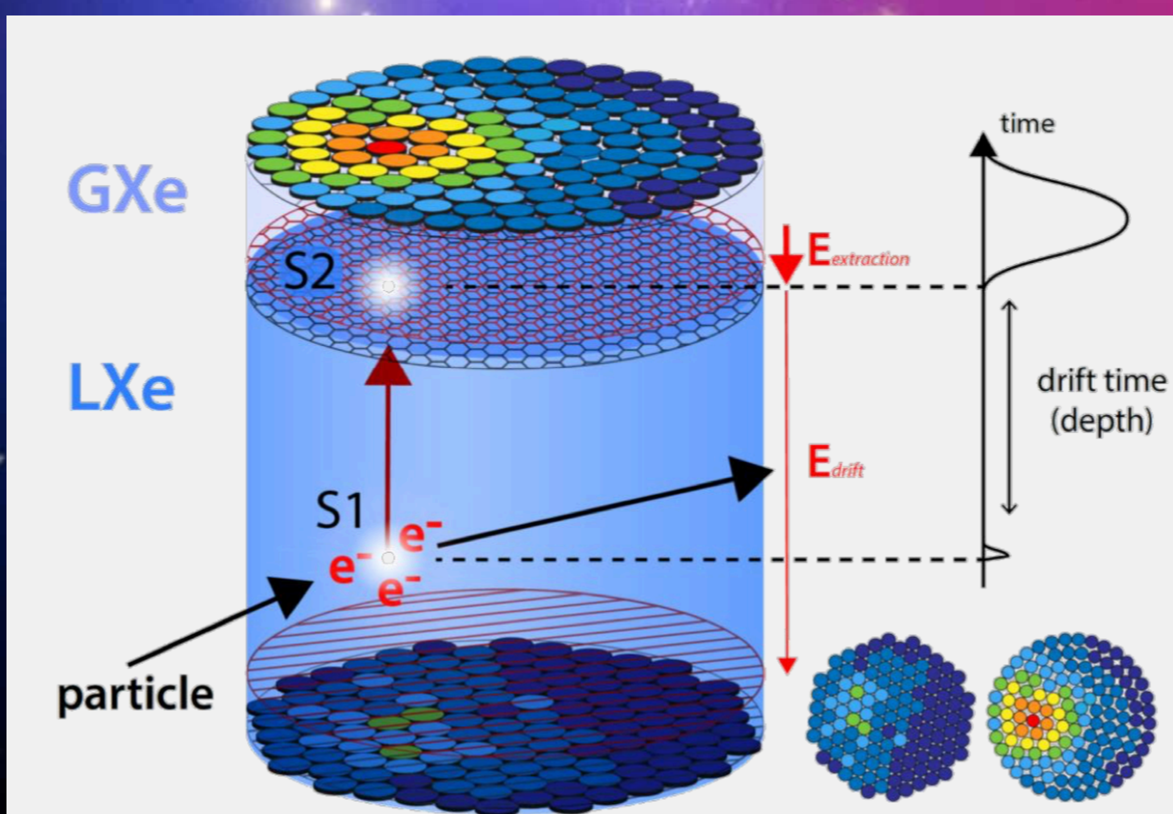
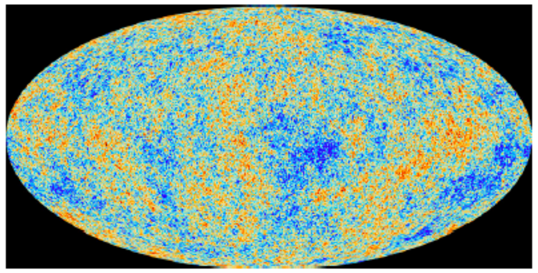
Liquid Detectors: LXe TPC for Dark Matter and Rare Event Search

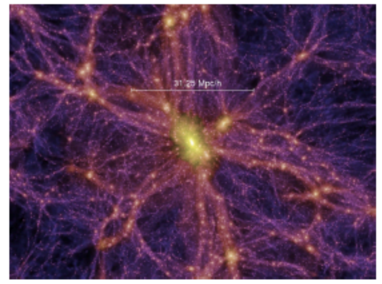


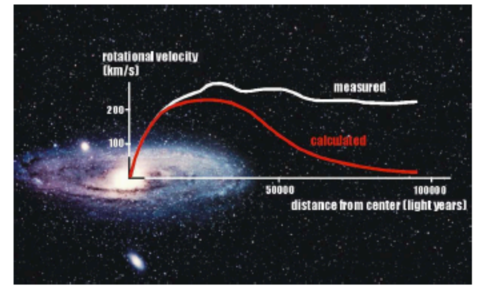
Marco Selvi
INFN Bologna

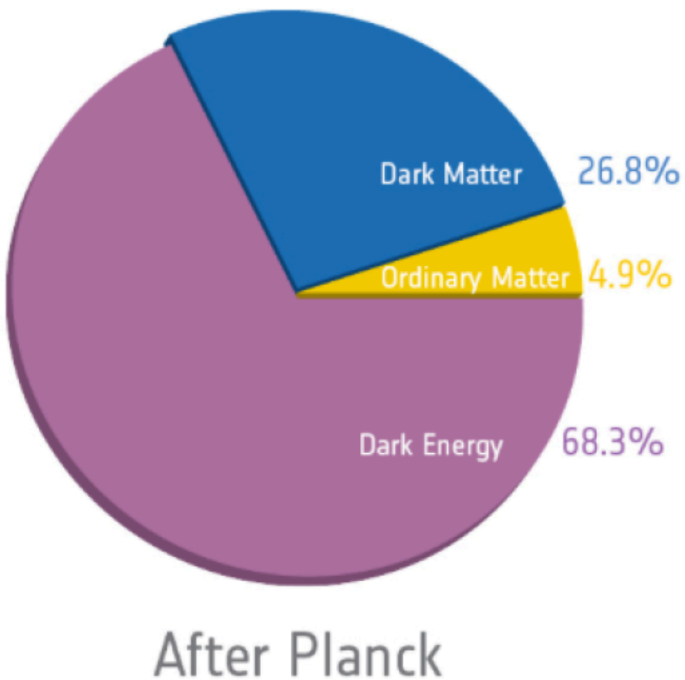
IFD2022, 18 October 2022, Bari

Particle Dark Matter









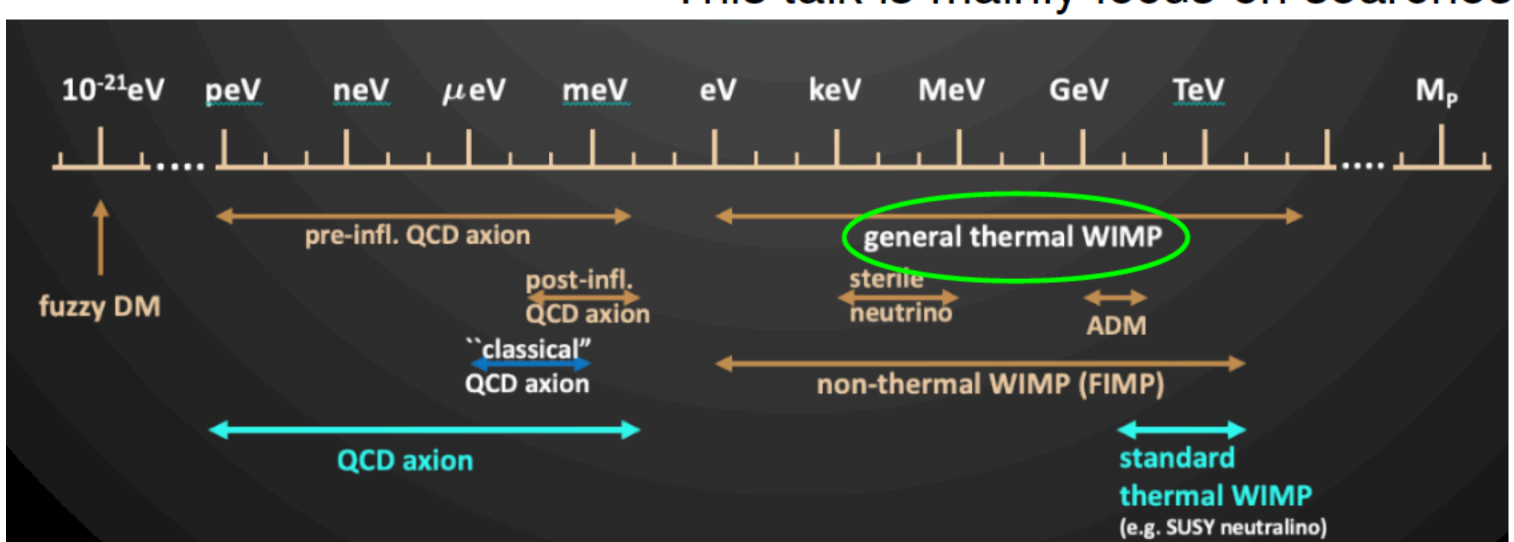
Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

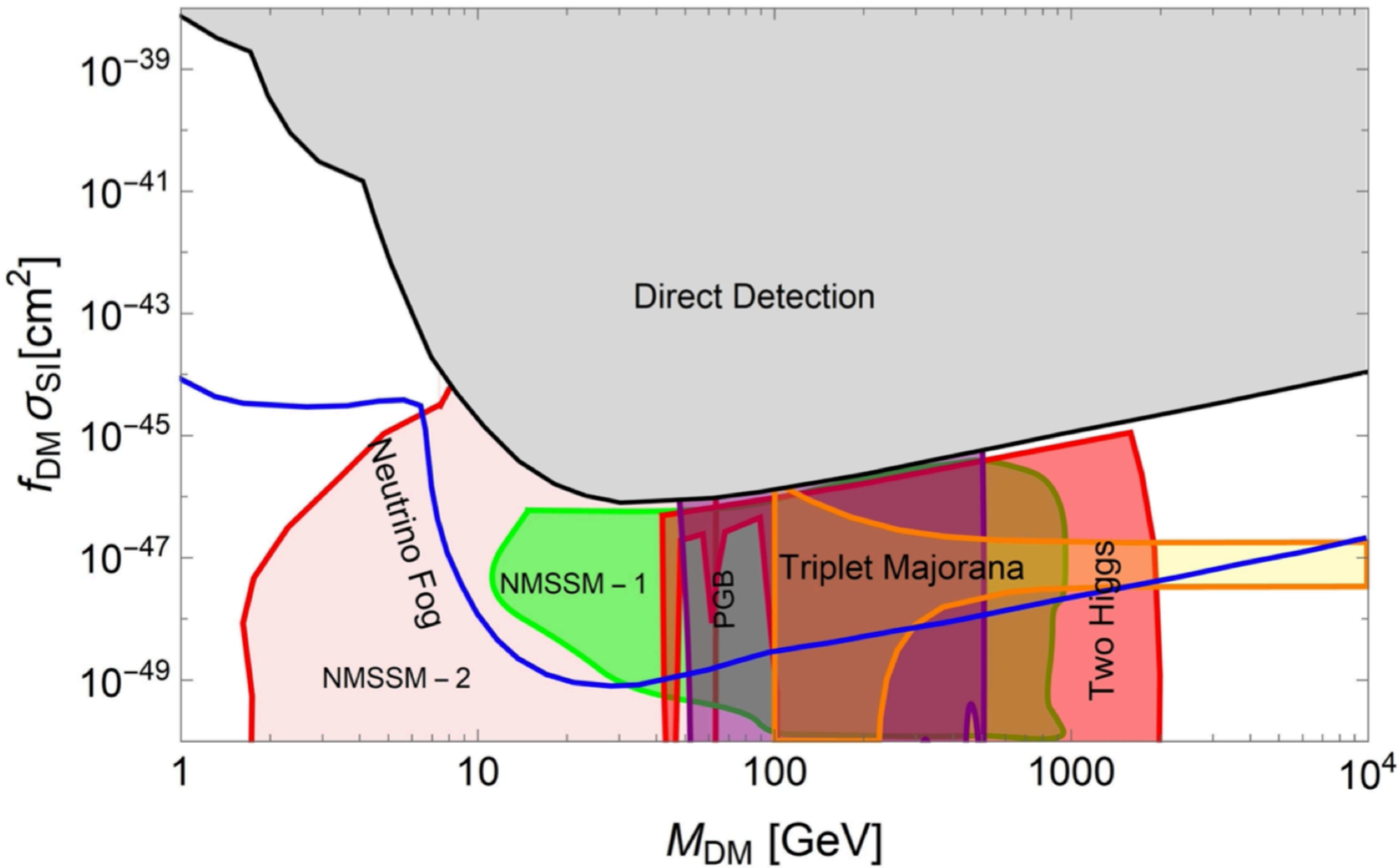
But dark matter could be non weakly-interacting or a completely different type of particle

→ This talk is mainly focus on searches for WIMPs

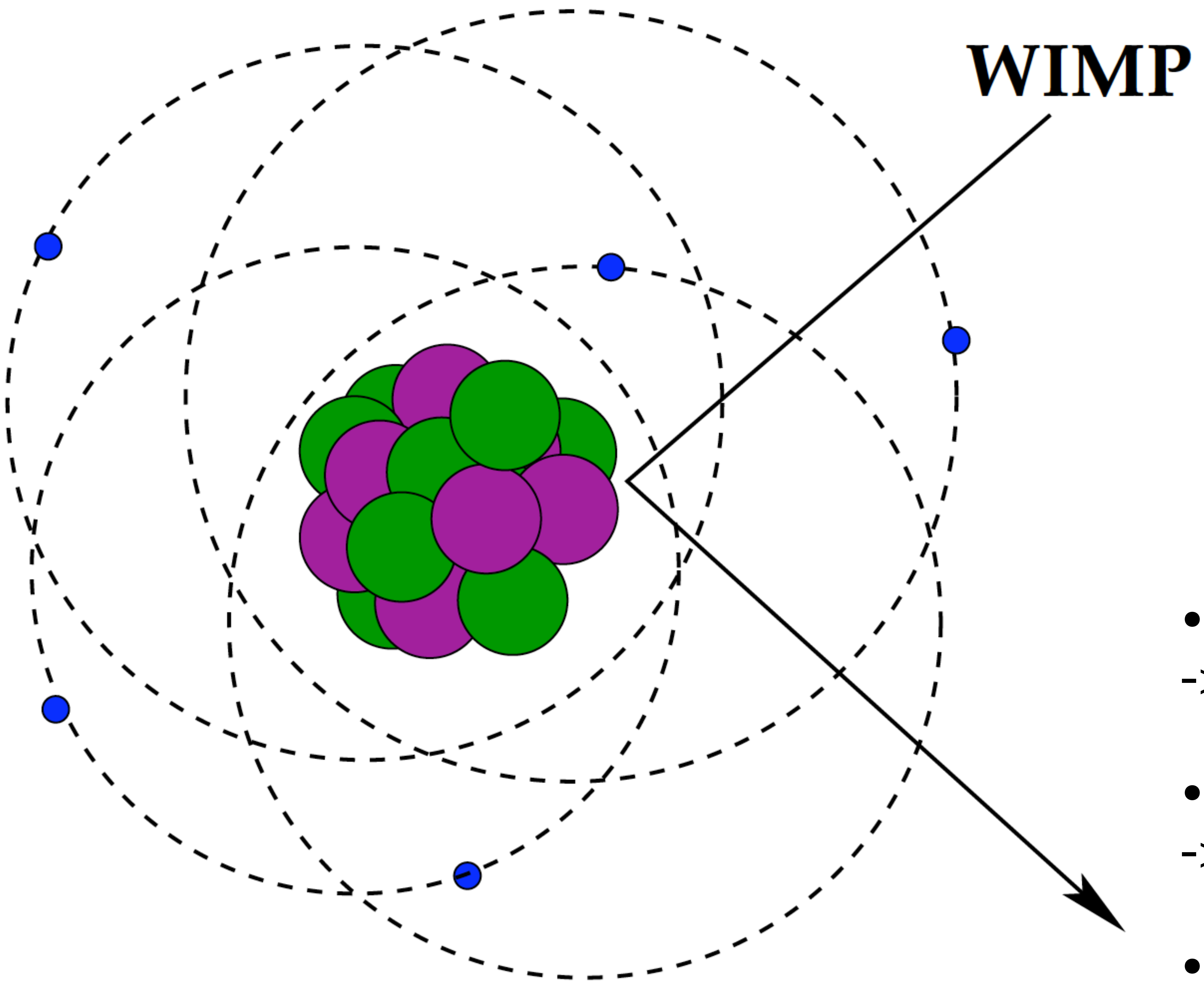


WIMP hypothesis is still alive

CF1 WP1 arXiv:2203.08084
Thanks to Ben Loer, PNNL +
Graciela B. Gelmini, UCLA



Direct Dark Matter Detection



$E_R \sim \mathcal{O}(10\,\text{keV})$

$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

- **Low rate (< ev/ton/yr)**
-> Large mass and time stability

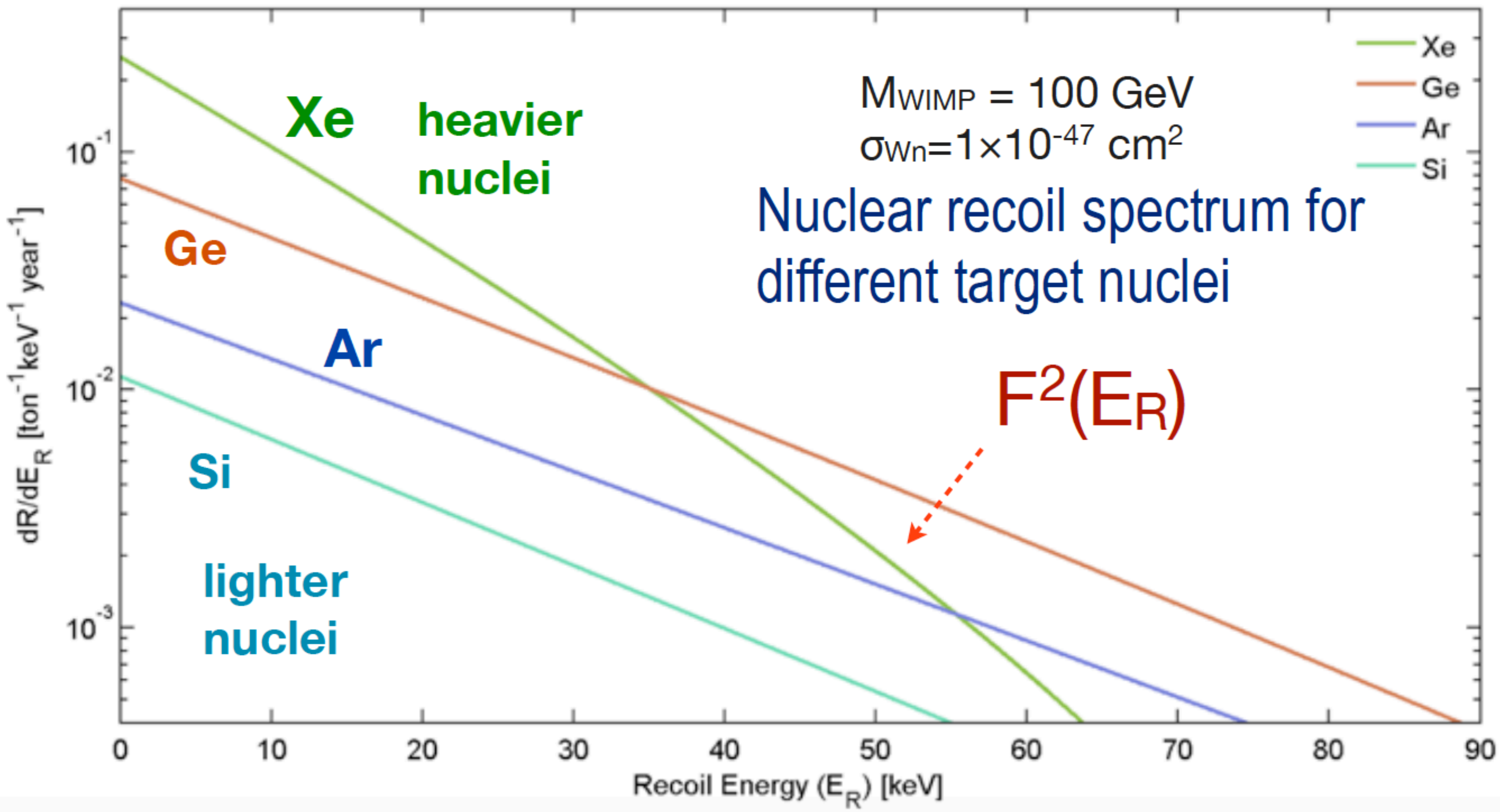
- **Low energy: O(keV)**
-> Small Energy Threshold

- **Very low background mandatory**
-> ER/NR discrimination

Nuclear Recoil Energy Spectrum

Rate after integration over WIMP velocity distribution

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Liquid Noble Detectors

- Large masses and homegeneous targets (LNe, LAr & LXe)

  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

	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

Liquid Noble Detectors: Double Phase TPC

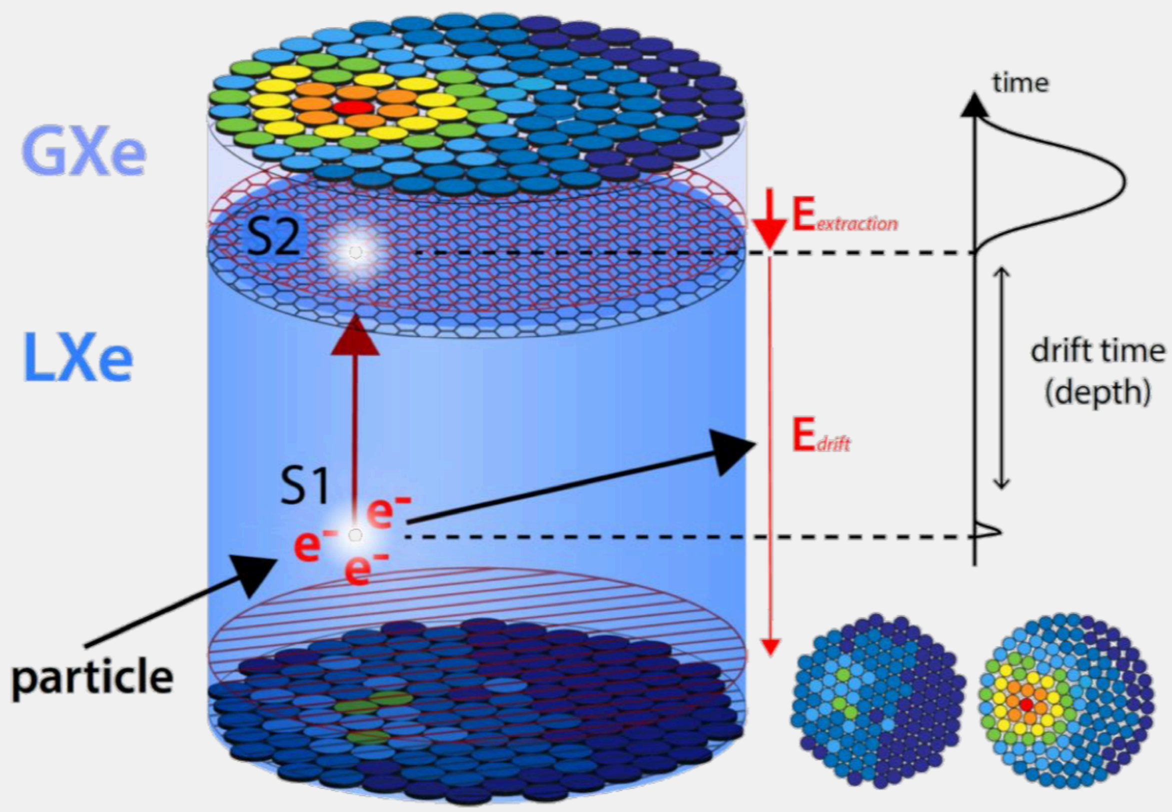


Image by L. Althüser

S1 light signal:
- prompt scintillation photons

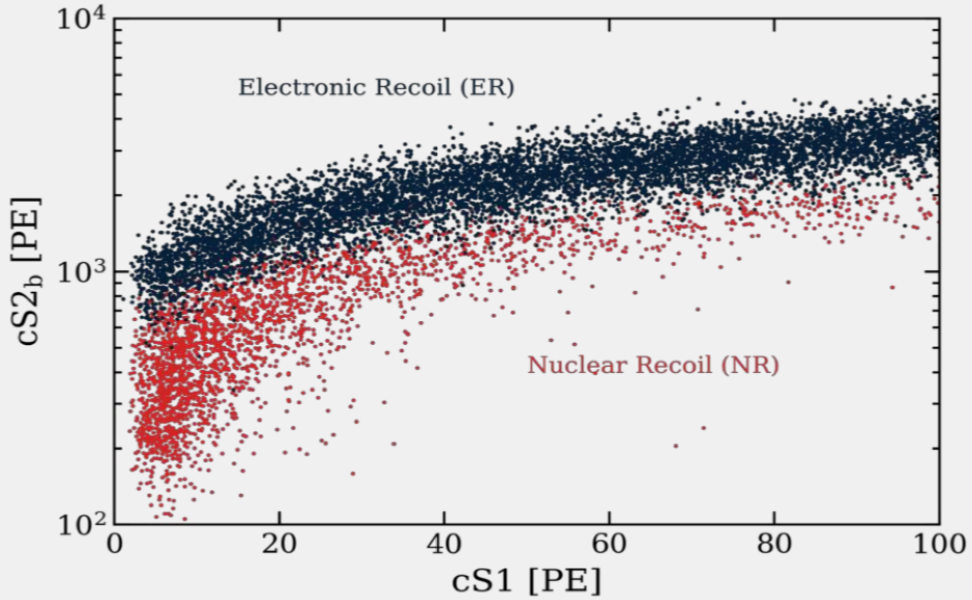
S2 charge signal:
- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

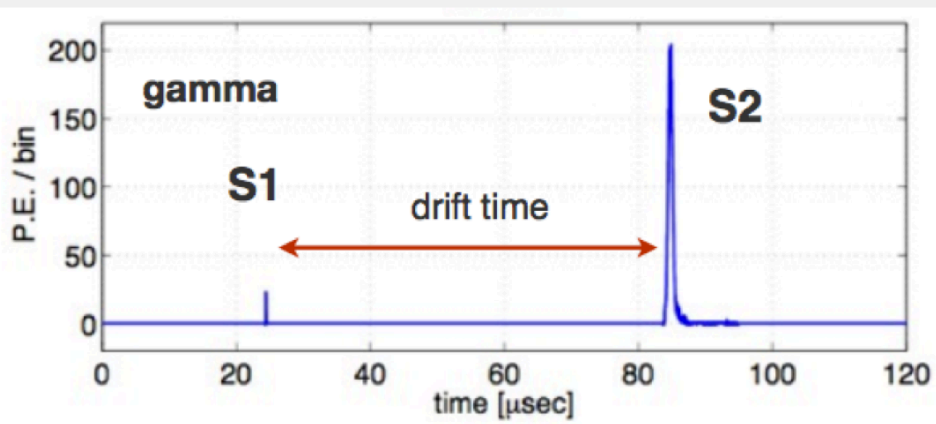
3D vertex reconstruction:
- X,Y: S2 hit pattern
- Z: drift time S2-S1

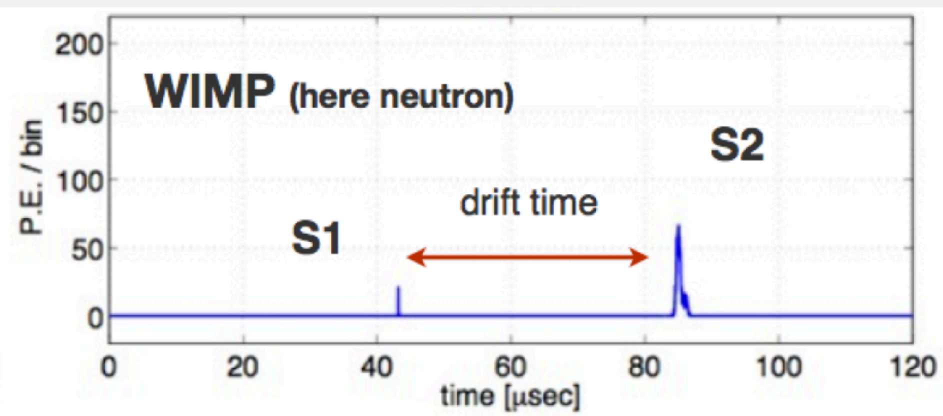
NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNs

ER (Electronic Recoils)
γ, β backgrounds

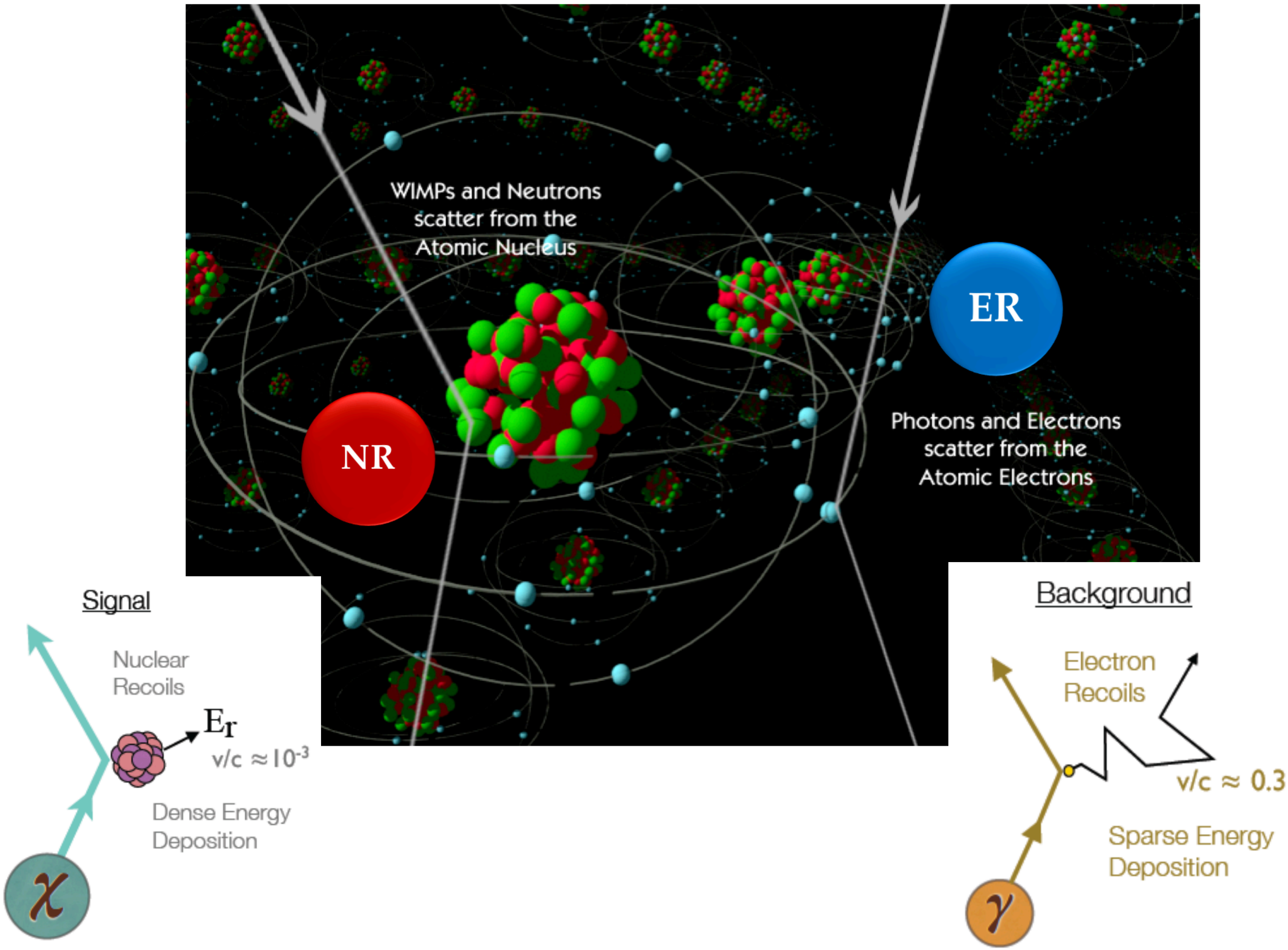
Discrimination from S2/S1
Larger for ER than NR



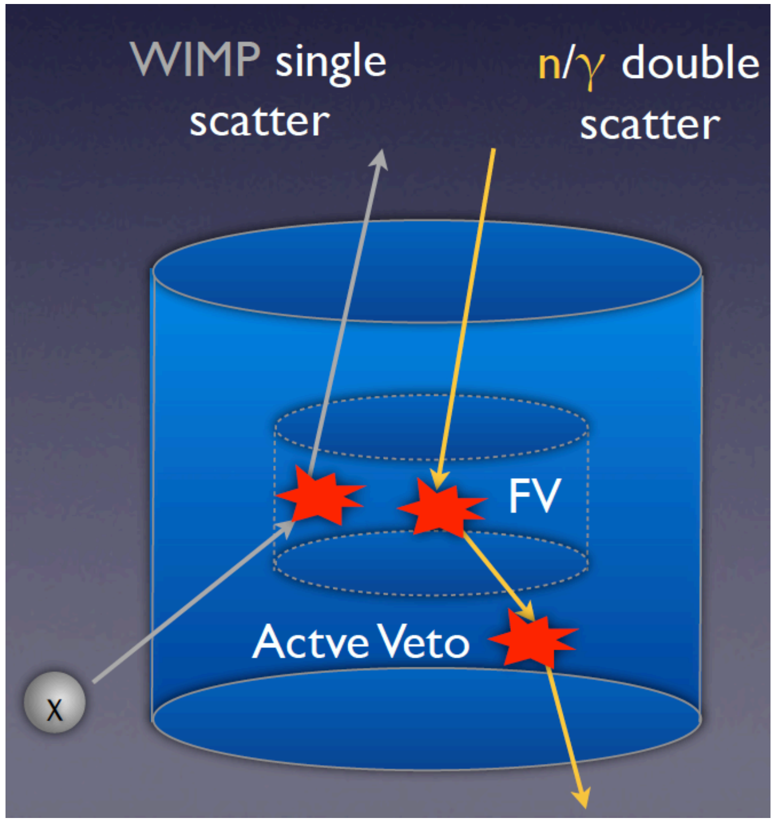




Backgrounds: Electron & Nuclear Recoils

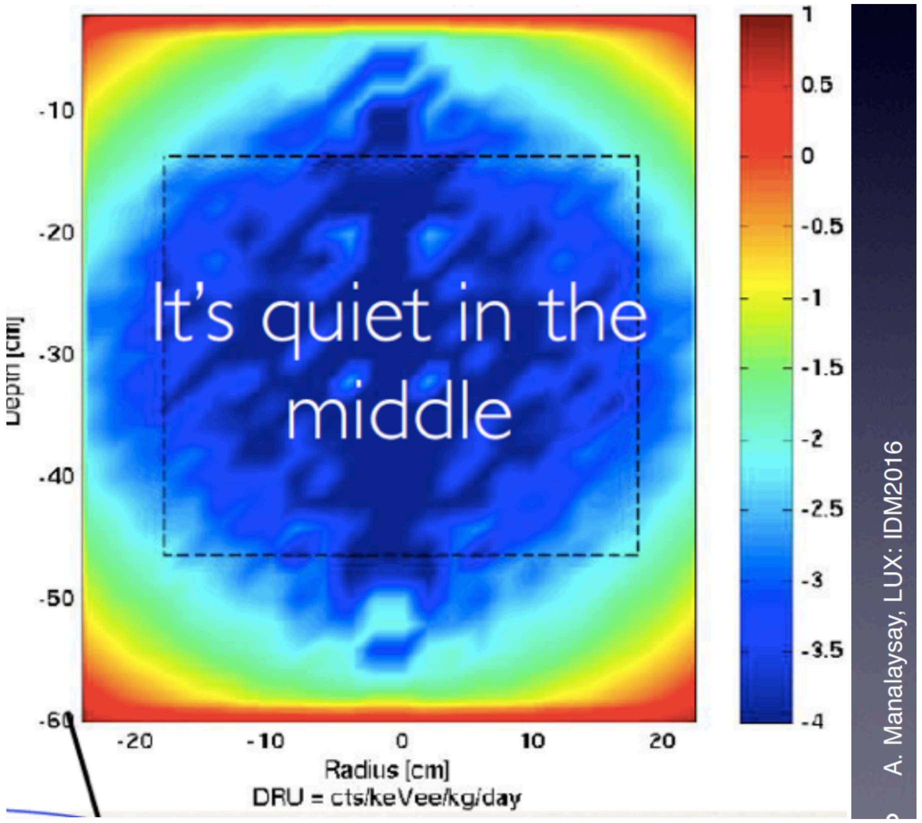


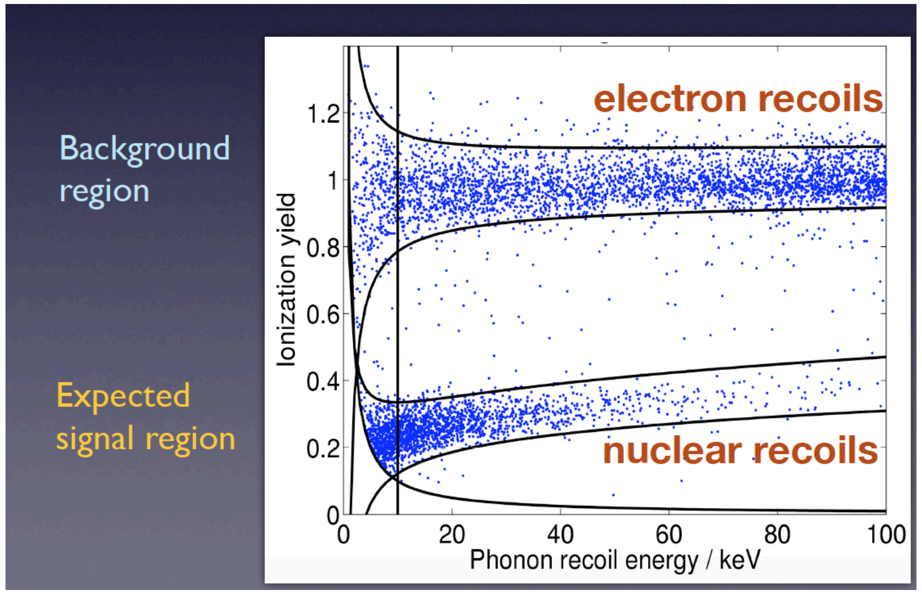
Backgrounds: external sources



- External γ's from natural radioactivity:
  - Suppression via self-shielding of the target
  - Material screening and selection
  - Rejection of multiple scatters & discrimination

- External neutrons:
  muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th contaminations



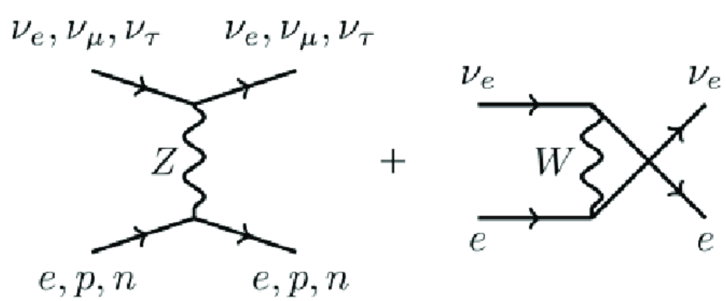


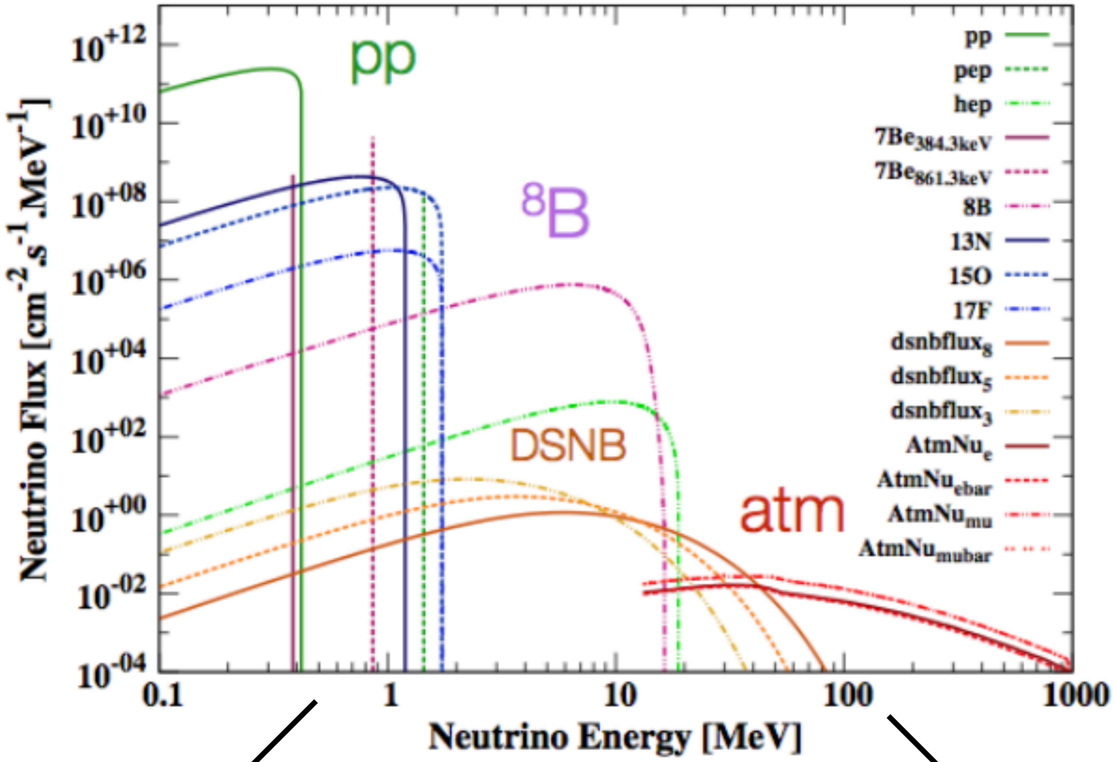
Backgrounds: internal sources

- Internal contamination in liquids:
  - ^{85}Kr: removal by cryogenic distillation/chromatography/centrifuges
  - Rn: removal using activated carbon, distillation, dust removal
  - Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*

The ultimate background from neutrinos

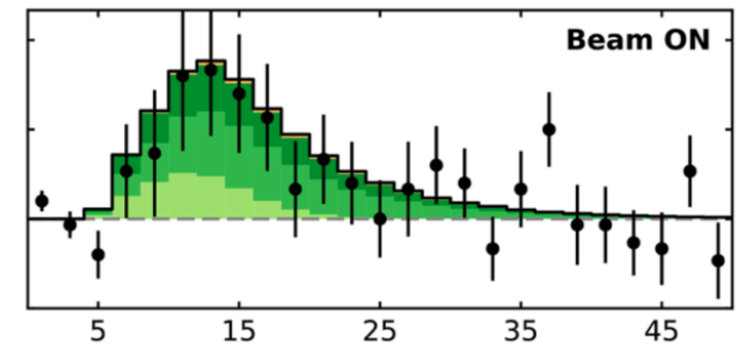
Background of today can be the signal of tomorrow !

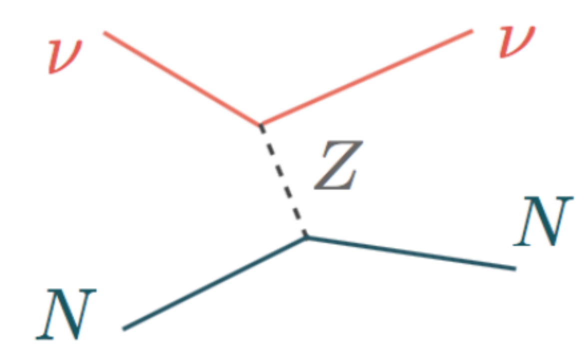




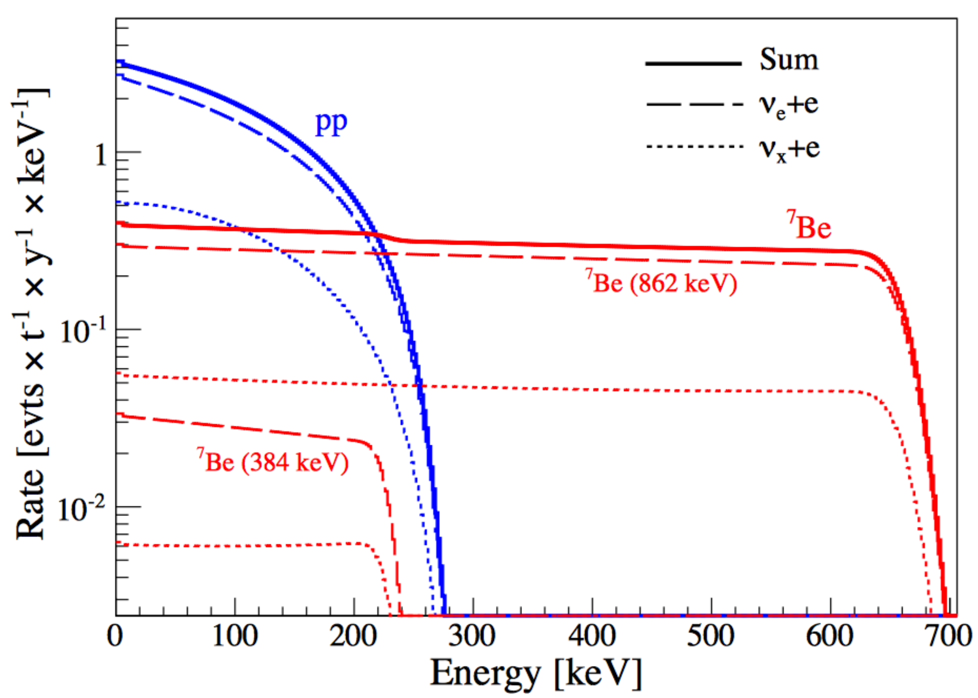
F. Ruppin et al., 1408.

COHERENT, Science, 2017

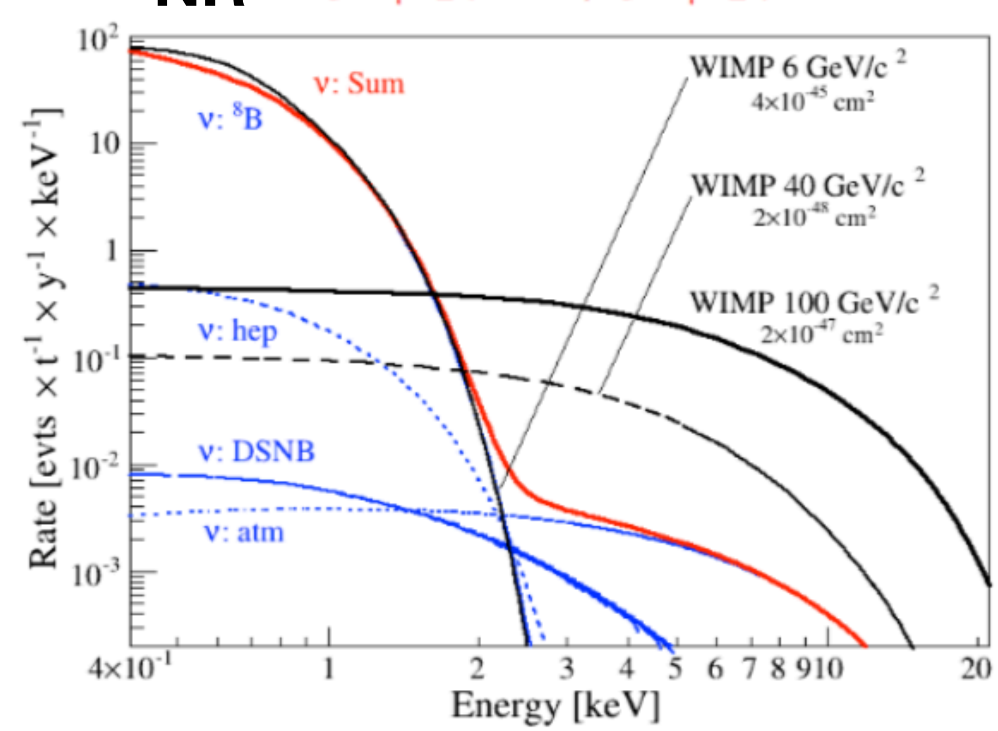




ER

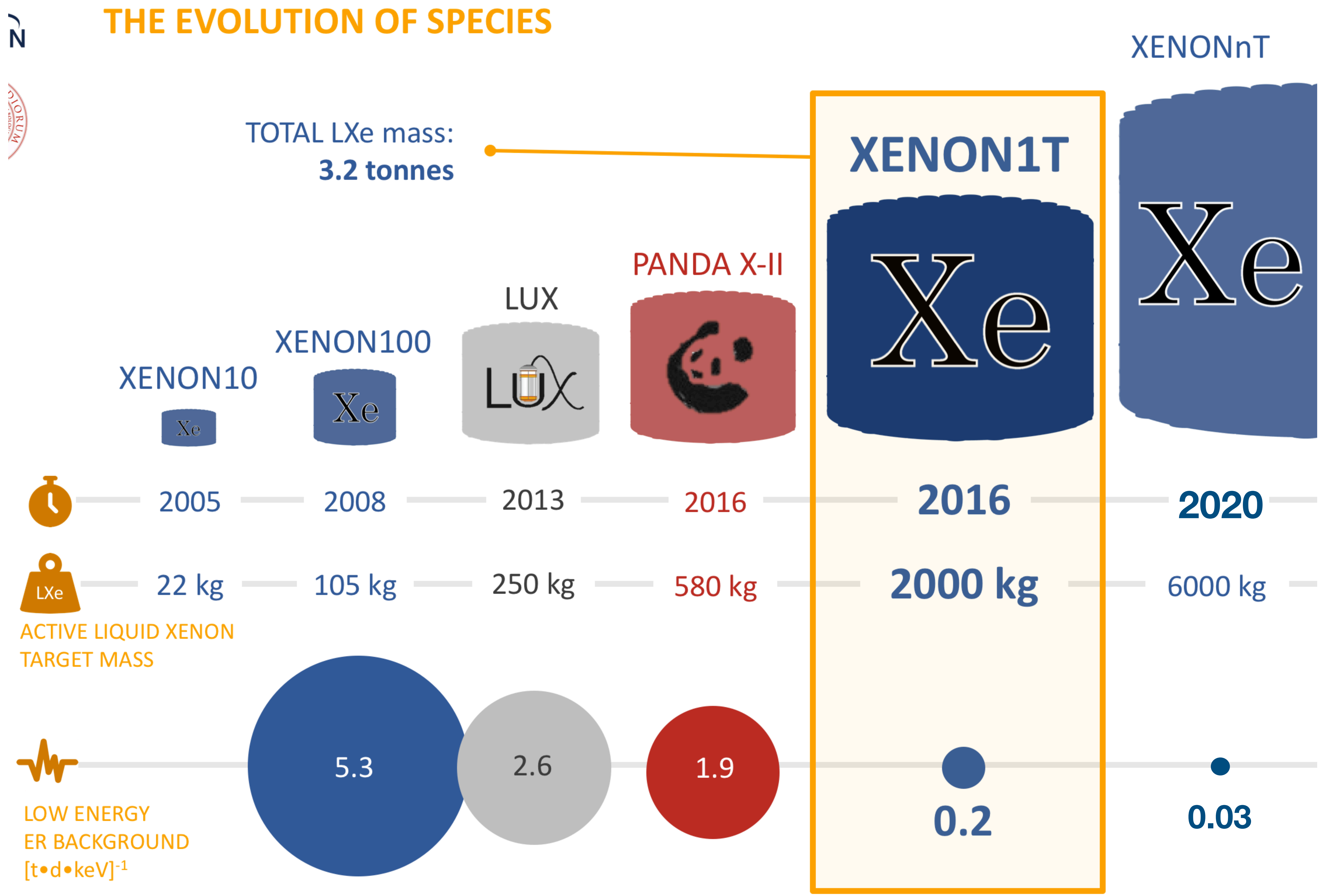


NR $\nu + N \longrightarrow \nu + N$

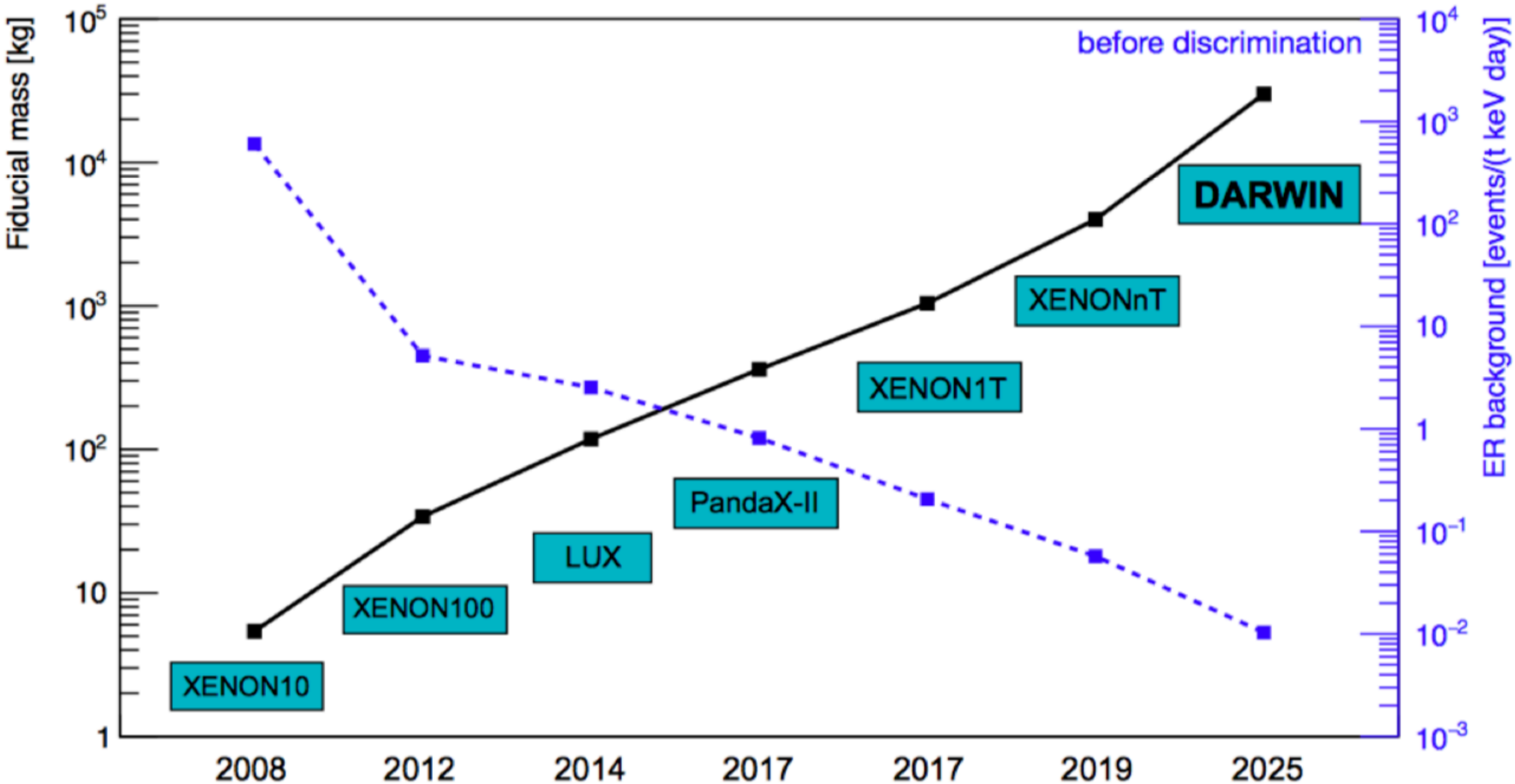


LB et al., JCAP01 (2014) 044

Evolution of LXeTPC detectors

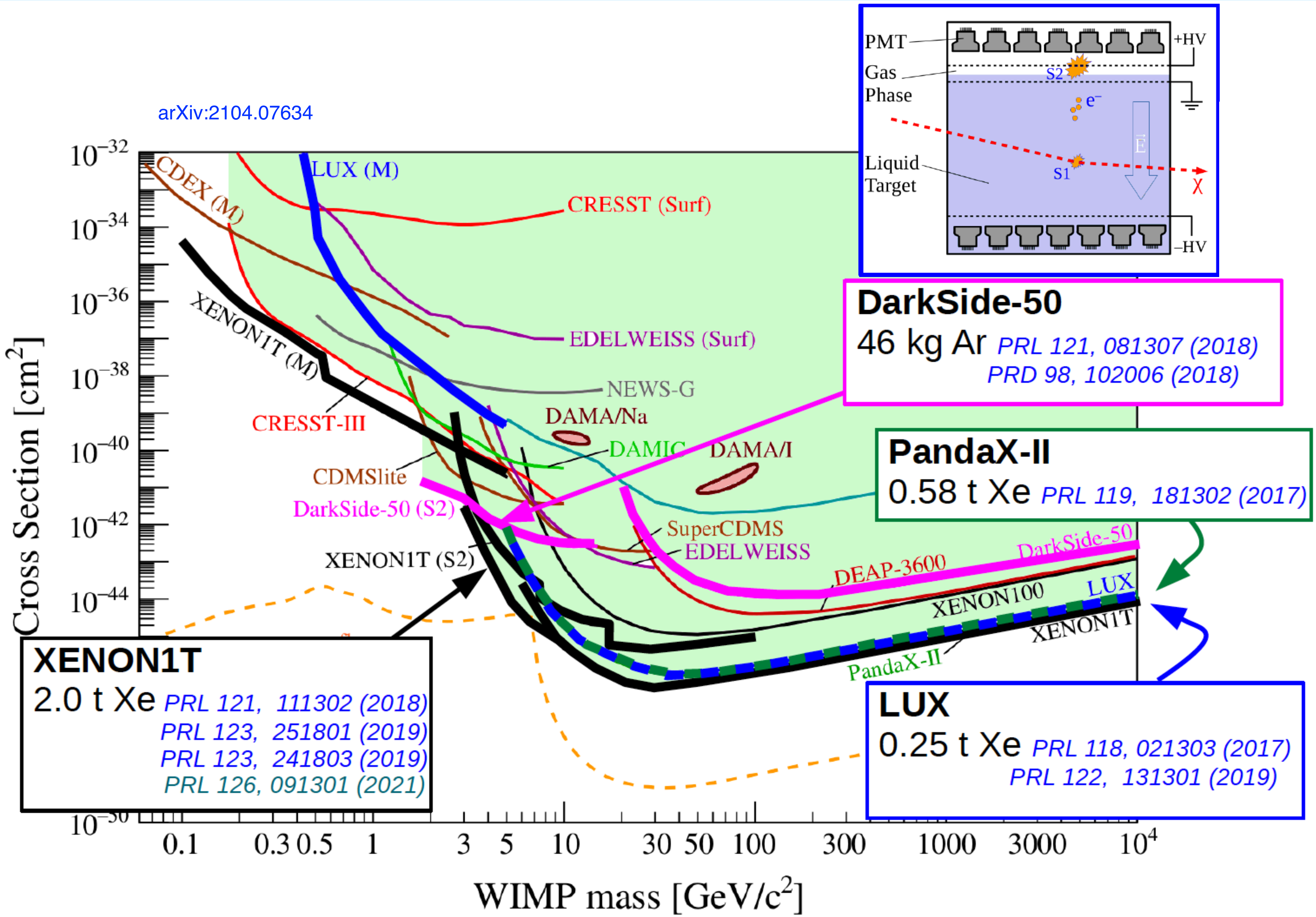


Evolution of LXeTPC detectors



(from T. Marrodan)

Summary of prev-gen Noble Liquid results



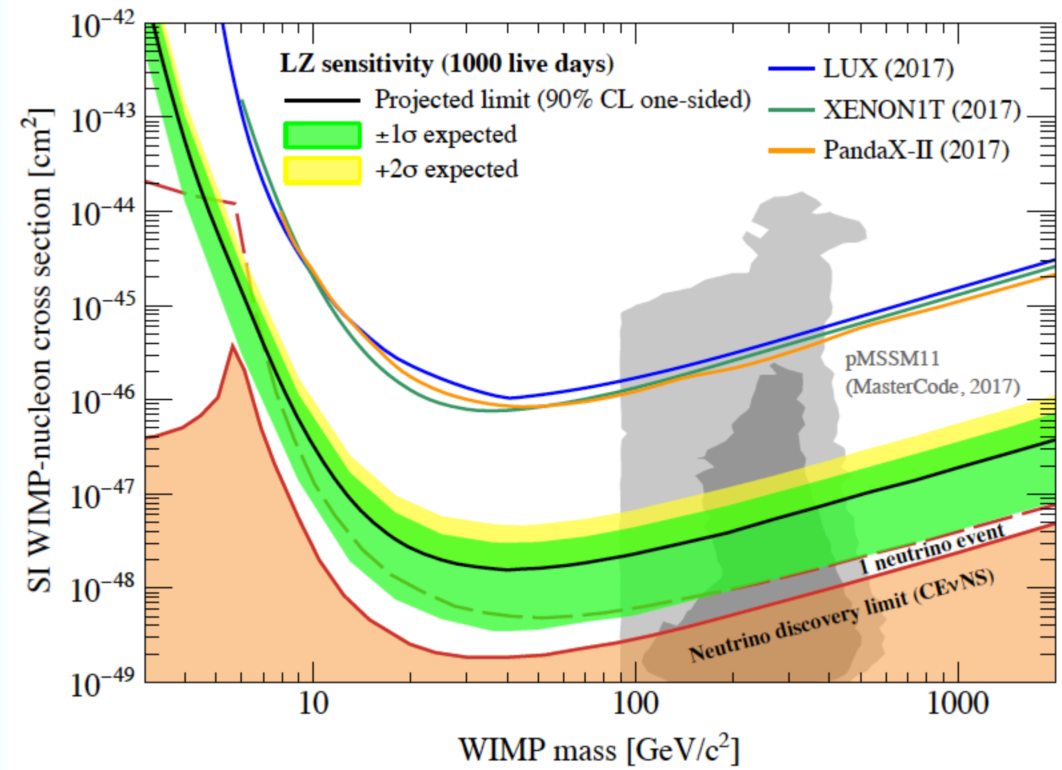
DarkSide-50
46 kg Ar *PRL 121, 081307 (2018)*
PRD 98, 102006 (2018)

PandaX-II
0.58 t Xe *PRL 119, 181302 (2017)*

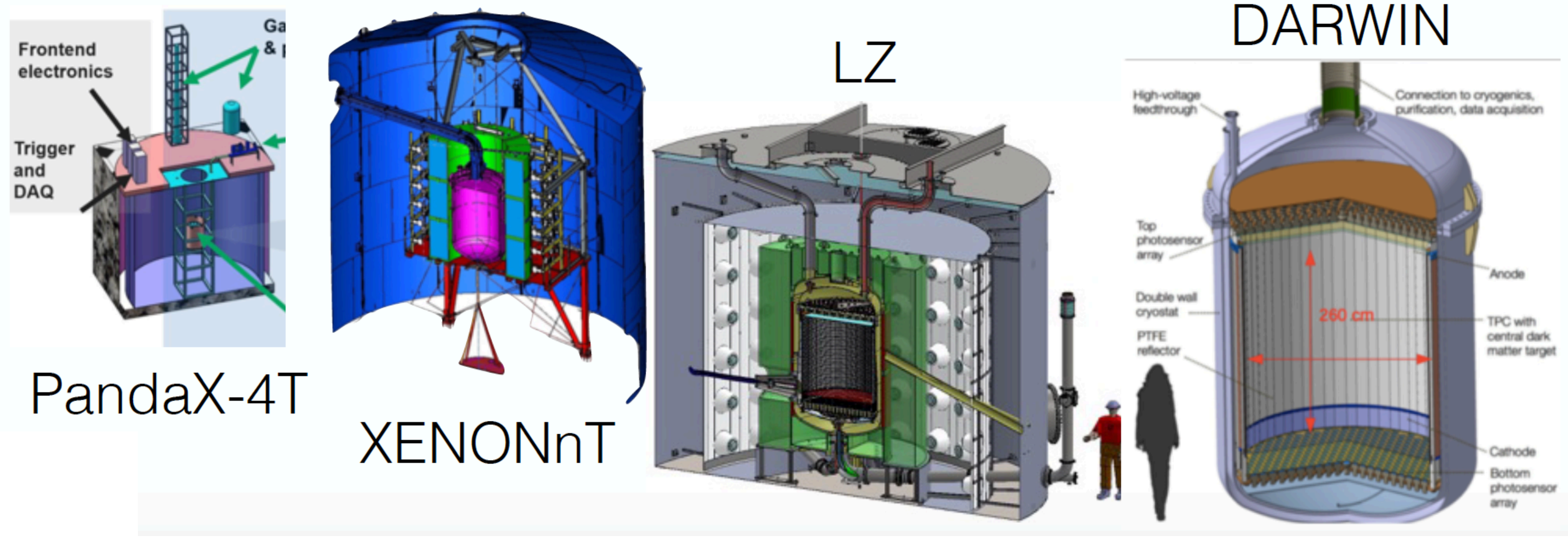
XENON1T
2.0 t Xe *PRL 121, 111302 (2018)*
PRL 123, 251801 (2019)
PRL 123, 241803 (2019)
PRL 126, 091301 (2021)

LUX
0.25 t Xe *PRL 118, 021303 (2017)*
PRL 122, 131301 (2019)

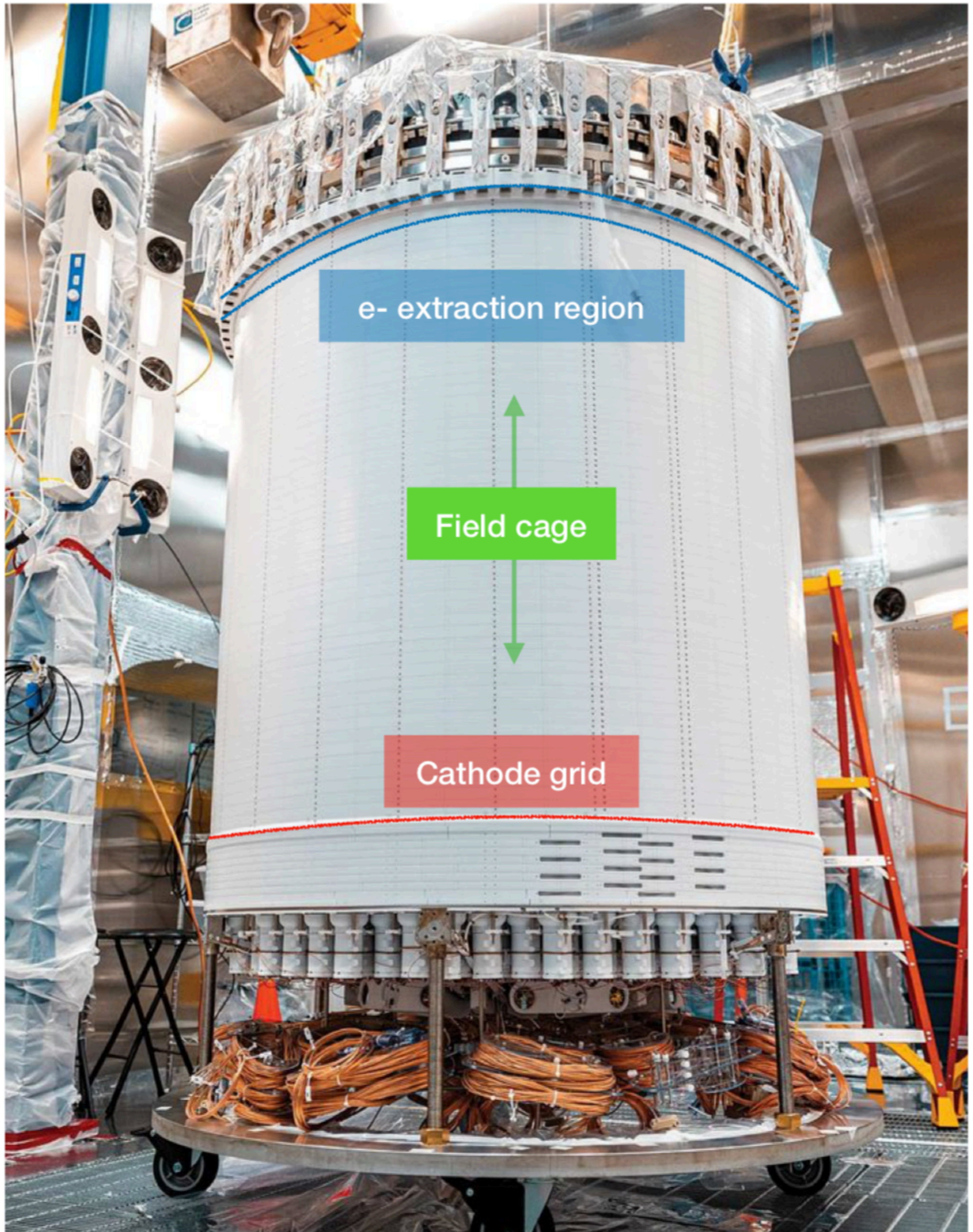
Current and next steps: LXe TPCs



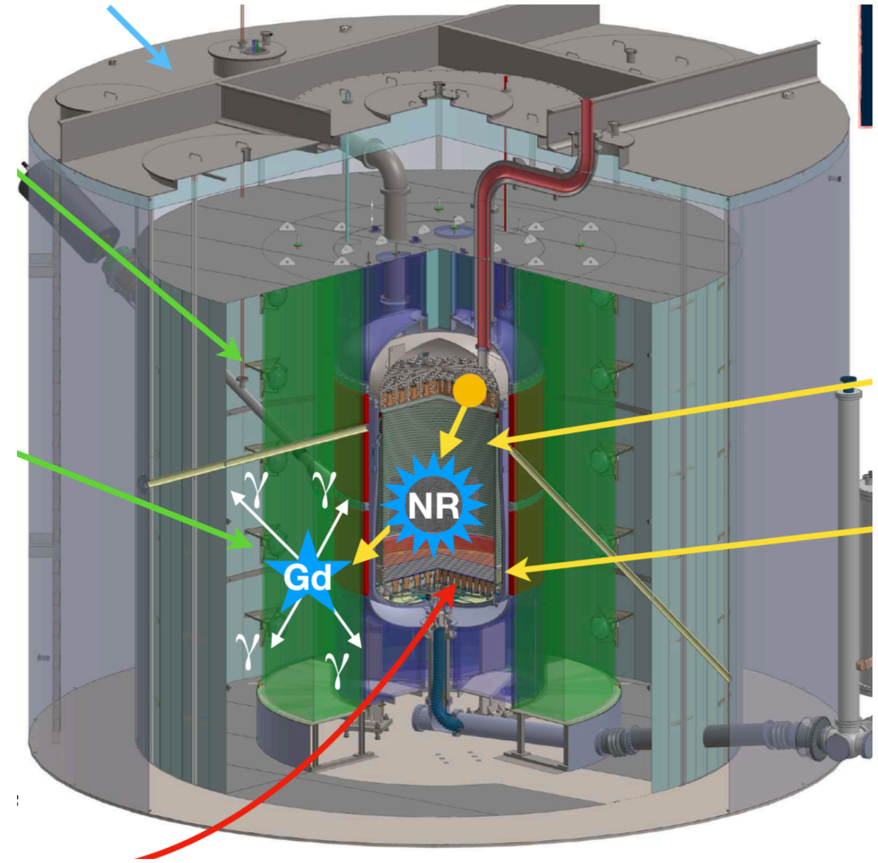
- Results from running experiments and secondary results from completed ones
- XENONnT: 2019 8t, 4t fiducial
- PandaX-4T: 2020 4t
- LZ:2020 10t, 5.6t fiducial
- DARWIN:2024 50t



LUX-ZEPLIN @SURF (US)



Construction in radon reduced clean room at surface assembly lab completed in 2019



- PTFE field cage maximizes light collection efficiency.
- 494 3" PMTs in total - Hamamatsu R11410-22.
- Woven electrode grids to generate electric-field in the active xenon region (7 tonnes of LXe)
- Nominal cathode voltage of -50 kV (drift field ~ 300 V/cm)
- ~ 2 tonne instrumented skin region between the outside of the TPC and the inner wall of the cryostat vessel.
- First (not blinded) results presented in July '22

LUX-ZEPLIN new results (July 2022)

Rn level:

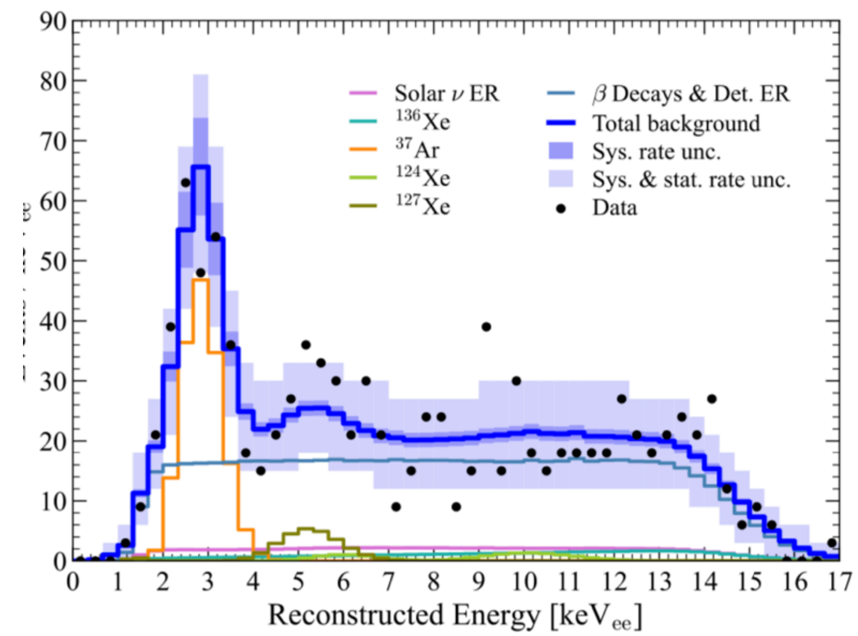
Rn222 (μBq/kg)	Pb214 (μBq/kg)	Po214 (μBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

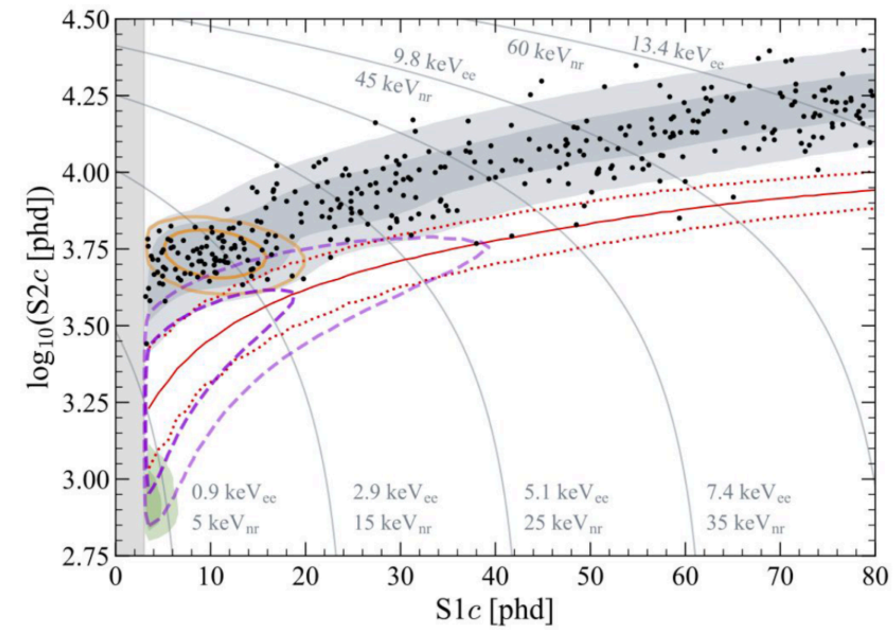
- Science Run 1 - ~3.5 month run, exposure is 60 live days x 5.5 tonnes fiducial
  - (7t active in TPC+2t Xe skin+17t Gd-loaded LS)

arXiv:2207.03764

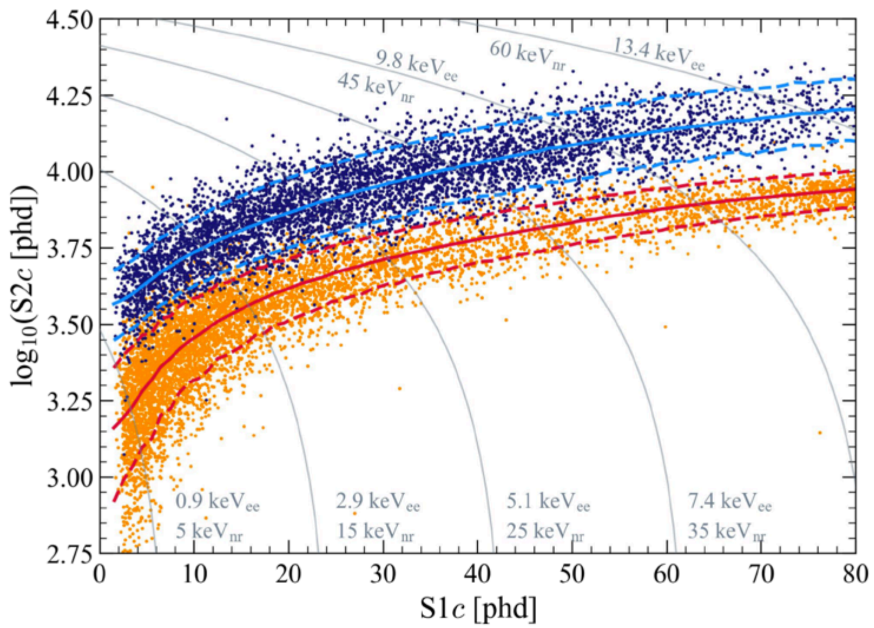
nVeto performances:

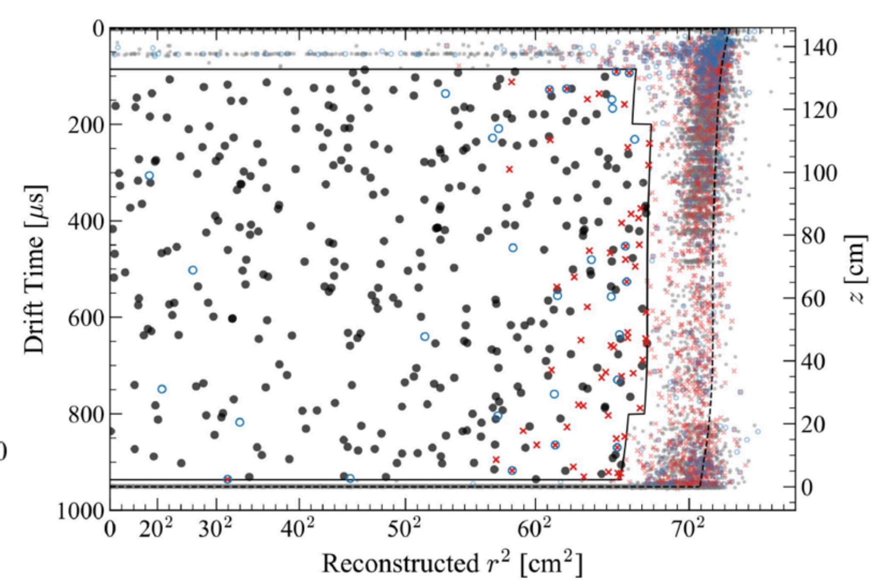
- OD neutron tag settings:
  - ≥ 200 keV
  - Δt ≤ 1200 μs
- Single-scatter neutron tagging efficiency [measured]: 88.5±0.7%
- Livetime hit: 5%

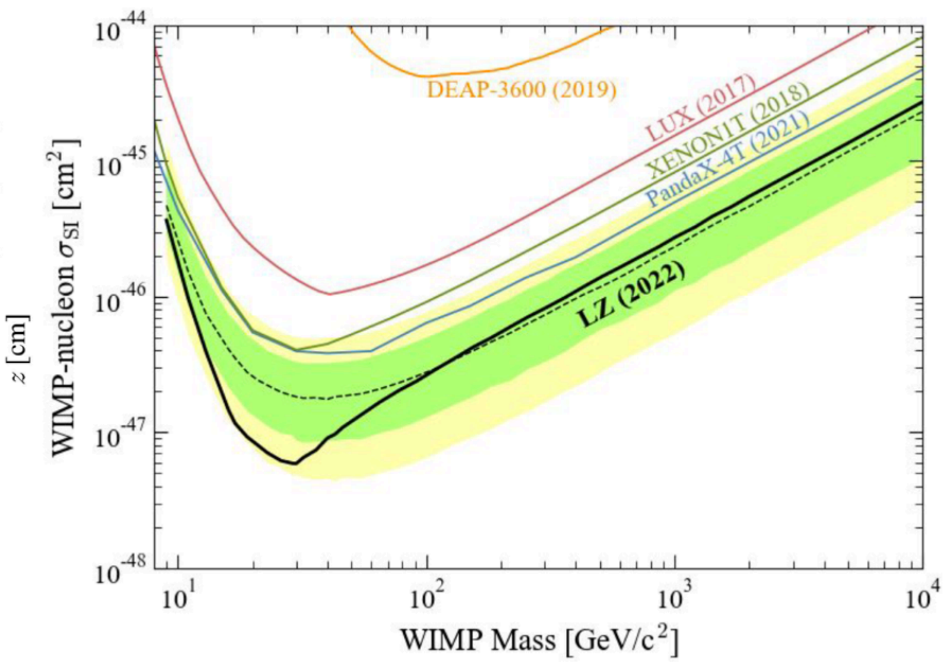




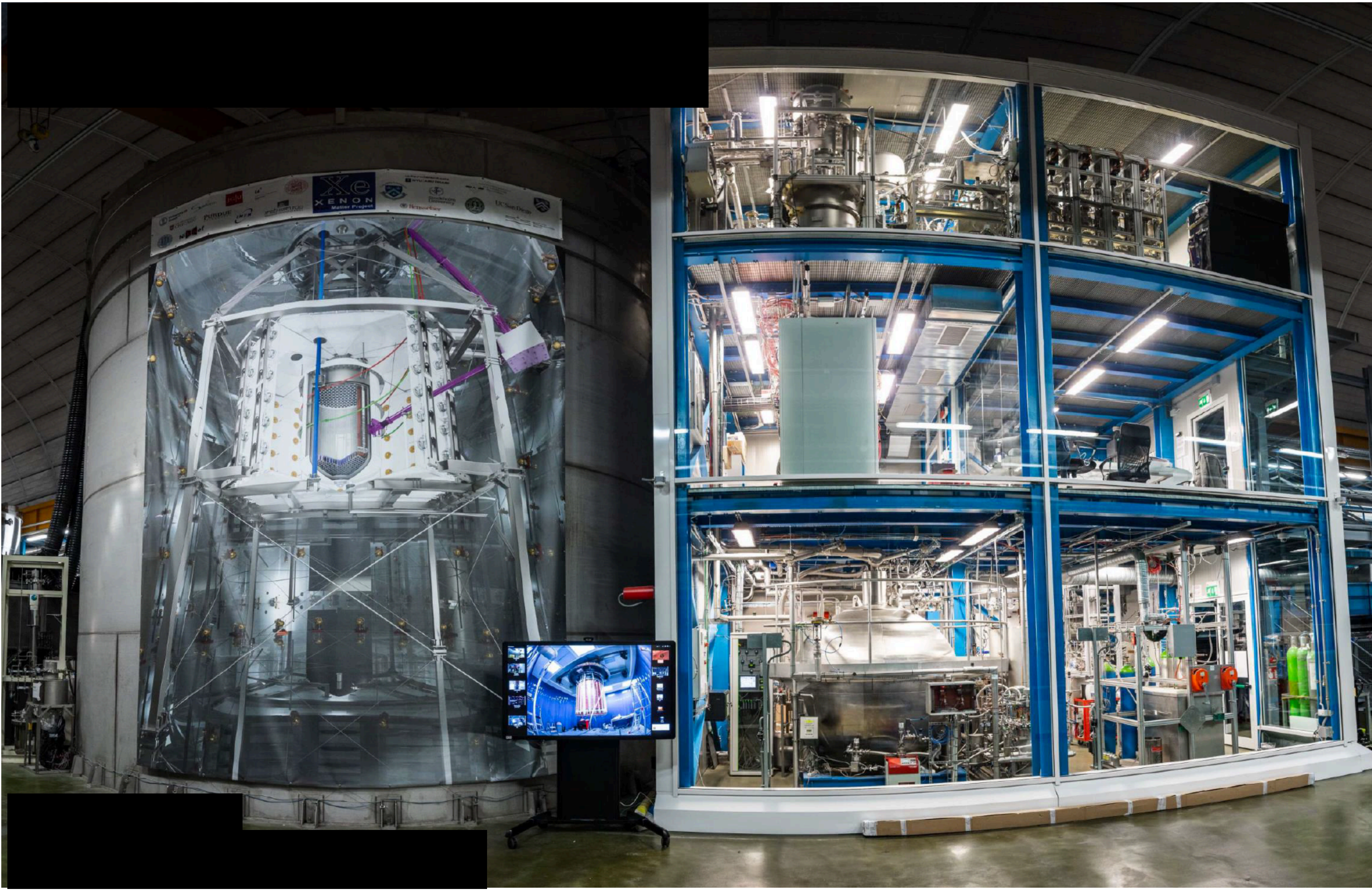
ER and NR calibrations:







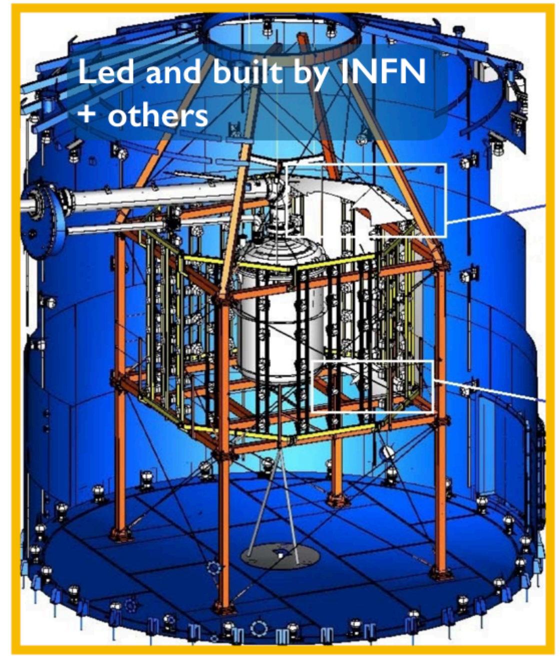
XENONnT @LNGS



XENONnT

Larger TPC

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



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

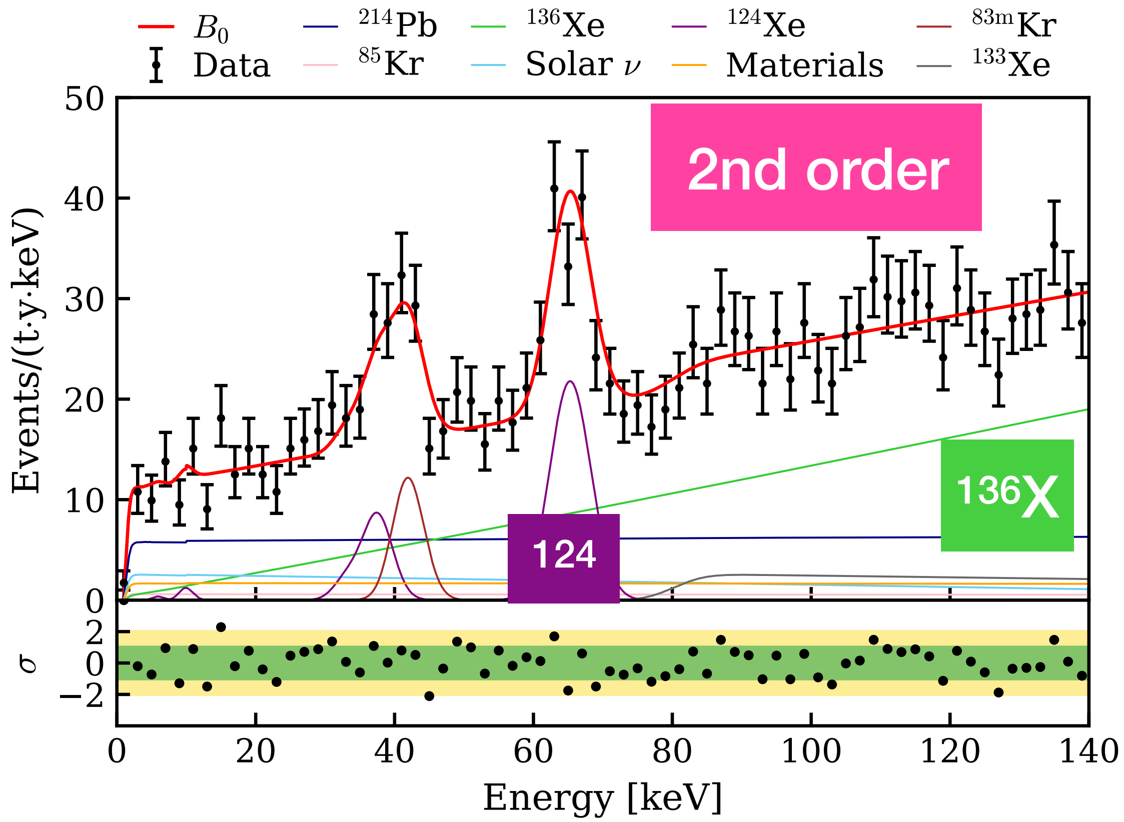
LXe purification

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

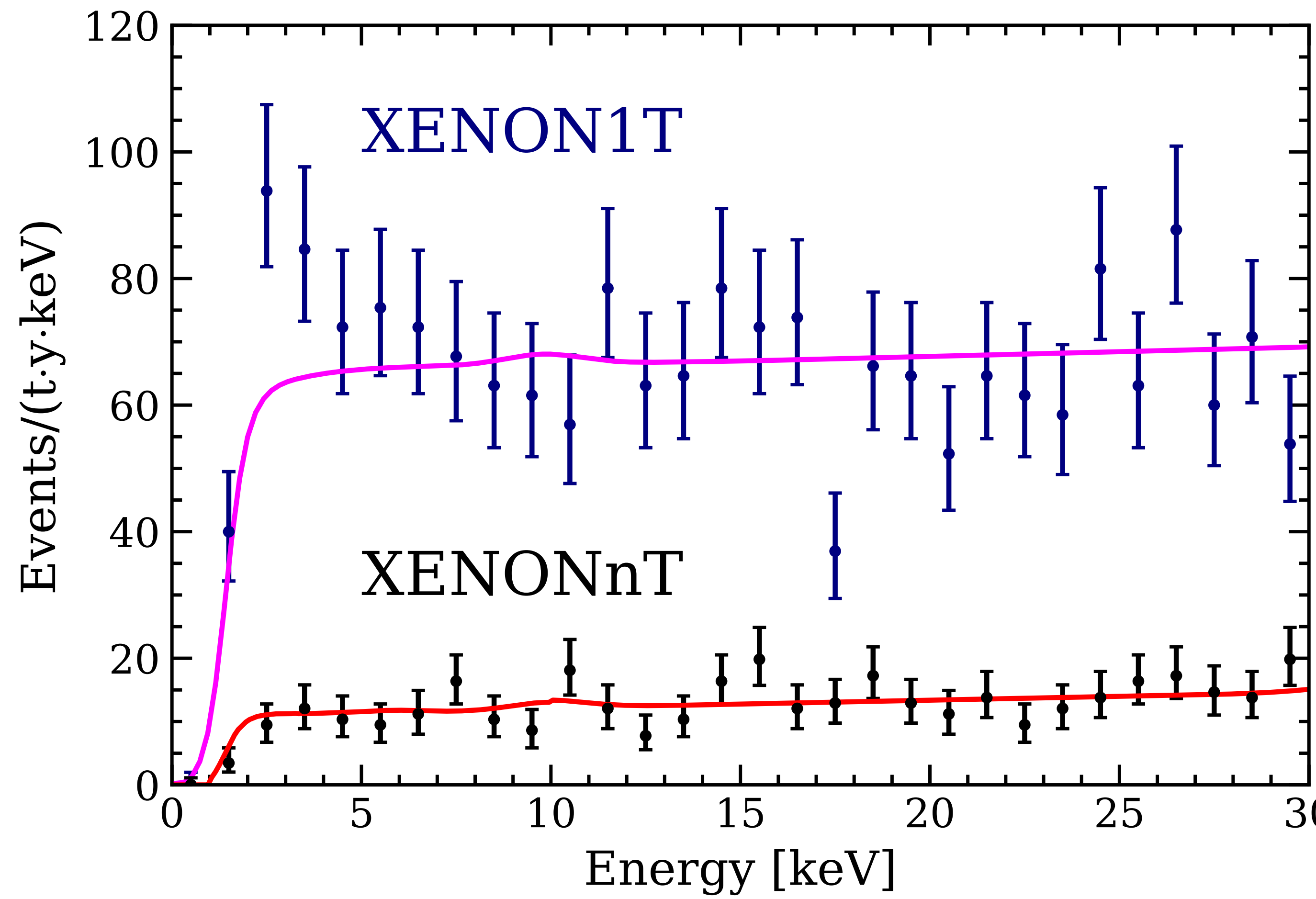
- Completed construction in 2020
- Commissioning in first half of 2021
- Currently in Science Run

XENONnT new results (July 2022)

Energy spectrum dominated by 2nd-order weak processes



Zoom in the low-energy region: no discrepancy from the bkg model



XENONnT key performances in SR0:
> 10 ms **electron lifetime,**
$1.77 \pm 0.01\ \mu$Bq/kg **radon concentration**

arXiv:2207.11330, published on PRL

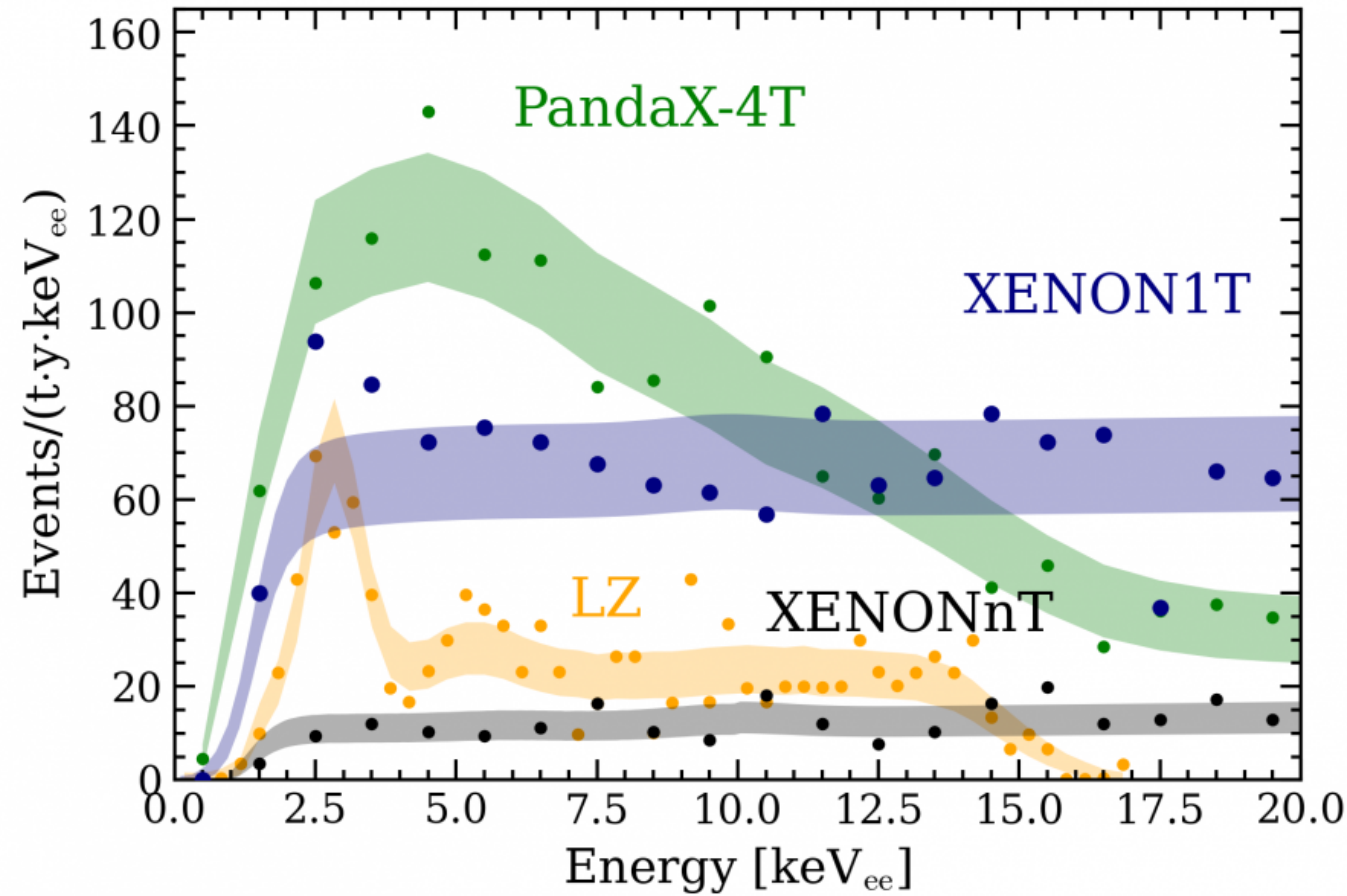
Excellent agreement with our background model.
Lowest ER background ever achieved in a DM experiment:
(16.1 ± 0.3) events/(t × yr × keV)

No trace of ^{3}H, even in the Tritium-enhanced run

Set new best limits on Solar Axions, ν magnetic moment, ALPs, …

Nuclear recoil data are still blinded
WIMP search results soon

Comparison of the ER bkg in LXe detector



XLZD -> next-gen LXe detector

XLZD Consortium

- MOU between LZ, XENON, DARWIN
- Successful XLZD meeting 27-29 June 2022 at Karlsruhe Institute of Technology
- https://xlzd.org/
- White paper (2203.02309)

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

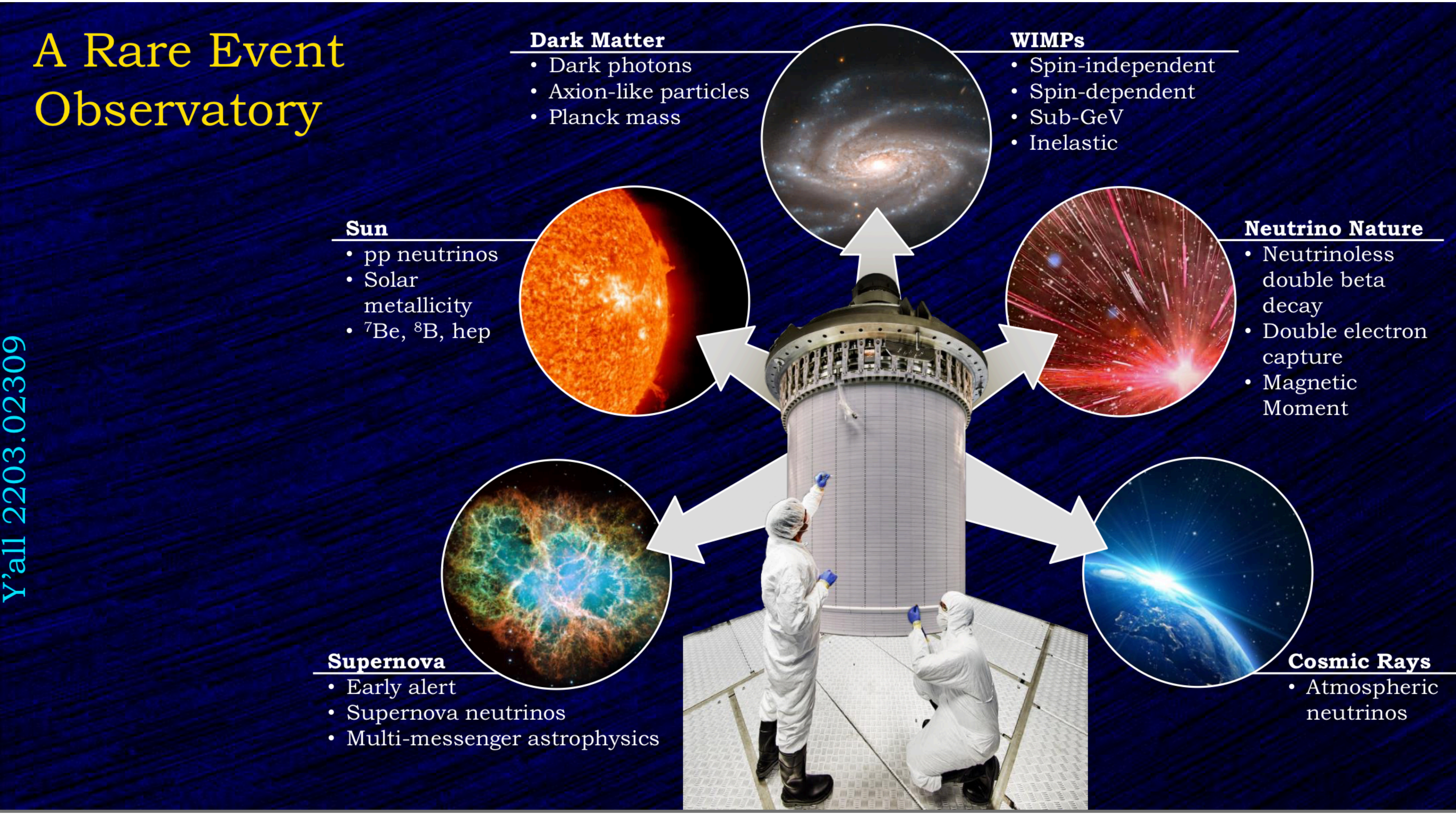
SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9] A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2] T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[20] B. Antunovic,[21,22] E. Aprile,[23] H.M. Araújo,[16] J.E. Armstrong,[24] F. Arneodo,[25] M. Arthurs,[14] P. Asadi,[26] S. Baek,[27] X. Bai,[28] D. Bajpai,[29] A. Baker,[16] J. Balajthy,[30] S. Balashov,[31] M. Balzer,[32] A. Bandyopadhyay,[33] J. Bang,[34] E. Barberio,[35] J.W. Bargemann,[36] L. Baudis,[5] D. Bauer,[16] D. Baur,[37] A. Baxter,[38] A.L. Baxter,[9] M. Bazyk,[39] K. Beattie,[40] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltrame,[42] M. Benabderrahmane,[25] E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert,[43,40] T.P. Biesiadzinski,[1,2] A.R. Binau,[9] R. Biondi,[45] Y. Biondi,[5] H.J. Birch,[14] F. Bishara,[46] A. Bismark,[5] C. Blanco,[47,19] G.M. Blockinger,[48]

SLAC A. Fan 20

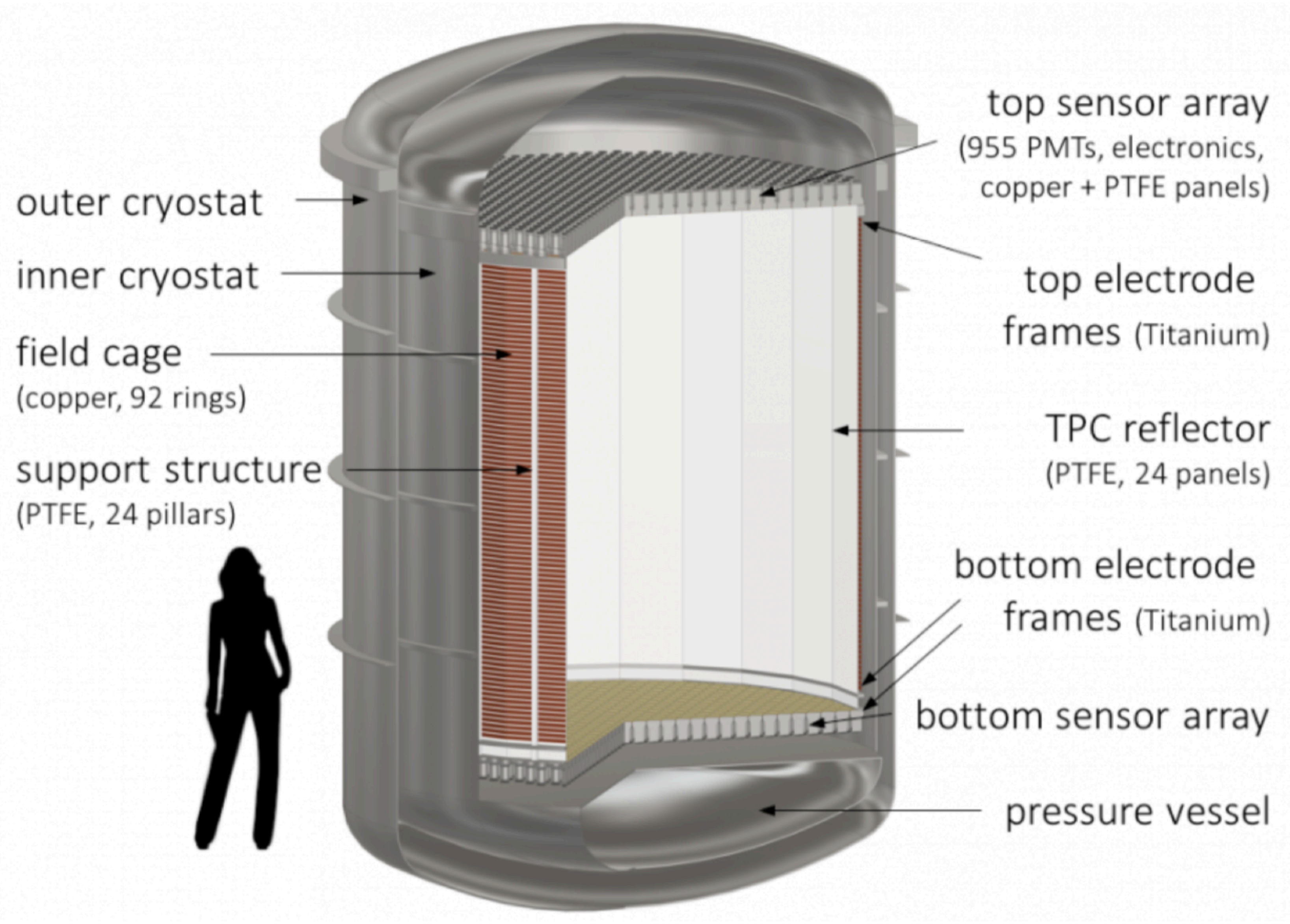
XLZD -> next-gen LXe detector

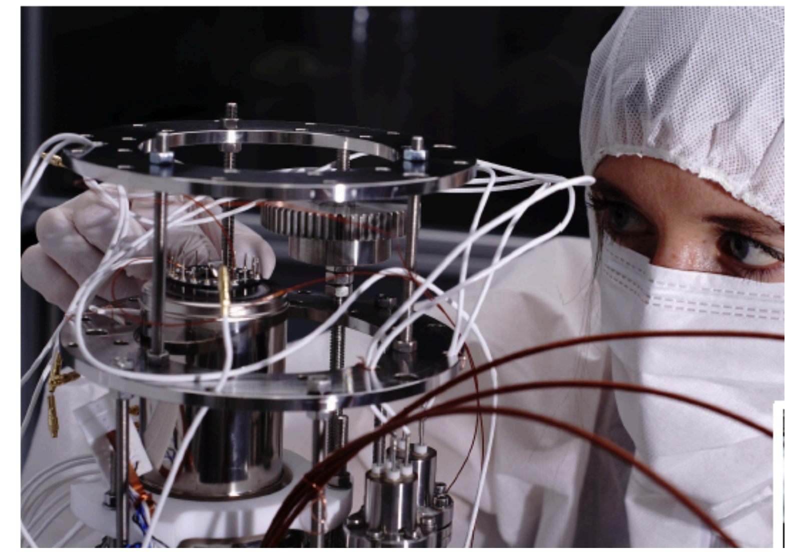


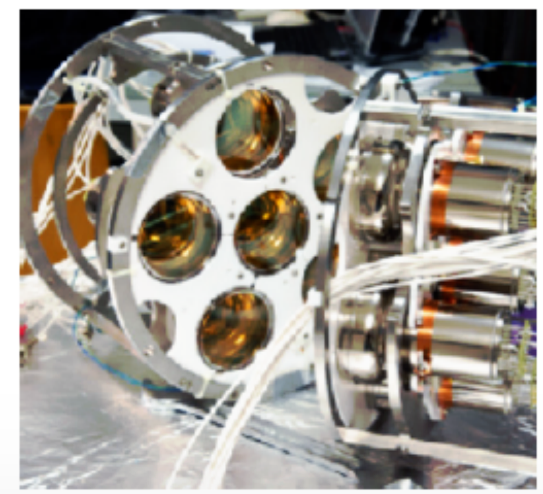
Y'all 2203.02309

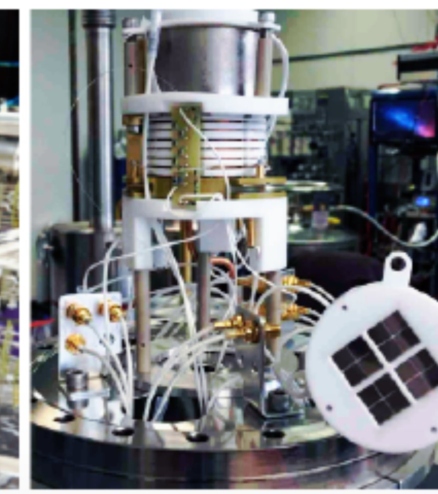
XLZD -> next-gen LXe detector (DARWIN)

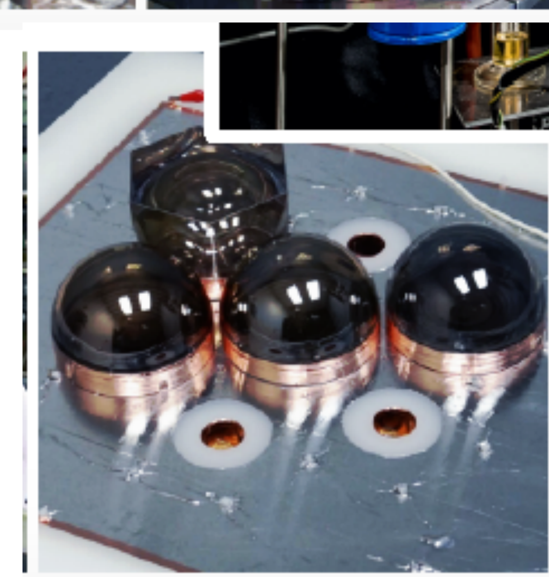
Various ongoing R&D on Rn, photosensors, electrodes











- Baseline design for a large liquid xenon dark matter detector
- TPC of about 2.6 m ⌀ & 2.6 m drift length
- 50 t LXe total mass (40 t inside the TPC)
- Decrease the Rn content by (another) factor 10

Main Challenges for next-gen LXe detectors

- **Xenon procurement**

  (costs and availability complicated by the Russia-Ukraine crisis)

- **Xenon handling**

  (cooling and purification already fit the requirements)

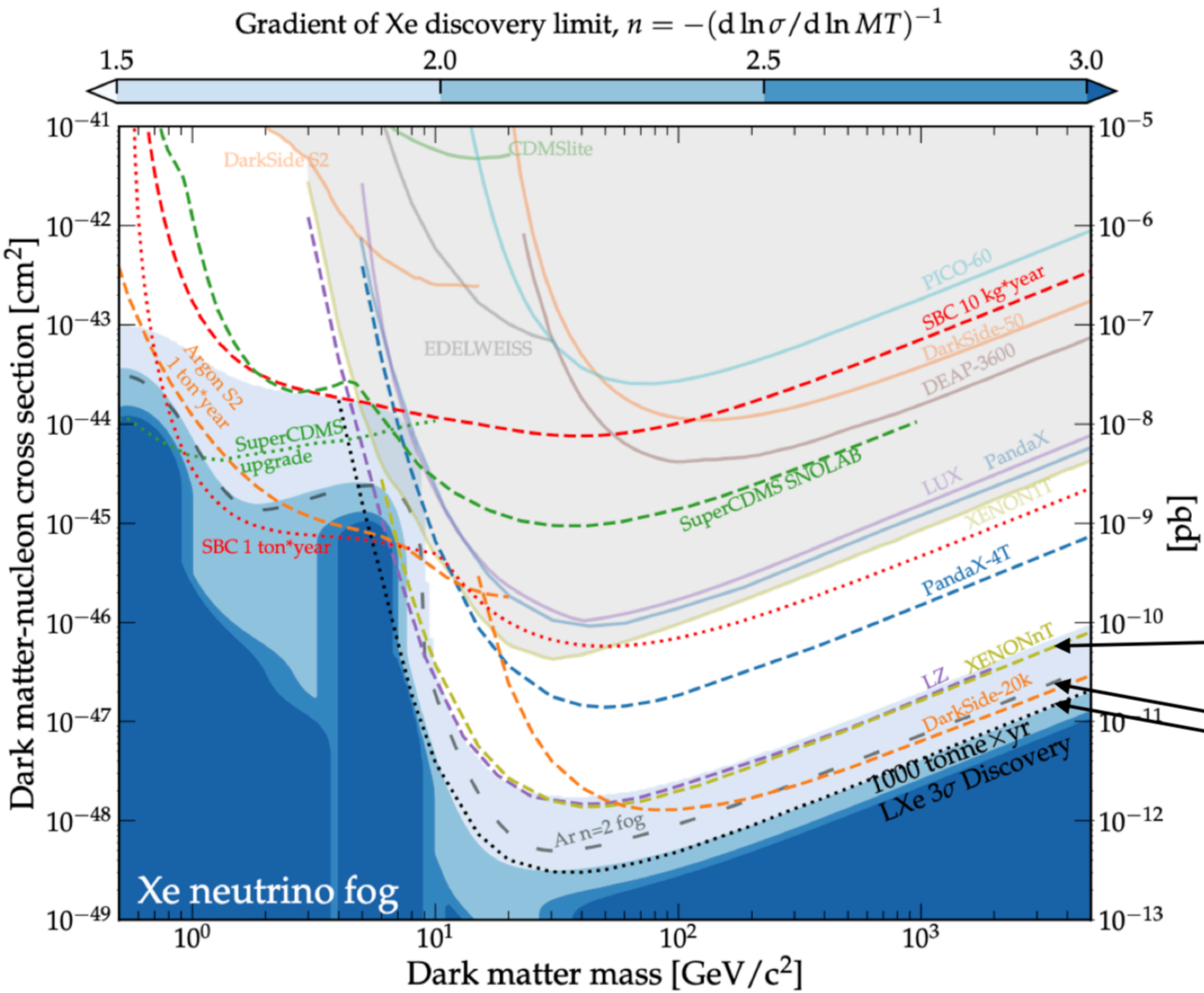
- **Rn removal**
- **Photosensors**
- **Electrodes**

} **(various ideas on the table, R&D ongoing)**
see A.D. Ferella speed talk

- **Neutron Veto**

  (see A. Mancuso speed talk)

Direct Detection of WIMPs by 2030?



nT, LZ projections

DarkSide-20k

DARWIN

Speed Talks on Liquid Detectors - IFD

SpeedTalks (7'):

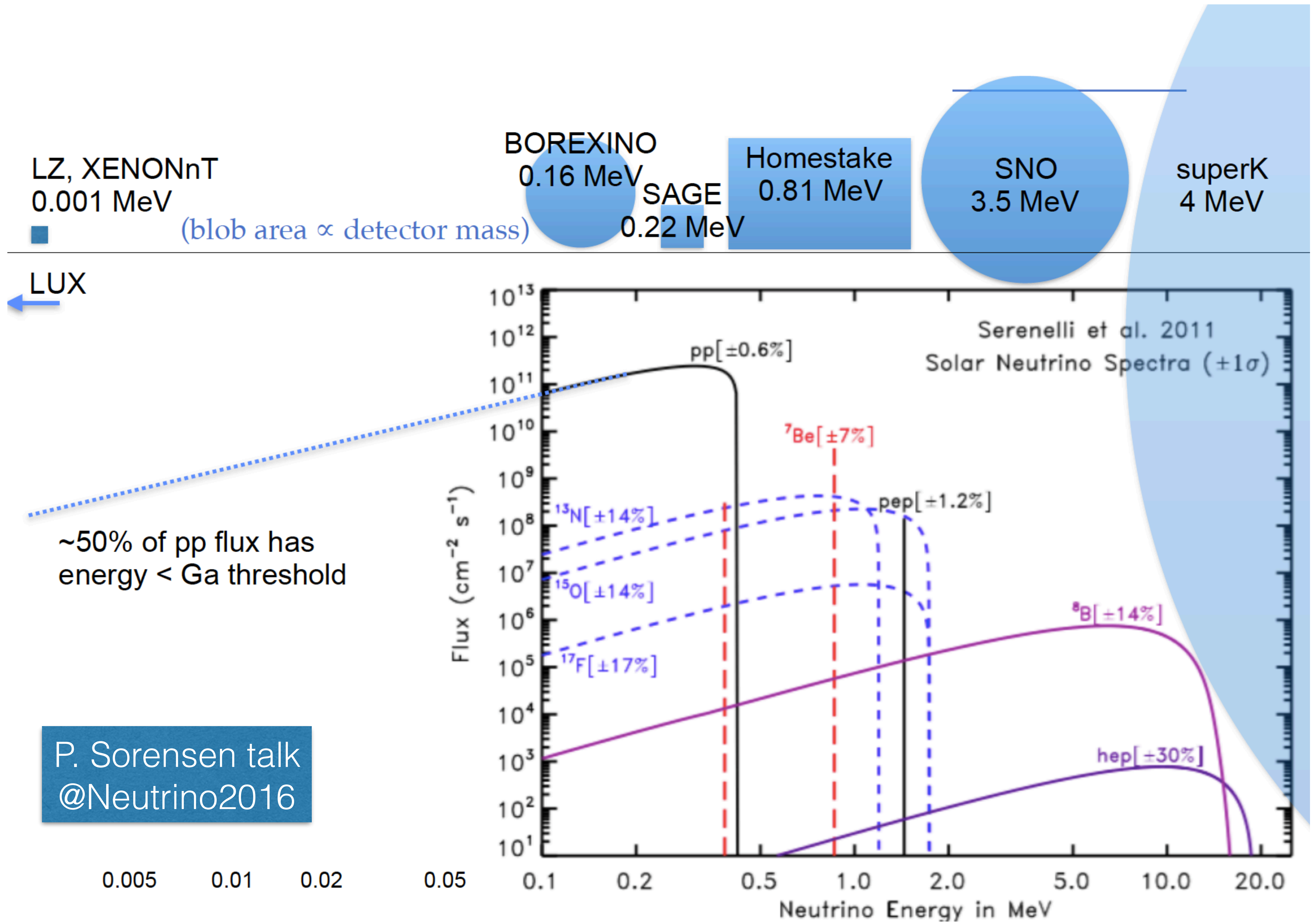
- F. Di Capua (Dark matter search with liquid argon)
- A. Falcone (SiPM per basse temperature)
- M. Torti (Tecnologia Power over fiber per Photon Detectors a temperature criogeniche)
- A. D. Ferella (New ideas on Photosensors & Electrodes for DARWIN, the Next-Gen LXe TPC)
- A. Mancuso (Gd-loaded water Cherenkov detector as neutron veto for rare event searches)
- F. Ferraro (Detection of Cherenkov light in liquid scintillators)
- A. Simonelli (ANDIAMO, an innovative acoustic neutrino telescope proposal)

Thanks !

Marco Selvi
INFN Bologna

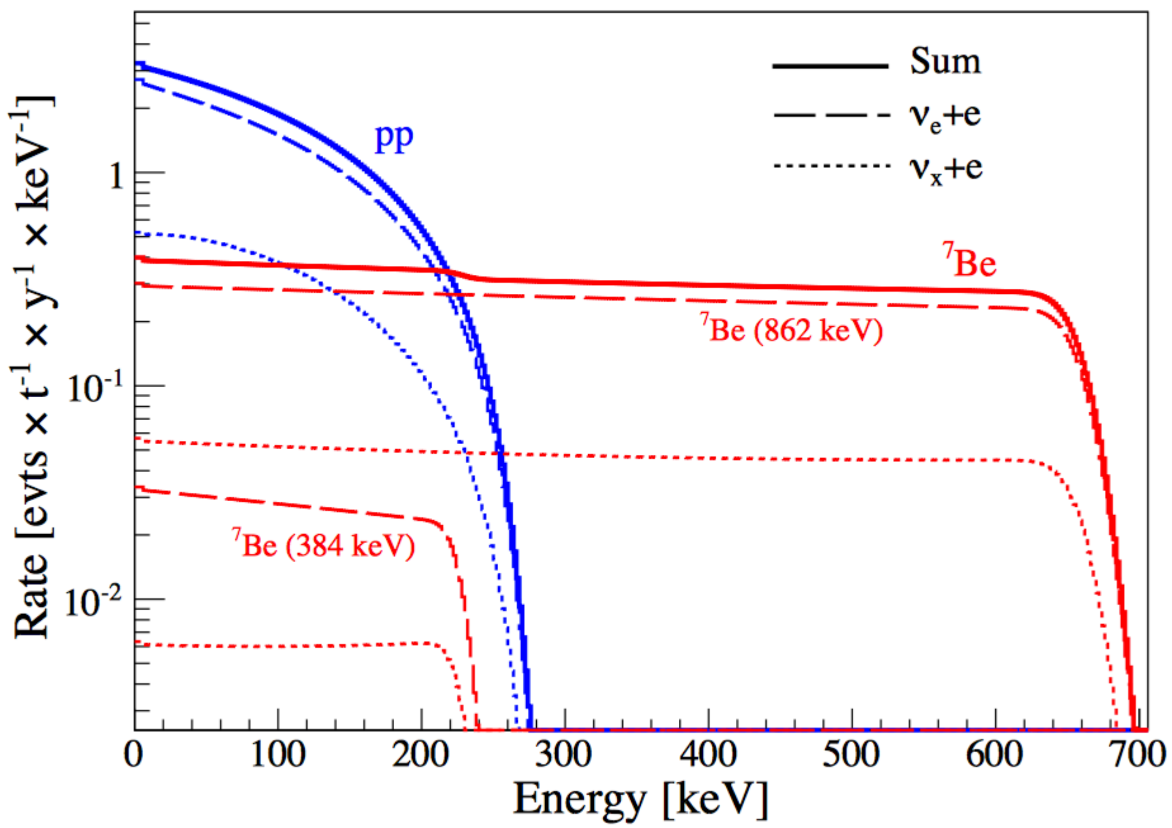
IFD2022, 18 October 2022, Bari

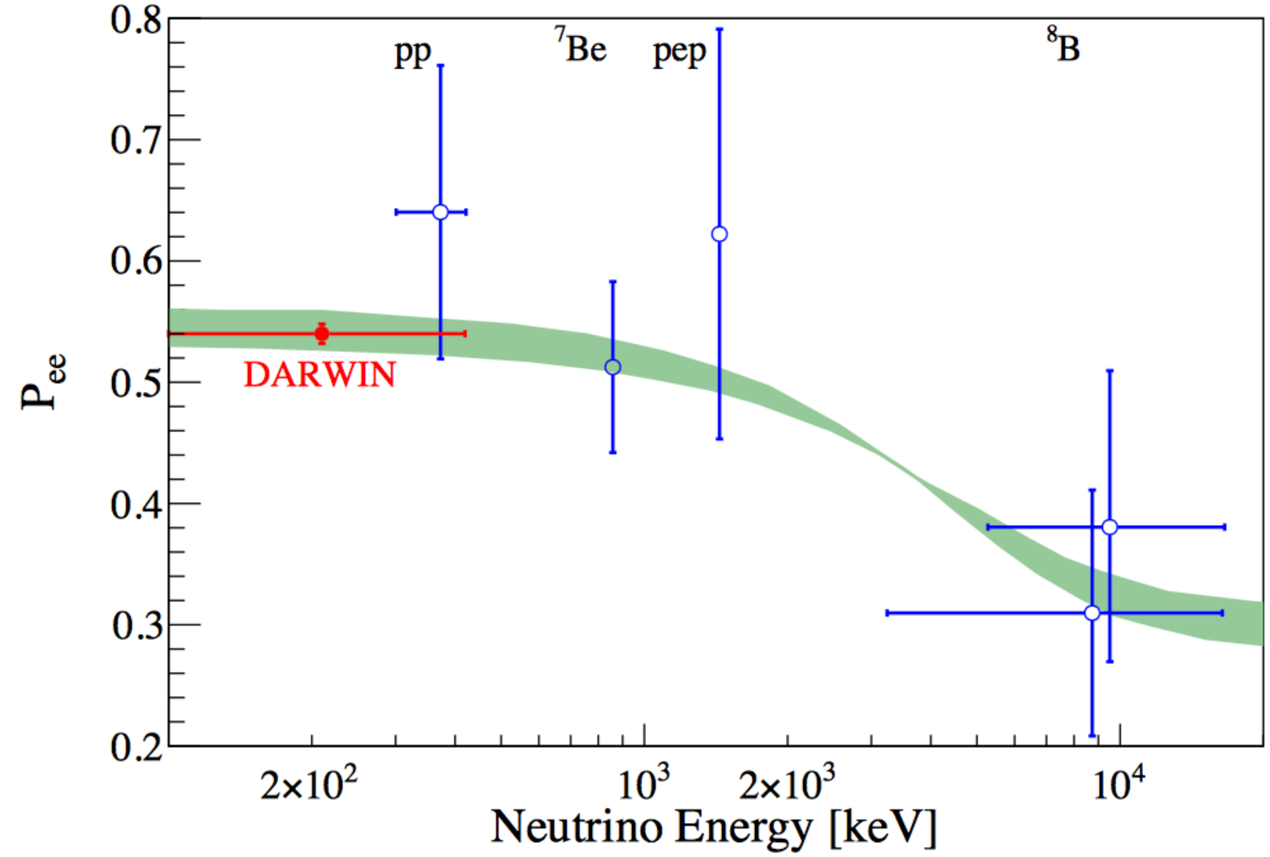
Solar neutrino & detectors



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

Neutrinos from SN

$\chi\nu$

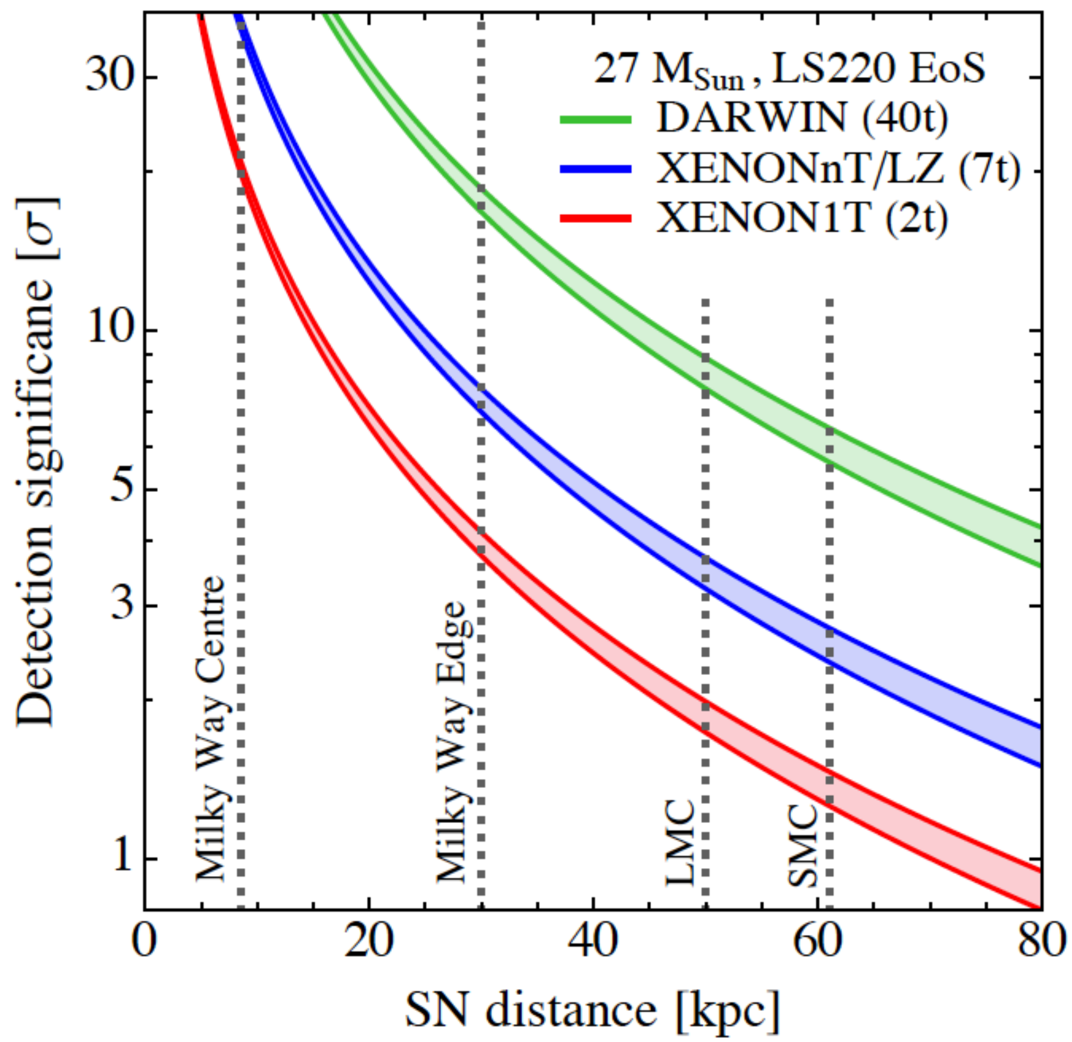
R. Lang, C. McCabe, S. Reichard, M.S., I. Tamborra,
"Supernova neutrino physics with xenon dark matter detectors", Phys. Rev. D 94 (2016) no.10, 103009.

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



0nu2beta search in DARWIN

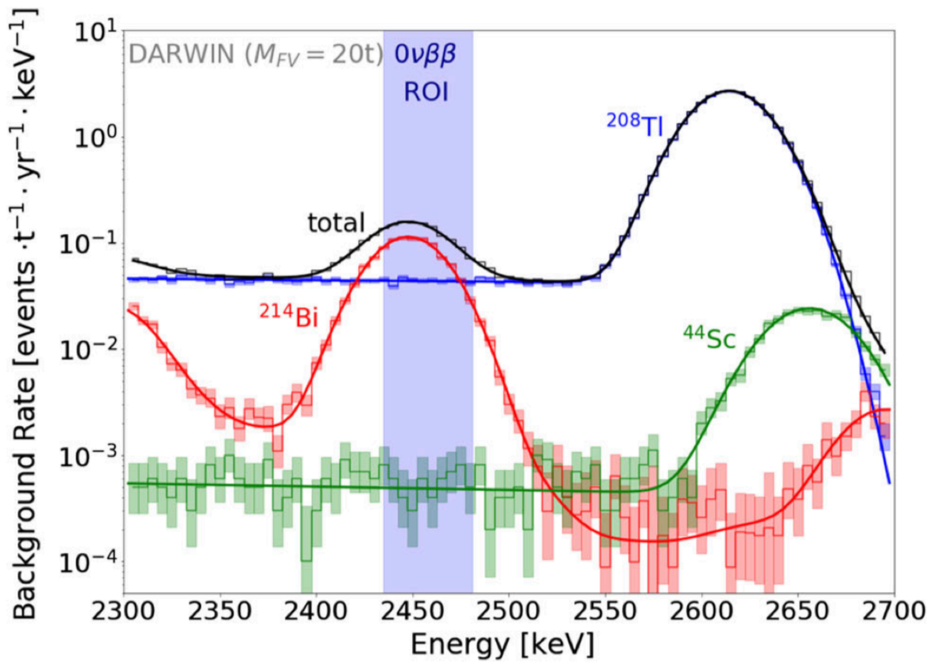
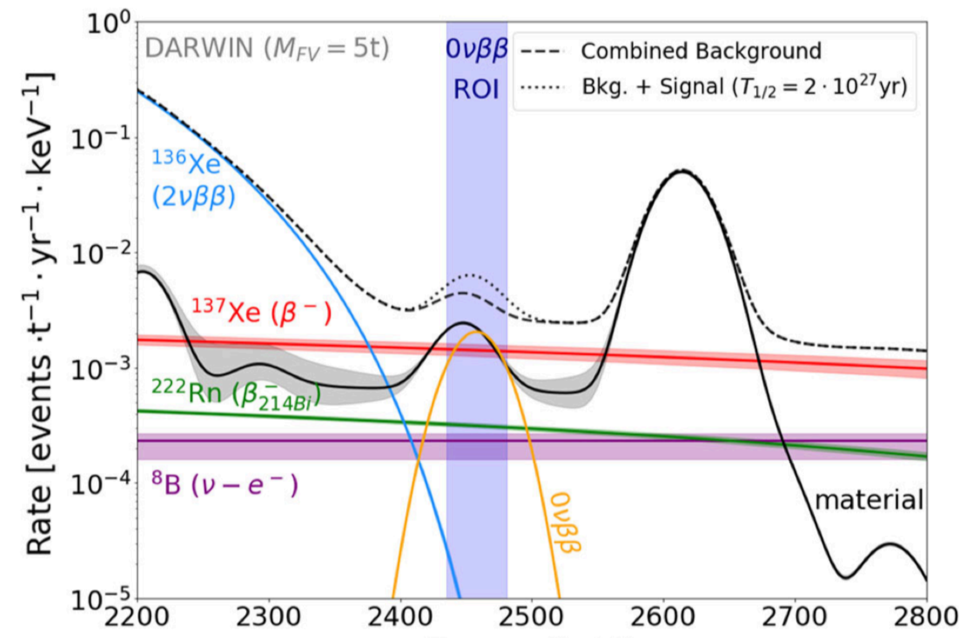
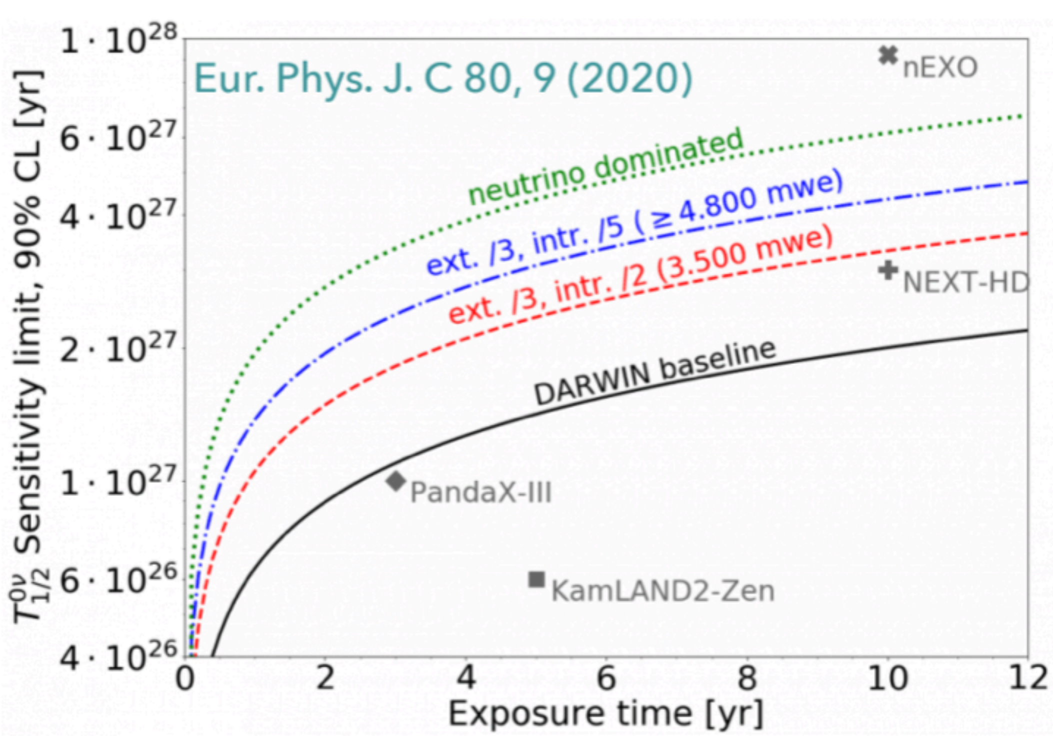


Fig. 5 Composition of the material-induced external background in the 20 t fiducial volume. Top: Relative contribution to the background in the $0\nu\beta\beta$-ROI by material and isotope. Bottom: Background spectra by isotope with the corresponding model fits. The relative contributions and spectral shapes are representative for smaller fiducial volumes





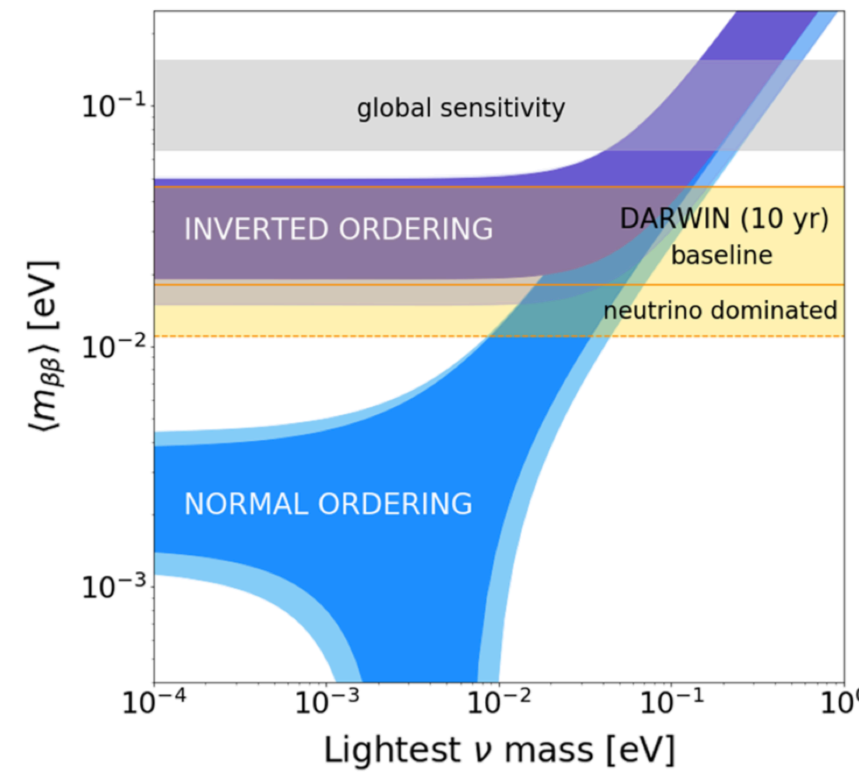
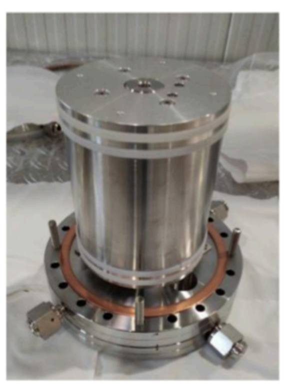


Fig. 9 Effective Majorana neutrino mass vs. lightest neutrino mass. The sensitivity reach after 50 t×years of exposure is shown for the baseline and the optimistic neutrino dominated scenario. The horizontal bands stem from the range of nuclear matrix elements [36]. Global sensitivity according to [38], oscillation parameters from [39,40]

Magnetically-coupled piston pump for high-purity gas applications

Gas purification

- Magnetically coupled piston pumps
- Stable performance with a flow of 100 slpm and compression of 1.5 bar



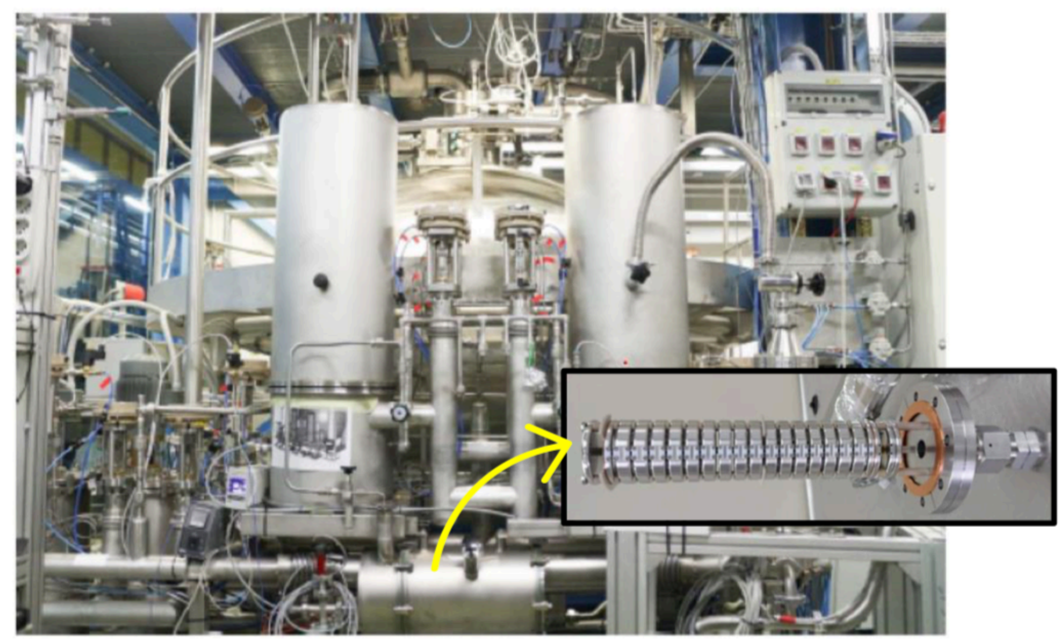
monolithic stainless-steel

Alternate polarity permanent neodymium bar magnets

Liquid purification

Liquid-phase purification for multi-tonne xenon detectors

- Novel liquid-phase purification system powered by cryogenic pumps
- Copper-impregnated spheres (Q5) for intense purification and ST707 pills filter for data taking period



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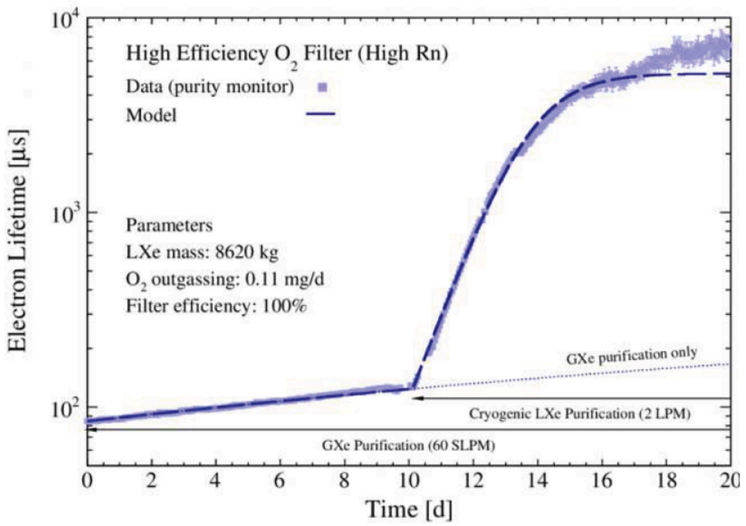
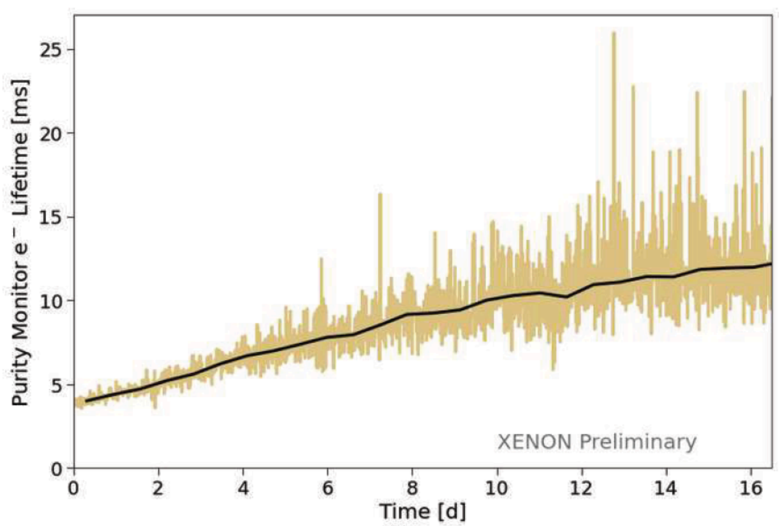


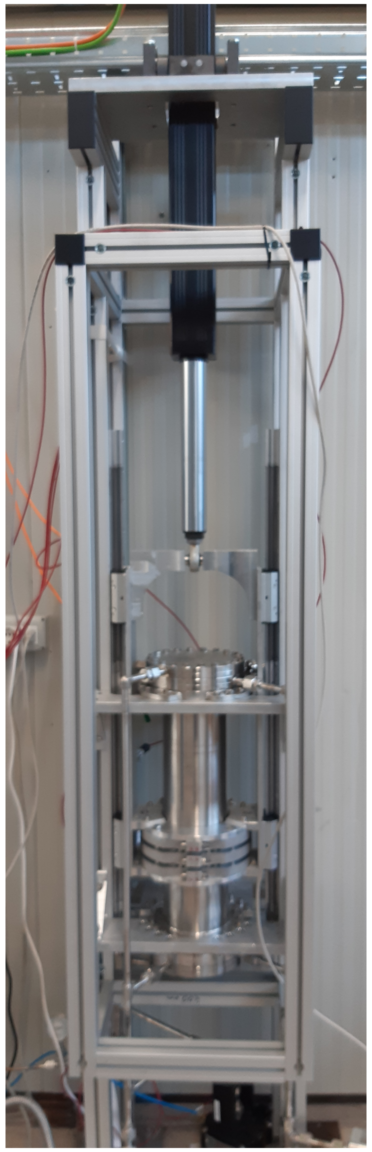


XENON1T

- 0.6 ms in SR1 ($0.9 \times \Delta t$ max)
- 1 ms after pump upgrade in SR2 ($1.4 \times \Delta t$ max)

Contributo anche del gruppo INFN-LNGS sia nella pompa Barber-Nichols per il ricircolo dello xenon liquido, sia per la seconda magnetic piston pump per il ricircolo in gas, realizzata custom al LNGS.

- High-flux purification (around 350 kg/h)
- Electron lifetime from 100 µs to 5 ms within 5 days (0.65 ms in XENON1T)
- e-lifetime during SR0 > 10 ms



XENONnT performances: Kr/Ar and Rn

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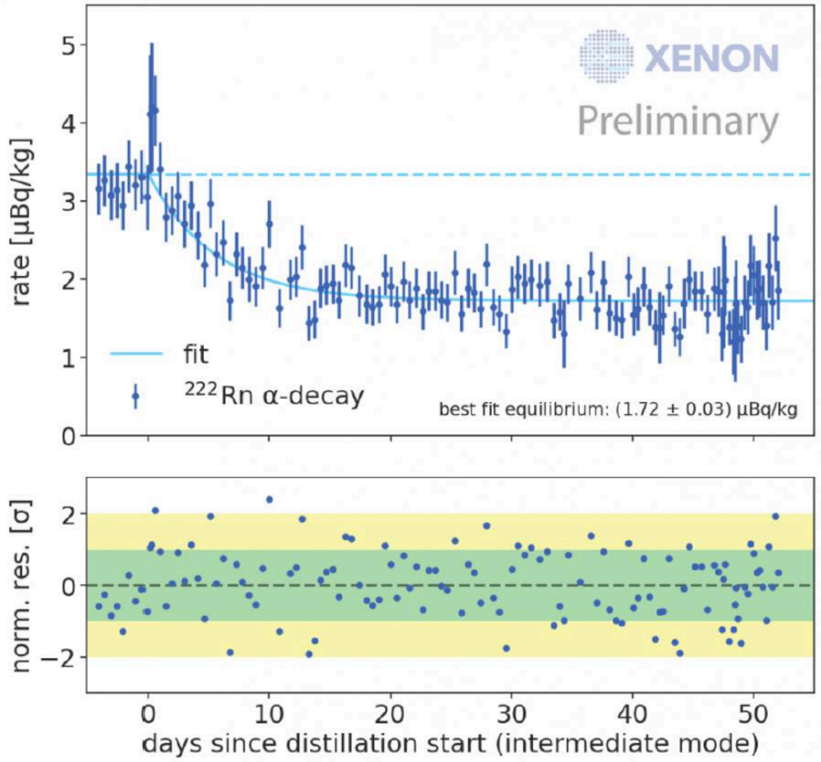
Radon distillation

Design, construction and commissioning of a high flow radon removal system for XENONnT

- Novel distillation column to separate Rn from Xe in the gas phase thanks to its lower vapor pressure
- 1.7 μBq/kg ^{222}Rn achieved, expected further reduction to reach XENONnT goal of 1 μBq/kg



Krypton distillation

Application and modeling of an online distillation method to reduce krypton and argon in XENON1T

- Kr/Ar distillation based on their higher vapor pressure compared to Xe at -96 °C (goal 100 ppq)
- Inherited from XENON1T