CF03: Cosmic Probes of Dark Matter Physics

SnowMass2021

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

July 19th, 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 require 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

Extreme Environments

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.**

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.**

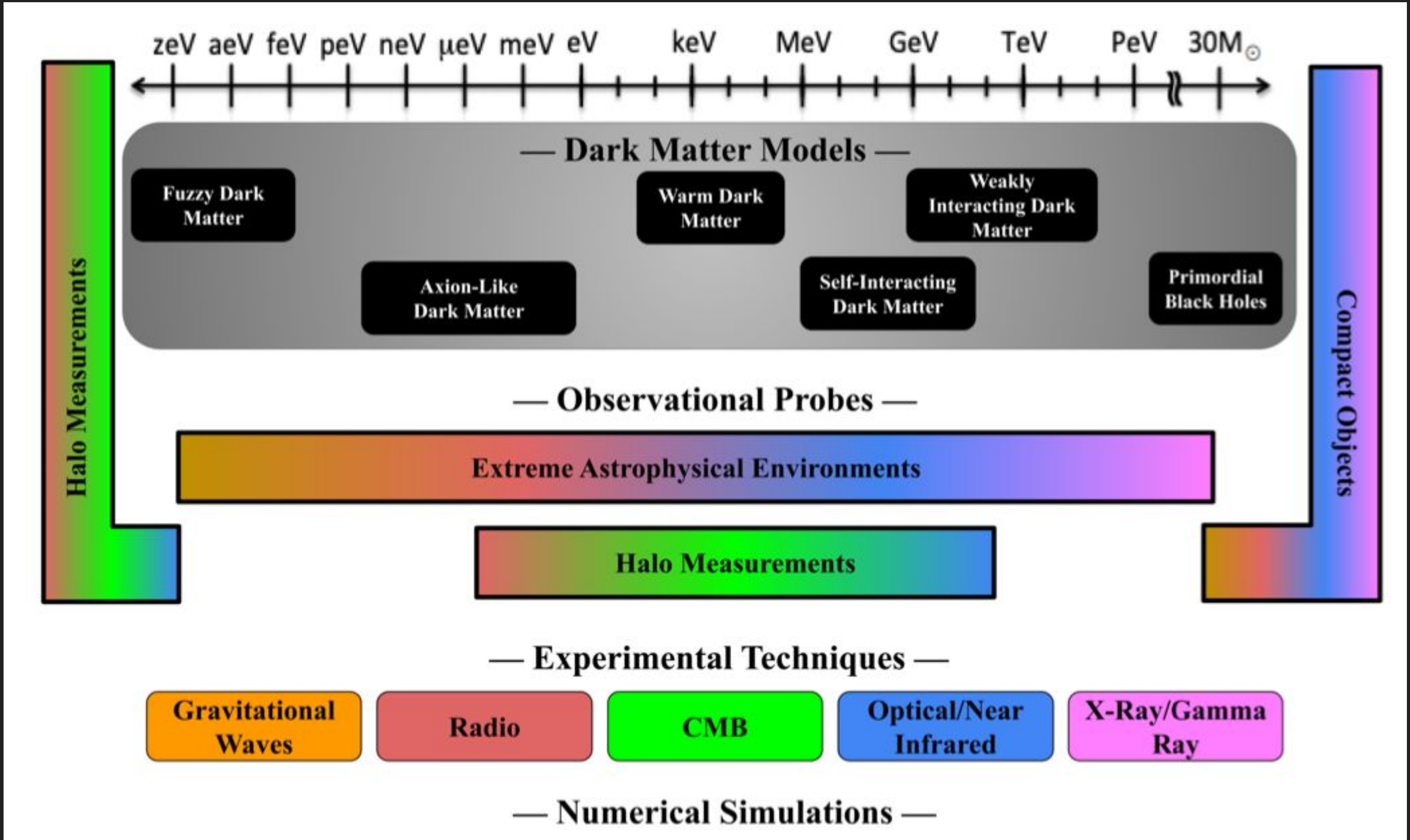
2. The ΛCDM model makes the strong, testable prediction that the mass spectrum of dark matter halos extends below the threshold at which galaxies form [5]. Sub-galactic dark matter halos are less influenced by baryonic processes making them especially clean probes of fundamental physics of dark matter. 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.**

Five Major Science Opportunities

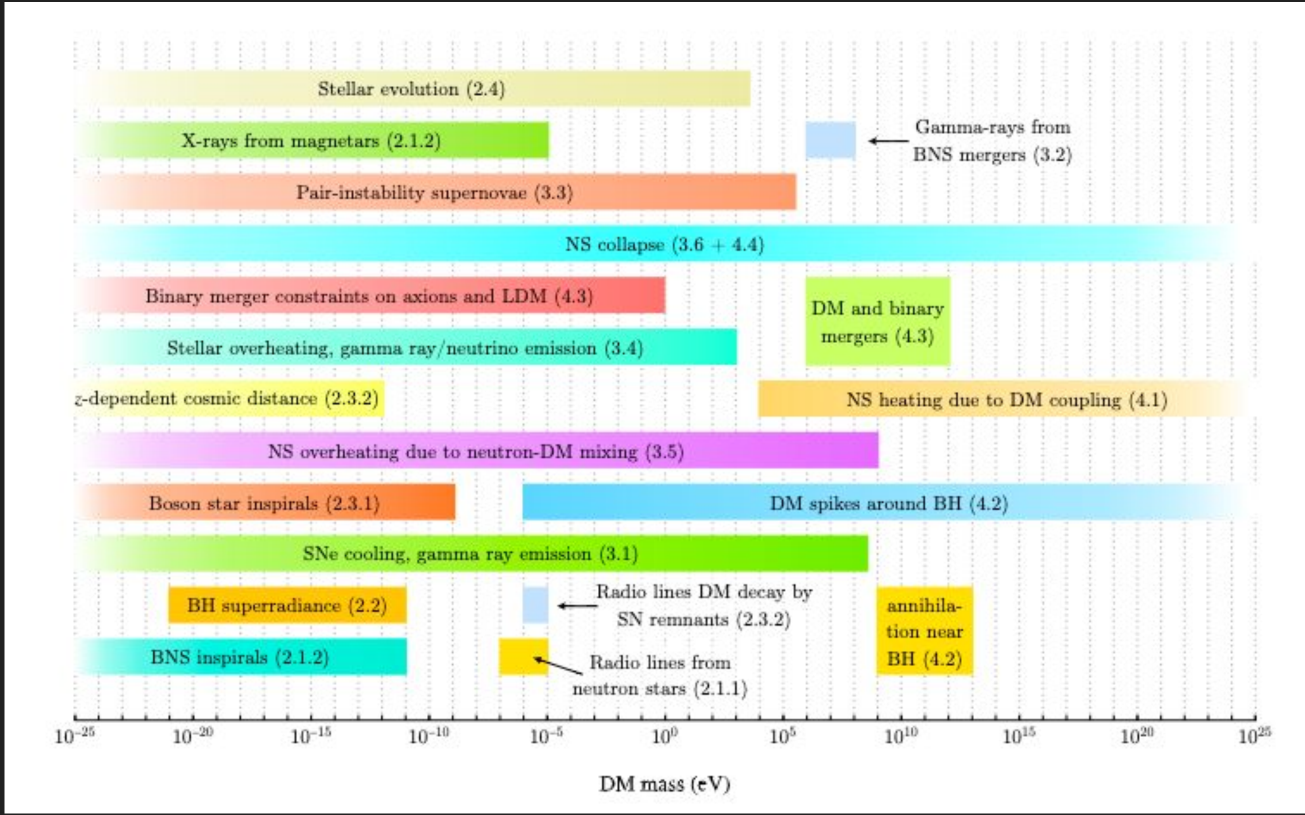
3. Extreme astrophysical environments provide unique opportunities to explore dark matter couplings to the Standard Model that are inaccessible with terrestrial experiments [8]. **Instruments, observations, and theorists that study extreme astrophysical environments should be supported as an essential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


zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M☉
— Dark Matter Models —
Fuzzy Dark Matter
Axion-Like Dark Matter
Warm Dark Matter
Self-Interacting Dark Matter
Weakly Interacting Dark Matter
Primordial Black Holes
— Observational Probes —
Extreme Astrophysical Environments
Halo Measurements
Halo Measurements
Compact Objects
— Experimental Techniques —
Gravitational Waves
Radio
CMB
Optical/Near Infrared
X-Ray/Gamma Ray
— Numerical Simulations —

Dedicated White Paper on DM searches with Extreme Environments



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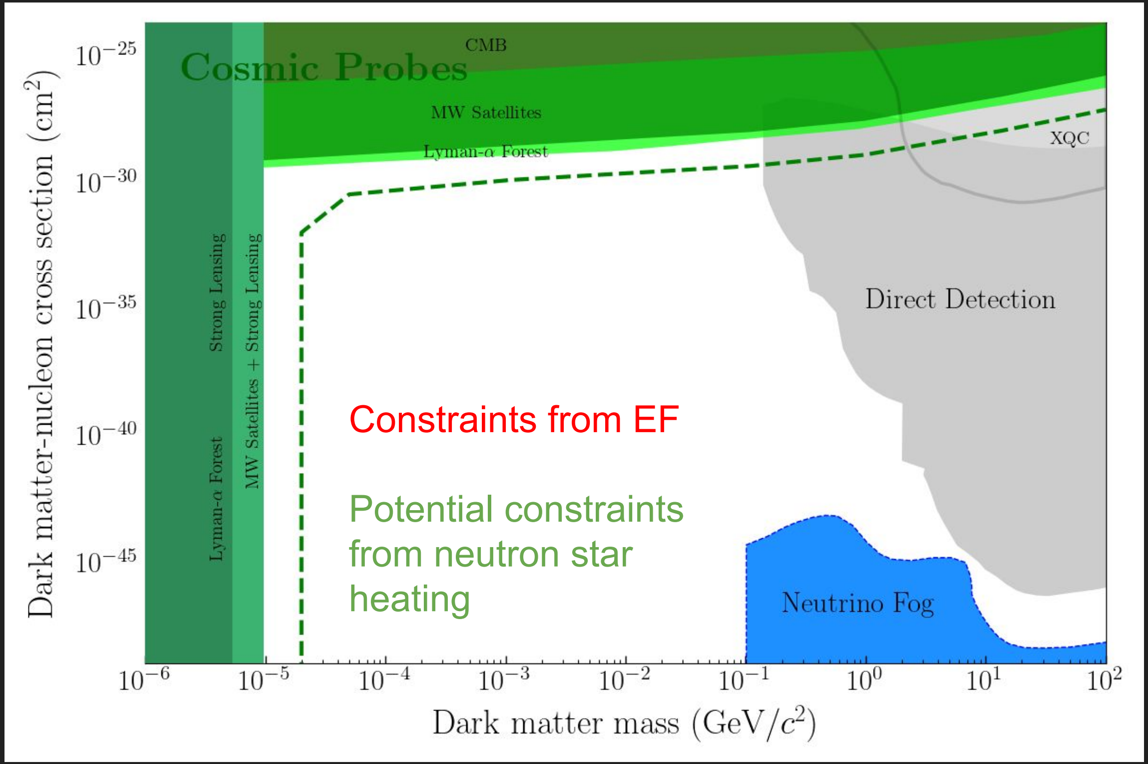
Observations of extreme astro objects across the EM spectrum + GWs can be sensitive to the full DM mass range, over 50 orders of magnitude!

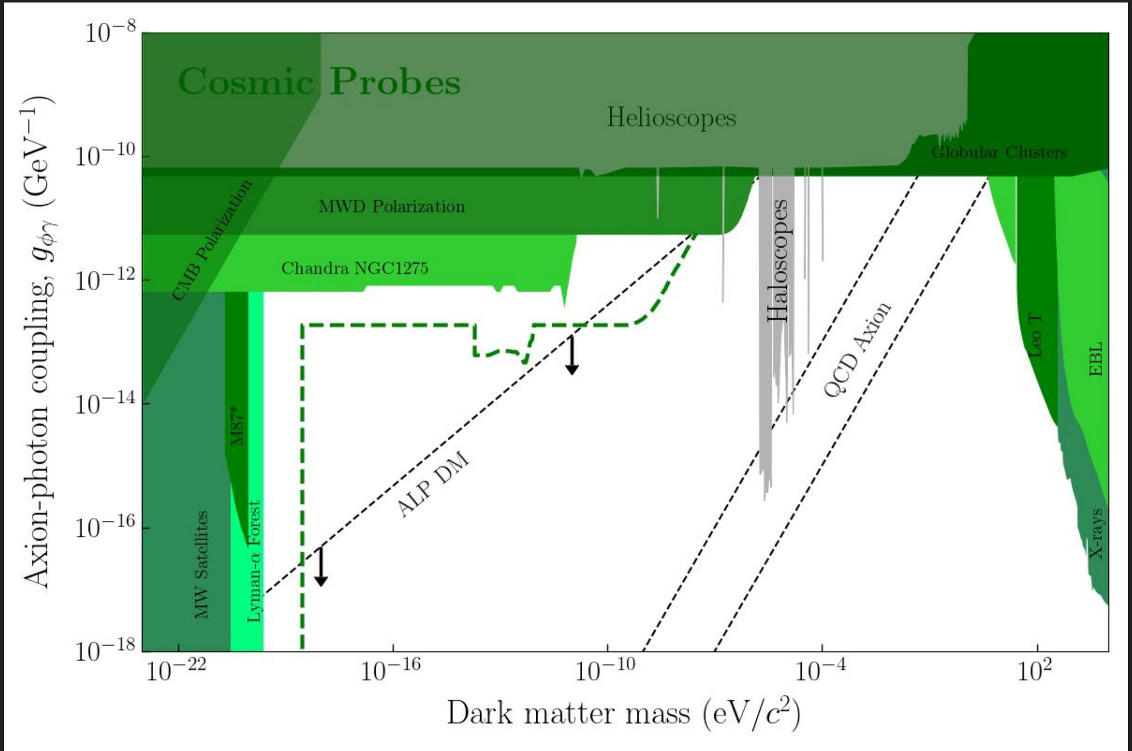
Complementarity with CF1 and EF



Dark matter-nucleon scattering cross section vs dark matter mass

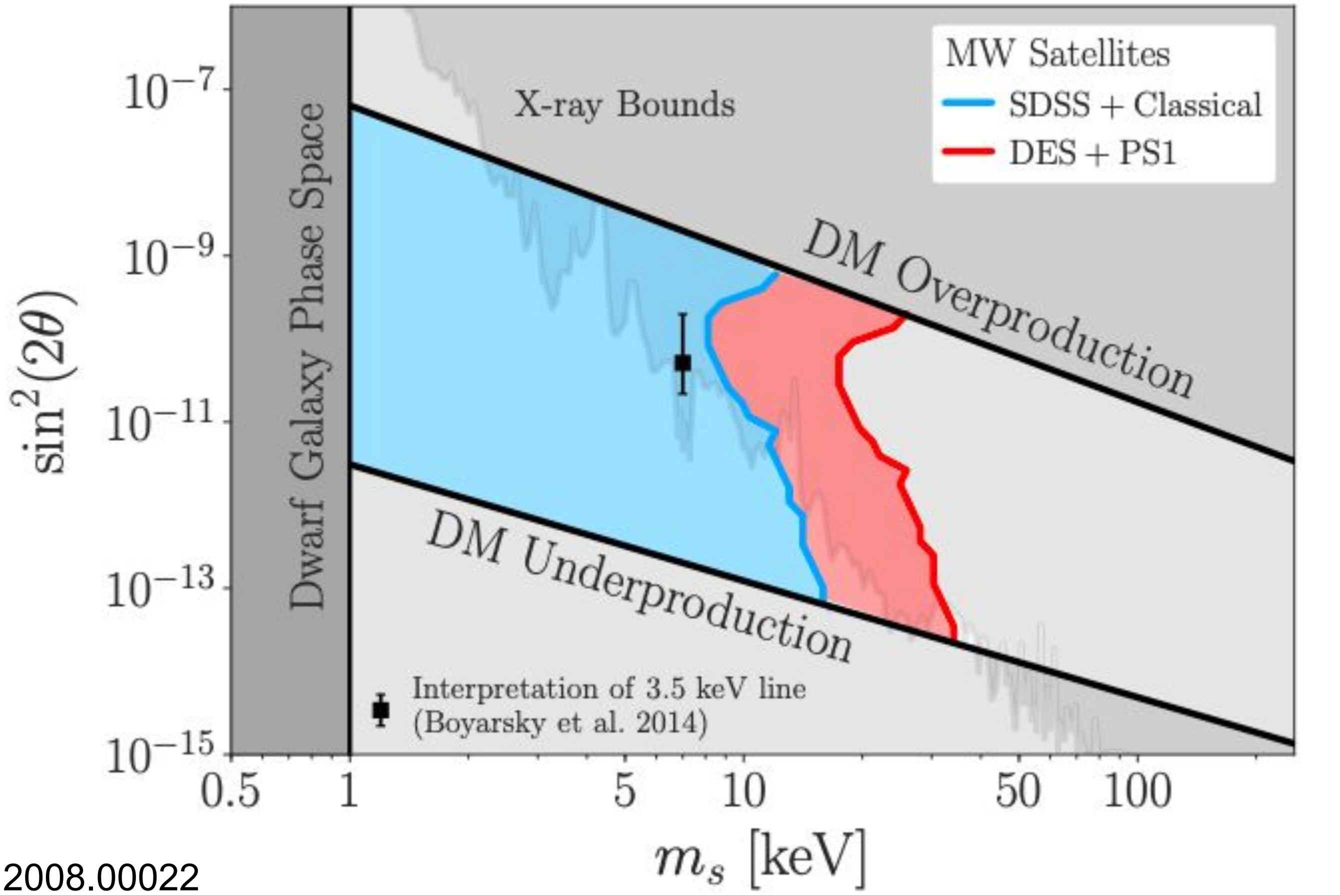
Projections come from assuming sensitivity to 10^5 Msun halos…

Complementarity with CF2



Axion/ALP-photon coupling vs dark matter mass
Projections come from a range of places…(caption could be very long)

Complementarity with Neutrino Frontier



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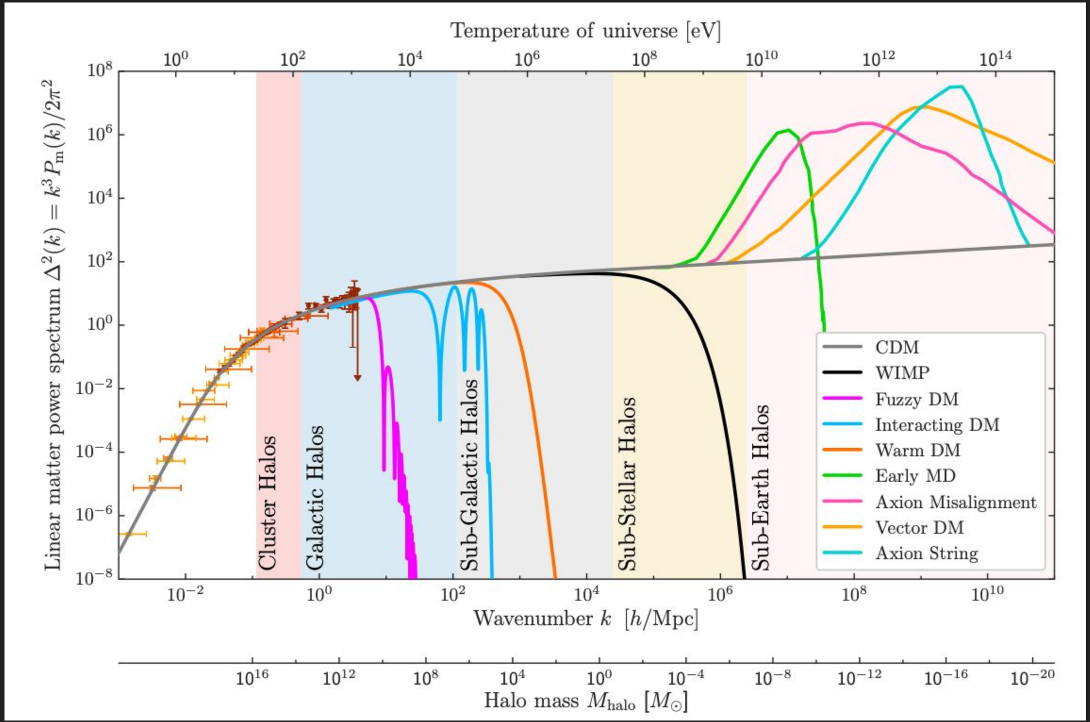
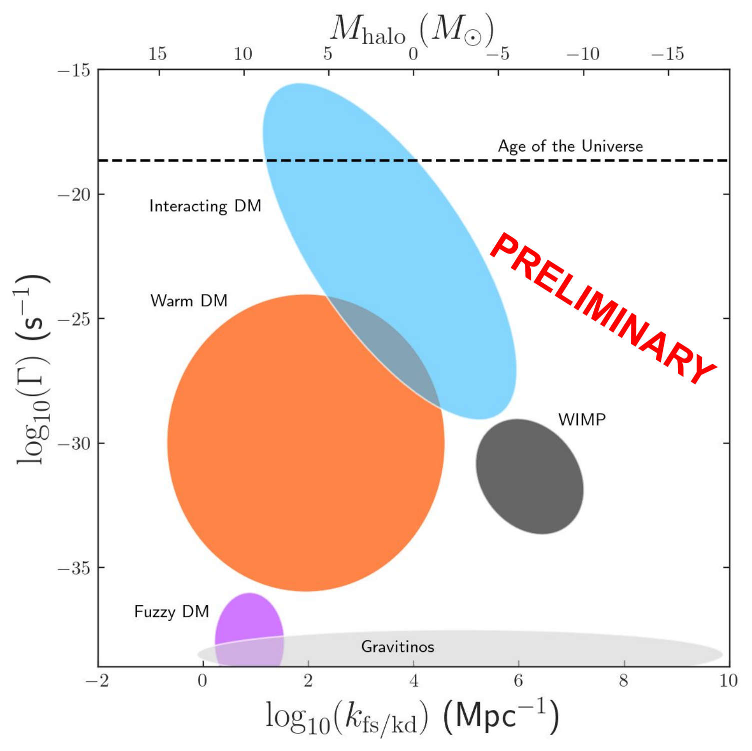
Dark Matter Halos

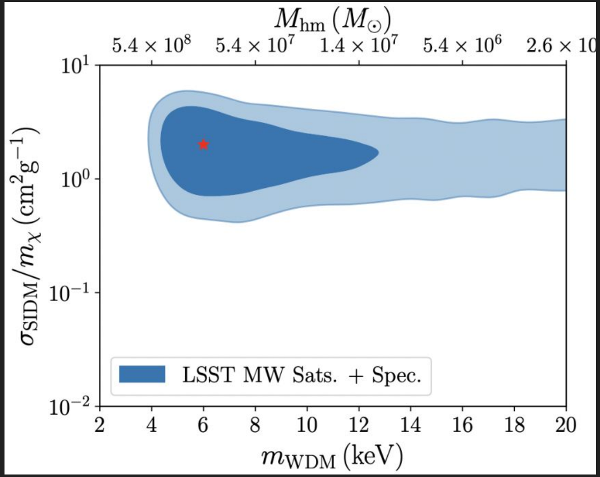


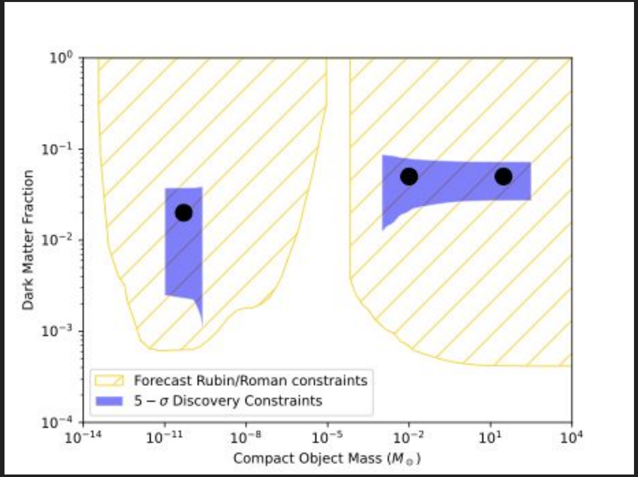


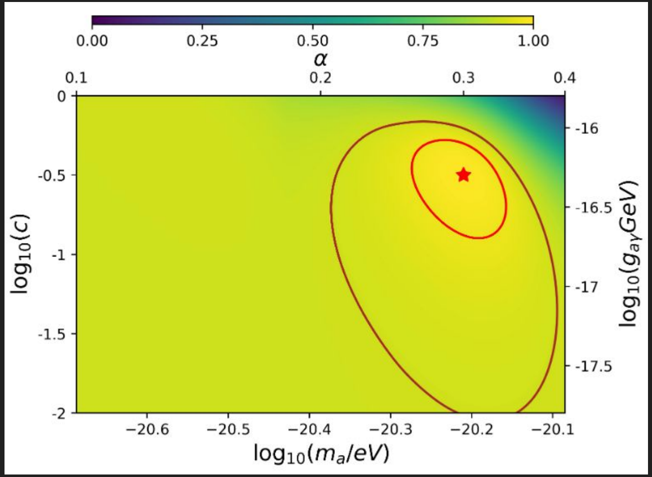
Connecting to your favored dark matter models
Mapping particle parameters to astrophysical observables

Exploring complementary figured inspired by Buckley & Peter 2017. From Nadler

Roadmap to New Physics







SIDM/WDM w/ Rubin LSST
(the plot needs updated)

Primordial black holes w/ Rubin/Roman

Axion-like particles w/ EHT

Goal: demonstrate that astrophysical uncertainties can be controlled in order to extract microphysical properties of dark matter.

Outlook

Whenever a new model of dark matter is proposed, we need to ask the question: “Is this consistent with our observations of the Universe?”. In this way, CF3 is complementary to all searches for dark matter

TF: Predictions on small-scale structure of the Universe; many light dark matter models may have large self-interacting cross sections and suppressed/enhanced matter power spectra, leading to novel signals in cosmic and astrophysical observations

CompF: To make concrete predictions and disentangle from baryon physics, we need numerical simulations of structure formation, and AI/ML for data analysis

IF: Instrumentation, detectors for future cosmic surveys

We are entering the era of precision astrophysical measurements of dark matter!