Xe
XENON
Dark Matter Project

The low energy electronic recoil excess in the XENON1T experiment

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on behalf of XENON Collaboration & X. Mougeot

Xe XENON Dark Matter Project

XENON Technical Meeting, May 12-14, 2020

XENON Collaboration: ~170 scientists

XENON Dark Matter Project

Columbia Nikhef Muenster KIT Stockholm Mainz MPIK, Heidelberg Freiburg

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Rice

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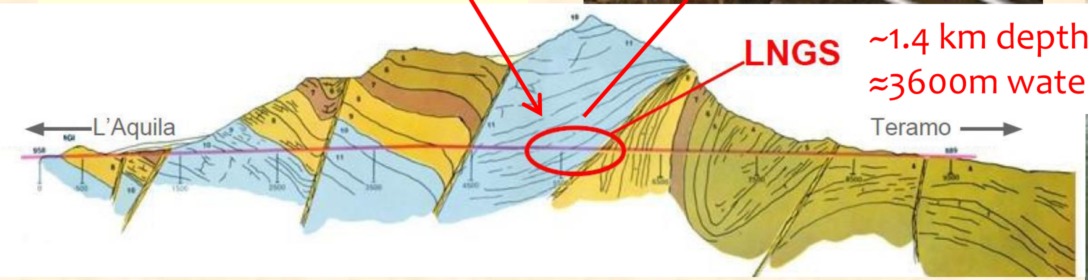
Purdue

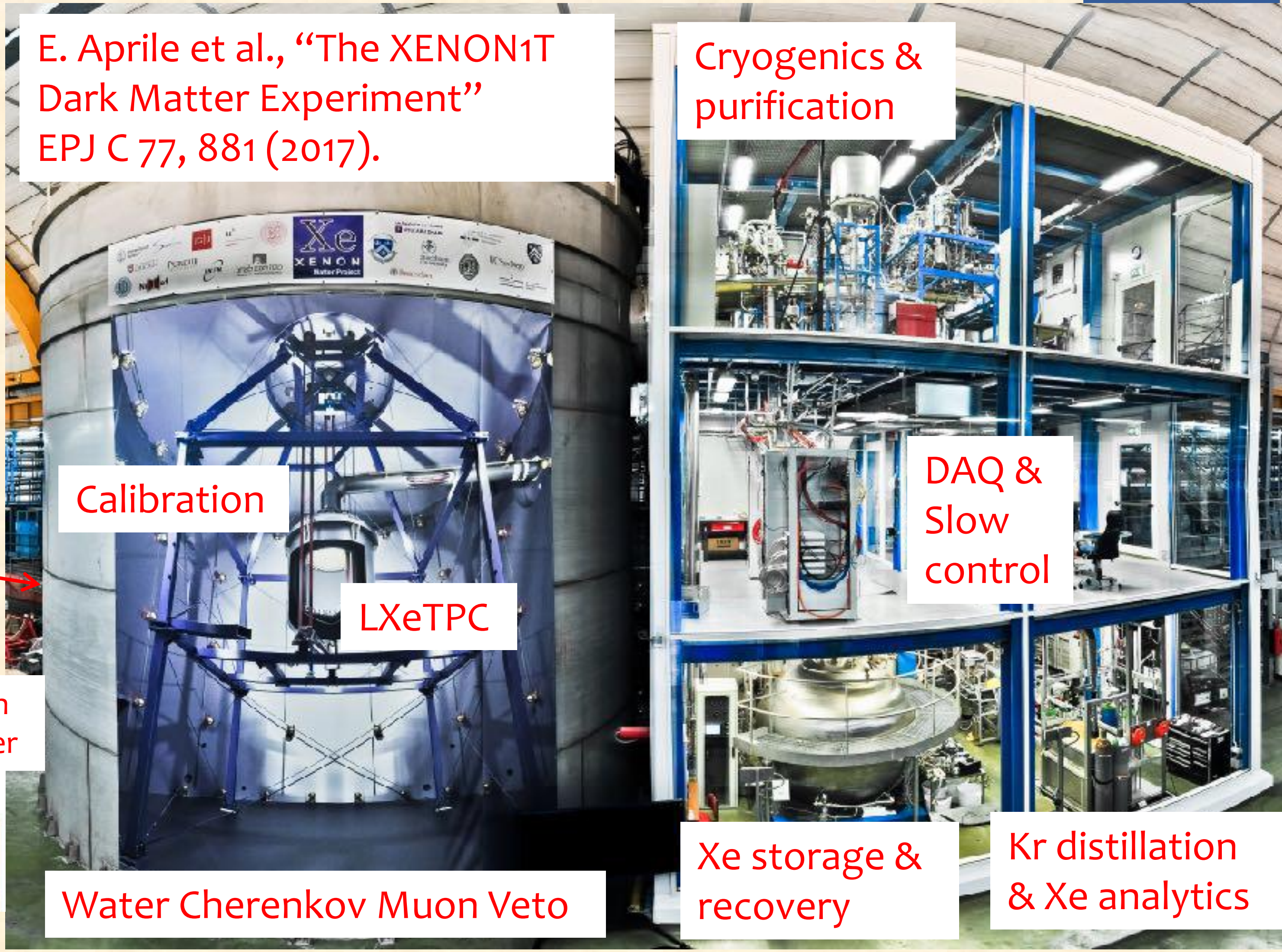
Coimbra Subatech LPNHE IJCLab L'Aquila Bologna LNGS Torino Napoli Weizmann NYUAD Kobe

The XENON1T detector at LNGS

The XENON1T detector searching for Dark Matter was operated in the underground Laboratori Nazionali del Gran Sasso in central Italy between 2015 and 2018



~1.4 km depth
≈3600m water



E. Aprile et al., “The XENON1T Dark Matter Experiment” EPJ C 77, 881 (2017).

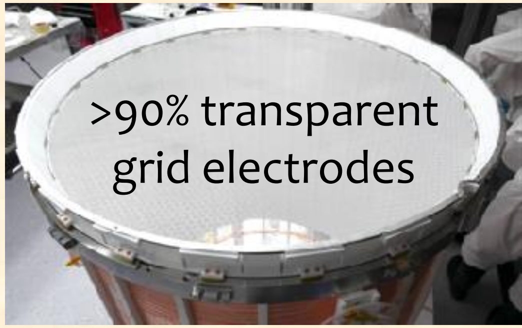
The Time Projection Chamber (LXe TPC)

~ 1 m diameter
~ 1 m drift length

2.0 t liquid xenon
(LXe) active mass

High reflectivity
PTFE

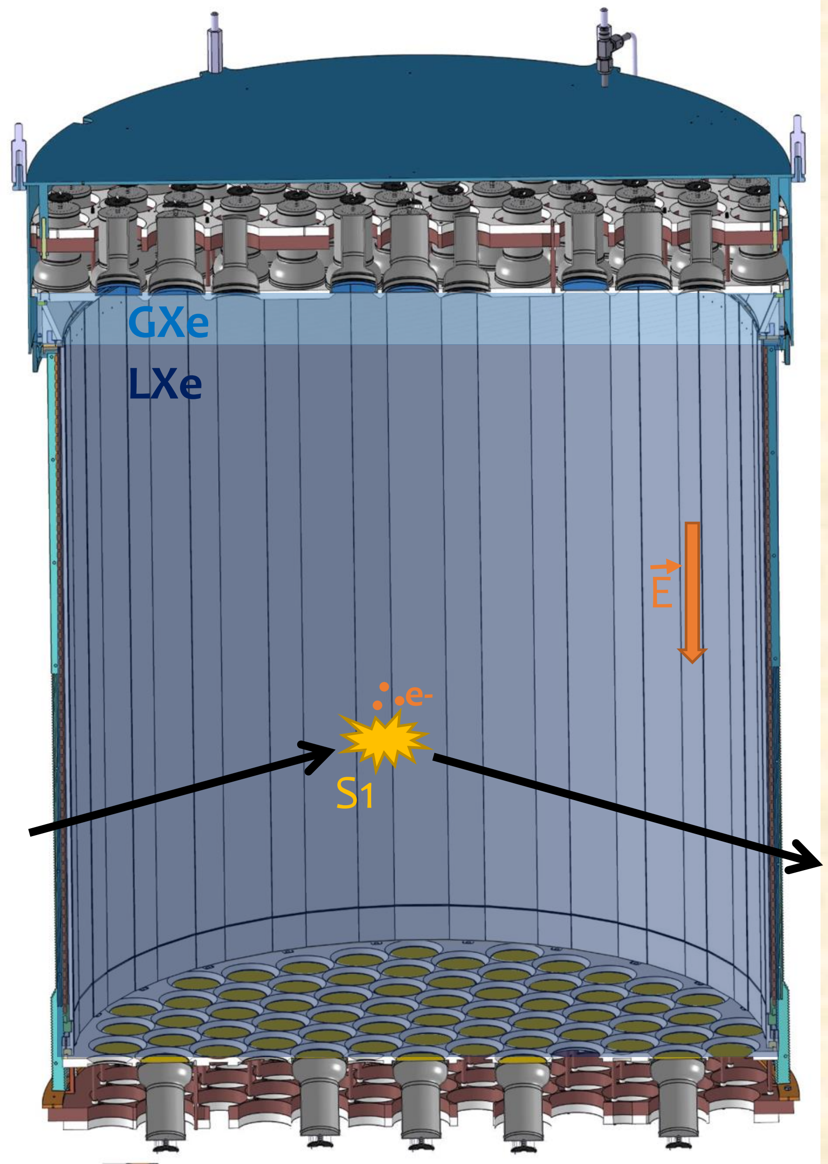
127 Top
PMTs



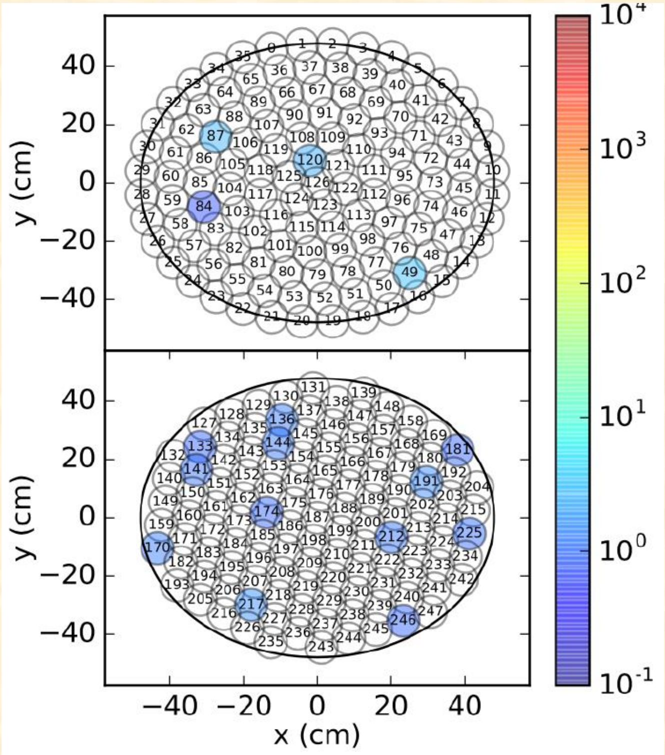
>90% transparent
grid electrodes

121 Top
PMTs

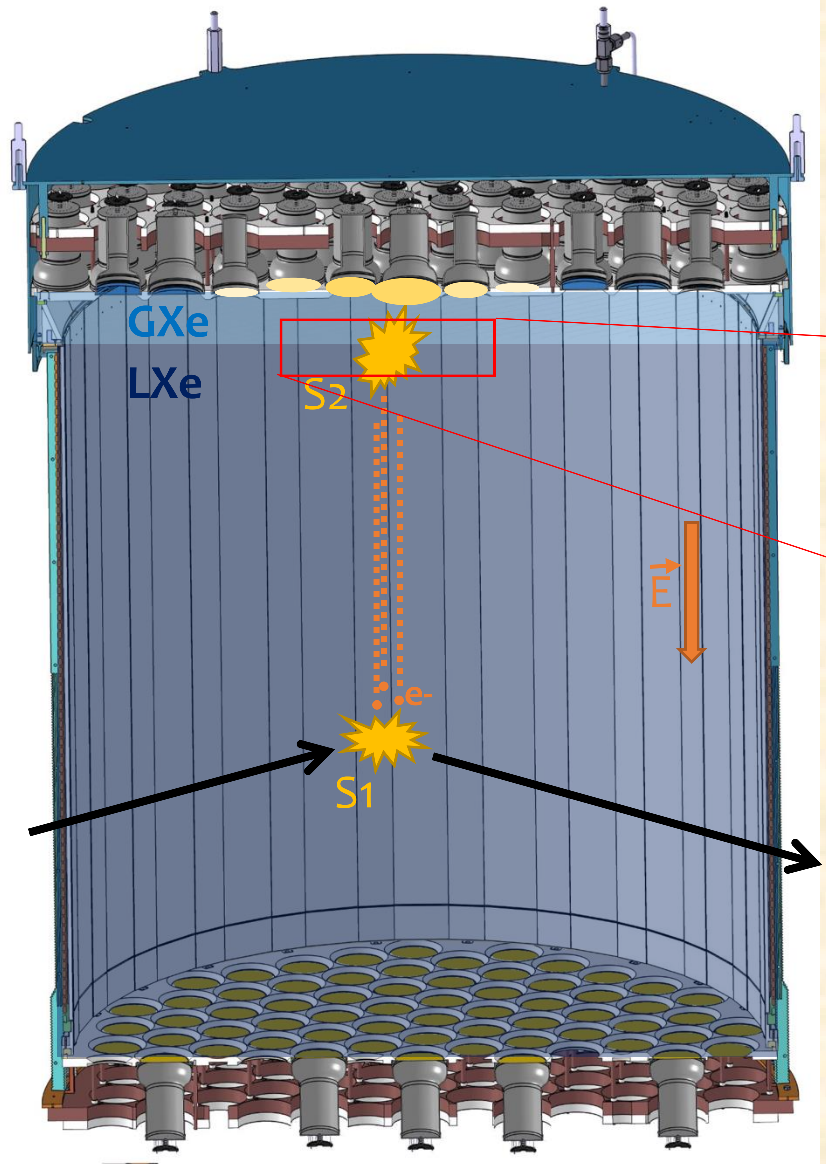
LXe TPC: principle of operation



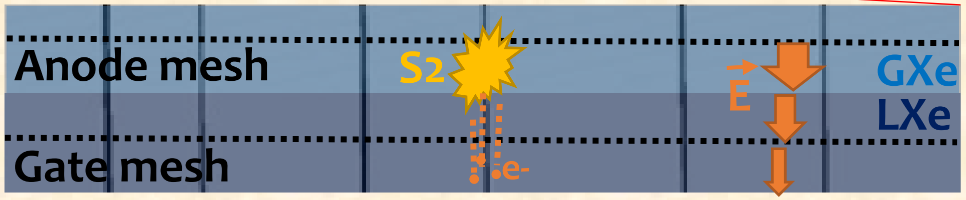
- Interaction in LXe produces prompt scintillation light (S1) and free electrons



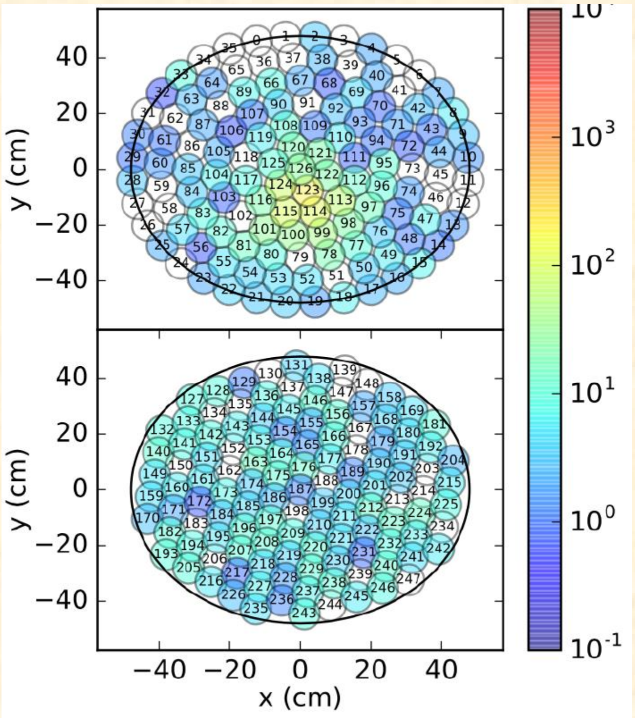
LXe TPC: principle of operation



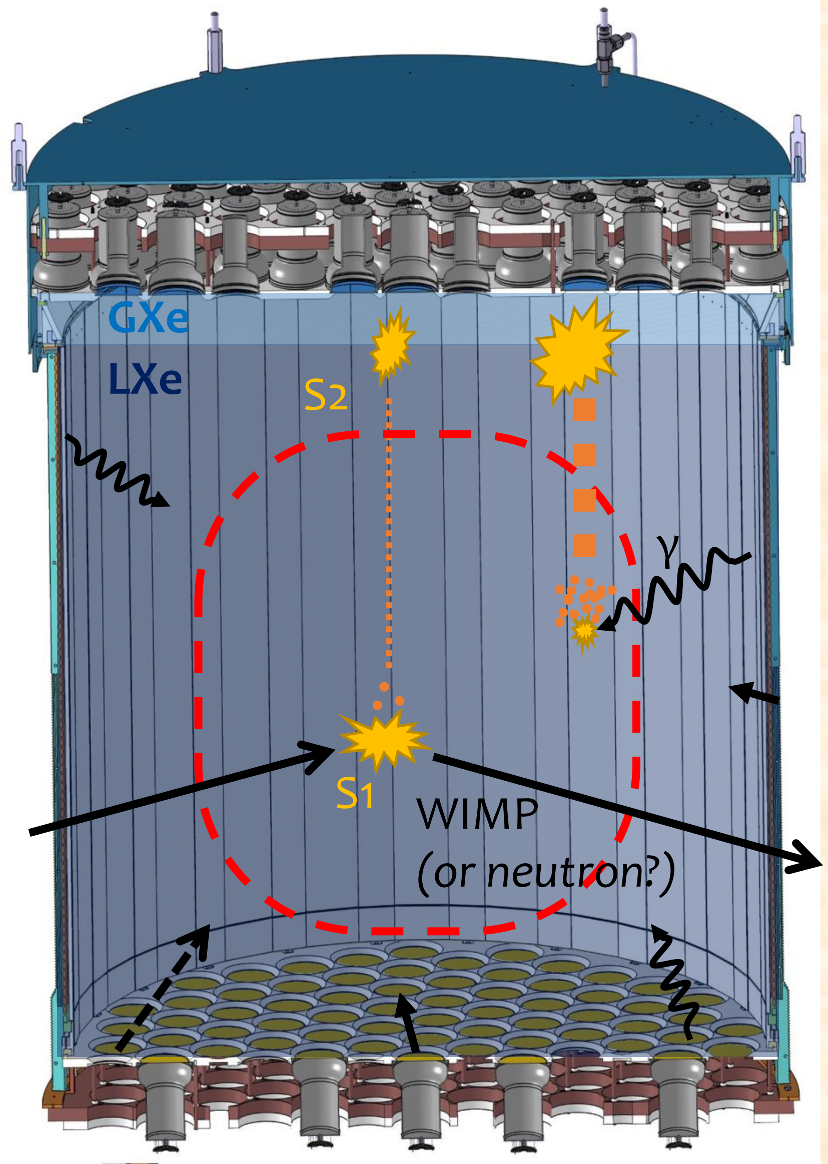
- Interaction in LXe produces prompt scintillation light (S1) and free electrons
- Electrons drifts towards the gas buffer, where they produce a delayed, proportional scintillation signal (S2)



- S2 distribution on top array provides the X-Y information of the interaction
- S2 delay from S1 provides Z information
  - Full 3D reconstruction of interaction point



LXe TPC: particle ID & background suppression



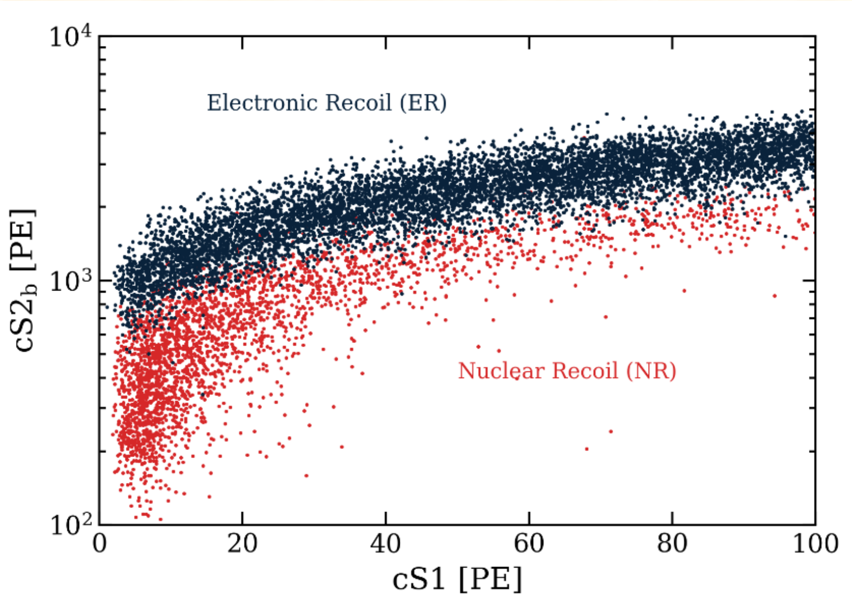
- S2 distribution on top array provides the X-Y information of the interaction
- S2 delay from S1 provides Z information

  ➡ Volume "fiducialisation"
  (Xe no long-lived unstable isotopes)

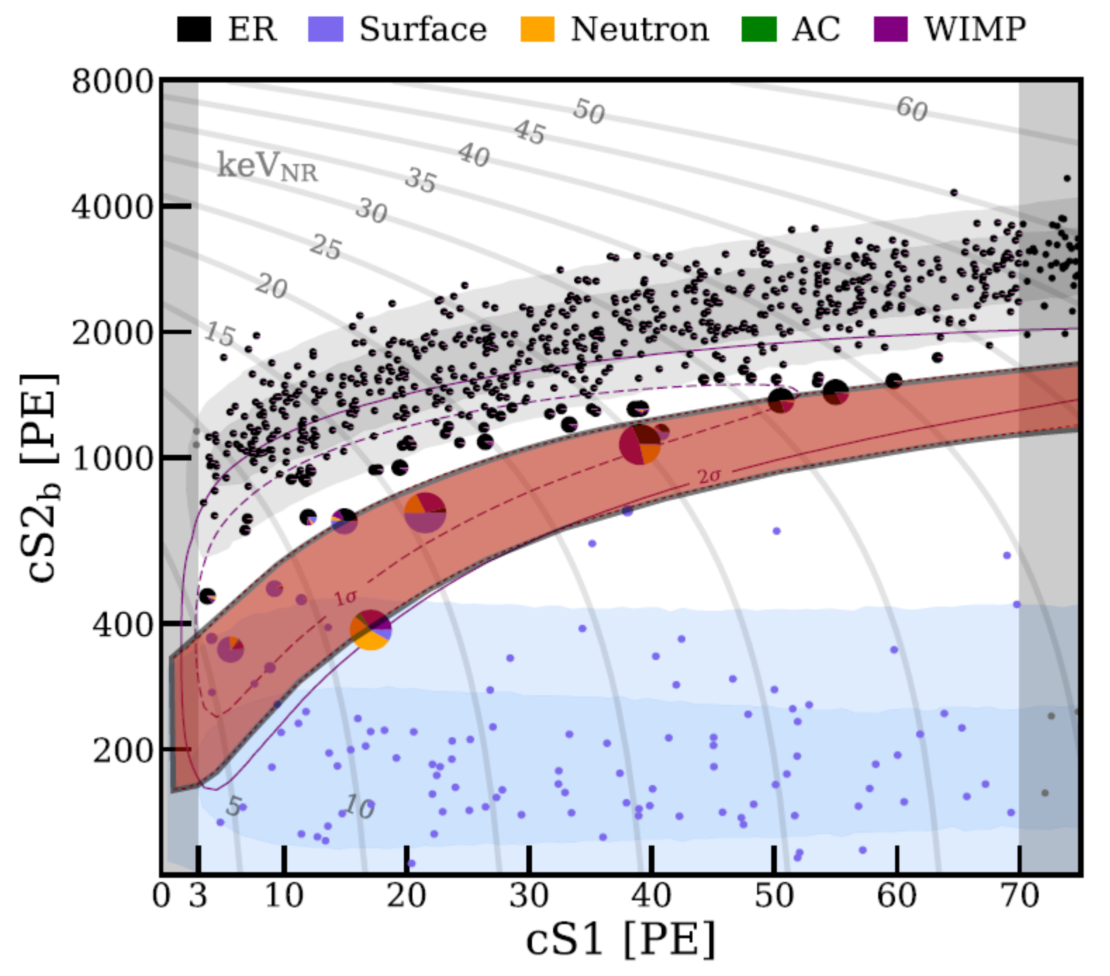
- The ratio S2/S1 provides particle ID (nuclear vs. electron recoil)

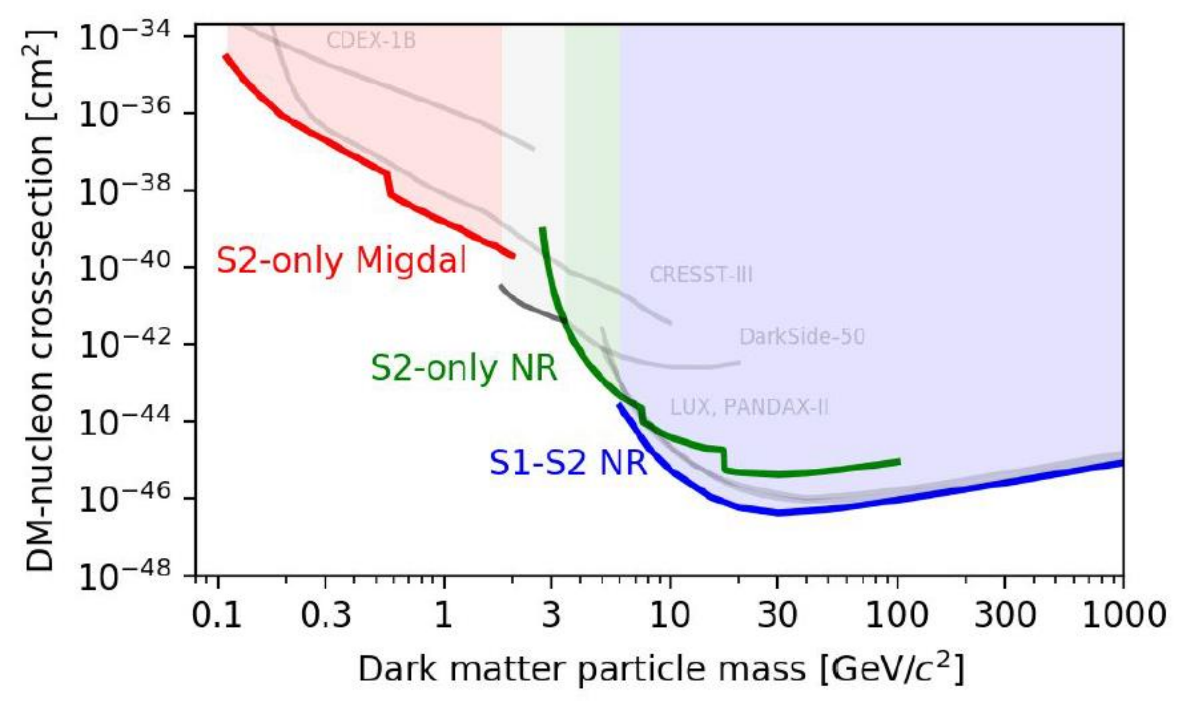
  ➡ WIMPs are searched among nuclear recoils
  (but also neutrons are there!)

(typical: >99.5% ER cut, keeping ~50% NR)



Nuclear recoils searches in XENON1T



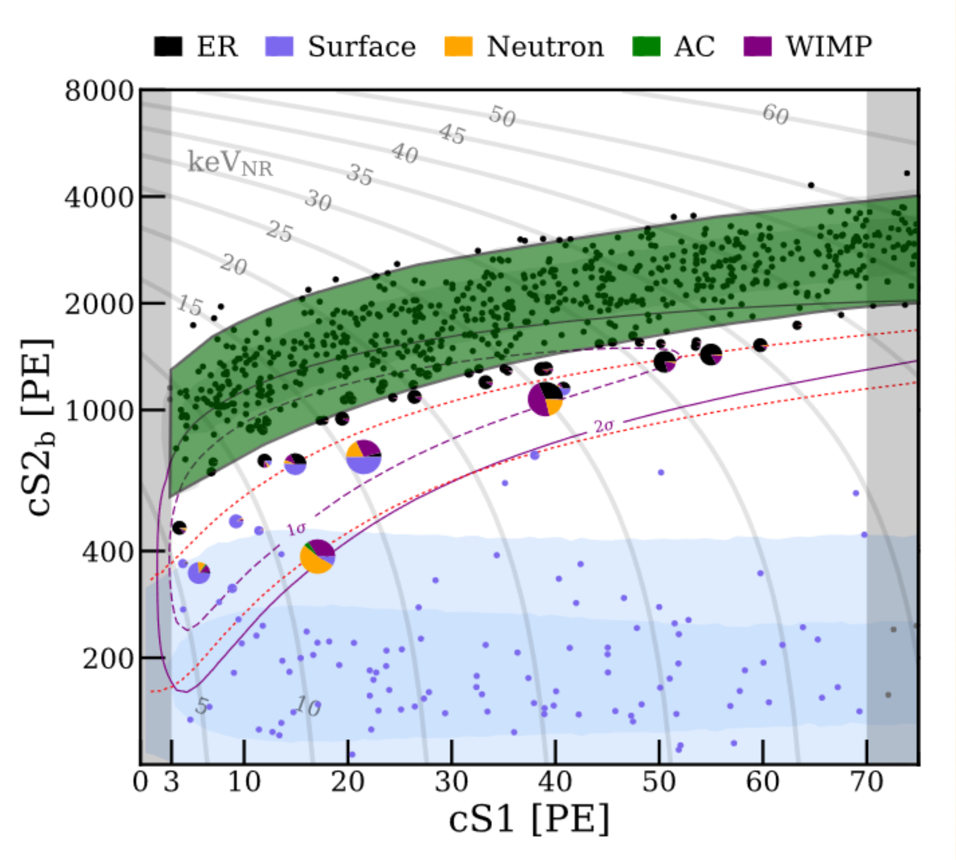


PRL 123, 241803 - Migdal effect

PRL 123, 251801 - Light dark matter

PRL 121, 111302 - Main WIMP search

But this talk will focus on electronic recoils



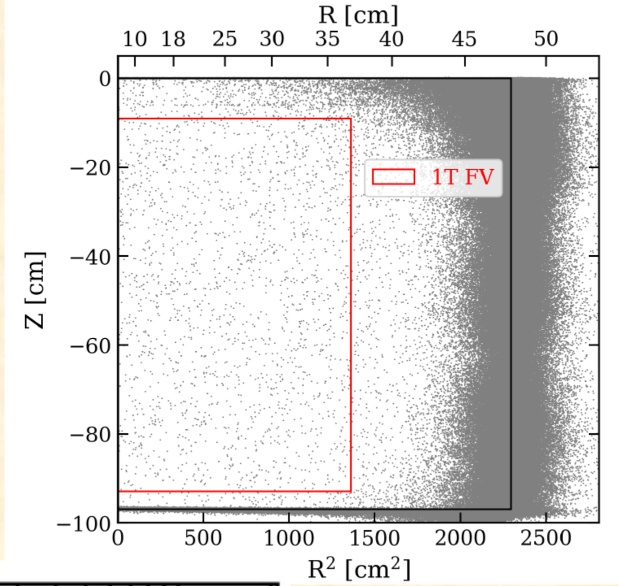
- Search for excess events over known background in XENON1T:
  - Low background in [1; 30] keV
    < 100 events / tonne / year / keV$_{ee}$
  - Low threshould
    ~ 1 keV$_{ee}$ (~5 keV$_{nr}$)
  - Large exposure
    ~ 1 tonne · year

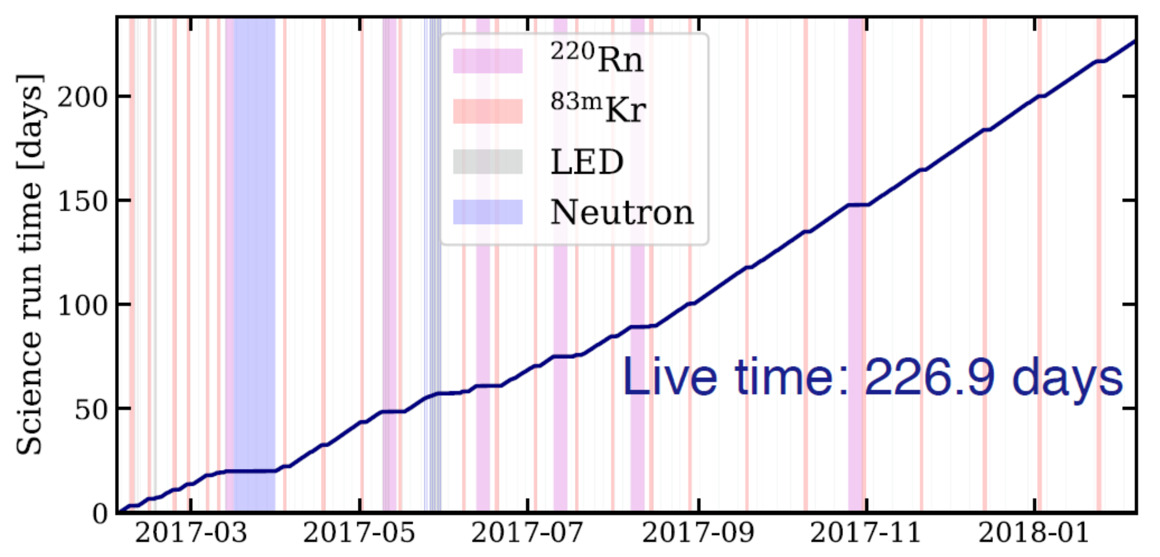
(Late) Outline of the talk

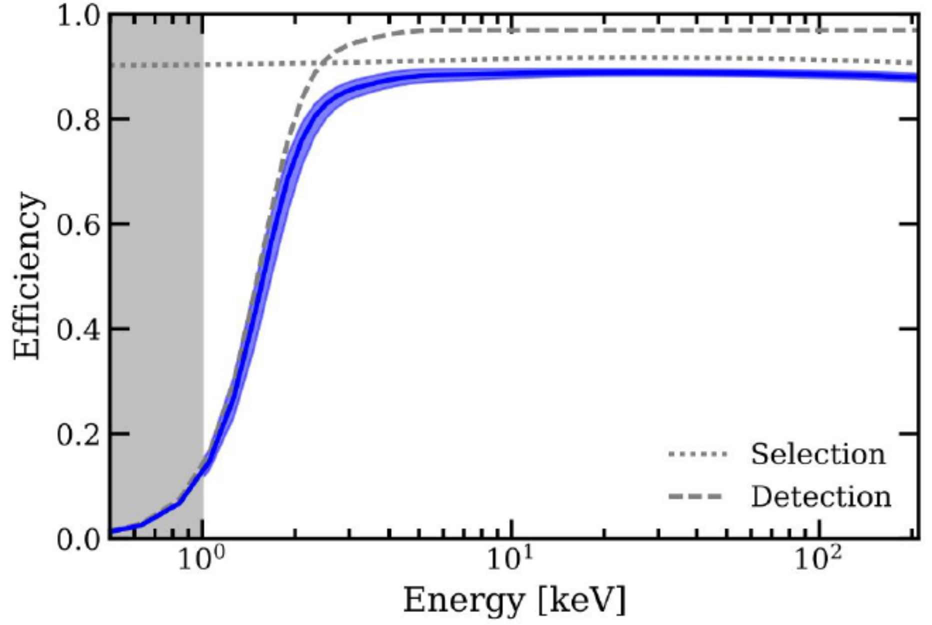
- **Who & Where?** Introduction on XENON1T and LXe Time Projection Chambers
- **What?** Excess electronic recoil events found over known background. Let's see:
  - Exposure, data analysis and energy reconstruction
  - Background model & excess below 7 keV
- **Sure?**
- **So?**
- **And then?**

Science Run 1 (SR1) exposure & data selection

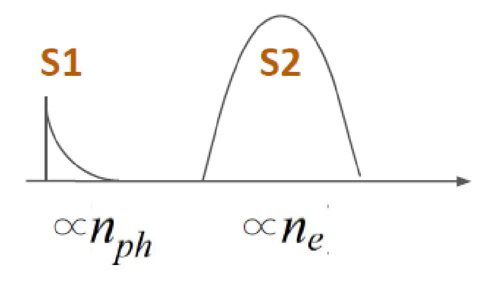
- Exposure 0.65 tonne year, 226.9 live days from Feb ‘18 to Feb ’19
- Single-scattering events within [1, 210] keV
- Same selections of published analyses, just higher S2 threshold
- Slightly smaller fiducial volume, 1 tonne cylinder
- Same methods for efficiency assessment



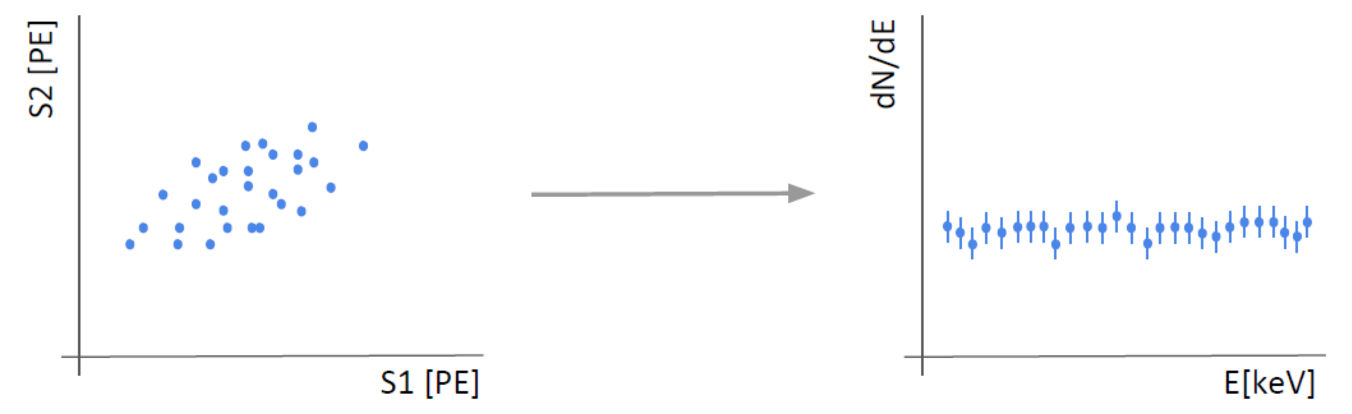




Energy reconstruction



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



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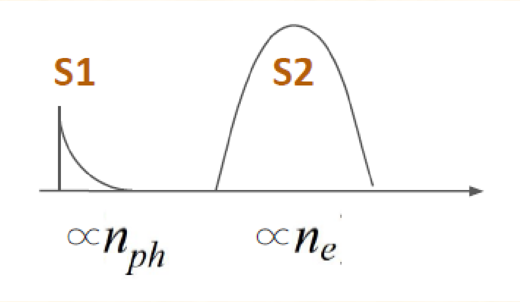

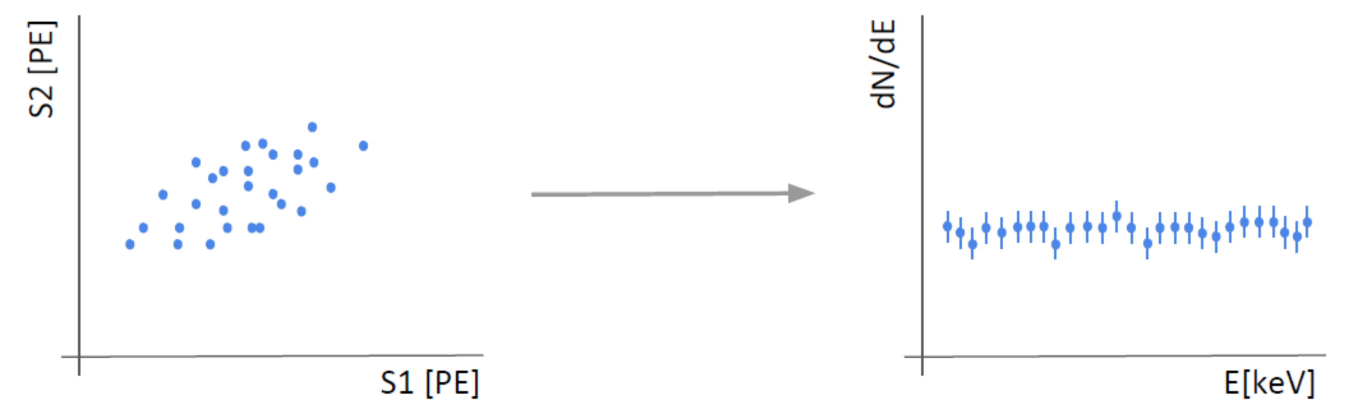

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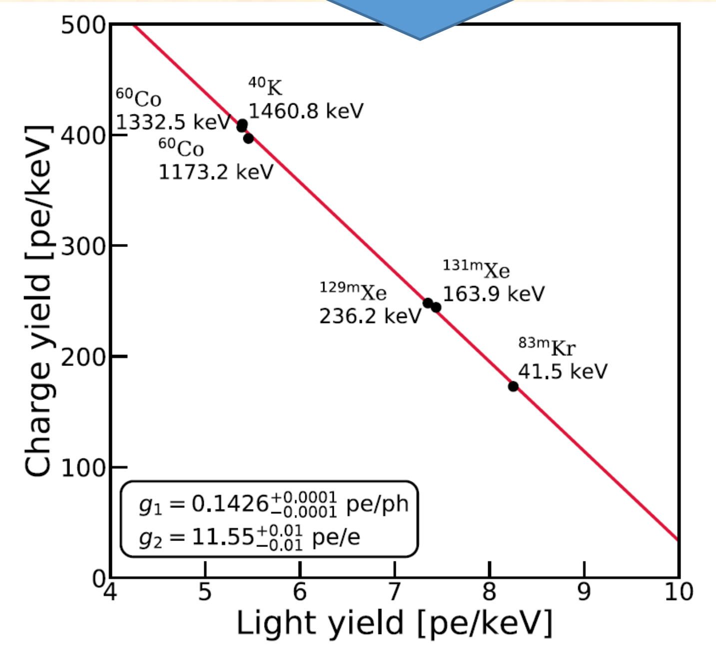
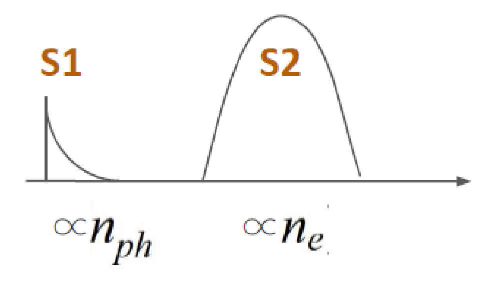


- g1 & g2 detector constants!

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

Energy reconstruction



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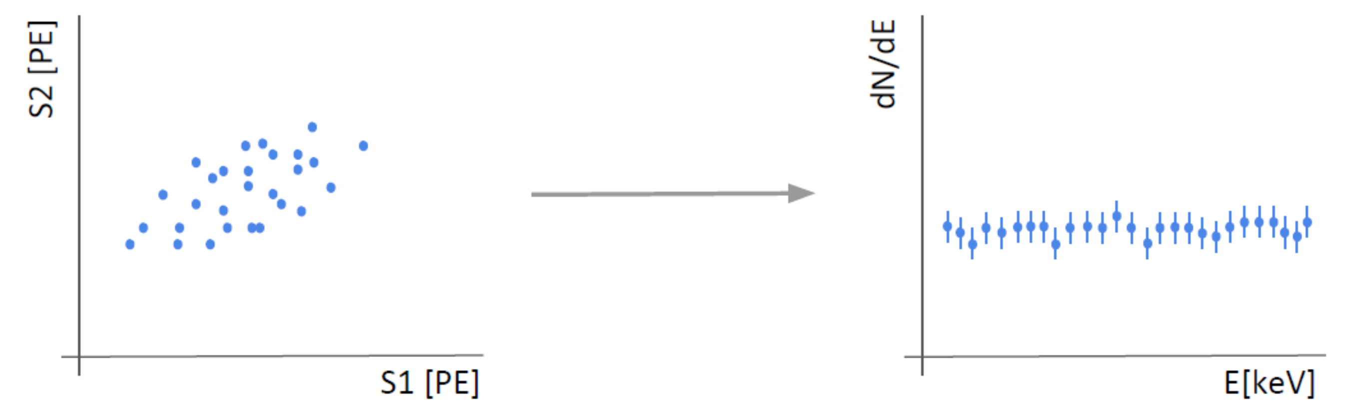

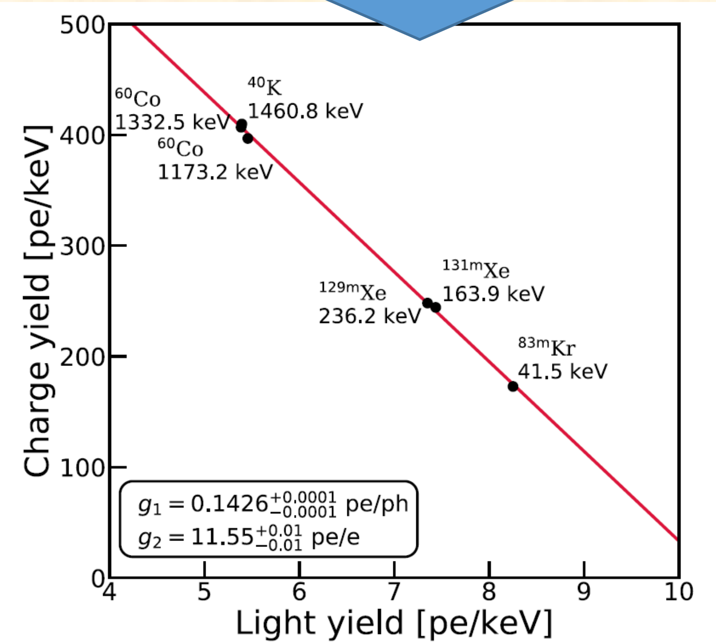

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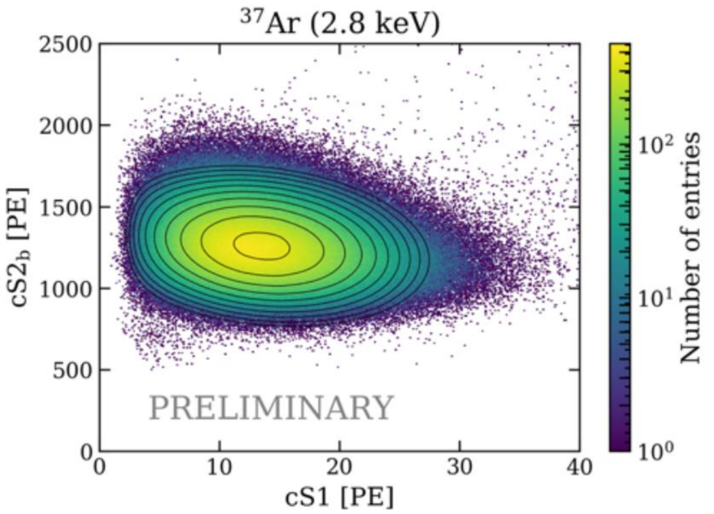
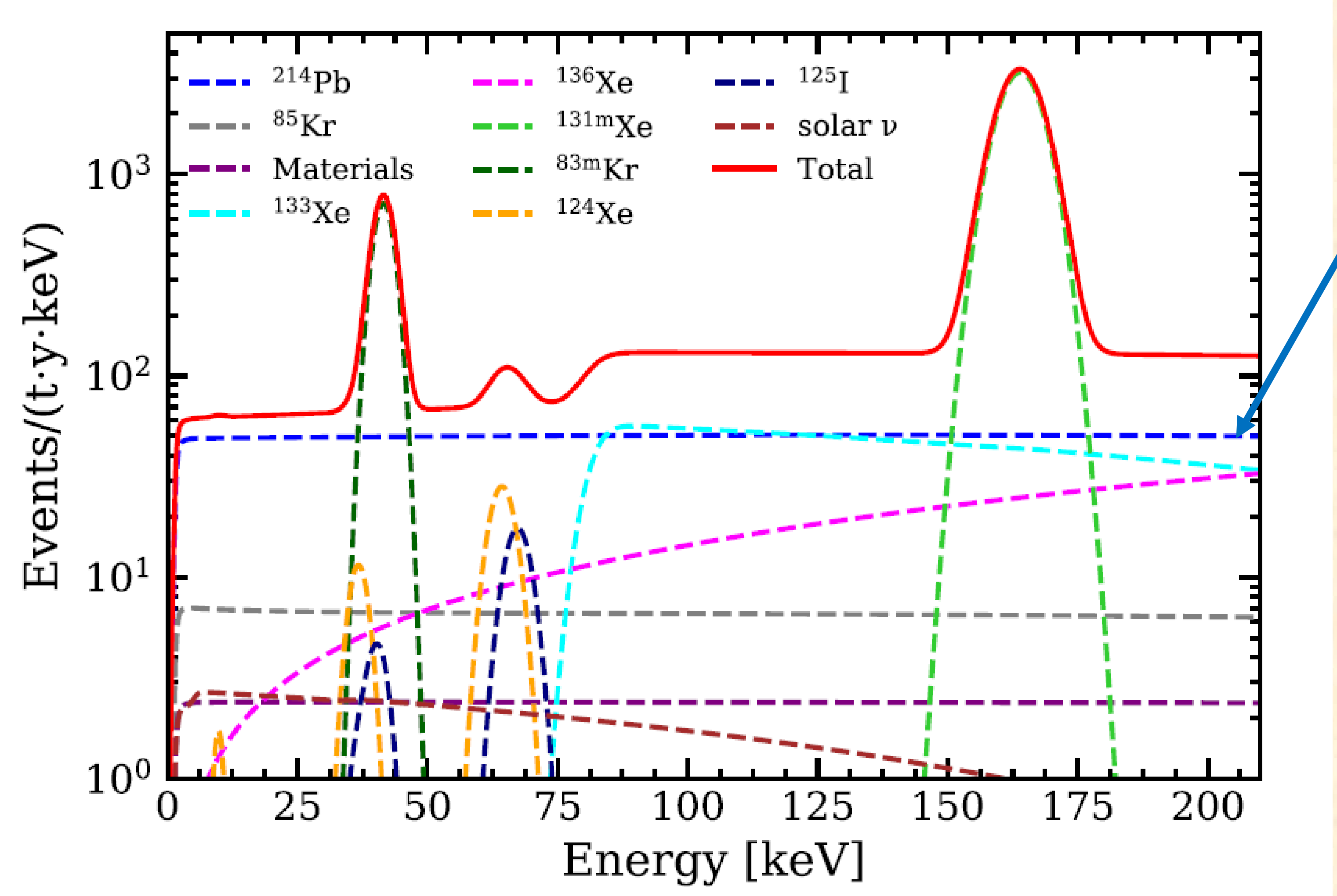


^{37}Ar calibration in Science Run 2

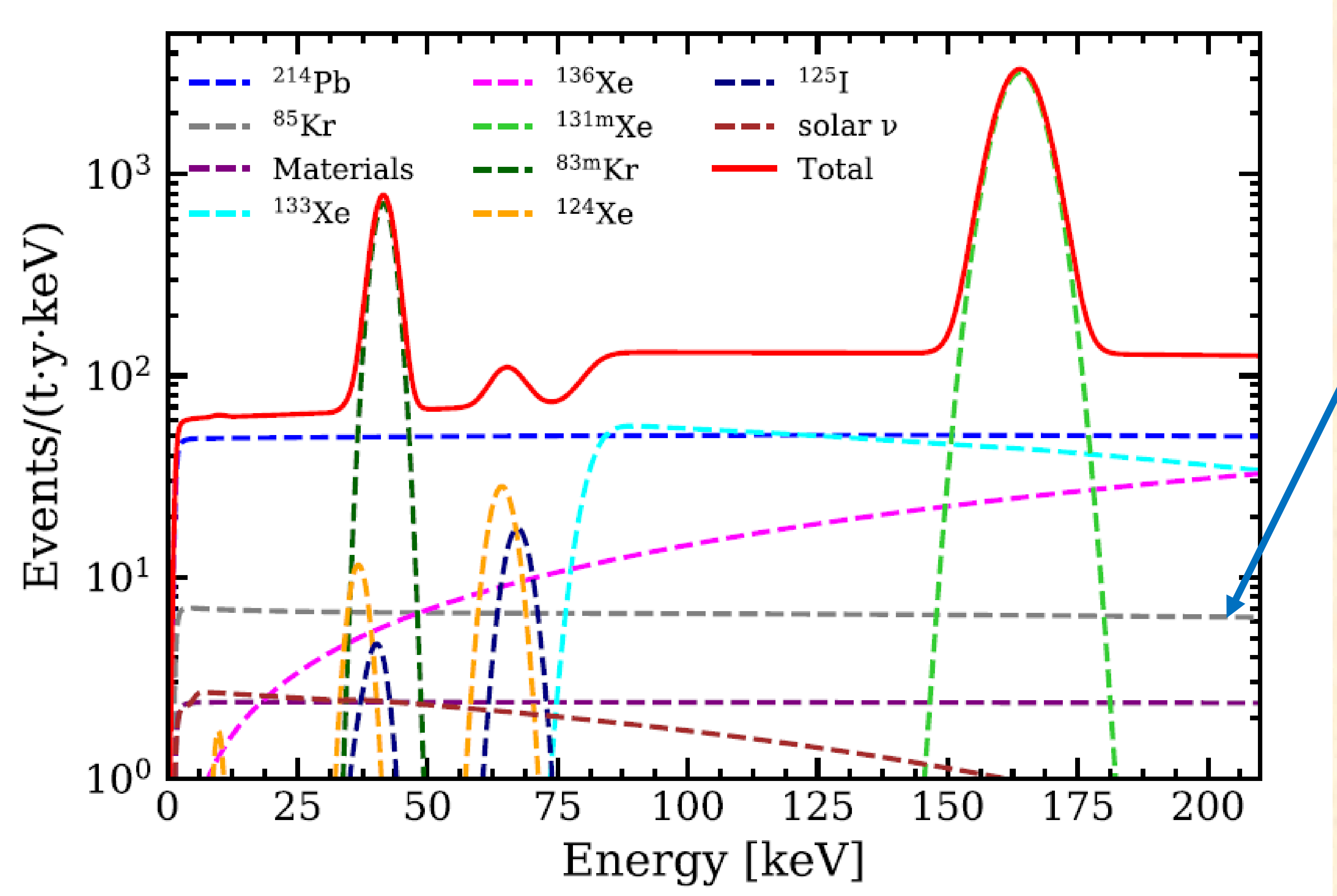
Background model (B_0), 10 components!



- Internal (uniform in volume):
  - ^{214}Pb (main contribution)

β emitter from the 222Rn decay chain. The other steps of the chain provide robust consistency checks for the ^{214}Pb rate.

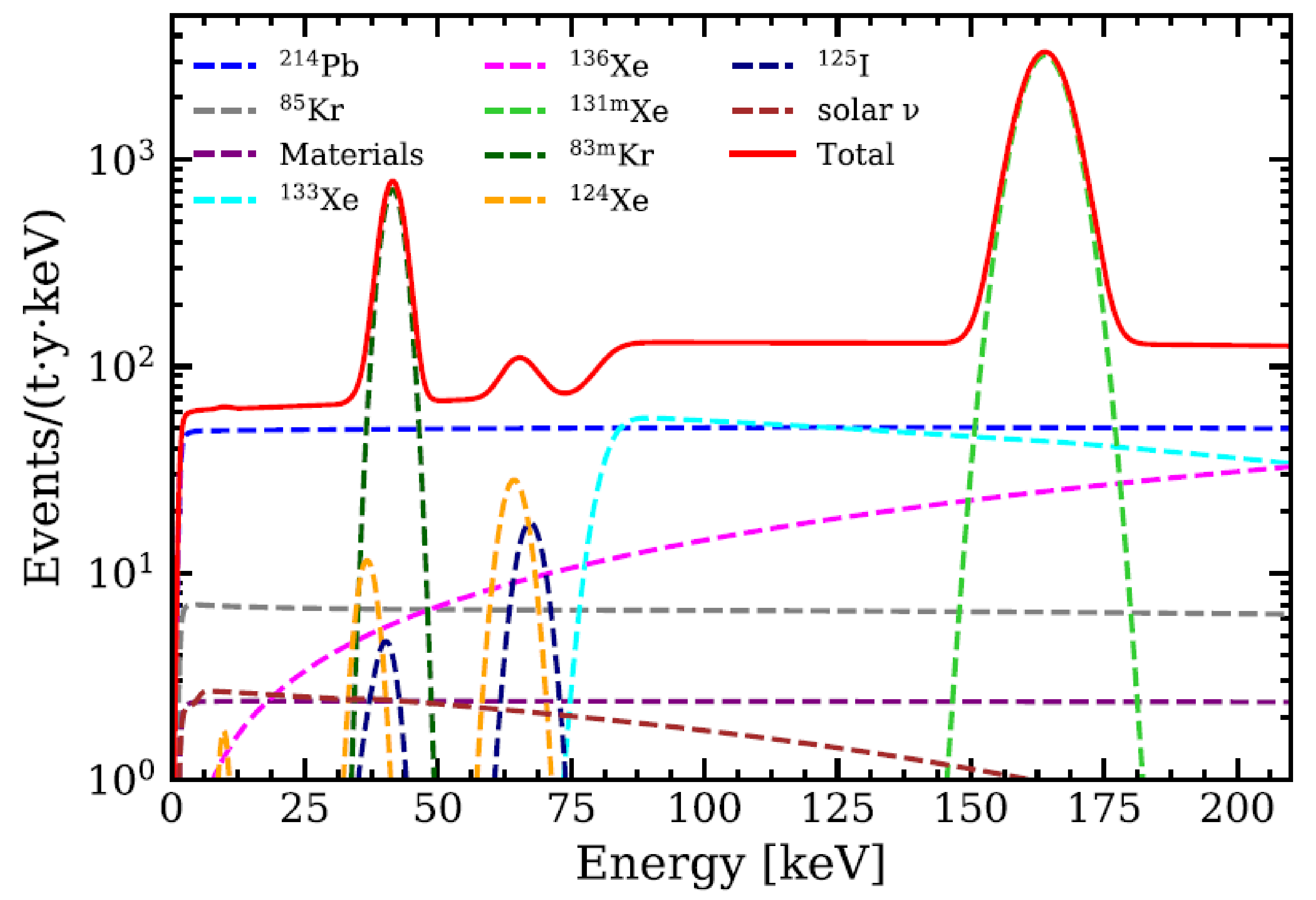
Background model (B_0), 10 components!



- Internal (uniform in volume):
  - ^{214}Pb (main contribution)
  - ^{85}Kr

This β emitter has been largely removed by means of cryogenic distillation before the beginning of SR1

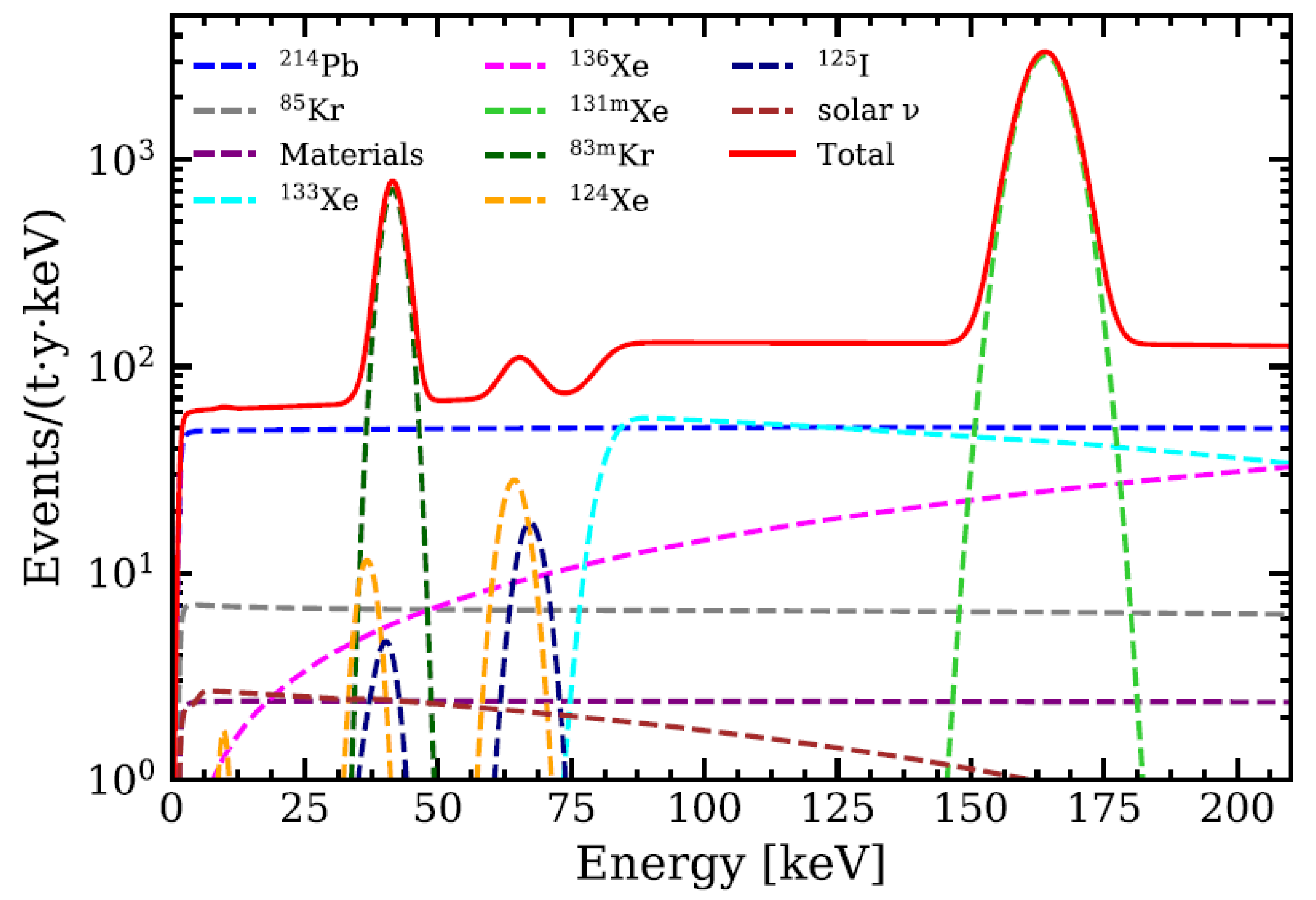
Background model (B_0), 10 components!



- Internal (uniform in volume):
  - ^{214}Pb (main contribution)
  - ^{85}Kr (distilled out)
  - ^{136}Xe, ^{124}Xe [Nature 568,532]

Ultra long lived isotopes (interestingly half-lifes measured with LXe TPC, EXO and XENON1T itself!)

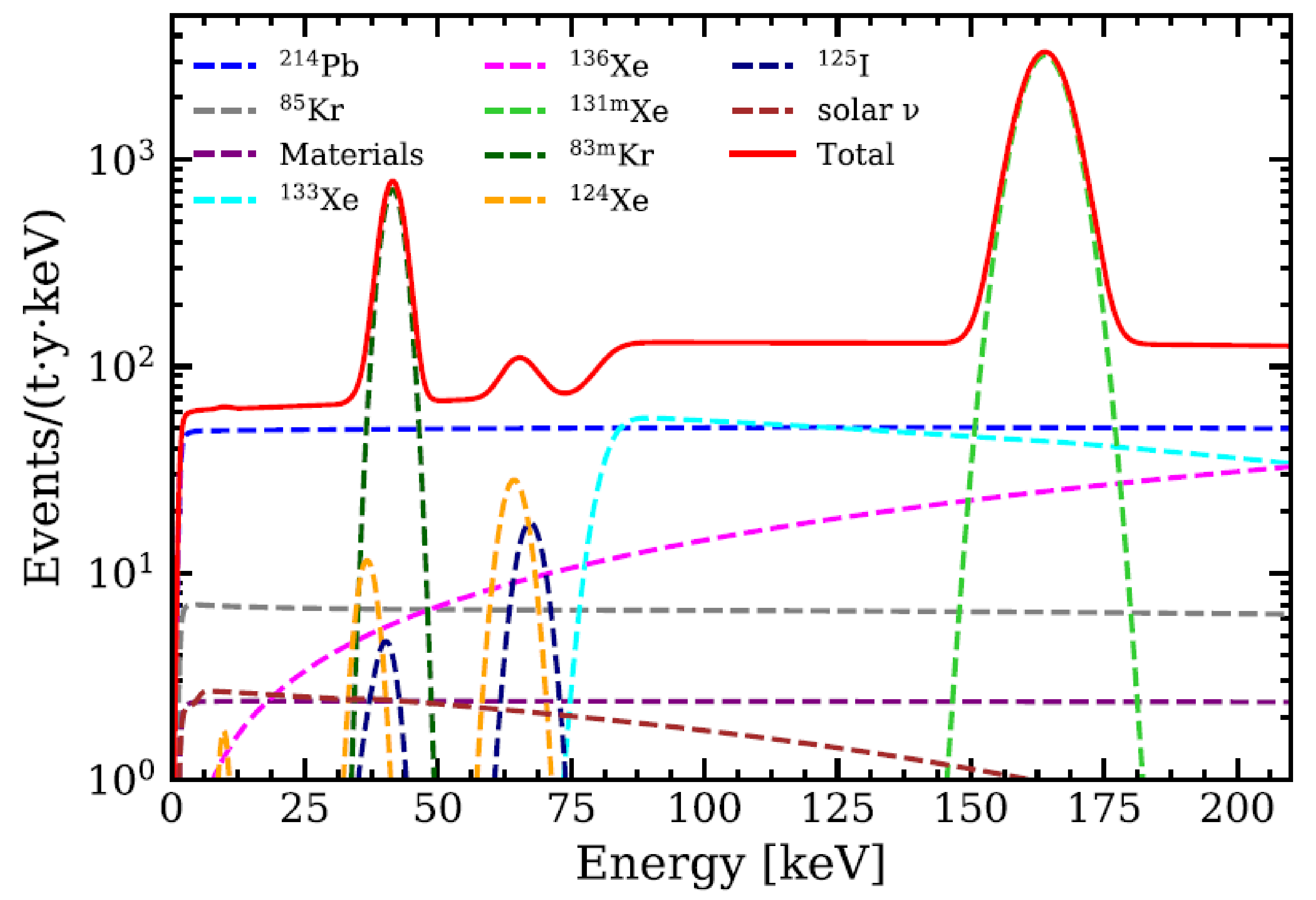
Background model (B_0), 10 components!



- Internal (uniform in volume):
  - ^{214}Pb (main contribution)
  - ^{85}Kr (distilled out)
  - ^{136}Xe, ^{124}Xe [Nature 568,532]
  - ^{83m}Kr

Unfortunately a defective valve allowed traces from the rubidium source (from which the calibration source ^{83m}Kr is obtained) to arrive to the gas system

Background model (B_0), 10 components!



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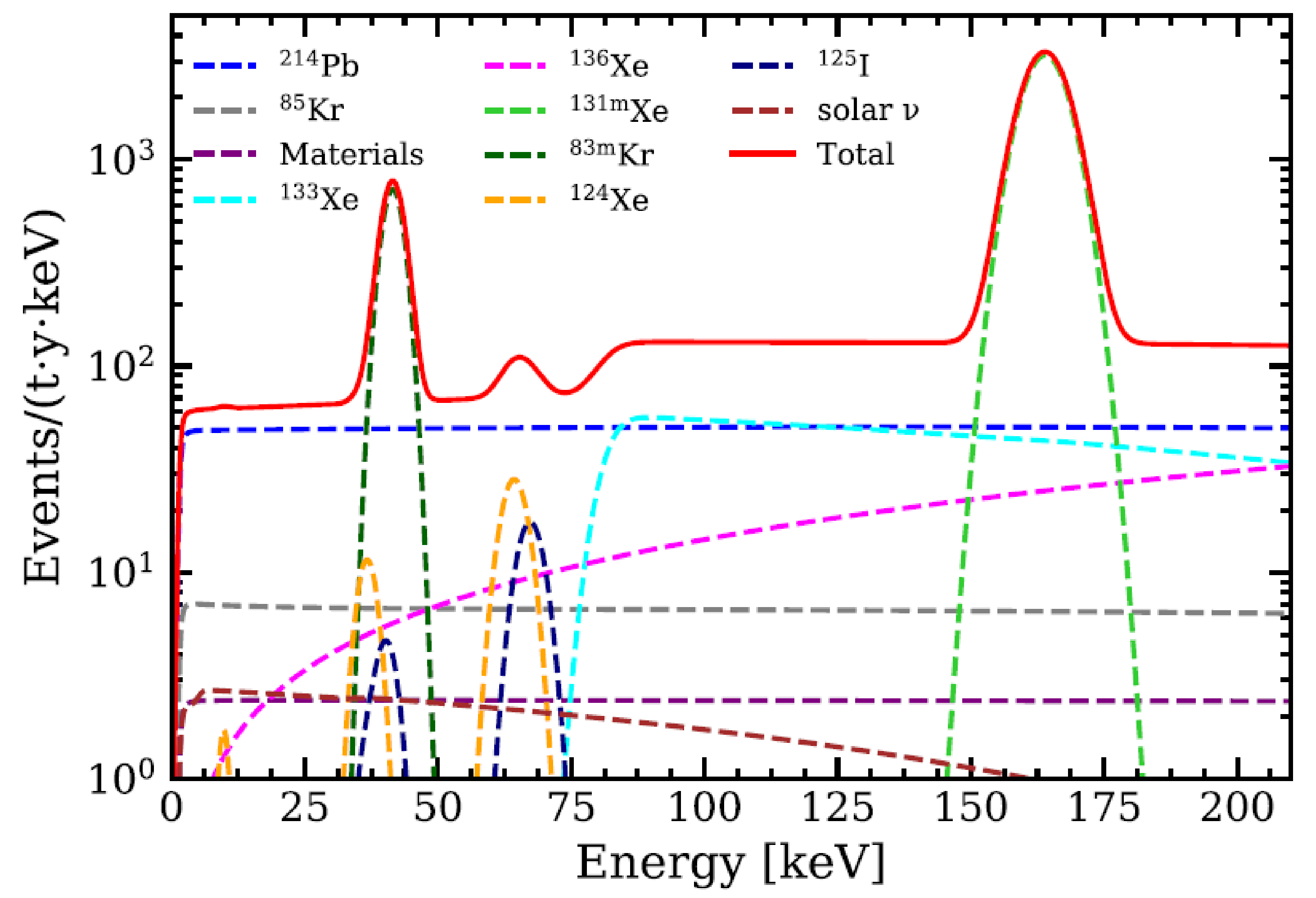
- Neutron induced
  - ^{131m}Xe, ^{133}Xe, ^{125}I
- Time-dependency required!

Background model (B_0), 10 components!



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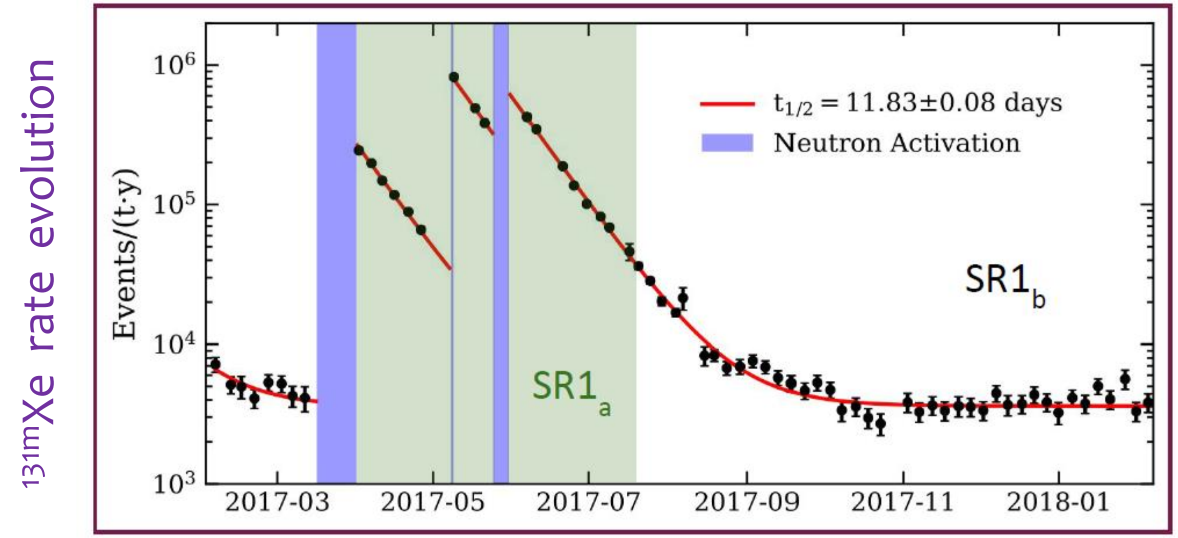
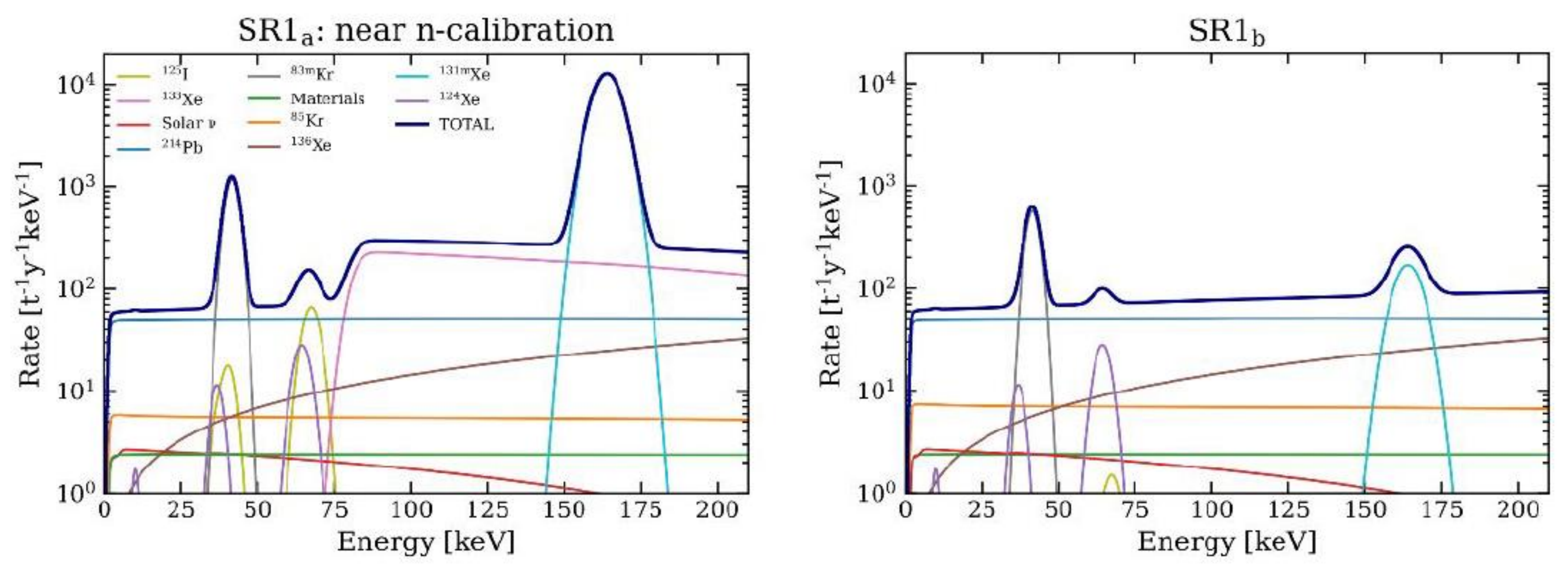
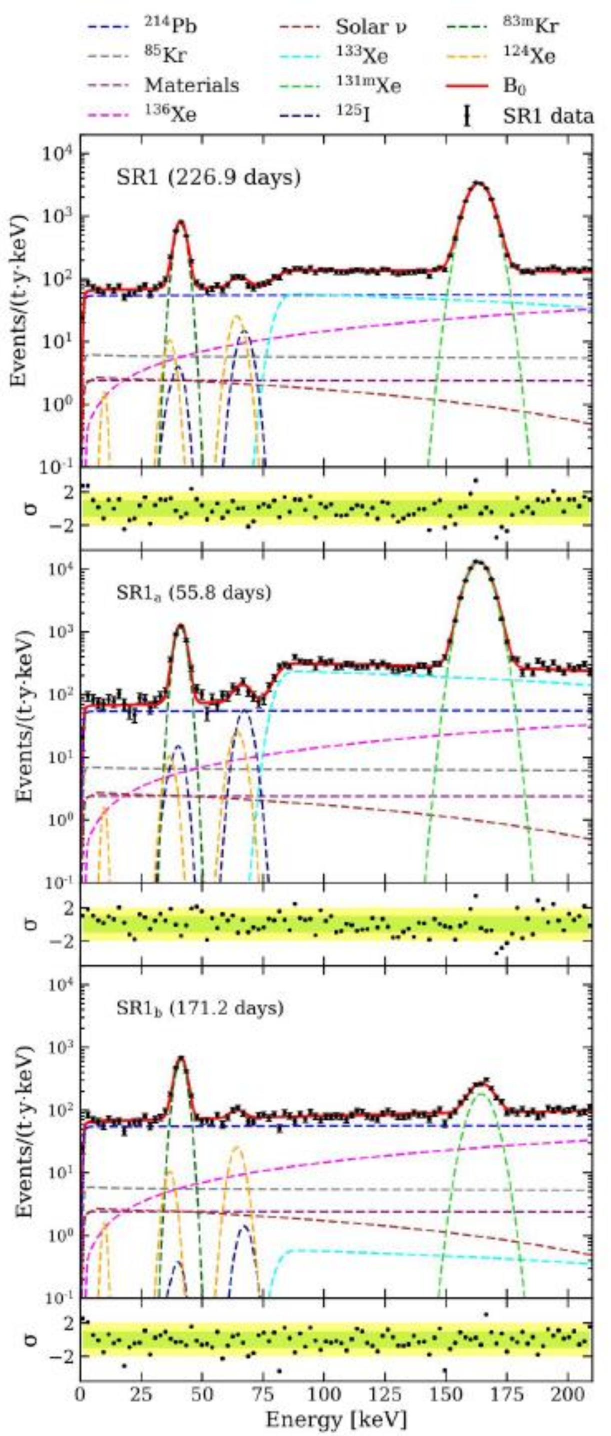
  - ^{83m}Kr (calibration source issue)
- Neutron induced
  - ^{131m}Xe, ^{133}Xe, ^{125}I
- Solar neutrinos
- Materials (radio-essay & GEANT4)
- Time-dependency required

SR1 partitioned due to neutron calibrations

- Two partitions to account for the activation during neutron calibration
- Simultaneous fit of the two datasets



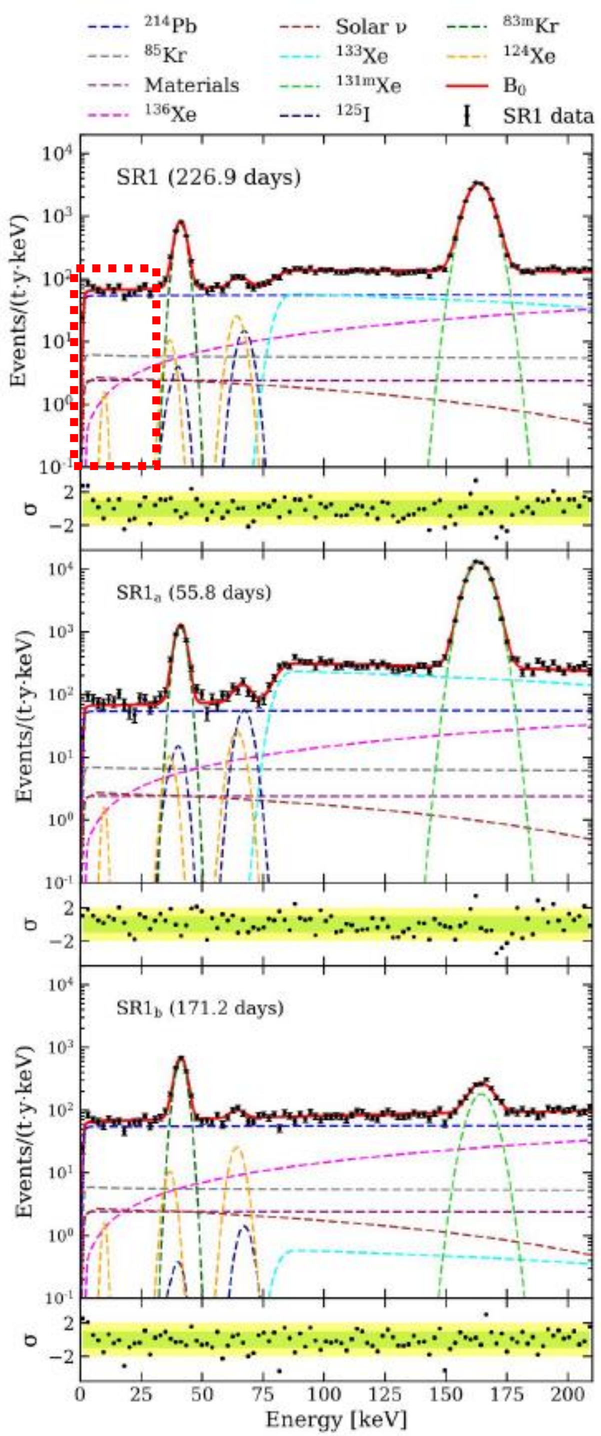




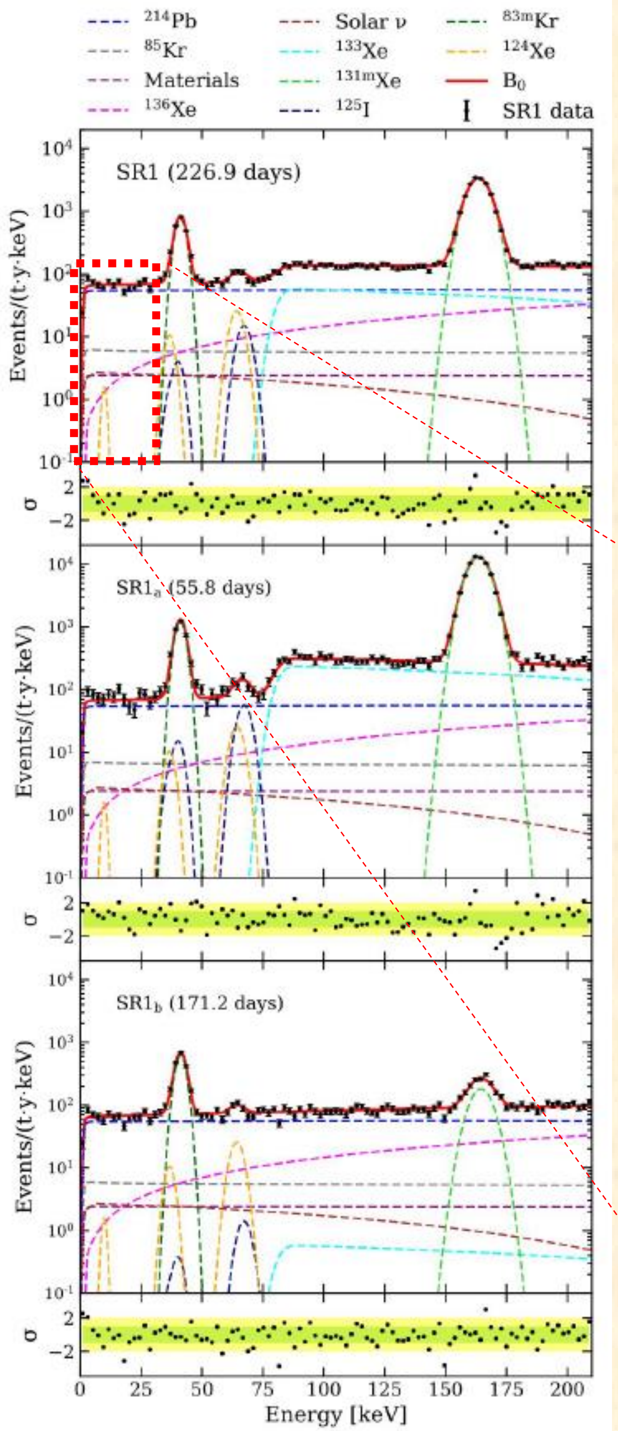
The fit to the data & the excess

- Unbinned profile likelihood analysis

The fit to the data & the excess



- Unbinned profile likelihood analysis
- (76 ± 2) events / (tonne·year·keV) in [1,30] keV
  Lowest background rate ever achieved in this energy range!



The fit to the data & the excess

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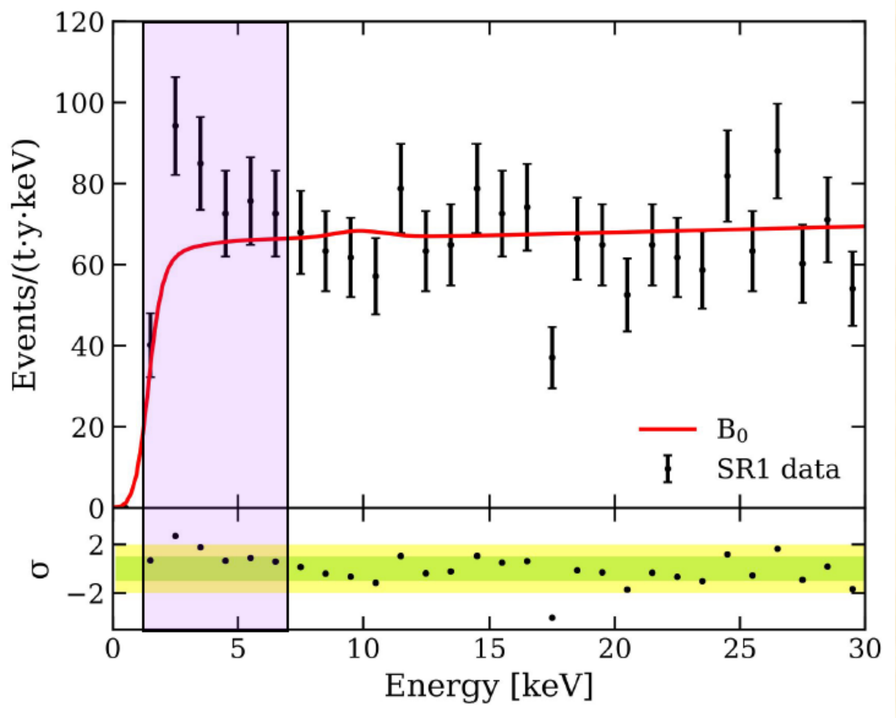
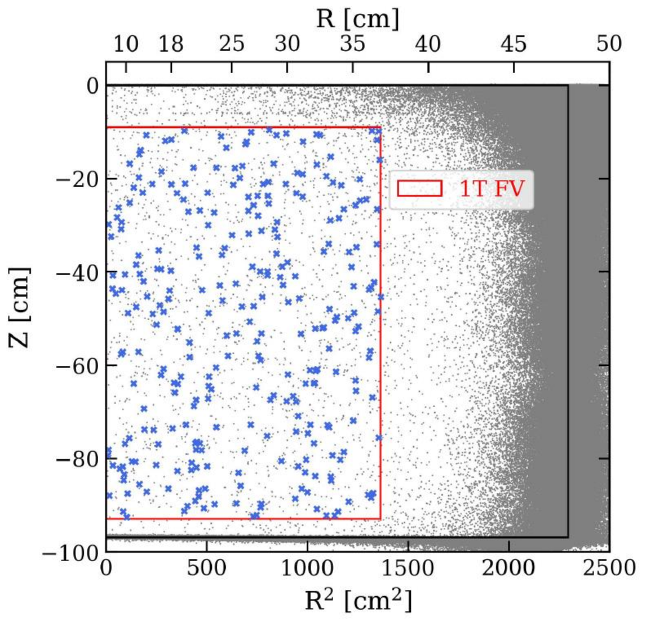


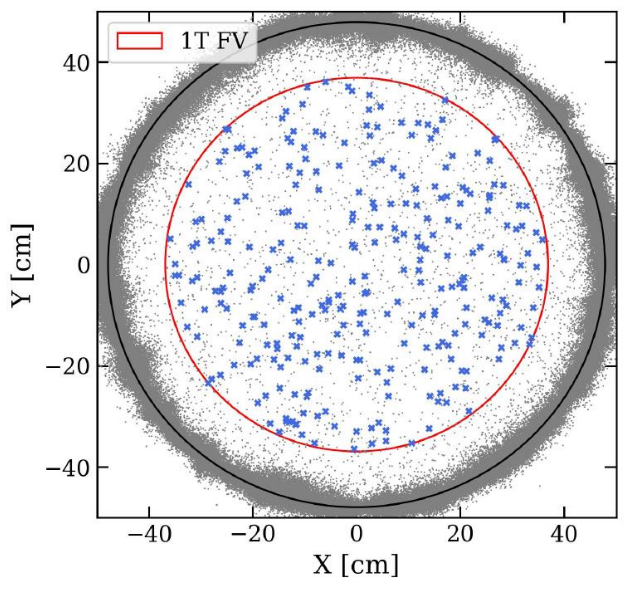
- 285 events observed vs. 232 ± 15 expected (best fit) between 1-7 keV

(3.3σ fluctuation in a naive estimate without proper likelihood ratio tests)

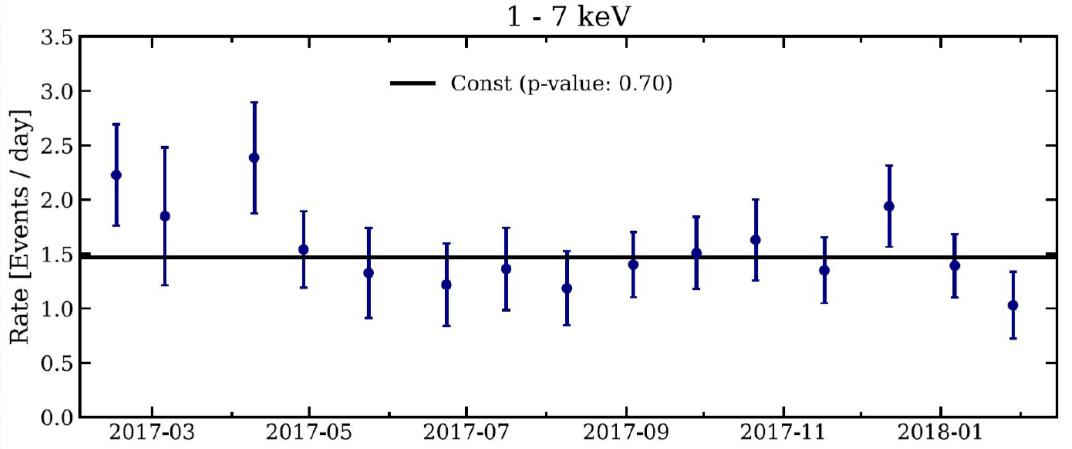
Space & time uniformity of the excess

[1, 210 keV] [1, 7] keV





Rate along SR1 of the events in 1-7 keV



- These events are uniformly distributed with the fiducial volume and the rate stays constant all along the SR1

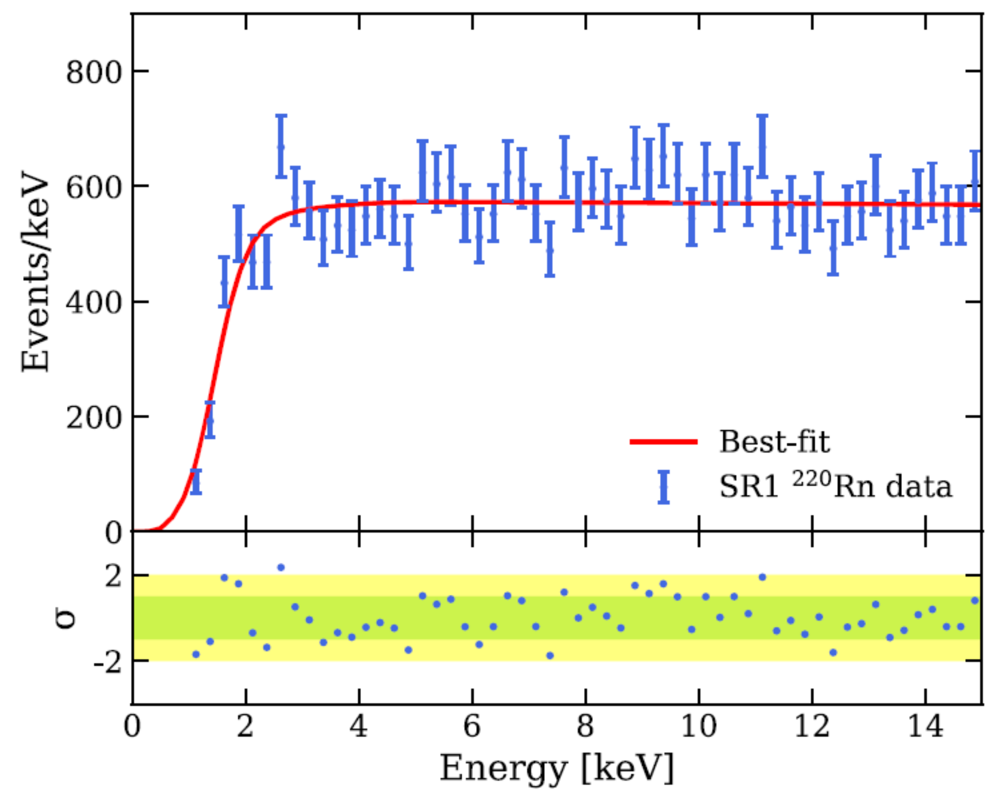
Next in the outline of the talk

- **Who & Where?** Introduction on XENON1T and LXe Time Projection Chambers
- **What?** Excess electronic recoil events found in the energy range 1-7 keV
- **Sure?** Let's check for:
  - Mis-modeling of energy reconstruction or efficiencies
  - Mis-modeling of background shape
  - Instrumental background
- **So?**
- **And then?**

Mis-modeling: energy reconstruction / threshold

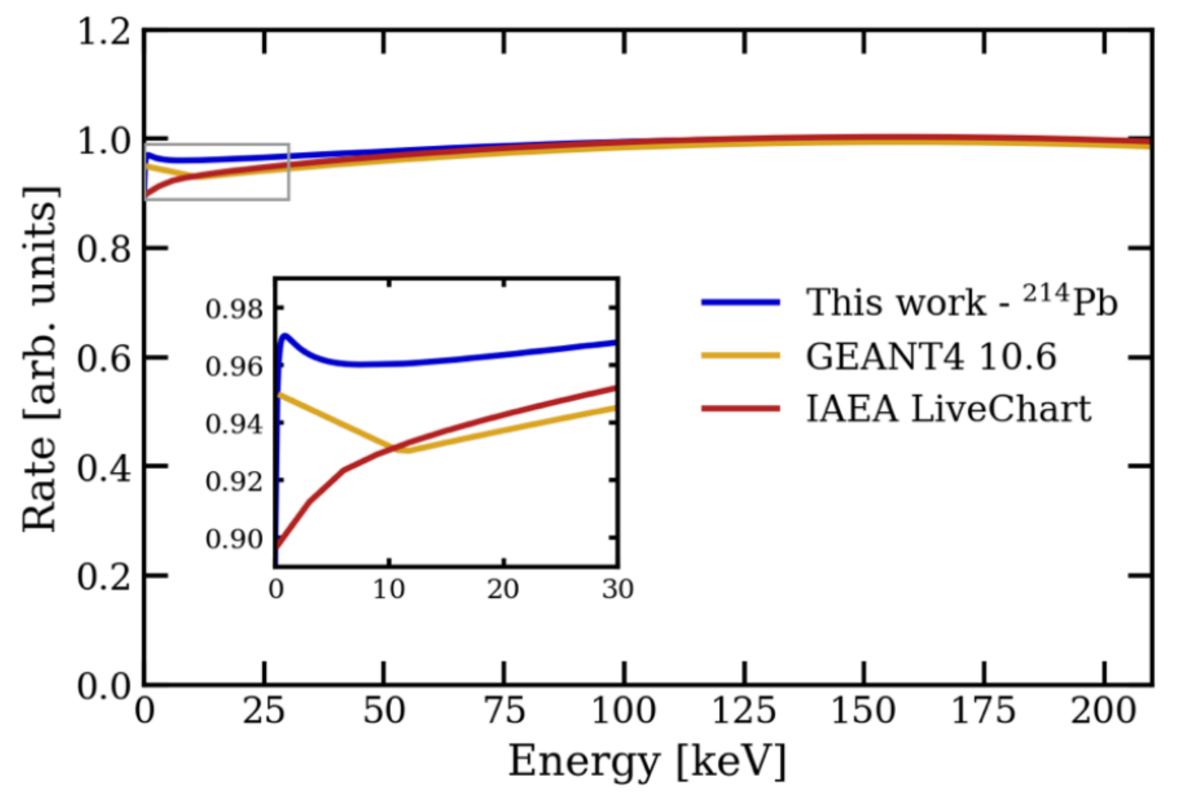
- The excess is not at our threshold fall-off. It persists:
  - if analysis threshold is doubled
  - with a profile likelihood in (S1, S2) space
  - if efficiencies are different within ±1 σ

- High statistics ^{220}Rn calibration data (^{212}Pb β spectrum similar to background ^{214}Pb) are reconstructed as expected
  - The good agreement (g.o.f. p=0.50) with the same analysis framework validates efficiencies & energy reconstruction



Mis-modeling of the background shape

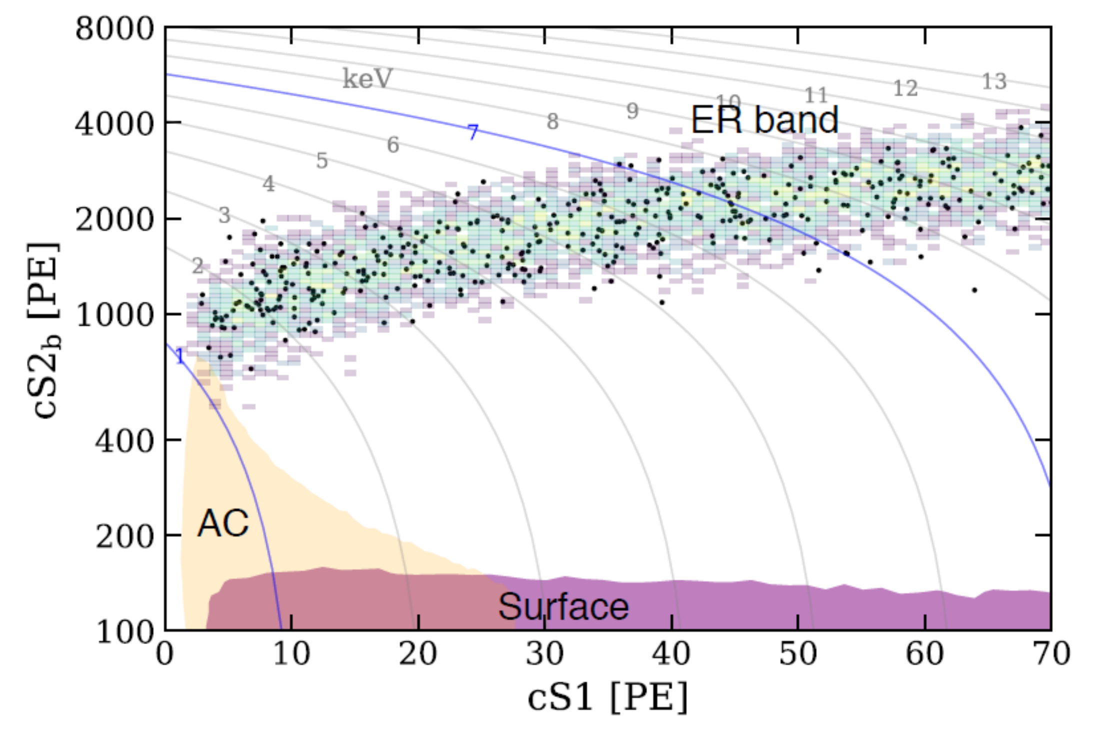
- Atomic screening and exchange effects can increase rate at low energies
- Theoretical calculation uncertainty on the ^{214}Pb beta decay shape < 6%
- >50% uncertainty required to explain the excess



Calculations from X. Mougeot (CEA Saclay)

Instrumental background

- Instrumental effects such as accidental coincidence (AC) between unrelated S1 and S2, or "surface event" (in which part of S2 is lost) are well-known and far from the ER band



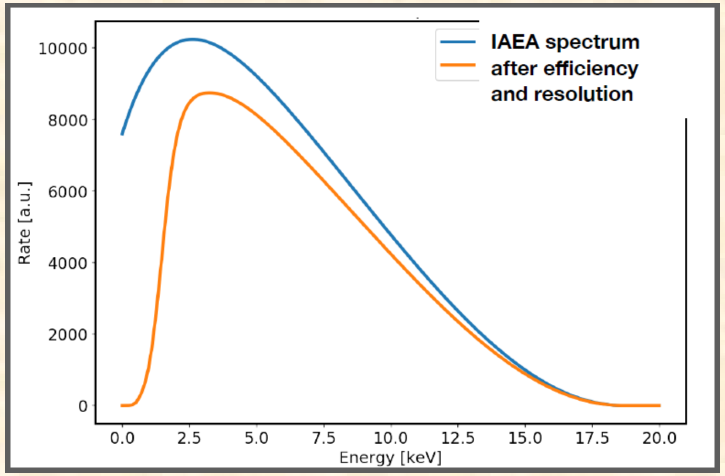
Next in the outline of the talk

- **Who & Where?** Introduction on XENON1T and LXe Time Projection Chambers
- **What?** Excess electronic recoil events found in the energy range 1-7 keV
- **Sure?** Checked for detector response or B_0 mis-modeling , or instrumental artifacts
- **So?** We interpreted the results as:
  - Unexpected traces of other isotopes, e.g. tritium
  - Observation of solar axions or an enhancement of neutrino magnetic moment
  - Others…
- **And then?**

We observed…
…unexpected traces of tritium?

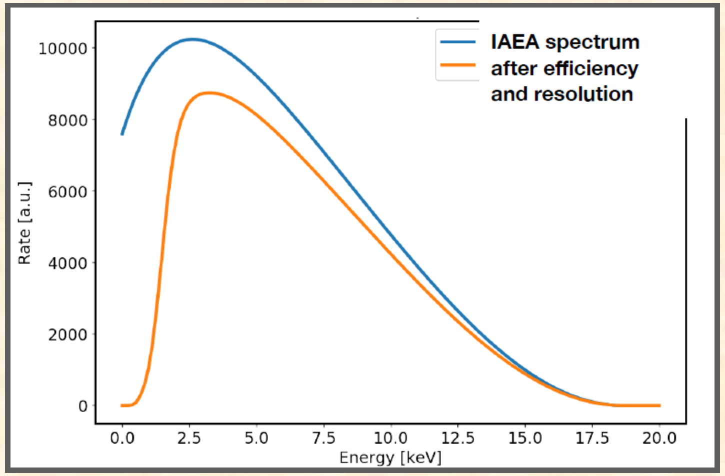
Unexpected traces of tritium

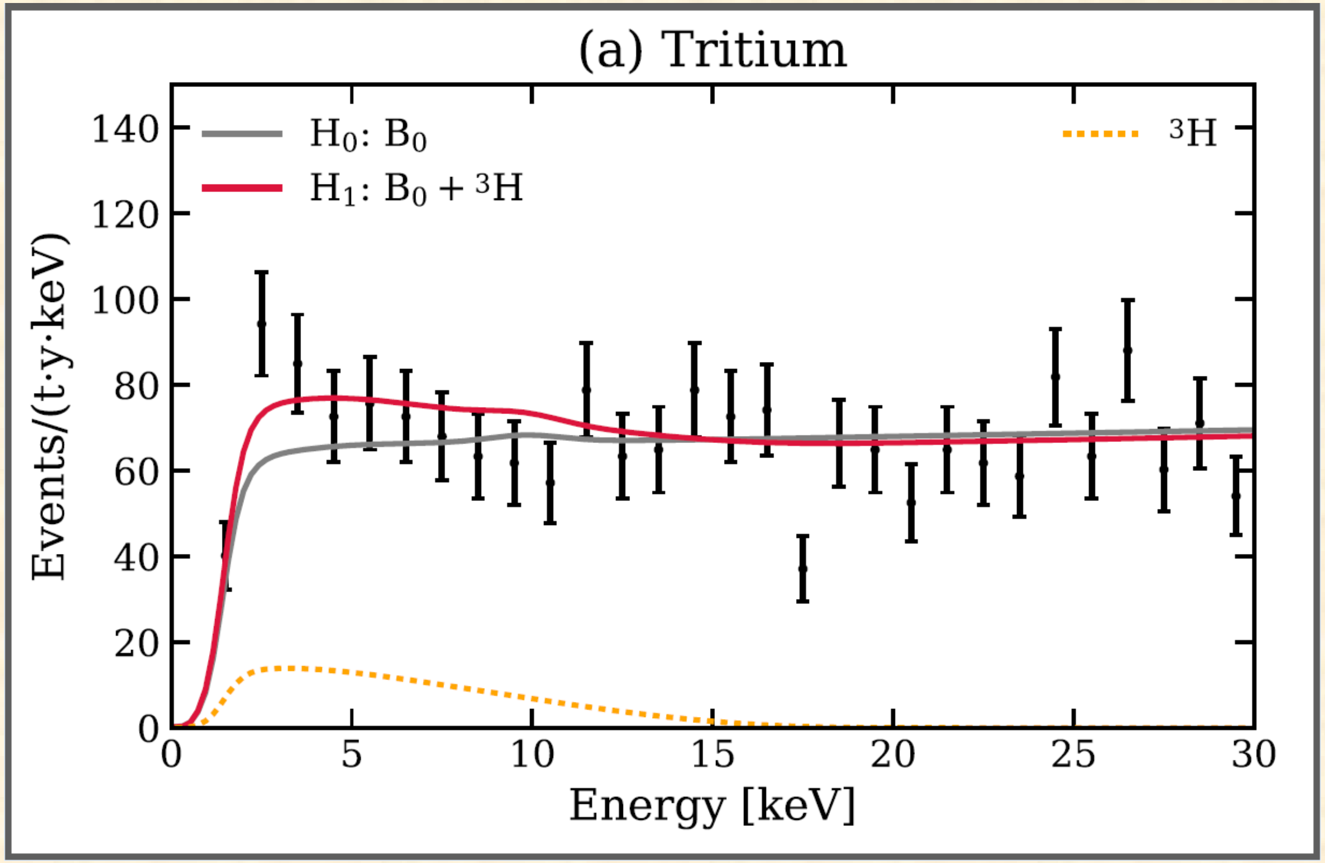
- Long-lived (12.3 y) low energy β emitter (Q-value 18.6 keV)



Unexpected traces of tritium

- Long-lived (12.3 y) low energy β emitter (Q-value 18.6 keV)
- Favored over B_0 at 3.2σ



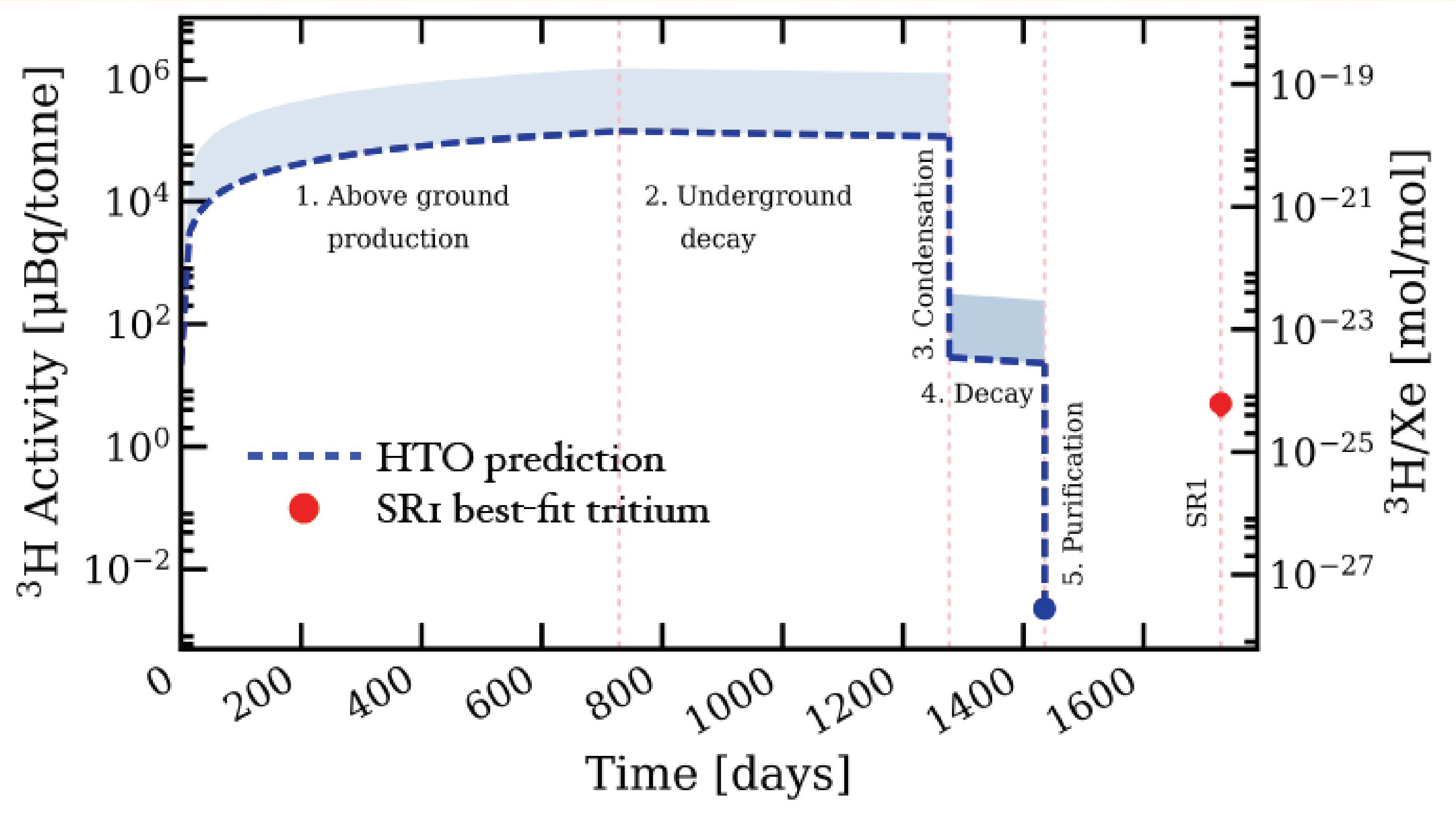


- Best fit rate (159±51) ev. / (t·y·keV)
- ^3H/Xe concentration:
  (6.2±2.0) × 10^{-25} mol/mol

Fewer than 3 tritium atoms per kg of xenon!

Tritium from cosmogenic activation of xenon?

- Cosmogenic activation of xenon produces ~32 tritium atoms / kg / day (Zhang, 2016)
- 1 ppm of water in xenon bottles implies formation of HTO
- Efficient removal (99.99%) in purification system (SAES getter with hydrogen removal unit)
- Xenon handling and purification makes this hypothesis unlikely



Tritium emanated from materials?

- Emanation from materials, in form of HTO or HT, in equilibrium with removal

Required ^{3}H:Xe to explain excess ~10^{-24} mol/mol

(*) No direct measurements

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- Emanation from materials, in form of HTO or HT, in equilibrium with removal

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Known atmospheric HTO:H2O
~10^{-17} mol/mol

Required H2O:Xe
>30 ppb

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>30 ppb

Ruled out by light yield measurement
H2O:Xe ~1 ppb

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Required H_2O:Xe
>30 ppb

Ruled out by light yield measurement
H_2O:Xe ~1 ppb

Assuming similarly(*) HT:H_2
~10^{-17} mol/mol

Required H_2:Xe
~100 ppb

(*) No direct measurements

Tritium emanated from materials?

- Emanation from materials, in form of HTO or HT, in equilibrium with removal

Required ^{3}H:Xe to explain excess ~10^{-24} mol/mol

Known atmospheric HTO:H2O
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Assuming similarly$^{(*)}$ HT:H2
~10^{-17} mol/mol

Required H2:Xe
~100 ppb

No constraints on H2:Xe

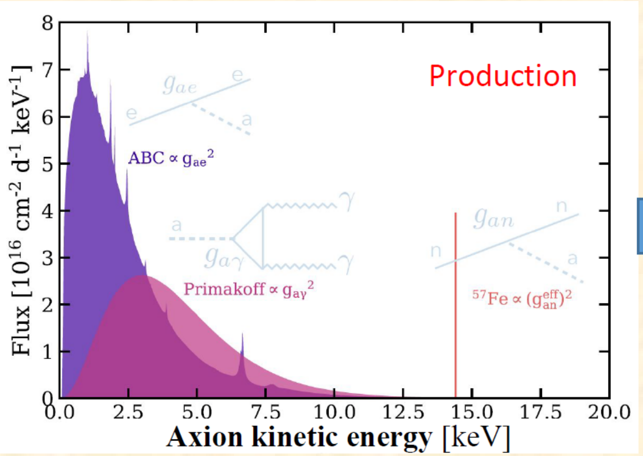
We cannot neither confirm nor completely rule out tritium hypothesis

(*) No direct measurements

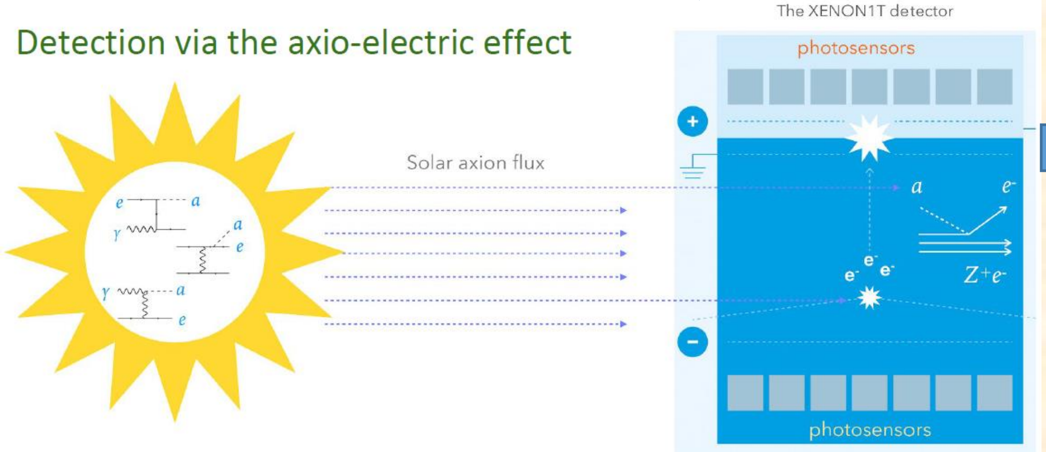
We observed…
…solar axions?

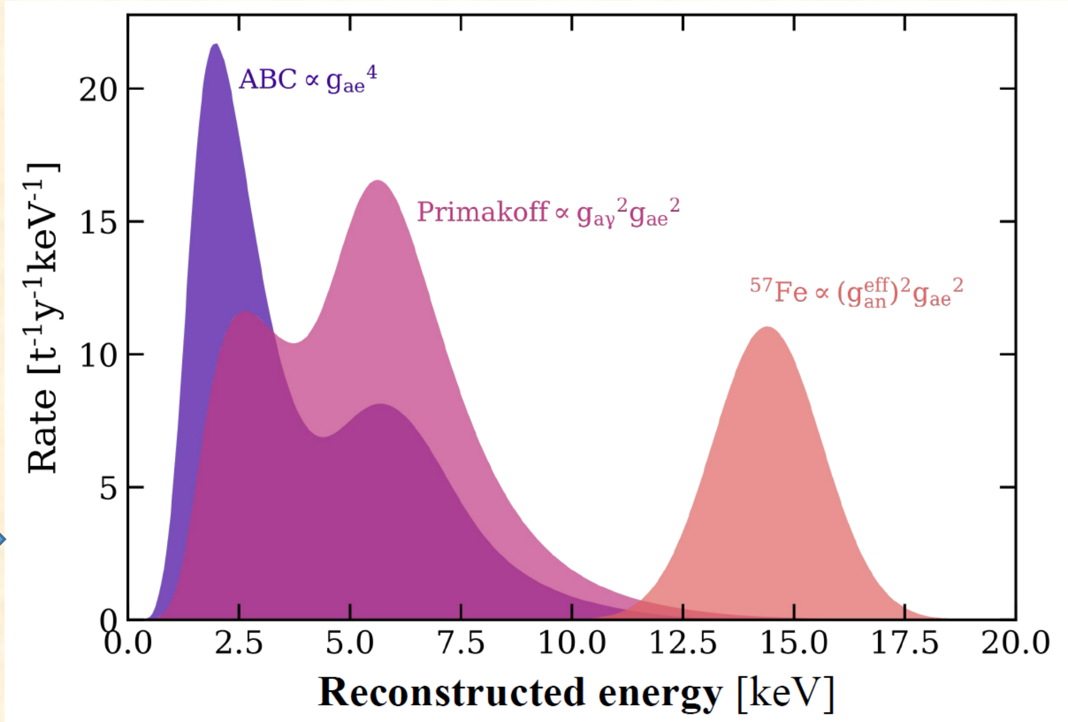
Observation of solar axions: signal model

- QCD axions address strong CP problem
- No Dark Matter axions detectable in XENON1T (here we look at axions from the Sun!)



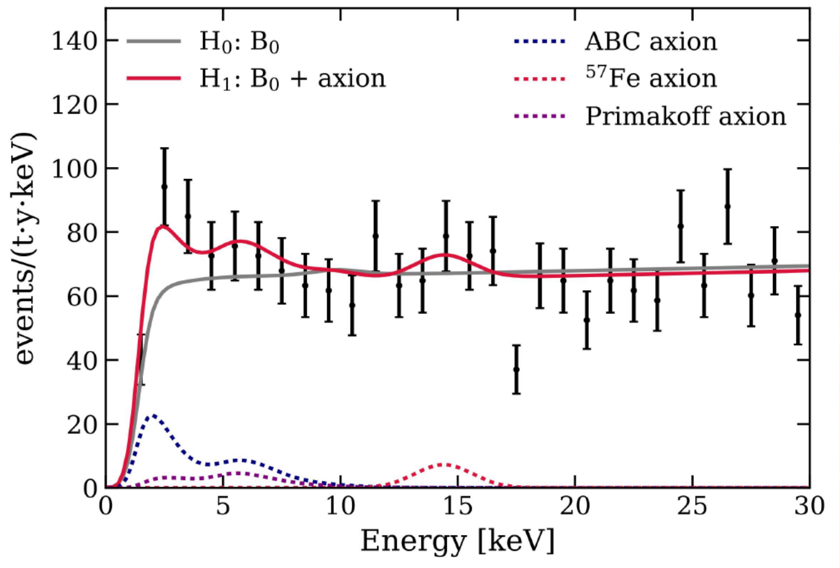
Model-dependent couplings to matter, we treat 3 production mechanisms as independent free parameters


Detection via the axio-electric effect

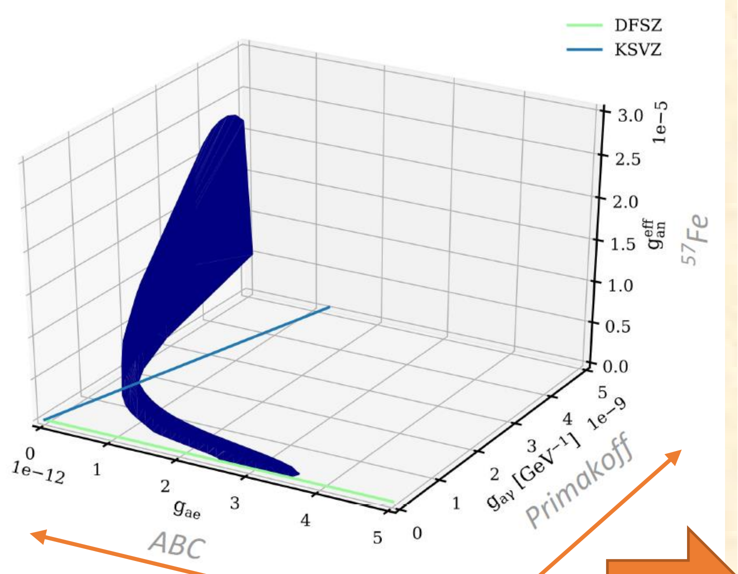


Observation of solar axions: result of the fit

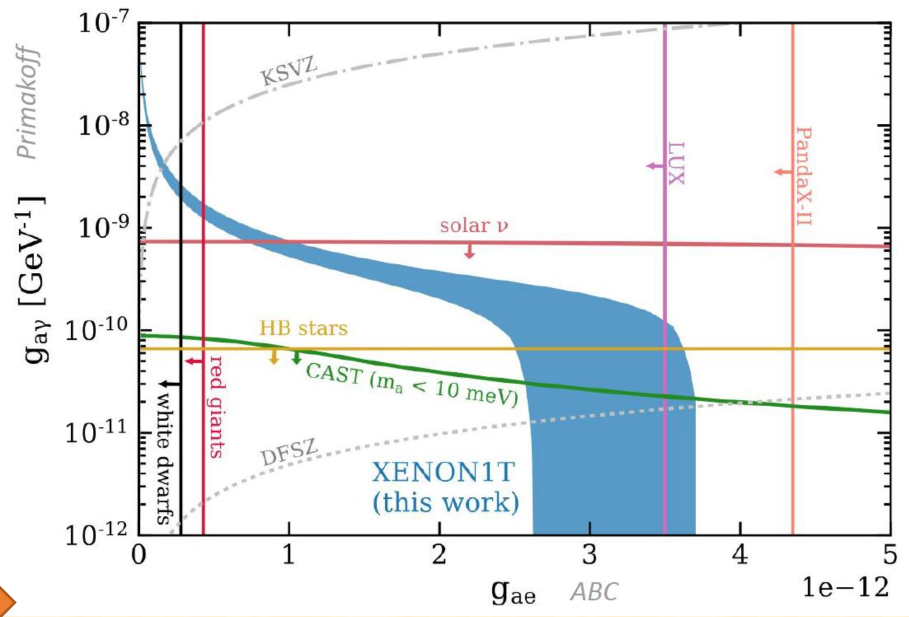
Favored over B0 at 3.4 σ



90% C.L. 3D contour



90% C.L. contour projection

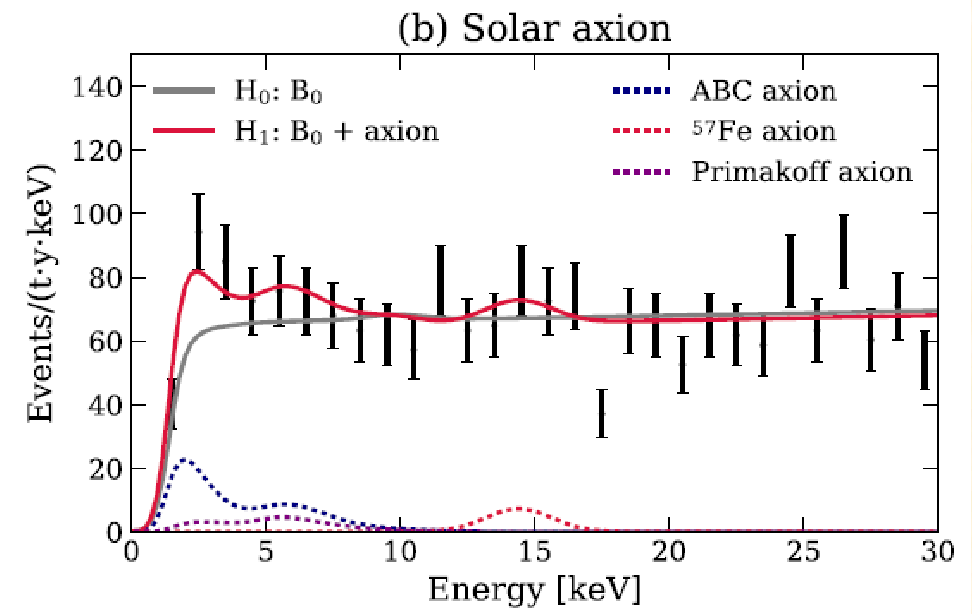


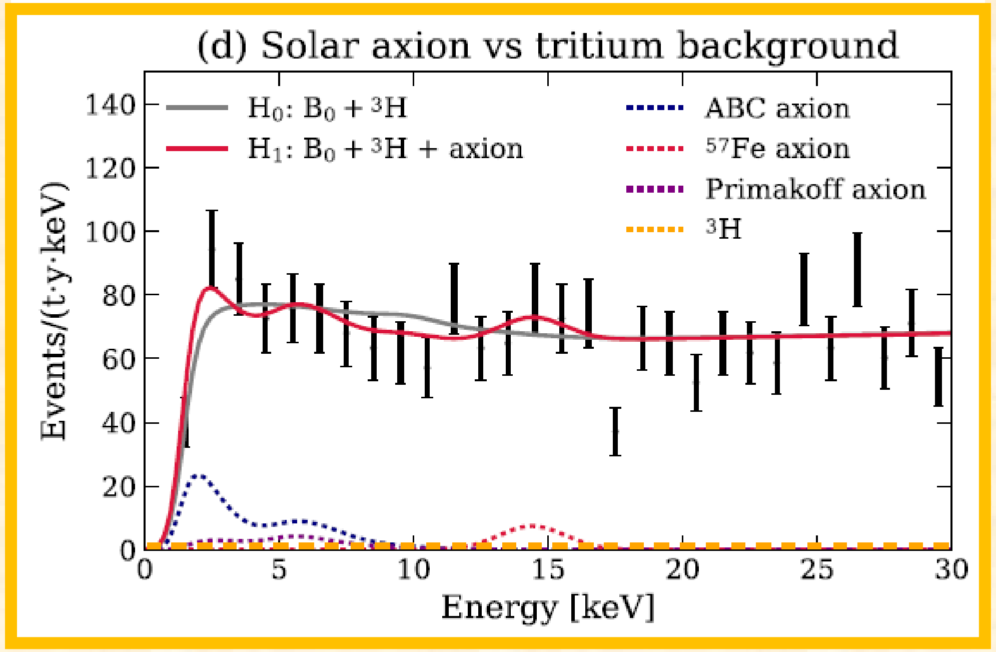
Results in tension with astrophysical constraints from stellar cooling

(tough in arXiv:2006.14598 Gao et al. shows that this is alleviated by taking into account the inverse Primakoff effect as detection process)

and in case of tritium contamination?

B_0 + ^{3}H null hypothesis


(b) Solar axion


(d) Solar axion vs tritium background

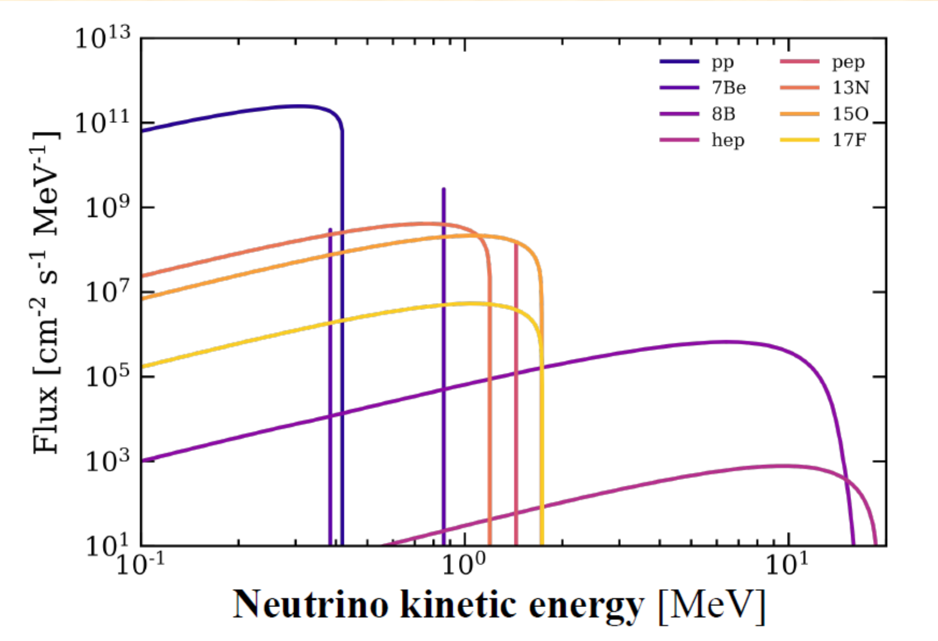
- Solar axion + ^{3}H + B_0 still favored over ^{3}H + B_0, but at 2.0 σ instead of 3.4 σ

- Despite that, the best fit results still in a negligible tritium contamination

We observed…
… a larger neutrino magnetic moment?

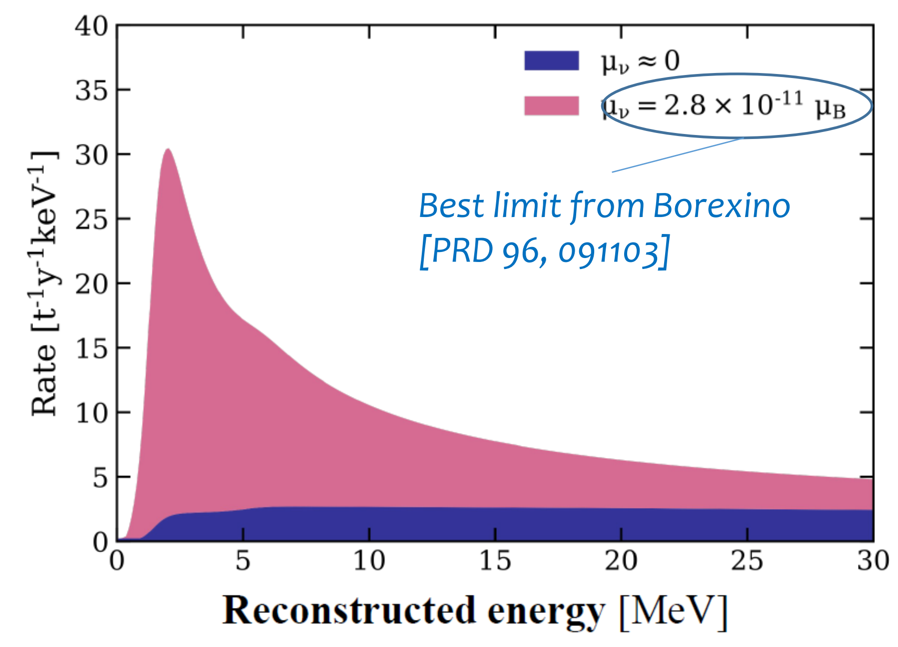
Enhanced μ_ν: implications & signal in XENON1T

- If the Standard Model is extended to allow for neutrino masses, then neutrinos can have also magnetic moments, order of 10^{-20} μ_B for Dirac ν.
- Larger values implies new physics ($\mu_\nu > 10^{-15}$ μ_B suggests Majorana neutrinos)



Solar neutrino spectrum

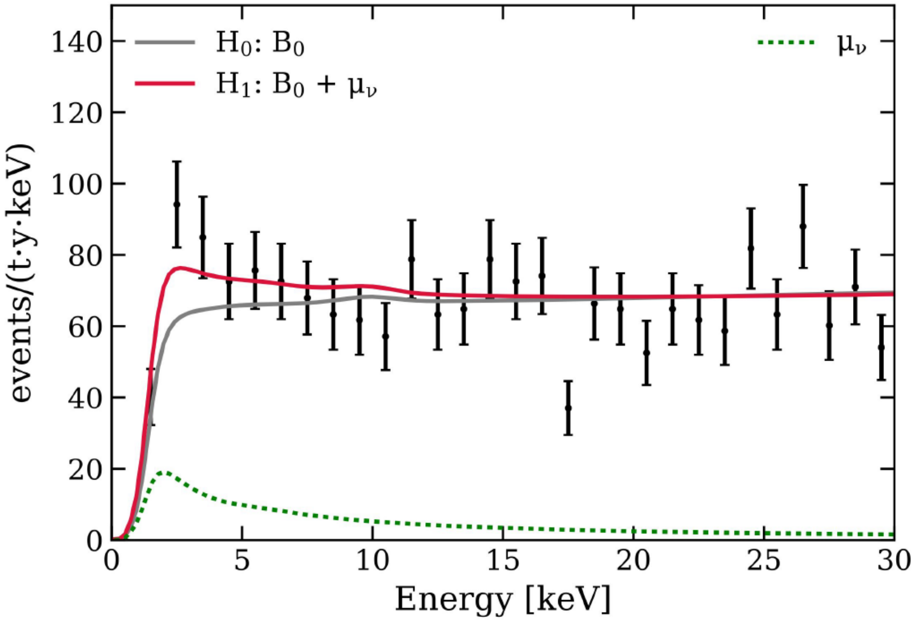
Detector efficiency & resolution applied



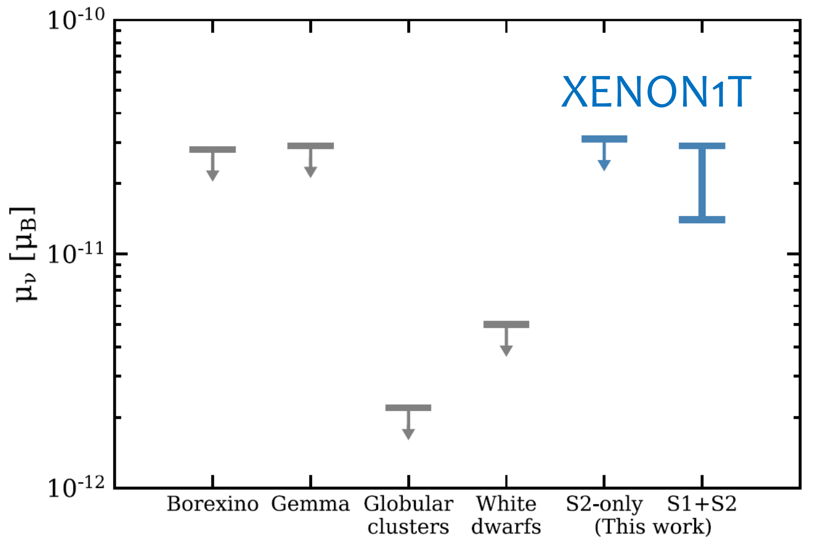
Best limit from Borexino [PRD 96, 091103]

Enhanced μ_ν: implications & signal in XENON1T

Favored over B0 at 3.2 $\sigma^{(*)}$



(*) Though it drops to 0.9 σ if the tritium hypothesis is included in the background B_0

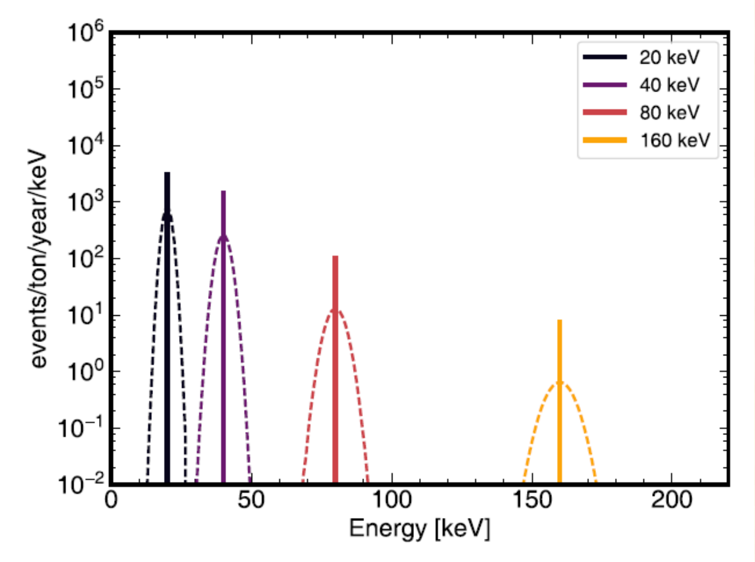


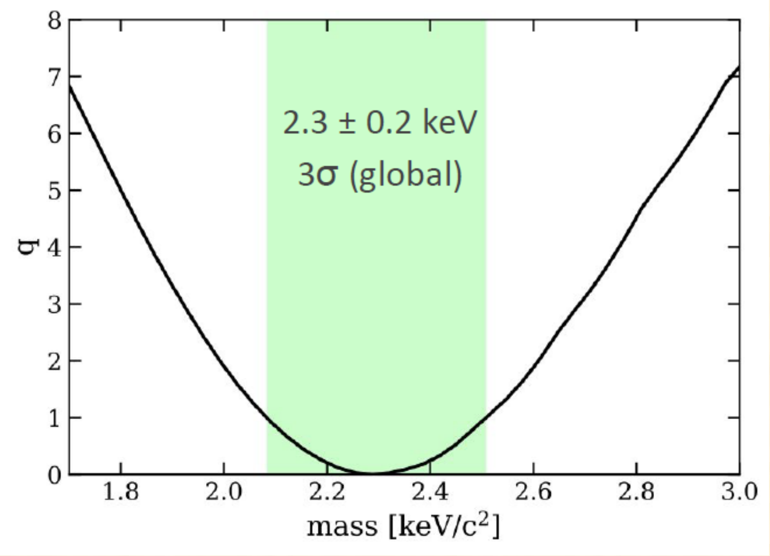
$\mu_\nu \in [1.4\,,2.9] \times 10^{-11}\mu_B$ at 90% C.L.

- In tension again with astrophysical observation (if no tritium can be confirmed)
- Dark Matter experiments have access also to neutrino physics!

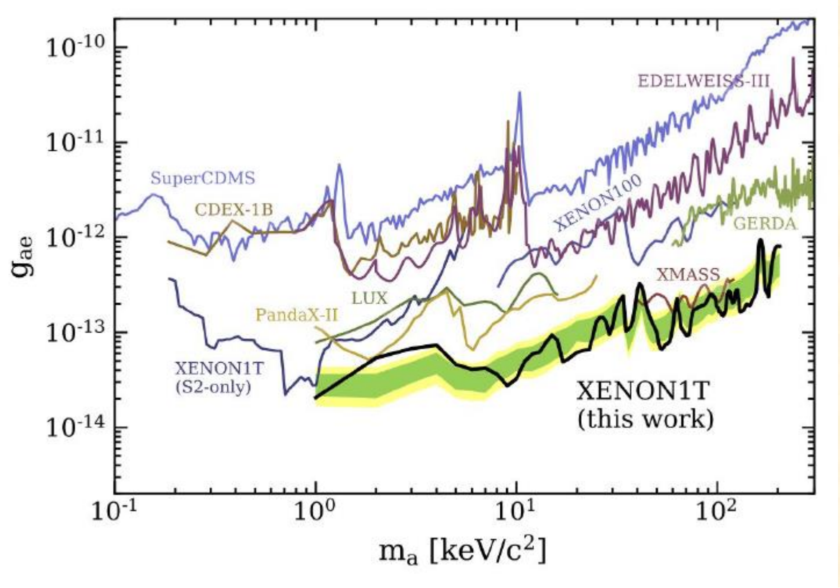
Other hypotheses…

Searching for mono-energetic peaks

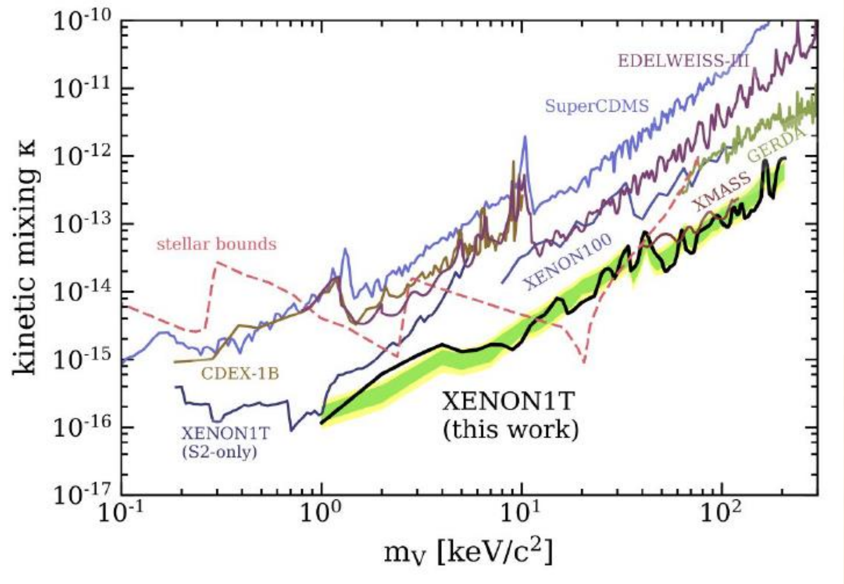




- Bosonic dark matter (ALPs, dark photons, …) generating mono-energetic peaks



Axion-like particles



Dark photons

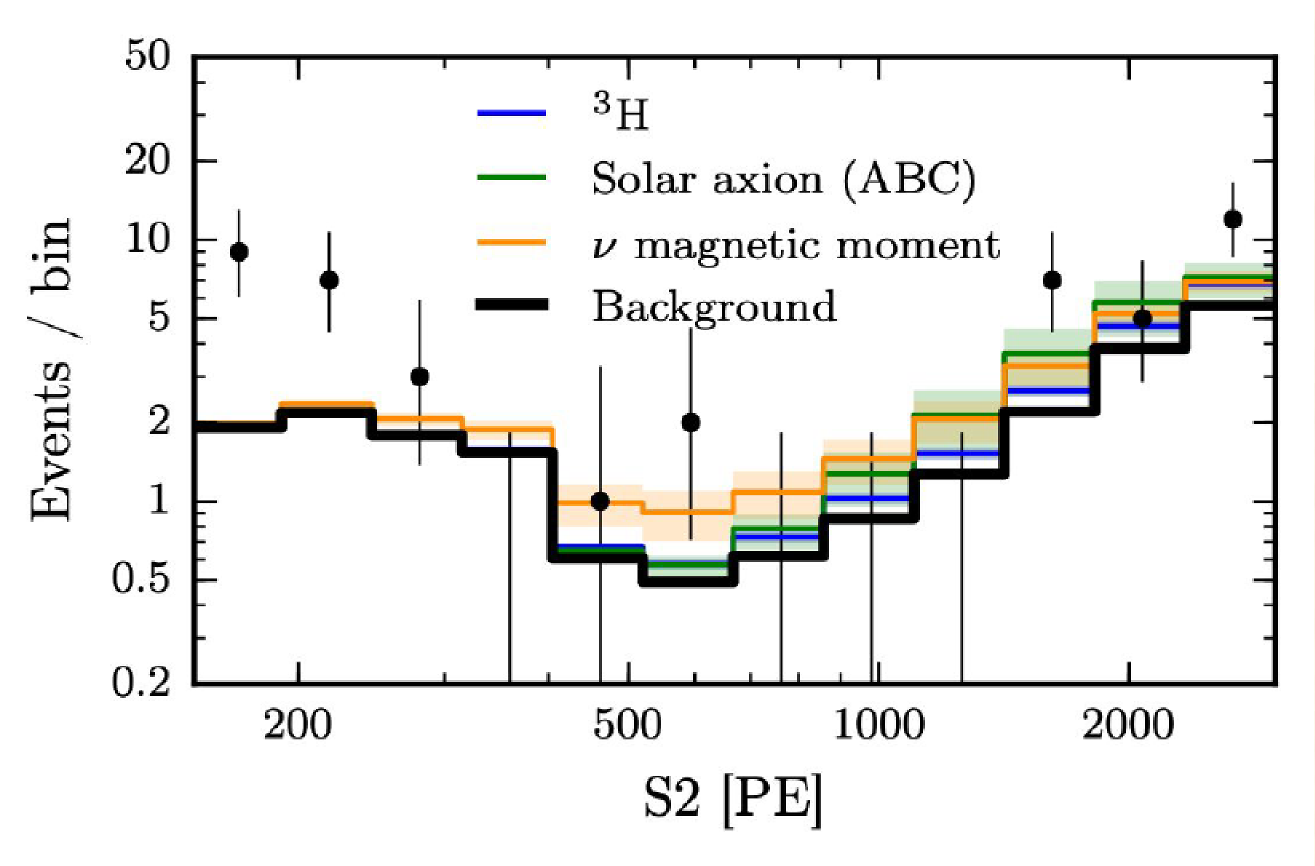
- Many new papers on arXiv

Last section of the talk

- **Who & Where?** Introduction on XENON1T and LXe Time Projection Chambers
- **What?** Excess electronic recoil events found in the energy range 1-7 keV
- **Sure?** Checked for detector response or B_0 mis-modeling , or instrumental artifacts
- **So?** Either tritium contamination, and/or observation of solar axions or enhanced neutrino magnetic moment
- **And then?**
  - Further checks (Science Run 2, S2-only analysis, ^{37}Ar traces)
  - XENONnT !

Cross check with S2-only analysis

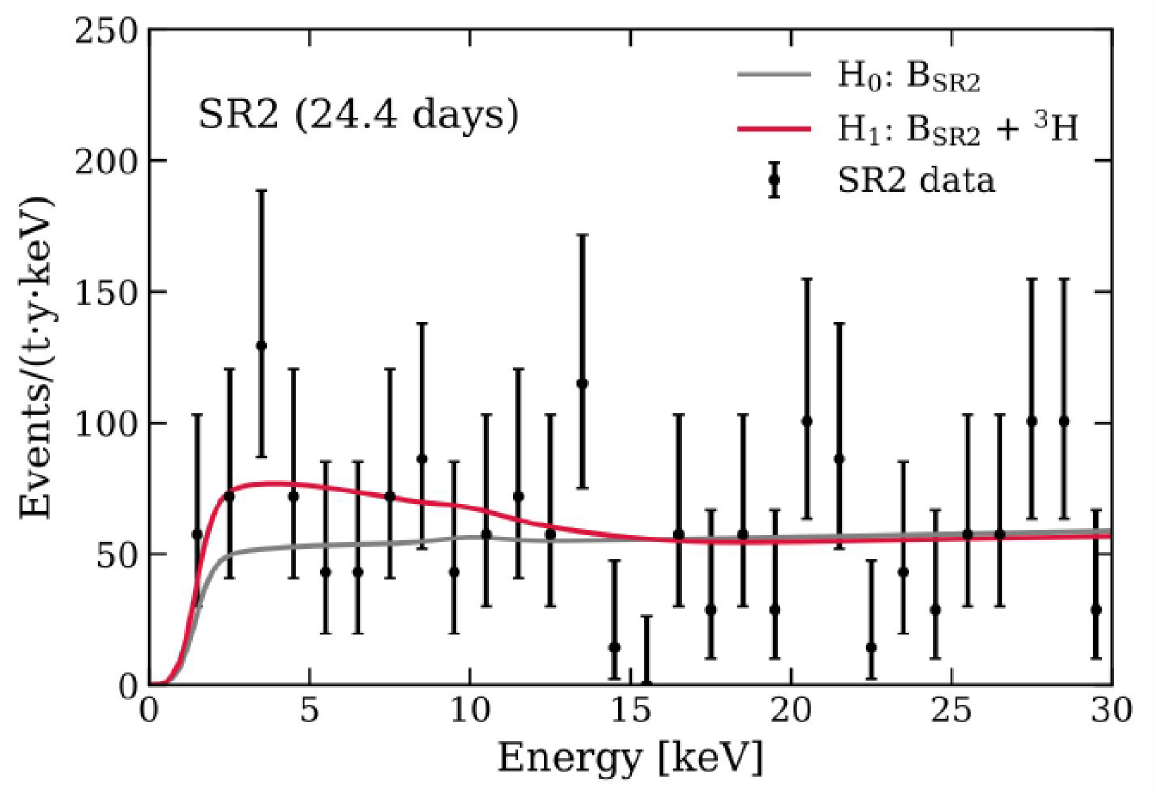
- No S1 signal required, so lower energy threshold at the cost of the no particle ID from S1/S2 ratio

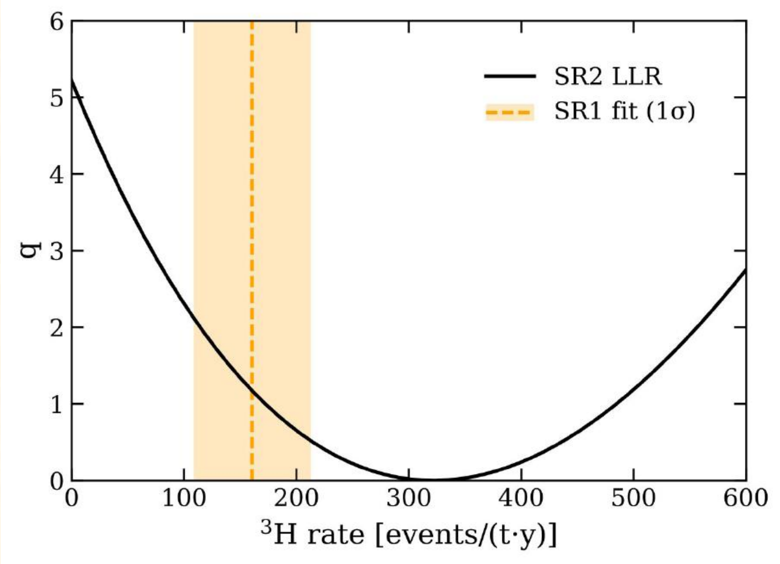


- $g_{ae} < 4.8 \times 10^{-12}$
- $\mu_\nu < 3.1 \times 10^{-11}\ \mu_B$
- Rate ^{3}H < 2256 events/t/y
- Consistent with this work

Cross-check tritium with Science Run 2 (SR2)

SR2 is an R&D science run with 20% improved background level, faster purification speed but reduced exposure



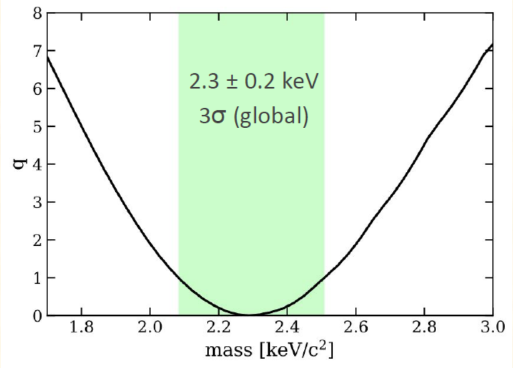


(320 ± 160) ev./t/y in SR2

(159 ± 51) ev./t/y in SR1

Consistent each other

Traces of ^{37}Ar contamination (2.8 keV)



- Best mono-energetic line fit at 2.3±0.2 keV, instead of 2.8 keV
- Argon content in Xe bottles completely removed before the beginning of SR1 by the cryogenic distillation campaign for the ^{85}Kr removal, even more effective with argon (proven by the ^{37}Ar calibration test in SR2 at the end of XENON1T)
- Next possibility, slowly introduced by an air leak:
  - XENON1T air leak < 1 liter / year, based on rare gas mass spectrometer measurements.
  - The ^{37}Ar abundance in the ventilation air of the LNGS has been measured < 3.2 mBq / m^3. Even a contamination of 5 mBq / m^3 is a factor 13 too low to explain the excess.

But XENONnT is coming soon!

XENONnT already under commissioning

×3
active volume

1/6
background

xe-pr@lngs.infn.it
www.xenonexperiment.org

Based on best-fit from XENON1T, XENONnT will discriminate axions from tritium in few months