Observation of excess electronic recoil events in XENON1T

On behalf of the
XENON collaboration
and X. Mougeot

arXiv:2006.09721

Andrea Molinario

6th Korea Meeting

Xe XENON Dark Matter Project

XENON Technical Meeting, May 12-14, 2020

XENON collaboration

XENON
Dark Matter Project

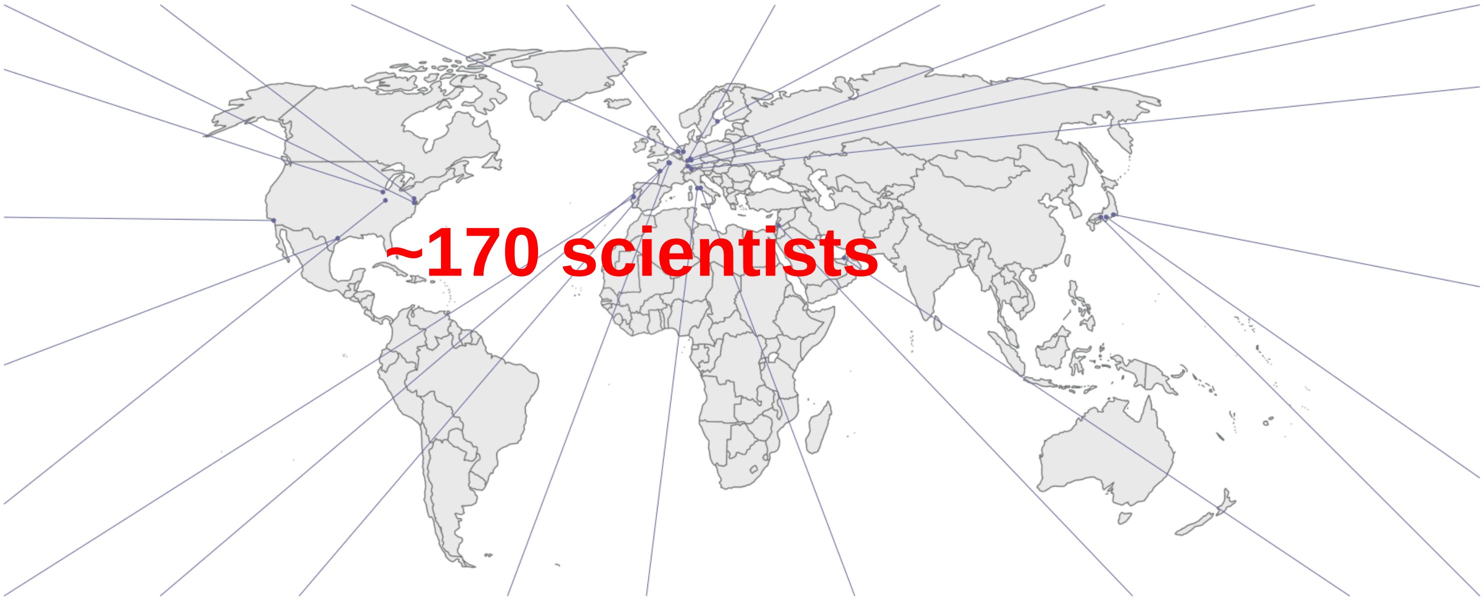
Columbia | RPI | Nikhef | Muenster | KIT | Stockholm | Mainz | MPIK, Heidelberg | Freiburg

Chicago

UCSD

Rice

Purdue



Zurich

Tokyo

Nagoya

Kobe

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

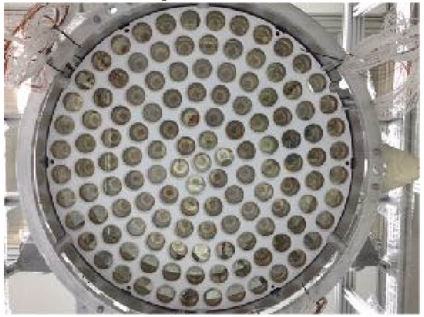
The XENON1T detector at LNGS

XENON1T operated underground at Laboratori Nazionali del Gran Sasso (Italy) from 2015 to 2018

~1.4 km rock coverage (3600 m w.e.) provides 10^6 reduction factor of μ flux

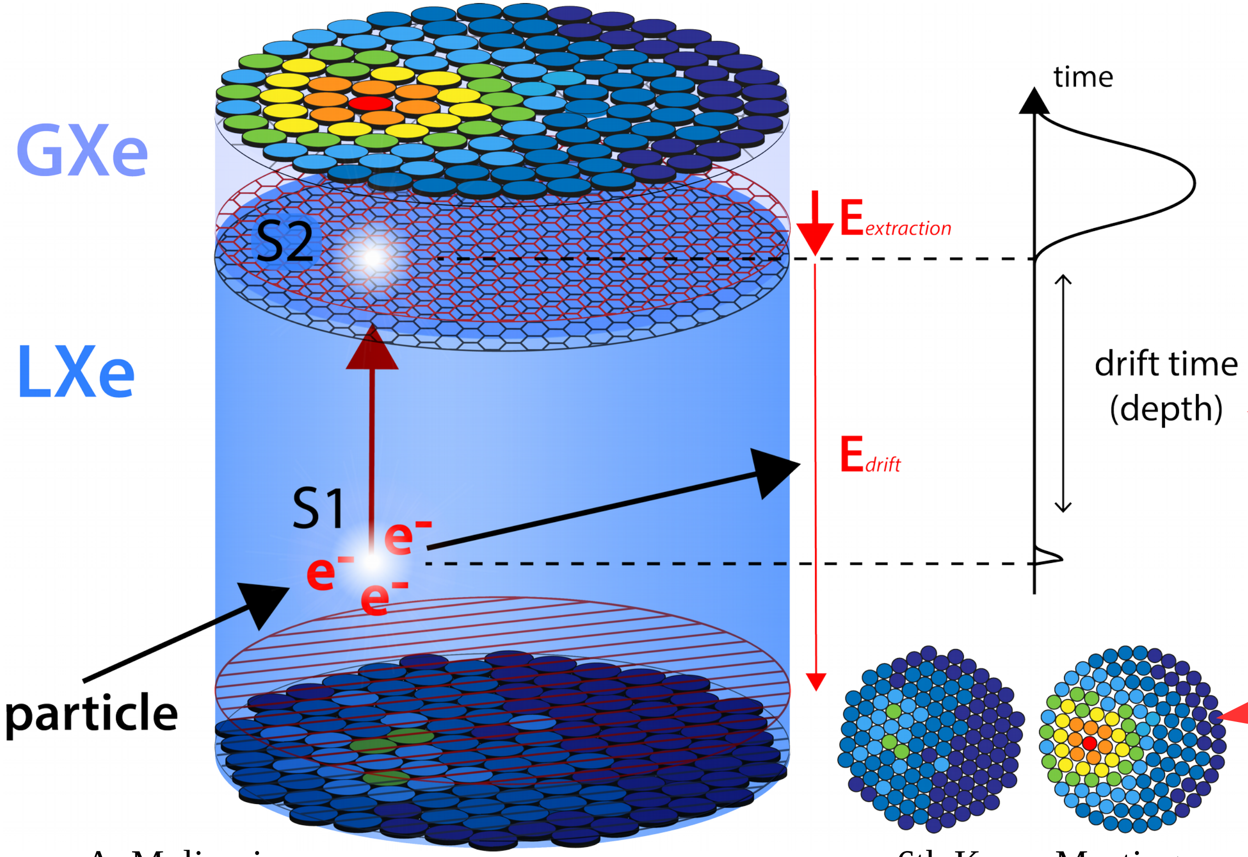
The Time Projection Chamber

127 Top PMTs



121 Bottom PMTs

Dual-phase Xenon TPC



S1 prompt scintillation

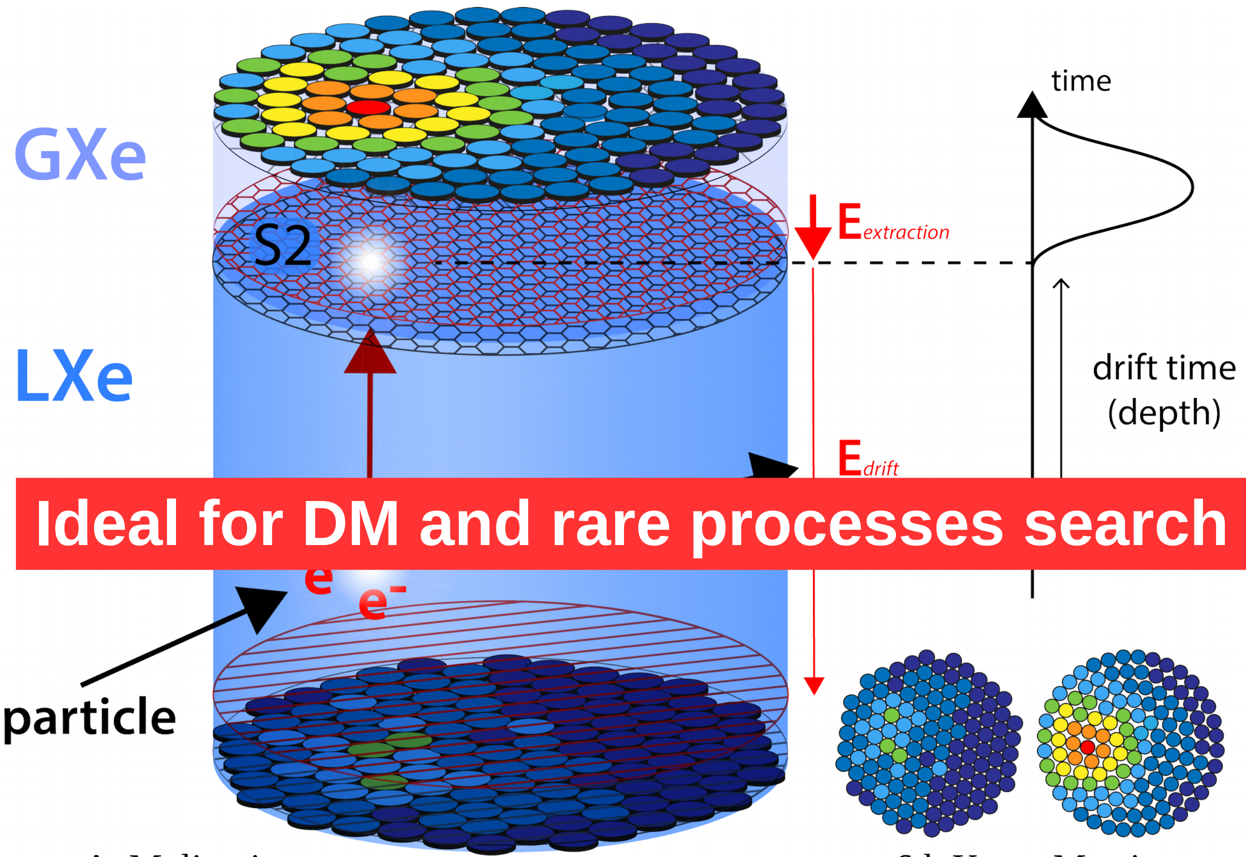
S2 proportional to ionization

S2/S1 different for electronic recoils (ER) and nuclear recoils (NR)

Drift time for the vertical position

Light pattern on top PMTs to reconstruct x-y position

Dual-phase Xenon TPC



Ideal for DM and rare processes search

Liquid Xenon

High density, self-shielding

Good scintillator

No long-living radioactive isotope

Time Projection Chamber

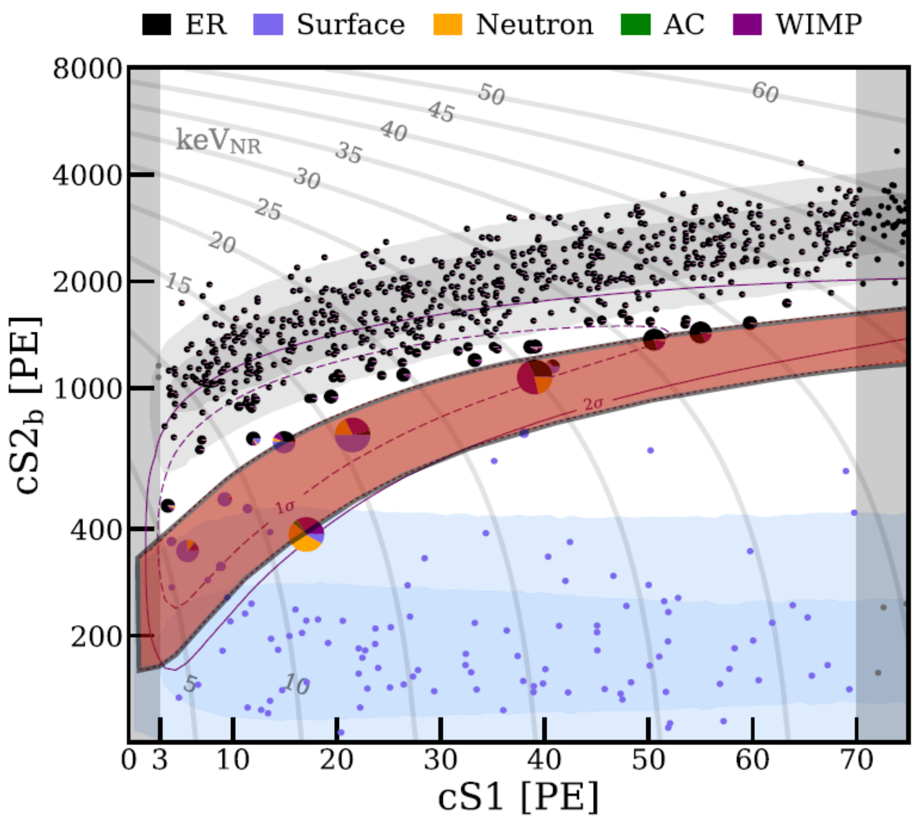
3D position reconstruction

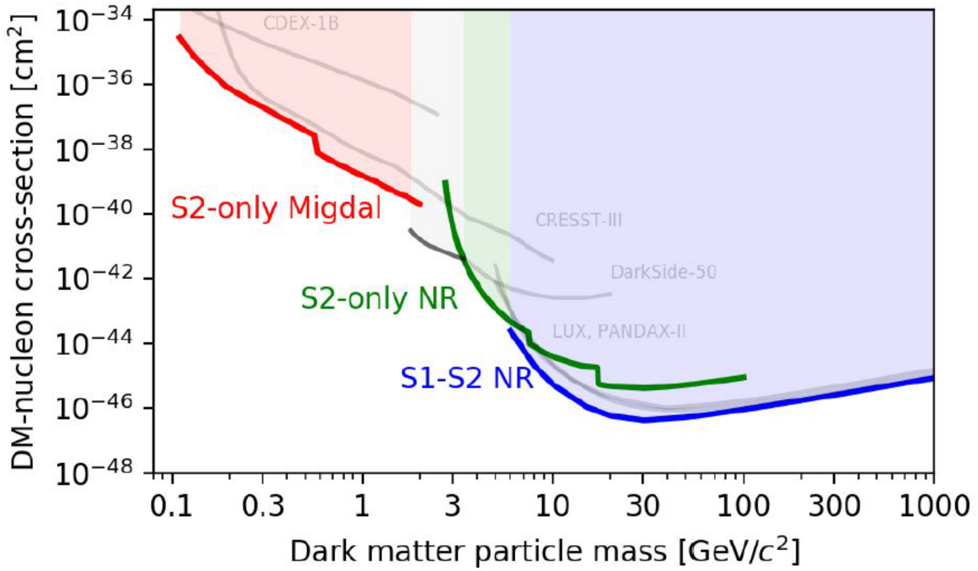
ER/NR discrimination

Multiple scatter rejection

Low energy threshold

Search in the nuclear recoil band

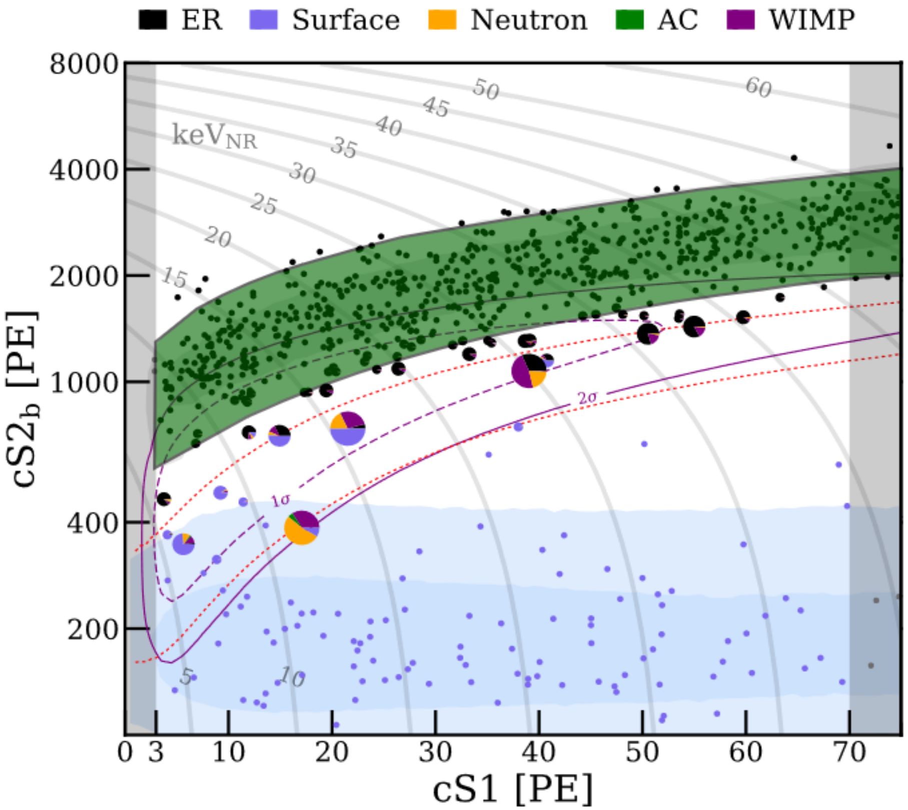




Best constraints on WIMP dark matter with masses > 3 GeV/c^2

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

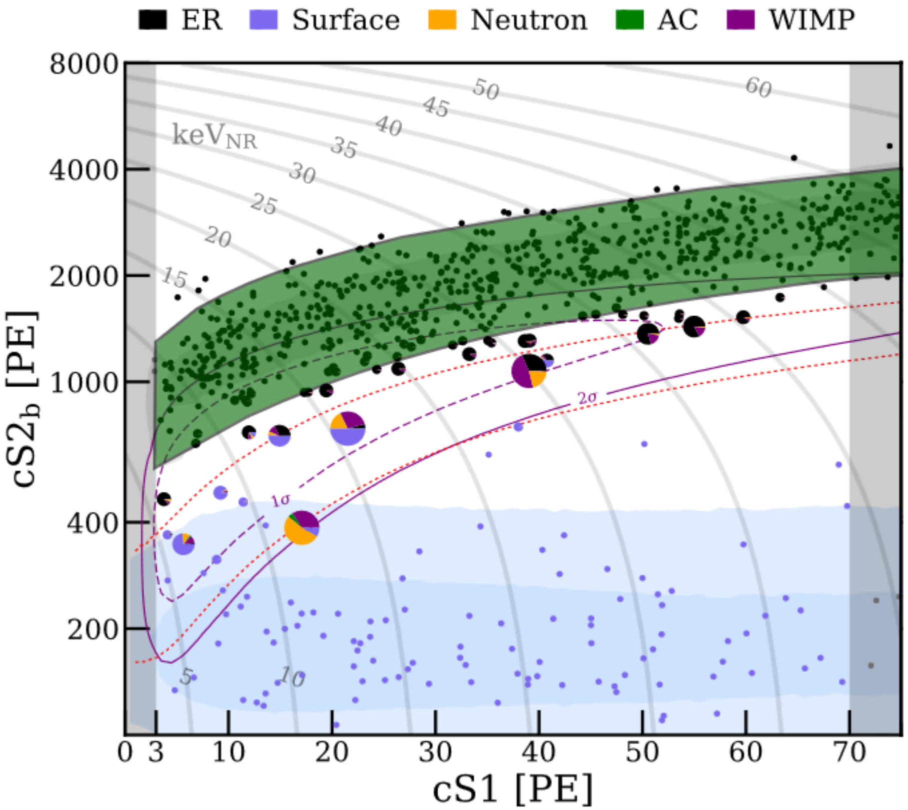
Search in the electronic recoil band



Look for axions from the Sun, ν magnetic moment (μ_ν), bosonic dark matter

Observed as an excess of events on top of known background

Search in the electronic recoil band



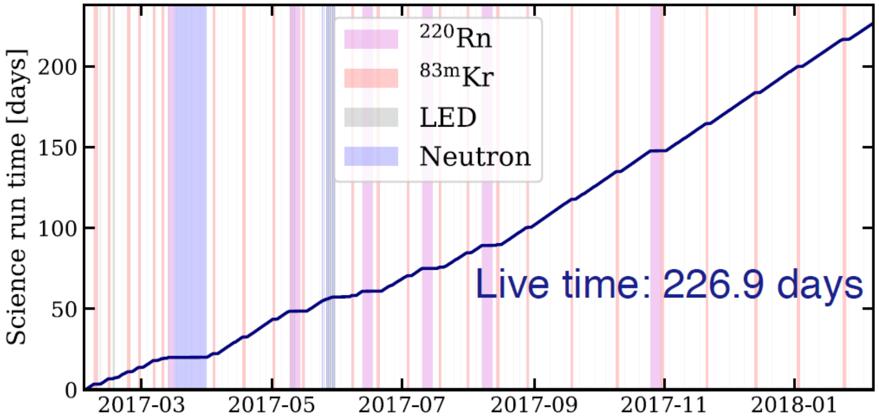
Look for axions from the Sun, ν magnetic moment (μ_ν), bosonic dark matter

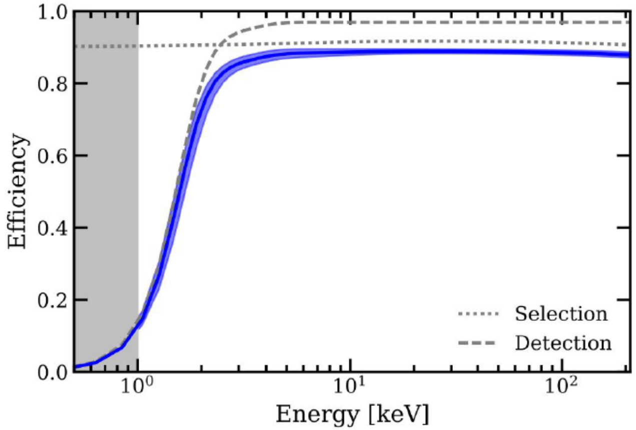
Observed as an excess of events on top of known background

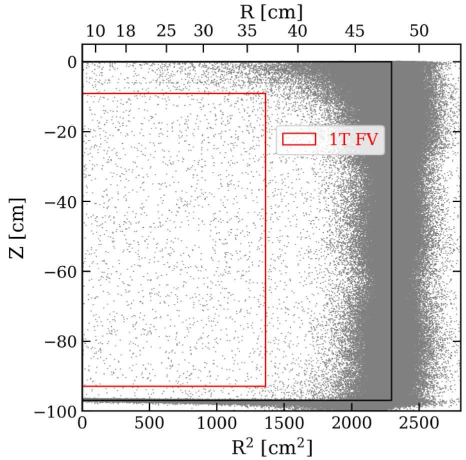
XENON1T features

Low background (< 100 events/tonne/year/keV_{ee})
Low energy threshold (~1 keV_{ee})
Large exposure (~1 tonne*year)

Data taking and selection





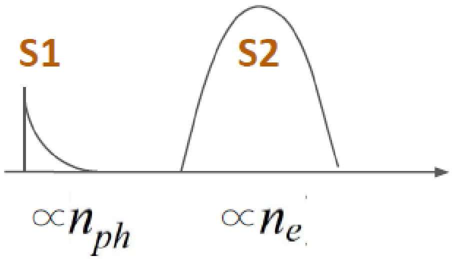


Science Run 1 (SR1): 2/2017- 2/2018
226.9 live days
0.65 tonne*year exposure

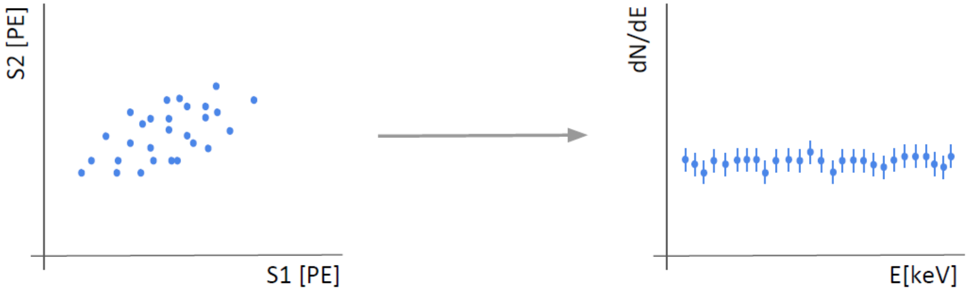
→ 3-fold PMT coincidence for S1 detection
→ Single scatter events in [1,210] keV_{ee}
→ Standard quality cuts with higher S2 threshold

1 tonne cylindrical fiducial volume

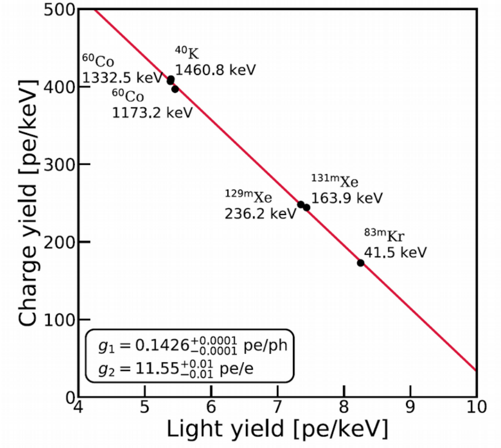
Energy reconstruction



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

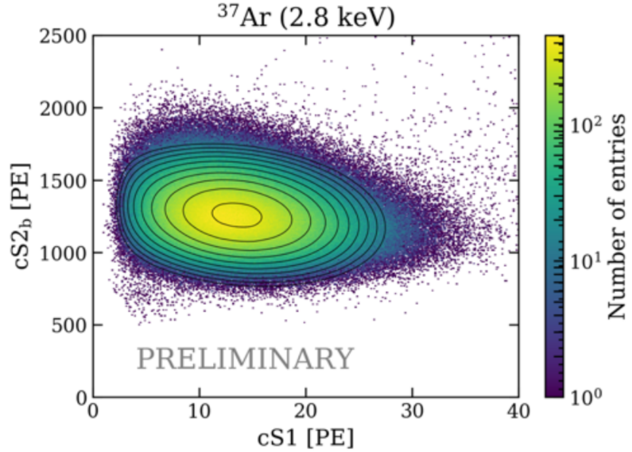


W = 13.7 eV/quanta

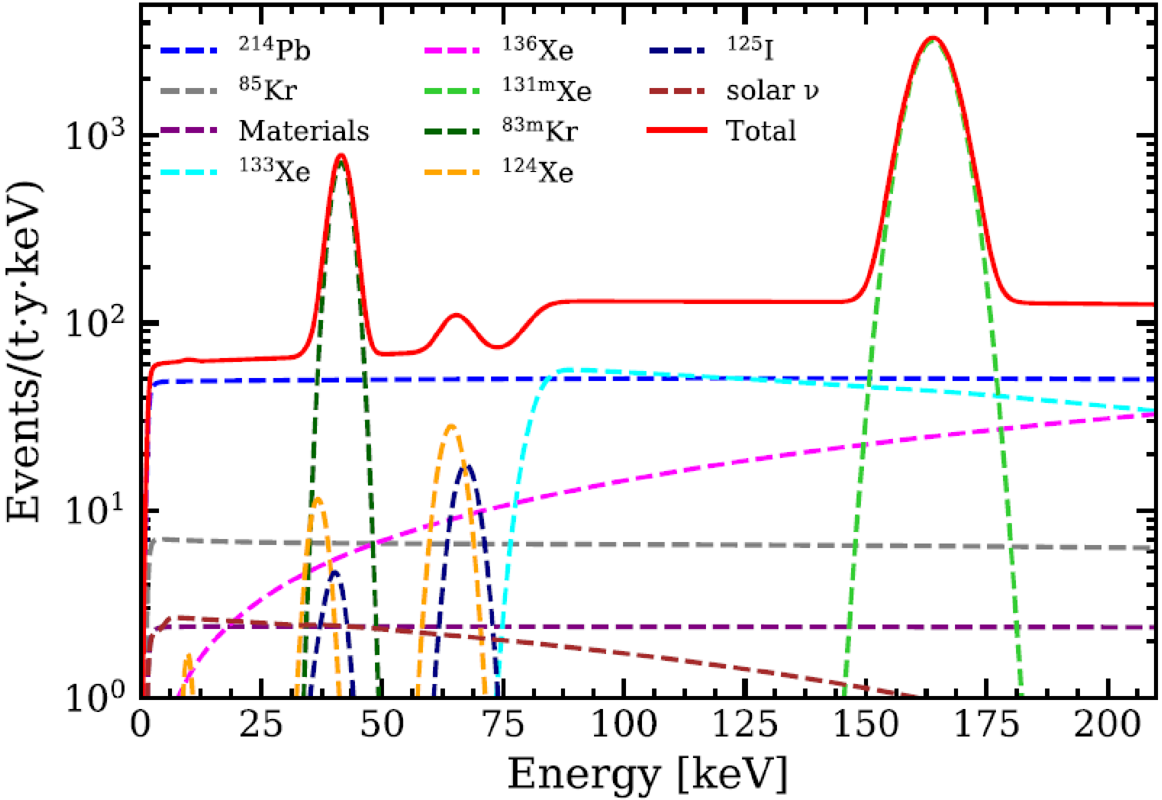


$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$

g1, g2 detector-dependent



Background model



Background model (B_0) has 10 components

Internal (uniform in volume)

^{214}Pb (from ^{222}Rn chain, main contribution)
^{85}Kr (reduced through cryogenic distillation)
^{136}Xe, ^{124}Xe
^{83m}Kr (traces due to calibration source issue)

Neutron-induced

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

External

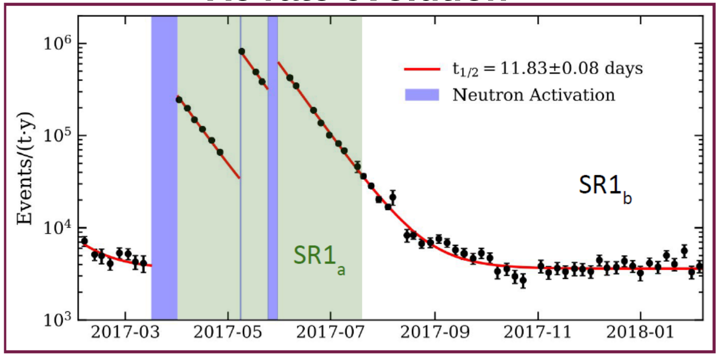
Solar ν
Materials (radio essay and GEANT4)

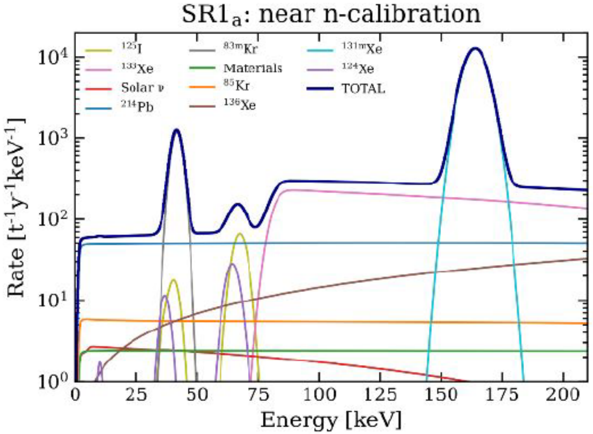
Background model

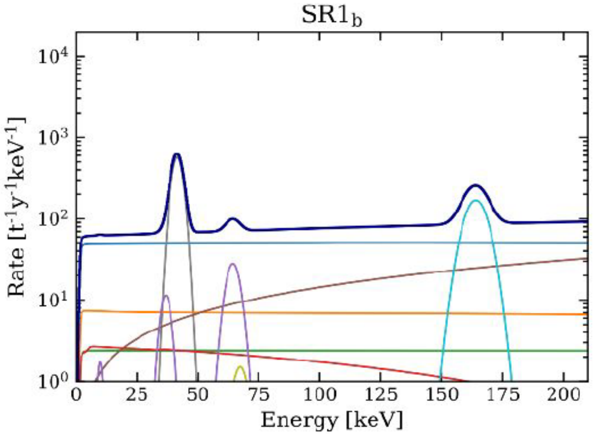
SR1 divided in two periods
$SR1_a$ (near neutron calibrations) and $SR1_b$

Simultaneous fit of the two periods

^{131m}Xe rate evolution



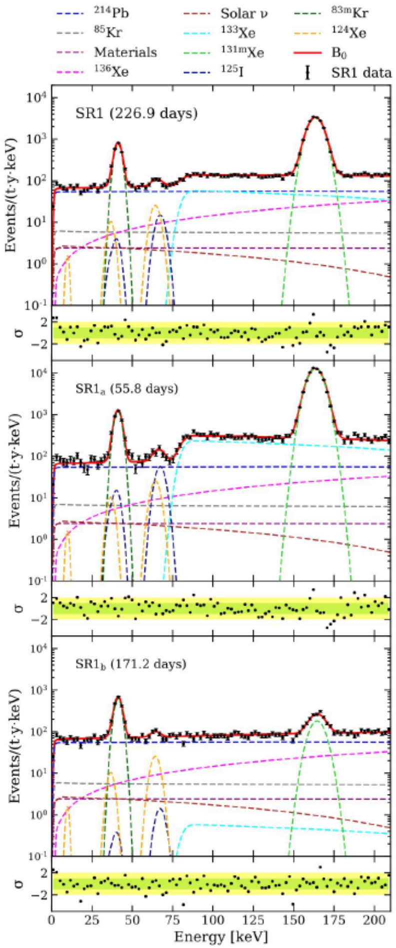




$SR1_b$
lower contribution of neutron-induced background

The fit to the data

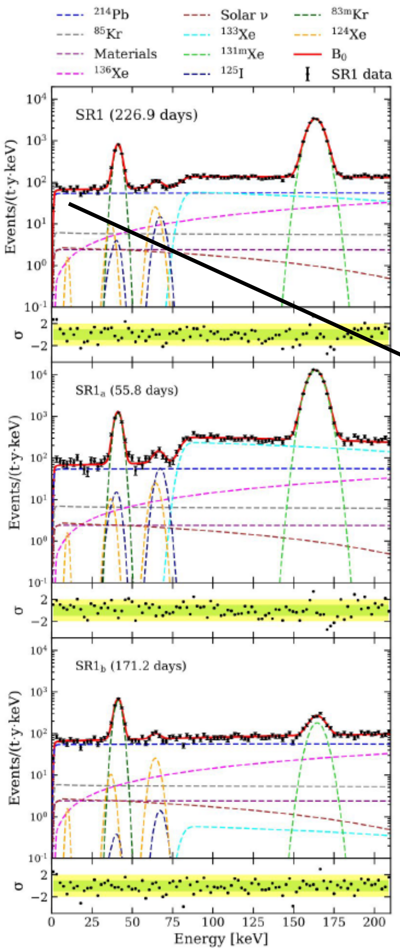
XENON Dark Matter Project



(76 ± 2) events / (tonne*year*keV$_{ee}$) in [1,30] keV$_{ee}$

Lowest ever achieved in this energy range!

The fit to the data



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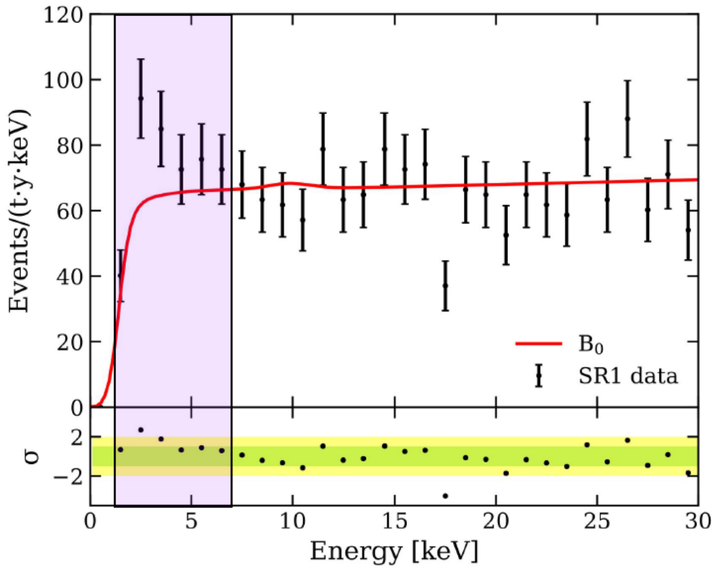


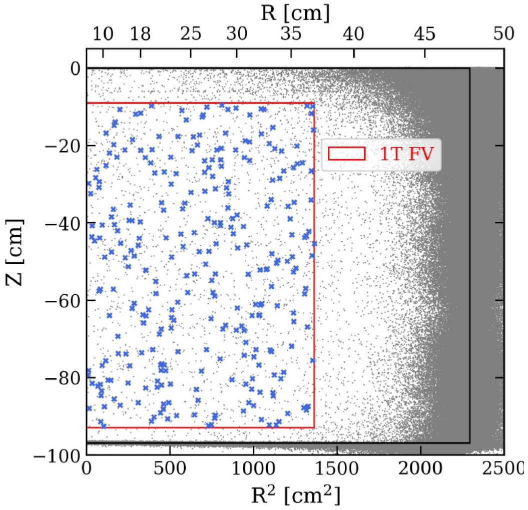
Excess observed in the [1-7] keV$_{ee}$ energy range

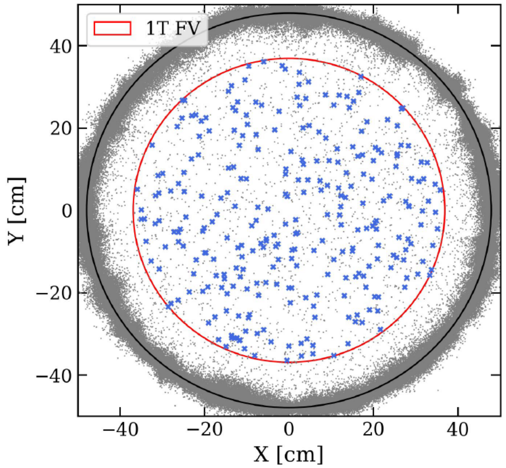
285 events observed vs 232±15 expected from best fit (3.3σ fluctuation – *naive estimate*)

Space and time distribution

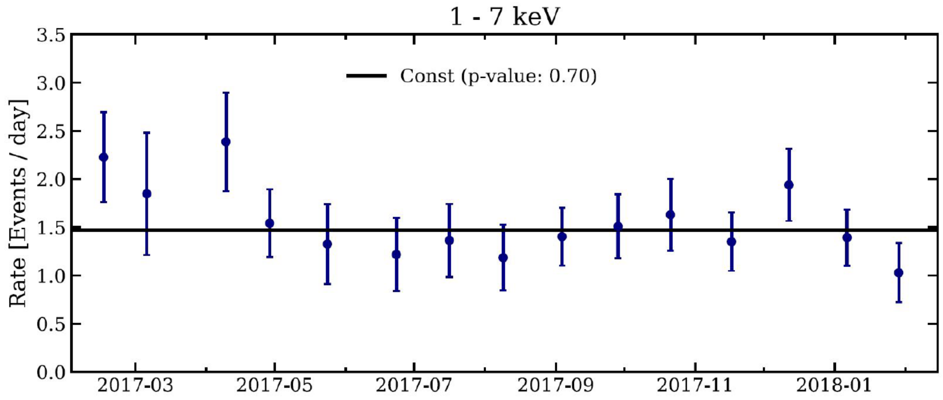
Spatial distribution

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



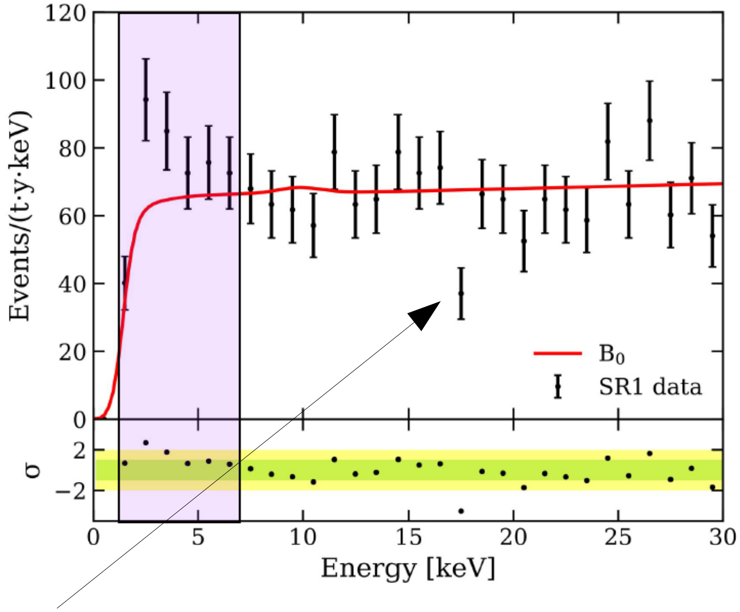


Temporal evolution



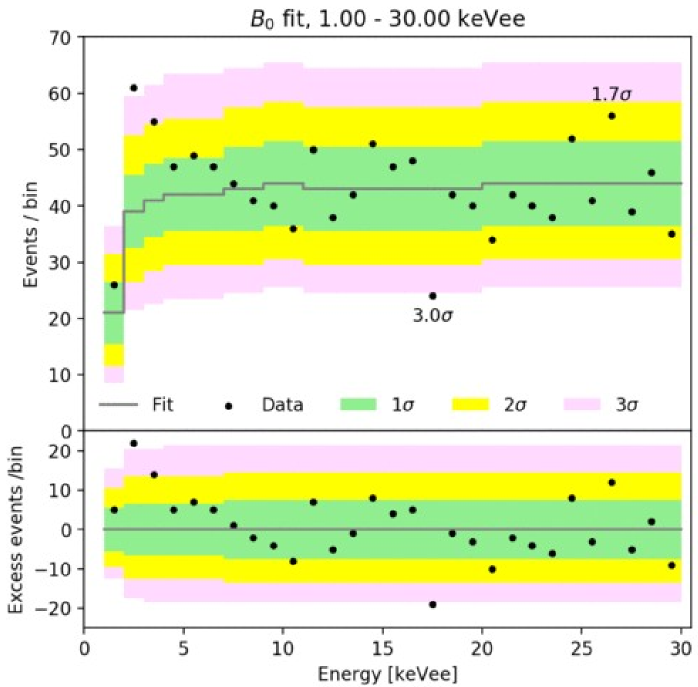
Events are uniformly distributed in the fiducial volume
Rate constant along SR1

A statistical fluke?



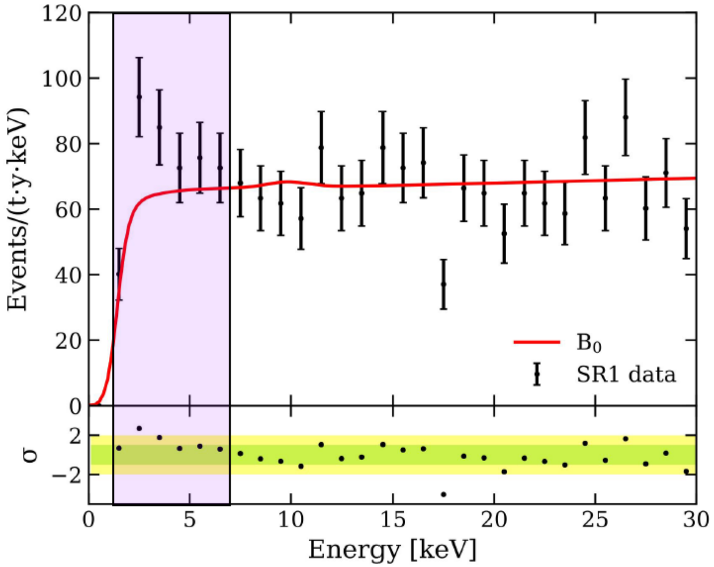
'Deficit' at ~18 keV
Local significance in 1.5-3.4 σ,
but global significance is 2.3 σ at most

Effect of changing the binning from 1-30 keV to 1.5-30.5 keV

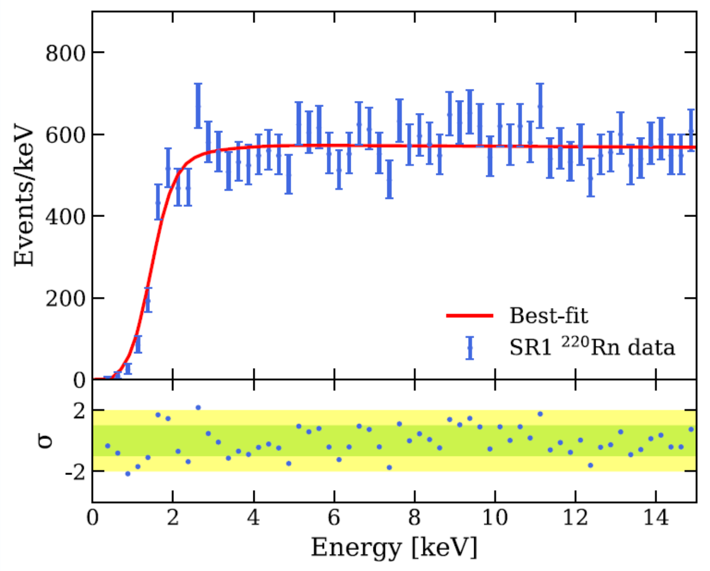


We use unbinned profile likelihood analysis

Possible mis-modeling?



Excess is not at our threshold fall-off
It persists if we
→ Change the analysis threshold
→ Fix efficiency at ±1σ
→ Perform (cS1, cS2) profile likelihood



^{220}Rn calibration data validate our model

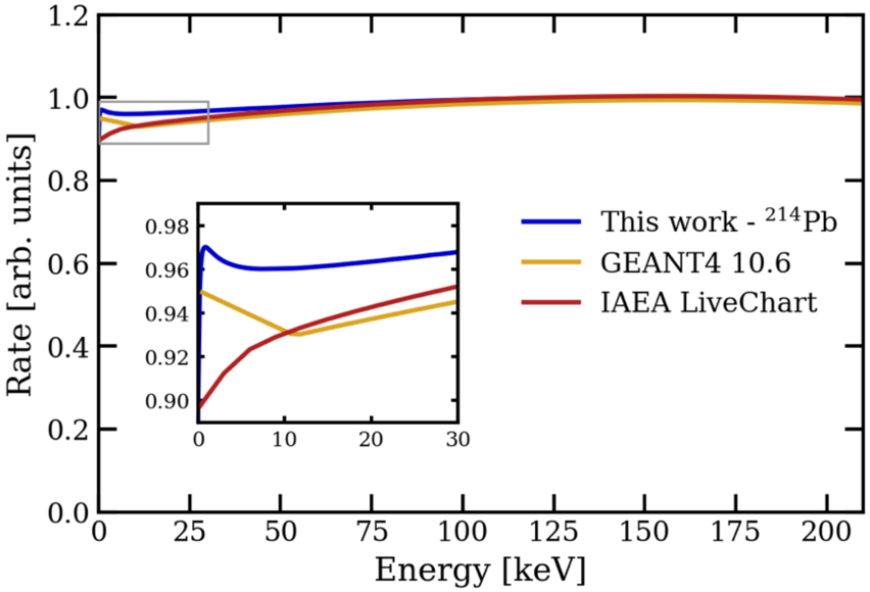
The perfect fit validates energy reconstruction and efficiencies
No large systematic is present

Possible mis-modeling?

Atomic screening and exchange effects can increase rate at low energies

6% uncertainty on the shape

50% required to explain the excess

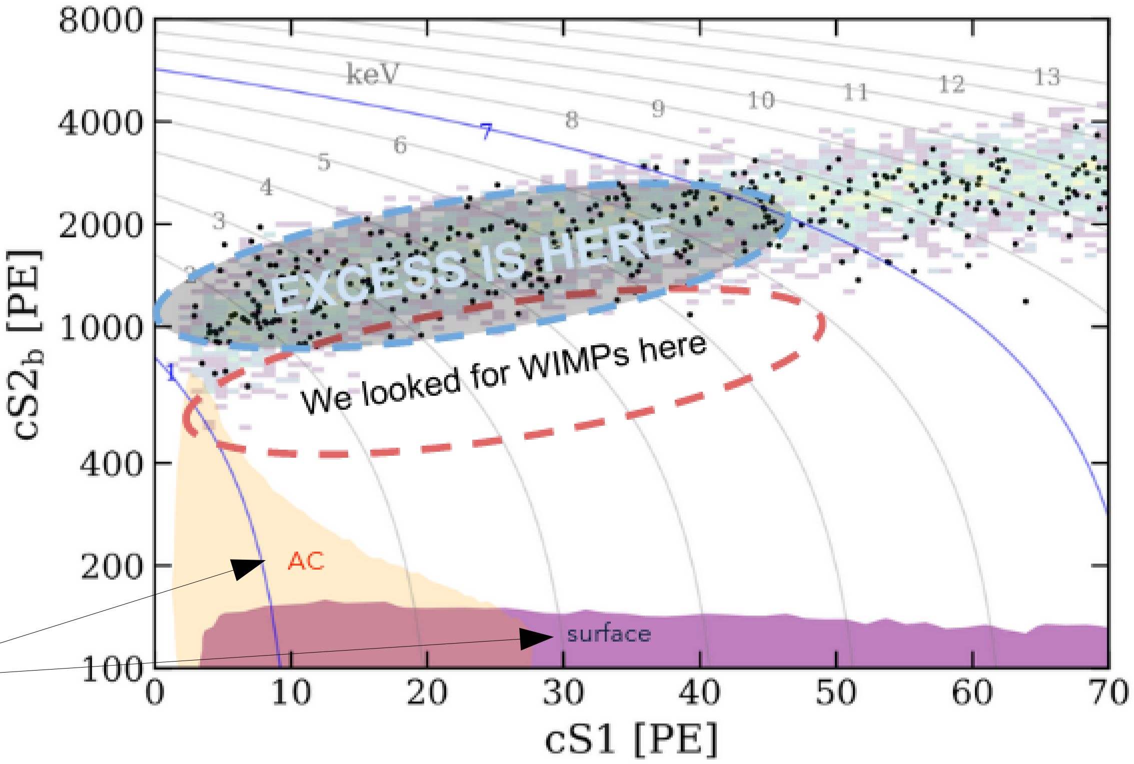


Calculations by X. Mougeot (CEA Saclay)

Instrumental effects?

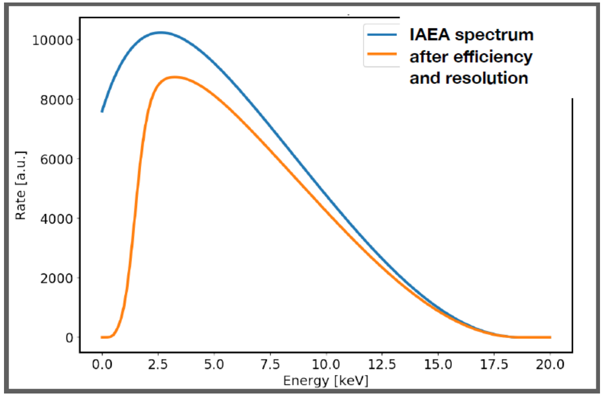
Excess is right next to our prime WIMP search region

No other event source relevant besides electronic recoils

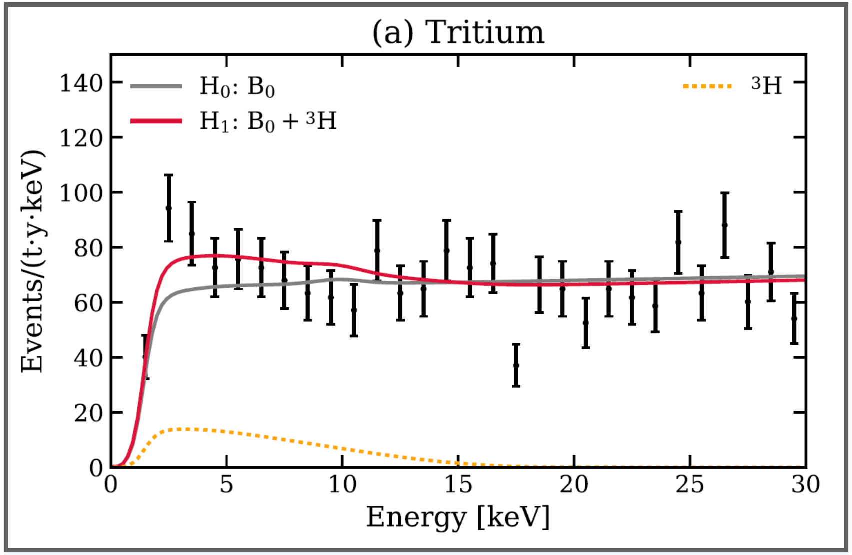


Accidental coincidence (AC) between unrelated S1 and S2 and surface events (part of S2 is lost) are well described and far from the ER band

The tritium hypothesis



Low energy β emitter (Q value 18.6 keV)
Long half life (12.3 y)



Favored over B_0 at 3.2σ

Fitted ^3H rate

(159±51) events/(tonne*year)

^3H:Xe concentration

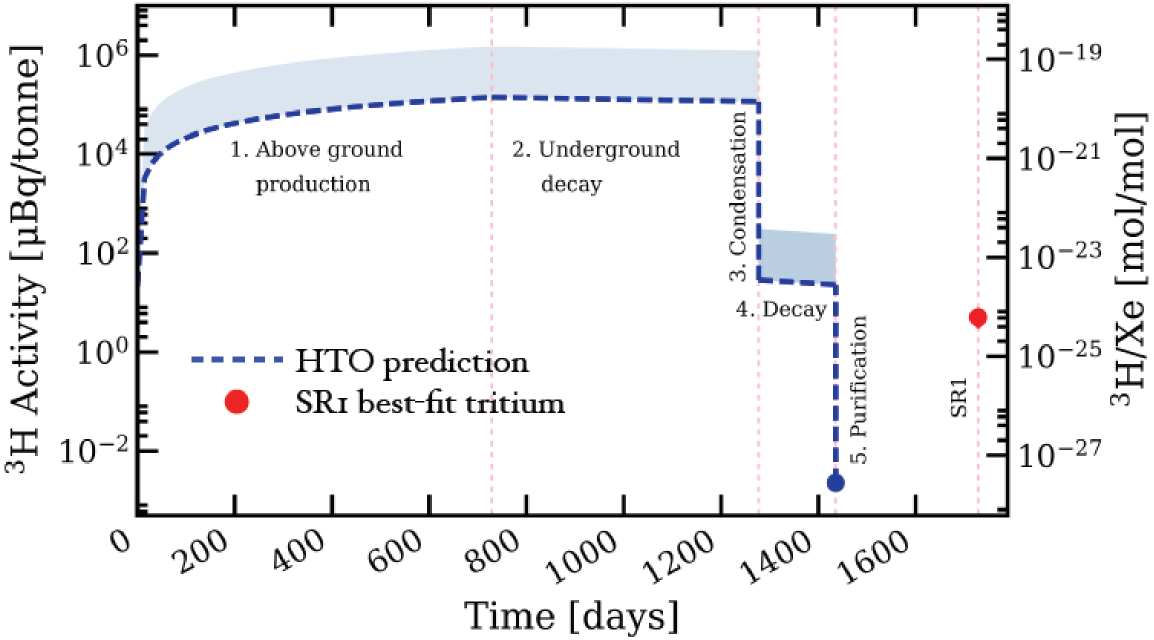
(6.2±2.0) * 10^{-25} mol/mol

A) Cosmogenic activation in Xe?

B) Emanation from materials?

The tritium hypothesis

A) Cosmogenic activation in Xe

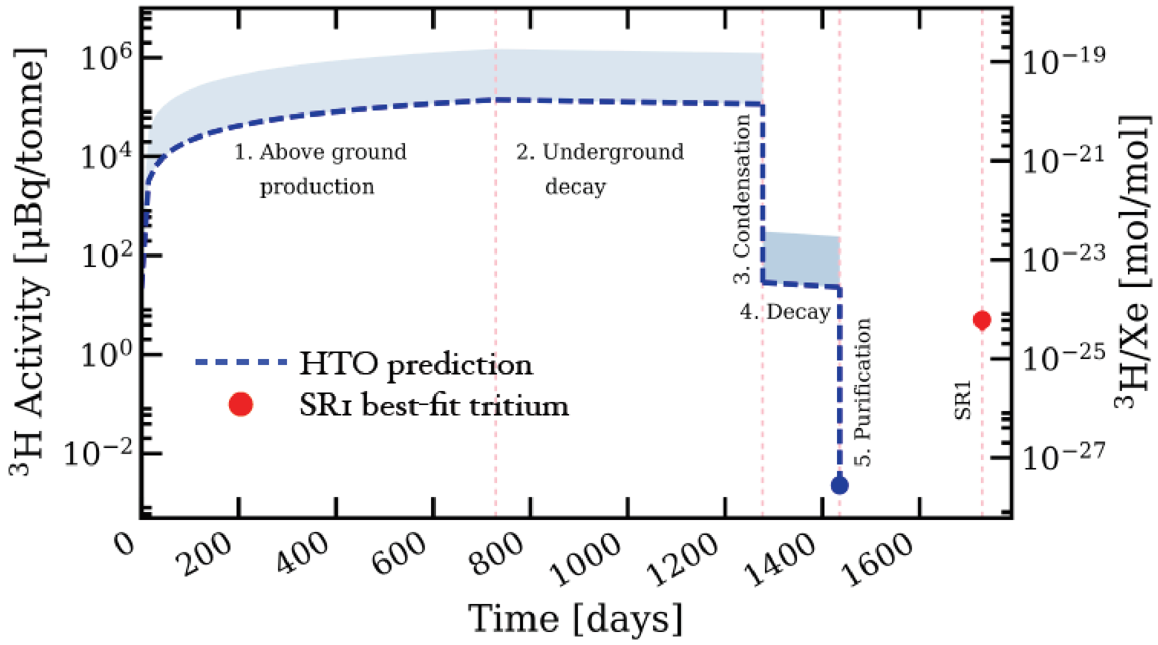


1 ppm of water in Xe bottles implies formation of HTO

Xe goes through efficient purification system (getter with hydrogen removal unit)

The tritium hypothesis

A) Cosmogenic activation in Xe



1 ppm of water in Xe bottles implies formation of HTO

Xe goes through efficient purification system (getter with hydrogen removal unit)

Hypothesis A) is unlikely

The tritium hypothesis

B) Emanation from materials

Materials would release HTO or HT
We need $^3H:Xe \sim 10^{-24}$ mol/mol

Atmospheric $HTO:H_2O \sim 10^{-17}$ mol/mol

Required $H_2O:Xe \sim 100$ ppb

Assuming $HT:H_2 \sim 10^{-17}$ mol/mol

Required $H_2:Xe \sim 100$ ppb

The tritium hypothesis

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Ruled out by light yield measurement
$H_2O:Xe \sim 1$ ppb

Assuming $HT:H_2 \sim 10^{-17}$ mol/mol

Required $H_2:Xe \sim 100$ ppb

No constraints on $H_2:Xe$

The tritium hypothesis

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$H_2O:Xe \sim 1$ ppb

Assuming $HT:H_2 \sim 10^{-17}$ mol/mol

Required $H_2:Xe \sim 100$ ppb

No constraints on $H_2:Xe$

We can neither confirm nor rule out tritium hypothesis

^{37}Ar contamination?

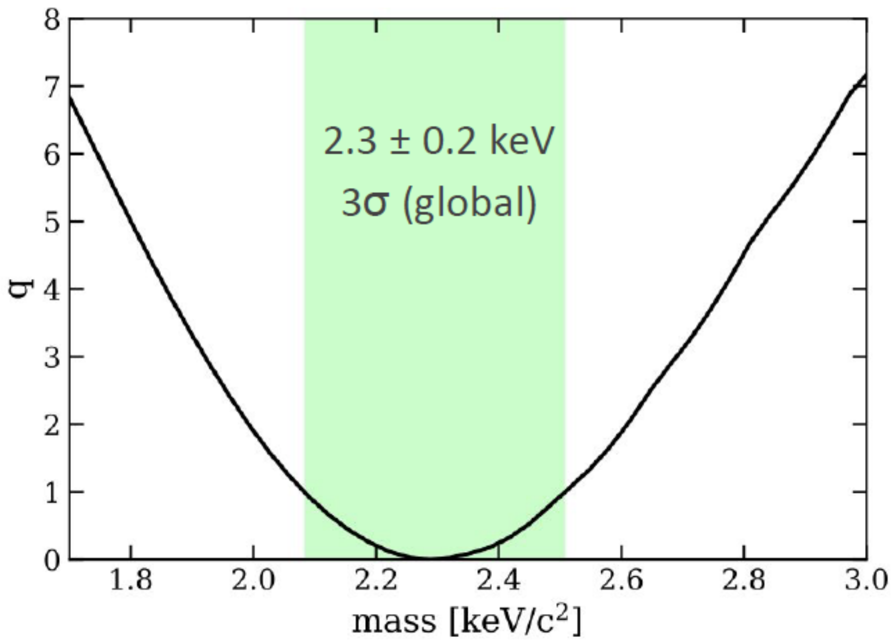
Air leak in XENON1T < 1 liter/year
(rare gas mass spectrometry constraints)

We need 3 liter/day air leak to account for the excess by ^{37}Ar contamination!

^{37}Ar gives monoenergetic line at 2.82 keV_{ee}

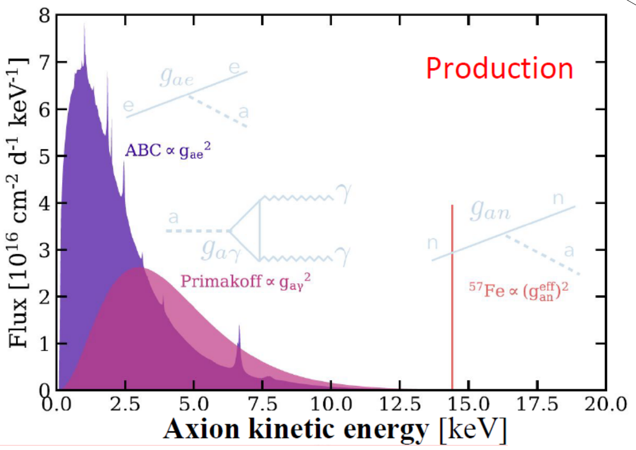
Best mono-energetic line fit at 2.3±0.2 keV_{ee}

Energy reconstruction in this energy range validated with ^{37}Ar calibration



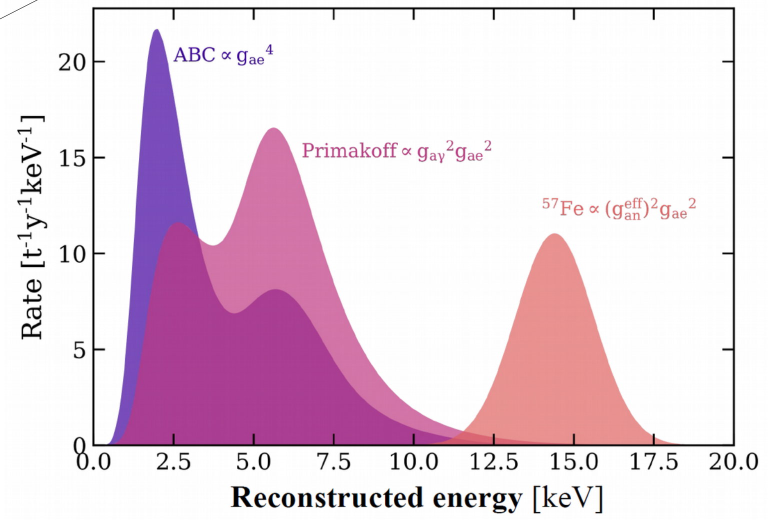
Testing signal models: solar axions

Production spectra



Detection in XENON1T via the axio-electric effect

Detected spectra

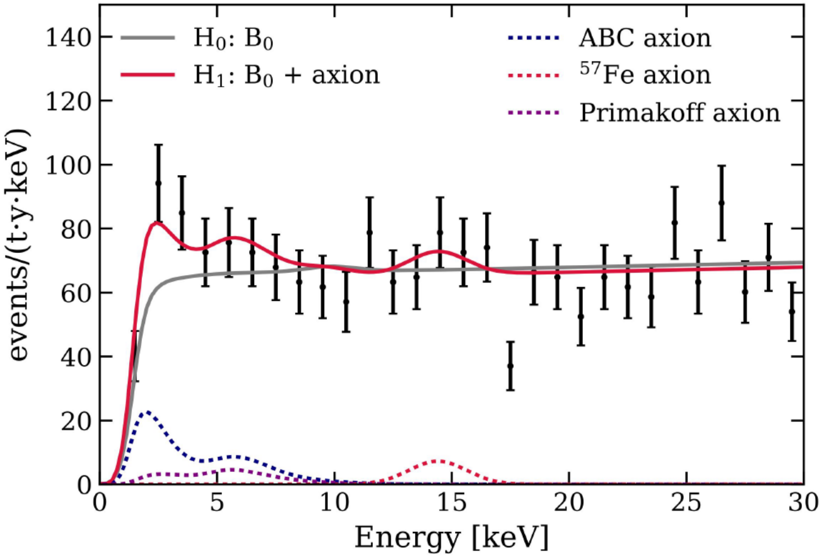


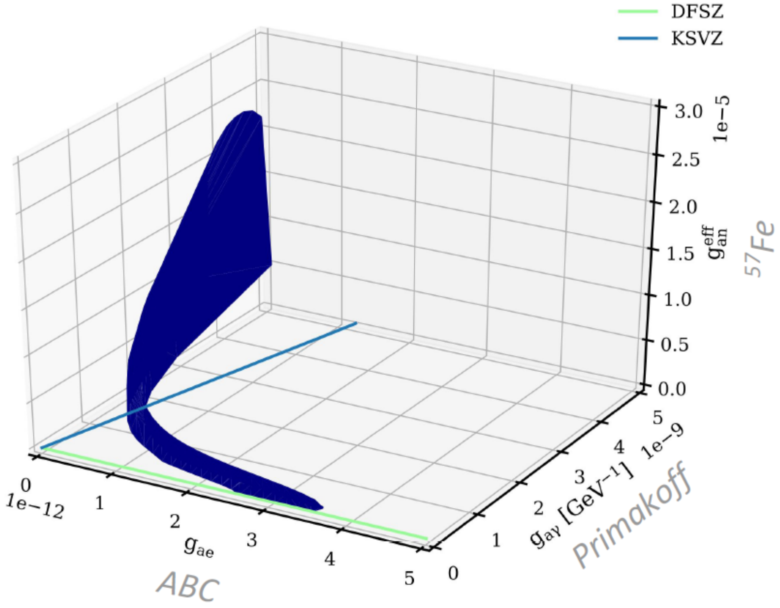
Look for axions produced in the Sun
Model-dependent couplings

We treat 3 production mechanisms as independent free parameters

Testing signal models: solar axions

Favored over B_0 at 3.5σ

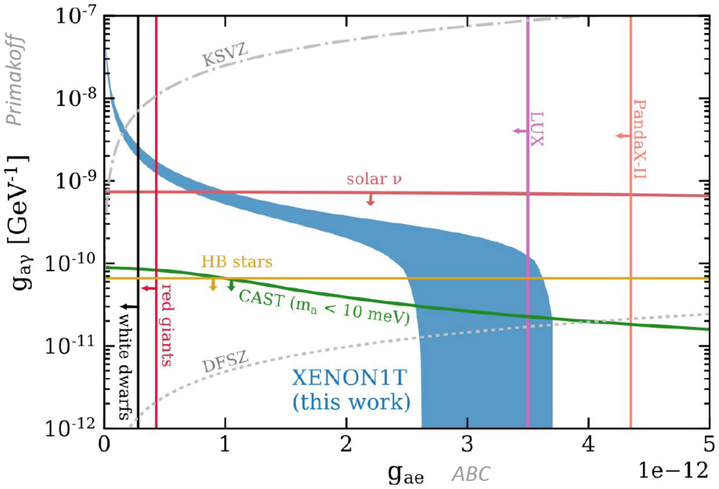




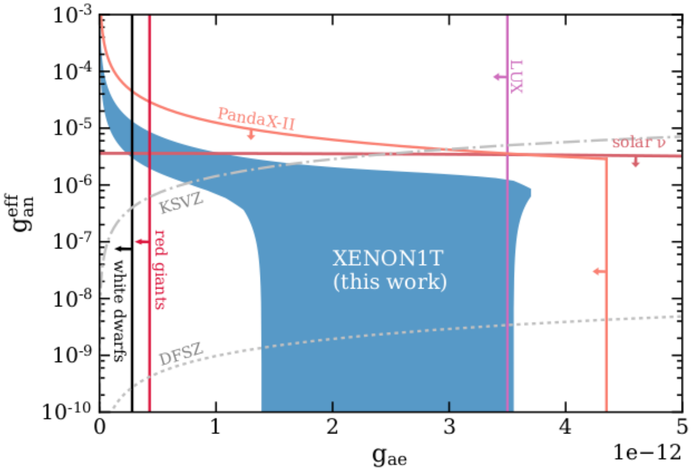
90% C.L. 3D contour

Testing signal models: solar axions

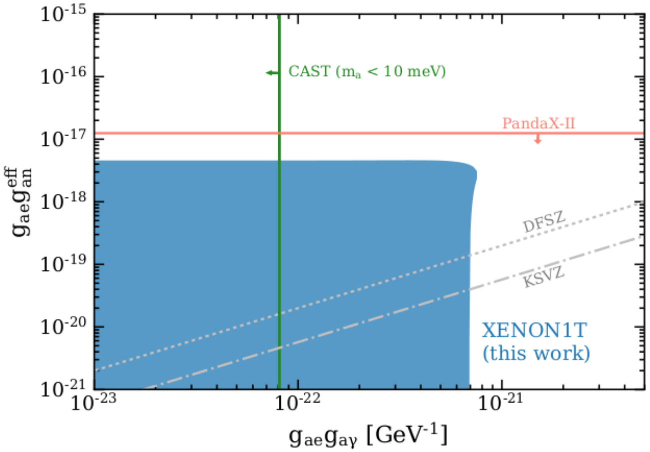
Contour projections



Primakoff-ABC



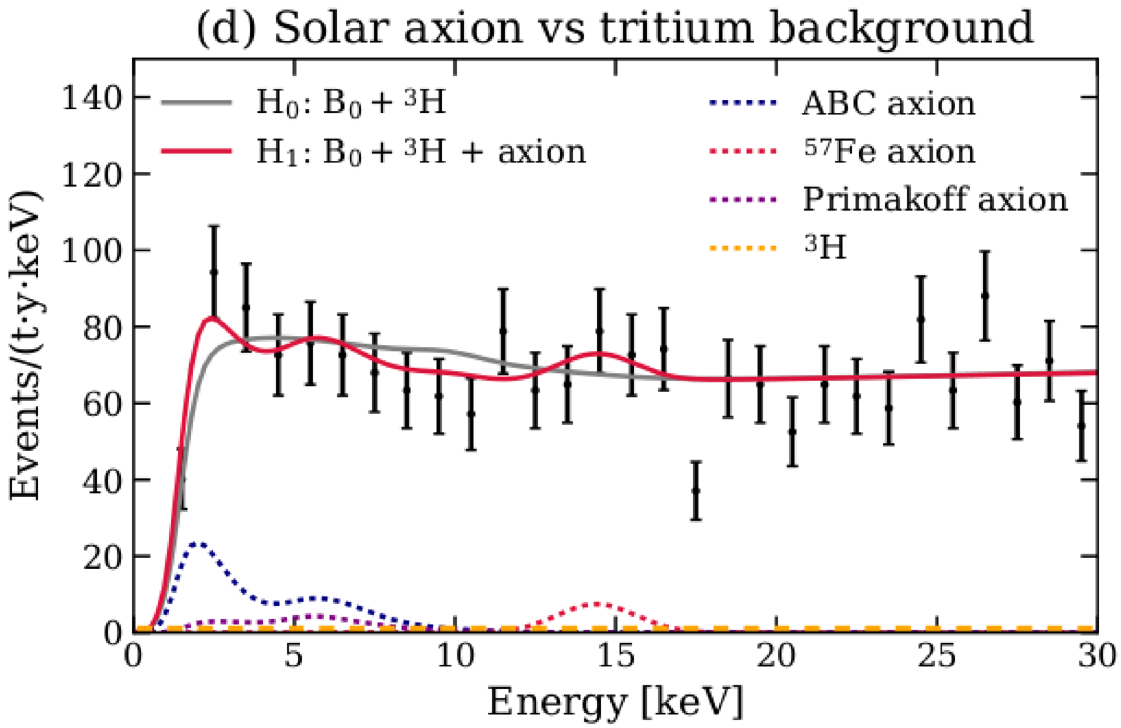
^{57}Fe-ABC



^{57}Fe-Primakoff

Tension with astrophysical constraints from stellar cooling

Testing signal models: solar axions



Include ^{3}H in the background

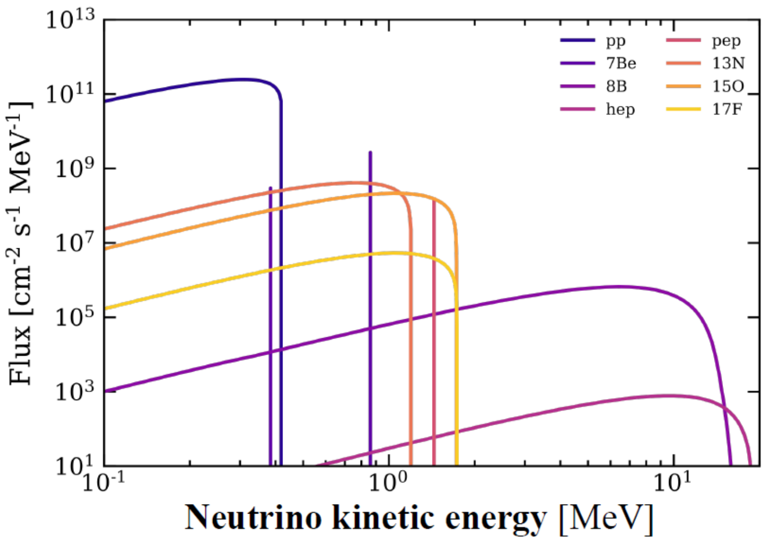
Solar axion hypothesis still favored (at 2.1σ) over B_0 + ^{3}H only

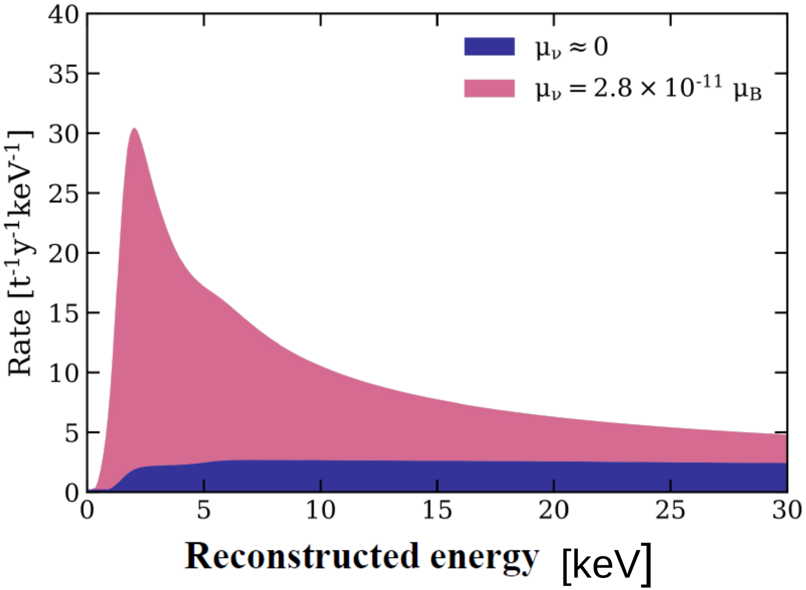
Negligible ^{3}H component

Testing signal models: enhanced μ_ν

Large value of μ_ν would point to new physics, a value of $\mu_\nu > 10^{-15}\ \mu_B$ implies Majorana ν

The detected solar ν spectrum would be enhanced

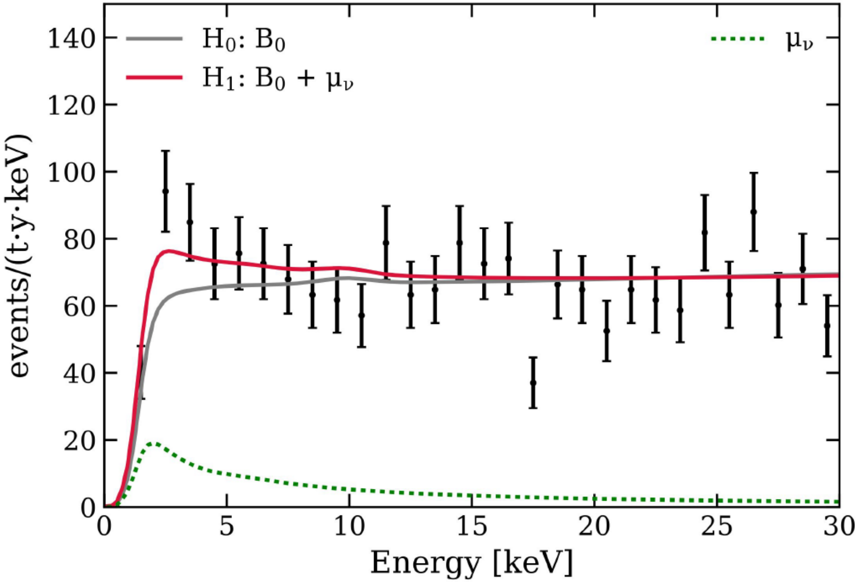


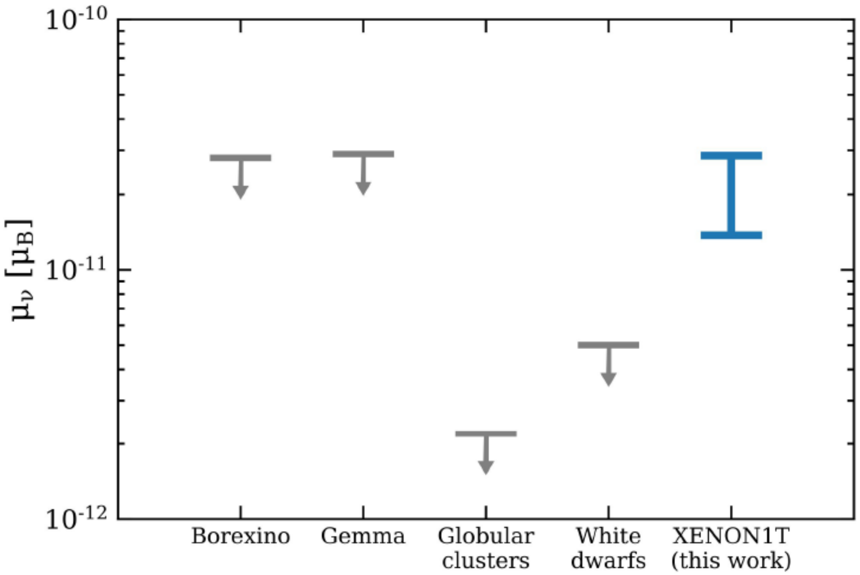


Testing signal models: enhanced μ_ν

Favored over B_0 at 3.2σ

0.9σ if ^3H added to B_0





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

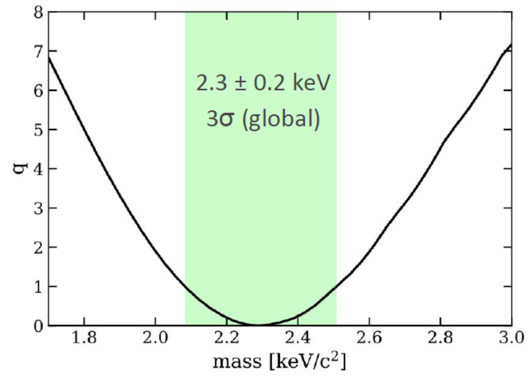
In tension with astrophysical observations

Testing signal models: bosonic DM

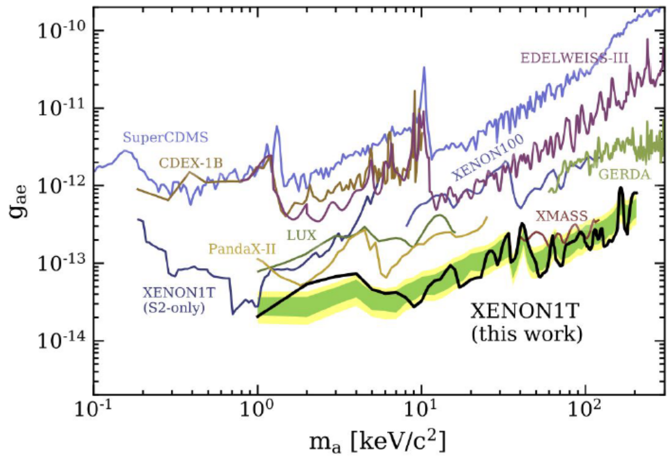
Axion-like particles (ALPs) and dark photons generating mono-energetic peaks

No global significance above 3σ for this search under background model B_0

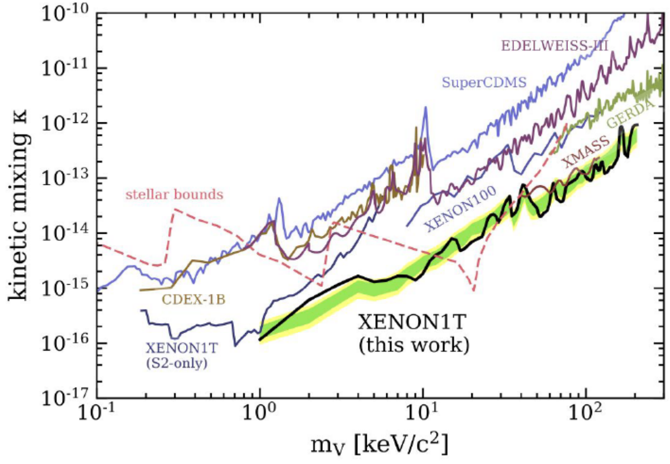
Favored mass value (2.3± 0.2) keV (3σ global)



ALPs

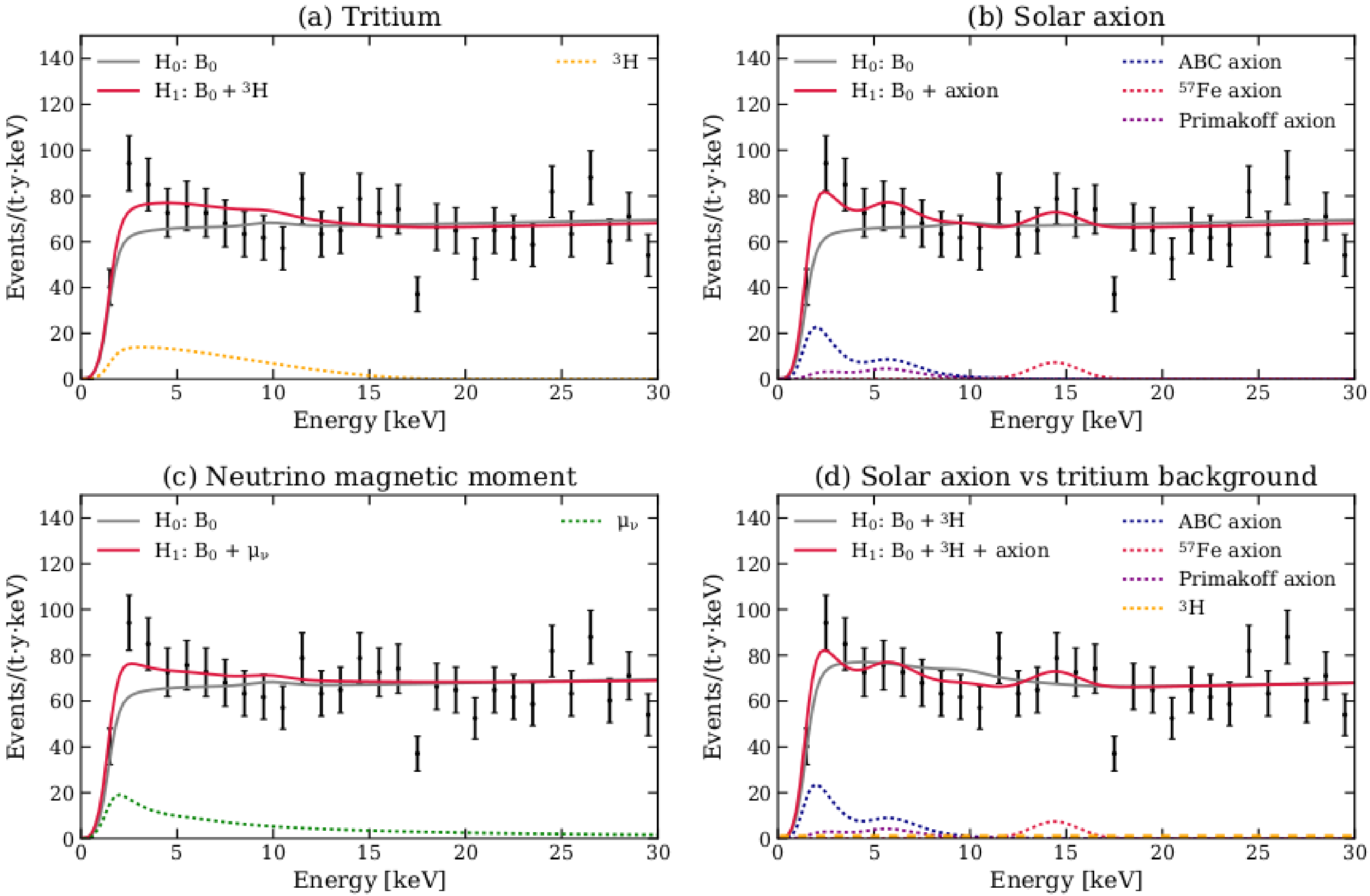


Dark photons



A recap

^{3}H favored over B_0 at 3.2σ



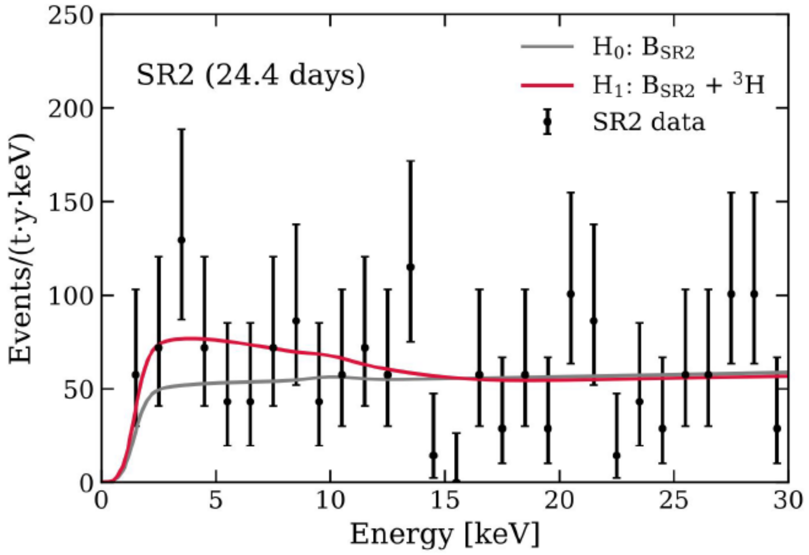
Solar axion favored over B_0 at 3.5σ

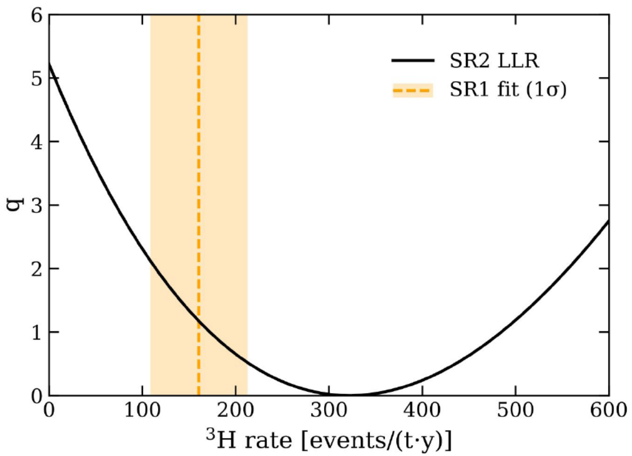
μ_ν favored over B_0 at 3.2σ

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

Additional checks

Check data from Science Run 2 (SR2), 24.4 additional days with 20% lower background due to improved purification





^{3}H hypothesis favored over B_0 at 2.3σ (320±160) events/(tonne*year)

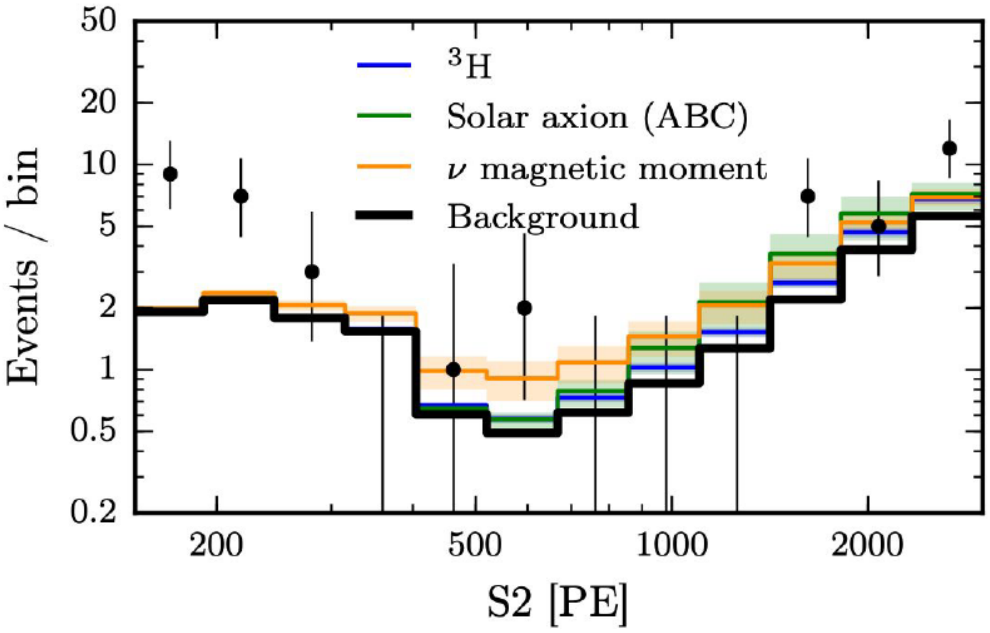
Consistent with SR1

Solar axion and μ_ν hypothesis favored at ~2σ

SR2 studies are inconclusive

Additional checks

S2-only approach: no request for an S1, ~200 eV energy threshold
(but no ER/NR discrimination, no 3D position reconstruction)



Bounds are consistent with results from main analysis

$g_{ae} < 4.8*10^{-12}$

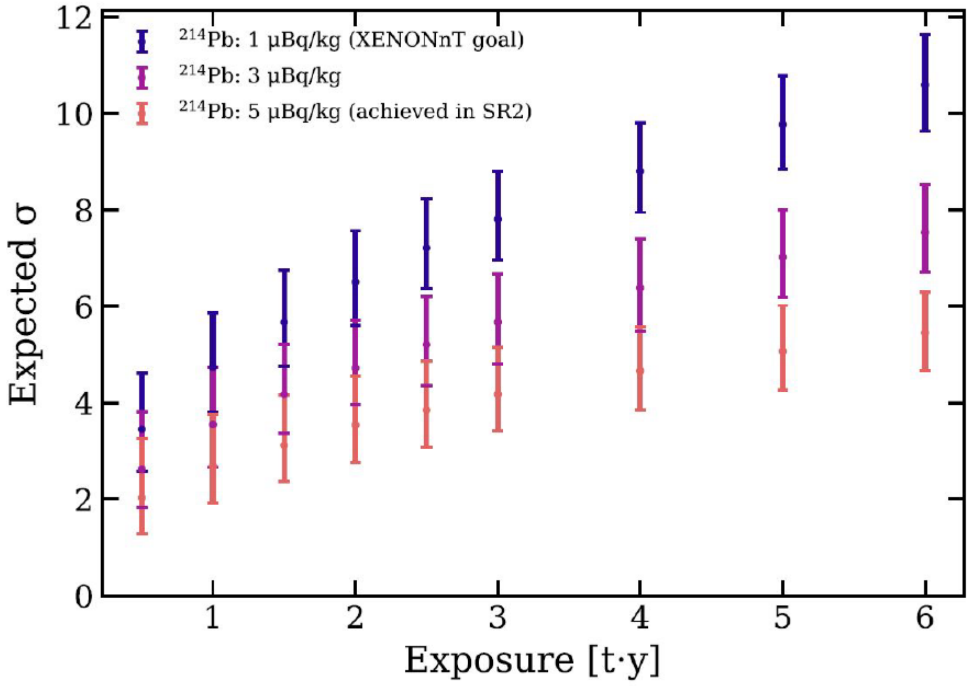
^{3}H rate < 2256 events/(tonne*year)

$\mu_{\nu} < 3.1*10^{-11}\ \mu_{B}$

Looking forward: XENONnT

×3
active volume

1/6
background



Discriminate axion hypothesis from ^{3}H with few months of data

Looking forward: XENONnT

NEW TPC

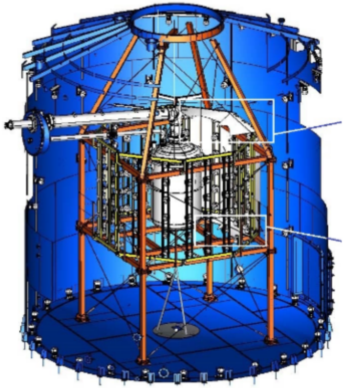
6 tonne active mass
(~4 tonne fiducial)

248 → 494 PMTs

NEUTRON VETO

0.2% Gd-doped water

120 PMTs
around cryostat

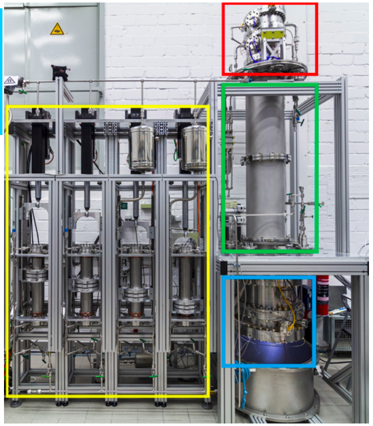


LXE PURIFICATION

Much faster Xe
purification speed

Rn DISTILLATION COLUMN

Reduce Rn from
pipes, cables,
cryogenic system



Looking forward: XENONnT

Commissioning ongoing