# New Ideas in Dark Matter 2017

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## 1 Introduction

Five directions for small experiments:

1. Low threshold direct detection: ultralight mediator, both DM-electron and DM-nuclear scattering experiments.

2. Light new-force carriers: QCD axions.

3. Accelerator experiment: beam dump, missing mass/energy, and visible mediator search.

4. Nuclear and atomic spectroscopy: micro-lensing probes of solar mass black hole dark matter.

5. Progress in theory: dark matter in nuclear, atomic, and condensed matter physics.

Ideas for dark matter: WIMPs, gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter.

Outline:
**Section IV**- New Avenues in Direct Detection
**Section V**- Detection of Ultra-Light (sub-eV) Dark Matter
**Section VI**- Dark Matter Production at Fixed Target, Collider Experiments
**Section VII**- New Candidates, Targets, and Complementarity

# 2 Science case for a program of small experiments

## 2.1 Broad Frameworks for DM Motivating Small Experiments

Two classes for small scale experiments

1. **Hidden-sector DM**: sub-GeV or lighter DM and/or mediator; thermal freeze-out DM, thermal DM with "secluded" annihilation, asymmetric DM, and very weakly coupled DM that "freezes in" without reaching equilibrium.

2. **Ultralight DM**: bosonic particles with sub-keV mass (QCD axion and generic light scalar, pseudo-scalar, and vector bosons coupled linearly to familiar matter)

## 2.2 The need for a Multi-Experiment Program

1. **Ultralight DM**: QCD axion from $10^{-12} - 10^{-2}$ eV

    - Related: measurement of axion mass constrain the energy scale of cosmic inflation; interplay between QCD axions and the electroweak hierarchy problem.
    - Searches: coherent field induced by axion DM.
    - Techniques: cavity resonators (ADMX G2) at high frequencies, lumped element resonators at medium frequencies, and nuclear magnetic resonance.

2. **Hidden-Sector DM**: keV to several GeV
    Difference in sensitivity of experiments:

    (a) Relativistic (accelerator) and non-relativistic(direct detection) probes of DM interactions.

    (b) Probe DM-DM and SM-SM (in addition to DM-SM) interactions: $1 - 100$ MeV the high-value target region for DM

    - DM self-interactions suggested as explanation of puzzles in small-scale cosmological structure.
    - $^{8}$Be anomaly, possible signal of new force interacting with nuclei and electrons- motivates followup nuclear experiments, isotope shift spectroscopy experiments and accelerator searches for new bosons with $\sim 10$ MeV masses.

(c) Experimental signals' dependence on the nature of mediator interactions with familiar matter:

3. **Further motivations and Opportunities**: Multi-solar-mass primordial black hole DM

   - LIGO observation of gravitational waves from colliding black holes motivates microlensing search (Sec. VII).
   - Can confirm/exclude possibility of intermediate mass black hole dark matter.
   - Across subdisciplines: astrophysics, cosmology, and nuclear, atomic, and condensed matter physics.

# 3 Theory Overview and Motivations

## 3.1 WIMPs

- Multi-GeV to TeV-scale WIMP masses: natural mass scales for particle in solving the hierarchy problem, or for a particle whose mass shares a common origin with the Standard Model Higgs.
- Much higher than a TeV or lower than several GeV (the Lee-Weinberg bound): small DM annihilation cross-sections, overabundance of thermal DM.

## 3.2 Hidden Sector DM

- Absence of sizable DM interactions with ordinary matter motivates: DM neutral under SM, but perhaps (?) charged under new forces.
- Arises in Hidden Valleys, and top-down string constructions, can live alongside TeV-scale Standard Model extensions, including supersymmetry and composite Higgs sectors.
- Motivation for interaction with SM:
  - "Portal" interaction
  - Realize DM abundance
- Lighter than the weak scale
- Low-mass region opens the possibility of cosmologically significant DM self-interactions, and enables new mechanisms for quasi-thermal DM production.

### 3.2.1 Benchmark Models of Hidden-Sector DM

(a) Mediators and their SM couplings
New force mediated by a vector or scalar boson, characterization of these interactions:

$$\mathcal{L}_V \supset V_\mu \bar{f}\left(g_f^V \gamma^\mu + a_f^V \gamma^\mu \gamma^5\right) f$$
$$\mathcal{L}_S \supset \bar{f}\left(g_f^S + \gamma_5 a_f^S\right) f\phi$$

for (axial) vector mediator $V_u$ or (pseudo)-scalar mediator $\phi$. Two important cases, "horizontal ports", the renormalization interactions of a standard model neutral boson compatible with all SM symmetries:

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} & \text{vector portal} \quad \Rightarrow \quad g_f^V \approx \epsilon e q_f \\ (\mu\phi + \lambda\phi^2)\, H^\dagger H & \text{Higgs portal} \quad \Rightarrow \quad g_f^S = \mu m_f / m_h^2 \end{cases}$$

where $B_{\mu\nu}, F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ are the hypercharge and dark $U(1)_D$ vector boson field strengths, $eq_f$ the electric charge of SM particle, $H$ the Higgs doublet, $m_f$ the mass of fundamental fermion $f$, and $m_h$ the SM Higgs mass.

Status of model-independent constraints on portal couplings:

- Vector portal: constrained by muon and electron magnetic dipole moments for sub-GeV mediators, and by precision electroweak physics for heavier mediators.
- Higgs portal: con- straints on these models from heavy meson decays.
- Coupling to SM global symmetry (like baryon or lepton number): limits on $e - \nu$ scattering and low-energy neutron scattering data, set constraints on new bosons coupled to lepton and baryon number, respectively.

(b) Coupling to the Dark Sector: a vector portal case study Focusing on vector mediators, consider dark sector matter with mass structure:

$$-\mathcal{L} \supset m_D \eta\xi + \frac{m_\eta}{2}\eta\eta + \frac{m_\xi}{2}\xi\xi + \text{h.c.(fermion)}$$
$$-\mathcal{L} \supset \mu^2 \varphi^* \varphi + \frac{1}{2}\rho^2 \varphi\varphi + \text{h.c.(scalar)}$$

where $\eta$ and $\xi$ are Weyl fermions with $U(1)_D$ charge $\pm g_D$ and $\varphi$ a complex scalar with $U(1)_D$ charge $g_D$. $m_D$ and $\mu$ are $U(1)_D$ -preserving mass terms and $m_\eta, m_\xi$, and $\rho$ are $U(1)_D$ breaking mass terms.

- Accelerator experiments suitable for: models with significant $U(1)_D$-breaking masses.
- Direct detection suitable for: models with small $U(1)_D$-breaking so that $m_{A'} \ll m_{DM}$ (higher cross DD cross section due to low momentum transfer).

### 3.2.2 Thermal Relic Targets

If DM sufficiently couples to SM as to reach thermal equilibrium $\rightarrow$ exists interaction that depletes its abundance.
DM coupled to a dark vector/scalar mediator can annihilate in two ways:

1. $m_\chi > m_{MED}$: "Secluded" annihilation into scalar mediators

2. $m_\chi < m_{A'}$: "Direct" annihilation into Standard Model fermions: s-channel mediator with cross section scaling

$$\langle \sigma v \rangle \sim \frac{g_D^2 g_{\rm SM}^2 m_\chi^2}{m_{\rm MED}^4}$$

   the dark coupling $g_D$ and mass ratio $m_\chi/m_{A'}$ are at most $O(1)$, so minimum SM-mediator coupling $g_{SM}$.

Important constraint on low-mass thermal DM: effect of late-time DM annihilation on the CMB power spectrum, so Planck data constrains the power injected by DM annihilation at $\sim eV$ temperatures. This constraint rules out secluded annihilation into vectors and direct annihilation of Dirac fermions through the vector portal.

Many DM models experience suppressed annihilation at low temperatures due to (one of):

- Velocity-suppression: e.g.p-wave annihilation processes
- Population suppression: leading annihilation process involves an excited state that decays between freeze-out and recombination eras.
- Particle-anti-particle asymmetry: annihilation in the early universe is sufficiently effective to cosmologically deplete the anti-particle.

### 3.2.3 Targets from quasi-thermal DM production

- **Asymmetric DM (ADM)**- DM relic abundance set by primordial asymmetry $\Rightarrow$ motivates DM masses of several GeV, or could be much lighter than proton.
- DM particles $\chi$ with masses near QCD confinement scale $\lambda_{QCD} \sim 100MeV$- could arise as mesons or baryons of a hidden- sector "mirror copy" of QCD.

  - Related to “Strongly Interacting Massive Particle” (SIMP) and ”Elastically Decoupling Relic” (ELDER) models.
  - Allowed mass range for SIMP or ELDER DM: 5 MeV (lower bound arising from CMB measurements) to 200MeV (upper bound from unitarity of $\chi$ self-scattering.

#### 3.2.4 Light mediators and Freeze-in

- If DM is very weakly coupled to SM and never thermalize $\rightarrow$ its abundance can “freeze in”.
- This mechanism was first noted in the contexts of gravitino, sneutrino, and sterile neutrino DM.
- DM production/annihilation cross-section orders of magnitude below thermal freeze-out level.

#### 3.2.5 Further Opportunities in hidden-sector physics

- New forces $\rightarrow$ consequences for physics of familiar matter and DM, motivating searches for
  - New bosons with weak coupling to the Standard Model
  - Effects of dark matter self-interactions on cosmological structure formation.

  Existence of light bosons with weak couplings to SM:

  1. Anomalous magnetic moment of the muon, $(g-2)_\mu$, with $\sim 4\sigma$ discrepancy. Leading explanation: a light weakly coupled boson with mass of order $10-100$ MeV and coupling to the muon around $10^{-3}$.
  2. Radius of the proton: measured by the 2S - 2P transition frequency in muonic hydrogen discrepant from e-p scattering. Explanation: a $\sim$ 10 MeV mass spin 1 boson with muon- specific couplings around $10^{-3}$.
  3. Rate of $\pi^0 \rightarrow e^+e^-$ measured by KTeV shows a $2-3\sigma$ deviation compared to Standard Model expectations.

4. Excess in transition of 18.15 MeV excited state of Beryllium-8 to its $0^+$ ground state, consistent with intermediate boson of mass $\sim$16.5 MeV and couplings of order $10^{-4} - 10{-}3$.

- Self-interacting DM is a solution to tension between simulation of galaxy formation and observations at smaller scale structures.
  - Fits suggest DM mass $10 - 100$ GeV, with dark force carrier of $10 - 20$ MeV.

## 3.3 Ultralight Dark Matter

The size of dwarf galaxies constrains the nature of sub-keV dark matter to be bosonic. Smallness of the boson mass suggests a connection to UV physics.

### 3.3.1 The QCD Axion

1. Multiple relevance:
   - Strong CP problem: explaining the puzzle of the vanishing neutron electric dipole moment.
   - Some DM production through vacuum relaxation, provide information on the scale of inflation.
   - Axions and axion-like particles generic in many UV theories.
   - May be related to the electroweak hierarchy problem.
2. QCD axion model described by a high mass scale $f_a > 10^9$ GeV, at which a postulated new global U(1) "Peccei-Quinn" symmetry is broken.
3. QCD axion mass range: $10^{-12}eV$ (lower bound arises from requiring $f_a$ not exceed the Planck scale) to $10^{-12}eV$ (upper bound arises from the neutrino pulse observed from SN1987A having a duration consistent with supernova cooling primarily via neutrino emission, thus placing a bound on the axion-nucleon coupling).
4. Models of cosmic inflation: dark matter production from vacuum relaxation, and from topological defect decay.

- If low mass axion with $m_a < 10 - 50\mu eV$ is discovered $\Rightarrow$ pre-inflationary axion scenario.
- if CMB B-modes discovered $\Rightarrow$ higher masses and post-inflationary axion scenario.

### 3.3.2 General phenomenology of sub-meV mass bosonic dark matter (including axions)

$10^{-22}$ eV to 1 keV.
Direct detection rely on Coupling coherently oscillating DM field to SM particles via:

- Electromagnetism: allows dark matter to transfer energy into electromagnetic fields to be detected via photon, voltage, or flux sensors
- QCD: gives a time-oscillating electric dipole moment (EDM) for nucleons which can be detected via nuclear magnetic resonance (NMR) techniques.
- Spins of fermions: cause the spins of electrons or nucleons to precess which can be detected via NMR or electron spin resonance.
- Scalar Couplings: give a force directly on SM particles, or can affect fundamental constants such as SM particle masses or charges.

### 3.3.3 Bosonic DM from meV-keV

Same experiments that are capable of searching for $keV - GeV$ mass DM via scattering.

# 4 New Candidates, Targets, and Complementarity (Sec. VII)

## 4.1 Experimental Anomalies and Hints

### 4.1.1 Anomalous Magnetic Moment of Muon

- $3.5\sigma$ discrepancy between experiment and theory in $(g-2)_\mu$.
- Interpretation: weakly-interacting particles with milli-charged couplings to muons and 1 to 100 MeV masses.
- Solution: light bosons with certain properties.

### 4.1.2 Proton Radius

1. – $5.6\sigma$ discrepancy between proton electric charge radius $r_E^p = 0.8751(61)$ measured from a combination of electron scattering and hydrogen spectroscopy (electron based), and $r_E^p = 0.8487(26)$ measured from muonic hydrogen spectroscopy (muon based).
2. Interpretation
   (a) Revision of the fundamental constants $r_E^p$ and Rydberg constant. Reexamination of lepton-nucleon scattering methodology. OR
   (b) New particles physics: physics beyon SM
      - Discrepancy between electron-based and muon-based measurements show $r_{\mu\mathrm{H}} < r_{e\mathrm{H}} \sim r_{e-p}$.
        Revision by 2S-4P splitting show discrepancy between bound state and electron-proton scattering determinations of the radius: $r_{e\mathrm{H}} \sim r_{\mu\mathrm{H}} < r_{e-p}$
      - Would be predicted by an attractive Yukawa force mediated by a force carrier with a mass between the atomic Bohr momentum ($\sim m_\mu \alpha$) and momentum transfers probed in scattering experiments – $\sim 50MeV$.
      - Solution include: dark photon model, with preferred parameter region $\kappa/m_{A'} \sim \Delta r/\sqrt{6} \sim 10^{-4}\mathrm{MeV}^{-1}$, where $\kappa$- kinetic mixing parameter.

#### 4.1.3 $^8Be$ Anomaly

1. – $6.8\sigma$ discrepancy reported by the ATOMKI group in their observations of the decays of excited $^8Be$ nuclei to their ground state, and an electron- positron pair $^8\text{Be}^* \to {}^8\text{Be}e^+e^-$.
   – In the distribution of $e^+e^-$ opening angles, appears dump-shaped excess above the SM internal pair creation background.
   – Interpretation: new boson X- a cascade decay of $^8\text{Be}^* \to {}^8\text{Be}X$, followed by $X \to e^+e^-$.
   – Solution: $\chi^2/\text{dof} = 1.07$ for milli-charged couplings and $m_X \approx$ 17MeV. Require real particle production of light, weakly coupled particles X.

2. Interpretation

   (a) New Particle Physics: several spin-parity assignments for X candidates.

   - Scalars forbidden by conservation of parity in nuclear decays, but pseudoscalars possible. Spin-1 bosons constrained hy null results from searches for $\pi^0 \to \gamma X$, but would work for particles that decouple from the decay. E.g. protophobic gauge bosons and axial vectors.
   - Protophobic vector candidate: milli-charged couplings to neutrons and electrons, suppressd couplings to protons.
     – Arises as the force carrier of a spontaneously broken $\text{U}(1)_B$ or $\text{U}(1)_{B-L}$ symmetry that kinetically mixes with a photon.
     – The predicted leptonic couplings can simultaneously ameliorate the discrepancy in $(g-2)_\mu$.
     – Could be tested by looking for similar decays in other nuclei, or testing the required electron couplings at $e^\pm$ beam based experiments.
   - Light gauge boson that predominantly couples axially to quarks: nuclear decay experiments.
   - Both highlights importance of experiments of leptonic and quark couplings of light hidden particles.

(b) Nuclear experiments

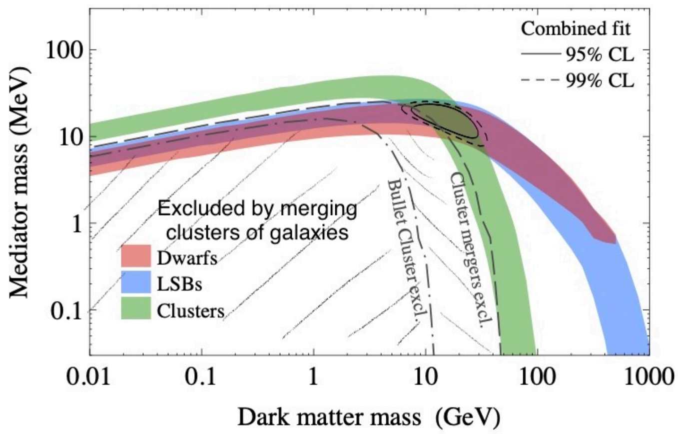
   - Advantage can be taken of X's long lifetime $\sim 10^{-13}$ sec.

## 4.2 Cosmology and Astrophysics

Complementarity of astrophysics and cosmological probes with three topics: small scale structure, cosmic microwave background, and supernovae.

### 4.2.1 Small Scale Structure

- Microphysical properties of dark matter also determines its cosmological clustering.
- Thermal DM: relative heaviness and electroweak-scale couplings with SM particles lead to non-relativistic freeze-out ("cold") with only minimal kinetic coupling to the SM.
  - Thermal DM/CDM paradigm makes striking prediction: the existence of a hierarchy of dense dark matter halos down to free-streaming and kinetic decoupling ($\sim$ Earth mass) scales $\rightarrow$ hierarchical structure formation (excellent description of distribution and properties of galaxies on large scales).
  - Unexplained puzzles on scales much smaller than the virial radius of galaxies. E.g. core-cusp problem, the missing satellites problem, and the too-big-to-fail problem.
  - Dark matter with self-interactions is a solution to the small-scale puzzles! Required ratio of scattering cross section to mass is comparable to the strength for neutron-proton scattering.
  - Simple model with DM interactions mediated by a single particle, the favored mediator mass is $\sim 1 - 100$ MeV.
  - Lensing searches to measure halo mass functions on small scales.




### 4.2.2 Cosmic Microwave Background

- Measurement of CMB can be used to set model-independent constraints on annihilating or decaying dark matter.
- Constraints arise from the production of extra free electrons (during cosmic dark ages) by the cooling of electromagnetically interacting particles produced by dark matter annihilation/decay.
- Bounds are particularly competitive for light DM with sub-GeV masses.

### 4.2.3 Supernovae

- Supernova 1987A- an environment of extremely high temperatures and nucleon densities during the core collapse supernova of a massive star.
- Rough agreement between predictions of core collapse models and observations of "neutrino burst" provide opportunity to set bounds on wide range of physics models.
  - Bounds on a dark sector model involving a dark photon. Exact calculation of the lifetime of dark photons below twice the electron mass (involve corrections to the Euler-Heisenberg Lagrangian).
  - Updates to finite-temperature effects on production and trapping of new particles.
  - Investigation of the impact of invisible decays (e.g. dark photon) on core collapse explosion.

## 4.3 Models and Relic Abundance

If dark matter is confined to have SM interactions, weak force is the only viable possibility, and TeV-scale particles are favored by relic density considerations (coincidence of WIMP miracle).
Once dark sectors considered, other mass scales may be preferred. For example, dark matter can be lighter and more weakly interacting and still have the correct relic density (WIMPless miracle). New particle candidates and masses favored by relic abundances:

1. Non-Abelian Dark Sectors and Strongly Interacting Dark Matter
   - Dark sectors with DM charged under non-Abelian SU(N) gauge group $\Rightarrow$ strongly interacting DM. (Note: dark sector with Abelian symmetries $\Rightarrow$ dark photons).
   - Hidden gluons (form into hidden glueballs below the confinement scale). $3 \rightarrow 2$ scattering processes keep hidden glueballs in kinetic equilibrium and deplete their number density (”cannibalization” mechanism).
   - Post-confinement, the self-interaction of hidden glueballinos can address small-scale structure anomalies.
2. SIMPs (strongly interacting massive particles) and ELDERs (elastically decoupling relic)
   - QCD confinement scale, $\lambda_{QCD} \sim 100$ MeV
   - Cannibalization processes lead to a thermal relic abundance consistent with observations.
   - Elastic scattering between SIMP/ELDER and SM can be mediated by a dark photon.
   - The ELDER scenario makes prediction for the cross section of elastic scattering between $\chi$ and electrons (this process sets the $\chi$ relic density).
3. Non-Abelian Dark Sectors at Fixed Target Experiments
   - Number of ways to realize DM matter scenario where DM is kept in kinetic equilibrium with the SM through a dark photon $A'$ but freezes out through cannibalization process. e.e. dark sectors of stable pions.

- Sensitive experiments: HPS, LDMX, SeaQuest and SHiP.

4. Co-annihilating Light Dark Matter

   - Representative of co-annihilating thermal relics: $\chi_1\chi_2 \to SM$, where $\chi_1$ the stable dark matter candidate and $\chi_2$ a heavier unstable dark sector state. After freeze-out $\chi_2$ is depleted and annihilation shuts off.
   - Hard to detect at direct detection, could only be tested with accelerator probes.
   - For few GeV to TeV, powerful probes involve $\chi_2 \to \chi_1 + SM$. For MeV to a few GeV, powerful probes involve $\chi_i N \to \chi_j N$ or $\chi_2 \to \chi_1 + SM$.

5. Sexaquark Dark Matter

6. Dynamical Dark Matter

   - The requirement of dark matter stability is replaced by a balancing of DM lifetimes against DM abundances across a large ensemble dark matter species with a broad spectrum of masses, lifetimes, and abundances.
   - DM candidate: the entire Dynamical Dark Matter ensemble.
   - Probe methods: At collider experiments, the distributions of relevant kinematic variables can be significantly modified (changes for standard experimental candels such as "mass edge").

## 4.4 Complementarity

New experiments and a few "exotic" dark matter candidates where novel experimental searches have been proposed.

1. Mixed WIMP/Axion Dark Matter

   - Models with both supersymmetry (yield neutralino WIMP) and Peccei-Quinn symmetry (yield axion DM) that simultaneously solve the gauge hierarchy and strong CP problems.

2. Future Argon Direct Detection Experiments- search for "conventional" DM (e.g. WIMPs) using more precise techniques.

3. Future Two-phase Xenon Experiments (Xenon, LUX, PandaX, LZ)

4. Cherenkov Telescope Array

   - Measurements of the cosmic-ray electron spectrum to several 10's of TeV or higher, depending on whether local sources or more exotic production mechanisms .

5. MeV Gamma-Ray Detectors

   - MeV "excesses" identified in the MeV diffuse extragalactic gamma-ray background and the Galactic MeV emission, compared to expected astrophysical background. Excess could be associated with DM decay.
   - DM in MEV mass range can generically produce detectable MeV gamma-ray signals compatible with constraints from BBN and CMB.

6. ATLAS and CMS Searches- provides stringent limits on dark matter production via spin-0 and spin-1 mediators.

7. LHCb Searches

   - Rare meson decays, where many light dark sector candidates are expected to be produced (e.g. dark photon)

8. Light Dark Matter at Neutrino Facilities

   - Probe light dark matter-nucleon coupling.
   - If DM interacts with quarks via a light mediator, a dark matter beam is produced along with the neutrino beam, DM particles then enter the near detector and scatter with nucleons inside. Challenge: suppression of neutrino background.
   - MiniBooNE (MB) collaboration

9. Trapped Atom Search for Sterile Neutrino Dark Matter

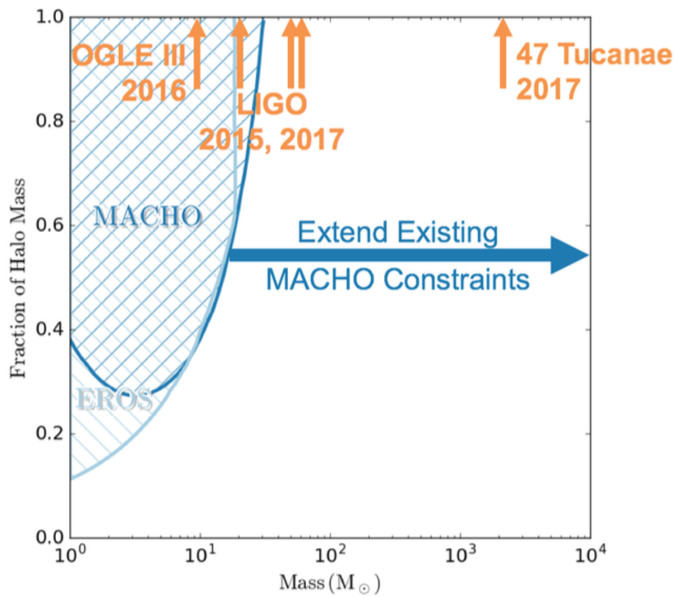
- HUNTER experiment: medical isotope, laser atom traps, MOTRIMS spectroscopic method.

10. Mirror Neutron Searches

    - Search for neutrino oscillations into a hidden dark sector.
    - Neutron oscillations are predicted by theories that postulate a parallel sector with identical particles and interactions as in the SM, such as mirror matter (also resolves parity violation of the weak force).
    - Big Bang nucleosynthesis and cosmological limits imply mirror matter should be colder than ordinary matter $\rightarrow$ helium-dominated with faster cosmological evolution.
    - Mirror matter could explain baryogenesis.
    - Ultracold neutron storage measurements place limits on the oscillation time: $\tau < 448s$ assuming no mirror magnetic field B', and $\tau < 10s$ when nonzero B' is considered.
    - A disappearance-regeneration "beam-dump" type experiment has been proposed.
    - High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, or National Institute of Standards and Technology Center for Neutron Re- search (NIST NCNR).

11. Microlensing Searches for Black Hole Dark Matter

    - LIGO's discovery of $30M_{\odot}$ black holes- possibility DM consists of MACHOs.
    - MAHCHO search from 1990's constrained MACHO mass below $15M_{\odot}$, and CMB and widec-binary constrained MACHO mass below $2M_{\odot}$ (recent studies show the astrophysical assumptions that the CMB and wide-binary constraints relied on were incorrect).




## 4.5 New Candidates, Targets, and Complementarity–Summary

- Investment in Theory

- Nuclear and Accelerator Tests of the $^8Be$ Anomaly - 17 MeV boson. Motivates: nuclear experiments (fast, cheap), isotope shift spectroscopy experiments, and accelerator searches for new bosons with mass $\sim 10 MeV$.

- Synergy with Cosmology and Astrophysics: precision cosmology now probes the microscopic particle properties of DM. Observations of the CMB and supernovae constrain regions of parameter space inaccessible to particle experiments. Small investments in simulations.

- Importance of the 1 to 100 MeV mass scale: SIMP, ELDER models, small scale structure puzzles existing anomalies including muon g-2 proton radius and $^8Be$ anomaly.

- Microlensing searches for Solar mass black hole DM.

# References

[1] J. Feng, P. Fox, W. A. Dawson, M. Ammons, T. Axelrod, G. Chapline, A. Drlica-Wagner, N. Golovich, and M. Schneider, "Us cosmic visions: New ideas in dark matter 2017 : Community report," 2017.