The XENON1T excess electron-recoil events

Guido Zavattini

University of Ferrara and INFN – Ferrara

XENON Bologna group

on behalf of the XENON collaboration.

On-line seminar at the

Birmingham Particle Physics group

XENON collaboration

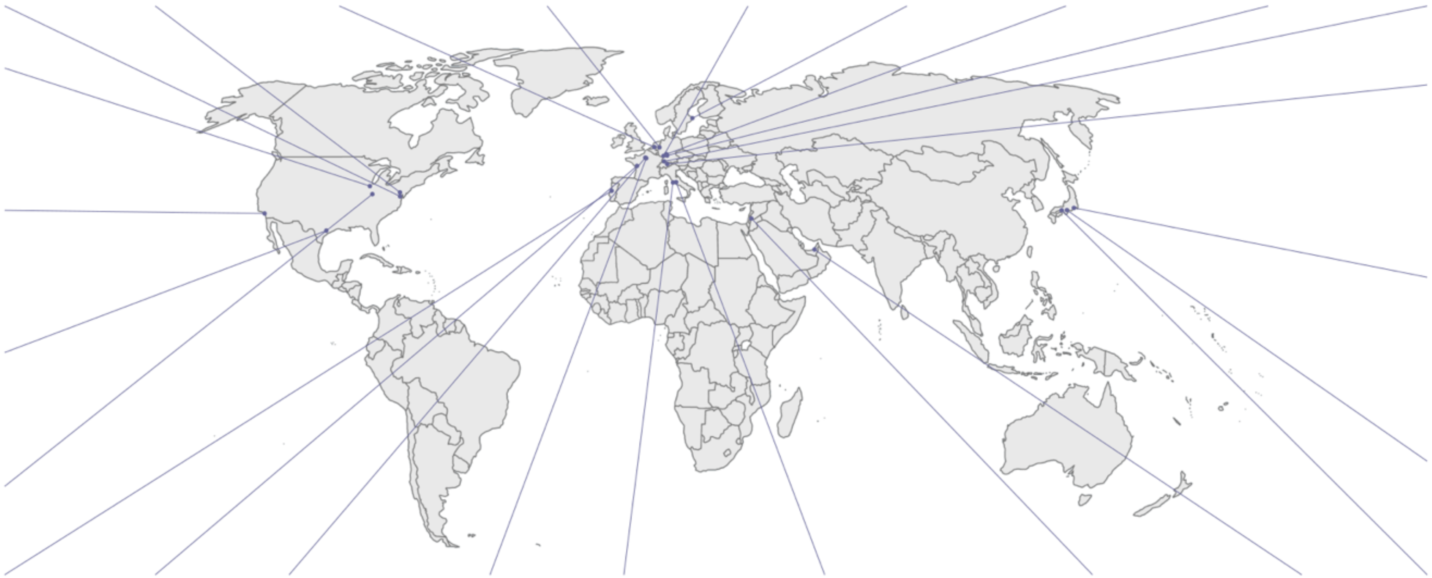
XENON Dark Matter Project

Netherlands, Germany, Sweden, Germany

Columbia, RPI, Nikhef, Muenster, KIT, Stockholm, Mainz, MPIK, Heidelberg, Freiburg

United States of America

Chicago, UCSD, Rice, Purdue



Switzerland

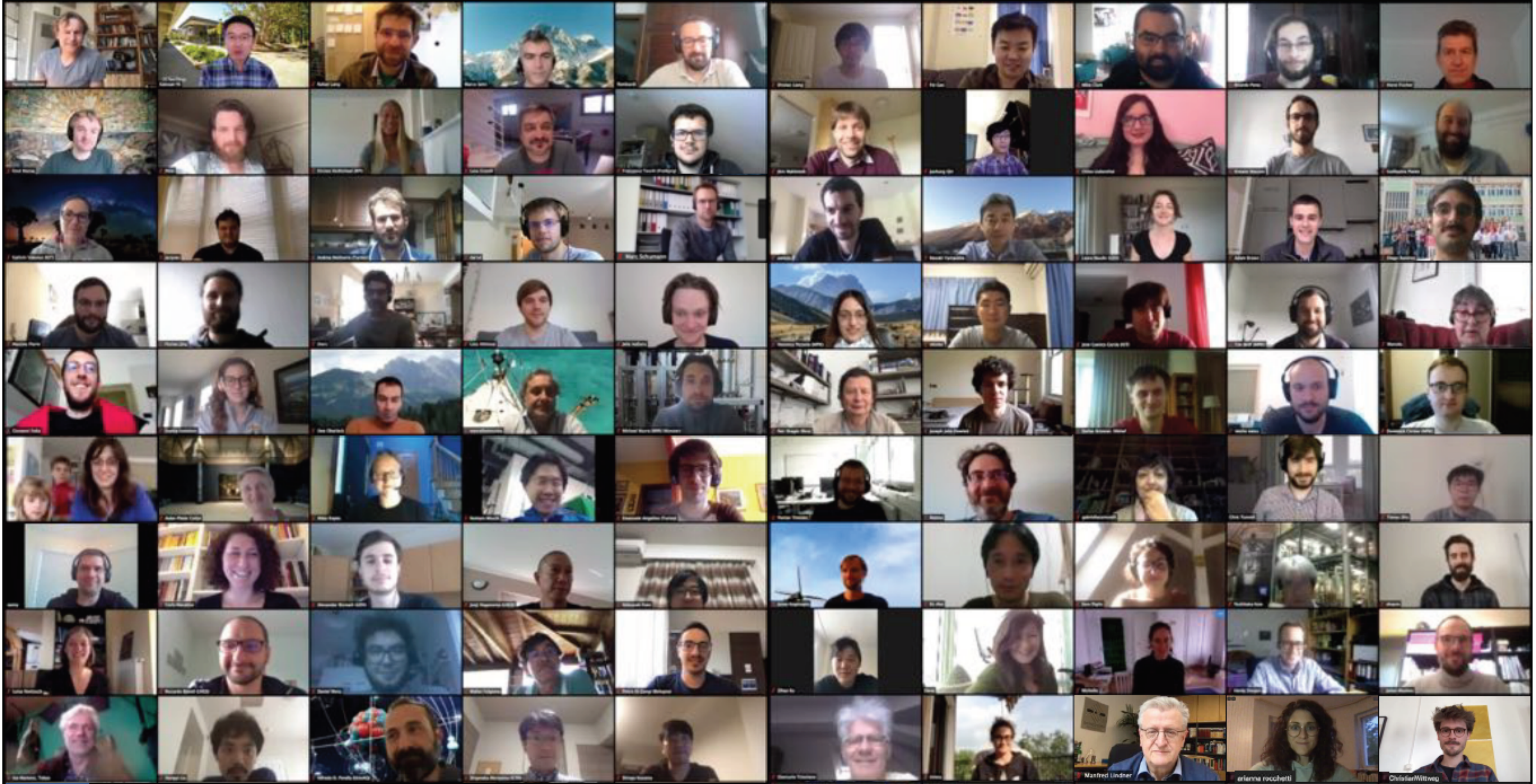
Zurich

Japan

Tokyo, Nagoya, Kobe

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

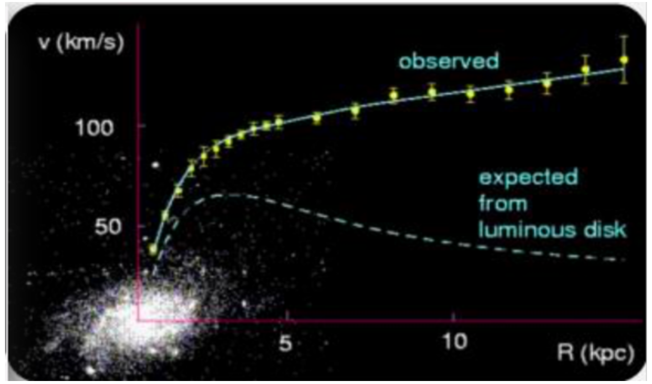
Portugal, France, Italy, Israel, Emirates



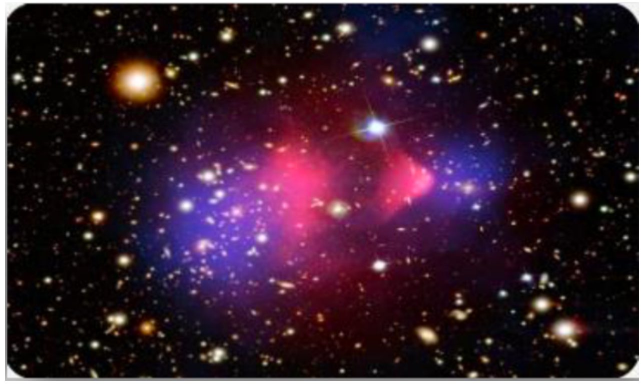
XENON Dark Matter Project

XENON Technical Meeting, May 12-14, 2020

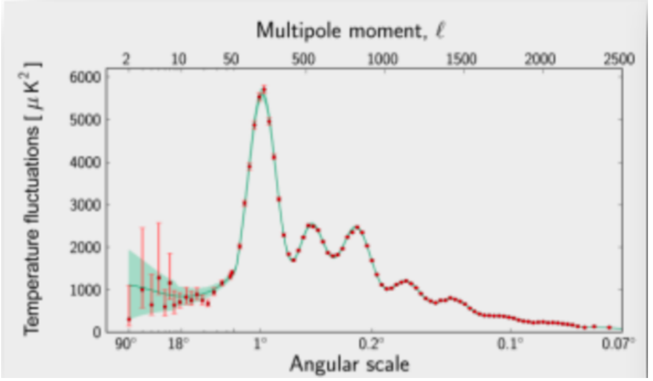
XENON collaboration – direct Dark Matter searches



Star velocity profile in galaxies



Bullet cluster



Cosmic microwave background anisotropy

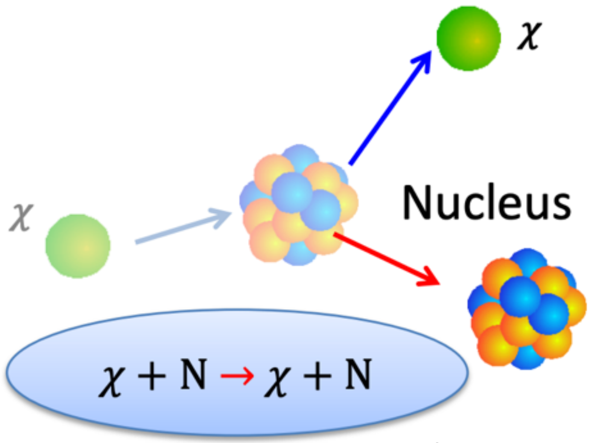
Indirect evidence:
Several observations on astronomical and cosmological scales indicate that about 27% of the mass-energy of the universe is 'Dark Matter' (does not couple electromagnetically) with an unknow composition. Only about 5% is ordinary matter.

Constraints on Dark Matter are:
- No electric charge
- No colour charge (strong interaction)
- No self interaction
- Stable or very long lifetime
- Interacts gravitationally

The XENON collaboration is searching for a direct interaction of Dark Matter particles with ordinary matter

WIMP searches

Nuclear recoil (NR)



Nuclear recoil energy
≈ 1 – 100 keV

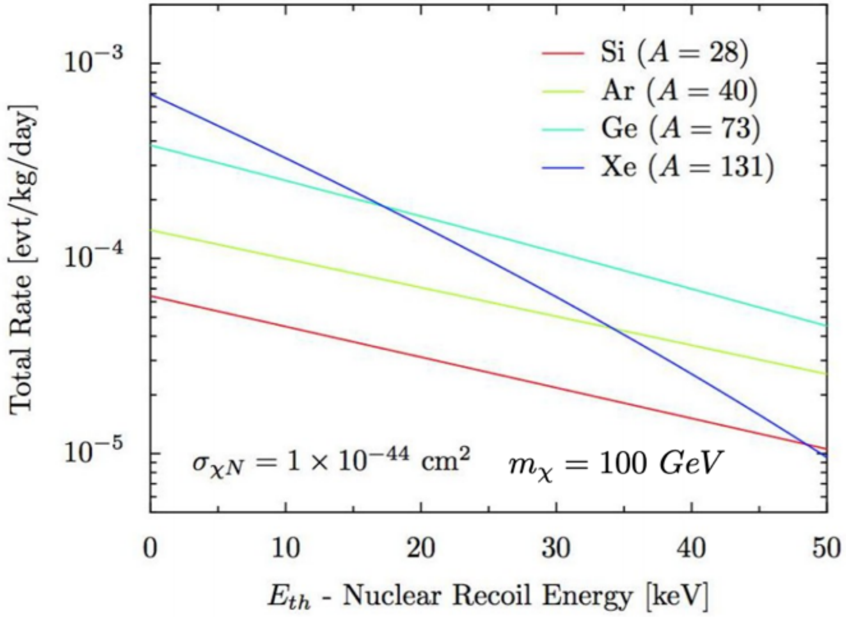
Backgrounds in the 1 – 100 keV nuclear recoil energy range

1) Electron recoils (ER) from γ and β decays generate background in the WIMP energy region

Need to distinguish NR events from ER events

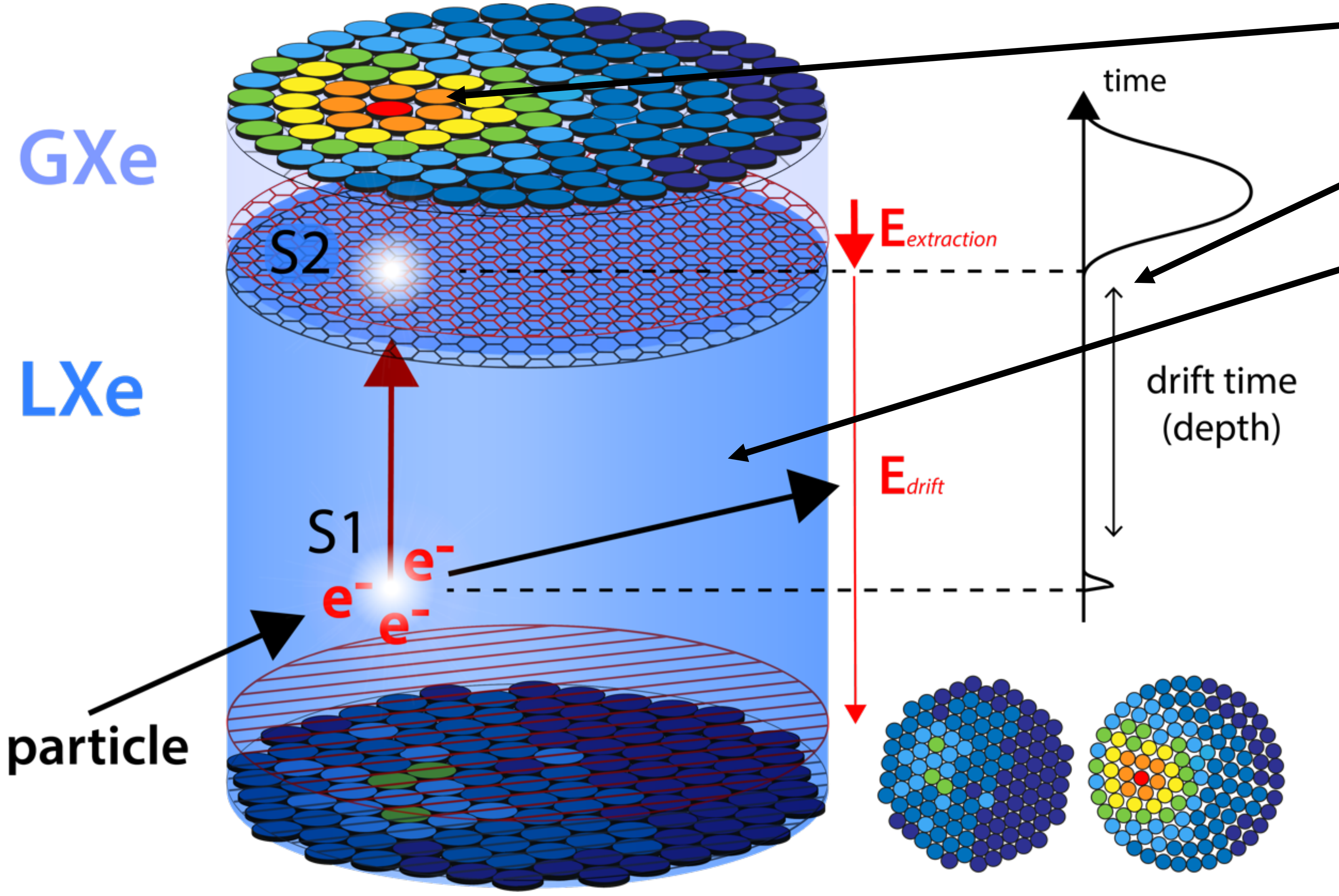
2) Nuclear recoils (NR) from radiogenic neutrons generate background in the WIMP energy region

Need to isolate these NR events from WIMP events



A liquid xenon Time Projection Chamber (TPC) is an excellent choice

Dual phase Time Projection Chamber (TPC): principle



Light distribution on top PMTs indicate the X – Y position of the event

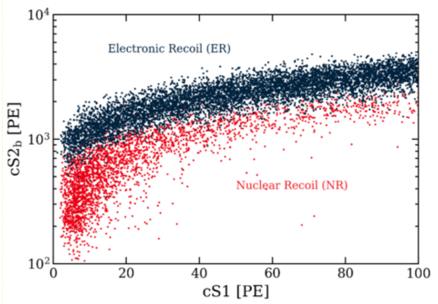
Drift time determines the Z coordinate

Can define a fiducial volume

S1 prompt scintillation

S2 proportional to the ionization of the incident particle

S2/S1 ratio is different for electron recoils (ER) and nuclear recoils (NR)



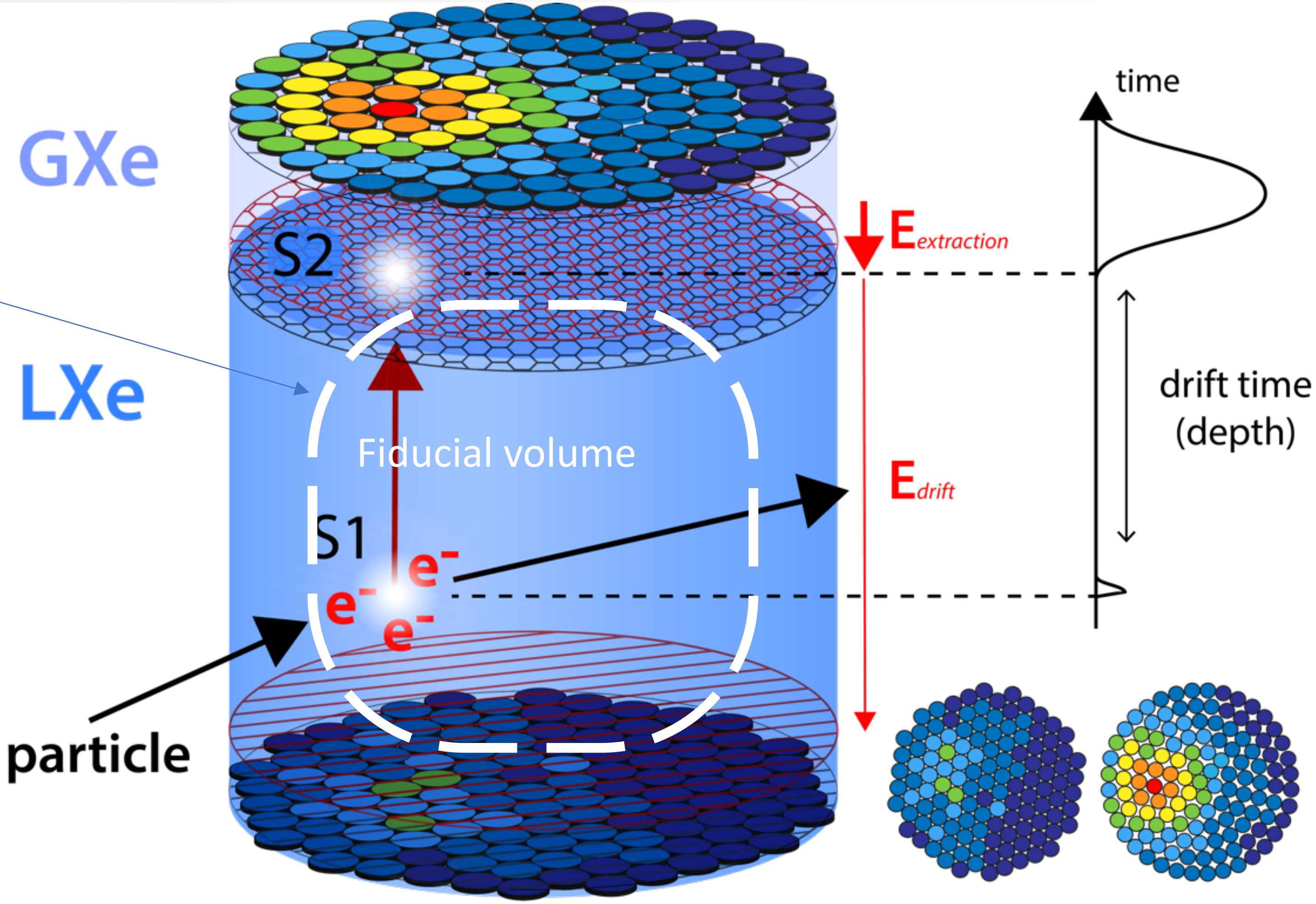
Dual phase Time Projection Chamber: why liquid xenon

Why liquid xenon

- High density, self shielding
- Good scintillator (178 nm)
- Absence of long half-life isotopes (internal background)

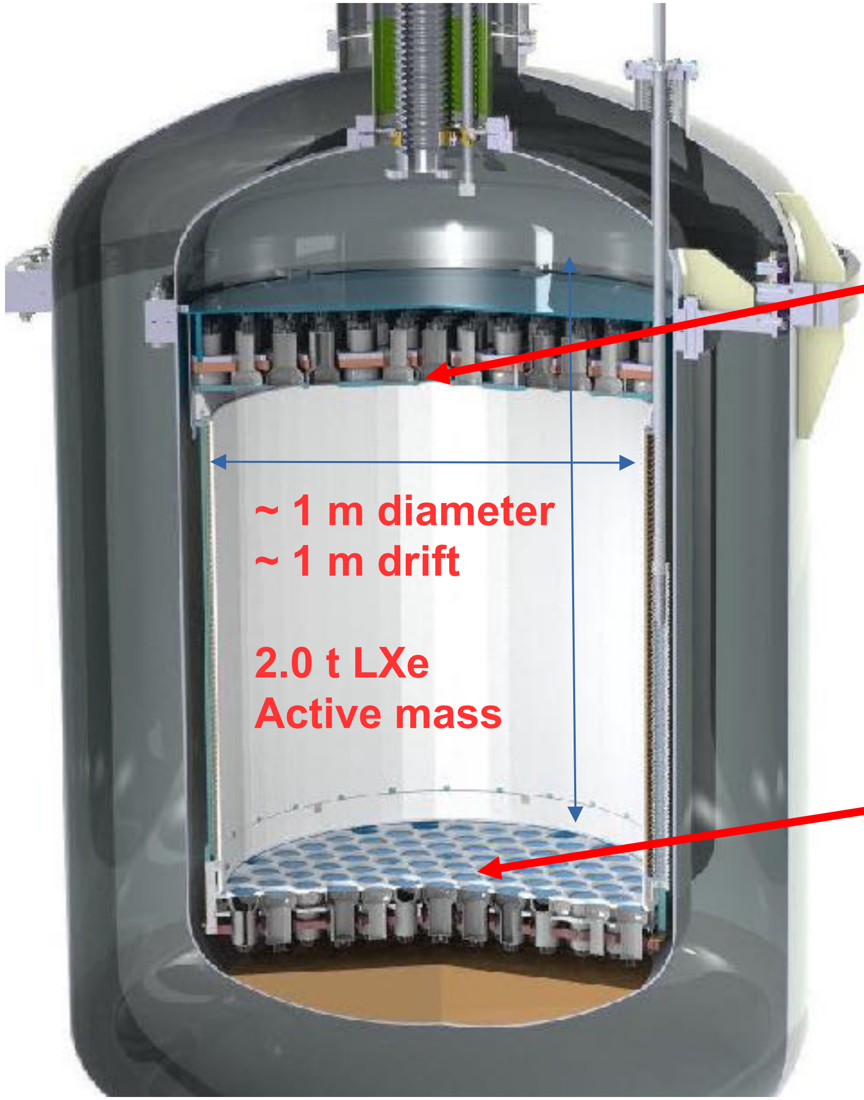
Time Projection Chamber

- 3D position reconstruction of events
- ER/NR discrimination
- Rejection of multiple events
- Low energy threshold

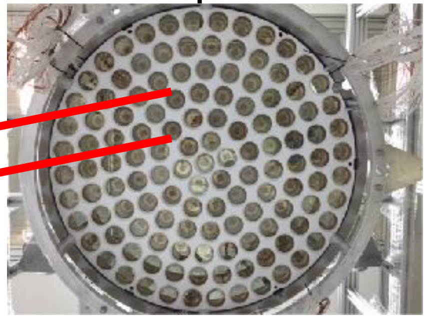


Ideal detector for searching for Dark Matter and rare processes

XENON1T Time Projection Chamber



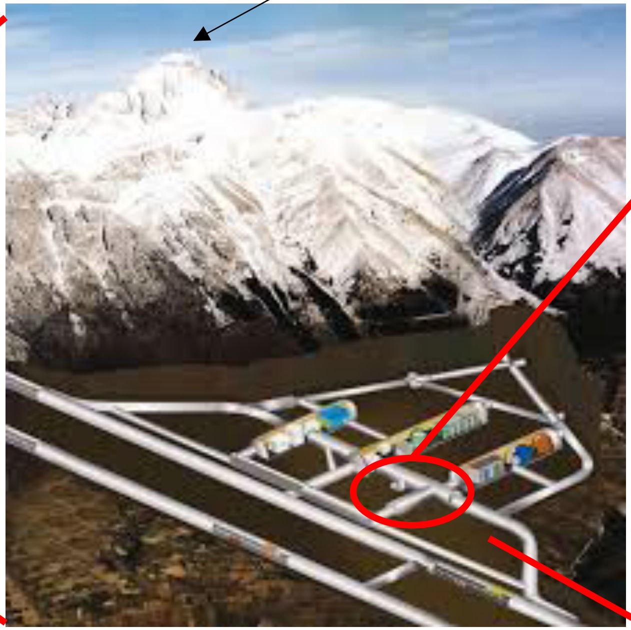
127 Top PMTs

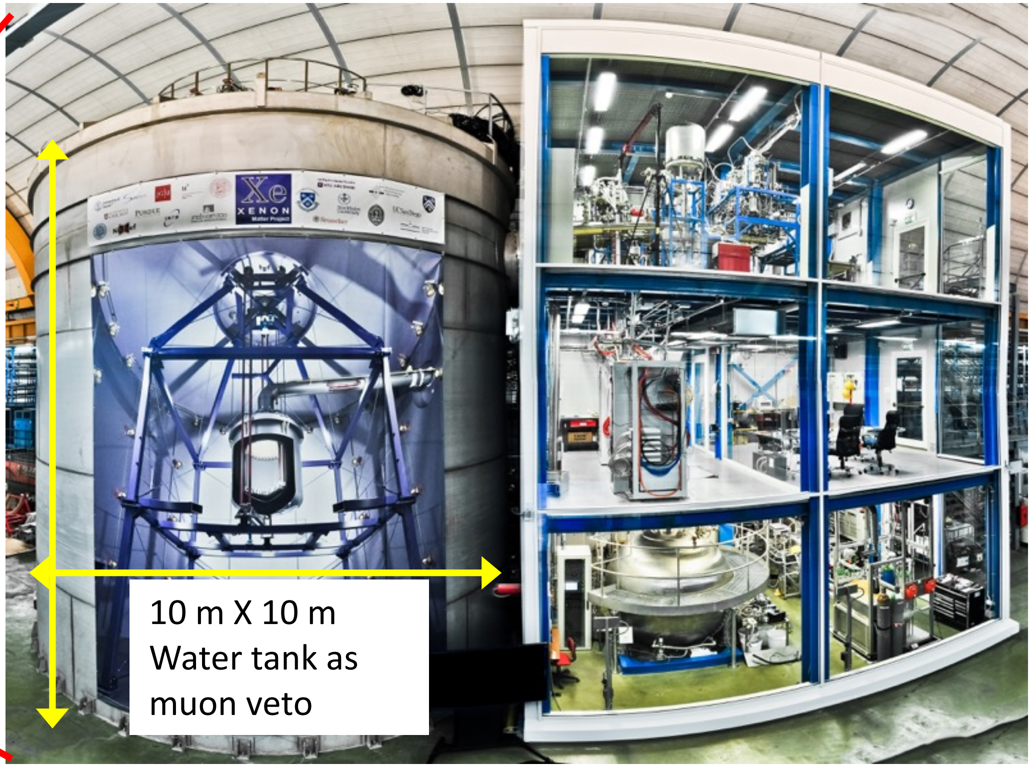


121 Bottom PMTs

XENON1T location: LNGS underground labs.

Gran Sasso, 2912 m (9554 ft)

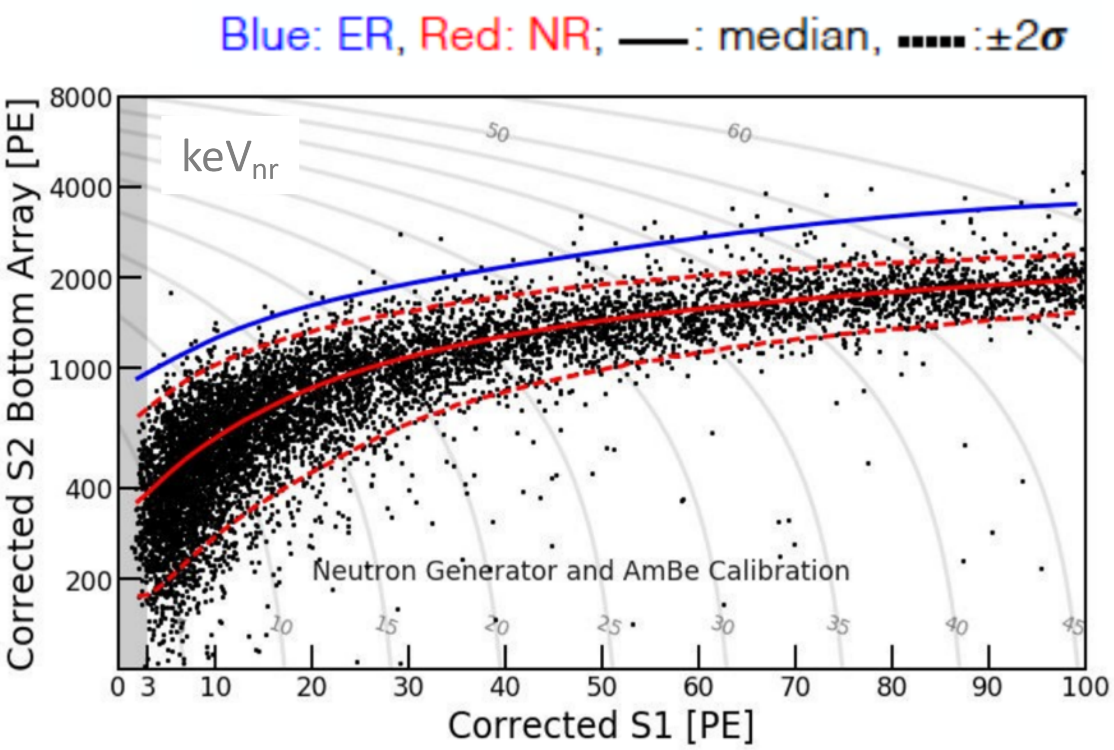




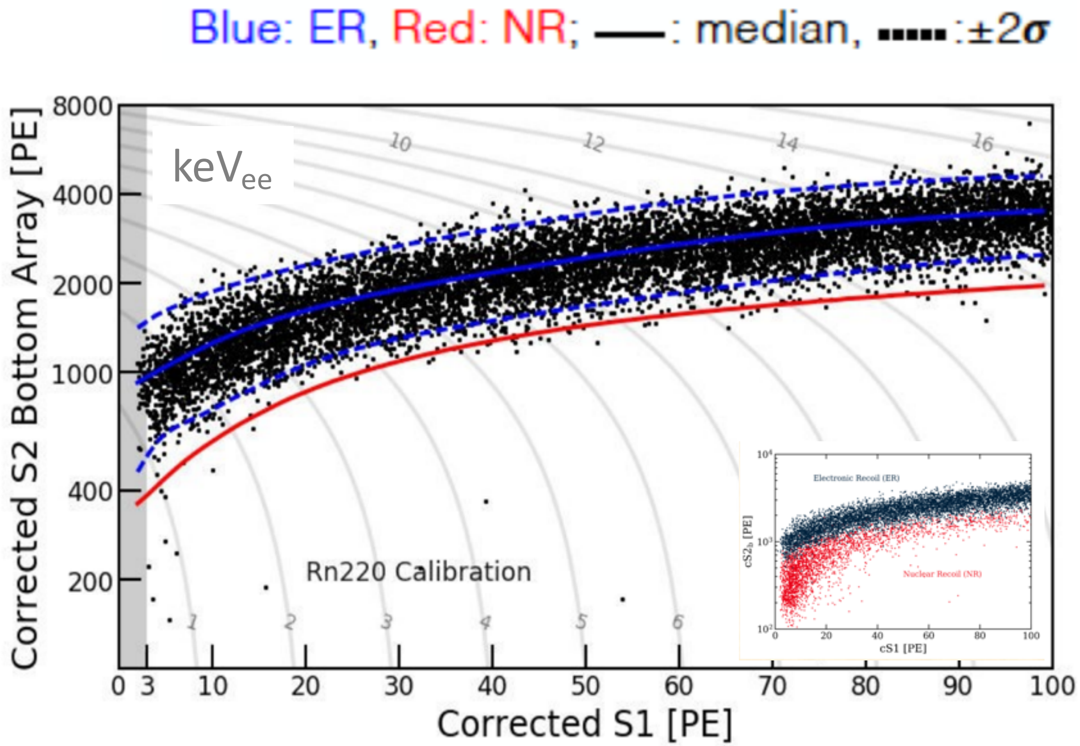
INFN - Laboratori Nazionali del Gran Sasso

- XENON1T detector is naturally shielded by ~ 1.4 km of rock (3600 m equiv. H_2O): muon flux reduction of 10^6.
- Further shielding is obtained with a Cherenkov muon veto water tank.
- Very careful choice of low radioactivity materials.
- Purification of the xenon (during filling and online cryogenic distillation)
- Self-shielding of the outer part of the detector thereby defining an internal fiducial volume.

NR vs. ER calibration



Nuclear recoil calibration with neutron generator



Electron recoil calibration with ^{220}Rn. β decay from ^{212}Pb generates low energy events with half-life 10.6 h

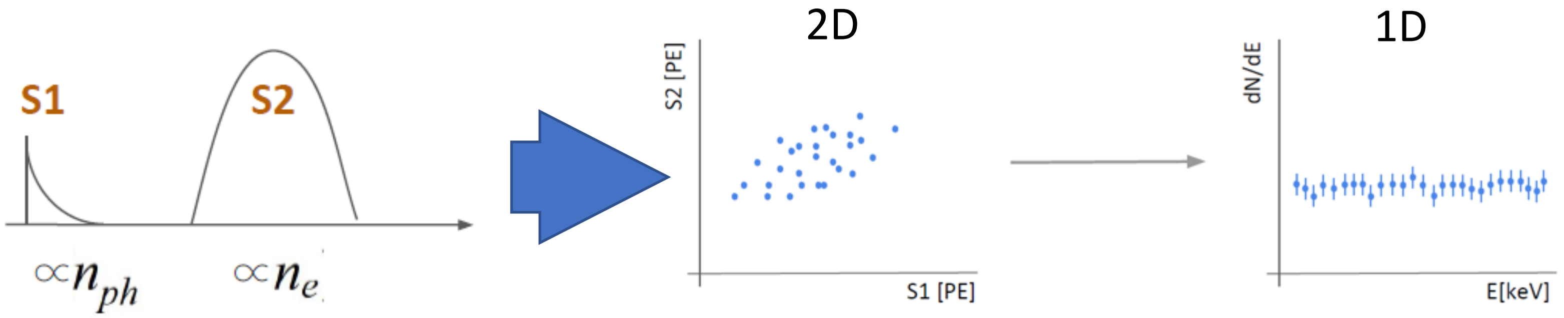
Some leaking of ER events into the NR band.

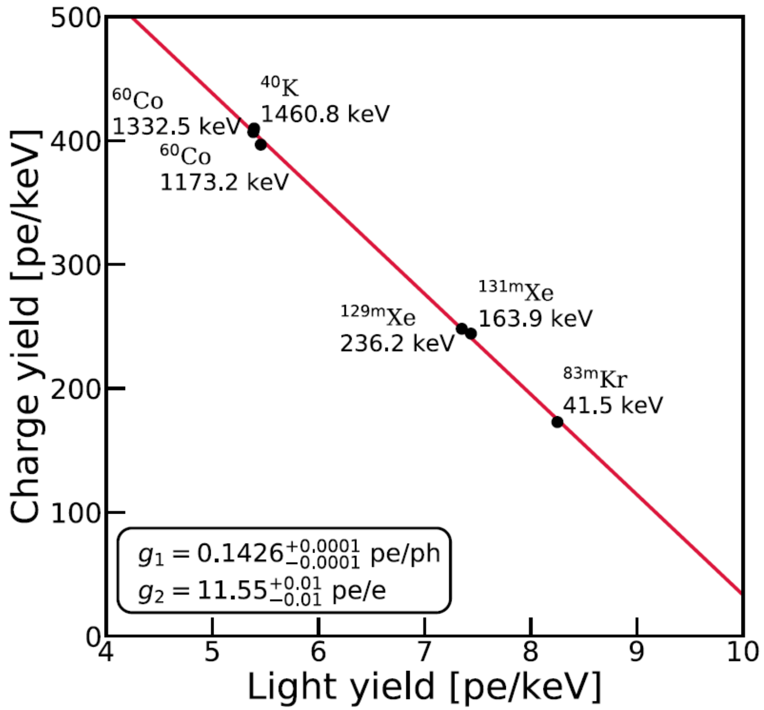
Electron recoil energy calibration

The primary interaction will generate both scintillation light (n_{ph}) and ionisation (n_e) in a proportion depending on the total deposited energy

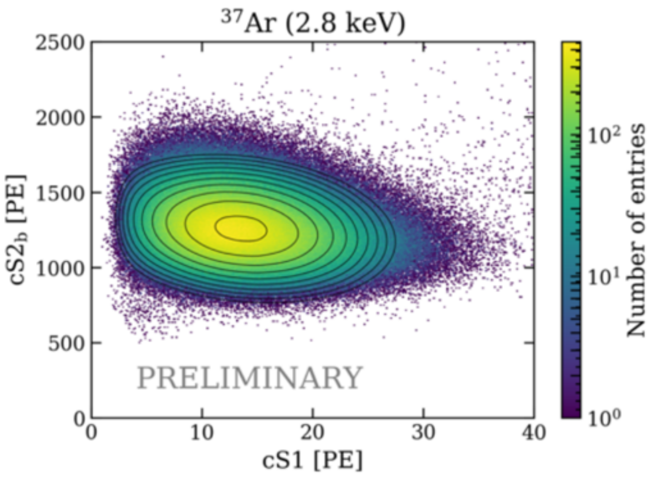
$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

W = 13.7 eV/quanta



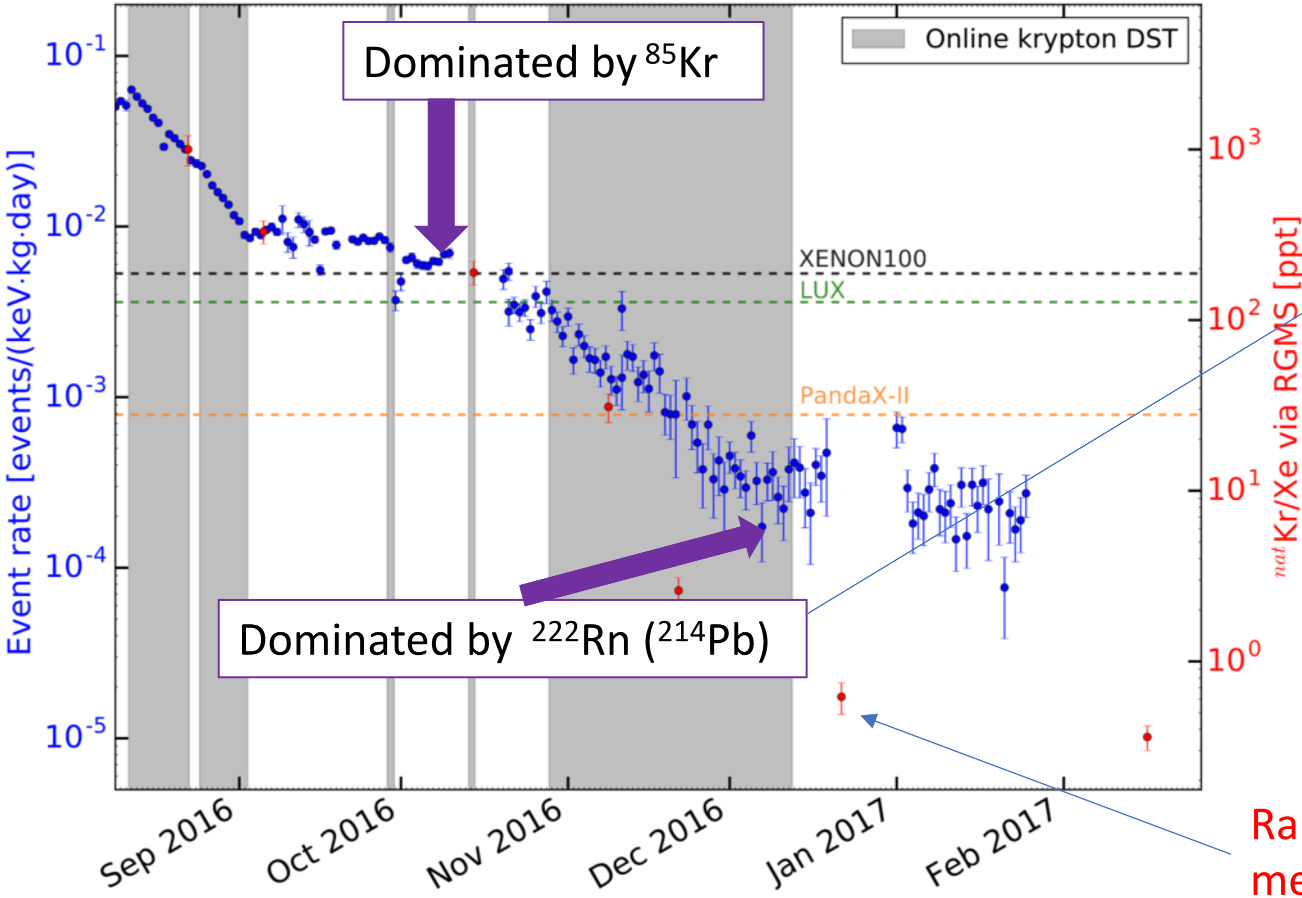


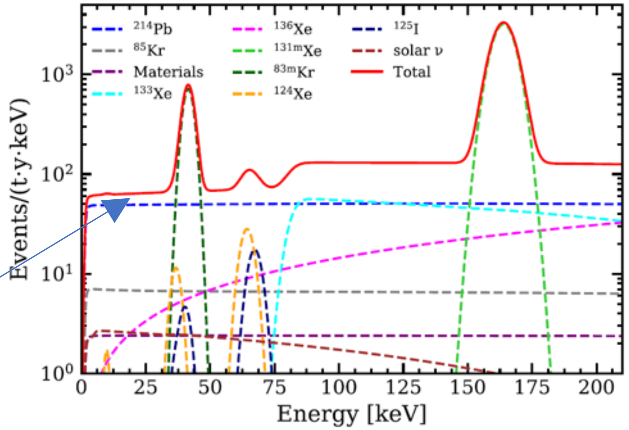
Example of calibration with ^{37}Ar. Peak at 2.8 keV



ER dominating background at low energy

In the low energy region, which is of interest for WIMP searches, the leaking of electron recoil events into the nuclear recoil region is dominated by ^{85}Kr and ^{222}Rn.

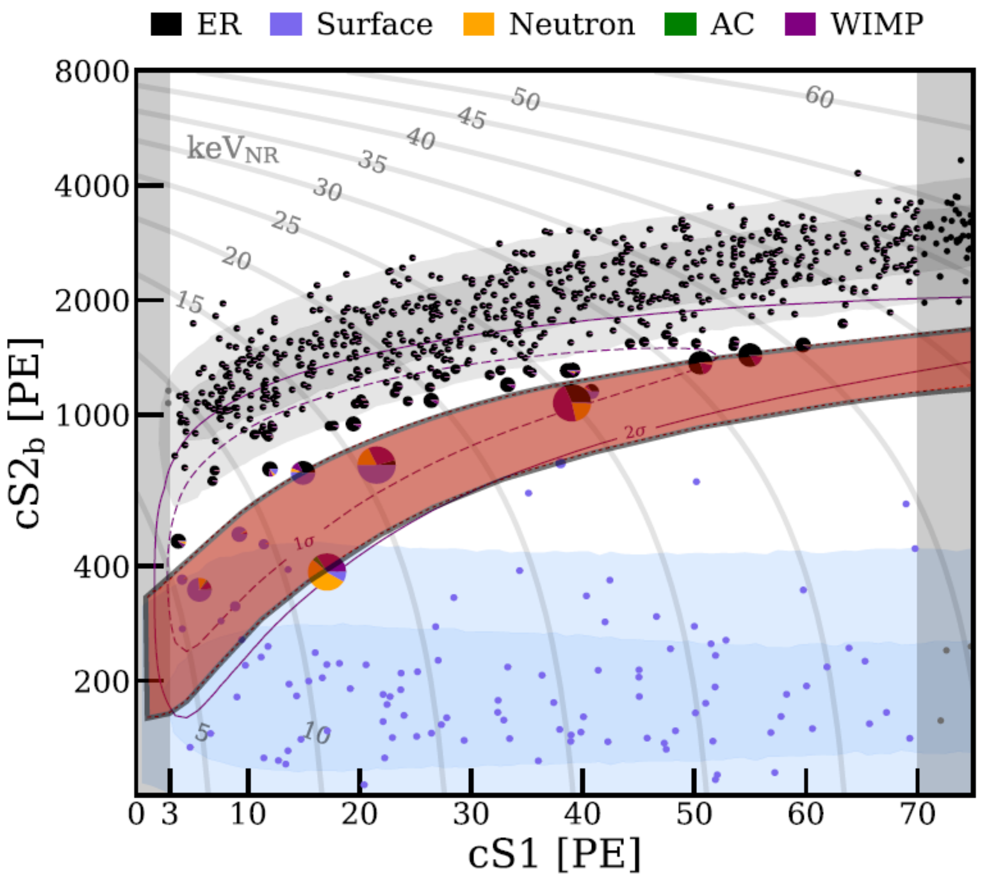


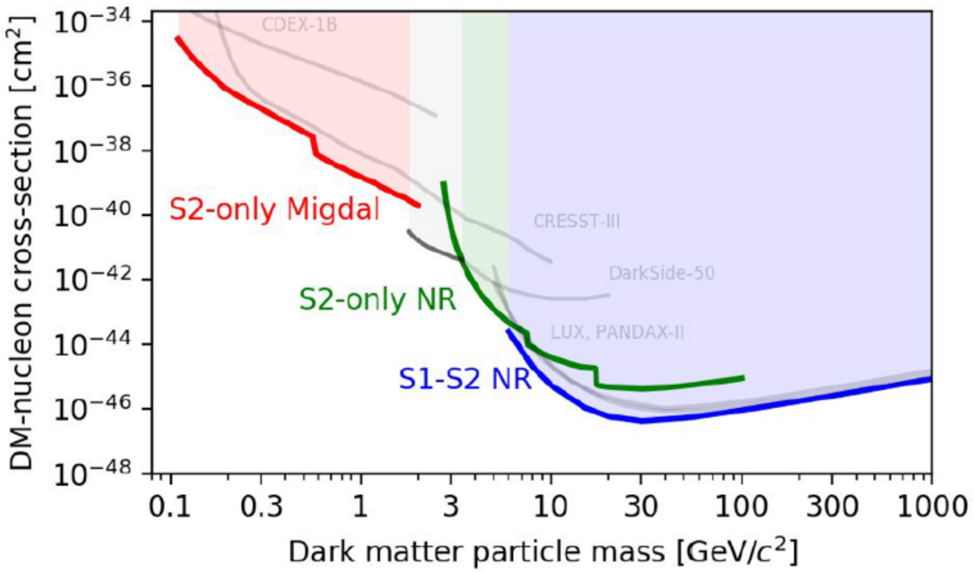


On-line distillation reduced the ^{85}Kr level resulting in a ^{222}Rn dominated background

Rare gas mass spectrometry measured ^{nat}Kr concentration

Nuclear recoil searches: 1 tonne-year data



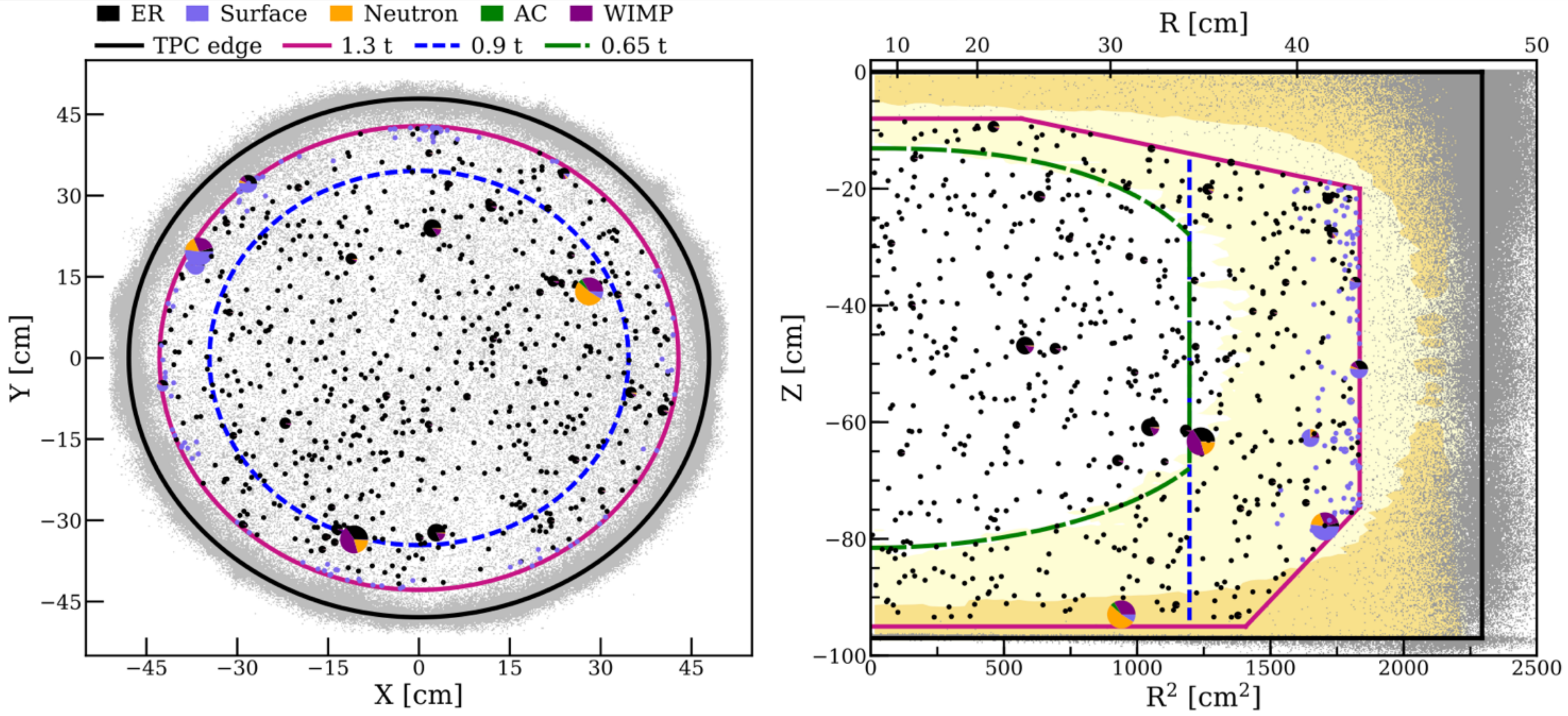


PRL 121, 111302 - Main WIMP search
PRL 123, 241803 - Migdal effect
PRL 123, 251801 - Light dark matter

Pie charts indicate the relative probabilities of the event to be of a certain class for a best fit to a 200 GeV/c^2 WIMPs with a cross-section of 4.6 x 10^{-47} cm^2. Their size is related to the WIMP probability

Best constraints on WIMP dark matter with masses > 3 GeV/c^2

Nuclear recoil searches – spatial distribution



Light grey dots: events outside the FV

Light and dark yellow: probability density percentiles of the radiogenic neutron background at 2σ and 1σ respectively

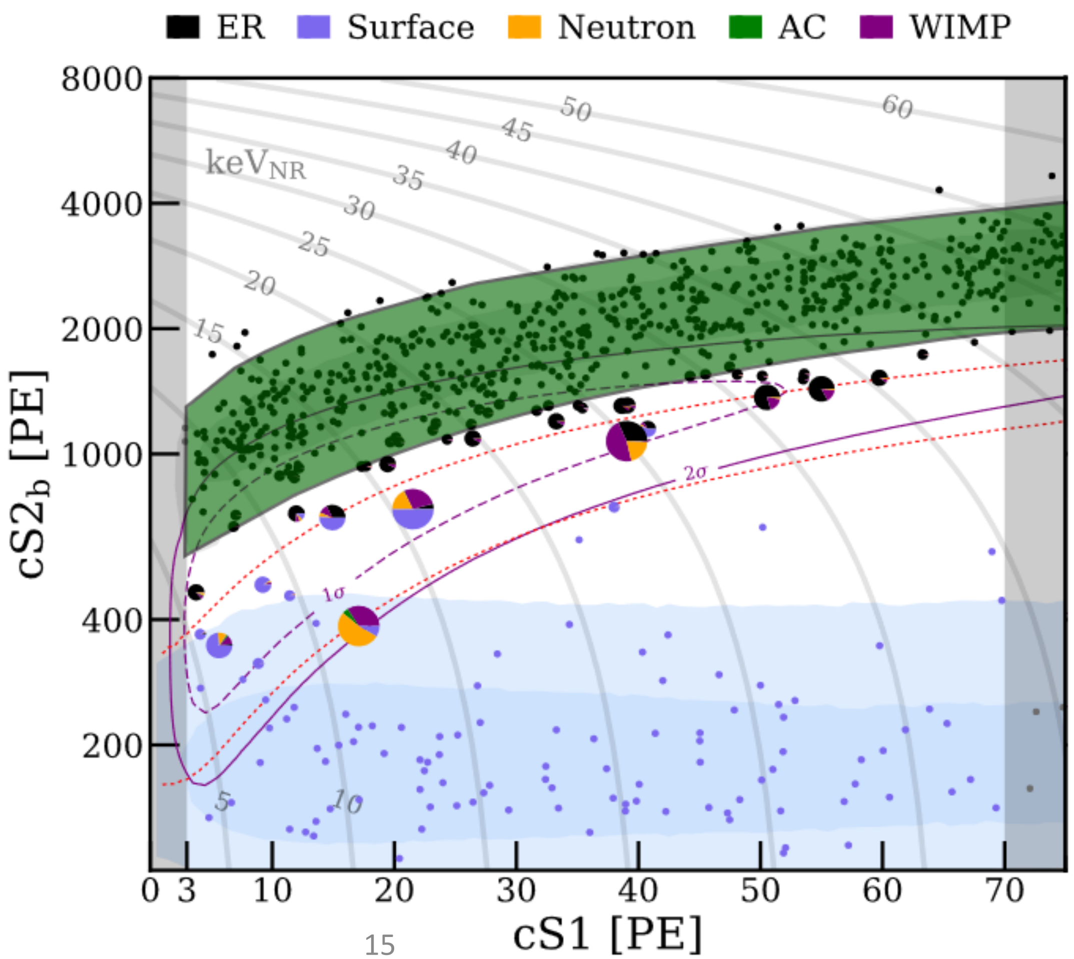
Pie charts indicate the relative probabilities of the event to be of a certain class for a best fit to a 200 GeV/c^2 WIMPs with a cross-section of 4.6 x 10^{-47} cm^2. Their size is related to the WIMP probability

Study of the electron recoil energy spectrum

Thanks to the low electron recoil background, the ER energy spectrum was also studied.

Search for: solar axions, neutrino magnetic moment (μ_v), bosonic Dark Matter

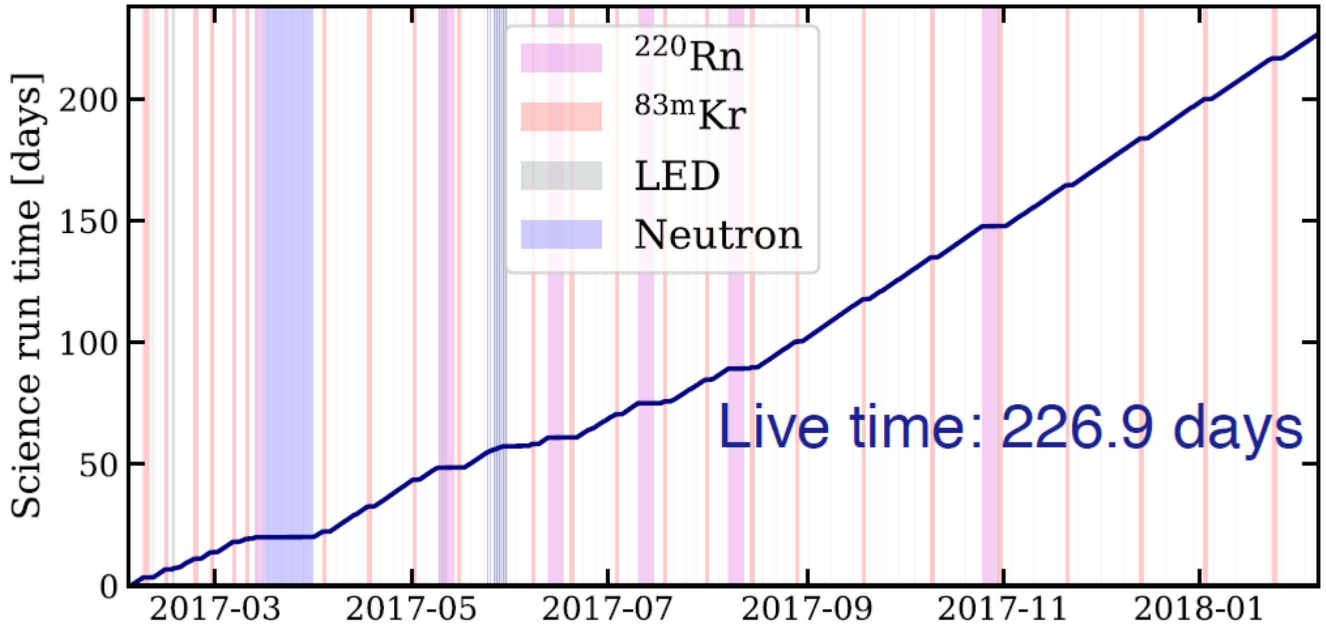
Would appear as excess events above the known background.



XENON1T characteristics

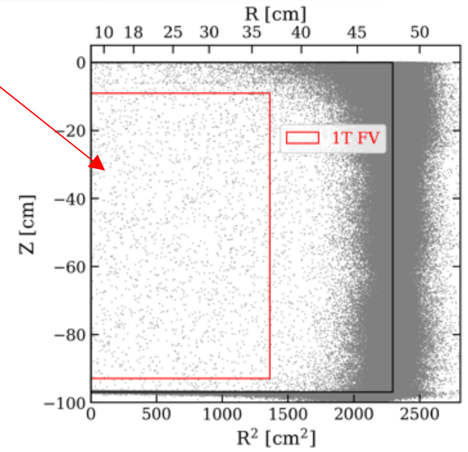
- Low background: < 100 ev/ton/anno/keV$_{ee}$
- Low energy threshold ~1 keV$_{ee}$ (5 keV$_{nr}$)
- Large exposure ~1 tonne*year

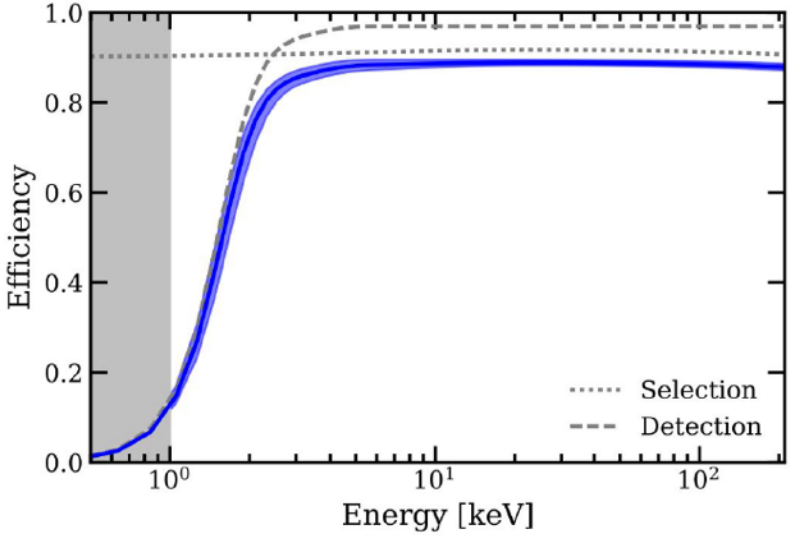
Data taking and event selection



Scientific run 1 (SR1): 2/2017- 2/2018
=> 226.9 live days = **0.65 tonne*year exposure**

1 tonne volume fiducial cylinder

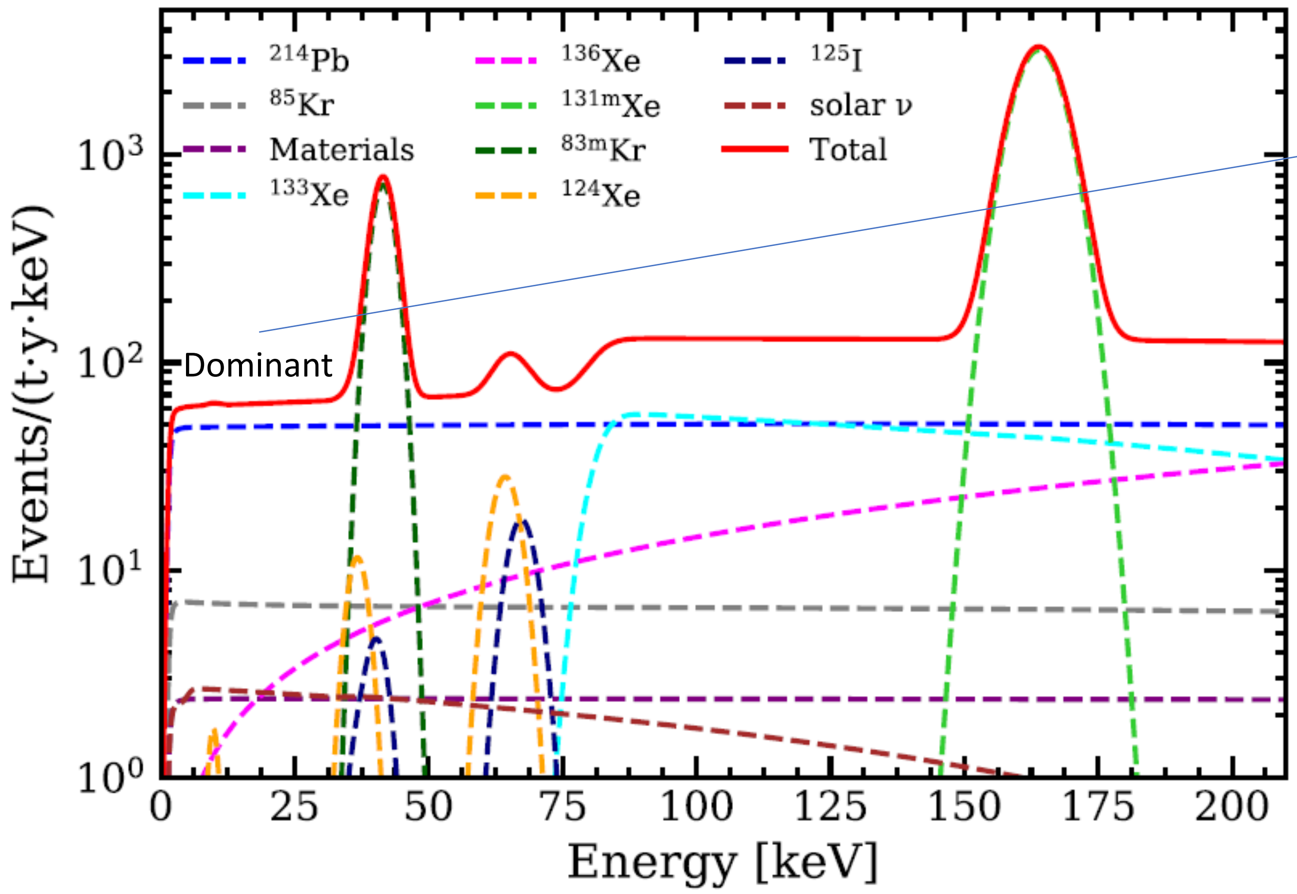




→ Selection S1: 3 PMT coincidence
→ Single scatter events in energy range [1,210] keV_{ee}

Background model

The B_0 background model contains 10 components



Internal (uniformly distributed)

^{214}Pb (from ^{222}Rn chain, dominating contribution)
^{85}Kr (reduced through cryogenic distillation)
^{136}Xe, ^{124}Xe
^{83m}Kr (residual traces from calibration)

Activated backgrounds

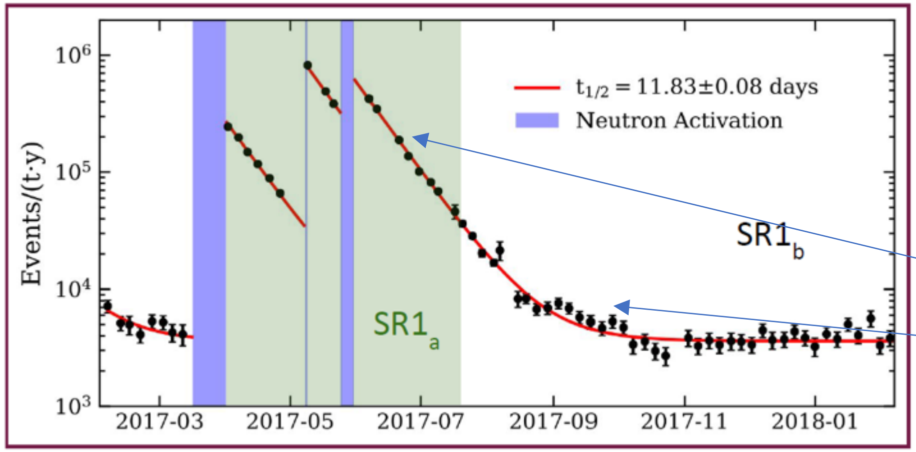
^{131m}Xe, ^{133}Xe, ^{125}I (time dependent)

External

Solar ν
Materials (radio assay and GEANT4)

Background fit to data

^{131m}Xe rate evolution after neutron calibration (activation)

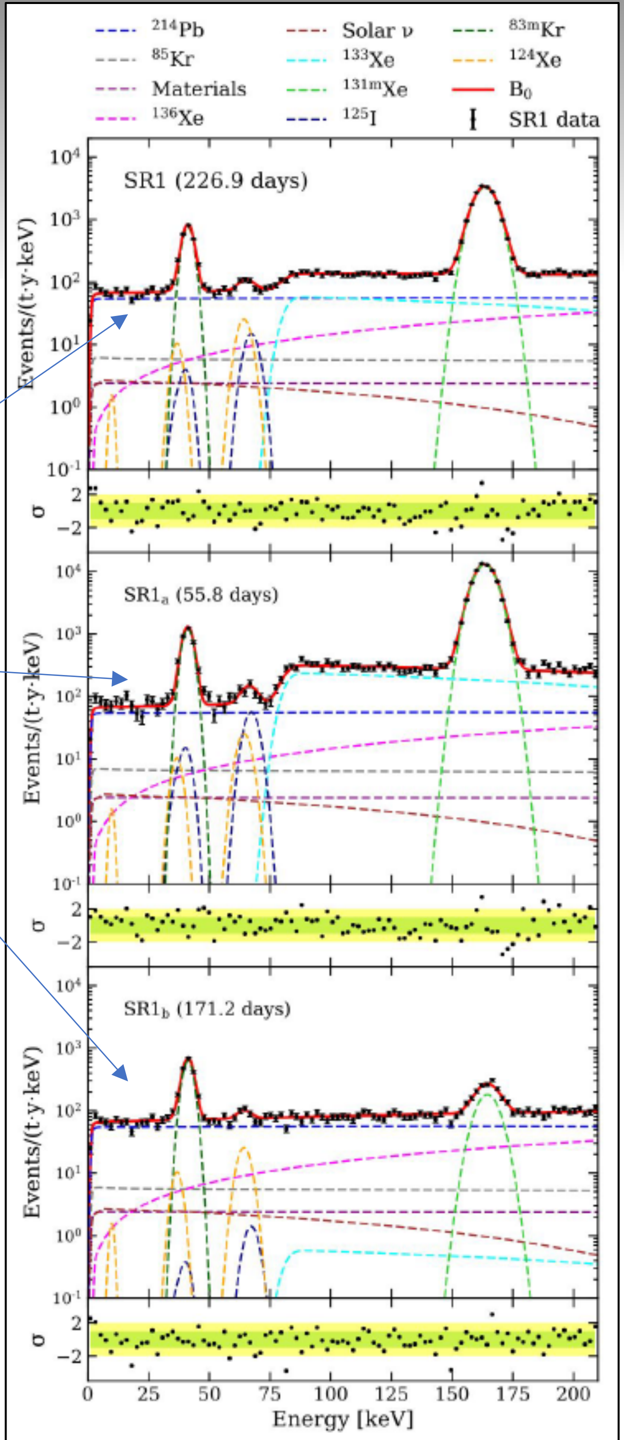


Background fit:

All 226.9 days

$SR1_a$: 55.8 days

$SR1_b$: 171.2 days

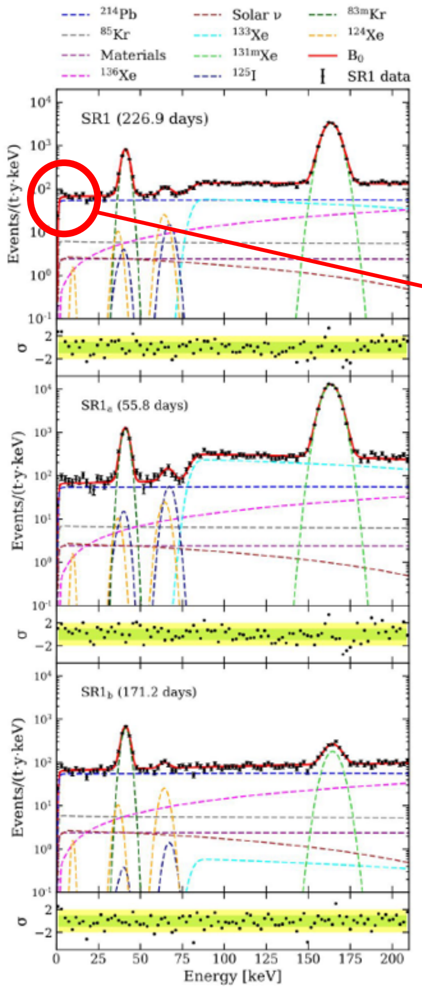


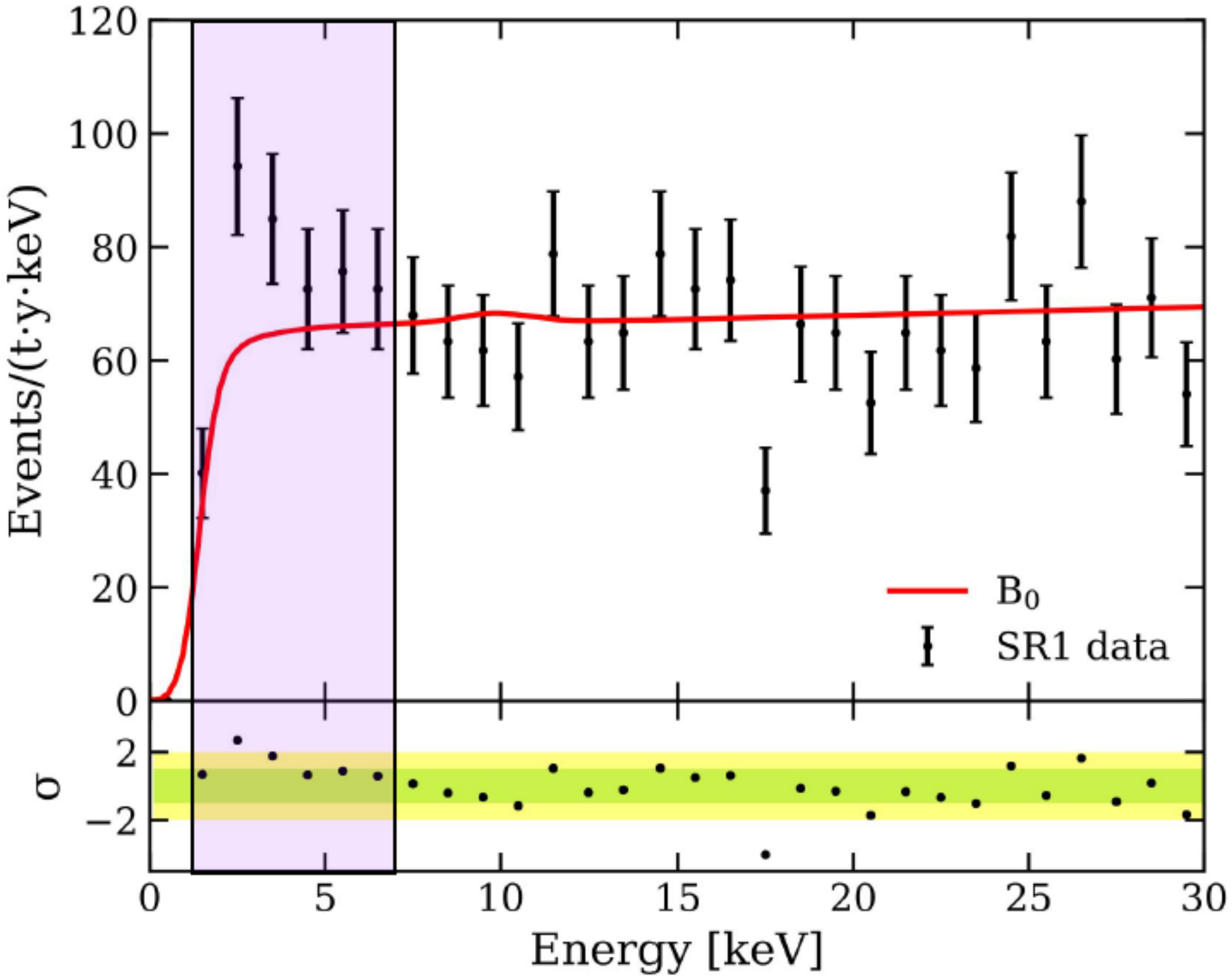
(76 ± 2) ev / (ton*y*keV$_{ee}$) in [1,30] keV$_{ee}$

Lowest background ever achieved in this energy range!

Good fit over most of the energy range

Fit with data – 1 to 7 keV



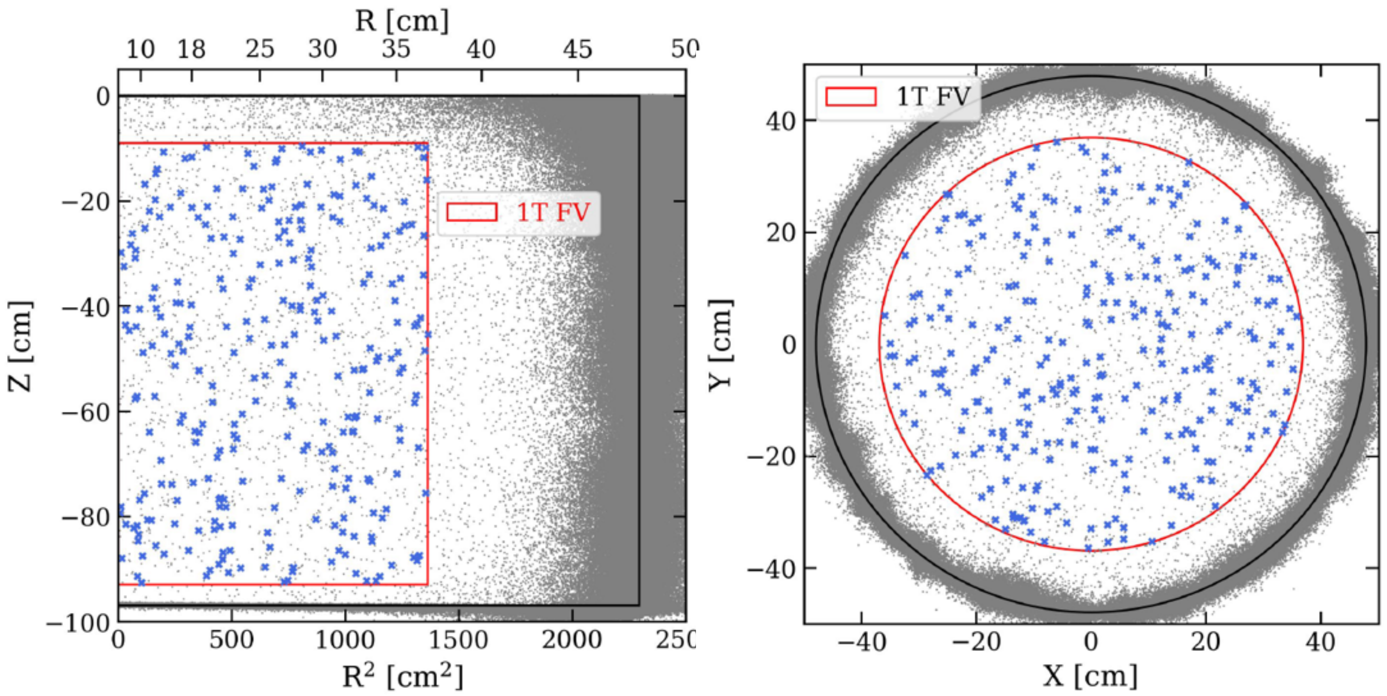


- **Excess of events between [1-7] keV_{ee}**
- 285 observed events
- 232±15 expected events from the best fit
- Would represent a 3.5σ fluctuation

PHYS. REV. D 102, 072004 (2020)

Spatial and temporal event distribution

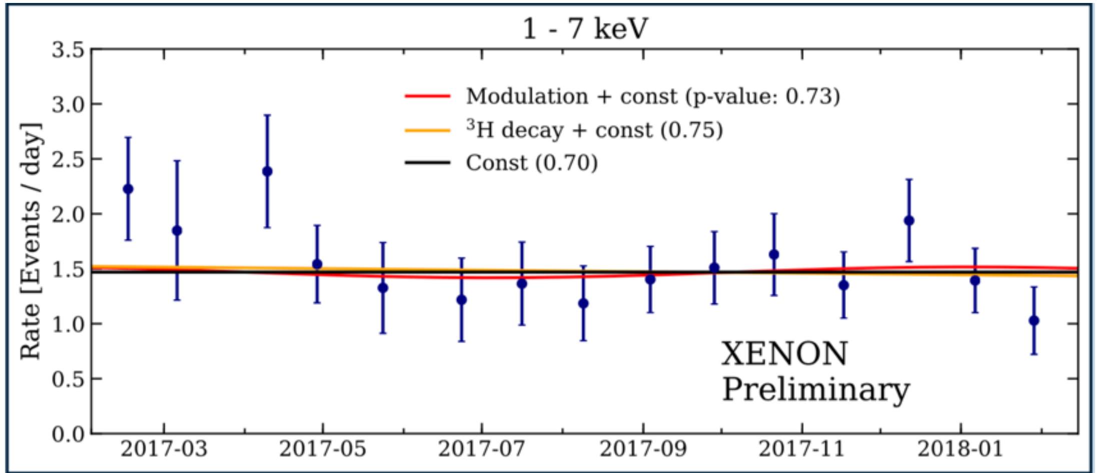
Spatial distribution



[1, 30 keV] [1, 7] keV

Events between 1 and 7 keV are uniformly distributed within the fiducial volume.

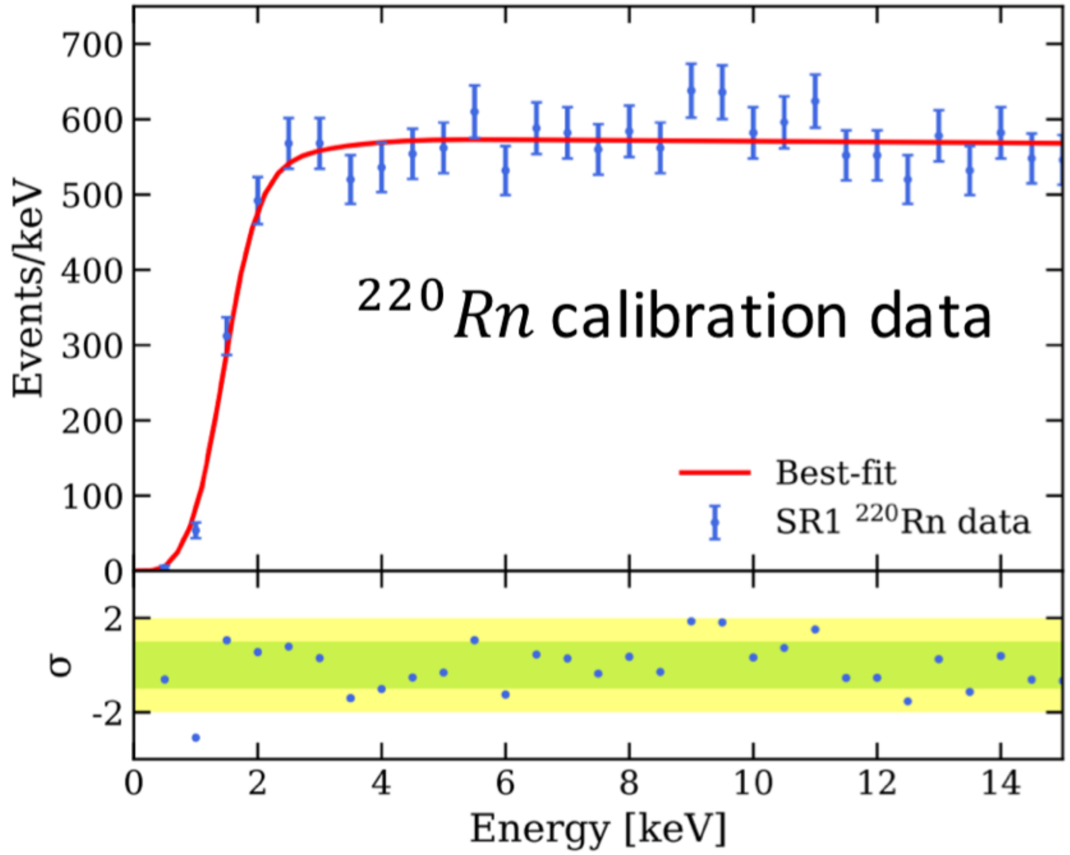
Temporal evolution



Event rate between 1 keV and 7 keV is compatible with a constant during SR1

Possible explanation - instrumental

- Incorrect reconstruction and description of efficiency?

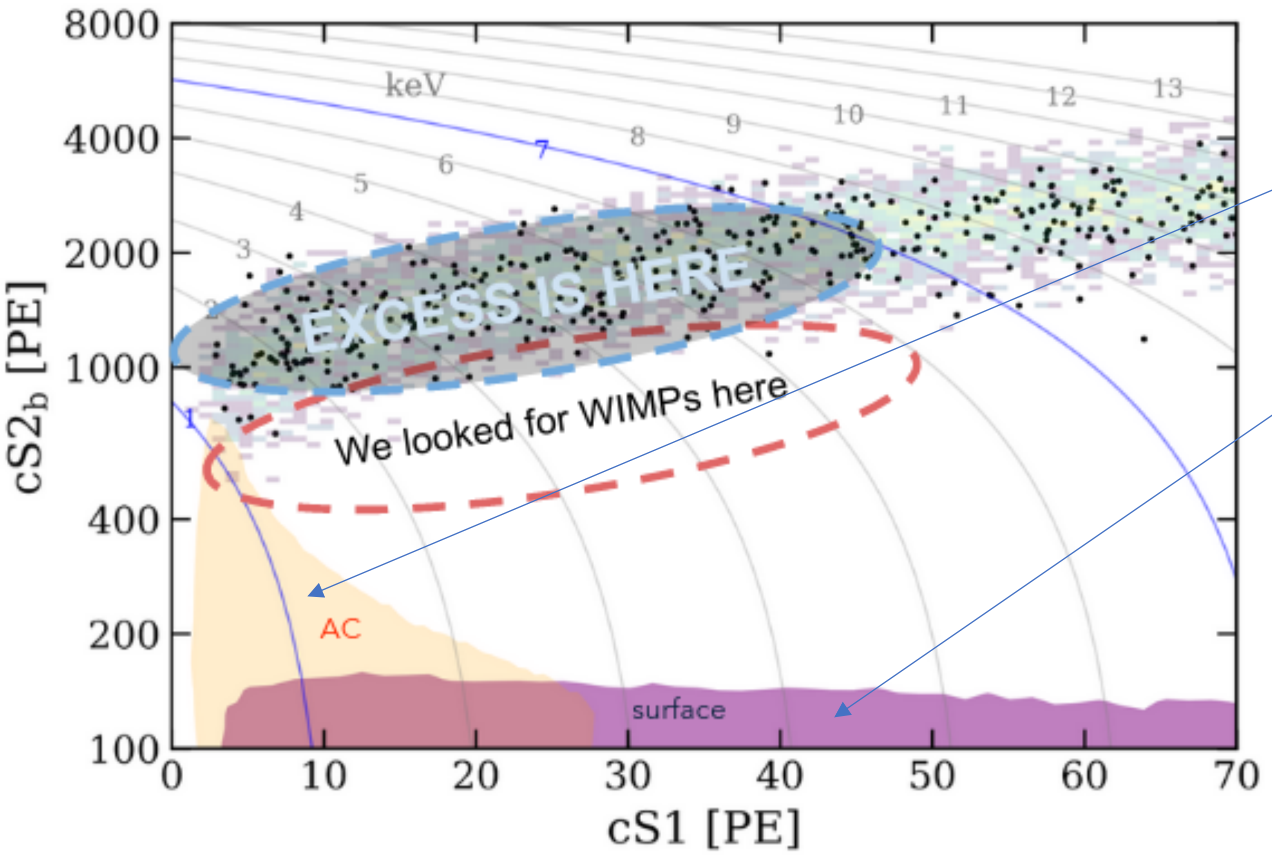


- Fit to ^{220}Rn (^{212}Pb) calibration data using same fit procedure
- No low energy distortions
- Validates the efficiency and reconstruction

Seems to be an unlikely explanation

Possible explanation - instrumental

- ER event band contamination from other classes of events?



- Leaking of Accidental Coincidences (AC) between S1 and S2 signals from uncorrelated events? No.

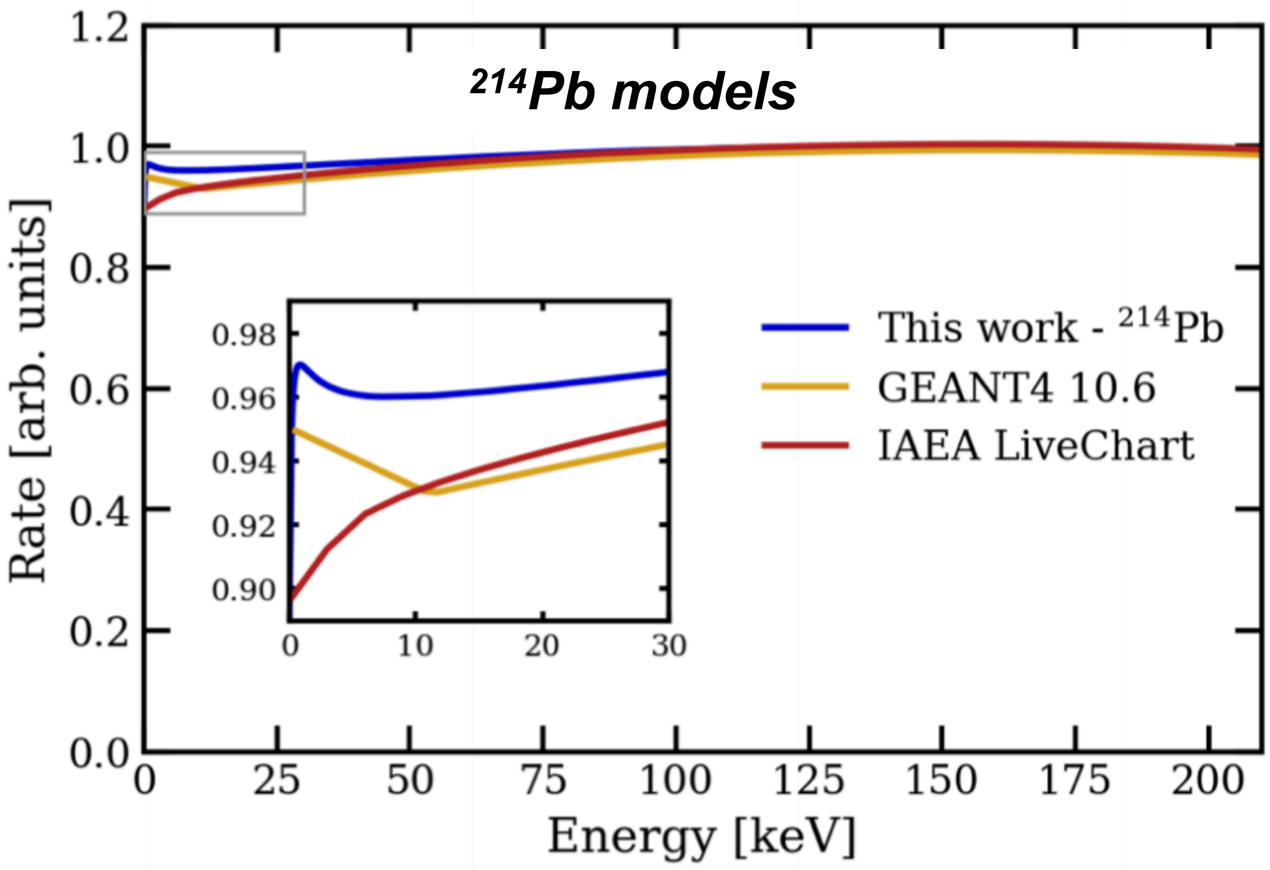
- Leaking from surface events (fraction of S2 is lost)? No.

Excess events are within the ER band. Unlikely explanation.

Possible explanation – background shape

XENON Dark Matter Project

- Corrections to background shape a low energies



- Exchange effects and atomic screening lead to rate increase at low energies.

- Recent calculation (X. Mougeot) of the ^{214}Pb spectrum at low energies is estimated to have an error of at most of 6%

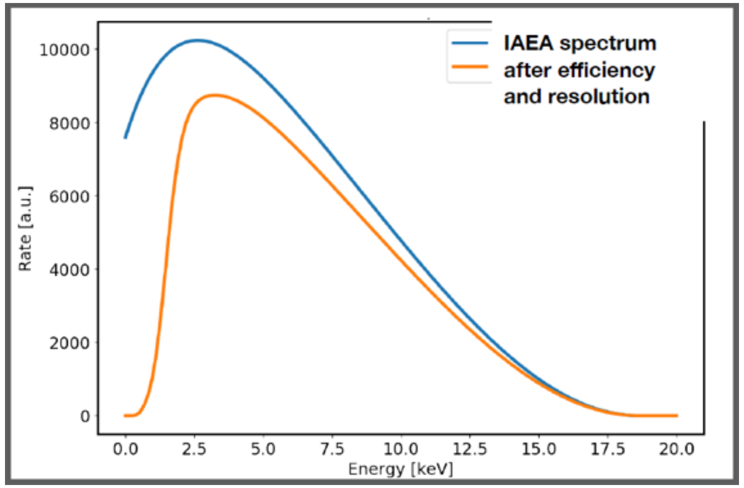
A 50% error is necessary to explain the data spectrum.

Unlikely explanation.

Forgotten contributions? – Tritium?

Tritium

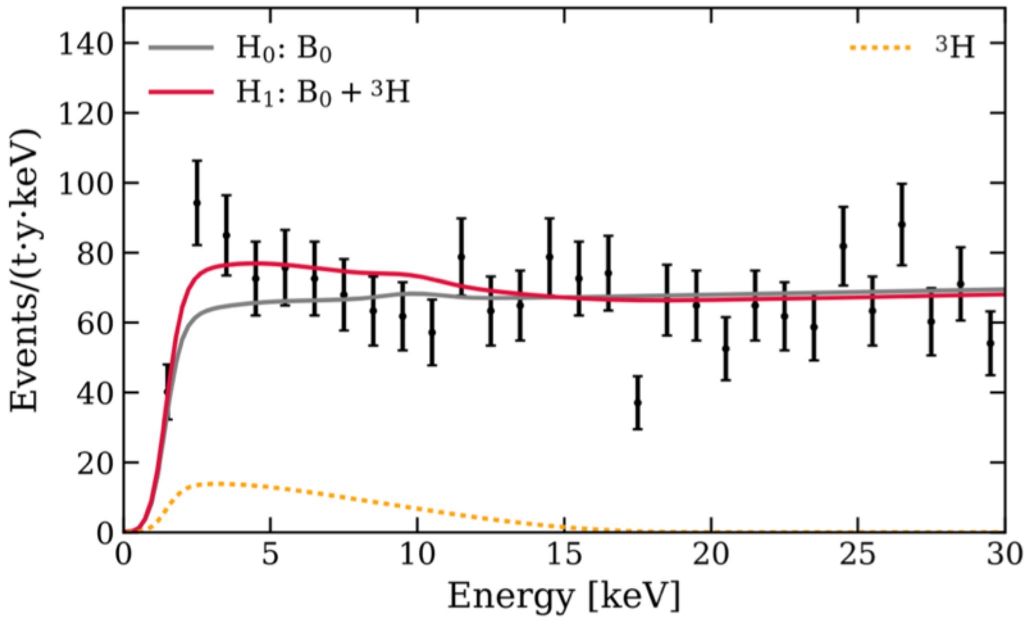
- Beta emitter with half-life of 12.3 y.
- Q value of 18.6 keV)



Energy spectrum before and after taking into account efficiency and energy resolution

Favoured over B_0 at 3.2σ

Rate from ^3H fit:
(159±51) events/(t*y)



^3H:Xe concentration
(6.2±2.0) * 10^{-25} mol/mol

Corresponds to ≈ 3 atoms of ^3H per kg of Xe

But from where?
A) Cosmogenic activation in Xe?
B) Emanation from materials?

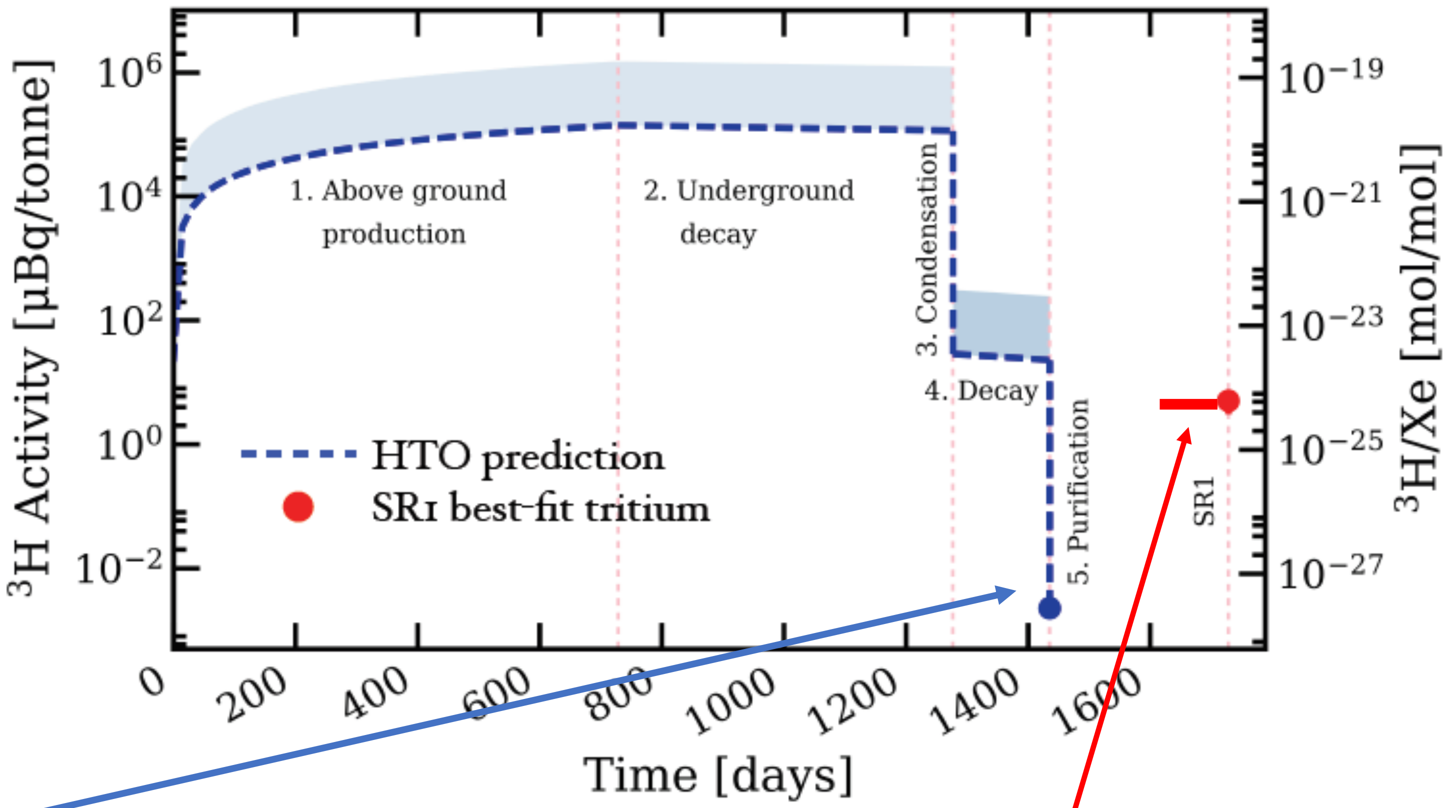
Possible origin of Tritium

A) Cosmogenic activation in Xe

Traces of water would imply the formation of HTO:

- Activation above ground: 32 tritium atoms per kg per day
- Slight decay during underground storage
- Condensation reduces contamination by factor ≈4000
- Purification with getters for hydrogen removal

Concentration from the fit indicates a factor 100 higher concentration than expected



T:Xe ~ 10^{-24} mol/mol

Hypothesis A) seems unlikely

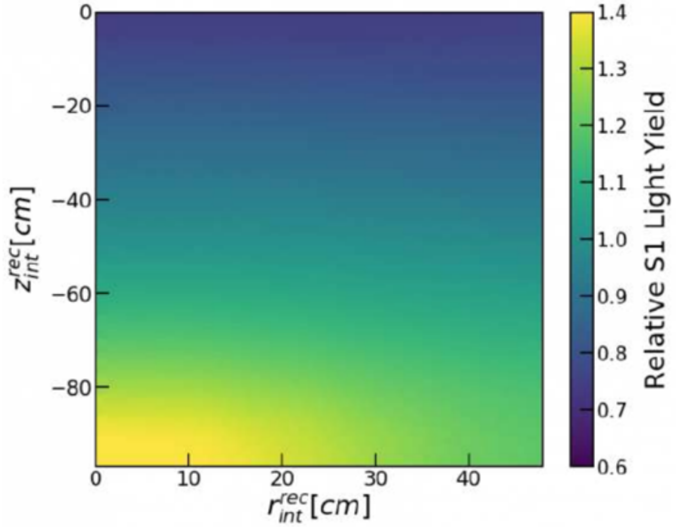
Possible origin of Tritium

B) Emanation from materials

Release of HTO or HT.

Natural abundance: HTO:H_2O ~ 10^{-17} mol/mol
To reach the measured concentration T:Xe ~ 10^{-24} mol/mol a H_2O:Xe ~ 100 ppb would be necessary

Light yield in XENON1T implies H_2O:Xe ~ 1 ppb



Natural abundance HT:H_2 ~ 10^{-17} mol/mol
Again H_2:Xe ~ 100 ppb

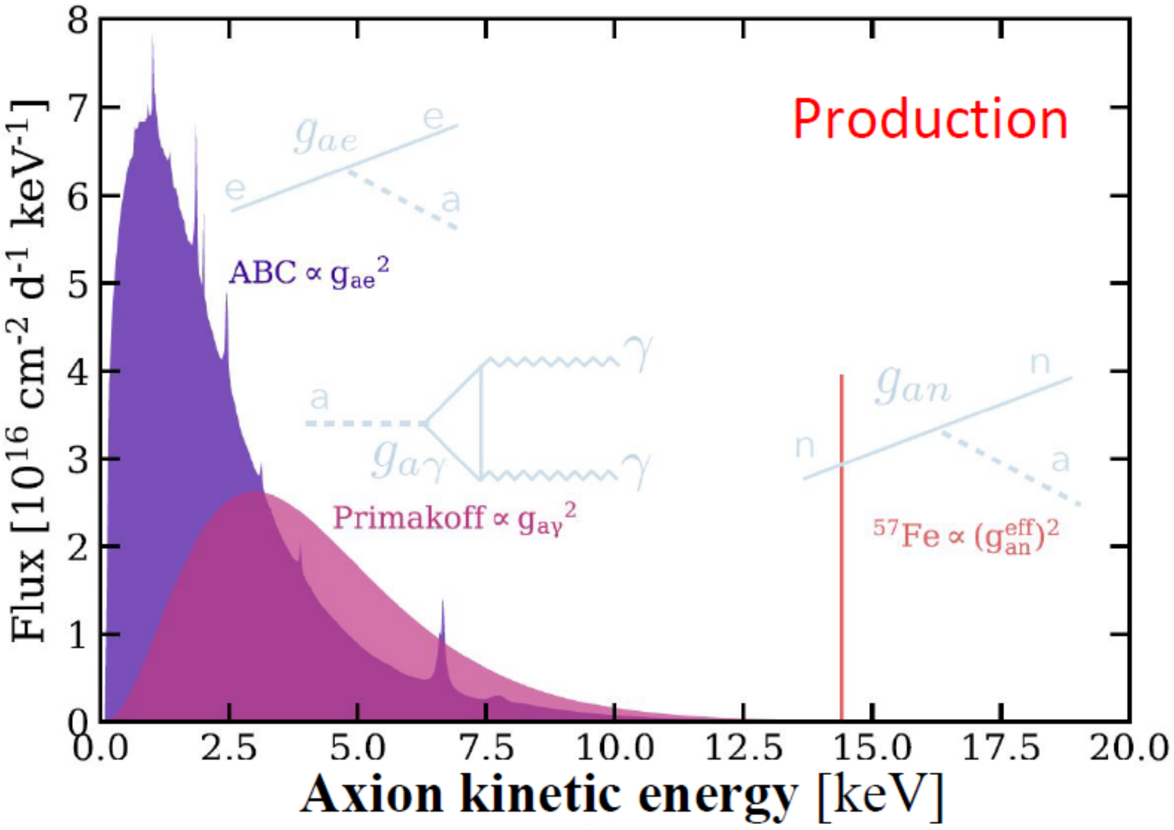
No constraints on the concentration H_2:Xe

Hypothesis B) cannot be excluded

Tritium conclusion: we can neither confirm nor rule out the tritium hypothesis

New physics? – Solar Axions

- **The Axion was originally introduced as a solution to the non-violation of CP in the strong interaction: known as the strong CP problem. It is considered as a Dark Matter candidate.**
- **Axions should be produced in the Sun if they exist.**



Different production mechanisms:

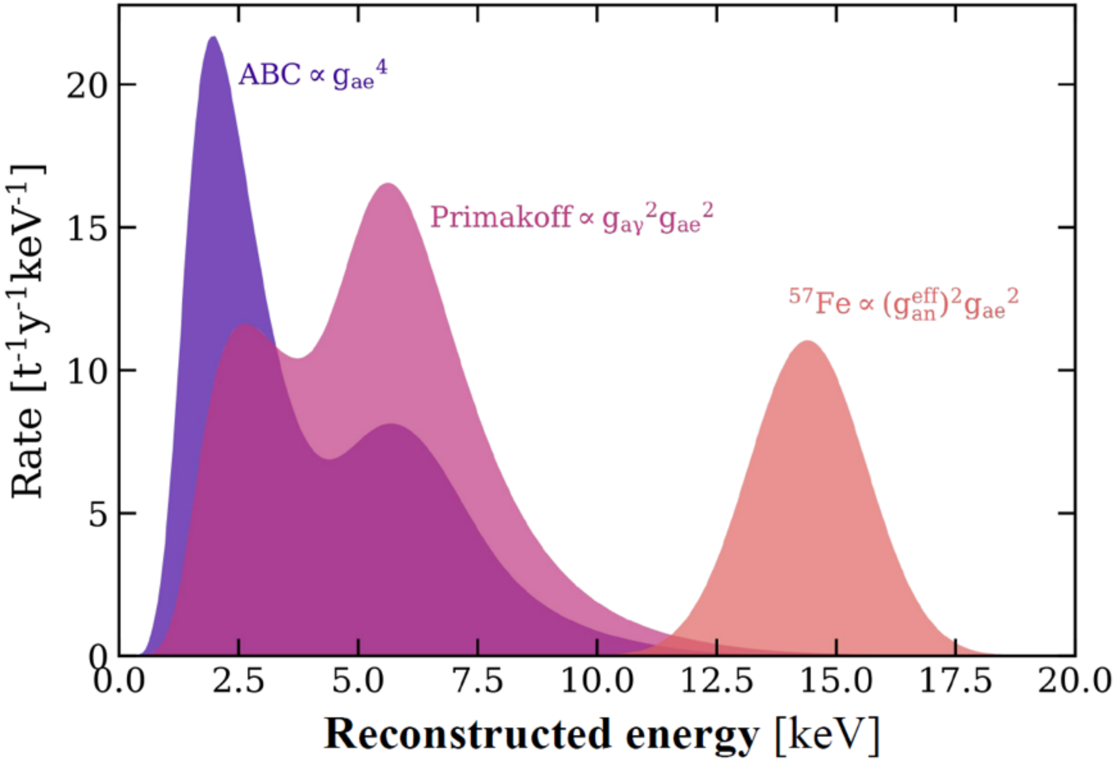
- Axion-electron coupling g_{ae}: Atomic recombination and excitation, Bremstrahlung, Compton. ABC axions.
- Axion-photon coupling $g_{a\gamma}$ via the Primakoff effect.
- Nuclear transition of the ^{57}Fe line at 14.4 keV parametrised by g_{an}^{eff}.

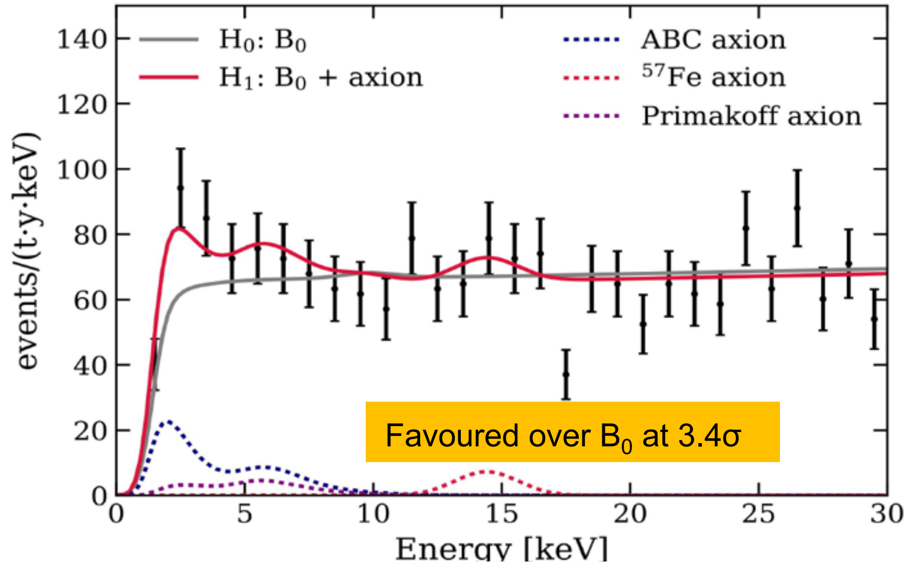
Detection in XENON1T is considered via the axio-electric effect proportional to g_{ae}^2.

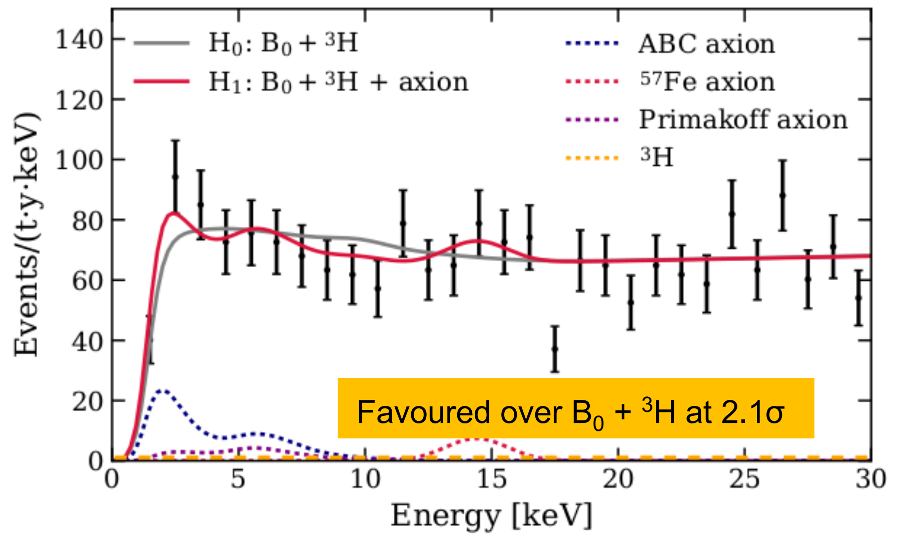
New physics? – Solar Axions

Detection via the axio-electric effect

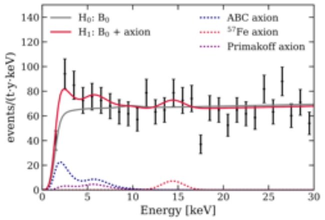
- Convolution with the detector resolution
- Efficiency corrections



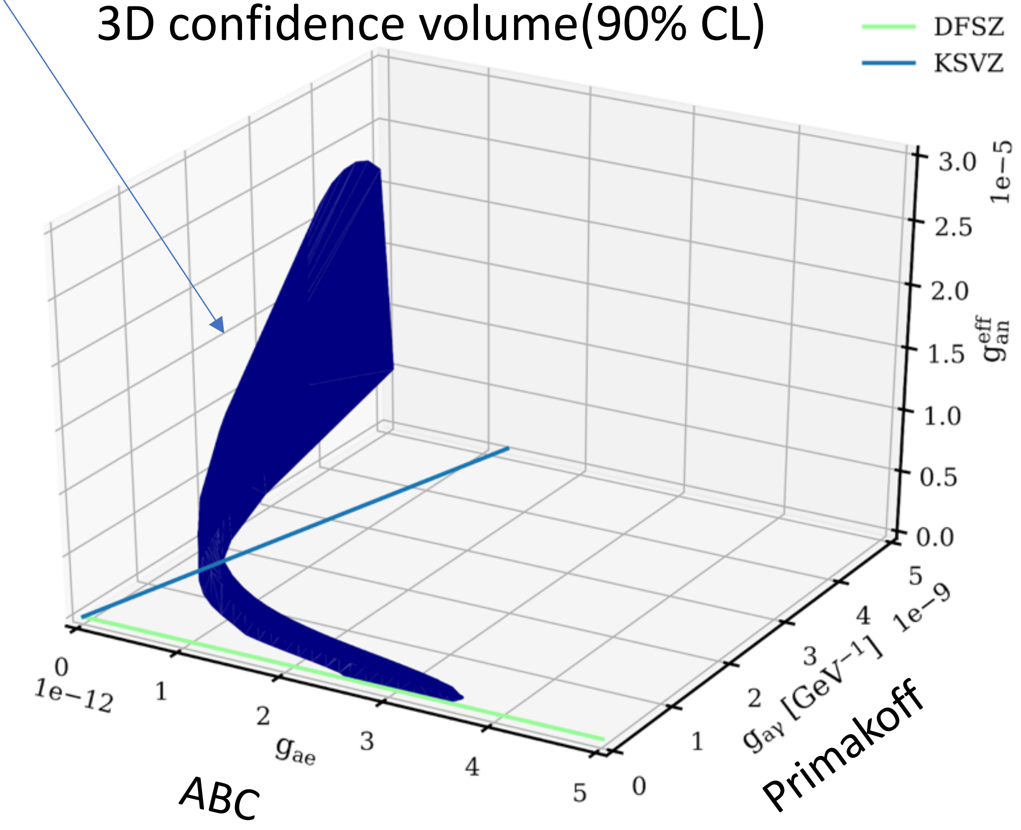


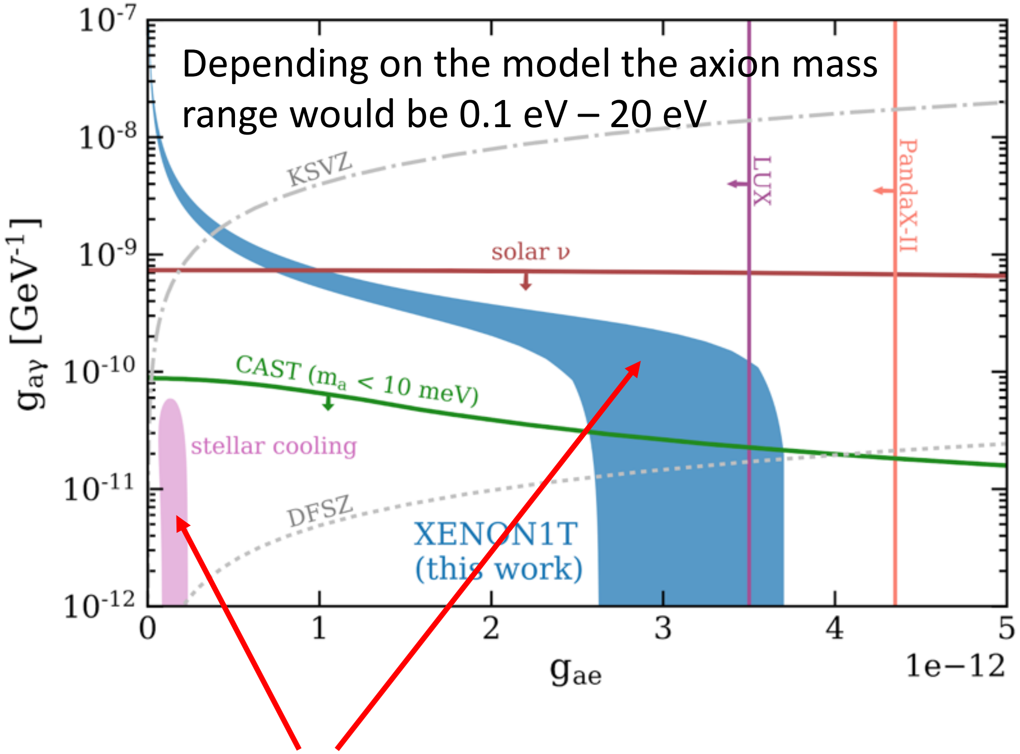


New physics? – Solar Axions



3D confidence volume(90% CL)





Axion hypothesis is favoured over B_0 at 3.4 σ

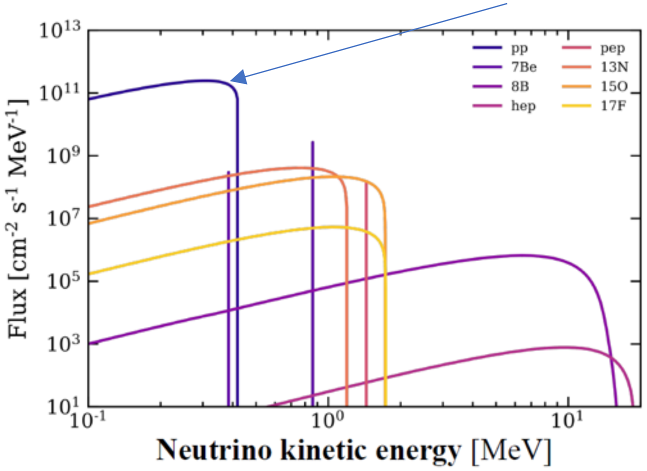
BUT: strong tension with astrophysical constraints from stellar cooling (per es. arXiv:2003.01100)

INTERESTING: Gao at al. (arXiv:2006.14598), Dent et al. (arXiv: 2006.15118) point out that this tension is alleviated by considering the inverse Primakoff effect in LXe in the detection.

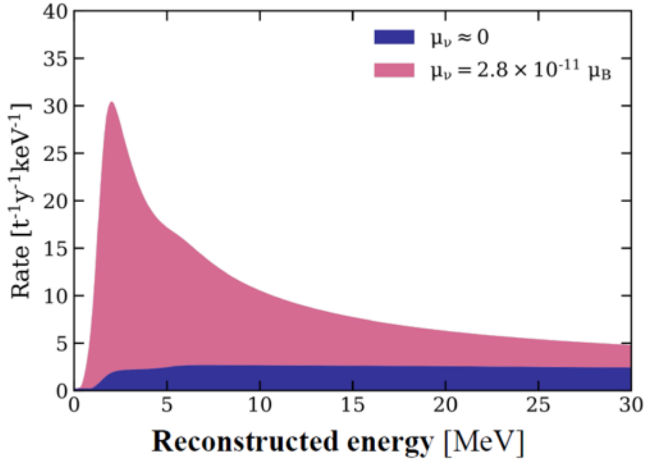
New physics? – μ_ν

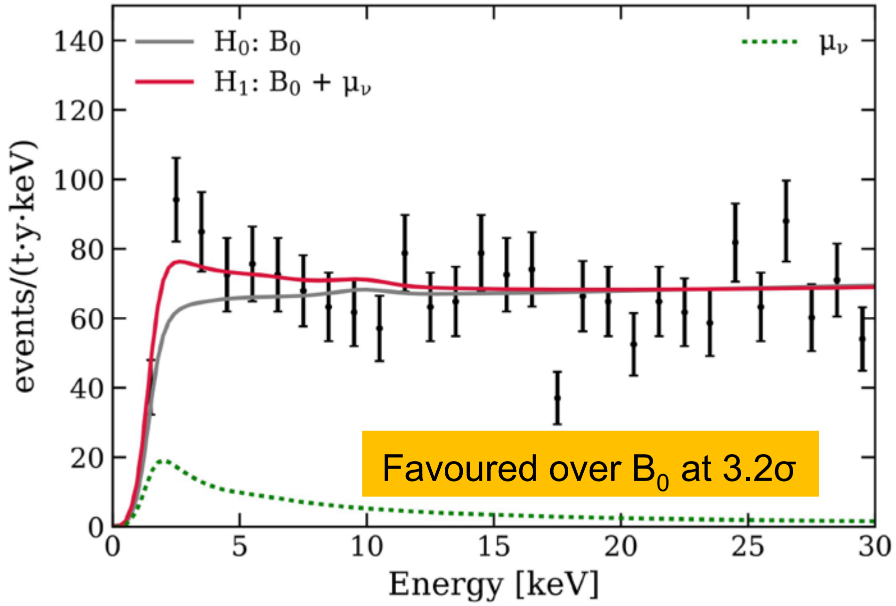
- Large values of the neutrino magnetic moment would imply new physics.
- Majorana neutrinos are expected to have μ_ν > 10^{-15} μ_B.
- Enhanced neutrino-electron elastic scattering cross section would occur.

Solar neutrinos from the pp reaction



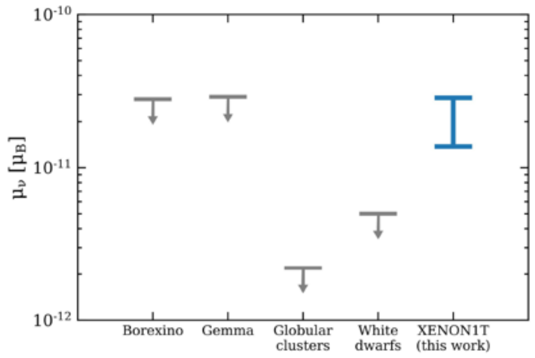
Energy spectrum





μ_ν between [1.4, 2.9] * 10^{-11} μ_B at 90% C.L.

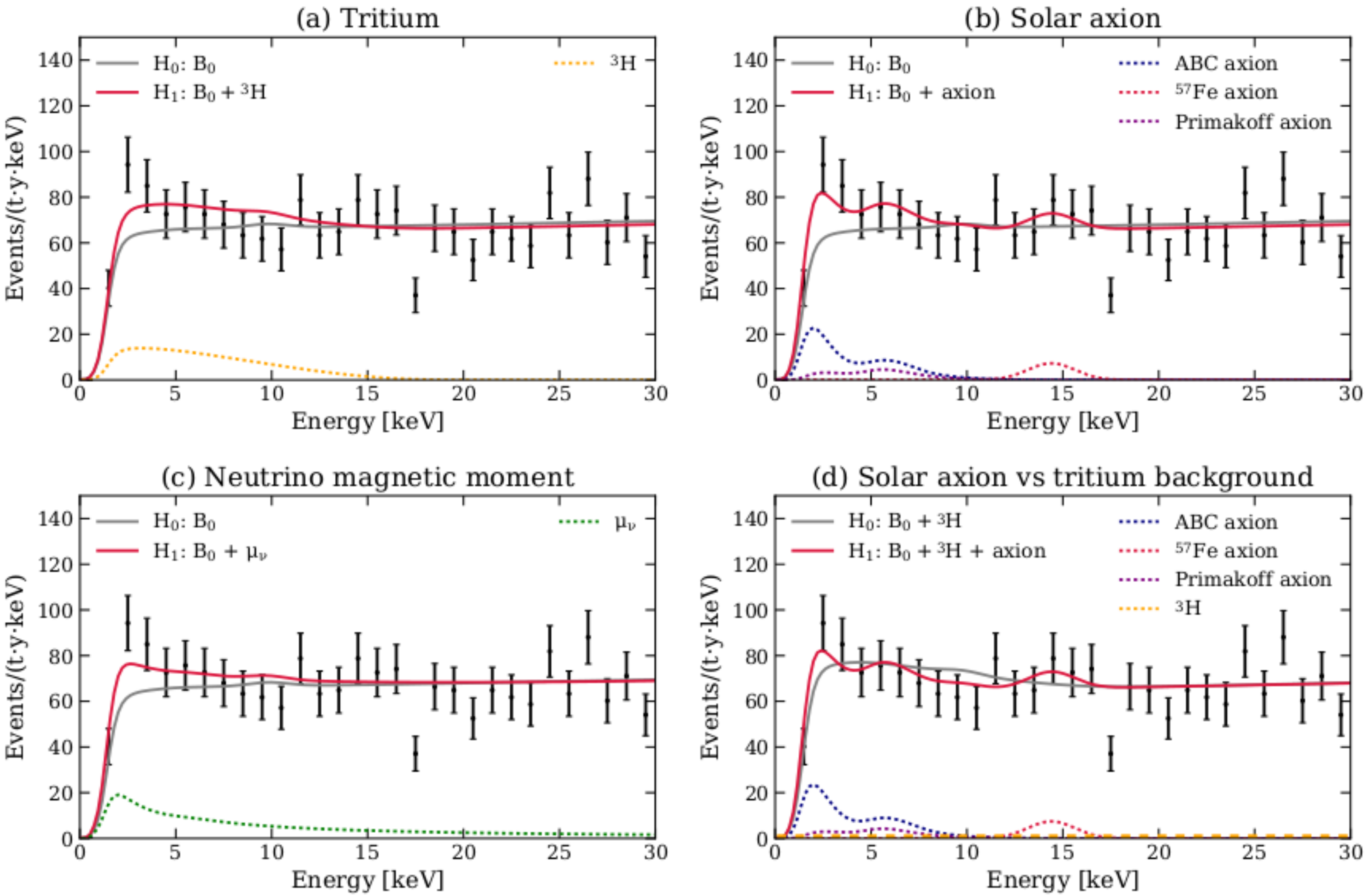
In contrast with astrophysical observations



Summarising

^{3}**H** favoured over B_0 at 3.2σ

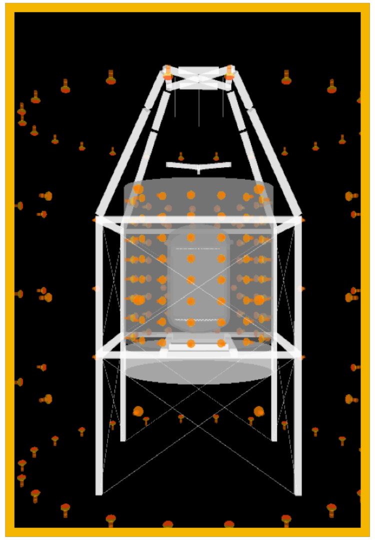
$\boldsymbol{\mu_\nu}$ favoured over B_0 at 3.2σ



Solar axion favoured over B_0 at 3.4σ

Solar axion Favoured over B_0 + ^{3}H at 2.1σ

XENONnT upgrade



Neutron veto

- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % $Gd_2(SO_4)_3$

Larger TPC

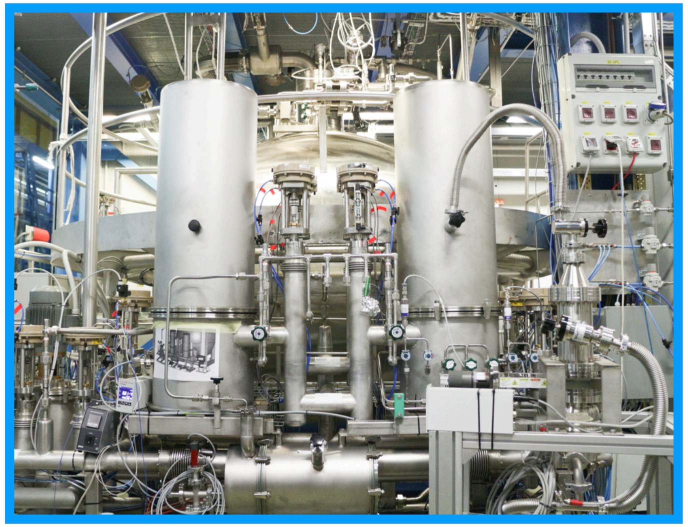
- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

ReStoX2

- Second Xe Recovery and Storage system
- Up to 10 t GXe capacity

^{222}Rn distillation

- Reduce Rn (^{214}Pb) from pipes, cables, cryogenic system
- New system

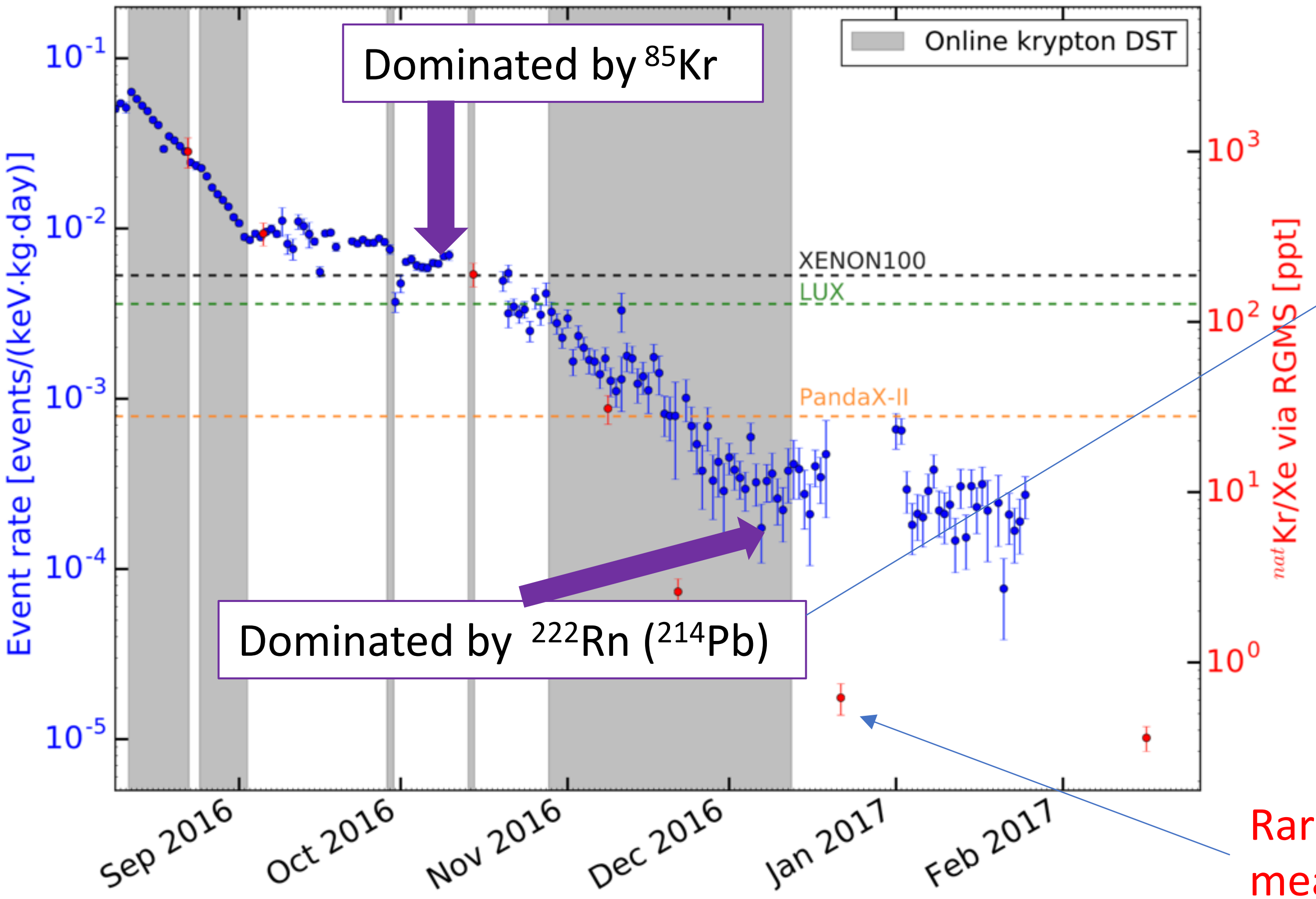


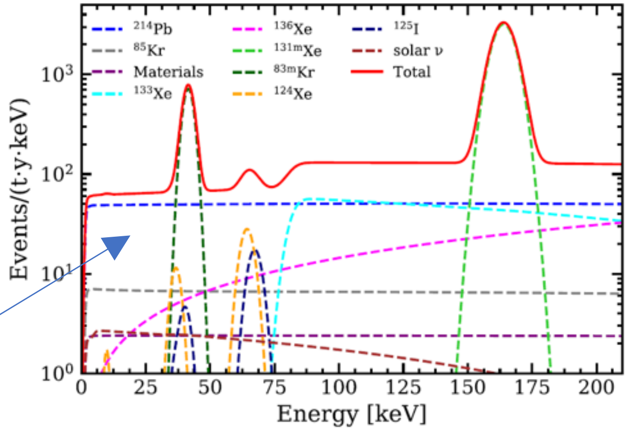
LXe purification

- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm

ER dominating background at low energy

In the low energy region, which is of interest for WIMP searches, the leaking of electron recoil events into the nuclear recoil region is dominated by ^{85}Kr and ^{222}Rn.



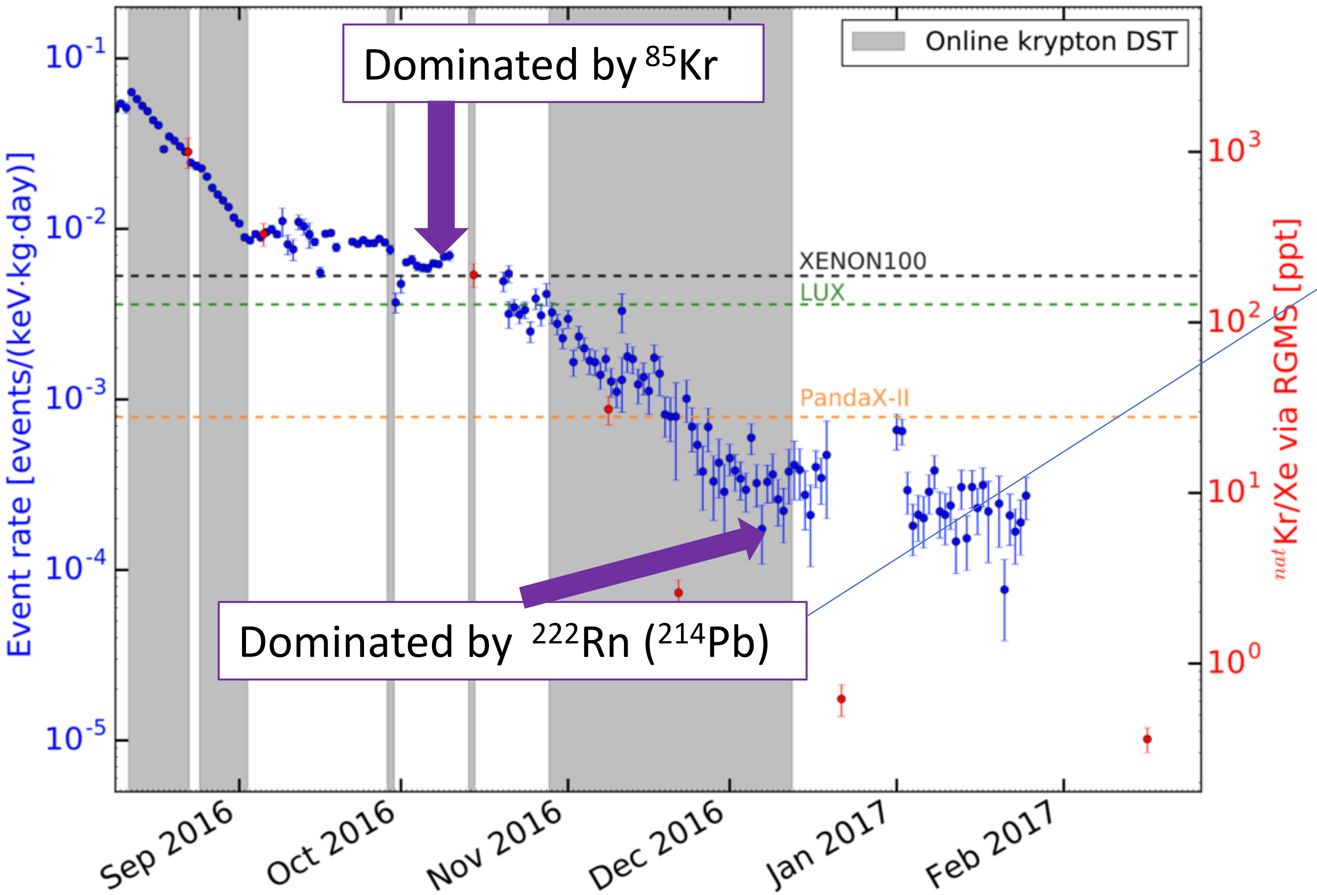


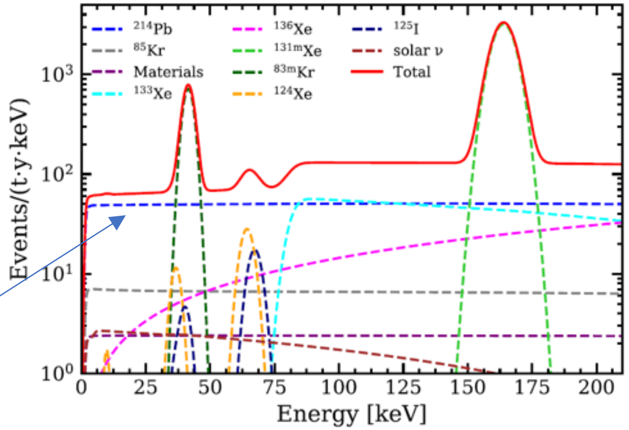
On-line distillation reduced the ^{85}Kr level resulting in a ^{222}Rn dominated background

Rare gas mass spectrometry measured ^{nat}Kr concentration

ER dominating background at low energy

In the low energy region, which is of interest for WIMP searches, the leaking of electron recoil events into the nuclear recoil region is dominated by ^{85}Kr and ^{222}Rn.





By improving the ^{222}Rn elimination via upgraded cryogenic distillation, the the NR background, now dominated by the leaking of ER events to the NR band, will be dominated by radiogenic neutrons

NEUTRON VETO

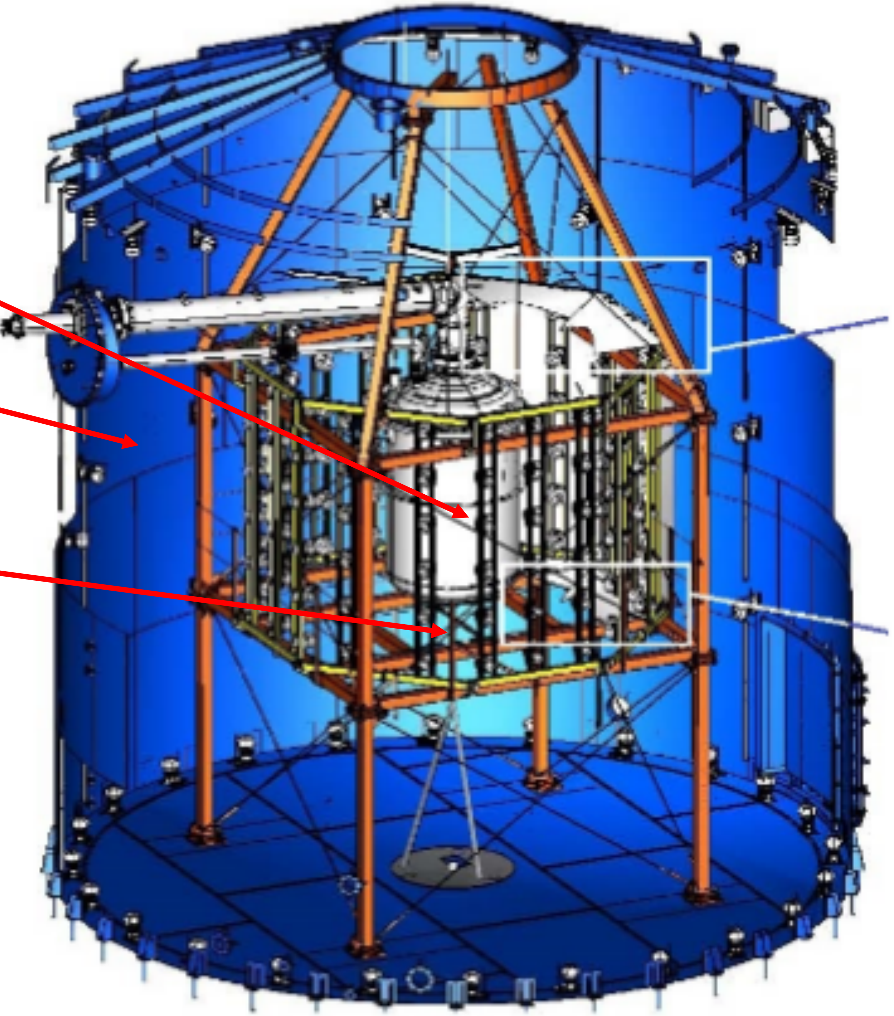
XENONnT

General structure of XENONnT

- Active mass: ≈ 6 tonne active
- Muon veto: ≈ 650 m^3 water + Gd
- Neutron veto: ≈ 50 m^3 water + Gd

With respect to XENON1T

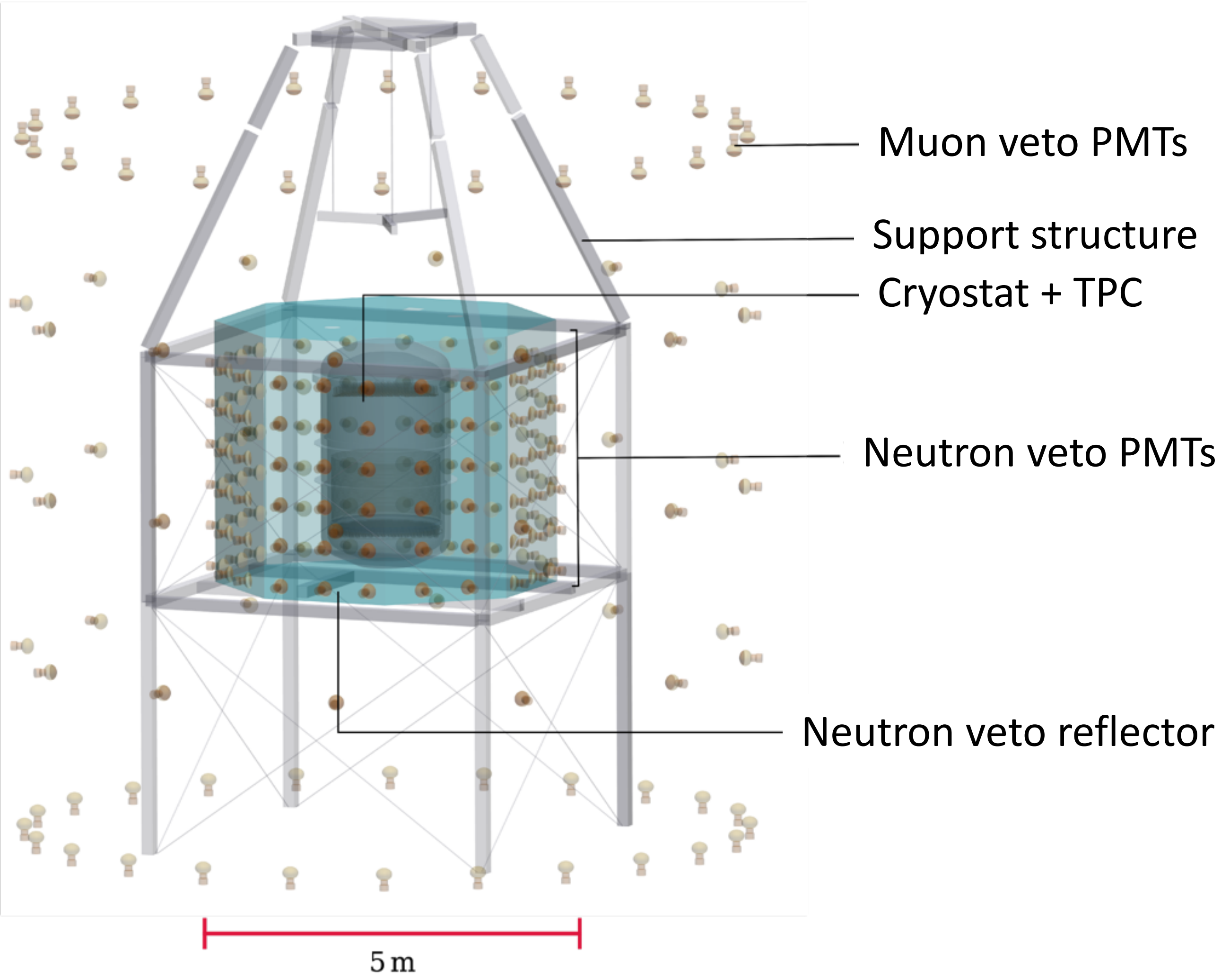
1/6 background	×3 active volume



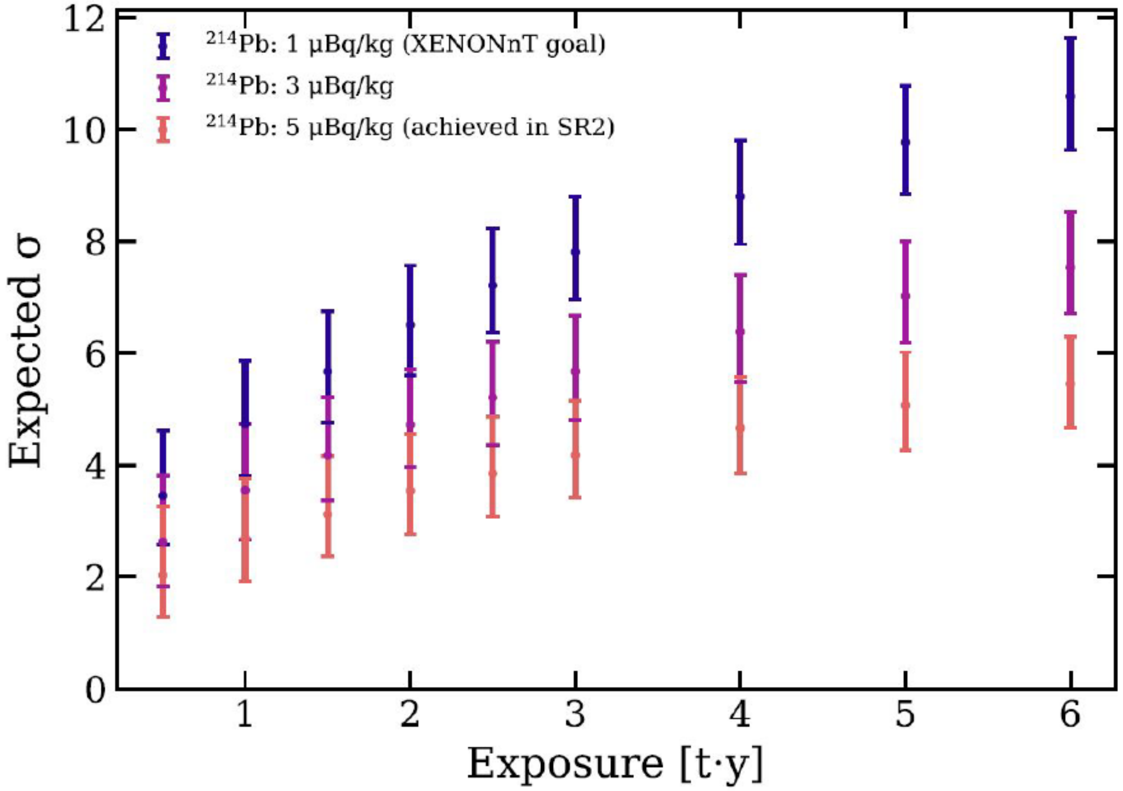
Neutron Veto

The Xenon TPC is surrounded by a double layer of water + Gadolinium

- The presence of the Gadolinium is to capture thermalised neutrons which have exited the central detector
- Internal layer is enclosed by white diffusing reflector. Cherenkov Light generated by a neutron capture in the Gadolinium is read by 120 dedicated PMTs.
- External layer composes the Muon Veto detector. Muons generate light via the Cherenkov effect.



XENONnT perspective



1/6 background

×3 active volume

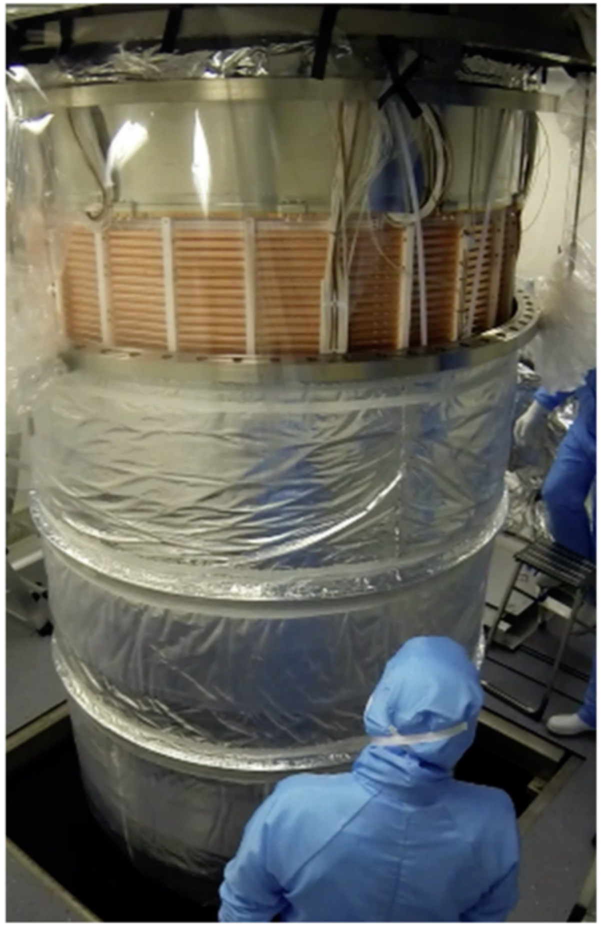
Within a few months it should be possible to clarify the situation

Arrival of the TPC inside the LNGS gallery

XENON Dark Matter Project

5 March 2020: TPC completed and transported underground **(8 March 2020: COVID19 national lock-down)**

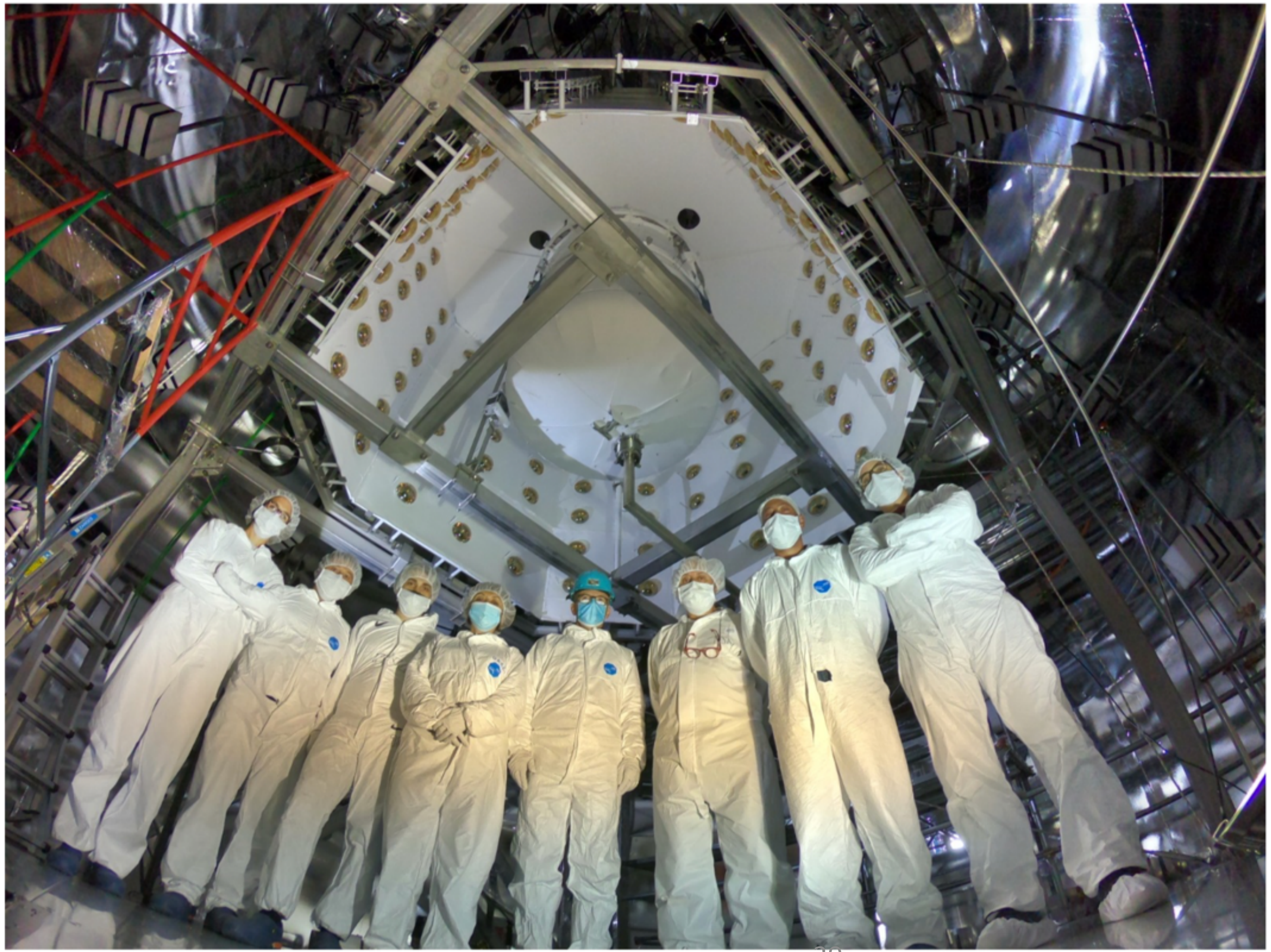
16 March 2020: closed the cryostat



Installation of the neutron veto

From August (started 27 July) installation of the nVeto and its integration with the calibration system.

Inside the water tank looking up into the neutron veto without the floor.
At the centre cryostat.



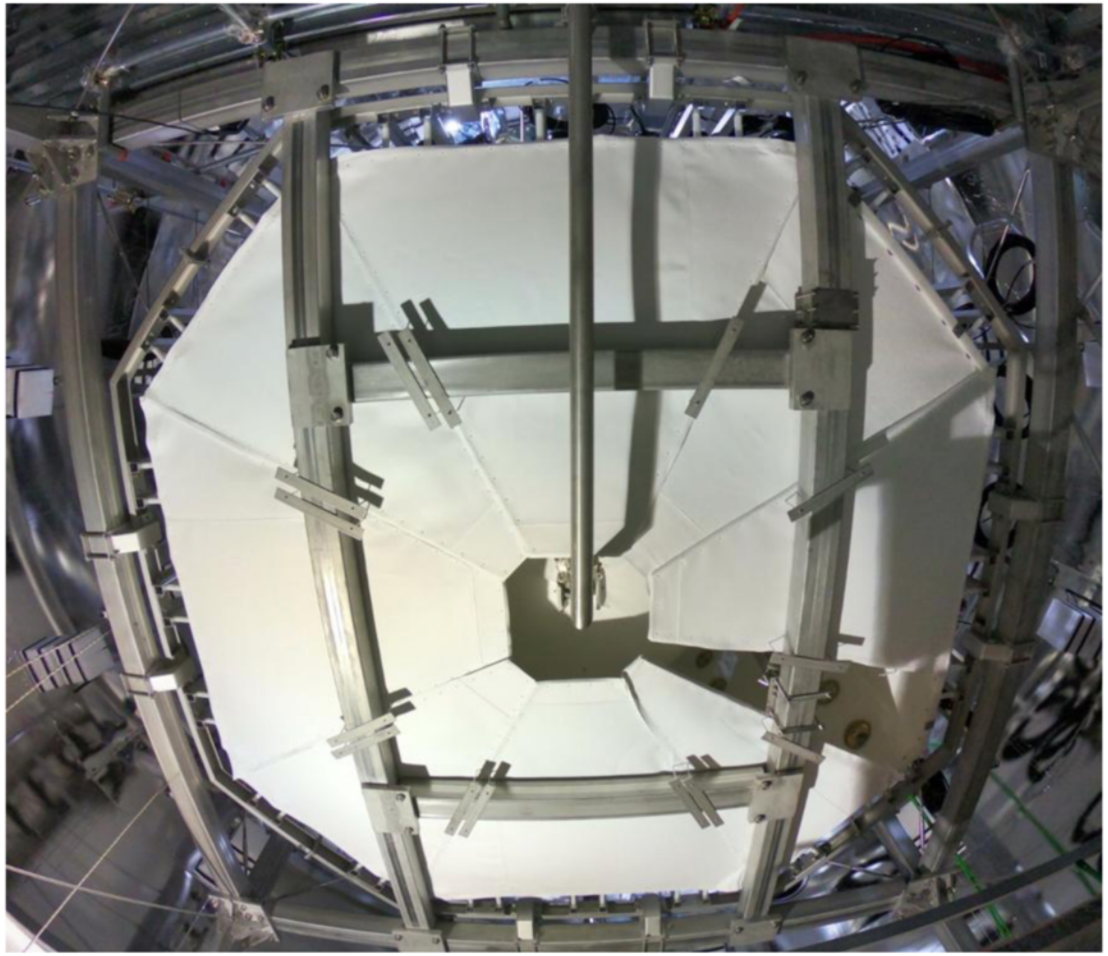
Installation of the neutron veto

Inside the neutron veto

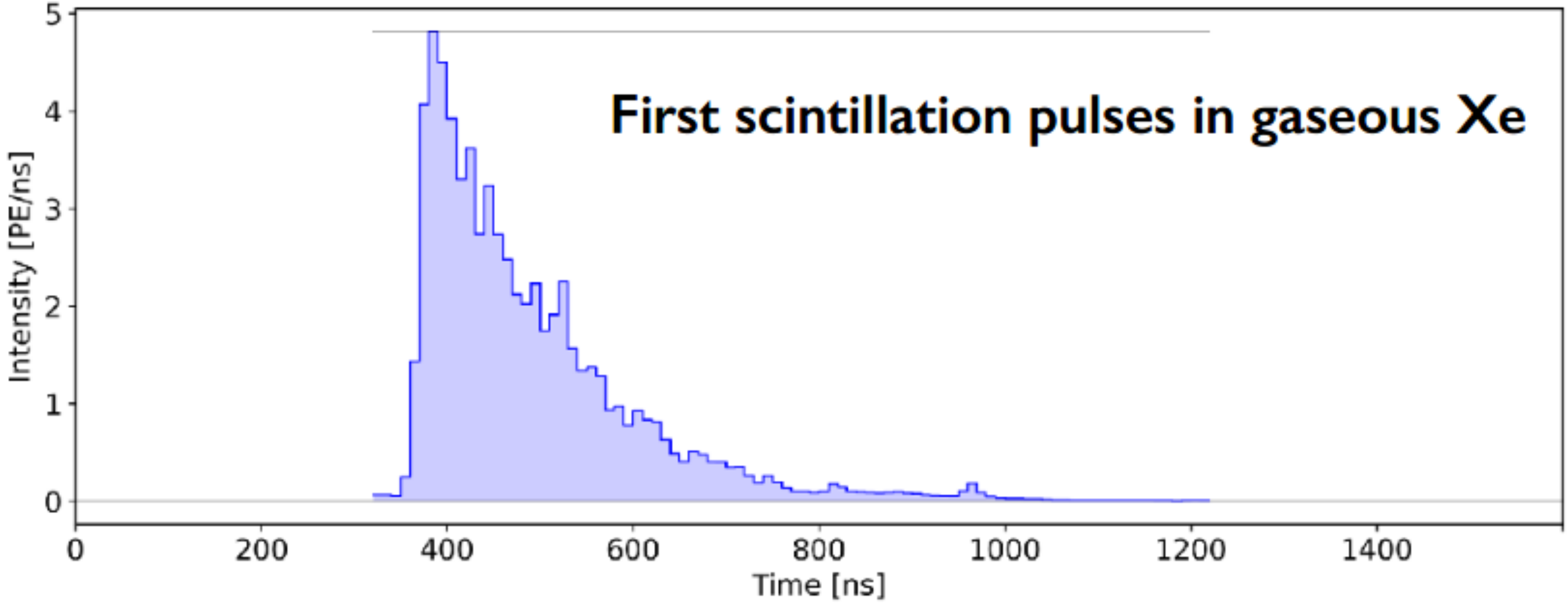
Last touches: roof, sides and cryostat cover almost complete

Inside the water tank

View from below showing the bottom pannels of the nVeto



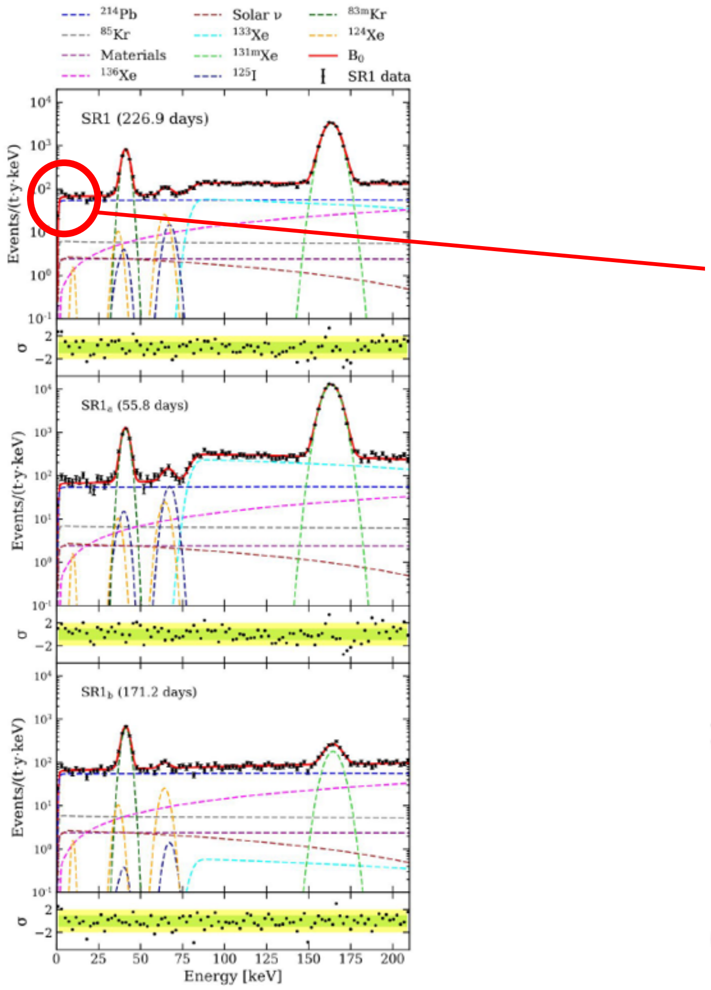
XENONnT



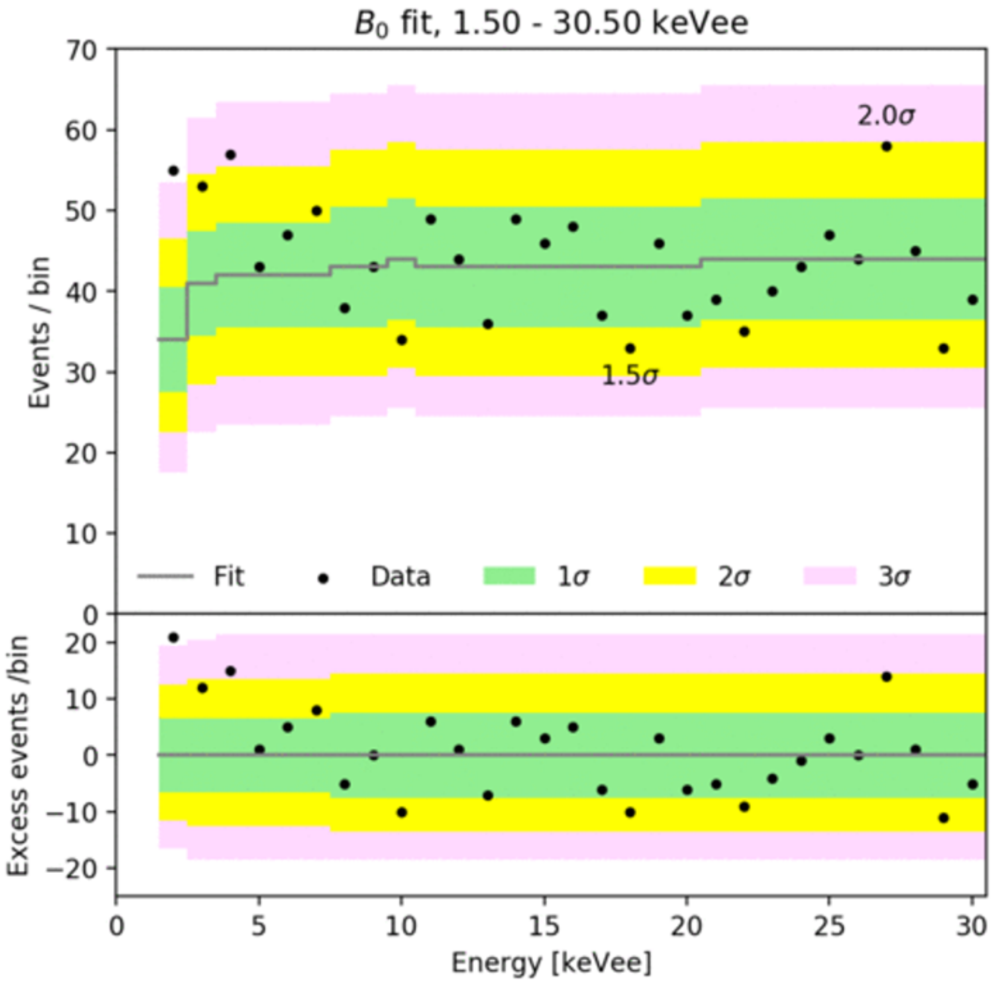
First scintillation pulses in gaseous Xe
Intensity [PE/ns]
5
4
3
2
1
0
0
200
400
600
800
1000
1200
1400
Time [ns]

Thank you!

Fit with data



Rebinned



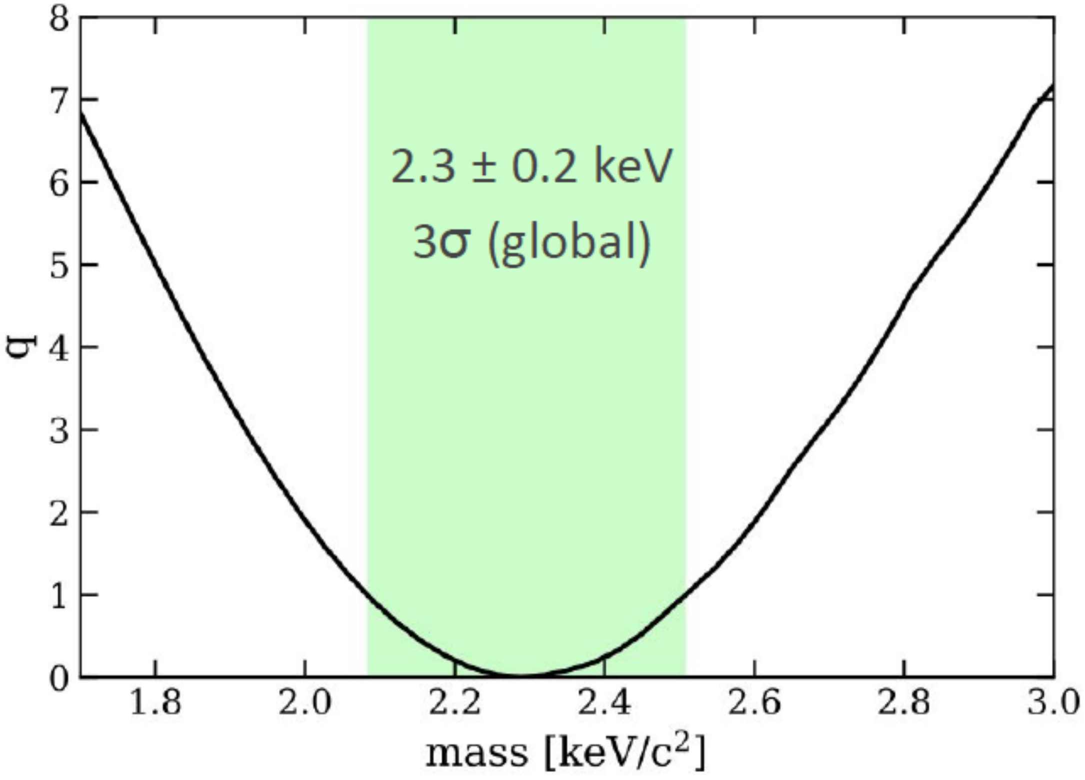
- **Excess of events between [1-7] keV$_{ee}$**
- 285 observed events
- 232±15 expected events from the best fit
- Would represent a 3.5σ fluctuation

^{37}Ar contamination?

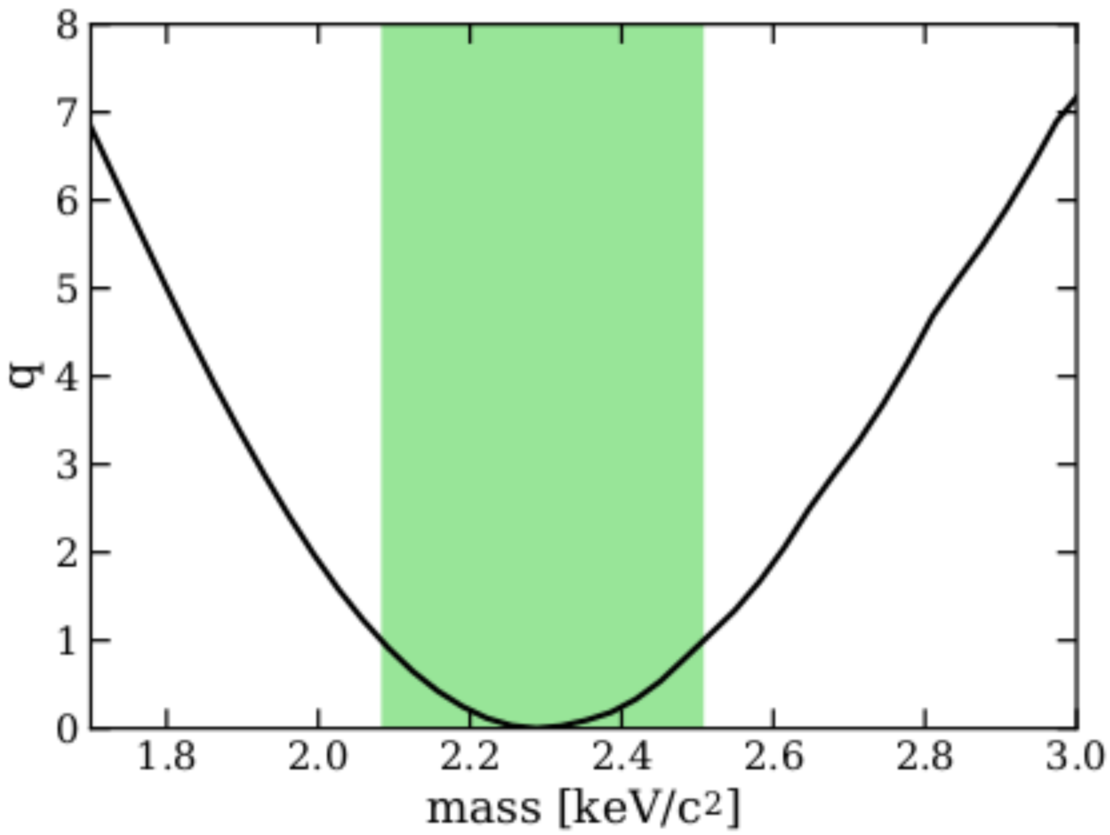
- Air leak in XENON1T < 1 liter/year (rare gas mass spectrometry constraints)
- Corresponds to < 5 ev/(t·y) in the ER band
- To explain the excess ER events one needs 65 ev/(t·y)

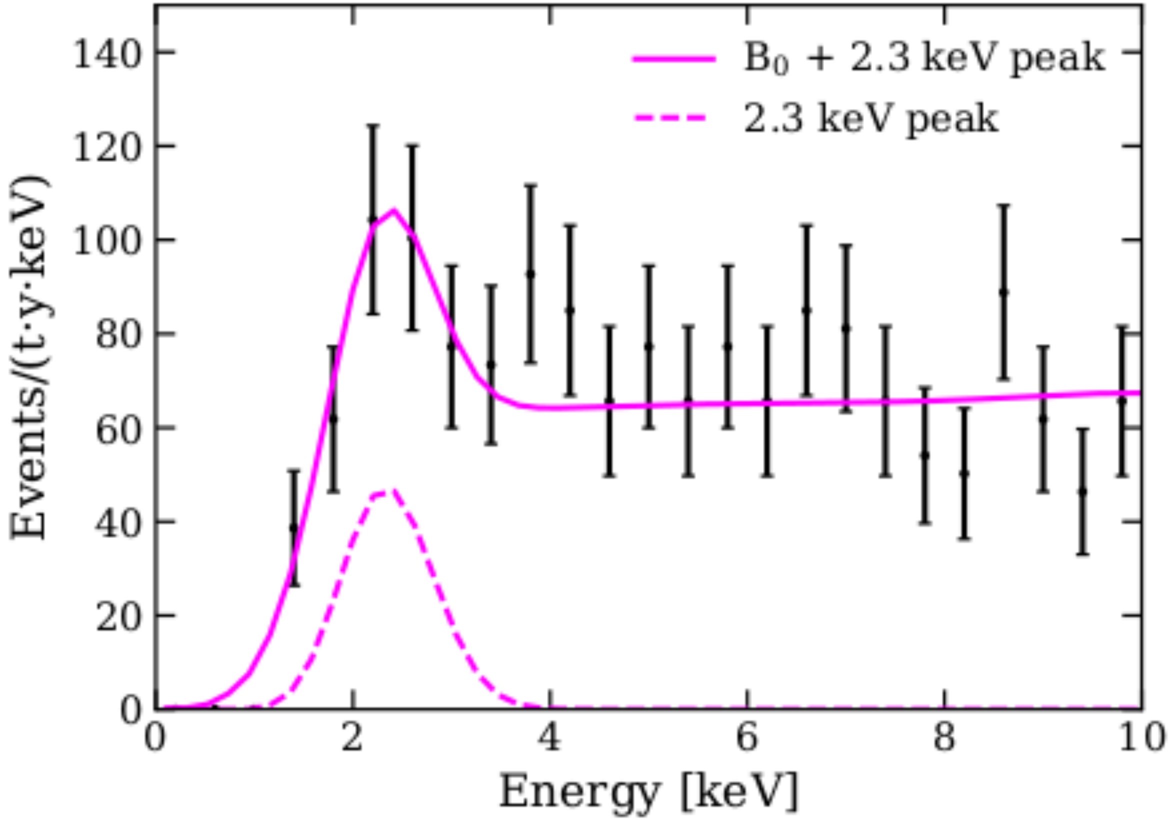
And

- ^{37}Ar gives monoenergetic line at 2.82 keV_{ee}
- Best mono-energetic line fit at 2.3±0.2 keV_{ee}
- Energy reconstruction in this energy range is validated with ^{37}Ar calibration



New Physics? Bosonic Dark Matter



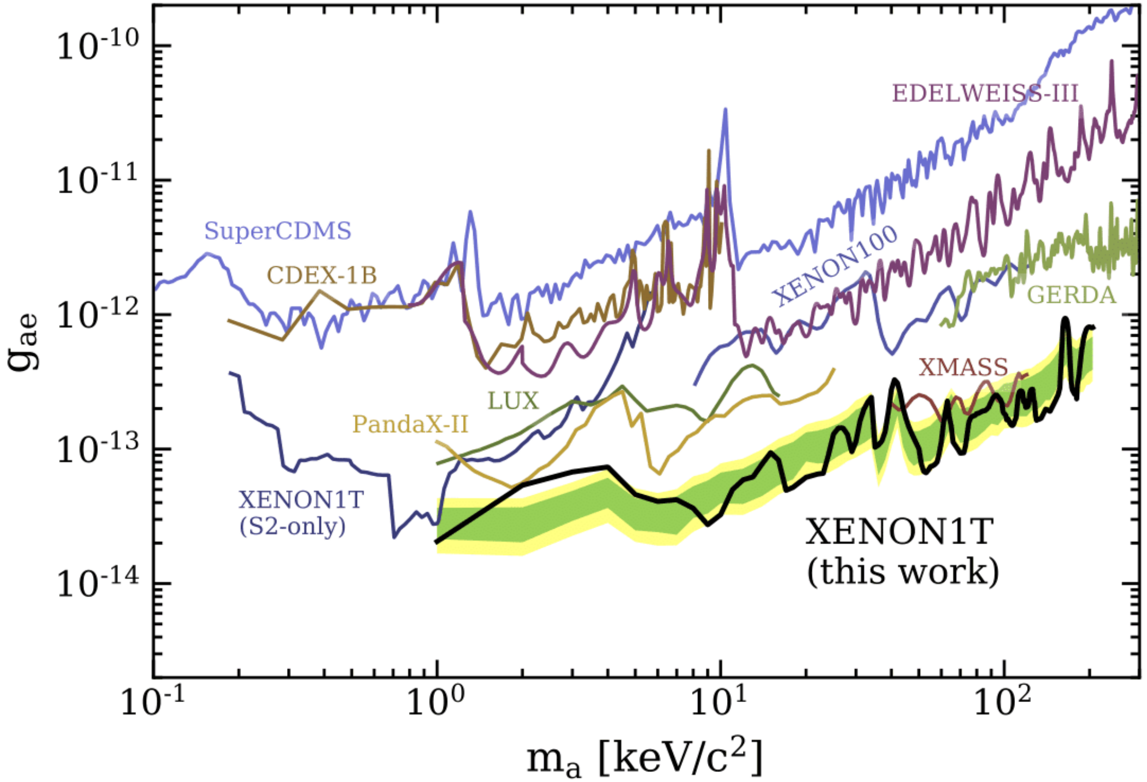


Fitting a monoenergetic peak to the ER escess events

New Physics? Bosonic Dark Matter

XENON Dark Matter Project

Axion-like particle



Dark photon