Dark Matter Direct Detection with Liquid Xenon

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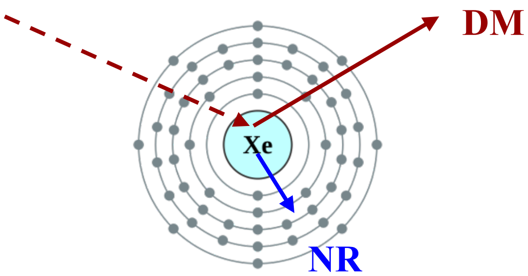
Revealing the history of the universe with underground particle and nuclear research 2019
Tohoku University, Sendai, March 7-9, 2019

How to detect dark matter directly?

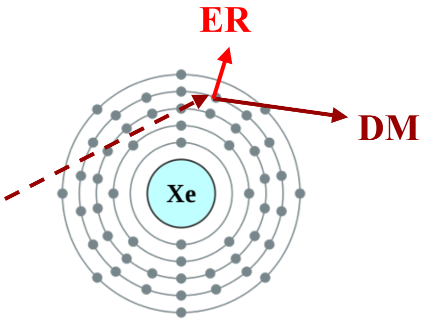
Via nuclear recoil (NR)

- Spin-independent DM
- Spin-dependent DM
- Pion-coupling WIMPs
- more than these: EFT approach
- Self-interacting DM



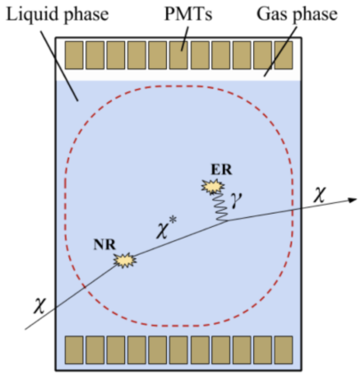
Via electronic recoil (ER)

- sub-GeV DM
- Dark photons
- Axion-like particles
- SuperWIMPs
- Axial-vector
- Luminous DM



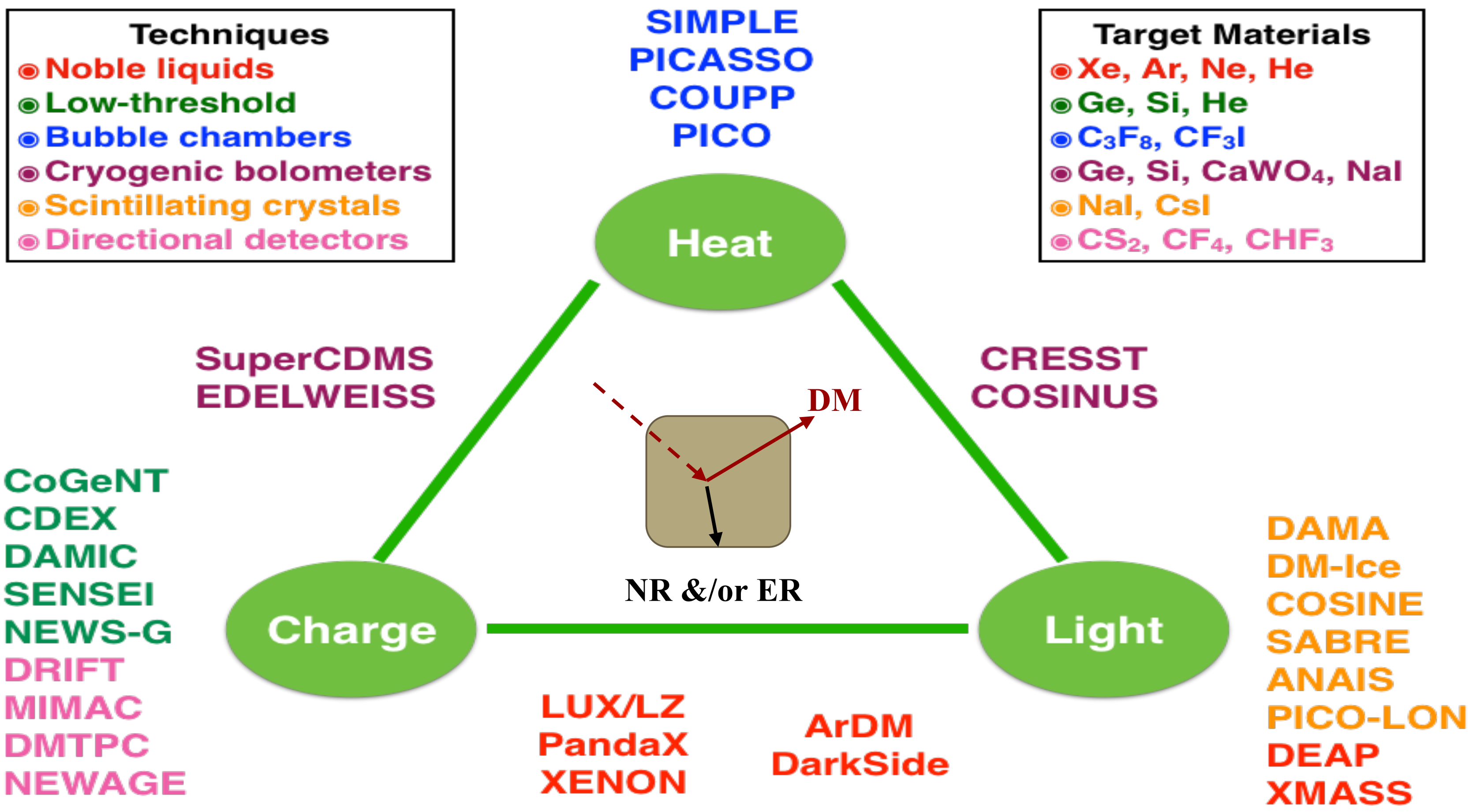
Or a mixture of ER & NR

- inelastic DM
- Magnetic inelastic DM
- Mirror DM
- Migdal/Bremsshtrahlung

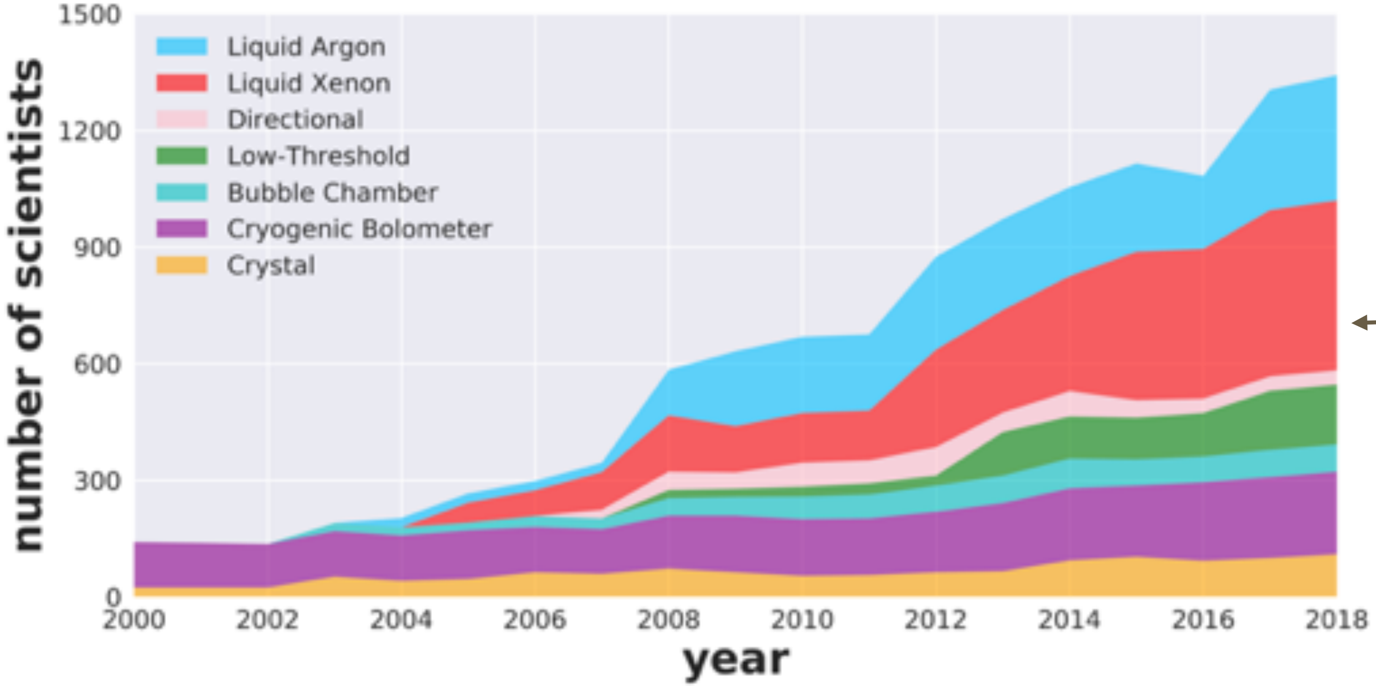


XENON100, arXiv:1704.05804

Detection techniques and target materials



A booming research field



this talk

What makes LXe the most favorable target?

Rich Physics Goals

- Probe many DM models
  - SI & SD & EFT
  - Inelastic etc.
  - Heavy or sub-GeV
  - ALPs, dark photon
  - etc.
- Neutrino astrophysics
  - Elastic scattering of solar neutrinos (pp)
  - CEvNS of B8 neutrinos
  - Supernova neutrinos
- Neutrino physics
  - 0vbb with Xe-136
  - DEC with Xe-124

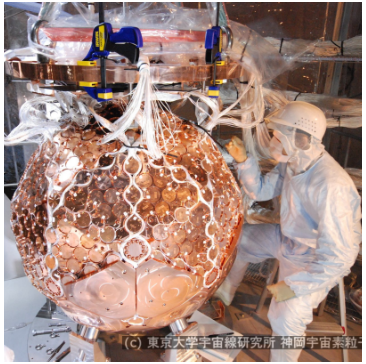
Mature Technology

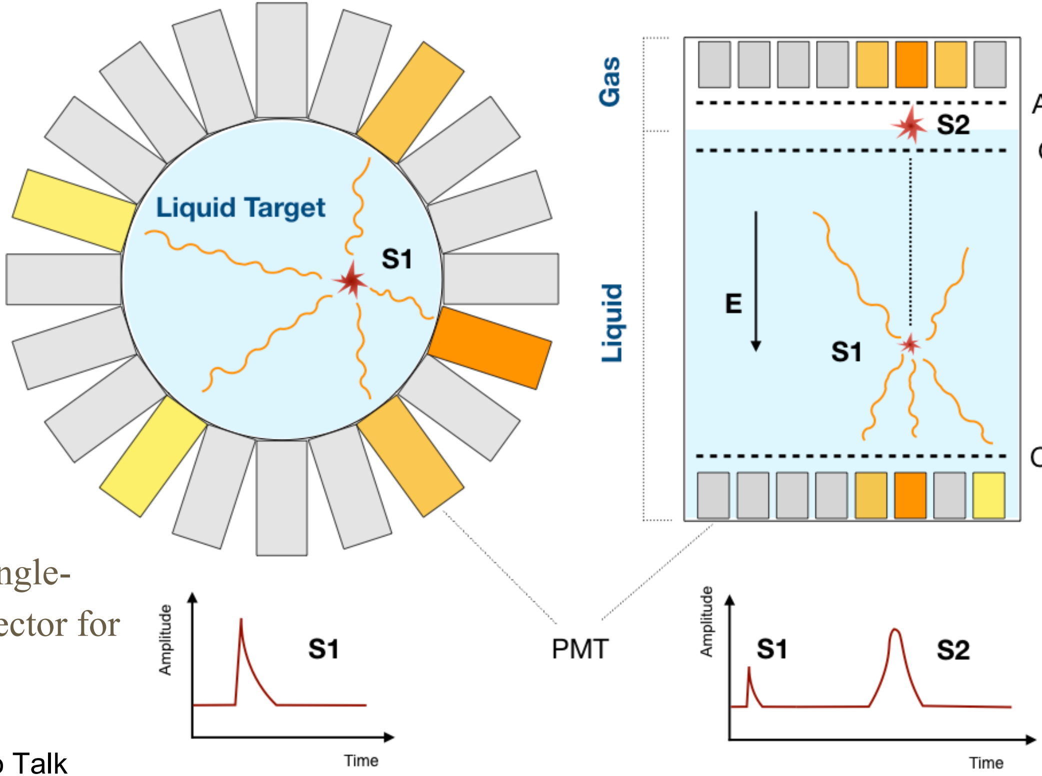
- Large target
  - online purification of the liquid/gas target
  - multi-ton target demonstrated
  - Next generation: 50~100 ton
- Low background
  - Intrinsically pure and purifiable
  - self-shielding
  - 3D localization
  - ER/NR discrimination
- Low threshold
  - keV threshold with both charge and light
  - O(10) eV threshold with charge only

How to build your LXe dark matter detectors?

Single phase

Two phase





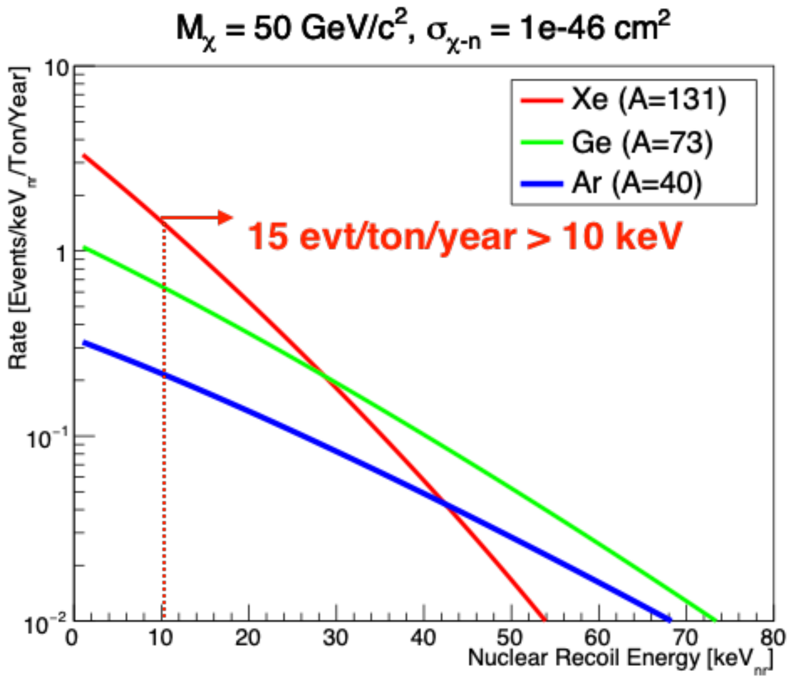
XMASS: the largest single-phase liquid xenon detector for dark matter

XENON1T: the largest two-phase liquid xenon detector ever built for dark matter

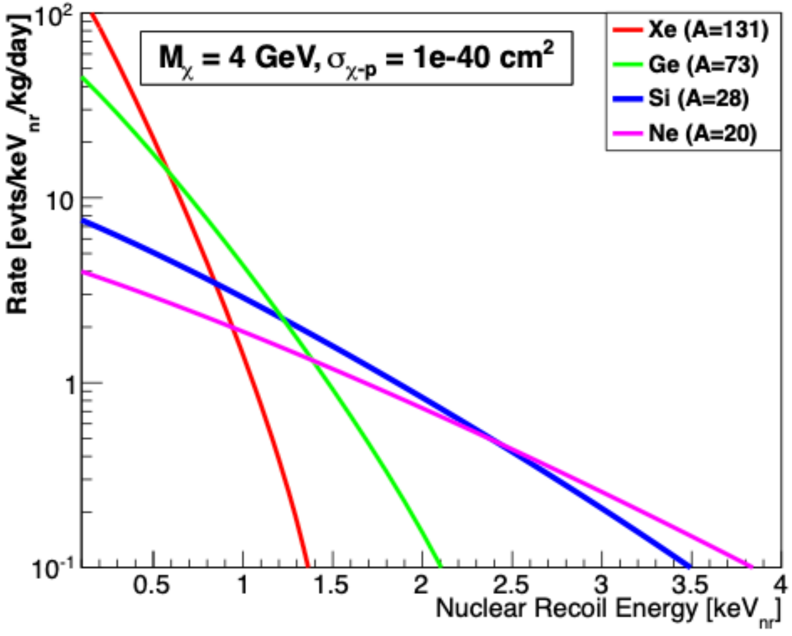
➔ Yasuhiro Kishimoto Talk

Rates for "standard" WIMP spin-independent interactions

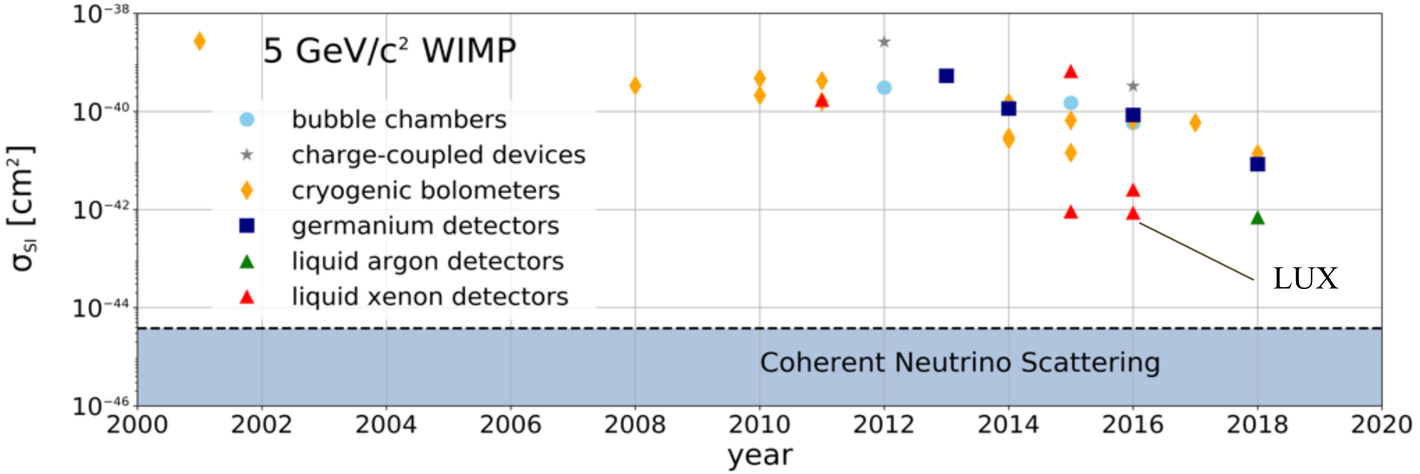
Heavy WIMPs

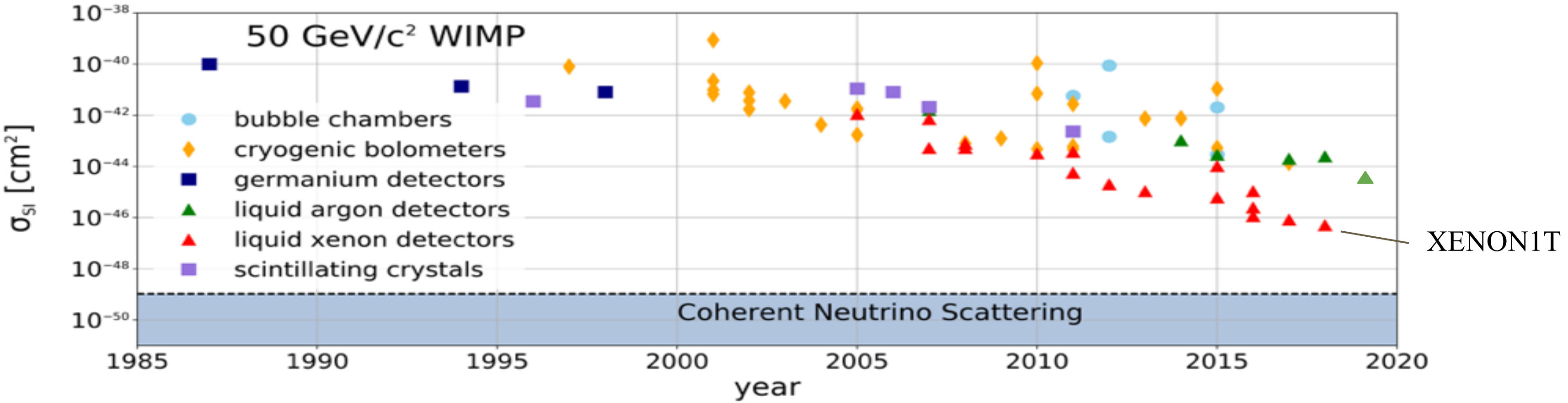


Low-Mass WIMPs

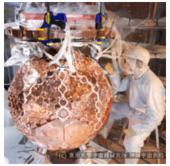


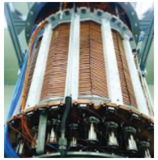
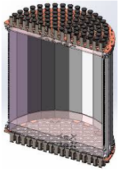
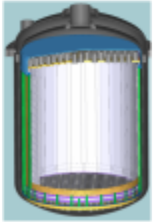
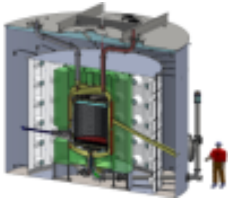
LXe detectors push the frontier of DM detection





The evolution of dark matter detectors with LXe

Concept of using LXe for DM Detection

DAMA/LXe, ZEPLIN, XMASS, XENON

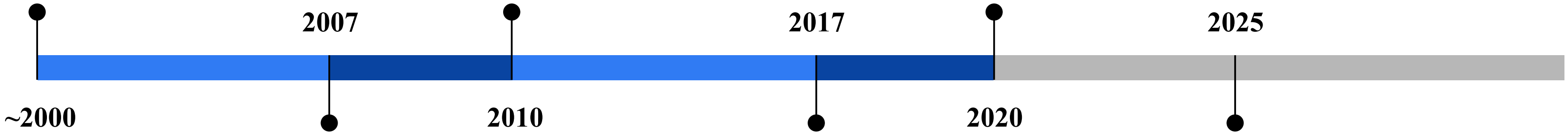
G1 Experiments (0.1~1 Ton)

XENON100, LUX, PandaX-I/II, XMASS

G2 Experiments (1~10 Ton, two-phase)

XENON1T/nT, PandaX-4T, LZ

XENONnT



First Results from Two-Phase Xe detectors

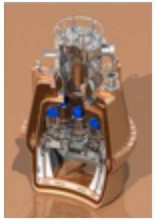
XENON10, ZEPLIN-II/III

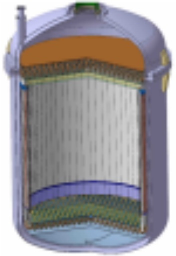
First results from the ton-scale detector

XENON1T

G3 Experiments (10~100 T, two-phase)

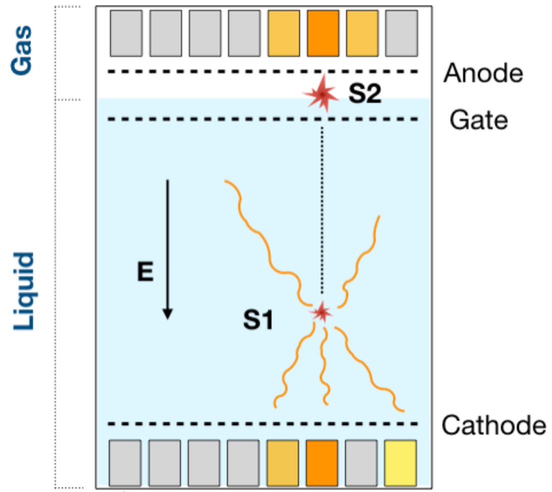
DARWIN, PandaX-30T

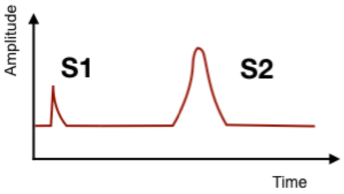



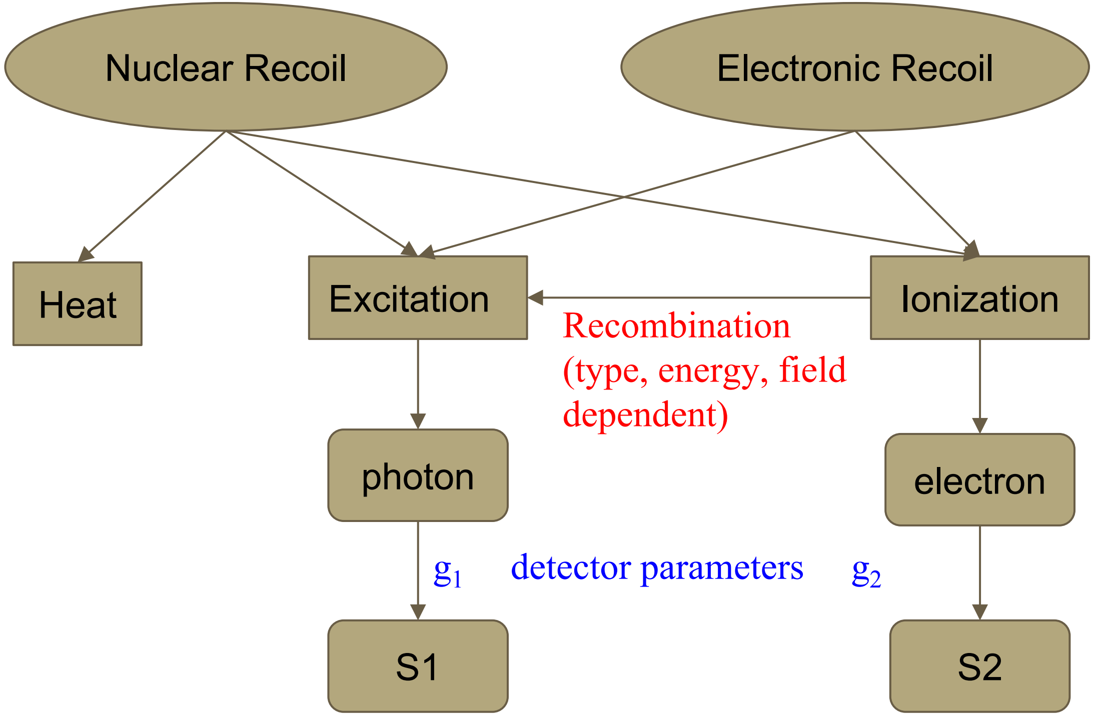



(size not in scale)

Understanding the signals (S1 & S2)







$$E_{obs} = (n_{ph} + n_e) \cdot W = (\frac{S1}{g_1} + \frac{S2}{g_2}) \cdot W$$

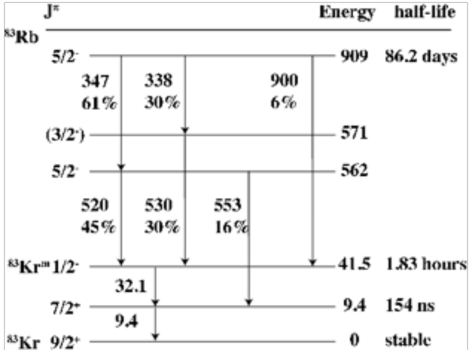
Years of effort to calibrate and understand LXe

AmBe

Rn220

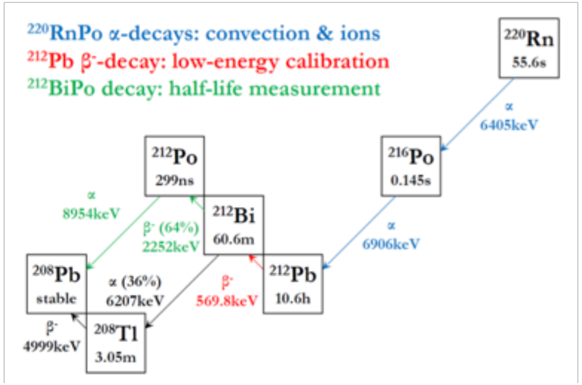
Kr83m

^{83m}Kr: to calibrate the energy response



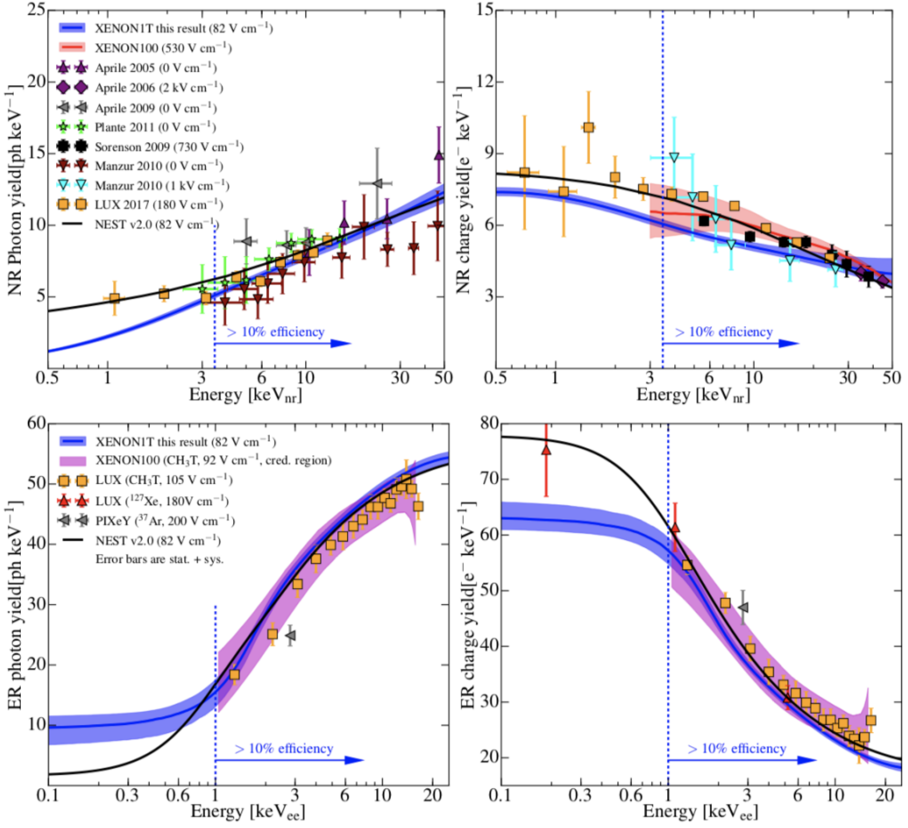
- External gamma rays: limitations
- Gaseous sources are developed:
  - ^{129m}Xe, ^{131m}Xe, ^{127}Xe, ^{83m}Kr, ^{37}Ar
  - Tritium (CH3T), ^{14}CH4, first in LUX
  - ^{220}Rn, first in XENON1T
- Nuclear recoils
  - Neutrons from AmBe or DD generator
  - High energy: DT?
  - Low energy: YBe?
  - Gaseous source??

^{220}Rn: to calibrate the Electronic Recoils (ERs)

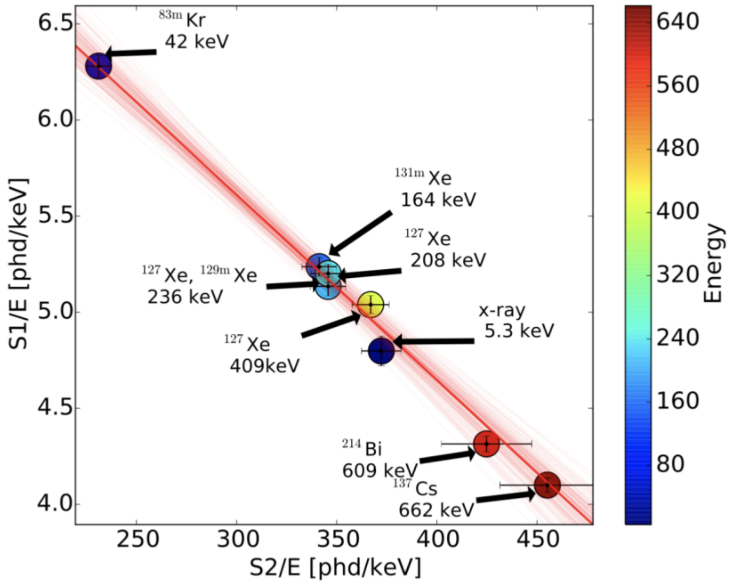


Calibrating LXe detectors: more accurate than ever

XENON1T, arXiv:1902.11297



LUX, arXiv:1712.05696

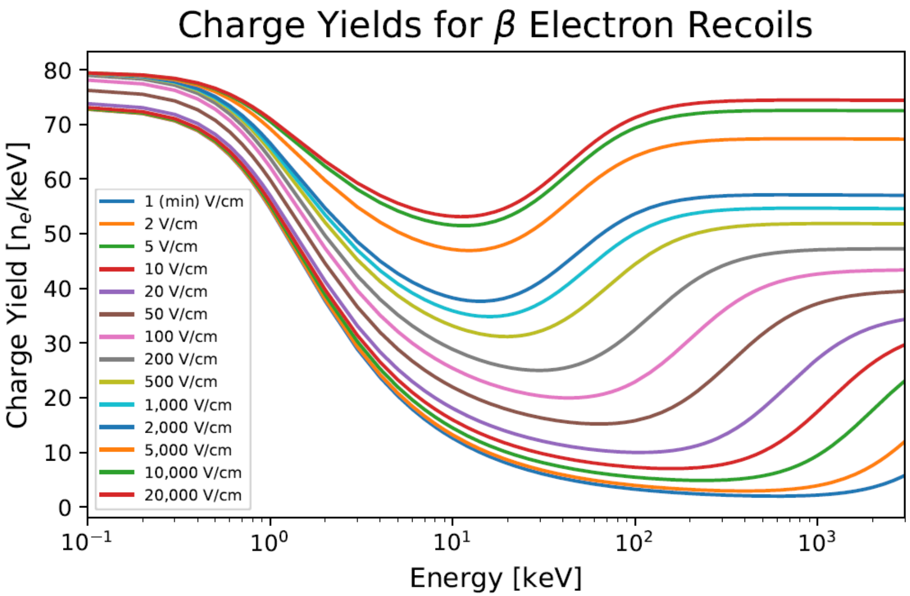


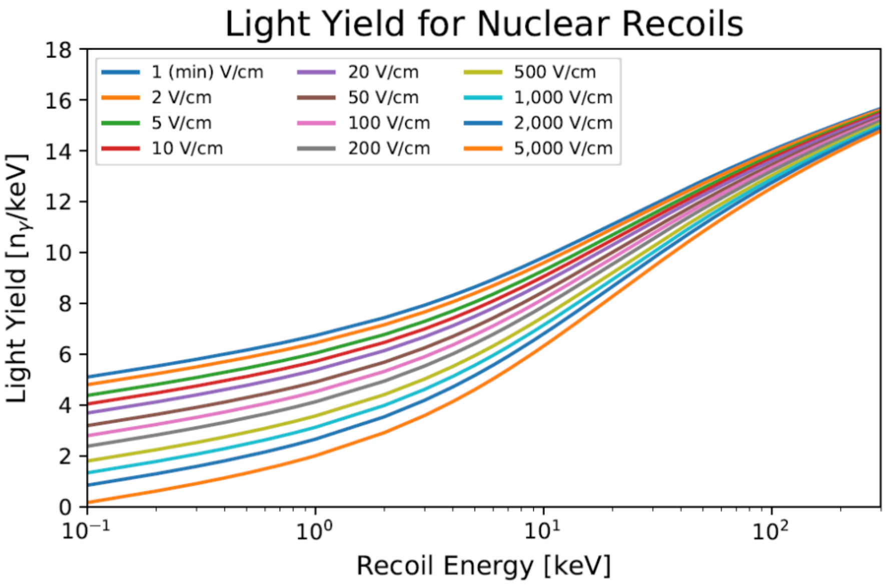
"Doke plot" to determine g1, g2 factors

Calibrating LXe detectors: more accurate than ever

Noble Element Simulation Technique (NEST) provides liquid xenon responses from global data fitting

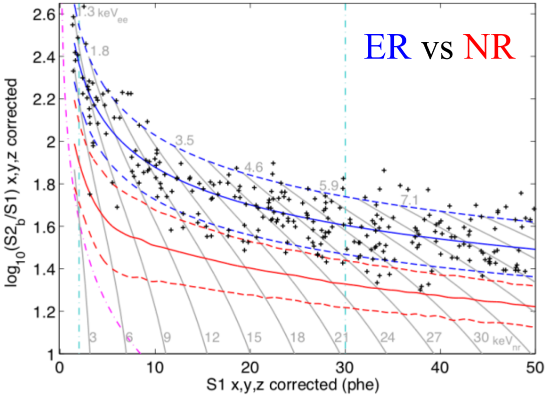
NEST v2.0 is now available: http://nest.physics.ucdavis.edu

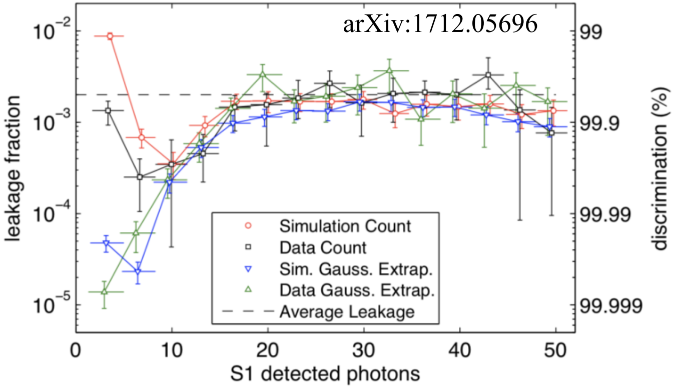




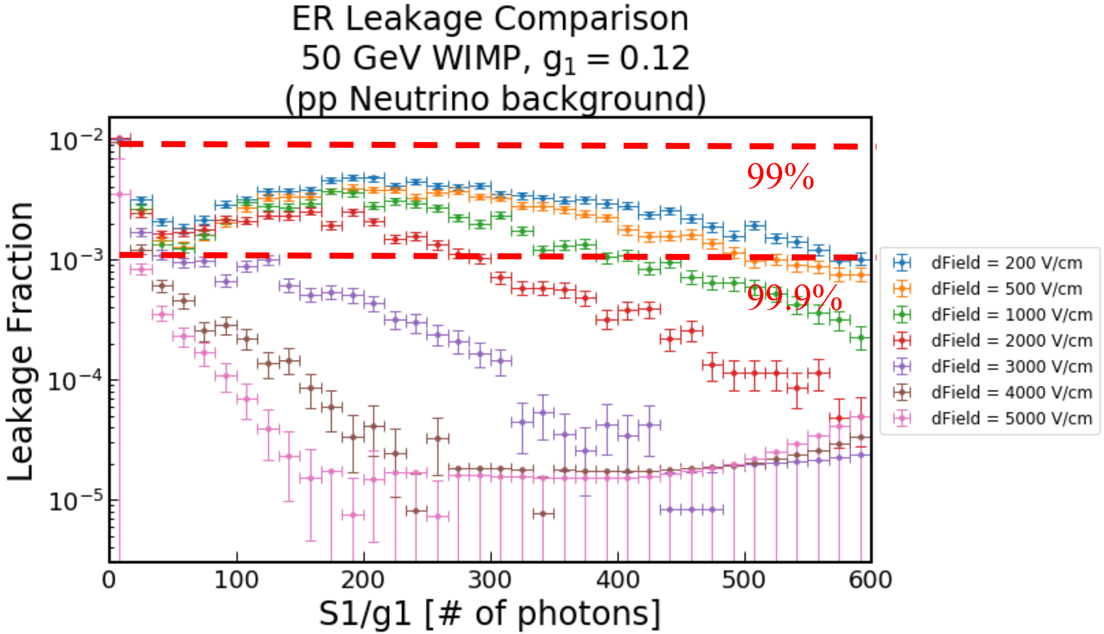
Using the S1 & S2 signals: ER/NR discrimination

LUX as an example





Most of LXe experiments show discrimination in the range of 99.5% to 99.9%. This is sufficient so far but it will become necessary to go above 99.9% for future experiment to suppress ER background events from solar neutrinos



Simulated results using NEST v2.0 (Zehong Zhao, UCSD)

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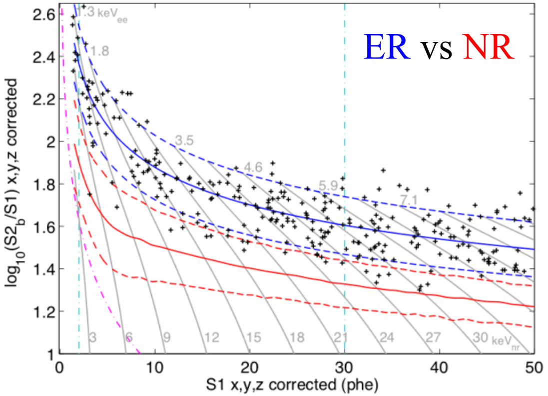
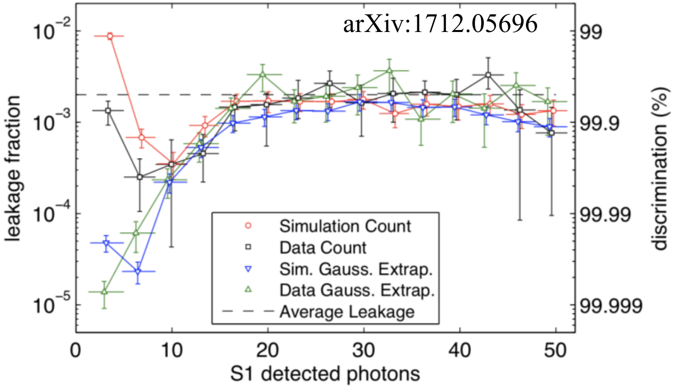
LUX as an example





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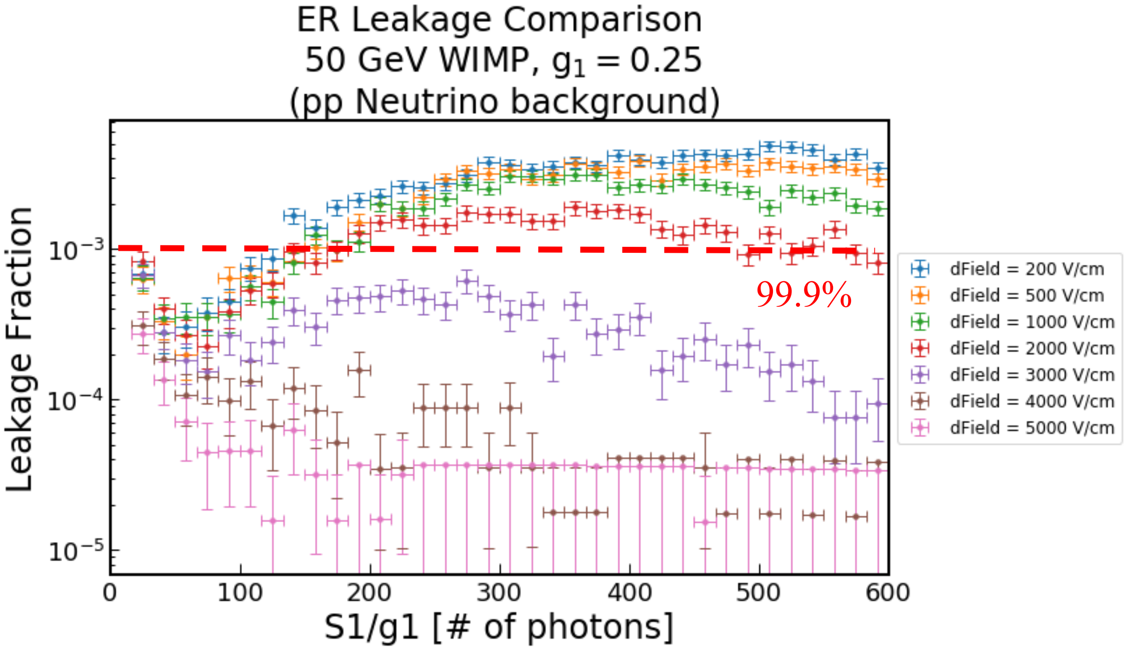
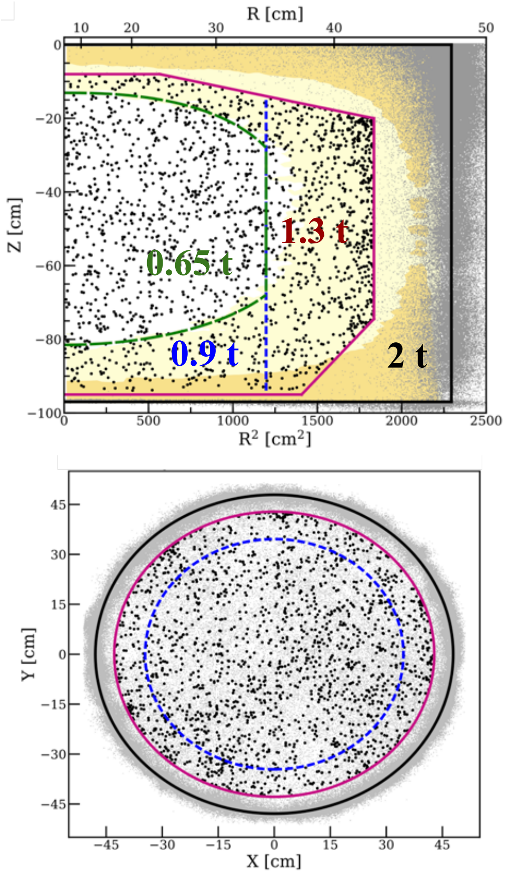


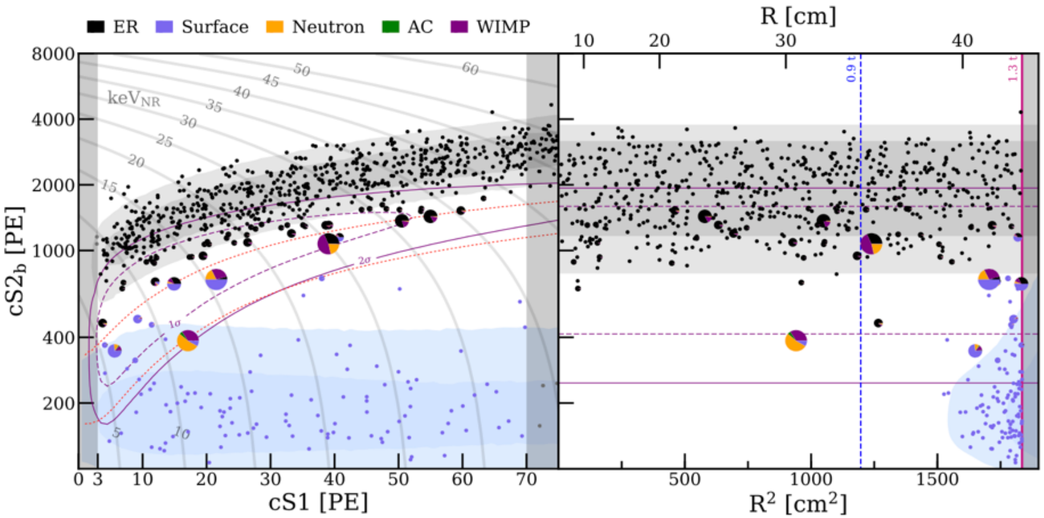
Simulated results using NEST v2.0 (Zehong Zhao, UCSD)

Using the S1 & S2 signals: positions and fiducialization

XENON1T as an example



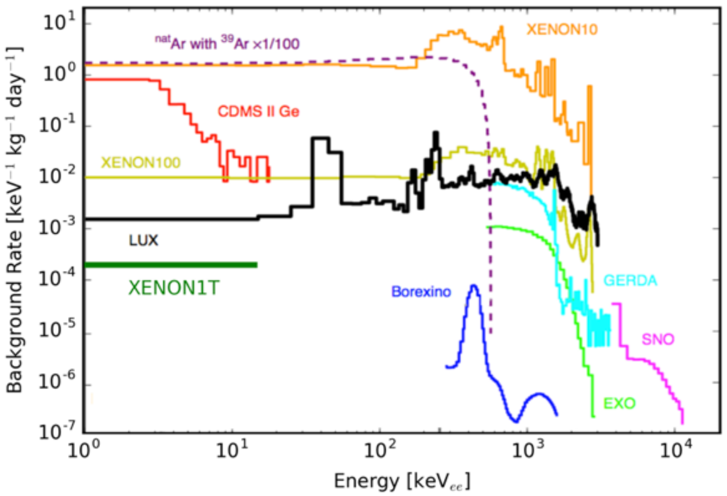
Combining ER/NR discrimination and fiducilization makes two-phase LXeTPC experiments very powerful in background rejection



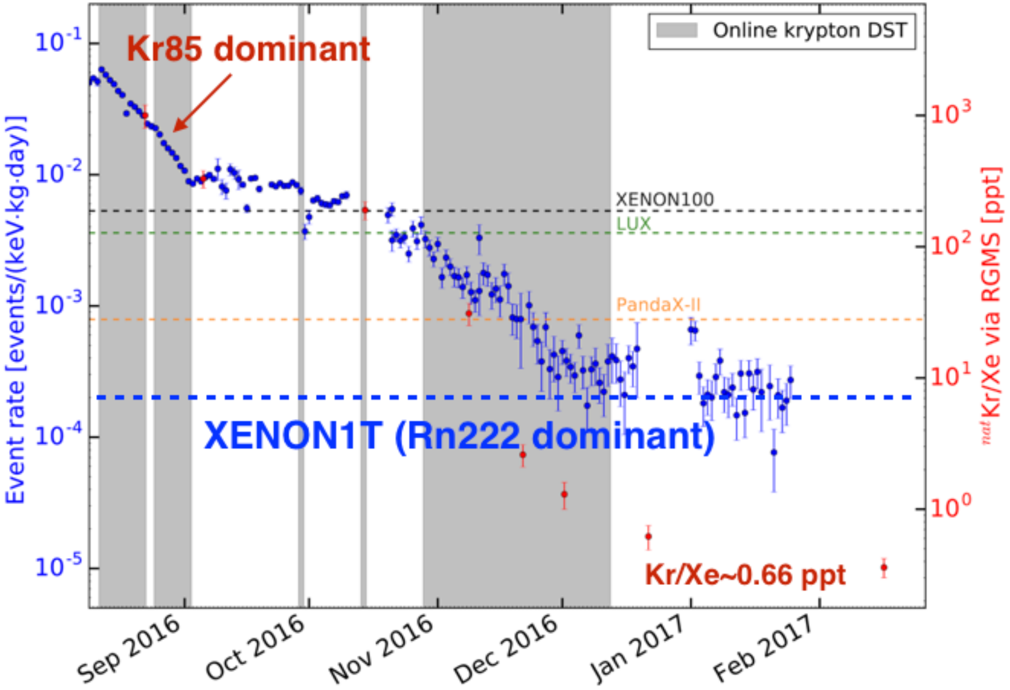
arXiv:1805.12562, PRL

Background reduction over the years

ER background rate before ER/NR discrimination



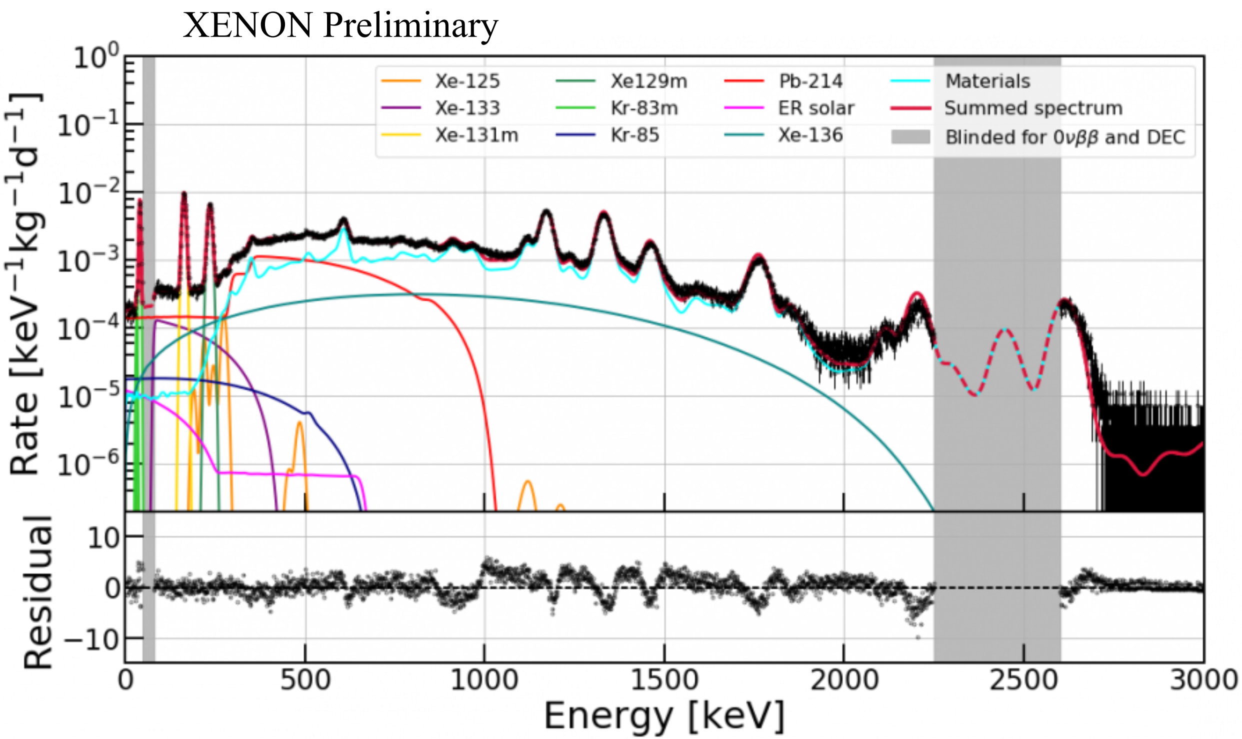
XENON1T, background rate evolution with online Kr-reduction (distillation)

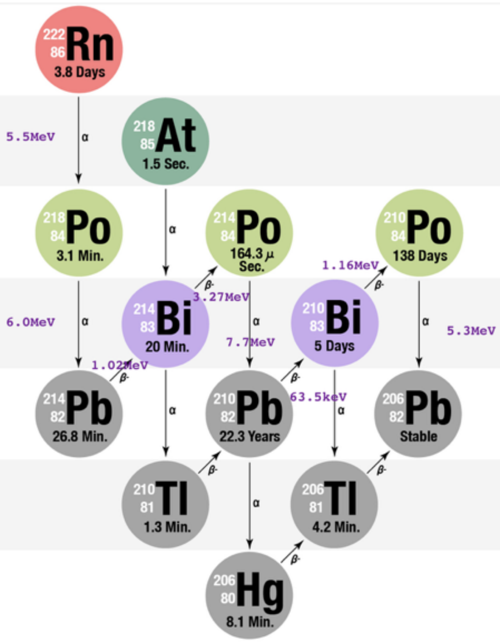


LXe experiments reduce ER background significantly thanks to:

- Low radioactive material selection
- Purification of xenon gas
- Powerful fiducilization

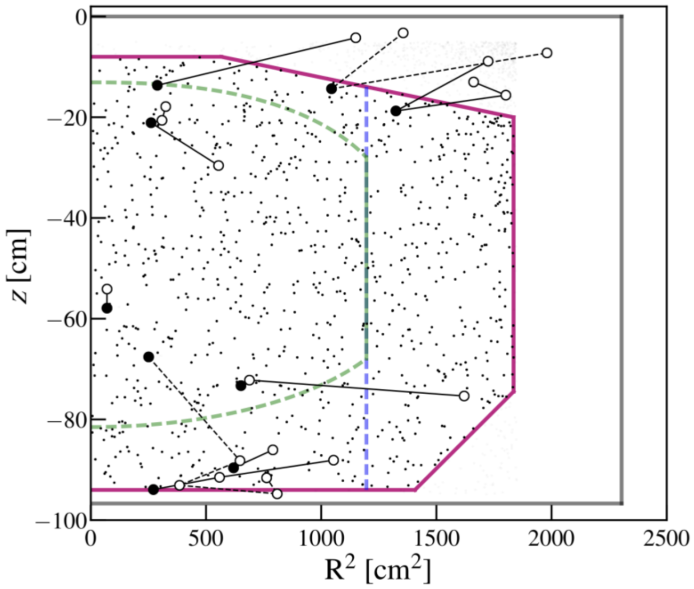
ER background: lowest achieved by XENON1T, but dominated by Radon in the bulk LXe

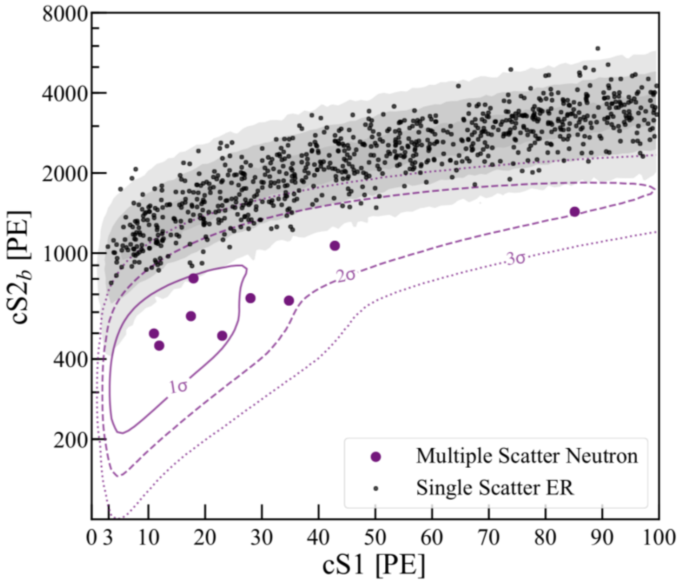




NR Background from neutrons

XENON1T, arXiv:1902.11297



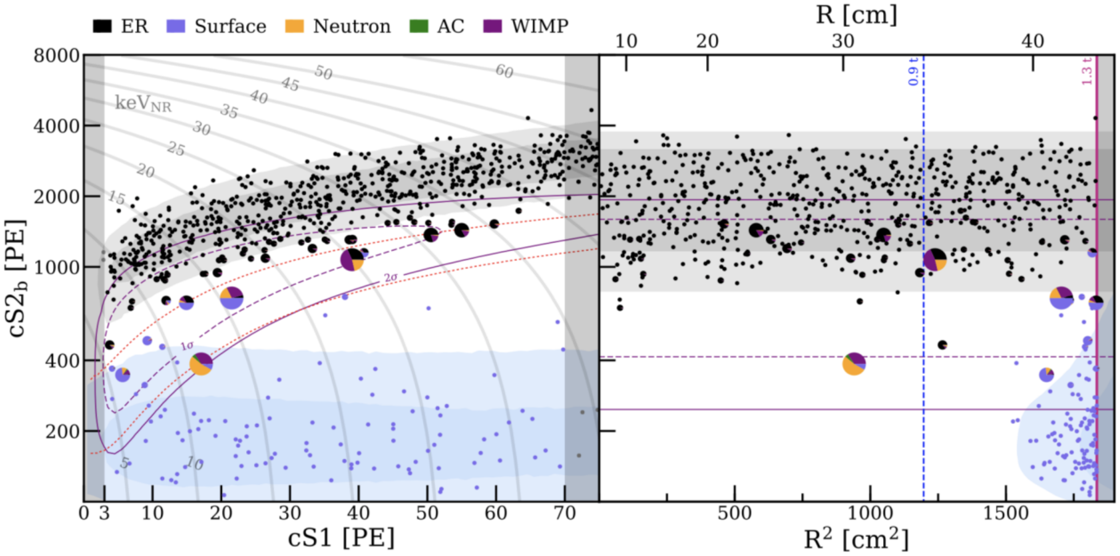


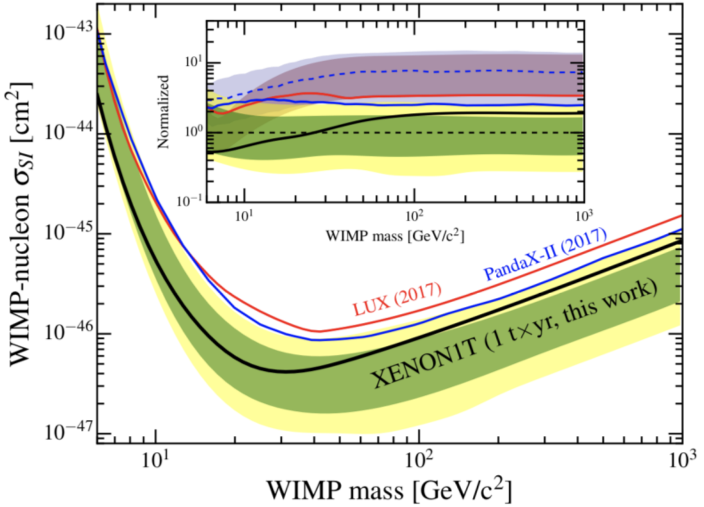
Neutrons make multiple scattering in LXe. Multiple scatter neutrons are rejected in DM search, but can be used to estimate single scatter neutron background. **Single NR background is a concern for the upcoming experiments.**

Highlight of Recent Dark Matter Results

XENON1T: largest exposure & lowest background

- Exposure: one tonne x year (Nov.22, 2016 ~ Feb.8, 2018)
- Dominant ER background: 82 events/ton/yr/keVee
- Best **Spin-independent** limit: 4.1 x 10^{-47} cm^2 at 30 GeV/c^2



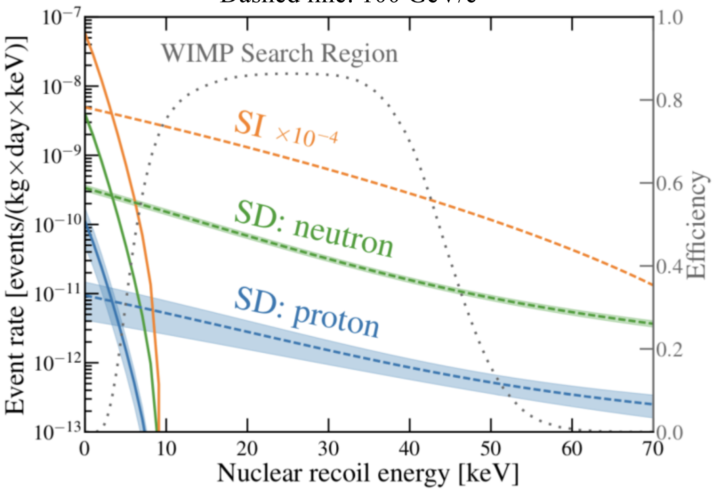


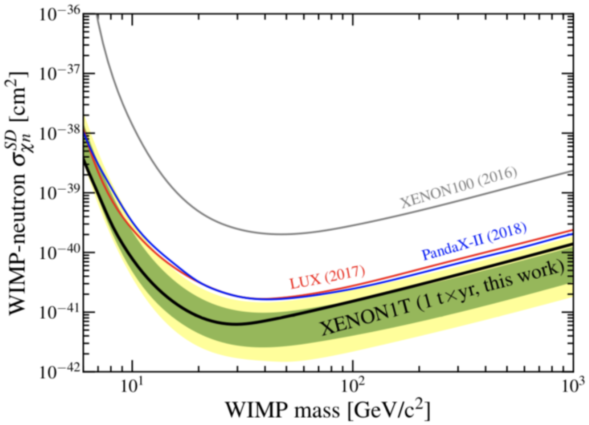
arXiv:1805.12562
Phys. Rev. Lett. 121, 111302 (2018)

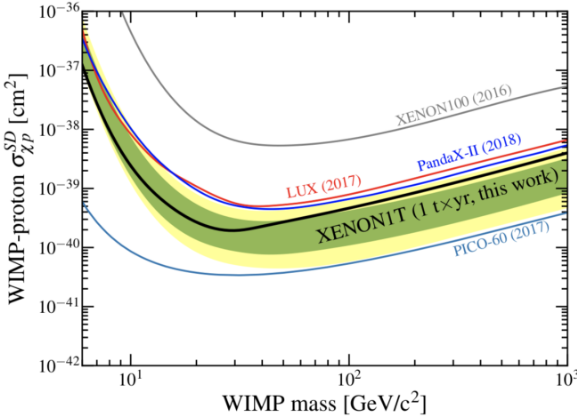
XENON1T: the best SD-neutron limits

- Best WIMP **Spin-Dependent** (neutron) limits: 6.3 x 10^{-42} cm^2 at 30 GeV/c^2

Solid line: 10 GeV/c^2
Dashed line: 100 GeV/c^2





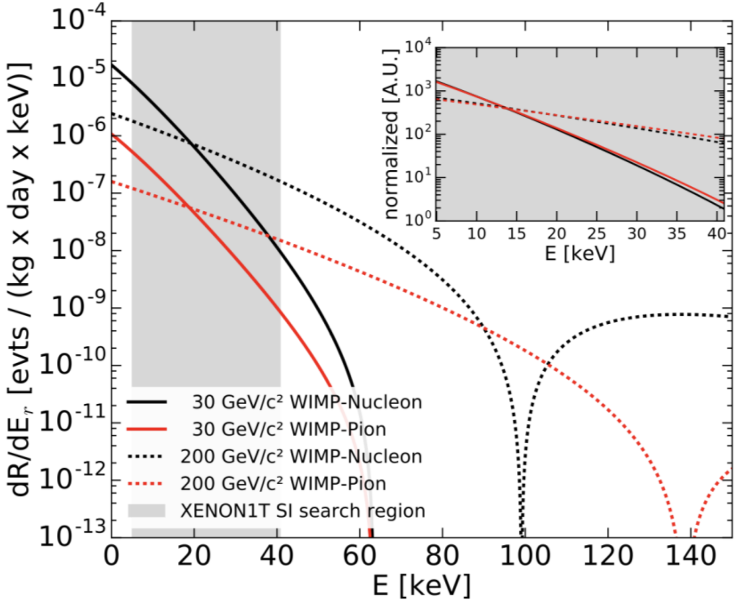


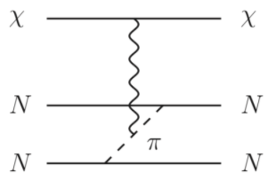
arXiv:1902.03234, submitted to PRL

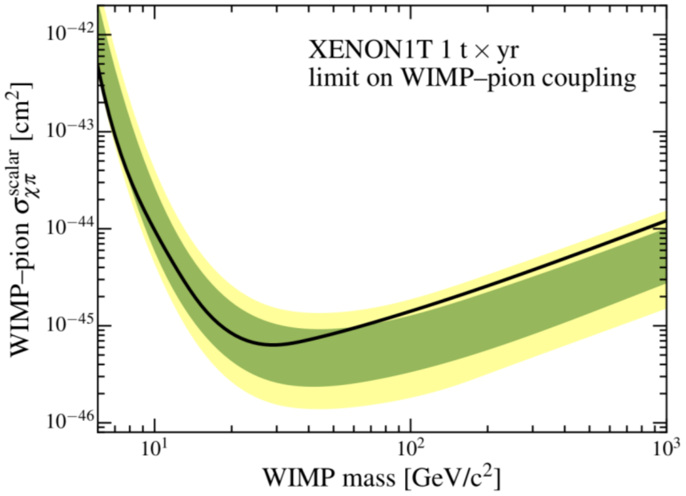
XENON1T: first results on WIMP-pion coupling

- Best **WIMP-pion** limit: 6.4 x 10^{-46} cm^2 at 30 GeV/c^2

For cross sections at 10^{-46} cm^2





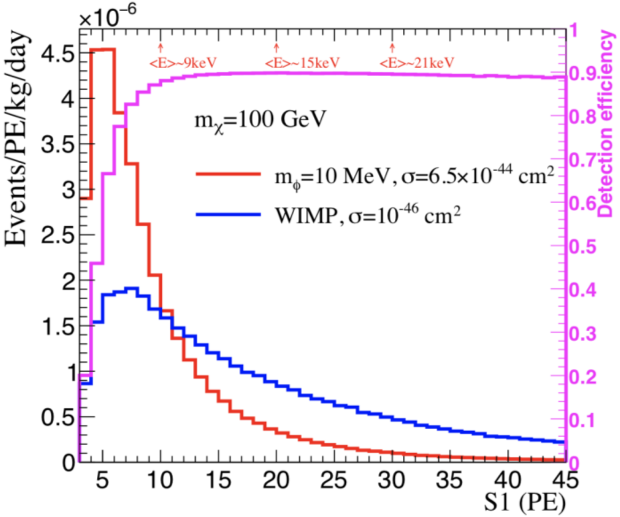


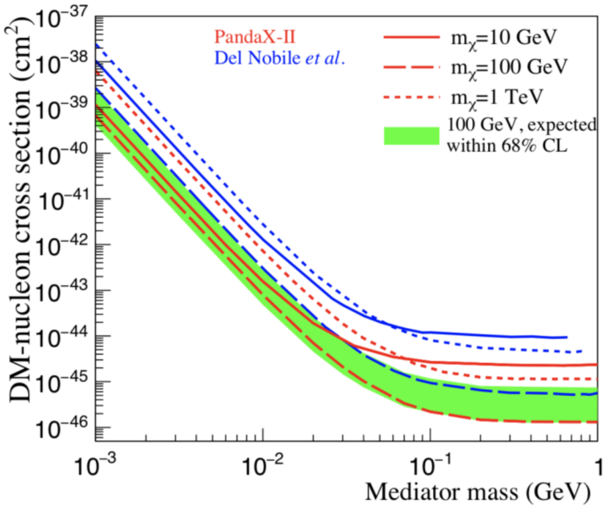
arXiv:1811.12482
Phys. Rev. Lett. 122, 071301 (2019)

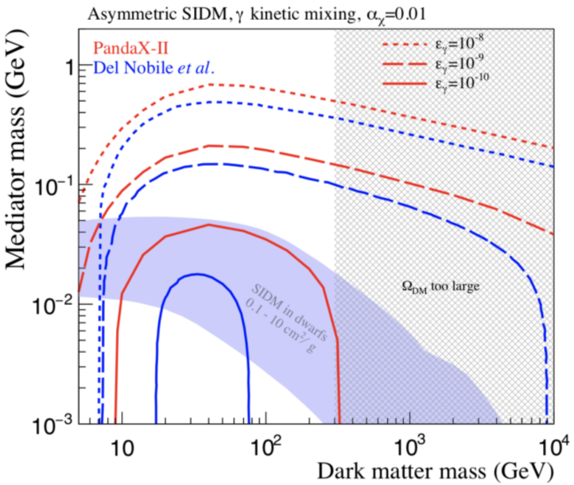
PandaX-II: constraints on the SIDM with a light mediator

- Exposure: 54 ton x day from 2016~2017 runs

$$\sigma(q^2)_{\chi N} = \sigma|_{q^2=0} A^2 \left(\frac{\mu}{\mu_p}\right)^2 \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} F^2(q^2)$$



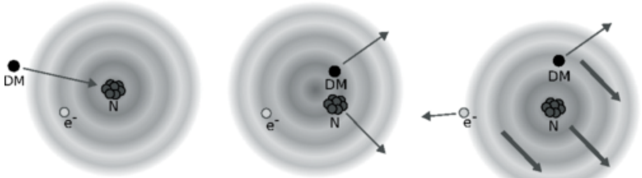




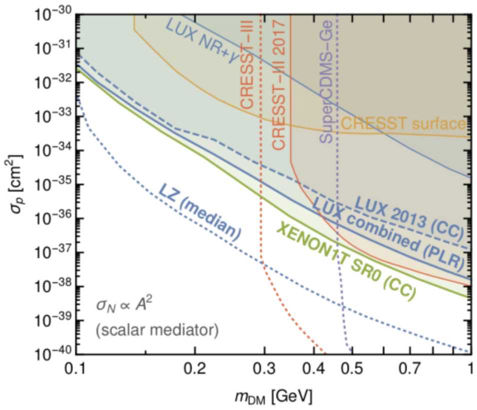
arXiv:1802.06912
Phys. Rev. Lett. 121, 021304 (2018)

Sub-GeV dark matter scattering

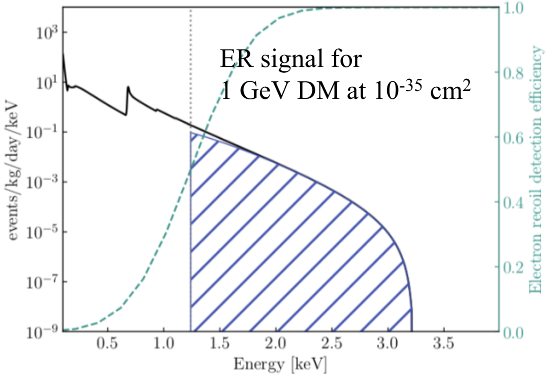
- NR from sub-GeV DM scattering: energy too low
- DM-nucleus scattering accompanied by a Bremsstrahlung photon or **“Migdal” electron**: **ER signal**

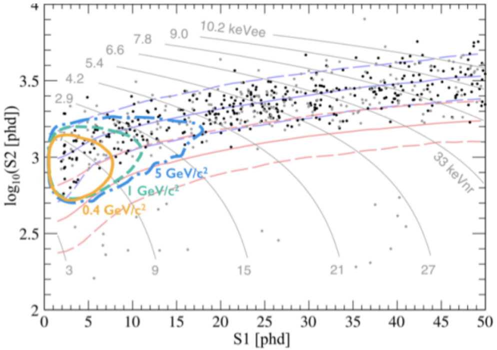


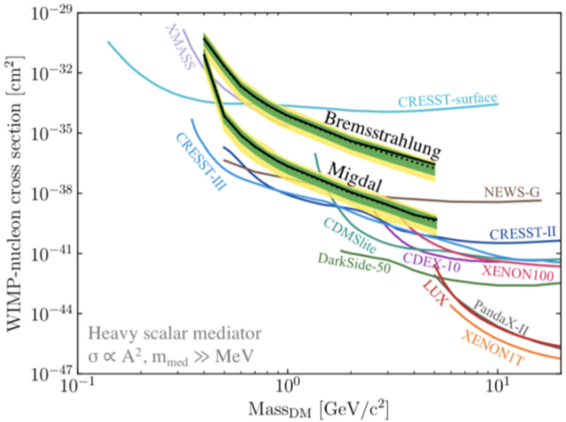
- **M. Ibe et al., JHEP 02 (2018) 194**
- Dolan et al., PRL **121**, 101801 (2018)



Dolan et al., Phys. Rev. Lett. **121**, 101801 (2018)

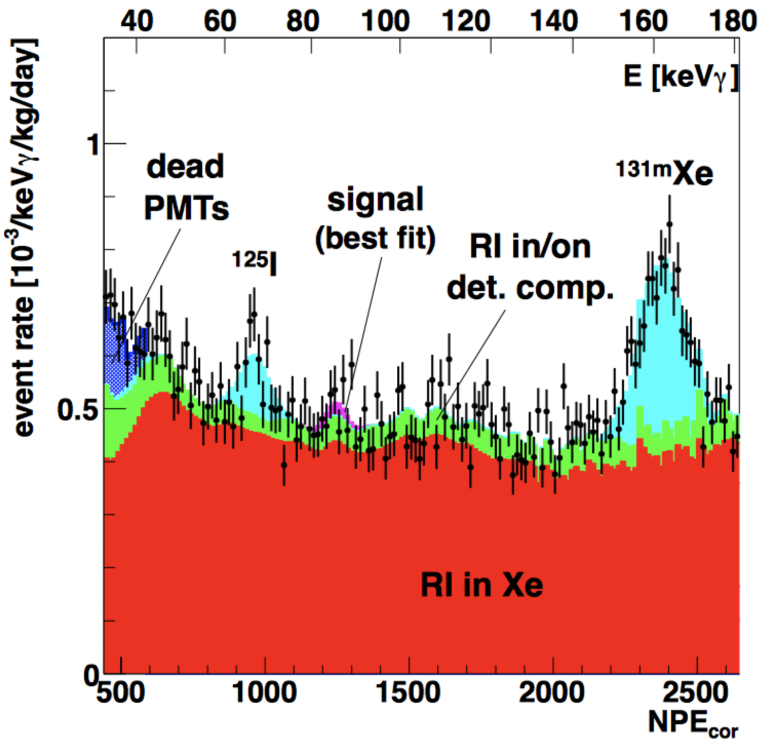


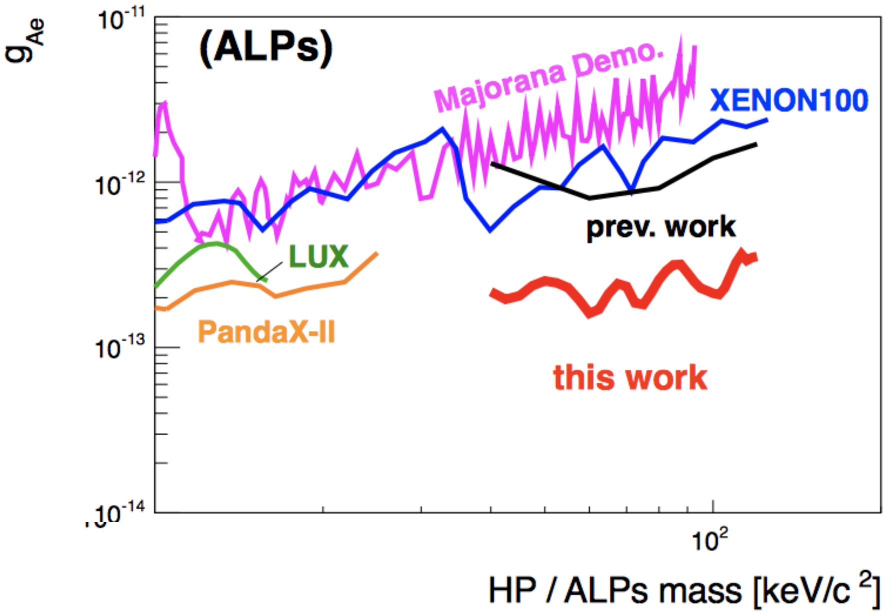




LUX, arXiv:1811.11241

XMASS constraints on dark/hidden photon and ALPs



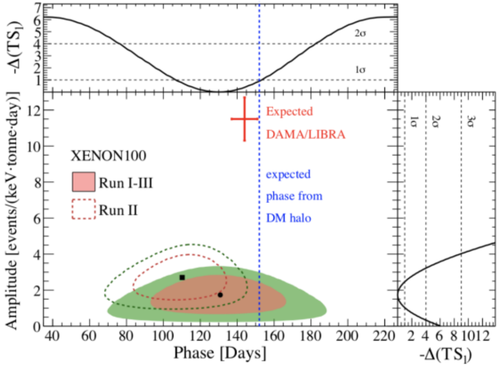


arXiv:1807.08516 (PLB)

Annual Modulation Signal Search

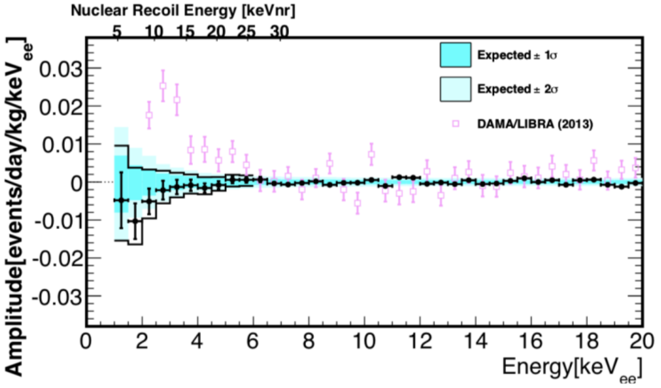
- Excluding the leptophic DM models favored by DAMA's modulation signals
- Demonstrate LXe detector's **long-term operational stability**.

XENON100, 4 years



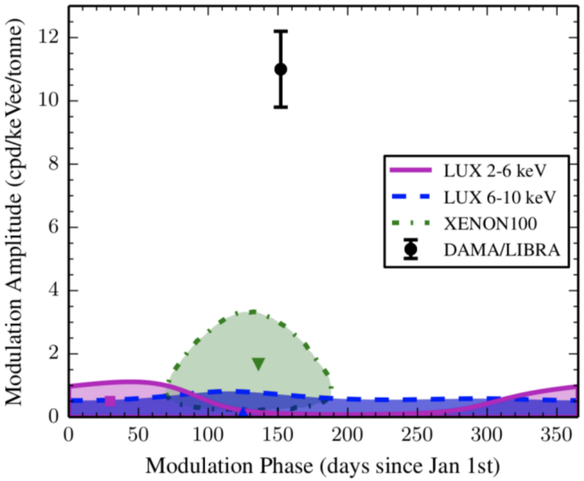
XENON, arXiv:1701.00769
PRL 118, 101101 (2017)

XMASS, 2.7 years data



XMASS, arXiv:1801.10096
PRD 97, 102006 (2018)

LUX, 20 months

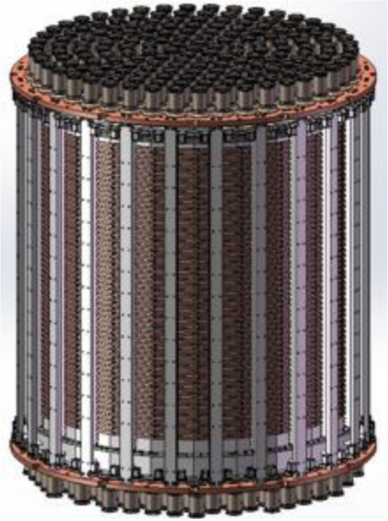


LUX, arXiv:1807.07113
PRD 98, 062005 (2018)

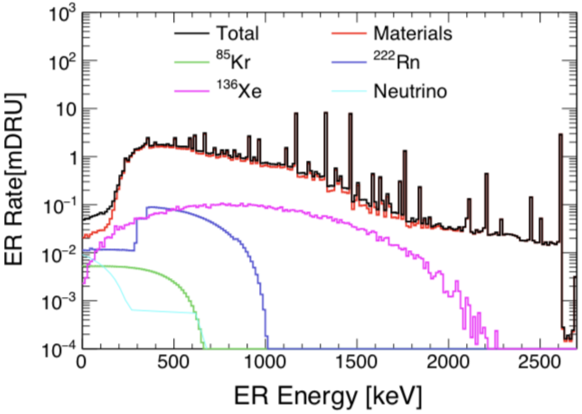
The Near Future: PandaX-4T, XENONnT, LZ

PandaX-4T

- A scale-up from PandaX-II at Jin-Ping Lab
  - 1.2 m diameter
  - 1.2 m drift length
  - 4-ton active LXe target
- Schedule:
  - assembly/commission: 2019~2020
  - Science data taking: 2020~2022
- Sensitivity reach:
  - SI interaction: 6 x 10^{-48} cm^2



arXiv:1806.02229

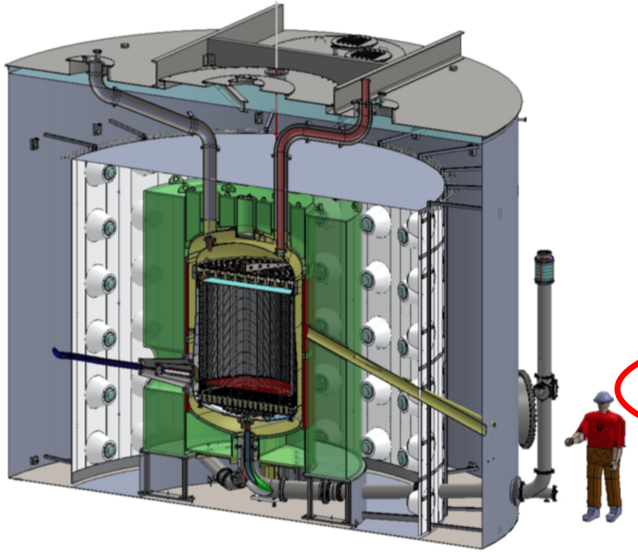


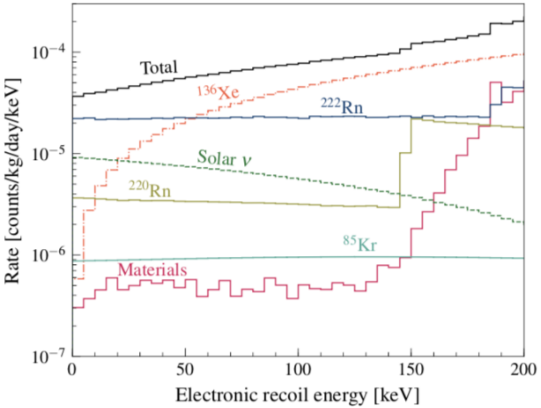
Summary of ER and NR backgrounds		
Source	ER in mDRU	NR in mDRU
Materials	0.0210±0.0042	$2.0 \pm 0.3 \cdot 10^{-4}$
^{222}Rn	0.0114±0.0012	-
^{85}Kr	0.0053±0.0011	-
^{136}Xe	0.0023±0.0003	-
Neutrino	0.0090±0.0002	$0.8 \pm 0.4 \cdot 10^{-4}$
Sum	0.049 ±0.005	$2.8 \pm 0.5 \cdot 10^{-4}$
2-year yield (evts)	1001.6± 102.2	5.7±1.0
after selection (evts)	2.5±0.3	2.3±0.4

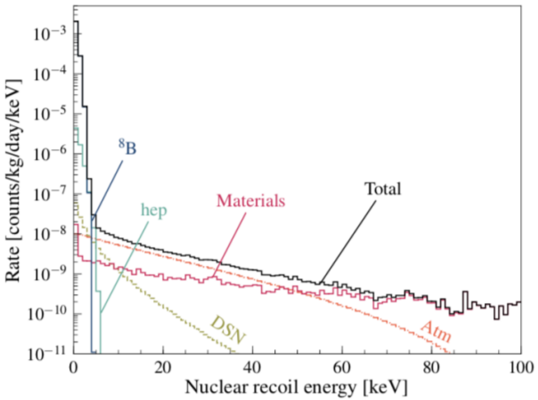
1 mDRU = 1 event/keVee/ton/day

XENONnT (talk by Shigetaka Moriyama)

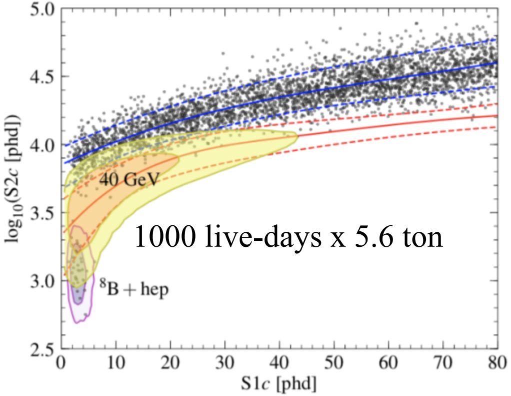
LZ







Parameter [units]	Value
TPC active height [m]	1.46
TPC inner diameter [m]	1.46
active LXe mass [kg]	7000
xenon skin thickness, side [cm]	4.0 - 8.0
inner cryostat diameter [m]	1.58 - 1.66
inner cryostat height [m]	2.59
outer cryostat inside diameter [m]	1.83
outer cryostat height [m]	3.04
GdLS tanks outer radius [m]	1.64
GdLS thickness, side [cm]	61
GdLS thickness, top [cm]	40 - 62
GdLS thickness, bottom [cm]	34.5 - 57
GdLS mass [t]	17.3
GdLS tanks, acrylic wall thickness [cm]	2.54
water thickness, GdLS vessels to PMTs [cm]	84
water tank diameter [m]	7.62
water tank height [m]	5.92
water mass [t]	228



arXiv:1802.06039

Construction underway NOW at SURF

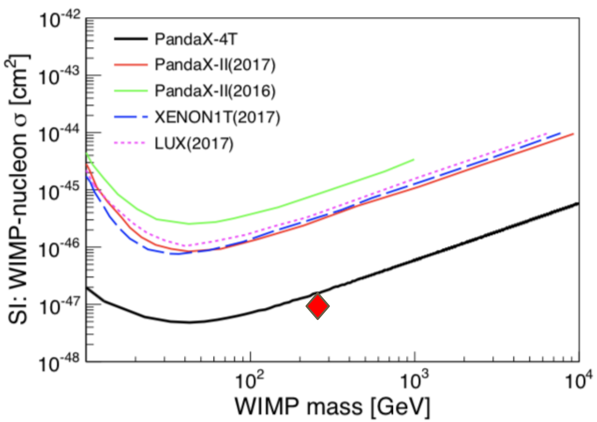
Technical challenges to be solved in these (G2) experiments

- Radon concentration in the bulk liquid xenon
  - Lowest achieved in XENON1T: 5~10 μBq/kg
  - Goal of the G2 experiments : 1~2 μBq/kg
  - Rn control, online distillation, charcoal adsorption
- Neutron background (neutron veto needed)
  - LZ: liquid scintillator
  - XENONnT: Gd-doped water (see **Poster by Ryuichi Ueno**)
- Long electron drift length (1.2~1.5 m)
  - Require >1 ms electron lifetime: fast/efficient purification
  - Need faster drift velocity to avoid too much diffusion: 30~100 kV on cathode
- Large diameter (1.2~1.5 m) TPC
  - Electron emission rate from gate/cathode electrodes needs to be controlled
  - Signal uniformity

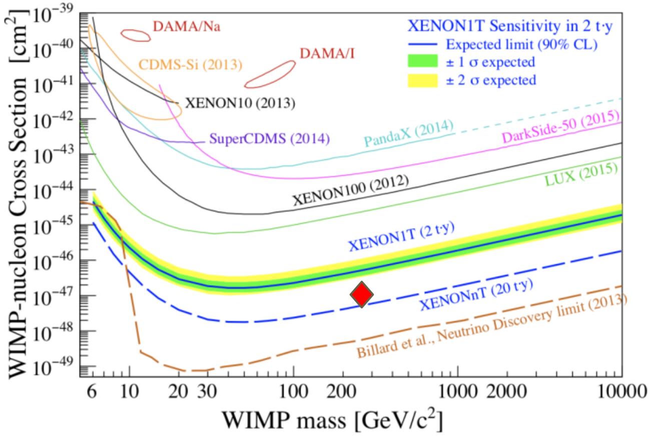
Dark Matter sensitivity reach in the next 5 years

◆ Benchmark point: 10^{-47} cm^2 at 250 GeV/c^2

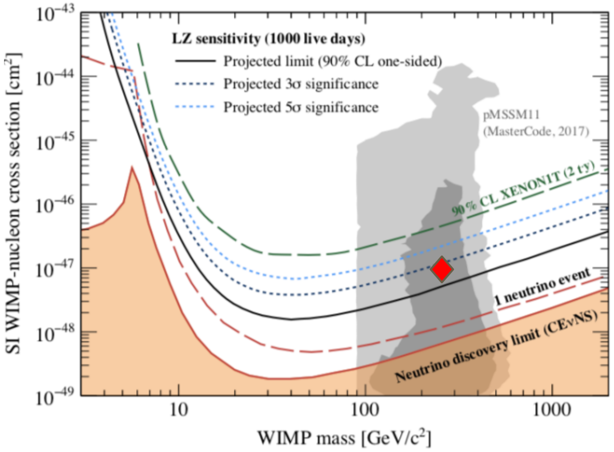
PandaX, arXiv:1806.02229



XENON, arXiv:1512.07501



LZ, arXiv:1802.06039



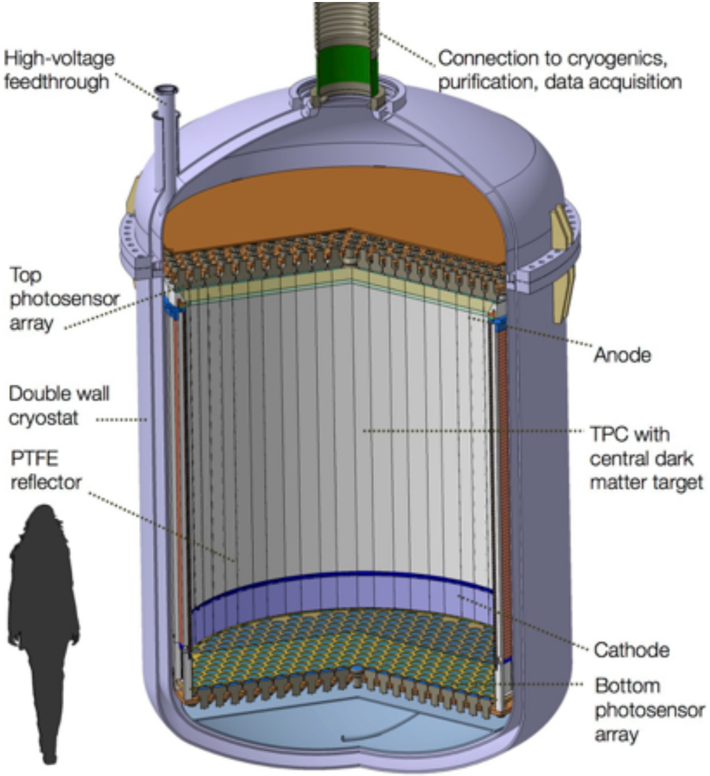
WIMP Dark Matter Detection in five years?

The G3 LXe Experiment

The case for a G3 LXe detector

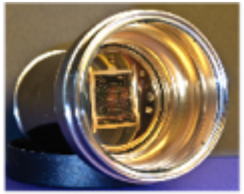
- As already demonstrated by past experiments, two-phase LXeTPC is an ideal choice for dark matter detection
- But science reach of the LXeTPC is more than dark matter…
  - Neutrinoless double beta decay (Xe-136)
    - 100-ton natural xenon contains 9 ton Xe-136!
  - Neutrino Astrophysics
    - Electron scattering: pp, Be-7, etc.
    - Coherent scattering: B-8, DSN, atmospheric neutrinos
- The call for **a global effort** to build the next generation (G3) LXe detector
  - LXe mass: at least 50 tonnes
  - Technical design & demonstration: 2020~2024
  - Construction: 2024~2025
  - Commissioning and Science data taking: 2025-2035

DARWIN: the G3 "Ultimate" dark matter detector



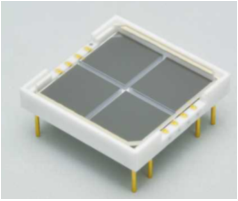
Baseline design:

- 2.6 m x 2.6 m TPC
- 40 ton active LXe target (total 50 ton)
- ~10 m^2 photo-sensor coverage (top/bottom)



3-inch PMT, R11410-21

4-inch PMT



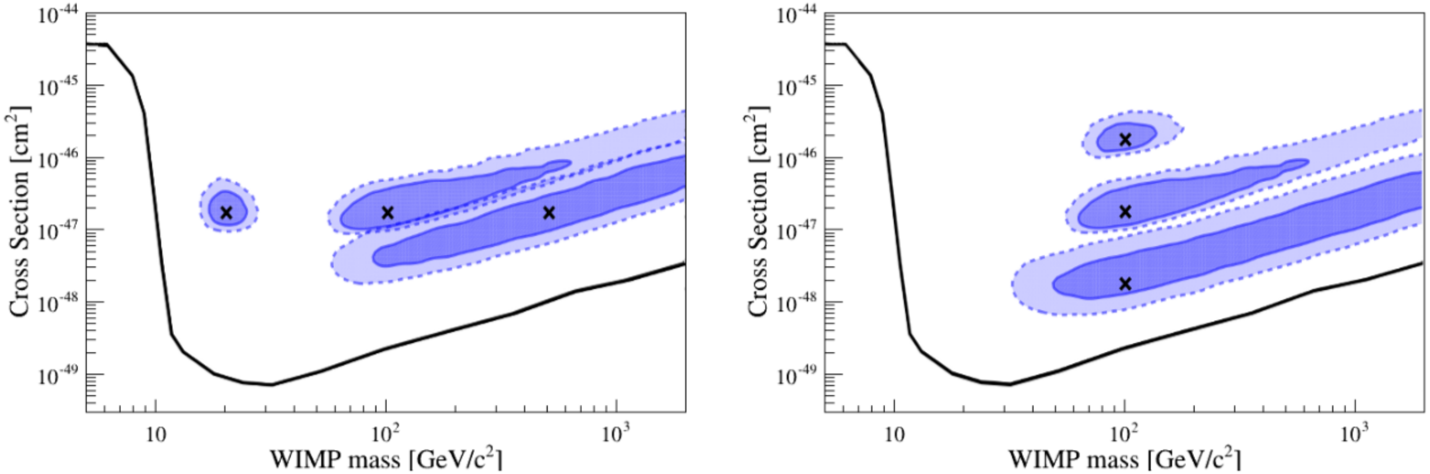
VUV-MPPC

https://darwin.physik.uzh.ch/

JCAP 11, 017 (2016)

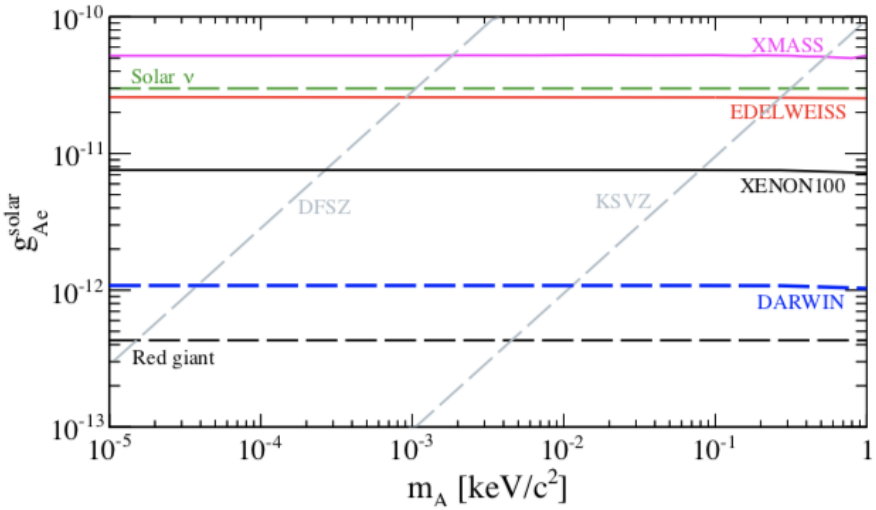
WIMP Spectroscopy with DARWIN

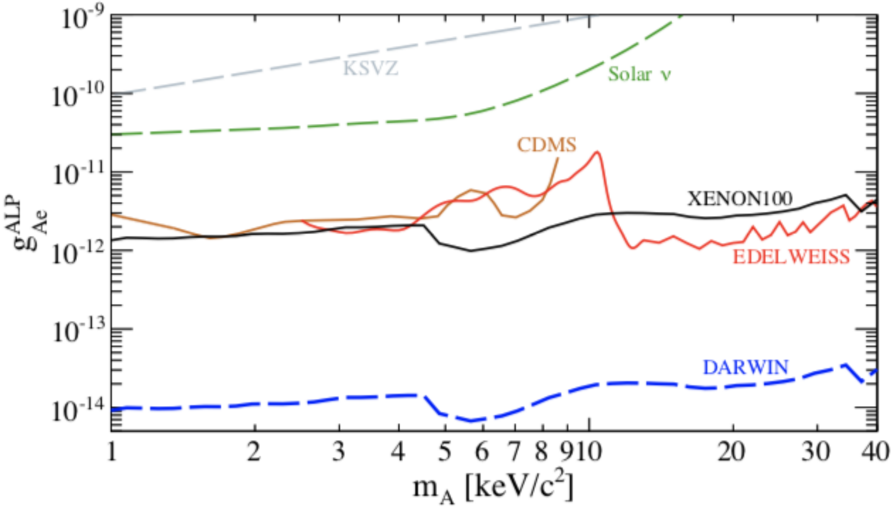
JCAP 11, 017 (2016)



1 and 2 sigma credible regions of simulated WIMP signals for SI interactions at various WIMP masses and cross-sections for a **200 ton x year** exposure in DARWIN

DARWIN sensitivity to solar axion and ALPs





Solar axion

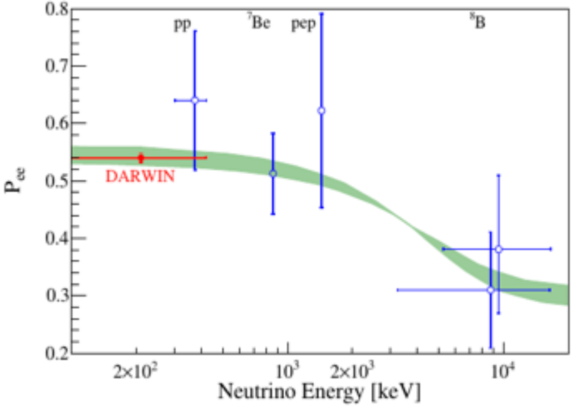
Galactic ALPs

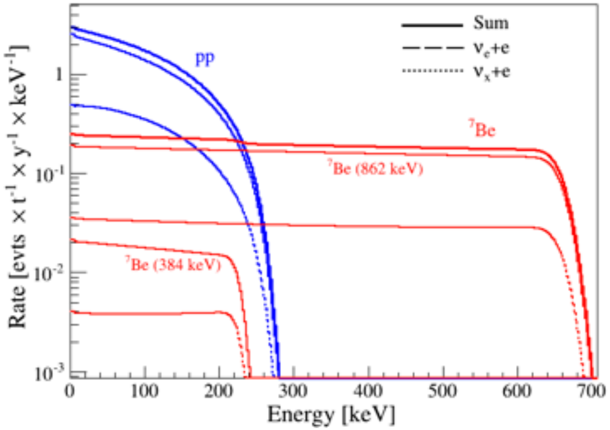
JCAP 11, 017 (2016)

JCAP 11, 017 (2016)

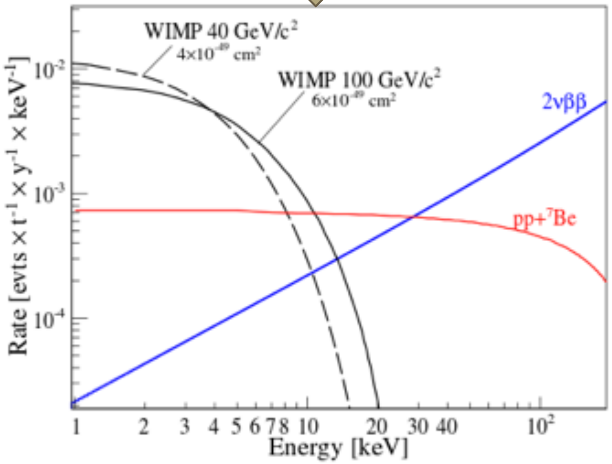
Solar neutrino-electron scattering in DARWIN

as signal





as background



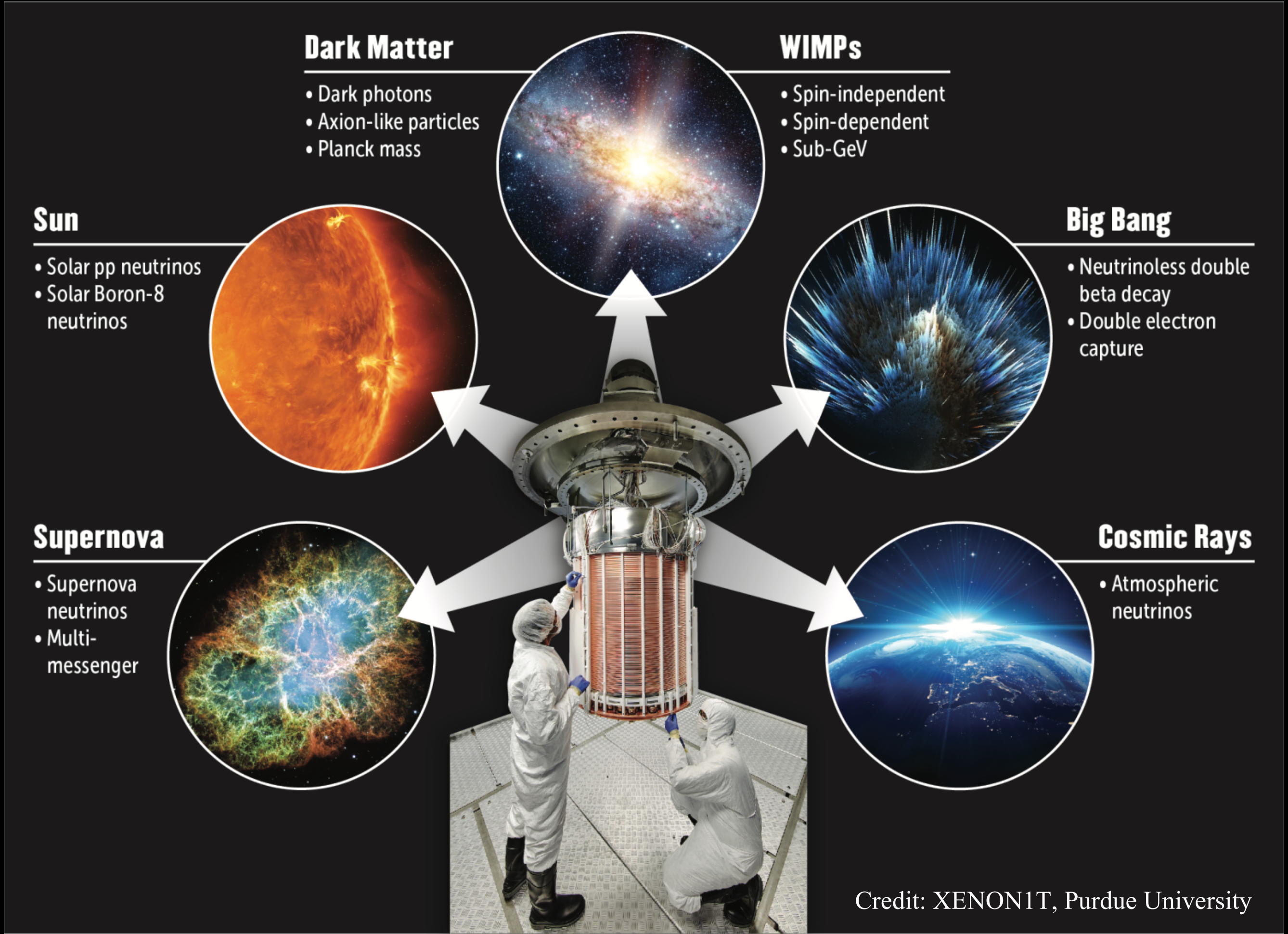
→ 2850 neutrinos per year (89% pp)
→ achieve 1% statistical precision on pp-flux with 100 t x y

Other physics channels:

- CEvNS
- 0vbb
- etc.

ER rejection efficiencies ~99.98% at 30% NR efficiency are required to reduce to sub-dominant level

Science Channels for the G3 LXe Experiment



Summary

- Liquid Xe has become **the most favorable target** for dark matter detection; **Ton-scale experiment** is already probing many interesting DM models.
- The upcoming G2 experiments (PandaX-4T, XENONnT, LZ) with **unprecedented low background** may give us a first glimpse of the nature of dark matter in 5 years.
- The G3 LXe experiment at 50~100 tonnes scale, e.g. DARWIN, will be **the ultimate dark matter detector** and may reveal the history of universe in nuclear, particle and astro-physics in the next two decades.

It's a golden time to work on liquid xenon experiments!