Observation of Excess Electronic Recoil Events in XENON1T

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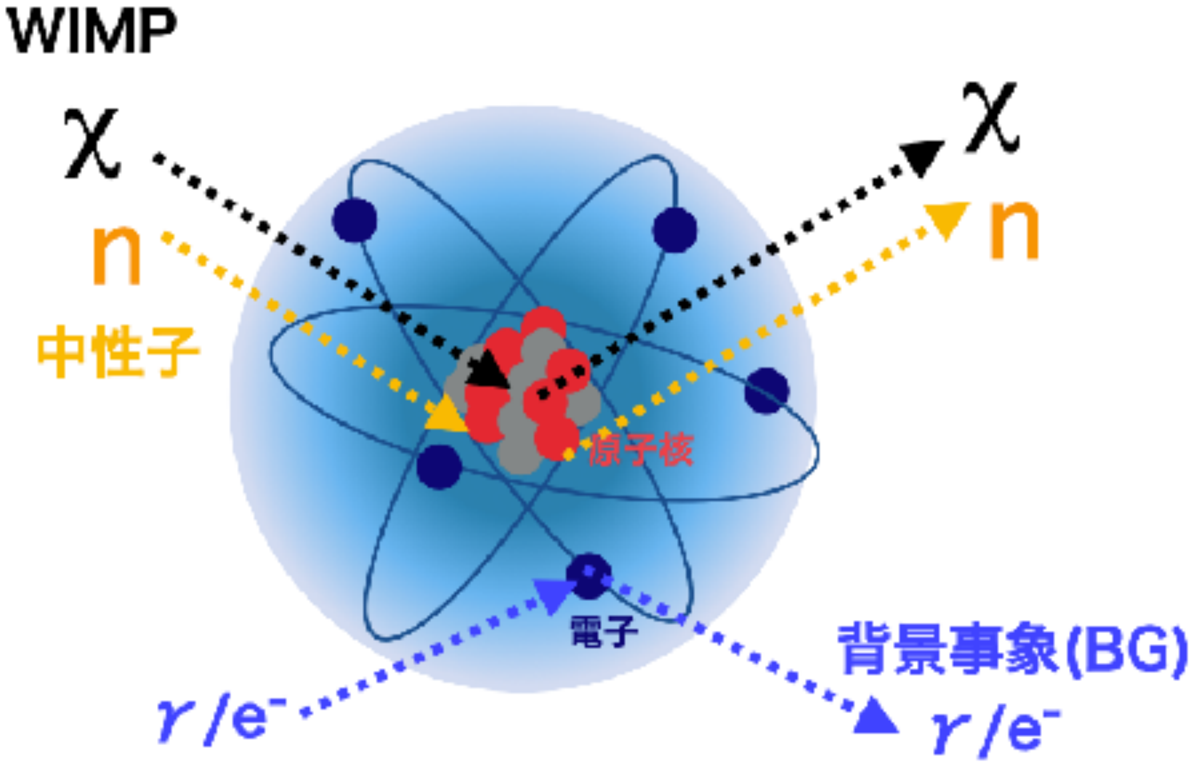
@基研研究会　素粒子物理学の進展２０２０

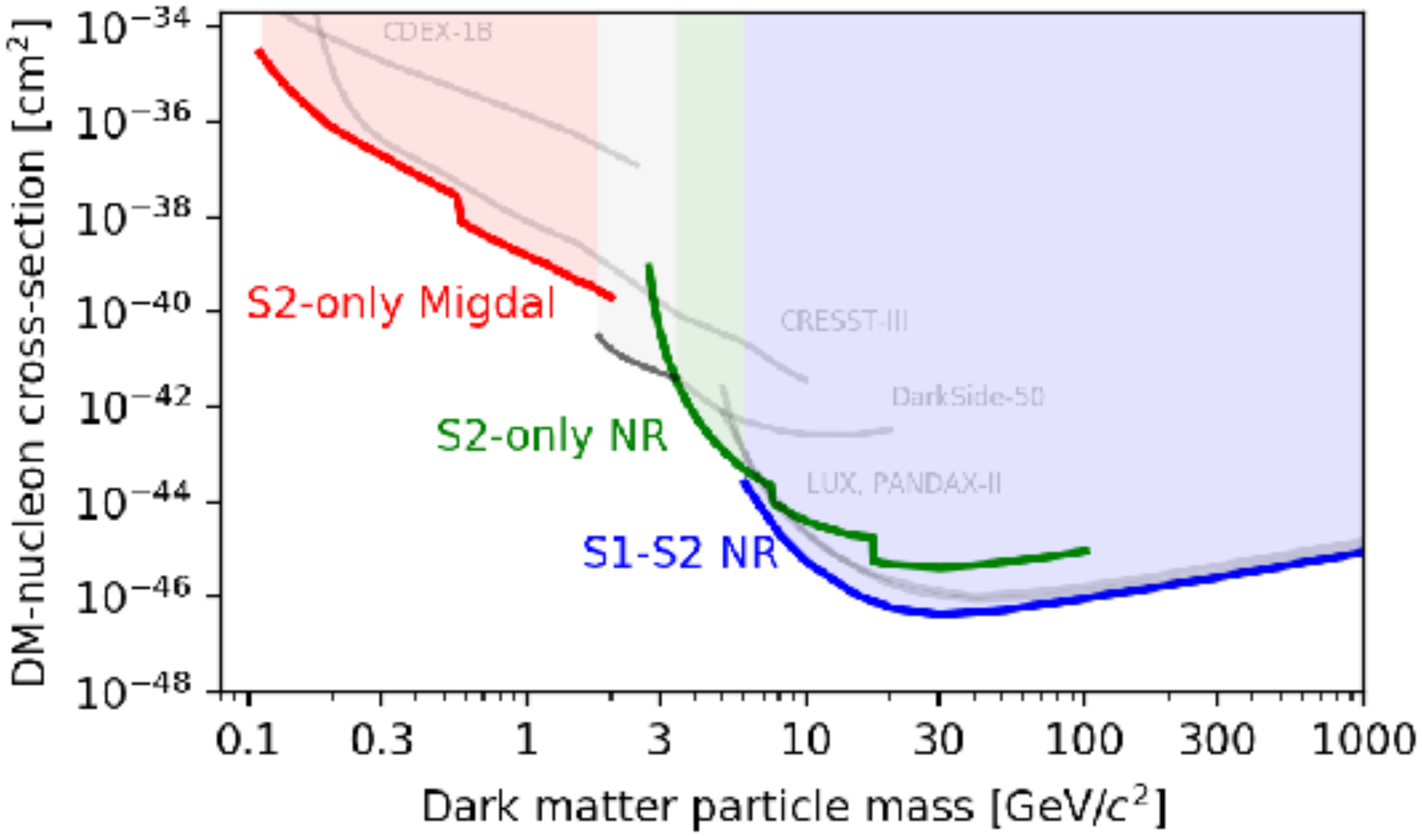
Direct Dark Matter Detection

WIMPの探索方法(直接探索)

確率は非常に小さいがWIMPも身の回りの物質(原子核)と相互作用をする(原子核反跳)。
原子核が受け取る反跳エネルギーを検出する(光, 電子, フォノン, etc)。



XENON1T実験のWIMP探索結果



XENON1T実験

- 液体キセノンを3.2トン(有効体積~1トン)を用いた直接探索実験
- 低質量&高質量の両極限(100MeV - TeV)で、世界で最も厳しい制限を与えている。
- 実験自体は既に終了していて、現在XENONnT実験へとアップグレード中(後述)

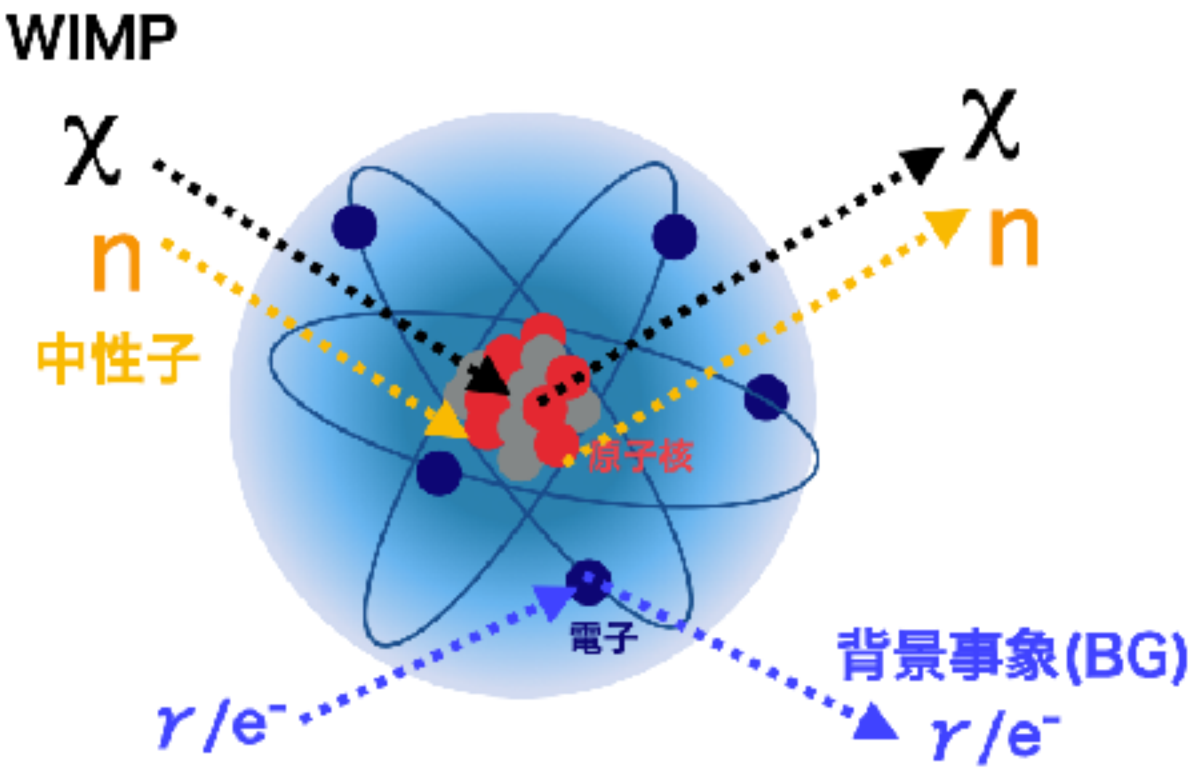
Direct Dark Matter Detection

太陽アクシオンや太陽ニュートリノの探索方法: 電子反跳

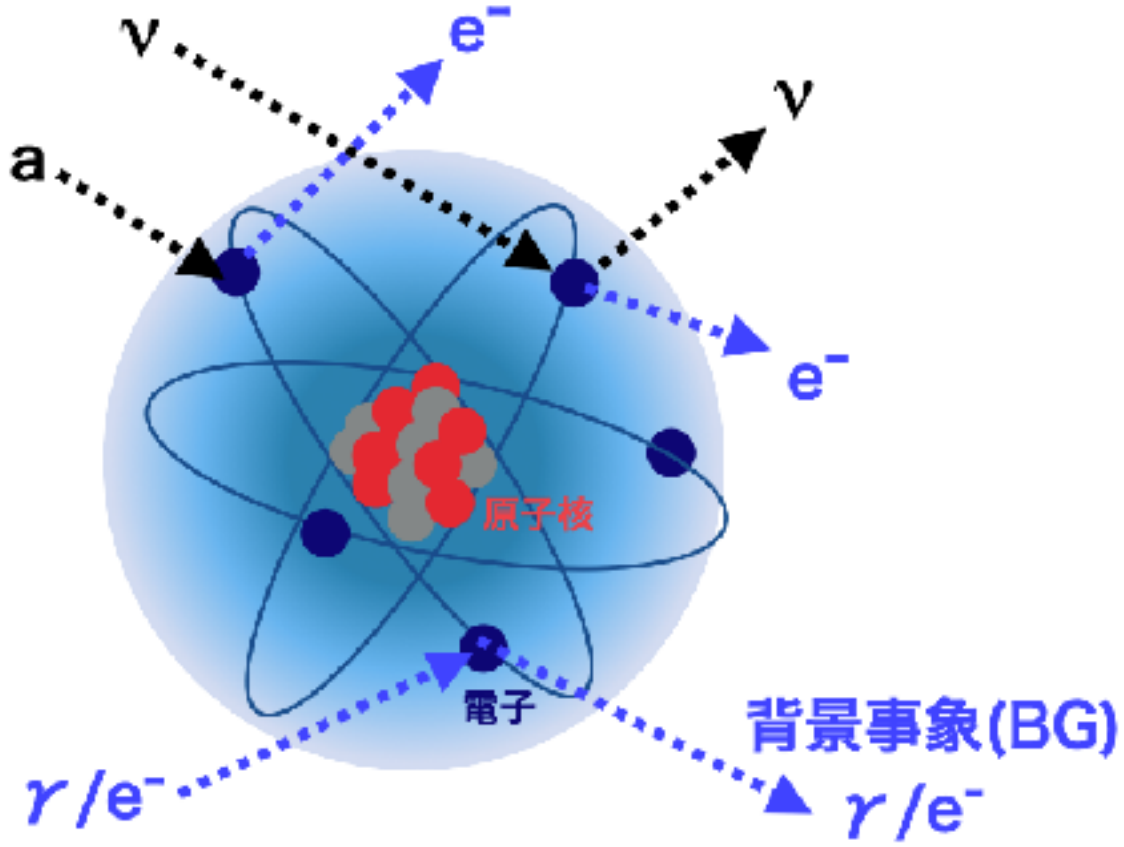
太陽アクシオン: Axio-electric effect (光電効果と似た効果, g_{ae})

太陽ニュートリノ: 電子散乱 (elastic scattering)

WIMPと原子核の相互作用 (原子核反跳)



太陽アクシオン・太陽ニュートリノ (今回はこちら！)



電子反跳事象の探索

- 通常、電子反跳事象はWIMP探索の背景事象(BG)
- WIMP searchと比べてBG量が多いので、BGをより精密に評価し、そこからの超過を探す

The XENON1T/nT Experiment @ LNGS in Italy

水に換算して3600mの深さに実験装置をインストール

Water tank

- 700 t of pure water

Cherenkov Muon Veto

- 84 8-inch PMTs (R5912)

External calibration

- ^{241}AmBe (NR)
- Neutron generator (NR)

Cryostat and support structure for TPC

TPC

- 248 3-inch PMTs (R11410-21, QE~34%@178nm)
- LXe mass: 3.2 t(total), 2.0t (active)

Cryogenics, and purification

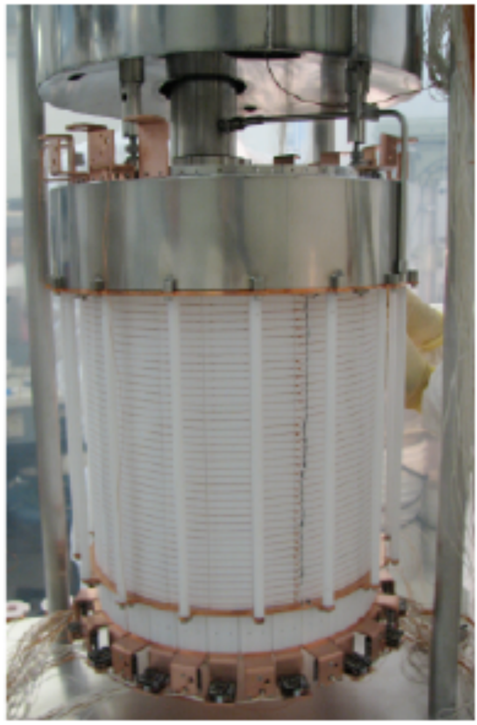
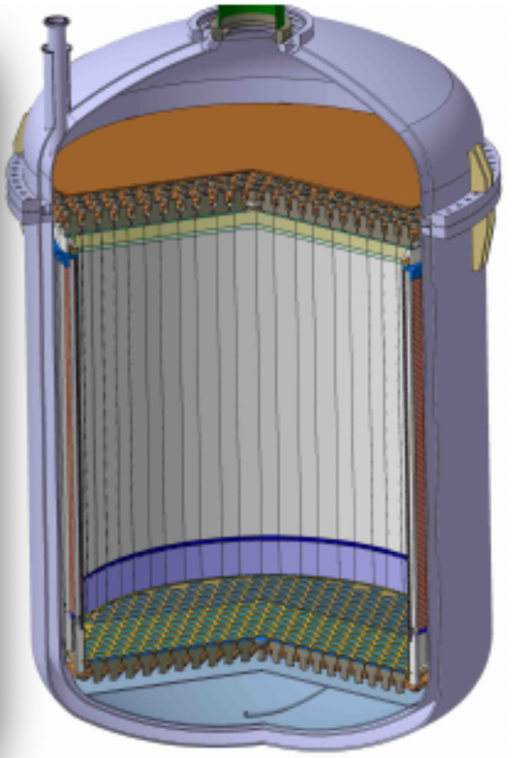
Internal calibration

- ^{83m}Kr (ER),
- ^{220}Rn (ER)

DAQ and slow control

Xenon storage (ReStoX), handling and Kr distillation

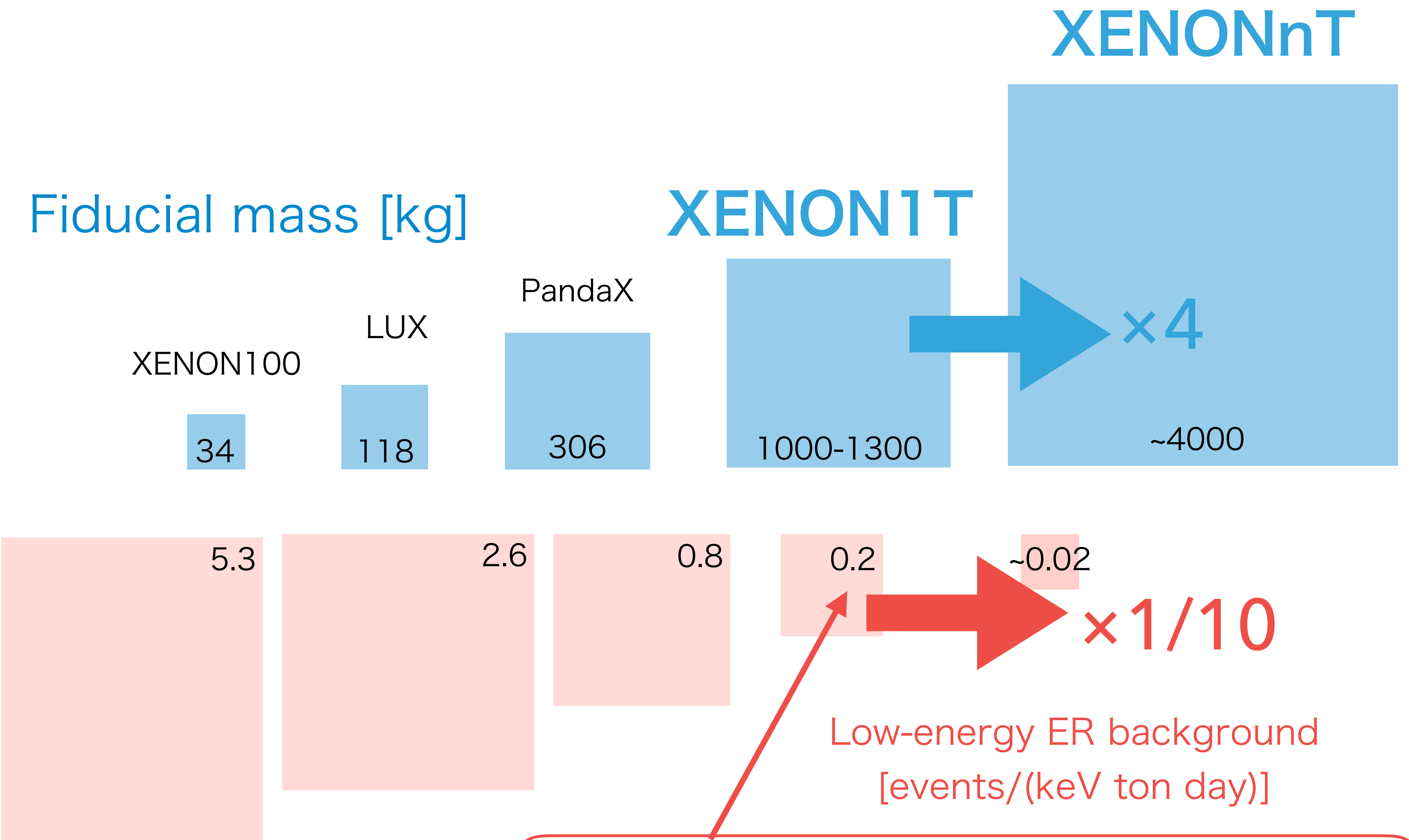
The XENON + DARWIN Program

XENON10	XENON100	XENON1T	XENONnT	DARWIN
				
2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2	$\sim 10^{-49}$ cm^2

昨日、ちょうど液体キセノンをfillし始めた！

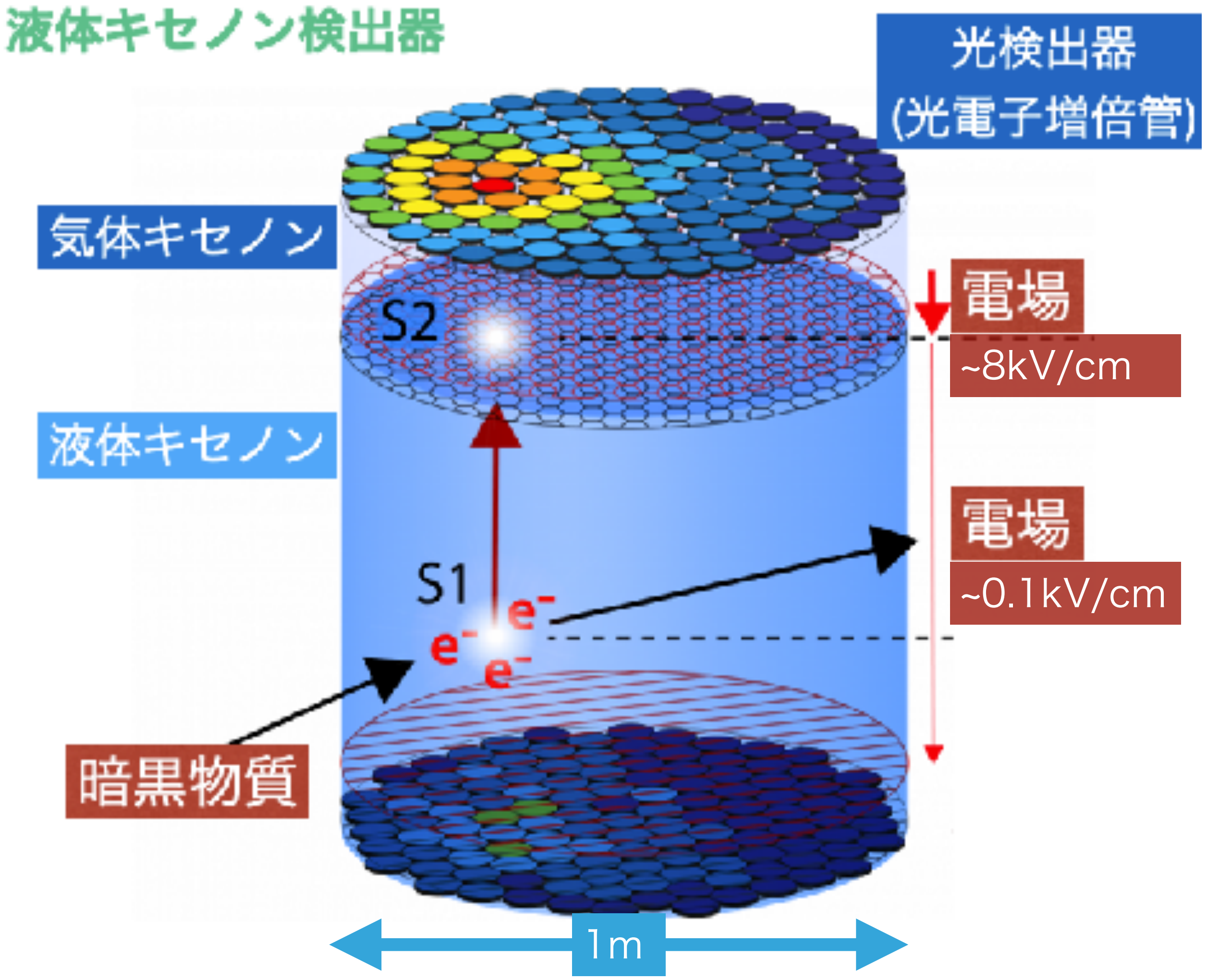
名大、神戸大、IPMUは先月末にDARWINにも参加！

History of LXe TPCs



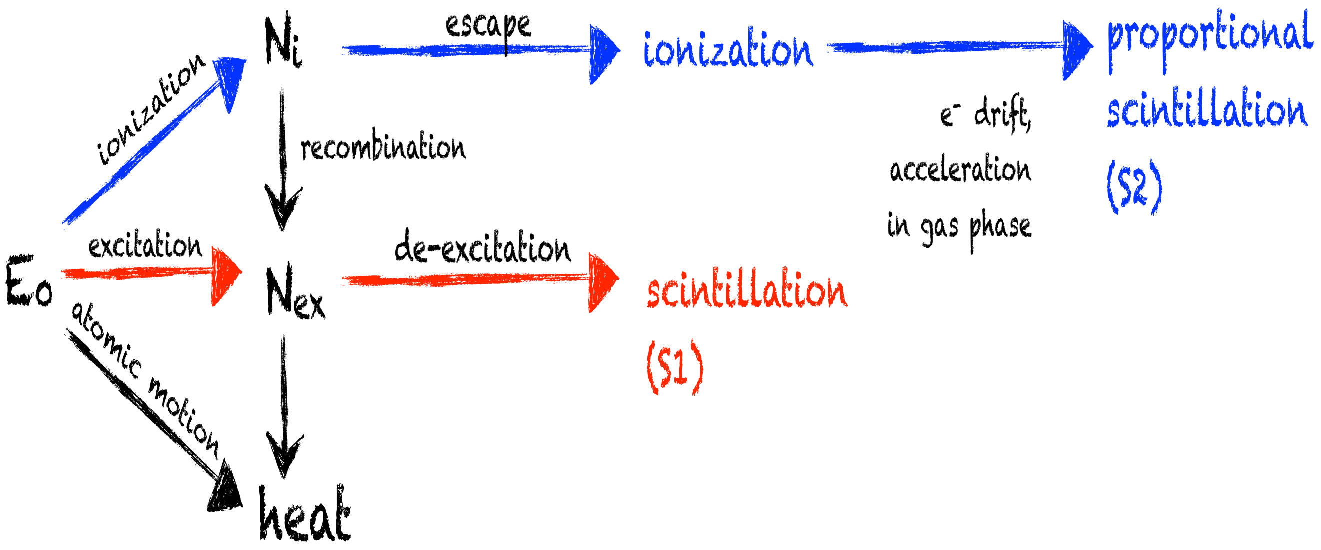
1トン・1keV当たり、約5日待って1電子反跳BG事象あるかないか

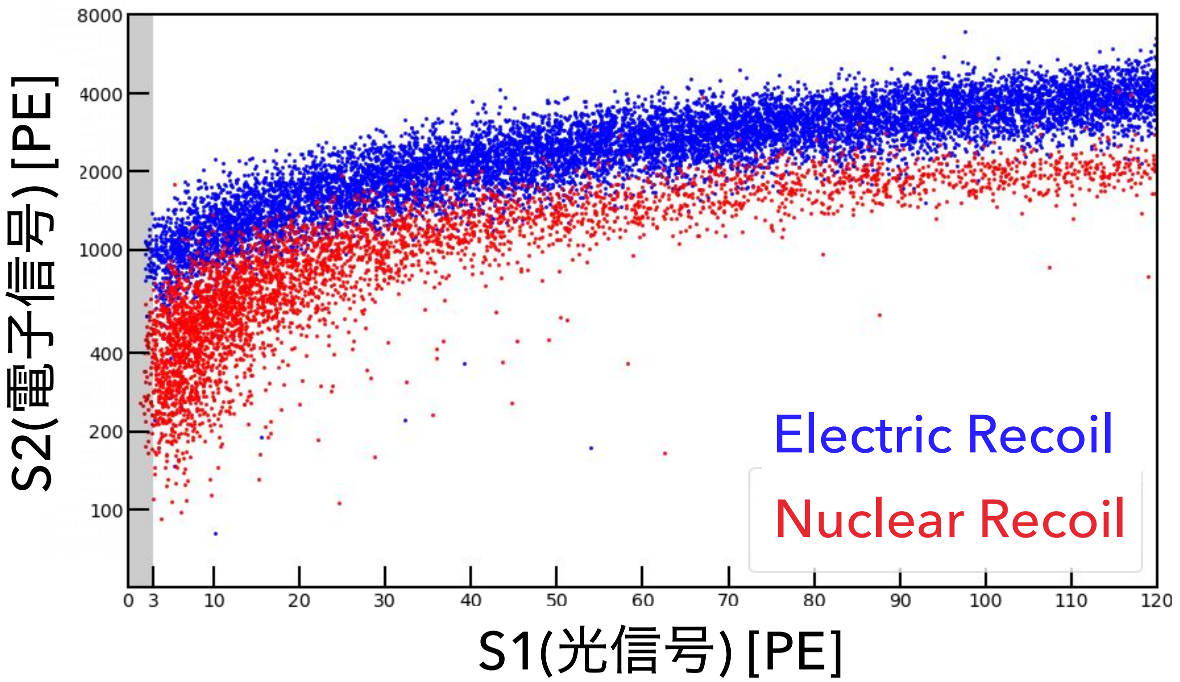
LXe TPC: Working Principle



- Primary scintillation light (**S1**) is produced promptly at the interaction site
- Ionization electrons drift up through the LXe in the applied electric field
- Some recombine with ions —> more scintillation light (**S1**)
- Others are extracted above the liquid surface into gas phase region, where they form secondary proportional scintillation light (**S2**)
- Event vertex reconstruction in 3D space
  - **X,Y position: S2 hit-pattern in top PMT array**
  - **Z position: electron drift time, Δt (s1, s2)**
- Particle type discrimination: **$(S2/S1)_{\gamma,e}$ > $(S2/S1)_{\mathrm{WIMP}}$**

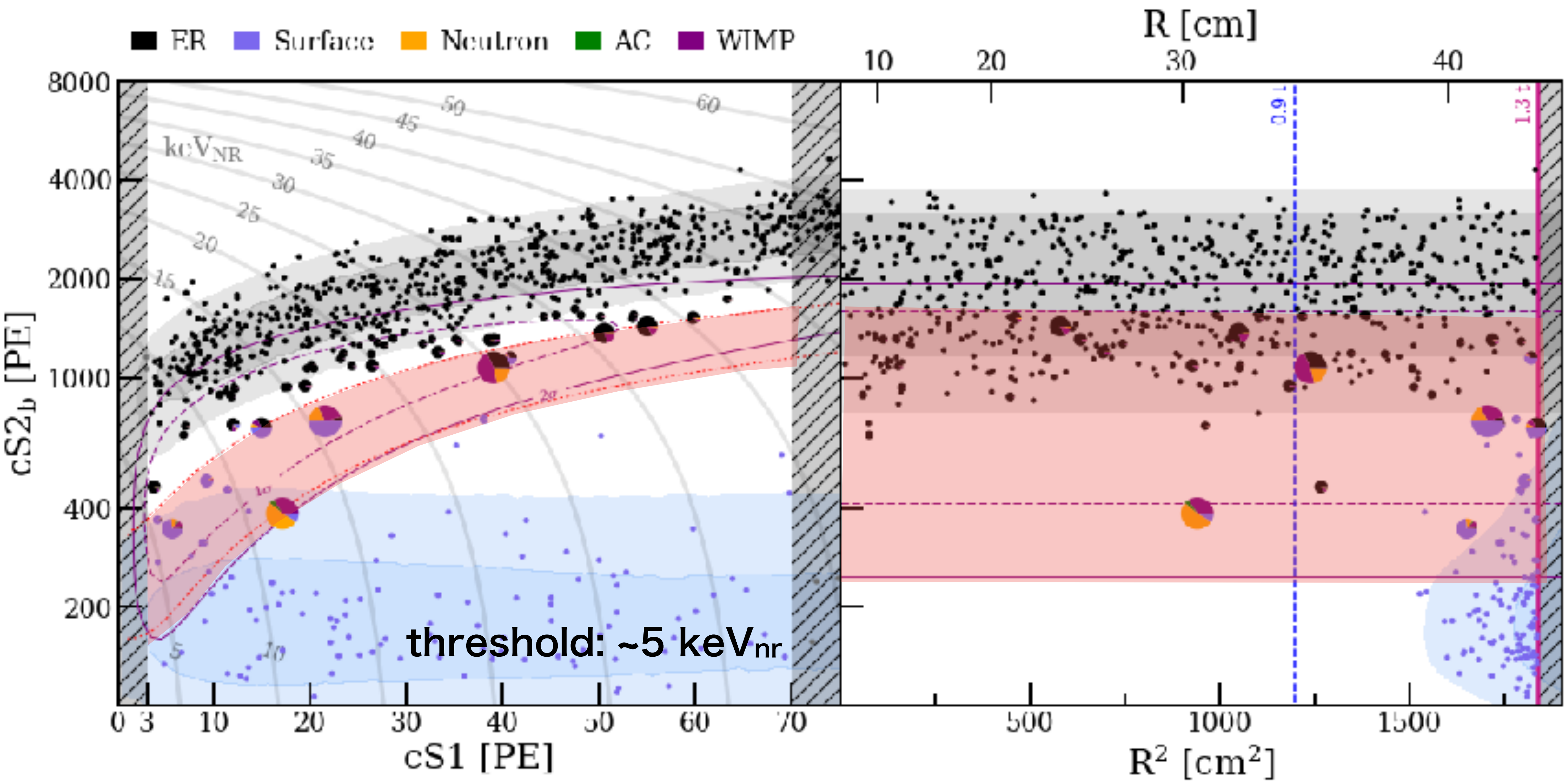
Electric Recoil Nuclear Recoil





XENON1T WIMP Searches - 2018 (NR Search)

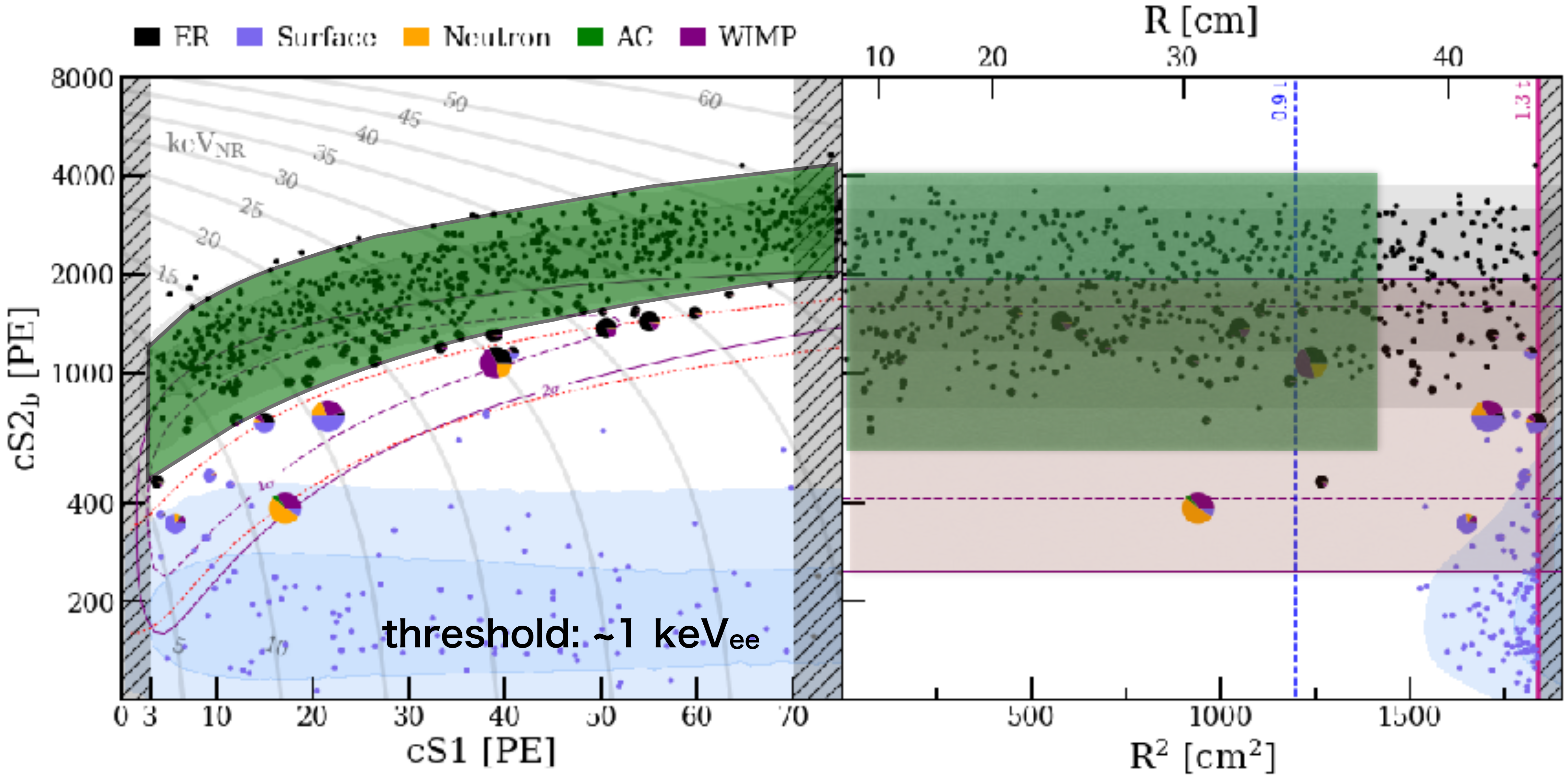
One ton-year of search for WIMPs induced nuclear recoils



Most stringent result on WIMP Dark Matter down to 3 GeV/c² masses

XENON1T Solar-Axion / ALPs Searches - 2020 (ER Search)

検出器部材からの放射線(ガンマ線)を除くため、有効体積はWIMPより小さい。



太陽アクシオンやALPs, Dark Photon探索における戦略

- 電子反跳BGの絶対量を減らす
- 既知のBG(放射性ラドン・クリプトンなど)を精密に評価し、超過を探す

Energy Reconstruction with LXe TPC

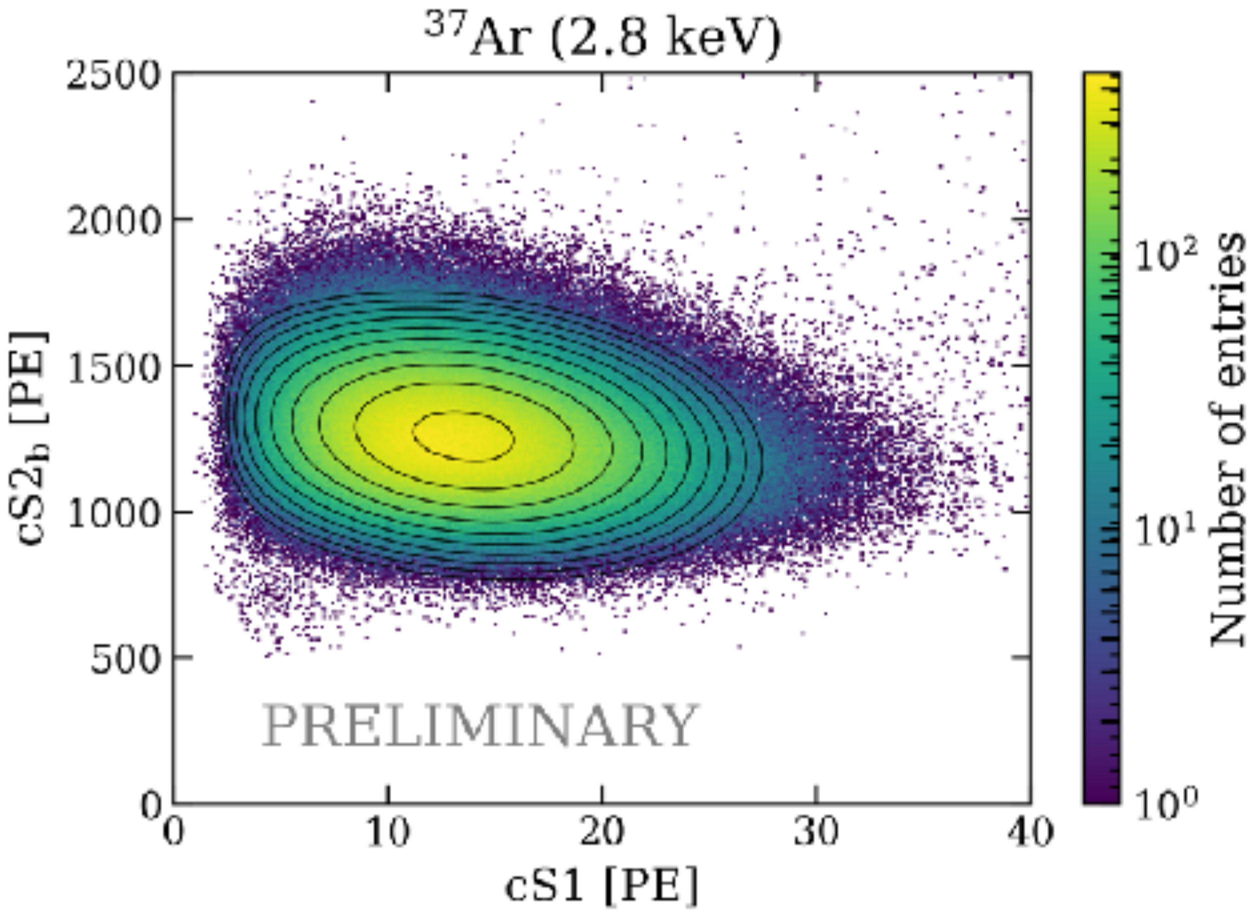
$$E = (N_{ph} + N_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

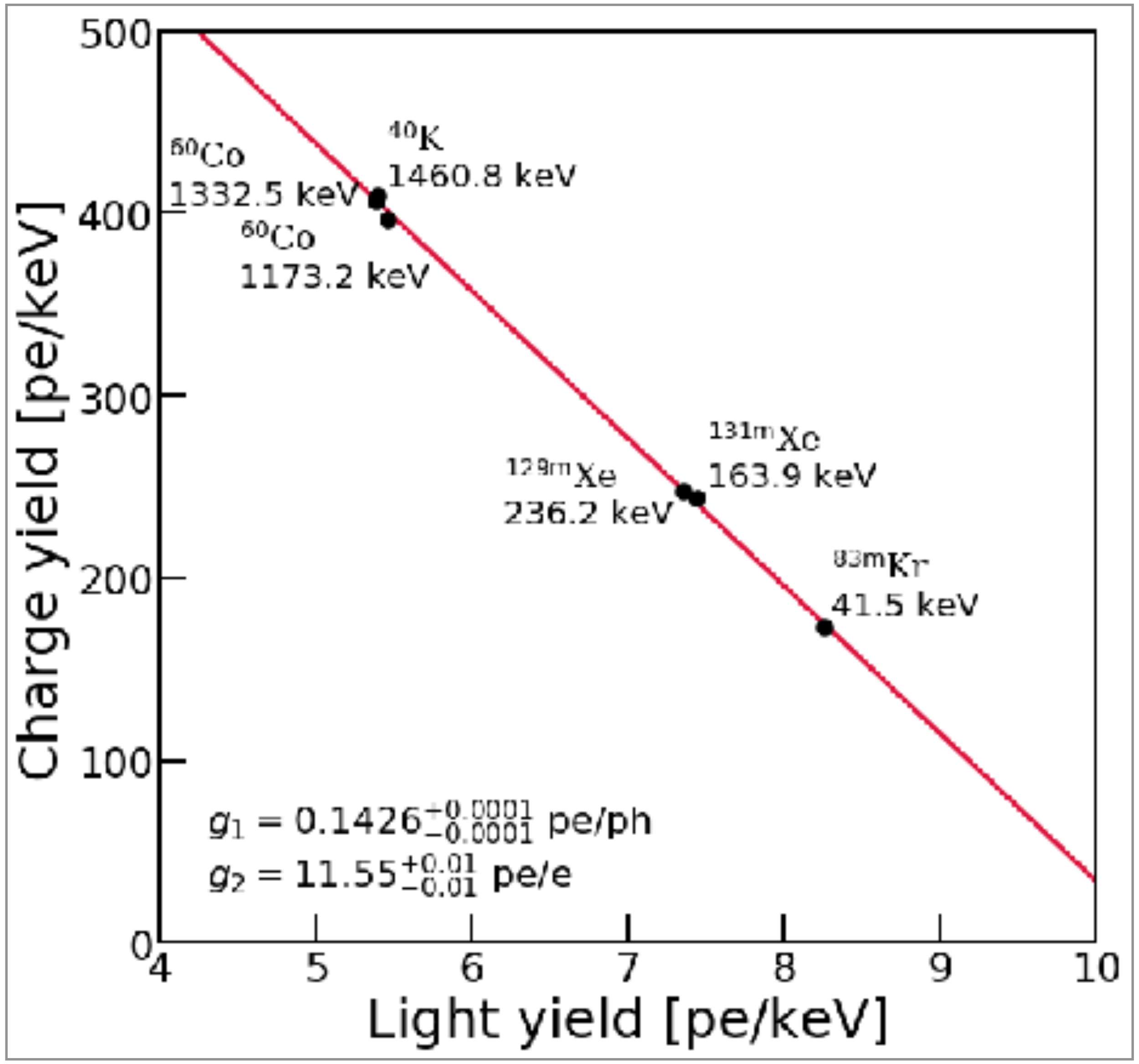
where W = 13.7 eV/quanta

S1, S2はPMTで測定される量!

g1 and g2: detector-specific gain constants

extract g1/g2 from calibration data, use it to reconstruct energy of each event





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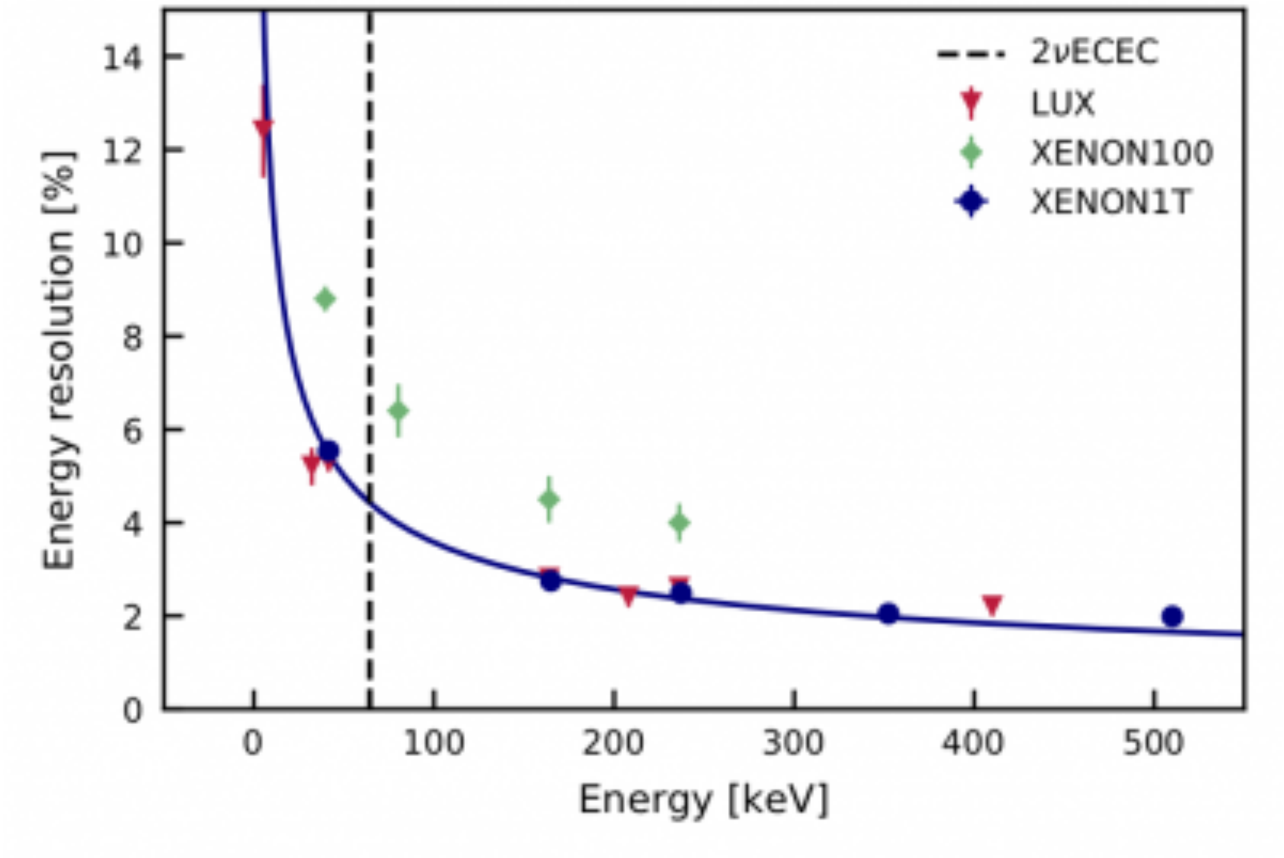
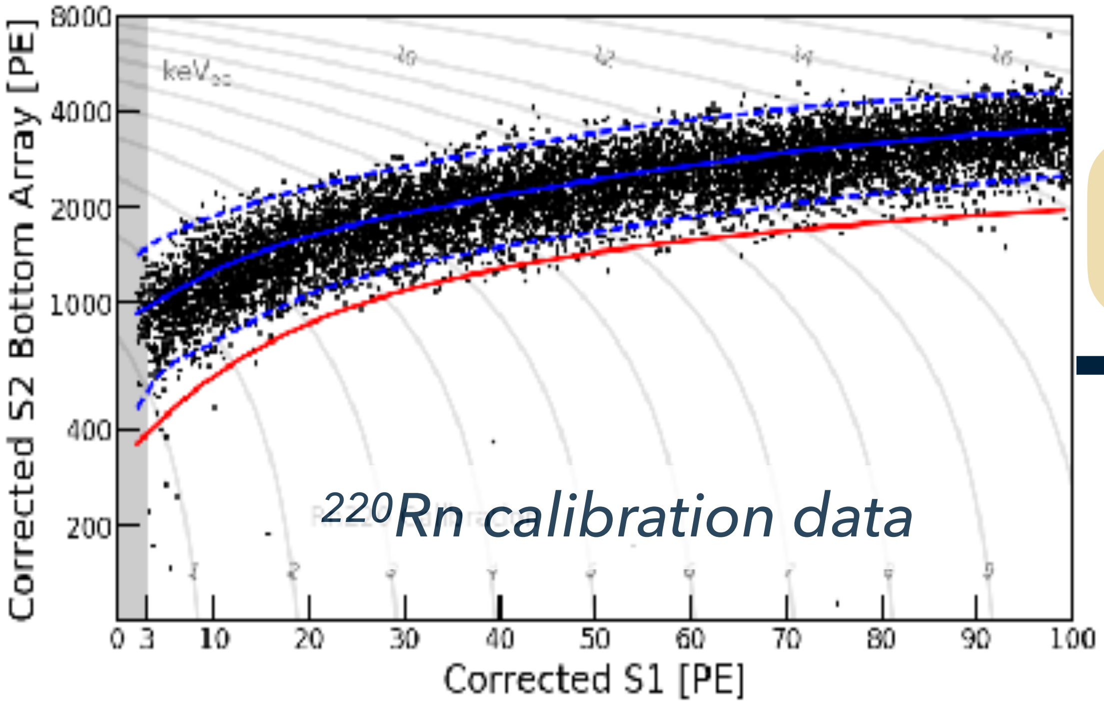
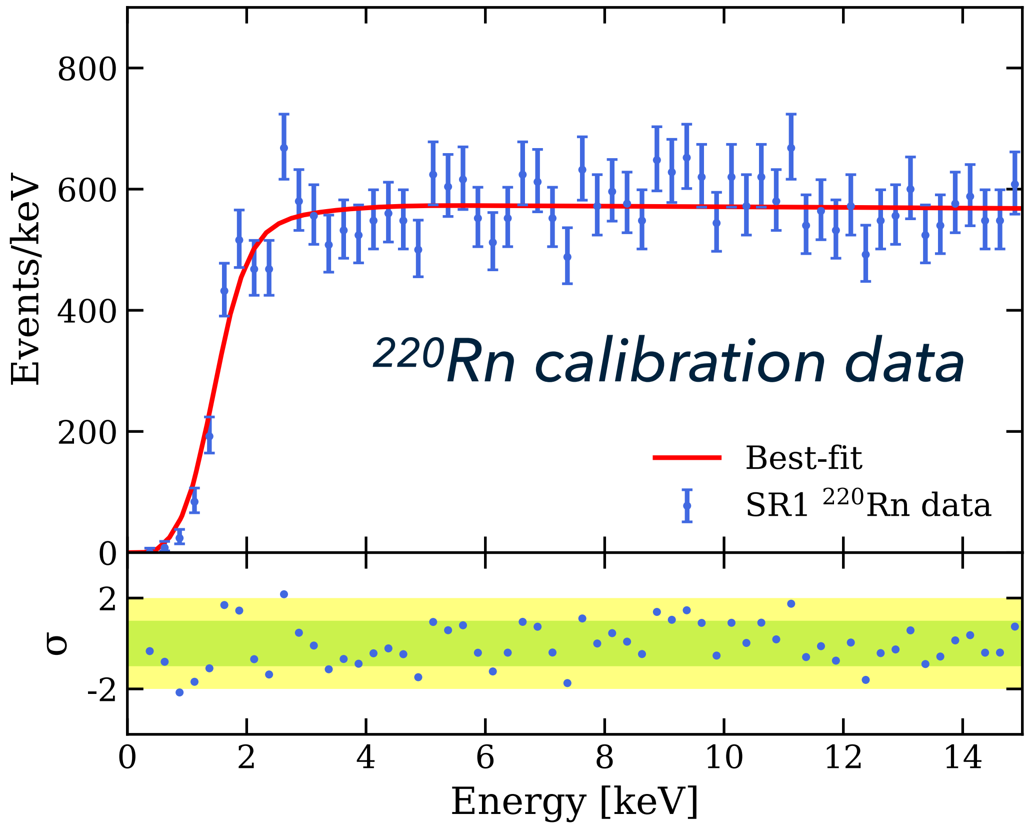




2D analysis in s1-s2 space

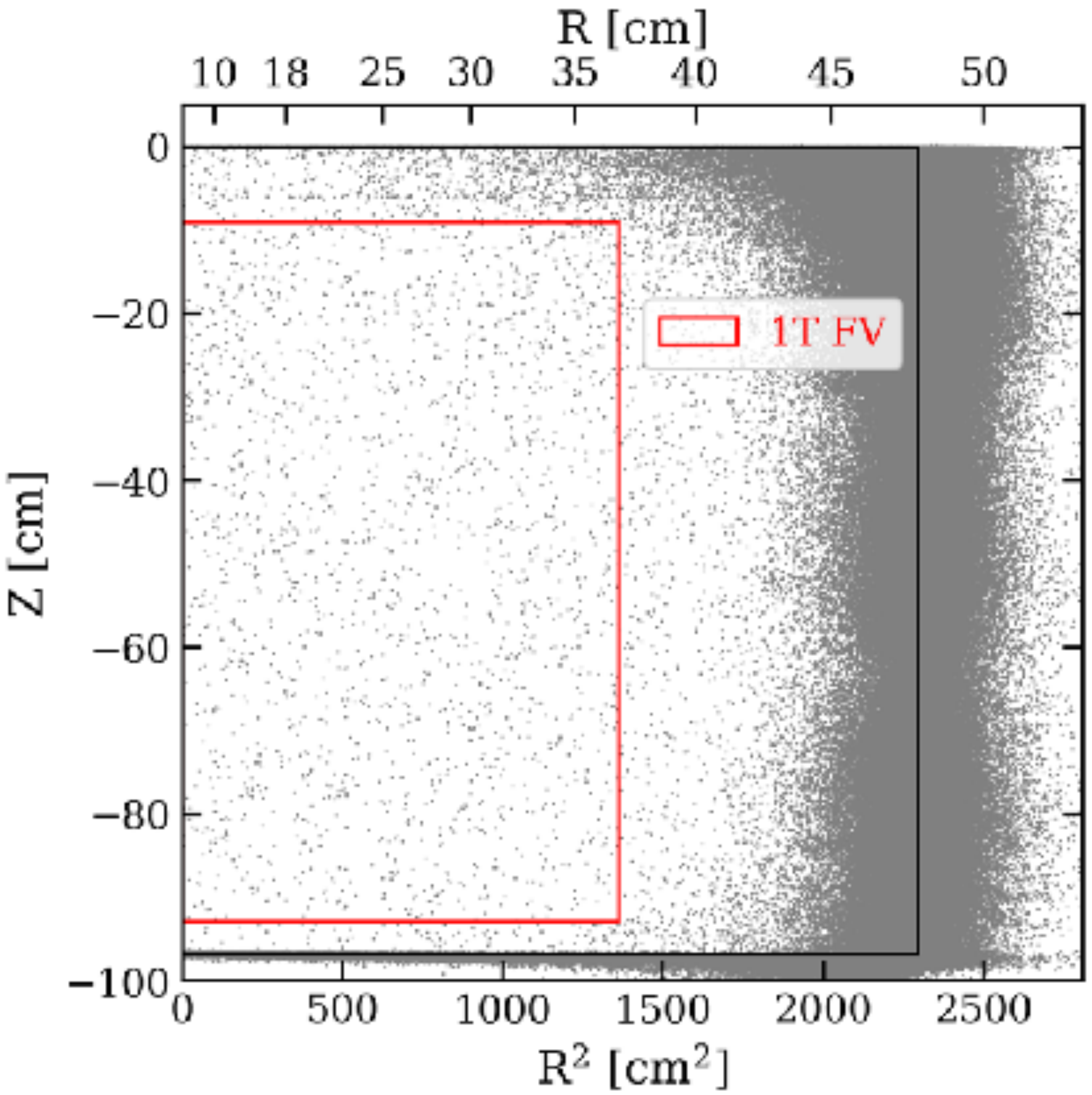
$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

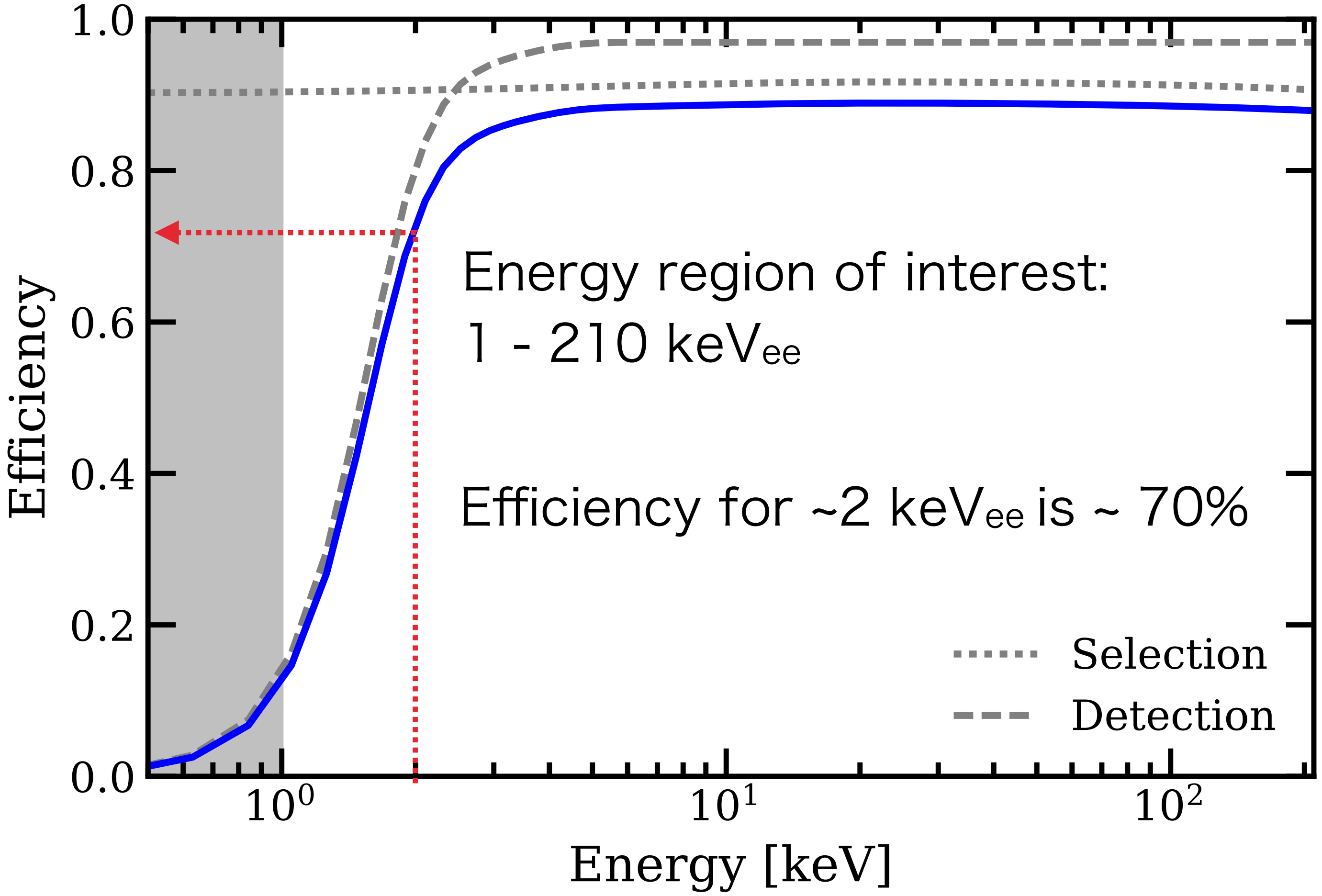


1D energy spectrum

Data Selection & Efficiency

- Fiducial volume 1042 kg
- Single-scatter events, standard data quality cuts
- Higher S2 threshold (> 500 pe) to remove instrumental BGs
- Detection efficiency is dominated by 3-fold PMT coincidence for S1 detecetion





Energy region of interest:
1 - 210 keV$_{ee}$

Efficiency for ~2 keV$_{ee}$ is ~ 70%

Signal Models

Solar-Axion: Production

Three components of solar axion flux

ABC g_{ae} (Atomic recombination and deexcitation, Bremsstrahlung and Compton)

axion-electron interactions
dominated by Bremsstrahlung and Compton

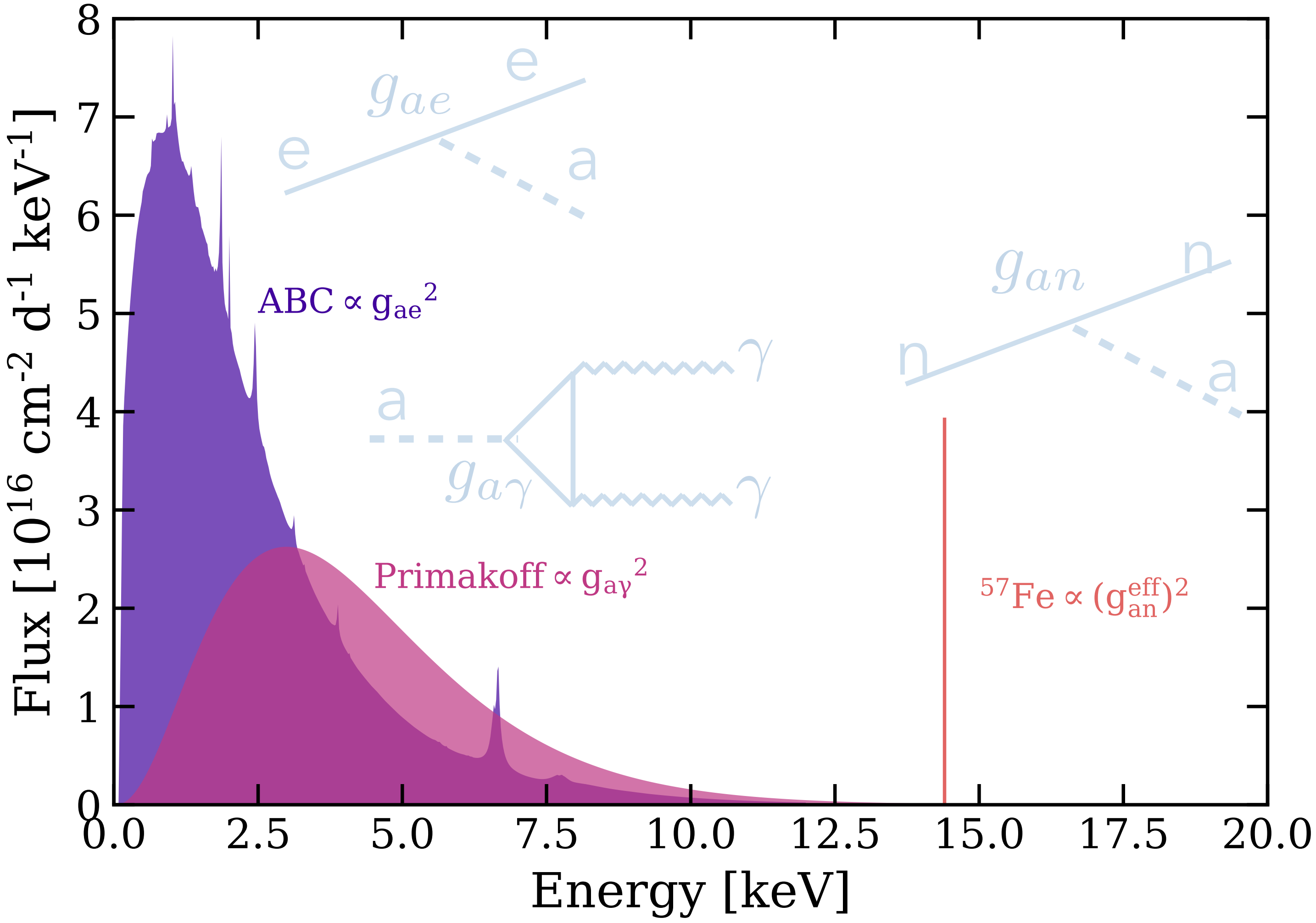
Primakoff: $g_{a\gamma}$

axion-photon coupling
axions produced from photon conversion induced by the electric field of ions and electrons in the Sun.

Fe-57 nuclear transition:

$$g_{an}^{\mathrm{eff}} = -1.19 g_{an}^{0} + g_{an}^{3}$$

mono energetic **14.4 keV** M1 transition
effective axion-nucleon coupling



Emerge with keV-scale energies
In principle, axions from all 3 couplings can be present at the same time.

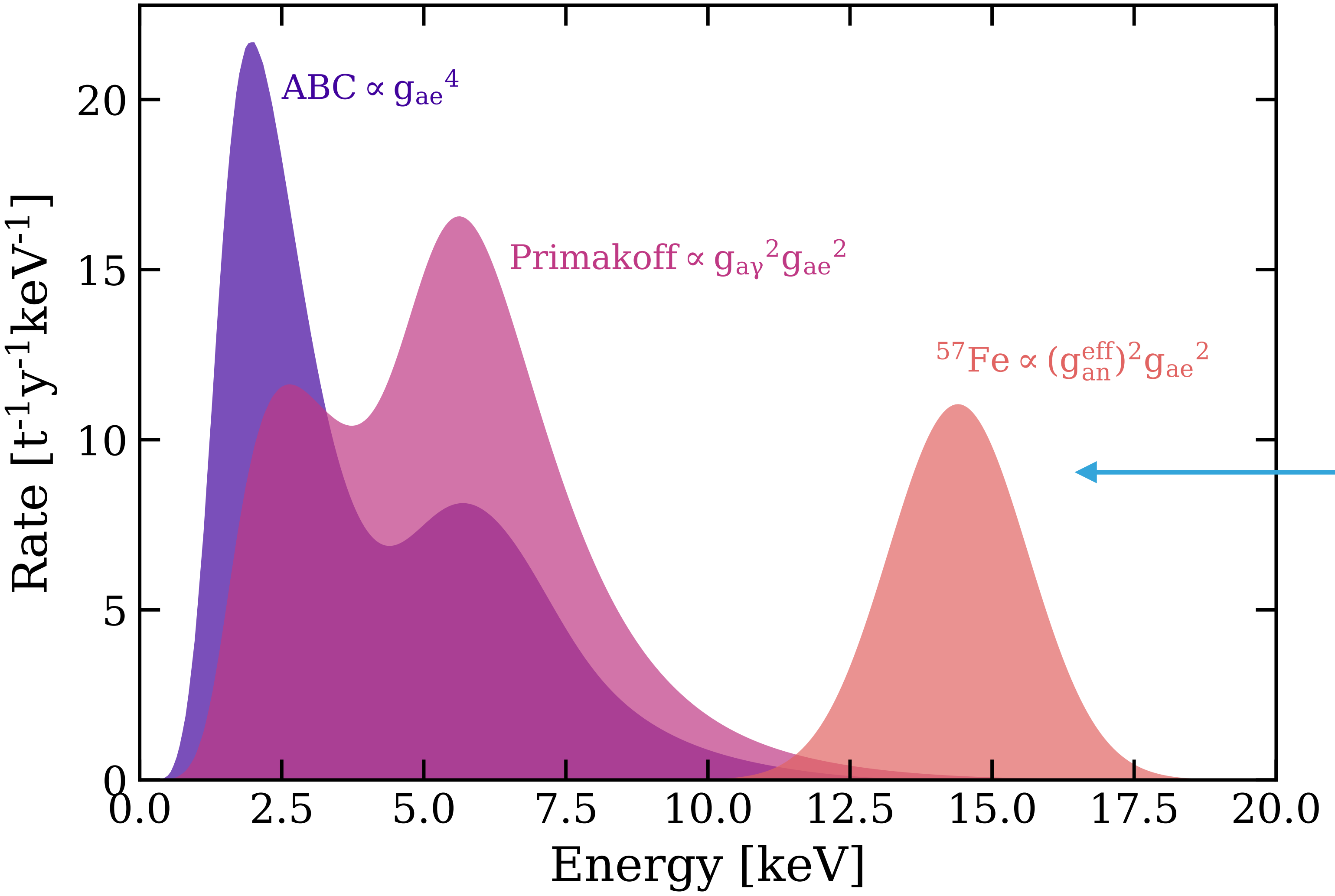
XENON1T sensitive to all 3 channels via
coupling to electrons g_{ae}
(electronic recoils via axio-electric effect).

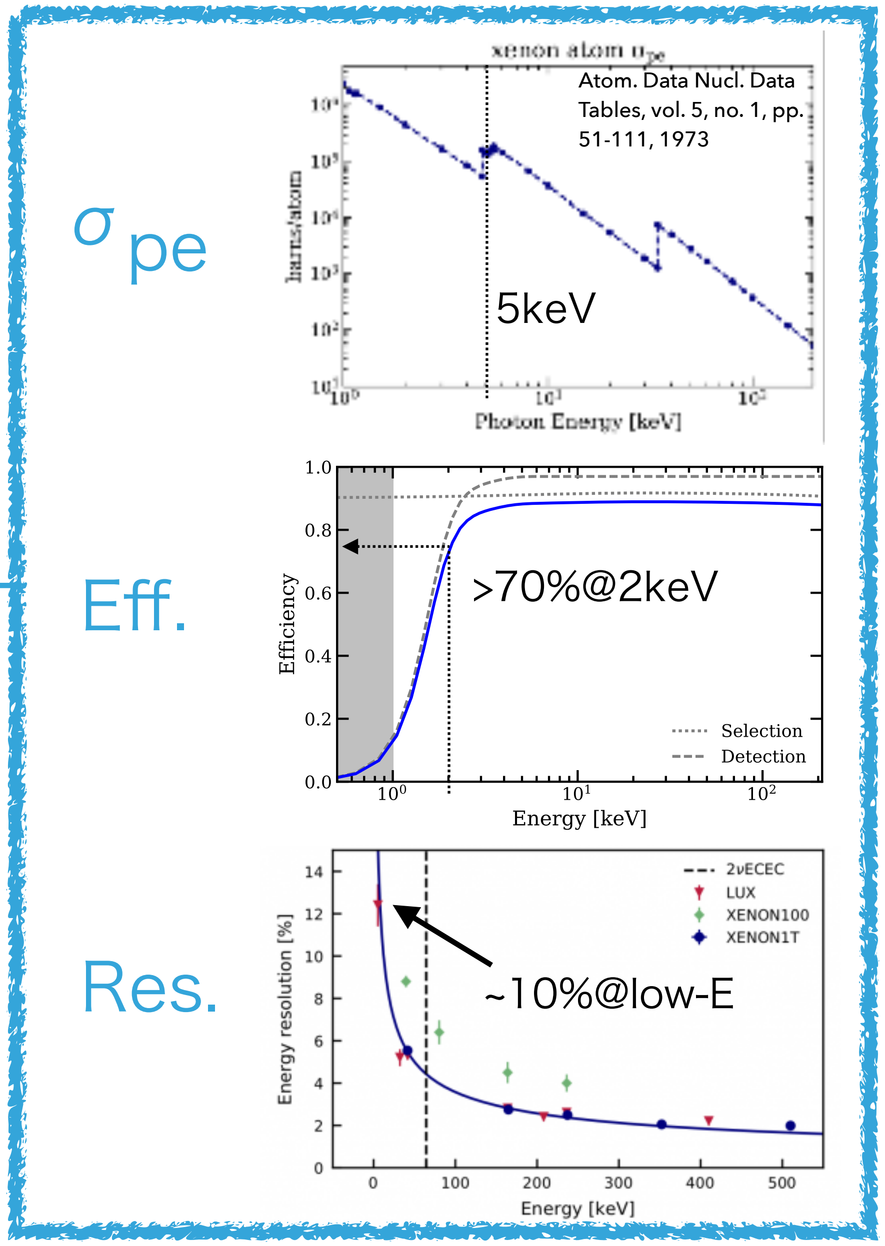
$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

β (Ea): velocity (energy) of axion

Solar-Axion: Detection

Expected rate in xenon convolved with detector effects (resolution, efficiency) and σ pe



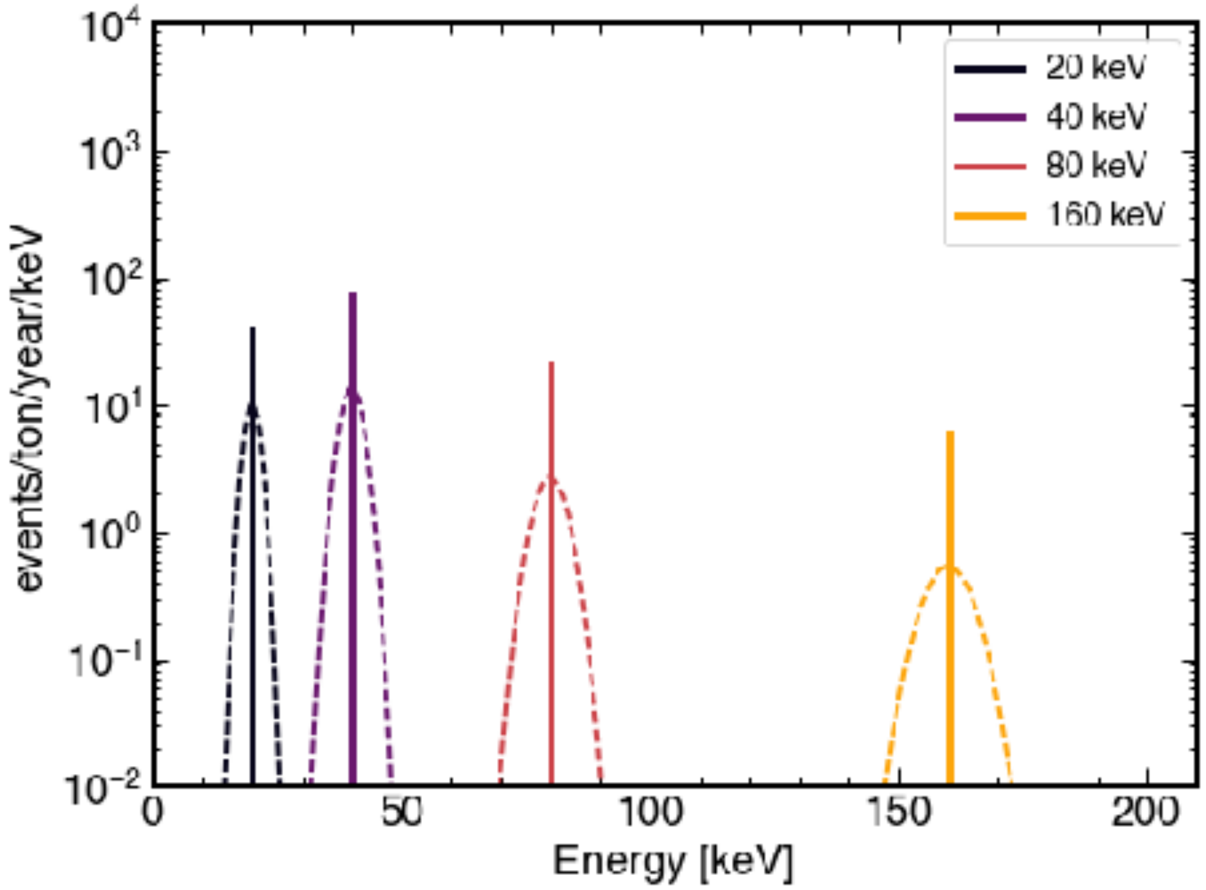


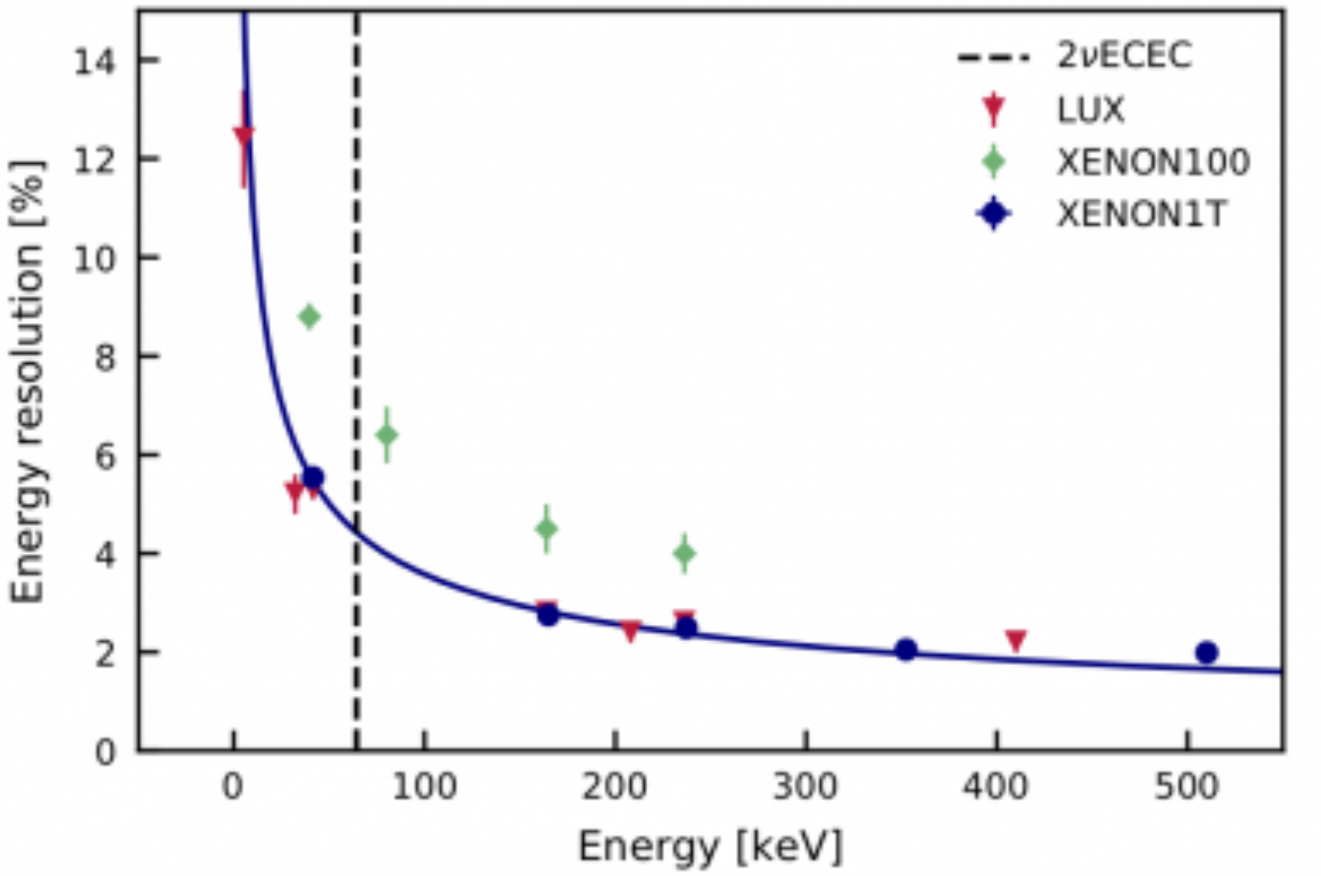
Atom. Data Nucl. Data Tables, vol. 5, no. 1, pp. 51-111, 1973

- For Primakoff and ^{57}Fe, can only deduce product of 2 couplings.
- All the three flux components are considered completely independent of each other —> Model-independent search: parameters of interest = $\boxed{g_{ae} \text{ vs. } g_{ae}g_{a\gamma} \text{ vs. } g_{ae}g_{an}^{eff}}$
- XENON1T is more sensitive to DFSZ model, where axions couple to electrons at tree level compared to KSVZ model (couples to electrons at loop level)

Axion-like Particle / Dark Photon

Assuming ALPs/dark photons are non-relativistic and make up all of the local dark matter, the expected signal is a mono-energetic peak at the rest mass of the particle





For ALPs

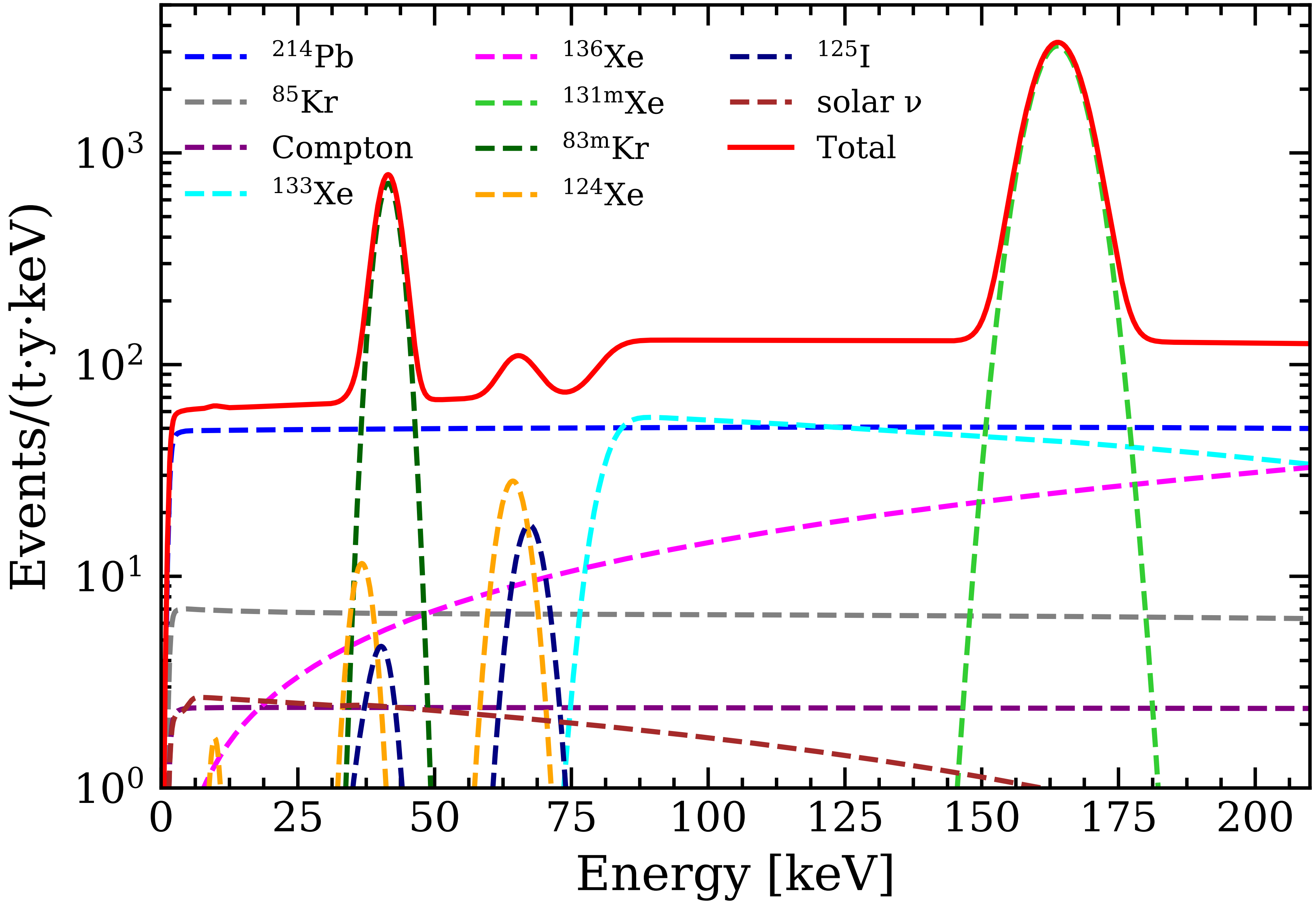
$$R \simeq \frac{1.5\times10^{19}}{A} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{\mathrm{keV}/c^2}\right)\left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

For dark photons

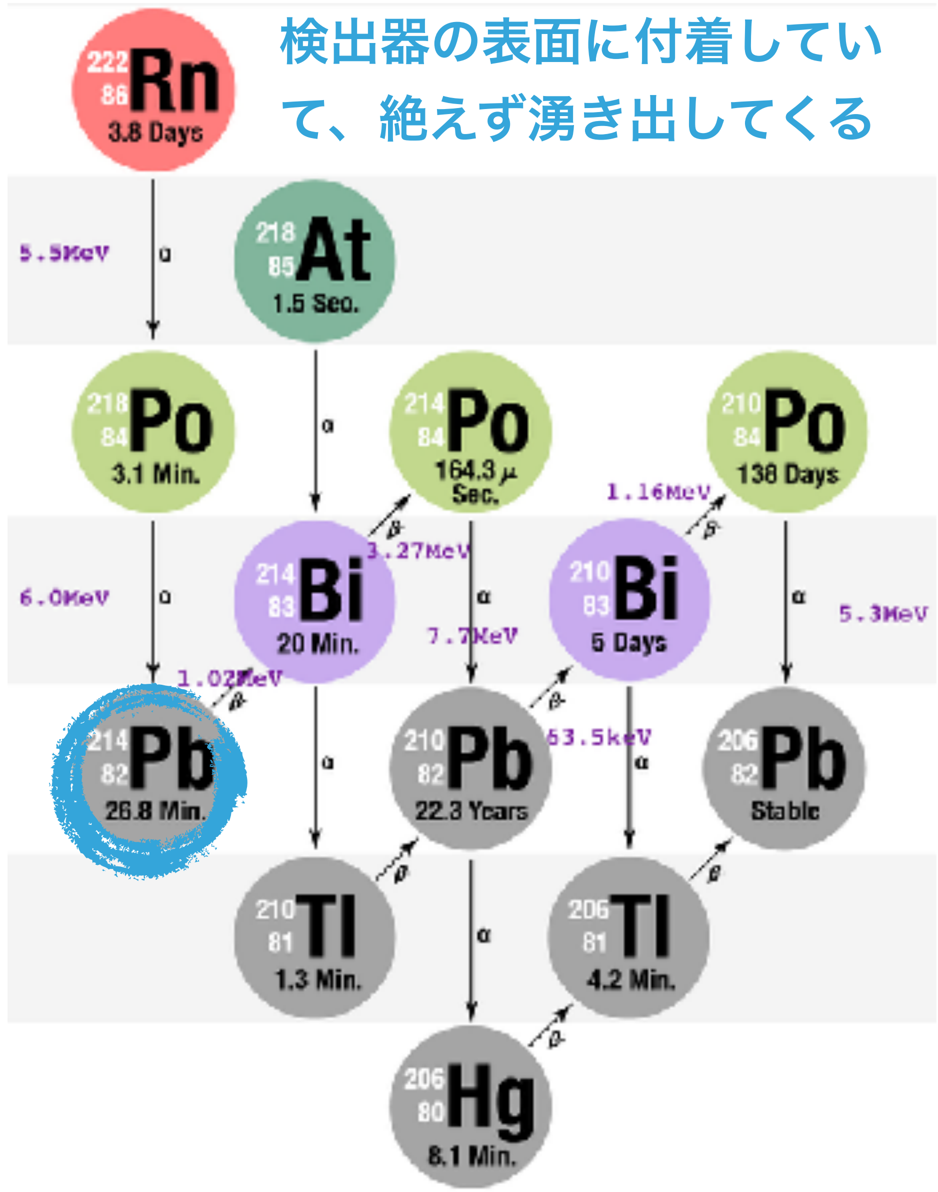
$$R \simeq \frac{4.7\times10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}/c^2}{m_{\mathrm{V}}}\right)\left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Background Models

Background Model



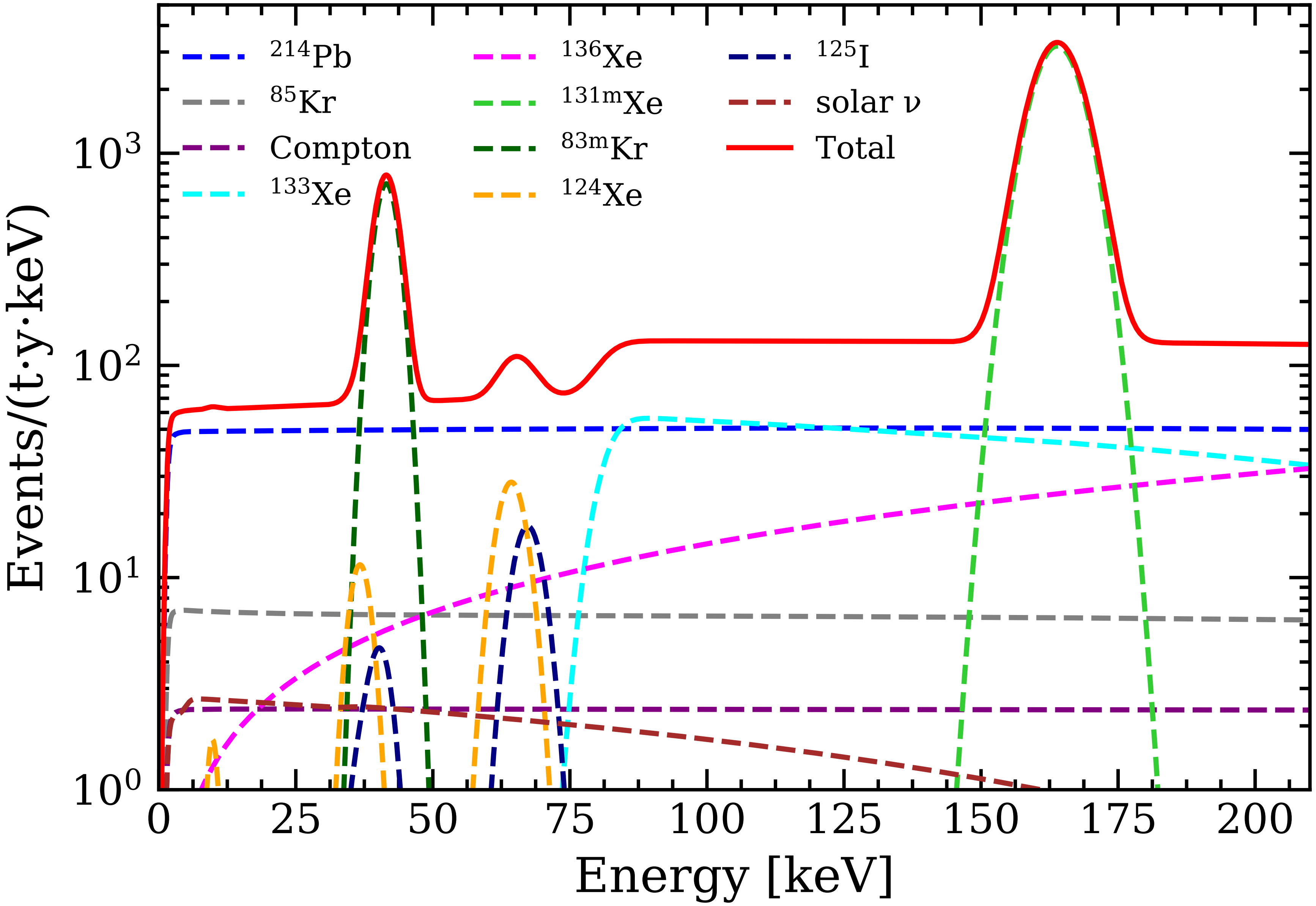
^{214}Pb: main ER BG



検出器の表面に付着していて、絶えず湧き出してくる

Predicted energy spectra based on detailed modeling of each background component
Rates constrained by measurements and/or time dependence

Background Model



10 Components

Internal Backgrounds

^{214}Pb ^{85}Kr

Intrinsic Backgrounds

^{124}Xe ^{136}Xe

solar neutrino

Activated Backgrounds

^{131m}Xe ^{133}Xe

^{125}I

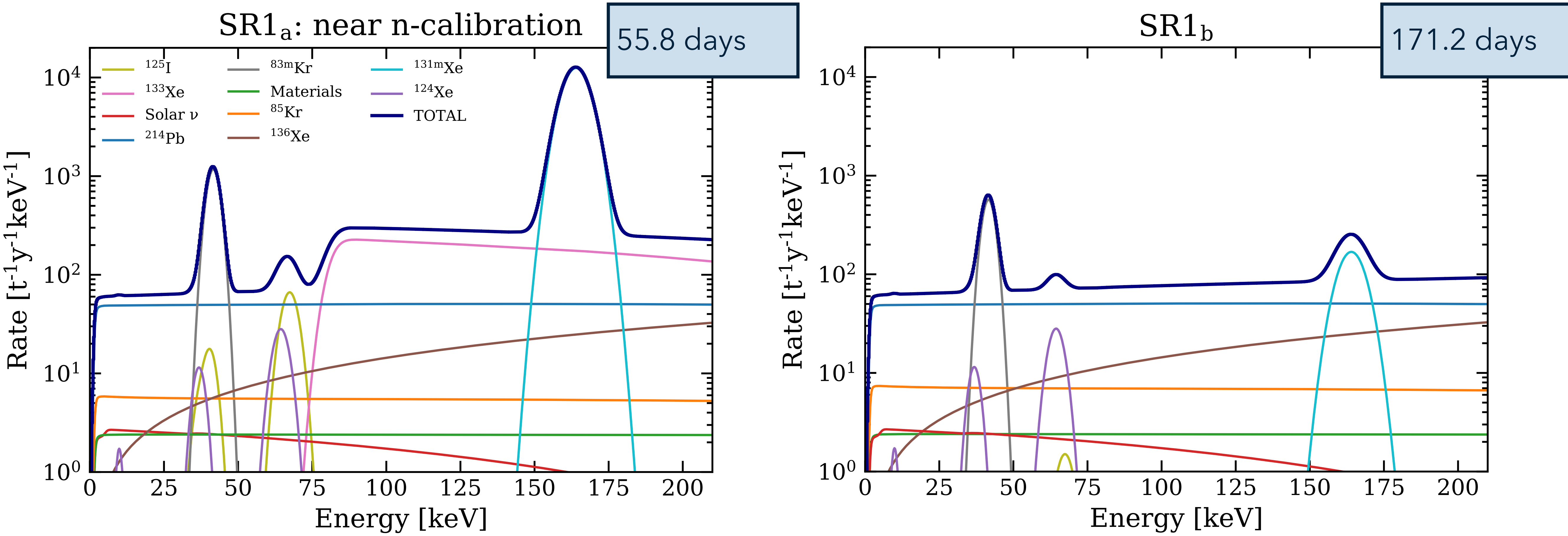
Contaminant Backgrounds

^{83m}Kr Materials

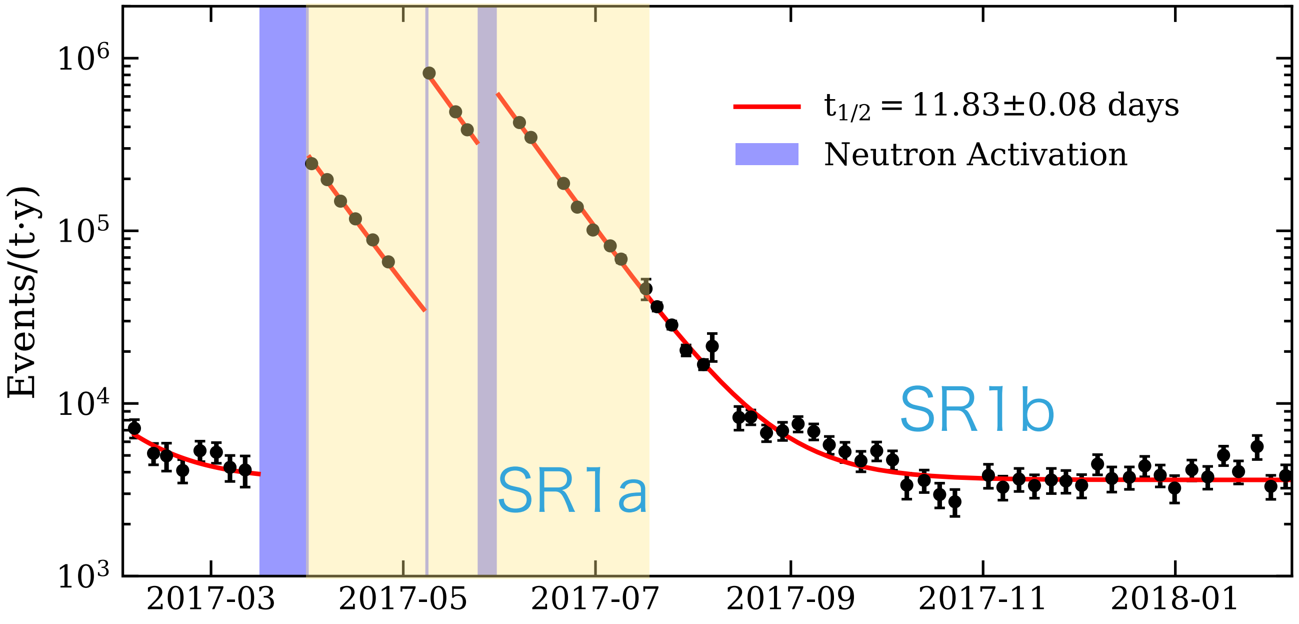
Predicted energy spectra based on detailed modeling of each background component

Rates constrained by measurements and/or time dependence

Background Model



Time-evolution and model of ^{131m}Xe (generated by neutron activation)



Divided into two datasets, fit simultaneously.

- SR1$_a$: <50 days from neutron calibration, includes more activated backgrounds
- SR1$_b$: the rest, less activated backgrounds
- background model denoted B_0

Fit to Data

Unbinned Profile Likelihood Analysis

$$\begin{aligned}\mathcal{L}(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = {} & \text{Poiss}(N|\mu_{tot}) \\ & \times \prod_i^N \left(\sum_j \frac{\mu_{b_j}}{\mu_{\text{tot}}} f_{b_j}(E_i, \boldsymbol{\theta}) + \frac{\mu_s}{\mu_{\text{tot}}} f_s(E_i, \boldsymbol{\theta}) \right) \\ & \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n), \qquad (14) \\ \mu_{\text{tot}} = {} & \sum_j \mu_{b_j} + \mu_s,\end{aligned}$$

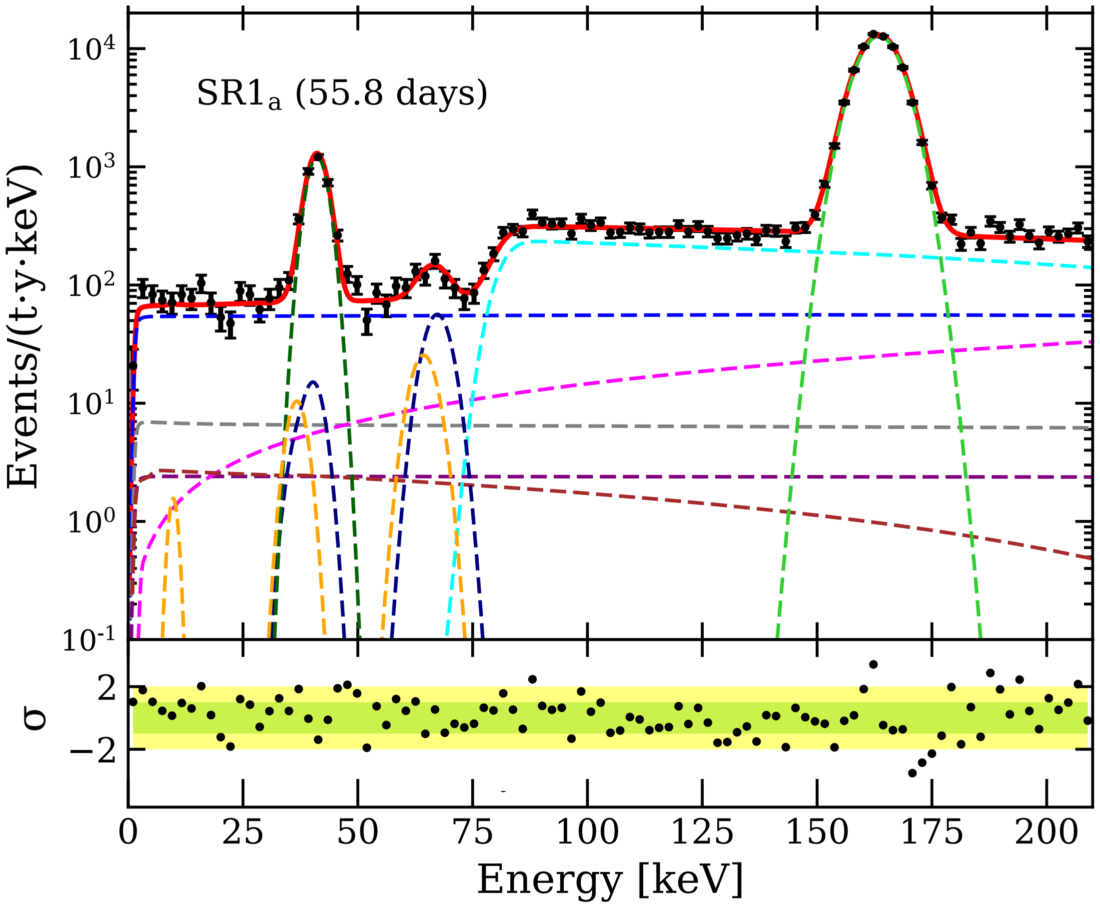
Profile over the nuisance parameters

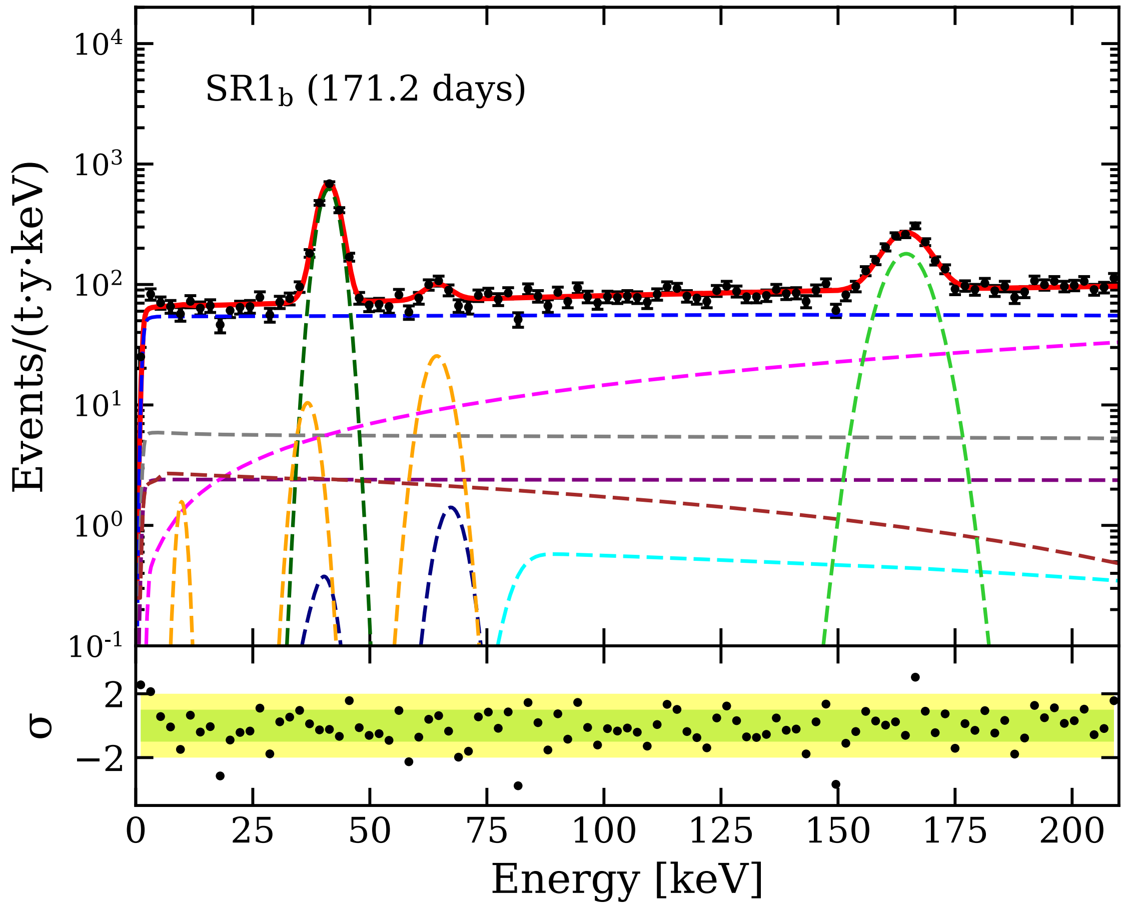
Combining the likelihoods of the 2 partitions

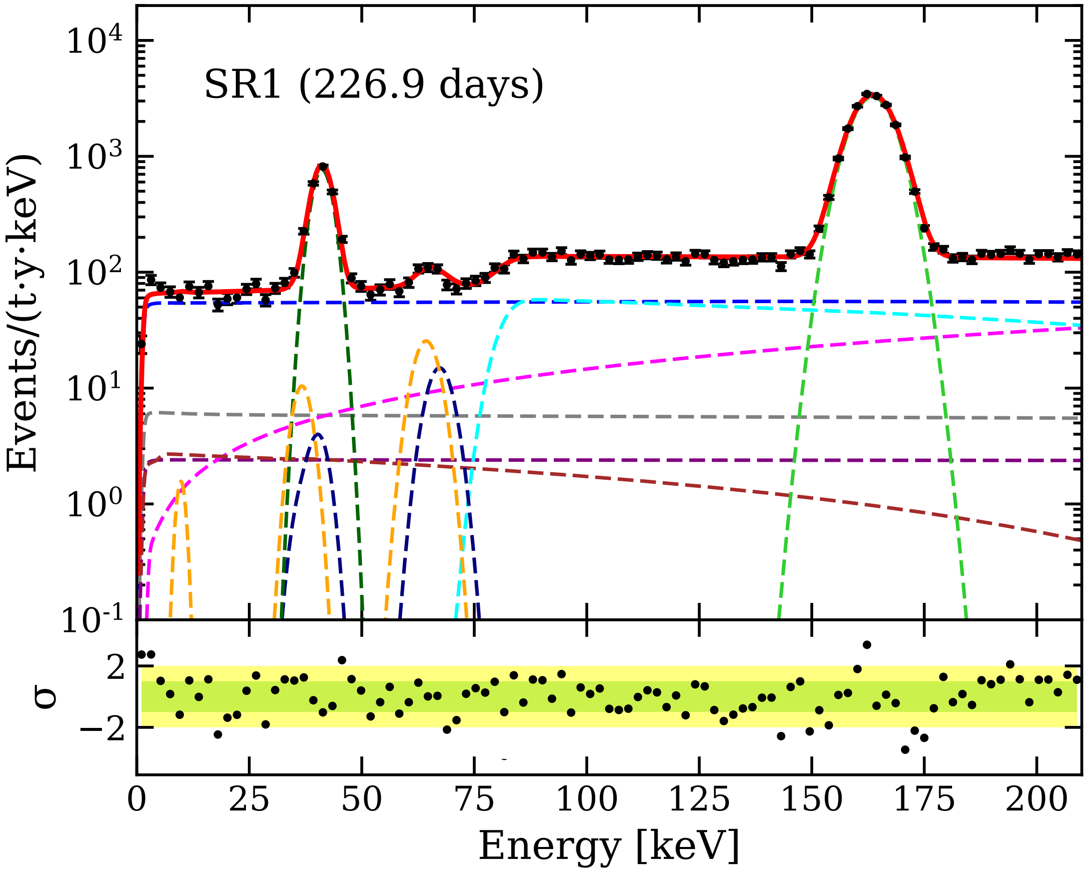
$$\boxed{\mathcal{L} = \mathcal{L}_a \times \mathcal{L}_b}$$

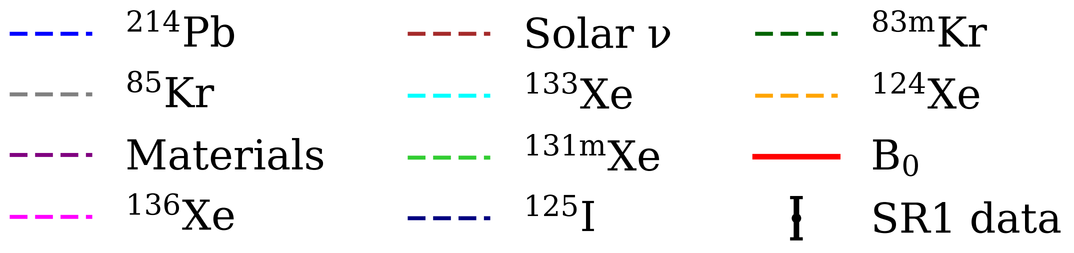
SR1a SR1b

Fit







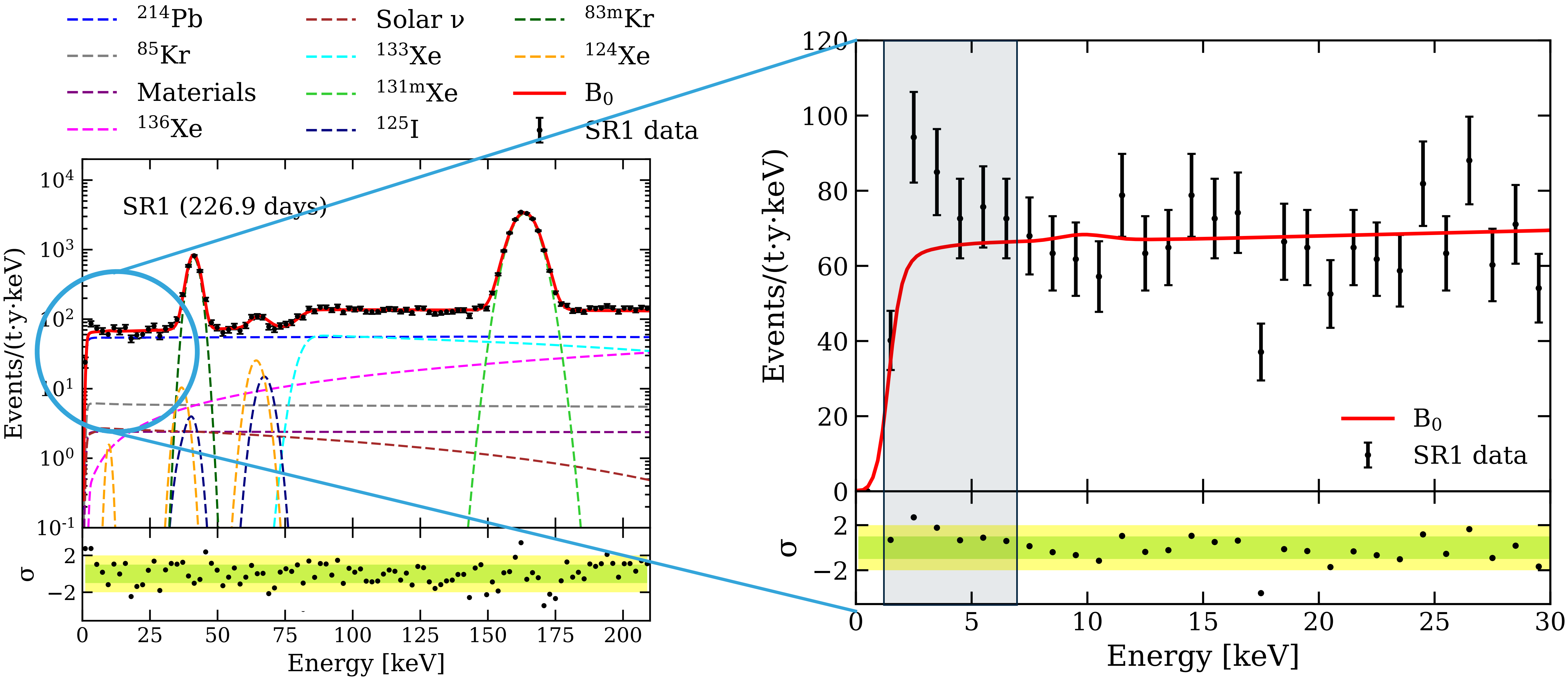


Decent matching across the whole energy range in 1-210 keV

(76 +/- 2) events/(t·y·keV) in [1, 30] keV

Lowest background rate ever achieved in this energy range!

Excess in 1–7 keV



Excess between 1-7 keV

285 events observed

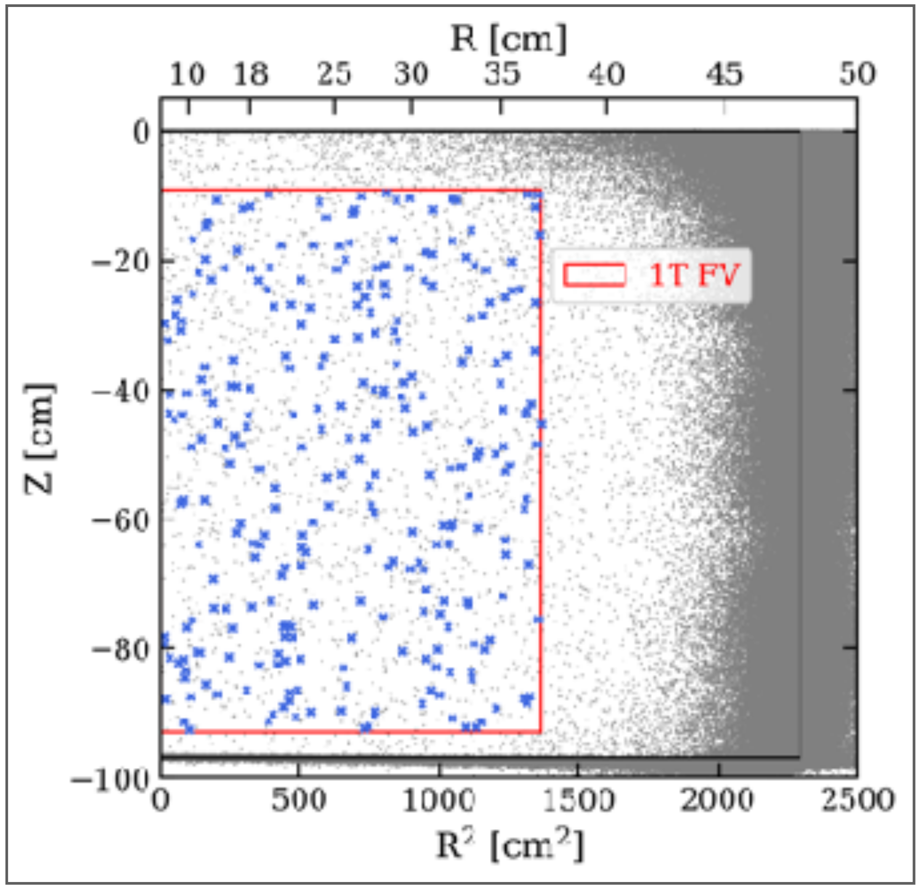
vs.

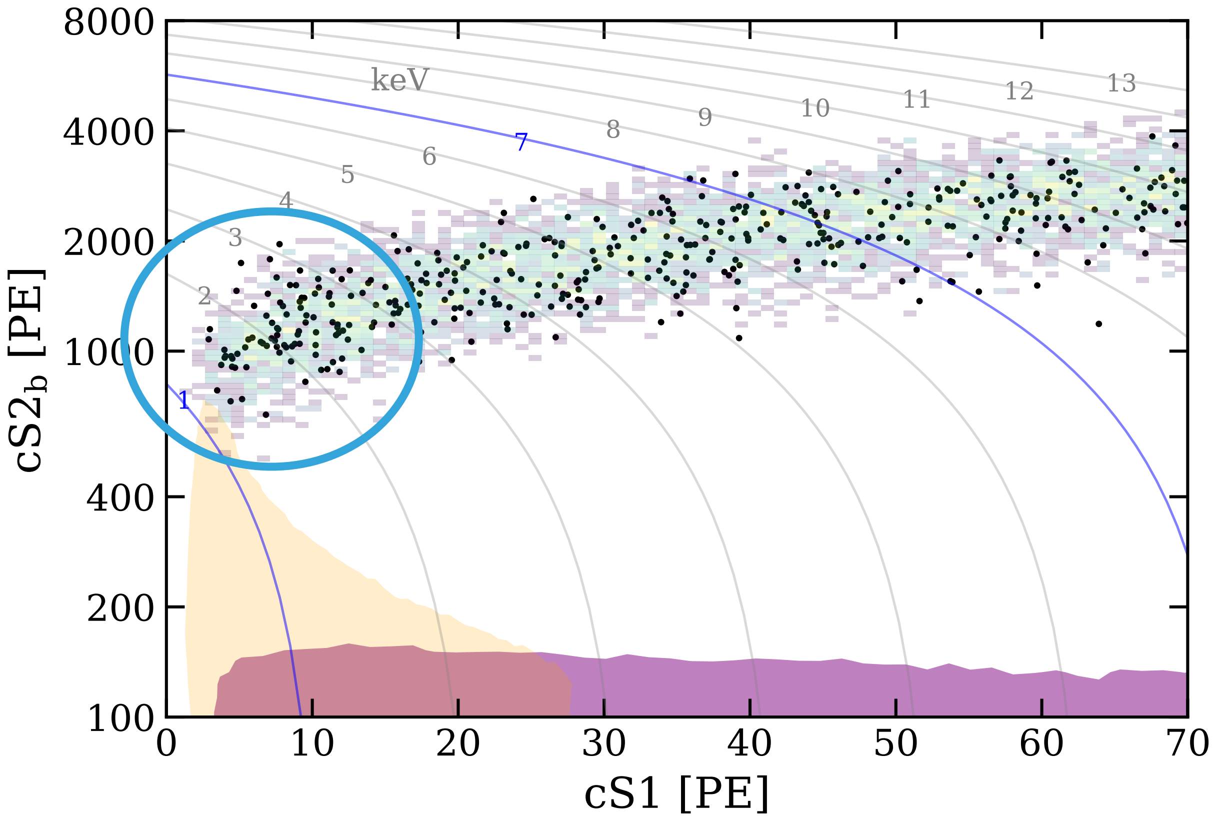
232 events expected (from BG-only best-fit)

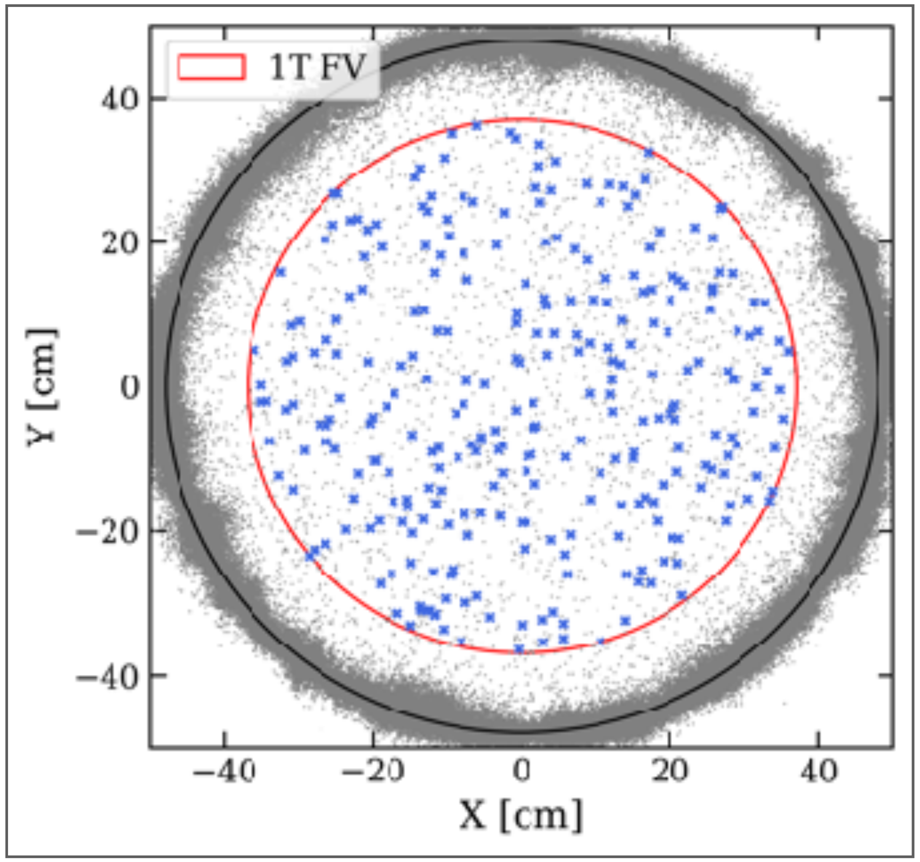
Would be a **3.3** $\boldsymbol{\sigma}$ Poissonian fluctuation

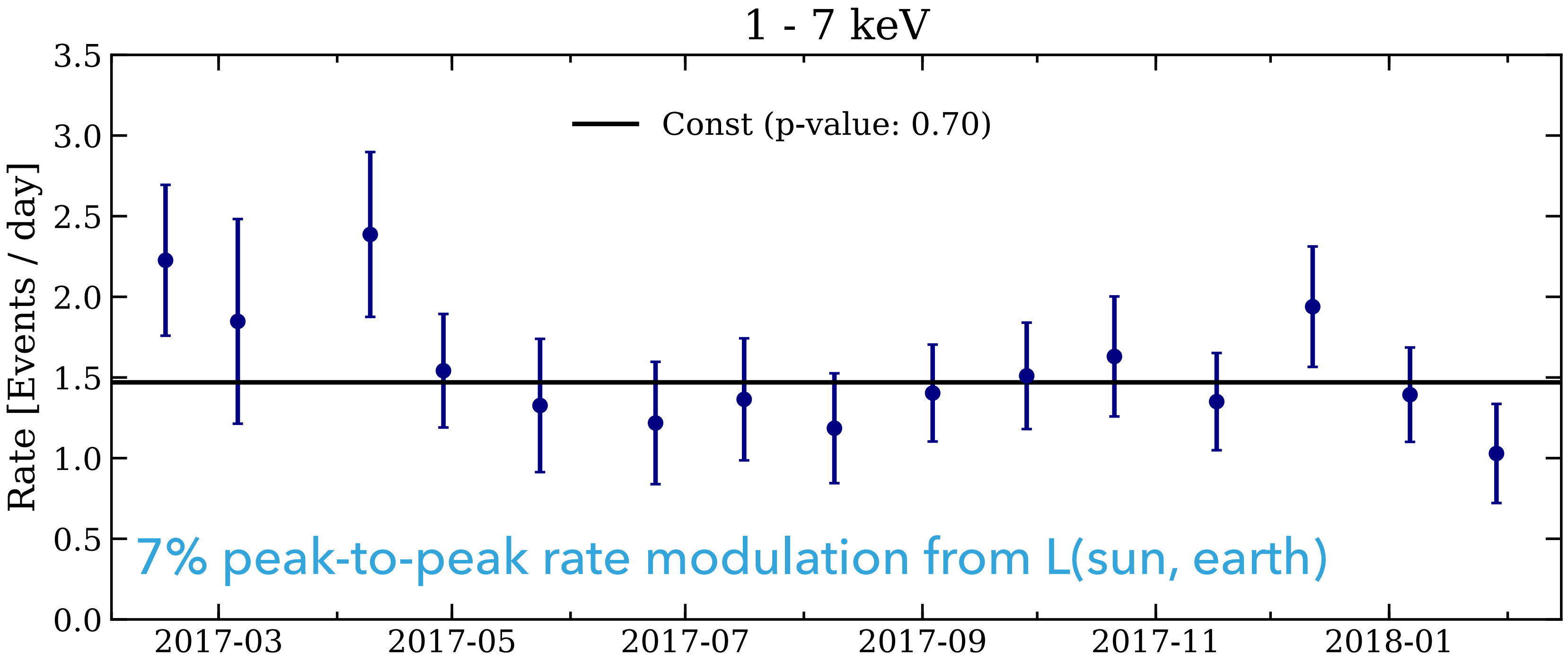
Are we missing something?

Event Location / Time-dependence





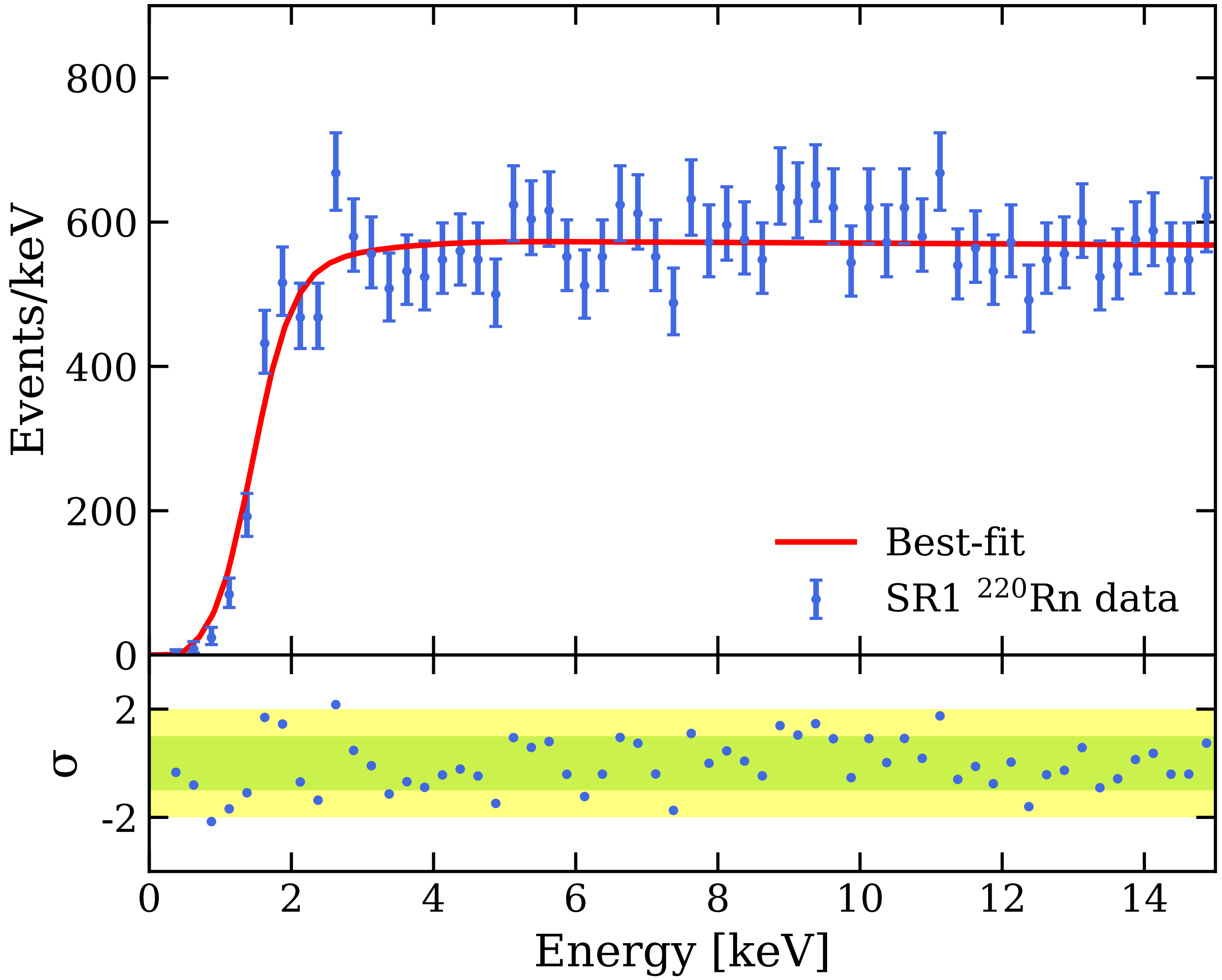




7% peak-to-peak rate modulation from L(sun, earth)

- Uniform in 3D-space and cS1/cS2b plane
- consistent with constant time (but with low statistics)

Efficiency / Reconstruction

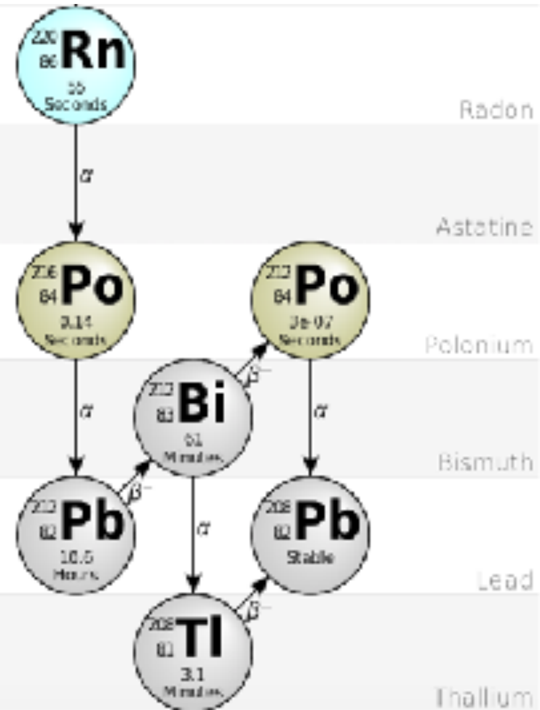


^{220}Rn calibration reconstructs as expected

Fit to ^{220}Rn (^{212}Pb) calibration data using same analysis framework

Validates efficiency and energy reconstruction

g.o.f p=0.58

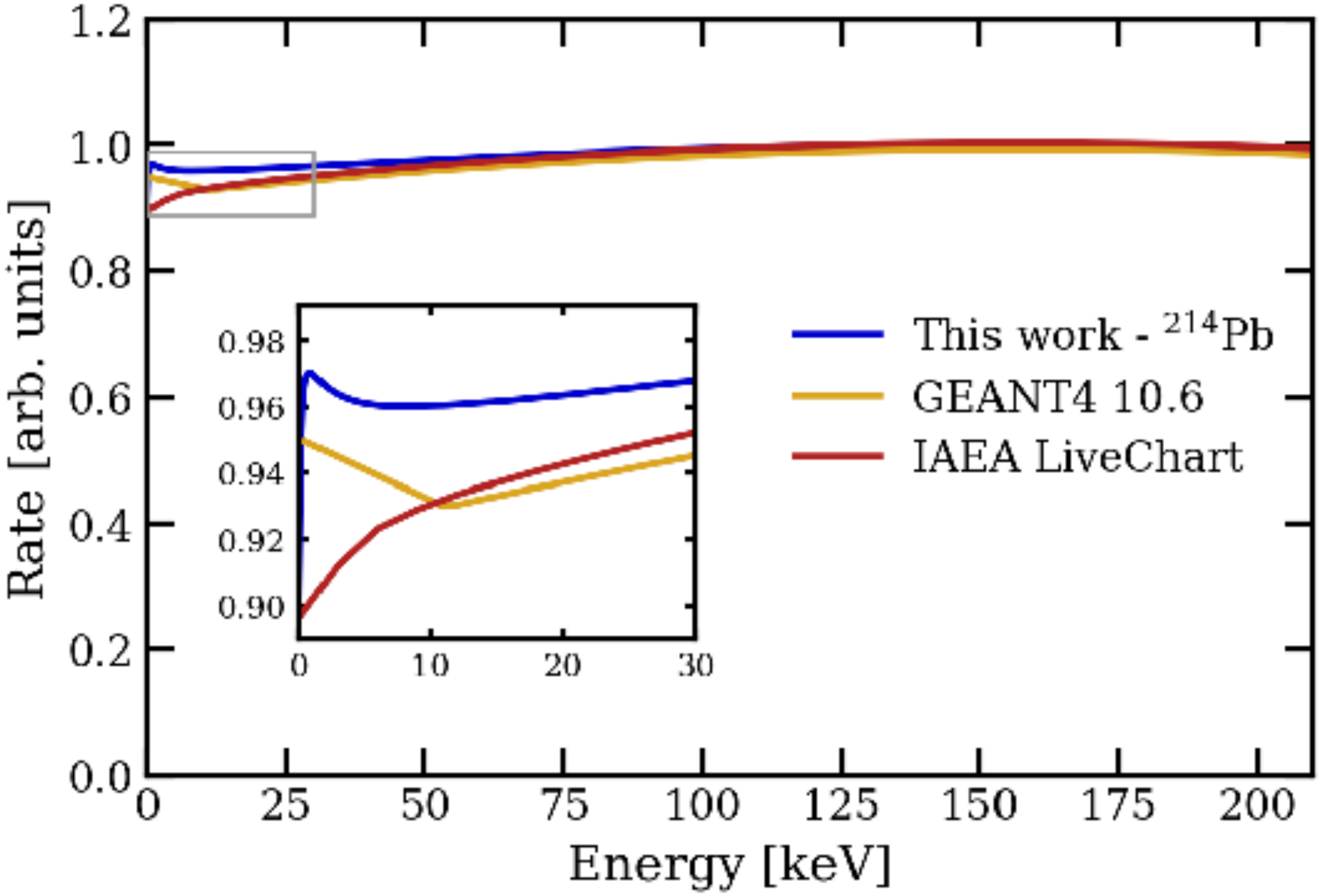


β-decay of Pb212 is used to calibrate detector’s response to ER background

Again, unbinned fit is performed here.

214Pb Spectrum Model

Calculated by X. Mougeot



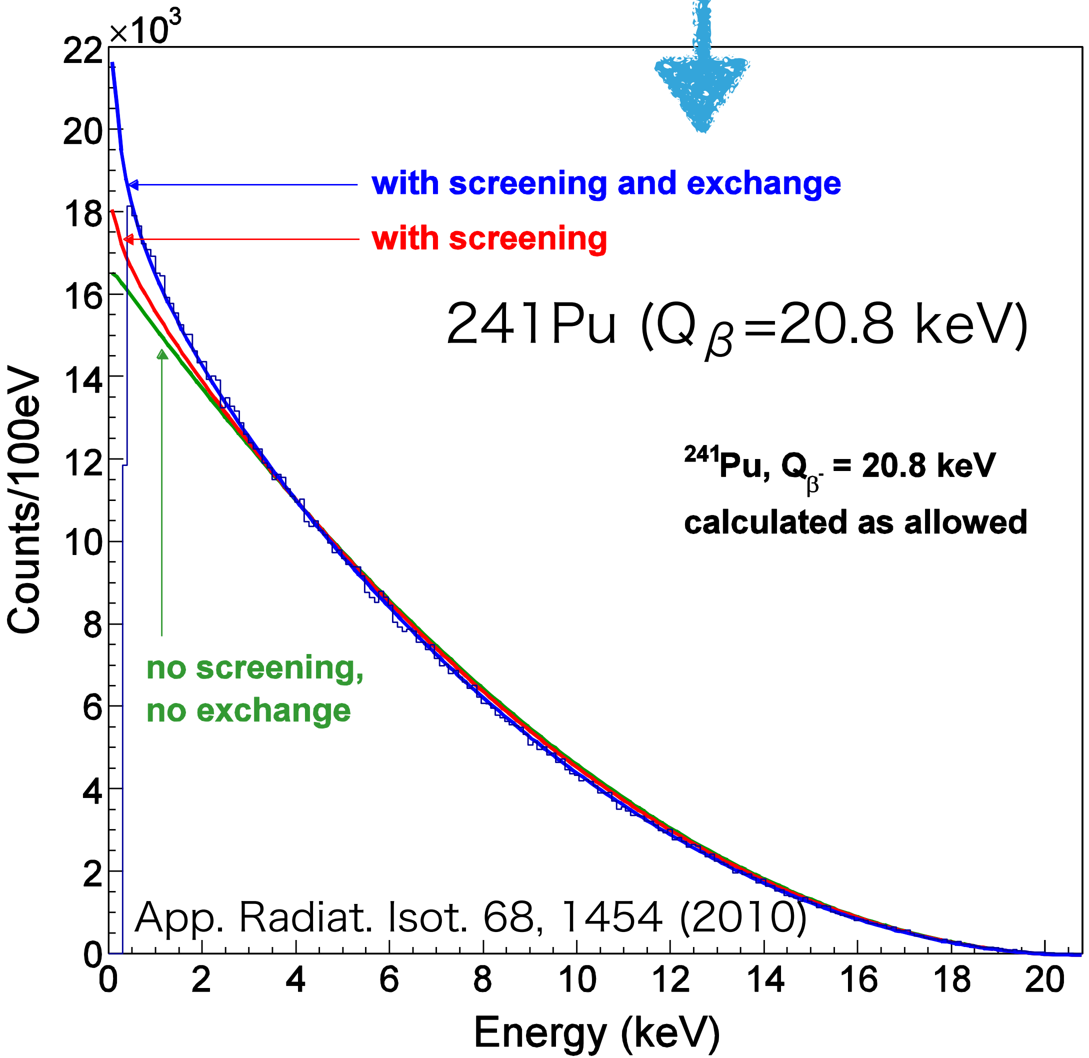
- IAEA model: No screening/exchange effects
- GEANT4 model: only screening effect
- This work: both screening/exchange effects

Atomic screening and exchange effects can increase rate at low energies.

~6% uncertainty on the shape

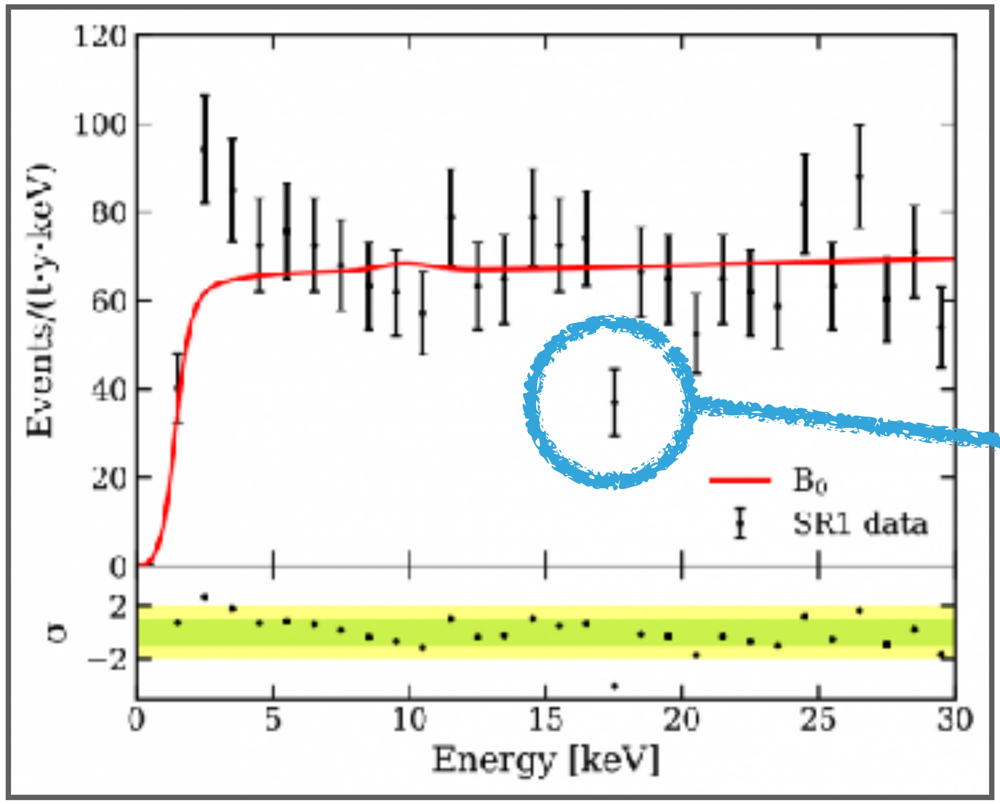
~50% needed to account for excess

Good agreement between measurements and calculation for 241Pu (Q_β=20.8 keV) and 63Ni (Q_β=67 keV)

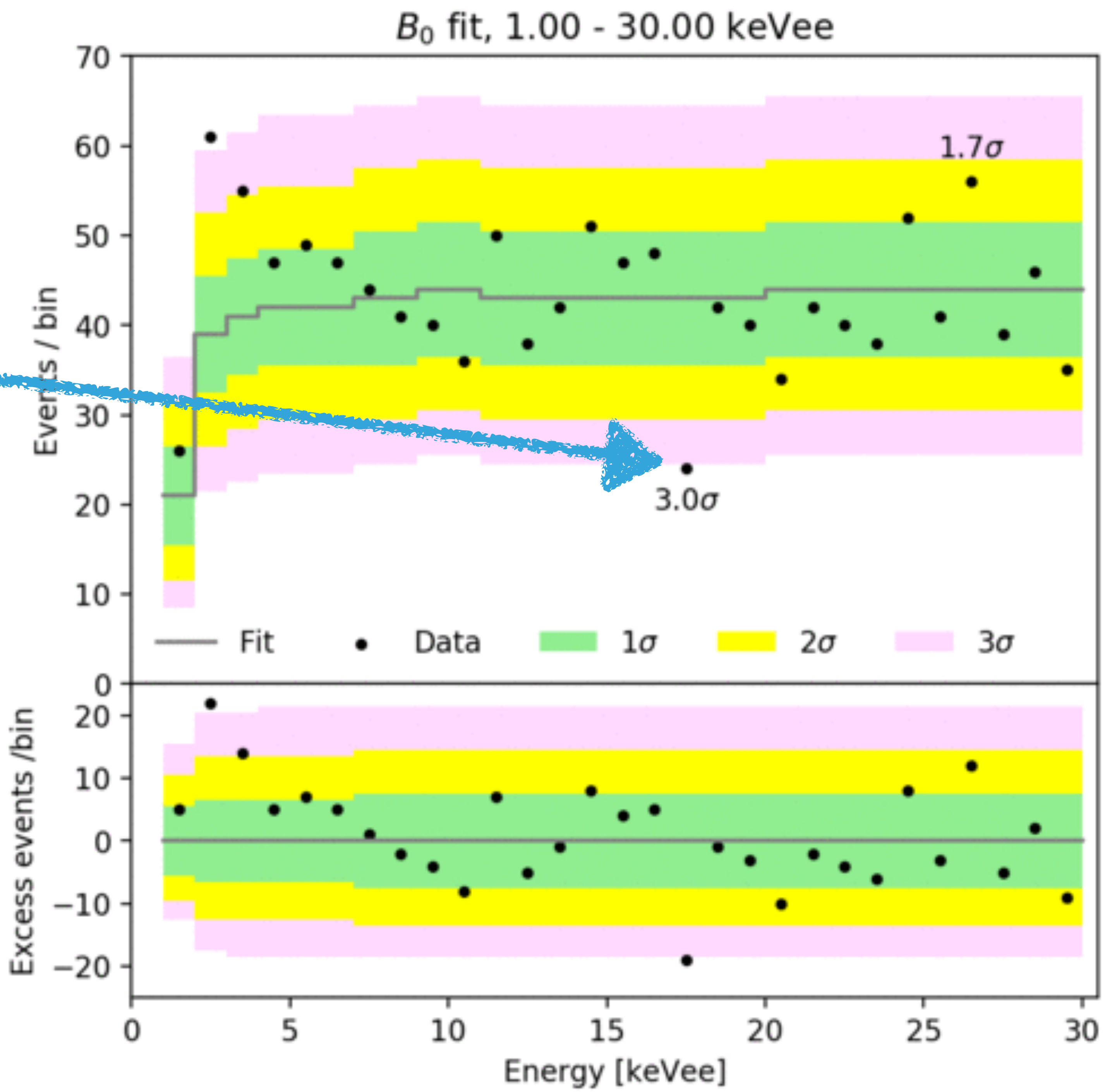


App. Radiat. Isot. 68, 1454 (2010)

Statistical Fluctuation?



statistical fluctuation? (see 17 keV dip)

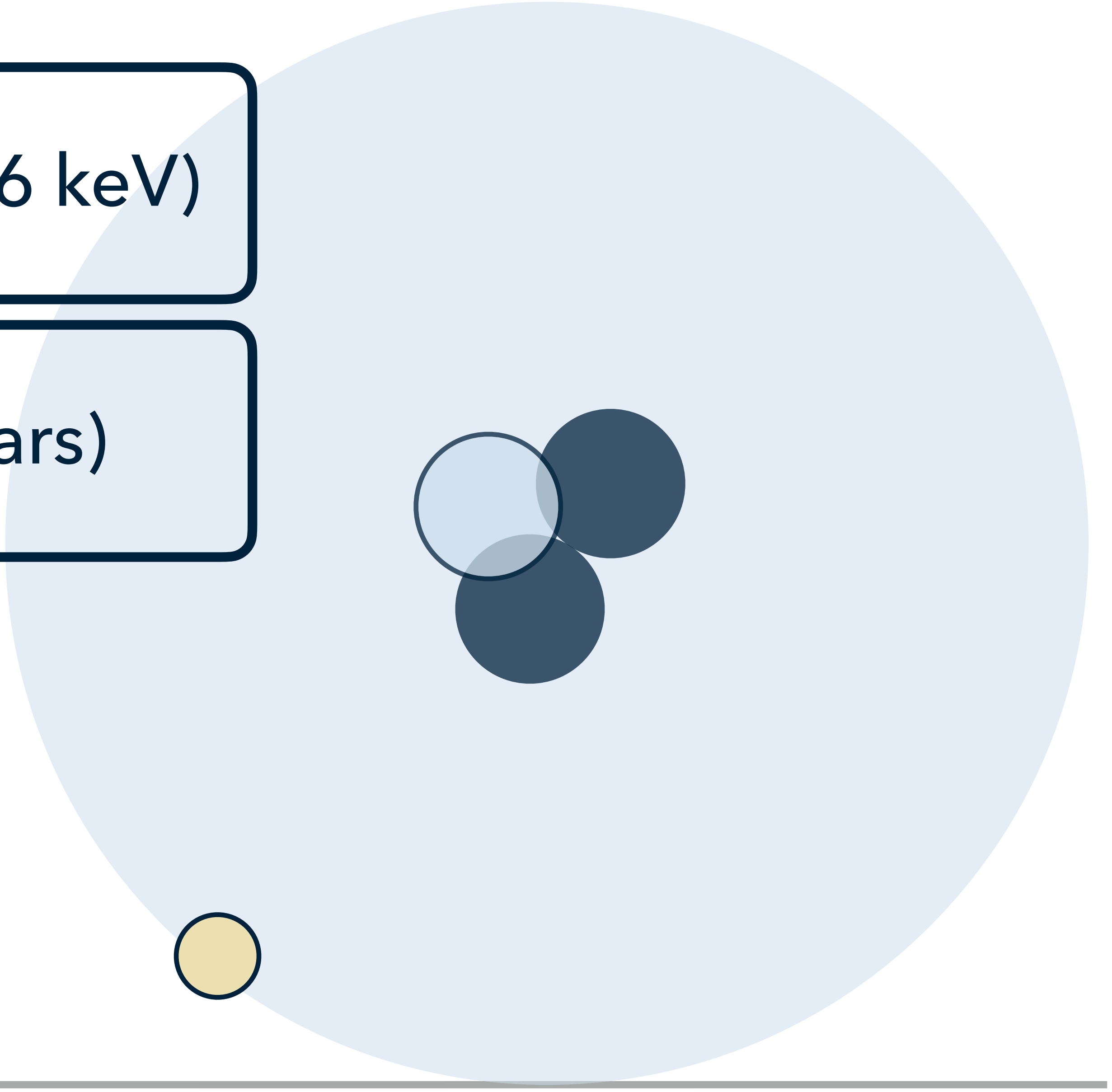


Note: we use an unbinned profile likelihood analysis

Tritium?

Low-energy (Q value 18.6 keV)

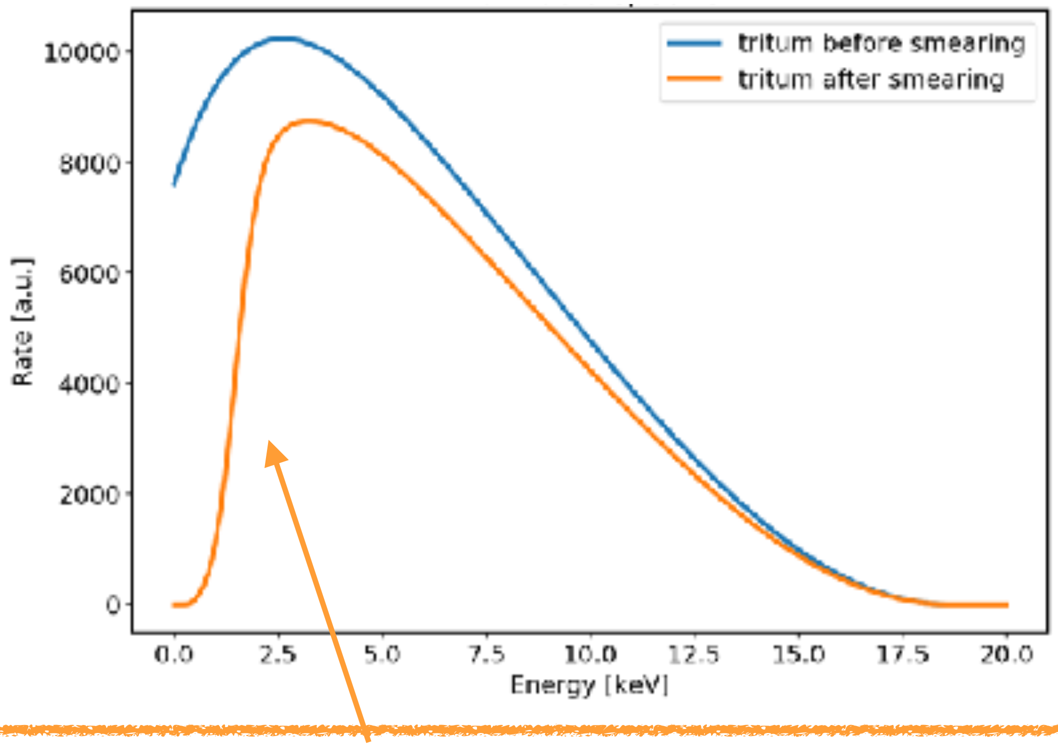
Long half life (12.3 years)

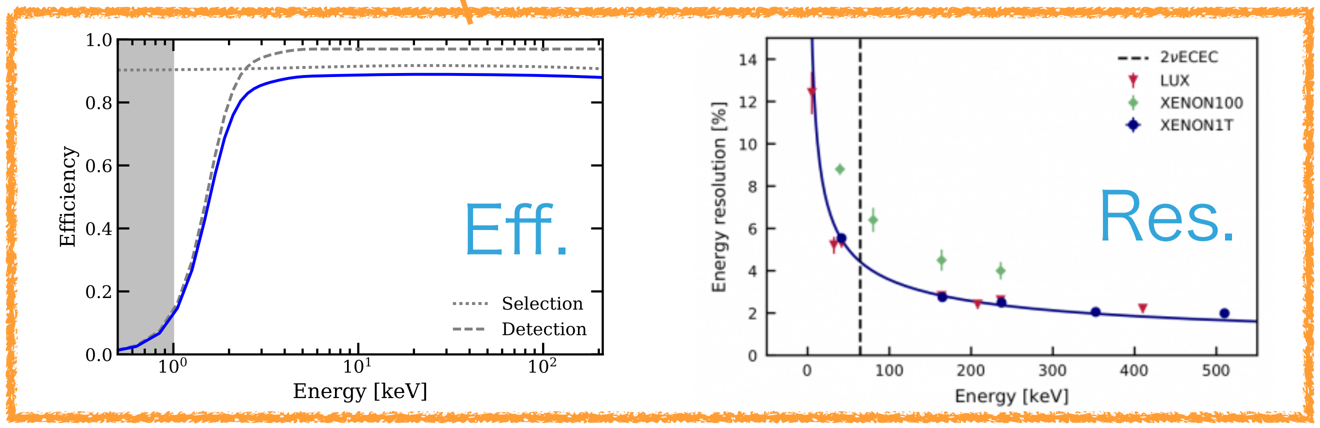


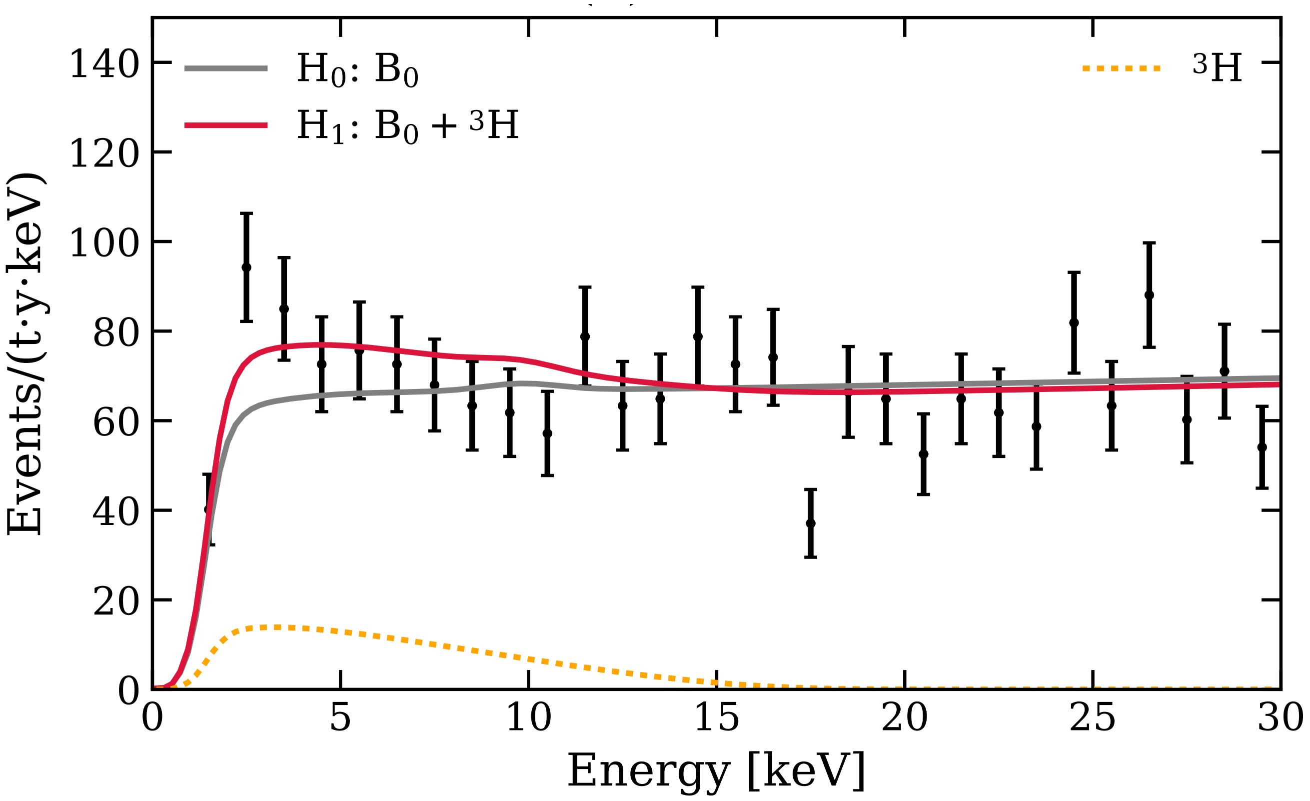
1. Cosmogenic production

2. Atmospherically abundant

Testing Tritium Hypothesis







Tritium favored over background-only at 3.2σ

Best-fit tritium rate:

$$159 \pm 51 \text{ events}/(\text{t} \cdot \text{y} \cdot \text{keV})$$

^{3}H half-life 12.3 years (too long to observe in SR1)

^{3}H:Xe concentration:

$$6.2 \pm 2.0 \times 10^{-25} \text{ mol/mol}$$

fewer than 3 tritium atoms per kg of xenon!

Testing Tritium Hypothesis

^{3}H:Xe concentration:

$$6.2 \pm 2.0 \times 10^{-25} \ \text{mol/mol}$$

→

fewer than 3 tritium atoms per kg of xenon!

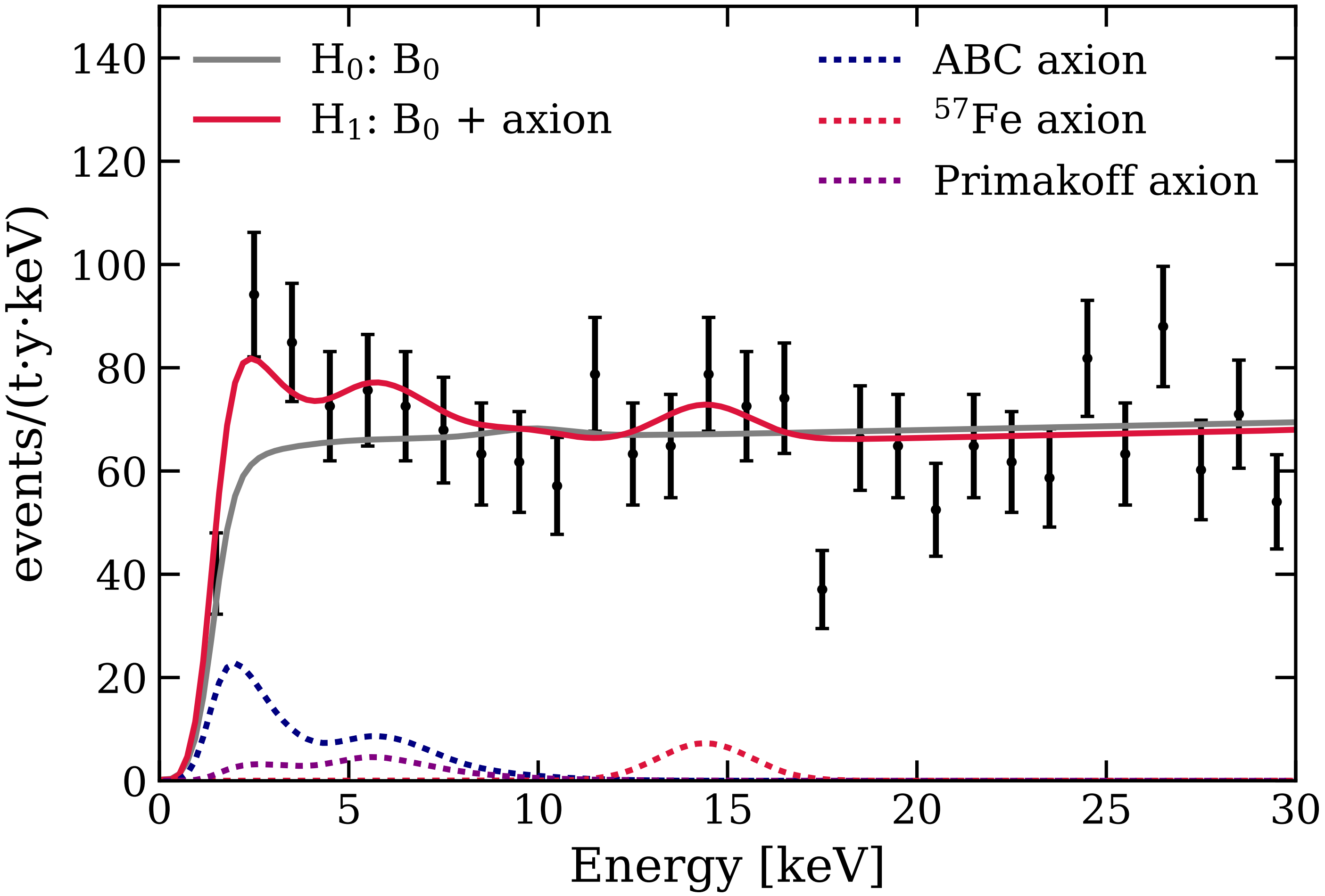
- 超過を説明可能なトリチウム量は少なすぎて現存するテクノロジーでは測定不可能！
- トリチウムだとすると、HTO or HTとして検出器中(ex: アウトガス)に混入しているはず
- H_2OやH_2の量から制限がかけられないのか？
    - HTOの可能性は低い (光信号が見えなくなってしまうので)
    - HTで説明するには、H_2のアウトガス量がO_2に比べて100倍以上必要 (ありえる？)
- 環境中トリチウムの振る舞い/定量評価/除去方法や我々の評価に関して、現在トリチウムの専門家に意見を聞いているところ (9/8の研究会でも議論予定)

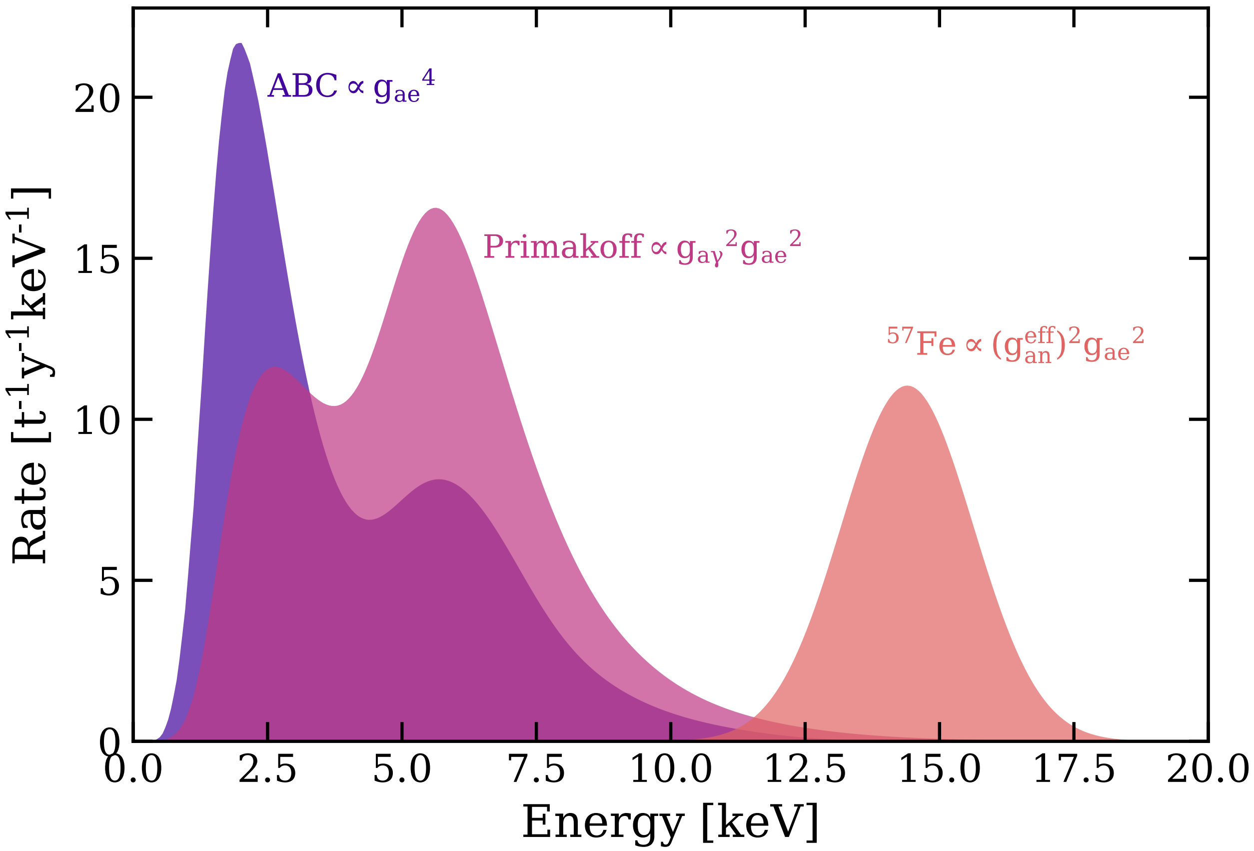
ダークマターの懇談会2020 online (darKONline2020)

http://ppwww.phys.sci.kobe-u.ac.jp/~newage/darkon2020/

Signals?

Solar-Axion Results

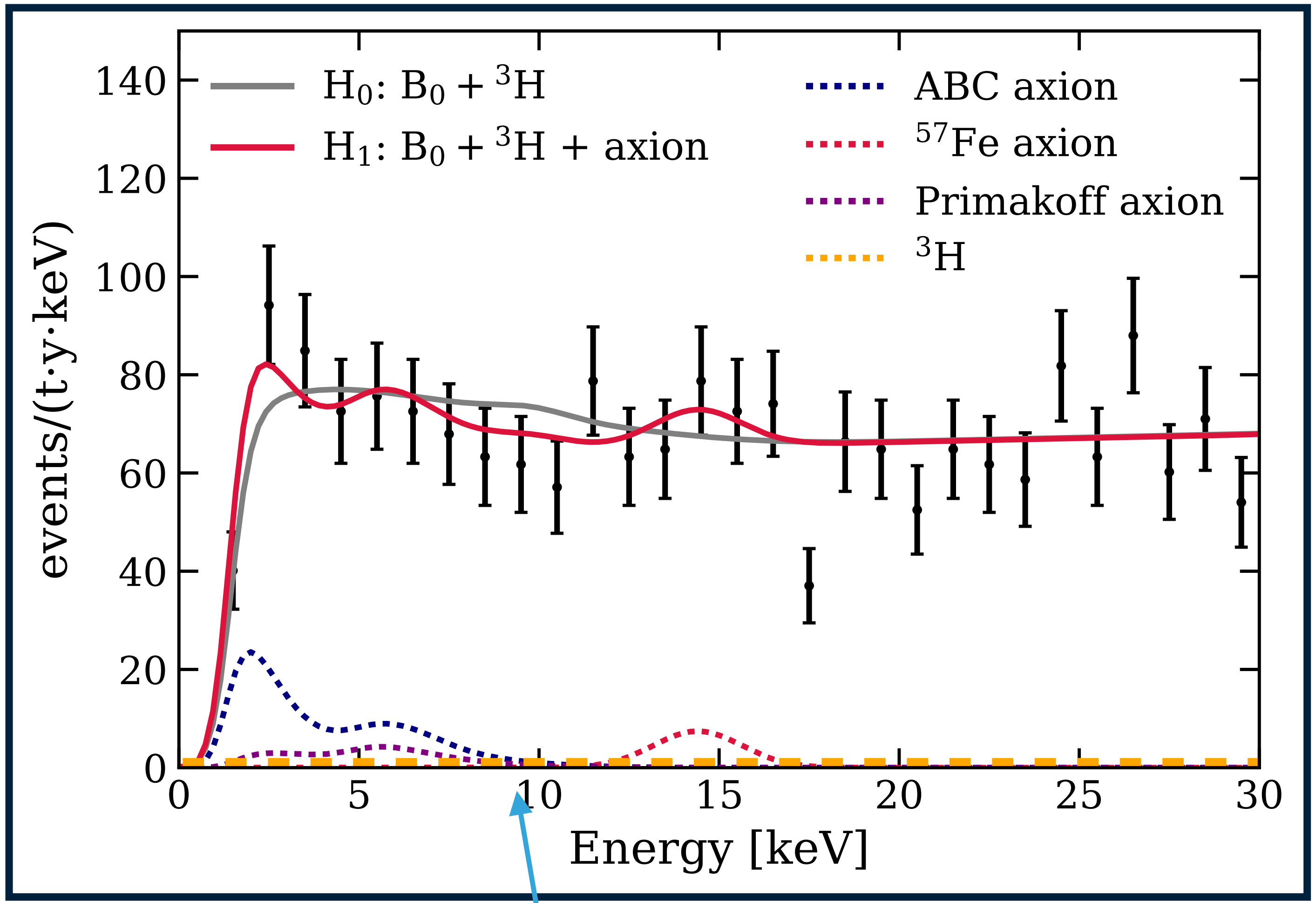


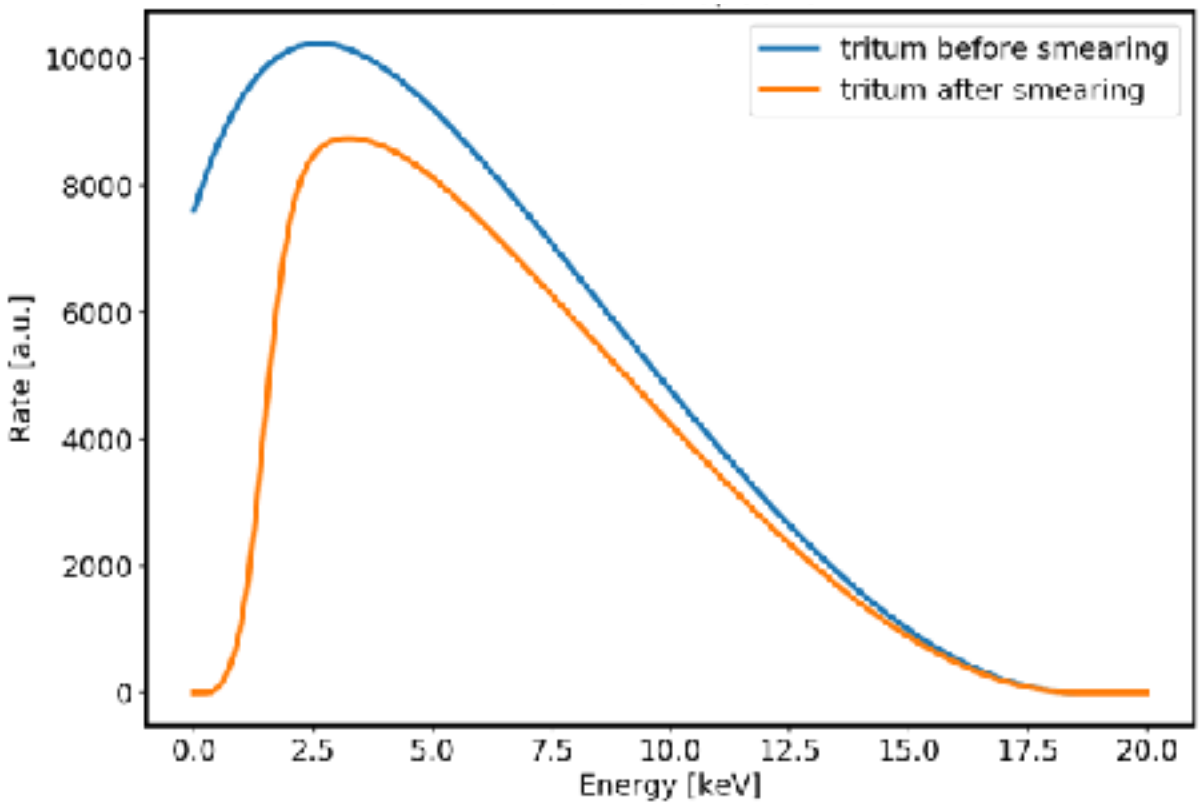


- All the three flux components are considered completely independent of each other
- Parameters of interest in the Profile Likelihood = $\boxed{g_{\mathrm{ae}} \text{ vs. } g_{\mathrm{ae}} g_{\mathrm{a}\gamma} \text{ vs. } g_{\mathrm{ae}} g_{\mathrm{an}}^{\mathrm{eff}}}$
- Significance determined using toy-MC methods

Axion favored over background-only at 3.5σ

Solar-Axion + Tritium



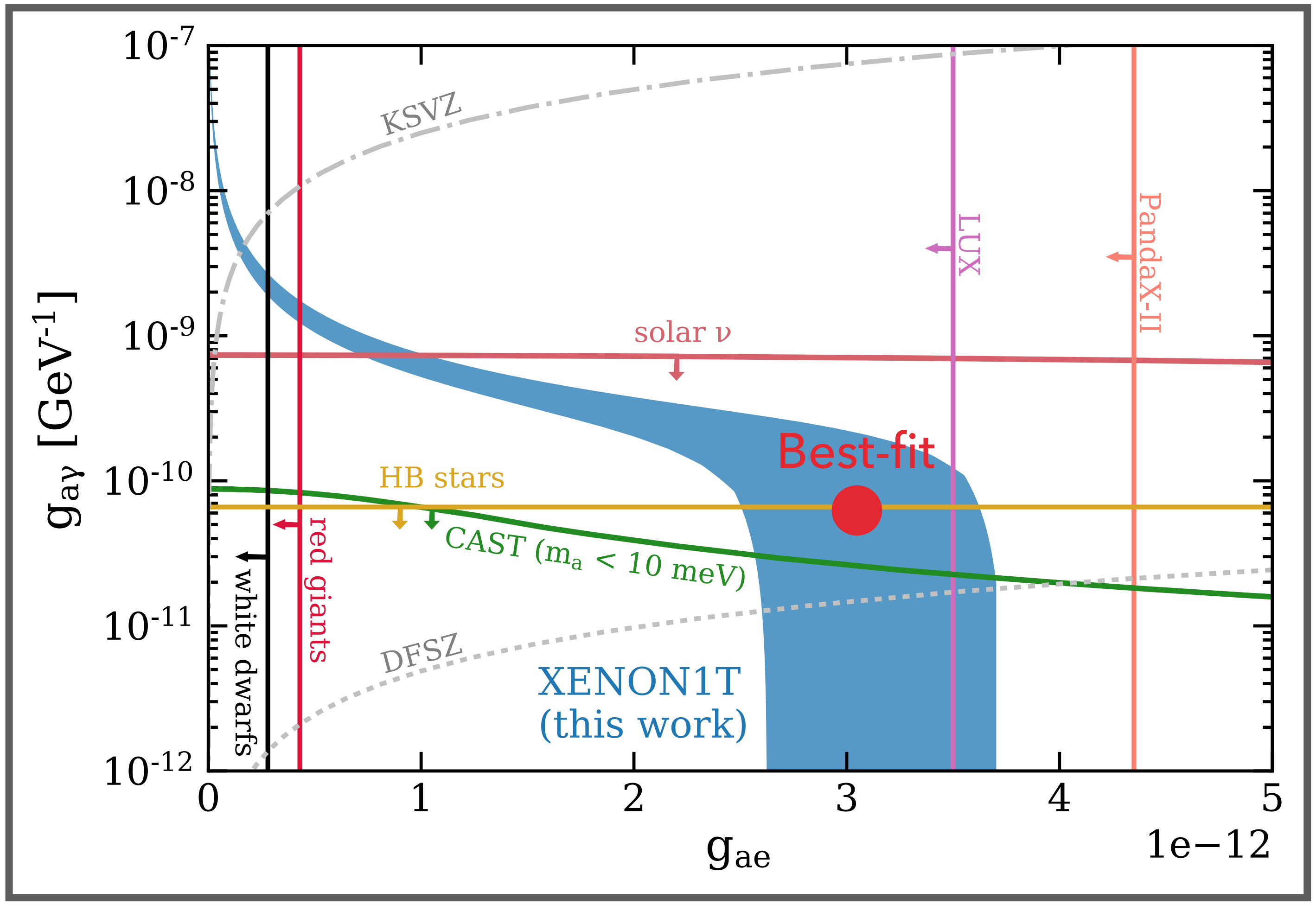


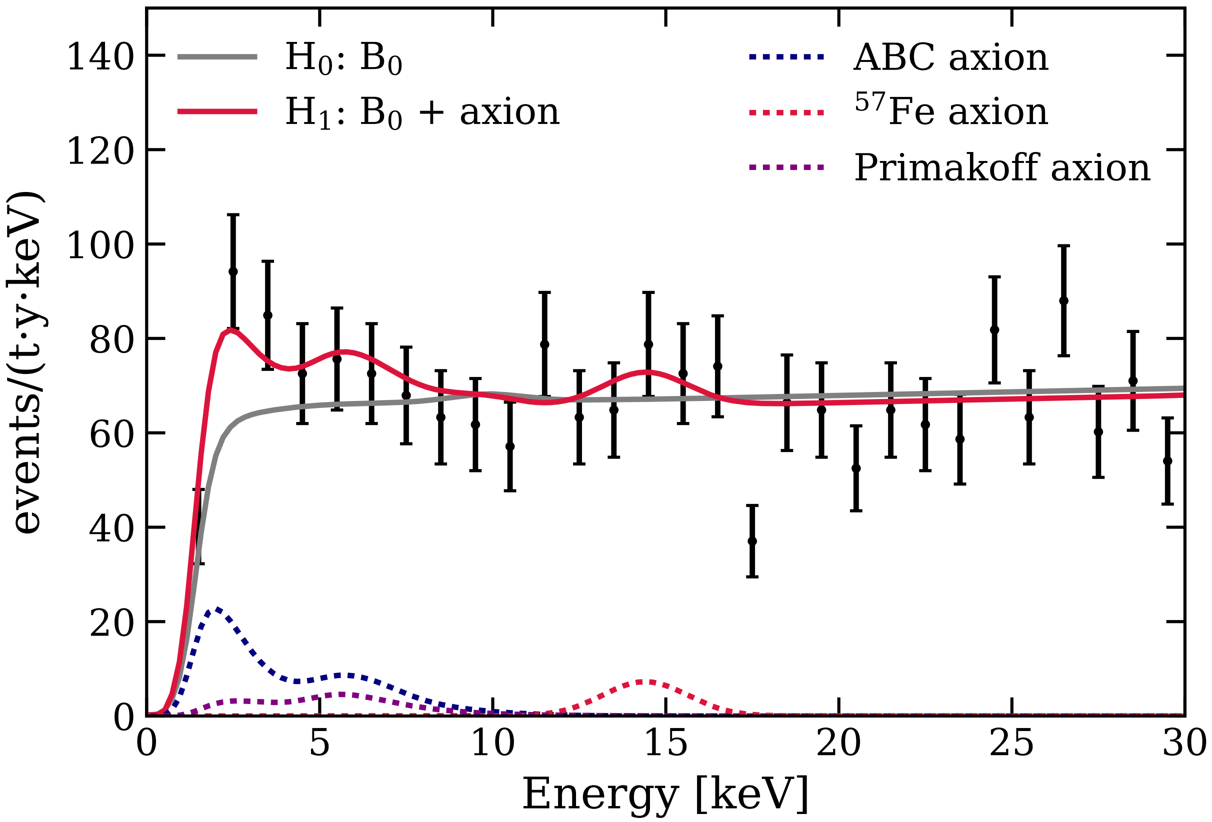
Axion + ^{3}H favored over ^{3}H hypothesis at 2.1σ

When both axion and tritium are included in the fit, the **best-fit of tritium is zero** — **in favor of axions.**

Solar-Axion Results

Parameters of interest in the profile likelihood $\boxed{g_{ac} \text{ vs. } g_{ac}g_{a\gamma} \text{ vs. } g_{ac}g_{an}^{\text{eff}}}$





ABC and Primakoff components are both low-energy signals, the favored region is anti-correlated in this space

—> suggests either a non-zero ABC component or non-zero Primakoff component.

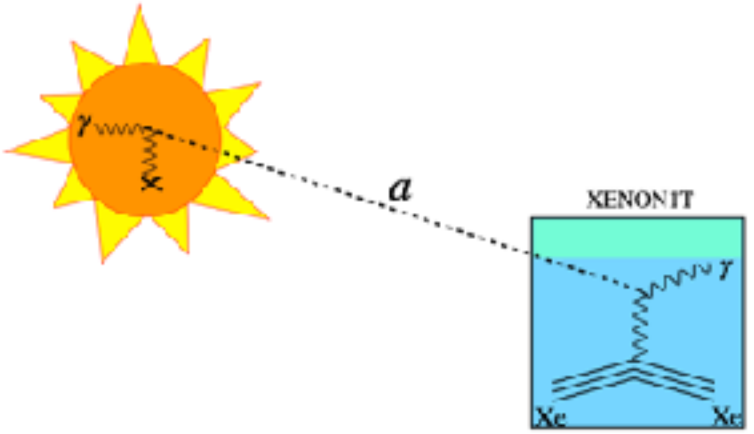
In tension with astrophysical constraints from stellar cooling bounds from the horizontal branch stars and red giants

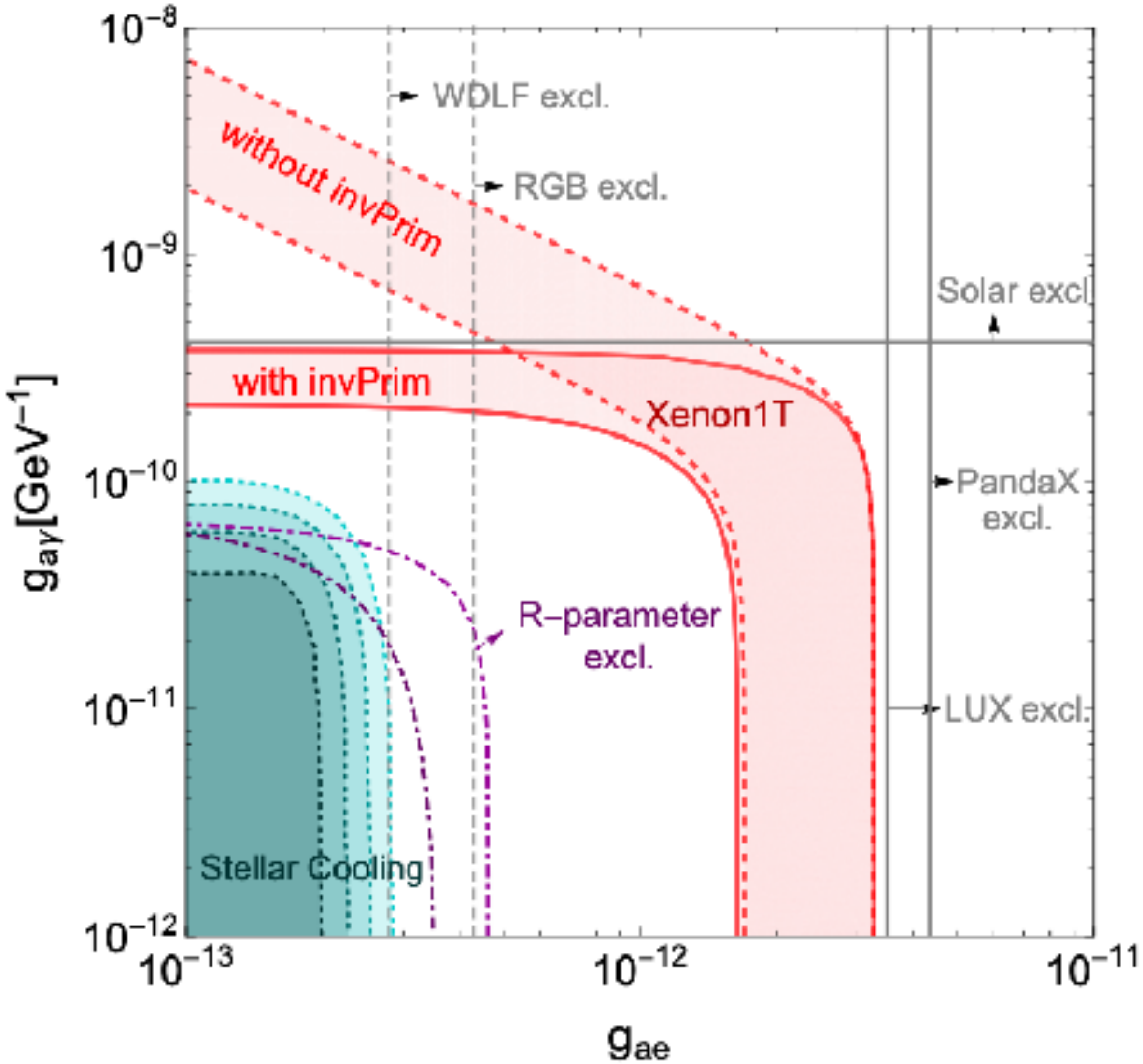
Inverse Primakoff Process?

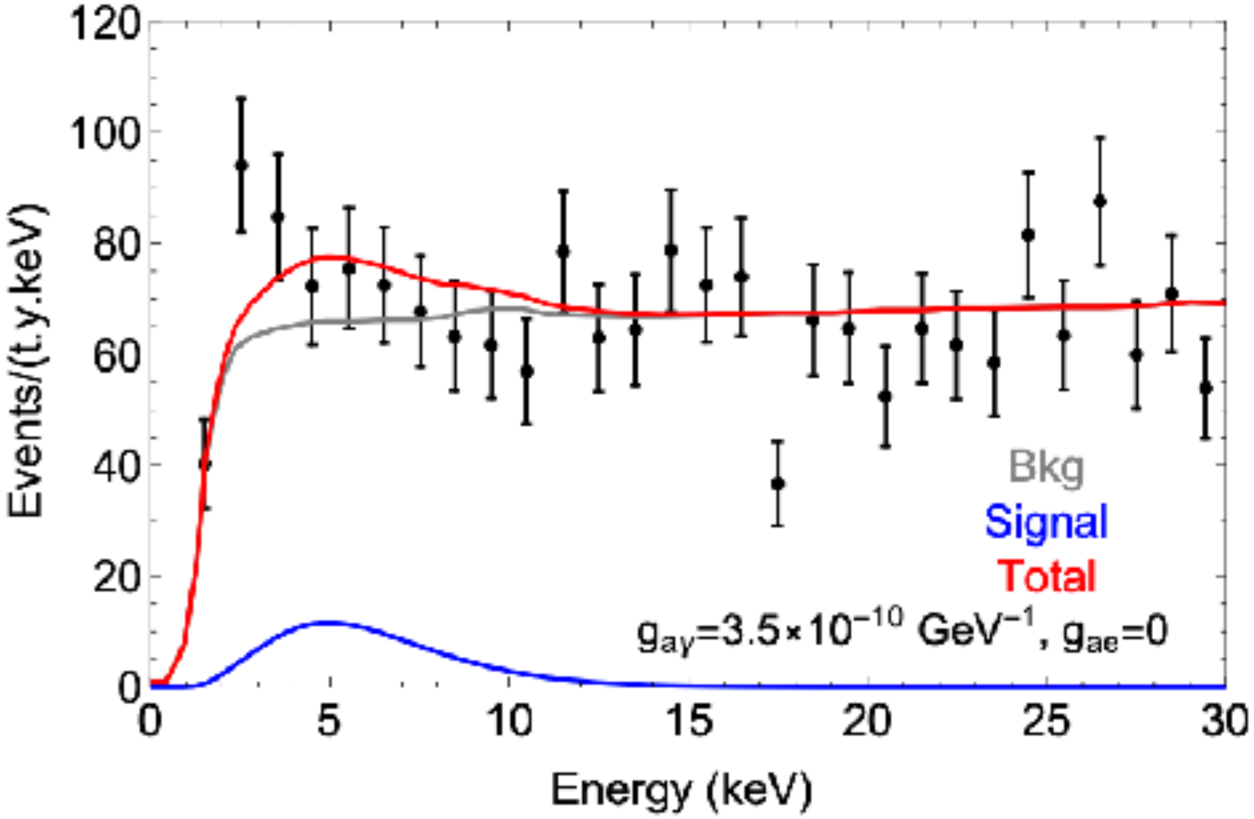
(arXiv 2006.14598v1)

Re-examining the Solar Axion Explanation for the XENON1T Excess

Christina Gao,[1] Jia Liu,[2] Lian-Tao Wang,[2,3] Xiao-Ping Wang,[4] Wei Xue,[5] and Yi-Ming Zhong[6]





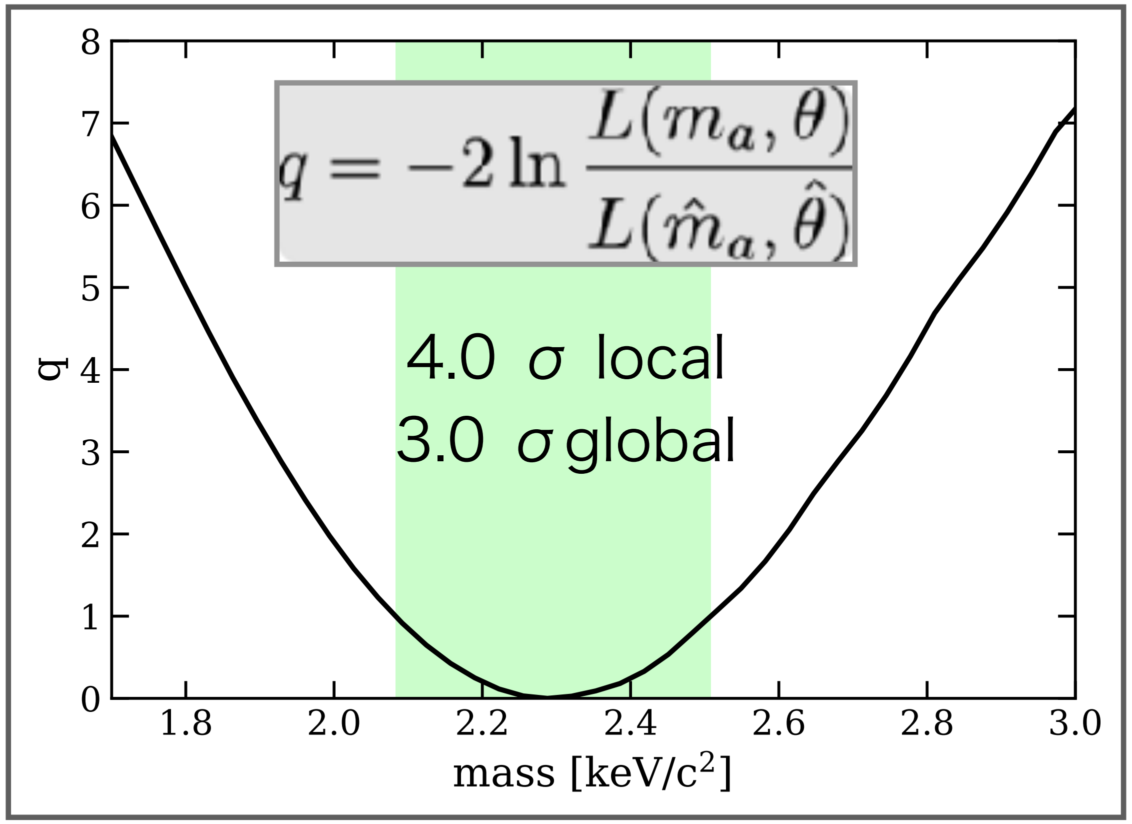


Considering inverse Primakoff process can weaken the tension with stellar cooling constraint

If inverse Primakoff process dominates, it will not fit the excess as good

Axion-like Particle / Dark Photon

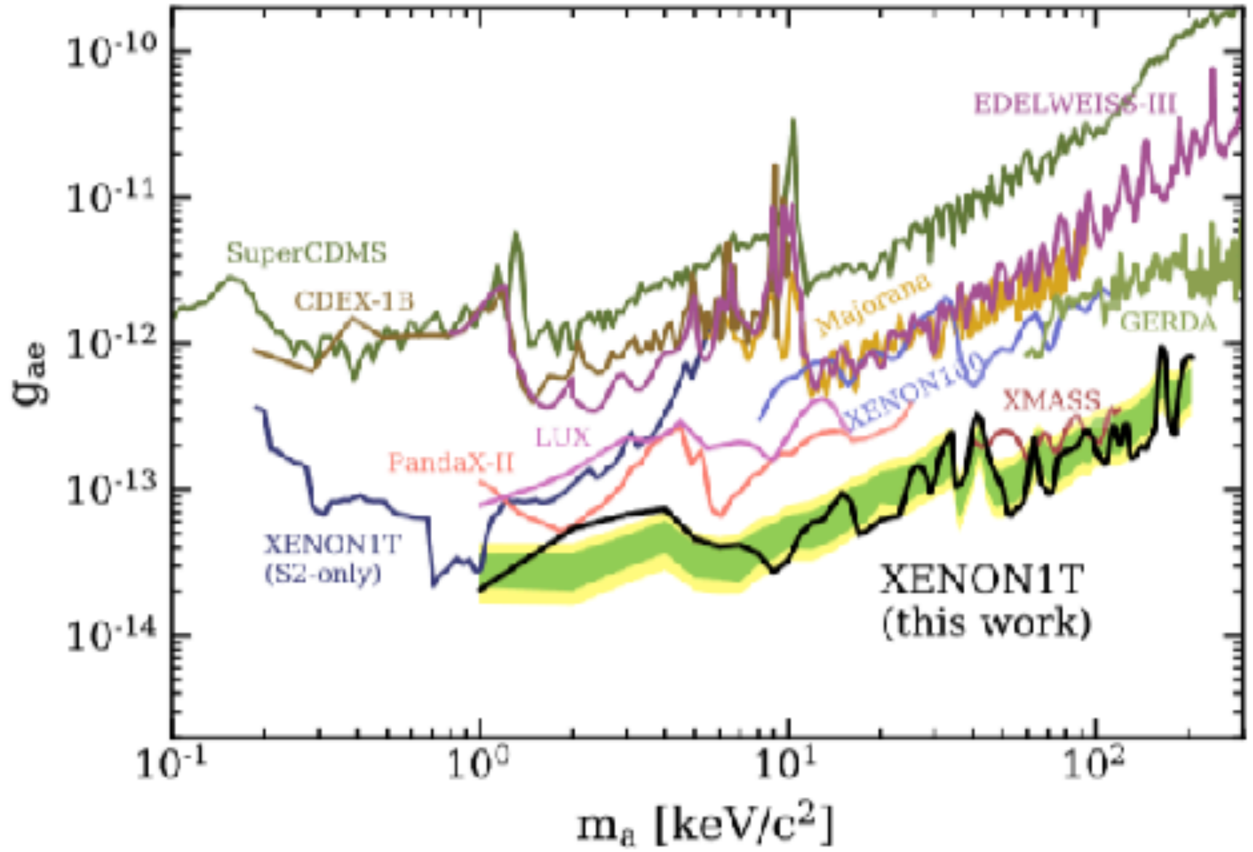
Fitting a mono-energetic peak to the excess: 2.3 +/- 0.2 keV

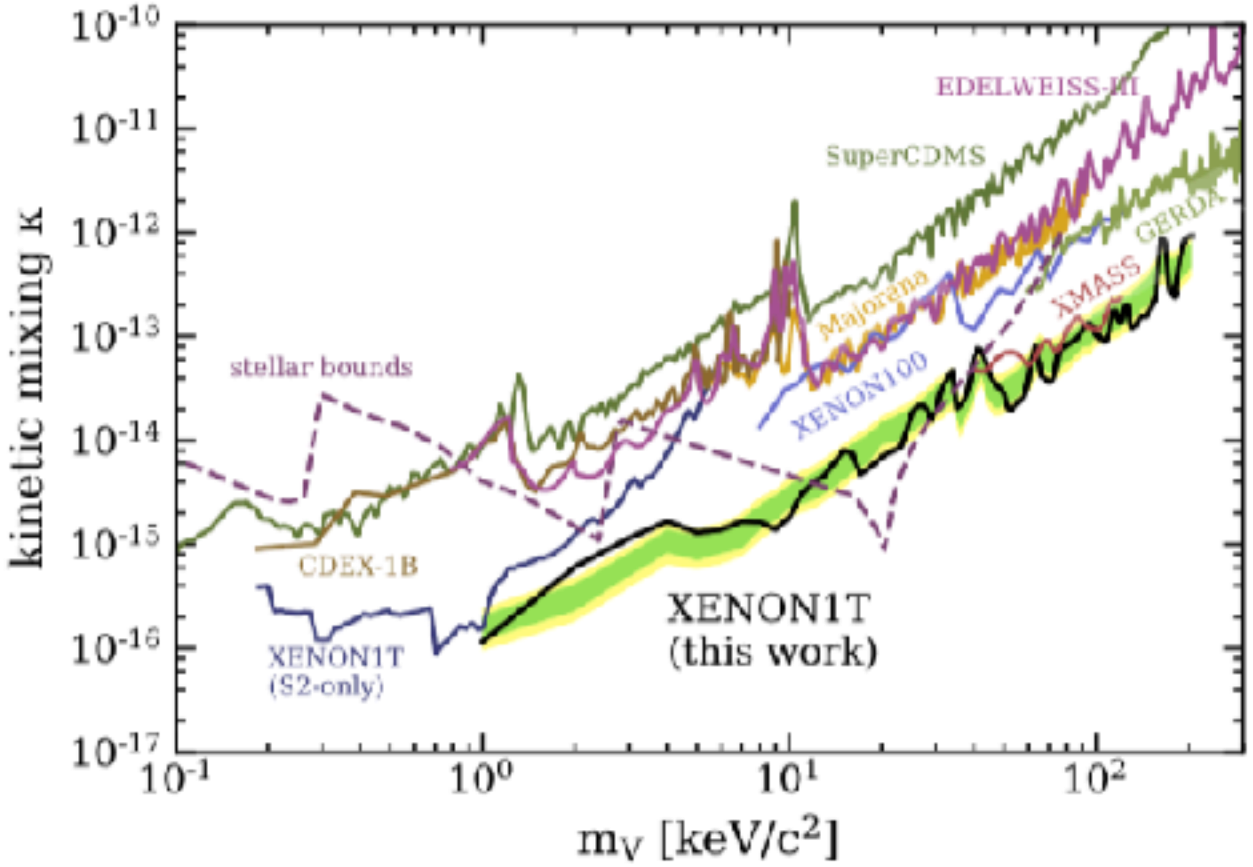


Best fit: ~60 events/tonne/year

4.0 σ local significance

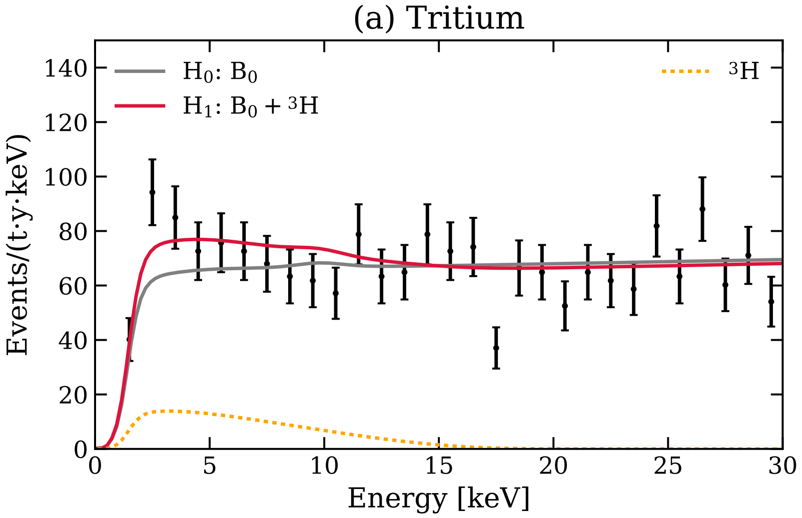
3.0 σ (global, considering look-elsewhere effect).

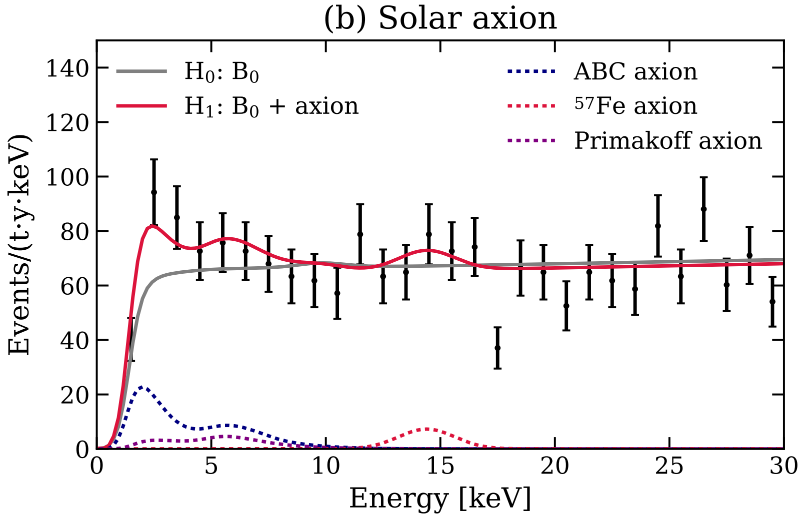




Summary and Interpretations of the Excess

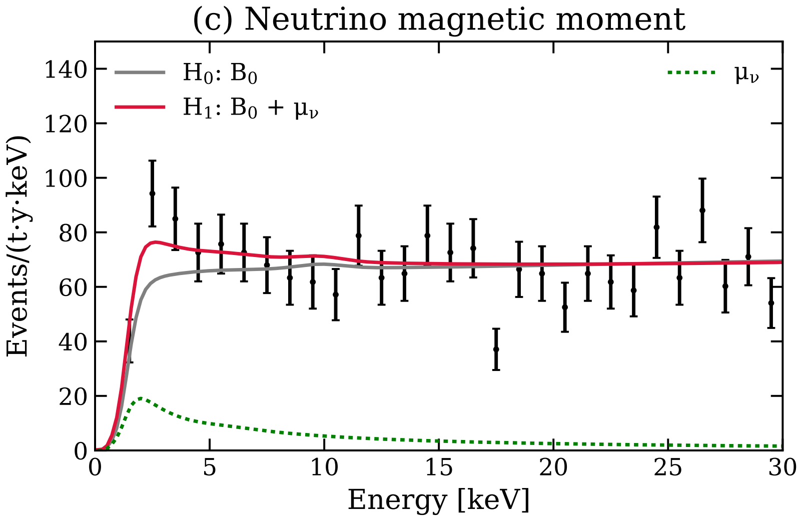
Tritium favored over background-only at **3.2σ**

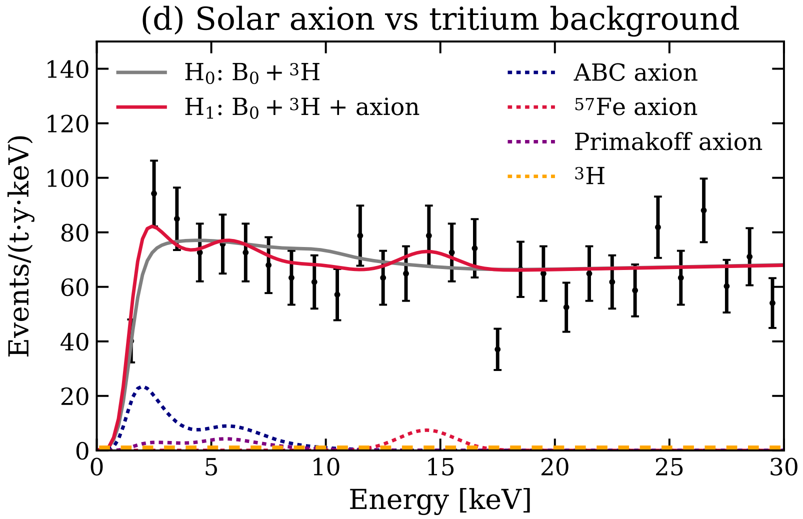

(a) Tritium


(b) Solar axion

Solar axion favored over background-only at **3.5σ**

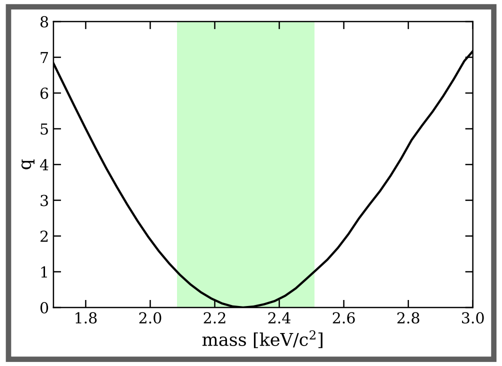
Neutrino magnetic moment (see backup slides) favored over background-only at **3.2σ**


(c) Neutrino magnetic moment


(d) Solar axion vs tritium background

Axion + **^{3}H** favored **over ^{3}H** hypothesis **at 2.1σ**

Monoenergetic peak at 2.3 +/- 0.2 keV favored over background-only at **3.0σ (global)**



What's Next?

XENONnT

Minimal Upgrade

The XENON1T infrastructure and sub-systems were originally designed to accommodate a larger LXe TPC.

Fiducial Xe Target

XENONnT TPC:

total Xe mass = ~8.4 t

target mass = 5.9t

fiducial mass = ~4 t

Total # of PMTs ×2: 494 PMTs

(253 top, 241 bottom)

Background

Record low-back levels in XENON1T dominated by ^{222}Rn-daughters.

Identified strategies to effectively **reduce ^{222}Rn by ~ a factor of 5-10**.

Fast Turnaround

Use XENON1T sub-systems, already tested

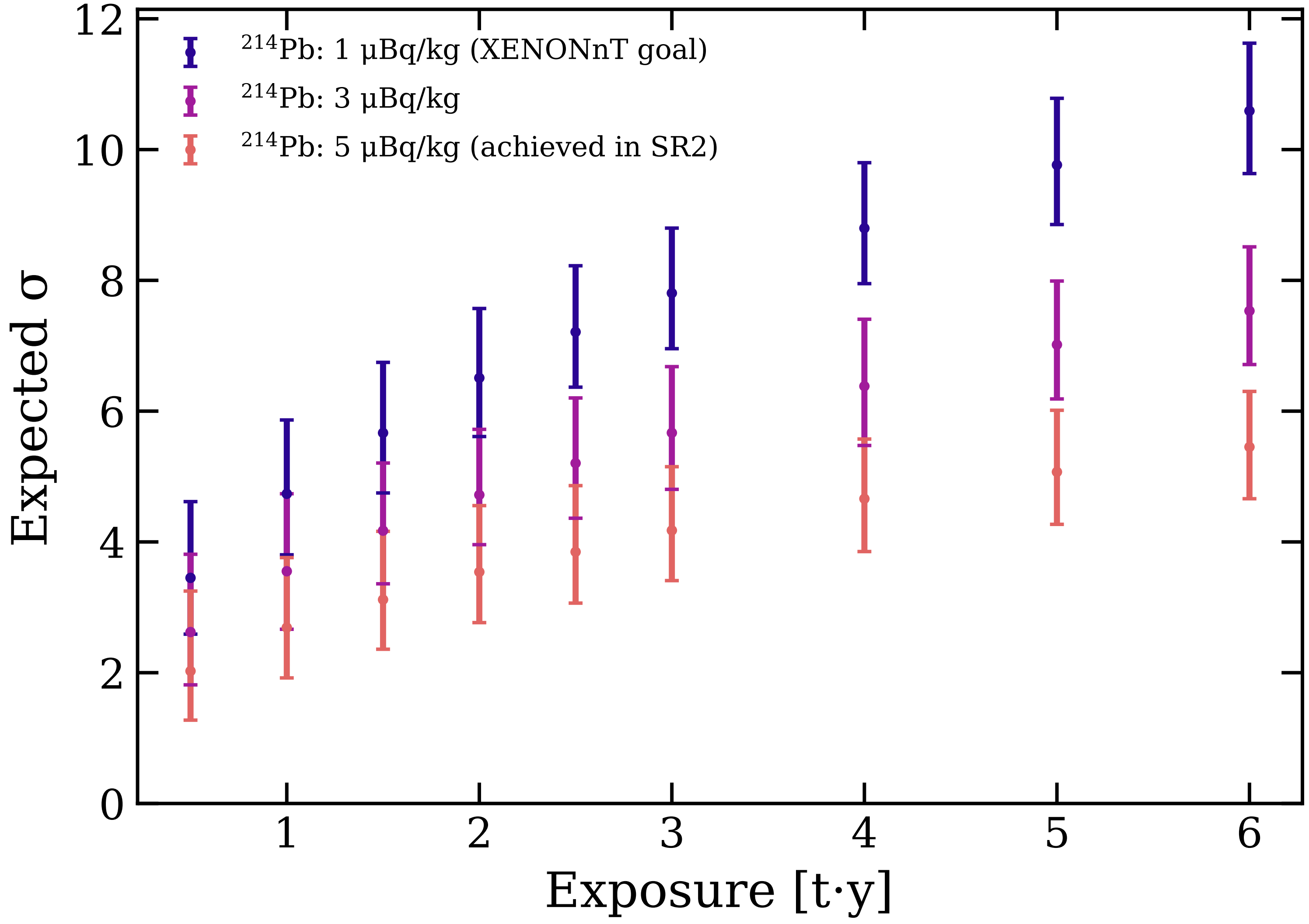
Just started filling Lee yesterday!!!

Data-taking will start quite soon

	Total Xe mass	Fiducial mass	TPC height, diameter	Number of PMTs	^{222}Radon background	Neutron reduction	SI sensitivity
XENON1T	3.2 ton	1.3 ton	1.0 m, 1.0 m	248	10 µBq/kg	Passive water shield	4.1x10^{-47} cm^2 @ 30 GeV
XENONnT	8.4 ton	~4 ton	1.5 m, 1.3 m	494	~2 µBq/kg	Active veto with Gd-loaded water	1.6x10^{-48} cm^2 @ 50 GeV with 5 years exposure

How much data do we need to conclude?

1Tで見つかったsolar-axionの信号量が本物だと仮定した際、どれくらい統計を貯めればトリチウムとエネルギースペクトラムの違いが明確になるか？



- 1Tで見つかったsolar-axionのbest-fitの信号量を仮定
- BGは214Pbがどれくらい減るか、3つのケースを想定
- Solar-axion + BG model(トリチウムなし)を用いて、pseudo-dataを生成
- これをaxion+BG+トリチウム(normalization free)でフィットして、トリチウム入りモデルを棄却するにはどの程度の統計が必要か調べた

XENONnT will discriminate axions from tritium with ~ few months of data

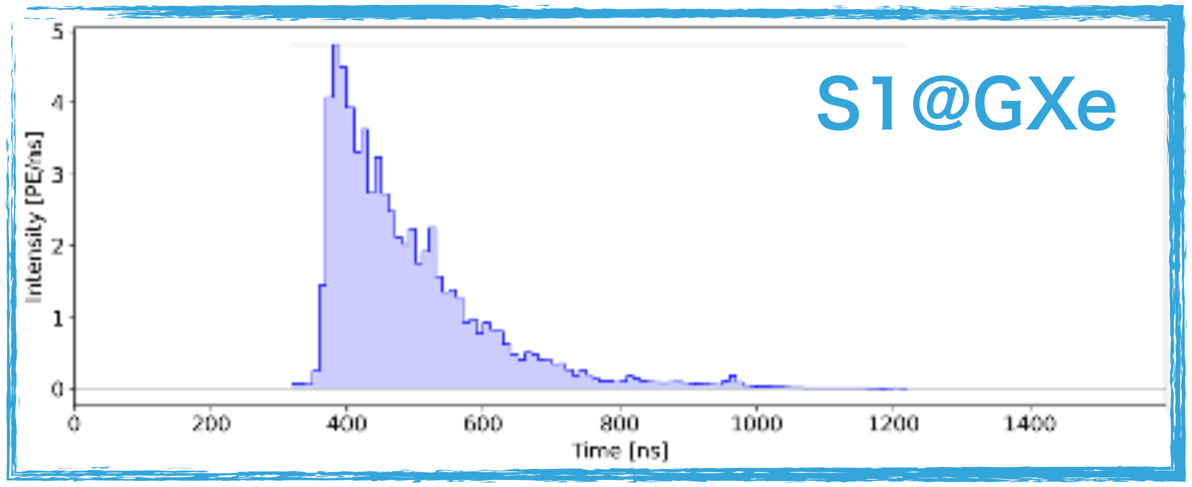
Summary

Solar axions favored over background at 3.5 sigma, but
a tritium background at 3.2 sigma can neither be confirmed nor excluded, and
there is a discrepancy with stellar constraints for axion-electron couplings...

ALP dark matter peak at 2.3 +/- 0.2 keV has **3.0 sigma global!**

It is too soon to draw any conclusions;

XENONnT is coming soon
Started LXe filling yesterday!



もっと詳細が知りたい方、どんな理論が考えられるか？
トリチウムの可能性の詳細な議論、他の実験でどうやって検証するか？

9/8(火)9:00-18:00

ダークマターの懇談会2020 online
(darKONline2020)

http://ppwww.phys.sci.kobe-u.ac.jp/~newage/darkon2020/

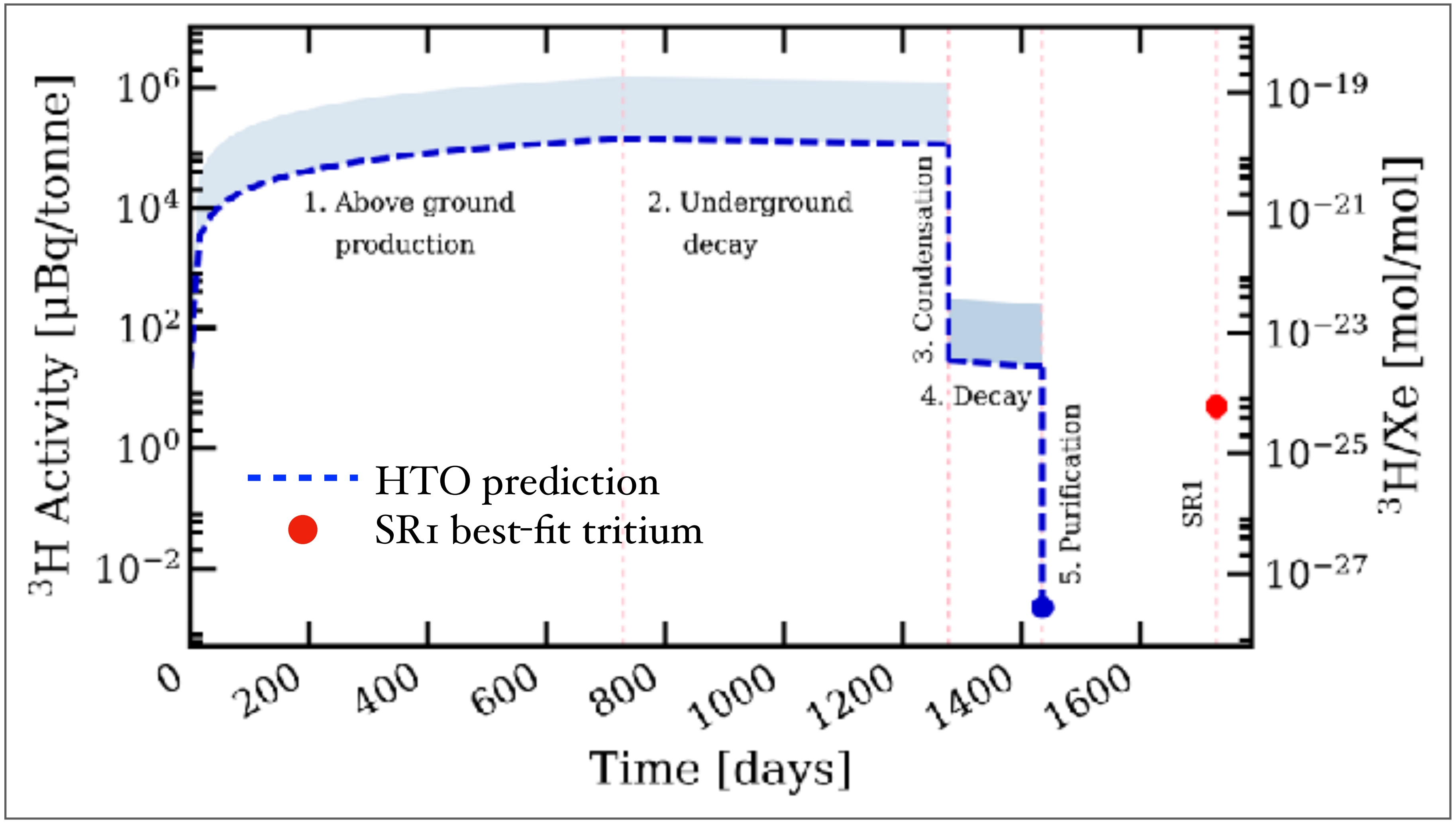
Back Up

1. Cosmic Activation of Xenon

Cosmogenic activation of xenon: ~32 tritium atoms/kg/day (Zhang, 2016)

1 ppm water in bottles implies tritium forms predominately HTO.

Efficient removal (99.99%) in purification system (SAES getter with hydrogen removal unit)



Tritiated water (HTO)

(note: tritium from activation While underground is negligible.)

Expected concentration more than 100x smaller than measured

From purification and handling, this component seems unlikely.

2. Atmospheric Abundance in Materials

What about T emanating from materials in equilibrium with removal?

*Hydrology measurements from IAEA nuclear database

HTO:H_2O concentration*	$5–10 \times 10^{-18}$ mol/mol
HT:H_2 concentration →	**Assuming same concentration as for H20**

Required (H_2O + H_2):Xe concentration to explain	**60–120 ppb**

Tritiated molecules can emanate into LXe target from water and hydrogen in detector materials in the form of **HTO** and tritiated hydrogen (**HT**). emanation in equilibrium with removal.

But…

H2O

H2O in XENON1T: O(1) ppb, otherwise can not detect light

H2

O2 in XENON1T: <1ppb, otherwise can not drift electrons

H2 ~100 ppb? -> ~100x higher than O2 possible?

Summary of Tritium Hypothesis

Many unknowns about tritium in a cryogenic LXe environment

- Radiochemistry, particularly isotopic exchange (formation of other molecules?)
- Diffusion properties of tritiated molecules
- Desorption and emanation
- For HT, no direct measure of either abundance or H2 concentration.

We can neither confirm nor exclude the presence of tritium.

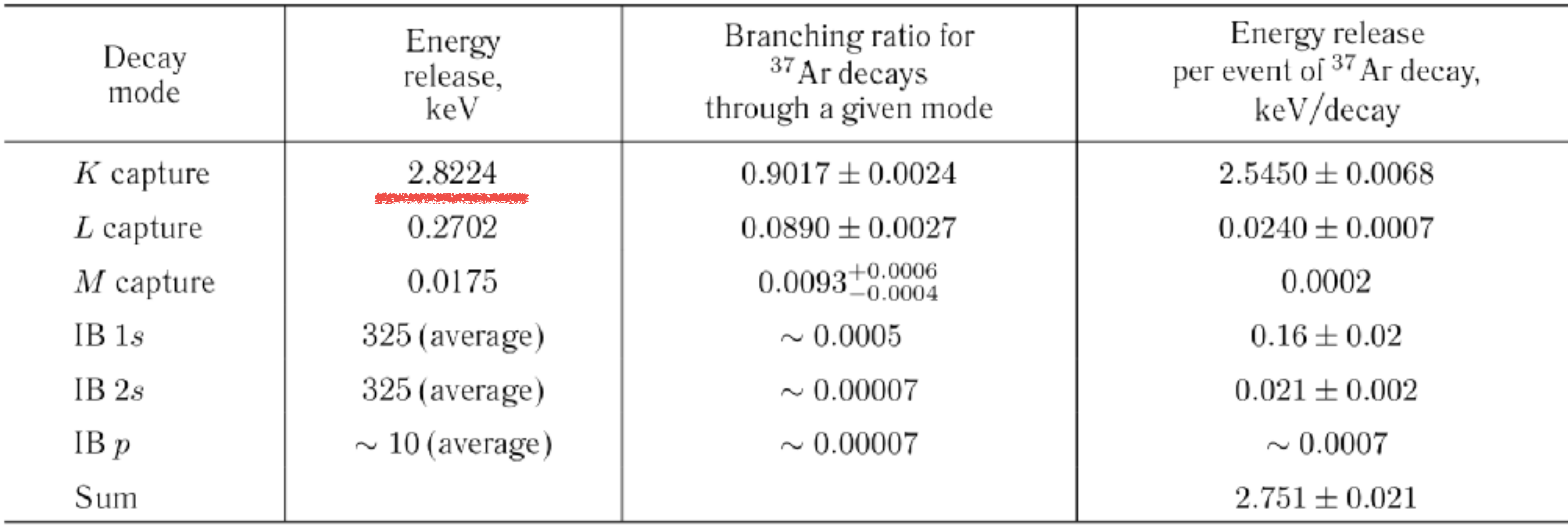
- We consider it a hypothesis, but don’t include it in the background model.
- Report additional results (but not constraints on signal parameters) with tritium included as a background component.

Ar37

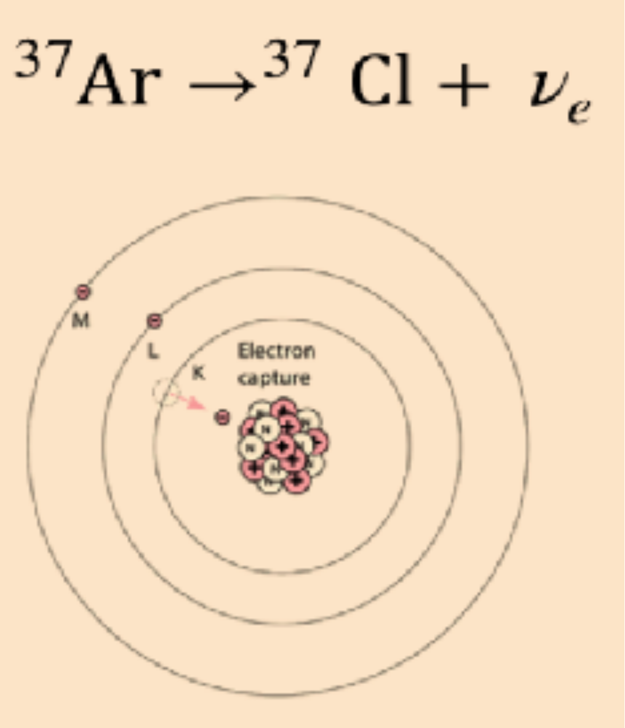
Physics of Atomic Nuclei volume 70, pages 300–310(2007)

Table 2. ^{37}Ar decay modes and released energy

$T_{1/2} = 35.0$ days



Decay mode	Energy release, keV	Branching ratio for ^{37}Ar decays through a given mode	Energy release per event of ^{37}Ar decay, keV/decay
K capture	2.8224	0.9017 ± 0.0024	2.5450 ± 0.0068
L capture	0.2702	0.0890 ± 0.0027	0.0240 ± 0.0007
M capture	0.0175	$0.0093^{+0.0006}_{-0.0004}$	0.0002
IB $1s$	325 (average)	~ 0.0005	0.16 ± 0.02
IB $2s$	325 (average)	~ 0.00007	0.021 ± 0.002
IB p	~ 10 (average)	~ 0.00007	~ 0.0007
Sum			2.751 ± 0.021



$$^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$

Ar37

Two possible ^{37}Ar contributions:

1. Its presence in the xenon gas before filling,
2. A possible air leak that could provide a constant source of argon.

1. Its presence in the xenon gas before filling,

- Removal time in distillation is ~1.8 day, directly demonstrated at 1T using a dedicated 37Ar source
- We had ~90 days of the online ^{85}Kr distillation before SR1 (22 orders of magnitude reduction)
- The isotopic abundance of ^{37}Ar is ~ 10^{-20}

Even if there were 1 ppm of ^{nat} Ar in the xenon originally, the ^{37}Ar concentration would have been reduced to a negligible level (~10^{-48} mol/mol)

Ar37

(sea-level) Ar37 activation rate of 51 atoms/(kgAr · day)

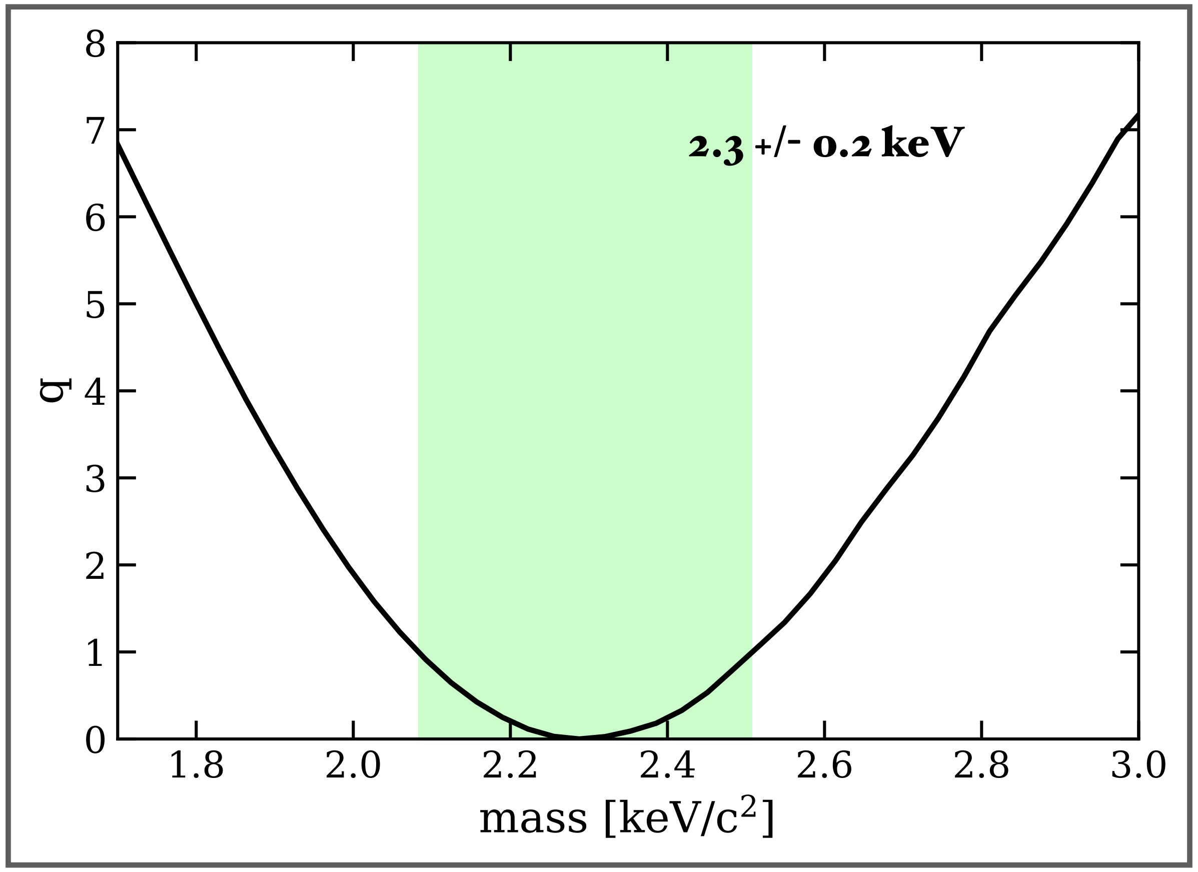
2. A possible air leak that could provide a constant source of argon.

Require: ~ 10^{-4} kg of argon per day, corresponding to a total air leak of ~ 3 L/**day**.

—> Ruled about by the ^{nat}Kr concentration, which increased by < 1 ppt/year during SR1 as informed by RGMS measurements

1-ppt/year increase in ^{nat}Kr would correspond to an air leak of ~ 1L/**year** in XENON1T.

Also TPC would not work in such a leaky condition because of O2…



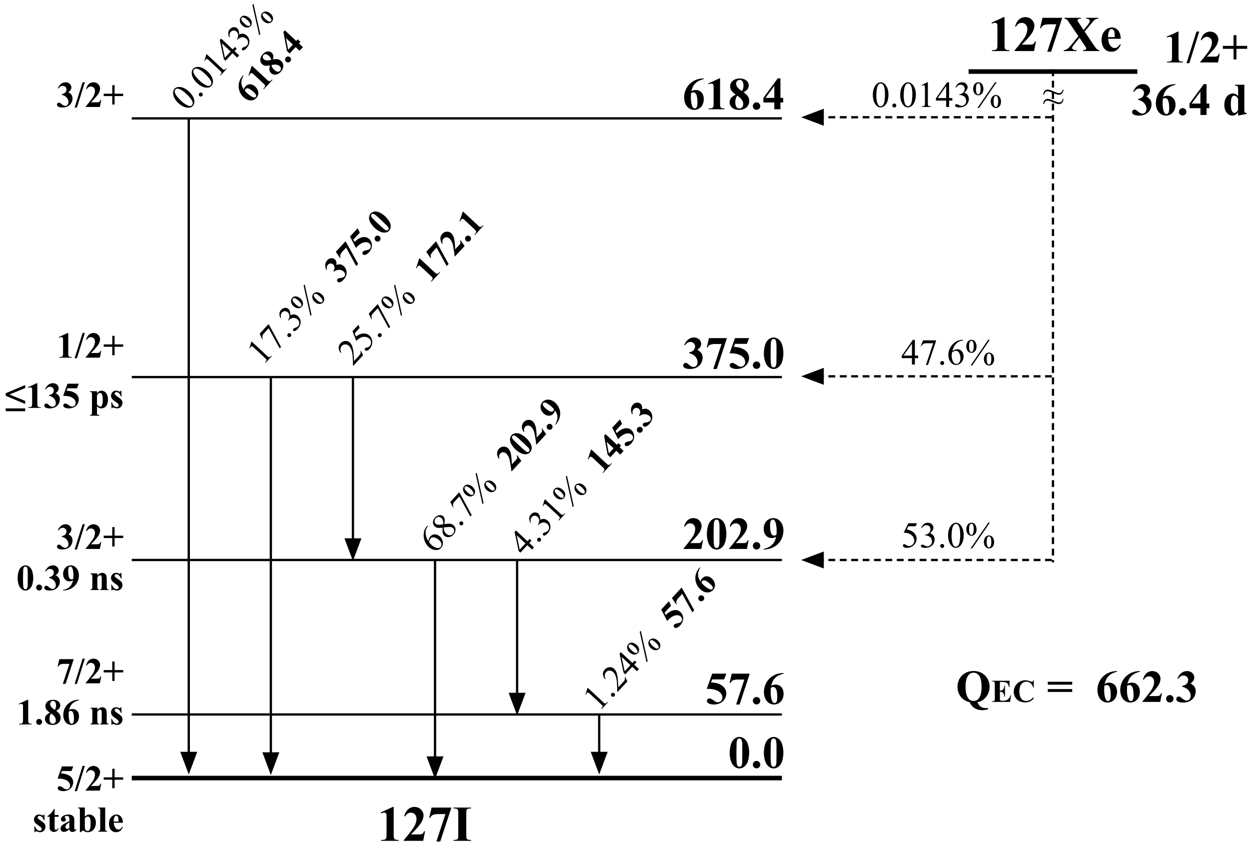
Best-fit mass is 2.3 +/- 0.2 keV, so far from 2.8 keV

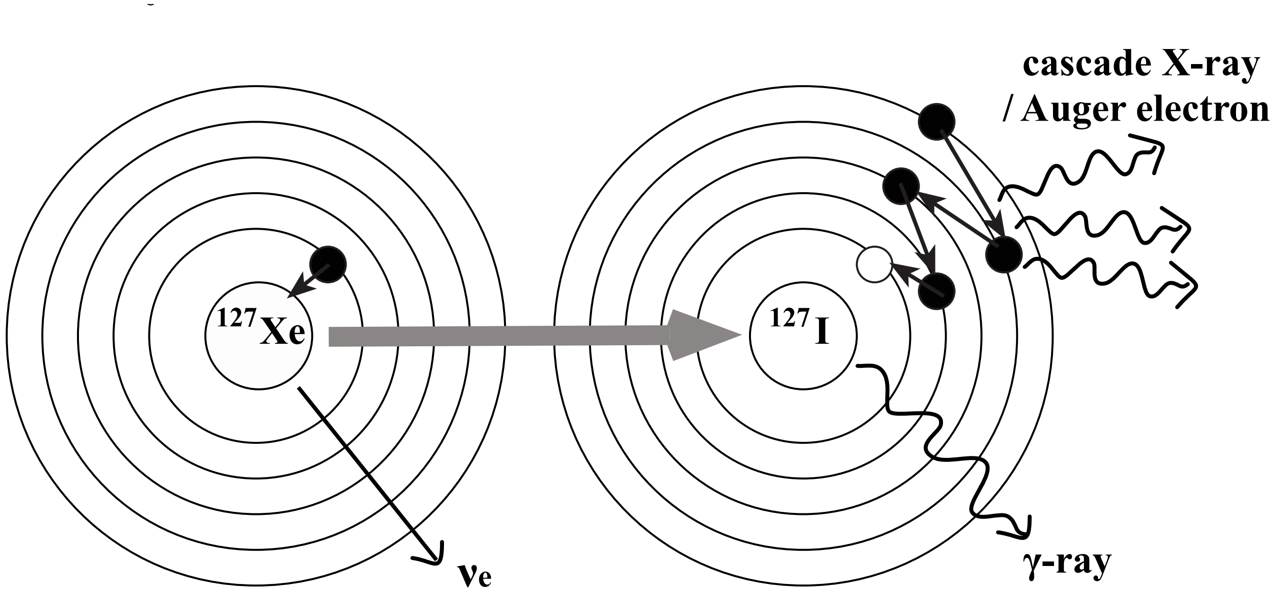
Xe127

^{127}Xe can be produced from cosmogenic activation of Xe at sea level;

Given the short half-life of 36.4 days and the fact that the xenon gas was underground for O(1) years before the operation of XENON1T

—> already decayed away





Phys. Rev. D 96, 112011 (2017)

Also we did not see high-energy γs that accompany X-rays
(We are using inner volume for this search, so there is a O(1)cm between FV and the detector wall)

214Pb Spectrum Model

Calculated spectra by X. Mougeot

Exchange effect

β electron is created in an atomic orbital of the daughter atom and the atomic electron which was present in the same orbital in the parent atom is ejected to the continuum.

This process leads to the same final state as the direct decay, i.e. one electron in the continuum, and is possible because the nuclear charge changes in the decay.

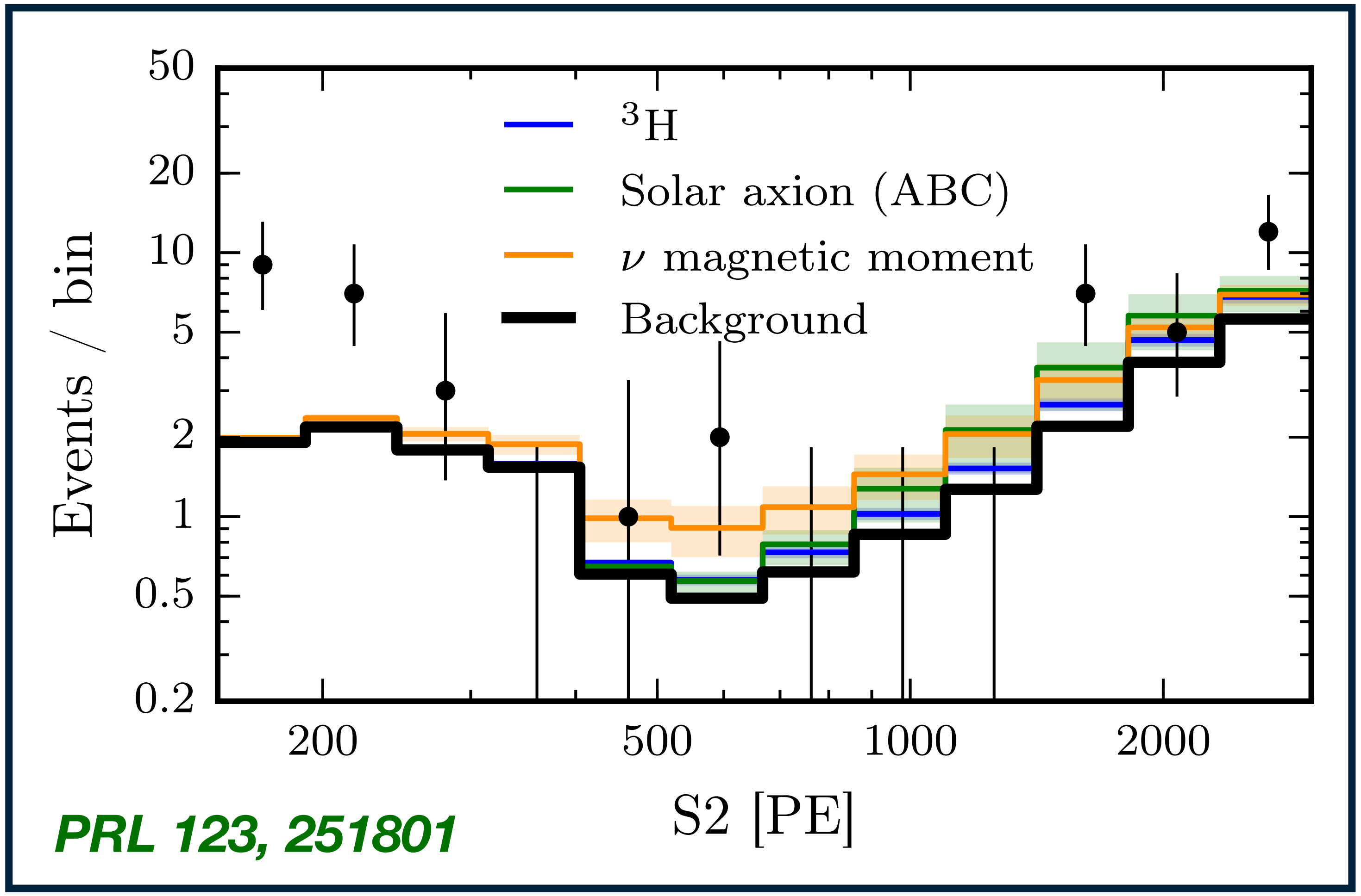
Screening effect

The electrons in bound states in the atom produce screening of the nuclear charge for the emitted beta particle. This change in electromagnetic field modifies the beta spectrum.

(The atomic screening effect corresponds to the influence of the electron cloud surrounding the daughter nucleus on the β particle wave function)

S2-ONLY ANALYSIS

S2-only = No requirement on S1s, allowing for a ~200 eV threshold



PRL 123, 251801

S2-only analysis allows for a lower energy threshold of 200eV

$\mu_\nu < 3.1 \times 10^{-11}\ \mu_B$

$g_{ae} < 4.8 \times 10^{-12}$

$R_{\mathrm{H3}} < 2256\ \mathrm{events/t/y}$

consistent with this work for all 3 hypotheses

larger upper limits, S2-only analysis is not sensitive to the excesss we found