INFN
Istituto Nazionale di Fisica Nucleare

Direct dark matter search with xenon detectors and their potential in neutrino physics

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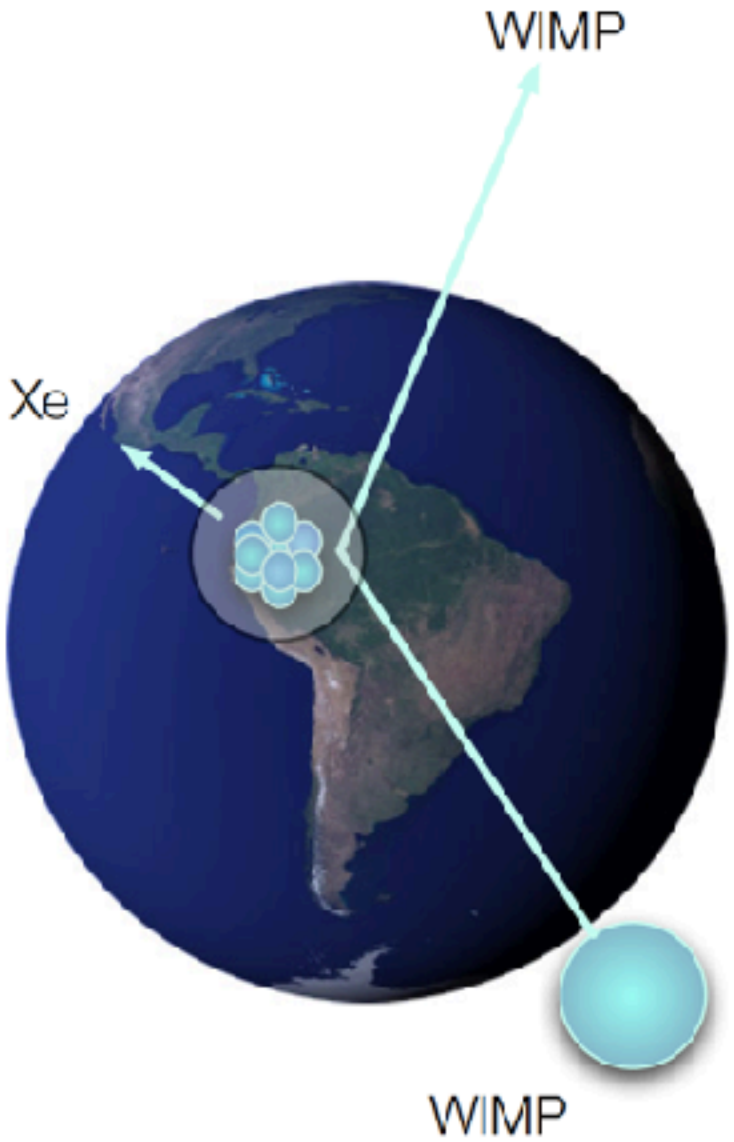
Marco Selvi
INFN Bologna

106° CONGRESSO NAZIONALE
SOCIETÀ ITALIANA DI FISICA
14-18 settembre 2020

PROVANDO E RIPROVANDO

WIMP direct detection



- Elastic collisions with nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

- and the expected rate:

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

N = number of target nuclei in detector
ρ_χ = local WIMP density, m_χ = WIMP mass
$\langle \sigma_{\chi N} \rangle$ = scattering cross section

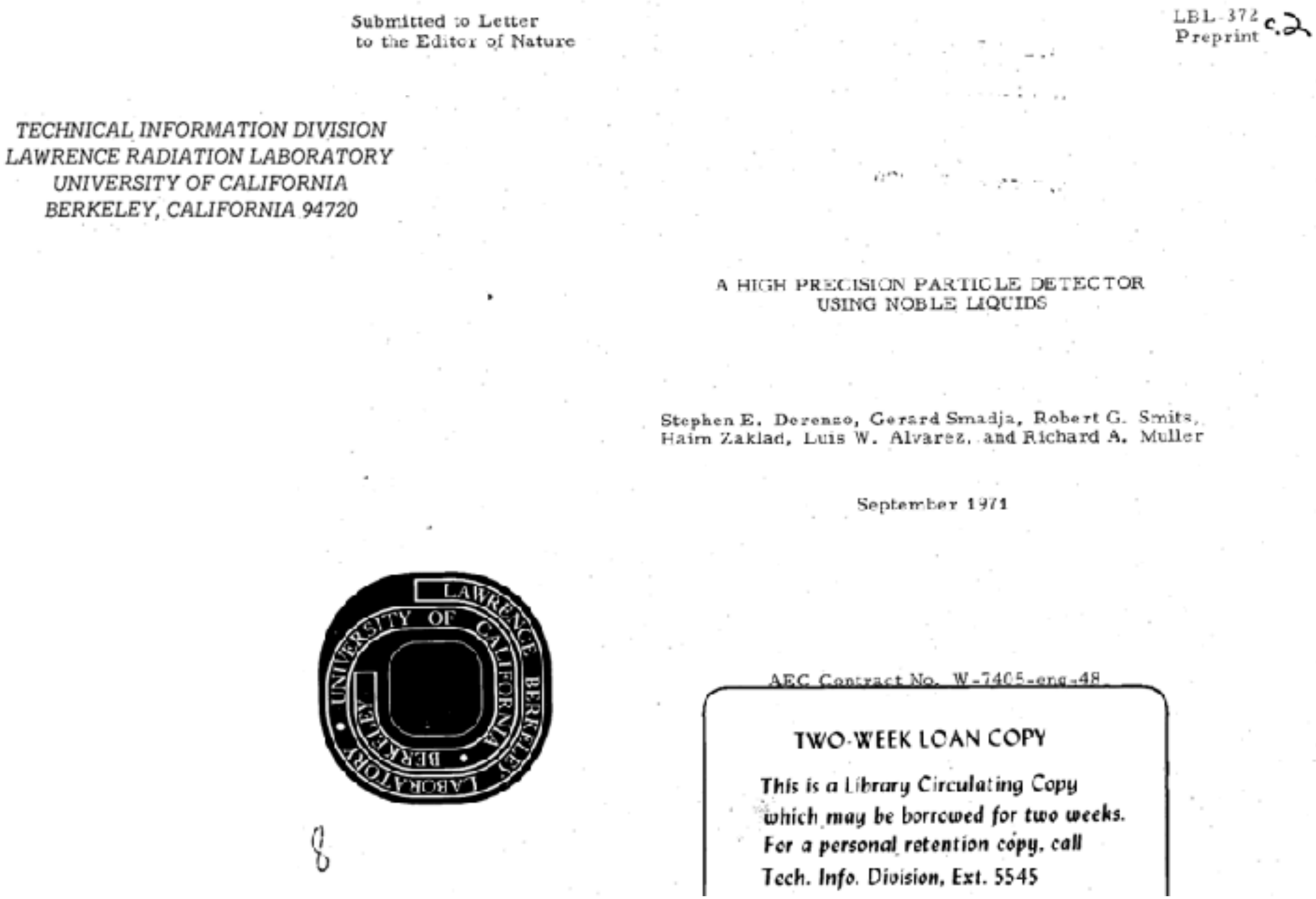
- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ sub-keV to few keV’s
  - Very low background and/or background discrimination
  - Long term stability

Which target ?

… choose Xenon !!

131.29 54
[Kr]$4d^{10}5s^25p^6$
Xe
Melting point: -111.9°C
Boiling point: -107.1°C
XENON

since 1968 (L. Alvarez)



Submitted to Letter
to the Editor of Nature

LBL-372 c.2
Preprint

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A HIGH PRECISION PARTICLE DETECTOR
USING NOBLE LIQUIDS

Stephen E. Derenzo, Gerard Smadja, Robert G. Smits,
Haim Zaklad, Luis W. Alvarez, and Richard A. Muller

September 1971

AEC Contract No. W-7405-eng-48

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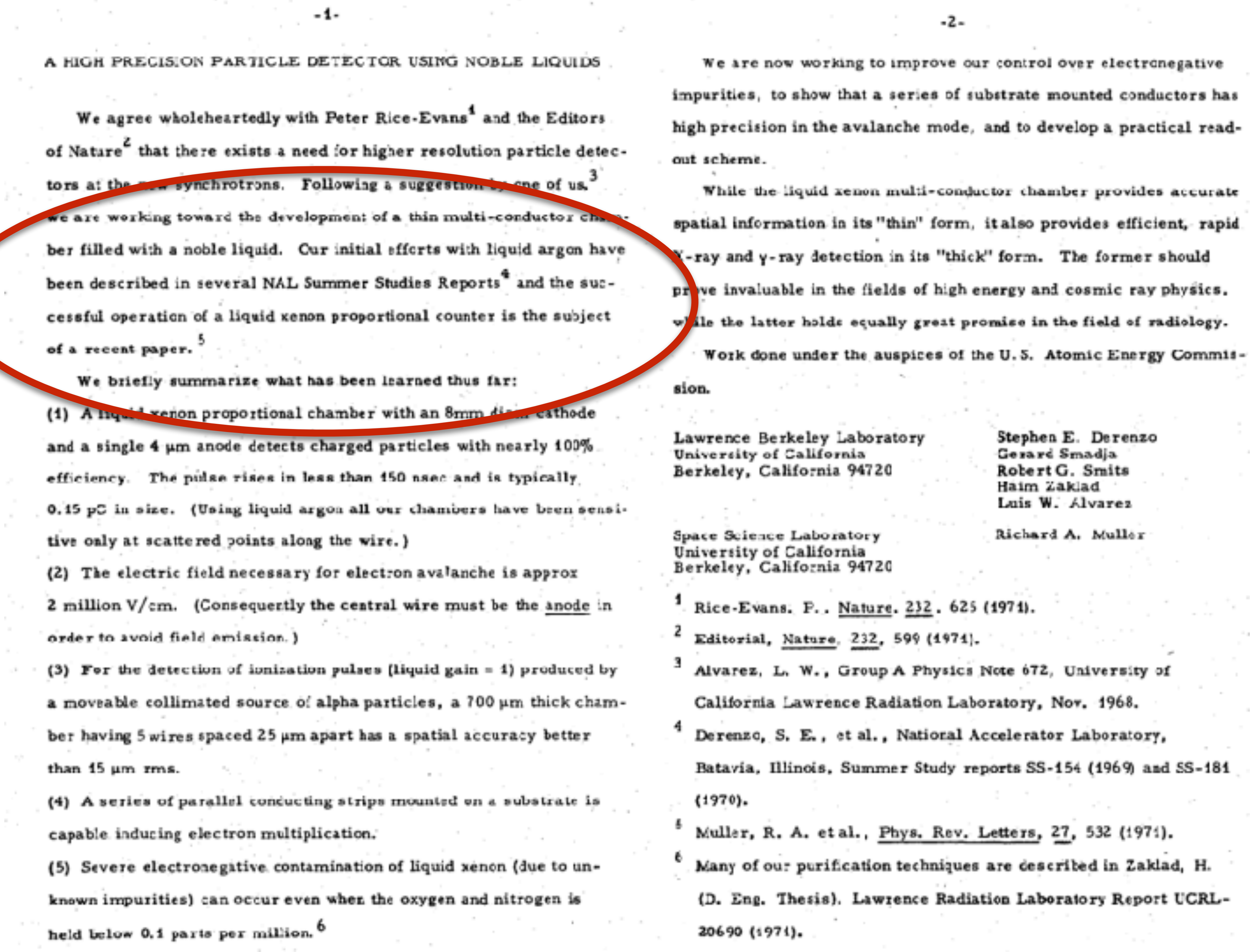


-1-

A HIGH PRECISION PARTICLE DETECTOR USING NOBLE LIQUIDS

We agree wholeheartedly with Peter Rice-Evans[1] and the Editors of Nature[2] that there exists a need for higher resolution particle detectors at the new synchrotrons. Following a suggestion by one of us,[3] we are working toward the development of a thin multi-conductor chamber filled with a noble liquid. Our initial efforts with liquid argon have been described in several NAL Summer Studies Reports[4] and the successful operation of a liquid xenon proportional counter is the subject of a recent paper.[5]

We briefly summarize what has been learned thus far:

(1) A liquid xenon proportional chamber with an 8mm diam. cathode and a single 4 μm anode detects charged particles with nearly 100% efficiency. The pulse rises in less than 150 nsec and is typically 0.15 pC in size. (Using liquid argon all our chambers have been sensitive only at scattered points along the wire.)

(2) The electric field necessary for electron avalanche is approx 2 million V/cm. (Consequently the central wire must be the anode in order to avoid field emission.)

(3) For the detection of ionization pulses (liquid gain = 1) produced by a moveable collimated source of alpha particles, a 700 μm thick chamber having 5 wires spaced 25 μm apart has a spatial accuracy better than 15 μm rms.

(4) A series of parallel conducting strips mounted on a substrate is capable inducing electron multiplication.

(5) Severe electronegative contamination of liquid xenon (due to unknown impurities) can occur even when the oxygen and nitrogen is held below 0.1 parts per million.[6]

-2-

We are now working to improve our control over electronegative impurities, to show that a series of substrate mounted conductors has high precision in the avalanche mode, and to develop a practical readout scheme.

While the liquid xenon multi-conductor chamber provides accurate spatial information in its "thin" form, it also provides efficient, rapid X-ray and γ-ray detection in its "thick" form. The former should prove invaluable in the fields of high energy and cosmic ray physics, while the latter holds equally great promise in the field of radiology.

Work done under the auspices of the U.S. Atomic Energy Commission.

Lawrence Berkeley Laboratory University of California Berkeley, California 94720	Stephen E. Derenzo Gerard Smadja Robert G. Smits Haim Zaklad Luis W. Alvarez
Space Science Laboratory University of California Berkeley, California 94720	Richard A. Muller

[1] Rice-Evans. P., Nature. 232. 625 (1971).

[2] Editorial, Nature, 232, 599 (1971).

[3] Alvarez, L. W., Group A Physics Note 672, University of California Lawrence Radiation Laboratory, Nov. 1968.

[4] Derenzo, S. E., et al., National Accelerator Laboratory, Batavia, Illinois, Summer Study reports SS-154 (1969) and SS-181 (1970).

[5] Muller, R. A. et al., Phys. Rev. Letters, 27, 532 (1971).

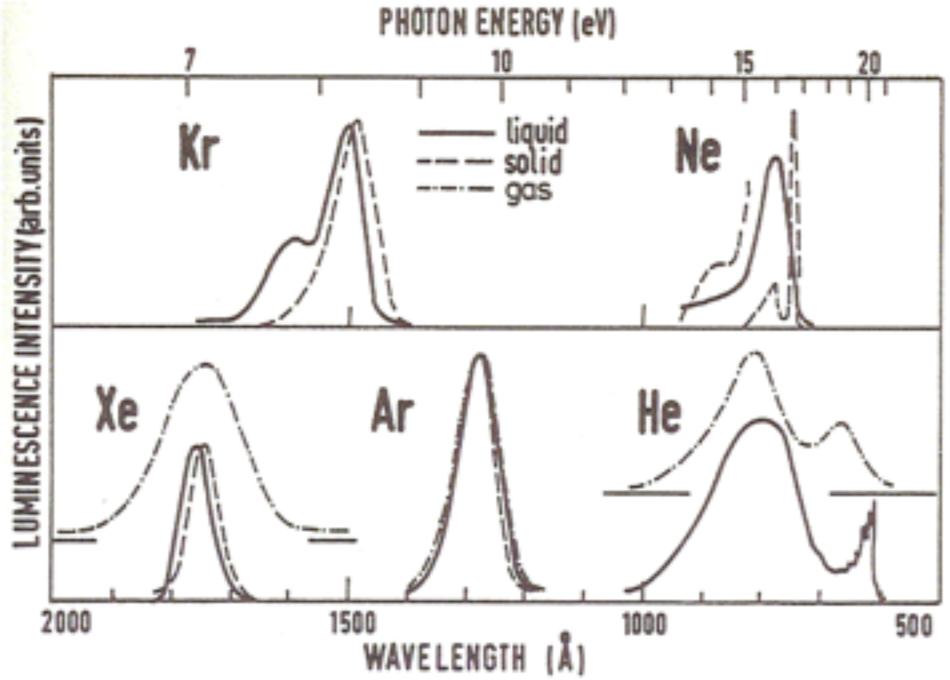
[6] Many of our purification techniques are described in Zaklad, H. (D. Eng. Thesis). Lawrence Radiation Laboratory Report UCRL-20690 (1971).

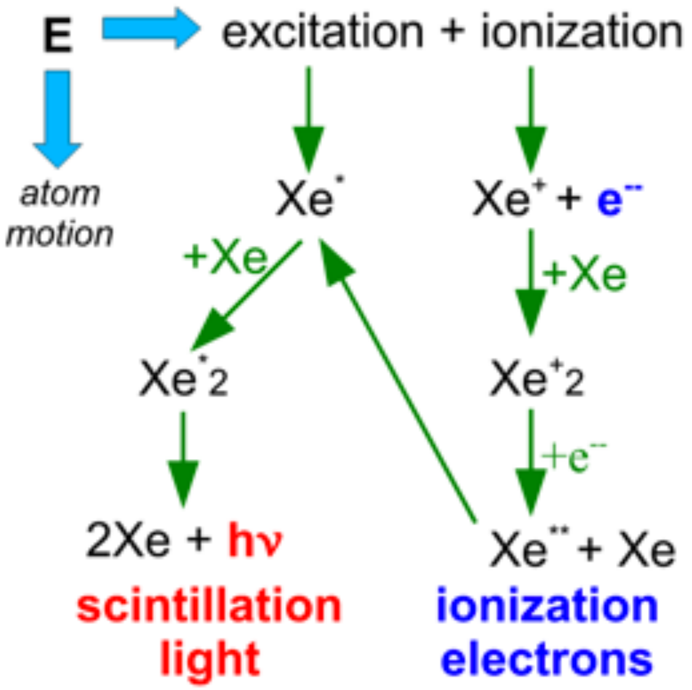
…then Compton telescopes, EM calorimeter, DM, $0\nu2\beta$, PET…

Xenon properties

	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ionization [e$^-$/keV]*	46	42	64
Scintillation [γ/keV]*	7	40	46

* for electronic recoils





E → excitation + ionization

atom motion

Xe^*

$Xe^+ + e^-$

+Xe

Xe^*_2

Xe^+_2

+Xe

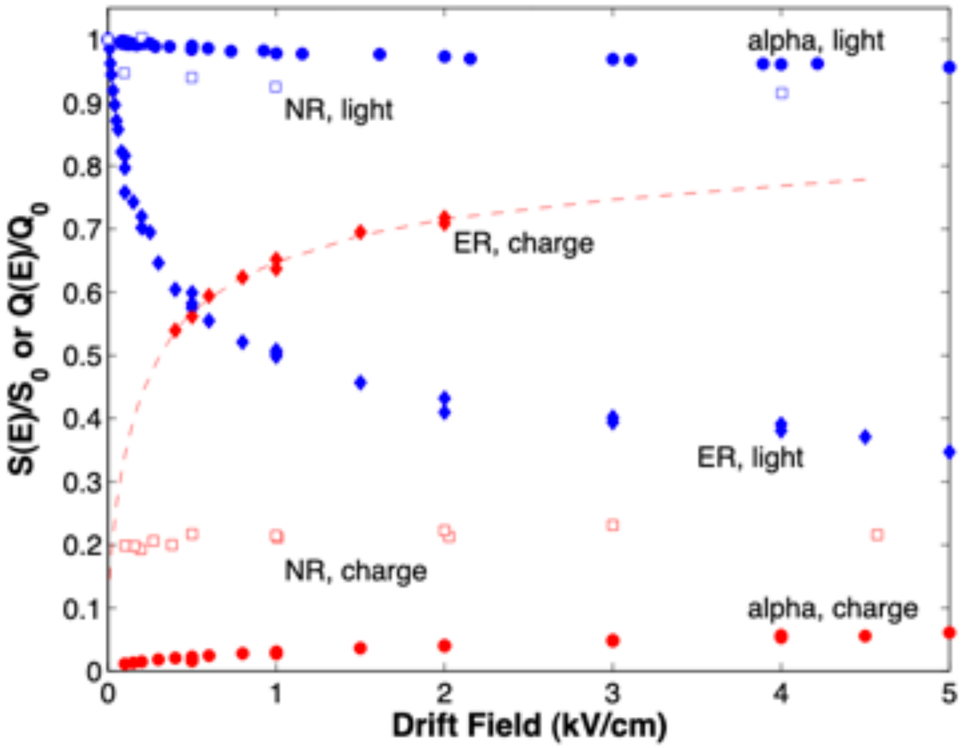
$+e^-$

$2Xe + h\nu$

$Xe^{**} + Xe$

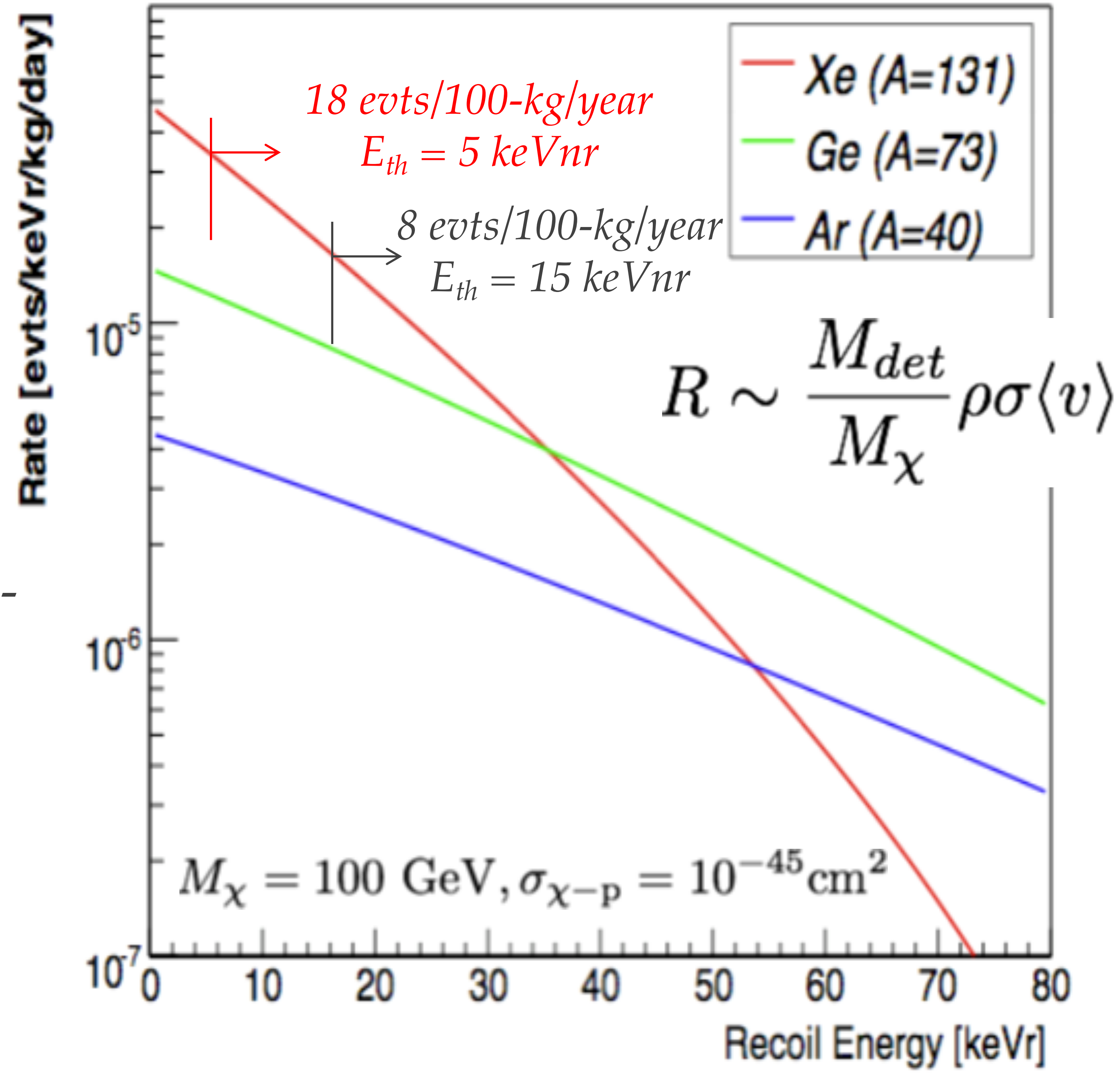
scintillation light

ionization electrons



Xenon properties

- High A: large number of SI interactions
- Self shielding: high Z=54 and and high density ϱ=2.83 kg/l
- Scalability: possibility to build compact detectors, scalable to larger dimensions
- Odd-nucleon isotopes: high A=131 with ~50% of odd isotopes. Good for SD.
- Wavelength 178 nm: no need for a wave-length shifter
- Intrinsically pure: ^{136}Xe has very small decay rate; Kr can be removed to <ppt
- Charge & light: highest yield among the noble liquids
- “Easy” cryogenics: -100 °C

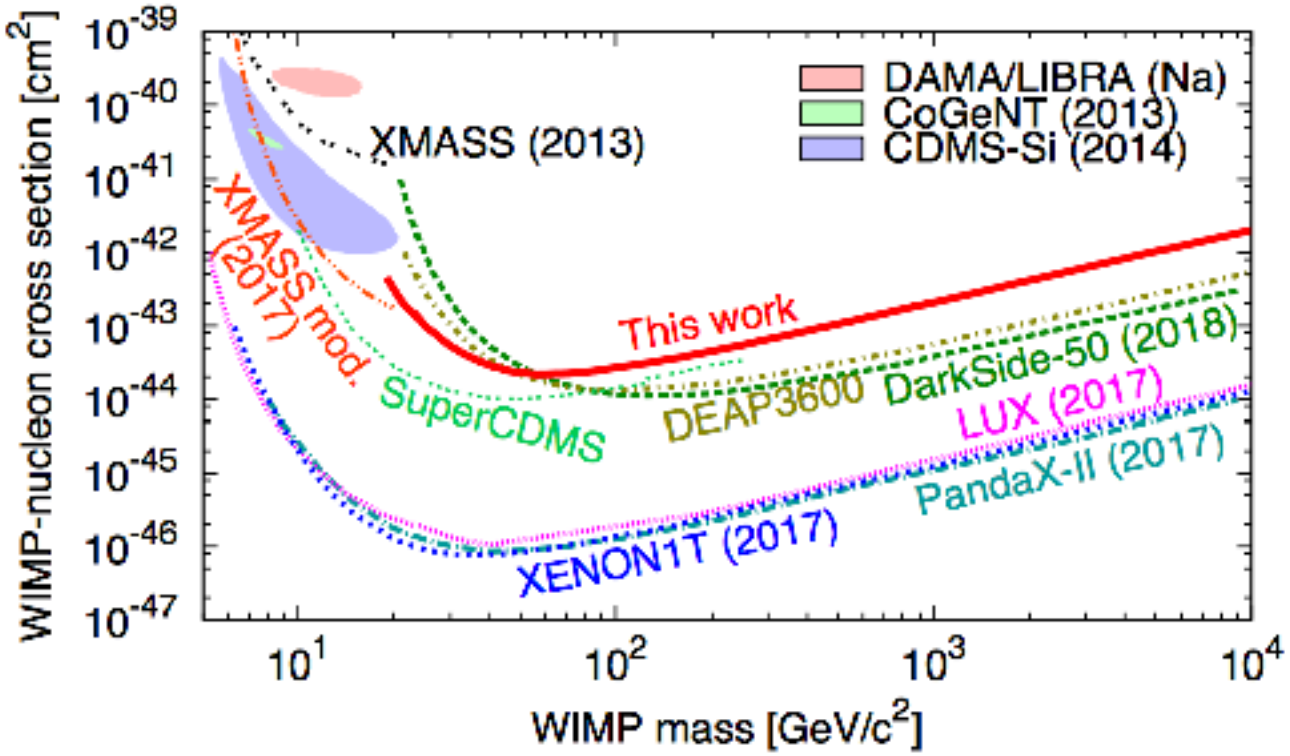


$$R \sim \frac{M_{det}}{M_\chi} \rho \sigma \langle v \rangle$$

LXe: Single Phase

XMASS - LXe detector at Kamioka, Japan

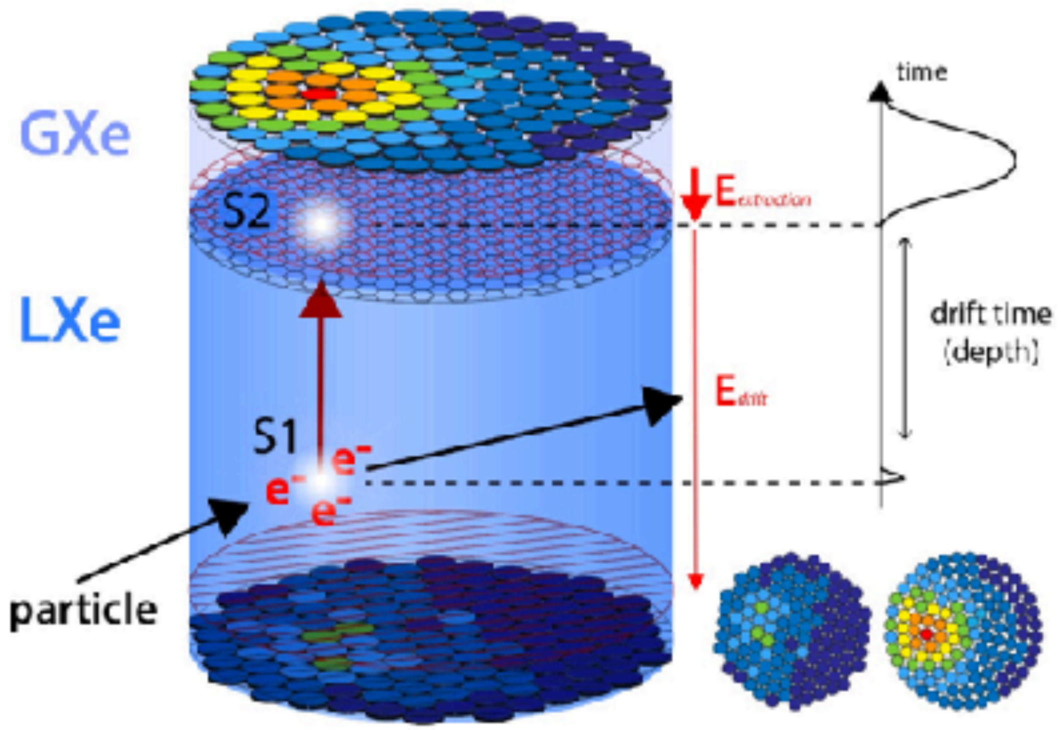
- 1 ton total LXe mass & 800 kg FV
- Ultra-clean PMTs directly in contact with the LXe target
- High light yield measured: 14.7 PE/keVee $E_{th} = 0.3\,\mathrm{keV}_{ee}$



LXe: Double Phase

LXe/GXe Time Projection Chamber

A. S. Barabash and A. I. Bolozdynia, 1989,JETP Lett.,49, 356.



- **S1 Light signal**

  Prompt scintillation photons
- **S2 Charge signal**

  Secondary scintillation in GXe from drifted electrons

👍 Energy reconstruction from combined S1 and S2

- **3D vertex reconstruction**

  X,Y from S2 pattern in top PMT array

  Z from drift time

👍 Volume fiducialization

👍 Single/multiple scatters discrimination

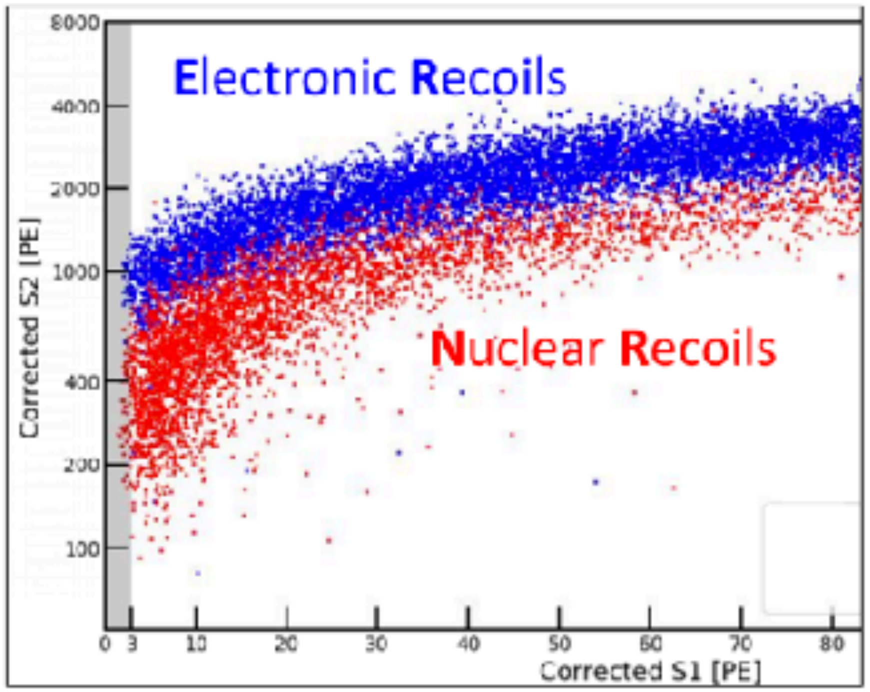
- **NR (Nuclear Recoils)**

  WIMP signal, neutrons, CNNS
- **ER (Electronic Recoils)**

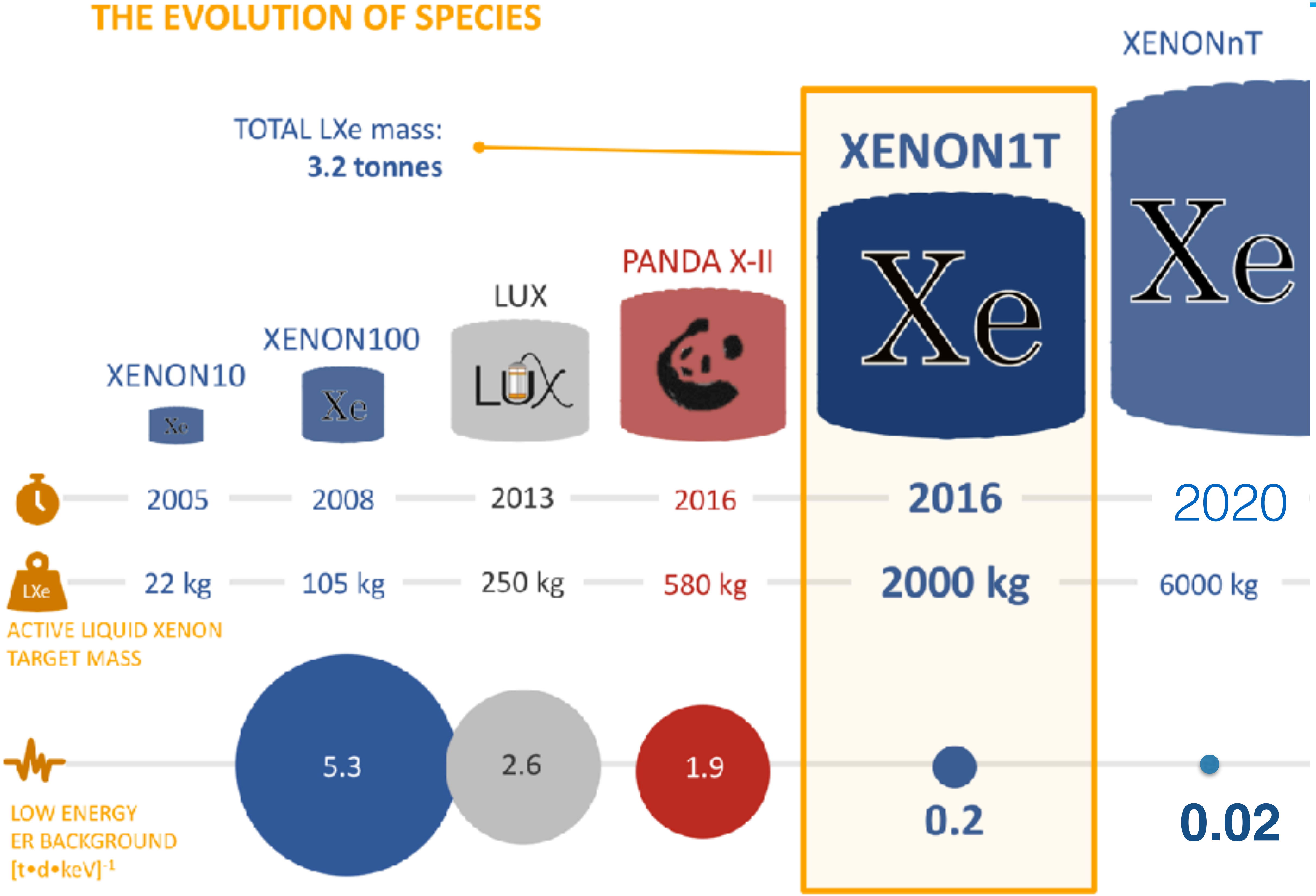
  γ, β backgrounds

👍 **Recoil type identification from S2/S1**

Larger for ER than NR



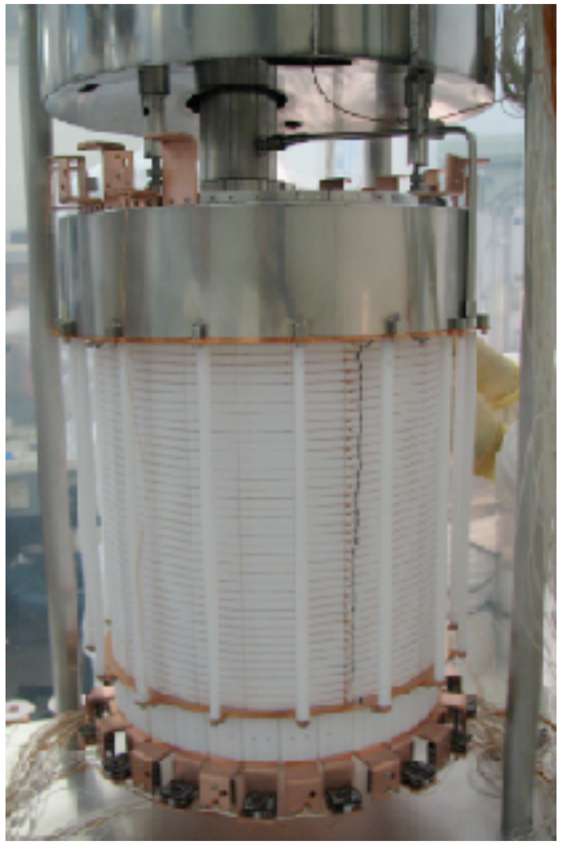
LXeTPC evolution



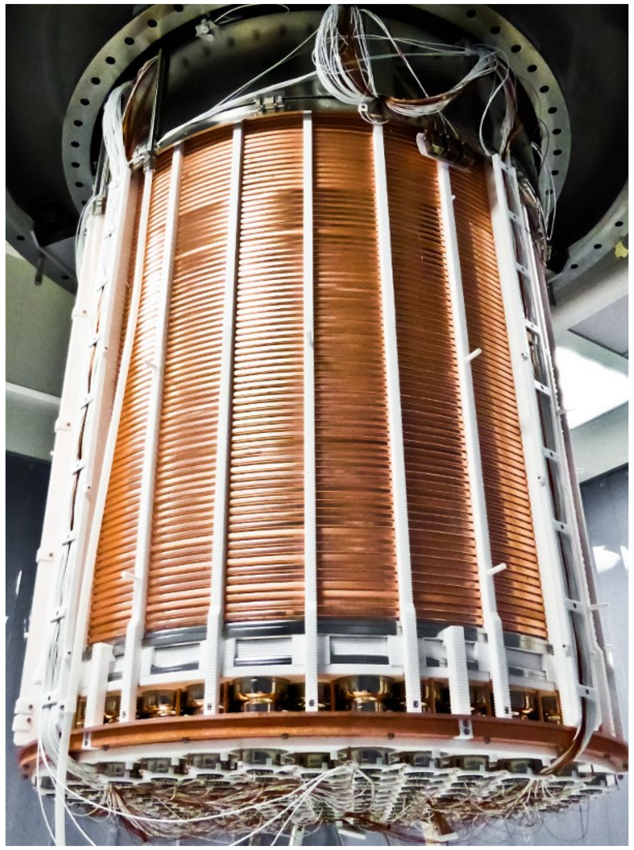
The XENON project @LNGS

XENON10

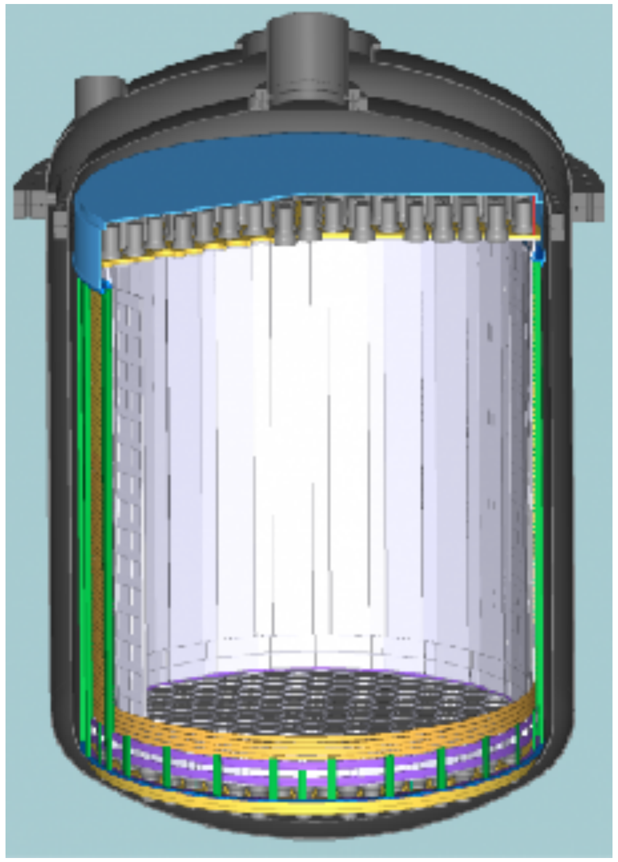
XENON100



XENON1T

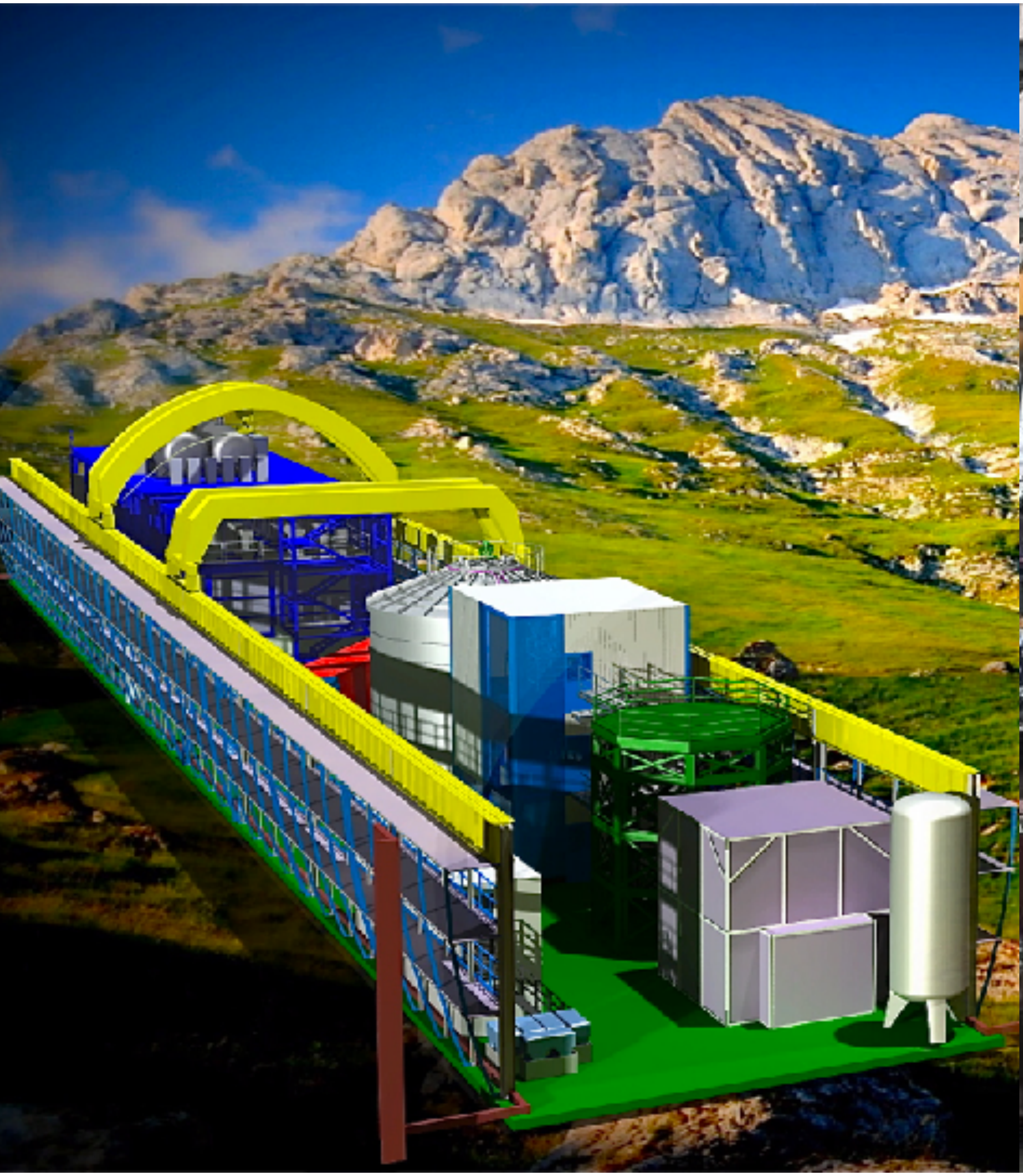


XENONnT



2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

The XENON1T Experiment @ LNGS



XENON1T: All Systems

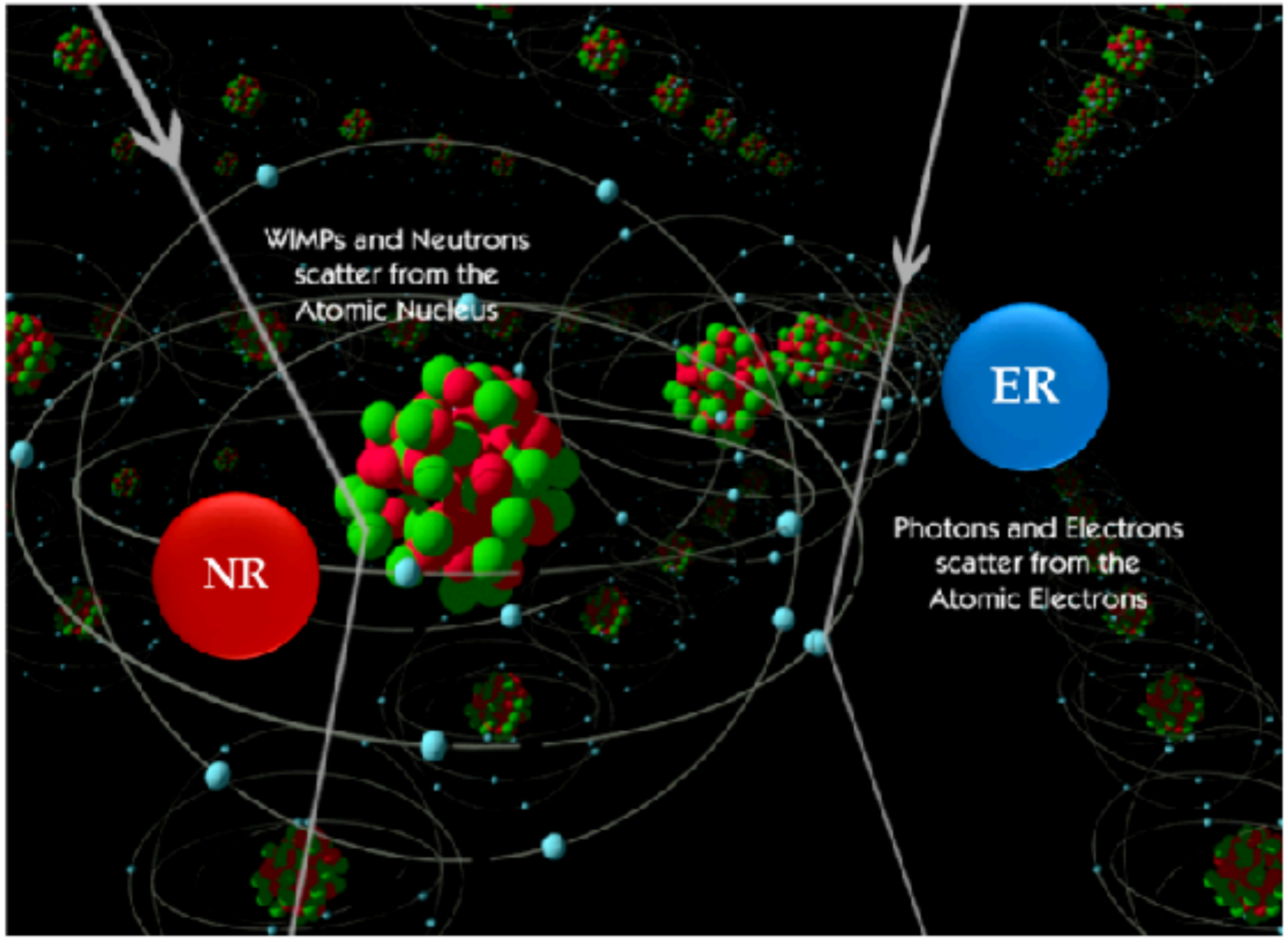
E. Aprile et al.,
“The XENON1T Dark Matter Experiment”,
EPJ C 77, 881 (2017).

The XENON1T TPC

3.2 t LXe @180 K
2.0 t active target
viewed by 248 PMTs
~1 meter drift length
~1 meter diameter

The largest liquid noble TPC ever operated for Dark Matter Search

ER and NR Backgrounds



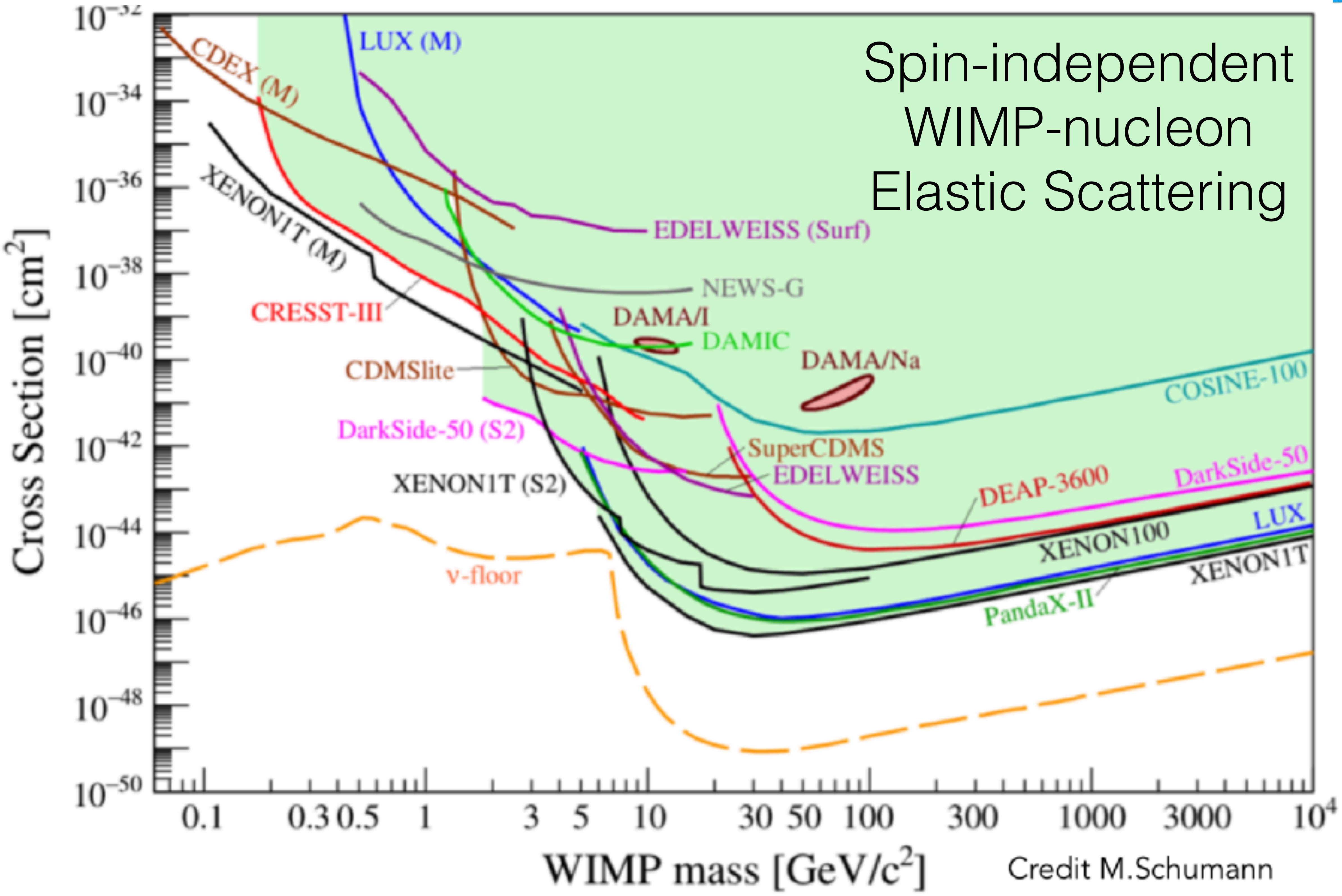
Electron recoils (ER):

- low energy Compton scatters from the radioactive contaminants in the detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs.
- Intrinsic contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe.
- Elastic scattering of solar neutrinos off electrons.

Nuclear Recoils (NR):

- Radiogenic neutrons: spontaneous fission and (α, n) reaction from the U and Th chains in the detector components.
- Muon-induced neutrons.
- Coherent scattering of neutrinos (mostly solar) off the Xe nuclei.

XENON1T results



Spin-independent
WIMP-nucleon
Elastic Scattering

Credit M.Schumann

PRL 121, 111302 (2018)
PRL 123, 251801 (2019)
PRL 123, 241803 (2019)

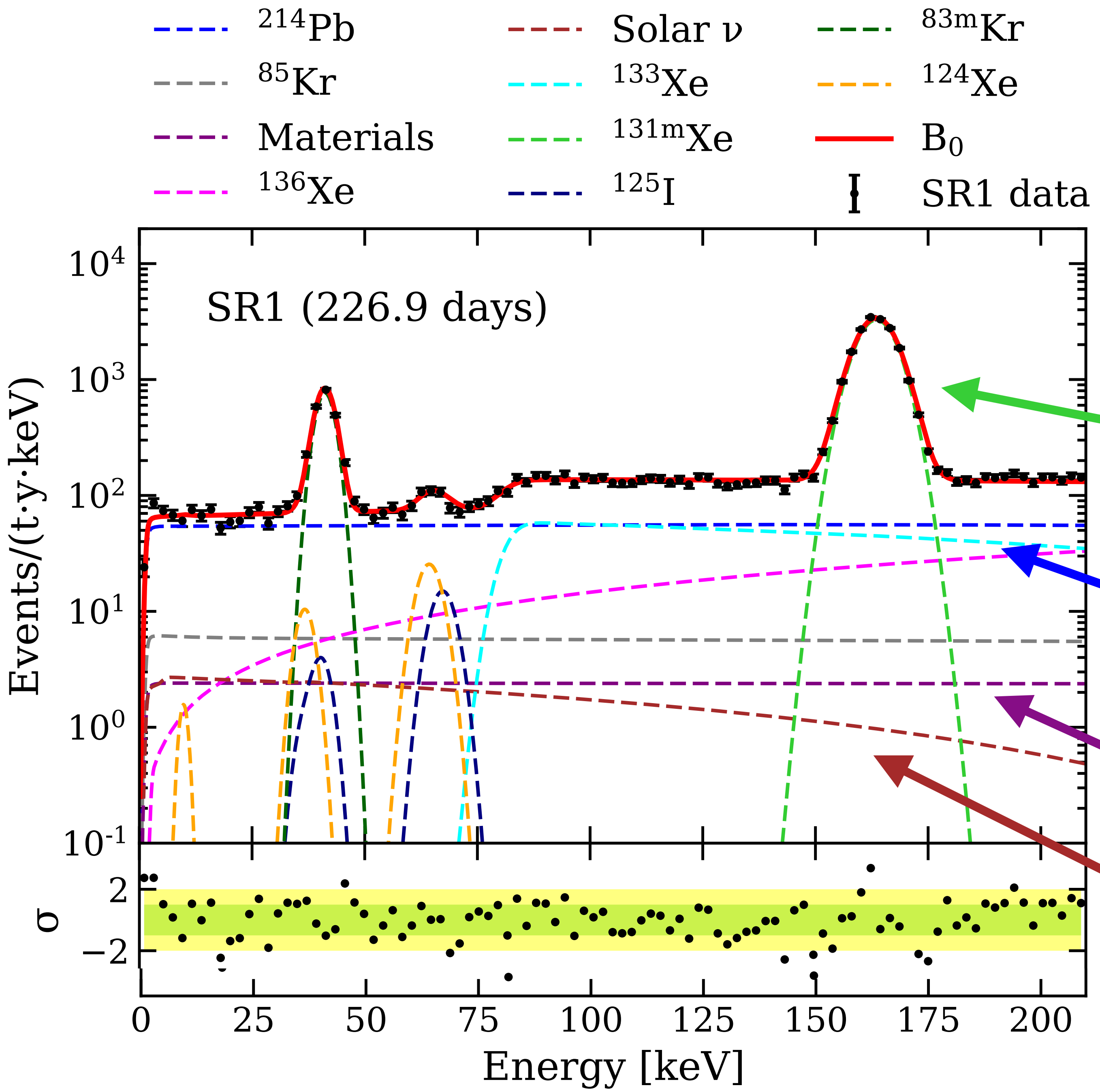
XENON1T results

World record ER background:

76 ± 2 events/keV/t/yr

in [1, 30] keV

(2.e-4 dru)



Neutron-activations
^{131m}Xe, ^{133}Xe, ^{125}I

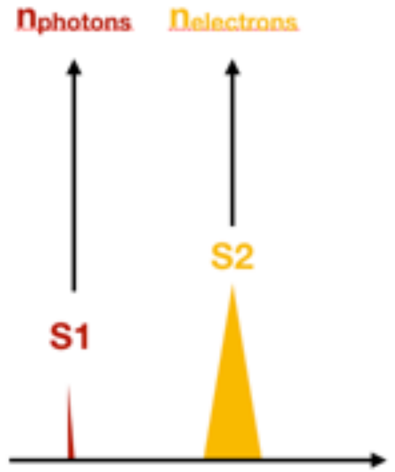
Intrinsic
backgrounds
^{214}Pb, ^{136}Xe, ^{124}Xe,
^{85}Kr, ^{83m}Kr

Detector material γ

Solar neutrinos

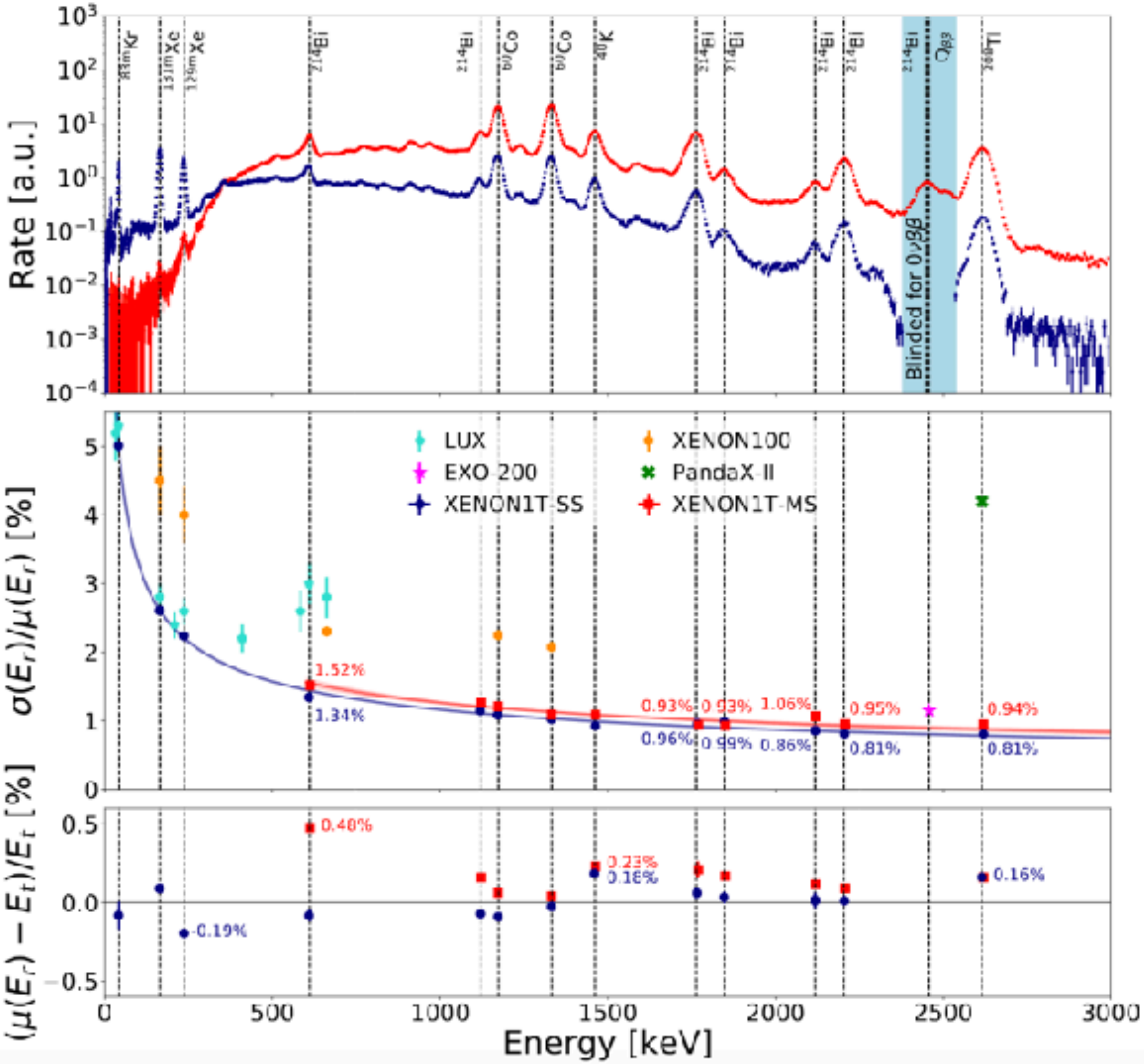
XENON1T results

$$E = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$$



WIMPs, **X-rays**, γ (E<200 keV), β-electrons

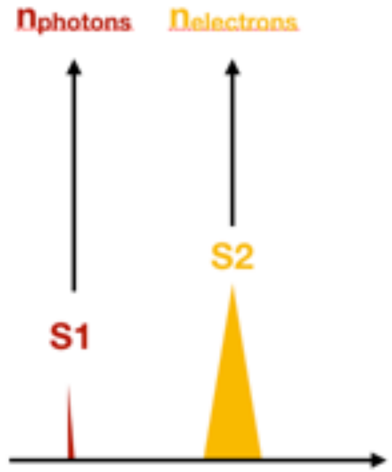
Reconstruct energy from combined S1 and S2 signals
Anti-correlation between light and charge for optimal resolution



Energy resolution and linearity in the MeV energy range
Eur. Phys. J. C **80 (2020) 8, 785 - arXiv:2003.03825**

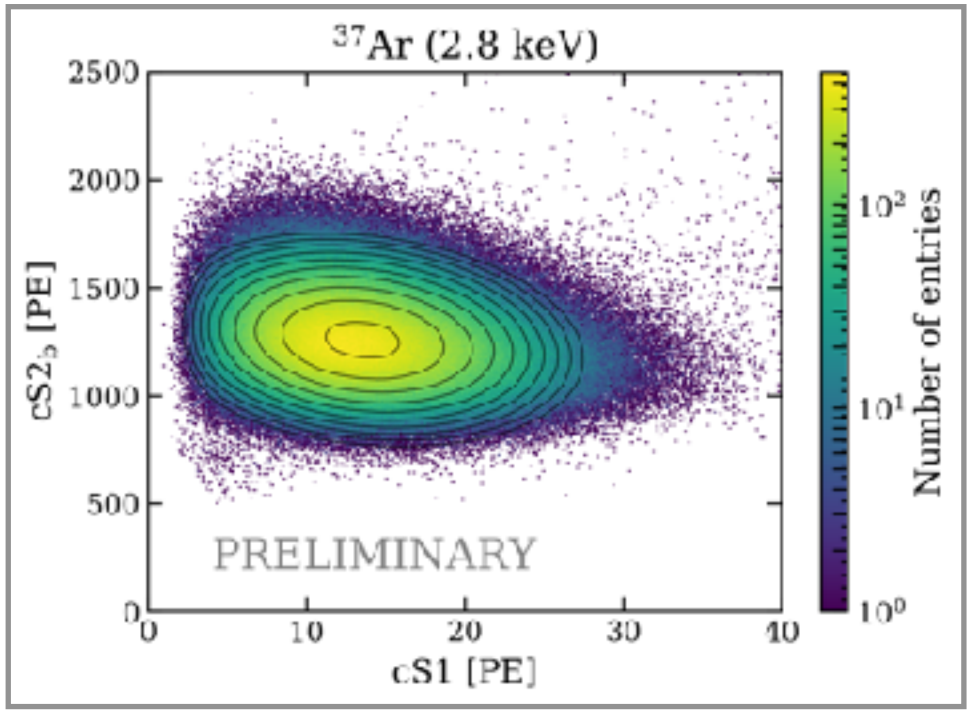
XENON1T results

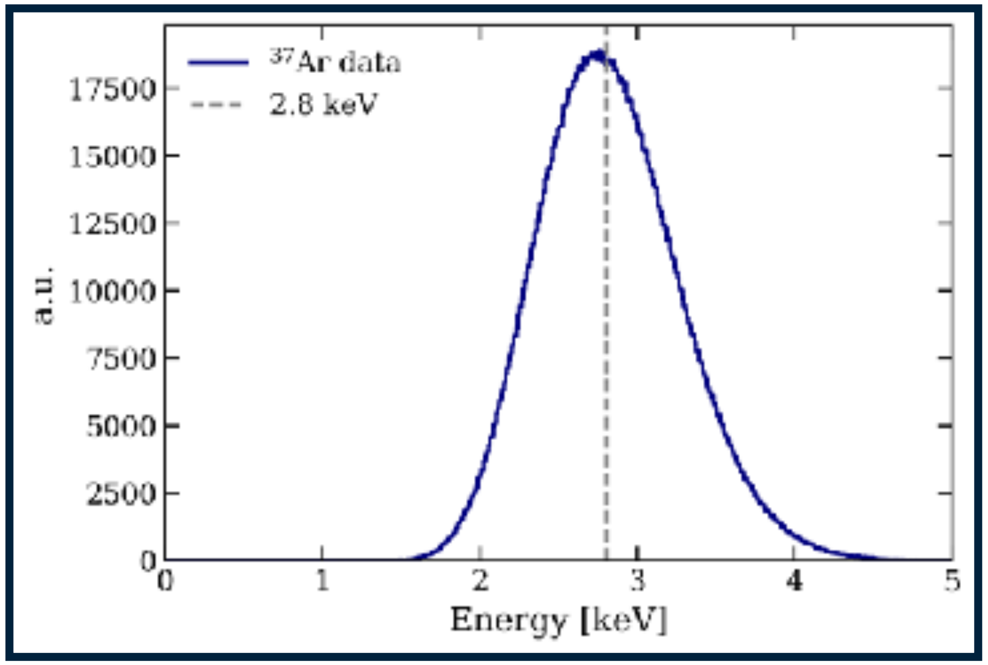
$$E = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$



WIMPs, **X-rays**, γ (E<200 keV), β-electrons

^{37}Ar calibration: 2.8 keV x-ray peak





Reconstruct energy from combined S1 and S2 signals

Anti-correlation between light and charge for optimal resolution

XENON1T results

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T
Published | 25 April 2019 | Nature 568, 532-535 (2019)

nature

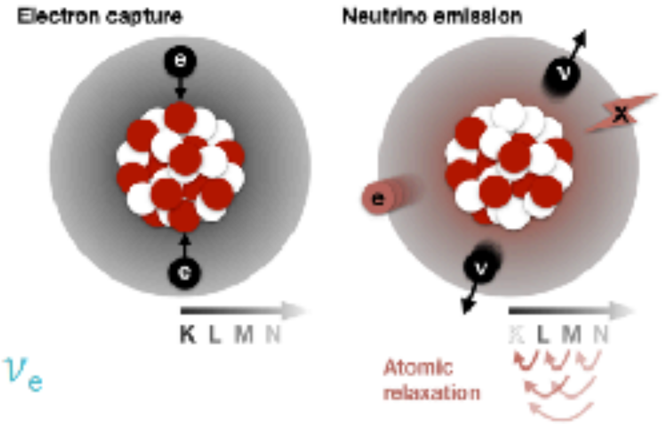
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

CAUGHT IN THE ACT

Dark-matter detector captures exotic nuclear decay in xenon PAGES

NATURE.COM

25 April 2019 £10



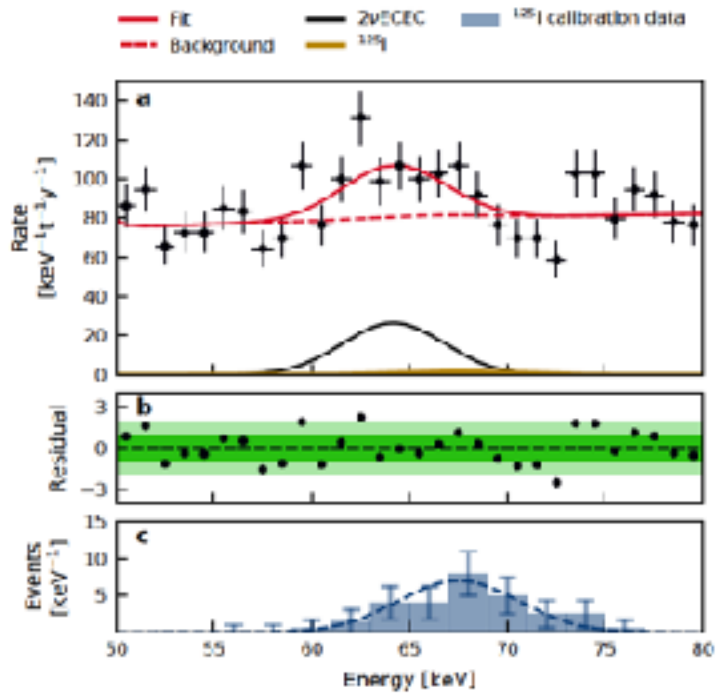
$^{124}\mathrm{Xe} \longrightarrow {}^{124}\mathrm{Te} + \nu_e + \nu_e$

- SIGNATURE: mono-energetic peak at (64.3 ± 0.6) keV
  Energy released by X-rays and Auger electrons (atomic relaxation)

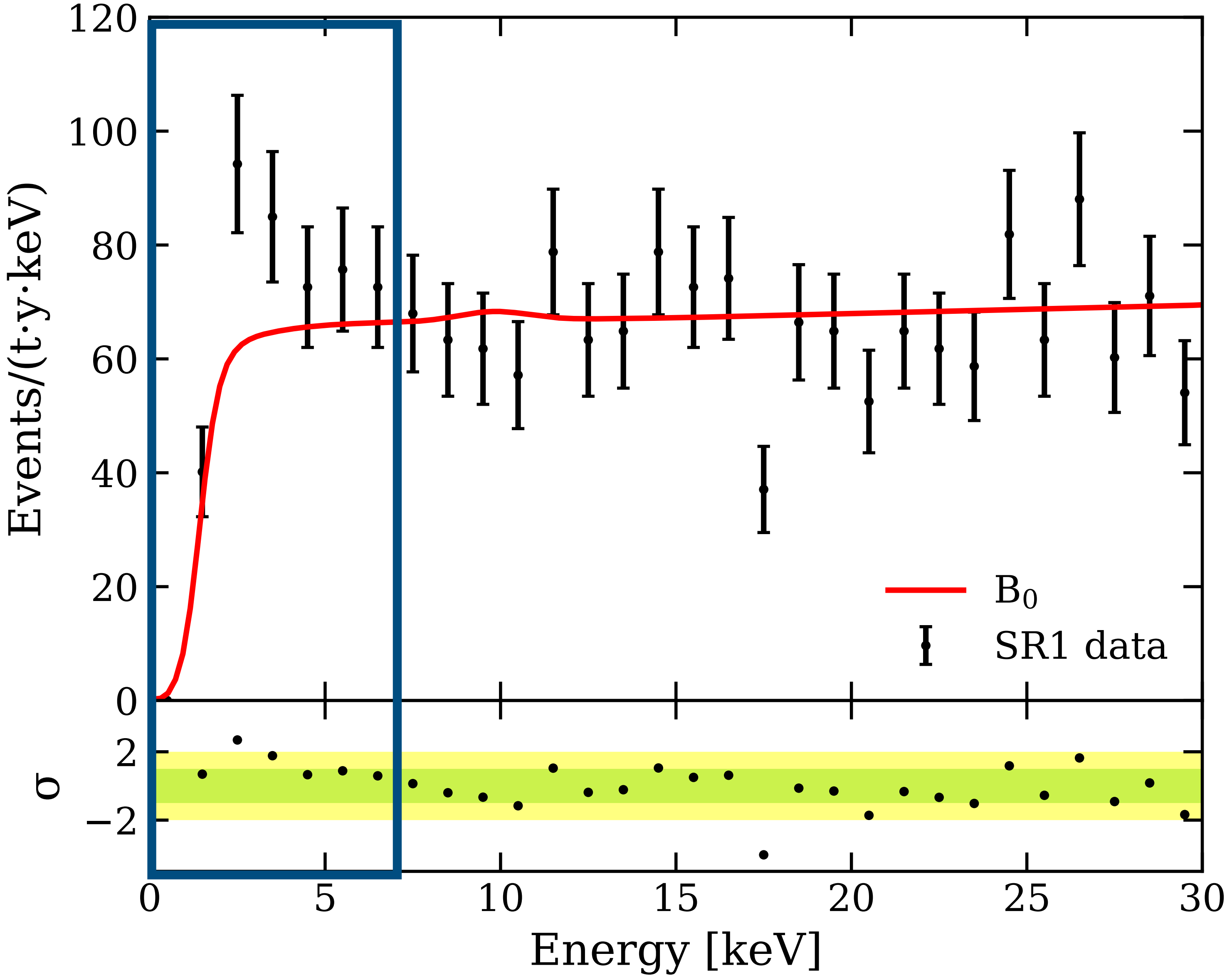
- **First observation of 2νECEC decay**

- The longest half-life ever measured
  $(1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ yr
  ~10^{12} times larger than the age of t

- XENON1T ENERGY RESOLUTION
  at 64.3 keV:
  (4.1 ± 0.4) %



XENON1T results



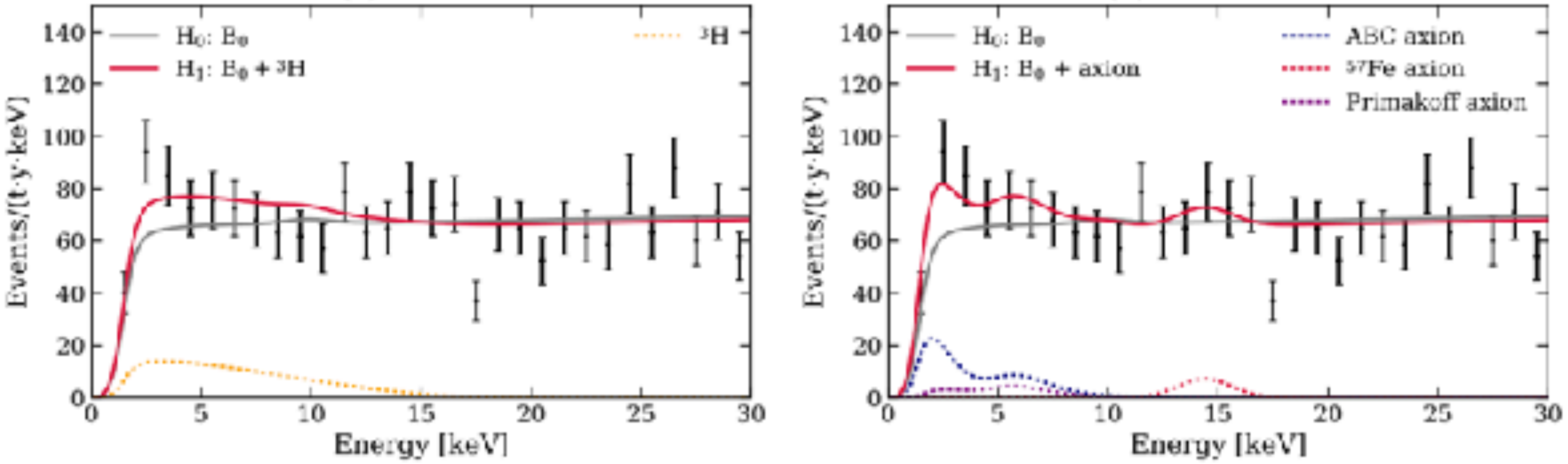
Observation of Excess Electronic Recoil Events in XENON1T
arXiv:2006.09721

XENON1T results

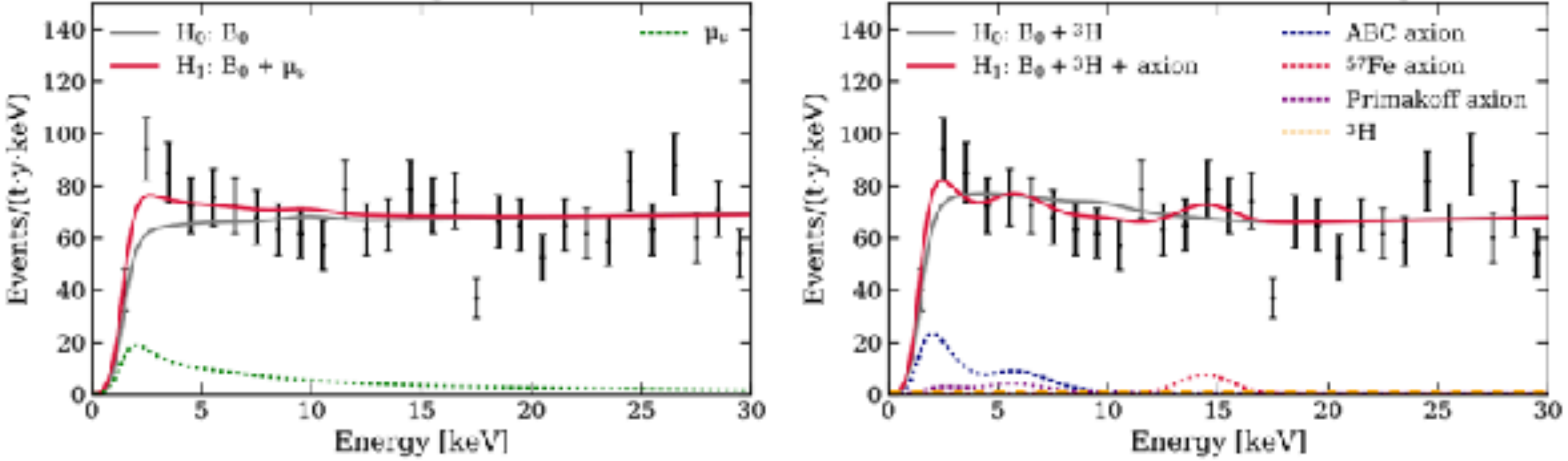
Tritium favored over background-only at **3.2σ**

Solar axion favored over background-only at **3.5σ**

(a) Tritium (b) Solar axion



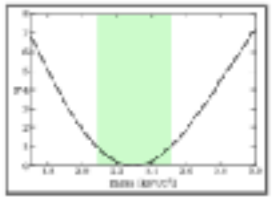
(c) Neutrino magnetic moment (d) Solar axion vs tritium background



Neutrino magnetic moment favored over background-only at **3.2σ**

Axion + ^{3}H favored **over ^{3}H** hypothesis **at** **2.1σ**

Monoenergetic peak at 2.3 ± 0.2 keV favored over background-only at **3.0σ (global)**

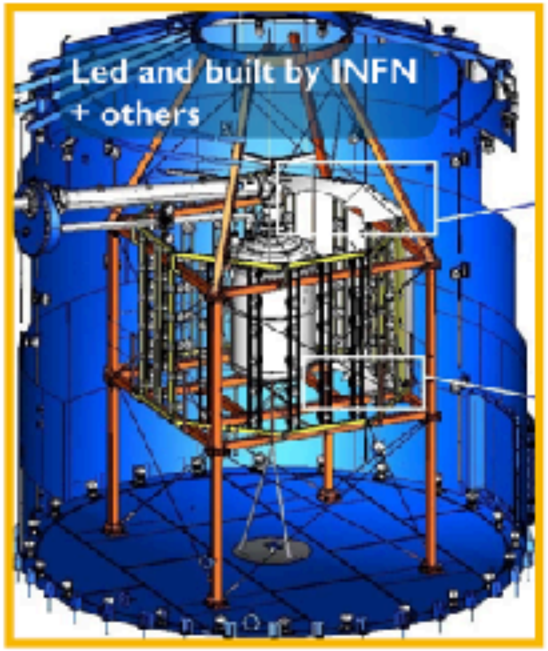


Observation of Excess Electronic Recoil Events in XENON1T
arXiv:2006.09721

next step: XENONnT

Larger TPC

- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs



Led and built by INFN + others

Neutron veto

- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % $Gd_2(SO_4)_3$

^{222}Rn distillation

- Reduce Rn (^{214}Pb) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

Led and built by INFN + others

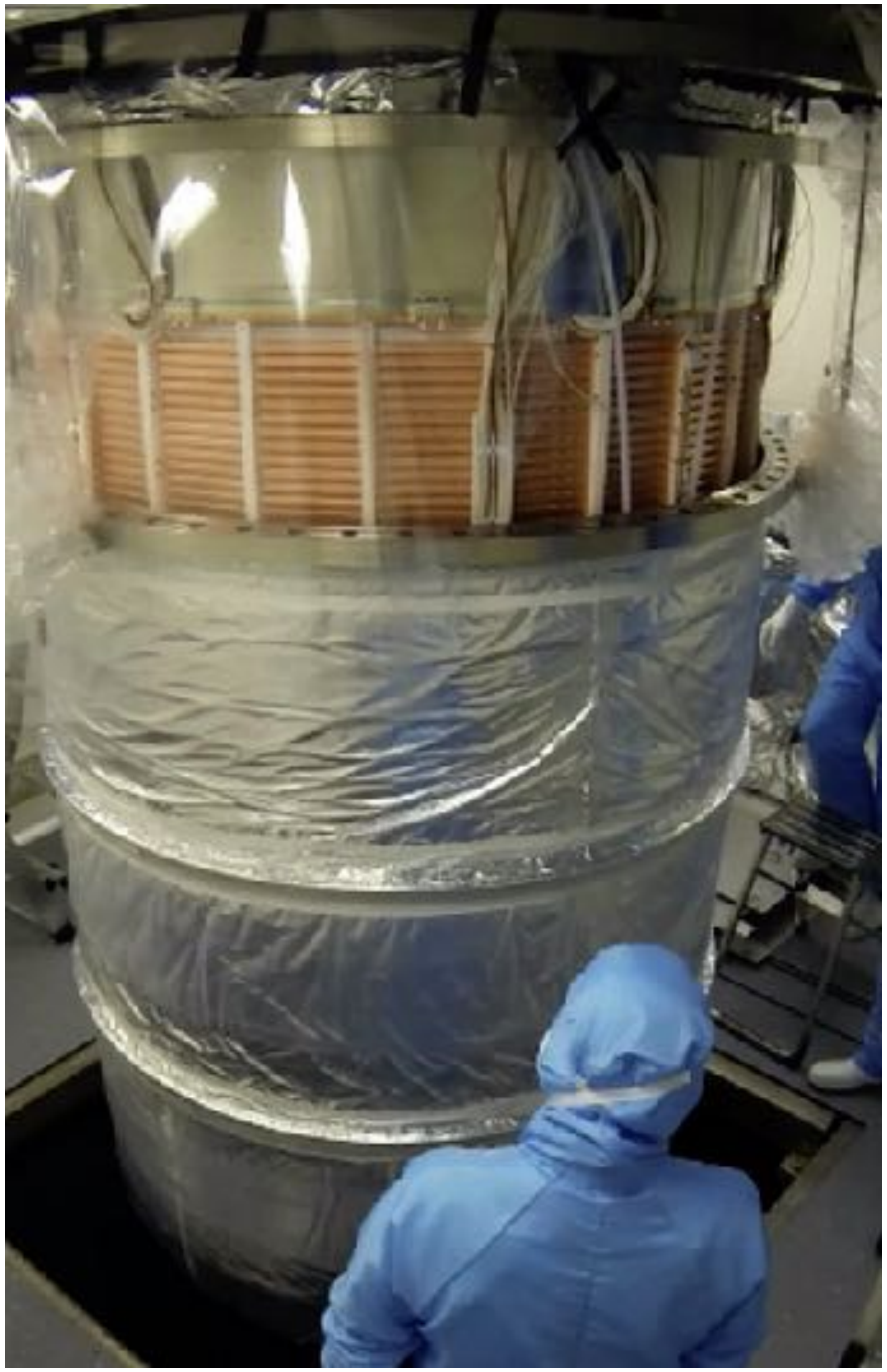
LXe purification

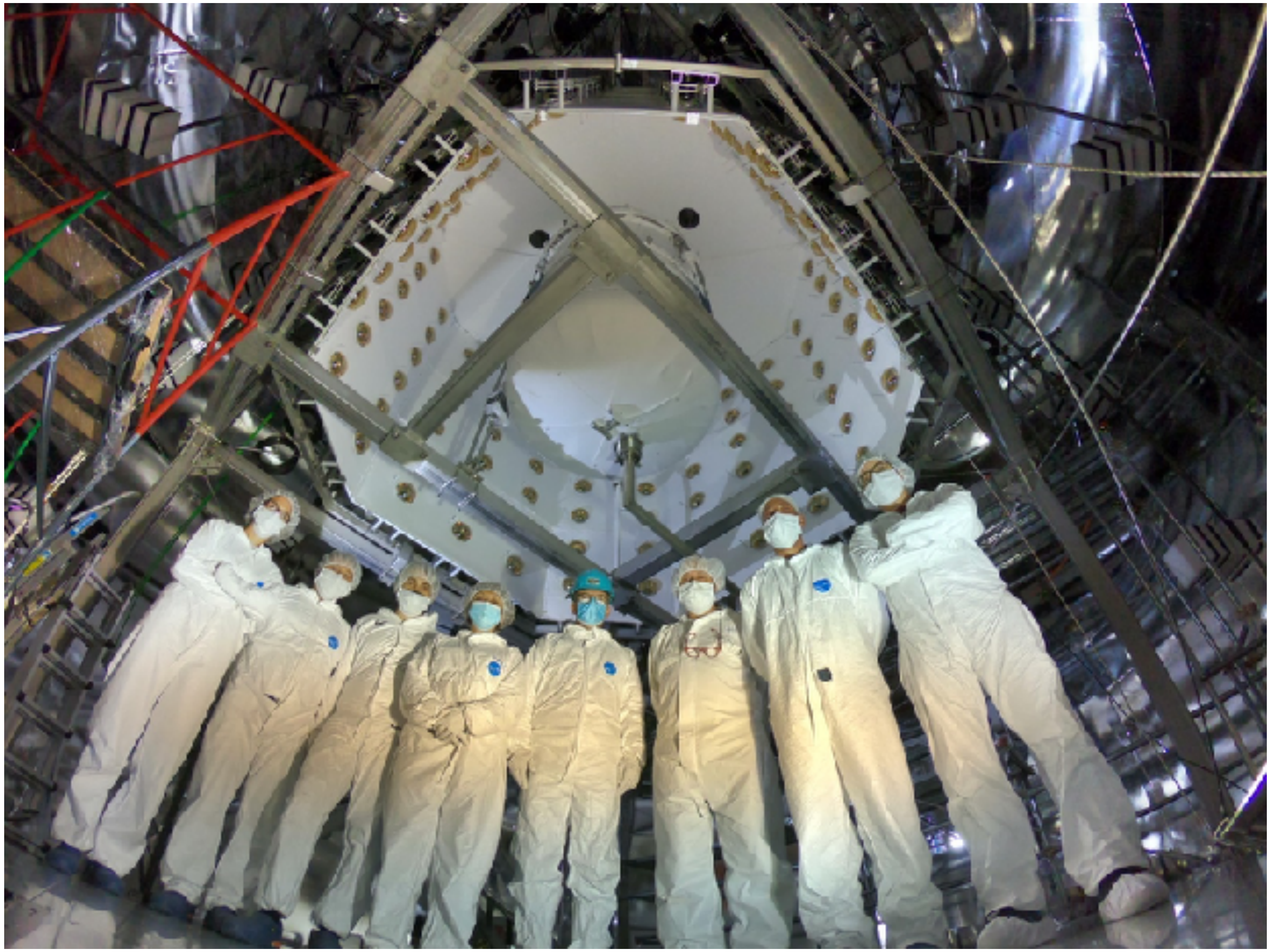
- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm

next step: XENONnT

16 March 2020:
closed the cryostat

11 Sep 2020:
completed nVeto installation

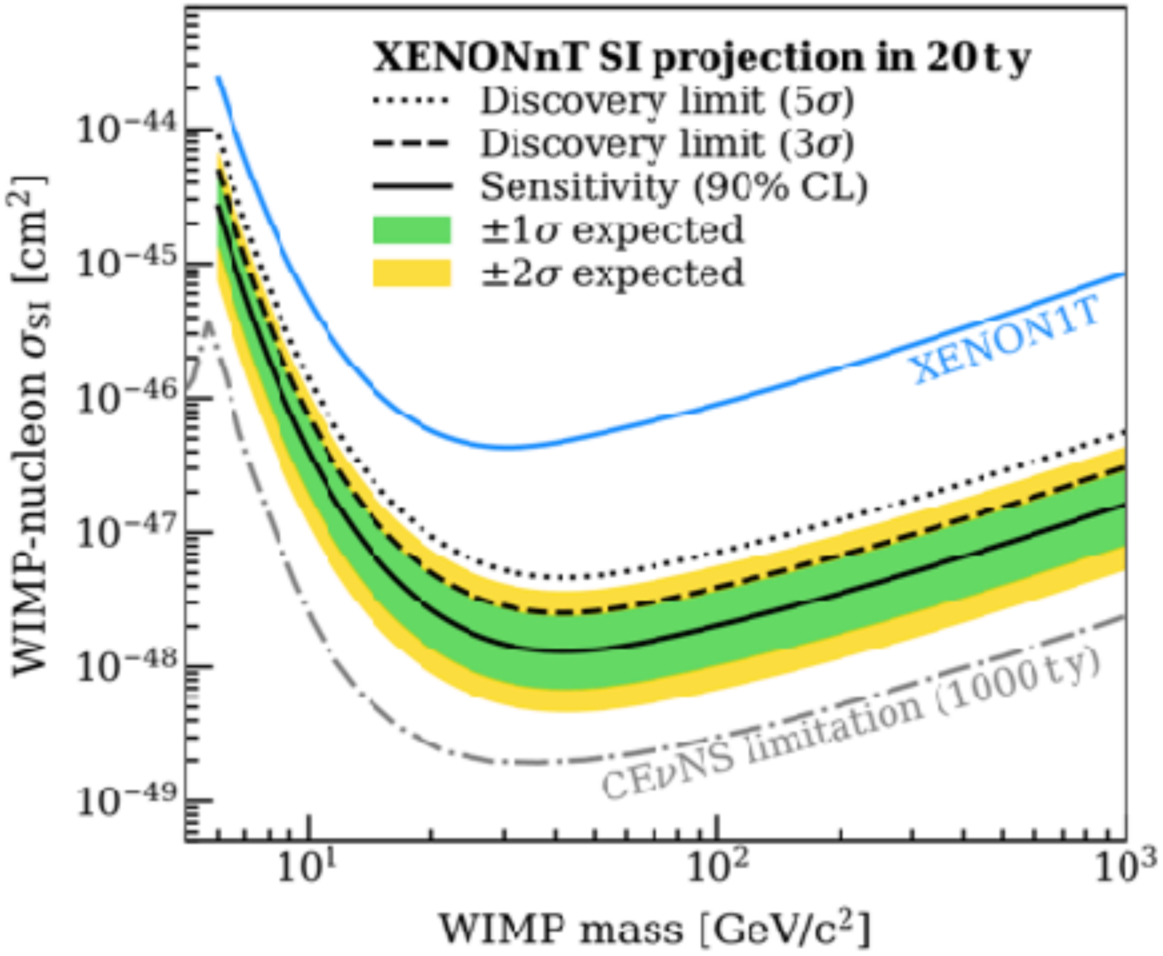


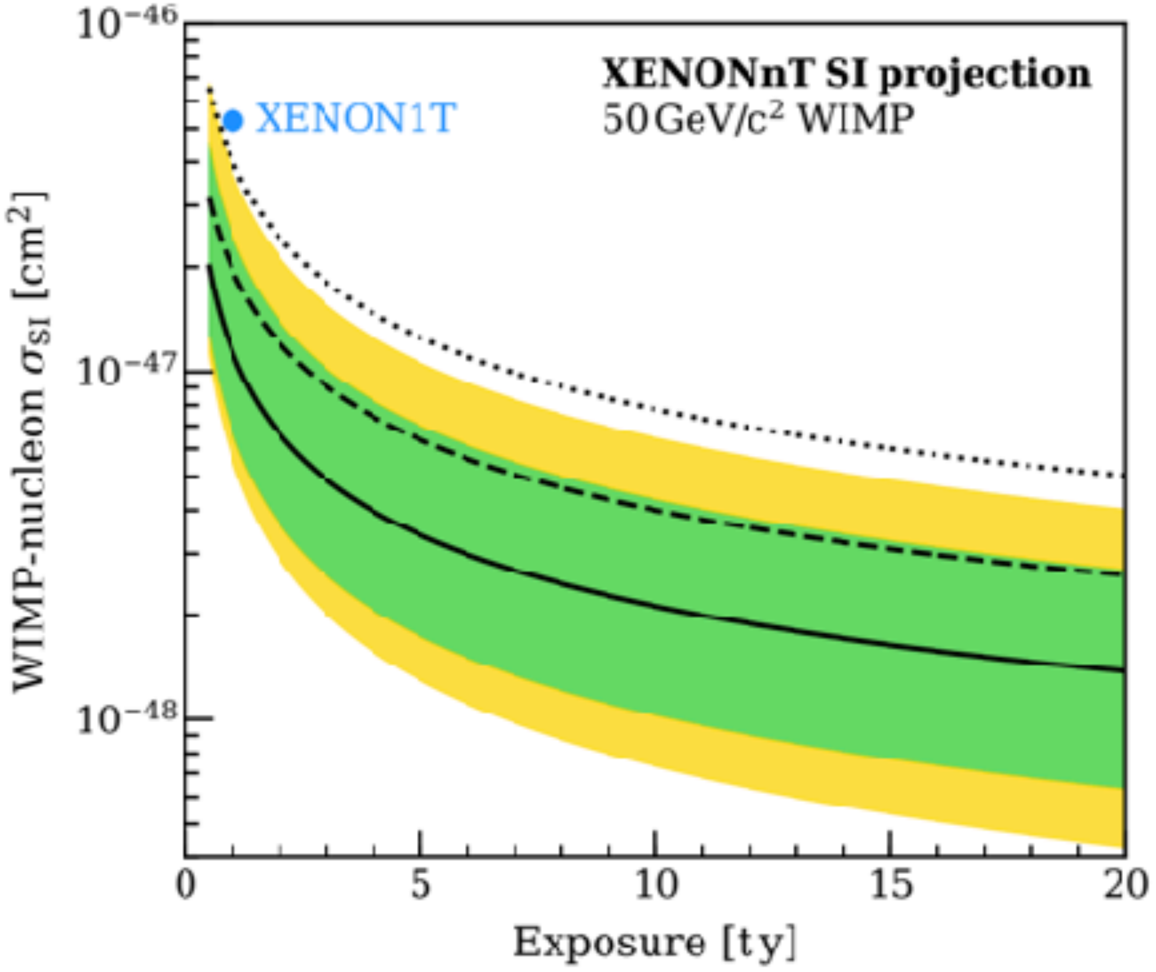


next step: XENONnT

arXiv: 2007.08796, submitted to JCAP

(Corresponding author: Pietro Di Gangi, post-doc INFN Bologna, MonteCarlo WG leader)



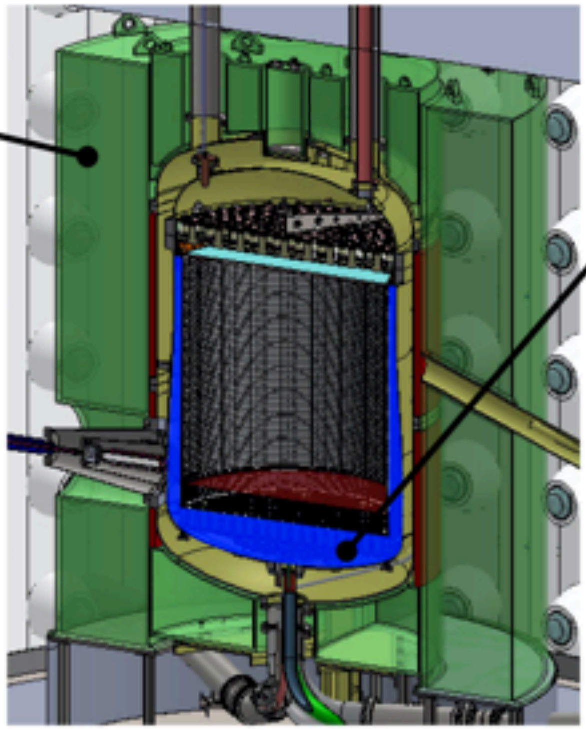


near future: LZ

The OD

- 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
- 120 8” PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons
- Observe ~8.5 MeV γ-rays from thermal neutron capture
- Draw on experience from Daya Bay

See talk by B. Penning
“The LZ Outer Detector”
DM16 Thu afternoon

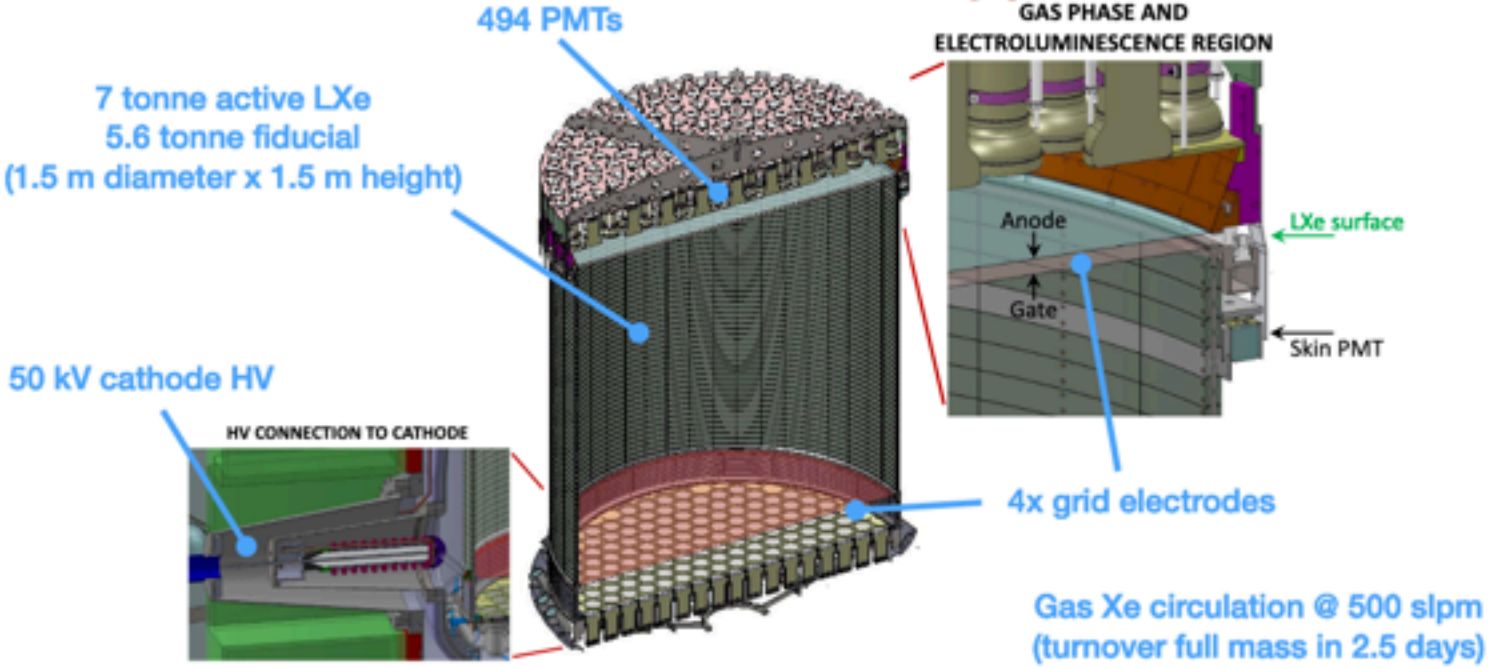


The Skin

- 2 tonnes of LXe surrounding the TPC
- 1” and 2” PMTs at the top and bottom of the skin region
- Lined with PTFE to maximize light collection efficiency
- Anti-coincidence detector for γ-rays

- **Tag individual neutrons and γ-rays**
- **Characterize BGs in situ**

→Enables discovery potential



494 PMTs

7 tonne active LXe
5.6 tonne fiducial
(1.5 m diameter x 1.5 m height)

50 kV cathode HV

4x grid electrodes

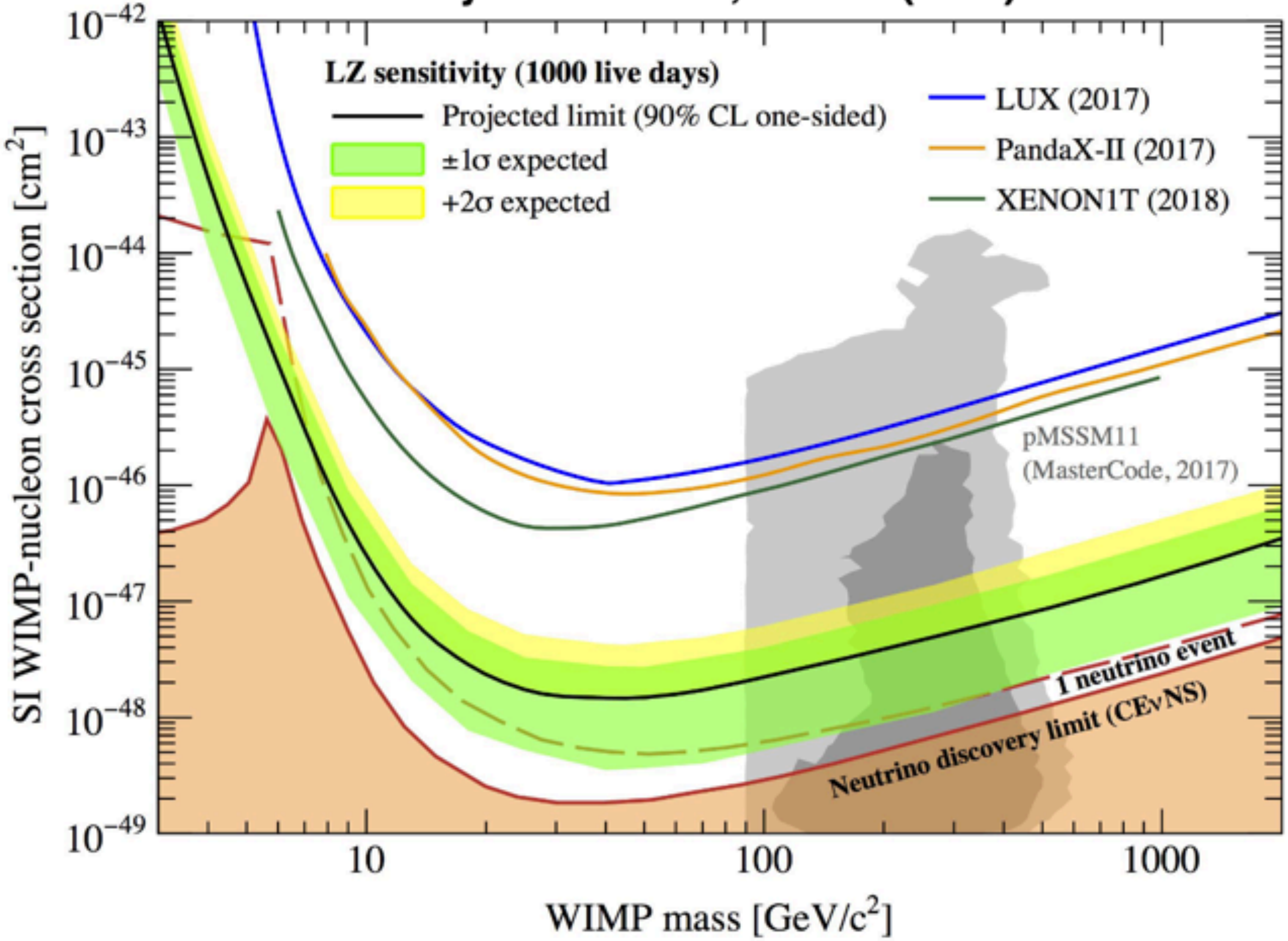
Gas Xe circulation @ 500 slpm
(turnover full mass in 2.5 days)

- Located in Sanford Underground lab, Lead (USA)
- 4300 m.w.e.
- 10^7 muon flux reduction

LZ TDR arXiv:1703.09144

near future: LZ

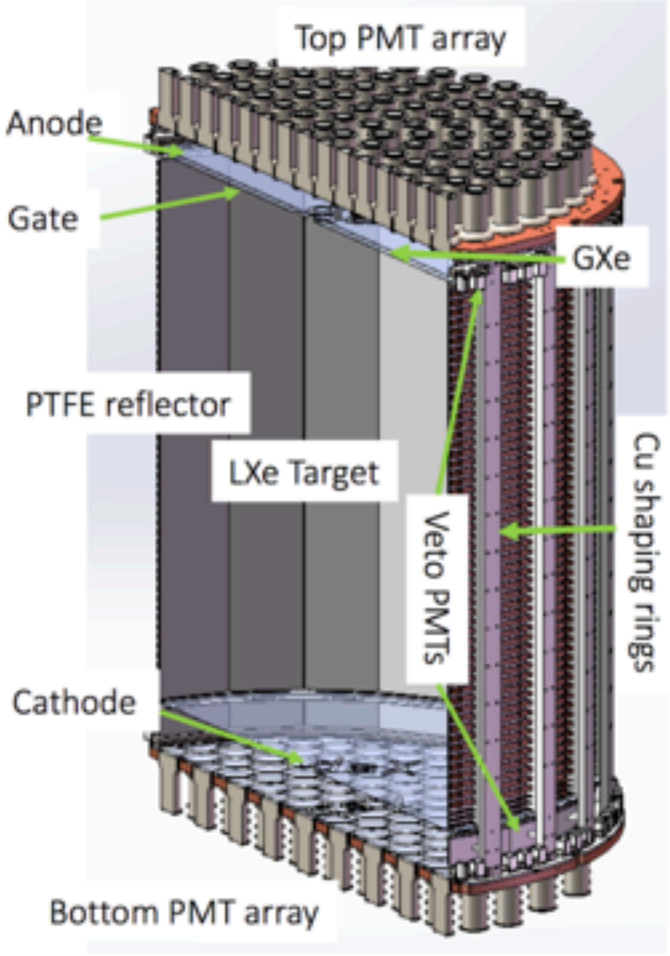
Phys. Rev. D 101, 052002 (2020)



90% CL minimum of 1.6 x 10^{-48} cm^2 at 40 GeV/c^2

near future: PandaX-4T

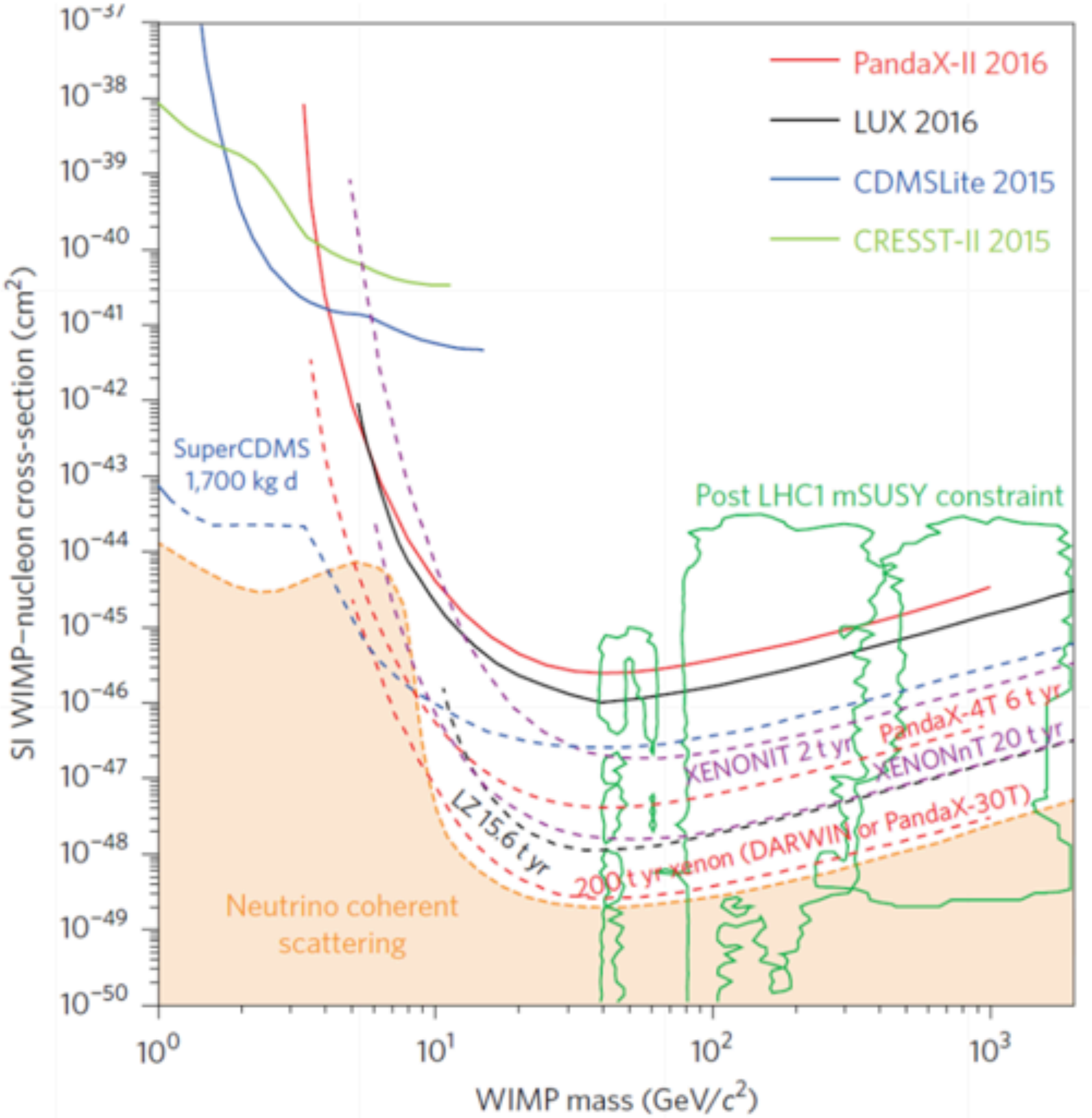
4-ton target with SI sensitivity ~10^{-47} cm^2



1.2m(H)x1.2m(D)

Designed field: drift (400 V/cm), extraction (6 kV/cm)

3-in PMTs, 169 top/199 bottom

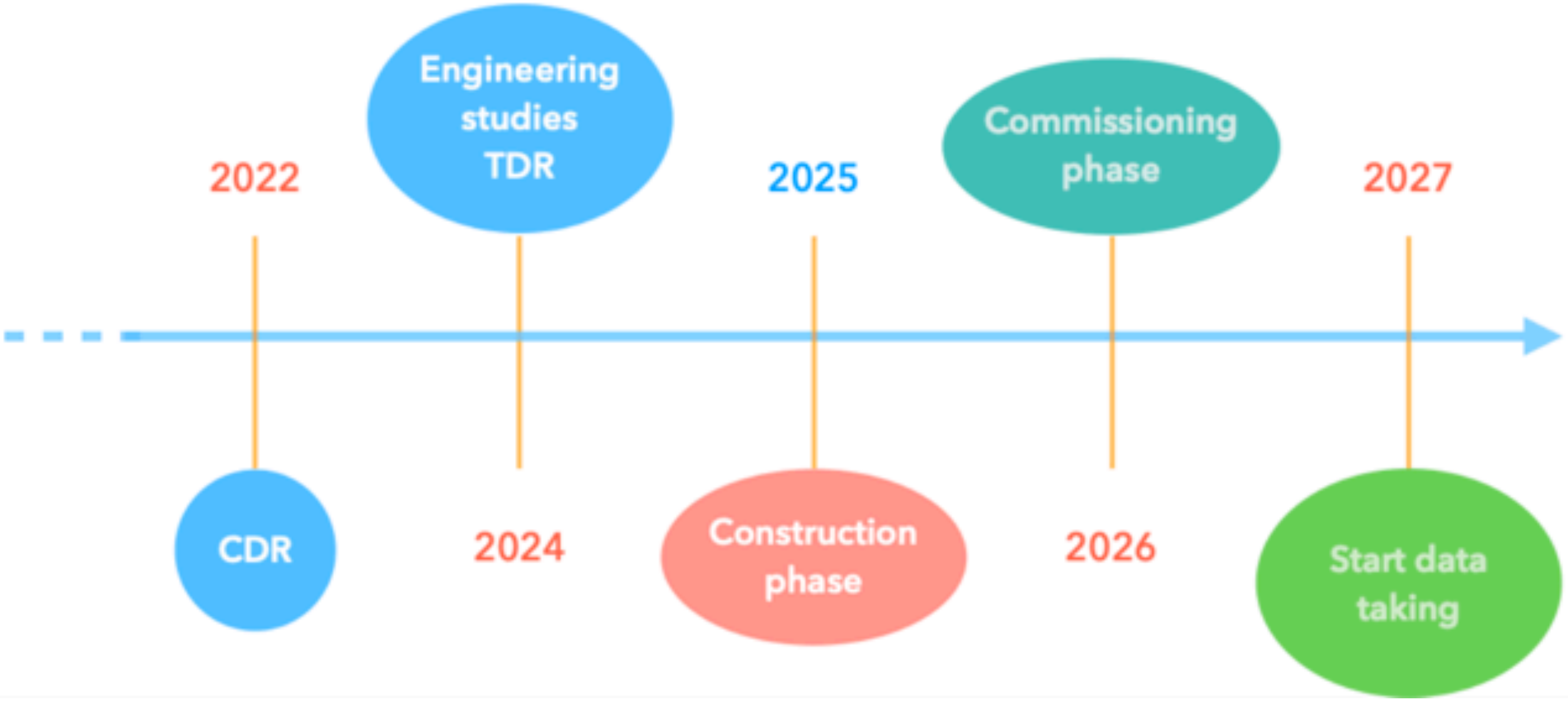


Nature Physics 13, 212-216 (2017)

future: DARWIN

www.darwin-observatory.org

29 institutions, 12 countries
Working towards a CDR and a TDR
DARWIN in the APPEC roadmap
CDR for 2022, Construction timeline 2025



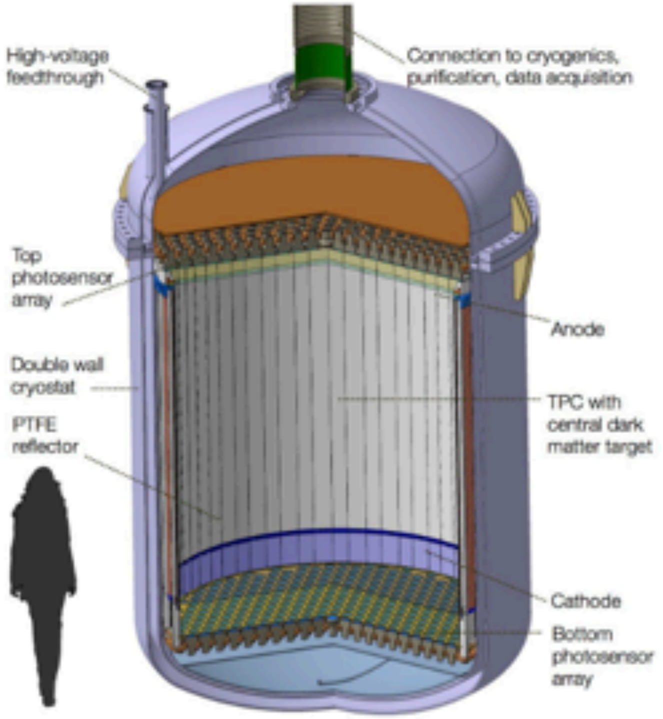
2022
CDR
Engineering studies TDR
2024
2025
Construction phase
Commissioning phase
2026
2027
Start data taking

future: DARWIN

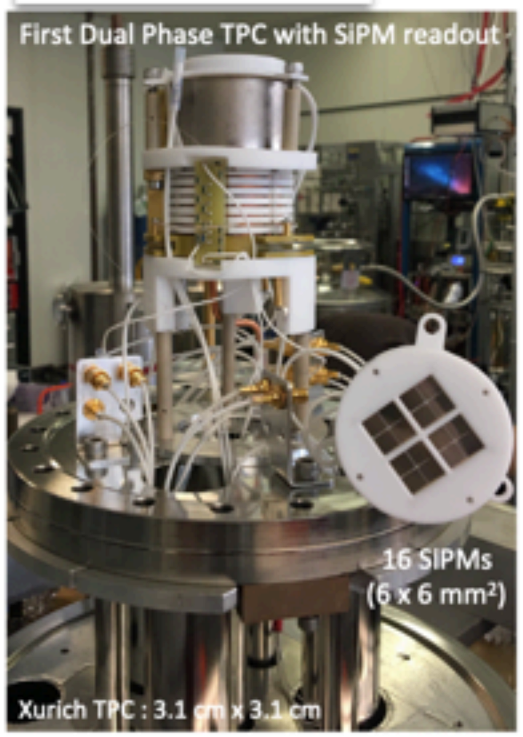
CHALLENGES

- Electron drift over 2.5 meters.
  HV more than -100 kV for drift field of 0.5 kV/cm
- Background: reduce ^{222}Rn (material screening, distillation) and (α,n) from PTFE
- Purification and distillation: need high speed for large quantity of LXe
- Light collection efficiency: 4pi photosensors

- Photosensors: high QE, low dark rate, stability



JINST 13 (2018) P10022

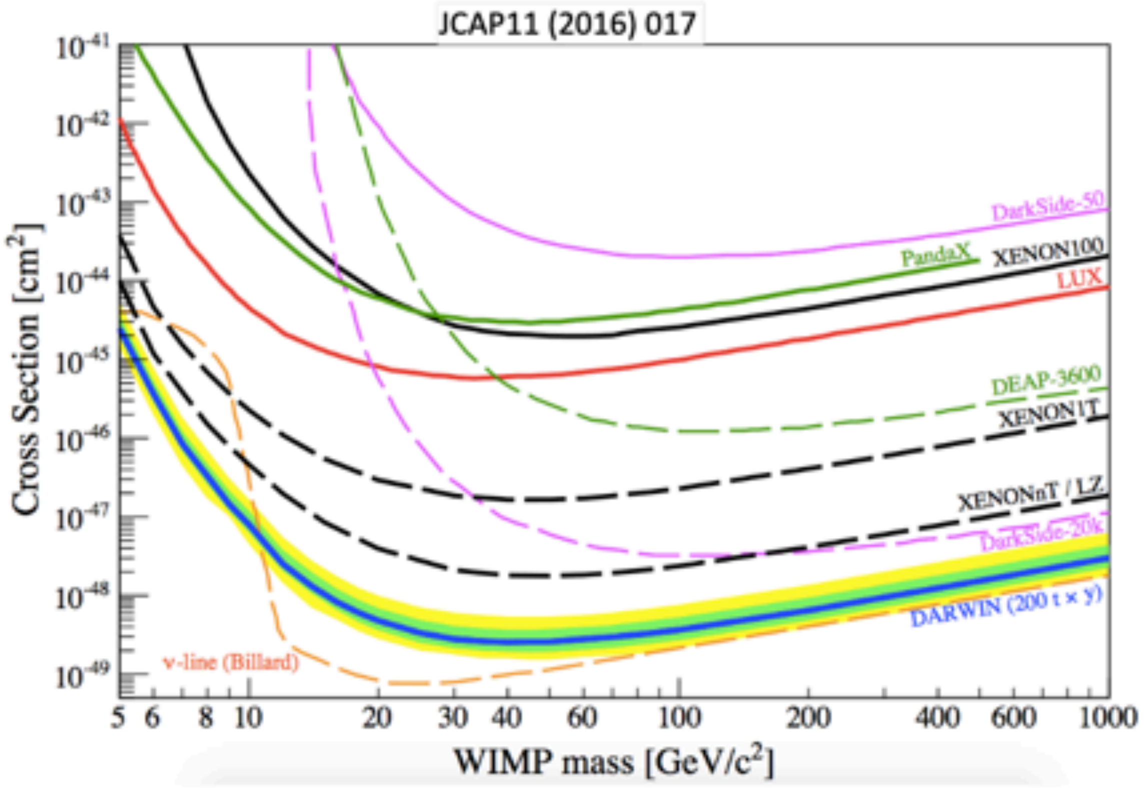

First Dual Phase TPC with SiPM readout

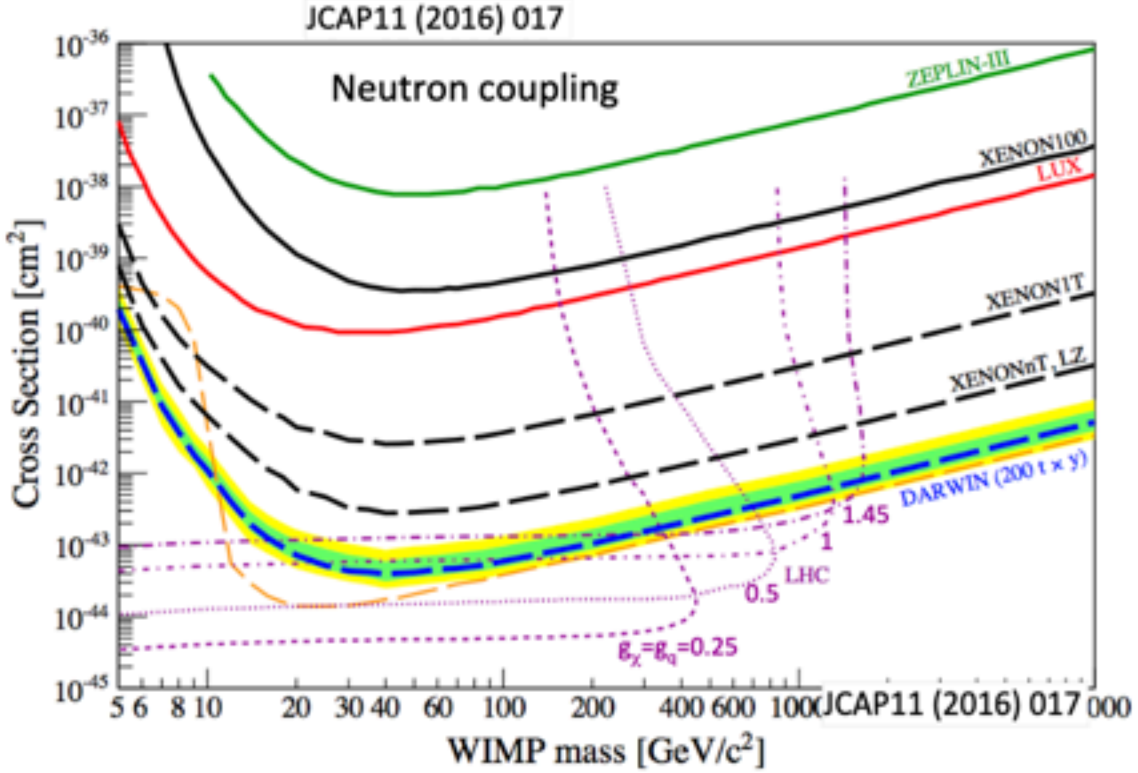
ULTIMATE (Uni Friburg)

Courtesy of F. Tönnies

Xenoscope (UZH)

future: DARWIN

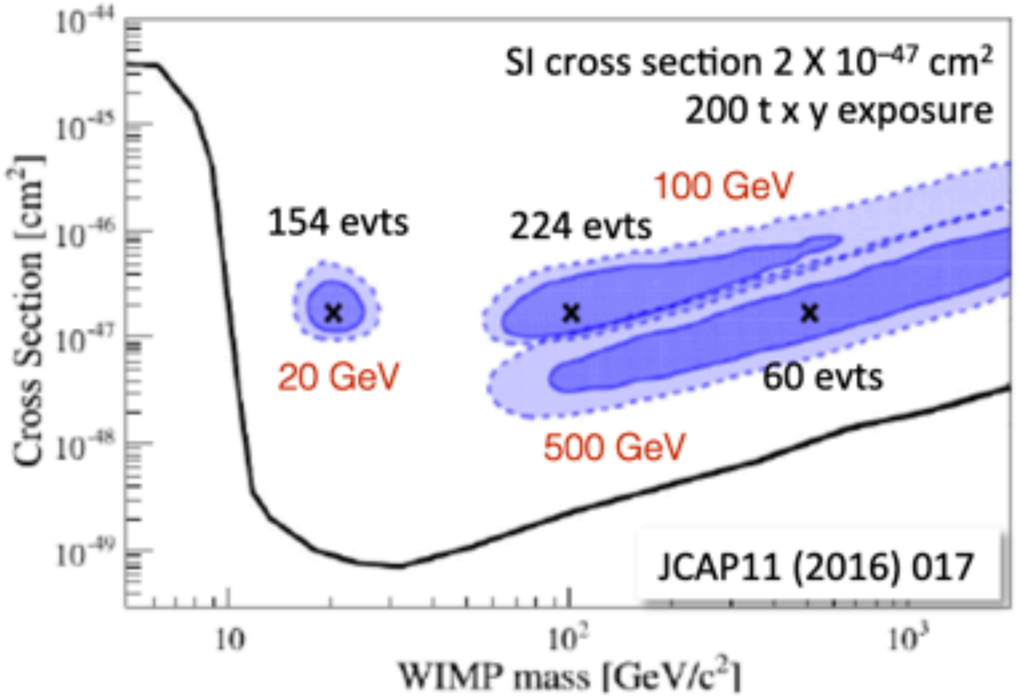




- **Huge dimensions: 2.6 m height x 2.6 diameter**
- **Huge exposure: 200 ton x year**
  - 50 tons of LXe
  - 40 tons of target
  - 30 tons fiducial
- **Sensitivity: ~10^{-49} cm^2**
- **99.98% ER rejection at 30% NR acceptance**
- **Light yield 8 PE/keV at 122 keV, Energy window 5-35 keV$_{NR}$**
- **Sensitivity: ~10^{-49} cm^2**

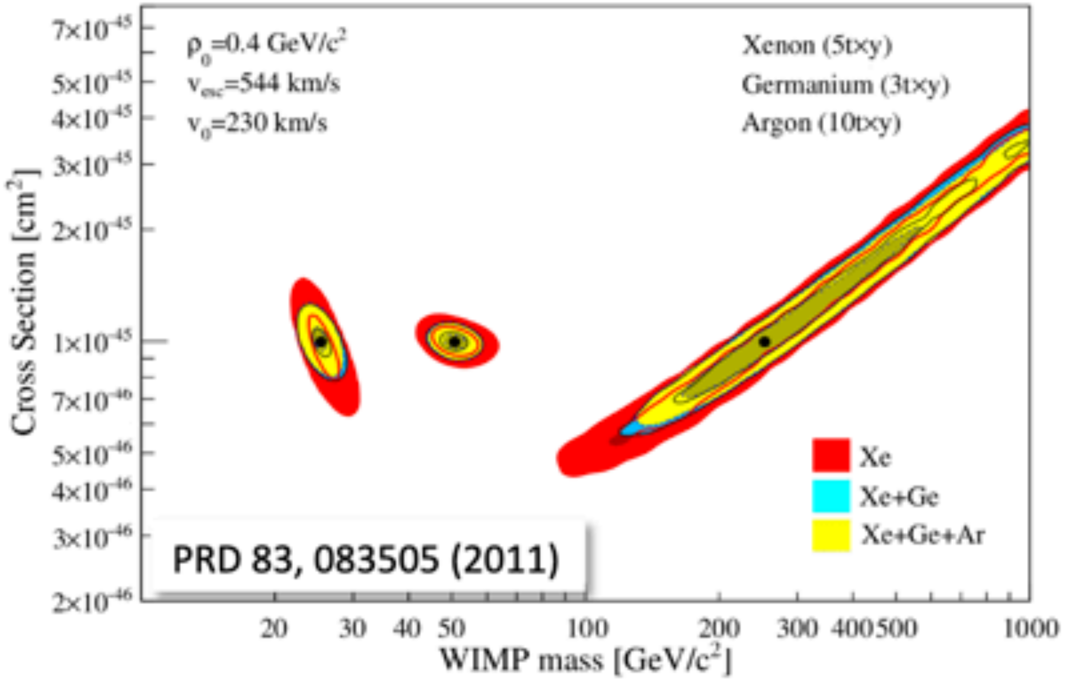
future: DARWIN

WIMP properties



JCAP11 (2016) 017

Target complementarity

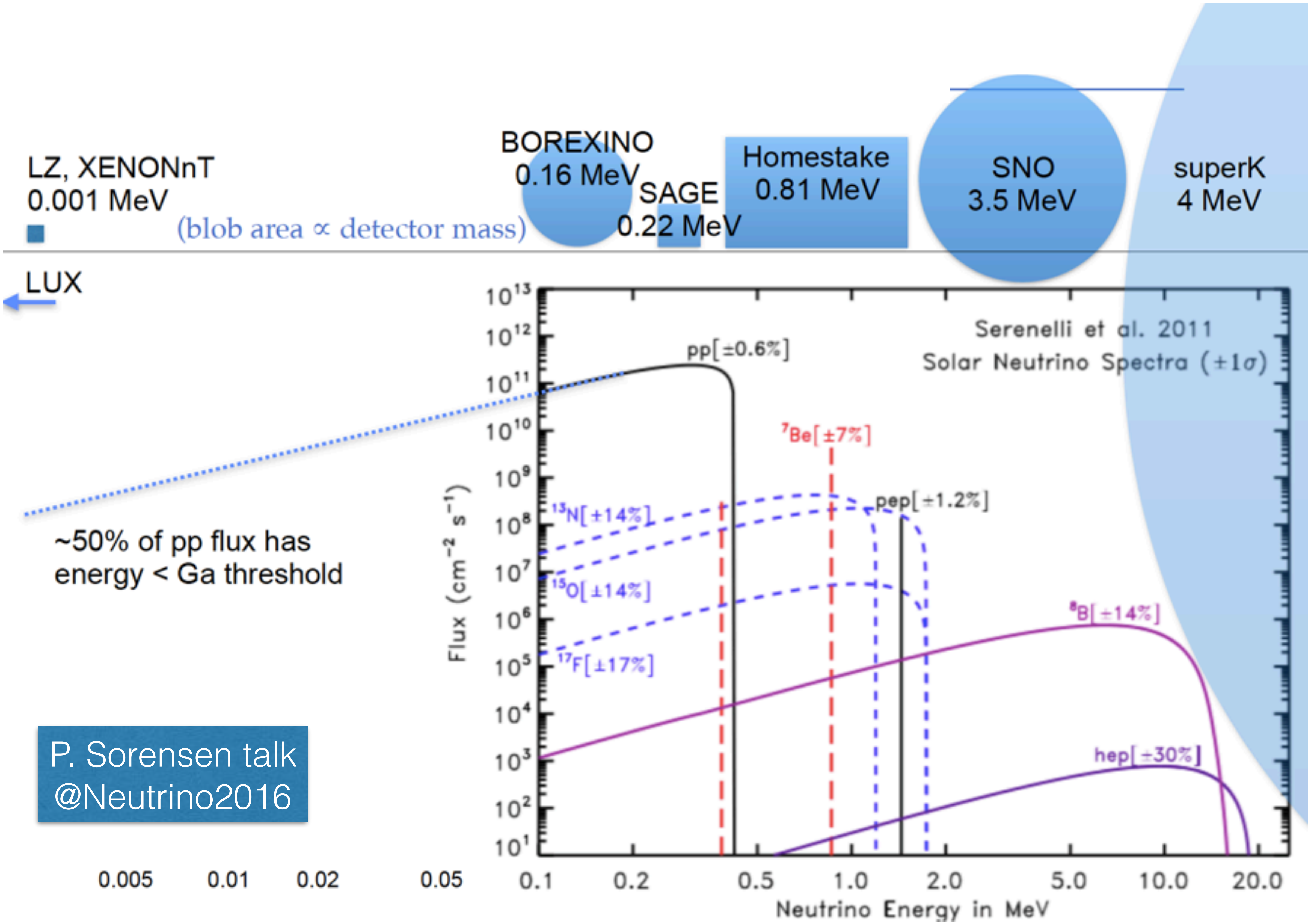


PRD 83, 083505 (2011)

- Reconstruction of WIMP mass and scattering cross section
- 1σ, 2σ credibility regions for 20, 100 and 500 GeV/c^2 marginalised over astrophysical parameters uncertainties
- Few 100 GeV can be constrained

- Parameters reconstruction improves with information from Ge detectors

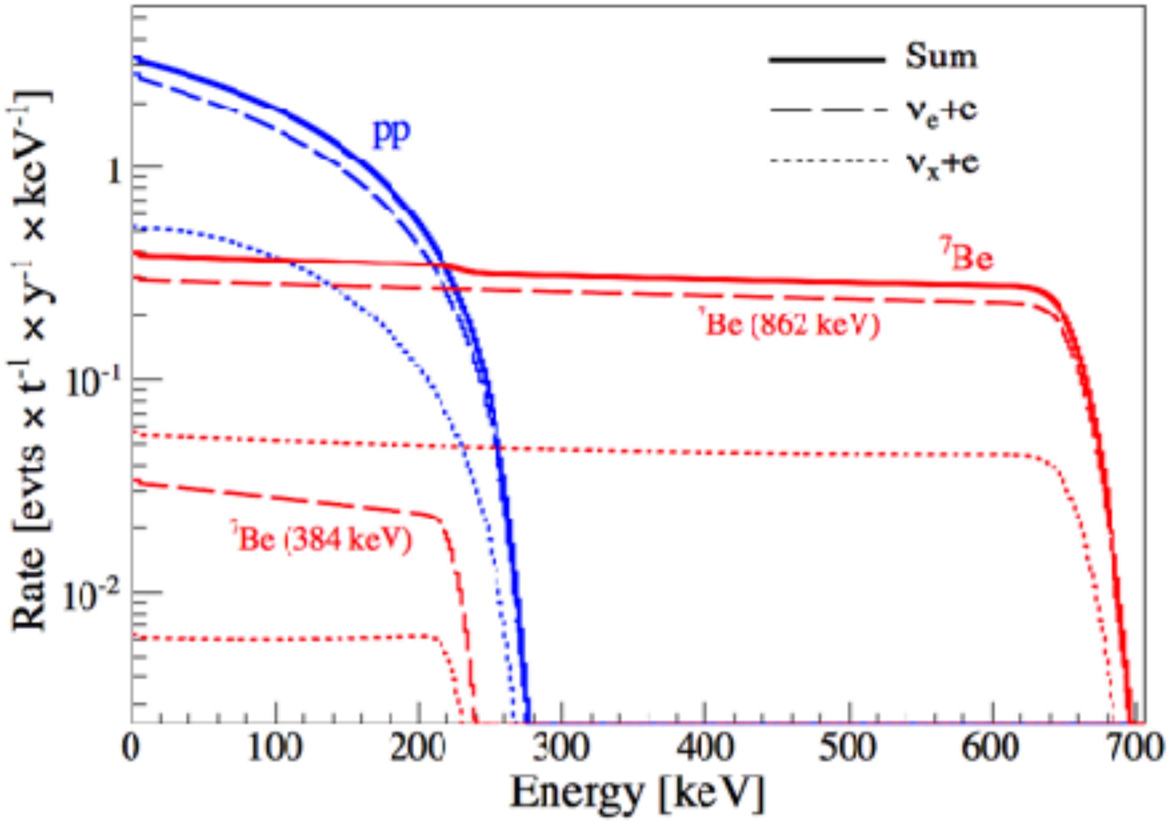
Solar neutrino & detectors



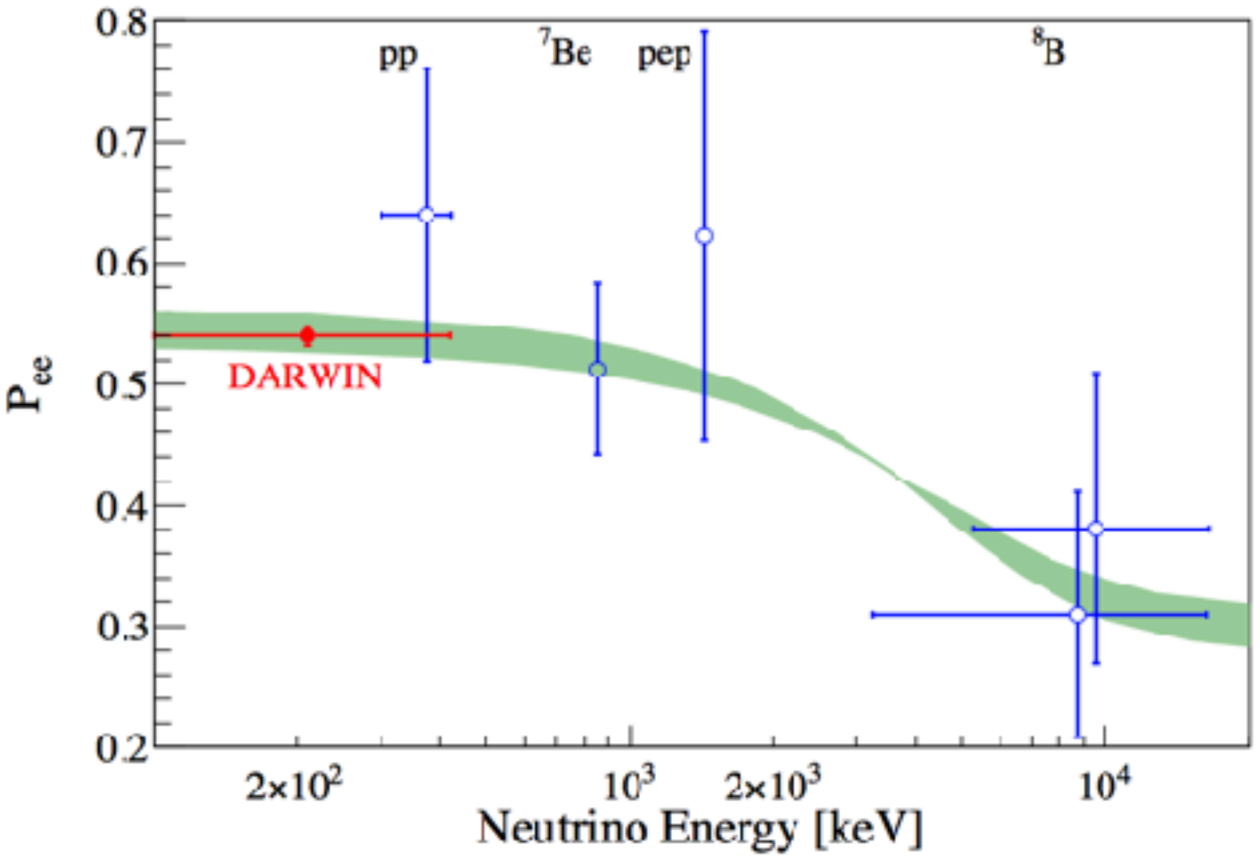
~50% of pp flux has energy < Ga threshold

P. Sorensen talk @Neutrino2016

Measuring pp neutrinos



JCAP 1611 (2016) no.11, 017

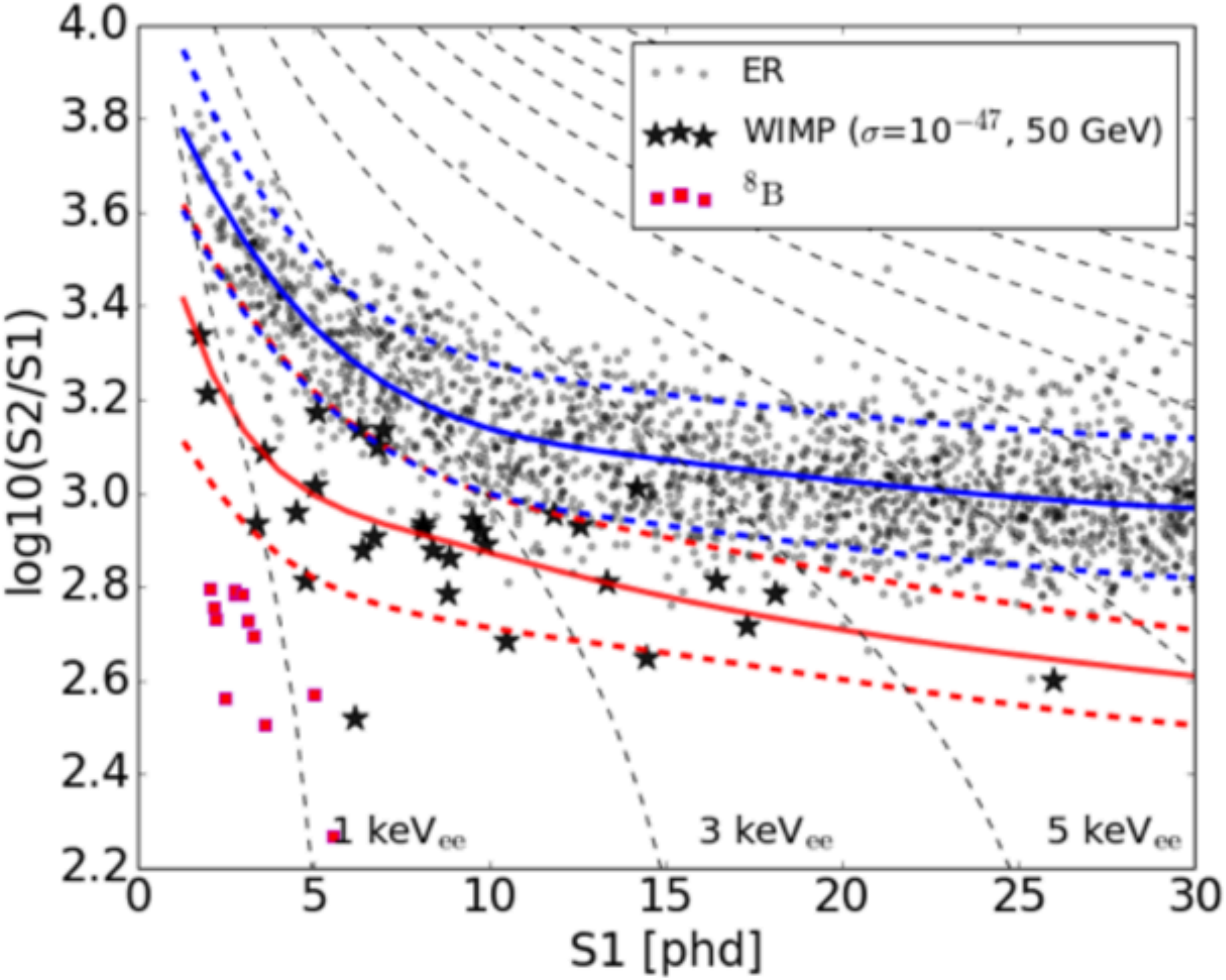


- XENONnT/LZ could reduce the uncertainty on the pp flux to 2.2% (currently Borexino is @10%)
- DARWIN (50t LXe) could bring this down further, to ~1%
- Need to reduce Rn by a factor >10

Solar neutrino NR

- Expect commissioning in 2019
- experiment goal is 1000 days live and 5.6 tonnes fiducial mass
- solar neutrino ER counts (window defined by plot axes): 233 pp, 19 ^{7}Be, a few ^{13}N
- Rn O(100)—O(1000) optimistic and pessimistic cases
  - both compatible with dark matter search goals, but the former makes neutrino physics much more convenient…
- solar neutrino NR counts: 7-70 ^{8}B

as seen by LZ / XENONnT



Neutrinos from SN

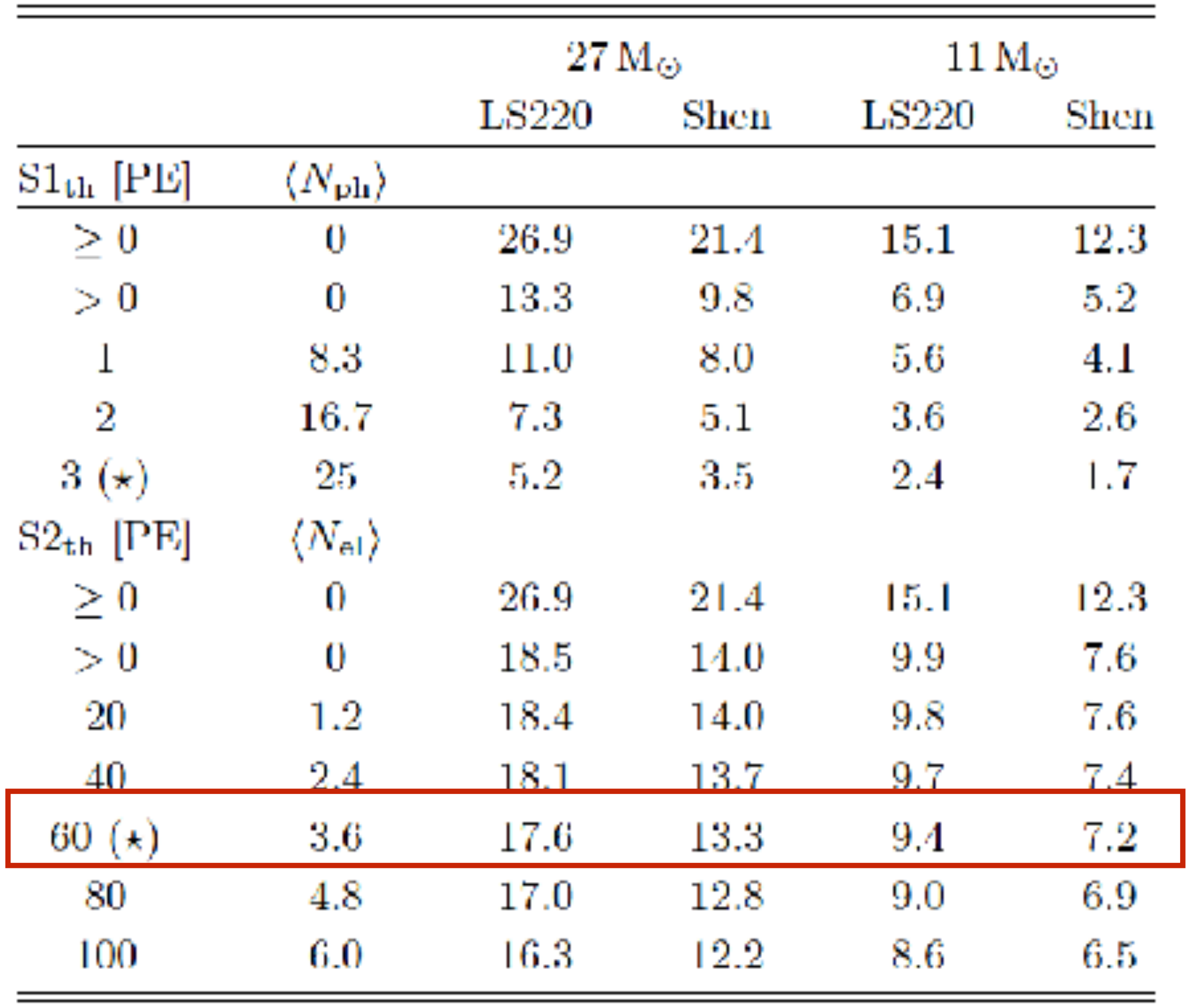
R. Lang, C. McCabe, S. Reichard, M.S., I. Tamborra,
"Supernova neutrino physics with xenon dark matter detectors", Phys. Rev. D 94 (2016) no.10, 103009.

CEvNS with xenon nuclei: not affected by neutrino oscillation

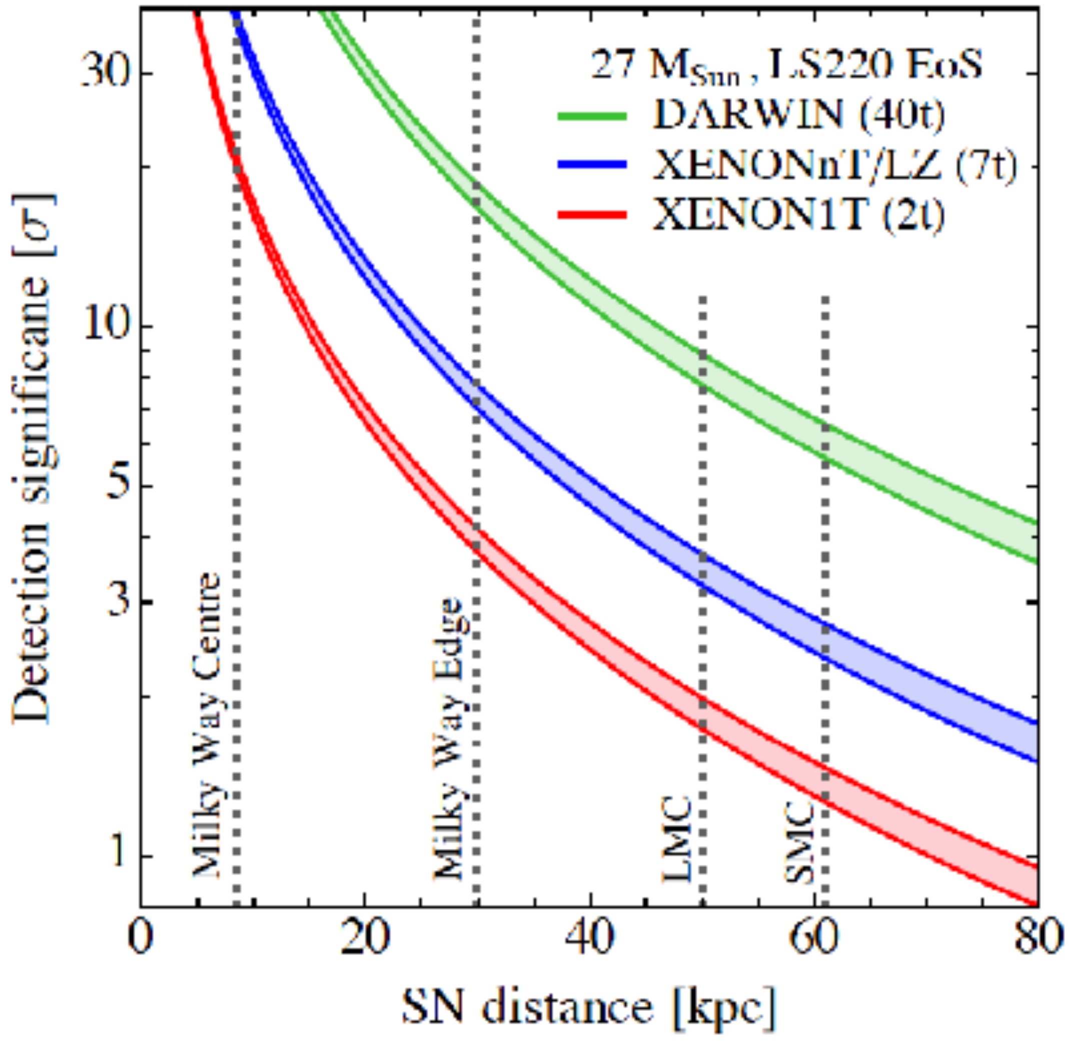
Low energy events -> S2-only analysis

(in the few s burst duration the background rate is small enough: 0.02 / (t s))

Events per ton of Xe



		$27\,M_\odot$		$11\,M_\odot$	
		LS220	Shen	LS220	Shen
$S1_{th}$ [PE]	$\langle N_{ph} \rangle$				
≥ 0	0	26.9	21.4	15.1	12.3
> 0	0	13.3	9.8	6.9	5.2
1	8.3	11.0	8.0	5.6	4.1
2	16.7	7.3	5.1	3.6	2.6
3 ($\star$)	25	5.2	3.5	2.4	1.7
$S2_{th}$ [PE]	$\langle N_{el} \rangle$				
≥ 0	0	26.9	21.4	15.1	12.3
> 0	0	18.5	14.0	9.9	7.6
20	1.2	18.4	14.0	9.8	7.6
40	2.4	18.1	13.7	9.7	7.4
60 ($\star$)	3.6	17.6	13.3	9.4	7.2
80	4.8	17.0	12.8	9.0	6.9
100	6.0	16.3	12.2	8.6	6.5

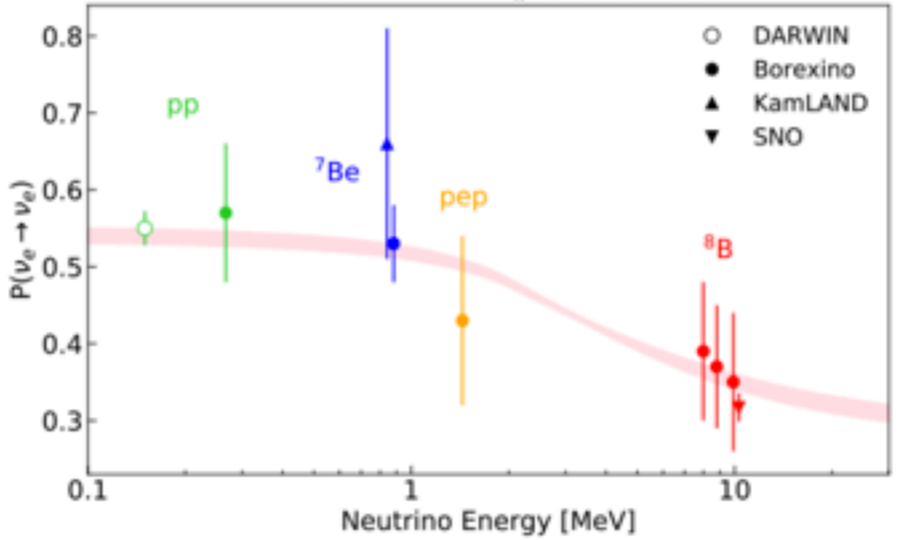


future: DARWIN

and more fundamental physics cases

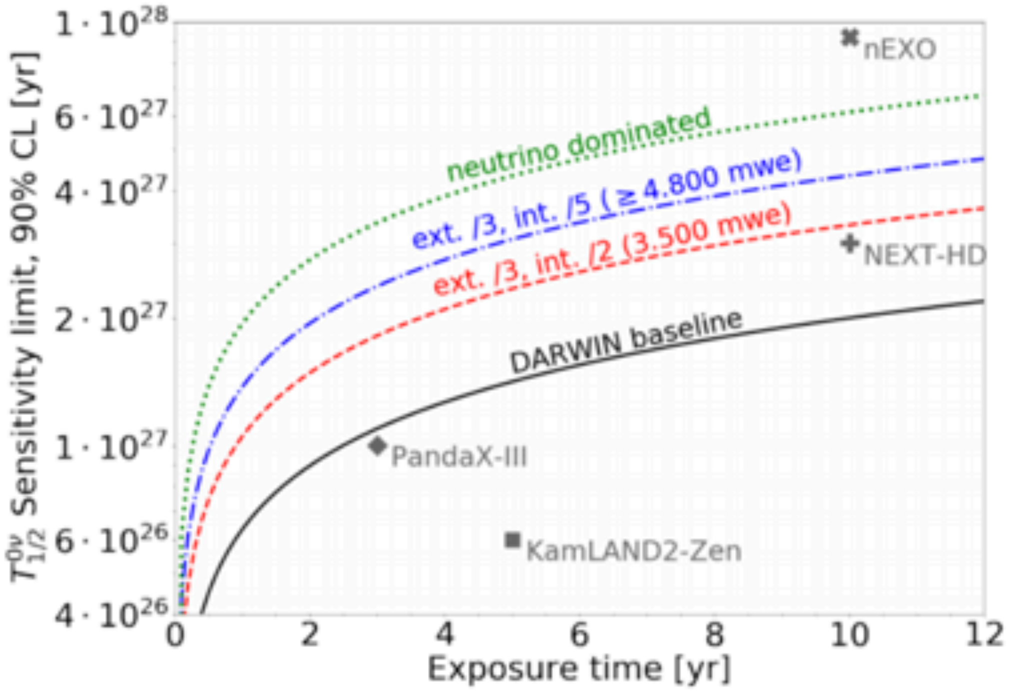
- **Solar neutrinos**

arXiv:2006.03114



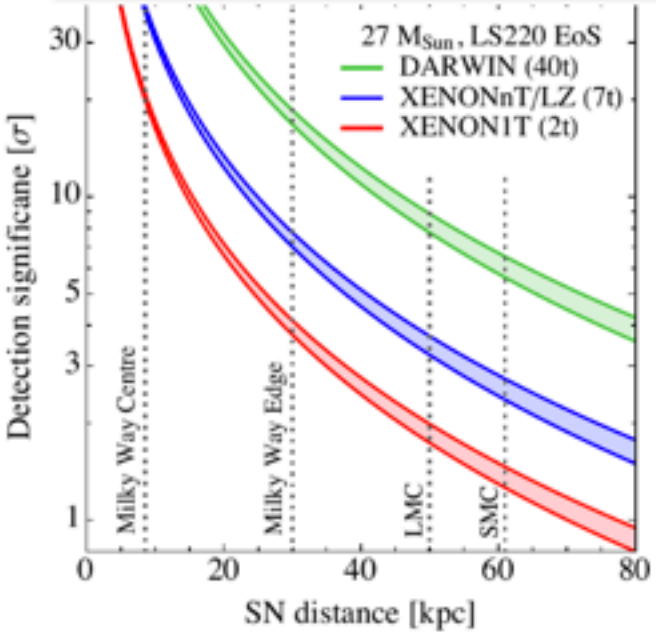
- **Neutrinoless double beta decay of ^{136}Xe**

arXiv:2003.13407



- **Coherent neutrino nucleus scattering**
- **SuperNova neutrinos**

Phys. Rev. D 94 (2016) no.10, 103009



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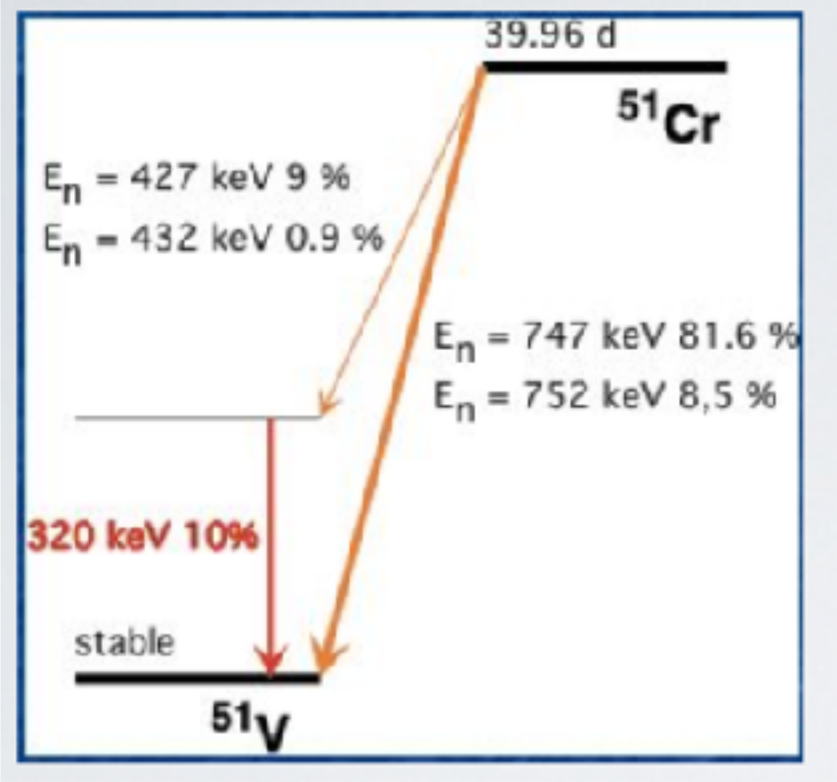
Neutrinos as ER calibration



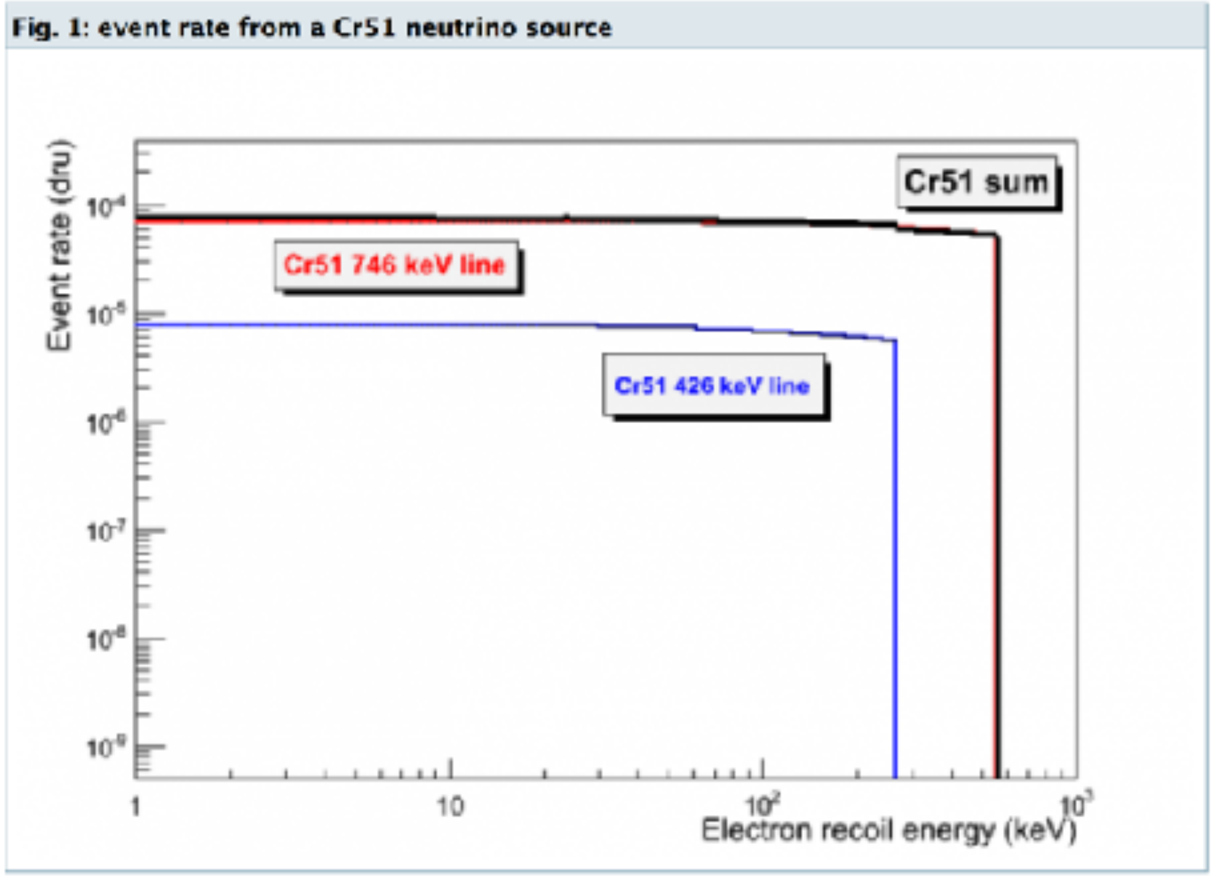


Fig. 1: event rate from a Cr51 neutrino source

With a 10 MCi ^{51}Cr source
~210 events / (t * day)

(only 6 in the low energy region of interest)

Neutrinos as NR calibration $\chi\nu$

- An O(10 MeV) beta-beam -> CNNS NR

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

30-6-2001

A novel concept for a $\bar{\nu}_e$ neutrino factory

P. Zucchelli [*]
CERN, Geneva, Switzerland

Abstract

The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. The current neutrino factory concept implies the production, collection, and storage of muons to produce beams of muon and electron neutrinos at equal intensities at the same time. Research and development addressing its feasibility are ongoing. In the current paper, a new neutrino factory concept is proposed, that could possibly achieve beams of similar intensity, perfectly known energy spectrum and a single neutrino flavour, electron anti-neutrino. The scheme relies on existing technology.

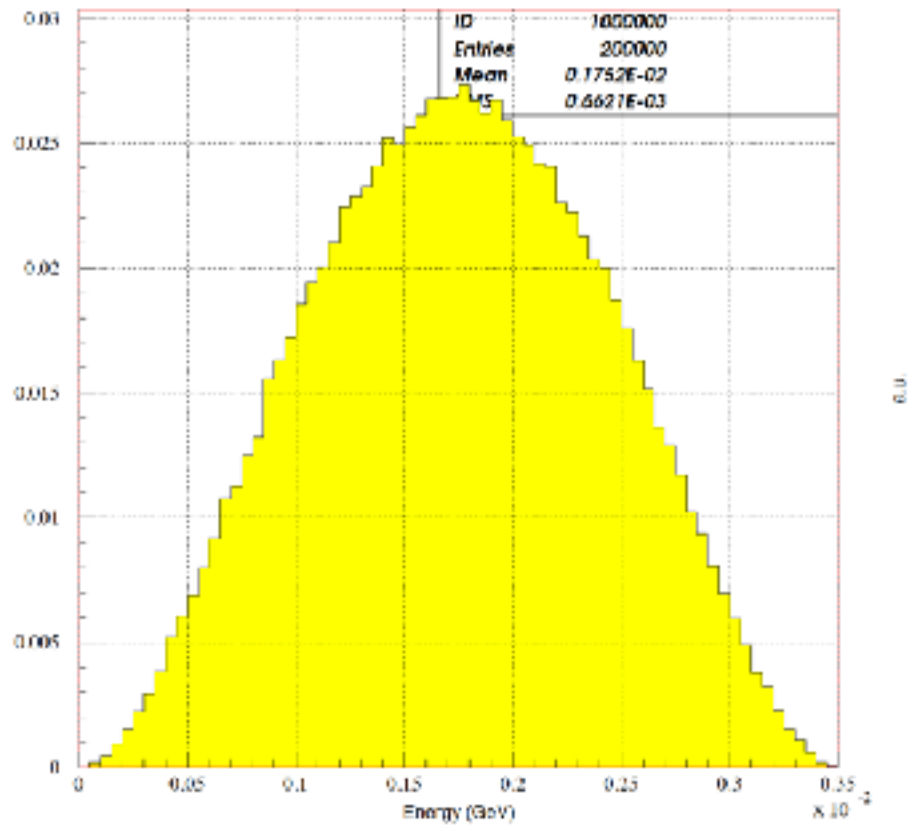


Figure 1: Neutrino energy spectrum in the centre-of-mass frame for a ^{6}He decay.

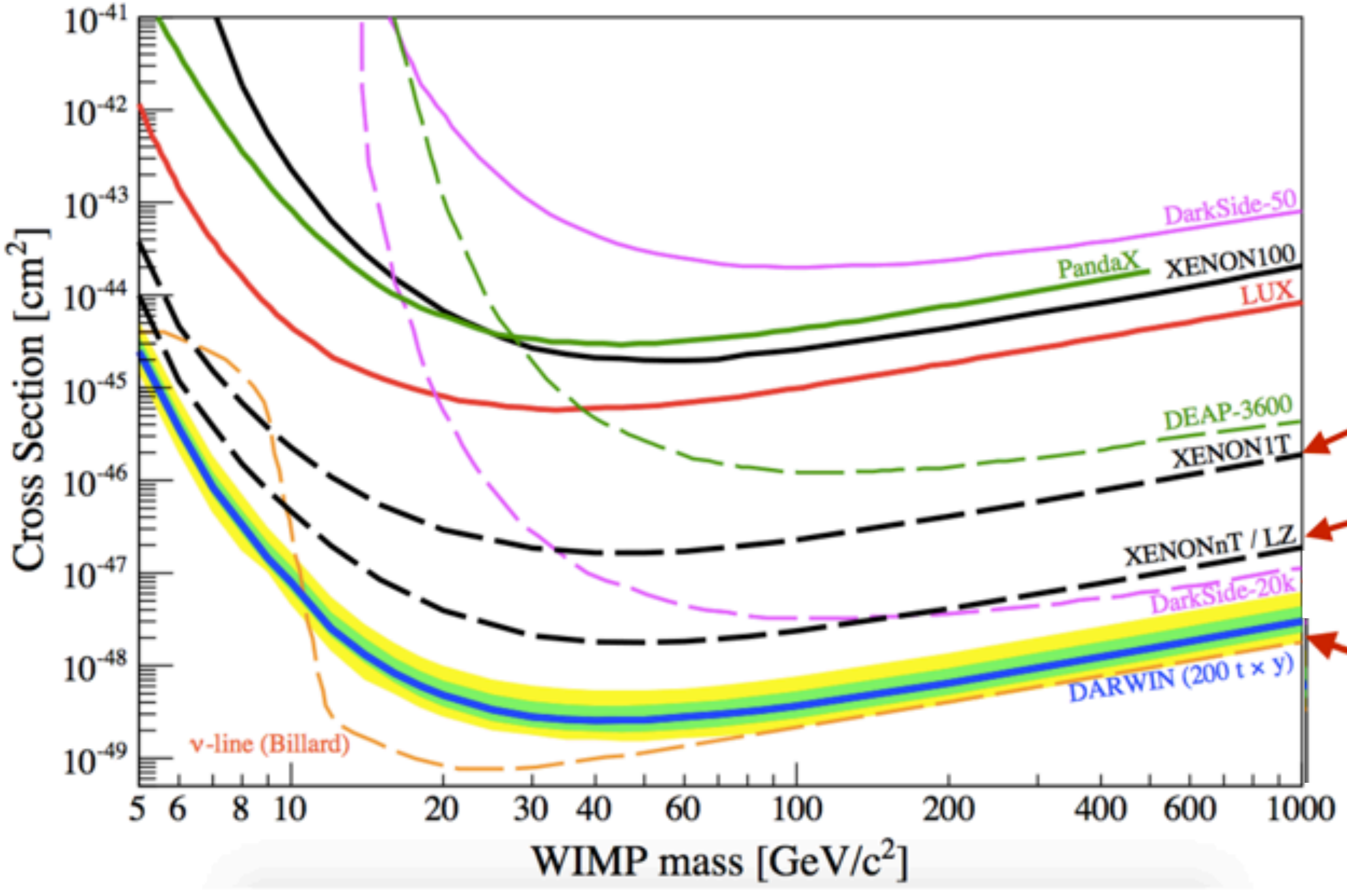
Accelerate an ^{6}He nucleus (end point at rest: 3.5 MeV) up to gamma = 10 (end point 70 MeV)

CNNS produce a *"few keV->tens of keV"* NR,
uniformly distributed in the detector,
with very well know energy spectrum.

Summary plot

Explore WIMP DM from $m_\chi \sim 5$ GeV/c^2

Spin-independent WIMP-nucleon interaction



Present

Near future (2020)

Future

INFN

Istituto Nazionale di Fisica Nucleare

Thanks !

Marco Selvi

INFN Bologna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14-18 settembre 2020