Prospective nationales "Physique des neutrinos et matière noire", GT06

Direct Detection with noble liquids

Luca Scotto Lavina, LPNHE
With contributions from Ar and Xe French communities

Bordeaux, 28/10/2019

DM search with noble liquids : two contributions

Search for WIMP dark matter with the dual phase liquid argon detector DarkSide-20k

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3 professors *(~3 FTE)* *13 supporters*
2 engineers

1 PhD

Direct dark matter Search with the experiments from the international XENON Collaboration

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1 researcher/engineer *(~6 FTE)*
2 engineers

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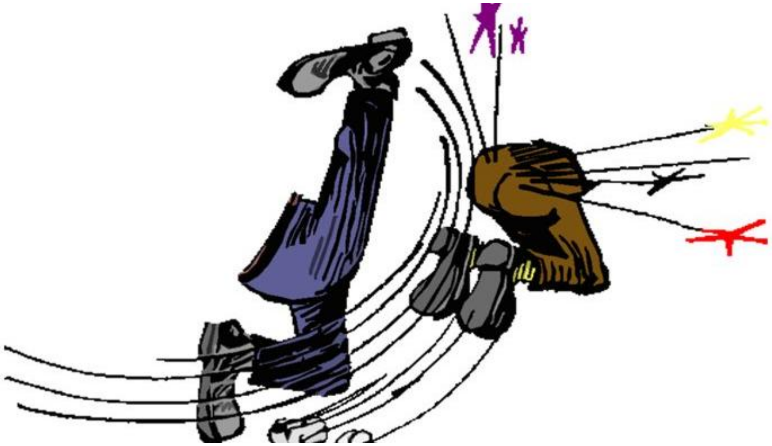
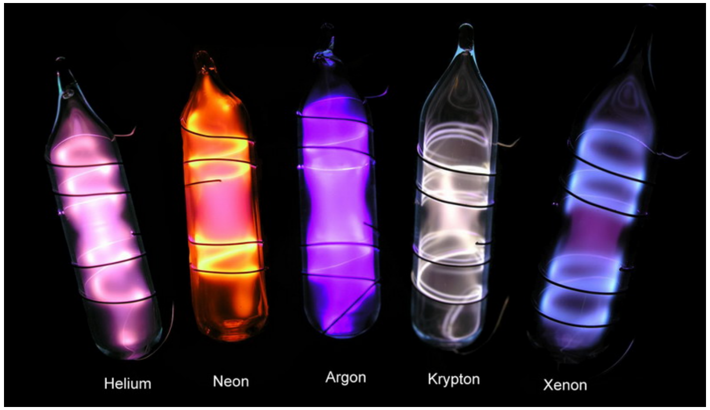
4 PhD

Direct Detection… with noble liquids





Direct detection in one phrase

WIMP elastically scatters off nuclei

Direct detection in one phrase, but…

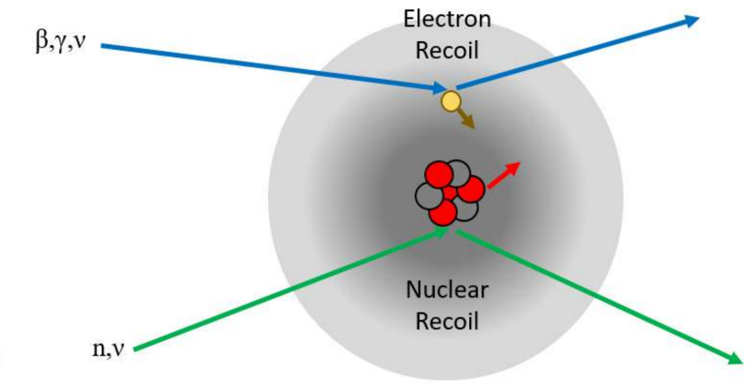
WIMP elastically scatters off nuclei

?　?　?

Direct detection in one slide

WIMP elastically scatters off nuclei → nuclear recoils

χ + N → χ + N



$$E = \frac{\mu^2 v^2}{m_N}(1 - cos\theta) \lesssim 100keV$$

$$v \sim 230\ km/s$$

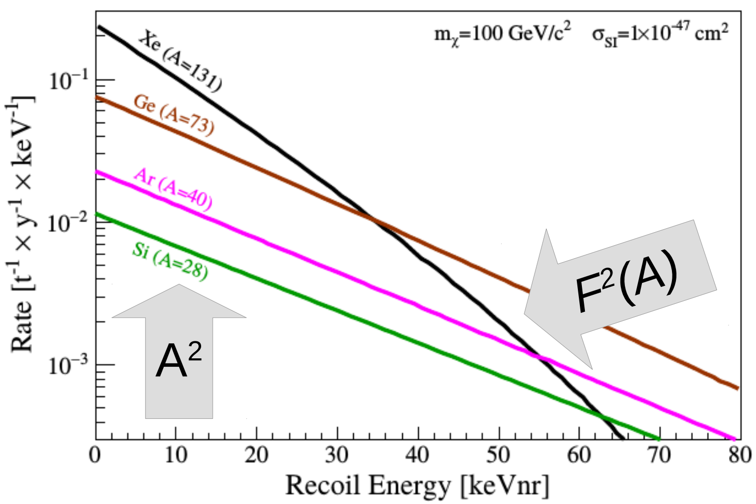
$$m_\chi = 10 - 10^4\ GeV/c^2$$

$$\rho_\chi \sim 0.3\ GeV/c^2/cm^3$$

$$\frac{dR}{dE} = \frac{\rho_\chi}{m_\chi}\frac{\sigma|F(E)|^2}{2\mu_p^2}\int_{v_{min(E)}}^{v_{esc}} d^3v \frac{f_\oplus(\vec{v},t)}{v}$$

Spin Independent : χ scatters coherently off of the **entire nucleus** A: σ ~ A^2

Spin Dependent : mainly **unpaired nucleons** contribute to scattering amplitude: σ ~ J(J+1)



Experimental challenge :

- low energy thresholds : O(1) keV
- very low backgrounds

Reducible backgrounds

Electronic Recoils (ER)

radiogenic, intrinsic, cosmogenic

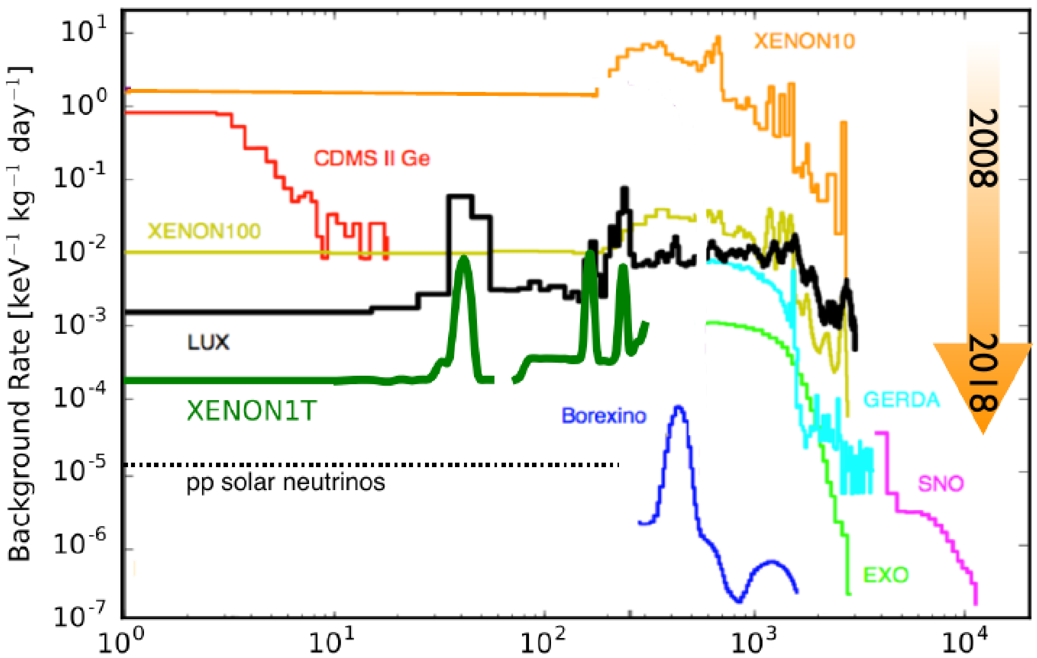
Source	E dependency	Xe	Ar
^{222}Rn	flat	*	*
Materials (cryostat, photosensors, TPC)	flat	*	*
^{85}Kr	flat	*	*
^{136}Xe 2νββ	∝ E @ low E	*	
^{39}Ar	∝ E @ low E		*

Nuclear Recoils (NR)

radiogenic, cosmogenic

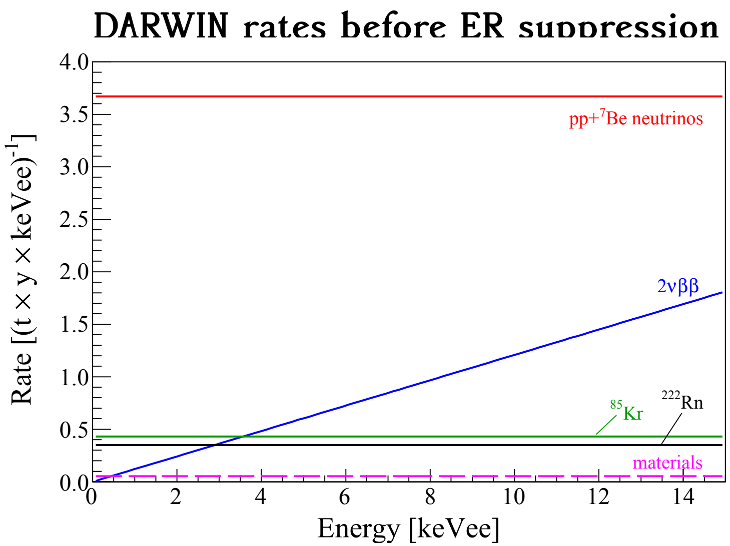
Source
Radiogenic neutrons : (α,n), spontaneous fission
Cosmogenic neutrons with a 14m x 14m⊘ water shield

Mitigation :
- deep underground site
- material screening
- instrumented veto system



Thanks to L. Baudis

Suppressing Electron Recoils



xenon

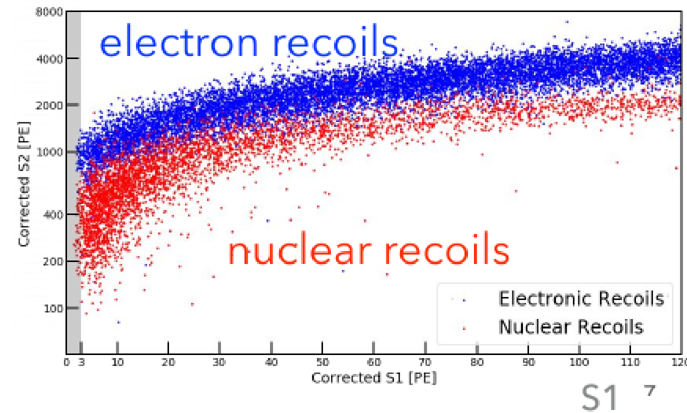
Intrinsic background :
$2\nu\beta\beta$ from ^{136}Xe
Subdominant with respect to neutrinos

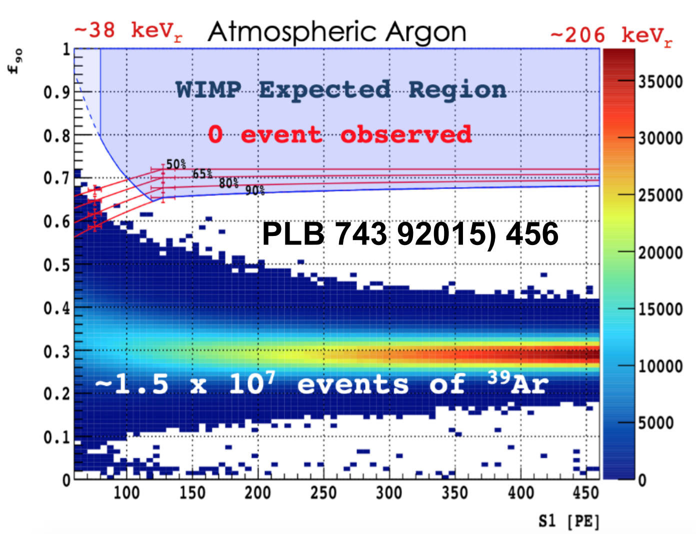
The goal is to keep other BGs subdominant as well

Main cut : S2/S1 ratio

Threshold : 3 keV

To reach the aimed goals, it is required an ER rejection > $5{\cdot}10^3$ (99.98% CL)





argon

Intrinsic background :
^{39}Ar from natural Argon

The goal is to keep it subdominant with respect to neutrinos

Main cut : S1 Pulse Shape Discrimination (PSD) in addition to S2/S1 ratio

Threshold : 38 keV

PSD rejection factor > 10^8

Accessible only with Argon :
- slow scintillation component (1000 ns)
- fast scintillation component (6 ns)

In addition:
- TPC filled with UAr
- ^{39}Ar (and ^{85}Kr) distillation with a 350m high column (ARIA project, in Sardinia)

DS20k is basically background free !

Irreducible backgrounds : neutrinos

Electronic Recoils (ER)

$\nu + e^- \rightarrow \nu + e^-$

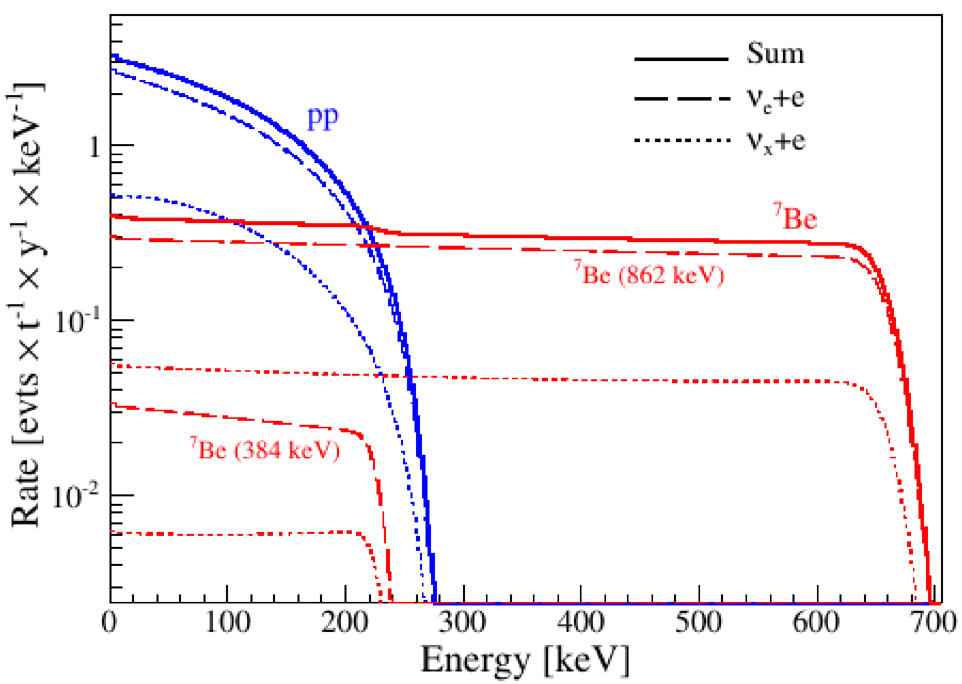
Solar : pp and ^{7}Be

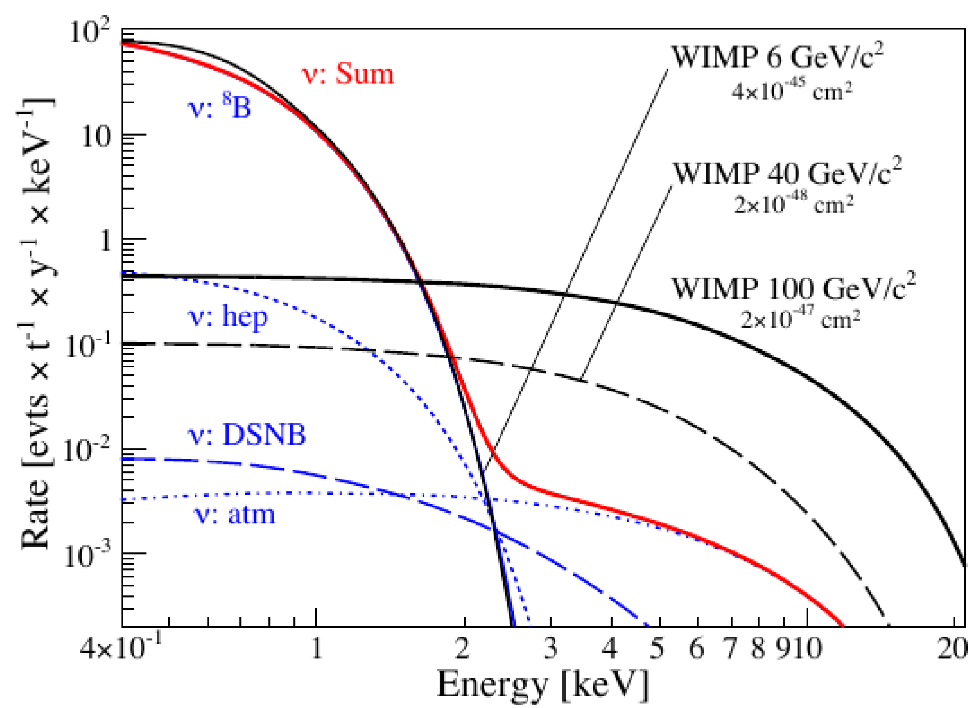
Nuclear Recoils (NR)

$\nu + N \rightarrow \nu + N$

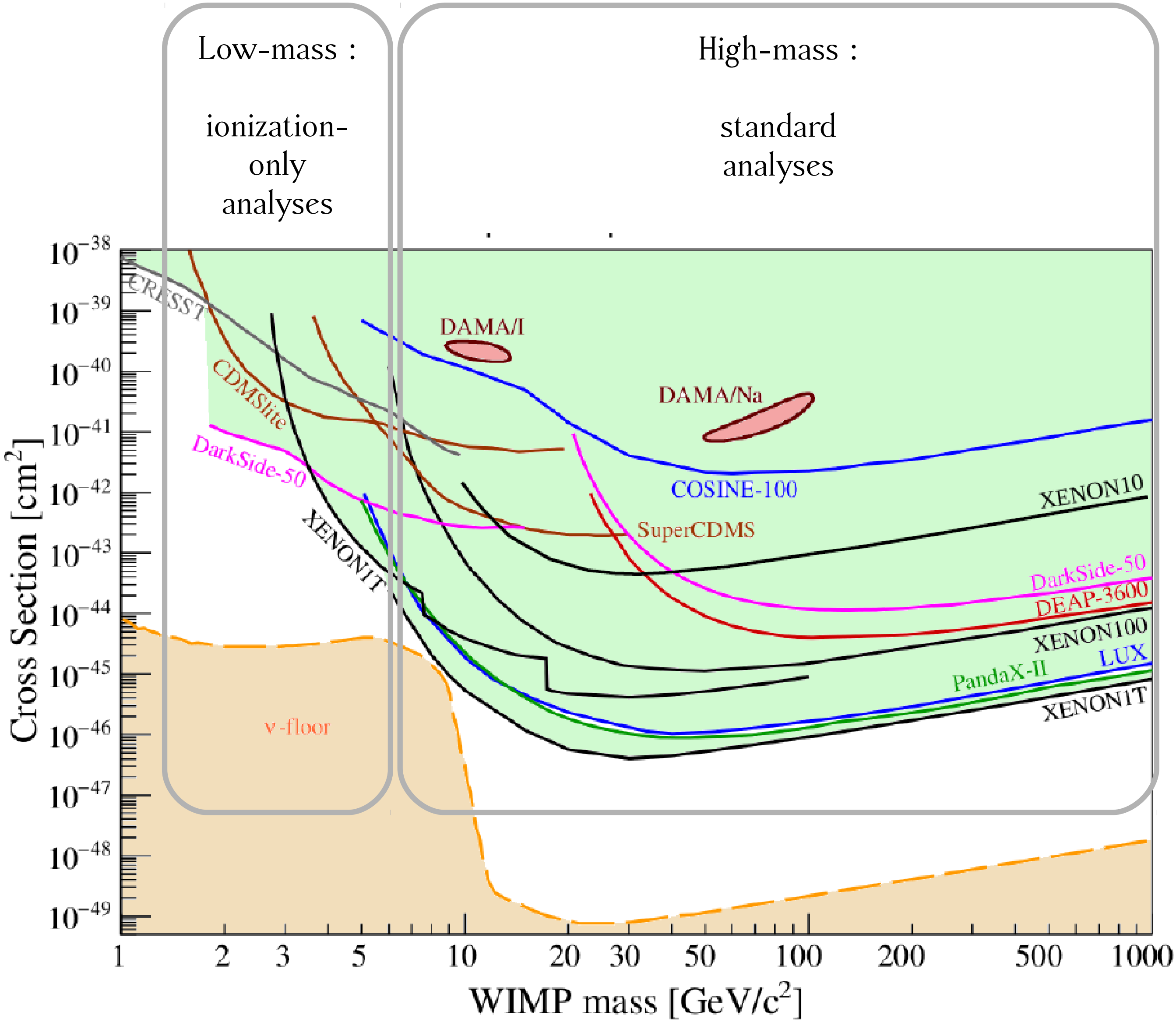
Coherent neutrino-nucleus scatter (CNNS)
- aka Neutrino Floor -

Solar : ^{8}B and hep, Atmospheric
Diffuse Supernova Background

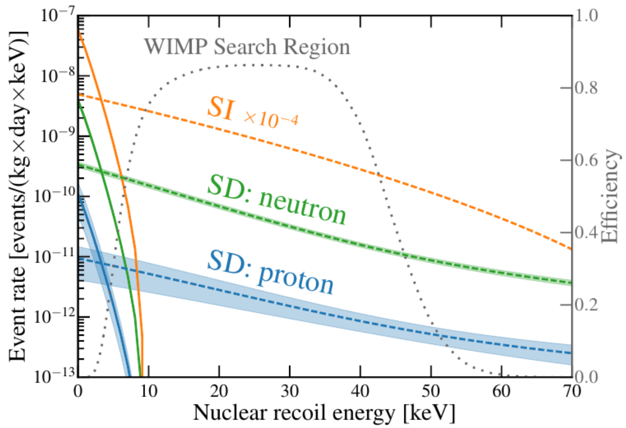




Direct detection today

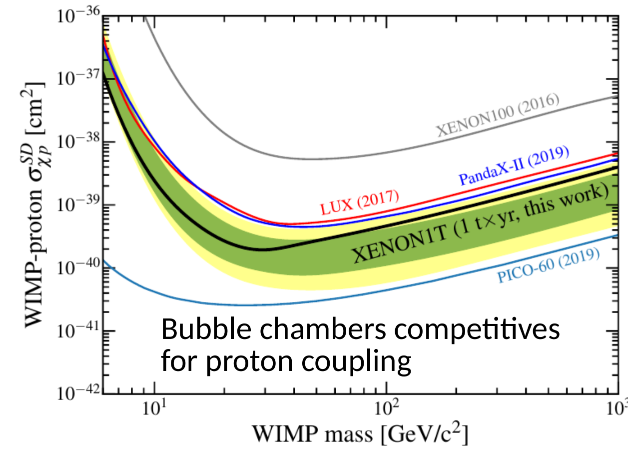


Spin-dependent interactions (xenon only)

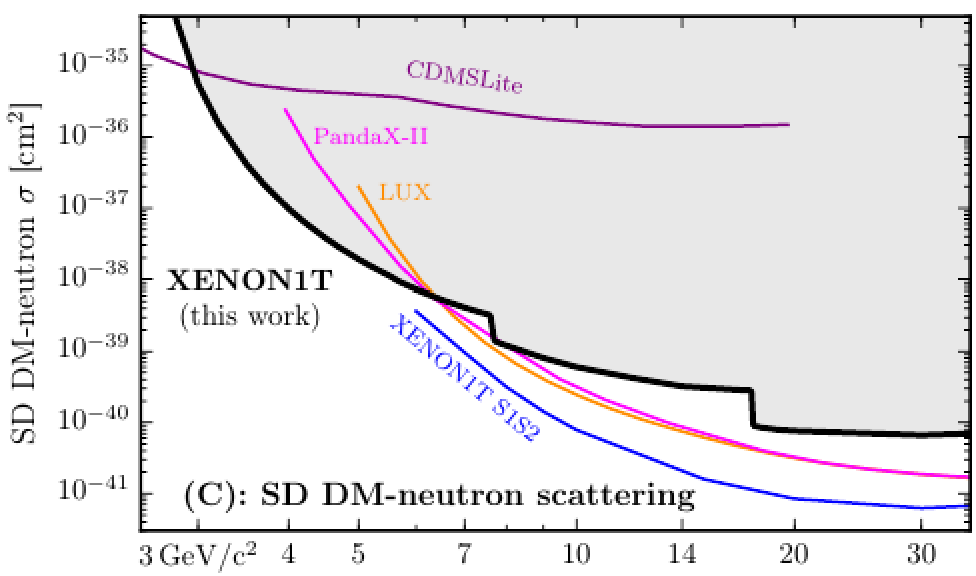


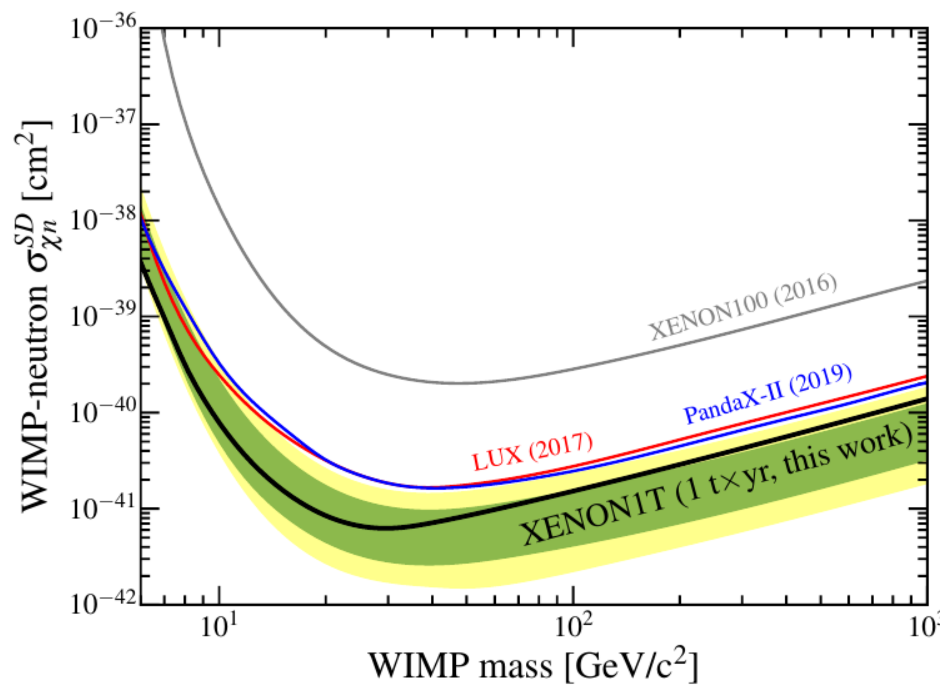
Xenon has both pair and unpair isotopes, allowing for scoping spin-dependent WIMP scattering

More in general, by using an effective field theory, it can scope the full set of operators

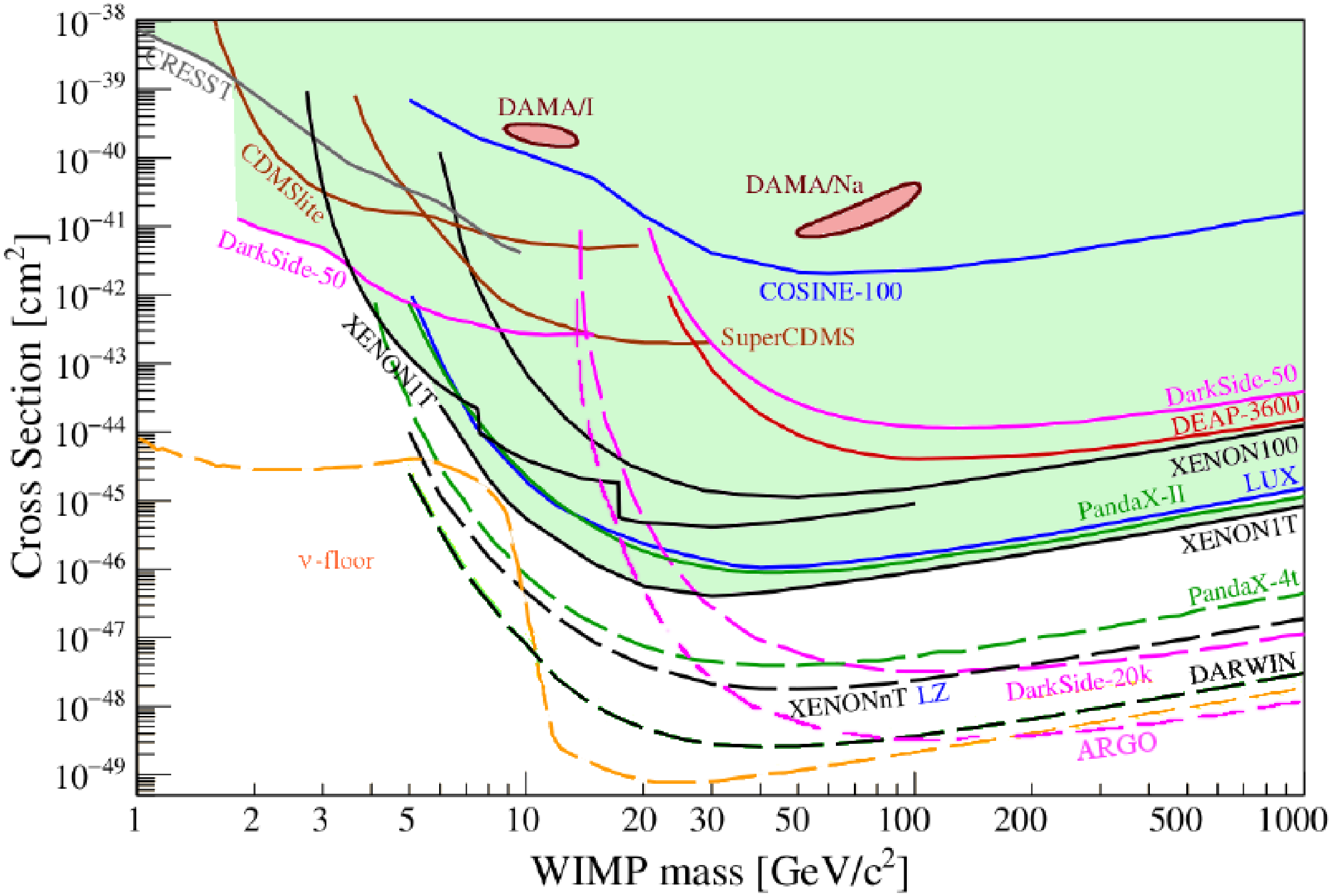


Low-mass (ionization only)





Scoping high masses in next years



Current results from :

XENON100 (2012)
DarkSide-50 (2015)
LUX (2016)
PandaX (2016)
XENON1T (2018)
DEAP-3600 (2019)

Coming soon :

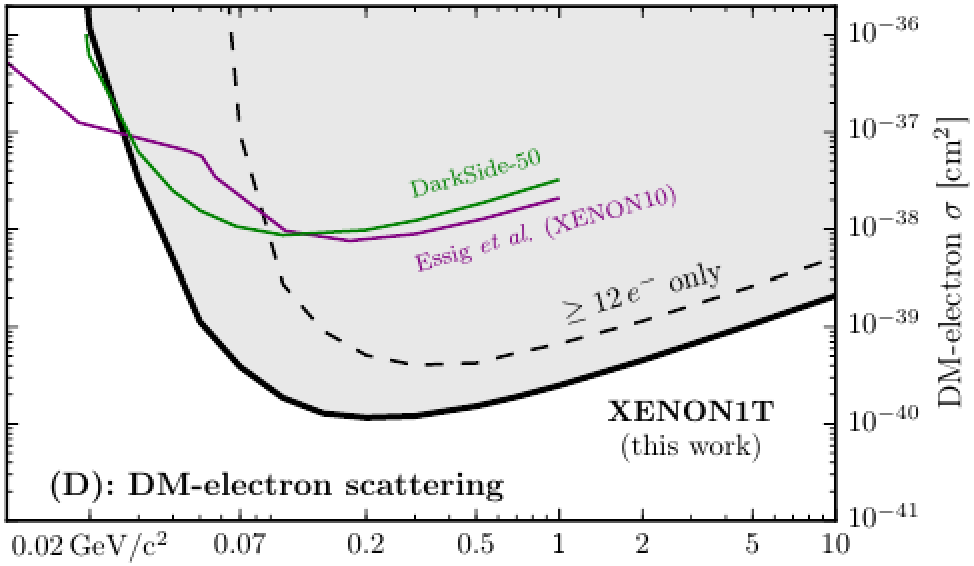
XENONnT (2020 → 2022)
LZ (2020 → 2022)
PandaX
DarkSide-20k (2023 → 2027)

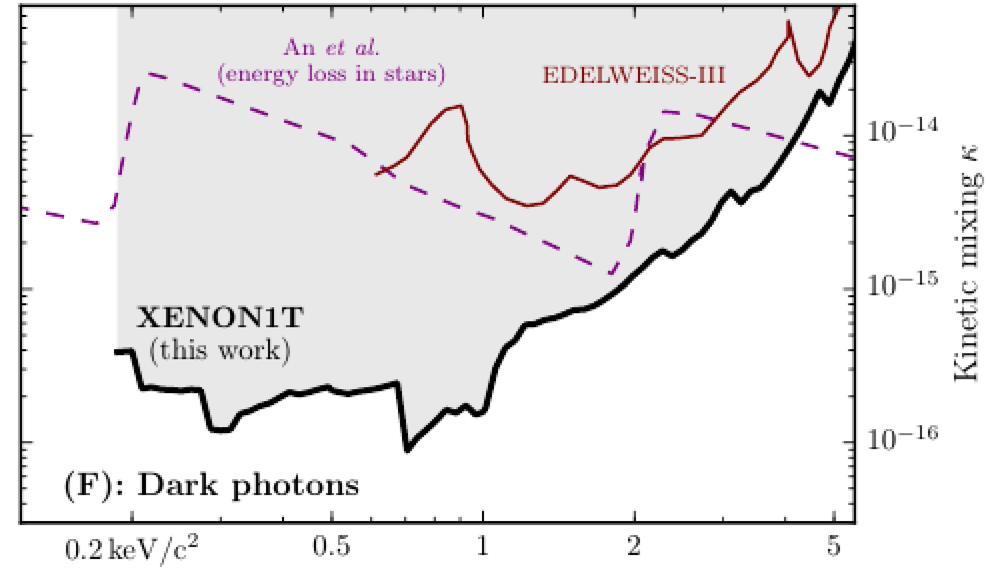
Third generation :

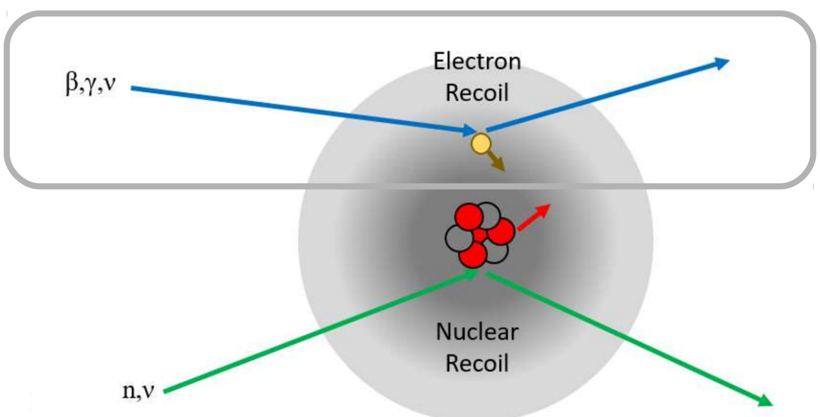
DARWIN (2026 → …)
ARGO (2028 → …)

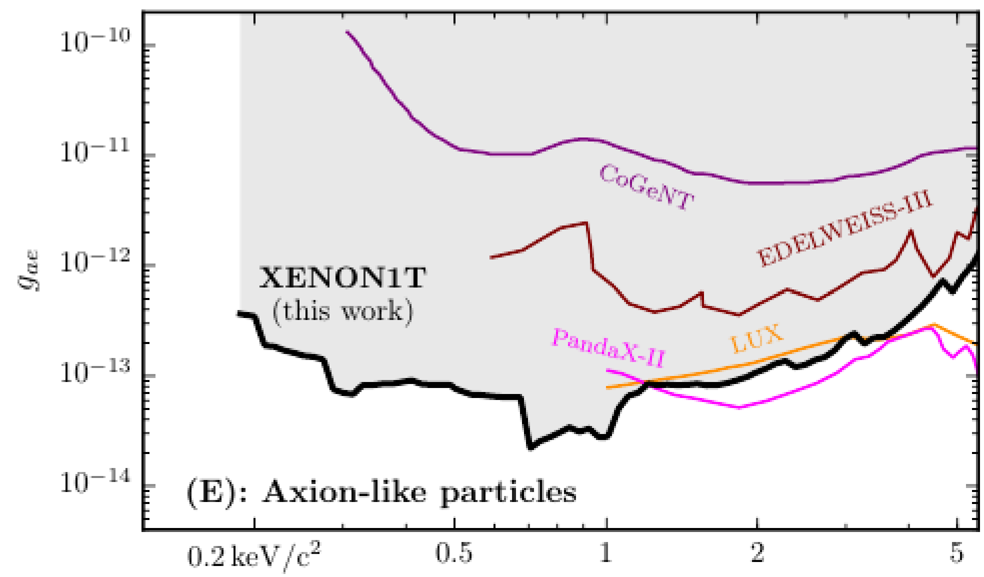
Strong international competition !
Results from XENONnT, LZ and PandaX-II will come out next year
As it happened so far (XENON100→LUX→PandaX→XENON1T), LXe experiments are competing to the hunt of dark matter

Scoping DM–electron scattering interpretation









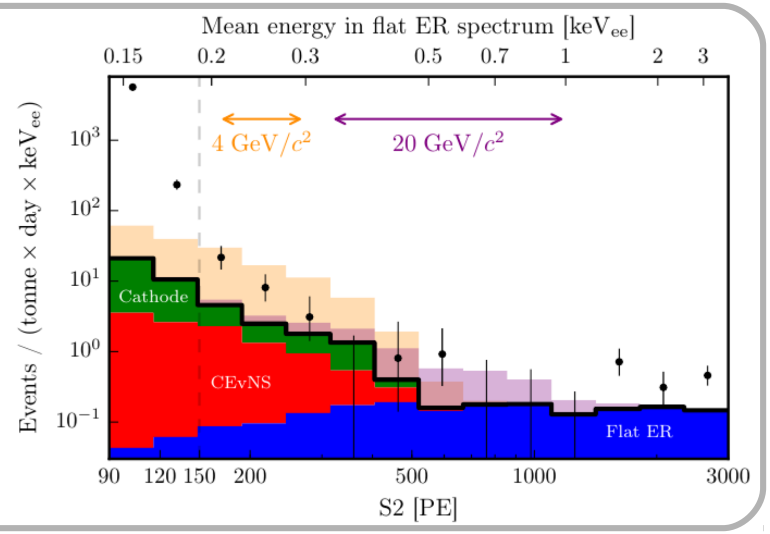
Scoping low masses in next years

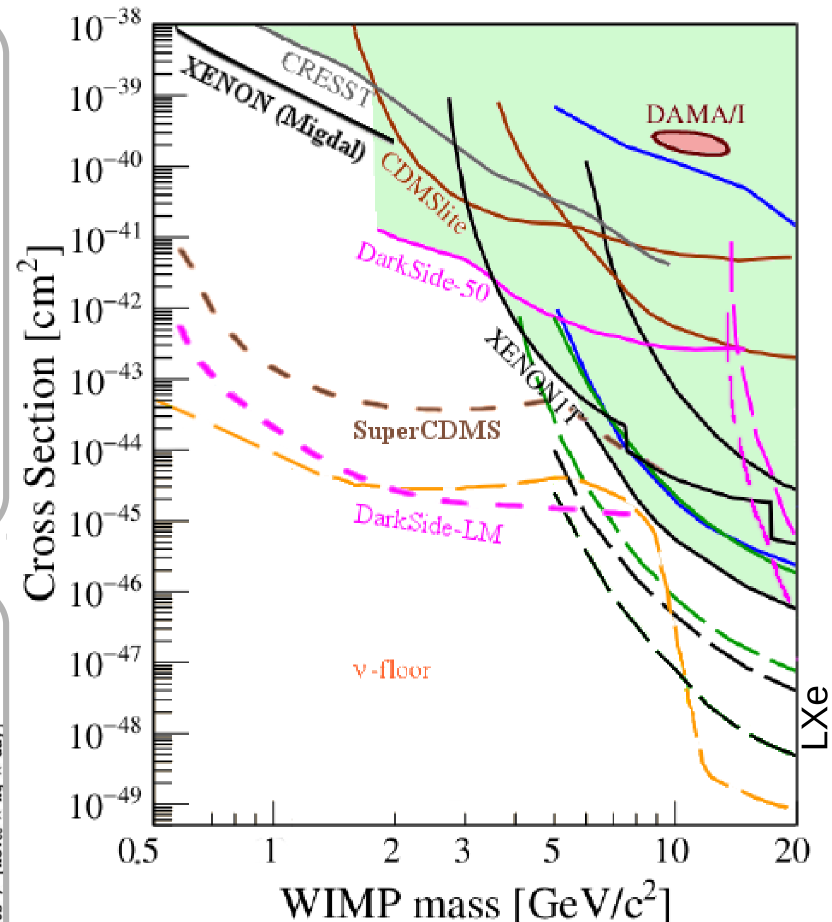
XENON1T :

S2-only analysis allows to go down to 4.5 e^-

Sensitivity down to 4GeV

Analysis using Migdal effect → extra sensitivity in range [0.080 – 2] GeV





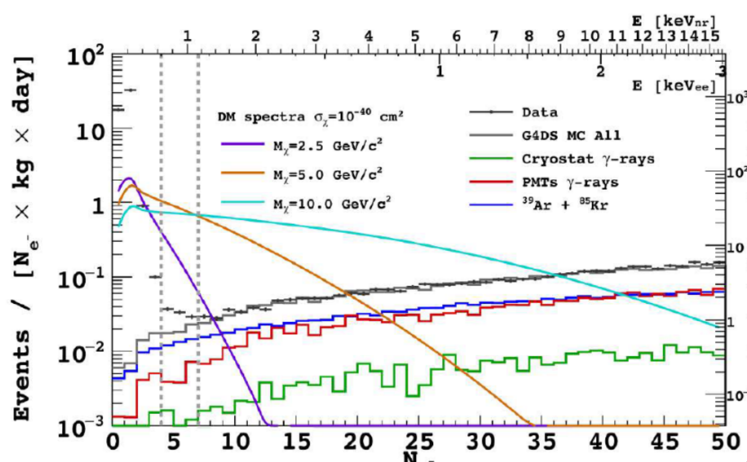
DarkSide-50k :

S2-only analysis allows to go down to 7 e^-

Argon has lower **A**

Sensitivity down to 2GeV

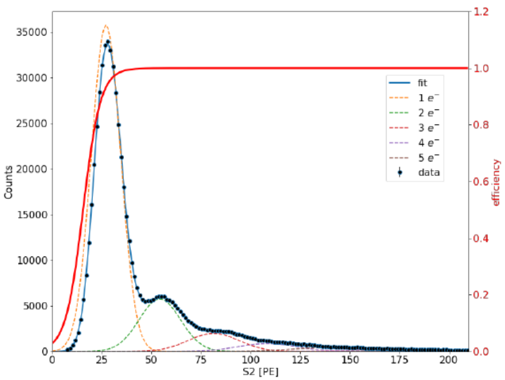
Crucial the NR Argon response performed by ARIS

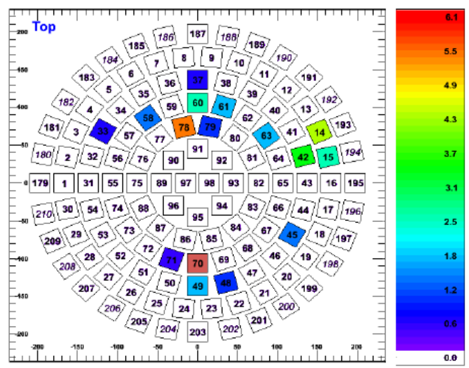


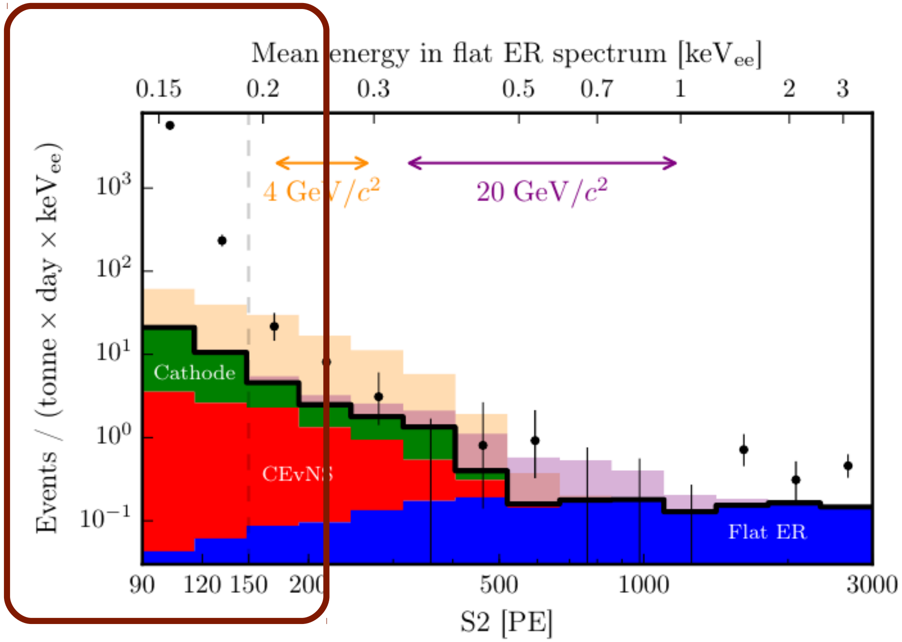
Large improvements at low mass WIMP will be obtained with DarkSide-LM in 2021-2022 (1t LAr in LNGS)

Challenges for very low-mass DM search

Isolated electrons are the main background for this analysis and the mayor obstacle to go below 1GeV

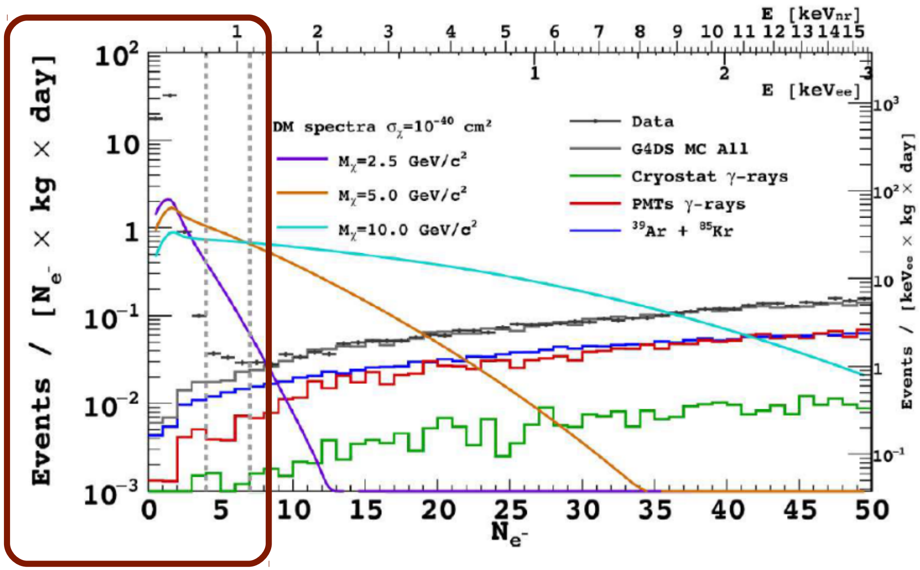






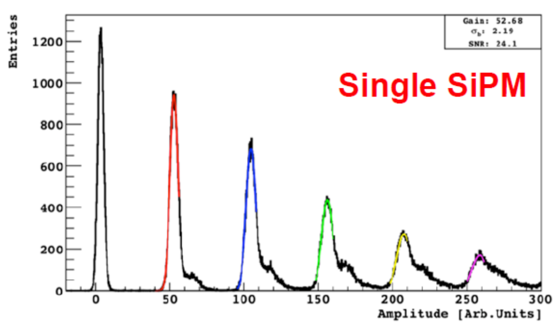
Possible reasons :

1) photo-dissociation of negatively charged impurities;
2) delayed extraction of trapped electrons at the liquid-gas interface
3) field emission from electrodes
4) neutralization of positive xenon ions at the cathode surface
5) long-lived bound states of excimers or weakly bound higher-energy states



Solutions to be investigated:

- Passivation of electrodes
- Optimization of electrodes geometry
- Minimization of metallic components
- Flushing electrons from surface
- Use of SiPM to improve resolution



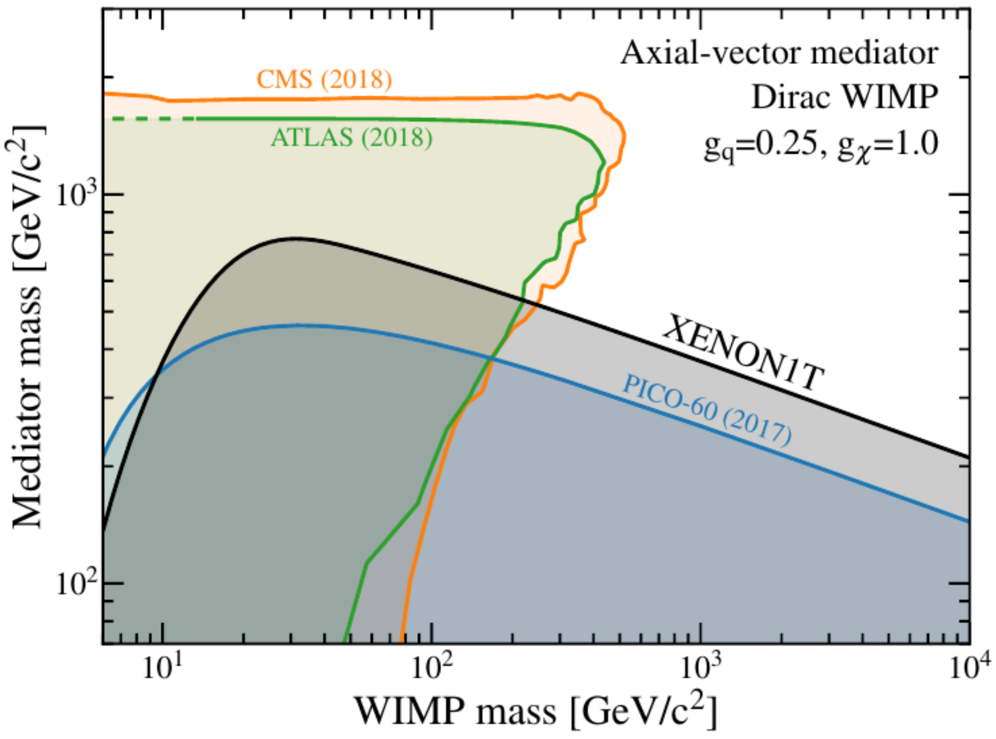
Complementarities with accelerators

Collider experiments : sensitive to WIMPs → collisions with missing transverse energy

Direct comparison with DDM search requires an interaction model with standard model

Comparison done by using reccomandations by the LHC Dark Matter Working Group, and frequently used by ATLAS and CMS :

Dirac fermion interacting with an axial-vector mediator



Status of DarkSide program

Collaboration : 300 members
merging of all world-wide LAr experiments (DEAP-3600, DarkSide-50, miniCLEAN, ArDM) → GADMC

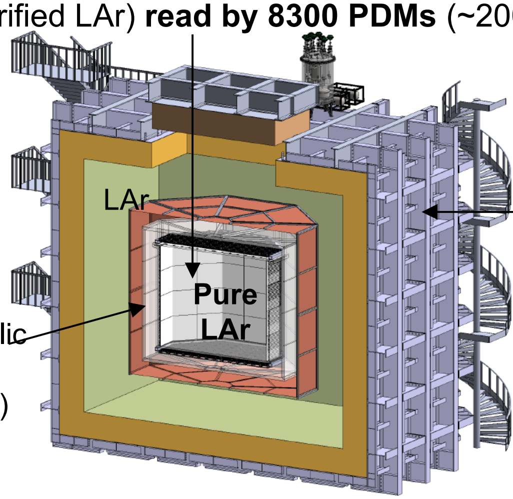
White Paper : 1707.08145
CERN recognized experiment (RE 27)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
DarkSide-Proto	CERN	GranSasso	GranSasso								
DarkSide-20k		CERN	CERN	Gran Sasso	Gran Sasso	Gran Sasso	Gran Sasso	Gran Sasso			
Argo							SNOLab (?)	SNOLab (?)	SNOLab (?)	SNOLab (?)	SNOLab (?)

Detector : DarkSide-50, leading sensitivity in low-mass WIMP (2-4 GeV/c^2)

Detector : DarkSide-20k, protoDUNE cryostat + SiPM
Goal : exploring GeV → TeV WIMP mass range (100 tons x year exposure)

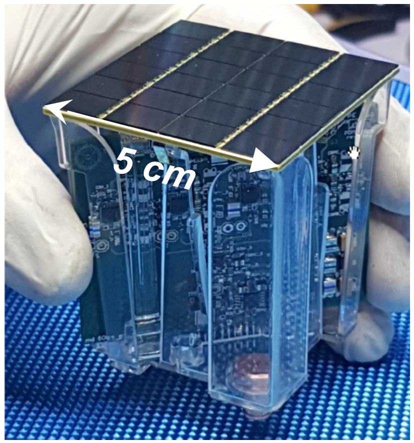
Largest Dark Matter TPC (3.5x3.5x3.5 m^3, 50t purified LAr) **read by 8300 PDMs** (~200k SiPM)



20t Gd-loaded acrylic to **veto neutron** (inc. ~100k SiPM)

Proto-DUNE (8.5x8.5x8 m^3, 700 t LAr) to **veto muons**. Designed at CERN

1 PDM = 24 SiPM



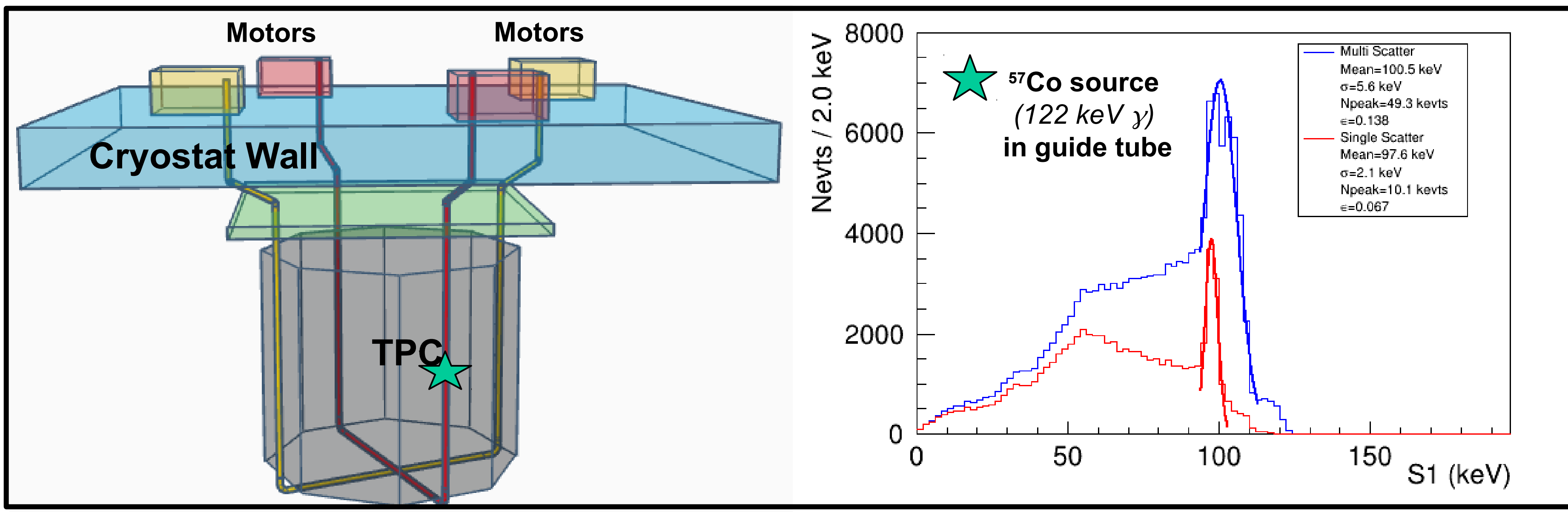
Production started at Lfoundry in Septembre 2019

DarkSide program in IN2P3

CS-IN2P3 recommentation in 2018 : plan a coherent IN2P3 program for DS-20k

APC and LPNHE members since 2012
New : CPPM (2019)

Hardware contribution: design, realize, install and commission guide tube system that will circulate neutron and γ sources in the final detector → energy / position calibration + MC tuning



Software contribution: Data reconstruction with advanced filtering algorithm to take full advantage of SiPM potentiality for S1 and S2 signal

Physics analysis : includes both efforts : 50 kg → 1 t *(low mass)* → 20 t LAr *(low+high mass)*

Other physics and IN2P3 synergies

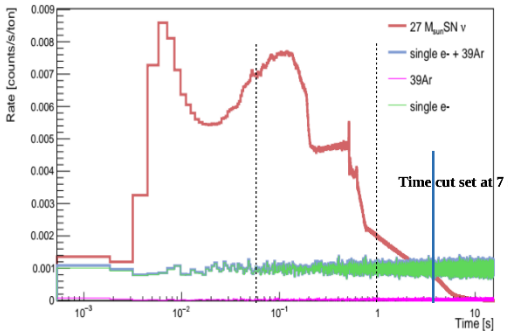
CNO Solar neutrino ($\nu_e \rightarrow \nu_e$)

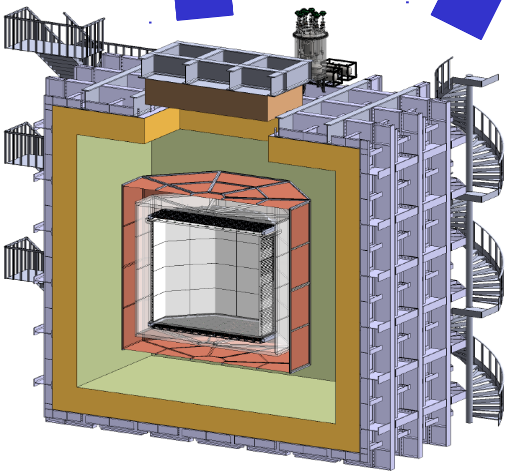
Excellent energy resolution allowing to detect CNO neutrinos (only unobserved component) using Argo with O(1-10)% on rates

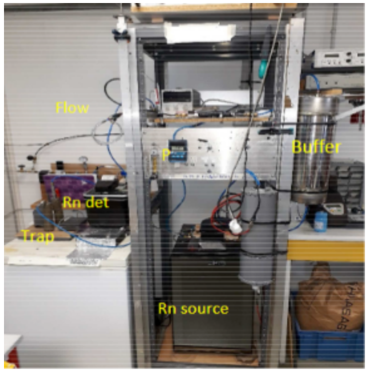
PET 10 ps challenge (1.5 mm resolution)

State of the art =200 ps with inorganic scint. Can benefit from fast light yield of LAr (LXe) + SiPM (Cerenkov radiation)

SuperNovae Neutrino via coherent scattering







DEEP UNDERGROUND NEUTRINO EXPERIMENT

-Same outside cryostat
-LAr TPC with some common pb

Radon mitigation

Not a major pb in DarkSide, but should be studied with care (use SuperNemo CPPM infrastructure)

Status of XENON program

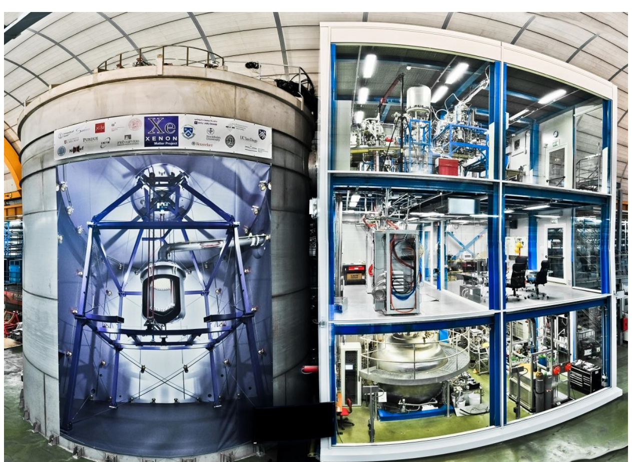
Collaboration : 170 members (over a LXe community of 500 people)

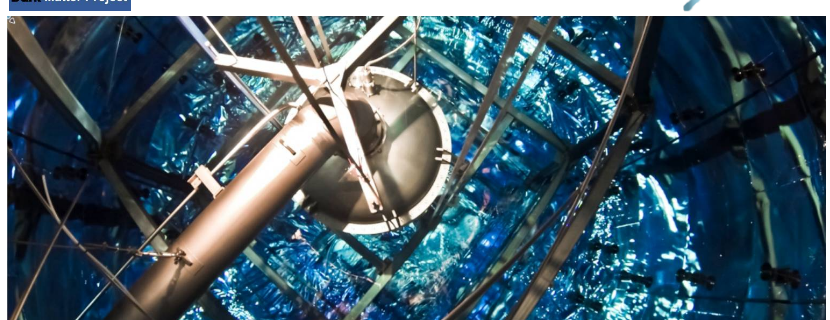
From US, Europe, Israel, Unites Arabs Emirates and Japan (members from X-Mass LXe experiment)

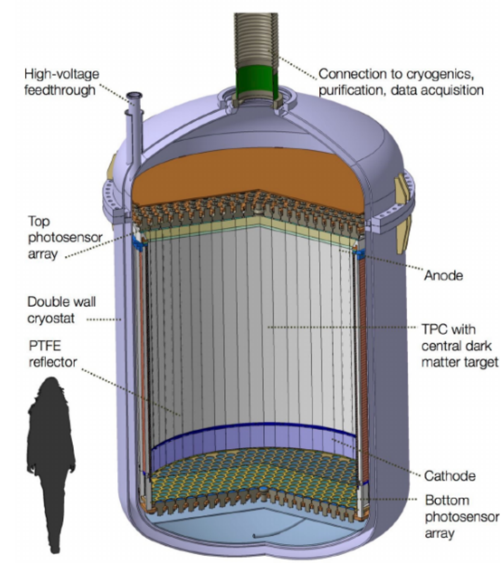
Detector : XENON1T, leading sensitivity in sub-GeV, GeV and multi-GeV mass range. Just few analyses are left

Detector : XENONnT, construction almost finished, most of subsystems in commissioning phase. Start data taking in winter
Goal : improve XENON1T by one order of magnitude, take data for longer period (annual modulation)

Detector : DARWIN, in design study. Larger Collaboration with respect to XENON and discussions with US for a unique G3 LXe experiment
Goal : reach neutrino floor, neutrino physics, astroparticle absevatory







XENON program in IN2P3 (1/2)

Master Project IN2P3

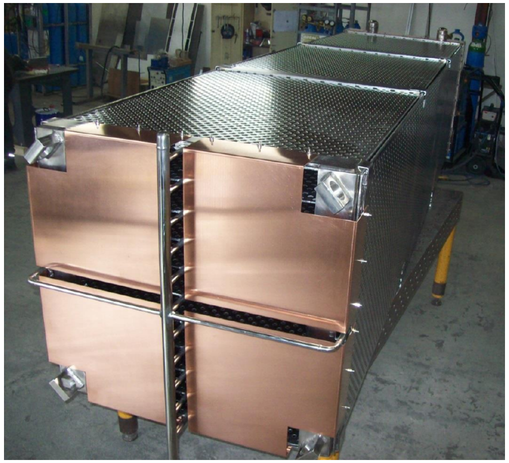
Subatech (since 2009), LPNHE (since 2016) and LAL (since 2017)

Hardware contributions :

1) design, construction, installation and commissioning of the Recovery and Storage of XENON1T (ReStoX)
2) design, construction, installation and commissioning of the Recovery and Storage of XENONnT (ReStoX2)
3) design, construction, installation and commissioning of the high voltage electrodes of XENONnT
4) design, installation and commissioning of the computing infrastructure in LNGS

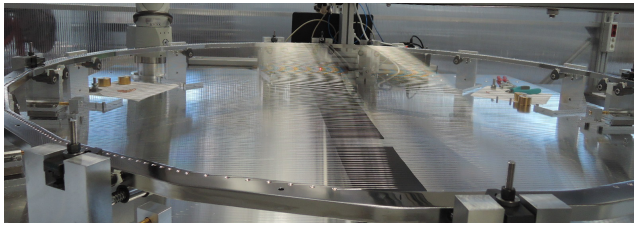
For all these 4 topics we are leading the coordination

ReStoX (7 tons LXe)



ReStoX2 heat exchanger

ReStoX2 (10 tons LXe)



XENONnT electrode

XENON program in IN2P3 (2/2)

Software contributions :

1) XENON VO GRID Administration
2) raw data processing and storage with GRID @ CC-IN2P3
3) Development and maintenance of the XENONnT Offline Data Quality Monitoring Tool (XoM)

Physics analysis :

Low-mass WIMP

Single electron signal (PhD thesis)

Leptophilic dark matter and Annual modulation (PhD thesis)

Neutrinoless double beta decay (PhD thesis)

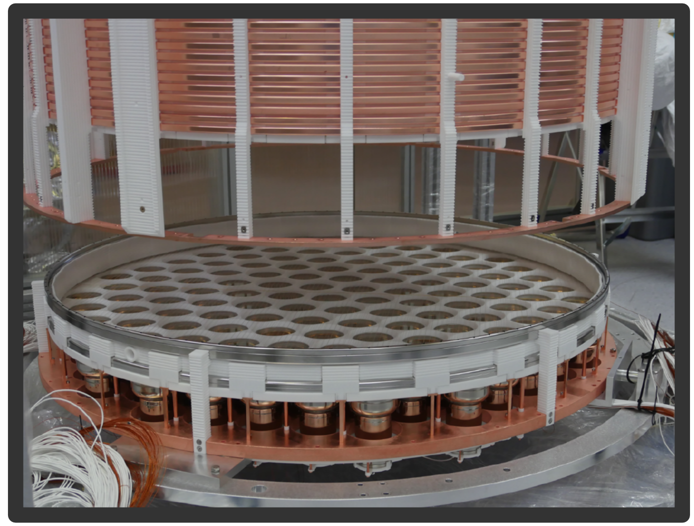
^{83m}Kr calibration

Detector stability (gains, electron lifetime)

Monte Carlo simulation (S2 gain and Gamma-X)

Other physics and IN2P3 synergies

Dark Matter physics



Impact on society

XEMIS in Subatech
Medical imaging based on 3-gamma compton. This will reduce the dose of patients during fonctional imagin therapies.

Prototype XEMIS1 succesfully completed and XEMIS2 is going to be installed in the CHU of Nantes

Impact on industry

orano
Giving nuclear energy its full value

Extraction of ^{136}Xe from radioactive waste and use it for science

Astroparticle physics

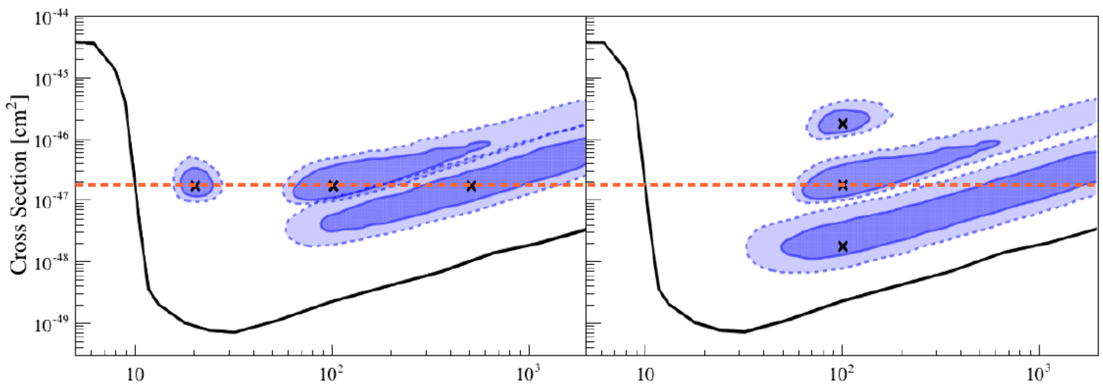
Neutrinoless double-beta decay
Double electron capture (with and without neutrinos)
Supernova neutrino bursts
Solar neutrinos
Atmospheric neutrinos
...

What if XENONnT (or LZ or PandaX-II) find a signal ?

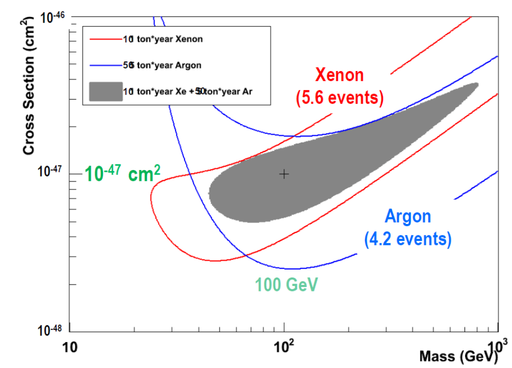
If the interaction is **Spin Independent**

It needs to be confirmed with larger detectors like DARWIN or DarkSide-20k

DARWIN and Argo could do spectroscopy (reference : XENON1T sensitivity) :



Capability of DARWIN on reconstructing the WIMP mass and cross section for various masses (20, 100, 500 GeV/c2) and cross sections



Crossing Argon and Xenon detectors can reduce the likelihood, but only for a WIMP at 100 GeV/c²

If the interaction is **Spin Dependent**

Argon or any pair target is useless. The only way is to re-run a xenon detector with different xenon isotopes (enrichment)

European and French reports

APPEC : Converge around 2019 on a strategy aimed at realizing worldwide at least one 'ultimate' Dark Matter detector based on xenon (~50 tons) and one based on argon (~300 tons), as advocated respectively by DARWIN and Argo

Scientific Council IN2P3 (28-Oct-2018)

Aujourd'hui, parmi les projets de détection directe de matière noire présentés, seuls XENON et DarkSide-50 sont opérationnels et au niveau de la rude concurrence internationale, dans des domaines de masse différents. La participation à ces projets est à soutenir et à renforcer en développant les équipes actuelles.

DarkSide :

Avis et recommandations

Le programme DarkSide présenté par ces groupes est ambitieux et vise une participation à toutes les étapes du projet, de DS-50 à GADMC. Le conseil recommande que le groupe se focalise sur quelques points clés de manière à maximiser son impact dans la collaboration. Le conseil recommande de trouver des forces humaines supplémentaires pour s'engager plus avant dans un projet de cette envergure.

*In 2019, CPPM has strengthen french activity with **technical contributions (calibration)***

XENON :

Avis et recommandations

L'expérience XENON dédiée à la recherche directe de la matière noire est parmi les expériences les plus performantes au niveau mondial dans ce domaine de recherche.

Pour XENON-France, nous recommandons de finaliser les analyses de données XENON1T, d'achever et de mettre en service ReSTOX2 et les TPC électrodes pour XENONnT, et, ensuite, de participer aux analyses de données XENONnT. Ces tâches correspondent à la feuille de route des laboratoires français présentée lors de ce conseil. Pour réaliser tous ces objectifs tout en maintenant l'engagement fort et très visible des chercheurs impliqués dans la collaboration, nous soutenons fortement les renforts demandés.

À plus long terme, nous recommandons la participation au projet DARWIN, qui est l'évolution naturelle de XENONnT, et nous encourageons les groupes français à participer aux études de conception et à clarifier le plus tôt possible leur rôle dans ce projet, ce qui permettra alors d'envisager une revue détaillée.

XENON-France plans to:

- *work on XENONnT **data analyis** for next 4 years (4 PhD thesis)*
- *continue **keeping in charge** the subsystems (hardware and software) on which are engaged*
- ***coordinate the DARWIN WP2** (liquid xenon handling) and participate to the **TPC design** (electrodes)*
- *work on **DARWIN MC simulations** for 0ubb sensitivity (paper in progress)*

Conclusions

So far the **WIMP high mass search** has been exclusively dominated by **LXe detectors**

Time sequence (year of hunting new, unexplored regions):

XENON10 (2008) → XENON100 (2009,2011,2012) → LUX (2013,2016) → PandaX (2016)→ XENON1T (2018)

and the **forthcoming XENONnT, LZ and PandaX-II (2020)**

5 orders of magnitude in 12 years !!!

In addition, they (and in particular XENON Collaboration) provided a rich series of physics measurements that go beyond the classical WIMP paradigm (axions, Mirror Dark Matter, SuperWIMPs, …) and beyond DM physics (0nbb, 2nECEC, …). Next **G3 generation (2026)** (500 people from LXe) will do more and better, reaching the neutrino floor.

Technology with **LAr detectors** is following. Very important to confirm a possible signal from LXe experiments.

Time sequence (year of latest publication):

DarkSide-50 (2015) → Deap-3600 (2019)

Will follow:

DarkSide-50 demonstrated an excellent sensitivity at low masses, down to 2GeV/c^2. New limits will come out **(spring 2020)**. **DarkSide-LM (2021)** plans to improve it by three orders of magnitude

DarkSide-20k will follow (2023), specifically meant for high mass WIMPs, followed by **Argo (2029)** that will reach the neutrino floor.

Material for discussions

A new physics case : neutrinos

Neutrino is background for Dark Matter search with noble liquids but it also offers a physics case of unvaluable richness !

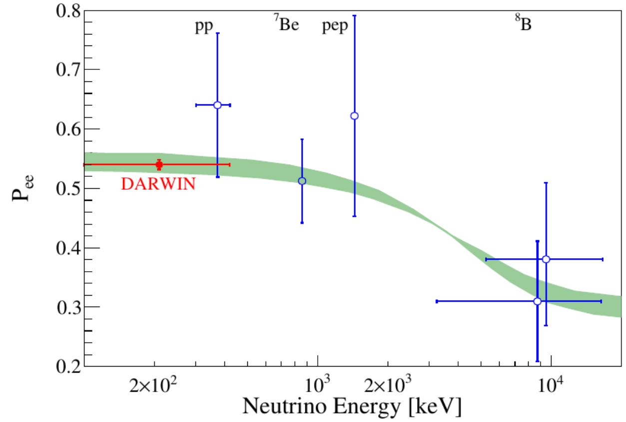
Electronic Recoils (ER)

$\nu + e^- \rightarrow \nu + e^-$

Scoping neutrino and solar models !

DARWIN case :
~ 2000 neutrino pp per year,
2% (1%) precision in 1 (5) years

Any deviation would imply new physics !



Nuclear Recoils (NR) from solar neutrinos

$\nu + N \rightarrow \nu + N$

DARWIN case : 90 events/t/y @ E>1keVnr
(~3000 CNNS events/year)

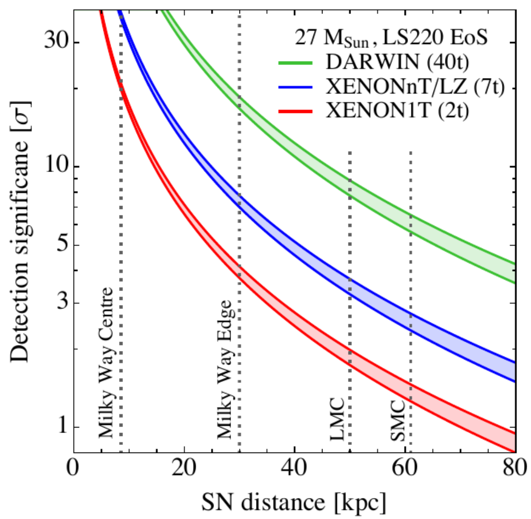
Any deviation would imply new physics !

Nuclear Recoils (NR) from supernova bursts

$\nu + N \rightarrow \nu + N$

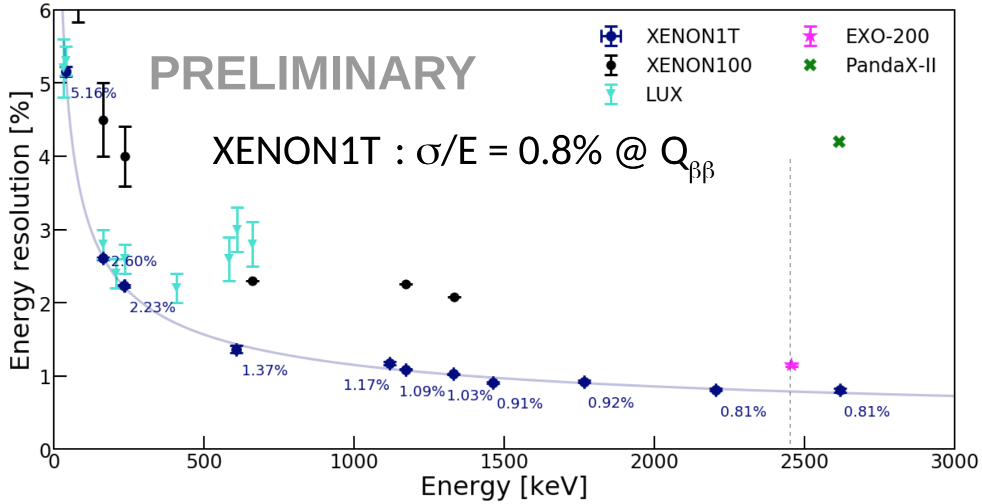
DARWIN case : O(10) MeV ν's → O(1) keV NR

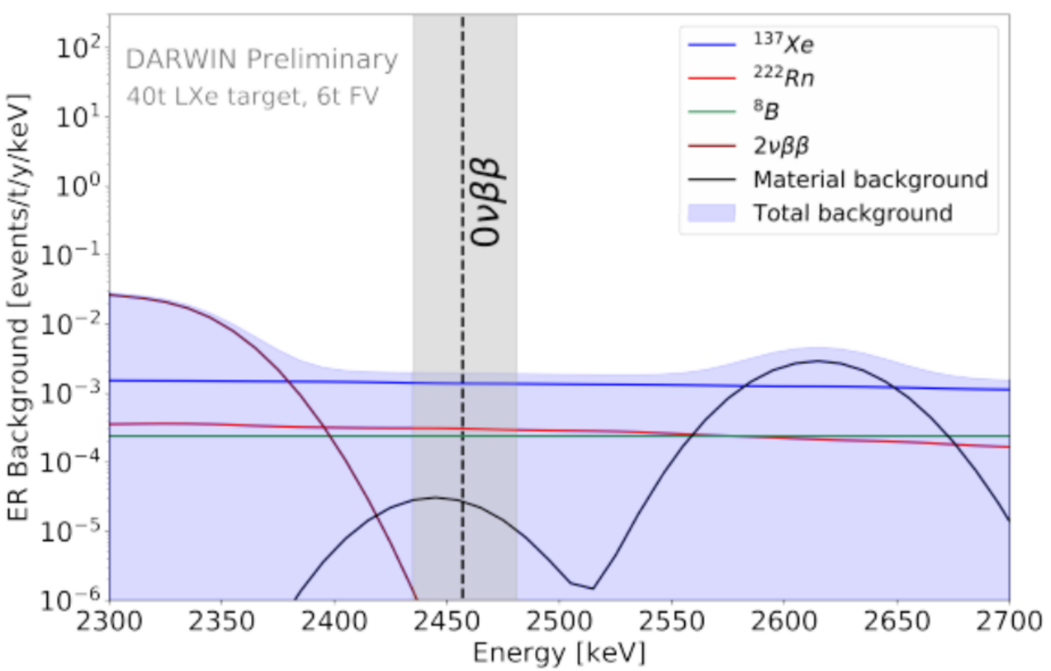
- → 5σ significance with a 27 $M_\odot$ progenitor far up to 65 kpc from Earth
  → 704 events @ 10 kpc



R. Lang et al., Phys.Rev. D94 (2016) no.10, 103009

Not only Dark Matter : neutrinoless double beta decay





Natural xenon contains 8.9% of ^{136}Xe

^{136}Xe: $Q_{\beta\beta}$ = 2458.7 ± 0.6 keV

DARWIN case :

Sensitivity to 0νββ by ^{136}Xe:

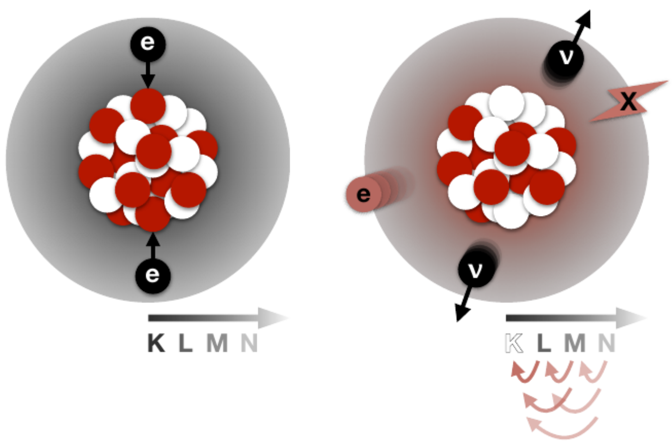
- $T_{1/2} > 2 \cdot 10^{27}$ yr (95% CL)

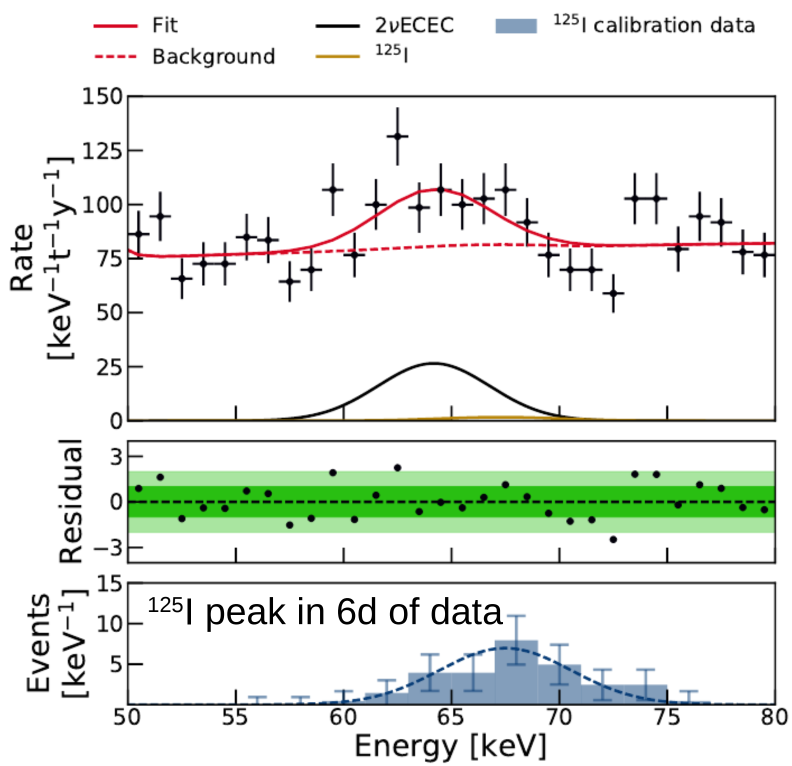
Assumptions:

- Fiducial mass 6 t ^{nat}Xe
  (needed stronger fiducialisation)
- ^{222}Rn: 0.1 µBq/kg
  (rate compatible with ^{8}B)
- σ_E/E = 1-2% at $Q_{\beta\beta}$
- DARWIN "ultimate" assumes negligible background from detector materials

Not only Dark Matter : double electron capture

Two-neutrino double electron capture (2νECEC) : 2 x (p + e$^-$ → n + ν_e)

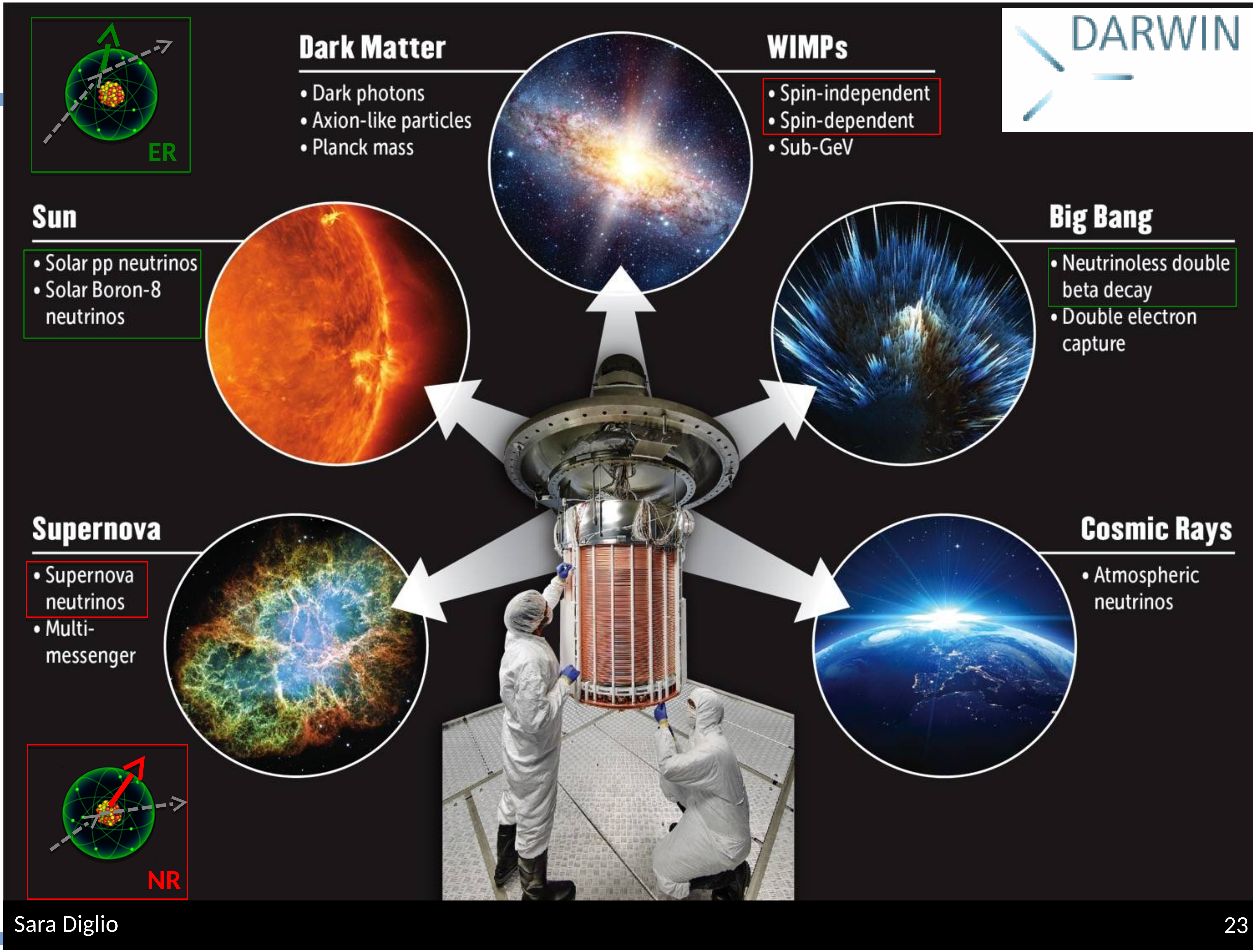




Results from XENON1T with ^{124}Xe

XENONnT will confirm the 2νECEC measurement and will also scope :

2ν EC β+,   2ν β+ β+,   0ν EC β+,   0ν β+ β+


ER
Dark Matter
• Dark photons
• Axion-like particles
• Planck mass
WIMPs
• Spin-independent
• Spin-dependent
• Sub-GeV
DARWIN
Sun
• Solar pp neutrinos
• Solar Boron-8 neutrinos
Big Bang
• Neutrinoless double beta decay
• Double electron capture
Supernova
• Supernova neutrinos
• Multi-messenger
Cosmic Rays
• Atmospheric neutrinos
NR
Sara Diglio
23

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ARGO : CNO neutrinos
JCAP 1608 (2016) 8, 017
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JCAP 01, 044 (2014), arXiv:1309.7024

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Phys.Rev. D94 (2016) no.10, 103009, arXiv:1606.09243

Double Electron Capture

$2 (p + e- \rightarrow n + \nu_e)$

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2v EC β+, 2v β+ β+,
0v EC β+, 0v β+ β+

Nature 568, 532–535 (2019), arXiv:1904.11002

Neutrinoless Double Beta Decay

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