Neutrino physics with Dark Matter detectors

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How do we search for Dark Matter?

Credit: ESO (Wide Field Imager view of the spiral galaxy NGC 247)

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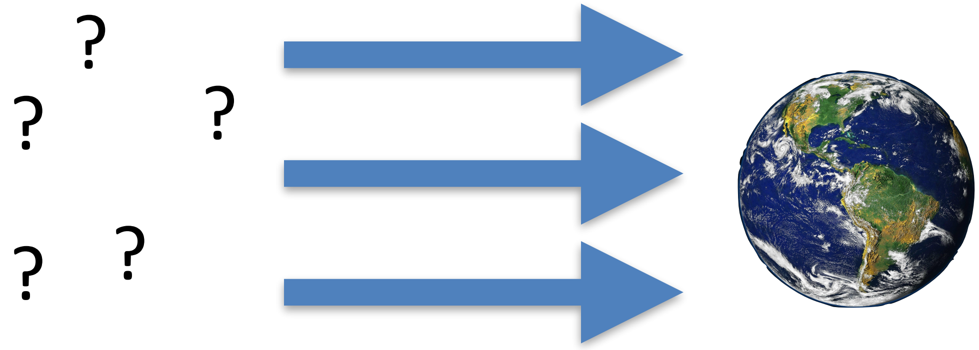
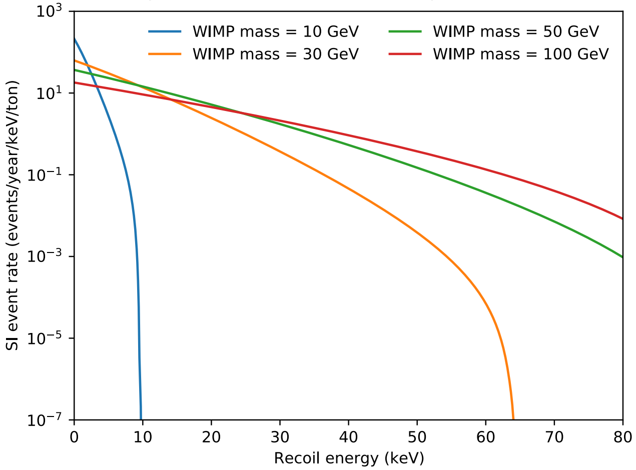


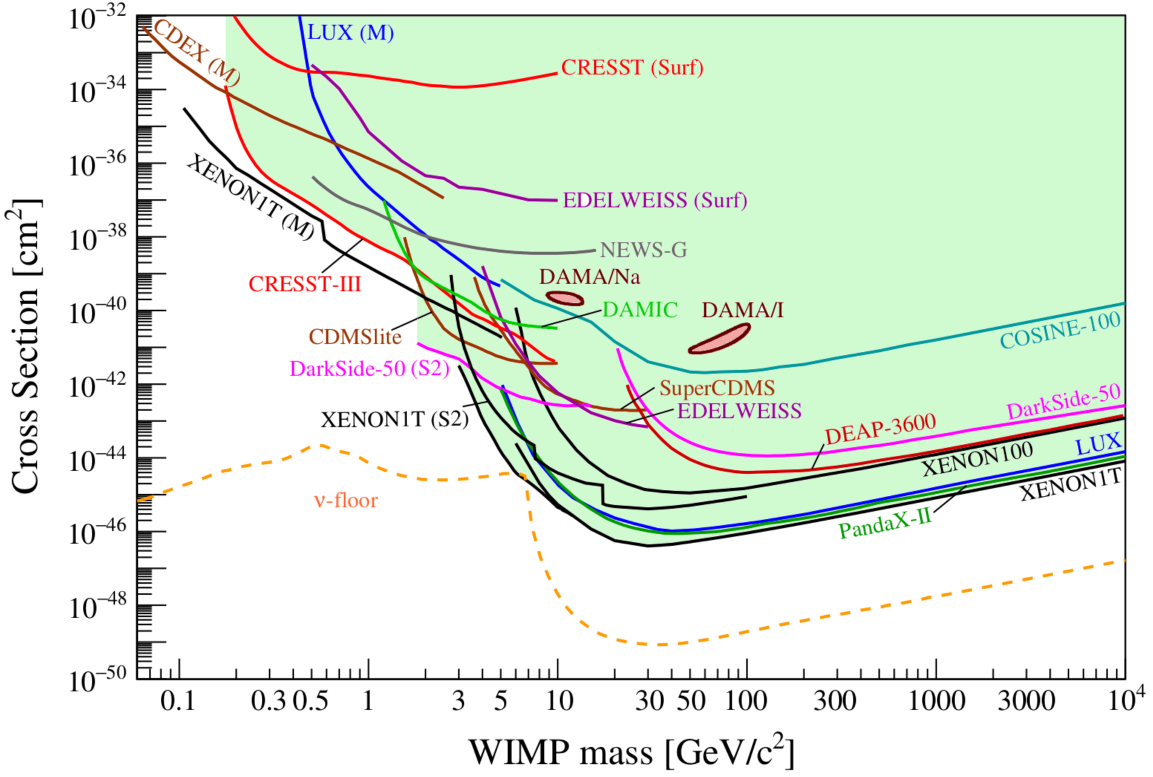
Expected recoil spectrum



- Wind of Dark Matter hits the Earth
- Interaction between Dark Matter and ordinary matter is elusive
- Need to create environment of very low background rate!
  —> Ultra-clean and underground!

Overview of Dark Matter searches

- Key to successful DM searches:
  - low energy threshold
  - large detector volume
  - low background rate
- **Vital features to analyses in neutrino physics**
- —> exploit synergies



arXiv:2104.07634

Science in Dark Matter detectors

Light dark matter

PRL 123, 251801 (S2-only)
PRL 123, 241803 (Migdal)

Bosonic dark matter

PRL 123, 251801 (low mass)

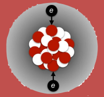
WIMP

PRL 121, 111302
PRL 122, 141301
PRL122, 071301
PRL 123, 251801
PRD 103, 063028

Axions

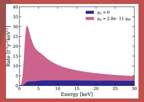
PRD 102, 072004 (2020)

Double-electron capture



Nature 568, 532–535
arXiv:2205.04158

Neutrino magnetic moment



PRD 102, 072004 (2020)

CEνNS

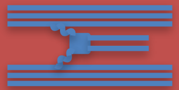
PRL 126, 091301 (2021)

Supernovae

10.1088/1475-7516/2021/03/043
PRD 94 103009

Neutrinoless double beta-decay

arXiv:2205.04158, EJPC 80, 785 (2020) (reconstruction), Phys. Rev. C **102**, 014602



Atmospheric neutrinos

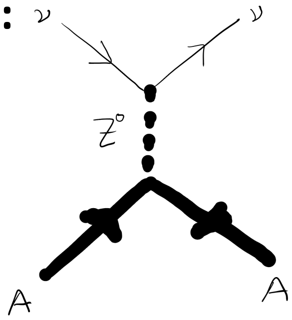
Phys. Rev. D 105, 043001, Phys. Rev. D 104, 115022

Coherent elastic neutrino nucleus scattering

$CE\nu NS$

$CE\nu NS$ in a nutshell:

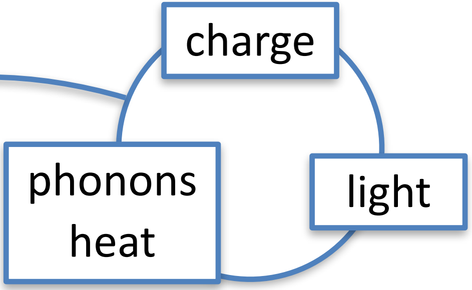
$\nu + \text{A} \rightarrow \nu + \text{A}$
SM process,
flavor blind,
no energy threshold,
$E_\nu < 50$ MeV



$CE\nu NS$

Signature:

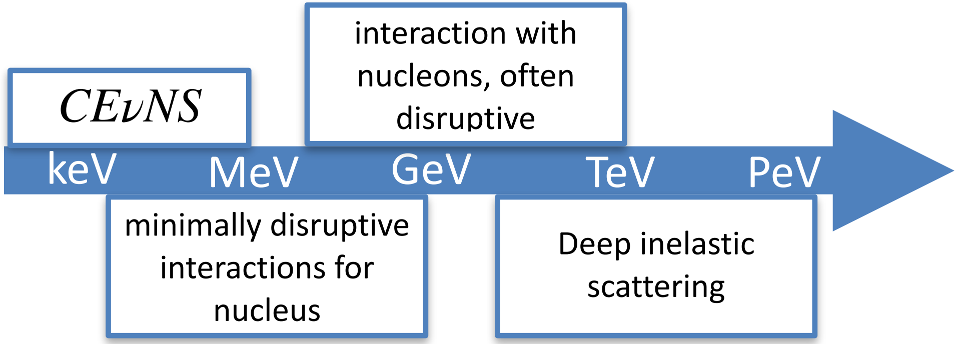
- tiny recoil of nucleus
- identical to WIMP Dark Matter



Irreducible background to Dark Matter searches

Neutrino sources for $CE\nu NS$:

- Sun (^{7}Be, ^{8}B)
- Atmosphere
- Diffuse Supernovae neutrino background (DSNB)
- Neutrino beam
- Reactor



$CE\nu NS$

$CE\nu NS$ in a nutshell:

$\nu + A \rightarrow \nu + A$

SM process,

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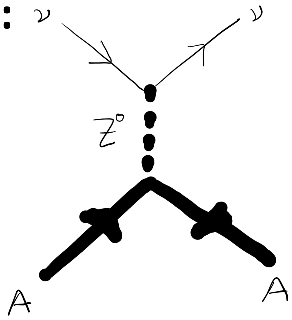
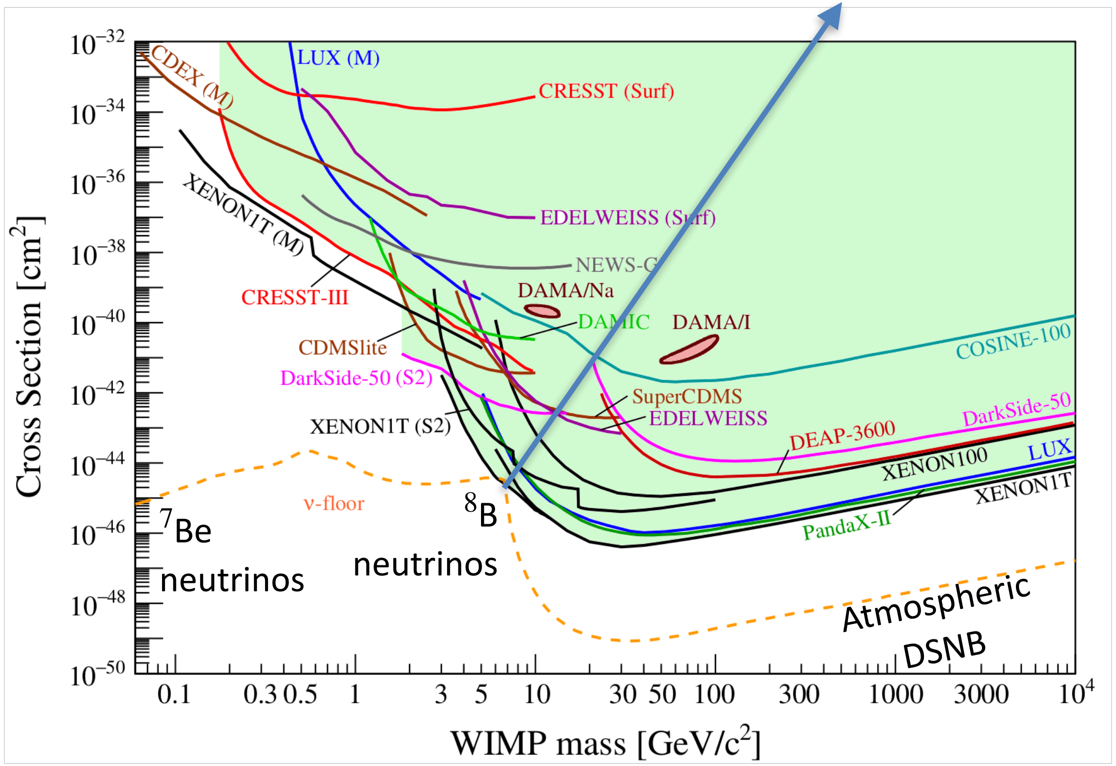


^{8}B detection from Sun likely to be first



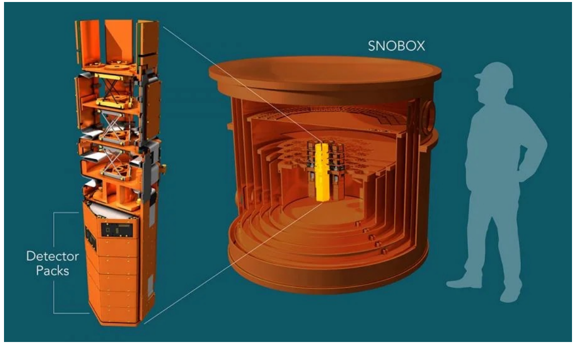
Only result from DM community so far from XENON:

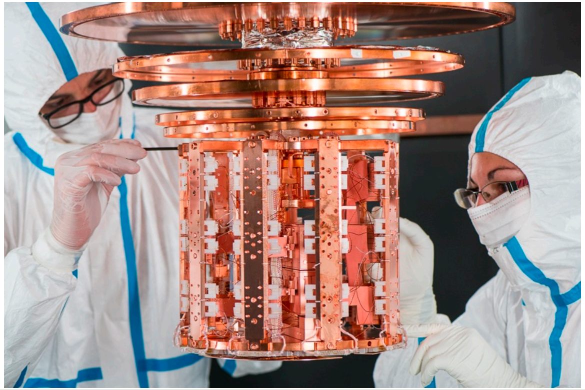
no detection

PRL 126, 091301 (2021)

Technologies for $CE\nu NS$

Recoiling nucleus creates: charge, light and heat from which only 2 can be read out.





SuperCDMS
EDELWEISS

high-purity germanium

Xe: XENON, LZ, PandaX,…
Ar: ArDM, DarkSide,…

cryogenic Ge, Si crystals

charge

2-phase noble liquid

phonons heat

light

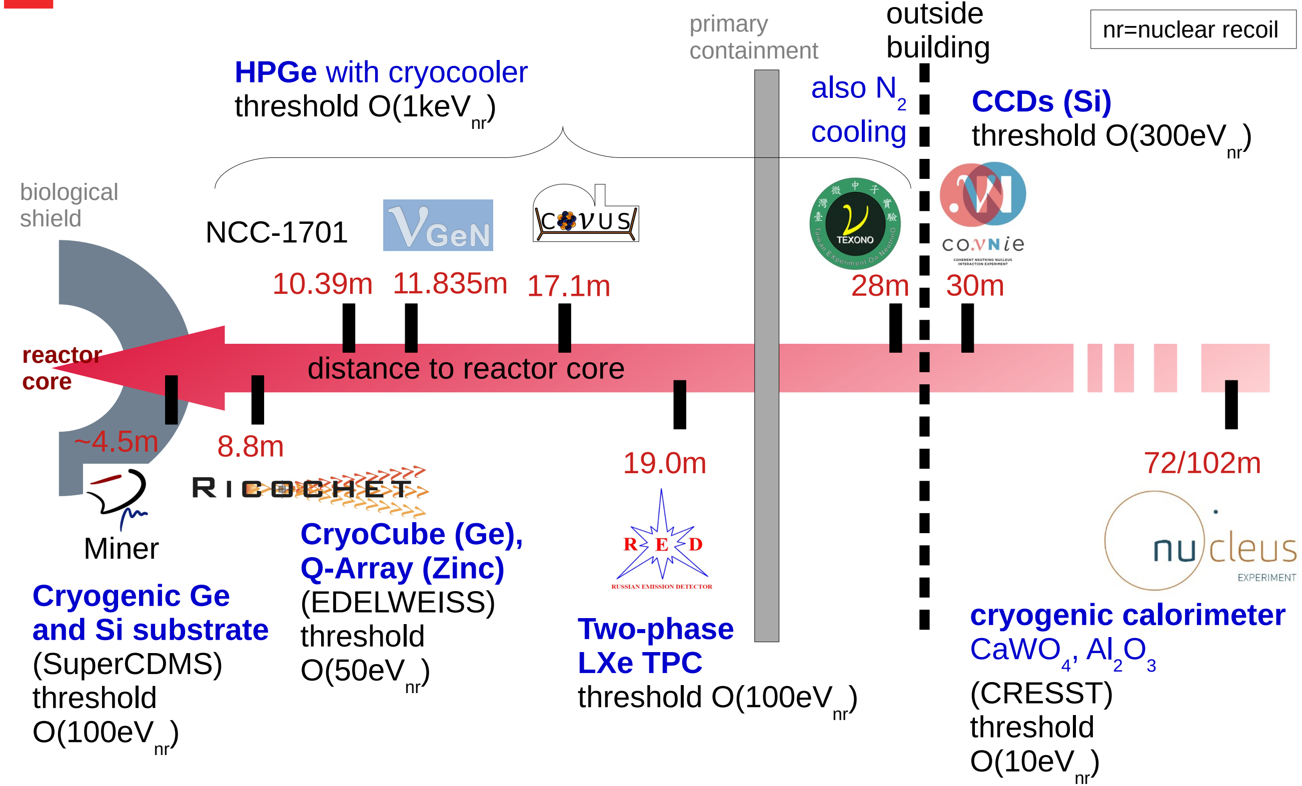
cryogenic calorimeters, $CaWO_4, Al_2O_3$, …

scintillating crystal, noble liquid

large target mass easily achievable

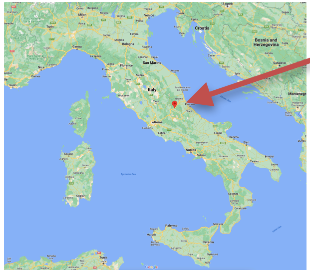
CRESST

CEνNS from reactors



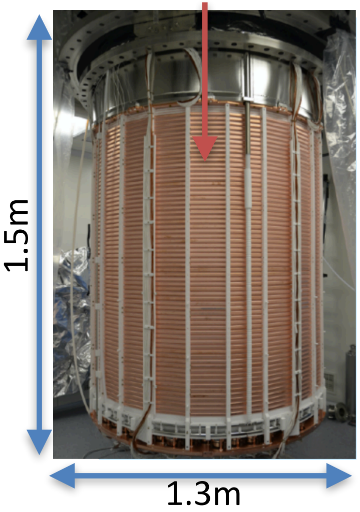
slide from J. Hakenmüller

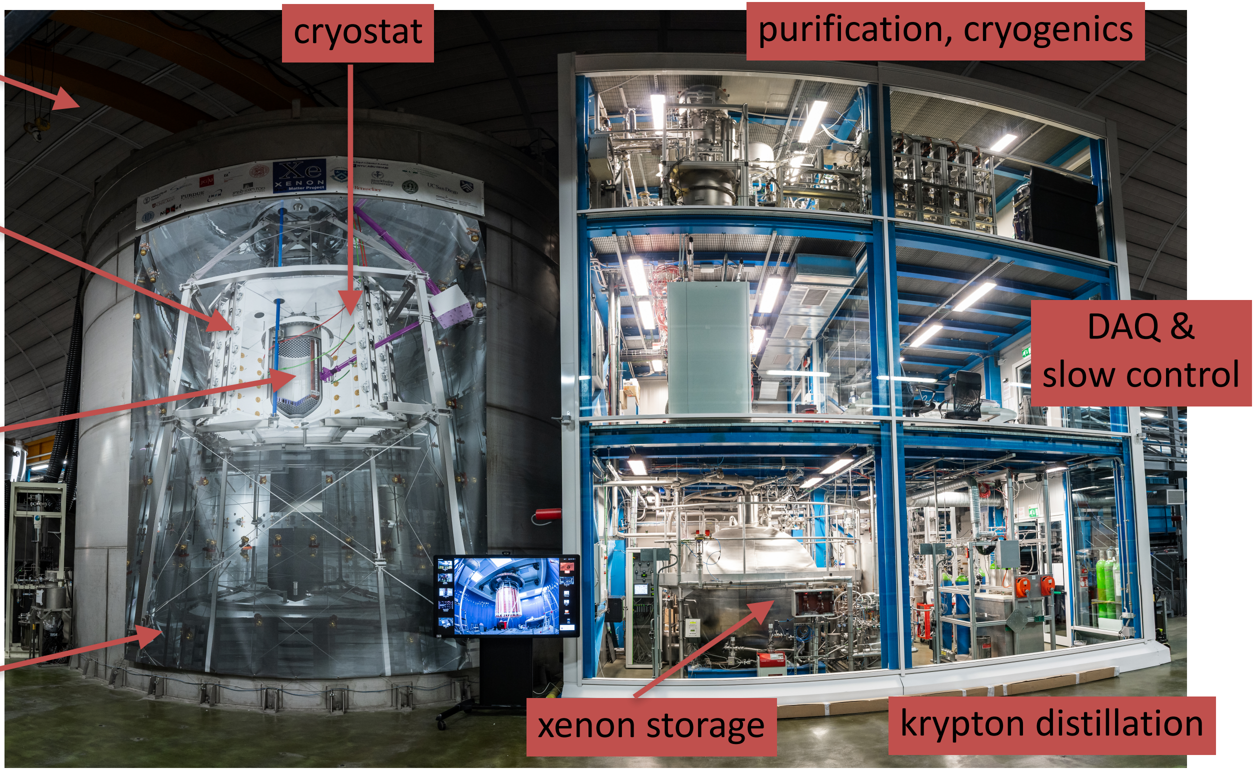
XENONnT Experiment



Laboratori Nazionali del Gran Sasso (LNGS)

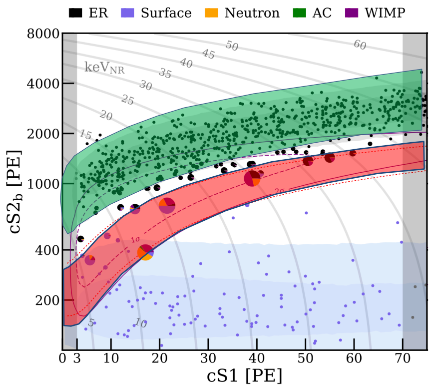
Filled with liquid xenon

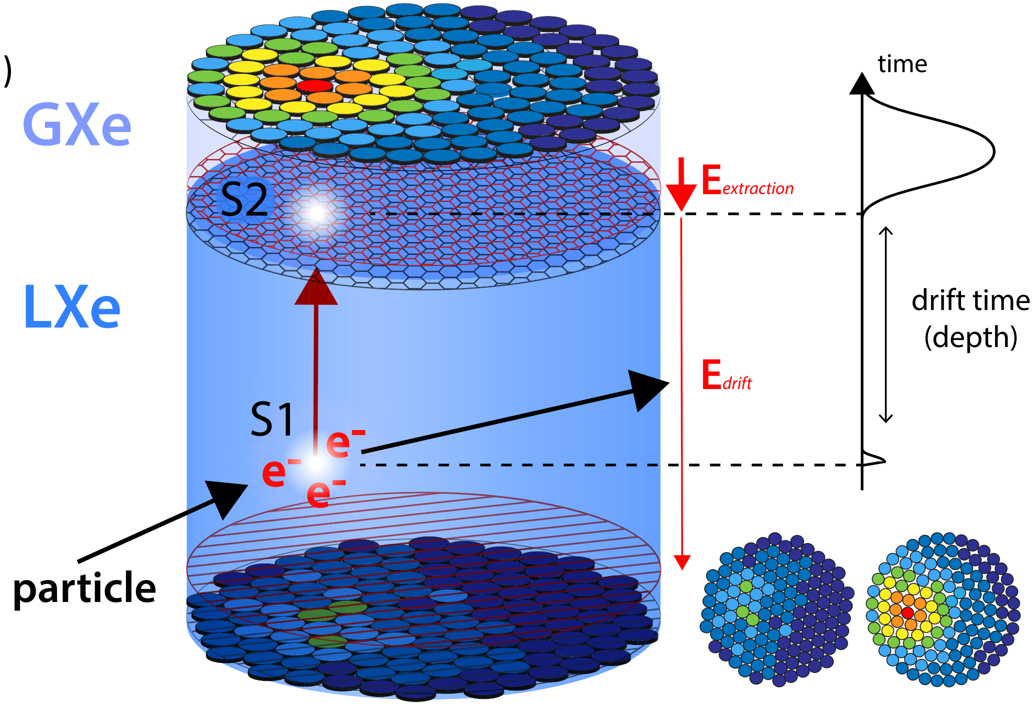




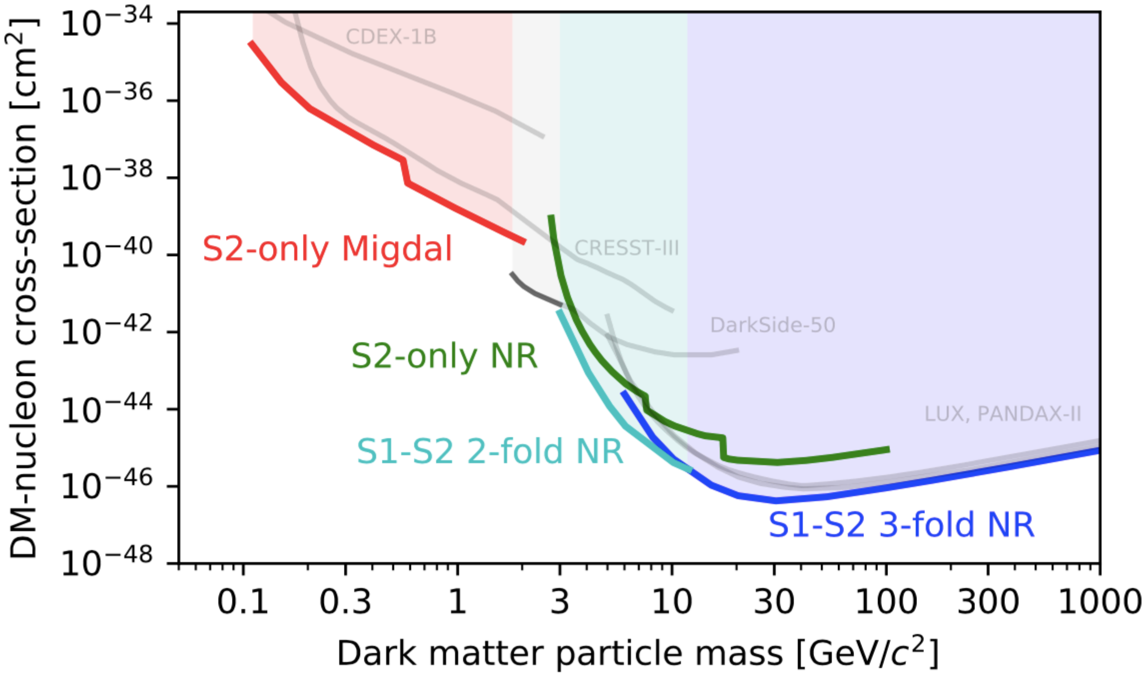
Signal generation

- Readout of: **Scintillation** and **ionization** signals
  - Prompt scintillation light (S1)
  - Secondary light due to drifted electrons (S2)
- Able to reconstruct:
  - position
  - energy
- discrimination between ER and NR





Dark Matter searches at XENON1T

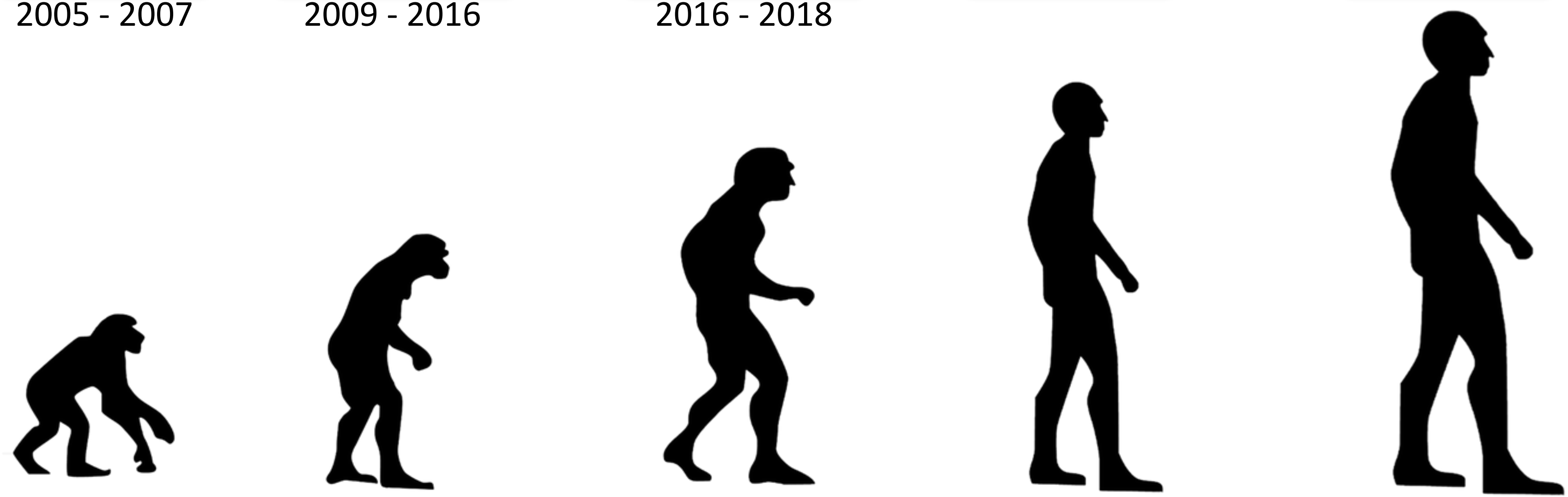


$$\frac{\mathrm{d}R}{\mathrm{dE}}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(v,t) \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}E}(E,v)\mathrm{d}^3 v$$

- limits are set on WIMP dark matter interaction with liquid xenon
- lower threshold can be achieved by lowering coincidence requirements
- spin-independent and spin-dependant analyses are carried out

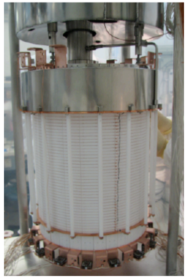
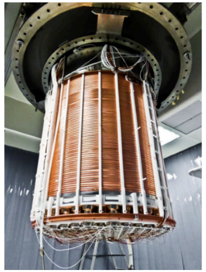
XENON project

15kg	161kg	3.2t	**8.6t**	50t
XENON10	XENON100	XENON1T	**XENONnT**	Darwin
2005 - 2007	2009 - 2016	2016 - 2018		



XENON project

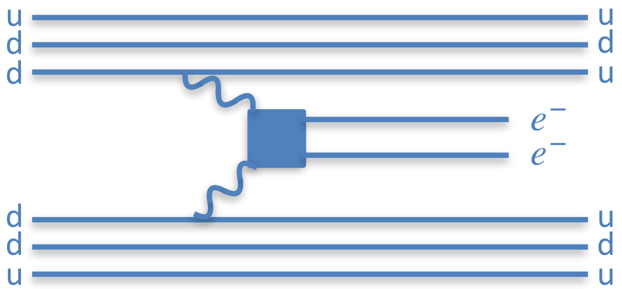
	XENON10	XENON100	XENON1T	XENONnT	Darwin
	15kg	161kg	3.2t	**8.6t**	50t
	2005 - 2007	2009 - 2016	2016 - 2018	**Now**	
exposure:	$0.87 \cdot$ kg yr	$48 \cdot$ kg yr	$1 \cdot$ t yr	**$20 \cdot$ t yr**	$200 \cdot$ t yr
BG level:	1	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-5}$	

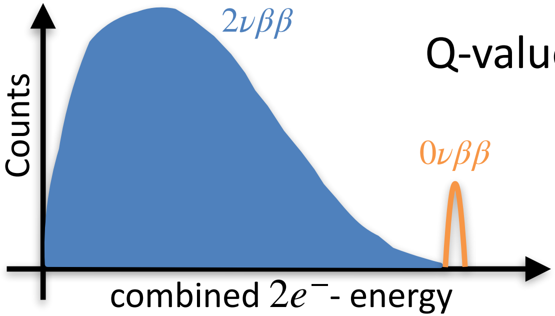

Neutrinoless double beta-decay

$$(0\nu\beta\beta)$$

Neutrinoless double beta-decay ($0\nu\beta\beta$)

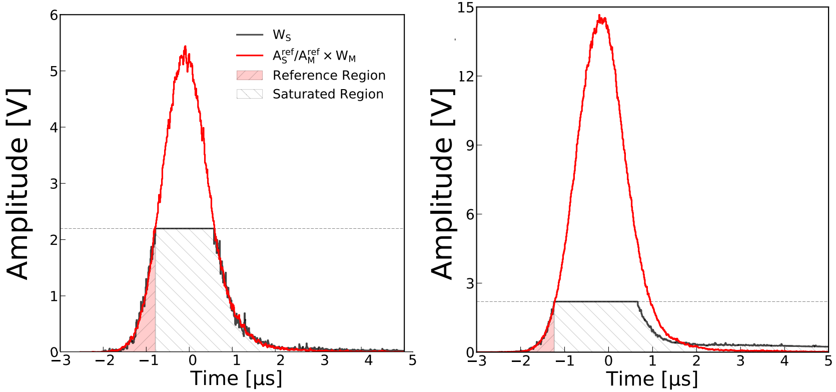


Expected signal:



Q-value: 2457.8keV

- Hints for:
  - Lepton number violation
  - Majorana neutrinos
- Large energy difference challenging:
  - Dark matter: O(keV)
  - $0\nu\beta\beta$: O(MeV)
    —> **dedicated correction needed!**
  - Nevertheless, excellent energy resolution of 0.8% in the MeV range.

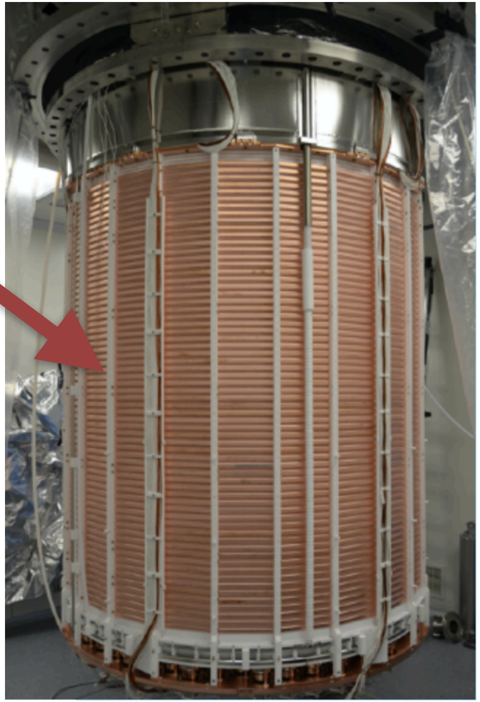


EPJ C (2020) 80:785

Neutrinoless double beta-decay

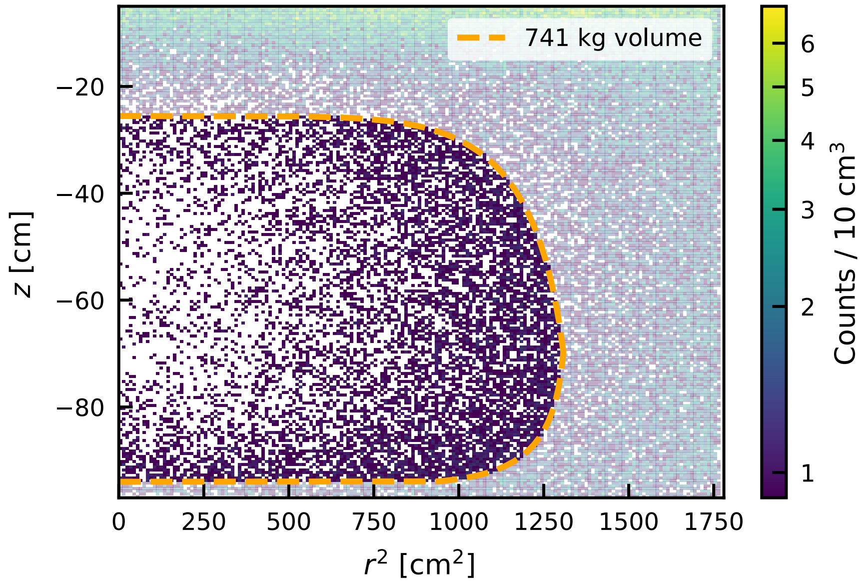
- ^{136}Xe is one the candidate isotopes to look for $0\nu\beta\beta$!
- Natural abundance of ^{136}Xe is 8.9%
  —> XENONnT contains several hundreds of kg of ^{136}Xe
- Even without enrichment good sensitivity

Filled with liquid xenon



Neutrinoless double beta-decay

- Exploiting 3D position reconstruction for fiducialisation of the analysis space
  —> 741 kg total mass of fiducial volume
- Science data blinded between 2300 and 2600 keV
- Lower limit at 90% CL from profiled likelihood:
  $T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24} yr$
- **Most stringent limit by a non-enriched dark matter detector!**



- Super-ellipsoidal shape to reduce material backgrounds while maintaining large signal acceptance

arxiv:2205.04158

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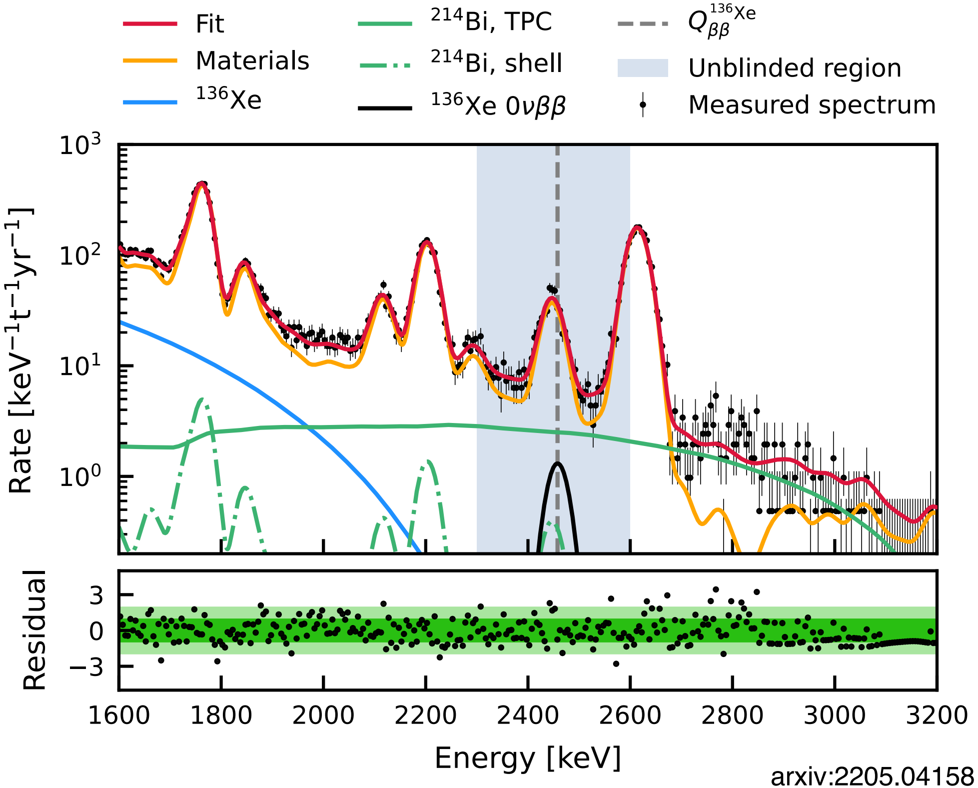
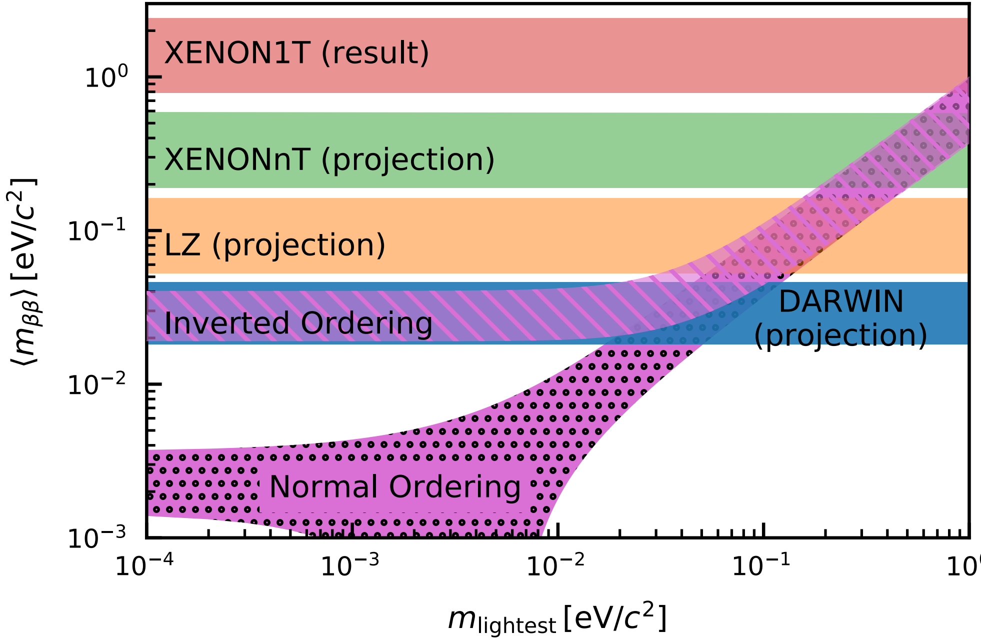


arxiv:2205.04158

Neutrinoless double beta-decay

- Promising projections for this technology in the upcoming generation of experiments
- More careful estimation of background components is needed due to larger size and lower background level
- Radiogenic and cosmogenic ^{137}Xe and ^{8}B solar neutrino scattering on atomic electrons taken into account



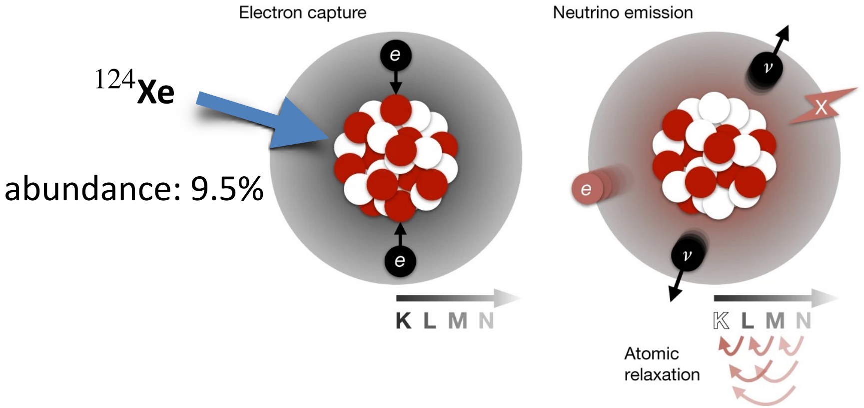
Eur. Phys. J. C 80, 808 (2020)
Phys. Rev. C 102, 014602 (2020)

arxiv:2205.04158

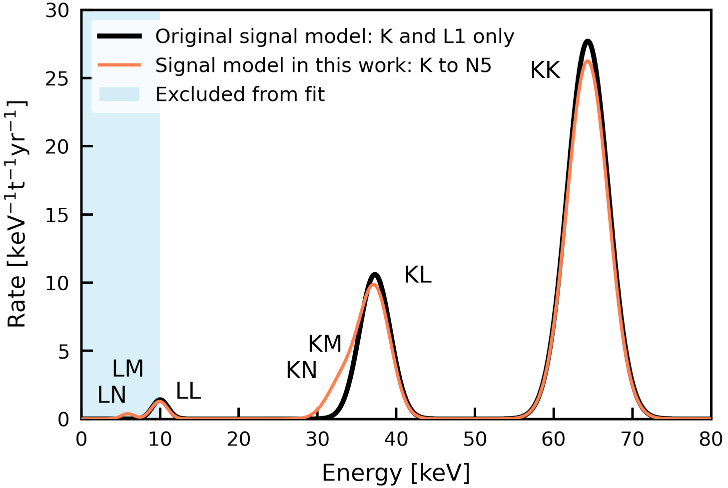
Two-Neutrino Double-Electron Capture

2vECEC

Two-Neutrino Double-Electron Capture



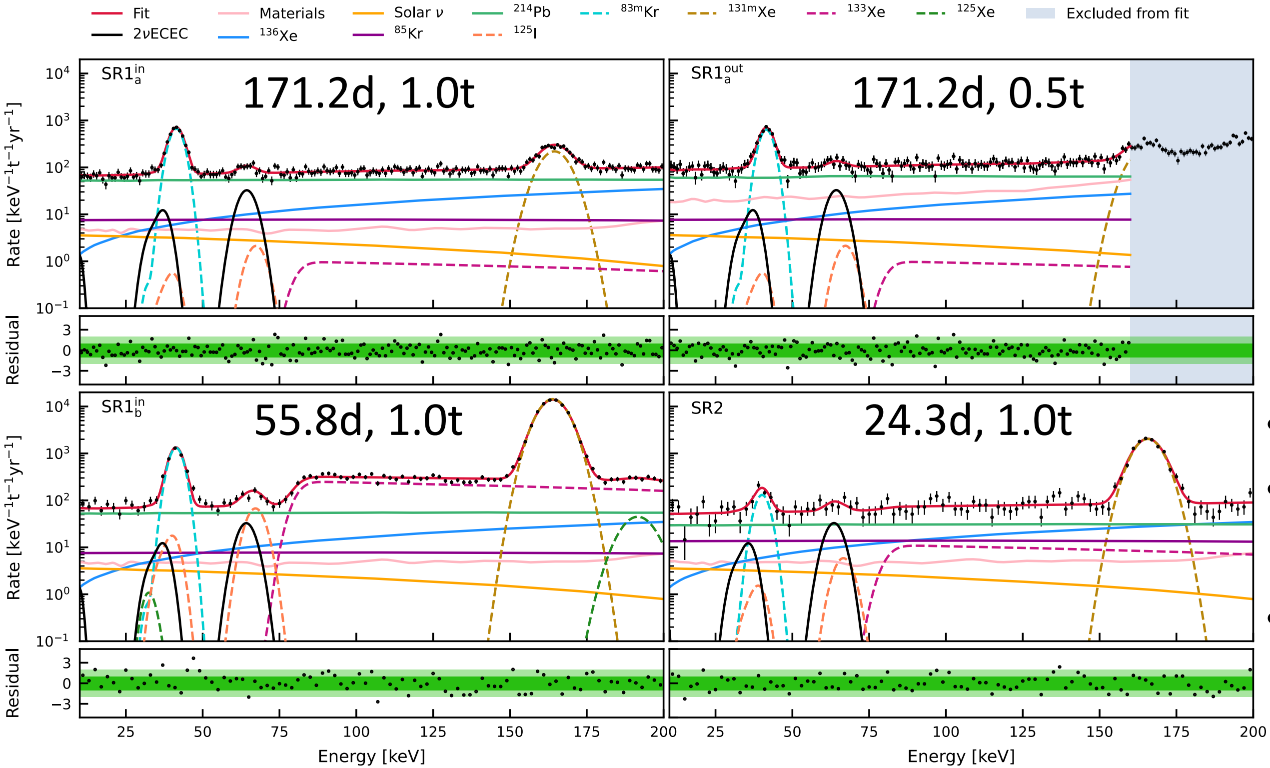
- Signal depends on the combination of atomic orbitals which capture the electrons
- KK-capture: 64.3 keV (72.4%)
- KL-, KM-, KN-capture: 32.4 - 37.3 keV (25.3%)
- LL-capture: 8.8 - 10.0 keV (1.4%)
- Rest: < 10keV (0.8%)

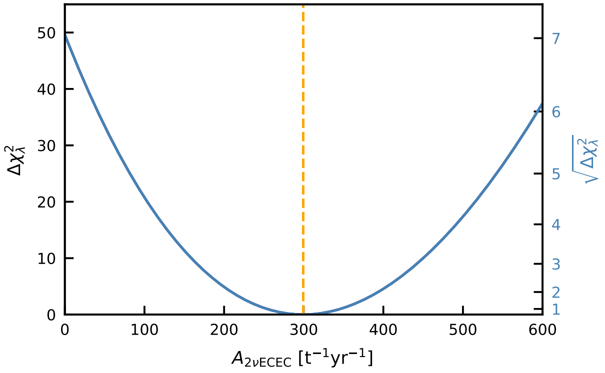


- Relative capture ratios calculated from overlap of K to N5 electron and nuclear wave functions

Nature 568, 532–535 (2019), arXiv: 2205.04158

Two-Neutrino Double-Electron Capture





- observed significance at 7.0σ
- best-fit rate: (300 ± 50) events/t/yr
- $T_{1/2}^{2\nu ECEC} = (1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\, yr$

Longest half-life ever measured directly!

fit performed considering different runs and background levels

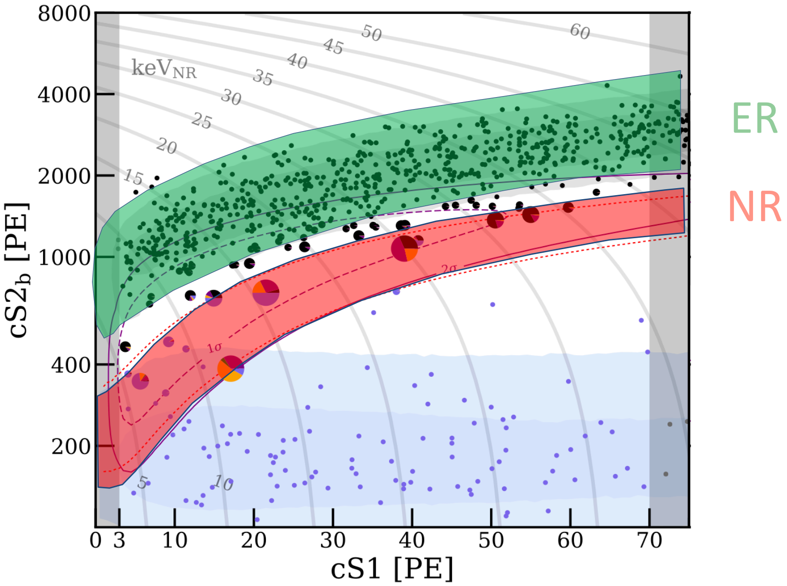
arxiv:2205.04158

XENON1T low energy excess

in the light of **neutrino magnetic moment**

XENON1T low energy excess

- Electronic recoil band also offers interesting physics at very low energies!
- Detector calibration allows convert the cS1 and cS2 signal into the deposited energy of an event in the detector
- Allows for comparison of data and MC prediction
- Looking for an excess above known background



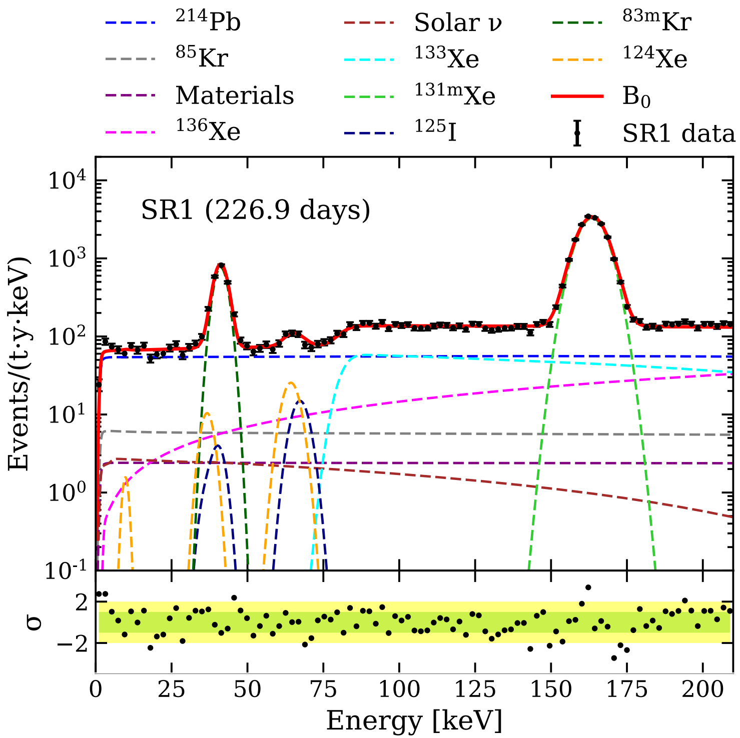
XENON1T low energy excess

PRD 102, 072004 (2020)

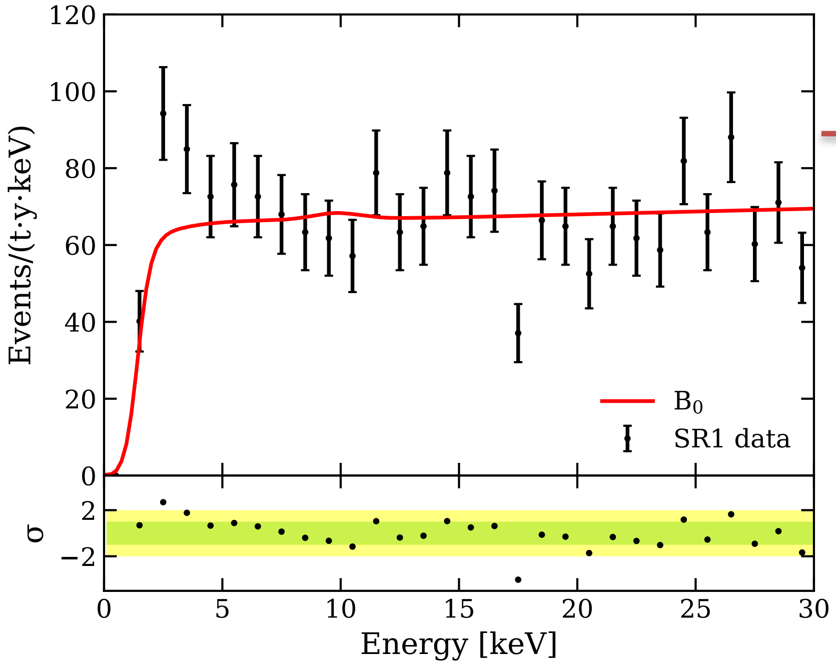
- Background model considers different background components
- Different data-partitions fitted simultaneously
- Overall good agreement between data and fitted model over a large fraction of the energy range
- Fitted rates are consistent with expectations

$$(76 \pm 2)\frac{events}{t \cdot yr \cdot keV} \text{ in } (1, 30) \text{ keV}$$

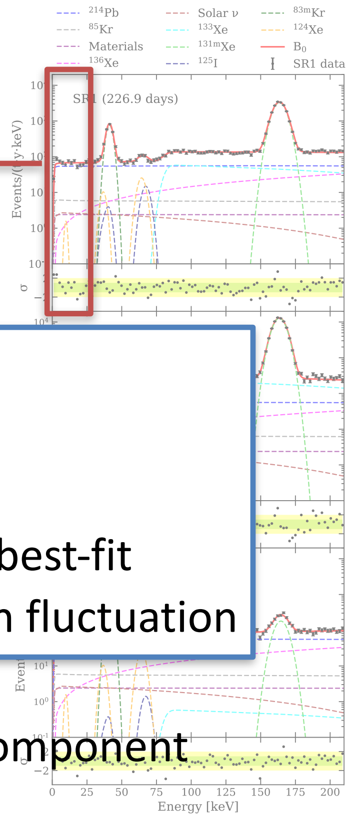
Lowest background rate ever achieved in this energy range!



XENON1T low energy excess



PRD 102, 072004 (2020)



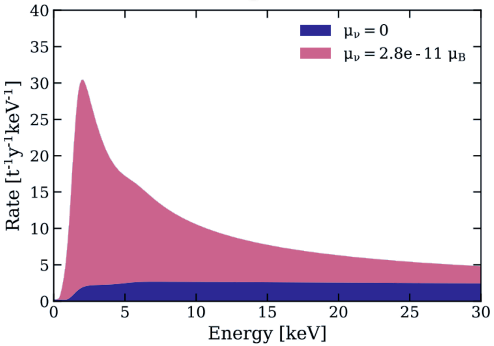
Excess between 1-7keV

- 285 events observed
- 232 events expected from best-fit
- Would be a 3.3σ Poissonian fluctuation

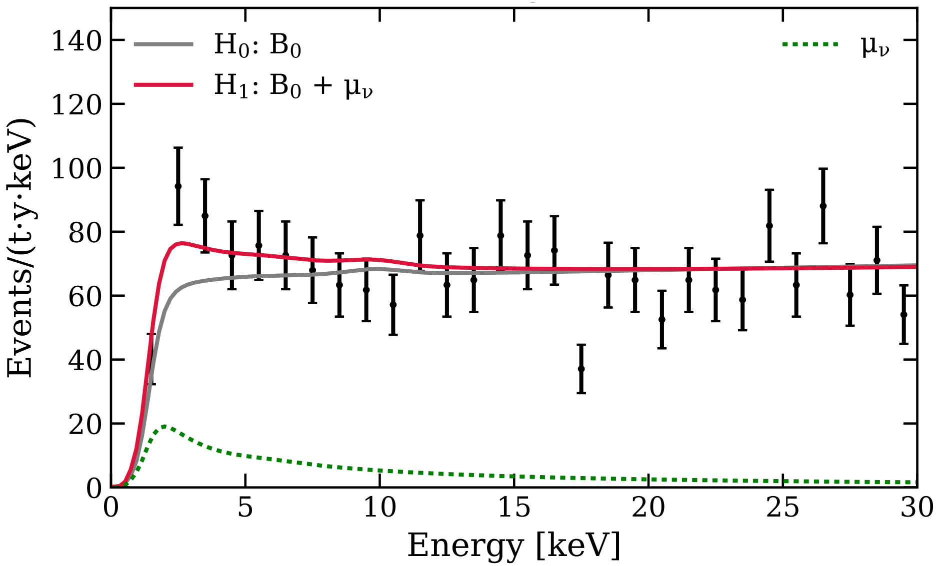
Caveat: We cannot constrain the impact from tritium as a background component

Neutrino magnetic moment

- Magnetic moment of the neutrino would cause interaction with electrons of xe-nuclei:



- Fit prefers a neutrino magnetic moment component over the background-only fit with 3.2σ

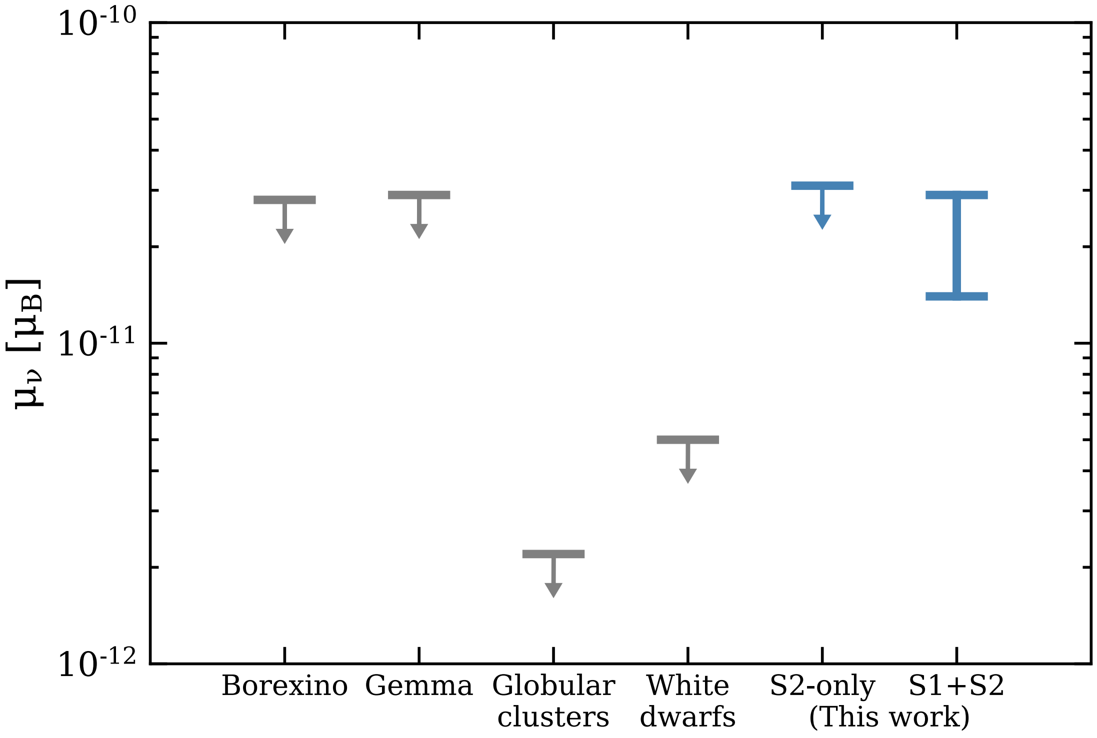


though it reduces to 0.9σ when also including a tritium component

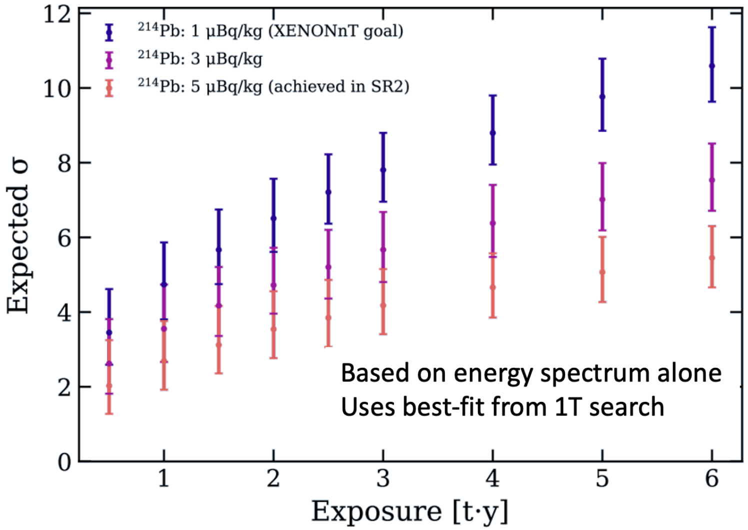
Neutrino magnetic moment

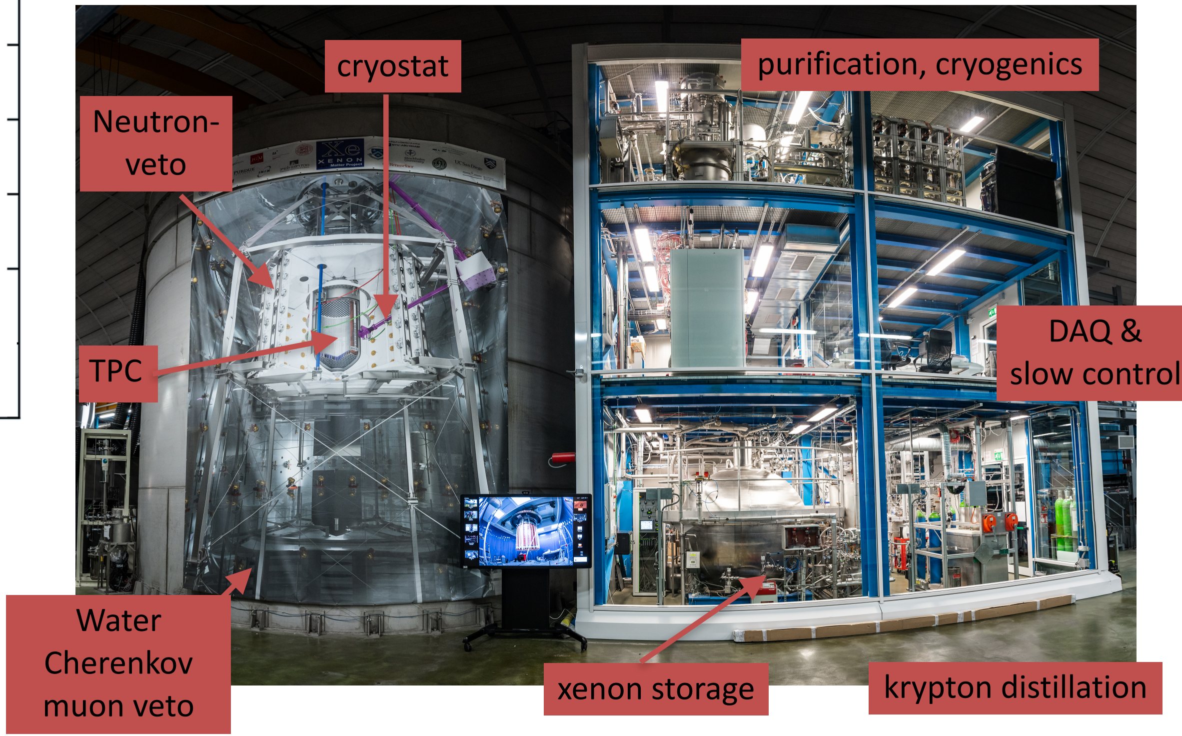
Context to other results:

- $\mu_\nu \in (1.4, 2.9) \times 10^{-11} \mu_B$ at 90% confidence level
- Compatible with other experiments, but in tension with astrophysical constraints
  arXiv:1910.10568, arXiv:1907.00115



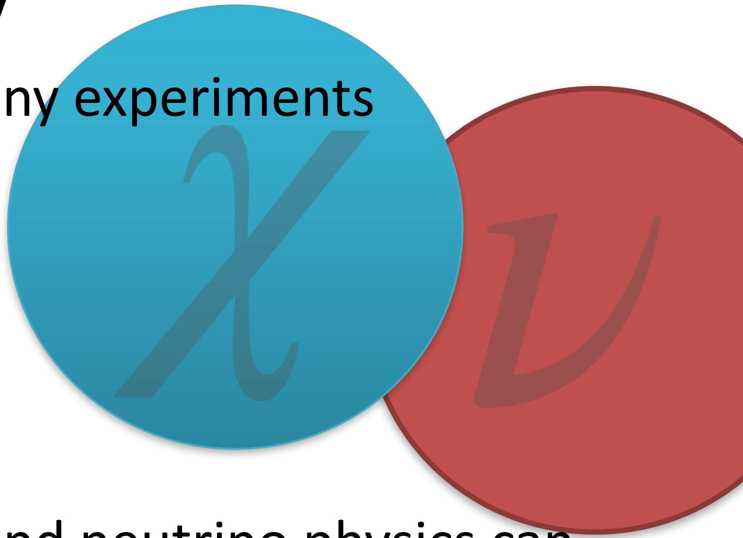
XENONnT Experiment





- 4 times larger fiducial volume
- ~1/6 reduced background level
- Data-taking ongoing
- possible to discriminate between new physics from tritium hypothesis **after a few months of data-taking**

Summary



- Search for dark matter a rich field with many experiments
- Different efforts ongoing which require
  - large active mass
  - low energy threshold
  - low background rate
- Synergies between dark matter searches and neutrino physics can be enhanced in the future
- Interesting neutrino physics already feasible with ongoing dark matter search machines