PSI Colloquium, Dec 7, 2023

Detecting collisions of Dark Matter with ordinary matter

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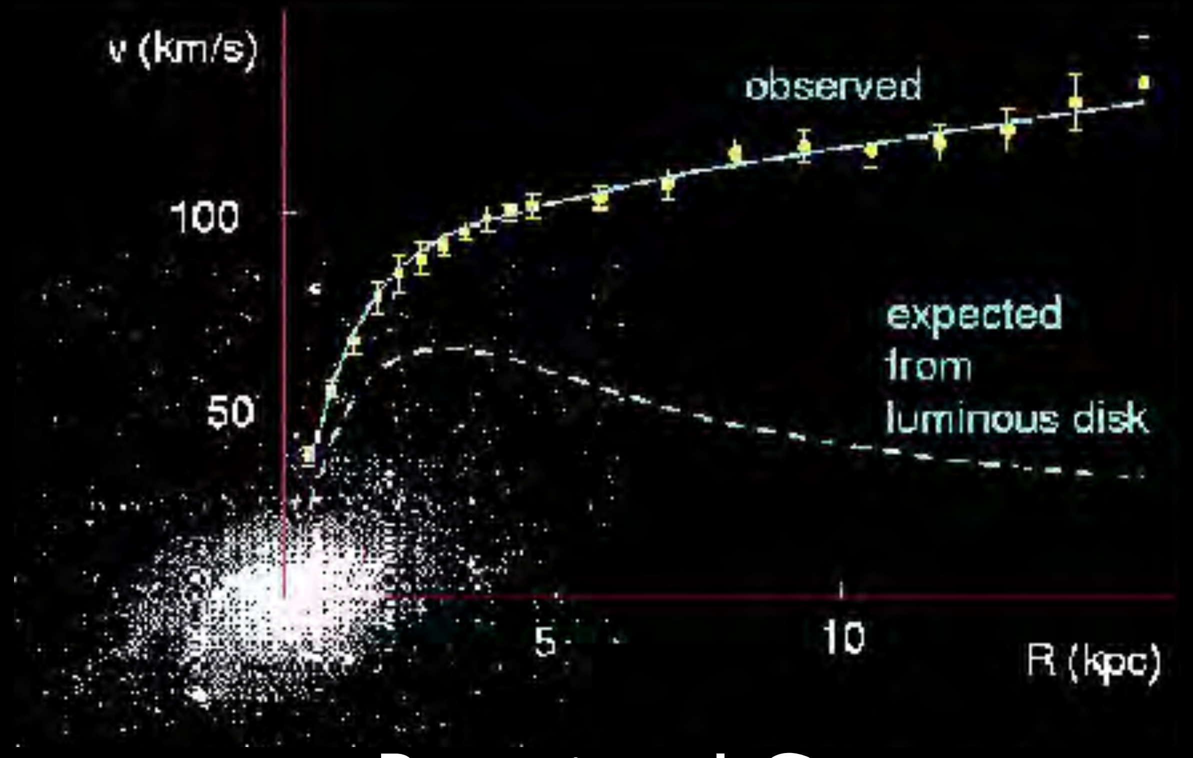
GRAPPA
GRavitation AstroParticle Physics Amsterdam

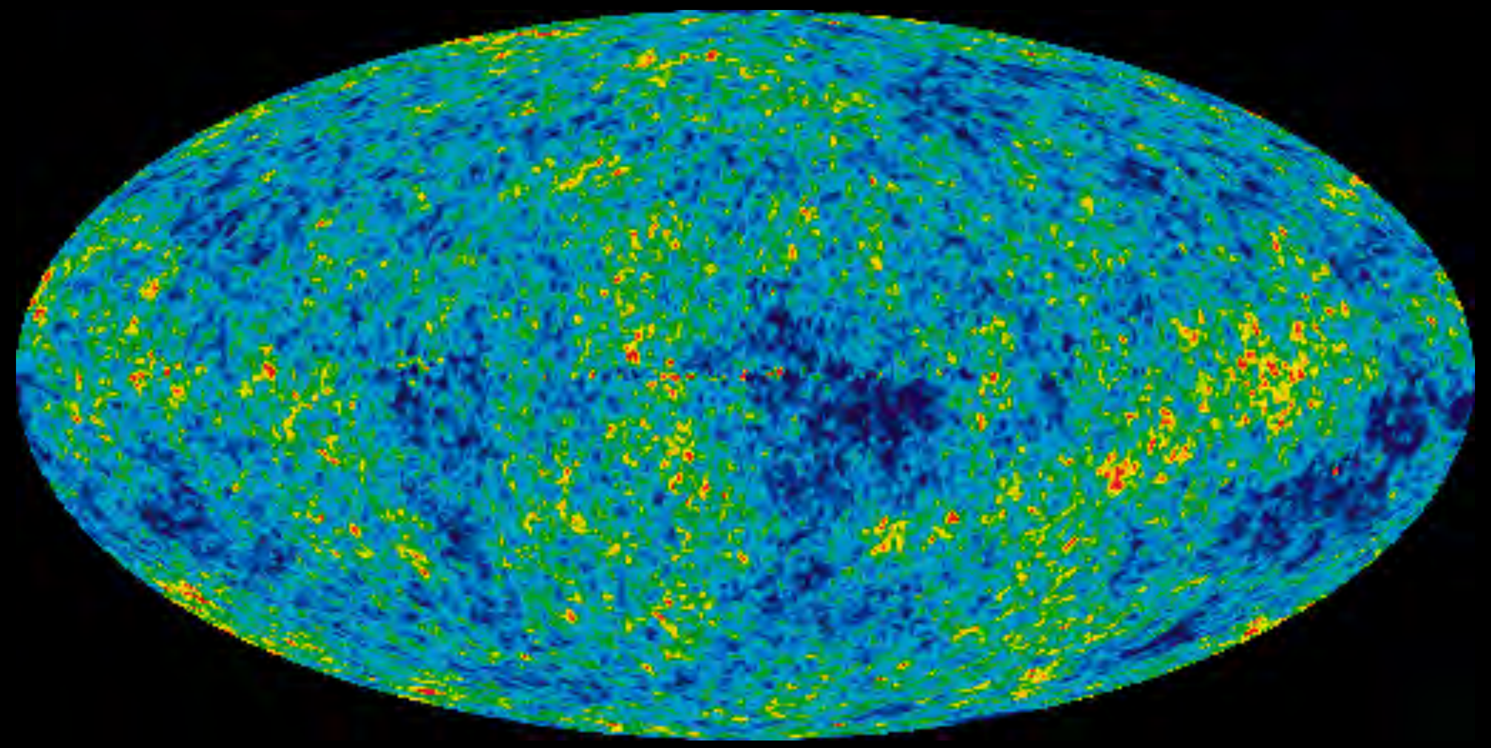
Nikhef

Much astrophysical evidence for Dark Matter



Rotational Curves

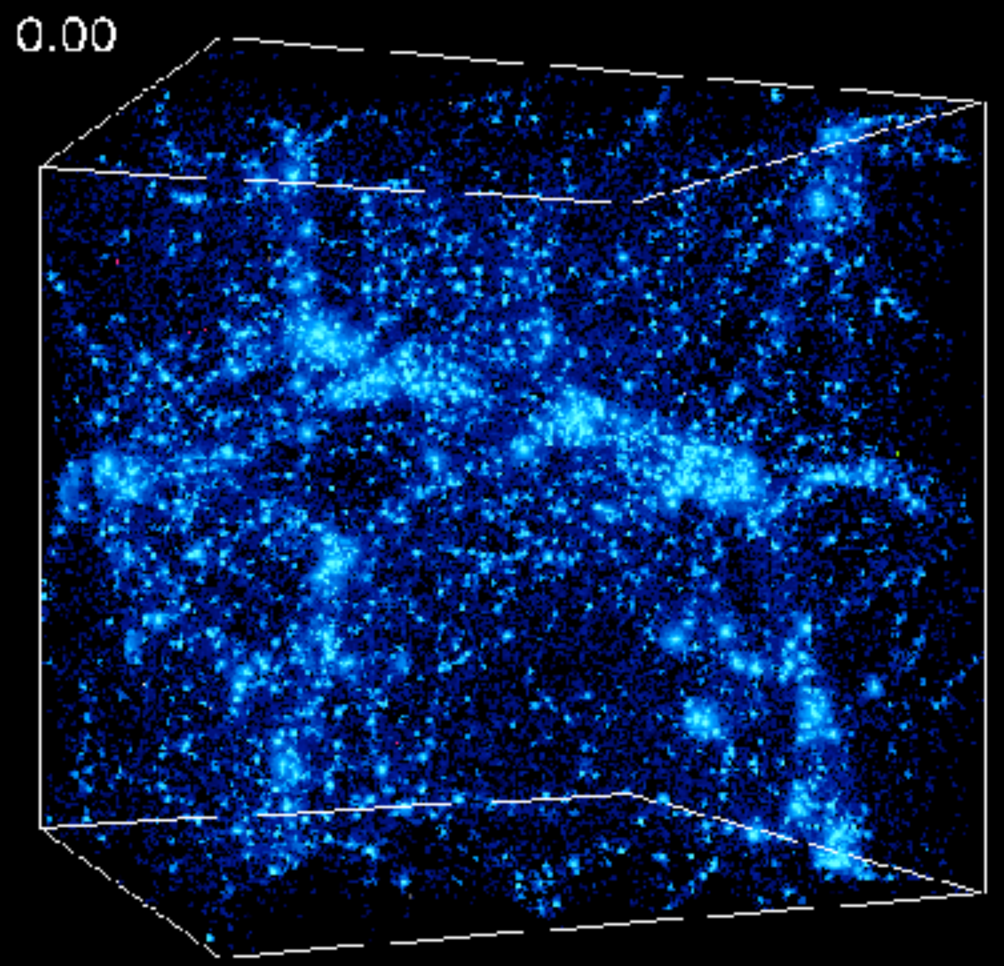
On **all** distance scales in the Universe!



Anisotropy in CMB

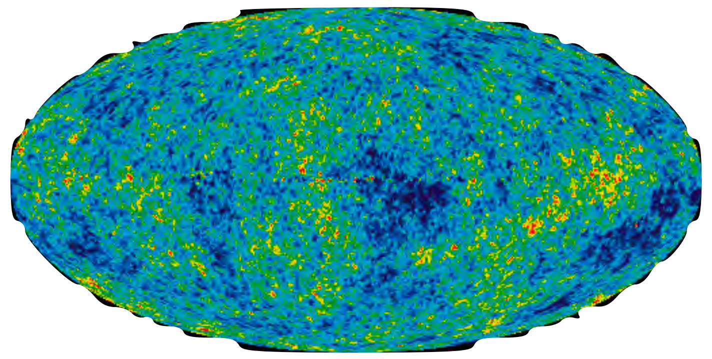
Weak Lensing

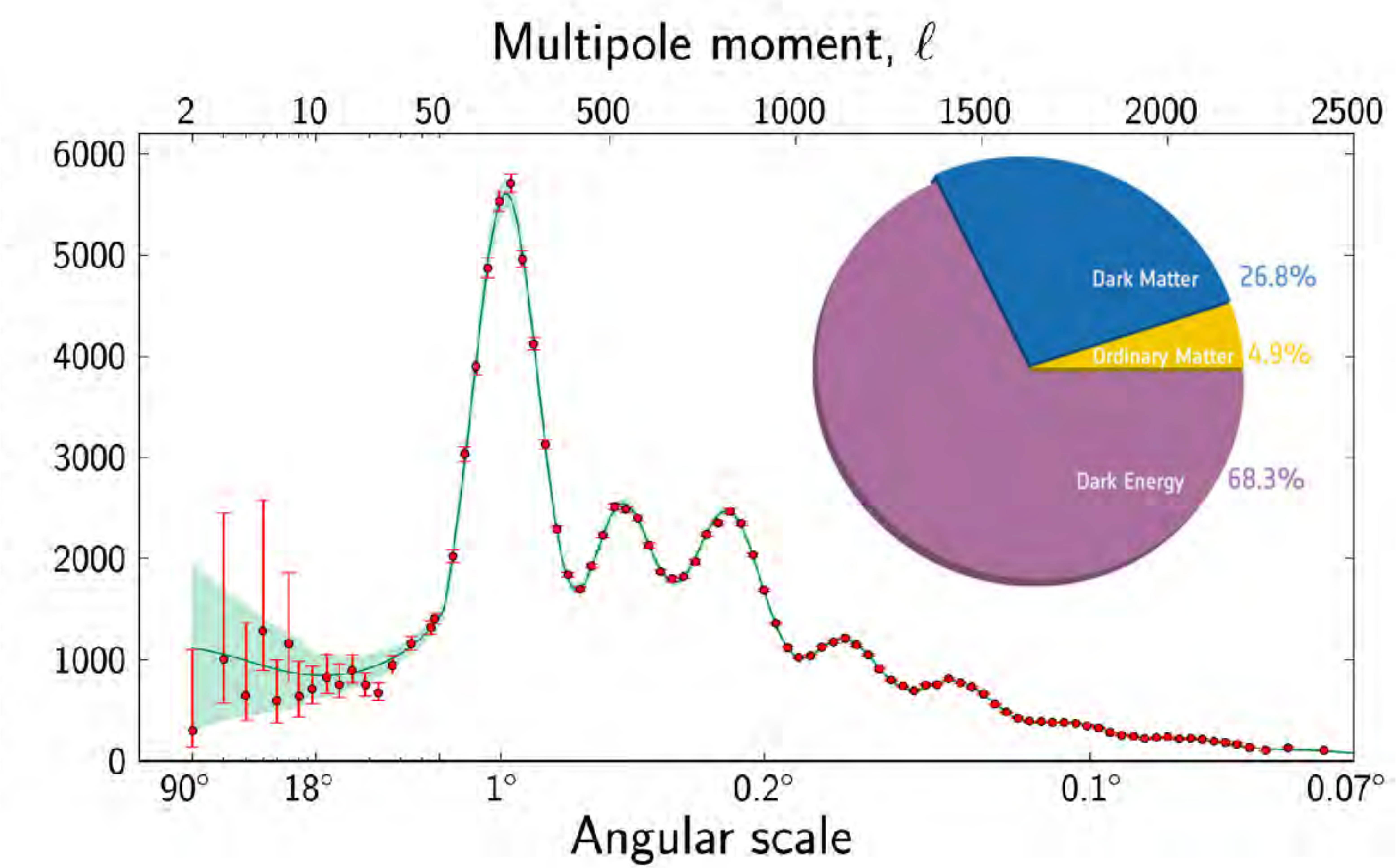
Galaxy Clusters



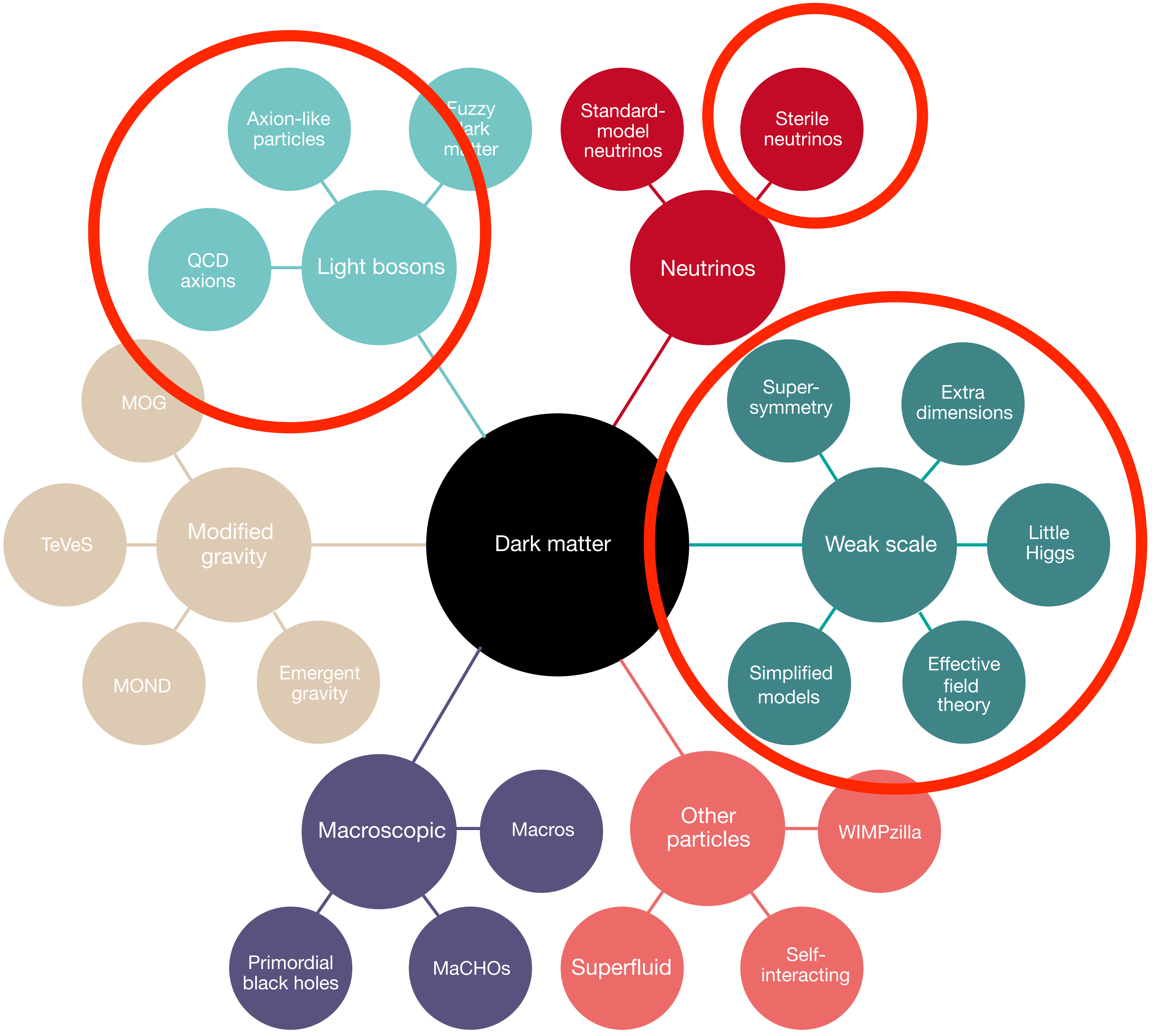
Large Scale Structure

Cosmological Evidence for DM





Dark Matter Candidates

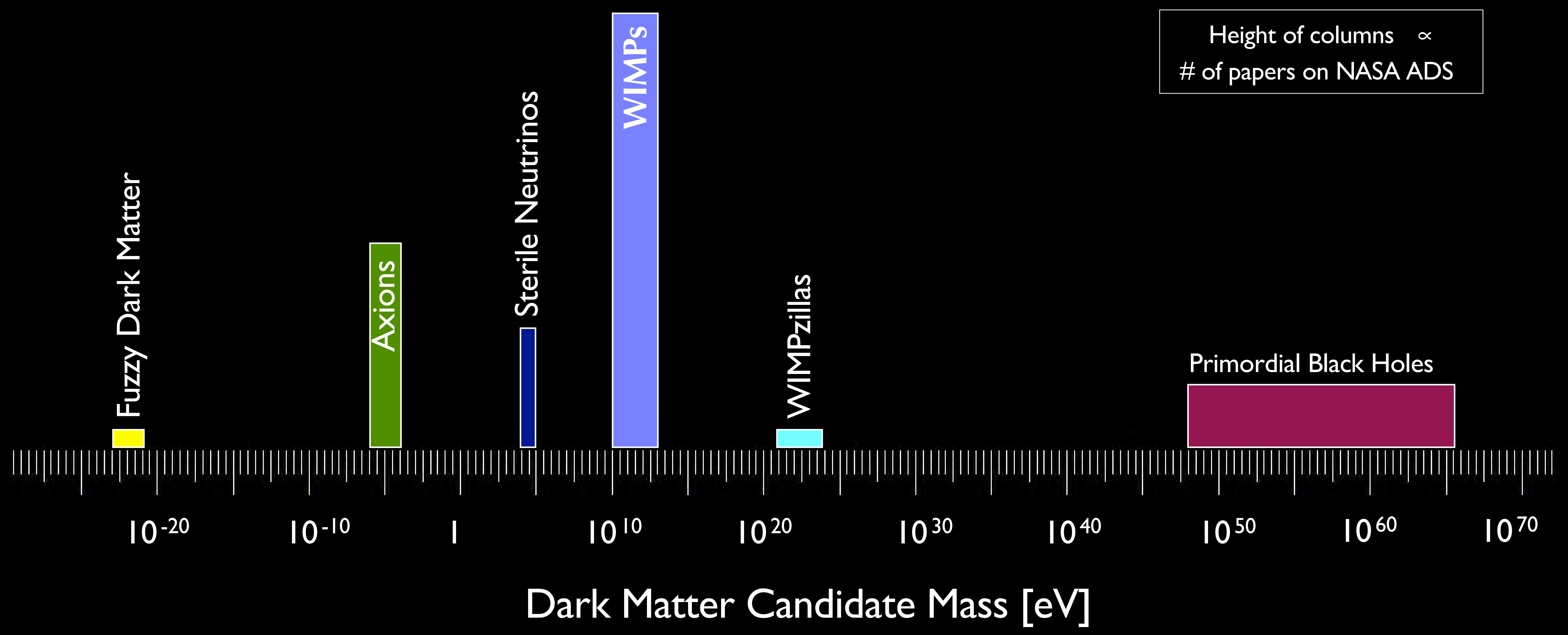


Weakly Interacting Massive Particle

Patrick Decowski - Nikhef/UvA

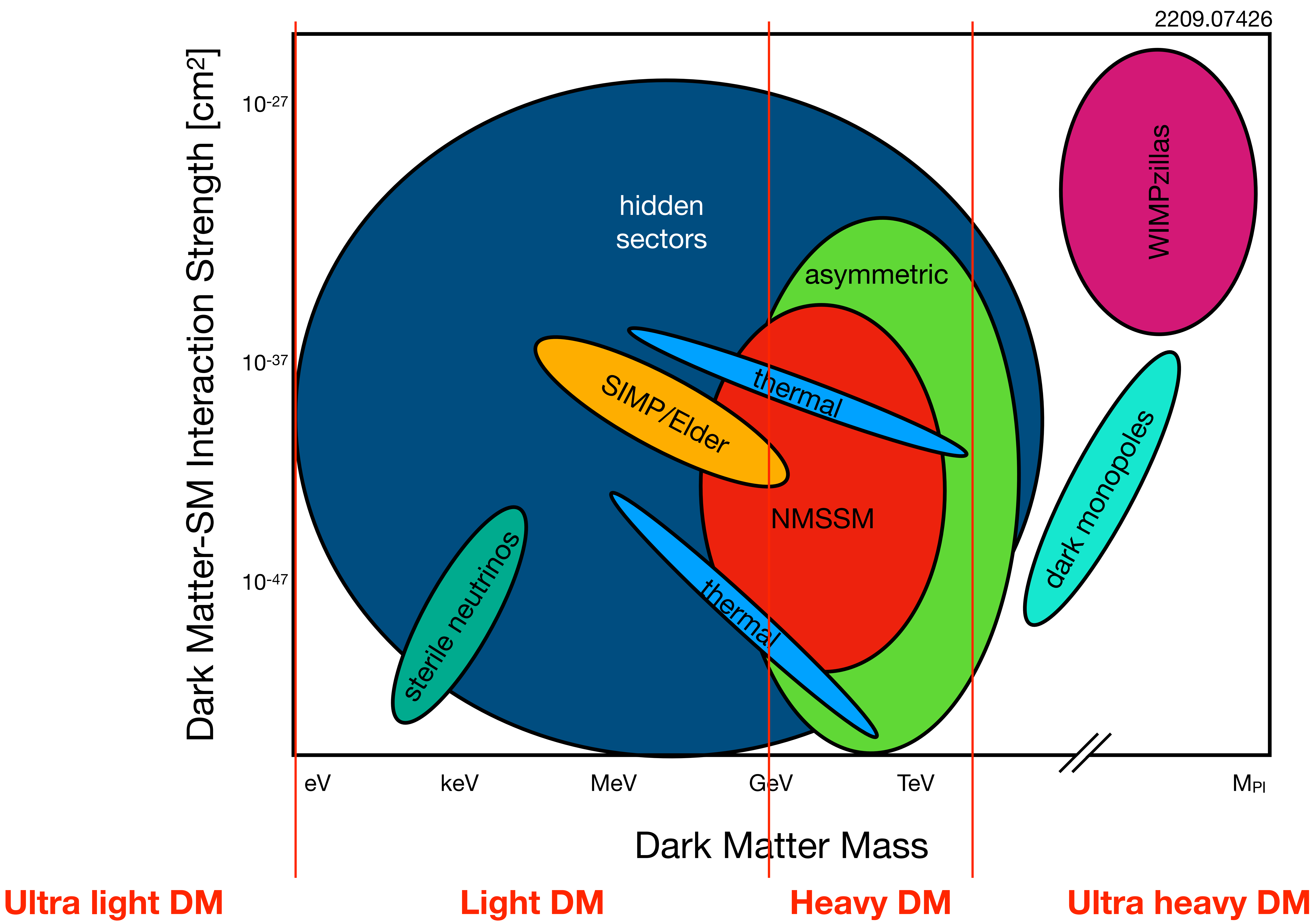
What is Dark Matter?

- Tens of dark matter models
- Candidates span 90 order of magnitude in mass, 40 orders of magnitude in coupling



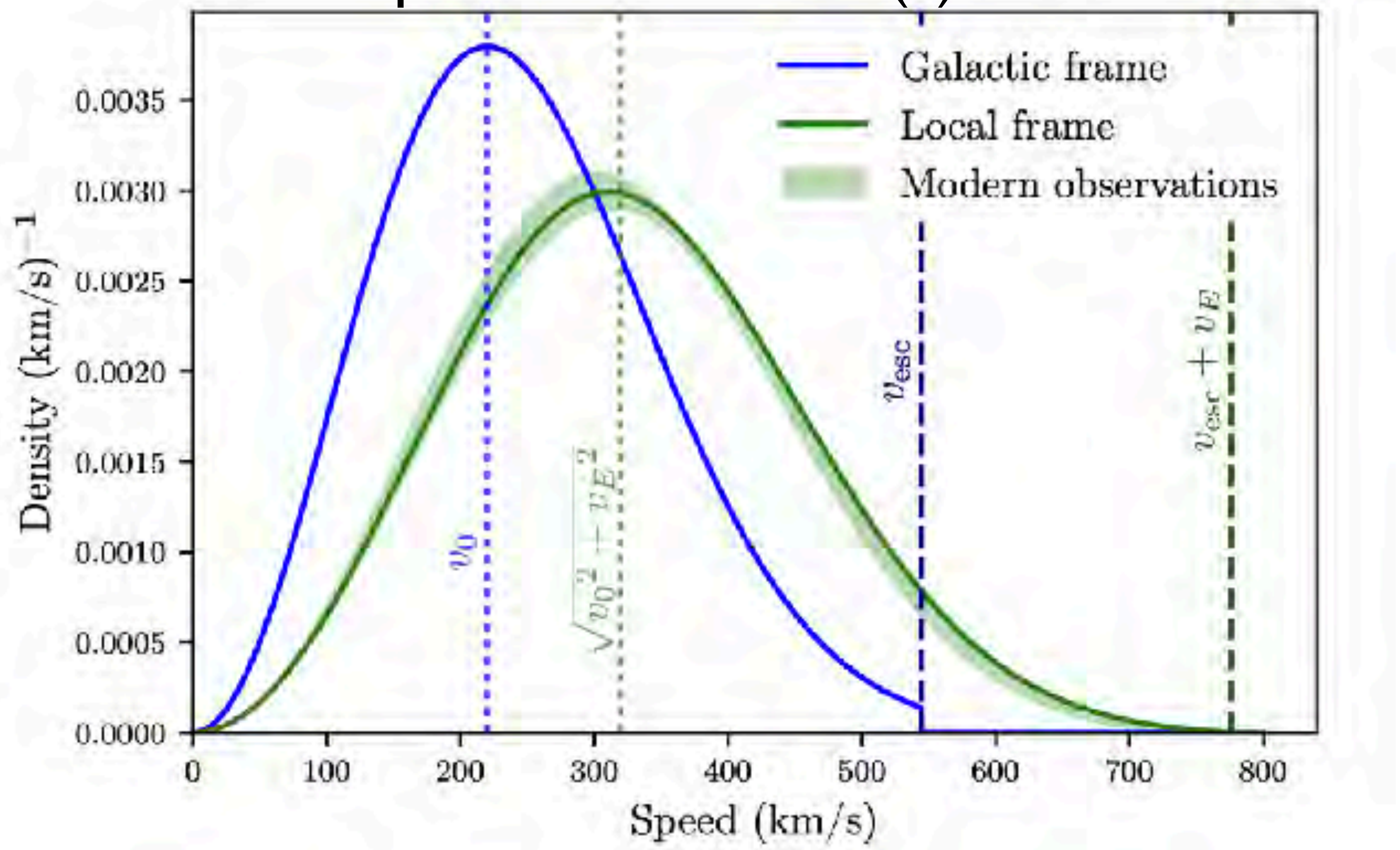
G. Bertone

Cartoon of Models



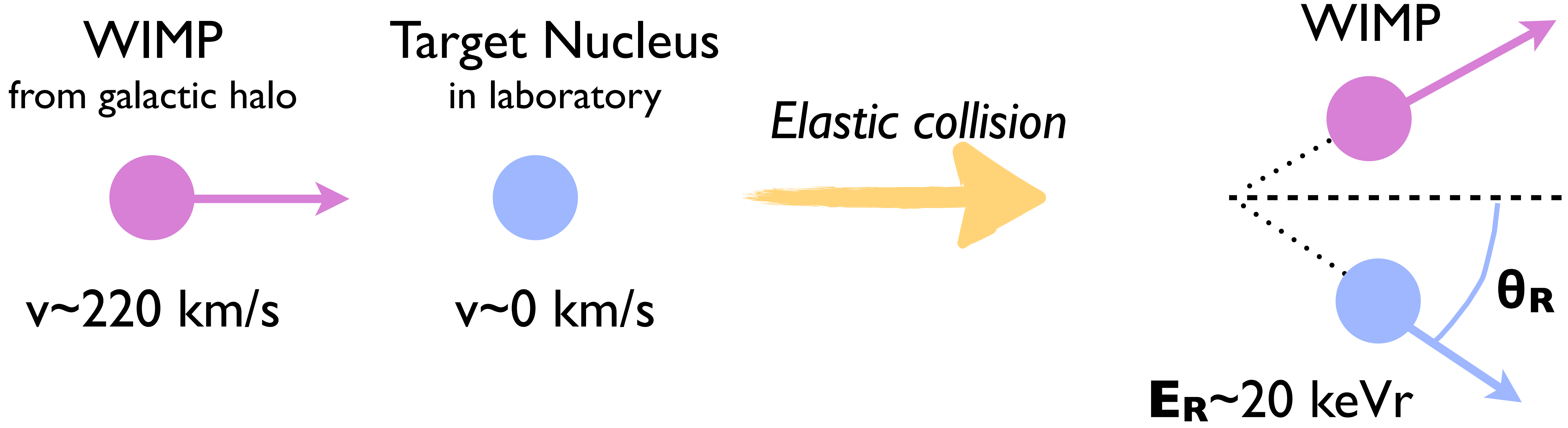
Detection of DM Particle Recoils

WIMP speed distribution f(v)



Assume WIMP is not only gravitationally interacting

M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).



$$E_R = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta)$$

$$v_{\min} = \sqrt{\frac{m_T E_{th}}{2\mu^2}}$$

What can be measured?

We measure:

$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\rm esc}} d^3v \frac{d\sigma}{dE_R} v f(v, v_e(t))$$

Need input from Astrophysics

Effective interaction Lagrangian (low E limit, $v_{WIMP} \sim 10^{-3}c$):

$$\mathcal{L}_{\rm eff} = f_q \overline{\chi}\chi\overline{q}q + d_q \overline{\chi}\gamma^\mu\gamma^5\chi\overline{q}\gamma_\mu\gamma^5 q + \ldots$$

Scalar Axial

with scalar (SI) and axial-vector (SD) couplings:

$$\frac{d\sigma}{dE_R} = \frac{m_T}{2\mu^2 v^2}\left[\sigma_{SI}F_{SI}^2(E_R) + \sigma_{SD}F_{SD}^2(E_R)\right]$$

WIMP-Nucleus Cross Section

Spin-independent cross section:

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

Better sensitivity with high A

Spin-dependent cross section:

Need nucleus with spin:

^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs (but no Ar!)

Nuclear model:

$\langle S_{p,n}\rangle = \langle N|S_{p,n}|N\rangle$

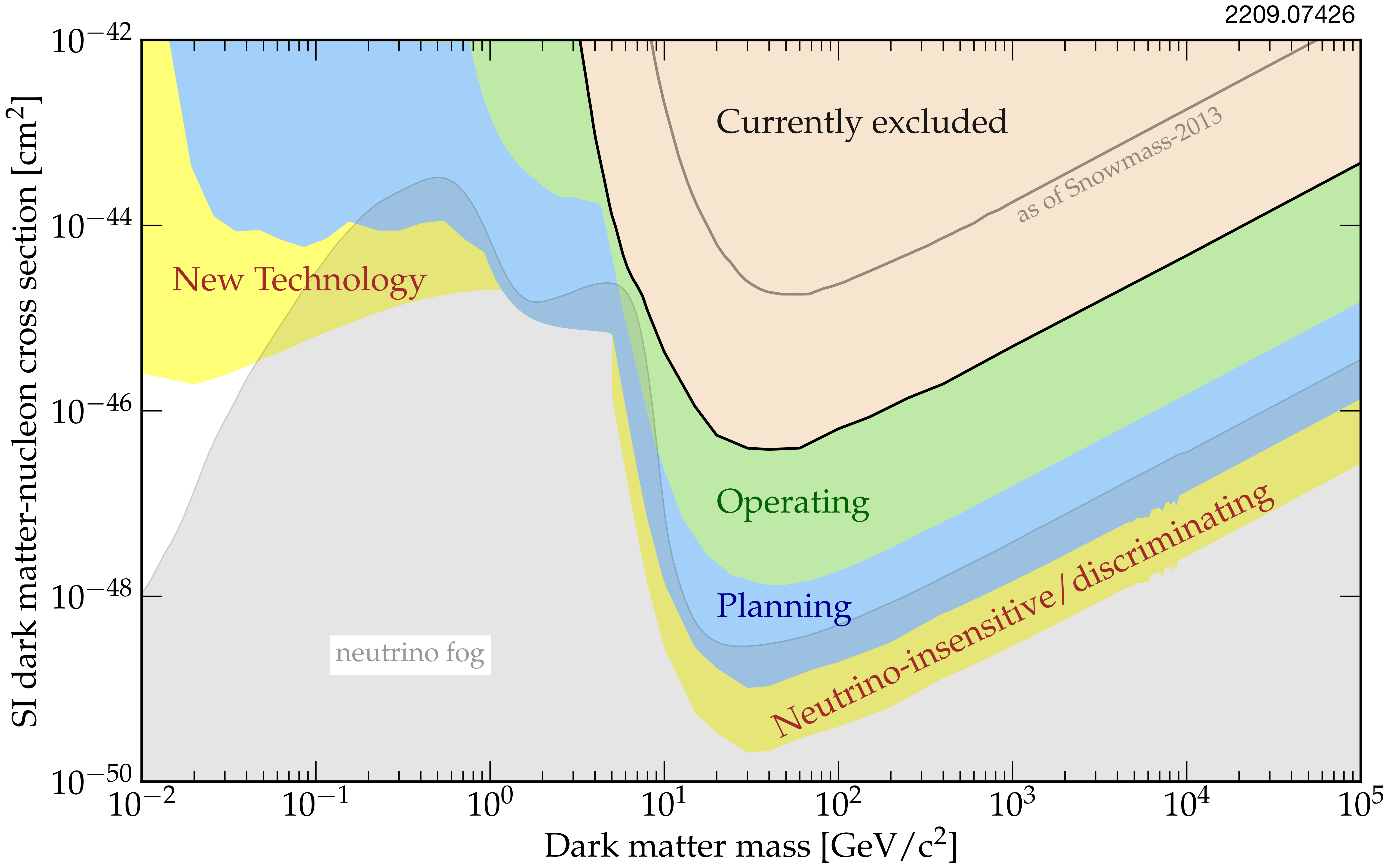
$$\sigma_{SD} = \frac{32\mu^2}{\pi}G_F^2\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Only axial vector describing state of nucleus as $q \to 0$

WIMP couplings to protons & neutrons

Analysis is done attributing **all** the (lack of) rate to SI or SD

~Current Spin-Independent Parameter Space



Energy Recoil Spectra

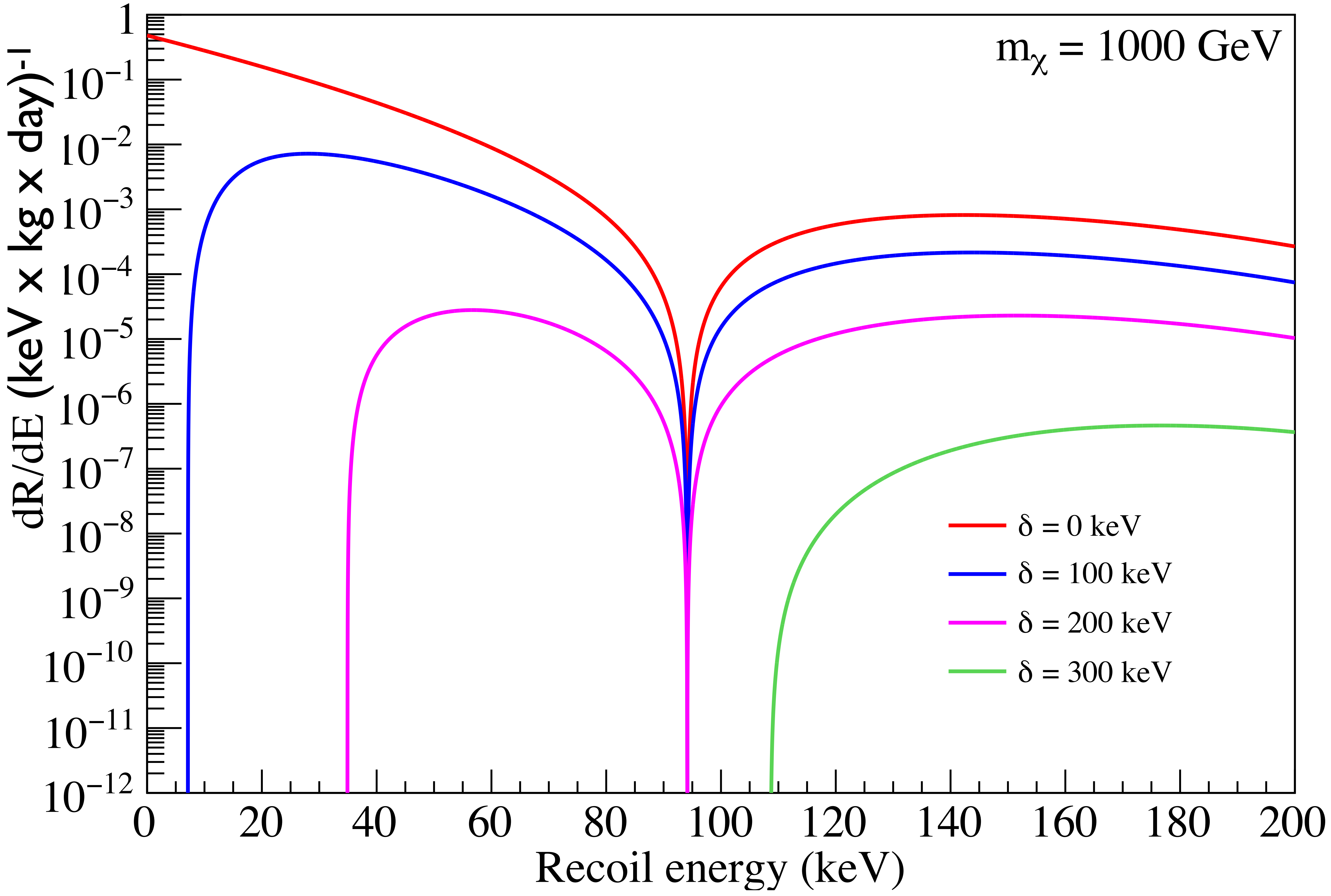
Inelastic Scattering: $\chi N \rightarrow \chi^* N$

Typically consider Elastic Scattering

δ is χ - χ^* mass splitting

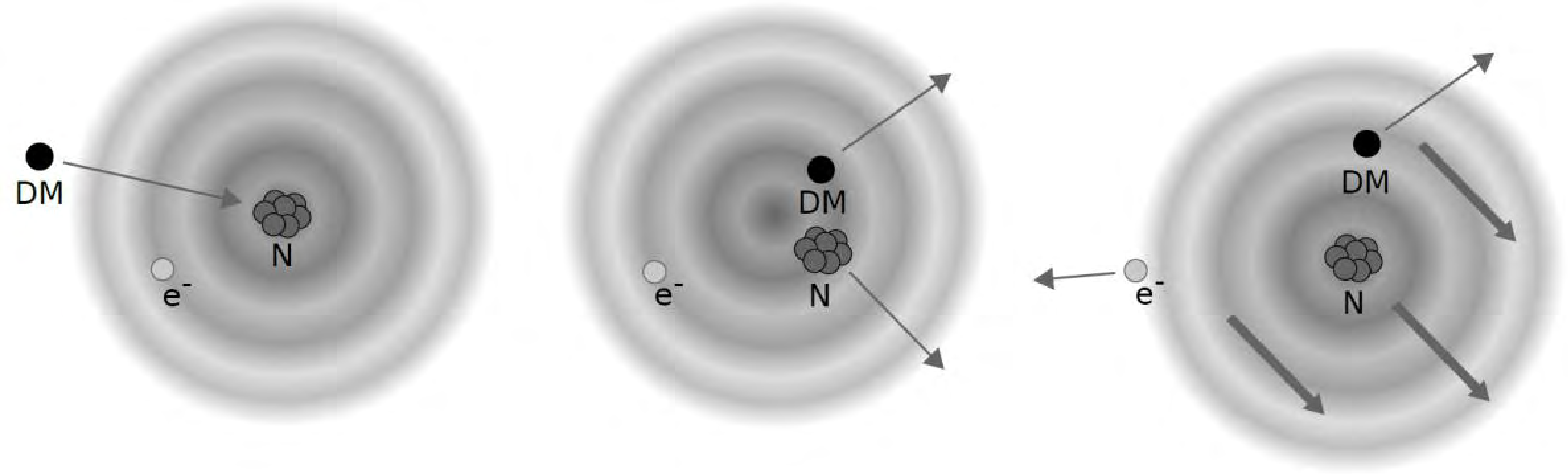
"Vanilla WIMP Model"

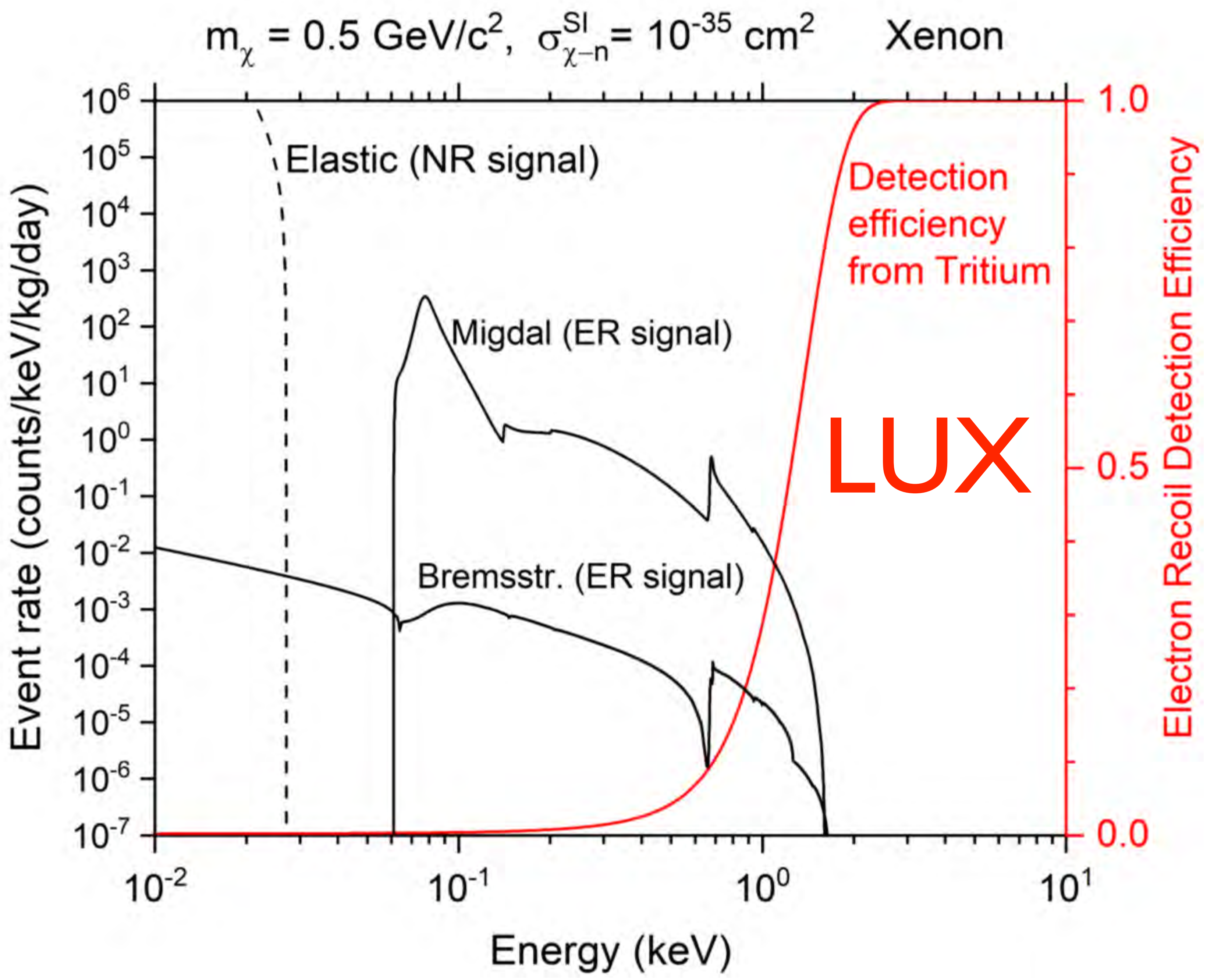
$$\beta_{min} = \sqrt{\frac{1}{2M_N E_{nr}}}\left(\frac{M_N E_{nr}}{\mu} + \delta\right)$$



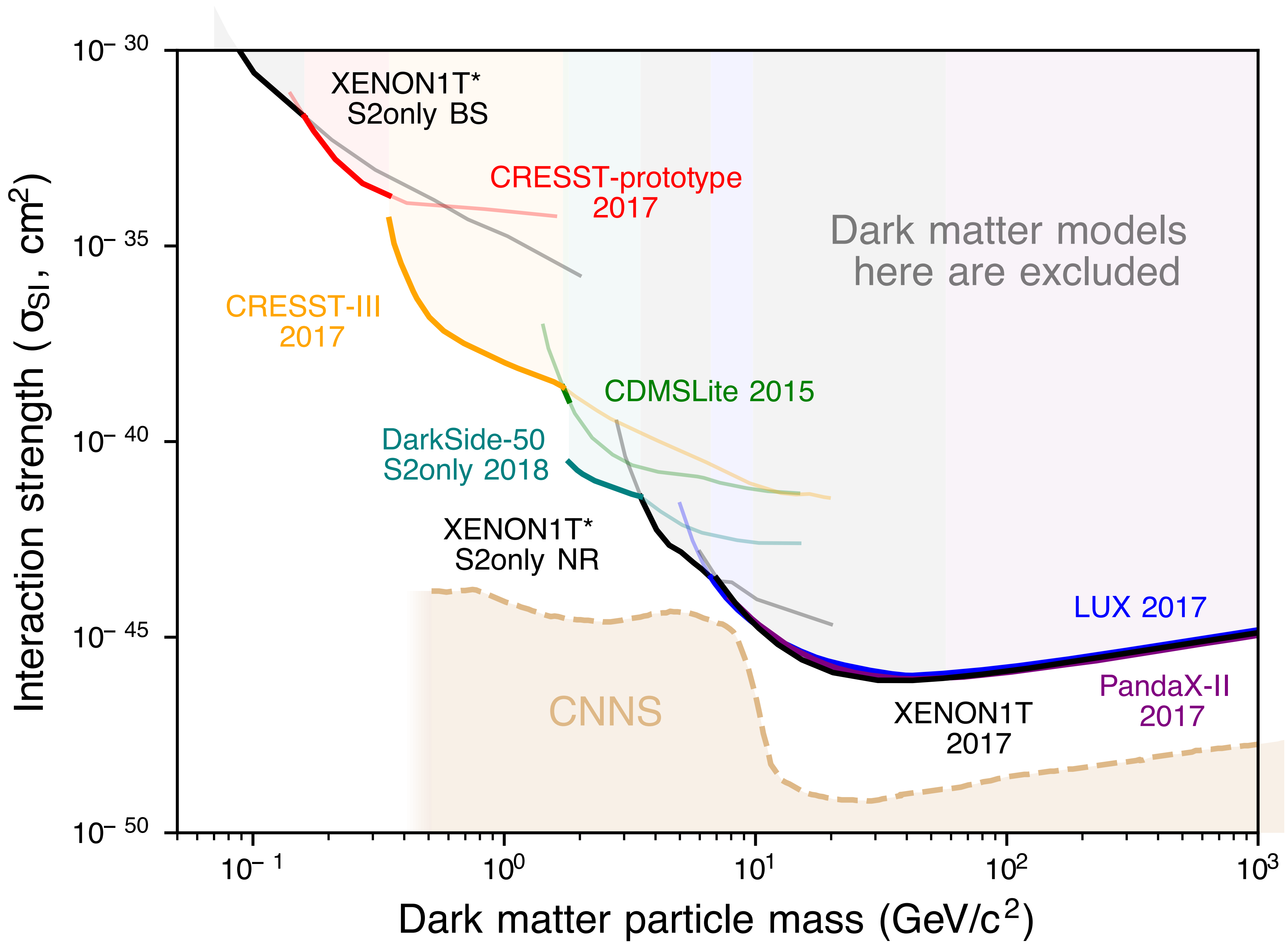
Searching for Sub-GeV WIMPs

"Migdal"-effect



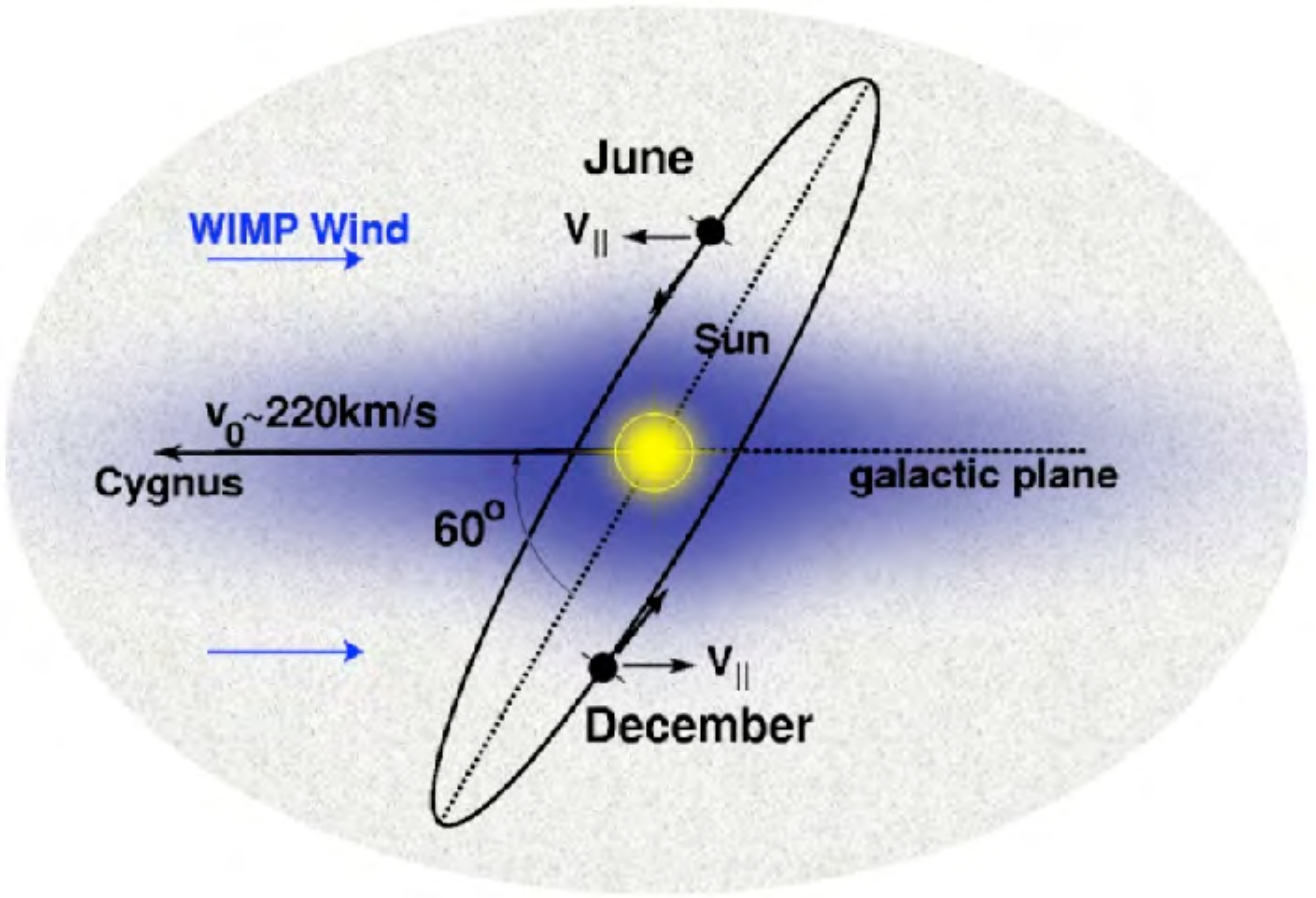


Other ways to get sub-GeV



Drive to be sensitive to sub-GeV mass DM

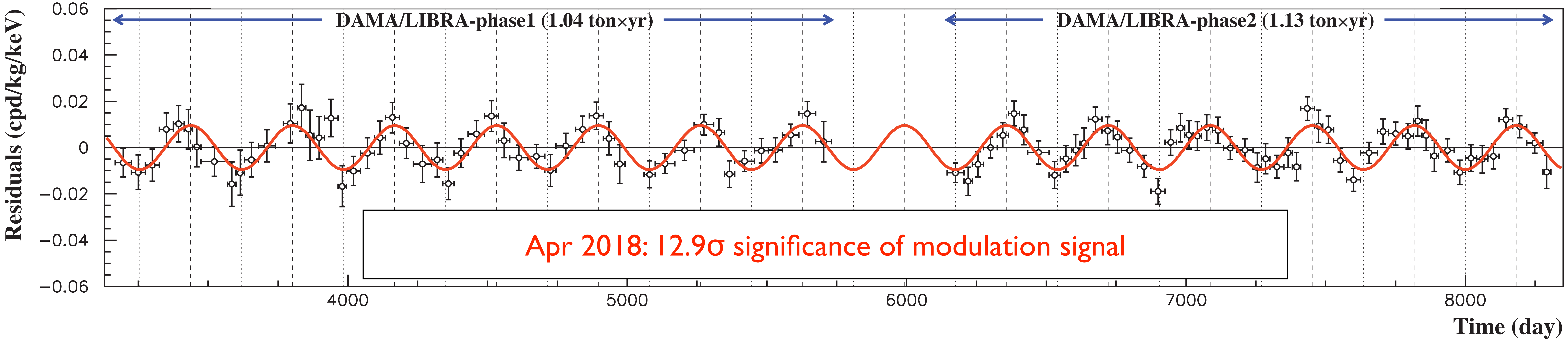
Use annual modulation: DM claim



- DAMA claim in NaI
- Several DM experiments investigating:
  - COSINE-100, SABRE, ANAIS, …
  - Manufacturing of Low BG crystals achieved
  - Southern hemisphere

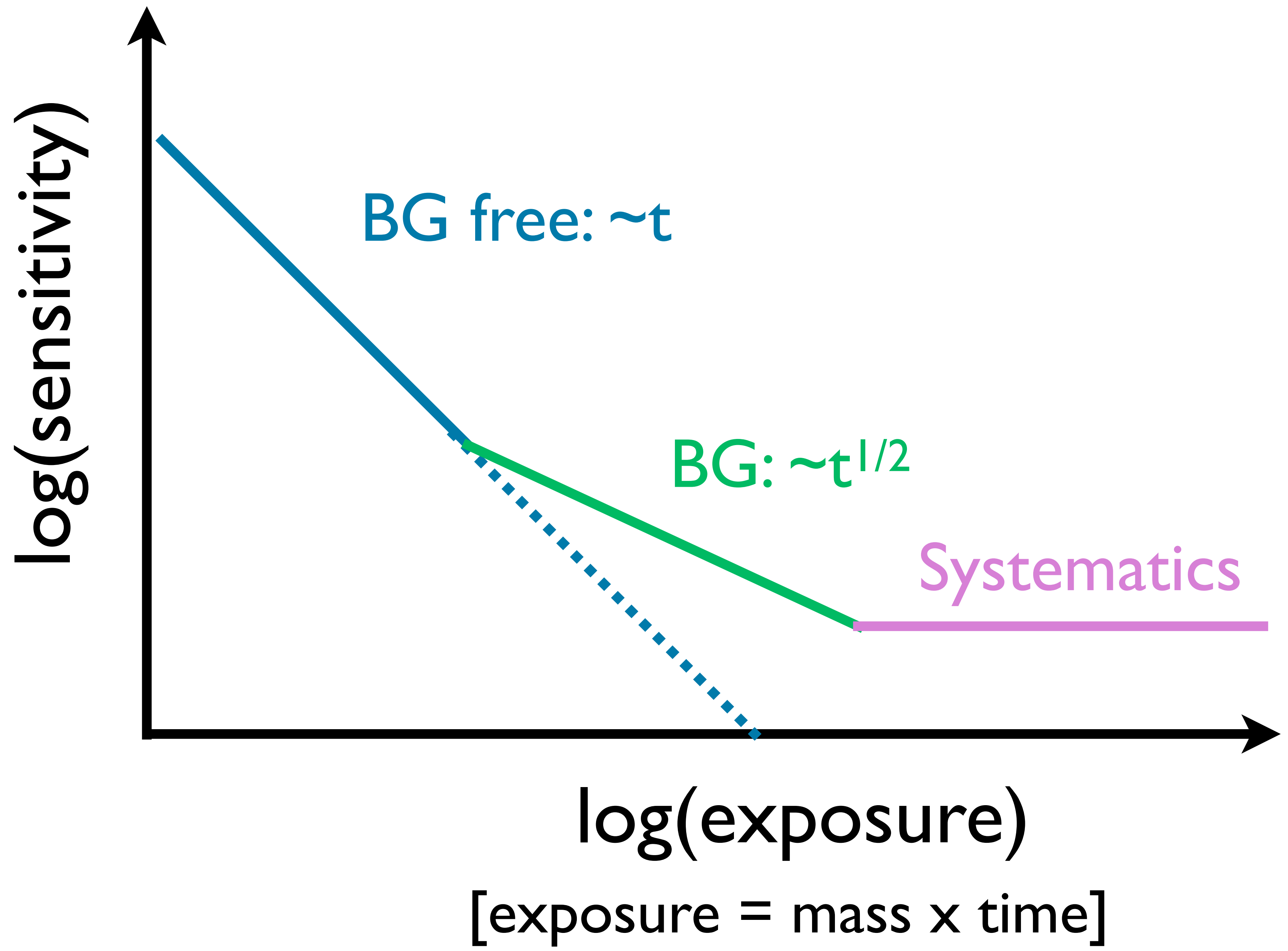
Modulation present in 2-6 keV, absent above 6 keV

arXiv:1805.10486



Minimizing Backgrounds

- Critical aspect of any rare event search - minimize backgrounds!
- Purity of materials
  - Copper, germanium, xenon among the cleanest with no natural occurring long-lived isotopes
  - Ancient lead, if free of ^{210}Pb
- Shielding
  - External U/Th/K backgrounds
- Krypton and Radon mitigation
- Material handling and assaying
  - Surface preparation, cosmic activation
- Underground siting and active veto
  - Avoid muon-induced neutrons
- Detector-based discrimination



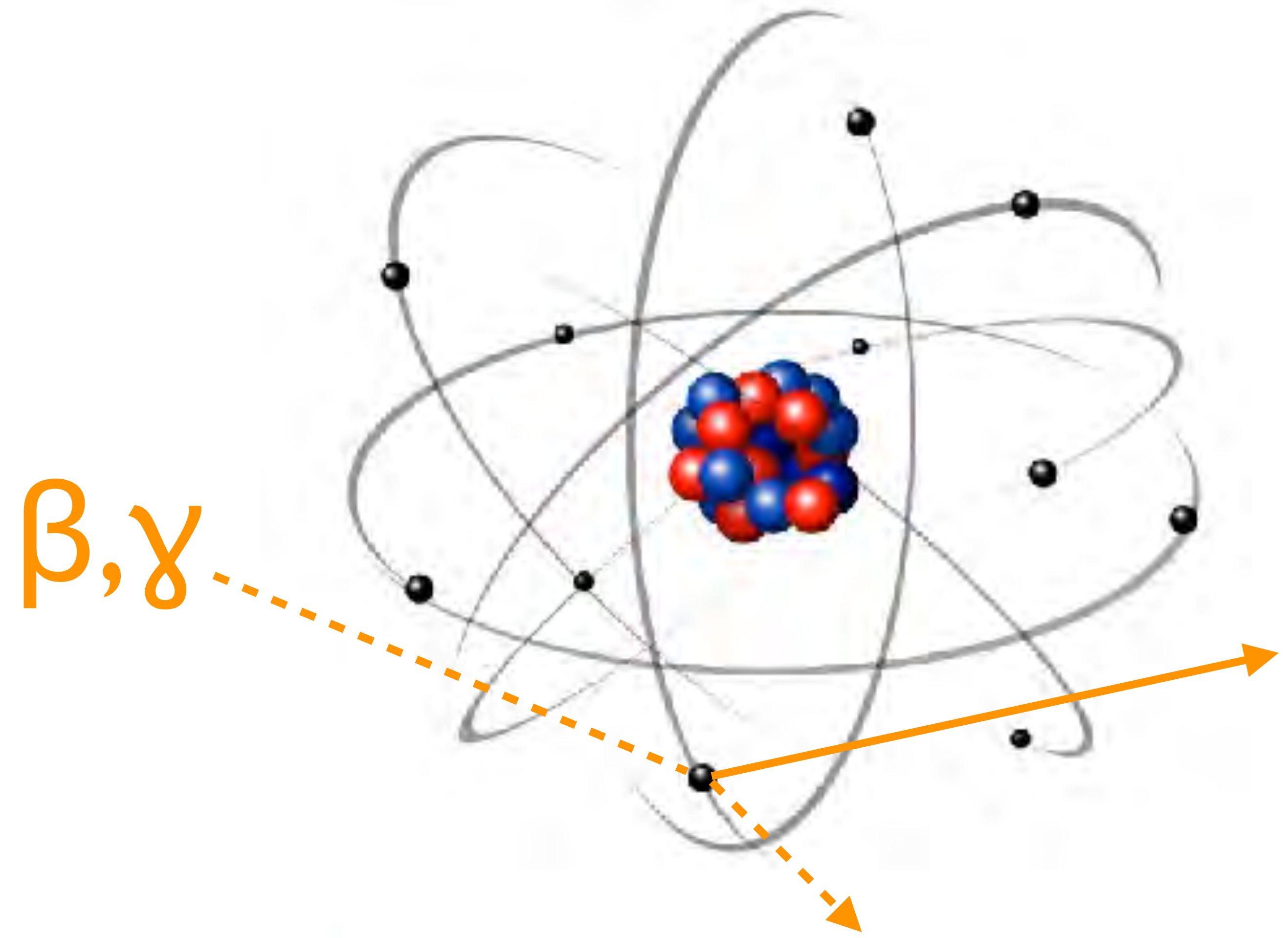
Current state-of-the-art: <1 ev/(**ton** · yr)

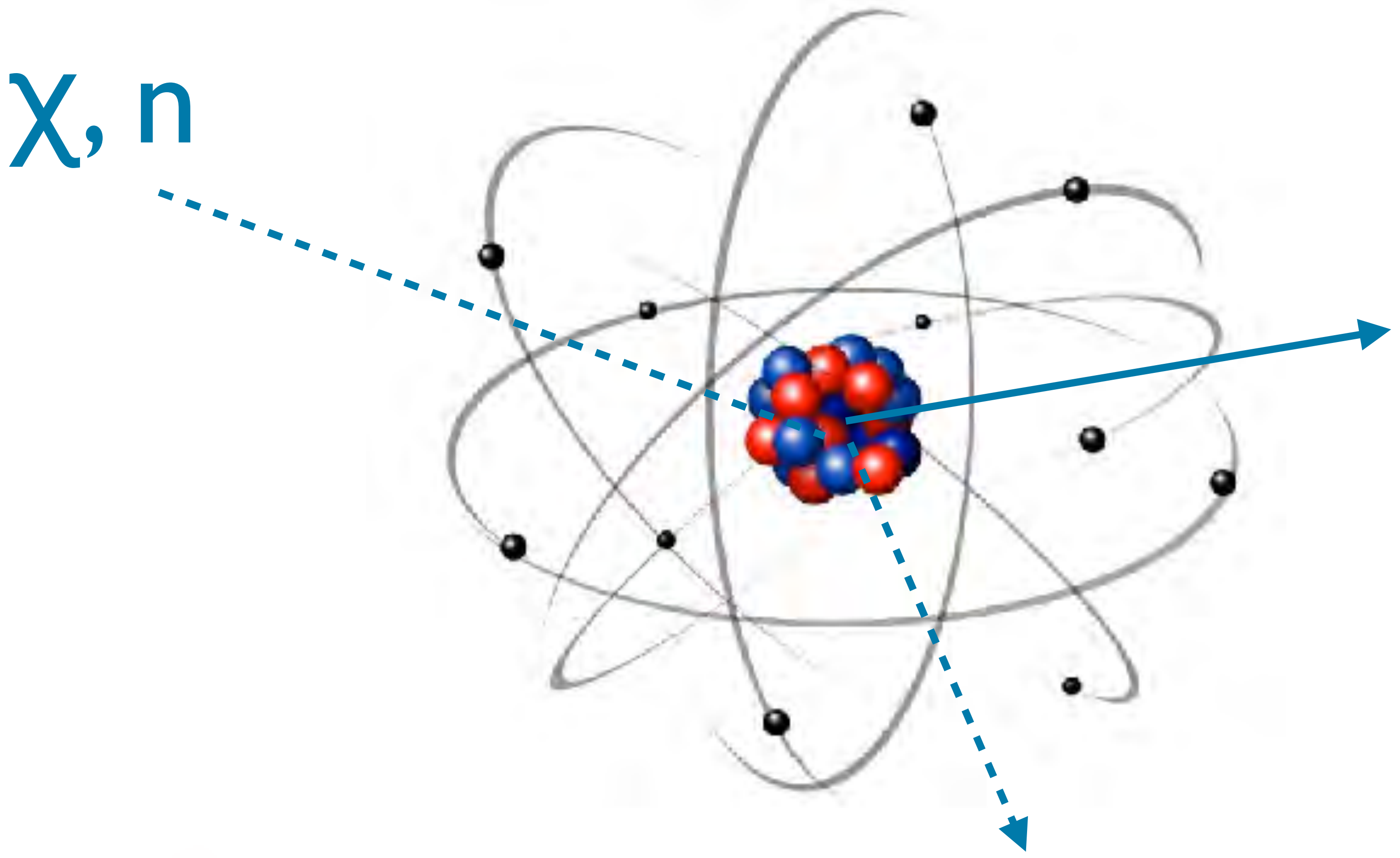
Underground Labs with DM Experiments

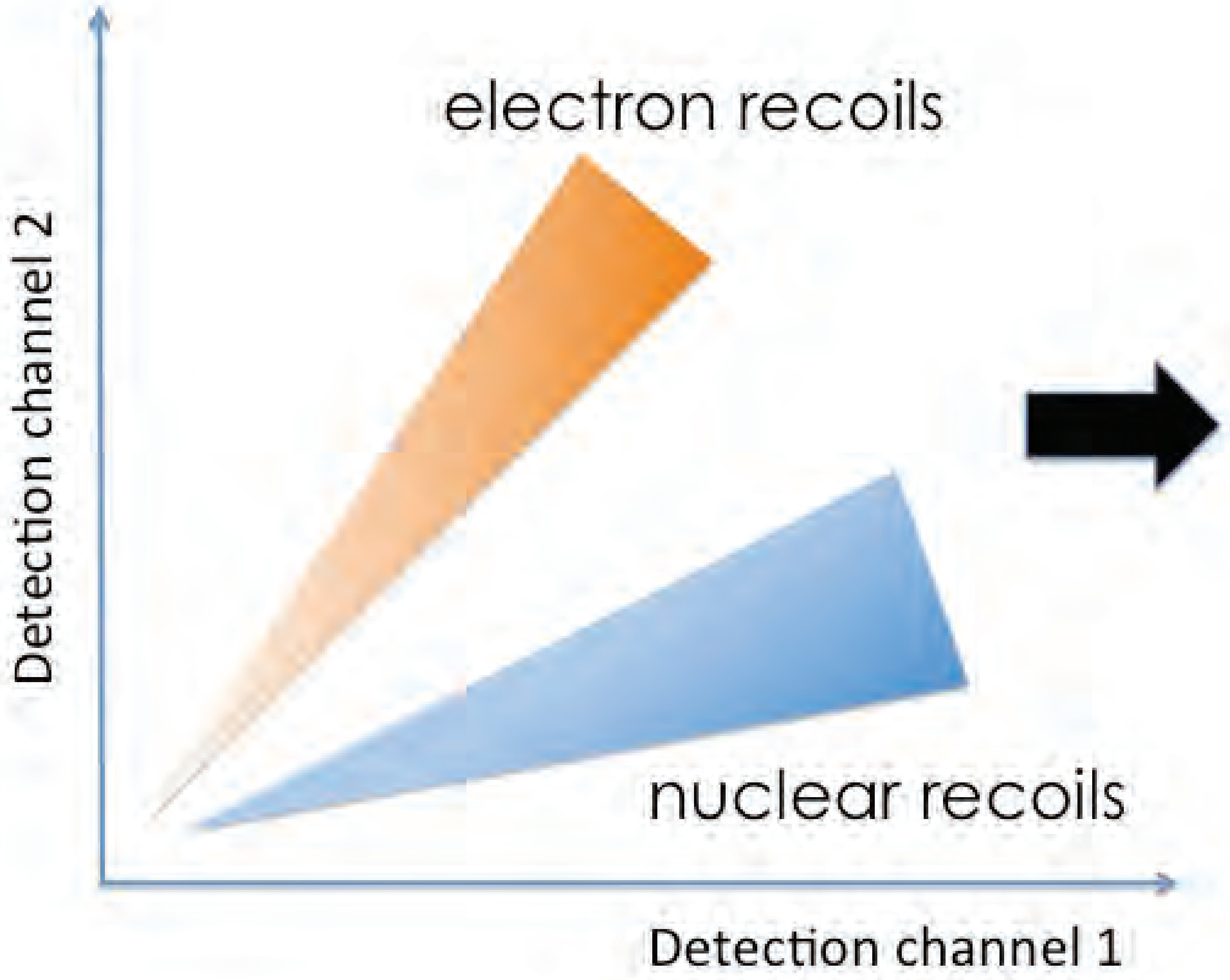
Need at least 1000m rock (~3000 mwe) overburden

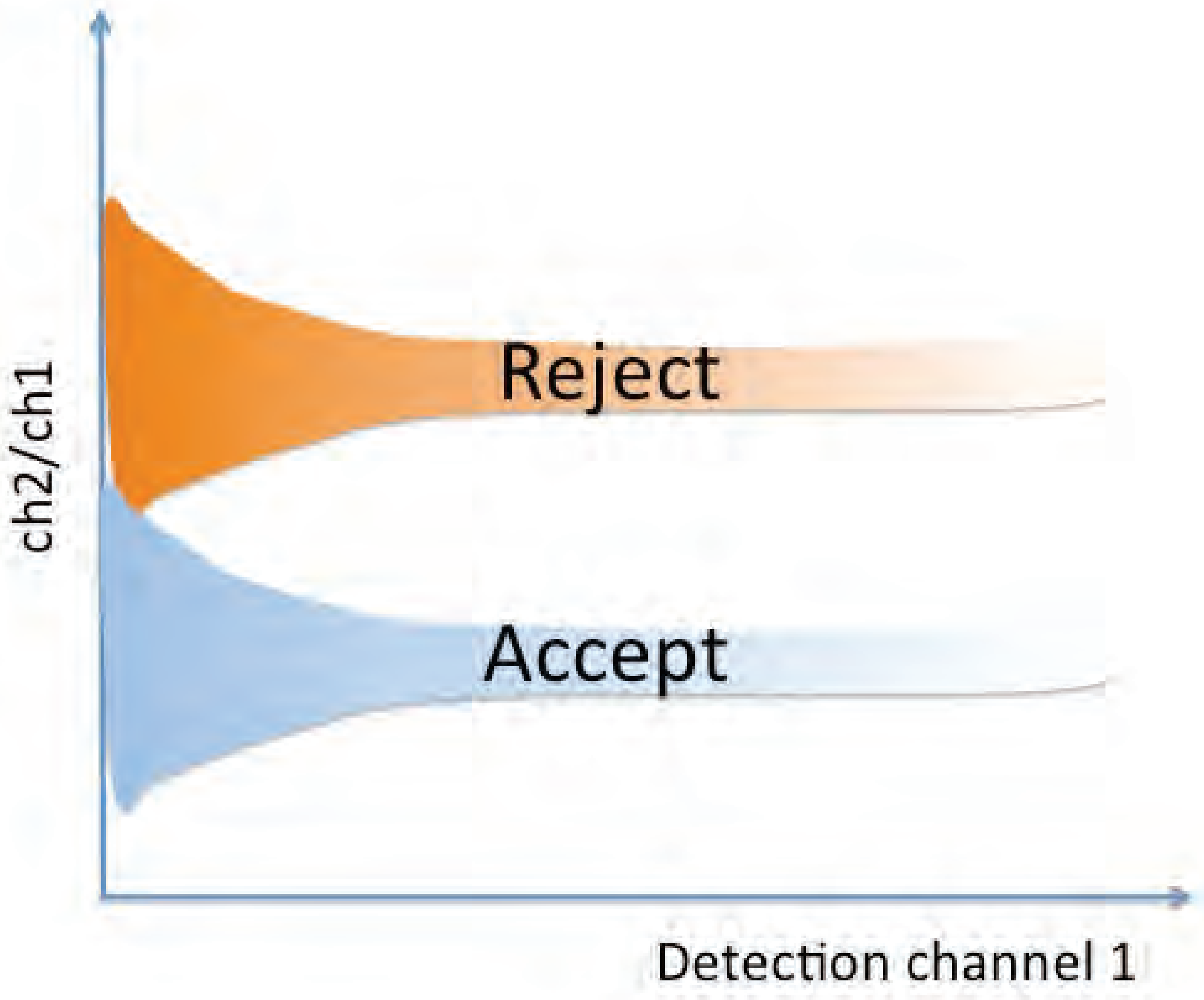
Reduces muon rate by ~10^5

Particle-dependent Response

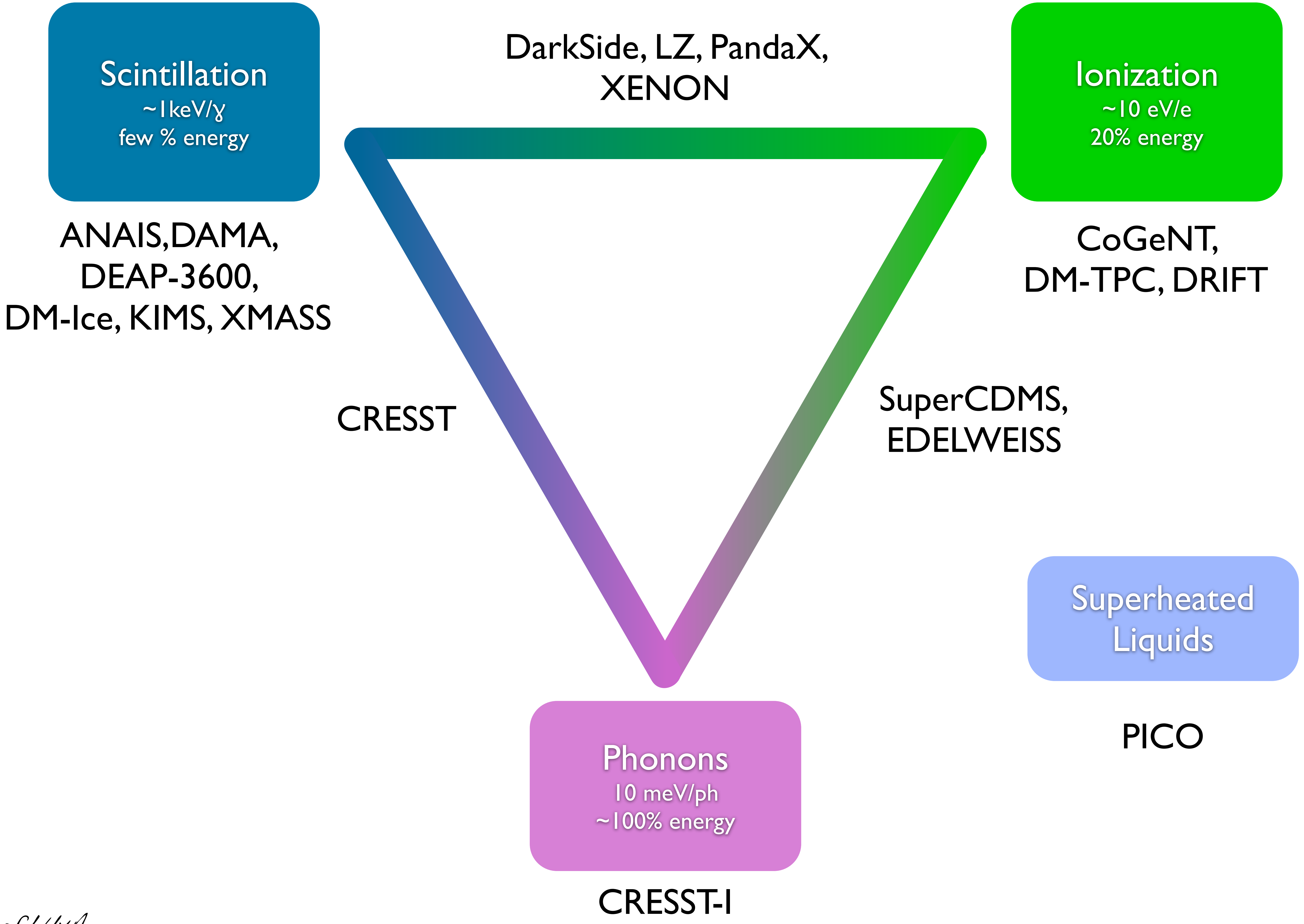








Detection Techniques



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Subatech Coimbra LPNHE Torino Bologna L'Aquila LNGS Napoli Weizmann NYUAD

XENON

27 institutions
and 167 collaboration members

https://xenonexperiment.org

@XENONExperiment

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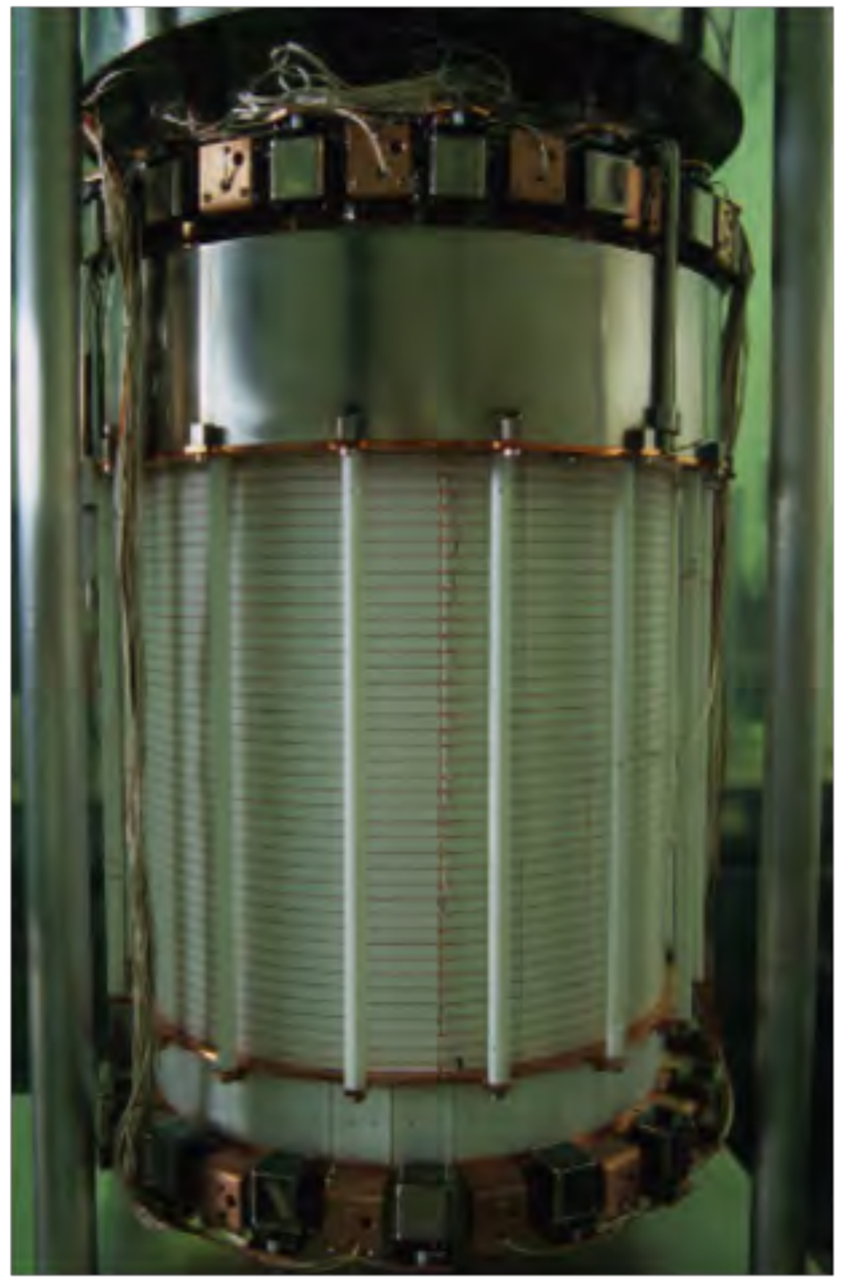
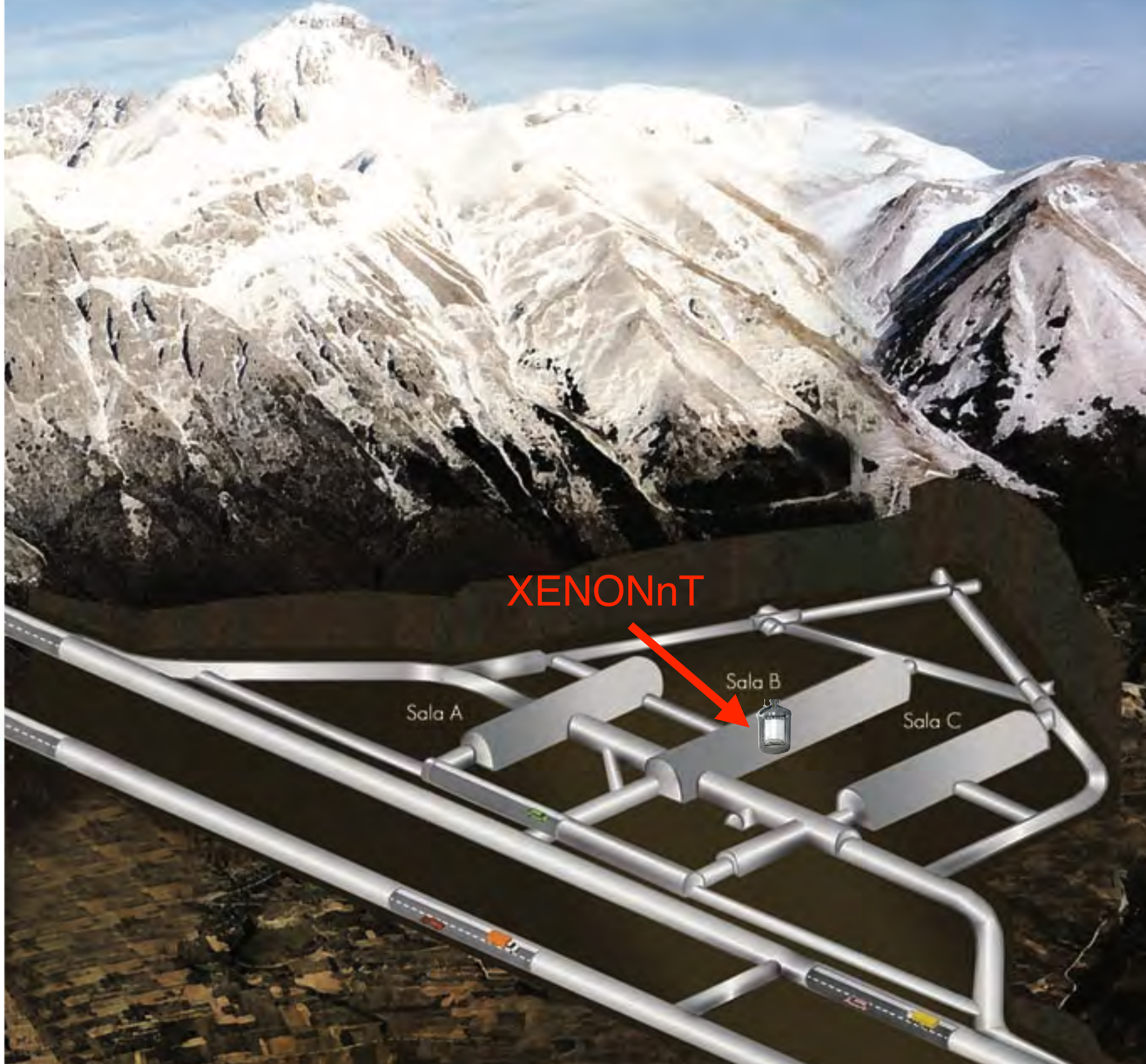
XENON Phases @ LNGS

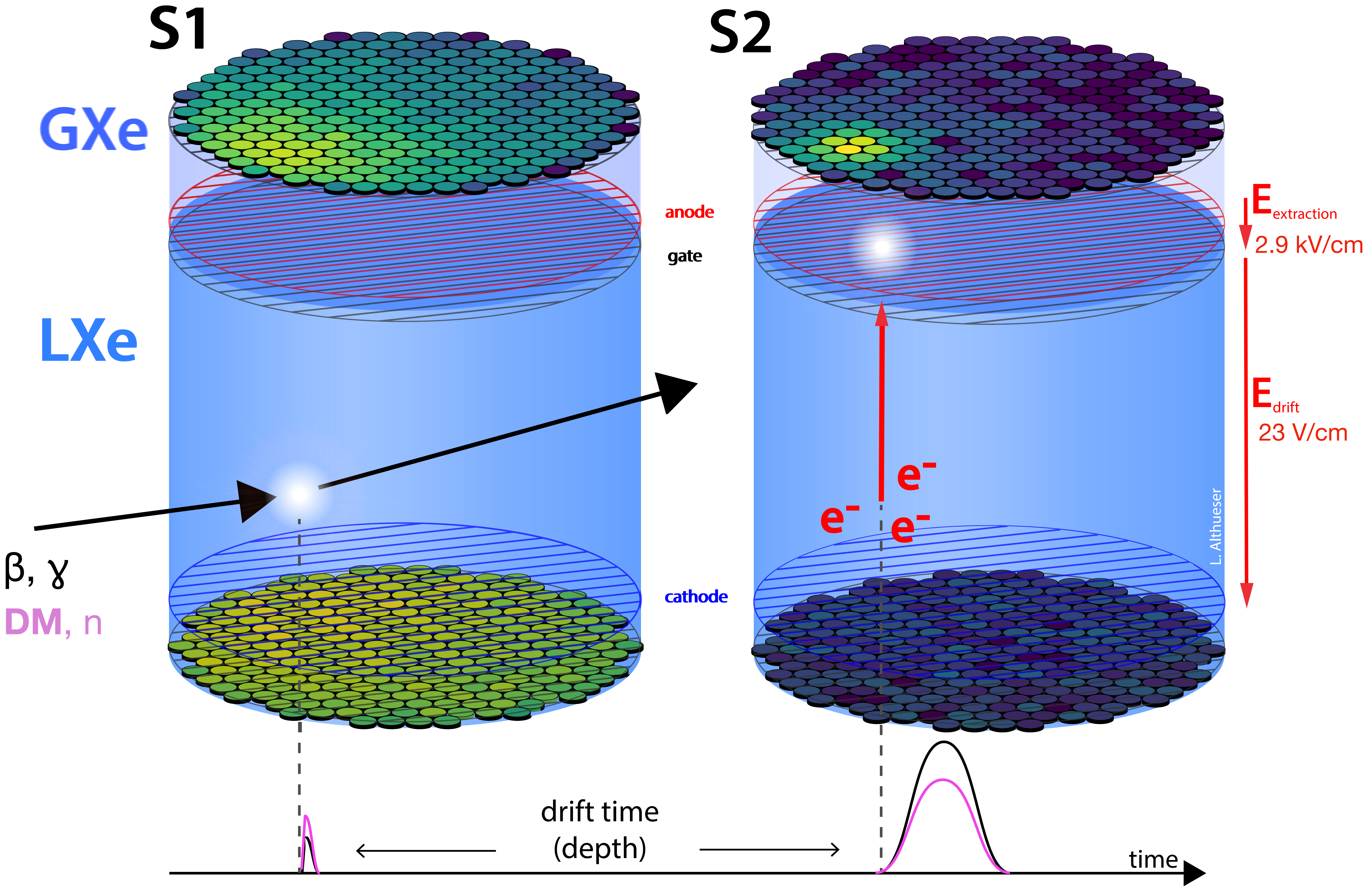



	XENON10	XENON100	XENON1T	XENONnT
	2005-2007	2008-2016	2012-2019	2020-2026
LXe target mass	14 kg	62 kg	2000 kg	5900 kg
	$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	4×10^{-47} cm^2	1.8×10^{-48} cm^2 [20 t-yr exposure]
ER BG rate	2M evts/(keV×t×yr)	1800 evts/(keV×t×yr)	82 evts/(keV×t×yr)	16 evts/(keV×t×yr)

Laboratori Nazionali del Gran Sasso

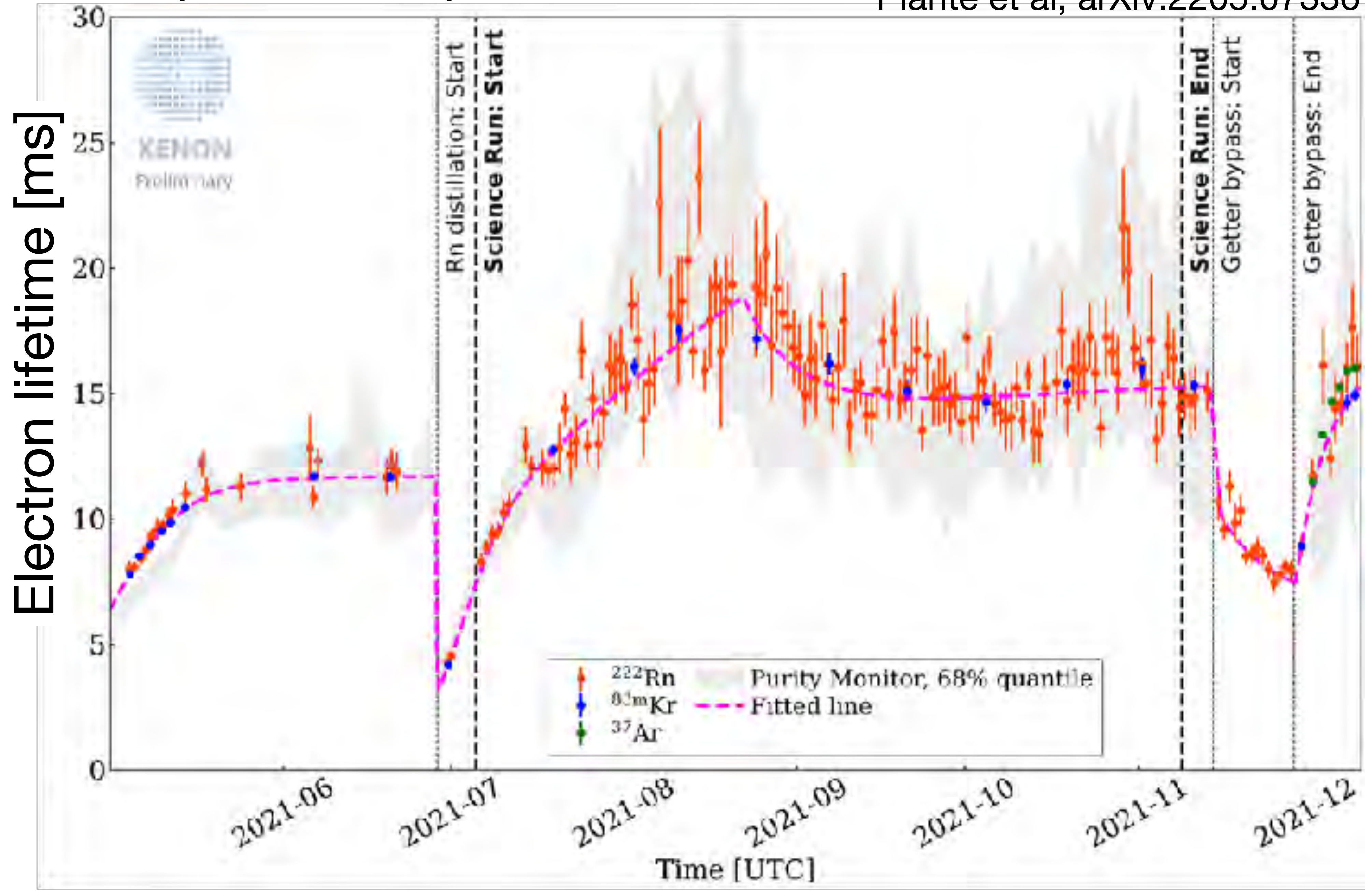


Detection Principle



Liquid xenon purification

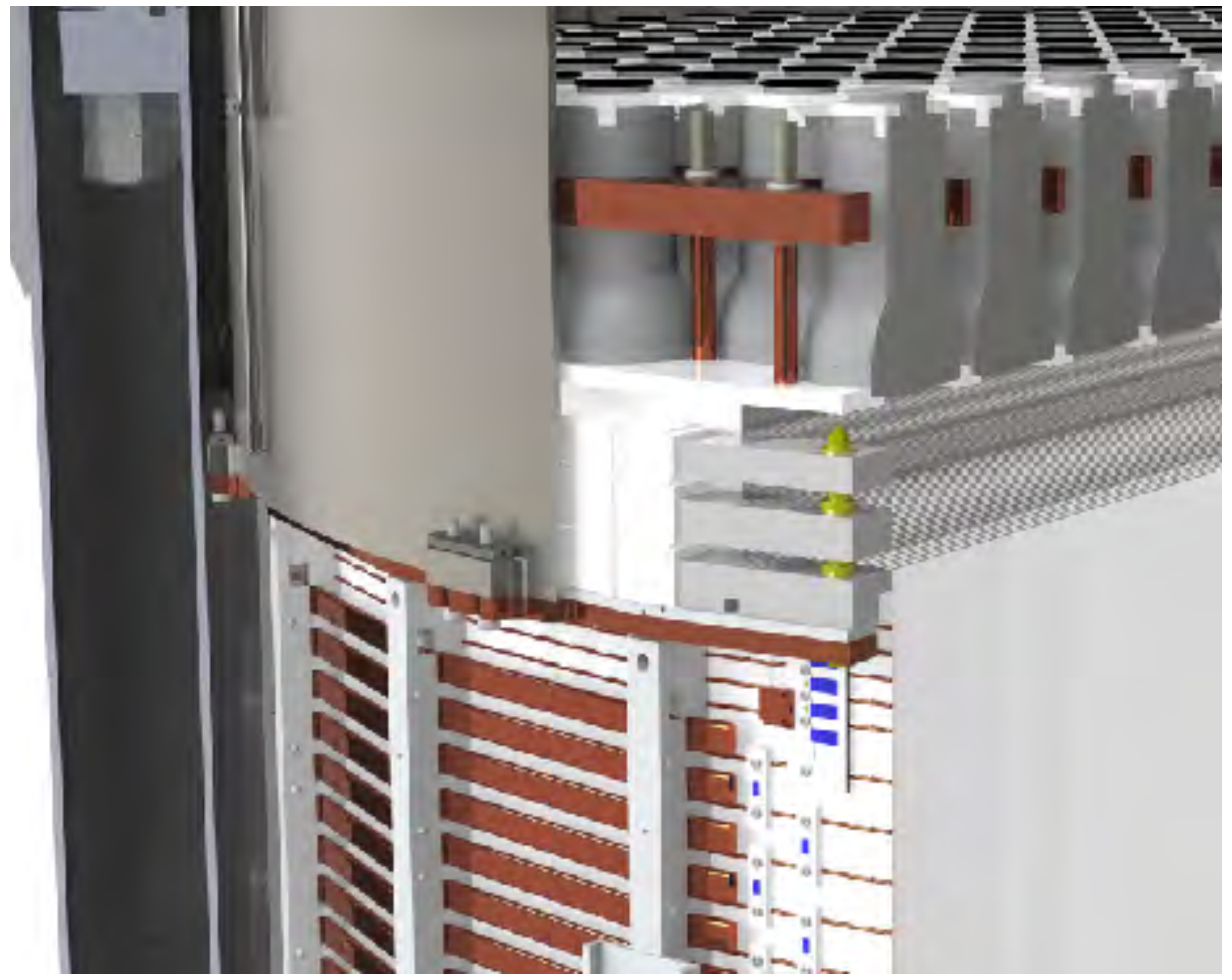
Plante et al, arXiv:2205.07336



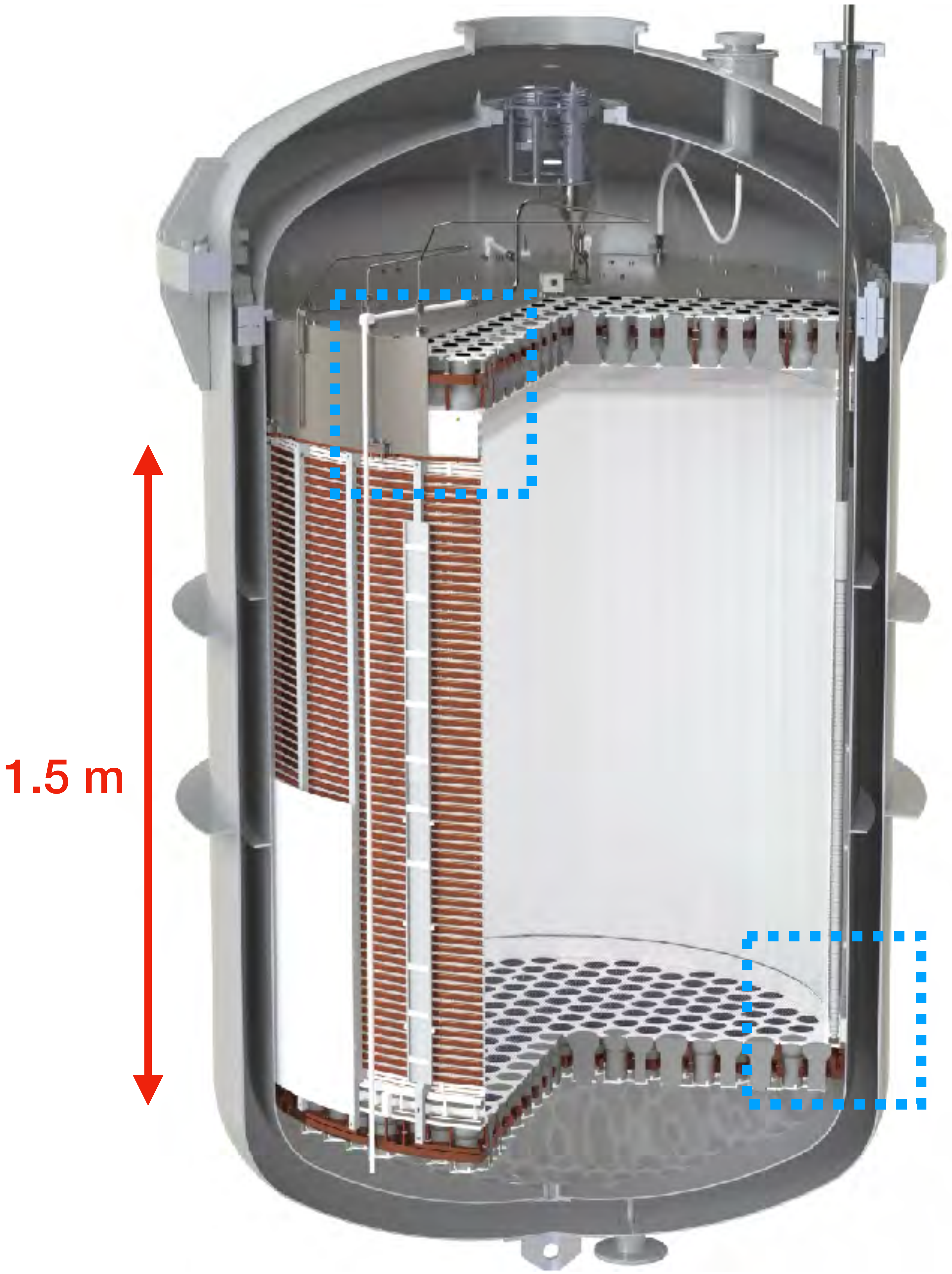
	Drift time [ms]	Electron lifetime [ms]
XENON1T	0.67	0.65
XENONnT	2.2	**~15**

ER / NR recoil discrimination: $\frac{S2}{S1}_{NR} < \frac{S2}{S1}_{ER}$

XENONnT Time Projection Chamber

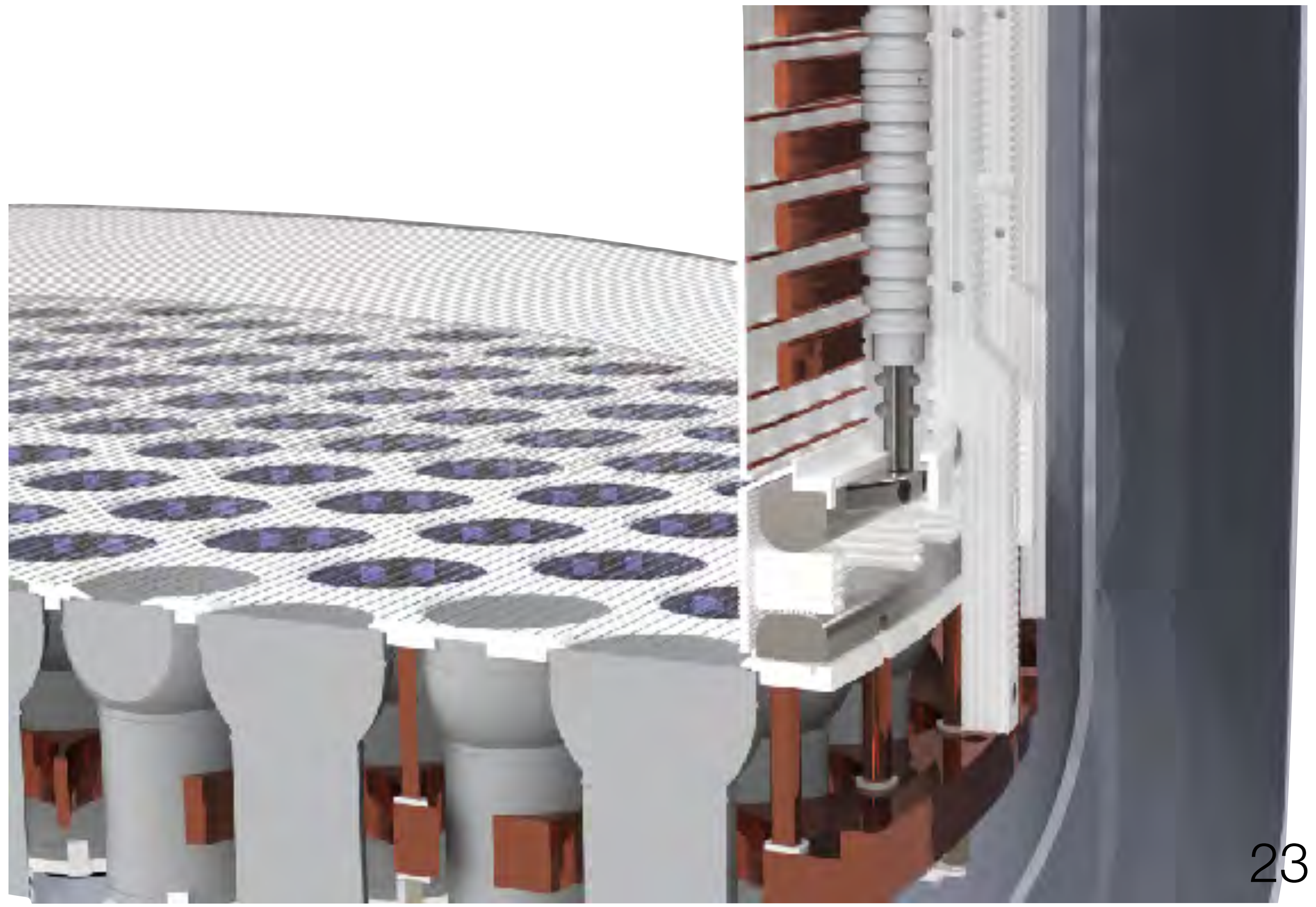


- 8.5 t of LXe total, 5.9 t in target
- 494 3-inch Hamamatsu R11410-3 PMTs
- 3 electrodes for drift and extraction fields
- 2 additional electrodes for PMT shielding

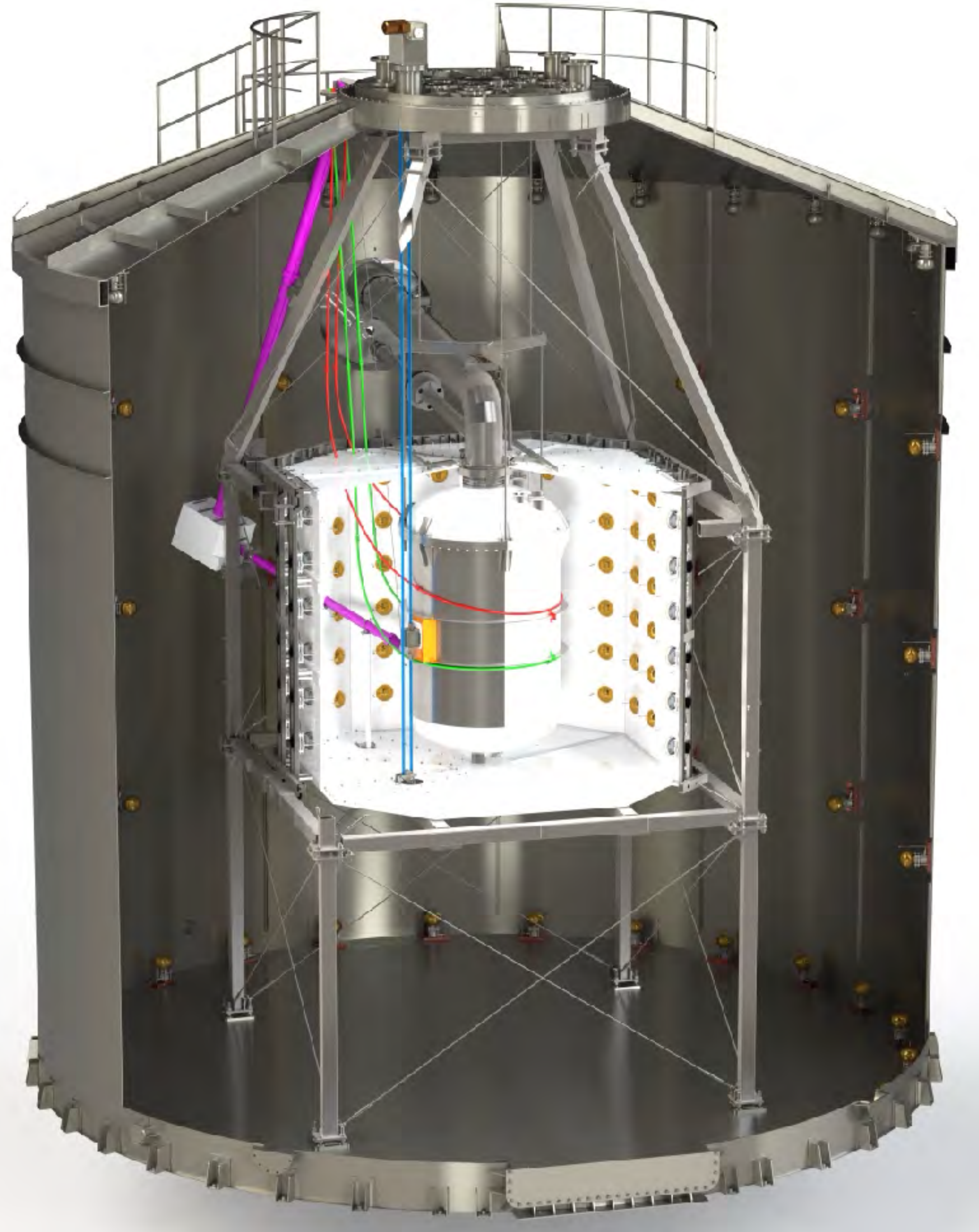


Calibration of detector response and efficiency:

- Internal sources: ^{37}Ar, ^{83m}Kr, ^{129m}Xe, ^{131m}Xe, ^{220}Rn
- External sources: AmBe, Th

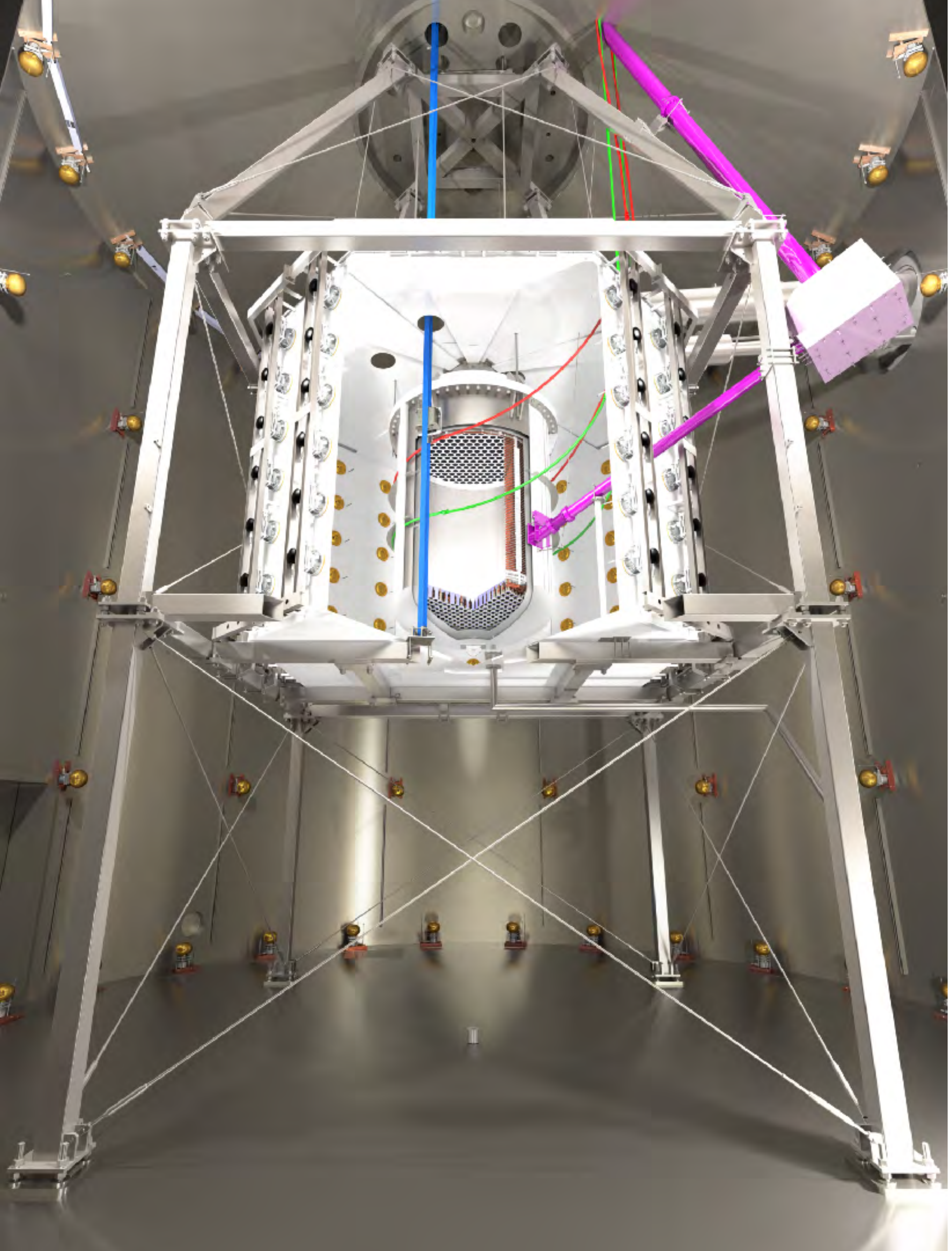
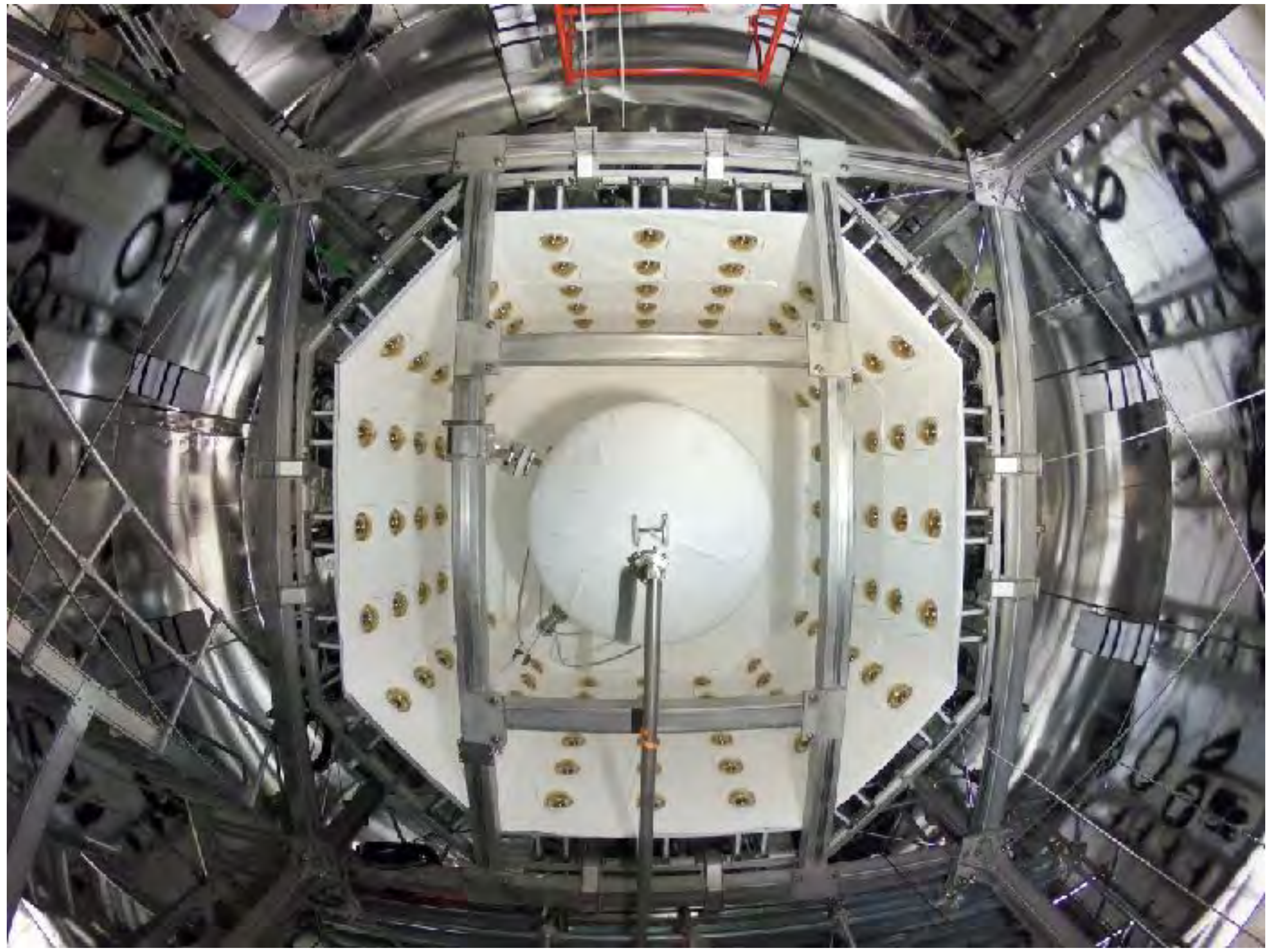


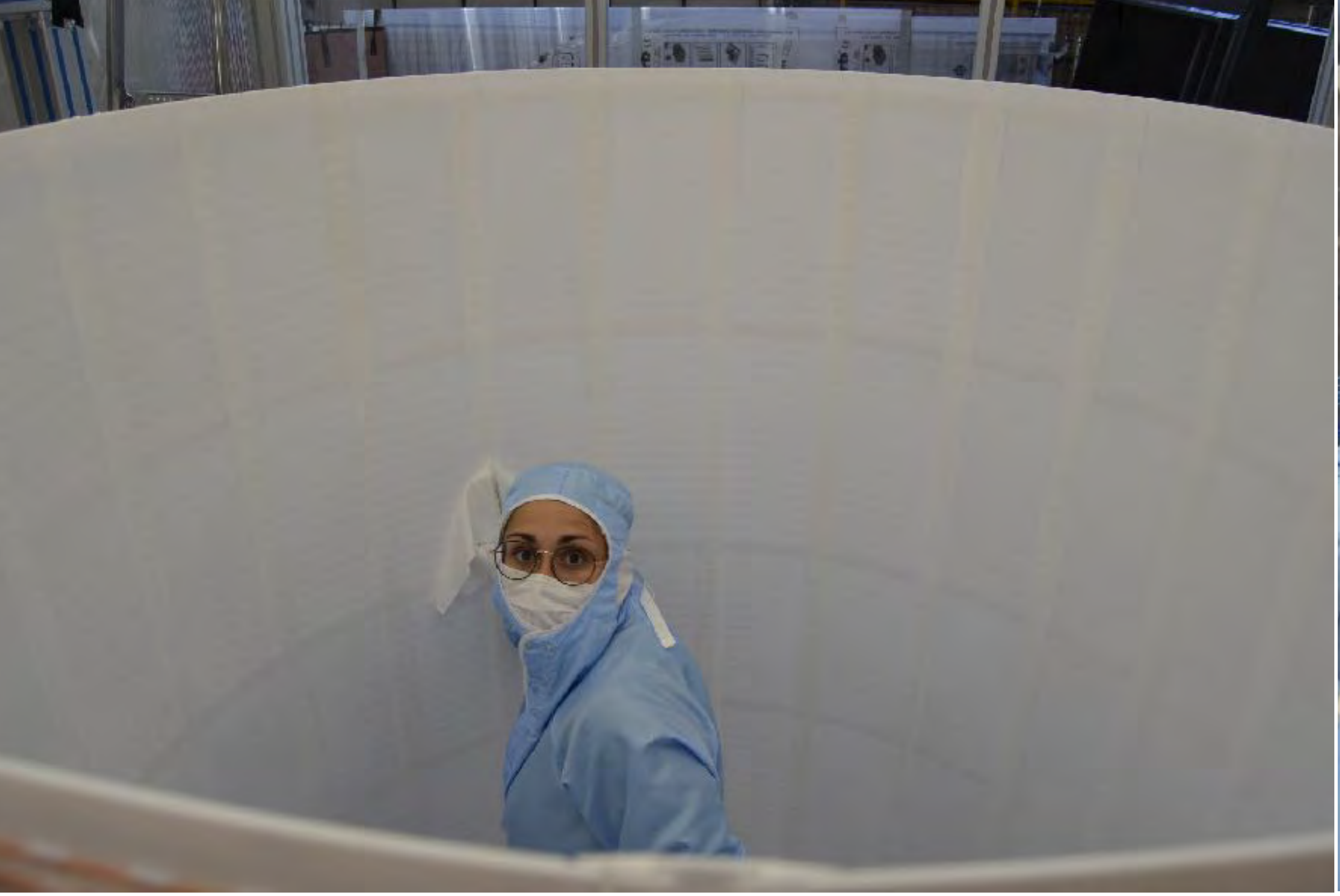
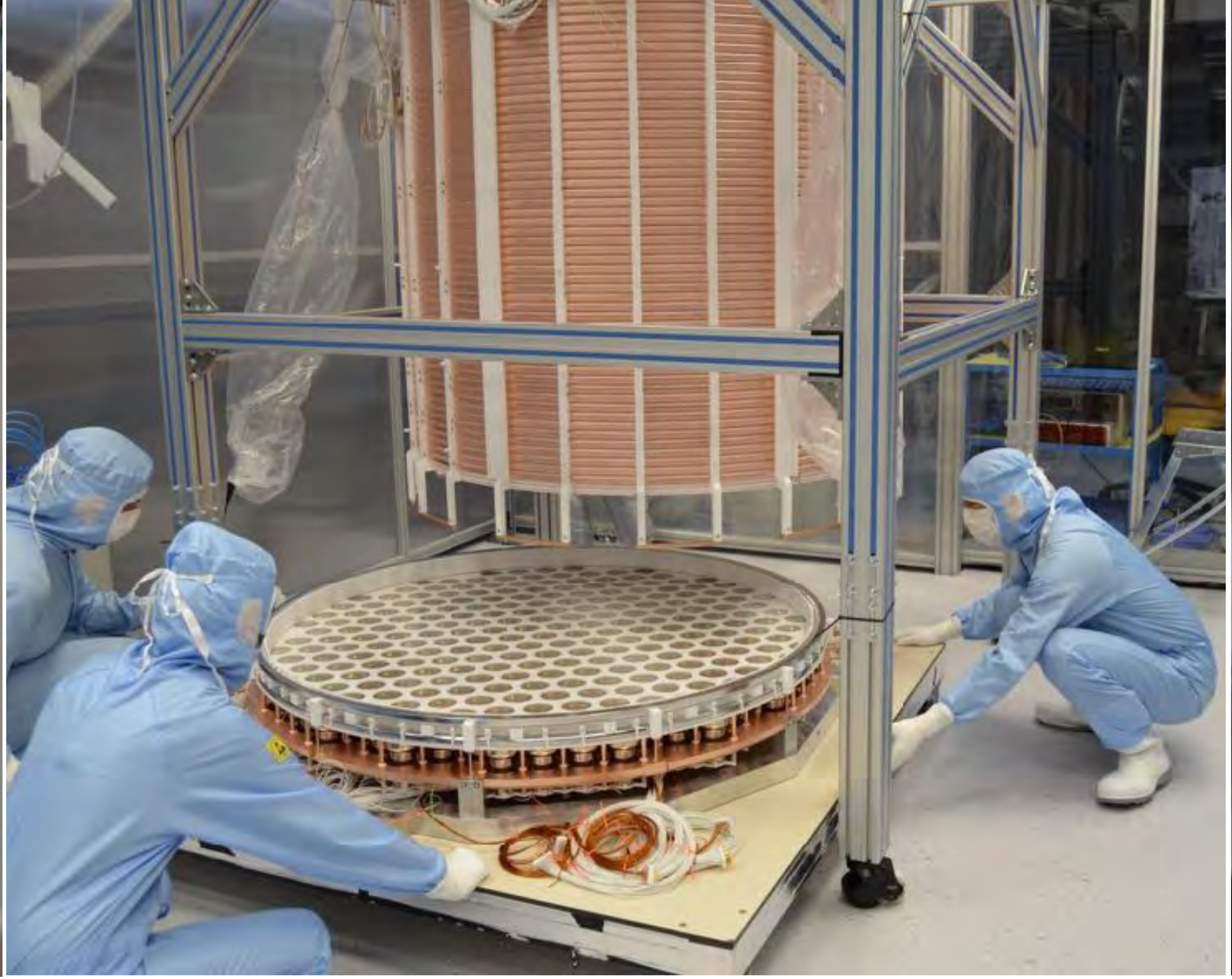
XENON1T → XENONnT Improvements



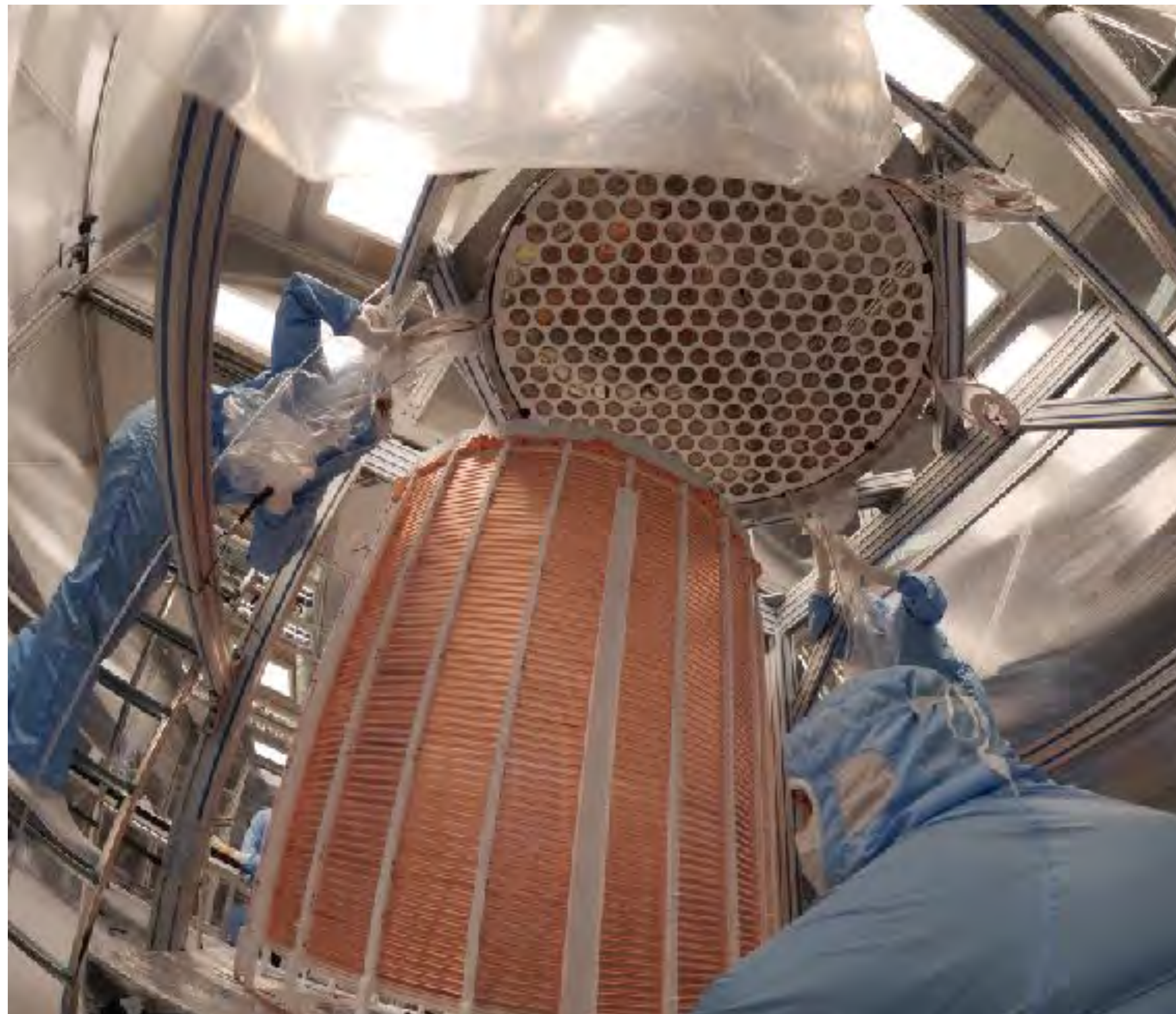
- Reused much of the XENON1T infrastructure
- Larger TPC: 2 t → 5.9 t LXe
- Improved cleanliness and radiopurity XENON, arXiv:2112.05629
- Liquid xenon purification system Plante et al, arXiv:2205.07336
- Radon distillation system Murra et al, arXiv:2205.11492
- Water Cherenkov neutron-veto
- New calibration systems and techniques
- Triggerless DAQ XENON, arXiv:2212.11032

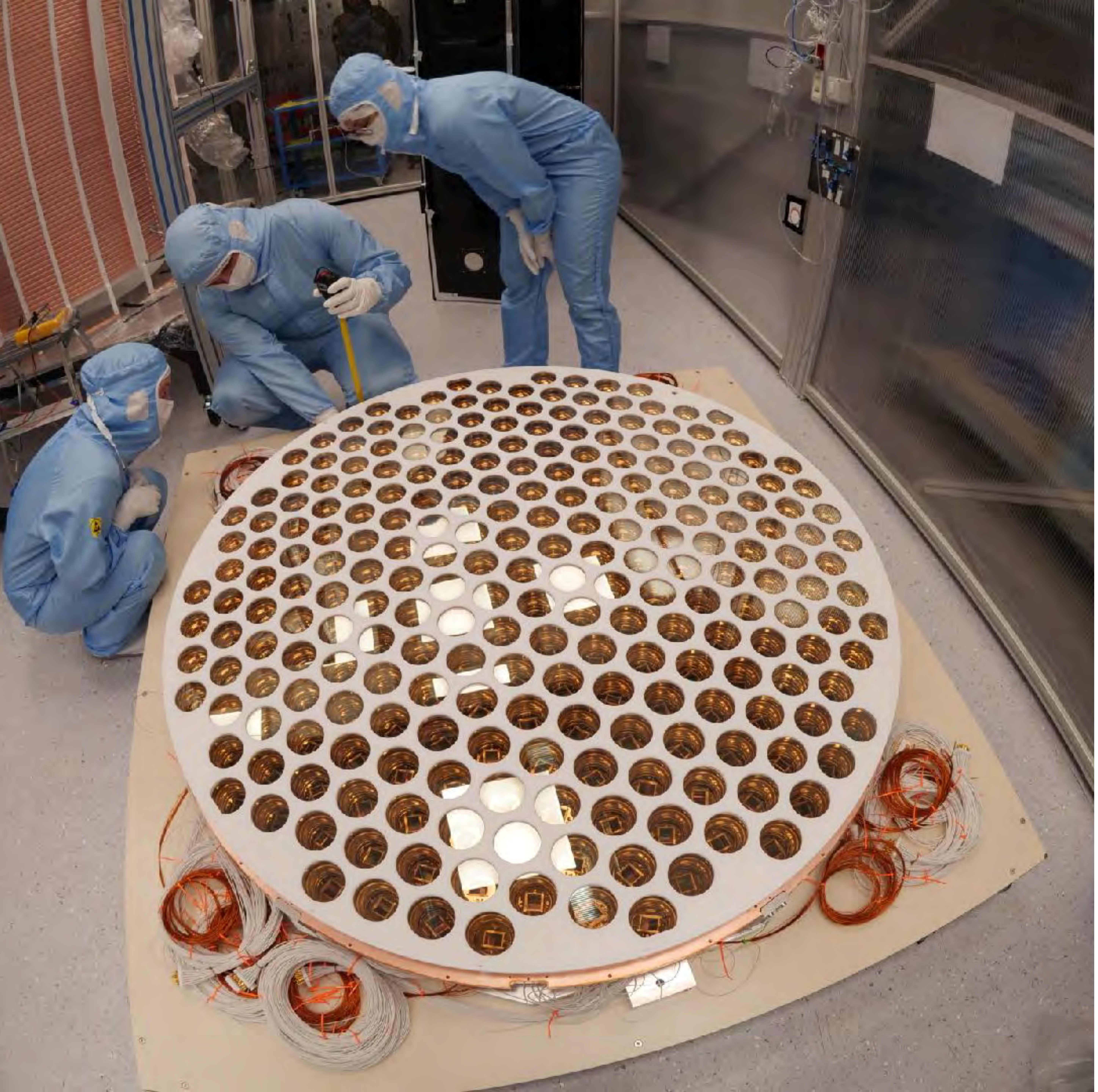

Xe
XENON
Matter Project

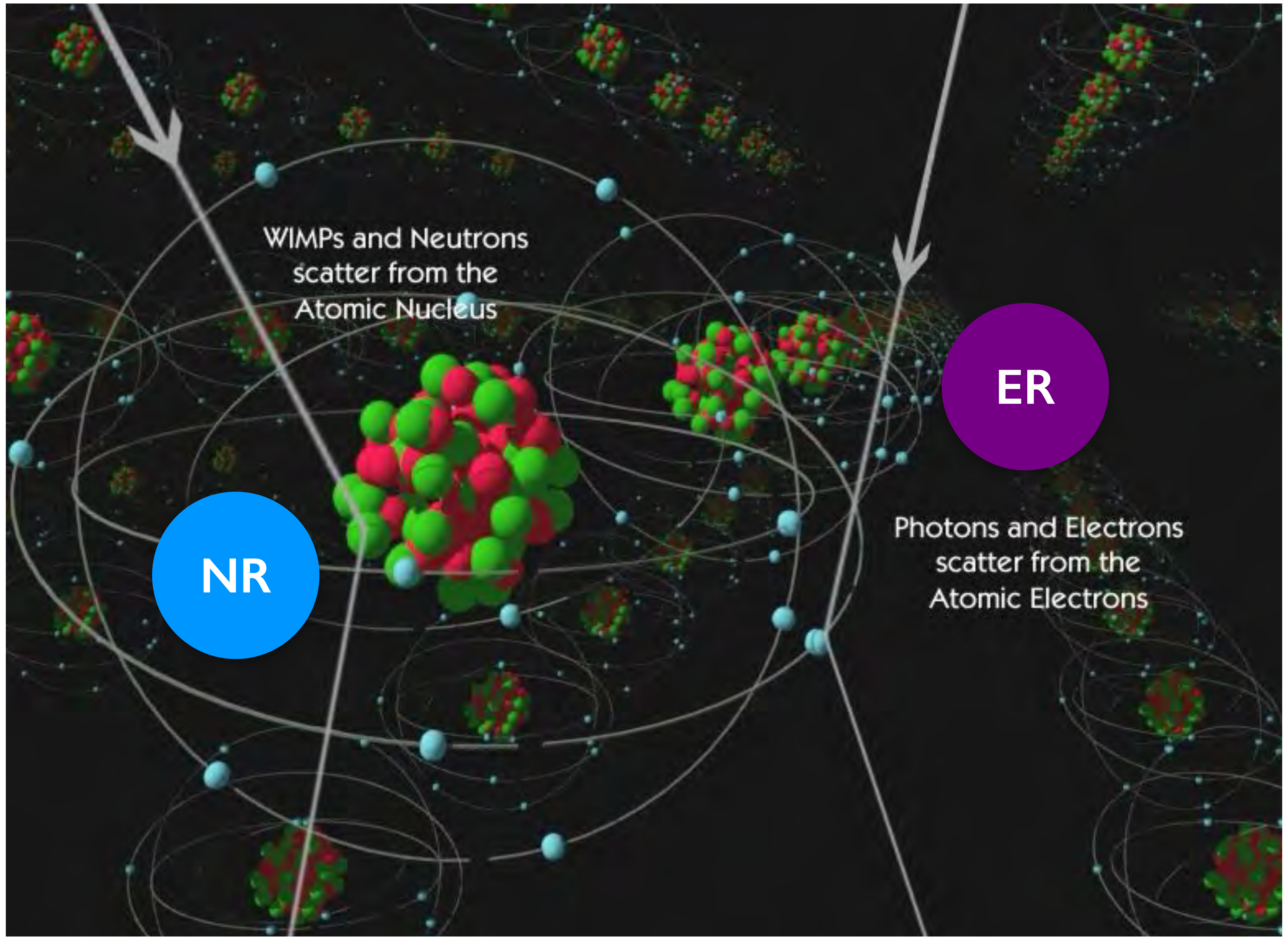











Main Backgrounds



Electronic recoils (ER):

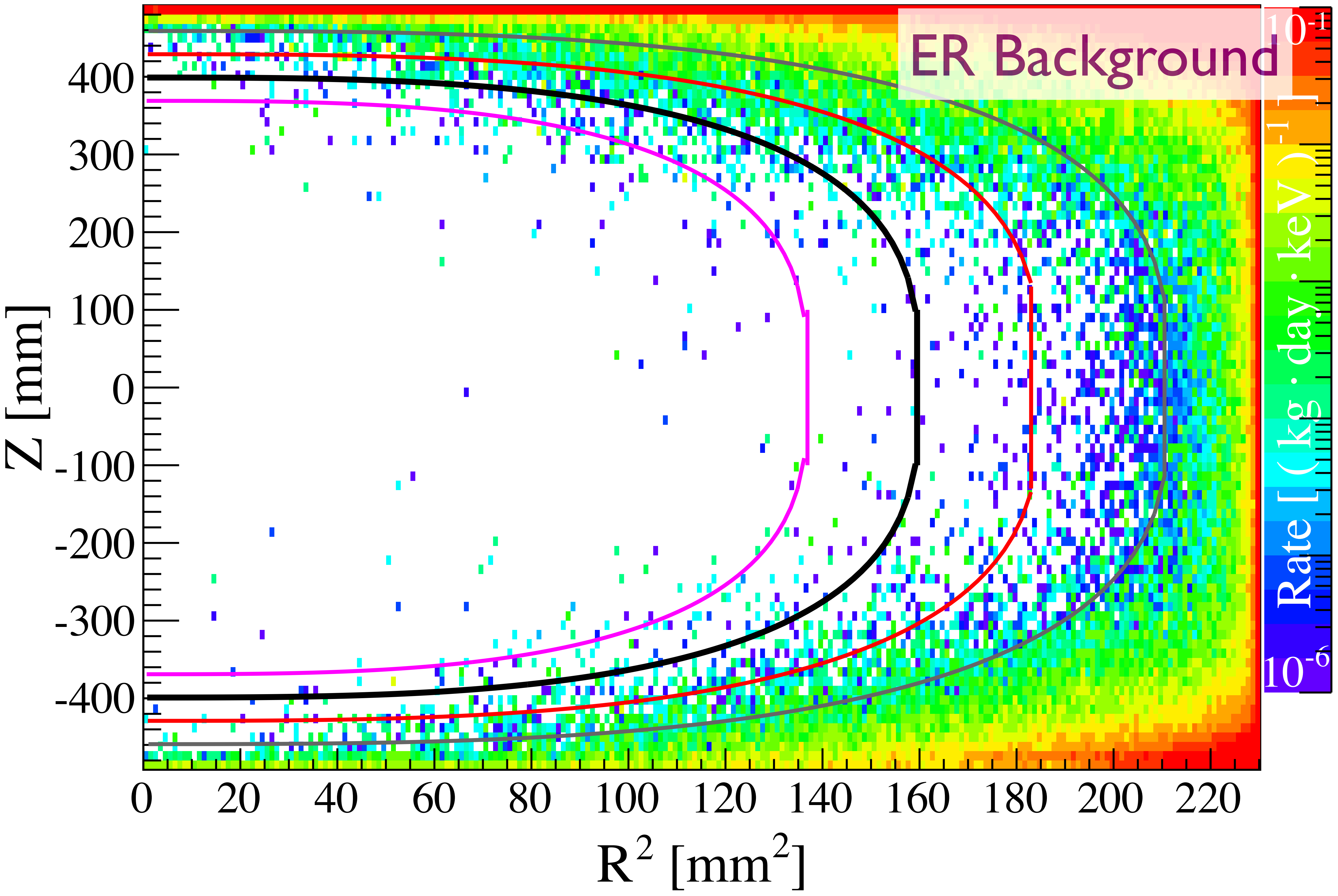
- **Materials**: Low energy Compton scatters from radioactive contamination in detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs
- **Solar neutrino** scattering off electrons
- **Intrinsic** contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe

Nuclear Recoils (NR):

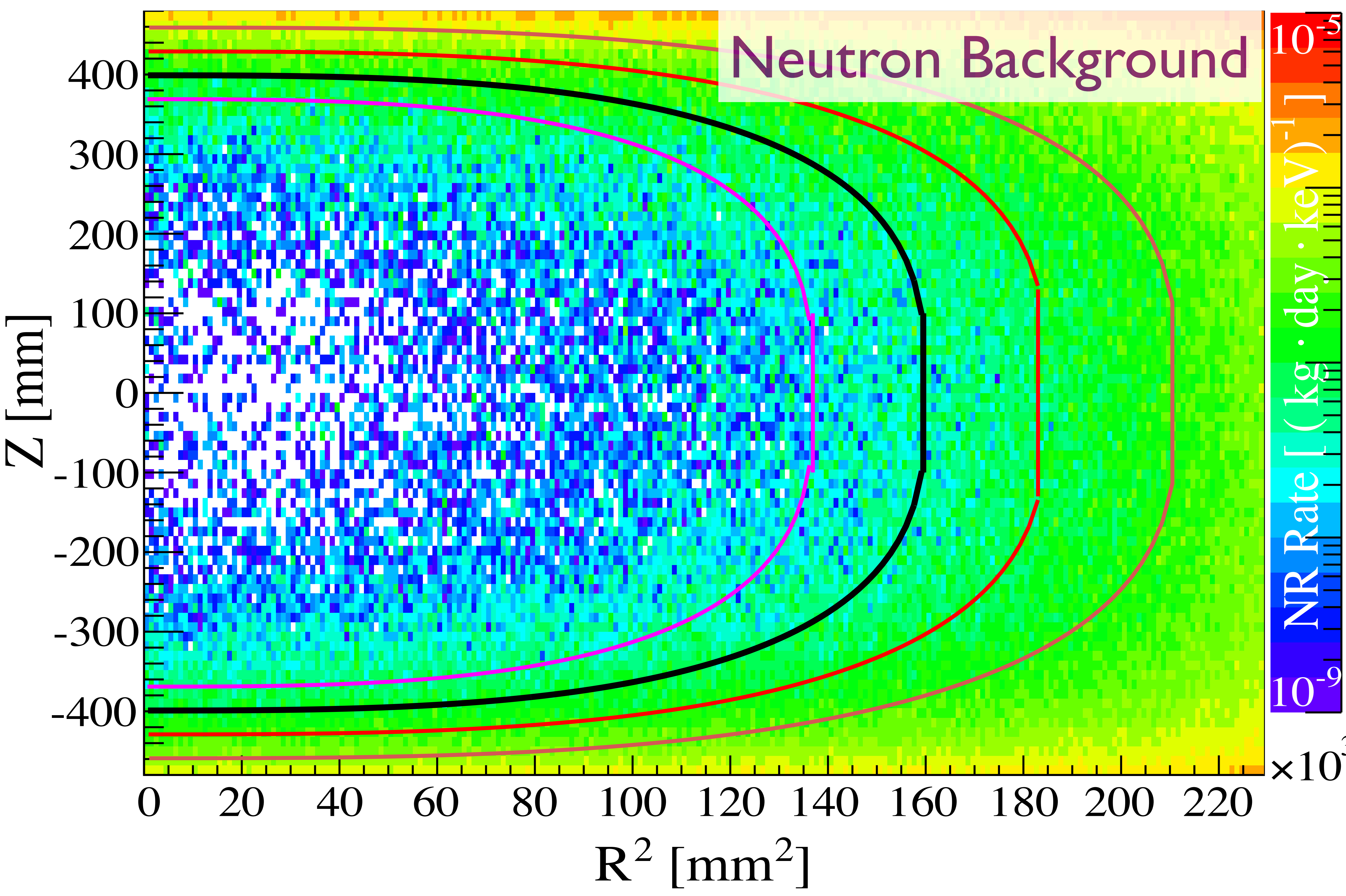
- **Radiogenic neutrons**: spontaneous fission and (α, n) reaction from the U and Th chains in detector components
- **Muon-induced neutrons**
- **Coherent scattering of neutrinos** (mostly solar) off Xe nuclei

LXe is self-shielding

Xe is a high-Z material

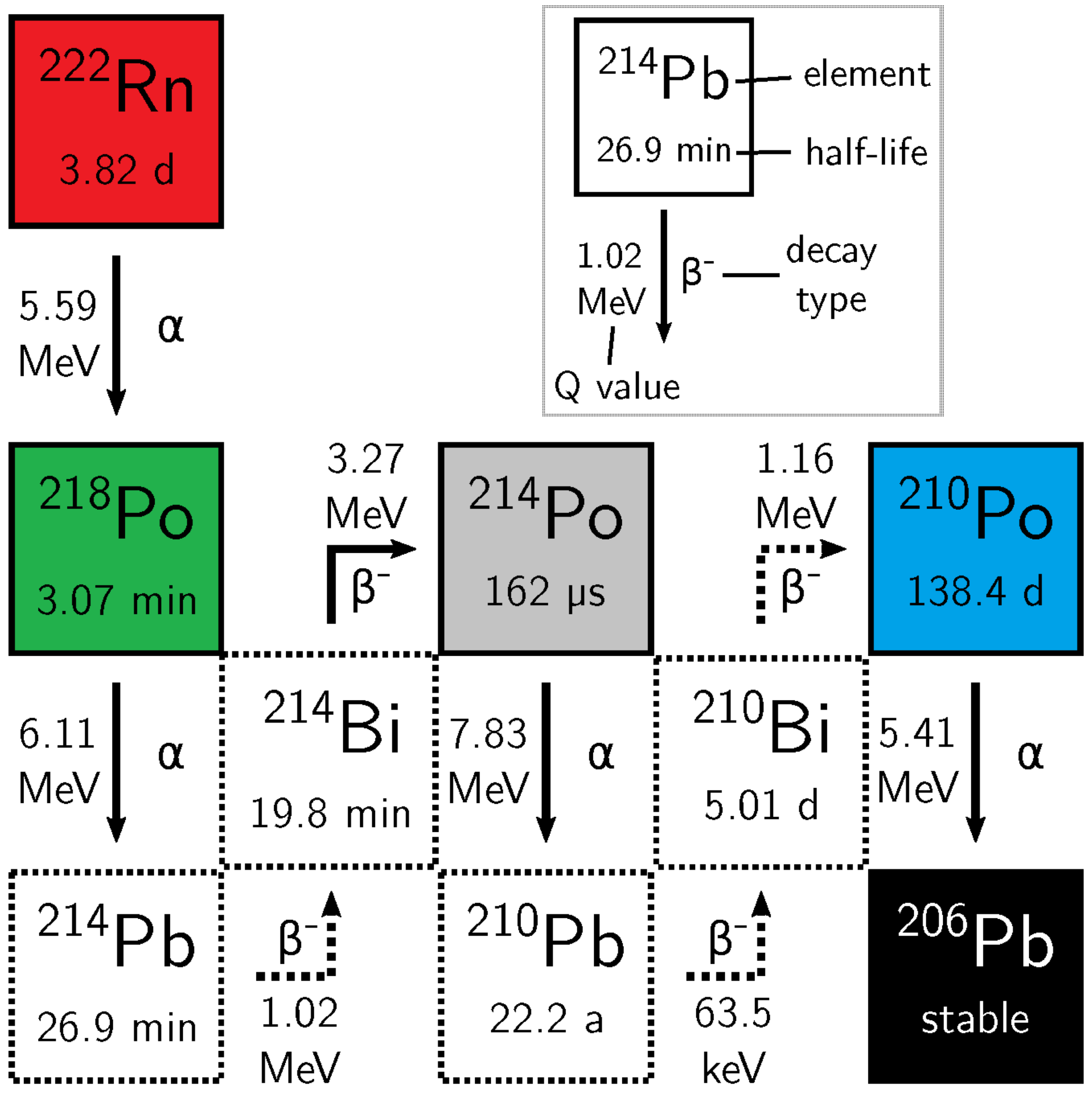


XENON1T



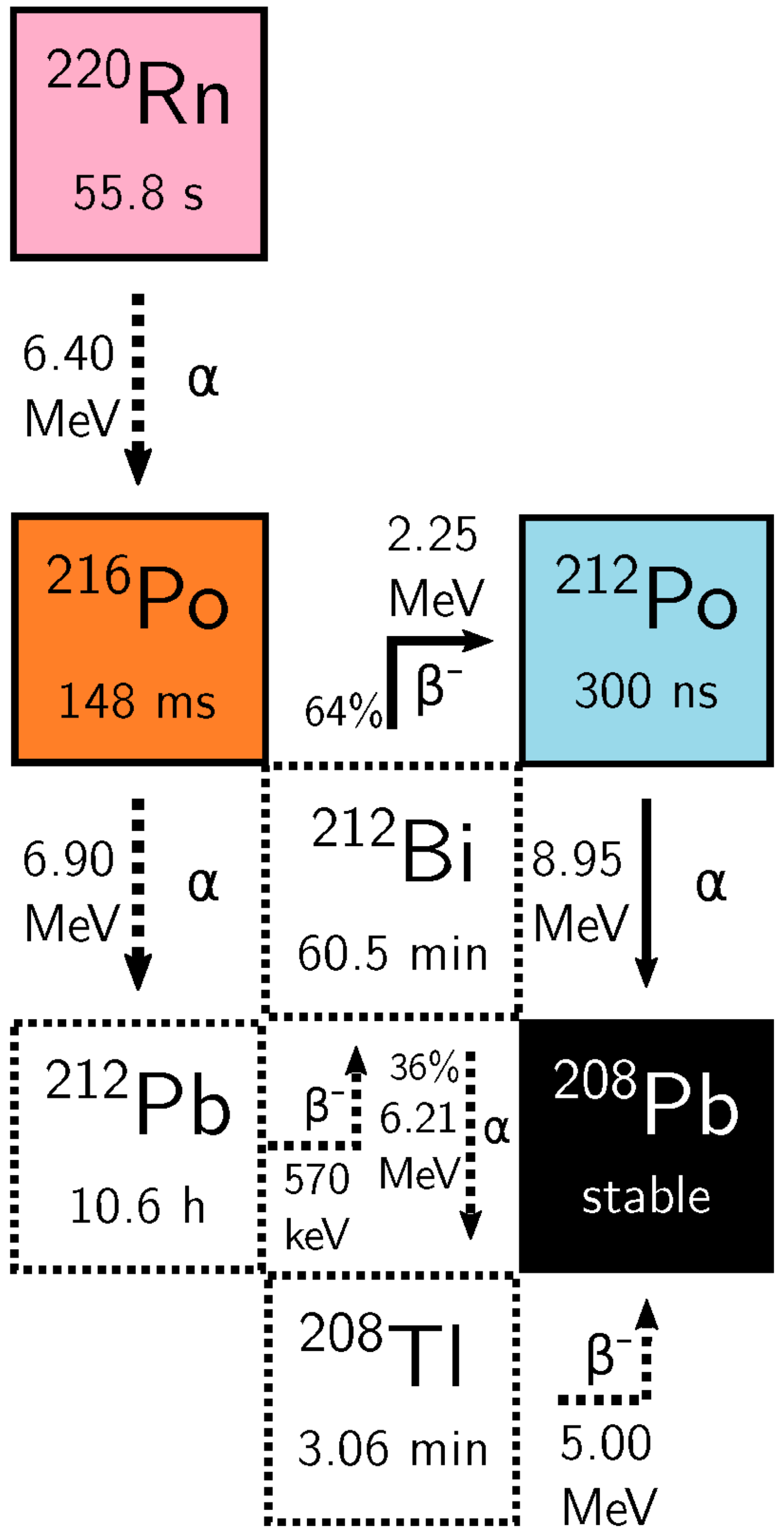
Radon decay chains

"Bad" Radon



Background

"Good" Radon



Calibration

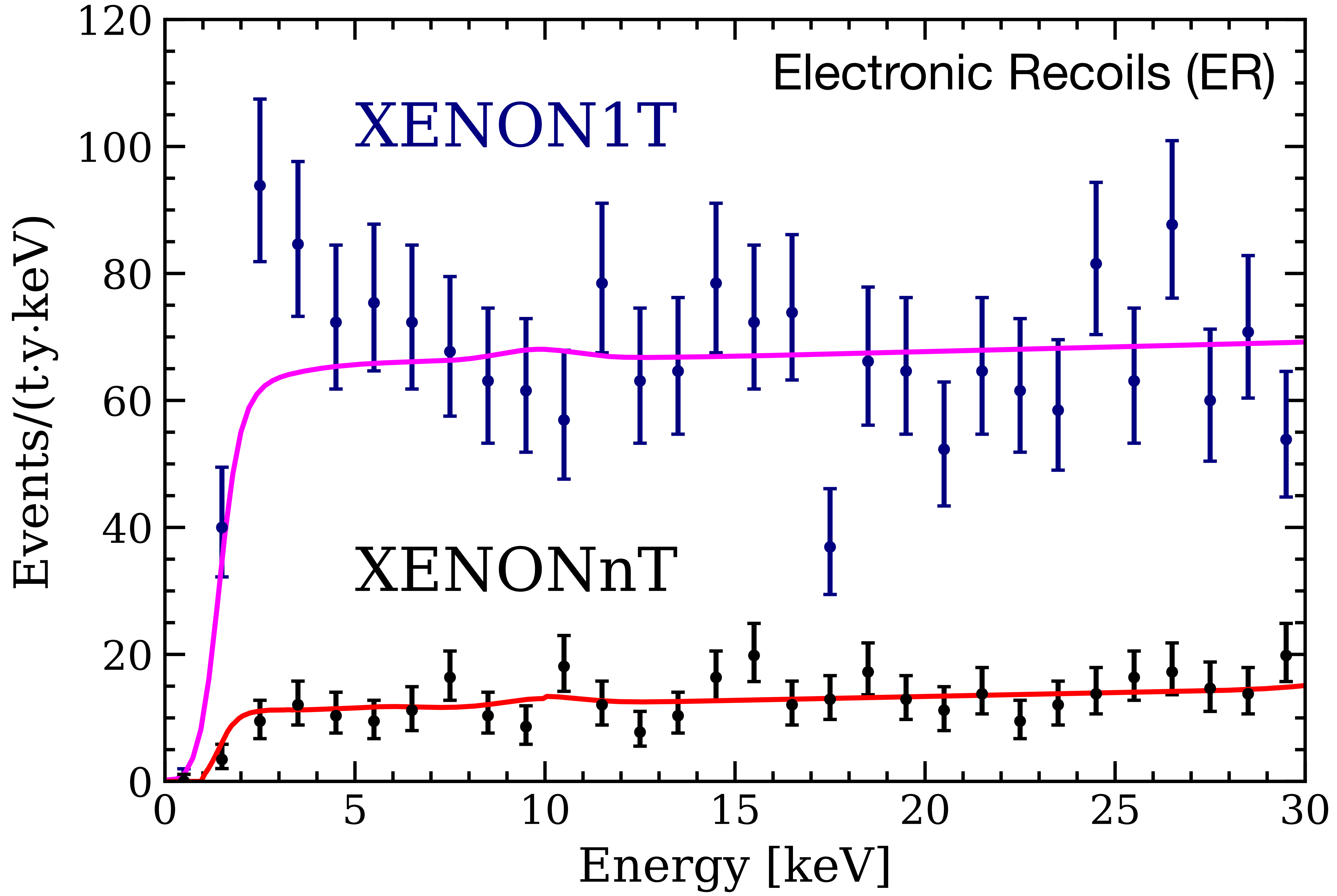
Background Mitigation

Murra et al, arXiv:2205.11492
XENON, arXiv:2112.05629

Background from intrinsic radioactive isotopes:

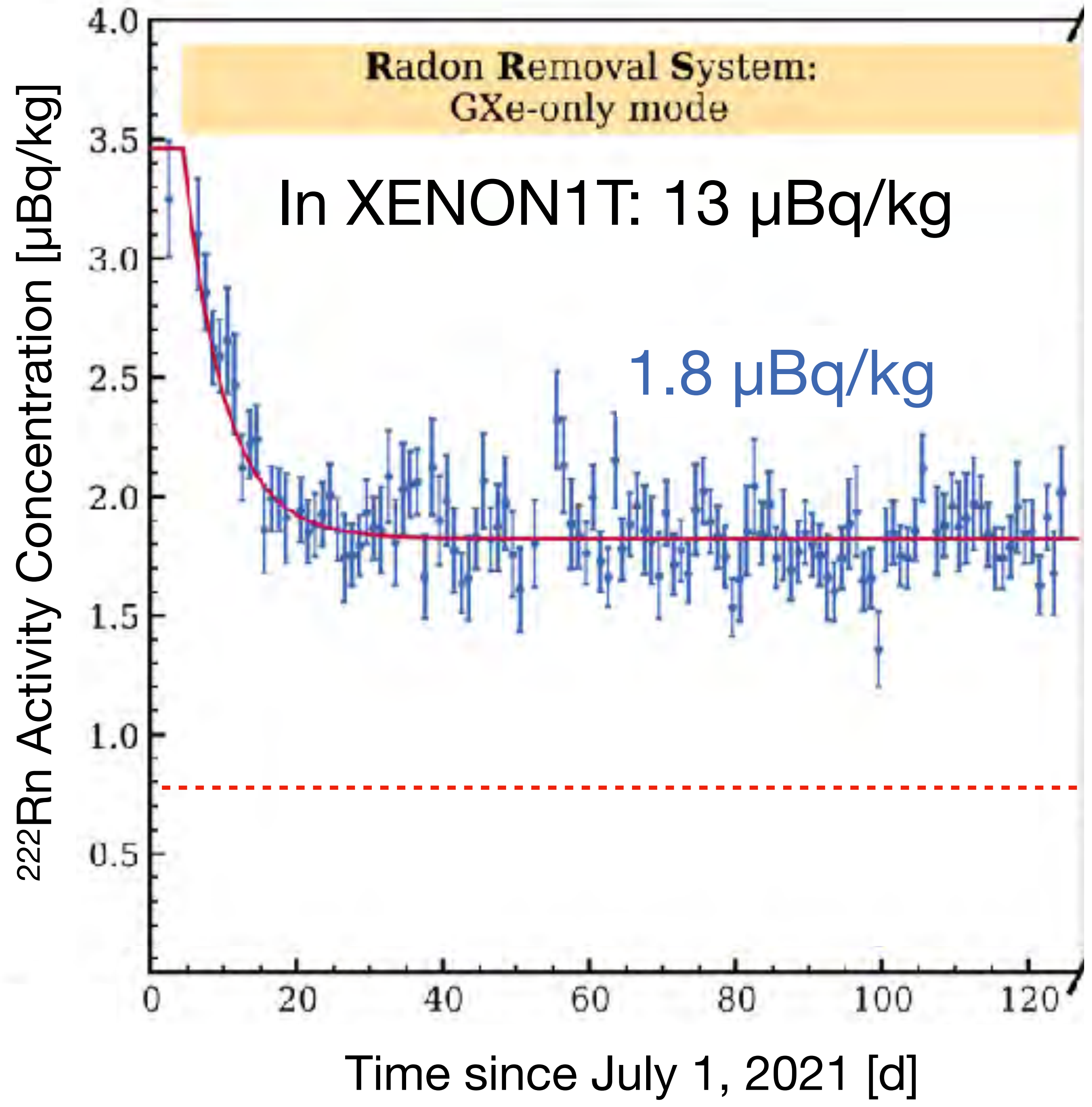
- ^{214}Pb (^{222}Rn daughter)
- ^{85}Kr

Careful screening, material selection and Continuous Radon Removal through distillation



(15.8 ± 1.3) events / (keV × t × yr)

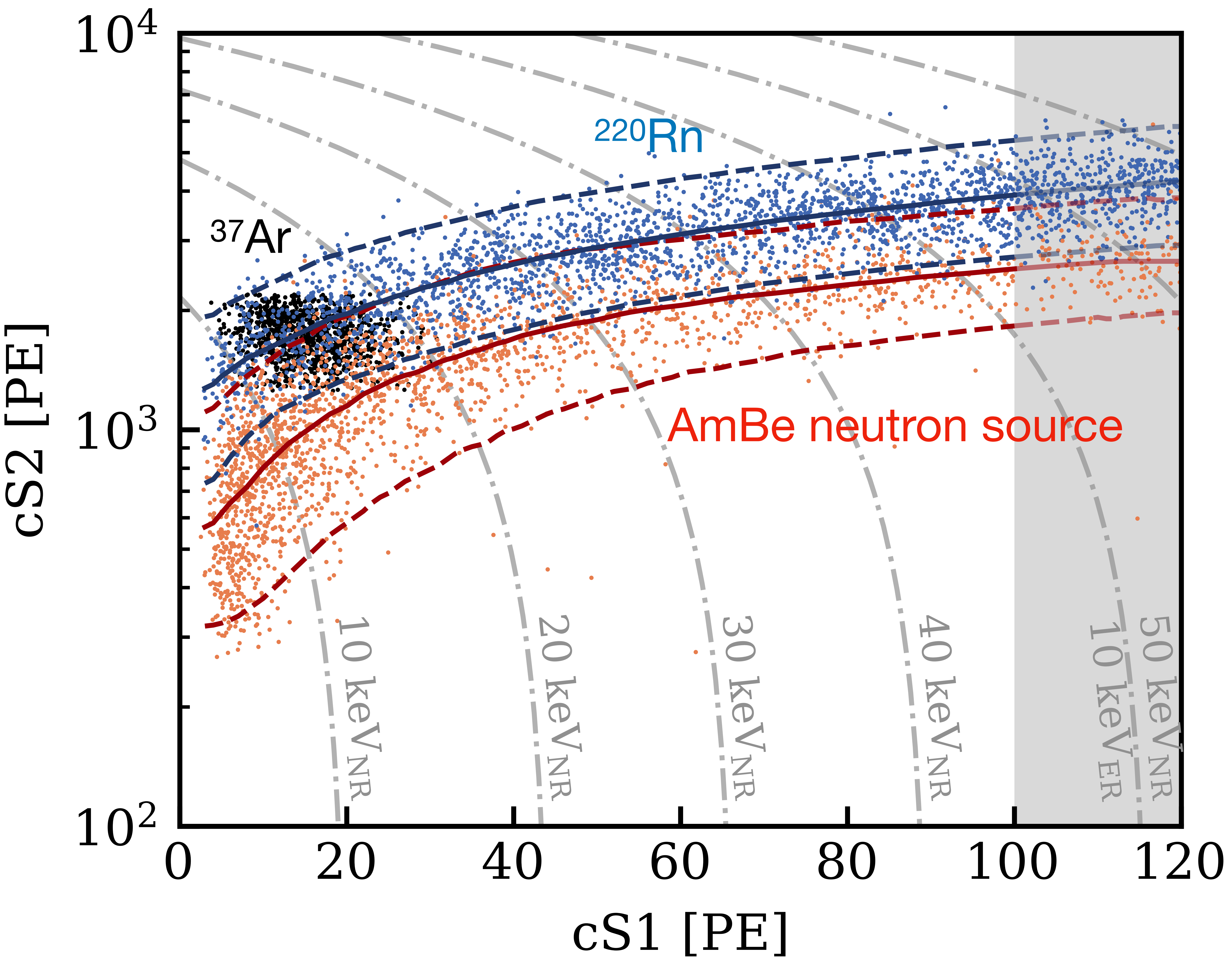
This Run (SR0)



Background ~5x smaller than in XENON1T

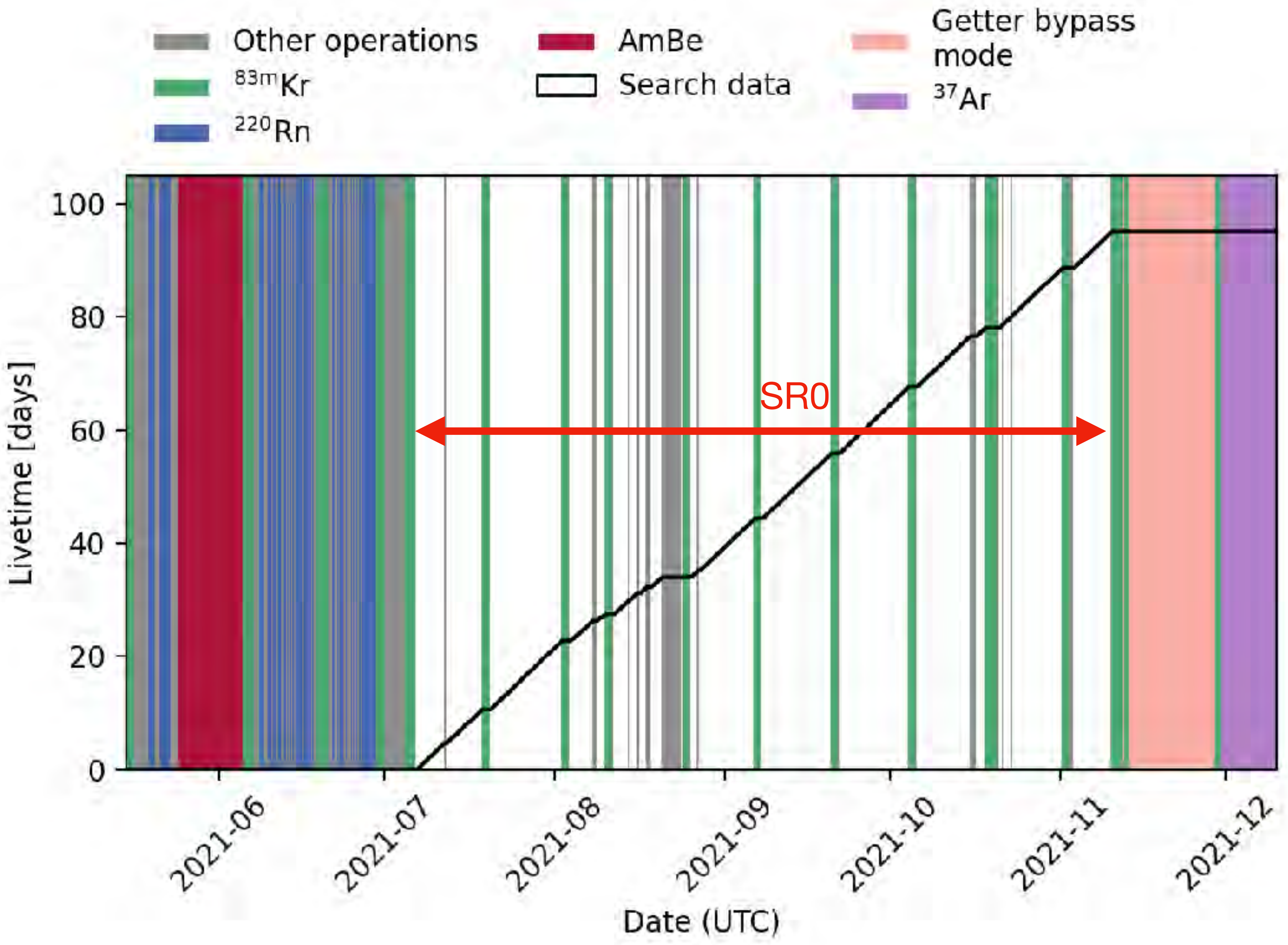
XENON, PRL 120, 161805 (2022)

Calibration of ER / NR Response



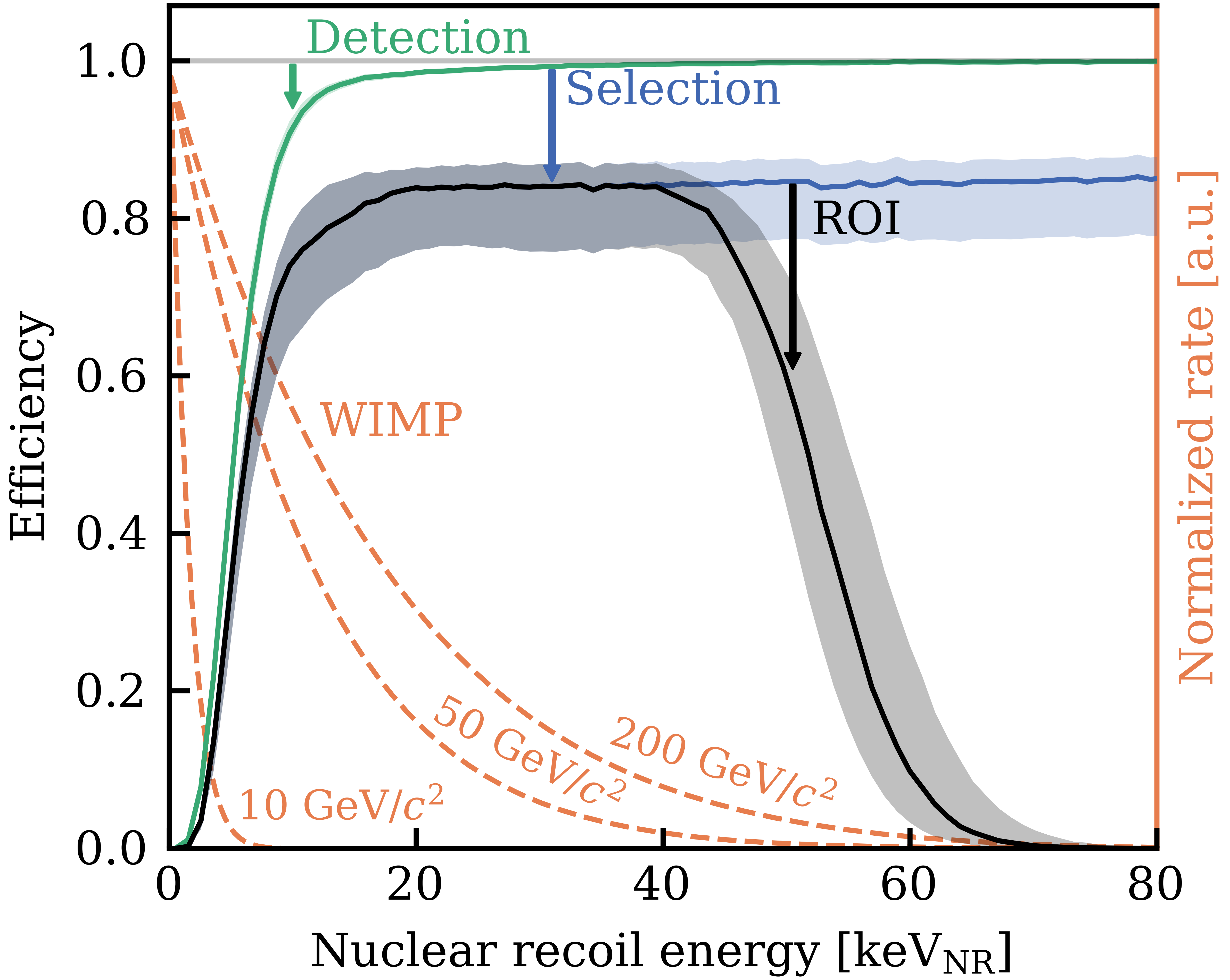
- **Calibration of ER** response using ^{220}Rn
  - Gives approximately flat energy spectrum
  - Used to validate cut acceptance
- Detector performance at low energy with ^{37}Ar
  - Mono-energetic line at 2.8 keV
  - High statistics
  - Removed via distillation column ($T_{1/2}$ = 35 d)
- **Calibration of NR** response with AmBe
- ER model based on combined fit
- Uncertainties propagated via Principal Component Analysis

Data Set: Science Run 0



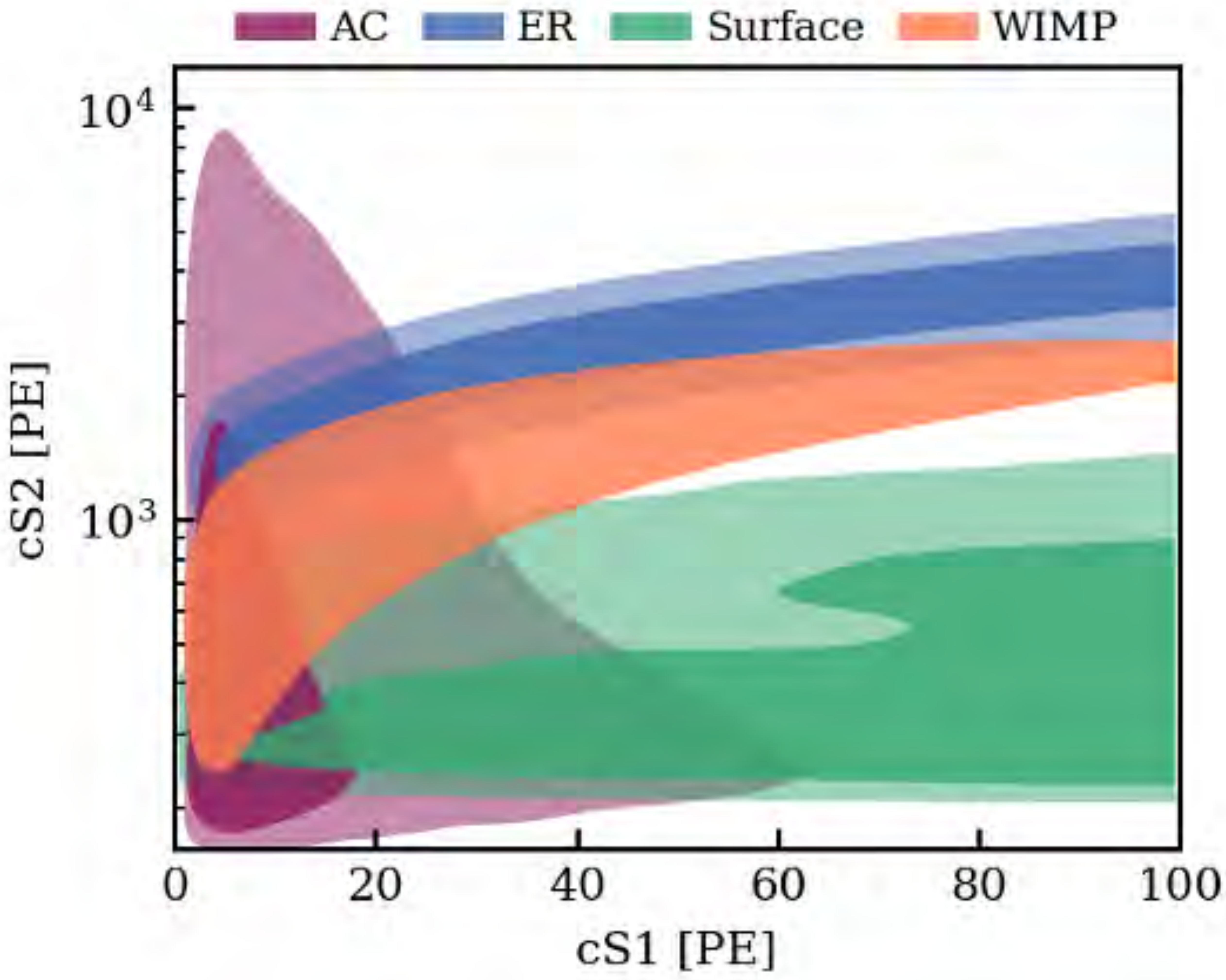
- SR0 Nuclear Recoil Search Data
- July 6 to Nov 10, 2021 (97.1 days)
- 95.1 days lifetime corrected
- (4.18 ± 0.13) tonne Fiducial Volume
- Exposure: 1.1 tonne-year
- Blind analysis

Efficiency



- Detection efficiency:
  - Threshold driven by 3-fold PMT coincidence for S1
  - Full waveform simulation
  - Data-driven methods from ^{83m}Kr and ^{37}Ar
- Data quality selection evaluated with calibration data
- ROI defined to fully contain WIMP spectra
  - cS1 [0 pe, 100 pe]
  - cS2 [$10^{2.1}$ pe, $10^{4.1}$ pe]
- Total acceptance > 10% for [3 keV_{NR}, 60 keV_{NR}]

Backgrounds



- Electronic Recoil (ER): Dominated by beta decay of ^{214}Pb from ^{222}Rn
- Accidental Coincidences (AC): random pairing of small S1 and S2 signals
- Surface/Wall: ^{210}Pb plate-out on the PTFE wall of the TPC → ^{210}Po α-decays
- Nuclear Recoil backgrounds:
    - CEvNS
    - Neutrons

WIMP Results

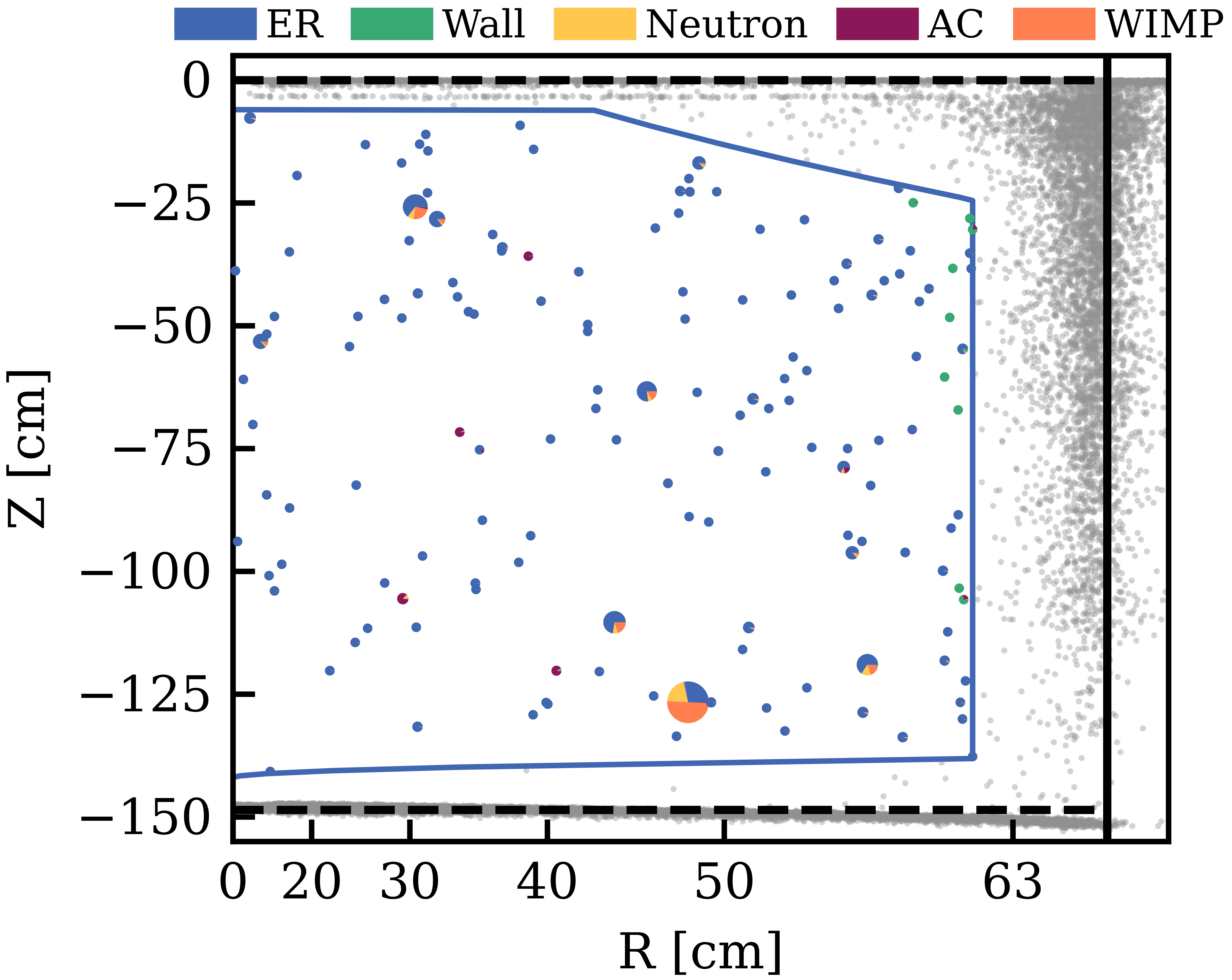
	Expectation
ER	134
Neutrons	$1.1^{+0.6}_{-0.5}$
CEvNS	0.23 ± 0.06
AC	4.3 ± 0.2
Wall	14 ± 3
Total	154
WIMP	
Observed	

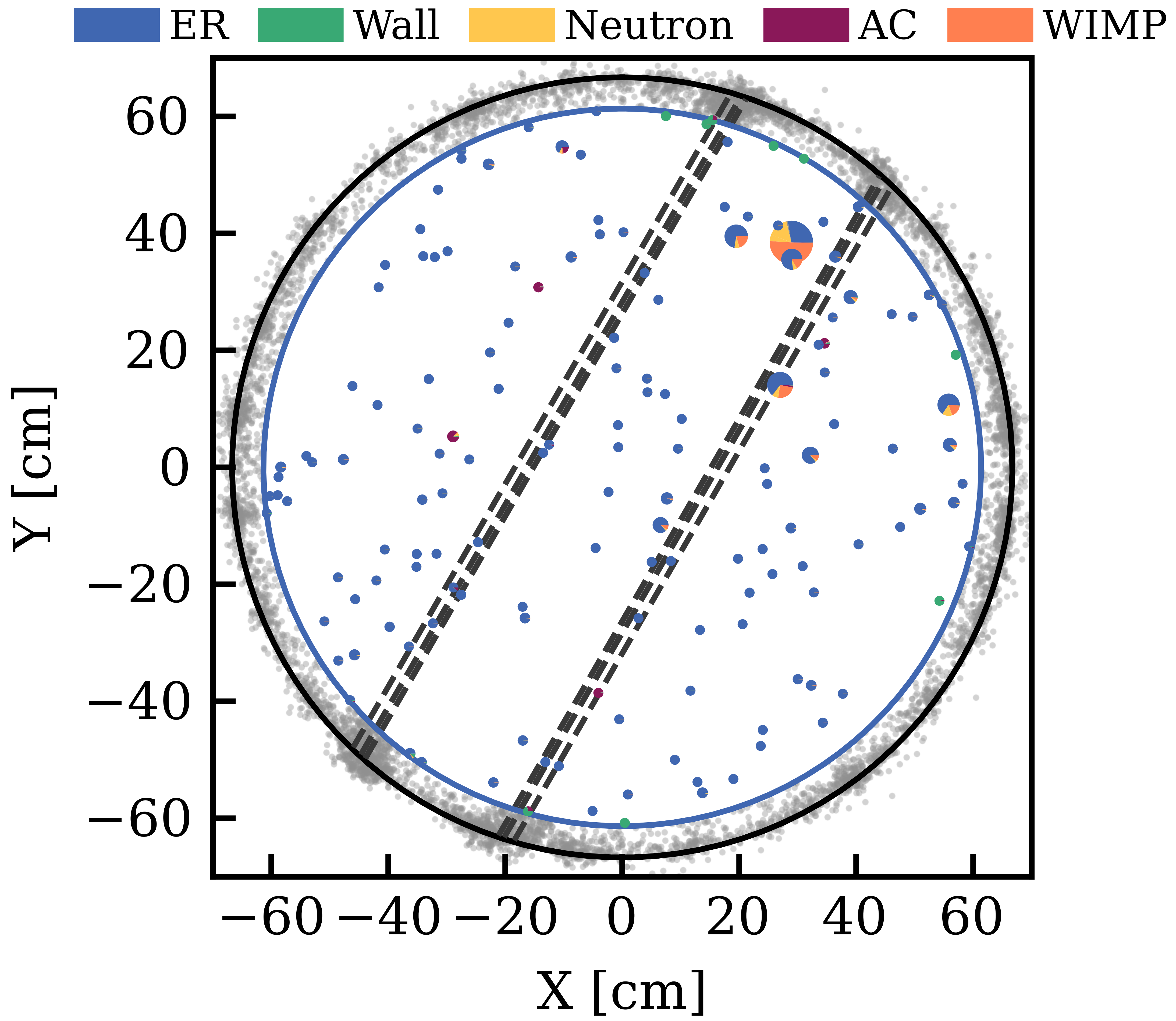
152 events in R

Best fit indicate

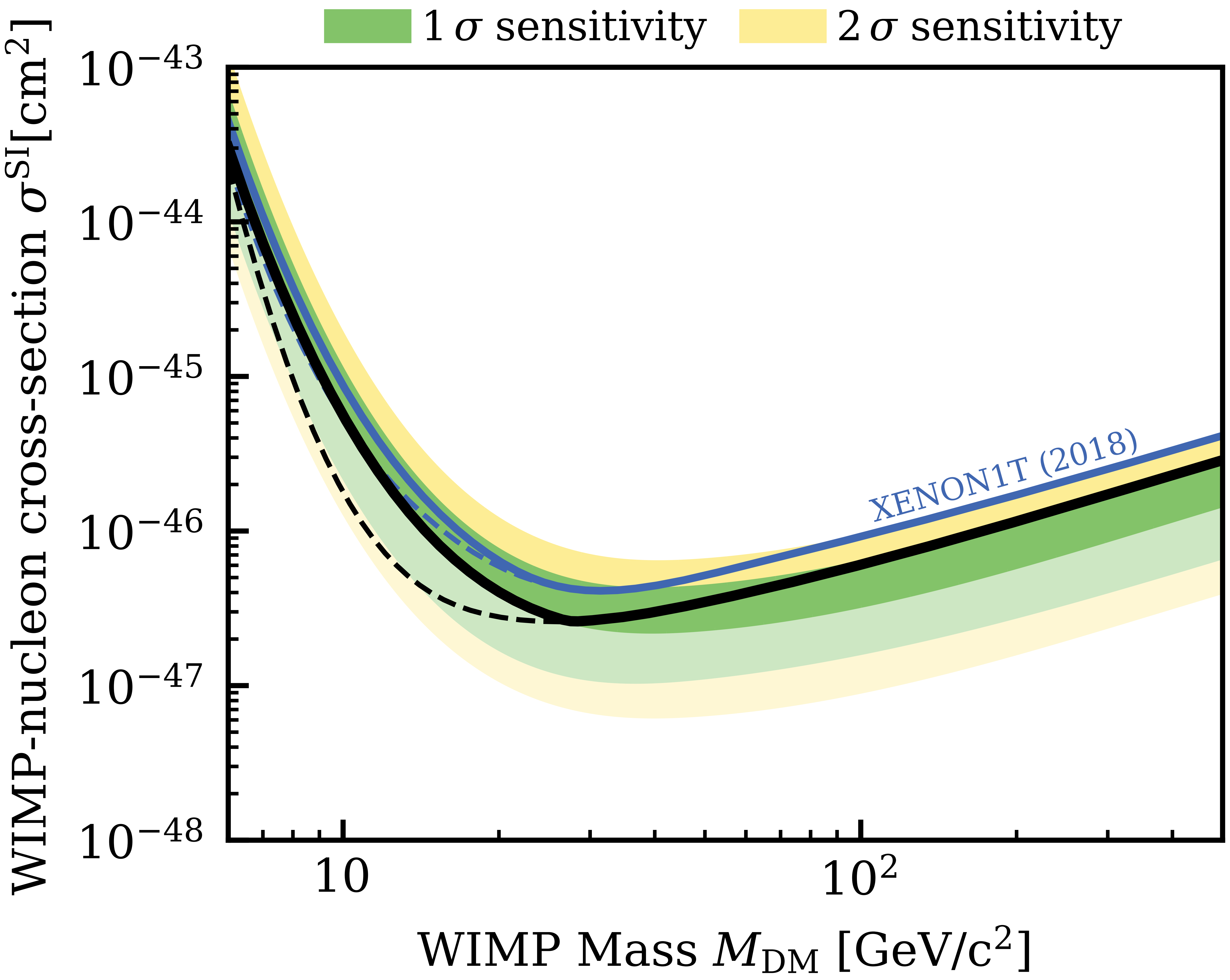
WIMP Results

- XY asymmetry in unblinded data
- Not observed in corrections, quality selection or calibration data





WIMP Spin-Independent Results



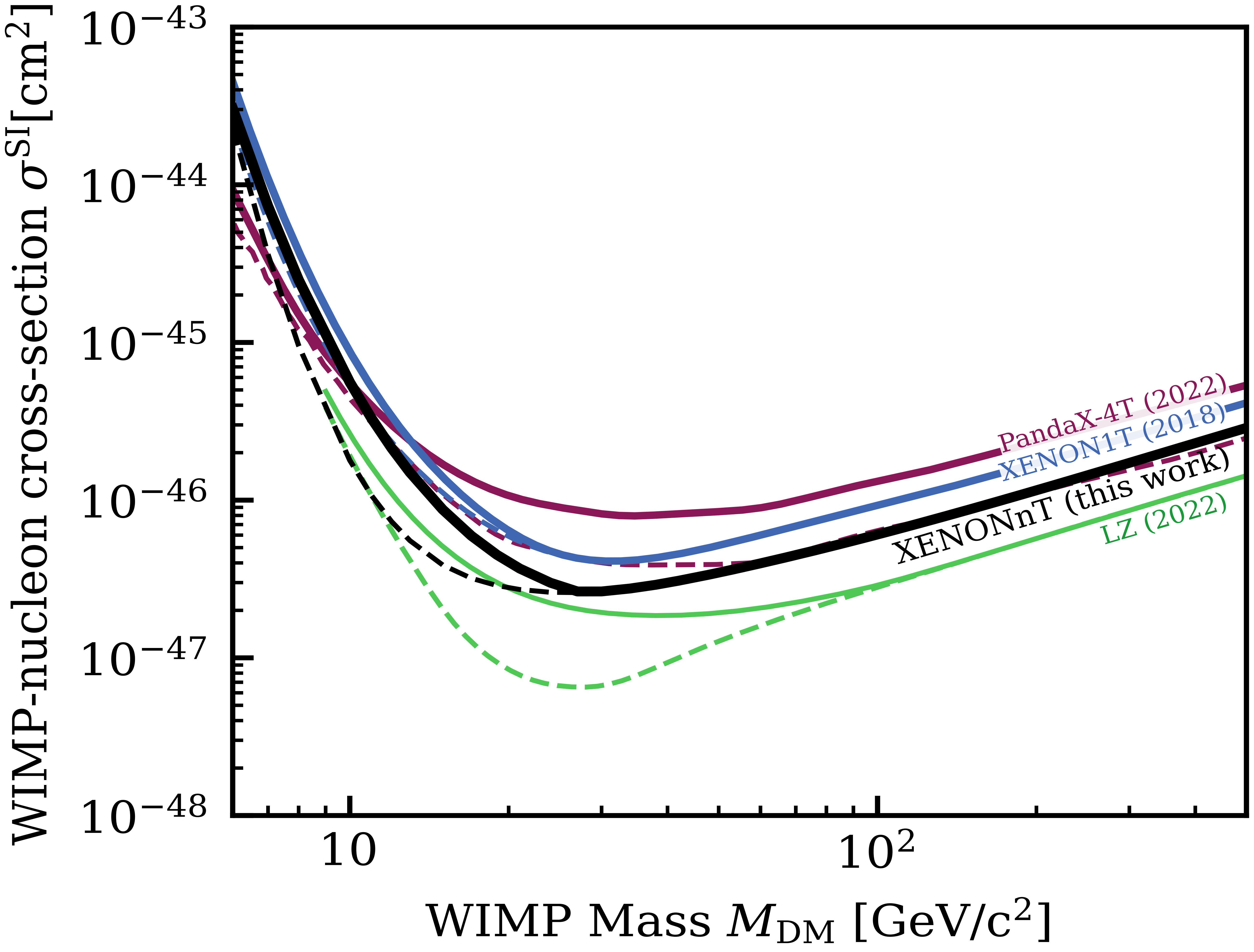
XENONnT 90% C.L. Power-Constrained Limit*

XENON, PRL 121, 111302 (2018)

*) arXiv:1105.3166, arXiv:2105.00599 with 50% [median] rejection power

WIMP Spin-Independent Results

Same conservative power-constraint applied to results of other recent LXe experiments

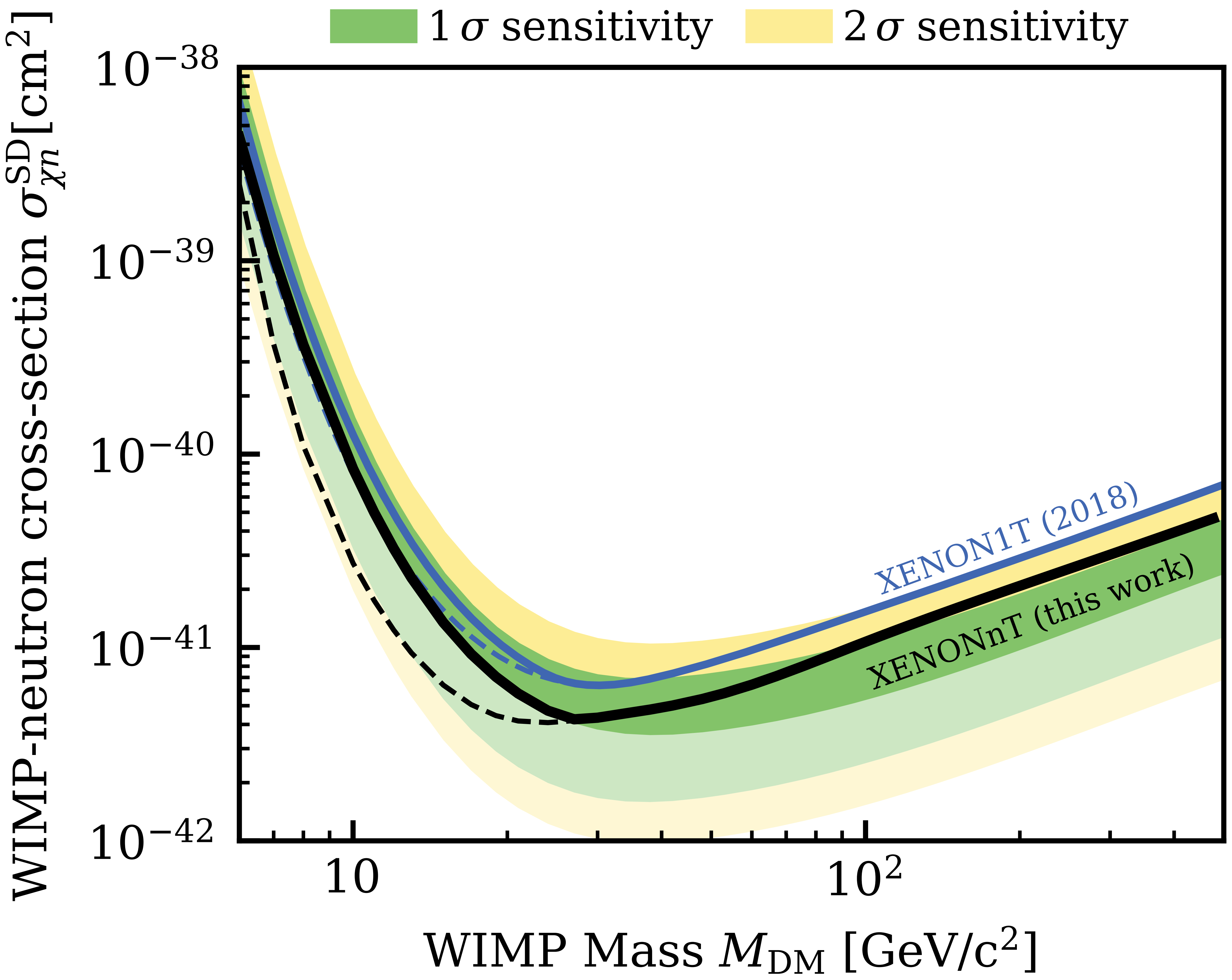


PandaX-4T, PRL 127, 261802 (2021)
XENON, PRL 121, 111302 (2018)
LZ, arXiv:2207.03764

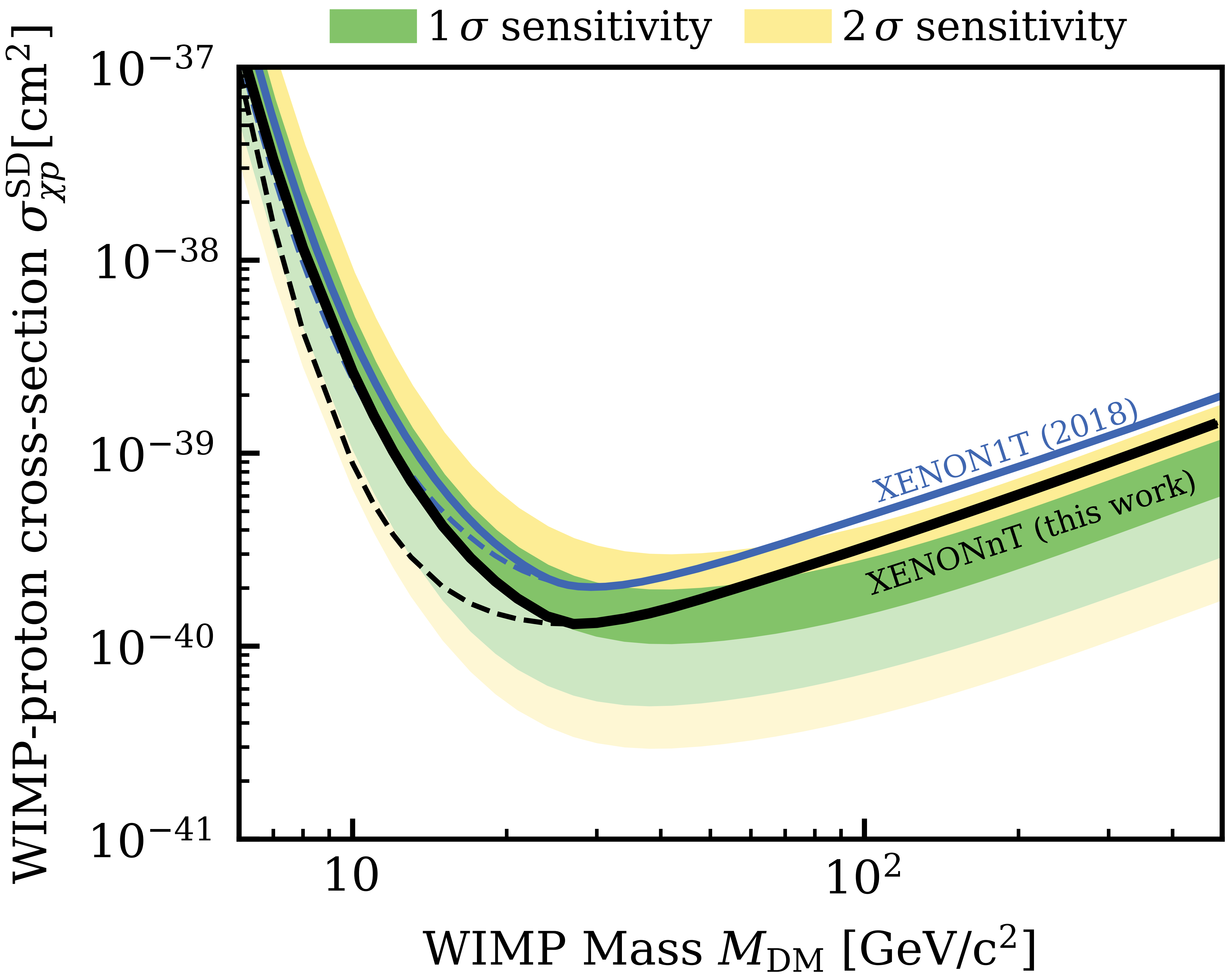
WIMP Spin-Dependent Results

Reinterpreting results as a purely spin-dependent coupling to ^{129}Xe and ^{131}Xe

WIMP - neutron coupling



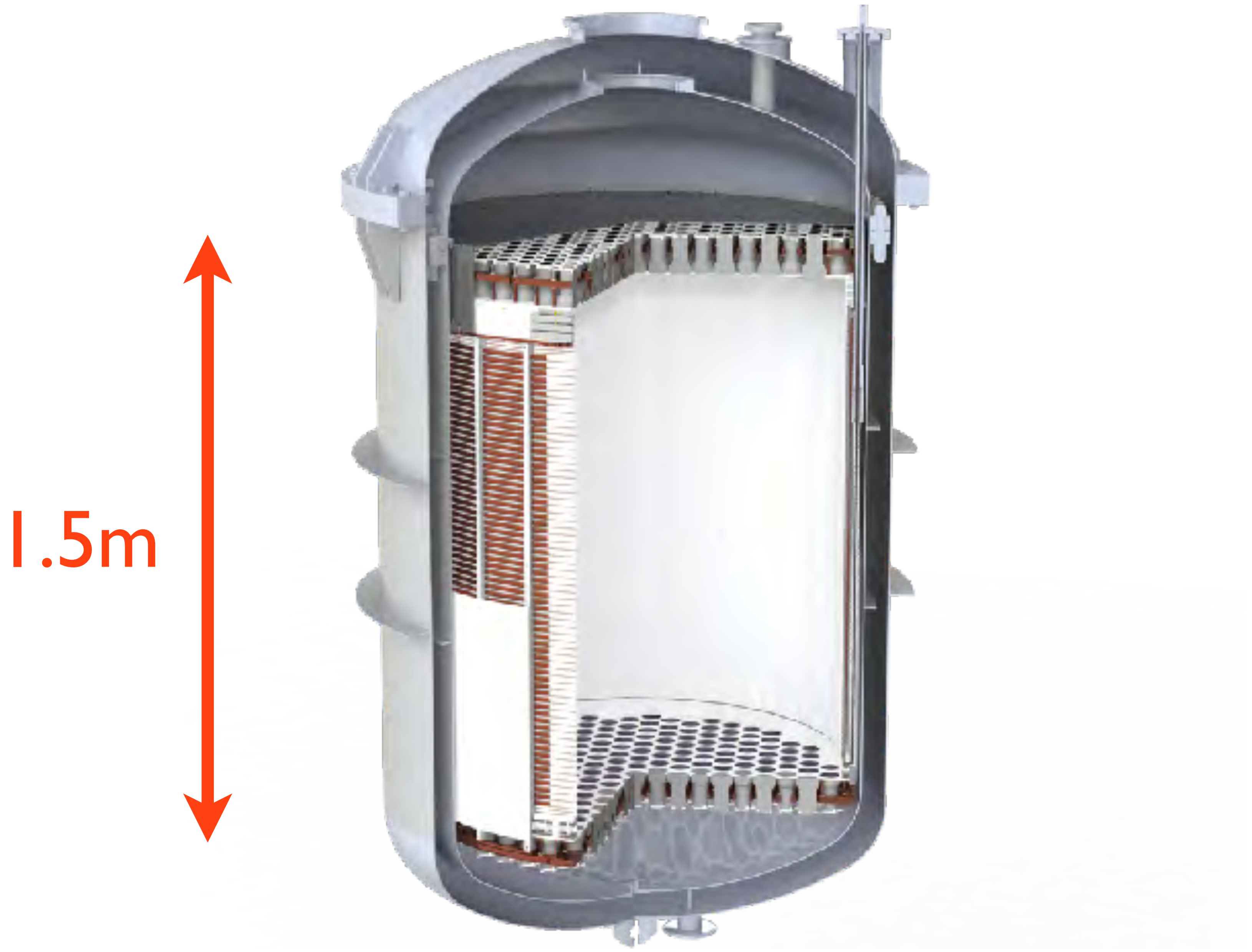
WIMP - proton coupling



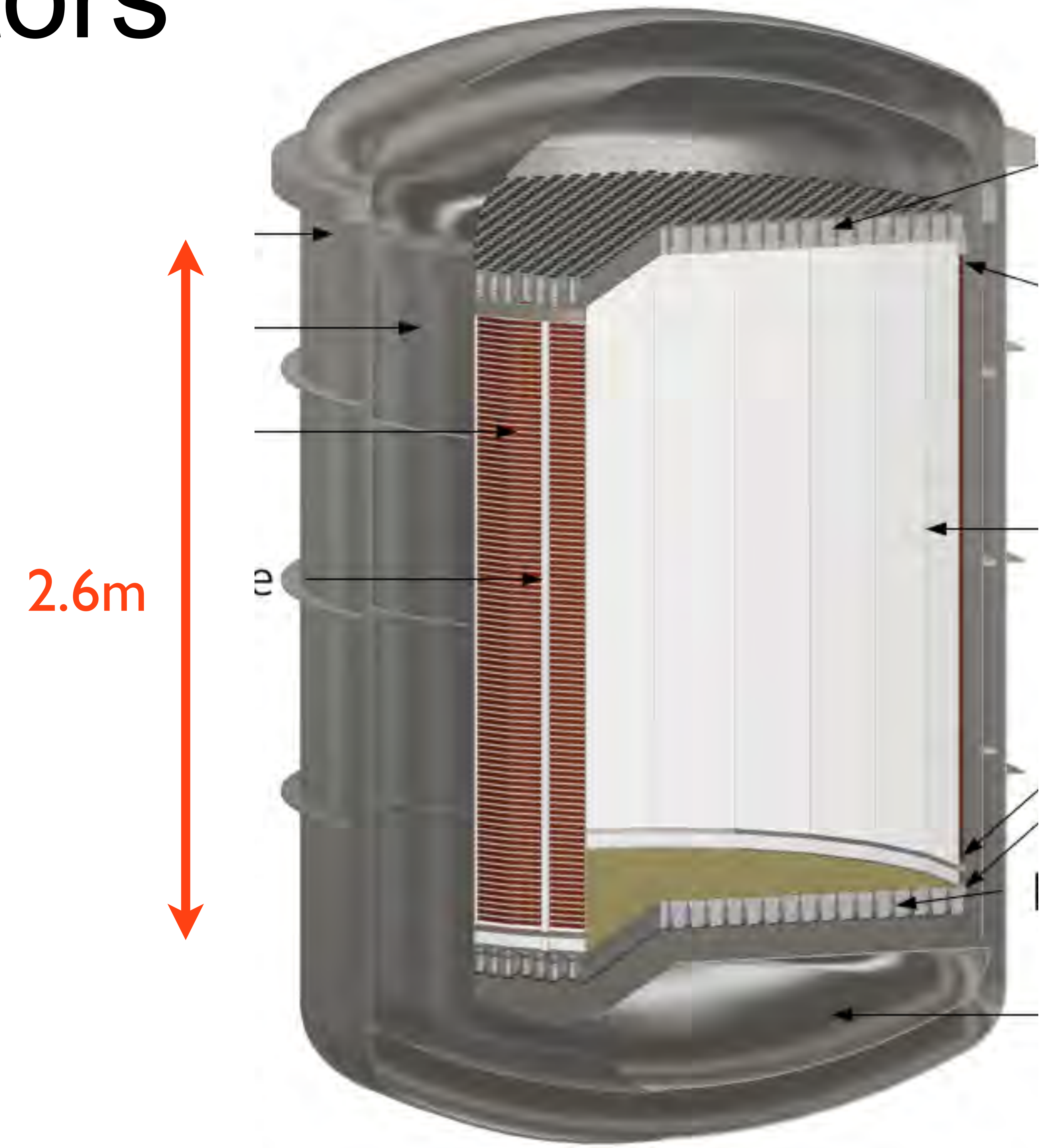
Even larger detectors

Natural xenon has 8.9% ^{136}Xe use it to study $0\nu2\beta$!

<u>XENON1T</u>
3.2 tons LXe
2015-2019



<u>XENONnT</u>
8.5 tons LXe
2021-



<u>DARWIN / XLZD</u>
60 tons LXe
2030-

XENON Coll, Phys. Rev. C 106, 024328 (2022); arXiv:2205.04158

DARWIN Coll, Eur. Phys. J. C 80, 808 (2020); arXiv:2003.13407

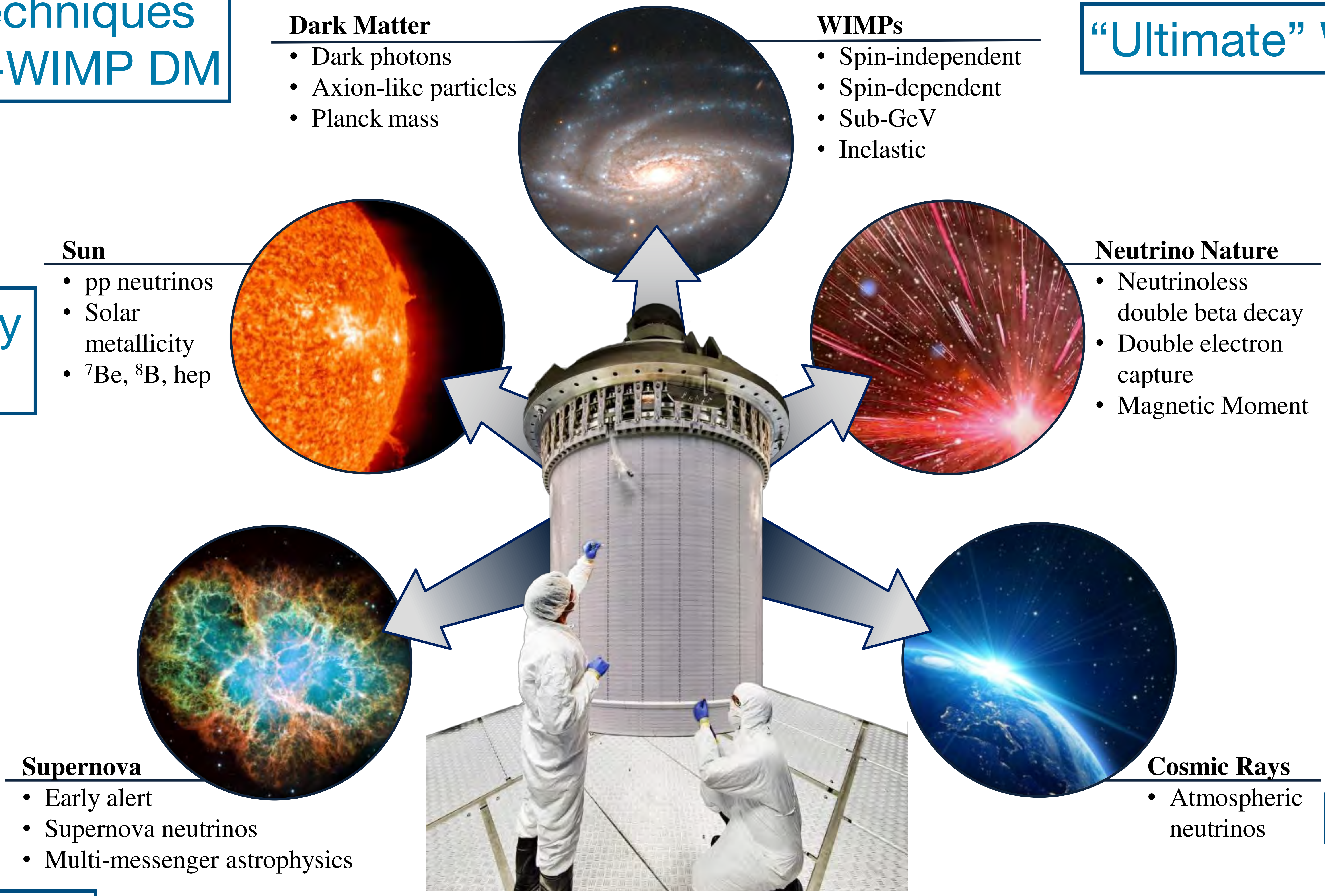
White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309

Ultra-low BG + new techniques allow to search for non-WIMP DM

"Ultimate" WIMP DM detector

Low-E complementarity with DUNE

Competitive with dedicated 0v2b exp



Atmospheric E_ν < 100 MeV

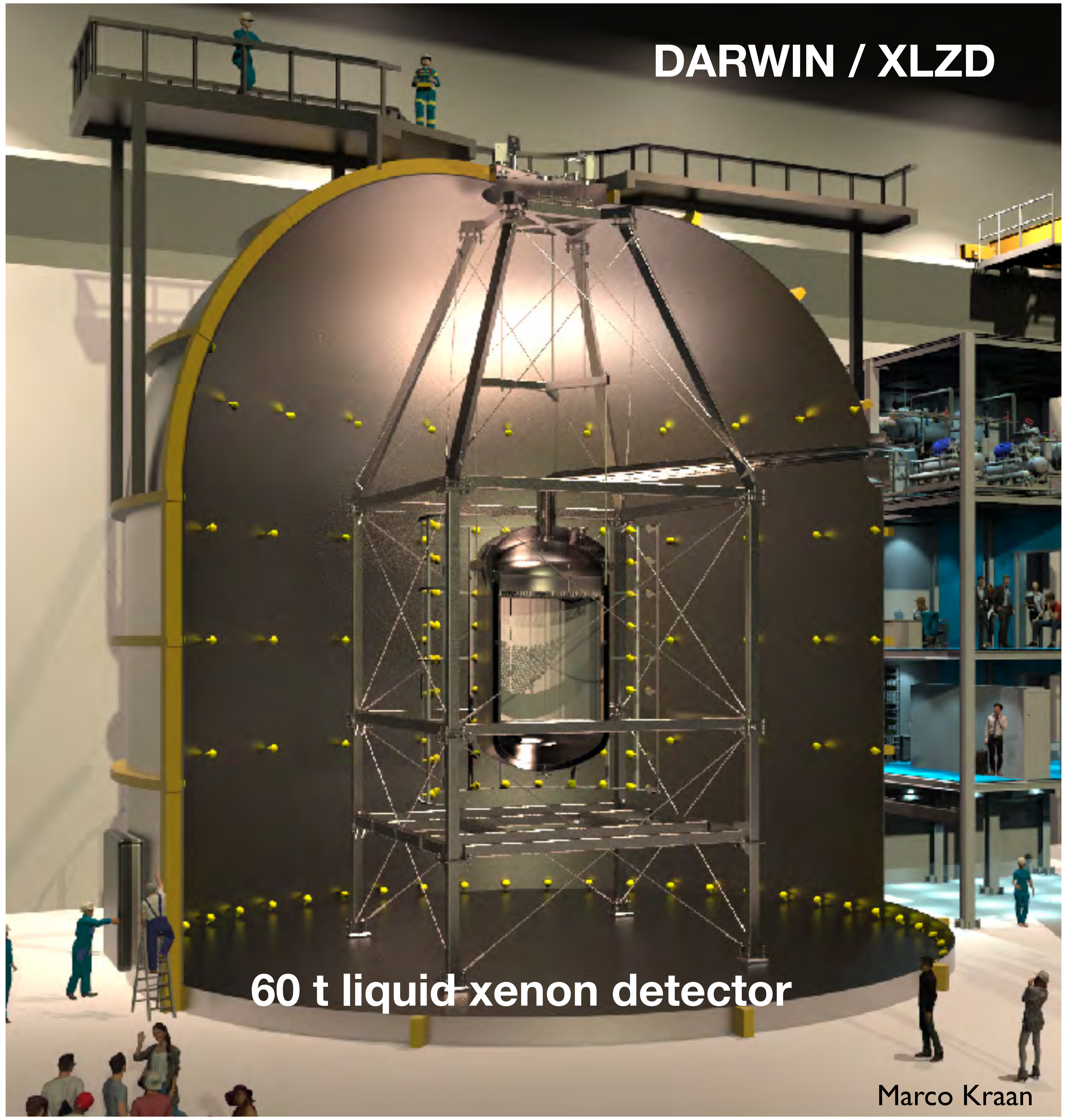
Detailed measurements if/when galactic SN occurs

Large liquid xenon mass and ultra-low backgrounds expand number of available physics channels

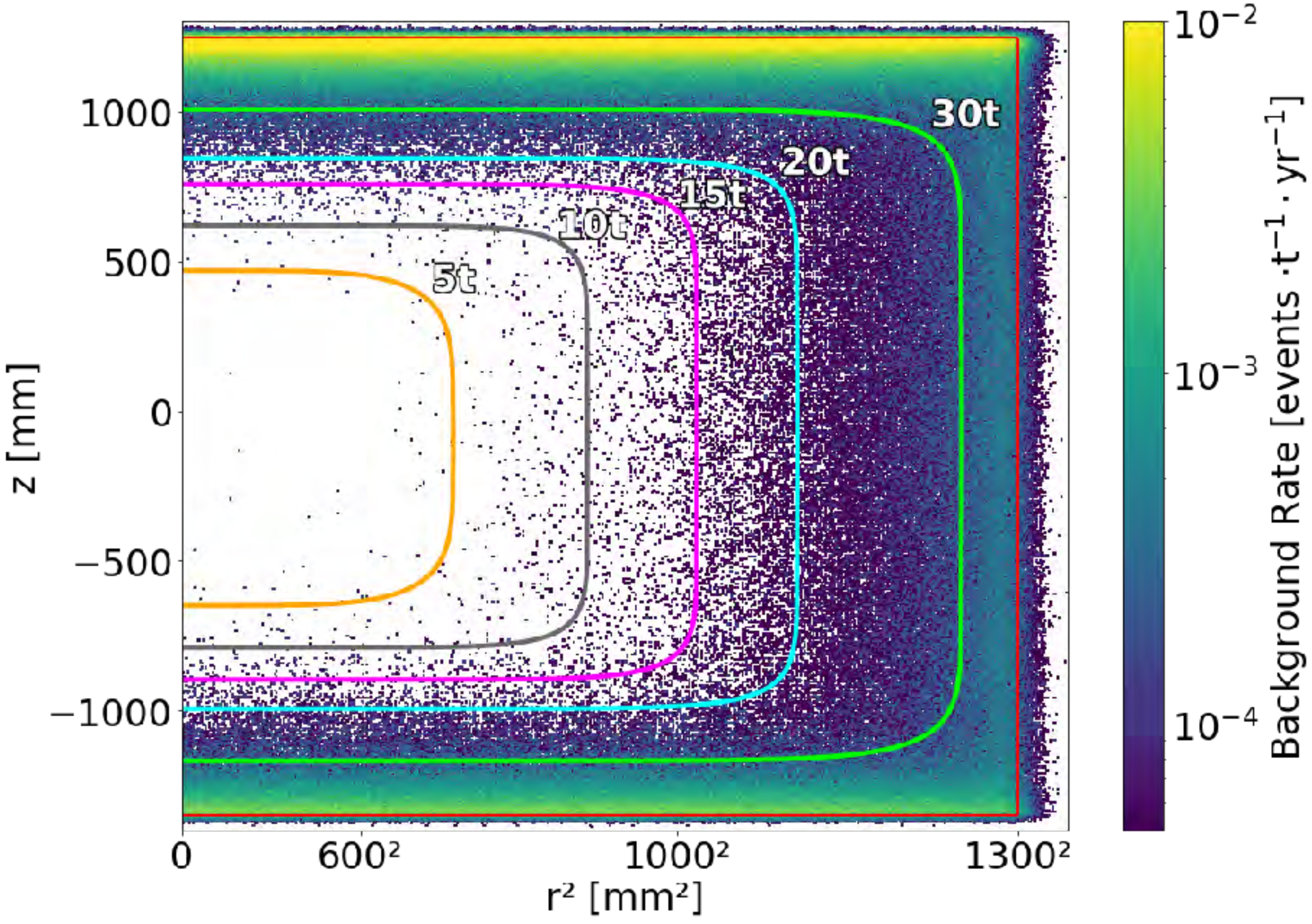
DARWIN Coll, Eur. Phys. J. C 80, 808 (2020); arXiv:2003.13407

DARWIN / XLZD

XLZD = XENON + LZ + DARWIN

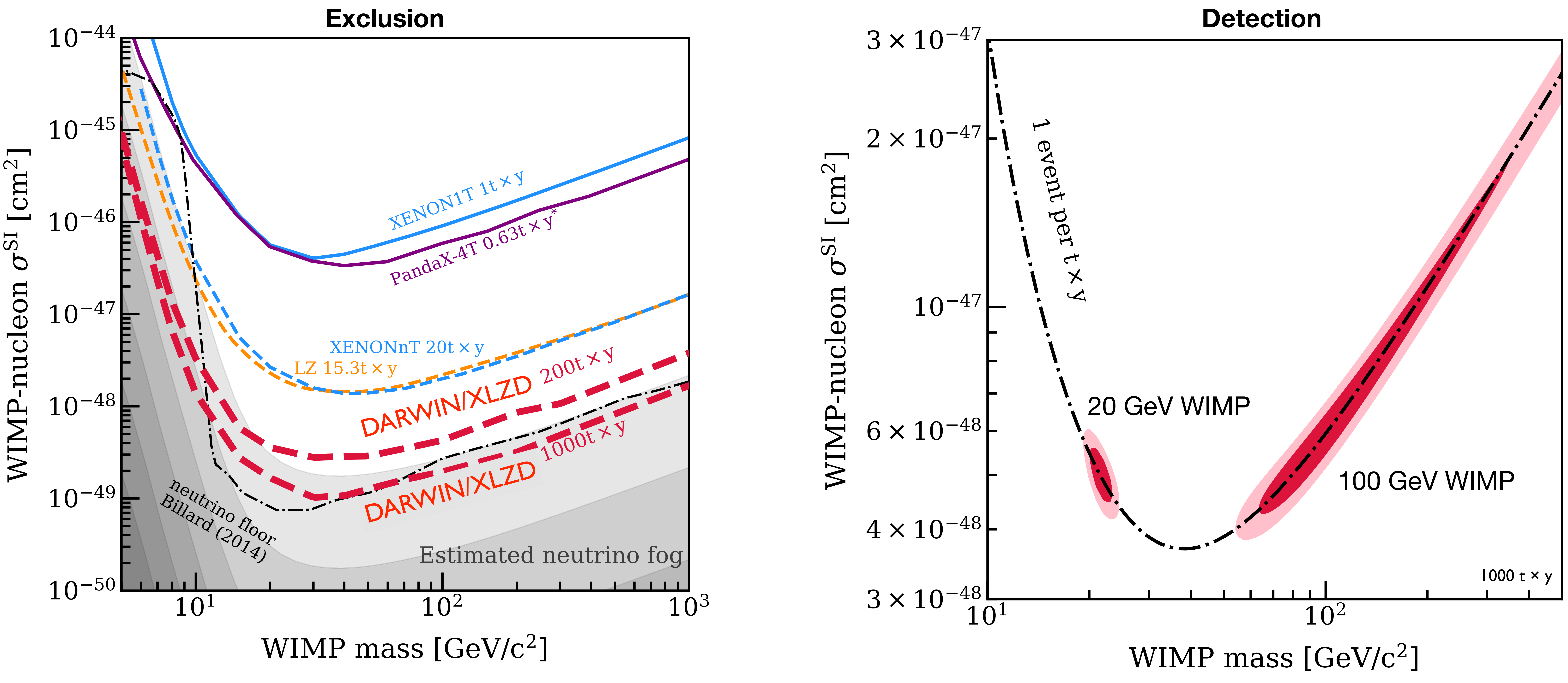


Self shielding of LXe



WIMPs in DARWIN / XLZD

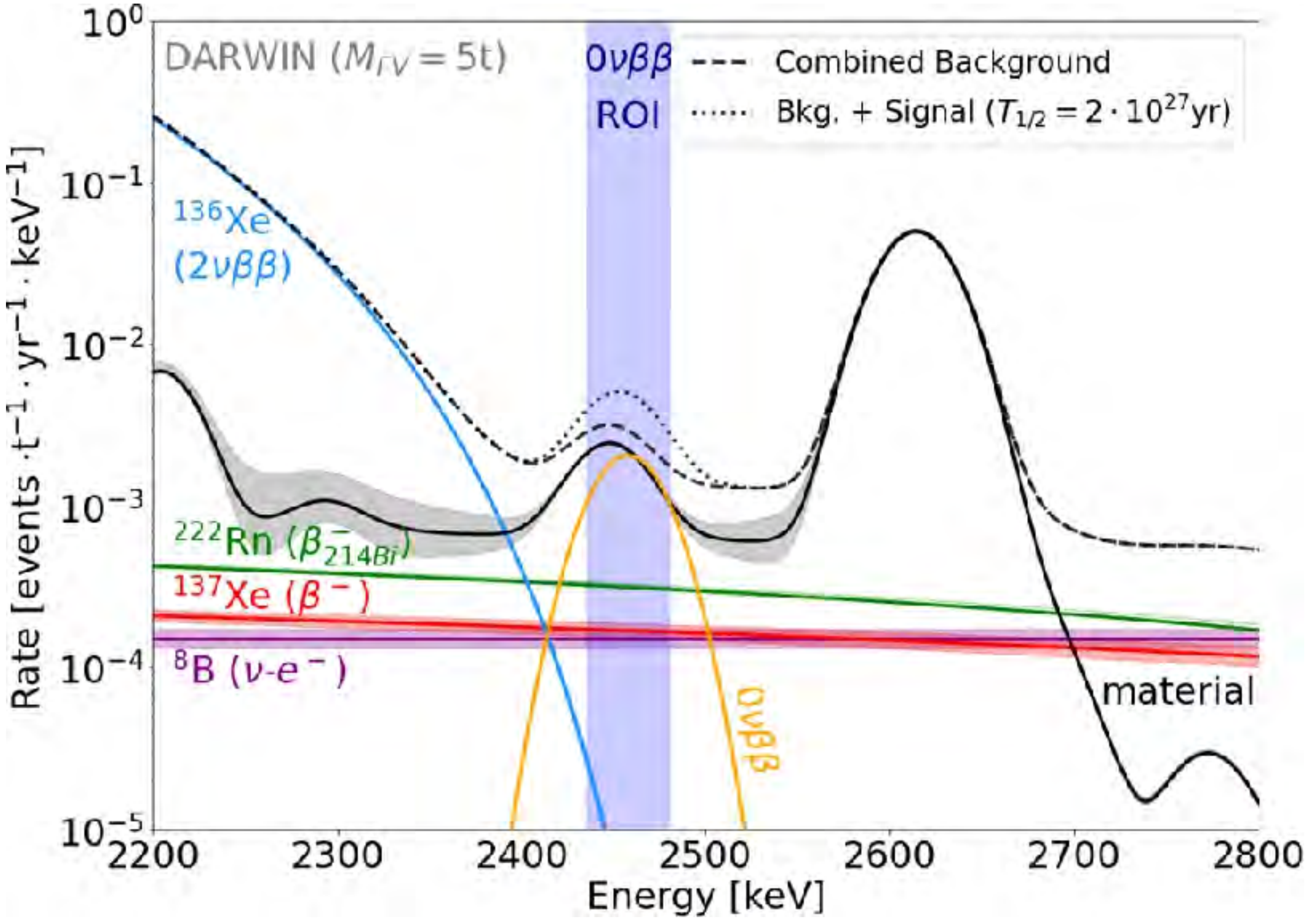
Explore the WIMP parameter space down to the neutrino fog

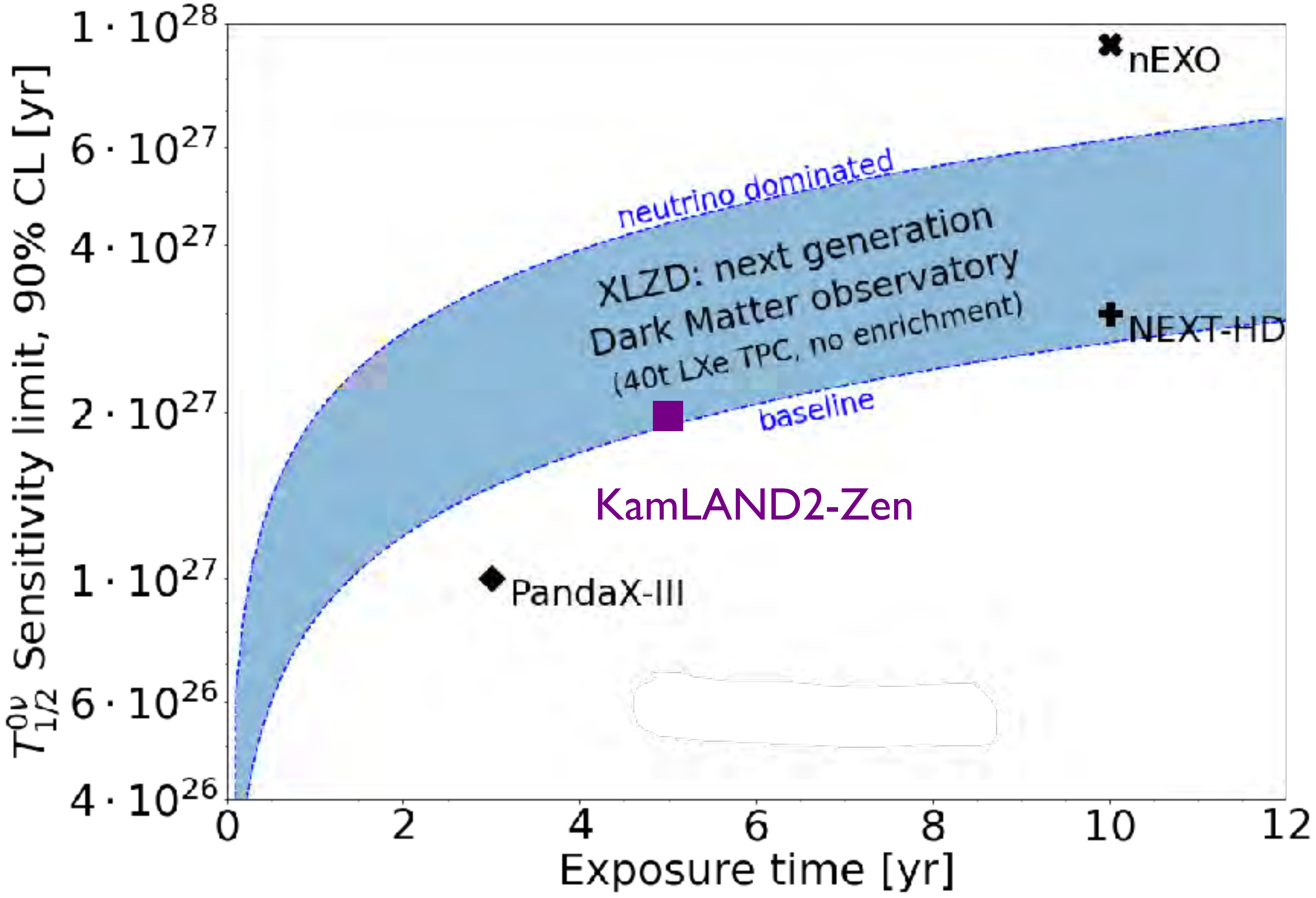


Neutrinoless Double Beta Decay

Is the Neutrino a Majorana particle?

Neutrinoless Double Beta Decay (0v2β) of ^{136}Xe: Lepton Number Violating Process



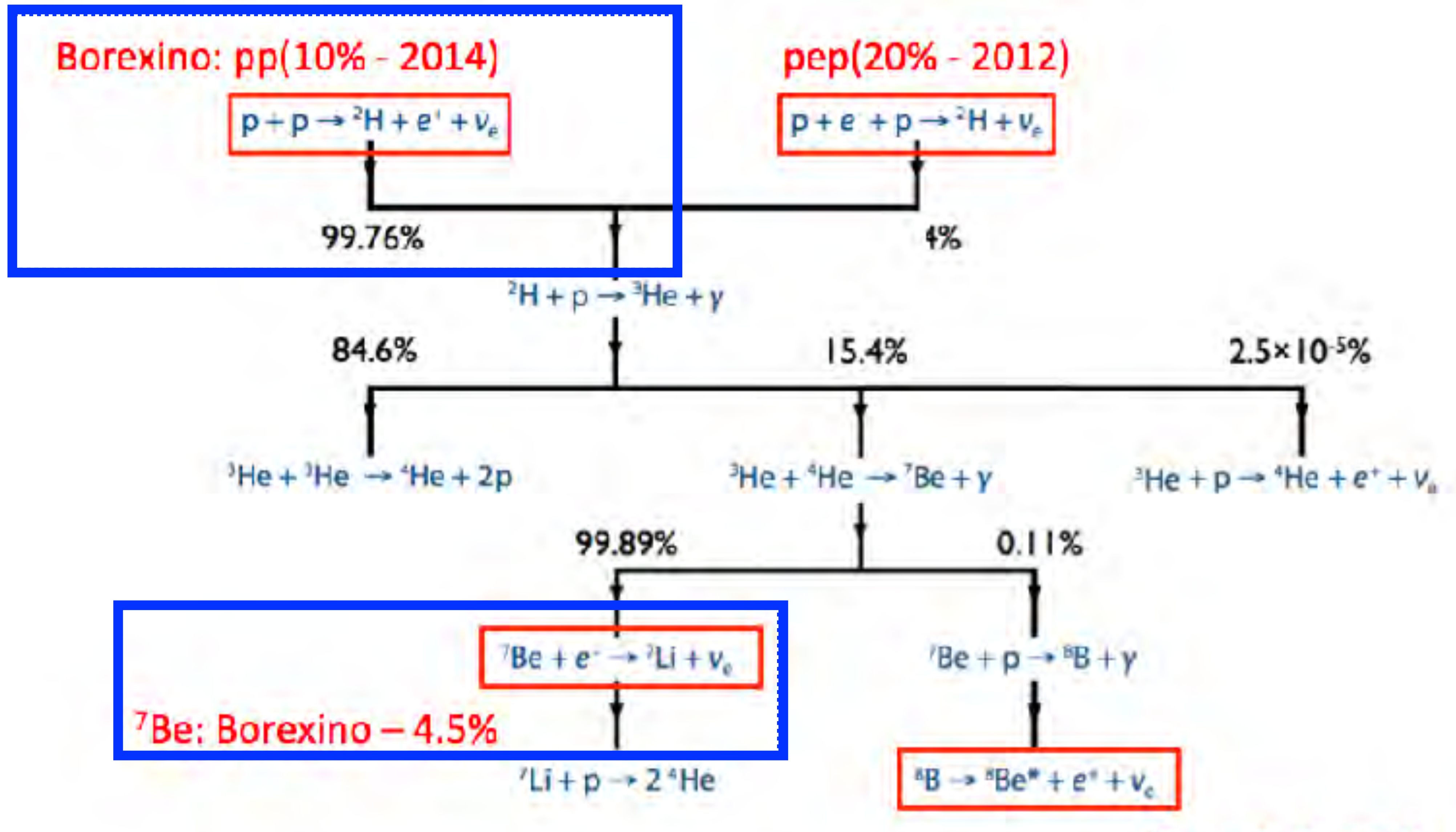


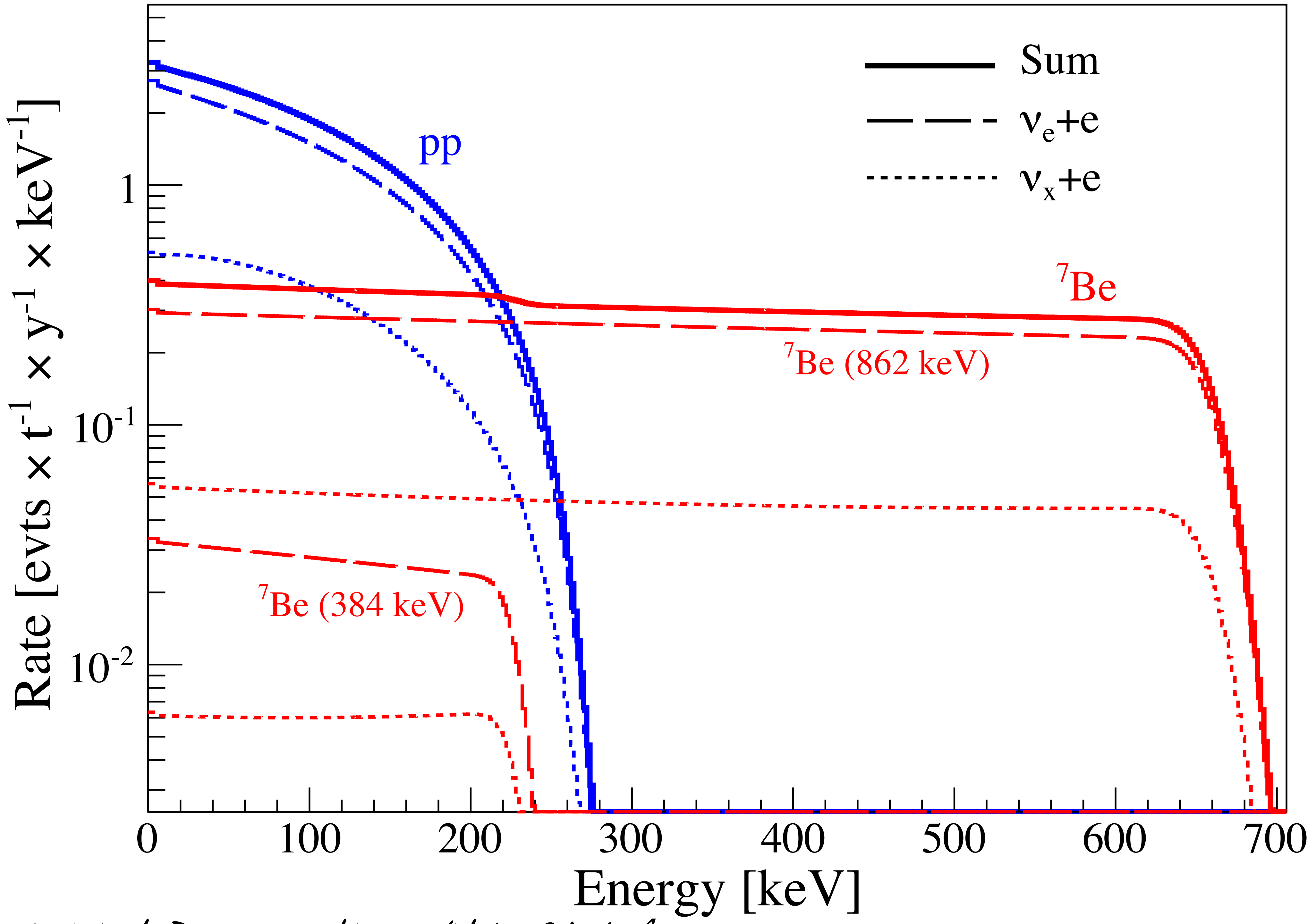
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$ → Half life is measure of effective majorana mass

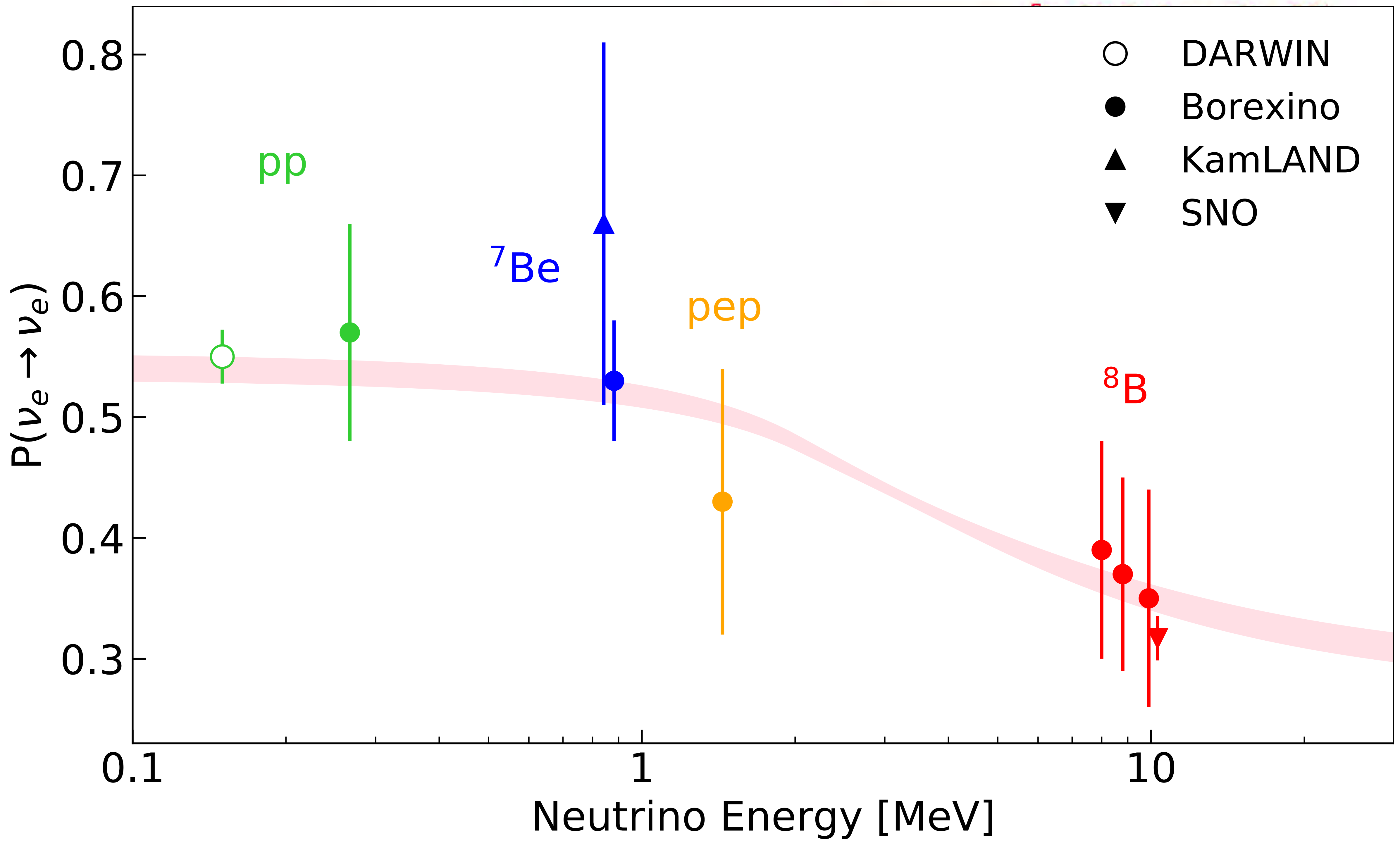
Solar Neutrinos

EPJC 80 (2020) 12, 1133; arXiv:2006.03114

- Neutrino-electron elastic scattering
- Real-time measurement of neutrino flux
  → 7.2 events/day from pp
  → 0.9 events/day from ^{7}Be
  (40 ton LXe detector)
- 2% (1%) *statistical* precision after 1 year (5 years)
  → constrain solar models
- Neutrino survival probability measurement
  → deviation from prediction indicates new physics







Summary

- We are probing the WIMP paradigm in a relevant parameter space
- The XENONnT experiment released first WIMP results in 2023
  - Data-taking is ongoing with reduced backgrounds, expect many more results, also on other physics topics to come out
- XENON + LZ + DARWIN collaborations have joined forces to build the next-generation LXe detector, 10x more sensitive than XENONnT, LZ
- The size and exquisitely low radioactive background will make DARWIN/XLZD a Rare Event Observatory with world-leading sensitivities to dark matter and neutrinoless double beta decay