CF03: Cosmic Probes of Dark Matter Physics

SnowMass2021

Conveners: Alex Drlica-Wagner, Chanda Prescod-Weinstein, Hai-Bo Yu

July 20th, 2022

CF03: Cosmic Probes of Dark Matter

Cosmological and astrophysical measurements provide the only robust, positive empirical measurements of dark matter.

Cosmic probes are unique in that they do not rely on the assumption that dark matter has interactions with normal matter beyond gravity; thus they are the most "expansive" (and could be the only viable) approach to the dark matter problem.

Cosmic probes is an emergent field that requires strong synergy among particle theorists, dynamists, simulators, observers, and experimentalists; need a new mechanism to support these emerging, collaborative efforts.

Cosmic probes are highly relevant and complementary to search efforts in CF1, CF2, CF7 and other frontiers, and there is strong experimental synergy with cosmological probes of dark matter, dark energy, and inflation (CF4, CF5, CF6).

Halo Measurements

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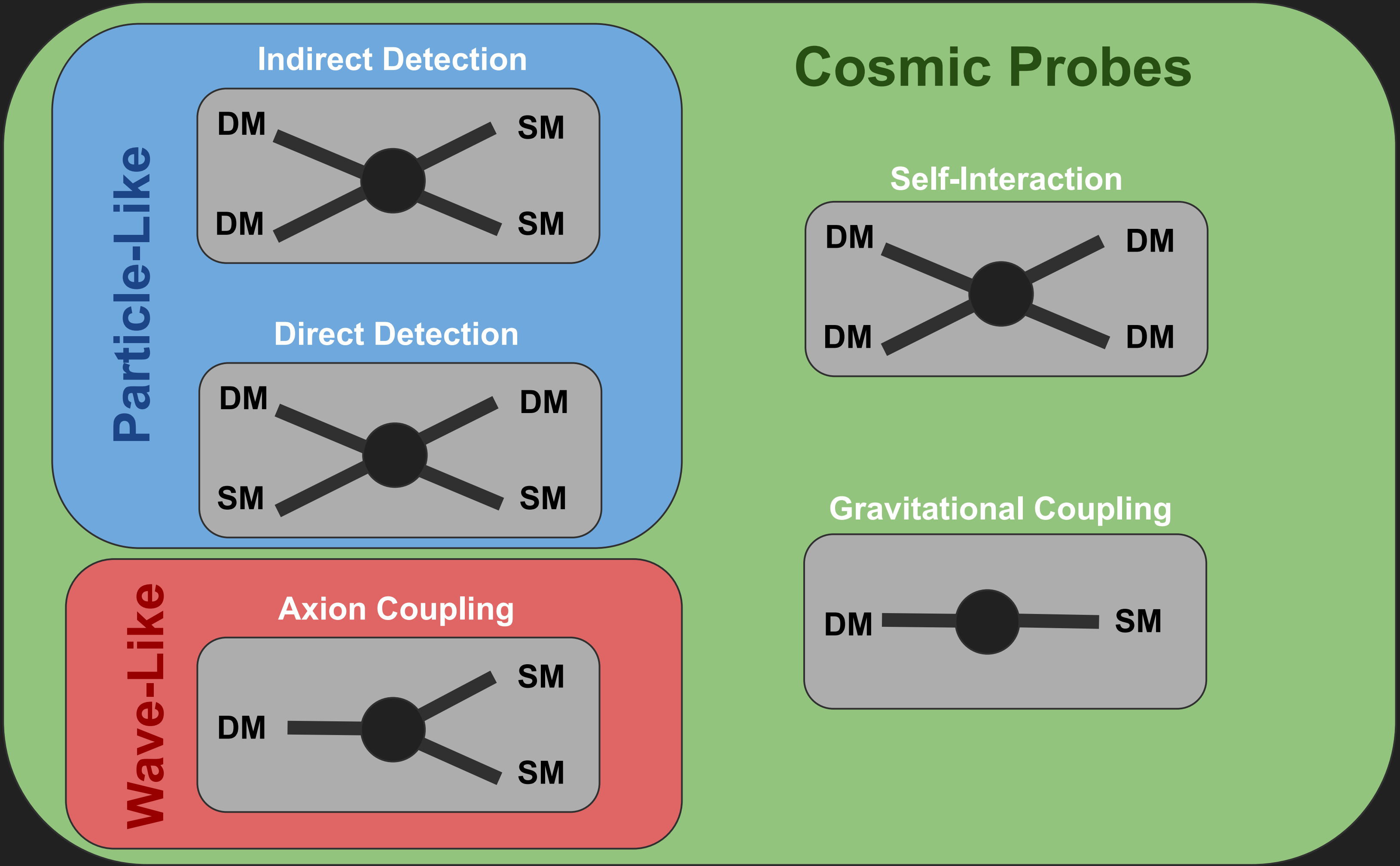
Extreme Environments



Cosmic Probes
Particle-Like
Indirect Detection
DM
DM
SM
SM
Direct Detection
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Wave-Like
Axion Coupling
DM
SM
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Self-Interaction
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DM
Gravitational Coupling
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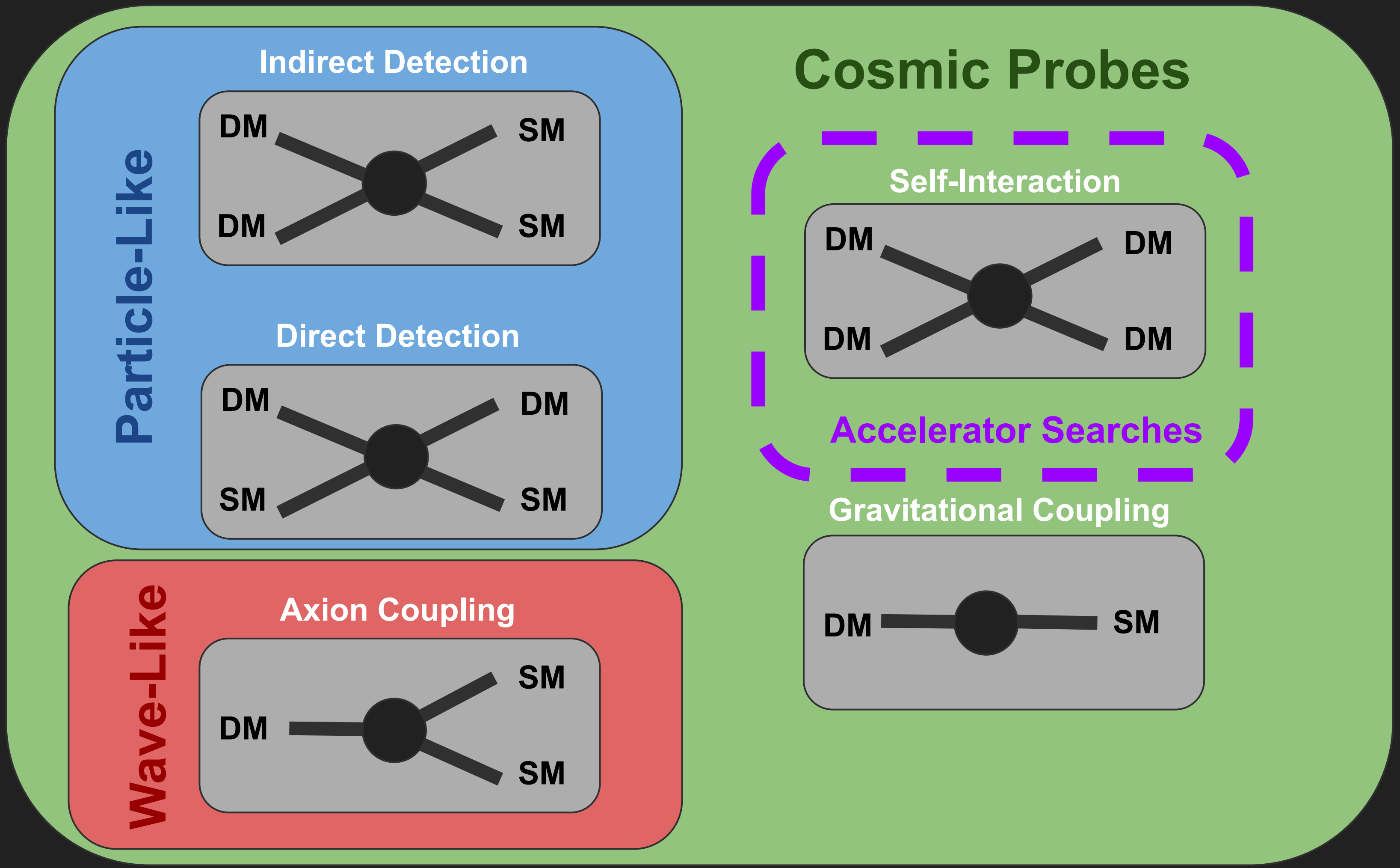
SM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Accelerator Searches
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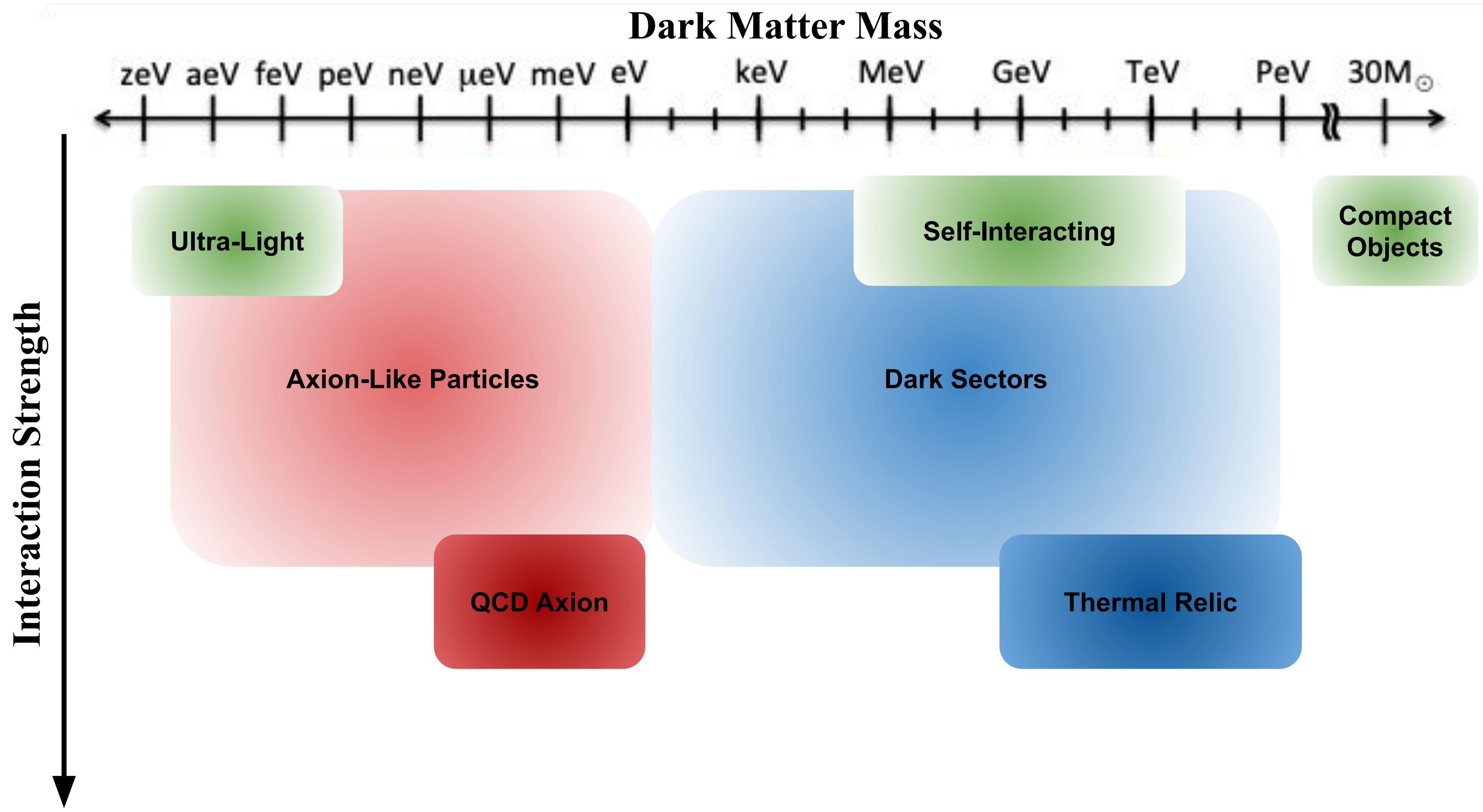
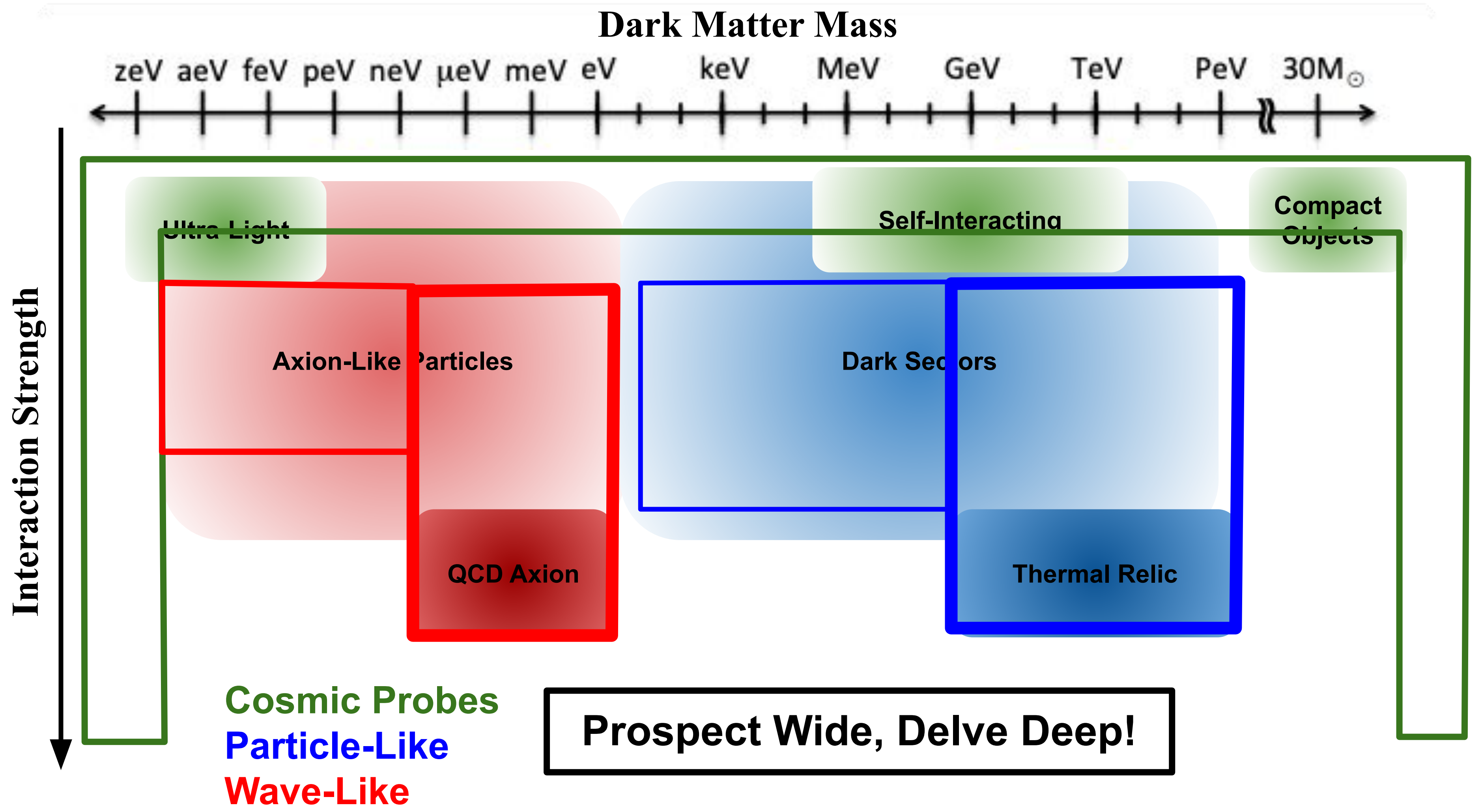


Dark Matter Mass
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
30M$_\odot$
Interaction Strength
Ultra-Light
Self-Interacting
Compact Objects
Axion-Like Particles
Dark Sectors
QCD Axion
Thermal Relic


Dark Matter Mass
zeV aeV feV peV neV µeV meV eV keV MeV GeV TeV PeV 30M⊙
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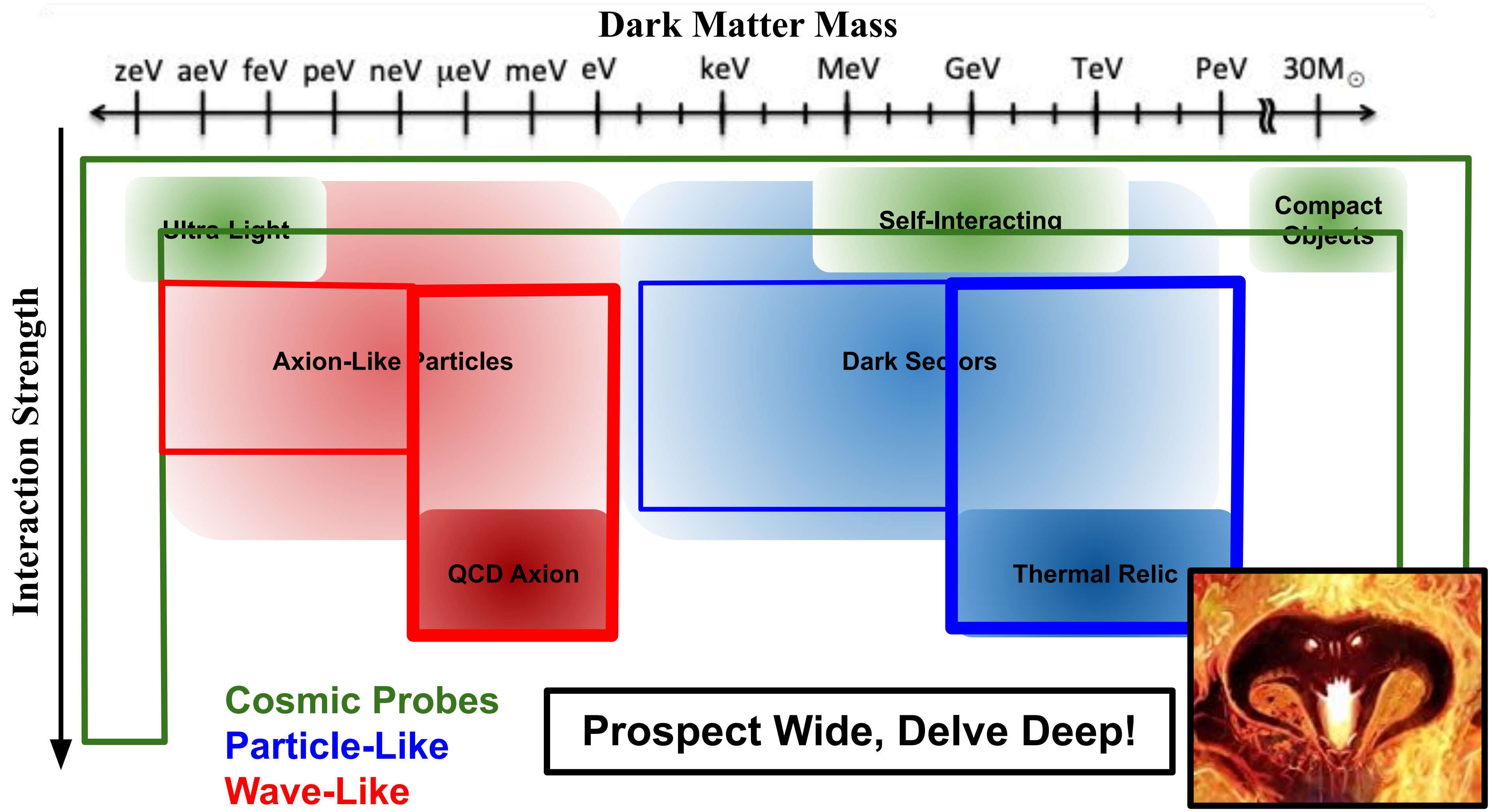
Prospect Wide, Delve Deep!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Letters of Interest and Solicited White Papers

- CF03 received **~75 Letters of Interest** from the community.
- Through a series of discussions (including the Community Planning Meeting), we arrived at a list of **5 solicited white papers** with designated facilitators. All have been submitted.
- CF03 has received **5 additional white papers** (to date). Other relevant white papers include **~15 white papers** submitted to other CF topical groups and other frontiers.

THANK YOU
white paper facilitators and authors!

Authorship extended to white paper facilitators and major contributors. Please contact us if you have contributed and want to be an author.

Cosmic Probes of Dark Matter

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(ADW: Authorship has been extended to white paper facilitators and major contributors. Please contact us if you feel that your contributions merit authorship.)

Draft of CF03 Report (v20220718): link

Comments and Feedback: link

Cosmic Probes of Dark Matter 1

3.1 Three Core HEP Community Priorities

- Current/near-future HEP cosmology experiments have direct sensitivity to dark matter particle physics [1–3]. **Cosmological studies of dark matter should be supported as a key component of the HEP Cosmic Frontier program due to their unique ability to probe dark matter microphysics and link the results of terrestrial dark matter experiments to cosmological measurements.**
- **The construction of future cosmology experiments is critical for expanding our understanding of dark matter physics.** Proposed facilities across the electromagnetic spectrum, as well as gravitational waves, can provide sensitivity to dark matter physics, as well as physics of dark energy and the early universe [4]. HEP involvement will be essential in constructing and operating these facilities, and optimizing their sensitivity to dark matter physics should be a core consideration in their design.
- Cosmic probes provide robust sensitivity to the microphysical properties of dark matter due to enormous progress in theoretical modeling, numerical simulations, and astrophysical data. **Theory, simulation, observation, and experiment must be supported together to maximize the efficacy of cosmic probes of dark matter physics.**

3.1 Five Major Science Opportunities

1. The Standard Model of particle physics and cosmology can be tested at unprecedented levels of precision by measuring the cosmic distribution of dark matter. These measurements span an enormous range of scales from the observable universe to sub-stellar-mass systems (e.g., the matter power spectrum, the mass spectrum of dark matter halos, dark matter halo density profiles, and abundances of compact objects) [7, 12, 13]. The fundamental particle properties of dark matter (e.g., particle mass, production mechanism, and interaction cross sections) can lead to observable changes in the distribution of dark matter. **Measurements of the distribution of dark matter should be supported as a key element of the HEP Cosmic Frontier program to understand the fundamental nature of dark matter.**

2. The ΛCDM model makes the strong, testable prediction that the mass spectrum of dark matter halos extends below the threshold at which galaxies form [5]. Sub-galactic dark matter halos are less influenced by baryonic processes making them especially clean probes of fundamental physics of dark matter. We are on the cusp of detecting dark matter halos that are devoid of baryons through several cosmic probes (e.g., strong lensing, the dynamics of stars around the Milky Way). **The HEP community should pursue the detection of dark matter halos below the threshold of galaxy formation as an exceptional test of fundamental dark matter properties.**

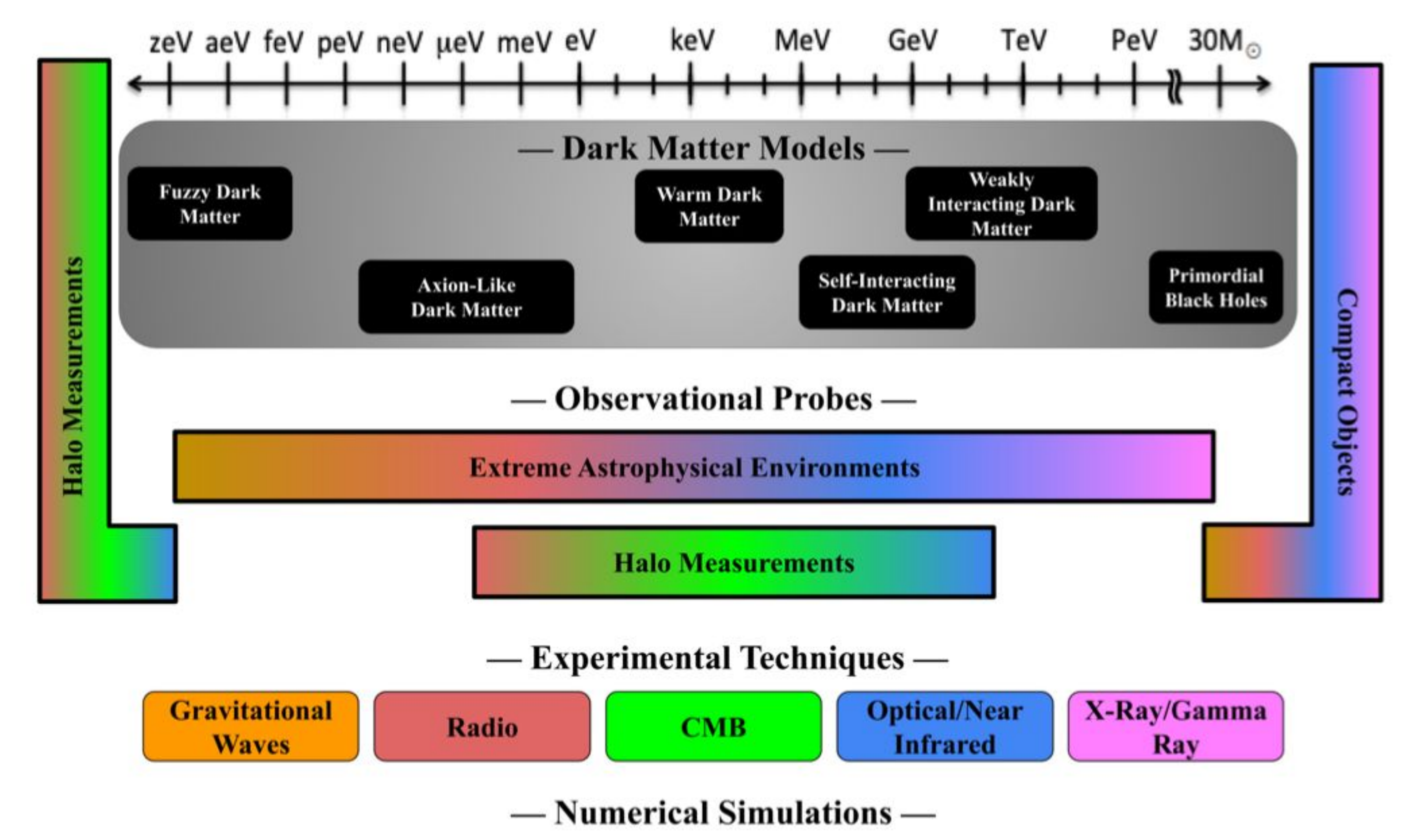
3.1 Five Major Science Opportunities

3. Extreme astrophysical environments provide unique opportunities to explore dark matter couplings to the Standard Model that are inaccessible with terrestrial experiments [8]. **Instruments, observations, and theorists that study extreme astrophysical environments should be supported as an essential means to constrain the expanding landscape of dark matter models.**

4. Numerical simulations of structure formation and baryonic physics play a key role in addressing particle physics questions about the nature of dark matter. **HEP computational resources and expertise can be combined with astrophysical simulation expertise to rapidly advance numerical simulations of dark matter physics.**

5. **The interdisciplinary nature of dark matter research calls for interagency mechanisms that support a comprehensive pursuit of scientific opportunities cutting across traditional disciplinary boundaries.**

3.2 - CF3 in a single figure…



3.3 Dark Matter Halos

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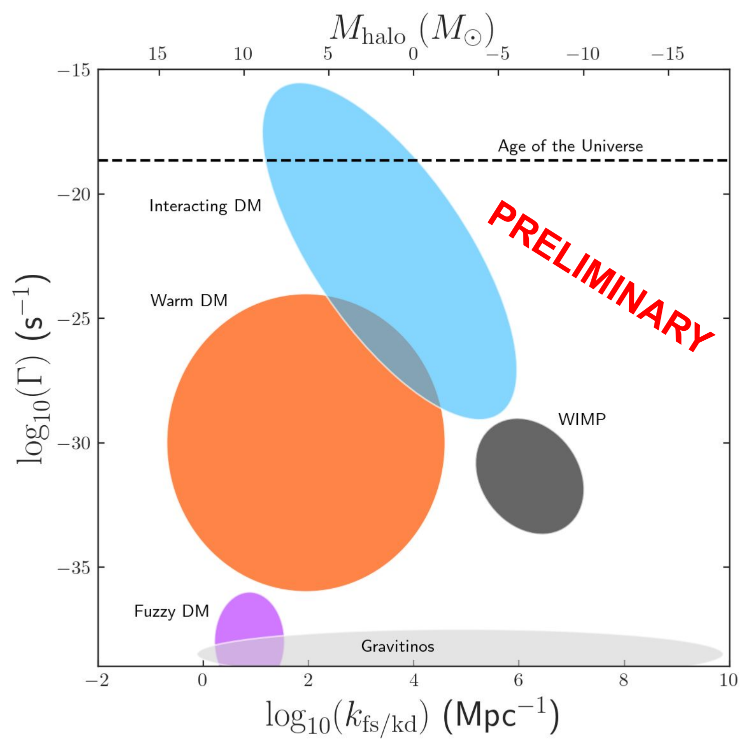
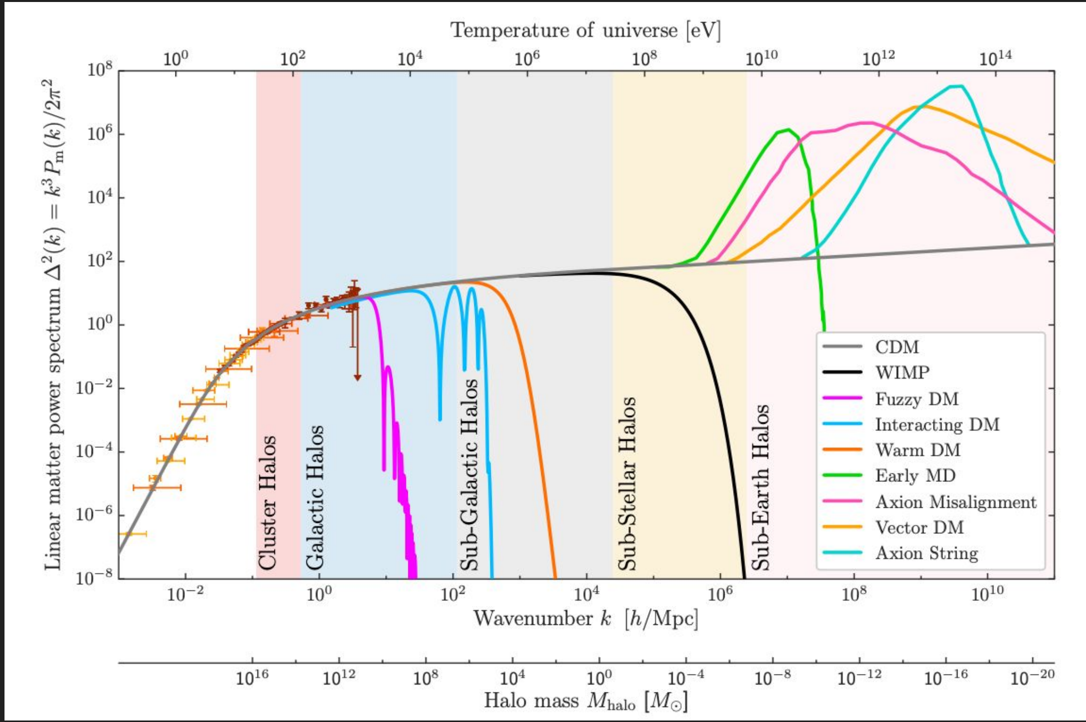
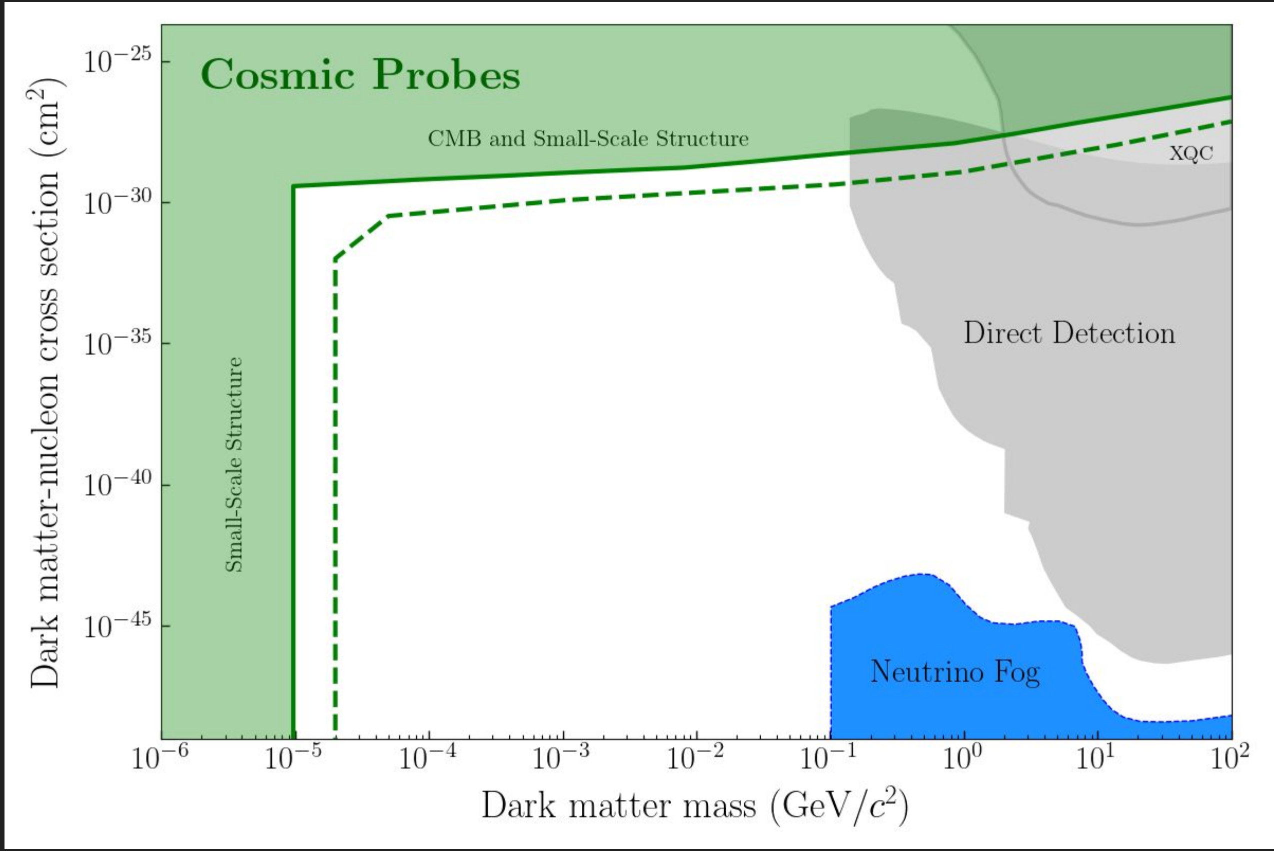




Dark matter particle physics changes the astrophysical structure and distribution of dark matter

3.3 Complementarity with CF1 (Halos)

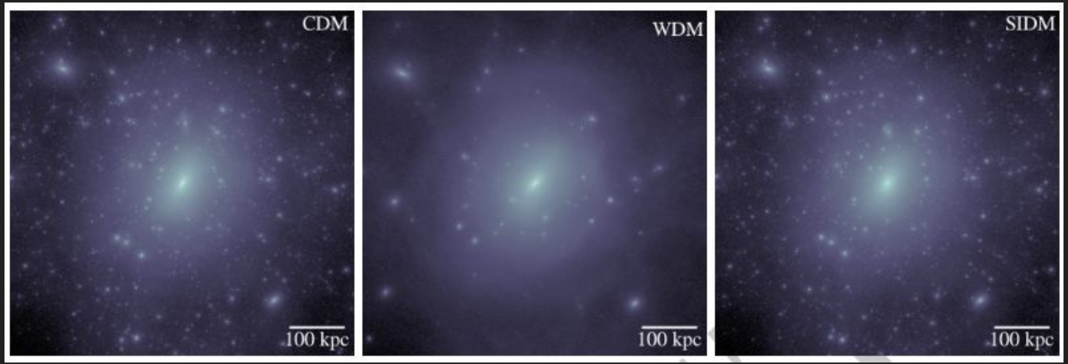


Dark matter-nucleon scattering cross section vs dark matter mass.

Projections come from assuming sensitivity to 10^5 Msun halos.

Still have some constraints to add (BBN and CR upscattering)

3.4 Numerical Simulations



Bullock & Boylan-Kolchin 2017

Numerical simulations are critically important to interpret cosmic observations in the context of specific dark matter particle models.

Collaborations between computation and particle theory is critical. Problem is well-matched to HEP computational resource and expertise.

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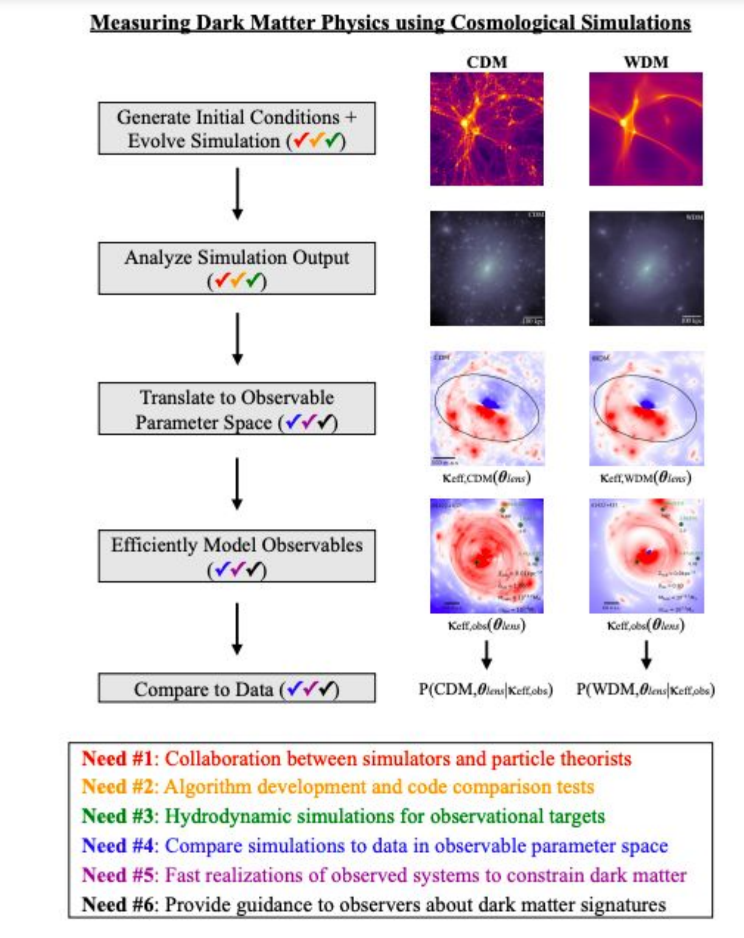

Example pipeline for translating between particle physics and observations.

3.5 Primordial Black Holes and the Early Universe

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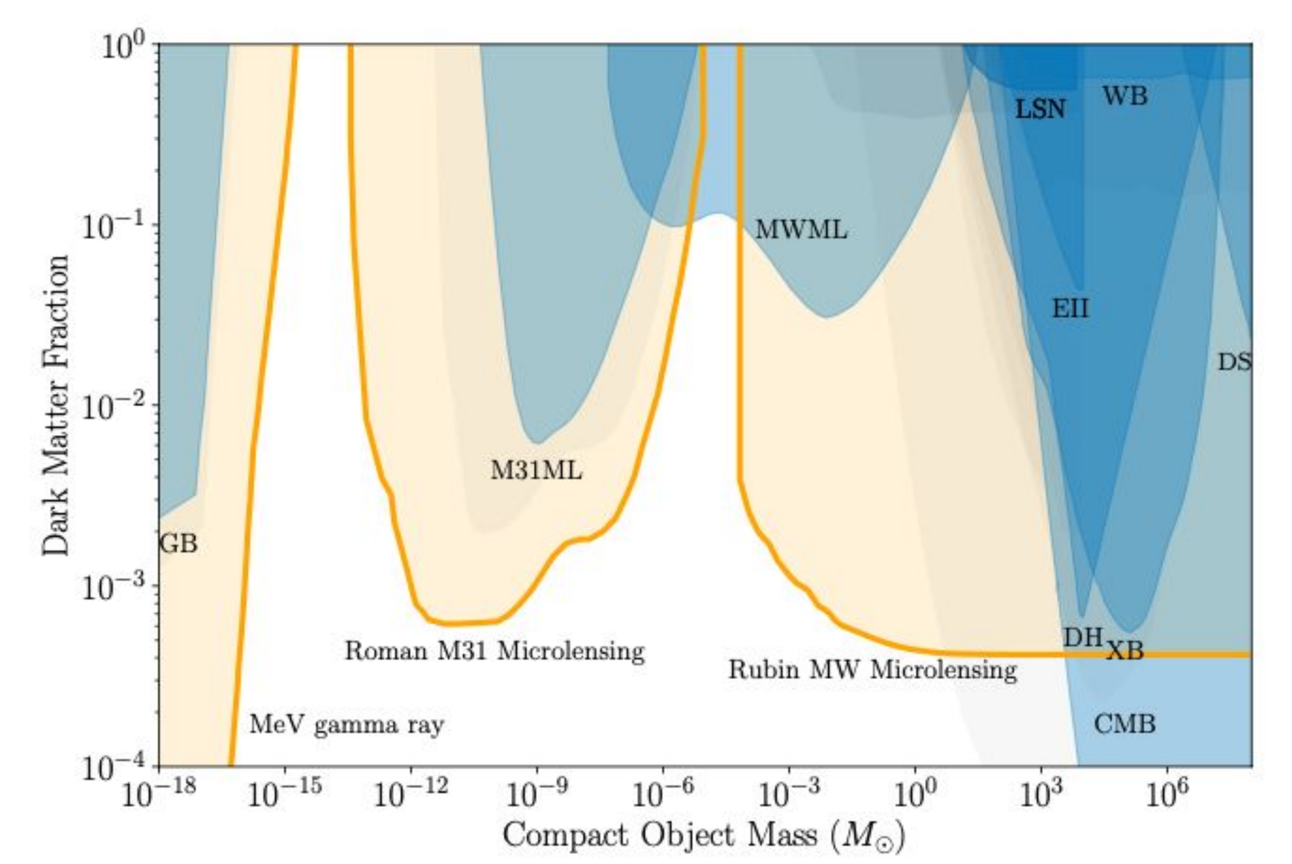
Primordial black holes may be our earliest window into the birth of the universe and energies between the QCD phase transition and the Planck scale.

Even if PBHs are a small fraction of dark matter, their discovery would have far-reaching implications



3.6 Extreme Environments in one Figure…

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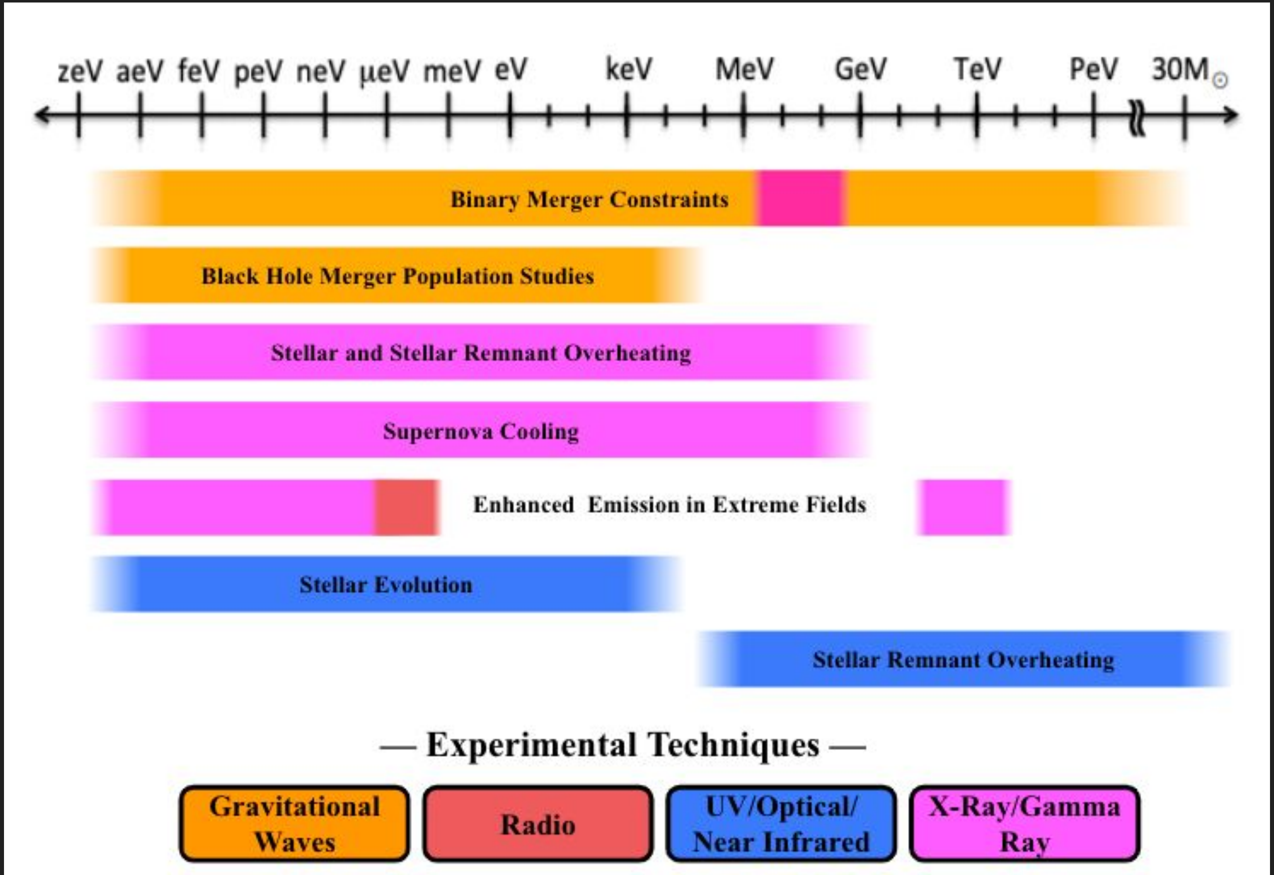
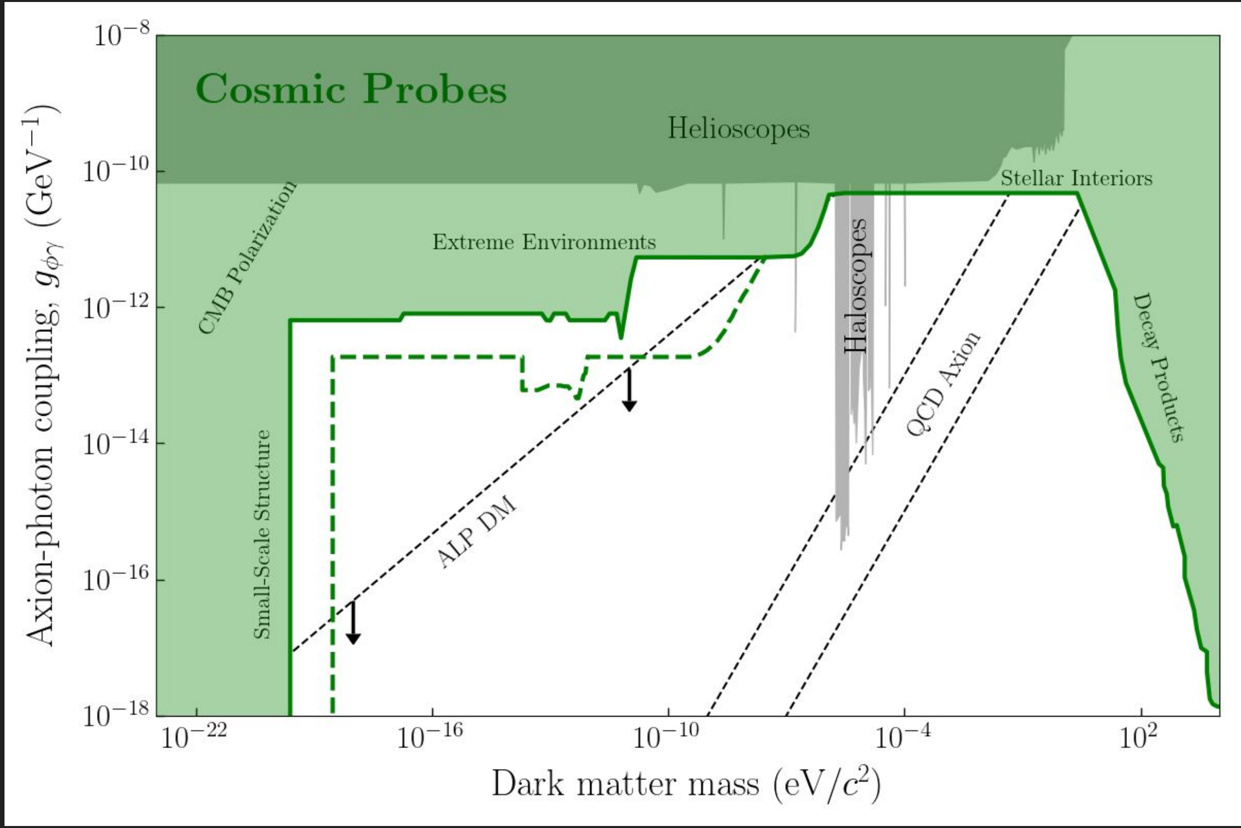
Extreme astrophysical environments (black holes, stellar remnants, and stellar interiors) provide unique opportunities to explore dark matter couplings to the Standard Model that are inaccessible with terrestrial experiments.

Support experiments, observations, and theoretical interpretation that probe extreme environments.



3.6 Complementarity with CF2 (Extreme Environments)



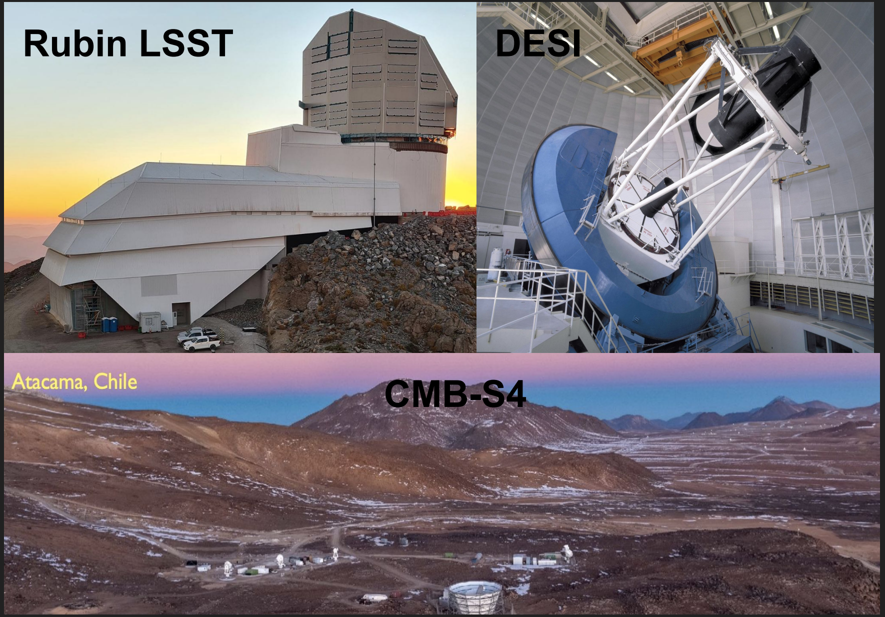
Axion-photon coupling vs dark matter mass.

Projections come from a range of places.

Still need to add black hole superradiance and dynamics constraints.

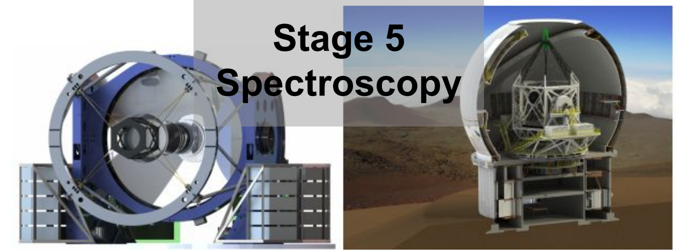
3.7 Facilities for Cosmic Probes of Dark Matter

Current/Near-Future Facilities

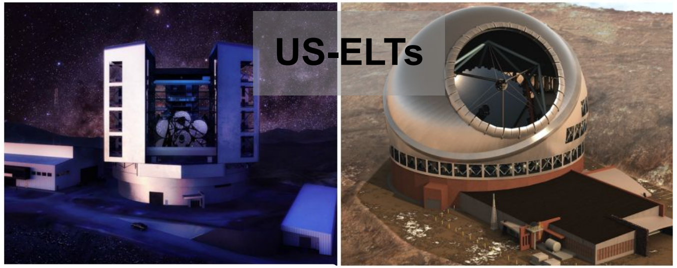


[2203.06200](https://arxiv.org/abs/2203.06200)

Future Facilities



CMB-HD



Radio Facilities

Gravitational Wave Facilities

Gamma-ray/ X-ray Telescopes

Radio Facilities

3.7 Facilities for Cosmic Probes of Dark Matter

- How do we best address the need from the facilities community?

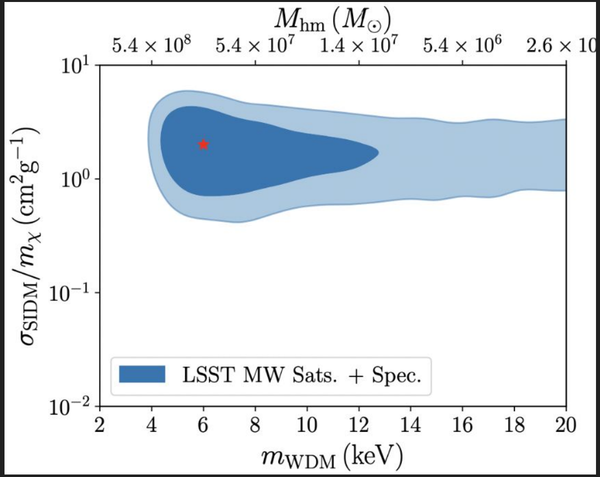
Dark matter physics associated with current and near-future facilities, such as DESI, Rubin, and CMB-S4, is extremely rich. Dark matter science should be supported within these projects on intermediate scales in parallel to studies of dark energy and inflation. Such a program will fully leverage the unprecedented capabilities of these facilities. On large scales, the construction of future cosmology experiments is critical for expanding our understanding of dark matter physics. HEP involvement will be essential for the design and construction of these facilities, and dark matter physics should be a core component of their scientific mission.

- We need to highlight the relevance of technology and expertise of the HEP community.
- We need provide more specific goals and quantitative estimates; these exist for some, but not all facilities.

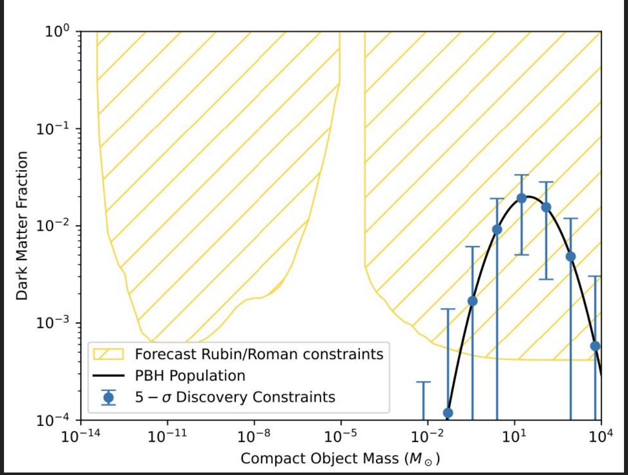
3.8 Tools for Comic Probes of Dark Matter Physics

- **Collaborative Infrastructure** - Support through existing HEP Projects (DESI, Rubin, CMB-S4)
- **New Support Mechanisms** - Cross-disciplinary support initiatives (future DMNI, cross-disciplinary funding)
- **Artificial Intelligence/Machine Learning** - Large complex data sets; need new tools to analyze them.
- **Cosmology Data Preservation** - Large legacy data sets; want to re-analyze for decades to come

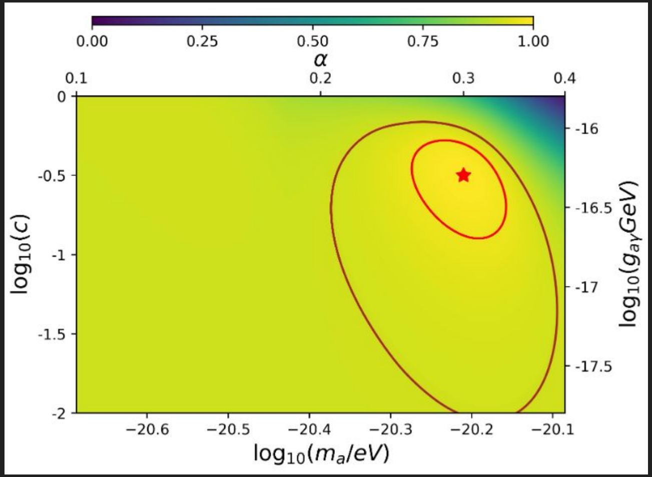
3.9 Roadmap to New Physics



SIDM/WDM w/ Rubin LSST and future



Primordial black holes w/ Rubin/Roman



Axion-like particles w/ EHT

Astrophysical uncertainties can be controlled and the extraction of fundamental dark matter properties is possible.

Summary Additional Discussion

Dark matter should be one of (if not the one) highest priority across Snowmass.

Current/near-future cosmic surveys provide direct access to dark matter model space.

Future cosmic survey facilities provide discovery potential across a wide range fo fundamental physics (dark energy, dark matter, inflation, early universe physics).

New mechanisms for cross-disciplenary support are needed to assemble the expertise needed to make concrete advances in cosmic probes of dark matter.

Cosmic probes of dark matter complement terrestrial searches (i.e., probe similar models in different parts of parameter space), inform terrestrial searches (i.e., tell us where the dark matter is and how it moves), and probe unique parameter space (i.e., self-interactions and gravitational interactions).

Feedback for Additional Discussion

“Although it is 100% true that everything positive we know about DM comes from astrophysics, this phrase makes a lot of appearances in the draft. I worry that it is close to the point of a few uses too many of the phrase, risking annoying the other dark matter constituencies.”

“... dark matter astrophysics is now a precision science. It wasn’t exactly this way a decade ago, and the progress the field has made on observations and precision theory calculations (in particular, on the simulation side) have been the catalysts for making it be this way.”

“...we need to have some more quantitative projections for sensitivity in order to have comparisons with other fields / science topics”

“I think there is a consideration of how astrophysical probes of dark matter fit into the whole cosmic frontier and what are our realistic goals of how astrophysical probes of dark matter will be featured in an overall cosmic frontier report.”

Feedback for Additional Discussion

“Need target models (if only cartoonish), since these are important for people outside the field and get reproduced a lot.”’

“The Dark Energy Task Force in 2006 was extremely powerful for motivating the experimental dark energy program (2012→today). Should we ask for a “Dark Matter Task Force” to assess cosmic dark matter experiments? Is it too risky to ask for this, since we run the risk of having nothing happen except this task force (i.e., need to wait for next Snowmass for any future facility support).”

Areas we need further improvement

- Be specific about the scientific goals in both observation and interpretation
- Specify a few key quantities related to dark matter physics, e.g., minimal halo masses, number of substructures, galaxy mass functions, density profiles and Neff…
- Specify ways of probing them (lensing, stream, general survey, spectroscopy), and the associated observational facilities (near-future, and future)
- Specify what tools are needed to interpret observation results and extract microscopic properties of dark matter

Many of these points have been discussed in the white papers to some extent; but we need to sharpen the relevant discussion in the summary report; the discussion related to the extreme environments in the summary report is more specific

Snowmass 2013 did not have a CF3… The result from the 2014 P5 →

The 2014 P5 report did not identify dark matter as a science driver for the large cosmic survey efforts (LSST, DESI, CMB-S4).

Faced resistence in expanding the scientific scope of these experiments to support dark matter research *even though* dark matter is a DOE mission priority.

We would like to avoid this happening again...

https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

CF3-pertinent sessions in Seattle (all times local)

Monday 7/18	10am-11am: CF3 discussion - discuss feedback and organize teams for outstanding needs for CF report
Tuesday 7/19	8am-12pm: CF/EF/RF/TF dark matter complementarity (20L) 8am-12pm: CF5,6,7 + 4567 complementarity/facilities session 8am-12pm: IF2 photon detectors 3.30pm-5pm: Paths to discovery at the Cosmic Frontier (half-plenary, 3 talks)
Wednesday 7/20	8am-12pm: all-CF discussion (23Q) will include presentation of key messages from topical groups, discussion of cross-topical-group plots, tables, etc for Frontier Report
Thursday 7/21	8am-12pm: all-CF discussion (24M) all CF report discussion, panel on synergies with between astrophysics and particle physics 5.30pm-7pm: Colloquium on Cosmic Frontier Probes of Fundamental Physics (plenary, introduction + panel)
Saturday 7/23	8am-12pm: IF/CF/NF instrumentation for dark matter and neutrino detectors (21G/22J, merged) - mostly organized by NF so far - talks and panel discussion, looking for dark matter contributors IF/CF/CompF instrumentation for the cosmic frontier (21H) TF/CF cosmic frontier theory (19K) - panel + talks
Sunday 7/24	10am-12pm: NF/CF/TF high energy and ultra-high energy astrophysical neutrinos

Thanks CF1 & CF2!

Timeline and Logistics

May 25th: Snowmass travel grant application deadline (link)

May 31st: Requested first draft for CF conveners (start to assemble CF report)

July 17th-26th: Snowmass meeting in Seattle.

July 31st: Snowmass reports due to Snowmass (do we know the actual deadline?)

Oct 30th: Final report due to APS + agencies?