US Cosmic Visions: New Ideas in Dark Matter

Summary of the March 2017 workshop focused on small-scale projects in the US Dark Matter search program

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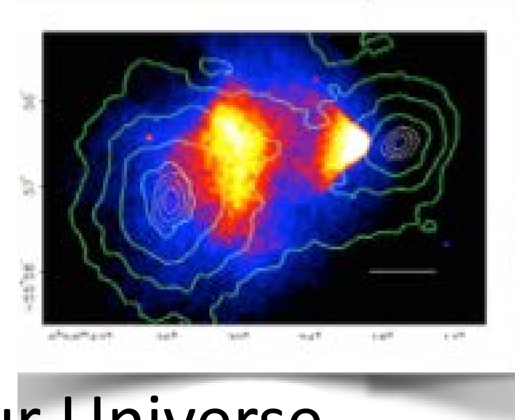
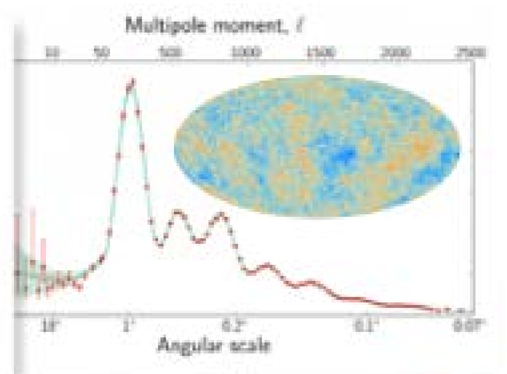
1. **New avenues in direct detection: e.g., sub-GeV, electron recoil.** Conveners:
   - Rouven Essig, Stony Brook (rouven.essig@stonybrook.edu).
   - Juan Estrada, Fermilab (estrada@fnal.gov).
   - Dan Mckinsey, UC Berkeley (daniel.mckinsey@berkeley.edu).
2. **Ultra-low mass (sub-eV) dark matter detection.** Conveners:
   - Aaron Chou, Fermilab (achou@fnal.gov).
   - Peter Graham, Stanford (pwgraham@stanford.edu).
3. **Dark matter production at fixed target and collider experiments.** Conveners:
   - Bertrand Echenard, Caltech (echenard@caltech.edu).
   - Eder Izaguirre, Brookhaven (eder@bnl.gov).
4. **New Candidates, Targets, and Complementarity.** Conveners:
   - Jonathan Feng, UC Irvine (jlf@uci.edu).
   - Patrick Fox, Fermilab (pjfox@fnal.gov).

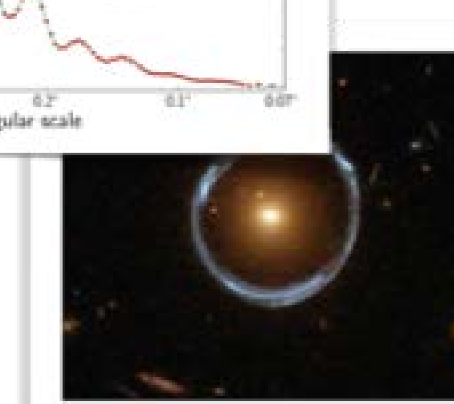
The scientific advisory committee is:

- Marco Battaglieri (co-chair), INFN (battaglieri@ge.infn.it)
- Roni Harnik, Fermilab (roni.harnik@gmail.com)
- Matt Pyle, UC Berkeley (mpyle1@berkeley.edu)
- Gray Rybka, U. Washington (grybka@uw.edu)
- Pierre Sikivie, Florida (sikivie@phys.ufl.edu)
- Tim Tait, UC Irvine (ttait@uci.edu)
- Natalia Toro (co-chair), SLAC (ntoro@slac.stanford.edu)
- Richard Van De Water, Los Alamos National Lab (vdwater@lanl.gov)
- Neal Weiner, NYU (neal.weiner.nyu@gmail.com)
- Kathryn Zurek, Lawrence Berkeley National Lab (kmzurek@lbl.gov)

A Universe of Dark Matter



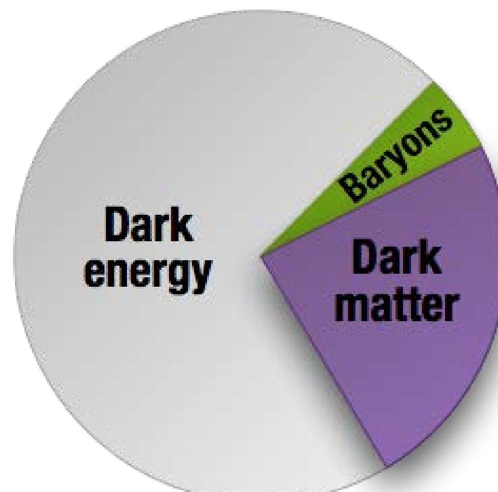




Overwhelming evidence for ubiquitous Dark Matter

- Its physics governs our Universe
- Its constituents are fundamentally different from familiar matter.

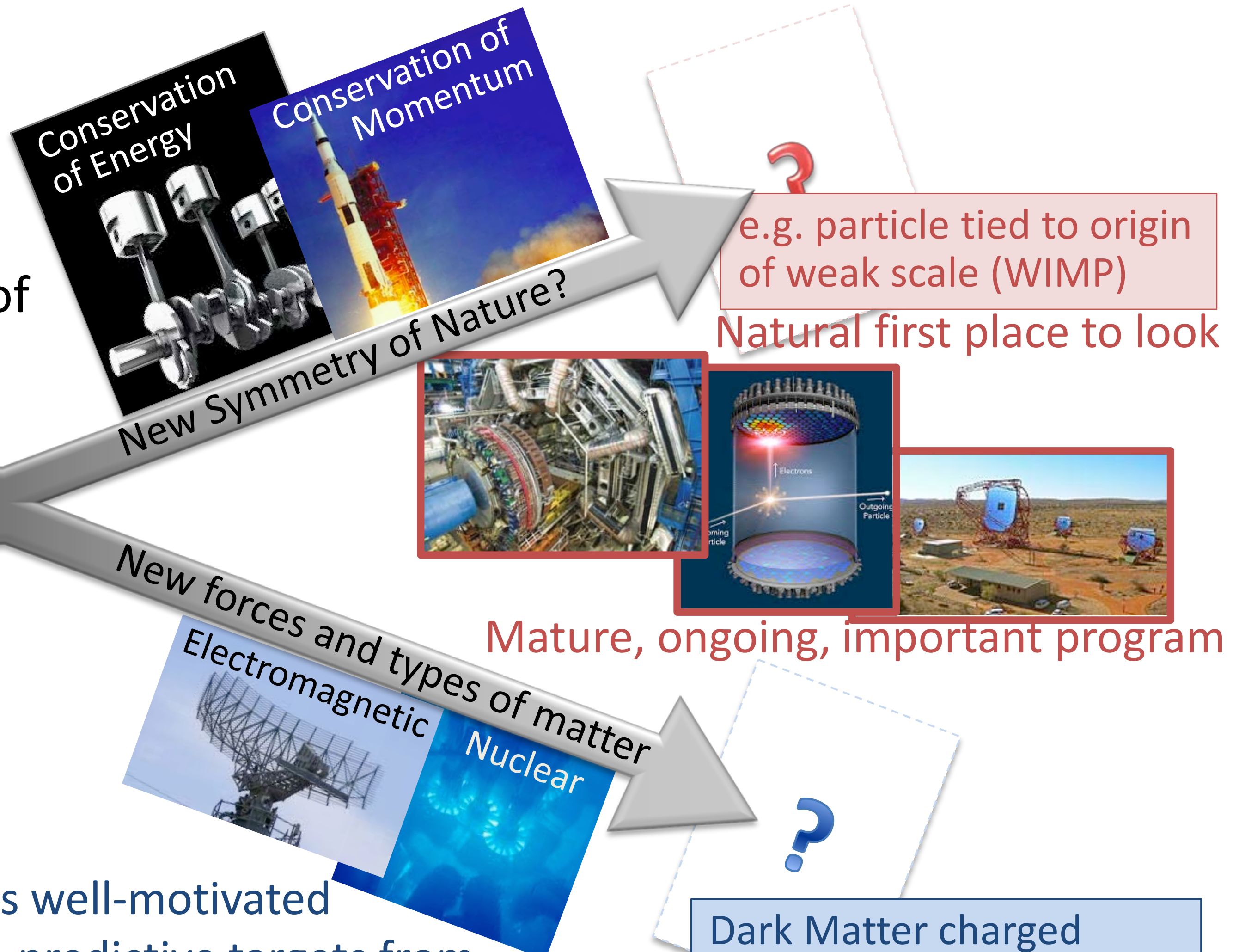
Nature and origin of Dark Matter are among the foremost open questions in fundamental science today.



High Stakes of Dark Matter Science

Uncovering the nature of Dark Matter can lead to fundamental advances,

at the level of the greatest historical discoveries of physics



- Recent theory highlights well-motivated frameworks with sharp, predictive targets from cosmology, fundamental physics, and anomalies in data
- New, cross-cutting experimental ideas bring them within reach (at low cost) → **Logical next step for Dark Matter science**

“New Ideas in Dark Matter” Workshop

- Investigating low-cost & high-impact opportunities in Dark Matter (DM) science
  - The G2 experiments (ADMX, LZ, and SuperCDMS) are flagships of the US Dark Matter program and obvious priority
  - Workshop focused on *complementary* science that can be done by small projects <$10M (some much less)
  - 100+ talks in 4 working groups, presenting new ideas, proposals, and science and R&D results

“New Ideas in Dark Matter” Workshop

- Working groups
  - New Avenues in Direct Detection
  - Ultra-low mass (sub-eV) DM Detection
  - DM Production at Fixed-Target and Collider Experiments
  - New Candidates, Targets, and Complementarity
- Timeline:
  - Organizing group (conveners & SAC) formed in February
  - Workshop March 23-25
  - First draft of whitepaper circulated to community May 17
  - Second draft to be circulated soon, aiming for whitepaper on arXiv by mid- to late-June

High-Level Conclusions

- Small-scale searches for Dark Matter are guided by a few key priorities – testing general principles and sharp targets
- Projects are ready to reach high-priority targets now, and there is a path forward, requiring further R&D, to do so comprehensively
- This new field is especially cross-cutting in the technologies, techniques, and facilities that enable it – fostering these connections is essential to the field's success

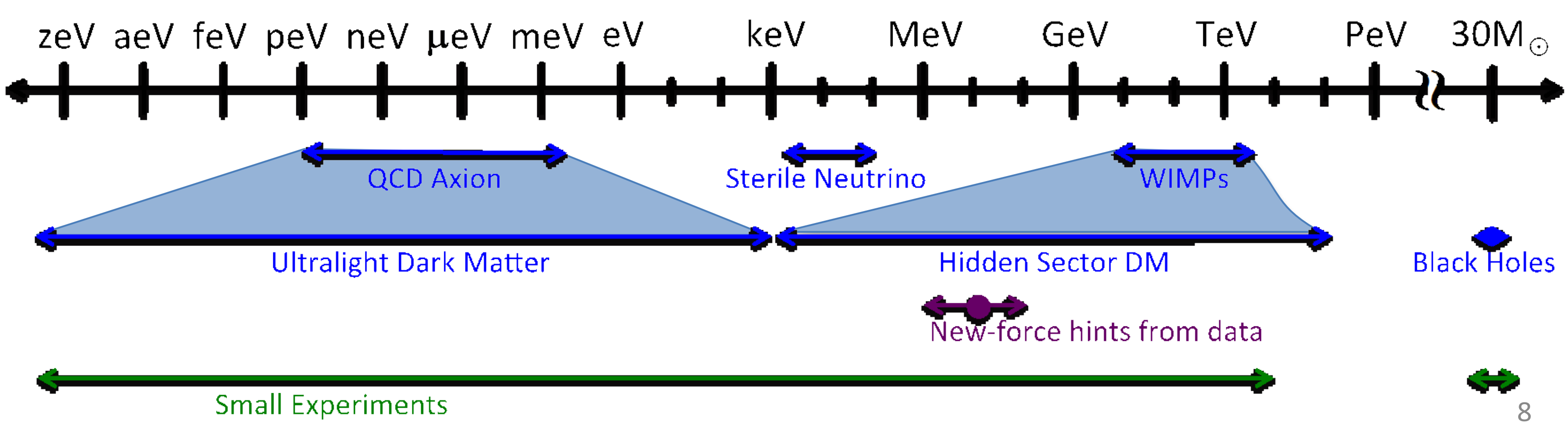
Small projects portfolio is a key part of the future of DM science!

Outline

- Strong motivation to explore DM parameter space beyond G2 sensitivity
- Innovative, low-cost ideas for small experiments with significant discovery opportunity
- Need a program of complementary experiments to comprehensively explore priority science targets

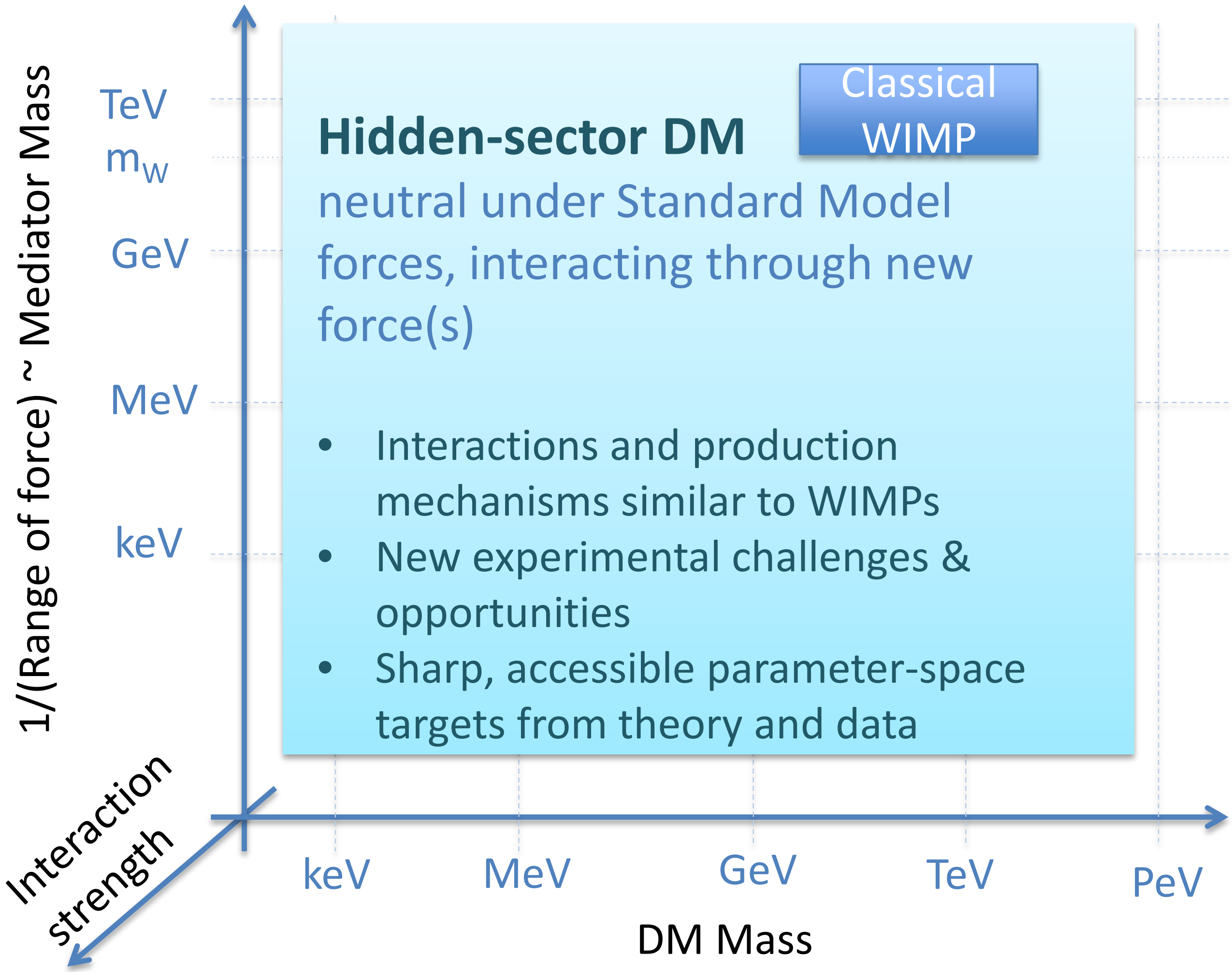
Priority Targets in Dark Matter Science

- WIMPs – extensively studied but important parameter space still to be explored
- New paradigm of hidden sector DM – modest generalization of WIMPs with large expansion of experimental possibilities
- QCD axion – just beginning to be explored
- Another new paradigm, ultralight DM, generalizes axion



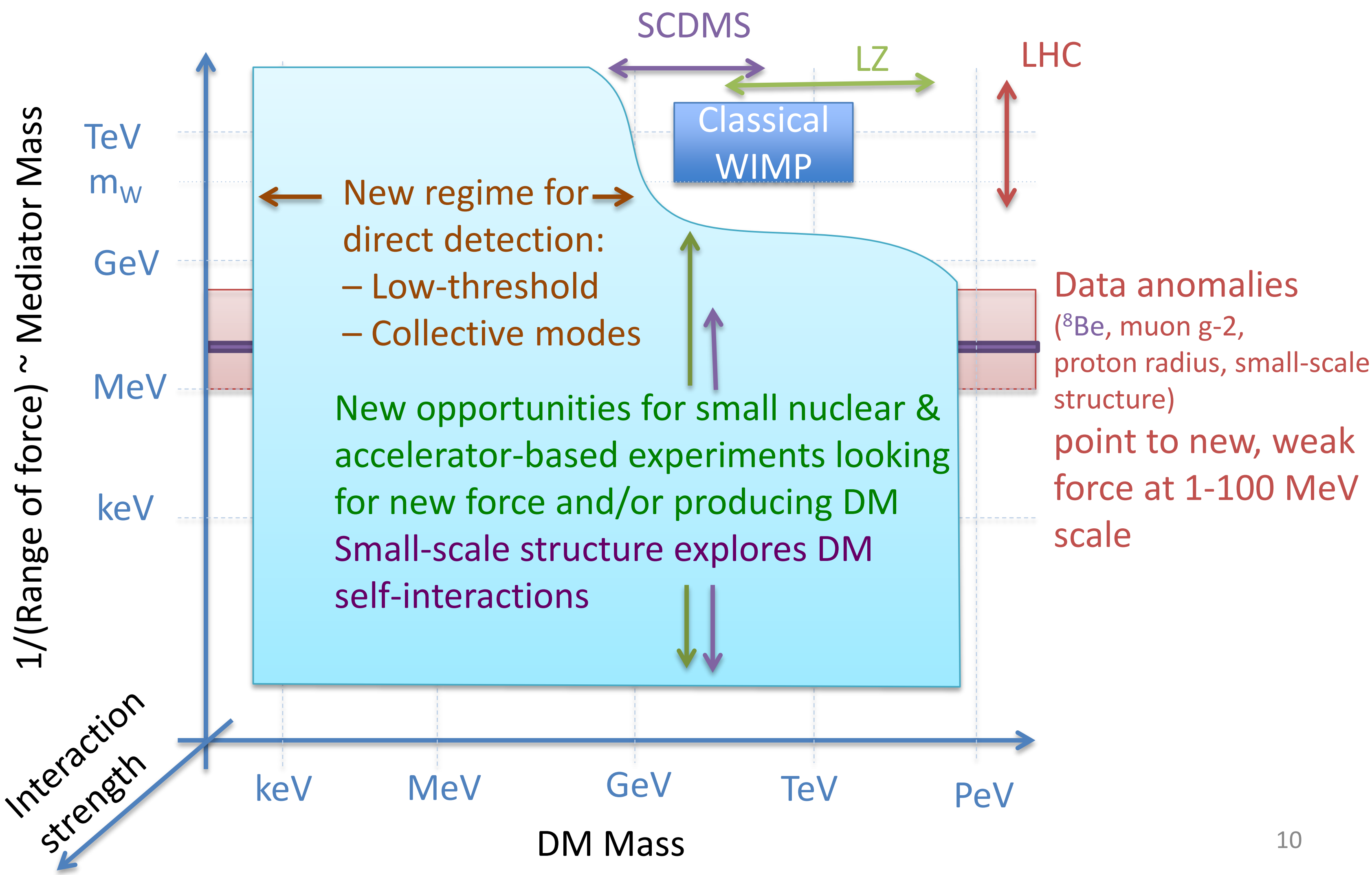
Hidden sector DM

Natural generalization of WIMPs!

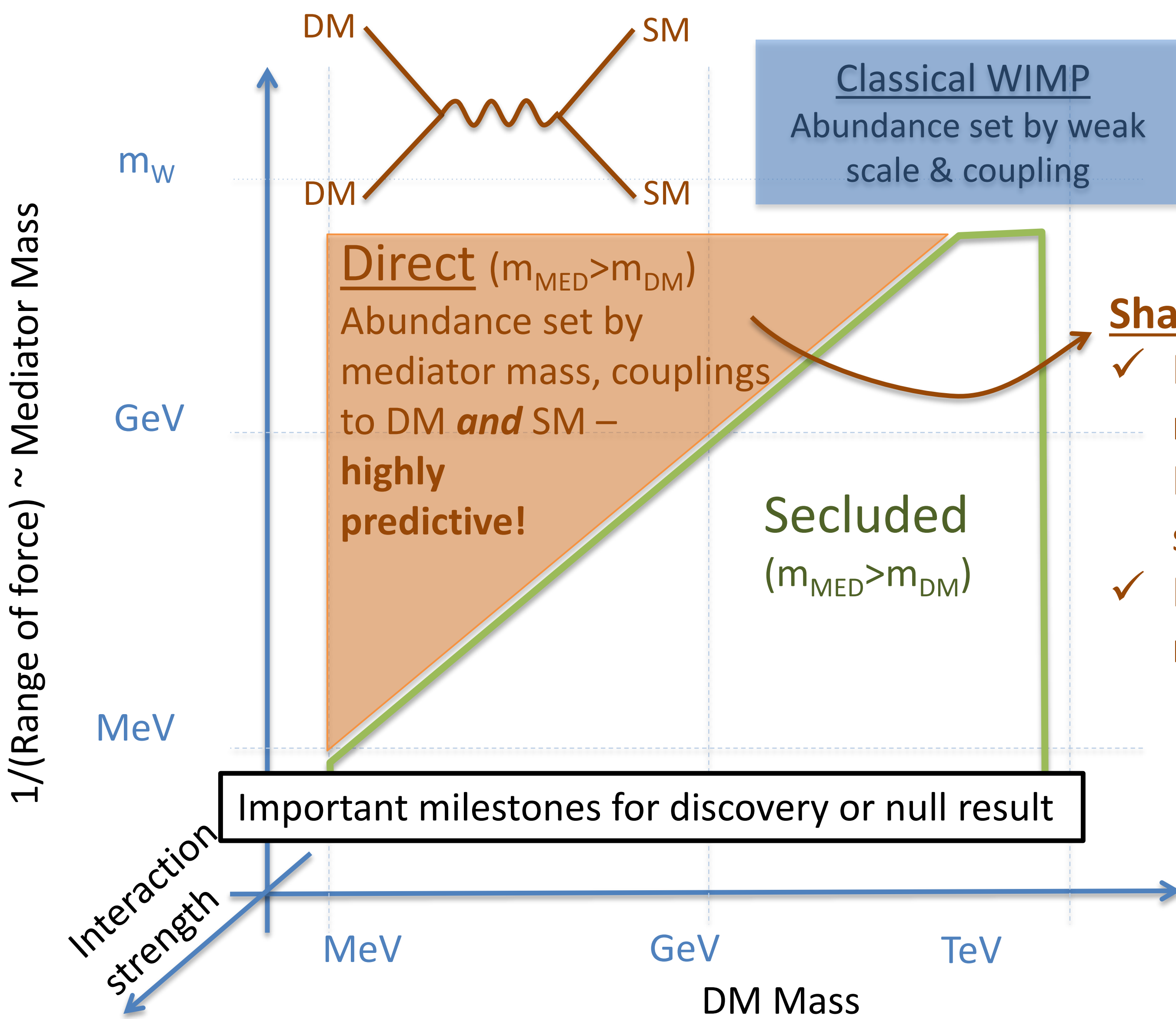


Hidden sector DM

Accessible to new experimental techniques!



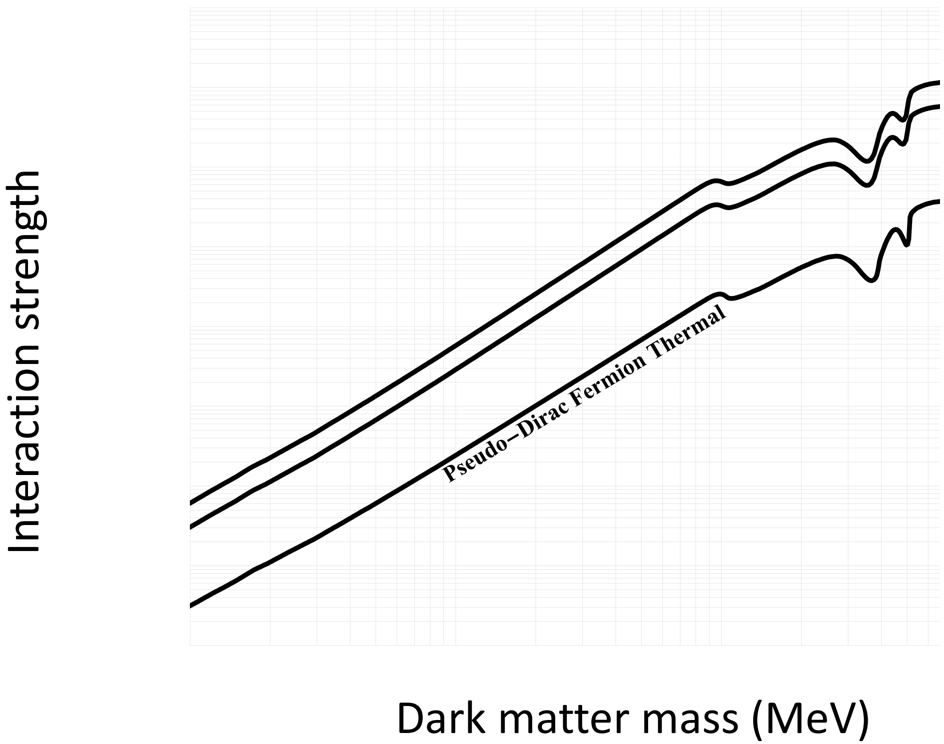
Thermal Sub-GeV DM



Sharp target

- ✓ Predicted scattering rate (also depends on DM spin & mass structure)
- ✓ Minimum production rate

Predictive Targets for Thermalized DM



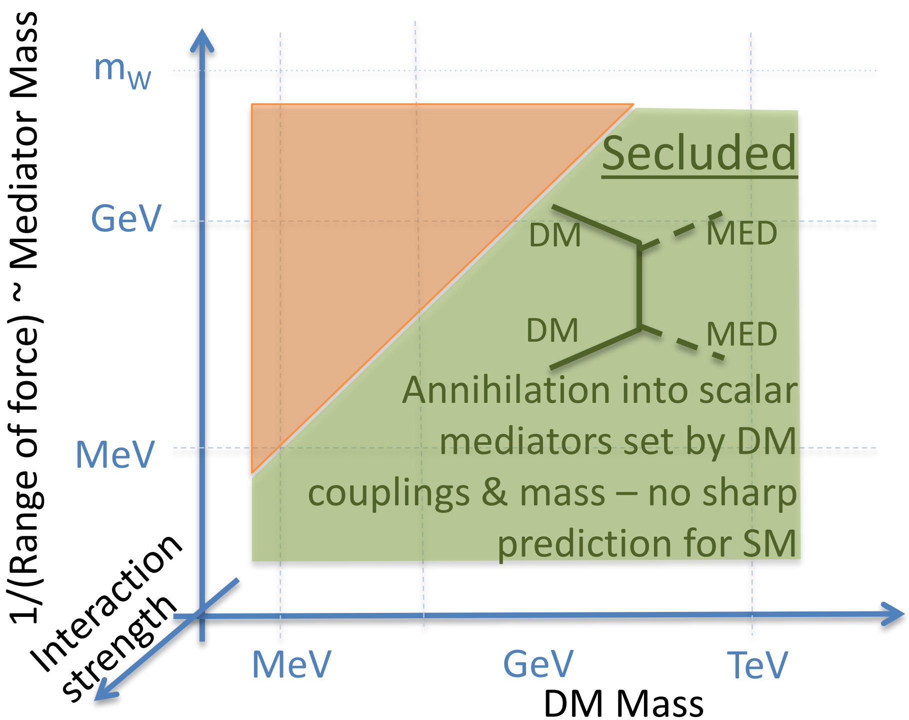
A series of sharp targets for DM thermally coupled to SM

- Direct thermal freeze-out → expected coupling vs. mass
- Minimum annihilation rate for asymmetric fermion DM

  (from CMB bounds – coupling target assumes direct annihilation)
- Minimum scattering rate for "SIMP/ELDER" (new force maintains *kinetic* but not *chemical* equilibrium until freezeout)

Motivation and Targets at Weaker Couplings

Secluded Thermal/Asymmetric DM



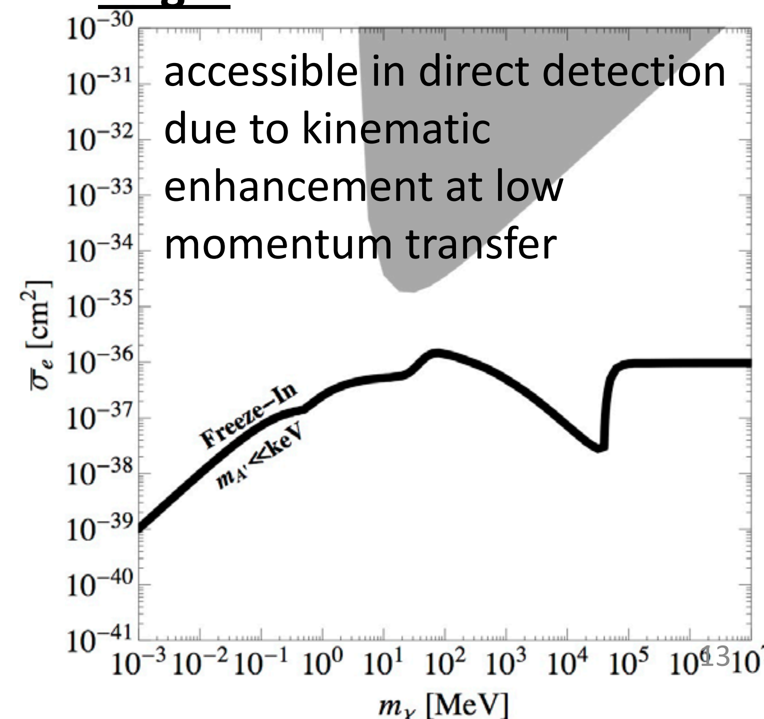
- Theoretically motivated loop-level couplings **are accessible**
- For keV-scale DM, very weak coupling favored by cosmology

Hidden-Sector freeze-in

Very weakly coupled DM never thermalizes, can ``freeze in''

$\alpha_D\, \epsilon^2 \sim 10^{-10}$ x thermal

- If $m_{MED} <<< m_{DM}$, **another sharp target** for direct detection



Hints of Hidden Sector Forces?

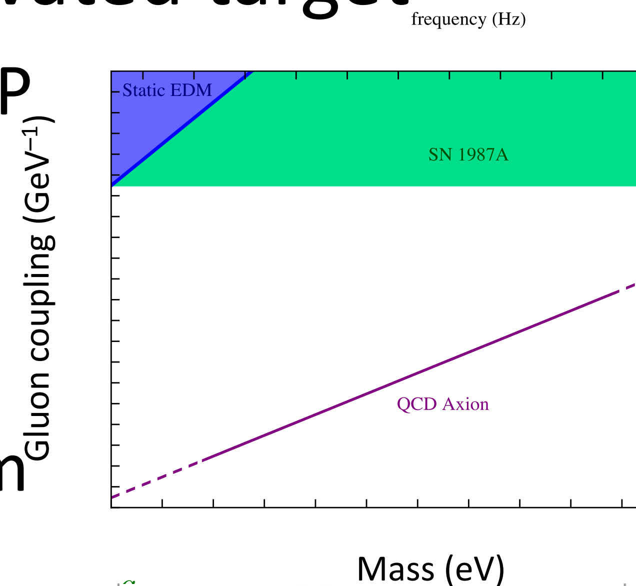
New forces can also alter the physics of familiar matter and of dark matter, separately–anomalies in data may be first hints of such effects

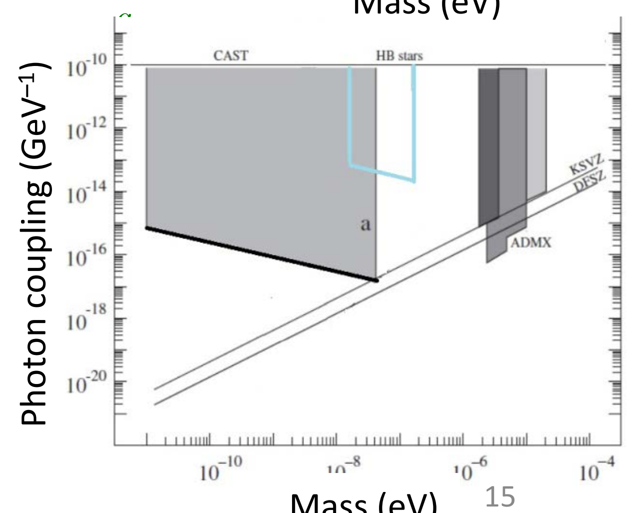
- Multiple anomalies can be explained by ~10–100 MeV boson with appropriate couplings to muons, quarks, and electrons of $O(10^{-3})$:
  - ~3σ: muon g-2
  - 5.6σ: proton radius from muonic hydrogen vs. e-p scattering
  - 2-3σ: KTeV $Br(\pi^0 \rightarrow e^+e^-)$
  - **These are sharp targets in SM coupling vs. mass**

- Discrepancies between small-scale cosmological structure data & simulation
  - baryonic effects?
  - compatible with DM self-interaction through **10–20 MeV boson**
- ATOMKI ^{8}Be decay anomaly
  - 6.8σ bump consistent with 17 MeV particle
  - Couplings roughly consistent with other anomalies
  - **Sharp target in coupling and mass**

Ultralight Dark Matter: Motivation

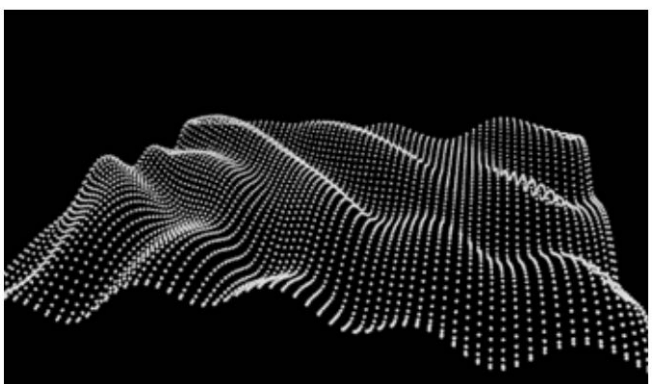
- QCD Axions: A particularly motivated target
  - Peccei-Quinn solution to strong CP problem implies light axion (10^{-12} to 10^{-2} eV) with predicted mass-coupling relation
  - Expect significant abundance from inflation or high-temperature phase transition
- Observational bound on DM mass is $>10^{-22}$ eV, entire mass range is theoretically natural



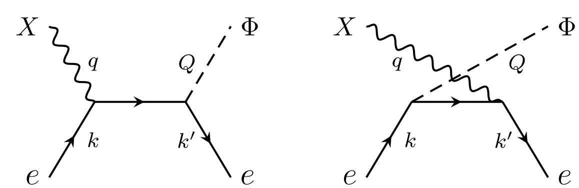


Ultralight (sub-keV) DM: Properties

- Occupation number >1 – Must be boson, *behaves as coherent field*
  - Field coupling to SM doesn't destabilize DM
- Can look for field coupling to matter or absorption of DM particles in detector



$$a(t) \; \square \; a_0 \cos(m_a t)$$



Detection Prospects

Search for classical background field with $\omega \sim m_{DM}/\hbar$

- Electromagnetic – DM drives a circuit
- QCD – oscillating nucleon EDM
- Fermion Spin precession in background field
- Scalar Couplings – 5th force, time-varying mass/charge

- Absorption especially useful for meV-to-keV, where high frequency complicates classical field detection

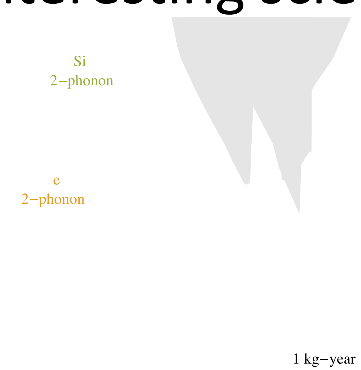
Experimental Directions

(in arbitrary order)

- New Avenues in Direct Detection
- Ultra-low mass (sub-eV) DM Detection
- DM Production at Fixed-Target and Collider Experiments
- New Candidates, Targets, and Complementarity

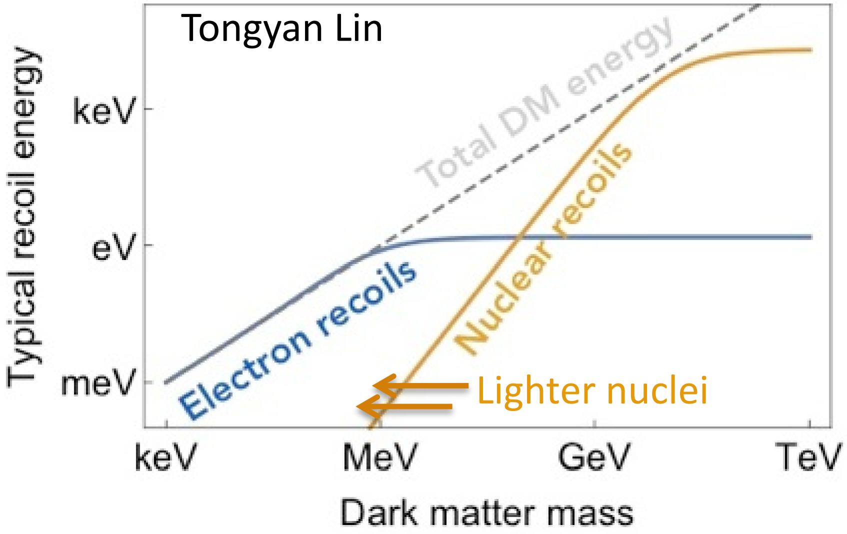
New Avenues in Direct Detection

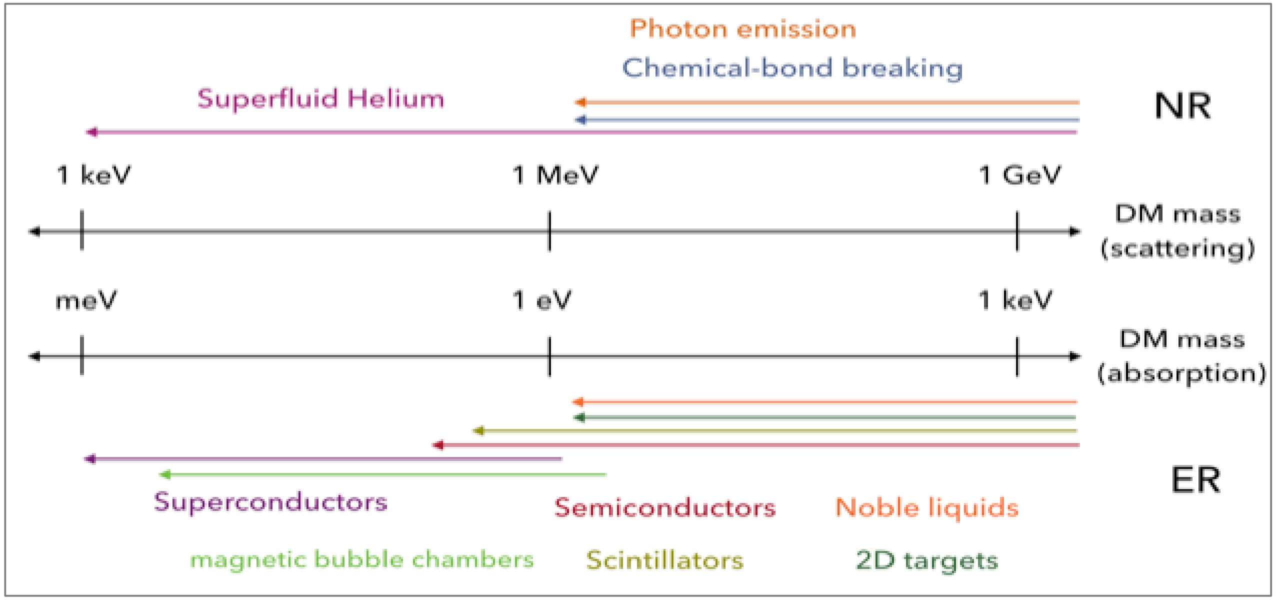
- Active, healthy community with several clear ideas to go beyond funded G2 experiments
- Small-scale projects *can* explore orders of magnitude beyond G2!
  - Spin-dependent WIMP-proton interactions
  - Searching for O(GeV) mass and lighter DM through both nuclear and electron interactions
    - Higher flux and cross-sections → interesting science even from gram-scale detectors
    - Same experiments also sensitive to absorption of meV-keV ultralight DM



Low-Mass Direct Detection

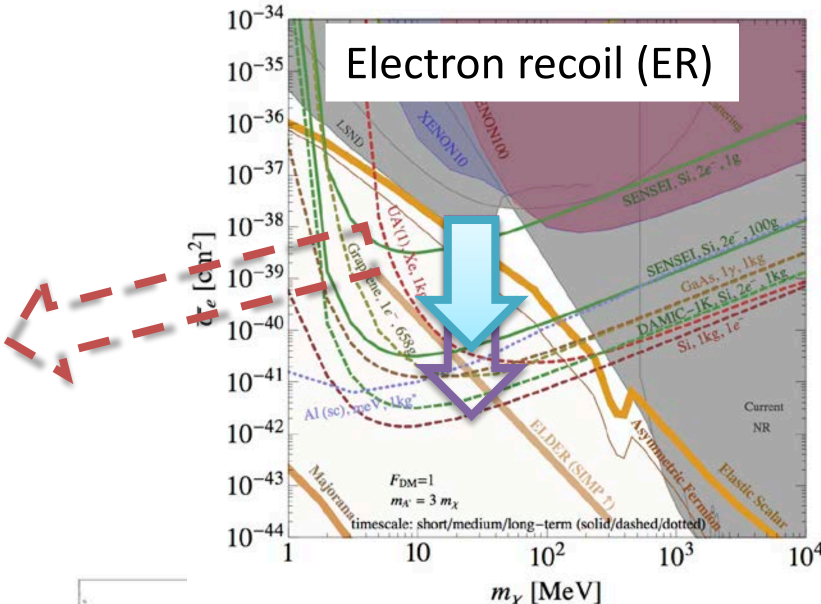
- Fundamental challenge: low-energy signal
- Calls for
  - Detecting DM scattering off electrons or low-mass nuclei
  - Exploiting low-threshold processes and new readout technologies





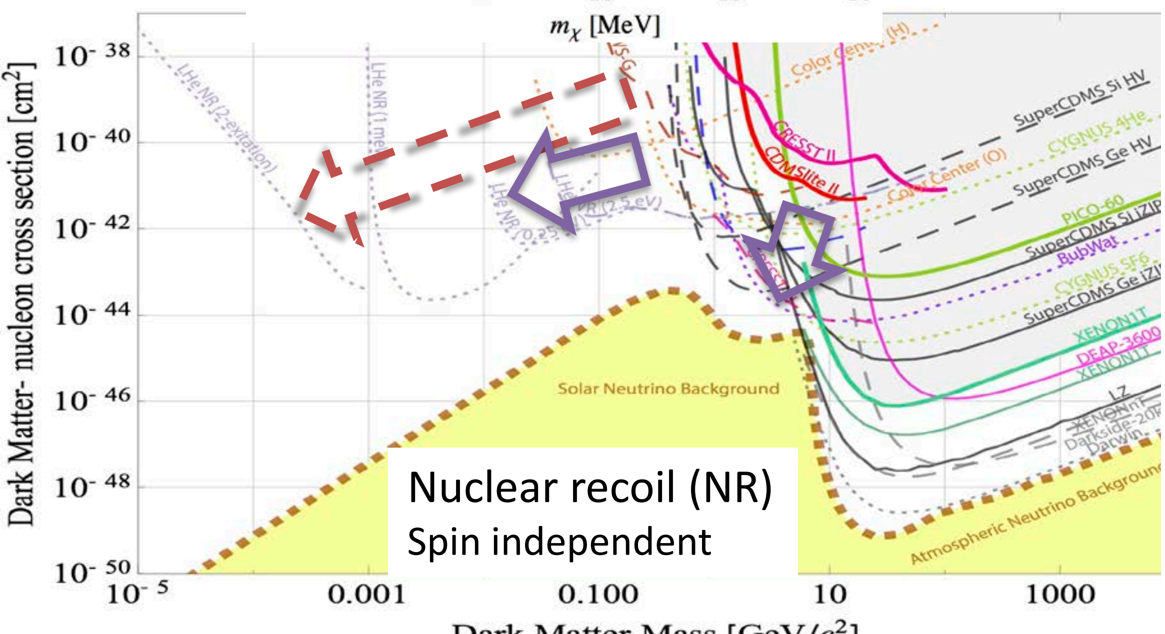
- Several projects ready now
- R&D needed to explore weaker coupling & lower masses

Experimental Prospects

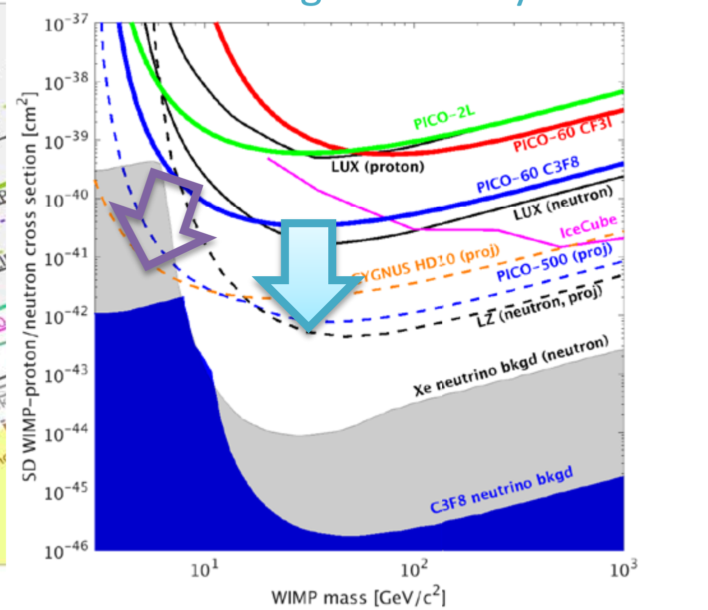


Explore hidden-sector targets:

- ER Projects ready now explore elastic scalar thermal relic, asymmetric, SIMP/ELDER, freeze-in (see slide 35)
- R&D needed to push to weaker couplings & MeV-mass NR
- Long-term R&D to reach keV masses



Opportunities to explore WIMP-*p* SD scattering also ready now



Ultra-Low Mass (sub-eV) DM Detection

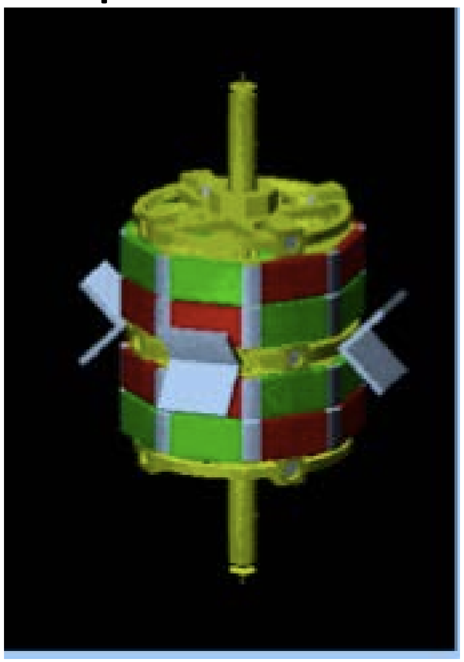
- Exploring DM masses from 10^{-22} to 1 eV

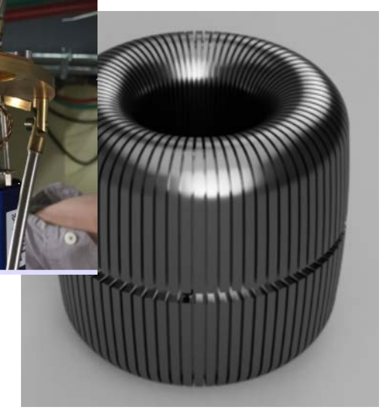
Sharp goal: explore full mass range for QCD axion dark matter

- Experiments look for collective effects of coherent DM field oscillating at $\omega \sim m_{DM}/\hbar$
  - Exploits high-precision sensor technology developed for other fields – technology development for DM search will impact these fields as well

Experimental Prospects

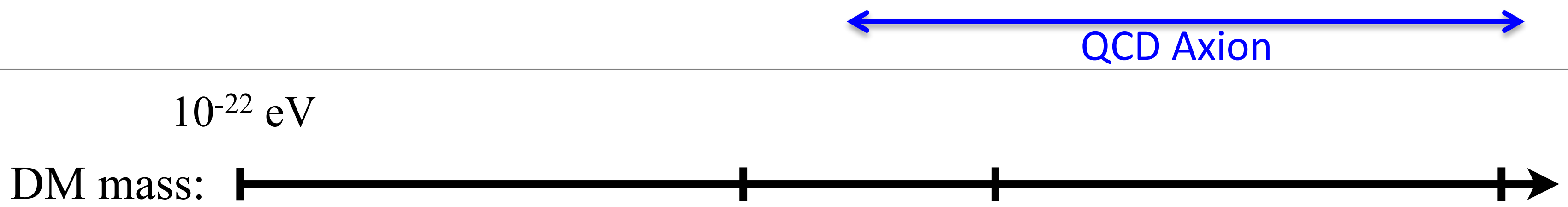
- Many projects currently building/operating pathfinder experiments or in advanced stages of hardware prototyping



- R&D funds useful now; project funding on several-year timescale will enable construction of <$10M full-sized detectors with significant reach into uncovered dark matter parameter space

Experimental Prospects



NMR

<u>Couplings</u>

DM Production at Fixed-Target and Collider Experiments

- Exploring hidden sector DM below O(GeV) mass

Sharp goal: reach thermal DM sensitivity in generic models

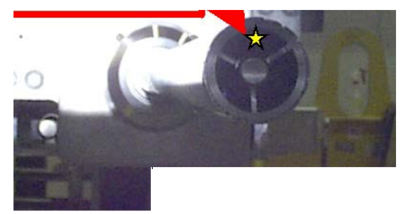
- Accelerators' ability to **produce** and **detect** new particles enables multi-faceted search for hidden sector DM and mediator
- New proposals make efficient use of US accelerator facilities (many outside HEP), existing detector technology, proven techniques

DM Production at Accelerators: Three Proven Techniques

- DM production
  - Missing mass
  - Missing energy/momentum

- Visibly decaying mediator production
  - Missing mass
  - Resonance
  - Displaced vertex

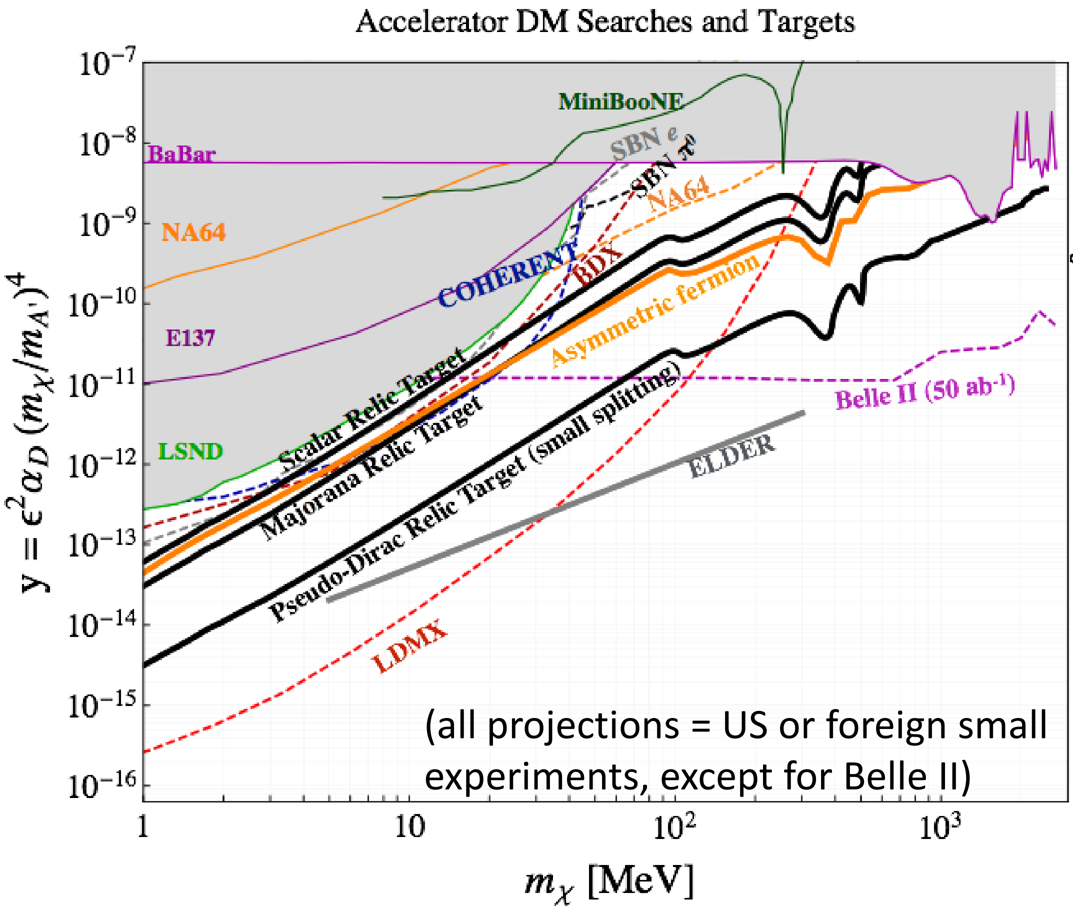
- DM production and scattering
  - *p* or *e* beam dump



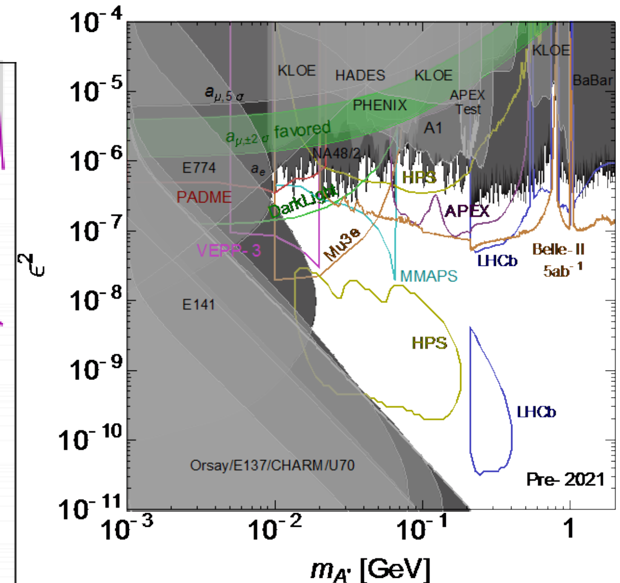
Already set powerful constraints on light dark matter, with clear path forward to reach key science targets

Experimental Prospects

Dark Matter searches – reaching thermal targets!



Mediator searches



Proton- and electron-beam experiments with thermal & asymmetric target sensitivity – ready to move forward now

New Candidates, Targets, and Complementarity

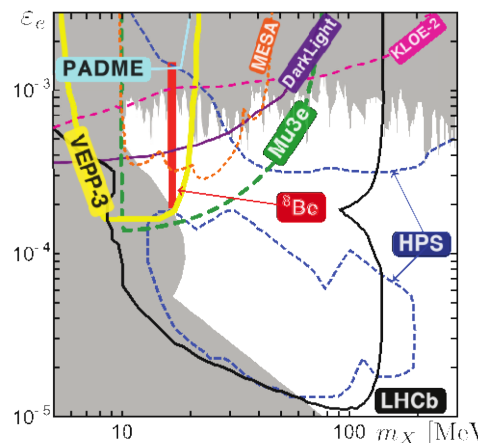
4th WG looked broadly at DM candidates motivated by anomalies in data or new theoretical ideas, and how to test them

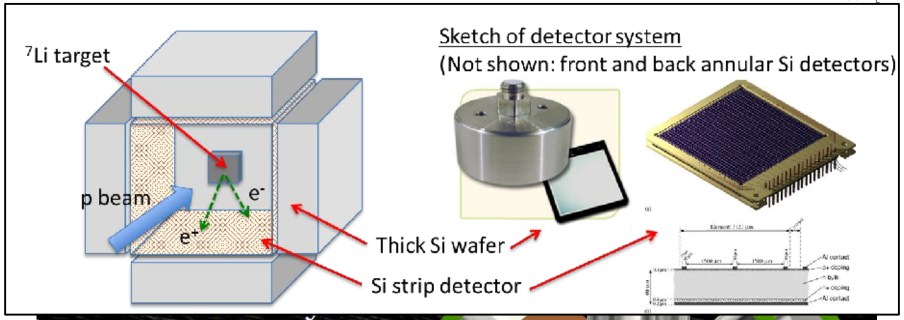
- ~30 $M_{\odot}$ black hole DM (motivated by LIGO events)
  - Motivates microlensing search with DECam and/or LSST
- Muon g-2, ^{8}Be, and new light force carriers
- Small-scale structure and DM self-interaction

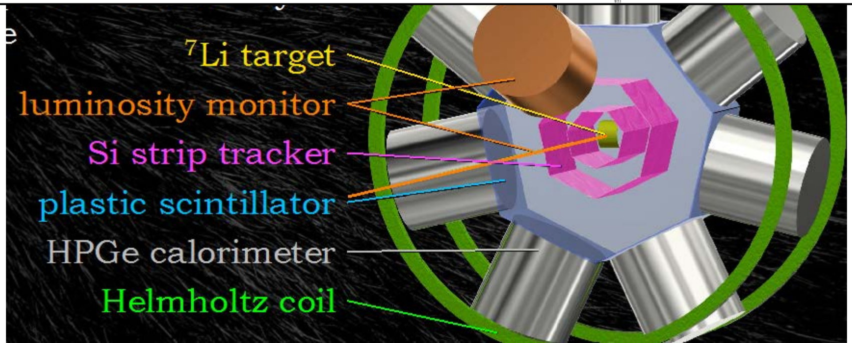
All suggestive of 1–100 MeV dark force

Testing Visible-Sector New-Force Anomalies

- Several particle interpretations of ATOMKI 17 MeV bump
  - protophobic vector
  - pseudo-scalar
  - axial-vector
  - Appears incompatible with nuclear physics effects
- Several ideas to confirm or refute this anomaly
  - Nuclear-decay experiments with superior mass resolution and statistics
  - Isotope shift spectroscopy
  - 1-2 year timescale, cost a fraction of the small projects threshold

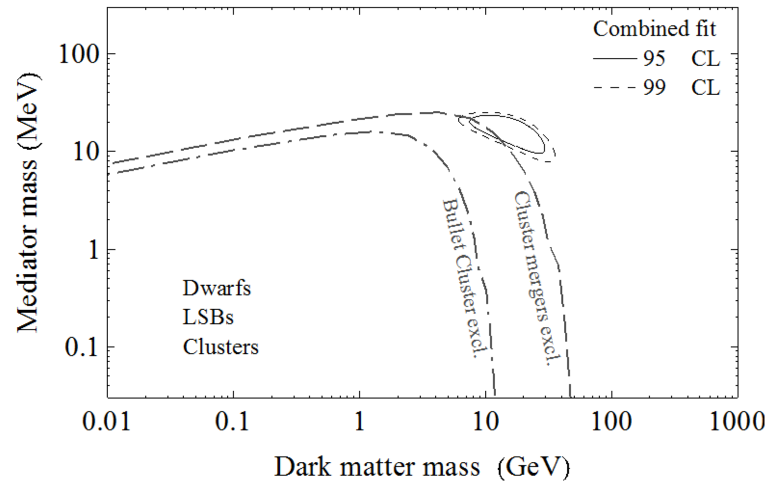






New-Force Anomalies: Dark Sector

- Outstanding problems in structure formation at small length scales: core-cusp problem, missing satellites problem, and too-big-to-fail problem



- Dark matter with significant self-interactions has been argued to retain successes of CDM on large scales, while economically solving small-scale puzzles

- Opportunities
  - Leverage DES and LSST to measure halo mass function on smaller scales
  - Theory and simulation key to interpreting these data

Importance of Theory

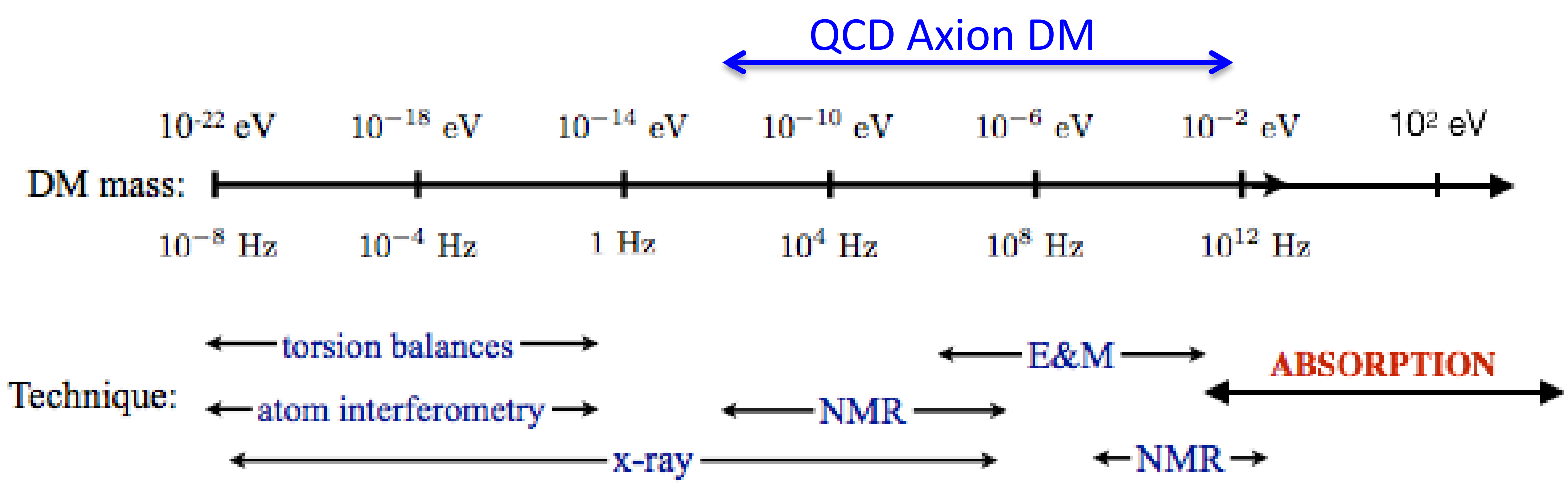
- Progress in theory has been a driving force behind many of these recent developments
  - New ideas for small-scale experiments
  - Innovative connections to other subfields
  - Cosmological and astrophysical simulation
- Investment in theory is essential to continued progress

Comprehensive Exploration of Ultralight and Hidden-Sector DM

The Case for a Program of Complementary Experiments

Ultralight Dark Matter

- More than one experiment needed to cover full mass range – each technique has natural frequency range

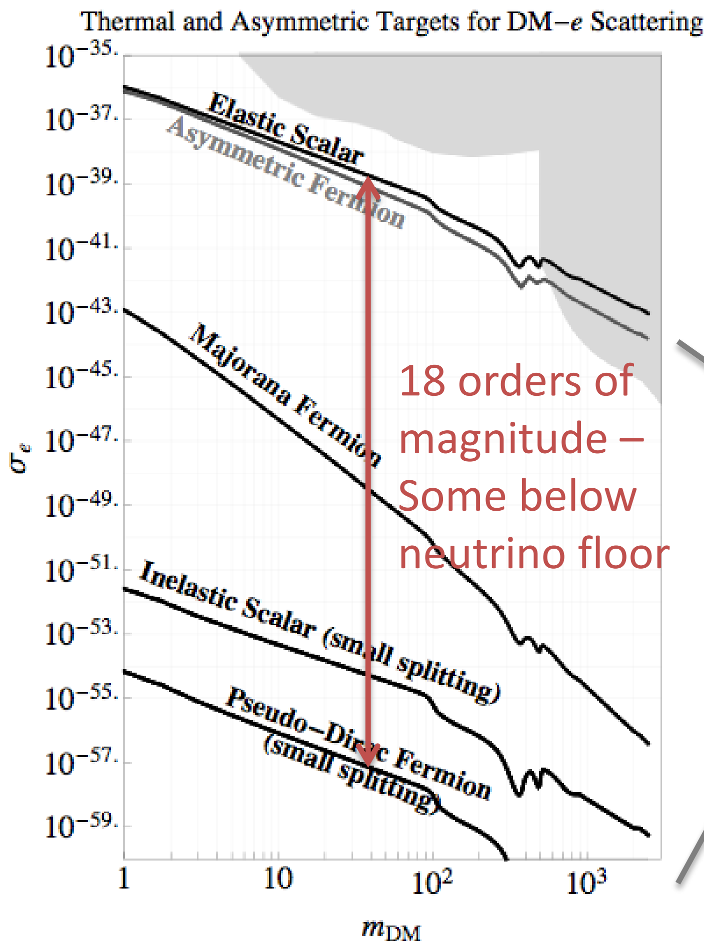


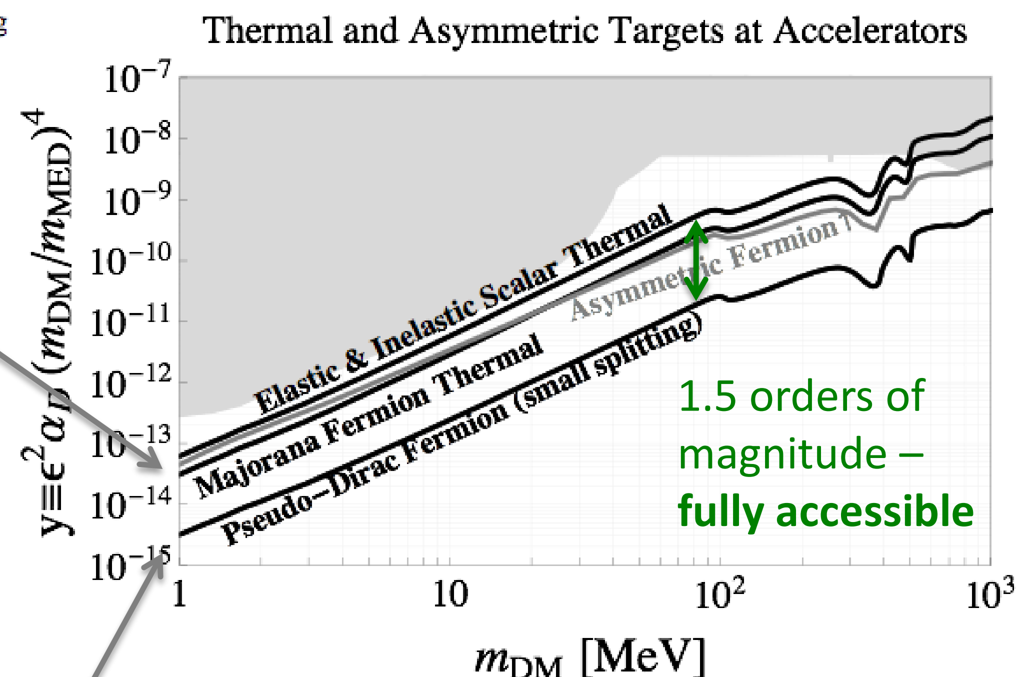
Hidden Sectors

- Complementary experiments with overlapping mass sensitivity explore different targets and provide different information
  - Relativistic and non-relativistic probes of DM have fundamentally different strengths
  - Experiments searching for new interactions within dark and visible sectors are equally important probes

Hidden Sectors: The Need for a Relativistic Probe

High-value targets accessible at accelerators ($v \sim c$) but invisible to direct detection ($v \sim 10^{-3}\,c$)

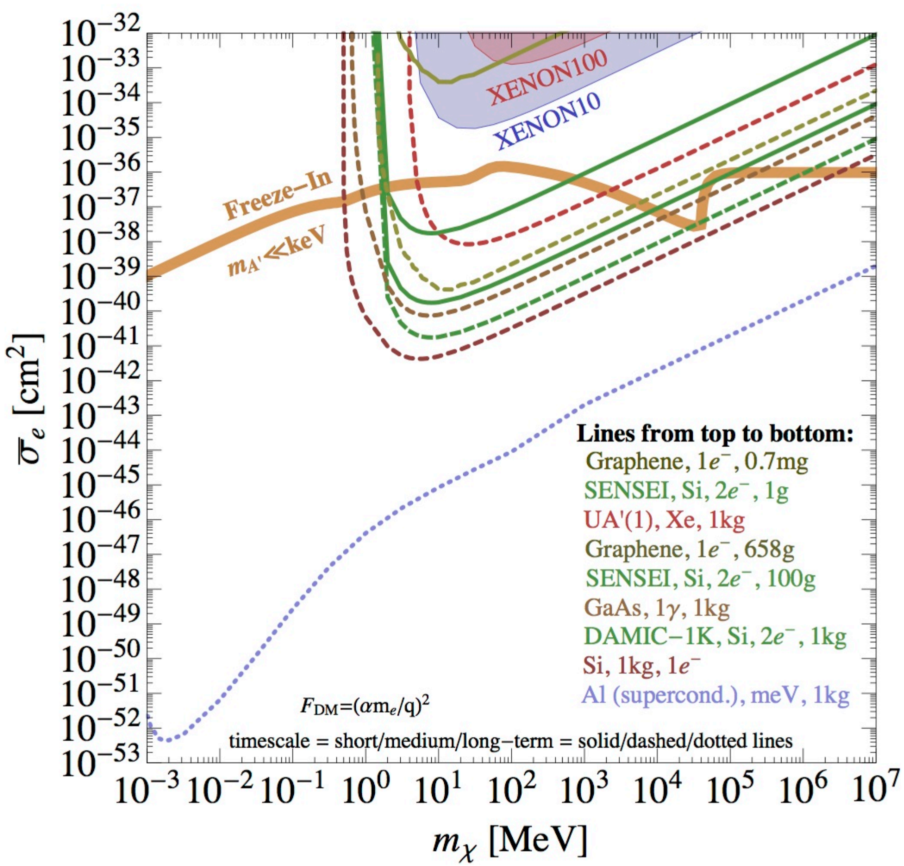




Accelerators are robust to details of DM mass structure

Hidden Sectors: The Need for a Non-Relativistic Probe

High-value targets accessible to direct detection (*v~10^{-3} c*) but invisible to accelerators (*v~c*)

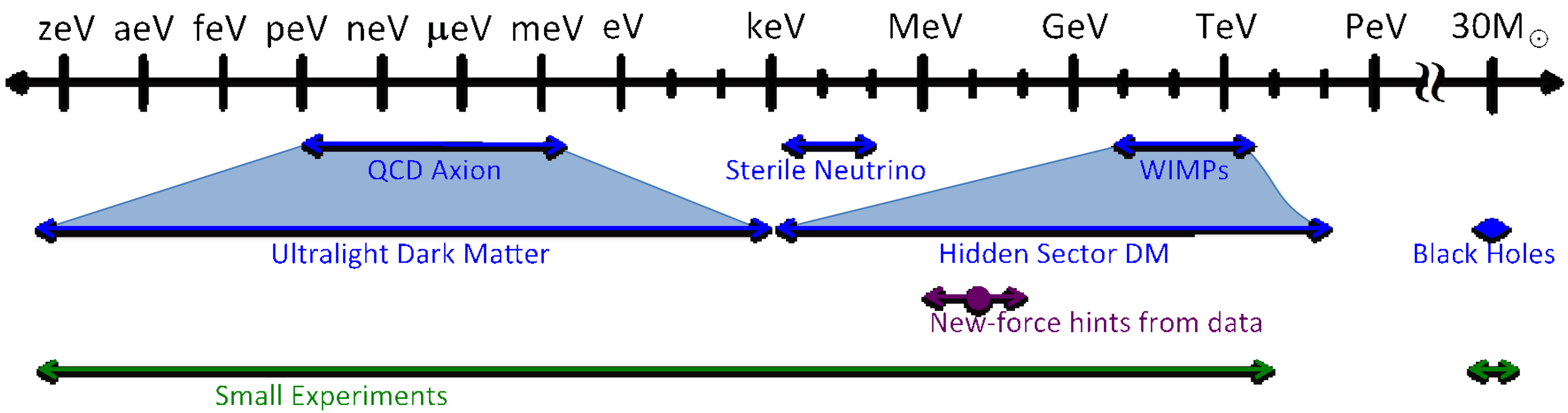


If $m_{mediator} << m_{DM}$, kinematic enhancement by up to 12 orders of magnitude gives direct detection access to very small DM-matter couplings – exemplified by freeze-in scenario

Different Techniques Provide Crucial Lessons

- Discovery in direct detection implies that a given particle constitutes all or part of the DM, but cannot disentangle the particle's couplings from its abundance
- Accelerator-based experiments provide clear probe(s) of particle properties & interactions, but not stability on cosmological timescales
- The new force at the heart of hidden sector DM may be most readily explored, not through DM-SM interactions, but through the new physics it induces within the DM or visible sector – anomalies in both sectors can be tested with small experiments!

Summary of Opportunities



Ultra-low mass (sub-eV) DM:

- Key priority: QCD Axion
- Pathfinder/R&D now
- Projects in several years

New candidates, targets, complementarity:

- Small investments ready now in several areas – e.g. black hole, small-scale structure, and nuclear anomaly searches

DM Production at Accelerators:

- Key priority: Hidden sector thermal & asymmetric targets (<GeV)
- Ready now

New Avenues in Direct detection:

- Diverse goals
- Projects ready now – hidden-sector(>MeV) & WIMP SD
- R&D efforts – keV-mass threshold & other capabilities

Conclusion

- Strong motivation to broadly explore priority targets of WIMP, hidden-sector and ultralight DM parameter space
- Innovative, low-cost ideas for small experiments (some mature, others requiring significant R&D) with significant discovery opportunity
- Need a program of complementary experiments to comprehensively explore priority science targets
- Doing so will leave legacy of profound discovery or robust, lasting knowledge about DM

Small projects portfolio is a key part of the future of DM science!