Status and prospects of Dark Matter direct detection experiments in the low (< 10 GeV) mass range

Susana Cebrián scebrian@unizar.es

Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Universidad Zaragoza

Laboratorio Subterráneo de Canfranc

Status and prospects of DM direct detection experiments in the low (< 10 GeV) mass range

- Direct detection of DM
- Searches for low mass DM
- Searches for distinctive signatures:
  - Annual modulation
  - Directionality
- New technologies

Susana Cebrián scebrian@unizar.es

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

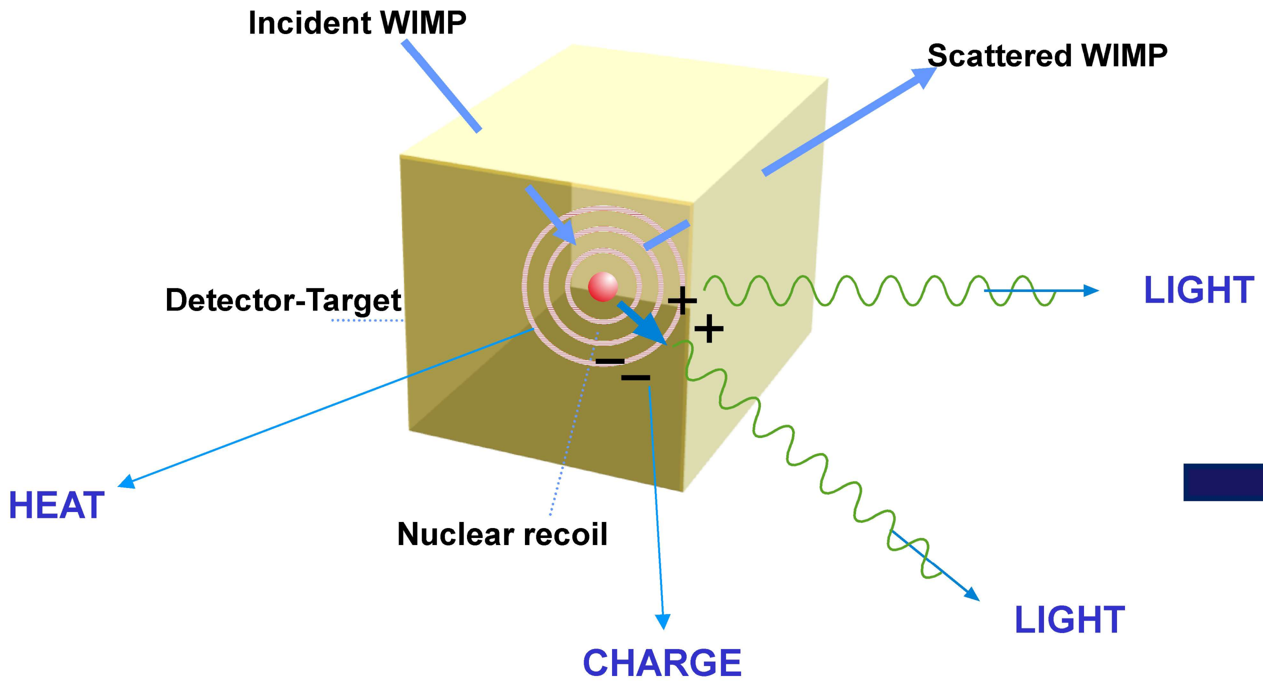
Universidad Zaragoza 1542

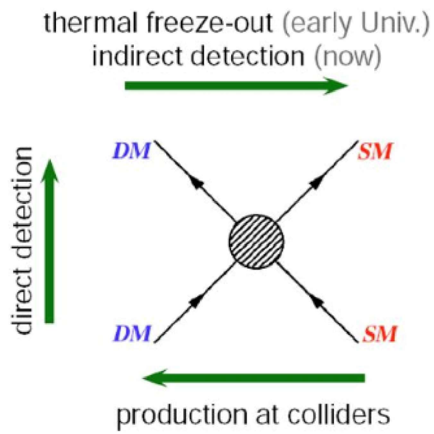
LSC Laboratorio Subterráneo de Canfranc

Direct detection of DM

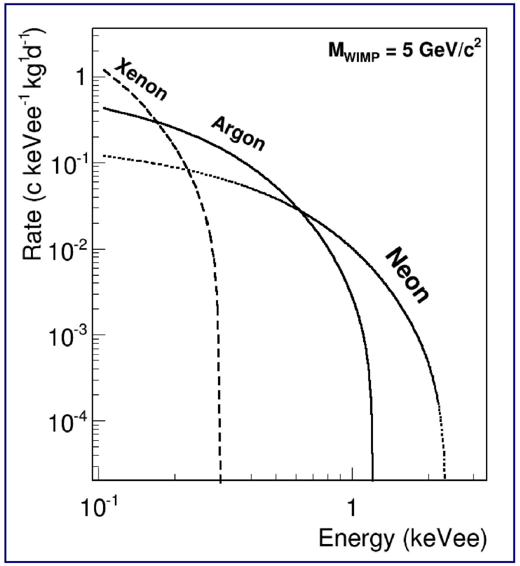
Different complementary strategies for **detection**

Direct detection: elastic scattering off target nuclei





$$\frac{dR}{dE_{\rm nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\rm min}}^{\infty} v f(v) \frac{d\sigma}{dE_{\rm nr}}\, dv$$



Challenge:

- rare signal → ultra **low background** conditions
- concentrated at very low energies → **low energy threshold**
- with continuum energy spectrum entangled with background → **distinctive signatures**

Direct detection of DM

The field is very active for more than three decades

- Using different **detection technologies**
- Focused on different **physics cases**

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioke
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	40,000 kg	200 t yr	Planning	2028	2033	LNGS / SURI
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Construction	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	NaI	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	NaI	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	NaI	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	NaI	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	NaI	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	NaI	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg		Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	SNOLAB
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Construction	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g		Running	2019		LSM
CRESST-II	Bolometer Scintillation	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillation	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Construction	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction	2021	2023	SNOLAB

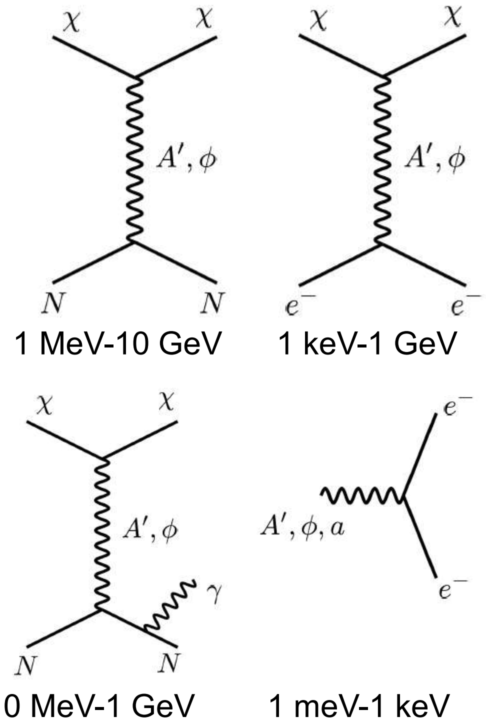
R. Gaitskell
The Identification of Dark Matter Conference (IDM2020) (Remote)

R&D
Planning
Construction
Running
Ended

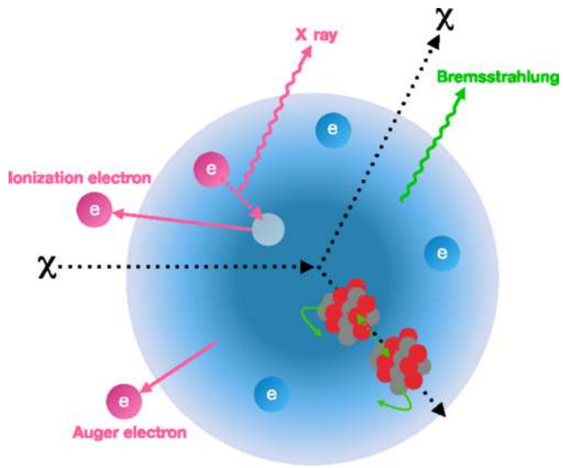
Direct detection of DM

Probe DM candidates **below the GeV scale**

- **lighter targets:** to keep kinematic matching
- lower **threshold**: to detect smaller signals
- change search **channel**: light WIMPs cannot transfer sufficient momentum to generate detectable nuclear recoils → absorption or scattering off by **nuclei (NR) or electrons (ER)**

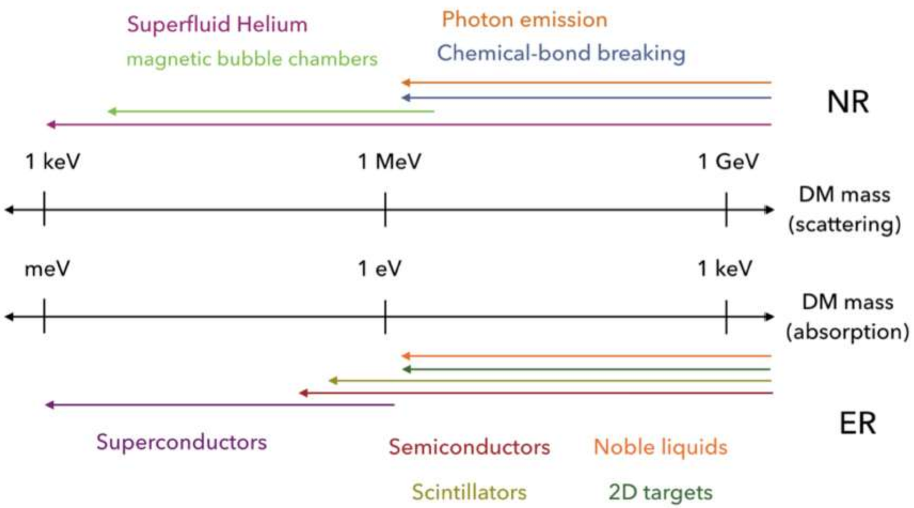


Proposed **Migdal effect:** WIMP-nucleus interaction can lead to excitation/ionization of the recoiling atom (additional signal larger for low mass DM)



E. Aprile et al, Phys. Rev. Lett. 123 (2019) 241803

US Cosmic Vision, arXiv:1707.04591



Status and prospects of DM direct detection experiments in the low (< 10 GeV) mass range

- Direct detection of DM
- **Searches for low mass DM**
  - **Bolometers**
  - **Liquid Xe and Ar detectors**
  - **Ionisation detectors**
  - **Bubble chambers**
- Searches for distinctive signatures:
  - Annual modulation
  - Directionality
- New technologies

Susana Cebrián scebrian@unizar.es

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Universidad Zaragoza 1542

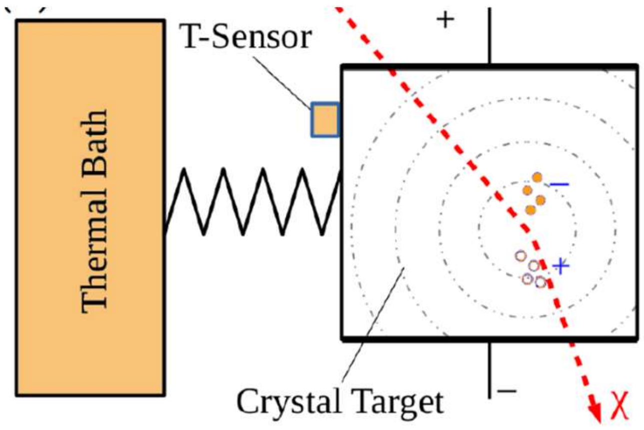
LSC Laboratorio Subterráneo de Canfranc

Low mass DM: Bolometers

Cryogenic detector: measurement of **phonons** (heat) by the tiny temperature increase induced
Simultaneous measurement of **ionization/scintillation** allows discrimination of ER and NR

+ excellent energy resolution, no quenching of heat
- difficult operation at mK, low mass crystals for low energy threshold (sub-100 eV_{nr})

→ **leading results in GeV and sub-GeV region**



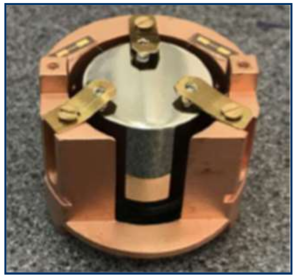
M. Schumann, J. Phys. G46 (2019)103003

EDELWEISS-III: at Modane lab (France)
24 **Ge** detectors, 870 g each, 200 eV_{ee} threshold
→ very good results at 5-30 GeV and limits also on ALP

L. Hehn et al, Eur. Phys. J. C 76 (2016) 10 548

EDELWEISS-subGeV: above ground and at Modane
33 g **Ge** bolometers
55 eV energy threshold (heat)
→ exploring DM mass down to 45 MeV (considering **Migdal effect**) and dark photons

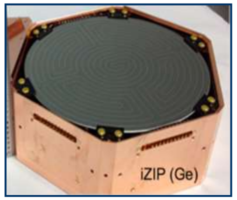
E. Armengaud et al, Phys. Rev. D 99 (2019) 082003
Q. Arnaud et al, arXiv:2003.01046

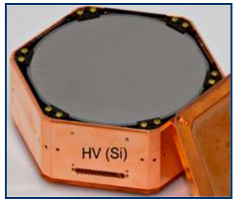


Low mass DM: Bolometers

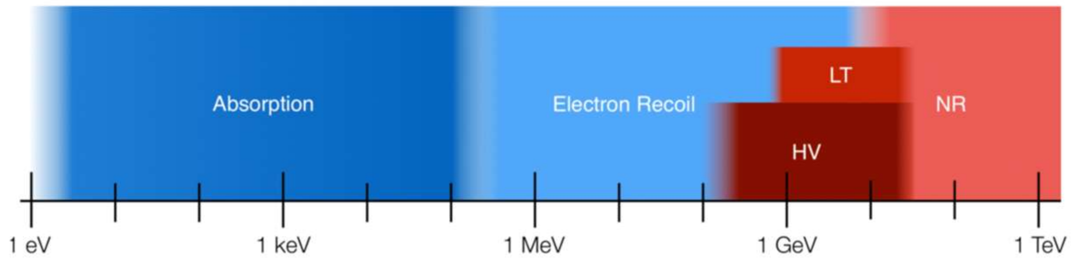
SuperCDMS: at Soudan lab (US)
15 **Ge** detectors, 600 g each, 70 eV threshold
Exploiting the Neganov-Trofimov-Luke (NTL) effect at high bias voltage (HV) to convert charge into heat
→ results down to 1.5 GeV from different analyses
R. Agnese et al, Phys. Rev. Lett. 120 (2018) 061802; Phys. Rev. D 99 (2019) 062001

0.93 g / 10.6 g **Si** detectors on surface → results on **e scattering** and dark photons / **nucleon scattering**
D. W. Amaral, et al, arXiv:2005.14067, I. Alkhatib et al, arXiv:2007.14289

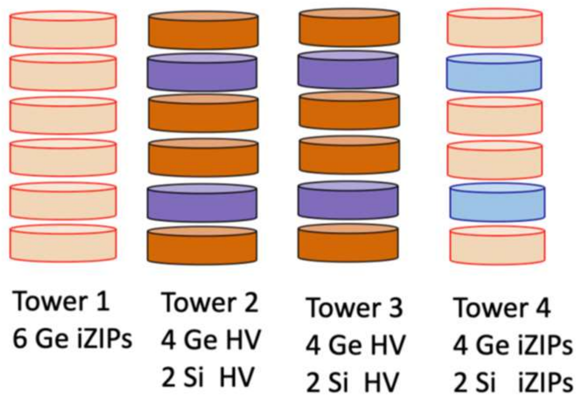




SuperCDMS: at SNOLAB (Canada)
Start mid-2021, 30 kg, **Ge** and **Si** NTL detectors



Traditional NR:	iZIP, Background free	>5 GeV
Low Threshold NR:	iZIP, limited discrimination	>1 GeV
HV Mode:	HV, no discrimination	~0.3 - 10 GeV
Electron Recoil:	HV, no discrimination	~0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimintion	~1 eV - 500 keV (peak search)



Low mass DM: Bolometers

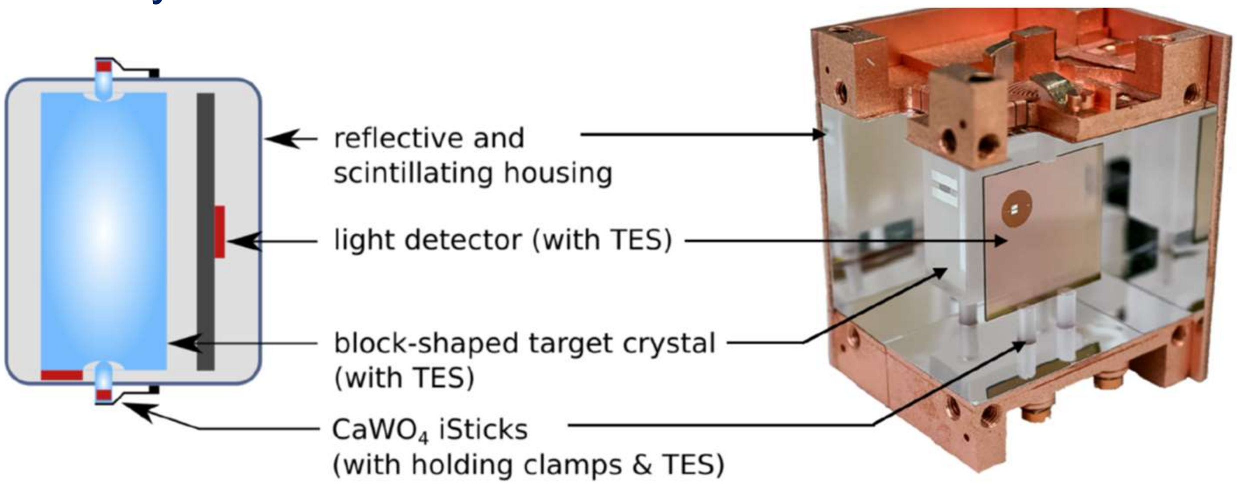
CRESST-III: at Gran Sasso lab (Italy)
10 24 g **$CaWO_4$** scintillating bolometers
15 mK
30 eV energy threshold achieved
Run 3 started on July 2020
→ best limits for WIMP-nuc down to 160 MeV
A.H. Abdelhameed et al, Phys. Rev. D 100 (2019) 102002

Phase 2:

100 crystals

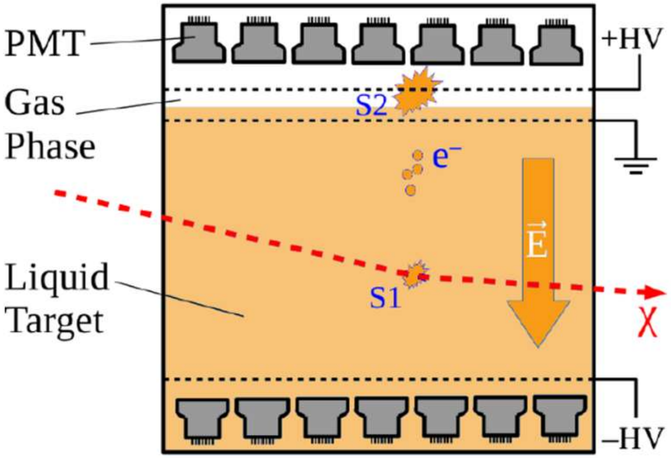
Goal 10 eV threshold

Alternative materials under study



Low mass DM: Liquid Xe detectors

Noble gases (Xe, Ar) scintillate and can be ionized
Liquid state: massive and compact DM targets
→ **leading results from a few GeV to TeV**

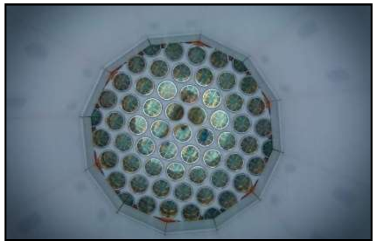


M. Schumann, J. Phys. G46 (2019)103003

Dual-phase liquid noble gas detector:
TPC measuring S1 primary scintillation +
S2 secondary scintillation from drifted e-
- + S1/S2 to distinguish ER and NR
- + 3D event reconstruction at mm (z from drift time)
- + Xe: SD interaction

XENON1T: at Gran Sasso
From 1 t y, 1 keV_{ee} (5 keV_{nr}) threshold
E. Aprile et al, Phys. Rev. Lett. 121 (2018) 111302
Only S2 signal, >0.4 keV_{ee}, results on **WIMP-e**
E. Aprile et al, Phys. Rev. Lett. 123 (2019) 251801

LUX: at SURF (US)
D.S. Akerib et al, Phys. Rev. Lett. 118 (2017) 021303
PANDAX-II: at Jinping (China)
X. Cui et al, Phys. Rev. Lett. 119 (2017) 181302
Q. Wang, arXiv:2007.15469
→ **strongest constraints >6 GeV**



Low mass DM: Liquid Xe detectors

Search for light DM enhanced by the **Migdal effect or Bremsstrahlung** looking for e recoils

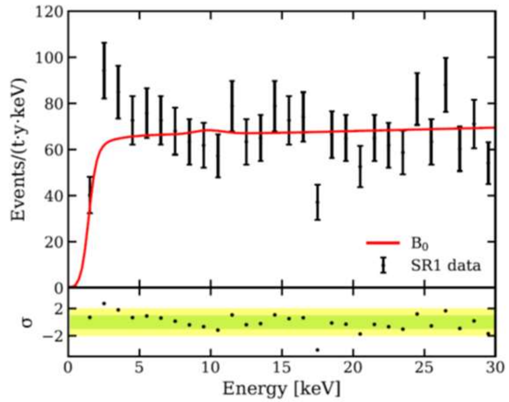
E. Aprile et al, Phys. Rev. Lett. 123 (2019) 241803

D.S. Akerib et al, Phys. Rev. Lett. 122 (2019) 131301

Many searches for **other DM models**: inelastic WIMP-nuc, WIMP-nuc Effective Interactions, bosonic Super-WIMPs, light mediators, dark photons…

Solar axions or axion coupling as an explanation of XENON1T excess of ER? →

E. Aprile et al, arXiv:2006.09721 [hep-ex]



Being built or commissioned (operation 2021-2025):

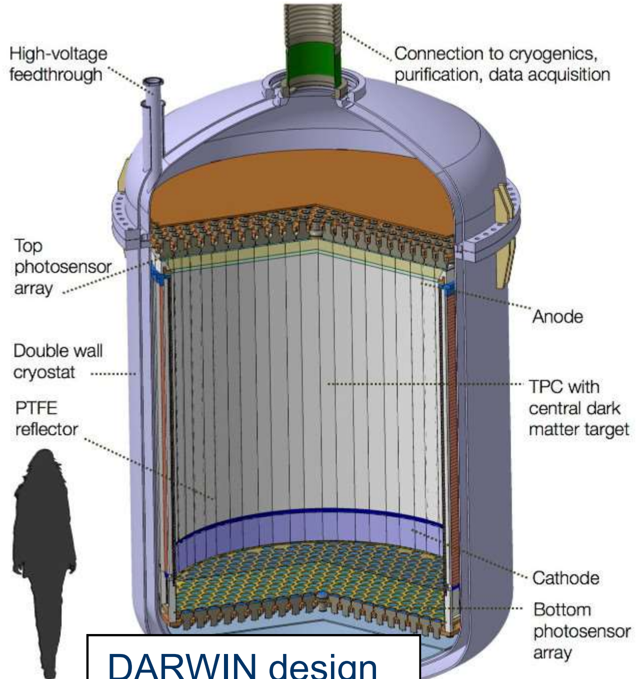
LUX-ZEPLIN (LZ): at SURF
7 t active mass

PANDAX-4T: at Jinping

XENONnT: at Gran Sasso
5.9 t active mass

DARWIN: at Gran Sasso?
40 t, target 200 t y, start 2027

Lowering LZ TPC into inner cryostat



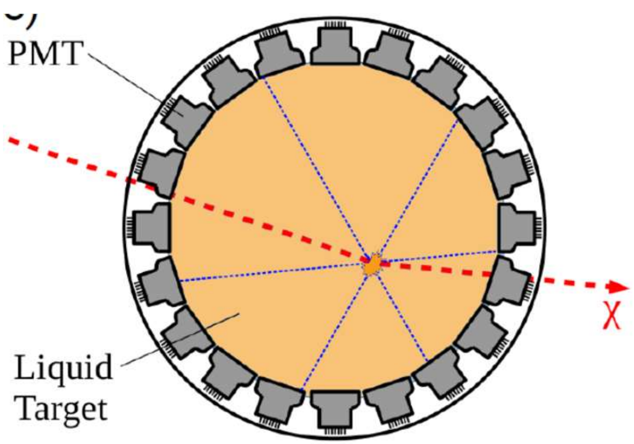
DARWIN design

Low mass DM: Liquid Ar detectors

Different scintillation pulse shape for ER and NR → very efficient PSD

Single-phase liquid Ar detector: measuring only scintillation.
+ PSD, position reconstruction

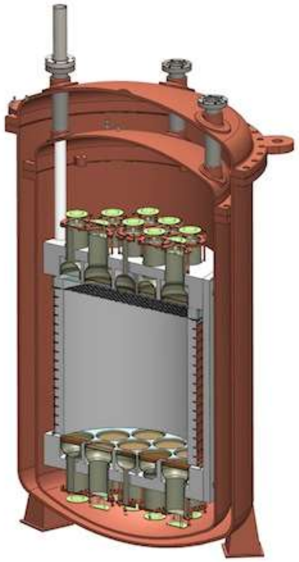
DEAP-3600: at SNOLAB
Results from 231 days
ER leakage probability of 4 10^{-9}
R. Ajaj et al, Phys. Rev. D 100 (2019) 022004



M. Schumann, J. Phys. G46 (2019)103003

Dual-phase liquid Ar detector:
S1/S2 measurement + PSD

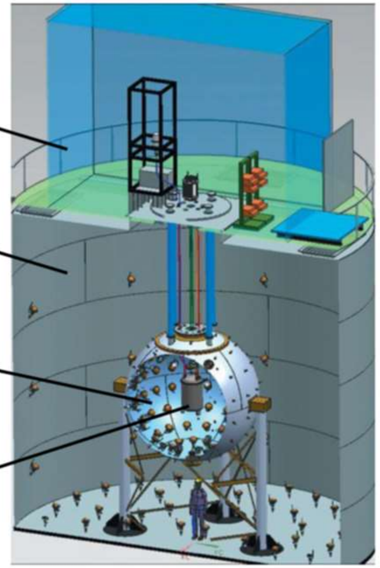
DarkSide-50: at Gran Sasso
Viability of underground Ar, with low ^{39}Ar
Results from 2 y
P. Agnes et al, Phys. Rev. D 98 (2018) 102006



Low mass DM: Liquid Ar detectors

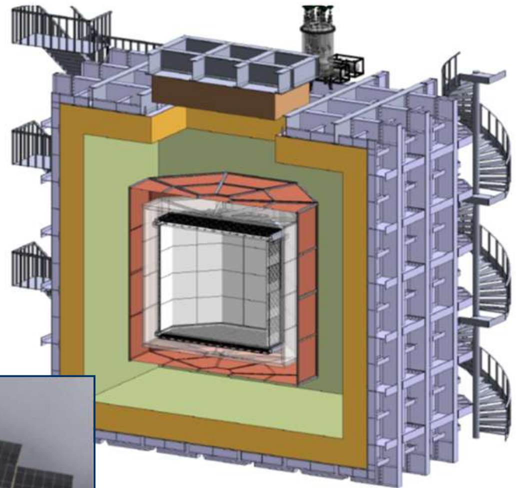
DarkSide-50: low mass DM search
Detecting S2 only
100 eV_{ee} threshold, 6786.0 kg d exposure
→ leading sensitivity at 1.8–3.5 GeV
P. Agnes et al, Phys. Rev. Lett. 121 (2018) 081307

→ results on **e scattering**
P. Agnes et al, Phys. Rev. Lett. 121 (2018) 101303.



GADMC: Global Argon DM Collaboration
Radiopure Ar from Urania+Aria facilities
Using SiPMs

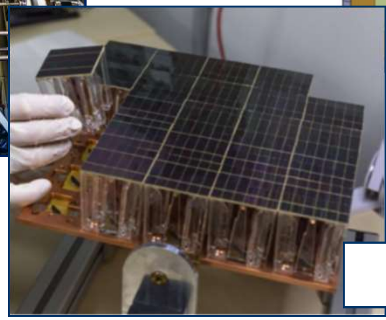

Distillation column for Aria



DarkSide-20k: at Gran Sasso
Acrylic vessels, atmospheric Ar veto
TPC 3.5 m long
Target: 200 t y exposure, start 2022

DarkSide-LowMass:
1 t, ultrapure Ar, vessel and SiPMs

ARGO: at SNOLAB (start 2029)
300 t fiducial mass
Atmospheric neutrinos as limiting background

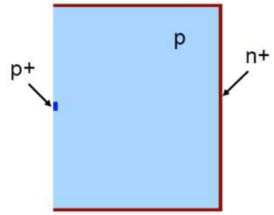

PDMs at mother board

Low mass DM: Ionization Ge detectors

Point-Contact Germanium detector: allow to reach sub-keV thresholds thanks to a very small capacitance, in combination with a large target mass.

+ Quite easy scalability, low background

- No ER/NR discrimination



As **CoGENT** detector (440 g) operated at Soudan

C. E. Aalseth et al, Phys. Rev. D 88 (2013) 012002

CDEX: at Jinping lab

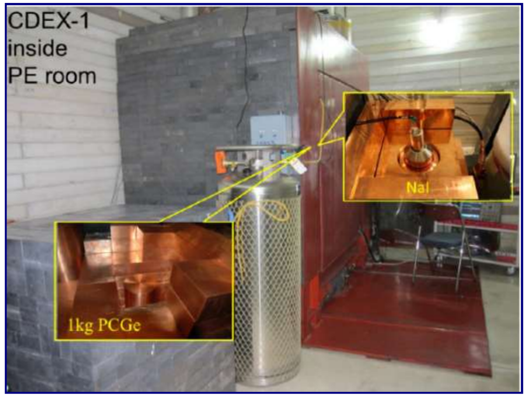
CDEX-1:

- Two detectors: CDEX-1A (915 g) and CDEX-1B (994 g)
- Improved threshold to 160 eV_{ee} in CDEX-1B
- Constraints on WIMP-nucleon **SI and SD** couplings from 737.1 kg d

L. T. Yang et al, Chin. Phys. C 42 23002 (2018)

including **Migdal effect**

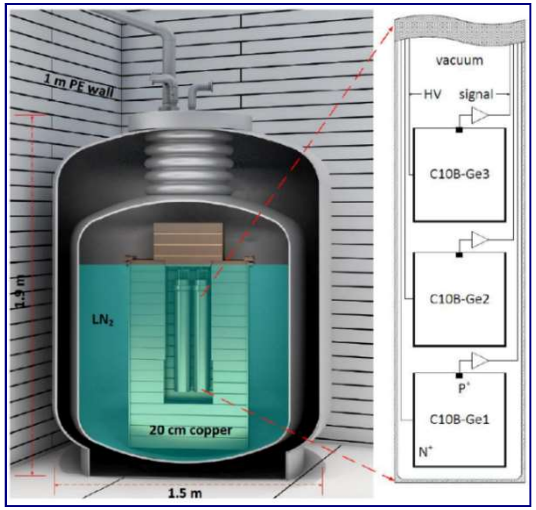
Z. Z. Liu et al, Phys. Rev. Lett. 123 (2019) 161301



CDEX-10:

- 10 kg detector array immersed in liquid N_2
- Analysis threshold at 160 eV_{ee}
- Constraints from 102.8 kg d

H. Jiang et al, Phys. Rev. Lett. 120 241301 (2018)

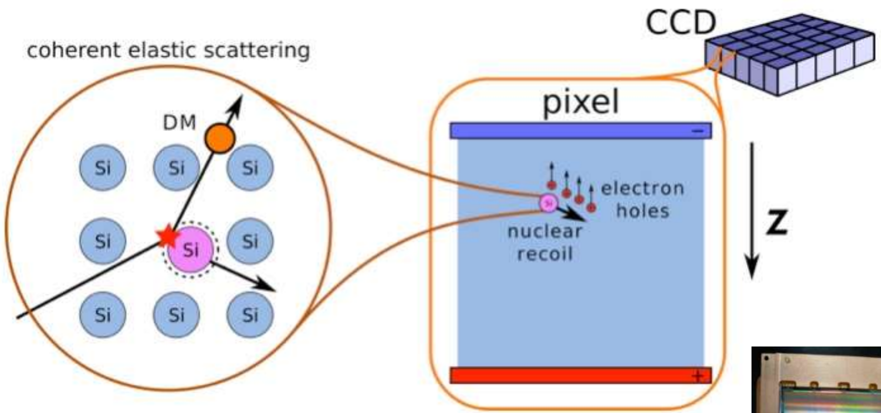


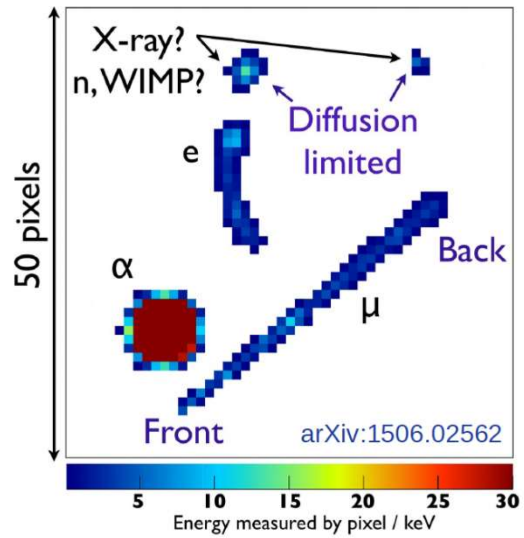
Working for **CDEX-100, CDEX-1T**: home-made Ge detectors

Low mass DM: Ionization Si detectors

Silicon charge-coupled devices (CCDs): charge produced in the interaction drifts towards the pixel gates, until readout.

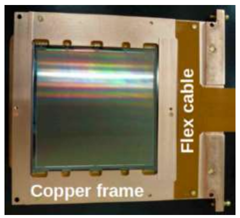
+ 3D position reconstruction possible: the depth of interaction correlated with the lateral charge diffusion
+ Effective particle identification and background rejection





DAMIC: at SNOLAB

- 7 CCDs (6 g each) since 2017
- Threshold 50 eV_{ee}

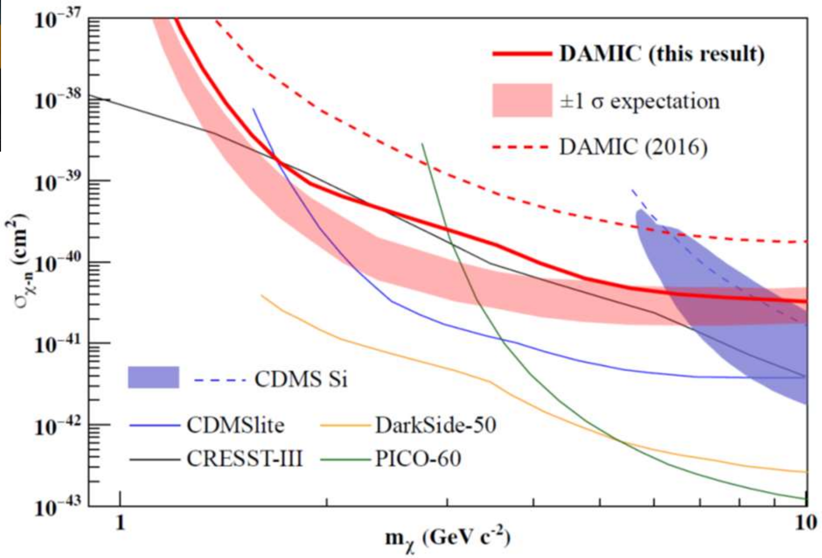


→ results also on **e scattering** and hidden photon DM

A. Aguilar-Arevalo et al, Phys. Rev. Lett. 118, 141803 (2017); Phys. Rev. Lett. 123 (2019) 181802

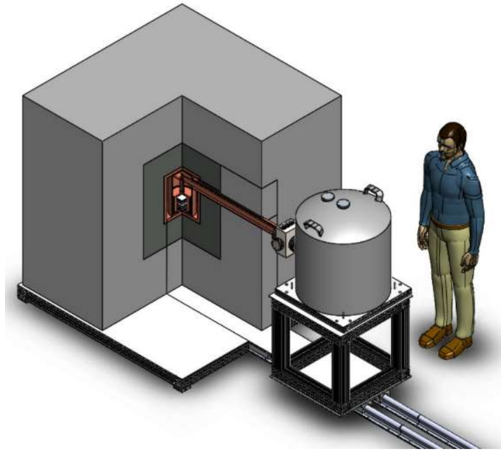
→ new results on **nucleon scattering** from 11 kg day: Excess of ionization events at 50-200 eV_{ee}?

A. Aguilar-Arevalo et al, arXiv:2007.15622



Low mass DM: Ionization Si detectors

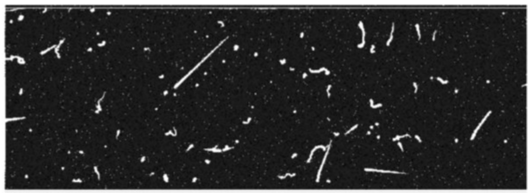
DAMIC-M: at Modane
- 50 CCDs (13.5 g each) for kg-year exposures
- Commissioning in 2023
- **Skipper readout:** multiple measurement of the pixel charge by on-chip readout scheme to reduce noise and achieve single electron counting with high resolution

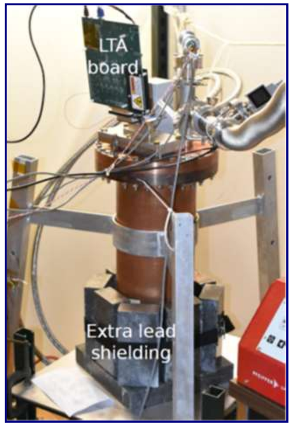


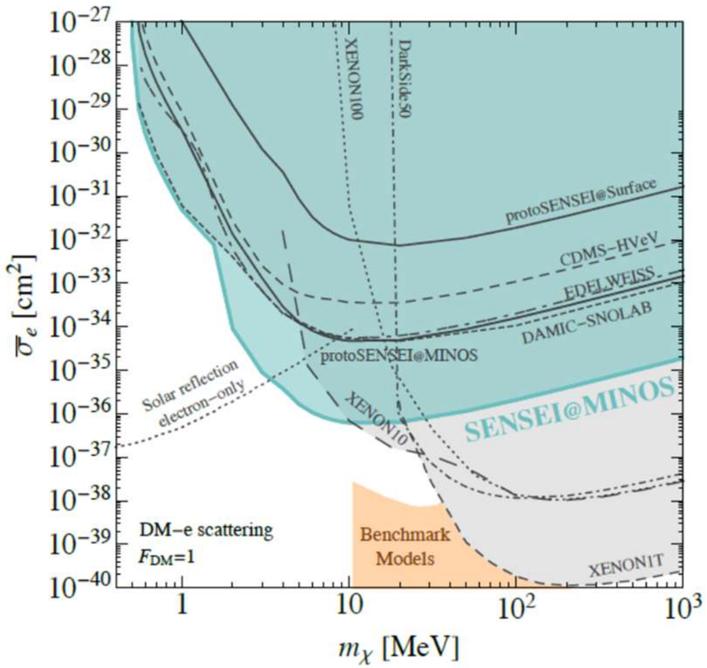
SENSEI: at Fermilab
- Prototypes with 0.0947 g and 2 g total active mass
- Operated at MINOS Hall (100 m underground)

→ constraints on **e scattering** and hidden-sector candidates

O. Abramoff et al, Phys. Rev. Lett. 122, 161801 (2019)
L Barak et al, arXiv:2004.11378



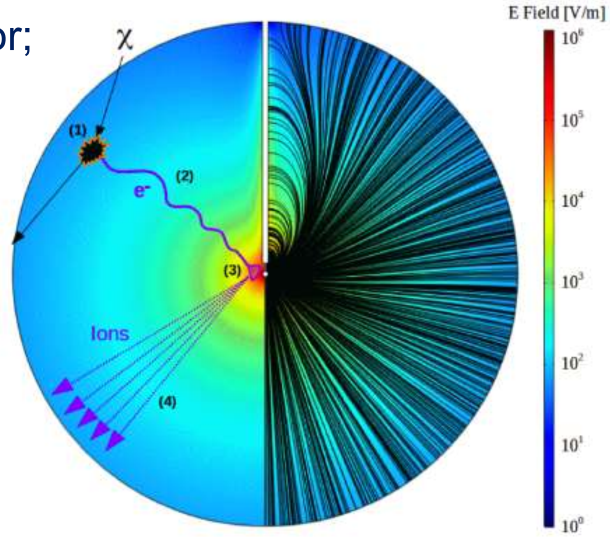




- Proposal to install a 100-g detector (48 CCDs) with custom-designed electronics at SNOLAB in 2021 (one CDD operating).

OSCURA: 10 kg in 2027

Low mass DM: Gas detectors



Spherical Proportional Counter: unconventional gas detector; able to achieve very low energy threshold thanks to very low capacitance (<1 pF) for a large volume.
Anode: small ball at the center, avalanche region.

I. Giomataris et al, JINST 2008 P09007

SEDINE detector: at Modane

- 60-cm NOSV copper sphere
- Filled with **Ne-CH_4**(0.7%) at 3.1 bar (280 g active mass)
- 42 d WIMP search run, 50 eV_{ee} threshold

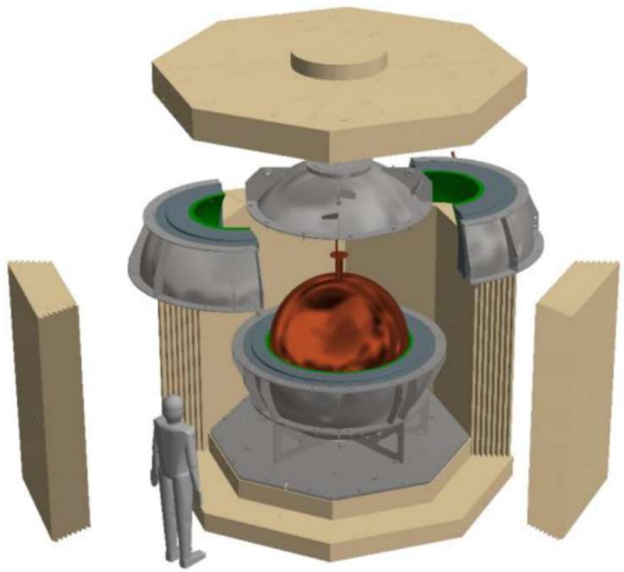
Q. Arnaud et al, Astropart. Phys. 97, 54 (2018)

NEWS-G: at SNOLab

- 140-cm low activity copper sphere, built in France, commissioning data with **CH_4**, now at SNOLAB
- Lighter targets: H, He
- Single electron response (gain, drift and diffusion times, …) characterized with a laser system

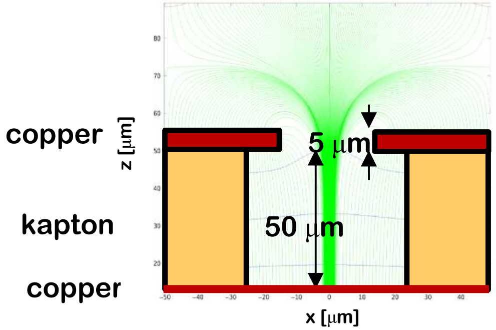
Q. Arnaud et al, Phys. Rev. D 99 (2019) 102003

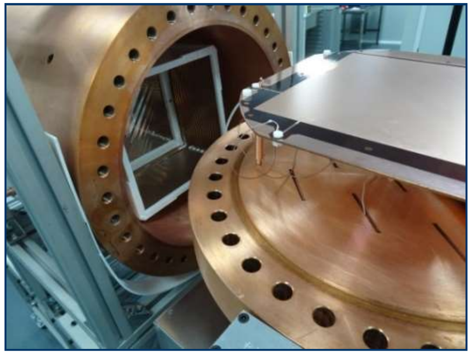
- Developing electroformed copper spheres with PNNL



Low mass DM: Gas detectors

HP TPC + Micromegas: gas TPC holding a pressurized gas at 10 bar equipped with micromesh gas structures (Micromegas) readouts





+ Event topology to discriminate backgrounds
+ Low intrinsic radioactivity
+ Scaling-up

I.G. Irastorza et al, JCAP 01 (2016) 034

F. J. Iguaz et al, Eur. Phys. J. C 76 (2016) 529

TREX-DM: at Canfranc lab (Spain)

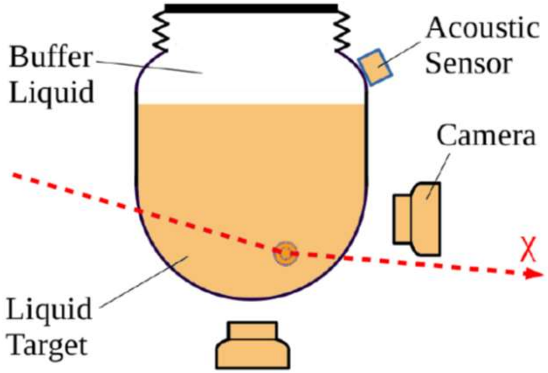
- ~24 l of pressurized gas (flexible target: ~0.3 kg **Ar**, ~0.16 kg **Ne** at 10 b)
- Commissioning runs with atmospheric Ar+1% iC_4H_{10} and Ne+2% iC_4H_{10}
- Largest Microbulk Micromegas 25x25 cm^2, built at CERN
- Prospects for threshold: down to 0.1 keV_{ee}

J. Castel et al, Eur. Phys. J. 79 (2019) 782

Low mass DM: Bubble chambers

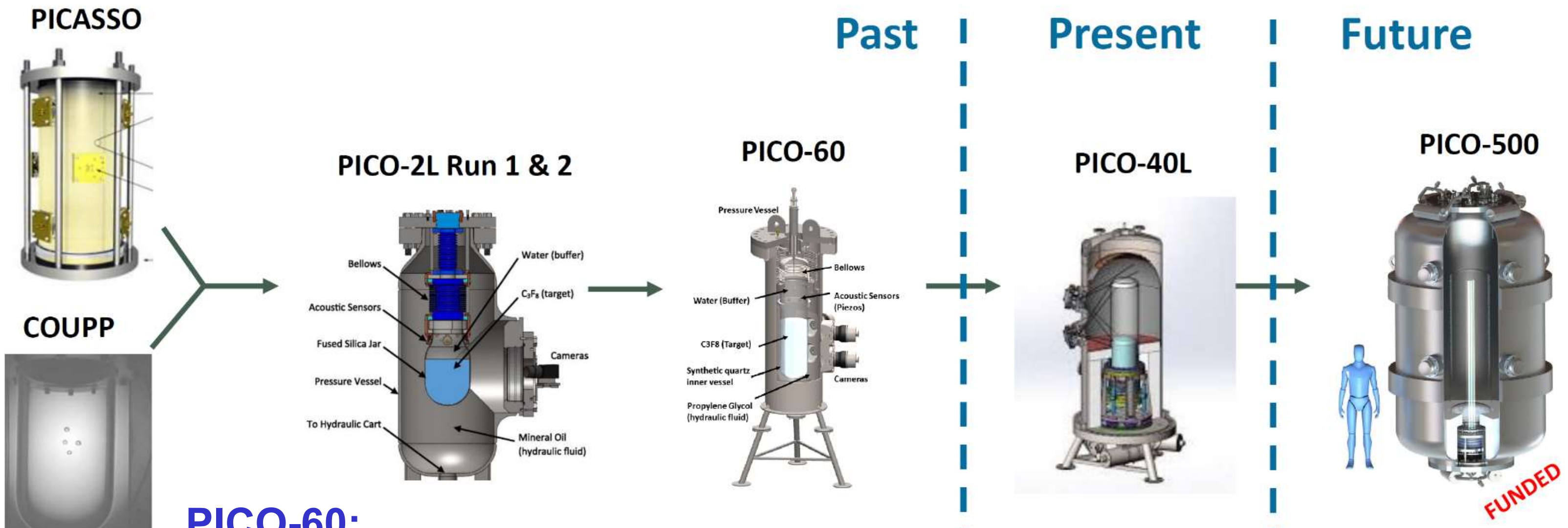
Bubble chamber: target liquids in metastable superheated state; sufficiently dense energy depositions start the formation of bubbles; read by cameras

+ Almost immune to electronic recoil background sources
+ Different targets, most containing ^{19}F, highest sensitivity to **SD p couplings**
- Threshold detector: no direct measurement of recoil energy



M. Schumann, J. Phys. G46 (2019)10303

PICO: merging **PI**CASSO and **CO**UPP collaborations since 2012



PICO-60:
- 52 kg of C_3F_8, 2.45 keV_{nr} threshold

→ best **SD WIMP-p** limit

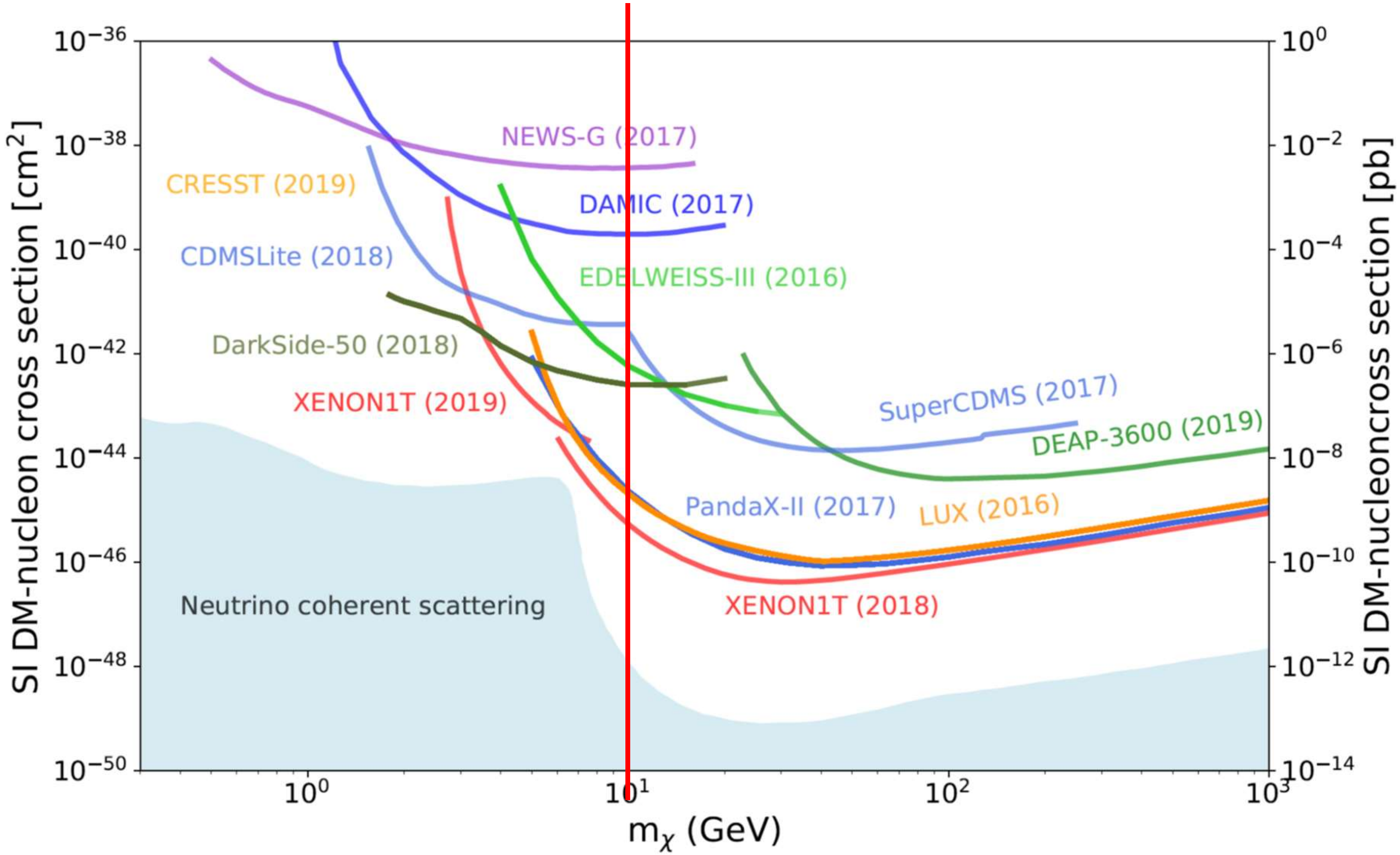
C. Amole et al, Phys. Rev. D 100 (2019) 022001

PICO-40L:
- Buffer-free concept, commissioning data

M. Bressler et al, 2019 JINST 14 P08919

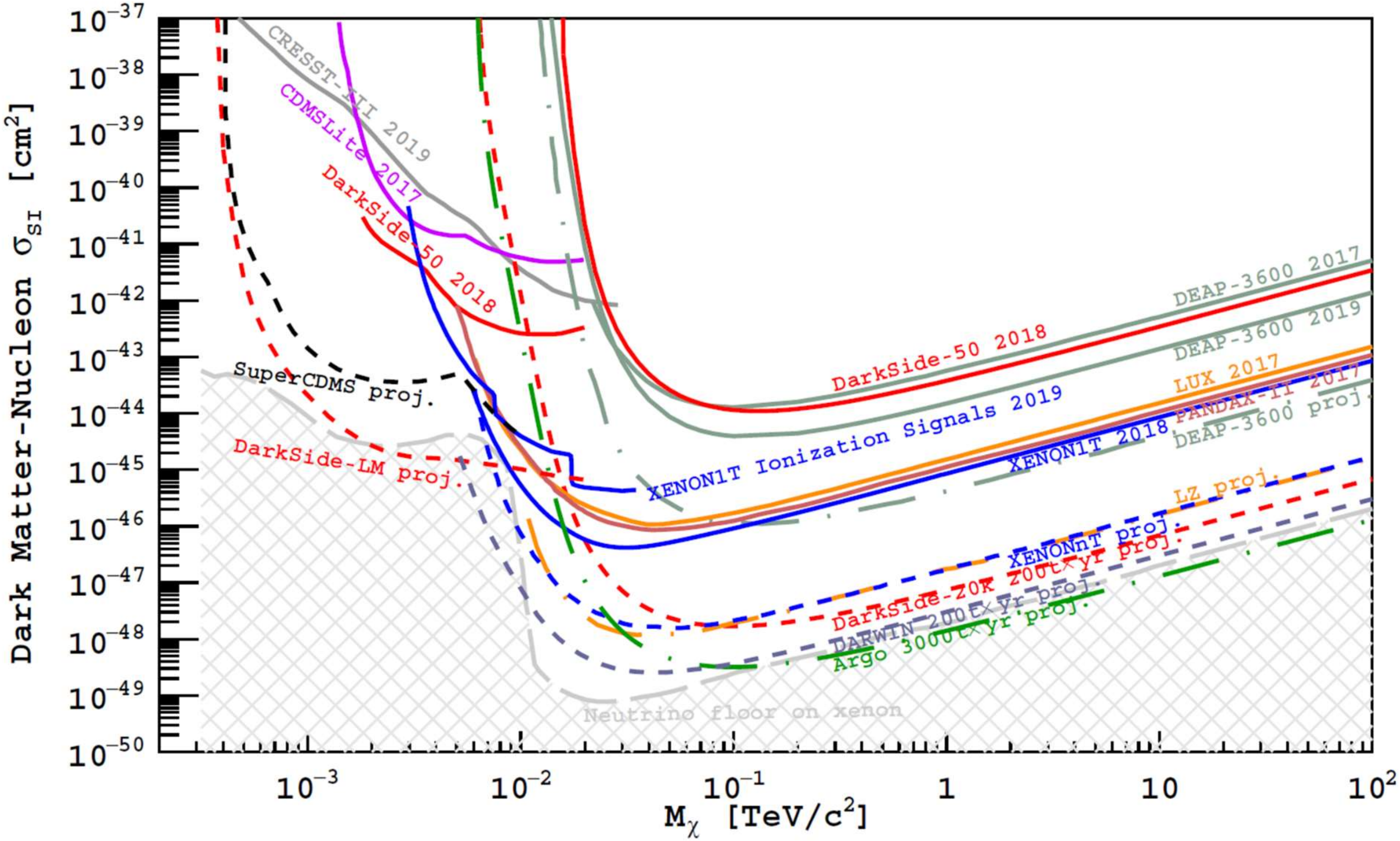
PICO-500:
- In design, start data taking in 2022

Low mass DM: summary of results (SI)



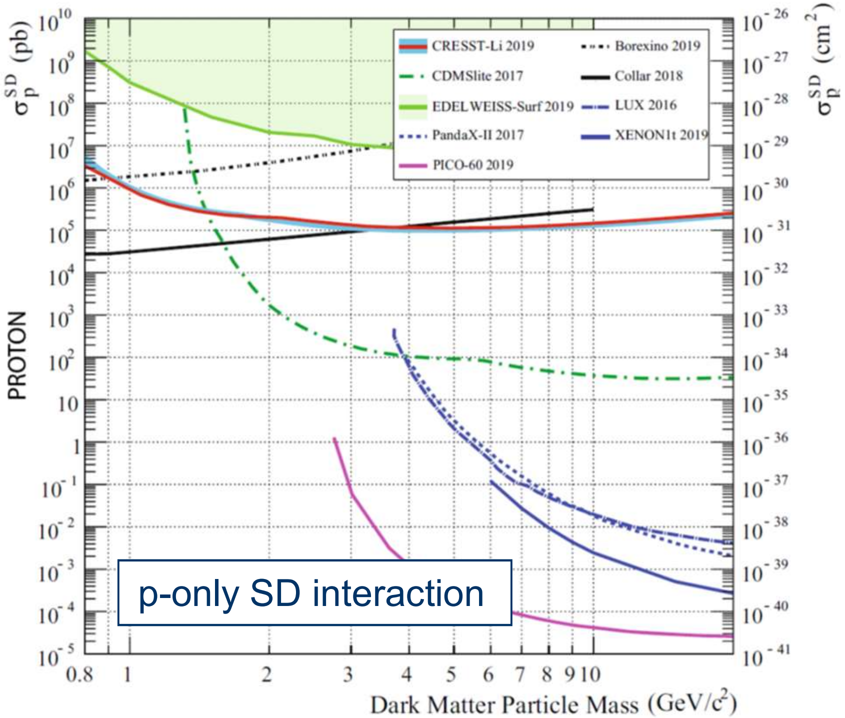
The Review of Particle Physics (2020), P.A. Zyla *et al.* Prog. Theor. Exp. Phys. 2020, 083C01.
Review on Dark Matter, L. Baudis and S. Profumo

Low mass DM: summary of prospects (SI)

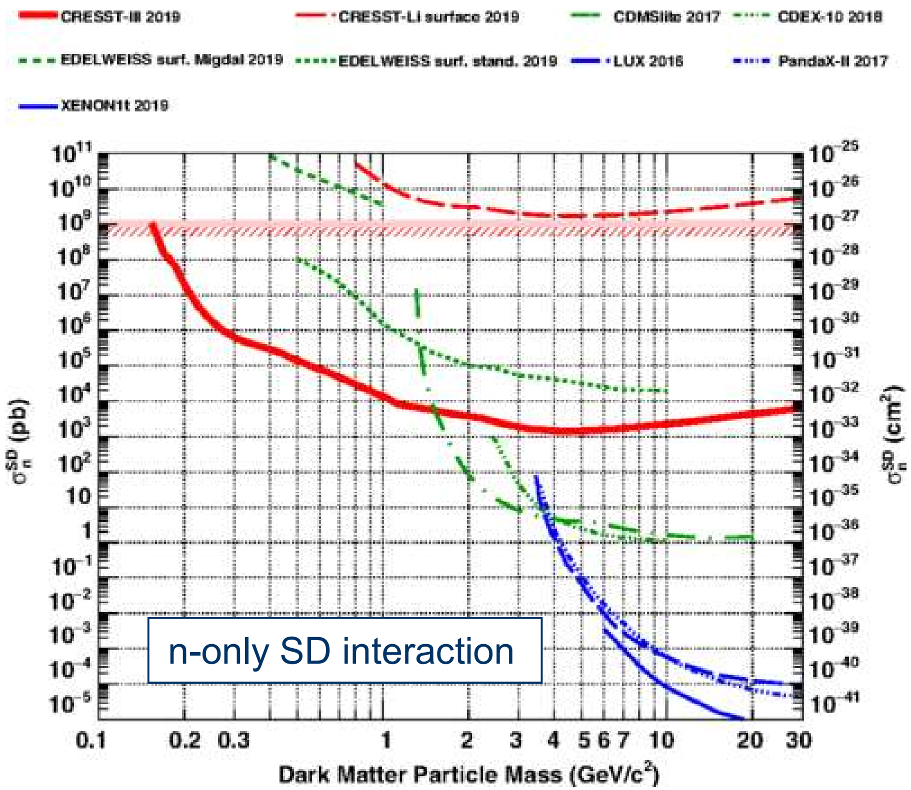


Physics Briefing Book
Input for the European Strategy for Particle Physics Update 2020
CERN-ESU-004, 10 January 2020
arXiv:1910.11775v2 [hep-ex]

Low mass DM: summary (SD)



A:H. Abdelhameed et al,
Eur. Phys. J. C 79 (2019) 630



A.H. Abdelhameed et al,
Phys. Rev. D 100 (2019)10 102002

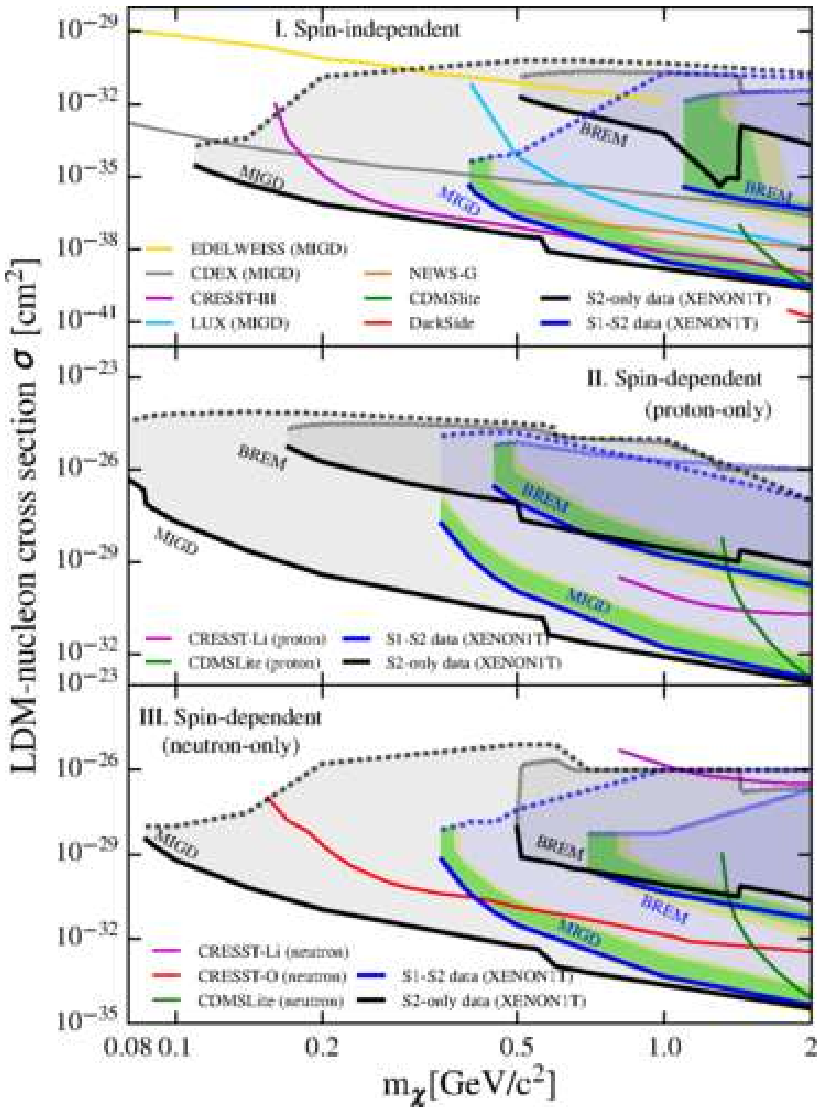
Many experiments sensitive not only to SI but also to SD interactions

CRESST: ^{7}Li
PICO-60: ^{19}F
CDMSlite, EDELWEISS: ^{73}Ge
LUX, PANDAX-II, XENON1T: ^{129}Xe+^{131}Xe

CRESST: ^{7}Li, ^{17}O
CDMSlite, CDEX-10 , EDELWEISS : ^{73}Ge
LUX, PANDAX-II, XENON1T: ^{129}Xe+^{131}Xe

Low mass DM: summary (SI, SD)

Improved sensitivity including **Migdal effect**



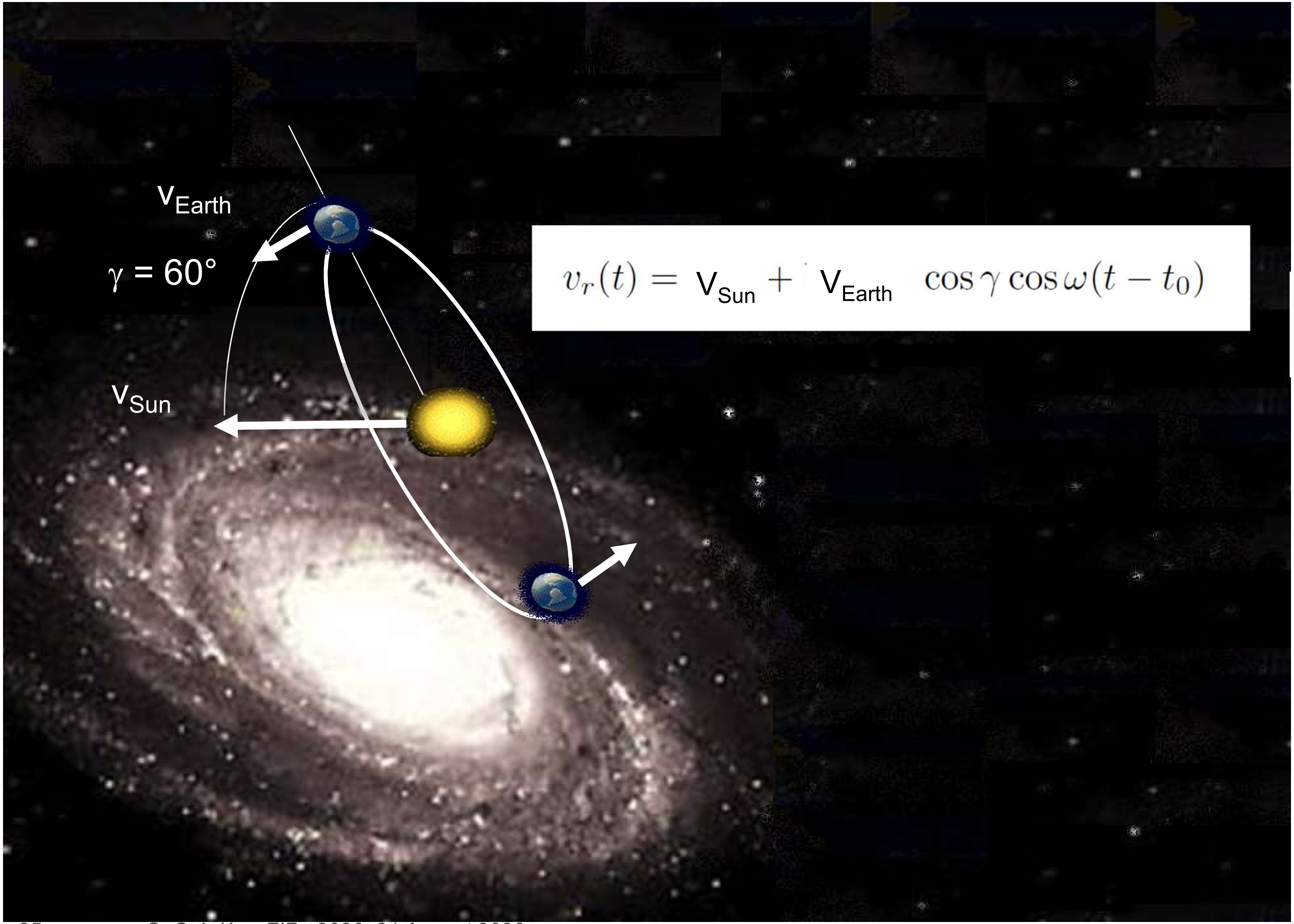
E. Aprile et al, Phys. Rev. Lett. 123 (2019) 241803

Status and prospects of DM direct detection experiments in the low (< 10 GeV) mass range

- Direct detection of DM
- Searches for low mass DM
  - Bolometers
  - Liquid Xe and Ar detectors
  - Ionisation detectors
  - Bubble chambers
- **Searches for distinctive signatures:**
  - **Annual modulation**
  - **Directionality**
- New technologies

Susana Cebrián scebrian@unizar.es

Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Universidad Zaragoza
Laboratorio Subterráneo de Canfranc



$$v_r(t) = V_{Sun} + V_{Earth} \cos\gamma \cos\omega(t - t_0)$$

Annual modulation

Distinctive signature in the interaction rate of WIMPs

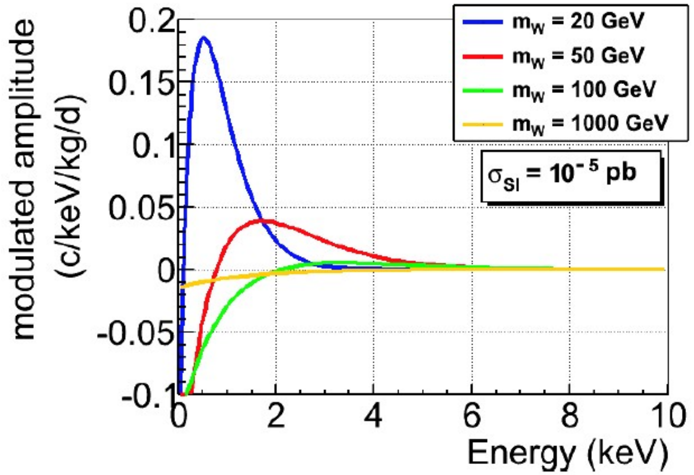
$$S_k(y) = S_{0,k} + (\frac{\partial S_k}{\partial y})_{y0} \Delta y \cos\omega(t - t_0) = S_{0,k} + S_{m,k} \cos\omega(t - t_0)$$

k energy bin, $y = \sqrt{\frac{3}{2}} \frac{v_r}{v_{rms}}$

- ✓ Cosine behaviour
- ✓ 1 year period
- ✓ Maximum around June 2nd
- ✓ Weak effect (1-10%)
- ✓ Only noticeable at low energy
- ✓ Should have a phase reversal at low energies

A. K. Drukier et al, Phys. Rev. D 33 (1986) 3495
K. Freese et al, Phys. Rev. D 37 (1988) 3388
K. Freese et al, Rev. Mod. Phys. 85 (2013) 1561

No background known to mimic the effect



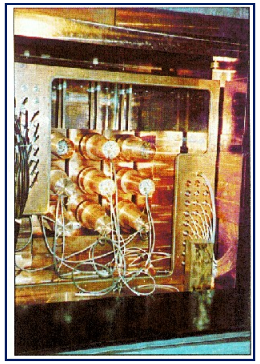
NaI(Tl) scintillator: cheap and robust detectors; new developments to get an ultra-low background and a low energy threshold

Annual modulation: DAMA / LIBRA

At Gran Sasso

DAMA/NaI & DAMA/LIBRA phase 1

DAMA/NaI (1995-2002)



- 9 × 9.7 kg NaI(Tl)
- Produced by St. Gobain
- 7 annual cycles

DAMA/LIBRA (2003-2010)

- 25 × 9.7 kg NaI(Tl)
- 7 annual cycles

R. Bernabei et al, Eur. Phys. J. C 73 (2013) 2648

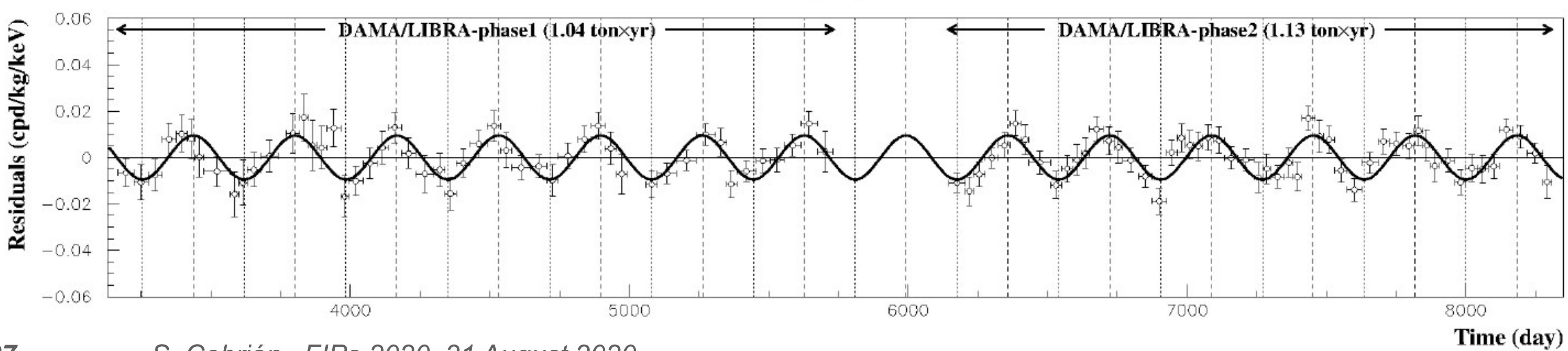
DAMA/LIBRA phase2 (2011-2018)

- PMTs replaced → software energy threshold at 1 keV_{ee}
- 6 annual cycles

R. Bernabei et al,
Nucl. Phys. At. Energy 19, 307 (2018)
Prog. Part. Nucl. Phys. 114 (2020) 103810

The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at **12.9σ CL** (2.46 ton × yr)

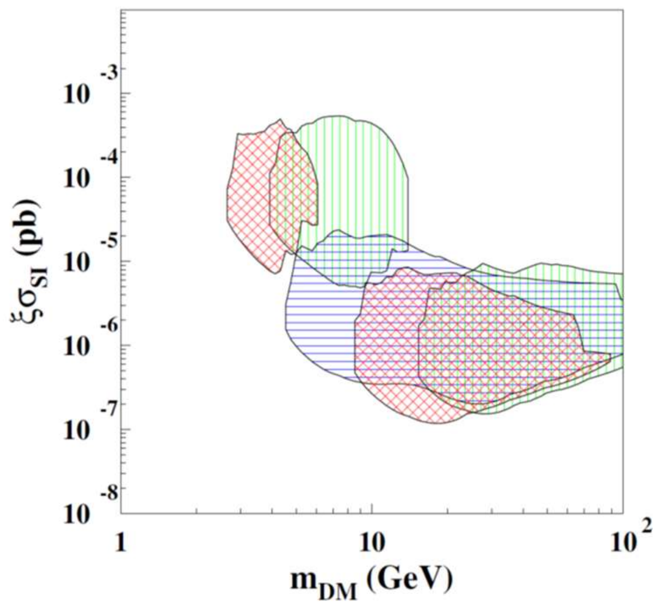
S_m=(0.0103±0.0008) cpd/kg/keV



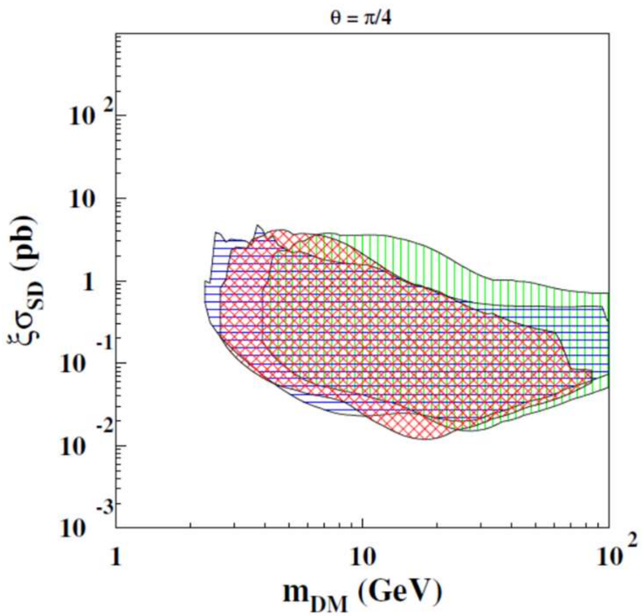
Annual modulation: DAMA / LIBRA

Improved **model-dependent corollary analyses after DAMA/LIBRA-phase2**: maximum likelihood procedure to derive **allowed regions** in the parameters' space of each considered scenario (going below 10 GeV) by comparing the measured annual modulation amplitude with the theoretical expectation ($S_{m,k}$)

SI elastic scattering



SD elastic scattering

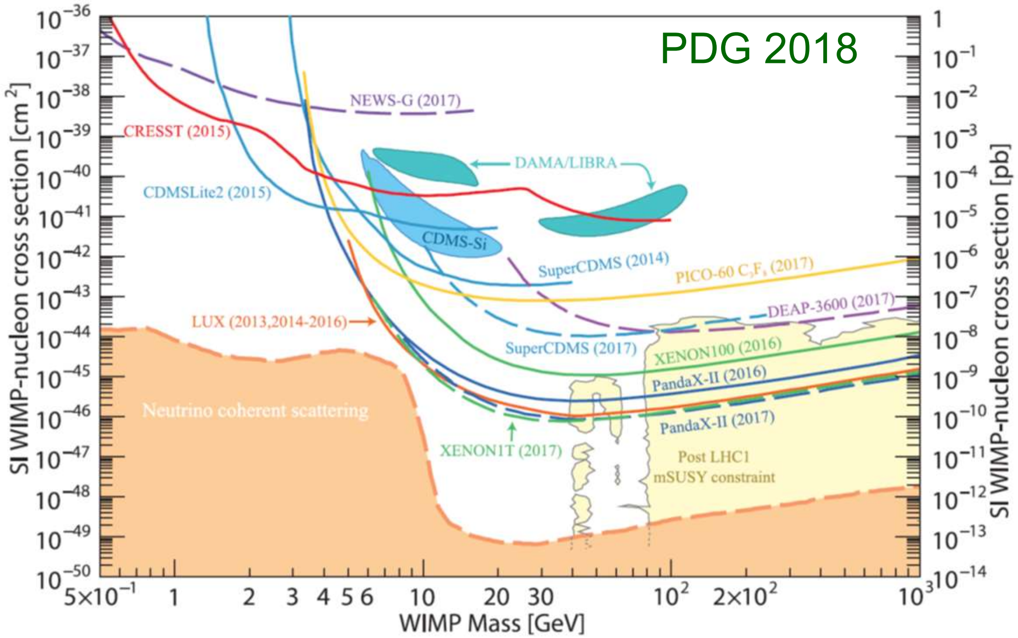


Q fixed
Q energy-dependent
channeling

Also scenarios with preferred electron interaction, preferred inelastic scattering, light DM, asymmetric and symmetric mirror DM

R. Bernabei et al, Nucl. Phys. At. Energy 20 (2019) 317
Prog. Part. Nucl. Phys. 114 (2020) 103810

Annual modulation



Strong **tension** when interpreting DAMA/LIBRA anual modulation signal as DM, even assuming more general halo / interaction models

A MODEL-INDEPENDENT PROOF/DISPROOF WITH THE SAME NaI TARGET IS MANDATORY

No annual modulation signal in other experiments:

XENON100

E. Aprile et al, Phys. Rev. Lett. 118, 101101 (2017)

XMASS

K. Abe et al, Phys. Rev. D 97, 102006 (2018)

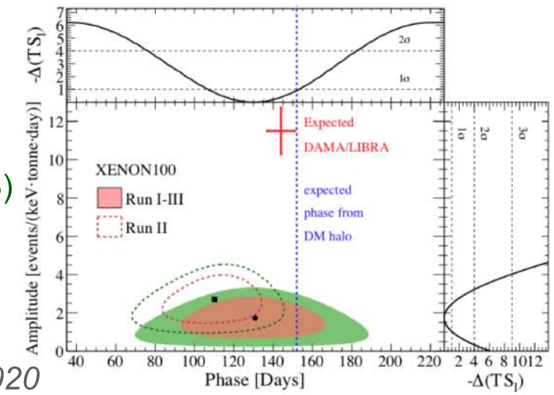
M. Kobayashi et al, Phys. Lett. B 795 (2019) 308

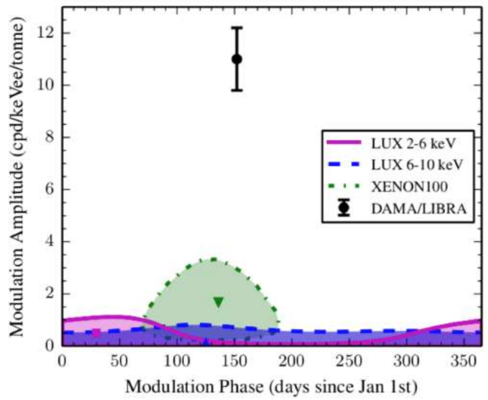
LUX

D.S. Akerib et al, Phys. Rev. D 98, 062005 (2018)

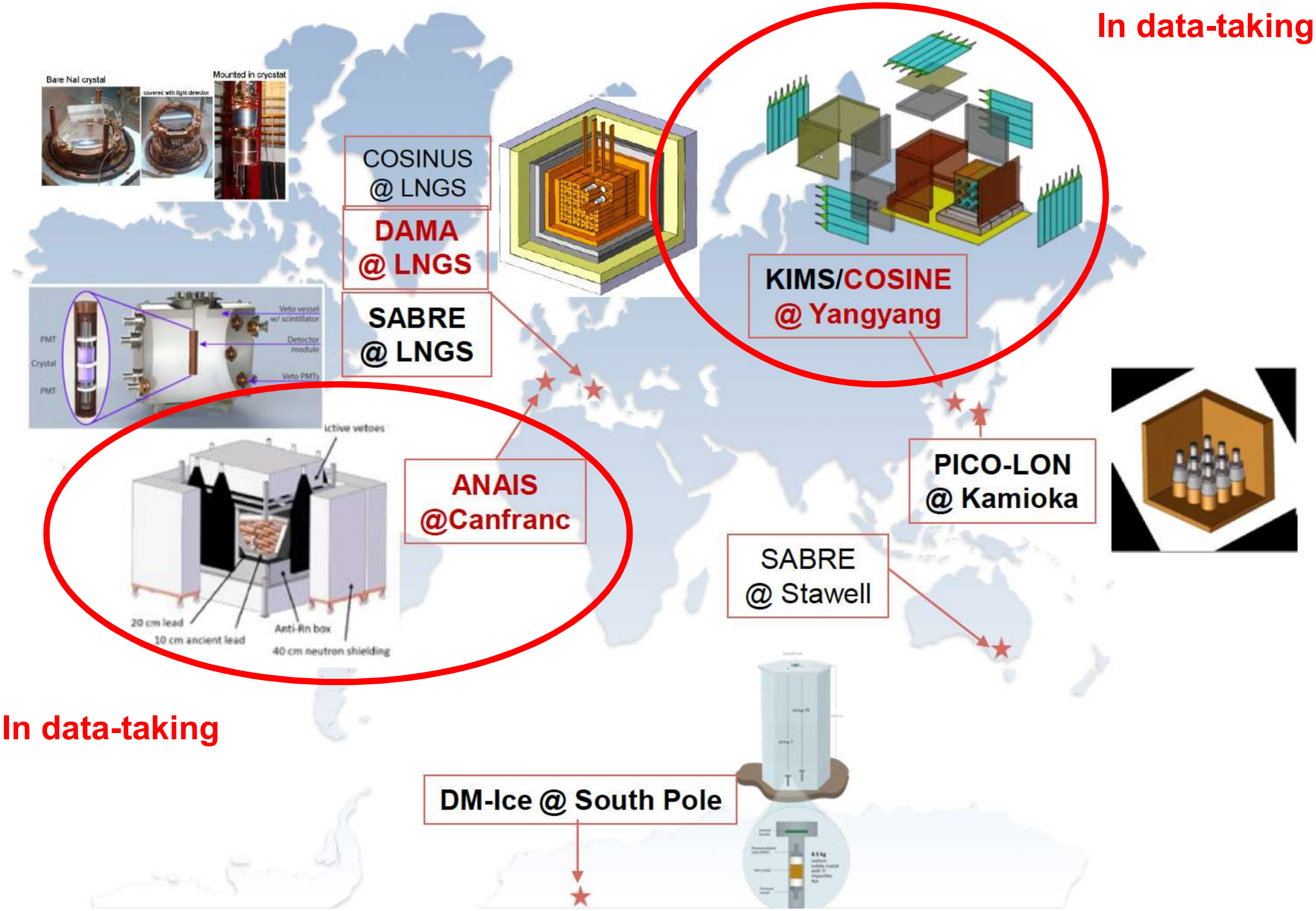
CDEX

L.T. Yang et al, Phys. Rev. Lett. 123, 221301 (2019)





Annual modulation



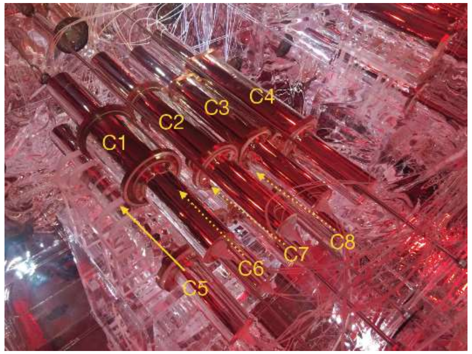
Annual modulation: COSINE-100

KIMS + DM-ICE

- At Yangyang lab (South Korea)
- 8 **NaI(Tl)** crystals from Alpha Spectra, 106 kg in total
- Inmersed in 2200 l of liquid scintillator
- Threshold at 2 keV_{ee}
- Physics run started in September 2016

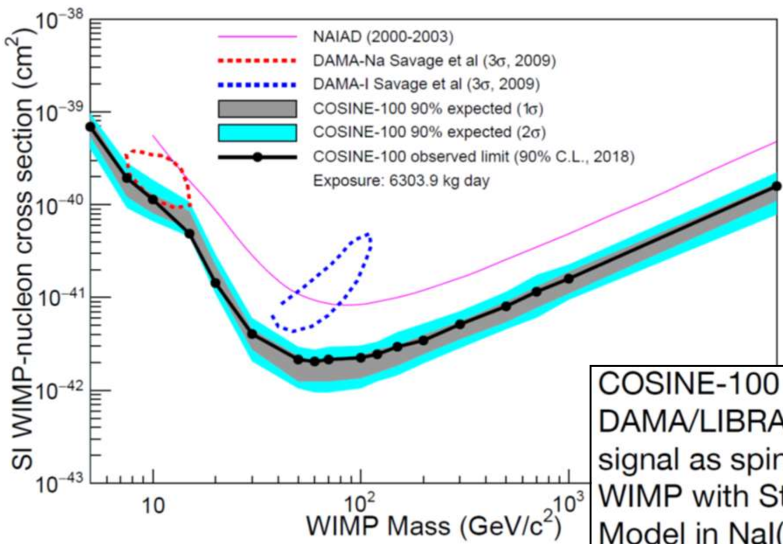
G. Adhikari et al
Eur. Phys. J. C (2018) 78:107

P. Adhikari et al
Eur. Phys. J. C (2018) 78:490



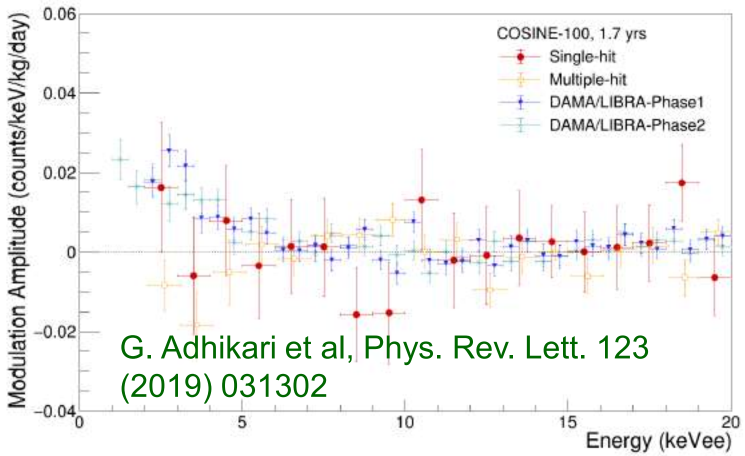
SI WIMP search: first 59.5 days
Fit for 2-20 keV background + WIMP

G. Adhikari et al, Nature 564 (2018) 83



COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin-independent WIMP with Standard Halo Model in NaI(Tl)

First annual modulation analysis: 1.7 y (crystals 1, 5 and 8 excluded) → **97.79 kg.y**



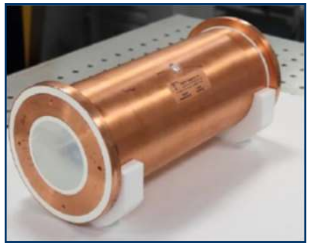
G. Adhikari et al, Phys. Rev. Lett. 123 (2019) 031302

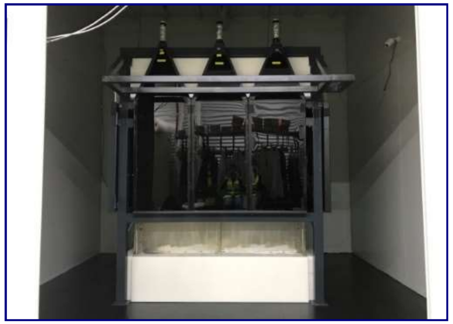
Best fit amplitude for 2 – 6 keV:

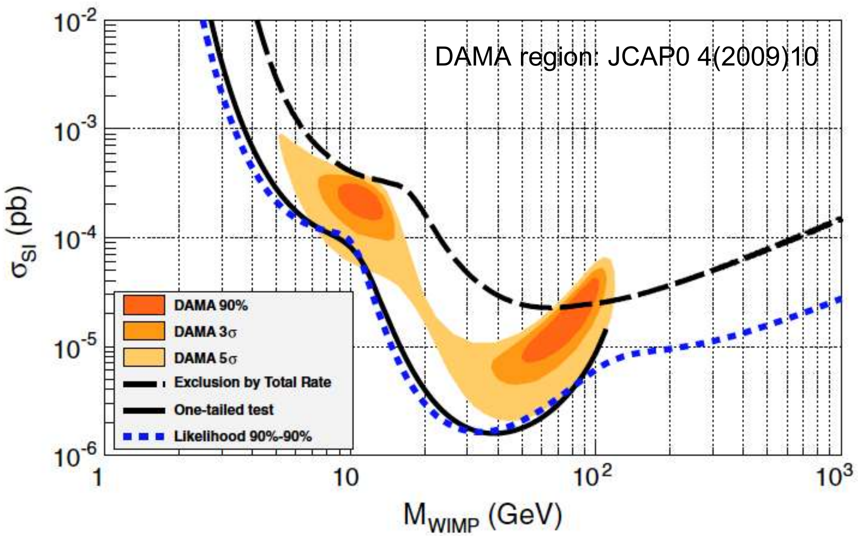
- 0.0083 ± 0.0068 cpd/kg/keV
- phase fixed at 152.5 day

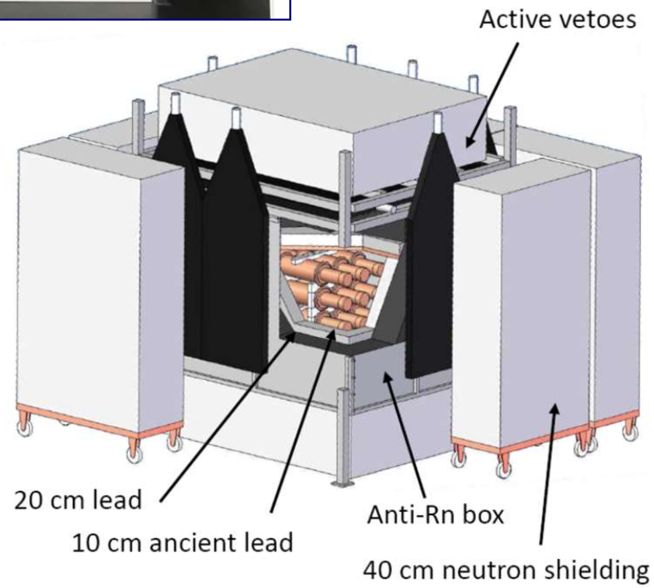
Annual modulation: ANAIS

- At Canfranc lab (Spain)
- 9 modules **NaI(Tl)** x 12.5 kg = 112.5 kg
- Built by Alpha Spectra (US)
- Dark matter run since August 2017
- Outstanding light collection of ~15 phe/keV for all modules allowing an energy threshold at 1 keV_{ee}
- Sensitivity to explore the 3σ DAMA/LIBRA region in 5 y, from measured background in 1-6 keV_{ee}







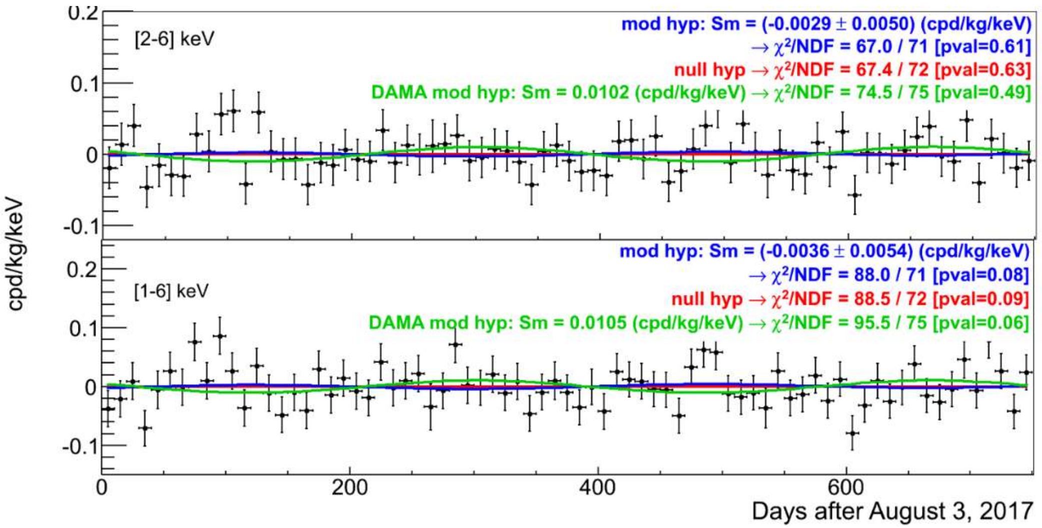


J. Amaré et al, Eur. Phys. J. C 79 (2019) 228; Eur. Phys. J. C 79 (2019) 412
I. Coarasa et al, Eur. Phys. J. C 79 (2019) 233

Annual modulation: ANAIS

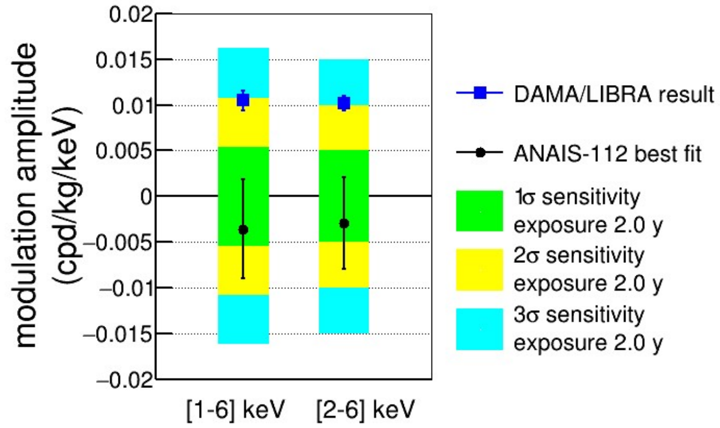
First results on annual modulation: August 2017-August 2019 (**2 y**)**→220.69 kg.y**

Least-squares fit to $R(t) = R_0 + R_1 \cdot exp(-t/\tau) + S_m \cdot cos(\omega \cdot (t+\phi))$



τ fixed from background model
ω fixed corresponding to 1 year period
φ fixed to have the cosine maximum in June, 2nd
S_m fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis

S_m best fits are **incompatible** with DAMA/LIBRA results at **2.6σ**



Null hypothesis well supported by the χ^2 test

Modulation hypothesis best fits for 2-6 and 1-6 keV

$$S_m = -0.0029 \pm 0.0050\ cpd/kg/keV$$
$$S_m = -0.0036 \pm 0.0054\ cpd/kg/keV$$

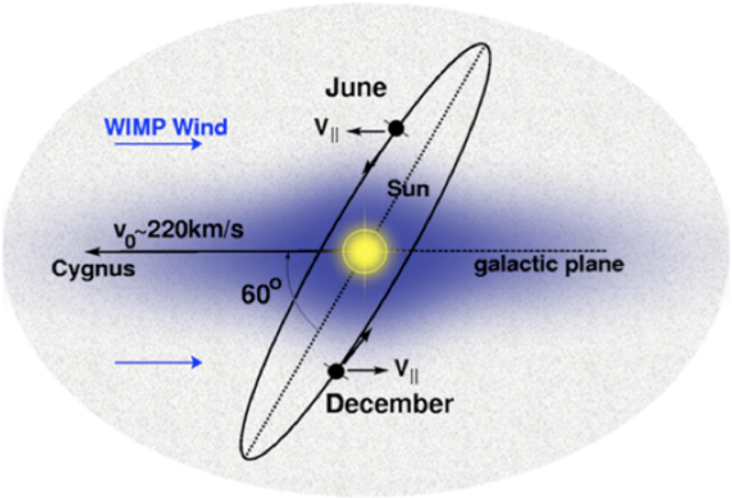
Results for **3 y** data to be released soon

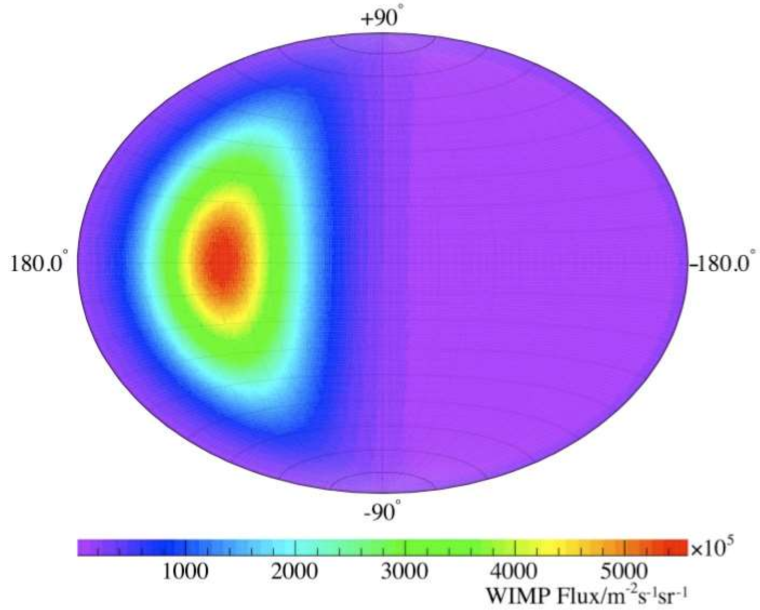
J. Amaré et al, Phys. Rev. Lett. 123 (2019) 031301
J. Amaré et al, J. Phys.: Conf. Ser. 1468 (2020) 012014

Directionality

Distinctive signature in the interaction rate of WIMPs

The average direction of the “WIMP wind" through the solar system comes from the constellation of Cygnus, as the Sun is moving around the Galactic center



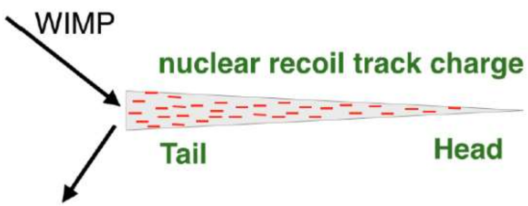


A **measurement of the track direction** of nuclear recoils could be used to distinguish a DM signal from background events (expected to be uniformly distributed) and to prove the galactic origin of a possible signal

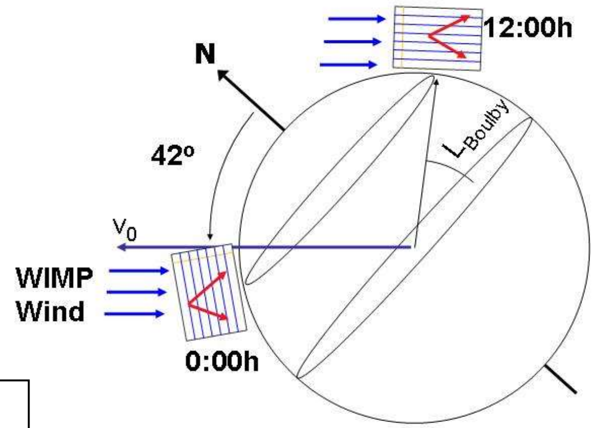
D.N. Spergel, Phys. Rev. D 37 (1988) 1353
S. Ahlen et al, Int. J. Mod. Phys. A 25 (2010) 1
F. Mayet et al., Phys. Rep. 627 (2016) 1

Directionality

Challenge: to reconstruct the track being very short (~1 mm in gas, ~0.1 μm in solids) for keV scale nuclear recoils



- To register direction (axis, sense) or at least a **head-tail asymmetry** (by measuring the relative energy loss along the track)
- **Daily modulation** of the WIMP direction due to the rotation of Earth

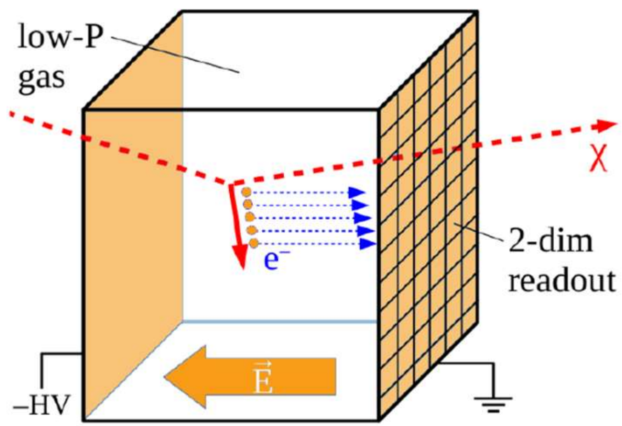


→ **Low pressure** (~0.1 atm) gas targets in **TPCs** with different electron amplification devices and track readouts, mostly based on CF_4 mixtures with ^{19}F

Multi-wire proportional chambers (MWPC)
Micro pattern gaseous detectors (MPGDs)
Optical readouts

J.B.R. Battat et al., Phys. Rep. 662 (2016) 1

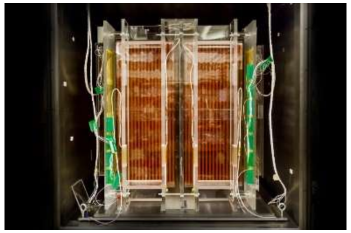
→ **Nuclear emulsions**

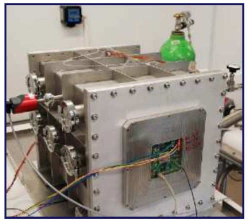


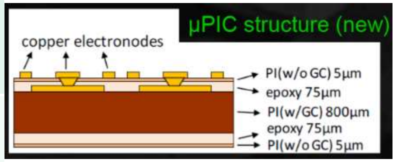
M. Schumann, J. Phys. G46 (2019)103003

Directionality

Experiment	Detector	Lab	Size	Ref
DRIFT	TPC+ Multi-wire Proportional Chamber	Boulby (UK)	1 m^3	J. B. R. Battat et al, Astropart. Phys. 91 (2017) 65
MIMAC	TPC+Micromegas	Modane (France)	1 m^3 in prep.	Y. Tao et al, arXiv:2003.11812
NEWAGE	TPC + micro-pixel chamber (μ-PIC)	Kamioka (Japan)		T. Ikeda et al, J. Phys.: Conf. Ser. 1458 (2020) 012042
DMTPC	TPC + optical readout	WIPP (US)	1 m^3 in prep.	C. Deaconu et al, Phys, Rev. D 95 (2017) 122002







- Measurement of directional nuclear recoils, 3D track observation, head-tail effect confirmed
- Limits for SD WIMP-p interaction

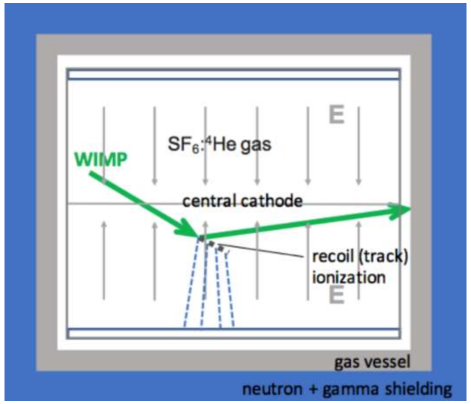
NEWSdm	Nuclear emulsion + optical readout	Gran Sasso	10 g Proto	N. Agafonova et al, Eur. Phys. J. C 78 (2018) 578

- Spatial resolution of 10 nm achieved

Directionality: CYGNUS

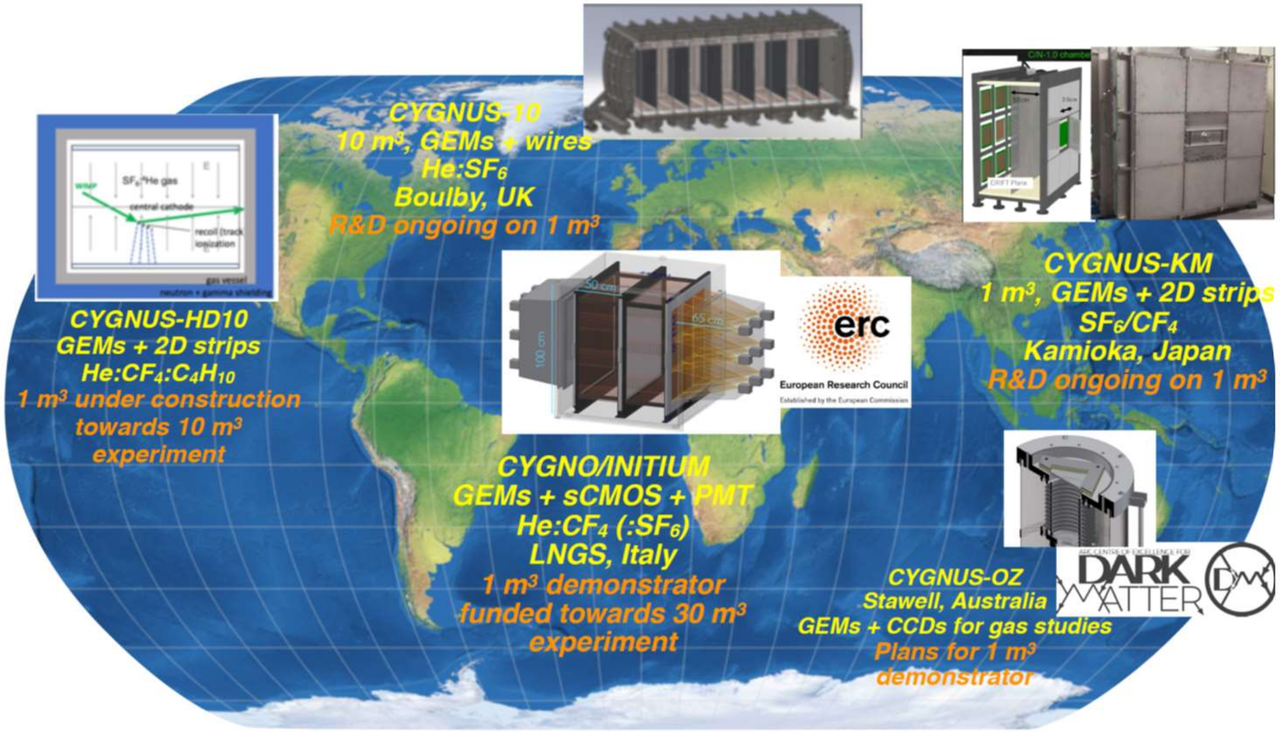
"A multi-site, multi-target Galactic Recoil Observatory at the ton-scale to probe DM below the neutrino floor and measure solar neutrinos with directionality"

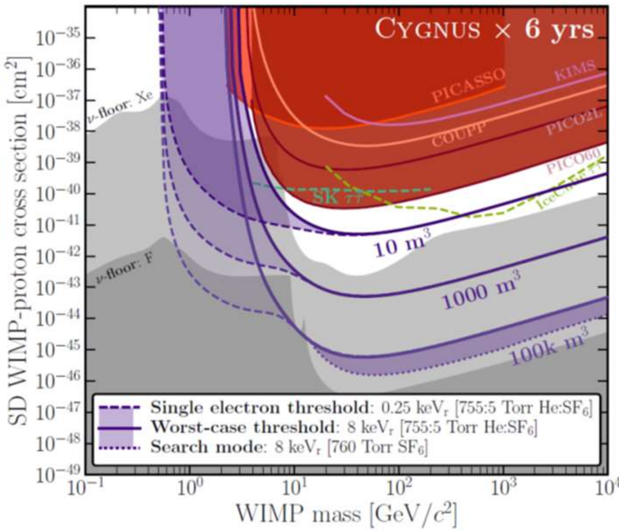
S.E. Vahsen et al., arXiv:2008.12587v1 [physics.ins-det]



Proposals for **CYGNUS detectors** in 5 labs:

- Different gas mixtures (higher, lower density): SF_6:He, CF_4
- Threshold at <1 keV_{ee}
- Volumes from 10 to 1000 m^3





S.E. Vahsen et al., arXiv:2008.12587

Status and prospects of DM direct detection experiments in the low (< 10 GeV) mass range

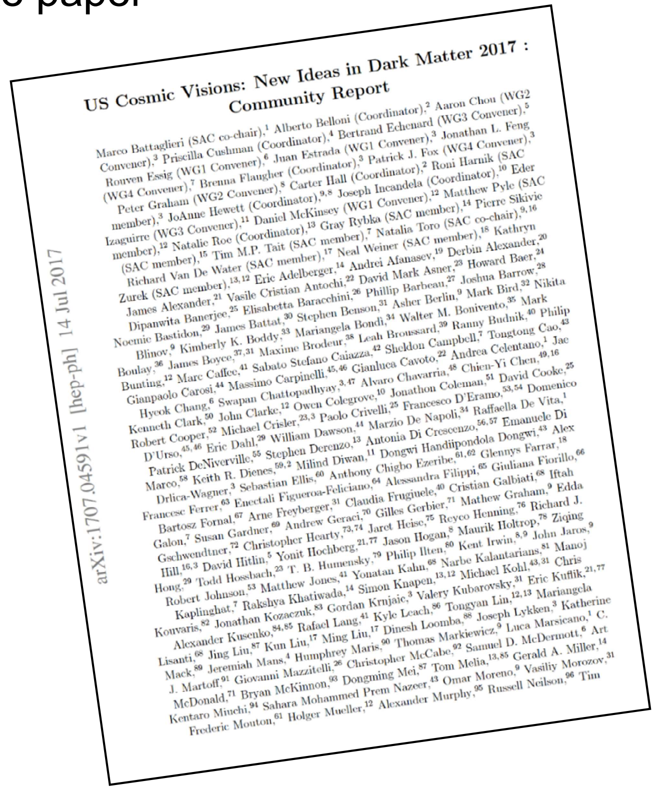
- Direct detection of DM
- Searches for low mass DM
  - Bolometers
  - Liquid Xe and Ar detectors
  - Ionisation detectors
  - Bubble chambers
- Searches for distinctive signatures:
  - Annual modulation
  - Directionality
- New technologies

Susana Cebrián scebrian@unizar.es

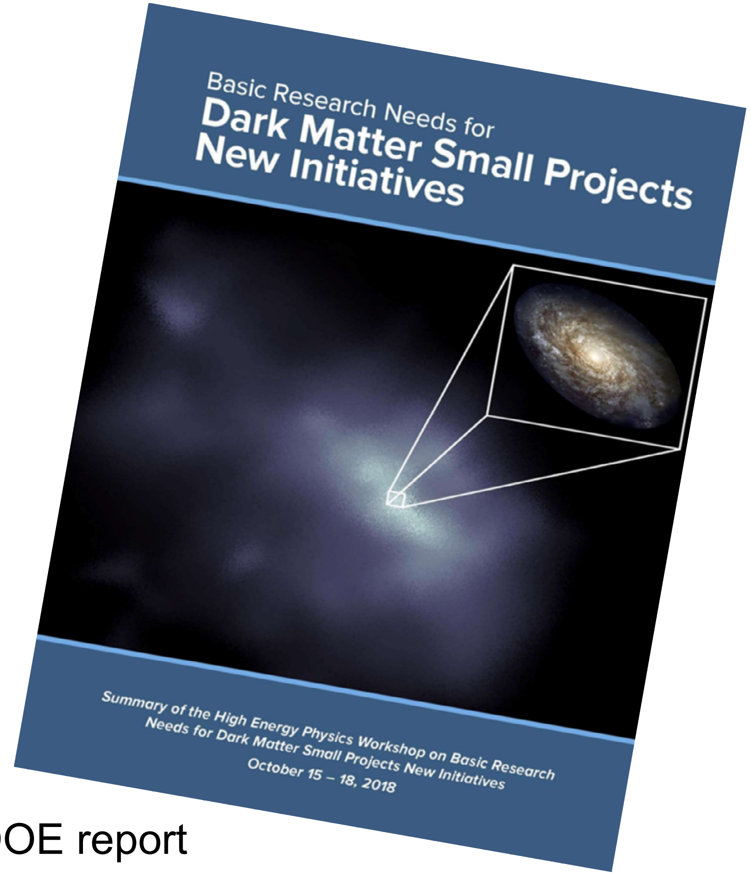
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza
Universidad Zaragoza
Laboratorio Subterráneo de Canfranc

New technologies

White paper


US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

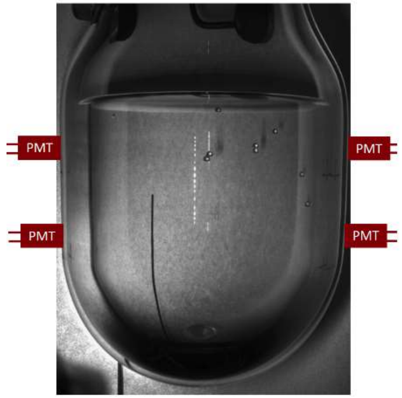


DOE report

To explore the **new DM landscape** with well-motivated candidates with eV-to-GeV masses through interactions with **advanced, ultra-sensitive detectors** based on recently developed technologies and novel ideas

New technologies

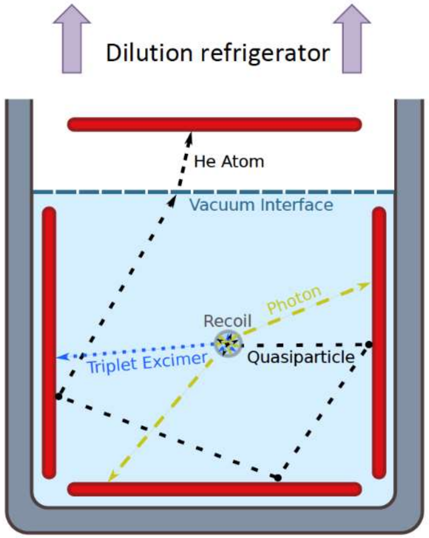
- **Scintillating Bubble Chambers:** extreme electron rejection and simple instrumentation of a bubble chamber and event-by-event energy resolution of a liquid scintillator
  Technique established for a 30 g **xenon bubble chamber**
  D. Baxter, et al., Phys. Rev. Lett. 118, 231301 (2017)
  SBC Collaboration: LAr chamber (10 kg) in preparation in Fermilab, to operate at SNOLAB in 2023



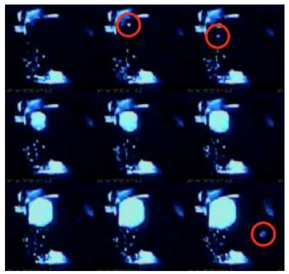
- **HeRALD** Helium Roton Apparatus for Light Dark Matter:

superfluid ^{4}He target + low temperature calorimeters as sensors (TES) to measure photons and quasiparticles (heat) by quantum evaporation

S.A. Hertel et al, Phys. Rev. D 100, 092007 (2019)



- **SnowBall:** using **supercooled water**, an incoming particle triggers crystallization of purified water. Camera for image acquisition. Tested with neutrons at -20ºC, insensitive to electron recoils
  M. Szydagis et al, arXiv:1807.09253



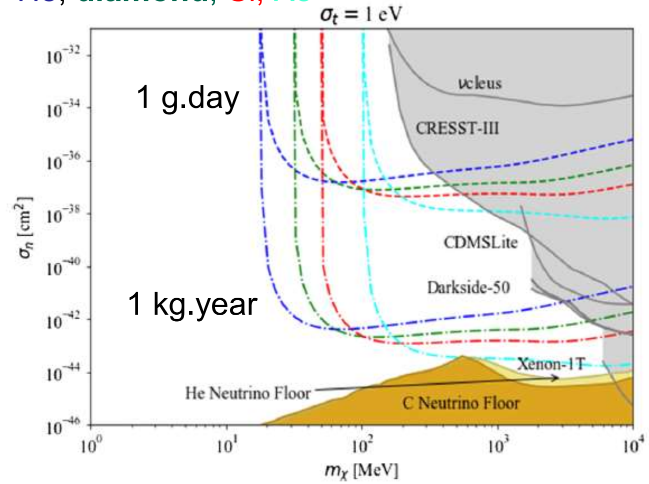
New technologies

- **Diamond detectors:** high purity lab-grown **diamond crystal** as target outfitted with **cryogenic phonon and charge readout**, to be sensitive to both NR and ER from dark matter scattering at MeV

  + C lighter than other semiconductor materials
  + Low noise (sub-eV theshold)

  N. Kurinsky et al, Phys. Rev. D 99, 123005 (2019)

He, **diamond**, Si, Xe

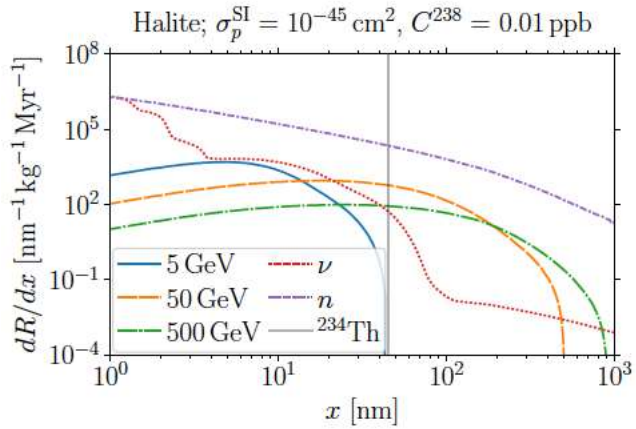


- **Paleo-detectors:** persistent **traces** left by DM interaction in **ancient minerals** are searched for. Different readout scenarios considered to achieve nm resolution.

  + Profiting from a large integration time

  Mineral optimization: to supress cosmogenic background, neutrons from ^{238}U contamination

  A. K. Drukier et al, Phys. Rev. D 99, 043014 (2019)



New technologies: recoil direction

- **Crystal defect spectroscopy:** WIMP-induced nuclear recoils in a diamond target would create an observable damage trail in the crystal that alters the strain pattern

  + Large target mass (a solid-state detector), ultra-fine spatial resolution (nm-scale)

  S. Rajendran, Phys, Rev. D 96 (2017) 035009

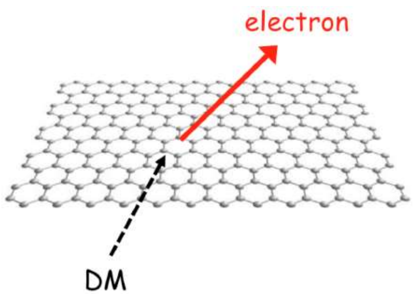
- **DNA strand detector:** DNA strands mounted onto a nm-thick gold foil could be severed by a recoiling gold atom kicked out by a WIMP.

  Biological techniques could allow to identify position of each severing event.

  A.K. Drukier et al, Int J. Mod. Phys. A 29 (2014) 1443007

- **Planar targets (Graphene):** planar targets make easier the determination of recoil direction (avoiding multiple interaction in bulk targets).

  S.Y. Wang, Eur. Phys. J. C 79 (2019) 561



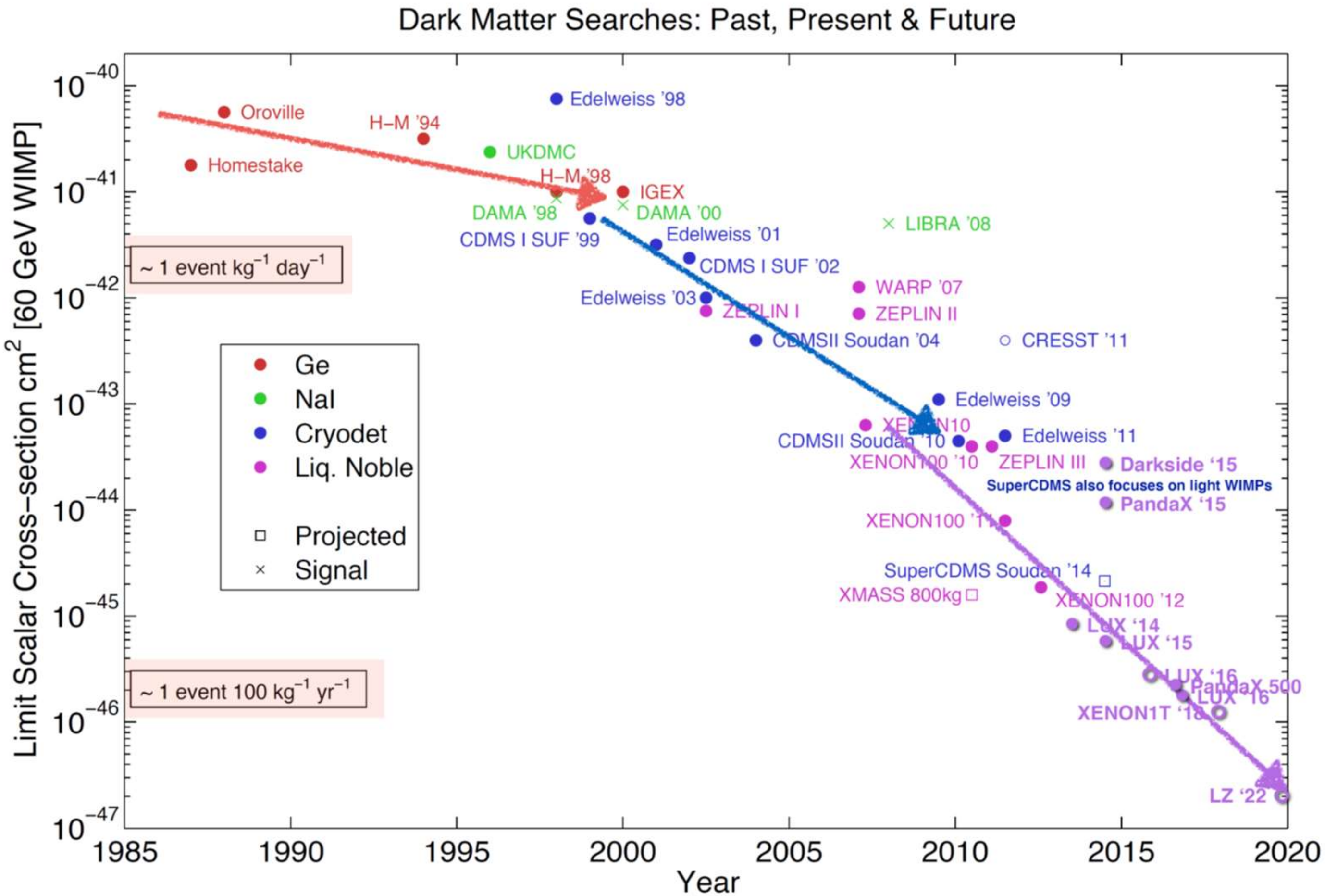
  PTOLEMY-G: Graphene FETs in stacked planar arrays with tunable meV band gaps, offering single-electron sensitivity

  E. Baracchini et al, arXiv:1808.01892

- **Anisotropic scintillators** ($ZnWO_4$), **columnar recombination** in LAr **(ReD program), carbon nanotubes**,…

Summary

Impressive improvement in the best limits set for DM-nucleus SI interactions



R. Gaitskell
The Identification of Dark Matter Conference (IDM2020) (Remote)

Summary

- For the direct detection of **low mass DM** best limits, on SD and SI interactions with nuclei and for electron scattering, come from several experiments based on very different detection techniques:
  - **Solid-state cryogenic detectors**: scintillating bolometers, small mass Ge and Si crystals.
  - **Liquid noble detectors** (Xe, Ar): operated in S2 only mode (charge collection).
  - Purely **ionization detectors**: Ge, CCDs, gas detectors.
  - **Bubble chambers.**

Use of light targets, achieving extremely **low energy thresholds** and/or searching for **different interaction channels** (enhancement by Migdal effect) are strategies followed and **new technologies** are in development.

- Important results (even if still with low significance) from **NaI(Tl) experiments** (COSINE-100, ANAIS-112) to solve the long standing conundrum of the DAMA/LIBRA **annual modulation** result.

- Construction of a DM detector with **directional sensitivity** is underway to prove the galactic origin of a possible signal

  Low-pressure TPCs with different readouts and **nuclear emulsions** explored.