Cosmic Frontier: Science Highlights

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Science Highlights
The Cosmic Frontier seeks to understand the fundamental physics that governs the behavior of the Universe and its constituents.
Dark Matter

The space of dark matter models encompasses a dizzying array of possibilities, representing many orders of mass and couplings.

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Aaron Chou, Thursday
But we have a plan!

‘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.

Aaron Chou, Thursday
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.**

...or **transformational discoveries!**

Aaron Chou, Thursday
Tracy Slatyer, Risa Wechsler, Tuesday
Thanks to investments recommended by the previous P5, the next decade will be a golden age for cosmological data, able to inform the deepest mysteries of fundamental physics.

Cosmic expansion history
Cosmic Microwave Background
Growth of Structure
Gravitational Waves
Current observations have revealed key properties of the Universe and its fundamental constituents. But there is still much left to learn.
‘Search Wide, Aim High’

The near term future will be collecting the data from DESI, completing and executing Rubin/LSST, and constructing CMB-S4, currently on track with CD0.

This program will make unparalleled progress toward understanding the dynamics of cosmic inflation and search for new physics.
Cosmological Probes

Longer term priorities are the roadmap to a future Stage V Spectroscopic Facility, and small projects and pathfinders toward new opportunities such as gravitational waves, 21cm, and Line-Intensity Mapping.
Timelines
Community Roadmap: Time Line

• Currently waiting to start construction on DMNI #1.
• A suite of small projects would provide a definitive axion measurement and search significant scalar/vector parameter.
• Community would like to pursue a common facilities for housing these experiments.

The rough categorization of direct detection techniques presented below is not intended to be exclusive. In addition, many of the techniques discussed span multiple categories. Solving the mystery of dark matter will take all the ingenuity that physicists can bring to bear, and supporting new ideas is a key component of a successful program.

4.4.1 Dark Matter Candidates with Mass Greater Than 10 GeV

For experiments seeking to probe down to the neutrino fog, it is helpful to further subdivide the DM mass space into $<1-10$ GeV and greater than 10 GeV. The latter category includes the canonical WIMP, and represents the most explored region of DM phase space by direct detection experiments. In this region, liquid xenon (LXe), liquid argon (LAr), and freon-based bubble chambers are the dominant technologies.

Cross Section [cm$^2$]

- Best Result (90% CL Limit)
- Sensitivity Goal

Figure 8: Figure adapted from [243]. Improvement in sensitivity to spin independent WIMP-nucleon coupling achieved by LXe (blue, for a mass of $\sim 40$ GeV/c$^2$) and LAr (red, for a mass of 100 GeV/c$^2$) experiments of increasing target masses with sensitivities (open squares) and the best achieved limits (filled circles), for both past (dark color) and future (light color) experiments at their start year. Cross section values and background rates are extracted from Ref. [177, 244–261].

Captions here, please
The U.S. particle physics community has just updated its vision for the future. The P5 report presents a strategy for the next decade and beyond that enables discovery and maintains our position as a global leader through specific investments by the Department of Energy's Office of Science and the National Science Foundation Directorate for Mathematical and Physical Sciences.

Particle physics is a highly successful, discovery-driven science. It explores the fundamental constituents of matter and energy, and it reveals the profound connections underlying everything we see, including the smallest and the largest structures in the Universe. Earlier investments have been rewarded with recent fundamental discoveries, and upcoming opportunities will push into new territory. Particle physics inspires young people to engage with science.

Particle physics is global. To address the most pressing scientific questions and maintain its status as a global leader, the U.S. must both host a unique, world-class facility and be a partner on the highest priority facilities hosted elsewhere.

Choices were required. The updated strategy recommends investments in the best opportunities, chosen from a large number of excellent options, in order to have the biggest impact and make the most efficient use of resources over the coming decade.

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- 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

Building for Discovery

The U.S. particle physics program is poised to move forward into the next era of discovery.
Pursue the physics associated with neutrino mass.

(You thought I was going to start with dark matter, didn’t you…?)

Cosmic Frontier observations offer unique and important perspectives on the parameters describing neutrino masses which can inform terrestrial searches.

Indirect information about CNB from cosmology

Cosmological observables...

- Light element abundances from primordial nucleosynthesis
- Cosmic microwave background anisotropies
- Large-scale matter distribution

\[ \Delta m^2 = 2.99 \pm 0.34 \text{ (95\% CL)} \]

At face value a factor of 30 tighter than current lab bound from KATRIN, \( \sum m < 0.12 \text{ eV} \) (95\% CL)

\[ \sum m_s < 0.12 \text{ eV} \text{ (95\% CL)} \]

\( N_{\text{eff}} = 3 \) remarkably consistent with Standard Model prediction under certain assumptions.

\( N_{\text{eff}} = 2.99 \pm 0.34 \text{ (95\% CL)} \)

Kate Scholberg, Friday
Identify the new physics of dark matter.

Delve deep, search wide!

The Cosmic Frontier is required to verify that any candidate new physics we discover is actually making up the dark matter we see.
Understand cosmic acceleration: dark energy and inflation.

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

Search wide, aim high!

The Cosmic Frontier offers unique handles on the physics of inflation and to search for ultra-weakly interacting particles.
Explore the unknown: new particles, interactions, and physical principles.

Where to even begin...!
Higgs in Space!

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Abstract

We consider the possibility that the Higgs can be produced in dark matter annihilations, appearing as a line in the spectrum of gamma rays at an energy determined by the masses of the WIMP and the Higgs itself. We argue that this phenomenon occurs generally in models in which the dark sector has large couplings to the most massive states of the SM and provide a simple example inspired by the Randall-Sundrum vision of dark matter, whose 4d dual corresponds to electroweak symmetry-breaking by strong dynamics which respect global symmetries that guarantee a stable WIMP. The dark matter is a Dirac fermion that couples to a $Z_0$ acting as a portal to the Standard Model through its strong coupling to top quarks. Annihilation into light standard model degrees of freedom is suppressed and generates a feeble continuum spectrum of gamma rays. Loops of top quarks mediate annihilation into $Z, h, Z_0$, providing a forest of lines in the spectrum. Such models can be probed by the Fermi/GLAST satellite and ground-based Air Cherenkov telescopes.

Higgs inflation

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Abstract

The properties of the recently discovered Higgs boson together with the absence of new physics at collider experiments allows us to speculate about consistently extending the Standard Model of particle physics all the way up to the Planck scale. In this context, the Standard Model Higgs non-minimally coupled to gravity could be responsible for the symmetry properties of the Universe at large scales and for the generation of the primordial spectrum of curvature perturbations seeding structure formation. We overview the minimalistic Higgs inflation scenario, its predictions, open issues and extensions and discuss its interplay with the possible metastability of the Standard Model vacuum.

The Higgs may not be the ‘go to’ tool for discovery in the Cosmic Frontier, but it has its important role to play!

The Cosmic Frontier contributes unique opportunities to the pursuit of the 2014 science drivers. It has strong synergies with the Energy, Neutrino, and Rare Processes Frontiers, benefits from essential connections with the Theory, Computational, Instrumentation, and Underground Facilities Frontiers, and offers interesting opportunities for the Community Engagement Frontier.
Dark Matter  Dark Energy  Inflation  Neutrinos  Exploring the Unknown
THANK YOU

(In particular to my CF coconveners and topical working group leaders, liaisons and contributors. The success of CF at Snowmass 2021 would have been impossible without you!)