Direct dark matter detection with XENON1T

Alexander Fieguth,
WWU Muenster,
on behalf of the XENON collaboration

Direct dark matter search

Recent results from XENON1T

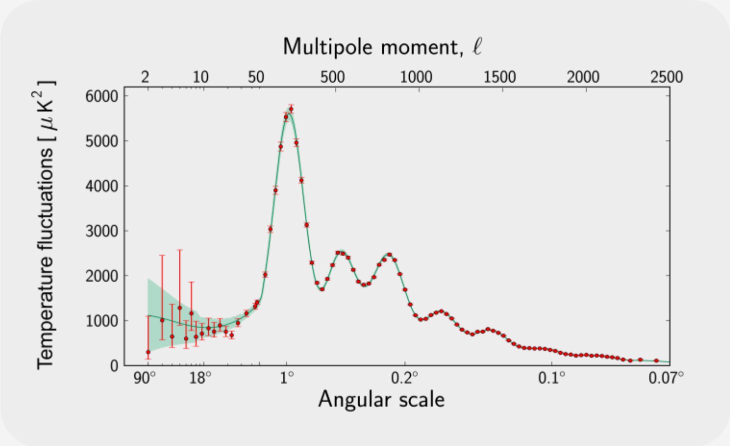
DBD searches with XENON1T

Direct dark matter search

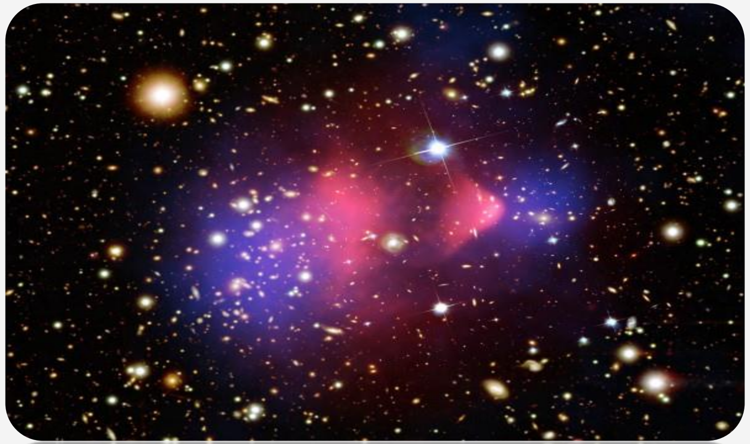
Recent results from XENON1T

DBD searches with XENON1T

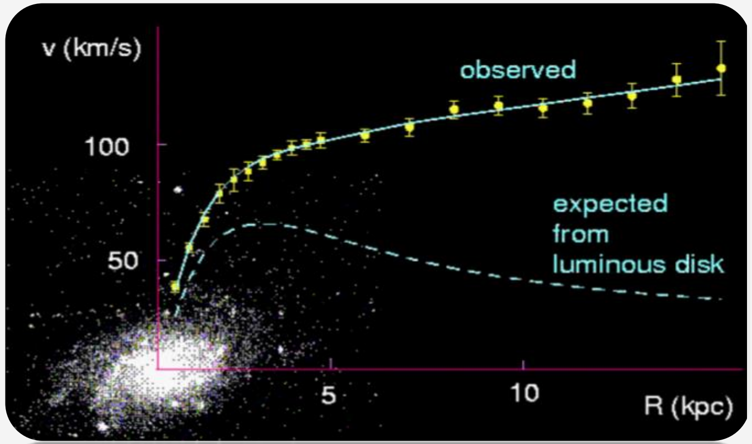
BELIEVE IN DARK MATTER – THERE ARE GOOD REASONS TO DO SO..



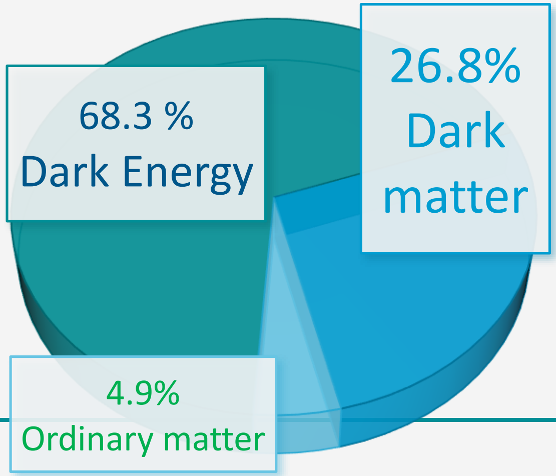
Cosmic microwave background
(from Planck)

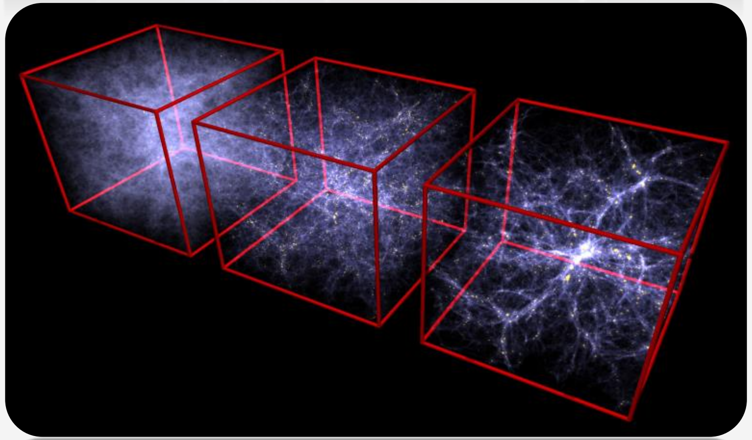


Bullet cluster
(from NASA)



Rotational curves
(from NASA)





Structure formation simulations
(by Springel et al.)

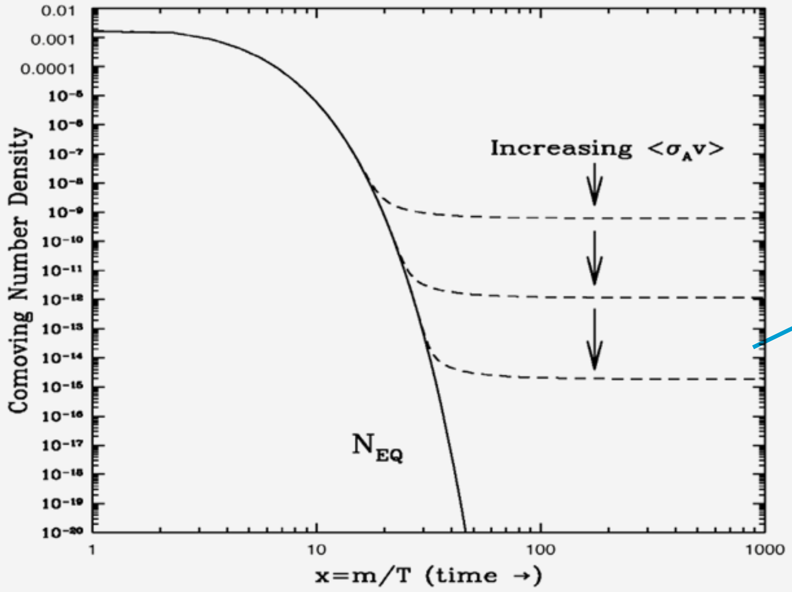
and there is more…

But what is the nature of dark matter?

WARNING:

This is a personal selection
(there are plenty candidates
out there, e.g. Axions, Sterile Neutrinos..)

WEAKLY INTERACTING MASSIVE PARTICLES
(WIMPS)



Annihilation rate on weak scale matches relic abundance

- Massive (GeV – TeV)
- Non-relativistic (cold)
- Interaction rate of the weak scale
- Neutral
- Stable on the time scale of the universe
- Arises from different theories (e.g. Neutralino from SUSY)

And how to detect it?

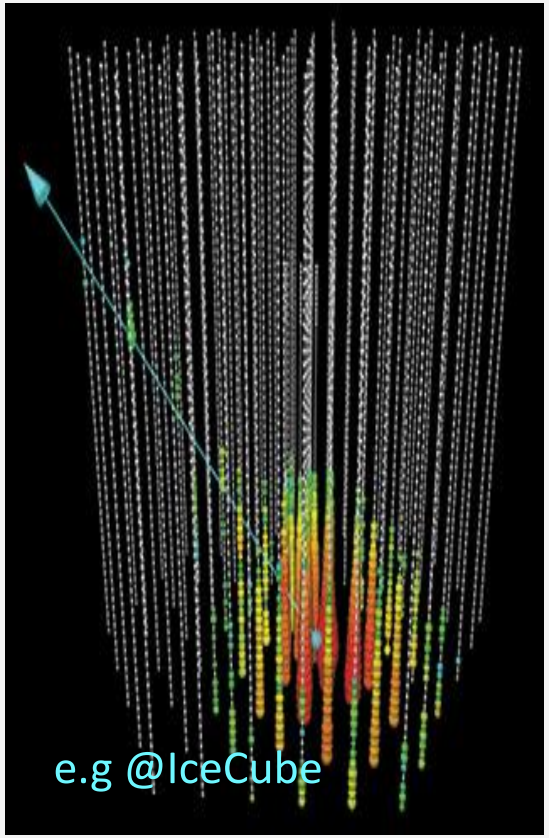
Collider Production

$p + p \rightarrow \chi + \bar{\chi} + X$

Direct detection

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

Indirect detection



$\chi + \bar{\chi} \rightarrow .. \rightarrow \gamma\gamma, \nu\bar{\nu}, ..$

And how to detect it?

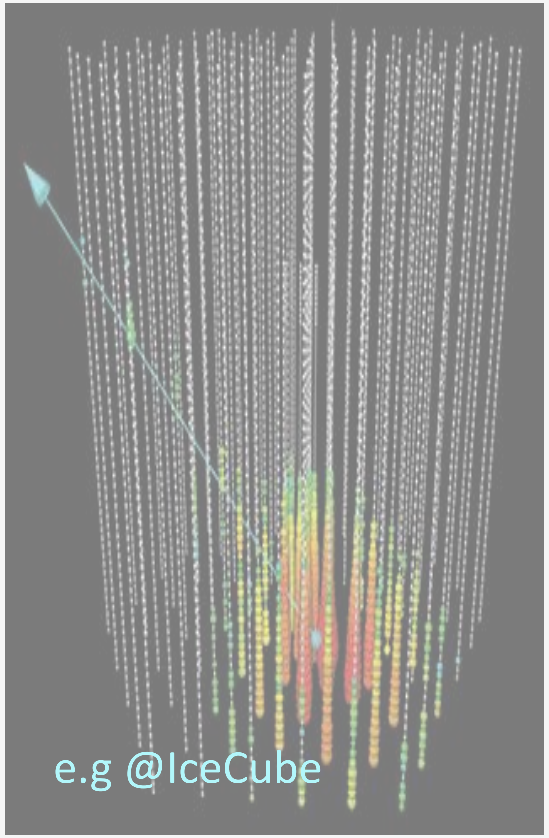
Collider Production

$p + p \rightarrow \chi + \bar{\chi} + X$

Direct detection

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

Indirect detection



$\chi + \bar{\chi} \rightarrow .. \rightarrow \gamma\gamma, \nu\bar{\nu},..$

The expected recoil spectrum (spin-independent interaction)

WIMP properties (measured by the experiment)

Astrophysical inputs* (given by chosen model)

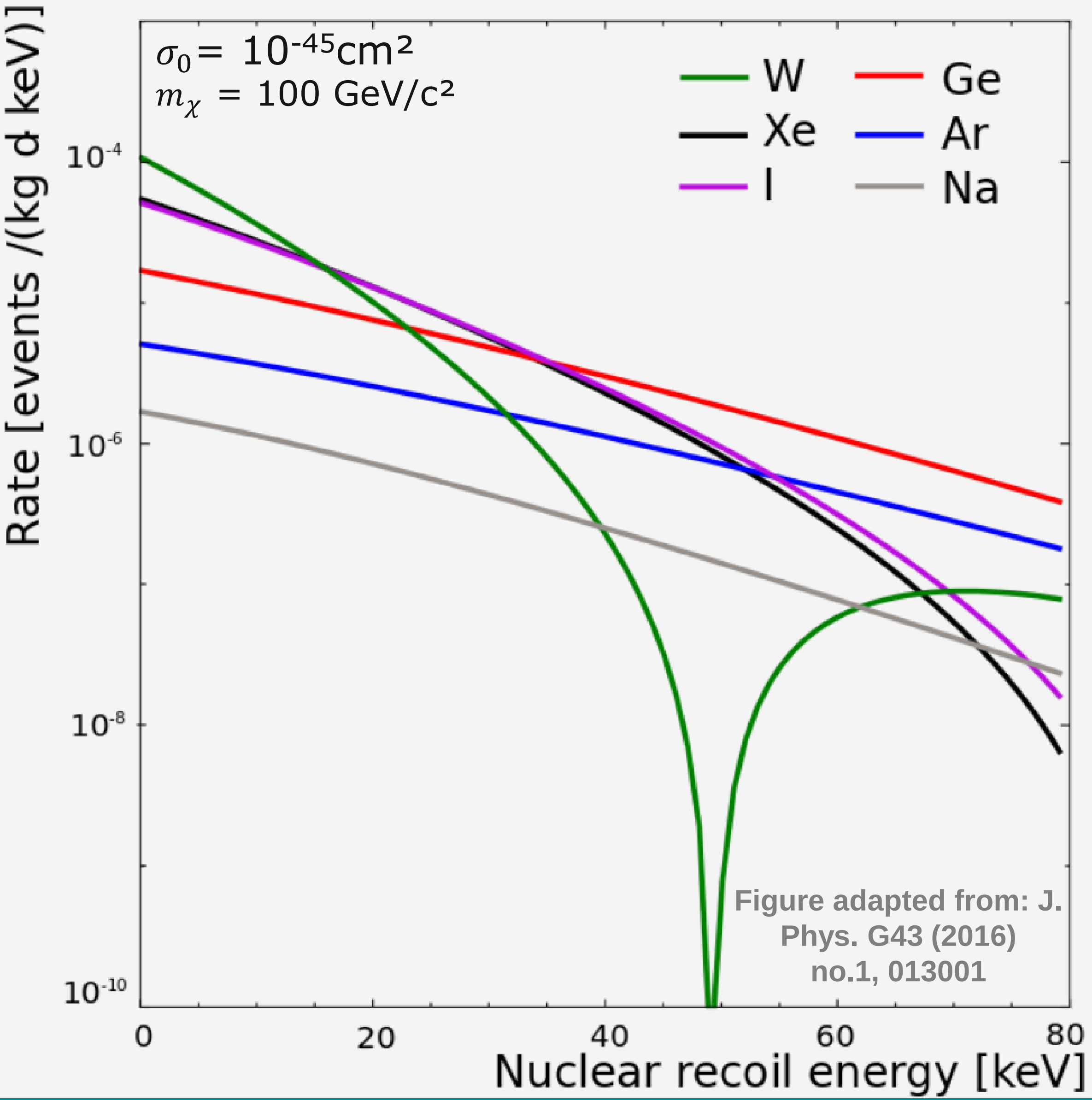
$$\frac{dR}{dE_R} \sim \frac{\sigma_0 A^2 F^2 \rho_0}{m_\chi \mu_r^2} \int_{v_{min}}^{v_{esc}} \frac{f(v,t)}{v} \, dv$$

Detector properties (set by the experiment)

* = simplified

Assumed standard halo model parameters with
ρ_0 = 0.3 GeV/cm³
v_0 = 220 km/s
v_{esc} = 544 km/s

Exponentially decreasing rate spectrum modified by the nuclear form factor



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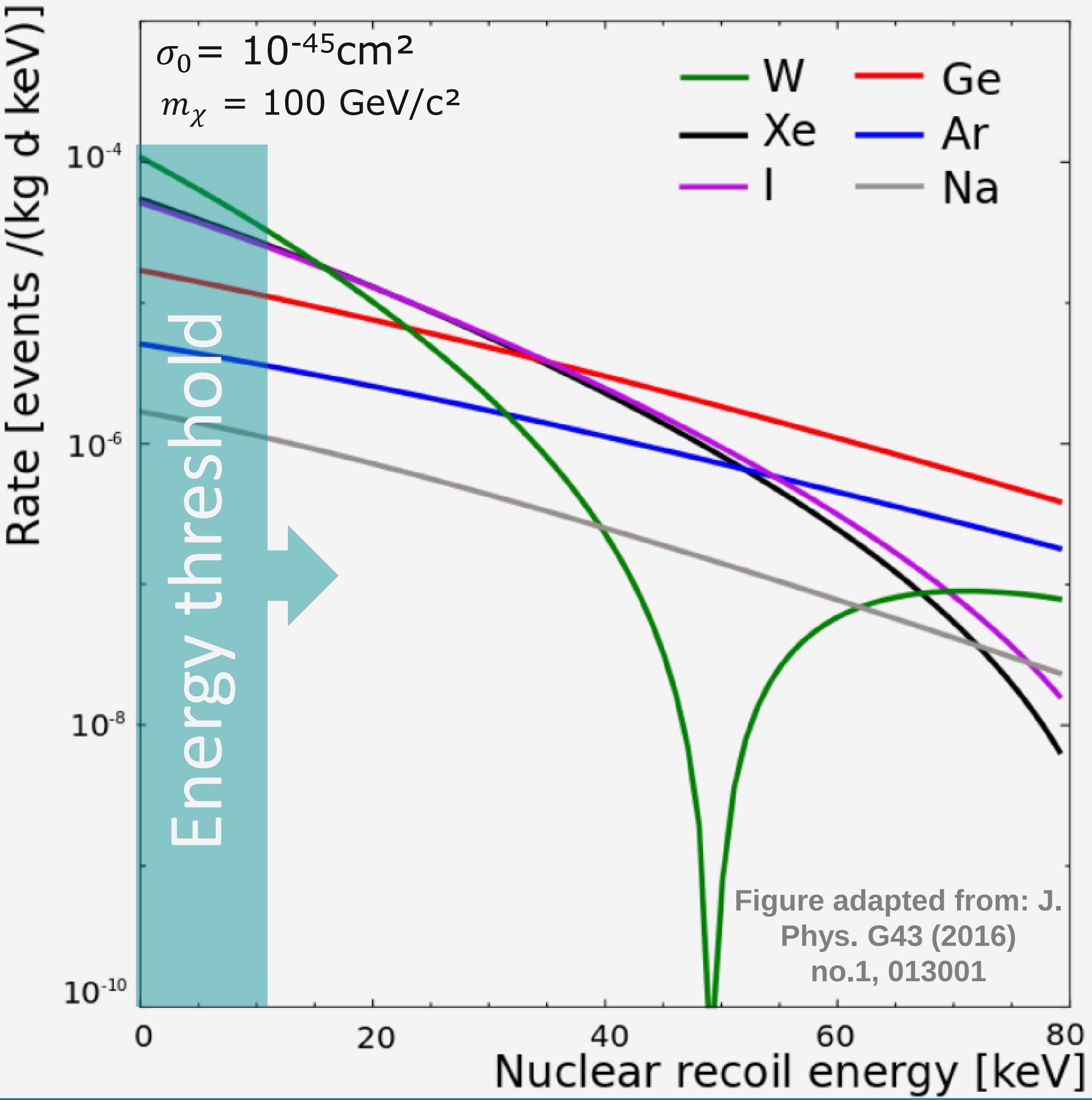


Figure adapted from: J. Phys. G43 (2016) no.1, 013001

Assumed standard halo model parameters with
ρ_0 = 0.3 GeV/cm³
v_0 = 220 km/s
v_{esc} = 544 km/s

Exponentially decreasing rate spectrum modified by the nuclear form factor

Depends strongly on the particular model
Large uncertainties

See e.g.
J.Phys. G44 (2017) no.8, 084001
for a review

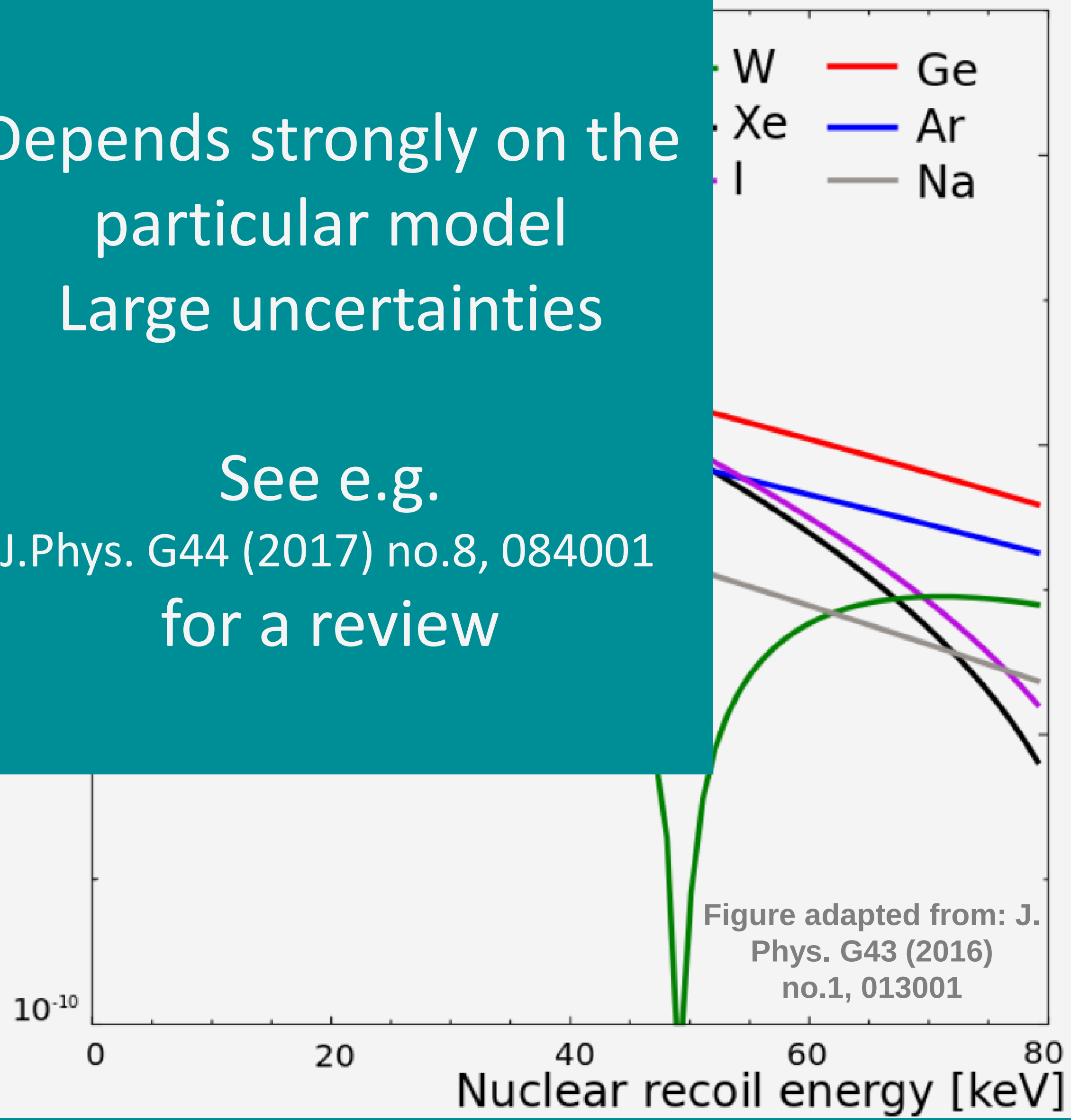


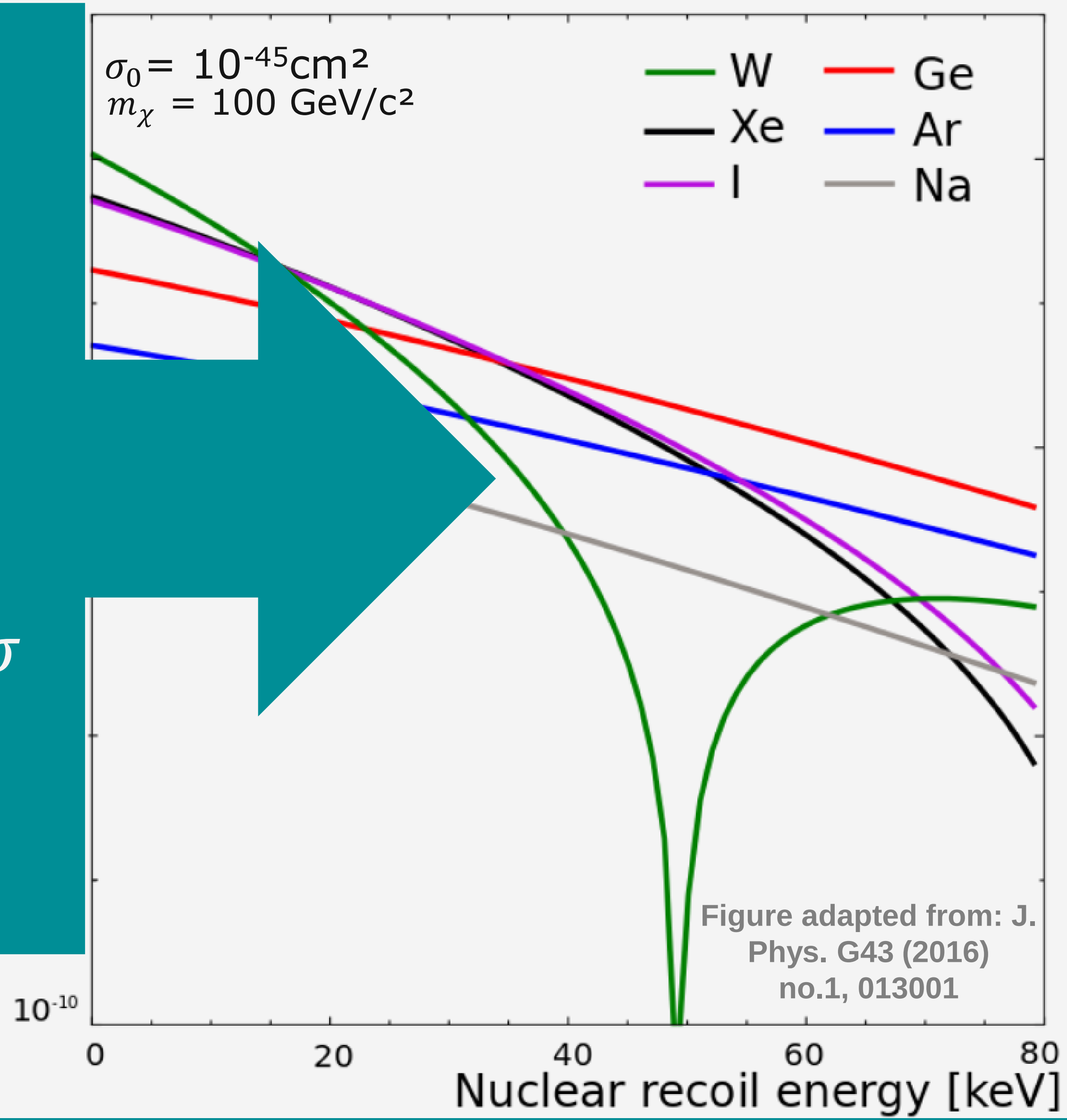
Figure adapted from: J. Phys. G43 (2016) no.1, 013001

Assumed stand
halo model
parameters w
ρ_0 = 0.3 GeV/c
v_0 = 220 km/
v_{esc} = 544 km

Exponentially decreasing rate spectrum modified by the nuclear form factor

Nuclear form factor depends on the iso-scalar SI WIMP-nucleus coupling ("Helm form factor approximation")

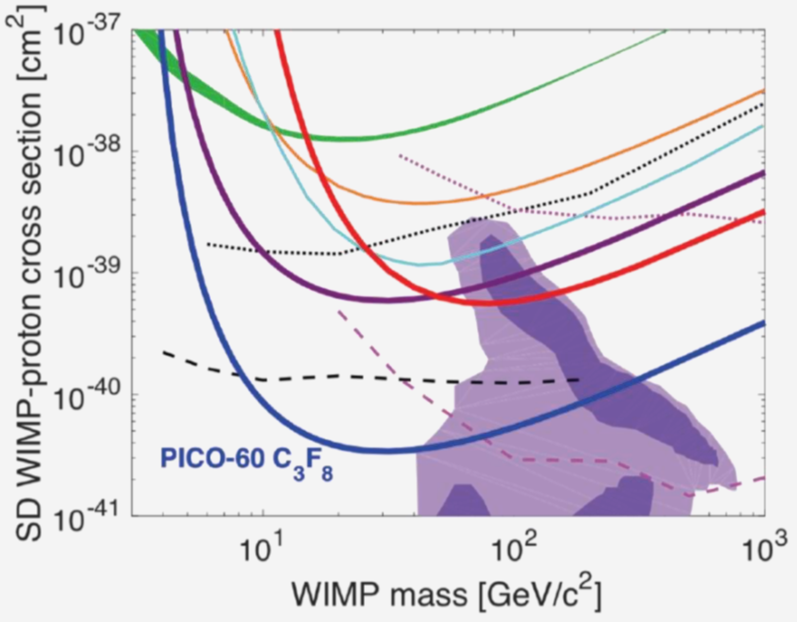
Measurement is not σ only but always $F\sigma$



See talk by W. Haxton today at 1:25 p.m. on effective theories of DDM

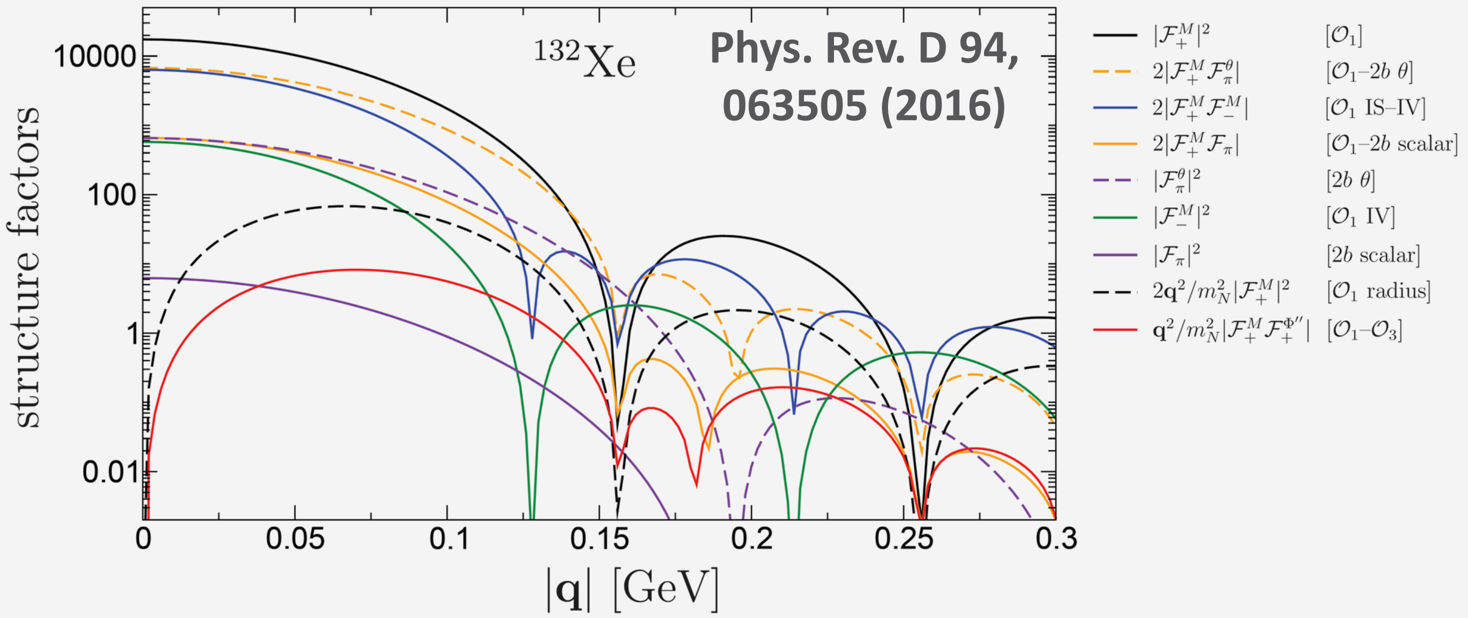
Other interaction channels?

Spin-dependent (SD) interaction between WIMPs and normal matter is already investigated



Phys.Rev.Lett. 118 (2017) no.25, 251301

Other spin-independent interaction channels are possibly realized in nature



see PRDD97 (2018) no.10, 103532 (Fieguth et al.) for a review on discrimination possibility in DDM detector

What do we measure?

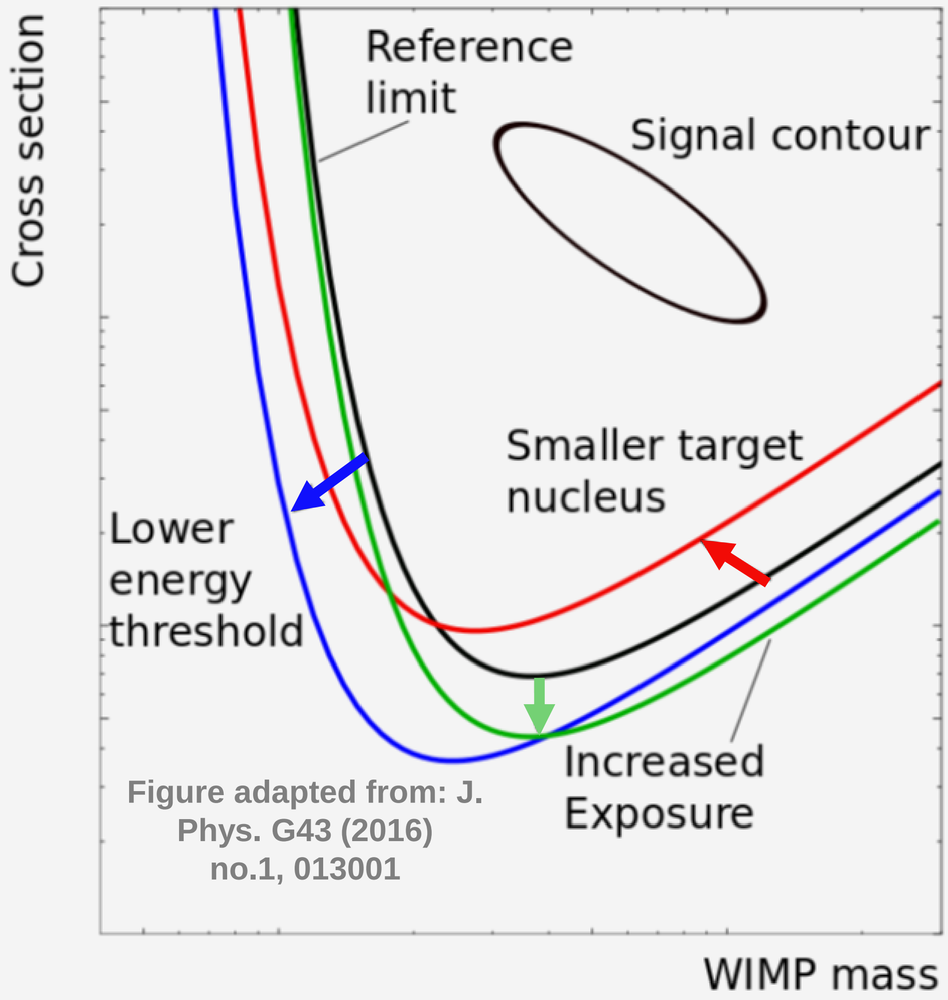
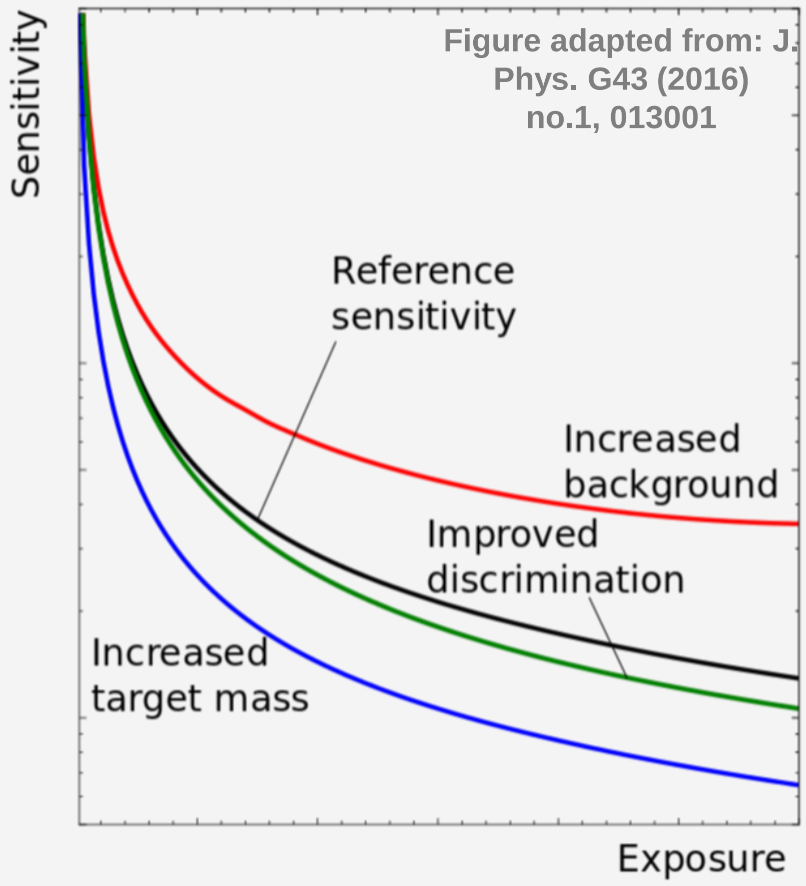


Figure adapted from: J. Phys. G43 (2016) no.1, 013001

Measure the cross section as a function of WIMP mass assuming an astrophysical model and nuclear interaction mechanism

How to optimize the sensitivity?

Maximize the signal to background ratio



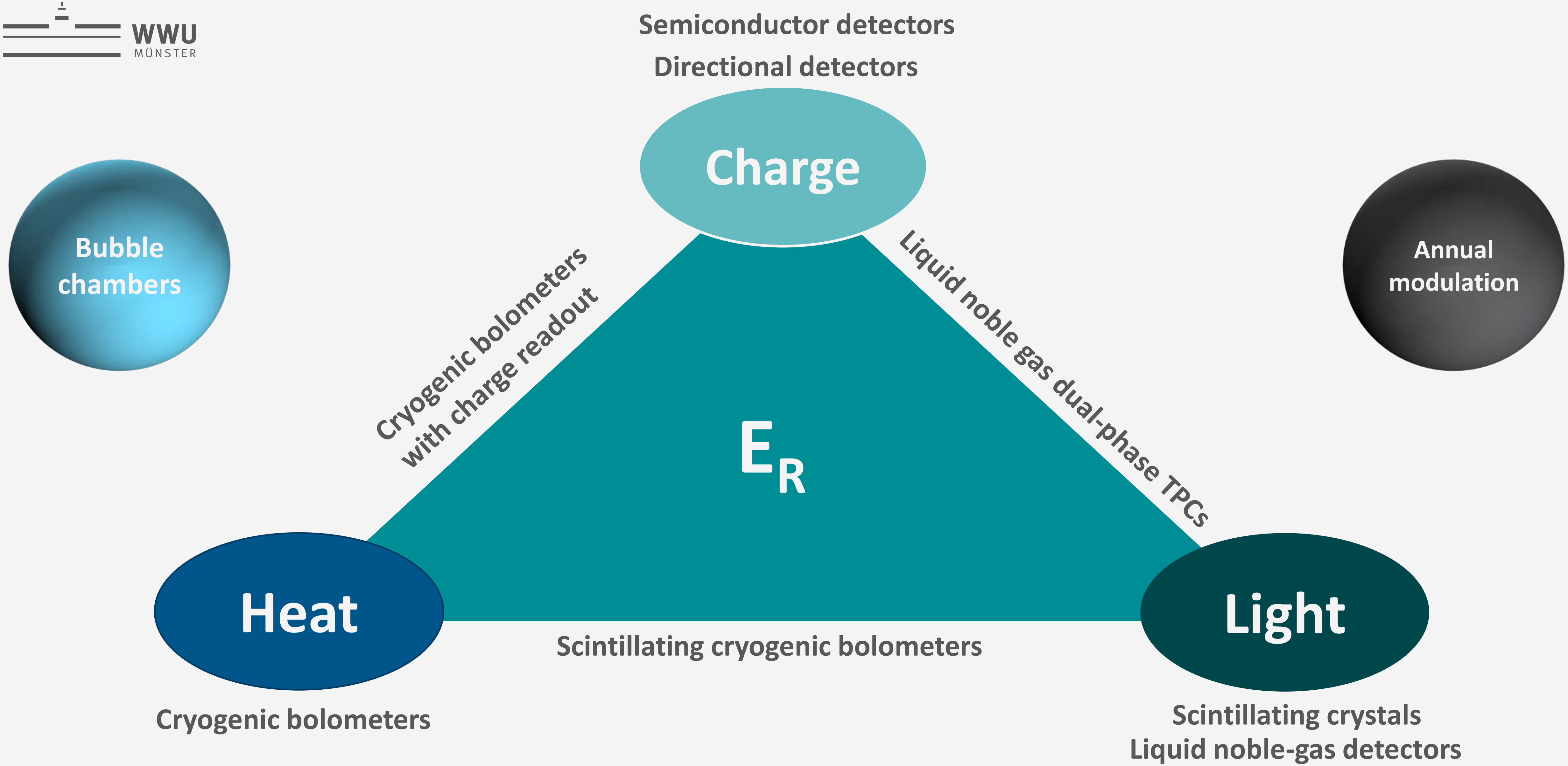
Backgrounds

Problem	External backgrounds (μ, γ)	Detector backgrounds (γ, n)	Intrinsic impurities or radioactive isotopes (β, γ, n)	Neutrinos, Coherent elastic neutrino nucleus scattering
Solution	Underground laboratories, shielding	Shielding, material screening	Purification	Directionality, Modulation, Inelastic channel

Backgrounds

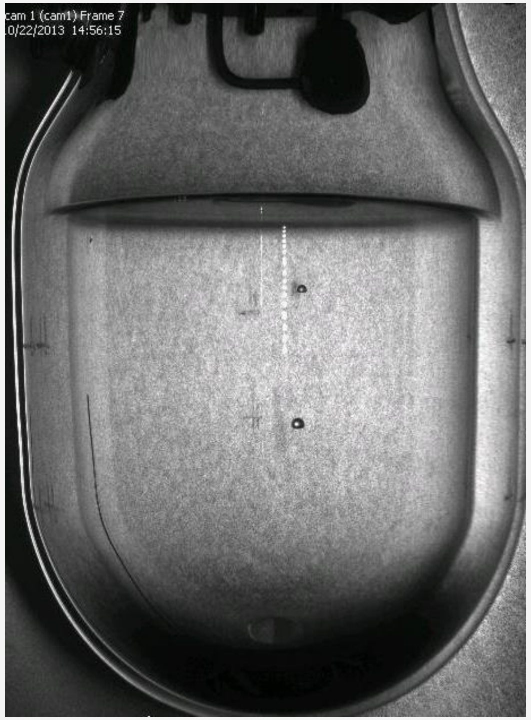
Problem	External backgrounds (μ, γ)	Detector backgrounds (γ, n)	Intrinsic impurities or radioactive isotopes (β, γ, n)	Neutrinos, Coherent elastic neutrino scattering
Solution	Underground laboratories, shielding	Shielding, material screening	Purification	Directionality, Modulation, Inelastic channel

PARTICLE IDENTIFICATION / DISCRIMINATION


Semiconductor detectors
Directional detectors
Charge
Bubble chambers
Annual modulation
Cryogenic bolometers with charge readout
Liquid noble gas dual-phase TPCs
E
R
Heat
Light
Scintillating cryogenic bolometers
Cryogenic bolometers
Scintillating crystals
Liquid noble-gas detectors

Bubble Chambers (PICO, SIMPLE, PICASSO, COUPP,..)

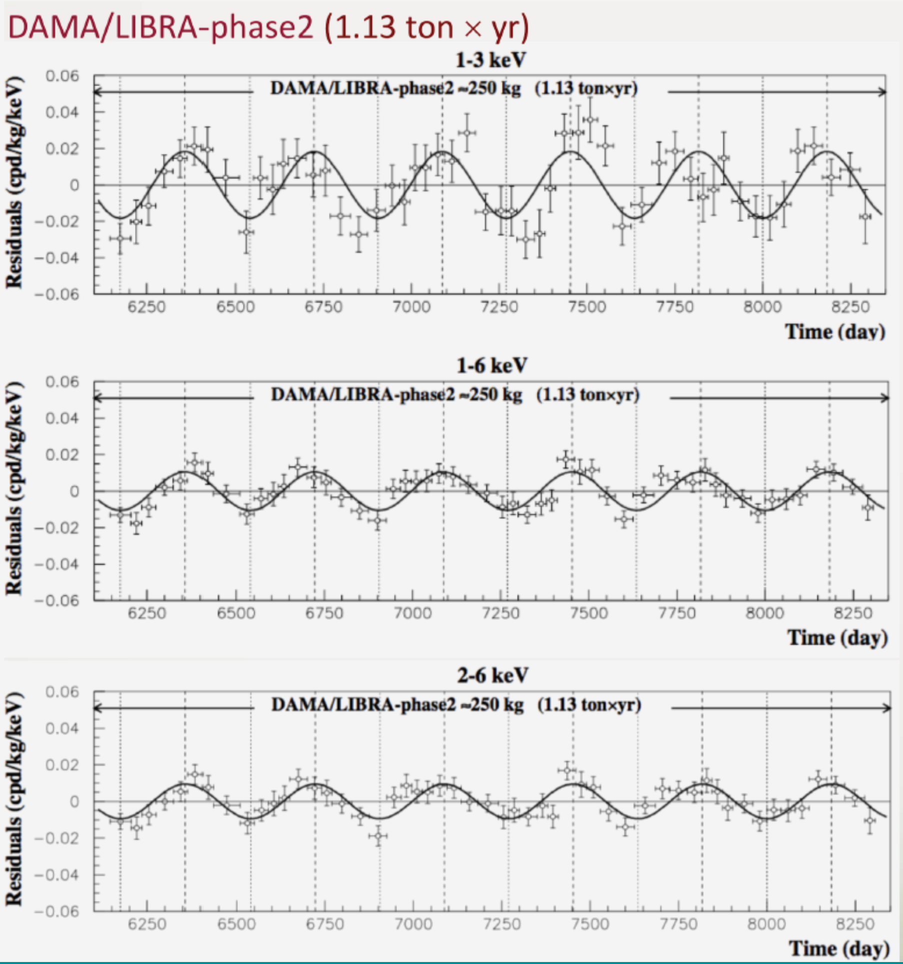
- Use of superheated liquids C_3F_8, C_4F_{10}, CF_3I
- Measurement of acoustic and visual signals
- Excellent rejection of electron recoils
- Discrimination of nuclear recoils from α-particles
- PICO provides the best SD WIMP-proton limits of all experiments



See talk by O. Harris today at 1:50 p.m. on latest results!

Annual modulation (DAMA vs COSINE-100, SABRE, ANAIS,..)

from R. Bernabei talk, Mar. 26, 2018, LNGS



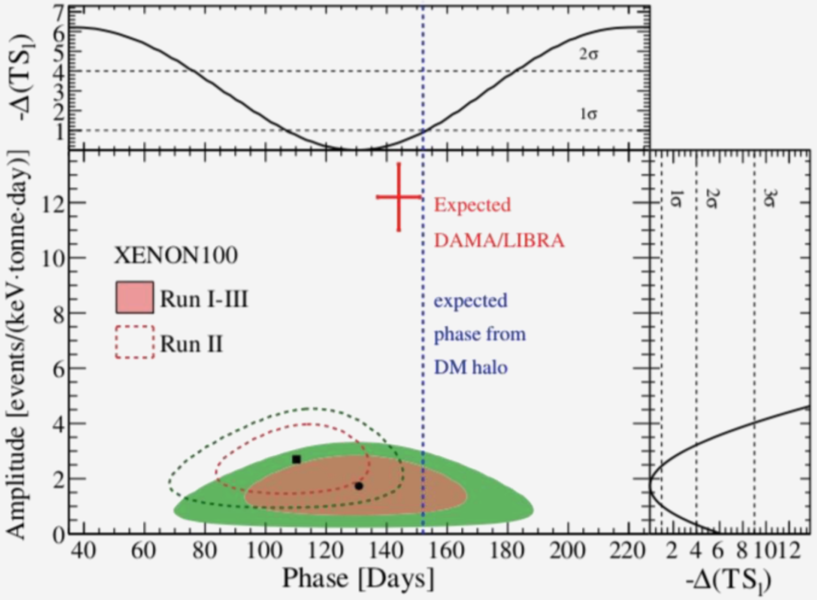
Sodium iodide (NaI) experiments to search for annual modulation signal (no discrimination)

DAMA/LIBRA claims to have seen dark matter with >>5σ-significance

NOT in agreement with various other targets

Need other NaI experiments to finally disprove

See talk by H. Lee at 11:30 a.m. on COSINE-100 results



XENON100 4-year ER modulation study, PRL 118, 101101 (2017)

Possible reason – unidentified background?
e.g. radioactive argon (McKinsey arxiv:1803.101110)

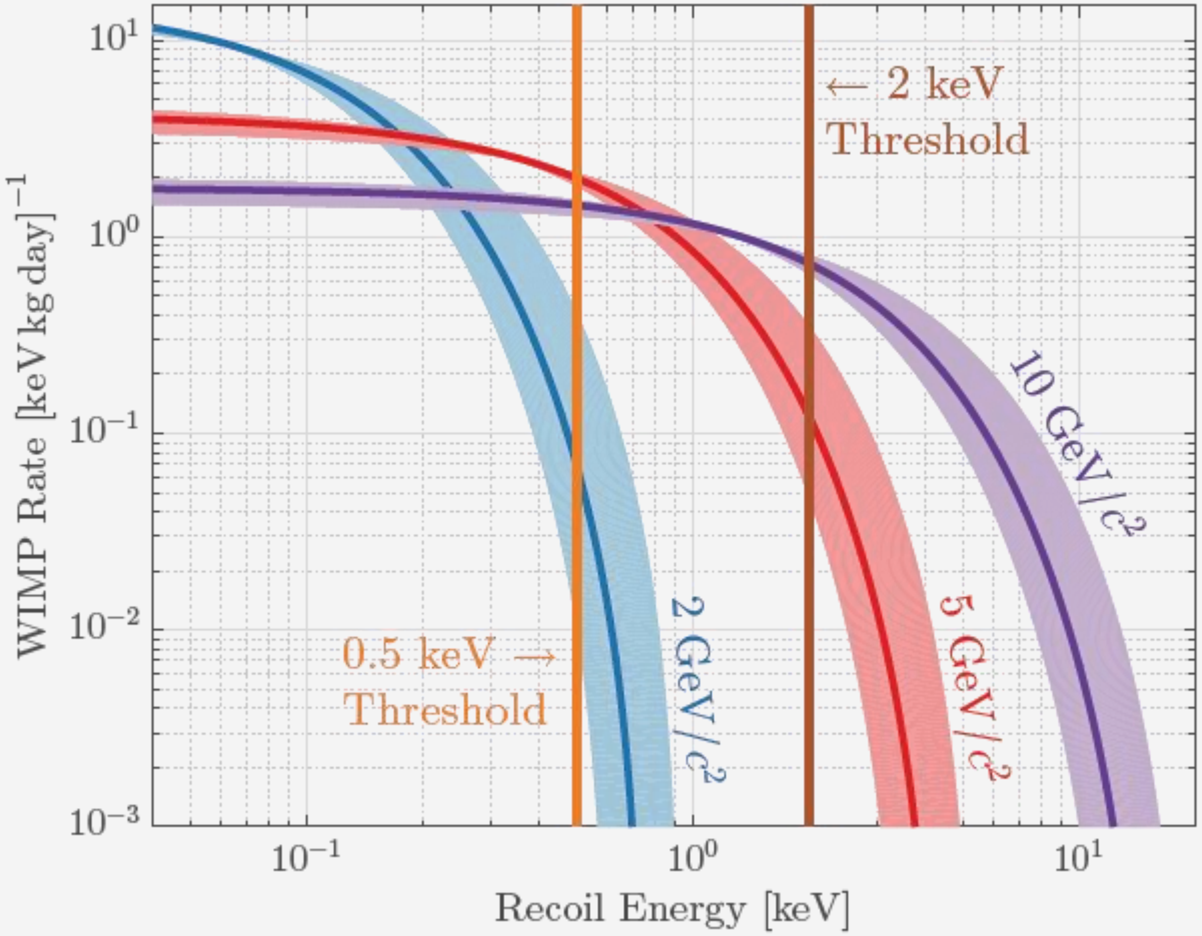
Low-mass dark matter searches (CRESST, SUPERCDMS,..)

Low mass searches often trade-off between low threshold and low background

Probing down to Sub-GeV WIMP masses

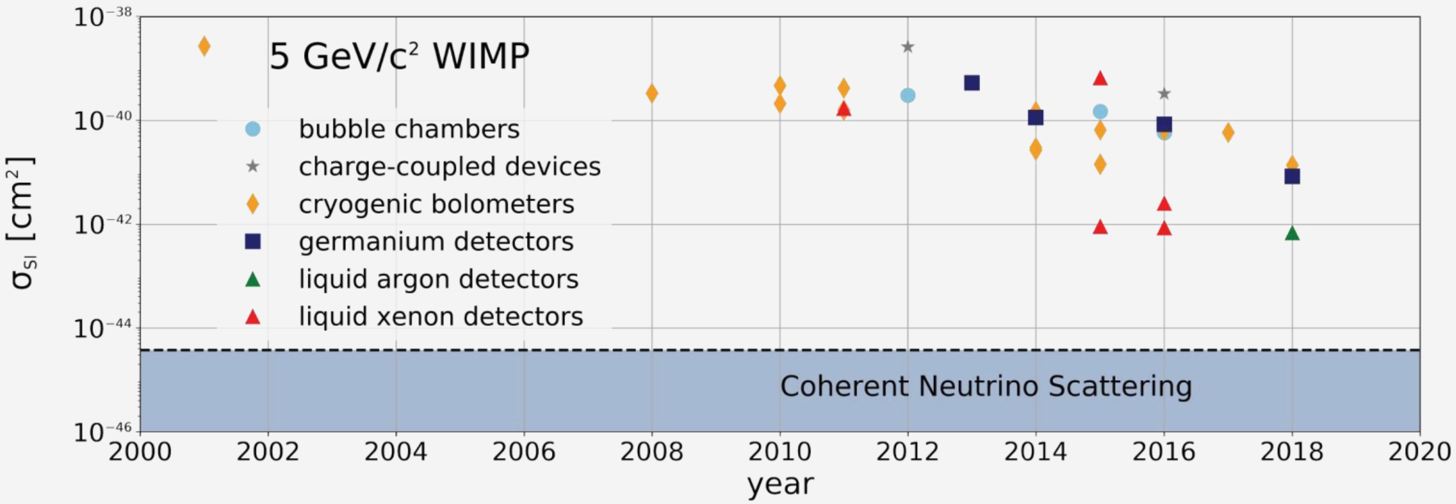
Different technologies with cryogenic bolometers being the most developed

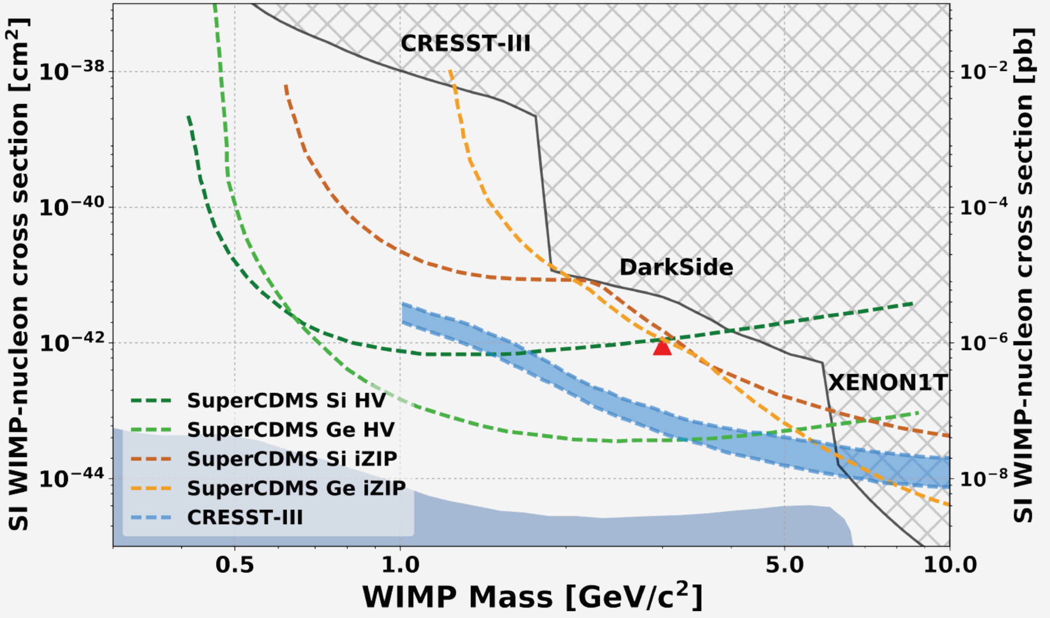
See talk by J. Orrell at 2:15 p.m. on SuperCDMS



Super-CDMS nuclear recoils

Low-mass dark matter searches < 10 GeV (CRESST, SUPERCDMS,..)



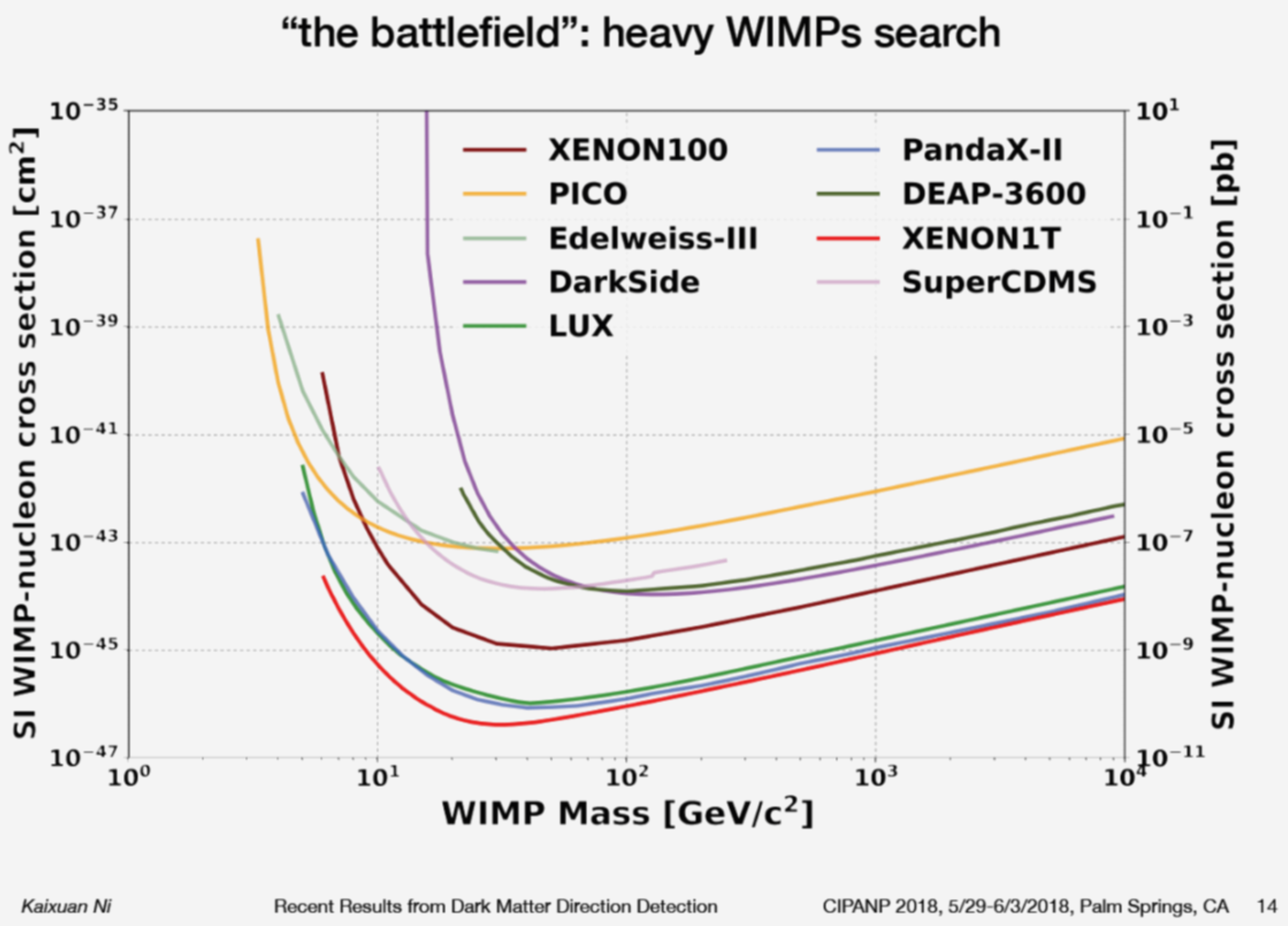


High-mass dark matter searches > 10 GeV

Search above a few GeV is lead by liquid noble gas TPCs (for SI)

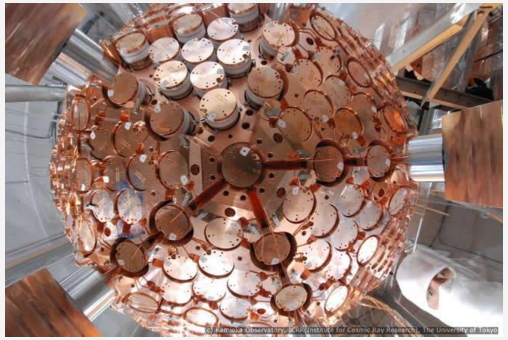
Argon and xenon with different advantages and disadvantages are used

Future upgrade of experiments with larger target masses are in construction

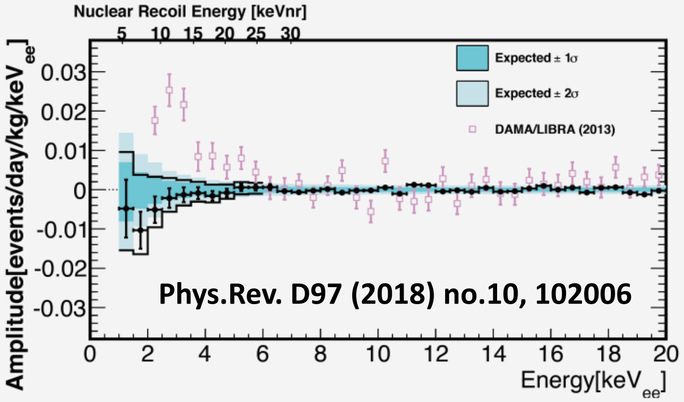


Single phase liquid noble gas TPCs (DEAP,XMASS)

XMASS (LXe)



832 kg target mass
800 live days of data

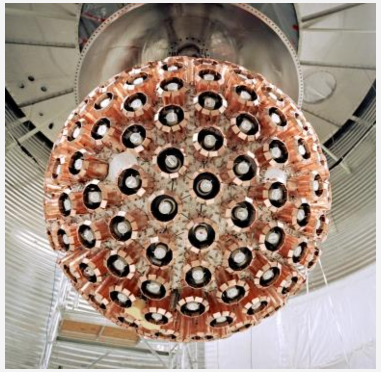


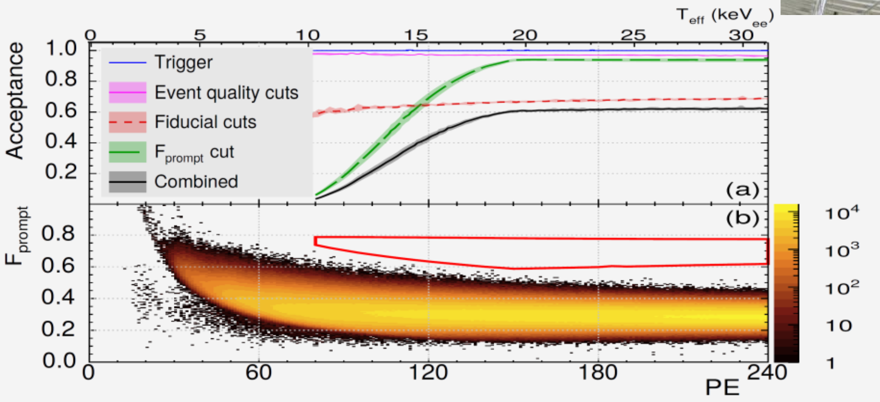
Various analyses beyond the standard dark matter interaction ongoing and published

See talk by K.Hiraide at 10:45 a.m.

DEAP3600 (LAr)

3600 kg target mass (max)
First days of data analyzed
Data taking ongoing





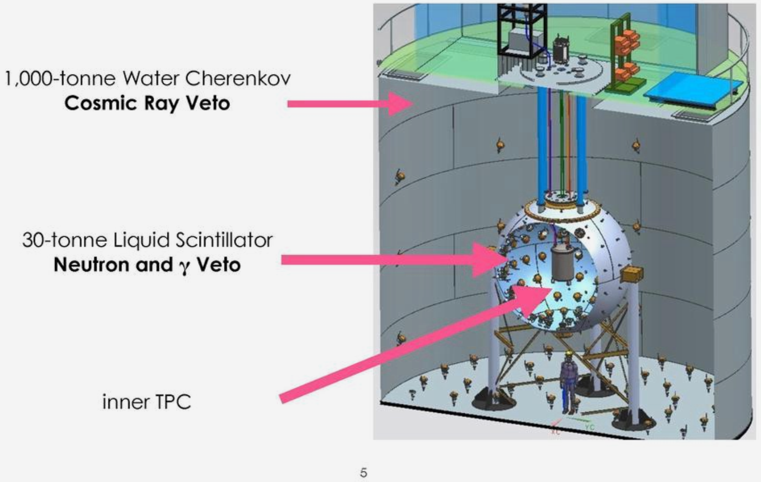
Particle discrimination with pulse shape discrimination (PSD) is excellent

See talk by M.Boulay at 9:45 a.m.

Phys. Rev. Lett. **121**, 071801

Dual phase TPCs - Argon (Darkside)

The DarkSide-50 detector

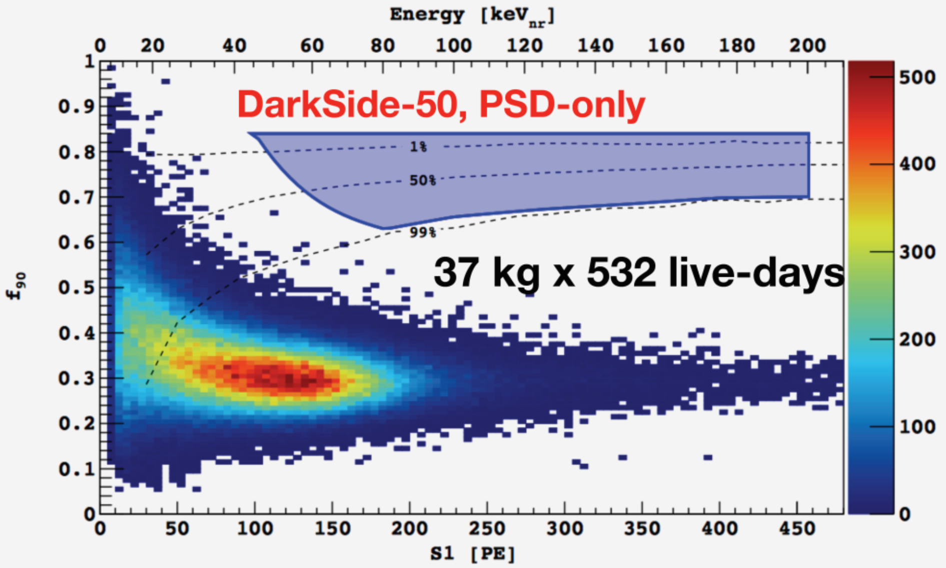


Taken from G.Giovanetti, KITP Apr. 18

S2-only analysis allows to push down threshold to below 1 keV

Phys. Rev. Lett. 121, 081307 (2018)

DarkSide-50, arXiv:1802.07198



Pulse shape discrimination allows for effective particle identification

Using low radioactivity (“underground”) argon to get rid of Ar-39

DarkSide-20k
20 tonne

For future 20 t argon detector distillation of Ar will be pursued in ARIA facility on Sardinia

See talk by J.Maricic at 4:00 p.m.

Dual phase TPCs - Xenon (LUX/LZ, PandaX, XENON)

LUX

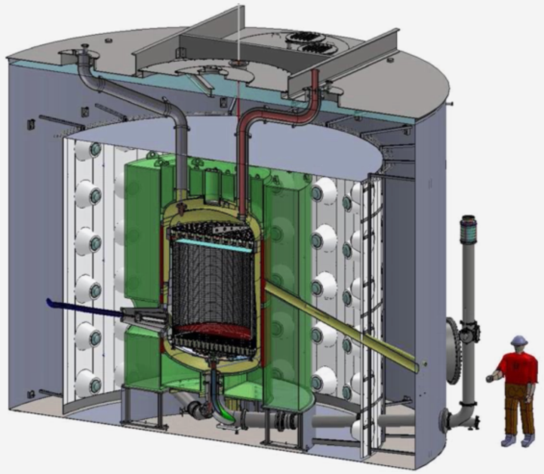
Total of 370 kg LXe
92 kg x yr exposure

See talk by S.Shaw at 11:05 a.m.

Various physics channels are checked beyond the standard SI dark matter analysis

PandaX-II

500 kg total LXe
148 kg x yr exposure



LZ

multi-ton
(7 t) LXe
Operation Apr. 2020

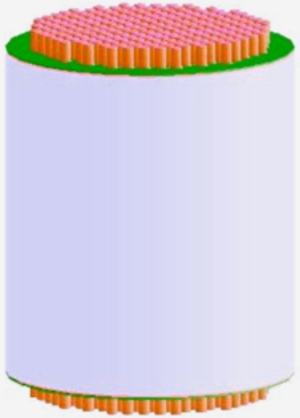
See talk by A. Manalaysay at 3:15 p.m.

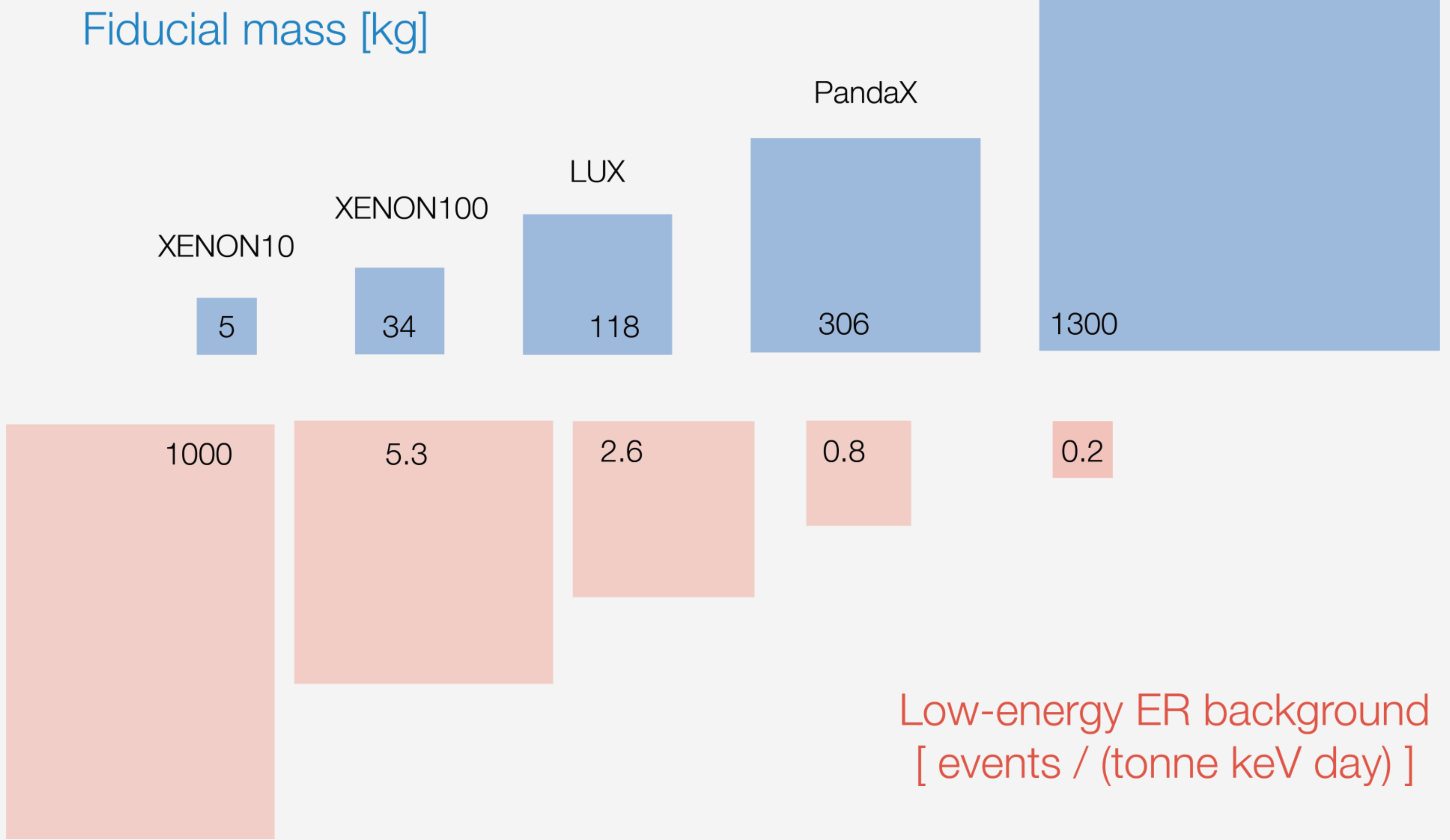
Multi ton detectors in construction

PandaX-4T:

multi-ton
(~4 t) LXe
Assembly 2019-2020

Sci.China Phys.Mech.Astron. 62 (2019) no.3, 31011




Fiducial mass [kg]
XENON10
5
XENON100
34
LUX
118
PandaX
306
XENON1T
1300
1000
5.3
2.6
0.8
0.2
Low-energy ER background
[events / (tonne keV day)]

Direct dark matter search

Recent results from XENON1T

DBD searches with XENON1T

XENON collaboration

170 scientists

27 institutions

11 countries

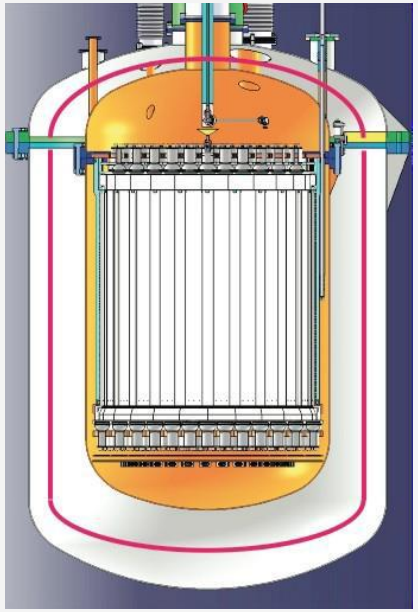
Columbia · RPI · Nikhef · Muenster · Stockholm · Mainz · MPIK, Heidelberg · Freiburg · Zurich

Chicago · UCLA · UCSD · Rice

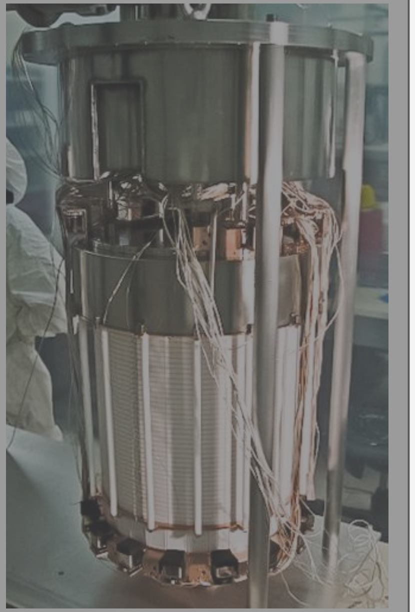
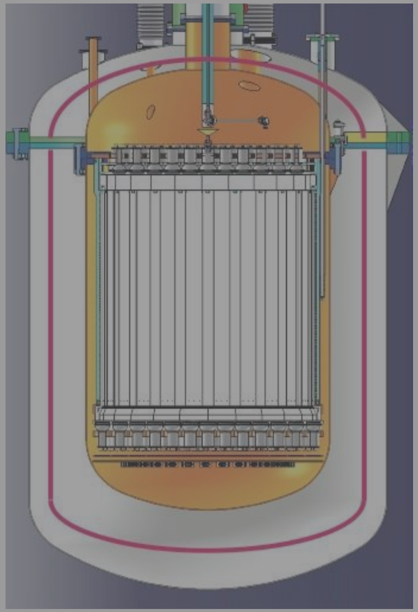
Tokyo · Nagoya · Kobe

Purdue · Coimbra · Subatech · LPNHE · LAL · Bologna · LNGS · Torino · Napoli · Weizmann · NYUAD

XENON Dark Matter Project

XENON10	XENON100	XENON1T	XENONnT	DARWIN
				
2005 - 2007	2008 - 2016	2012 - 2018	2019 - 2024	2020+
25 kg	161 kg	3200 kg	~ 8400 kg	~ 50 000 kg
$\sim 10^{-43}$ cm²	$\sim 10^{-45}$ cm²	$\sim 10^{-47}$ cm²	$\sim 10^{-48}$ cm²	$\sim 10^{-49}$ cm²

See talk by S. Kazama at 3:35 p.m.

XENON10	XENON100	XENON1T	XENONnT	DARWIN
				
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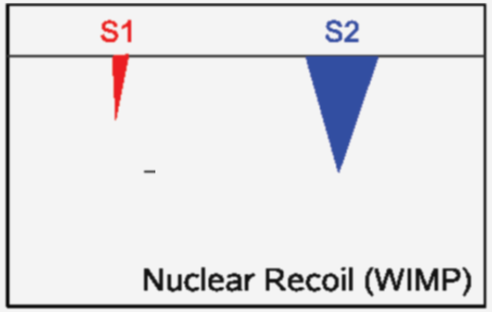
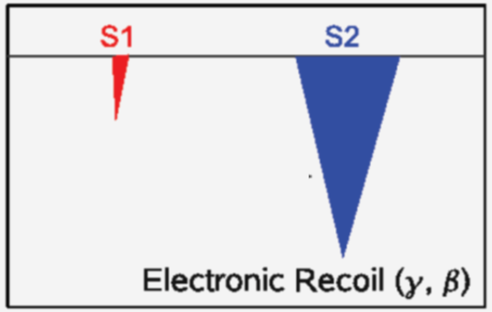
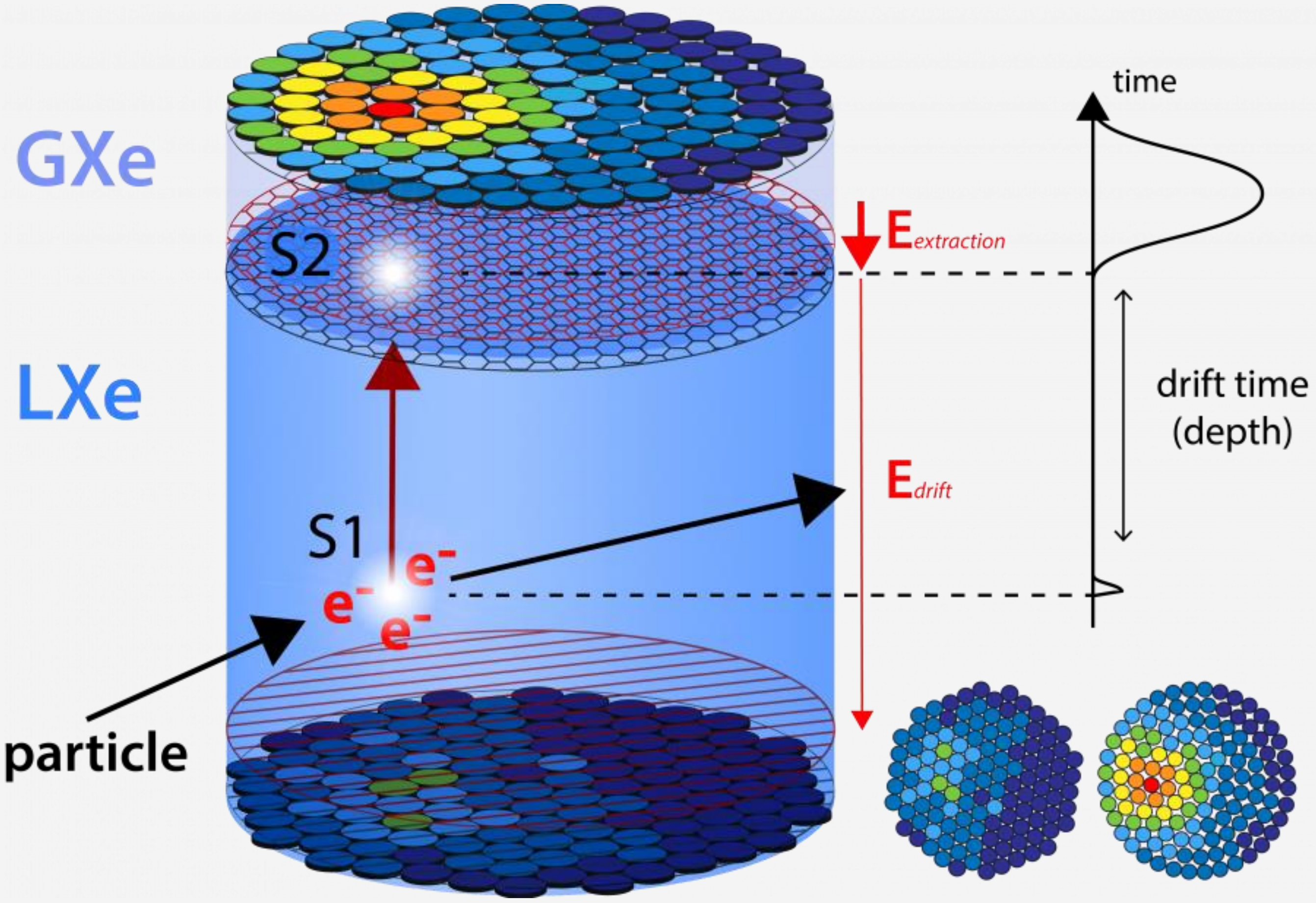
$\sim 10^{-43}$ cm²	$\sim 10^{-45}$ cm²	$\sim 10^{-47}$ cm²	$\sim 10^{-48}$ cm²	$\sim 10^{-49}$ cm²

Dual-phase liquid noble gas time projection chamber (TPC)

Discrimination possible







Full 3-D position reconstruction possible

z-position
from drift time
Resolution ~O(mm)

x,y-position
by hit pattern (S2)
Resolution ~O(mm)

XENON1T @LNGS

Water tank
700 t ultra-pure water
+
Muon veto
84 PMTs

External Calibrations
AmBe, Cs-137, Th-228, D-D neutron generator

Cryostat

TPC
3.2 t LXe
248 PMTs

Cryogenic
+
Purification
+
Internal Calibrations
Kr-83m, Rn-220

DAQ
+
Slow control

Distillation column
Kr, Rn removal

Xe Storage and Recovery
Up to 7 tons

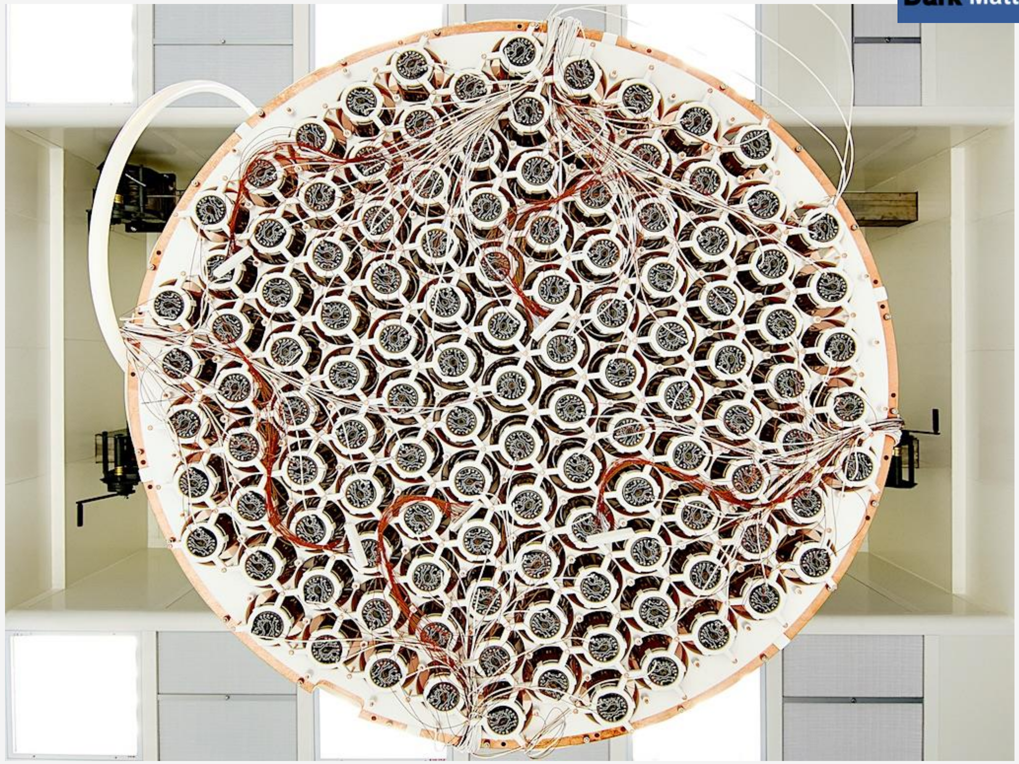
Bottle rack

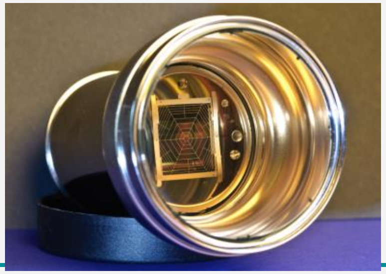
Eur. Phys. J. C. (2017) 77:881

The XENON1T TPC

2 t xenon within the TPC (of 3.2 t total)
~ 1 m drift length
~ 1 m in diameter

Highly reflective PTFE walls



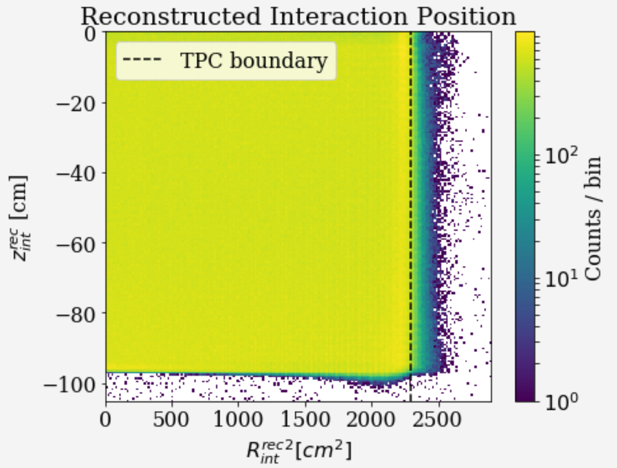


248 Low-background Hamamatsu R11410-21 3-inch PMTs

EPJC 75 (2015) 11, 546

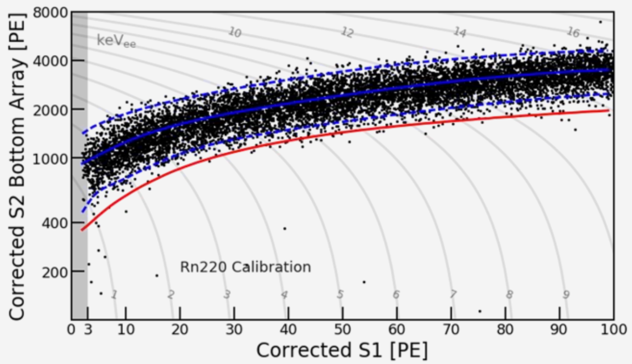
Calibration sources

^{83m}Kr



Internal ER source
Monoenergetic (9.4 & 32.1 keV)
Short lived ($t_{1/2}$ = 1.83 h)
Monitoring detector stability
Characterize detector

^{220}Rn



Internal ER sources
Continuous spectrum
No impact after a few days
($t_{1/2}$ = 10.6 h)
Used for ER band determination

Neutron generator (+AmBe)

External NR sources
On/Off cycle
High neutron flux (2000 n/s)
Used for NR band determination

Electronic recoil backgrounds

^{85}Kr and ^{222}Rn (^{214}Pb)

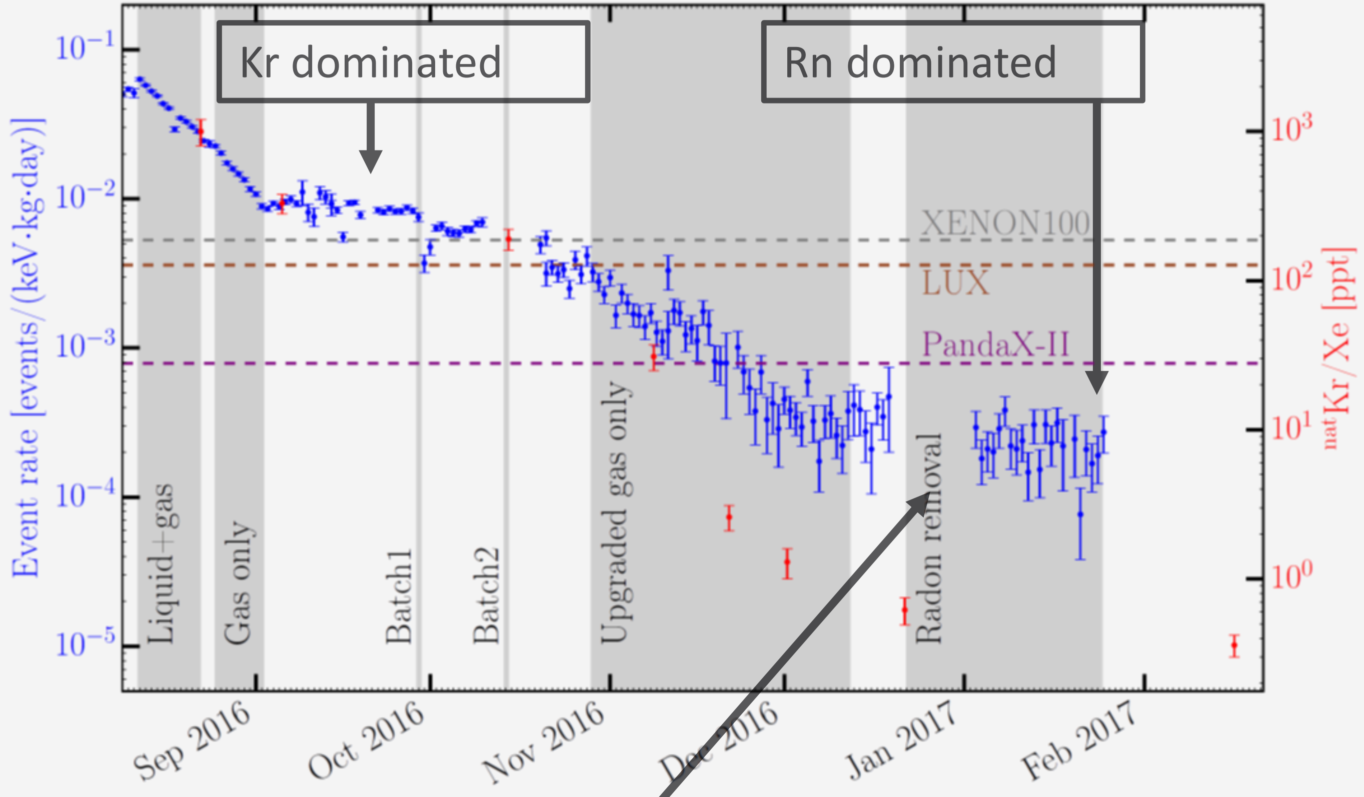
→ Leakage events from the low energy β-spectrum contaminate ROI for dark matter search
→ Material screening to avoid radon emanation
→ Krypton reduction by cryogenic distillation

^{nat}Kr/Xe in SR1:
(0.66 ± 0.11) ppt

^{222}Rn/Xe in SR1:
(13.3 ± 0.8) μBq/kg

Type	Fraction [%]
^{222}Rn (^{214}Pb)	85.4
^{85}Kr	4.3
solar ν	4.9
Materials	4.1
^{136}Xe	1.4

Expectations in 1 t FV, in [1,12] keVee, single scatters, Pb-214 = 10μBq/kg, **before ER/NR discrimination**



Eur. Phys. J. C. (2017) 77, 275
Eur. Phys. J. C. (2017) 77, 358

JCAP 04, 027 (2016) with updated SR1 values

Radon further reduced by ~20% with cryogenic distillation during 2nd half of SR0

Nuclear recoil backgrounds

Cosmogenic neutrons

Induced by cosmic muons. Reduced to negligible contribution by rock overburden, water passive shield and active Cherenkov Muon Veto.

JINST 9, P11006 (2014)

Coherent Elastic neutrino-nucleus scattering (CEνNS)

Mainly from ^{8}B solar ν. Constrained by flux and cross section measurement. Irreducible background at very low energy (< 1 keV)

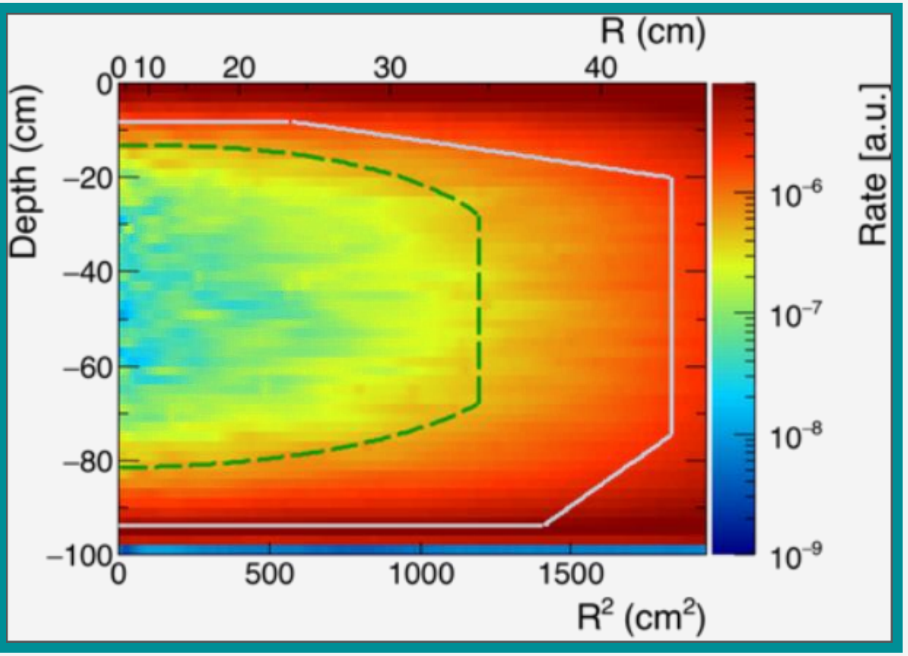
Radiogenic neutrons

From (α,n) and spontaneous fission in detector's materials. Reduced via radiopure material selection, scatter multiplicity and fiducialization.

Eur. Phys. J. C. (2017) 77:890

Type	Fraction [%]
Cosmogenic neutrons	<2.0
Radiogenic neutrons	96.5
CEνNS	2.0

Expectations in 1 t FV, in [4,50] keVnr, single scatters



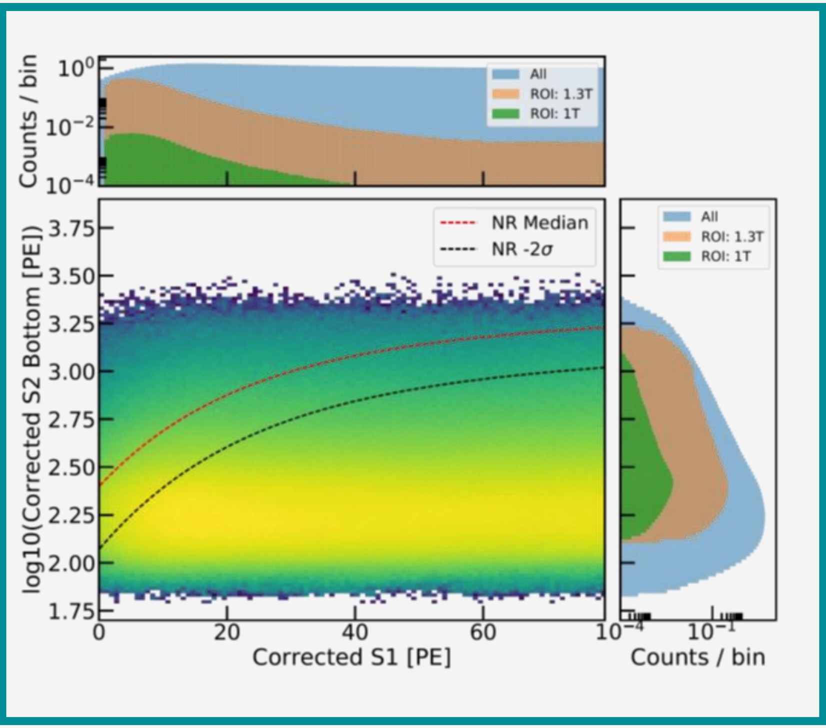
Other backgrounds

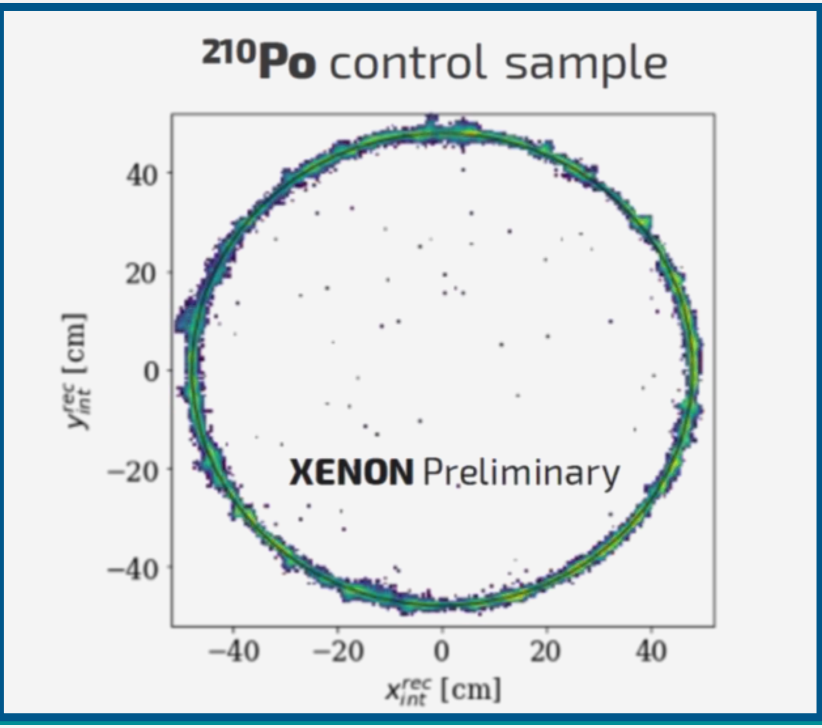
Surface events

- ^{210}Pb from ^{222}Rn chain plates out on PTFE surfaces.
- S2 signal losses when ^{210}Pb β-decay happens on surface.
  → **leakage into signal region**
- Data driven model based on ^{210}Po surface control samples.

Accidental coincidence

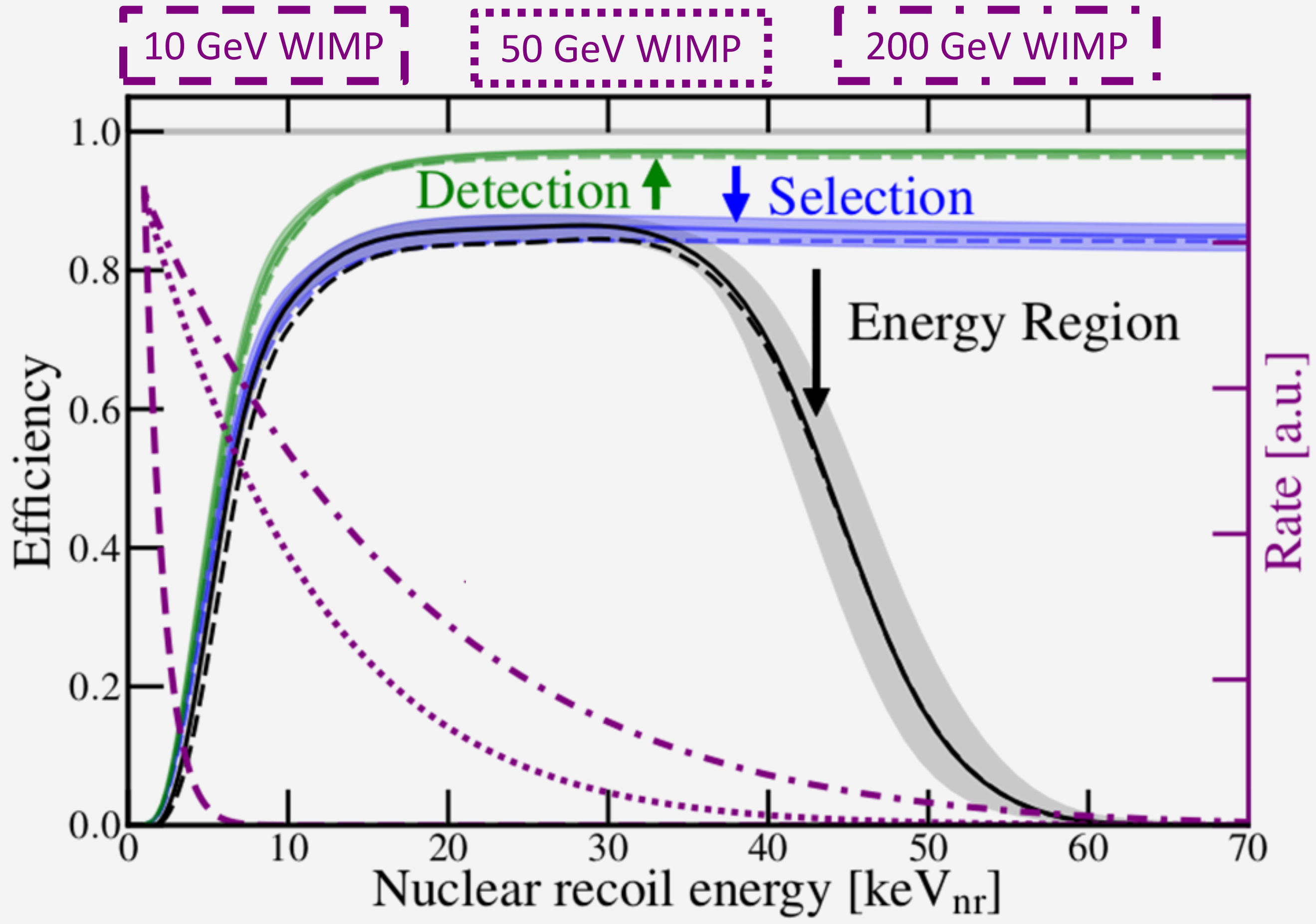
- Lone-S1 signals may accidentally coincide (AC) with lone-S2 signals. → **fake interactions**
- Empirical model verified with ^{220}Rn calibration data and background sidebands.



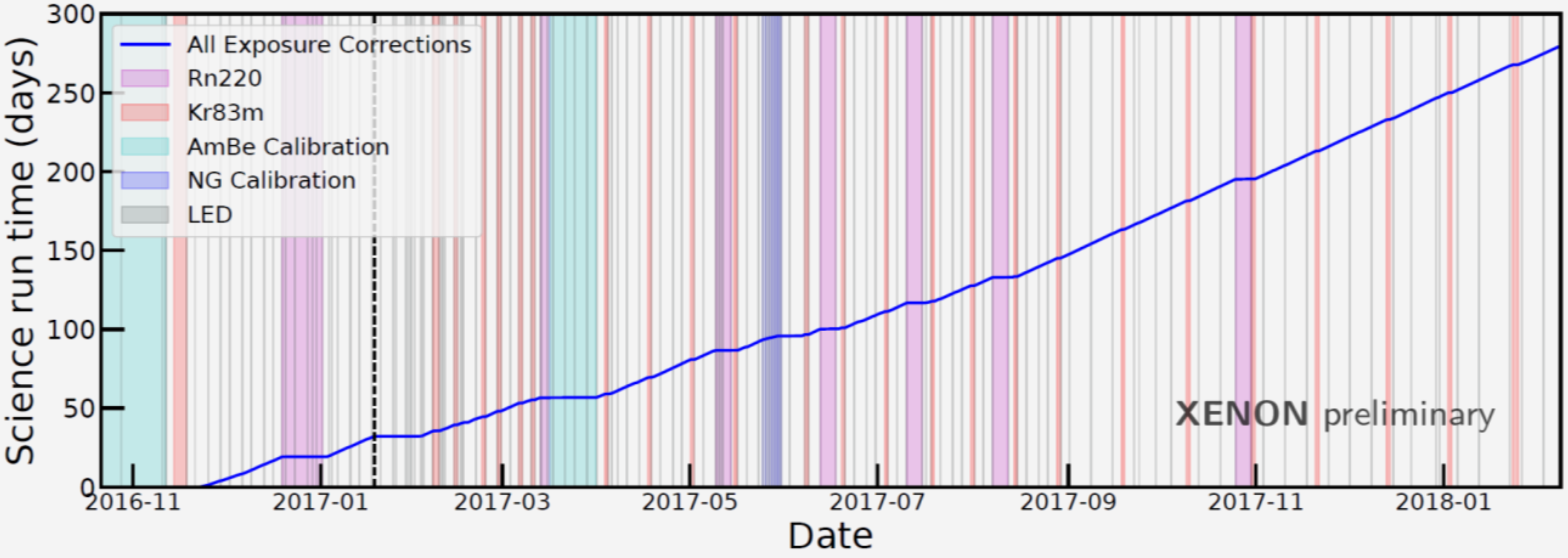


Signal efficiency

- Detection efficiency dominated by PMT 3-fold coincidence requirement
- Selection efficiencies estimated from control or MC data samples
- Search region defined within 3-70 PE in S1



Data set (one tonne x year exposure)



Science Run **0** (**SR0**) 32.1 days
PRL 119, 181301

Science Run **1** (**SR1**) 246.7 days
PRL 121, 111302

The result presented today combines **both** science runs for 278.8 days total livetime.
→ **1 tonne x year** exposure given **1.3 tonne fiducial volume.**

Signal region **blinded** for SR1, **re-blinded** for SR0 + **salted**.

Calibration results

Electronic **R**ecoils

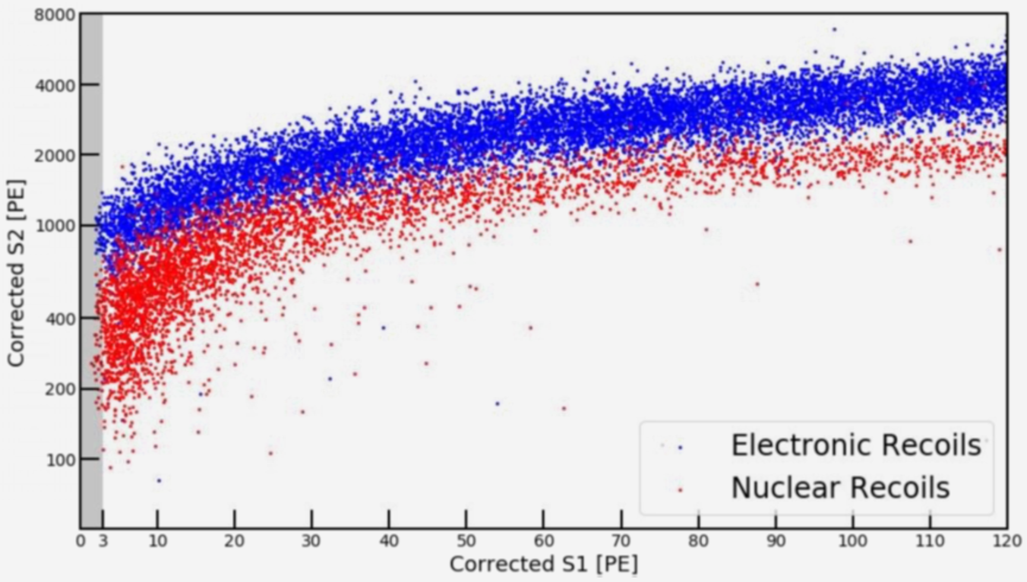
-

^{220}Rn

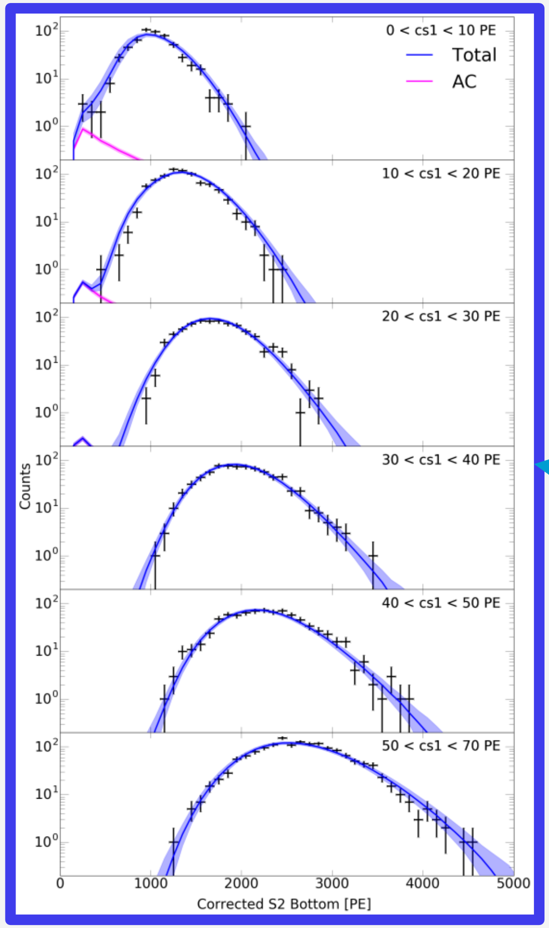
Nuclear **R**ecoils

-

Neutron generator



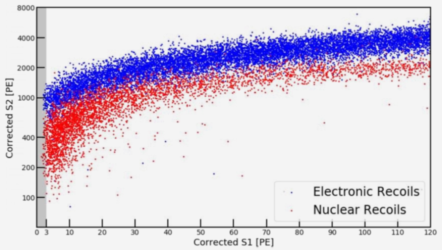
Calibration results



Electronic Recoils

-

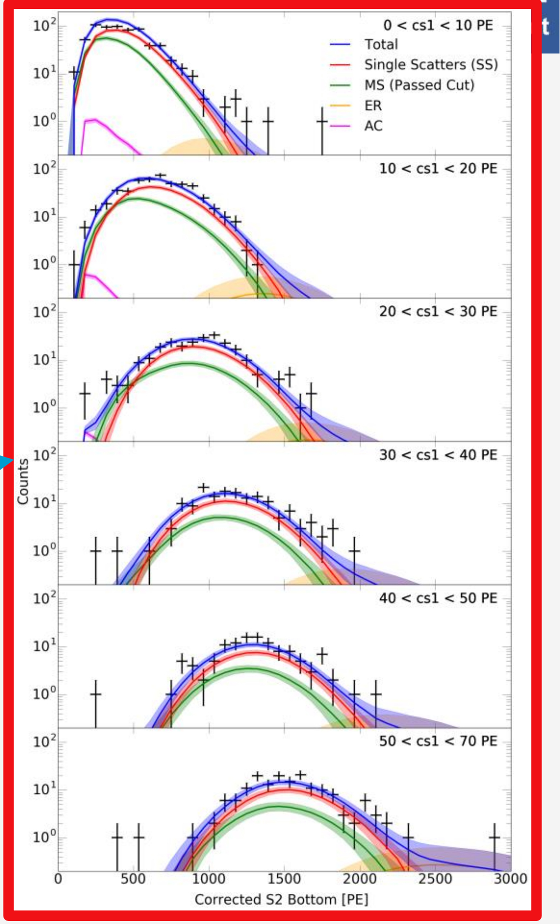
^{220}Rn



Nuclear Recoils

-

Neutron generator

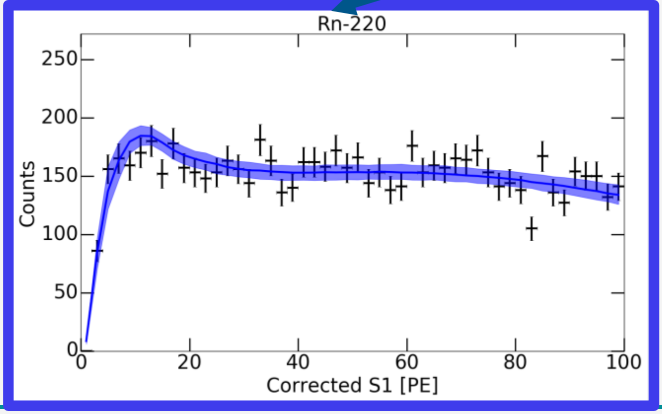


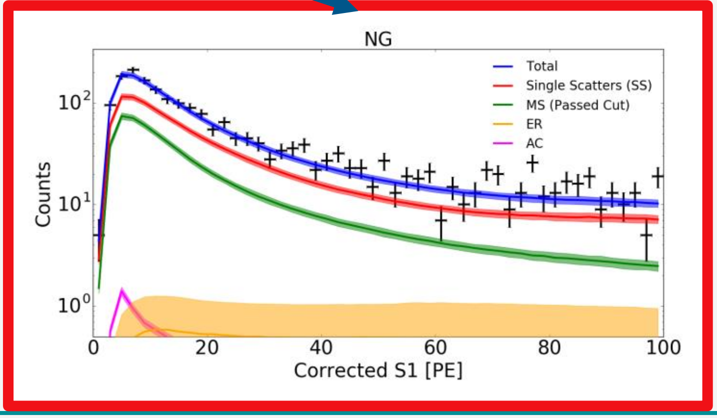
Particle propagation with detailed detector geometry and LXe physics modeled.

Parameters tuned and constrained by calibration data.

S2 projections in S1 slices

S1 projection





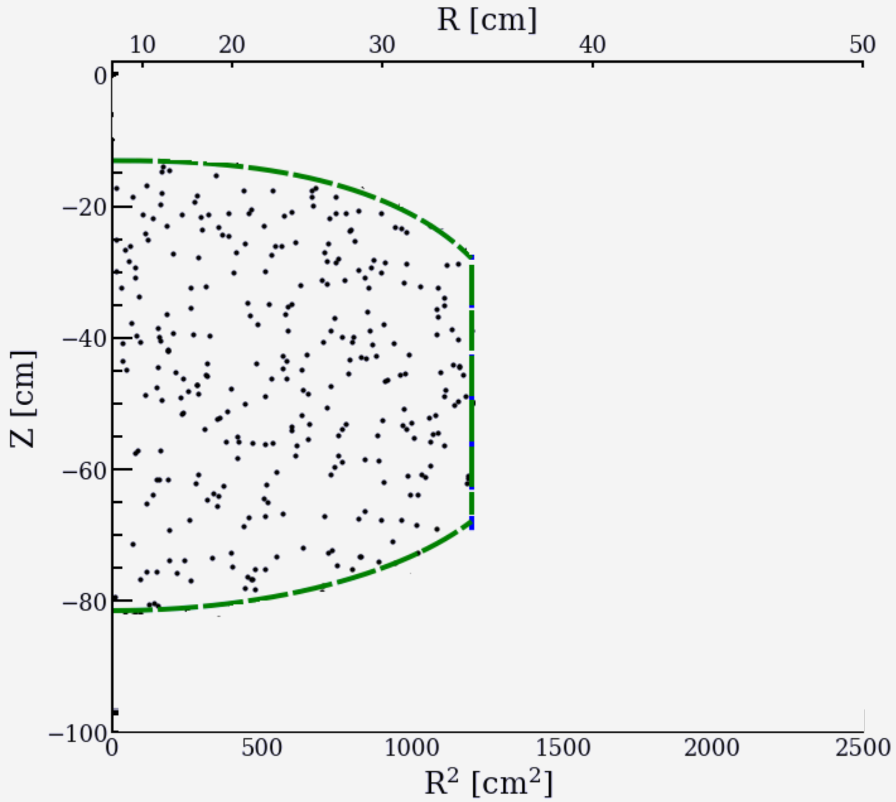
~99.7% ER rejection in NR reference region [NR median,-2σ]

Background predictions – core volume

NR reference region

Between NR median and -2σ quantile.

	0.65 t
Type	**NR reference**
ER	0.6 ± 0.13
neutrons	0.14 ± 0.07
CEνNS	0.01
AC	$0.04^{+0.02}$
Surface	0.01
Total BKG	**0.8 ± 0.14**



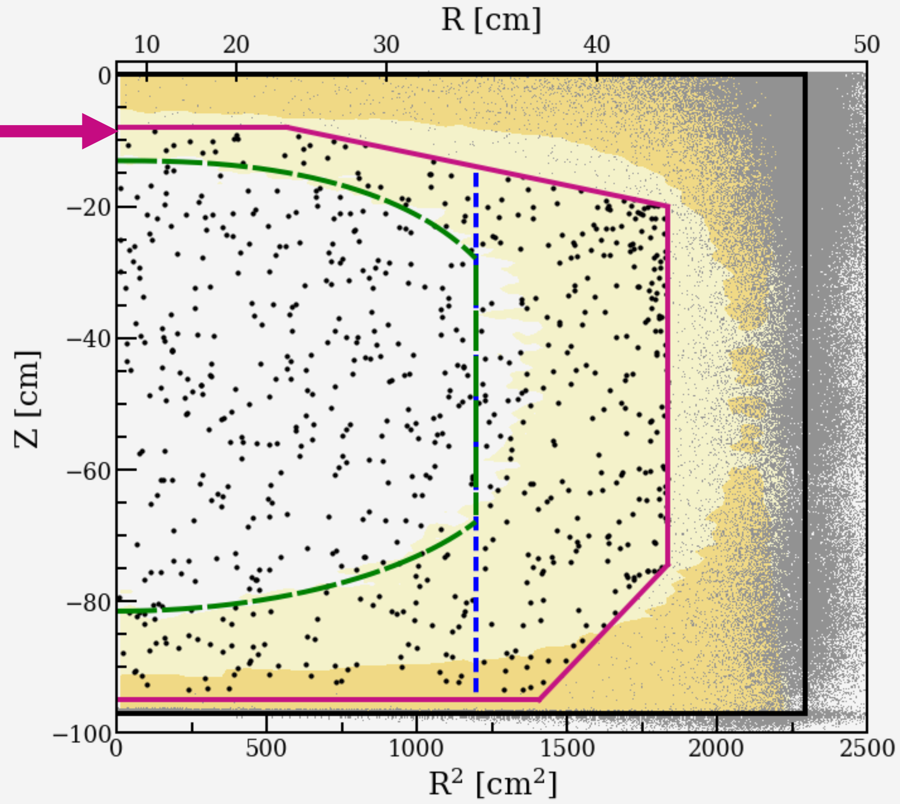
Classical box counting with hard discrimination cut just for illustration!

Background predictions – full volume

Full fiducial (1.3 t)

No selection in discrimination space

	1.3 t
Type	Full ROI
ER	627 ± 18
neutrons	1.43 ± 0.66
CEνNS	0.05 ± 0.01
AC	$0.47^{+0.27}$
Surface	106 ± 8
Total BKG	735 ± 20



Instead of using a hard discrimination criteria, a likelihood is given depending on the position in discrimination space

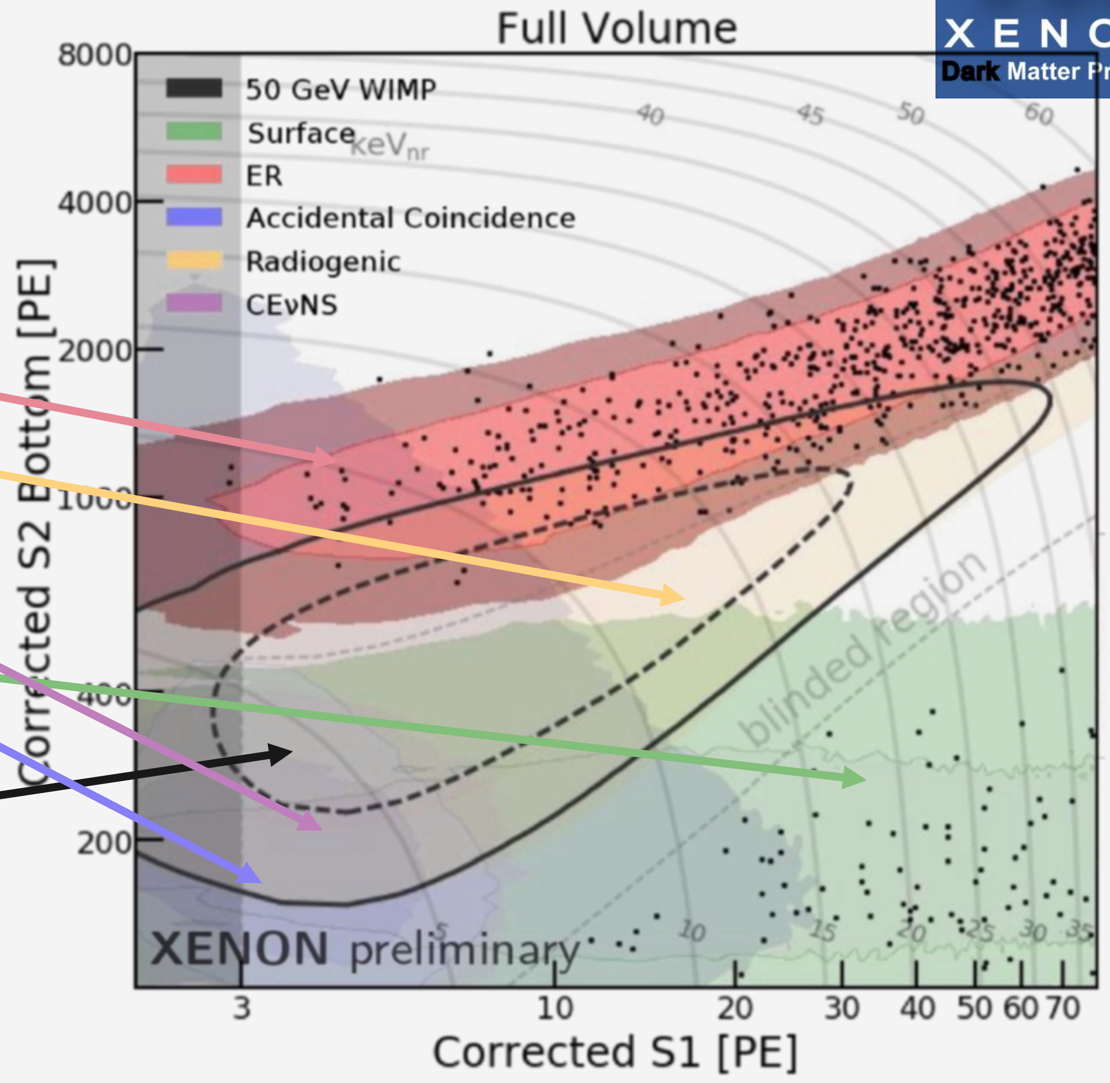
Background predictions – full volume

	1.3 t
Type	Full ROI
ER	627 ± 18
neutrons	1.43 ± 0.66
CEνNS	0.05 ± 0.01
AC	$0.47^{+0.27}$
Surface	106 ± 8
Total BKG	735 ± 20

Background models

In 4-dimensional space:
S1, S2, R,Z

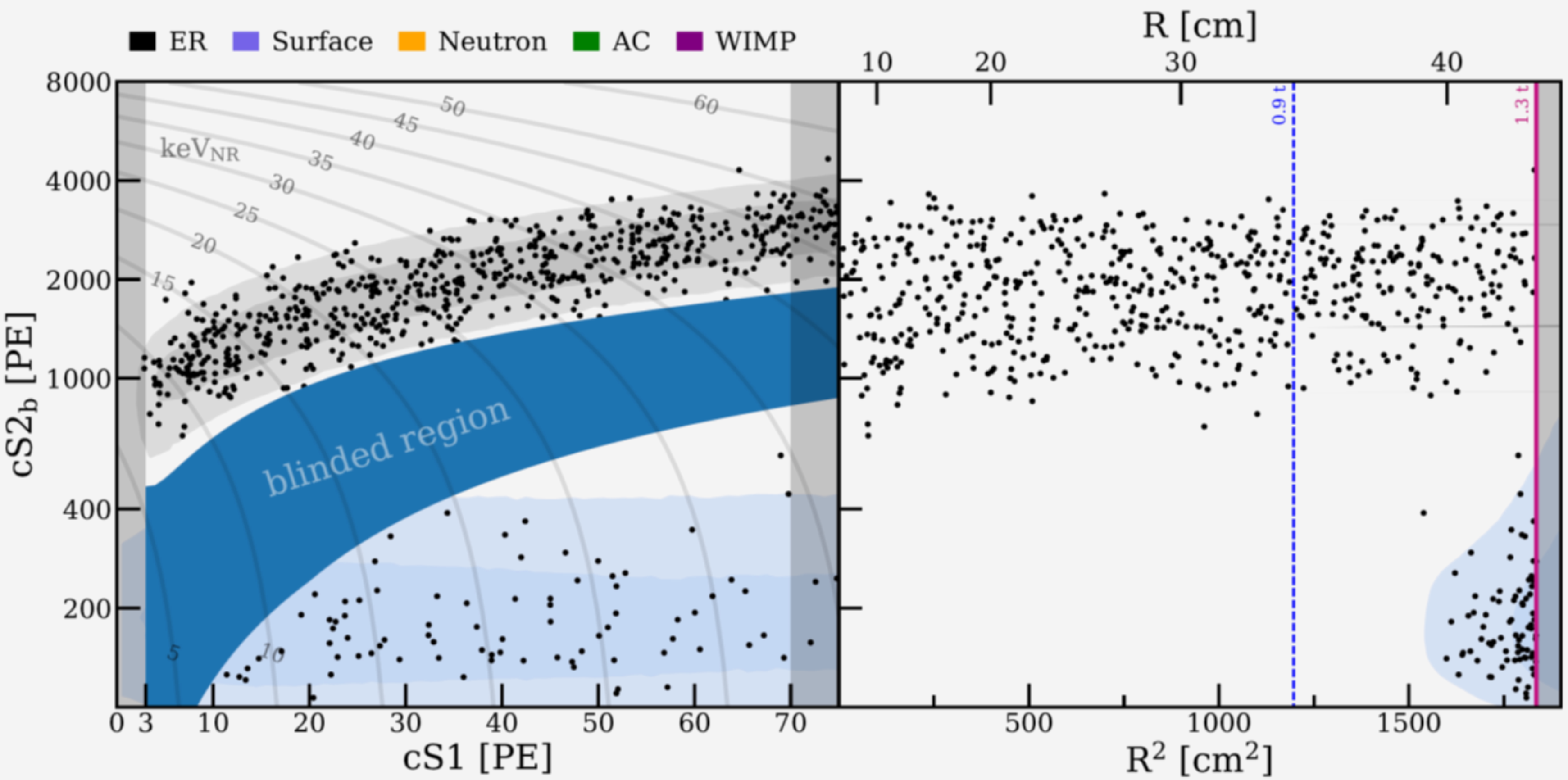
WIMP
50 GeV/c^2



Statistical inference

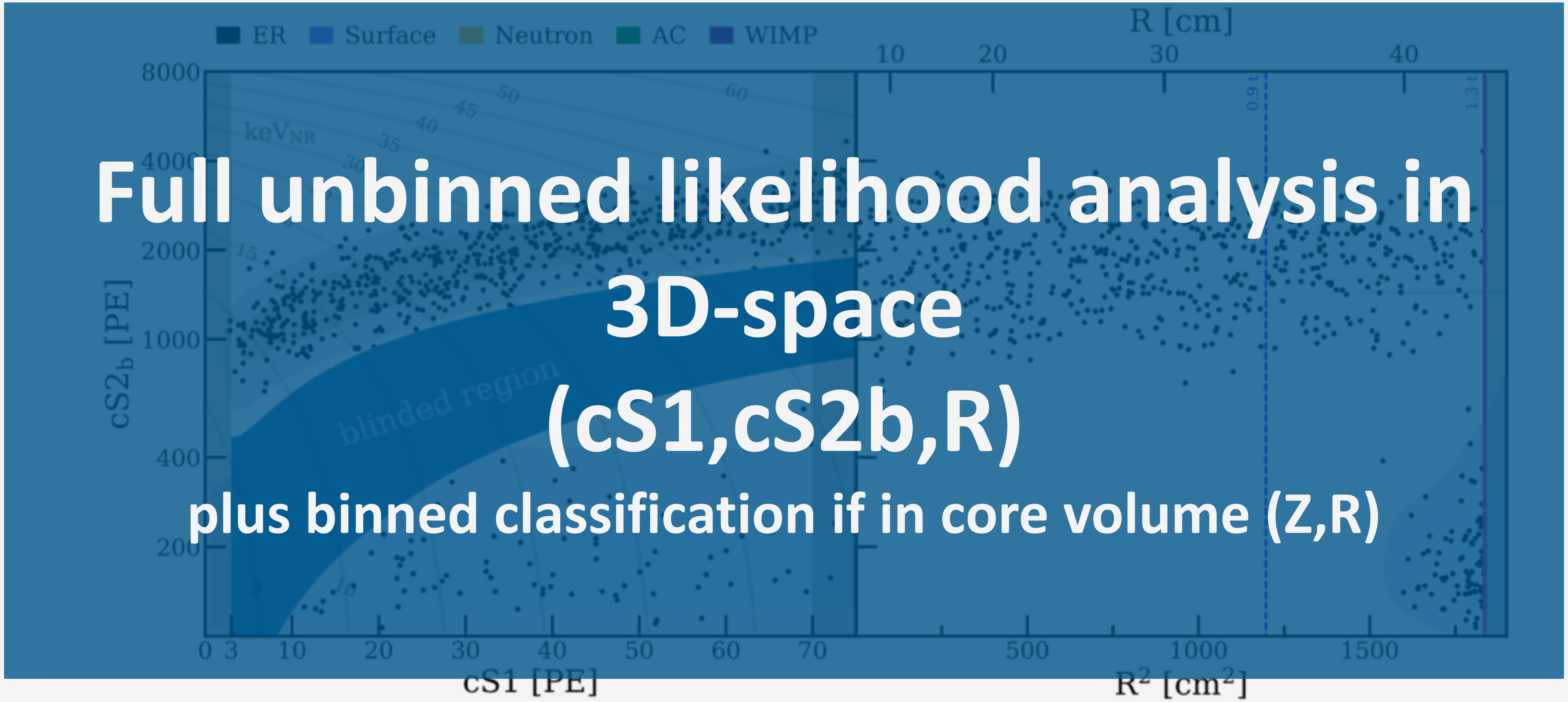
Done with PLR analysis in 1.3 t fiducial volume and full (S1,S2) space, corresponding to [4.9, 40.9] keVnr and [1.4, 10.6] keVee.

Analysis space before unblinding

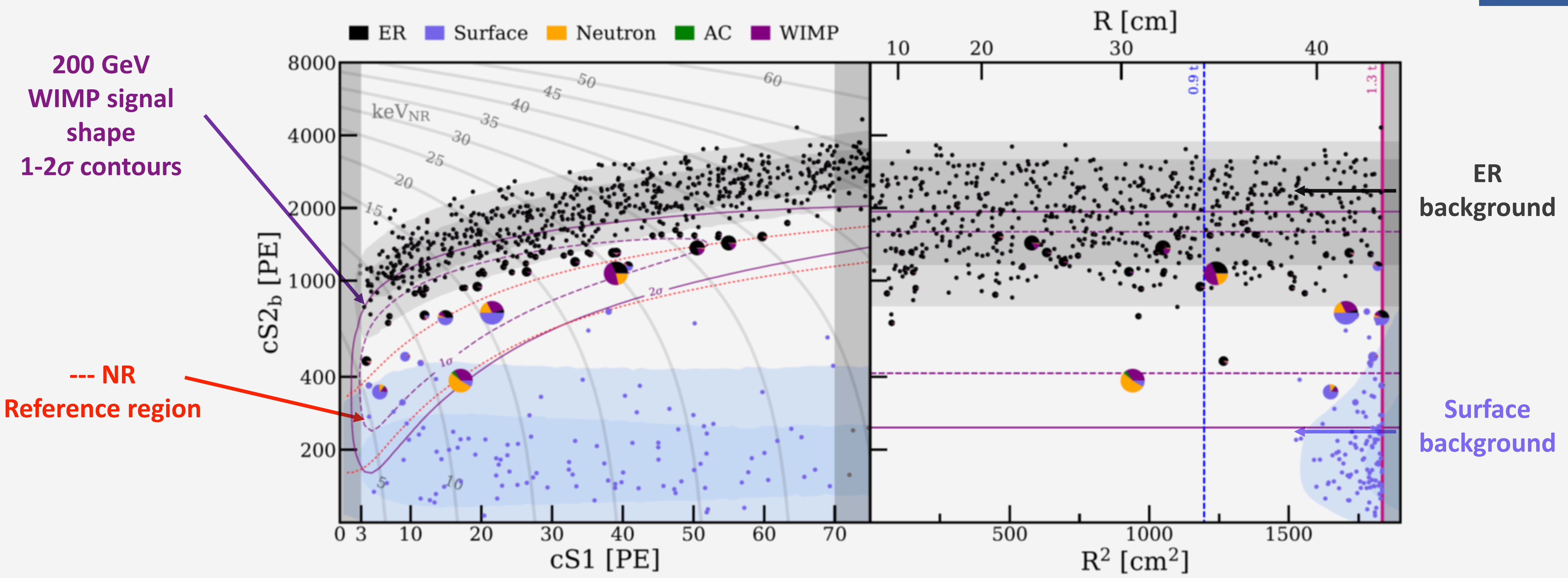


Full unbinned likelihood analysis in 3D-space (cS1,cS2b,R)

plus binned classification if in core volume (Z,R)



Results: Unblind + Desalt!

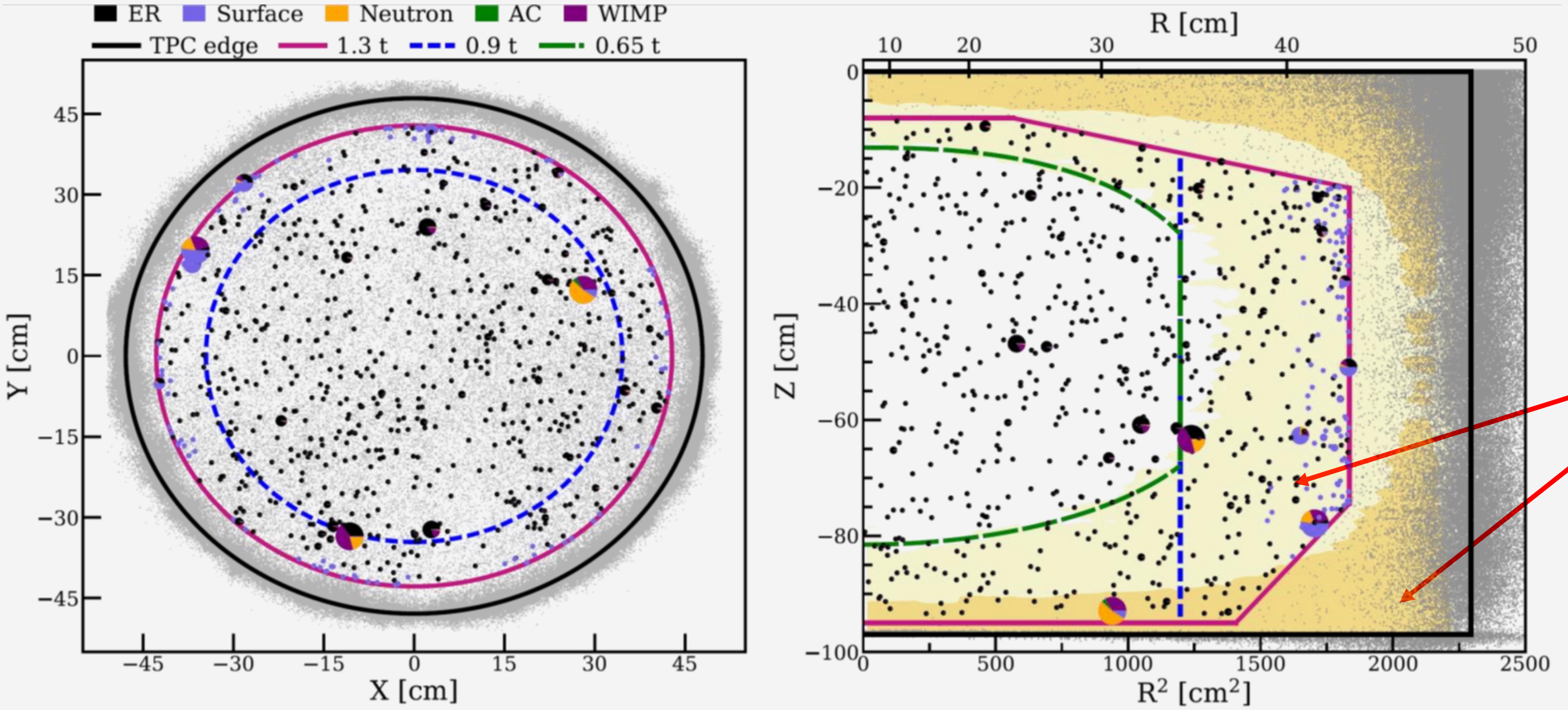


Larger charts → Larger WIMP probability

Pie charts

Events passing all selection criteria are shown as pie charts representing the relative PDF from each component for the best-fit model for 200 GeV WIMP (σ_{SI}=4.7 · 10^{-47} cm^2).

Distribution in the detector



Neutron **background**
1-2σ contours

Core volume (0.65 t)

Distinguish WIMPs over neutron background

Final result of one tonne x year of XENON1T

Sensitivity

7 times improved compared to previous generation experiments (LUX, PANDAX-II)

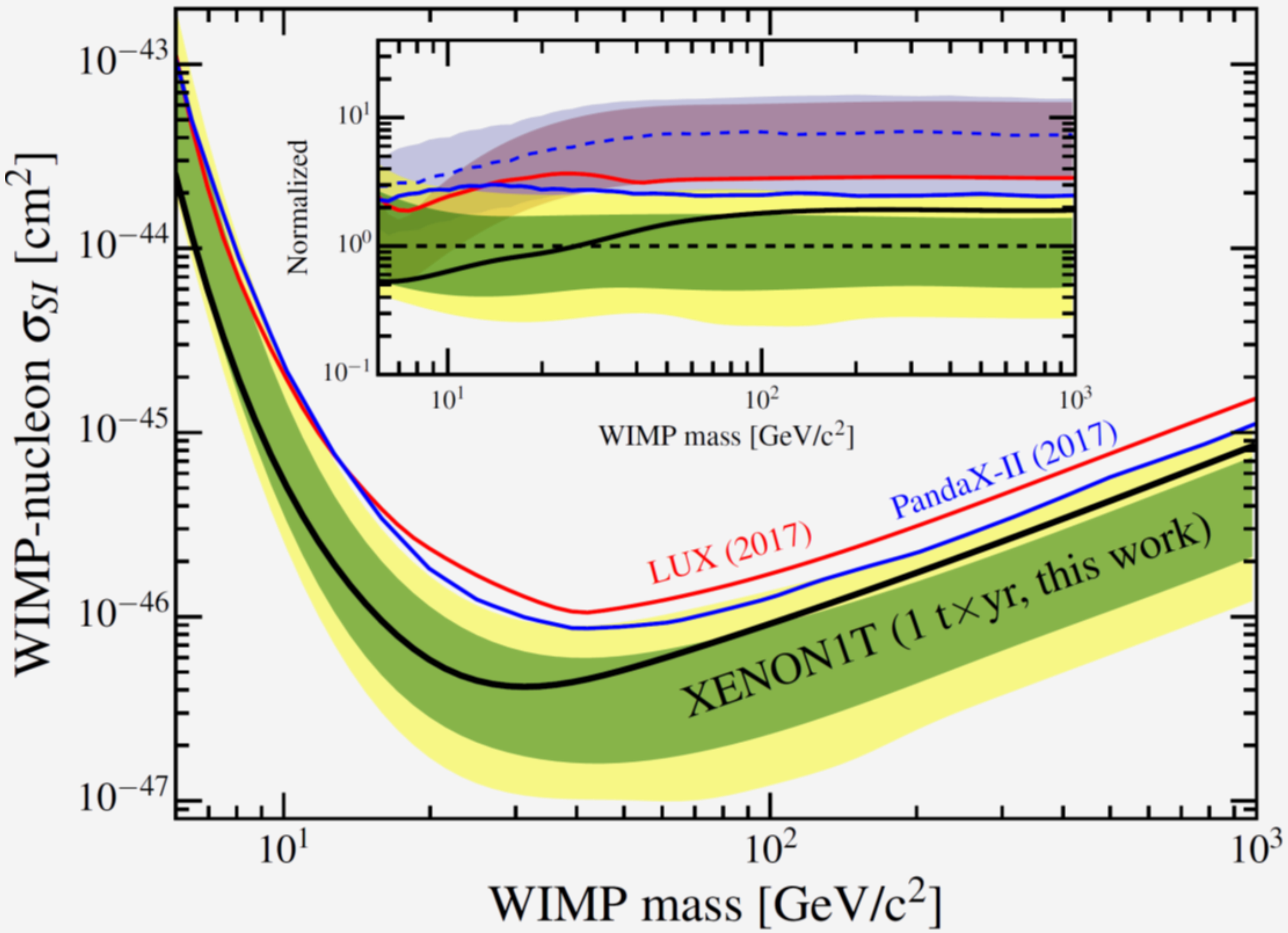
Limit

~1σ under-fluctuation for masses ≲ 8 GeV/c²
while over-fluctuation at higher masses

Minimum

σ_{SI} < 4.1 · 10^{-47} cm² at 30 GeV/c²

Phys.Rev.Lett. 121 (2018) no.11, 111302



Direct dark matter search

Recent results from XENON1T

DBD searches with XENON1T