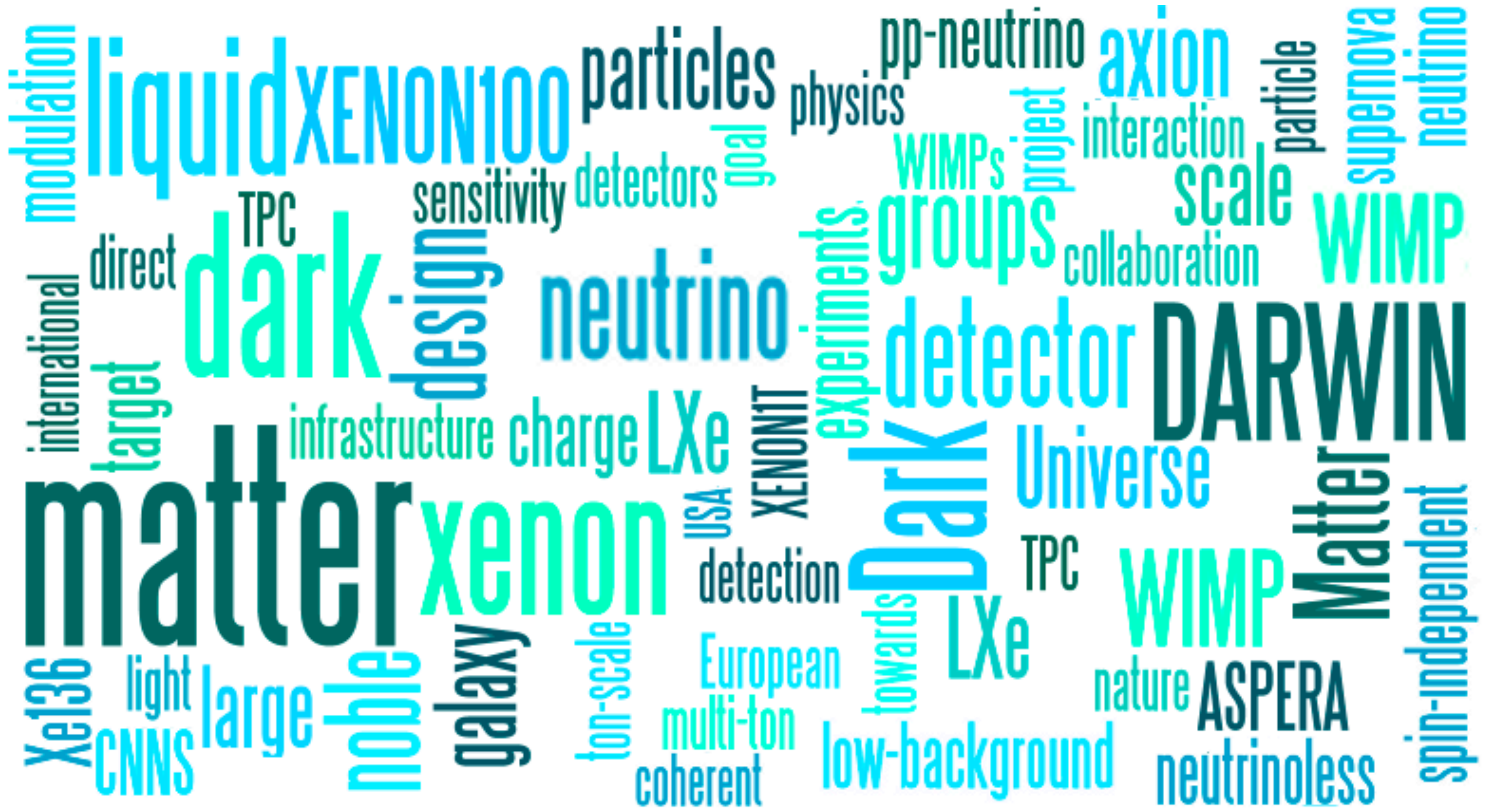
DARWIN : a next-generation liquid xenon observatory for dark matter and neutrino physics

Yanina Biondi on behalf of the DARWIN collaboration,
Universität Zürich
09.10.2019

DARWIN

erc

University of Zurich[UZH]

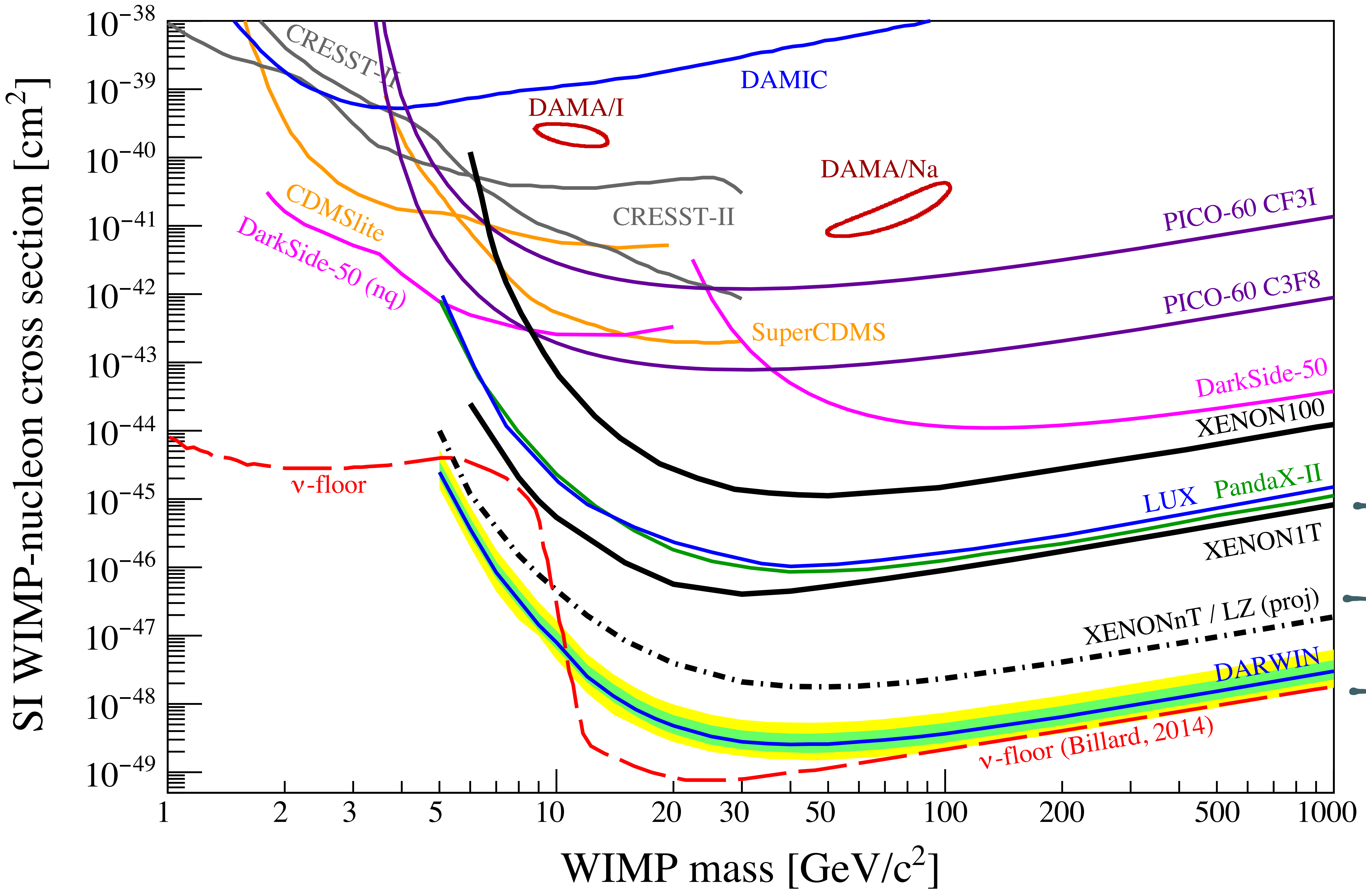


www.darwin-observatory.org

CONTENTS

THE WIMP LANDSCAPE 2019

Spin independent cross section for WIMPs



DARWIN Collaboration, JCAP 1611 (2016) 017

- The highest sensitivity to WIMPs above 5GeV/C² comes from experiments using liquid noble gases are as target (Xe,Ar).
- Lower cross sections will require much larger detectors. DARWIN with 40t aims to increase 100-fold the current sensitivity

→ Current limits

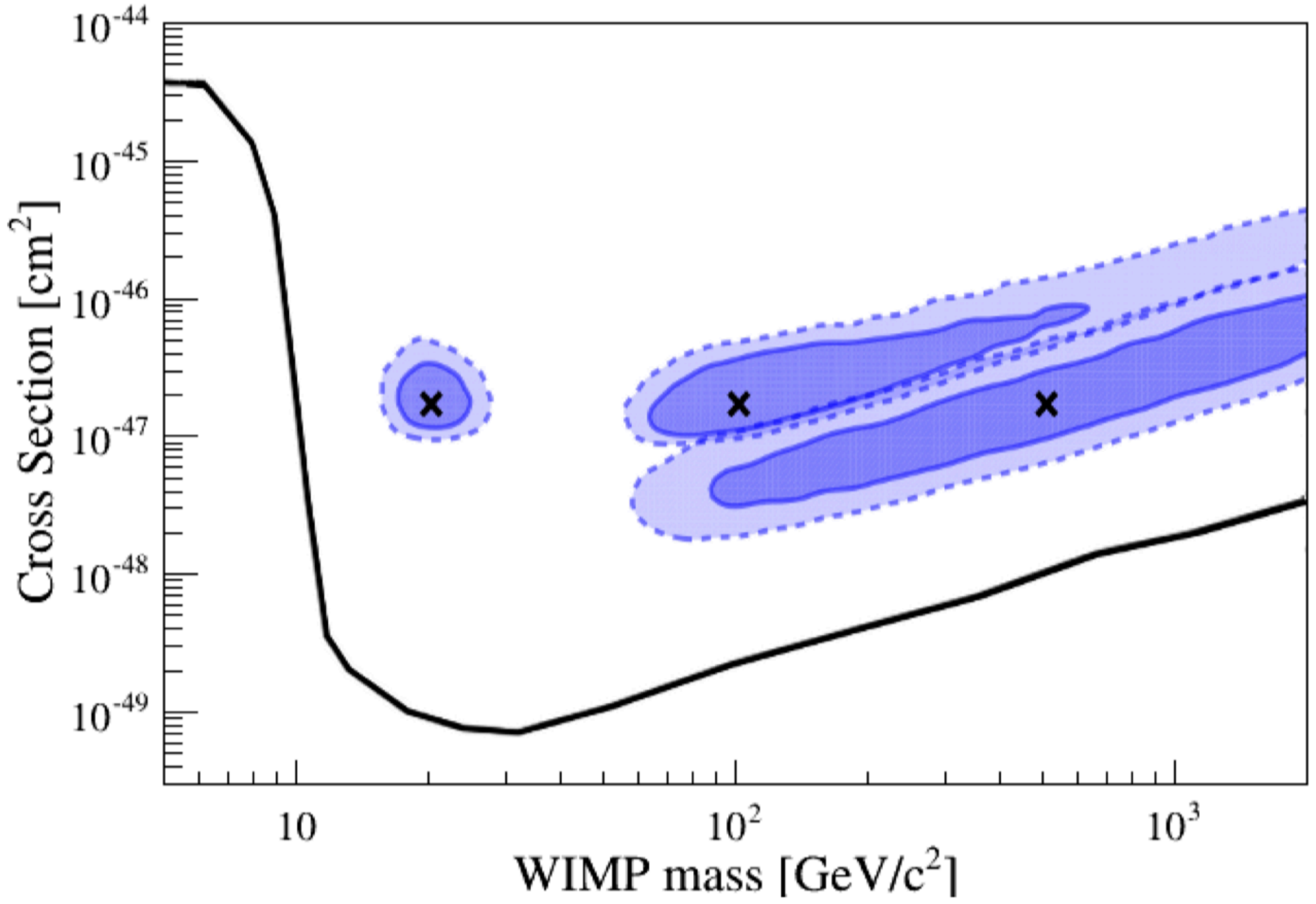
→ Future sensitivities

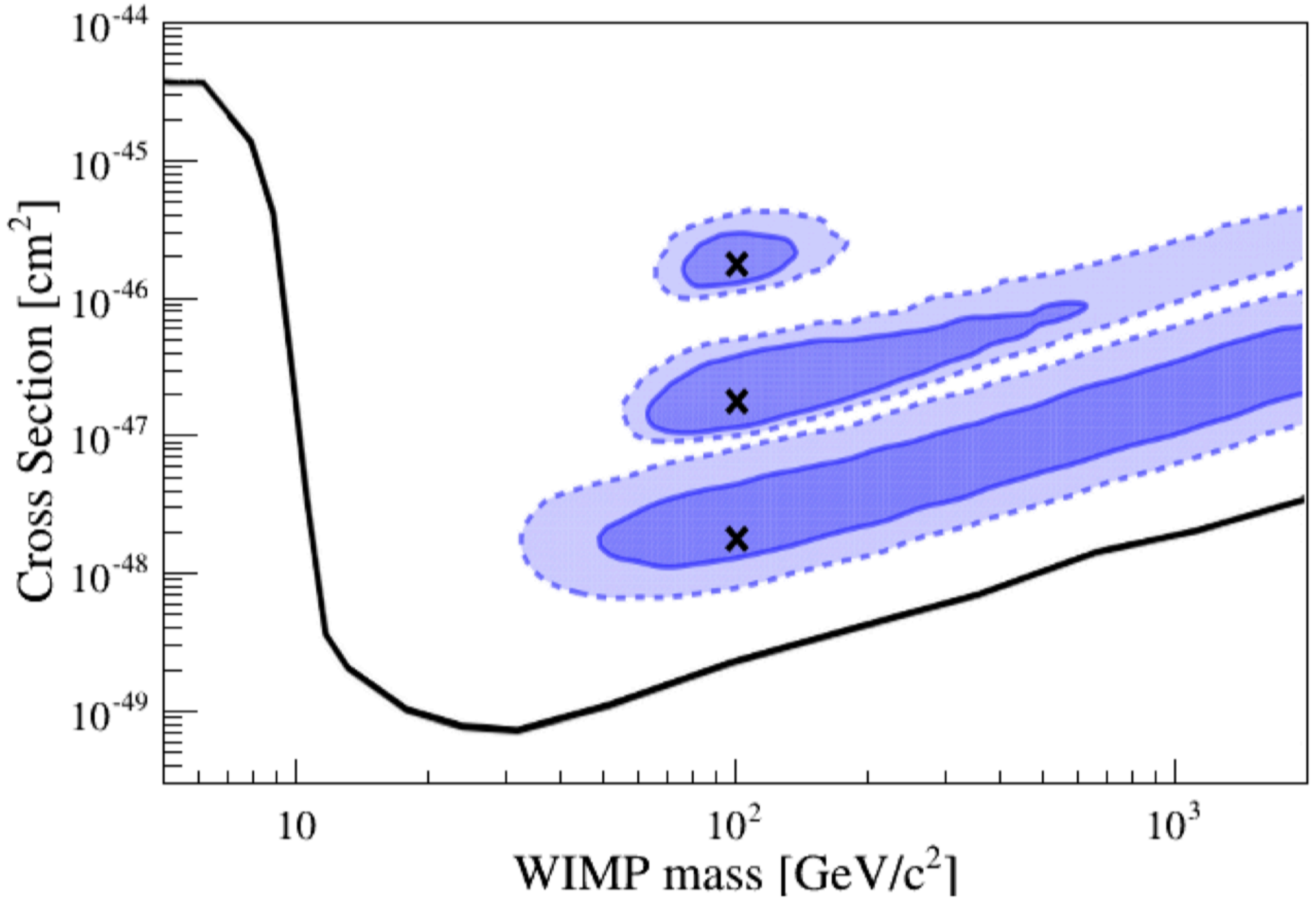
→ Ultimate reach before reaching the neutrino floor

SPIN INDEPENDENT INTERACTIONS

Left: Reconstruction for three different WIMP masses of 20 GeV/c^2, 100 GeV/c^2 and 500 GeV/c^2 and a cross section of 2×10^{-47} cm^2 , close to the sensitivity limit of XENON1T.

DARWIN Collaboration, JCAP 1611 (2016) 017

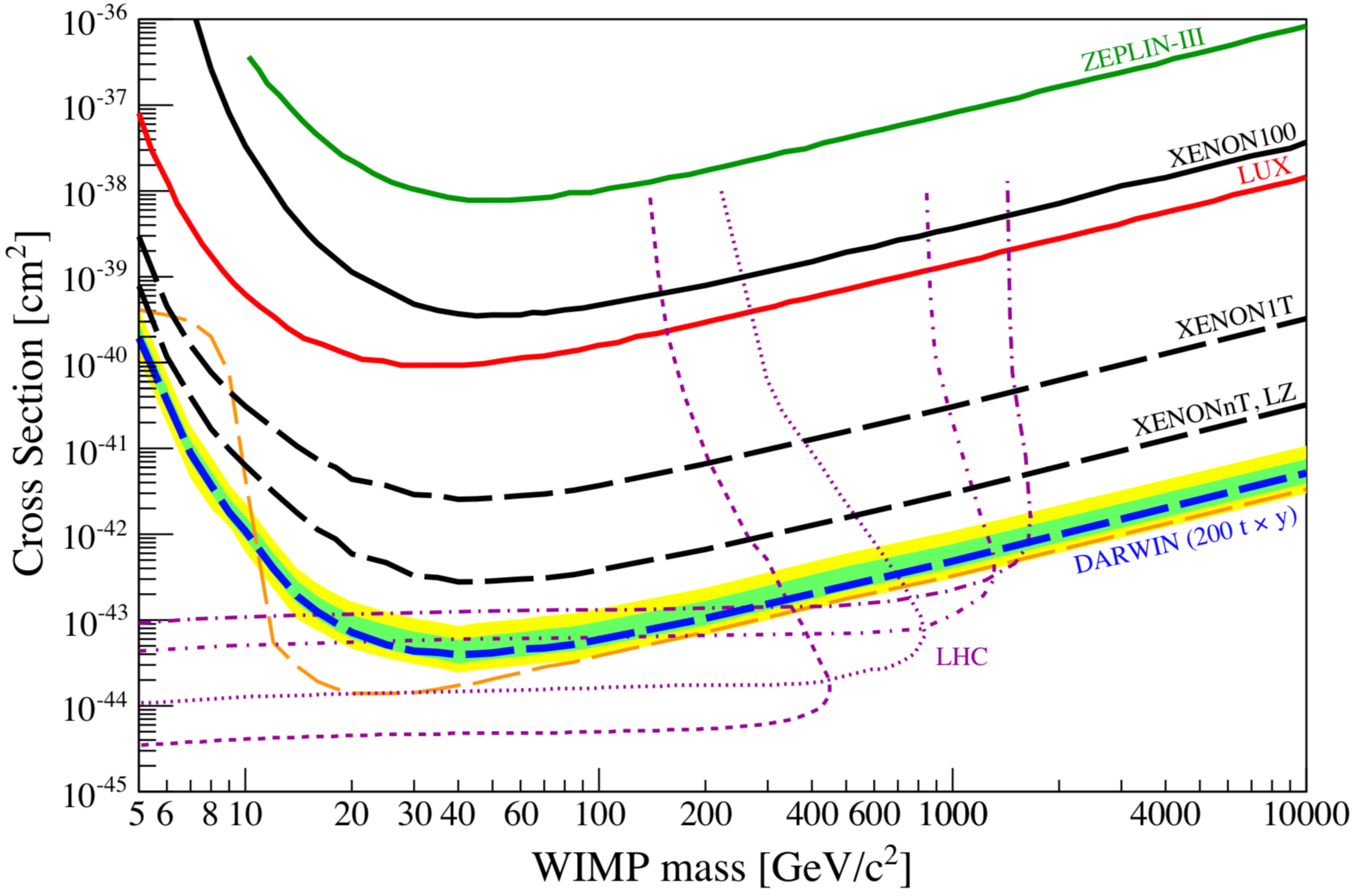




Right: Reconstruction for cross sections of 2×10^{-46} cm^2, 2×10^{-47} cm^2 and 2×10^{-48} cm^2 for a WIMP mass of 100GeV/c^2. The black curve indicates where the WIMP sensitivity will start to be limited by neutrino-nucleus coherent scattering.

THE WIMP LANDSCAPE 2019

DARWIN would have an excellent sensitivity to spin-dependent interactions, especially for ^{129}Xe, that can be extended to axial vector couplings as well.



DARWIN Collaboration, JCAP 1611 (2016) 017

- Most of the spin in xenon is carried by neutrons, WIMP neutron scattering dominates.
- Constrain a new region in WIMP mass-mediator mass space
- Assumption: Dirac fermion and an s-channel interaction with quarks, mediated by a spin-1 particle of mass mmed with an axial-vector coupling to both the WIMP and the quarks (mediator couples equally to all quark flavors)

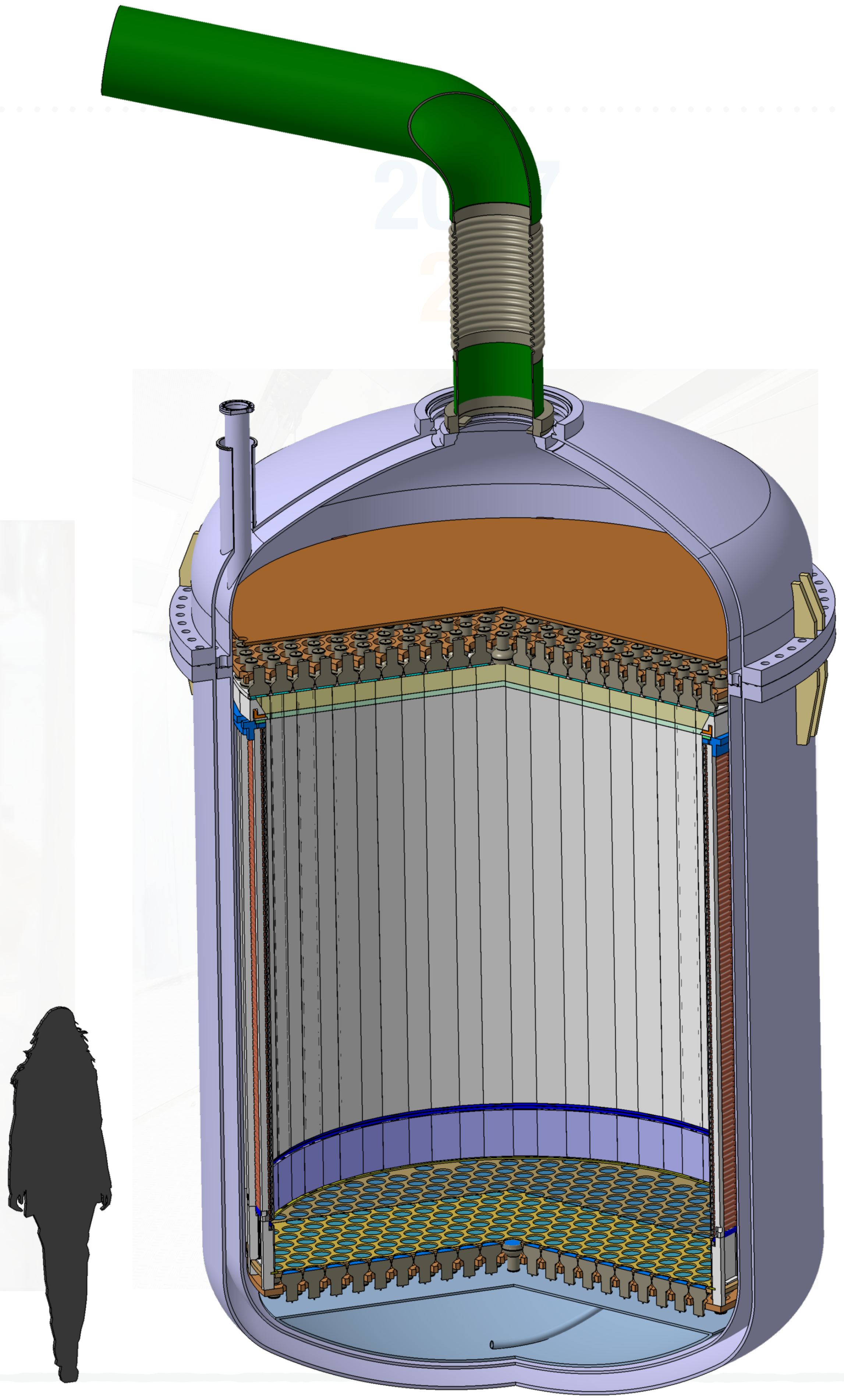
XENON EVOLUTION

2008
10 kg

XENON10

2012
100 kg

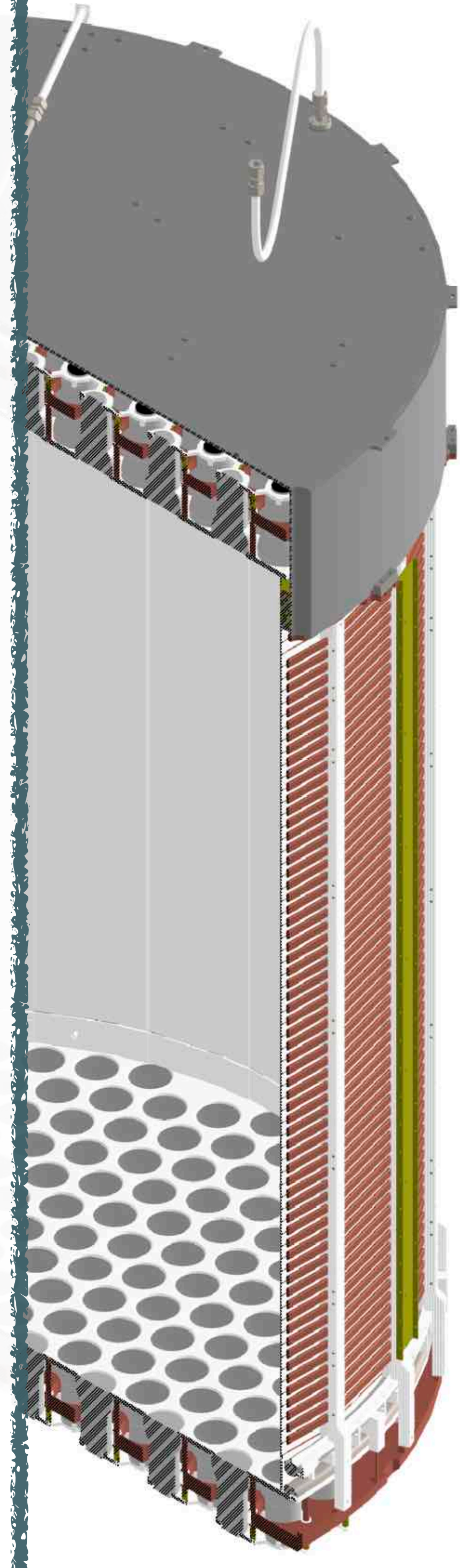
XENON100



2025
40 t

DARWIN

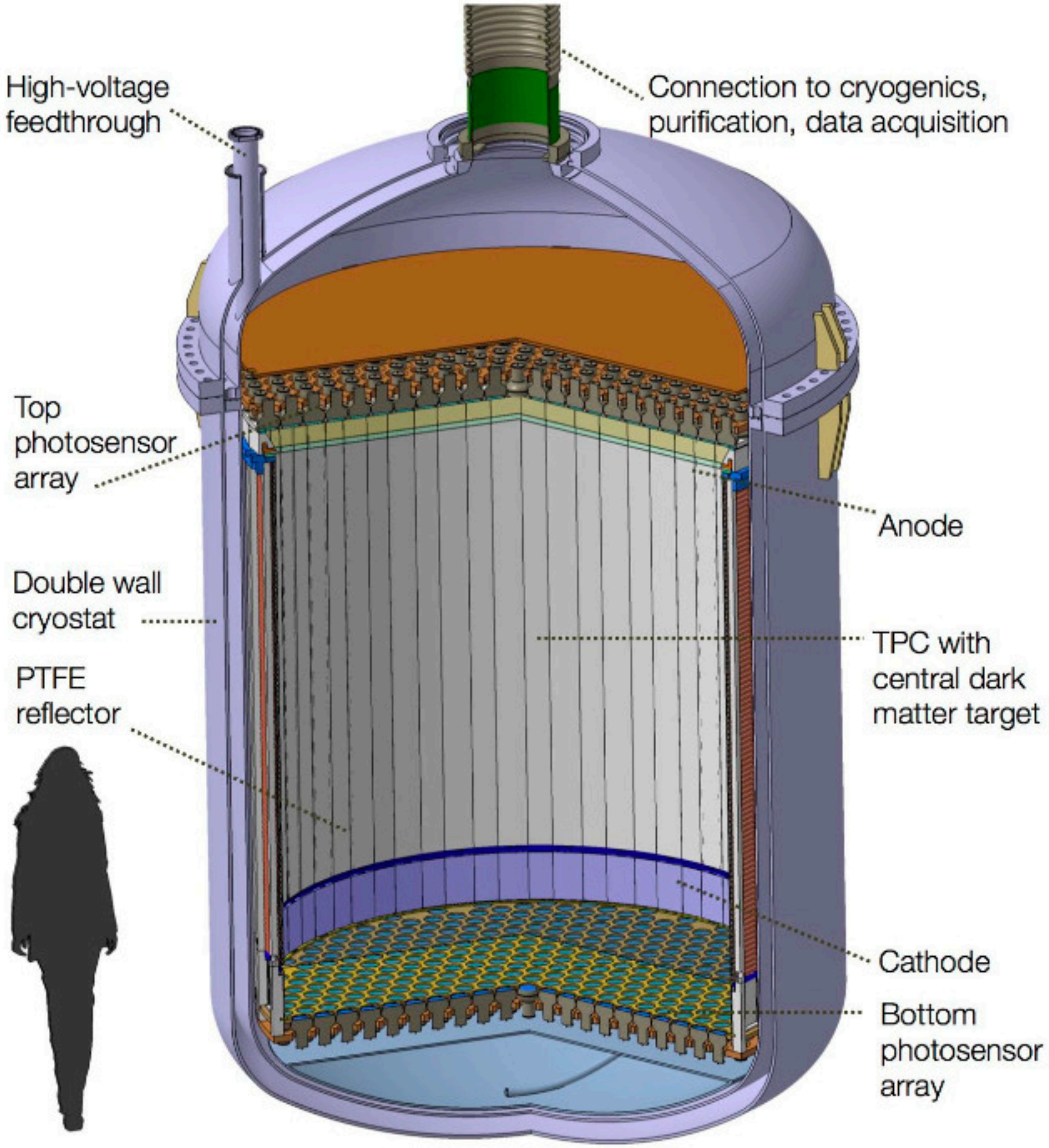
2019
5.9 t



XENONnT

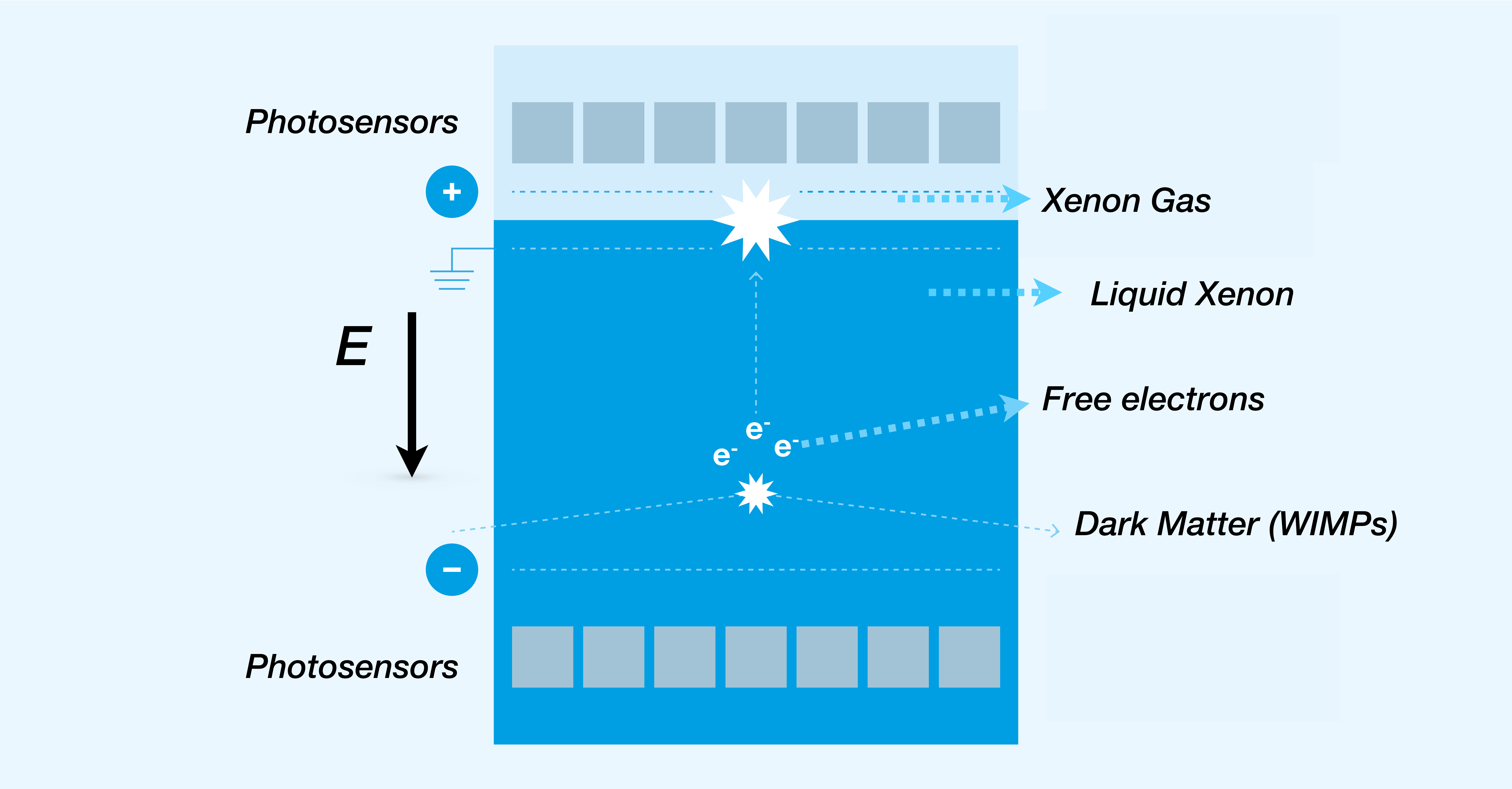
DARWIN DESIGN: AMBITIOUS 50 TONS LXE TPC OBSERVATORY

- ✦Dual-phase Time Projection Chamber (TPC).
- ✦50t total (40 t active) of liquid xenon (LXe).
- ✦Dimensions : 2.6 m diameter and 2.6 m height.
- ✦Two arrays of photosensors (top and bottom).
- ✦PMTs, SiPM and other technologies are being considered
- ✦Drift field ~0.5 kV/cm.
- ✦Low-background double-wall cryostat.
- ✦PTFE reflector panels & copper shaping rings.
- ✦Outer shield filled with water (14 m diameter)
- ✦Neutron veto



DARWIN Collaboration, JCAP 1611 (2016) 017

DUAL PHASE XENON TIME PROJECTION CHAMBER



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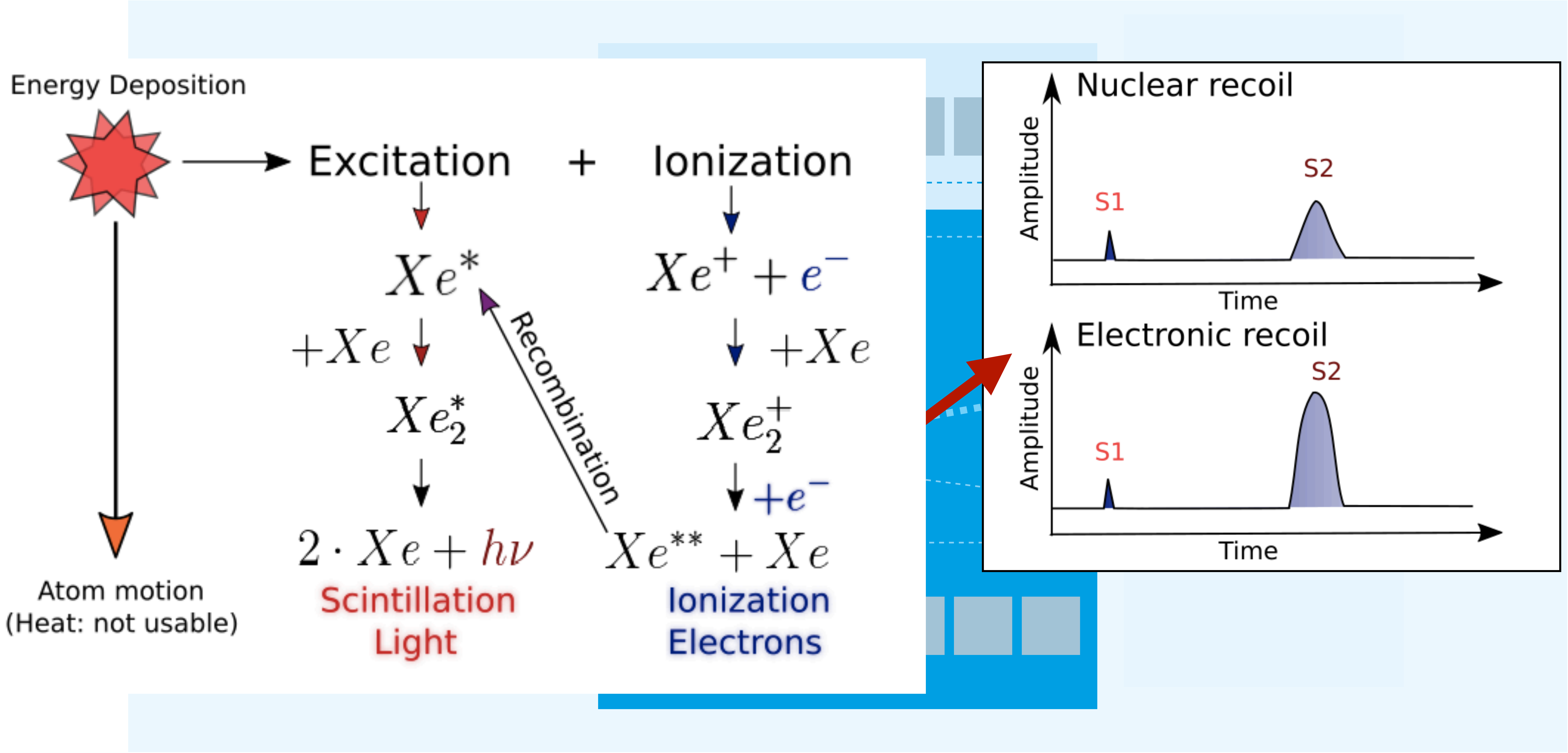
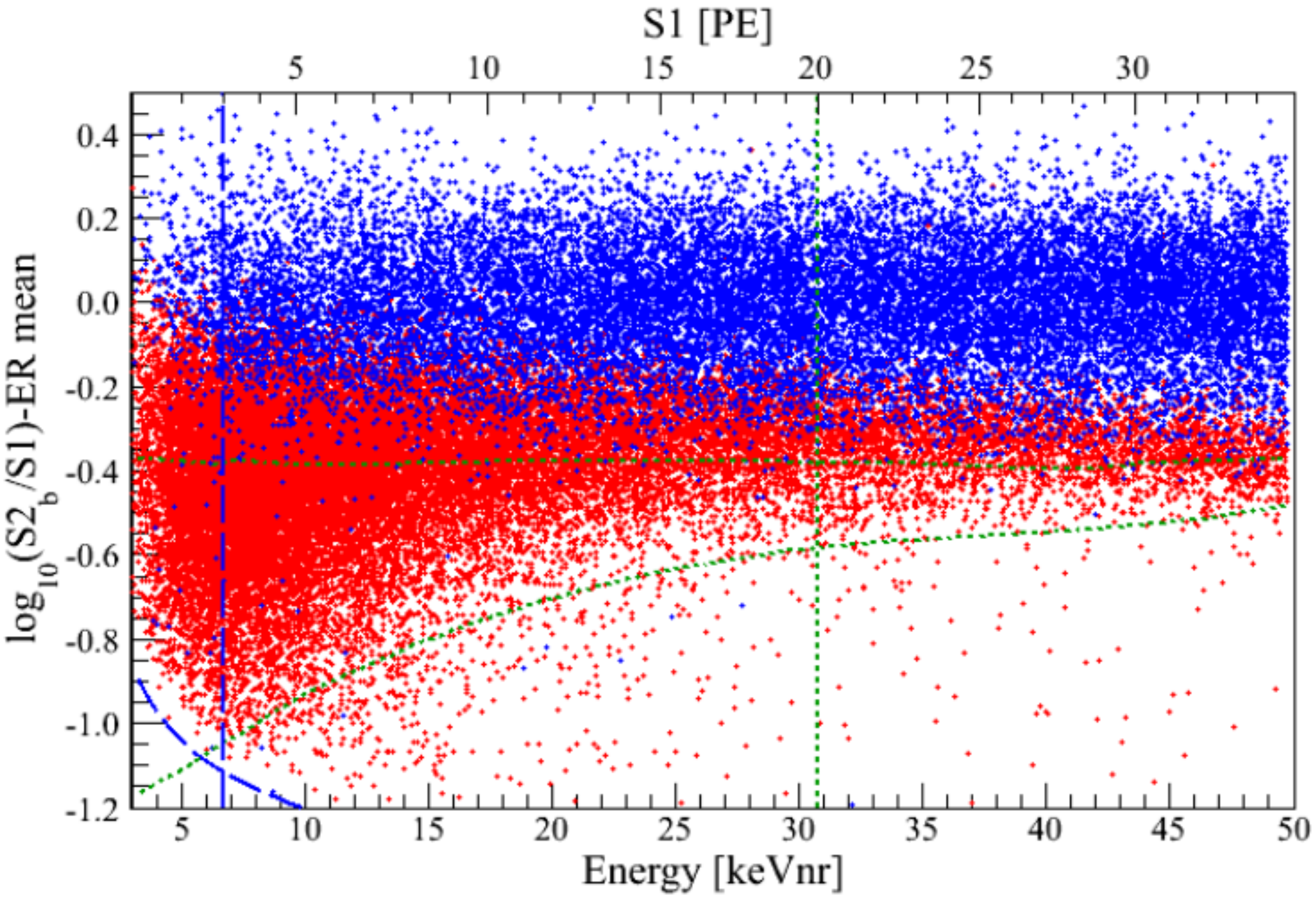


INTERACTIONS IN LIQUID XENON

DARWIN



From XENON100: Low energy calibration of liquid xenon detectors,
Teresa Marrodán Undagoitia, MPIK Heidelberg, May 2013

Scattering off atomic electrons, excitations, etc
Electronic Recoil (ER)

Coherent Scattering off Xe nucleus
Nuclear Recoil (NR)

DARWIN aims for 99.98 ER rejection with 30% NR acceptance

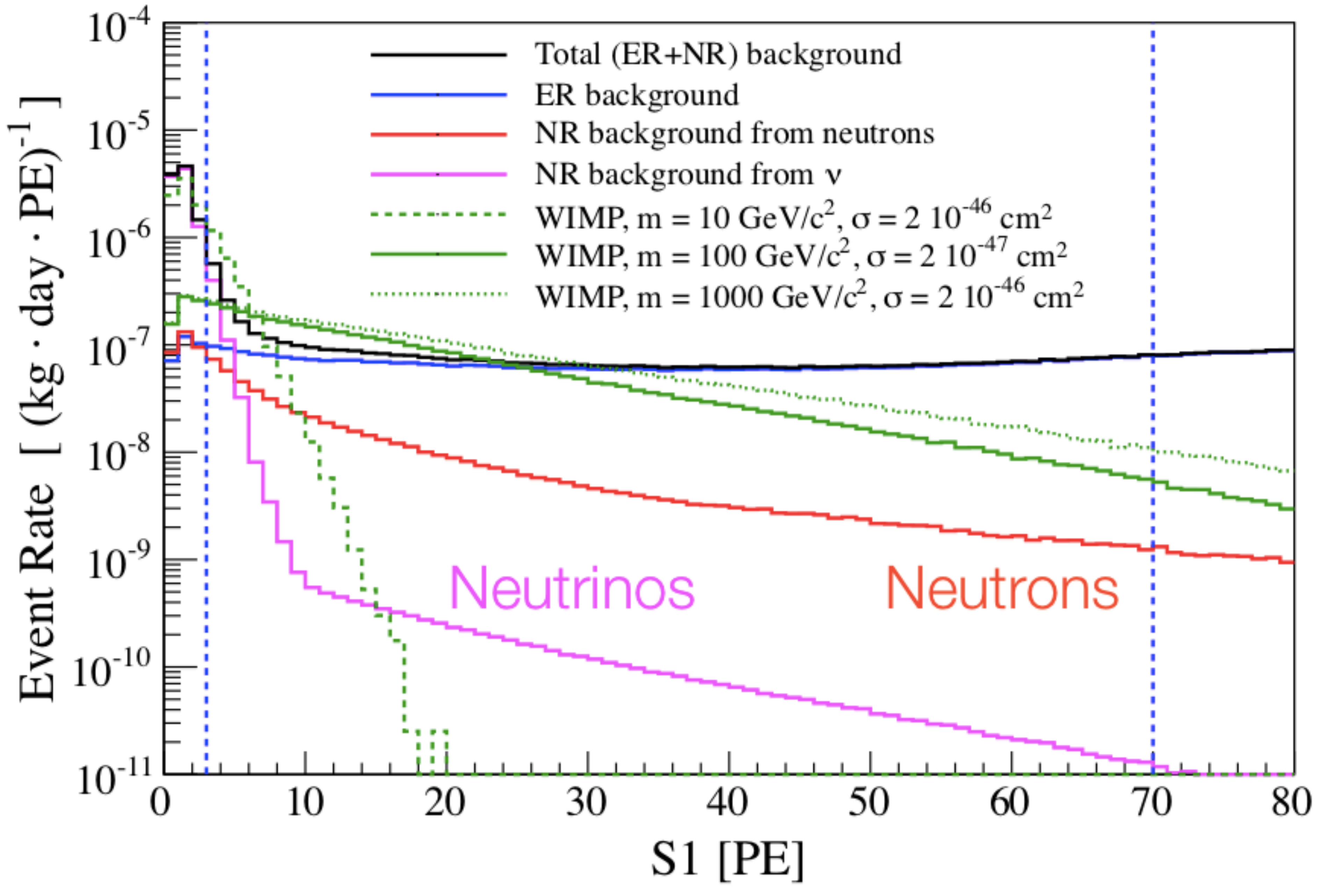
ELECTRONIC AND NUCLEAR RECOILS IN LIQUID XENON

DARWIN

The background budget is given by:

Electronic recoil
Extrinsic from materials
Intrinsic from LXe
Solar Neutrinos

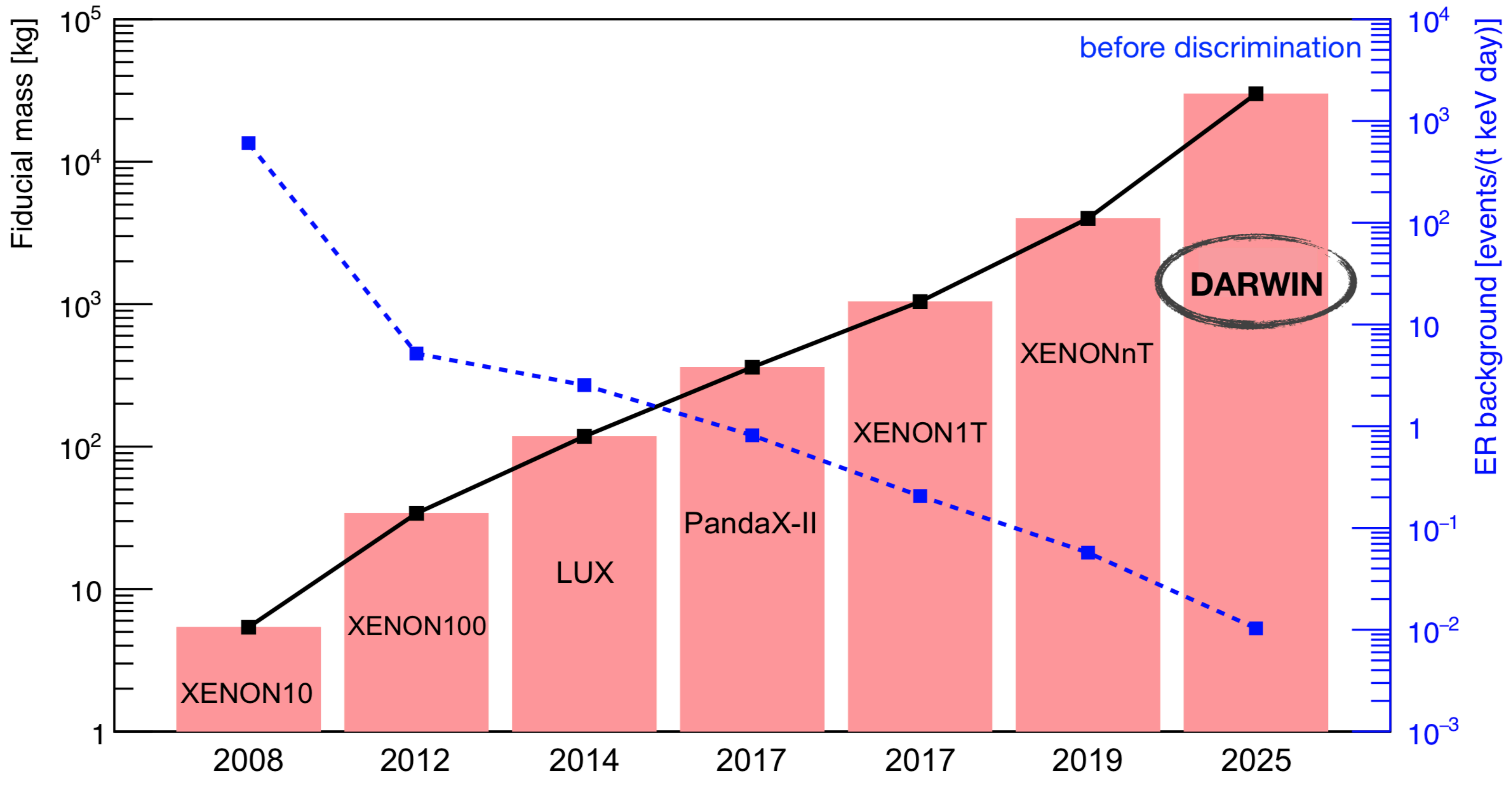
Nuclear recoil
Neutrons from materials
Cosmogenic activation
CNNS



Physics reach of the XENON1T dark matter experiment

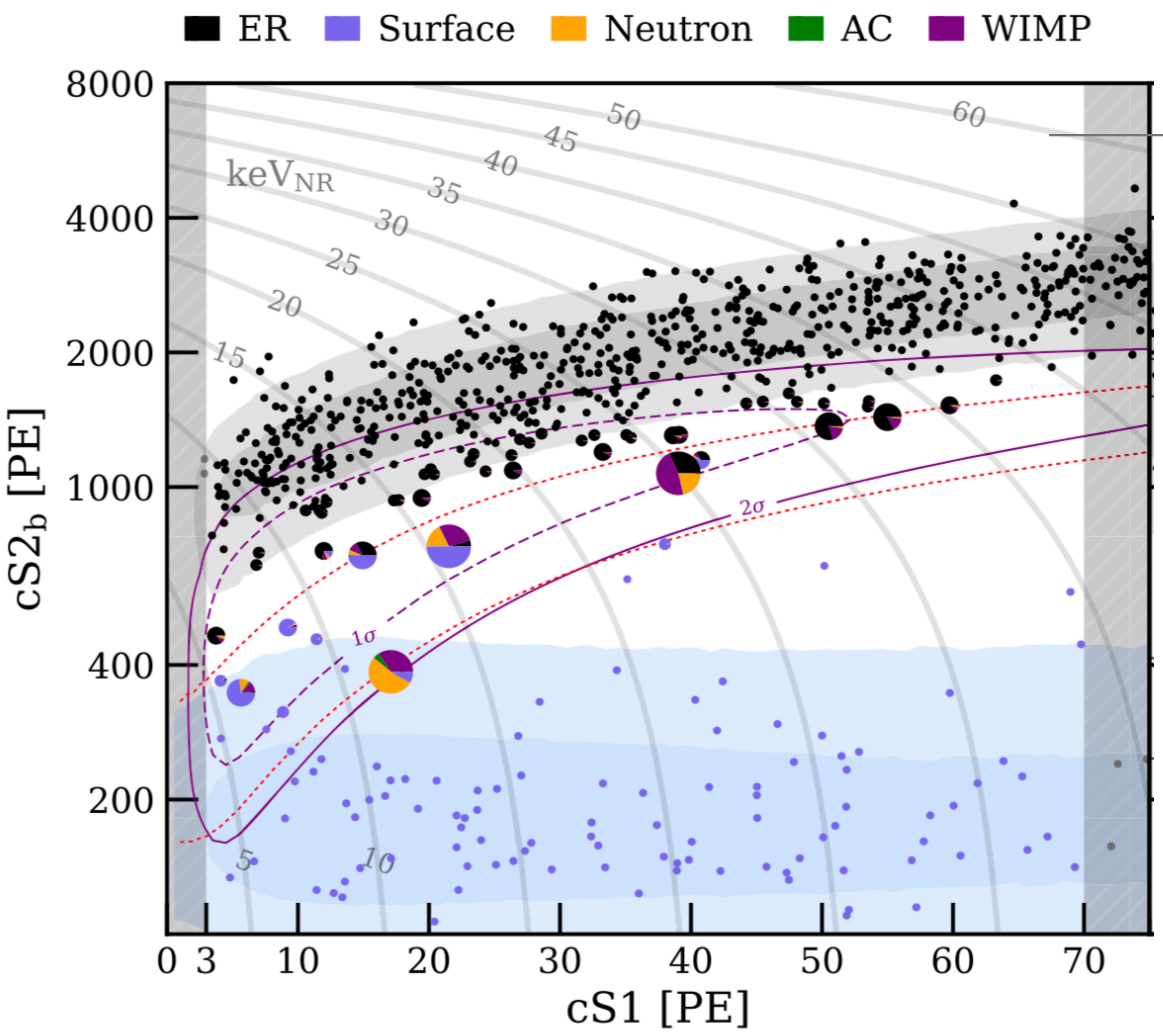
XENON Collaboration (E. Aprile (Columbia U.) et al.) CAP 1604 (2016)

Self shielding from LXe and fiducialization help to reduce most backgrounds



WHICH SIGNALS DO WE EXPECT TO SEE IN EACH S1–S2 REGION?

DARWIN



keV NR equivalent

- Piecharts: relative PDF from the best fit of 200 GeV WIMPs with 4.7x10^{-47} cm^2

Dark Matter Search Results from a One Ton-Year Exposure of XENON1T PHYSICAL REVIEW LETTERS 121, 111302 (2018)

DARWIN SCIENCE PROGRAM: MORE THAN DARK MATTER SEARCHES

Given its projected low background and large mass, DARWIN will be sensitive to other rare physics processes such as:

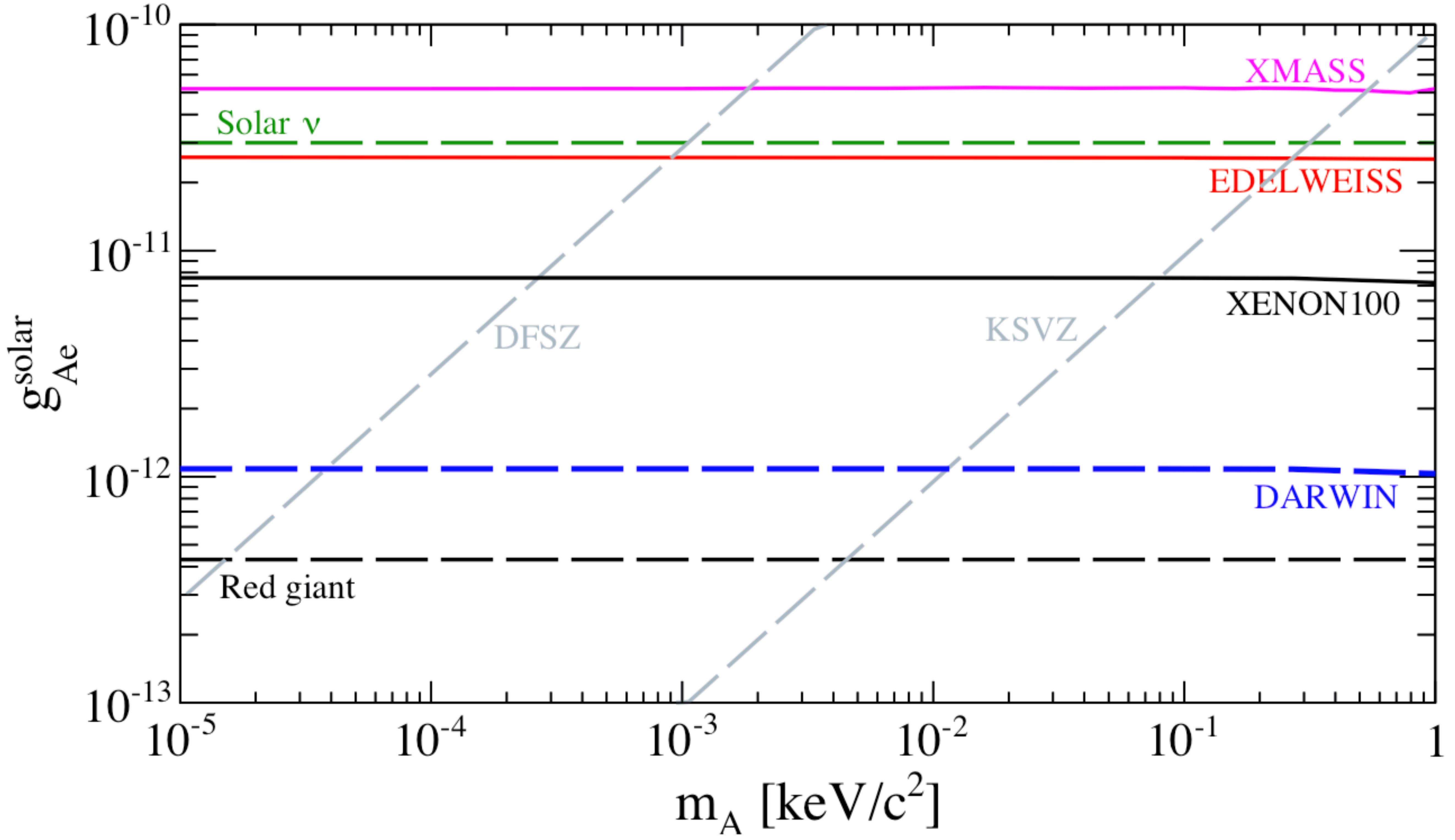
- Solar Axions and Axion Like Particles
- ER — Low energy Solar Neutrinos: pp, ^{7}Be
- Neutrinoless Double Beta Decay
- Coherent Neutrino Nucleus Scattering
- NR — Supernova Neutrinos

Solar Axions and Axion Like Particles

Axions couple with electrons and lead to atomic ionisation ⇒ ER

Galactic Axions and ALPs are well-motivated DM candidates

Sensitivity of DARWIN to solar axions



Solar axions can be produced via Bremsstrahlung, Compton scattering, axio-recombination and axio-deexcitation

DARWIN: towards the ultimate dark matter detector. Journal of Cosmology and Astroparticle Physics, 2016

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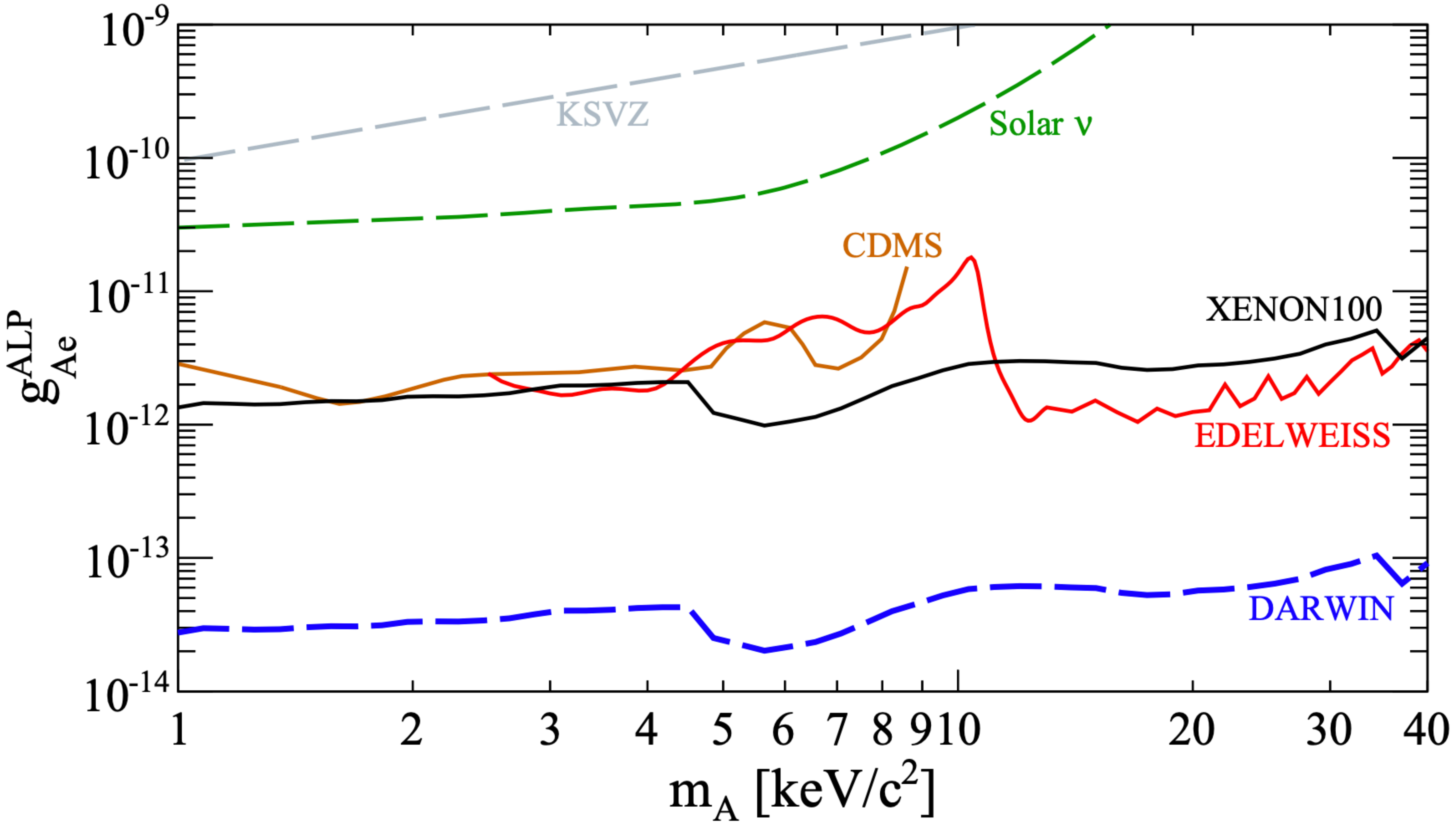

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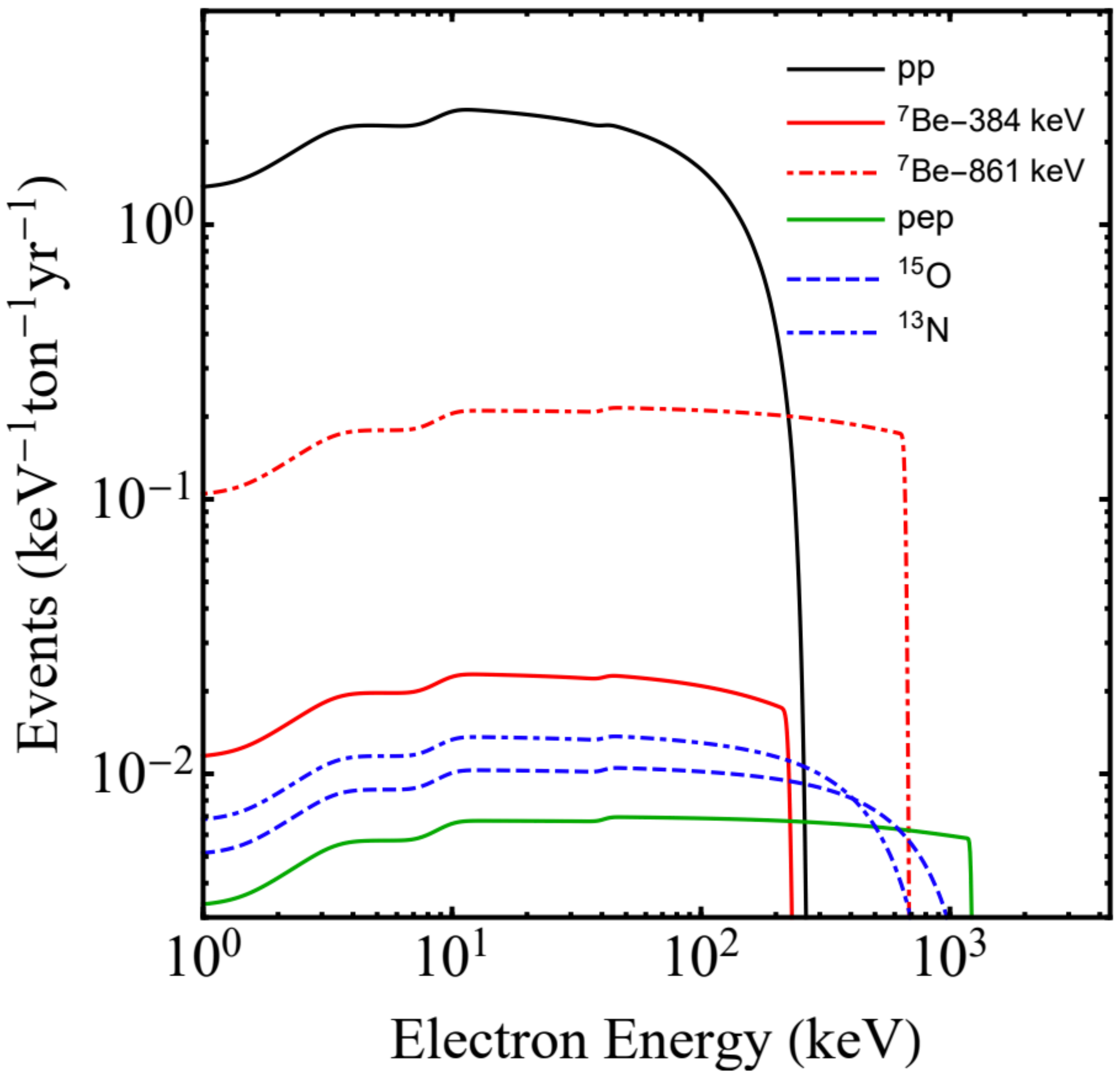
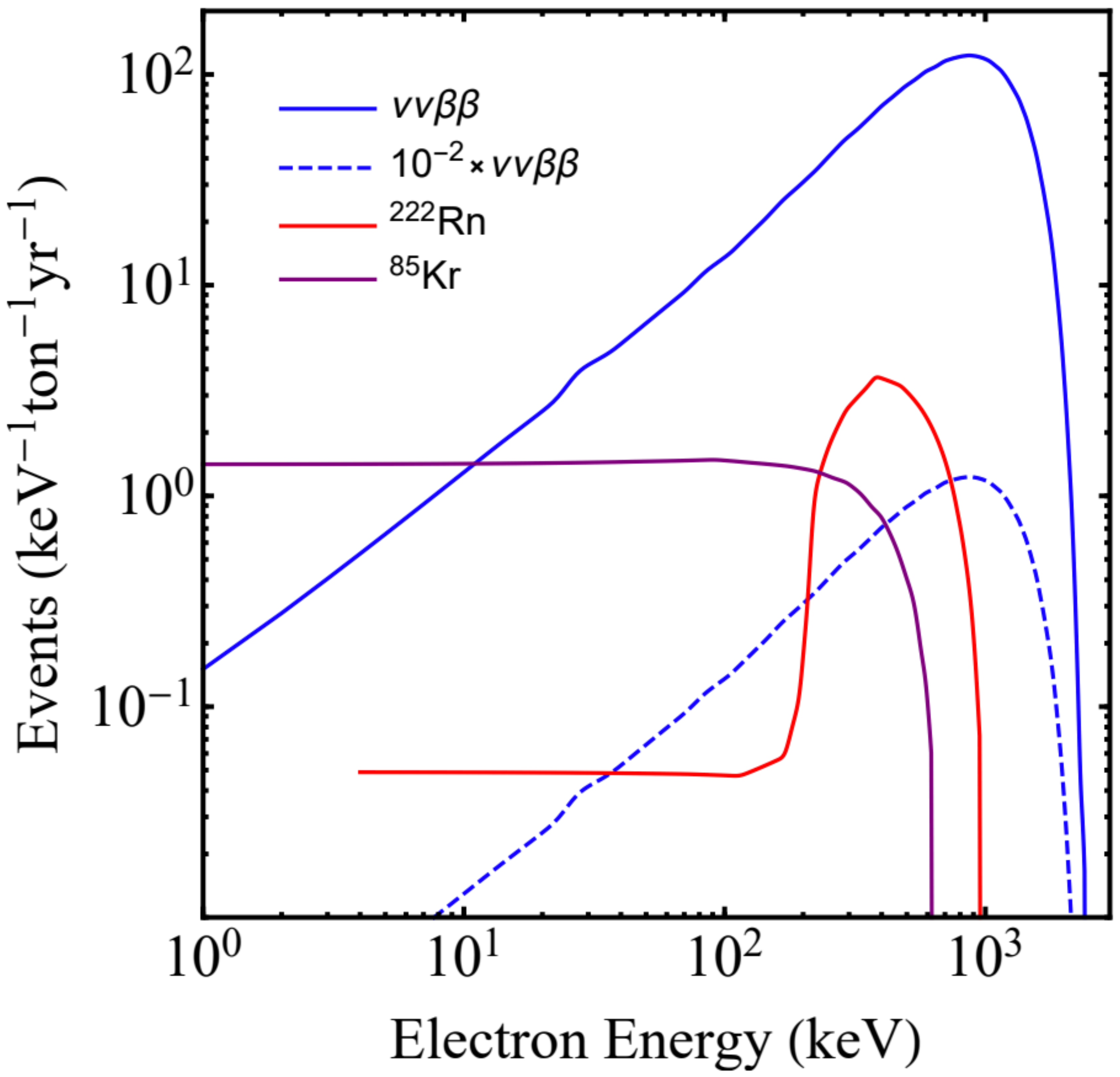
Low energy Solar Neutrinos: pp, ^{7}Be

pp and ^{7}Be-neutrinos more than 98% of the total neutrino flux predicted by the SSM

$$\nu + e \rightarrow \nu + e$$





CNO Solar Neutrinos in Next-Generation Dark Matter Experiments J. Newstead Phys. Rev. D 99, 043006 (2019)

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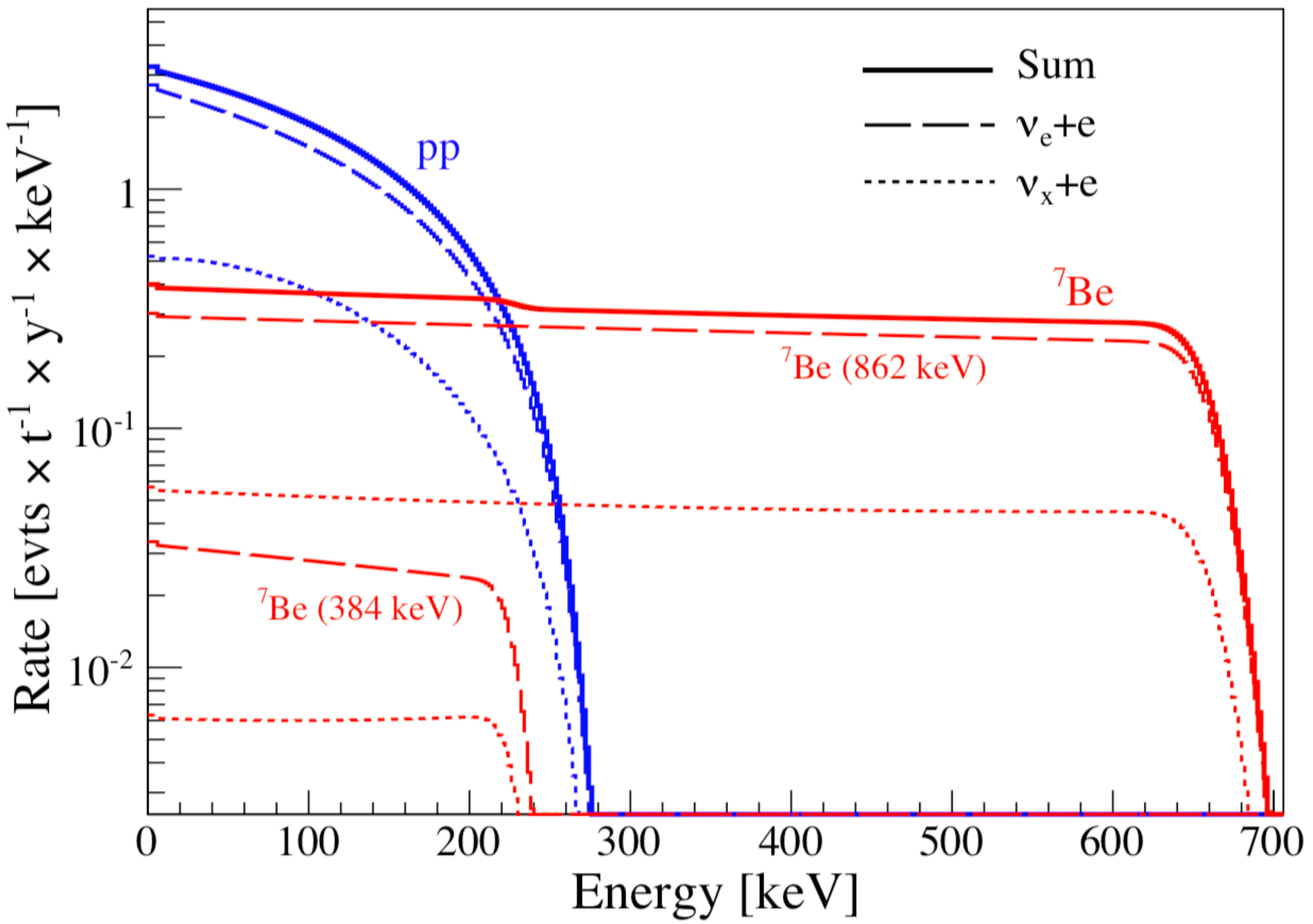
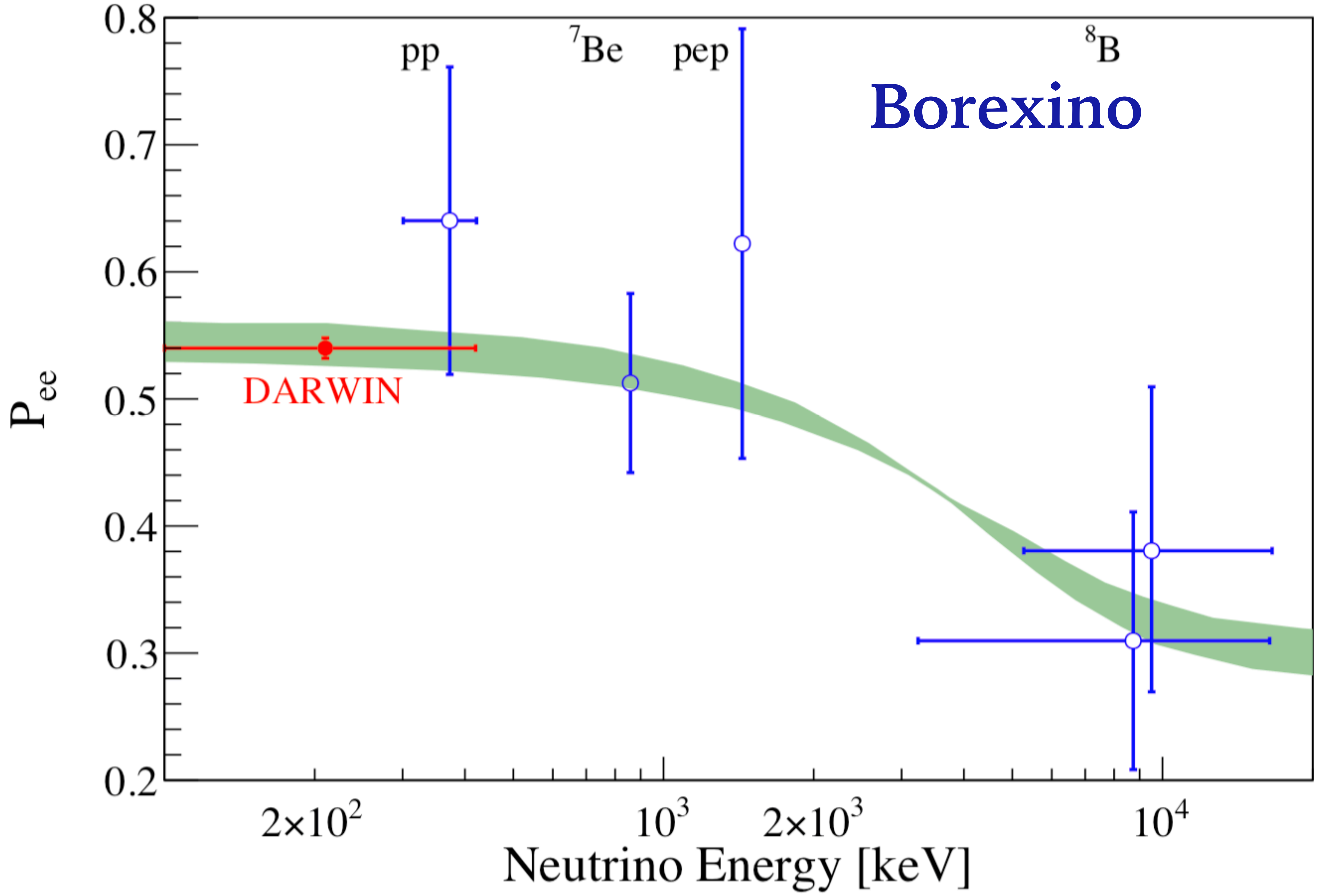
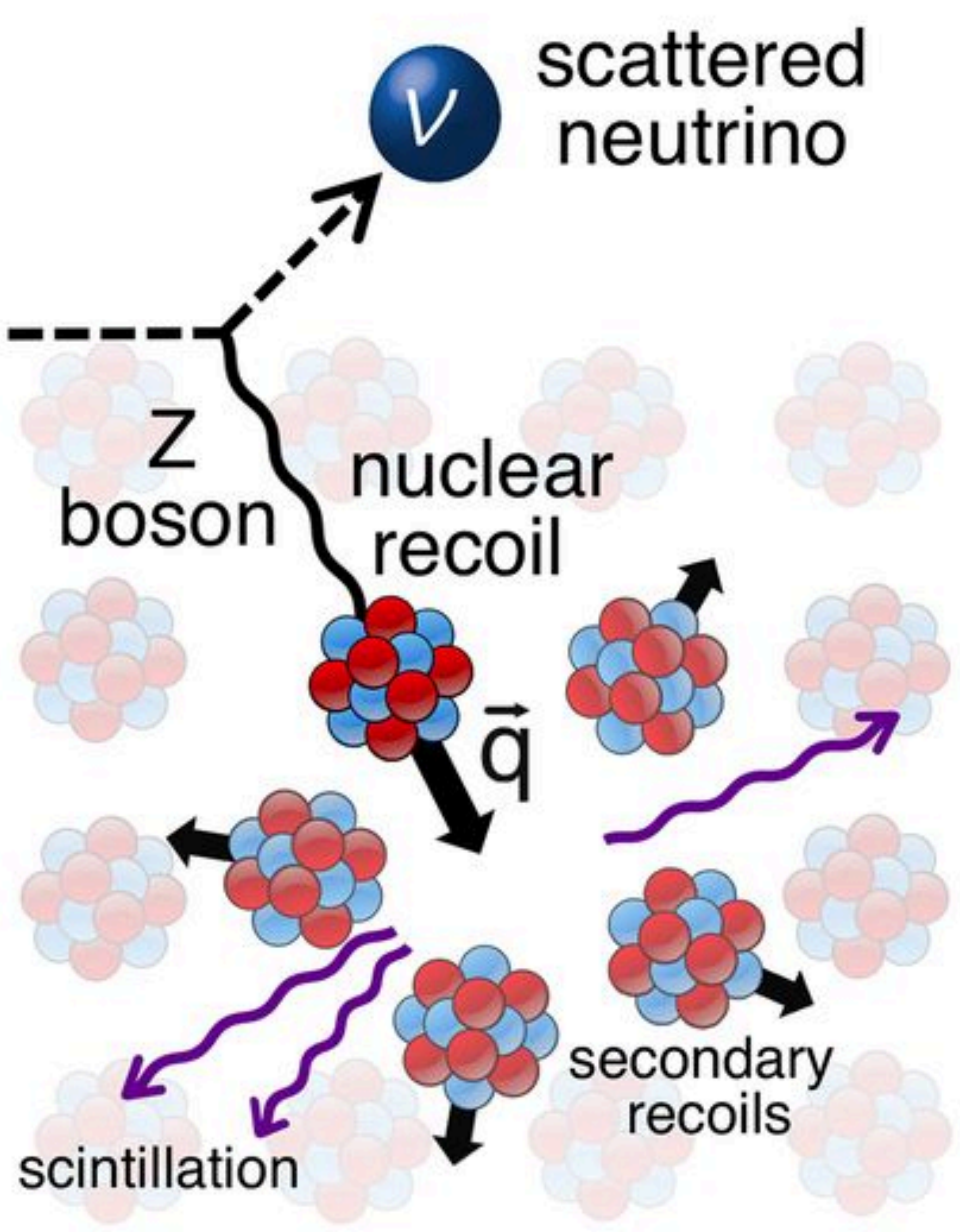




5 years of data taking for precision ~1%

Neutrino physics with multi-ton scale liquid xenon detectors,Journal of Cosmology and Astroparticle Physics 2014

Coherent Neutrino Nucleus Scattering



Observation of coherent elastic neutrino-nucleus scattering 10.1126/science.aao0990

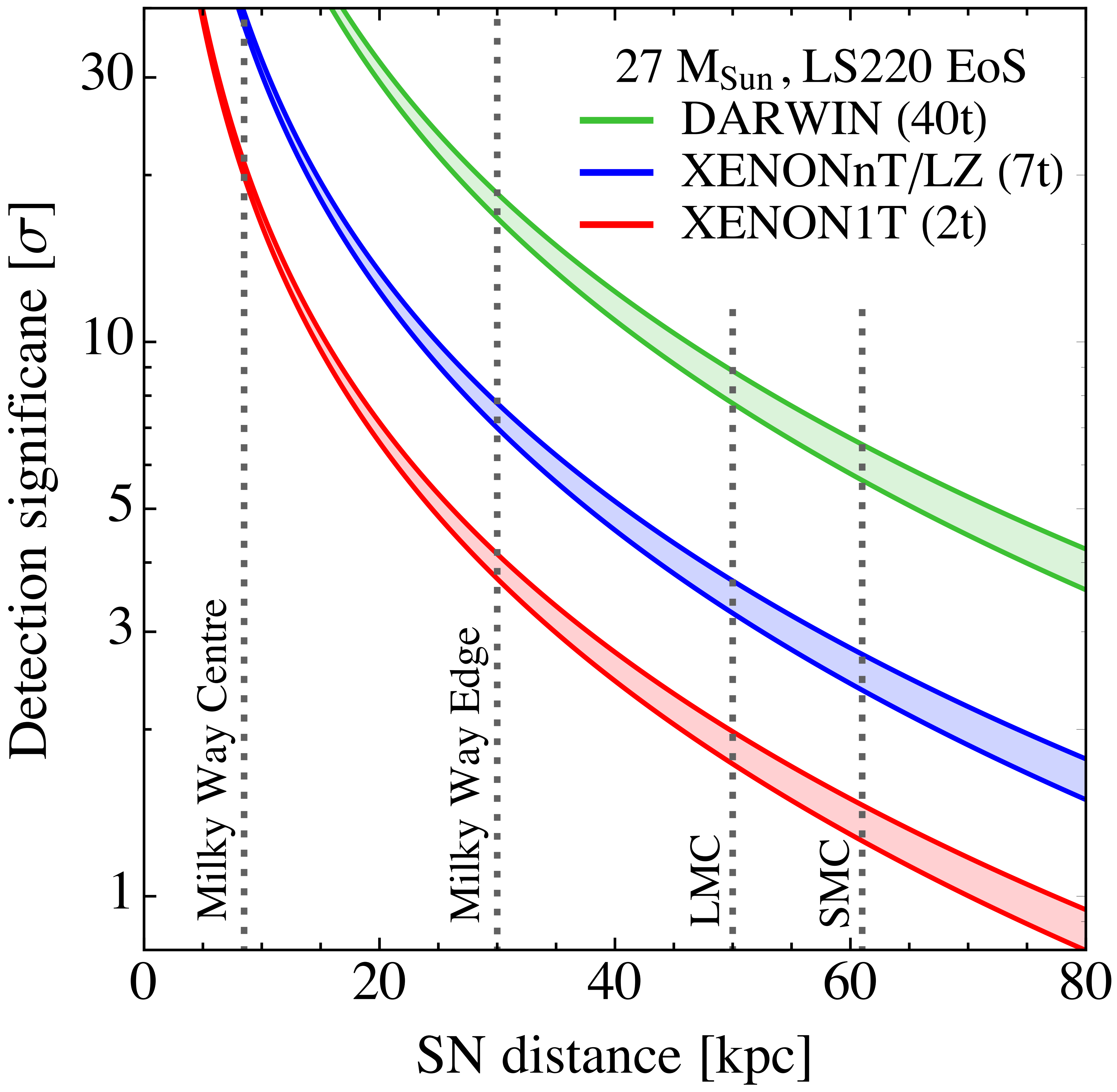
. E. Strigari, Neutrino Coherent Scattering Rates at Direct Dark Matter Detectors, New J. Phys.

> The rate of low-energy signals in all multi-ton WIMP detectors will eventually be dominated by interactions of cosmic neutrinos via CNNS

The largest CNNS rate comes from the relatively high-energy ^{8}B solar neutrinos which produce nuclear recoils $\leq$3 keV$_{nr}$.

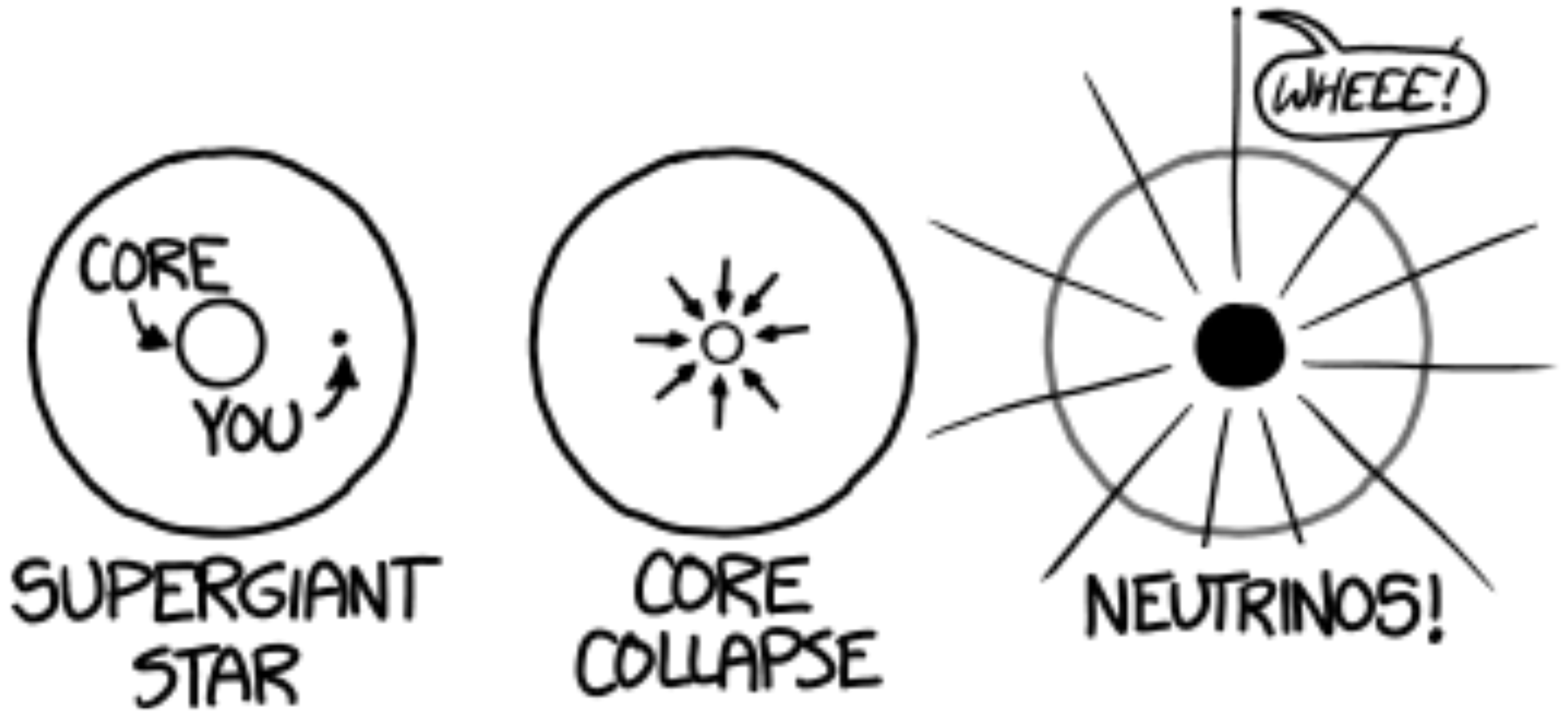
DARWIN will be able to detect and study this process

Coherent Neutrino Nucleus Scattering



DARWIN would be sensitive to all six neutrino species via neutral current interactions

Including neutrinos and anti-neutrinos that are emitted by core-collapse supernovae in a burst lasting a few tens of seconds



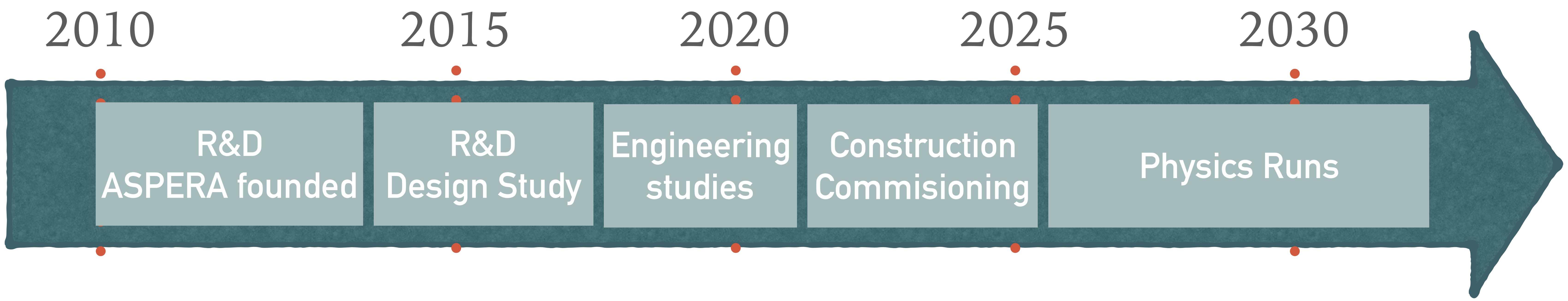
Source: xkcd

Supernova neutrino physics with xenon dark matter detectors: A timely perspective, Lang, Rafael F. et al, Phys. Rev. D, 2016

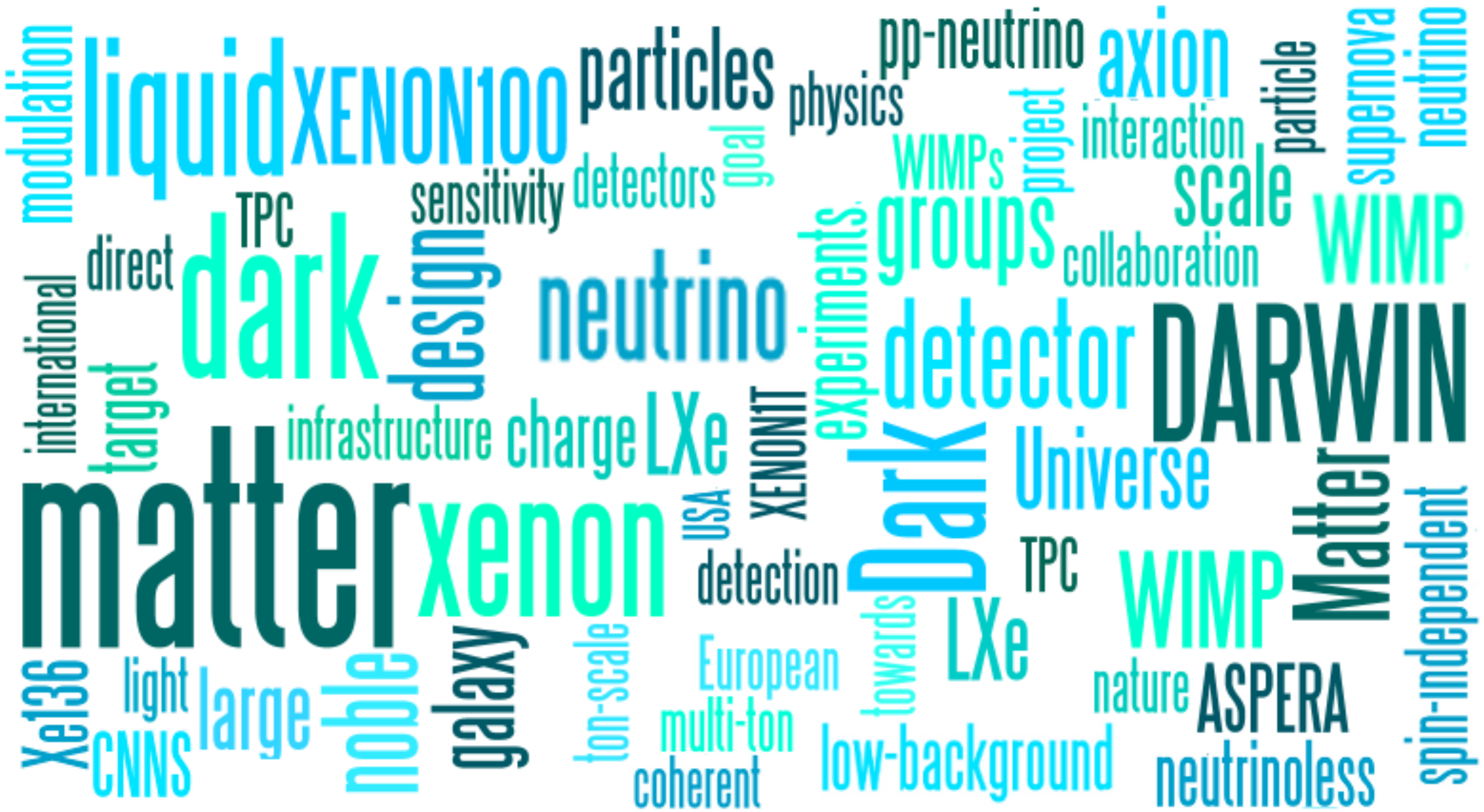
Dark matter astrophysical uncertainties and the neutrino floor. 10.1103/PhysRevD.94.063527

DARWIN

CURRENT STATUS OF DARWIN



- 29 groups from 12 countries
- DARWIN is on the APPEC roadmap
- Working towards a CDR and TDR
- Synergy with XENONnT R&D

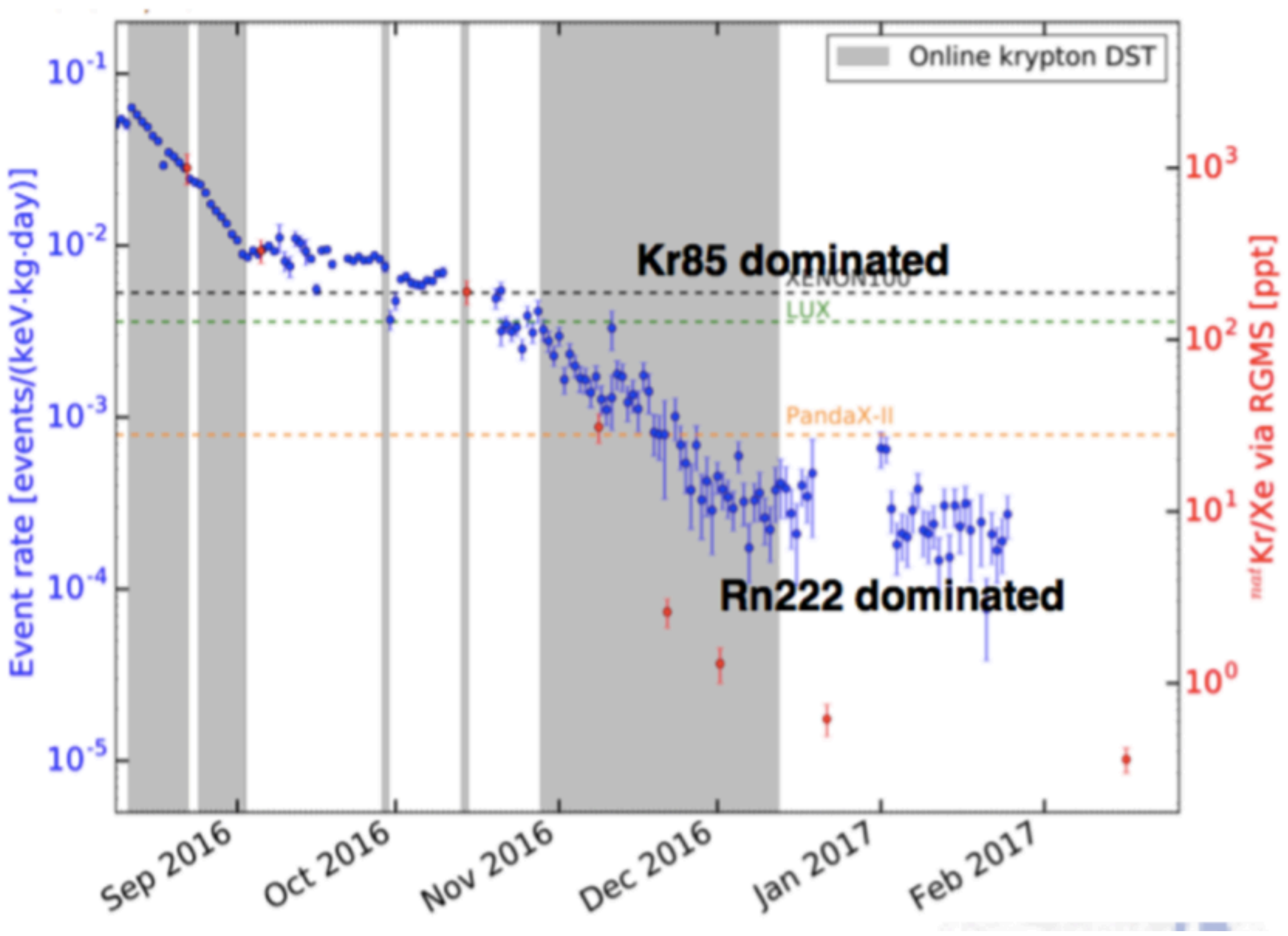


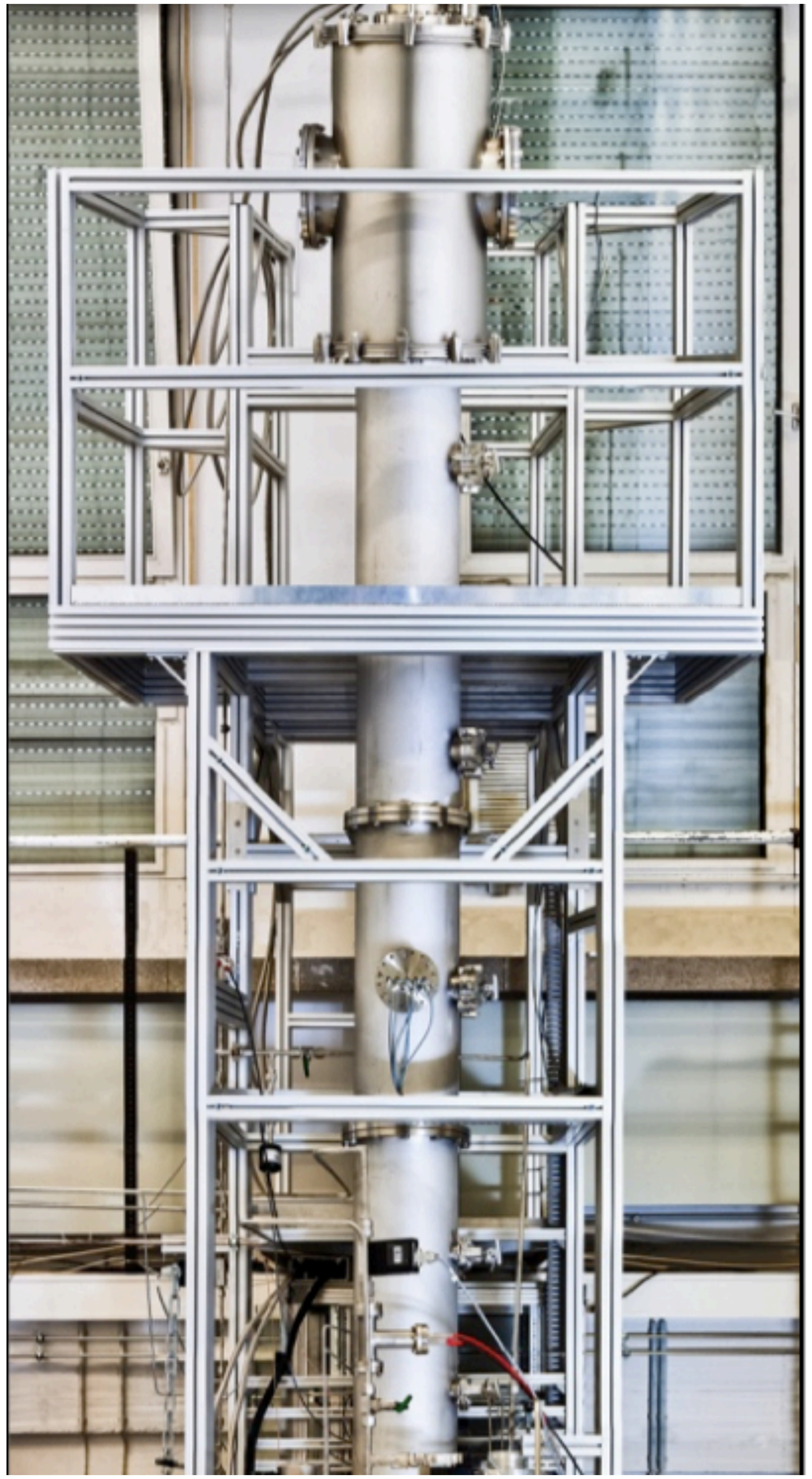
DESIGN CHALLENGES

Scale related :

- Longer drift length ⇒ Deliver the necessary HV
- Increased mass ⇒ Cryogenics, LXe purification…
- Detector response ⇒ Calibration, Corrections, Readout
- Optimization of Cryostat Design

XENON1T

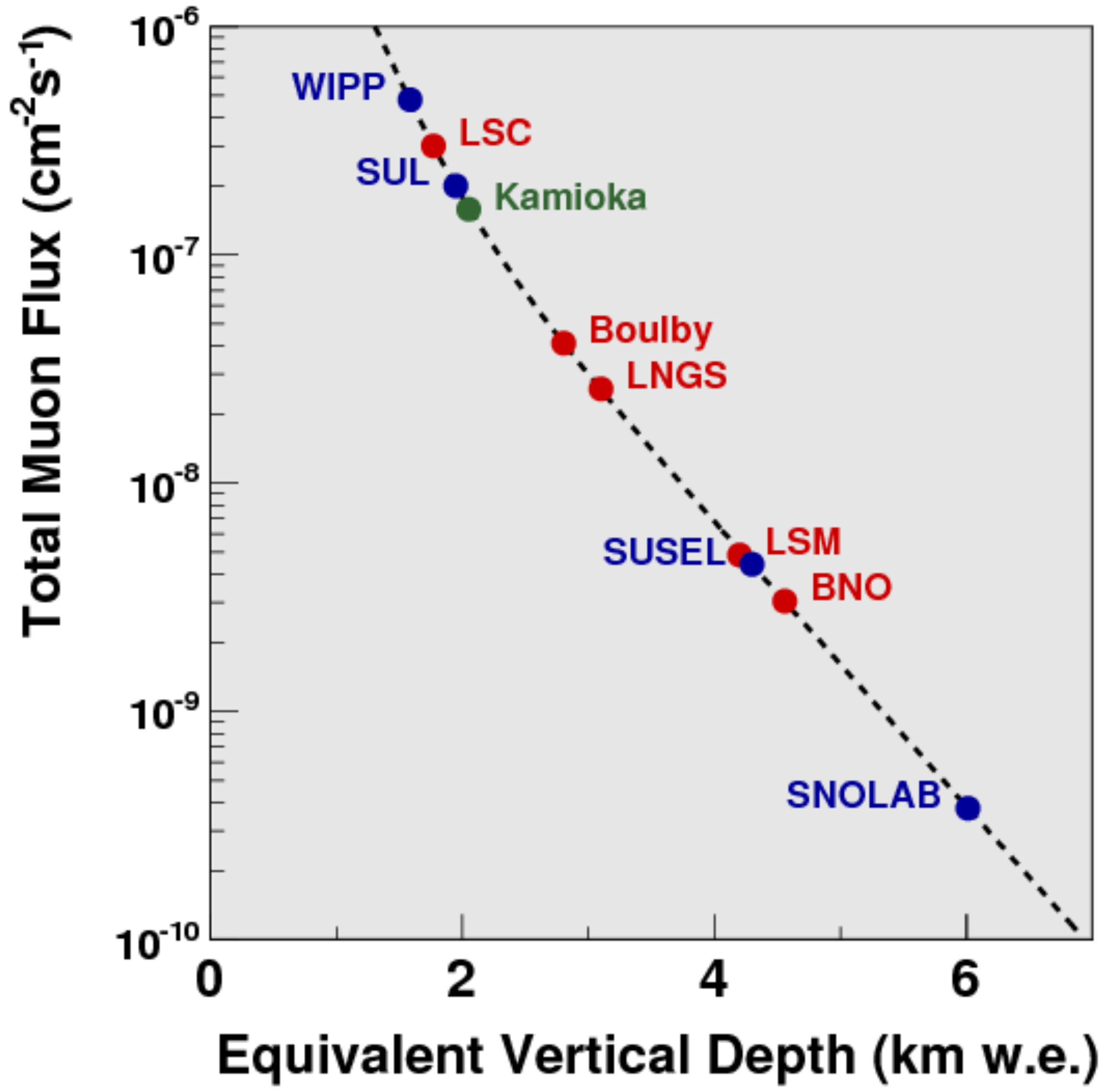




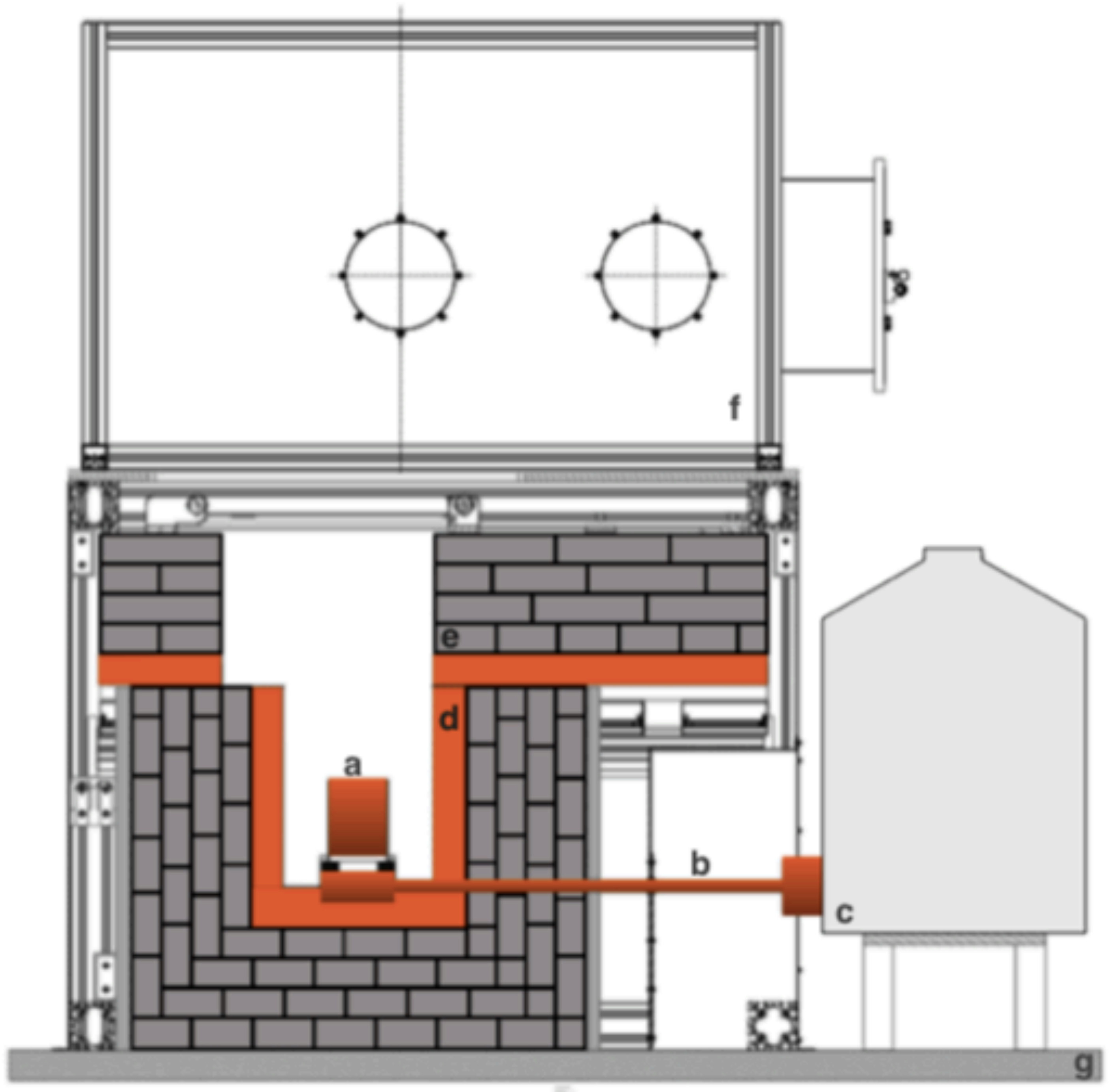
DESIGN CHALLENGES

Backgrounds:

- Active background suppression ⇒ distillation
- Techniques to select clean materials ⇒ gamma and Rn screening
- Techniques to monitor LXe purity at required level
- Cosmogenic background ⇒ go deep enough, add μ-veto and n-veto



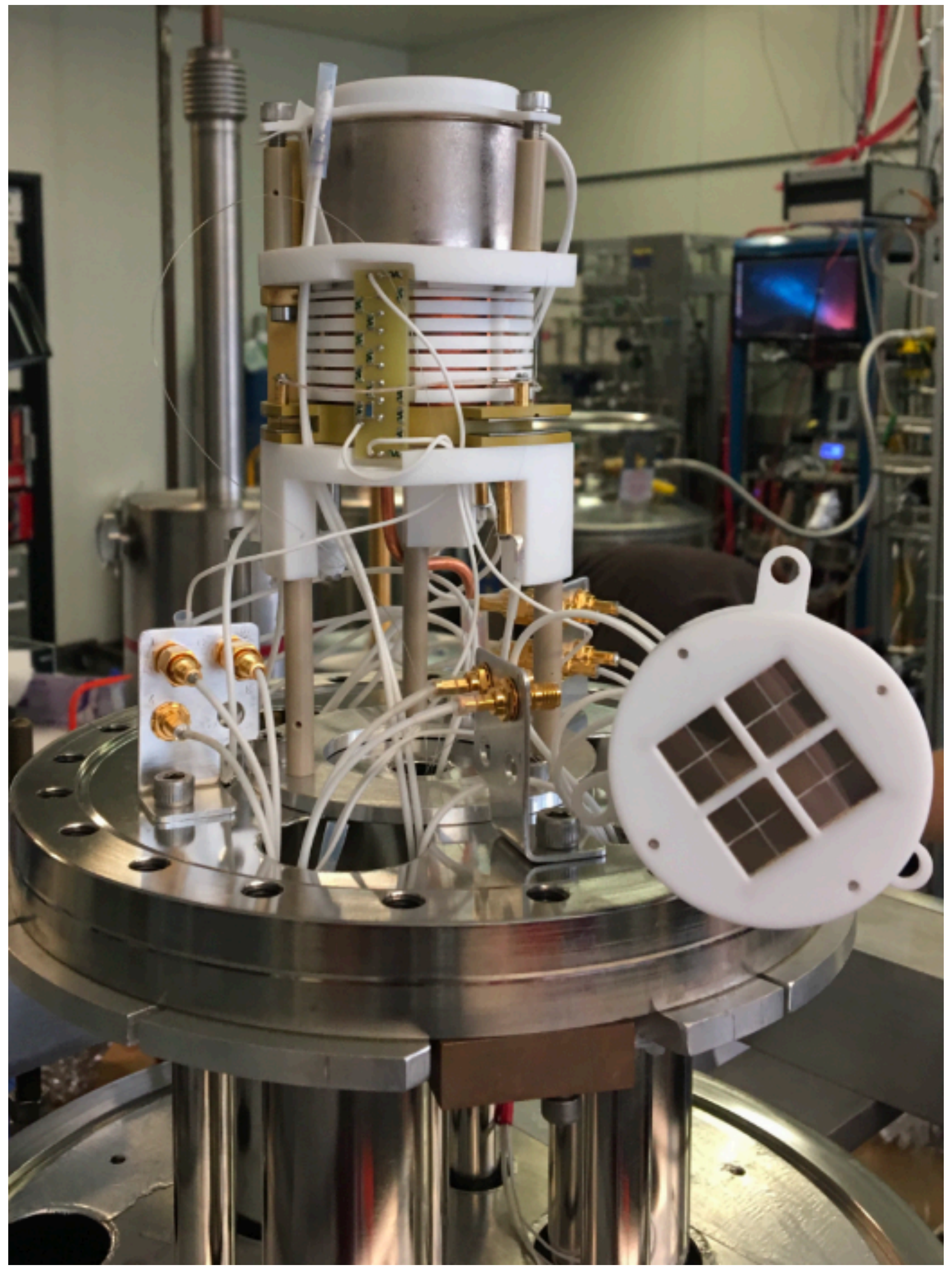
GATOR facility at LNGS



LOCAL R&D SETUPS FOR DARWIN AT U. ZURICH

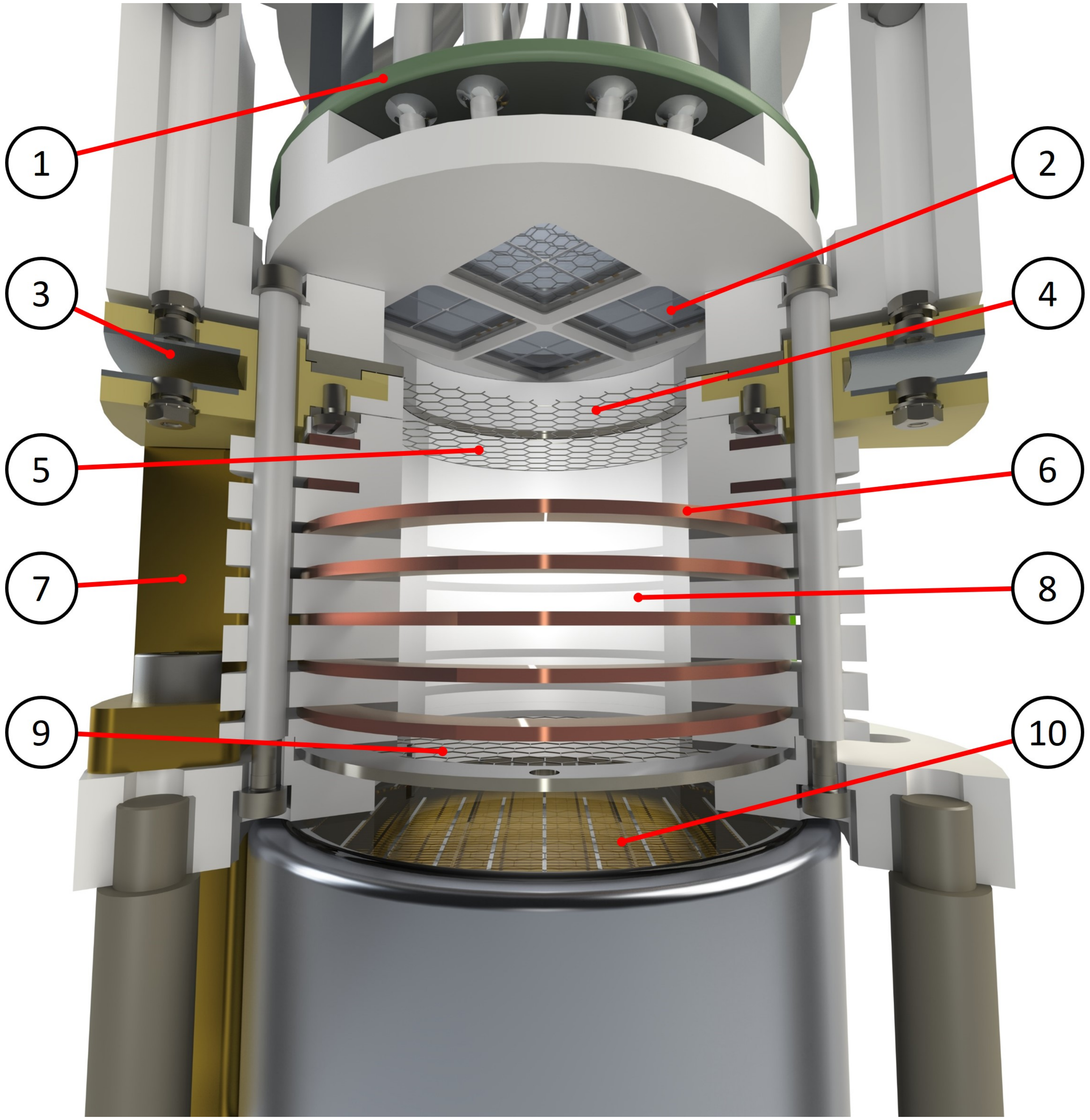
DARWIN Demonstrator – A 2.6m height TPC for electron drift proof of principle and future facility for testing

XURICH II – First dual-phase xenon TPC with SiPM readout and ultra-low energy calibration with 37-Ar



LOCAL R&D SETUPS AT U. ZURICH : XURICH II

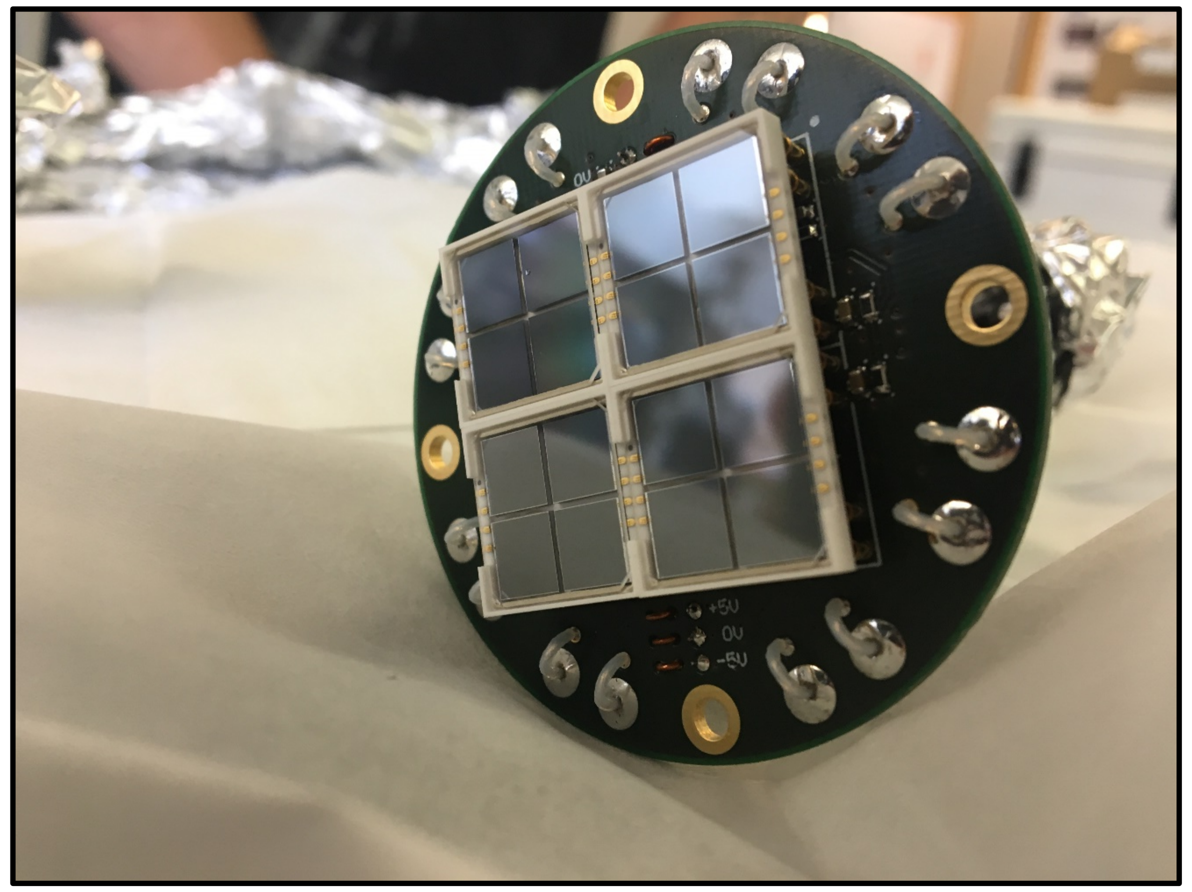
- Small-scale (31 mm (d) × 31 mm (h)) dual-phase TPC designed to study interactions in LXe < 50 keV
- 2 × 2 S13371 VUV-4 MPPCs from Hamamatsu in the top array – 16 channels!
- Mounted on ×10 pre-amplifier board
- 2-inch R9869 PMT from Hamamatsu at the bottom
- Up to 1 kV/cm drift field
- 10 kV/cm extraction field
- SiPM upgrade in Summer 2018, since then 12 months of stable operation



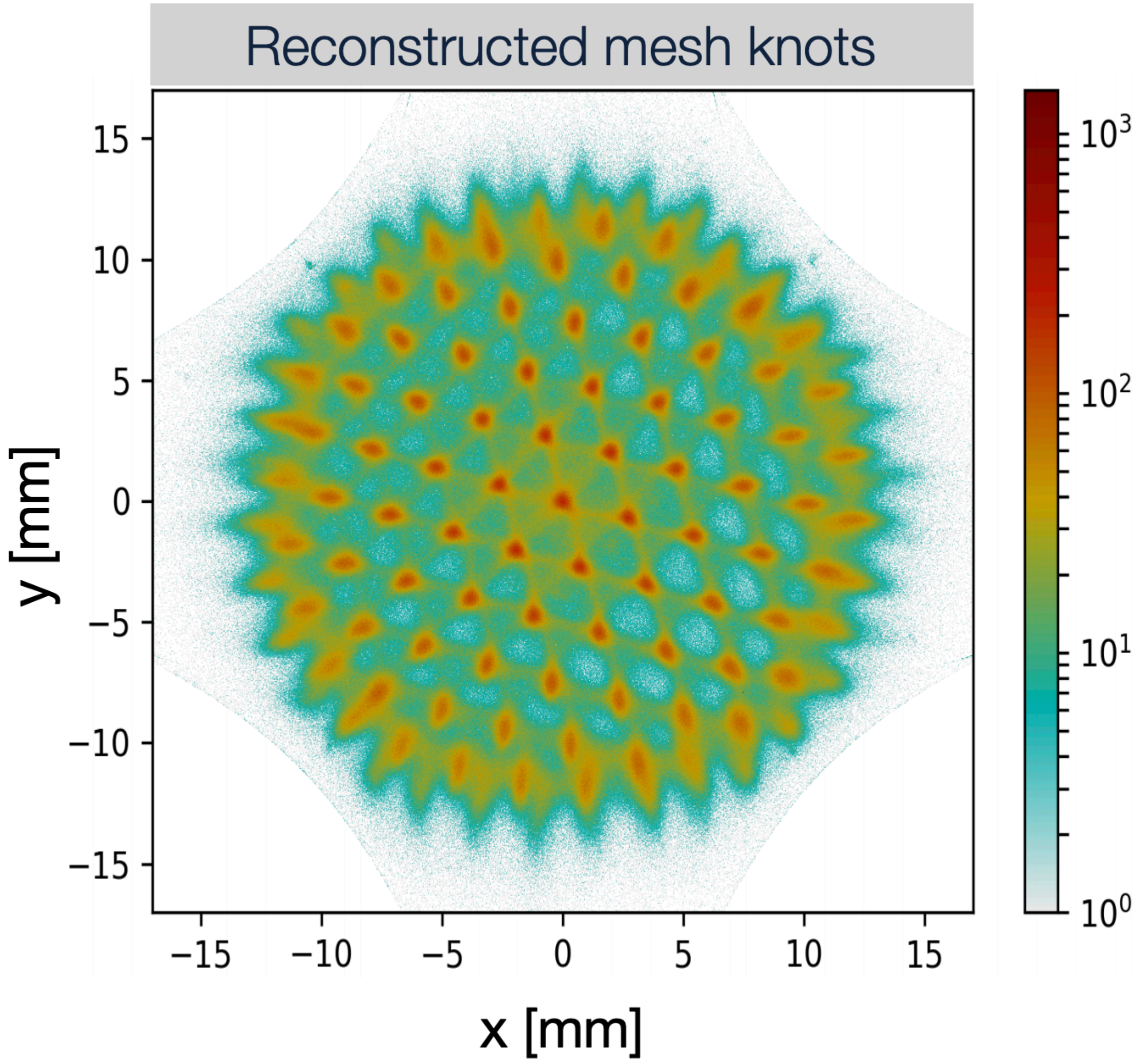
Eur. Phys. J. C78 (2018) 351

LOCAL R&D SETUPS AT U. ZURICH : XURICH II

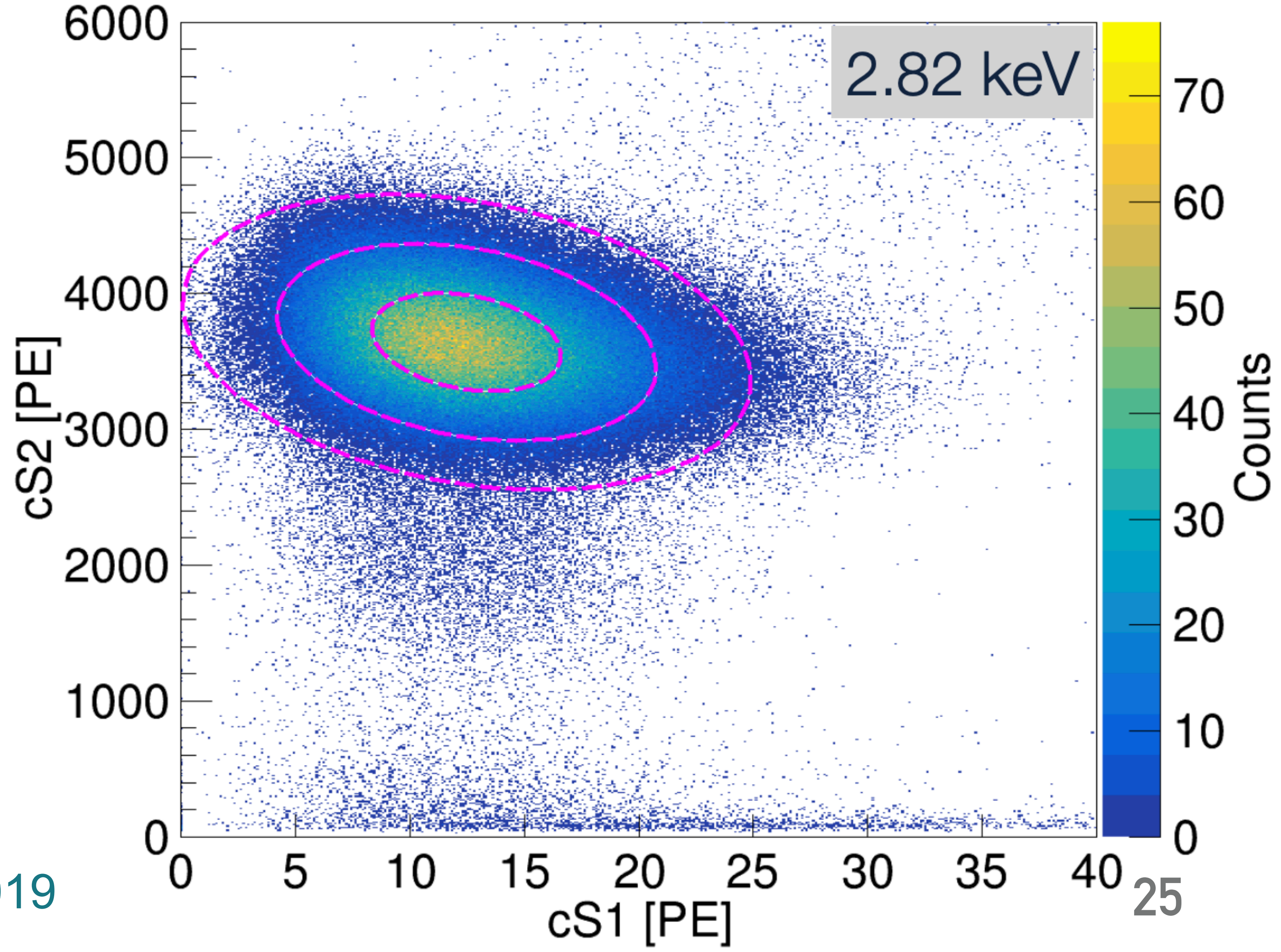
- 2×2 S13371 VUV-4 MPPCs (12×12) mm^2 from Hamamatsu, each has 4 (6×6) mm^2 independent segments, (50×50) µm^2 cells
- Operational voltage: 51.5 V
- Photon detection efficiency ~24 % at 178 nm
- Dark Count Rate: 0.8 Hz/mm^2 at LXe temperature
- Optical Crosstalk Probability ~3 %



SiPM arrays of Xurich-II with custom-made pre-amplified base



^{37}Ar calibration preliminary results!



More about Xurich II:
Kevin Thieme, LIDINE 2019

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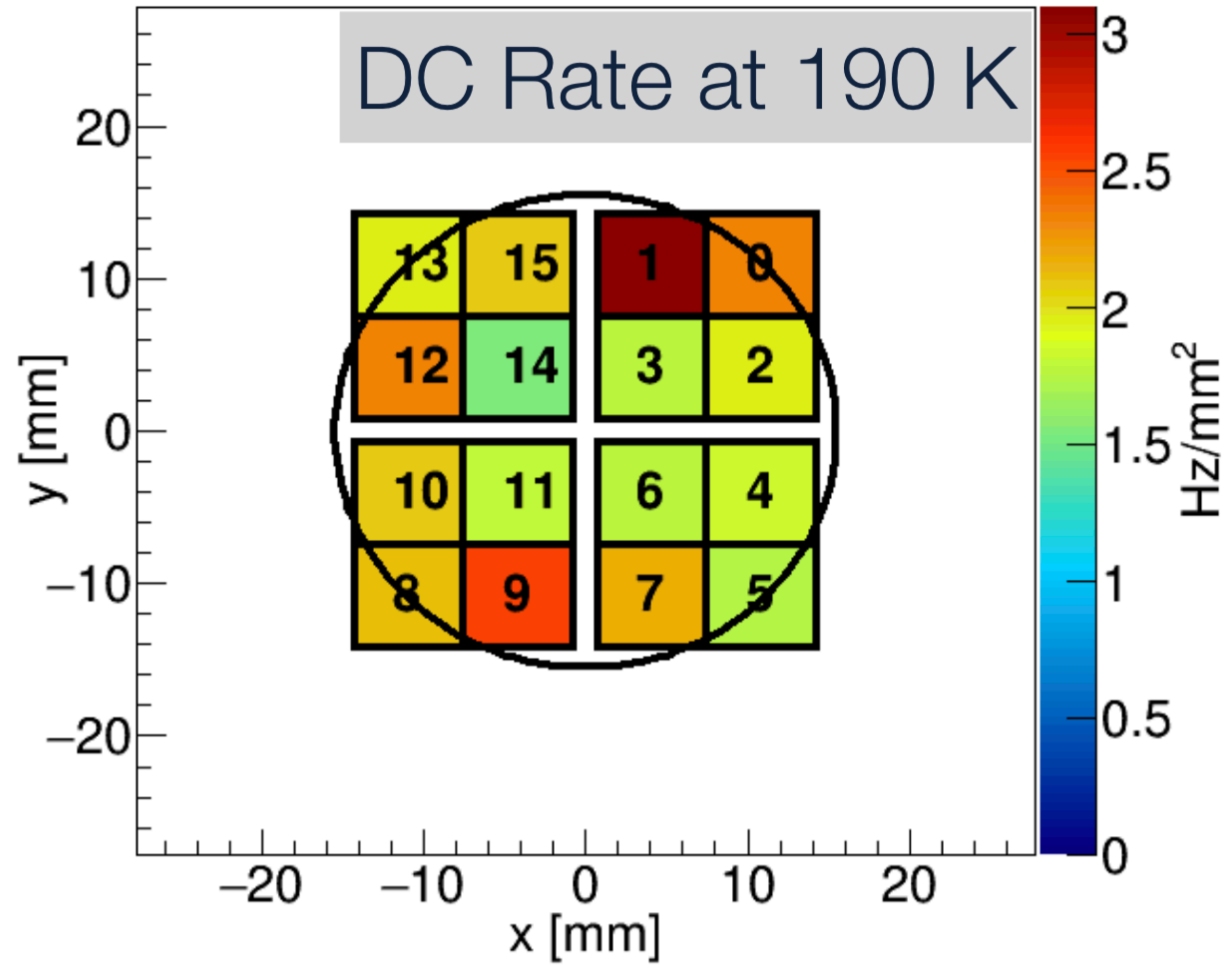

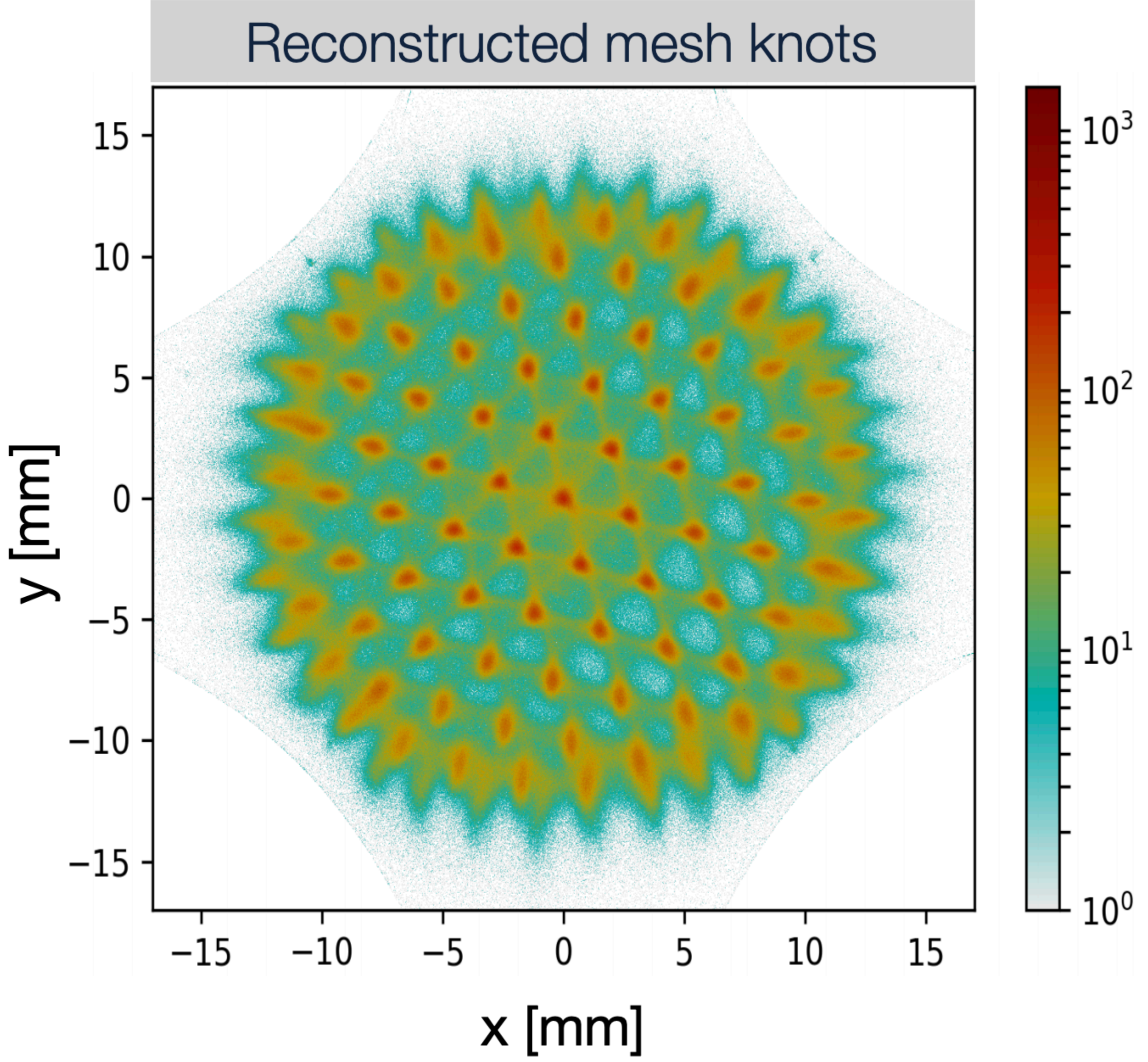

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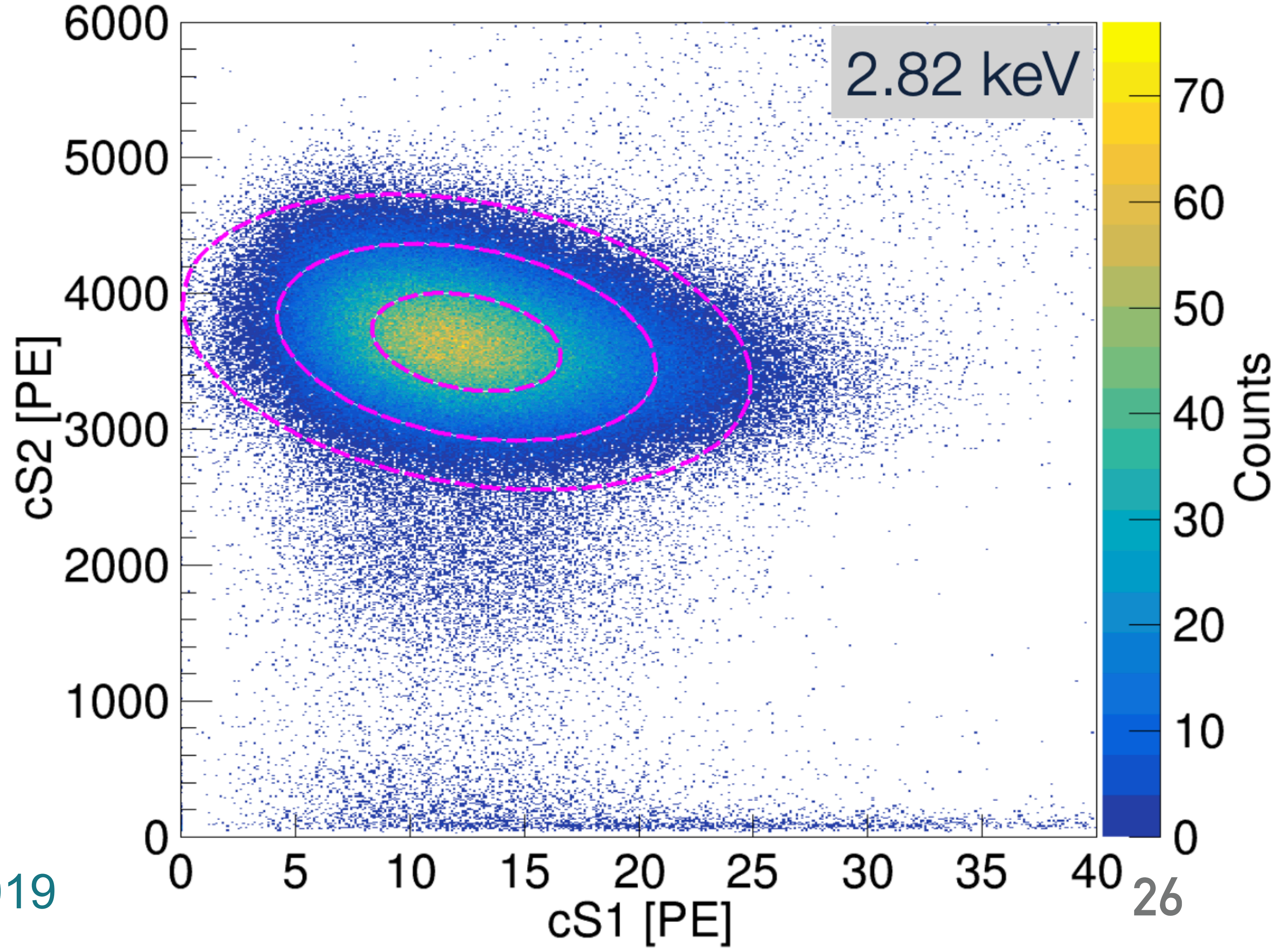


More about Xurich II:
Kevin Thieme, LIDINE 2019

LOCAL R&D SETUPS AT U. ZURICH : DARWIN DEMOSTRATOR

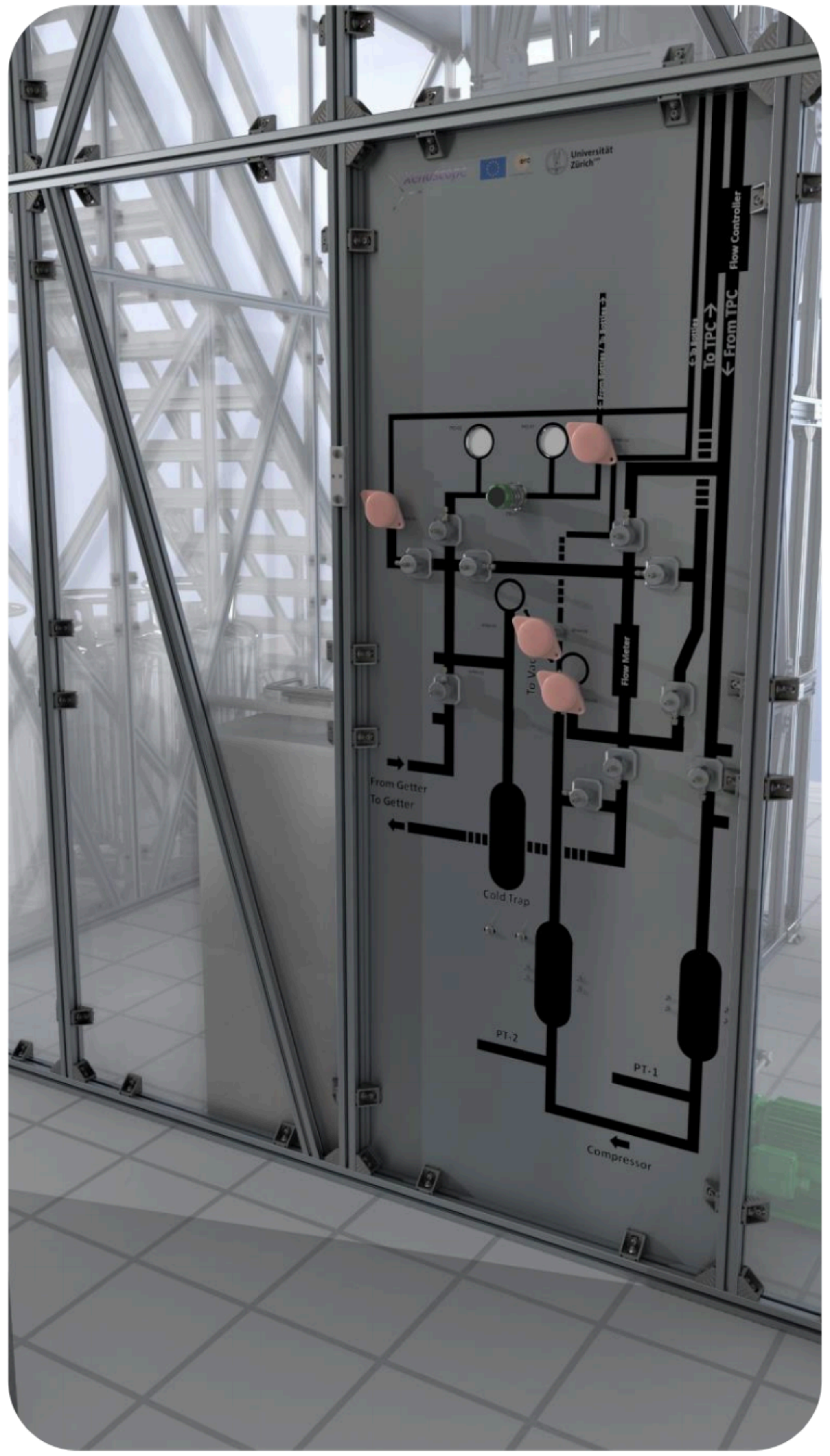
Construction and commissioning of a 2.6m height Xenon TPC

Plan: Render from beginning this year

Frame built August 2019!

LOCAL R&D SETUPS AT U. ZURICH : DARWIN DEMOSTRATOR

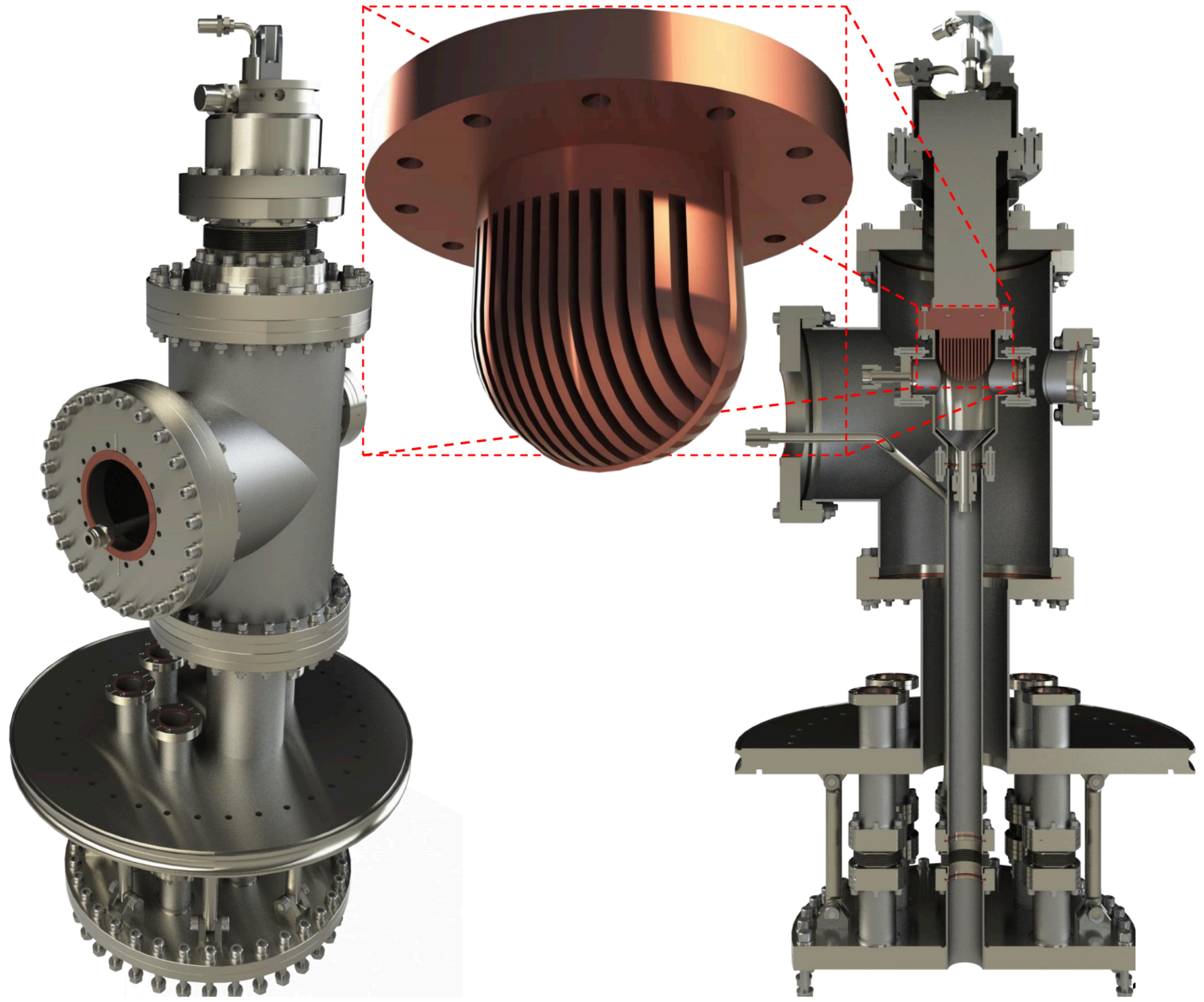
DARWIN

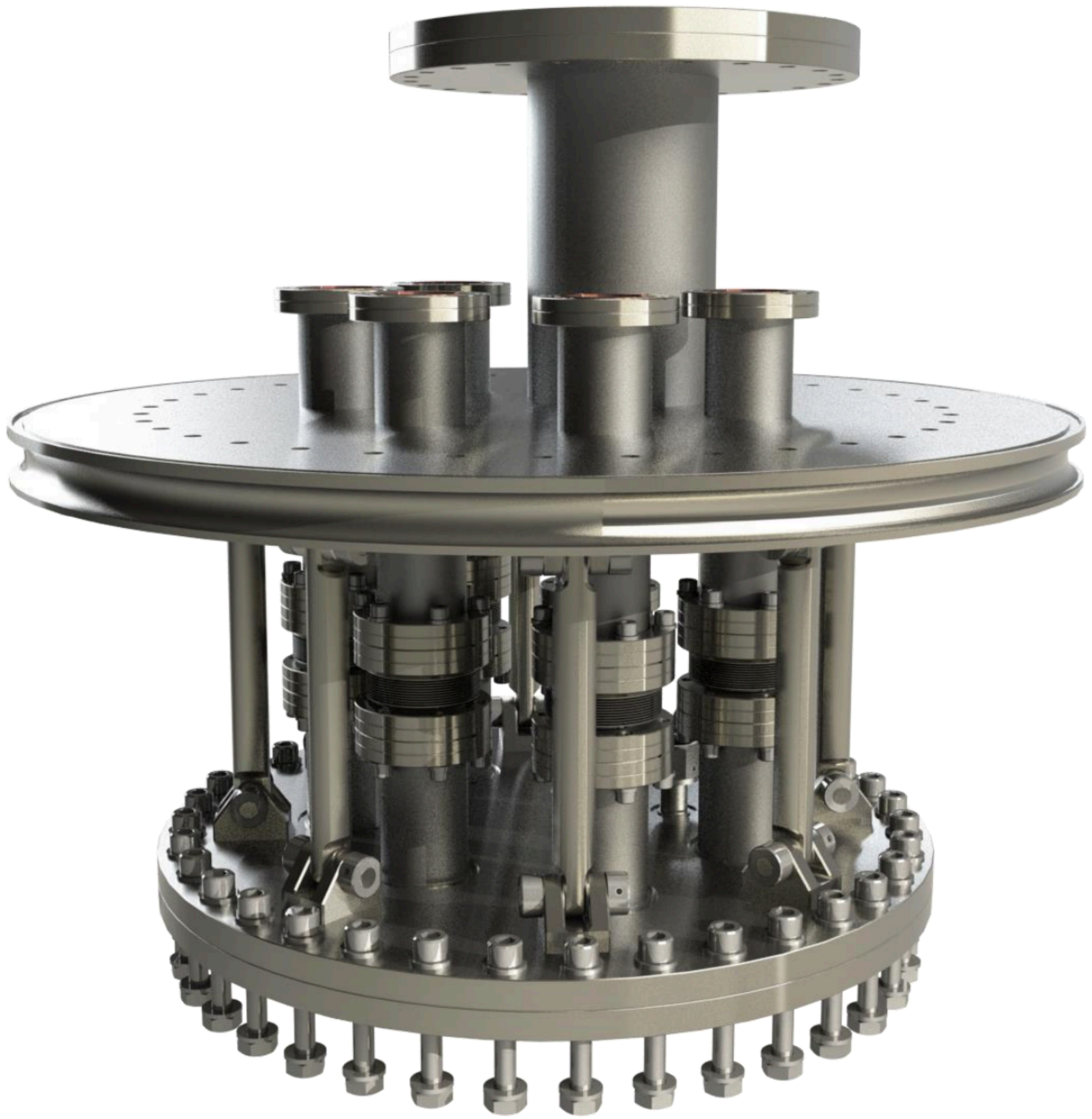


Gas system will be completed by the end of the year

- The cooling tower houses a PC-150 PTR from Iwatani
- Spherical cold head to maximise LXe contact time
- Work in progress

Currently performing various simulations and designs.





Top flange revised with engineering group for thermal and mechanical stability

SUMMARY DARWIN DESIGN, GOALS AND CHALLENGES

- DARWIN will be the ultimate liquid xenon dark matter detector
- DARWIN will also provide a unique opportunity for other rare event searches such as:
  Low Energy solar neutrinos
  Neutrinoless double-beta decay
  CNNS
  Axions and axion-like particles
- DARWIN : growing collaboration, currently **29 groups from 12 countries**.

DARWIN SCIENCE PROGRAM: MORE THAN DARK MATTER SEARCHES

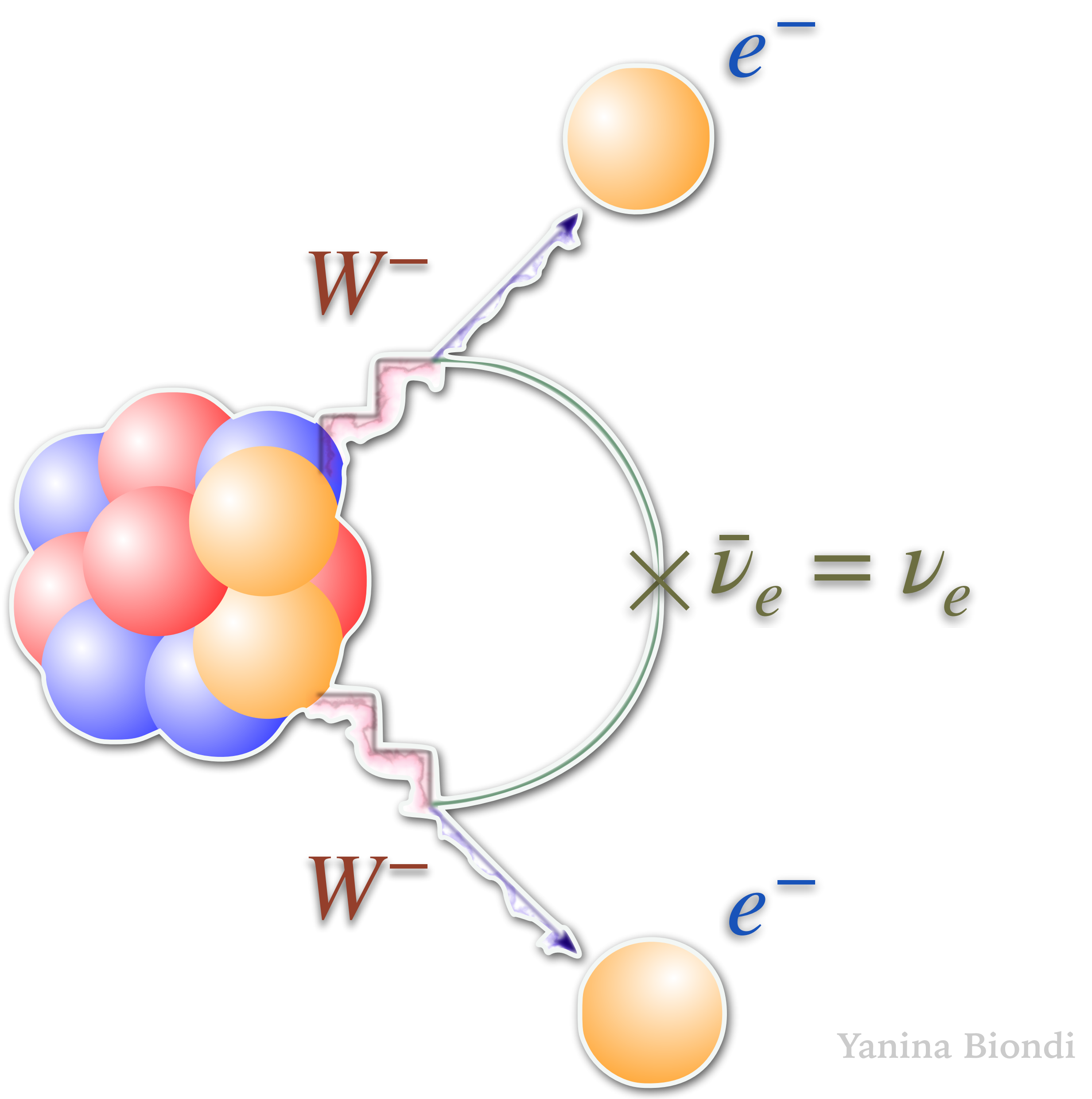
Given its projected low background and large mass, DARWIN will be sensitive to other rare physics processes such as:

ER

- Solar Axions and Axion Like Particles
- Low energy Solar Neutrinos: pp, ^{7}Be
- Neutrinoless Double Beta Decay

NR

- Coherent Neutrino Nucleus Scattering
- Supernova Neutrinos

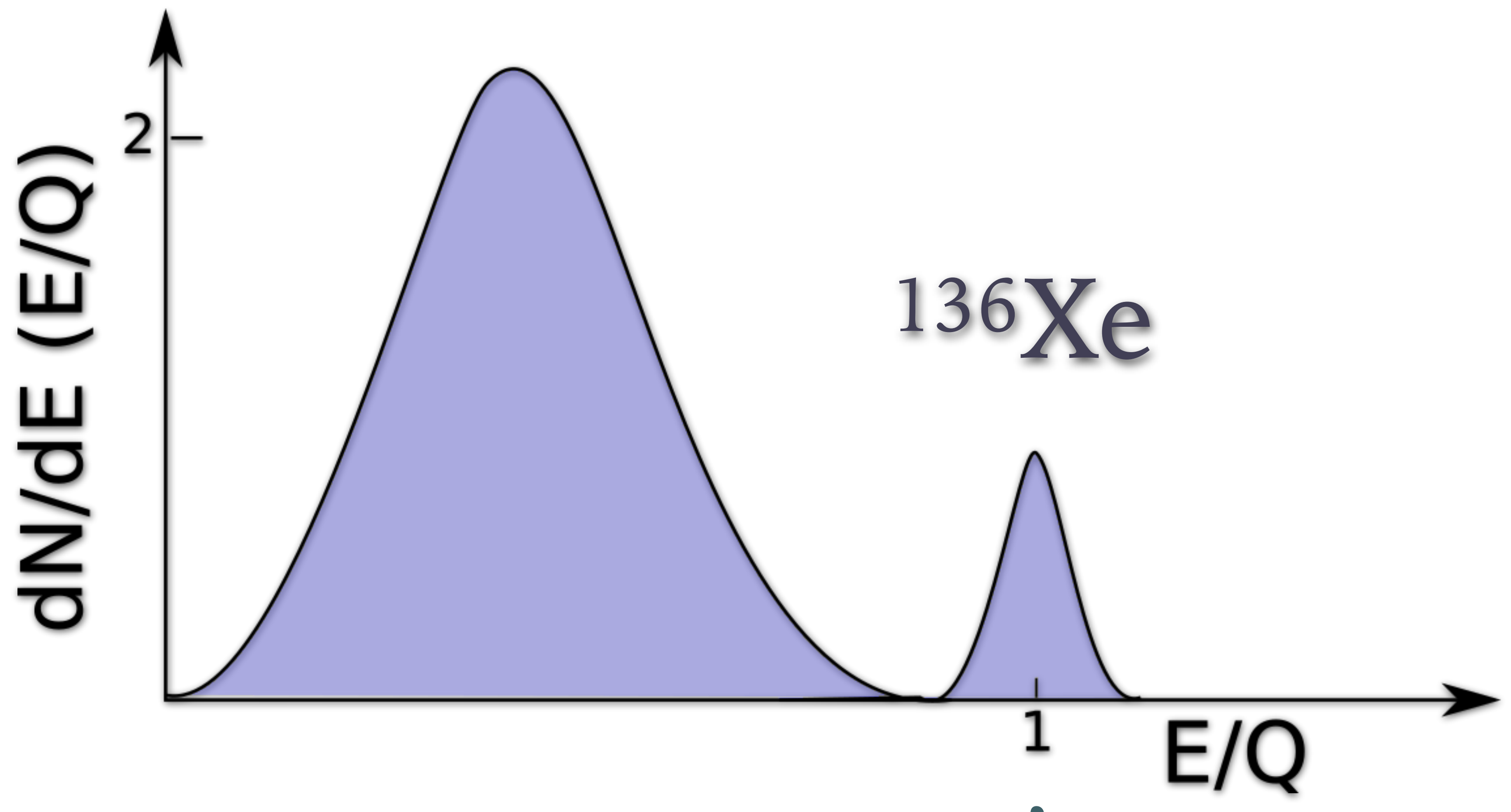


Exchange of a Majorana neutrino

$$\mathscr{L}^{\mathrm{L}}(x) = -\frac{1}{2}\sum_{l',l} \bar{\nu}_{l'L}(x) M^L_{l'l} \left(\nu_{lL}\right)^c(x) + \mathrm{h.c.}$$

NEUTRINOLESS DOUBLE BETA DECAY: A WINDOW TO NEW PHYSICS

DARWIN provides the opportunity to study this process for free



$$T^{0\nu}_{1/2} \propto f \cdot a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Signal coverage ~ 0.76 for FWHM
Natural abundance 8.9%   Efficiency 90%

- ^{136}Xe has a natural abundance of 8.9% in natural Xe, ~3.5 t in 40t

$$Q = (2457.83 \pm 0.37) keV$$

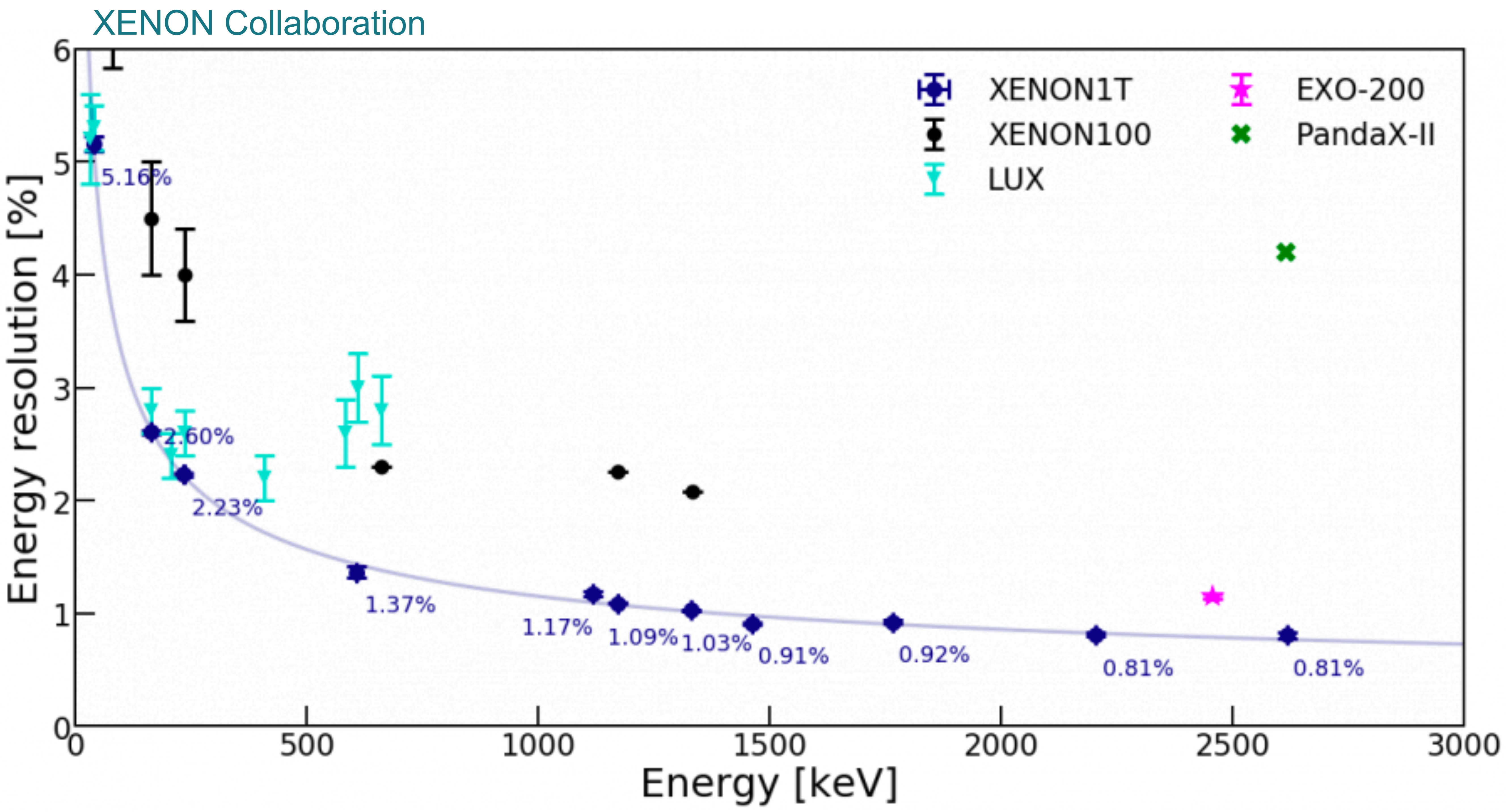
Above the region of interest for WIMPs

- Expected Energy resolution of ~0.8% at 2.5 MeV
- Ultra-low background environment achieved via xenon purification and screening campaigns

ENERGY RESOLUTION IN LXE TPC

The XENON1T Collaboration reached an unprecedented energy resolution, below 1% at Q-value, in a dual phase TPC.

- Improvements for high-energies:
  - Saturation Correction
  - Peak clustering
  - After-pulse removal



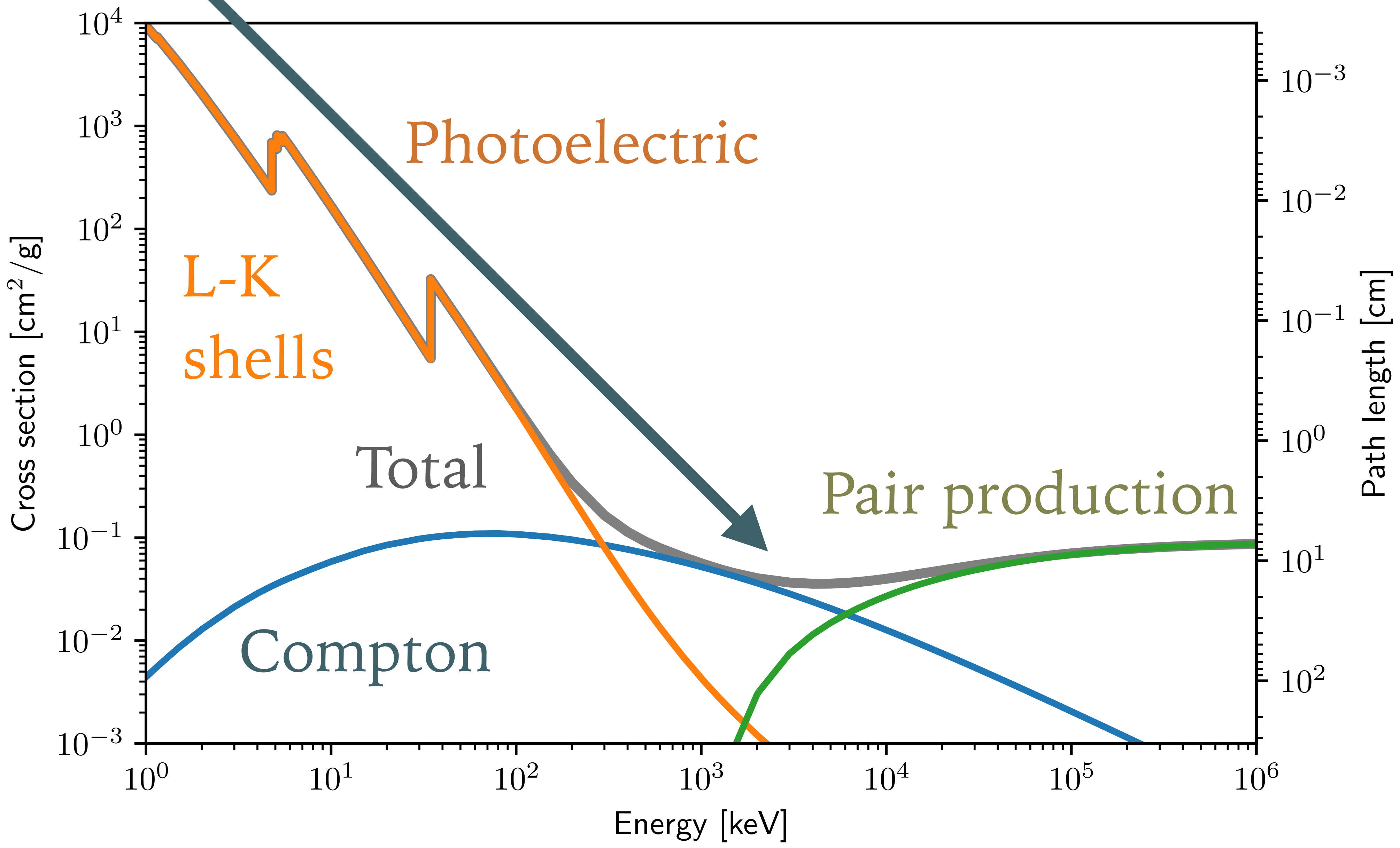
Energy resolution fit

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E[keV]}} + b$$

BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

Materials

Mostly gammas from detector components with low attenuation in LXe due to their energy



Contaminants in LXe

^{222}Rn in the LXe

$2\nu\beta\beta$

$T_{1/2} = (2.165 \pm 0.075) \times 10^{21} y$

Cosmogenic

^{137}Xe from cosmogenic activatio

Solar neutrinos

Irreducible ^{8}B solar neutrinos

EXO Collaboration, J.B. Albert et al., Phys. Rev. C 89 (2014) 015502.

BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

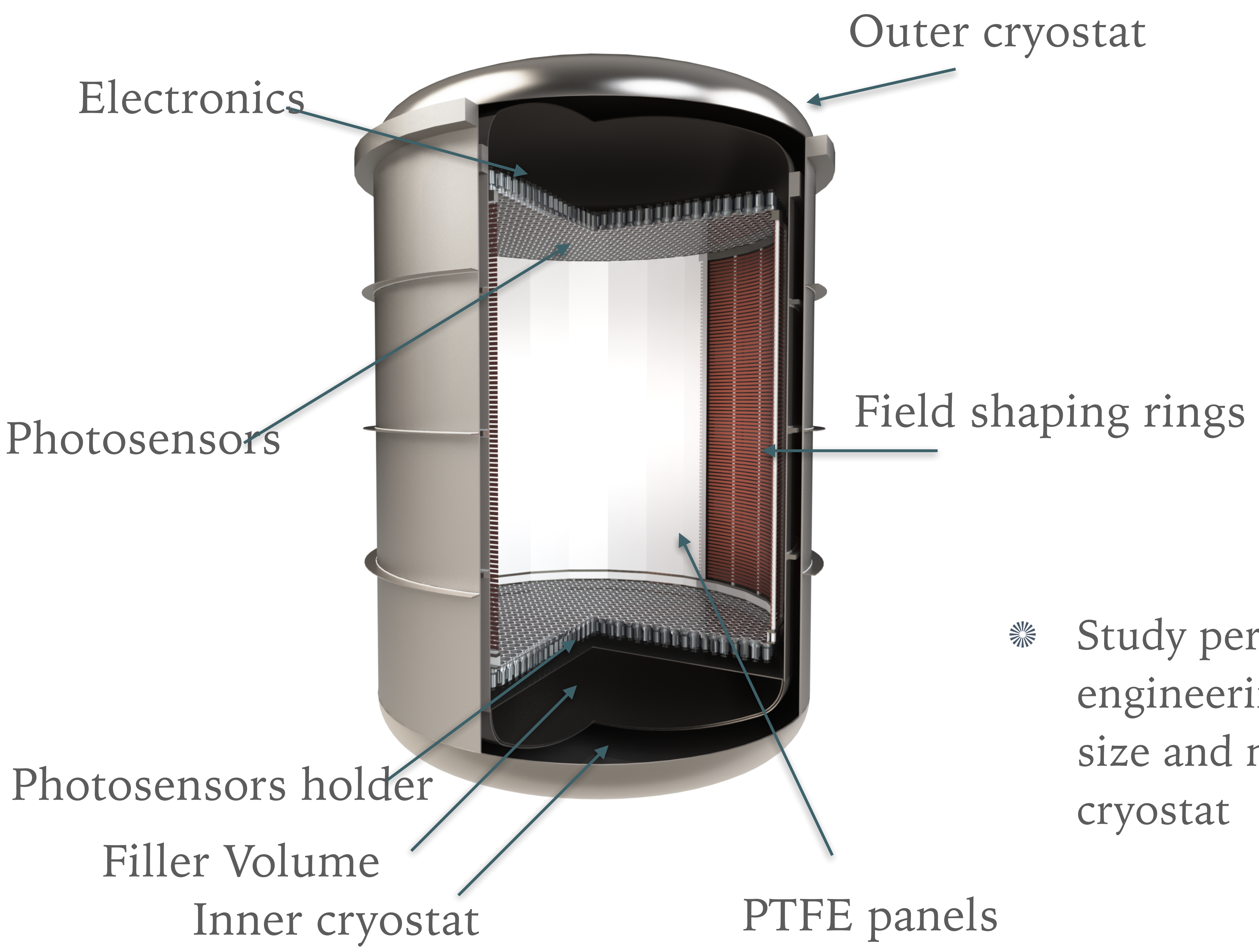
Materials

Critical components for the background are fully simulated in detail
Elements under consideration: Photosensors (PMT, SiPM,…)

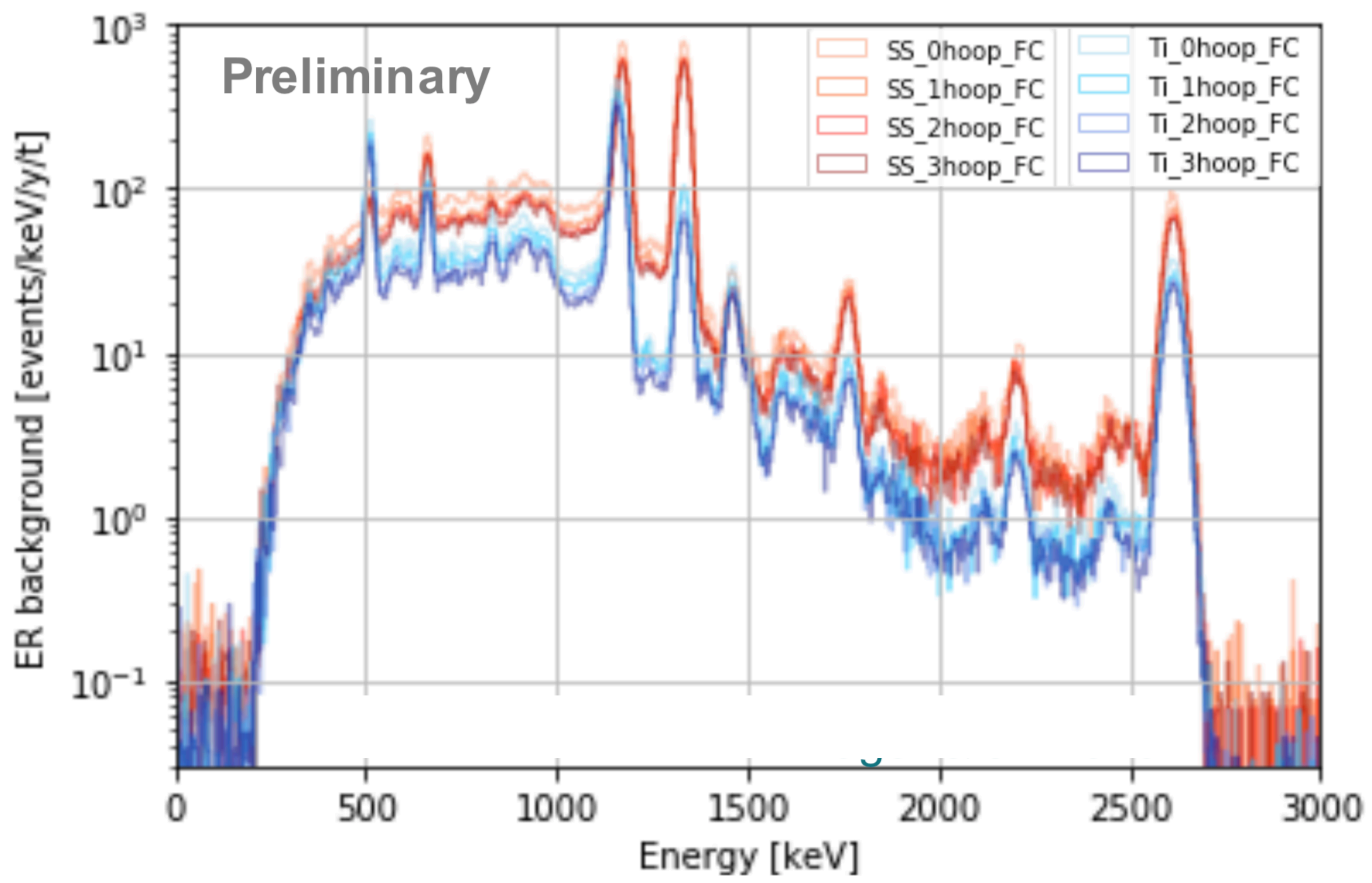
XENON Collaboration, Eur. Phys. J. C (2017) 77: 881.

Materials	Mass [kg]	^{226}Ra*	^{228}Th*	^{60}Co*
Ti	5717.7	<0.09	0.23	<0.03
PTFE	301.2	0.07	<0.06	<0.02
Cu	1199.3	<0.035	<0.026	<0.02
Cirlex	7.6	17.7	3	<0.10
SiPM[1]	5.7	<0.0075	<0.0092	-
PMT[2]	378.8	0.6	0.6	0.84

[1] per cm^2
[2] per unit
* mBq/kg



- Study performed by the engineering group to optimise size and materials for the cryostat



LZ Collaboration, *Physics* 96 (2017): 1-10.

BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

DARWIN

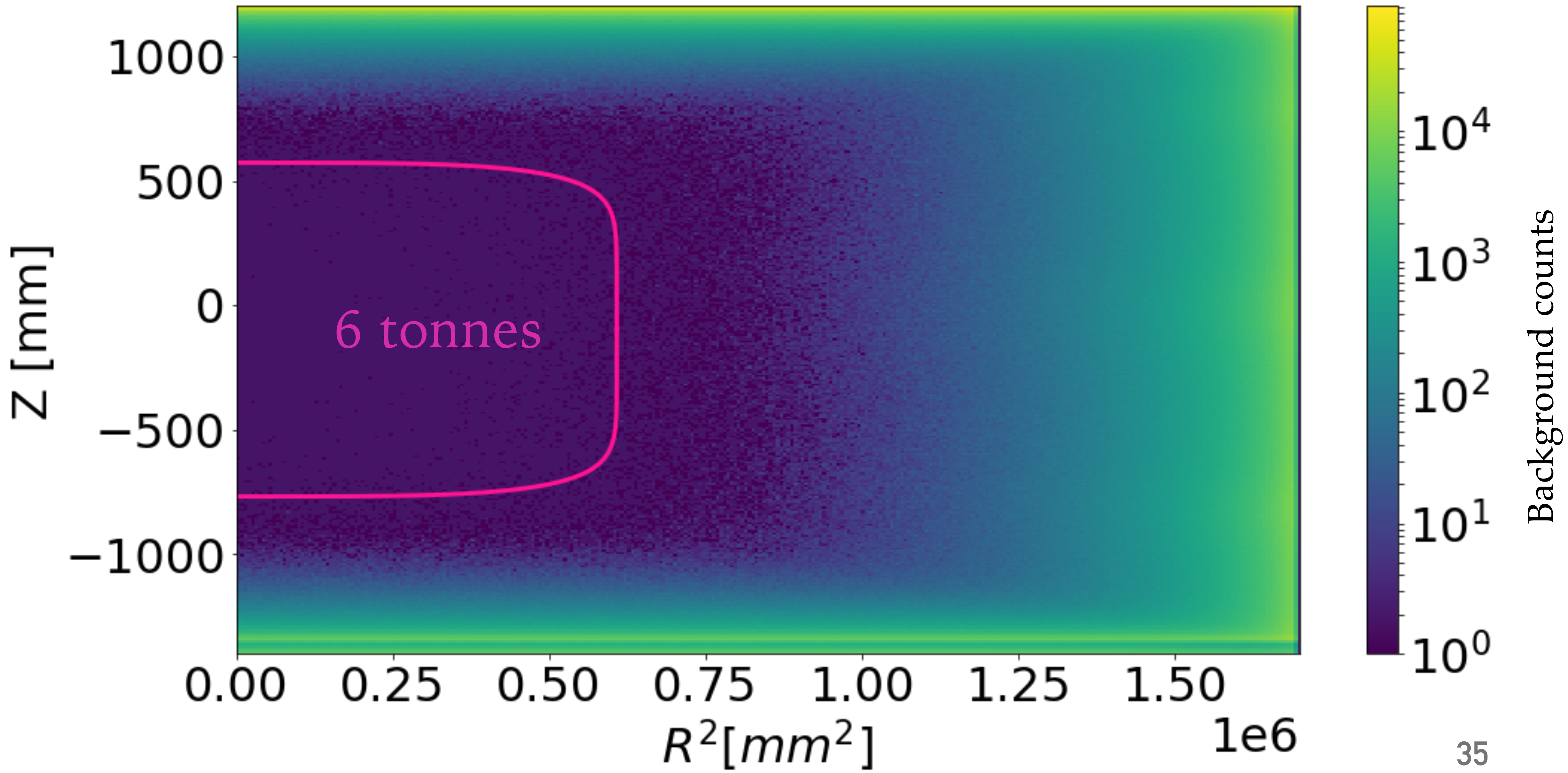
Materials

Background contribution per material component

- Cryostat was optimised with Ti material and stiffeners for low mass
- Different photosensors: SiPM, PMTs (shown below)
- Superellipsoid fiducial volume cut

Single Scatter ~ 15 mm resolution
(very conservative)
~99% of signal events end in SS spectra

Preliminary



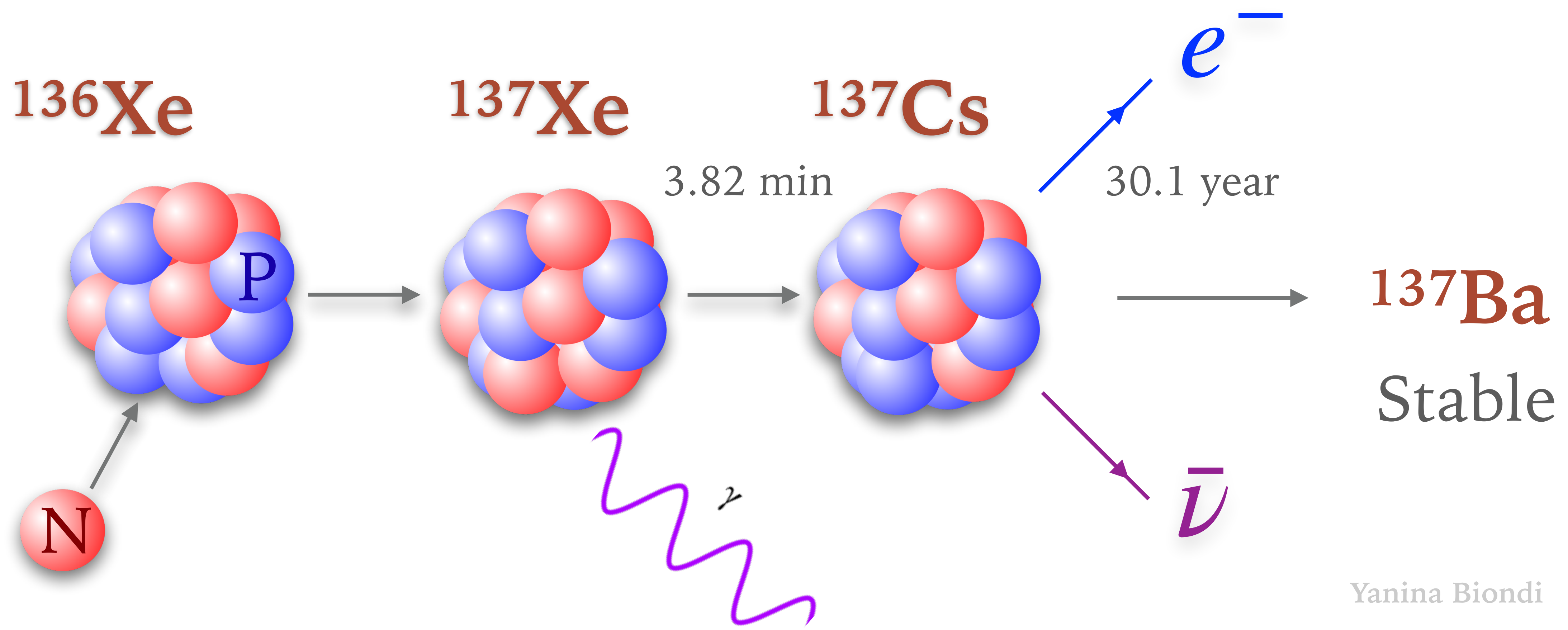
BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

DARWIN

Cosmogenic

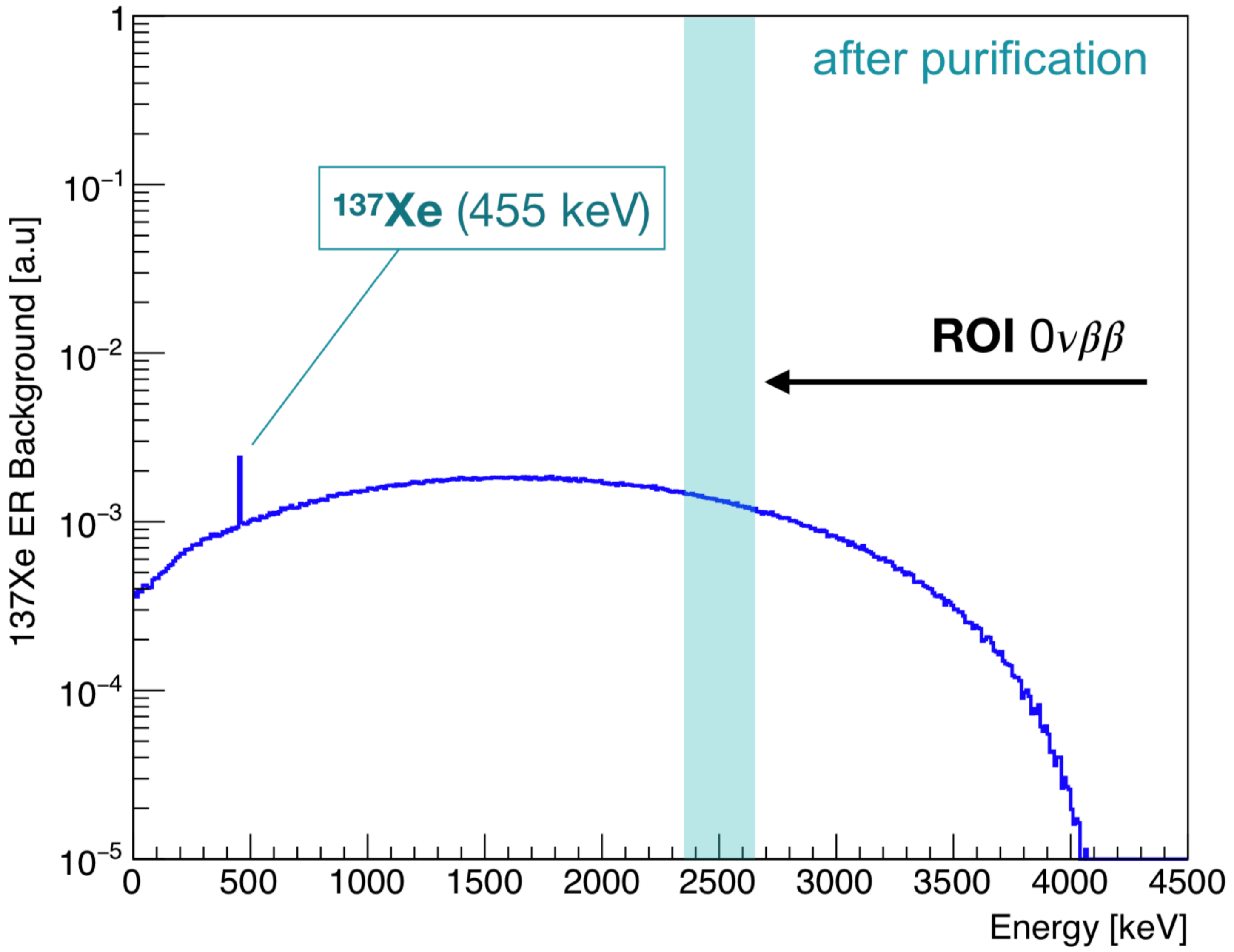
^{137}Xe from cosmogenic activation underground

- ^{137}Xe beta decays with a Q-value of **4173 keV**
- **Uniform** background inside the detector
- Primary background from betas



- Neutrons from natural radioactivity in the rock/concrete ✗
- Neutron from natural radioactivity in detector's ✗ materials
- Muon induced neutrons in the rock and concrete ✗
- Muon induced neutrons in the materials of the detector

^{137}Xe is mainly produced when muon-induced neutrons are captured by ^{136}Xe



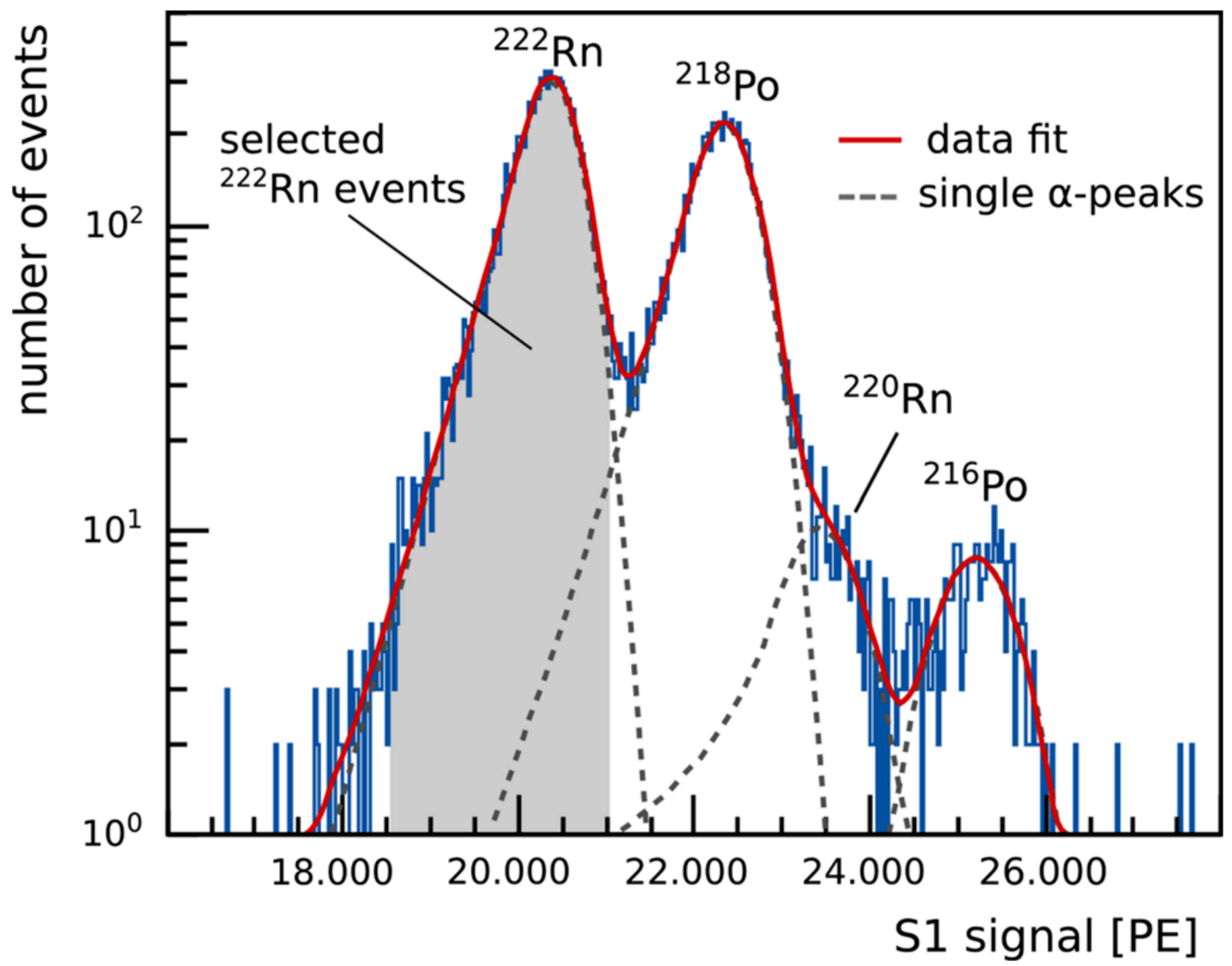
Production rate for ^{137}Xe in LNGS: 6.7 atoms/t/y

BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

Contaminants in LXe

- The noble gas ^{222}Rn ($T_{1/2} \approx 3.8$ days) from ^{226}Ra ($T_{1/2} \approx 1600$ years), mixes with the xenon with beta decays from this chain.
- ^{214}Pb and daughters a**dhere** to material surfaces (**plate-out**) and can lead to **(α, n) reactions**
- Contamination assumption $0.1 \mu Bq/kg$

XENON Collaboration, Eur. Phys. J. C (2017) 77:358

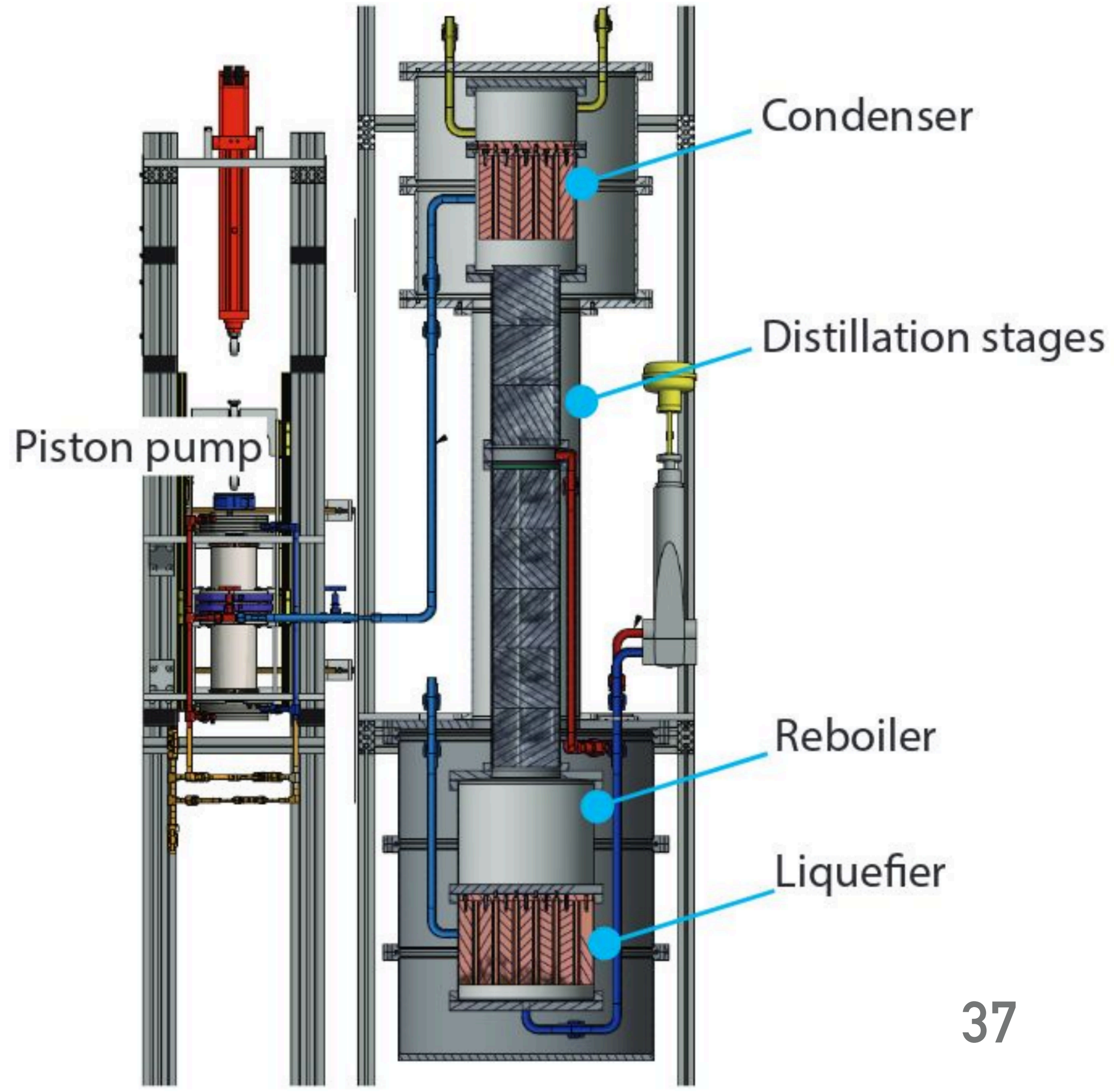


Bi-Po : 99.8% tagging efficiency and suppression

Removal by cryo-distillation columns

More info in Michael Murra’s Poster

XENON Collaboration



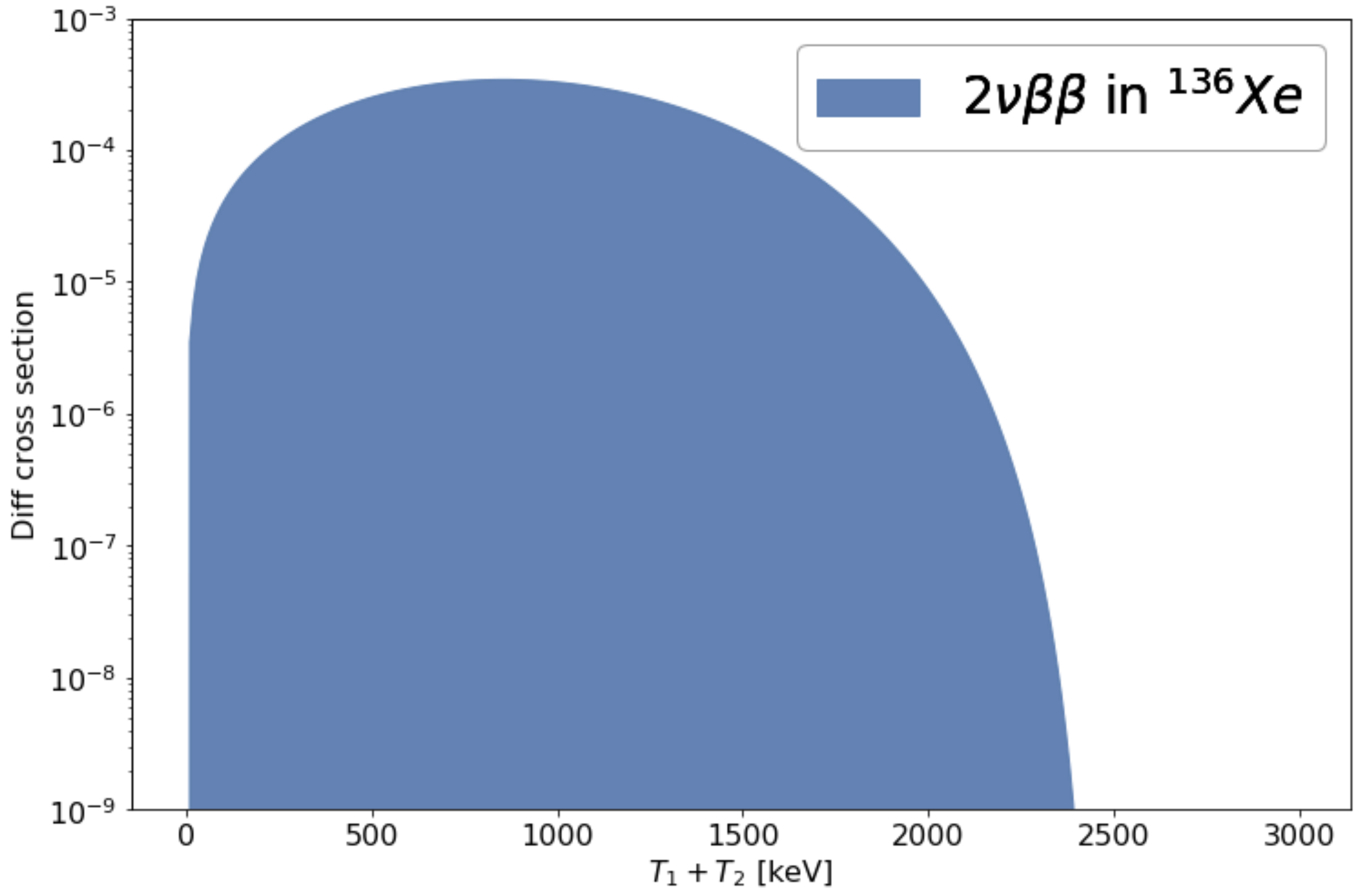
BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

DARWIN

$2\nu\beta\beta$

Double beta decay of two neutrons:

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2}$$



Solar neutrinos

Irreducible ^{8}B solar neutrinos

$$\nu + e \rightarrow \nu + e$$

Neutrino electron scattering with the target LXe

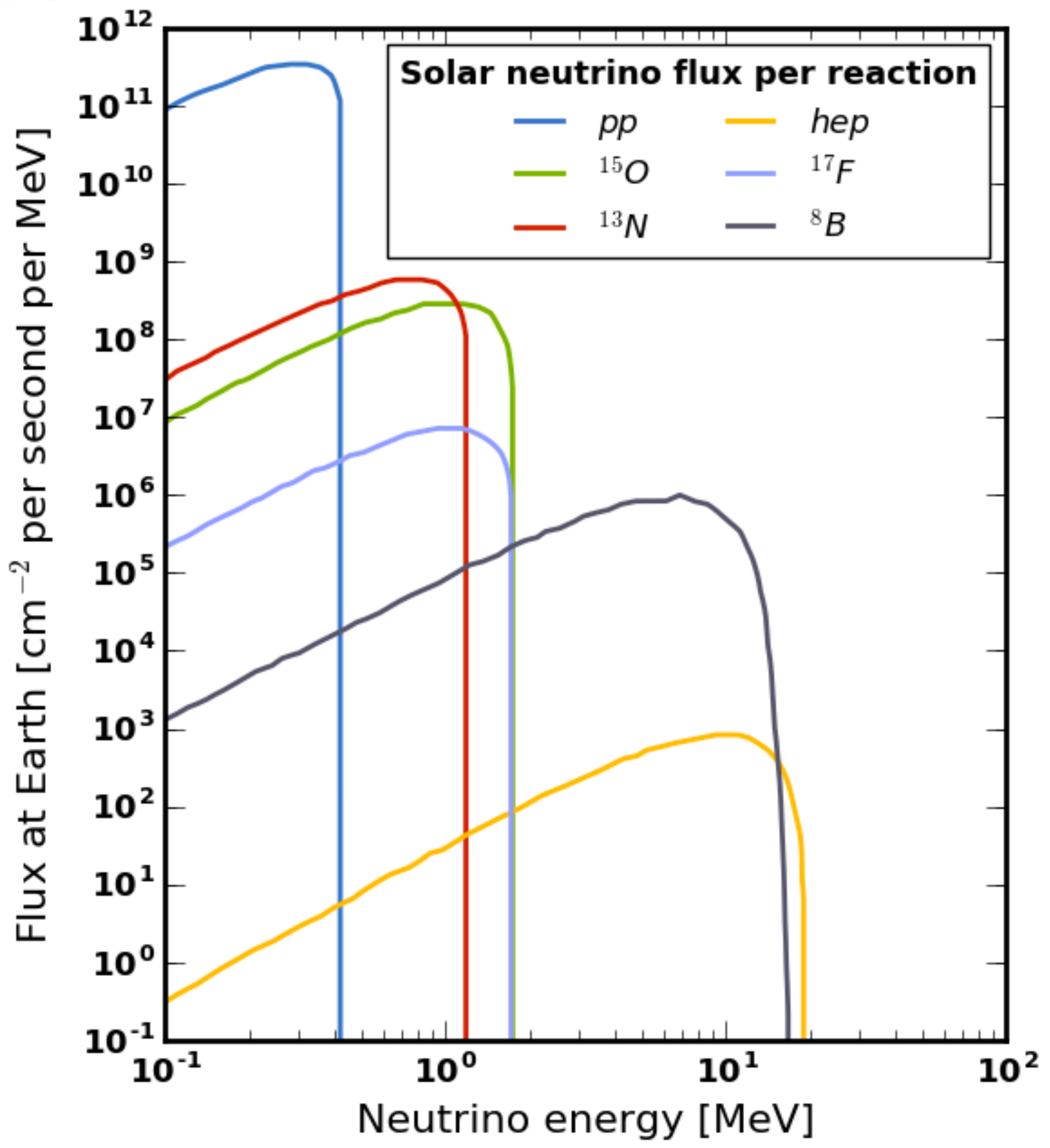
$$\phi_{\nu e} = 5.82 \times 10^6 cm^{-2} s^{-1}$$

$$P_e = 0.534$$

$$\sigma_{\nu e}(\sigma_{\nu\mu}) = 59.4 \times 10^{-45} (10.6 \times 10^{-45}) cm^2$$

Bahcall, J. Serenelli, A.,Basu, S

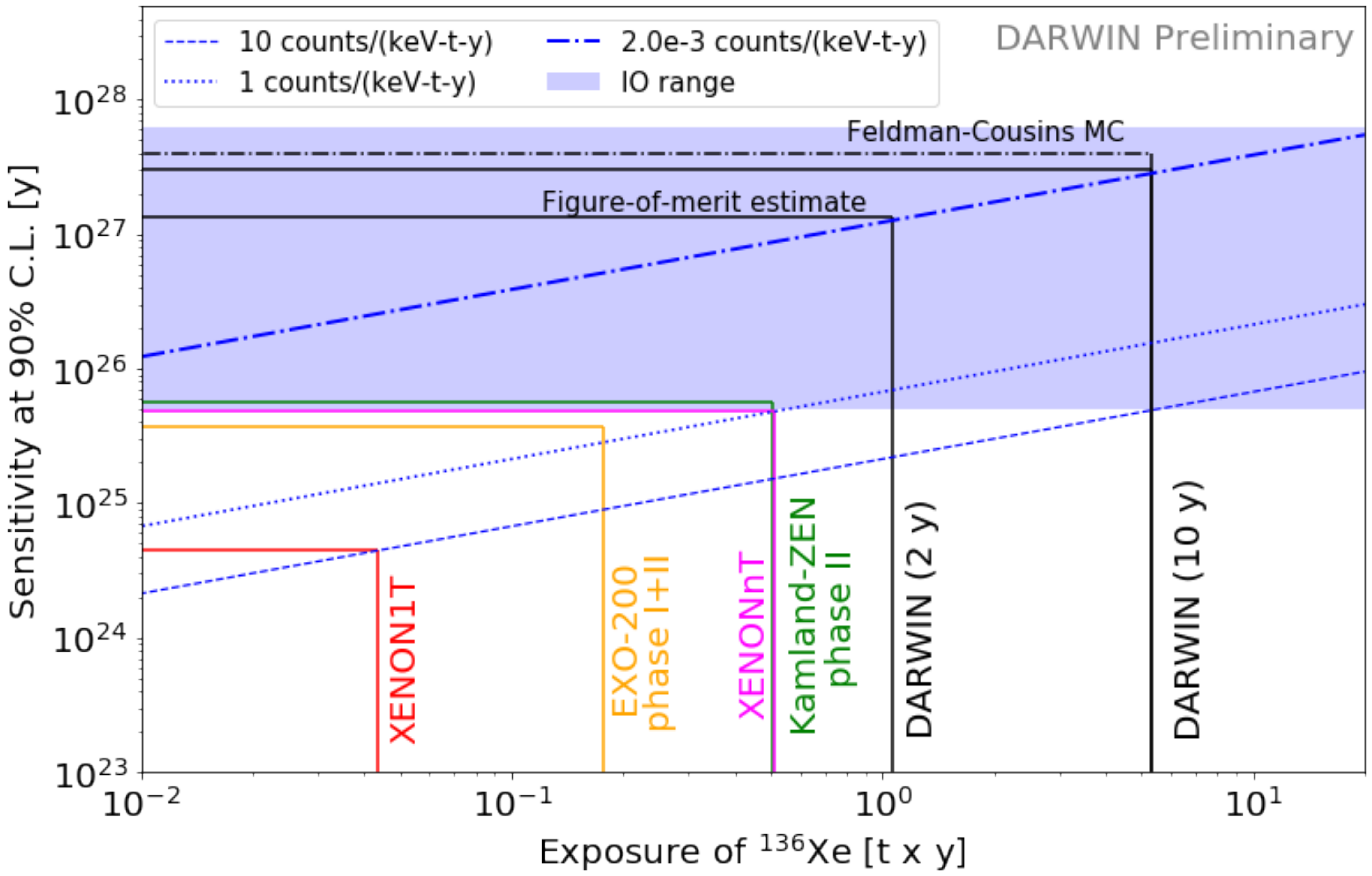
Astrophys. J. **621**: L85–L88



Baudis, L., et al. "Neutrino physics with multi-ton scale liquid xenon detectors." *JCAP* 2014.01 (2014): 044.

DARWIN'S BACKGROUND BUDGET

DARWIN



Contributions in
ROI 2435-2481 keV* SS spectra:

Background	Events/(t y keV)
^{8}B	2.4×10^{-4}
^{137}Xe	1.4×10^{-3}
^{136}Xe	3.7×10^{-7}
^{222}Rn	3.0×10^{-4}
Materials	$f(M_{fiducial})$

* FWHM with energy resolution 0.8%,
PMT for both arrays scenario
~15 mm resolution x-y-z

SUMMARY NEUTRINOLESS DOUBLE BETA DECAY IN DARWIN

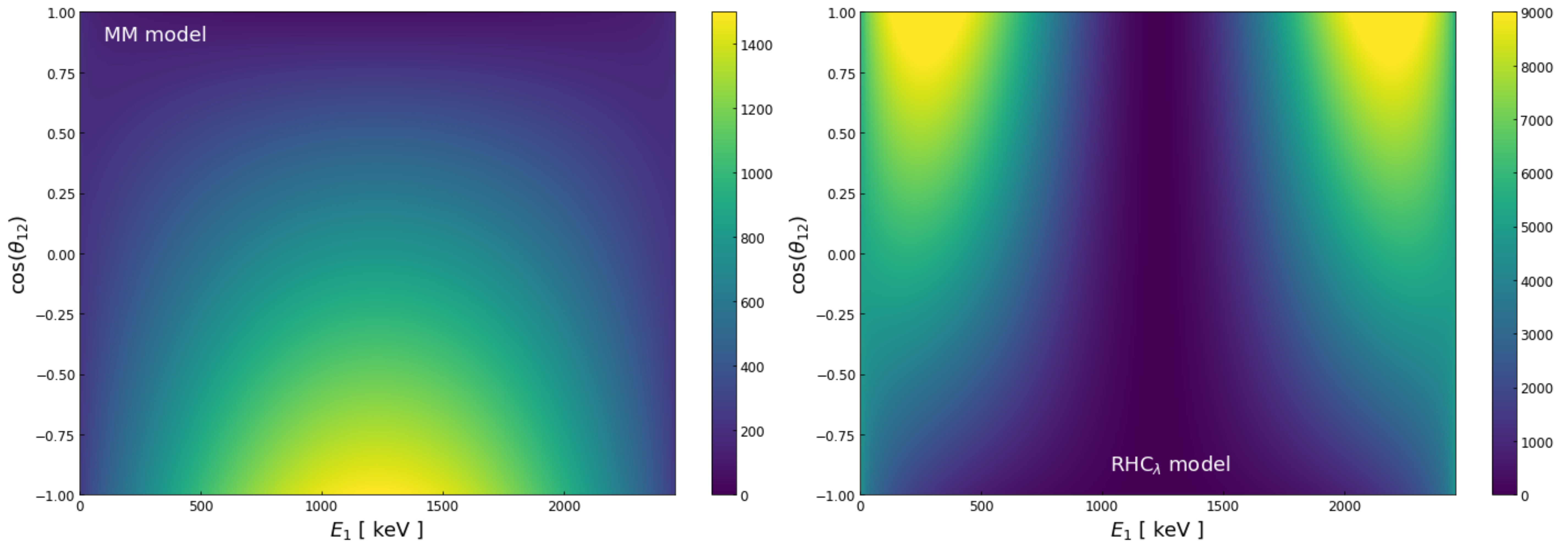
- Full assessment of background contribution for the neutrino-less double beta decay channel successfully performed
- ^{137}Xe was calculated and simulated for the first time as a background in Laboratori Nazionali del Gran Sasso, one of the potential locations of DARWIN
- SiPM are strong alternative candidates for photosensors that imply less background
- The study will continue performing simulations for SiPM(and/or other lower activity photosensors) scenario
- Statistical tests for the sensitivity are being performed

Thanks for your attention!

BACK UP SLIDES

TOPOLOGY OF NEUTRINOLESS DOUBLE BETA DECAY IN LXE

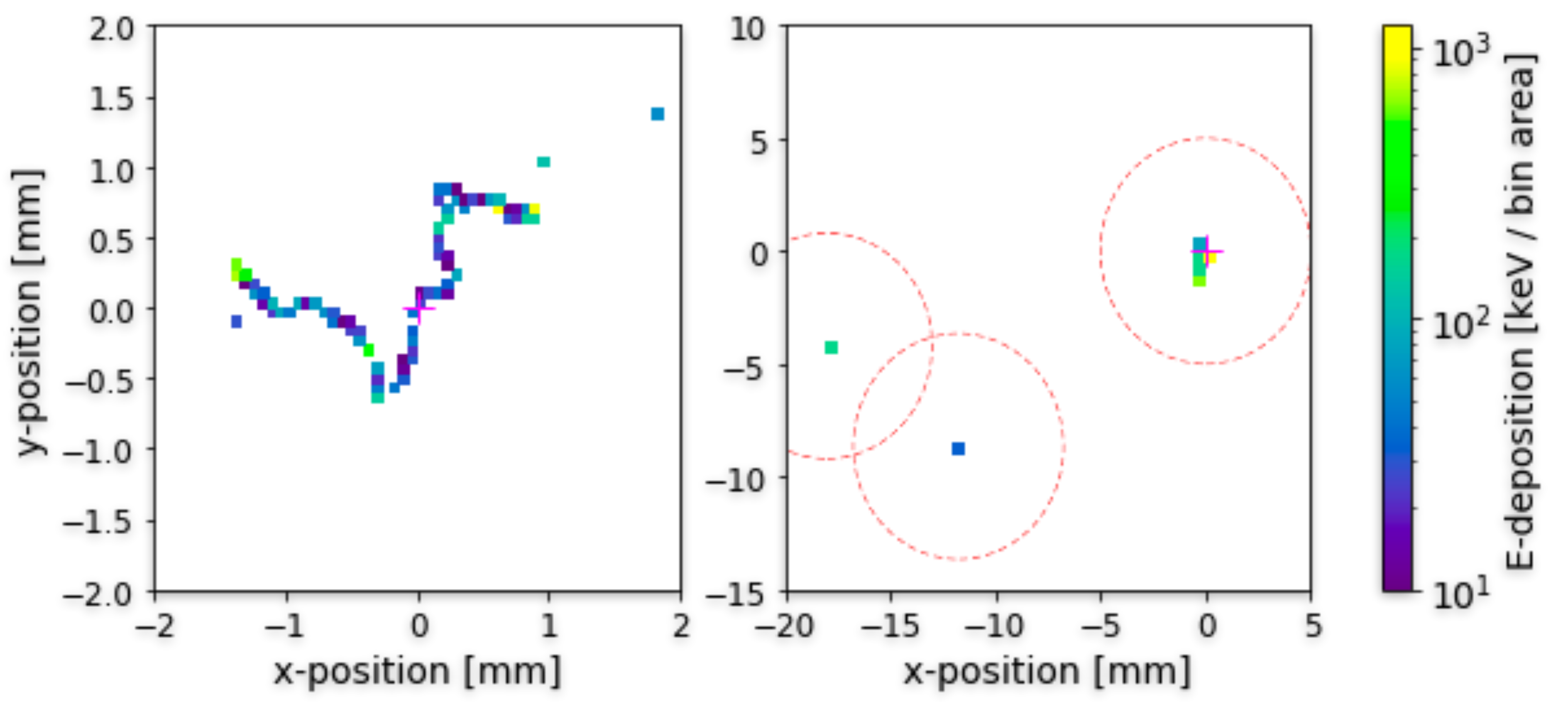
Energy per electron and angle between the two depends on the yet unknown decay mechanism.

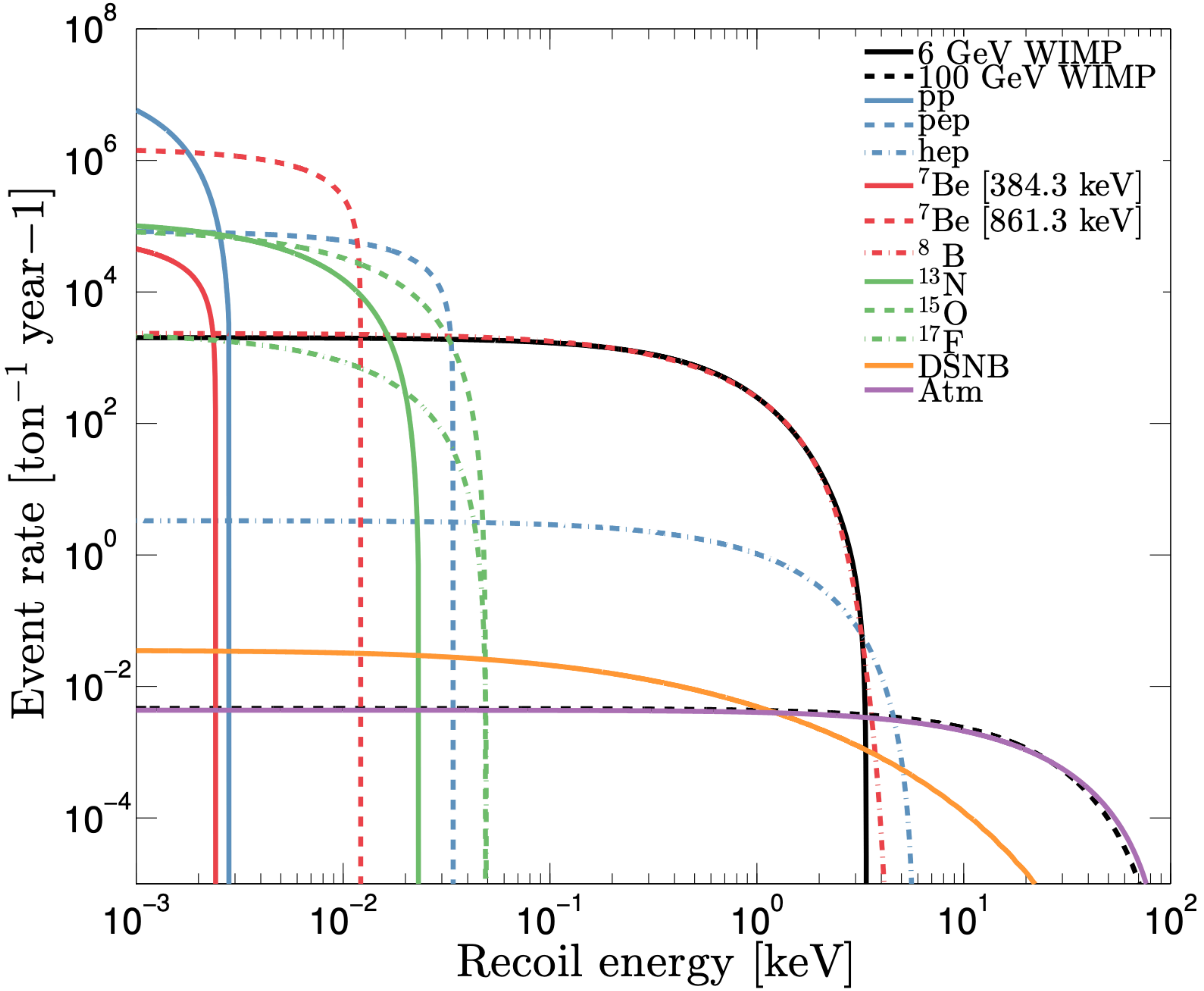


Model assuming mixing mechanism and emission back to back

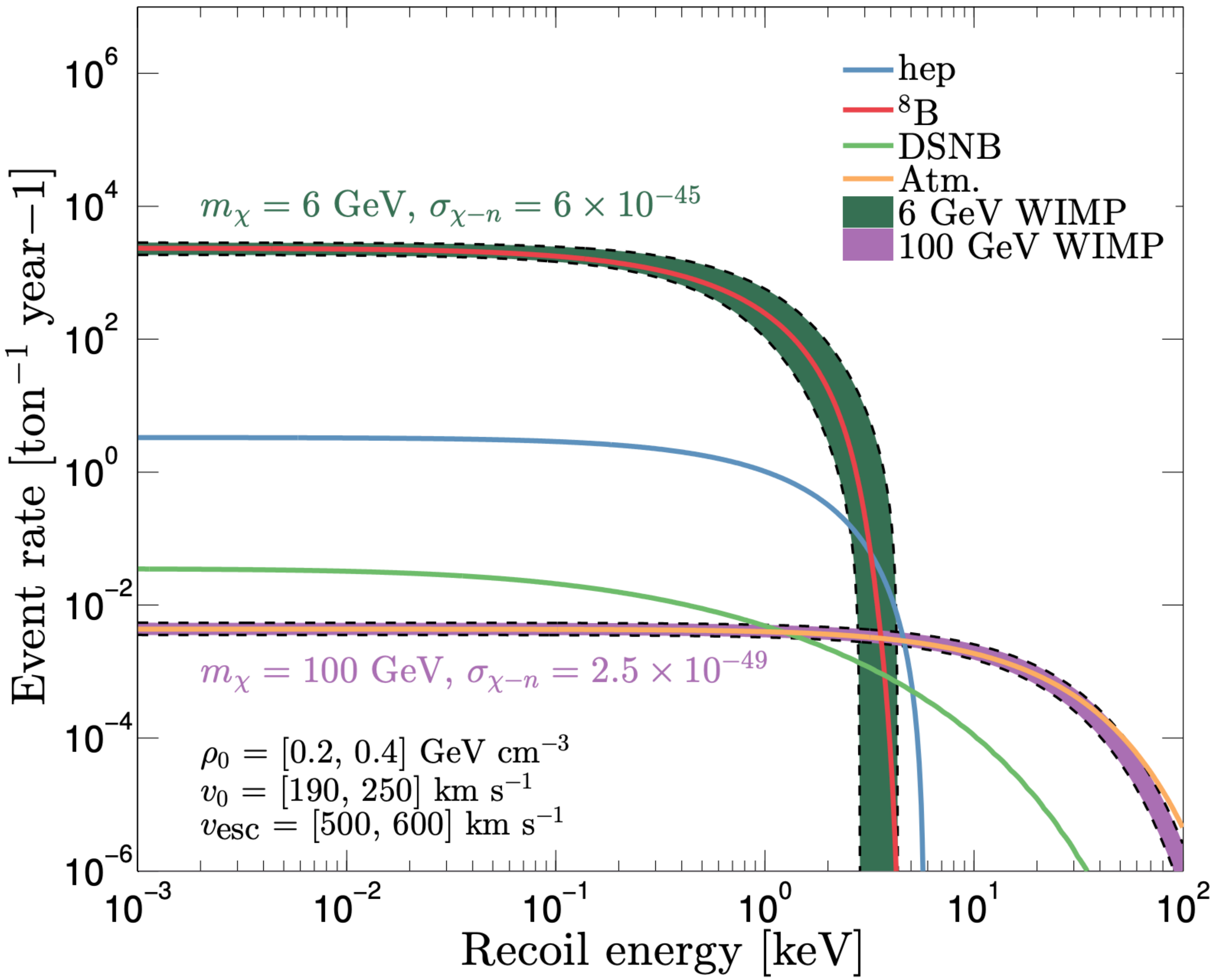
In liquid xenon the electrons thermalise within O(mm) resulting in a single-site (SS) signal topology

Bremsstrahlung photons emitted during electron thermalisation. Infrequently photons with energies above a few 100 keV can cross O(cm) distances before interacting

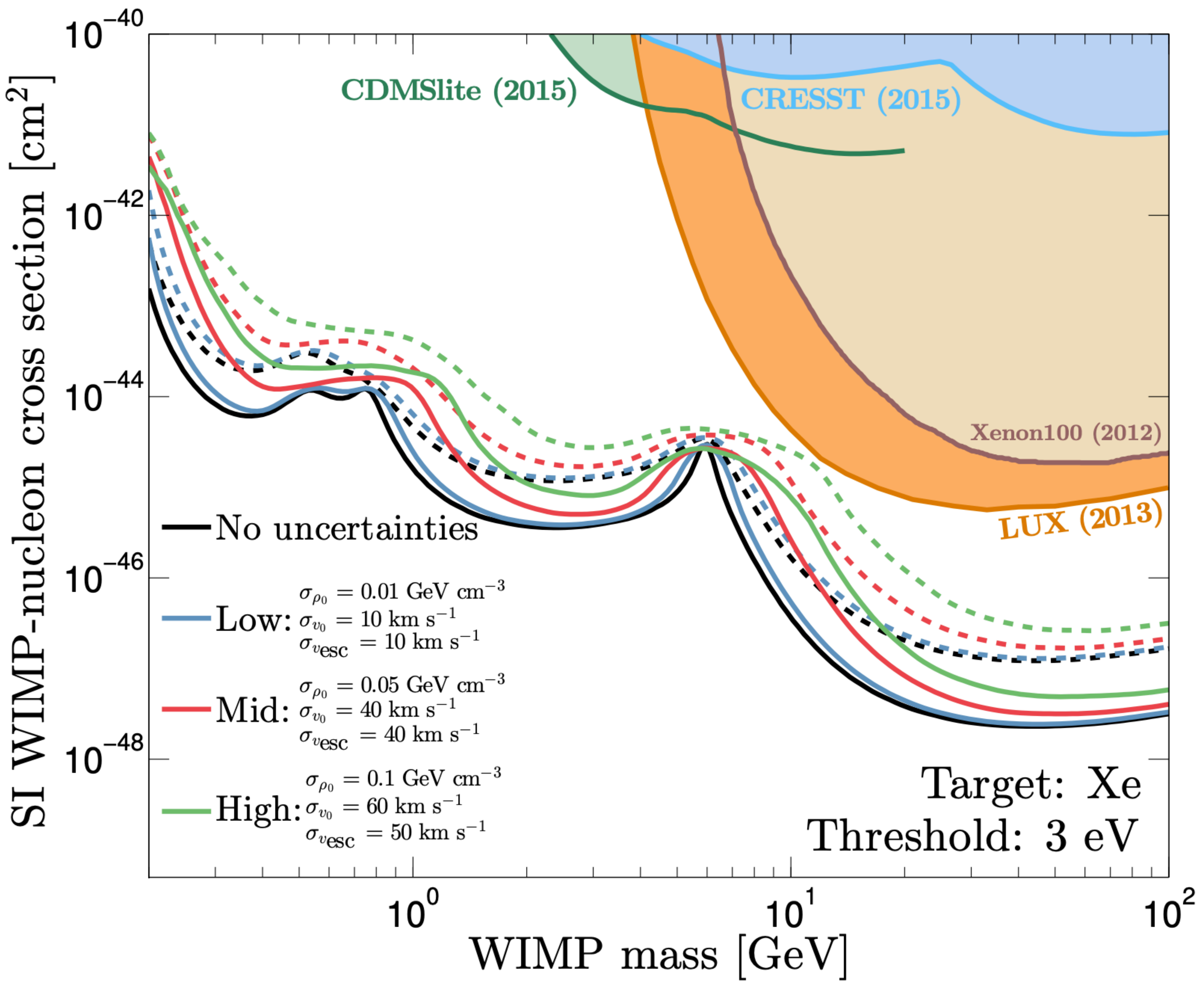




O'Hare, Dark Matter Astrophysical uncertainties and the neutrino floor



O'Hare, Dark Matter Astrophysical uncertainties and the neutrino floor



O'Hare, Dark Matter Astrophysical uncertainties and the neutrino floor

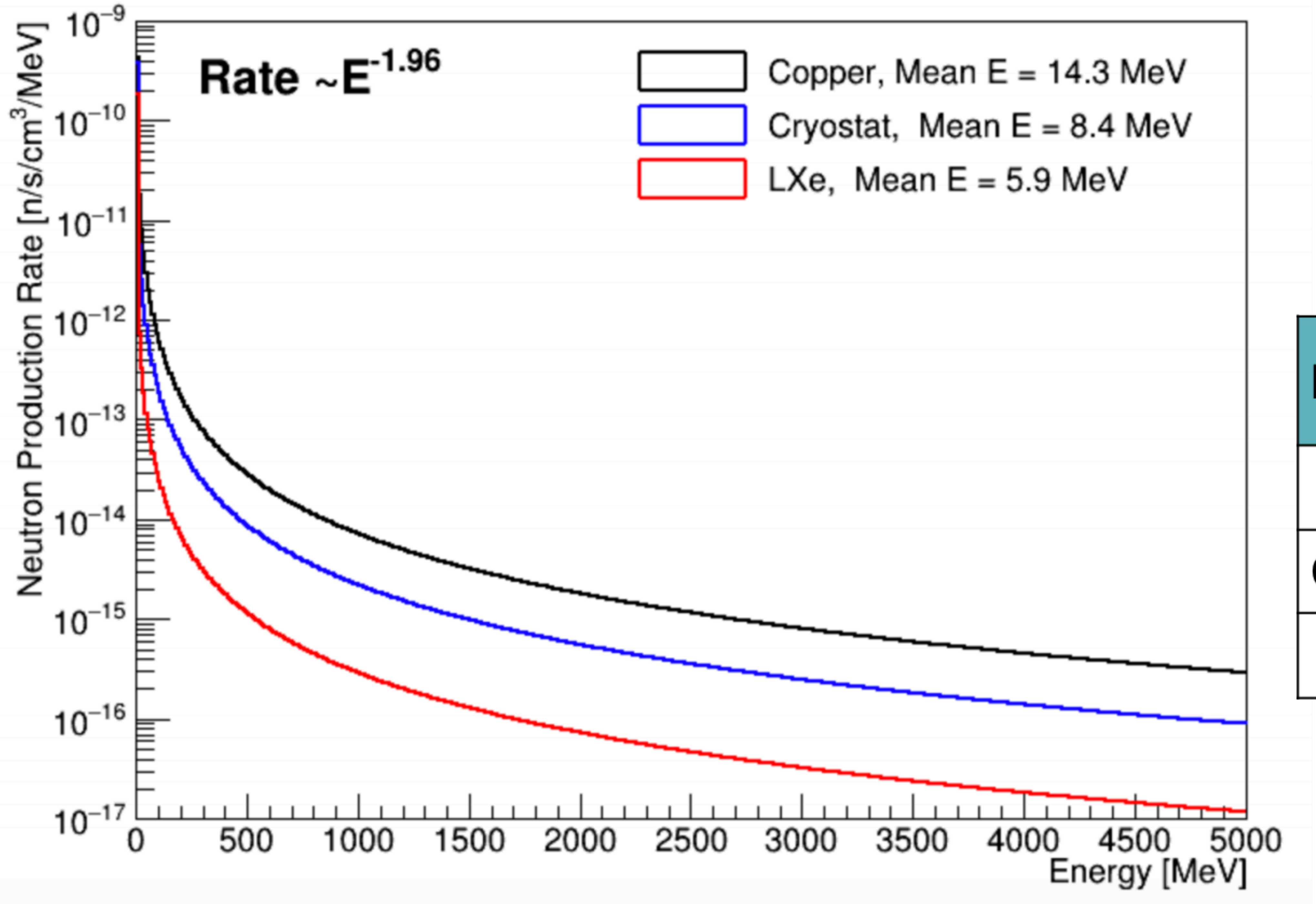
MUON-INDUCED NEUTRONS: MORE REALISTIC MODEL

DARWIN

NEW

- We simulate the neutrons following a power-law energy spectrum
- The total neutron production rates per material still from XENON100

Several references propose a power law for this spectrum, quoting values from E^{-1} to E^{-2} [1].



Approach: reproduce at the same time the total neutron production rate and the mean energy

Material	n Production Rate [n/s/cm³]	Mean Energy [MeV]
Copper	0.47×10^{-8}	14.8
Cryostat	0.39×10^{-8}	8.3
LXe	0.19×10^{-8}	5.7

$\sim E^{-1.96}$

MUON-INDUCED NEUTRONS: NEW SIMULATIONS

DARWIN

We repeat the same process with the new energy spectrum

- simulate neutrons
- propagate them through the detector until the LXe
- count number of Xe^{137}

Comparison with the previous results

Table 2: 136Xe Neutron Captures in DARWIN

Material	Volume in DARWIN [m3]	#simulated neutrons	137Xe Isotopes (Previous Result)	137Xe Isotopes(NEW)
Copper	0.07604	1e6	247	**234**
Cryostat	1.07684	1e6	72	**89**
LXe	16.9740	1e6	247	**252**

Table 3: 137Xe Production Rate

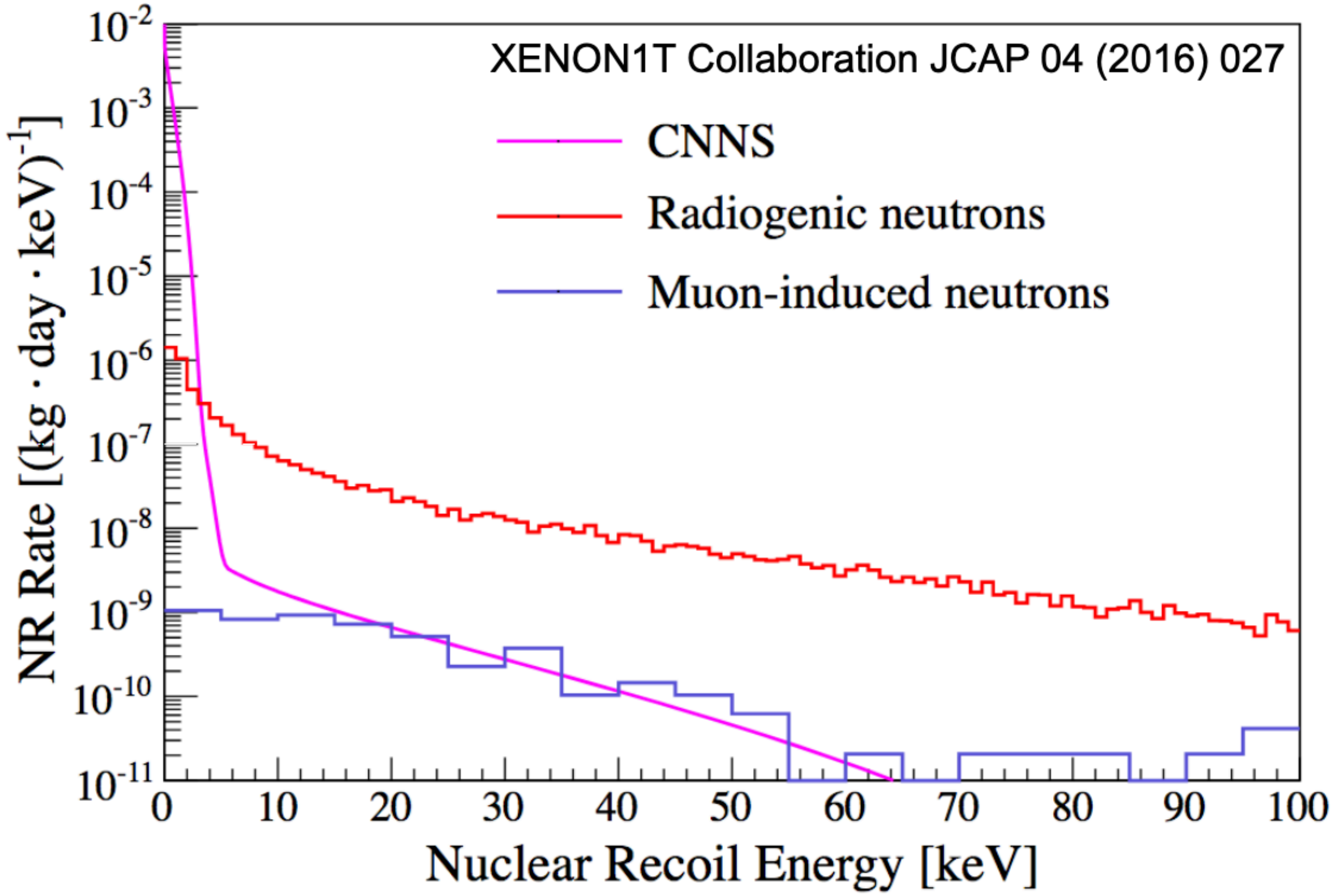
Material	Production Rate [atoms/kg/year] (OLD RESULT)	**Production Rate [atoms/kg/year] (NEW RESULT)**
Cooper	$7.39 \cdot 10^{-5}$	$6.72 \cdot 10^{-5}$
SS	$2.40 \cdot 10^{-4}$	$2.97 \cdot 10^{-4}$
LXe	$6.34 \cdot 10^{-3}$	$6.50 \cdot 10^{-3}$
Total	$6.66 \cdot 10^{-3}$	$6.86 \cdot 10^{-3}$

the power law spectrum accounts for **an increase of 3%** in the production rate of the Xe^{137}

QUESTION:

DARWIN

Why are the muon-induced neutrons the main contribution here while for the dark matter search they are negligible?



- This is not the number of muon-induced neutrons in the detector
  - Nuclear recoils in 1t FV
  - Single scatter events
  - 99.5% reduction of NRs in coincidence with a muon crossing the water tank
  - 70% reduction of NRs in coincidence with a muon shower (muon outside the tank)

However

- Although the reduction the neutrons still inside
- Neutrons multi-scatter

Muon-induced neutrons in the materials:

Their production is abundant, but they are mainly created inside an hadronic shower. They will enter the FV with a large number of gammas or other particles and the probability to produce a single scatter is extremely low