Direct detection of Dark Matter

Review from the APPEC committee report: arXiv:2104.07634

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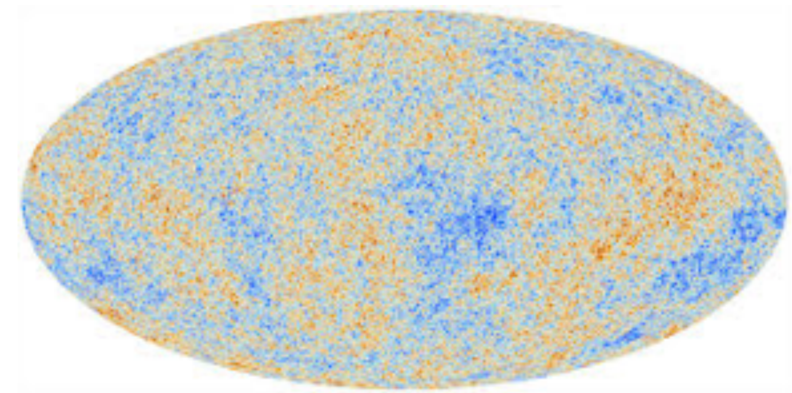
GDR détecteurs, June 23rd, 2021

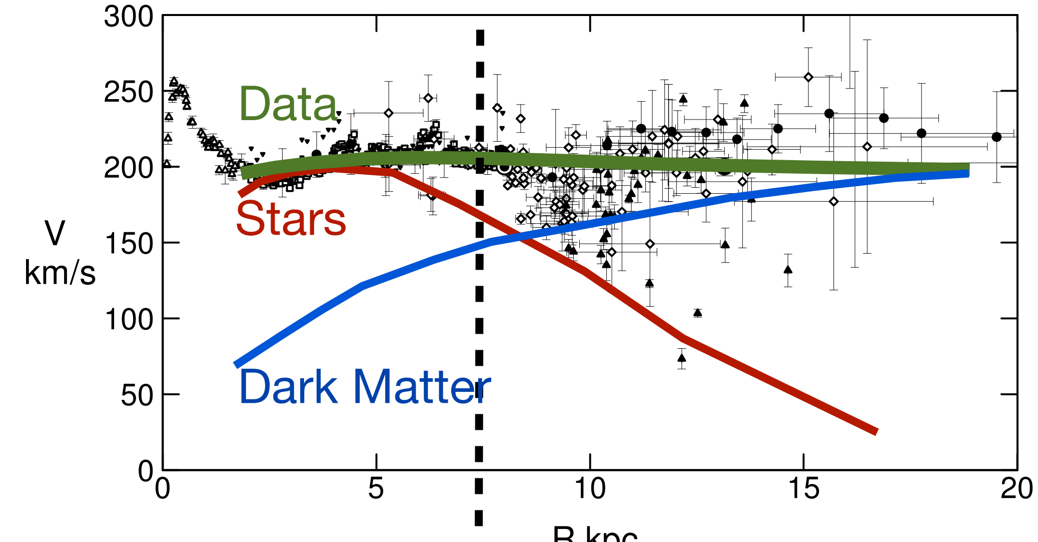
Introduction: *Direct detection in a nutshell*

From precision cosmology (CMB, BAO, ...):

~26% of the matter/energy content of the universe is made of non baryonic Dark Matter



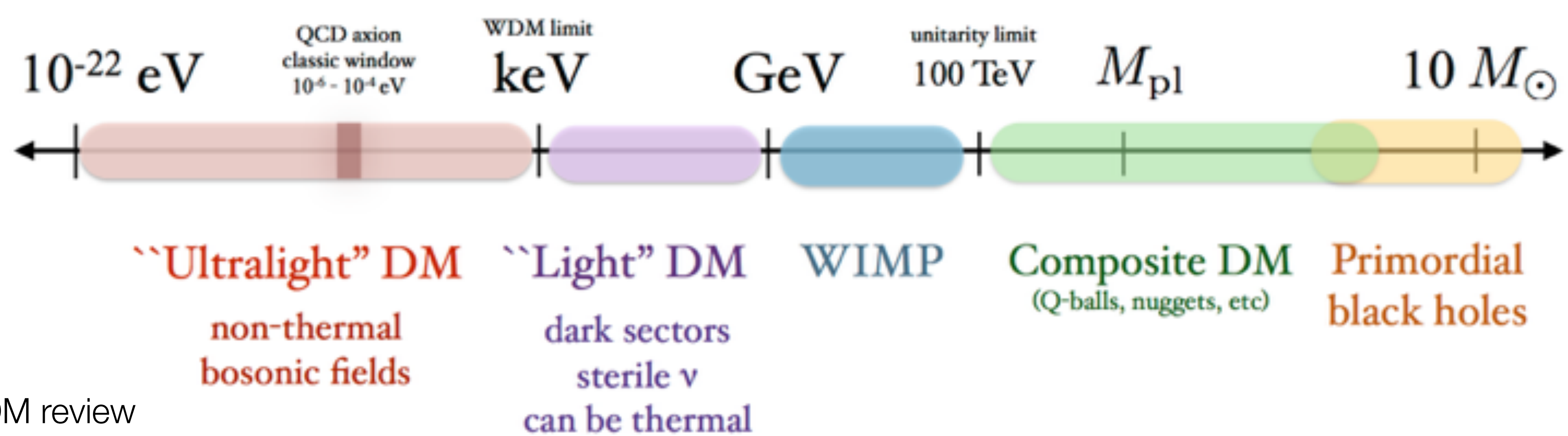
Local Dark Matter density: 0.3±0.1 GeV/cm^3



From rotation velocity measurement of galaxies:

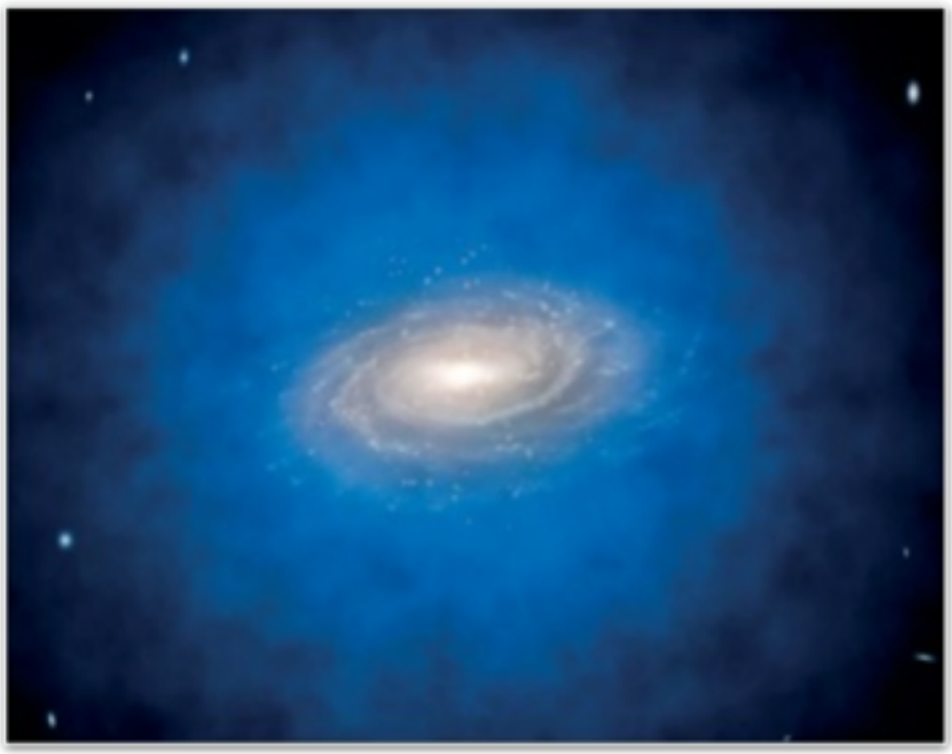
Spiral galaxies are embedded in Dark Matter halo that outweights the luminous part by a factor ~10

Dark matter candidate:



Courtesy: T. Lin

Introduction: *Direct detection in a nutshell*



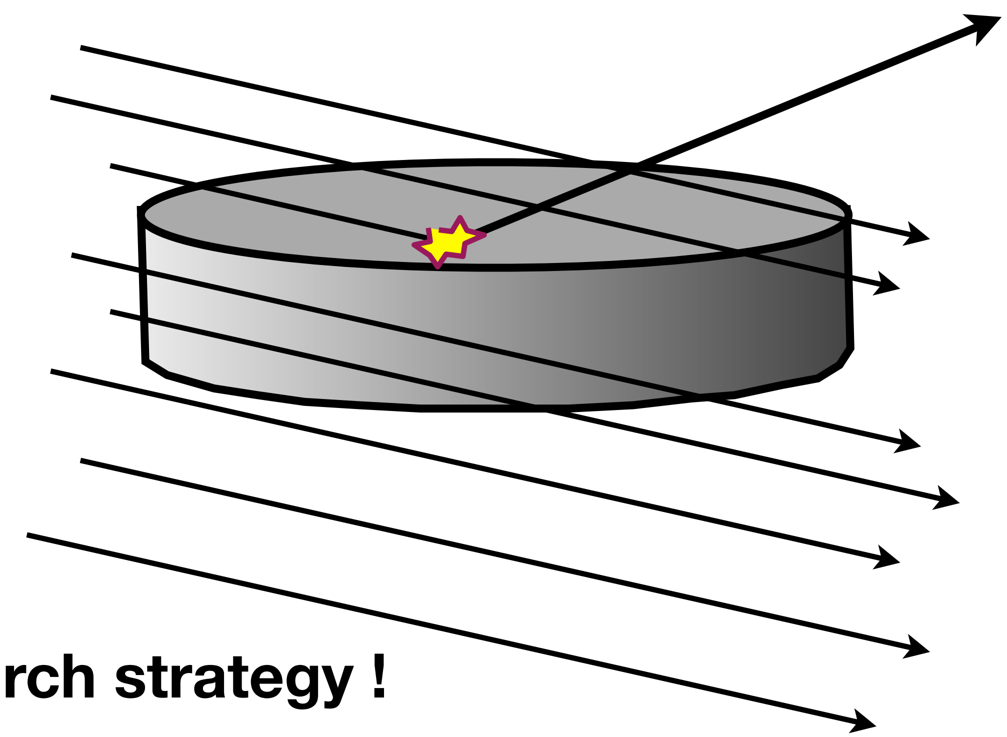
Assuming WIMP-like DM and basic assumptions:

- MB distribution with mean velocity: 300 km/s
- Local dark matter density: 0.3 GeV/cm^3
- Mass of Dark Matter particle: 100 GeV
- Dark Matter flux ~ 100,000 particles/cm^2/s

~ 20 million particles/hand/s

Expected WIMP-nucleus scattering rate in a Ge detector:

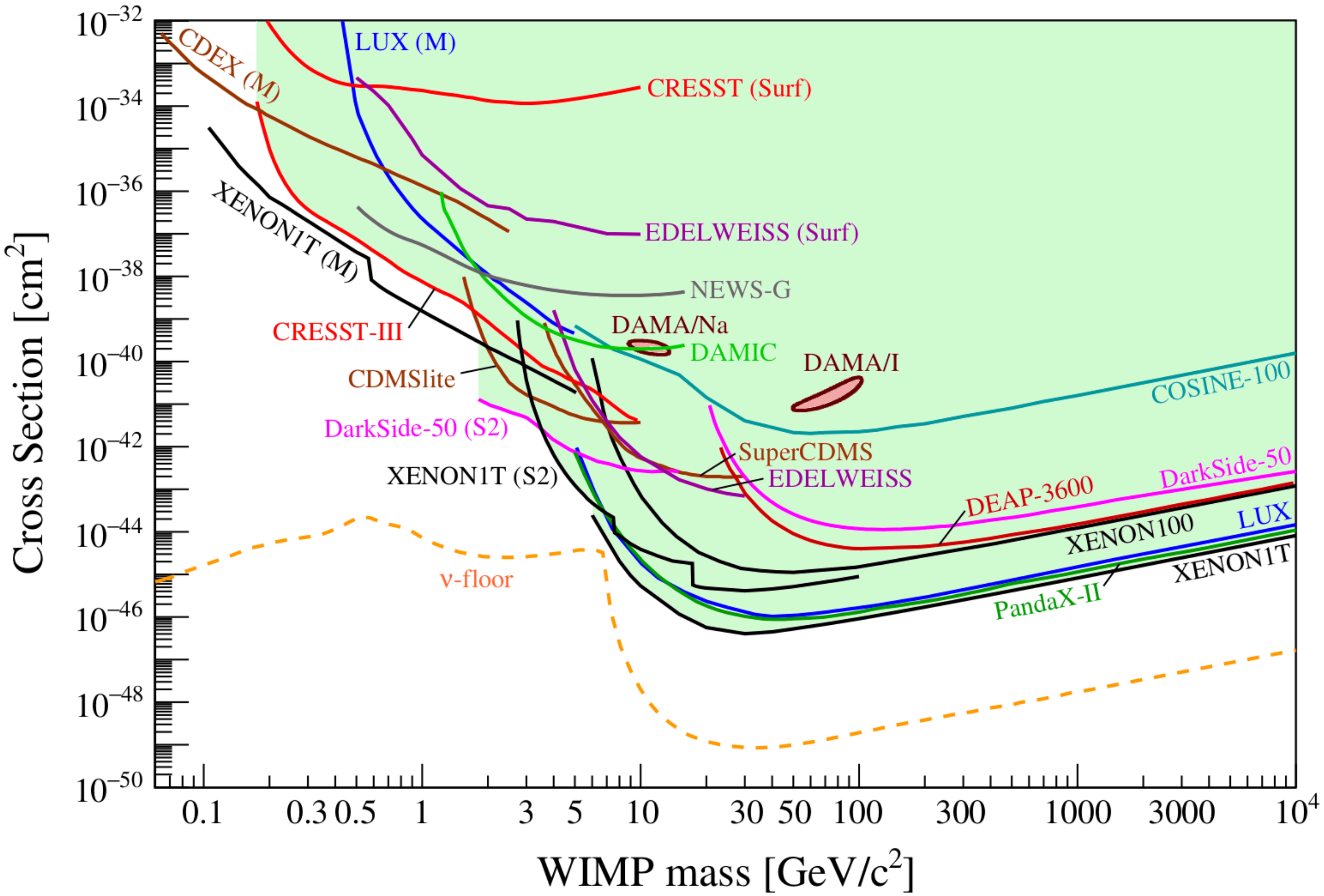
- « Weak scale » cross-section of 10^{-38} cm^2
- Spin-independent coupling
- Rate: **~ 20 recoils/kg/day**
- Mean recoil energy: **~ 10 keV**
- **Direct detection is a very promising dark matter search strategy !**



Suggested by Goodman and Witten (PRD 1985)

Direct detection: *State of the art*

J. Billard et al., APPEC committee report (2020)



(M) stands for Migdal based results
(Surf) stands for results obtained from surface operations
(ν-floor) corresponds to the irreducible cosmic neutrino background

Present status of direct detection:

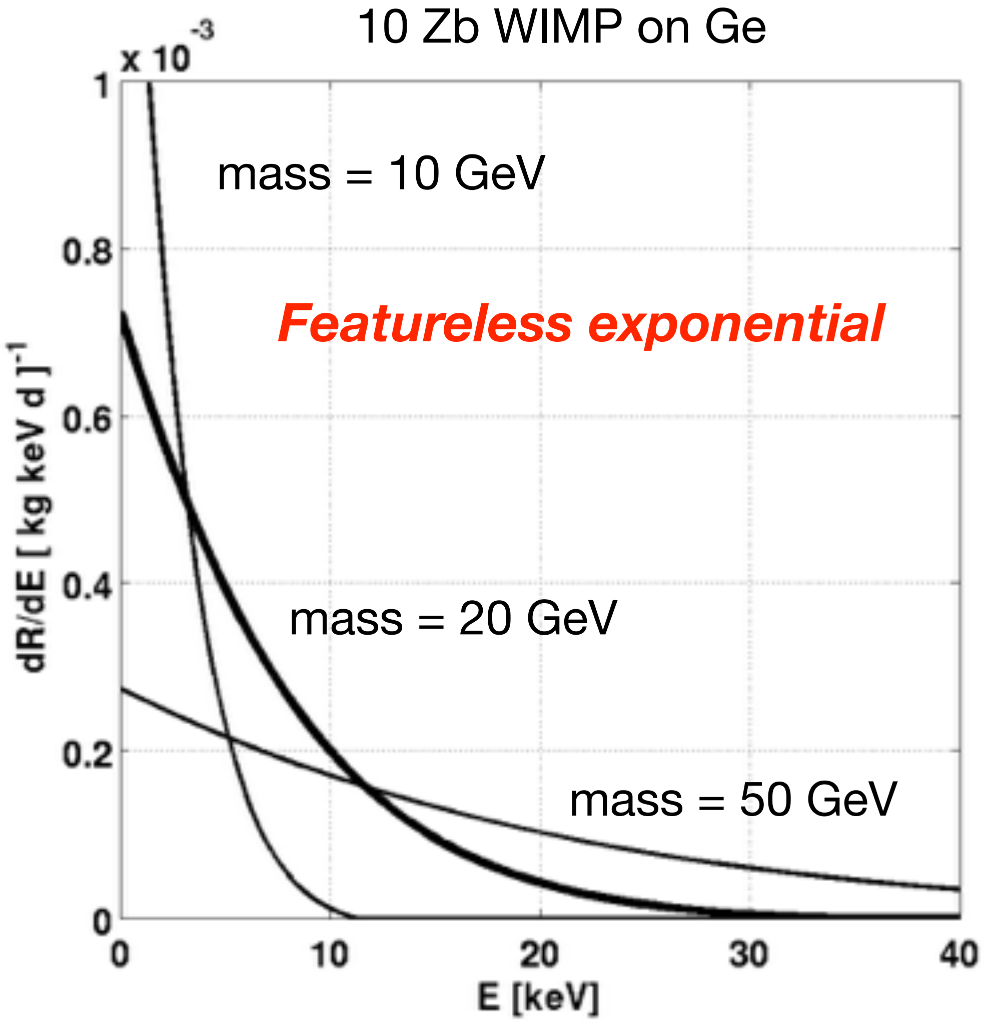
- About 25 experiments worldwide are aiming at directly detect dark matter
- Aside from the DAMA claim, no evidence of a positive DM detection down to 10^{-46} cm^2
- Low WIMP mass region (<10 GeV): cryogenic and ionization based experiments
- High WIMP mass region (>10 GeV): single and dual phase noble gas detectors

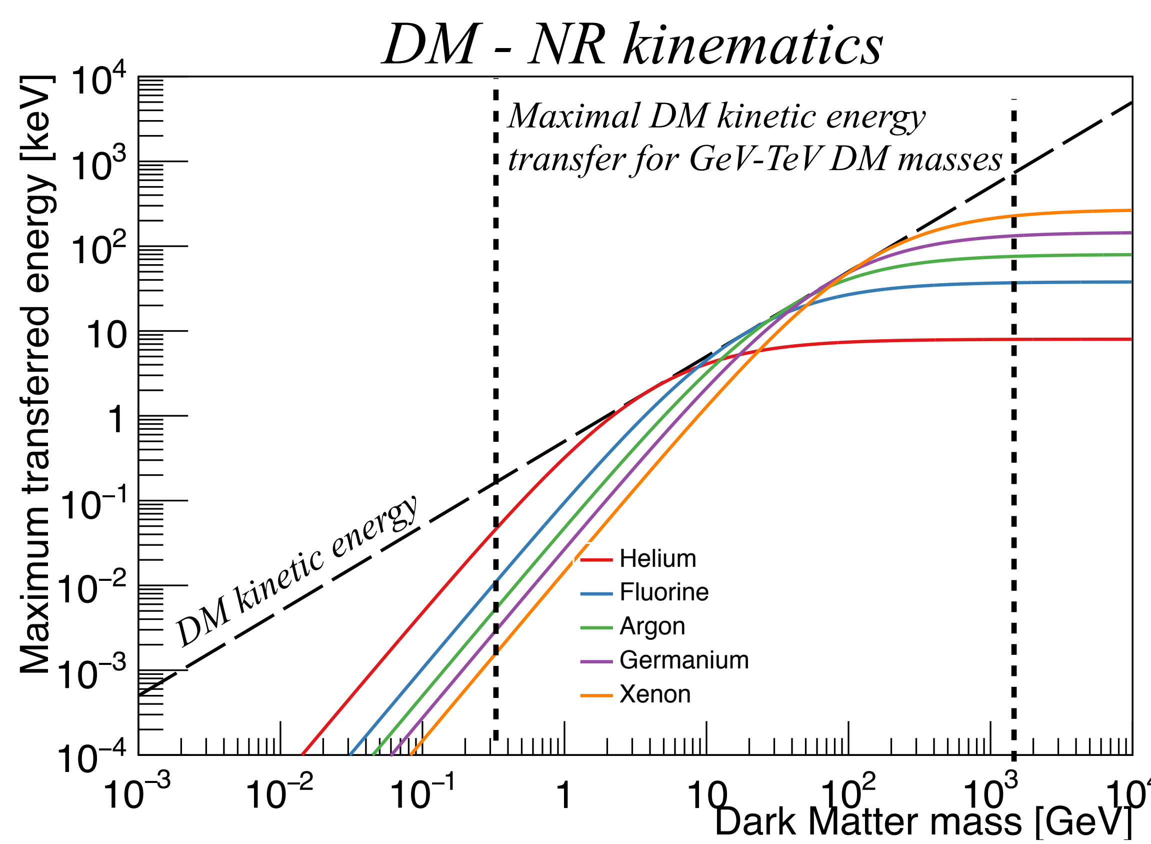
Direct detection: *DM-nucleus signal*

Differential event rate:

- Astrophysics
- Nuclear physics
- Particle physics

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\frac{\sigma_0}{m_\chi} F^2(E_r)\, \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$

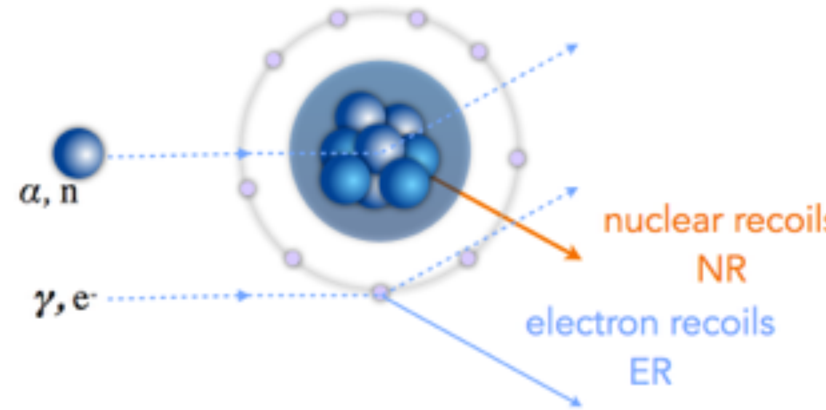




- Lighter targets are optimized for light DM candidates
- For DM masses below GeV use low-momentum (low effective mass) final states (e.g., electron, phonon)

Direct detection: *DM-nucleus backgrounds*

A few signal events observed during the experiment's exposure yield a high statistical significance



ER background sources:

- long-lived natural radioisotopes (^{238}U, ^{232}Th chains and their daughters, e.g. ^{214}Pb; ^{40}K)
- cosmogenic activation (e.g., ^{3}H, ^{39}Ar)
- anthropogenic isotopes (e.g., ^{60}Co, ^{85}Kr, ^{110m}Ag, ^{137}Cs)
- elastic collisions of low-energy solar neutrinos with atomic electrons

α background sources:

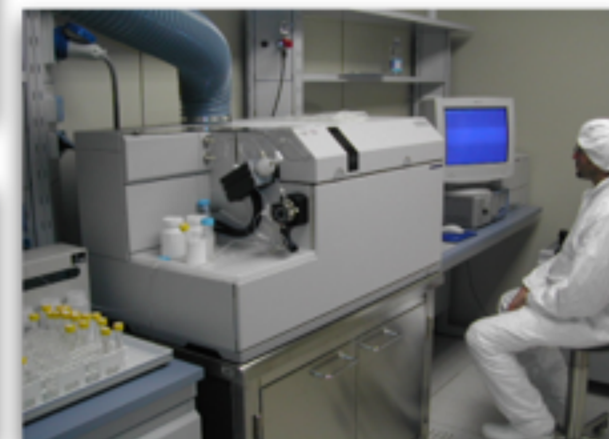
- radioactivity from detector surfaces with a fraction of the **α**-energy lost in insensitive detector regions.

NR background sources:

- radiogenic neutrons from (**α**;n) and spontaneous fission reactions
- cosmogenic neutrons induced by cosmic ray muons
- coherent and elastic scattering of neutrinos off target nuclei (*neutrino floor*)

Direct detection: *Background mitigation strategies*

Laboratory	LNGS	LSC	LSM	Boulby
Country	Italy	Spain	France	UK
Depth (m.w.e.)	3600	2450	4800	2820
Muon Flux (mu/m²/s)	3×10^{-4}	3×10^{-3}	5×10^{-5}	4×10^{-4}
Volume (m3)	180000	8250	3500	4000
Access Road	Road	Road	Road	Shaft
Personnel	O(100)	O(10)	O(10)	O(5)
DM Experiment	8	2	3	1



Deep Underground Laboratories **:**

- reduction of cosmogenic neutrons and material activation
- four major laboratories in Europe

Radiopurity *of detector and target material:*

- Material screening

Experiment design:

- Passive and active shielding (Pb, mu-veto, …)

Cleanliness*:*

- (^{222}Rn-abated) cleanrooms

Purification *of target material:*

- during production process (e.g., crystal growth)
- at procurement level (e.g., low-^{39}Ar UAr; cryogenic distillation, chromatography)
- during data taking

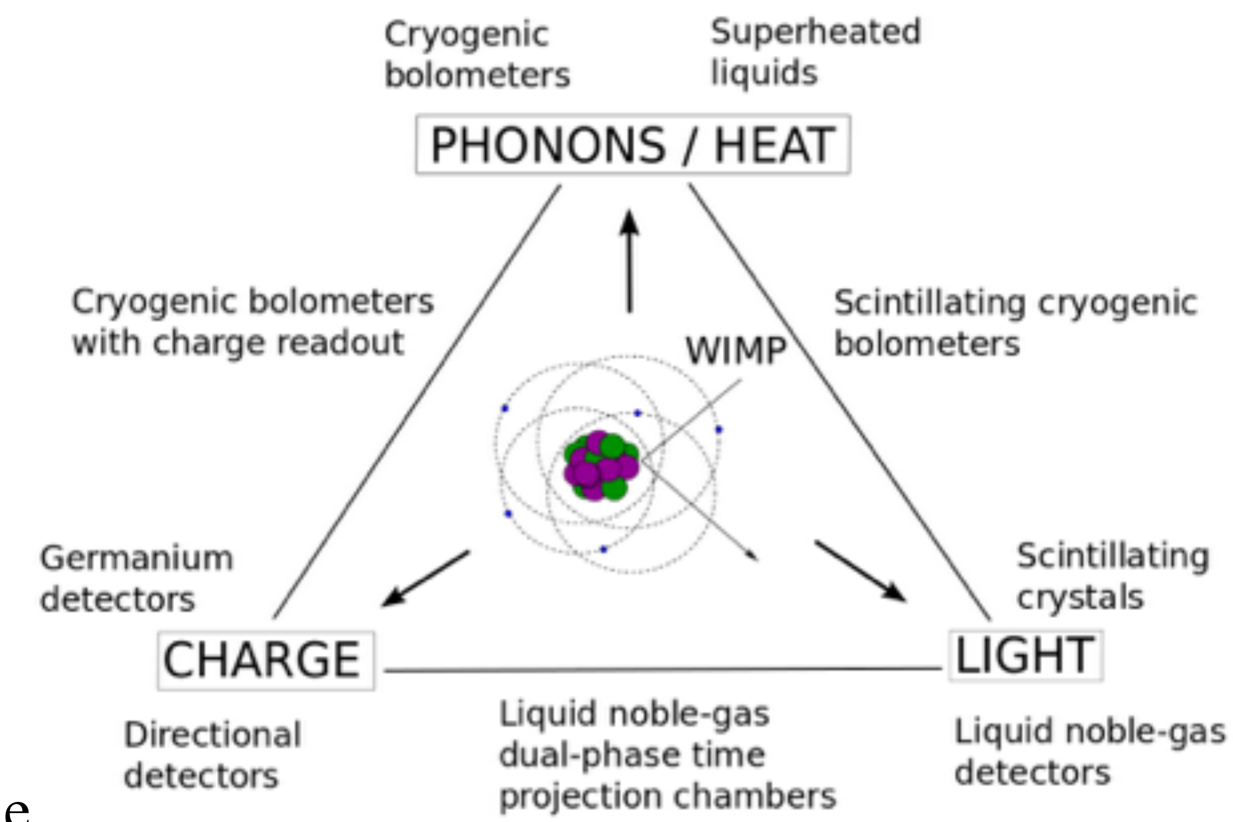
Direct detection: *Background mitigation strategies*

Fiducialisation:

- self-shielding of the detector
- requires position reconstruction or surface signal discrimination techniques

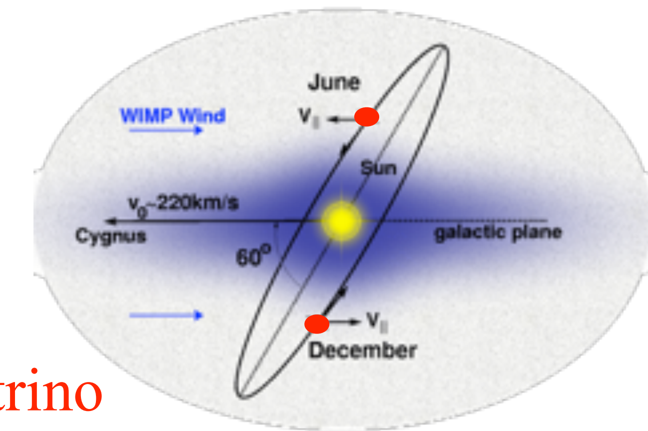
Active rejection and particle identification (ER/NR):

- measuring two out of the three de-excitation channels (heat, scintillation, ionisation)
- scintillation light PSD (argon)
- bubble nucleation and acoustic rejection (bubble chambers: **PICASSO**, **COUPP**, **PICO**)
- single scatter, veto, and timing

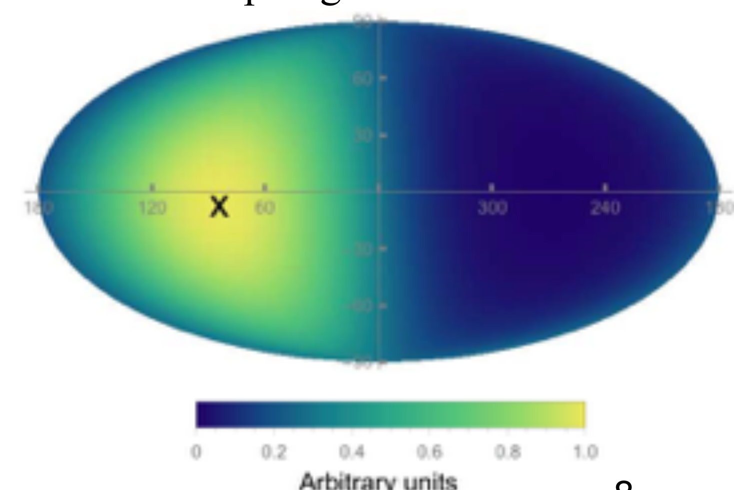


Exploiting the galactic origin of the DM signal:

- annual modulation: ~5% effect
- directional detection: $O(1)$ asymmetry
  - unique capability to overcome the neutrino background

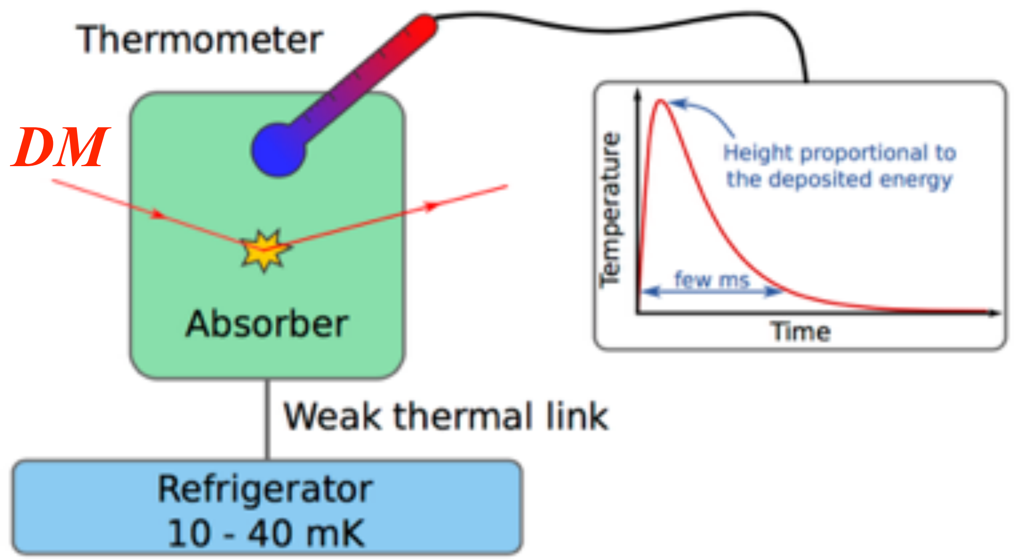


Recoil map in galactic coordinates

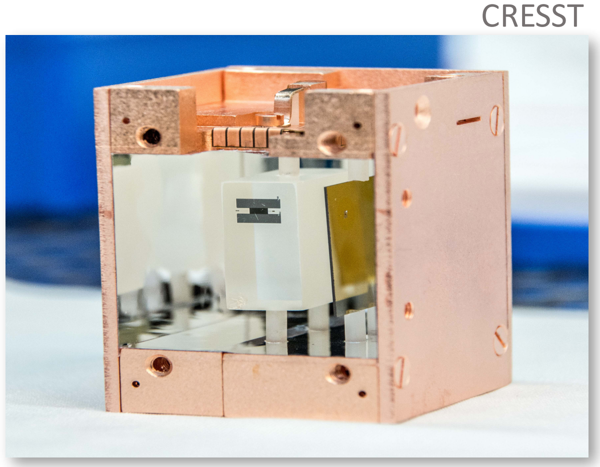


F. Mayet et al., Phys. Rep. 2016

Detector technologies: *Cryogenic experiments*

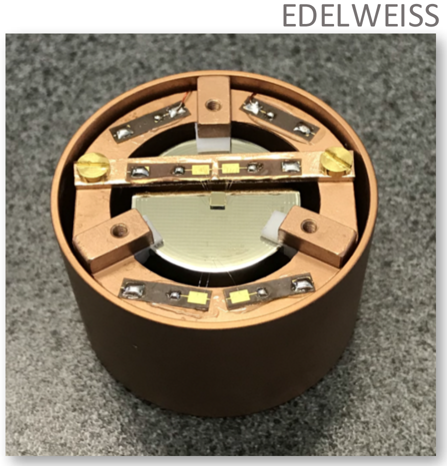


CRESST



24g $CaWO_4$

EDELWEISS



33g Ge

Cryogenic phonon readout:

- Direct measurement of the recoil energy
- From thermodynamics, ultimate energy resolution is: **~eV (RMS) for ~ 10 g detectors**
- Leading technology in the MeV-GeV mass range
- Scaling to ton-scale is challenging (highly segmented)
- Technology being exploited for CEvNS (RICOCHET)

Semiconductors (Ge, Si): EDELWEISS and SuperCDMS

- Particle ID thanks to ionization/heat ratio
  - *Can be extended to 100 eVnr-scale with dedicated low noise electronics*
- Can be operated at high voltages to reduce the effective ionisation energy threshold
  - *No ER/NR identification in such mode*
  - *Sensitivity to single-e/h pair*

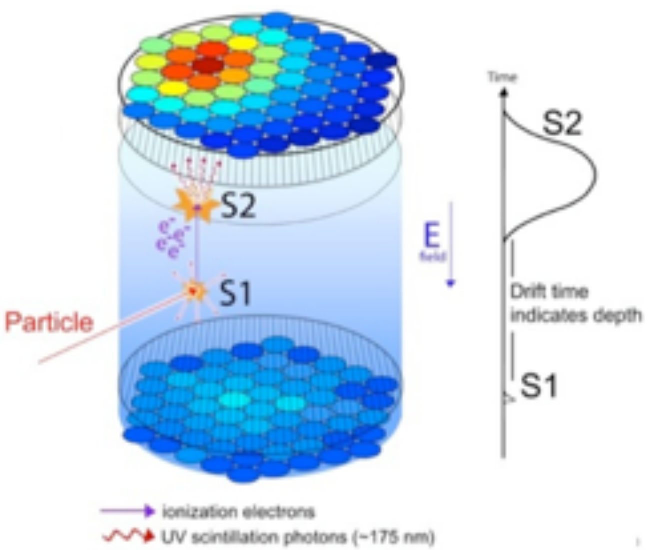
Scintillating crystals (Al_2O_3, $CaWO_4$): CRESST

- Particle ID thanks to scintillation/heat ratio
  - Limited to recoil >1 keVnr due to low light yield

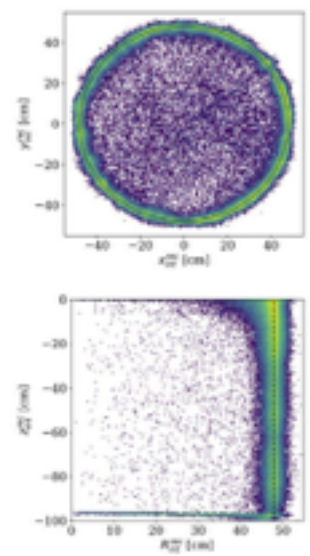
Ten-year perspective and beyond:

- Aiming for the solar neutrino floor in the 1-to-5 GeV mass range and **extending the DM search down to the meV mass range** using HV operation for DM-e coupling, and DM-phonon (acoustic and optical) coupling

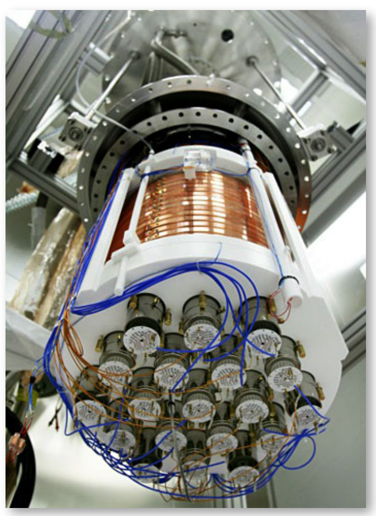
Detector technologies: *Noble gas experiments*



DarkSide



XENON



Noble gas experiments

- Single-phase liquid argon **DEAP3600**
  - *fiducialisation and PSD*
- Dual-phase TPC liquid and gas:
  - Xenon: **LUX, XENON-1T, PandaX**
  - Argon: **DarkSide-50**
  - *fiducialisation, light/ionization-yield, PSD (Ar)*

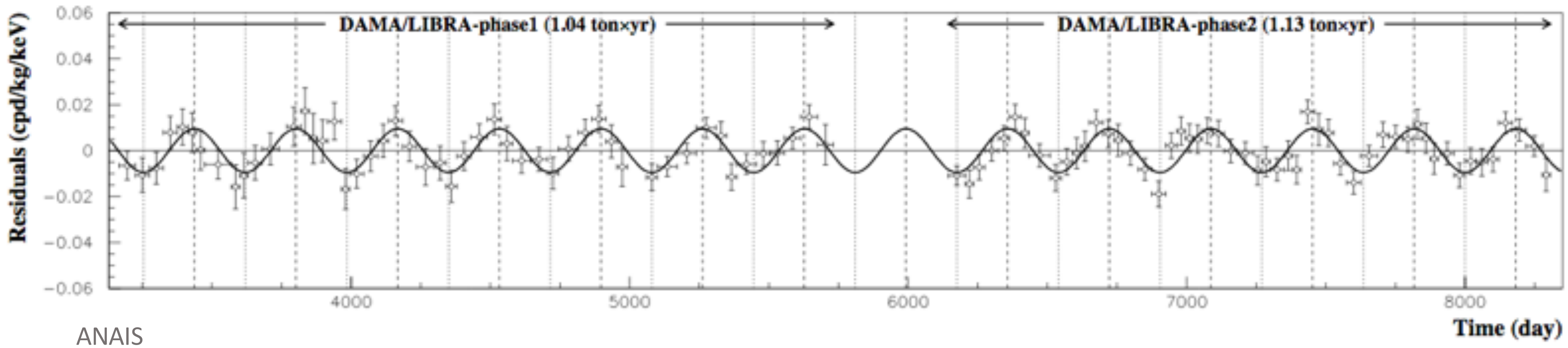
- Monolithic detectors with controlled backgrounds
- Scalable technology *(provided high Xe and Ar purification)*
- Benefits from the A^2 boost factor from SI interaction and the lowest achieved backgrounds *(self-shielding)*
- *Ideal for WIMP-like scenario leading technology for DM masses above 5 GeV*
- *Also very competitive in various DM searches*

Ten-year perspective and beyond:

- Aiming for the atmospheric neutrinos but ***first 8B neutrino detection is just around the corner !***
- The LAr groups have formed the Global Argon DM Collaboration to build DarkSide-20k, and its successor, the 400-t ARGO detector
- On the Xenon side, LZ and XENONnT are under commissioning, and R&D is ongoing to build the next-to-next generation 40-t DARWIN detector

Detector technologies: *NaI(Tl) scintillators*

Solving the long-standing mystery of the DAMA/LIBRA annual modulation signal



ANAIS

DAMA/LIBRA:

- 2.46 ton-year exposure of NaI crystals with **no discrimination**
- Claim for a 12.9σ DM induced annual modulation over 20 annual cycles
- In strong tension with existing limits but… **We can't explain this modulation…**

COSINE

Dedicated NaI experiments to address this conundrum:

- **ANAIS-112**: after 3 years of data taking, result incompatible with DAMA (>2σ)
- **COSINE-100**: active vetoing of ^{40}K, 3σ coverage of DAMA after 5 years
- **SABRE**: High purity NaI crystals and active vetoing of ^{40}K, in both hemispheres
- **COSINUS**: NaI cryogenic detectors with active PID from heat and scintillation

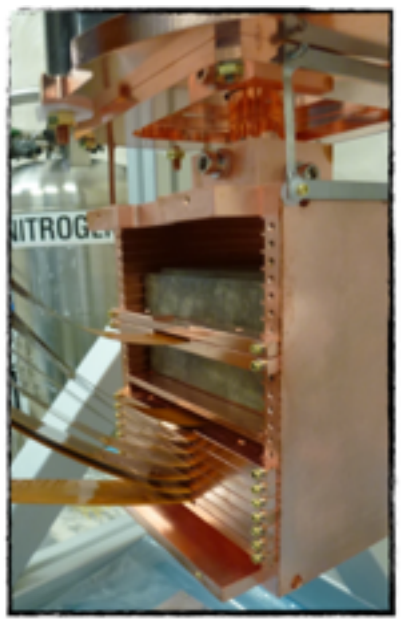
Ten-year perspective and beyond:

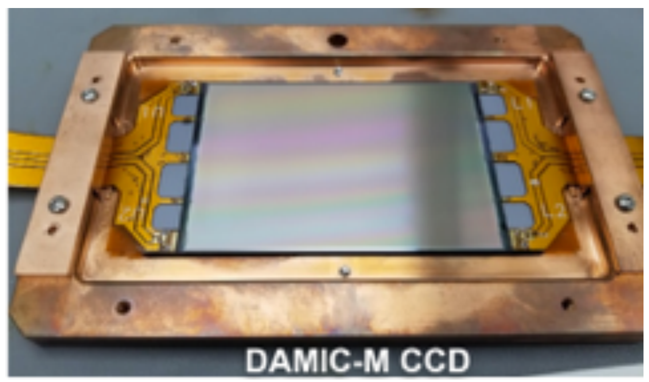
- Mainly solve the DAMA/LIBRA mystery in rejecting or confirming its DM detection

Use same crystals to alleviate all possible degeneracies from target dependent interactions, halo physics and calibrations

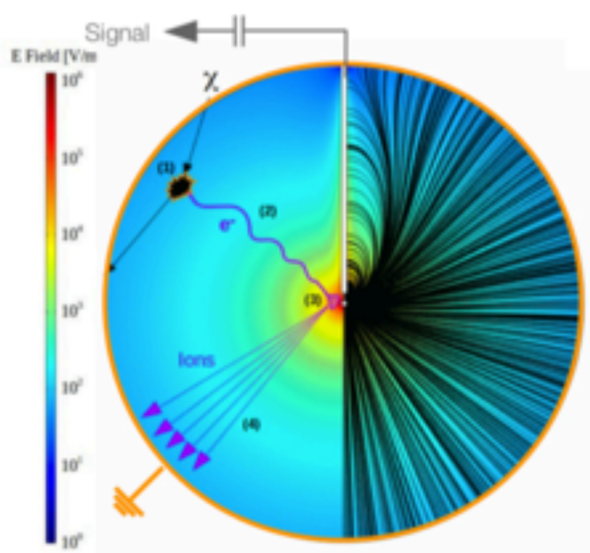
Detector technologies: *Ionization detectors*

DAMIC





NEWS-G



Si-CCD: DAMIC, DAMIC-M and SENSEI

- ionization in Si (w_{eh} = 3.8 eV)
- 3 dimensional fiducialisation
- skipper CCD readout noise < 0.07e^- and ultra low leakage current of about 5×10^{-22} A/cm^2
- Sensitivity to DM-NR limited by ionization yield and target payload (~ kg-scale) but among leading experiments for light DM searches (DM-e and HS-DM)

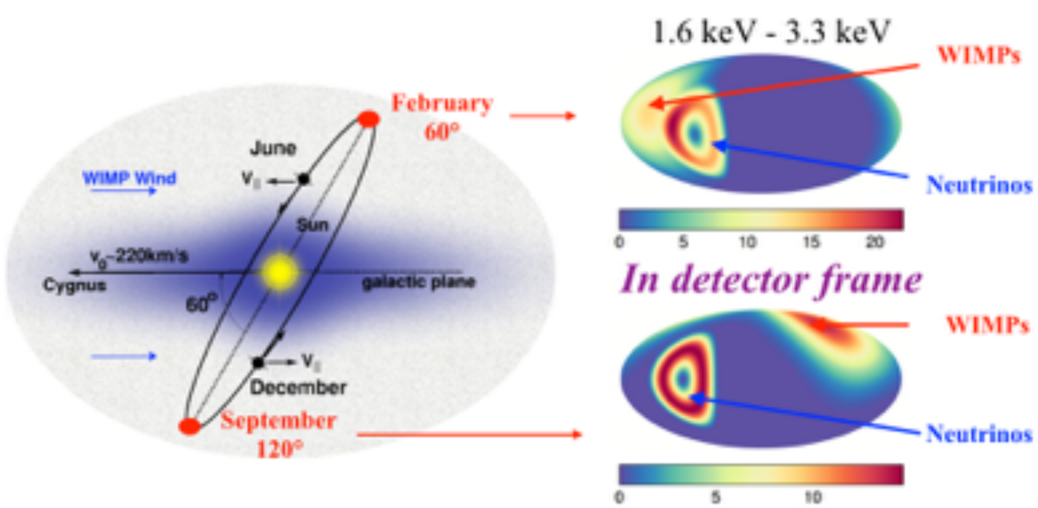
Gaseous Spherical Proportional Chamber: NEWS-G

- ionization in Neon gas (w_{ion} = 36 eV)
- fiducialisation: radius and hemisphere (achinos)
- can be operated with variety of gases and pressures
- single-e^- sensitivity thanks to exquisite resolution
- focus on light target nuclei (H, He, Ne) for optimized sensitivity to low WIMP mass

Ten-year perspective and beyond:

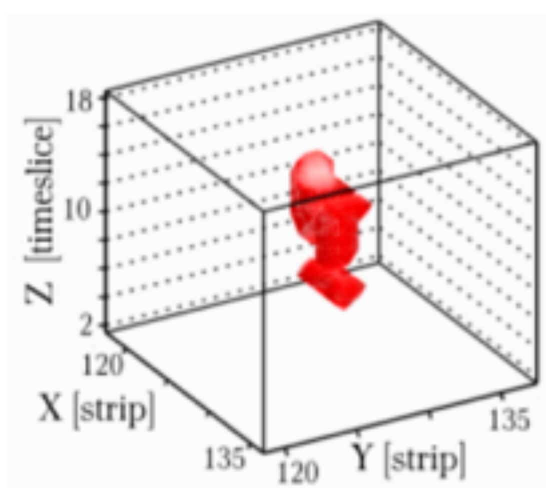
- Detectors with single-electron sensitivity are uniquely sensitive to hidden sector DM, through DM-electron interactions.
- NEWS-G will deploy a serie of SPCs with larger payloads to reach the solar neutrino floor

Detector technologies: *Directional detectors*



MIMAC

6 keV ^{19}F track



Directional detection strategy:

- Directional detection aims at measuring both the recoil energy and track (direction and sense)
- Unambiguous proof of a galactic origin of the signal
- Almost immune to the neutrino background
- Unique way to probe the nature of DM from both particle physics and astrophysics (DM distribution)
- The key challenge is scalability (*O*(100) grams so far)
- Ongoing projects *(gaseous TPC)*: **DRIFT, DM-TPC, NEWAGE, D^3, CYGNO,** and **MIMAC**

MIcro-TPC Matrix of Chambers: MIMAC

- Bi-chamber, mixture of $CF_4 + CHF_3 + C_4H_{10}$ @ 30 mb
- 3D track reconstruction and fiducialisation
- ER/NR rejection from track topology
- Detection threshold *O*(100) eVee
- Angular resolution <10^{o} for ^{19}F recoils >10 keVnr

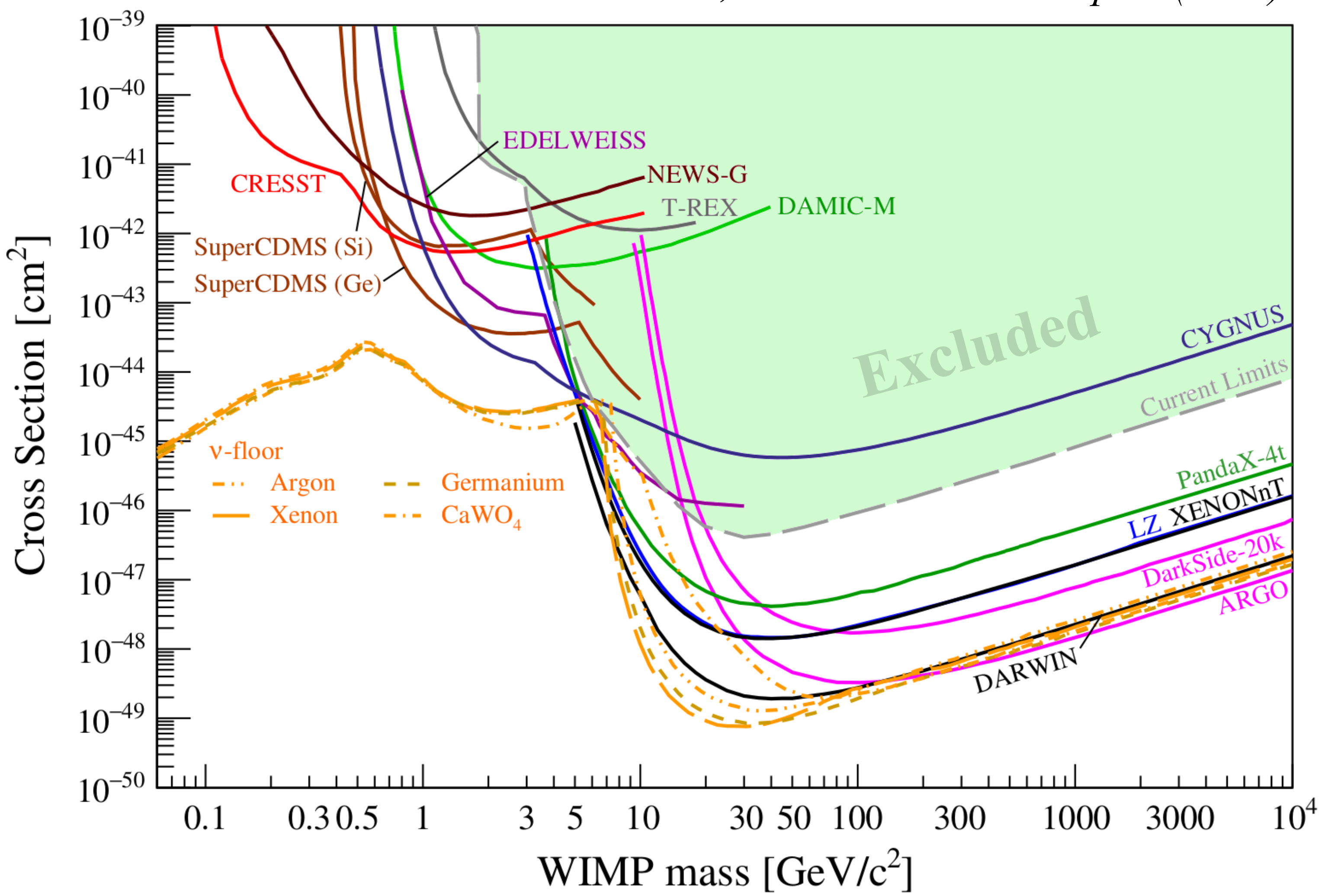
Ten-year perspective and beyond:

- 1 m^3 MIMAC detector is under construction for increased sensitivity to DM
- CYGNUS proto-collaboration formed carrying out R&D to determine the optimum configuration for a large target mass directional detector

Detector technologies: *Projections* *(limited to standard WIMP)*

Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale	Ref.
Cryogenic bolometers (Section 4.6.1)								
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.	[348]
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.	[349]
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running	[153]
LXe detectors (Section 4.6.2)								
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.	[267]
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.	[271]
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.	[276]
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	~2026	[244]
LAr detectors (Section 4.6.3)								
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running	[157]
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running	[140]
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023	[350]
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD	[350]
NaI(Tl) scintillators (Section 4.6.4.1)								
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running	[135]
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running	[306]
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running	[311]
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.	[312]
COSINUS-1π	LNGS	NaI	~1	AM	1×10^{-43} @ 40	3×10^{-4}	2022	[315]
Ionisation detectors (Section 4.6.4.2)								
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running	[351]
DAMIC-M	LSM	Si	~0.7	SI	3×10^{-43} @ 3	0.001	2023	[319]
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running	[136]
NEWS-G	SNOLAB	Ne,He		SI			comm.	[325]
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.	[328]
Bubble chambers (Section 4.6.4.3)								
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running	[352]
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	[346]
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D	[345]

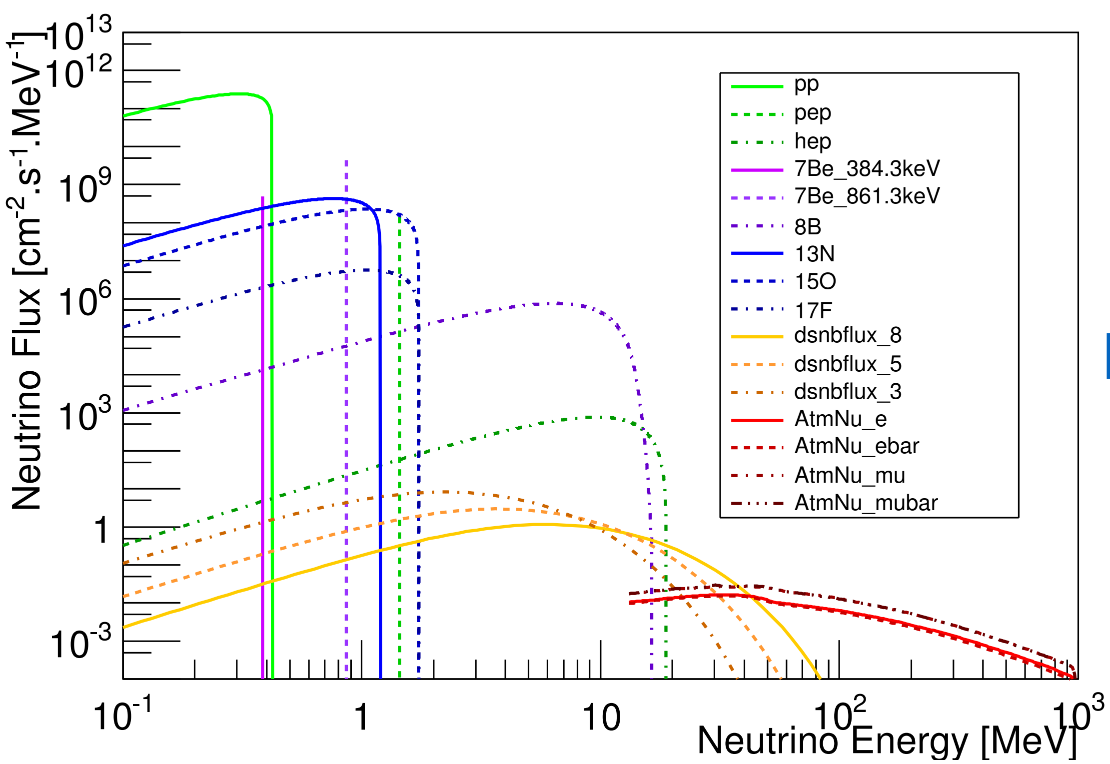
J. Billard et al., APPEC committee report (2020)



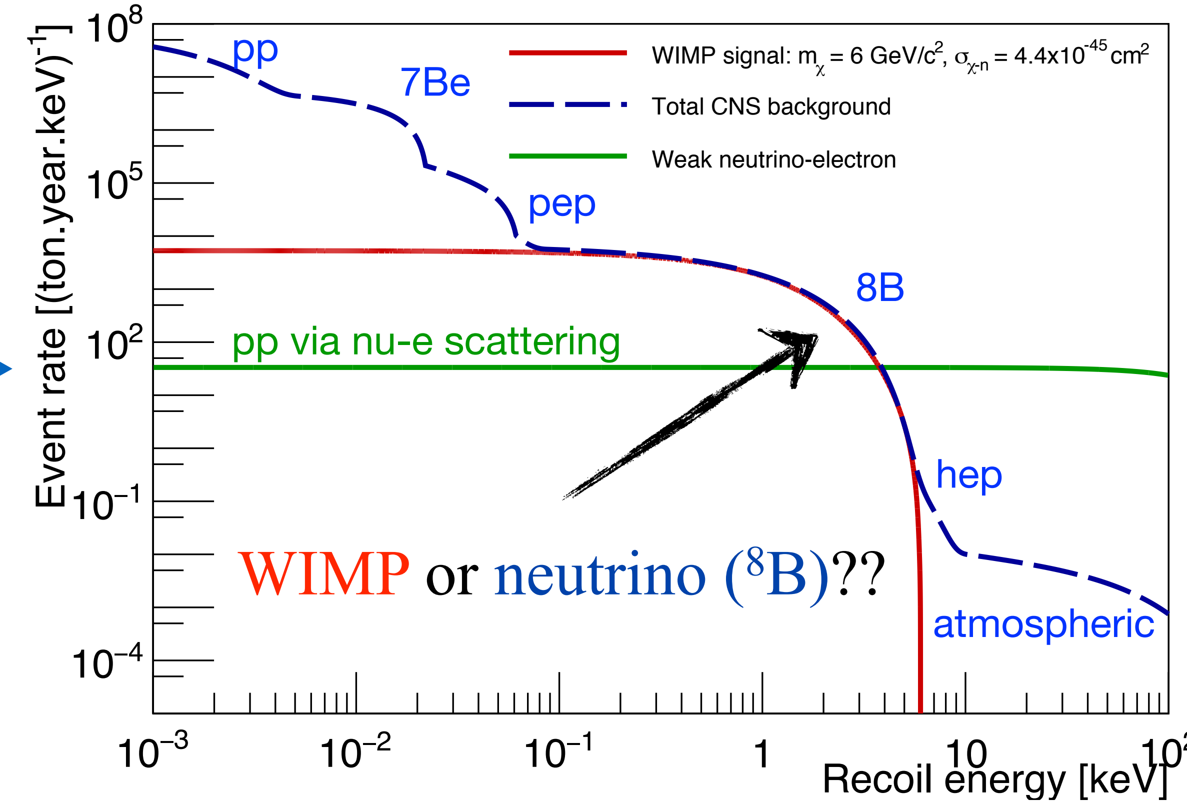
- The low-mass region, from ~100 MeV/c^2 to ~5 GeV/c^2, will be best explored by the cryogenic bolometers (**CRESST, EDELWEISS, SuperCDMS**) with their extremely low-energy thresholds and background rejection capabilities down to the lowest energies.
- Interactions of DM particles in the mass range of 1 − 100 MeV/c^2 will be best searched for by detectors with a sensitivity to single electrons (e.g., **DAMIC-M, NEWS-G, EDELWEISS**)
- The exploration of the medium to high-mass range requires very large exposures and will be dominated by the massive LAr (**DarkSide-20k, ARGO**) and LXe TPCs (**XENONnT, LZ, PandaX-4T, DARWIN**).
- Diversified approach needed to probe the broadest experimentally accessible ranges of particle mass and interactions!

Backup

Direct detection: *The irreducible neutrino background*



J. Billard et al., PRD 89 (2014)



- Cosmic neutrinos (solar, DSNB, and atmospheric) will soon become the **ultimate background to direct detection of Dark Matter** via their coherent and elastic scattering on nuclei (CENNS)
- 1 keV threshold: **100 evt/ton/year on Ge**
- For some DM masses, the CENNS and DM signal are similar enough so that they can hardly be separated **inducing a fundamental limitation on the reachable DM cross section**