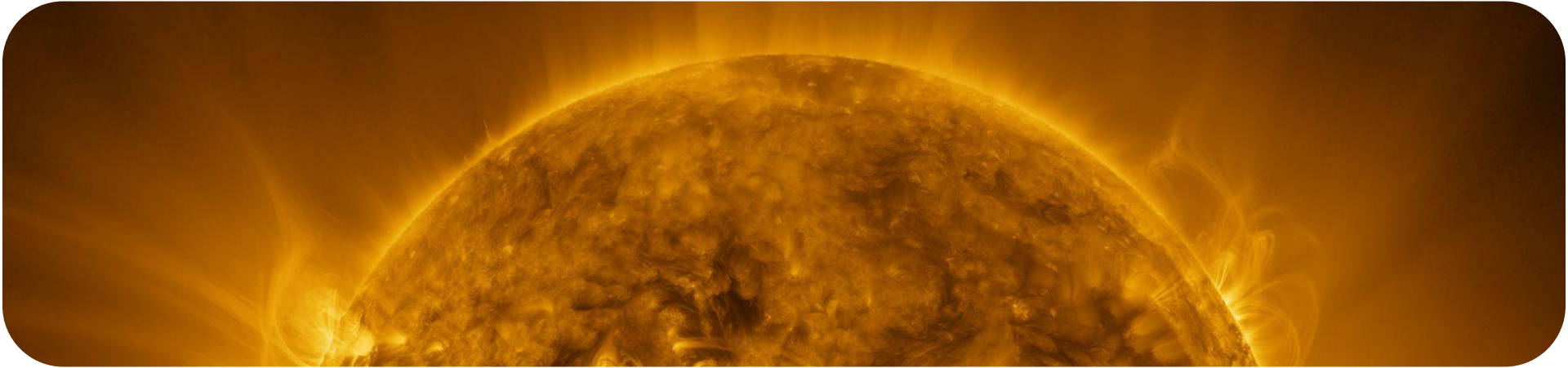


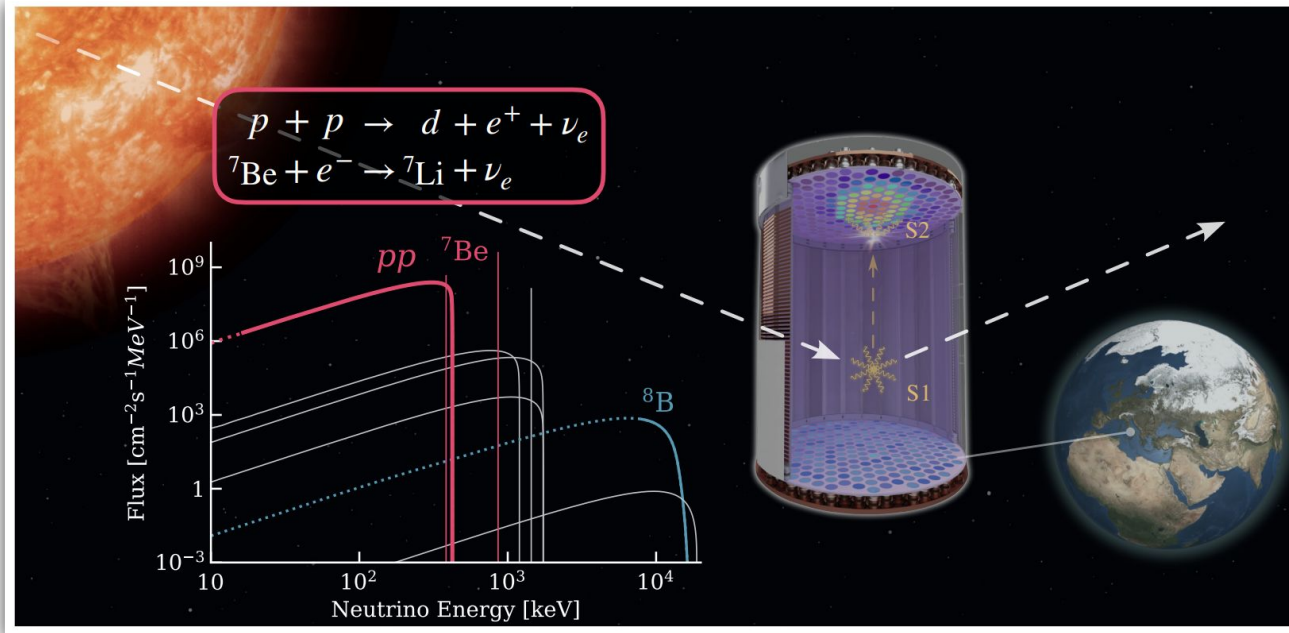
Measurement of solar neutrinos at the keV scale by XENONnT and R&D efforts towards XLZD



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Solar neutrinos

Messengers from the sun



In 1930s, Hans Bethe - fusion powers stars, including the Sun

- ❖ During this process, solar neutrinos are emitted:
 - Proton-proton (pp) - most abundant (~90%)
 - ${}^7\text{Be}$ - second most abundant (~10%)

Low-energy solar neutrinos - probe for particle physics & astronomy

- ❖ MSW-LMA mechanism of ν oscillation & measured mixing parameters
- ❖ Directly confirm the Standard Solar Model (SSM)
- ❖ Open the door to BSM physics

XENONnT

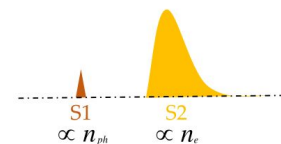
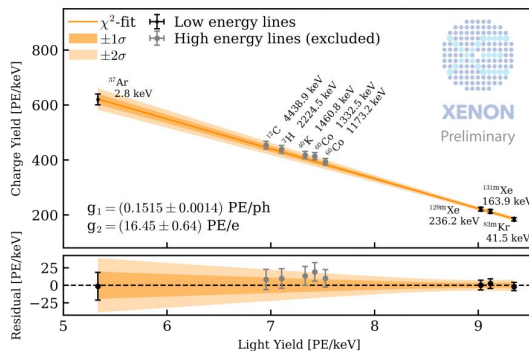
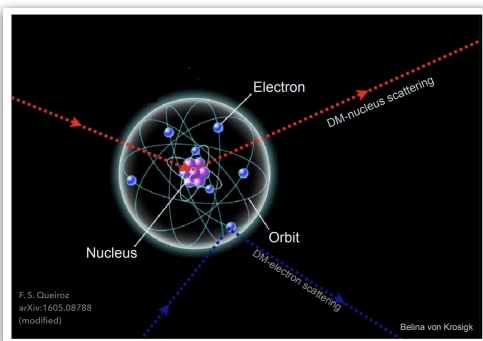
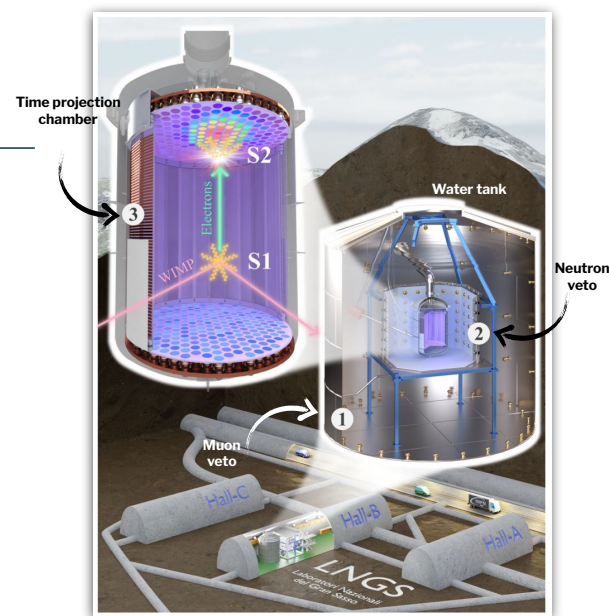
Going beyond Dark Matter detection - measurement of solar neutrinos

XENONnT detector

- ❖ Ultra-low radioactive background detector
- ❖ Low energy threshold ($\mathcal{O}(1)$ keV ER)
- ❖ 5.9 t active target & large exposure

Multiple channels for solar neutrino measurement:

- ❖ MeV scale: via the **nuclear recoil** (^8B , hep, ...)
- ❖ keV scale: via the **electronic recoil** (pp + ^7Be)



$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2} \right) \cdot W \quad \Rightarrow \quad \frac{S2}{E} = -\frac{g2}{g1} \frac{S1}{E} + \frac{g2}{W}$$

$$y = b + mx$$

$g1$ and $g2$: detector-specific gain constants

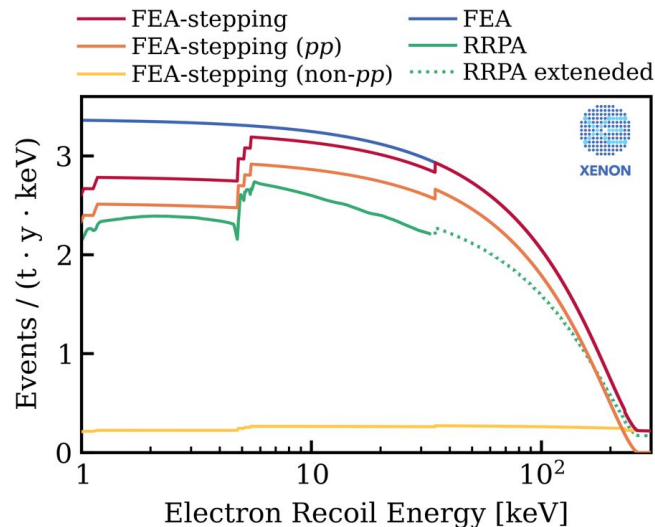
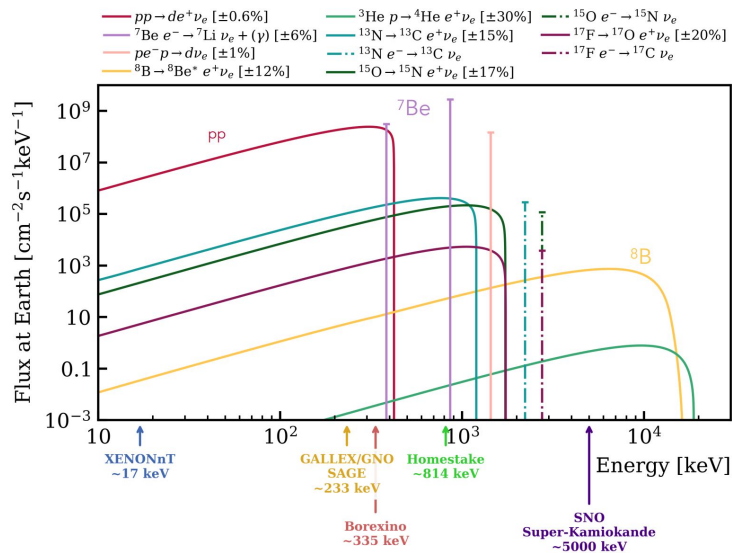
S1 & S2 for energy scale determination

Solar-pp Neutrino measurement

Measurement channel & expected signal

Electronic recoil from elastic ν -electron scattering

- ❖ Contributions from pp (~90%) and ^7Be (~10%)
- ❖ Sensitive to all flavours ($\sigma_{\mu,\tau} / \sigma_e \approx 0.154$)
- ❖ Electronic recoil energy threshold of ~1 keV
 - Solar- ν energy threshold ~17 keV

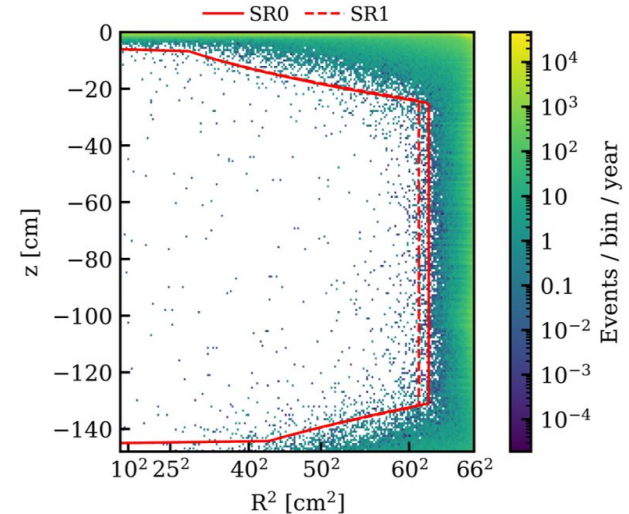
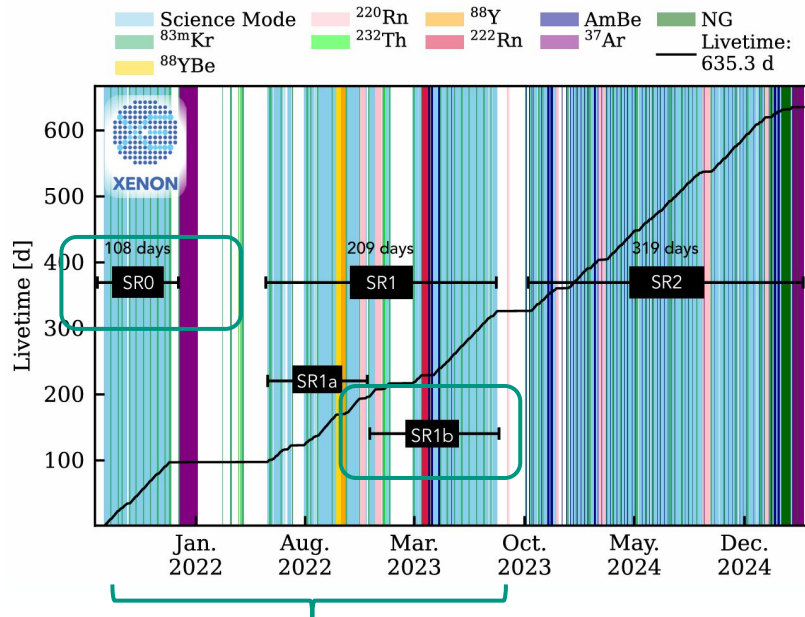


Signal topology: Single-site electronic recoil interaction

- ❖ Free Electron Approximation (FEA) + stepping corrections for binding energies of xenon shells
- ❖ **ROI:** Energy range of 1-140 keV

Solar-pp Neutrino measurement

Data & backgrounds



Total livetime - 214 days (exposure of 2.46 tonne x year)

- ❖ Science Run 0 (SR0): July 6th, 2021 - November 10th, 2021
- ❖ Science Run 1 (SR1): May 19th, 2022 - August 8th, 2023
- ❖ SR1a is not used due to higher background level

Fiducial volume based on material reduction

~ 4.13 (4.24) tonnes for SR0 (SR1b)

Solar-pp Neutrino measurement

Backgrounds

External backgrounds:

- ❖ γ -rays, radioactivity from detector materials

Intrinsic background (^{214}Pb , ^{212}Pb , ^{85}Kr , ^{136}Xe $2\nu\beta\beta$, ^{124}Xe DEC)

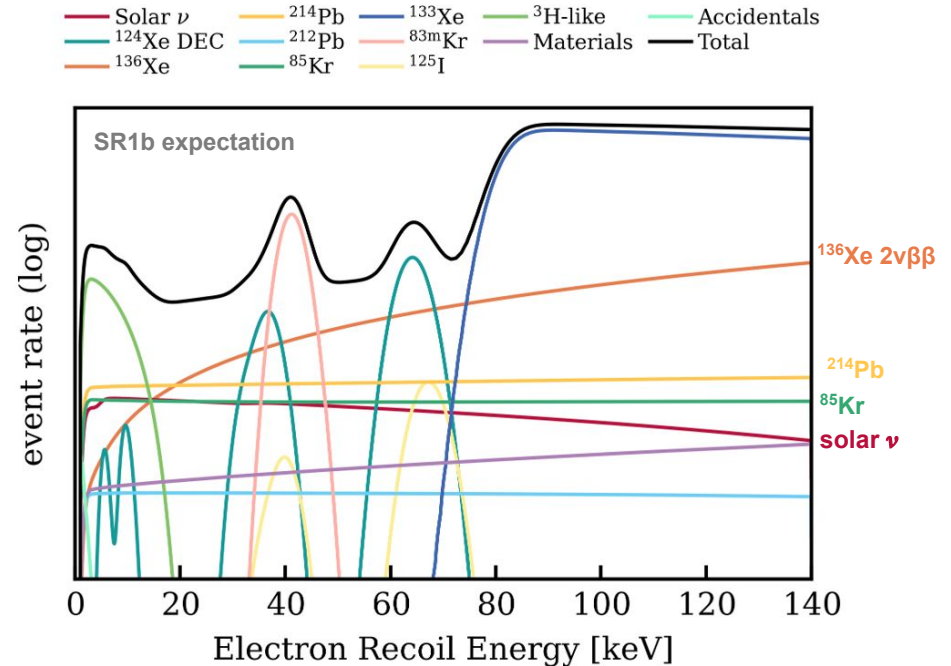
- ❖ Naturally present in xenon
- ❖ Emanation from detector materials

Neutron activation (^{133}Xe , ^{125}I)

- ❖ Activation products, especially post-NR calibration

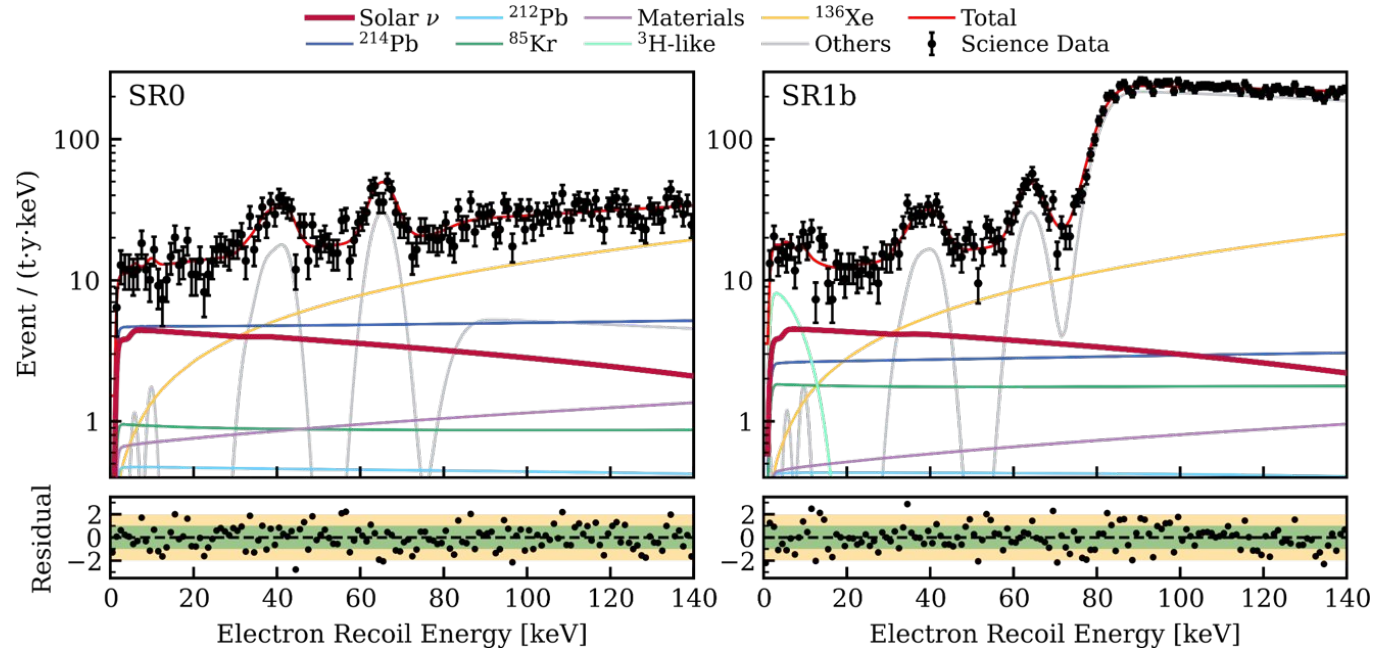
Other components:

- ❖ External contamination of the LXe target (^3H -like in SR1)
- ❖ Remnants from bi-weekly calibrations ($^{83\text{m}}\text{Kr}$)
- ❖ Accidental coincidence - spurious events



Solar-pp Neutrino measurement

Fitting the data



Combined unbinned likelihood fit for SR0 + SR1b

Results

Observation of solar neutrino-electron scattering

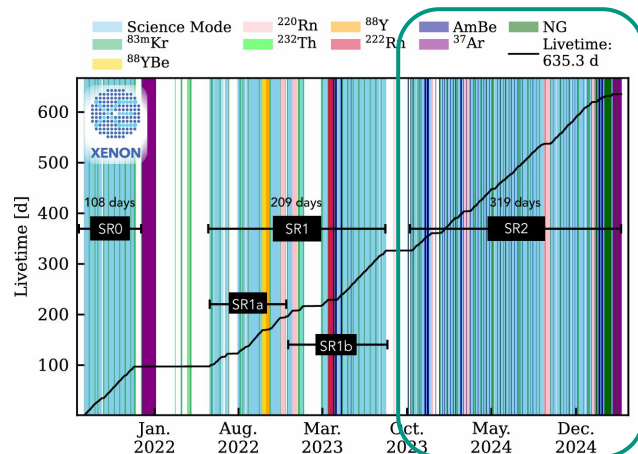
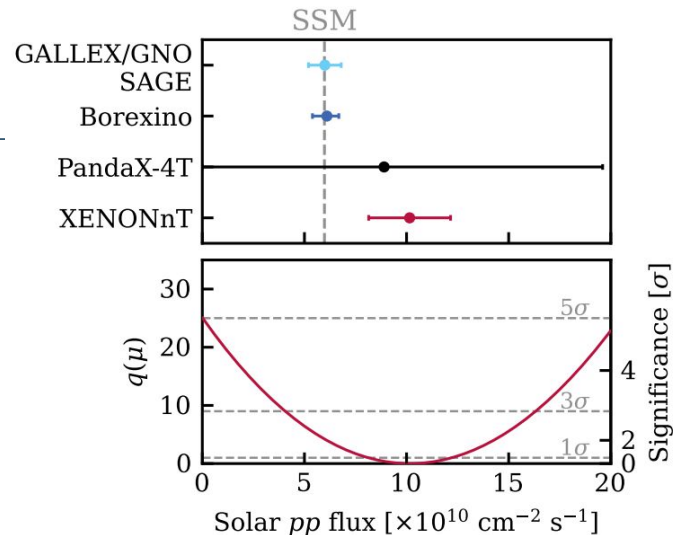
Likelihood ratio test to determine solar neutrino significance

- ❖ H_0 : Absence of solar neutrinos (background only)
- ❖ H_1 : Presence of solar neutrinos (signal + background)
- ❖ Rejected null hypothesis at 5σ

Results

- ❖ Lowest low-energy ER background achieved in LXe
- ❖ Measured solar pp flux of $(10.2 \pm 2.0) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$
 - Fixed ratio between ^7Be and pp neutrinos
- ❖ Measured flux consistent with Borexino results at 1.9σ
- ❖ First measurement of solar- ν with $E < 230 \text{ keV}$!
- ❖ **Pre-print now on: [arXiv:2608.29450](https://arxiv.org/abs/2608.29450)**

SR2 data are being analysed - results will come soon!

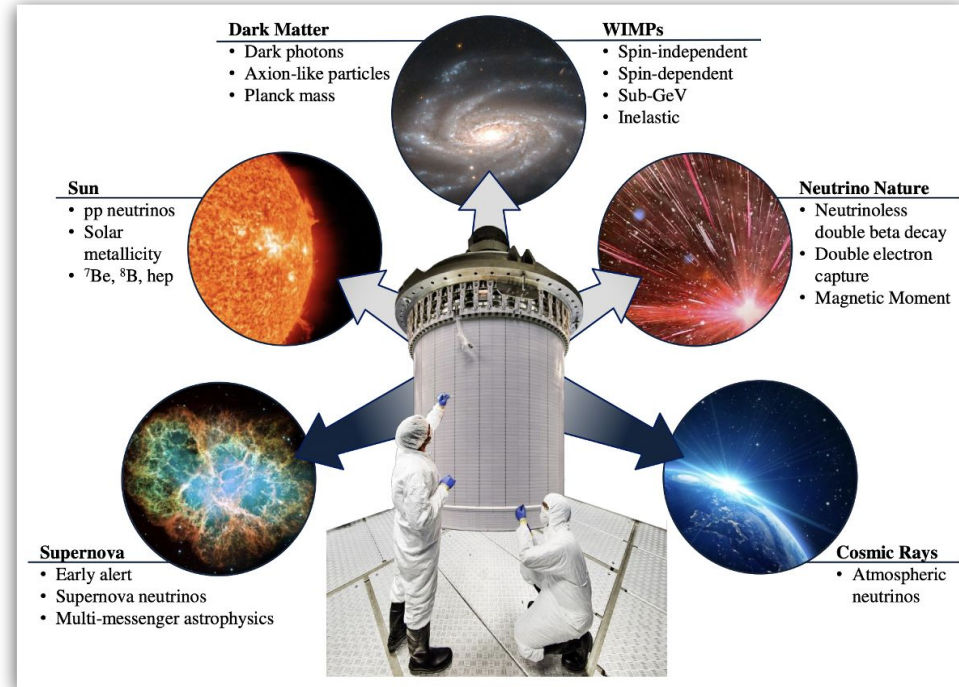


Xenon-based astroparticle observatory

Where do we go from here?

- ❖ **Solar neutrinos ($pp + {}^7\text{Be}$)**
 - arXiv:2608.29450
- ❖ **Solar neutrinos ${}^8\text{B}$ via $\text{CE}\nu\text{NS}$ & low-mass Dark Matter**
 - Phys. Rev. Lett. **137**, 091807
 - Phys. Rev. Lett. **133**, 191002
- ❖ **WIMP Dark Matter**
 - Phys. Rev. Lett. **135**, 221003
- ❖ **Neutrinos** from supernovae, from in & beyond the Milky Way
- ❖ ... and much more ...

LXe TPC has the potential to become the ultimate rare event detection technology!



Physics White Paper: *J. Phys. G* 50, 2023



400+ members from 80+ institutions

Website: xlzd.org

XENON10

2005 - 2007



15 kg

XENON1T

2008 - 2016



161 kg

XENON100

2016 - 2019



3.2 t

XENONnT

2020 - Now

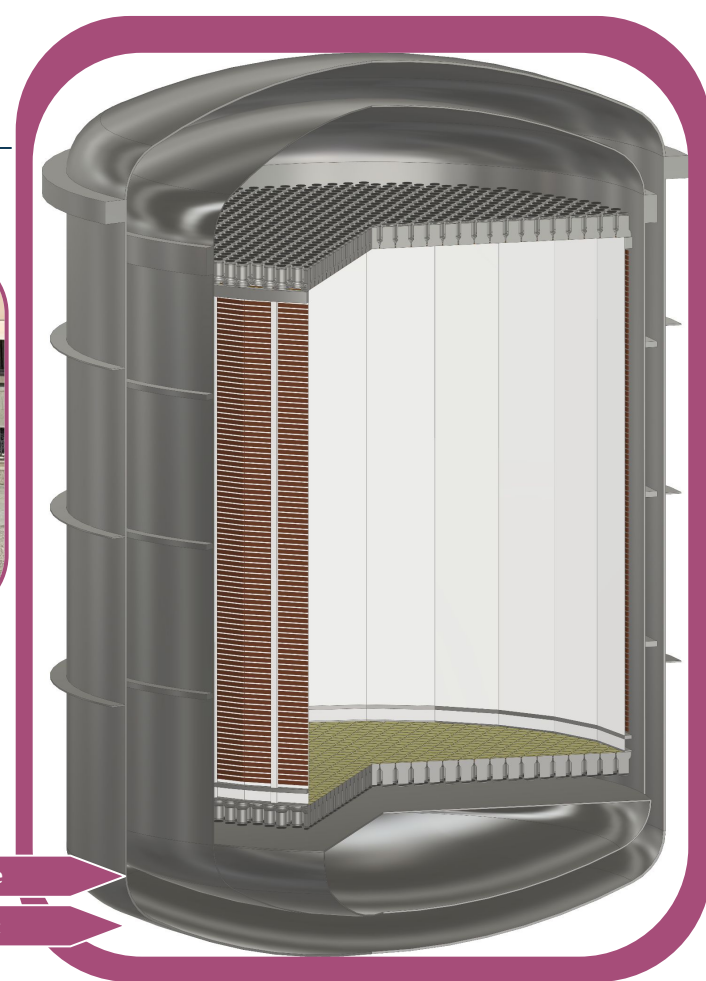


~8.6 t

Future



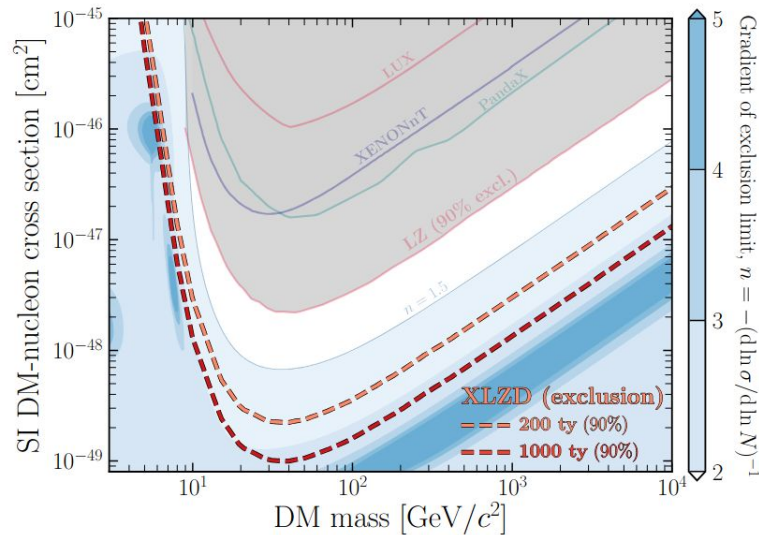
~60 t



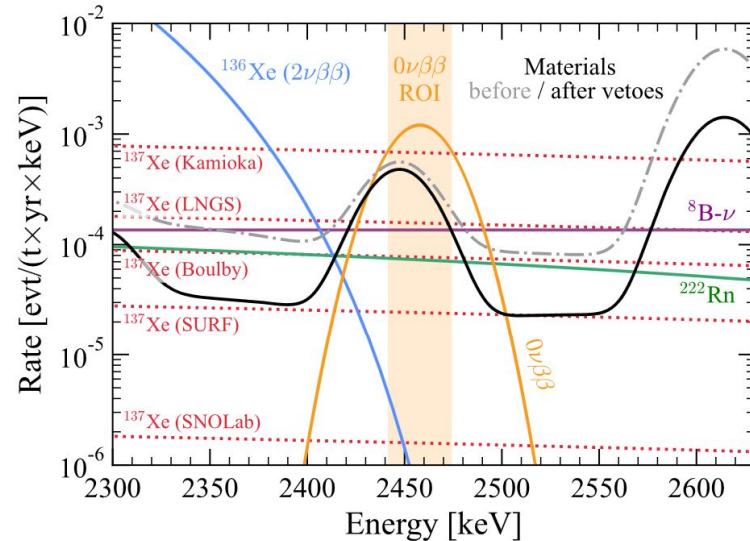
Science program with XLZD

Ultimate xenon-based rare event observatory

- ❖ Search for **WIMP Dark Matter down to the “neutrino fog”**
- ❖ Explore other Dark Matter models (Dark photons, ALPs,...)
- ❖ Provide **competitive constraints on $0\nu\beta\beta$** , study solar & supernovae neutrinos



XLZD Design Book: *Eur. Phys. J. C* 85, 1192 (2025)

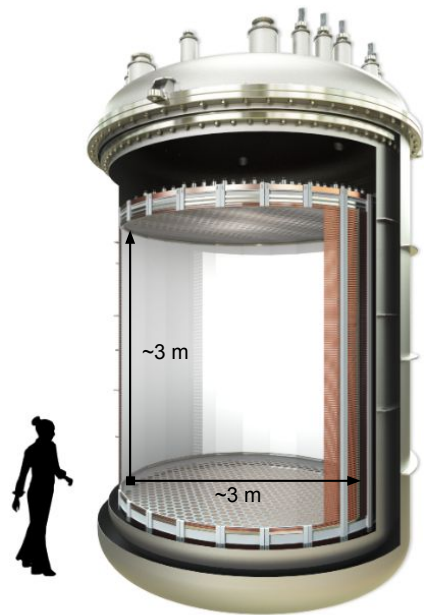


J. Phys. G: Nucl. Part. Phys. **52** 045102 (2025)

Physics White Paper: *J. Phys. G* 50, 2023

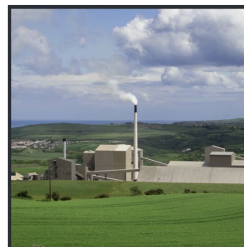
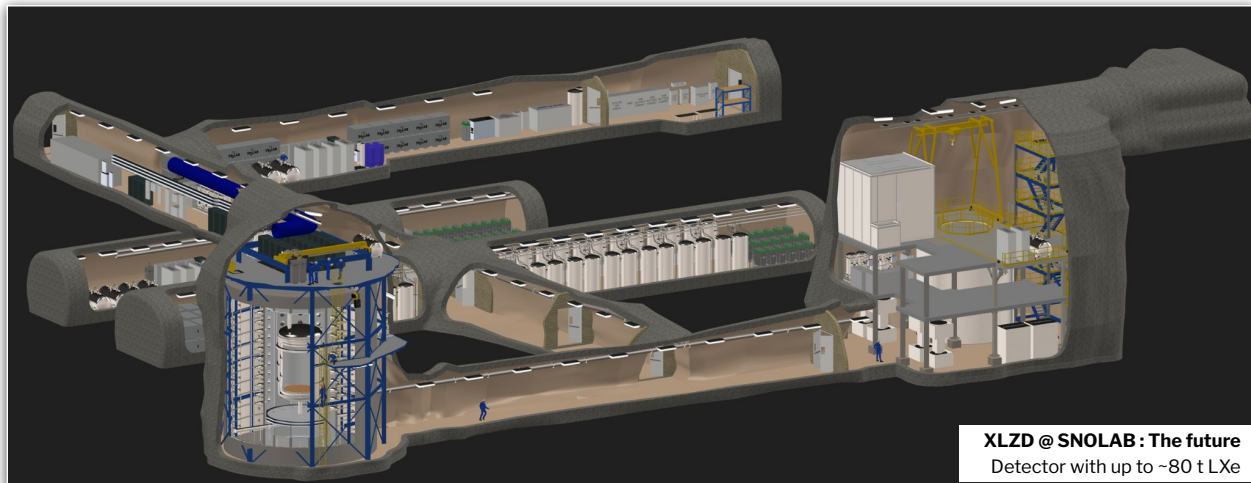
XLZD - Next-generation xenon-based observatory

Interdisciplinary worldwide R&D efforts to tackle technical challenges



Nominal design

- ❖ ≥ 60 t LXe TPC (78 t in total)
- ❖ 3" PMTs (other sensors are studied)
- ❖ Active n-veto & μ -veto



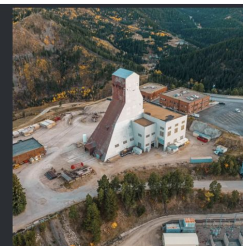
Boulby
North Yorkshire, UK



LNGS
Gran Sasso, Italy



SNOLAB
Ontario, Canada

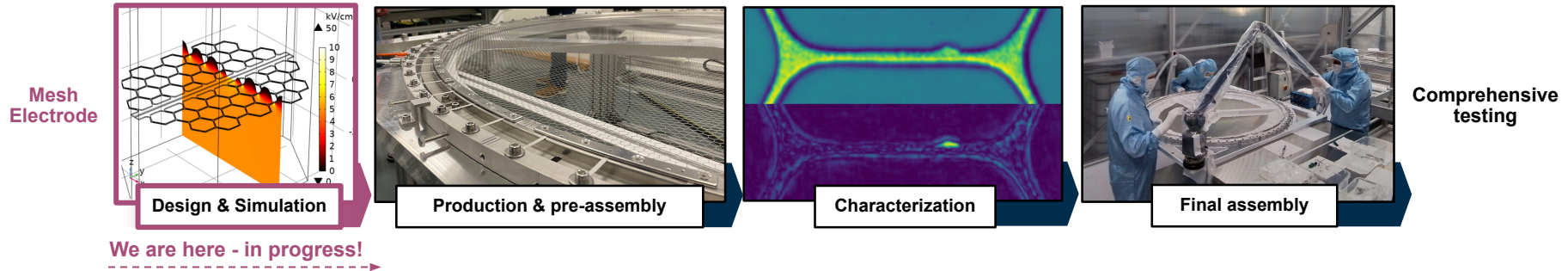


SURF
South Dakota, USA

Yanina Biondi

R&D towards **XLZD** @KIT

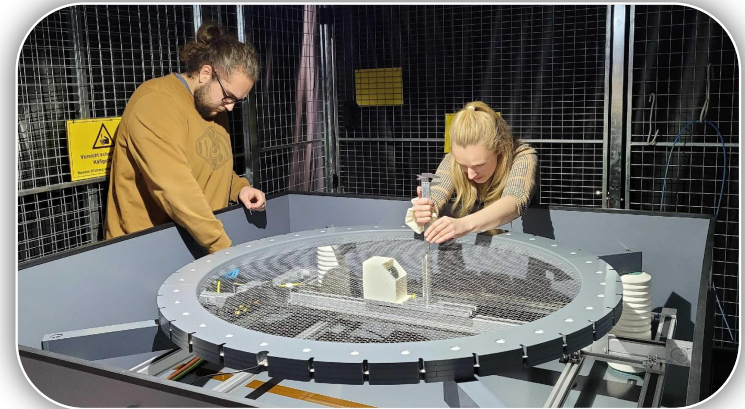
Electrode development - from automated production to quality assurance



Joint R&D with robotics (KIT-IRS) & material sciences (KIT-IAM)

- ❖ **Electrode design & construction at 3 m scale**
 - Modular electrode frame design & simulations
 - Automated laser-welding for assembly & repair
- ❖ **Automated electrode scanning system for QA & QC**
 - Modular, optical (multi-channel) & HV characterization in GAR
- ❖ **Electrode treatment - passivation, coating**
 - Mitigate & prevent unwanted electron emission

Robotic scanning system prototype @KIT



R&D towards **XLZD** @KIT

MOTION - xenon TPC platform for high voltage technologies R&D

- ❖ Liquid xenon time projection chamber hosting up to **80 kg**
- ❖ Power supply of up to **-200 kV** to bias the cathode

Planned & ongoing R&D

- ❖ Systematic study of **HV delivery & breakdown in LXe**
- ❖ Diagnostics of **HV components** (feedthrough, electrodes, couplings)
- ❖ **Monitoring of systematics:**
 - Effects of electronegative purity, surface and pressure
- ❖ **Electronegative impurity monitors:**
 - Single walled carbon nanotubes (KIT-INT and KIT-IMS)
- ❖ Cold electronics
- ❖ Tritium calibration



Summary & outlook

From XENONnT to XLZD

XENONnT v1.0 : 2021 - 2025 (~7 tonne x years exposure)

- ❖ **SR2 data will bring new results!**
- ❖ Searches for WIMPs
- ❖ Solar pp and ^7Be neutrinos via elastic scattering at the keV scale
- ❖ DM search in high-E nuclear recoil region (the “LZ event”)

XENONnT v2.0 : 2026 - onwards

- ❖ Successful upgrade & commissioning
- ❖ Improved detector performance: ~ 110 V/cm, extraction efficiency of $>90\%$
- ❖ **Science Run 3 calibrations & data taking are underway!**

XLZD (XENON-LZ-DARWIN)

- ❖ Aim to build & operate ≥ 60 t LXe TPC
- ❖ Interdisciplinary R&D program across 80+ institutes
- ❖ **Strong & comprehensive scientific case:**
 - Explore WIMP parameter space down to the “neutrino fog”
 - Other Dark Matter models (Dark photons, ALPs,...)
 - Solar/SN neutrinos, $0\nu\beta\beta$ -decay ... and more...

