Dark Matter - Dark Sector Summary

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on behalf of the Dark Matter–Dark Sector Group
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Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
Dark Matter/Dark Sector Introductory talk  [H. Murayama]

- Dark Matter exists, awaiting for discovery
- In general, Dark Sectors may exist, too
- Very little clue on mass scales now
- WIMP still main paradigm, but we are marching to the neutrino floor
- Many new ideas on lighter dark matter and how to test them
- Vibrant area and need more data!
1) How do we search for DM, depending on its properties? What are the main differences between light Hidden Sector DM and WIMPs? How broad is the parameter space for the QCD axion?

2) What are the most promising experimental programs, approved or proposed, to probe the different DM possibilities in a compelling manner?

3) How to compare results of different experiments in a more model-independent way?

4) How will direct and indirect DM Detection experiments inform/guide accelerator searches and vice-versa?
### Session 1 (1.5 hours) – *Introduction and Synergies* - Scientific Secretary: K. Zurek
- Talk 1: Dark Sectors and DM Models: from Ultralight to Ultraheavy  
  (25+5) H. Murayama (Berkeley and Tokyo)
- Talk 2: Dark Matter Direct Detection Searches  
  (25+5) J. Monroe (London)
- Talk 3: Indirect DM Detection Overview  
  (15+5) C. Weniger (Amsterdam)

### Session 2 (2.5 hours) – DM at Colliders (joint w/ BSM)  
Scientific Secretaries: C. Doglioni (Lund), M. McCullough (CERN)
- Talk 4: How can/will Direct and Indirect DM Searches guide DM Searches at Accelerators?  
  (25+5) M. Lisanti (Princeton)
- Talk 5: Theory: DM at Colliders  
  (25+5) M. McCullough (CERN)
- Talk 6: Experiment: DM at Colliders  
  (60) All

### Session 3 (1.5 hours) – *Axions/ALPs* - Scientific Secretaries: J. Jaeckel (Heidelberg), B. Doebrich (CERN)
- Talk 7: Ultra-light DM (ALPS) Theory and Overview  
  (25+5) P. Agrawal (Harvard)
- Talk 8: ALPs: Lab Searches  
  (15+5) A. Lindner (DESY)
- Talk 9: ALPs: Helioscope Searches  
  (15+5) I. Irastorza (Zaragoza)
- Discussion for Axions/ALPs  
  (30) All

### Session 4 (2.5 hours) – *Fixed Target/Beam Dump* - Scientific Secretaries: G. Krnjaic (Fermilab), K. Petridis (Bristol)
- Talk 10: Theory and Overview  
  (25+5) C. Frugiuele (Weizmann)
- Talk 11: Lepton Beams: LDMX@eSPS (NA64++ AWAKE ++)  
  (12+3) R. Poettgen (Lund)
- Talk 12: Proton Beams: SHiP@BDF QCD  
  (12+3) E. Graverini (EPFL)
- Talk 13: General Perspective  
  (15+5) C. Vallee (Marseille)
- Discussion for Fixed Target/Beam Dump  
  (70) All
Dark Matter Candidates: Very little clue on mass scales

Too small mass ⇒ won’t “fit” in a galaxy!

- Ultralight Dark Matter
- Pre-Inflationary Axion
- Post-Inflationary Axion
- QCD Axion
- WIMPs
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPless DM
- Asymmetric DM
- Freeze-In DM
- SIMPs / ELDERS
- Black Holes
- From MACHOs searches
Dark Matter Candidates: Very little clue on mass scales

Folding in assumptions about early universe cosmology we can motivate more specific mass scales

Thermal Equilibrium in early Universe narrows the viable mass range

Explorable at accelerator based DM searches: collider and fixed target/beam dump experiments

Phenomenology of low mass region [MeV-GeV] thermal DM is quite different from Standard WIMP

==> Demands light mediator/s that in themselves are a search target
Dark Sectors

What is meant by a dark sector?
A Hidden sector, with Dark matter, that talks to us through a Portal

Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP’s)
Over next few decades, important advancements in both astrophysical and terrestrial probes will test WIMPs and Dark Sectors.
Indirect Detection Searches for Dark Matter

C. Weniger’s talk

No conclusive signals from indirect DM searches so far

But, slow and steady progress being made on indirect searches in many fronts

- Diffuse gamma rays, e.g. Galactic Center GeV Excess
- 3.5 keV “Sterile Neutrino decay”
- Antiproton excess from cosmic rays
- Neutrinos from DM annihilation in the Sun

It is possible that in the future it will be a convincing signal from one or more indirect DM searches

This will have large impact on Direct Detection and Accelerator based DM searches
Tests of Small-Scale Structure

Vogelsberger et al. (2016)

Low-mass dark matter halos that do not contain galaxies

Mass distribution depends on fundamental properties of dark matter

CDM predicts an abundance down to Earth-scale masses ($\sim 10^{-6} \, M_\odot$)

SIDM example that suppresses formation of low-mass subhalos:

Dissipative dark sectors can also affect small-scale structure

Observational constraints on subhalo masses powerful test of dark sectors

Lots of new data coming from e.g. Gaia, LSST

M. Lisanti’s Talk
WIMP Direct Detection Searches

Marching down to the Neutrino Floor

J. Monroe’s talk
WIMP Standard Candles

- Still a viable solution for Thermal DM (e.g. in many SUSY extensions/regions)
- Being broadly probed by Direct and Indirect detection as well as Collider experiments

**Pure Wino DM**

- Thermal abundance requires Wino mass of about 2.9 TeV
- DD: just above the neutrino floor. Ballpark of DarkSide 20k-200t-yr, DARWIN 200t-yr and Argo 3000t—yr.
- ID: Wino only constitutes all the DM for density profiles not generically produced in simulations of Milky Way-like galaxies
- @ Hadron Colliders: Disappearing tracks
- @Lepton Colliders: Reach close to kinematic limit plus precision measurements extended reach

See more details on Colliders in P. Sphicas’ talk

Talks by Lisanti, Monroe and McCullough
WIMP Standard Candles
- Still a viable solution for Thermal DM (e.g. in many SUSY extensions/regions)
- Being broadly probed by Direct and Indirect detection as well as Collider experiments

Pure Higgsino DM
- Thermal abundance requires Higgsino mass of about 1.1 TeV
- DD: Suppressed. Deep in neutrino floor region
- ID: Bounds strongly dependent on halo morphology.
- @ Hadron Colliders: Disappearing tracks
- @Lepton Colliders: Reach close to kinematic limit plus precision measurements extended reach

See more details on Colliders in P. Sphicas’ talk

Talks by Lisanti, Monroe and McCullough

Departures from pure Higgsino (mixings with bino/singlino) can lead to rich phenomenology.
New accelerator based searches for MeV - GeV dark matter

Dark Portals [Vector, (Pseudo)Scalar, Neutrino] at Beam Dumps (e.g. NA62++, SHiP)

E. Graverini’s talk

Production of long-lived dark particle decaying to SM particles

Rate $\sim \epsilon^4$

$\epsilon$ defines dark photon- photon mixing

Production of dark particle decaying to DM pair.

DM scatters inside the detector

Rate $\sim \epsilon^4$
New accelerator based searches for light dark matter

Dark Portals at fixed targets: Missing Energy/Momentum (e.g. NA64++, LDMX)

R. Poettgen’s talk

Production of dark particle decaying to DM particle pair, inferred from Missing Energy/momentum

Rate $\sim \varepsilon^2$

The beam is the signal, DM not observed
Dark photons/scalars → SM particles

SHiP is a proposed beam dump experiment using 400 GeV protons from the SPS.

Current limits
- Most studied in the past
- Current limits still dominated by old projects
- Strong revived worldwide competition to NA62++, AWAKE++, and FASER for this channel
- Unique reach of SHiP at high mass/low coupling

Worldwide prospects

CERN prospects

Millicharged Particles

Dark Scalars

\[ m_{A'} = 0 \]

Strong competition of milliQan to a long run of NA64++. A short term few-months run could still be of interest for \((g-2)_{\mu}\).

Complementary reach of projects in terms of couplings.

Mass reach fixed by meson masses.

Beam dump is complementary to collider-based searches for feebly interacting particles (FIP).

See P. Sphicas’ talk for details on Collider reach.
Heavy Neutral Leptons (HNL)

Heavy Neutral Leptons could be connected to generation of neutrino masses, leptogenesis and appear in models of neutrino portals to the dark sector.
LDMX is a proposed fixed target experiment with an electron beam

Hosting options:

- LCLS-II at SLAC 4 - 8 GeV
- eSPS at CERN 3.5 - 16 GeV

Accelerator of different techniques are complementary among themselves and with DD experiments and may yield additional information on dark sectors
Invisible dark photon decay

\[ \sigma^{\text{DD}} \propto y / m^4 \]

Direct detection cross section depends only on “y” for given mass (up to subleading corrections)

Accelerator searches are complementary to direct detection, where the cross sections may have velocity or loop suppression

https://cds.cern.ch/record/2640784

C. Frugiuele and R. Poettgen’s talks
Axion/ALP and other sub-eV Dark Sector target space

QCD axion
- Solves Strong CP problem
- Natural Dark Matter candidate
  Important target for experimental searches

Many Beyond the Standard Model scenarios contain
- Axion-like particles
- General light dark sector particles
  Probe wider parameter regions including different scenarios

Motivates a variety of non-accelerator experiments
QCD Axions as Dark Matter

Simplest realization described by its mass & parameter $f_a$ that characterizes its couplings to SM particles

There are a number of cosmological mechanisms to populate axion DM

P. Agrawal’s talk
QCD Axions as Dark Matter

Current constraints on axion-photon coupling from direct searches (Haloscopes and Helioscopes) and astrophysical bounds

Extended models allow enhanced axion-photon coupling

Wider target for QCD Axion Searches

P. Agrawal’s talk
Axion/ALP searches: Mature Key Techniques

Helioscopes
- Build on success of CAST hosted by CERN
- Proposed BabyIAXO, leads to IAXO, with large discovery potential

Haloscopes
- ADMX (US) is leading the field
- In Europe, MadMax is new key player
- Smaller efforts developing new techniques

Light-shining-through-walls
- ALPS II is well underway
- STAX is a new idea RF based
- JURA is long term plan

Searches relevant for both QCD Axions and more general Axion-like particles (ALPs)

Lindner and Irastorza’s talks
Big Questions

1) How do we search for DM, depending on its properties? What are the main differences between light Hidden Sector DM and WIMPs? How broad is the parameter space for the QCD axion?

2) What are the most promising experimental programs, approved or proposed, to probe the different DM possibilities in a compelling manner?

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We have started to address the big questions by
• looking at the experimental probes of the DM realm,
• evaluating the complementarity of different approaches
• attempting to compare their correlated impacts

This summary emphasizes the well defined targets of QCD axion DM & MeV-GeV thermal DM
Comments from the Discussion Sessions

Need for better coordination

- Consensus emerged on the need for more coordination between accelerator based, direct detection and indirect detection dark sector searches, for common interpretation of results.
- This will also be of fundamental importance to validate, through different channels, a possible dark matter discovery.
- To address this issue, it was recommended to make profitable use of the initiative of APPEC on the EuCAPT Astroparticle Theory Centre.
- This offers a strong opportunity to collaborate with working groups such as the LHC DM and Physics Beyond Colliders and the many recognized dark sector experiments using different approaches.

See talk by T. Montaruli, EPPSU Granada
Comments from the Discussion Sessions

Need for technology support and exchange between communities

• Technology challenges are shared between and beyond the communities engaged in dark matter searches.

• CERN and other large European National labs has relevant expertise and infrastructure for most/many of the big challenges, including vacuum over large volume, cryogenics, photosensors, liquid argon detectors, design and operation of complex experiments, software and data processing.

• Expanded support for dark matter research at CERN would stimulate knowledge transfer, increase coordination and synergies between experiments, and add guidance and coherence to the overall program.
THANK YOU

Submission inputs summarized in back up slides
Back up slides
Category: Facilities and experiments with “Dark Side” as key topic
(Id62) Argon : WIMP
(Id97) DARWIN: WIMP
(Id9) NA64++: middle mass
(Id12) SHiP : middle mass
(Id27) IAXO: WISP
(Id35, 50) AWAKE: WISP
(Id112) ALPII, JURA, IXAO, MADMAX etc : WISP
(Id113) VMB : WISP
(Id161) MAGIS-1K : WISP

Category: Facilities and experiments with “Dark Side” as a topic
(Id64) GW : WISP
(Id36) eSPS : middle mass
(Id94) FASER @ LHC : middle mass
(Id1) Sterile Neutrino at CERN : middle mass
(Id11) Belle II: middle mass
(Id137) Short Base-line neutrino at FNAL FCC: middle mass
(Id131) LBNF/DUNE : middle mass
(Id151) HI @ LHC : middle mass
(Id75) MATHUSLA: WIMP and middle mass

Continue.
(Id132, 133, 135) FCC: WIMP and middle mass
(Id136) HE-LHC: WIMP and middle mass
(Id152) HL-LHC: WIMP and middle mass
(Id77,145) ILC, CLIC: WIMP and middle mass

Category: Synergies on a global scale
(Id84) APPEC
(Id42,60,20) PBC study
(Id70) Neutrino global network

Category: National roadmaps and community
(Id40) Russia
(Id68) Slovenia
(Id69) Germany astroparticle
(Id78) Slovenia
(Id82,134) UK
(Id130, 138,165) Italy LNF, INLF
(Id149.150) US
Old Sociology, we used to think:

- Need to solve problems with the SM (hierarchy problem, strong CP, etc)
- Top down BSM thinking → great if new theory (SUSY, Extra Dim, …) also gives a DM solution as a byproduct

New Sociology,

- Need to explain dark matter on its own
- Great if the DM solution also helps to elucidate important issues
  - Strong CP, Baryogenesis, ….
A collider discovery will need confirmation from DD/ID for cosmological origin

A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction

A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

Summary plot for direct detection/colliders

Example of Complementary reach for future colliders and future DD for benchmarks considered (this case: scalar mediator)

C. Doglioni’s Talk

See P. Sphicas’ talk
Light Dark Matter eXperiment

individually measure up to $10^{16}$ electrons on target (EoT), missing energy & missing (transverse) momentum
a discovery machine for weakly coupled LLPs, with a complementary detector for $\nu$ physics and LDM scattering signatures

- large geometrical acceptance: long volume close to dump
- zero background with spectrometry, PID and VETO taggers
## BEAM DUMP PROJECTS AT CERN

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>PERIOD</th>
<th>BEAM</th>
<th>PARTICLES ON TARGET</th>
<th>SIGNATURE</th>
<th>MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA64++(e)</td>
<td>2015-24</td>
<td>e 100 GeV</td>
<td>$\sim 5 \times 10^{12}$</td>
<td>invisible &amp; visible $e^+e^-$</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>eSPS/LDMX</td>
<td>&gt; 2026</td>
<td>e 16 GeV</td>
<td>$10^{16}$</td>
<td>invisible</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>AWAKE++</td>
<td>&gt; 2026</td>
<td>e $\sim 50$ GeV</td>
<td>$\sim 10^{15}$</td>
<td>visible $e^+e^-$</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>NA62++</td>
<td>&gt; 2022</td>
<td>p 400 GeV</td>
<td>$10^{18}$</td>
<td>visible</td>
<td>DP, DS, HNL, ALPs</td>
</tr>
<tr>
<td>SHiP</td>
<td>&gt; 2026</td>
<td>p 400 GeV</td>
<td>$2 \times 10^{20}$</td>
<td>recoil &amp; visible</td>
<td>DP, DS, HNL, ALPs</td>
</tr>
<tr>
<td>NA64++(µ)</td>
<td>&gt; 2022</td>
<td>µ 160 GeV</td>
<td>$5 \times 10^{13}$</td>
<td>invisible</td>
<td>DZ$_{\mu}$, ALPs</td>
</tr>
</tbody>
</table>

**NB: CERN offers unique opportunities with both lepton and hadron beams**  
LHCb and LHC-LLP dedicated projects (FASER, milliQan, CODEX-b, MATHUSLA) have also sensitivity in similar mass range

C. Vallee’s Talk
IAXO & BabyIAXO

- IAXO: conceived as a large-scale new generation axion helioscope
- Realistic design choices lead to SNR >10^4 x CAST
  - SC magnet: rely on CERN expertise with large detector SC magnets
  - X-ray optics: rely on cost-effective techniques developed by x-ray astronomy community
  - Detector: rely on low-background techniques from underground physics.
- DESY is a ideal host for IAXO. Expertise/capabilities complementary to collaboration.
- BabyIAXO, intermediate step towards IAXO:
  - Prototyping & risk mitigation for IAXOBabyIAXO is well “on track” for implementation at DESY
  - The IAXO collaboration encompasses the needed know-hows and has already secured a substantial fraction of the resources. The project relies on the 15+ year experience with CAST.
  - BabyIAXO timeline: leads to commissioning by 2023

I. G. Irastorza’s Talk
Axion/ALP/ultralight scalar searches: rapidly developing new technologies

EDMs
• NMR probes or dedicated storage ring to probe axion-gluon couplings

Atom interferometers (GR)
• MAGIS and AION atom gradiometers with sensitivity to ultralight dark matter

Technology exchange beyond communities:
Examples
• X-ray astronomy (IAXO)
• Condensed Matter
• Quantum Sensing (All)
Dark sector program focus beyond WIMPs

The current and planned WIMP searches have a well-defined goal of extending direct detection search sensitivity to the “neutrino floor” in coordination with searches at colliders and improving indirect probes.

Similar coordinated programs with well-defined targets are contemplated for two other major dark sector possibilities:

1. Axions
2. MeV-GeV thermal dark matter

Axions
For the scenario where a QCD axion is a major component of dark matter, most of the relevant parameter space can be covered by a search program that combines multiple haloscope technologies, helioscopes, and laboratory “light-shining-through-walls” experiments.

Requires lab hosting and support for operations of larger experiments Requires support for relevant emerging technologies, e.g. quantum sensors
Dark sector program focus beyond WIMPs:

MeV-GeV thermal dark matter

Well-defined target that complements WIMP searches; compelling reach can be provided by a program combining new beam dump and fixed target based experiments, collider searches, and new direct detection experiments enabled by emerging technologies.

- Leverage on successful current experiments: LHC, NA62, NA64
- Beam dump facility at CERN SPS would be a critical and unique resource
- Opportunity for global coordination, e.g. LDMX at multiple sites
- Requires support for emerging technologies