Revealing the nature of neutrinos with XENON direct dark matter detector and future perspectives

XENON

DARWIN


Credit: Fernando Urquijo

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on behalf of the XENON and DARWIN Collaboration

18th Rencontres du Vietnam

Neutrino Physics | Quy Nhon

Subatech

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

cnrs

Nantes Université

The XENON Collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | UCSD | Rice | Purdue

Tsinghua | Tokyo | Nagoya | Kobe

~170 scientists | **27 institutions** | **12 countries**

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

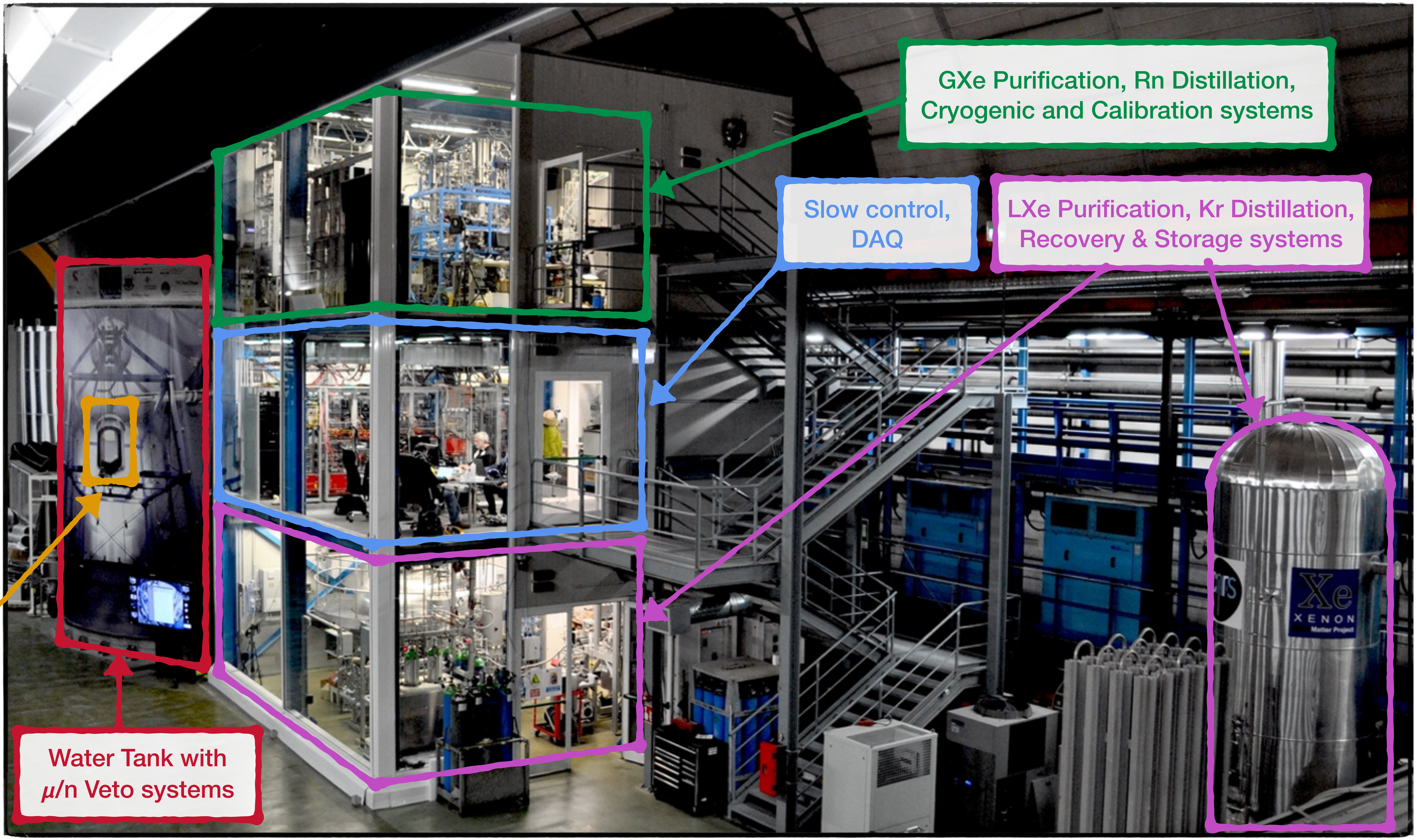
Main Goal: Direct detection of WIMP dark matter candidate

Laboratori Nazionali del Gran Sasso - LNGS

Underground Laboratory:
1500 m overburden
(3600 m.w.e)

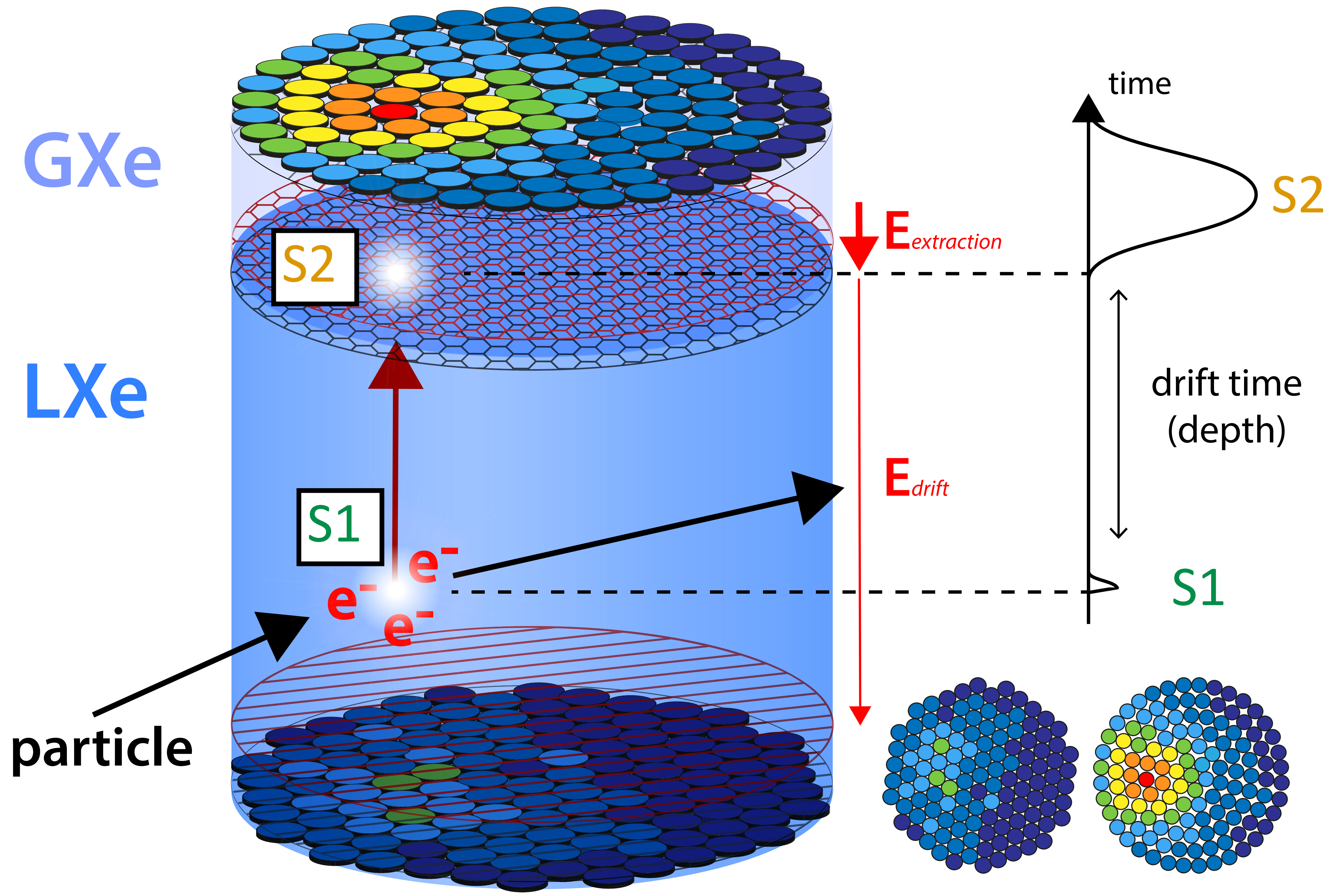
Main Detector:
Dual-Phase Time projection Chamber

How does it work?



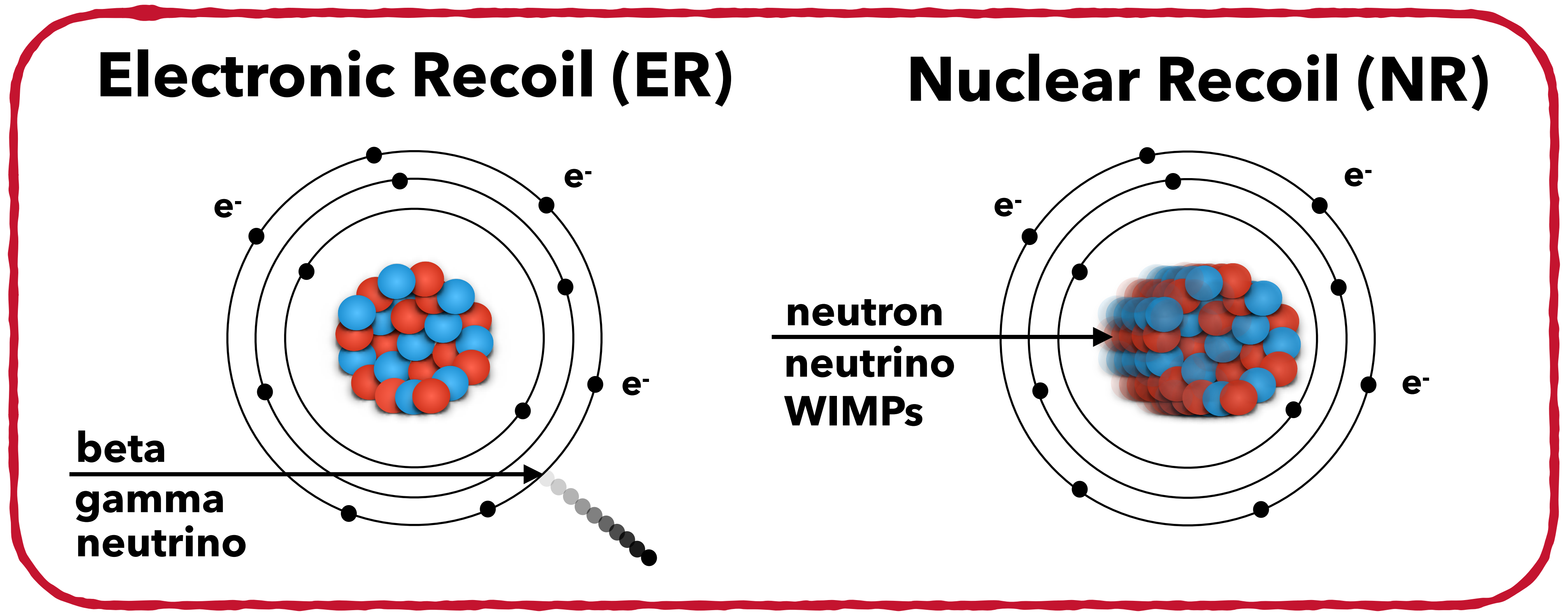
Dual-phase Time Projection Chamber

Working Principle:



Readout of scintillation and ionization signals:

- Prompt light signal (**S1**)
- Secondary light in GXe from drifted electrons (**S2**)



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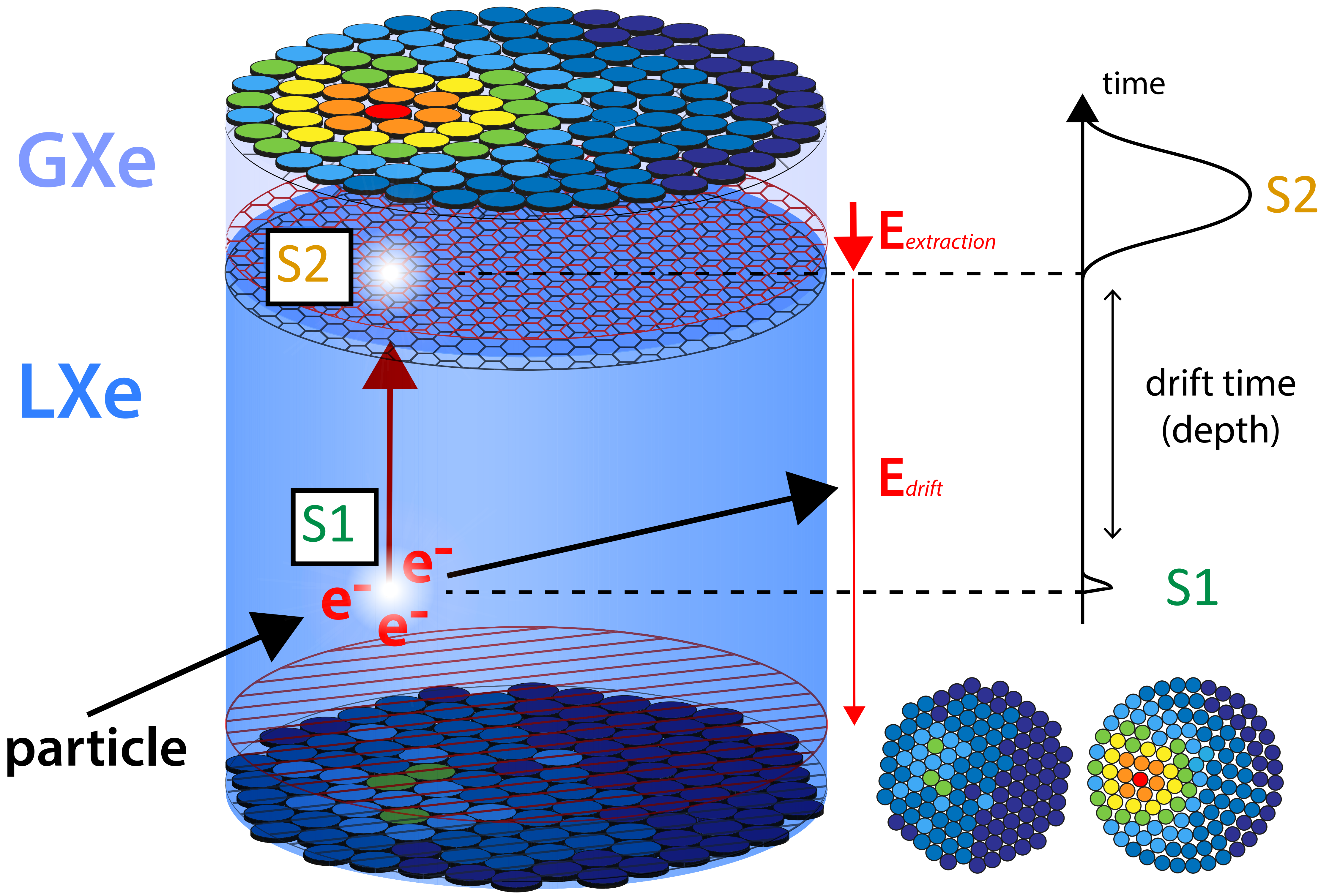
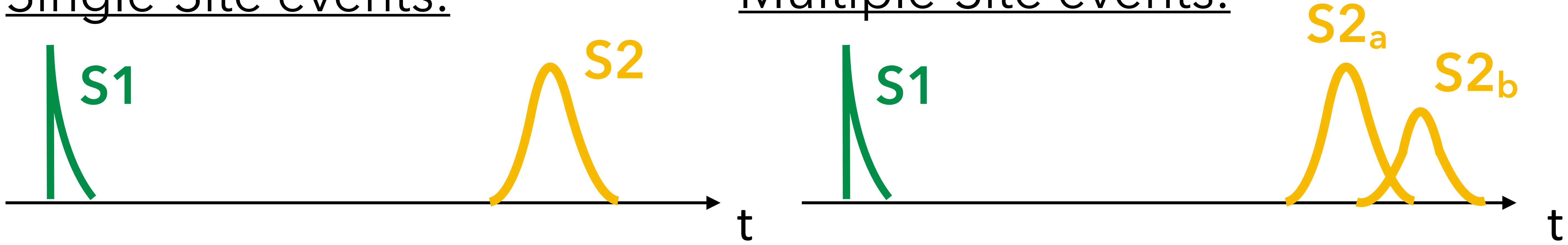


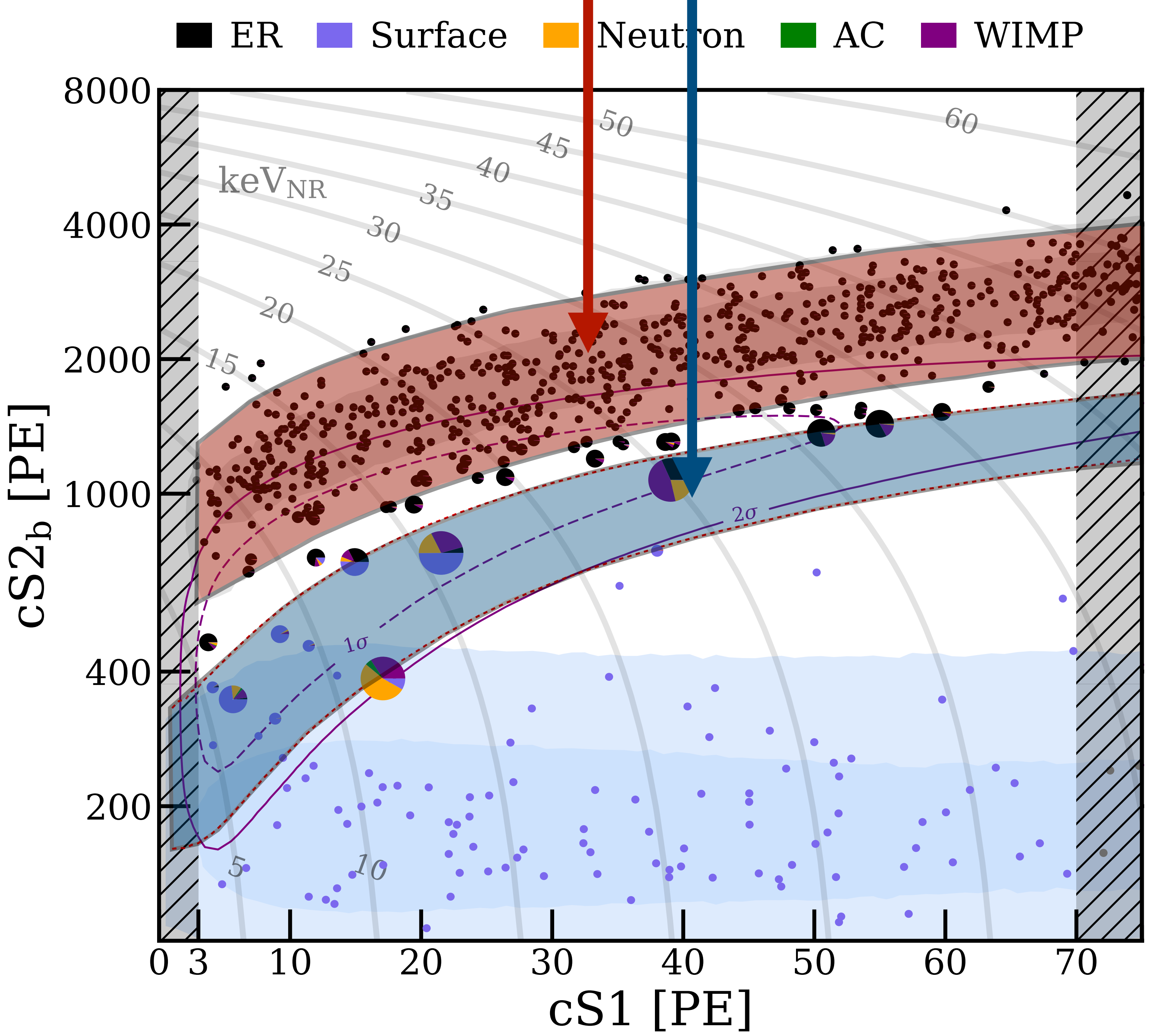
Single-Site events:

Multiple-Site events:



Readout of scintillation and ionization signals:

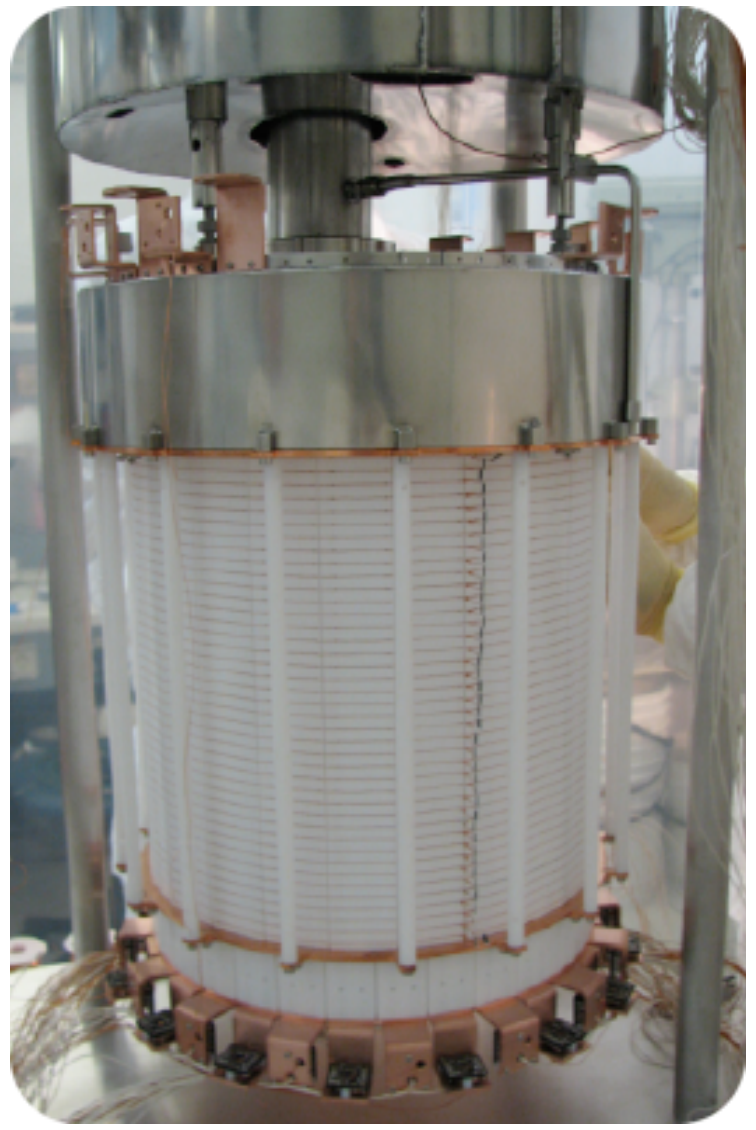
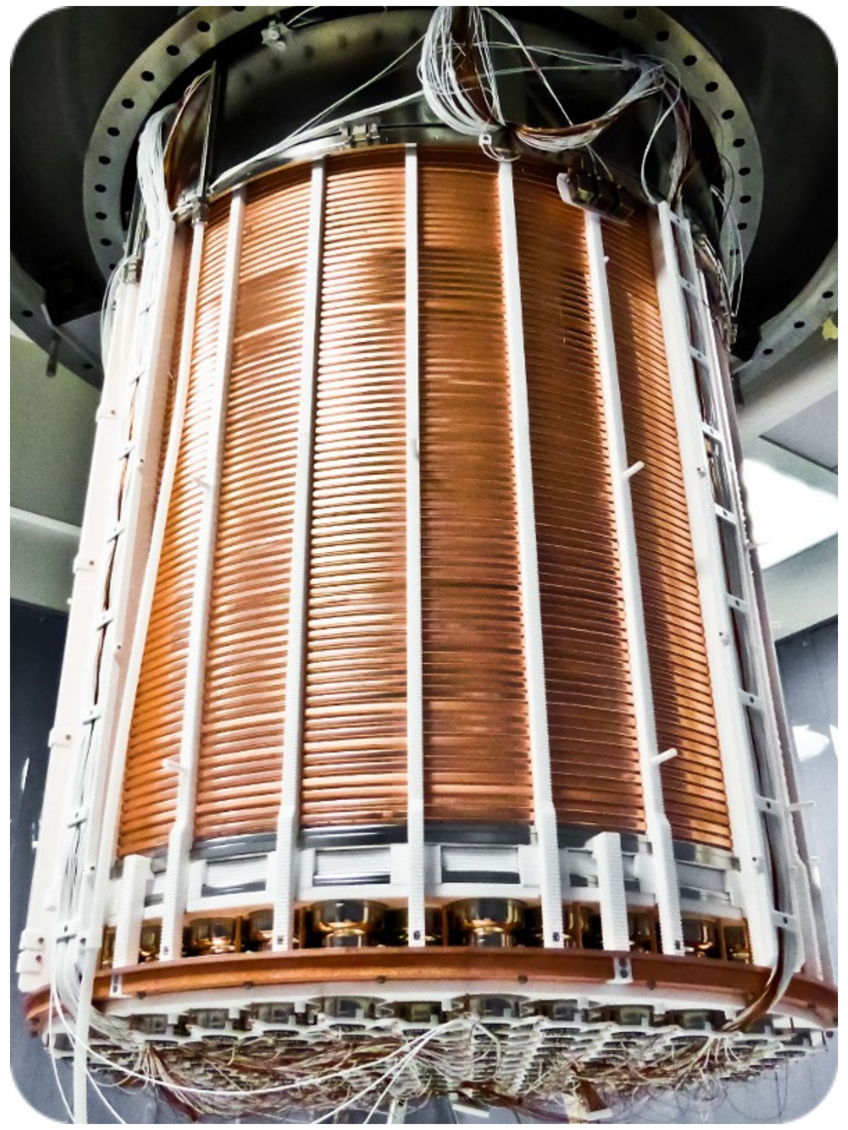
- Prompt light signal (**S1**)
- Secondary light in GXe from drifted electrons (**S2**)
- Reconstruction of position (**x, y, z**), energy (**E**) and interaction type (**ER**/**NR**) through **S1**/**S2** ratio



REFERENCES PRL 121, 111302 (2018) | ARXIV:1805.12562

The XENON project history

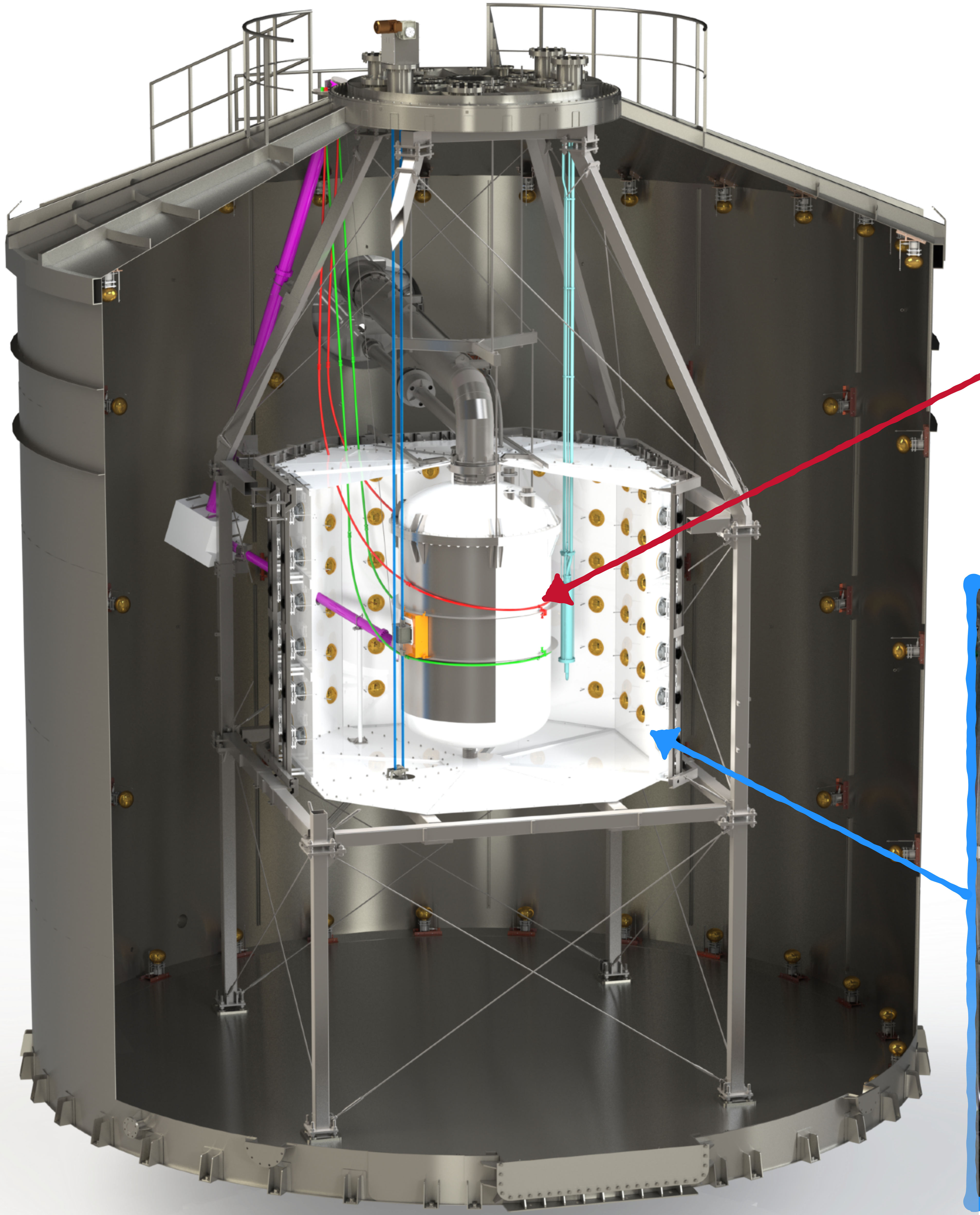
Present


	XENON10	XENON100	XENON1T	XENONnT	
Time	2005	2008	2016	2021	
Active mass	15 kg	62 kg	2.0 t	5.9 t	
Background	~1000	5.3	0.2	*0.04	$[t.day.keV]^{-1}$
Sensitivity	$\sim 10^{-44}$	$\sim 10^{-45}$	$\sim 10^{-47}$	*$\sim 10^{-48}$	$[cm^2]$

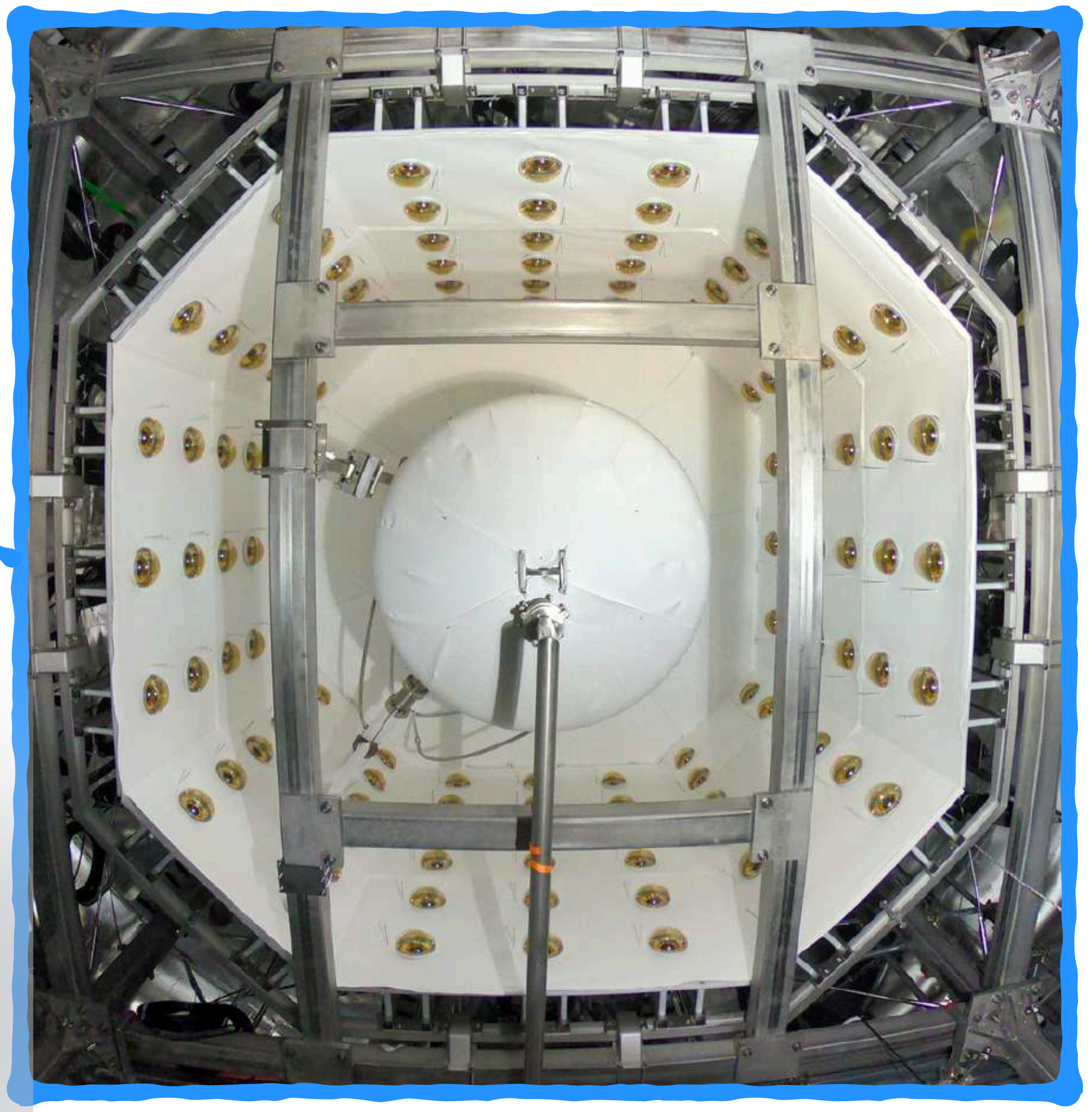
* → Projections

XENONnT: Fast upgrade from XENON1T



New Larger TPC:

- **x3 larger volume wrt XENON1T**
  - 2.0 t → 5.9 t LXe active mass.
  - ~1 m → ~1.5 m drift length.
  - ~1 m → ~1.3 m diameter.
  - 248 → 494 3″ PMTs.



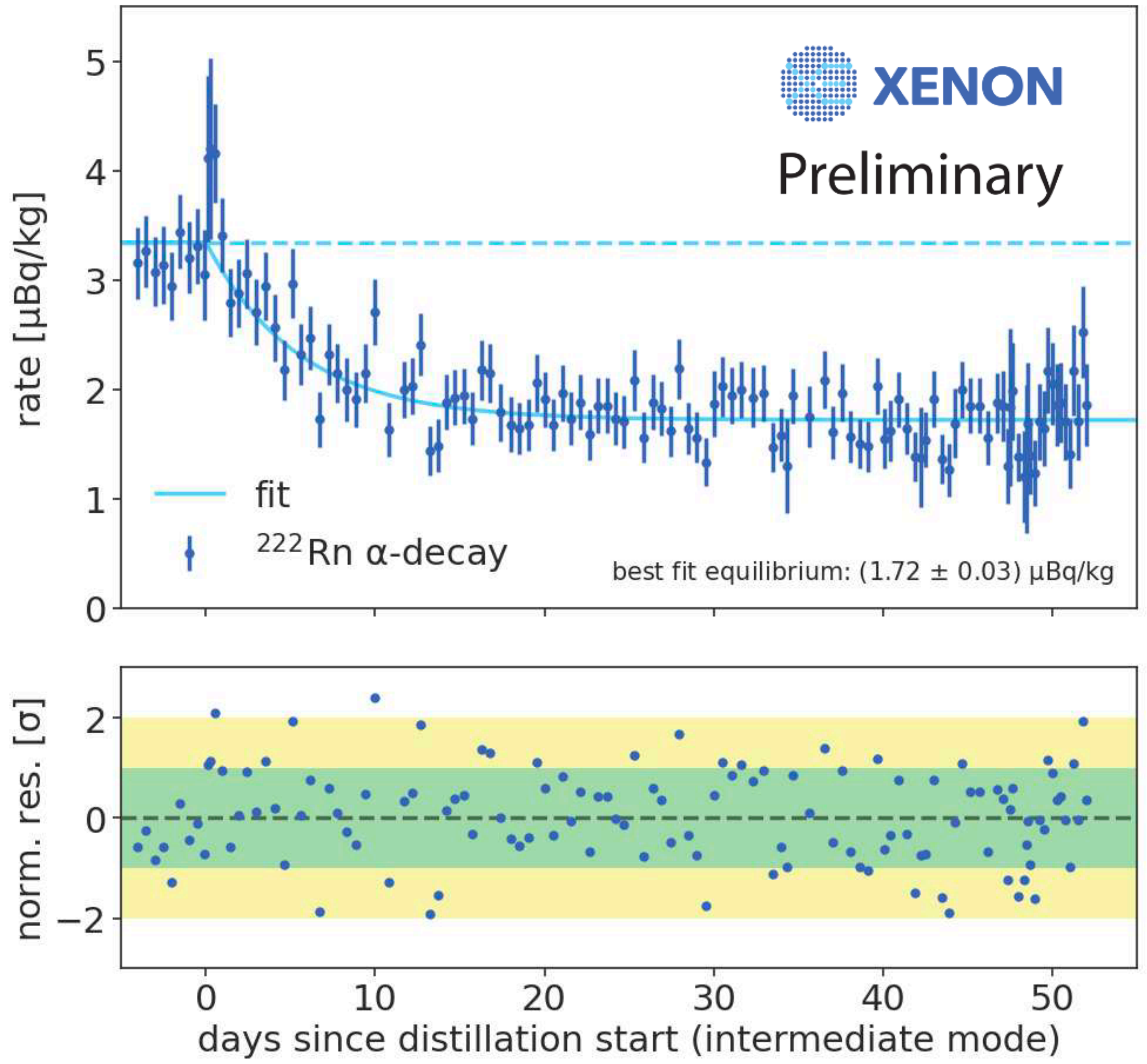
New Neutron Veto:

- **Further reduce NR backgrounds.**
- Gd-loaded (0.2 %) Water Cherenkov instrumented with 120 8″ PMTs.
- 87 % (~65 %) projected neutron tagging efficiency with Gd-loaded (pure) water.

XENONnT: Fast upgrade from XENON1T

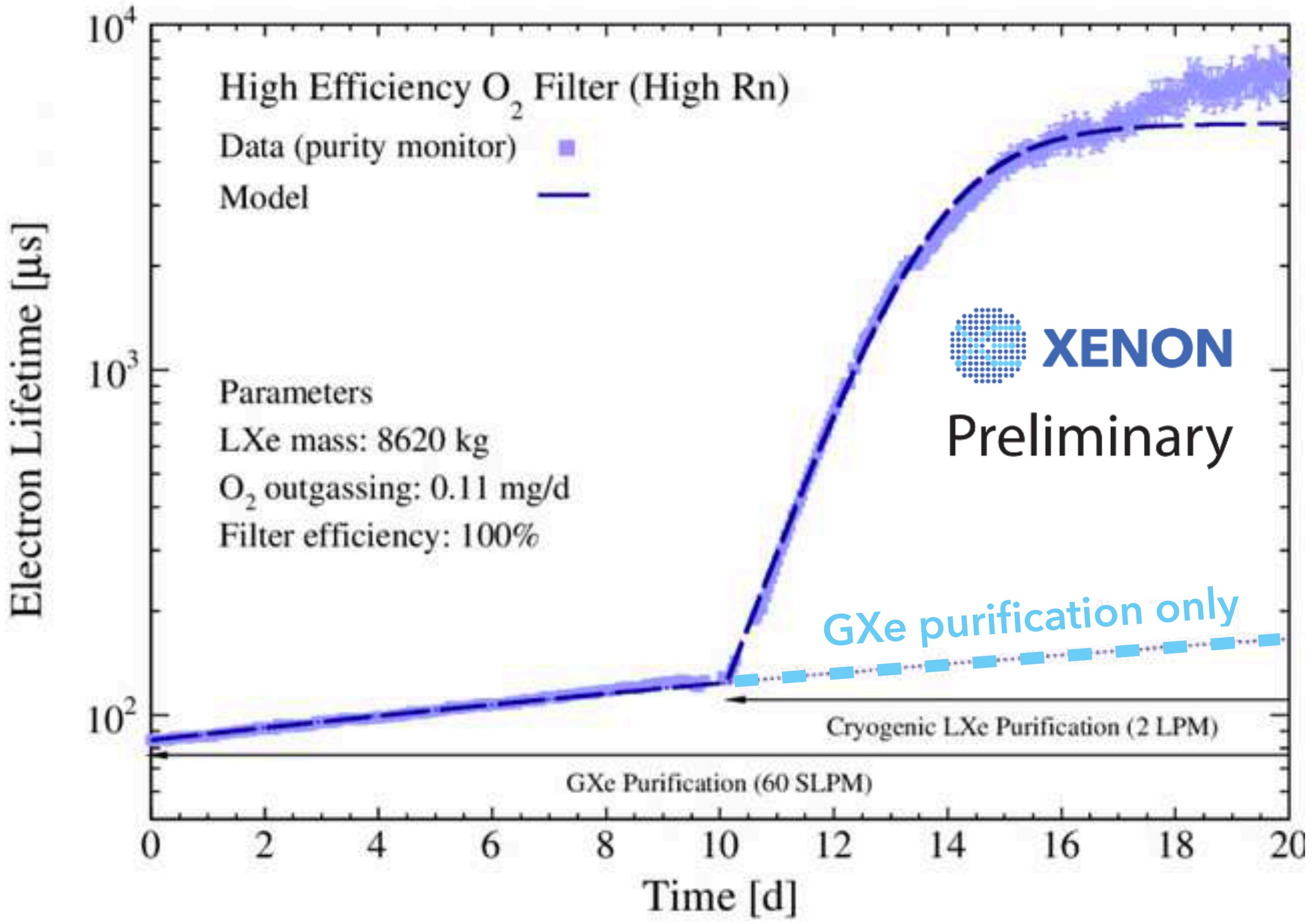
New Radon Distillation Column:

- 1.7 µBq/kg ^{222}Rn/Xe concentration during first science run.
- **< 1.0 µBq/kg already achieved** using the full potential of the Rn column.
  → **Lowest value achieved in LXe TPC**



New Liquid Xenon Purification:

- High-flux purification (~ 350 kg/h)
- **Increased purity (> 10 ms) leads to improved signal detection.**



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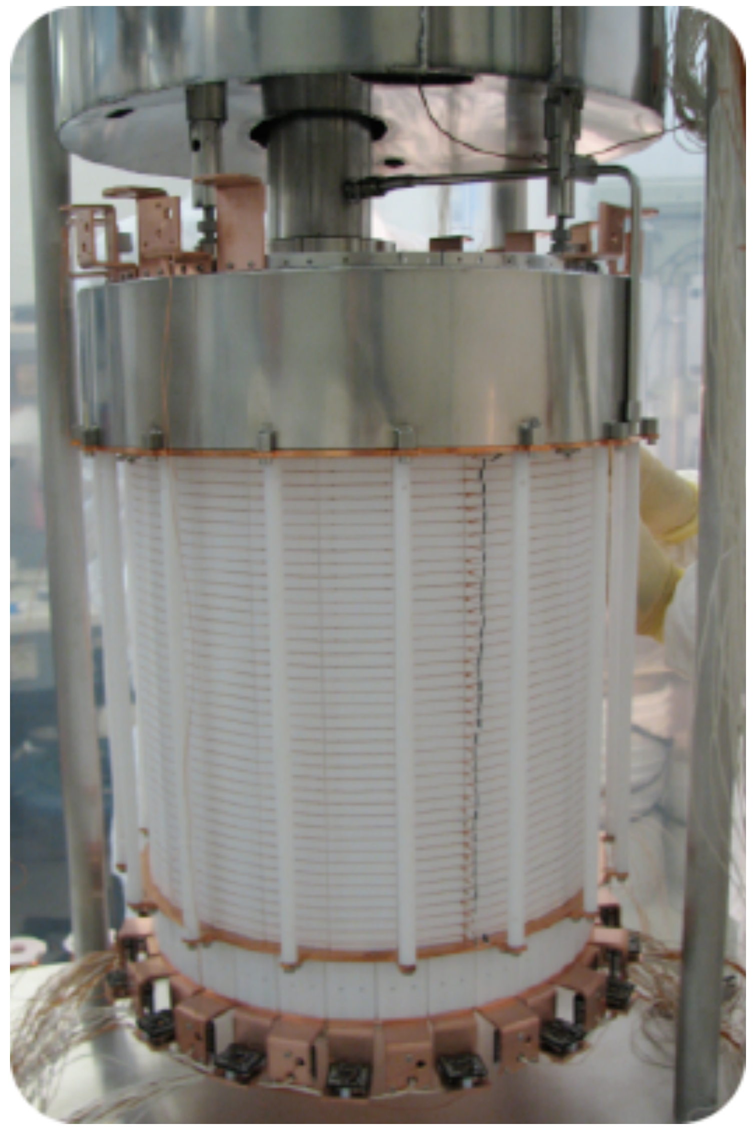
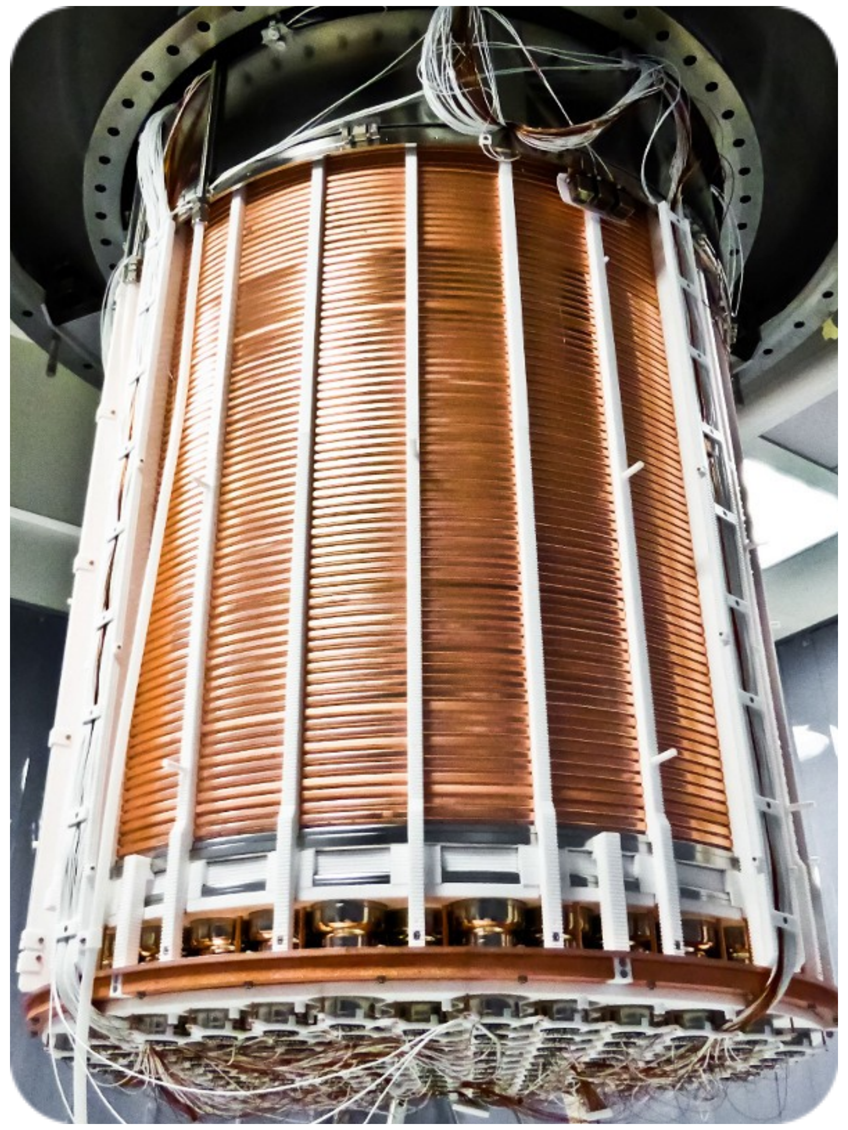


End of the Story?

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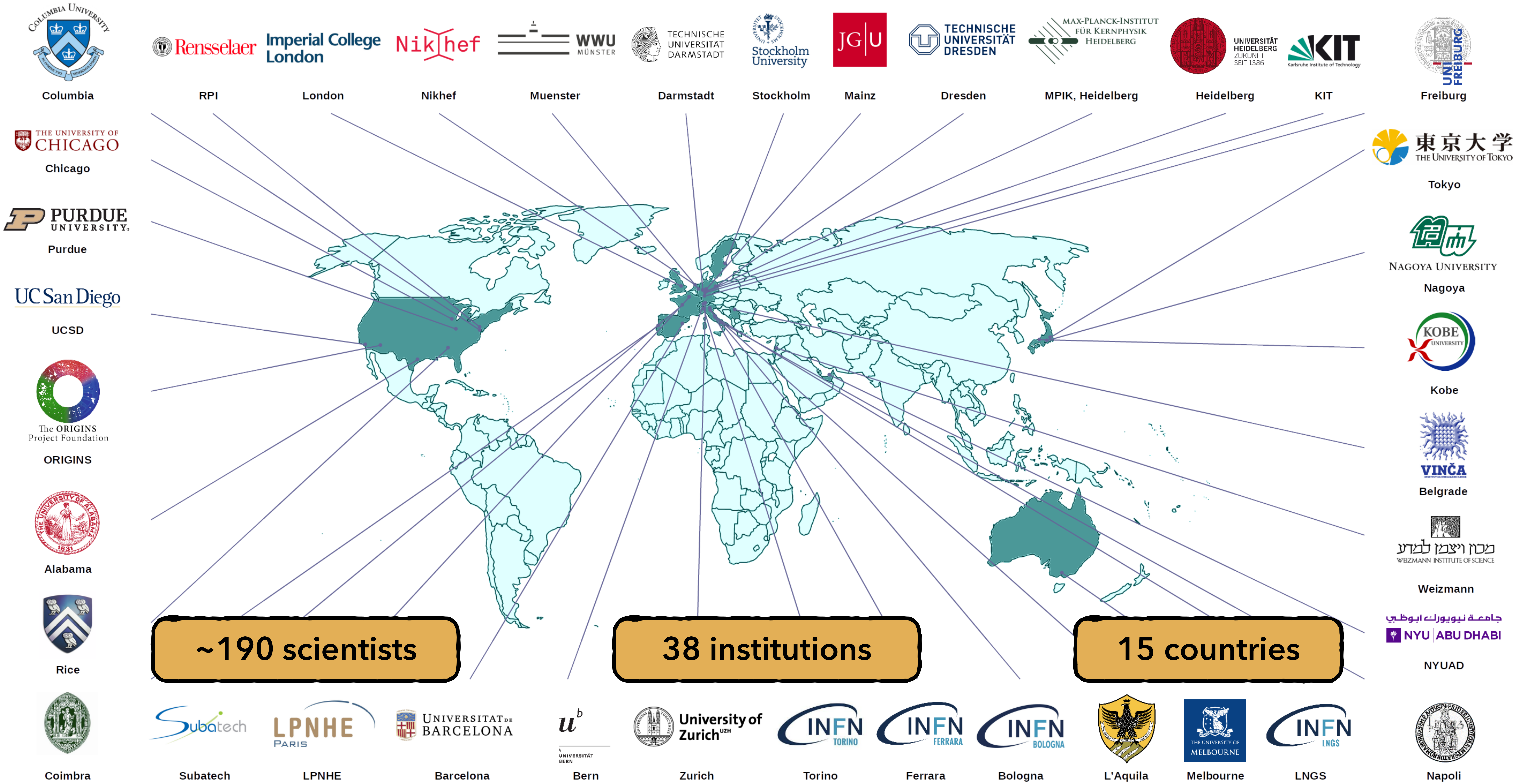
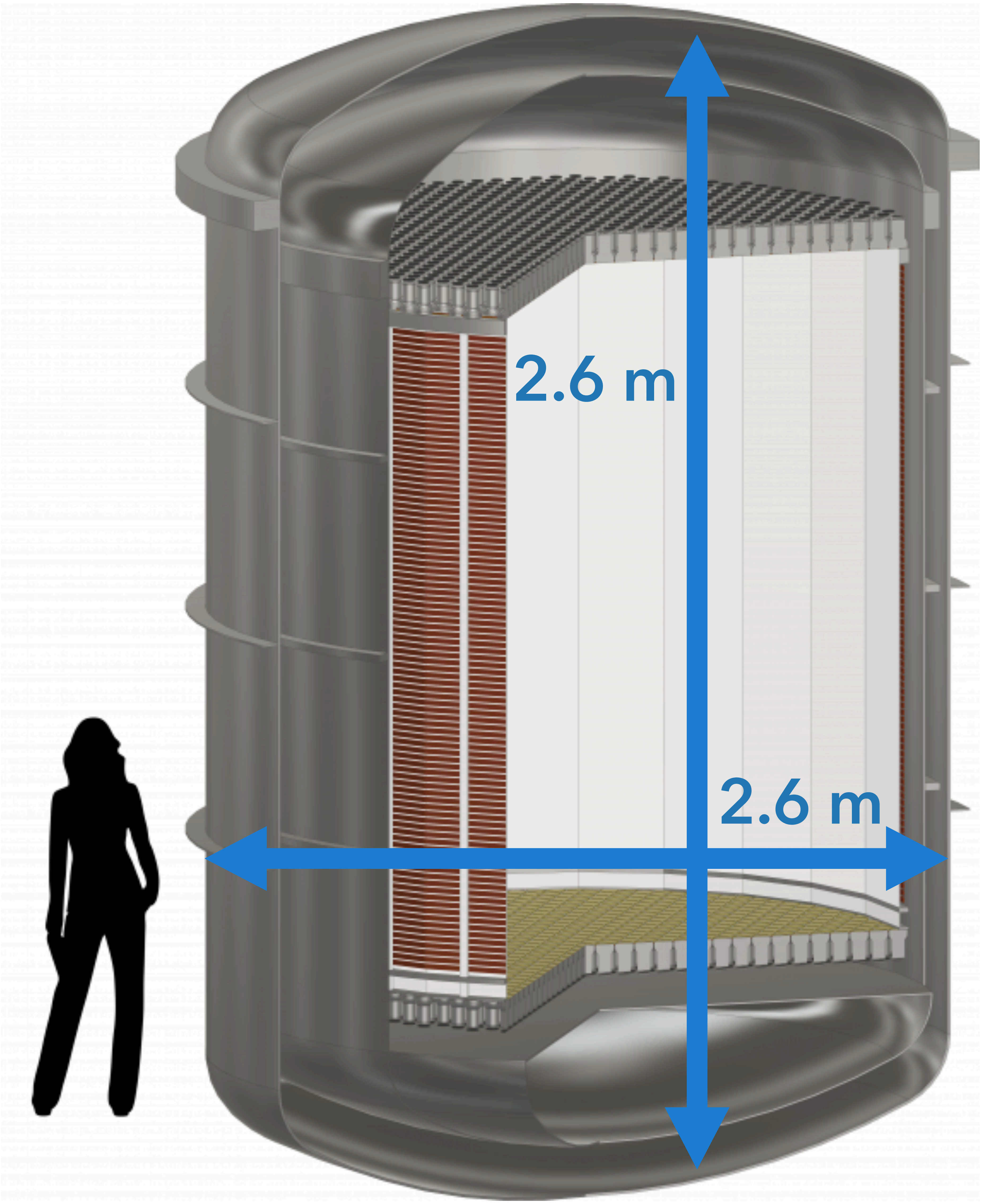
Future: The DARWIN Collaboration



The DARWIN baseline design

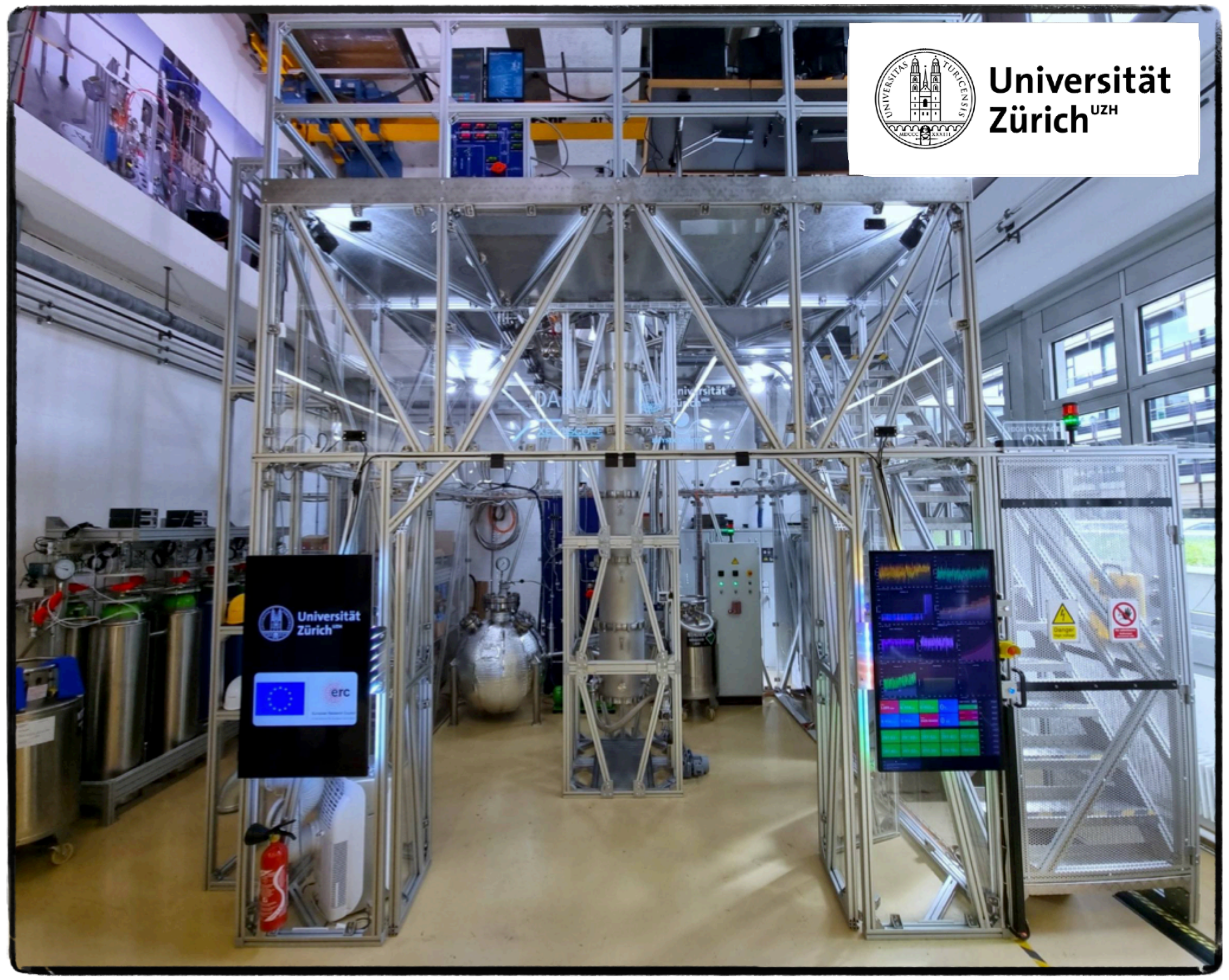


- Two-phase LXe/GXe TPC; aspect ratio 1 (⌀=h).
- 50 t of LXe (40 t active mass).
- Top and bottom photosensors (1800 3″ XENON PMTs).
- PTFE Reflector and Cu field-shaping rings.
- In-situ purification plus krypton and radon distillation for background mitigation.
- Veto detectors: water Cherenkov for muons with Gd doping for neutrons.

DARWIN Demonstrators

Vertical demonstrator: *Xenoscope*

- 2.6 m tall TPC.
- Test new photosensors.
- Test electron drift over 2.6 m (purification & high-voltage).



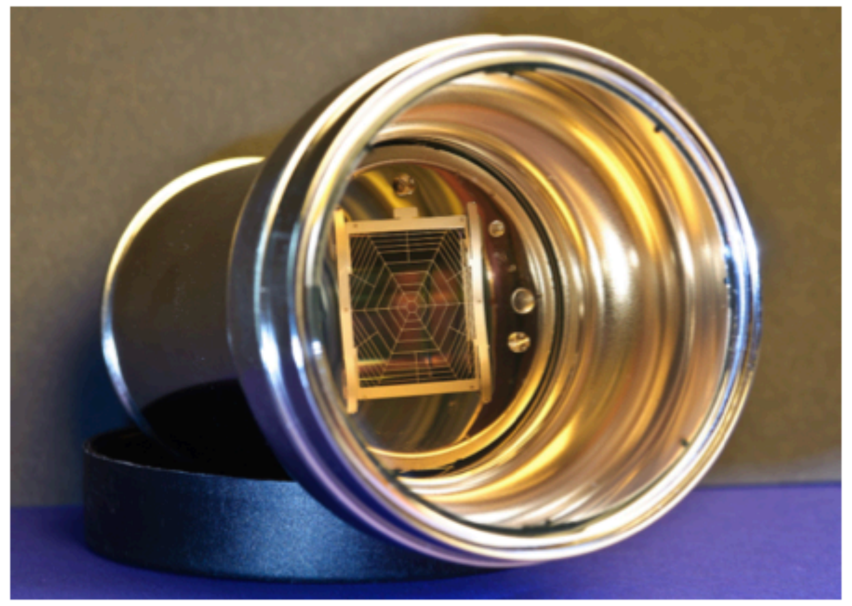
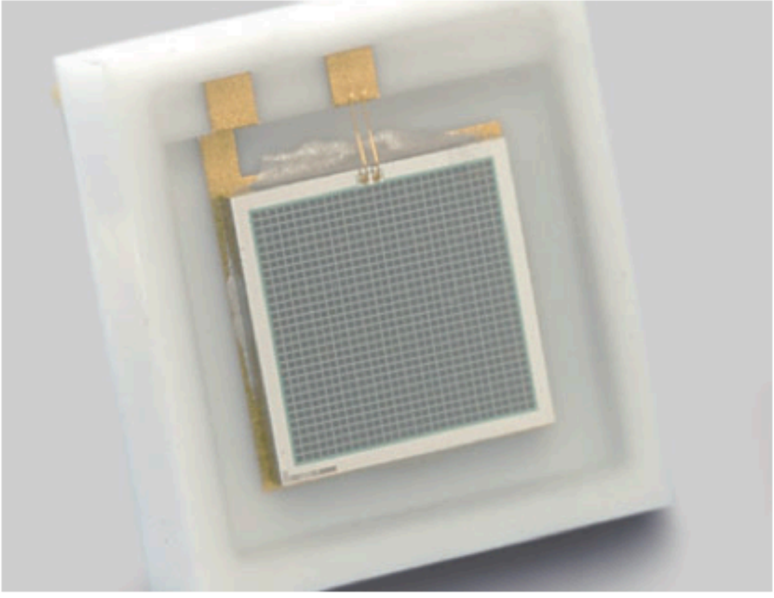
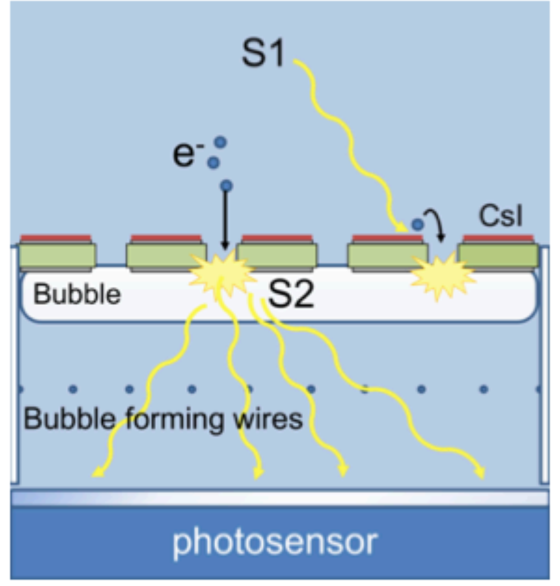
Horizontal demonstrator: *Pancake*

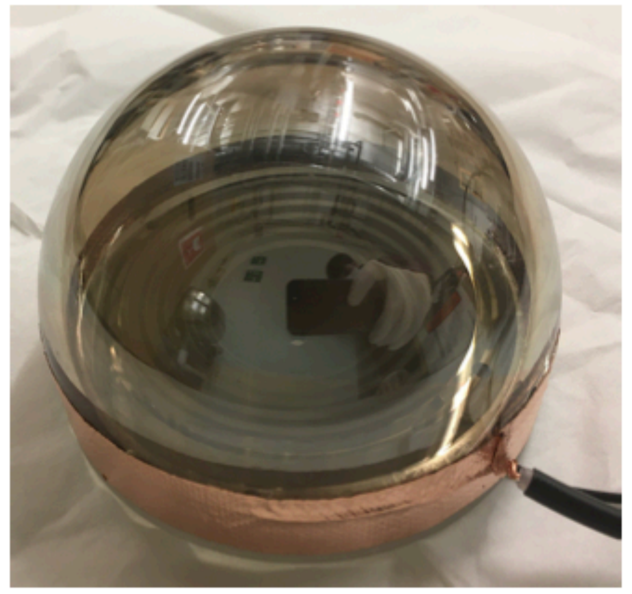
- 2.6 m Ø TPC in double-walled cryostats.
- Test electrodes mechanical stability, sagging & uniform S2-amplification.

Active R&D ongoing

Photosensors

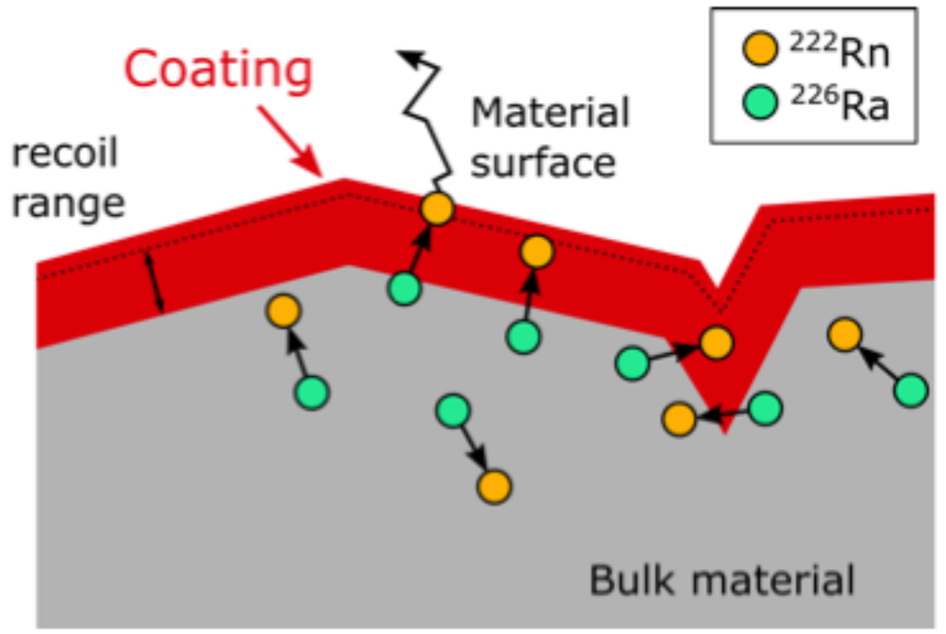
- Lower radioactivity PMTs, high position resolution SiPMs, hybrid photosensors for improved light collection, etc.



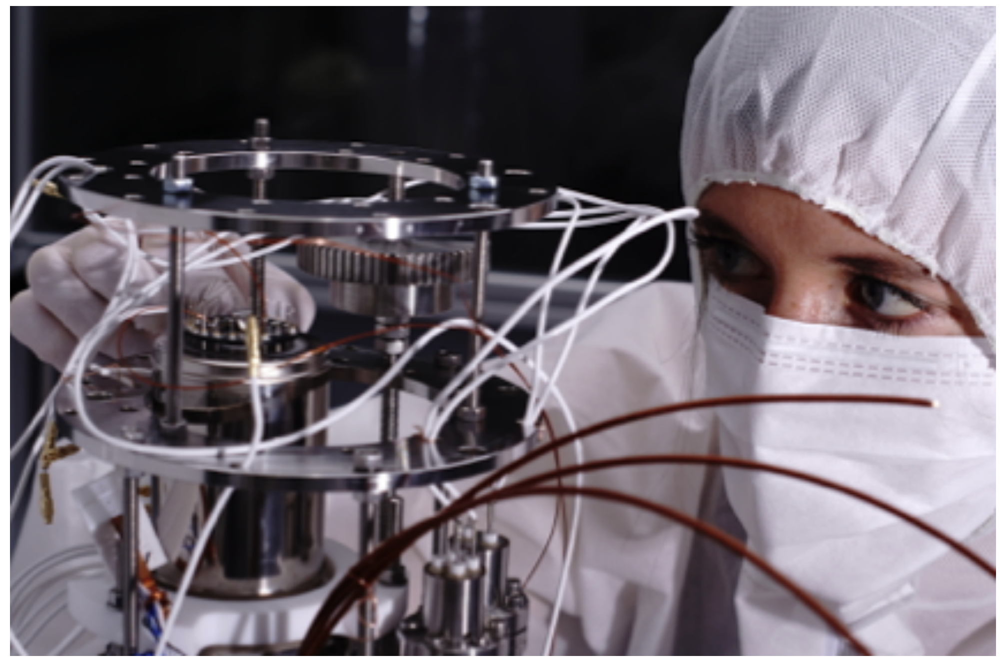
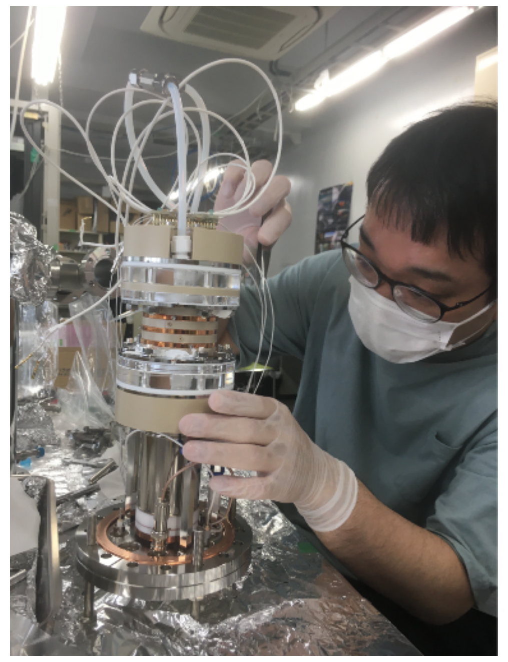

Background mitigation

- Materials screening, Xenon purification, distillation, Rn emanation mitigation



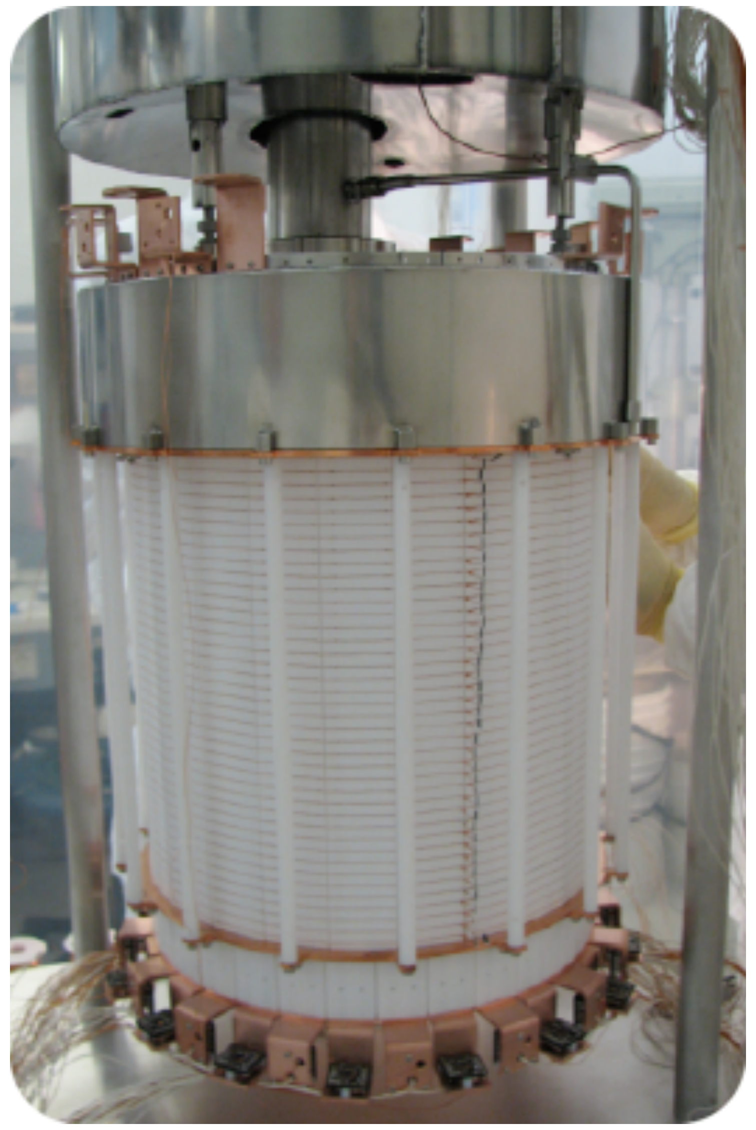
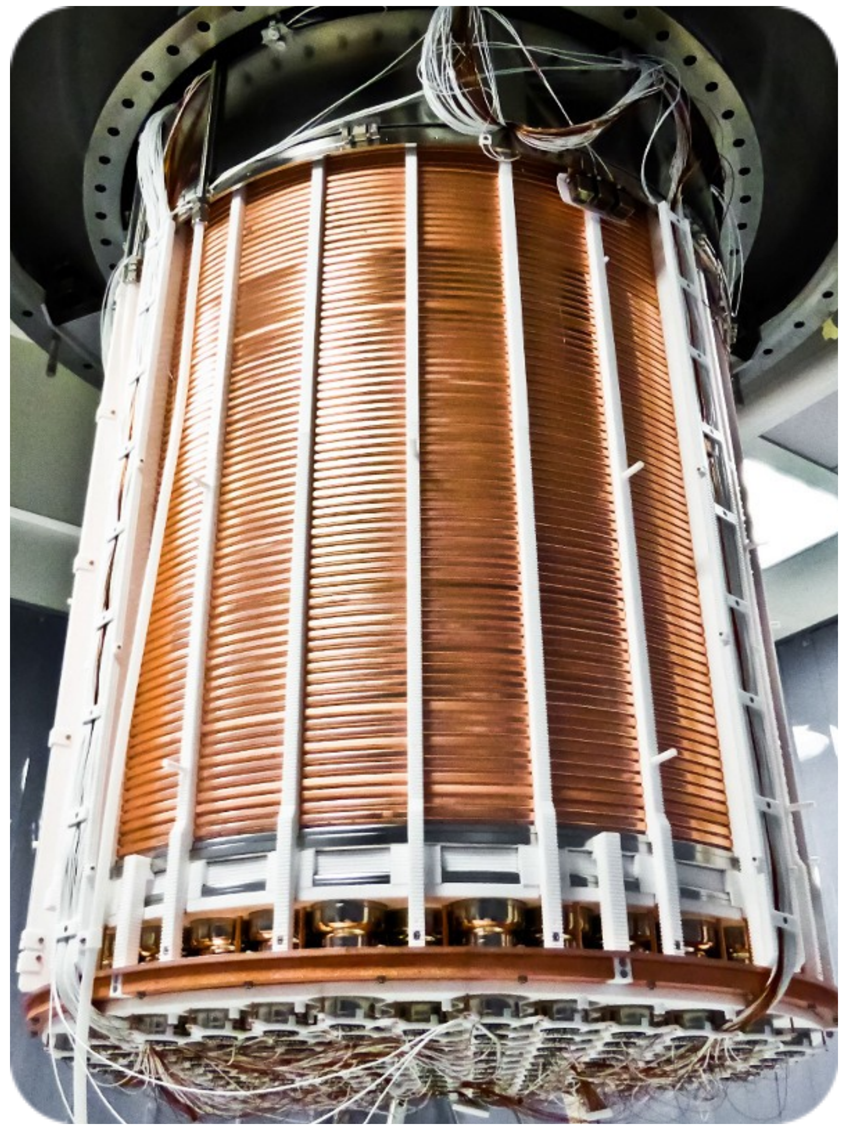
Detector design

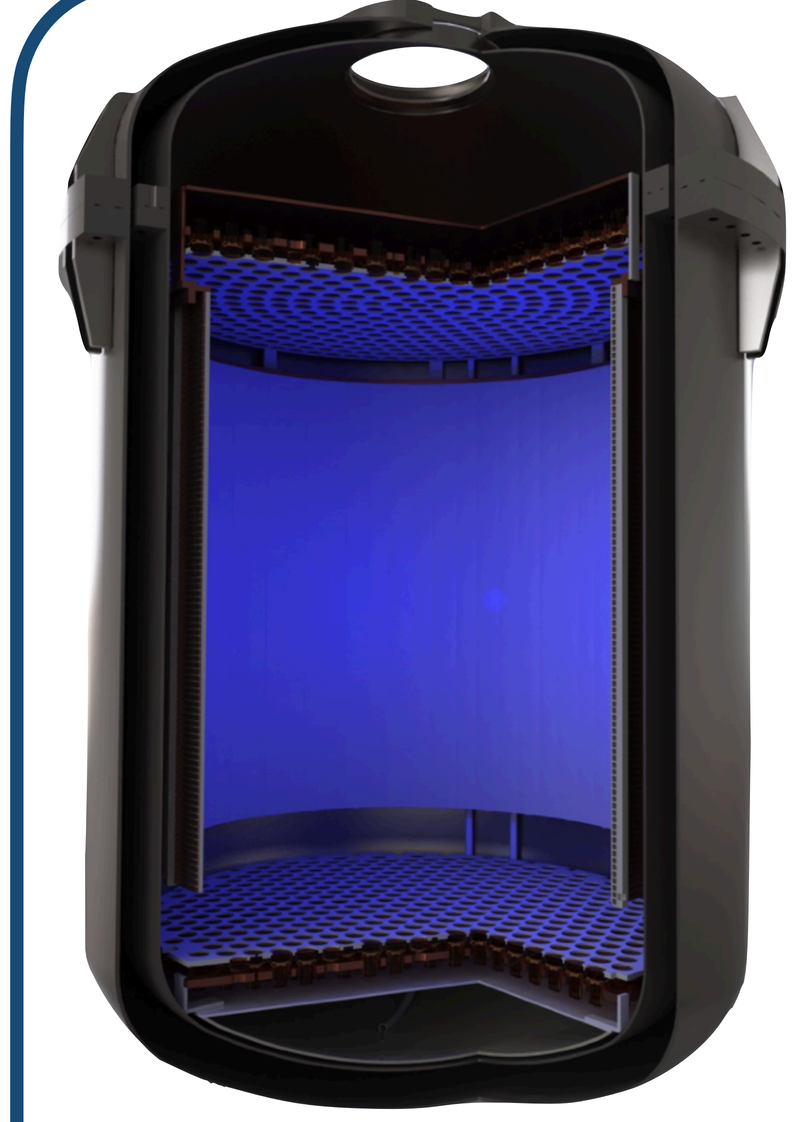
- Sealed/hermetic TPCs, Single-phase TPCs, aspect ratio optimisation

Future perspectives

	Present	Next Generation



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Background [t.day.keV]$^{-1}$	**~1000**	**5.3**	**0.2**	***0.04**	***0.005**
Sensitivity [cm^2]	**~10^{-44}**	**~10^{-45}**	**~10^{-47}**	***~10^{-48}**	***~10^{-49}**

* → Projections

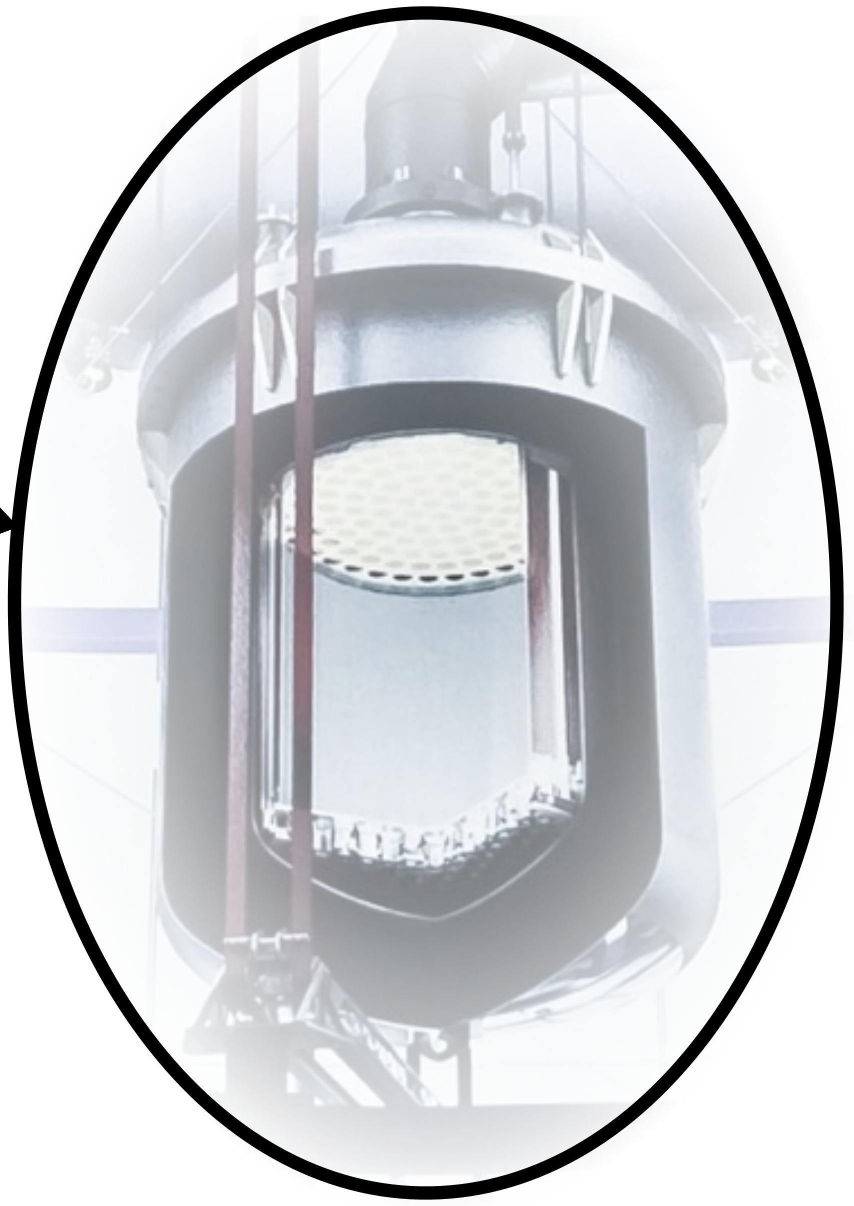
Physics Goals: Towards LXe Observatory

WIMPs

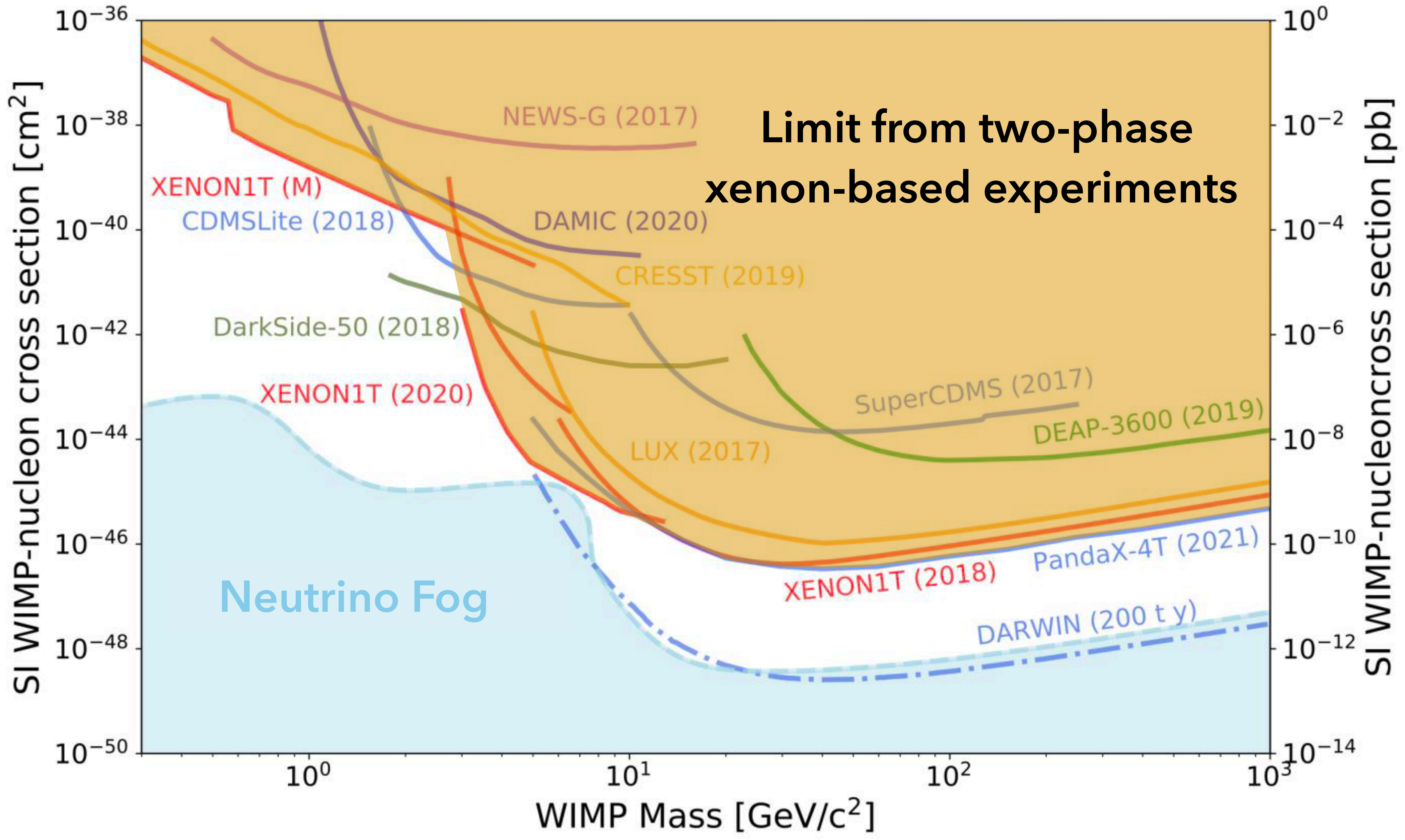
- Spin-independent
  - ➡ PRL 119, 181301
  - ➡ PRL 121, 111302
- Spin-dependent
  - ➡ PRL 122, 141301
- Sub-GeV
  - ➡ PRL 122, 071301
  - ➡ PRD 103, 063028

Dark Matter

- Light DM
  - ➡ PRL 123, 241803
  - ➡ PRL 123, 251801
- Bosonic DM
  - ➡ PRD 102, 072004



REFERENCES | ADAPTED FROM PARTICLE DATA GROUP (2020)



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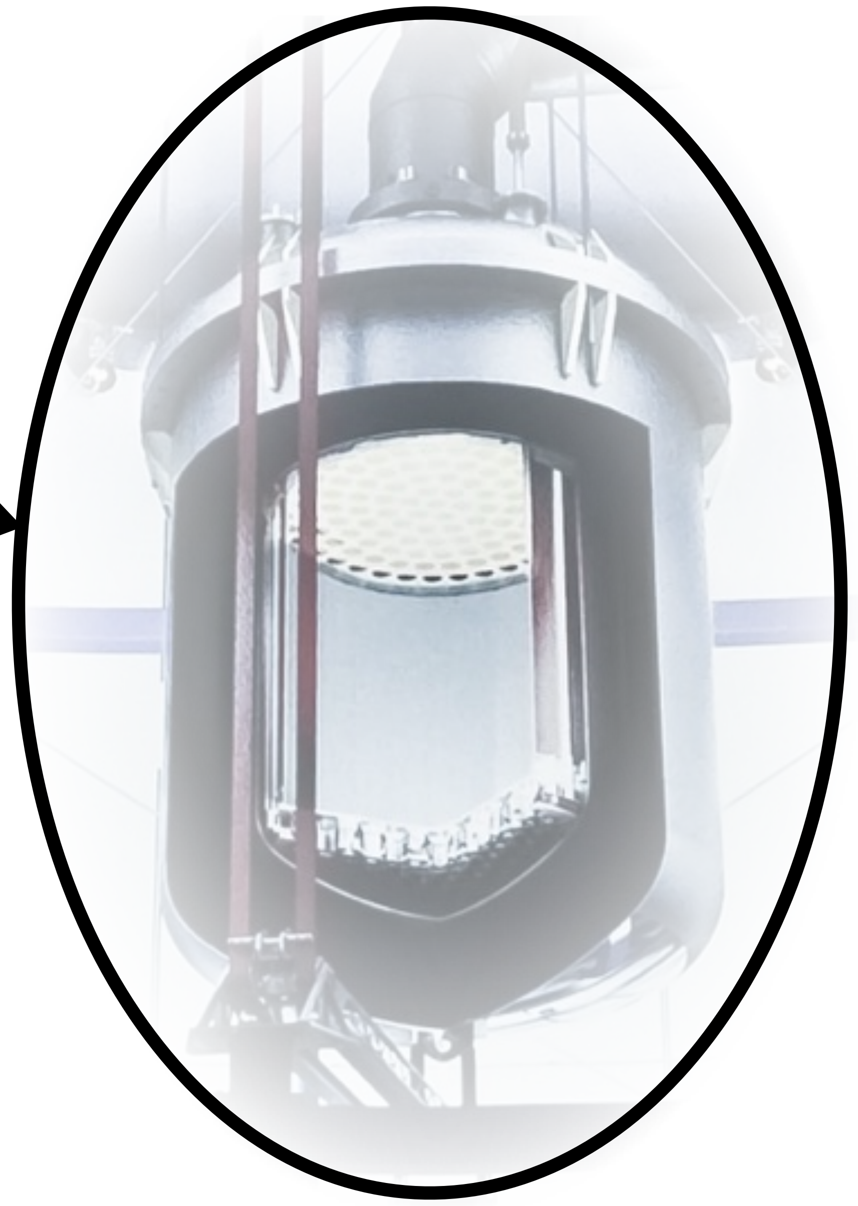

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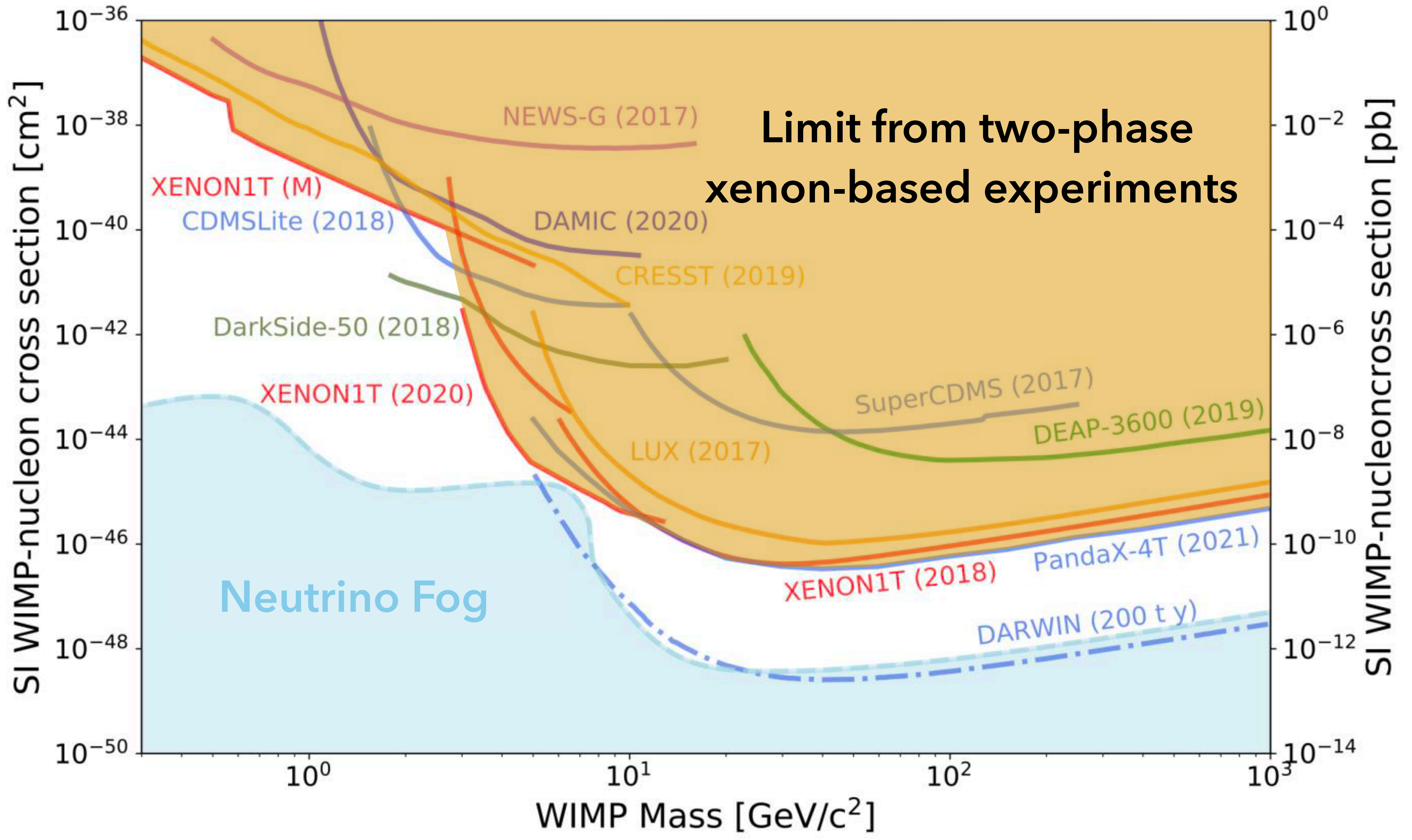

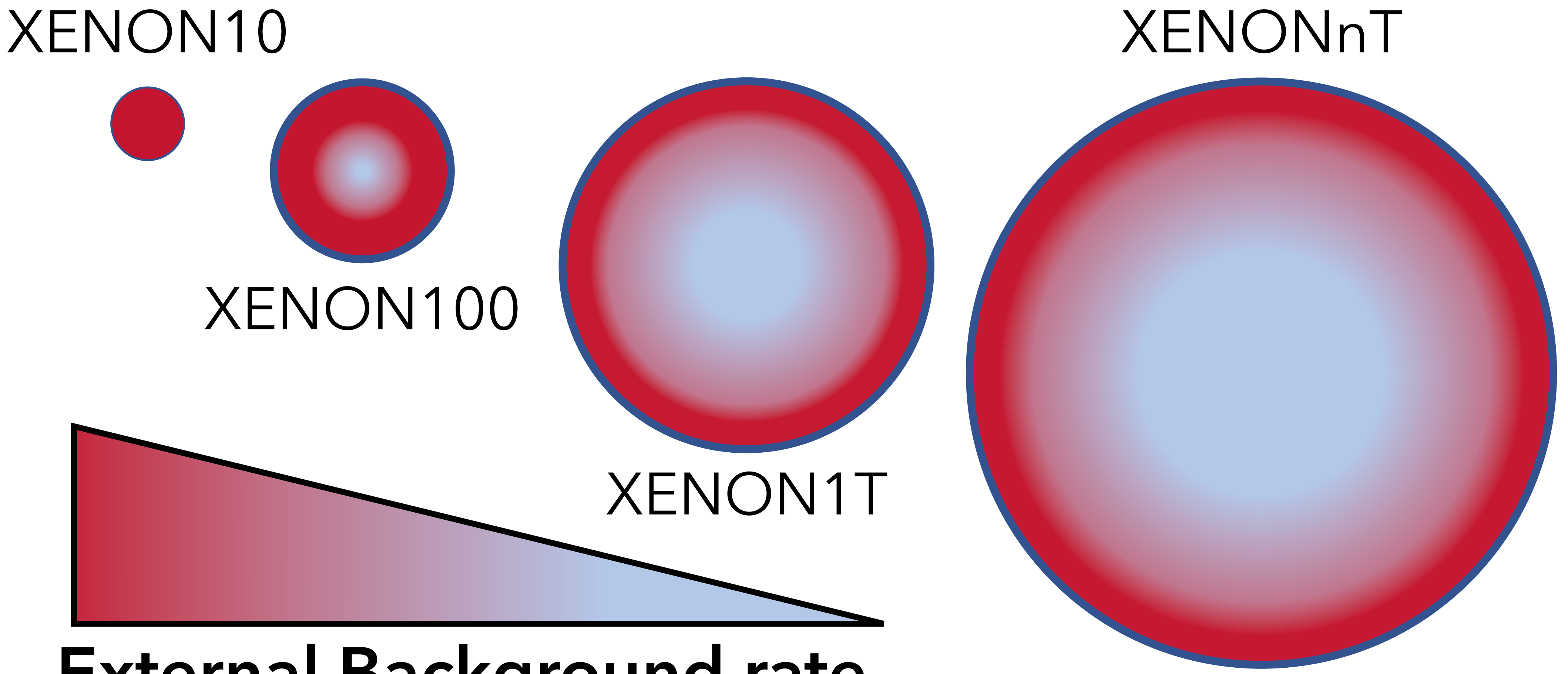

Heart of the detector more and more quiet
→ Probe New physics

Physics Goals: Towards LXe Observatory

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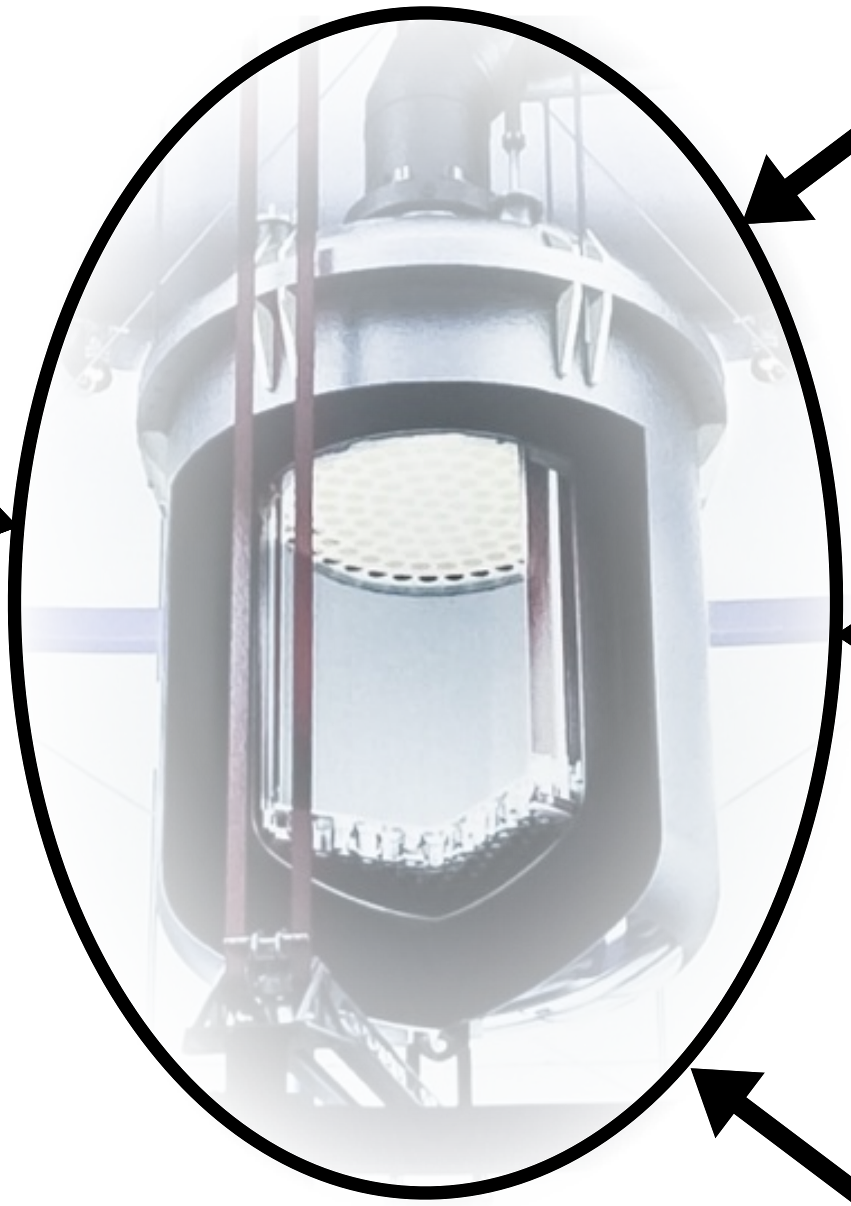
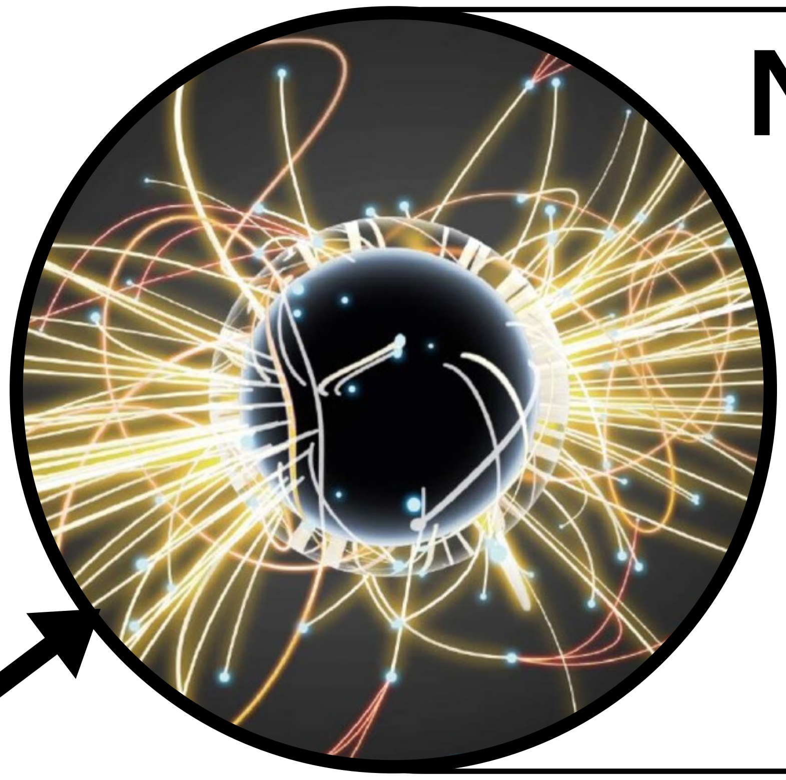
Today's Topic



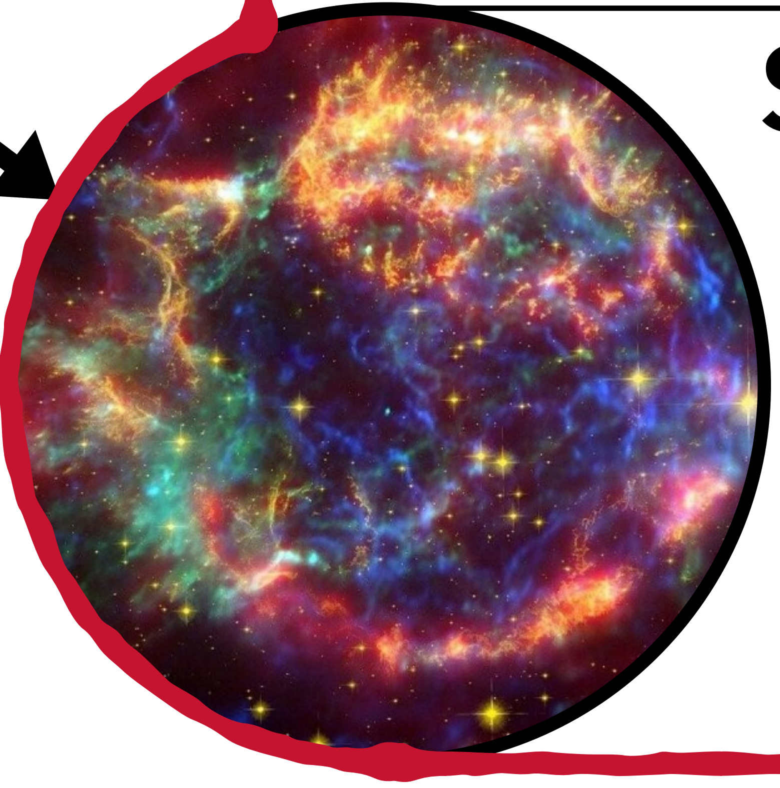


Nuclear/Particle Physics

- 2νECEC capture
  - ➡ Nature 568, 532
- 0νββ decay
  - ➡ EPJC 80:785 (2020)

Sun

- Solar ^{8}B CEvNS
  - ➡ PRL 126, 091301
- Solar pp neutrinos
  - ➡ EPJC 80:1133 (2020)
- Solar axions
  - ➡ PRD 102, 072004



Supernova

- Supernova neutrinos
  - ➡ PRD 94,103009

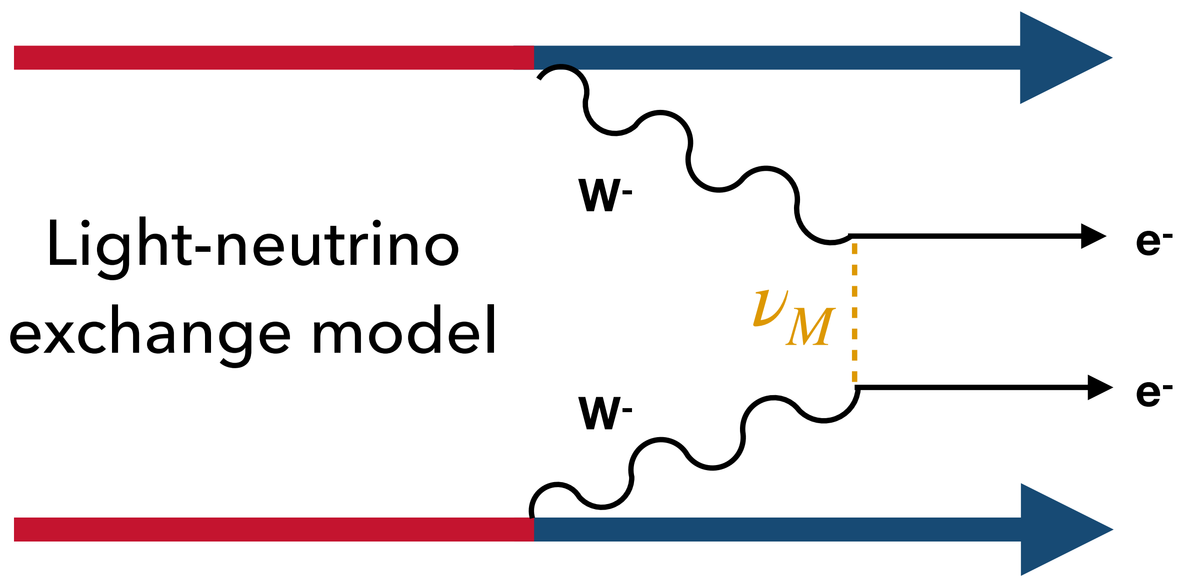
Astrophysics

Heart of the detector more and more quiet
→ Probe New physics

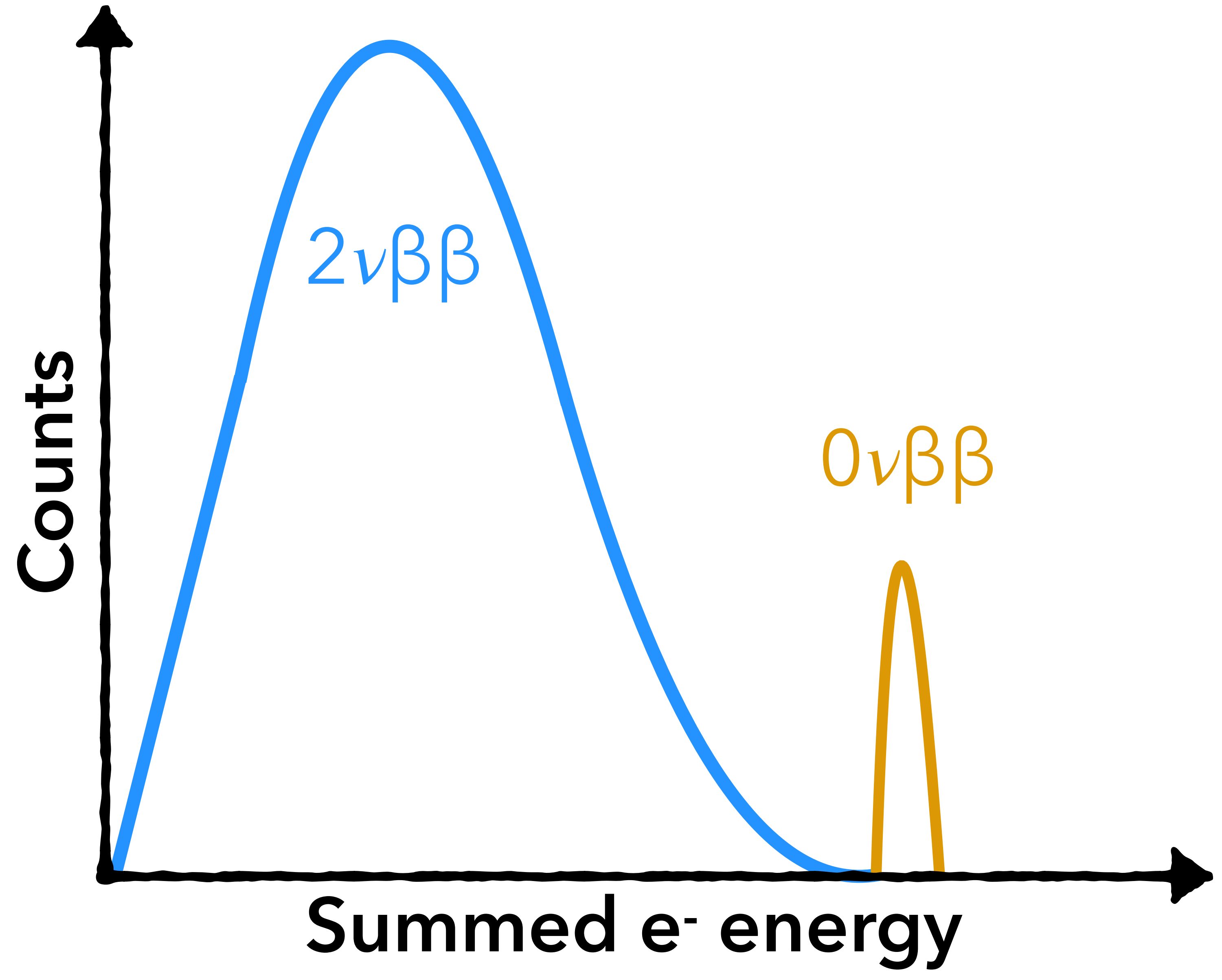
What is the True nature of Neutrino?

Neutrinoless Double Beta decay (0νββ):

- One of the best probe to answer this question.
- Lepton Number Violation → BSM Physics.
- ^{136}Xe candidate Isotope with a **natural abundance of 8.9%**.
- **Signal signature:** Single-Site events with a total deposited energy $Q_{\beta\beta}$ = 2457.83 keV
  - High Shielding power of Xenon (<3mm for e- @ $Q_{\beta\beta}$)



$$(A,Z) \longrightarrow (A,Z+2) + 2e^-$$



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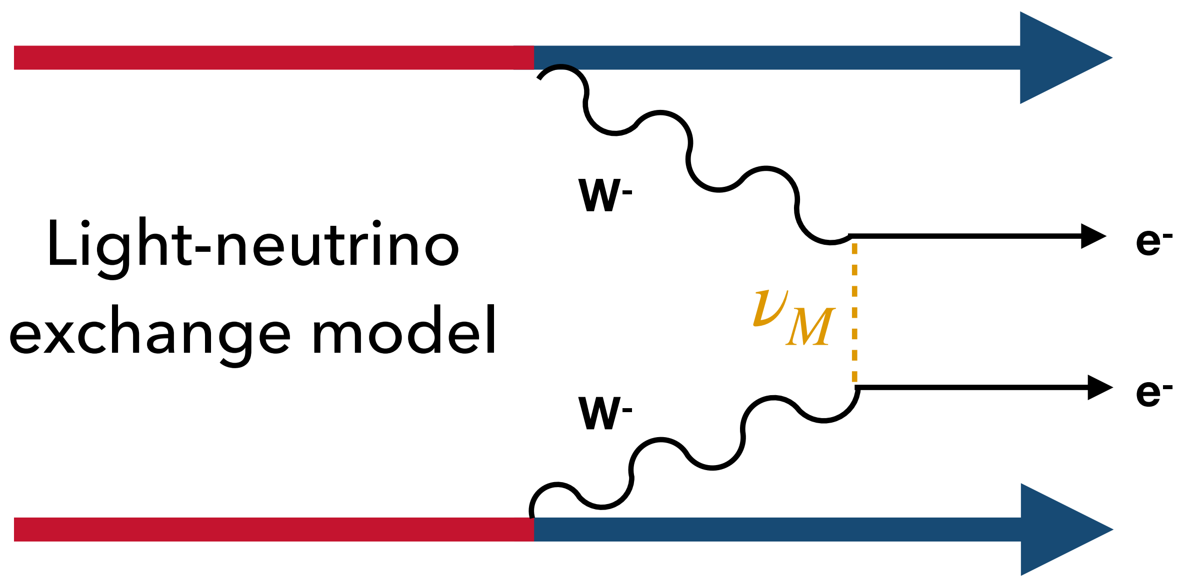

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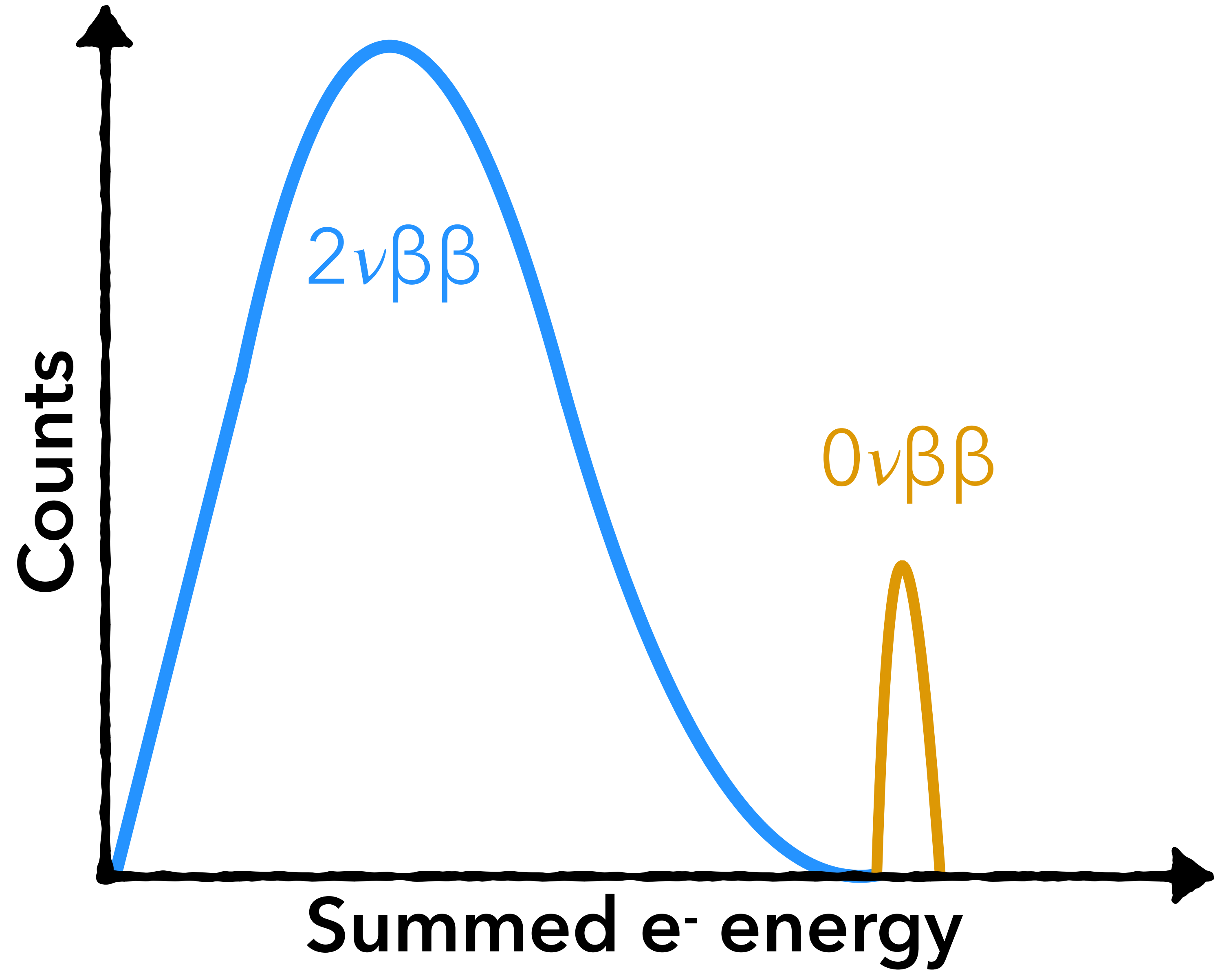
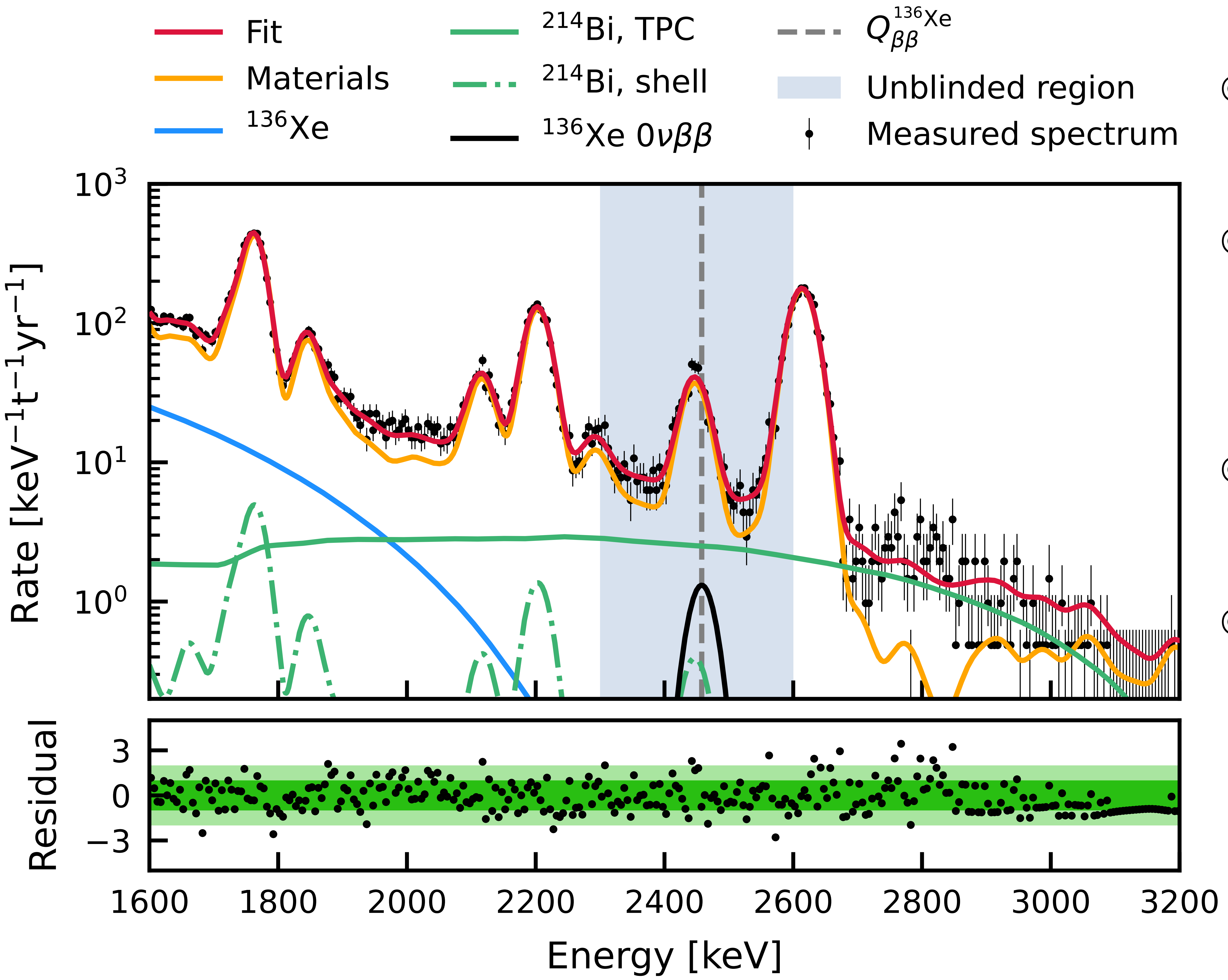


From low to high energy analysis

- **High-Energy reconstruction improvements** yield energy resolution of σ_E/E = 0.8 % at $Q_{\beta\beta}$ in XENON1T.
  - Already confirmed/improved by LZ reaching 0.6 %.

REFERENCES | EPJC 80:785 (2020) | ARXIV:2003.03825

0νββ Blind analysis in XENON1T



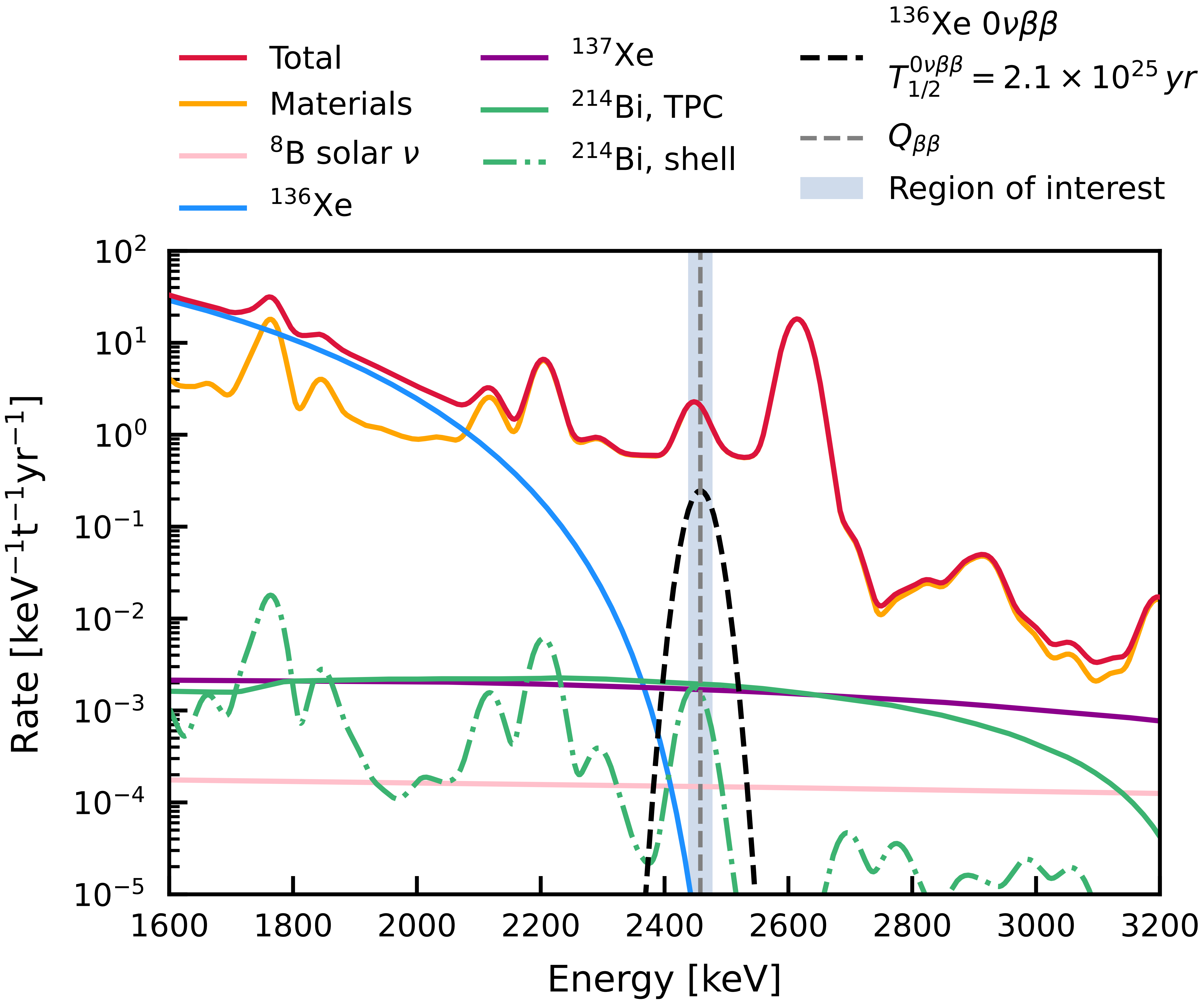
Paper Submitted to PRC
arXiv:2205.04158

- Science data blinded between 2300 and 2600 keV.
- Single-Site events in a 741 kg fiducial volume with optimal signal to background ratio.
- Background components according to expectation.
- Lower limit at 90 % CL from profiled likelihood ratio:

$$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}\ \mathrm{yr}$$

Most stringent limit to date by a non-enriched dark matter detector

$0\nu\beta\beta$ Sensitivity projection for XENONnT



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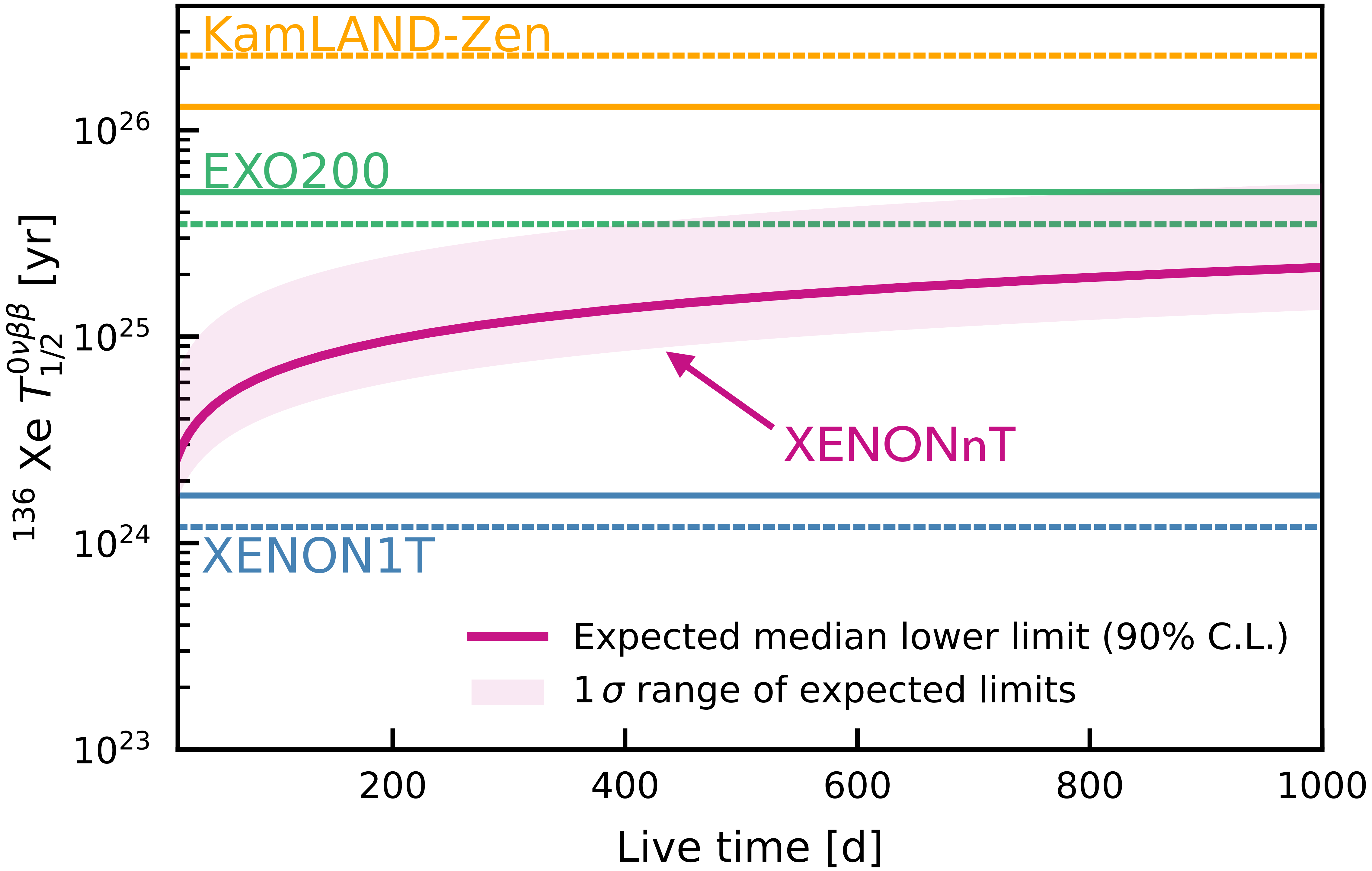
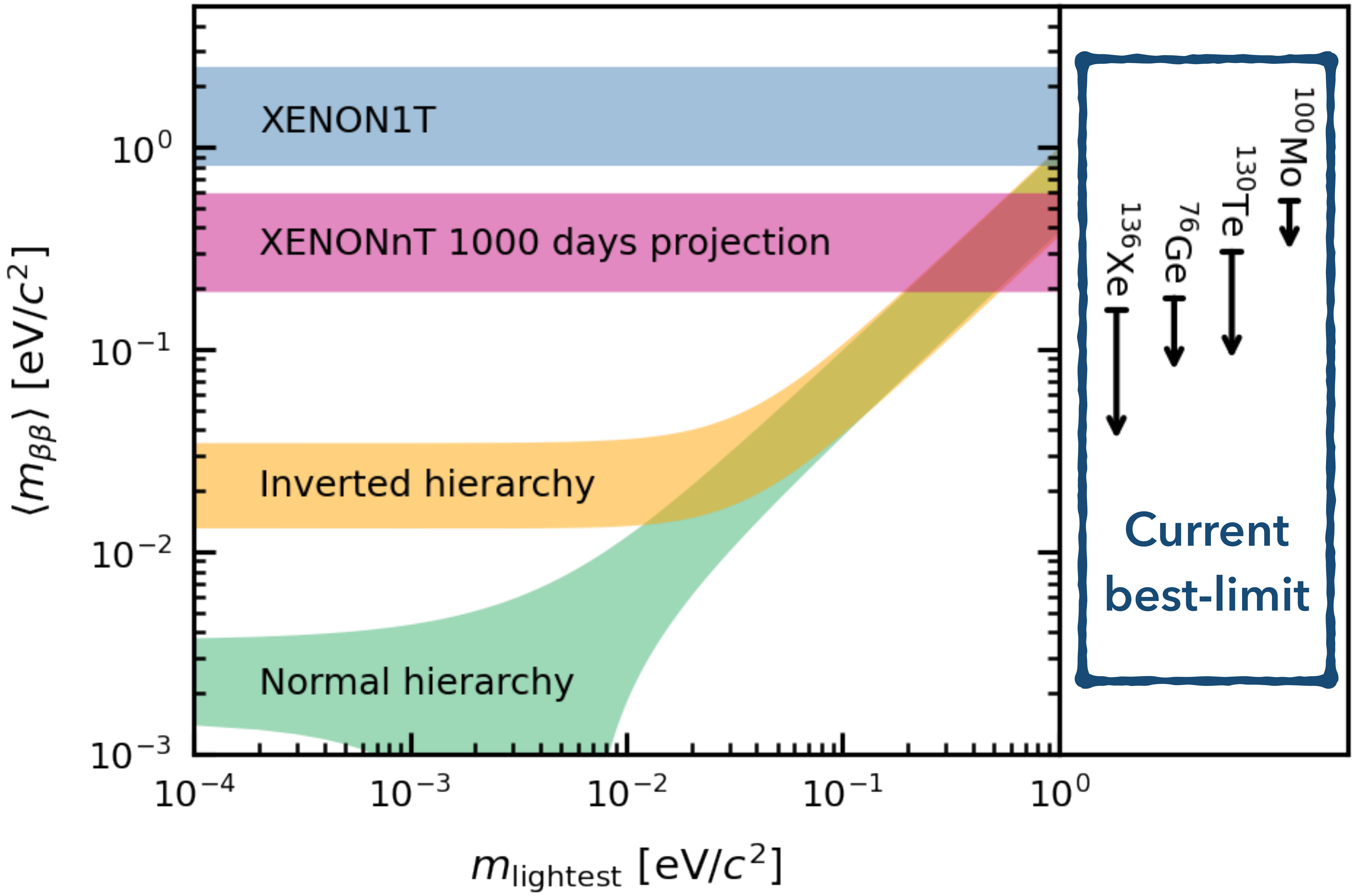
- Follow analysis method developed in XENON1T.
- 1088 kg optimal fiducial volume according to XENONnT materials backgrounds.
- **^{137}Xe β-decay from radiogenic and cosmogenic n-activation** as well as **^{8}B solar neutrinos-electrons scattering** are also considered due to overall lower background.
- Projected sensitivity at 90% CL:

$$T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}\,\mathrm{yr}$$

$0\nu\beta\beta$ Sensitivity projection for XENONnT

Comparison with dedicated experiments:



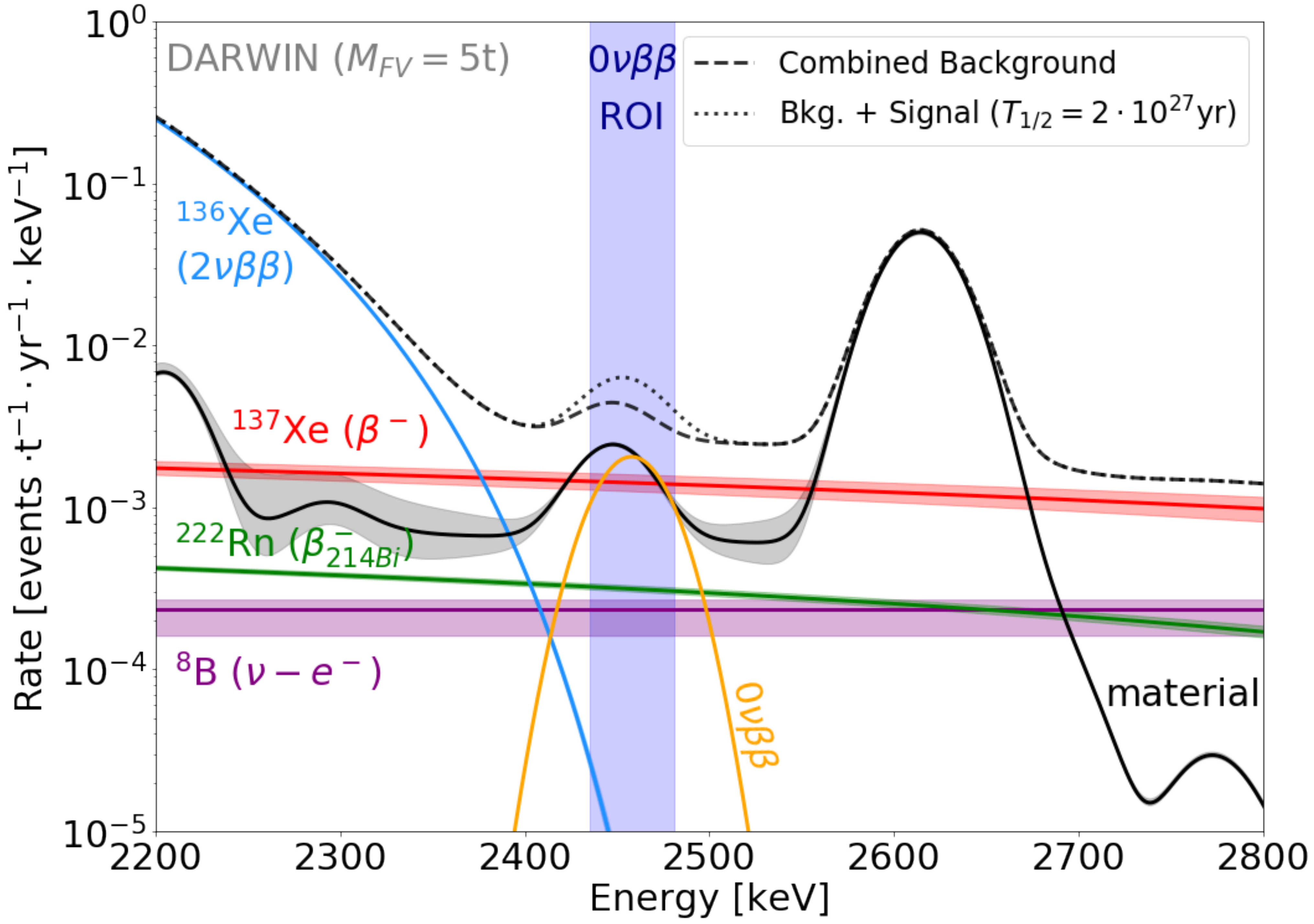


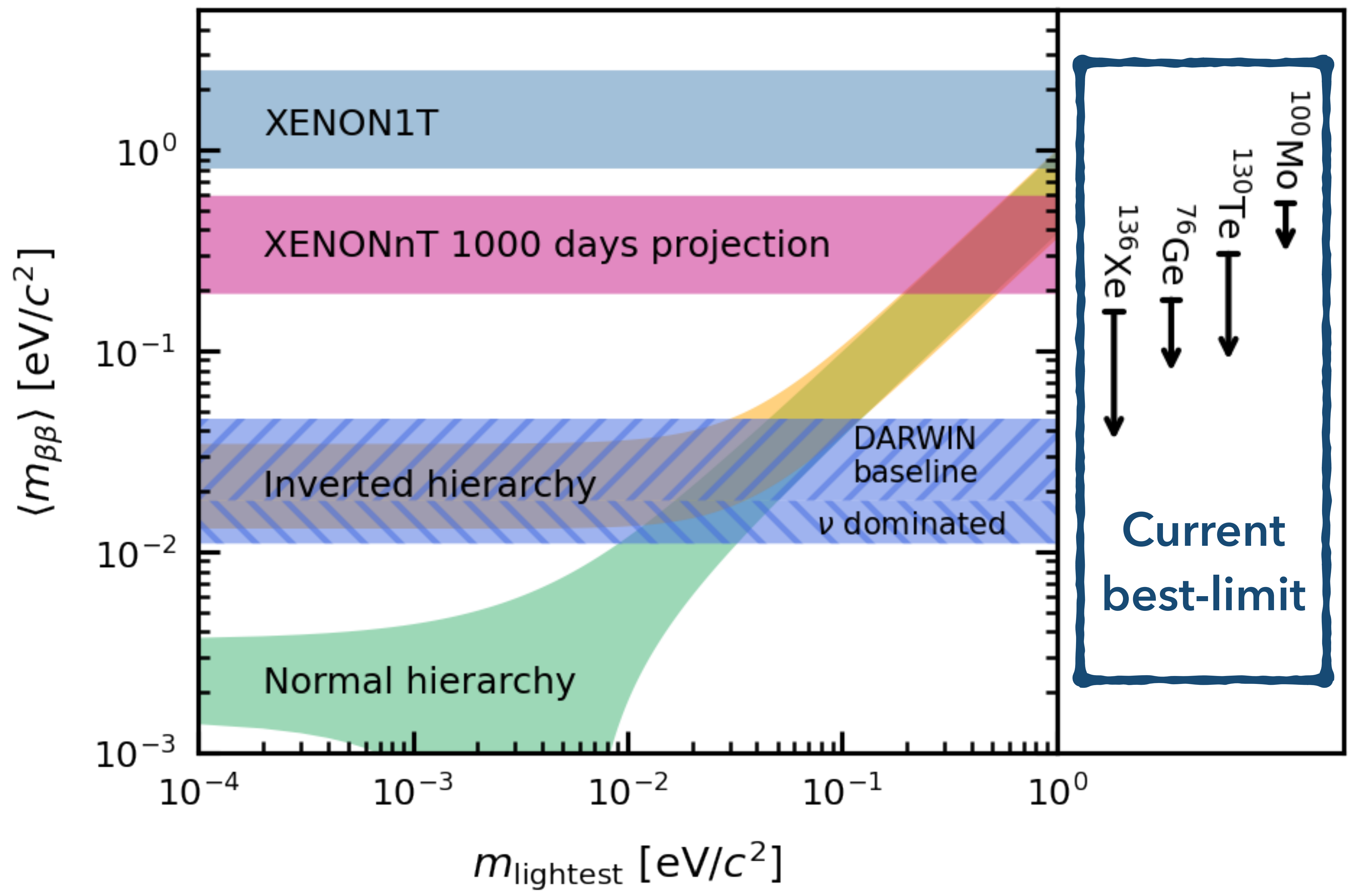
- Not competitive with dedicated experiments due to:
  - Non-enriched target.
  - Background optimization for DM searches (SS Cryostat).
- **Result demonstrates feasibility in future xenon DM experiments.**

$$\langle m_{\beta\beta} \rangle^2 = \frac{m_e^2}{G_{0\nu} \left| M_{0\nu} \right|^2 T_{1/2}^{0\nu}}$$

$$m_{\beta\beta} < 0.19 - 0.59\,\text{eV}/c^2$$

$0\nu\beta\beta$ Perspective with DARWIN





- **Baseline scenario:** 50 tons of LXe and 10 years lifetime.
- Materials backgrounds reach intrinsic backgrounds level **using 45t of LXe as shielding**.
- DARWIN approaches sensitivity of the future tonne-scale $0\nu\beta\beta$ experiments while being dedicated to DM search.

Explore inverted hierarchy of neutrino mass ordering

	Baseline	ν dominated
$T_{1/2}^{0\nu\beta\beta}$	$> 2.4 \times 10^{27}$ yr	$> 6.2 \times 10^{27}$ yr
$m_{\beta\beta}$	$< 0.18 - 0.46\,\text{eV}/c^2$	$< 0.11 - 0.28\,\text{eV}/c^2$

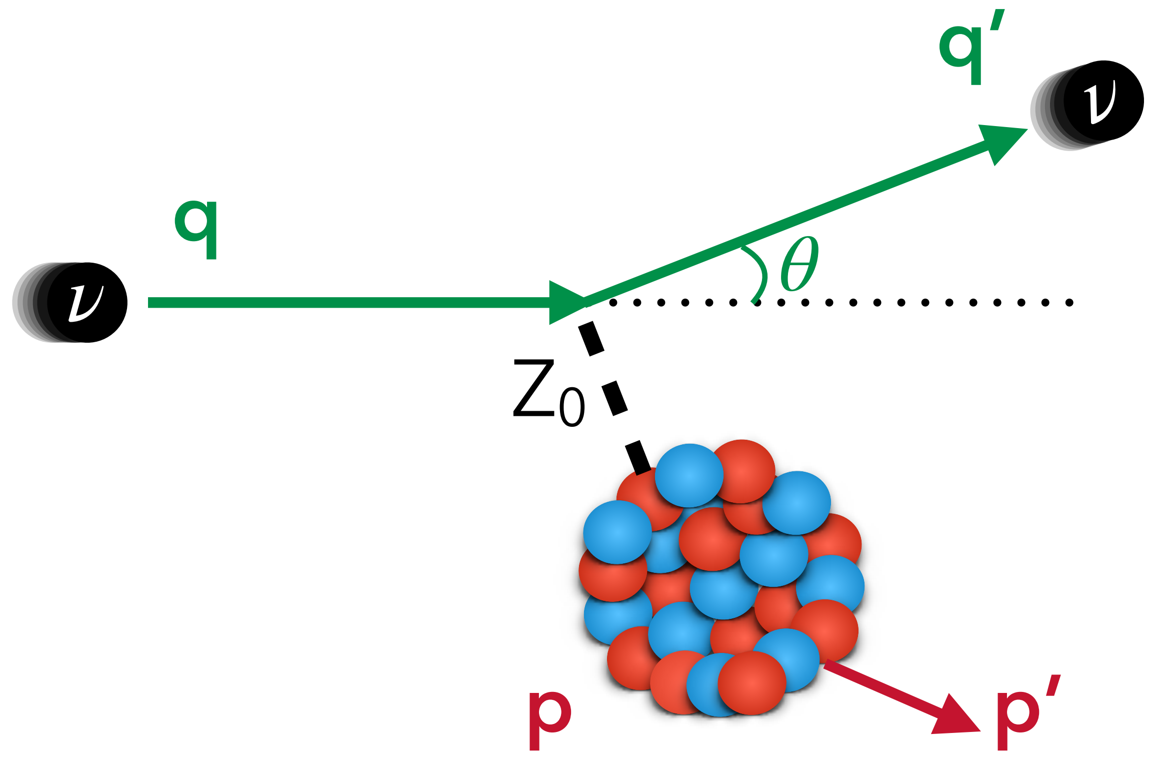
REFERENCES | EPJC 80:808 (2020) | ARXIV: 2003.13407

Solar Neutrinos

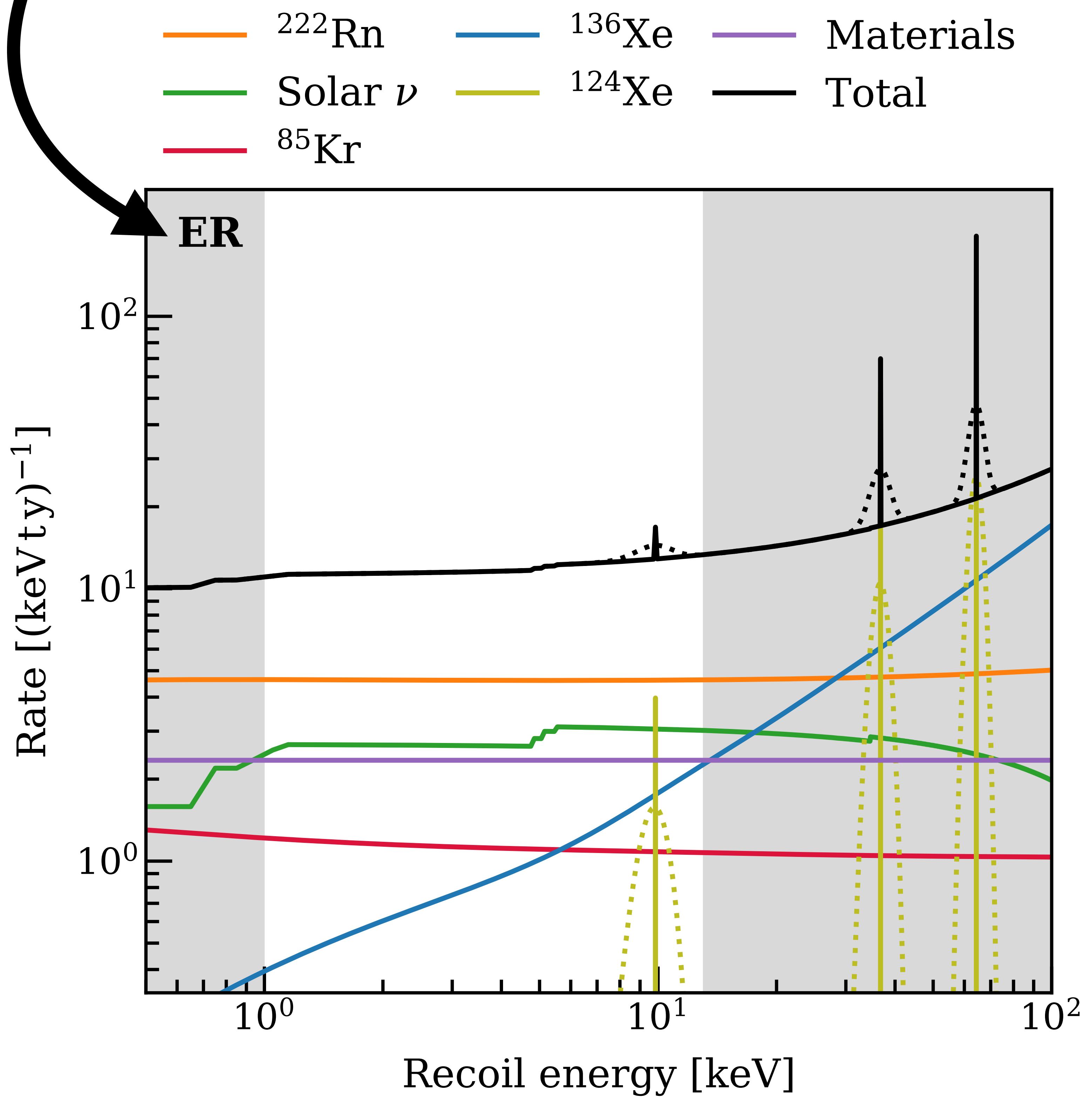
Neutrino Interactions:

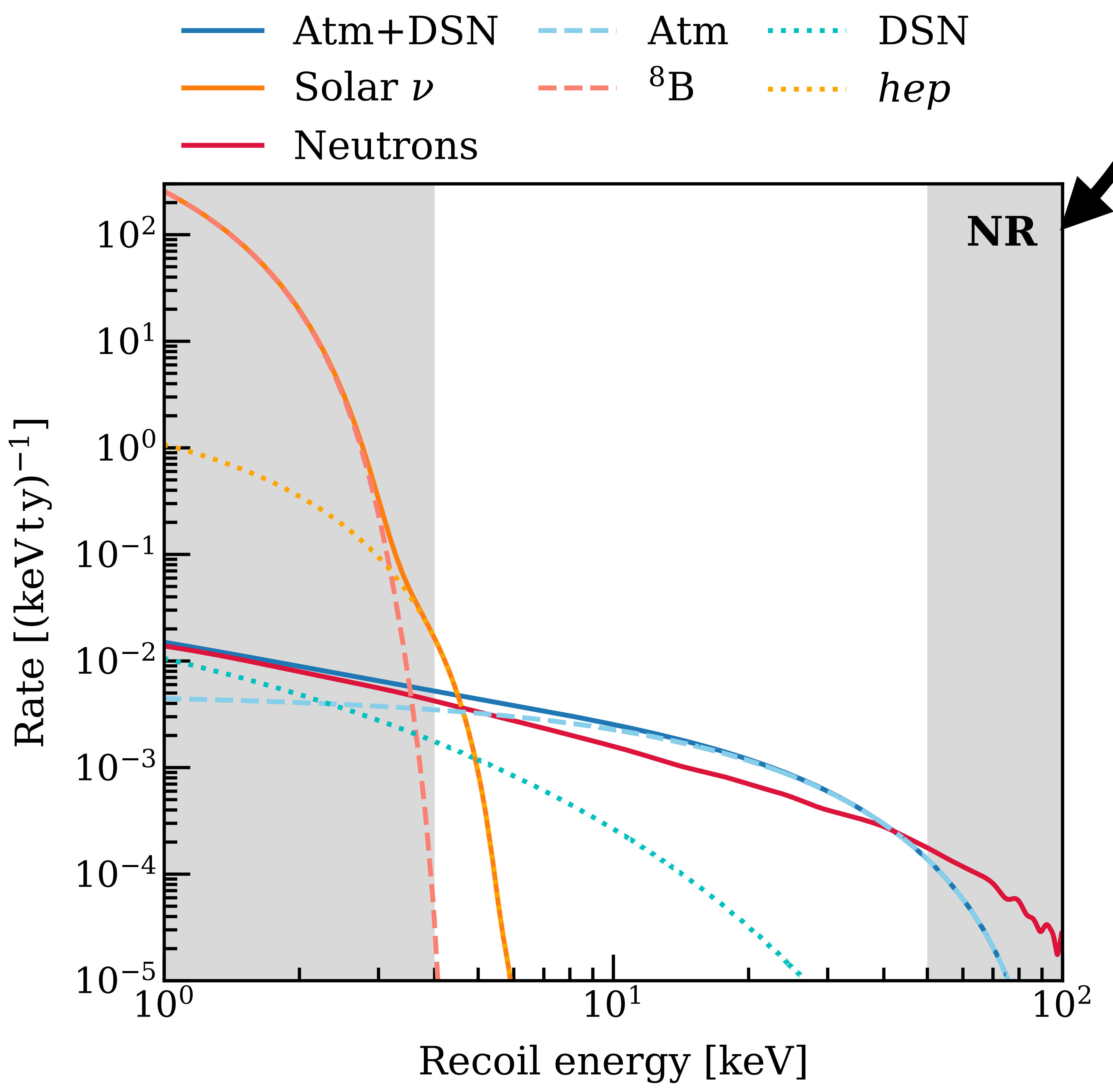
Electron elastic scattering
Charged and Neutral Current (CC & NC)

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
Neutral Current (NC)



WIMP background projection in XENONnT





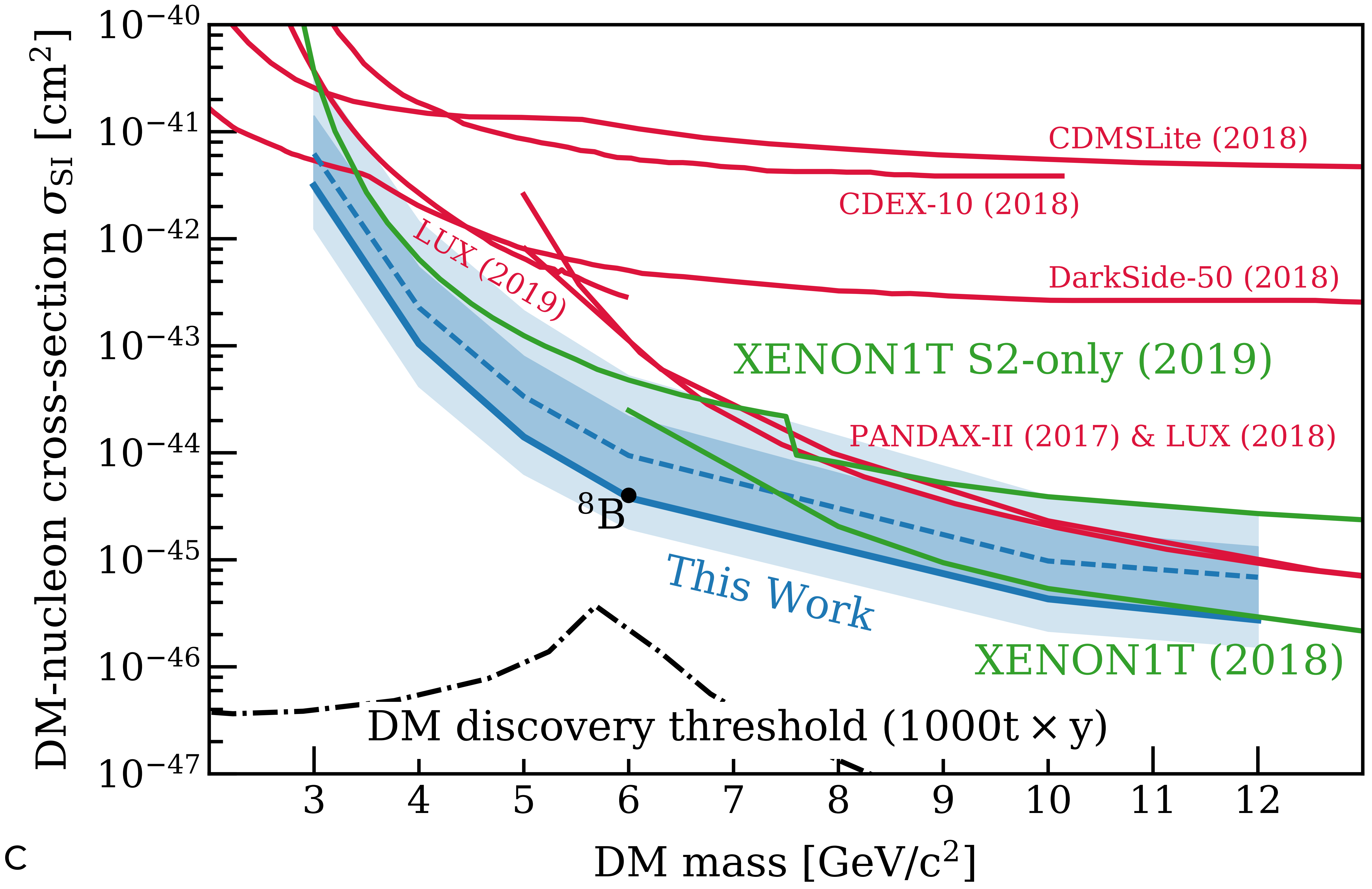
- **Irreducible background** source for direct detection DM experiments.
- Already relevant in XENONnT.
- Can be seen as a **signal** too!

REFERENCES JCAP 11, 031 (2020) | ARXIV:2007.08796

^{8}B CEvNS interaction

XENON1T Result:

- No positive detection of CEvNS signal:
  - Use lowered threshold to set **improved low-mass WIMP limits down to 3 GeV/c²**.
- First observation of CEvNS events from ^{8}B solar neutrinos is **expected with XENONnT.**



Next generation perspectives:

- Precise measurement of the neutral current component of the solar ^{8}B neutrino flux.
- Hep branch, Diffuse supernova, and Atmospheric neutrinos will be no longer negligible.

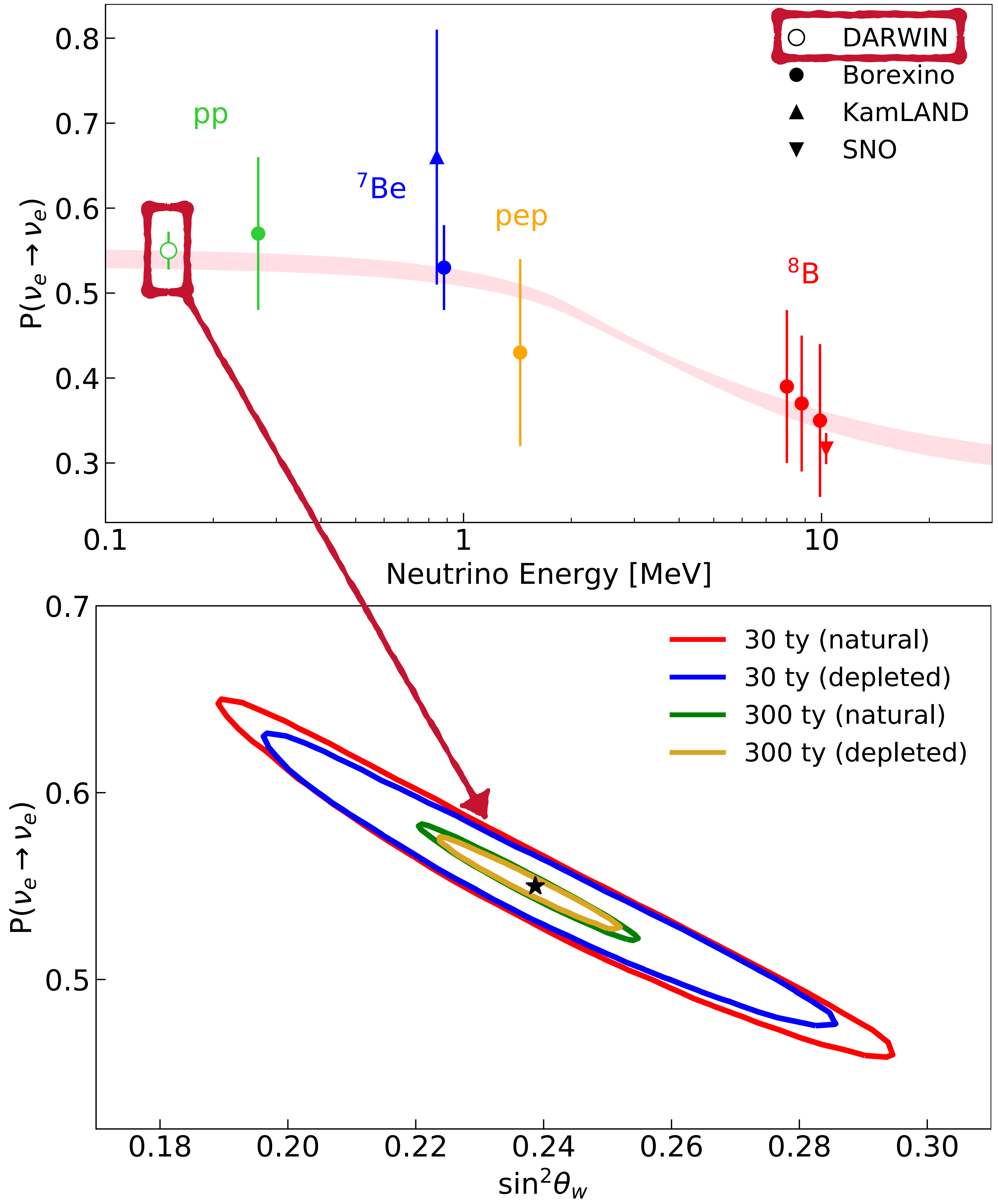
REFERENCES | PRL 126, 091301 (2021) | ARXIV:2012.02846

ν-e⁻ elastic scattering in DARWIN

- **Excellent precision in solar neutrino flux measurement:**
  - 0.15 % precision for pp neutrino.
  - 1 % for ^{7}Be neutrino
  - Scenario: 30 t FV mass (300 t.yr exposure)
  - Assuming 0.1 µBq/kg $^{222}Rn/Xe$ concentration

Precise measurements of electronic solar neutrino survival probability and electroweak mixing angle using pp neutrino

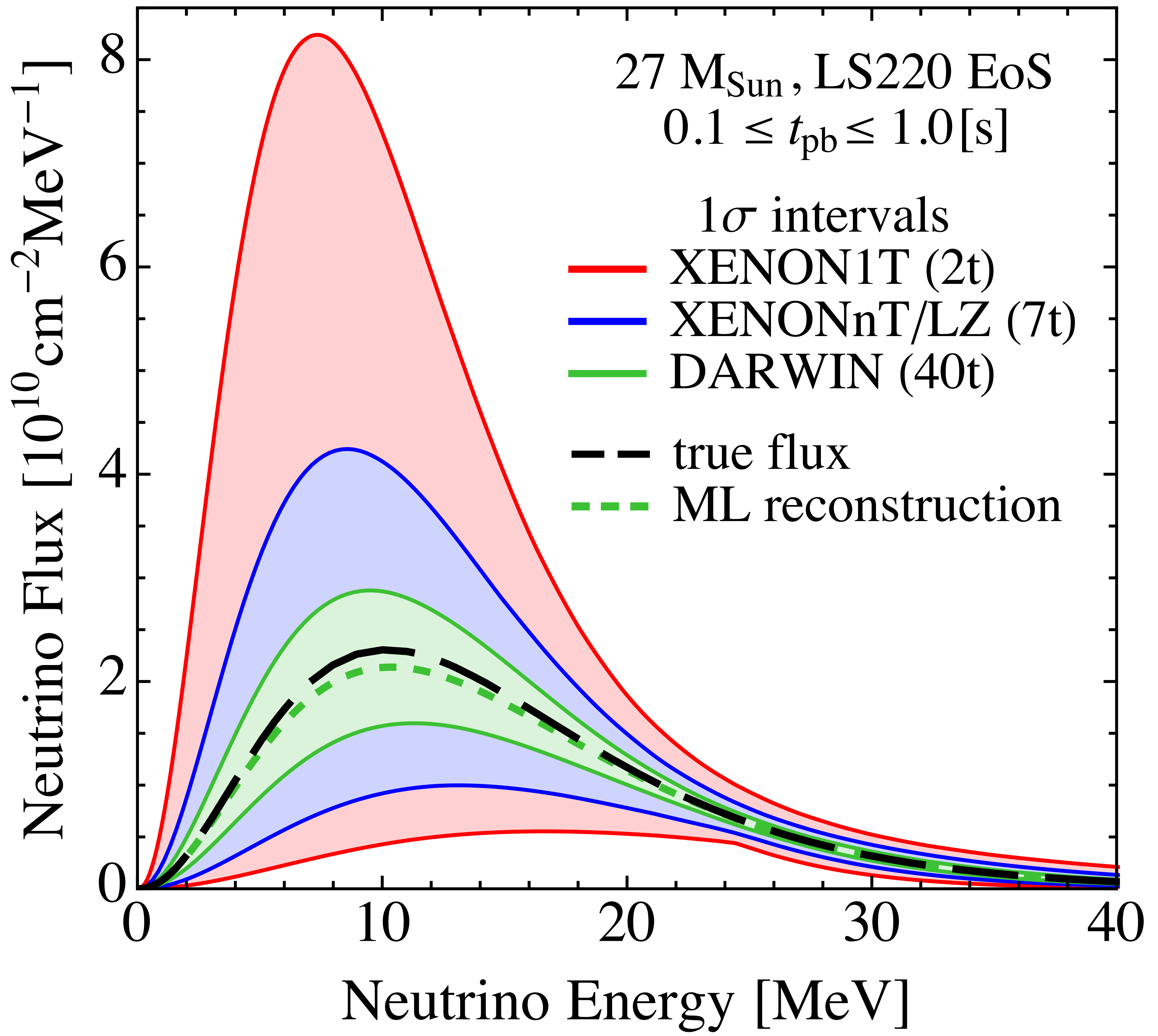
- **First measurement of $\sin^2\theta_W$ in this energy range**, but with larger uncertainty than those at higher energies.
  - $\sin^2\theta_W$ uncertainty → 5.1 %
  - P_{ee} uncertainty → 4.0 %

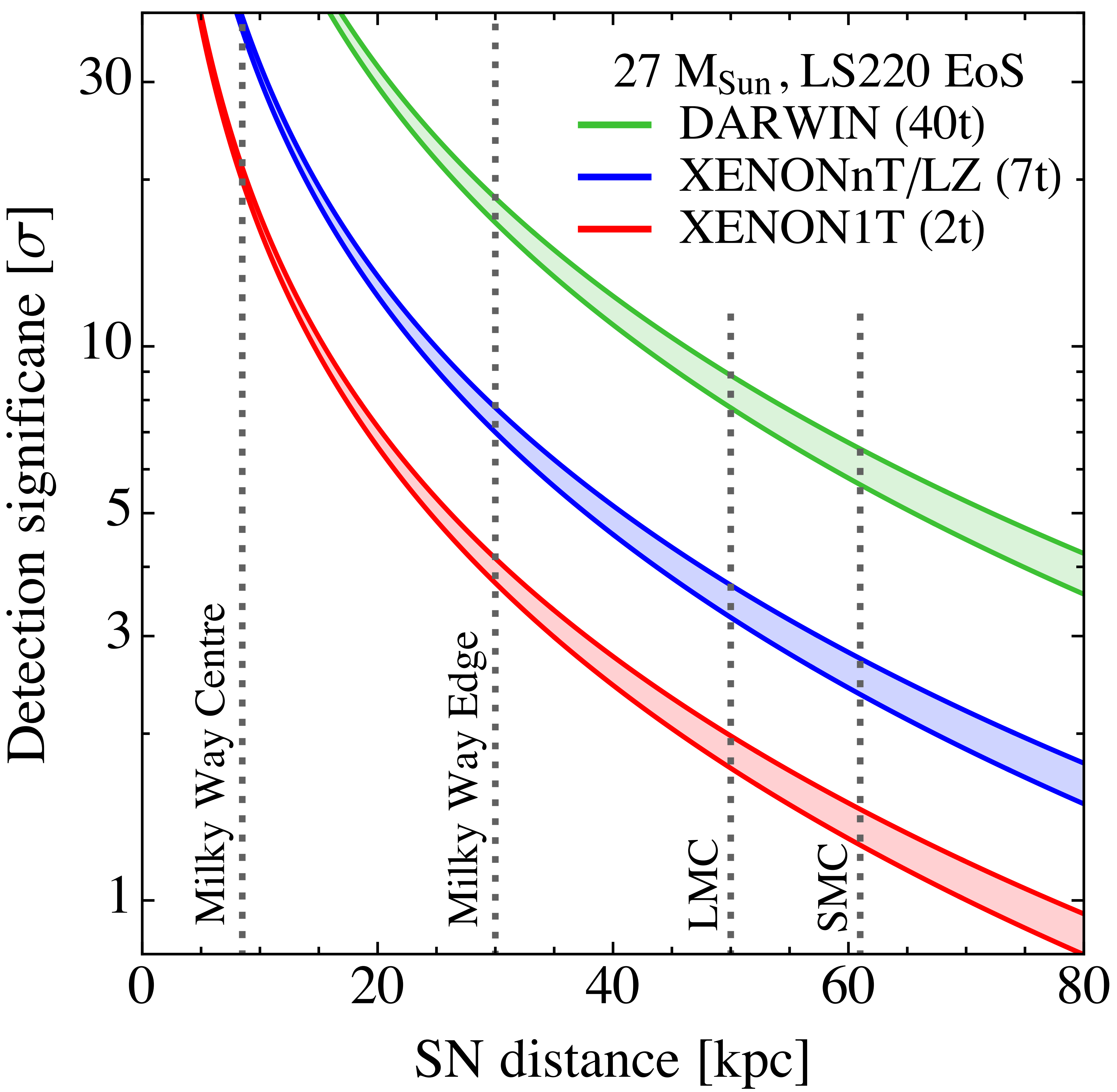


REFERENCES | EPJC 80:1133 (2020) | ARXIV:2006.03114

Supernova Neutrino

- **Flavor blinded measurement** of neutrino flux **through CEvNS** events for the community .
- **Contribution to** the upgraded SuperNova Early Warning System (**SNEWS-2.0**) with XENONnT and DARWIN.





REFERENCES PHYS.REV.D 94 (2016) 10, 103009 | ARXIV:1606.09243

Summary & Outlook

- **Xenon dual-phase TPCs are leading the race in the quest for the direct detection of WIMP dark matter candidate and already demonstrated their scalability.**

- **Broadening of the physics program towards neutrino physics with the current and next generation of detector** (0νββ, CEvNS, solar neutrinos, etc).

Merger of leading collaborations for a
future DARWIN/G3 Xenon-based experiment

XENON DARWIN LZ

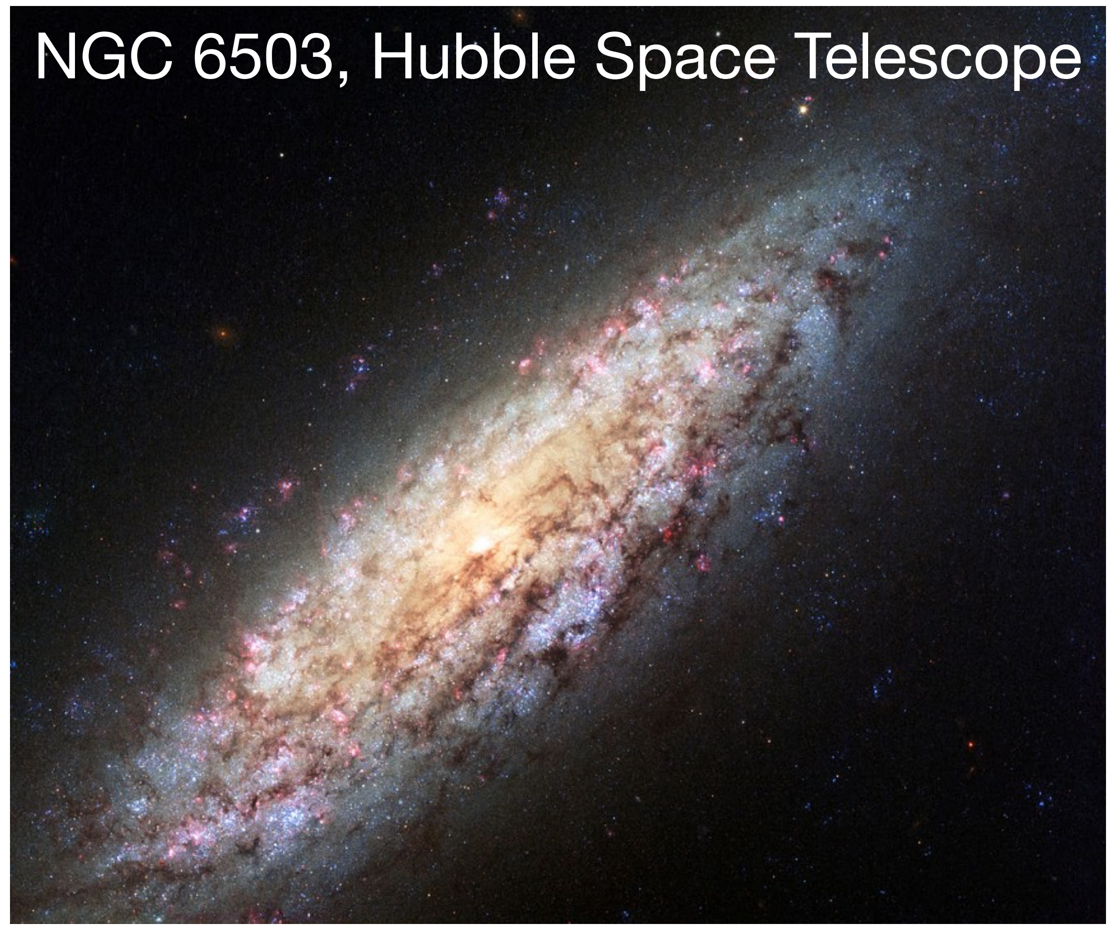
xlzd.org

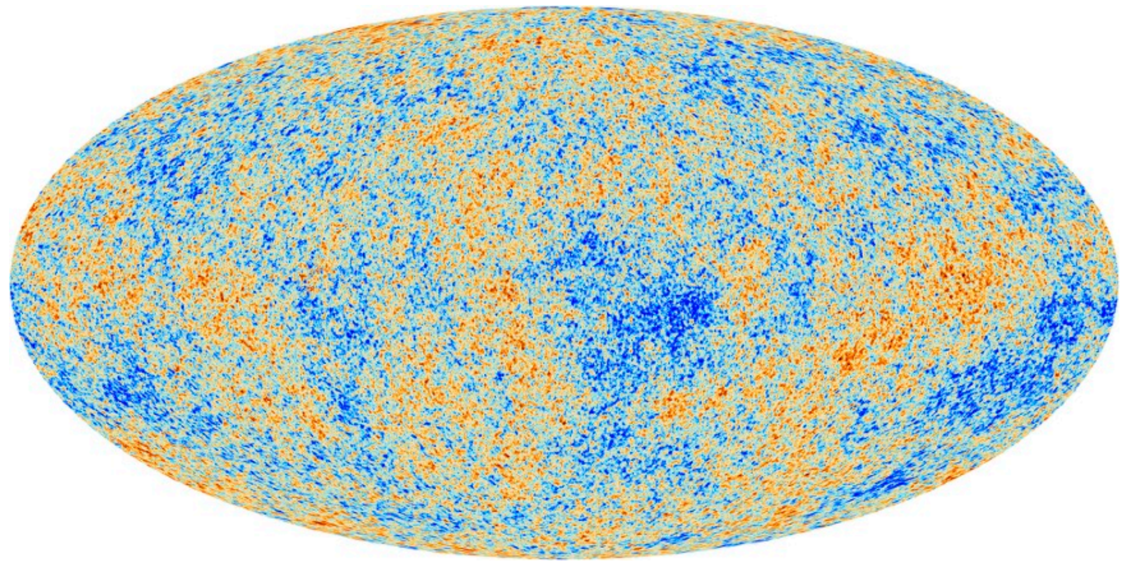
- Consortium between XENON/DARWIN and LUX-Zeplin (LZ) established on July 2022 → **XLZD**
- **Memorandum of understanding** signed July 6, 2021.
- Community Whitepaper with combined science goals, background considerations, priorities:

Community Whitepaper
arXiv:2203.02309

Back-up: Dark Matter

Evidence of a missing mass in the universe at different scale of the Universe:





CMB, Planck

20-60 kpc → 2-10 Mpc → >4 Gpc

- **Properties:**
  - Stable or long-lived
  - Neutral & Non-luminous
  - Massive
  - Non-relativistic

Vast landscape of dark matter model on a large energy range:

XENON project goal → WIMPs

Fuzzy DM	…	Axions/ALPs	Sterile ν	WIMPs	…	Primordial Black Holes
~10^{-21}eV		~meV	~keV	~GeV		~M_p

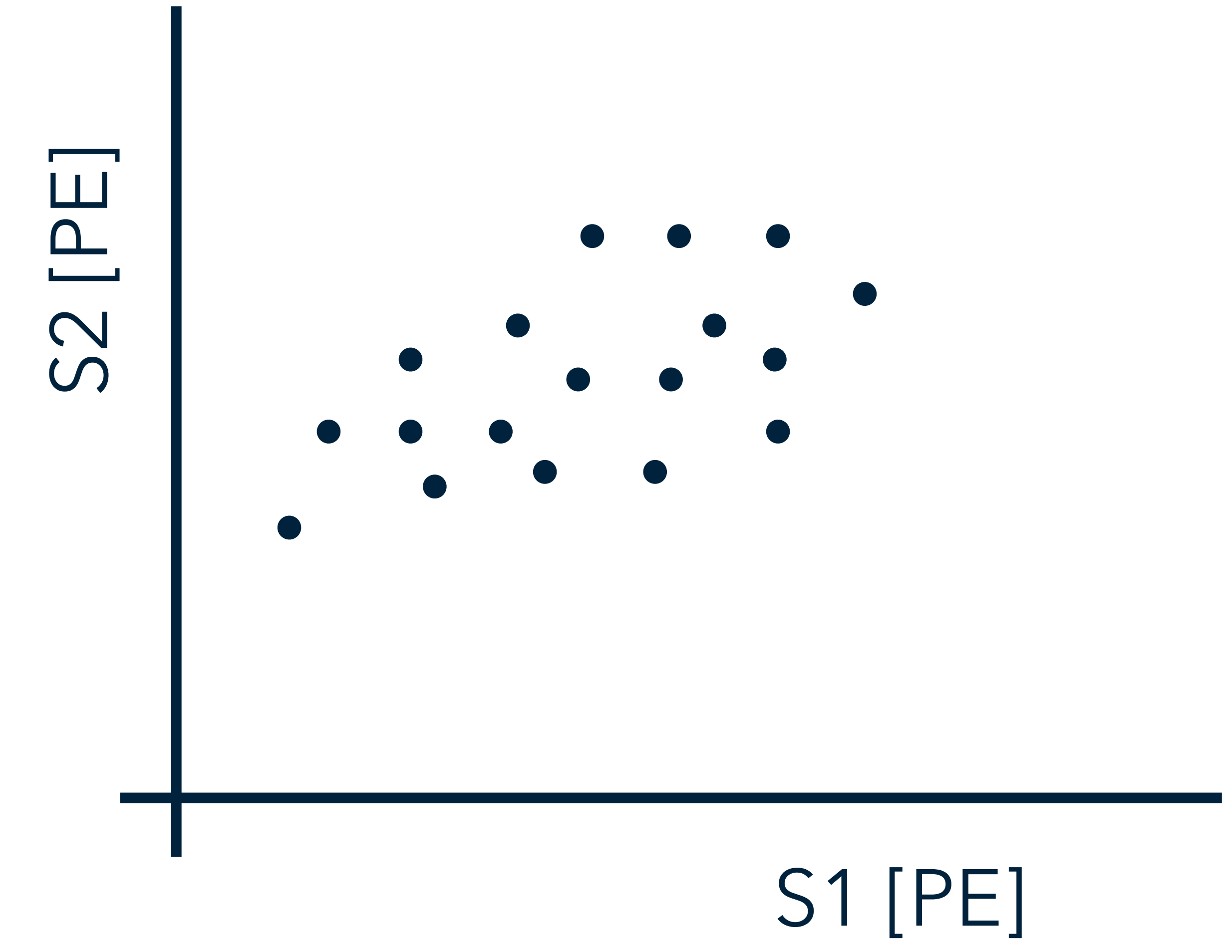
DM mass →

Credits: Michael Murra

Back-up: Energy reconstruction

Combined energy reconstruction from S1 and S2:

2D analysis

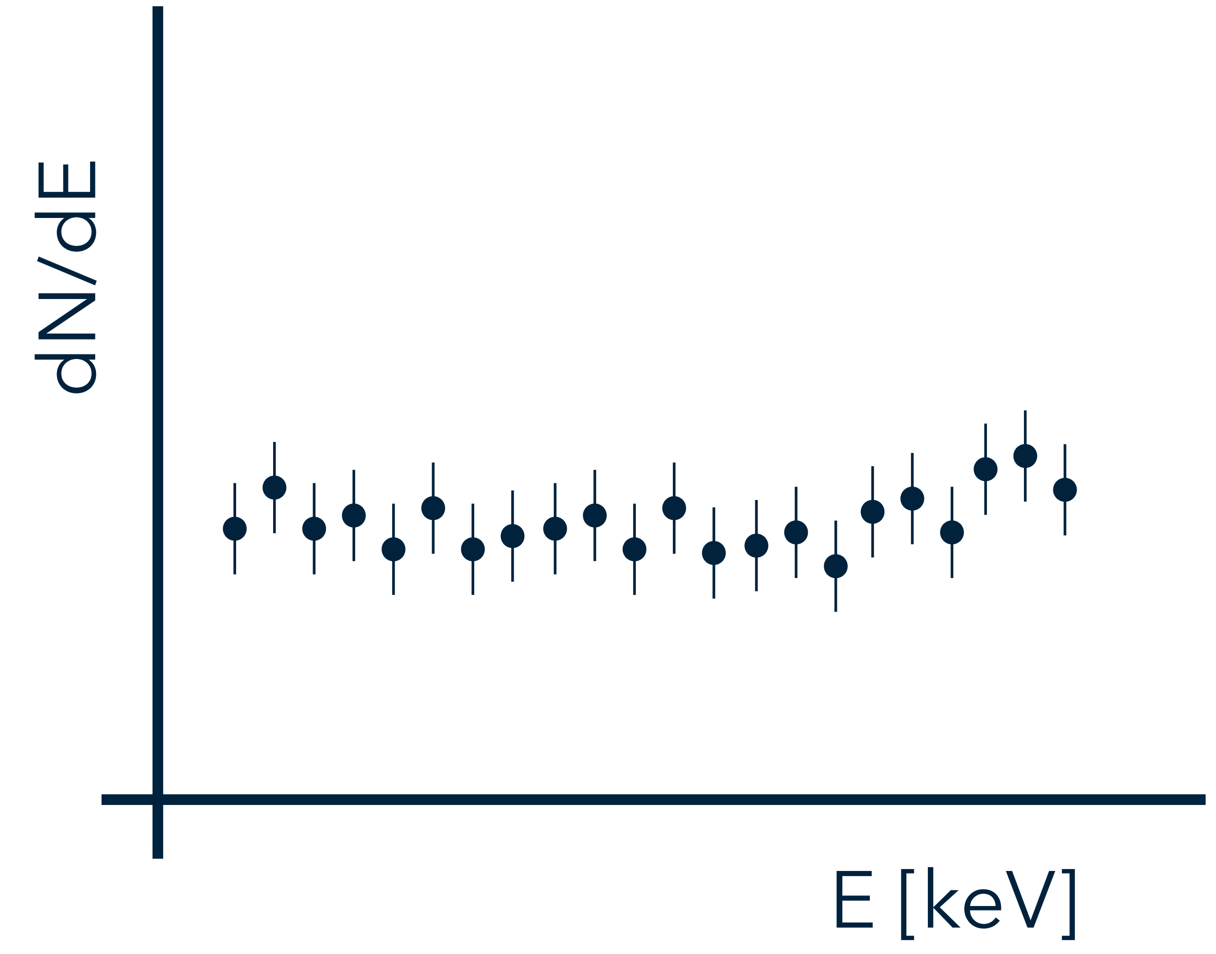


$$W = 13.7 \text{ eV/quantum}$$

$$E = W(n_{ph} + n_e)$$

$$E = W\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

1D analysis

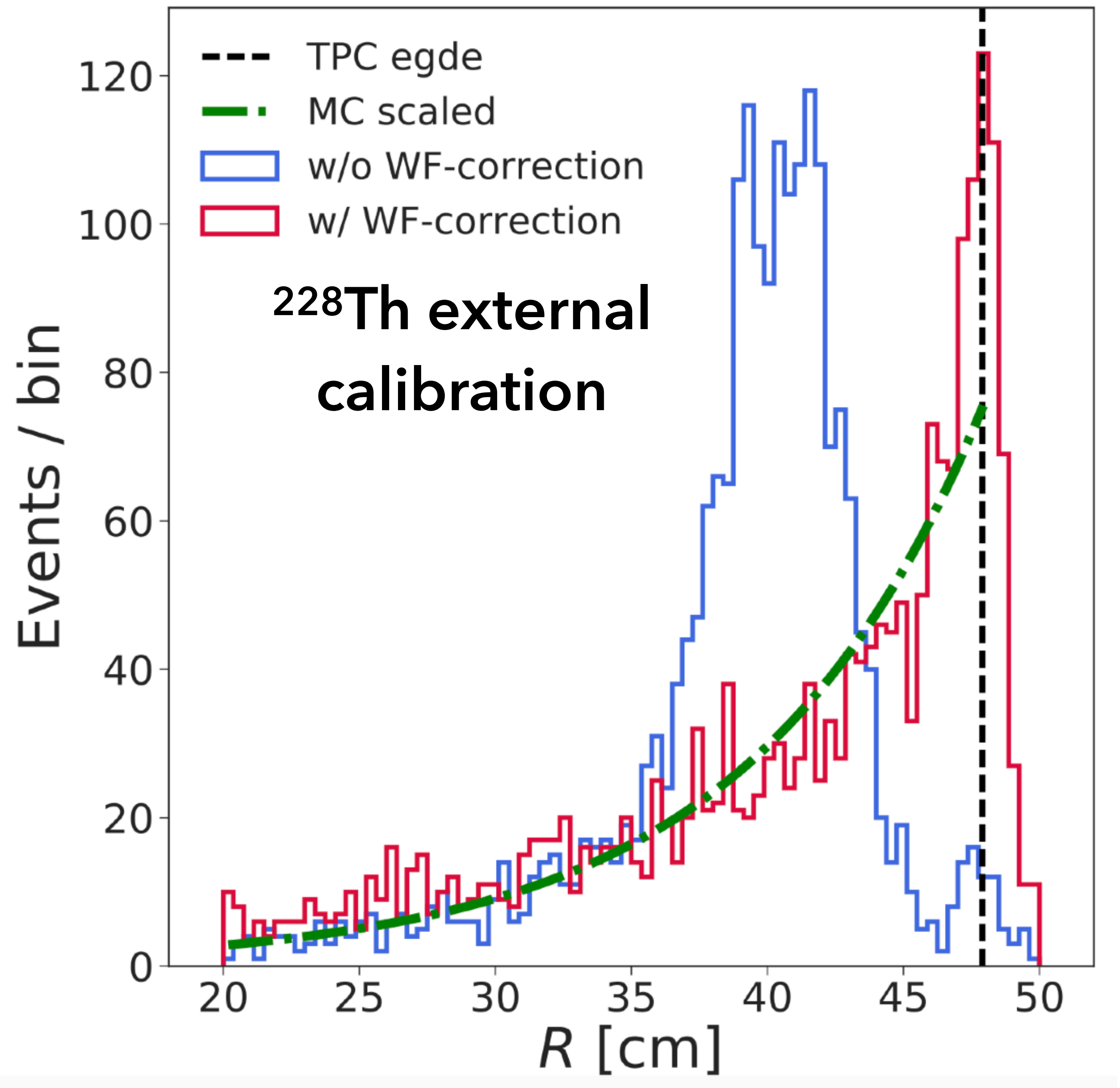


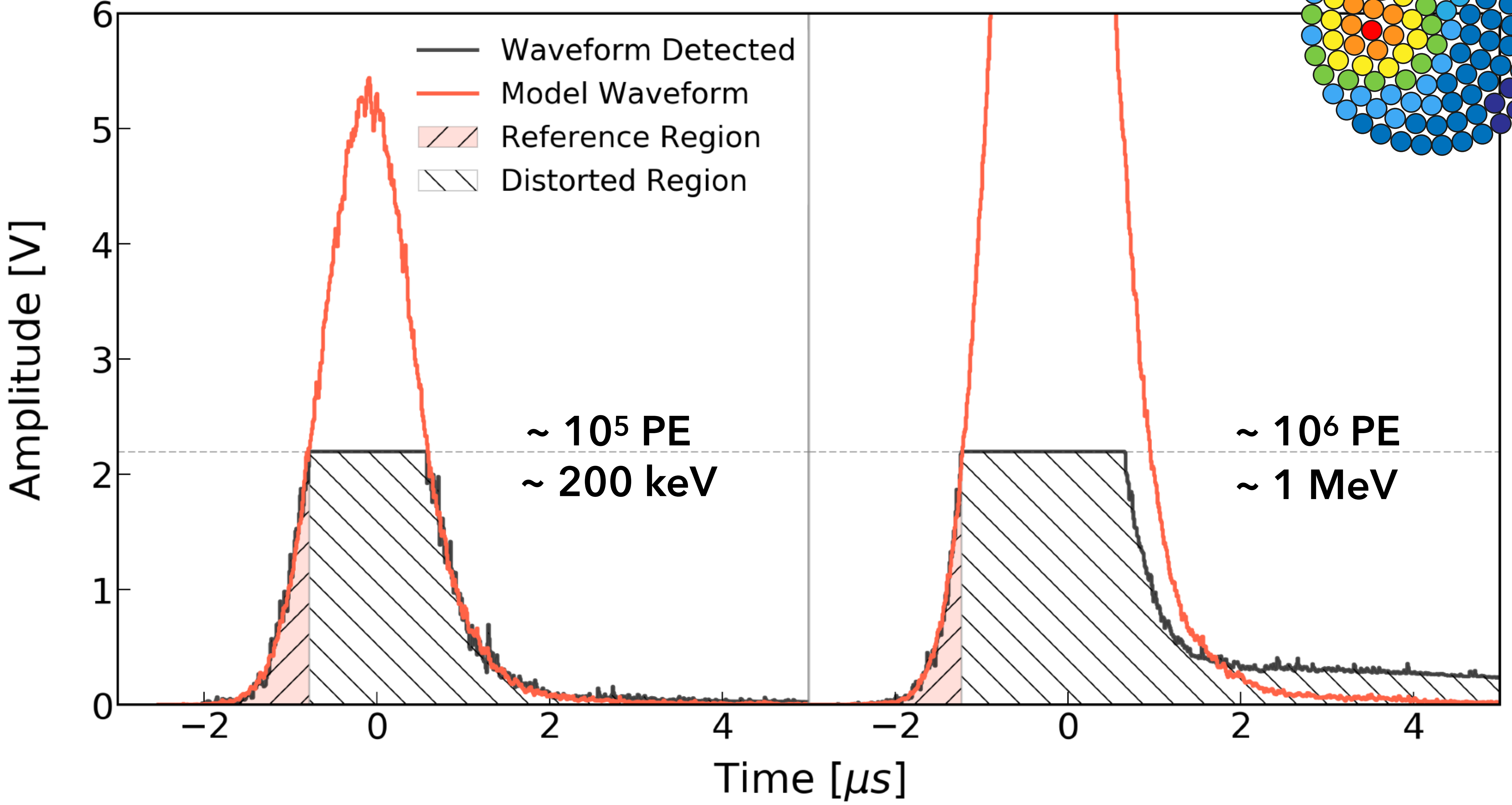
- Energy reconstruction based on detector-dependent parameters:
  - **g1: photon detection efficiency.**
  - **g2: charge amplification factor.**

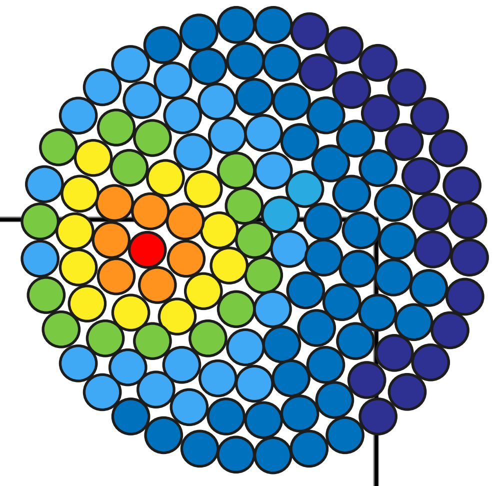
→ **Determined through severals calibrations**

Back-up: High-energy improvements 1

S2 Pulse Saturation Correction:







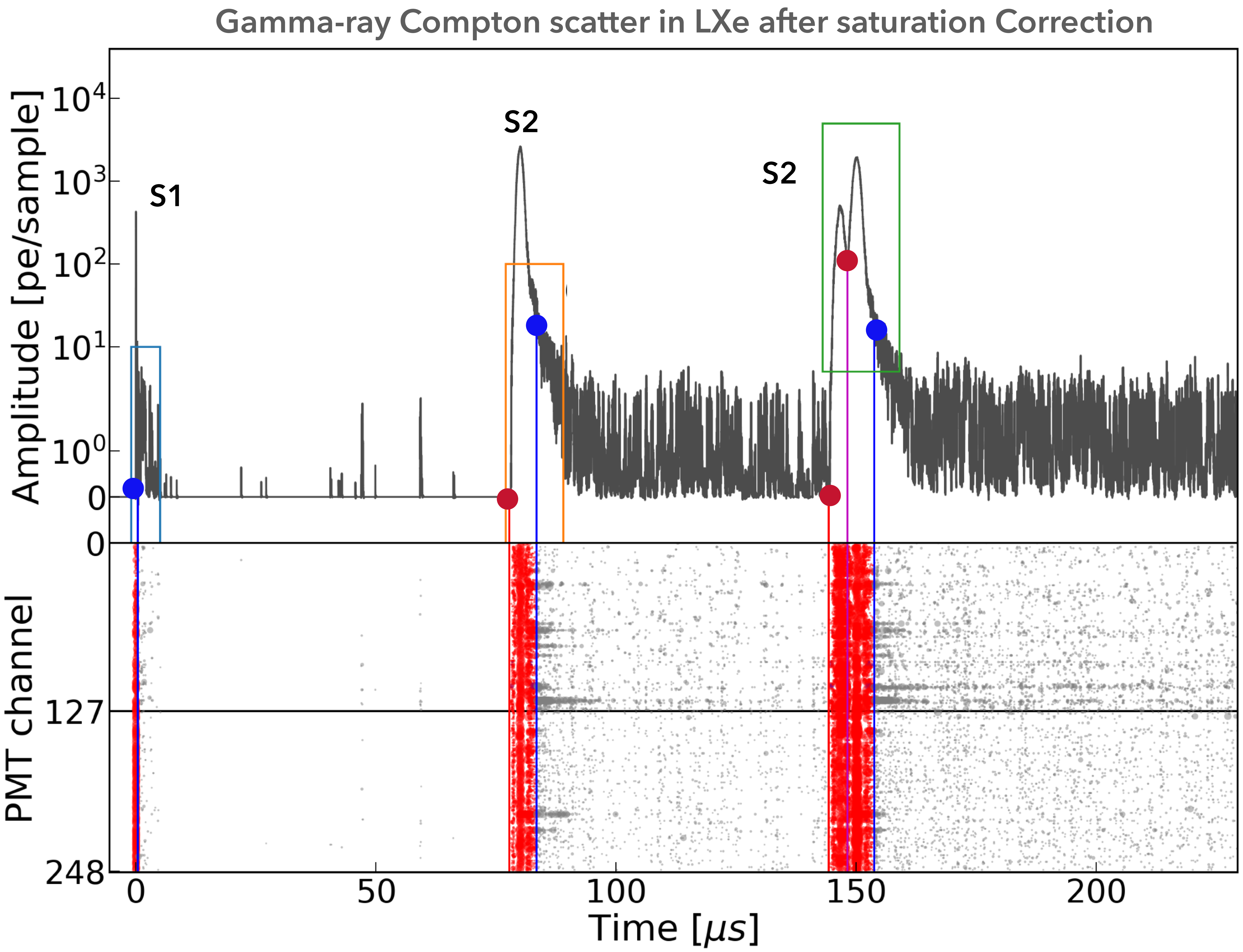
- Saturation correction using non-saturated PMT channels.
- Model waveform is scaled accordingly to the reference region.
- Validation of the correction with calibration.

$$\frac{A^S_{ref}}{A^M_{ref}} \cdot W_S$$

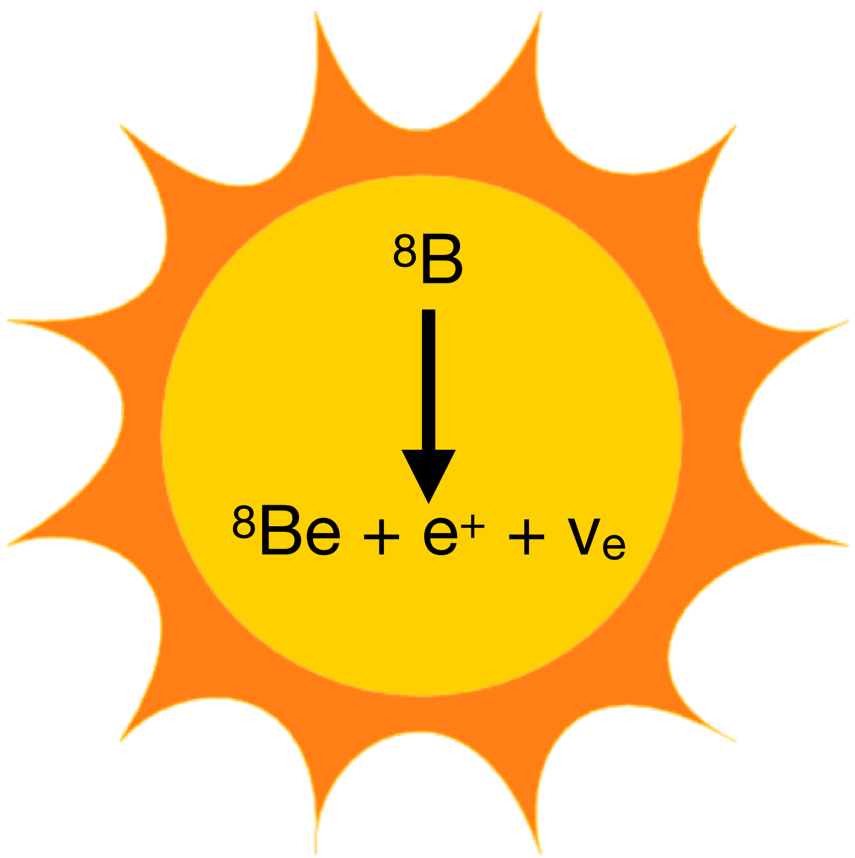
Back-up: High-energy improvements 2

Identification of primary and secondary signals:

- Secondary signals can induce fluctuations in the reconstructed energy.
- New algorithms developed to improve the peak clustering at HE:
  - Local minima algorithm
  - Cutoff amplitude algorithm
- Distinguish SS and MS interactions and remove tails

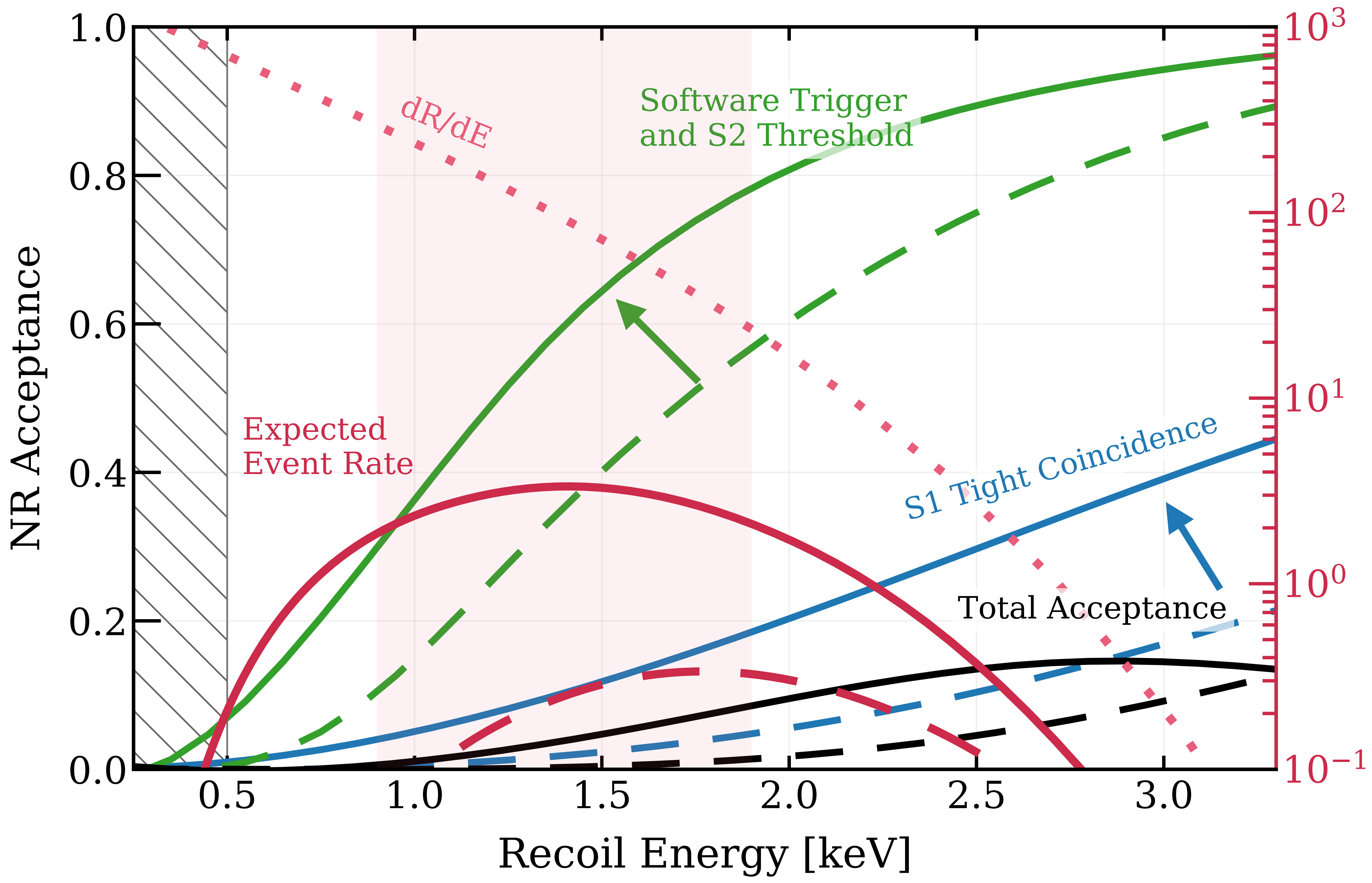


Back-up: ^{8}B CEvNS interaction



- In XENON1T ^{8}B CEvNS falls far below our previous analysis threshold.
  - 0.01% signal acceptance!

- Improvements in energy threshold required.



Lowering Energy Threshold :

- Energy threshold driven by:
  - S1 tight coincidence: ~~3~~ → 2 PMTs see light within 50 ns
  - S2 threshold: Require S2s > ~~200~~ → 120 PE (4 e^-)

Isolated S1s due to e.g. spurious firing of 2+ PMTs…

…get paired with **isolated S2s**

- 100-fold increase in Accidental Coincidences background:
  - High energy events → subsequent AC events.
  - Compensated with ML-classifier cut.

REFERENCES
PRL 126, 091301 (2021) | ARXIV:2012.02846