Peter Onyisi (U Texas at Austin)	Amy Roberts (UC Denver)	
CompF06	Quantum computing	Travis Humble (ORNL)	Gabriel Perdue (FNAL)	Martin Savage (U Washington)	
CompF07	Reinterpretation and long-term preservation of data and code	Kyle Cramner (NYU)	Sabine Kraml (Indiana)	Matias Carrasco Kind (Illinois/ NCSA)	

Computational Frontier Recommendation:

Computing as a P5 science driver - 2022

Computing is essential to all experiments and many theoretical studies

- Data volumes, detector complexity, precision required in calculations and simulation will continue to grow in near- and far-future experiments and surveys
- Size and complexity of the software and computing is commensurate with that of the experimental instruments; projects may also need software-detector codesign
- Software and Computing (S&C) is a global endeavor, efforts should be coordinated with worldwide partners

S&C technologies are changing the face of high energy physics

- Trend towards computing hardware heterogeneity and specialization, and increased use of high-performance computing facilities
- AI/ML not on the horizon in 2013, now widespread in every HEP area
- Quantum computing is entering the stage with potential impact on quantum many-body systems, event generators, data analysis, etc.

Underground Facilities & Infrastructure Frontier

Co-Conveners

This Frontier covers requirements for underground science to succeed, including underground lab development, low background methods, and interdisciplinary synergies.







Laura Baudis (U. Zurich)

Jeter Hall (SNOLAB)

Kevin Lesko (LBNL)

John Orrell (PNNL)

Topical Group		Topical Group co-Conv			
			Co-conveners		
UF01	Underground Facilities for Neutrinos	Accelerator Neutrinos Tim Bolton	<u>Ονββ</u> Patrick Decowski Danielle Speller		Neutrinos Albert de Roeck Astronomical v Gabriel Orebi Gann
UF02	Underground Facilities for Cosmic Frontier	LXe DM Kaixuan Ni Low Mass Scott Hertel	<u>LAr DM</u> Emilija Pantic		Particle DM Hugh Lippincott Jodi Cooley Instrumentation Eric Dahl
UF03	Underground Detectors	<u>Gravity Waves</u> Laura Cadonati			Instrumentation Frontier Maurice Garcia-Sciveres
UF04	Supporting Capabilities	Radon Richard Schnee	<u>Cleanliness</u> Alvine Kamaha	Low Background Assay Brianna Mount	
UF05	Synergistic Research	Nuclear Astrophysics Daniel Robertson	Geo-microbiology TBD	Geo-engineering TBD	QIS, QC Maurice Garcia-Sciveres
UF06	An Integrated Strategy for Underground Facilities and Infrastructure	Laura Baudis Jeter Hall Kevin Lesko John Orrell			Early Career Pietro Giampa William Thompson

Underground Facilities & Infrastructure Frontier (UF) supports the execution of science from other Frontiers, notably:

- Neutrino Frontier
- Cosmic Frontier
- Rare Processes and Precision Frontier
- Frontier Objectives & Goals
 - Determine science programs performing research in underground facilities
 - Collect information on existing underground facilities & infrastructure (supply)
 - Collect current/future needs for science in underground facilities (demand)
 - Compare demand to supply (gap analysis)
 - Analyze to generate a recommendation for an integrated strategy for underground facilities & infrastructure

Community Engagement Frontier

Co-Conveners:

The objective is to improve and sustain strategic engagements with our communities in order to draw support for and strengthen the field of particle physics, while playing key roles in serving those communities.



Kétévi Assamagan (BNL)



Breese Quinn (Mississippi)

Topical Group		Topical Group co-Conveners			
Comm01	Applications & Industry	Farah Fahim (FNAL)	Alex Murohk (RadiaBeam)	Koji Yoshimura (Okayama)	
Comm02	Career Pipeline & Development	Sudhir Malik (UPRM)	Julia Hogan (Bethel Univ.)	Aneliya Karadzhiniva-Ferrer (Ruđer Bošković Institute)	
Comm03	Diversity & Inclusion	Mu-Chun Chen (UCI)	Johan Bonilla (UC-Davis)	Carla Bonifazi (UFRJ)	Cindy Lin (SNOLAB)
Comm04	Physics Education	Randy Ruchti (Notre Dame)	Sudhir Malik (UPRM)	Sijbrand de Jong (Radboud)	
Comm05	Public Education & Outreach	Sarah Demers (Yale)	Kathryn Jepsen (SLAC)	Don Lincoln (FNAL/Notre Dame)	A. Muronga (Nelson Mandela)
Comm06	Public Policy and Government Engagement	Rob Fine (Rochester)	Louise Suter (FNAL)	Brajesh Choudhary (Delhi)	
Comm07	Environmental and Social impacts	Ken Bloom Véronique Boisvert Mike Headley (Nebraska) (Royal Holloway) (SDATA/SURF)			

Community Engagement Frontier

CEF: Frontier-wide

Major Goals

 It is critical that we all agree on the importance of everyone working together to organize and develop our ongoing efforts in CE in a coherent manner focused on improving our HEP community and achieving the vision for our field

• A structure must be established within HEP for taking ownership and responsibility for implementing CEF

recommendations and *monitoring* their progress across the entire field

Structural Change

- All stakeholders form a P5-equivalent panel to shepherd CEF recommendations
 - Must have direct connection to multiple streams of resources
 - As opposed to P5: agencies fund/implement projects, so P5 lives within DOE/NSF
- Review CEF integration in Snowmass
 - Perhaps do major work on field-wide CEF planning asynchronously, enhance participation

Specific areas in need of targeted support

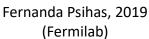
- Staffing for the group tasked with implementation and monitoring
- Research and surveys on existing work and activities
- Developing monitoring and evaluation tools/rubrics
- Tangible support for researchers participating in all areas of Community Engagement
 - o e.g. in grant, hiring, performance reviews

Snowmass Early Career

DPF EC Early Career representatives

- (1). To represent early career members and promote their engagement in the Snowmass 2021 process and
- (2) to build a long-term HEP early career community that persists after the Snowmass process.







Sara Simon, 2020 (Fermilab)



Julia Gonski, 2021/2022 (Columbia)

- Who we are: early career (EC) physicists brought together by Snowmass process
 - Historically "Snowmass Young"
 - Building on a huge amount of EC interest during original nomination call (April 2020)
- "Early Career" = ~10 years from highest degree guideline, including engineers/technicians; guideline not a hard rule!

It is crucial to engage our early career colleagues:

- #1 motivation: physics and science for junior colleagues
- Educate the next generation
- Discussions on special issues/problems relevant to EC
- Build a community

Two arms of the organization:

Snowmass
Coordination:
collaboration of
EC liaisons for
each frontier

Core
Initiatives:
Snowmassindependent
offshoot

A message from HEPAP (JoAnne Hewett)

Passing the Baton

Put Captions Here



Snowmass was WONDERFUL!!!

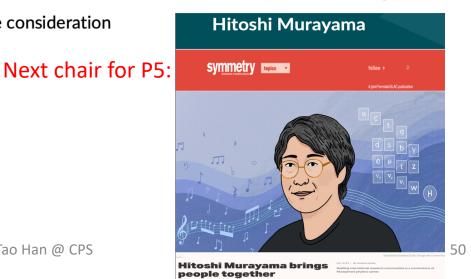
Snowmass results will be critical input to P5

The hard work was impressive and is an important documentation of visions for our field

Turning towards P5

- Every idea presented at Snowmass will receive due consideration
- Report is not written
- Decisions are not made
- P5 will take a fresh look at our project program
- P5 is a process and the process will be followed

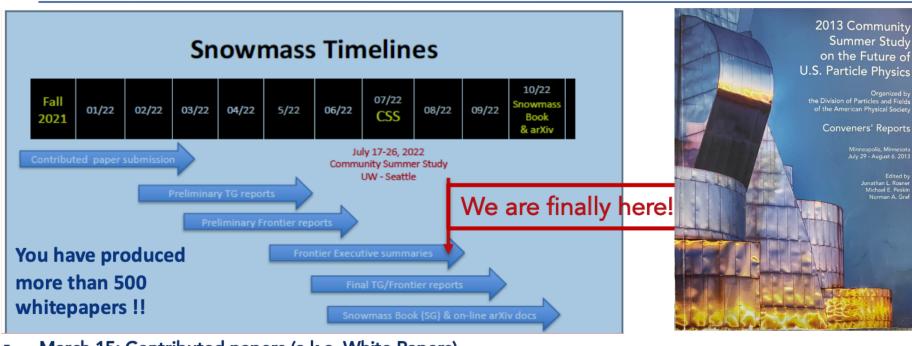




8/5/22

Timeline for Snowmass Book





- March 15: Contributed papers (a.k.a. White Papers)
- May 31: Preliminary Topical Group Reports
- June 30: Preliminary Frontier Reports
- July 17 26: Converge on reports for all the frontiers and produce executive summaries representing the views of their communities and providing the basic input needed for P5
- September: draft Executive Summary and Report Summary
- October- November: Snowmass Book finalized and ready for submission

- Cover from Snowmass
 2013 report, ~ 350 pages
- The new report will be ~500 pages
- All Contributed Papers will remain part of the permanent record of Snowmass

Snowmass 2021 Summary

(Prisca Cushman)



The Beginning of a new era

The underlying landscape is becoming visible

The peak is fundamentally connected to the unseen mountain range

The failure of minimal extensions to the Standard Model implies a much richer sector to explore.

With all the new experiments ready to push deeper into every frontier, we all feel the excitement of being poised for an explosion of new data and answers to the questions posed a decade ago.

Future perspectives are bright & exciting!