First results of XENONnT on dark matter search

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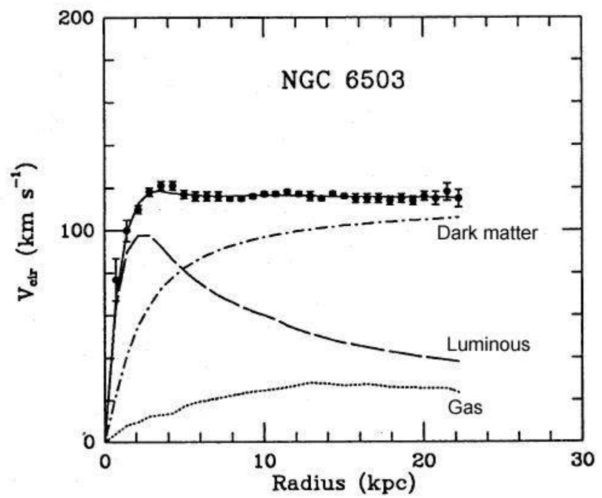
16/10/2023

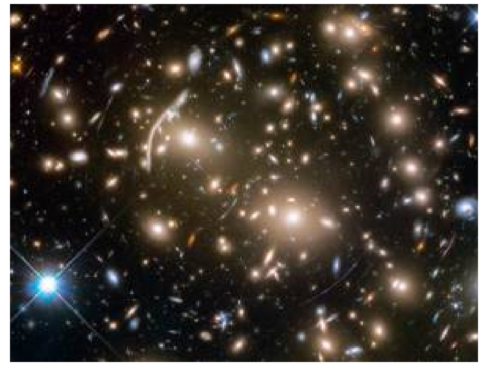
Seminar at CPPM, Marseille

XENON

Hints for a dark component of the Universe



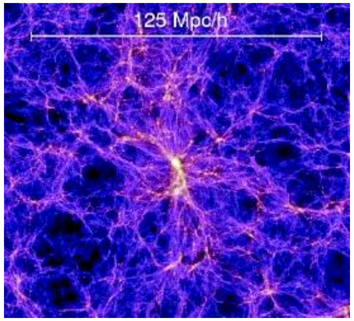
Flat velocity of stars
beyond visible disk size
implies the existence
of an unseen mass distribution



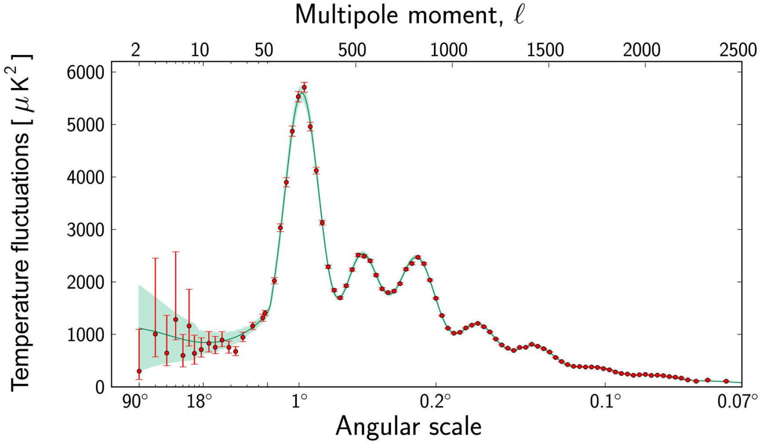
Unknown Matter
responsible of
gravitational lensing

Existence
of **dwarf galaxies**
can be understood
if there is enough
mass around
which is not seen

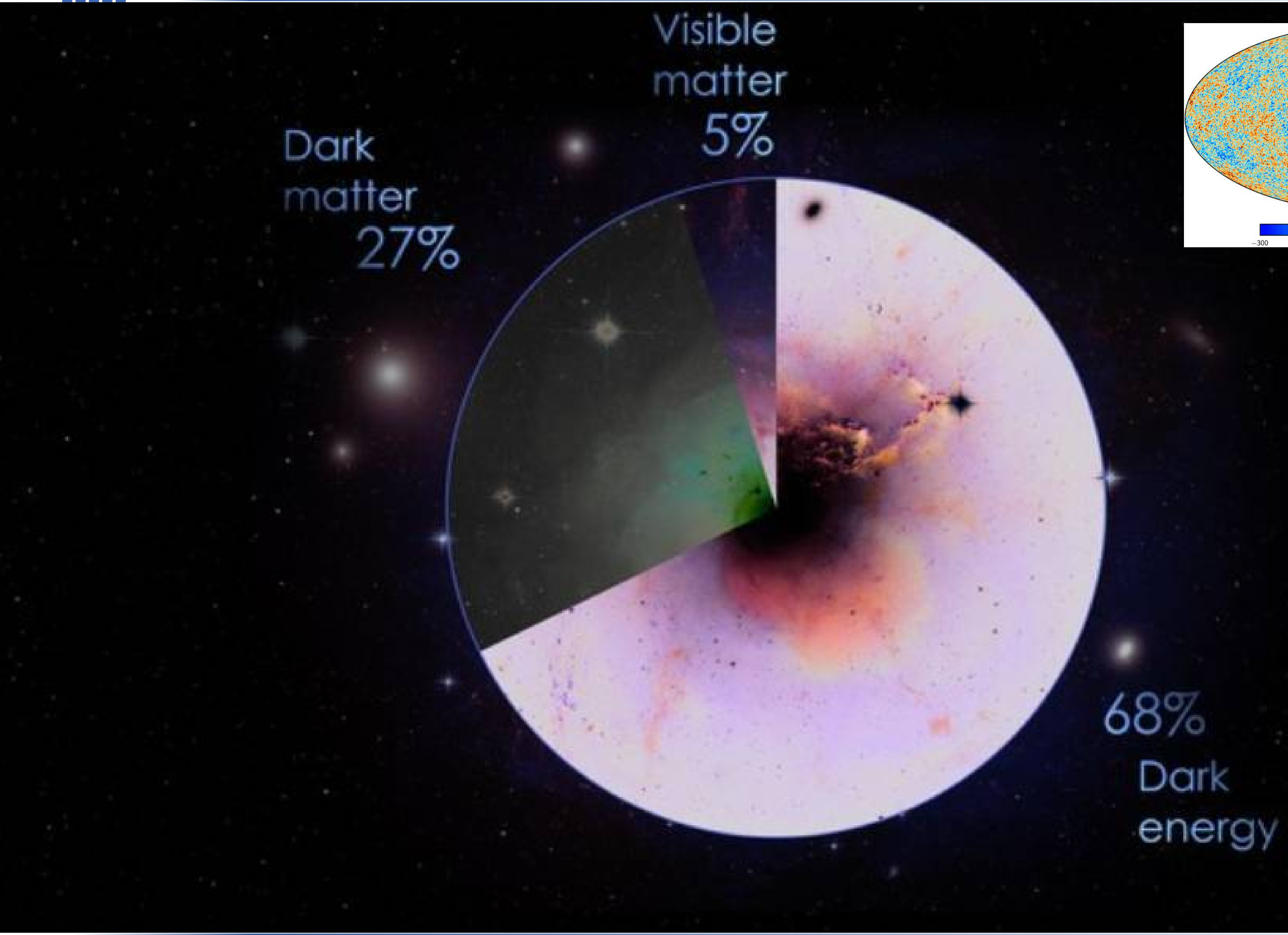
Cold dark matter
to be consistent
with formation of
large scale structures

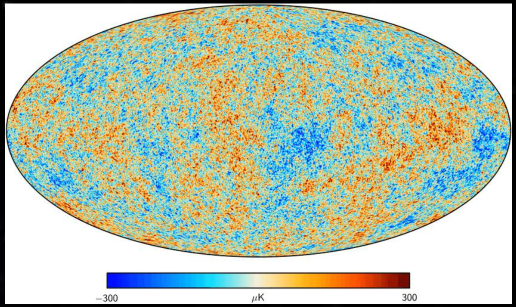


Anisotropies in CMB
allow a measurement
of dark matter density



What the Universe is made of ?



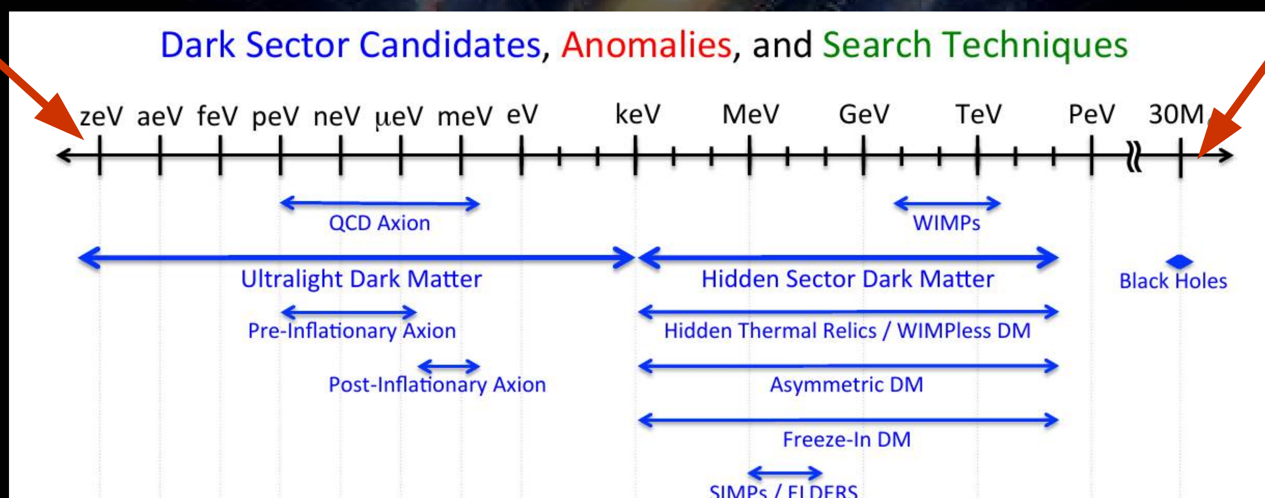


ΛCDM

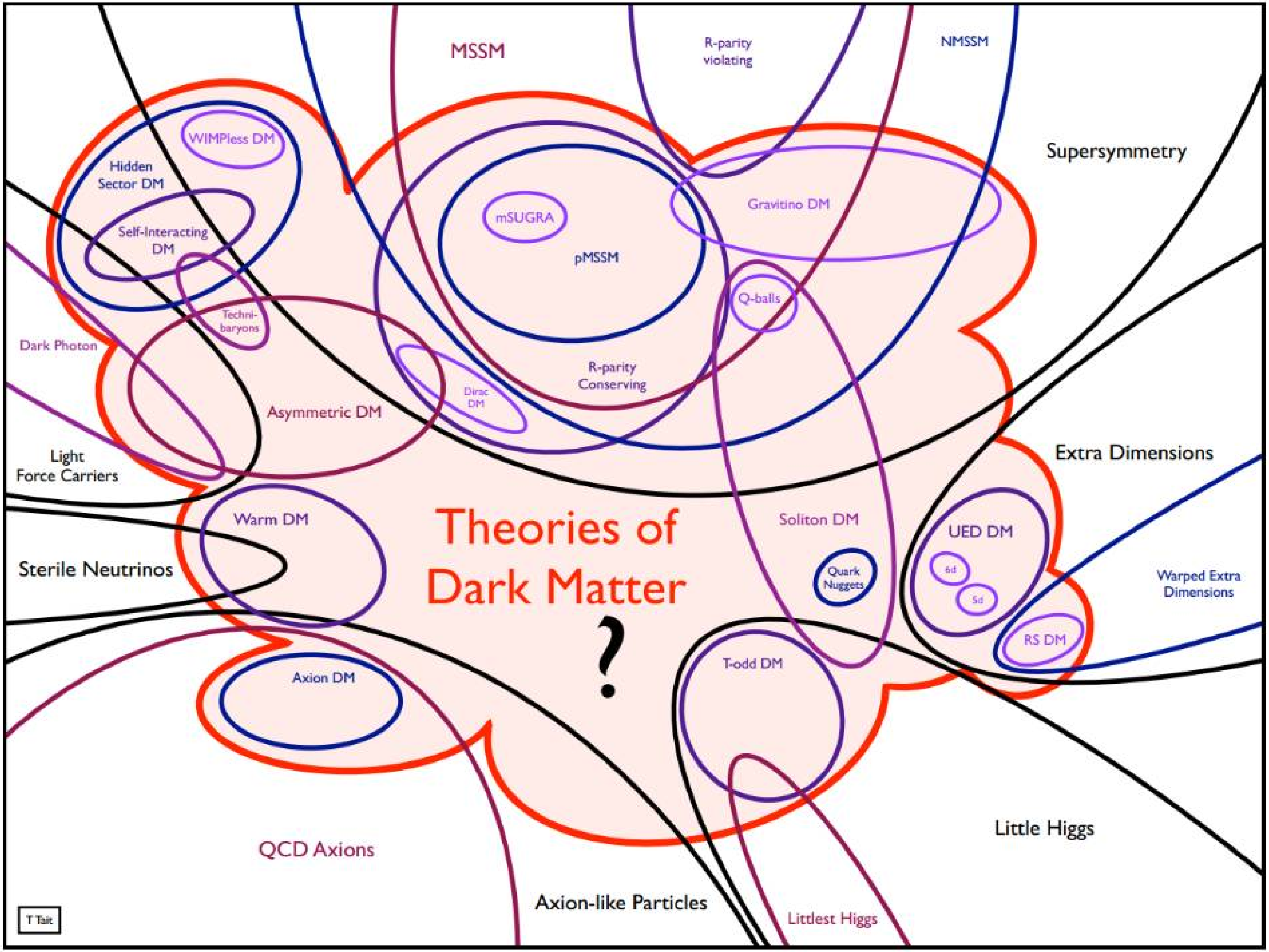
from 10^{-22} to 10^{+67} eV

Forbidden to be all of DM as de Broglie wavelength would be too large to fit inside dwarf galaxies

From "wave-like" ultralight boson, axion… **… to primordial black holes**



Plenty of theories that could explain Dark Matter

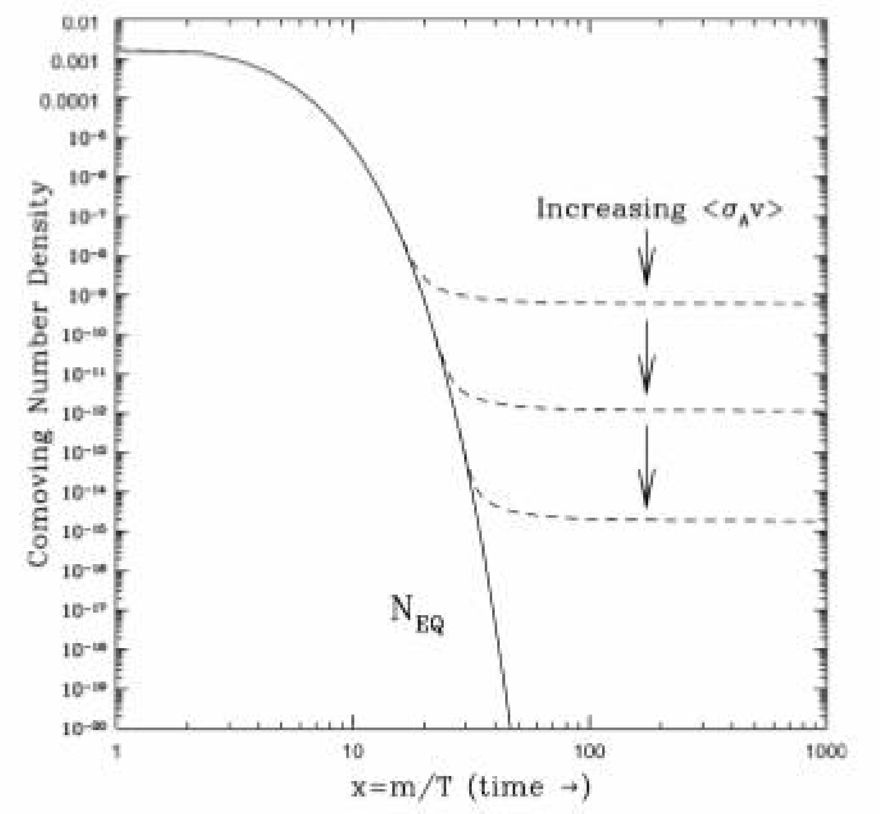


The abundance of a particle is related to its cross section: $\Omega_{DM} \sim < \sigma_A v >^{-1}$

The Weakly Interacting Massive Particle (WIMP) is the most popular candidate:

- weak scale cross section
- non-relativistic particle
- mass 100 GeV – 1 TeV

$$\frac{dn_\chi}{dt} = -\langle \sigma_a v \rangle \left[(n_\chi)^2 - (n_\chi^{eq})^2 \right] - 3Hn_\chi$$



Dark Matter halo

Dark Matter is required to be:

- Neutral
- Non-baryonic → weakly interacting
- Cold (non-relativistic) → large scale structure
- New Particle → neutralino, Kaluza-Klein particle, axion, gravitino …

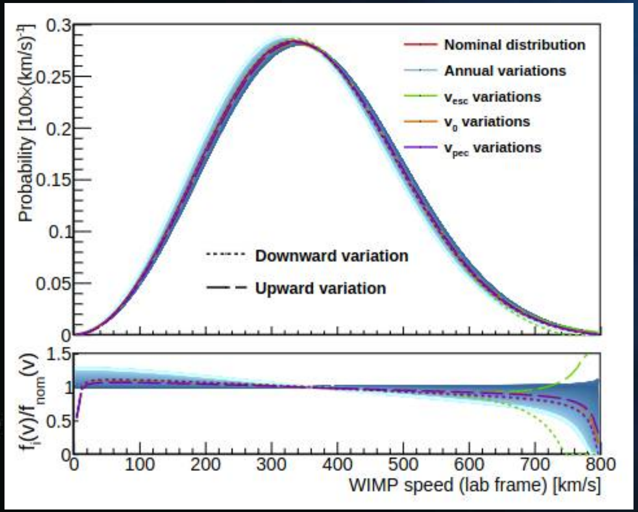
Its local density should be:

$\rho_\chi = 0.3 \pm 0.1$ GeV/cm^3

(J. Bovy and S. Tramaine, Astrophys.J. 756 (2012) 89)

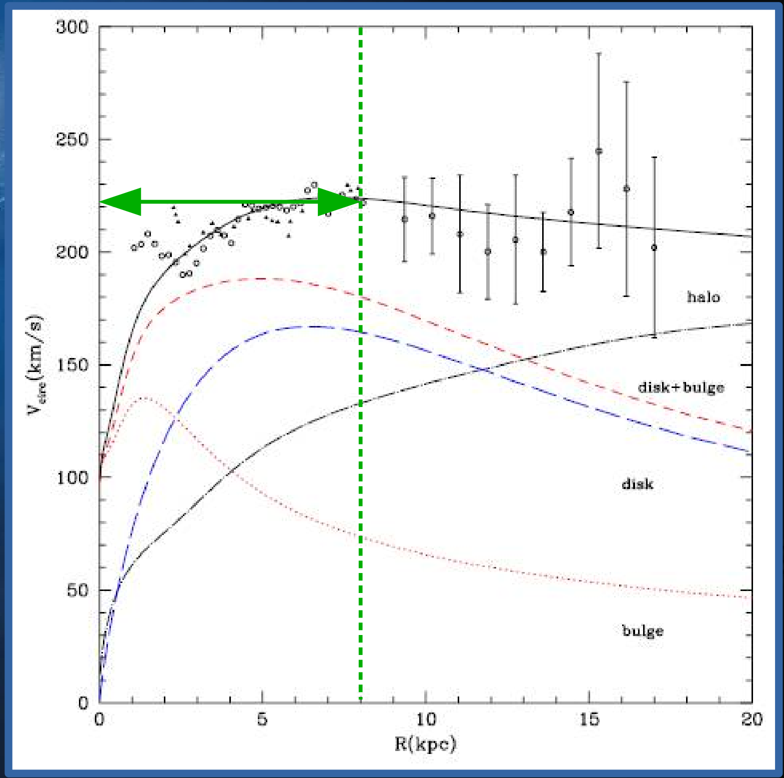
Its speed distribution should be:

Baxter et al., Eur. Phys. J. C 81, 907 (2021)



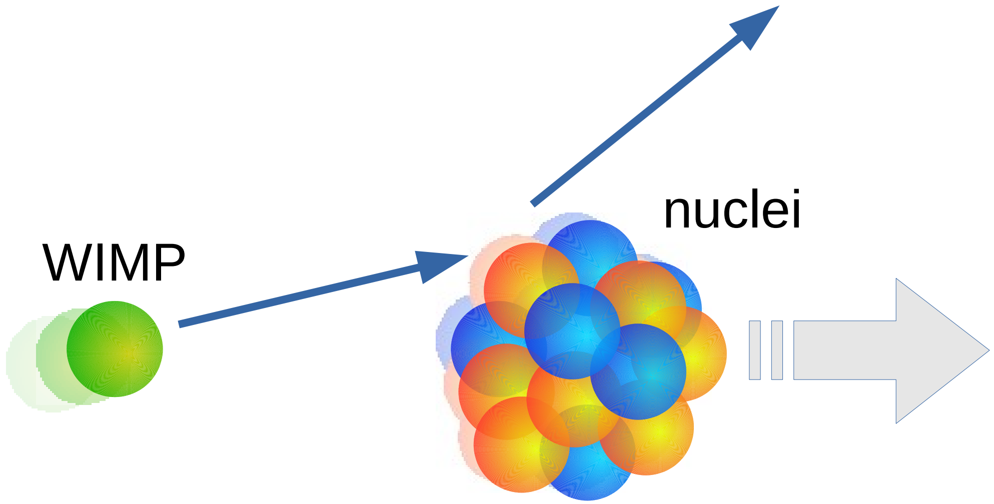
8 kpc

Sun



The direct detection principle

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils



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

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

For example, by assuming :

Small energy recoil !

- WIMP mass: M_χ = 100 GeV/c^2
- WIMP velocity: v_0 = 220 km/s

we have the average recoil energy: $E_0 = \frac{1}{2} M_\chi v_0^2 \sim$ 30 keV

Differential rate

WIMP-nucleus cross section (model dependent, spin)

0.3 GeV/cm[3]

Nuclear form factor (depends on atomic nuclei)

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

Small event rate !

WIMP-nucleus reduced mass

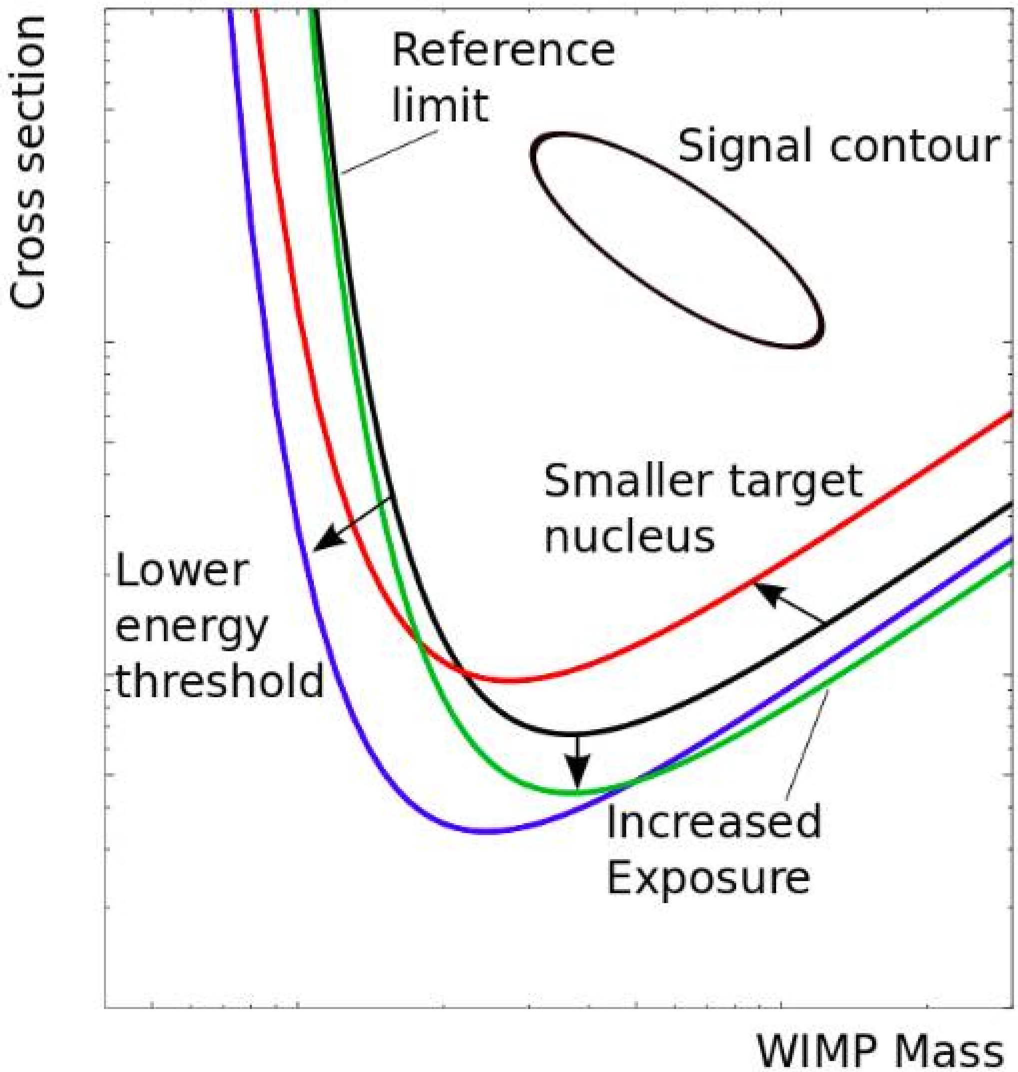
$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

Motion dynamics

- Maxwellian distribution for DM velocity is assumed
- v = velocity on target
- v_{min} = minimum required to produce recoil energy
- v_{max} = galactic escape velocity (~ 500 – 650 km/s)

Result of a direct detection experiment

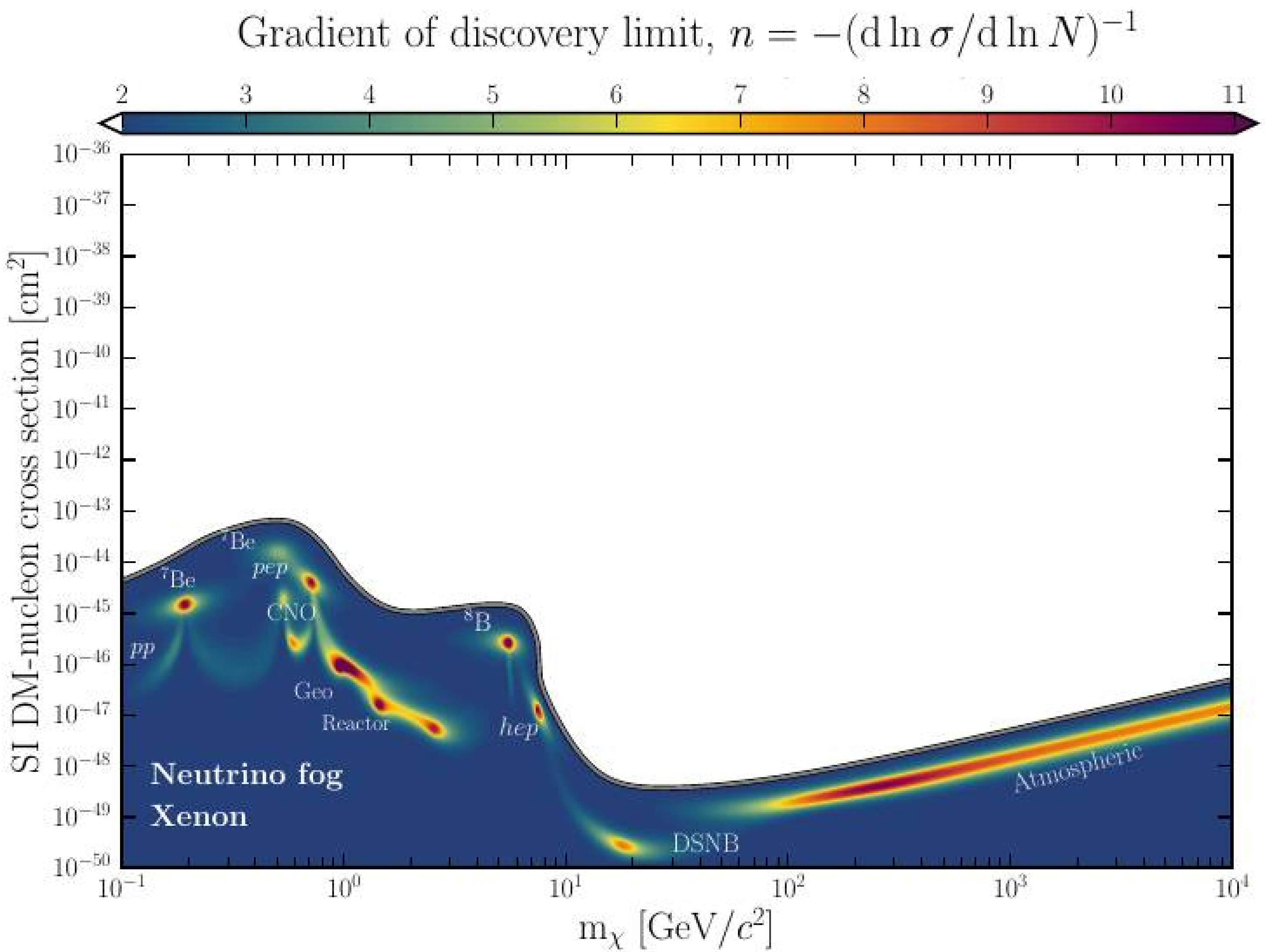
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



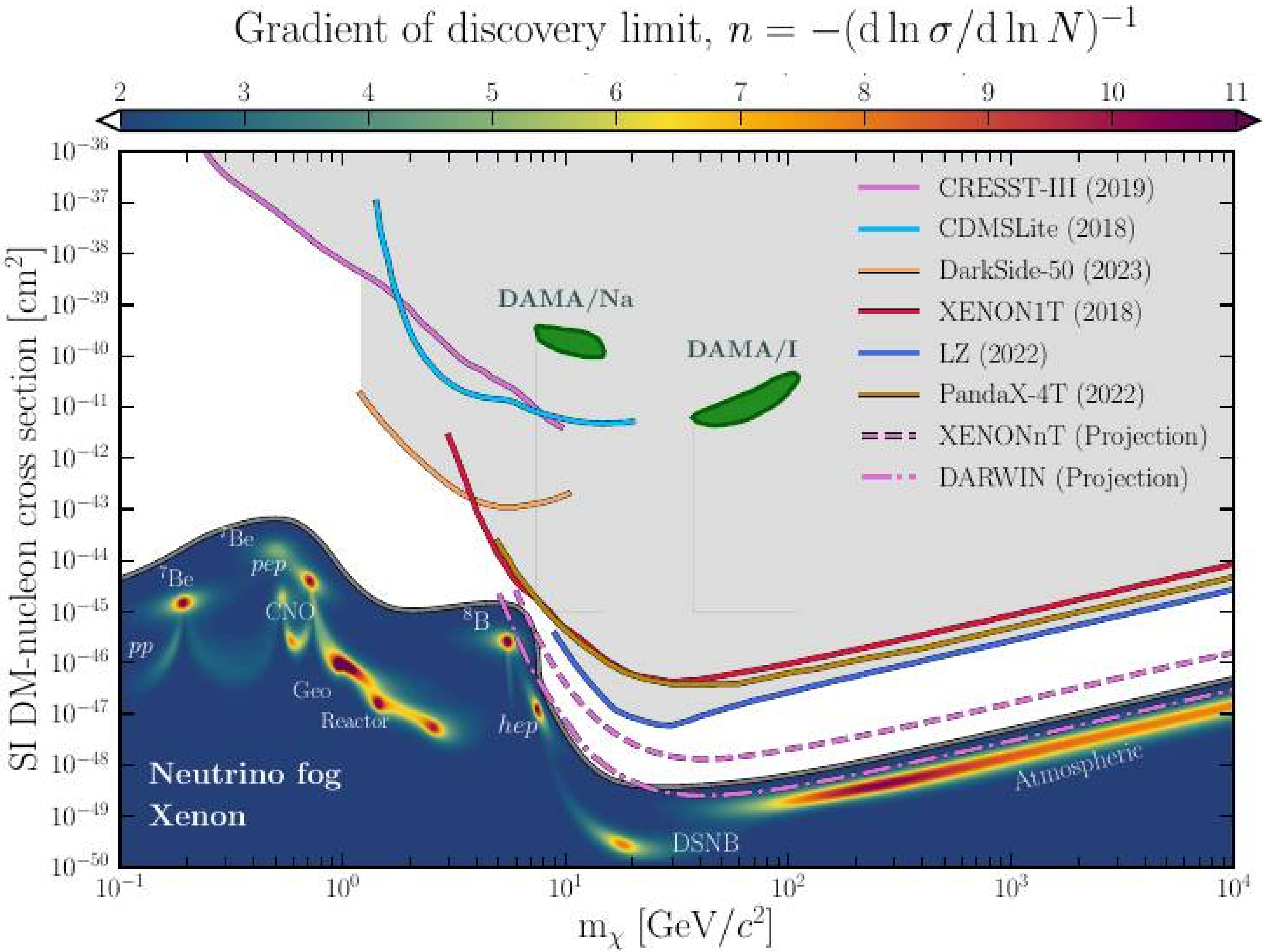
Positive signal
- Region in σ_χ versus m_χ

Zero signal
- Exclusion of a parameter region
  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters = m × t

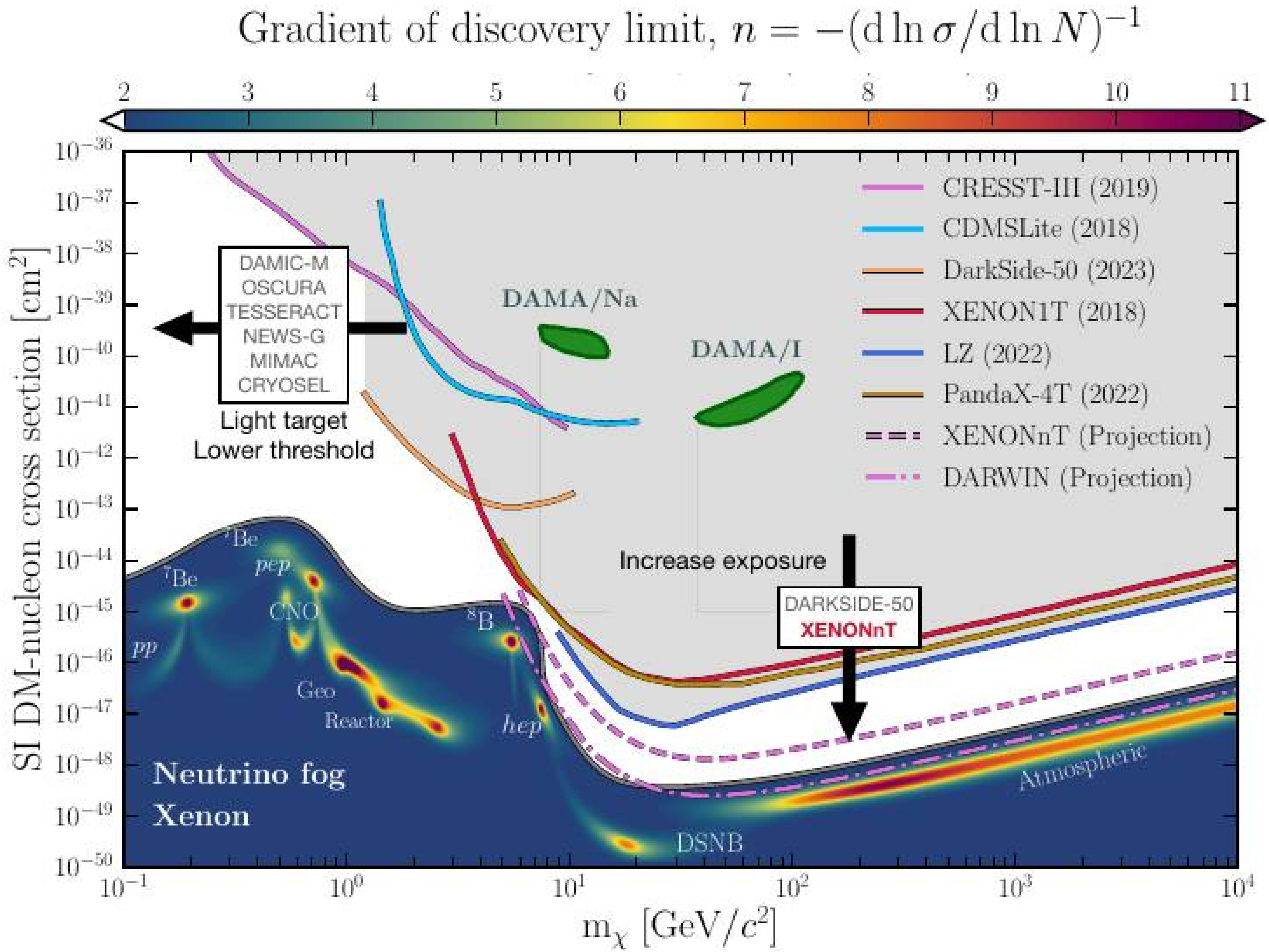
Playground and neutrino fog



Current scenario



Still two regions to explore



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**

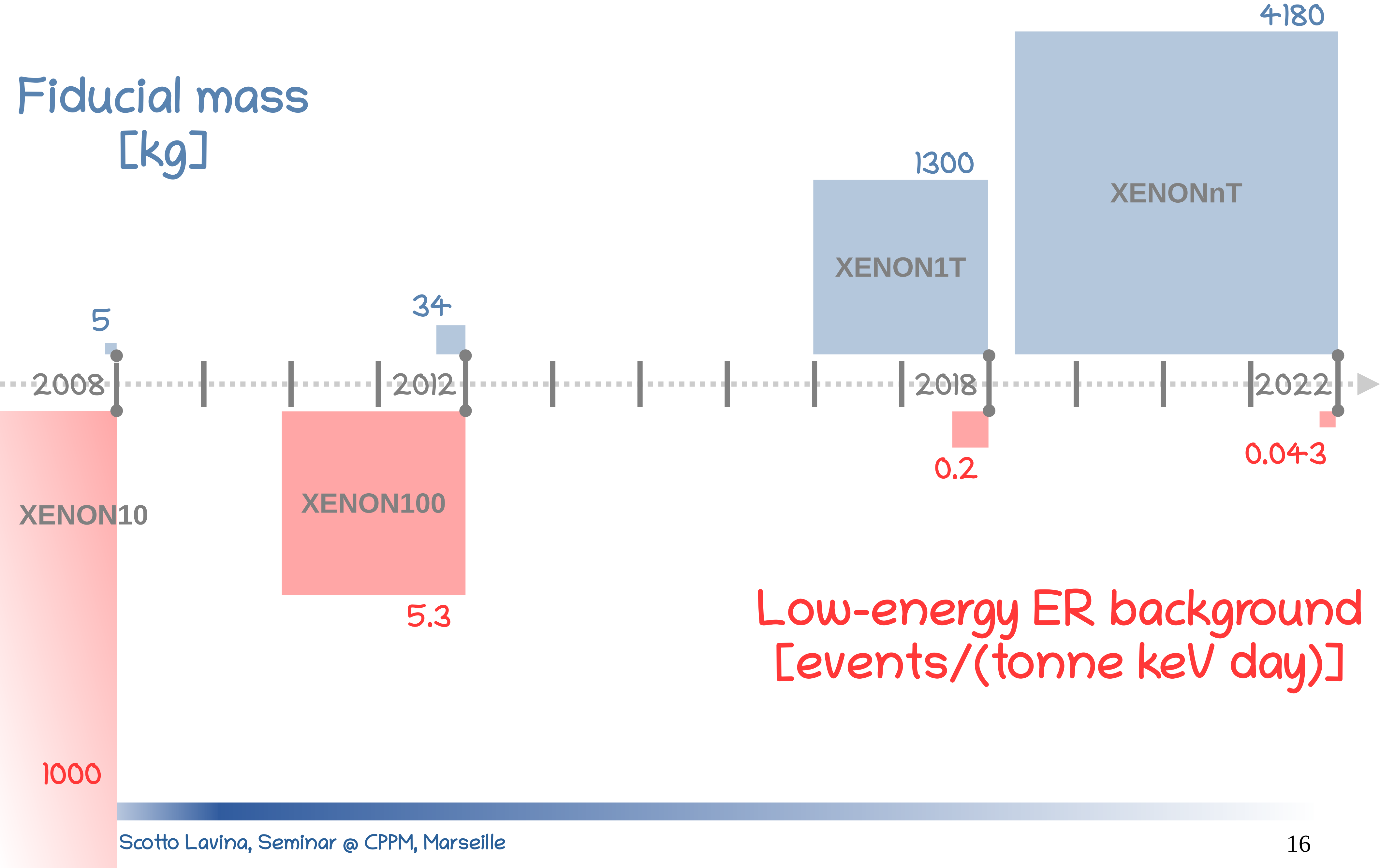
Subatech · Coimbra · LPNHE · Torino · Bologna · L'Aquila · LNGS · Napoli · Weizmann · NYUAD

The XENON Project

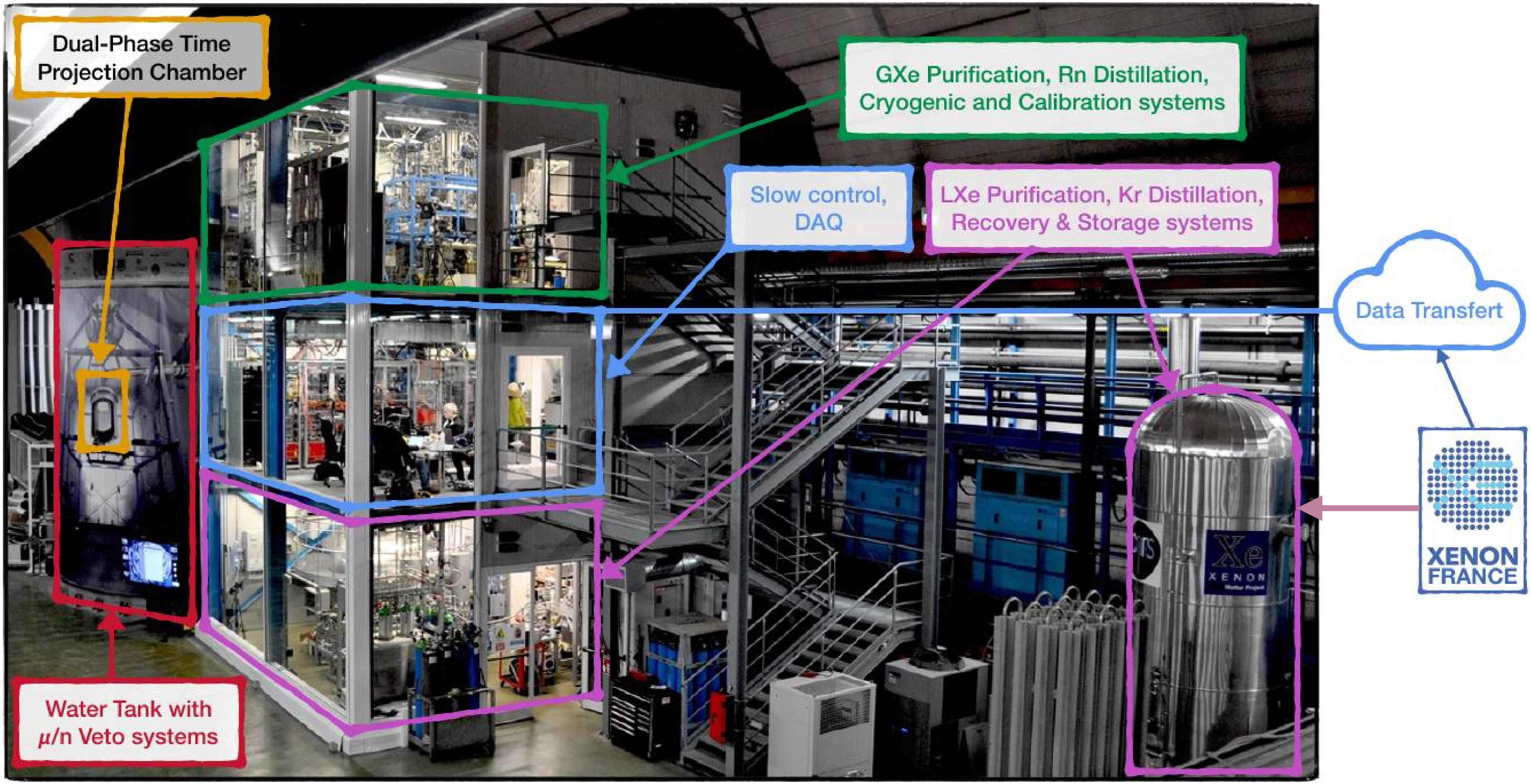
- **Fourth generation of XENON experiment**
  - ➡ Based on the same detection technology: **dual-phase Time Projection Chamber**
  - ➡ Already **demonstrated the scalability** of this technology
- Operating at the **INFN - Laboratori Nazionali del Gran Sasso** (LNGS)
  - ➡ **Underground laboratory with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

Bigger and more silent



The XENONnT detector



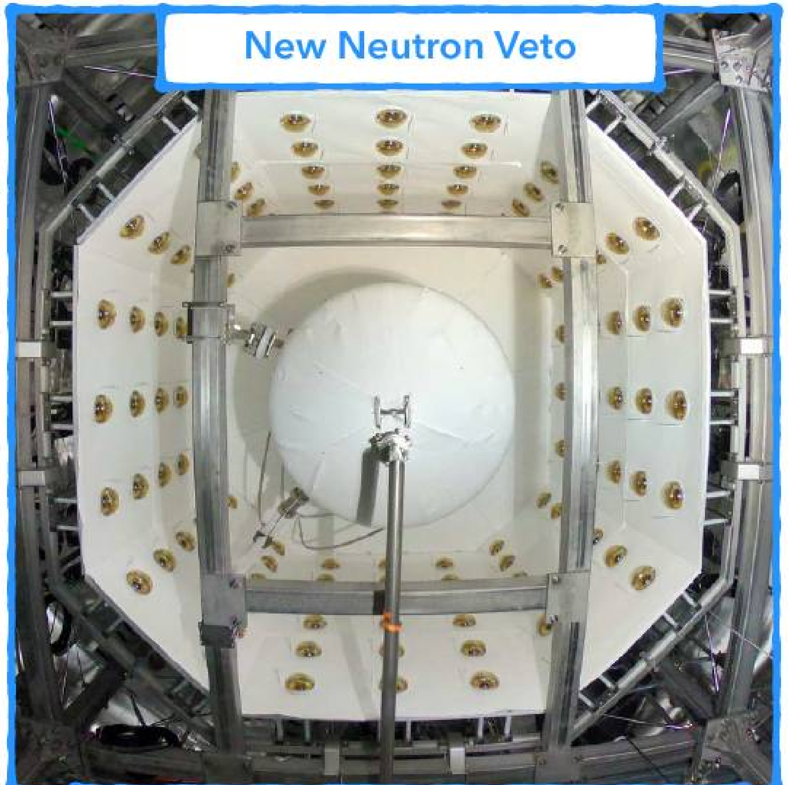
Improvements with respect to XENON1T

New Radon Distillation Column

New Liquid Xenon Purification

Increased purity > 10 ms e- lifetime

New Neutron Veto



87 % (~60 %) projected neutron tagging efficiency with Gd-loaded (pure) water

New fast recovery system to handle our larger xenon inventory

ReStoX 2

Improvements with respect to XENONnT

New Larger TPC

- x3 larger volume w.r.t. XENON1T

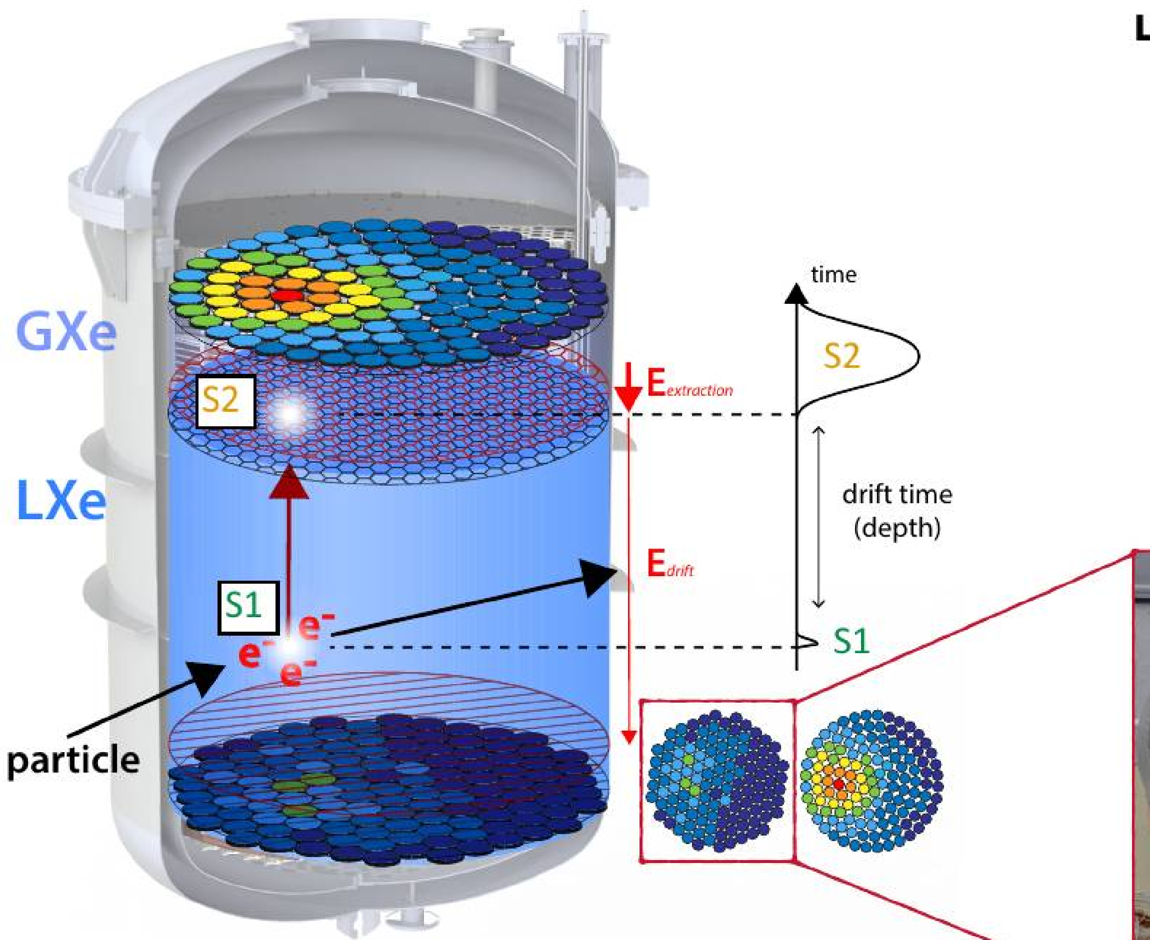
★ 2.0 t → 5.9 t LXe active mass

★ ~1 m → ~1.5 m drift length

★ ~1 m → ~1.3 m diameter

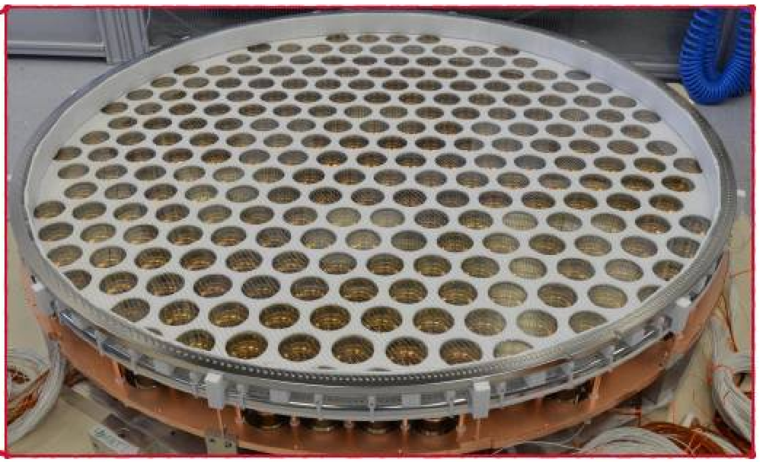
★ 248 → 494 3″ PMTs

TPC Detection Principle



Light and Charge readout

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



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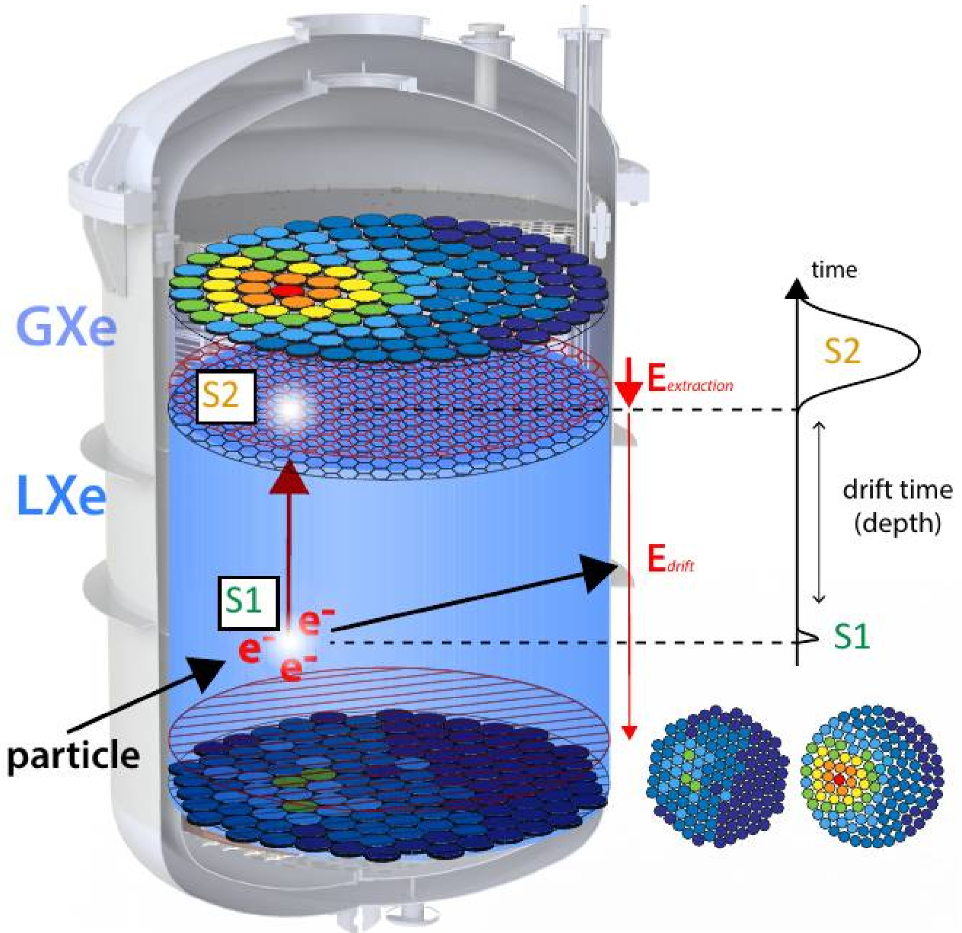

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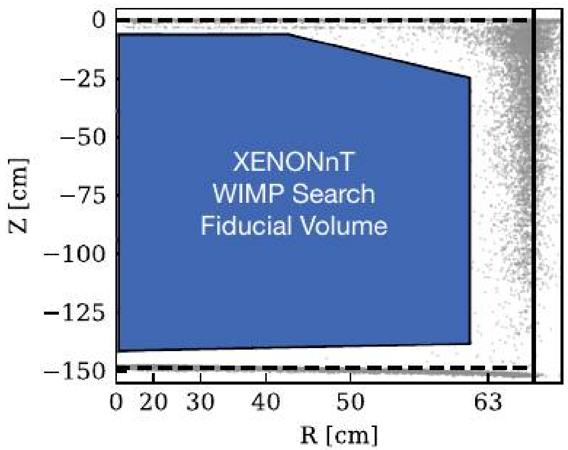
Event reconstruction

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



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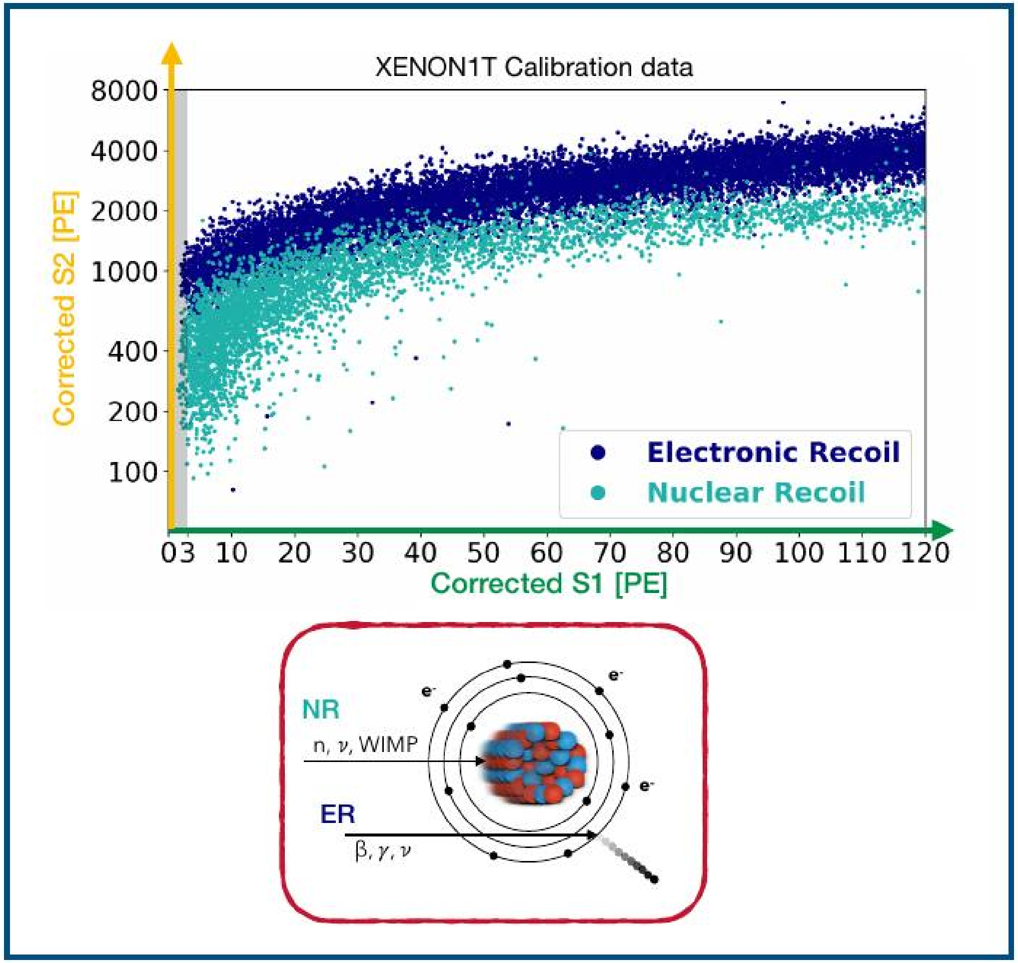

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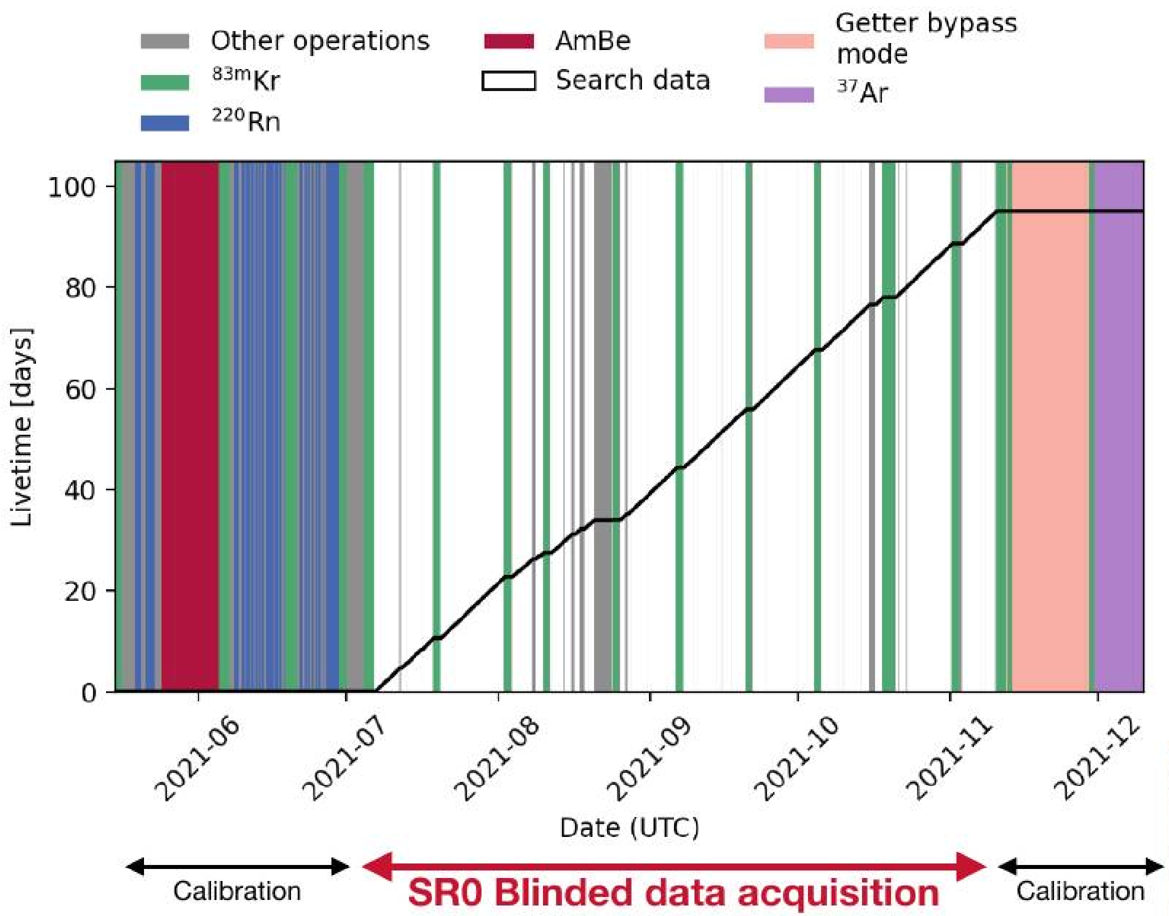
Particle discrimination

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

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

XENONnT Science Run 0



Science run summary

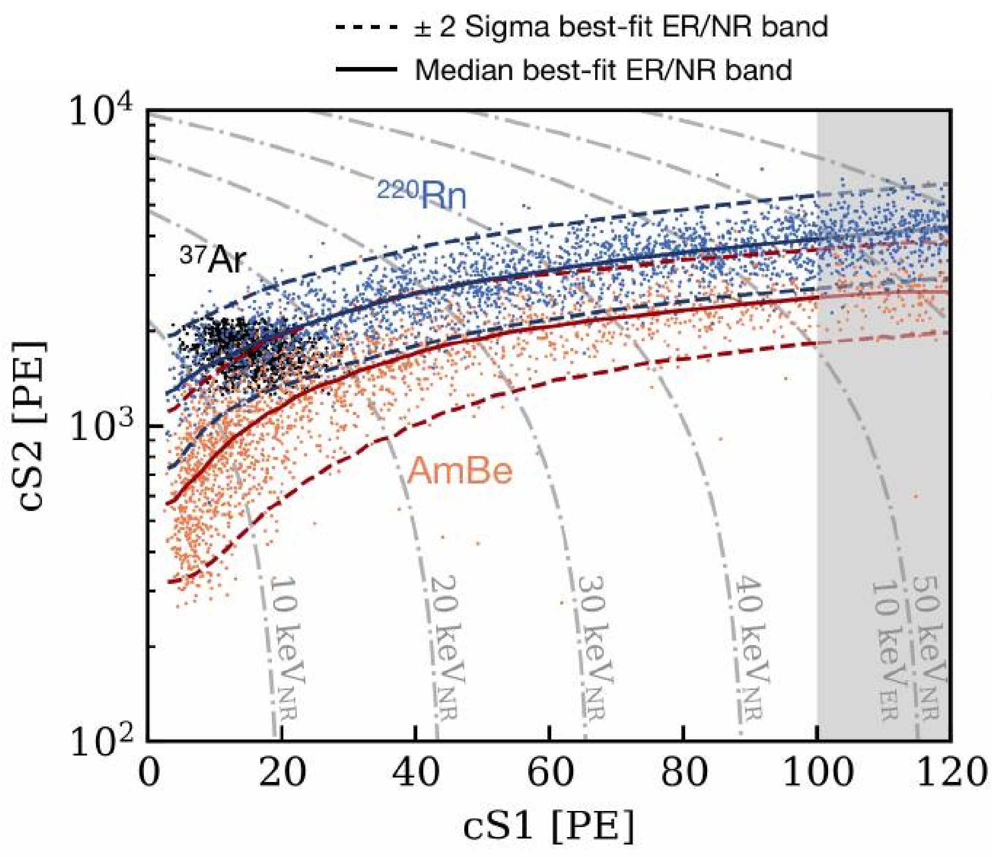
- July 6 to Nov 10, 2021 (97.1 days)
- 95.1 days lifetime corrected
- 4.18 ± 0.13 tonnes Fiducial Volume
- Exposure: 1.1 tonne-year
- **Blinded data analysis**

Detector configuration

- Drift field: 23 V/cm
- Extraction field: 2.9 kV/cm (~50% e^- extr. eff.)
- 477 out of 494 PMTs working (~3.4% loss)
- **LY & CY stable at 1% and 1.9% respectively during blinded data taking**

XENON FRANCE

Detector Calibration



Fraction of ER events below NR median is 1.1 %

Signal Characterisation and Correction

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Selection

- ^{83m}Kr internal calibration source:
  - ➡ 2 successives IC @ 32.2 keV & 9.4 keV
  - ➡ Building block of the signal correction
  - ➡ Details in an upcoming analysis paper

Electronic Recoil Calibration

- ^{220}Rn internal source
  - ➡ ^{212}Pb β-decay offer ~flat energy spectrum in ROI
- ^{37}Ar internal source
  - ➡ ER line from K-Shell @ 2.8 keV
  - ➡ Validate detector performances & study threshold

Nuclear Recoil Calibration

- External AmBe neutron source
  - ➡ Clear NR selection via coincident 4.4 MeV γ in nVeto

Threshold and efficiency

Detection efficiency

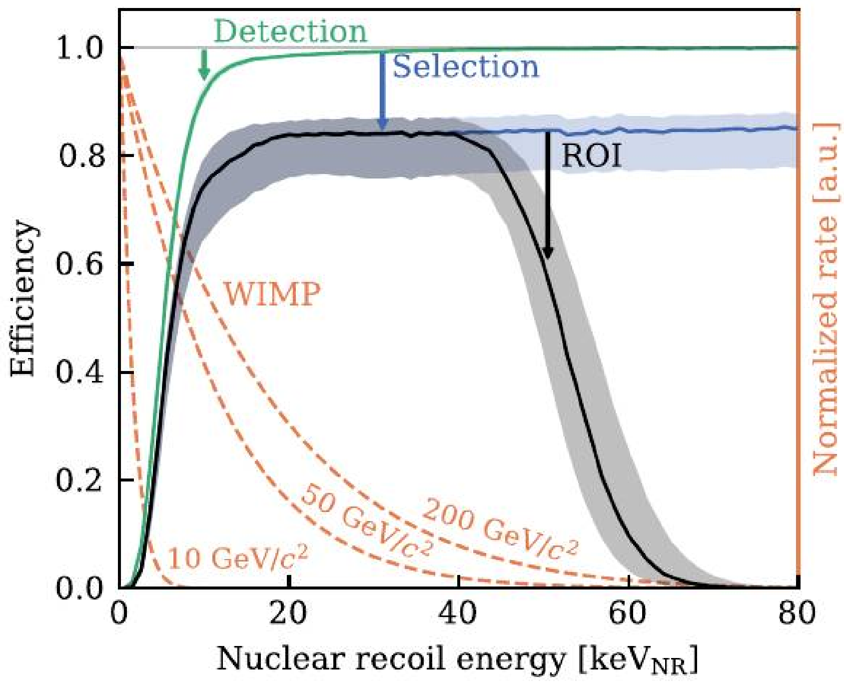
- Threshold driven by a 3-fold PMT coincidence for S1
- Validation with waveform simulation and data-driven methods

Selection efficiency

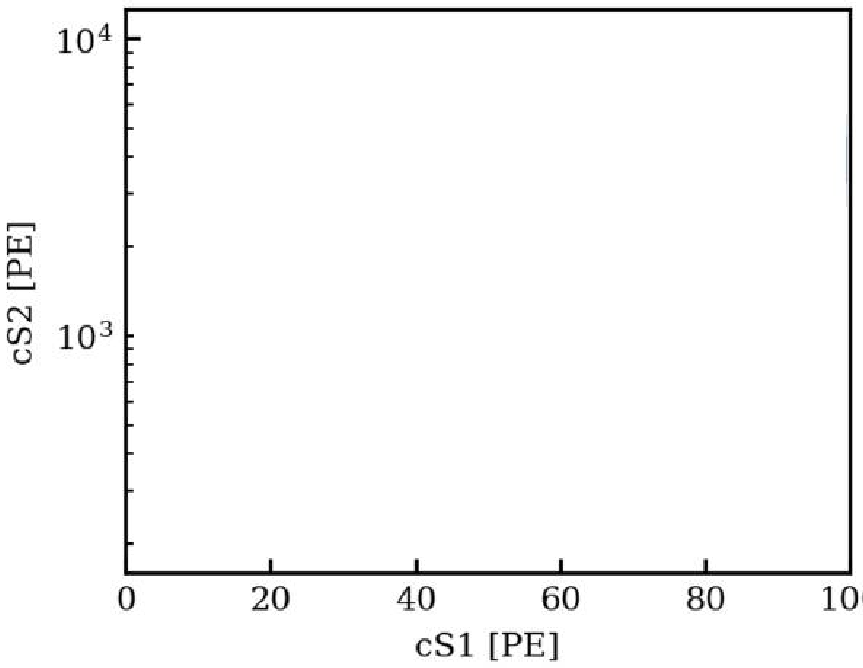
- Select Single Scatter interaction
- Quality cut evaluated using calibration data
  - ➡ Details in an upcoming analysis paper

Region of Interest (ROI)

- cS1: [0, 100] PE
- cS2: [$10^{2.1}$, $10^{4.1}$] PE



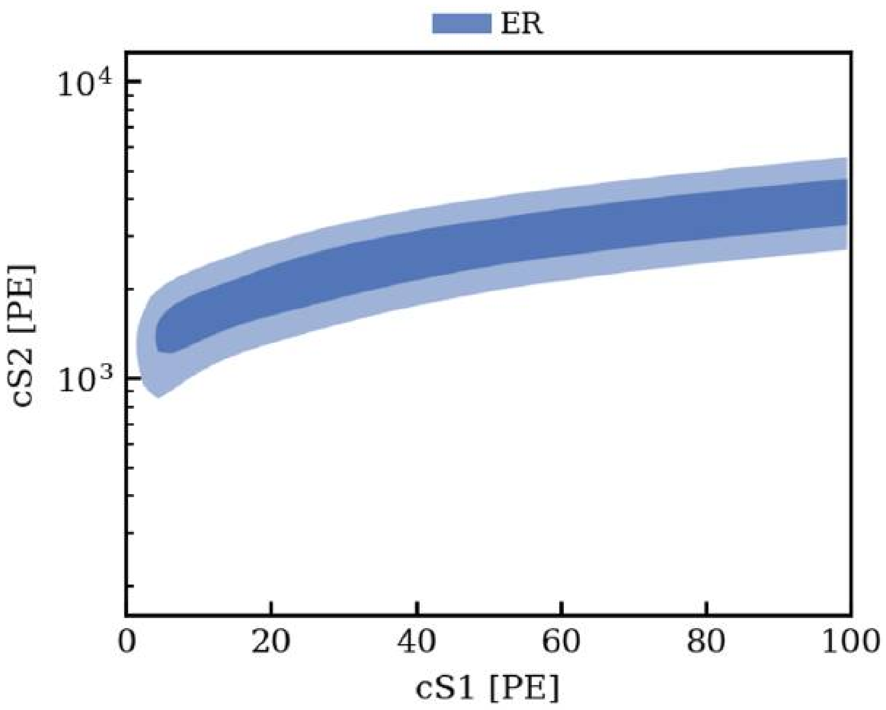
Signal and background models



Signal and background models

Electronic recoils

- Dominated by β-decay of ^{214}Pb (intrinsic to the LXe target)
- Suppressed by ER/NR discrimination



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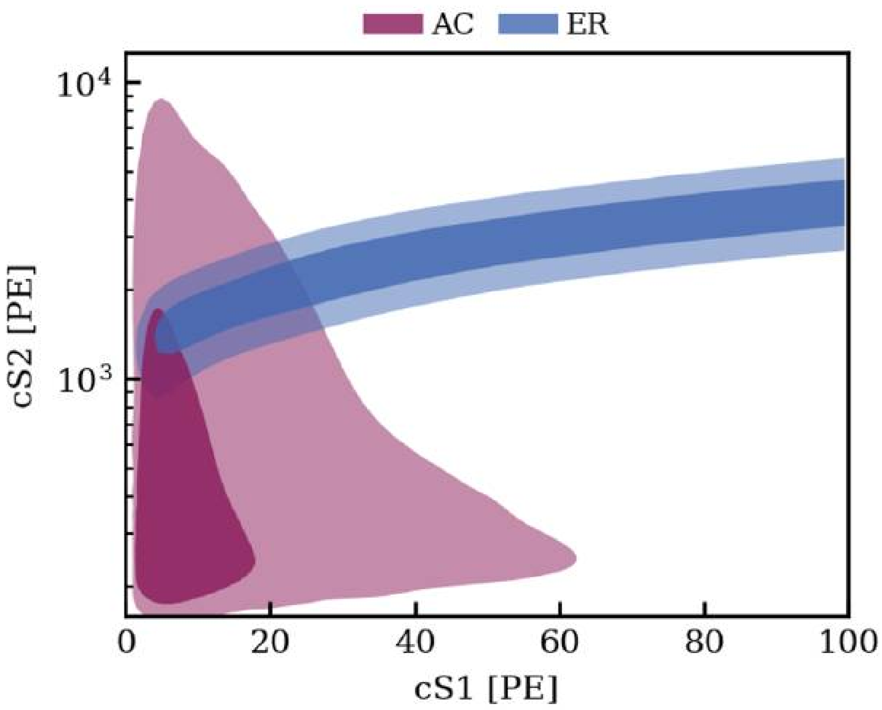
- Random pairing of isolated S1 & S2 signals
- Suppressed by dedicated analysis cuts



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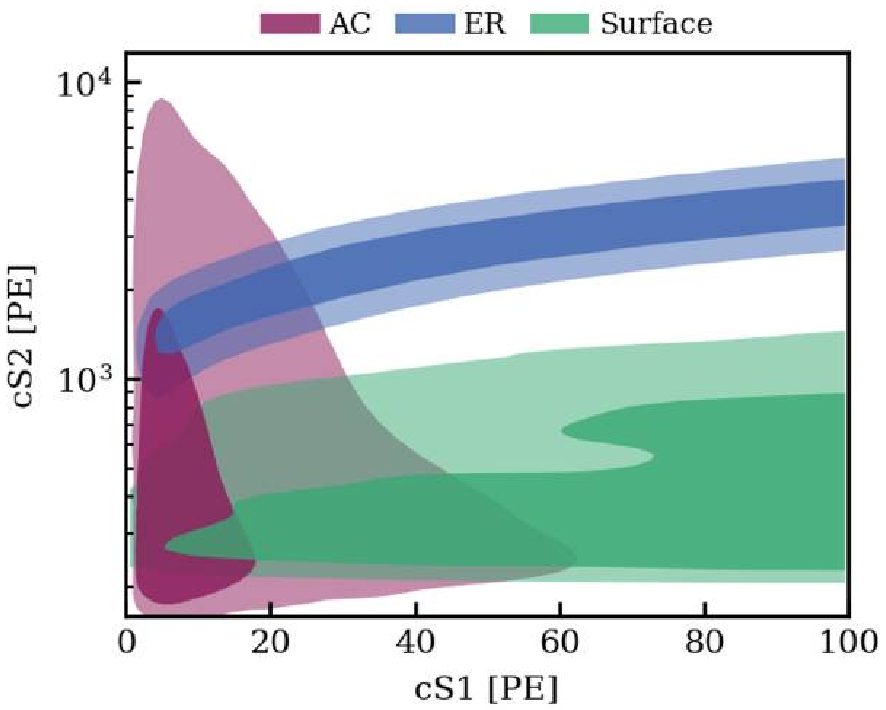
Surface

- ^{210}Pb plate-out on PTFE walls of the TPC
- Suppressed by FV.



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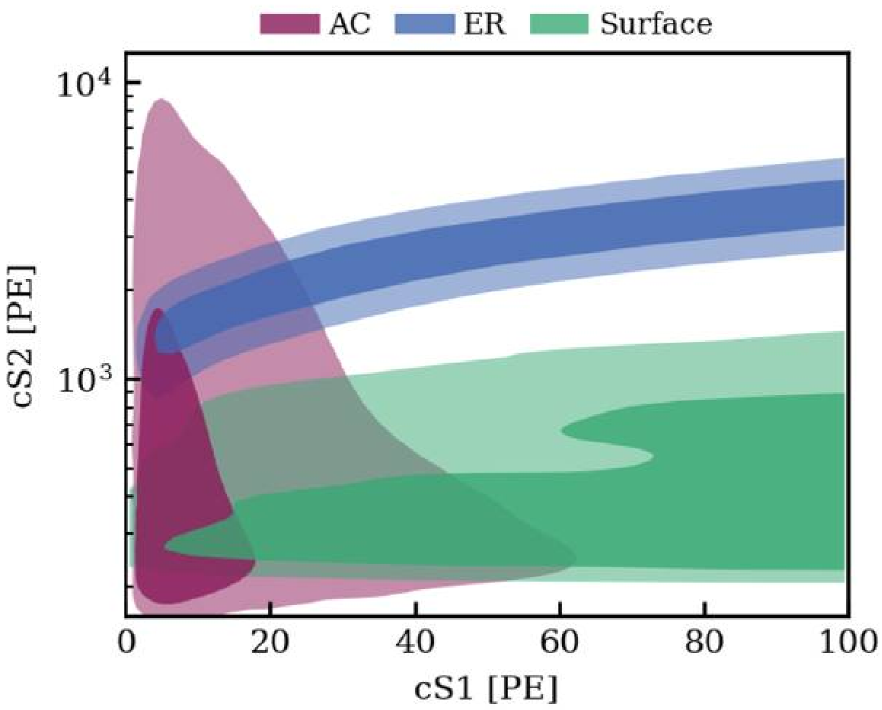
Nuclear recoils

- Radiogenic neutrons spontaneous fission & (α, n)-reactions
  - ➡ Rate prediction from NV tagging ~ 1.1 events
- Cosmogenics are negligible after μVeto
- ^{8}B CEνNS constrained by flux



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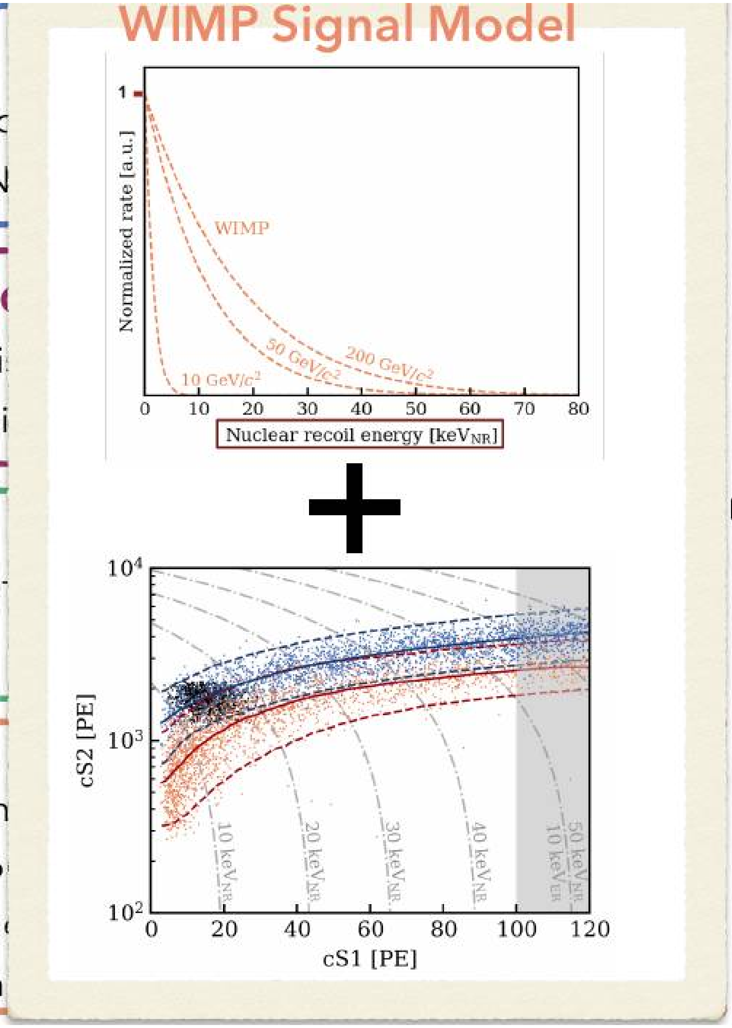

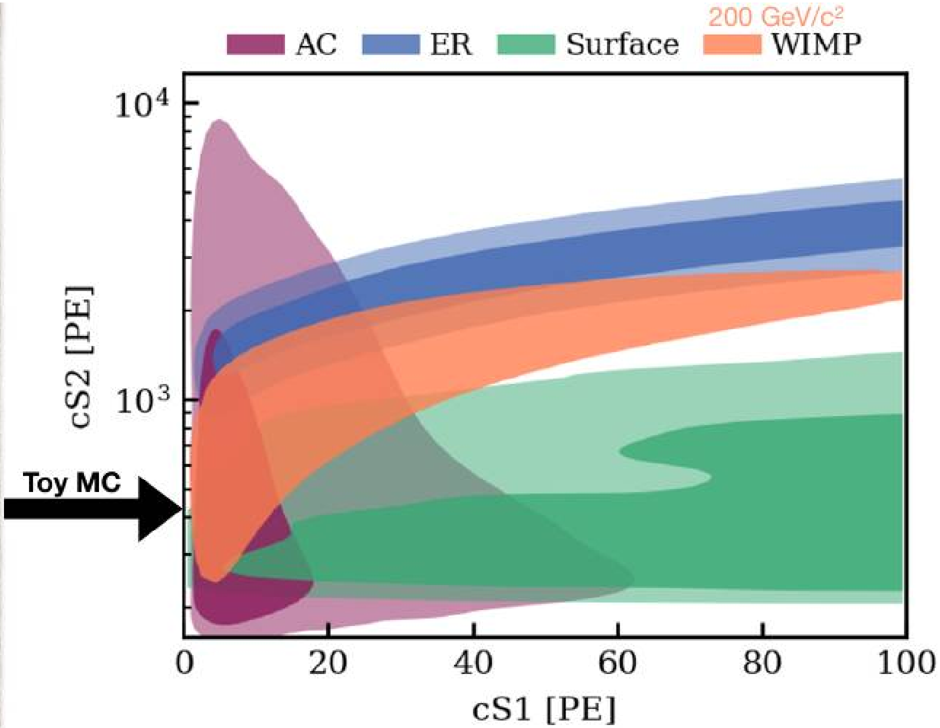

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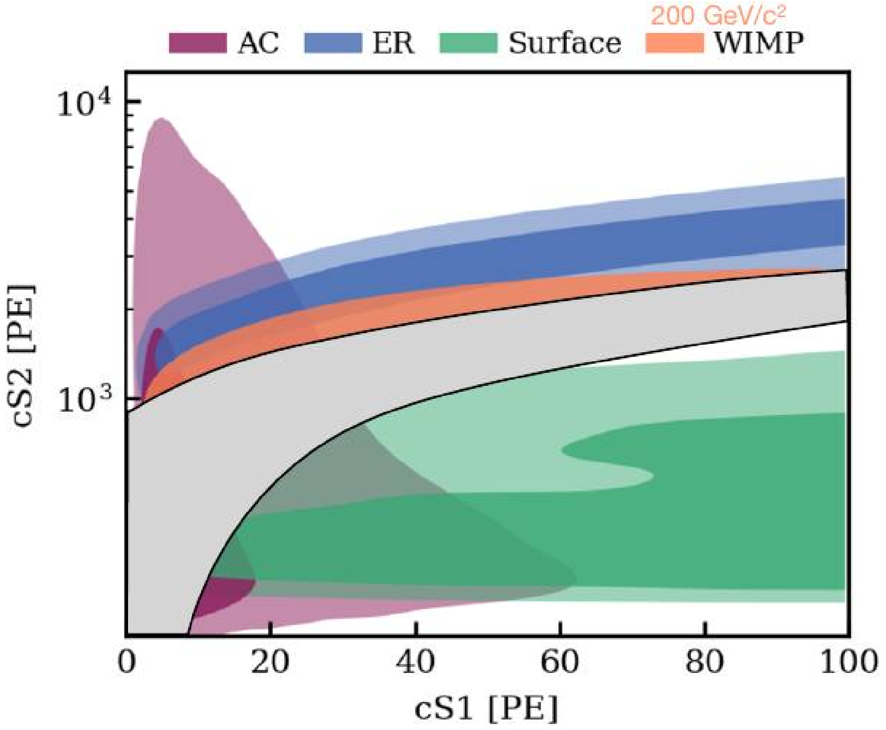
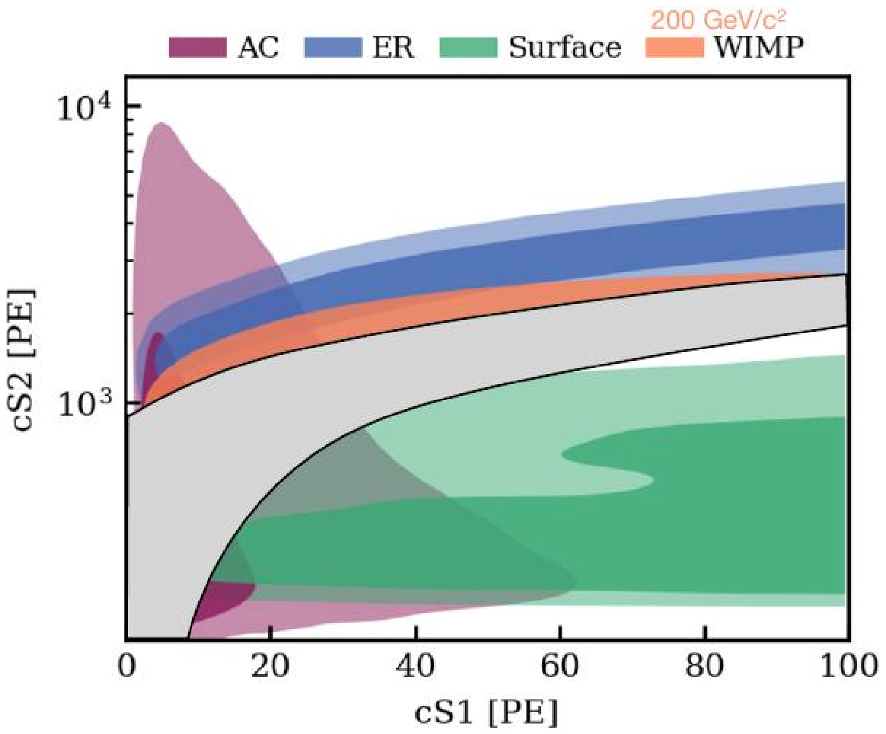


We are performing a blinded data analysis!

WIMP results

	Expectation
ER	134
Neutrons	$1.1^{+0.6}_{-0.5}$
CEvNS	0.23 ± 0.06
AC	4.3 ± 0.2
Surface	14 ± 3
Total	154
200 GeV/c² WIMP	-
Observed	-

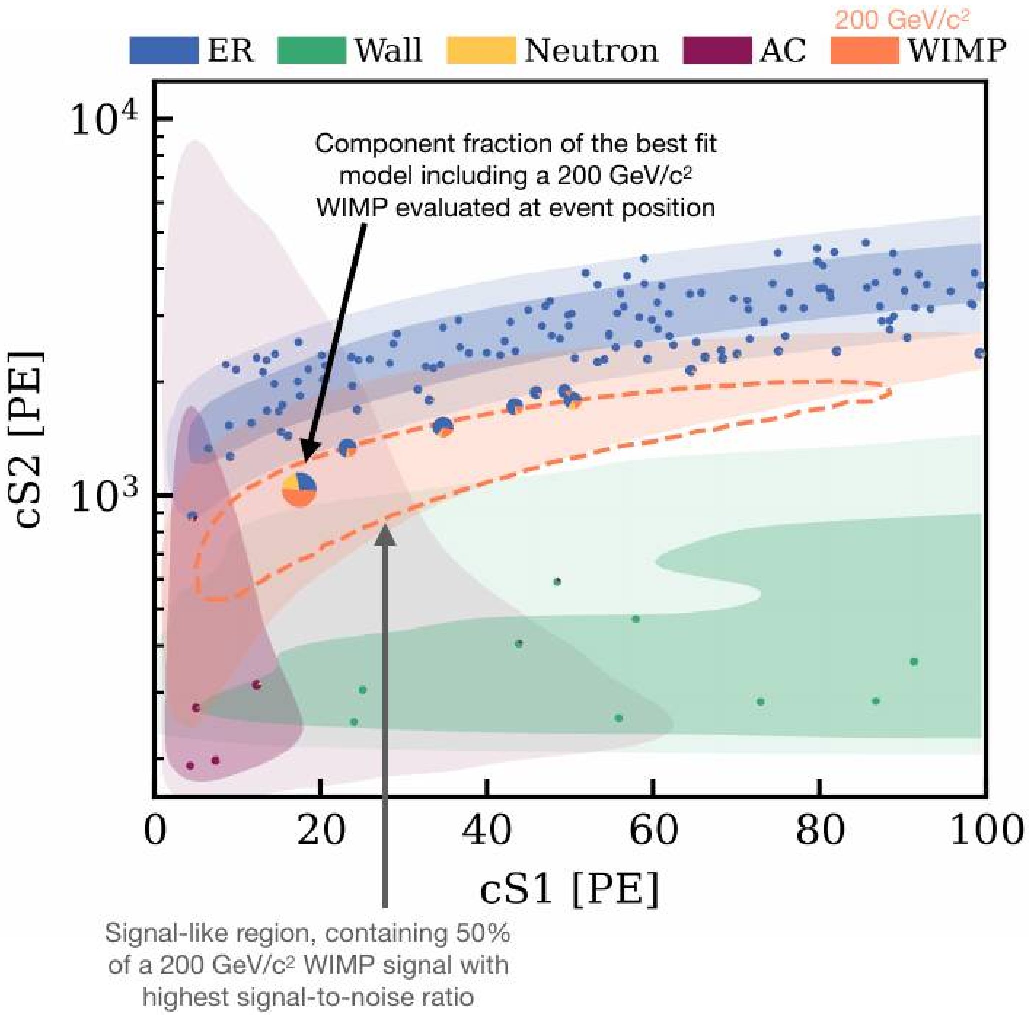


WIMP results

Unblinding

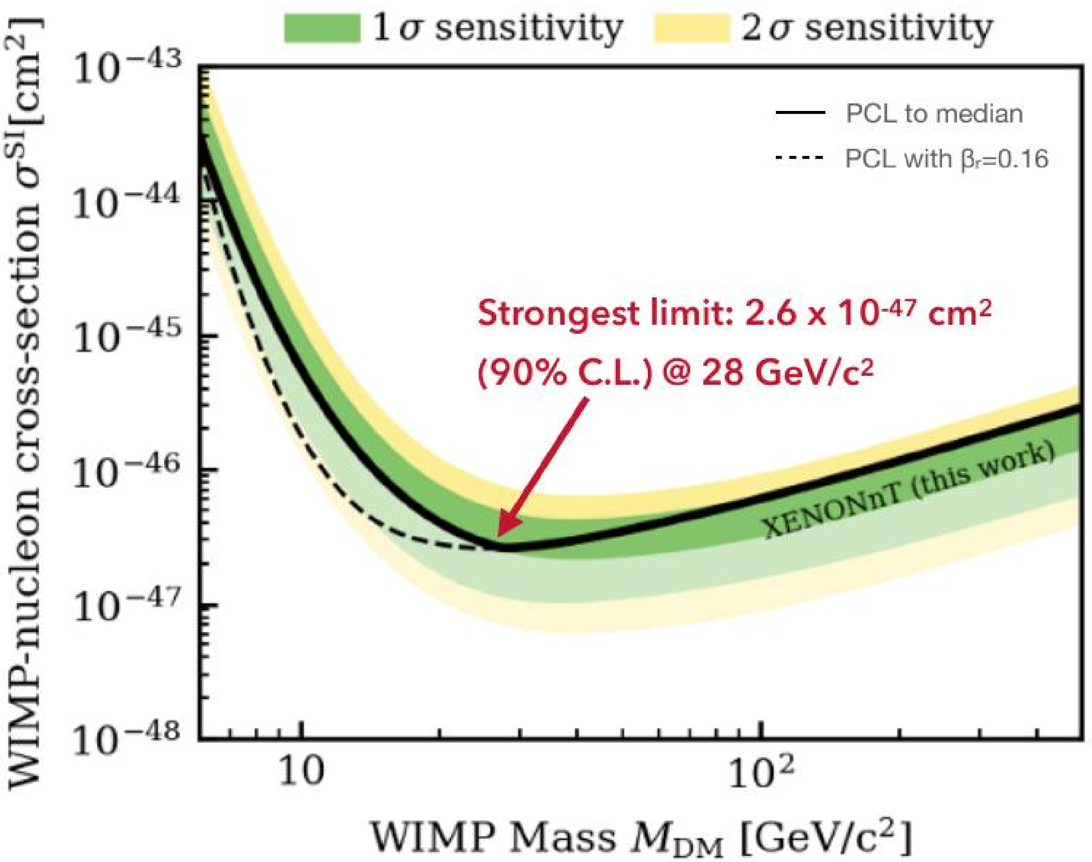
	Expectation	Best Fit
ER	134	135^{+12}_{-11}
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.15
Surface	14 ± 3	12^{+0}_{-4}
Total	154	152 ± 12
200 GeV/c² WIMP	-	2.4
Observed	-	152

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



WIMP Spin-Independent 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

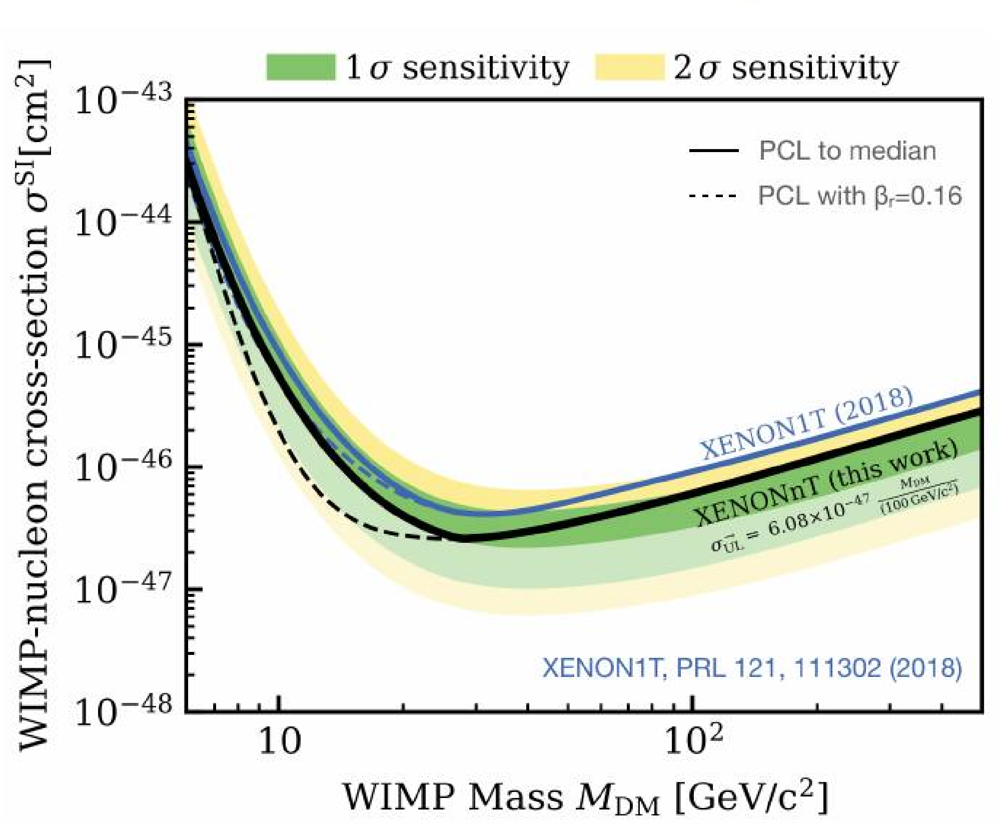


[1] D. Baxter et al, "Recommended conventions for reporting results from direct dark matter searches" [EPJC 81 (2021)]

[2] G. Cowan, K. Crammer, E. Gross, O. Vitells, "Power-Constrained Limits". arxiv:1105.3166

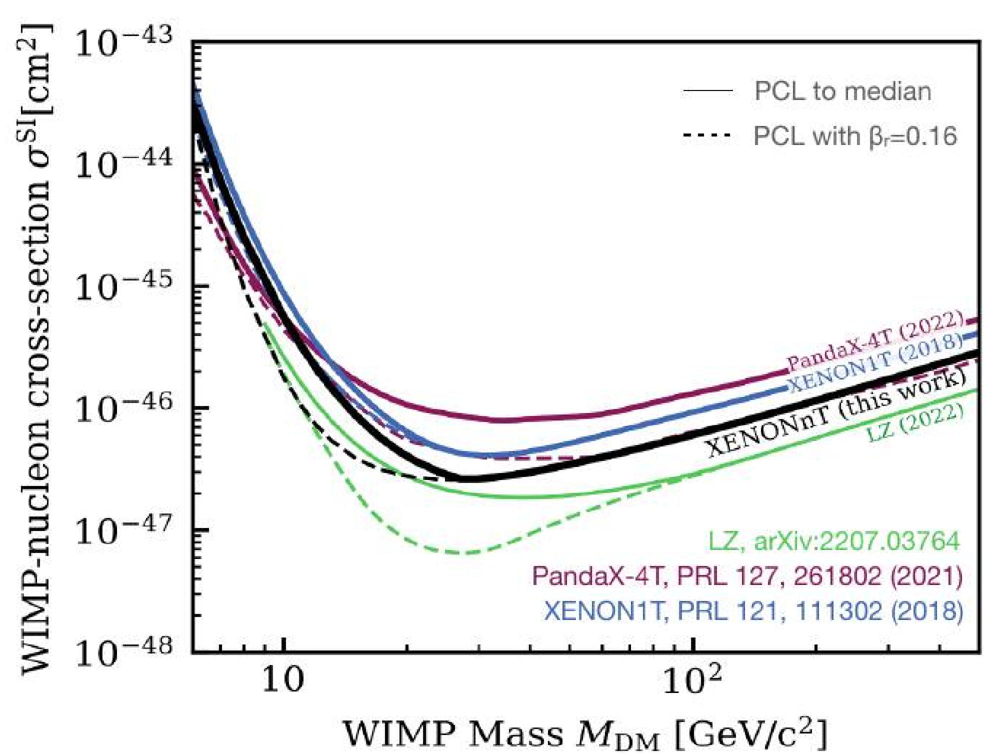
Comparison with recent results

From **blinded** analyses



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

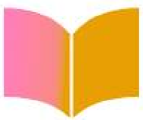
From **non-blinded** analyses



Same PCL applied to results of other recent LXe experiments

Summary

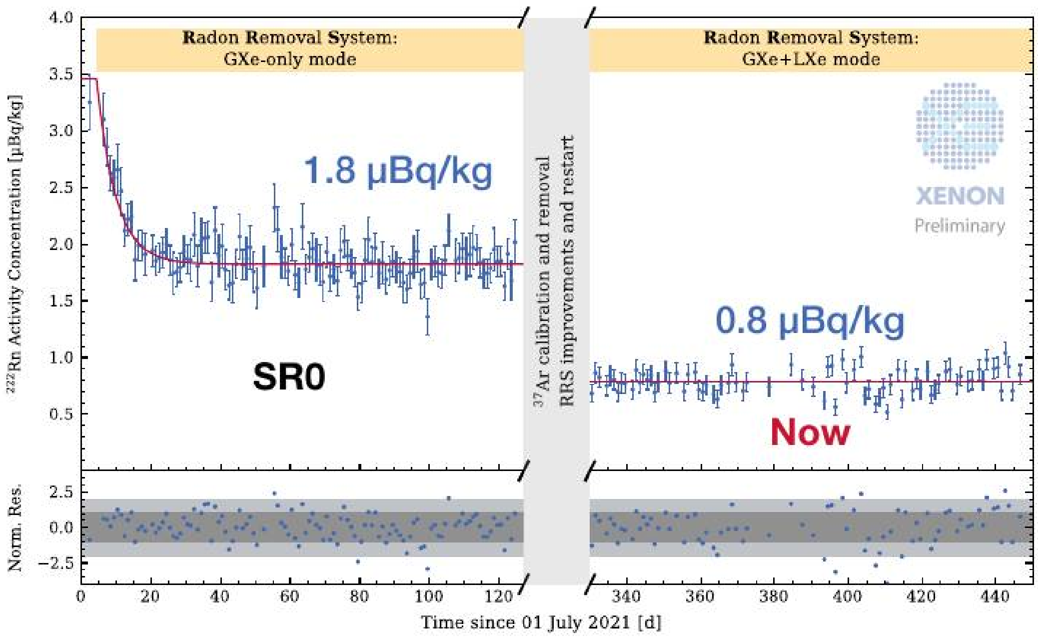
- **XENONnT SR0** → blinded Dark Matter search with 1.1 t x yr exposure
- **SI limit of 2.6 x 10^{-47} cm² (90% C.L.) @ 28 GeV/c²**
- **Unprecedented low-ER background**
  - ➡ ~ 16 events / (t . y . keV)



XENONnT WIMP result
arXiv:2303.14729

Prospects

- Further reduction of ER background by improved radon distillation flow path
- Gd-loaded water in the nVeto will improve our neutron tagging efficiency
- And even more physics!



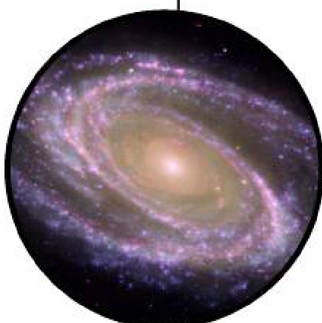
Even more physics to come !

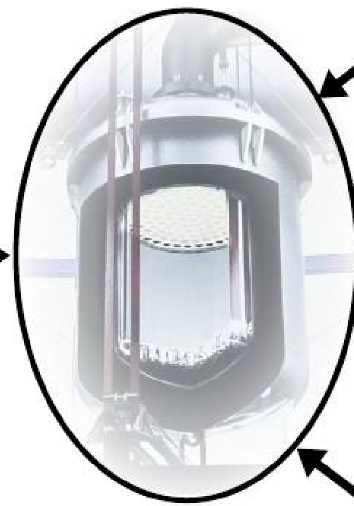
WIMPs

- Spin-independent
  - ➡ PRL 119, 181301
  - ➡ PRL 121, 111302
- Spin-dependent
  - ➡ PRL 122, 141301
- Sub-GeV
  - ➡ PRL 122, 071301
  - ➡ PRD 103, 063028

Dark Matter

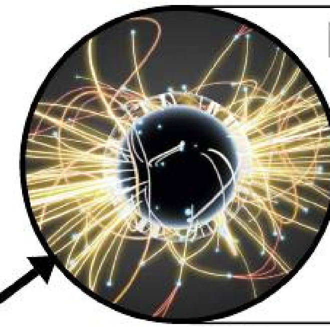
- Light DM
  - ➡ PRL 123, 241803
  - ➡ PRL 123, 251801
- Bosonic DM
  - ➡ PRD 102, 072004





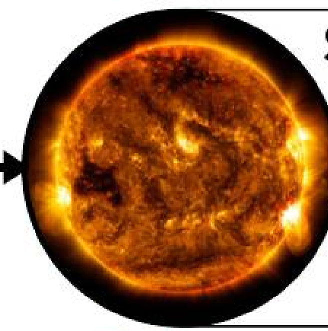
XENON FRANCE

Contribute to the broadening of the physics goal of XENONnT



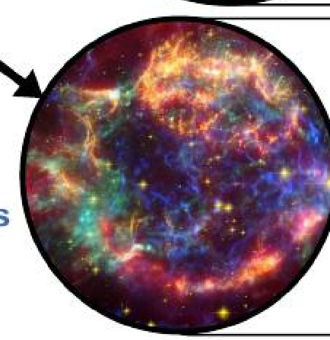
Nuclear/Particle Physics

- 2νECEC capture
  - ➡ Nature 568, 532
- $0\nu\beta\beta$ decay
  - ➡ EPJC 80:785 (2020)



Sun

- Solar ^{8}B CEvNS
  - ➡ PRL 126, 091301
- Solar pp neutrinos
  - ➡ EPJC 80:1133 (2020)
- Solar axions
  - ➡ PRD 102, 072004

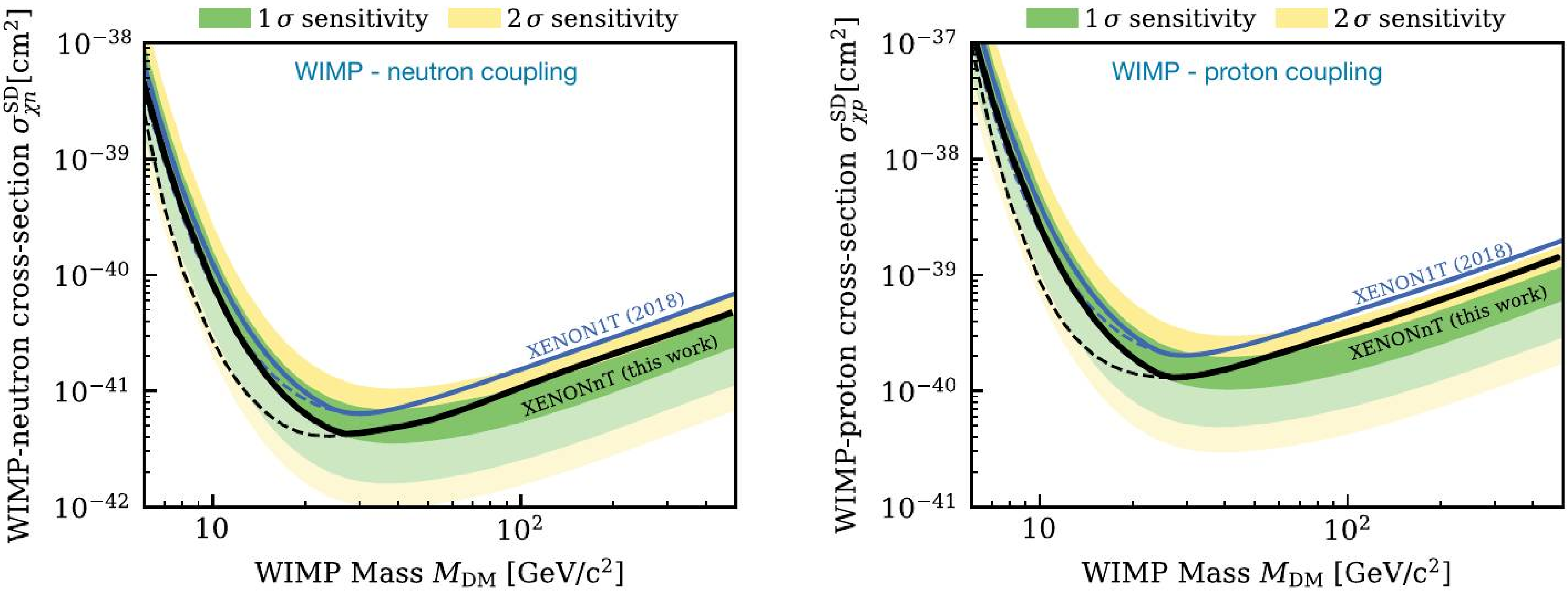


Supernova

- Supernova neutrinos
  - ➡ PRD 94,103009

WIMP Spin-Dependent limits

Reinterpreting results as a purely spin-dependent coupling to ^{129}Xe and ^{131}Xe



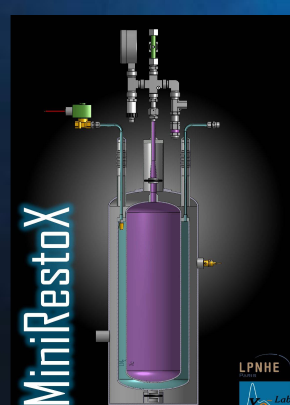
Current contributions of XENON-France

XENONnT

Operations :
- Data Transfer Manager
- Data Quality Manager
- XOM : offline monitoring tool
- Distributed storage with GRID
- Computing administration
- Analysis tools

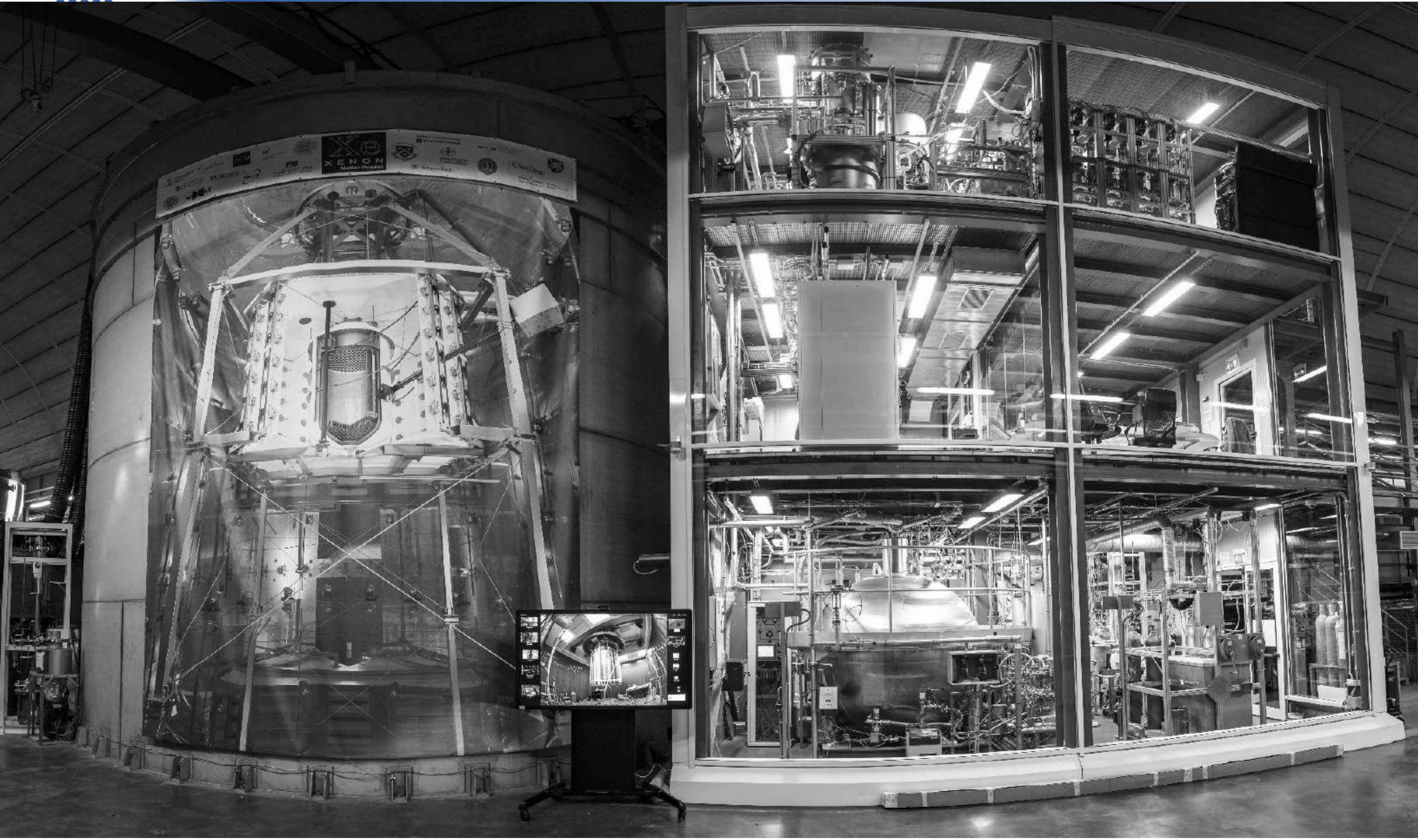
Analysis :
- S2-only search
- Neutrinoless double beta decay
- S2 signal simulation
- CEvNS Solar neutrinos
- Supernova neutrinos

XeLab



R&T for next generation detectors
- Floating electrodes
- Single electrons background
- LN2-based cooling systems
- Open-source slow control systems

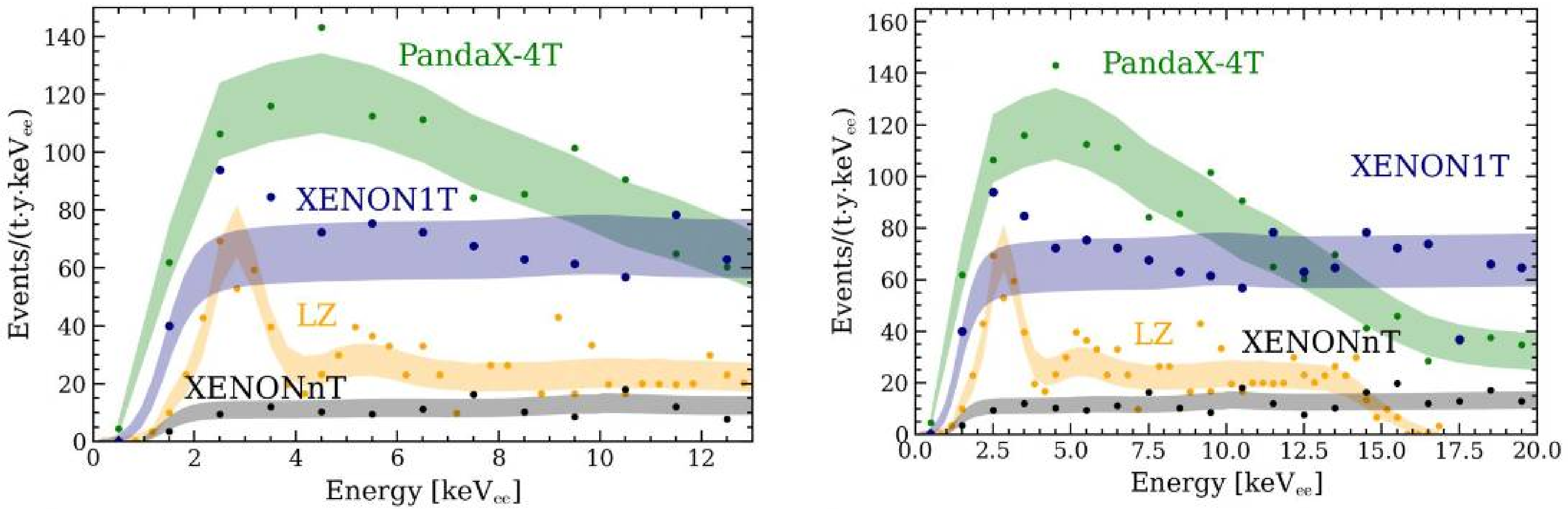
Thanks



xenonexperiment.org @XENONexperiment @xenonexperiment @xenon_experiment

Backup

Electron recoil background comparison



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