Recent Results from XENON1T and future perspectives for the direct dark matter search with XENONnT

Carla Macolino
(L'Aquila Univ. and INFN)
on behalf of the XENON collaboration

Online talk at
Les Rencontres de La Thuile

09.03.2021

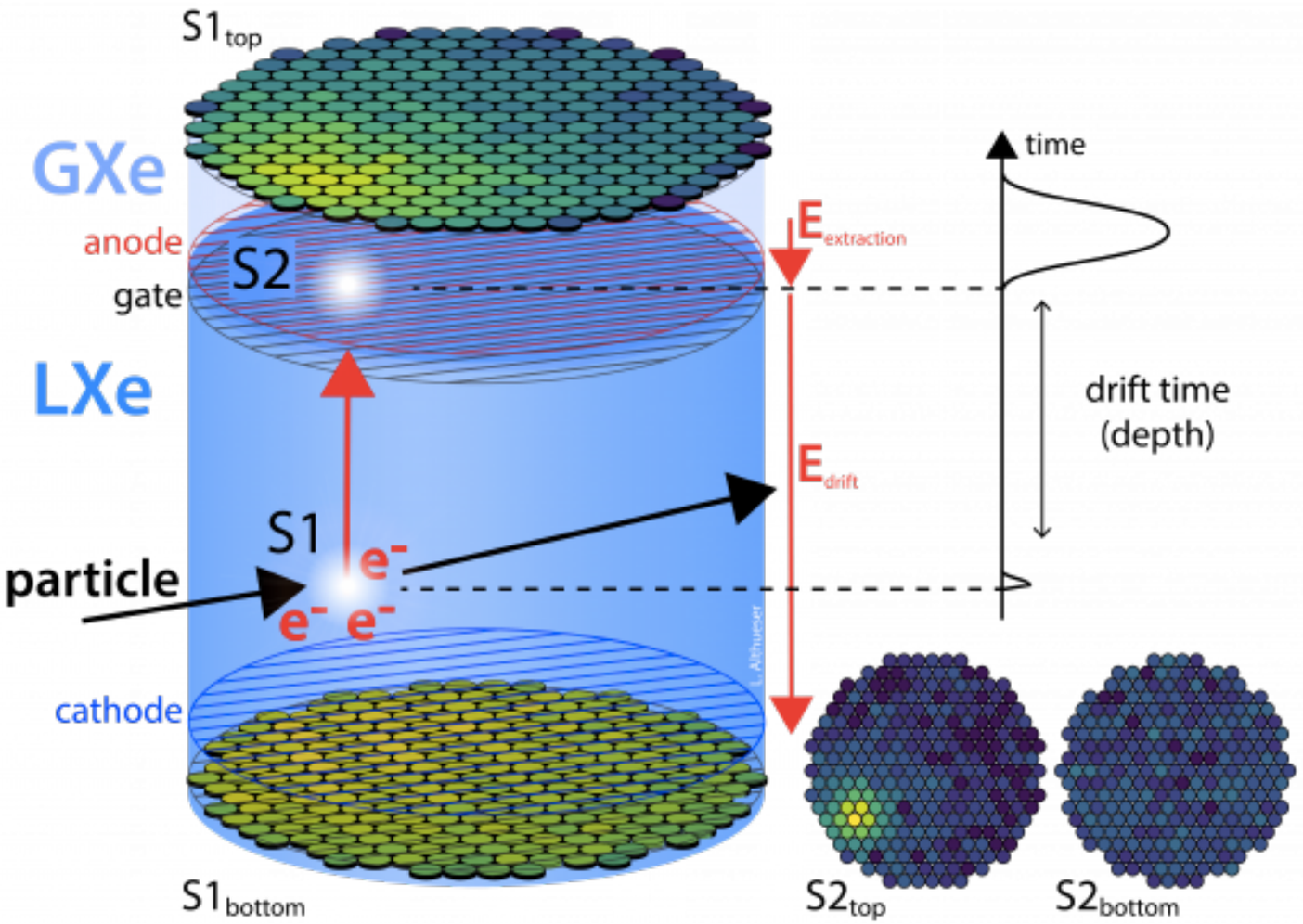
The XENON collaboration

27 institutions, 11 countries, 170 scientists

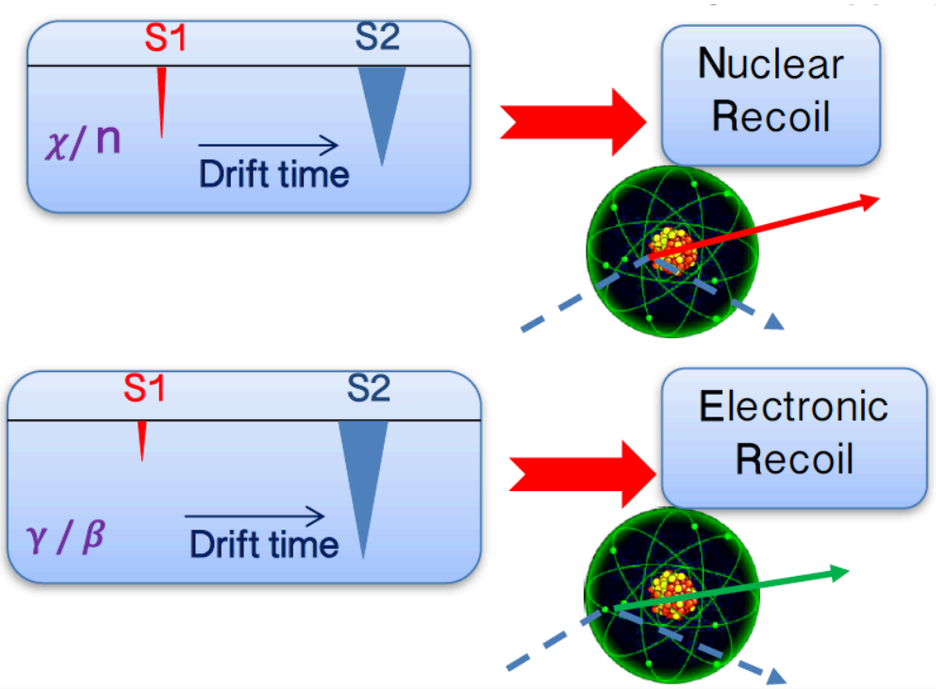
The XENON collaboration

Main goal: direct detection of dark matter with a dual-phase Xenon TPC

XENON: direct dark matter search with a dual-phase TPC



S1: prompt scintillation (light)
S2: proportional scintillation from electron drift and extraction into gas (charge)



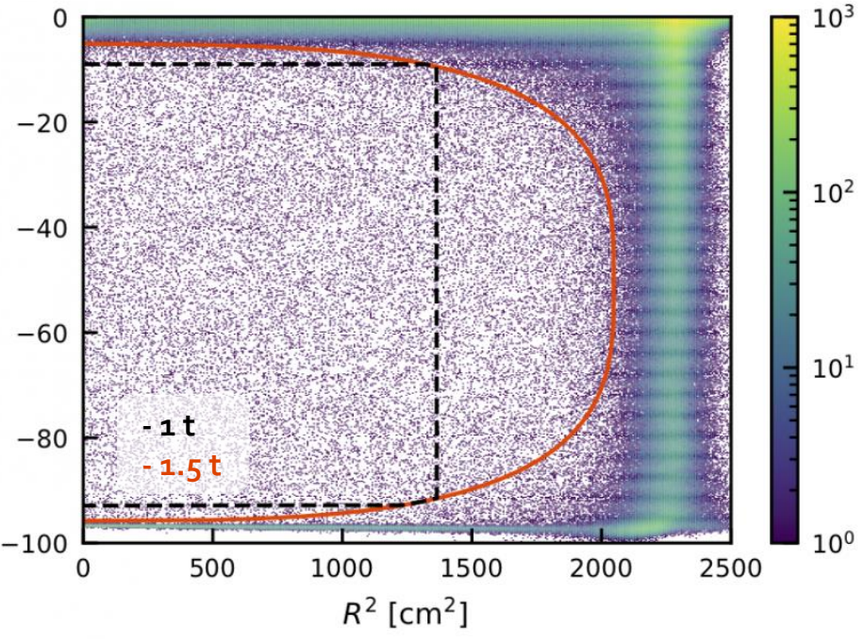
- **Energy:** from S1 and S2
- **3D position reconstruction:**
  - x and y from S2 pattern on top PMT array
  - z (depth) from drift time
- **Electron and nuclear recoil discrimination**

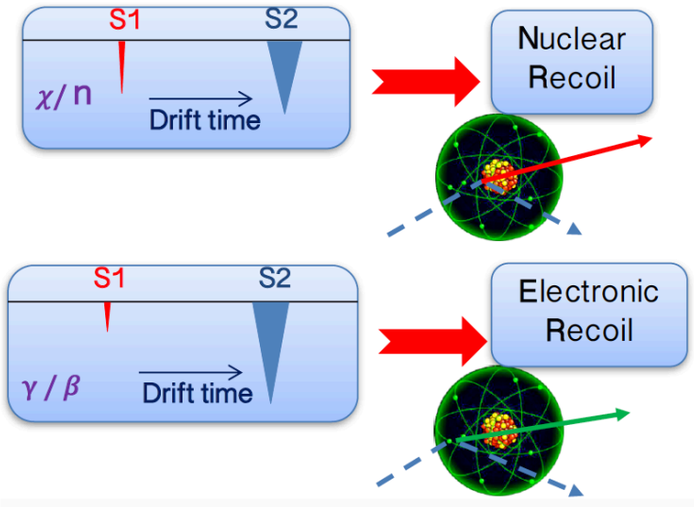
$$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$$

XENON: direct dark matter search with a dual-phase TPC

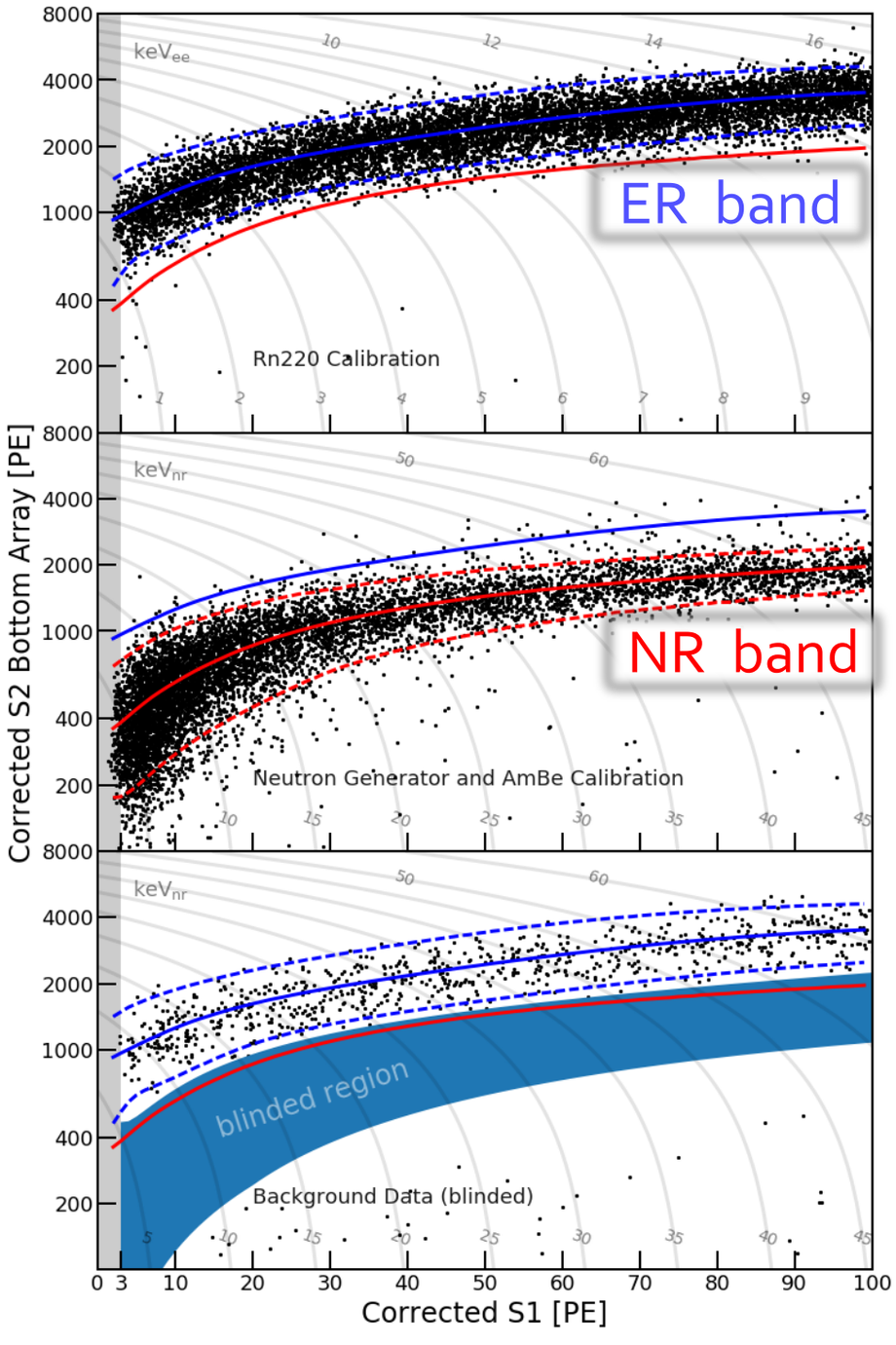
- **FIDUCIALIZATION**
- **PARTICLE IDENTIFICATION (n, beta, gamma, alpha, WIMP)**
- **ER/NR DISCRIMINATION**

S1: prompt scintillation (light)
S2: proportional scintillation from electron drift and extraction into gas (charge)

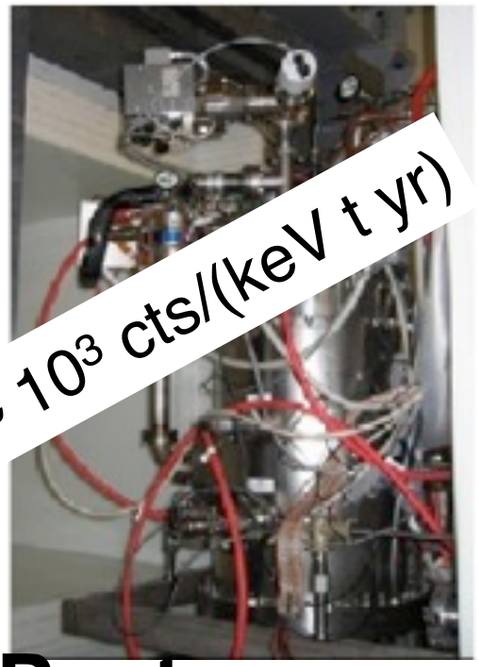
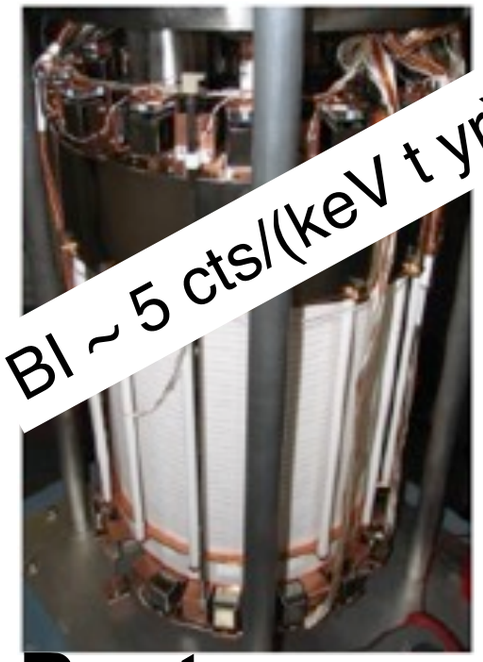
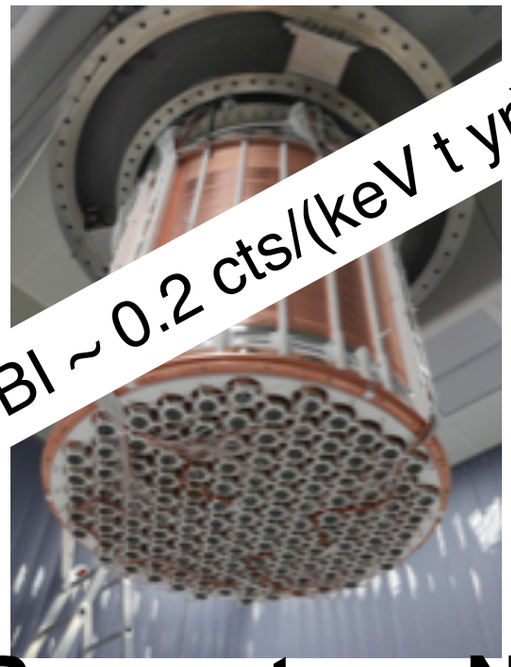
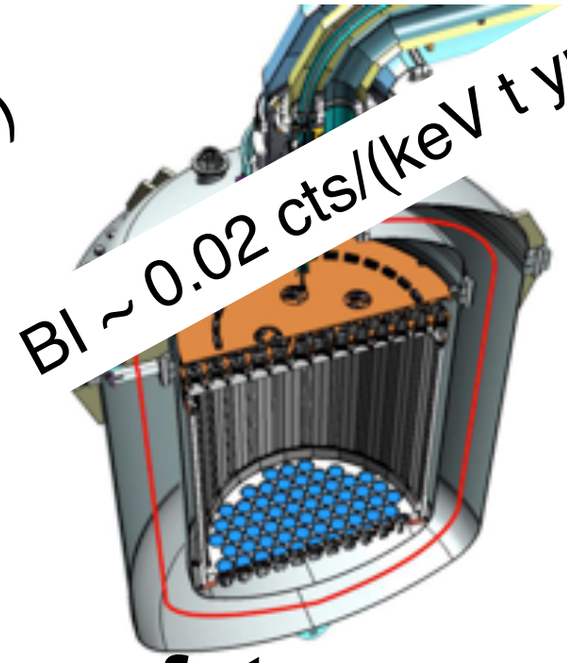




$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$



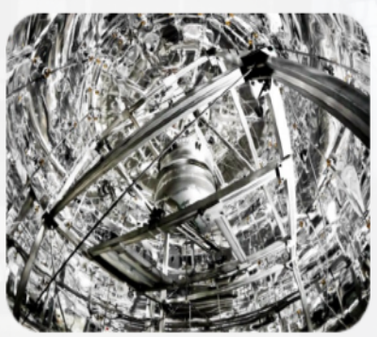
The XENON project

XENON10	XENON100	XENON1T	XENONnT
2005—2007	2008—2016	2012 – 2019	2020 — 2026
			
BI ~ 10^3 cts/(keV t yr)	BI ~ 5 cts/(keV t yr)	BI ~ 0.2 cts/(keV t yr)	BI ~ 0.02 cts/(keV t yr)
Past	**Past**	**Present**	**Near future**
Total mass : 25 kg	Total mass : 161 kg	Total mass : 3.2 t	Total mass ~8.5 t
Target mass: 14 kg	Target mass: 62 kg	Target mass: 2 t	Target mass: ~5.9 t
Drift TPC: 15 cm	Drift TPC: 30 cm	Drift TPC: 96 cm	Drift TPC: 148.5 cm
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	Limit ~ 10^{-47}cm^2	Sensitivity ~ 10^{-48}cm^2

The XENON1T experiment @ LNGS (Italy)

1500 m overburden
(3600 m.w.e.)

TPC



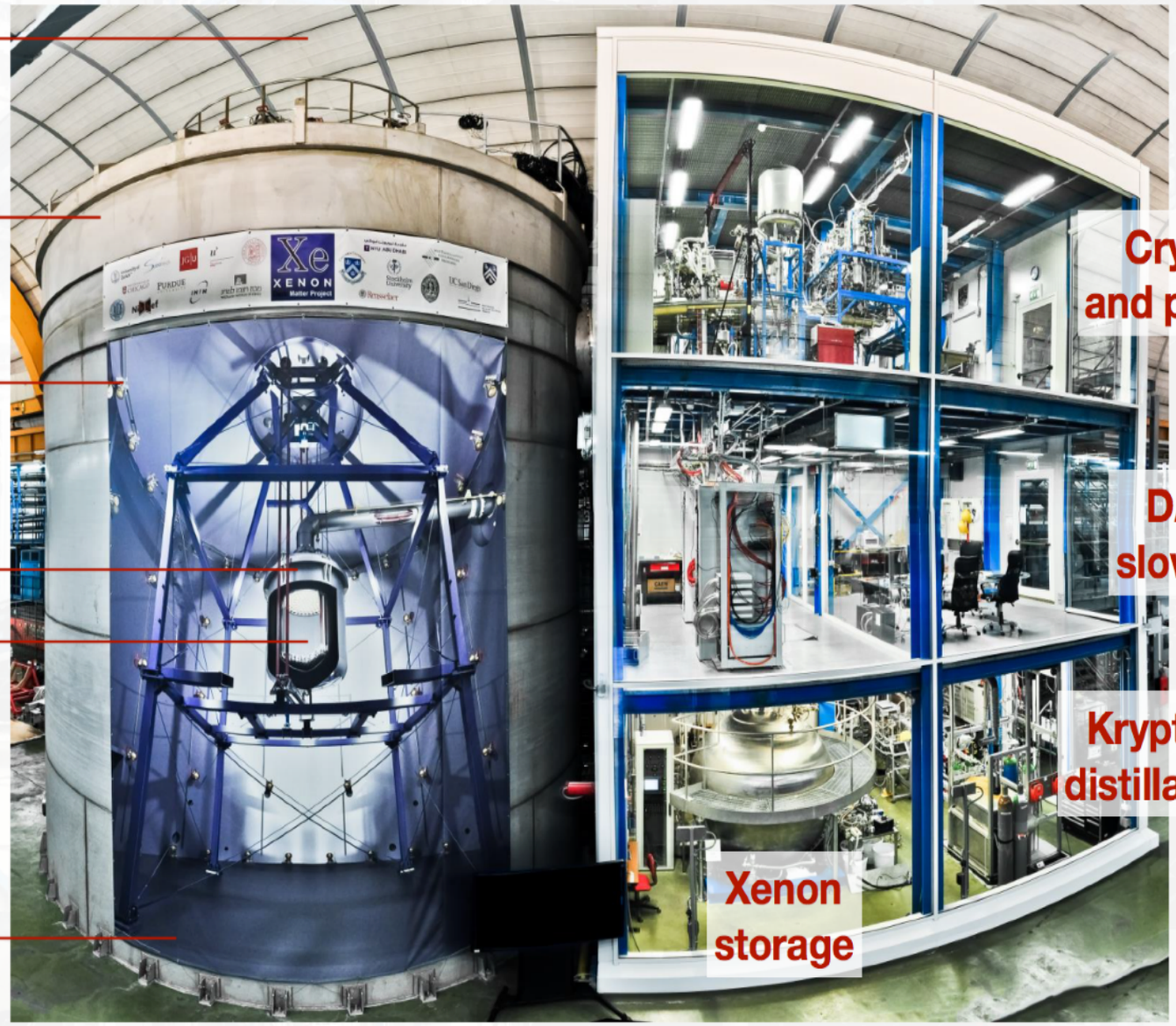
Water Cherenkov
muon veto

LNGS hall B

700 t
pure water

84
8“ PMTs

Cryostat



Cryogenics
and purification

DAQ and
slow control

Krypton
distillation

Xenon
storage

Google street view: tinyurl.com/lngstour

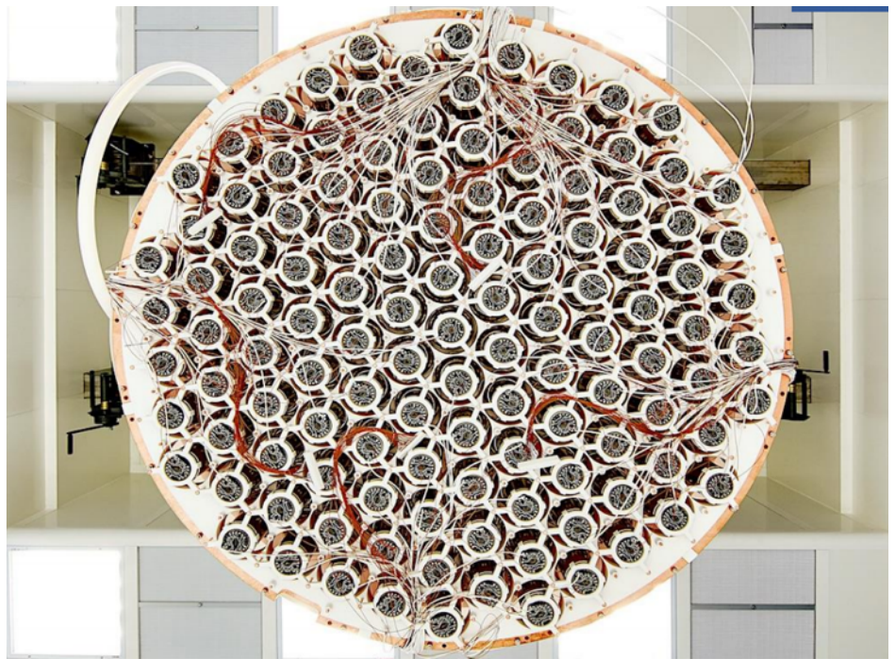
TPC inside the Water Tank + Ancillary systems: purification, Krypton distillation, cryogenics, DAQ, slow control, Xenon storage

The XENON1T TPC

- 3.2 t LXe in total @180K
- 2 t in the TPC
- 97 cm drift, 96 cm diameter
- Drift field ~100V/cm

C. Macolino

Highly reflective PTFE walls



248 3-inch PMTs

- 35% QE @ 178nm
- Digitize at 100MHz
- SPE acceptance ~94%

EPJC 75 11 (2015)

The XENON science program

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XENON

WIMP search

-Spin independent
-Spin dependent
-Low-E (sub GeV) DM
-Dark photons
-Axion-like particles

Neutrino properties

-Neutrinoless double-beta decay of ^{136}Xe
-Double-electron capture in ^{124}Xe
-Neutrino magnetic moment

SuperNovae

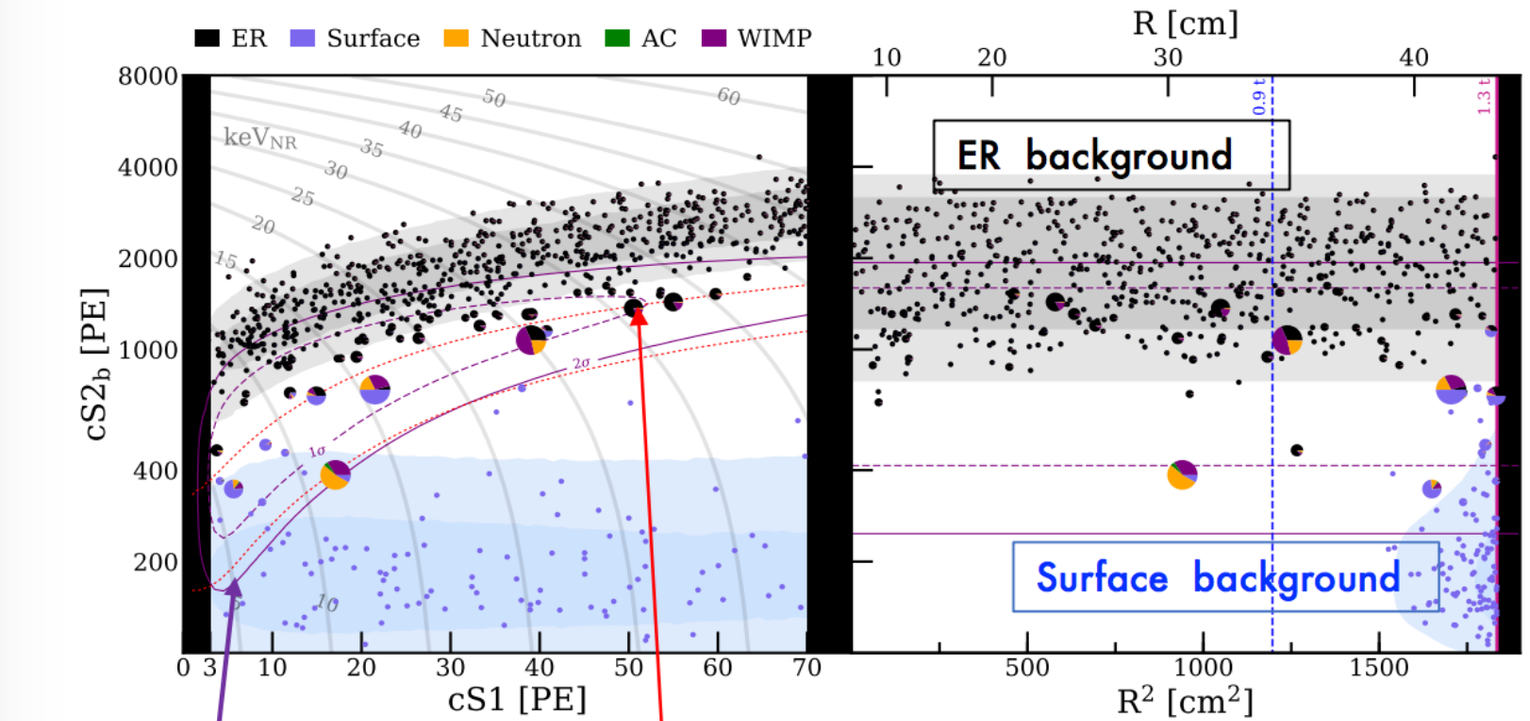
-Supernova neutrinos
-Multi-messenger information for DM experiments

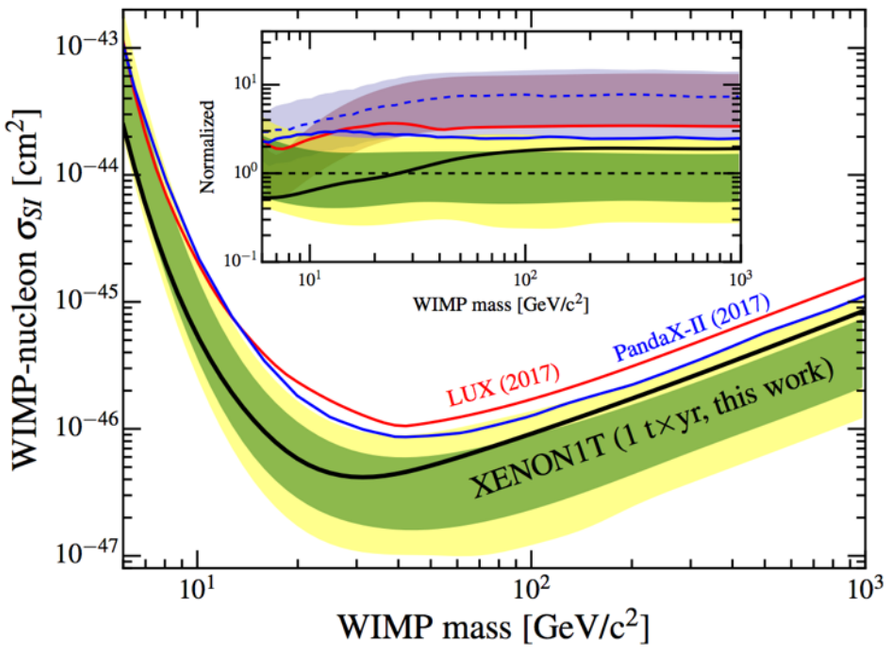
From the Sun

-Solar axions
-^{8}B solar neutrinos
-pp neutrinos

SI WIMP search results

- 1 tonne*year exposure
- 4-dimensional profile likelihood
- 3 continuous (cS1, cS2bottom, R) and one discreet (inner, outer)





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Editors' Suggestion

Dark Matter Search Results from a One Ton-Year Exposure of XENON1T

E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. Lett. **121**, 111302 – Published 12 September 2018

- **XENON1T is 7 times more sensitive compared to previous experiments (LUX, PandaX-II)**
- **Most stringent 90% confidence level upper limit on WIMP-Nucleon cross section at all masses above 6 GeV**
- **σ_{SI} below $4.1 \cdot 10^{-47}$ cm² at 30 GeV/c²**

S2-only and Migdal analyses

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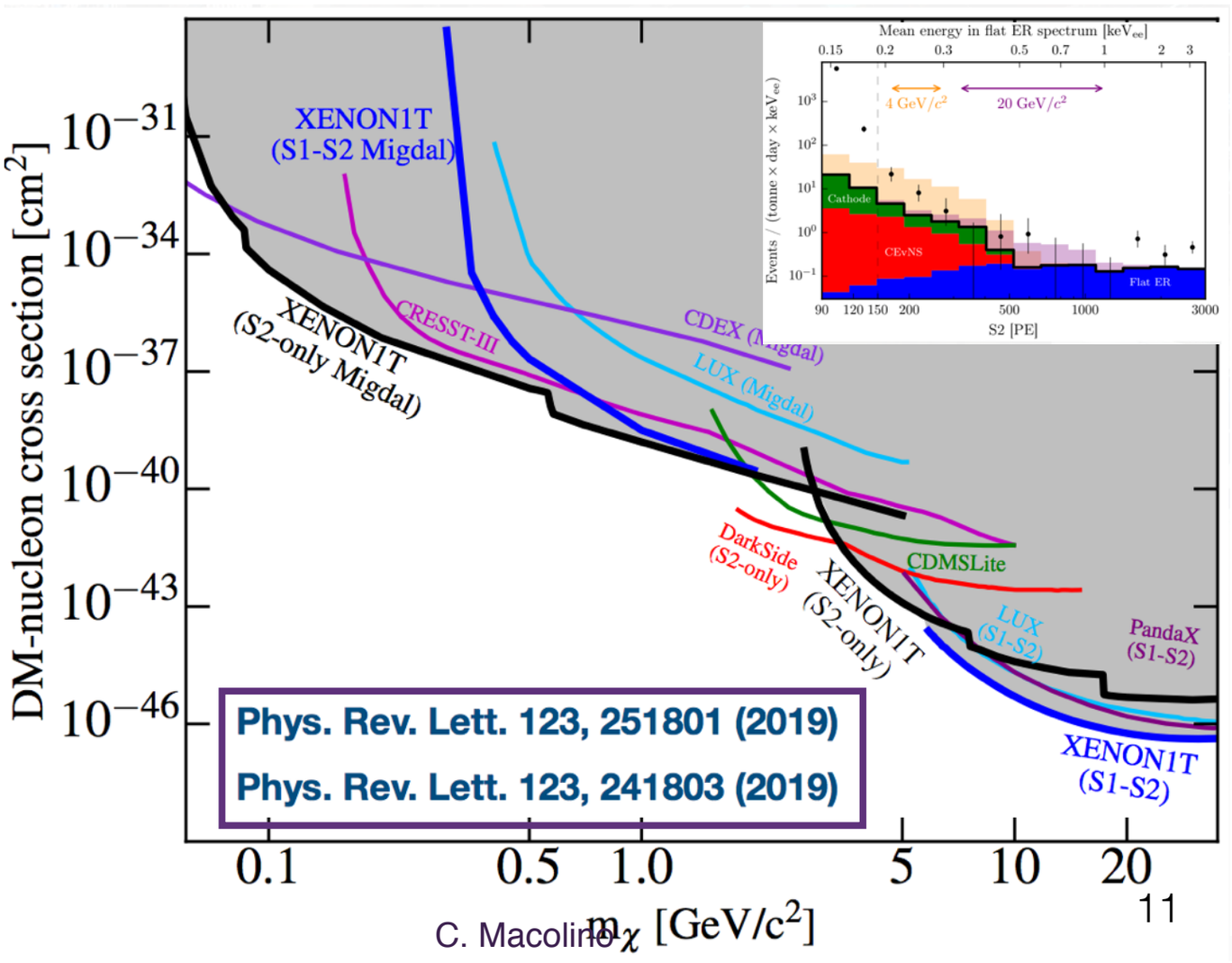
XENON

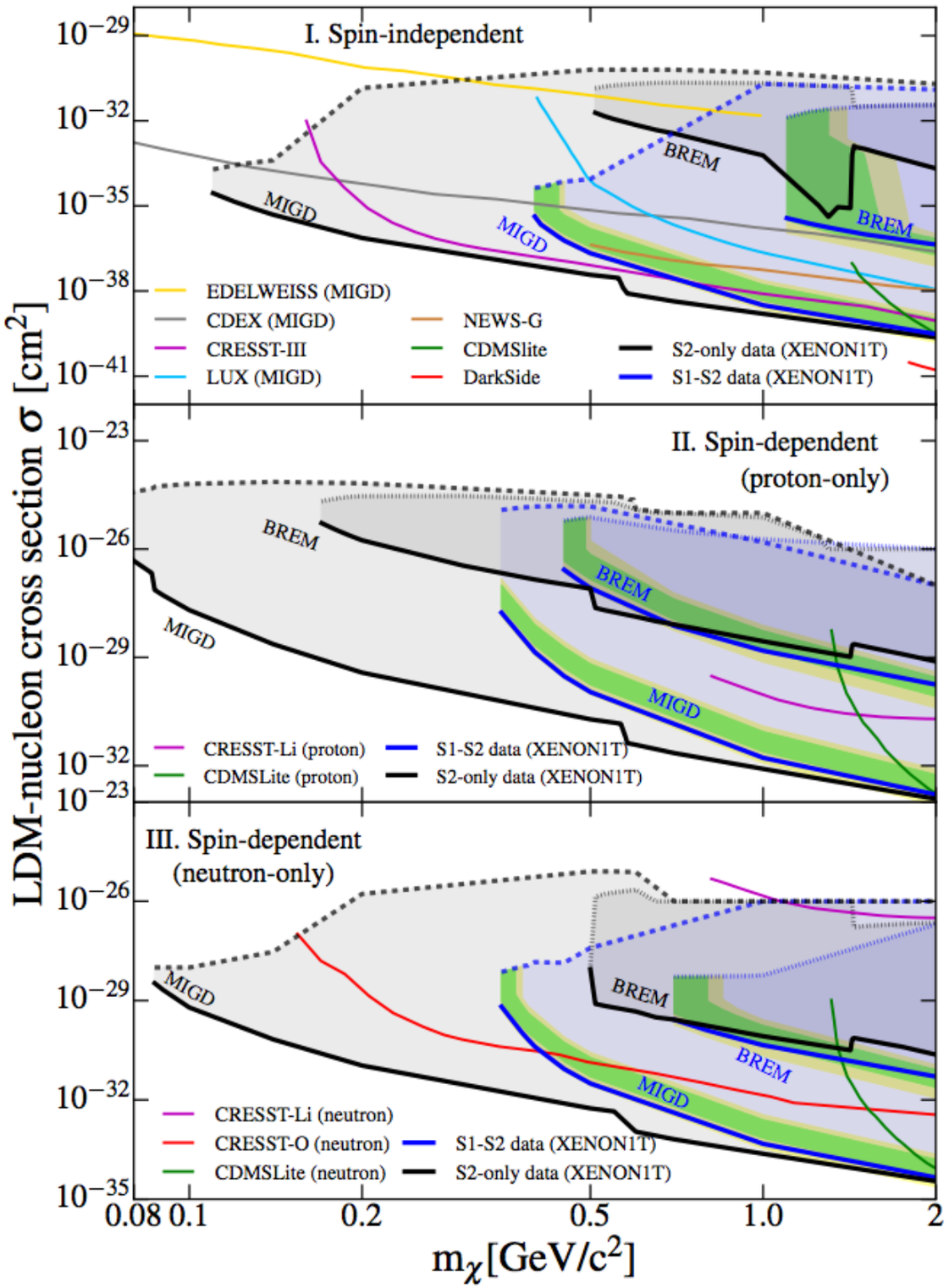
Different interaction

- Migdal effect
- Bremsstrahlung effect

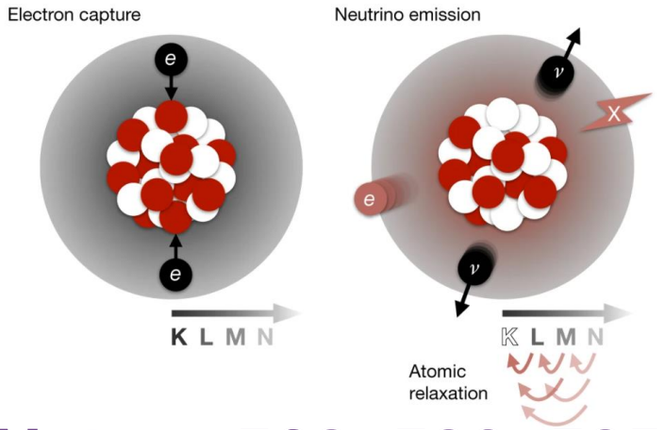
Lower threshold

- Ionization-only (S2) analysis (limit)

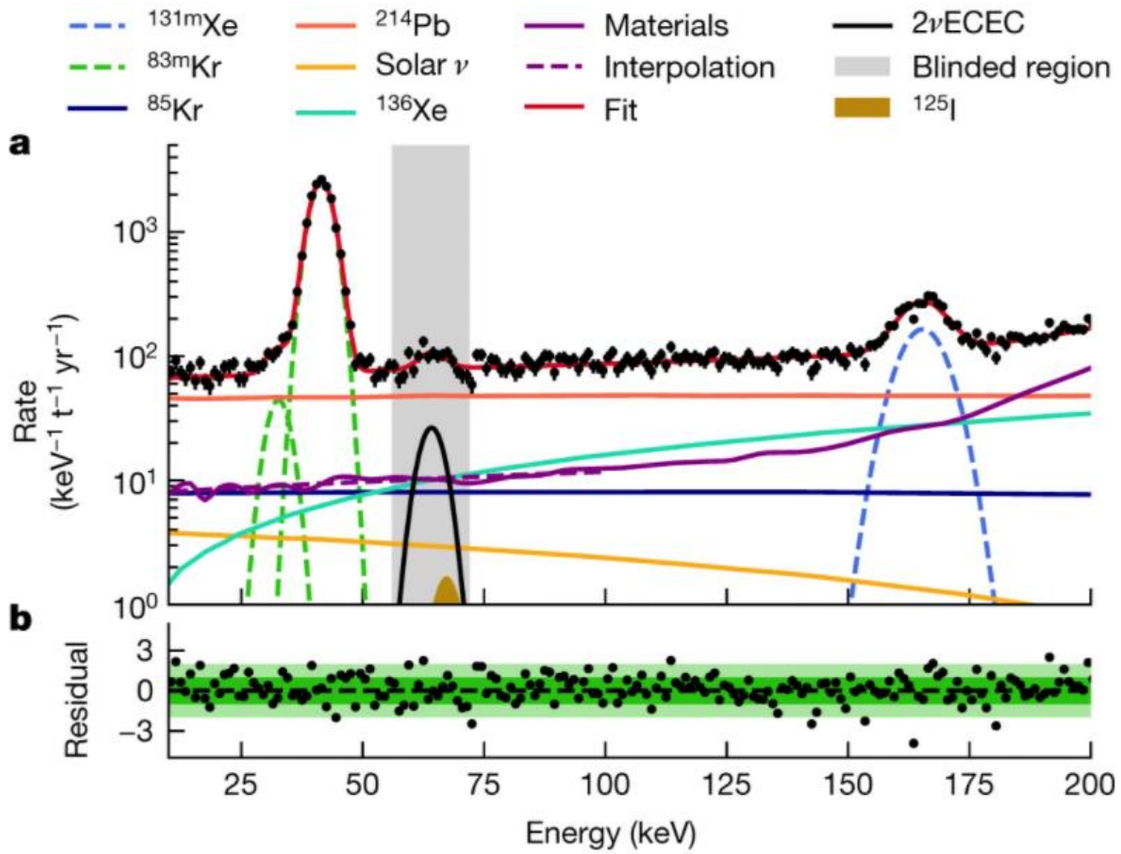




Double electron capture of ^{124}Xe

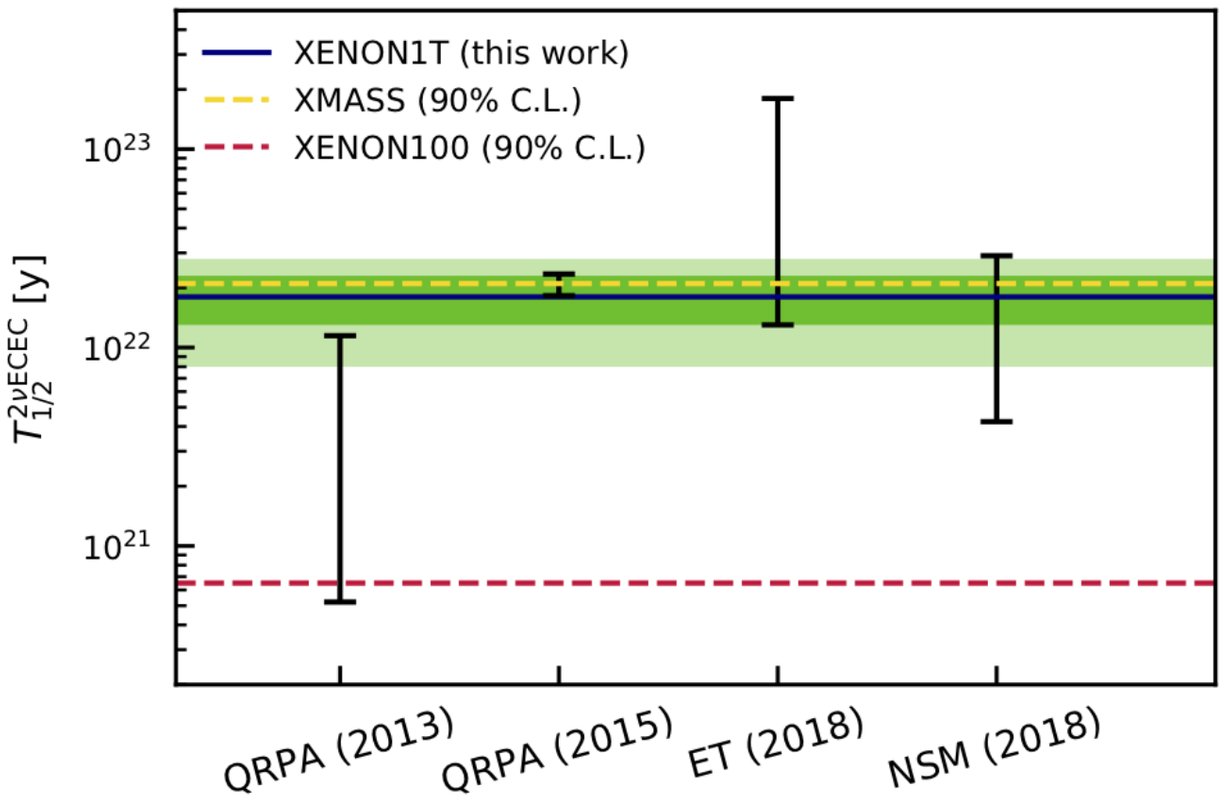


Nature 568, 532–535 (2019)



^{124}Xe ECEC:

- **Longest half-life ever measured directly:**
  1.8×10^{22} yr at 4.4σ significance
- Important observable for nuclear structure models
- Sensitivity achieved thanks to highly radiopure detector
- Step towards search for 0vECEC



Low energy electron recoil excess

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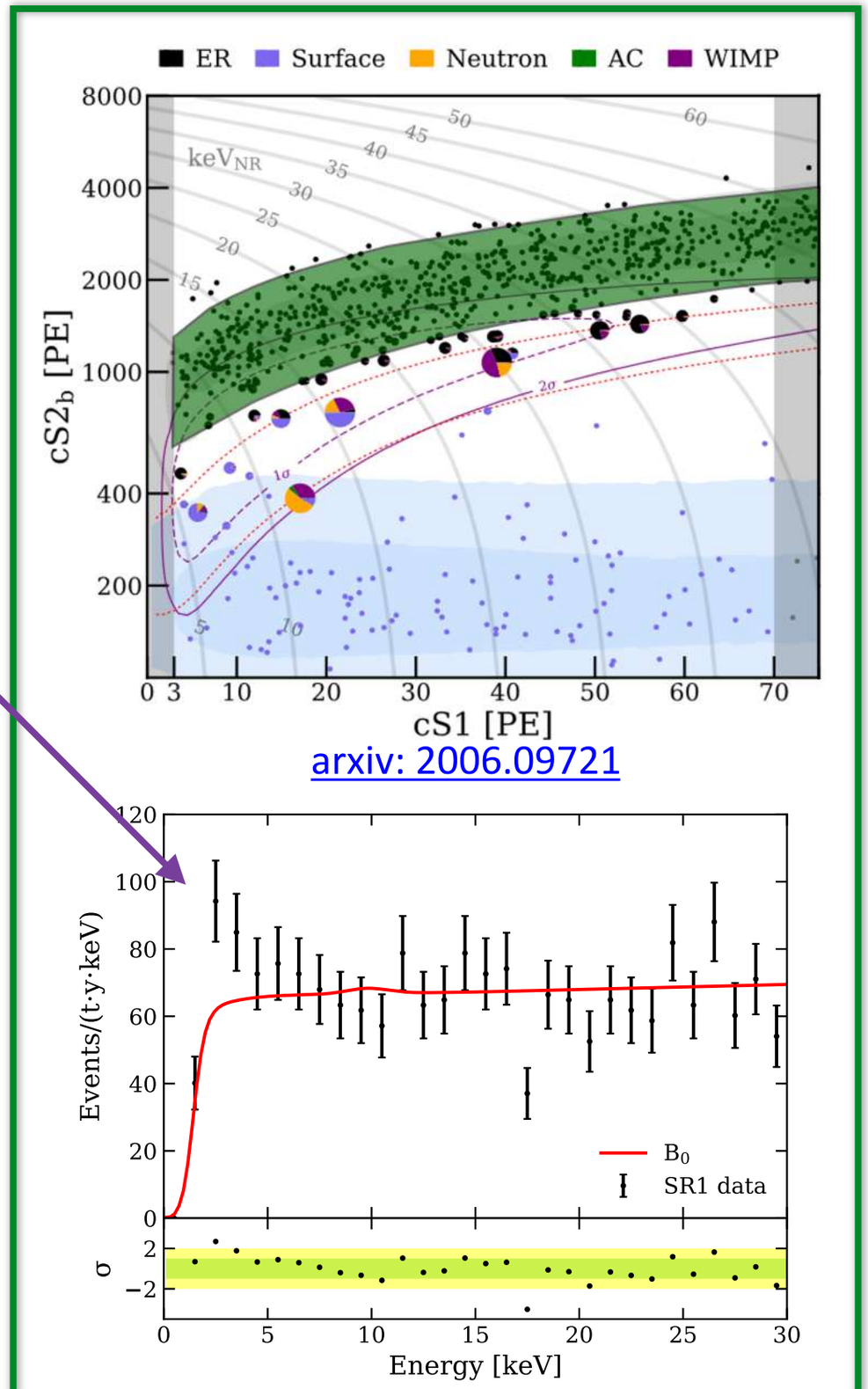
Electron Recoil with energy < 30 keV:

- **Excess between 1-7 keV**
- 285 events observed vs. (232 +/- 15) predicted
- would be a 3.3σ fluctuation
- Lowest background ever achieved in this energy range

Not considered background ?
the Tritium hypothesis
OR
New Physics?

- **Solar axions**
- **Anomalous neutrino magnetic moment**
- **Bosonic dark matter**
- **many other possible interpretations…**



arxiv: 2006.09721

Phys. Rev. D 102, 072004 (2020)

Low energy electron recoil excess

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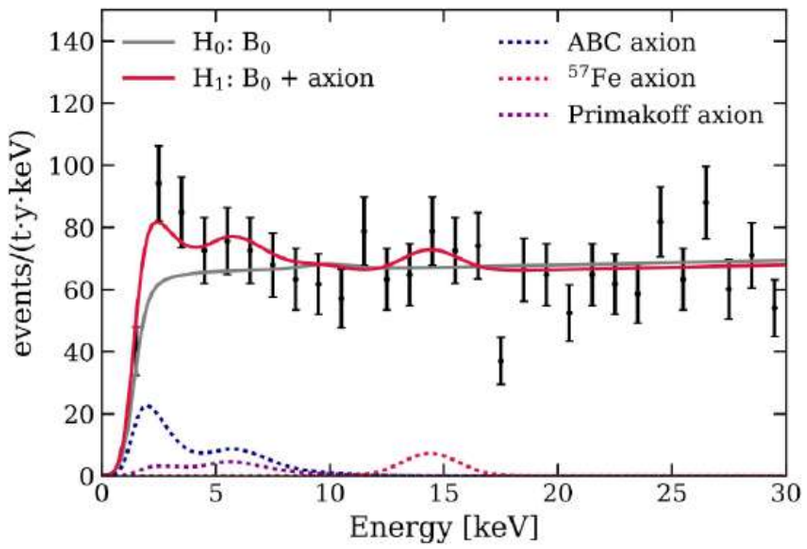
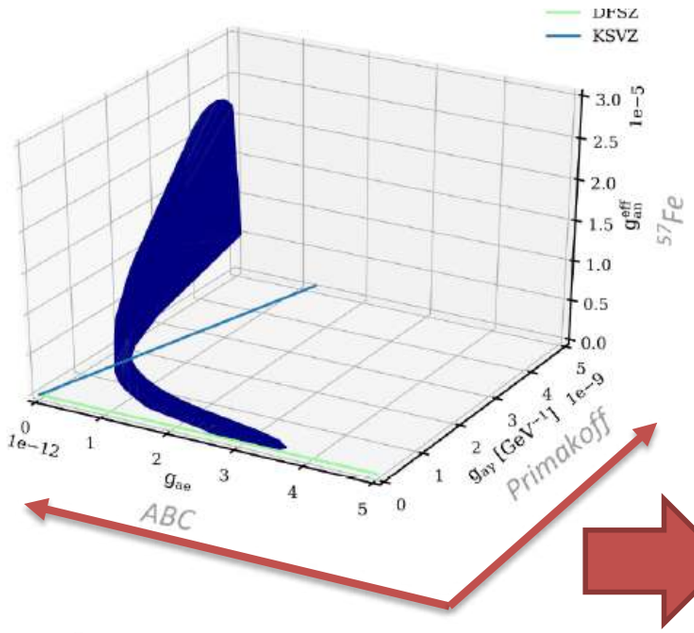
New physics ? Solar axions

Favoured over background at 3.4σ*

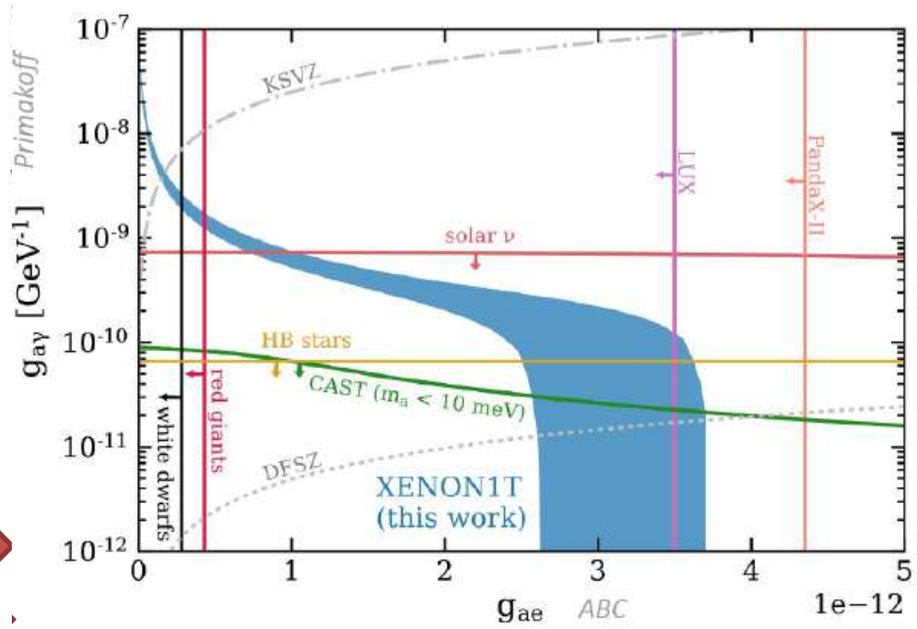
* Drop to 2.1 σ if $H_0=B_0+{}^3H$

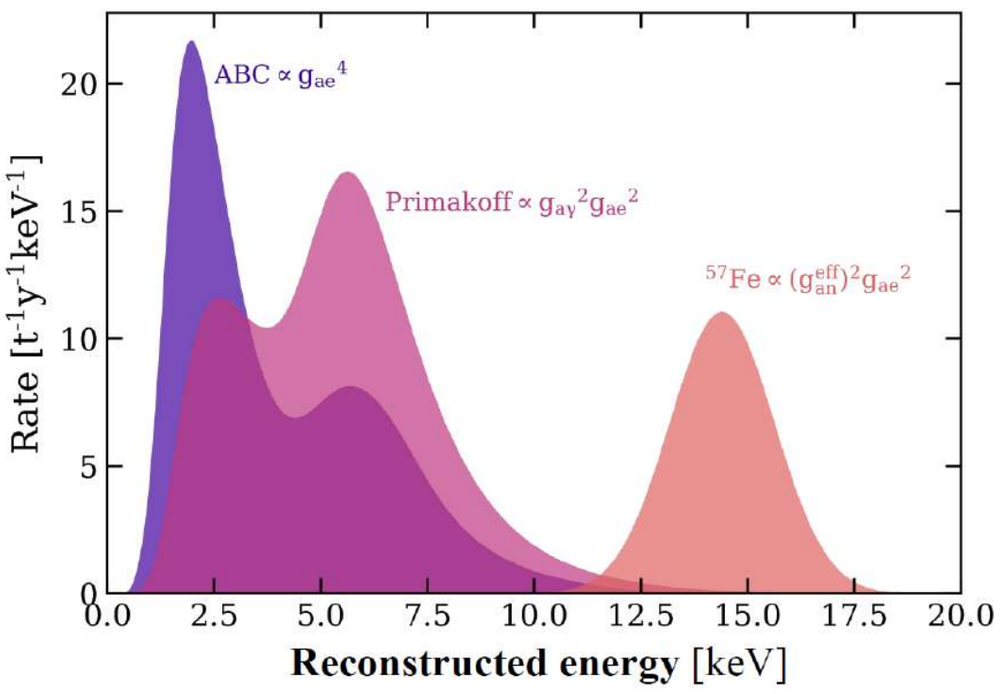


90% C.L. 3D contour



90% C.L. contour projection





Phys. Rev. D 102, 072004 (2020)

- **Result in tension with astrophysical constraints (axions cool off stars too much)**
- **Gao at al. (arXiv:2006.14598), Dent et al. (arXiv: 2006.15118): point out that the tension is relaxed if axions are considered to originate via the Primakoff conversion of photons only**

Low energy electron recoil excess

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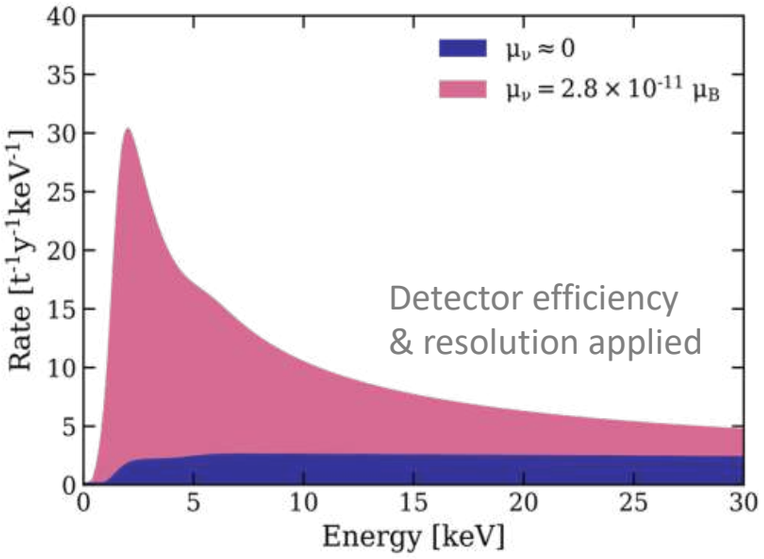
New physics ? Neutrino magnetic moment

- In many extensions of the Standard Model neutrinos acquire mass and also electromagnetic properties
- Can generate important effects in astrophysical environments
- Majorana neutrinos are predicted to have large magnetic moments ($\mu_\nu > 10^{-15}\ \mu_B$)

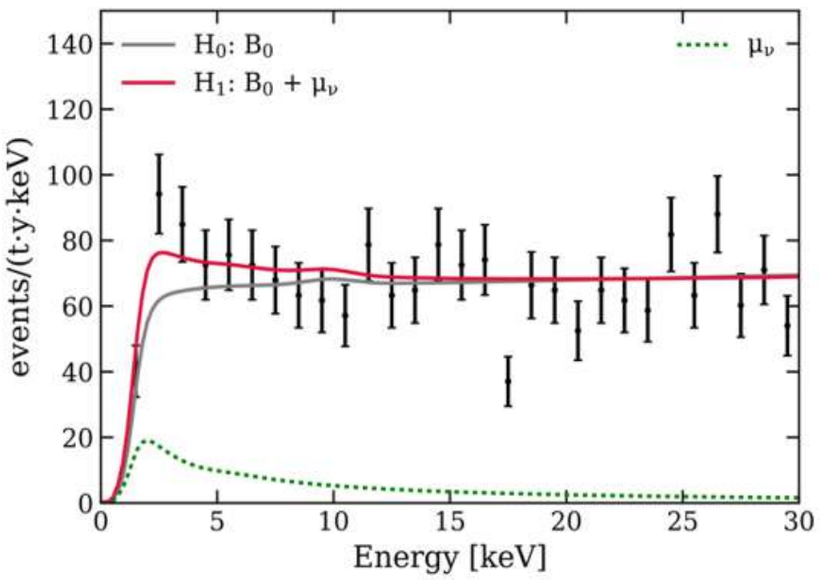
Source: neutrinos from the Sun (pp-reaction)
Detection: elastic scattering off electrons

Phys. Rev. D 102, 072004 (2020)

Would lead to higher cross-section

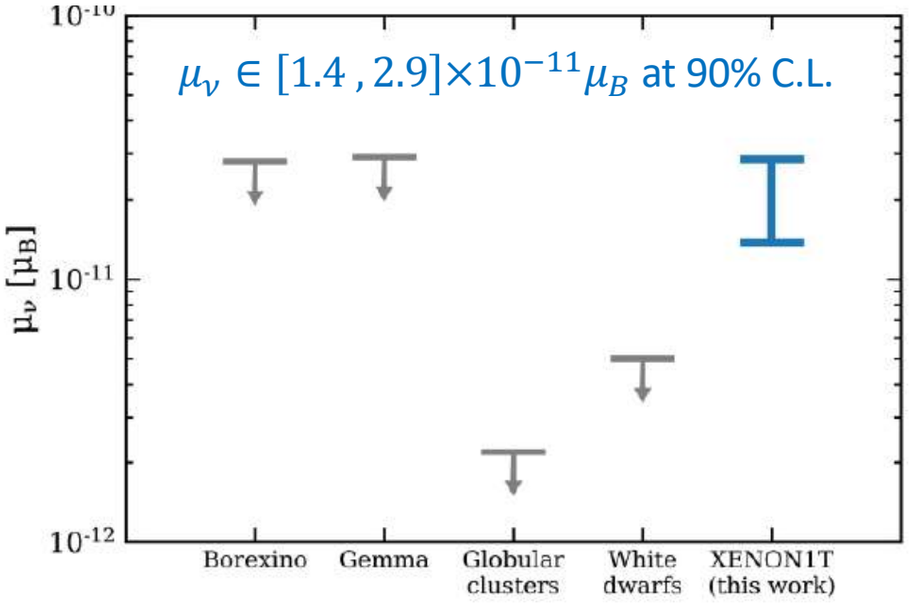


Favoured over background at 3.2σ*



* Drop to 0.9 if $H_0=B_0+{}^3H$

In tension with astrophysical limits



Low energy electron recoil excess

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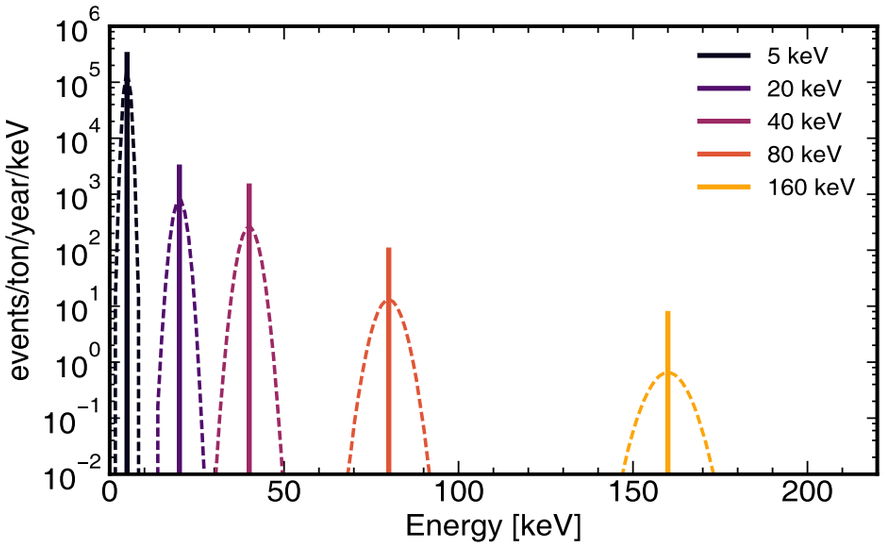
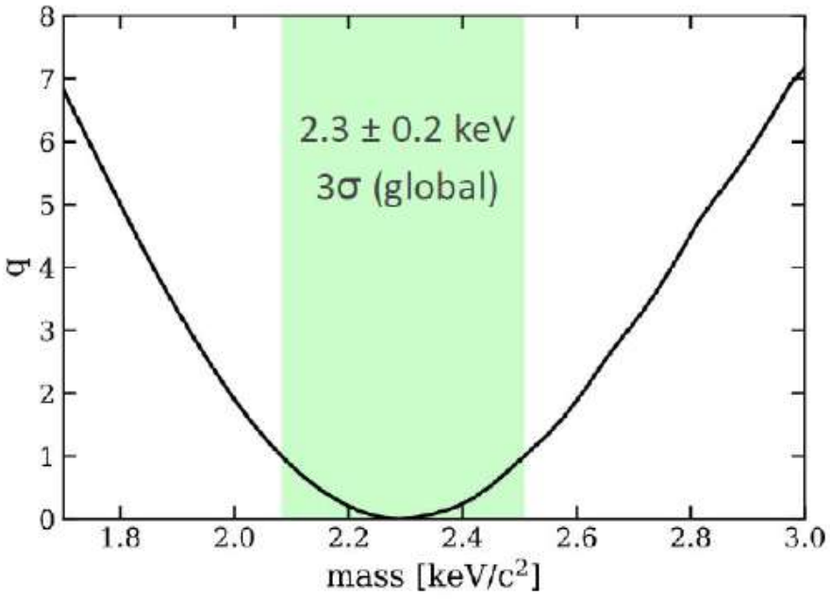
New physics ? Bosonic dark matter

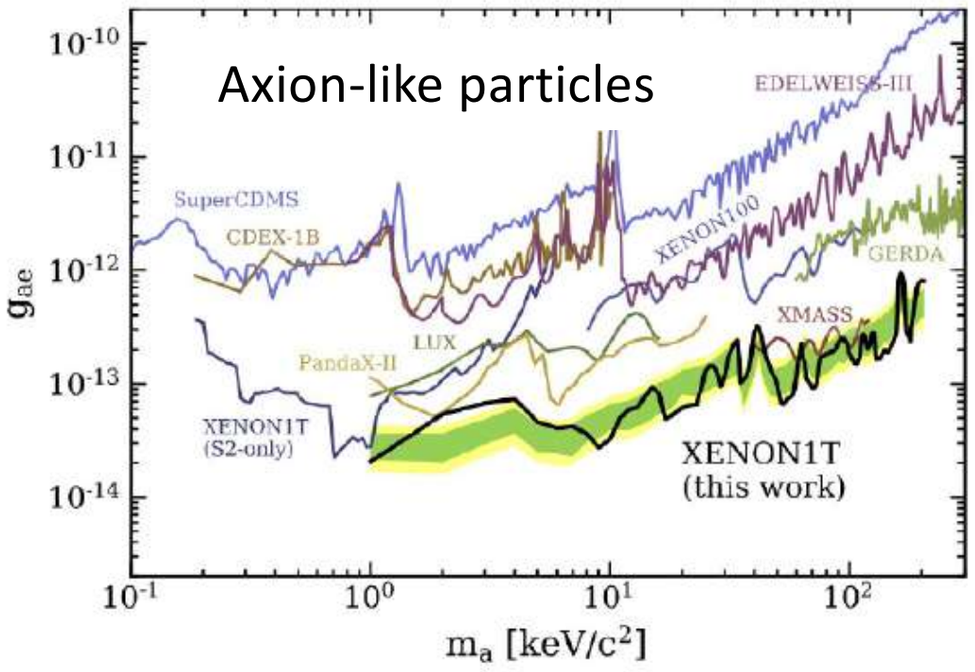
keV relic dark matter: ALPs, SuperWIMPs, dark photon

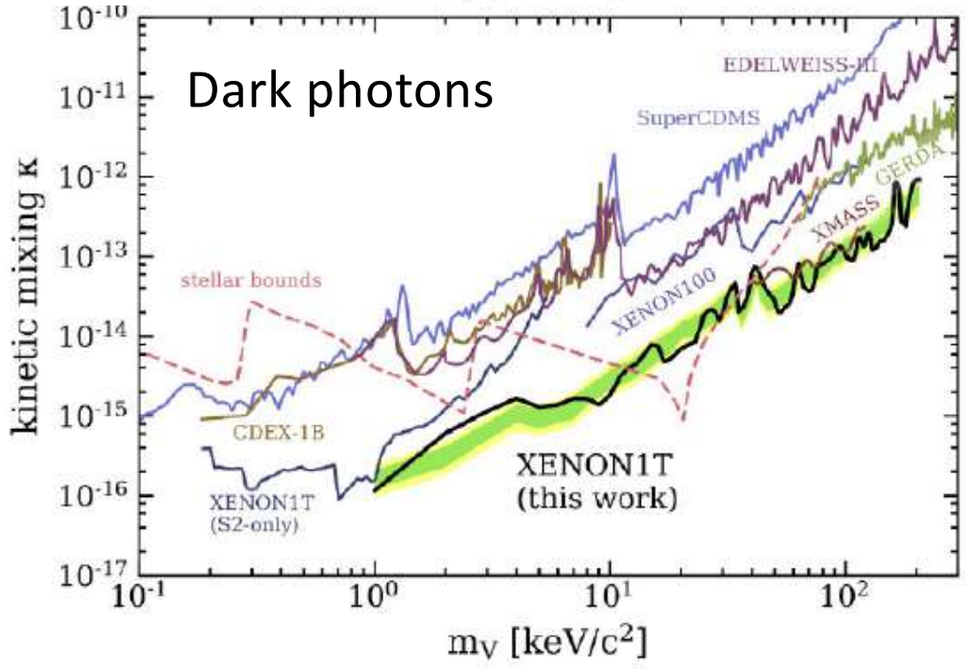
Search for mono-energetic peaks
Most significant at 2.3 keV, No excess above 3σ





Phys. Rev. D 102, 072004 (2020)





CEνNS of ^{8}B neutrinos

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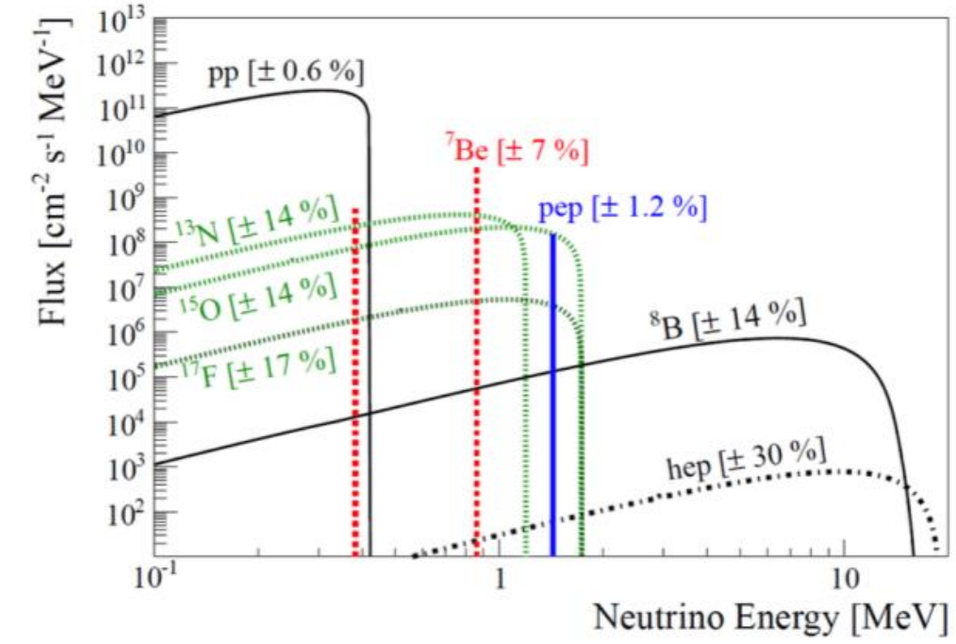
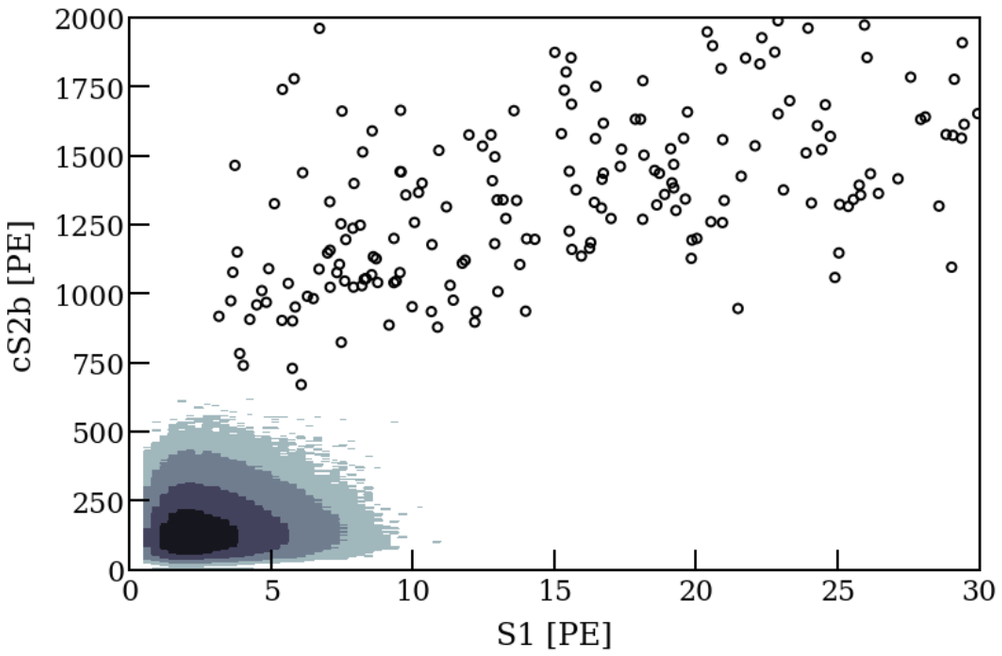
Coherent Elastic Neutrino-Nucleus Scattering for ^{8}B neutrinos from the Sun

- Irreducible background to WIMP search
- Lower detection threshold from 2-fold coincidence

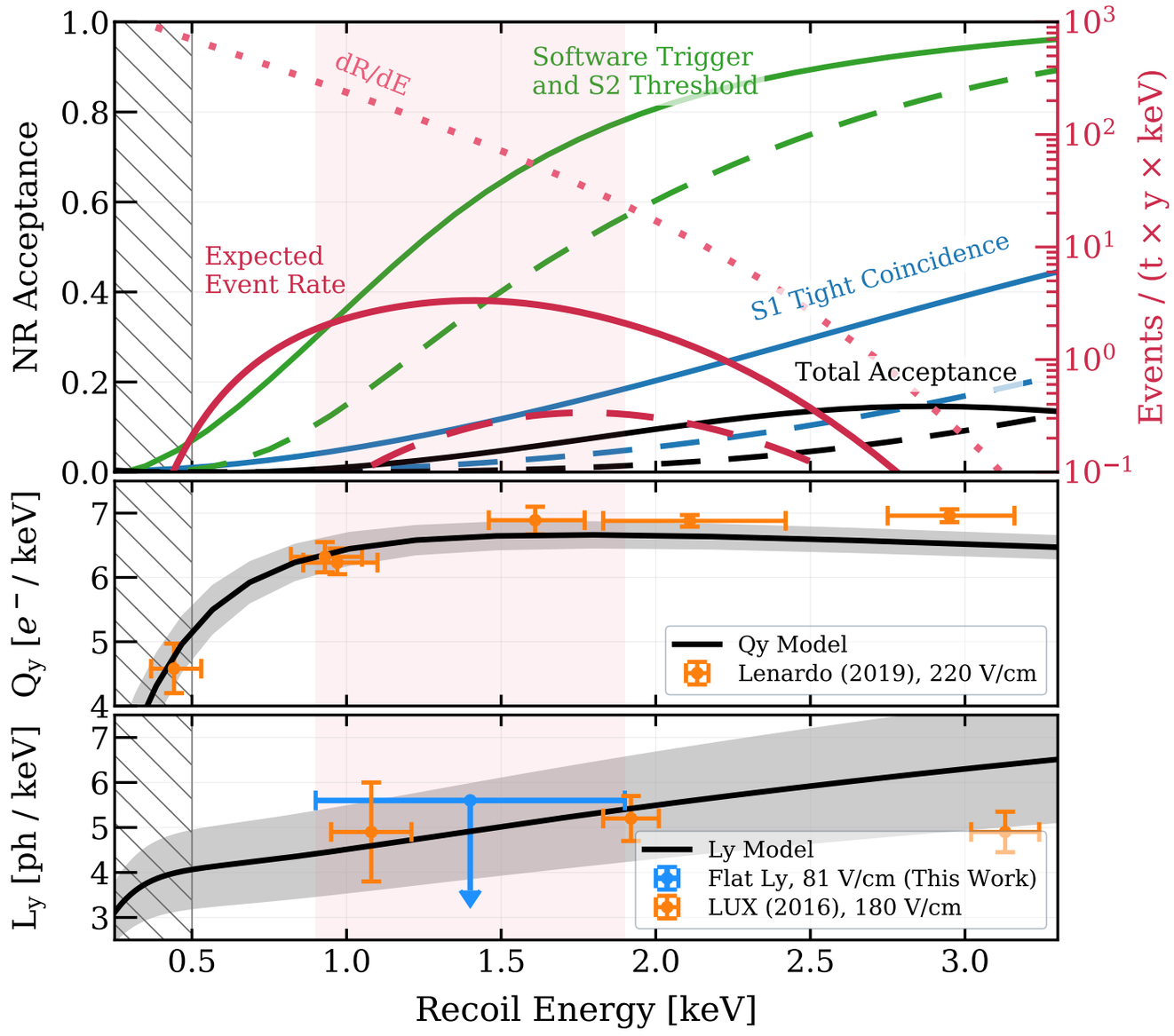




C. Macolino

Phys. Rev. Lett. 126, 091301 (2021)

arXiv:2012.02846



CEνNS of ^{8}B neutrinos

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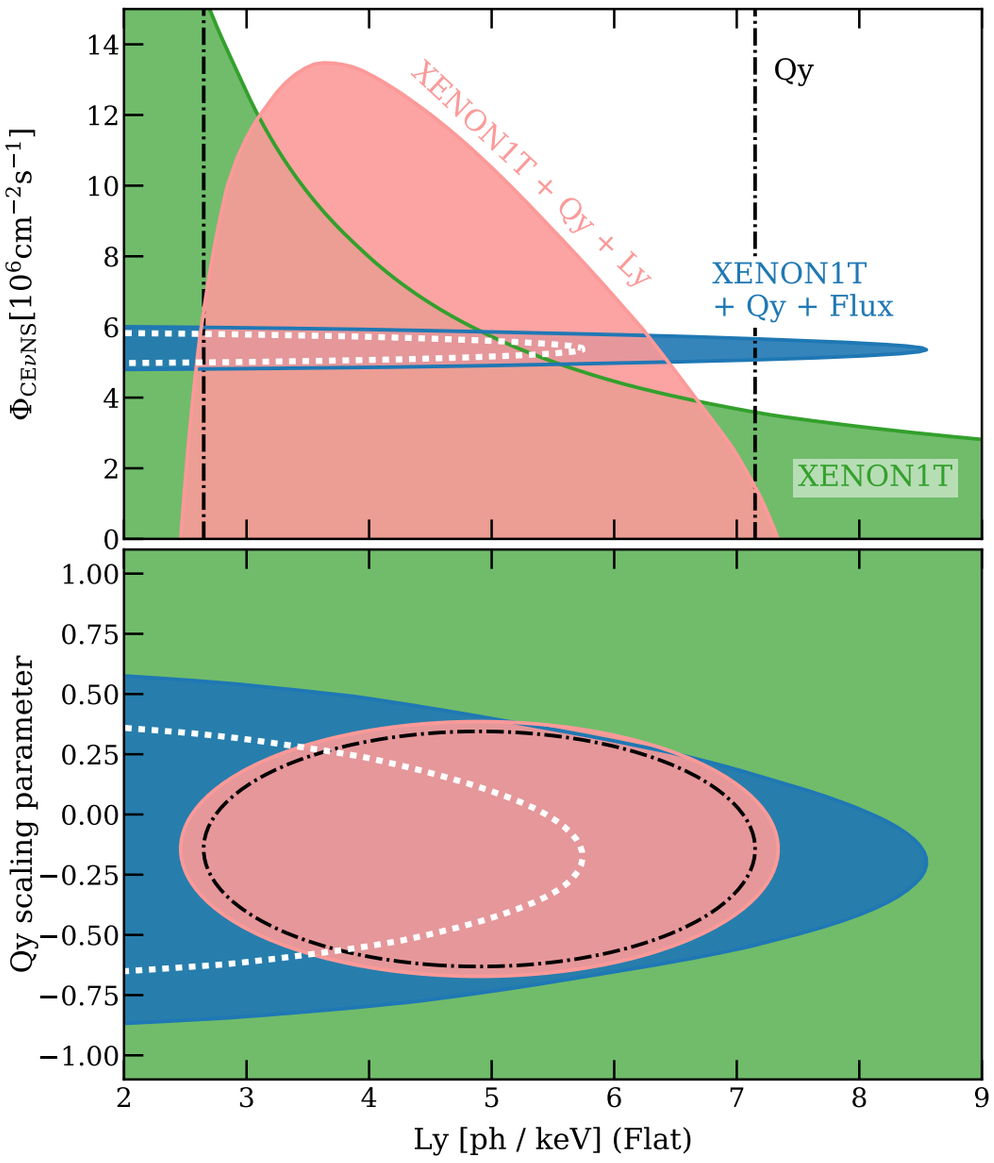
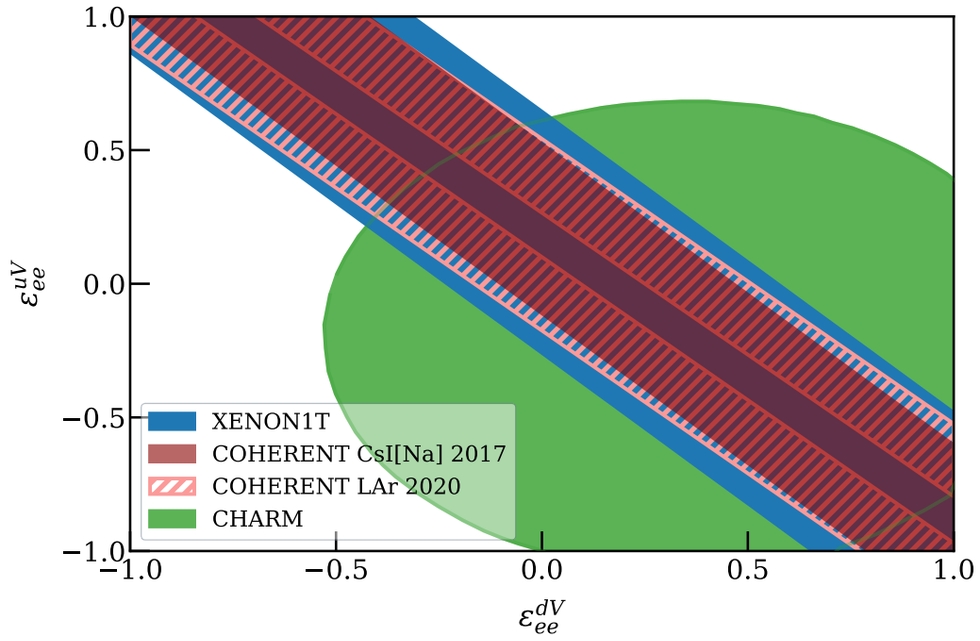
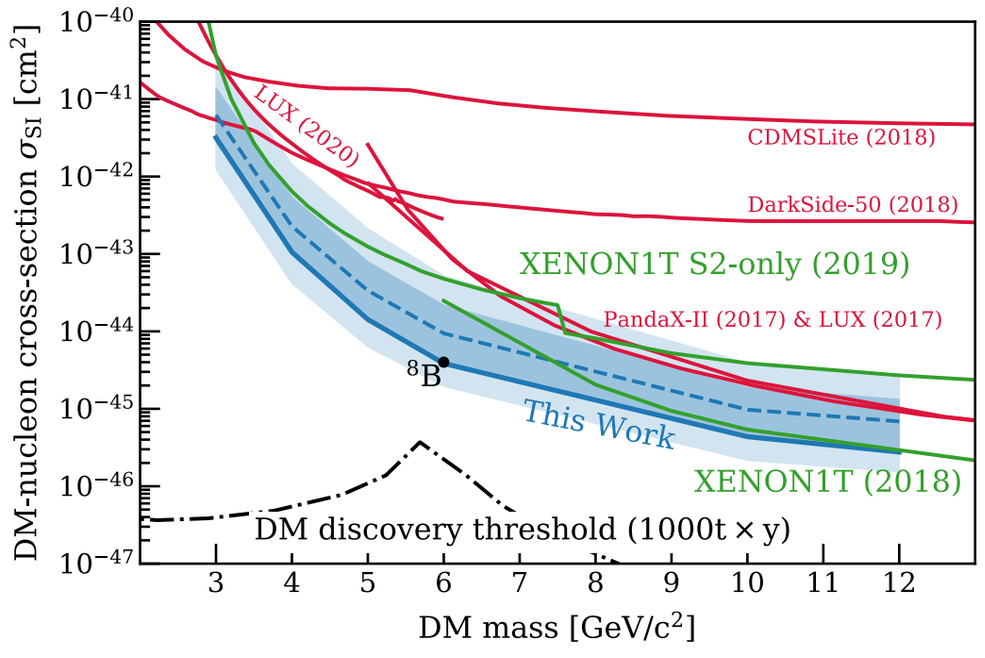
XENON

Coherent Elastic Neutrino-Nucleus Scattering for ^{8}B

- No excess observed in a 0.6 tonne*year exposure
- Non detection of solar neutrinos to constrain:
  - light yield and ionization yield
  - light dark matter between 3-11 GeV/c²







Phys. Rev. Lett. 126, 091301 (2021)
arXiv:2012.02846

XENONnT: the next detector

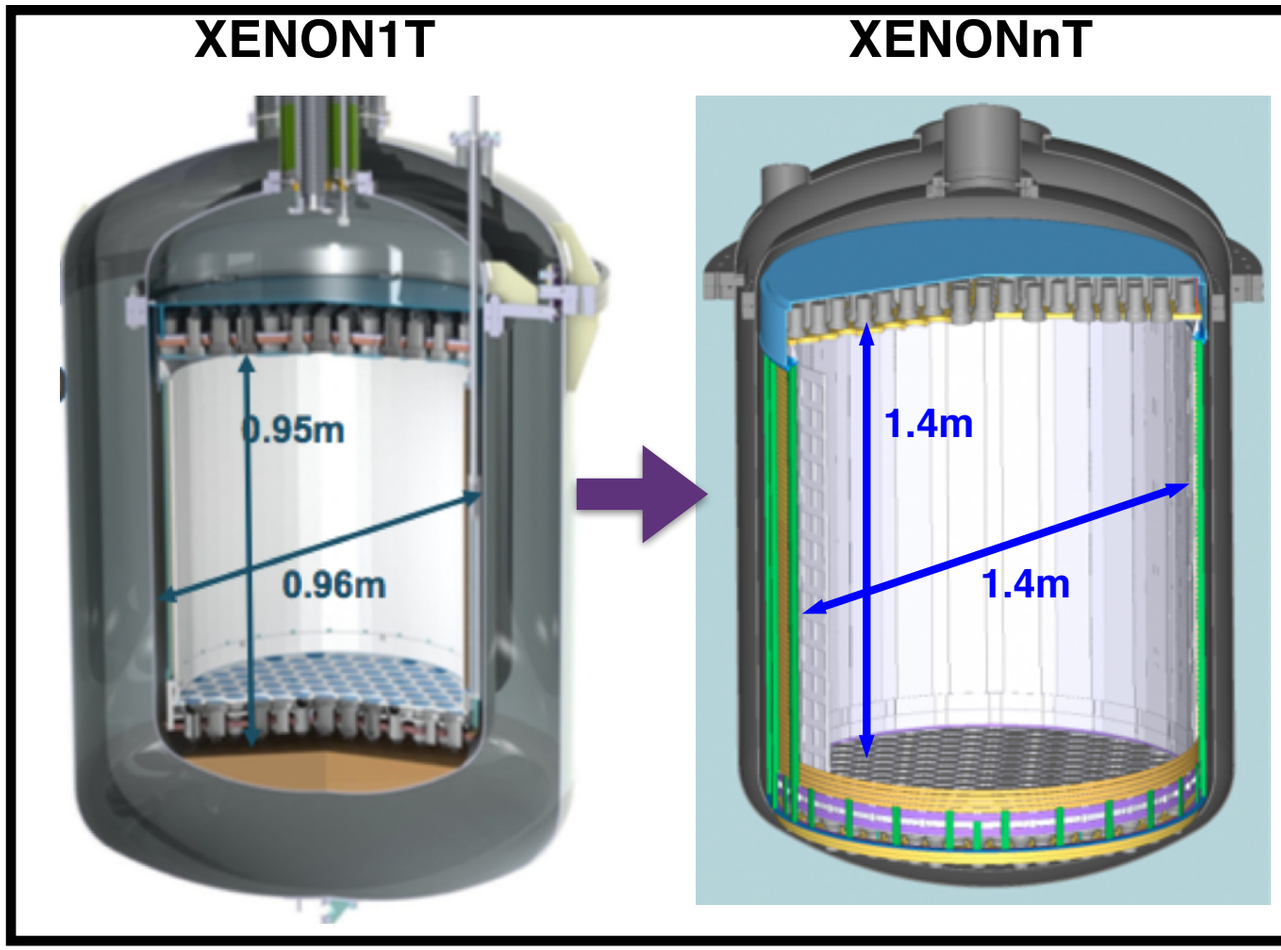
Università degli Studi dell'Aquila

XENON

5.9 t liquid Xe (3x XENON1T)

494 PMTs

Liquid Xe purification system (~1500 slpm)



Background reduction:

- Material selection and screening
- Radon distillation column
- Radon-free purification pump

Active neutron veto with Gd loaded water

High energy readout

XENONnT: the next detector

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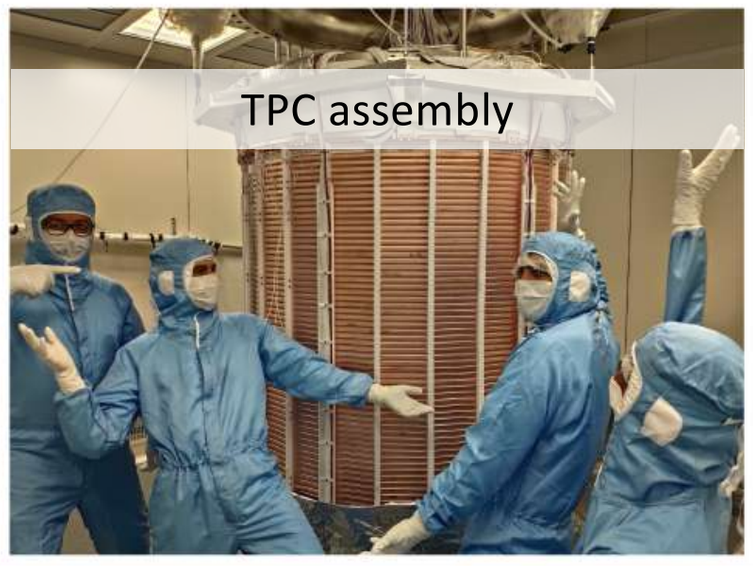
XENON

Installation finished during the 2020 lockdown

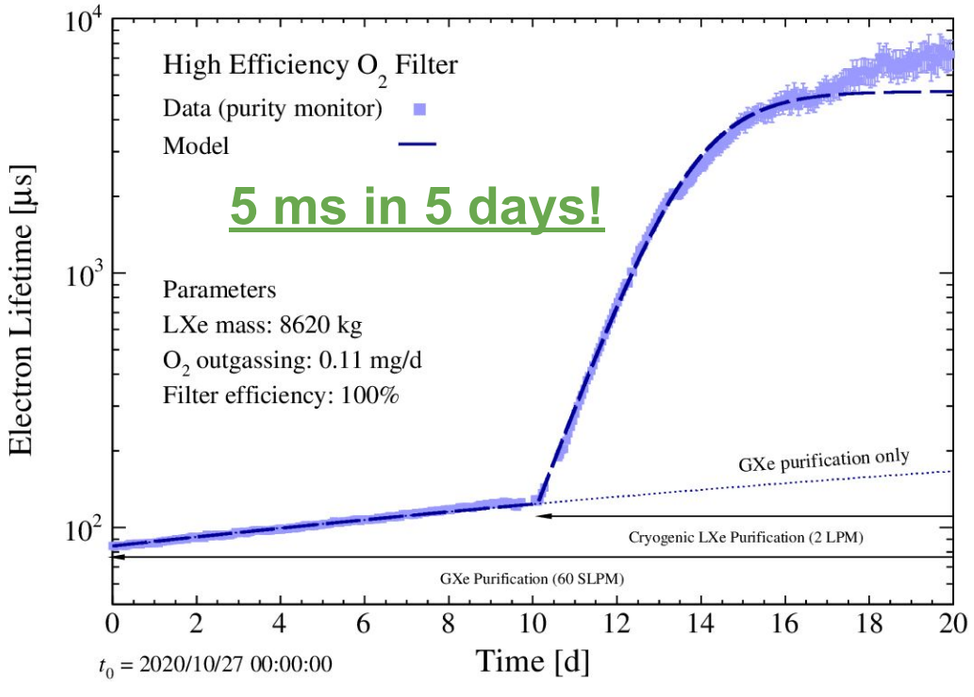


thanks to the dedication and effort of XENON collaborators during the Covid pandemic

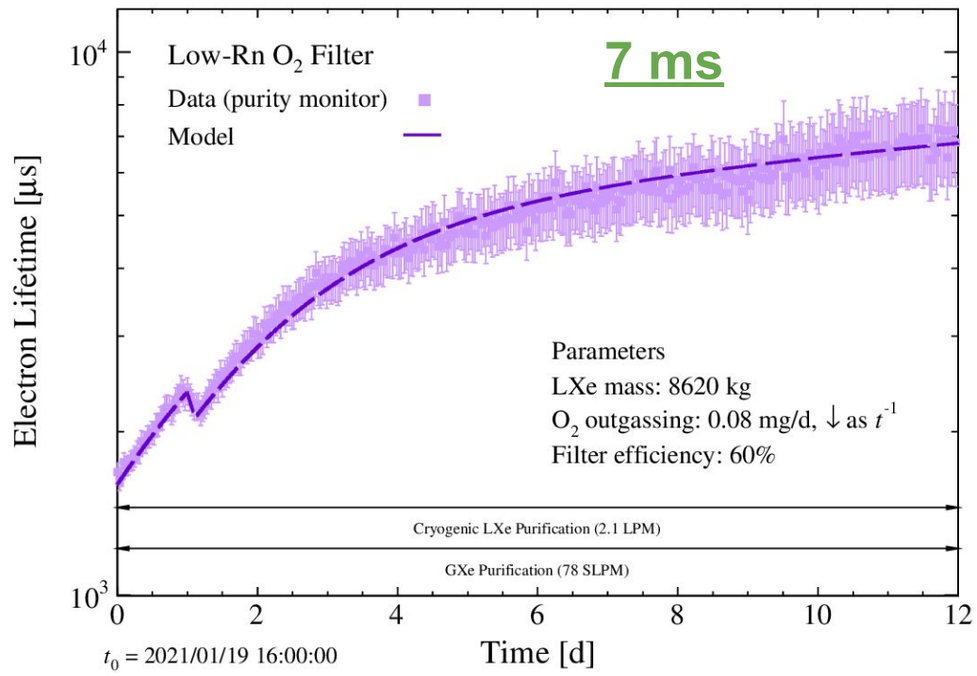
XENONnT: the next detector

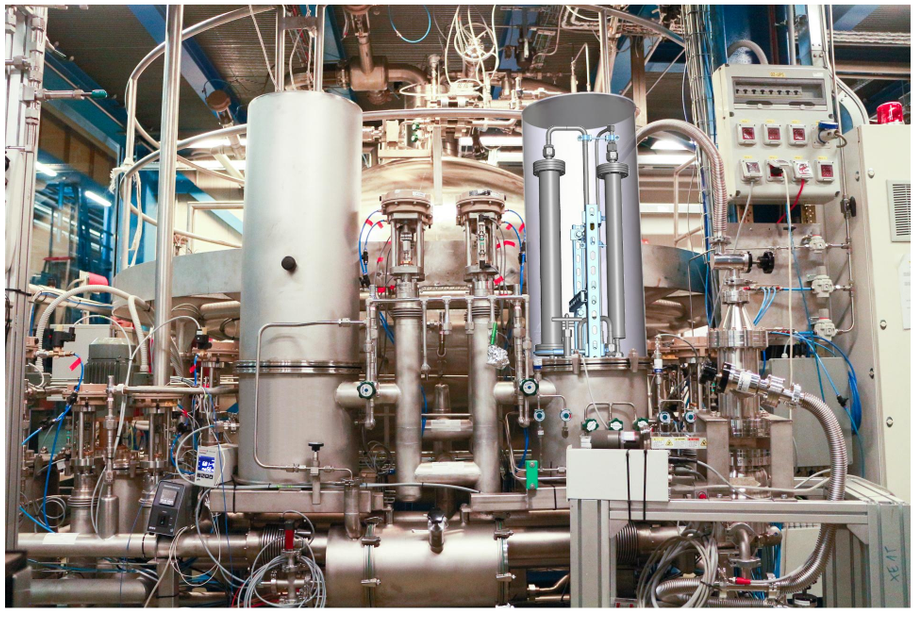
XENONnT: Status of Cryogenics and Purification

- Cryostat filled with ~8.6 t of LXe
  - 6 wks for cool down and filling through gas purifiers (high temperature getters)
  - Started LXe circulation and electron lifetime measurements with dedicated purity monitor
- Initial purification of LXe volume with GXe purification system @ 60 slpm
- Cryogenic LXe purification
  - Started with a high-efficiency O_2 filter (copper on alumina support)
  - Electron lifetime went from 100 us to 5 ms in 5 days!
  - Continuous improvement with decrease in outgassing
  - Reached >10 ms after ~1 month of operation



- Switch to O_2 filter with ultra-low Rn emanation
  - Reached electron lifetime of >7 ms

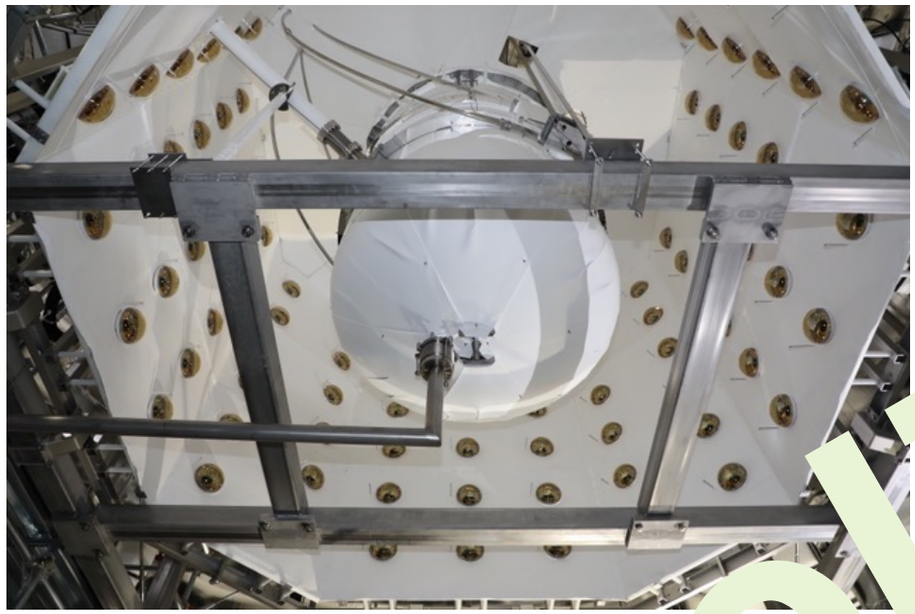


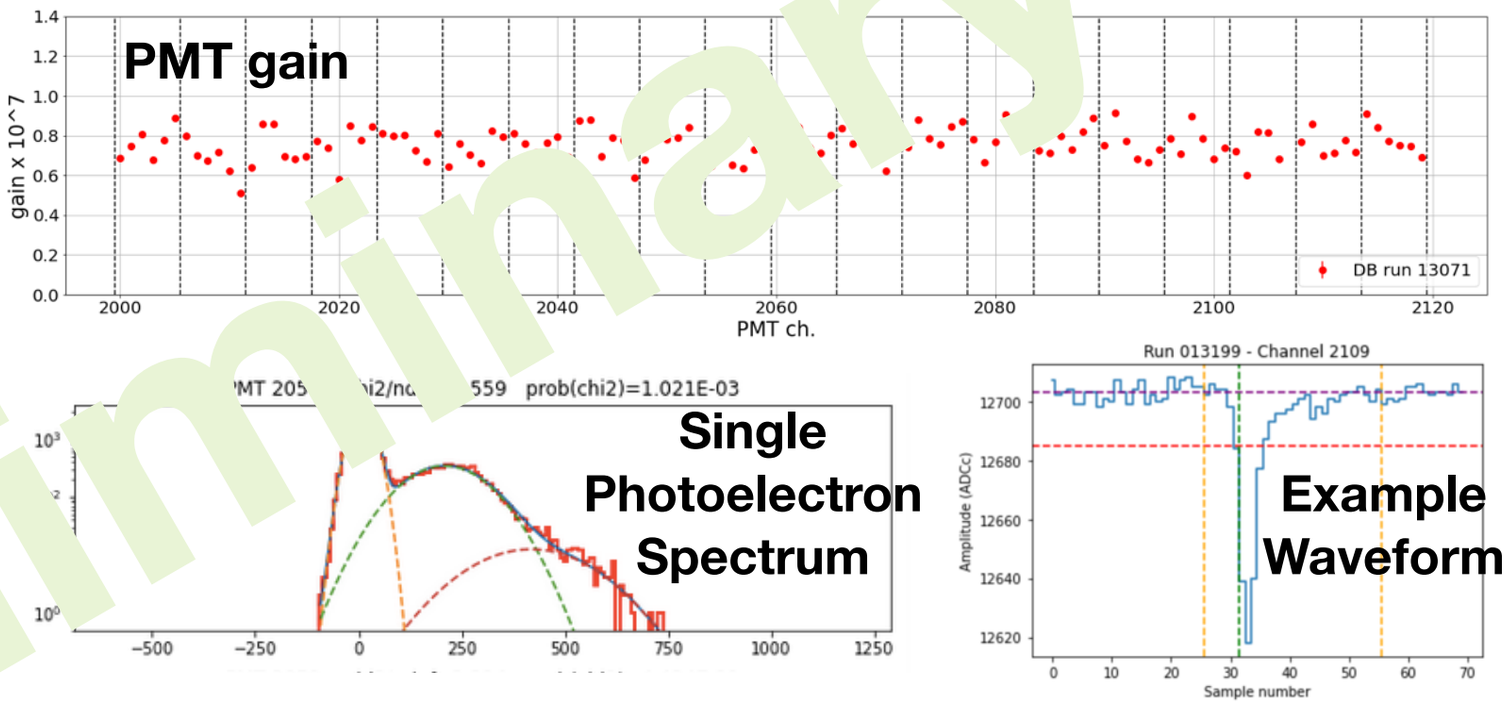


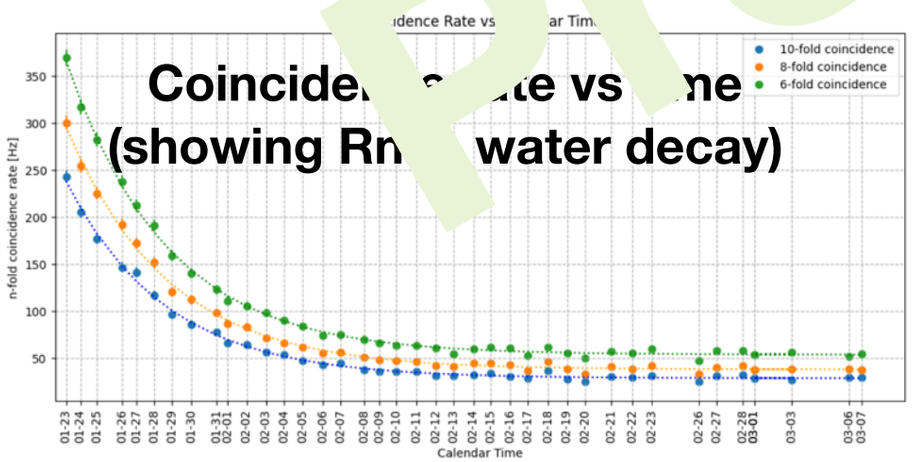
XENONnT: the next detector

Neutron veto

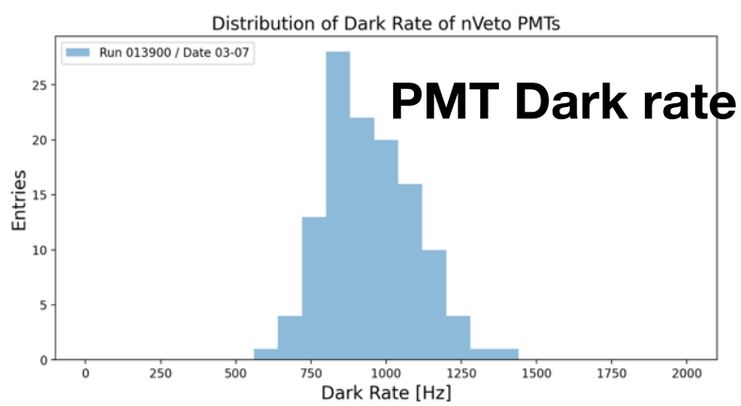
120 8” PMTs to detect Cerenkov light from n-capture, inside a high reflectivity volume around the cryostat.
Under commissioning since the tank has been filled with demi-water in De ember 2020.

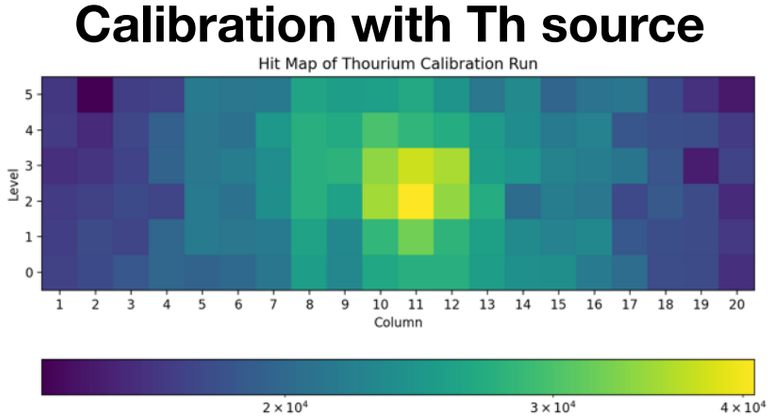






Coincide te vs me (showing Rn water decay)





XENONnT: the next detector

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

XENON

XENONnT radon removal system

Key performance parameter

- Basic concept proven:

EPJ C77 (2017) 358, arXiv:2009.13981

- Flow: 0.4 l/min LXe = 200 SLPM = 70 kg/h
- Radon reduction of factor 2 for type 1

sources for XENONnT (8.5 t LXe)

Cryogenic distillation column

- LXe inlet and outlet
- Cooling concept:

top condenser: LN_2/Xe heat exchanger

output liquefaction: Xe/Xe heat exchanger in reboiler (heat pump concept)

- Reflux ratio R = 0.5
- 45 m² packing material surface

Radon-free compressor

- 4 cylinder magnetically-coupled piston pumps

(EPJ C78 (2018) 604)

- Phase-shifted synchronized movement
- Flow: 200 slpm, ΔP: 2 bar
- Radon emanation: (0.30±0.05) mBq

Status of the system

- Thermodynamic stability successfully tested
- Radon removal ongoing using XENONnT as radon monitor
- Promising preliminary result – data coming soon

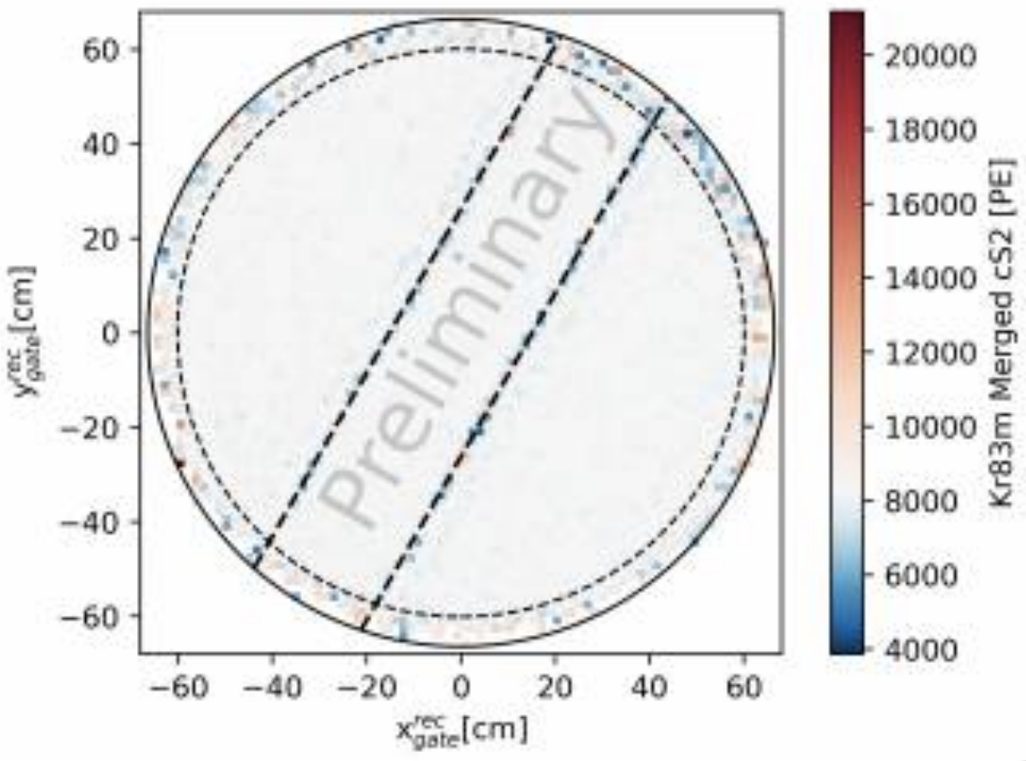
XENONnT: the next detector

Università degli Studi dell'Aquila

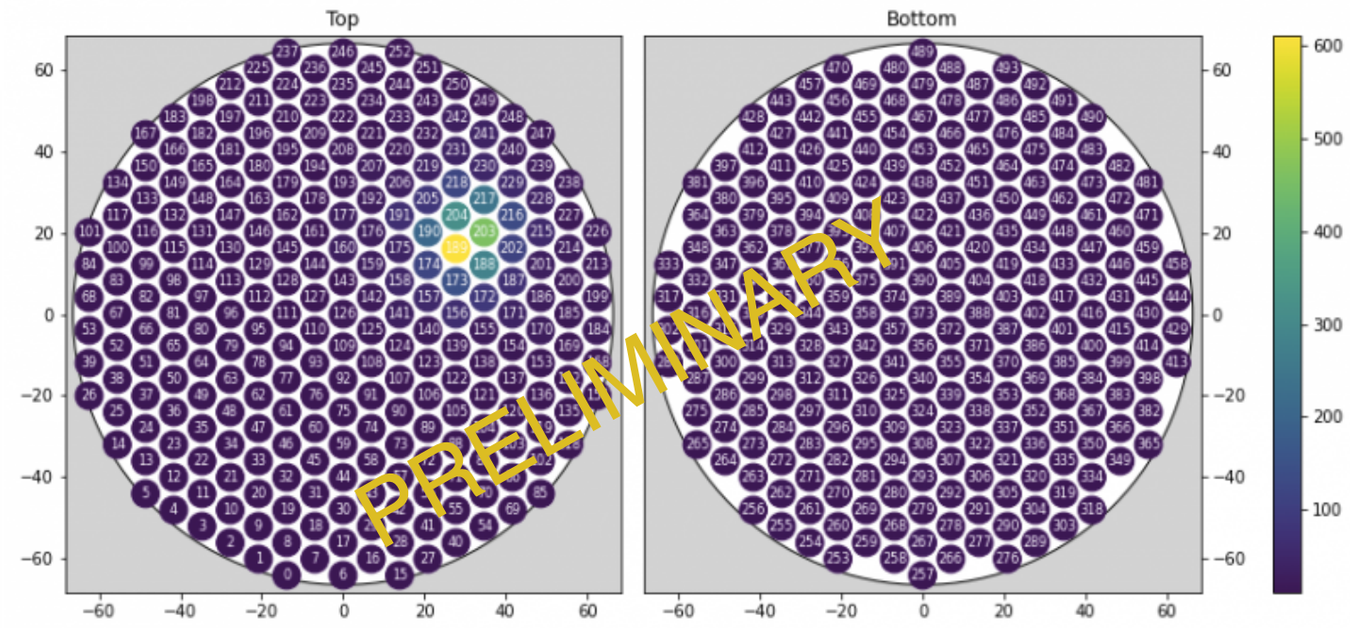
XENON

Commissioning data from XENONnT

- **The cS2_tot xy distribution from Kr83m events with the S2s from 32.1keV and 9.4keV decays merged**



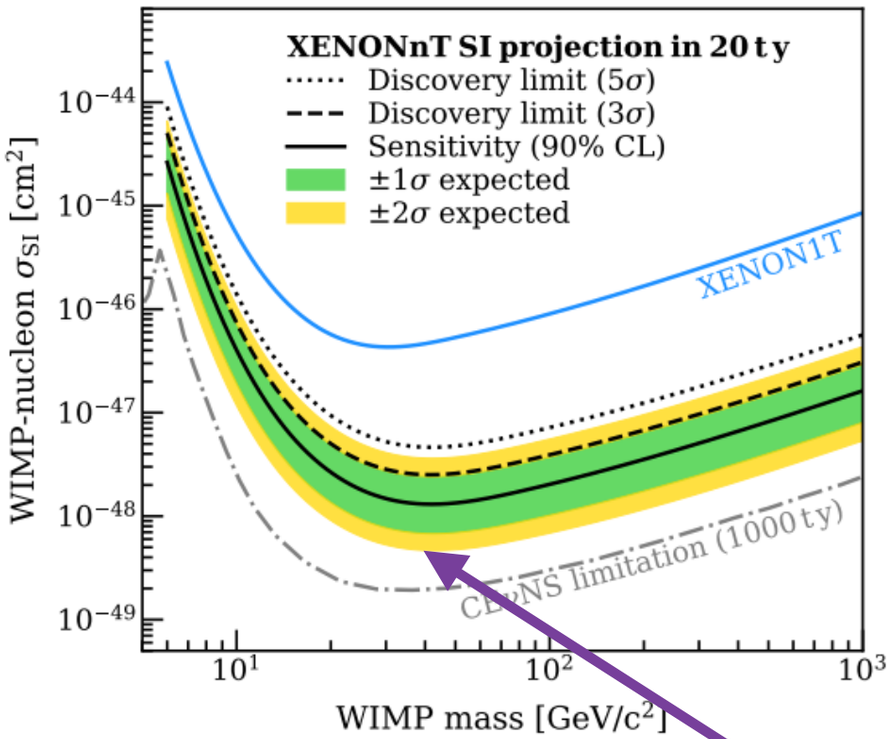
- **Sum waveform and S2 hitpattern of a krypton calibration event**

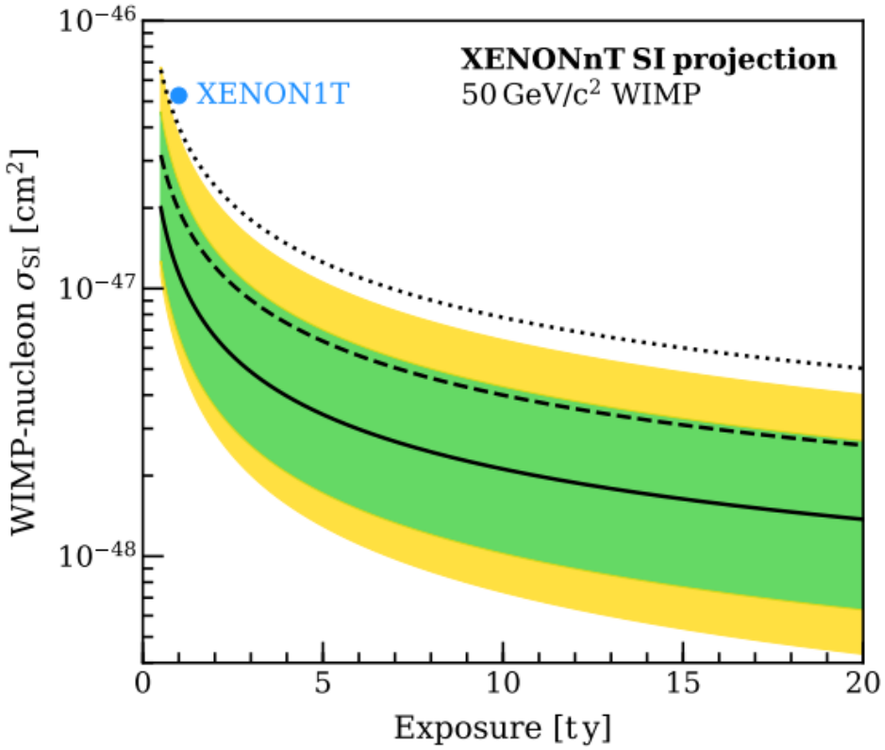


Study of commissioning data is ongoing

XENONnT: the next detector

Sensitivity





The XENONnT sensitivity paper: JCAP 11 (2020) 031
arXiv:2007.08796

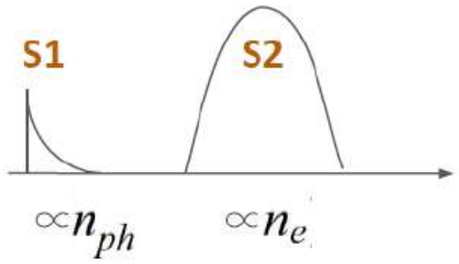
Detect this dark matter by 2025!

- **XENONnT TPC + neutron veto+Purification and Distillation systems installed and operational**
- **Commissioning data currently available**
- **First science run soon!**

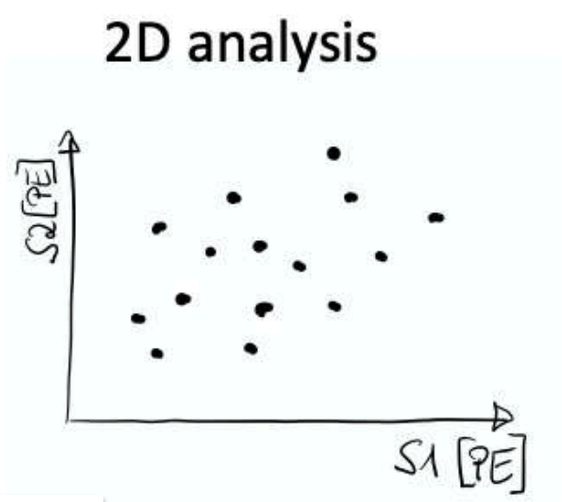
Backup

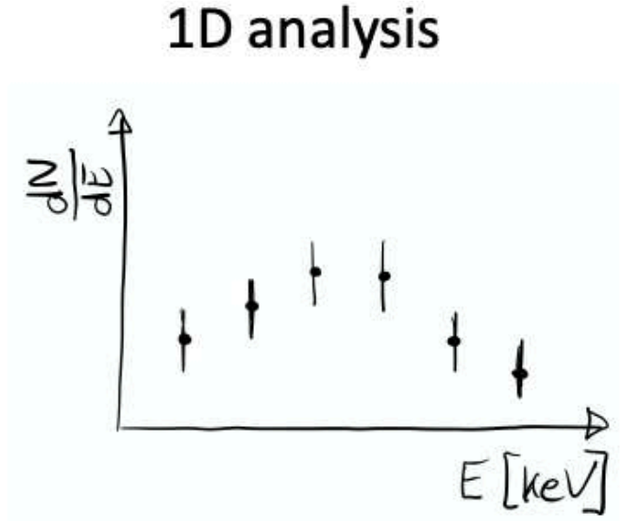
Energy calibration

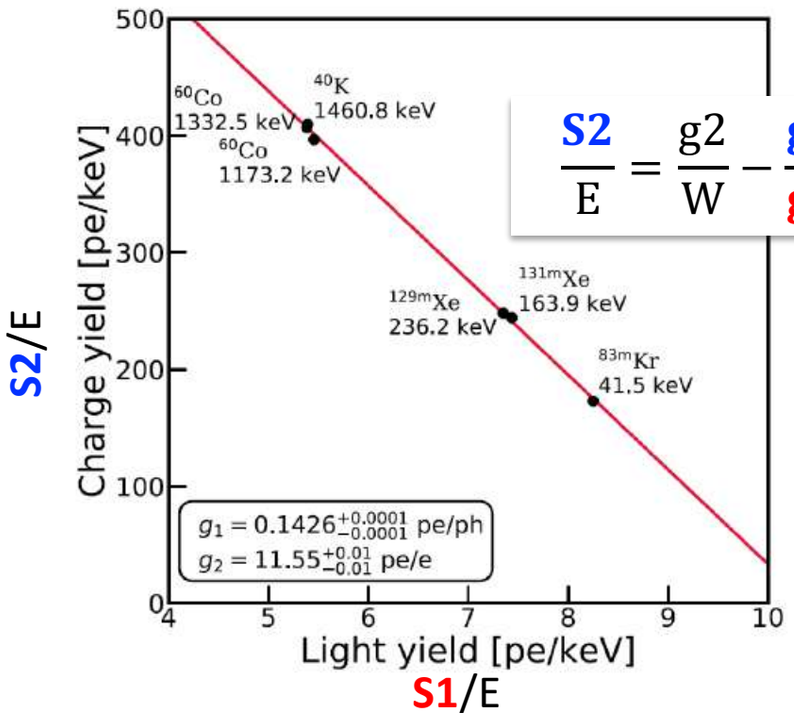
Energy reconstruction



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







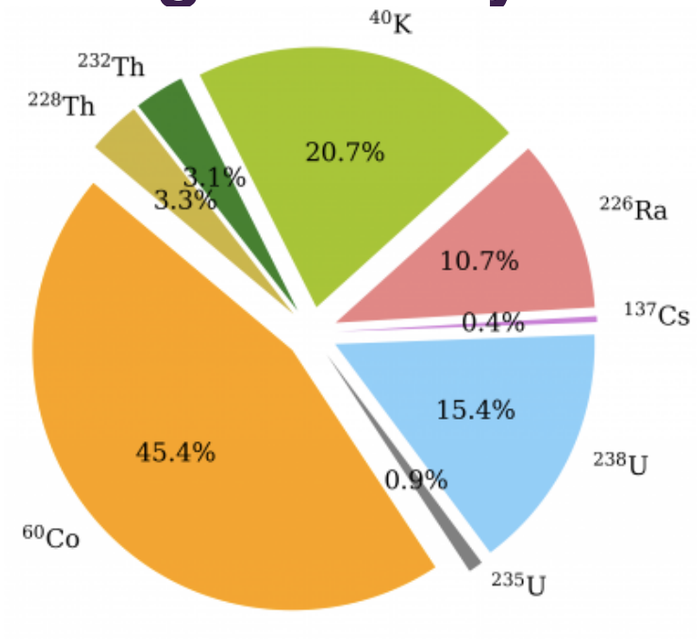
$$\frac{\mathbf{S2}}{\mathrm{E}} = \frac{\mathrm{g2}}{\mathrm{W}} - \frac{\mathbf{g2}}{\mathbf{g1}}\frac{\mathbf{S1}}{\mathrm{E}}$$

- **2D analysis** : use of both **S1** and **S2** signals
- Determination of scintillation (**g1**) and ionization (**g2**) gains with calibration data

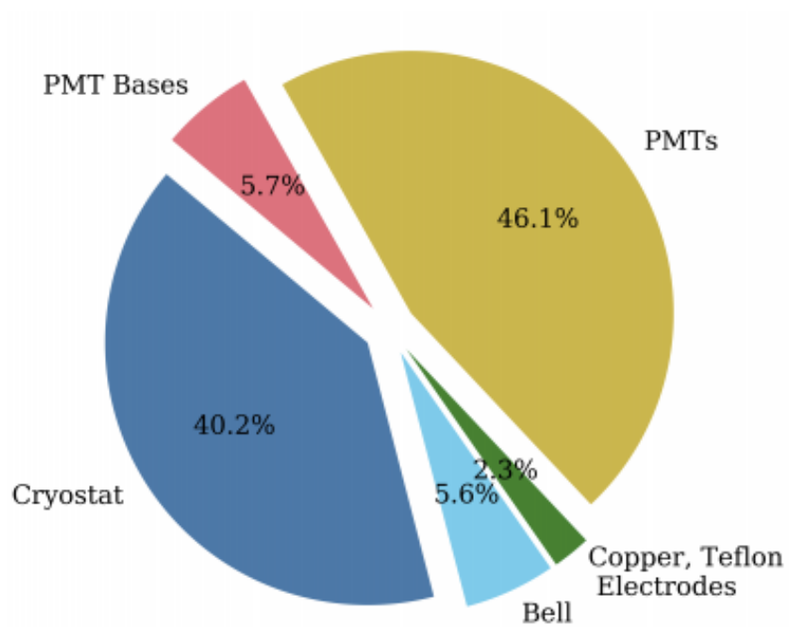
→ **1D analysis** : **Combined energy scale as analysis space**

Background

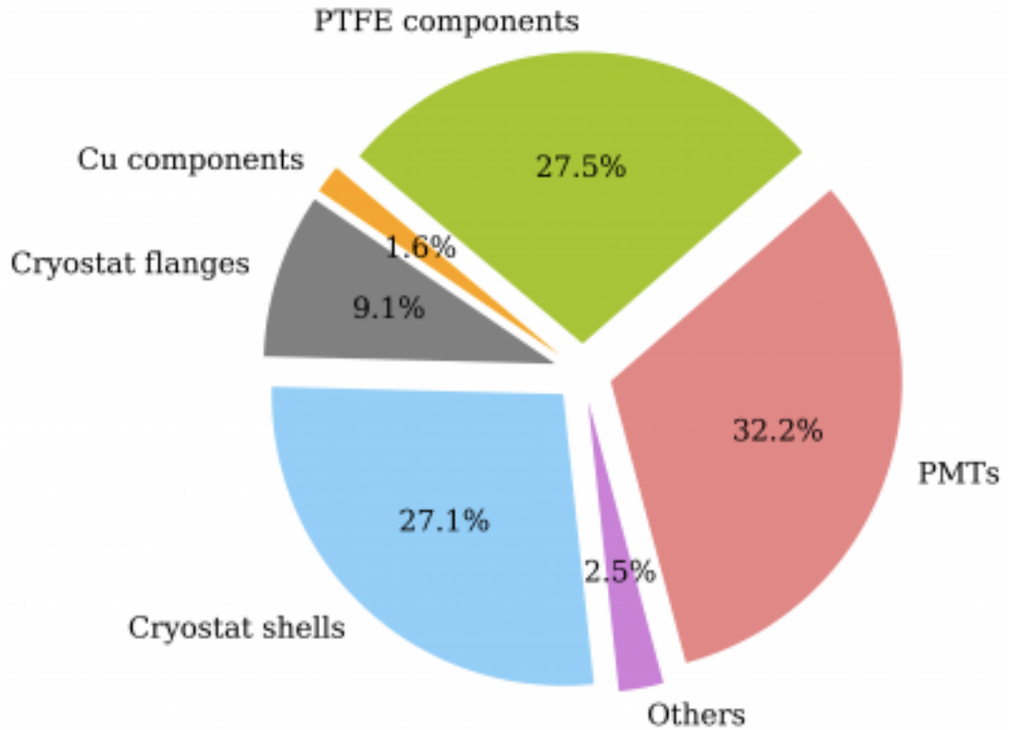
ER background by isotope



ER background by material

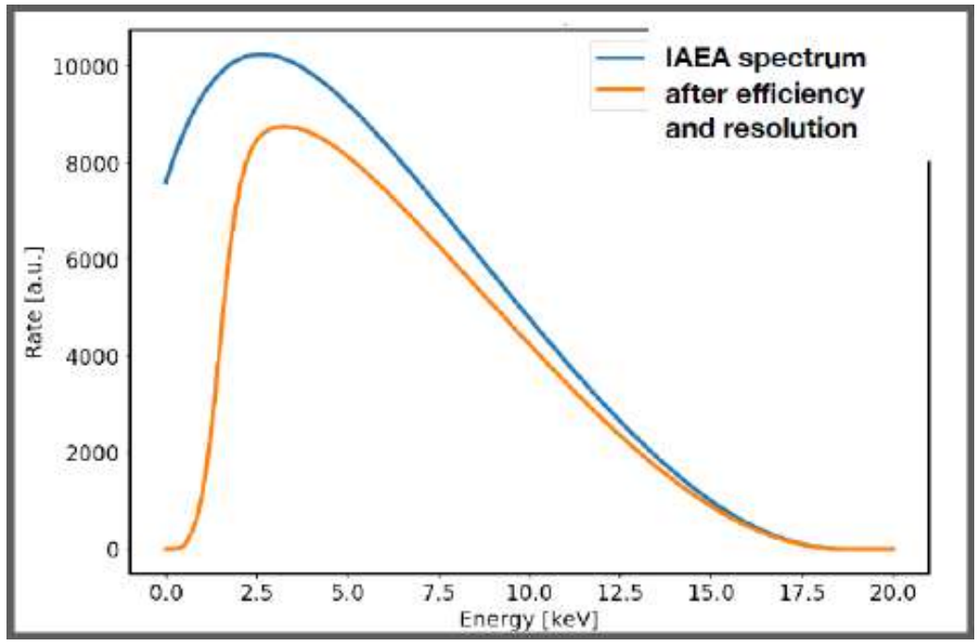


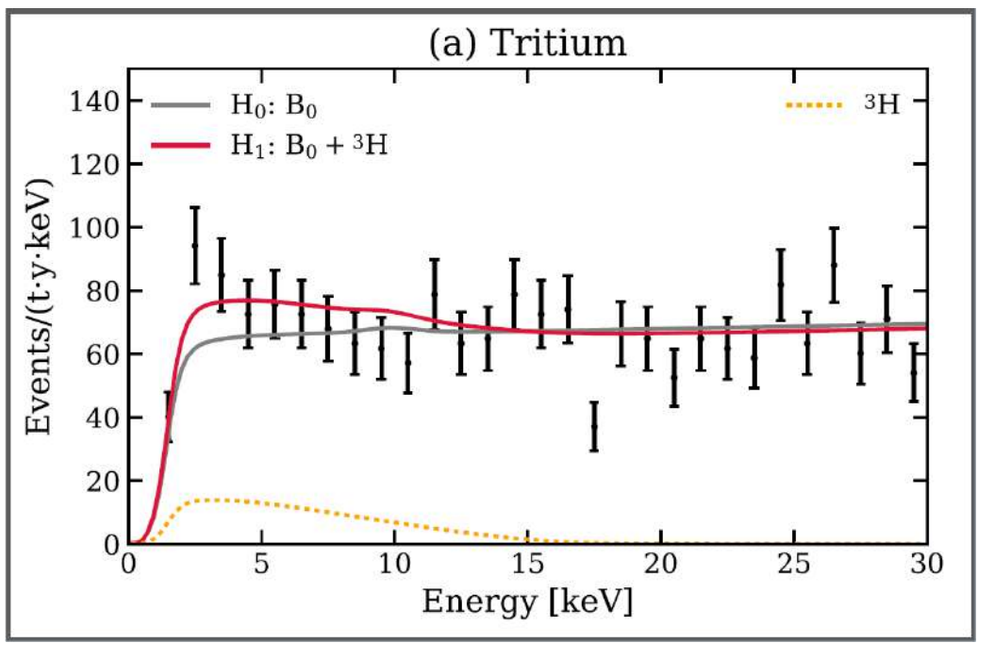
NR background by material



Low energy electron recoil excess

The Tritium hypothesis

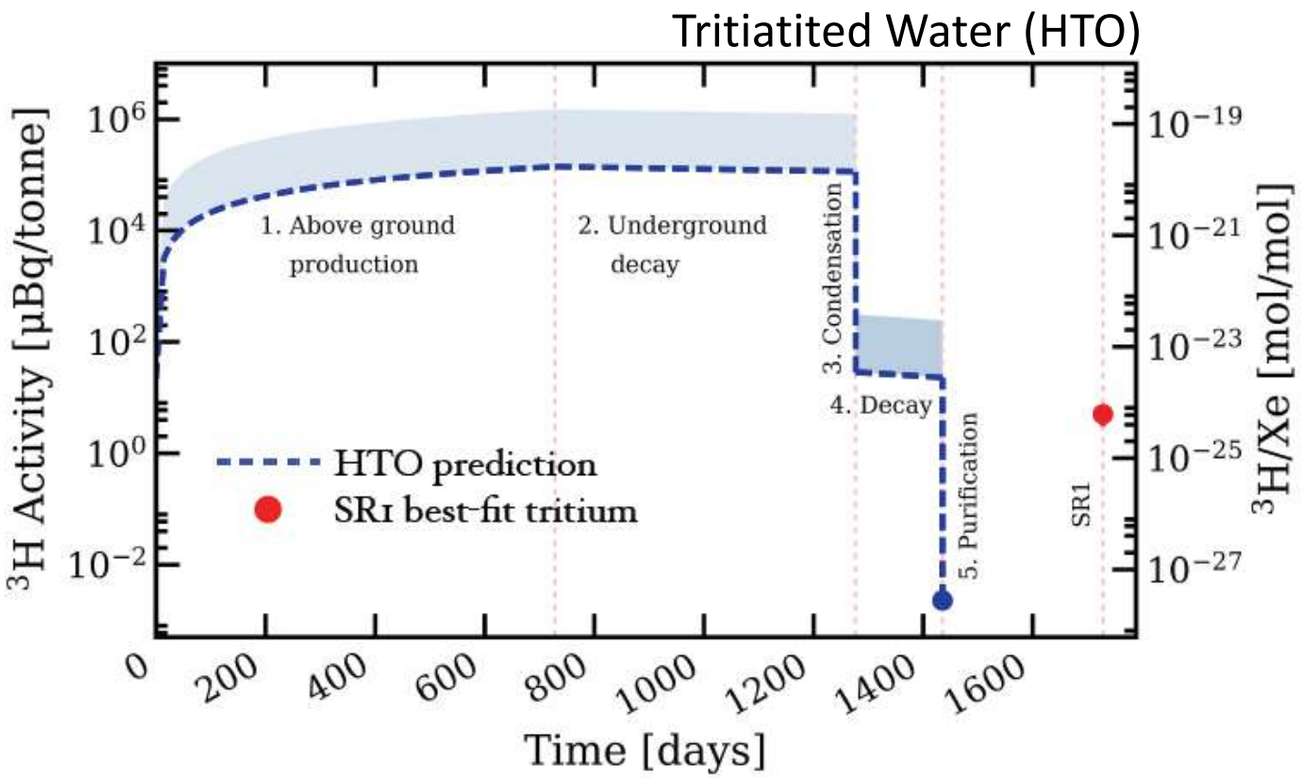




- **Long lived beta emitter (Q-value 18.6 keV, $t_{1/2}$=12.3 y)**
- **Cosmogenic activation of Xe or atmospheric abundance**
- **Favoured over background (B_0) at 3.2σ**
- **Best fit rate: (159 +/- 51) evts/(t*y*keV)**
- **^{3}H/Xe concentration: (6.2 +/- 2.0)*10^{-25} mol/mol**
- **3 tritium atoms per kg of Xenon**

Low energy electron recoil excess

The Tritium hypothesis



Very unlikely to explain the excess with the tritium hypothesis: predicted rate x100 lower

1. **Xenon gas stored above ground (32 tritium atoms/(kg day)) 1ppm of water implies formation of HTO**

2. **Xenon gas moved underground and decay**

3. **Xenon into the ReStoX storage vessel: ~x4000 reduction as water condenses and remains on the vessel walls**

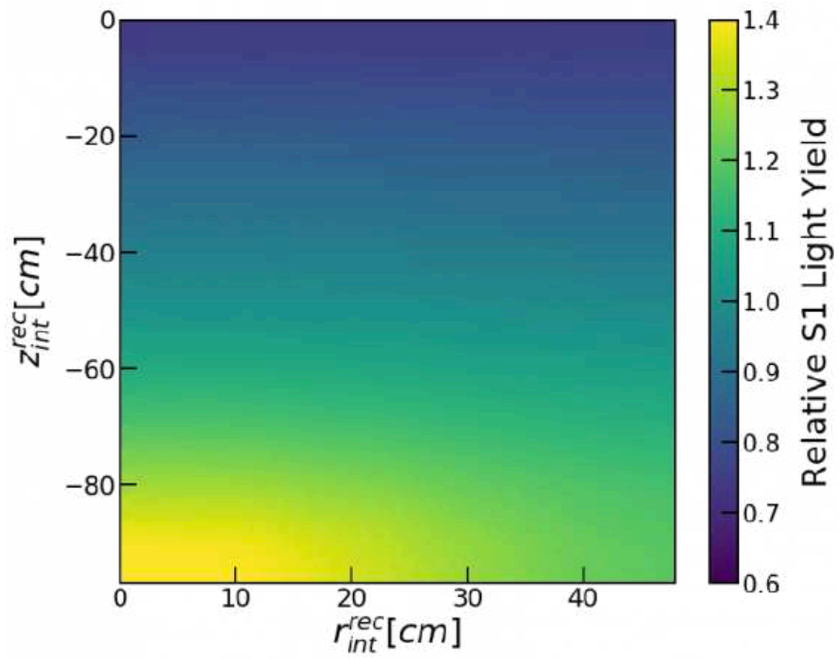
4. **Further decay until detector filling**

5. **When filling the detector Xenon is efficiently purified (99.99%) in dedicated hydrogen removal unit**

Low energy electron recoil excess

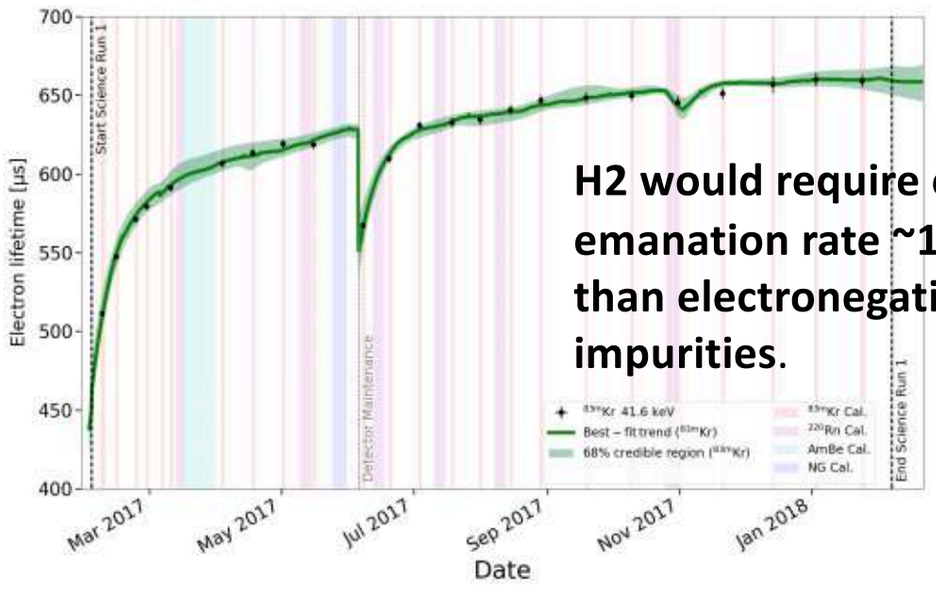
The Tritium hypothesis

HTO:H2O concentration (or HT:H2) = (5-10)*10^{-8} mol/mol
Required concentration to explain the excess = 60-120 ppb



TRITIATED WATER (HTO)

From the light yield one derives O(1) ppb H2O:Xe
too low



H2 would require equilibrium emanation rate ~100x higher than electronegative impurities.

TRITIATED HYDROGEN (HT)

From the electron lifetime one derives < 1 ppb O_2-equivalent impurities
?