The XENON Project

XENONnT, associated R&D (XeLab) and future experiments (DARWIN)

Luca Scotto Lavina – DR, LPNHE
on behalf of the XENON-France team

Prepared for the IN2P3 Scientific Council
October 23rd 2023

Theoretical introduction ? No, just a claim

At *Jardin des Plantes* in Paris

Weak flavour

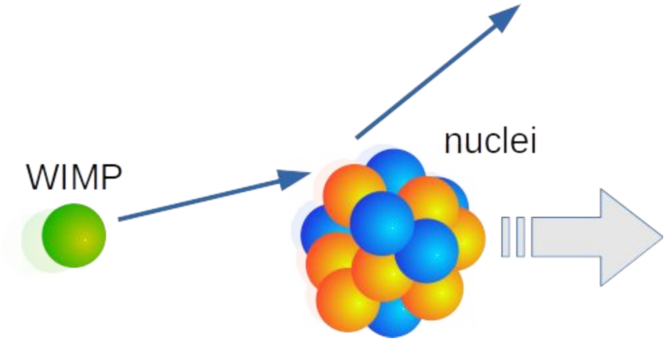
Undetectable below -20°C (no noble liquids)

Sold at 4.5€/kg (rather cheaper than noble liquids)

The WIMPs direct detection principle in a nutshell

WIMP elastically scatters off nuclei in targets, producing nuclear recoils

$$\chi + N \rightarrow \chi + N$$



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

Low-energy recoils

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v_{\min}(E_R)}^{v_{\max}} d^3v \frac{f_\oplus(\vec{v}, t)}{v}$$

Low event rate
~ event/(t y keV)

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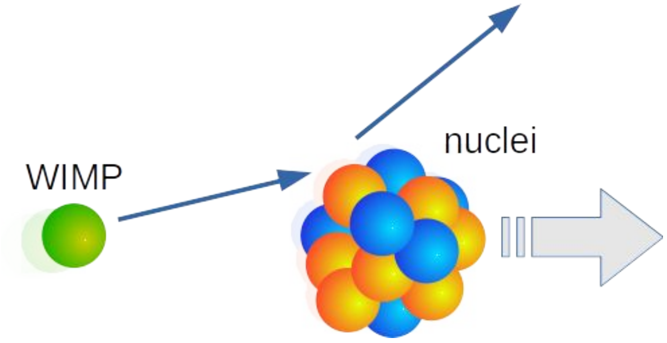

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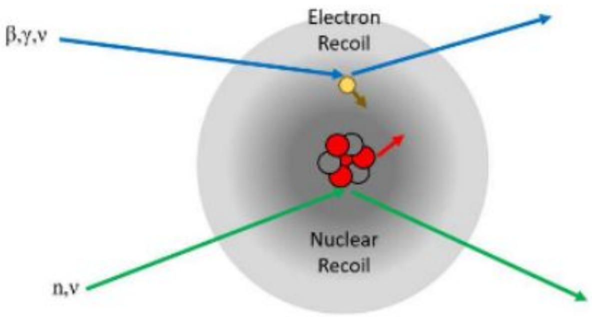
Low event rate
~ event/(t y keV)

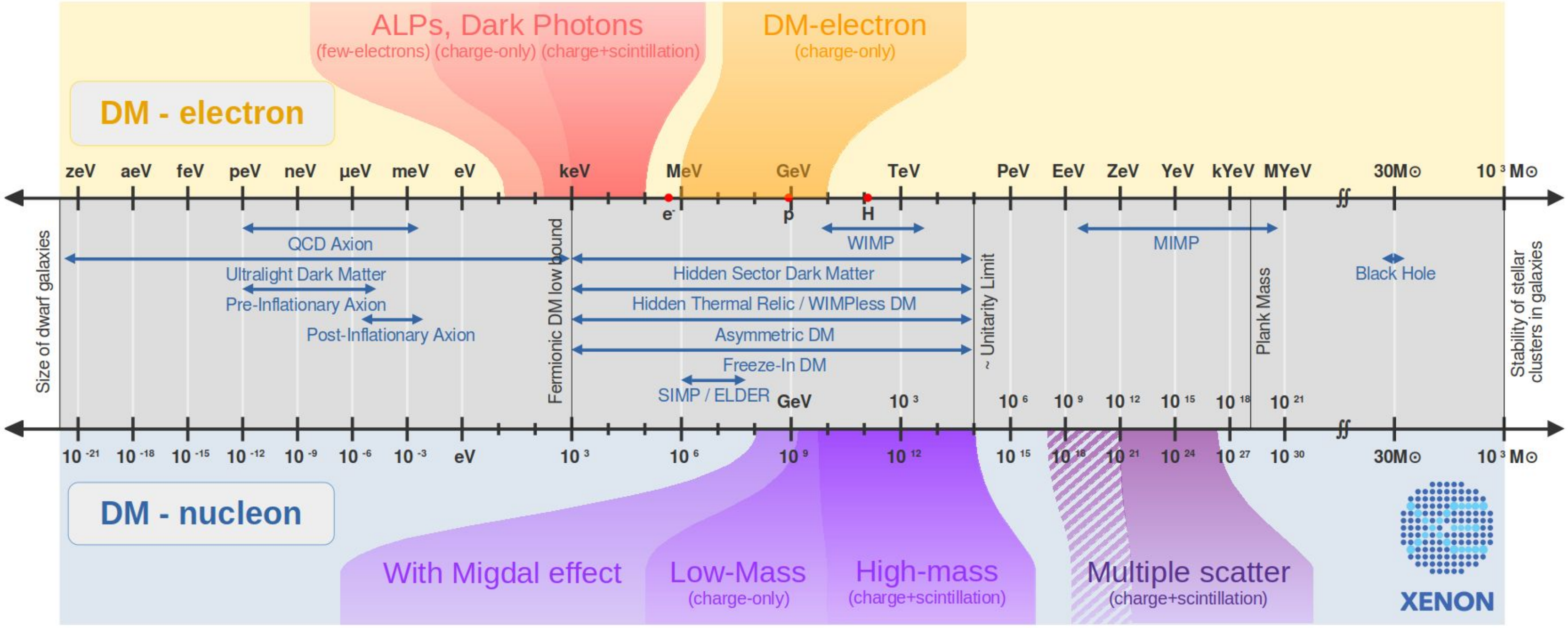
But, wait…

Dark Matter direct detection principle in a nutshell



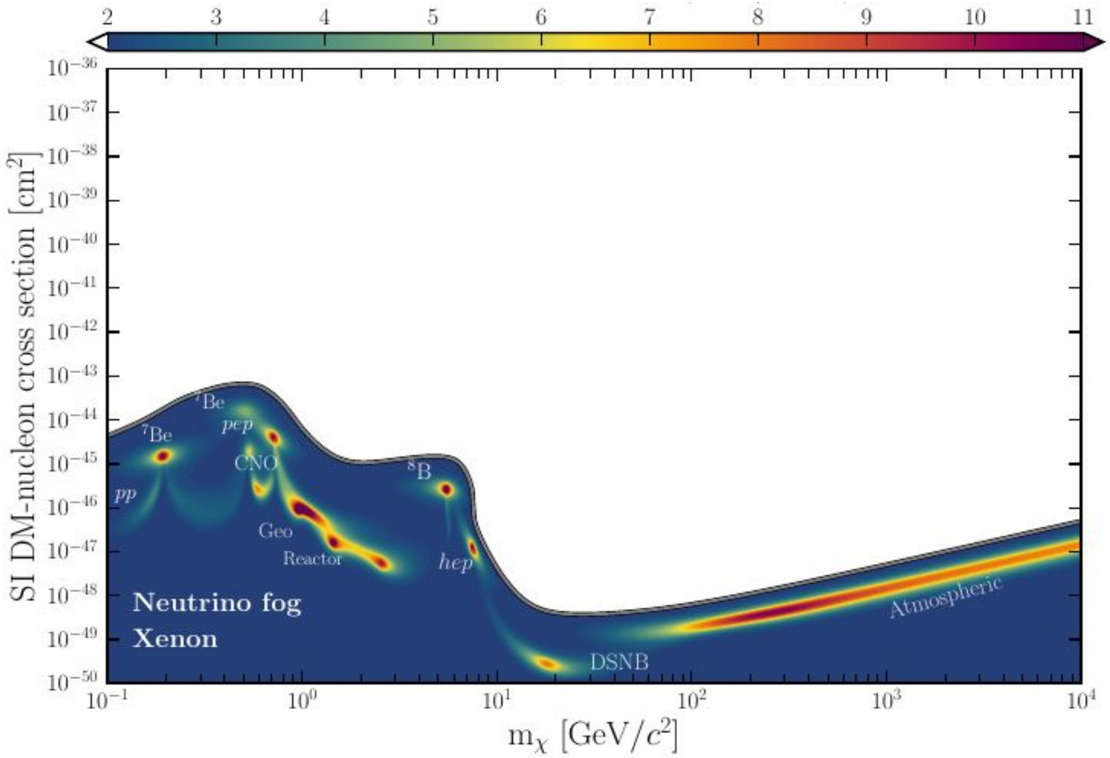
- Nuclear Recoils (NR)
  - SI elastic scattering
  - SD elastic scattering
  - WIMP-pion coupling
  - Mirror DM
- Electronic Recoils (ER)
  - Dark Photons
  - Bosonic SuperWIMPs
  - Magnetic dark matter
  - Solar axions and Axion-like Particles
  - Luminous DM
- Both (NR+ER)
  - Inelastic DM
  - Multiply-Interacting Massive Particles (MIMPs)
  - Migdal Effect and Bremsstrahlung

The scoped mass domains in a visual way



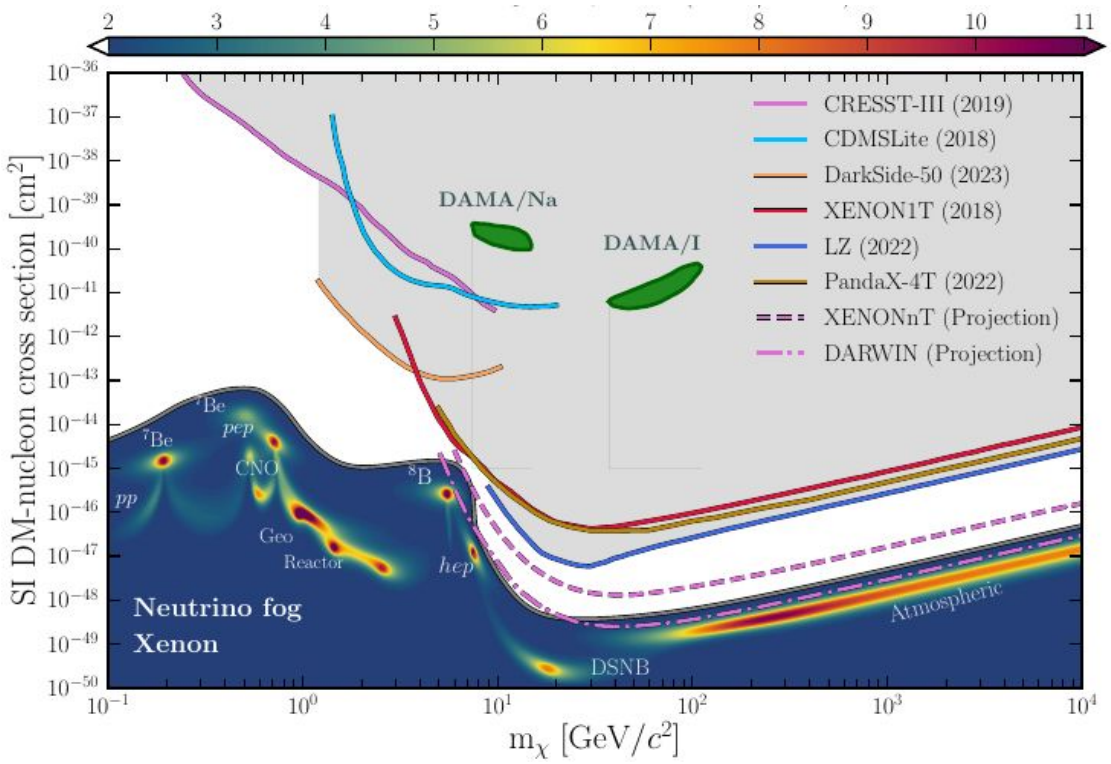
Playground and neutrino fog

Gradient of discovery limit, $n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$



Current scenario

Gradient of discovery limit, $n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$



The XENON Collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | UCSD | Rice | Purdue

Tsinghua | Tokyo | Nagoya | Kobe

~180 scientists

27 institutions

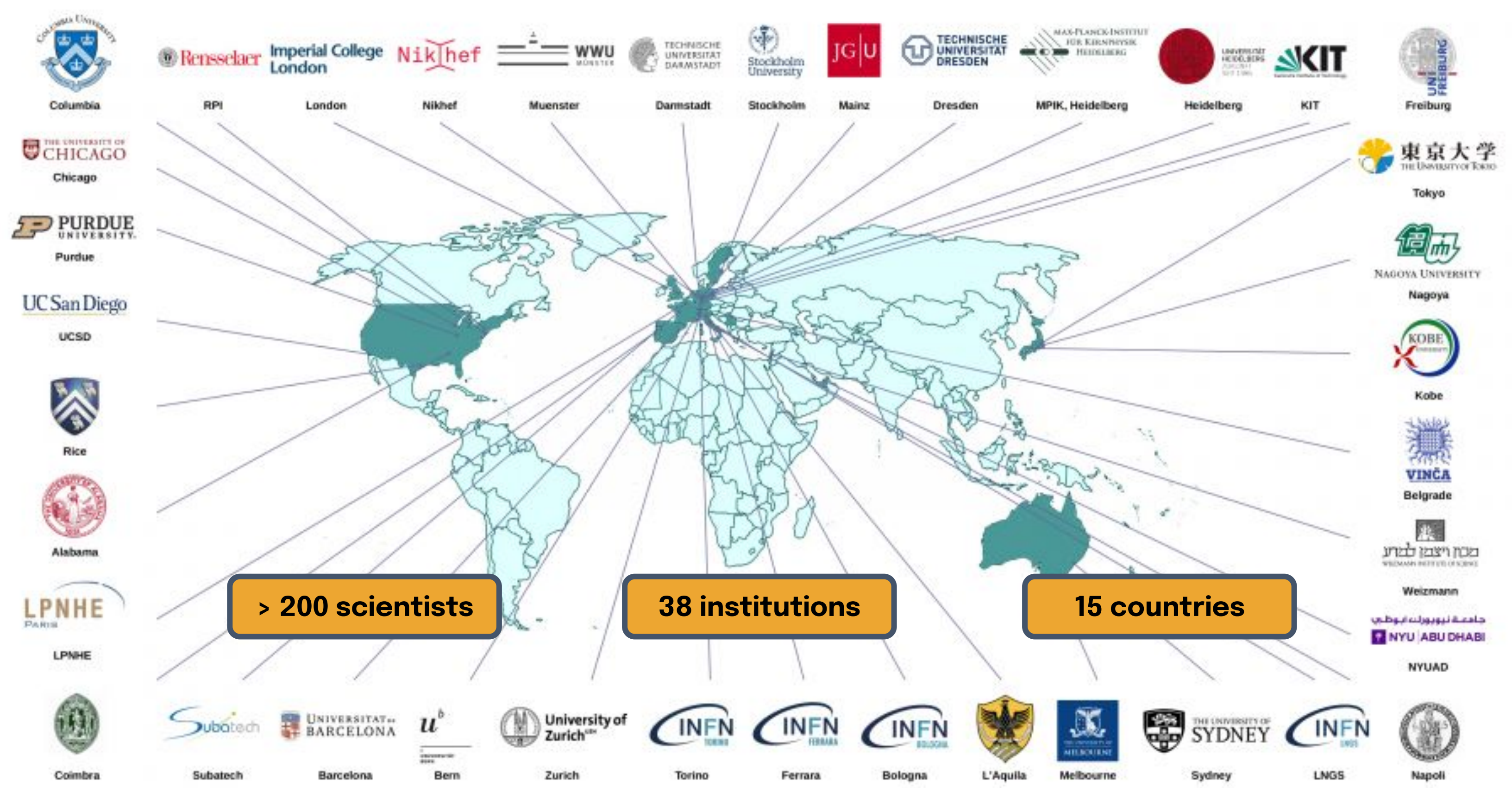
11 countries

Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

XENON Collaboration

XENON Collaboration Meeting @ LPNHE, Paris, Sept 2023

The DARWIN Collaboration



The XLZD Consortium and the *White Paper*

xlzd

XENON

LUX-ZEPLIN

DARWIN

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9]
A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2]
T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[20]
... F. Arneodo,[25] ...
M. Bazyk,[39] K. Beattie,[40] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltrame,[42] M. Benabderrahmane,[25]
E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert,[43,40] T.P. Biesiadzinski,[1,2]
A.R. Binau,[9] R. Biondi,[45] Y. Biondi,[5] H.J. Birch,[14] ...

599 authors **141 institutions** **24 countries**

https://arxiv.org/abs/2203.02309

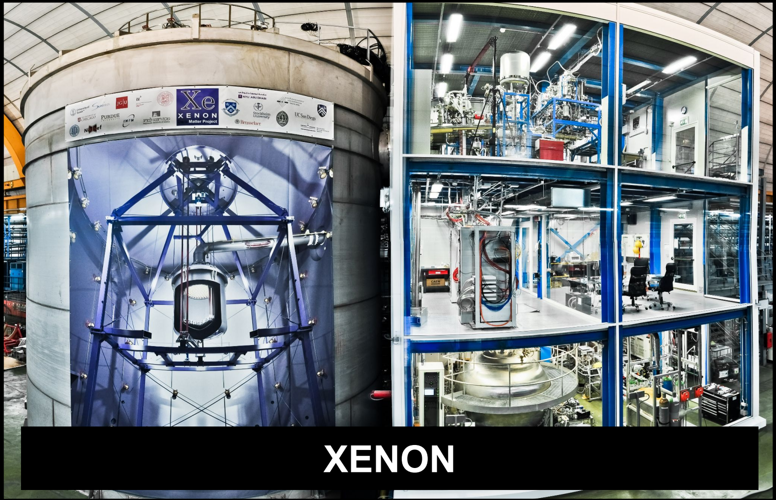
The XENON Project

- **Fourth generation of XENON experiment**
  - ➡ Based on the same detection technology: **dual-phase Time Projection Chamber**
  - ➡ Already **demonstrated the scalability** of this technology
- Operating at the **INFN - Laboratori Nazionali del Gran Sasso** (LNGS)
  - ➡ **Underground laboratory with 1500 m overburden** (3600 m.w.e)

	XENON10	XENON100	XENON1T	XENONnT	DARWIN
Operation period	2005-2007	2008-2016	2012-2019	2020-2026	2030
Xenon mass	14 kg Xe target	62 kg Xe target	2 t Xe target	5.9 t active Xe 8.5 t total Xe	~40 t active Xe ~50 t total Xe
Height **Diameter**	15 cm 20 cm	30 cm 30 cm	96 cm 97 cm	148 cm 133 cm	~2.6 m ~2.6 m

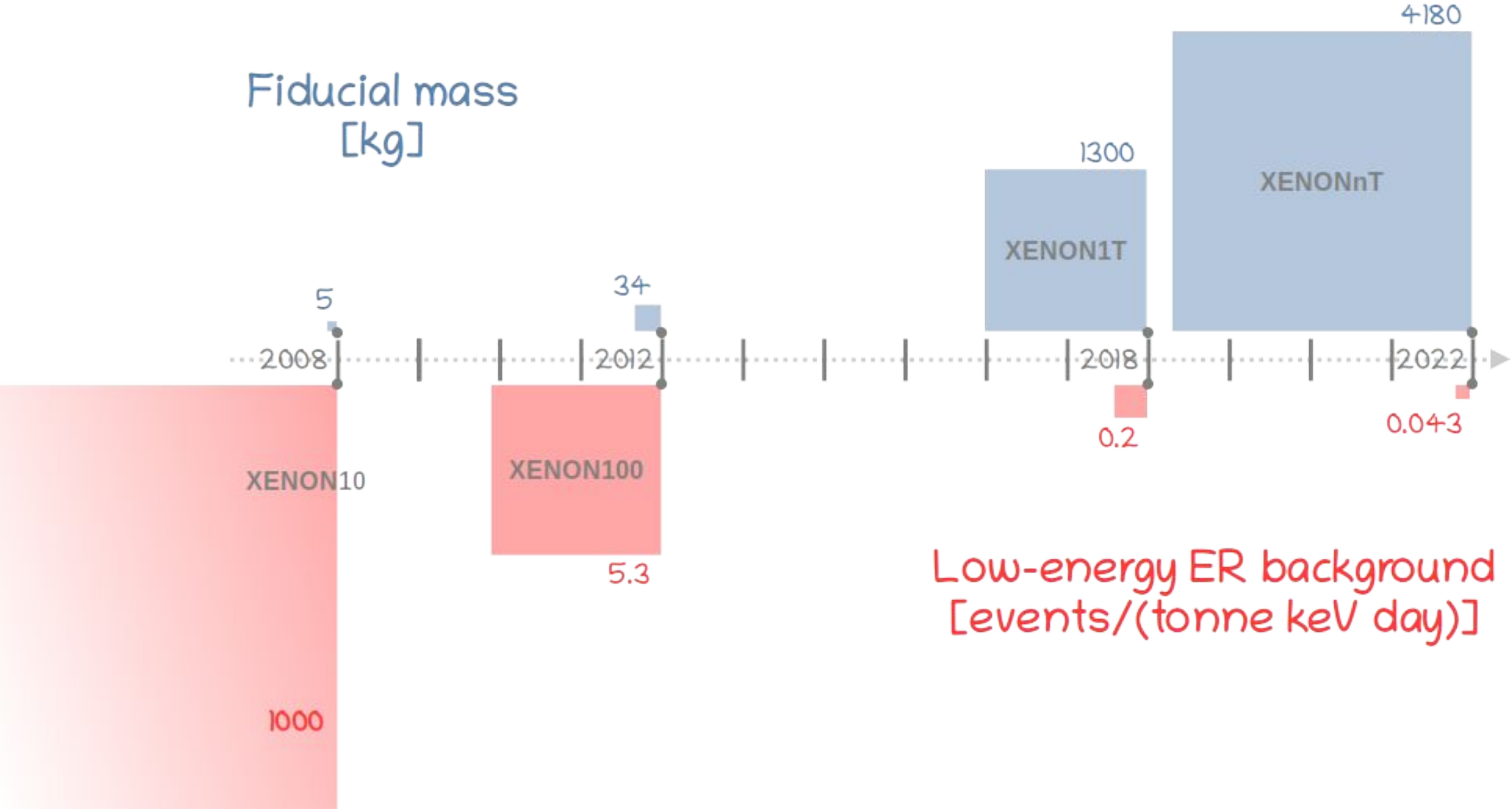

Italy


Gran Sasso National Park
Corno Grande (2912m)
Gran-Sasso-Massiv
1400 m
LNGS
Laboratori Nazionali del Gran Sasso
L'Aquila ◄ A24 ► Teramo


XENON

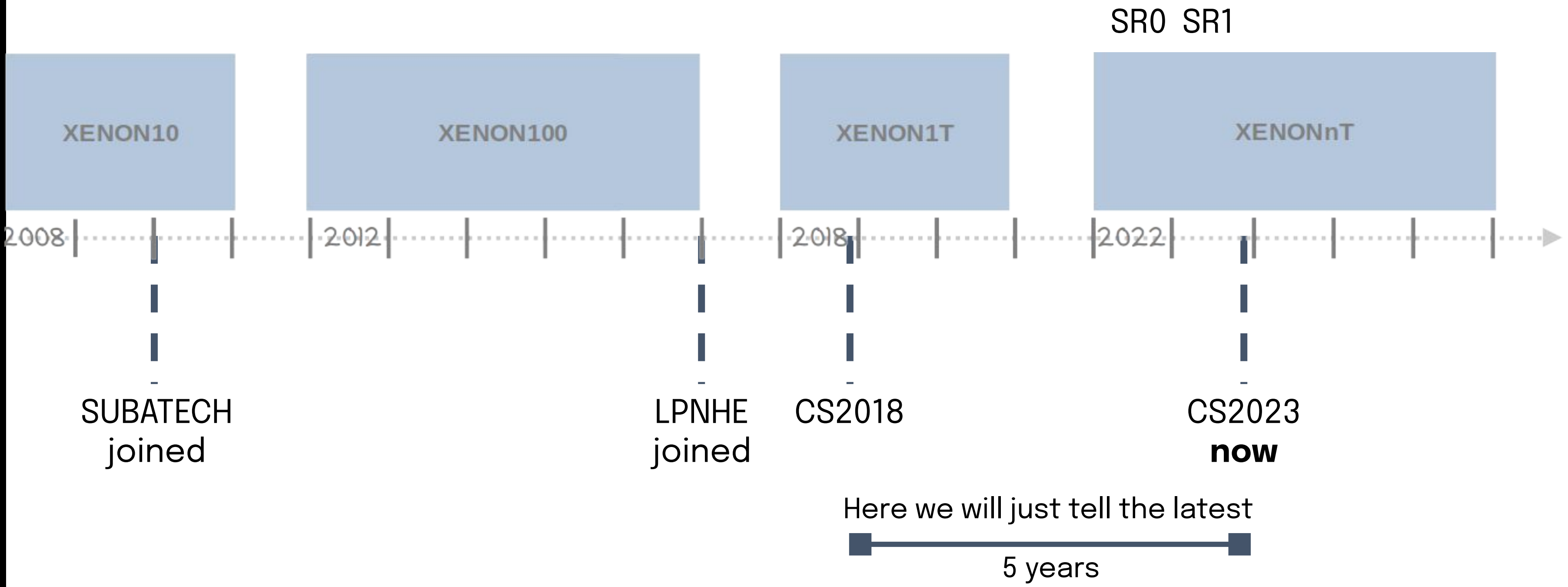

LNGS

Bigger and more silent



Relevant dates for IN2P3

Blue bands = science data taking



Recommendations of CS2018

de XENON-France composé d'environ 8 chercheurs permanents et doctorants et de 2 ITA, la contribution de l'IN2P3 à l'expérience - construction du détecteur, étalonnage et analyses - est significative et visible mais potentiellement trop faible.

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.

Recommendations of CS2018

- Reinforce the groups

- Complete XENON1T analyses

- Installation and commissioning of ReStoX2
- TPC electrodes for XENONnT
- Data analysis of XENONnT

- Participate to DARWIN Project
- Participate in the design studies
- Clarify the role on this Project

Plus . . .

- Leading computing for XENONnT
- Improving Geant4 simulations
- Data Quality Monitoring for XENONnT
- User Management Tools for XENON

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Growth of XENON-France

Lost a group (LAL, 1 CR), increased by a factor x2.3 in 5 years

Laboratory	Name	Position
SUBATECH	Dominique Thers	Maitre Assistant IMT Atlantique, HDR, PI XENON
	Jean Pierre Cussonneau	Maitre Assistant IMT Atlantique
	Julien Masbou	Maitre de Conference Université de Nantes
	Sara Diglio	CR CNRS/IN2P3 (starting from November the 1st 2018)
	Joaquim Navarro Palacio	Postdoc CNRS/IN2P3
	Chloé Therreau	PhD CNRS/IN2P3
LPNHE	Luca Scotto Lavina	CR CNRS/IN2P3, HDR, PI XENON
	Ernesto Lopez Fune	Postdoc CNRS/IN2P3
	Jean-Philippe Zopounidis	PhD CNRS/IN2P3
LAL	Carla Macolino	CR CNRS/IN2P3, PI XENON

SUBATECH [Researchers = 1,1 FTE, Engineers+Technicians = 0,6 FTE, Postdocs = 1 FTE, Students = 5 FTE]

- Dominique Thers, IMT Atlantique (PI XENON)
- Sara Diglio, IN2P3 CR
- Julien Masbou, Nantes Université MdC
- Yajing Xing, postdoc IN2P3, contract ends in December 2023
- Johan Loizeau, IMT-Atlantique PhD
- Marina Bazyk, IMT-Atlantique & The University of Melbourne PhD
- Lorenzo Principe, CNRS PhD (joint CNRS-The University of Melbourne)
- Owen Stanley, The University of Melbourne (joint CNRS-The University of Melbourne)
- Anantakrishnan Ravindran, IMT Atlantique (AUFRANDE program)
- Eric Morteau, IMT Atlantique IR (on XeLab)
- Arnaud Cadiou, IN2P3 IR (on XeLab)
- Julien Simmonneau, IN2P3 IR (on XeLab)

LPNHE [Permanent researchers = 2 FTE, Engineers+Technicians = 1,1 FTE, Postdocs = 2 FTE, Students = 3 FTE]

- Luca Scotto Lavina, IN2P3 DR (PI, XENON IN2P3 coordinator, scientific coordinator of XeLab)
- Bernard Andrieu, IN2P3 CR (joined in 2020, formerly in neutrino group)
- Erwann Masson, postdoc IN2P3, contract ends in October 2023
- Frederic Girard, postdoc IN2P3, 2-years contract started in May 2023
- Layos Daniel Garcia, IN2P3 PhD
- Quentin Pellegrini, Sorbonne PhD
- Yongyu Pan, Sorbonne-CSC PhD (CSC = China Scholarship Council)
- Romain Gaior, IN2P3 IR Electronics (*chercheur experimentaliste*)
- Olivier Dadoun, IN2P3 IR Informatics
- N. Garroum, IN2P3 IR Informatics (technical coordinator of XeLab)
- Y. Orain, IN2P3 AI Mechanics (on XeLab)

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XENON1T data analyses - French contributions

- **Different dark matter models that can be probed:**
  - Low-E Nuclear Recoils (NR)
    - **SI elastic scattering**
    - SD elastic scattering (LXe-specific)
    - WIMP-pion coupling
    - Effective Field Theory on WIMPs (+iDM) (LXe-specific)
    - Mirror DM
  - **Electronic Recoils (ER)**
    - **Dark Photons**
    - **Bosonic SuperWIMPs, Magnetic dark matter**
    - **Solar axions and Axion-like Particles**
    - **Luminous DM**
  - Both (NR+ER)
    - Inelastic DM
    - **Annual modulation search**
    - Low mass WIMPs (<10GeV)
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- **New physics can be scoped:**
  - Neutrinos
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    - Solar Dark Photons

SUBATECH Calibrations, stability, charge and light gains

LPNHE PhD thesis, Corresponding author

LPNHE PhD thesis

SUBATECH PhD thesis, Corresponding author

Intermezzo 1: how a dual-phase LXe TPC works

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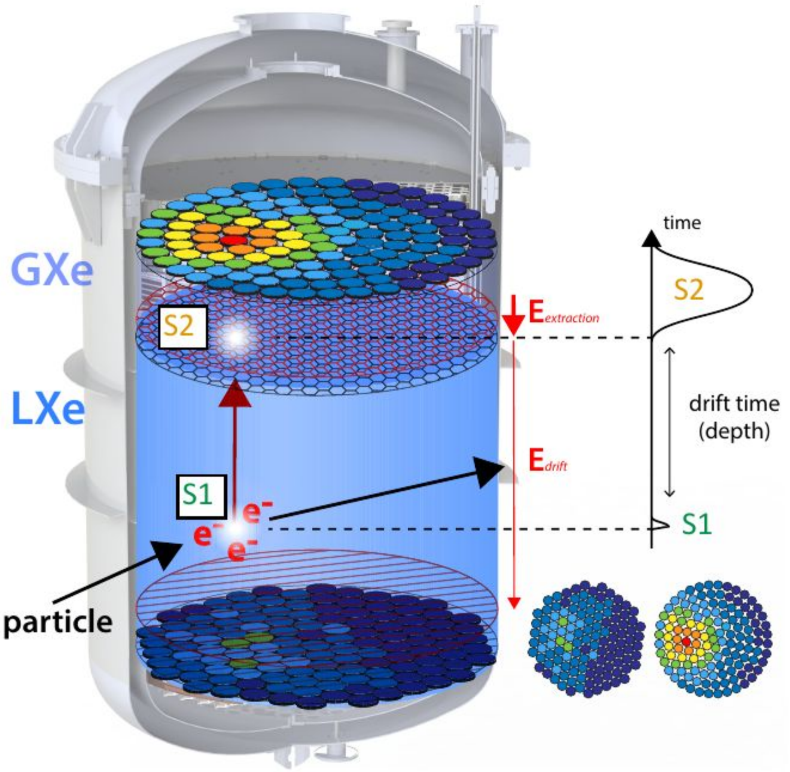
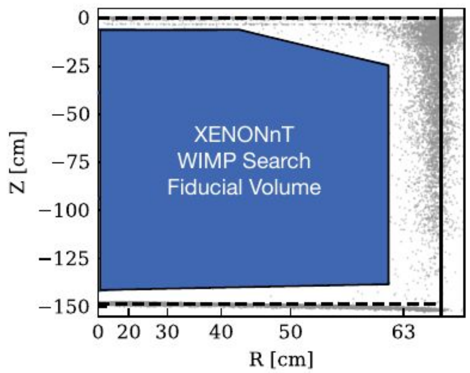


Light and Charge readout

- Prompt scintillation signal (**S1**)
- Secondary proportional scintillation signal in GXe from drifted electrons (**S2**)

Event reconstruction

- **3D Position:**
  - **Z** from drift time
  - (**X**, **Y**) from PMTs hit pattern
- **Energy** → $E = W \cdot (n_{ph} + n_e)$



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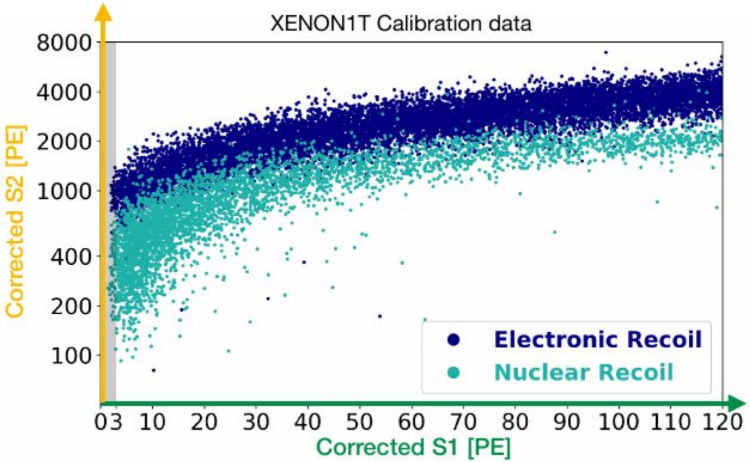

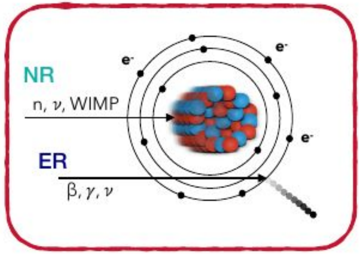

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Particle discrimination

- Interaction type **Nuclear Recoil (NR)**/**Electronic Recoil (ER)** through **S1**/**S2** ratio

$$\left(\frac{S2}{S1}\right)_{NR} < \left(\frac{S2}{S1}\right)_{ER}$$

XENON1T data analyses

Phys. Rev. Lett. 121, 111302 (2018), Link, arXiv:1805.12562

Spin-Independent elastic scattering 1 tonne x year

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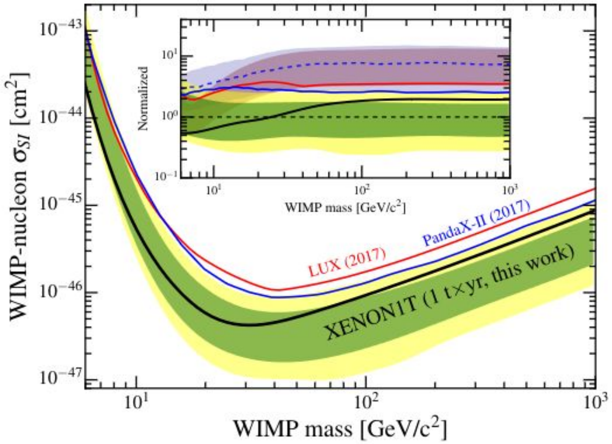

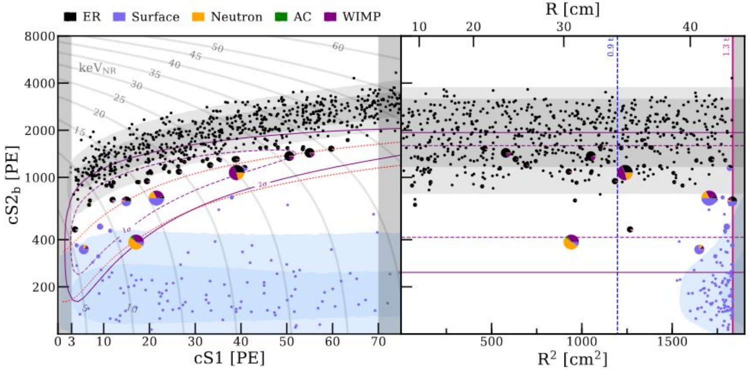

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Phys. Rev. Lett. 122, 141301 (2019), arXiv:1902.03234

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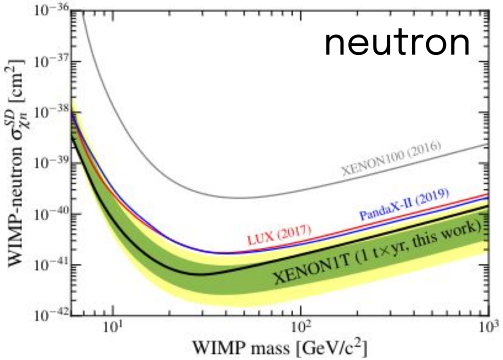
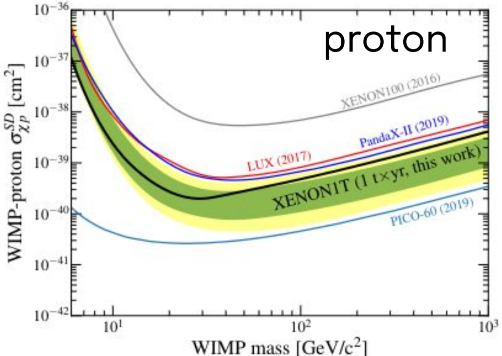
Spin-Dependent elastic scattering

$$\frac{dR}{dE_r} = \frac{2\rho_\chi}{m_\chi}\int \frac{d\sigma^{SD}}{dq^2} v f(\vec{v}) d^3v, \quad \frac{d\sigma^{SD}}{dq^2} = \frac{\sigma^{SD}_{\chi N}}{3\mu_N^2 v^2}\frac{\pi}{2J+1}S_N(q),$$

Possible only thanks to a mixture of **even and odd isotopes** present in natural xenon





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Phys. Rev. Lett. 122, 071301 (2019), arXiv:1811.12482

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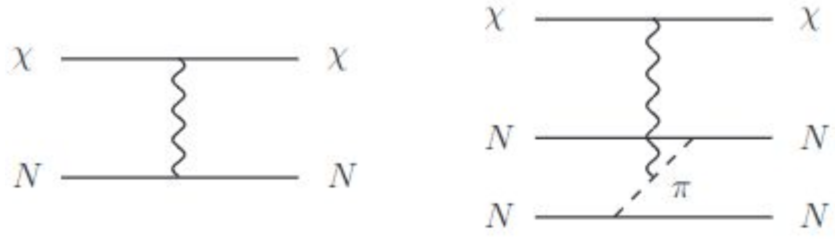
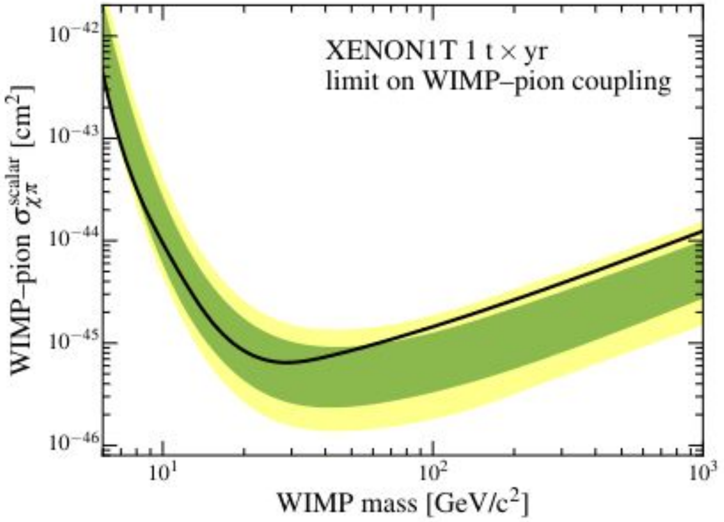
Elastic scattering with WIMP-pion coupling





XENON1T data analyses

Submitted, under review, arXiv:2210.07591

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Scattering treated with an Effective Field Theory

Sum of all possible operators. Exclusion limit on each coefficient

$$\mathcal{L}_{\chi\ EFT} = \sum_{\mathrm{d},a,q(g)} \frac{C^{a,(\mathrm{d})}_{q(g)}}{\Lambda^{\mathrm{d}-4}} \mathcal{Q}^{(\mathrm{d})}_{a,q(g)},$$

Type	Abbrev.	Operator ($\mathcal{Q}$)	Dimension	Coherent enhancement	Coefficients
Magnetic Dipole	-	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	5	Partial	C_F
Electric Dipole	-	$\bar{\chi}\sigma^{\mu\nu}\chi \tilde{F}_{\mu\nu}$	5	Yes	$\tilde{C}_F$
Vector⊗Vector	VV	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	6	Yes	$C^{VV}_{u,d,s}$
Axial-vector⊗Vector	AV	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}q$	6	Yes	$C^{AV}_{u,d}$
Tensor⊗Tensor	TT	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	Yes	$C^{TT}_{u,d,s}$
Pseudo-tensor⊗Tensor	$\widetilde{TT}$	$\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi\bar{q}\sigma_{\mu\nu}q$	6	Yes	$\tilde{C}^{TT}_{u,d,s}$
Scalar⊗Scalar	SS	$\bar{\chi}\chi m_q\bar{q}q$	7	Yes	$C^{SS}_{u,d,s}$
Scalar-gluon	S_g	$\alpha_s\bar{\chi}\chi G^a_{\mu\nu}G^{\mu\nu}_a$	7	Yes	C^S_g
Pseudo-scalar - gluon	$\tilde{S}_g$	$\alpha_s\bar{\chi}i\gamma_5\chi G^a_{\mu\nu}G^{\mu\nu}_a$	7	Yes	$\tilde{C}^S_g$
Pseudo-scalar⊗Scalar	PS	$\bar{\chi}i\gamma_5\chi m_q\bar{q}q$	7	Yes	$C^{PS}_{u,d,s}$
Spin-2	-	$\bar{\chi}\gamma_{\mu}i\partial_{\nu}\chi\bar{\theta}^{\mu\nu}_{q(g)}$	8	Yes	$C^{(2)}_{u,d,s,g}$
Axial-vector⊗Axial-vector	AA	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$	6	No	$C^{AA}_{u,d,s}$

XENON1T data analyses

Phys. Rev. D 106, 022001 (2022), arXiv:2112.12116

XENON FRANCE

- **Different dark matter models that can be probed:**
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    - Solar axions and Axion-like Particles
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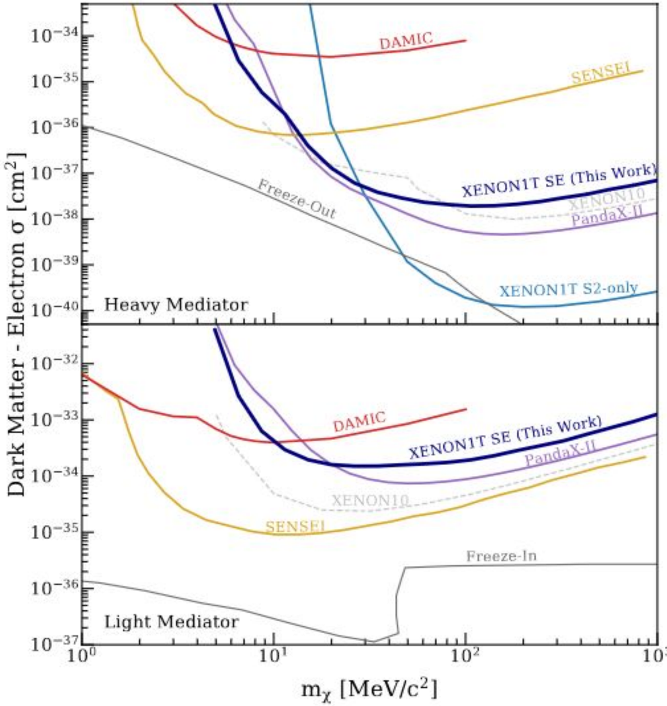
DM-electron scattering → fermion or scalar boson DM candidate scatters off an electron bound in a xenon atom



LPNHE main contribution, corresponding author J.P. Zopounidis (PhD thesis)

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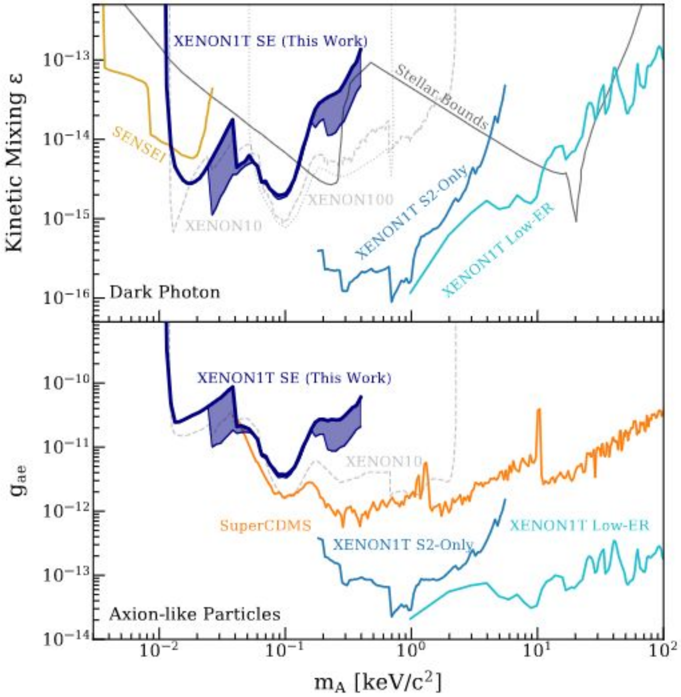
Vector-boson DM → dark photons
Pseudo-scalar DM → axion-like particles (ALPs)



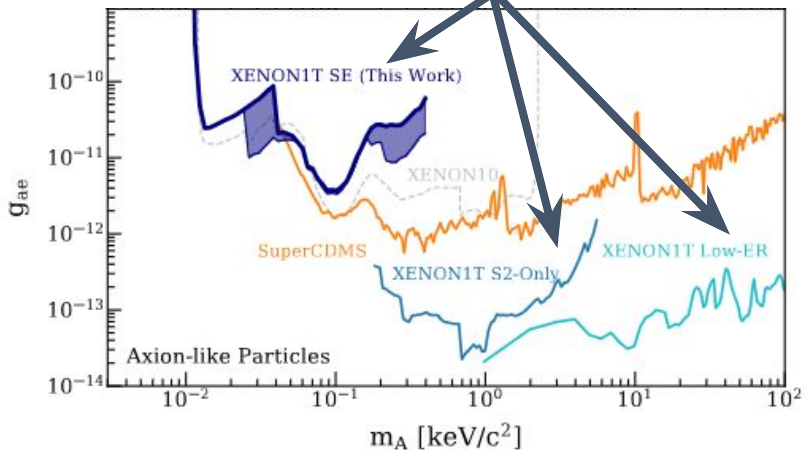
LPNHE main contribution, corresponding author J.P. Zopounidis (PhD thesis)

Intermezzo 2: “S1+S2”, “S2-only” and “SE” analyses

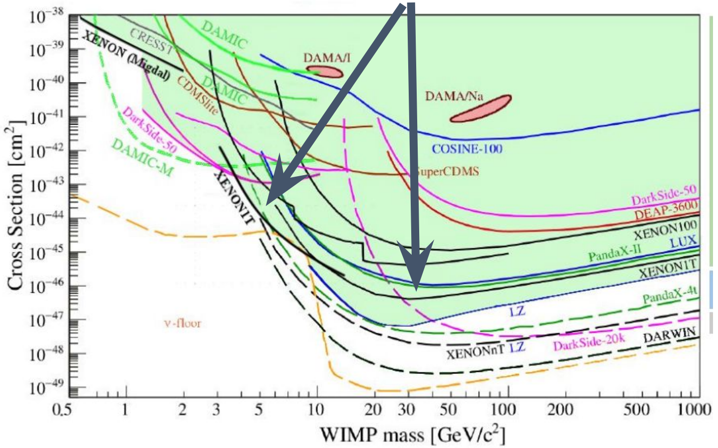
There are **three strategies to analyse data**, each of them opens us the door to different DM masses :

- The **S1+S2** one, aka: the **“Standard WIMP analysis”**
  - You profit of the S2/S1 ratio to separate ER from NR and the precise 3D fiducialization
- The **S2-only** one, aka: the **“Low-energy WIMP analysis”**
  - You renounce the S1 information: low down energy threshold, lose some background cuts
- The **SE** one, aka: the **“Single or few electrons analysis”**
  - You count every single electron or electron clusters (usually up to 5 clusters)

Example for Electron Recoils



Example for Nuclear Recoils



XENON1T data analyses

Phys. Rev. D 106, 022001 (2022), arXiv:2112.12116

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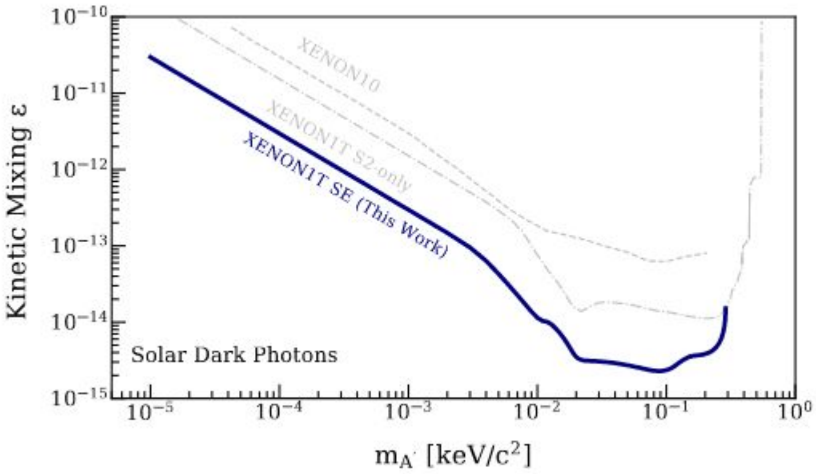
    - **Solar Dark Photons**

Solar Dark Photons

Higher kinetic energy wrt relic Dark Photons → boosted the 2-5 electrons spectrum

Polarization not isotropic



LPNHE main contribution, corresponding author J.P. Zopounidis (PhD thesis)

XENON1T data analyses

Phys. Rev. D 103, 063028 (2021), arXiv:2011.10431

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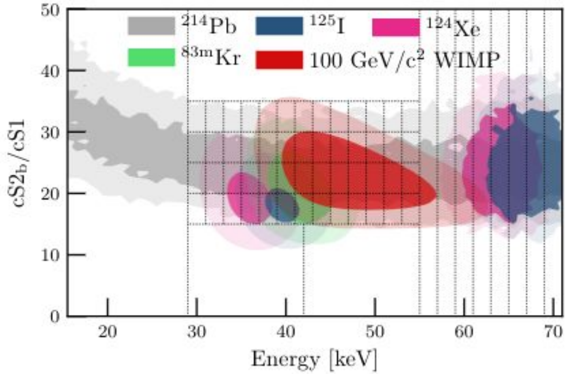
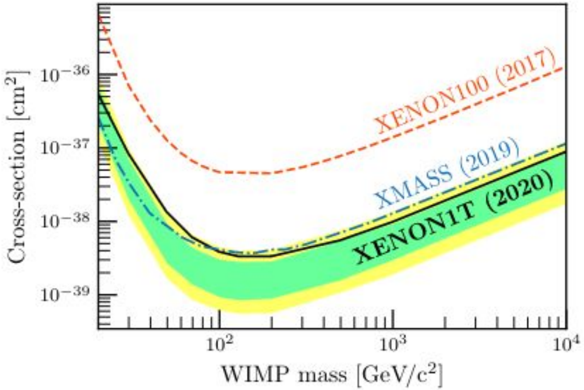
Inelastic Dark Matter

Target nucleus left excited after scattering

→ Extra ɣ-ray





^{129}Xe :

- lowest excited state
- 26% abundant
- $3/2^+ \rightarrow 1/2^+$
- ɣ @ 39.6 keV
- half-life 0.97 ns

XENON1T data analyses

XENON100: Phys. Rev. Lett. 118, 101101 (2017), arXiv:1701.00769
XENON1T: J.P. Zopounidis, PhD thesis, https://tel.archives-ouvertes.fr/tel-03793329

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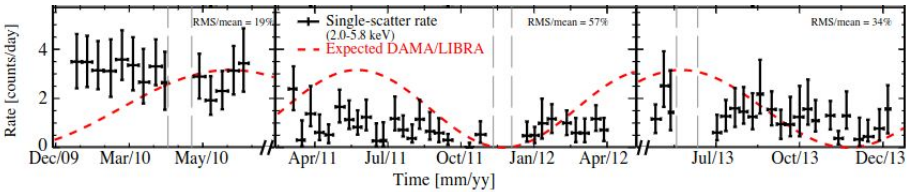
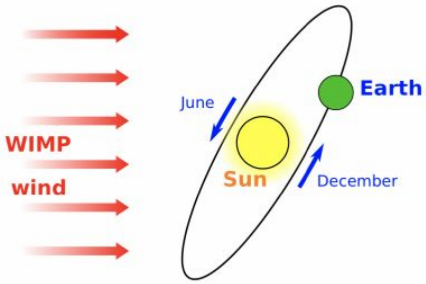
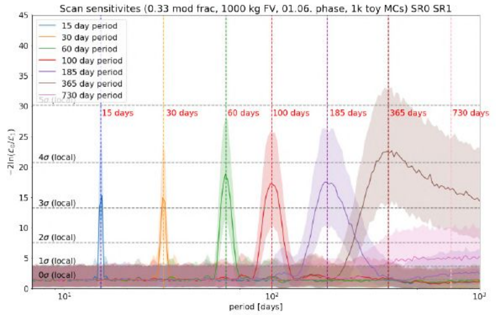
Annual modulation

Two publications with XENON100 with 4 years of data:







XENON1T study done at LPNHE, J.P. Zopounidis (PhD thesis)

XENON1T data analyses

Phys. Rev. Lett. 130, 261002 (2023), arXiv:2304.10931

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Search for MIMPs (Multiply-Interacting Massive Particles)

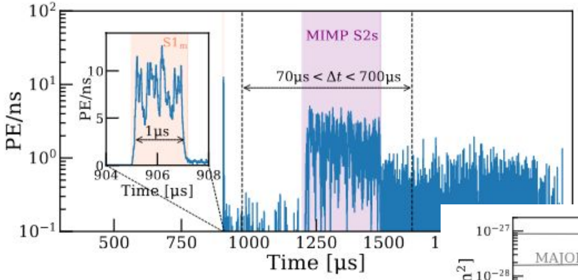
Heavy DM particles with mass close to Plank mass

Background: muons (0.05 with 219.4 days exposure)

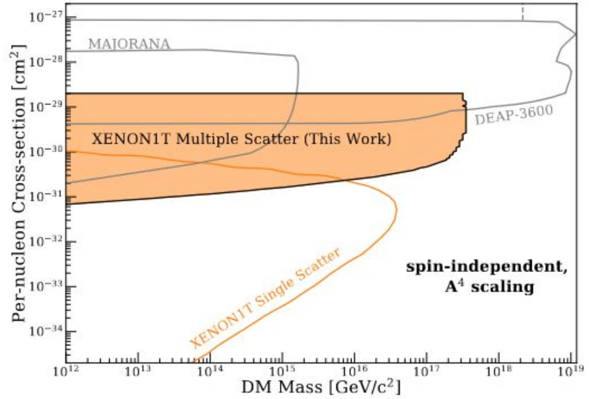
$$\frac{d\sigma^{SI}_{A,\chi}}{dq^2} = \frac{\mu^2_{A,\chi}}{\mu^2_{nucleon,\chi}} A^2 |F_A(q)|^2 \frac{d\sigma^{SI}_{nucleon,\chi}}{dq^2}$$

$$\frac{\mu^2_{A,\chi}}{\mu^2_{nucleon,\chi}} \xrightarrow{m_\chi \gg m_A} A^2$$

Coherent enhancement



Even Plank scale physics is within reach of direct DM experiments !



XENON1T data analyses

Phys. Rev. Lett. 123, 241803 (2019), arXiv:1907.12771

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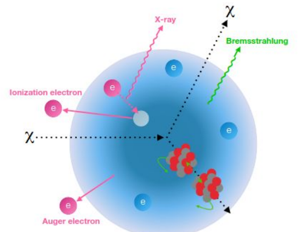
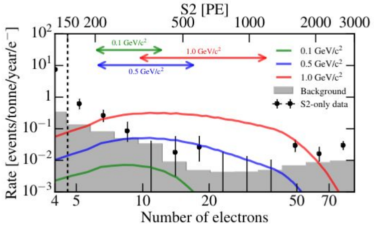
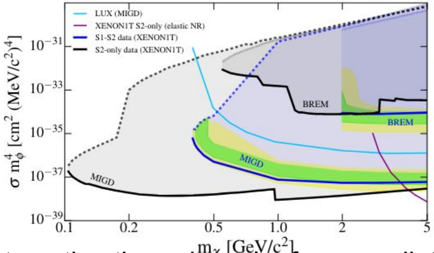
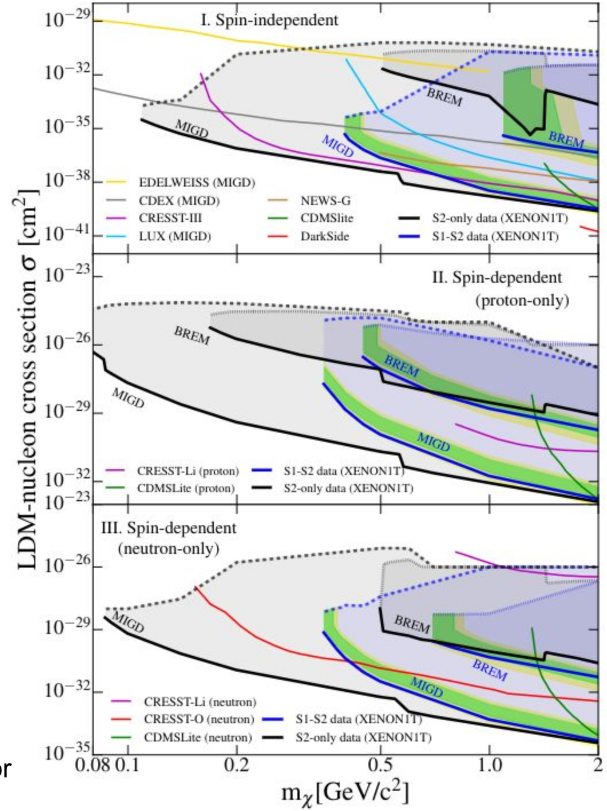
Enhancements due to Midgal or Bremsstrahlung







Interaction through scalar force mediator



XENON1T data analyses

Phys. Rev. Lett. 126, 091301 (2021), arXiv:2012.02846

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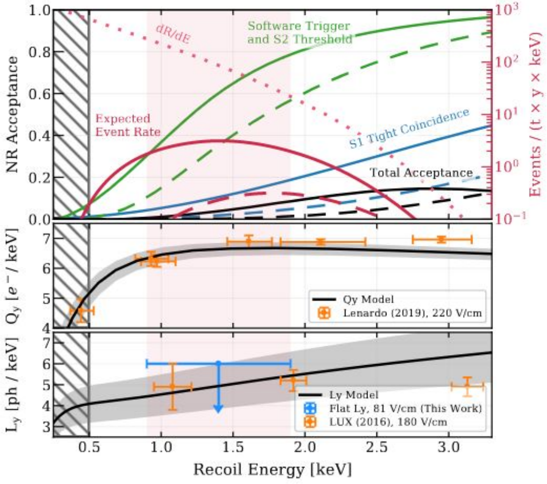
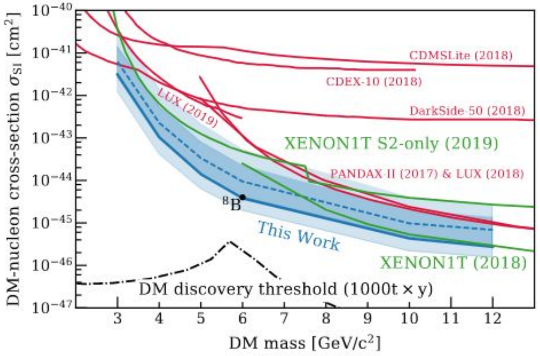
Solar ^{8}B neutrinos

Reached multiple goals:

- Develop new techniques to **improve sensitivity** near the threshold
- Quantify the **^{8}B neutrinos** component in our background (6 events observed in the ROI, 5.38 background expected, whose 2.11 from CEvNS)
- Improve our DM limit at low masses





XENON1T data analyses

Eur. Phys. J. C 80, 785 (2020), arXiv:2003.03825
C. Therreau, PhD thesis, https://hal.science/tel-02926324v1

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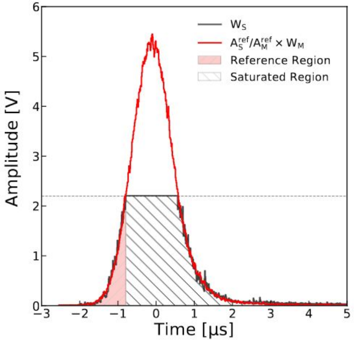
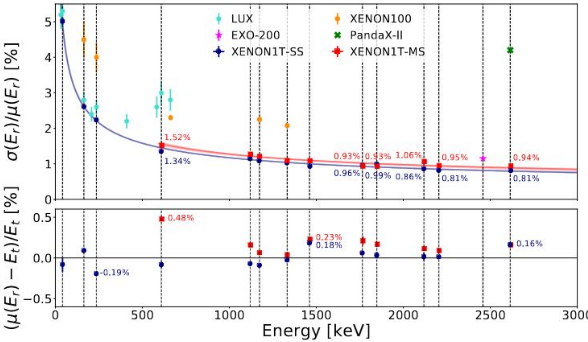
Neutrinoless double-beta decay with ^{136}Xe

Solved limitation of PMTs saturation with post-processing corrections

Energy resolution : 0.8% @ 2.46 MeV (E = 81 V/cm)





SUBATECH energy saturation and resolution, C. Therreau (PhD thesis)

XENON1T data analyses

Phys. Rev. C 106, 024328 (2022), arXiv:2205.04158
M. Pierre, PhD thesis, https://hal.science/tel-04216774v1

XENON FRANCE

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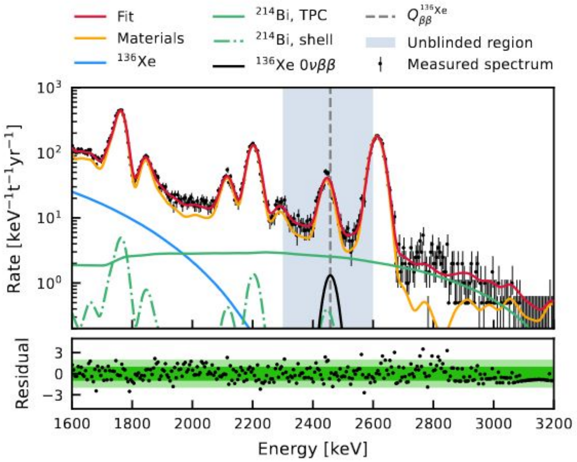
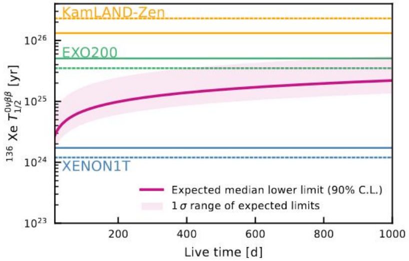
Neutrinoless double-beta decay with ^{136}Xe

Isotopic abundance ~8.5%
Isotope exposure of 36.16 kg x year





$$T_{1/2}^{0\nu\beta\beta} > 1.2\times10^{24}\ \text{yr at } 90\,\%\ \text{CL}$$

Background estimation E. Masson (postdoc)
SUBATECH main contribution, corresponding author M. Pierre (PhD thesis)

XENON1T data analyses

Nature 568, p.532-535, 2019, arXiv:1904.11002
Phys. Rev. C 106, 024328 (2022), arXiv:2205.04158

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Two-neutrinos Double Electron Capture in ^{124}Xe

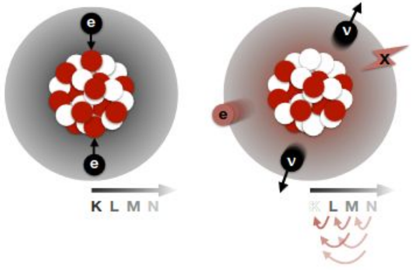
The longest rare event ever measured directly

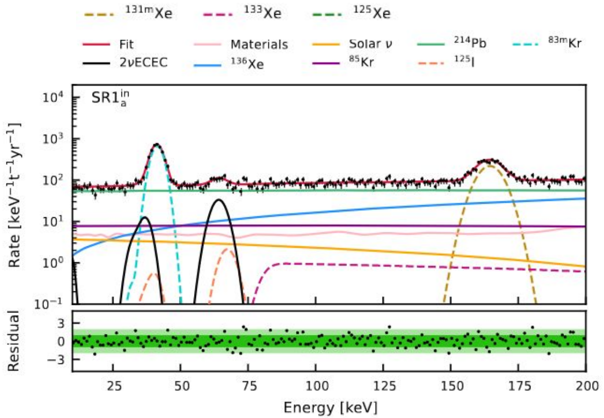
Isotopic abundance 0.0994%, exposure 0.87 kg x year

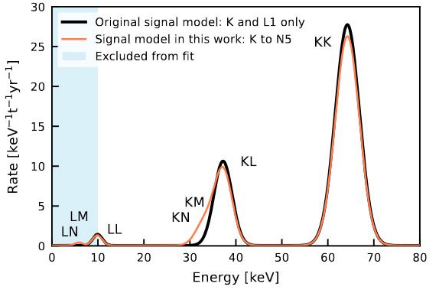
Significance 4.4σ first (Nature), then 7σ (PRC)

KL-, KM-, KN- and LL-captures

$$T_{1/2}^{2\nu ECEC} = (1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{yr}$$







SUBATECH main contribution, corresponding author M. Pierre (PhD thesis)

XENON1T data analyses

Submitted, under review, arXiv:2306.11871

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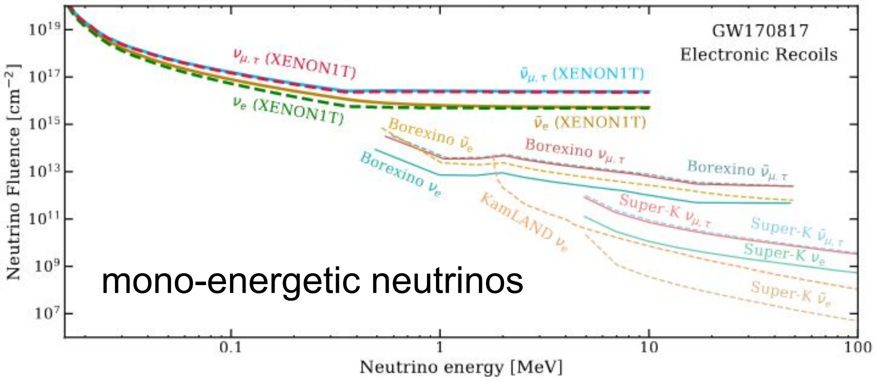
Search for events associated with Gravitational Waves

Search for signals close in time (± 500 seconds) to GW observed by LIGO and Virgo

Scoped: GW170104, GW170729, GW170817, GW170818, GW170823

Constrain mono-energetic neutrinos and BSM particles with GW170817



mono-energetic neutrinos

mono-energetic BSM particles $N_{\mathrm{ER}} = N_T \, \epsilon \, \sigma_{\mathrm{BSM}} \, F_{E_{\mathrm{BSM}}}$

$\sigma_{\mathrm{BSM}} F_{E_{\mathrm{BSM}}} < 10^{-29}\ \mathrm{cm}^2/\mathrm{cm}^2 \quad E_{\mathrm{BSM}}$ in $[5.5\text{–}210]\ \mathrm{keV_{ee}}$

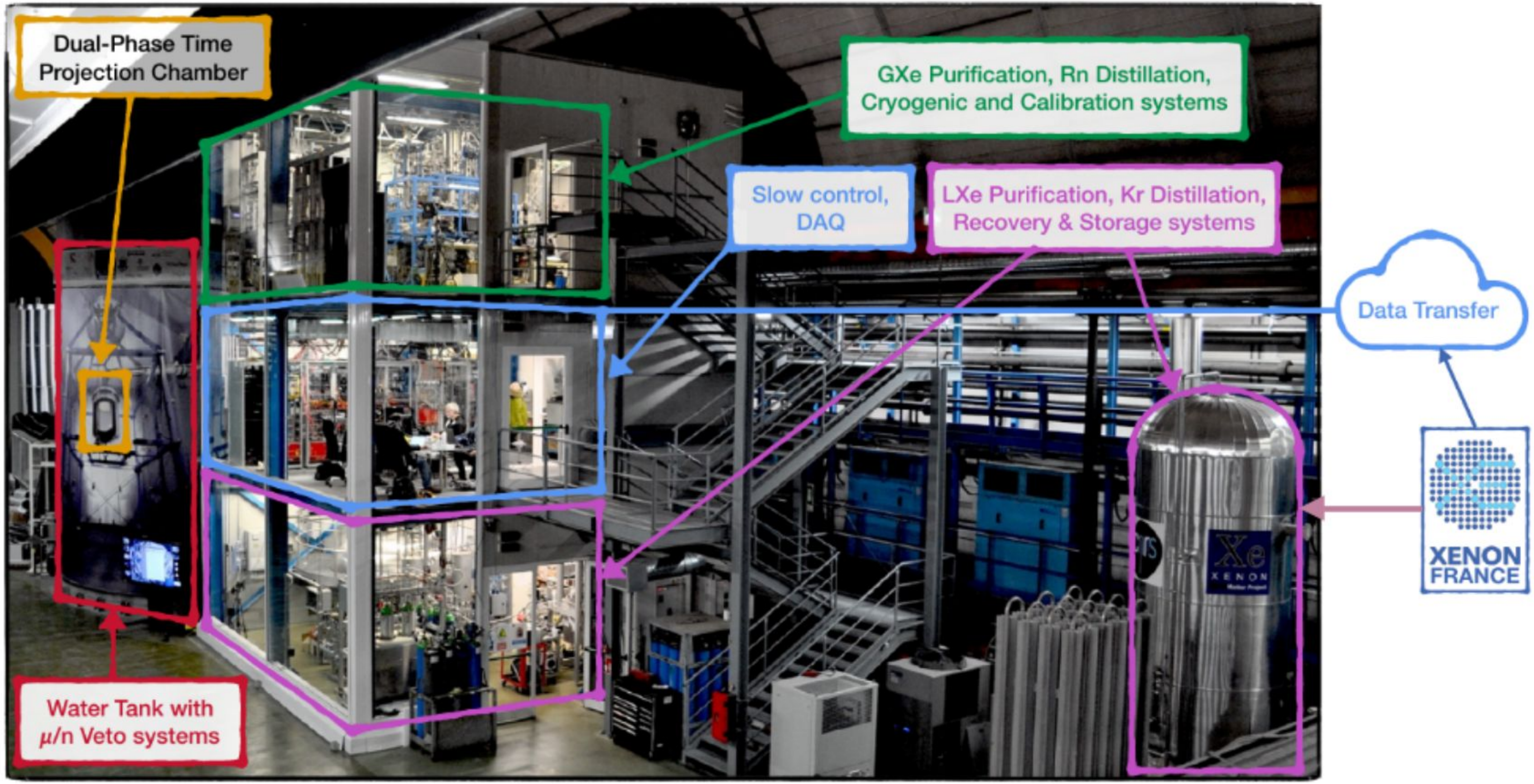
Recommendations of CS2018

- Reinforce the groups
- Complete XENON1T analyses
- Installation and commissioning of ReStoX2
- TPC electrodes for XENONnT
- Data analysis of XENONnT
- Participate to DARWIN Project
- Participate in the design studies
- Clarify the role on this Project

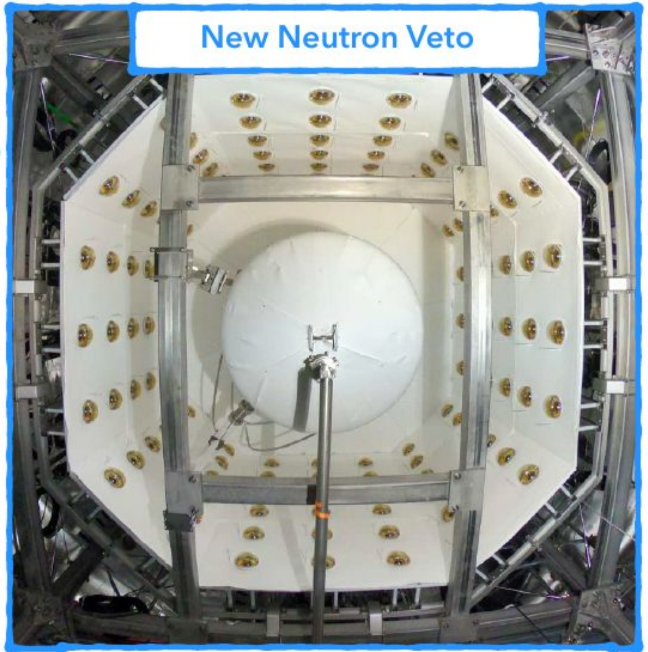
Plus . . .

- Leading computing for XENONnT
- Improving Geant4 simulations
- Data Quality Monitoring for XENONnT
- User Management Tools for XENON

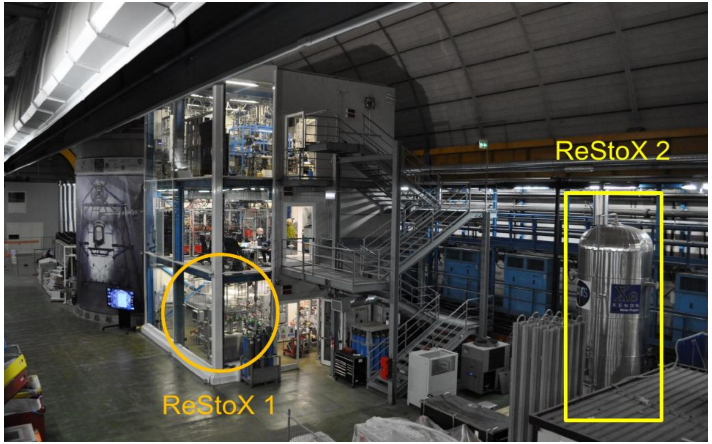
From XENON1T to XENONnT, the advantages of quick updates

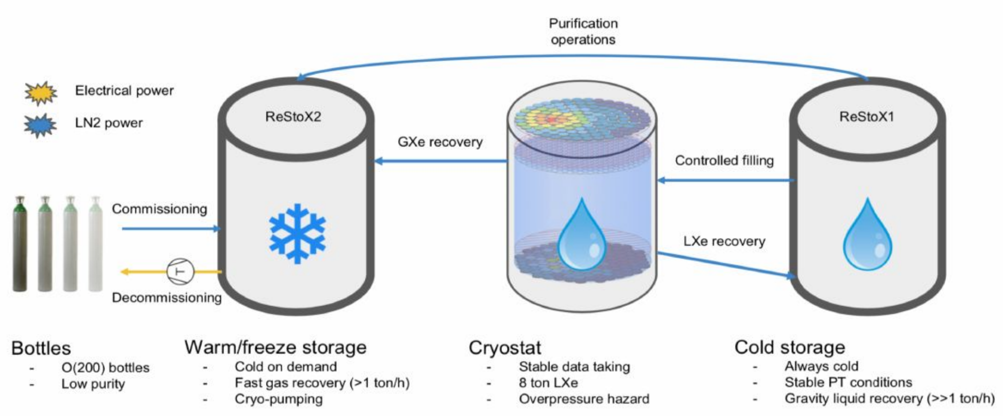


From XENON1T to XENONnT, the advantages of quick updates



The Recovery and Storage System of XENONnT (ReStoX2)





ReStoX1 : Columbia, Subatech and Mainz

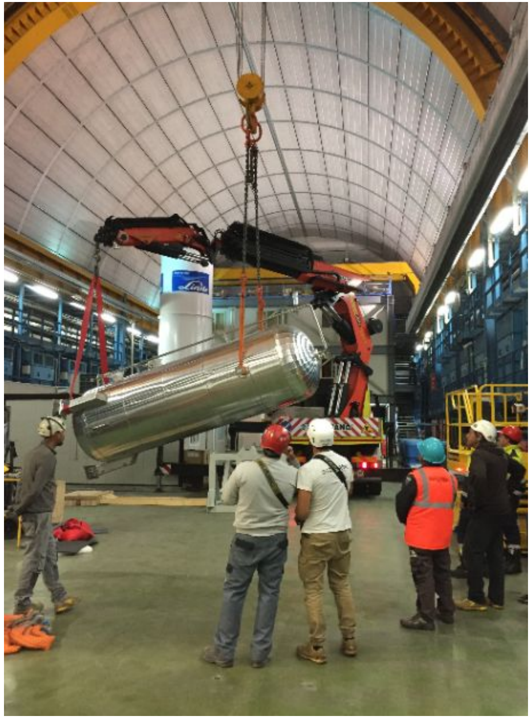
ReStoX2 : 100% contribution of XENON-France (Subatech, LPNHE, LAL). LPNHE contributed with the inner heat exchanger (DATE), SUBATECH with the vessel. Funded by IN2P3 and the two regions : *Pays de la Loire* and *Île-de-France* (DIM-ACAV+)

Reached a fast recovery with a rate of 1 tonne / hour !

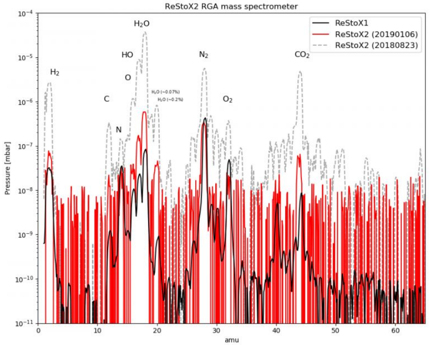
Description	ReStoX2
Dimension	(1.45 m, 5.5 m) cylinder
Phase	GXe, LXe, SXe
Maximum pressure	71.5 bar
Capacity	10 t
Recovery speed	$\sim 1000\,\mathrm{kg/h}$
LN_2 consumption in operation	0 kg/d
LN_2 consumption for recovery	$\sim 8000\,\mathrm{kg}$

The Recovery and Storage System of XENONnT (ReStoX2)

Installation

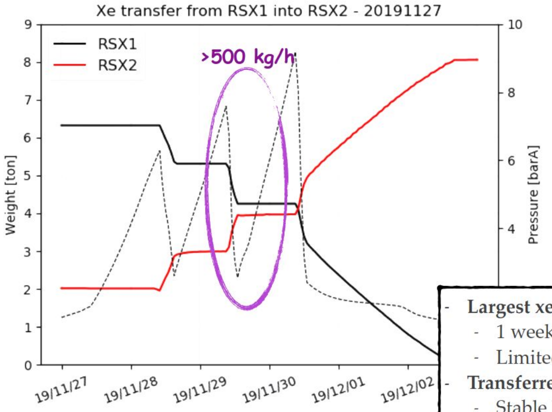


Vacuum and purity checks



Filling from bottles

First recovery test from ReStoX1 to ReStoX2



- Largest xenon transfer
  - 1 week operation
  - Limited RSX1 evaporation
- Transferred 6300 kg of xenon
  - Stable long-term performance
  - Peak speed of 500 kg/h

XENONnT data analyses (so far)

- **Different dark matter models that can be probed:**
  - Low-E Nuclear Recoils (NR)
    - SI elastic scattering
    - SD elastic scattering (LXe-specific)
  - Electronic Recoils (ER)
    - Dark Photons
    - Axion-like Particles
- **New physics can be scoped:**
  - Neutrinos
    - Neutrino magnetic moment
  - Rare events
    - Double electron capture (LXe-specific)
  - New particles
    - Solar axions

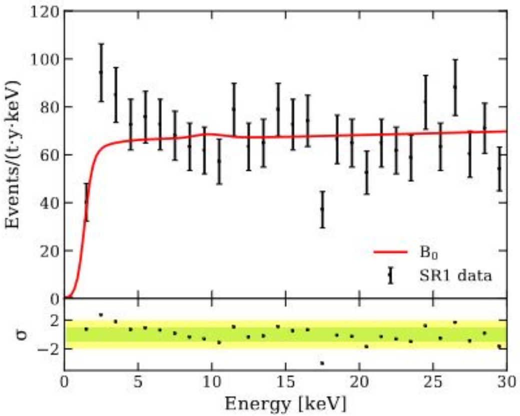
Electronic recoils (2022)

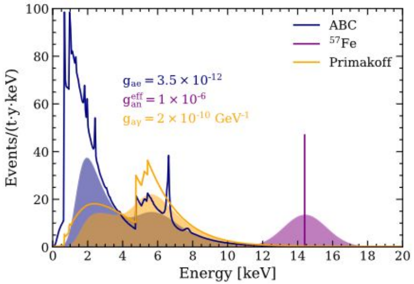
Nuclear recoils (2023)

Why electronic recoils first?

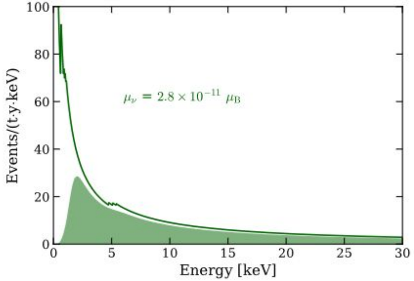
XENON1T: excess of low-energy ER

Phys. Rev. D 102, 072004 (2020), arXiv:2006.09721
XENON Collaboration + X. Mougeot (CEA)

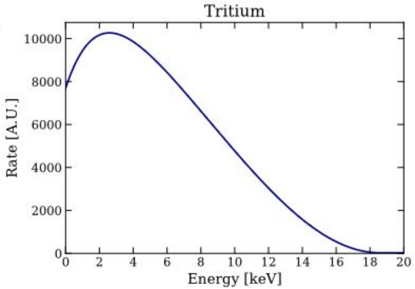




Solar axions?

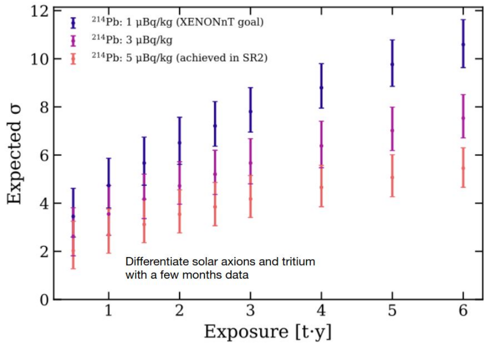


Solar neutrinos with enhanced magnetic moment ?



Or simply some unexpected Tritium-based molecule ?

Let's ask it to XENONnT!

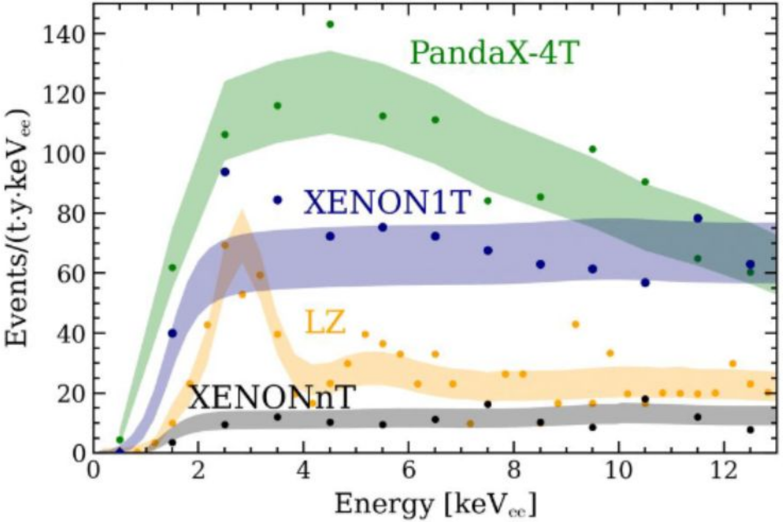


And, you see, we are always conservative…

XENONnT ER analysis

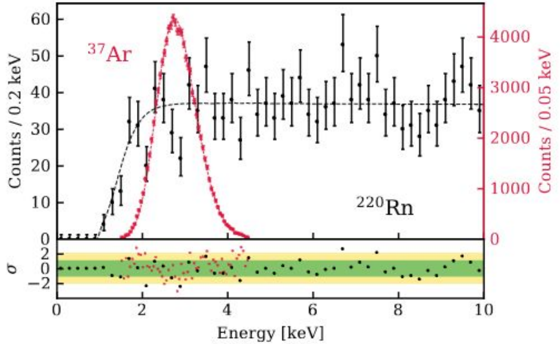
Phys. Rev. Lett. 129, 161805 (2022), arXiv:2207.11330

The lowest background ever reached!

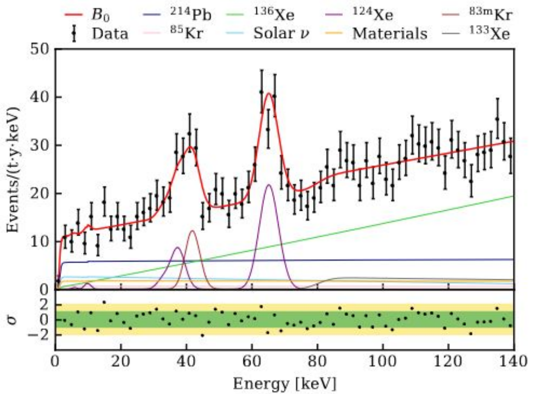


PandaX-4T, PRL 129, 161804 (2022)
XENON1T, PRD 102, 072004 (2020)
LZ, arXiv:2207.03764
XENONnT, PRL 129, 161805 (2022)

Calibration at low energy with ^{37}Ar

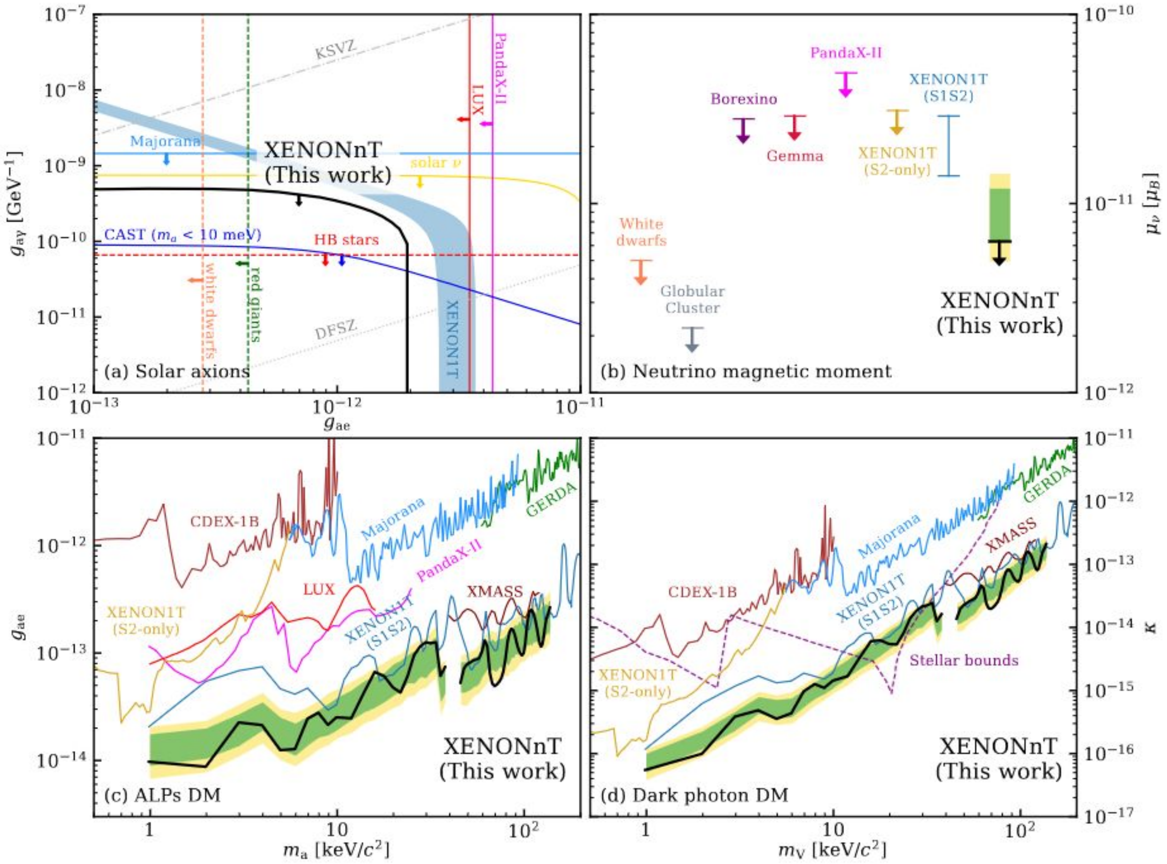


Data fit using the background model



XENONnT ER analysis

Phys. Rev. Lett. 129, 161805 (2022), arXiv:2207.11330



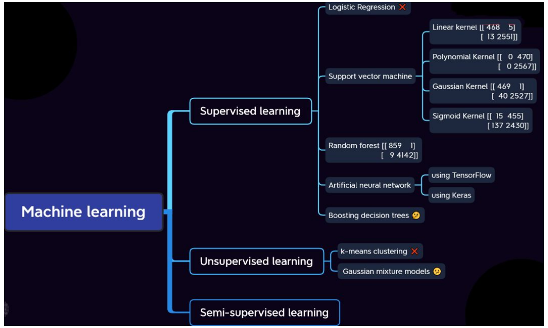
Strongest limit on neutrino magnetic moment

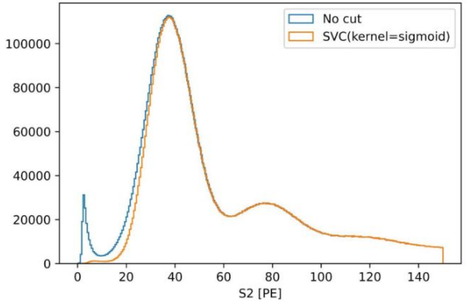
$$\mu_\nu < 6.4 \times 10^{-12}\,\mu_B$$

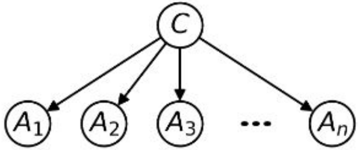
AI in XENONnT

Phys. Rev. D 108, 012016 (2023), [arXiv:2304.05428](https://arxiv.org/abs/2304.05428)

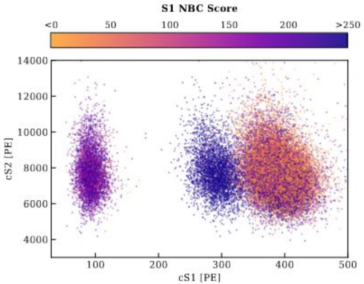
Key point is the S1 vs S2 discrimination at low energies



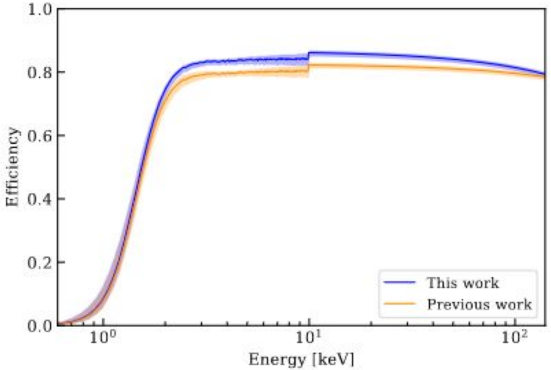




$$P(C, A_1, \ldots, A_n) \propto P(C) \prod_{i=1}^{n} P(A_i \mid C)$$



Bayesian network revealed to be the most efficient, replacing most of the cuts from standard analysis, with an overall gain of 3% in efficiency



Use of AI for discrimination, pioneered at LPNHE (S.e.M. Ahmed Maouloud PhD thesis)

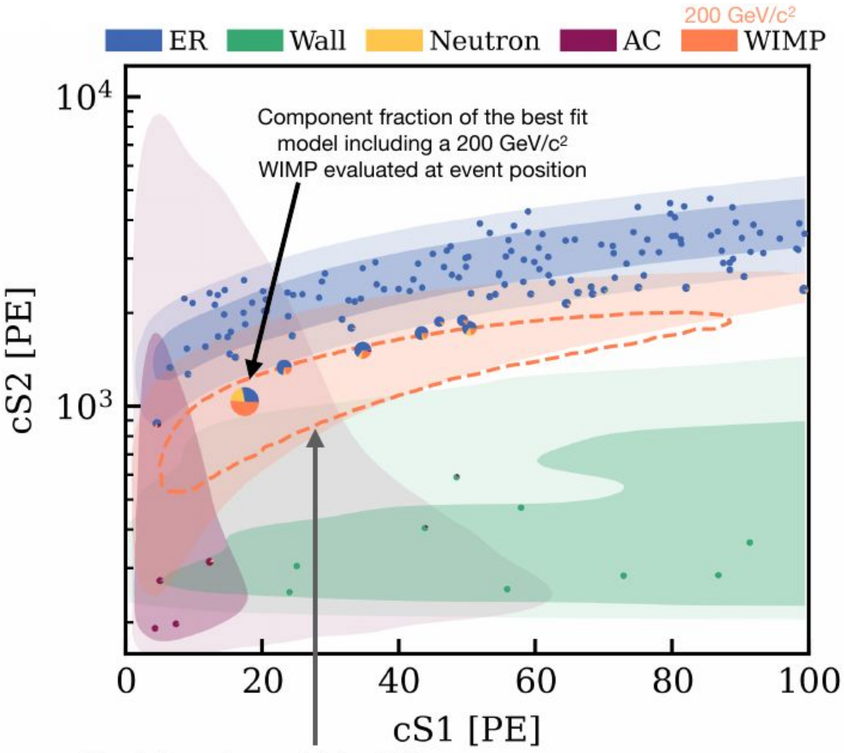
XENONnT NR analysis

Phys. Rev. Lett. 131, 041003 (2023), arXiv:2303.14729

Unblinding

	Expectation	Best Fit
ER	134	135^{+12}_{-11}
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.15
Surface	14 ± 3	12^{+0}_{-4}
Total	154	152 ± 12
200 GeV/c² WIMP	-	2.4
Observed	-	152

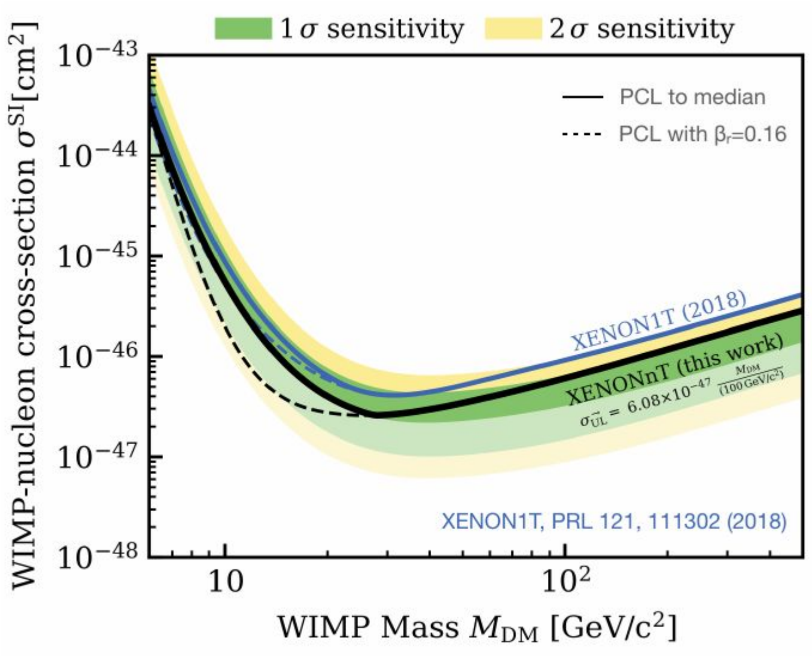
- 152 events in ROI, 16 in blinded region
- Profile log-likelihood-ratio test statistic
  - ➡ **No significant excess observed**



XENONnT NR analysis

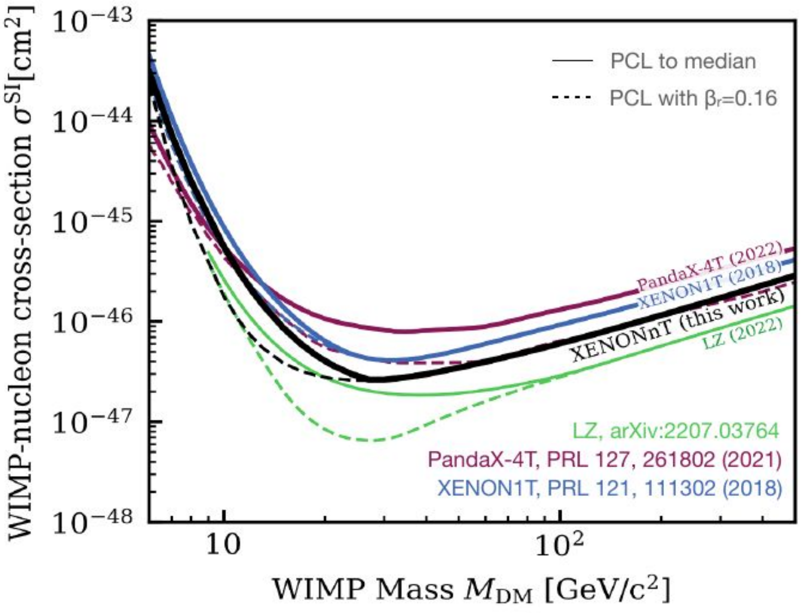
Phys. Rev. Lett. 131, 041003 (2023), arXiv:2303.14729

XENON1T-blinded VS XENONnT-blinded



Improved w.r.t. XENON1T by a factor x1.6 with a similar exposure

XENONnT-blinded VS LZ/PandaX-4T-not-blinded

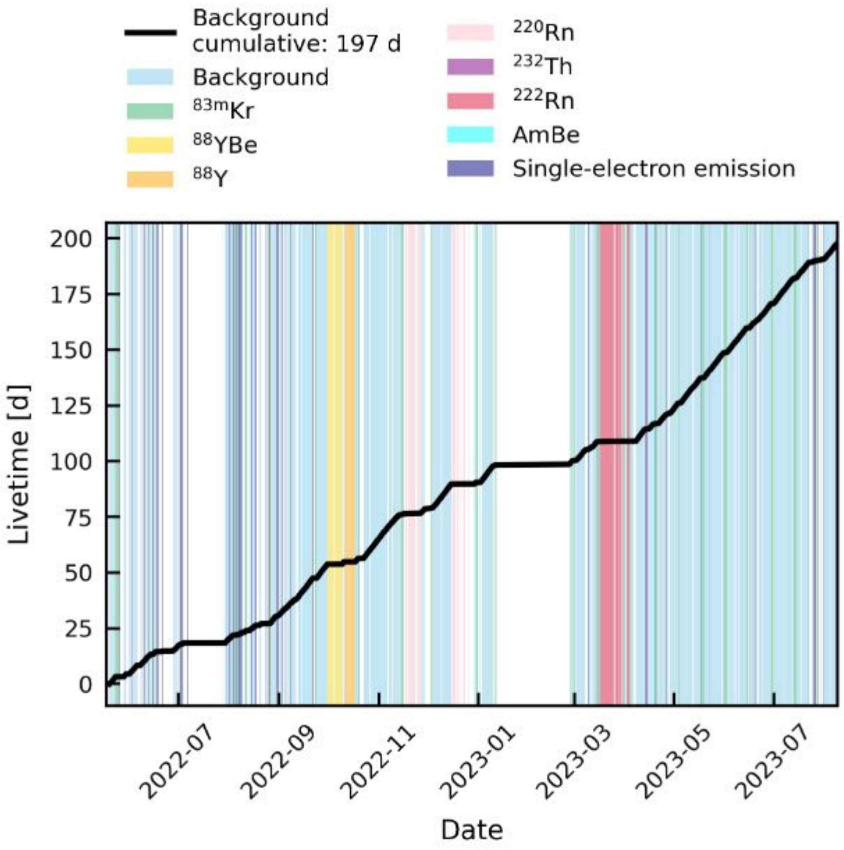


Same PCL applied to results of other recent LXe experiments

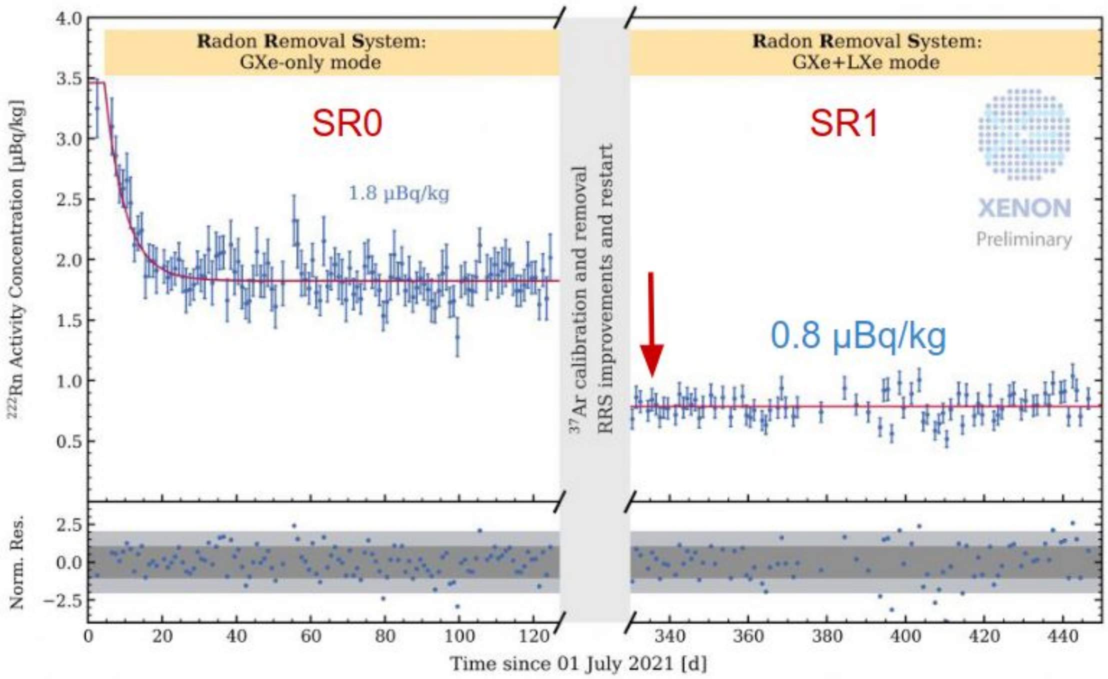
Completion of Science Run SR1

XENONnT data taking during SR1

- May 19, 2022 to August 8, 2023
- Currently 197 days live time
- + 24 days with localized single-electron emission potentially to be recovered
- Stable PMT gains (< 3% rms) with single PE acceptance > 92%
- Stable nVeto performance with ultrapure water
- Exposure tripled over SR0 results
- Priority analyses: WIMPs and CEvNS (^{8}B solar neutrinos)
- + multiple other science channels



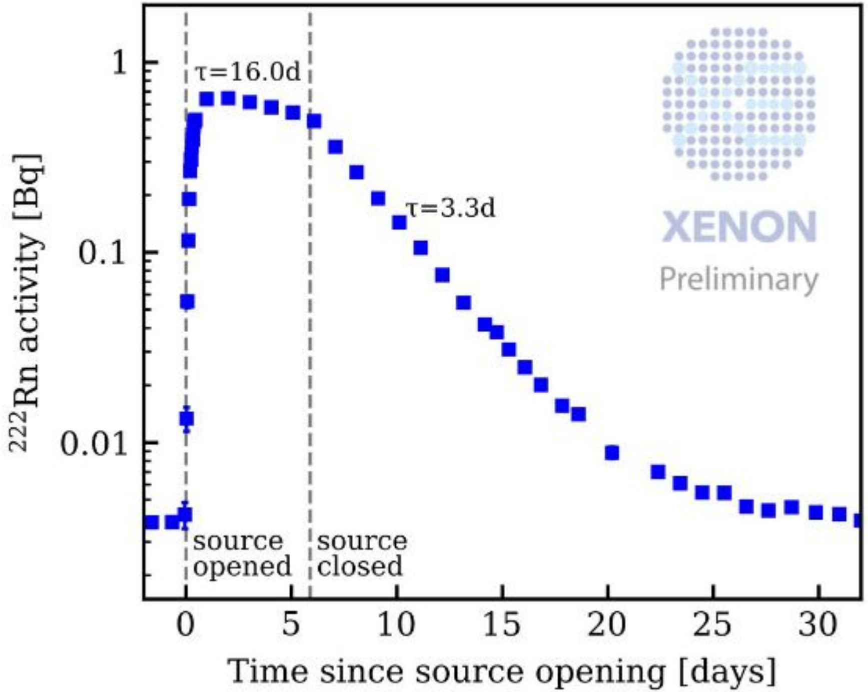
Reduction of ^{222}Rn activity from SR0 to SR1



World-leading ER background further reduced by a factor 2.2

Calibration with novel ^{222}Rn source

- Rn distillation system enables calibration with ^{222}Rn
- We can calibrate the shape of our main ER background!
- Removal of ^{222}Rn with Rn removal time of τ = 3.3 d



Future analyses on XENONnT and beyond

7 PhD theses!
no postdoc

XENONnT

- **Different dark matter models that can be probed:**
  - Low-E Nuclear Recoils (NR)
    - Low mass WIMPs and solar ^{8}B neutrinos (CEvNS) - **Q. Pellegrini PhD (LPNHE)**
  - Both (NR+ER)
    - S2-only WIMPs (<10GeV) - **Y. Pan (LPNHE)**
    - Migdal Effect and Bremsstrahlung - **L. Principe (SUBATECH-Melbourne)**
- **New physics can be scoped:**
  - Neutrinos
    - High-energy events - **M. Bazyk (SUBATECH-Melbourne)**
    - Neutrinoless double-beta decay - **J. Loizeau (SUBATECH)**
    - Neutrinos from Supernovae - **L. Daniel Garcia (LPNHE)**

DARWIN

- **O. Stanley (SUBATECH-Melbourne)**
  - Sub-GeV DM candidates exploiting the Midgal effect
  - Slow Control and PMT characterization in the XeLab R&T project

XENON FRANCE

Recommendations of CS2018

- Reinforce the groups

- Complete XENON1T analyses

- Installation and commissioning of ReStoX2
- TPC electrodes for XENONnT
- Data analysis of XENONnT

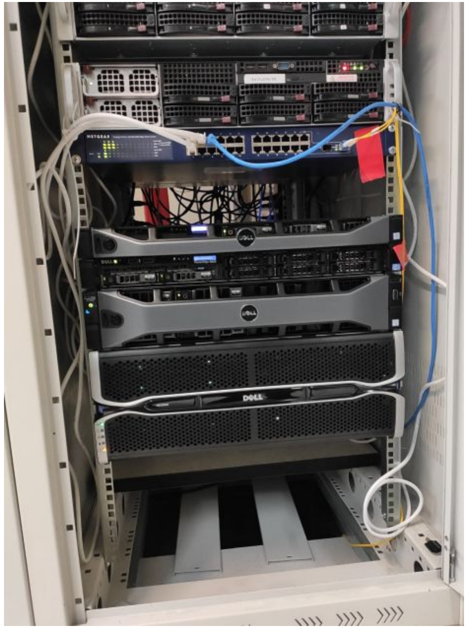
- Participate to DARWIN Project
- Participate in the design studies
- Clarify the role on this Project

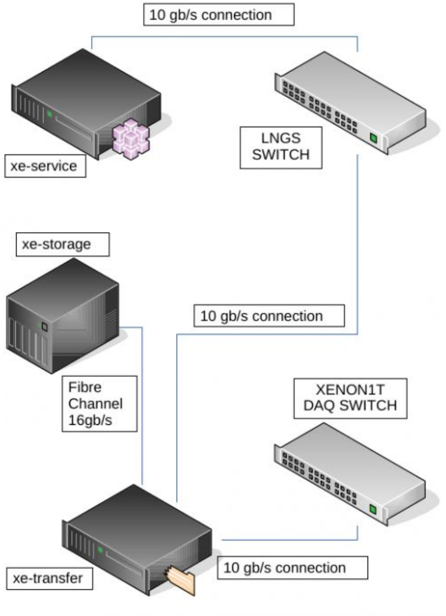
Plus . . .

- Leading computing for XENONnT
- Improving Geant4 simulations
- Data Quality Monitoring for XENONnT
- User Management Tools for XENON

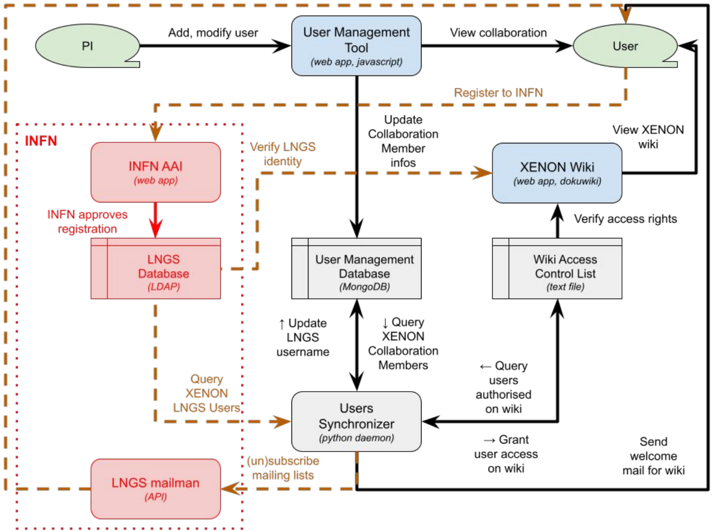
Leading Computing for XENONnT

LPNHE: Design, installation, commissioning and operations of the computing infrastructure at LNGS



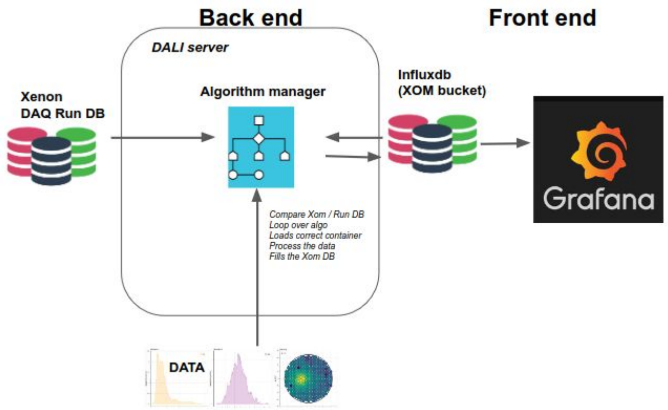


LPNHE: XENON Users Management Tools

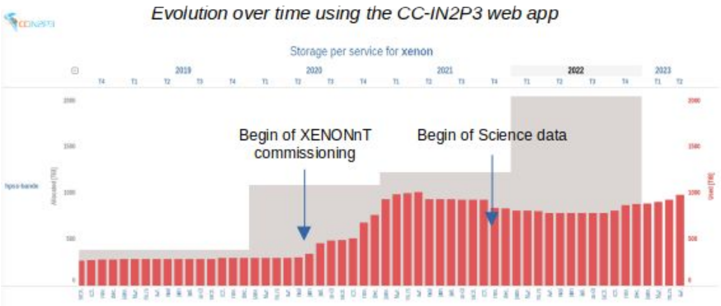


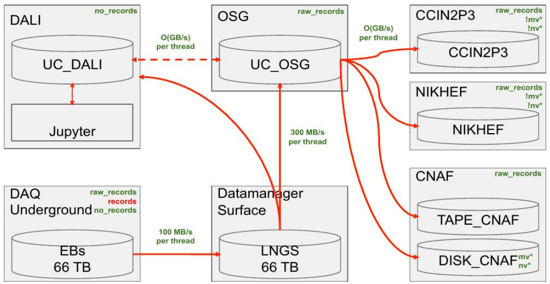
Leading Computing for XENONnT 2/2

LPNHE: Development of the XENONnT Offline Data Quality Monitoring Tool (XoM)
https://github.com/XENONnT/xom



LPNHE: Development of the data manager software for XENONnT (aDMIX). High usage of CC-IN2P3 (2.5PB of HPSS, 4M HS06.Hour)
https://github.com/XENONnT/admix/



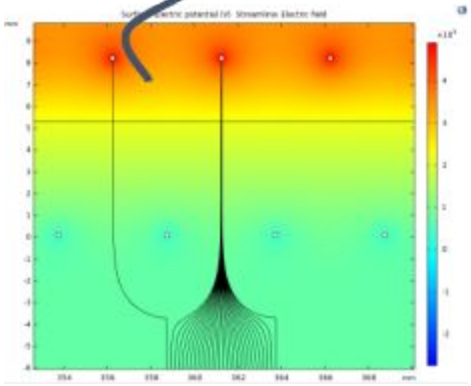


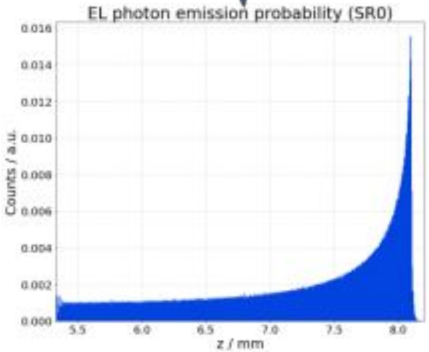
Monte Carlo Simulations

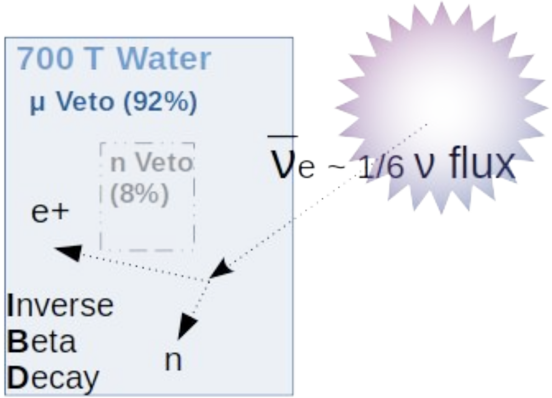
Improvement of the Geant4 simulation software

Accomplished goals:

- More realistic geometry and physics on **electrodes** (sagging and transverse wires on gate mesh and anode)
- Simulation of the **optical photons** produced by the electroluminescence of the electrons extracted in gas
- Data/MC comparison (scintillation process, **shadowing effect**, uniformity of the signal…)
- Improved simulations and digitization of **Neutron Veto** and **Muon Veto** data

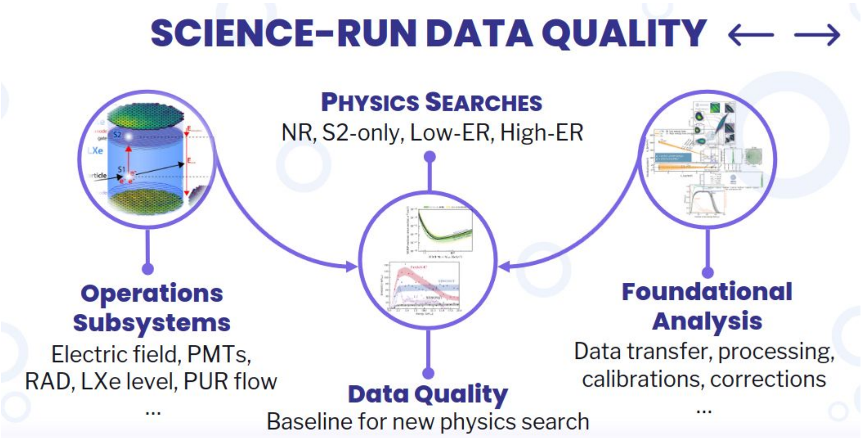






Responsibilities on operations of the detector

SUBATECH: Data Quality Manager (2023)



SUBATECH: Run Coordinator (2022)

One of the heaviest tasks:

- Handle the coordination with shifters
- Handle of the alarms
- Bridge between on-site operations and Collaboration Board
- Safety (especially during Covid time)

Both roles from postdocs (now leaving)

Recommendations of CS2018

- Reinforce the groups

- Complete XENON1T analyses

- Installation and commissioning of ReStoX2
- TPC electrodes for XENONnT
- Data analysis of XENONnT

- Participate to DARWIN Project
- Participate in the design studies
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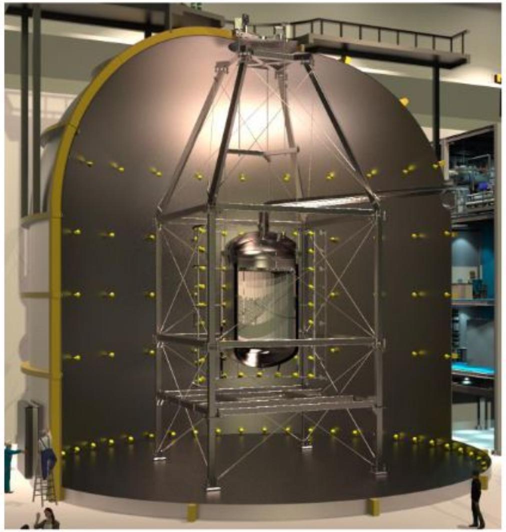
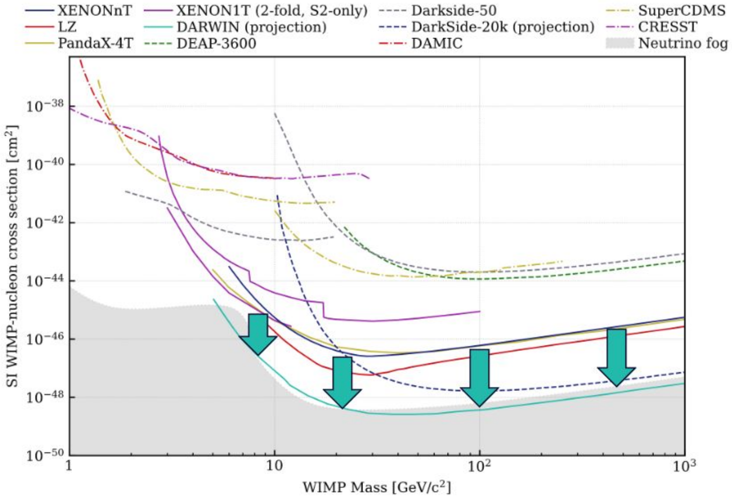
Plus . . .

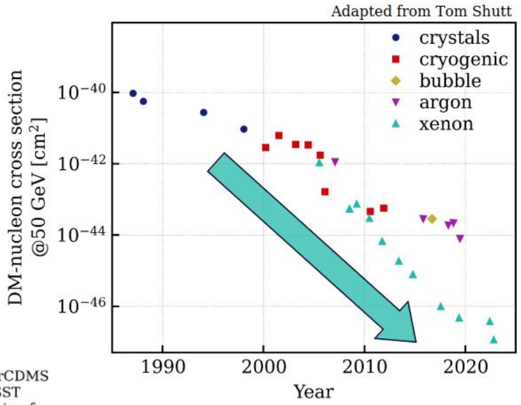
- Leading computing for XENONnT
- Improving Geant4 simulations
- Data Quality Monitoring for XENONnT
- User Management Tools for XENON

DARWIN Project - the baseline

- 2.6 m diameter x 2.6 m height
- 40 t LXe active target
- Two arrays of photosensors (1910 3” PMTs)
- 24 PTFE reflector walls
- Passive and active muon and neutron vetos
- Located at LNGS







Conceptual Design Report (CDR) ongoing

The XLZD Consortium

- Consortium merging DARWIN/XENON and LUX-ZEPLIN
- Common effort to build the next generation LXe TPC

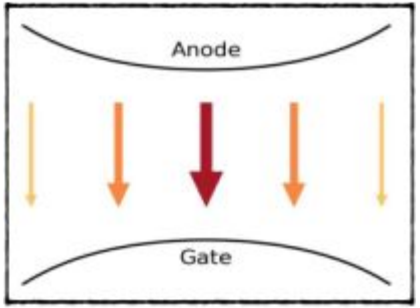
- First meeting online in 2021
- MoU signed July 2021
- General meetings in KIT 2022 and UCLA 2023
- Meeting regularly and active internal working groups and structure

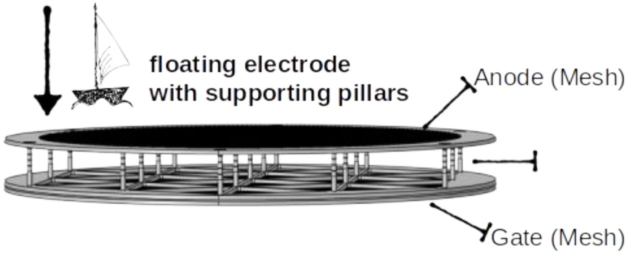
Community white paper: *J. Phys. G: Nucl. Part. Phys.* 50 013001 (2023)

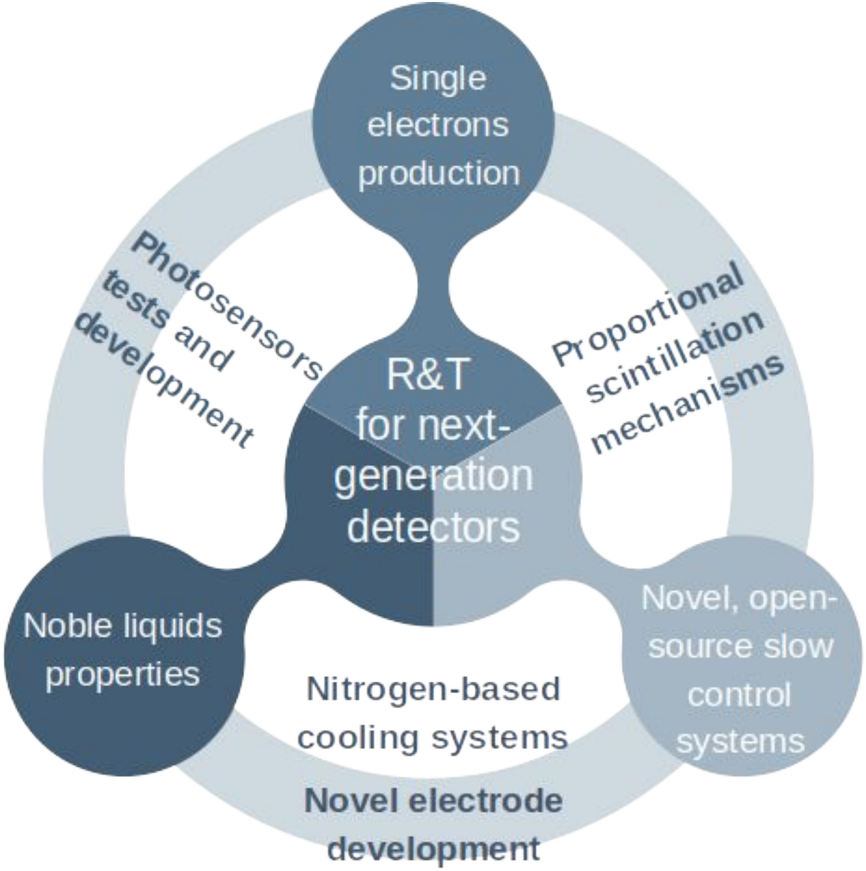
xlzd.org

With a larger Collaboration, we are more ambitious and plan for a long roadmap to complete DARWIN. We approach to an experiment whose cost is close to 200M€

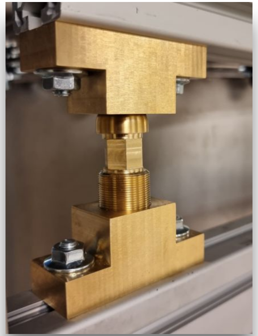
The IN2P3 XeLab R&T Project







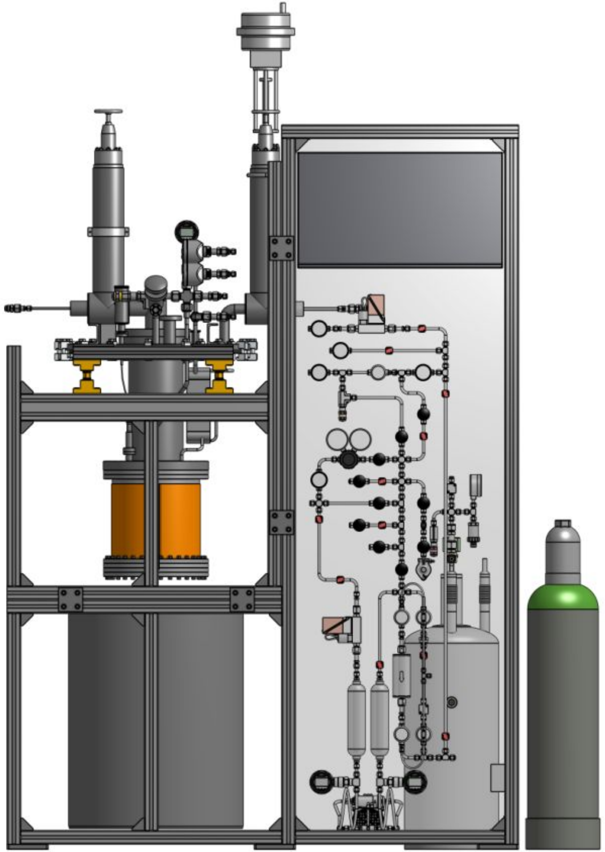
The R&D in France: XeLab and its cryogenic system

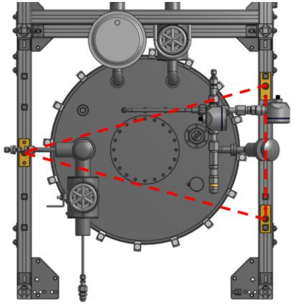


R&D
Levelling system

R&D
Three-way heat exchanger

R&D
Cryostat LN2-cooling with copper belt



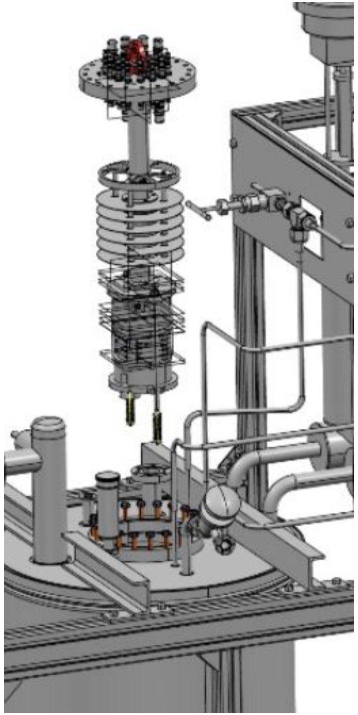


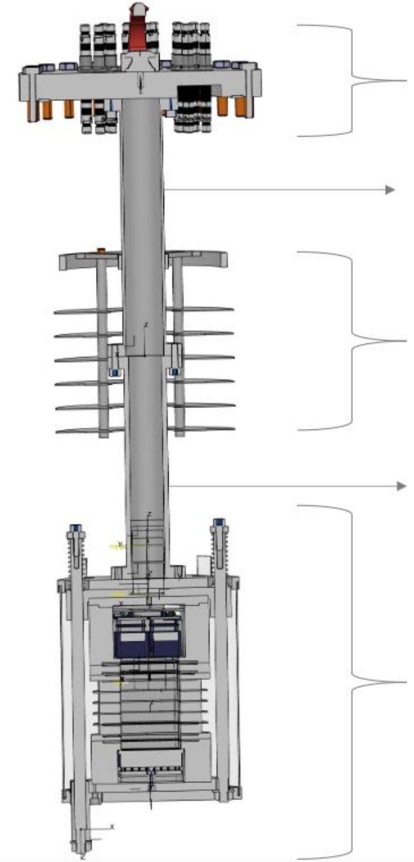
Three levelling systems to define a plane

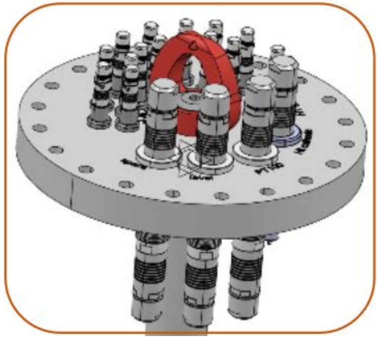
R&D
Storage and recovery system

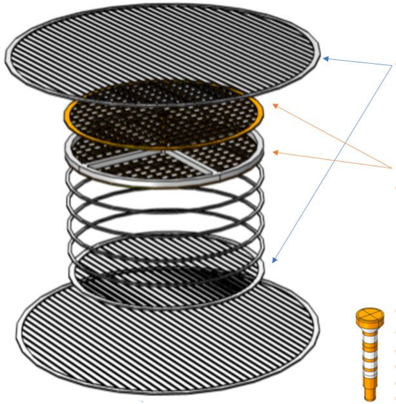
R&D
Slow Control with RevPI

The R&D in France: XeLab and its TPC









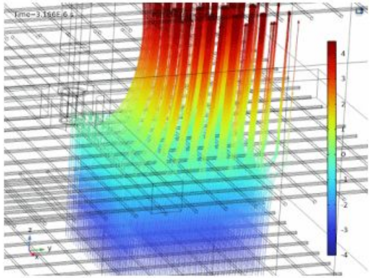
The R&D in France: XeLab and its TPC

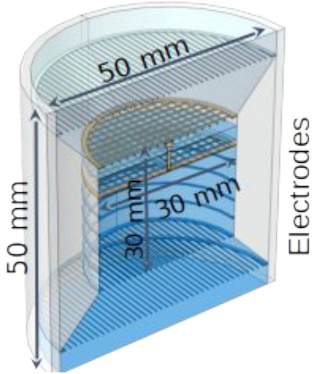
R&D
Candidates for the pillar material:

- **Fe2O3/YSZ ceramic [1]**
- **High-Density Polyethylene (HDPE) [2]**
- Polytetrafluoroethylene (PTFE)
- Ultra-high molecular weight polyethylene (UHMW)
- Polyether ether ketone (PEEK)
- Polyoxymethylene (POM)

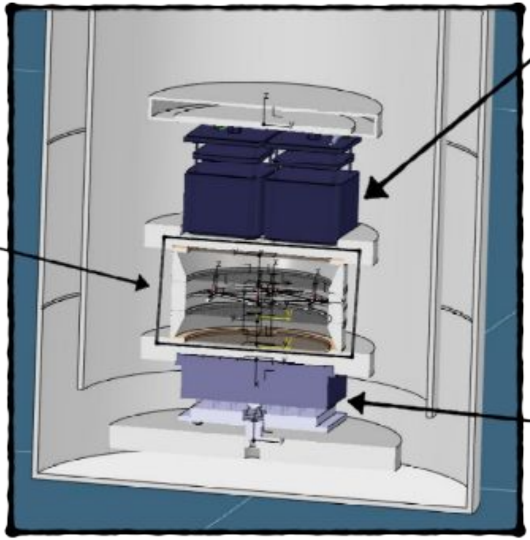
[1]https://arxiv.org/abs/2305.12899
[2]https://iopscience.iop.org/article/10.1088/1748-0221/13/10/P10002

Full electron drift in LXe simulated with COMSOL Multiphysics (IN2P3 licence)





Electrostatic and further mechanic simulation with COMSOL and Ansys



Hamamatsu R8520-406
Effective area: 20.5 x 20.5 mm

Hamamatsu R12699-406-M4
2 x 2 multianode
Effective area: 48.5 x 48.5 mm

New PMT from Hamamatsu, candidate for DARWIN and other future 3rd generation detectors
Will be tested in Collaboration with Melbourne (PhD O. Stanley)

XeLab in the ECFA roadmap

ECFA Detector R&D Roadmap: TF2 Liquid Detectors → https://indico.cern.ch/event/1214404/

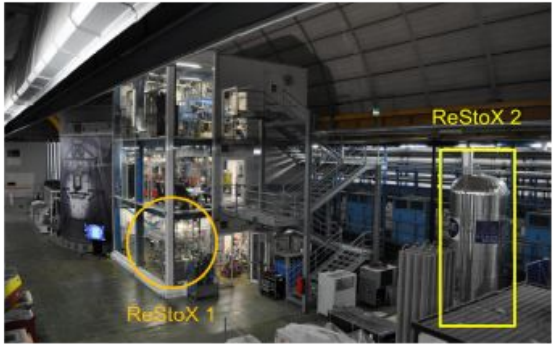
XeLab

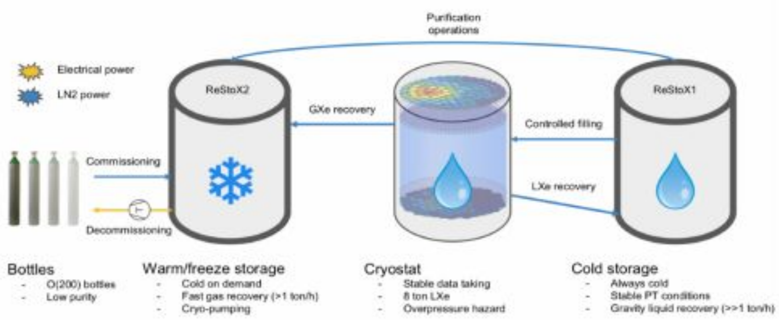
WP 1: Charge Readout	WP 2: Light Readout	WP 3: Target Properties	WP4: Scaling-up challenges
1.1: Pixels	2.1: Increased sensor QE	3.1: Doping & isotope loading	4.1: Radiopurity & bkg mitigation
1.2: Electroluminescence & charge amplification	2.2: WLS & increasing light collection	3.2: Purification	4.2: Detector & target procurement/production
1.3: Dual (charge + light)	2.3: Improved sensors for LS/Water	3.3: Light emission & transport	4.3 Large-area readout
1.4: Charge to light		3.4: Microphysics & characterization	4.4: Material properties
1.5: Ion detection			

- **Berkeley Lab (US)**, Yuan Mei
- **LIP-Coimbra (Portugal)**, Vitaly Chepel
- **LPNHE (France)**, Luca Scotto Lavina
- **NIKHEF (Netherlands)**, Auke Pieter Colijn
- **UC Riverside (US)**, Shawn Westerdale
- **UC San Diego (US)**, Kaixuan Ni
- **UC Santa Barbara (US)**, David Caratelli
- **University of Freiburg (Germany)**, Fabian Kuger
- **University of Mainz (Germany)**, Alexander Deisting
- **Weizman Institute of Science (Israel)**, Amos Breskin

Design of a new storage system → "ReStoX3"

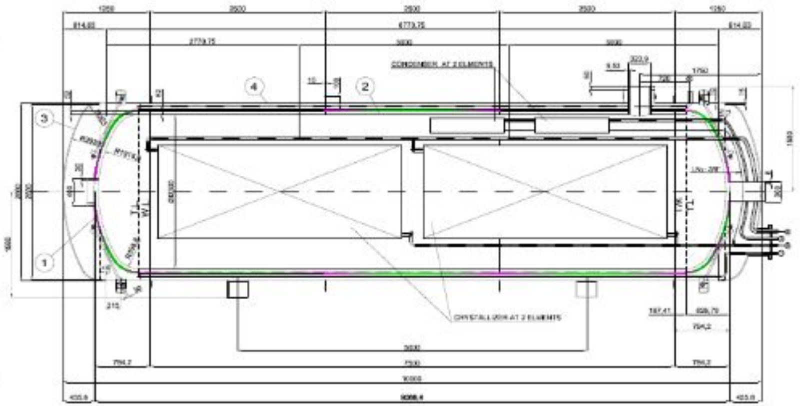
XENON1T/nT





Two storage systems just for historical reasons

Next Generation



The performances of ReStoX1 and 2 in a single system

Design study done thanks to the *Étoile Montante* Project (J. Masbou) funded by Pays de la Loire

R&D in Collaboration with Germany: DMLab

CNRS / Helmholtz Foundation (DMLab):

- DARWIN identified as the only DDM detector for WIMPs
- https://dmlab.in2p3.fr/
- Julien Masbou as PI for DARWIN

Three axes of common work for DARWIN:

- Liquid xenon technology
- Electrodes
- Computing

R&D in Collaboration with Australia

XEnon Time Projection Chambers : **R&D** for Future Generation Experiments,
searching for **D**ark **M**atter and investigating the nature of neutrinos (**ν**)

PI : Sara Diglio (CR, SUBATECH)

- International Emergin Action (IEA) SUBATECH – Melbourne : 2021 – 2023
- 4 Joints PhD (cotutelle) SUBATECH – Melbourne
  - 1 IMT Atlantique – Melbourne (end jan 2025) : *High Energy analysis with XENONnT and future LXe experiments*
  - 2 CNRS – Melbourne (end fall 2025): *Search for low mass Dark Matter via the Migdal effect in XENONnT and future LXe experiments*
  - 1 AUFRANDE program (end fall 2026) : *Alternative-to-WIMPs Dark Matter searches with XENONnT and future LXe experiments*

2024 – 2028 : Willing to extend the collaboration
--> Submitted International Research Project proposal

Conclusions

XENON Project is healthier than ever:

- XENON1T physics production completed
- XENONnT: first ER and NR papers. Soon, a rich series of studies (even more than XENON1T)
- The required manpower to lead the analysis efforts in France is a critical point

DARWIN is a long-term project:

- Ultimate dark matter search and astroparticle observatory. Community enlarged with XLZD
- Expected to start data taking not before 2032, but there will be a multi-stage strategy before
- Invest on liquid xenon technology (cooling systems, storage and recovery) and computing

XeLab is an R&T project funded by IN2P3 meant to improve next-generation detectors:

- R&T on: liquid xenon technology (LN2 cooling systems, storage and recovery), electrodes, slow control
- Aimed growth of manpower and regular funding for next three years

Thanks for your attention

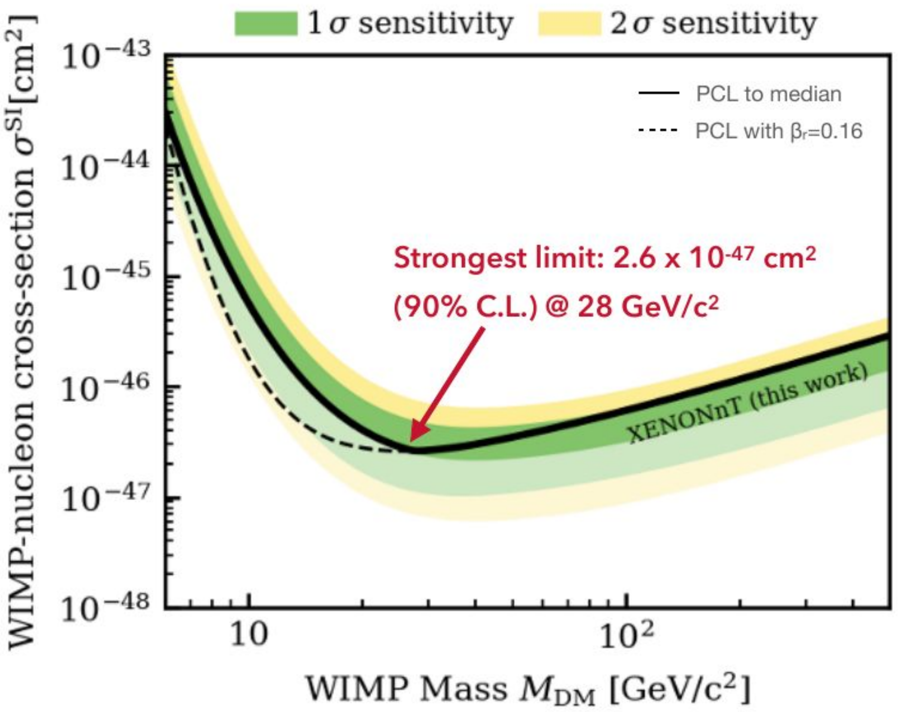
If you read here, you hadn’t enough

Timeline for current and next-generation experiments

Année	2023	2024	2025	2026	2027	2028	2029	2030	2031
Projects									
XENON									
LZ					?				
PandaX xT		?				?			
DARWIN/XLZD 0									
DARWIN/XLZD									
R&D									
XeLab									

Power-Constrained Limit

- **Community had agreed on prescriptions for Power-Constrained Limit (PCL)** [1]
  - ➡ **Wrong prescription for PCL critical threshold β_r** in [1] (β_r = 0.16), defined on discovery power instead of rejection power w.r.t. [2]
  - ➡ Choice of minimum rejection power of 50% (β_r = 0.50) , i.e. **constrain limit to median of sensitivity band**
  - ➡ **Conservative choice** before the community re-discuss the topic and agree on a specific value

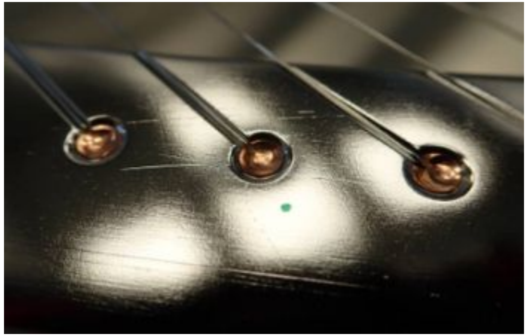


[1] D. Baxter et al, "Recommended conventions for reporting results from direct dark matter searches" [EPJC 81 (2021)]
[2] G. Cowan, K. Crammer, E. Gross, O. Vitells, "Power-Constrained Limits". arxiv:1105.3166

Contribution of XENONnT on electrodes

Design and construction from LAL (-> IJCLab)

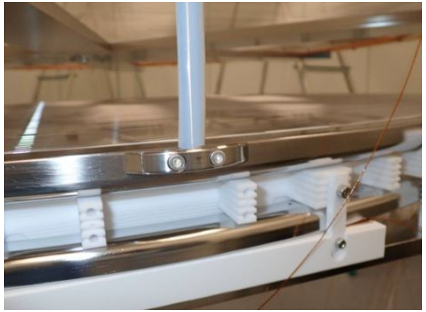
Wires fixing



Cold tests in LN2

Sid (LPNHE) during the procedure of passivation of electrodes

High-voltage tests



Great know-how on electrodes, unfortunately lost because of departure of IJCLab

Science goals

Dark matter

- WIMP-search
  - Spin-independent
  - Spin-dependent
- Sub-GeV
- Dark photons
- Axion-like particles

JCAP 10, 016 (2015)

Solar neutrinos

- ^{8}B spectrum
- pp neutrinos detection
- Solar axions

Eur. Phys. J. C 80, 12 (2020)
Phys.Rev.D 106 (2022)

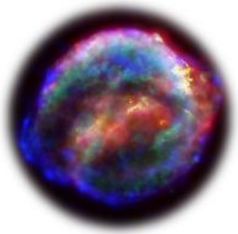
Atmospheric neutrinos

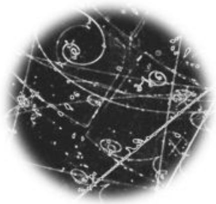
PRD 104 (2021)

Supernova neutrinos

- Actively communicate with SNEWS
- Multi-messenger in DM experiments

PRD 94, 103009 (2016)
Phys.Rev.D 105 (2022)





Neutrino properties

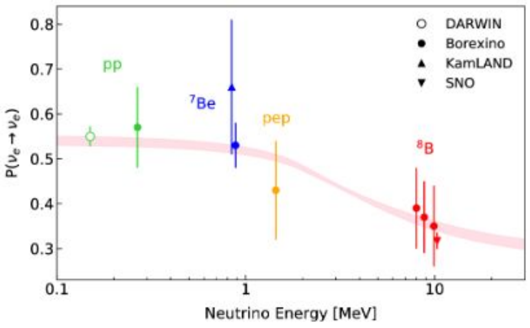
- Double beta decay of ^{136}Xe
- Double-electron capture in ^{124}Xe
- Neutrino magnetic moment

Eur. Phys. J. C 80, 9 (2020)

Neutrino goals

Solar neutrinos searches with electron scattering

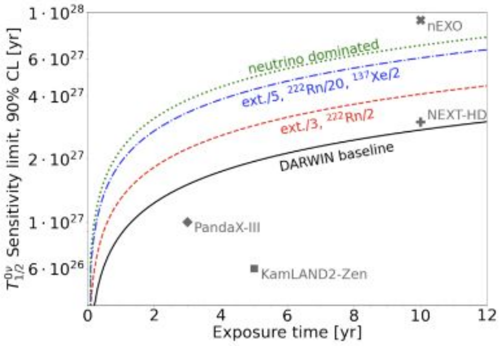
- Measurement of pp, ^{7}Be, ^{13}N, ^{15}O and pep flux
- Constrain the weak mixing angle
- Distinguish high and low metallicity solar models



J. Aalbers et al. (DARWIN Collaboration) Eur. Phys. J. C 80, 1133, 2020

Neutrinoless double beta decay of ^{136}Xe

- Probe the Dirac/Majorana nature of the neutrino
- $Q_{\beta\beta} = 2458\ keV$
- Sensitivity: $T_{1/2}^{0\nu} = 3.0 \times 10^{27}\ yr\ (90\%\ C.L.)$ after 10 years of data taking



Eur. Phys. J. C 80, 808 (2020)

CEvNS

- Measurement of ^{8}B solar neutrino flux
- Measurement of atmospheric neutrinos
- Multi-messenger astrophysics via SN neutrinos