Direct Detection of Dark Matter*

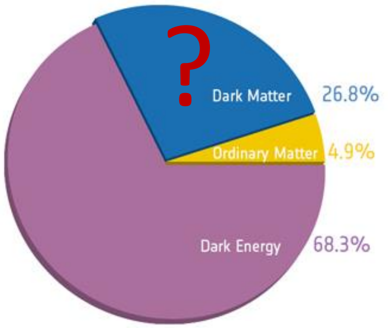
* In Europe, or with a substantial European involvement (in a global context)

APPEC Committee Report

2104.07634, Reports on Progress in Physics 85 (2022) 5, 056201

Committee:
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

Leszek Roszkowski
Astrocent CAMK and NCBJ, Warsaw, Poland



Evidence: convincing but so far based only on gravity

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

APPEC: AstroParticle Physics European Consortium
https://www.appec.org/

(from A. Haungs (KIT) – APPEC chair) **AstroParticle Physics European Consortium**

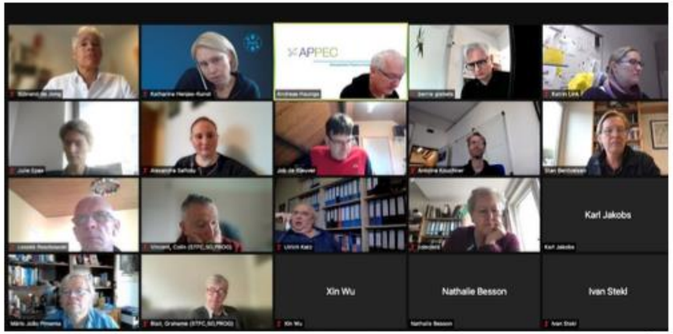
APPEC tasks

APPEC

Guarantee Coordination of European Astroparticle Physics in Europe between funding agencies and visibility at Ministry level through:

- Structured scientific advising (SAC, dedicated panels to specific challenges)
- Development and update of roadmaps based on scientific strategies and financial considerations
- Establish relations with other bodies in companion fields
- Initiate activities within Horizon Europe
- Express collective views on APP in international fora
- Organize Town meetings
- Support relevant meetings/schools of the community
- Organize TechFora and Open Calls
- Engagement with society (Outreach, Education,...)
- Contribute to Working Groups (R&D panel, Individual Recognition, Early Scientist career, Science WGs) and Organizations (EuCAPT...) and JENA

to support the Astroparticle Physics community



GA: since 2020 Online-meetings only

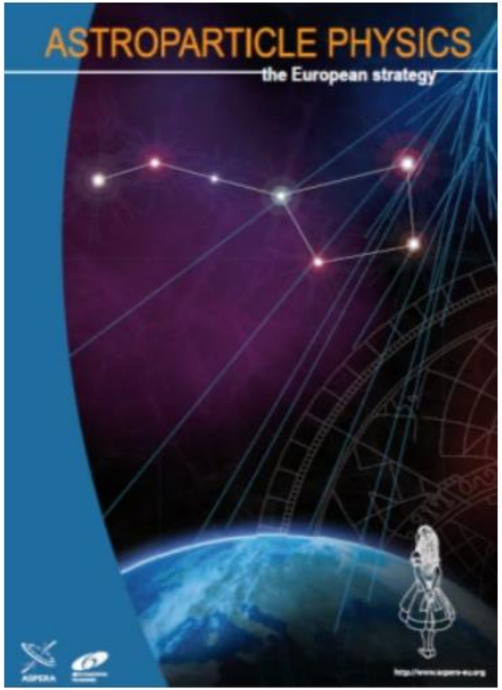
(from A. Haungs (KIT) – APPEC chair)

APPEC Roadmaps

https://www.appec.org/roadmap

APPEC

2008



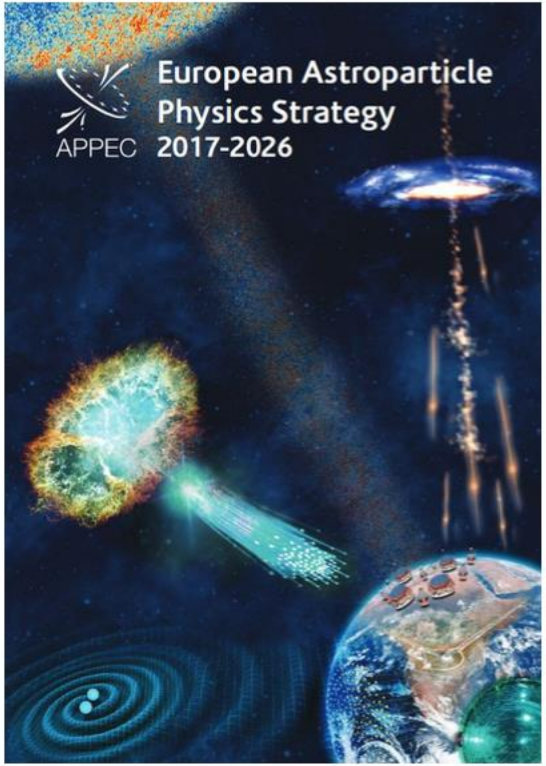
2011

2017

(from A. Haungs (KIT) – APPEC chair)

APPEC scientific topics

- High-energy gamma rays
- High-energy neutrinos
- High-energy cosmic rays
- Gravitational waves
- Dark Matter
- Neutrino mass and nature
- Neutrino mixing and mass hierarchy
- Cosmic microwave background
- Dark Energy
- Astroparticle theory
- Detector R&D
- Computing and data policies
- Unique infrastructures



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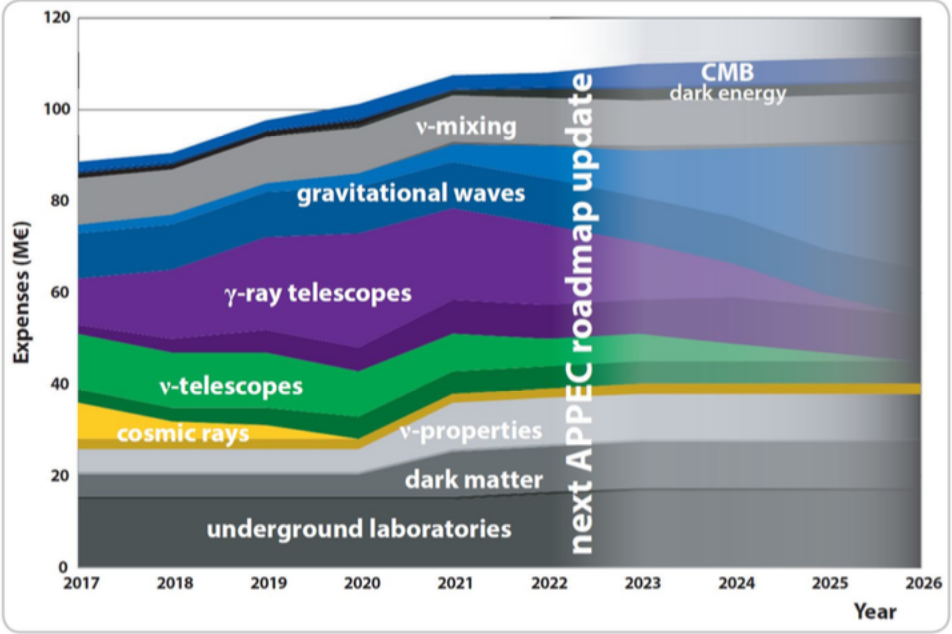
(from A. Haungs (KIT) – APPEC chair)

Midterm Evaluation of the Roadmap



From Roadmap 2017: Projected annual capital investment

- A resource aware roadmap
  (darker colors also show M&O of RI)
- Midterm Evaluation: Preparation of roadmap update
  - Direct Dark Matter working group
  - Double Beta Decay APPEC Sub-Committee
  - Multi-Messenger Discussion Workshop
  - European DUL Coordination
- Goals
  - Identify new developments and new topics
  - Update recommendations
  - Update time and cost line
- Timeline
  - Provide information to the communities (2021)
  - Discussion at the Town Meeting 9+10/6/2022 (Berlin) https://indico.desy.de/event/25372/

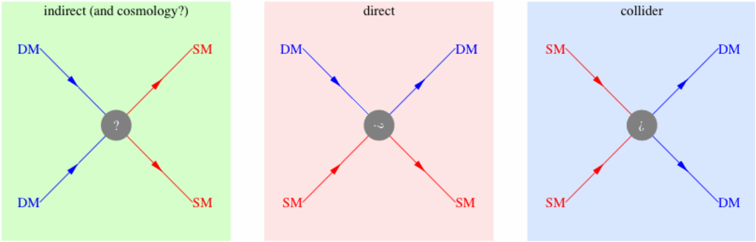
APPEC DM DD Committee mandate:

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?

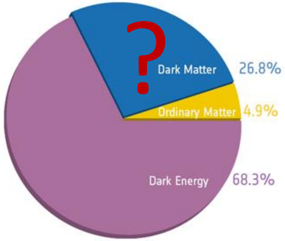


Indirect Detection (ID) **Direct Detection (DD)** **Production at colliders**

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?

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 $\Omega h^2 \sim 0.1$

- **standard (thermal) WIMP**

  mass: ~GeV to TeV, int's: ~(sub)EW

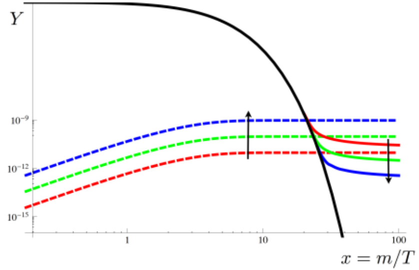
- **general (thermal) WIMP**

  mass: ~eV to ~100 TeV, int's: *not only* (sub)EW

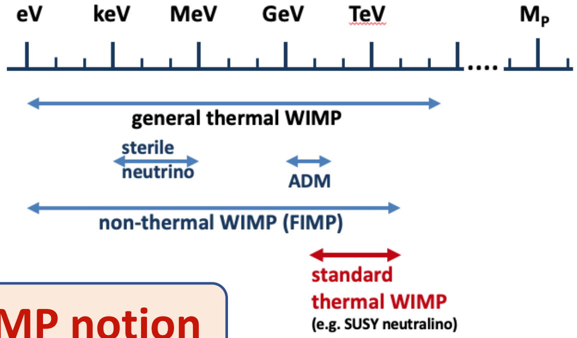
- **non-thermal WIMP (FIMP)**

  mass: ~eV to ~100 TeV, int's: 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

Claims of WIMP's death have been grossly axeggerated

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:

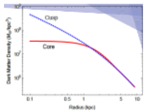
Omega*h^2=0.1 → <sigma$_{ann}$ v> ~ 3x10^{-26} cm^3/s

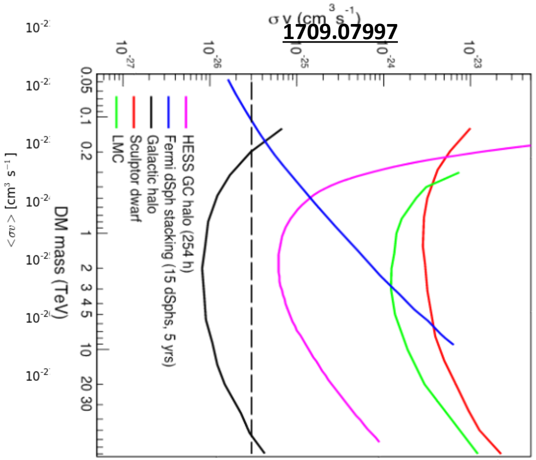
$$\Omega h^2 \simeq \frac{0.1}{\frac{\langle \sigma_{\rm ann} v \rangle}{3\times 10^{-26}\,{\rm cm^3/s}}}$$

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

Within ~order of magnitude

1709.07997





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”

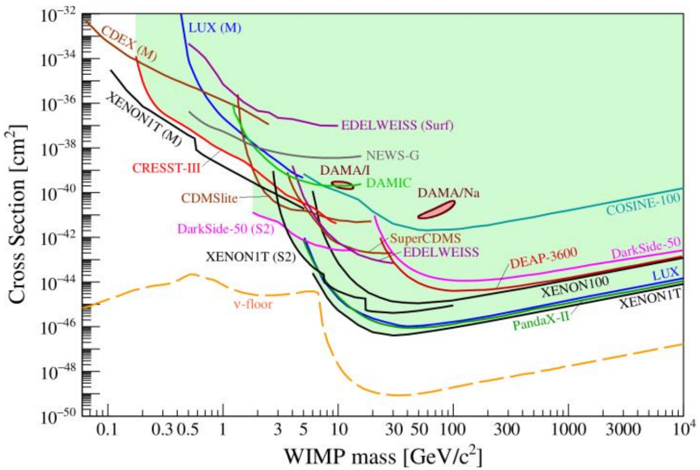
(except for ADM)

Is there an analogous ``benchmark” c.s. for direct detection 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:
- Gravitational waves -- nearly 40 years of null searches
- 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)

Axion

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

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

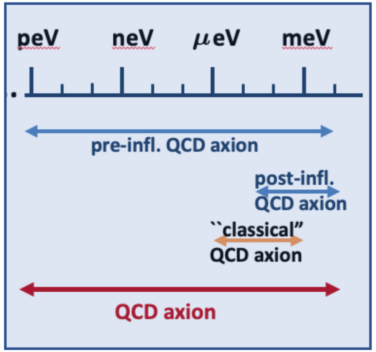
$$d_n \sim 10^{-16}\theta\, e \cdot {\rm cm}$$

$$\text{expt}: \quad \theta < 10^{-10}$$

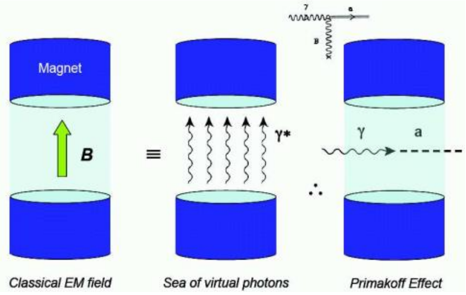
Several cosmological scenarios

(benchmark) QCD axion

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



Primakoff effect

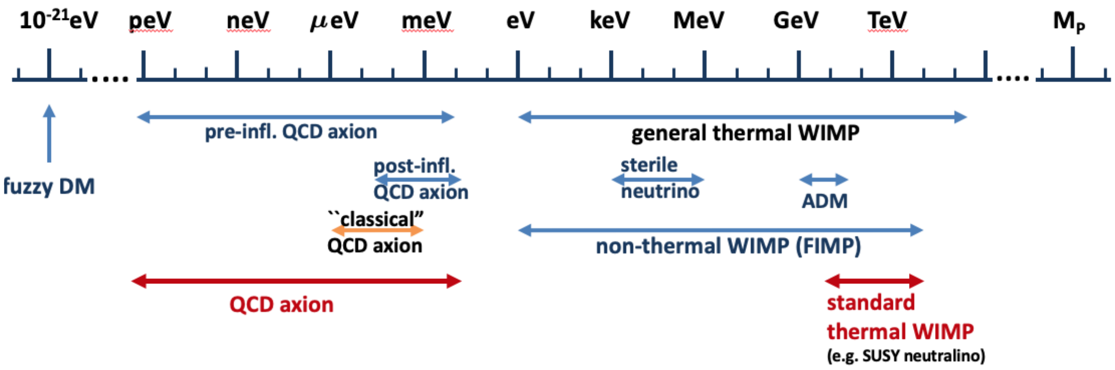


ALPs (axion-like particles)

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

+a/ALP-electron coupling

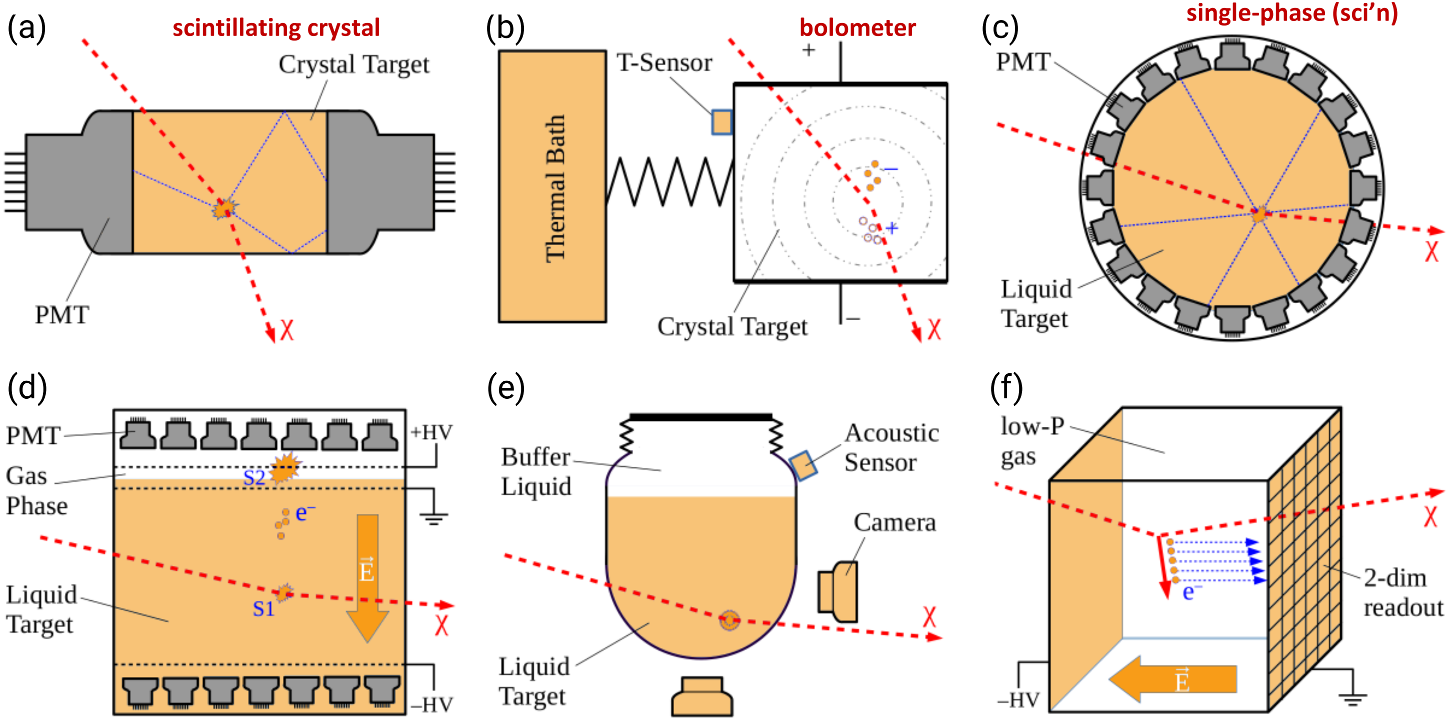
Dark matter (WIMP and axion/ALP) search arena



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



scintillating crystal

bolometer

liquid noble gas

single-phase (sci’n)

liquid noble gas

dual-phase TPC
(sci’n S1 + ion’n S2)

bubble chamber

directional

M. Schumann

Main: nuclear recoil

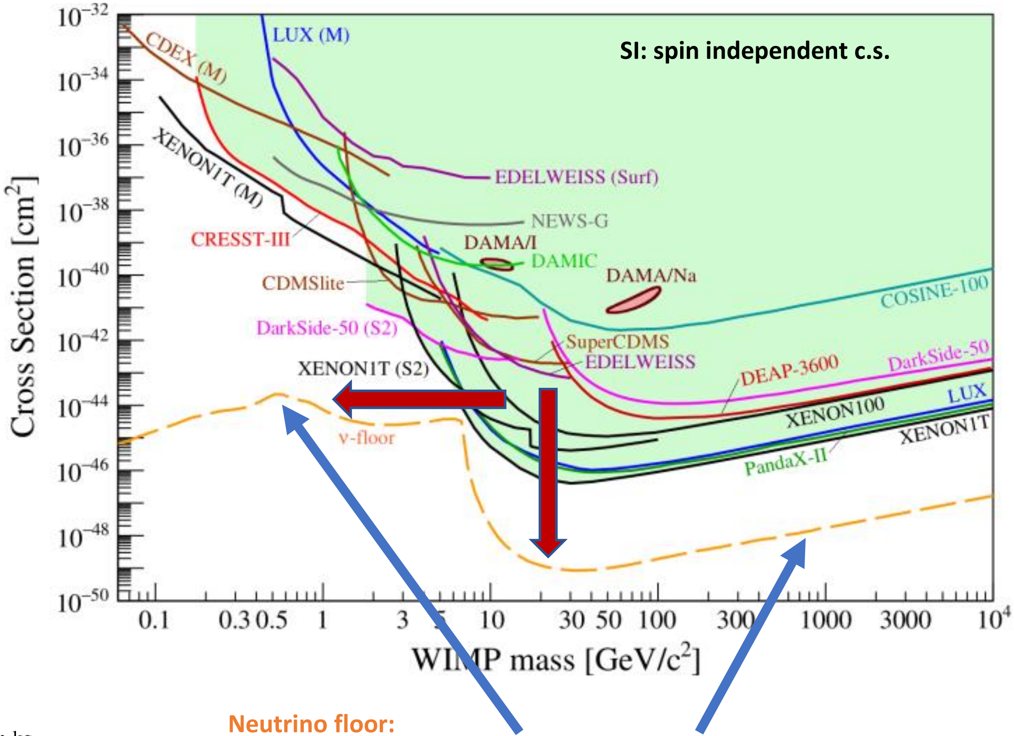
Lower mass: electron recoil

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 (2021):



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

Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2 @ GeV/c^2]	Exposure [t× year]	Timescale
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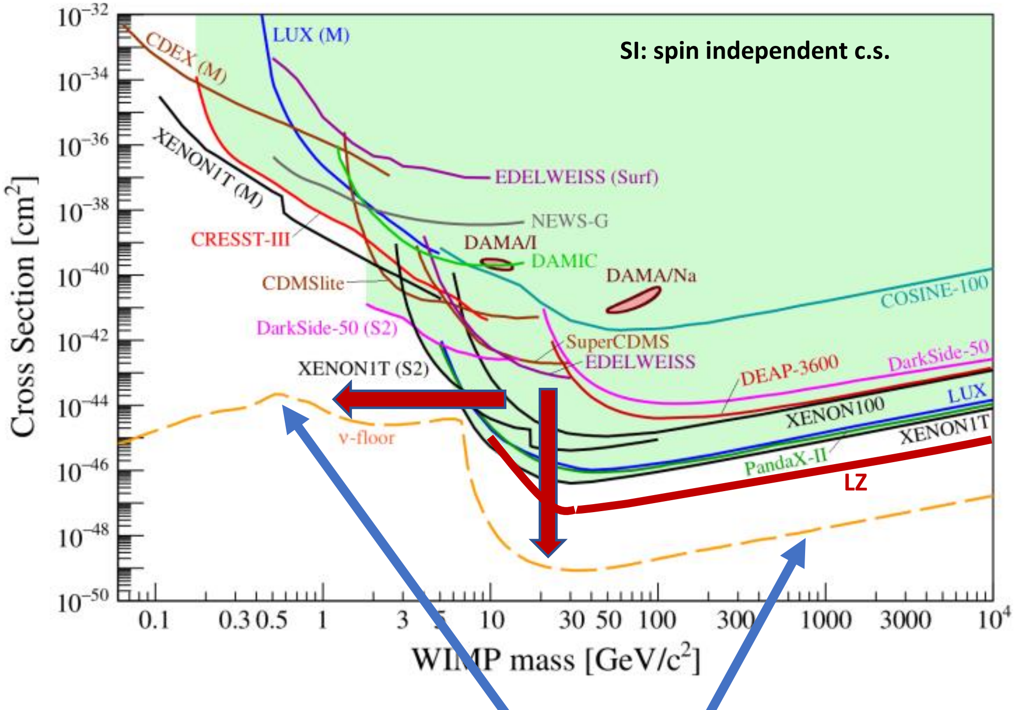
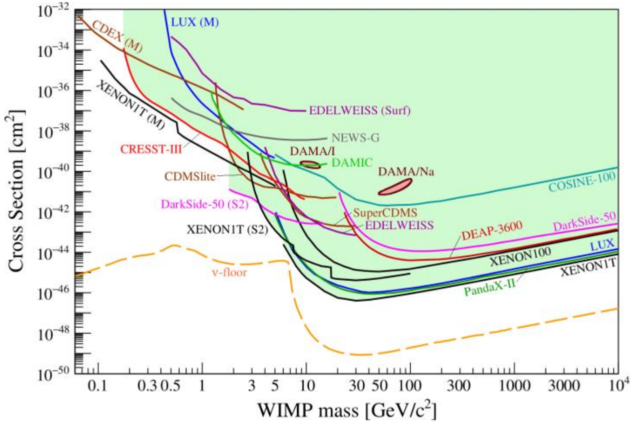
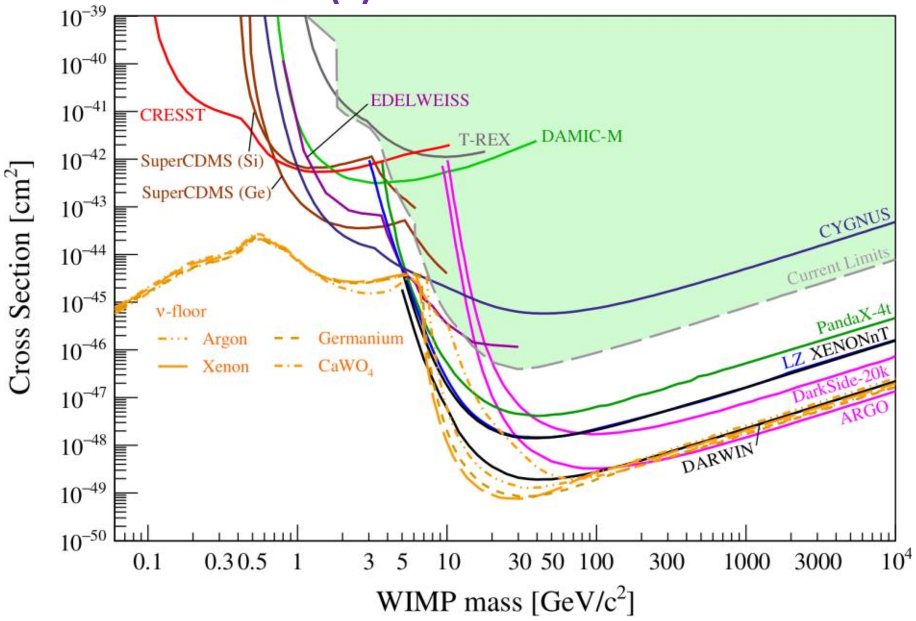


Neutrino floor:
Coherent interactions of solar or atmospheric neutrinos with nuclei

Present



Next decade(+)

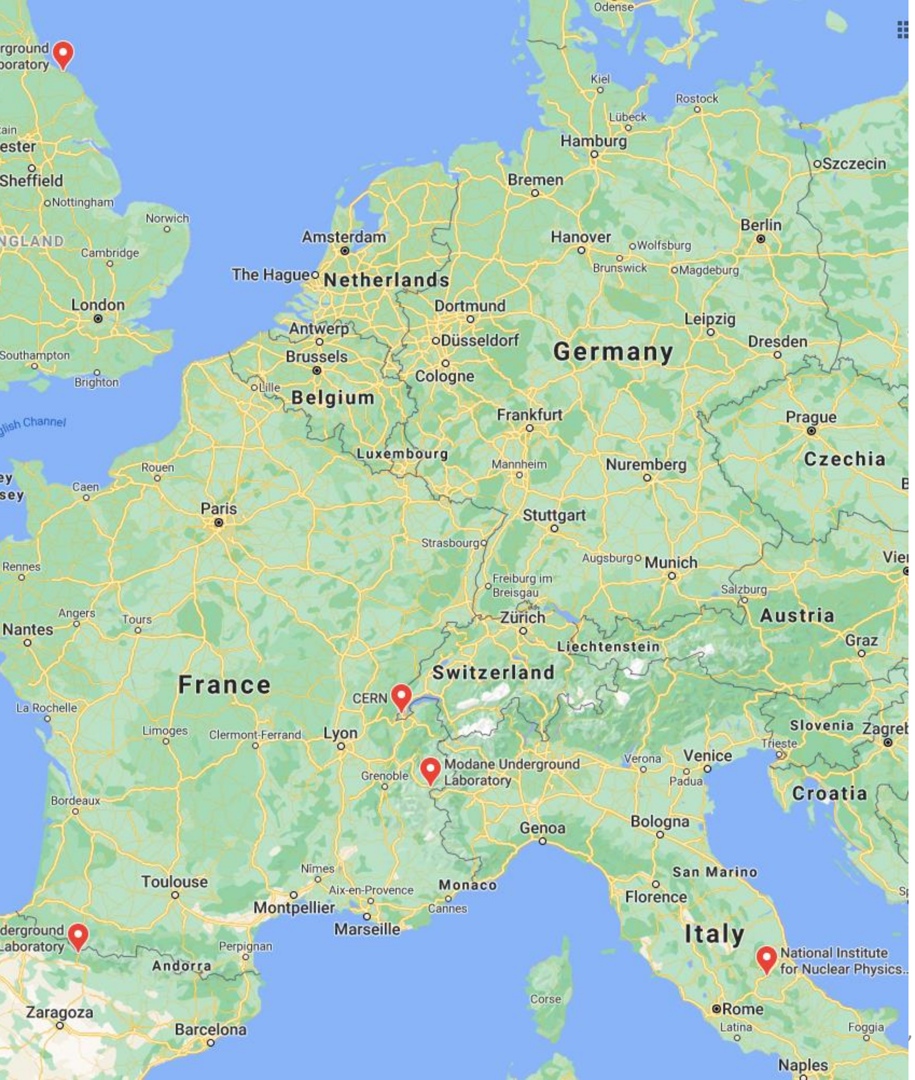


Recommendation 3. The experimental underground programmes with the best sensitivity to detect signals induced by dark matter WIMPs scattering off the target should receive enhanced support to continue efforts to reach down to the so-called neutrino floor on the shortest possible timescale.

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), …

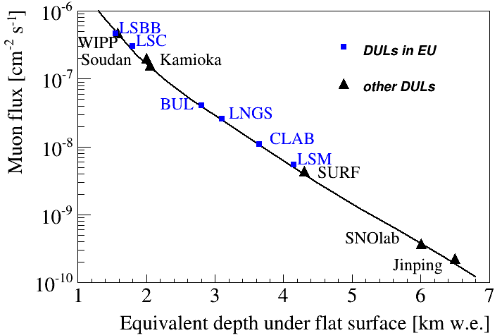
Recommendation 4. European participation in DM search programmes and associated, often novel, R&D efforts, that currently do not offer the biggest improvement in sensitivity should continue and be encouraged with view of a long-term investment in the field and the promise of potential interdisciplinary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



European UG Laboratories

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

Table 12: Main features of the large European underground laboratories hosting DM experiments: Laboratori Nazionali del Gran Sasso (LNGS), Laboratorio Subterraneo de Canfranc (LSC), Laboratoire Subterrain de Modane (LSM), and Boulby Underground Laboratory (Boulby). *Only projects running or under commissioning.



UG laboratory infrastructure

See talk by Aldo Ianni

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

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

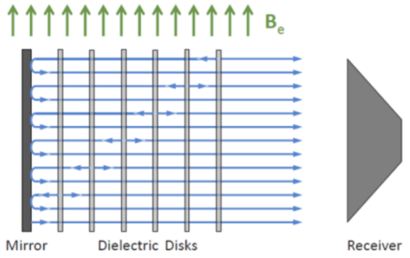
- **It would enhance synergies from developing common technologies, …**

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

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



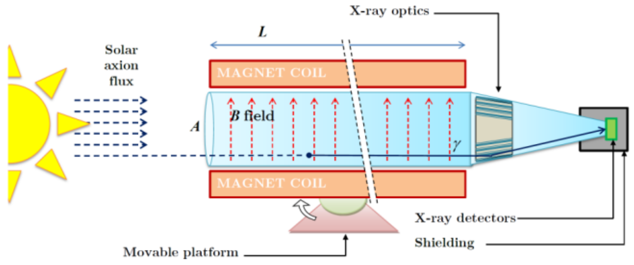
dielectric haloscope

Infrastructure needs:

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

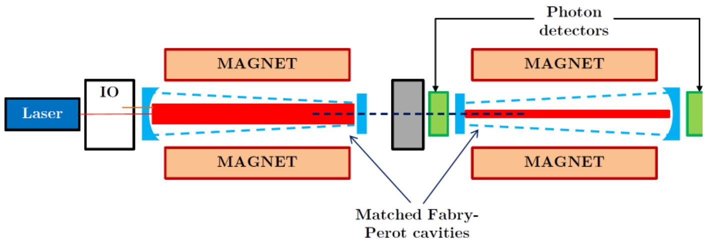
Large superconducting magnets

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



IaXO helioscope

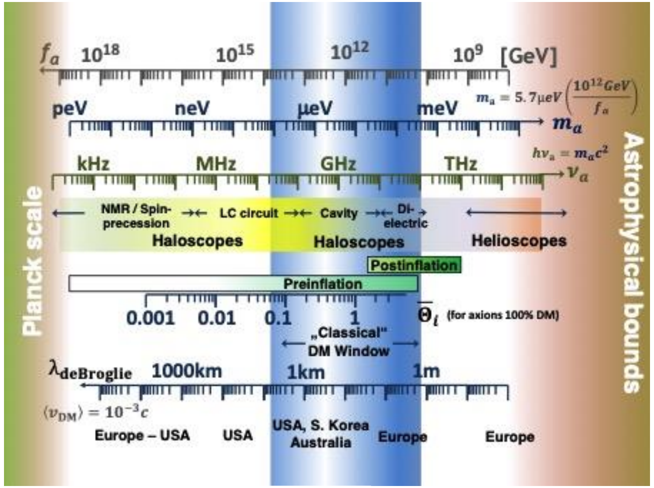
- ➢ **Laboratory:** Produce axion/ALP, detect photon

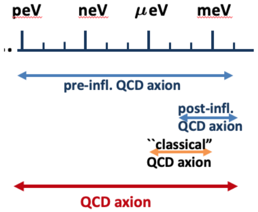


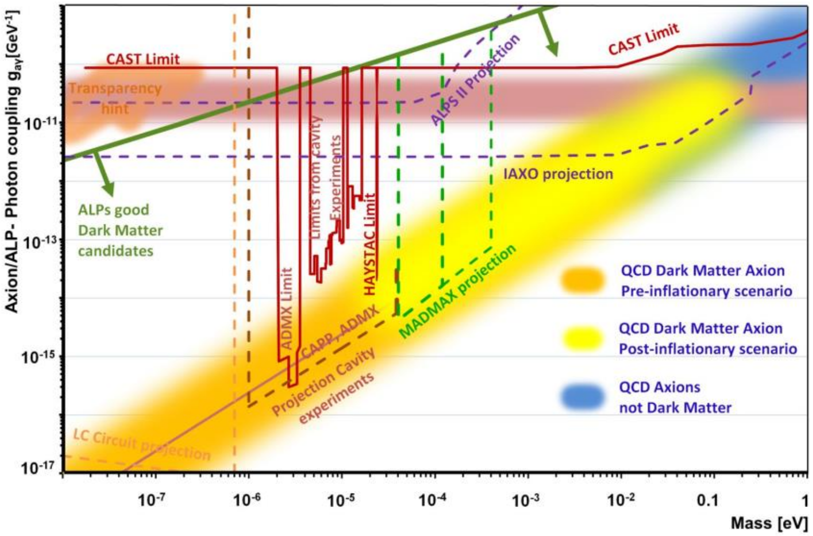
LSW: light-shining-through-the-wall

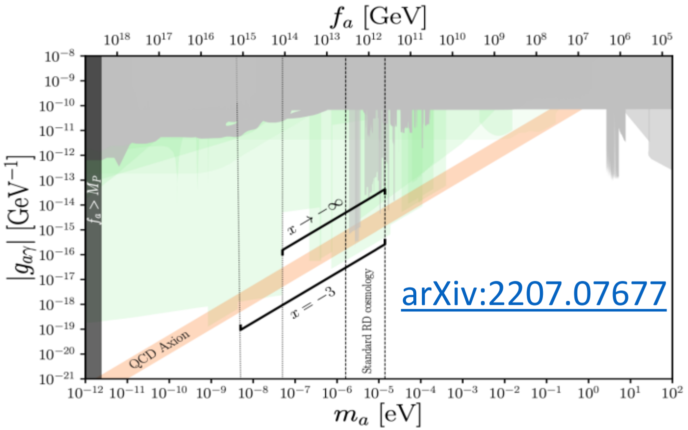
Solar axion/ALP, mass ~> keV

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





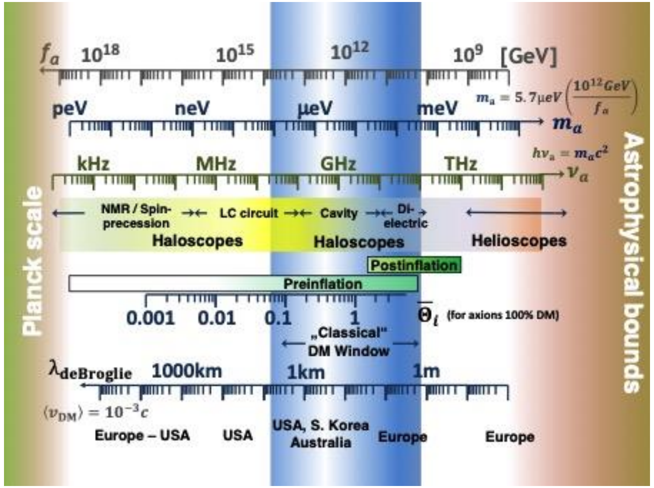


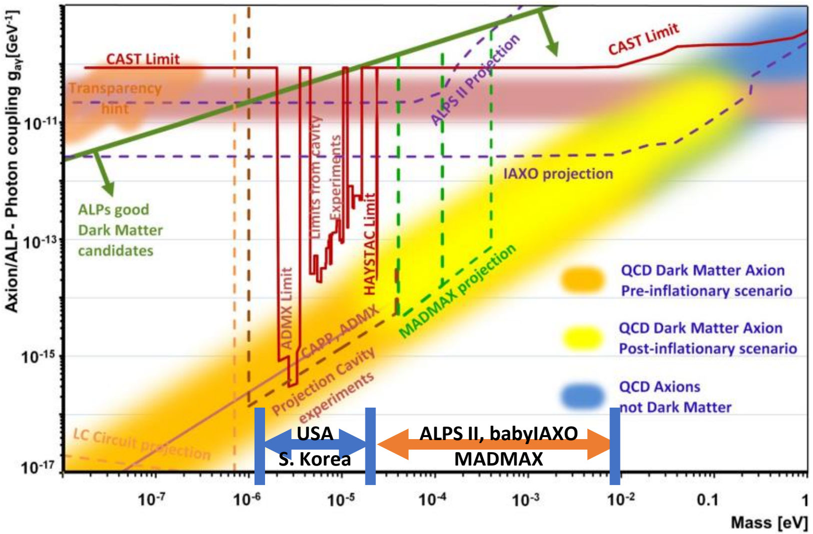


arXiv:2207.07677

Axion mass is not confined to ``standard" range of ~10^{-6}eV to ~10^{-5}eV

- **Pre- or post-inflation scenarios**
- **on-standard Big-Bang Cosmology**
- **…**





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.

Theory

- **Essential to elucidate the nature of DM**
  - **inspiration, ``new physics", candidates, ideas, …**
  - **broader context: particle physics, BB cosmology, astrophysics, …**
  - **full assessment of data from DD, ID, colliders, … in particle models**
  - **interpretation of various anomalies, hints, effects, …**
  - **numerical tools, packages, ….**

- **European astroparticle (DM) theory is world class**

Recommendation 7. Continuing dedicated and diverse theoretical activity should be encouraged not only in its own right but also as it provides some highly stimulating, and mutually beneficial, interdisciplinary environment for DM and new physics searches.

Broader context: DD searches for DM and ….

See talk by Joachim Kopp

WIMP:

- **Neutrino physics**
  - Solar
  - Atmospheric
  - Supernova
- **0nu DBD + other rare decays**

  Common needs: low bknd, large target volume

  Ge & Xe isotopes

  ^{136}Xe: limit

  DARWIN-size: sensitivity ~ of dedicated DBD
- **Other…**
  - Neutrino magnetic moments
  - New neutrino interactions
  - Dark photons
  - …
- **Collider (LHC):**
  - Discovery of EW-scale WIMP → impact on future of collider programme
  - Signal of ``new physics" at EW-to-TeV scale → inspiration for DM searches

Axion/ALP:

- High-field large-aperture magnets
- Single-photon detectors
- Low-loss RF techno & cavities
- Optical cavities and lasers
- NMR techno & spin coupling
- Very-low bgnd X-ray detectors
- Cryogenic engineering
- …

Summary and conclusions:

❖ WIMPs: European DD search is world class

Amid increasingly strong competition: USA, China, S. Korea, …

- **mass: > few GeV: Leading technology: liquid gas TPCs**
  - **XENON1T: best limit on SI c.s. → LZ (July 2022)**
  - **XENONnT: running**
  - **LAr: ambitious global programme developing [DS-50 --> DS-20k + DEAP-3600 → ARGO (300k)]**
  - **In both LXe and LAr: concrete plans set for next decade+:**
    - **DARWIN (LXe) and ARGO (LAr): to reach down to (atm.) neutrino floor**
- **Sub-GeV < mass < few GeV: Leading technology: bolometers**
  - **CRESST & Edelweiss capable of competing with SuperCDMS**
    - **Plans to reach down to within factor of 10 above (solar) neutrino floor**
  - **Dedicated sub-GeV searches (use WIMP-electron coupling)**
- **NaI scintillators: aim at verifying DAMA/LIBRA claim using annual modulation**
- **Directional detectors: currently not as sensitive, long run: key, merging (→ CYGNUS?)**
- **Plenty of highly innovative R&D, many synergies with neutrino and collider (CERN)**
- **Infrastructure for 21st century: European Laboratory of Underground Science**

❖ Axion/ALPs: leader in solar axion/ALPs searches, catching up in QCD axion search

- Aim: become leaders in complementary searches to currently world-leading (ADMX)
- **Plenty of highly innovative R&D, many synergies with collider and applied physics**

❖ Theory: world-class and essential