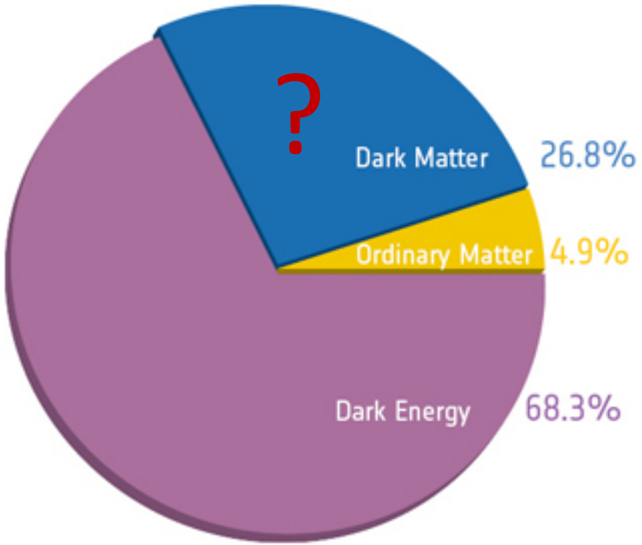
Direct Detection of Dark Matter

APPEC SAC Subcommittee Report
Current v1.02 (9 October 2020)

Subcommittee:
Julien Billard (France) – EDELWEISS
Mark Boulay (Canada) – DEAP-3600
Susana Cebrian (Spain) – ANAIS
Laura Covi (Germany) – theory
Giuliana Fiorillo (Italy) – DARKSIDE
Anne Green (UK) – theory
Joachim Kopp (Germany) – theory
Béla Majorovits (Germany) – MADMAX (axion)
Kimberly Palladino (USA → UK) – LZ
Federica Petricca (Germany) – CRESST
Leszek Roszkowski (Poland) – theory (chair)
Marc Schumann (Germany) – XENON



Evidence: convincing but so far based only on gravity

Mass range: nearly 50 orders of magnitude
Interactions: from gravitational up to (electro)weak+

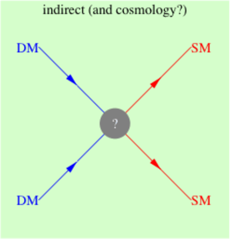
Our mandate:

The main points defining scope of the report:

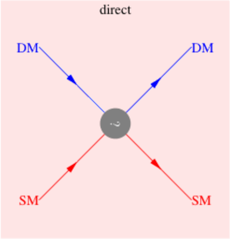
To aid in the discussions and to devise concrete recommendations for the next steps in direct DM detection in the next decade, the DM direct detection committee should provide an assessment of the current and future scientific opportunities in non-accelerator DM searches over the next 10-year period, in particular delivering:

- The global context of DM particle searches…
- An inventory of existing DM experiments and the technologies adopted by these…
- A comparative SWOT analysis of existing, planned and proposed technologies for DM direct detection with the potential to surpass current sensitivities in the next decade with the eventual goal of reaching or surpassing the so-called neutrino floor…
- An assessment of the required infrastructure in Europe
- A list of (possible) technological and scientific synergies between the different direct detection technologies and with research and R&D outside of this field...
- An inventory of physics, astronomy or other research that can be done in addition to DM direct detection with the various technologies
- In addition it would be important to discuss if such other research can be done even within the specifically proposed DM experiments
- Synergies with other experiments of indirect, accelerator and cosmology DM searches should also be considered, including possible technical and R&D synergies, e.g., with CERN, other laboratories and industry
- Any other recommendations within the scope of DM direct searches that the committee deems relevant

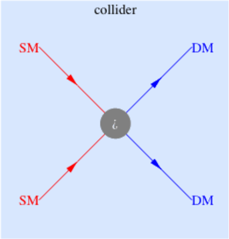
DM: particle or not?



Indirect Detection (ID)



Direct Detection (DD)

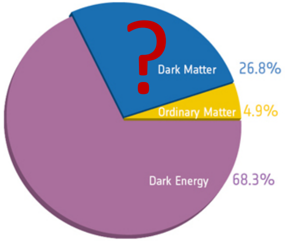


Production at colliders

prime suspect: some new particle outside the SM

Alternatives:

- Primordial black holes
- Modified gravity
- …



Scientific objectives of DD searches:

(i) to detect a signal of DM particle direct interaction with the detector, and

(ii) to determine its mass and interaction cross section, or else

(iii) to experimentally exclude the broadest accessible ranges of both quantities

> **Recommendation 1.** The search for dark matter with the aim of detecting a direct signal of DM particle interactions with a detector should be given top priority in astroparticle physics, as a positive measurement will provide the most unambiguous confirmation of the particle nature of dark matter in the Universe.

What is DM?

Theorist's view:

- **Many different approaches, ideas, frameworks, ….**

Co-scattering DM
1705.08450, 1705.09292,…

iDM
hep-ph/0101138, …

Impeded DM
1609.02147,…

Secluded DM
0711.4866, …

Selfish DM
1504.00361,…

Co-decaying DM
1607.03110, …

Forbidden DM
Griest-Seckel, 1505.07107, …

Cannibal DM
1602.04219, …

Semi-annihilating DM
1003.5912, …

Boosted DM
1405.7370, 1503.02669…

<Your choice> DM
1811.xxxx

… and many other

→ **Seemingly only limited by our ability to invent new names …**

What is DM?

For the purpose of this report:

Experimenter's view:

WIMP: weakly interacting massive particle

Two prime *classes* of candidates:

- WIMP
- axion

Candidates in both classes are:

- very strongly motivated by theory
- discoverable
- calculable
- …

They have not been invented to solve DM problem:

- **WIMP: predicted in many beyond SM (BSM) frameworks**
- **Axion: by-product of PQ solution to strong CP problem**

What does one mean by ``the WIMP”

(many) DM theorists: relic with Ωh^2 ~0.1

- **standard (thermal) WIMP**

  mass: ~GeV to TeV, ints: ~(sub)EW

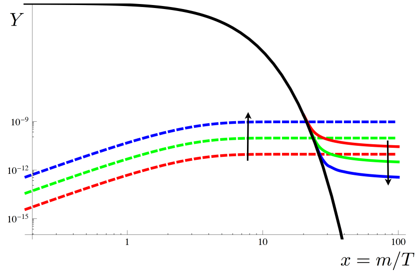
- **general (thermal) WIMP**

  mass: ~eV to ~100 TeV, ints: *not only* (sub)EW

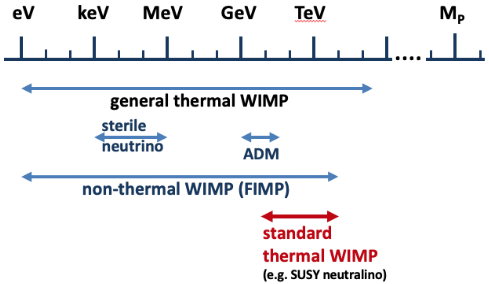
- **non-thermal WIMP (FIMP)**

  mass: ~eV to ~100 TeV, ints: usually << thermal WIMP

thermal: thermally produced via freeze-out



non-thermal: DM from freeze-in, etc



(many) DM experimentalists:

- **any ``theory WIMP”-like particle that can be searched for in ug detectors**

In Report we adopted (pragmatic) experimentalists’ WIMP notion

Experimental DM search should be inspired, but not limited, by theory

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ⓘ
Science
The Universe is out there, waiting for you to discover it.

WIMPs on Death Row

Posted on July 21, 2016 by woit

Main arguments raised against (thermal) WIMP as DM:

- **Searches have been going on for so long, with null results**
- **``most" of the allowed c.s. ranges have been ruled out, with only small remaining window left**

Is the WIMP hypothesis dead?

~GeV < mass < ~TeV

Expectations for (thermal) WIMP

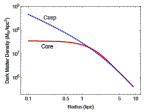
- electroweak interactions involved in production in early Universe
- Freeze-out:

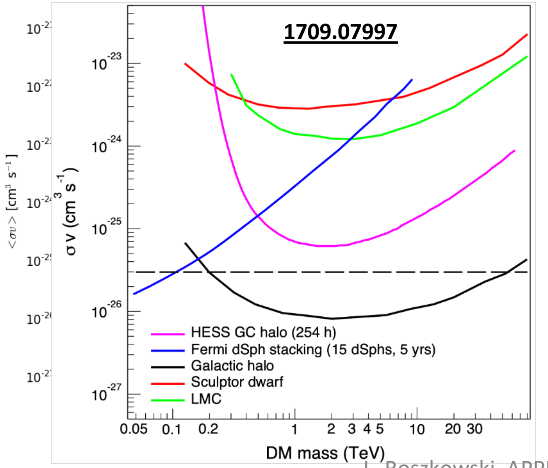
Omega*h^2=0.1 → <sigma$_{ann}$ v> ~ 3x10^{-26} cm^3/s

$$\Omega h^2 \simeq \frac{0.1}{\frac{\langle \sigma_{\rm ann} v\rangle}{3\times 10^{-26}\,{\rm cm}^3/{\rm s}}}$$

Within ~order of magnitude

- sigma*v of 3x10^{-26} cm^3/s – natural target for ID searches





Still large astrophysical uncertainties:

- Halo profiles
- Galactic center (+foreground)
- Size and distribution of DM clumps
- ...

Once the ``thermal benchmark" region is explored, then the WIMP hypothesis will become ``disfavoured"

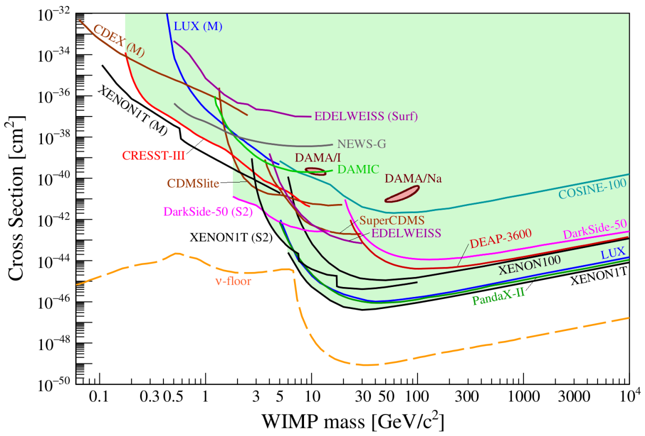
(except for ADM)

Is there an analogous ``benchmark” c.s. for DD searches?

No!

Theoretical predictions:
- are model dependent
- lower limits depend on theoretical expectations/assumptions
- Are known to have ``blind spots” of vanishing DD c.s.

➡ Still unexplored ranges of c.s. are a priori as probable as already excluded ones



DD target: reach down to ``neutrino floor”

Claims that thermal WIMP as DM is ``disfavored” are unfounded.

``GeV-scale thermal WIMPs: Not even slightly ruled out”

Leane, et al, 1805.10305

Lessons to learn from:
- Higgs boson search at the LHC: most of mass range ruled out before discovery was made in a ``tiny’’ ~15 GeV window (predicted by SUSY)
- Gravitational waves -- nearly 40 years of null searches

Axion

See talks by Laura Covi and Béla Majorovits

- a – pseudo-goldstone boson by–product of PQ solution of strong CP problem
- global $U(1)$ group spontaneously broken at scale $f_a \sim 10^{11}\,\mathrm{GeV}$
- two main frameworks:
  - DFSZ axion: add two doublets
  - KSVZ axion: add heavy single quark with mass $m_Q \sim f_a$
- $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$
- $m_a \simeq 10^{-5}\,\mathrm{eV} \Leftrightarrow \Omega_a \simeq 1$
- DM axion search: resonant cavity $a\gamma \to a\gamma$
- solar axion search: $\gamma\gamma \to a \to \gamma\gamma$

expt sensitive to cosmologically subdominant a

$$\mathcal{L}_{\mathrm{QCD}} : \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

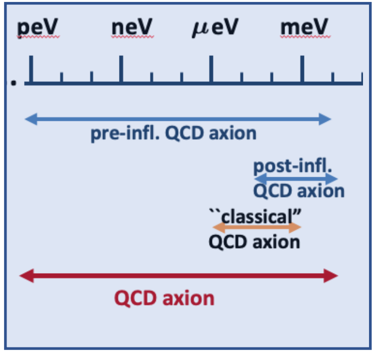
$$d_n \sim 10^{-16}\theta\, e\cdot \mathrm{cm}$$

$$\mathrm{expt}: \ \theta < 10^{-10}$$

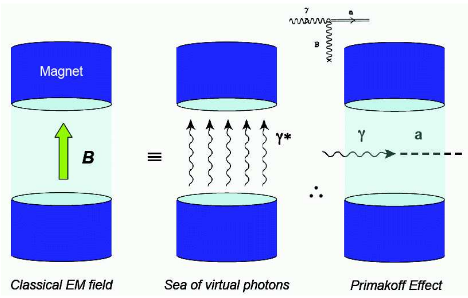
Several cosmological scenarios

(benchmark) QCD axion

$$m_a = 5.7(7)\,\mu\mathrm{eV}\, \frac{10^{12}\,\mathrm{GeV}}{f_a}$$



Primakoff effect

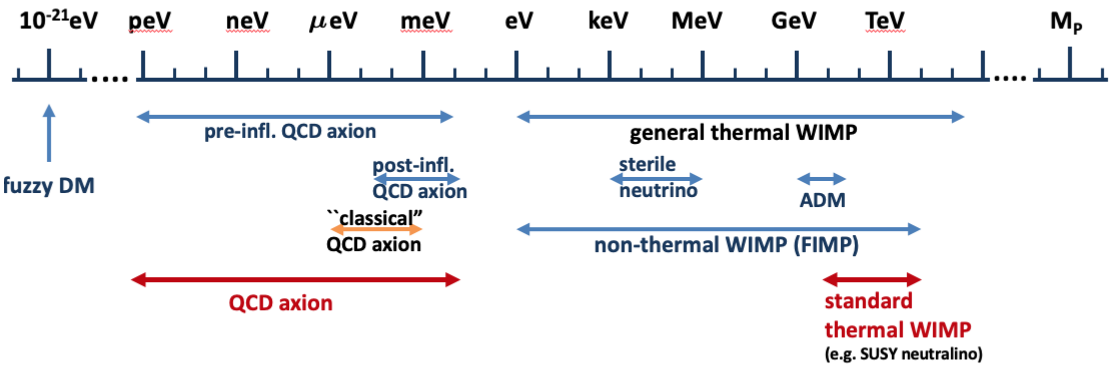


ALPs (axion-like particles)

- **any pseudoscalar that couples to two photons**

+a/ALP-electron coupling

Axion/ALP and WIMP search arena

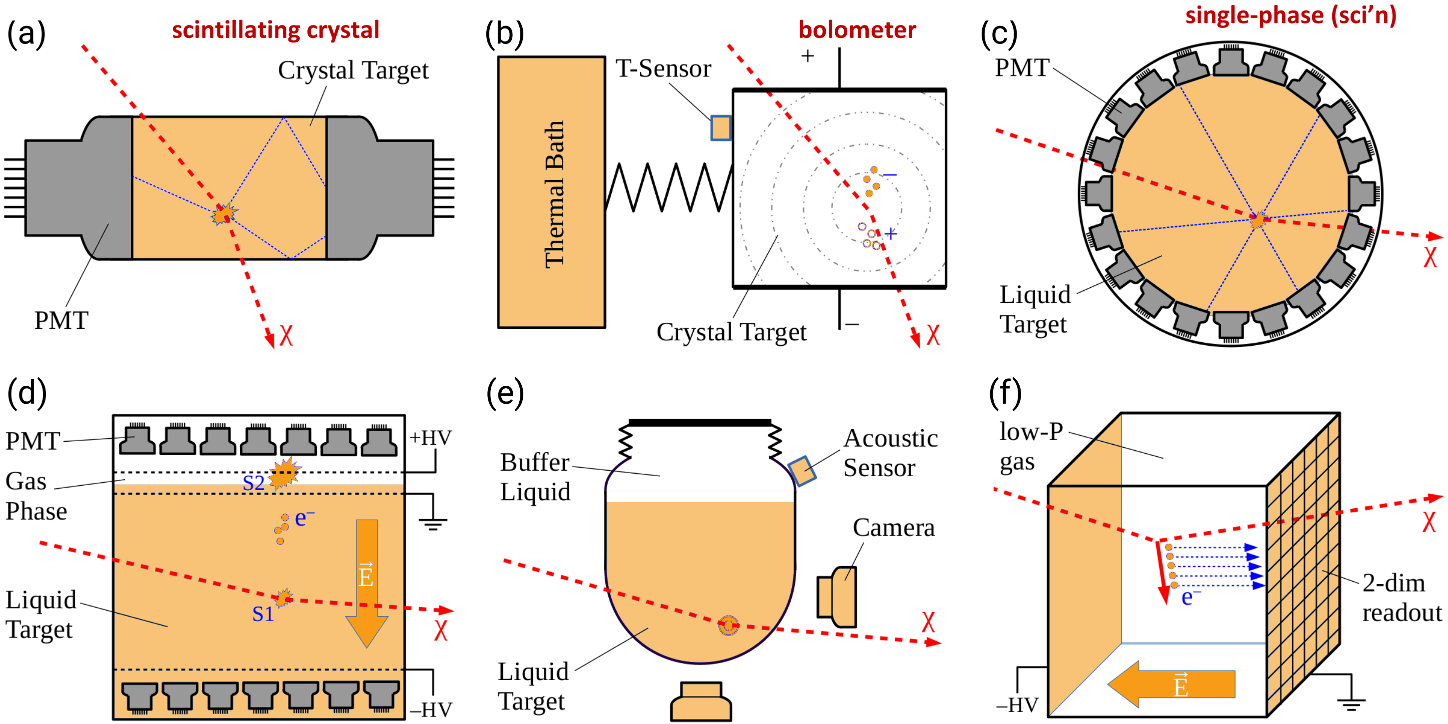


Report: experimental DM search to be inspired, but not limited, by theory

Recommendation 2. The diversified approach to probe the broadest experimentally accessible ranges of particle mass and interactions is needed to ensure the most conservative and least assumption-dependent exploration of hypothetical candidates for cosmological dark matter or subdominant relics.

DD of WIMP DM: Search techniques

See talk by Federica Petricca



liquid noble gas

dual-phase TPC

(sci'n S1 + ion'n S2)

bubble chamber

directional

M. Schumann

Main: nuclear recoil

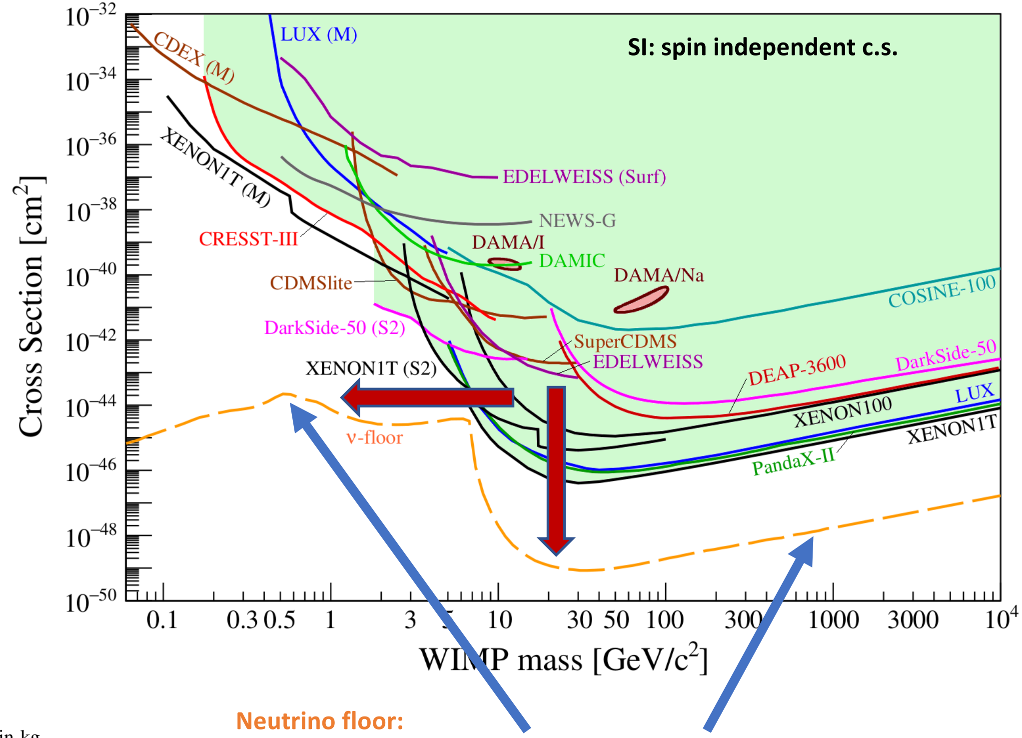
Lower mass: electron recoil

Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale
Cryogenic bolometers (Section 4.6.1)							
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running
LXe detectors (Section 4.6.2)							
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	~2026
LAr detectors (Section 4.6.3)							
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD
NaI(Tl) scintillators (Section 4.6.4.1)							
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.
COSINUS-1π	LNGS	NaI	~1	AM	1×10^{-43} @ 40	3×10^{-4}	2022
Ionisation detectors (Section 4.6.4.2)							
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running
DAMIC-M	LSM	Si	~0.7	SI	3×10^{-43} @ 3	0.001	2023
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running
NEWS-G	SNOLAB	Ne,He		SI			comm.
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.
Bubble chambers (Section 4.6.4.3)							
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running
PICO-500	SNOLAB	C_3F_8	1 t	SD	$\sim 1 \times 10^{-42}$ @ 50		in prep.
Directional detectors (Section 4.6.5)							
CYGNUS	Several	He:SF_6	10^3 m^3	SD	3×10^{-43} @ 45	6 y	R&D
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D

Table 1: Current, upcoming and proposed experiments for the direct detection of WIMPs. Mass is given in kg unless explicitly specified. The experiments' main detection channel (Ch) is abbreviated as: SI (spin independent WIMP-nucleon interactions), SD (spin dependent), AM (annual modulation). The sensitivity is reported for this channel, assuming the quoted exposure. Note that many projects have several detection channels. comm. = experiment under commissioning.

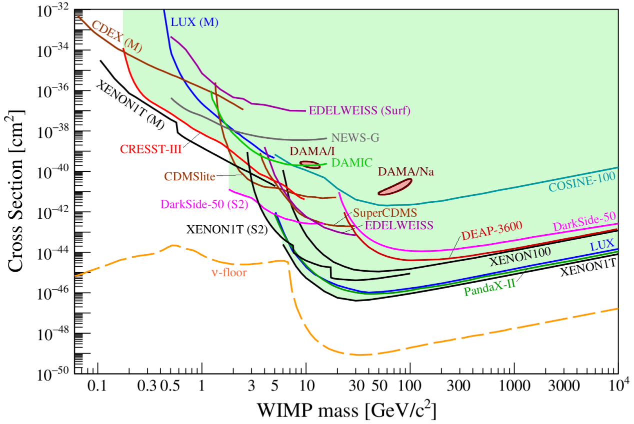
*No decision yet. A CDR for LNGS is being prepared.

Present:

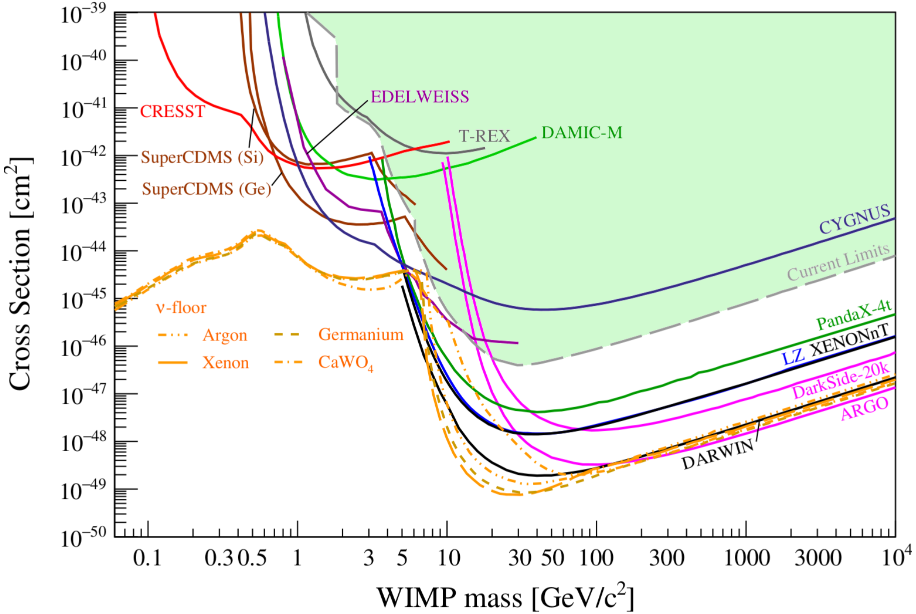


Neutrino floor:
Coherent interactions of solar or atmospheric neutrinos with nuclei

Present



Next decade(+)



Recommendation 3. The experimental underground programmes with the best sensitivity to detect signals induced by dark matter WIMPs scattering off the target should receive enhanced support to continue efforts to reach down to the so-called neutrino floor on the shortest possible timescale.

Beyond currently leading efforts..

- verify DAMA/LIBRA claim (NaI scintillators)
- directional detectors: once WIMP DM detected, will become key to confirm its halo origin
- very light WIMP mass regime <~ MeV: much R&D in the USA, little in Europe
- various innovative R&D in many experimental programmes, links to other branches of science, hi-tech, medicine (PET), …

Recommendation 4. European participation in DM search programmes and associated, often novel, R&D efforts, that currently do not offer the biggest improvement in sensitivity should continue and be encouraged with view of a long-term investment in the field and the promise of potential interdisciplinary benefits.

Infrastructure

Laboratory	LNGS	LSC	LSM	Boulby
Country	Italy	Spain	France	UK
Depth (m.w.e)	3600	2450	4800	2820
Muon Flux ($\mu/\mathrm{m}^2/\mathrm{s}$)	3×10^{-4}	3×10^{-3}	5×10^{-5}	4×10^{-4}
Volume (m^3)	180000	8250	3500	4000
Access	Road	Road	Road	Shaft
Personnel	O(100)	O(10)	O(10)	O(5)
DM Experiments*	8	2	3	1

See talk by Giuliana Fiorillo

WIMP searches:
deep underground labs

General needs: stable conditions, low radioactivity (muon, Rn,…), dedicated infrastructure: cleanrooms, cryostats, radiopure electronics, ug storage of large amounts of (cryogenic) noble gases, ….

Cooperation with large laboratories – especially CERN -- would be highly beneficial

- **It would enhance synergies from developing common technologies, …**

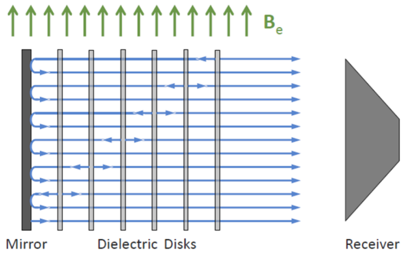
e.g. LAr:
common technologies
with (proto)DUNE

Recommendation 5. The long-term future of underground science in Europe would strongly benefit from creating a distributed but integrated structure of underground laboratories for the 21st century. This strategic initiative would be most efficiently realised by forming the *European Laboratory of Underground Science*.

Axion/ALP Searches

See talk by Béla Majorovits

- **Haloscopes:**
  - Cavity
  - Dielectric
  - Dish antenna
  - Plasma
  - Topological insulators
  - NMR technique
  - …



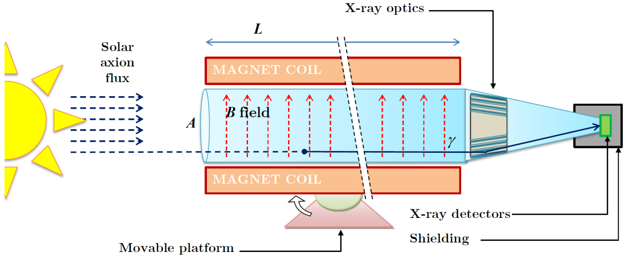
dielectric haloscope

Infrastructure needs:

- large halls
- stable, low em bgnd
- cryogenic infrastructure

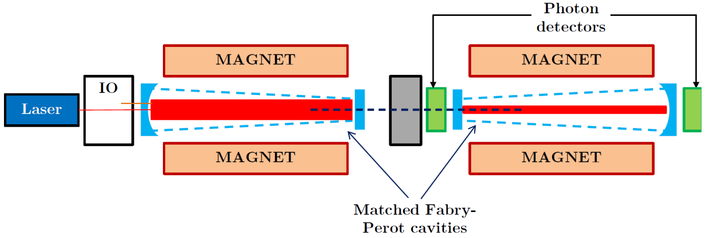
Large superconducting magnets

- **Helioscopes:** Use dipole magnets pointing at the Sun



IaXO helioscope

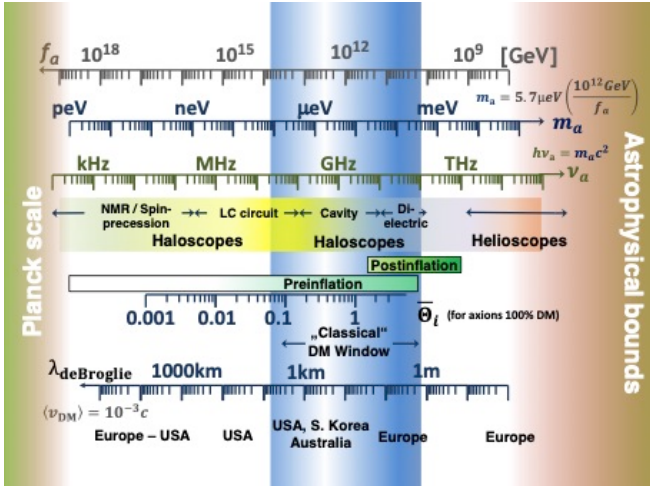
- **Laboratory:** Produce axion/ALP, detect photon

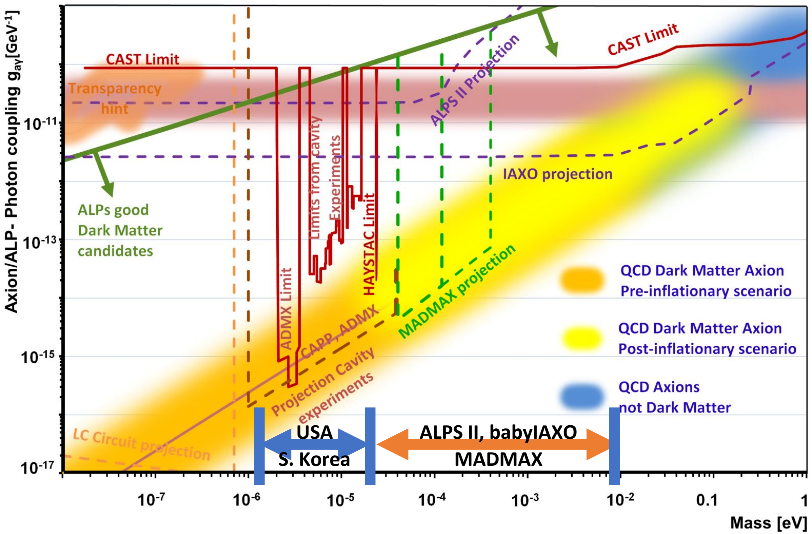


LSW: light-shining-through-the-wall

Solar axion/ALP, mass ~> keV

- **Low-background experiments:**
  - Limits from XENON100, PandaX, LUX, XENON1T





Recommendation 6. European-led efforts should focus on axion and ALPs mass ranges that are complementary to the established cavity approach and this is where European teams have a unique opportunity to secure the pioneering role in achieving sensitivities in axion/ALP mass ranges not yet explored by experiments conducted elsewhere. In parallel, R&D efforts to improve experimental sensitivity and to extend the accessible mass ranges should be supported.