Dark Matter - Dark Sector Summary

Shoji Asai and Marcela Carena

on behalf of the Dark Matter–Dark Sector Group

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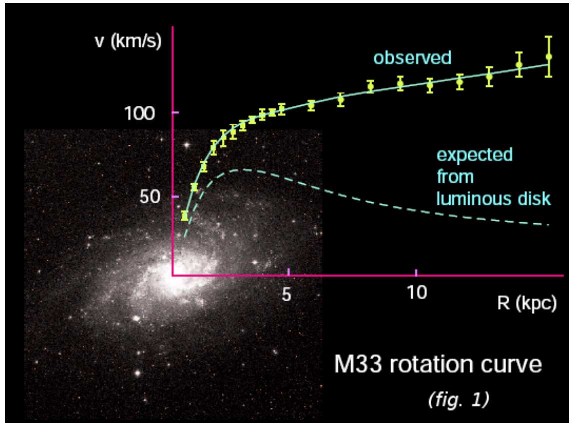
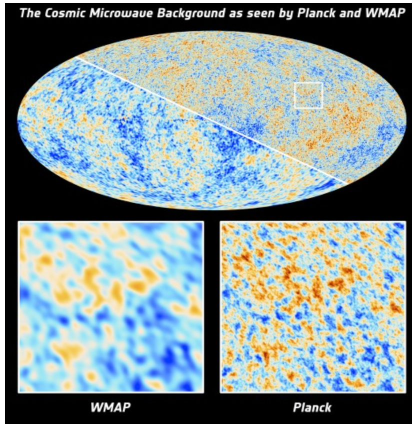
Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain

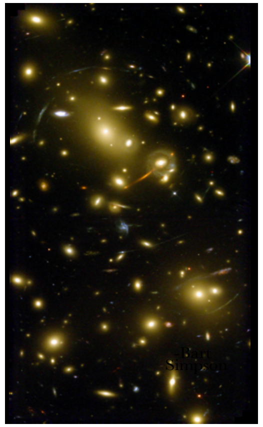
Dark Matter/Dark Sector Introductory talk

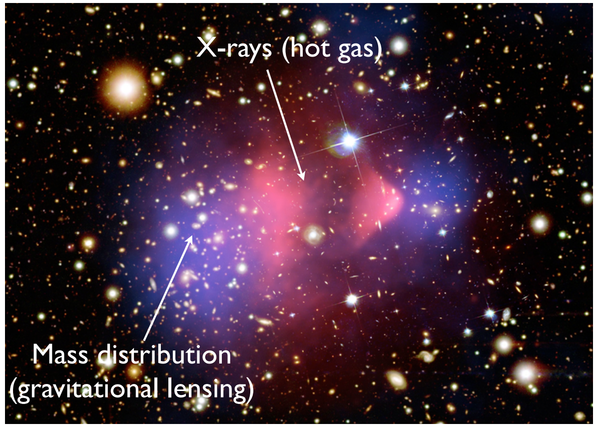
[H. Murayama]

- 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!

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?

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?

Dark Matter and Dark Sector Parallel Sessions, May 13-14, 2019

European Strategy Update

Monday afternoon

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 (25+5) C. Doglioni (Lund)
- Discussion for Sessions 1 and 2 (60) All

Tuesday afternoon

Session 3 (1.5 hours) – Axions/ALPs - Scientific Secretaries: J.Jaeckel (Heidelberg) , B.Doebrich (CERN)

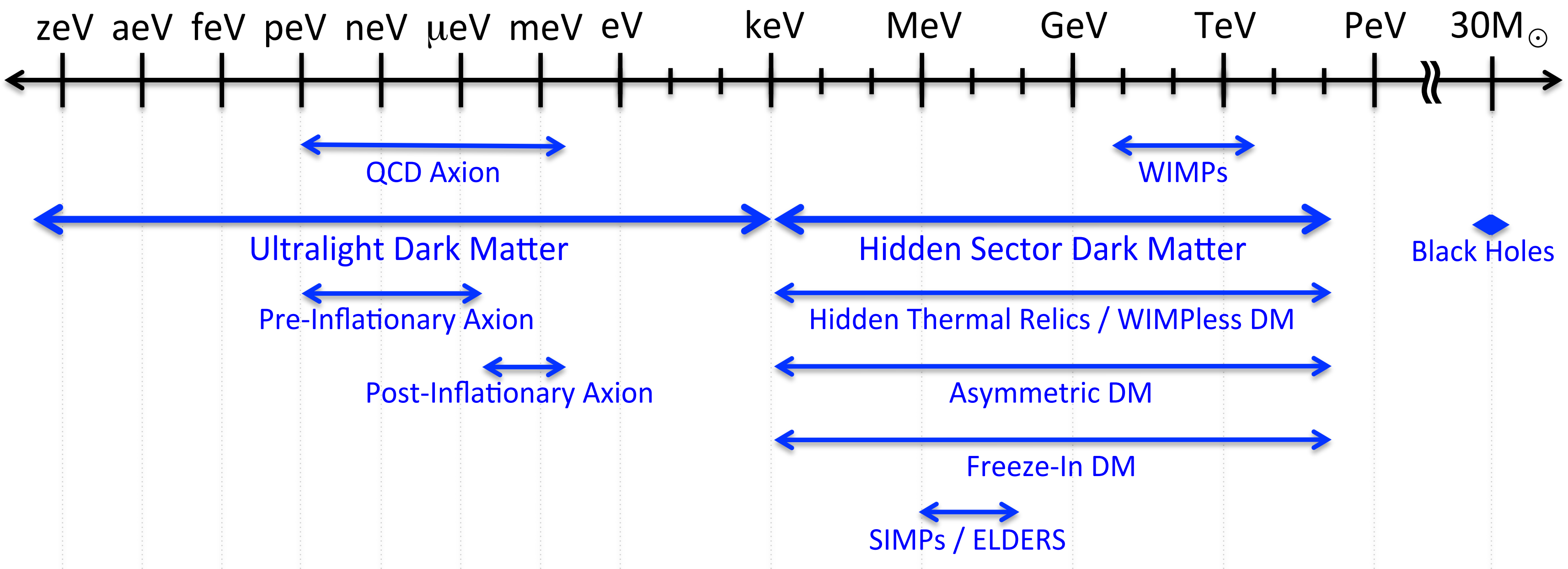
- Talk 7: Ultra-light DM (ALPS) Theory and Overview (25+5) P. Agrawal (Harvard)
- Talk 8: ALPs: Lab Searches (15+5) A. Lindner (DESY)
- Talk 9: ALPs: Helioscope Searches (15+5) I. Irastorza (Zaragoza)
- Discussion for Axions/ALPs (30) All

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!

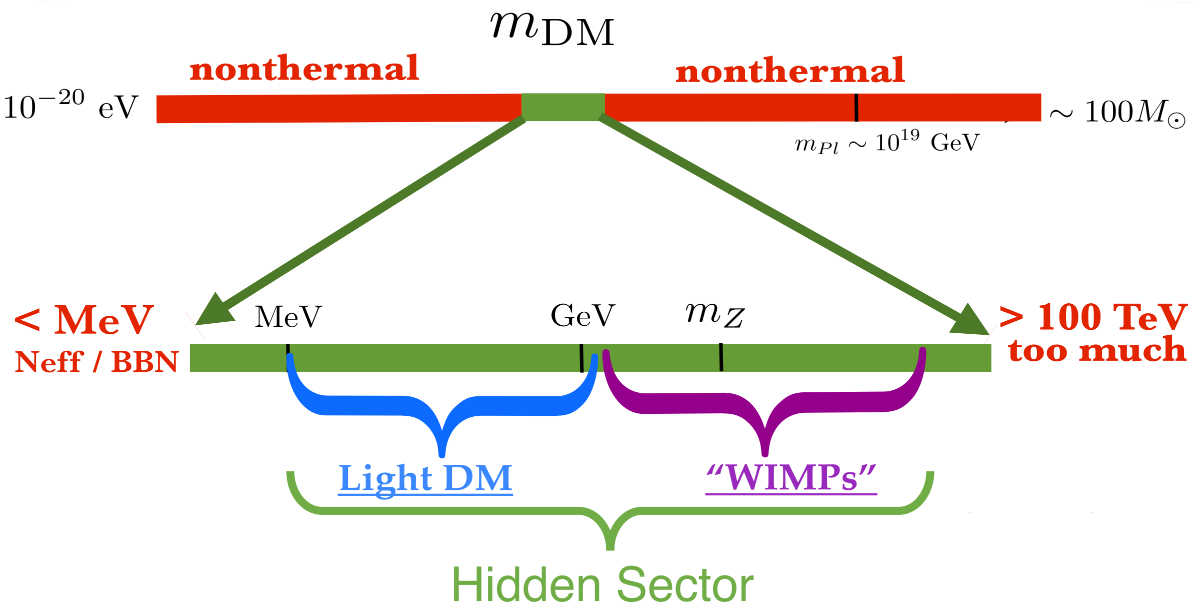


From MACHOs searches

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



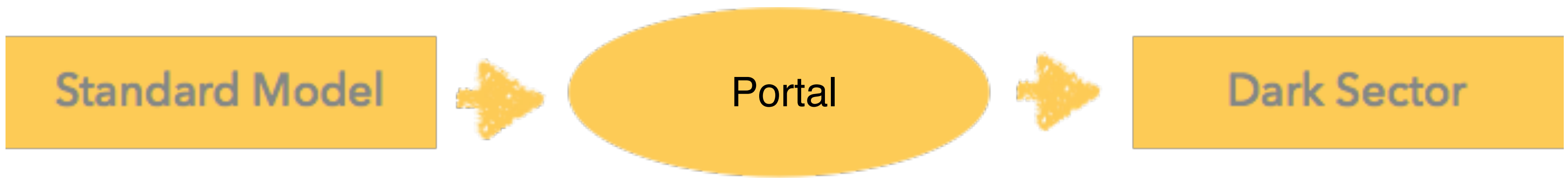
Explorable at accelerator based DM searches: collider and fixed target/beam dump experiments

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

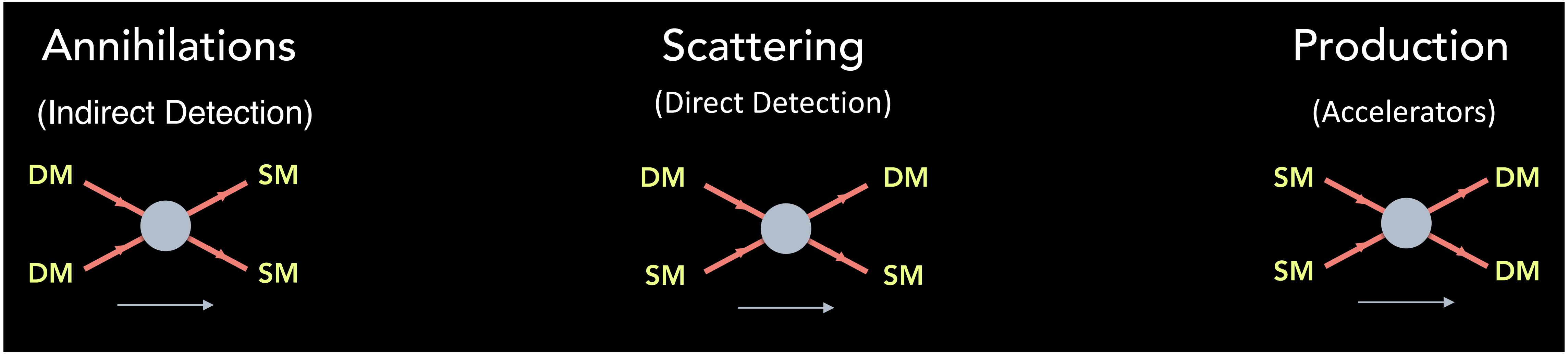
→ Multiple new states in the dark sector, including Dark Matter candidates

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



M. Lisanti's Talk

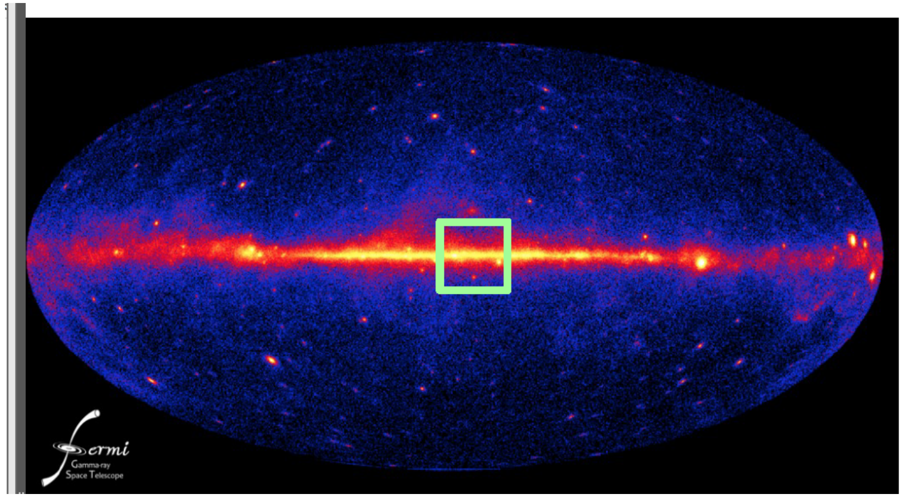
Indirect Detection Searches for Dark Matter

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

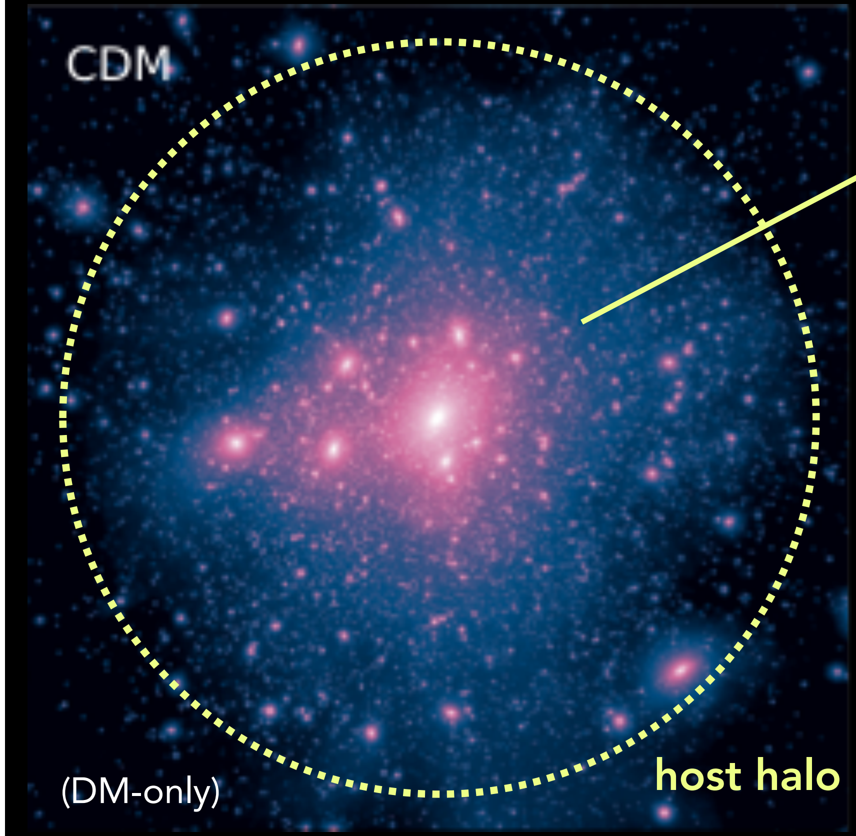
- Diffuse gamma rays, e.g Galactic Center GeV Excess
- 3.5 keV "Sterile Neutrino decay"
- Antiproton excess from cosmic rays
- Neutrinos from DM annihilation in the Sun



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)

Dark Matter Subhalos

Low-mass dark matter halos that do not contain galaxies

Mass distribution depends on fundamental properties of dark matter

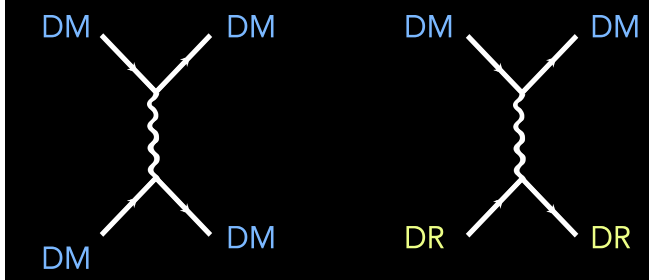
CDM predicts an abundance down to Earth-scale masses (~10^{-6} $M_\odot$)

M. Lisanti's Talk

SIDM example that suppresses formation of low-mass subhalos:

Dark Matter Self Interacting

Scattering off Dark Radiation



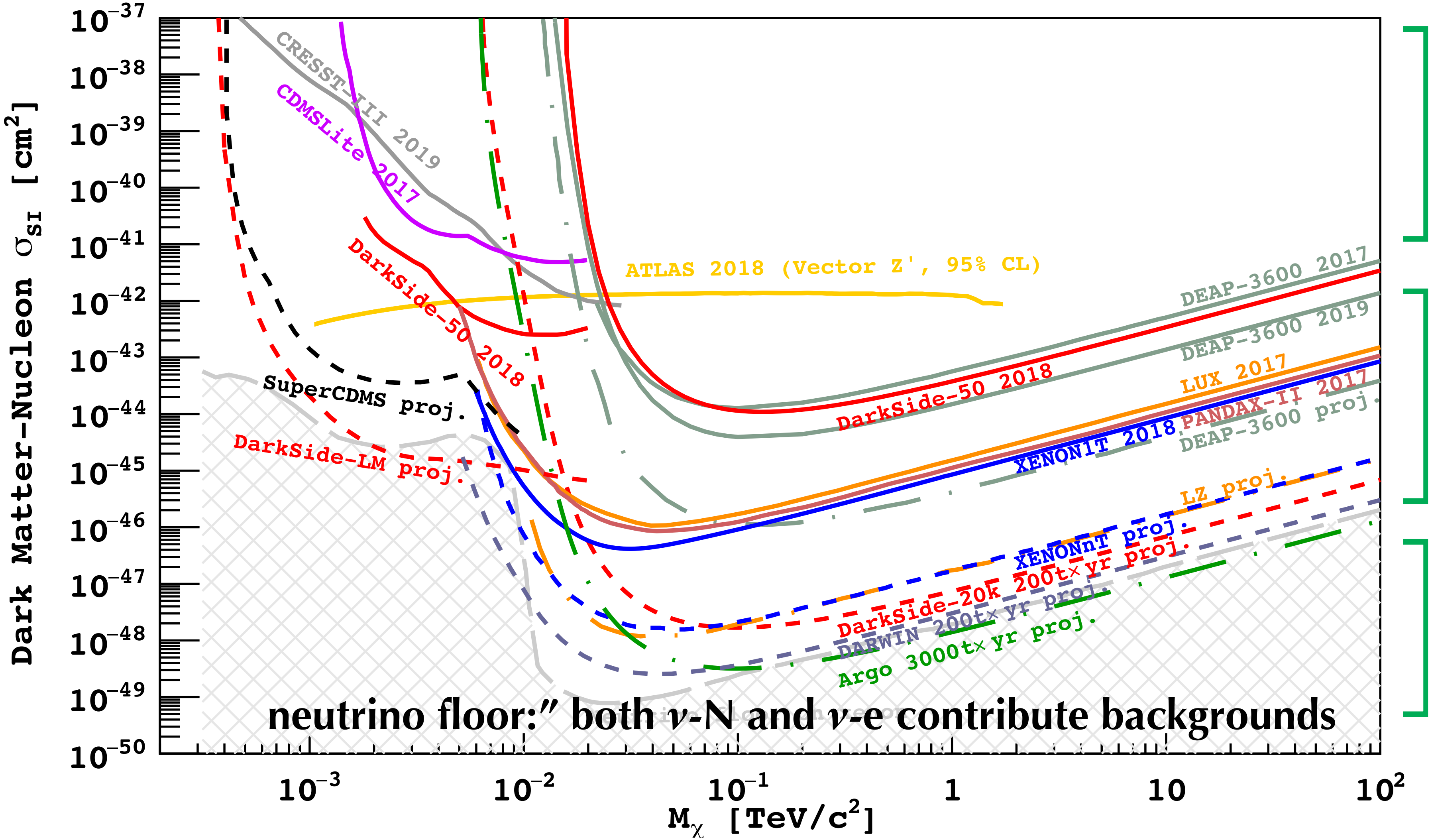
Dissipative dark sectors can also affect small-scale structure

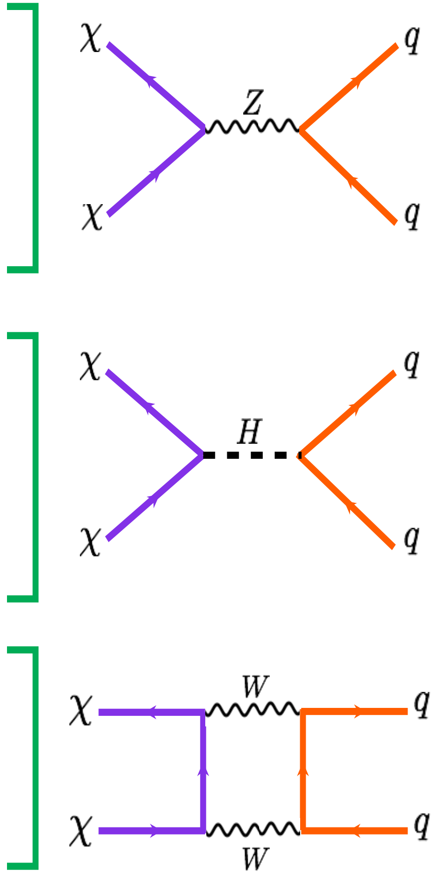
Observational constraints on subhalo masses powerful test of dark sectors

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

WIMP Direct Detection Searches

Primary Weak Interactions





Marching down to the Neutrino Floor

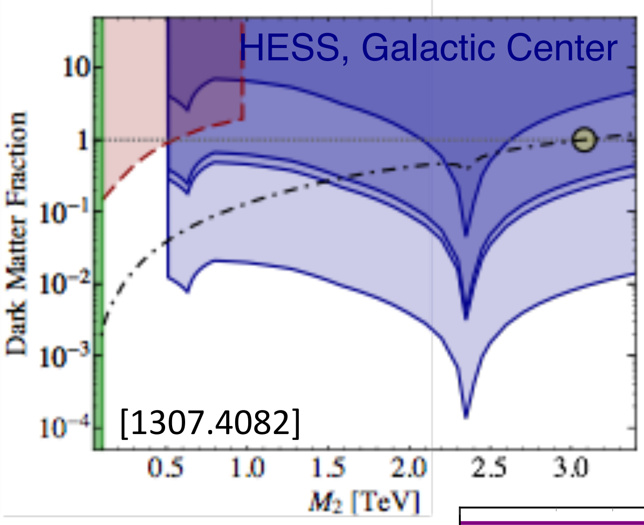
J. Monroe's talk

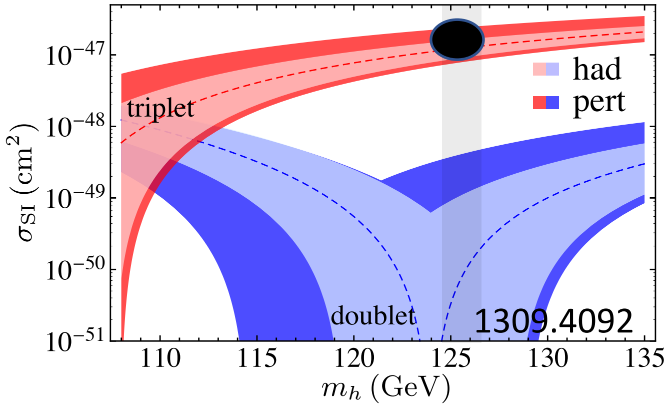
WIMP Standard Candles

- 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

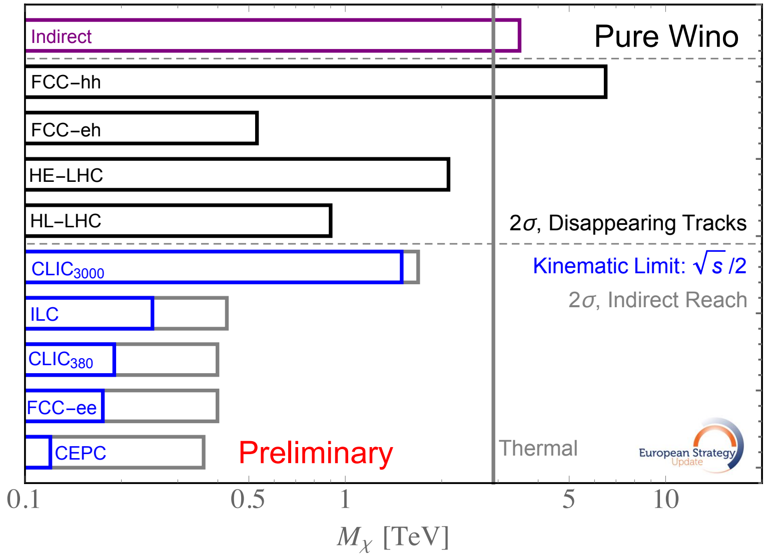
Pure Wino DM

- 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

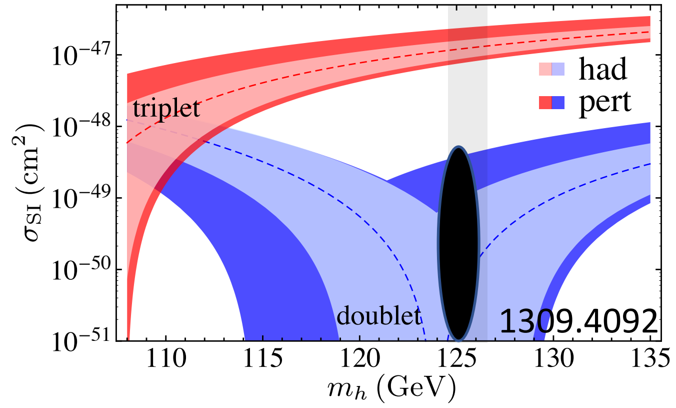
Talks by Lisanti, Monroe and McCullough

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

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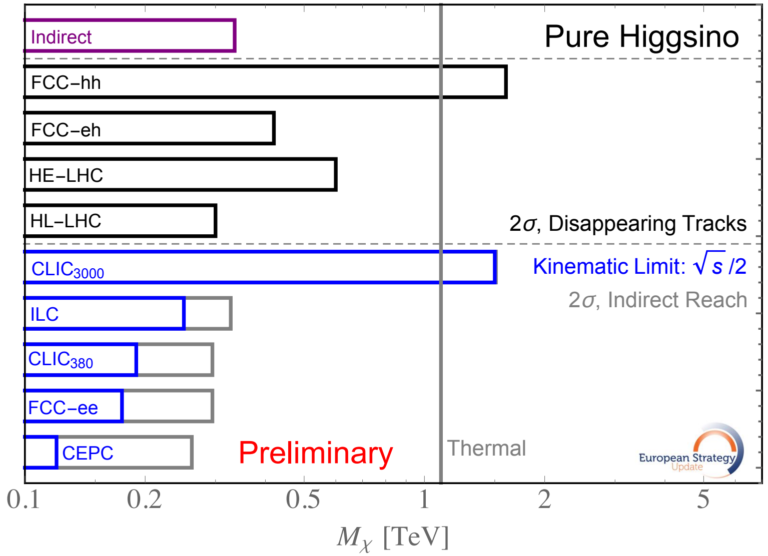
Talks by Lisanti, Monroe and McCullough

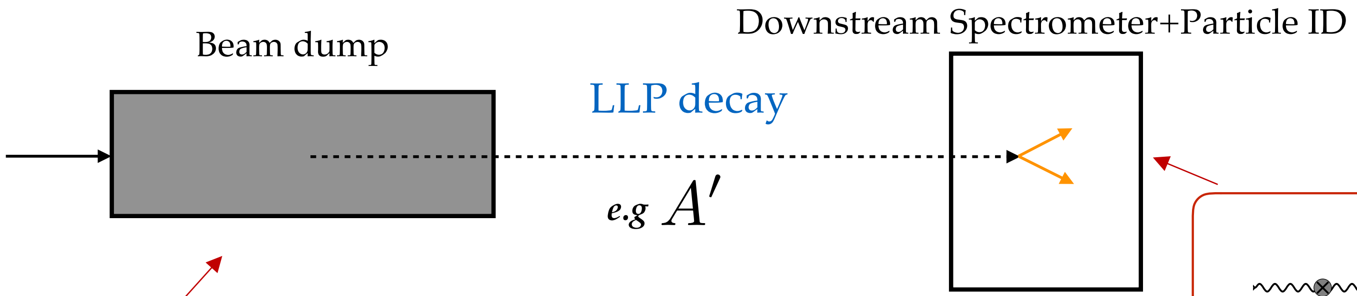
Departures from pure Higgsino (mixings with bino/singlino) can lead to rich phenomenology.



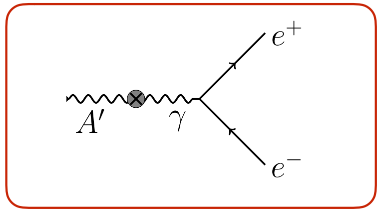
New accelerator based searches for MeV - GeV dark matter

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

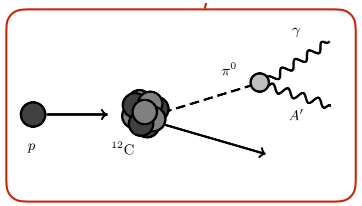
E. Graverini's talk



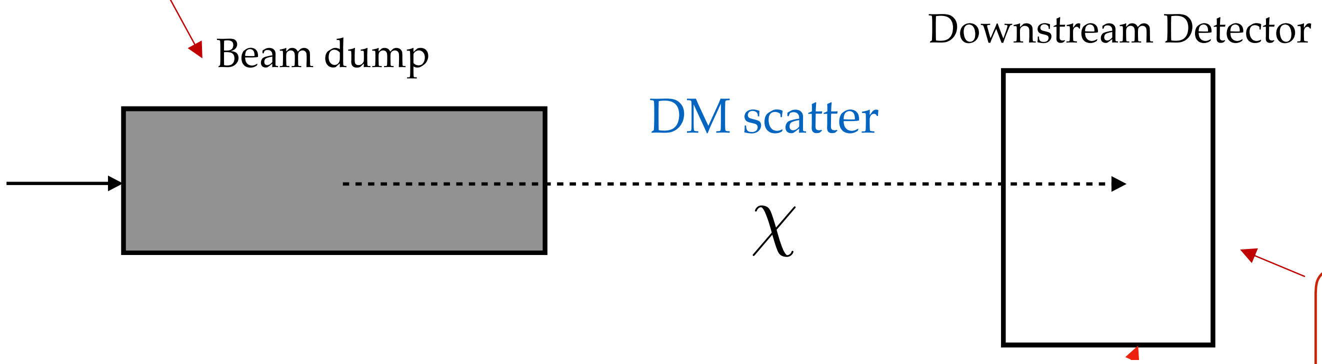
Production of long-lived dark particle decaying to SM particles



Rate ~ ε^4

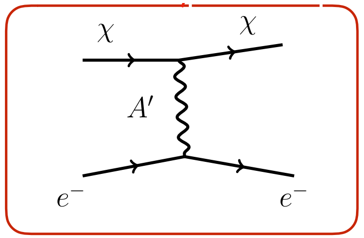


ε defines dark photon- photon mixing



Production of dark particle decaying to DM pair.

DM scatters inside the detector

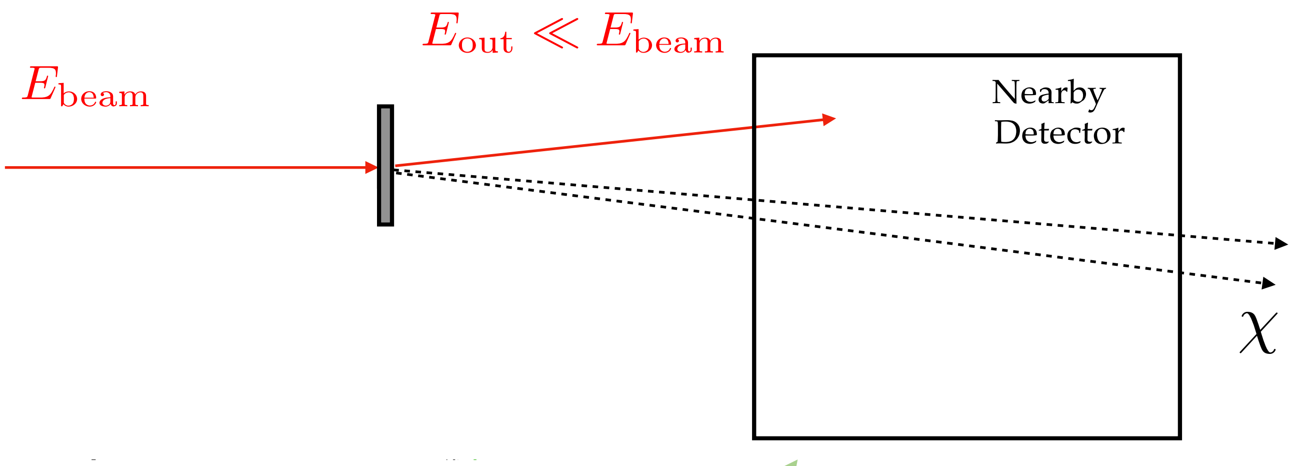


Rate ~ ε^4

New accelerator based searches for light dark matter

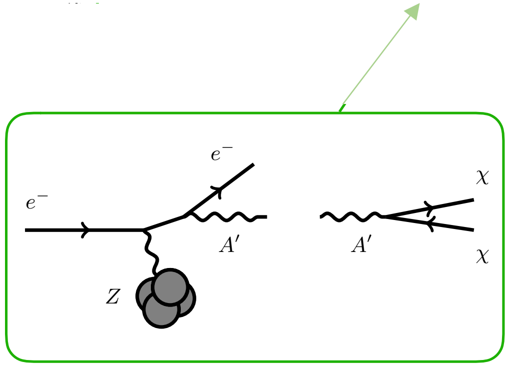
Dark Portals at fixed targets: Missing Energy/Momentum (e.g. NA64++, LDMX)

R. Poettgen's talk



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

Rate ~ ε^2

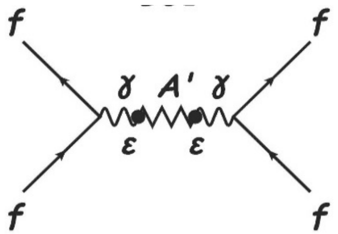


The beam is the signal, DM not observed

Dark photons/scalars → SM particles

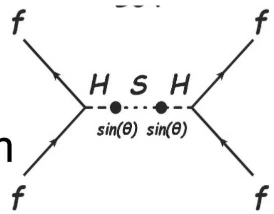
C. Vallee’s Talk

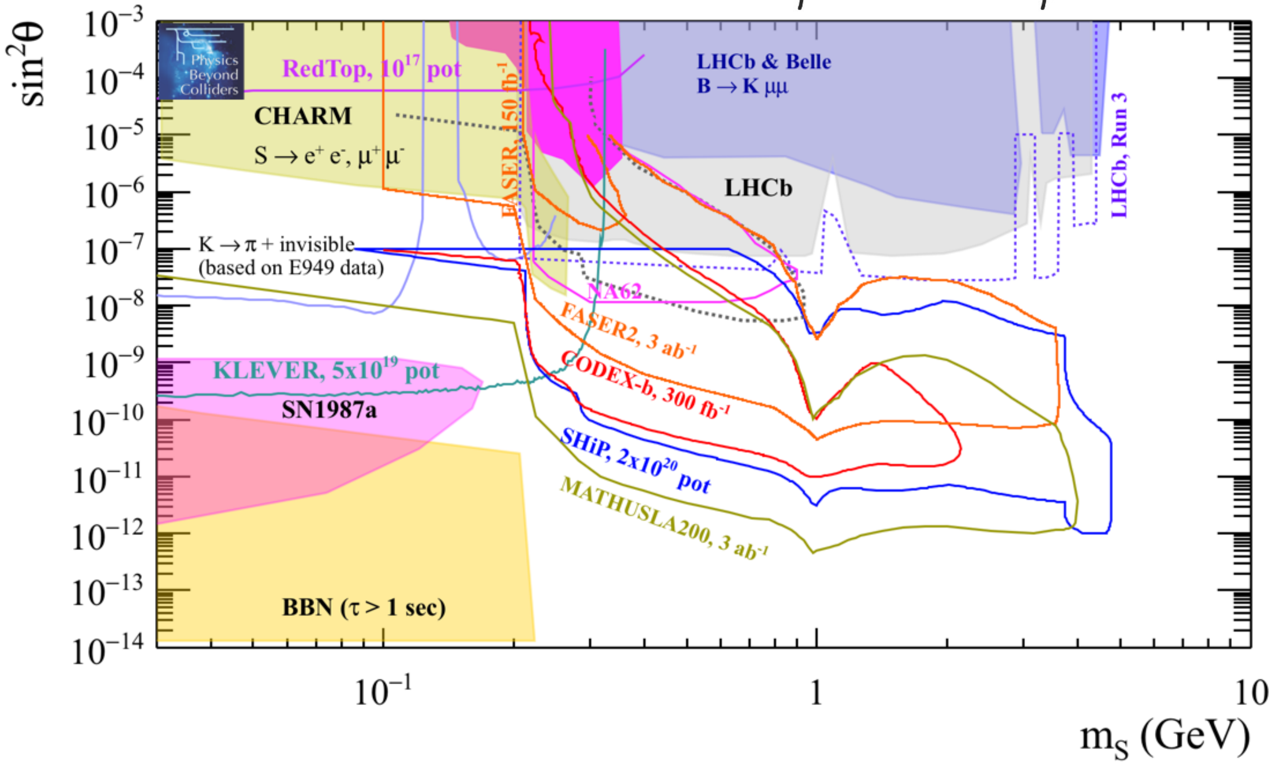
Schematic diagram

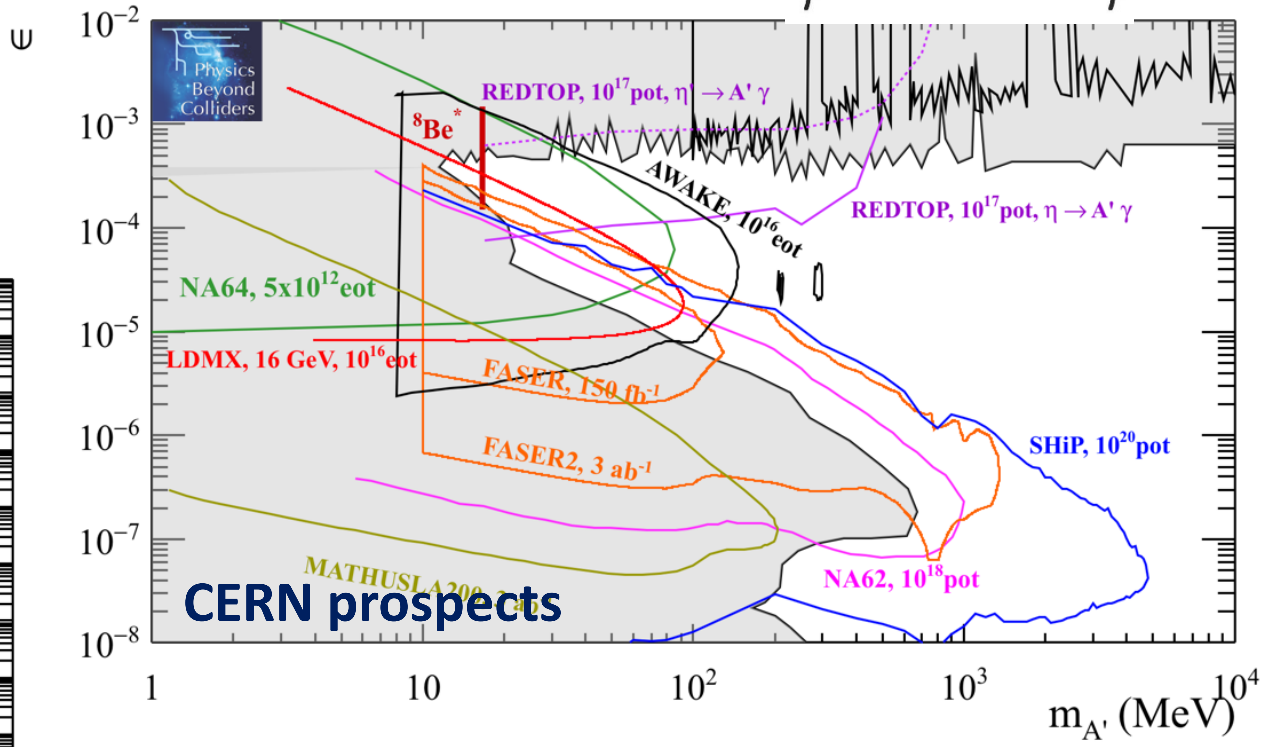


SHiP is a proposed beam dump experiment using 400 GeV protons from the SPS

Schematic diagram







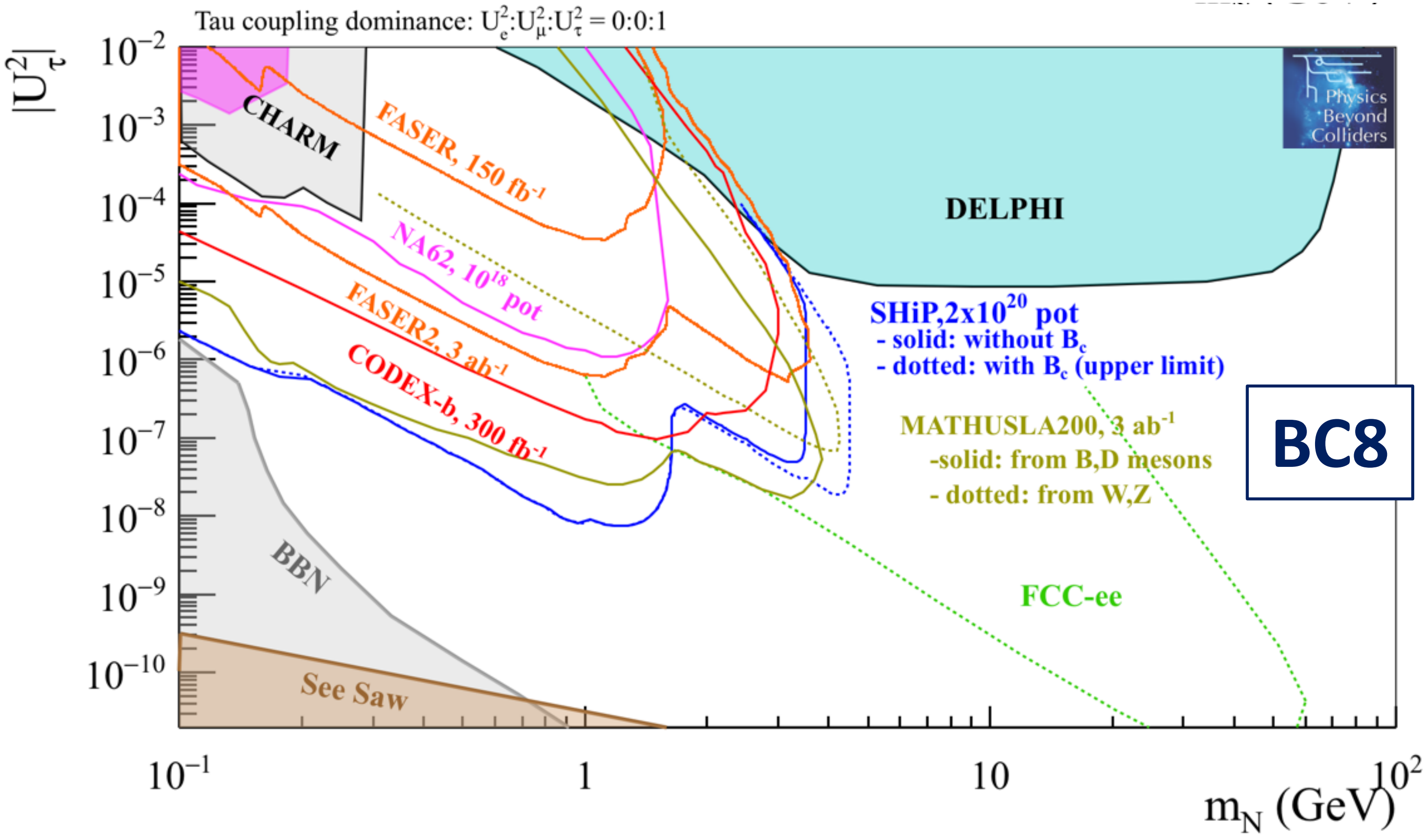
Beam dump is complementary to collider based searches for feebly interacting particles (FIP)

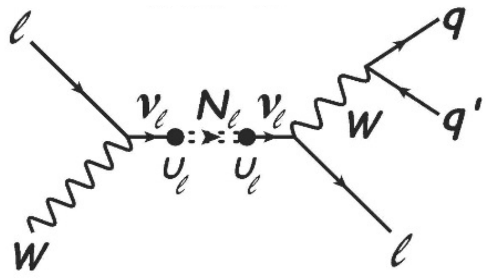
See P. Sphicas’ talk for details on Collider reach

Heavy Neutral Leptons (HNL)

C. Vallee's Talk

Heavy Neutral Leptons could be connected to generation of neutrino masses, leptogenesis and appear in models of neutrino portals to the dark sector





Schematic diagram

See P. Sphicas' talk for details on Collider reach

Invisible dark photon decay

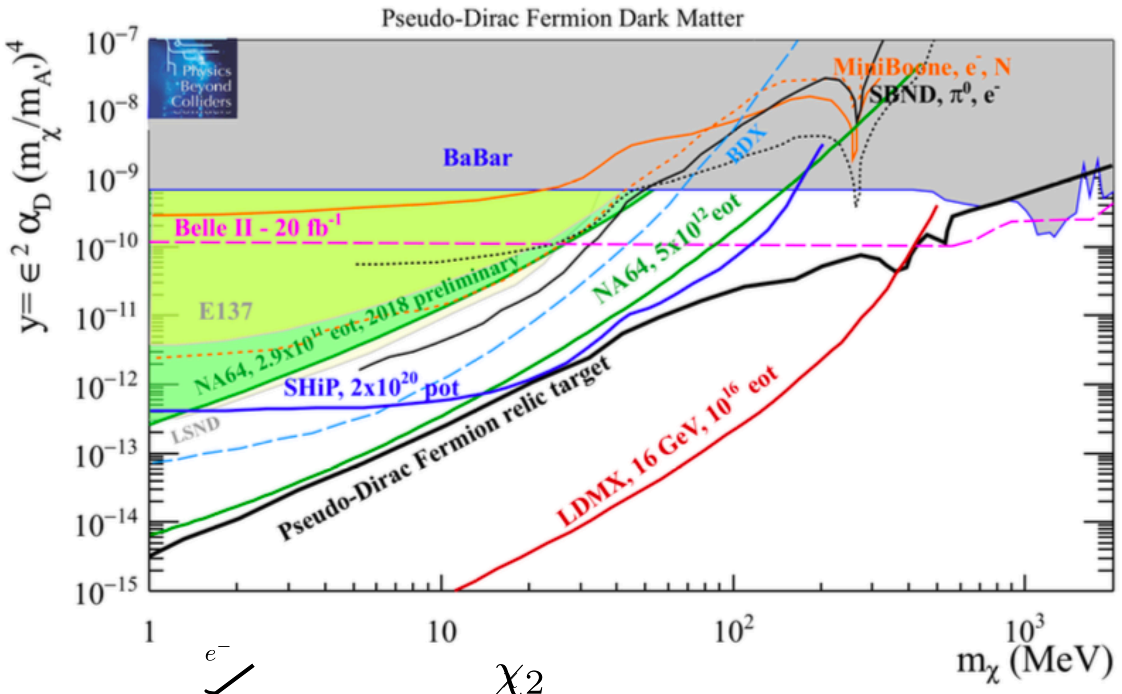
C. Vallee's Talk

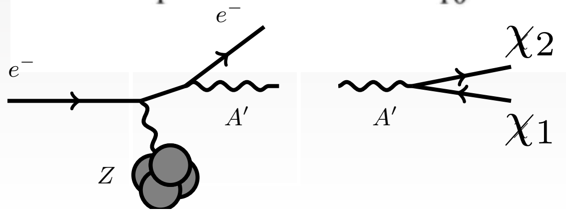
LDMX is a proposed fixed target experiment with an electron beam

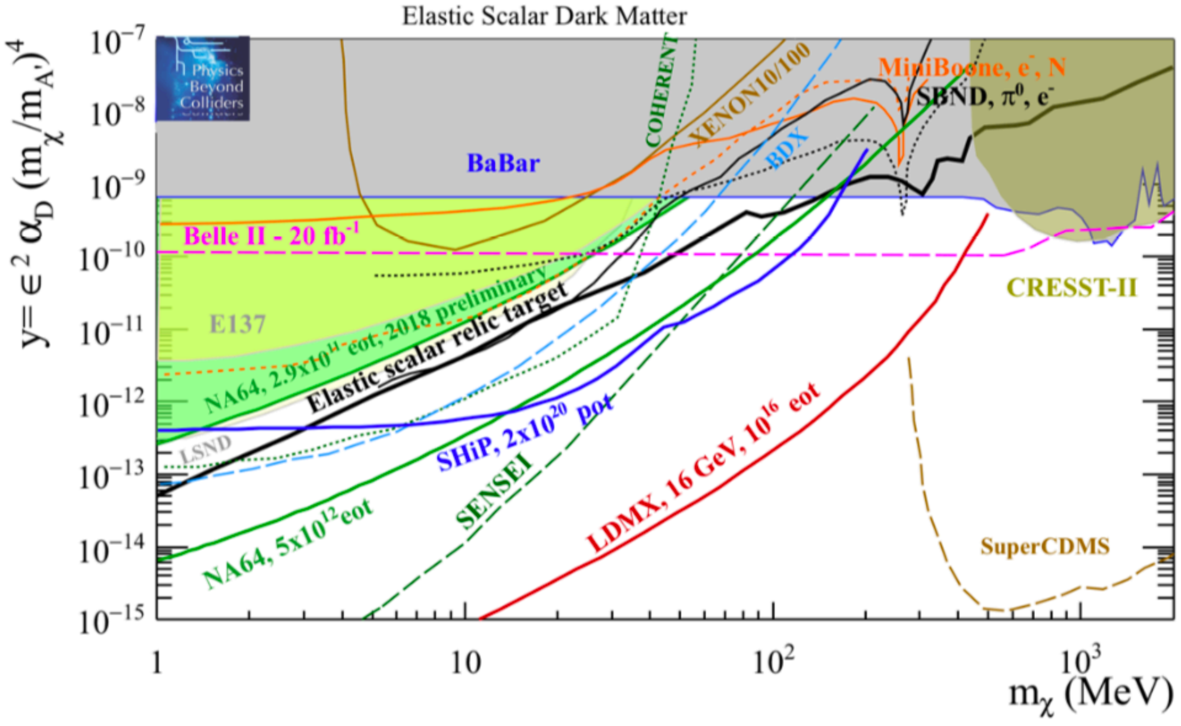
Hosting options:

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

Physics Beyond Colliders at CERN- Beyond the Standard Model Working Group Report (2019) **arxiv: 1901.09966**





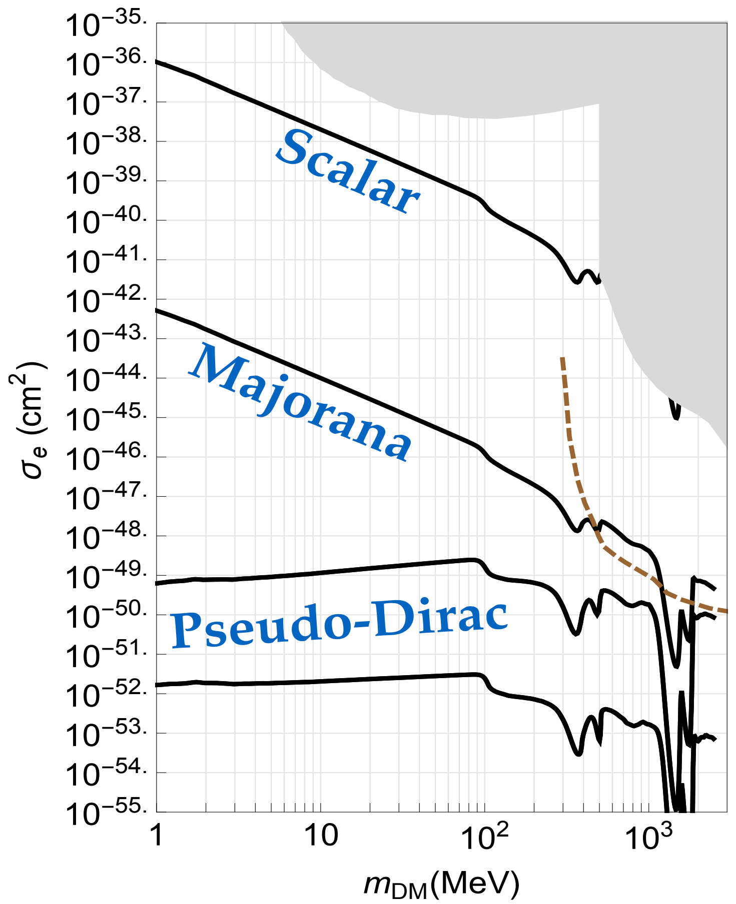


$$m_{A'} = 3m_\chi \quad \alpha_D = 0.1$$

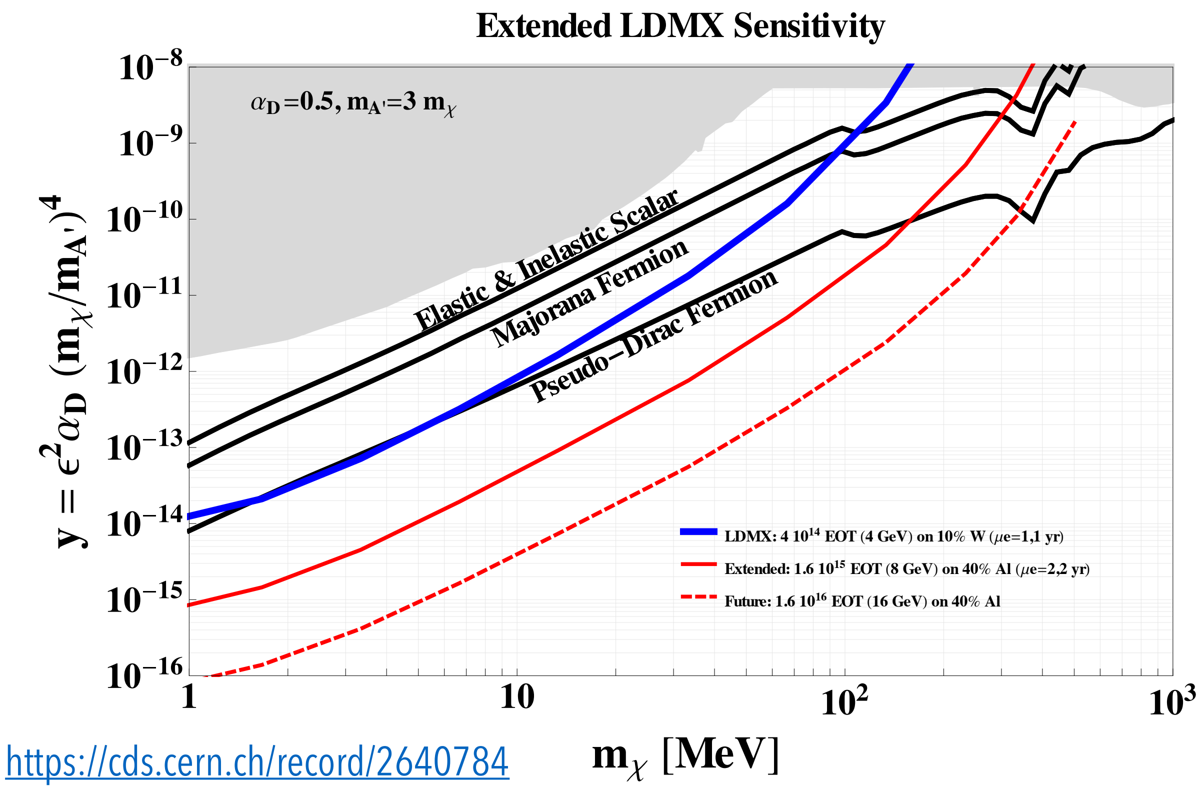
Accelerator of different techniques are complementary among themselves and with DD experiments and may yield additional information on dark sectors

Invisible dark photon decay

$\sigma^{DD} \propto y / m_\chi^4$



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



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

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

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

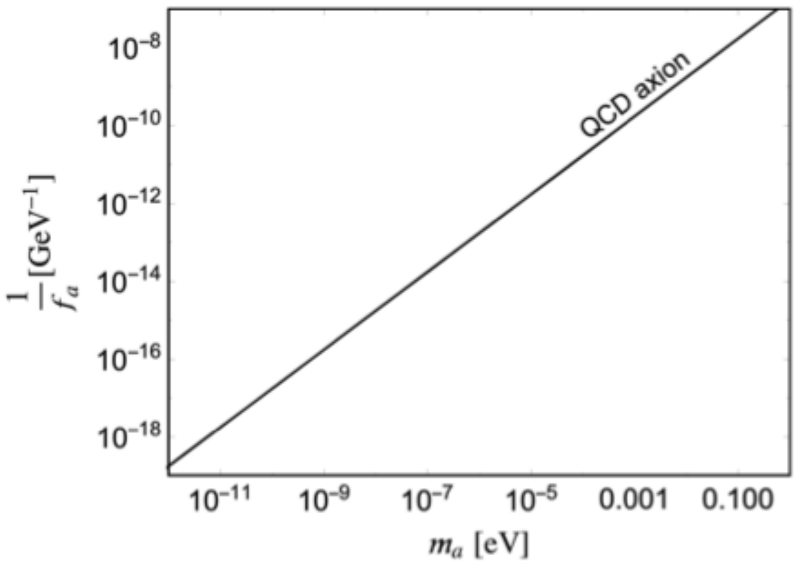
- Axion-like particles
- General light dark sector particles

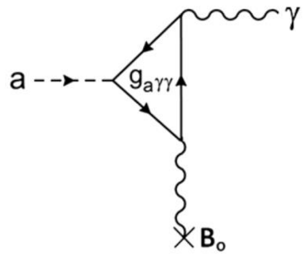
Probe wider parameter regions including different scenarios

Motivates a variety of non-accelerator experiments

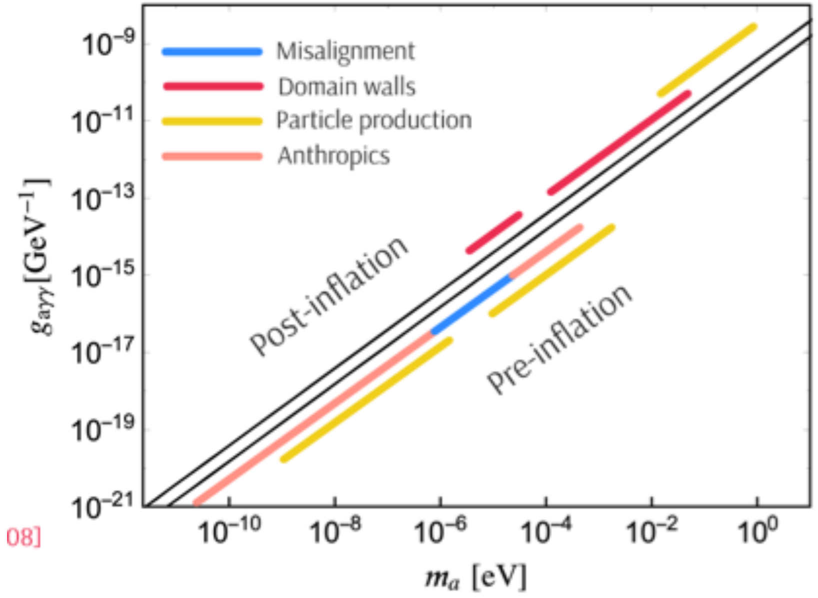
QCD Axions as Dark Matter

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





$$\frac{a}{f_a}\underbrace{\frac{\alpha}{8\pi}\left[\frac{E}{N}-1.92\right]}_{\frac{1}{4}g_{a\gamma\gamma}}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

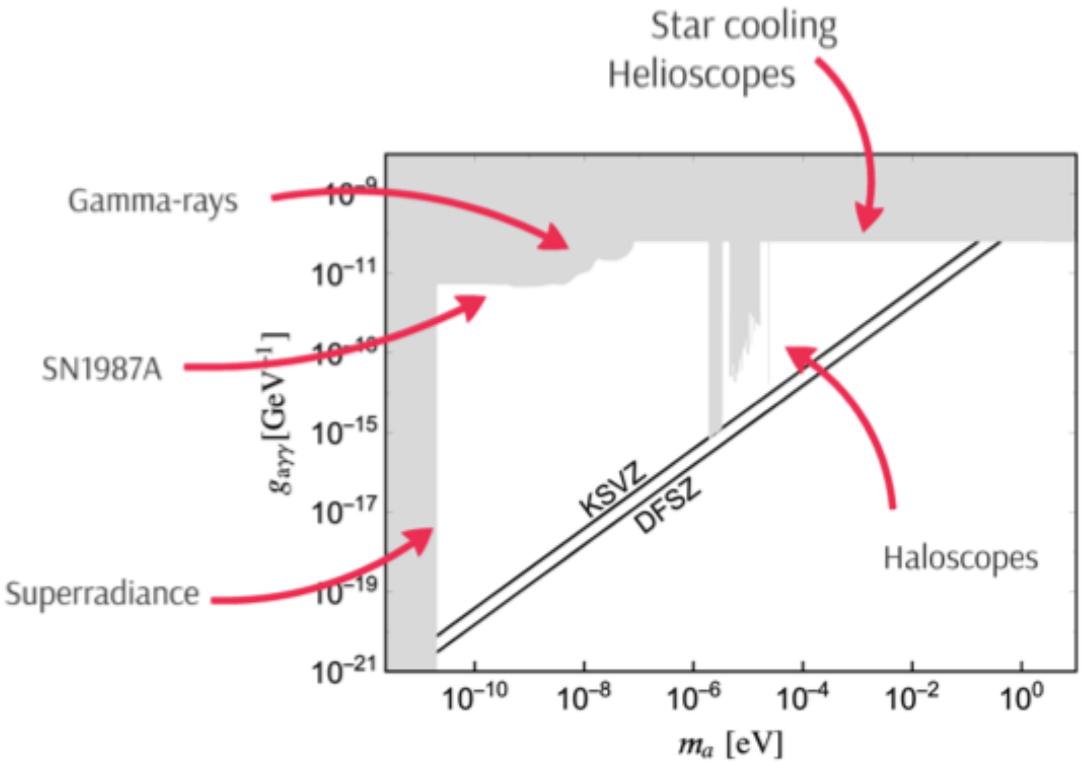


There are a number of cosmological mechanisms to populate axion DM

P. Agrawal's talk

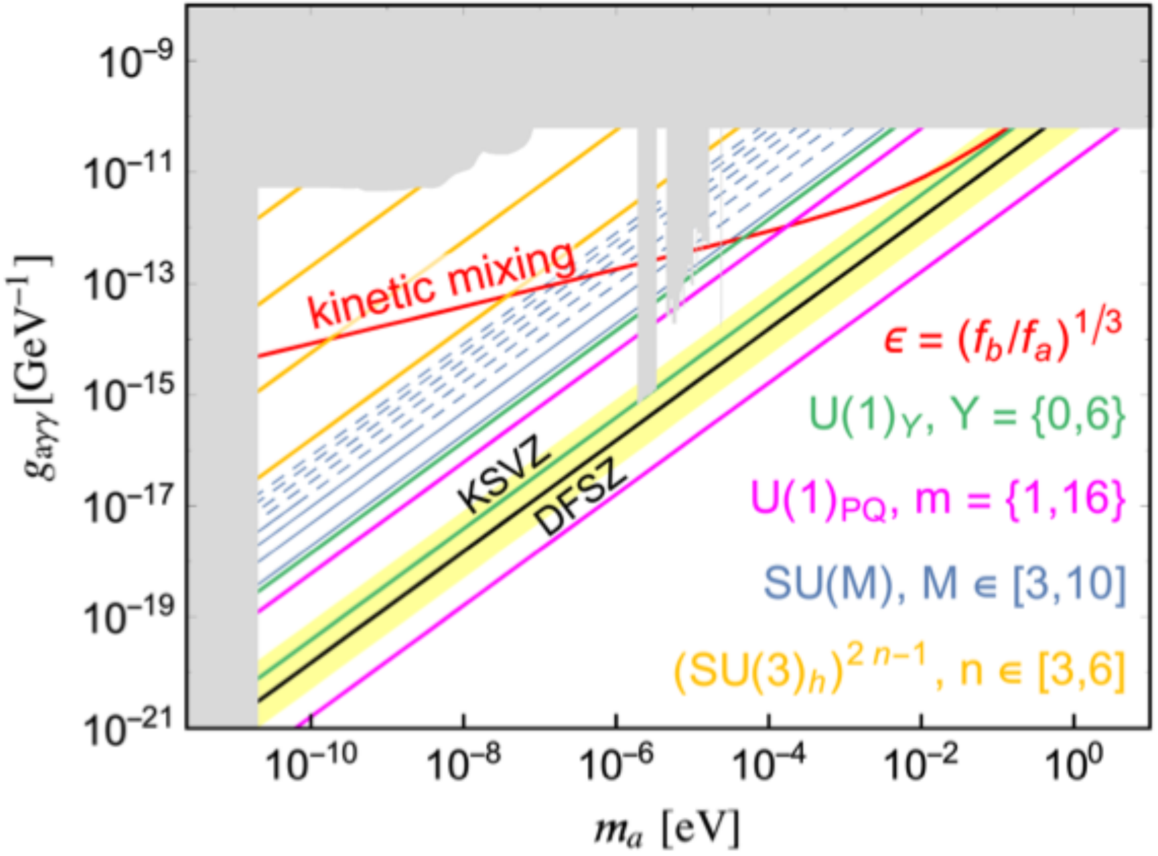
QCD Axions as Dark Matter

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



Extended models allow enhanced axion-photon Coupling

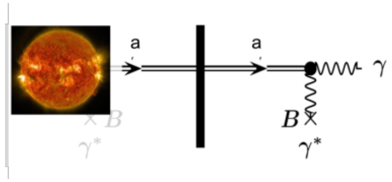
Wider target for QCD Axion Searches



P. Agrawal's talk

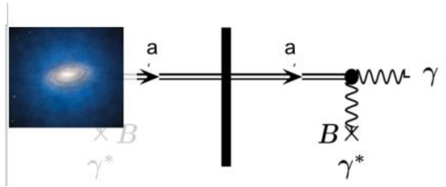
Axion/ALP searches: Mature Key Techniques

Helioscopes



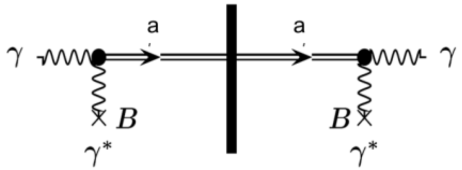
- Build on success of CAST hosted by CERN
- Proposed BabyIAXO, leads to IAXO, with large discovery potential

Haloscopes



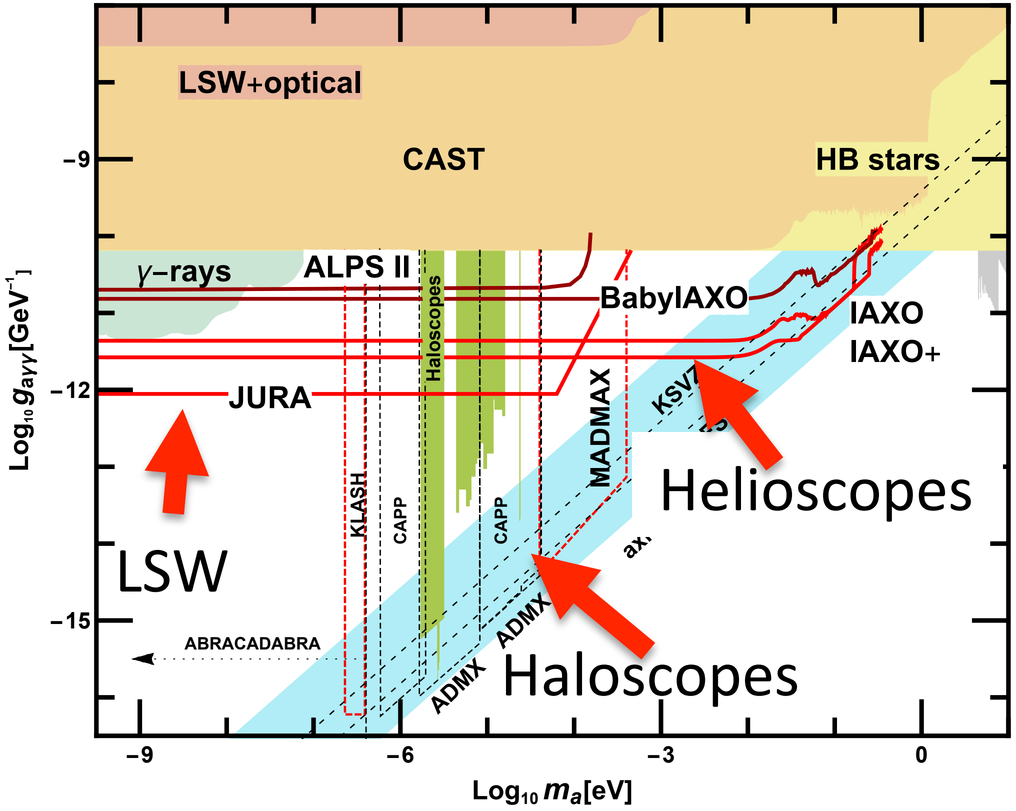
- ADMX (US) is leading the field
- In Europe, MadMax is new key player
- Smaller efforts developing new techniques

Light-shining-through-walls



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

Lindner and Irastorza's talks



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

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?

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?

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

Inputs considered

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 mas
(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

Dark Matter: A paradigm change [H. Murayama]

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,

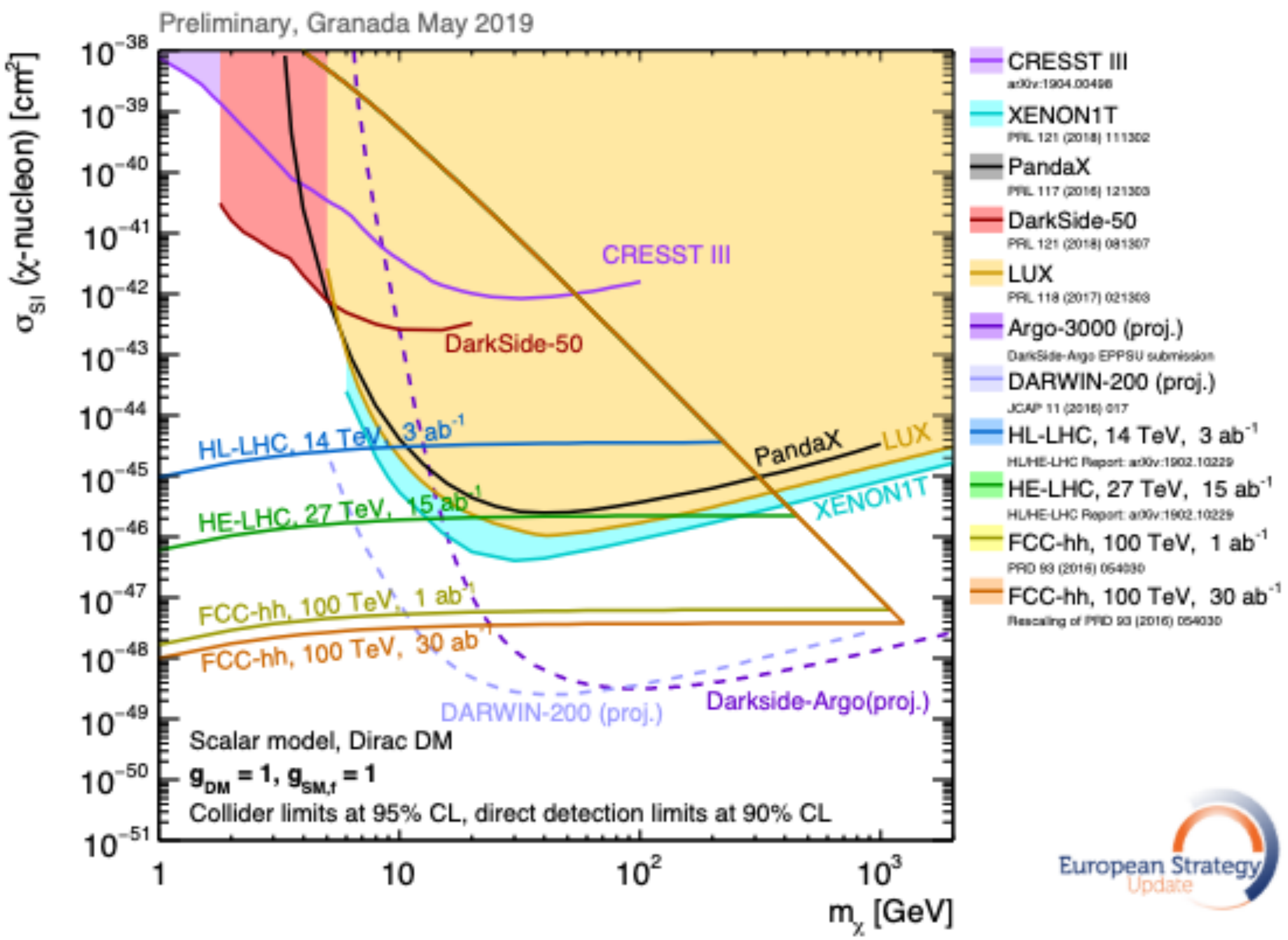
- Need to explain dark matter on its own
- Great if the DM solution also helps to elucidate important issues
  - Strong CP, Baryogenesis, ….-

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

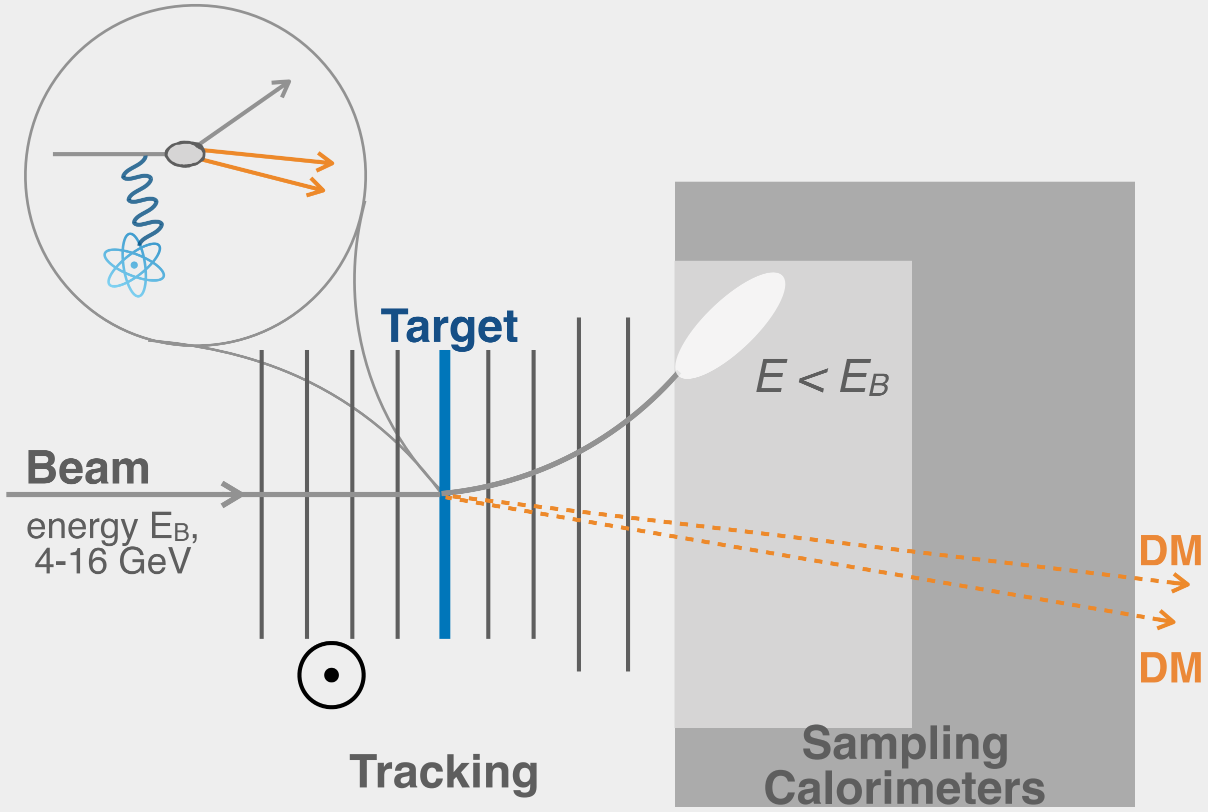
See P. Sphicas' talk



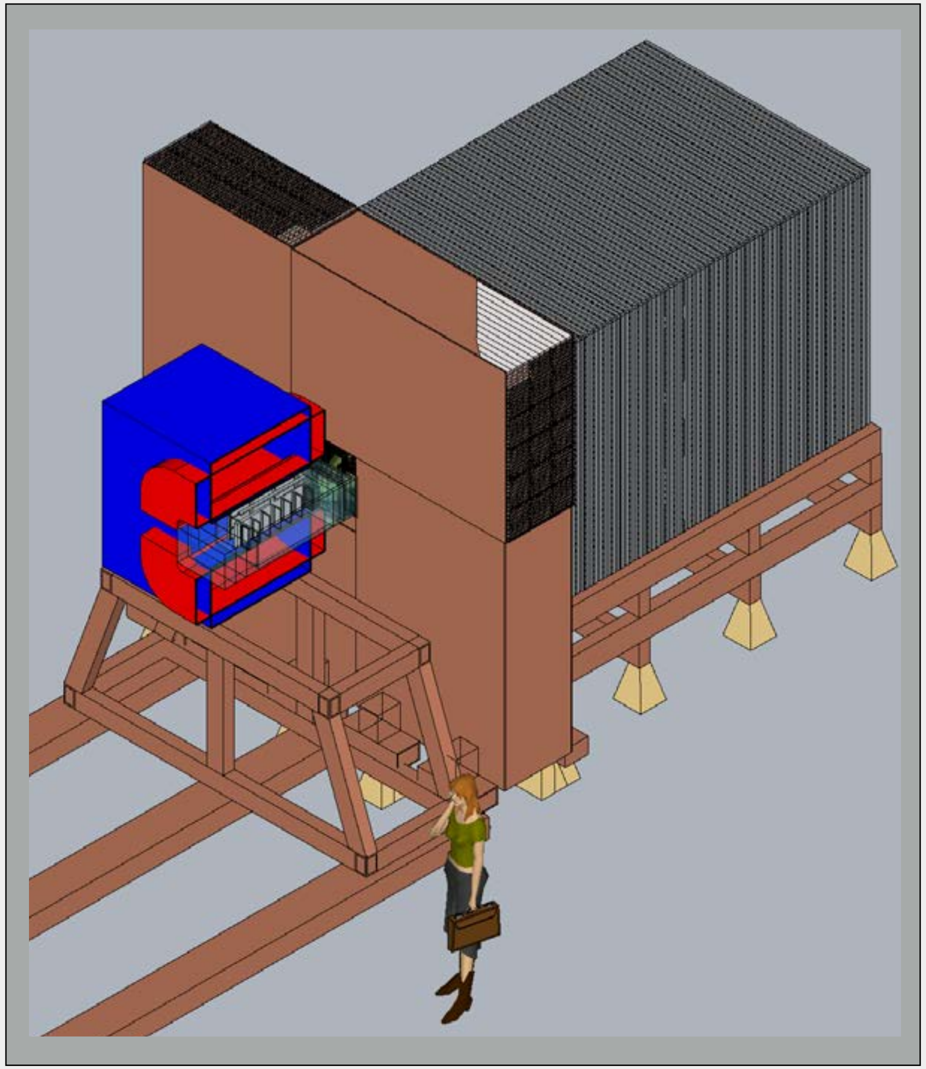
- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

LDMX

Light Dark Matter eXperiment



individually measure up to 10^{16} electrons on target (EoT),
missing energy & *missing (transverse) momentum*



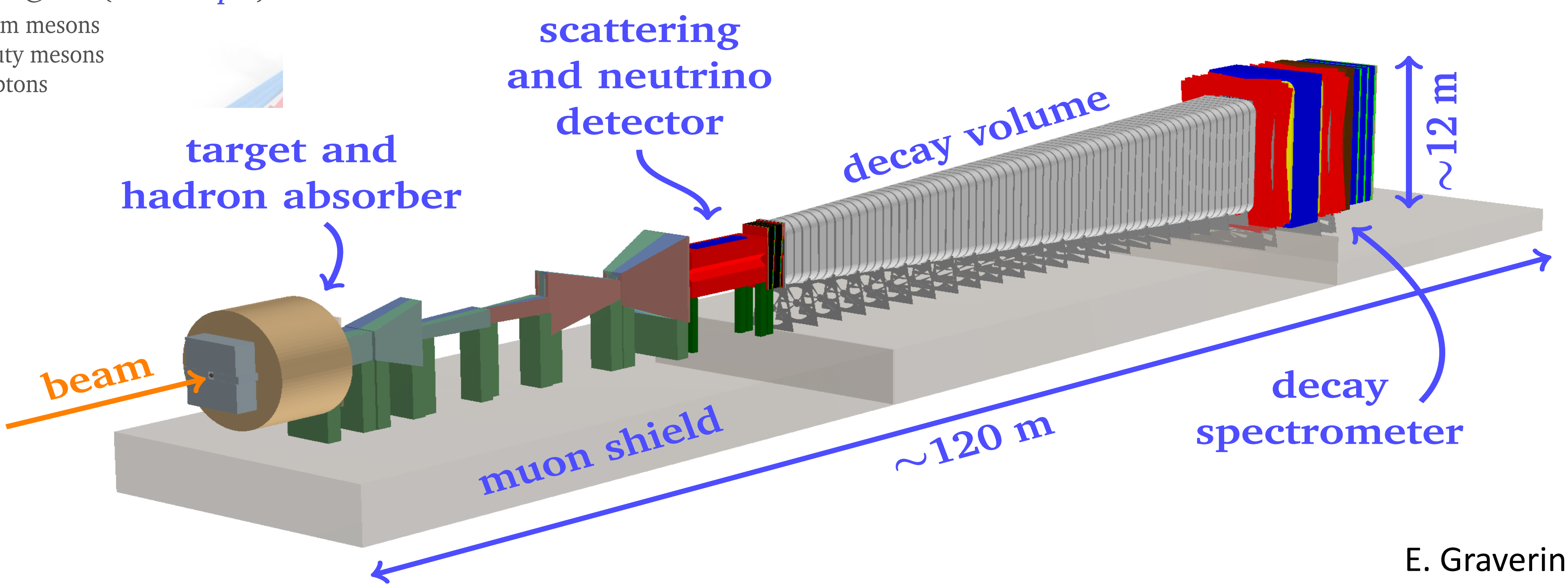
small-scale experiment

SHiP

5 years of BDF @ SPS (2×10^{20} *pot*):

- 10^{18} charm mesons
- 10^{14} beauty mesons
- 10^{16} τ leptons

The SPS provides a unique high-intensity beam of 400 GeV protons: ideal setting for a CERN-based **Beam Dump Facility** (BDF)



E. Graverini's talks

- **a discovery machine for weakly coupled LLPs**, with a complementary detector for ν 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

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
NA64++(e)	2015-24	e 100 GeV	~5 10^{12}	invisible & visible e^+e^-	DP, ALPs
eSPS/LDMX	> 2026	e 16 GeV	10^{16}	invisible	DP, ALPs
AWAKE++	> 2026	e ~50 GeV	~10^{15}	visible e^+e^-	DP, ALPs
NA62++	> 2022	p 400 GeV	10^{18}	visible	DP, DS, HNL, ALPs
SHiP	> 2026	p 400 GeV	2 10^{20}	recoil & visible	DP, DS, HNL, ALPs
NA64++(μ)	> 2022	μ 160 GeV	5 10^{13}	invisible	DZ_{μ}, ALPs

NB: CERN offers unique opportunities with both lepton and hadron beams

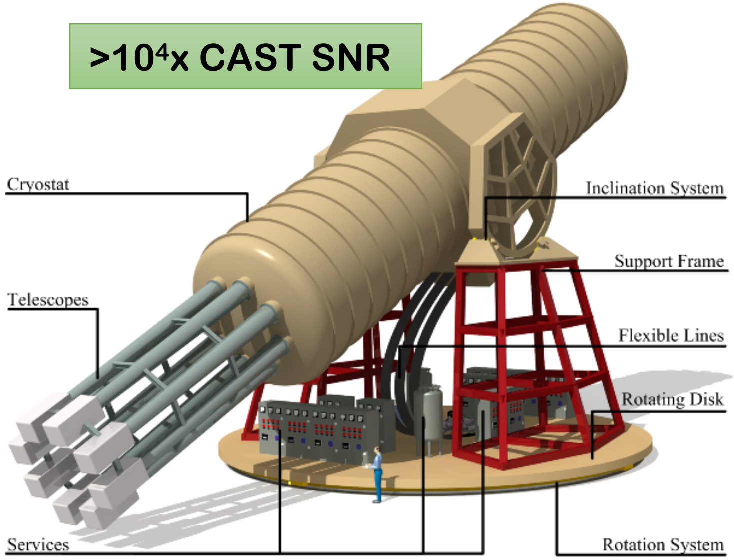
LHCb and LHC-LLP dedicated projects (FASER, milliQan, CODEX-b, MATHUSLA) have also sensitivity in similar mass range

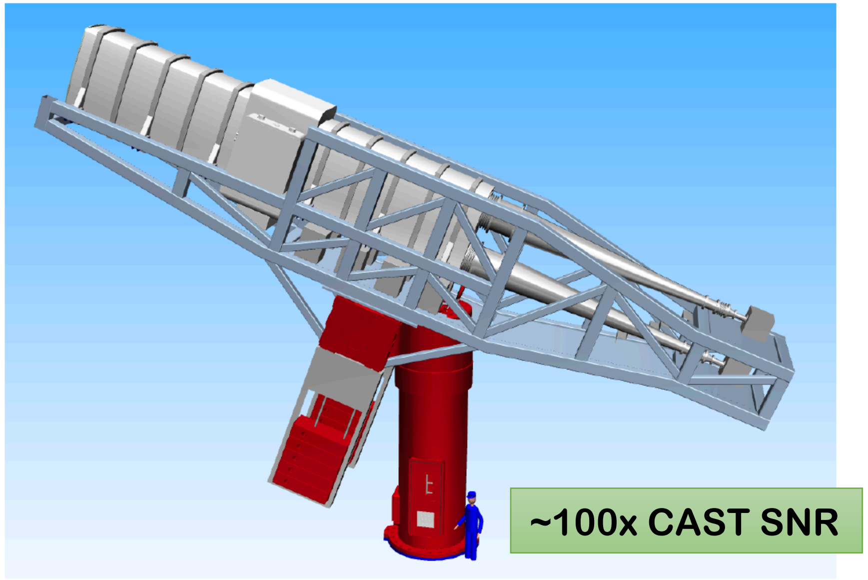
C. Vallee's Talk

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

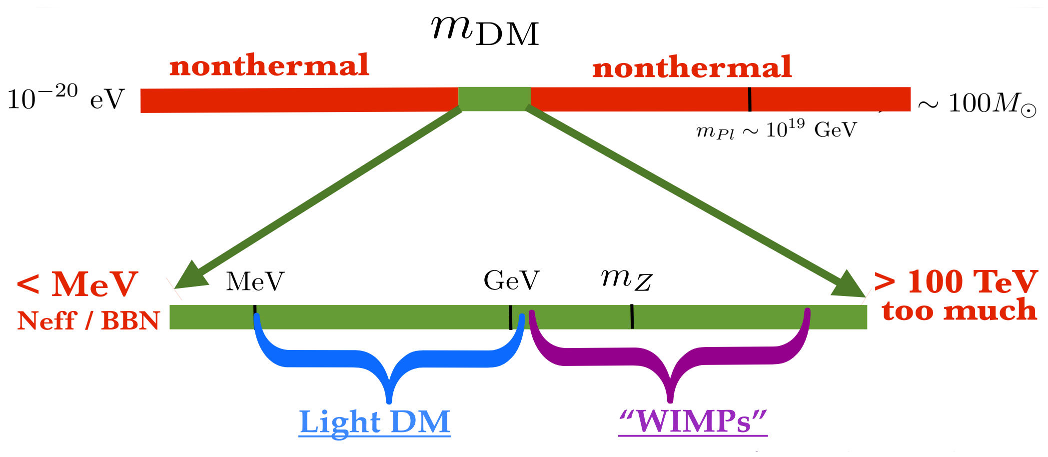
For the scenario where a QCD axion is a major component of dark matter, most of the relevant parameter space can be covered by a search program that combines multiple haloscope technologies, helioscopes, and laboratory “light-shining-through-walls” experiments.

Requires lab hosting and support for operations of larger experimentsRequires 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