Swiss National Science Foundation

Universität Zürich[UZH]

Dark matter searches with dual-phase xenon TPCs

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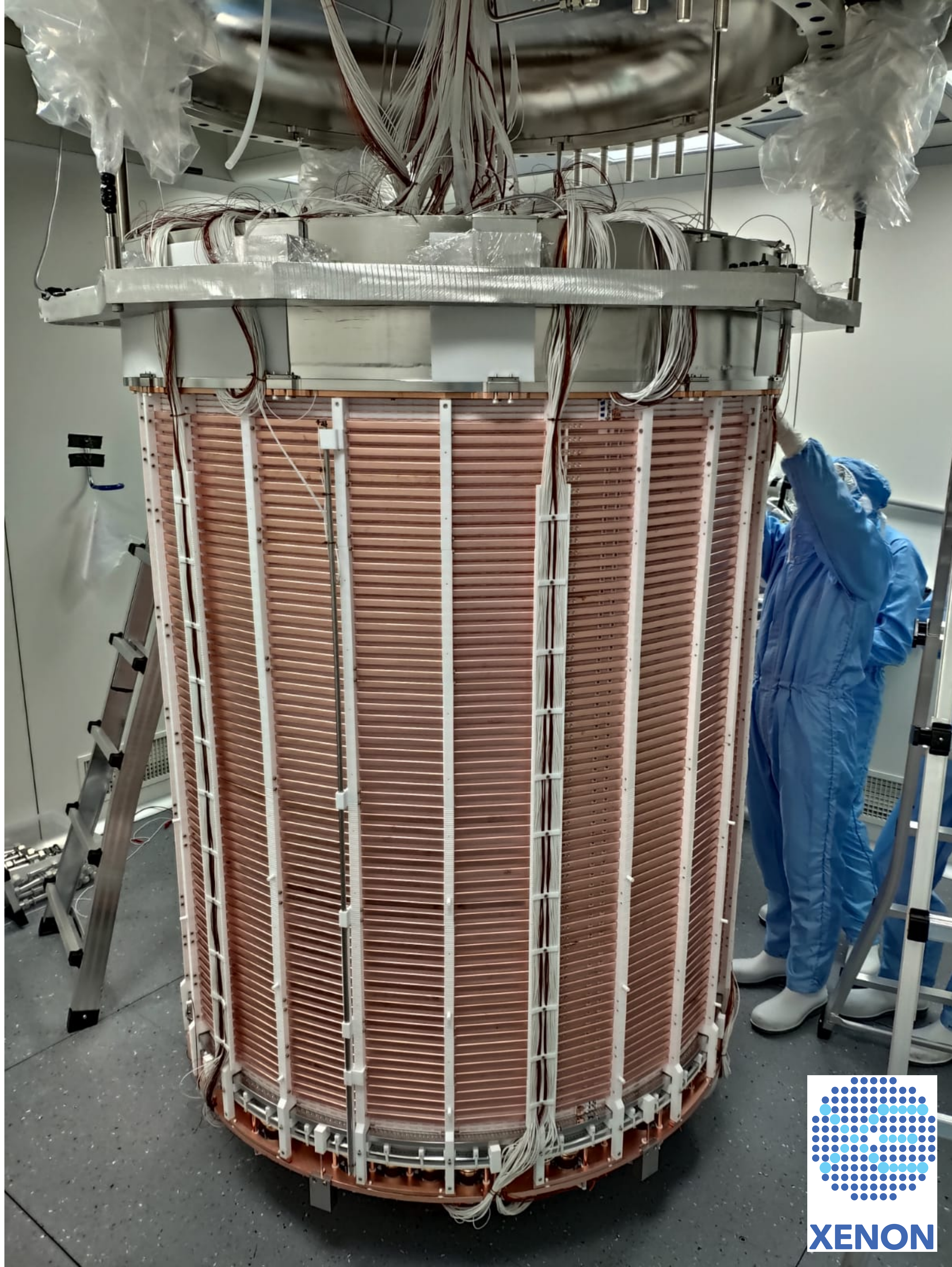
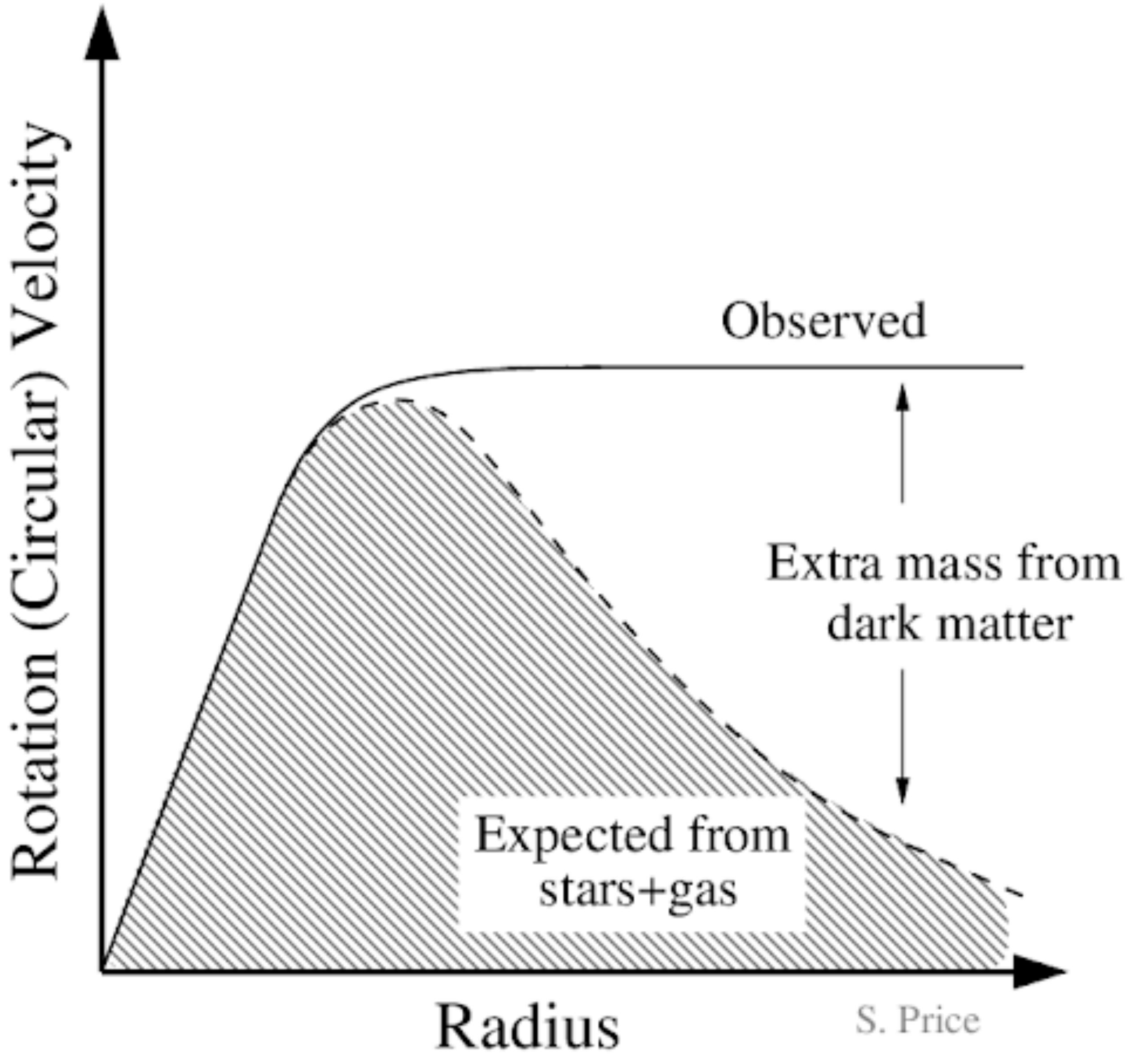
TECHNISCHE UNIVERSITÄT DRESDEN



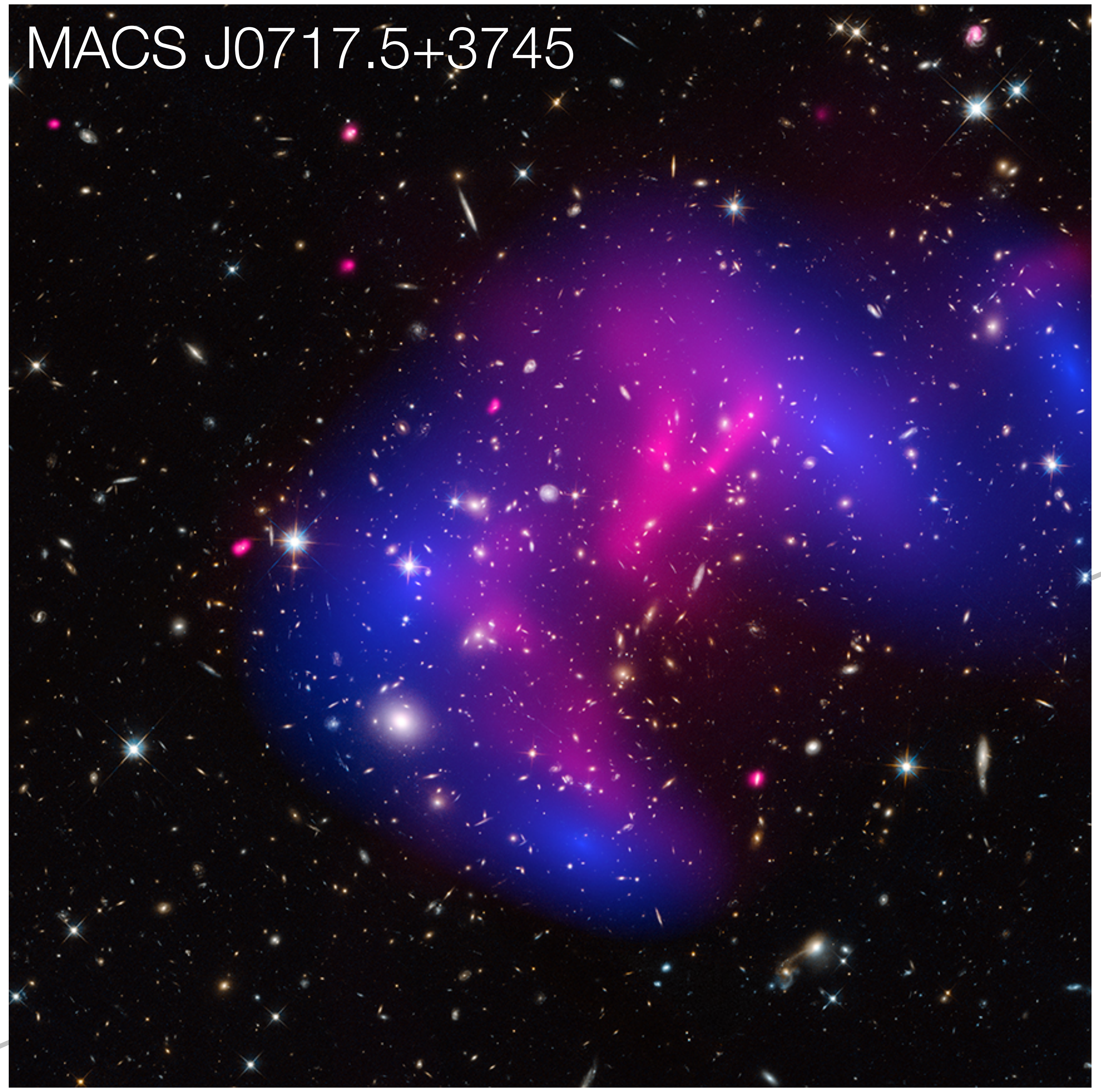
Cosmological observations

- 1933 F. Zwicky: observation of the velocity dispersion of galaxies in the Coma cluster
  - Mass 400 larger than expected from the visible mass
  - Define the “Dunkel Materie”
- 1978 V. Rubin et al.: dependency of the rotation curves of stars on the distance form the galactic center → Later confirmed by gravitational lensing and X-rays spectroscopy

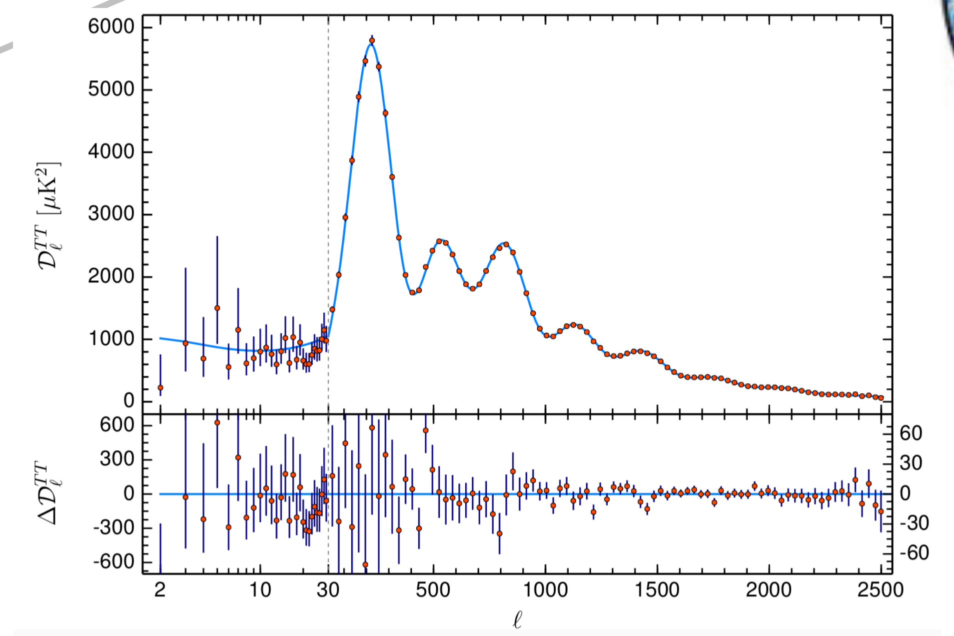


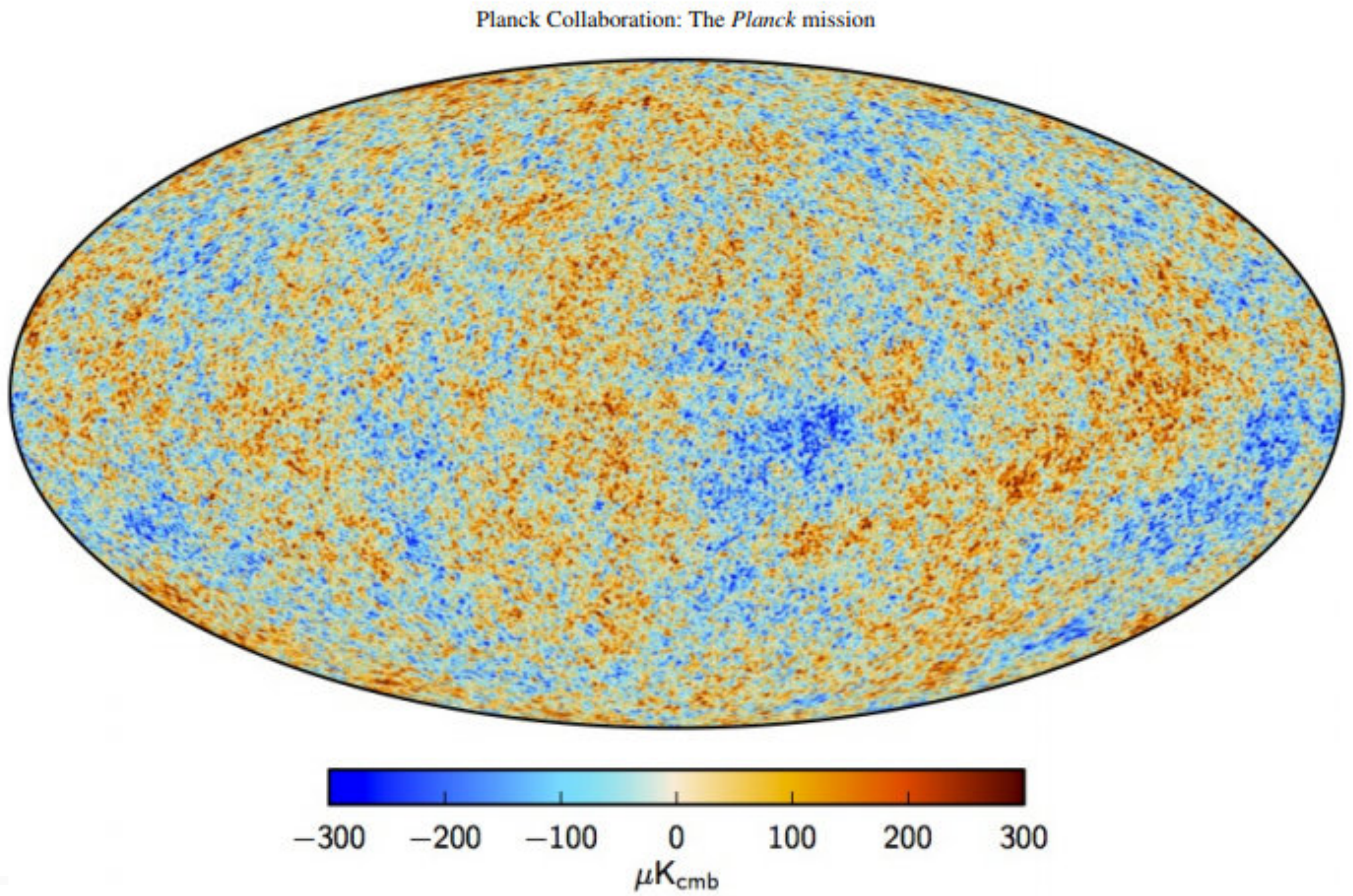
Cosmological observations

- Colliding galaxy clusters:
  - Hot gas and baryonic matter in X-rays
  - Where most of the mass is concentrated, from gravitational lensing



- Anisotropies in the cosmic microwave background (CMB):
  - Density distribution during recombination time*
  - Fluctuation order 10^{-5} matches with presence of DM
  - DM density x5 higher than baryonic matter

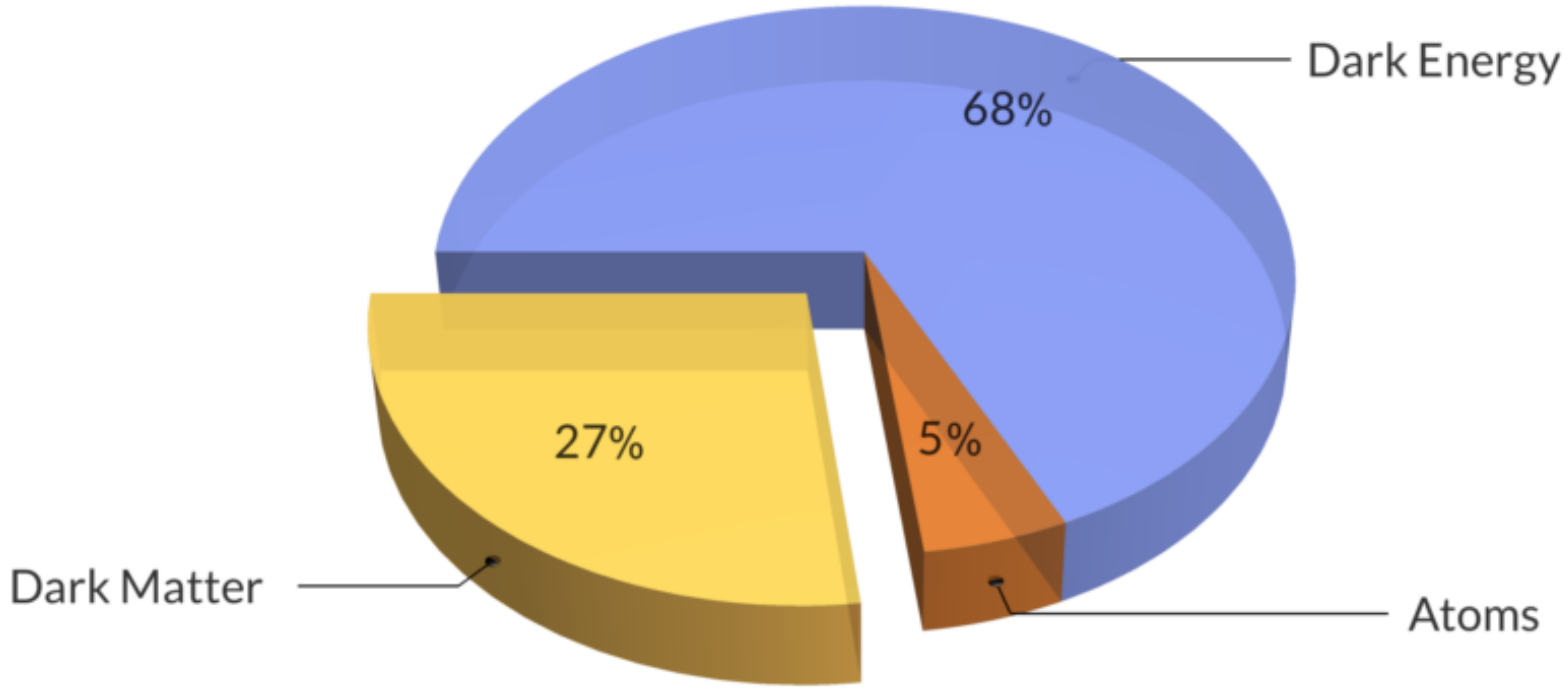


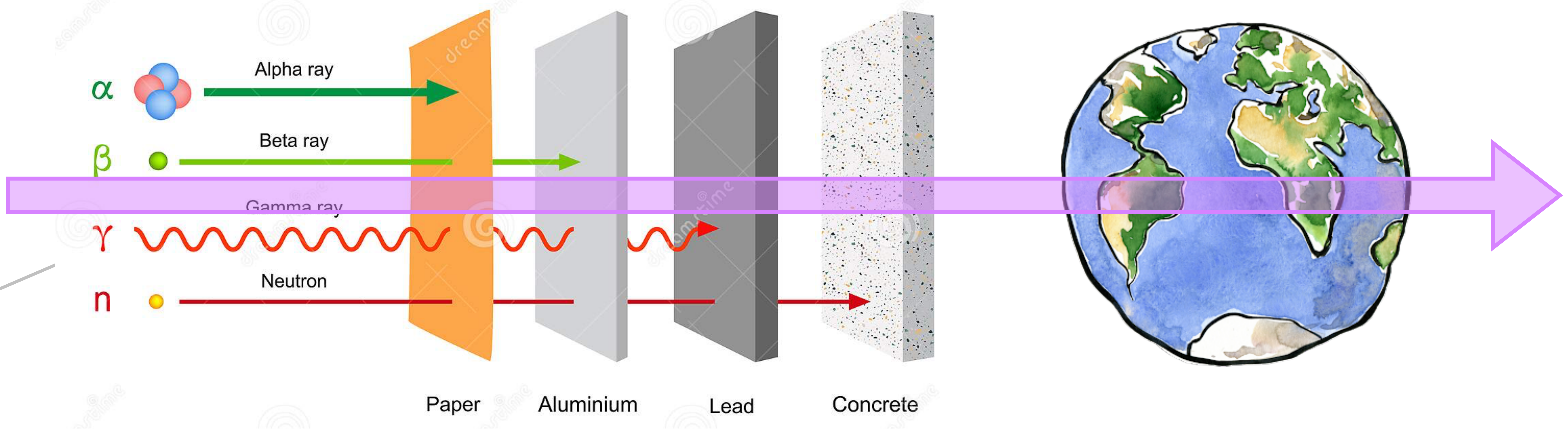


*charged electrons and nuclei became bound, ~370’000 yr after Big Bang

Dark matter

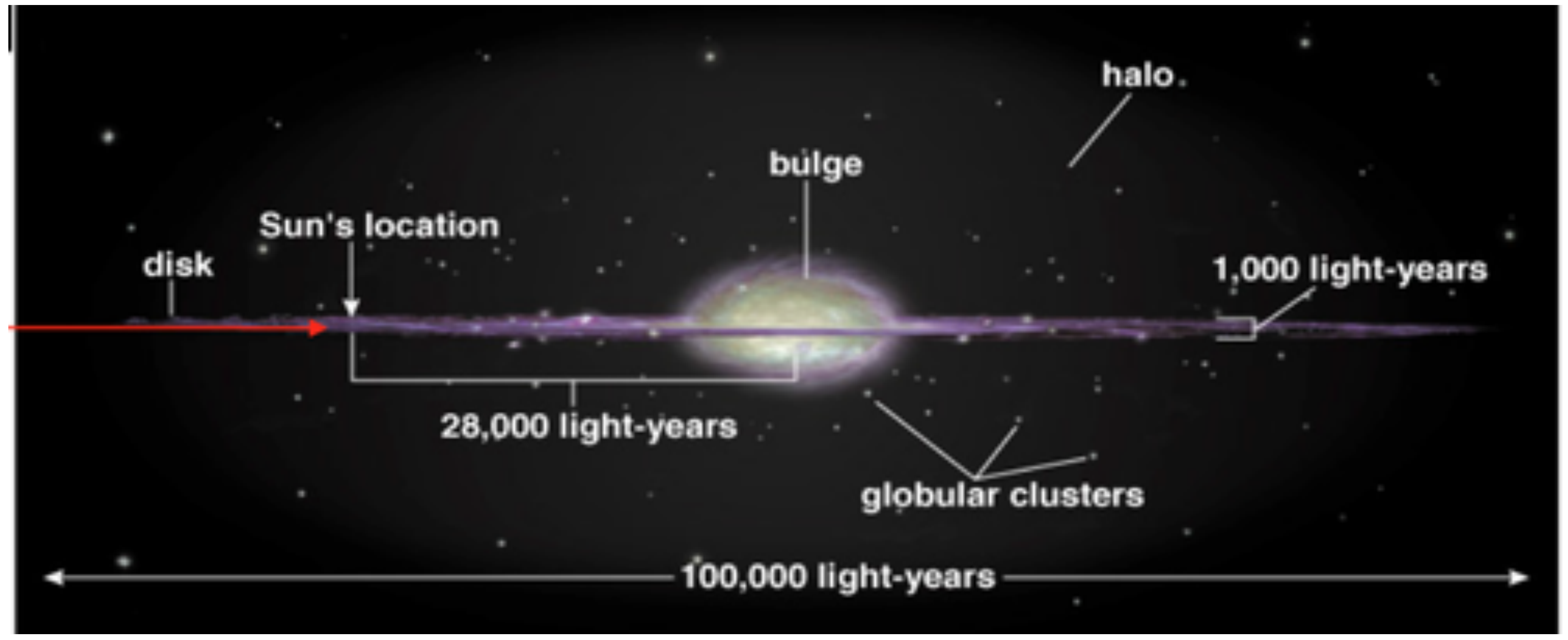
- DM constitute ~84% of the matter in the Universe
- Non baryonic
- Electrically neutral
- Neither absorbing nor emitting light
- Interact gravitationally
- Can DM interact through weak force?

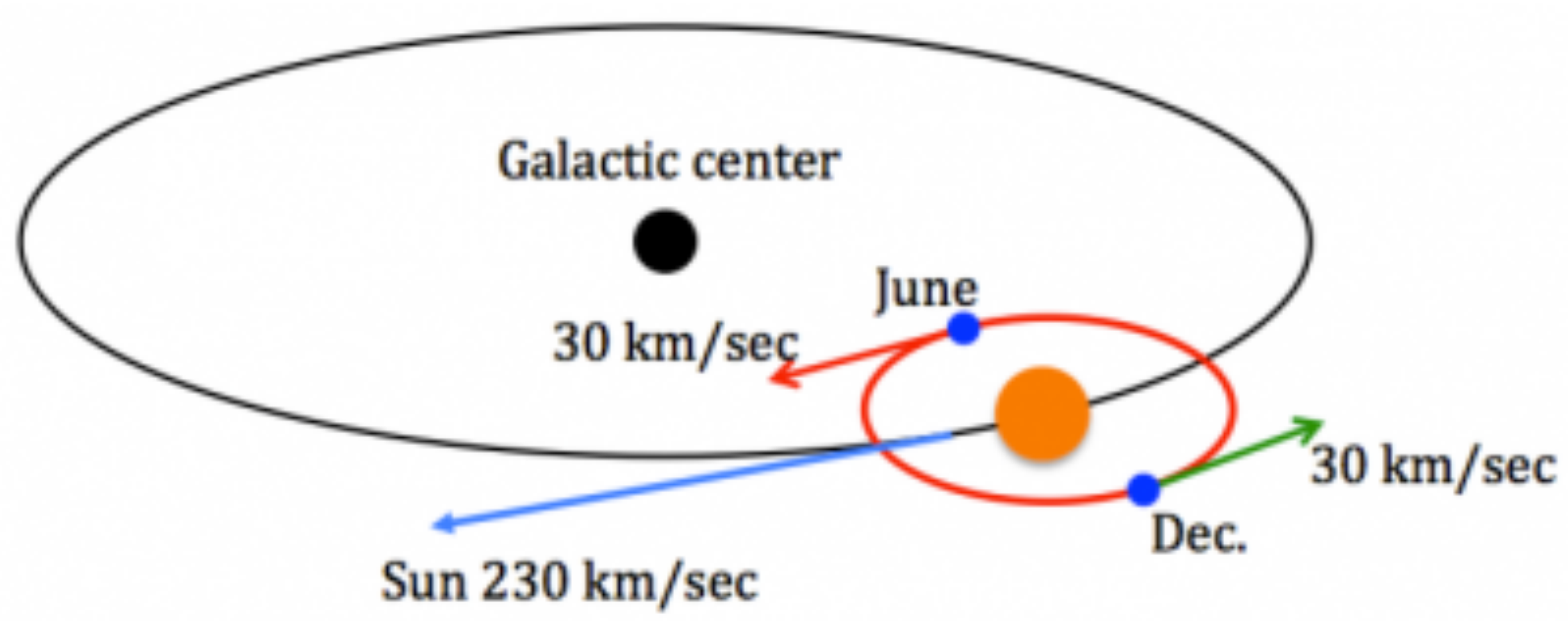


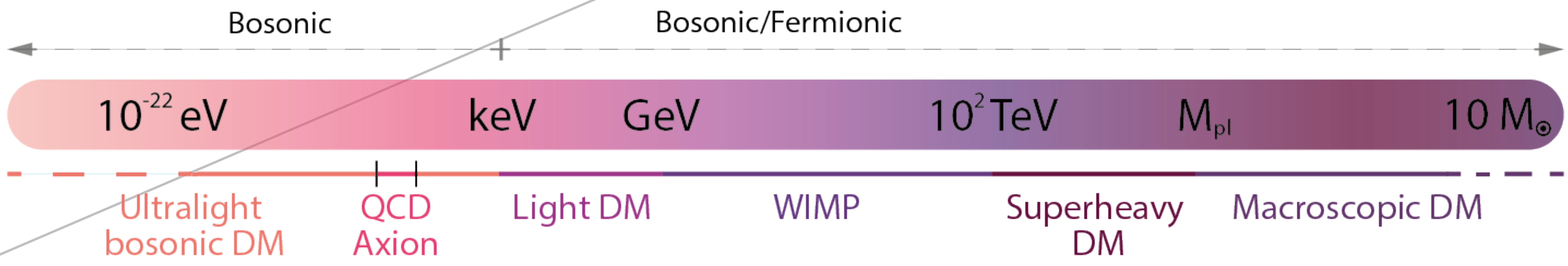


Dark matter models

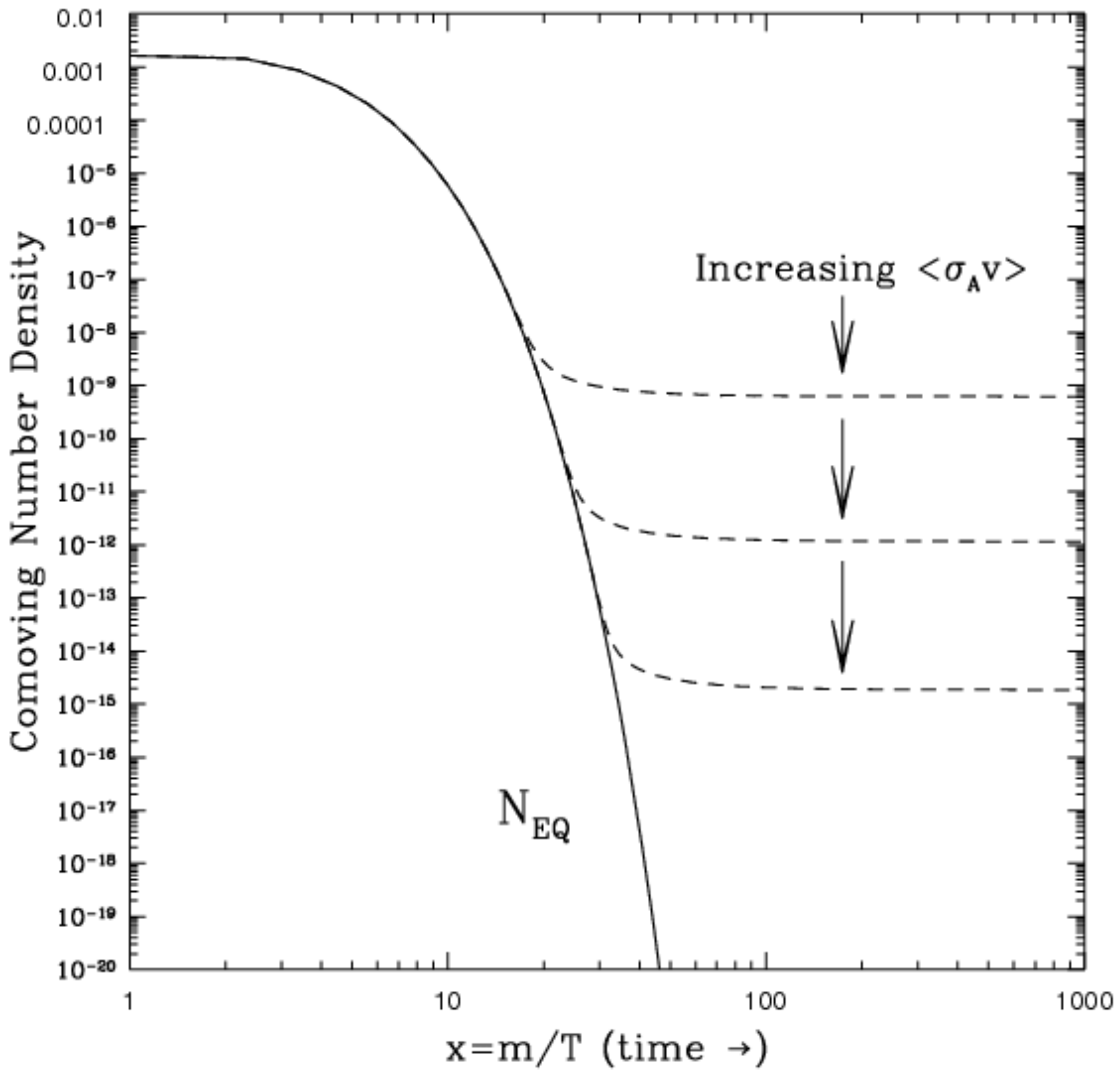
- Halo model: isothermal sphere at the center of the galaxy with density $\rho(r) \propto r^{-2}$
- Sun moving around the Galactic center and Earth moving around the Sun → Expected annual modulation of DM







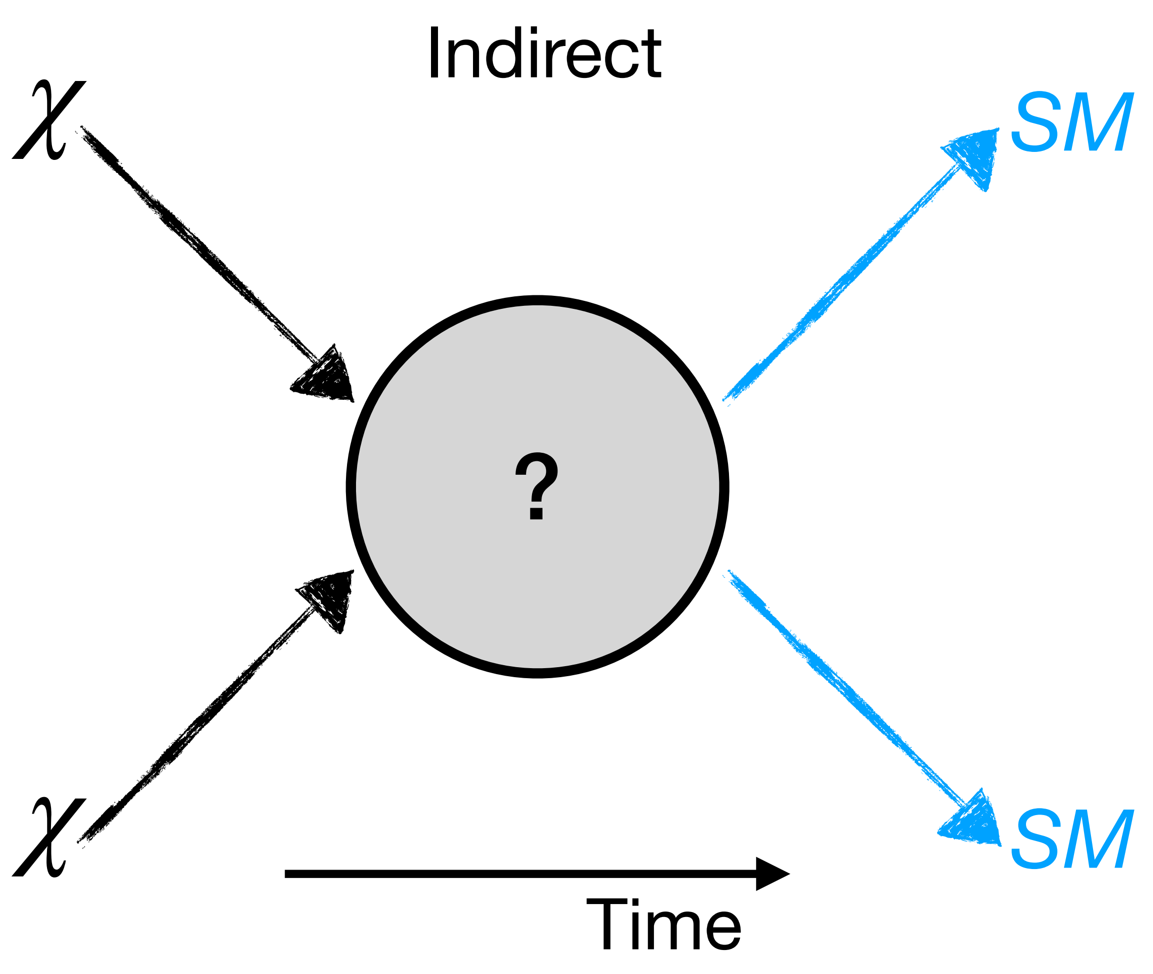
Freeze-out and WIMP miracle

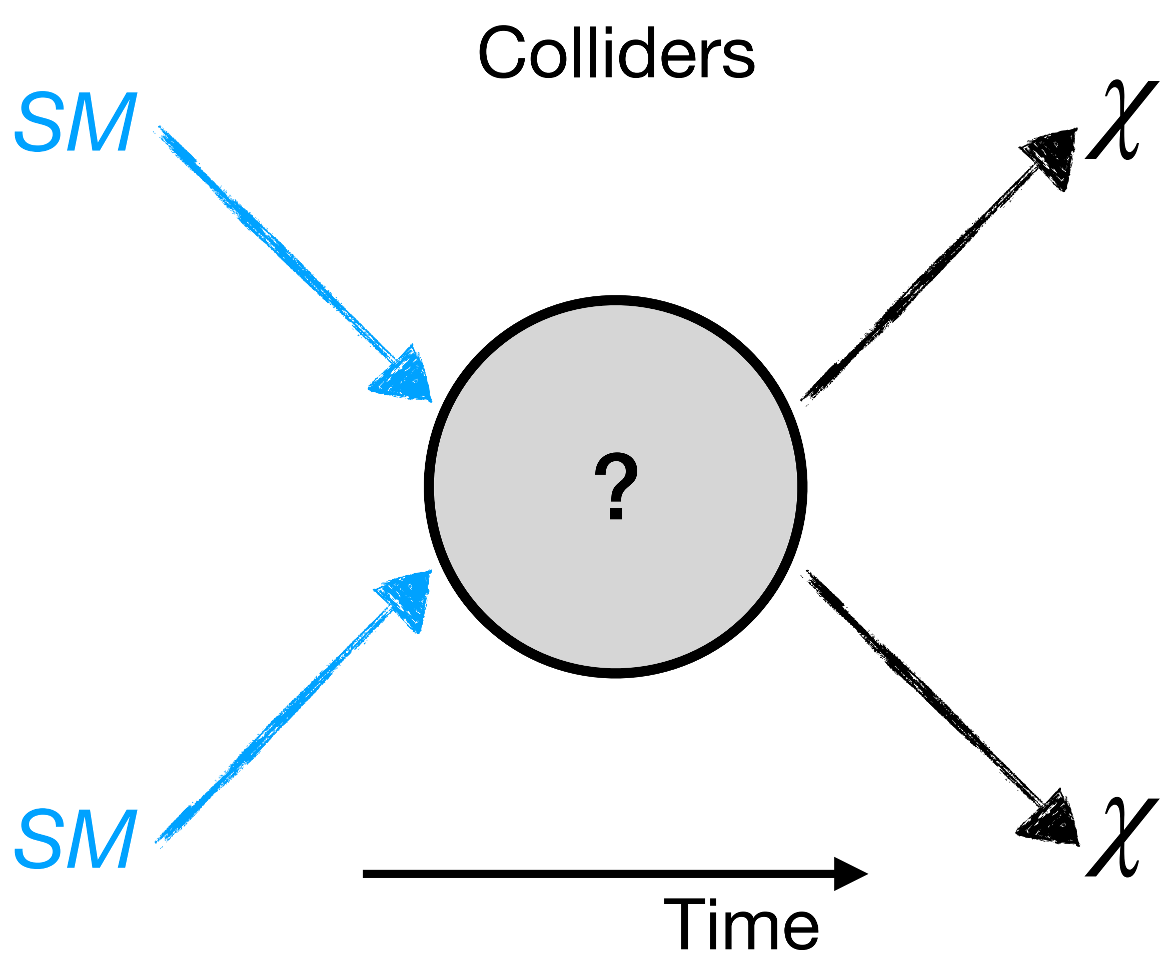


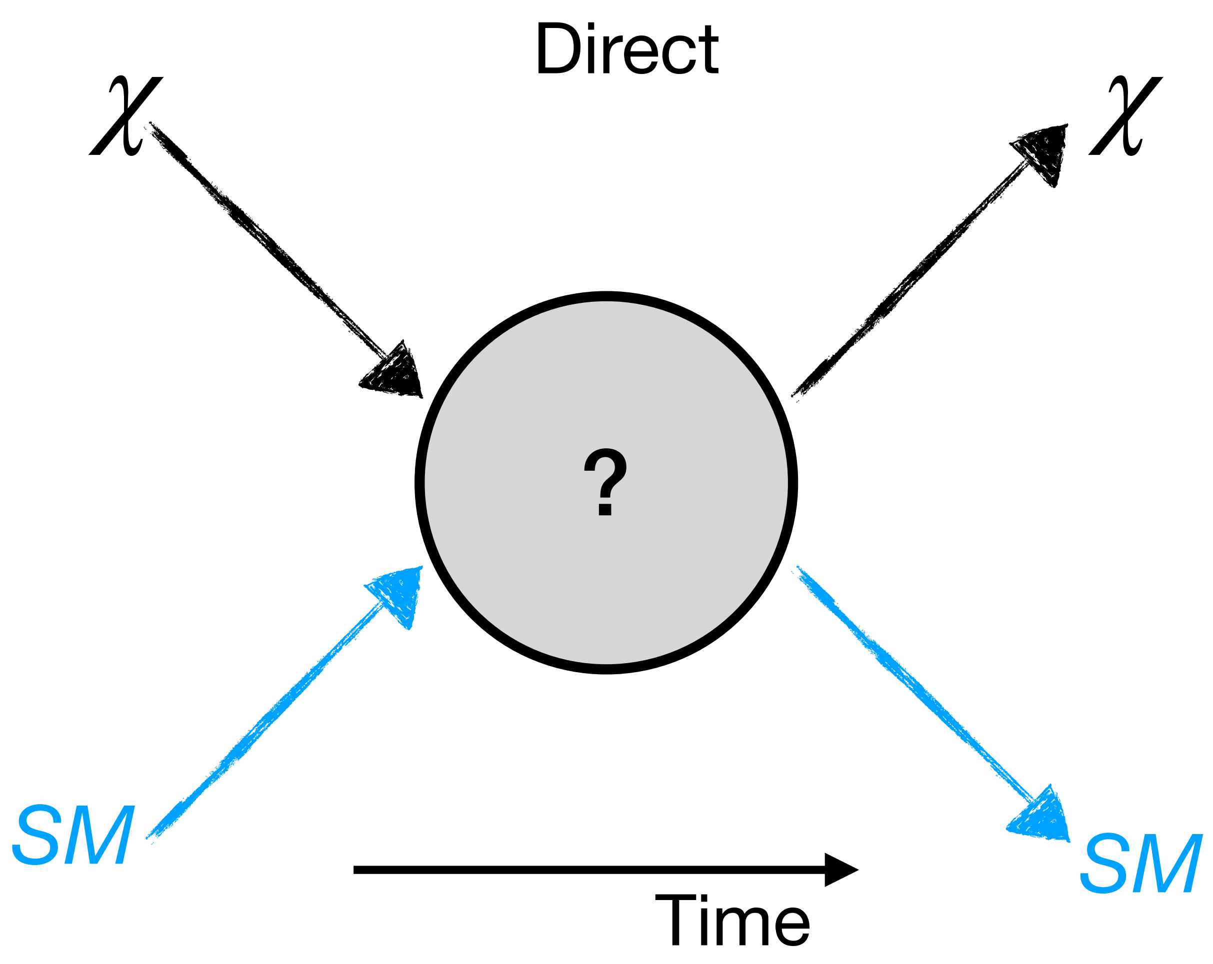
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi(eq)}^2\right)$$

- Relativistic particles in thermal equilibrium
- Cooling down some particles become non-relativistic and their number density reduces
- Time evolution to reach equilibrium:
  - Annihilation cross section and particle flux
  - Universe expansion
- When universe expansion is dominant annihilation stops → freeze-out
- Considering the annihilation cross section of the weak interaction, the relic density is Ω = 0.3
- Observed value for DM is Ω_{DM} = 0.26

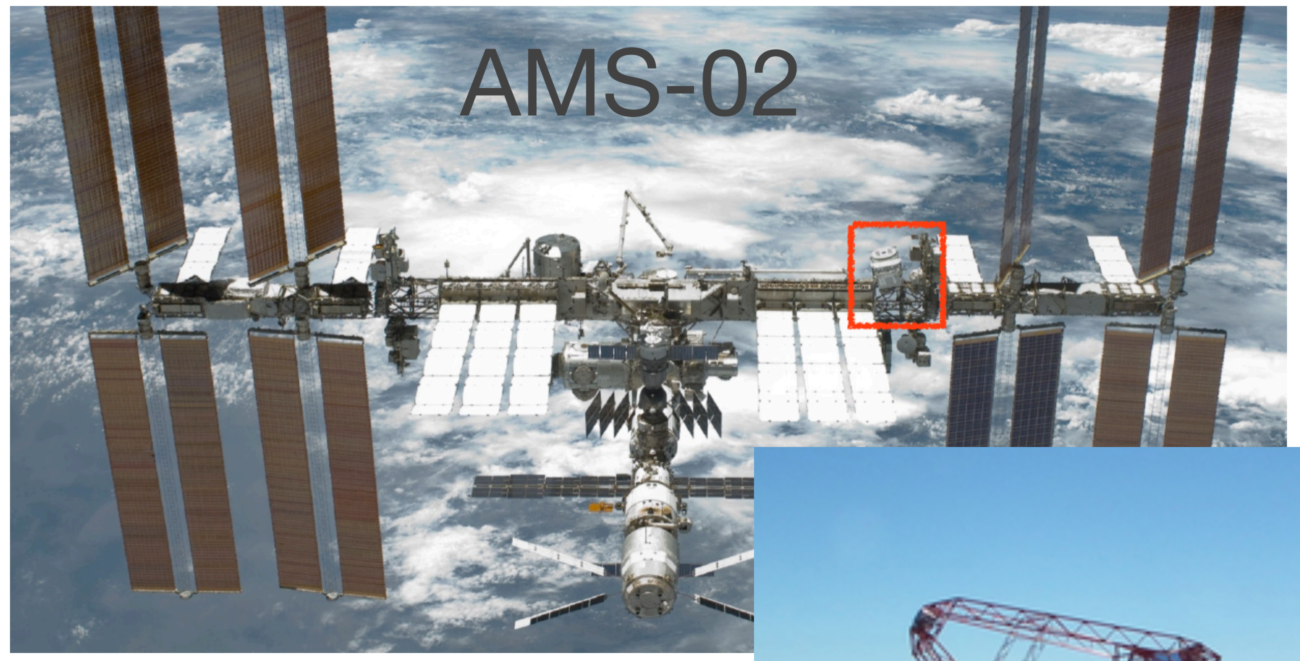
Detection techniques



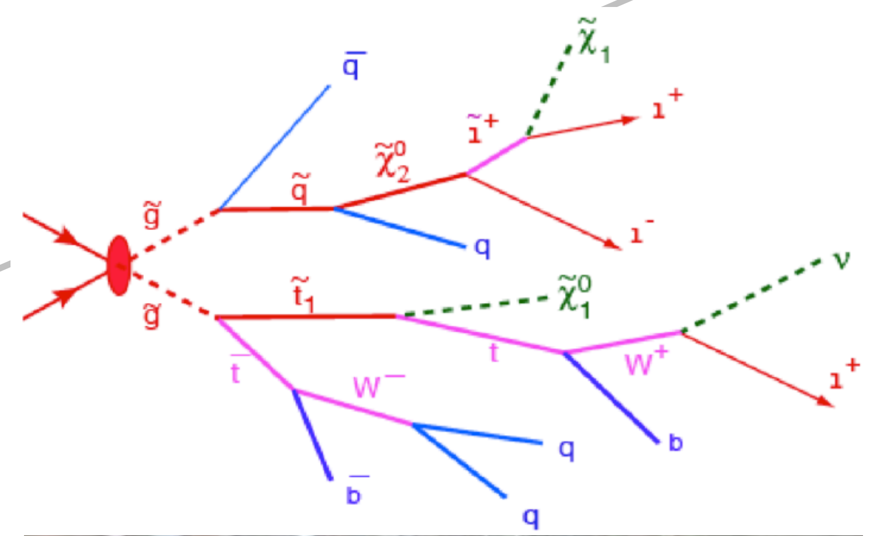




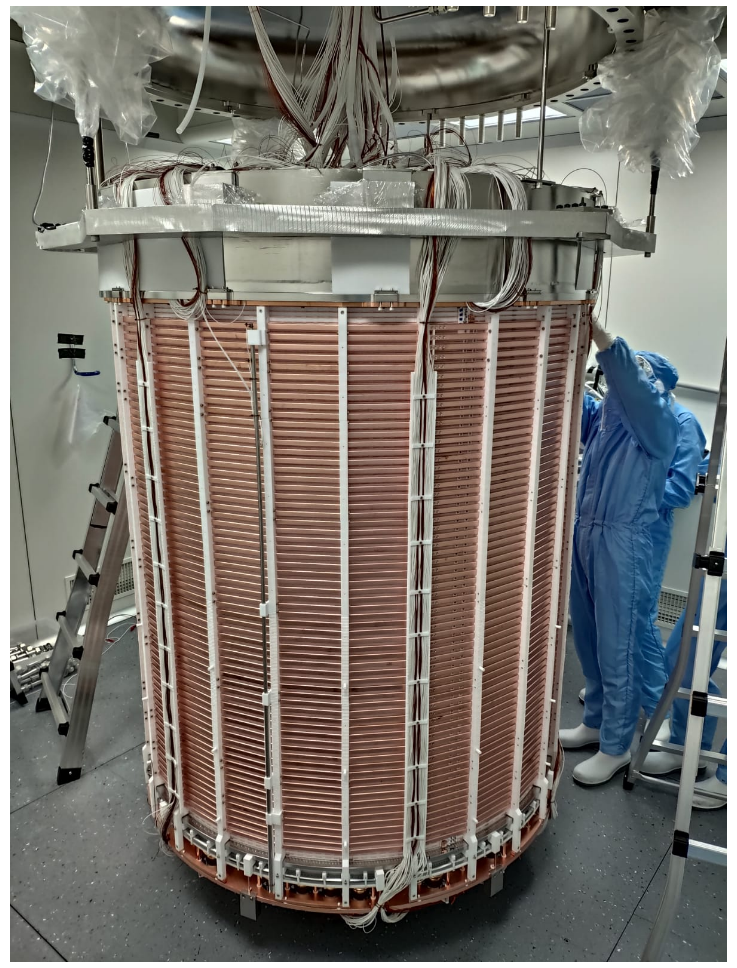
Observation of annihilation products



Production at colliders



Interaction in detector material



Direct detection

Detection by scattering of WIMP off target nucleus → nuclear recoil signature

$$\frac{dR}{dE_{nr}} = \frac{M_T}{m_N} \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{esc}} \epsilon(E_{nr})\, v \bullet f(\vec{v}) \frac{d\sigma_{\chi,N}}{dE_{nr}}\, dv$$

Astrophysical inputs:

- Local DM density near the Sun: $\rho_0 \simeq 0.3$ GeV cm^{-3}
- WIMP velocity distribution $f(v)$ assumed to follow Maxwell-Boltzman distribution → depends on the circular velocity around the galactic center: $v(r_{sun}) \simeq$ 220 km/s
- Escape velocity: $v_{esc} \simeq$ 544 km/s

Detector physics:

- Target material: atomic mass m_N and total mass M_T
- Energy threshold v_{min} and detection efficiency $\epsilon(E_{nr})$

Particle physics:

- DM-nucleon scattering cross section $\sigma_{\chi,N}$
- Assumed low momentum transfer

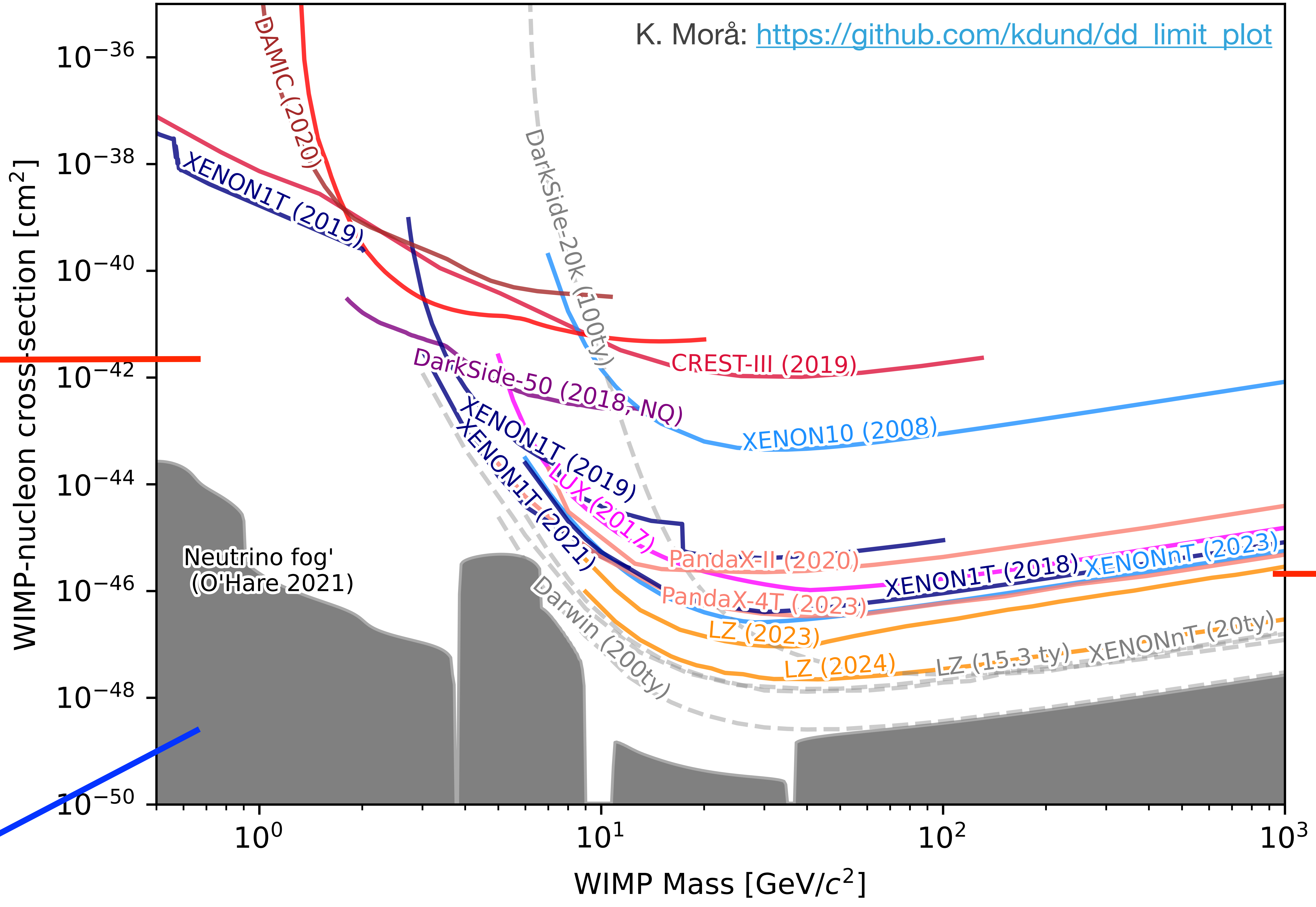
$$\frac{d\sigma_{\chi,N}}{dE_{nr}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_0^{SI}\, F_{SI}^2(E_{nr}) + \sigma_0^{SD} F_{SD}^2(E_{nr})\right]$$

- Spin-independent scattering usually assumed: $\sigma_0^{SI} \propto A^2$

Figure by Hammann, R.

Current scenario

Lower threshold and detection efficiency



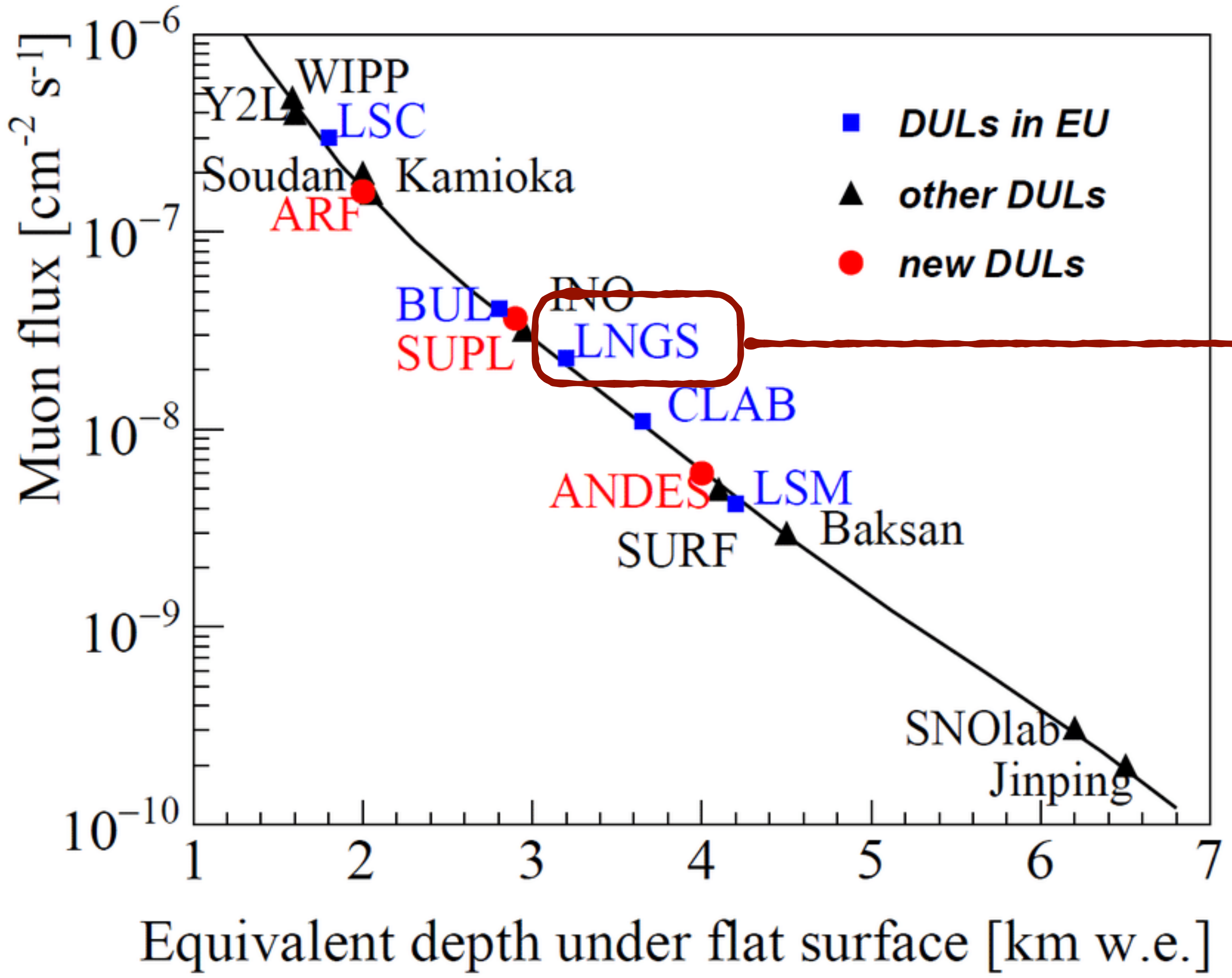
Discovery would allow to delimitate a signal contour region

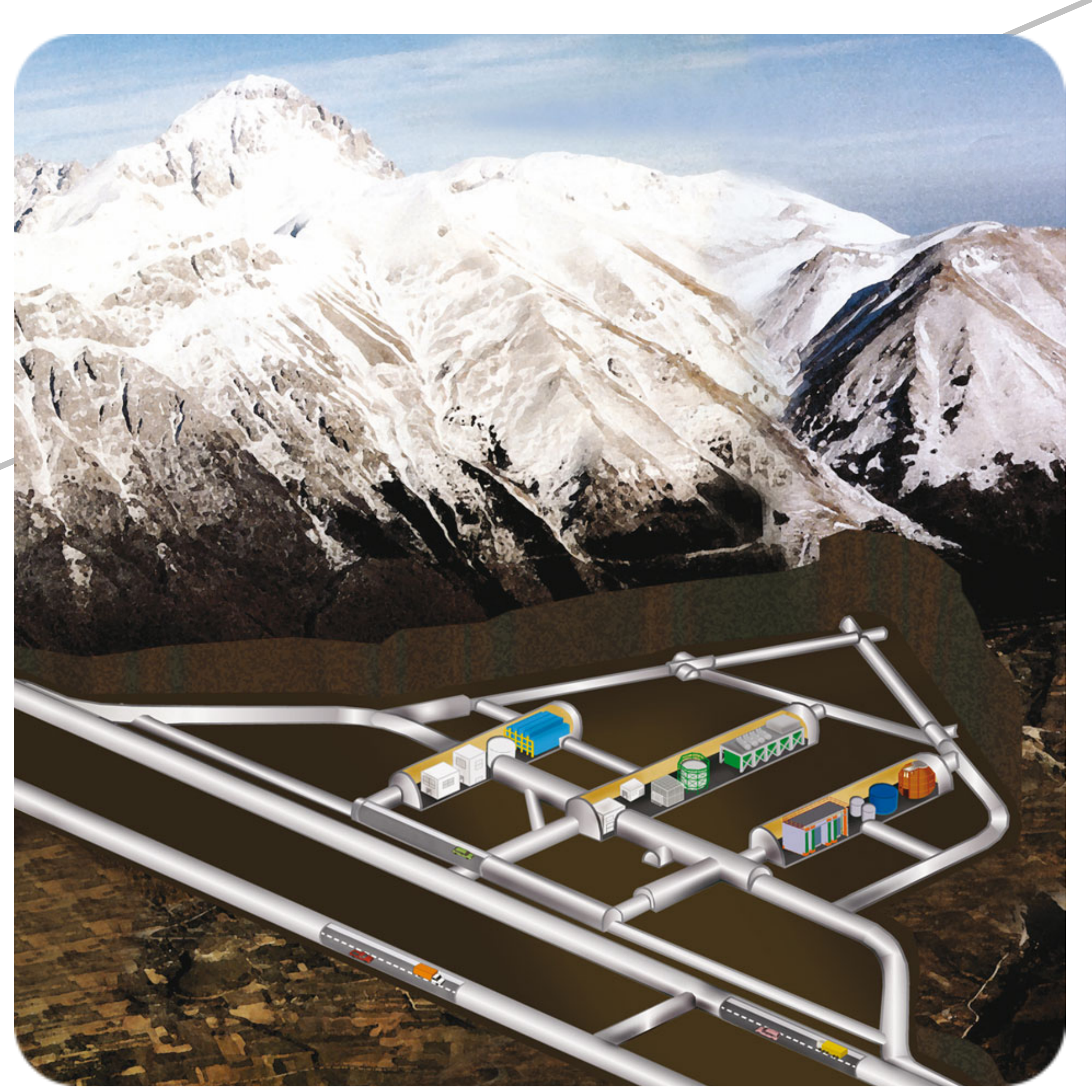
Increase exposure

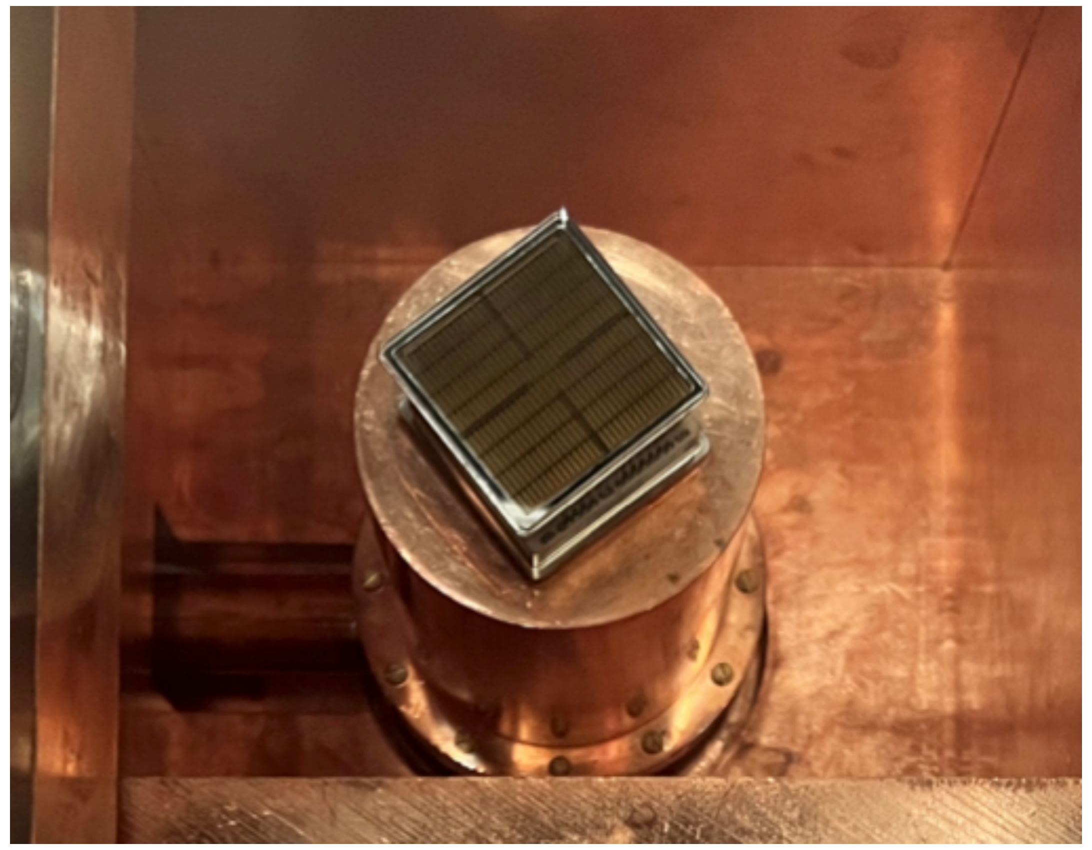
CEνNS

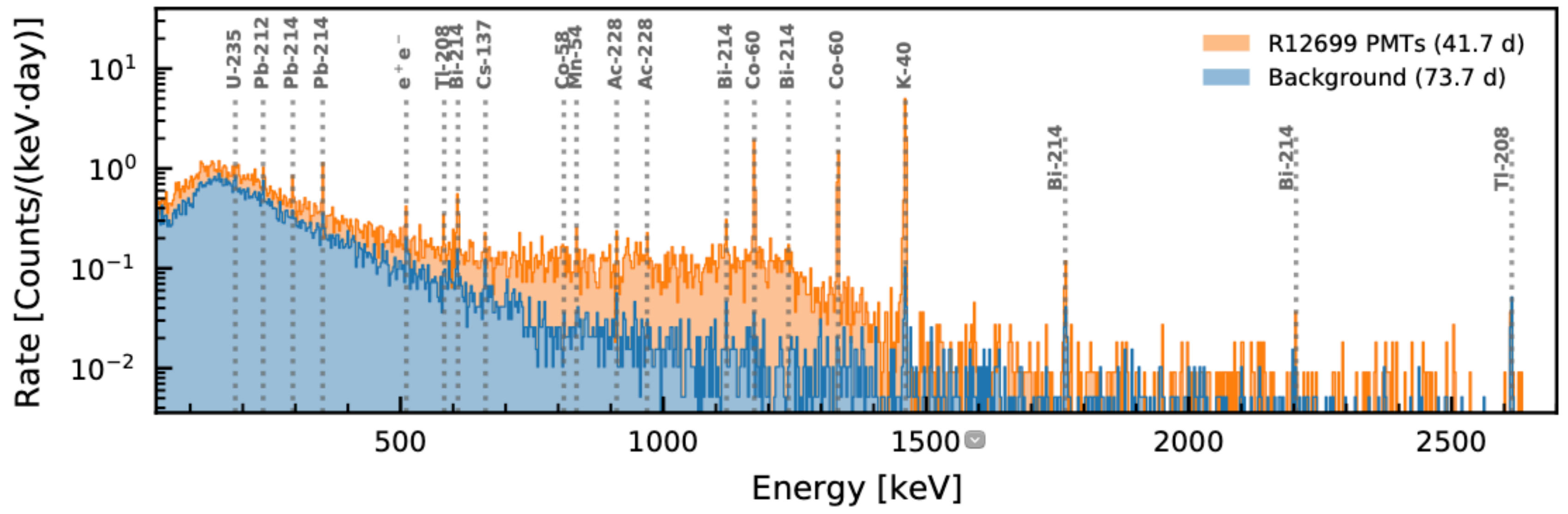
The first line of background mitigation

- Several underground laboratories around the world - sometimes in mines → rock to shield from cosmic rays
- Selection of ultra pure materials
- Material cleaning and handling in controlled environment (cleanroom)
- Material radioessay for contaminant tracing
- Active vetoes

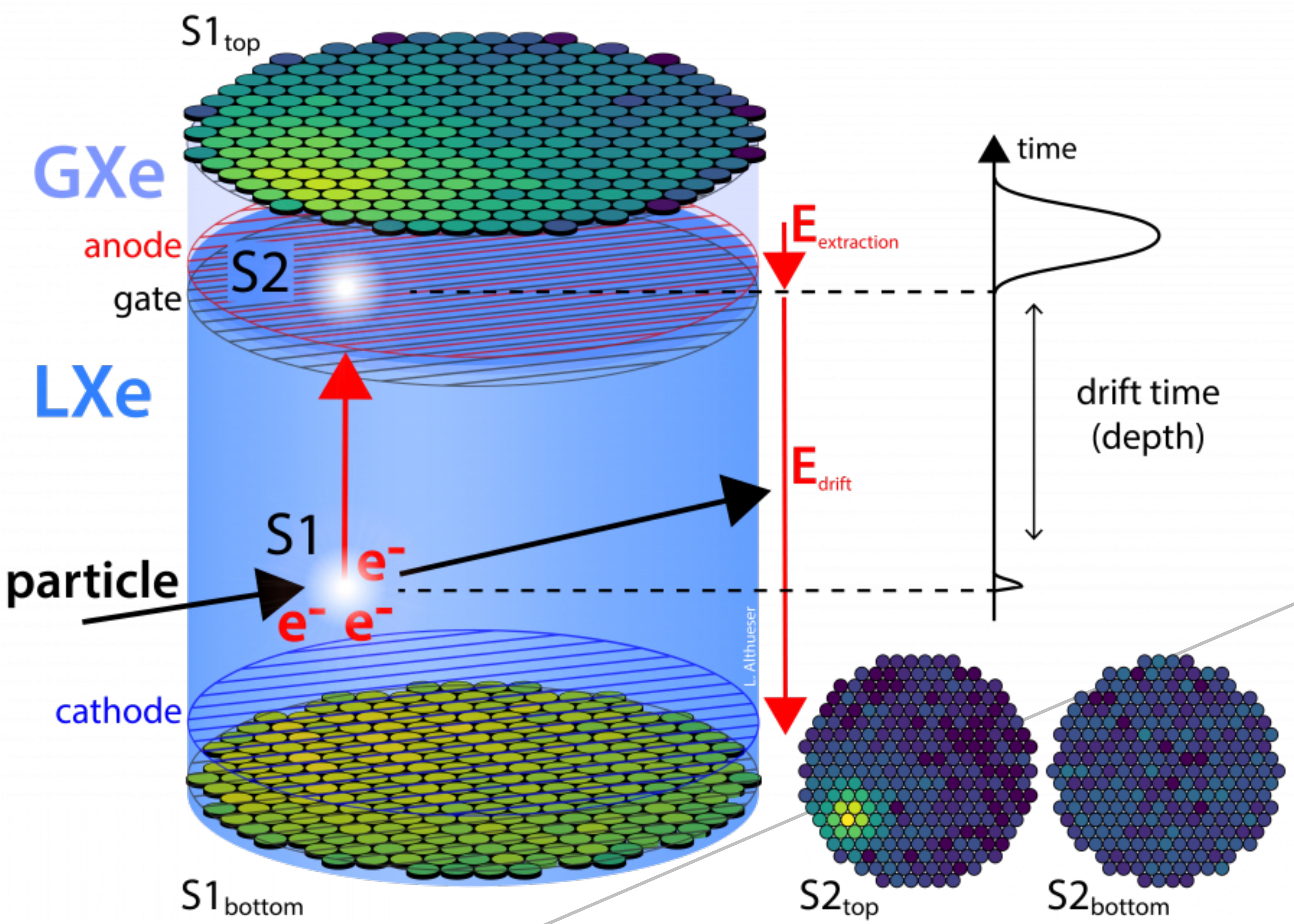




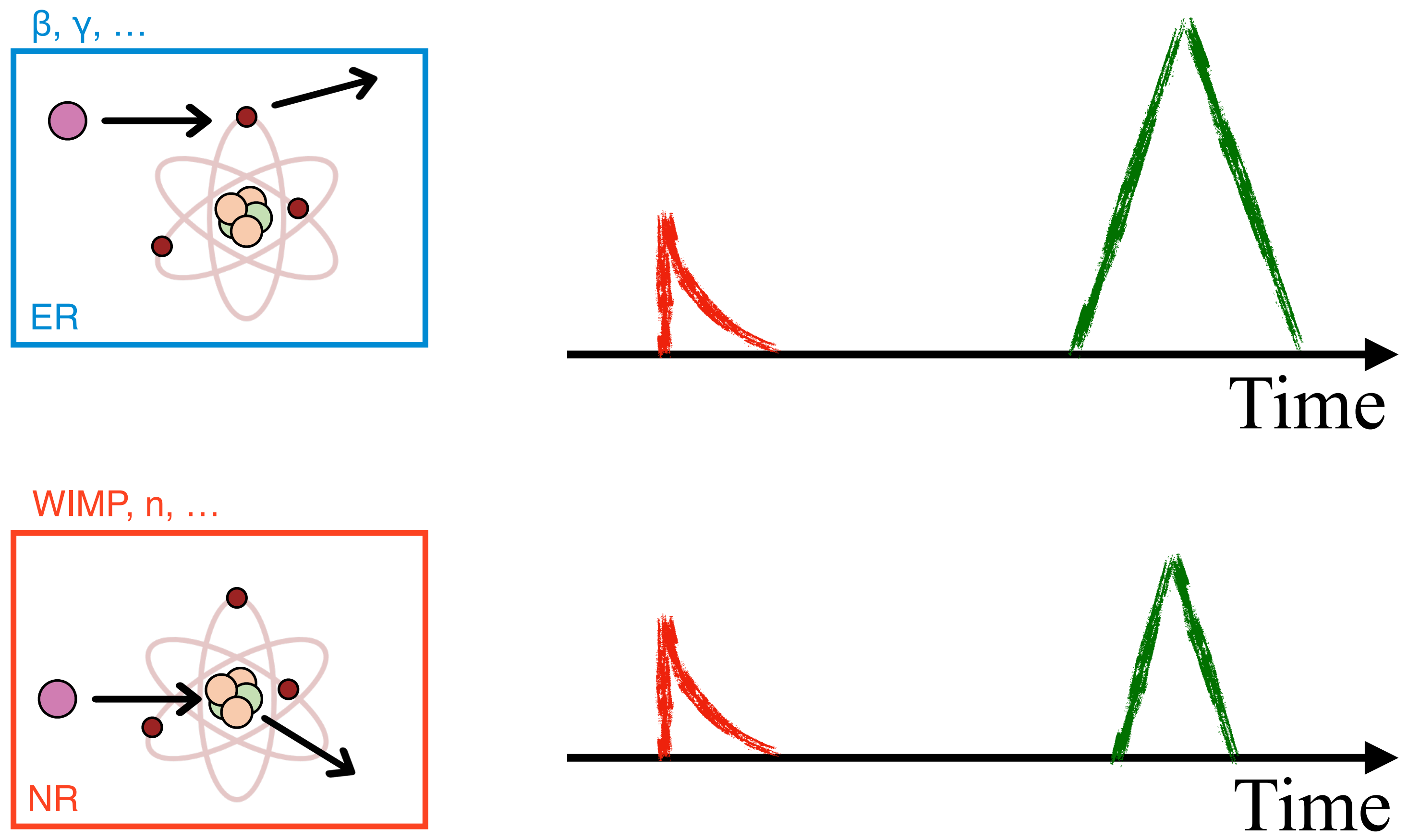




Dual-phase xenon TPC



- Measure scintillation light (S1) and ionisation signal (S2)
- 3D position reconstruction:
  - *x-y* from photosensor arrays
  - *z* from delay time between S1 and S2
- Electronic and nuclear recoil discrimination from S1/S2 ratio



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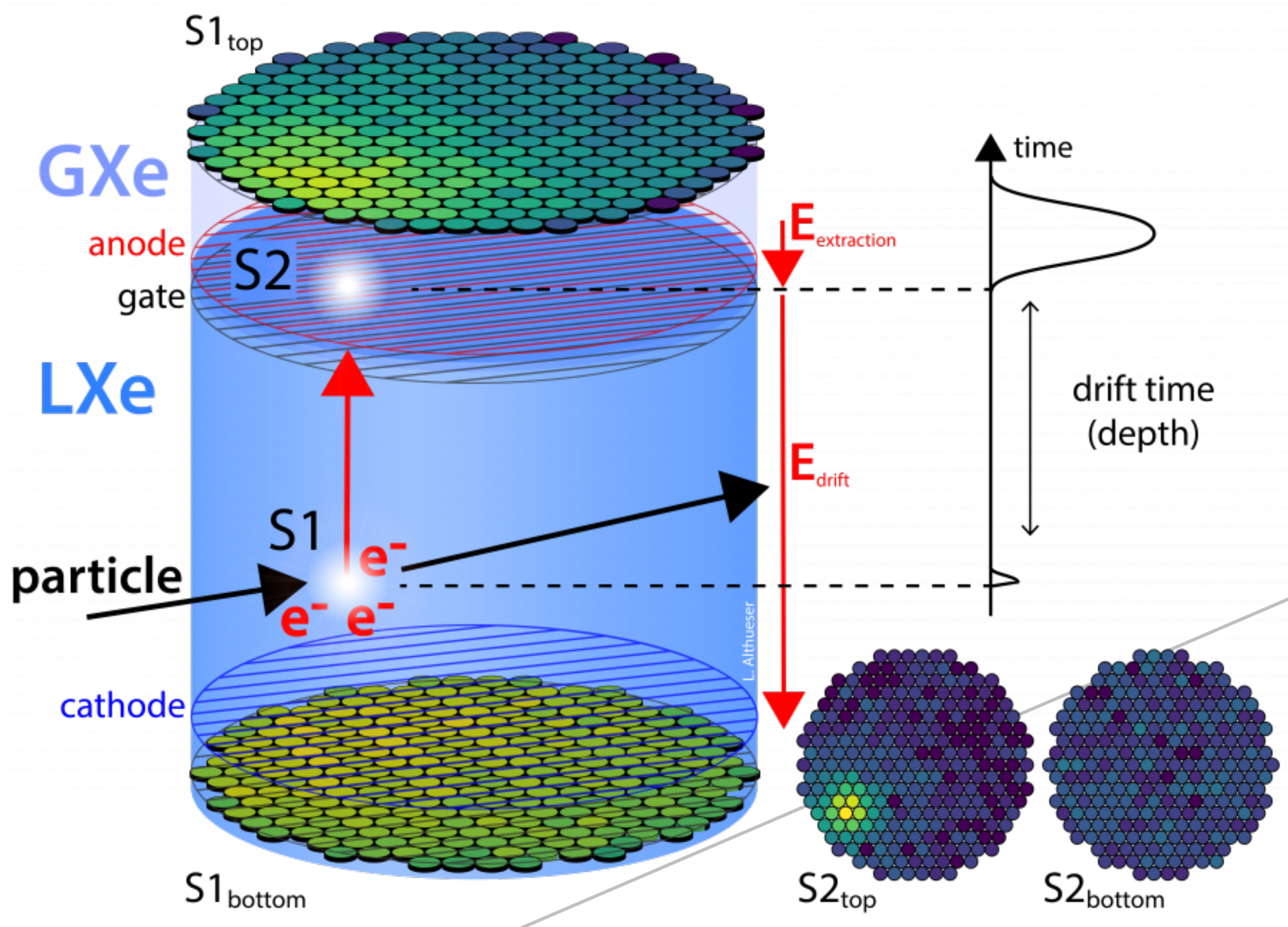

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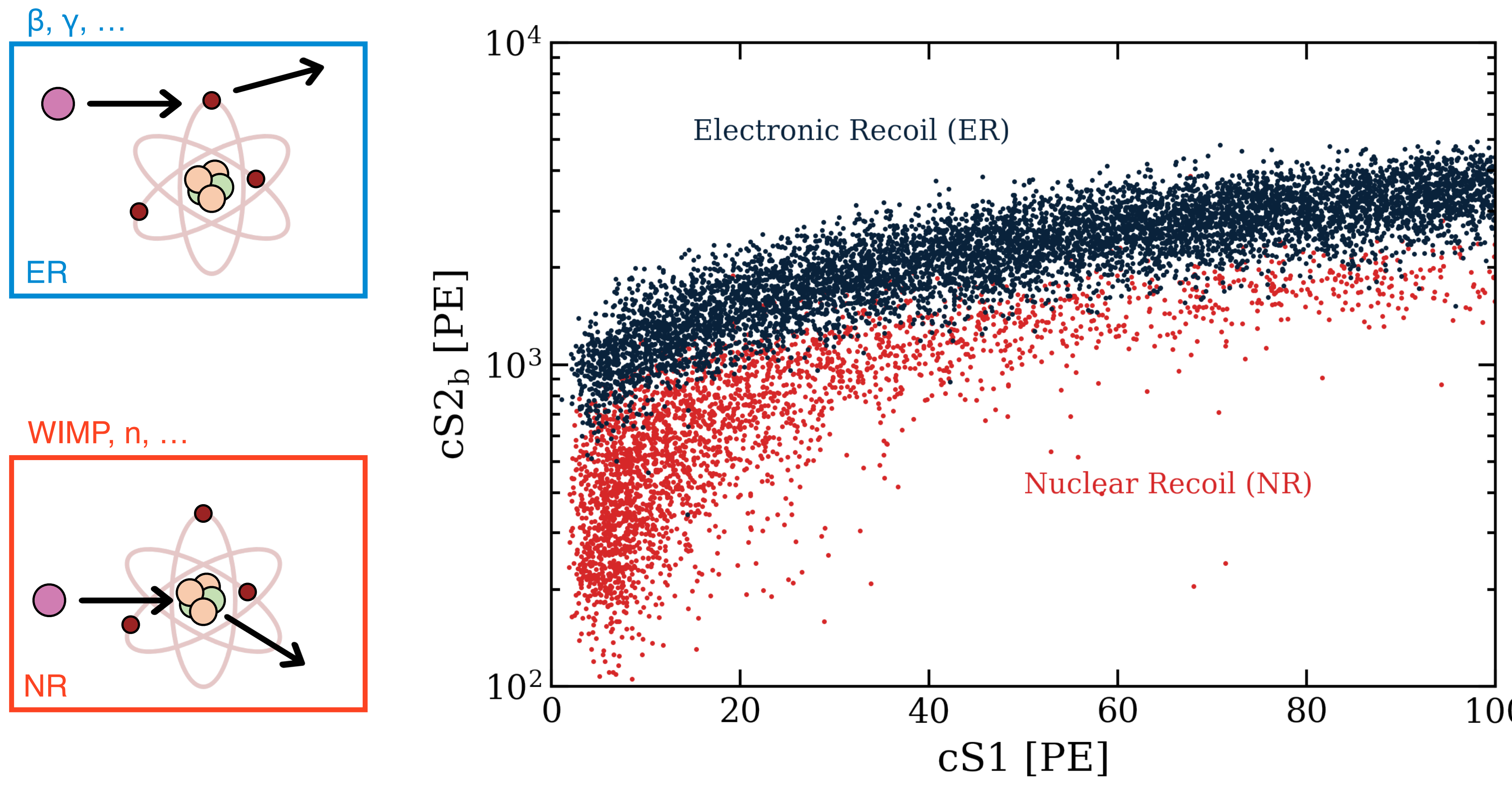
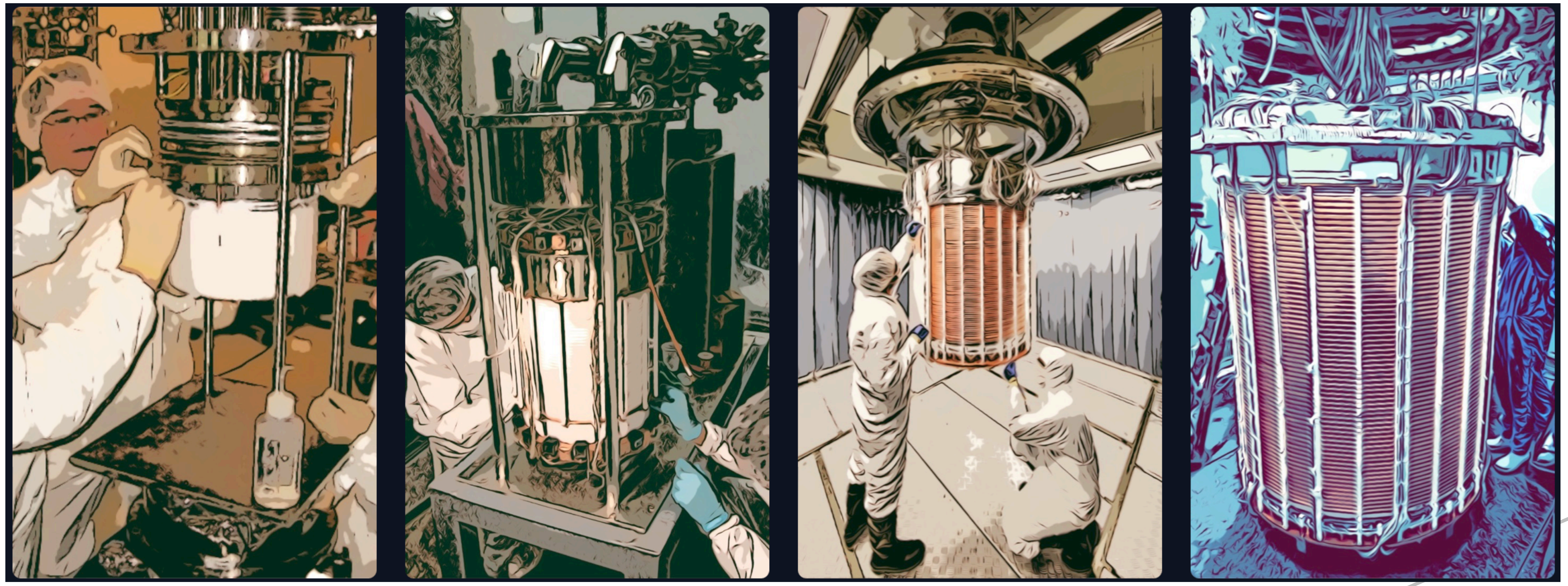


The XENON collaboration

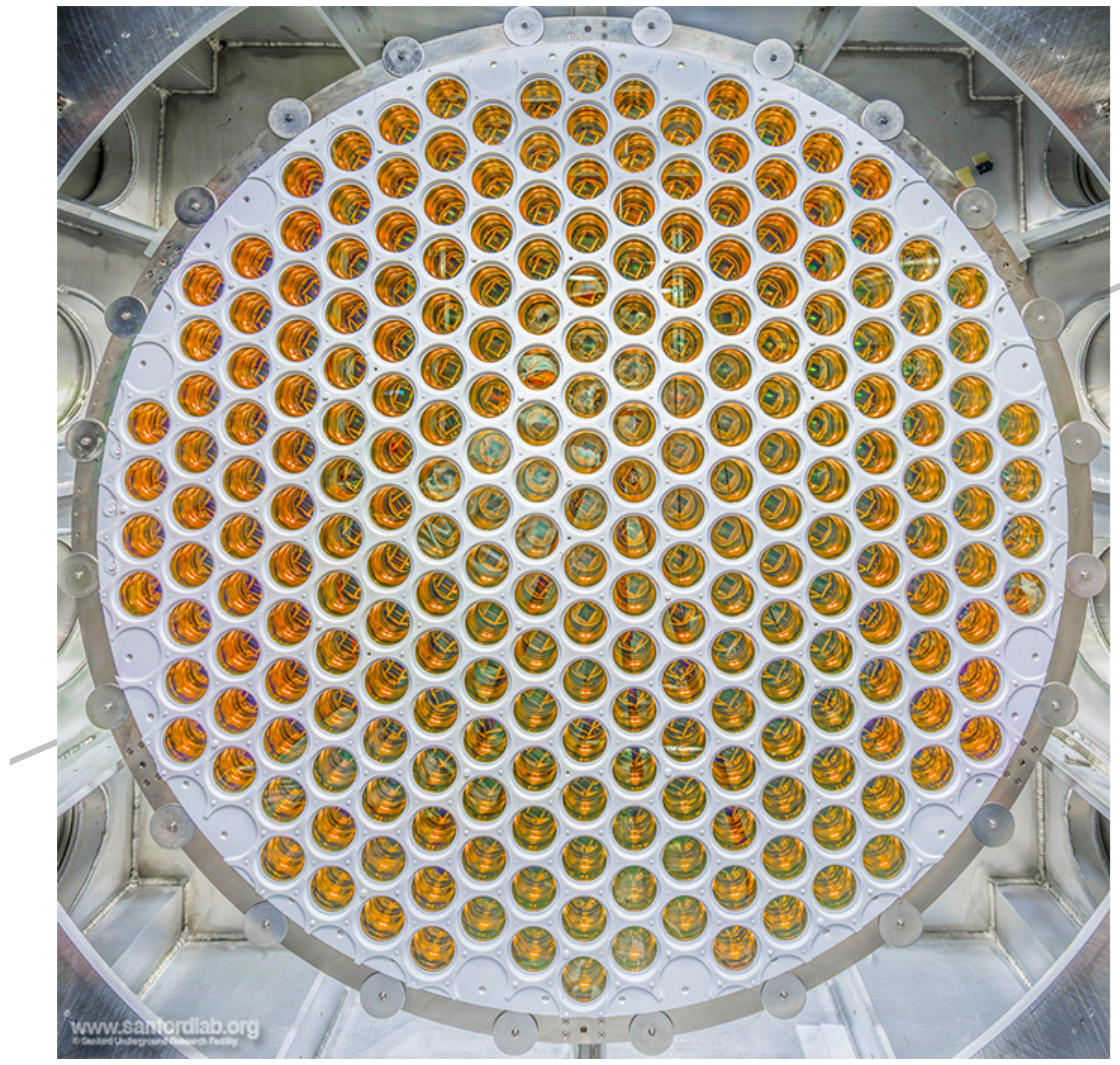


XENON10	XENON100	XENON1T	XENONnT	XLZD
25 kg LXe	160 kg LXe	3200 kg LXe	8500 kg LXe	78 t LXe
600 $[t\ d\ keV]^{-1}$	5.3 $[t\ d\ keV]^{-1}$	0.2 $[t\ d\ keV]^{-1}$	0.04 $[t\ d\ keV]^{-1}$	Reduce background down to pp level

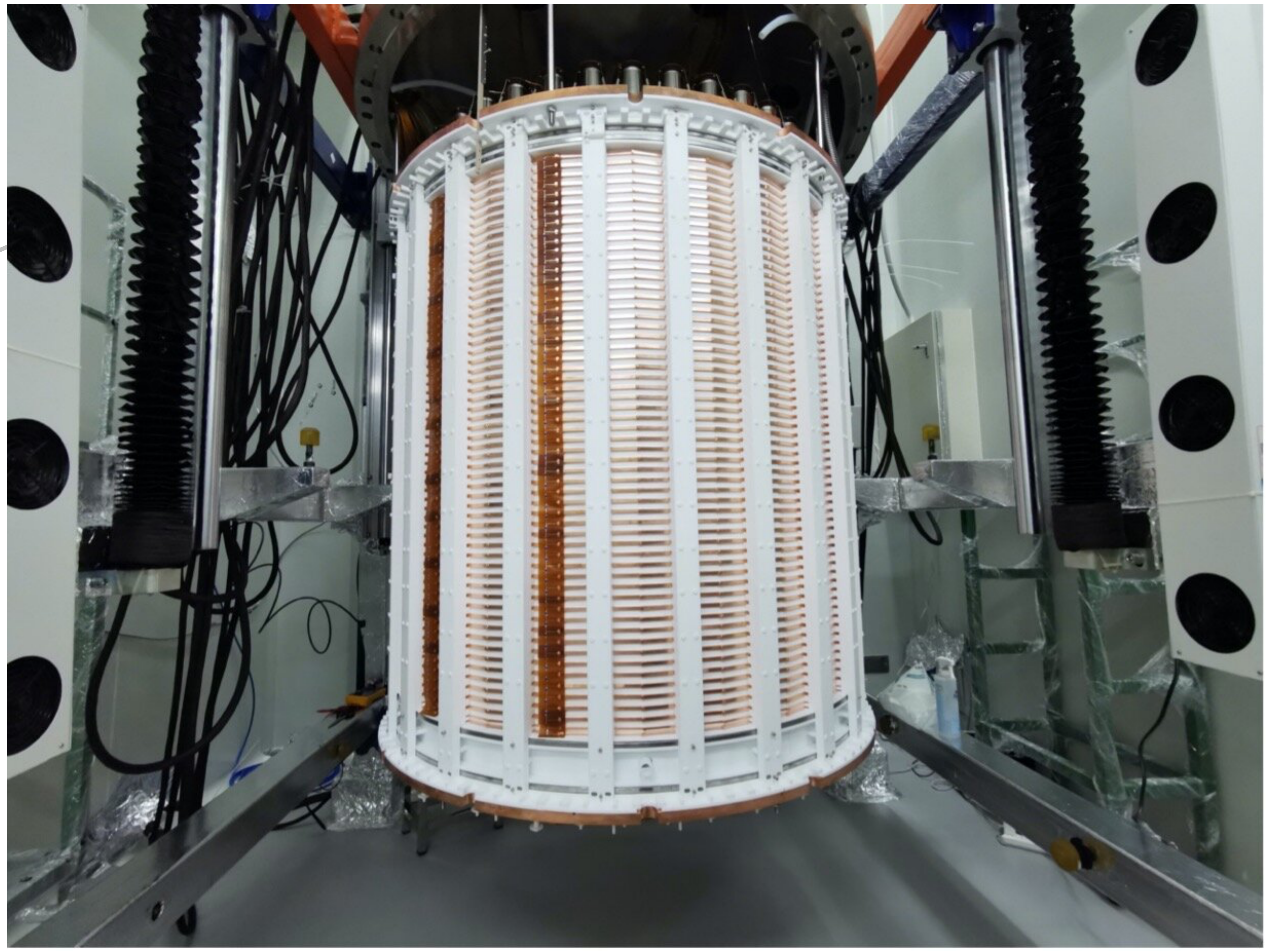
Started in 2006 — 2008 — 2015 — 2020 → - - - →

LZ and PandaX-4T

- LZ (LUX-ZEPPELIN):
  - US-UK lead, located at SURF
  - ~10 tonnes of LXe, ~7 tonnes active
  - Part of the XLZD collaboration

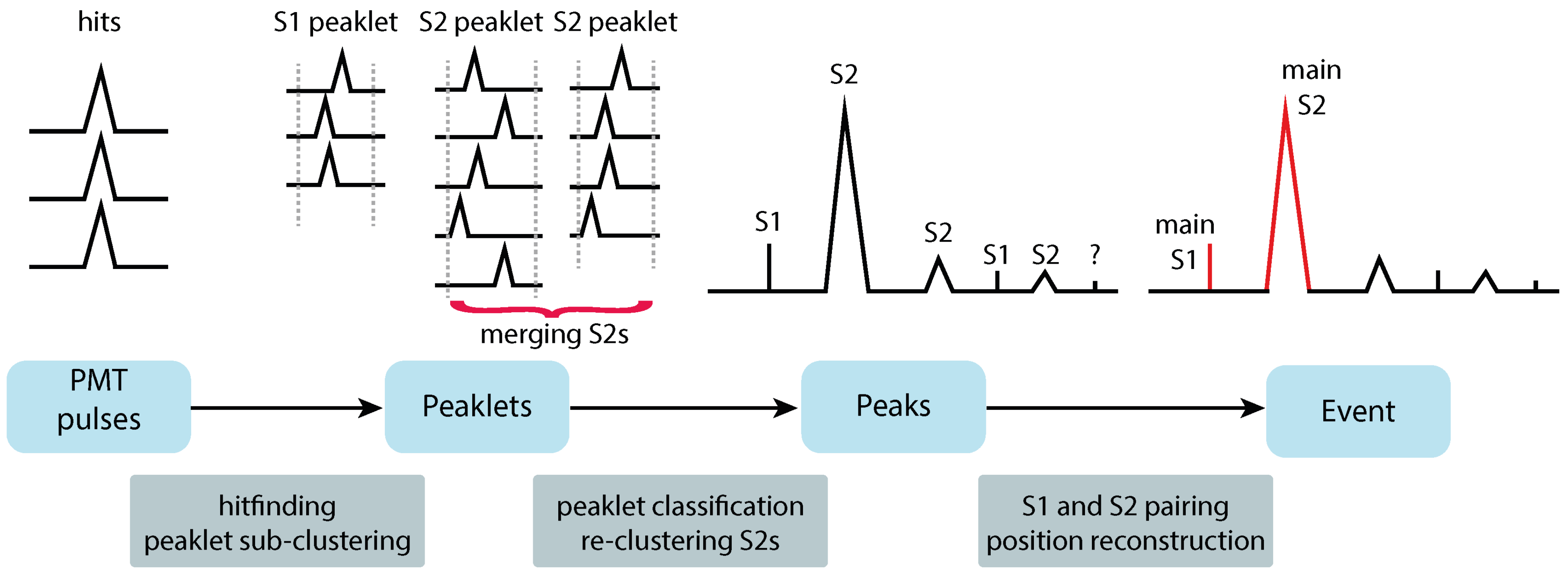


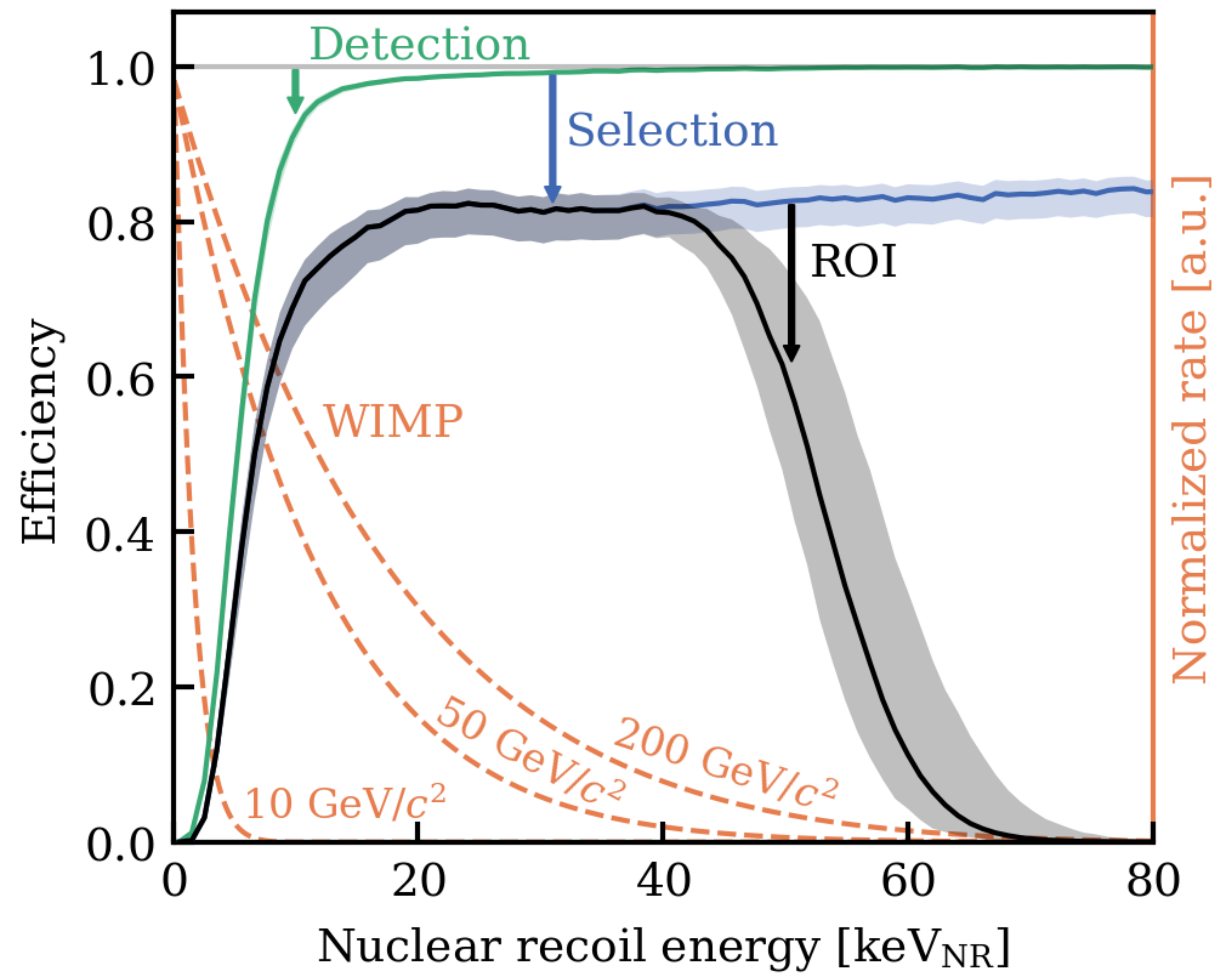
- PandaX-4T:
  - China lead, located at CJPL
  - ~6 tonnes of LXe, ~4 tonnes active
  - Upgrade to PandaX-XT



Analysis in a nutshell

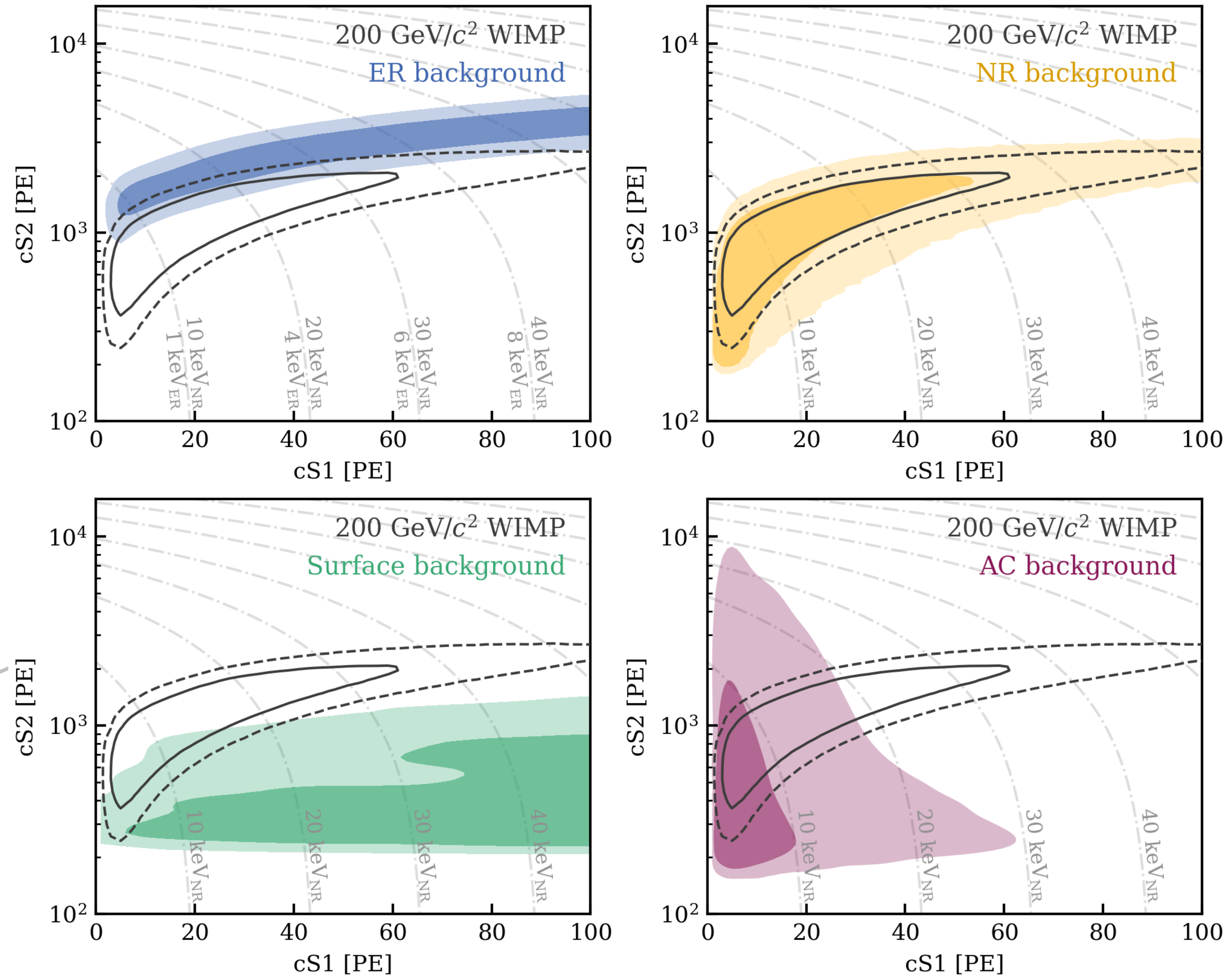
- Processing pipeline for peak and event reconstruction and classification → Each event is an interaction in the active volume of the TPC with one main S1 and S2
- Signals position reconstruction corrected for field distortions
- S1 corrected for light collection efficiency
- S2 corrected for electron mean free path + electron extraction efficiency + amplification gain
- Data quality and selections: veto tagging, fiducialization, single scatter, PMTs pattern,….
- Detector response modelling
- Background modelling
- Inference





Background contributions

- ER Background
  - Dominated by radon background
  - Sub-dominant ^{85}Kr background
- Surface Background
  - ^{210}Pb plate-out at the PTFE walls leading to ^{210}Po α-decays with electron loss
  - Suppressed by fiducial volume cut
- Accidental Coincidences
  - Random pairing of isolated S1 and S2 signals
  - Suppression using a gradient BDT cut based on S2 shape, R and Z information
- NR Background
  - Radiogenic neutron rate constrained by NV tagging
  - CEvNS constrained from solar ^{8}B neutrino flux

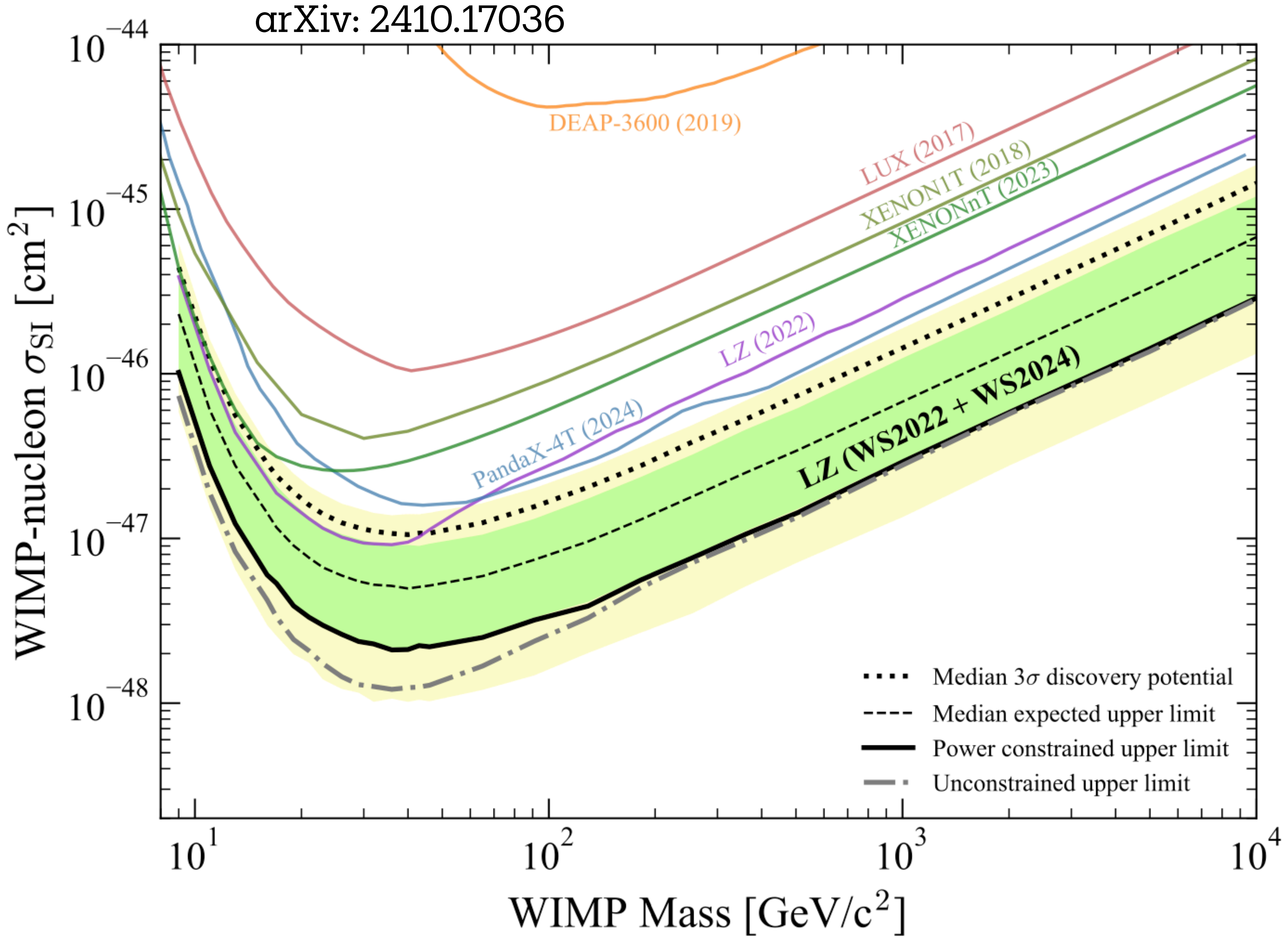


WIMP spectrum derived by folding the theoretical rate with the NR response model

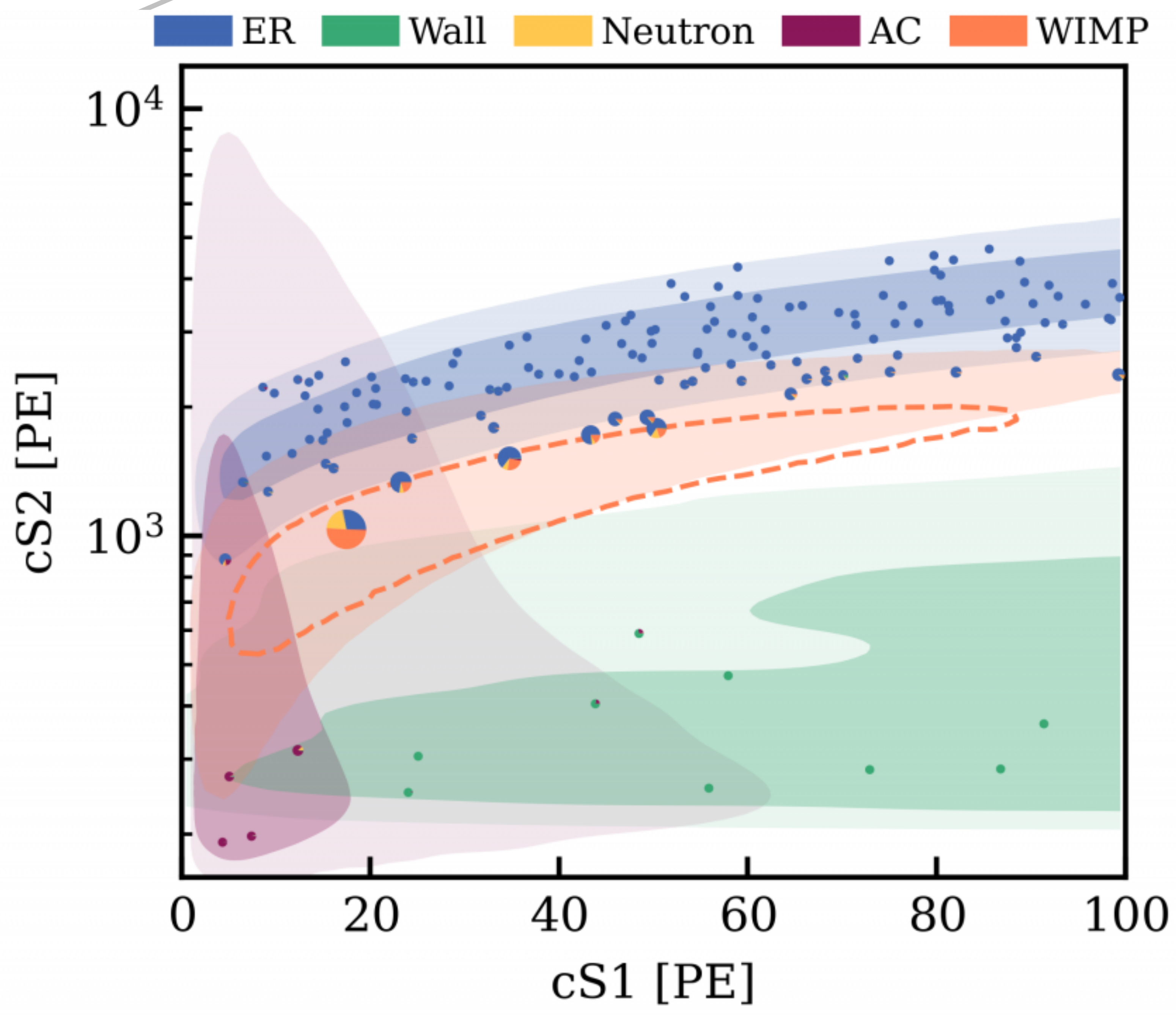
WIMP latest results

- LZ latest data-release set most stringent limit on SI-WIMP cross section
- XENONnT latest releases in 2023 - new results coming soon!
  - Lowest ER background rate measured in DM detector: (15.8±1.3) events/(t yr keV)
- Several DM channels on both NR and ER channels: SD-WIMP, axions, ALPs, bosons dark matter, …

arXiv: 2410.17036



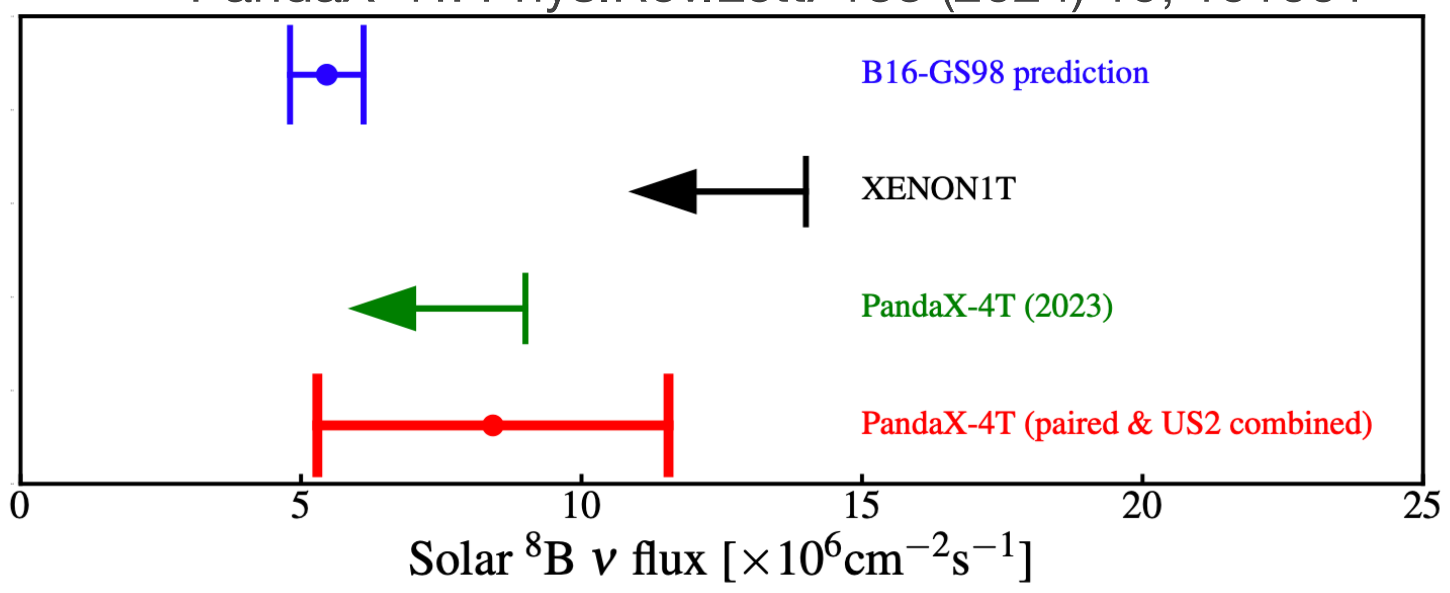
Phys. Rev. Lett. 131, 041003 (2023)



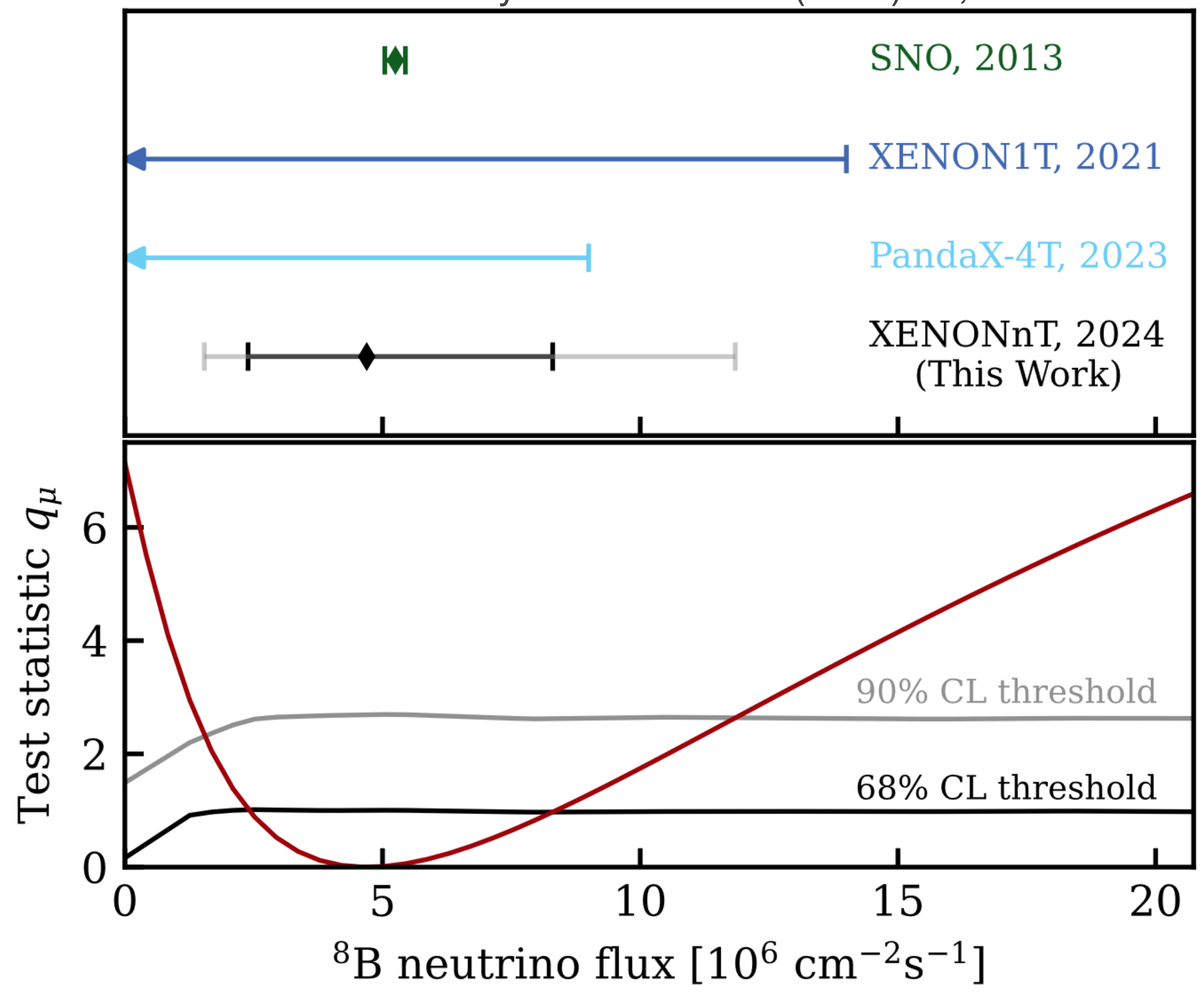
CEνNS: coherent elastic neutrino nucleus scattering

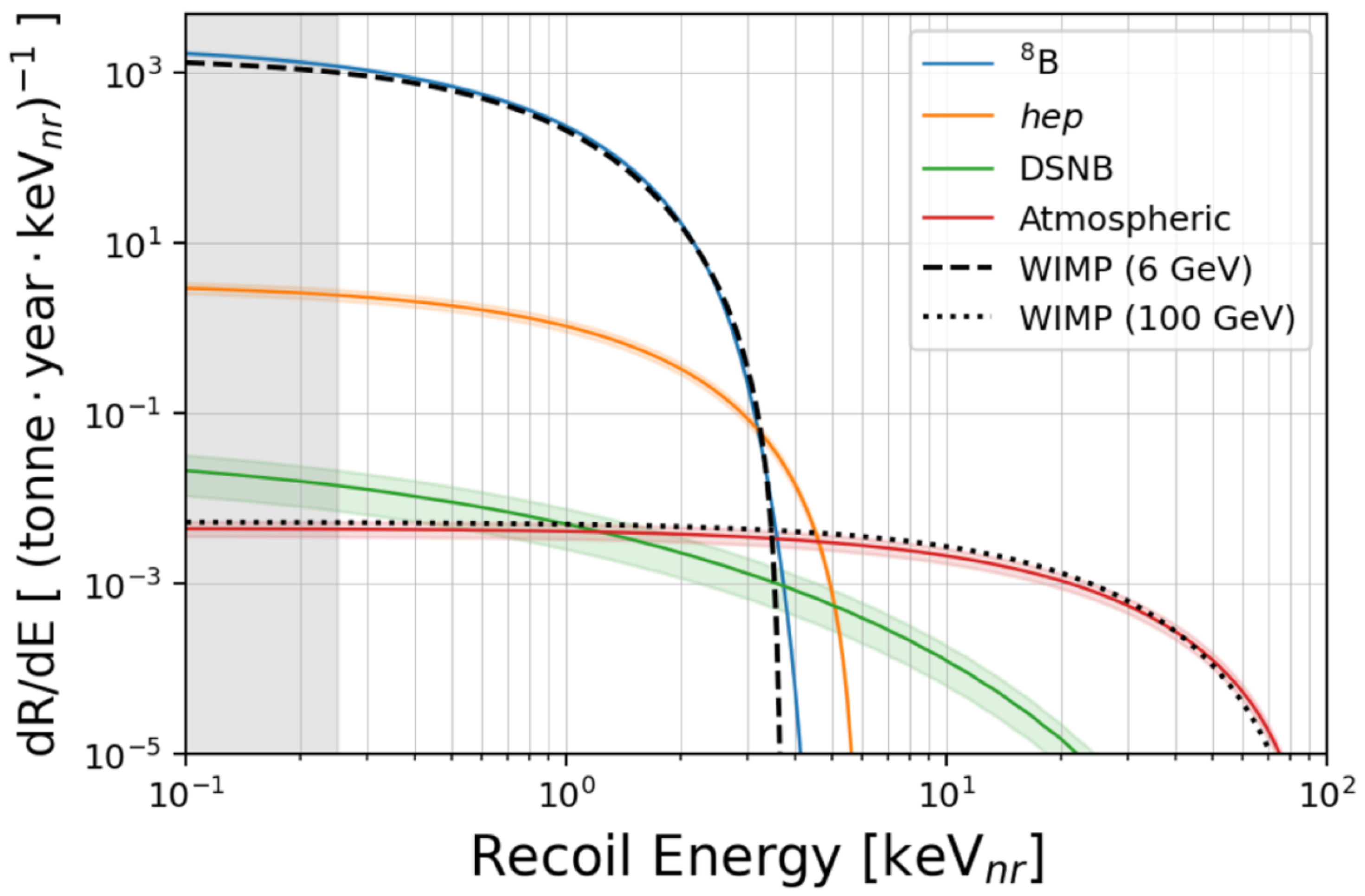
- Measurement of ^{8}B solar neutrinos through CEνNS in XENONnT at 2.73σ and PandaX-4T at 2.64σ
- First CEνNS measurement with Xe
- Low energy deposit: >90% recoils below 2.1 keV → Lowering PMT coincidence threshold from 3 to 2 and calibration with external ^{88}YBe source in XENONnT
- Analysis with S2-only signals in PandaX-4T
- Mimic 6 GeV WIMP single scatter NR signal → no discrimination in the neutrino fog

PandaX-4T: Phys.Rev.Lett. 133 (2024) 19, 191001



XENONnT: Phys.Rev.Lett. 133 (2024) 19, 191002



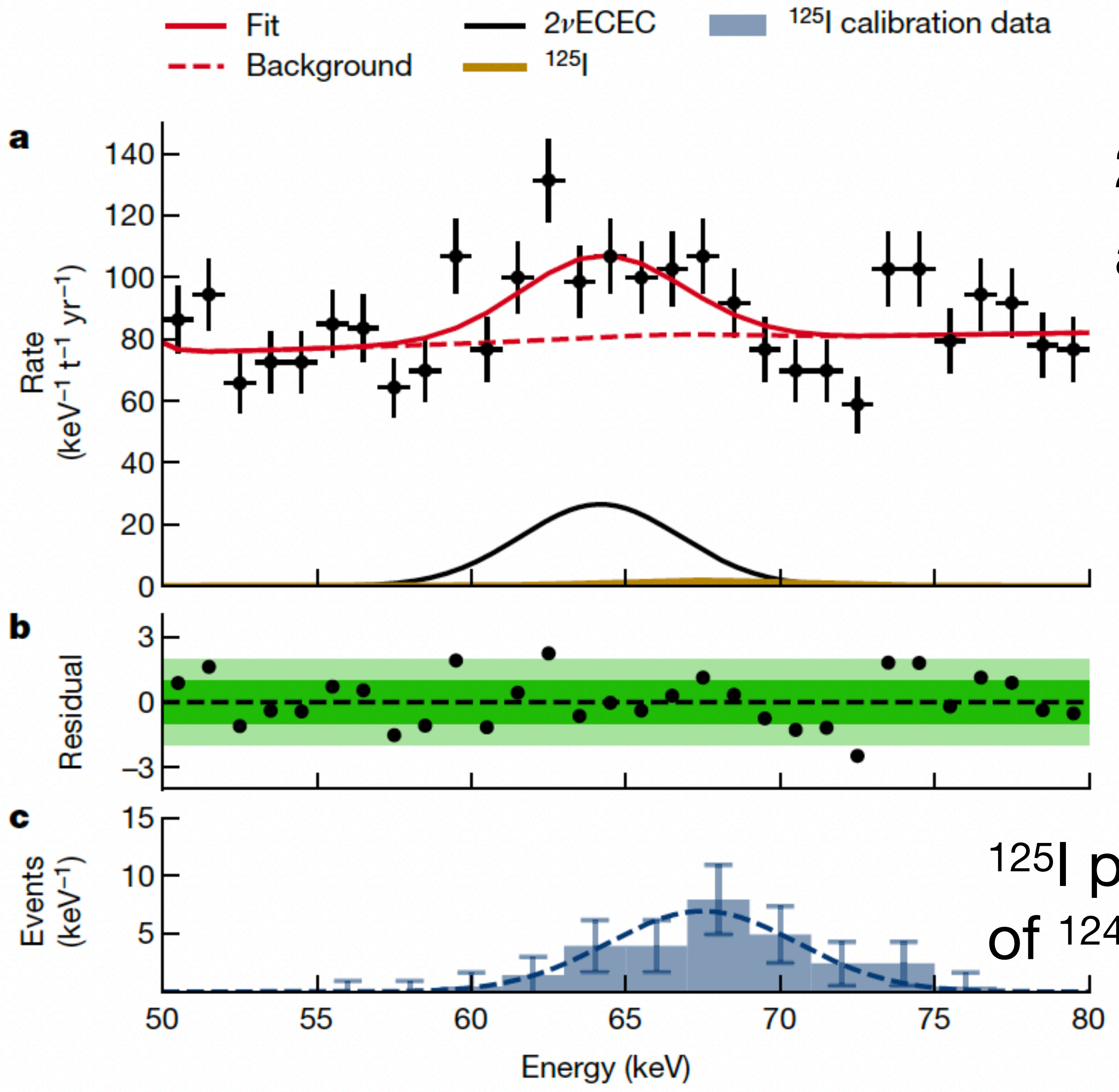


Double weak decays in xenon

- Since XENON1T work on extending energy reconstruction to the MeV region (from keV region of WIMP search)
- 2νECEC of ^{124}Xe measured directly for the first time in XENON1T

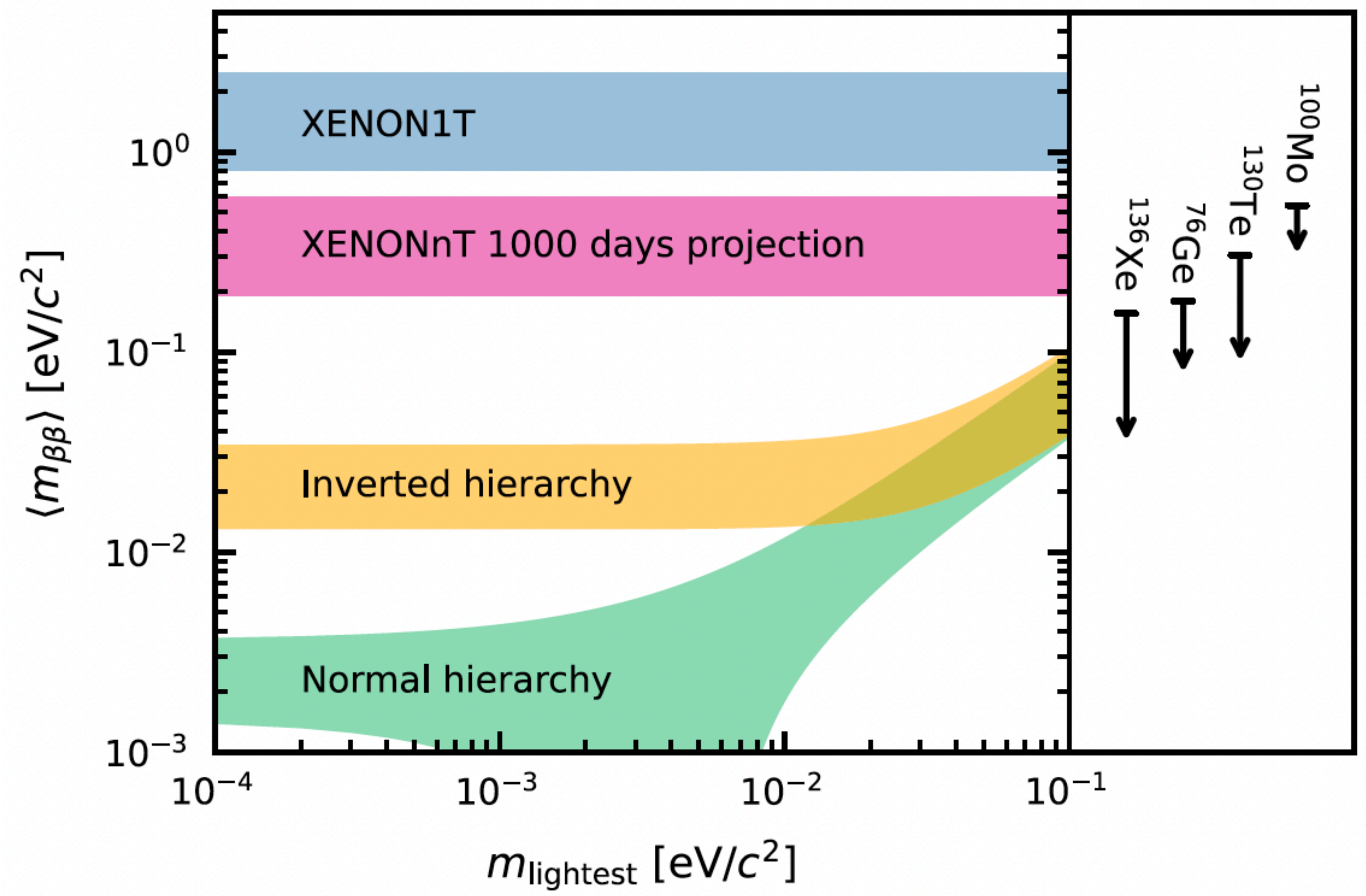
$$T_{1/2} = (1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{yr}$$

- Several other double weak decays under study:
  - 0νECEC, 2ν/0νECβ+, 2ν/0νβ+β+ of ^{124}Xe
  - 2ν/0νββ of ^{136}Xe
- 0νββ sensitivity not yet competitive with dedicated experiments but will be in next-generation experiment (XLZD)



2νECEC KK peak at 64.2 keV

^{125}I produced by activation of ^{124}Xe at 67.3 keV

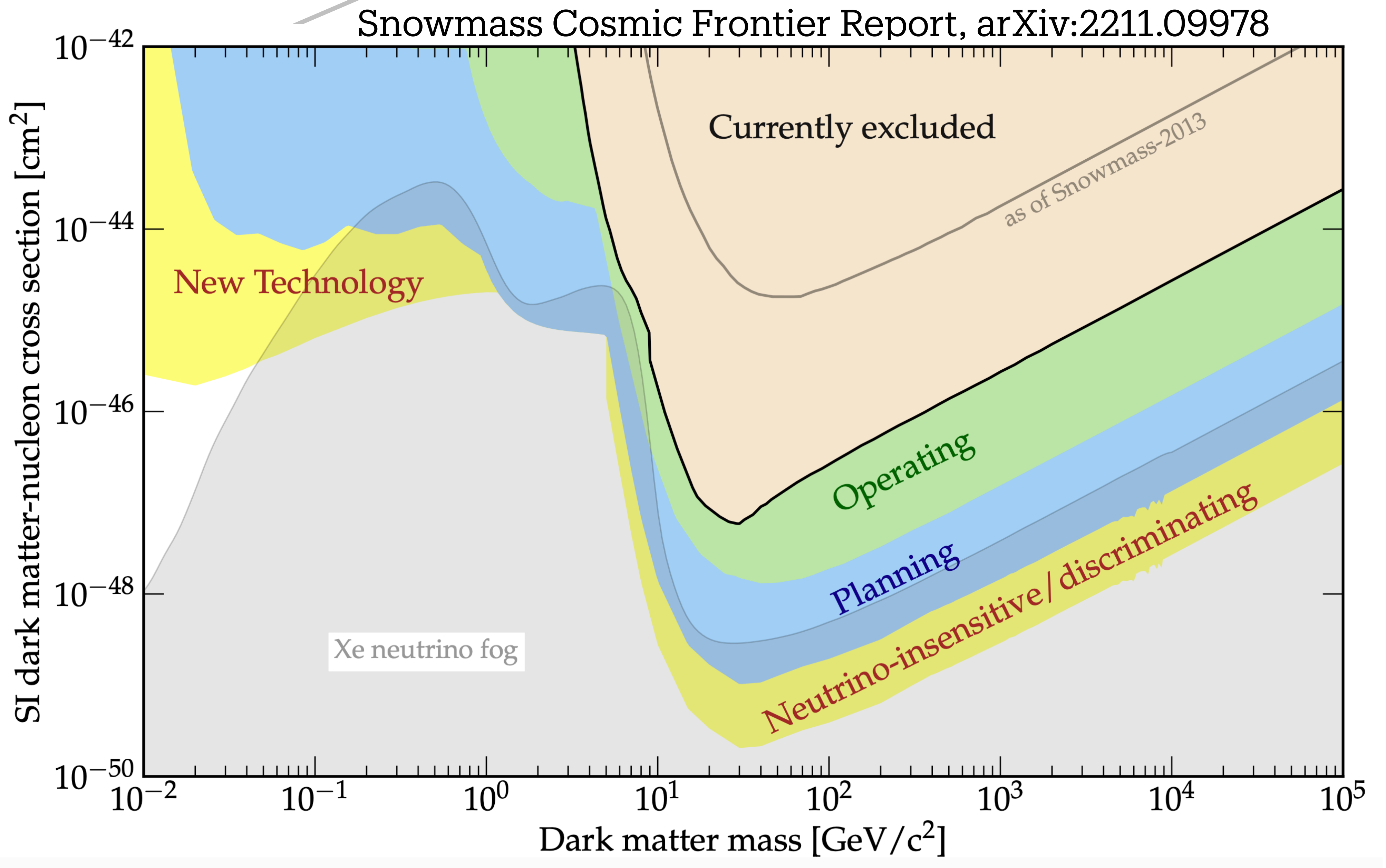


Nature 568 (2019) 7753, 532-535
Eur.Phys.J.C 80 (2020) 8, 785
Phys.Rev.C 106 (2022) 2, 024328

DARWIN and XLZD

- DARWIN collaboration:
  - R&D on next generation dual-phase TPC
  - ~200 members from 35 institutions around the World

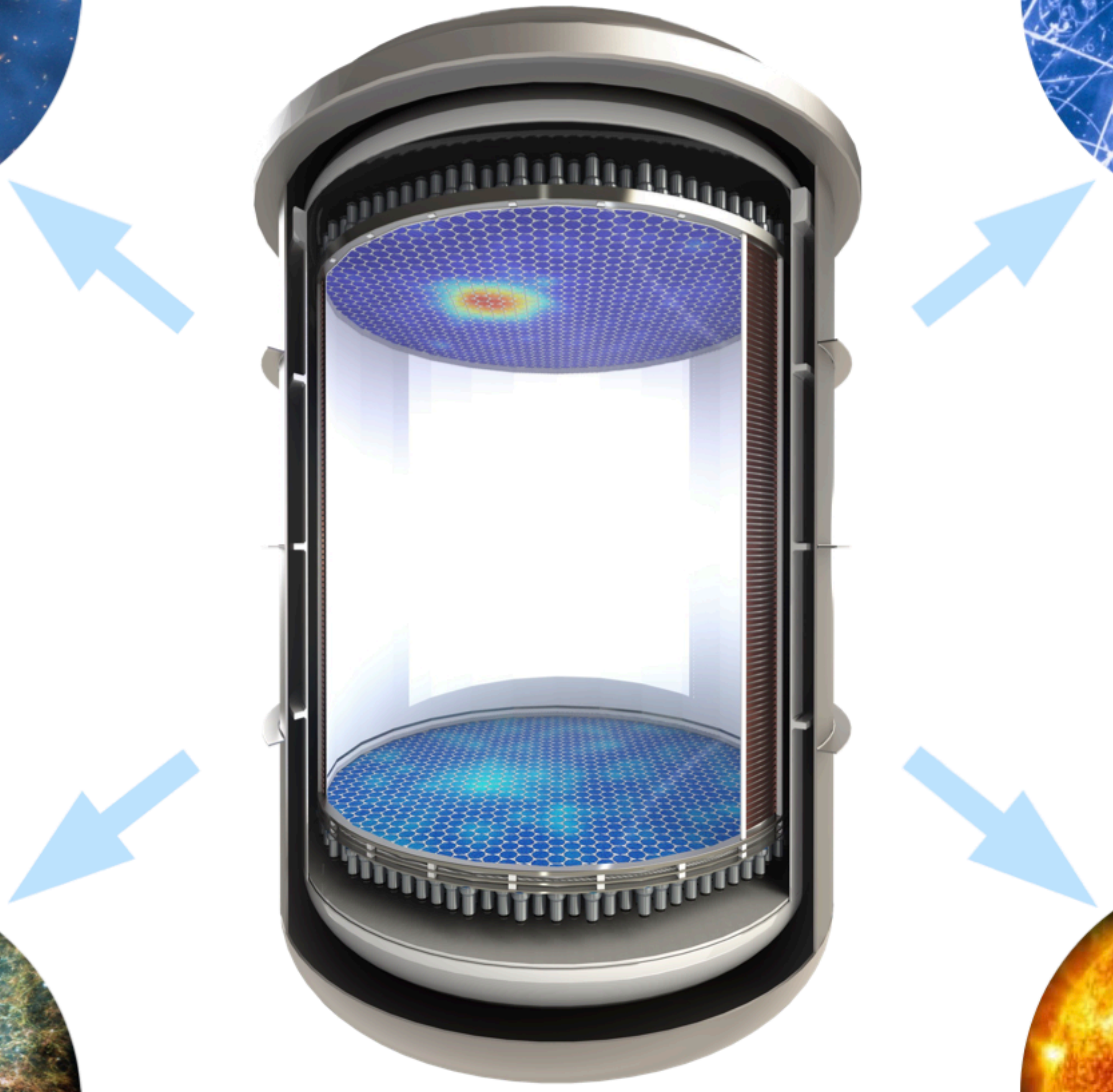
- XLZD: XENON-LZ-DARWIN
  - WIMP search down to the neutrino fog
  - Merging the collaborations to strengthen knowledge and resources



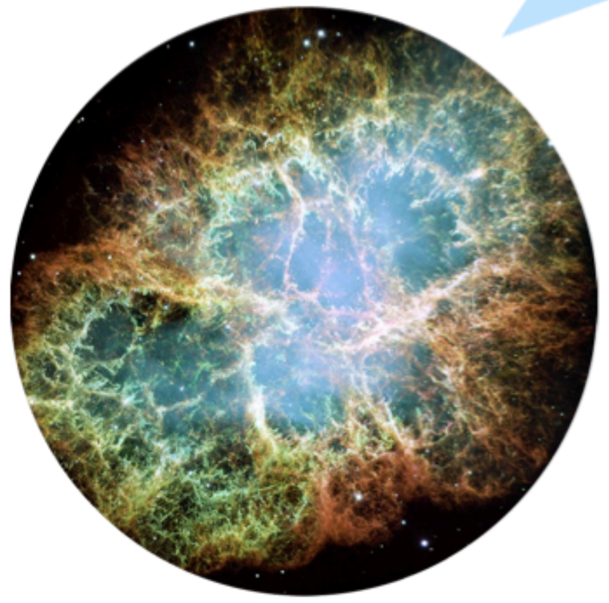
Science channels

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture



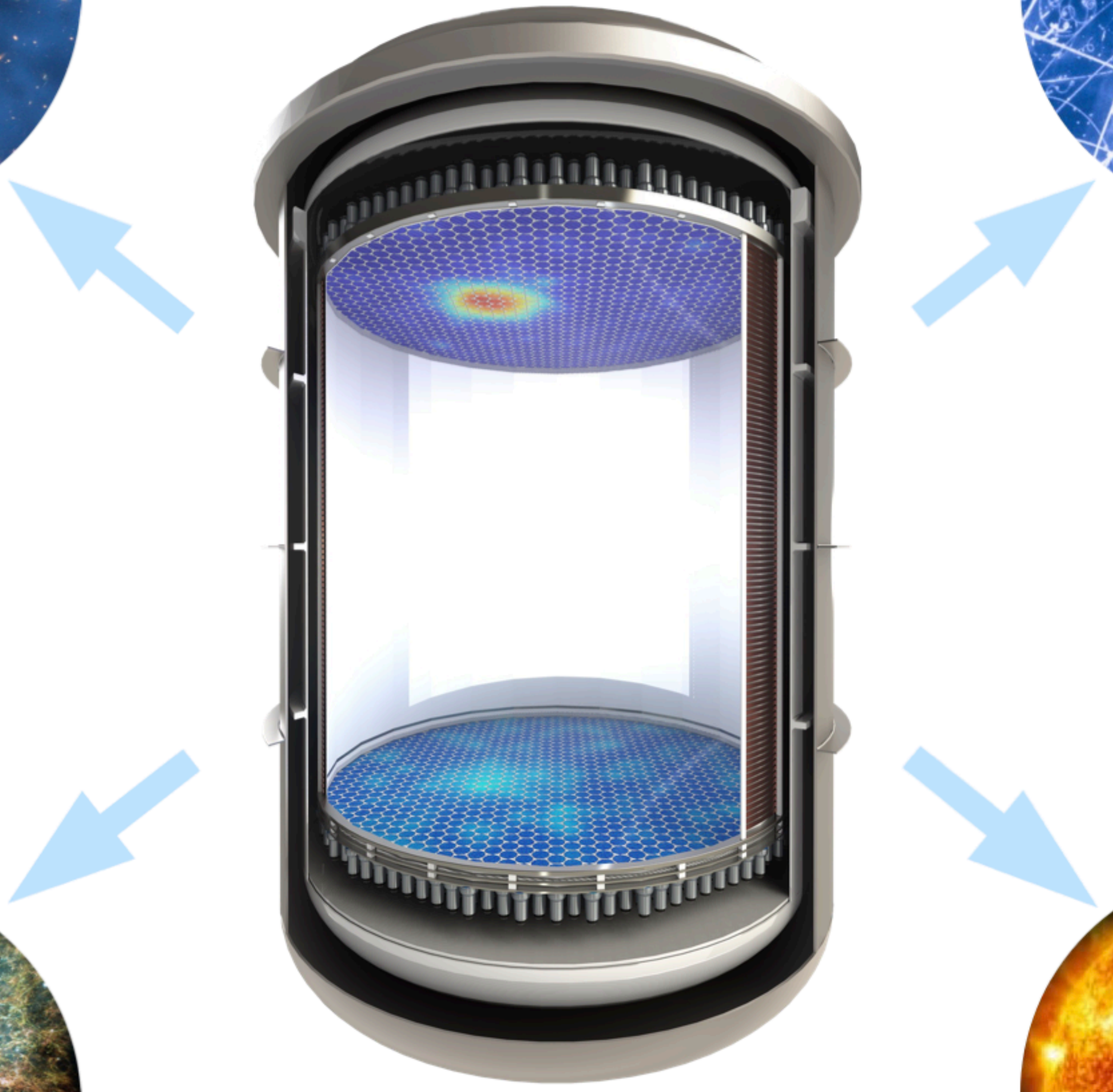
Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics



Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

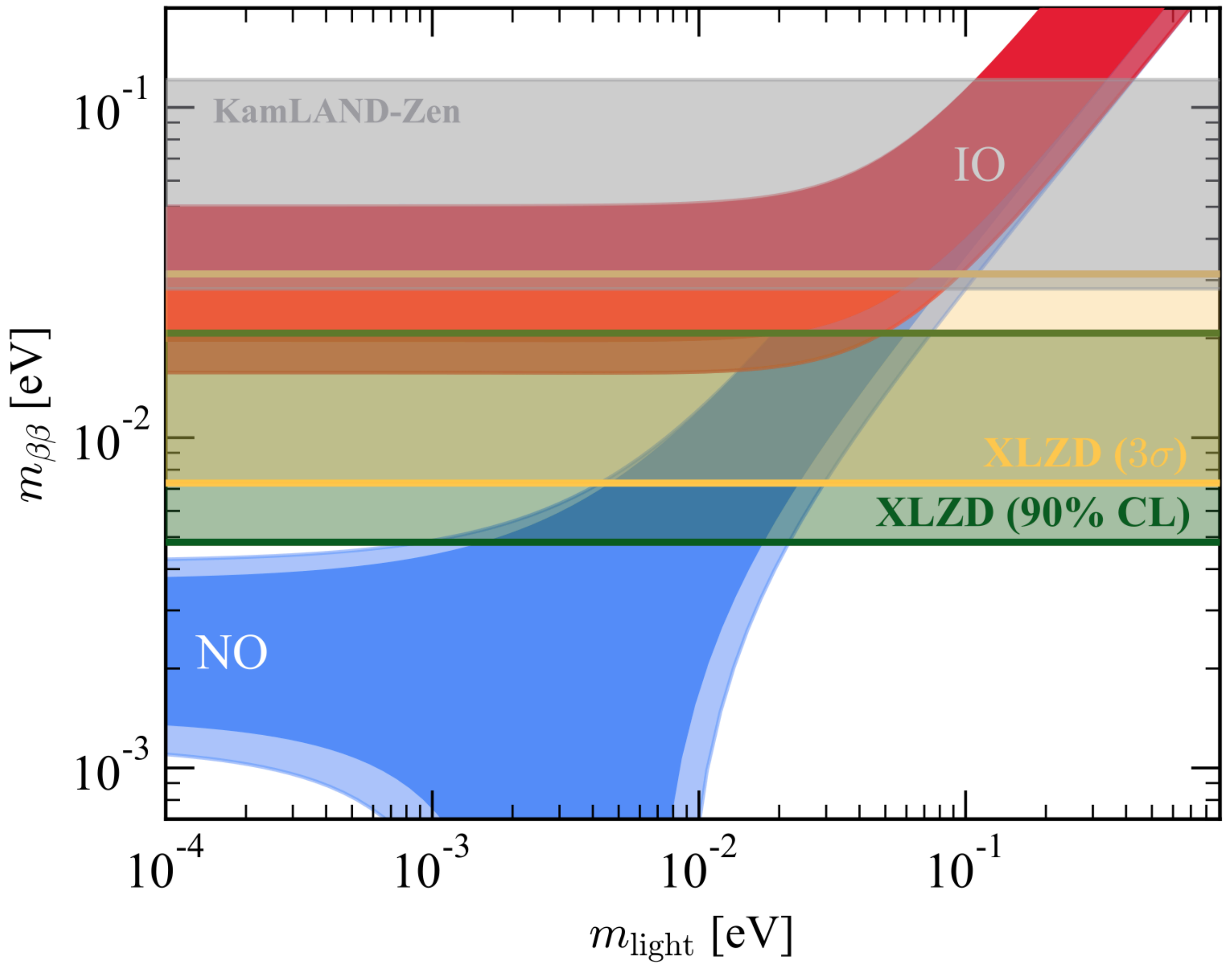
Science channels

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons



Neutrino nature

arXiv: 2410.19016



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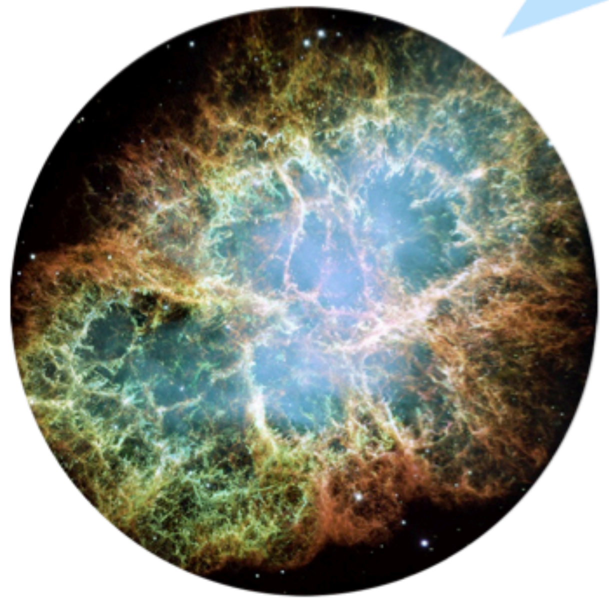
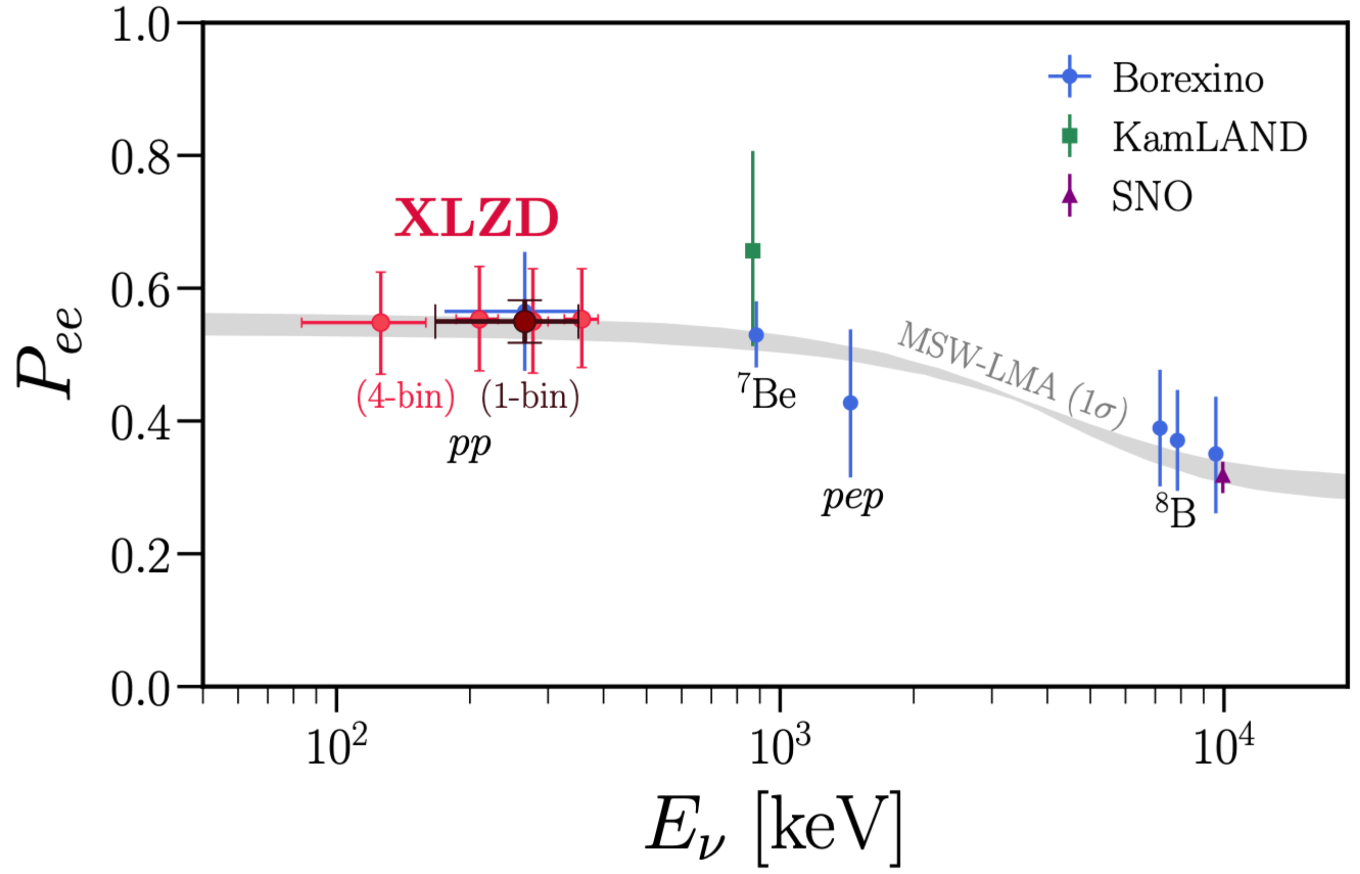


Sun

arXiv: 2410.17137



WIMPs

- Search for medium to high WIMP masses
- Conservative scenario for ~200 tonnes × year exposure:
  - 90% exclusion sensitivity for SI cross section dow to 2×10^{-49} cm^2 at 40 GeV mass
  - 3σ discovery at SI cross section 7×10^{-49} cm^2 at 40 GeV mass
- Reach the limit of the neutrino fog with ~1000 tonnes × year exposure
  - 3σ discovery at SI cross section 3×10^{-49} cm^2 at 40 GeV mass

Figure by C. O'Hare

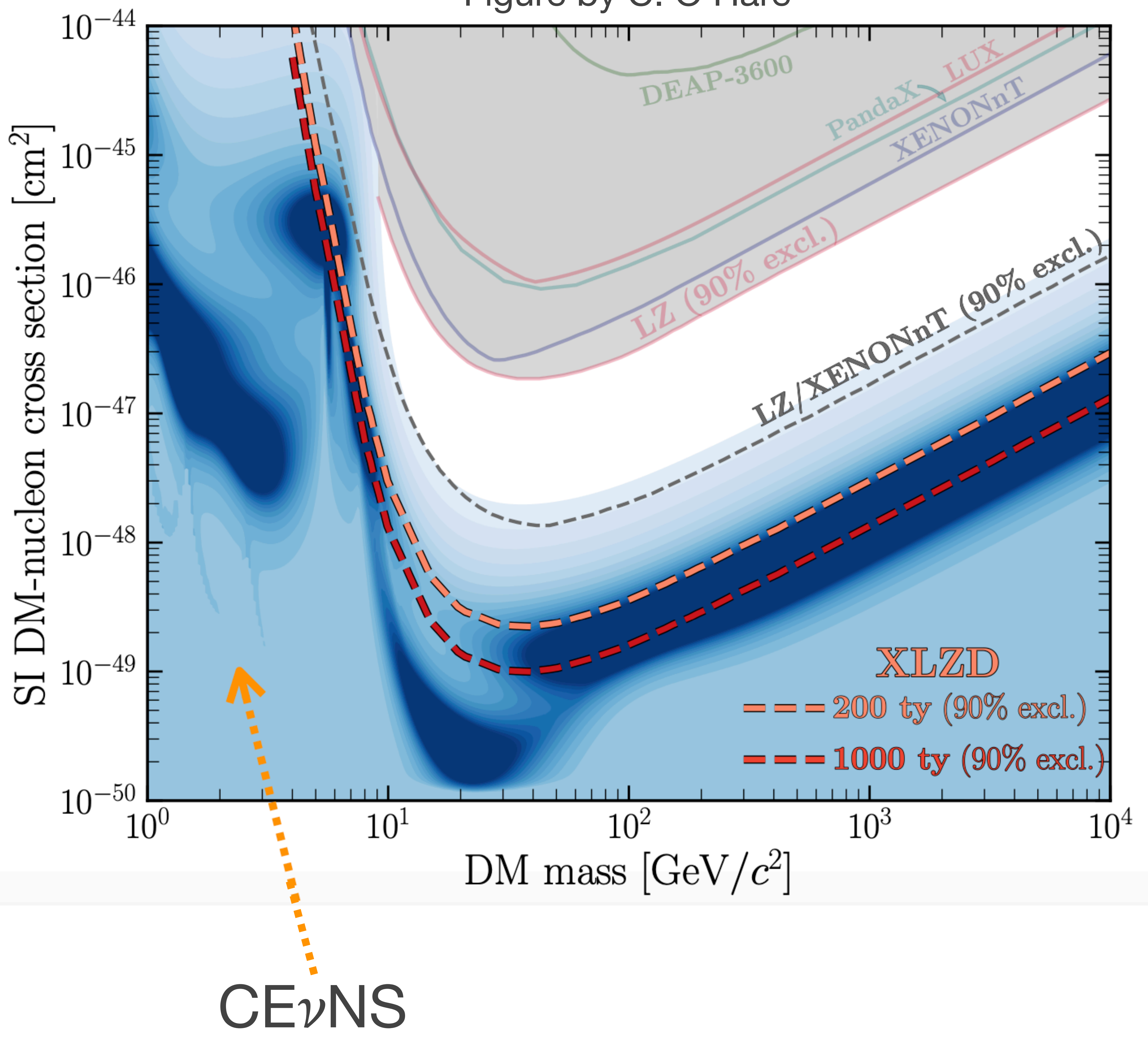


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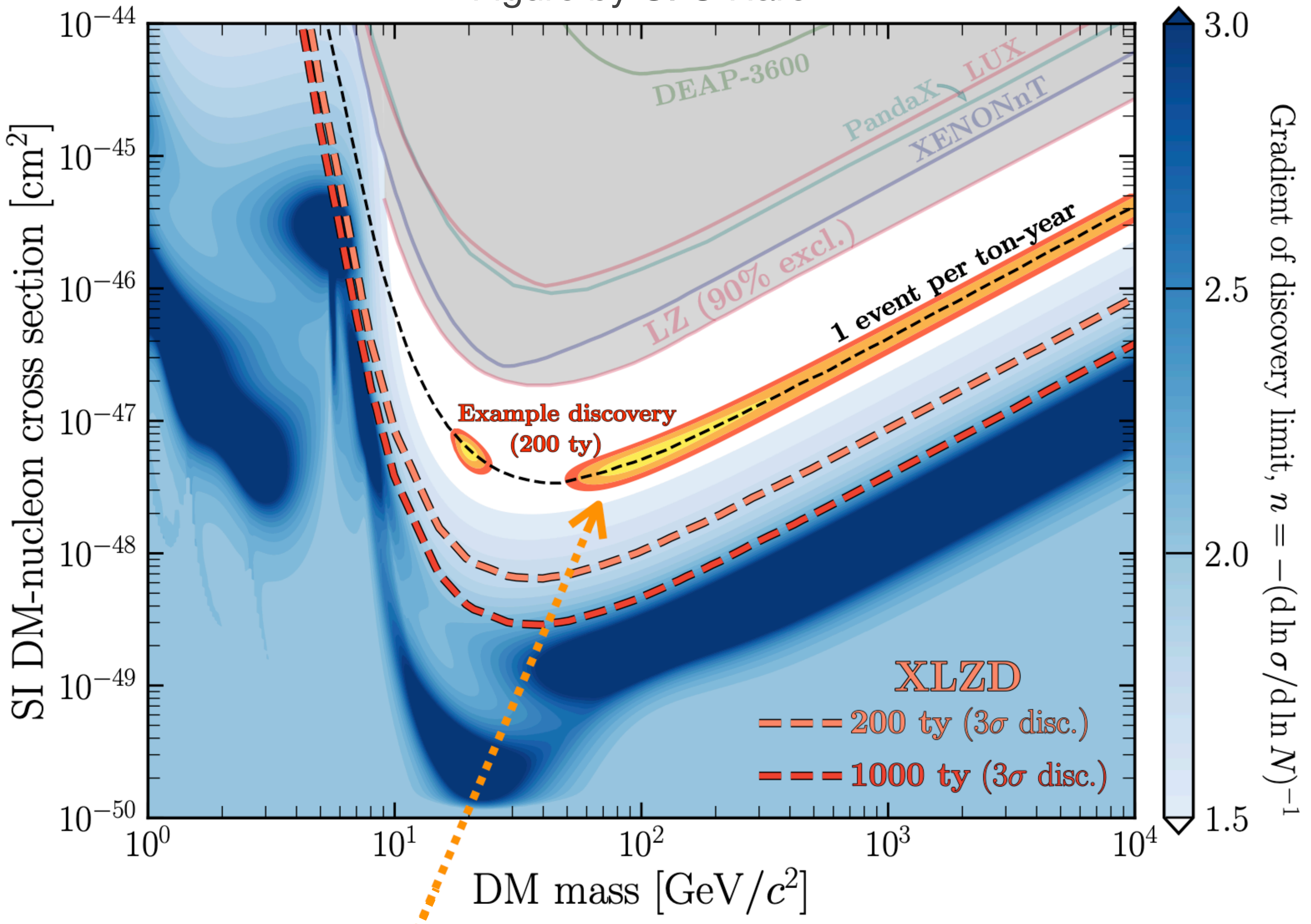
Figure by C. O'Hare

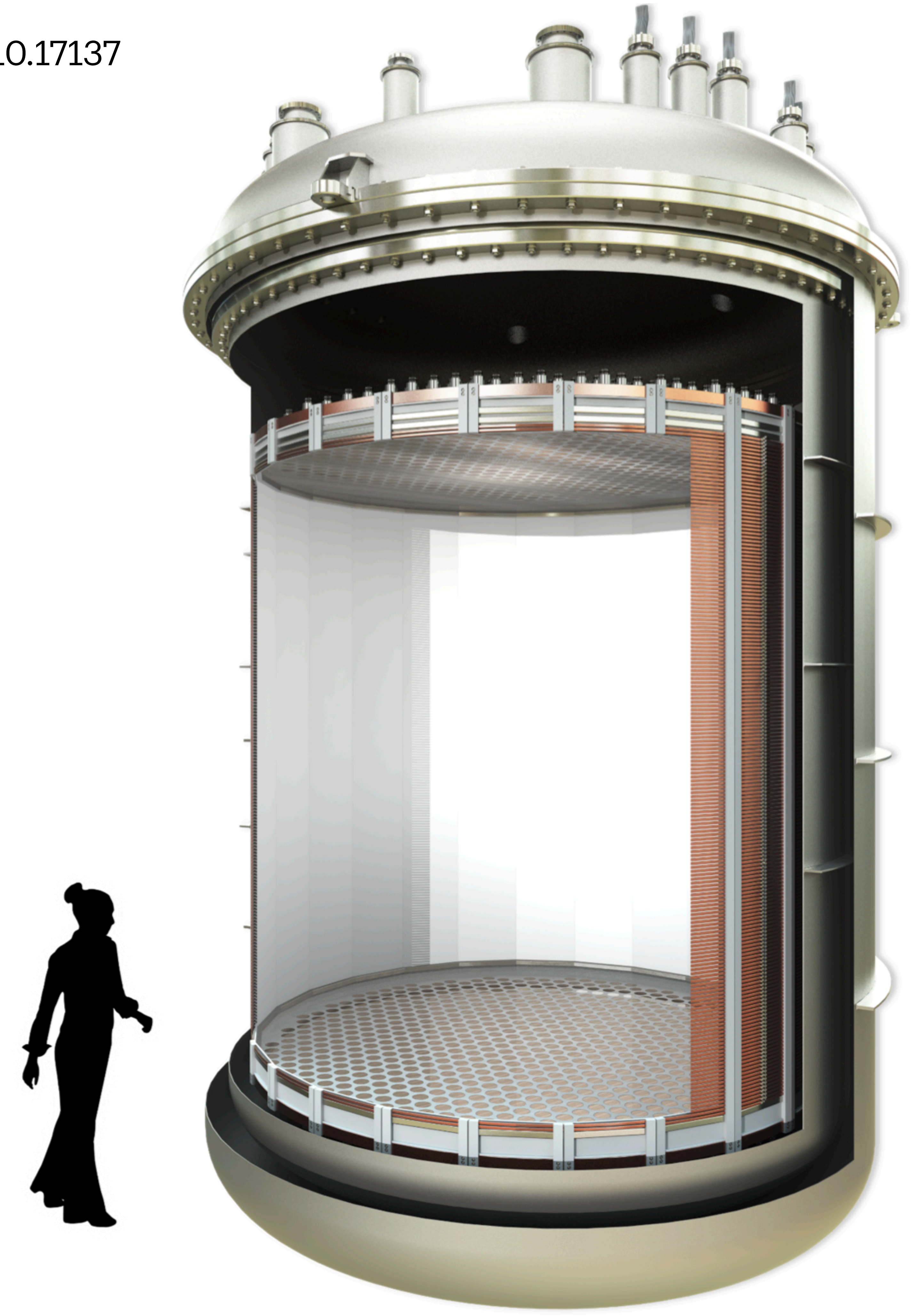


1,2,3 σ confidence intervals

XLZD detector baseline

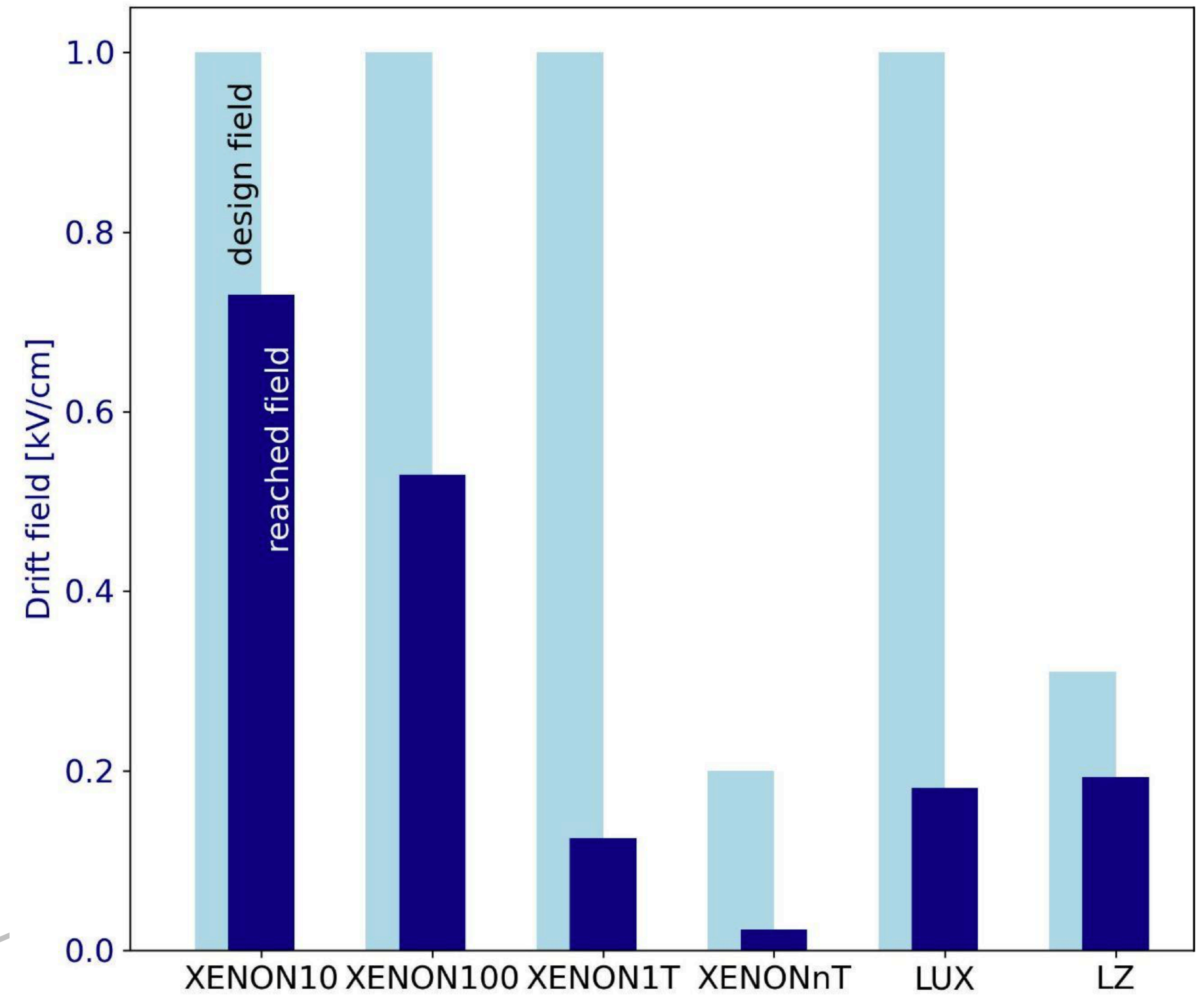
- ~3 m diameter x ~3 m height
- 78 t/60 t LXe mass/active target → could be increased to 80 t active mass
- Two arrays of photosensors → baseline design with ~2400 3” PMTs
- Double-walled low-background Ti cryostat + LXe “skin” around the TPC
- Drift field of 240-290 V/cm and extraction field of 6-8 kV/cm for optimal discrimination between ER and NR
- Passive and active muon and neutron shielding with gadolinium to enhance neutron capture cross-section
- Possible locations: LNGS, Boulby, SURF

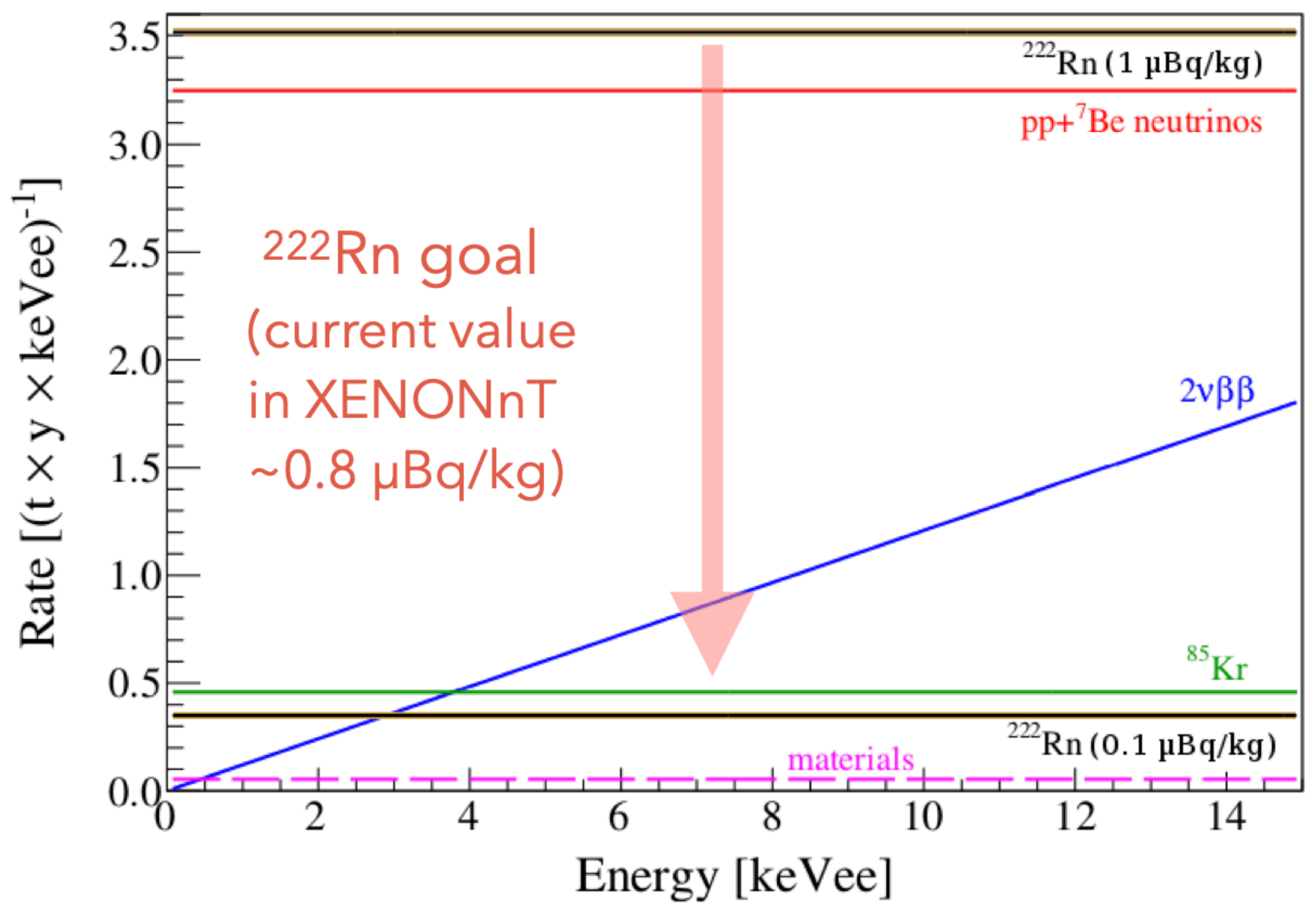
arXiv: 2410.17137



Challenges

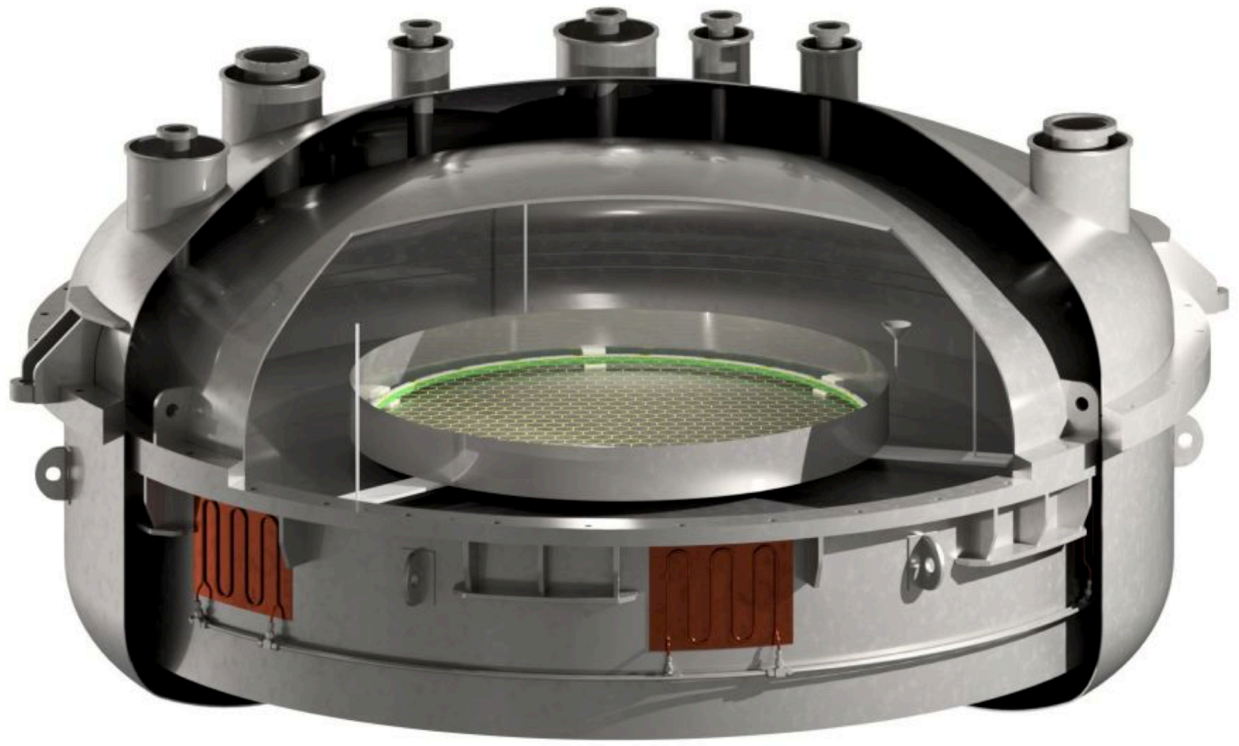
- High-voltage delivery:
  - Currently drift of ~23 V/cm in XENONnT and ~193 V/cm in LZ
  - Electrodes design and construction
  - Electric field homogeneity
- Liquid xenon purity
- Background mitigation
- Light collection efficiency
- Photosensors performance

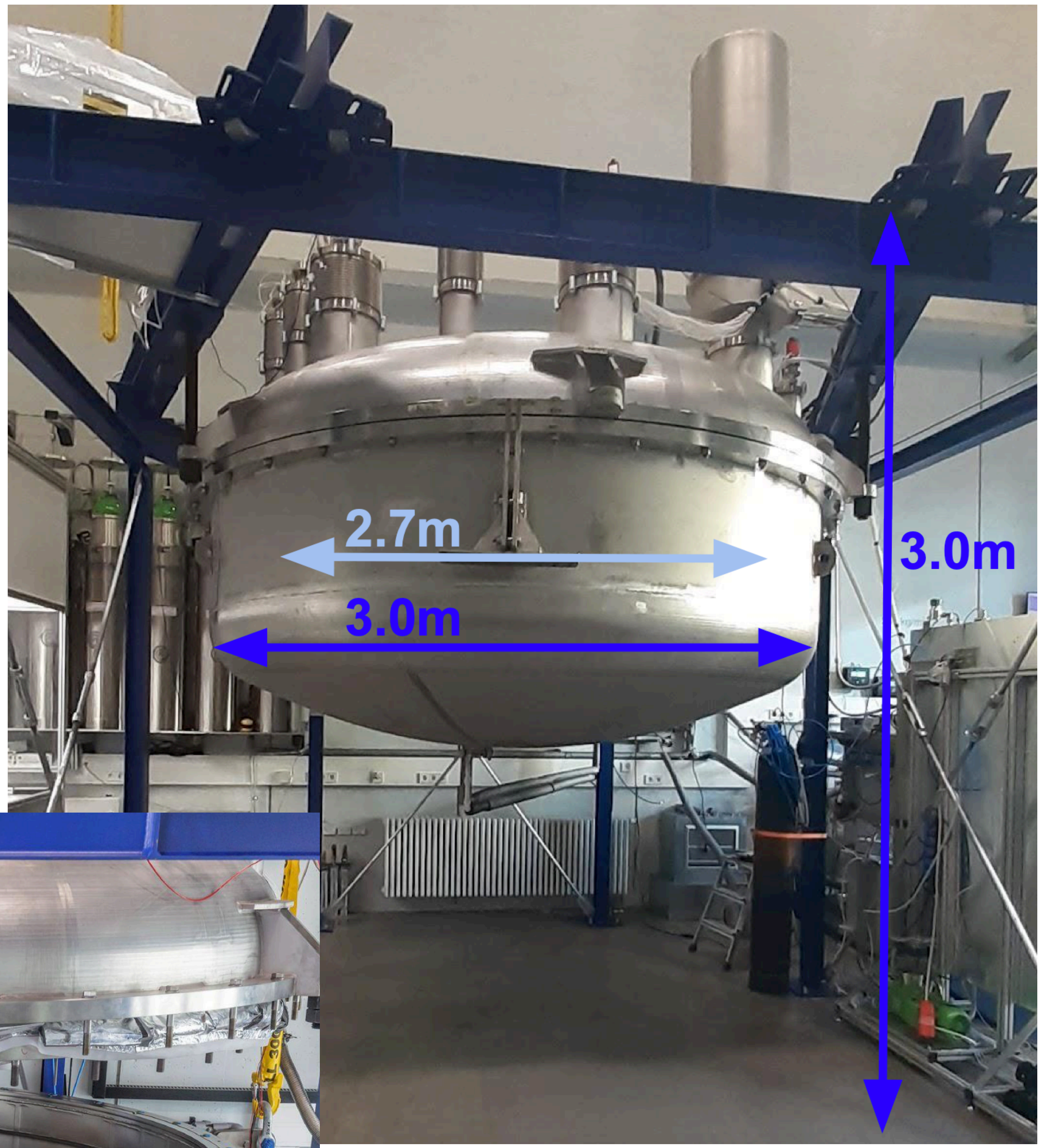




Pancake at Uni Freiburg

- Testing of grids:
  - Wire sagging
  - Hotspots / electron emission
  - Large scale cooling
- 5t stainless steel cryostat with 380 kg of xenon
- Flat floor design and possibility of using open top vessel
- Successful 3 months commissioning
- Next step: instrumentation with photosensors, test of electrodes and HV





JINST 19 (2024) P05018

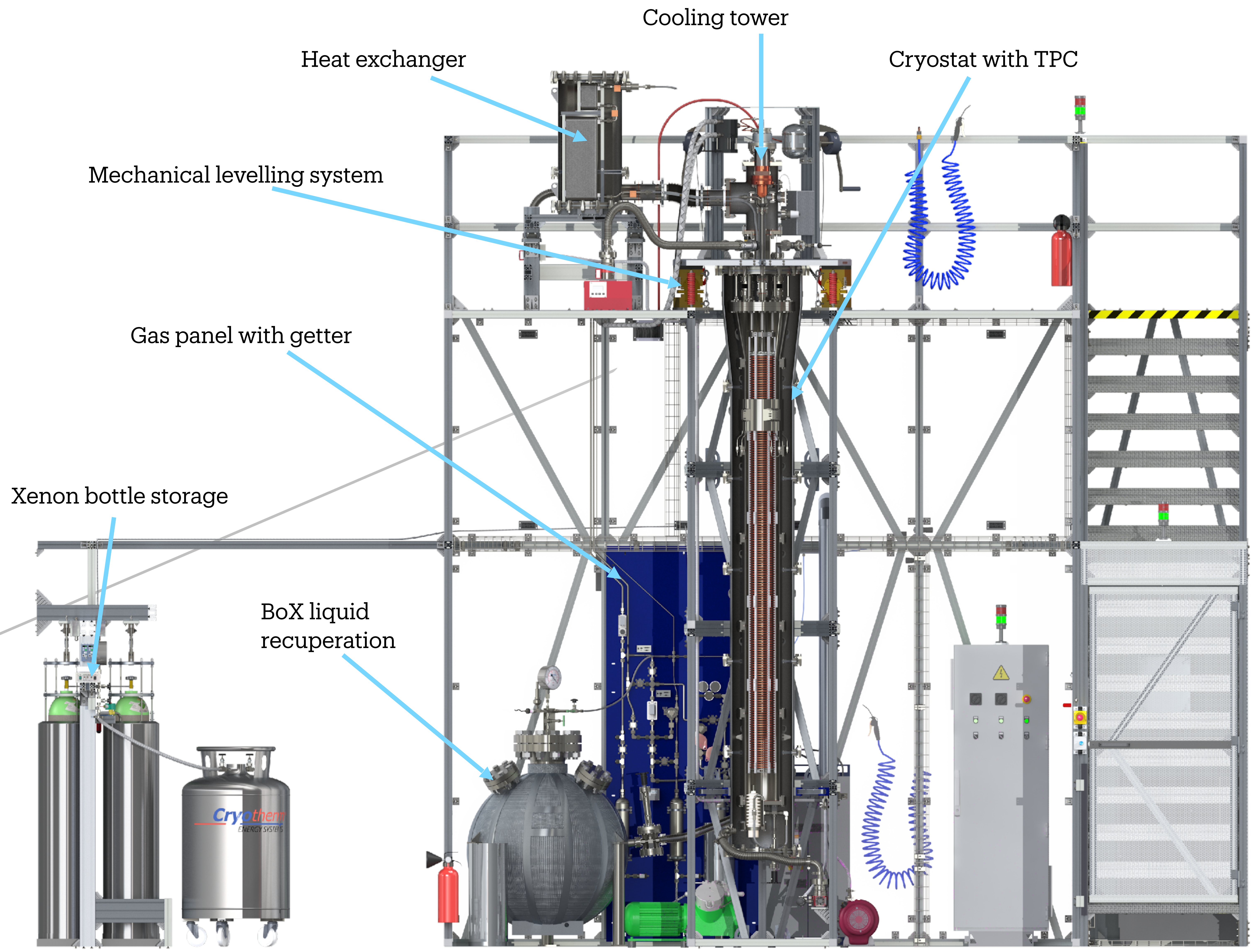
Xenoscope at UZH

- Vertical demonstrator with goals:
  - Electron drift over 2.6 m
  - Electron cloud diffusion
  - Custom HV
  - Xenon optical properties
- ~400 kg of xenon mass
- Phase 1: purity monitor → completed
- Phase 2: modular TPC → just commissioned

JINST 16, P08052 (2021)

Eur. Phys. J. C 83, 717 (2023)

arXiv: 2411.08022



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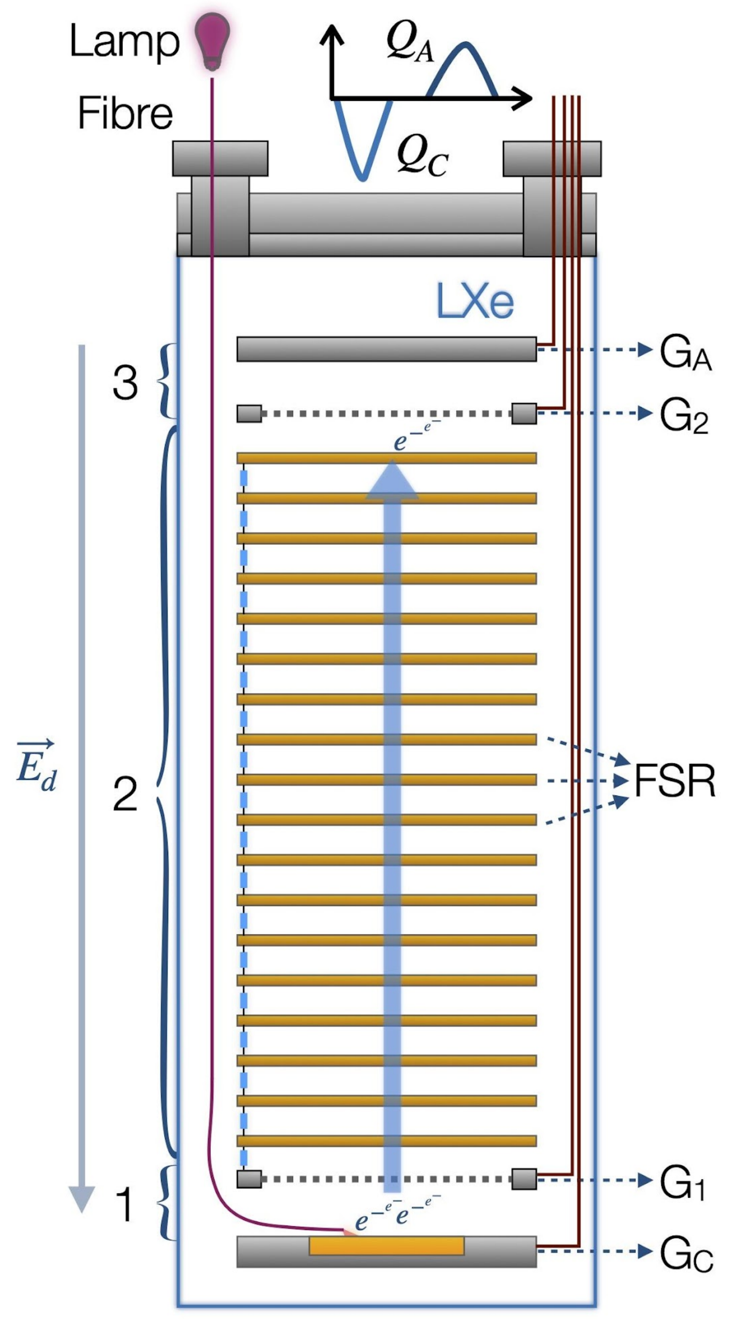
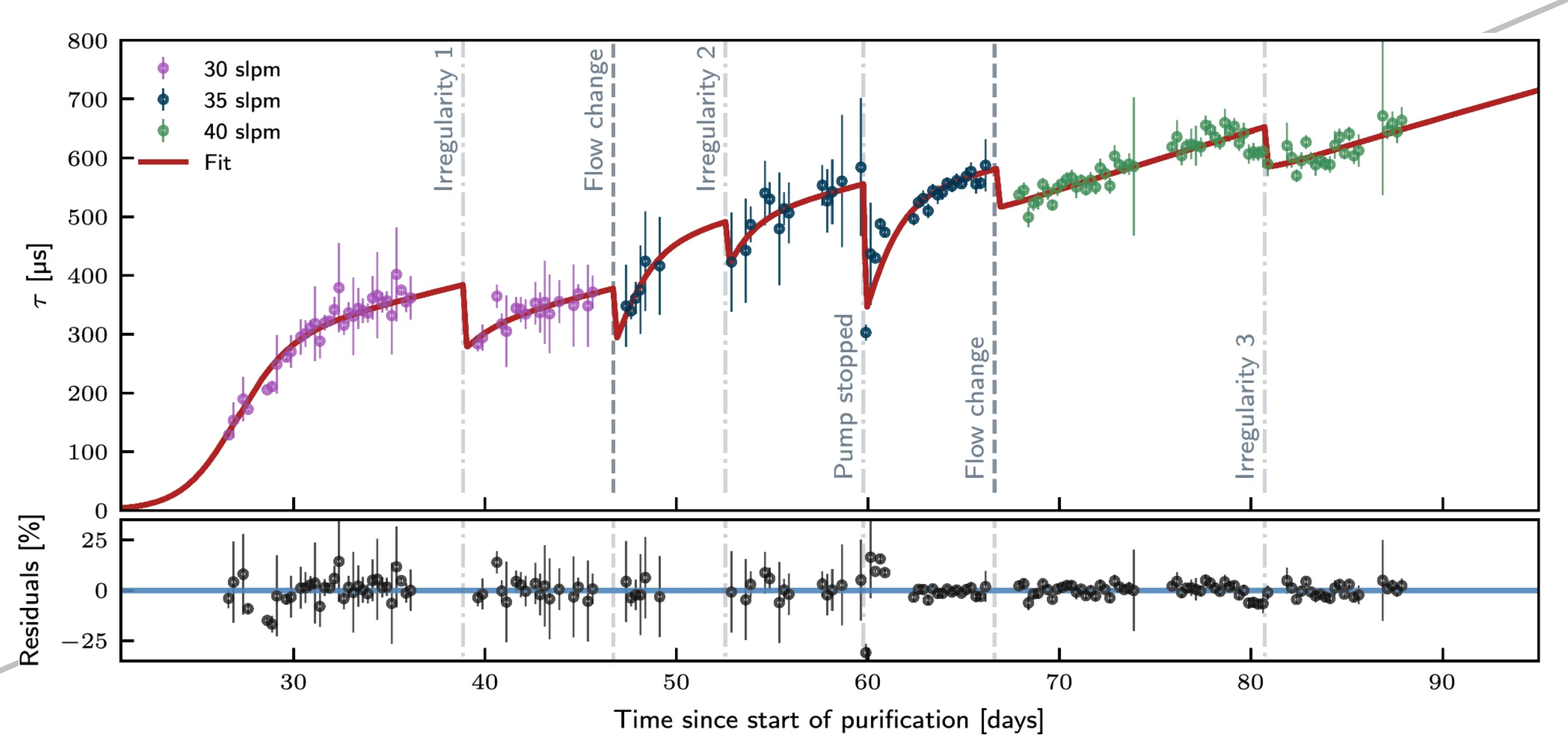
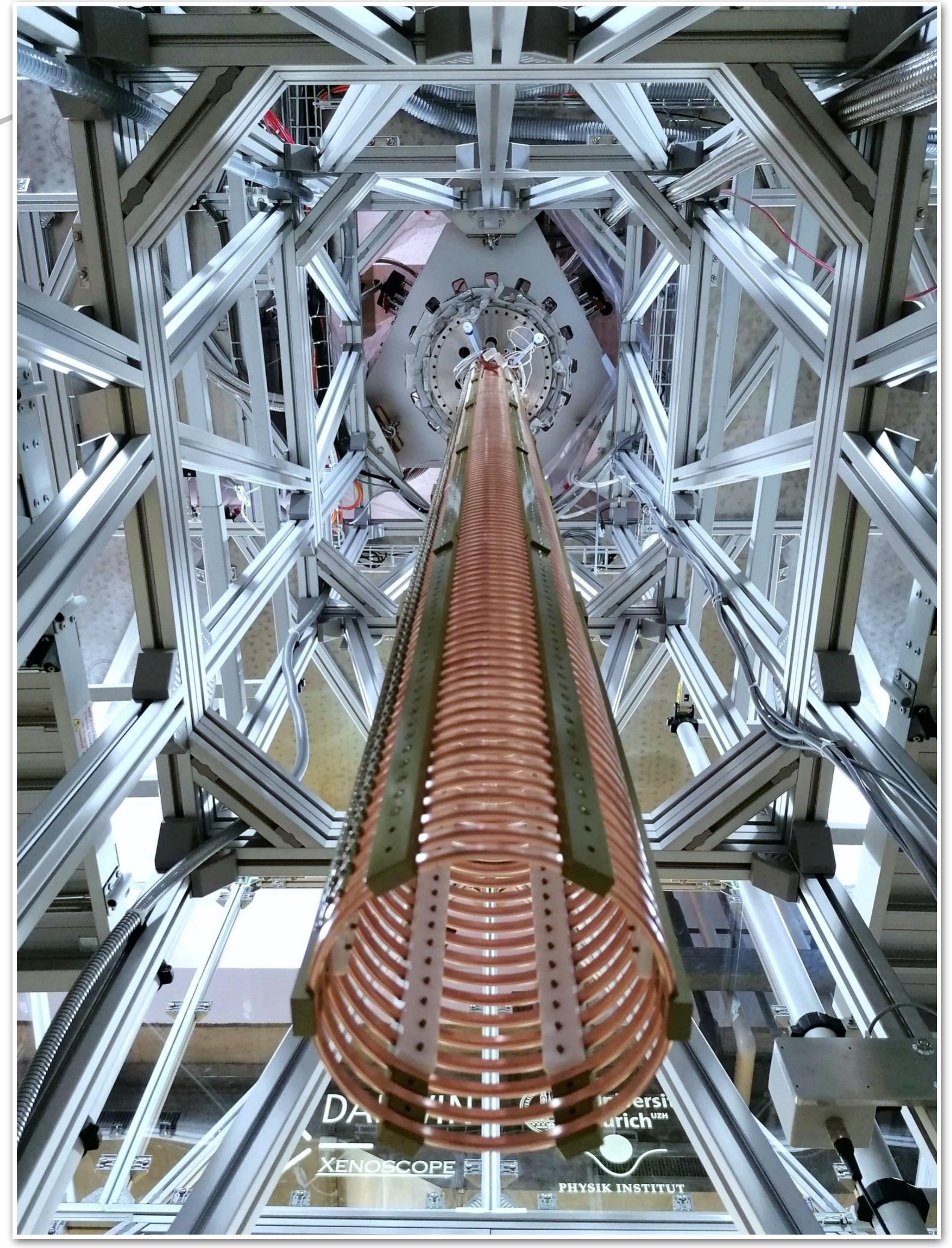


- Purity monitor:
  - Drift length: 53.1 cm
  - Light from xenon flash lamp (190 - 200 nm) injected via optical fiber into photocathode
  - Flow limited to 40 slpm → ongoing improvement of the gas system to reach higher circulations
  - Electron lifetime monitor (+ drift velocity and diffusion)

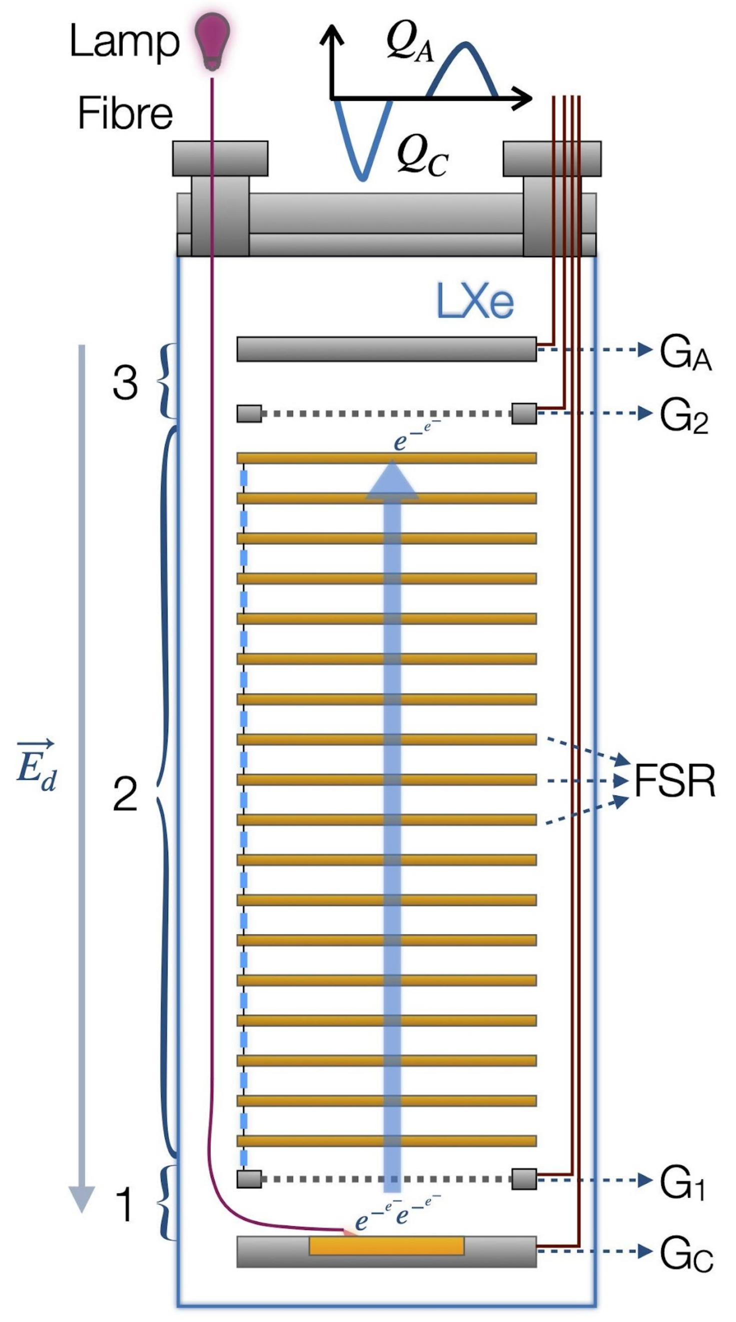
JINST 16, P08052 (2021)
Eur. Phys. J. C 83, 717 (2023)
arXiv: 2411.08022

- Dual-phase TPC:
  - 173 shaping rings - 16 cm diameter
  - Top SiPM array
  - HV up to 50 kV
  - Levelling system with levelmeters and weir





Xenoscope at UZH



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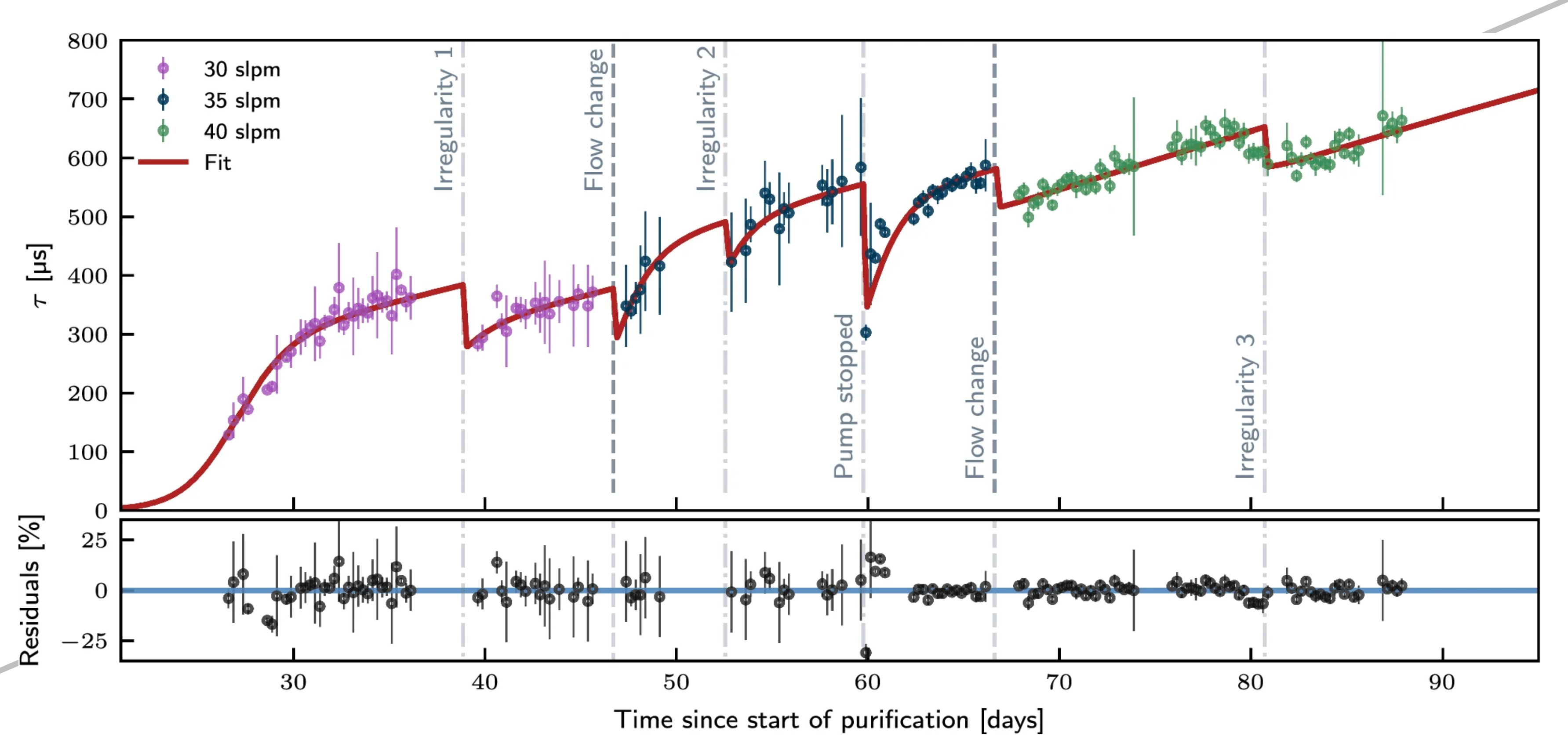
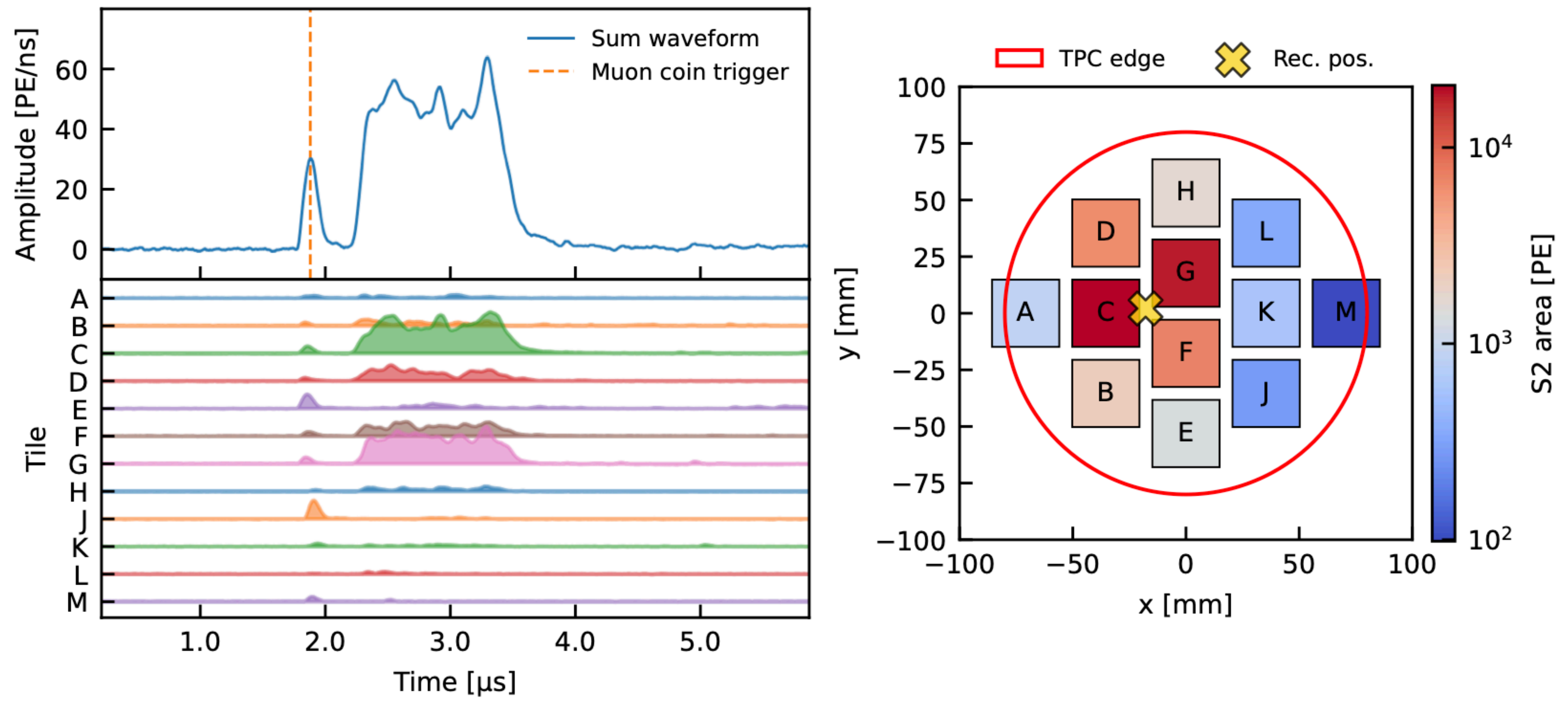


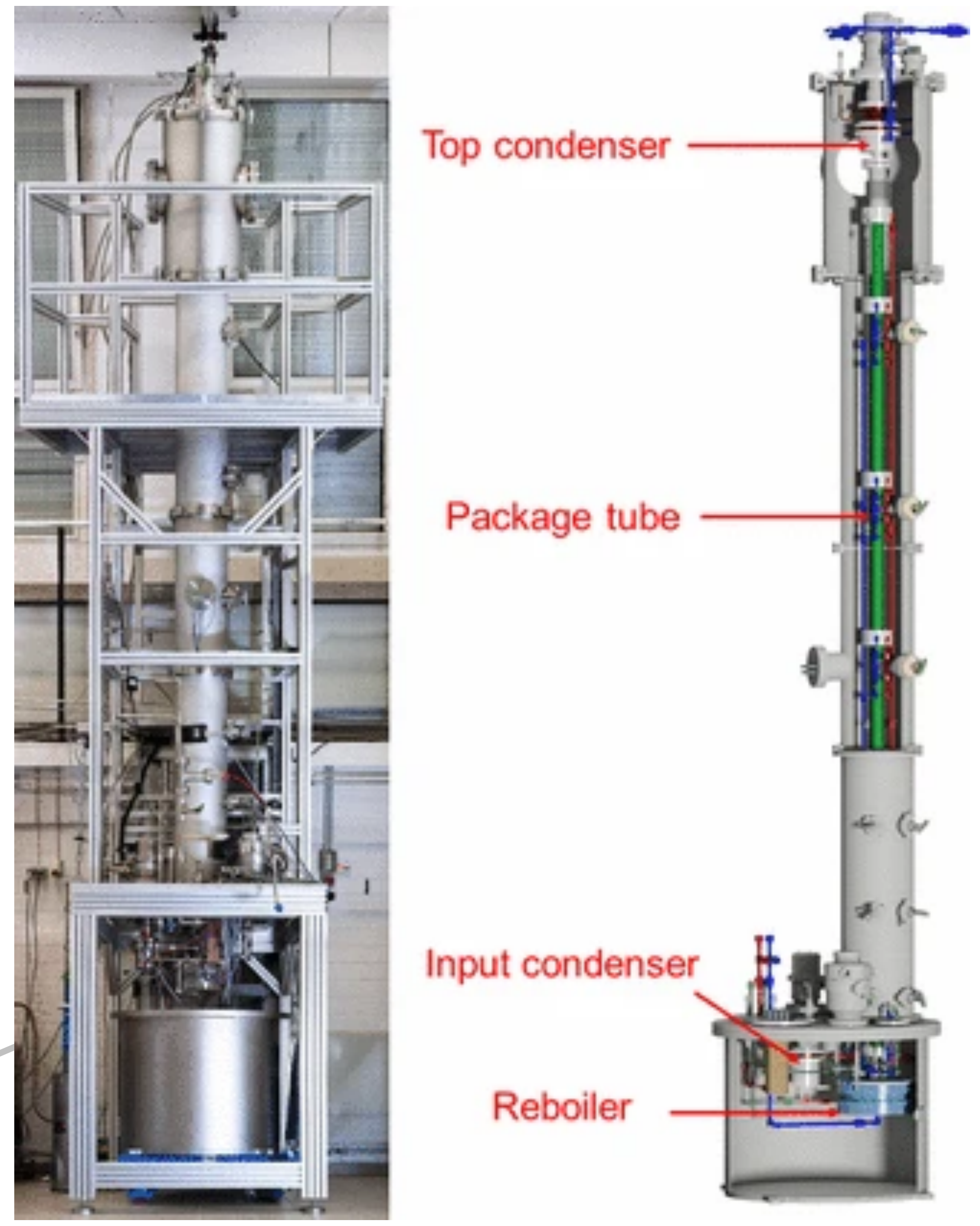
S1-S2 signals in dual-phase TPC mode!



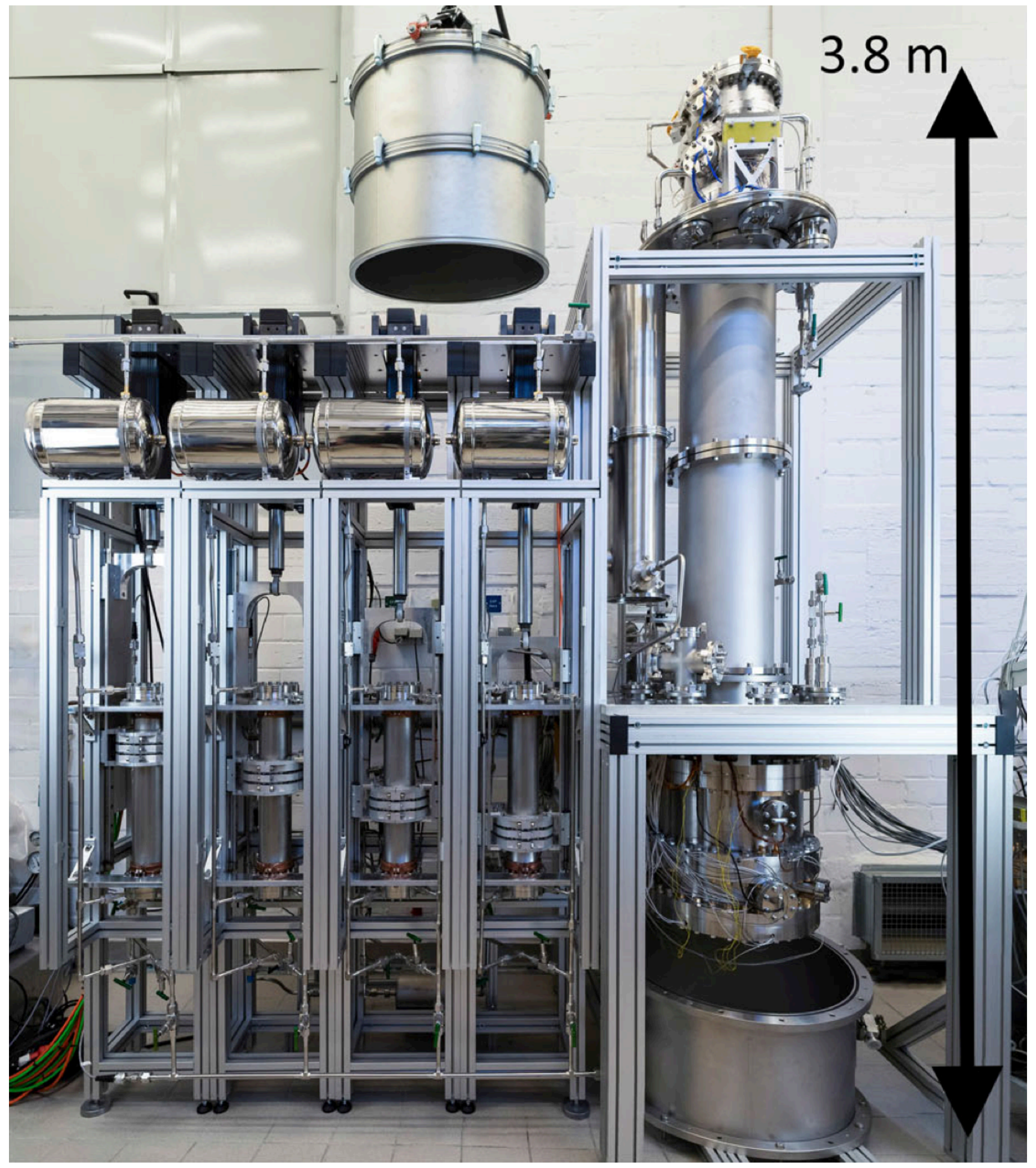
Background mitigation

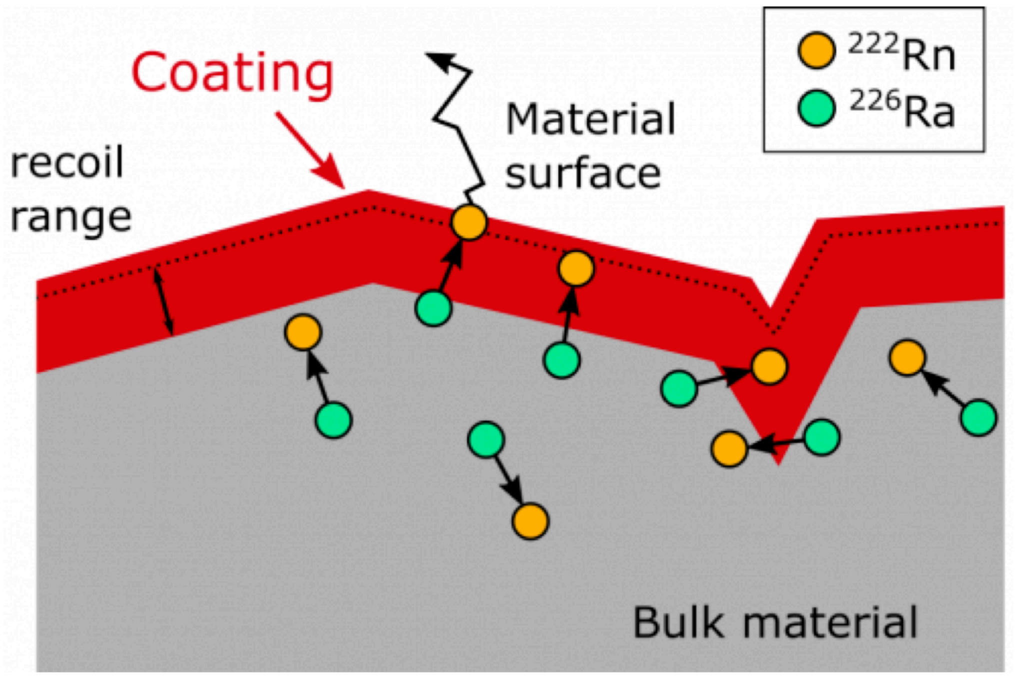
- ^{85}Kr distillation → goal of 0.1 ppt ^{nat}Kr already achieved <0.026 ppt
- ^{222}Rn distillation column → goal of 0.1 μBq/kg (achieved 0.8 μBq/kg) below ER from solar pp neutrinos
- Coating techniques against radon emanation (electrochemical deposition of Cu)
- Fast recirculation in liquid to reduce impurities, with radon-free filters and pumps
- Radio-pure materials with low Rn-emanation
- Software radon-background reduction techniques

Eur. Phys. J. C (2017) 77:275



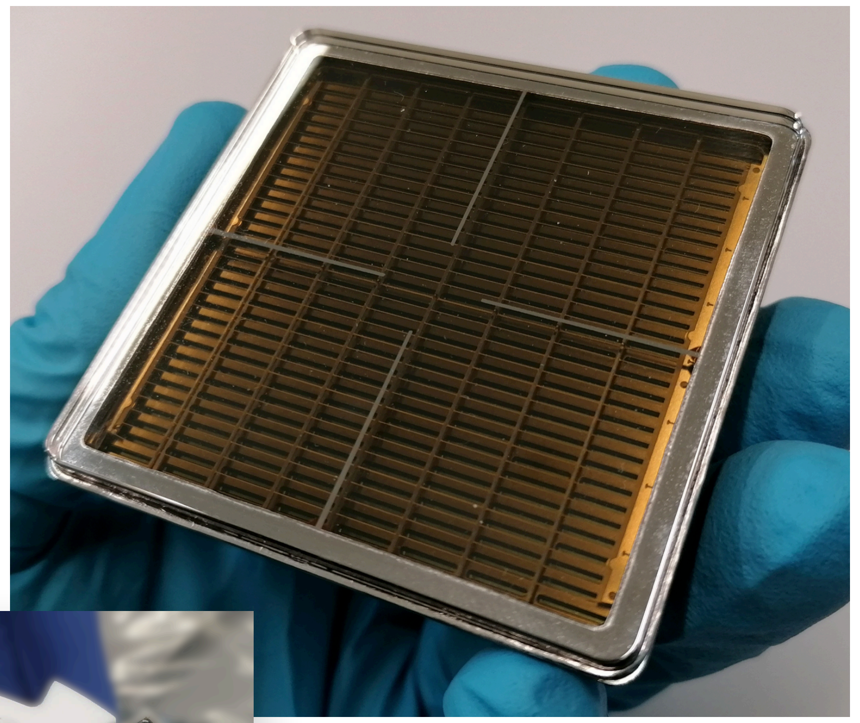
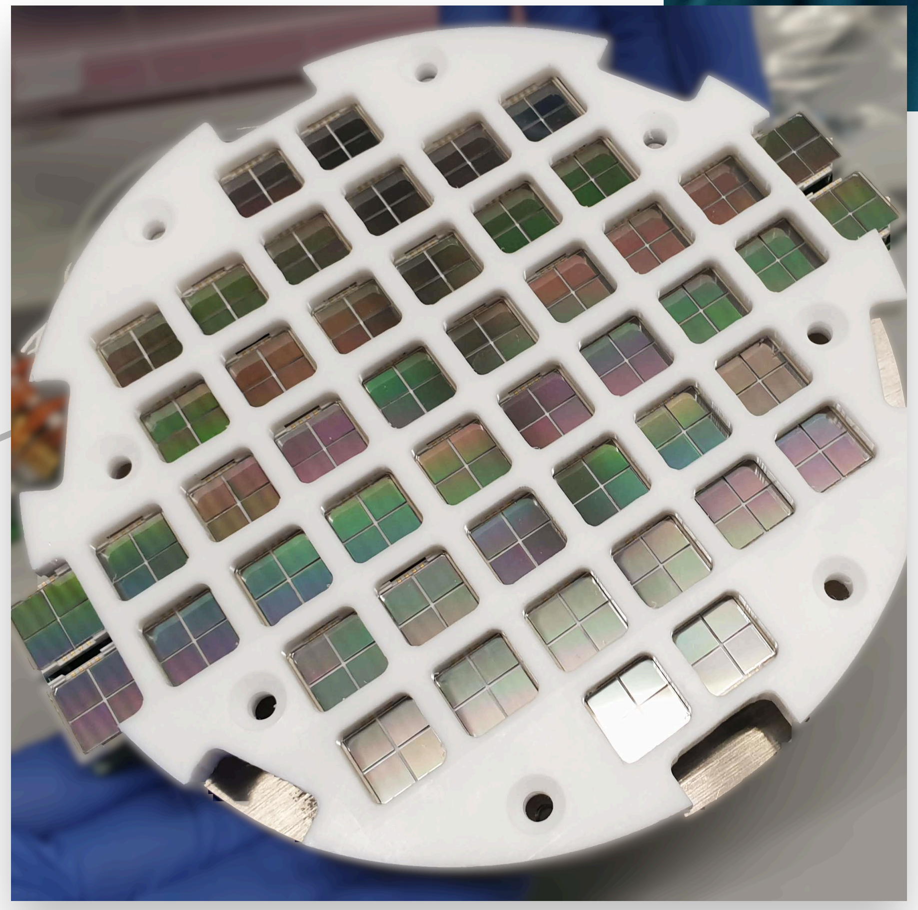
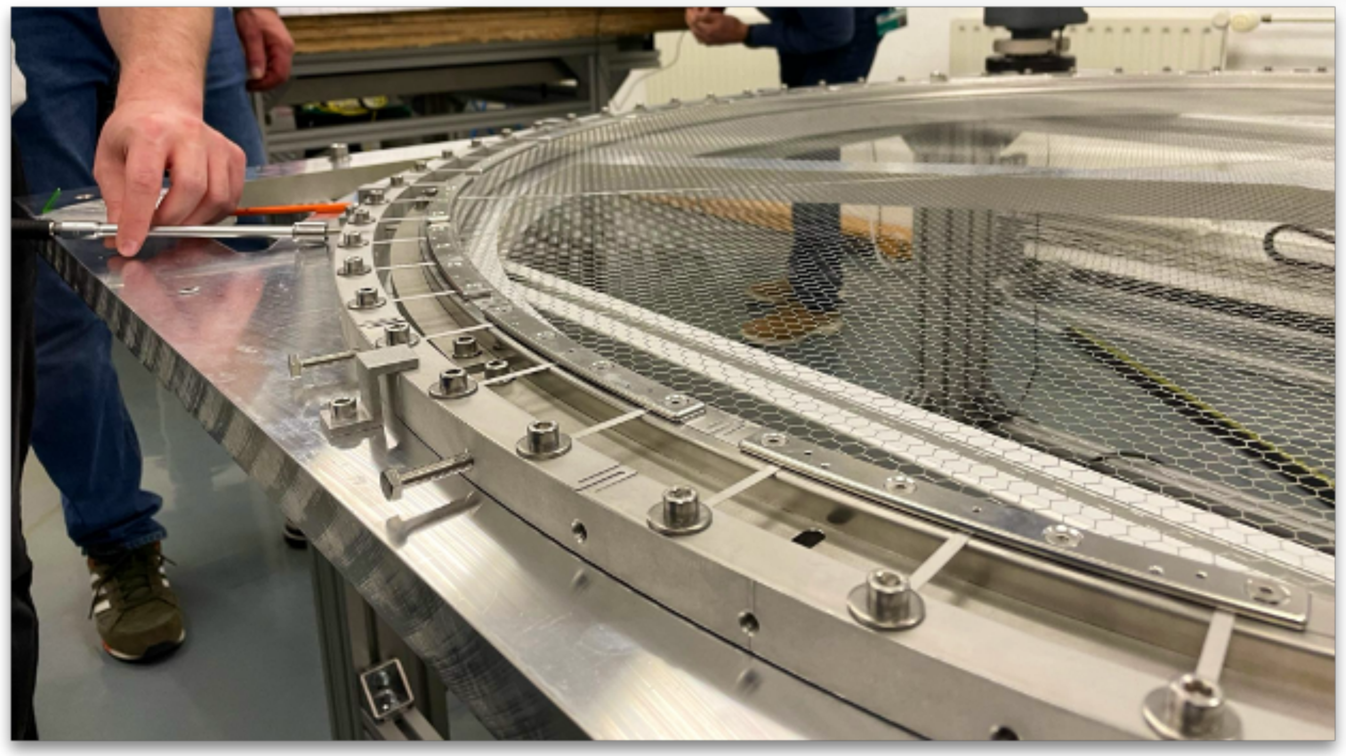
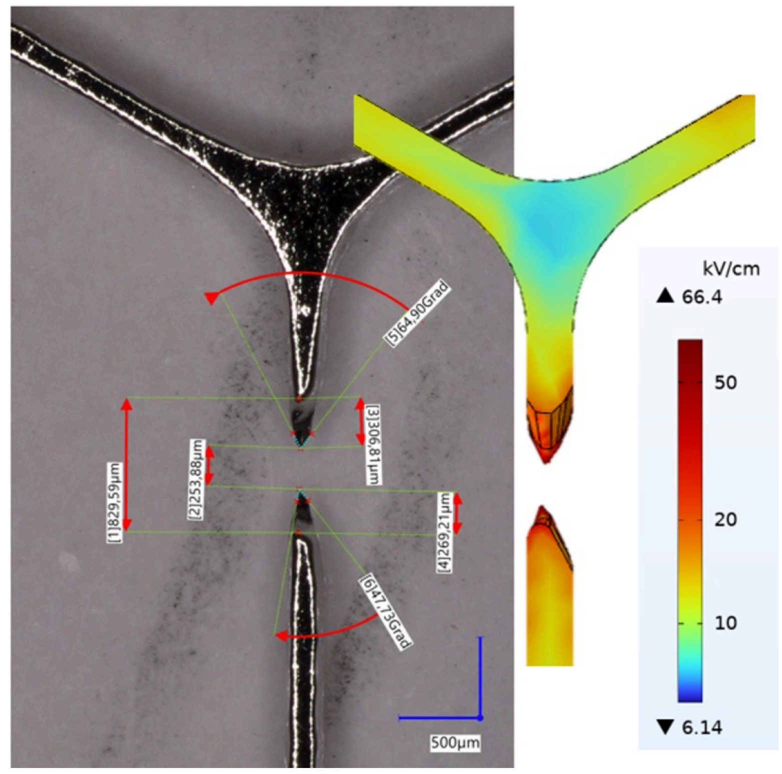
Eur. Phys. J. C (2022) 82:1104





Photosensors and grids

- Photosensors:
  - Radiopurity improvement on 3” PMTs (used in XENONnT/LZ)
  - Testing of Square 2” PMTs → lower buoyancy and sub-ns rise time
  - Testing of 12x12 mm^2 MPPC of VUV4 SiPMs → low-radioactivity, cheap but higher dark count rate
  - Other photosensors under study (digital SiPM, hybrid sensors,…)
- HV and grids - design, production, quality testing and repair of electrodes:
  - Stretching, sagging and flatness of meshes
  - Diagnostic of defects and reparation with laser welding
  - Electrode surface treatment and coating
  - Study electron and photon emission

Conclusions

- Dual-phase xenon TPCs set most stringent constraints on WIMP dark matter searches
- Next generation detector will reach the neutrino fog - directionality needed afterwards
- Active community working on R&Ds to develop the required technology
- Very low background and large mass allow to investigate many other physics channels

Thank you for your attention