電子散乱事象の超過 @XENON1T実験

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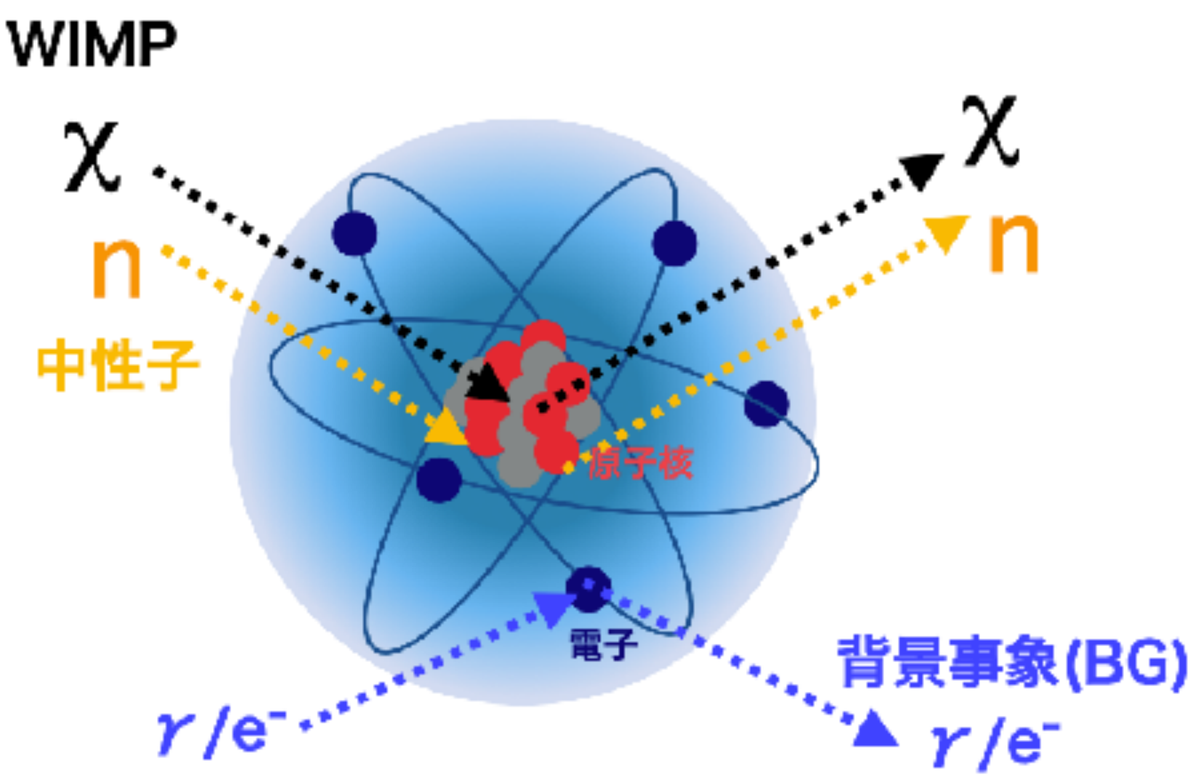
@ダークマター懇談会2020

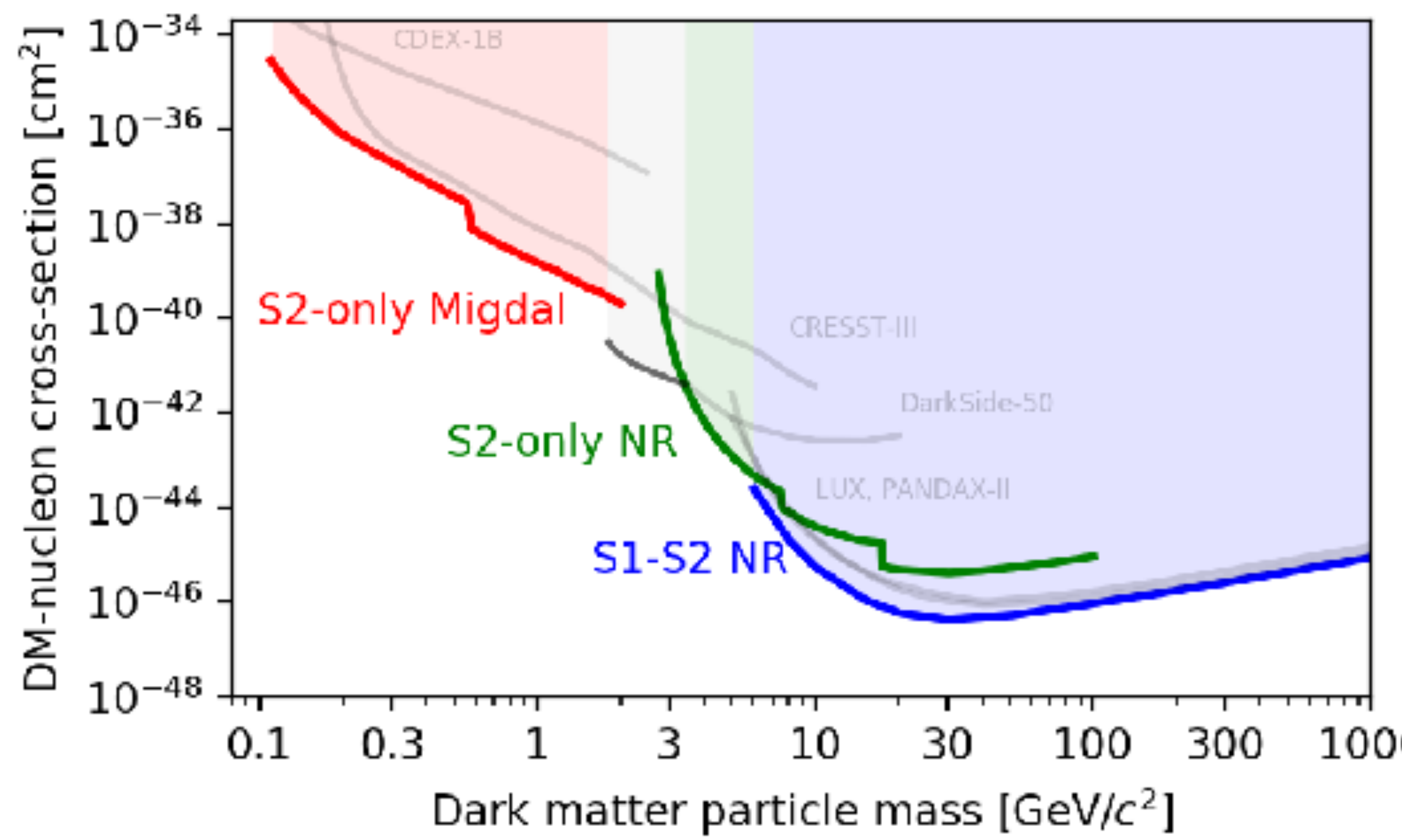
暗黒物質の直接探索

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 for XENON1T実験)。



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(小林くんのトーク)

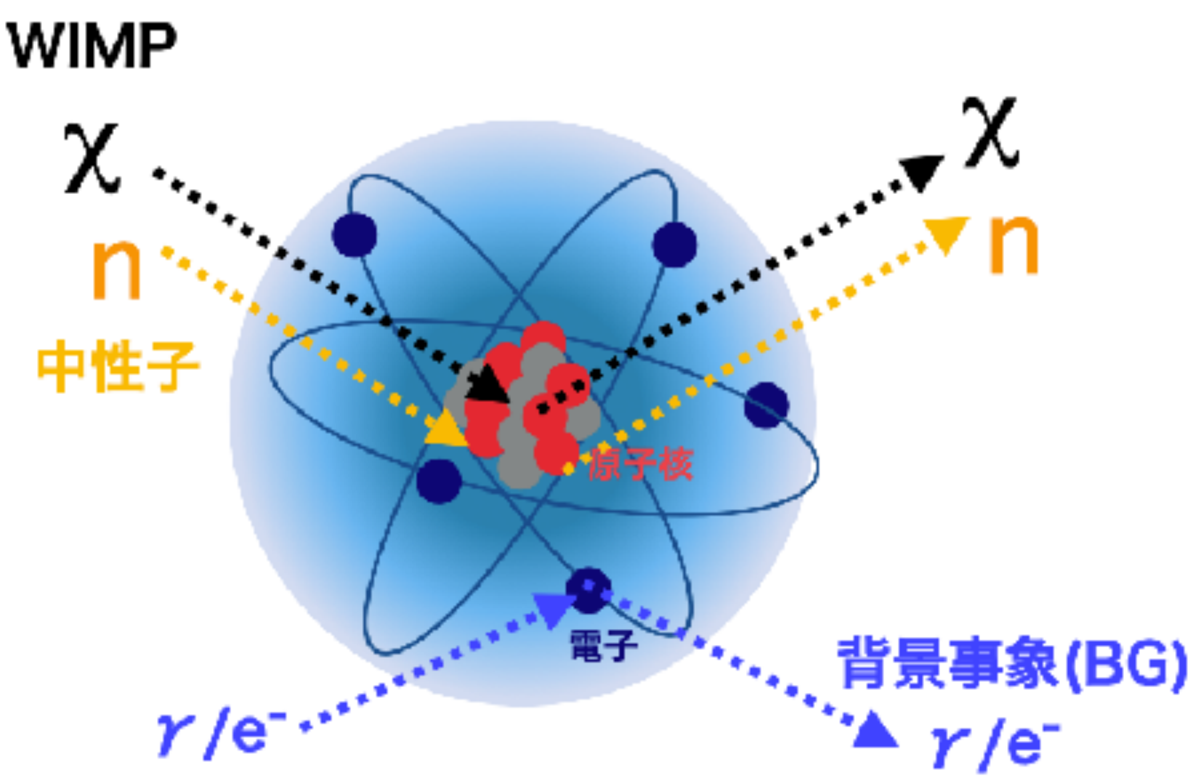
暗黒物質の直接探索

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

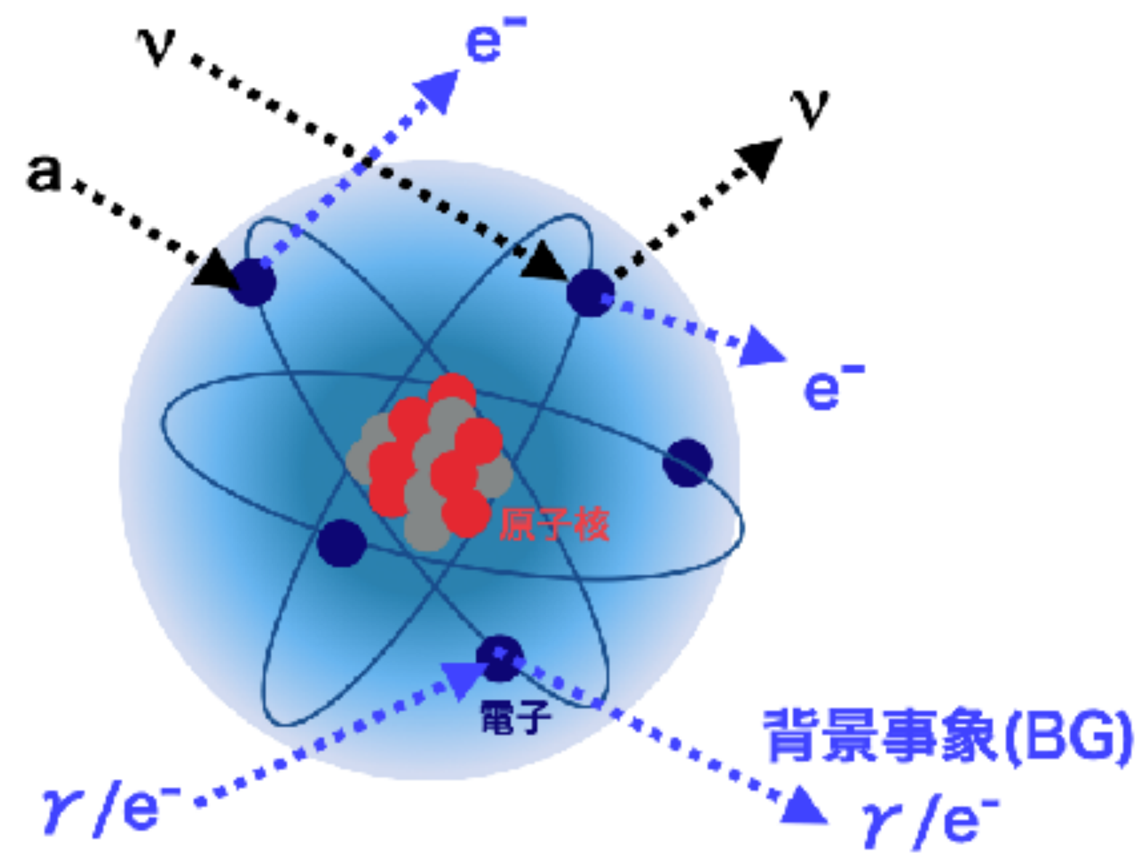
太陽アクシオン: Axio-electric effect (光電効果と似た効果, g_{ae})

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)



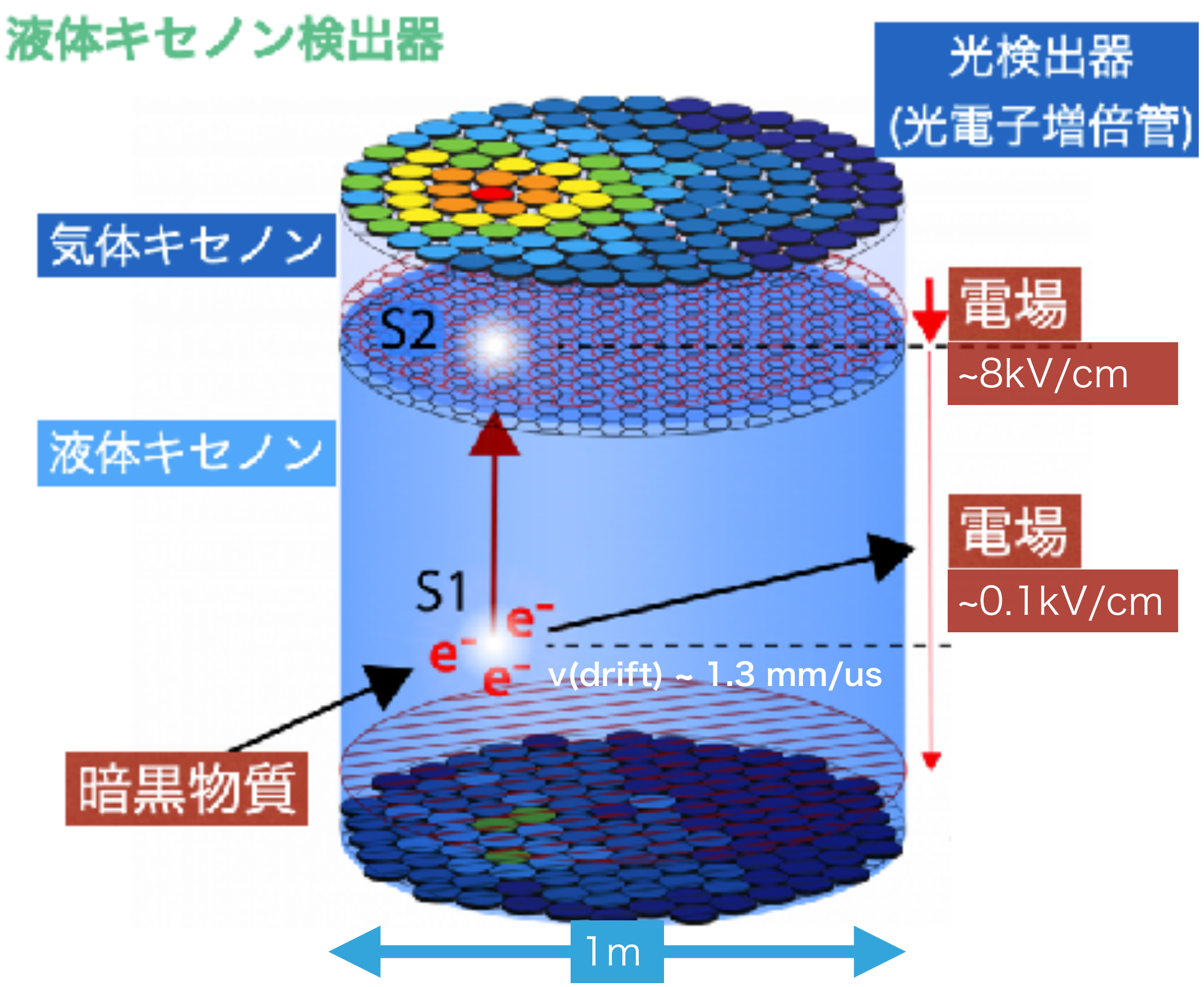
太陽アクシオン・太陽ニュートリノ (今回はこちら！)



電子反跳事象の探索

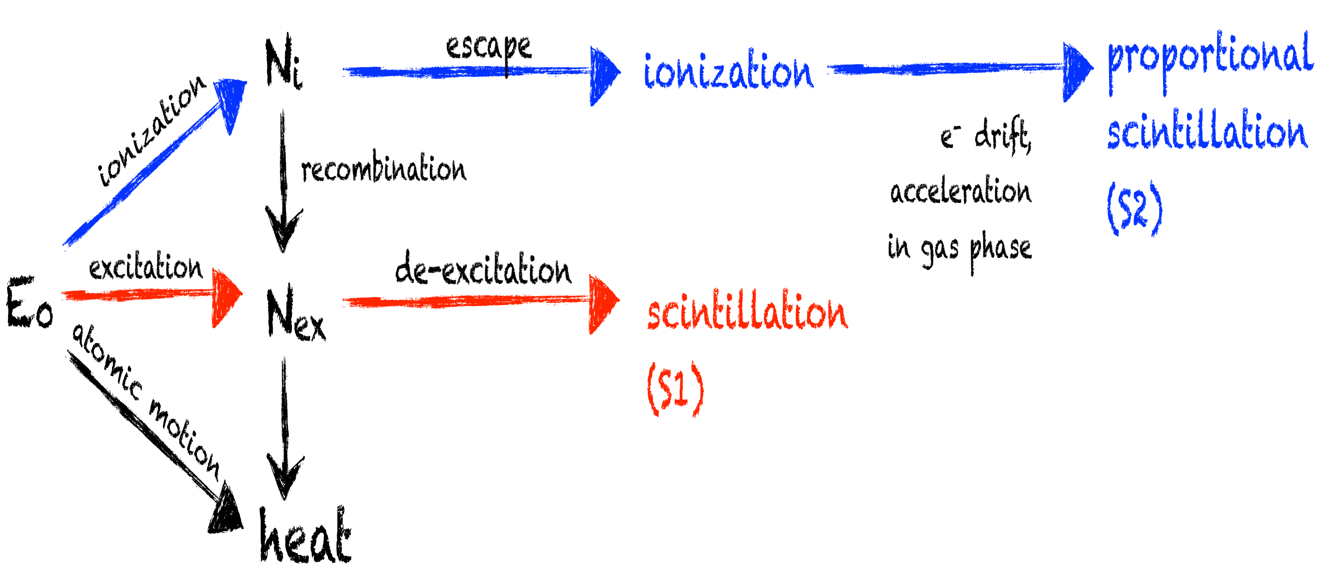
- 通常、電子反跳事象はWIMP探索の背景事象(BG)
- WIMP searchと比べてBG量(ex: 放射性ラドン・クリプトンなど)が多いので、BGをより精密に評価し、そこからの超過を探す

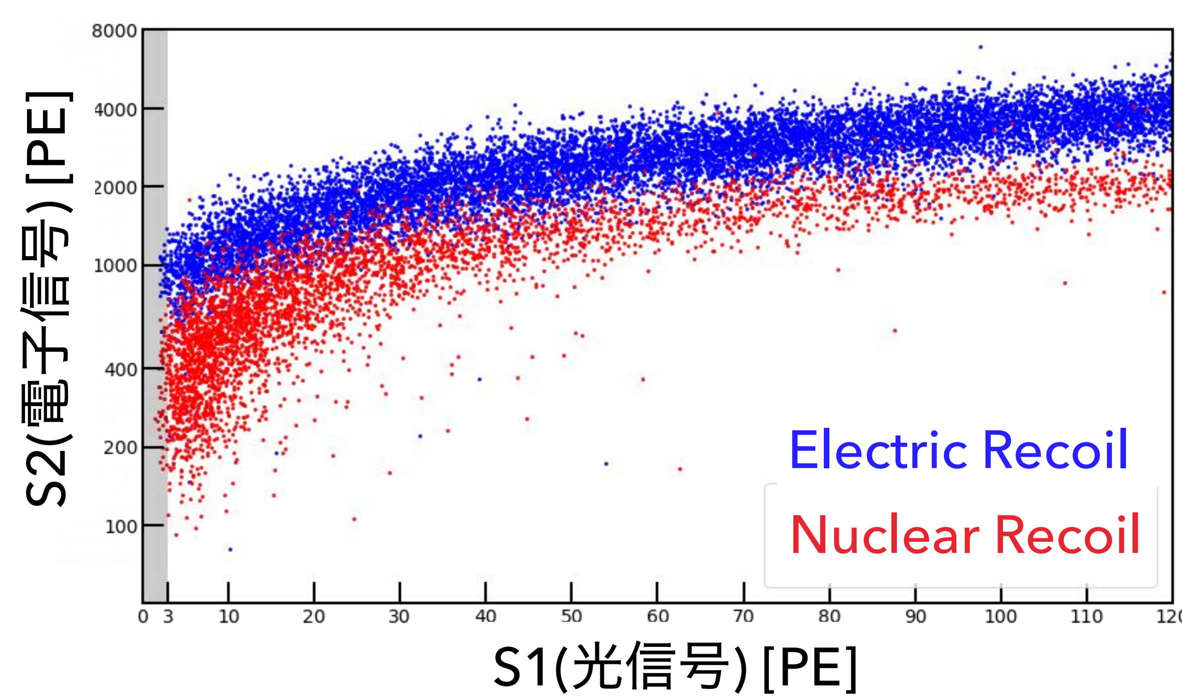
LXe TPC: Working Principle



- 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: **$(S2/S1)_{\gamma,e}$ > $(S2/S1)_{WIMP}$**

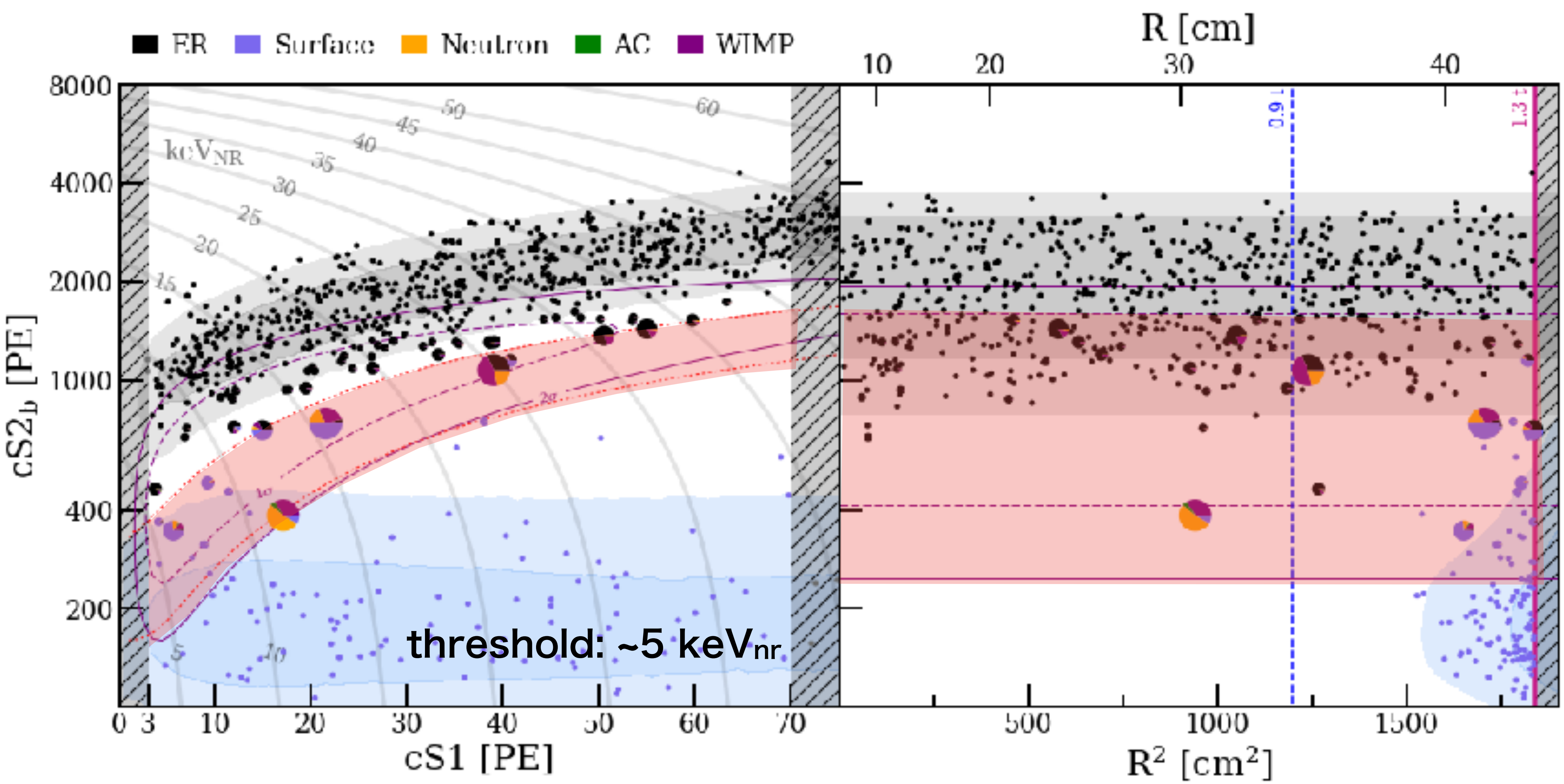
  Electric Recoil   Nuclear Recoil





XENON1T WIMP Searches – 2018 (NR Search)

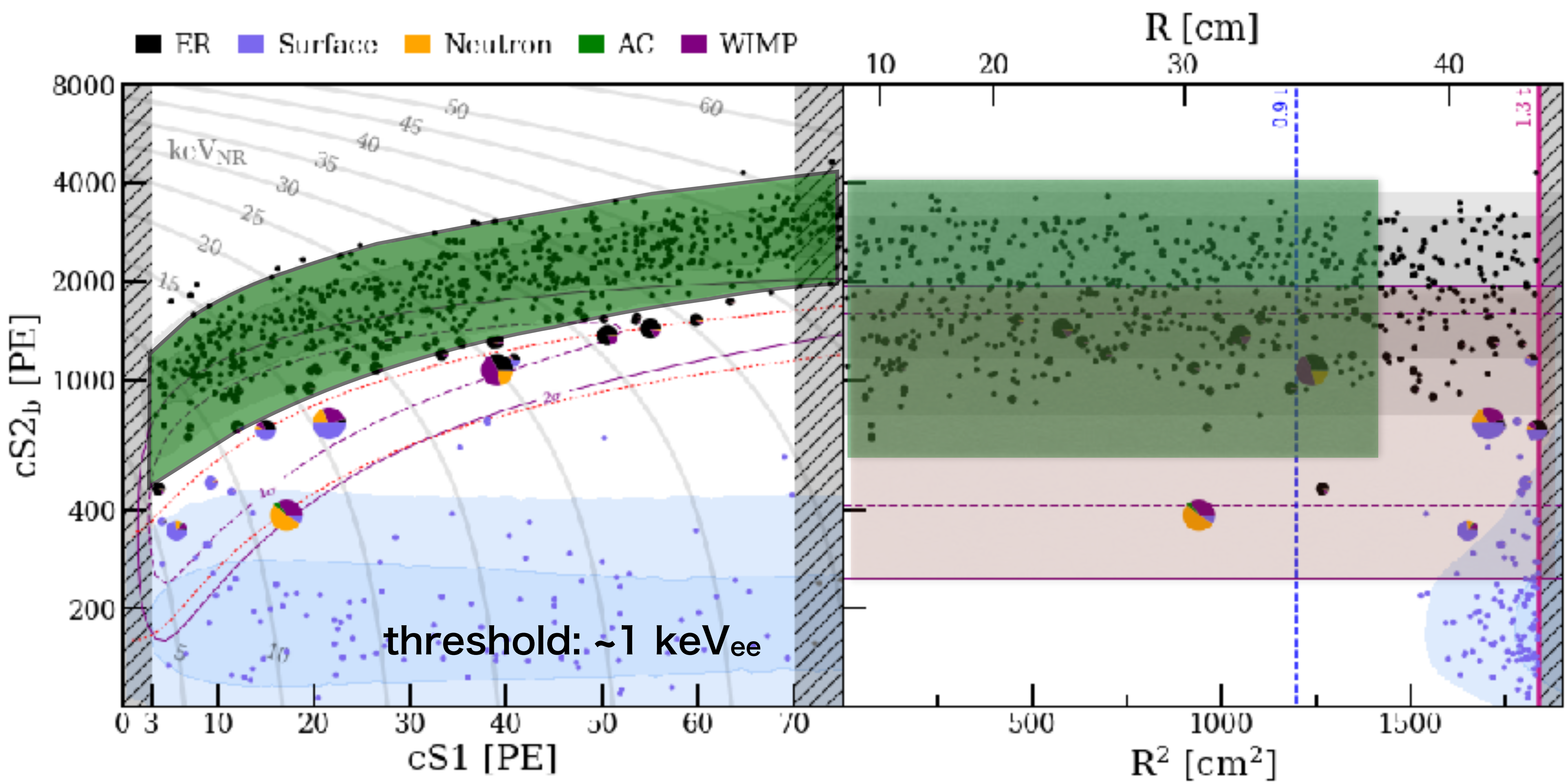
One ton-year of search for WIMPs induced nuclear recoils



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。

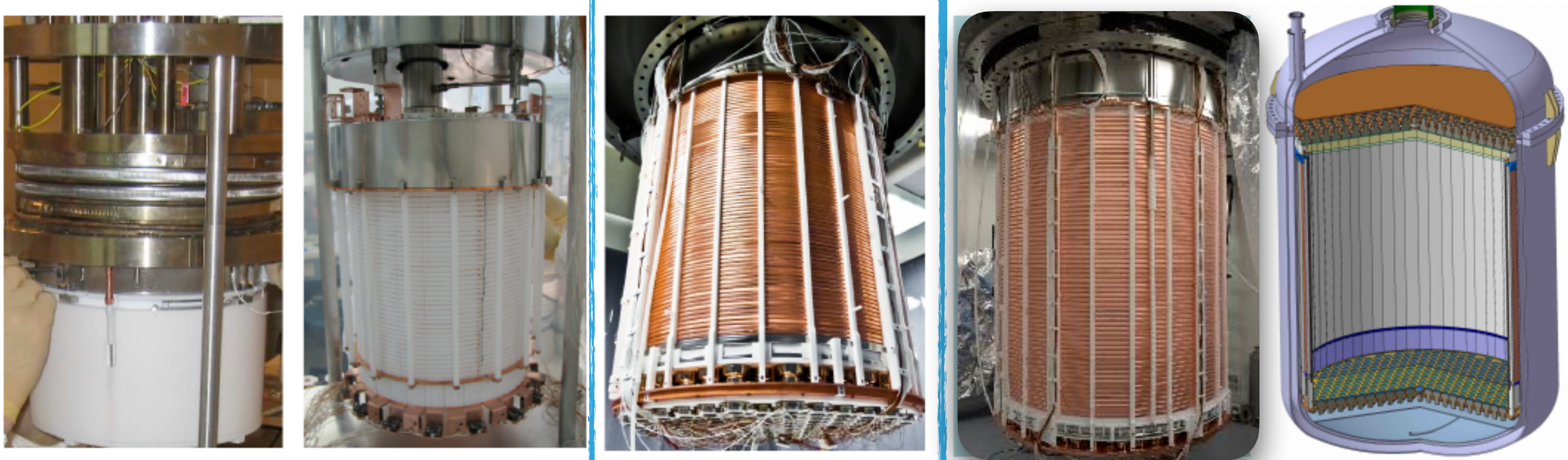


太陽アクシオンやALPs, Dark Photon探索における戦略

- 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

XENON1T Detector

The XENON + DARWIN Program

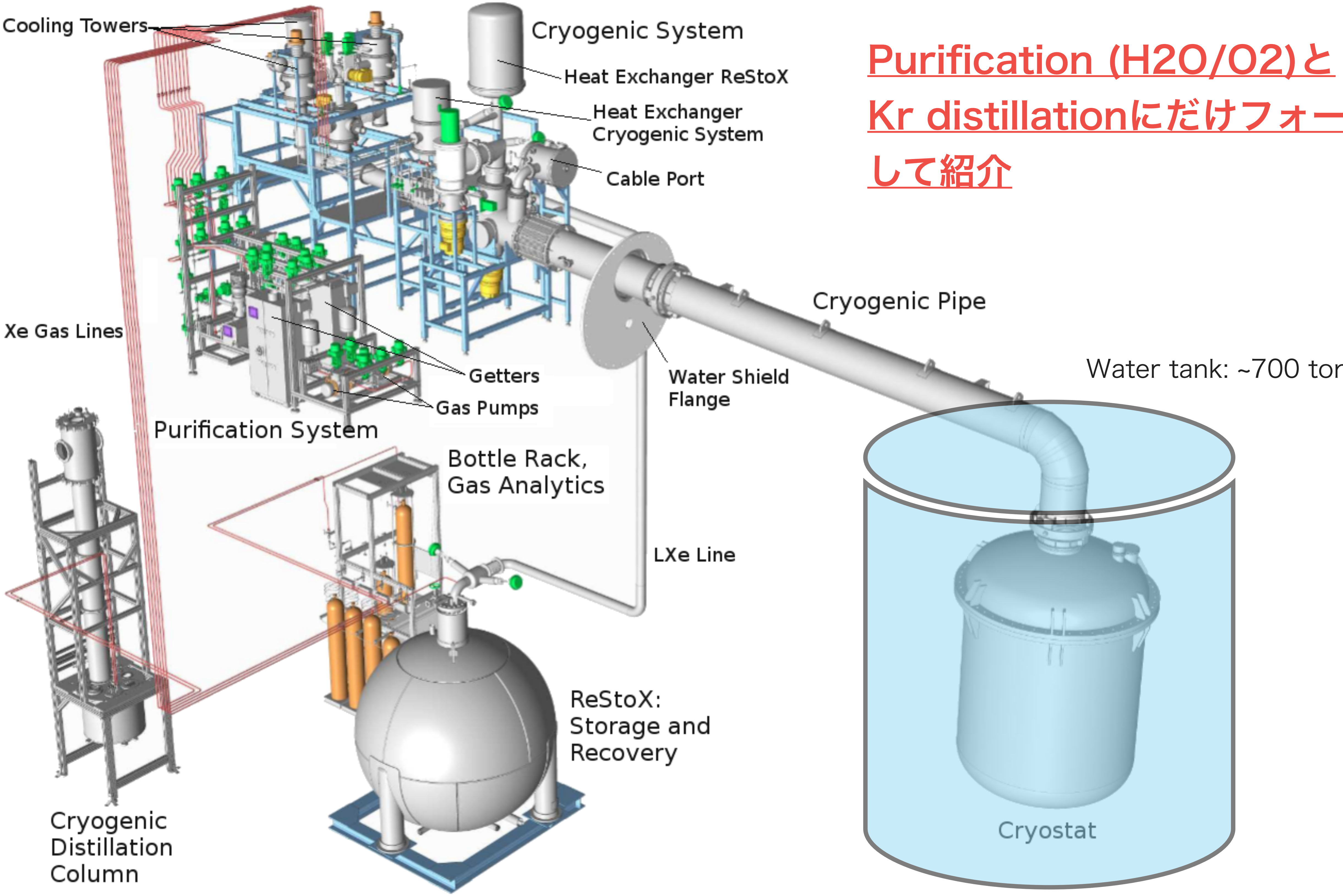


XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

先週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！

The XENON1T Experiment @ LNGS in Italy

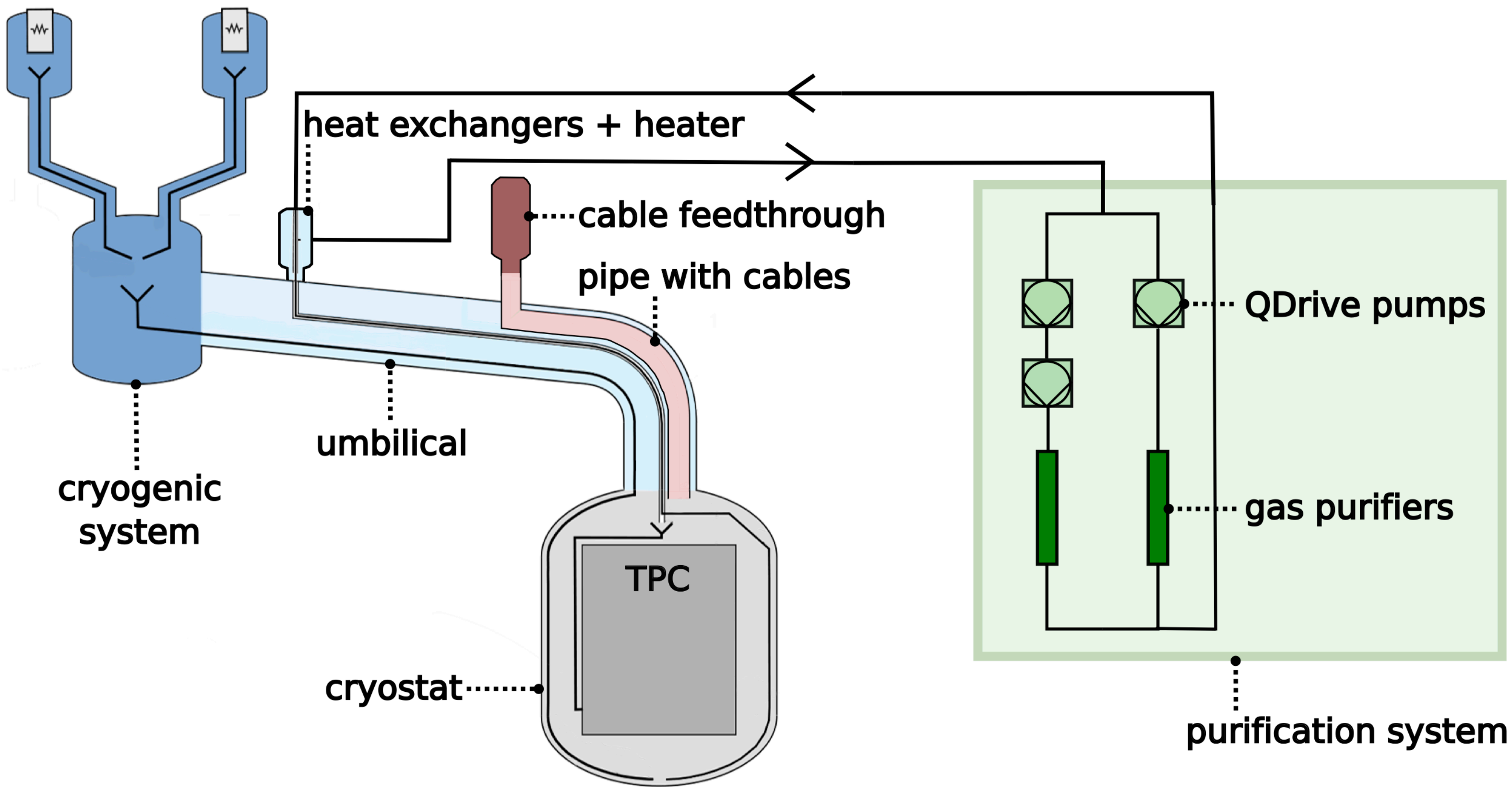


Purification (H2O/O2)と
Kr distillationにだけフォーカスして紹介

248 3-inch PMTs (R11410-21, QE~34%@178nm)

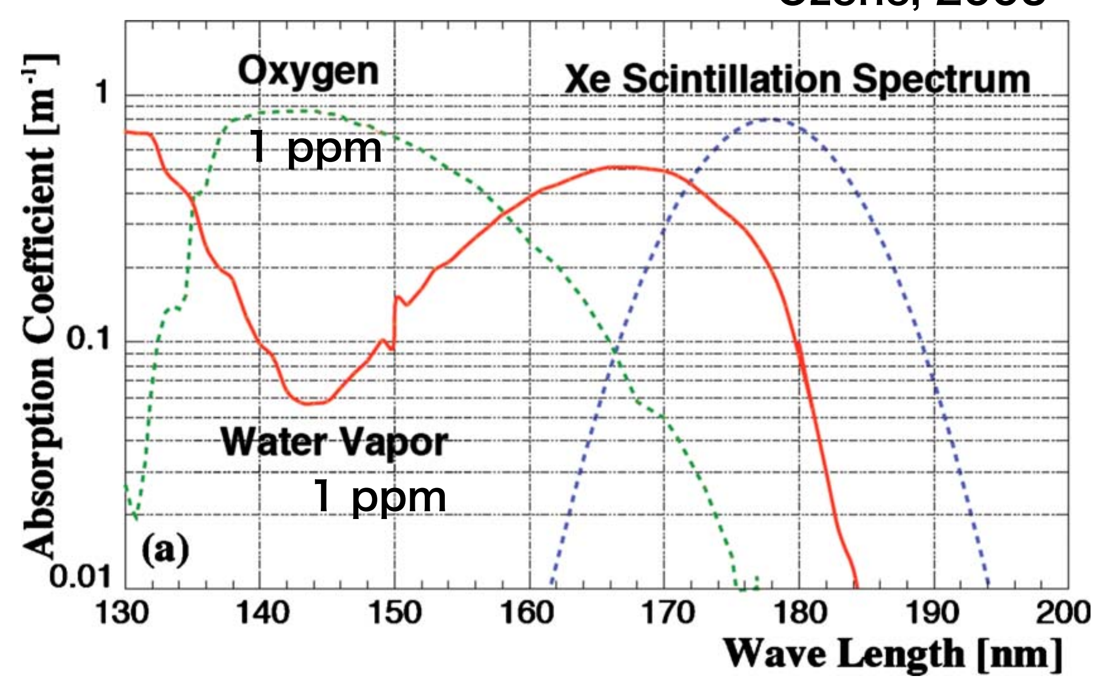
LXe mass: 3.2 t(total), 2.0t (active)

GXe Purification

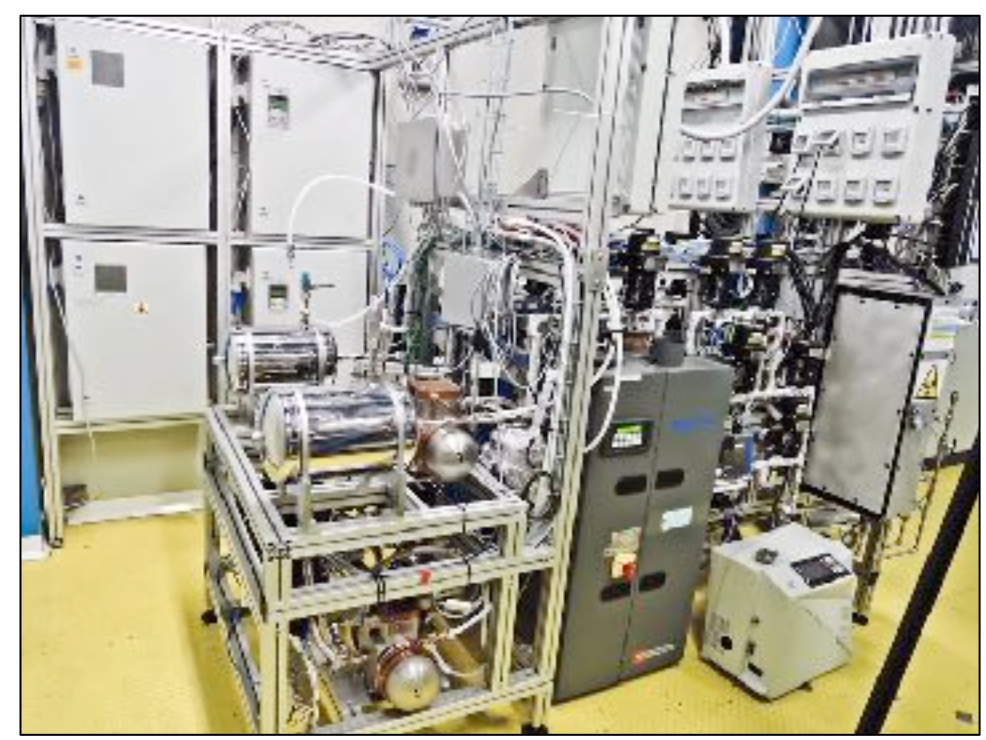


S1光の吸収

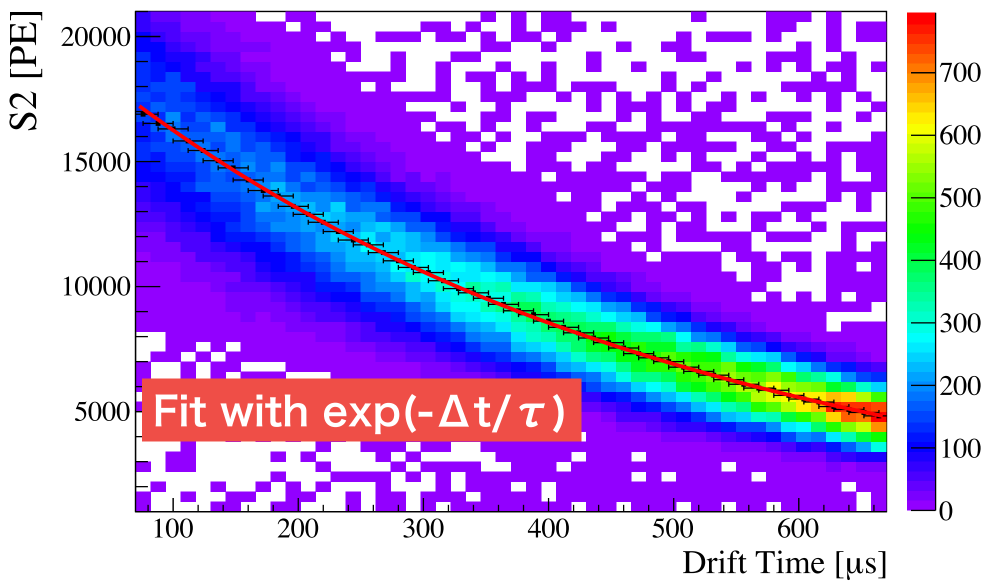
Ozone, 2005

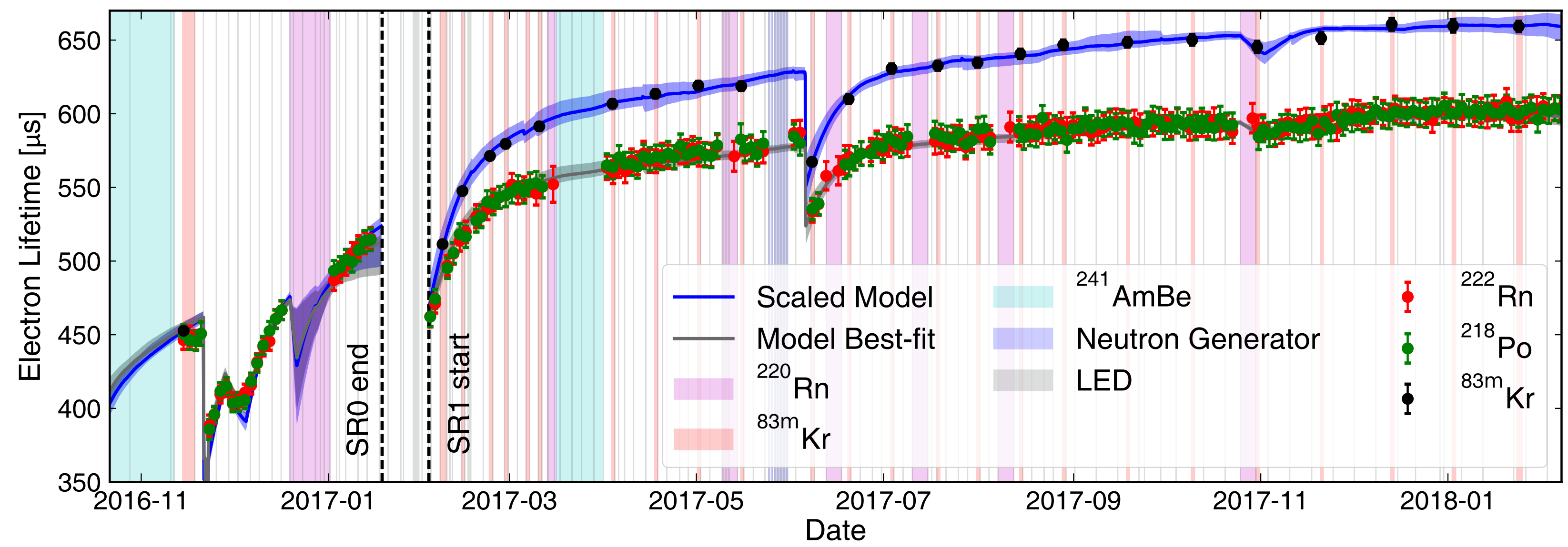


- Electronegative impurities in the Xe gas and from outgassing reduce both photon (S1) and electron (S2) signals.
- To detect light S1 signals efficiently, need O(1) ppb H_2O concentration. (Tiger Optics HALO+ H_2O monitor used for purity measurement)
- To drift electrons over 1 meter requires < 1ppb (O_2 equivalent)
- Solution: continuous gas circulation at high flow through heated getter material (Zr-V-Fe getter, 400°C) with hydrogen removal unit
- SAES PS4-MT50-R (O2, H2O, CO, CO2, H2, N2, CH4: ~ppb)
- Total flow rate of 54 slpm driven by up to 3 pumps.



GXe Purification

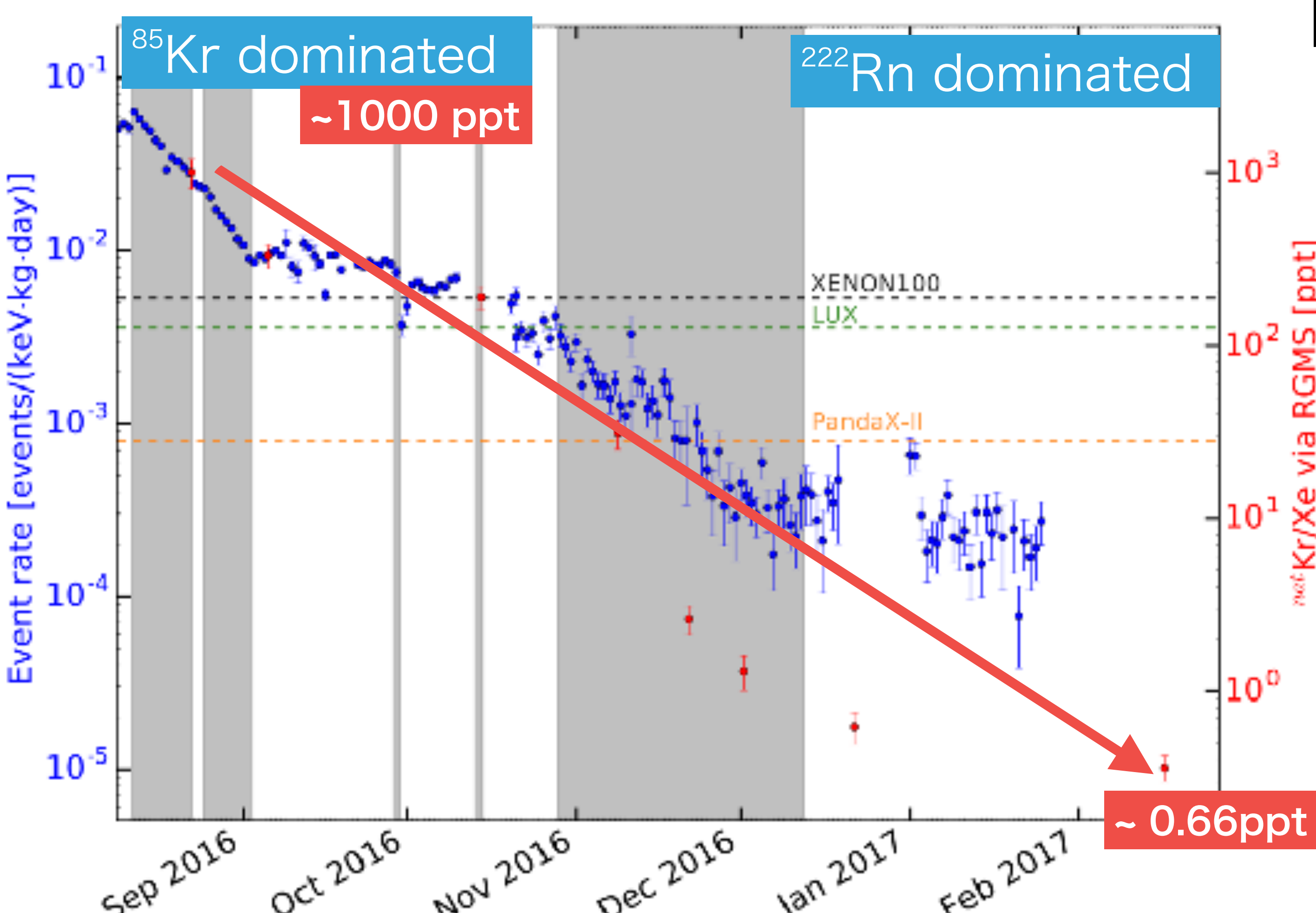


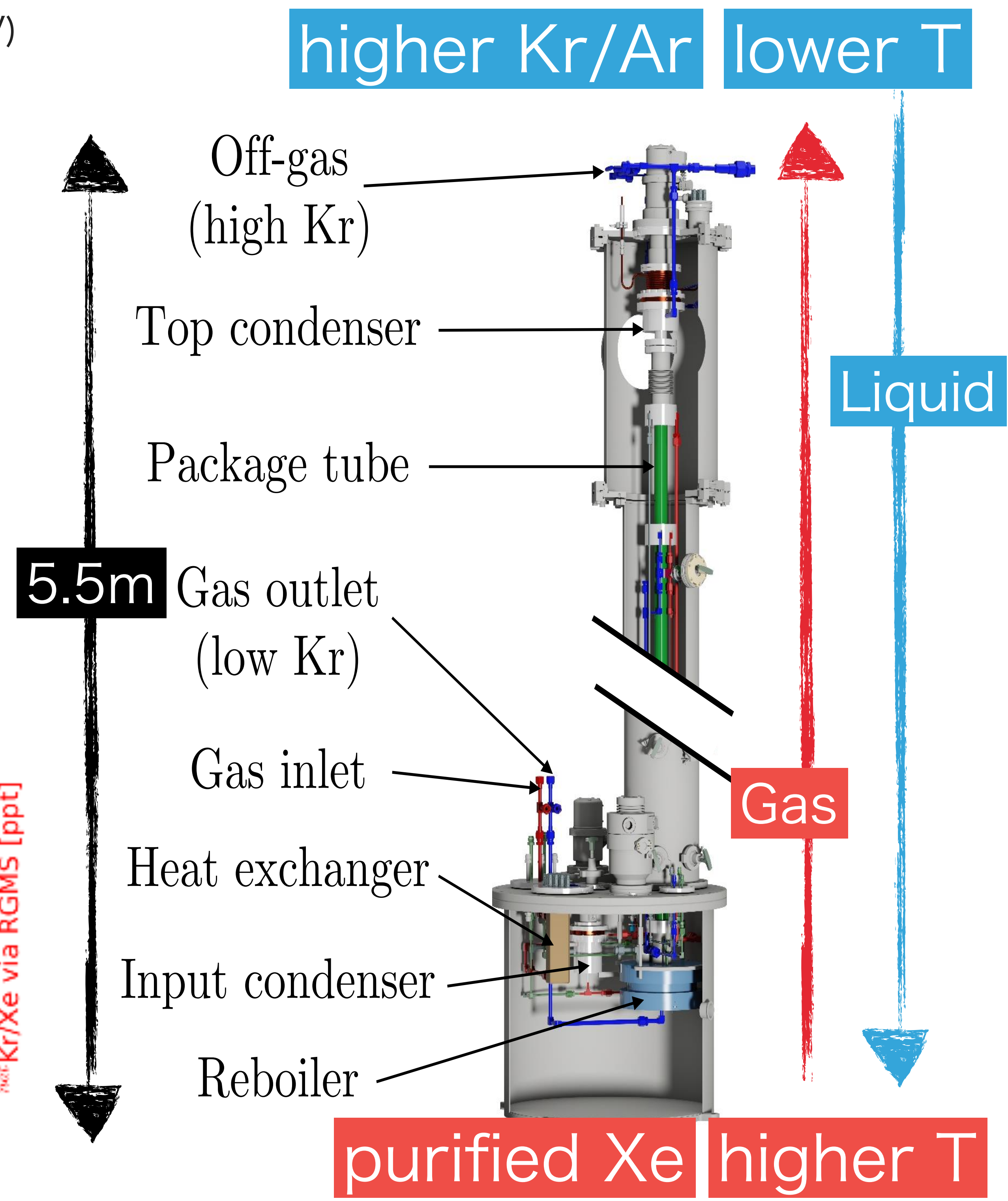


- Solution: continuous gas circulation at high flow through heated getter material (Zirconium)
- SAES PS4-MT50-R (O2, H2O, CO, CO2, H2, N2, CH4: ~ppb)
- Total flow rate of 54 slpm driven by up to 3 pumps.
- 650us of e-lifetime —> oxygen equivalent impurity concentration of ~ 0.5ppb.
- XENON1T TPC length ~ 650us drift time

Kr (and Ar) Distillation

- Commercial Xe: 1 ppm - 10 ppb ^{nat}Kr,
- ^{85}Kr is unstable ($T_{1/2}$ = 10.8 y, β-decay with Q-value = 687 keV)
- Solution: 5.5 m cryogenic distillation column
- Utilizes different vapor pressure:
  - Kr: 20900 mbar@178K, Xe: 2010 mbar@178K
- Feeding flow rate: 8.3 SLPM (3kg/h)
  - Thermodynamically stable up to 18 SLPM (6.5 kg/h)
- Measured separation: 6.4×10^5 @8.3 SLPM, < 48 ppq (RGMS)





Energy Reconstruction

Energy Reconstruction with LXe TPC

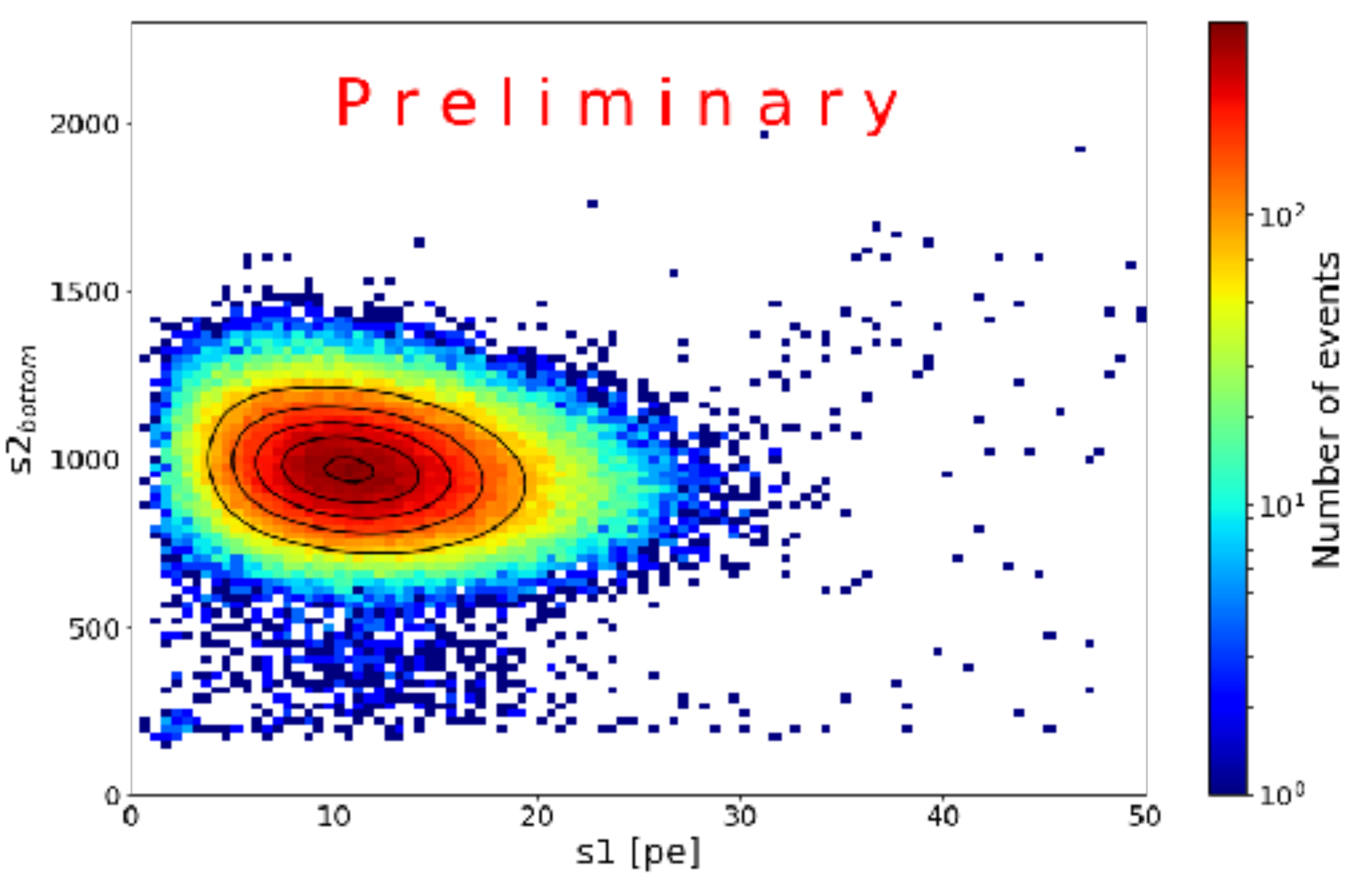
$$E = (N_{ph} + N_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

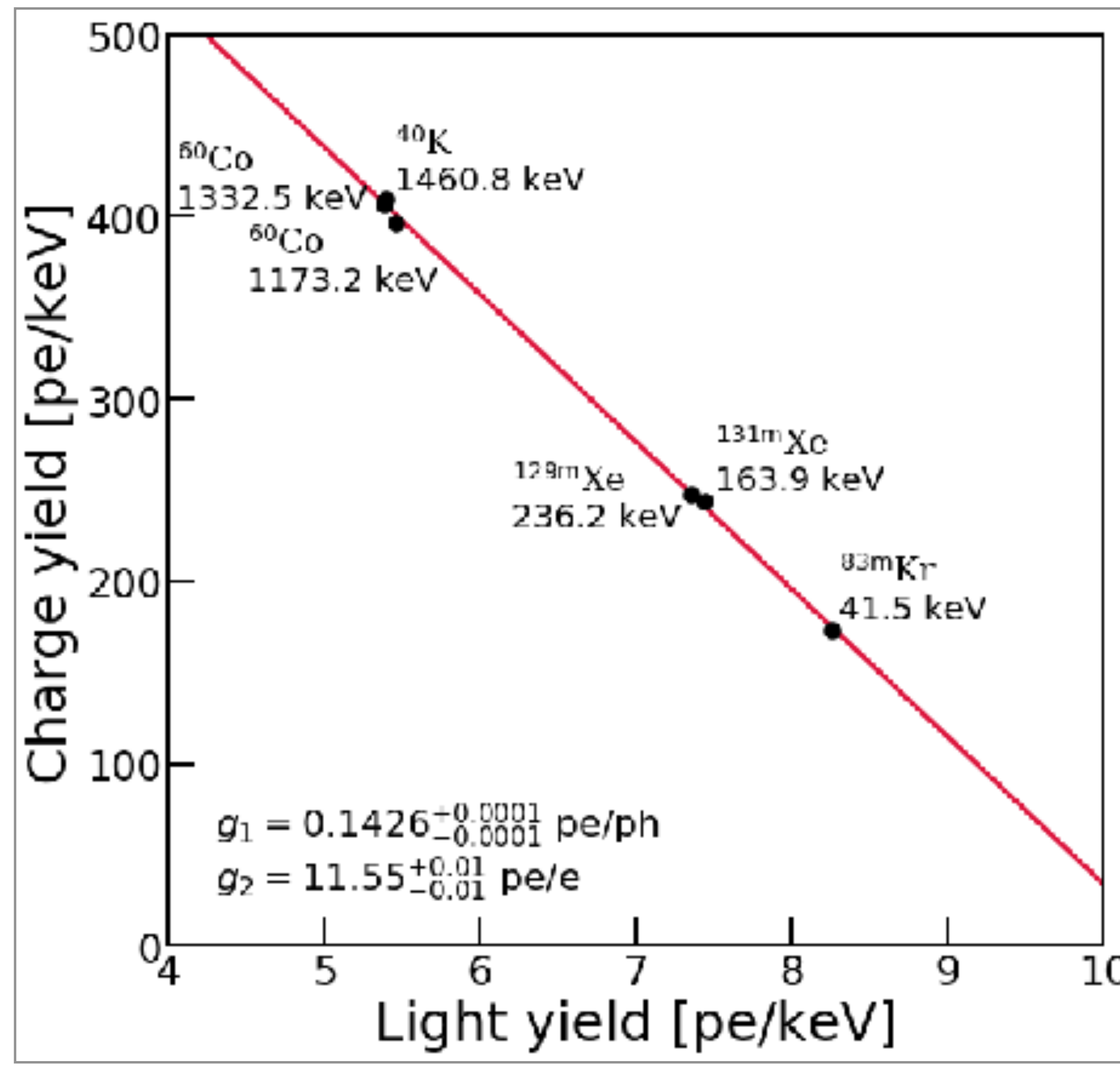
where W = 13.7 eV/quanta

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





Energy Reconstruction with LXe TPC

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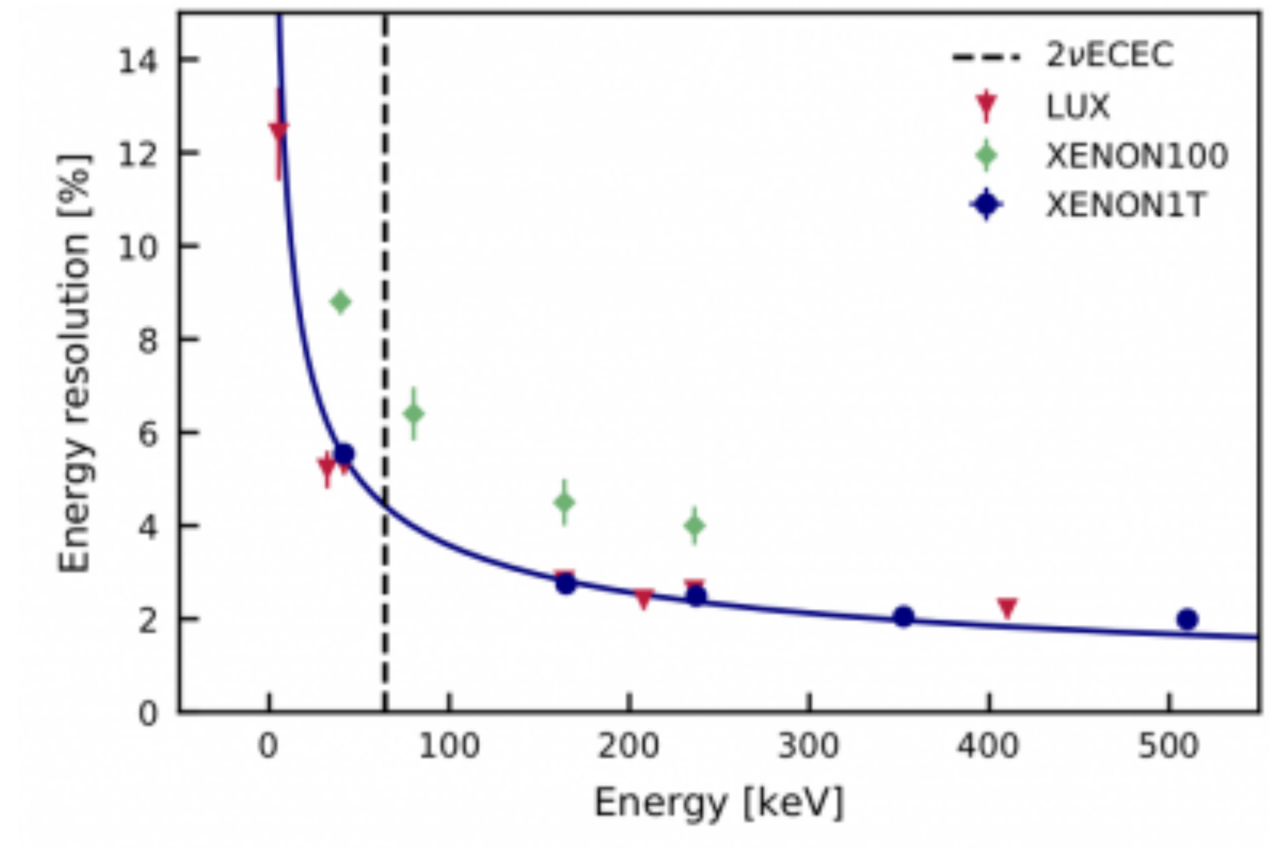
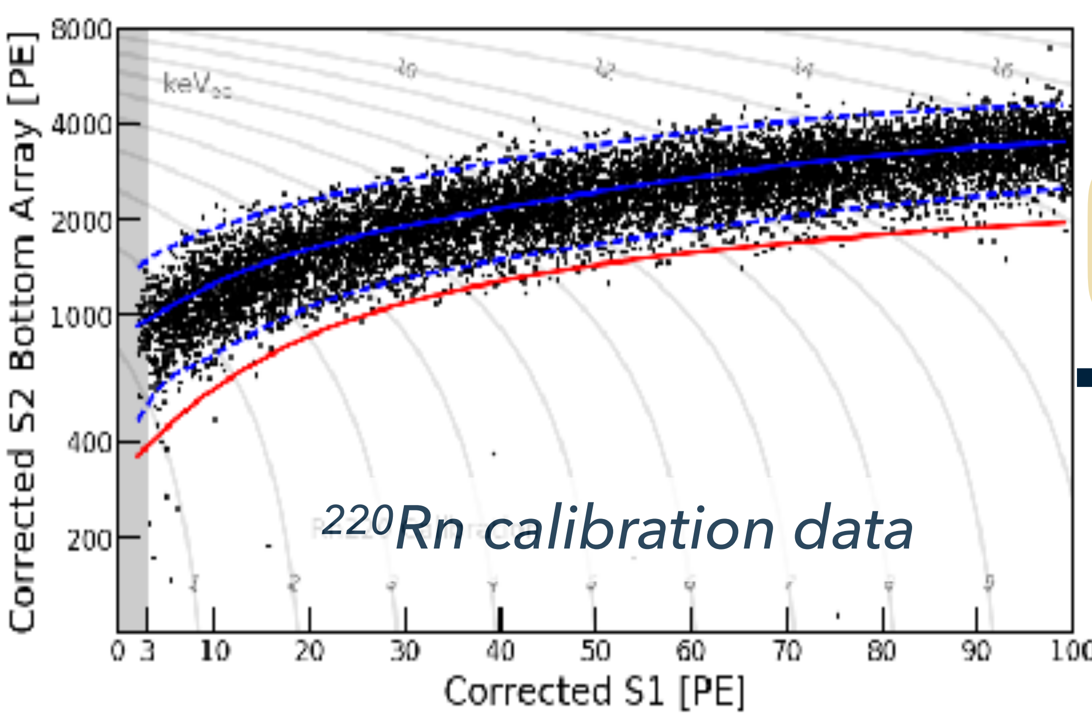


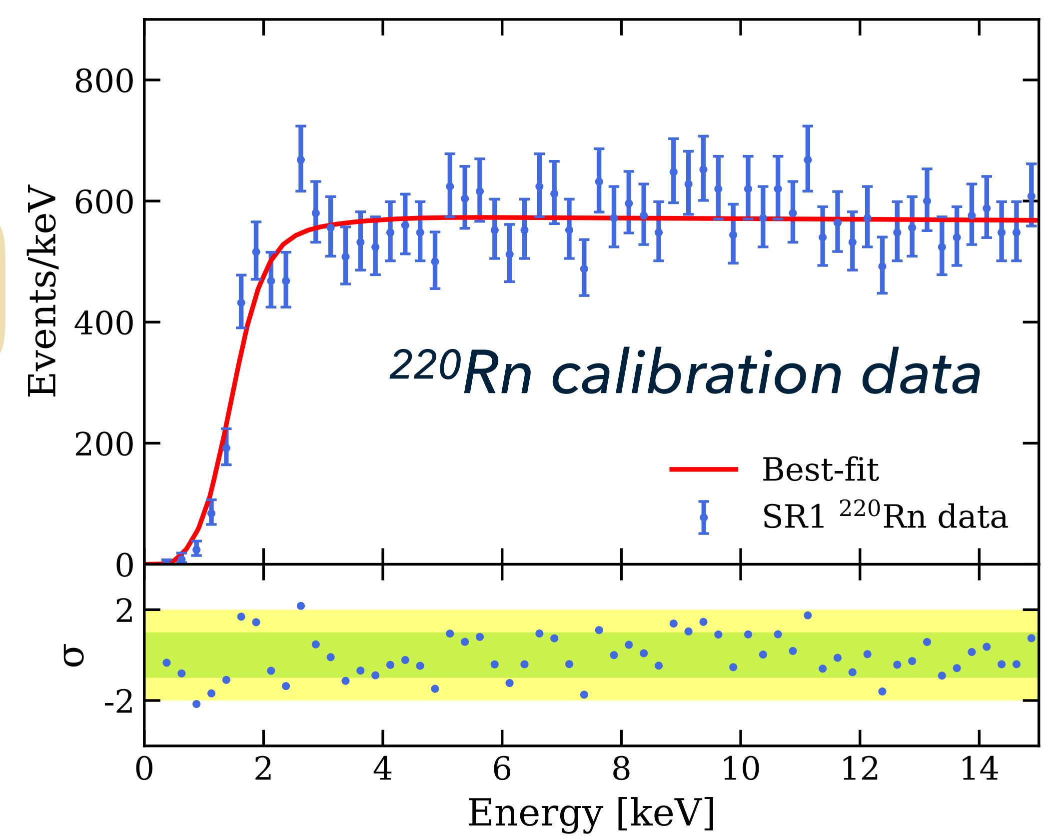
g1 and g2: detector-specific gain constants

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



2D analysis in s1-s2 space

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

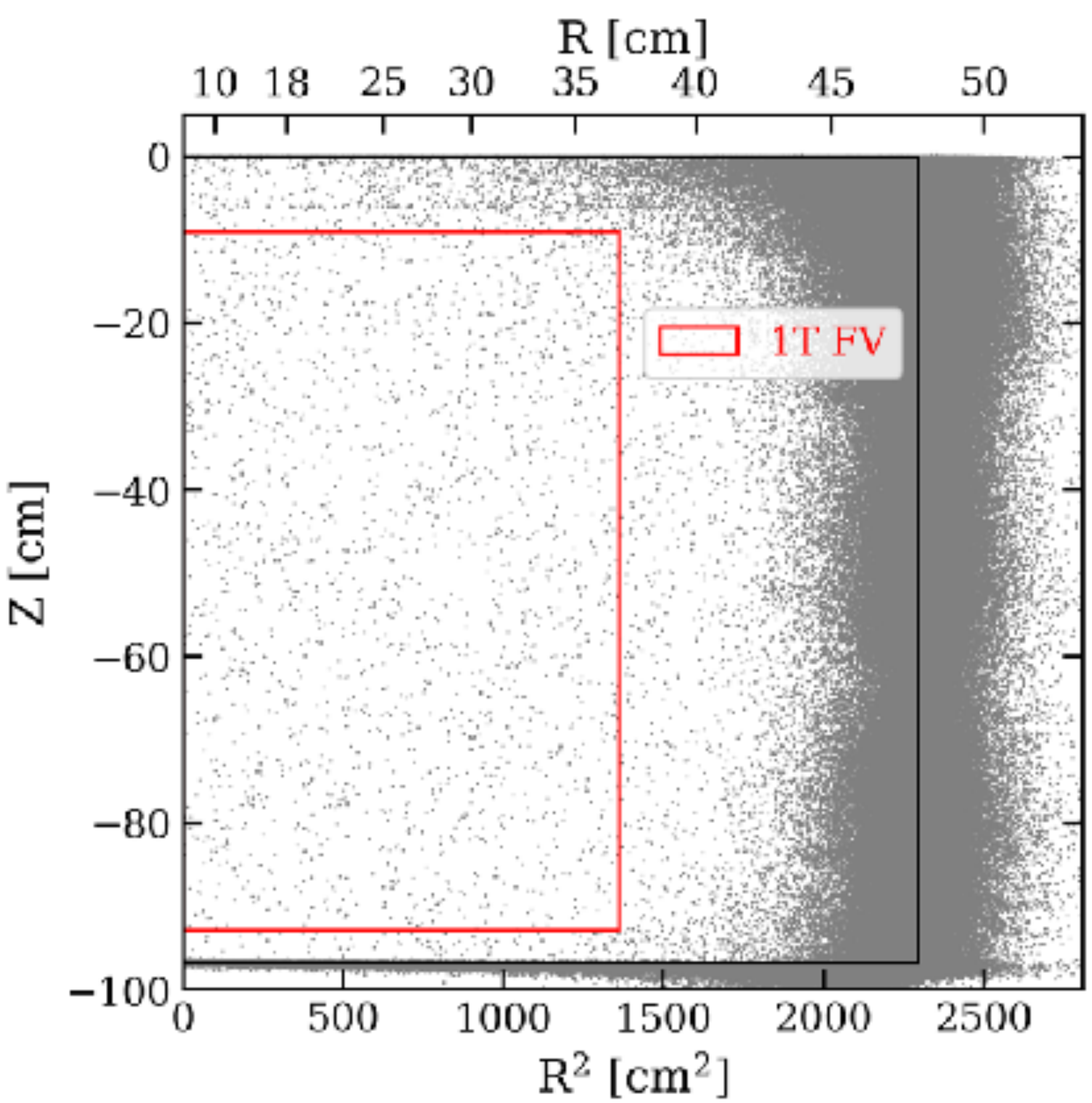


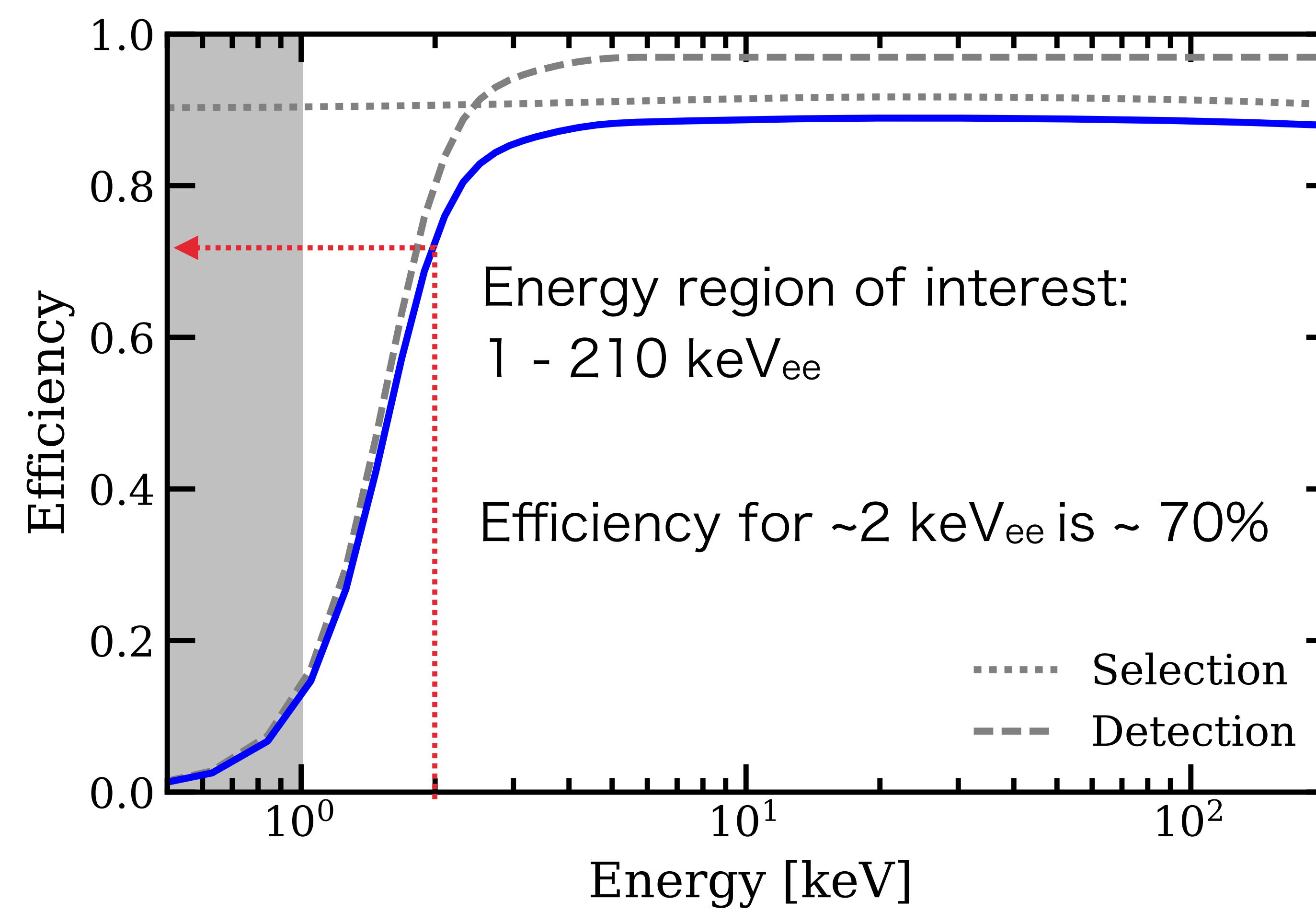
1D energy spectrum

Signal Models

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





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: $g_{a\gamma}$

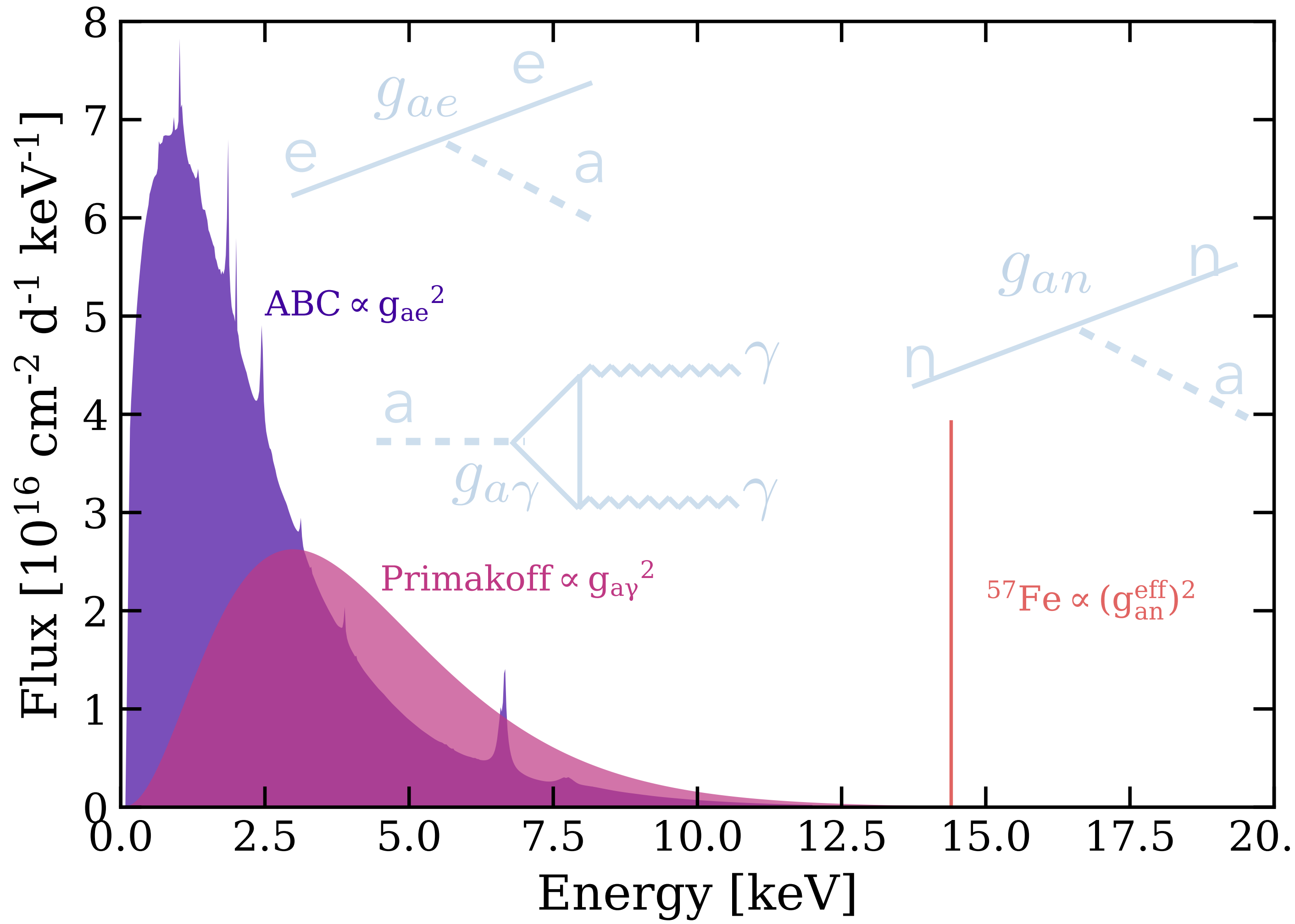
axion-photon coupling
axions produced from photon conversion induced by the electric field of ions and electrons in the Sun.

Fe-57 nuclear transition:

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

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.



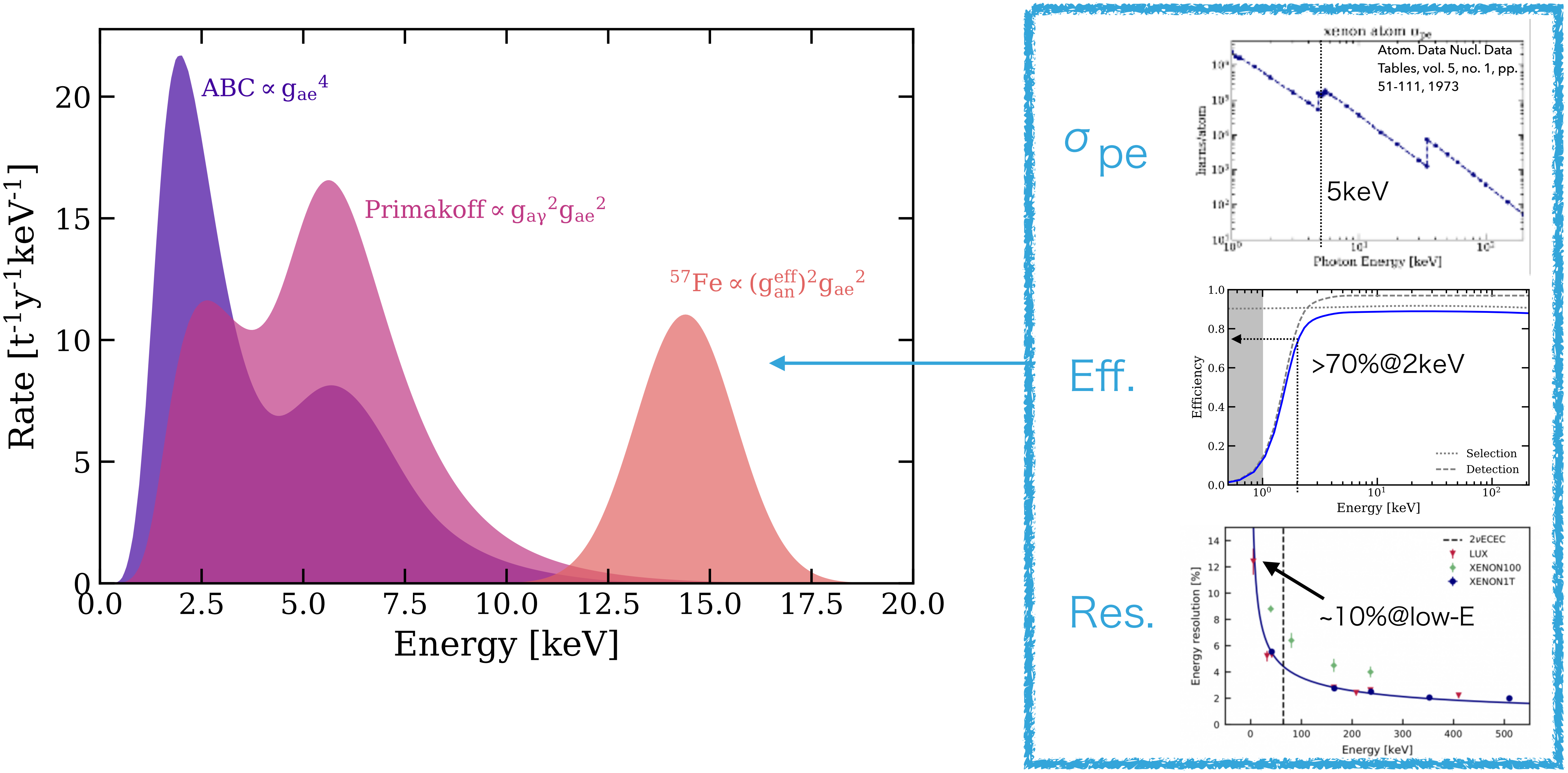
XENON1T sensitive to all 3 channels via **coupling to electrons** g_{ae} (electronic recoils via axio-electric effect).

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

β (Ea): velocity (energy) of axion

Solar-Axion: Detection

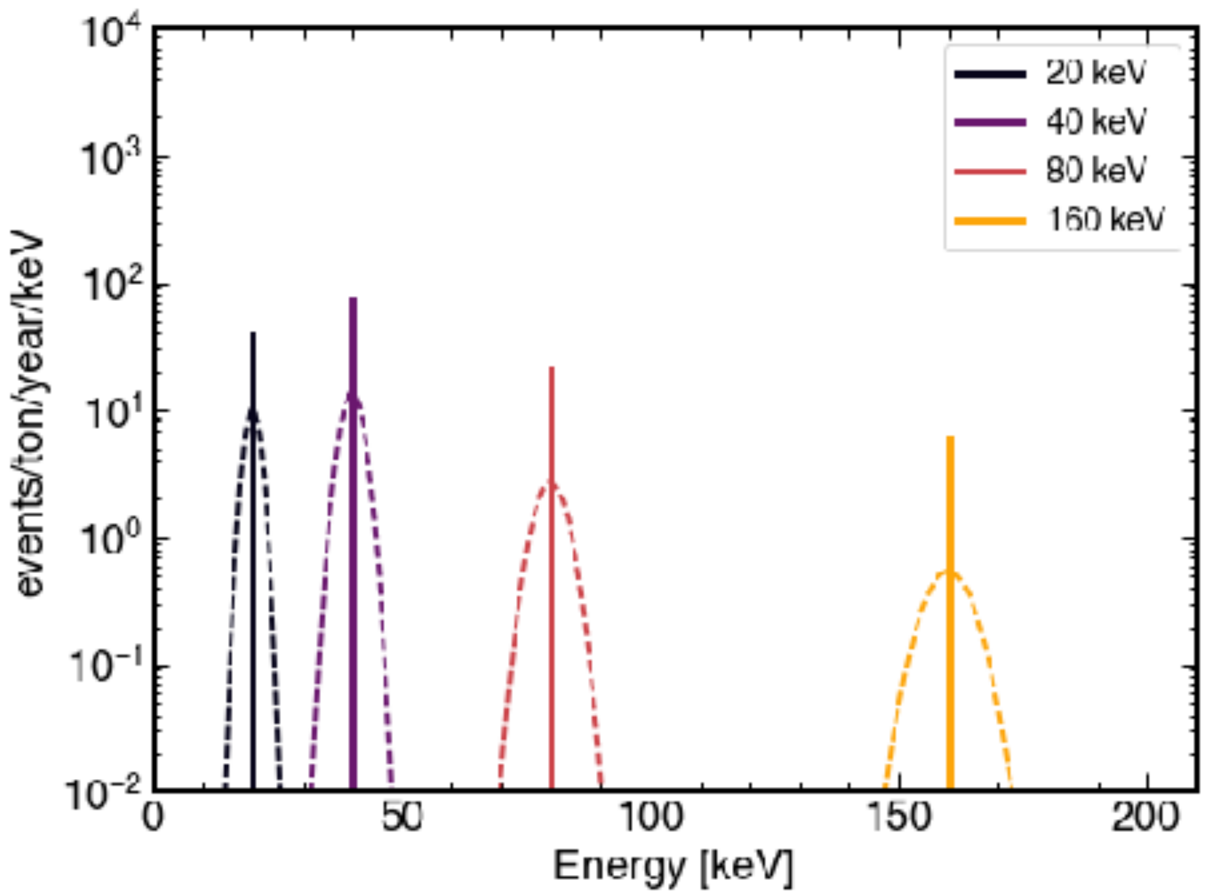
Expected rate in xenon convolved with detector effects (resolution, efficiency) and σpe

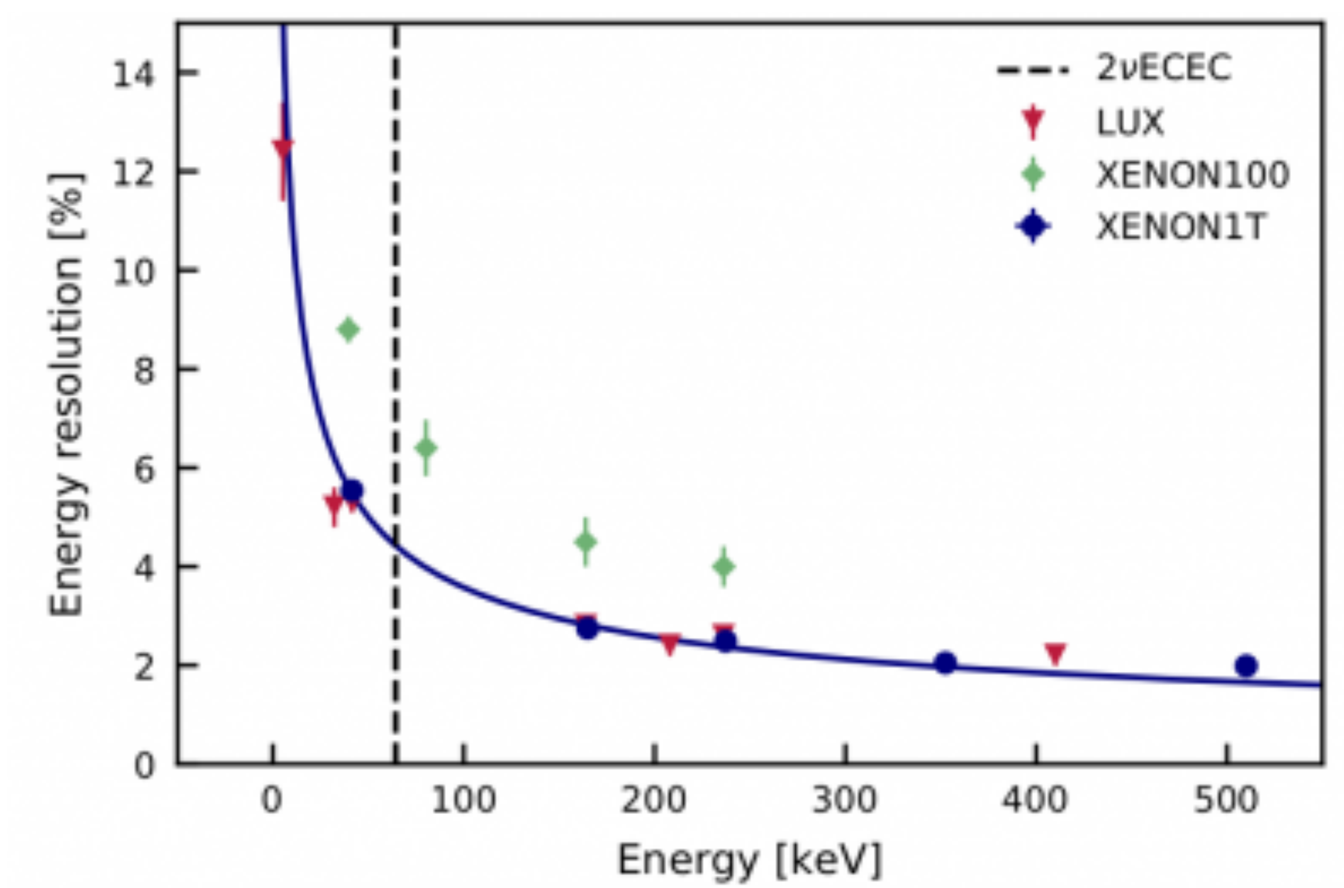


- For Primakoff and ^{57}Fe, can only deduce product of 2 couplings.
- All the three flux components are considered completely independent of each other —> Model-independent search: parameters of interest = g_{ae} vs. $g_{ae}g_{a\gamma}$ vs. $g_{ae}g_{an}^{eff}$
- XENON1T is more sensitive to DFSZ model, 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

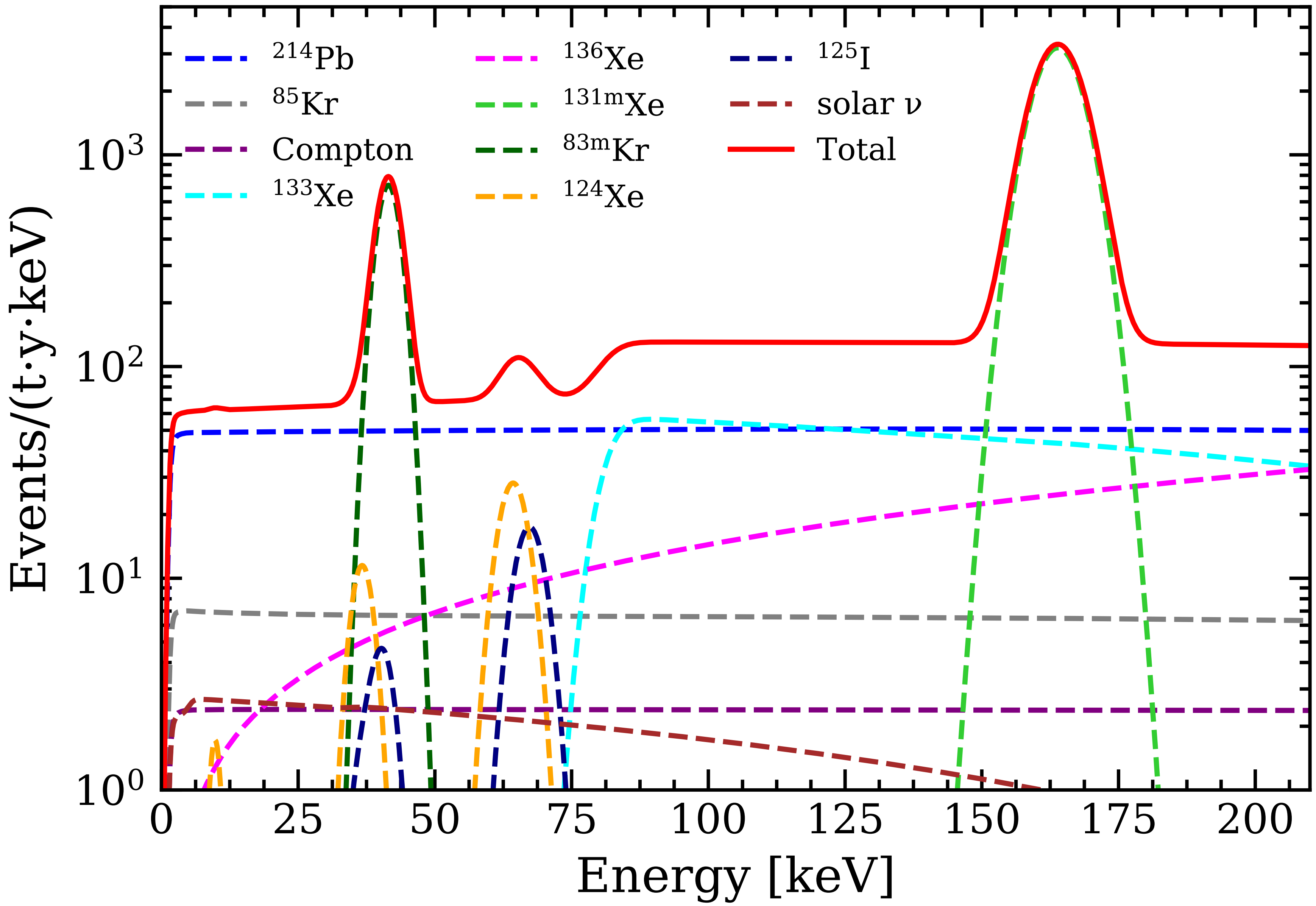
$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{\mathrm{keV}/c^2}\right) \left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

For dark photons

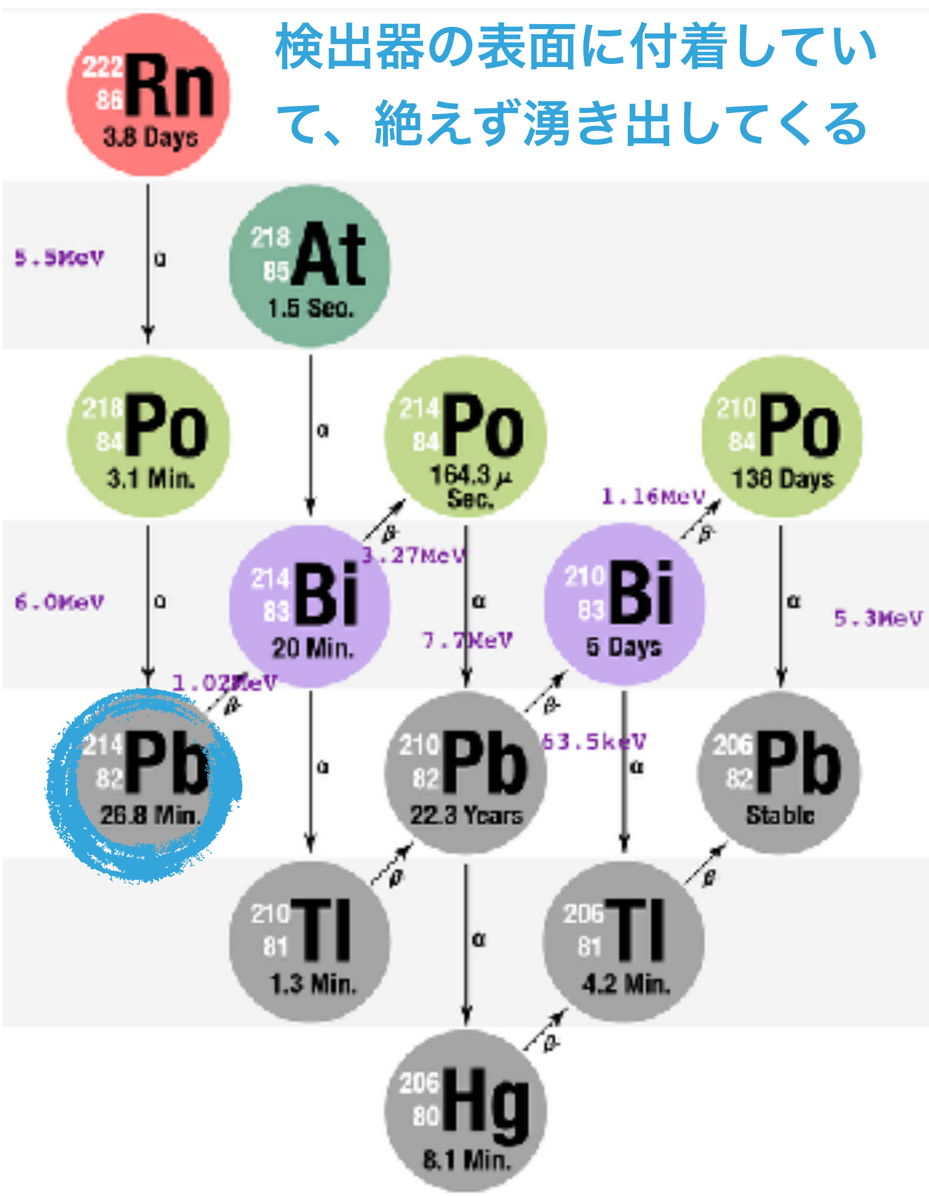
$$R \simeq \frac{4.7 \times 10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}/c^2}{m_{\mathrm{V}}}\right) \left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Background Models

Background Model

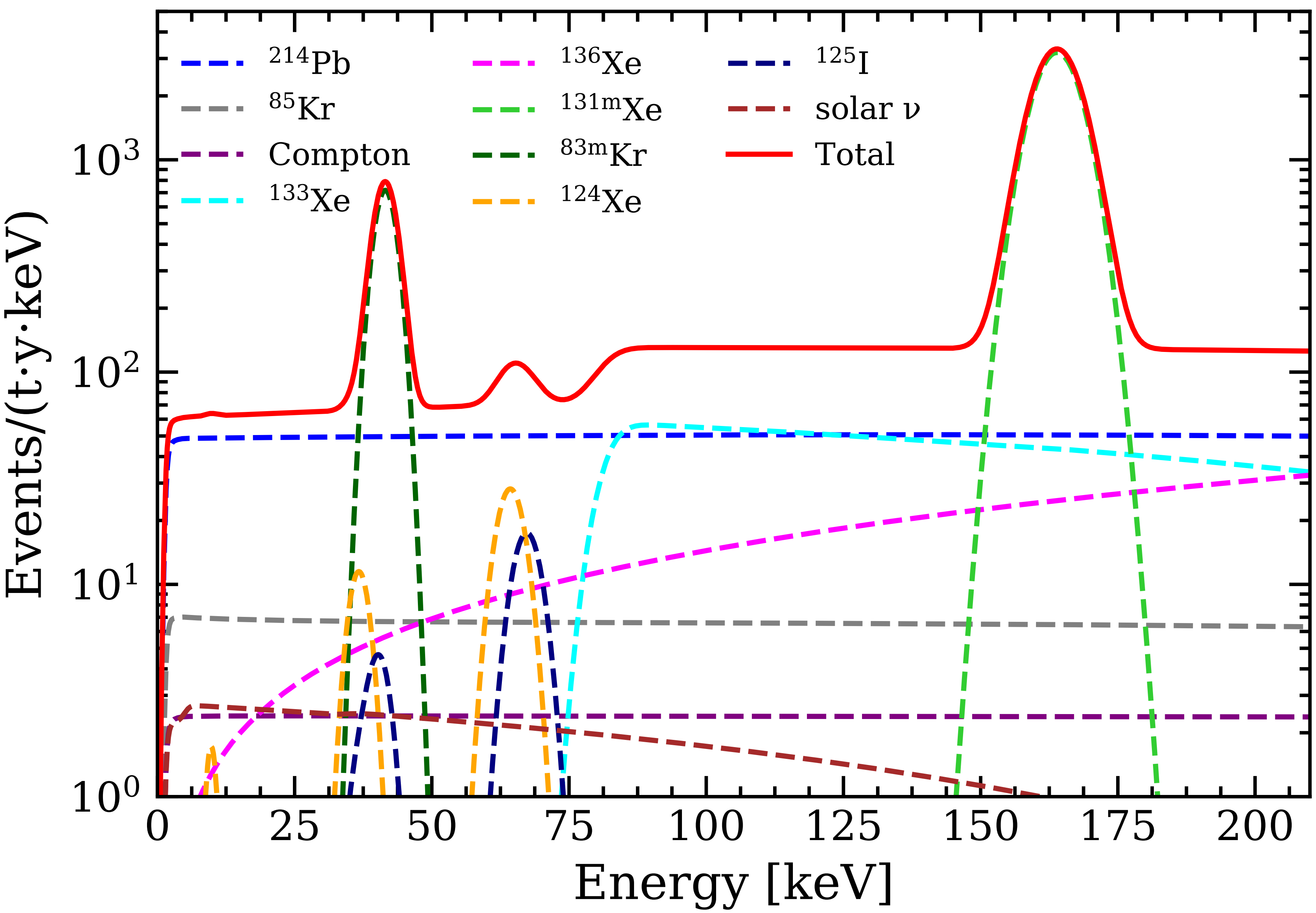


^{214}Pb: main ER BG



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

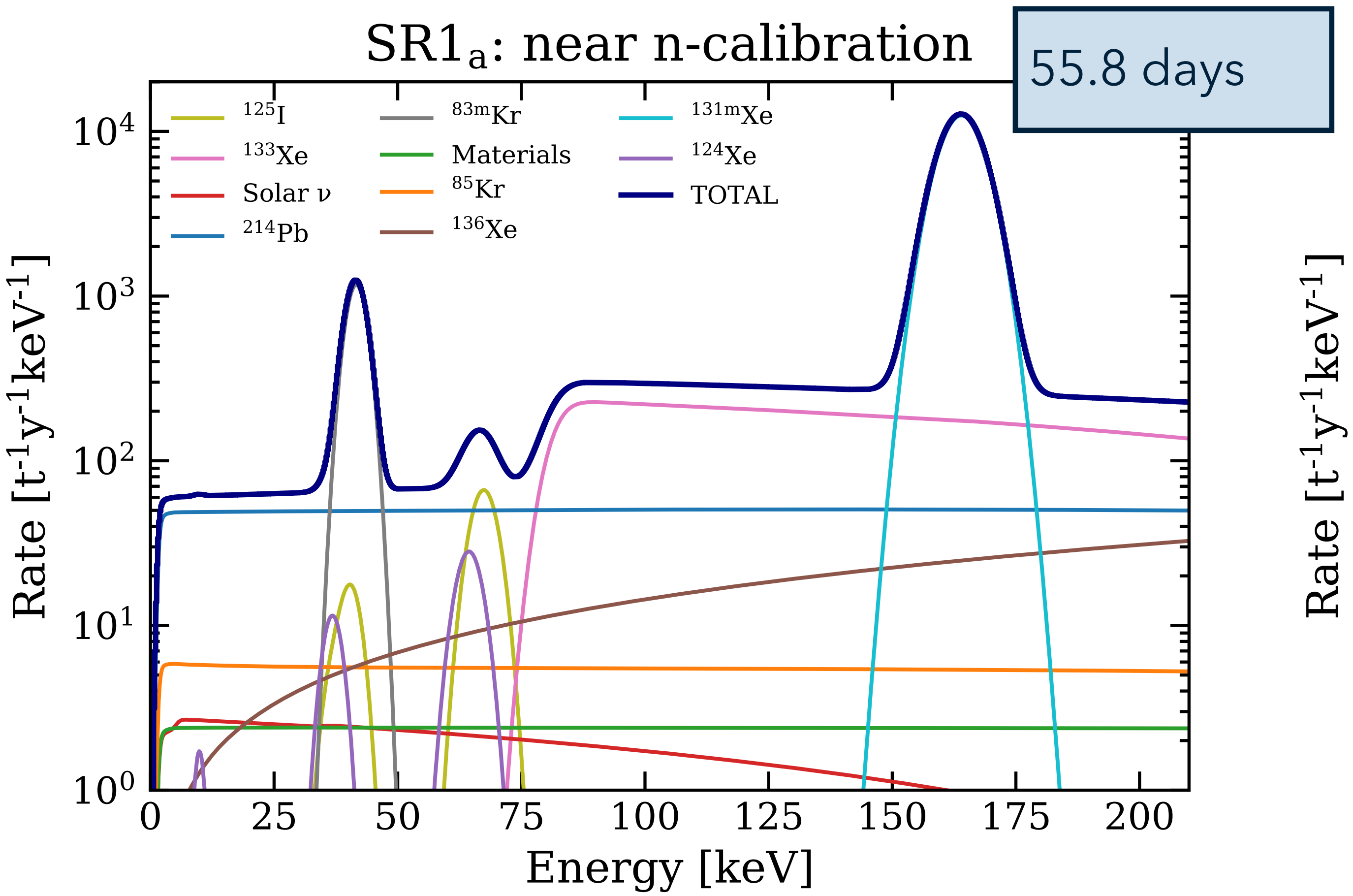
Contaminant Backgrounds

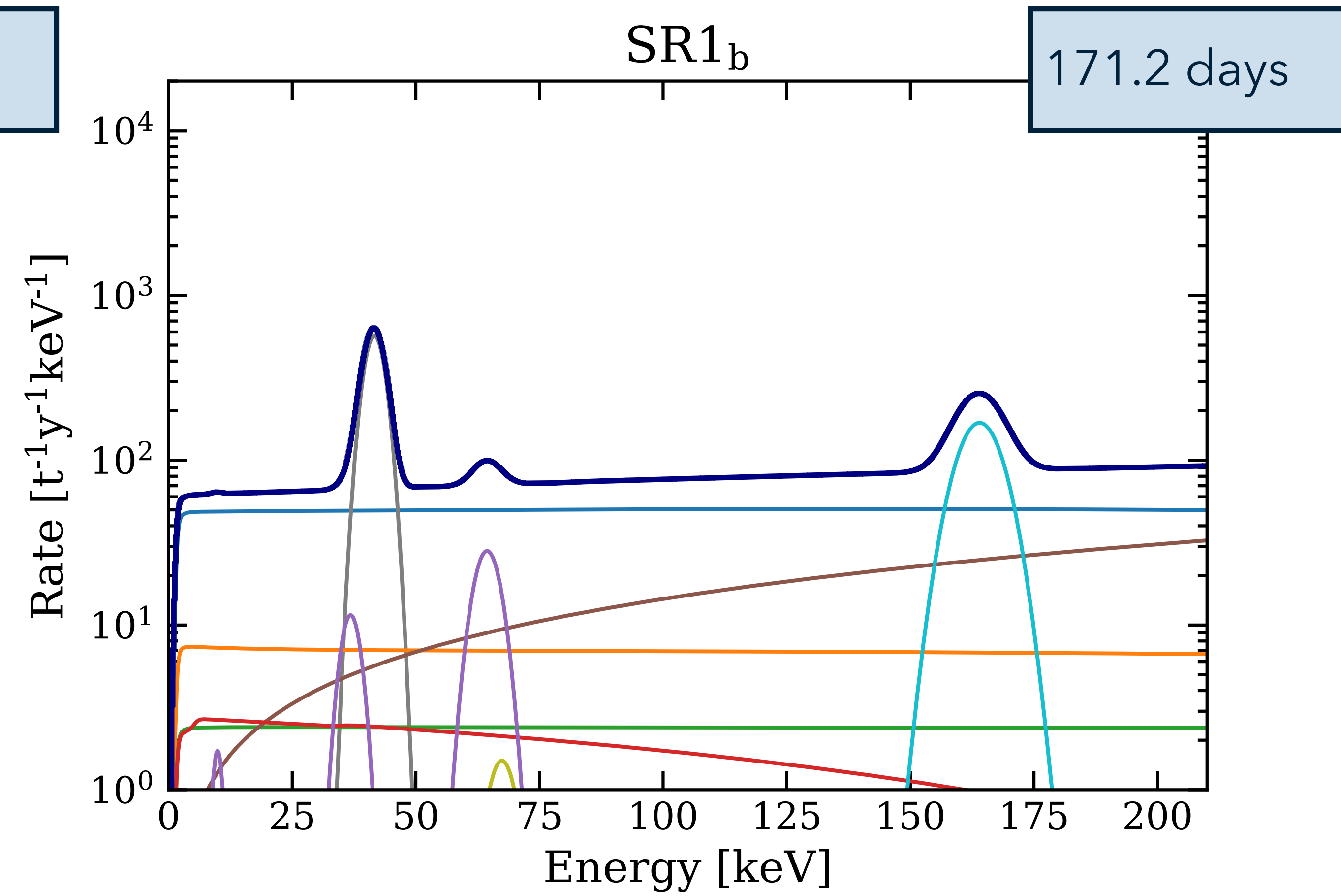
^{83m}Kr Materials

Predicted energy spectra based on detailed modeling of each background component

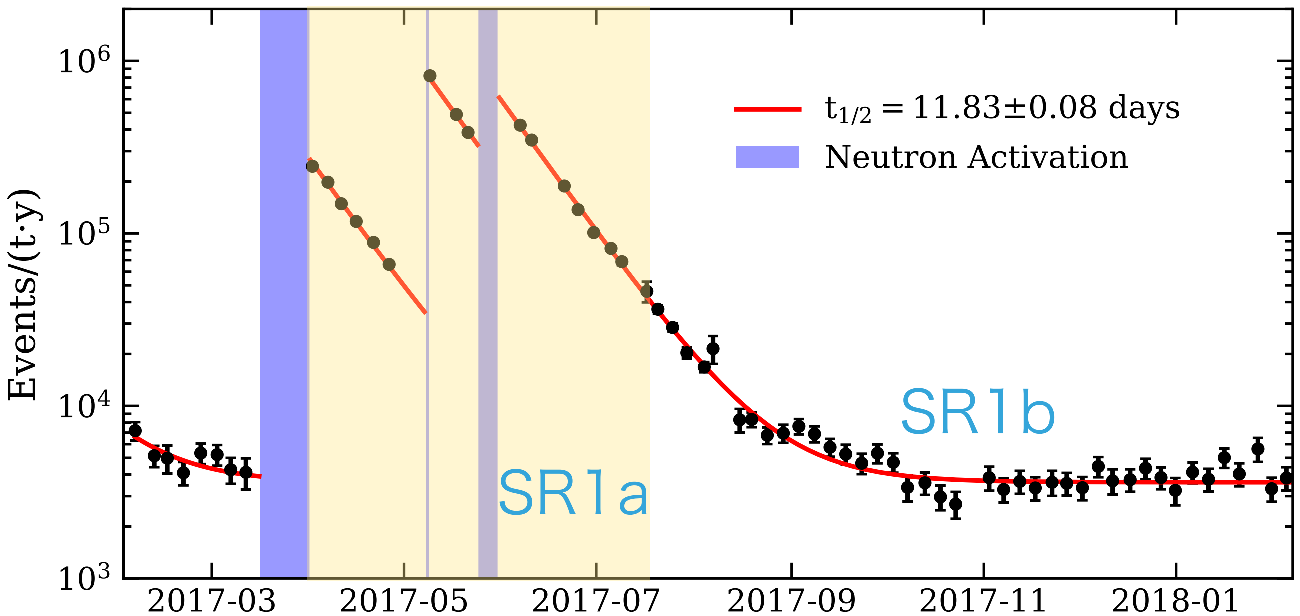
Rates constrained by measurements and/or time dependence

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

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

$$\mu_{\text{tot}} = \sum_j \mu_{b_j} + \mu_s,$$

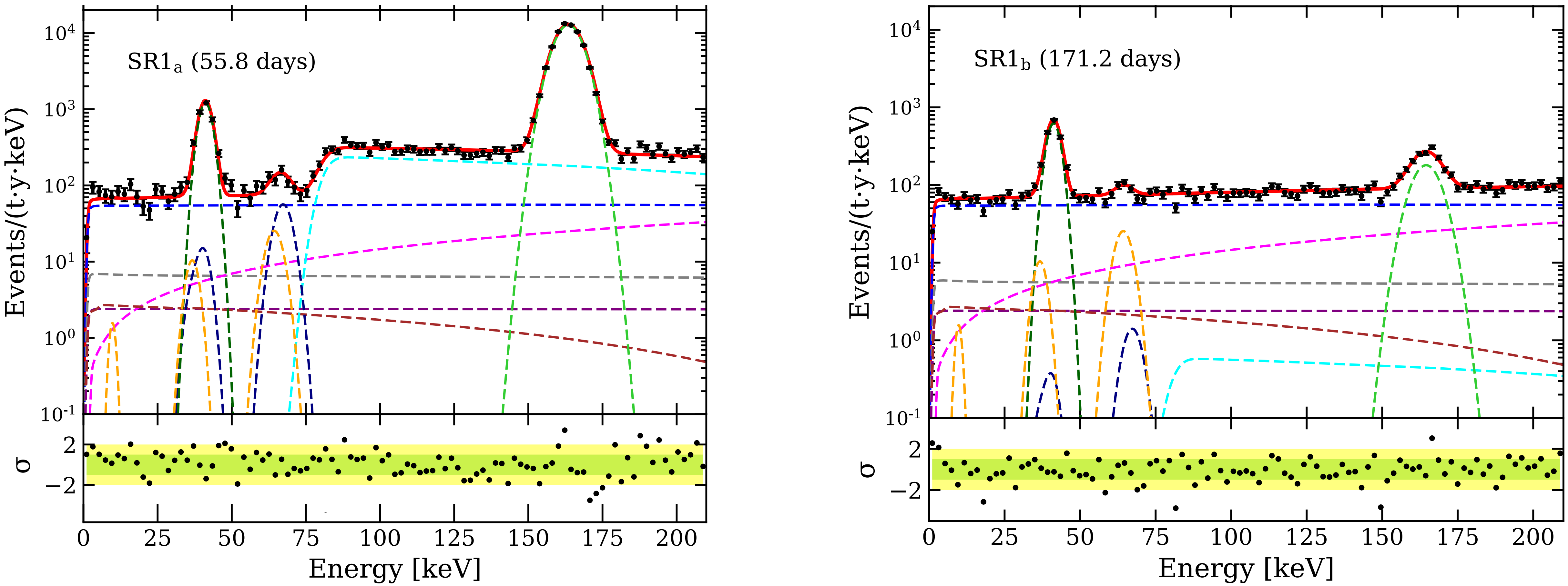
Profile over the nuisance parameters

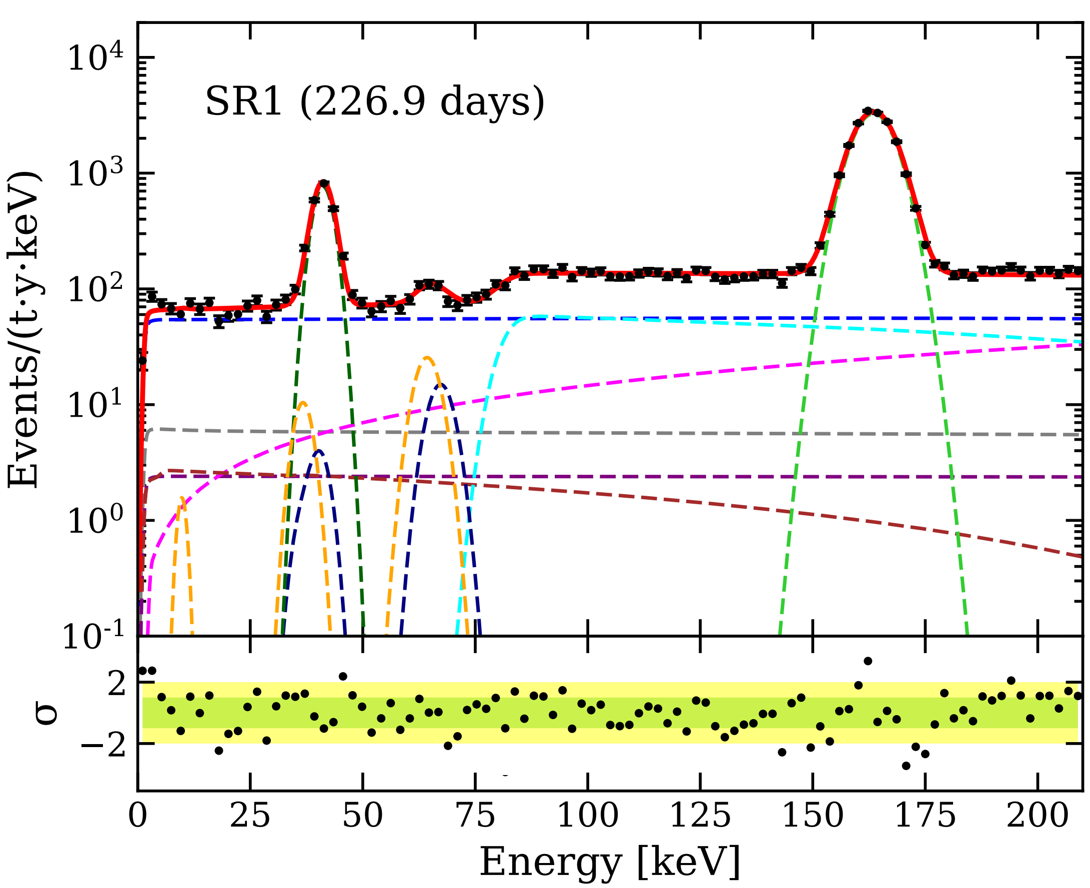
Combining the likelihoods of the 2 partitions

$$\mathcal{L} = \mathcal{L}_{\text{a}} \times \mathcal{L}_{\text{b}}$$

SR1a SR1b

Fit



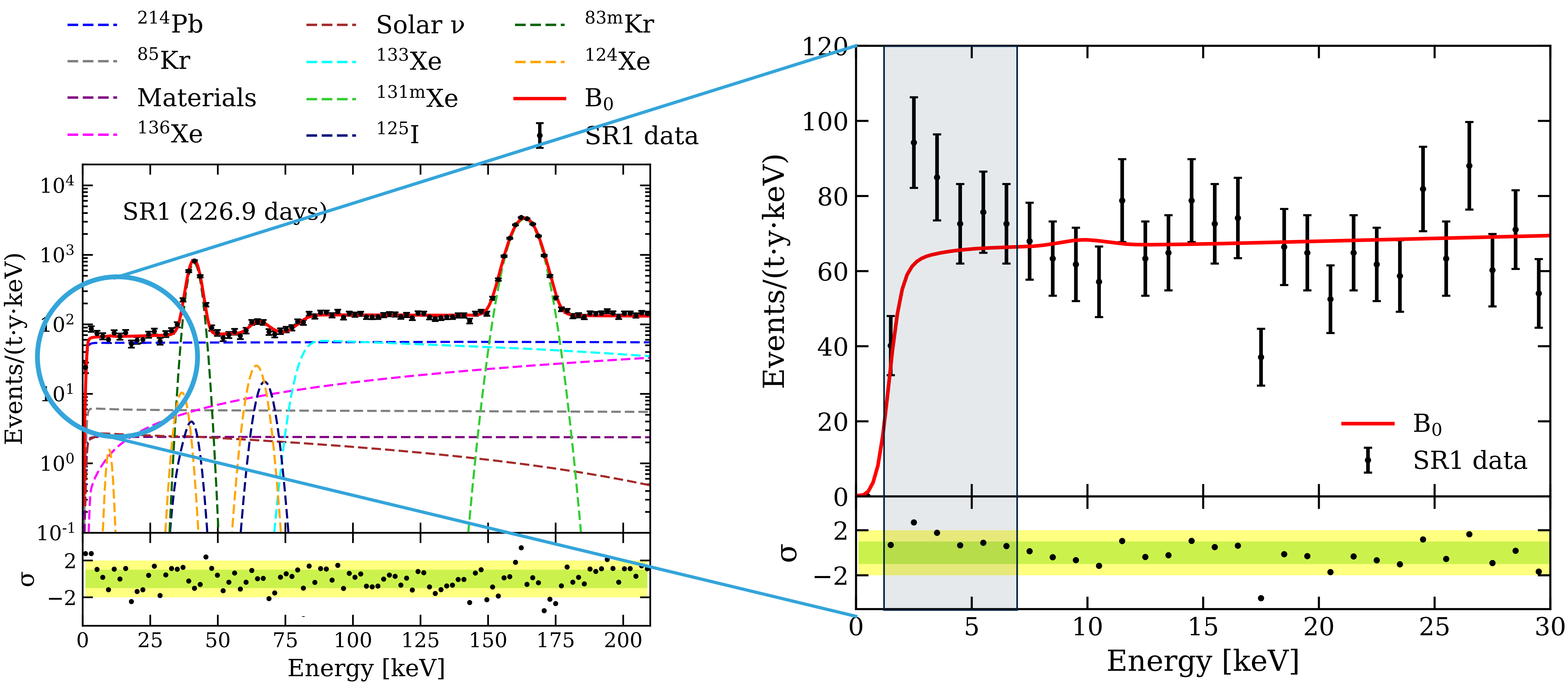


Decent matching across the whole energy range in 1-210 keV

(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

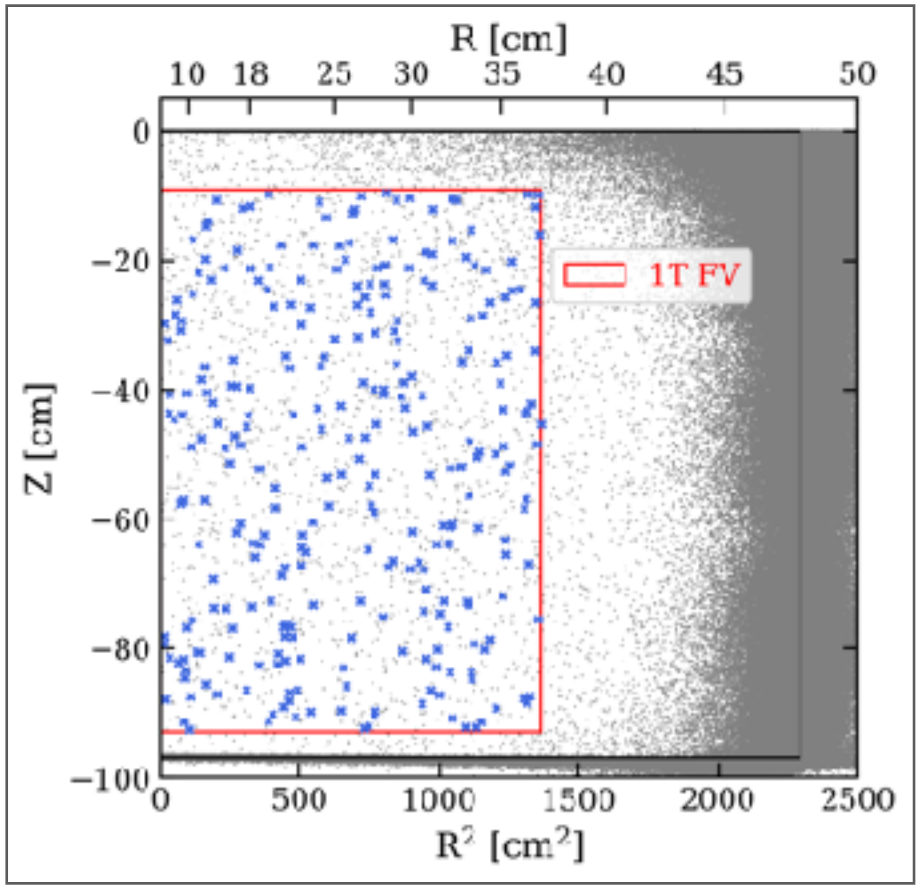
vs.

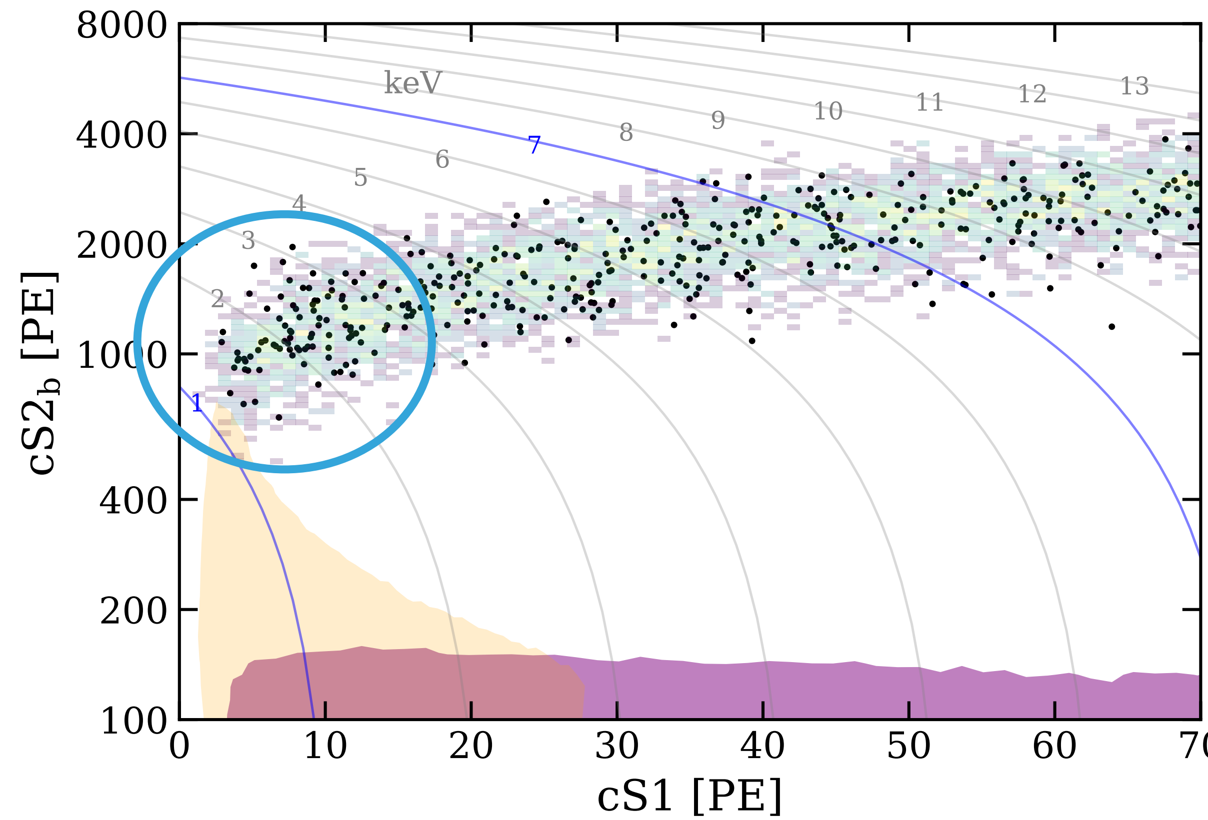
232 events expected (from BG-only best-fit)

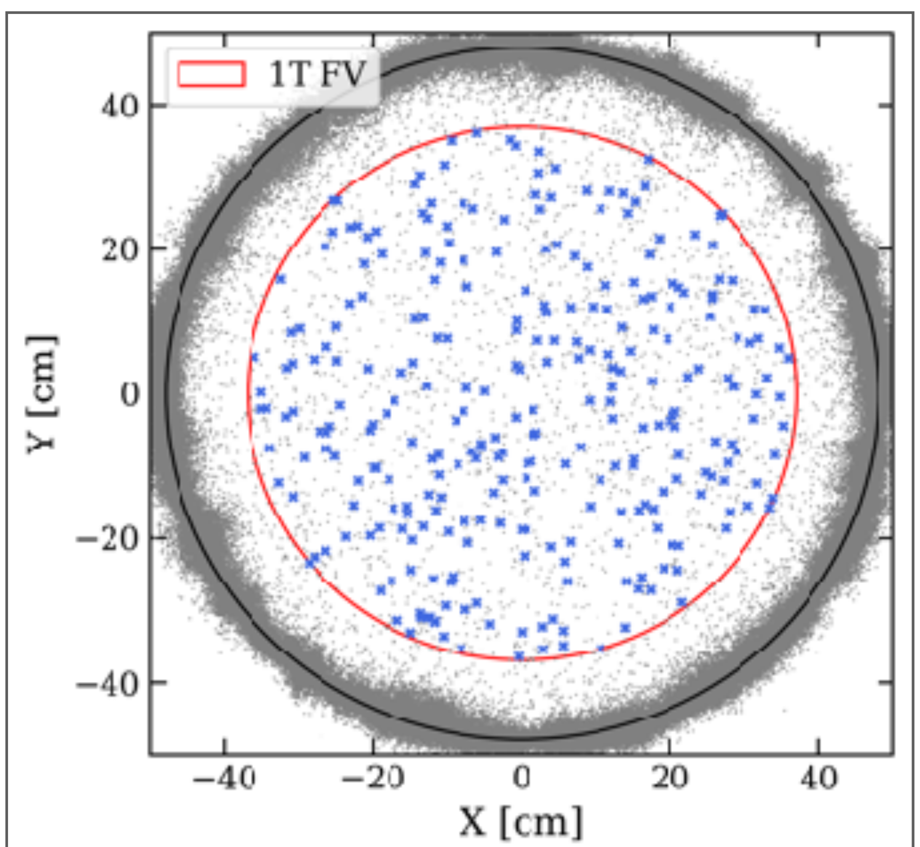
Would be a **3.3σ** Poissonian fluctuation

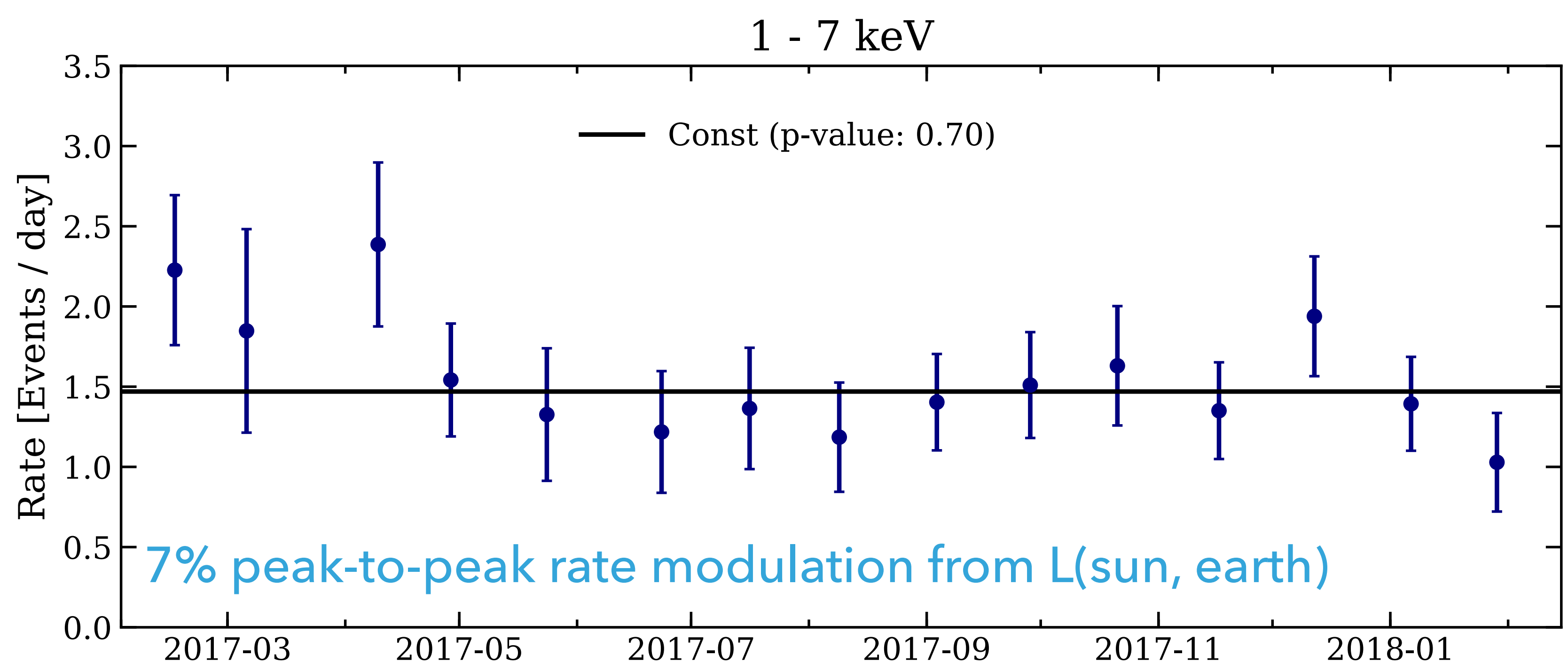
Are We Missing Something?

Event Location / Time-dependence



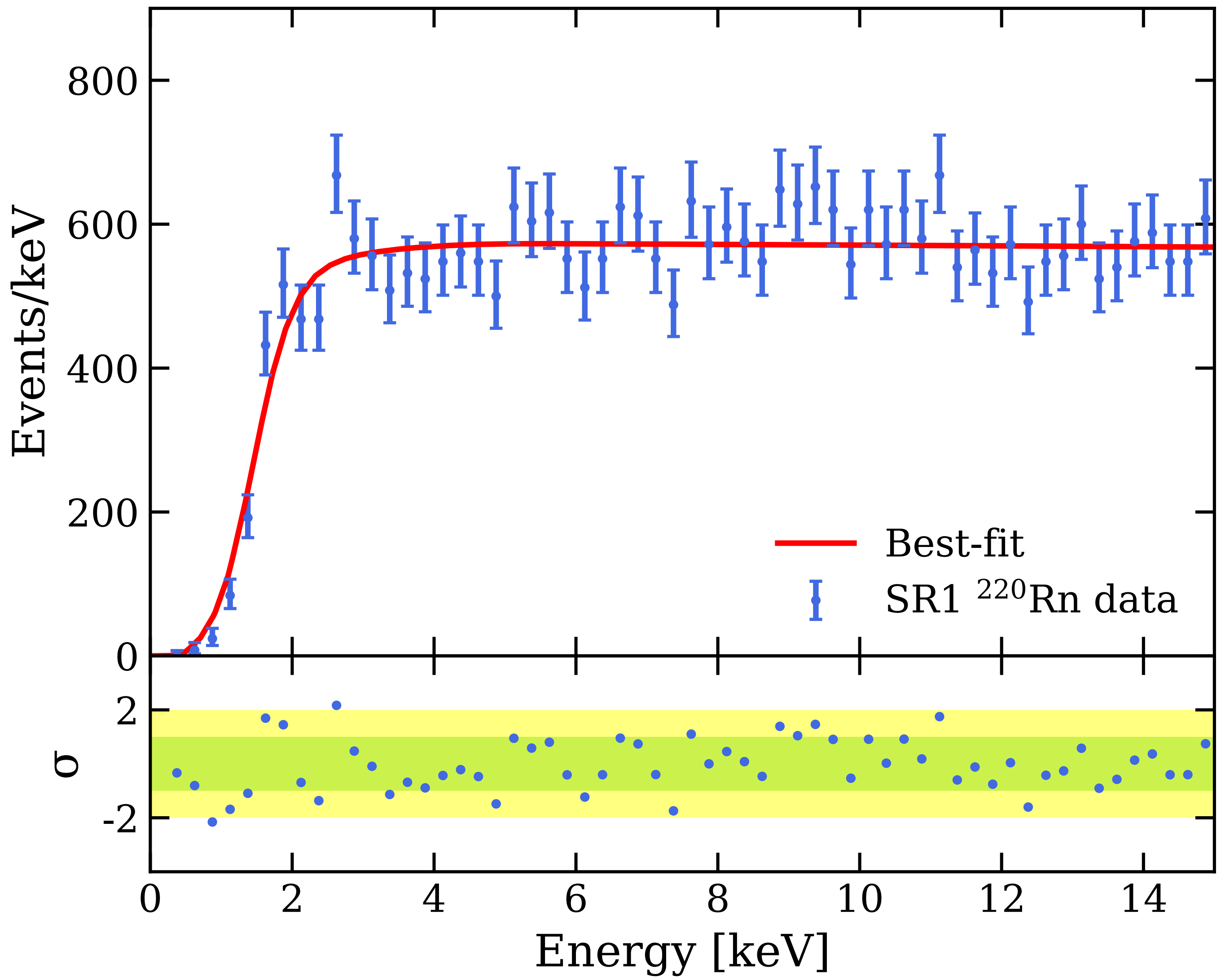






- Uniform in 3D-space and cS1/cS2b plane
- consistent with constant time (but with low statistics)

Efficiency / Reconstruction

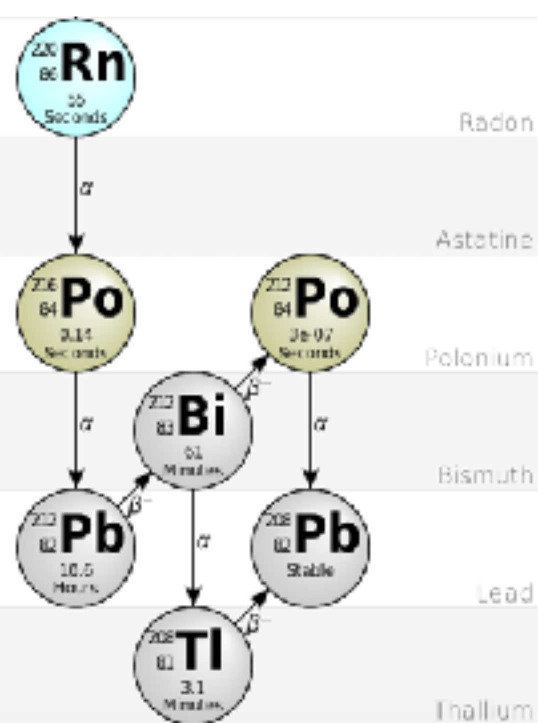


^{220}Rn calibration reconstructs as expected

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

Validates efficiency and energy reconstruction

g.o.f p=0.58

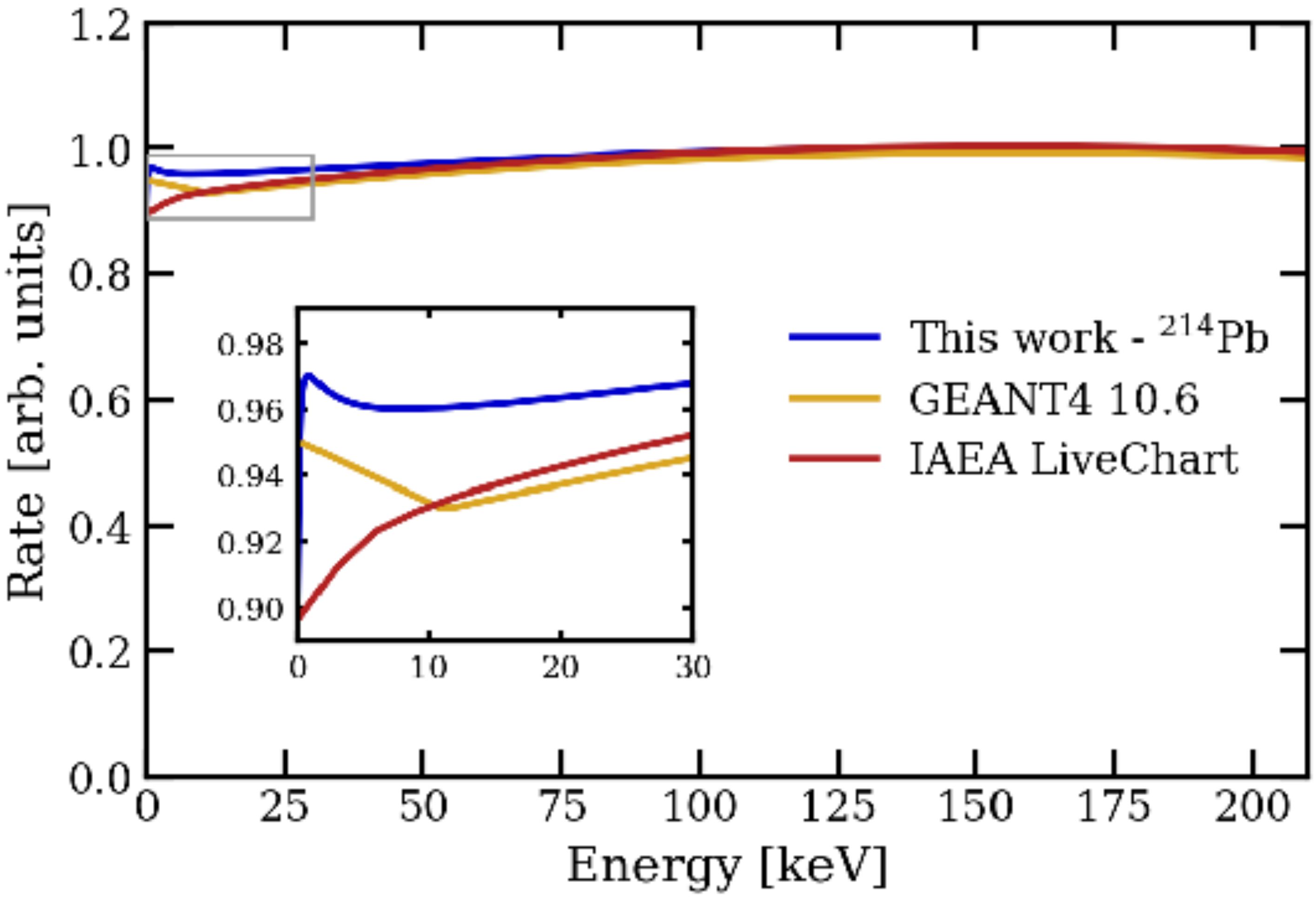


β-decay of Pb212 is used to calibrate detector's response to ER background

Again, unbinned fit is performed here.

214Pb Spectrum Model

Calculated by X. Mougeot



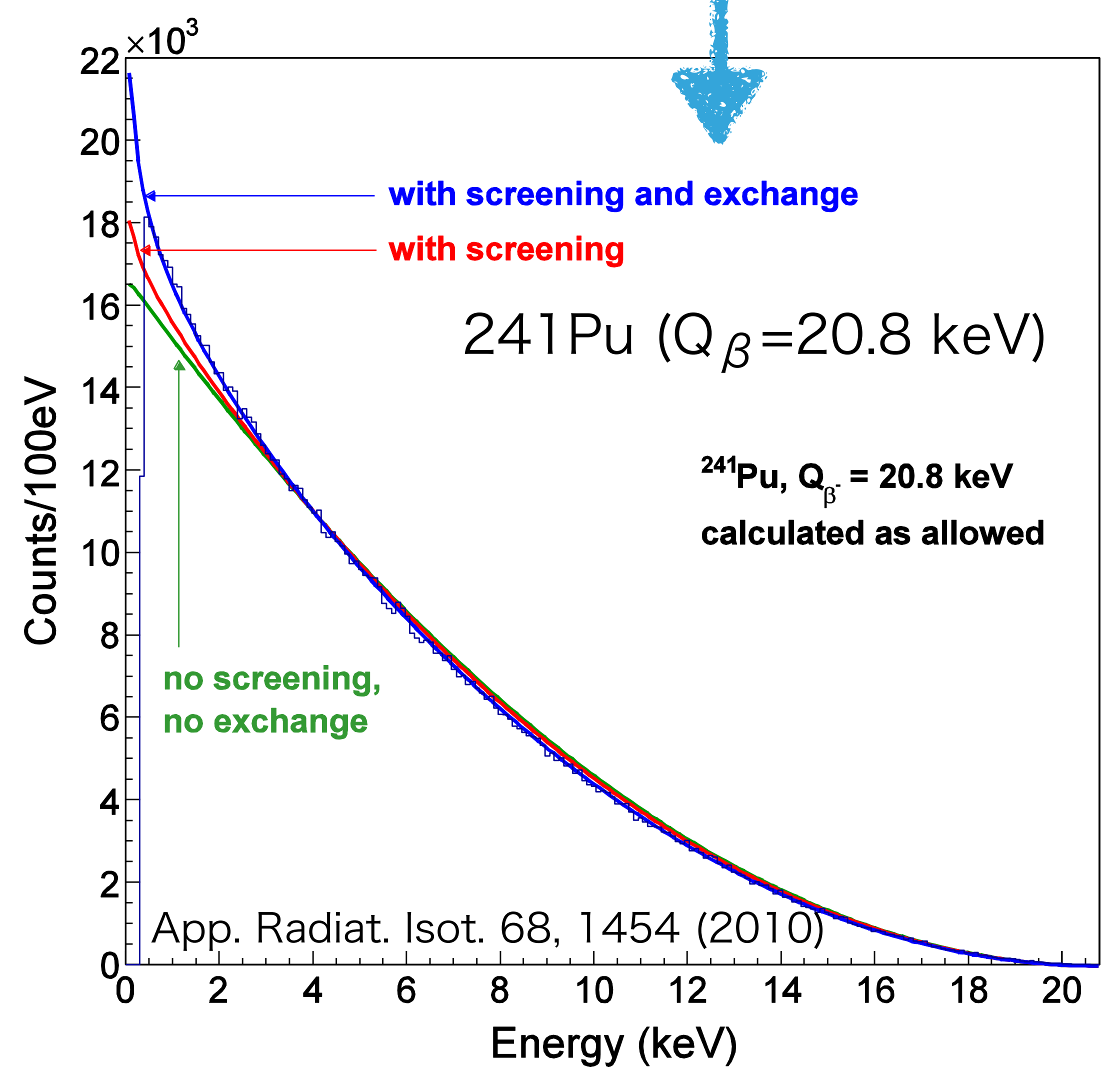
- IAEA model: No screening/exchange effects
- GEANT4 model: only screening effect
- This work: both screening/exchange effects

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

~6% uncertainty on the shape

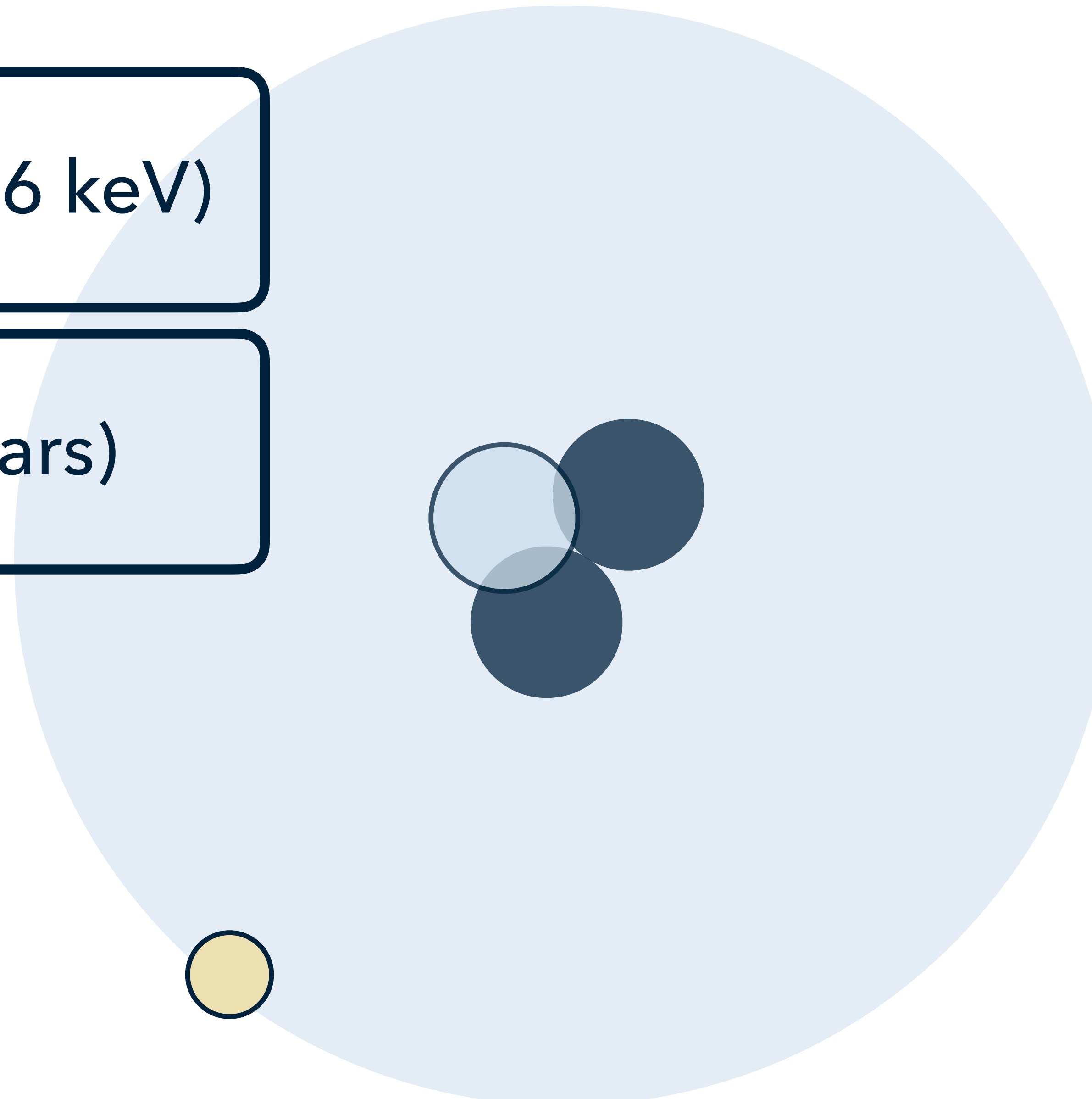
~50% needed to account for excess

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



Low-energy (Q value 18.6 keV)

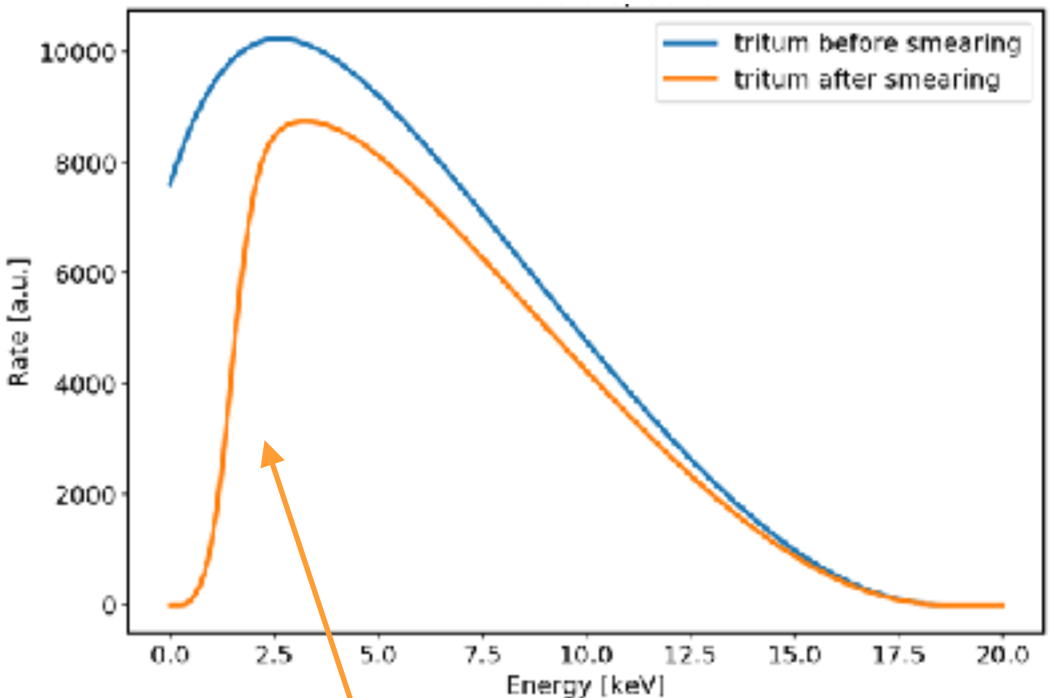
Long half life (12.3 years)

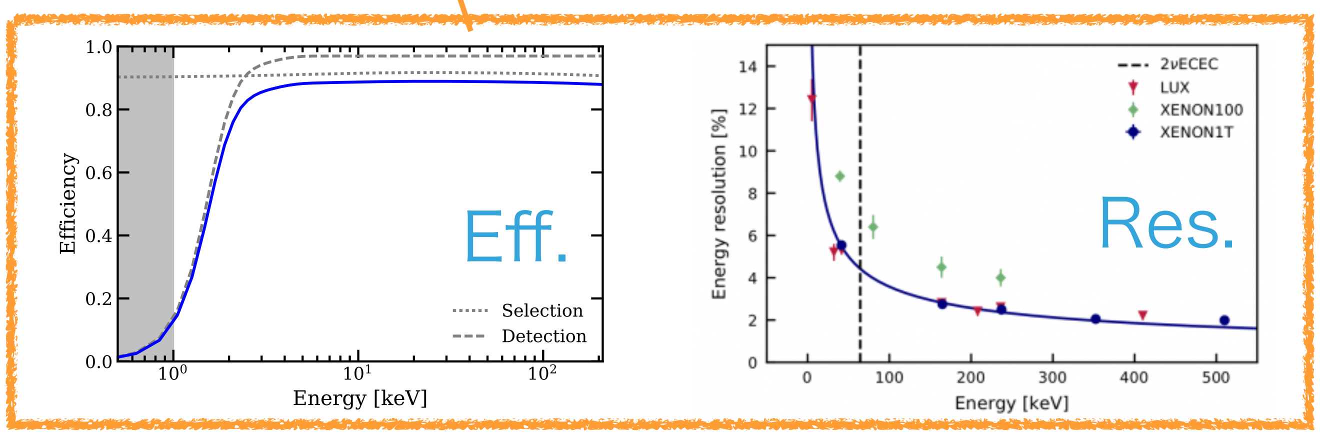


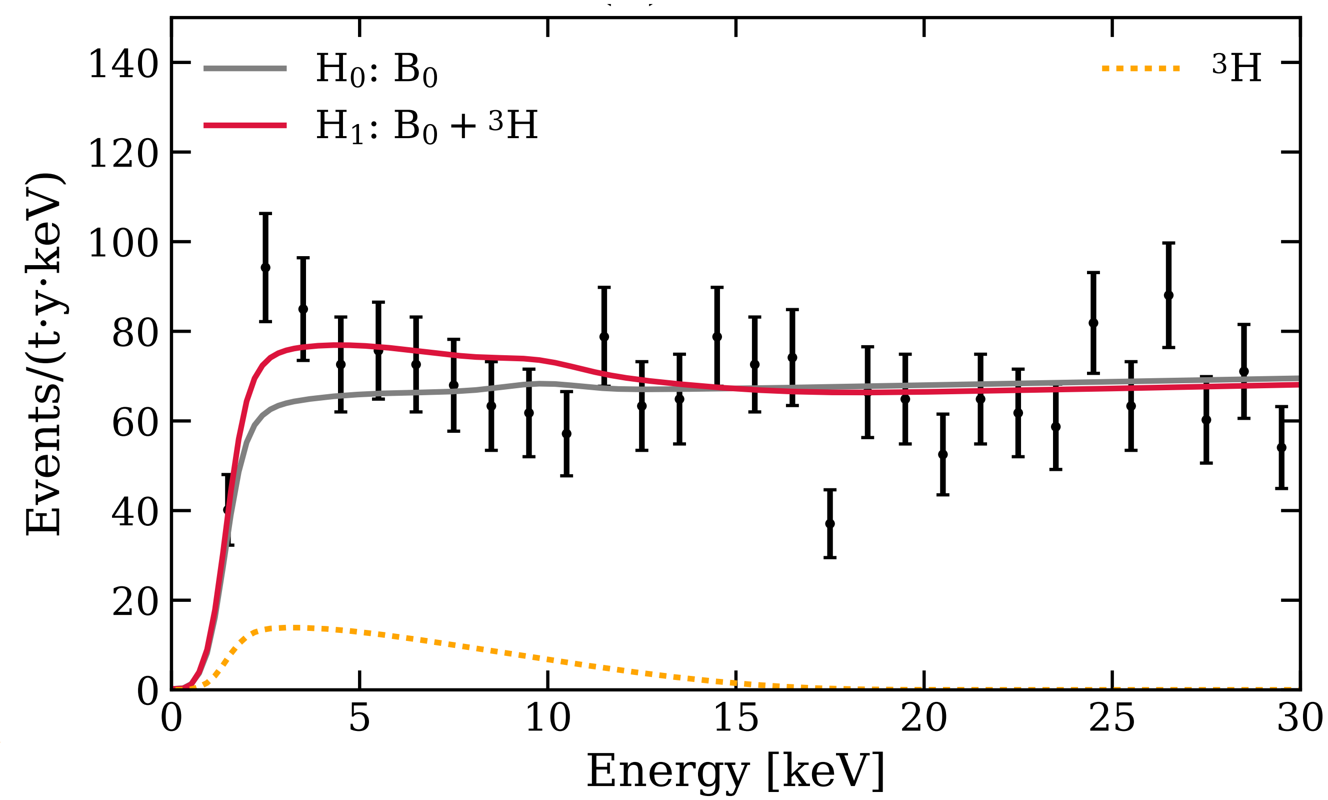
Tritium?

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:

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

fewer than 3 tritium atoms per kg of xenon!

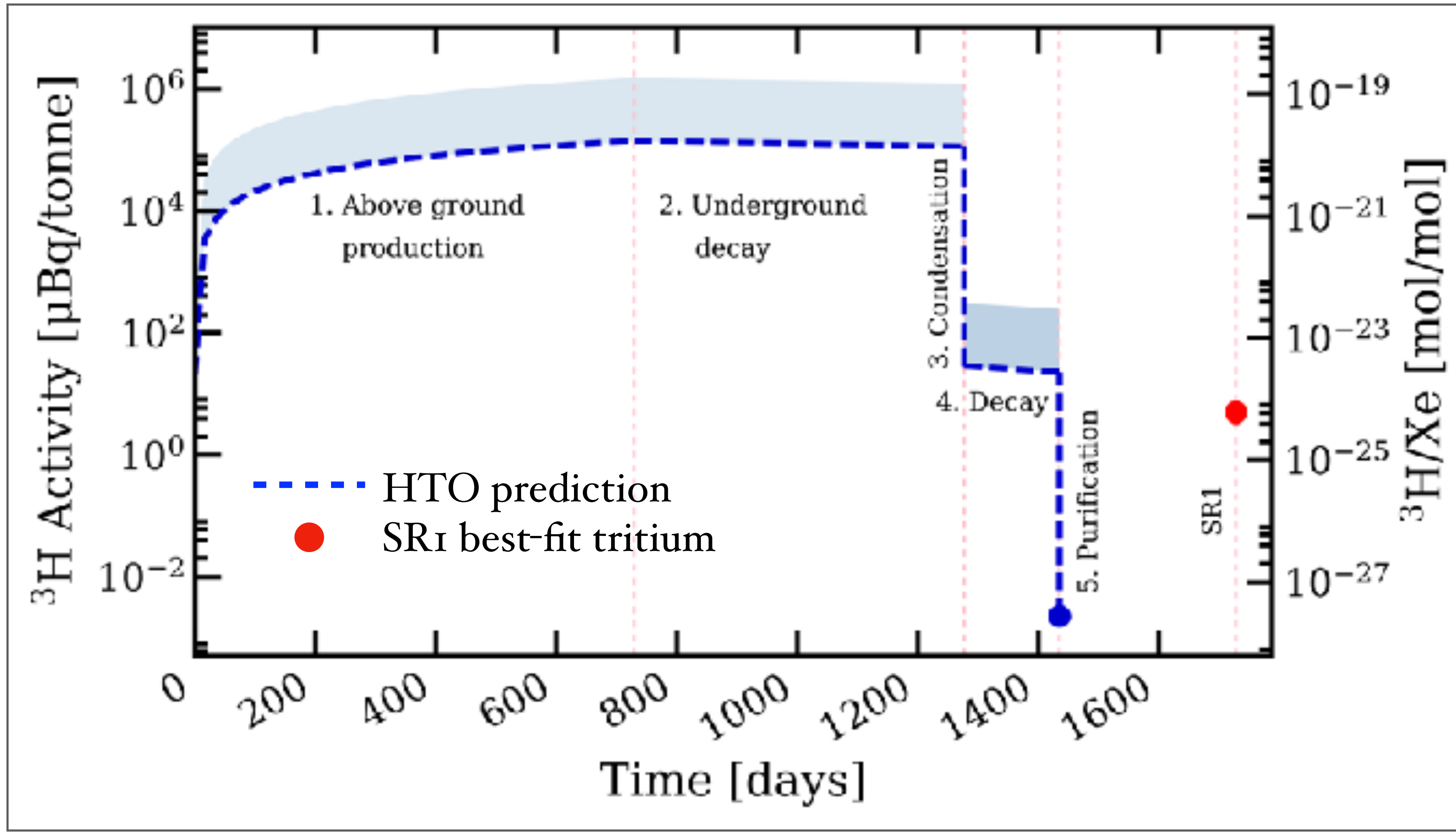
1. Cosmic Activation of Xenon

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…

H20

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.

→ 柿内さんのトーク！

We can neither confirm nor exclude the presence of tritium.

Ar37? (時間があれば)

1. In-situ production?

2. Atmospherically abundant?

3. Air leak?

Ar37

^{37}Ar K-electron capture to the ground state of ^{37}Cl ($^{37}Ar \rightarrow {}^{37}Cl + \nu e$)

- **Half-lifetime of 35 days & 2.8 keV energy in X-rays & Auger e⁻ s**
- Calibration with ^{37}Ar performed in XENON1T at the end of SR2

—> good understanding of the detector at those energies

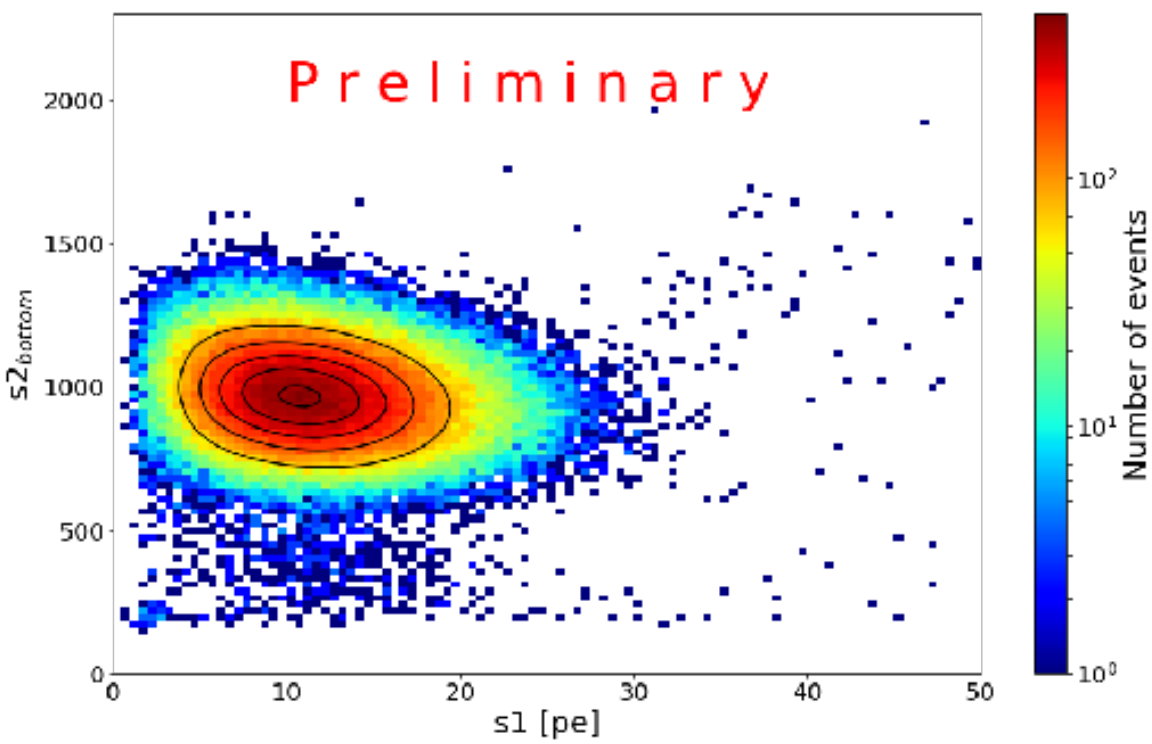


Table 2. ^{37}Ar decay modes and released energy

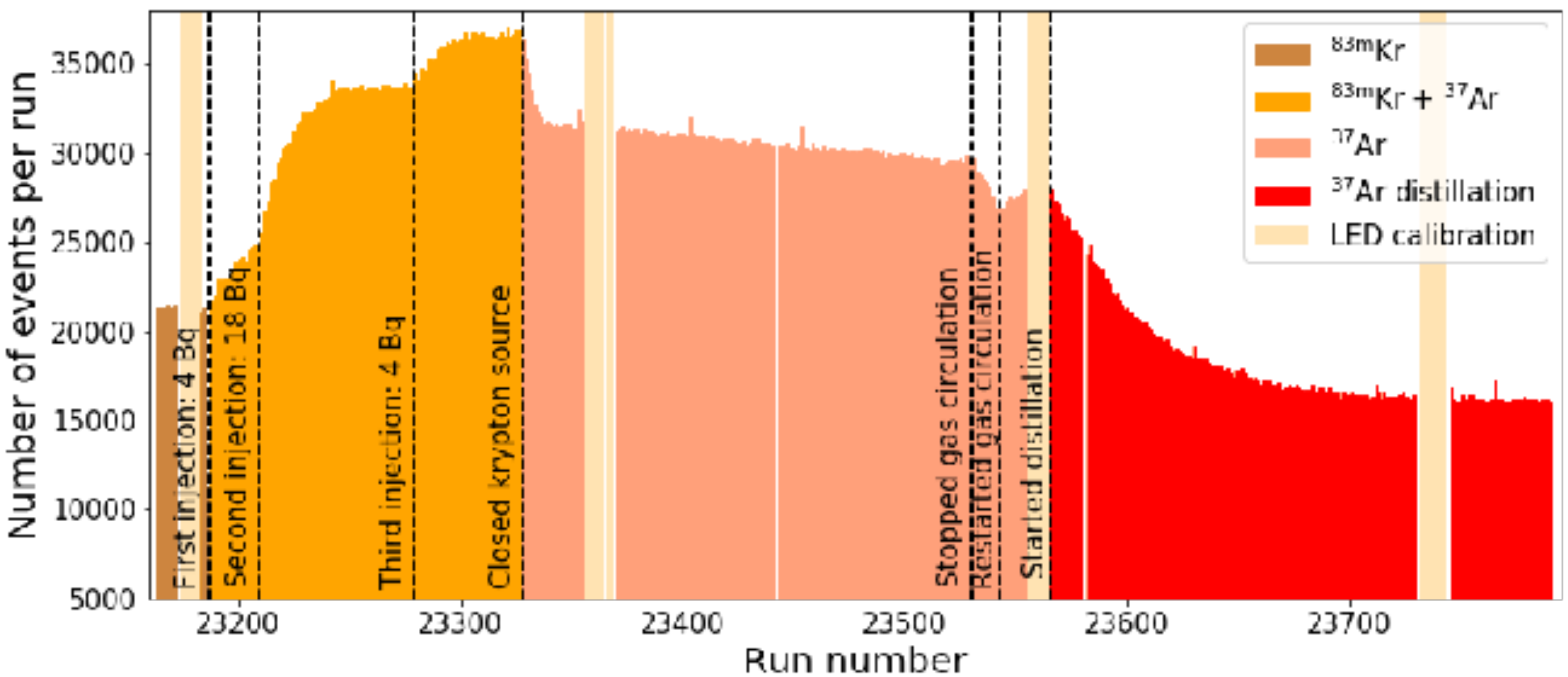
Decay mode	Energy release, keV	Branching ratio for ^{37}Ar decays through a given mode	Energy release per event of ^{37}Ar decay, keV/decay
K capture	2.8224	0.9017 ± 0.0024	2.5450 ± 0.0068
L capture	0.2702	0.0890 ± 0.0027	0.0240 ± 0.0007
M capture	0.0175	$0.0093^{+0.0006}_{-0.0004}$	0.0002
IB 1s	325 (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

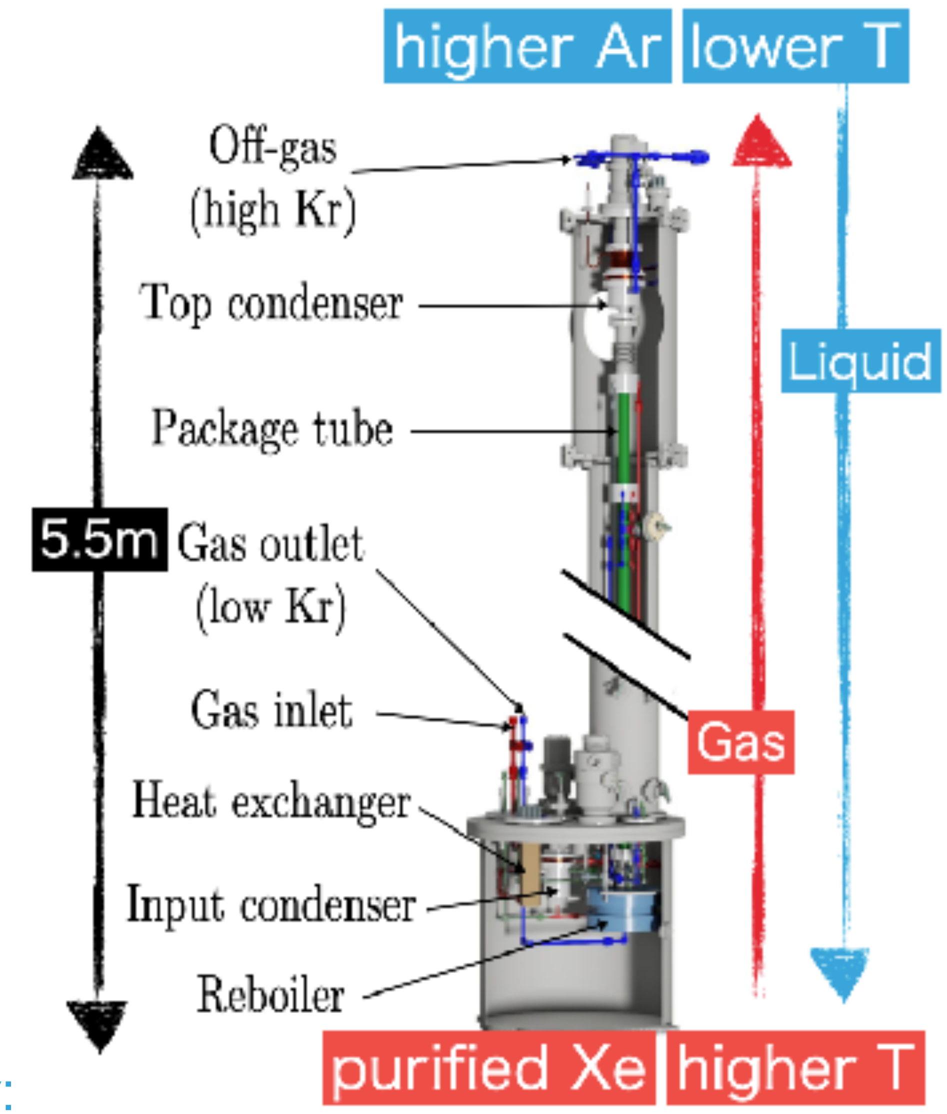
Physics of Atomic Nuclei volume 70, pages 300–310(2007)

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.
3. In-situ production: neutron reactions with ^{36}Ar or ^{40}Ca

Ar37 Distillation





Possible ^{37}Ar contributions:

1. Its presence in the xenon gas before filling

—> Argon is strongly reduced by 90 days of distillation & decay: combined time constant ~ 1.8 days, >10 times faster than decay

2. A possible air leak that could provide a constant source of argon. —> ~ 3 L/day air leak

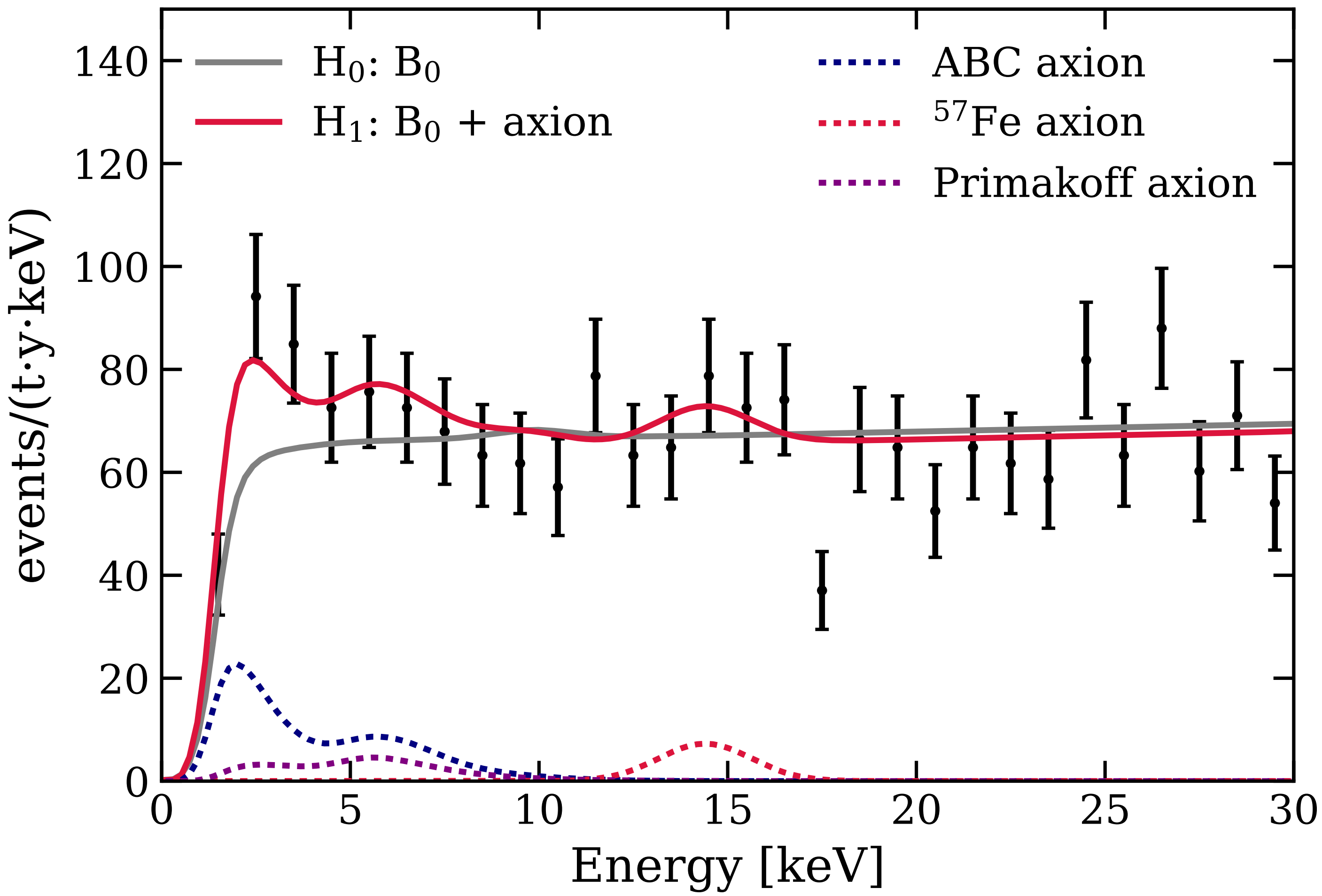
—> ruled out by ^{nat}Kr measurement (RGMS, < 1ppt increase/yr = ~1L/year air leak)

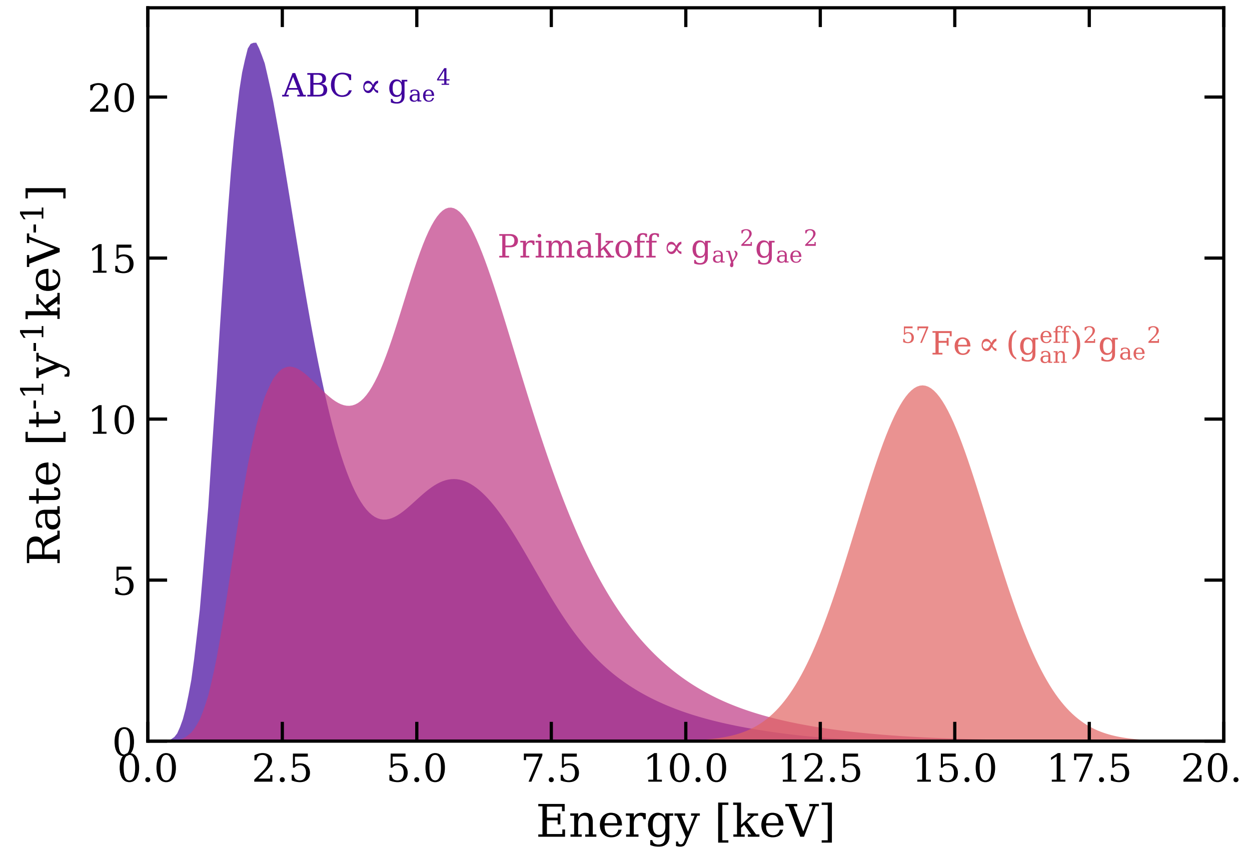
3. In-situ production: neutron reactions with ^{36}Ar or ^{40}Ca

—> Negligible

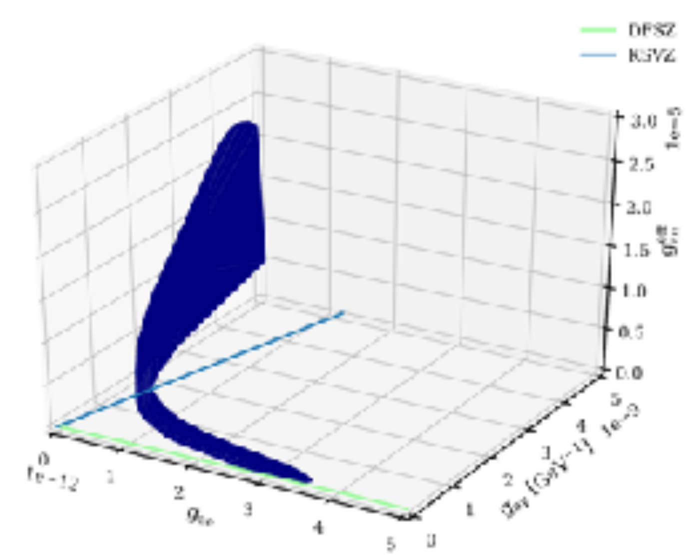
Signal Interpretation?

Solar-Axion Results



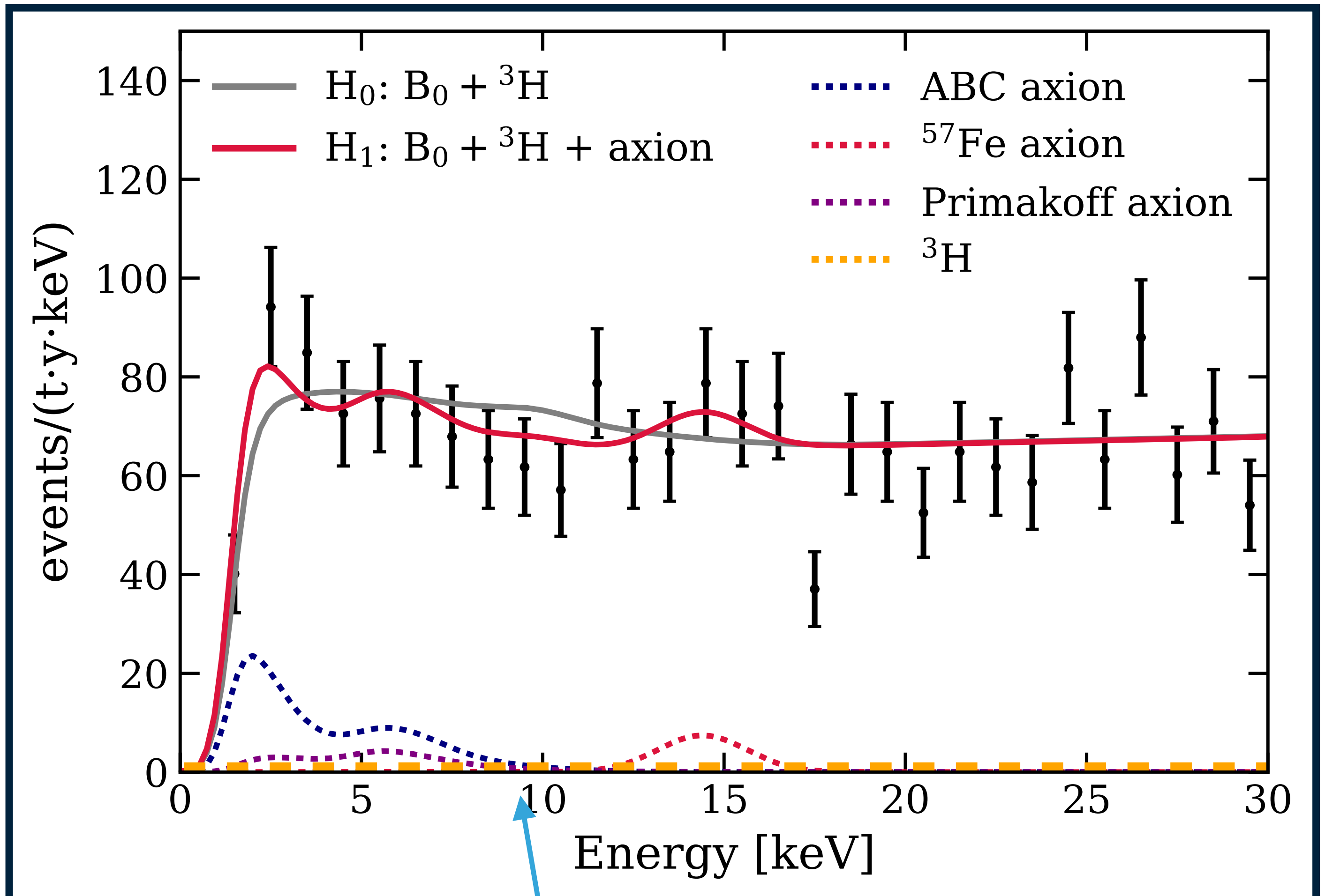


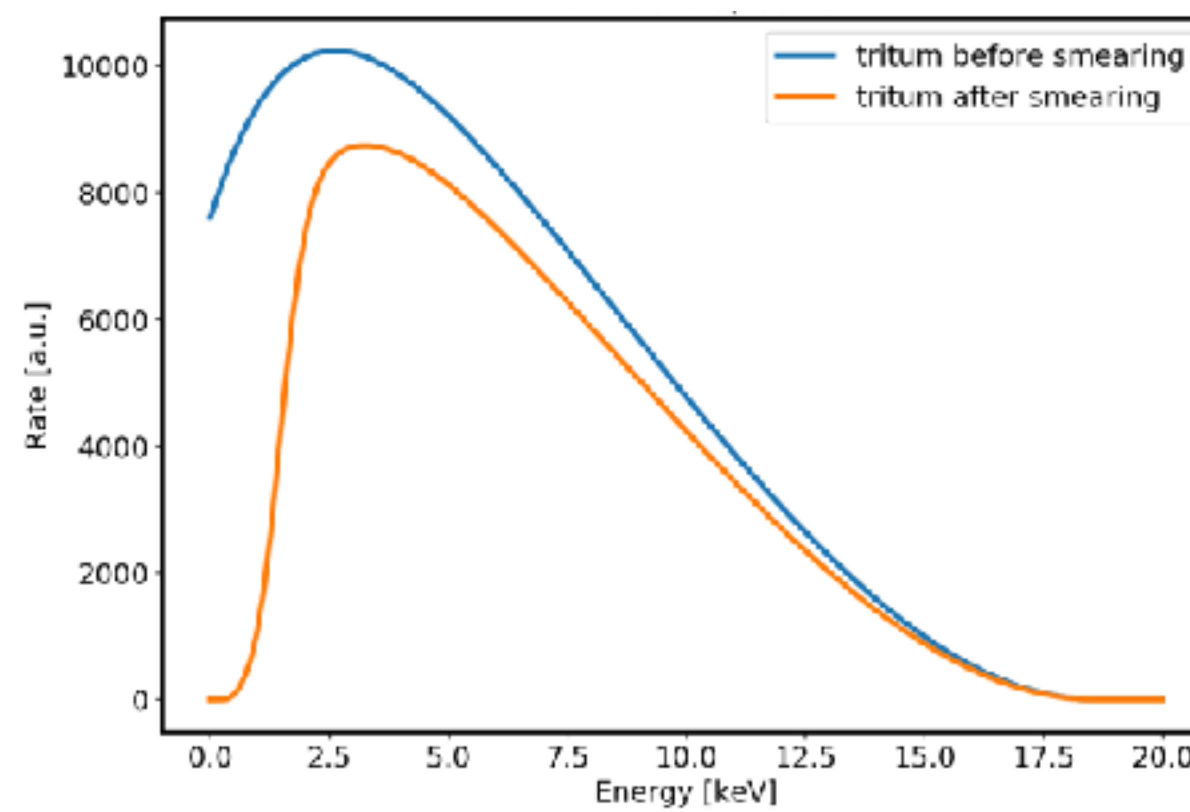
- All the three flux components are considered completely independent of each other
- Parameters of interest in the Profile Likelihood = g_{ae} vs. $g_{ae}g_{a\gamma}$ vs. $g_{ae}g_{an}^{eff}$
- Significance determined using toy-MC methods



Axion favored over background-only at 3.5σ

Solar-Axion + Tritium



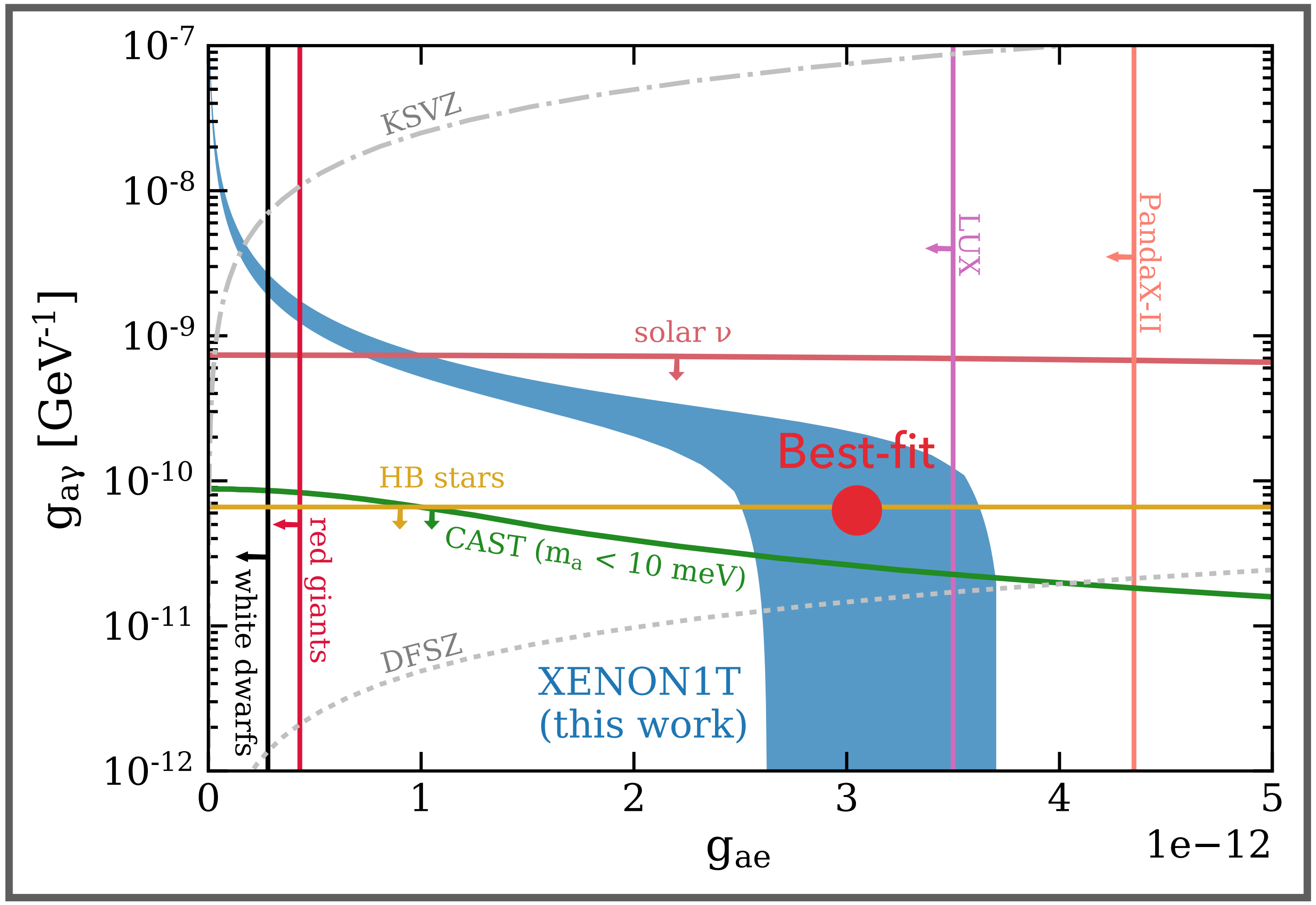


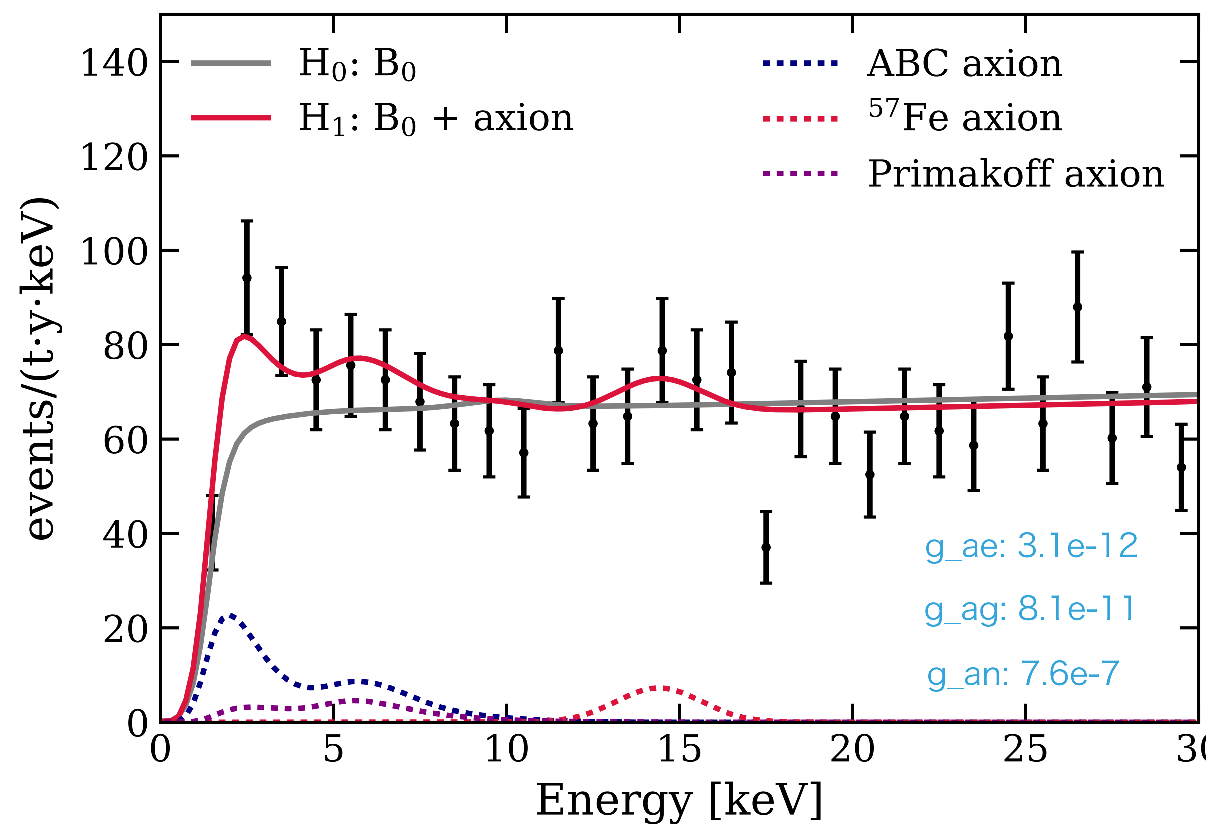
Axion + ^{3}H favored over ^{3}H hypothesis at 2.1σ

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 g_{ae} vs. $g_{ae}g_{a\gamma}$ vs. $g_{ae}g_{an}^{eff}$





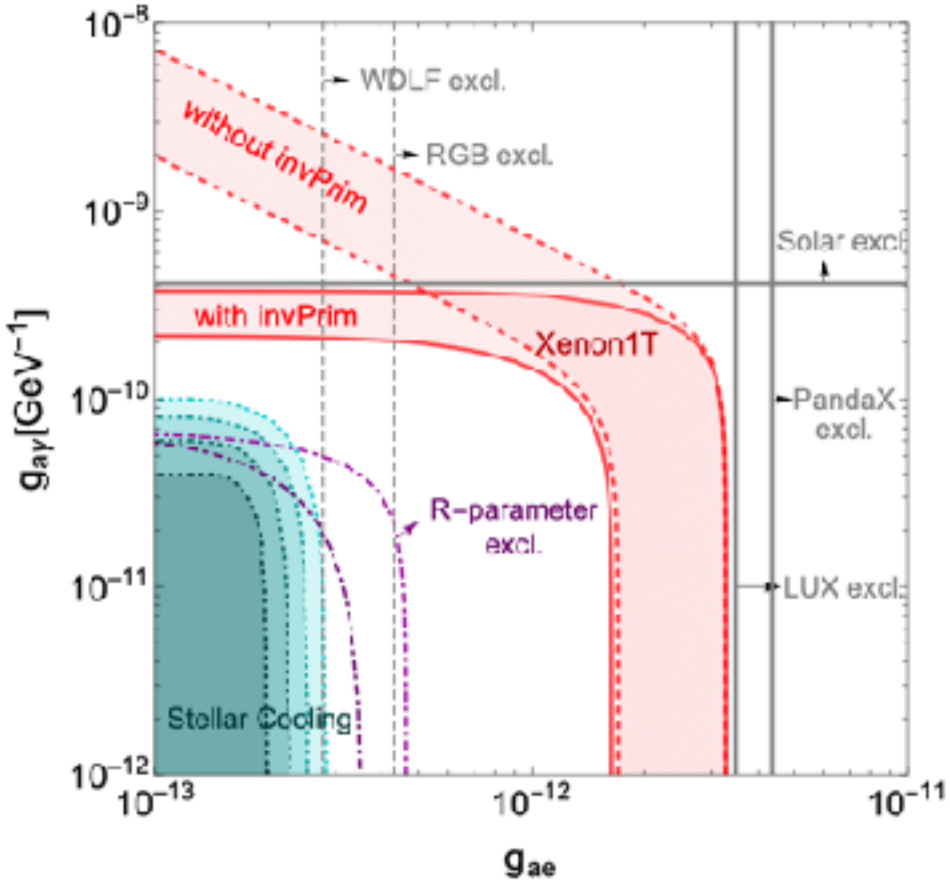
ABC and Primakoff components are both low-energy signals, the favored region is anti-correlated in this space

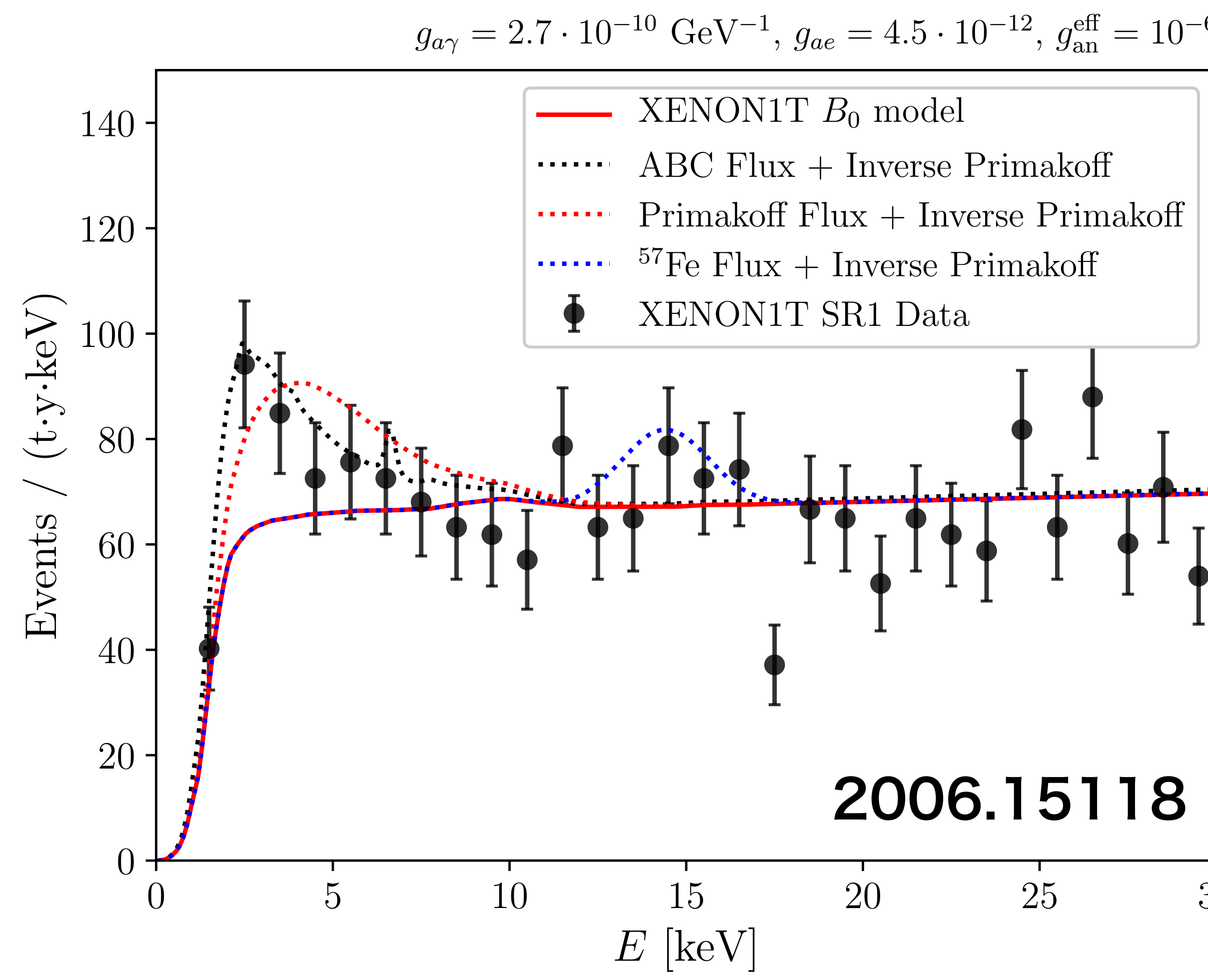
—> suggests either a non-zero ABC component or non-zero Primakoff component.

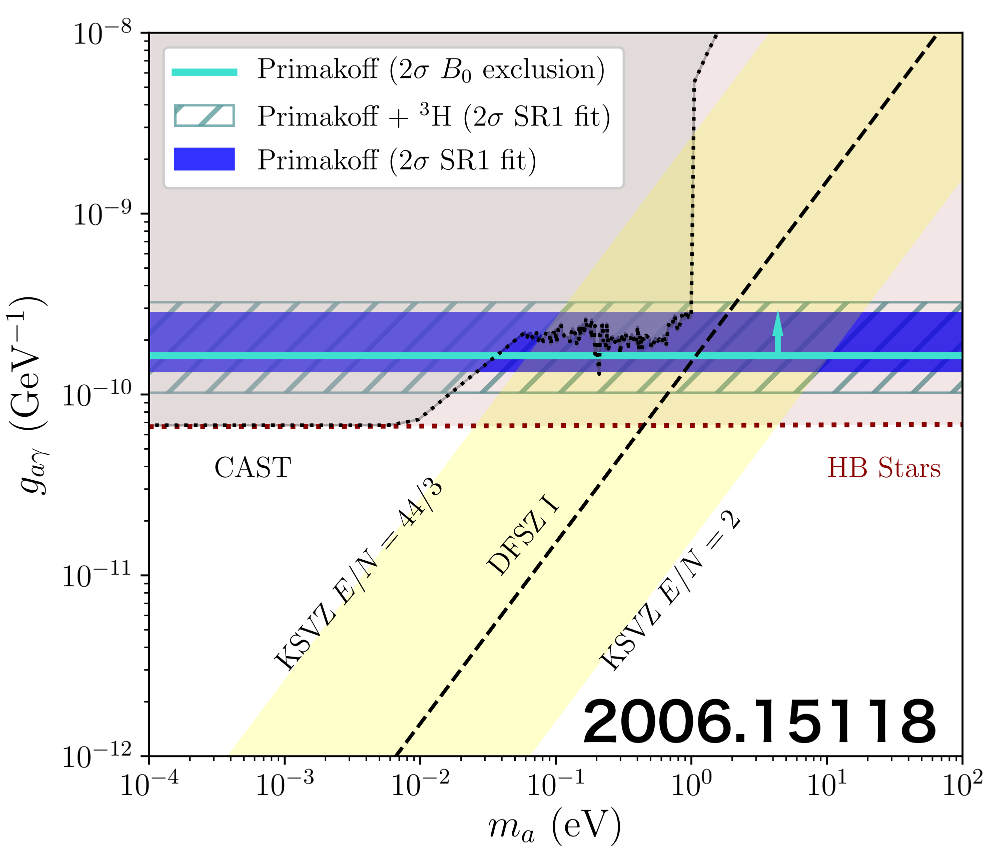
In tension with astrophysical constraints from stellar cooling bounds from the horizontal branch stars and red giants

Inverse Primakoff Process?

2006.14598





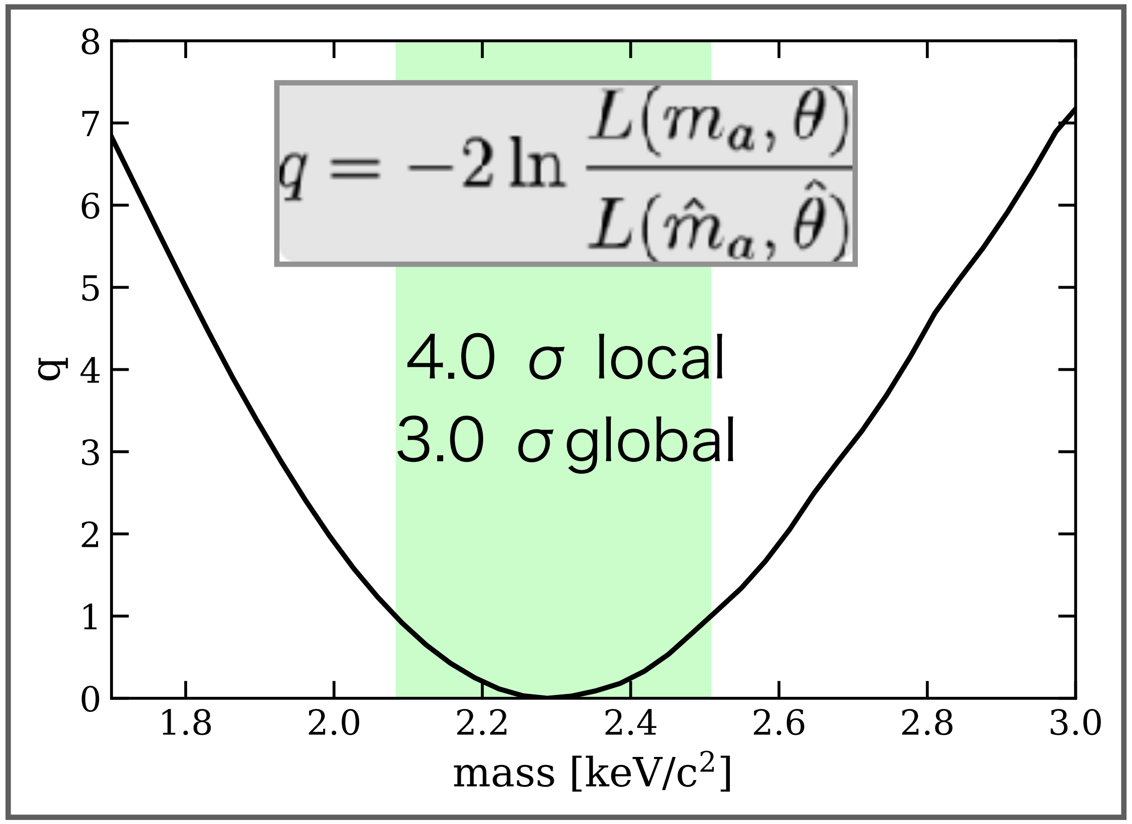


Considering inverse Primakoff process can weaken the tension with stellar cooling constraint

XENON1T has a good sensitivity also for g_aγ!

Axion-like Particle / Dark Photon

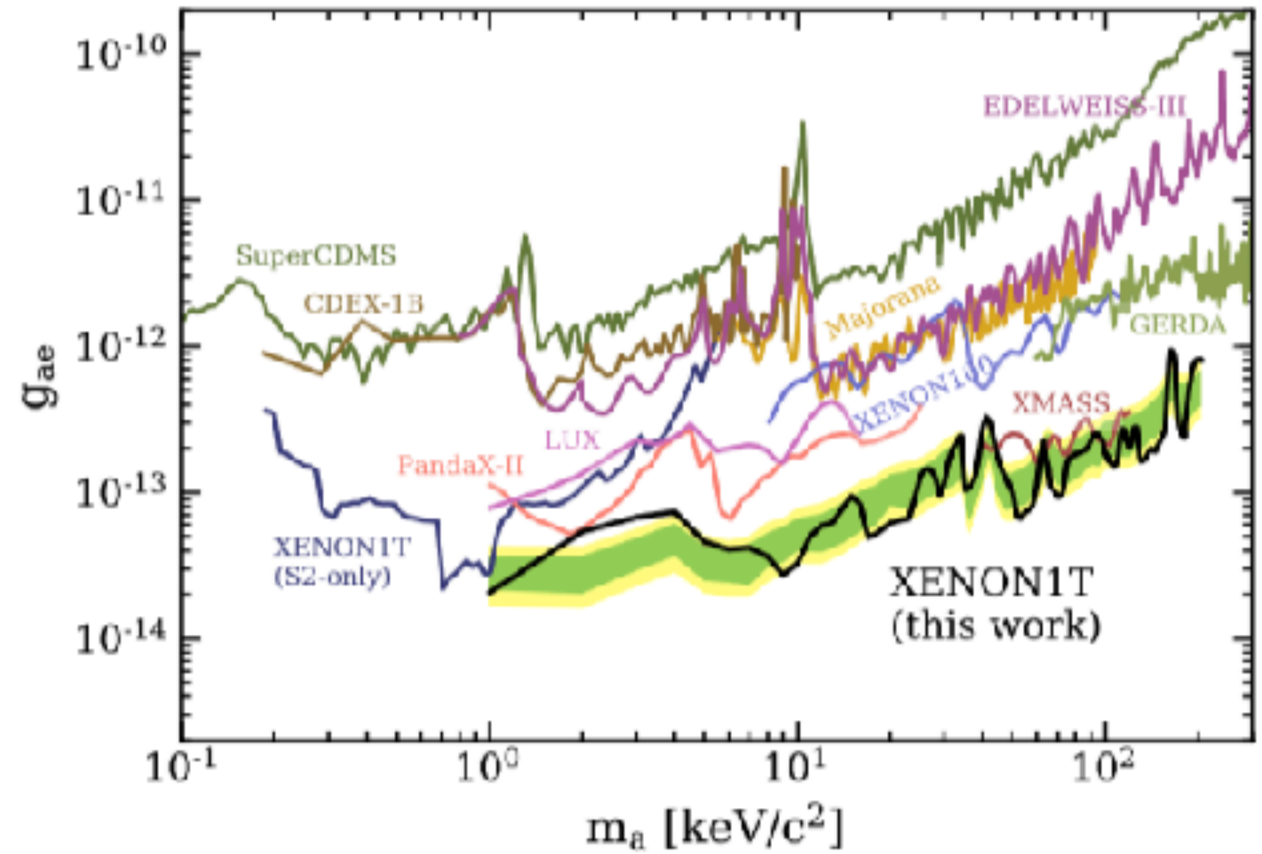
Fitting a mono-energetic peak to the excess: **2.3 +/- 0.2 keV**

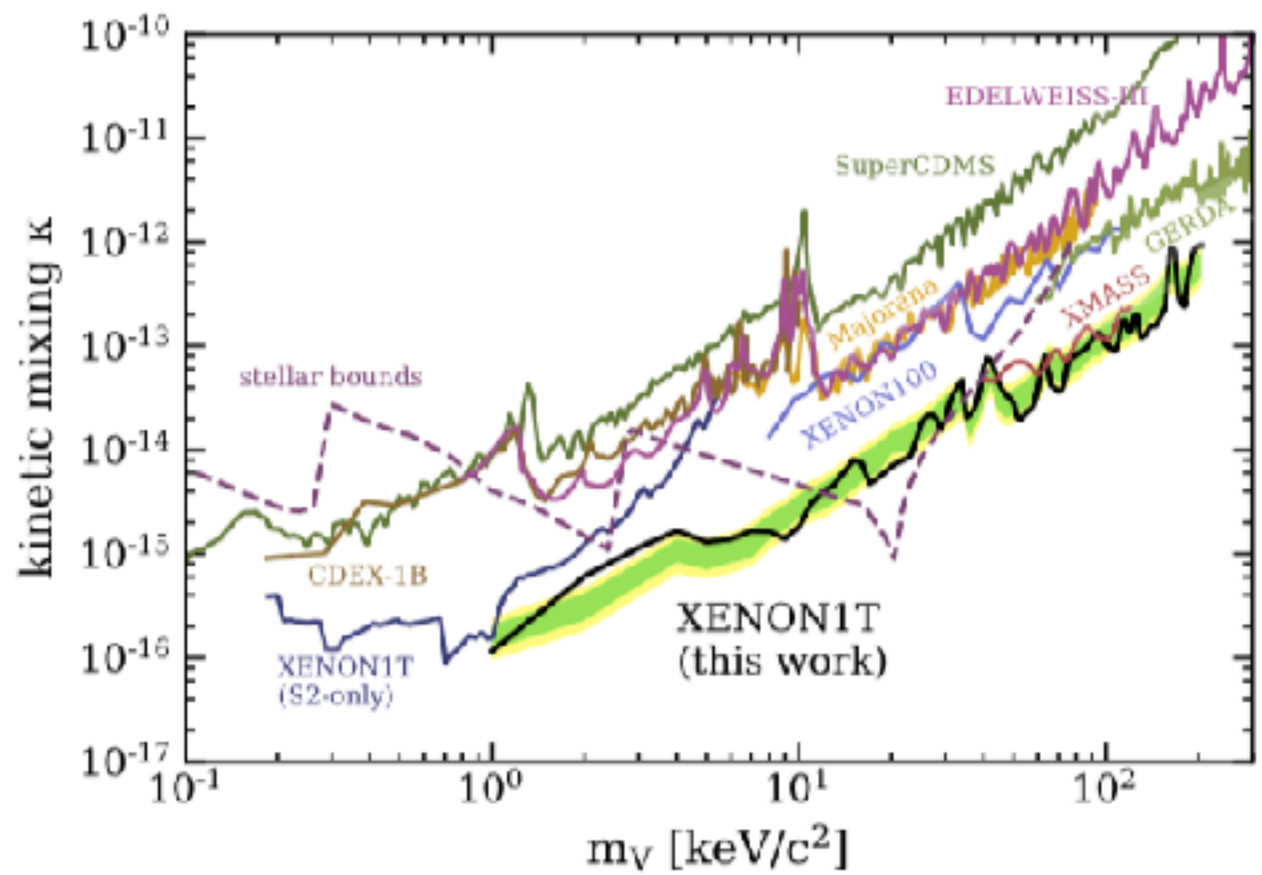


Best fit: ~60 events/tonne/year

4.0 σ local significance

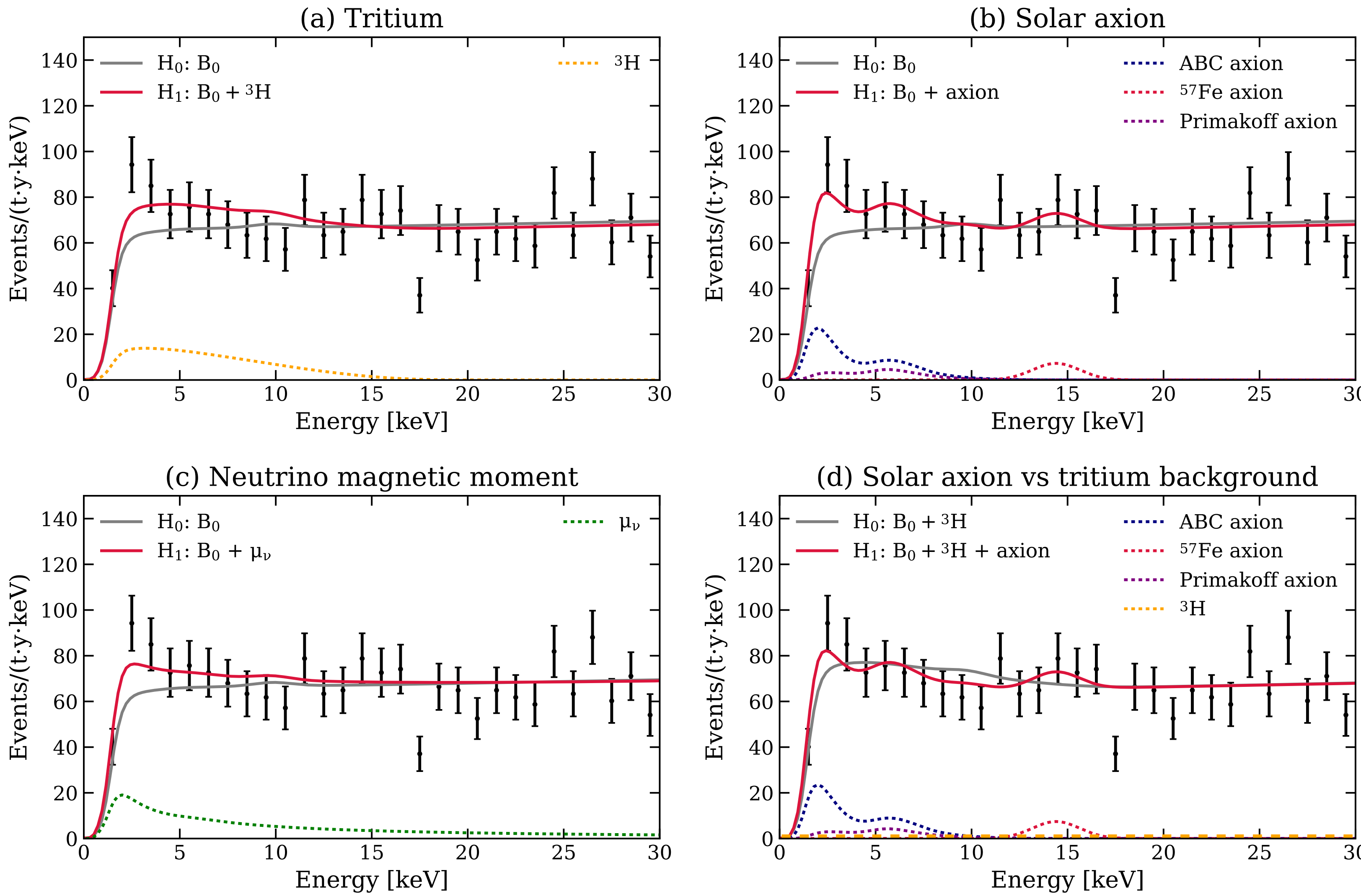
3.0 σ (global, considering look-elsewhere effect).





Summary

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



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

g_ae: 3.1e-12

g_ag: 8.1e-11

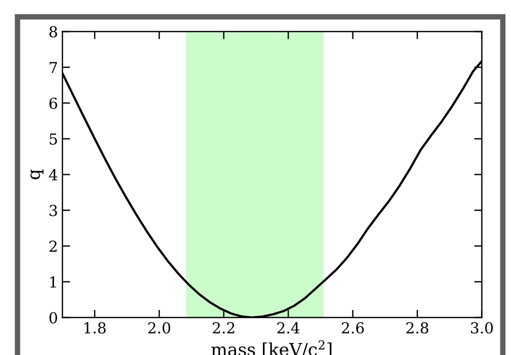
g_an: 7.6e-7

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

μ_v: 2.3e-11

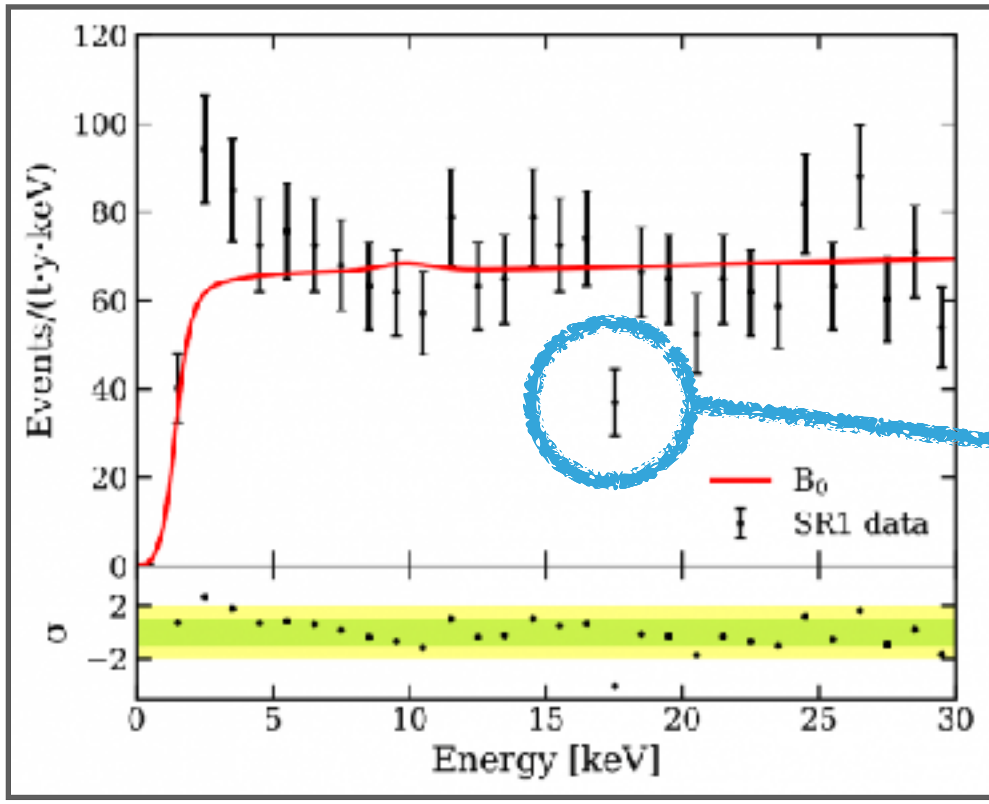
Axion + ^{3}H favored **over ^{3}H** hypothesis **at 2.1σ**

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

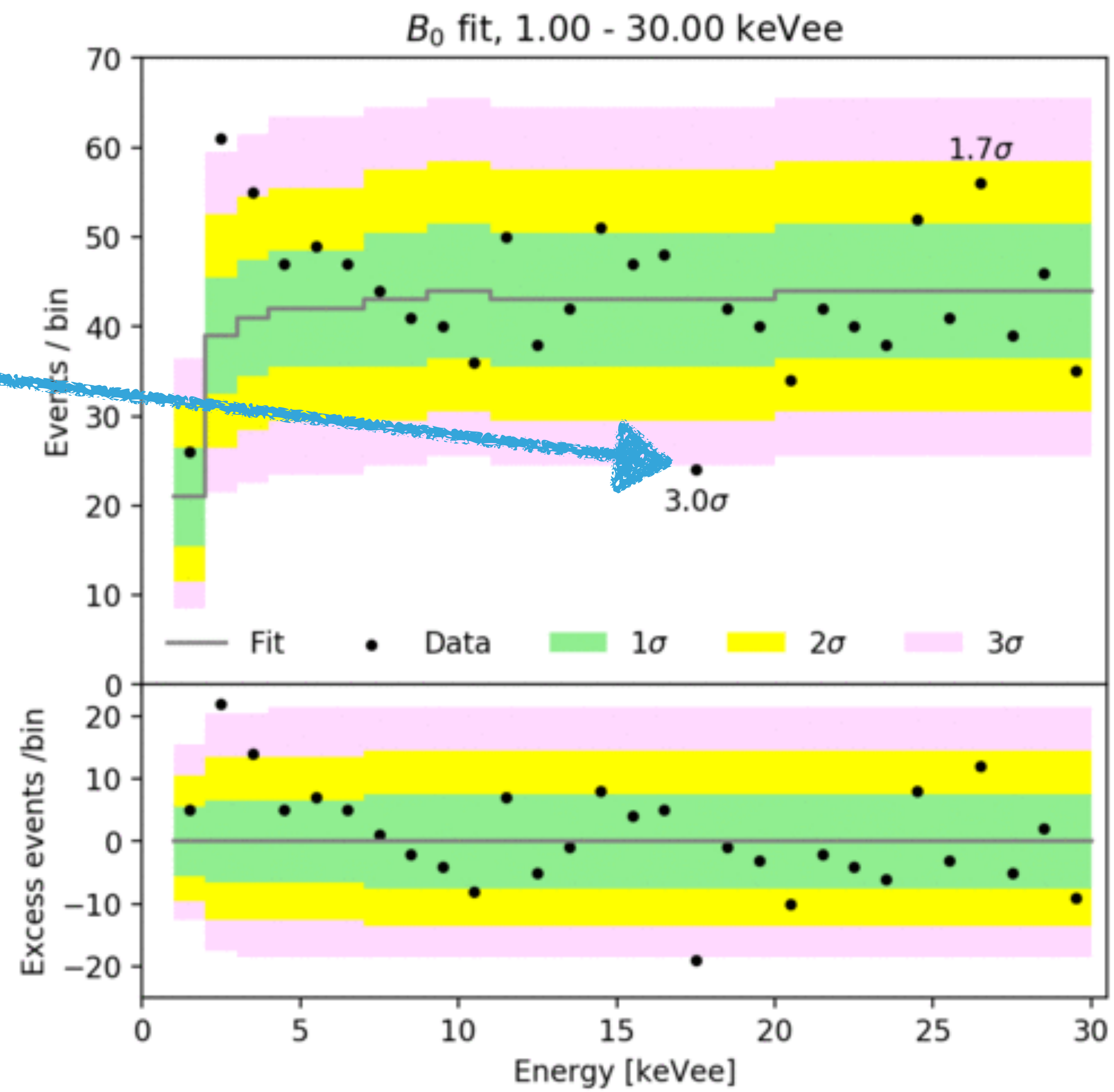


Back Up

Statistical Fluctuation?



statistical fluctuation? (see 17 keV dip)



Note: we use an unbinned profile likelihood analysis

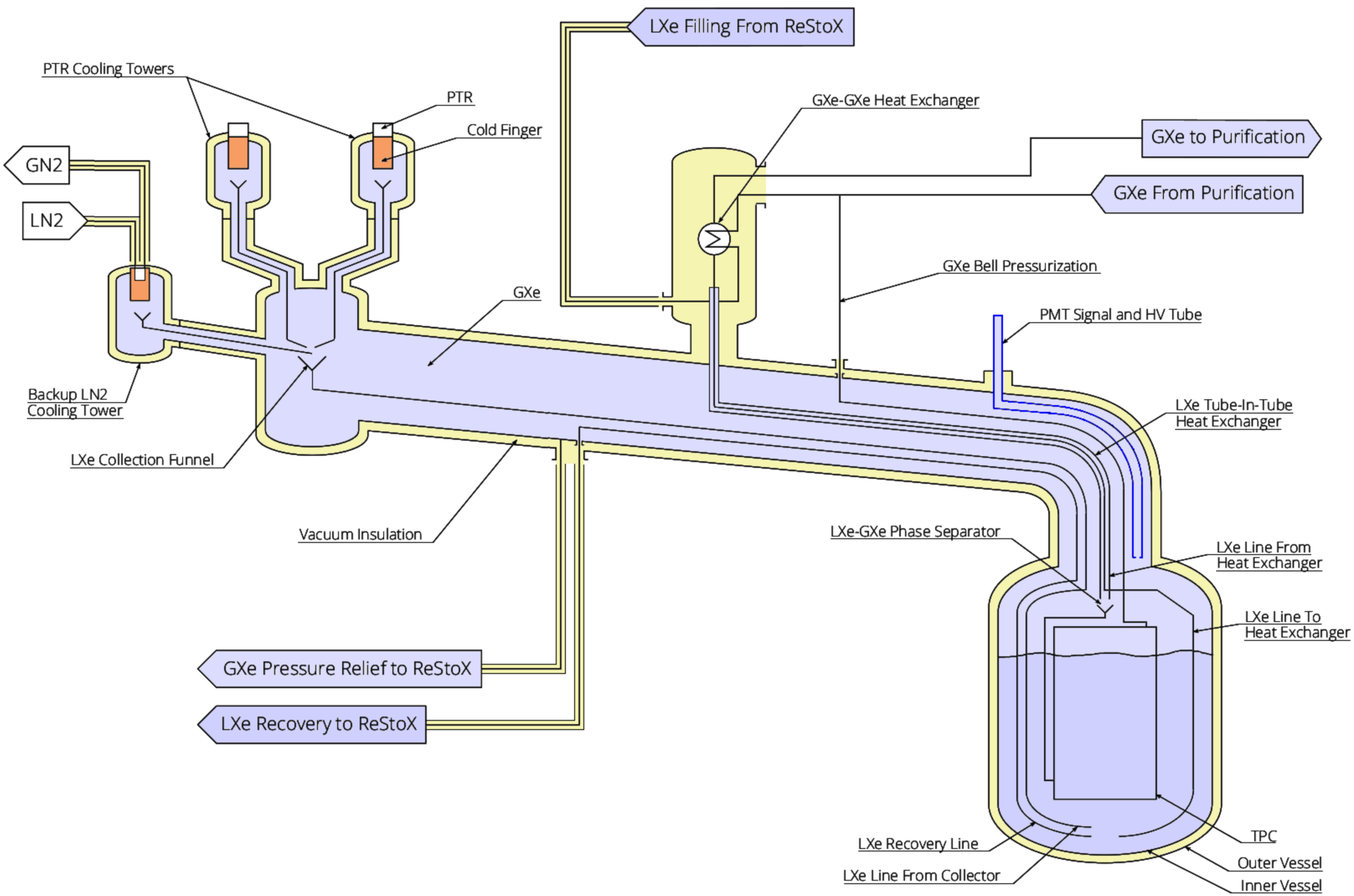


Fig. 7 The cryogenic system of XENON1T: cooling is provided by means of three redundant cold heads (two pulse-tube refrigerators (PTR), 1 LN_2), installed on individual cooling towers located outside of the water shield. The liquefied xenon runs back to the main cryostat in a 6 m long vacuum-insulated cryogenic pipe, through which all connections to the TPC are made with the exception of the cathode bias voltage which is not shown in the figure. The connections to the systems for xenon purification and storage (ReStoX) are also shown. Figure not to scale.

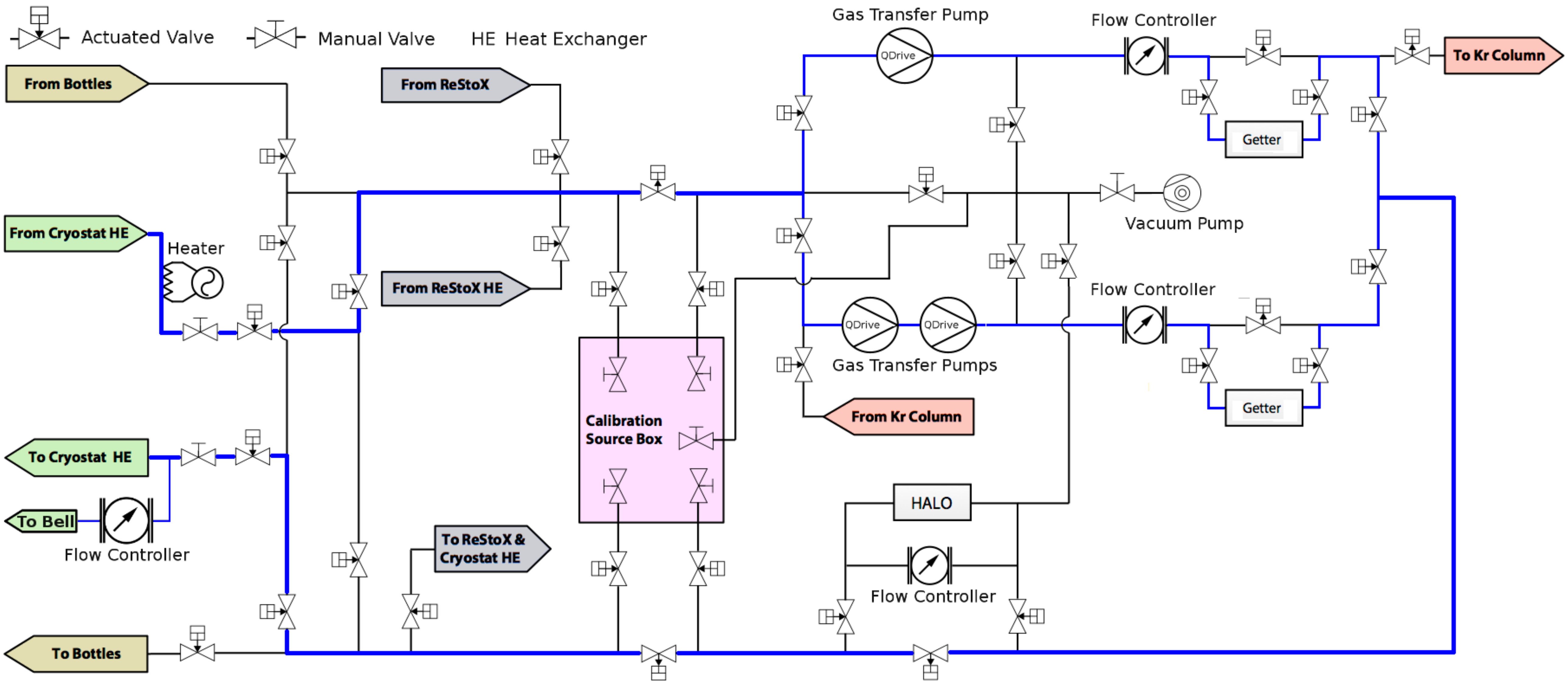


Fig. 8 Piping and instrumentation diagram (P&ID) of the XENON1T purification system. The system also serves as the main interface to the other components of the gas-handling system (see figure 9) and allows the insertion of short-lived isotopes for calibration. Some instrumentation such as temperature and pressure sensors, as well as several access ports are omitted for clarity. The path of the xenon gas during standard purification is indicated in blue.

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)

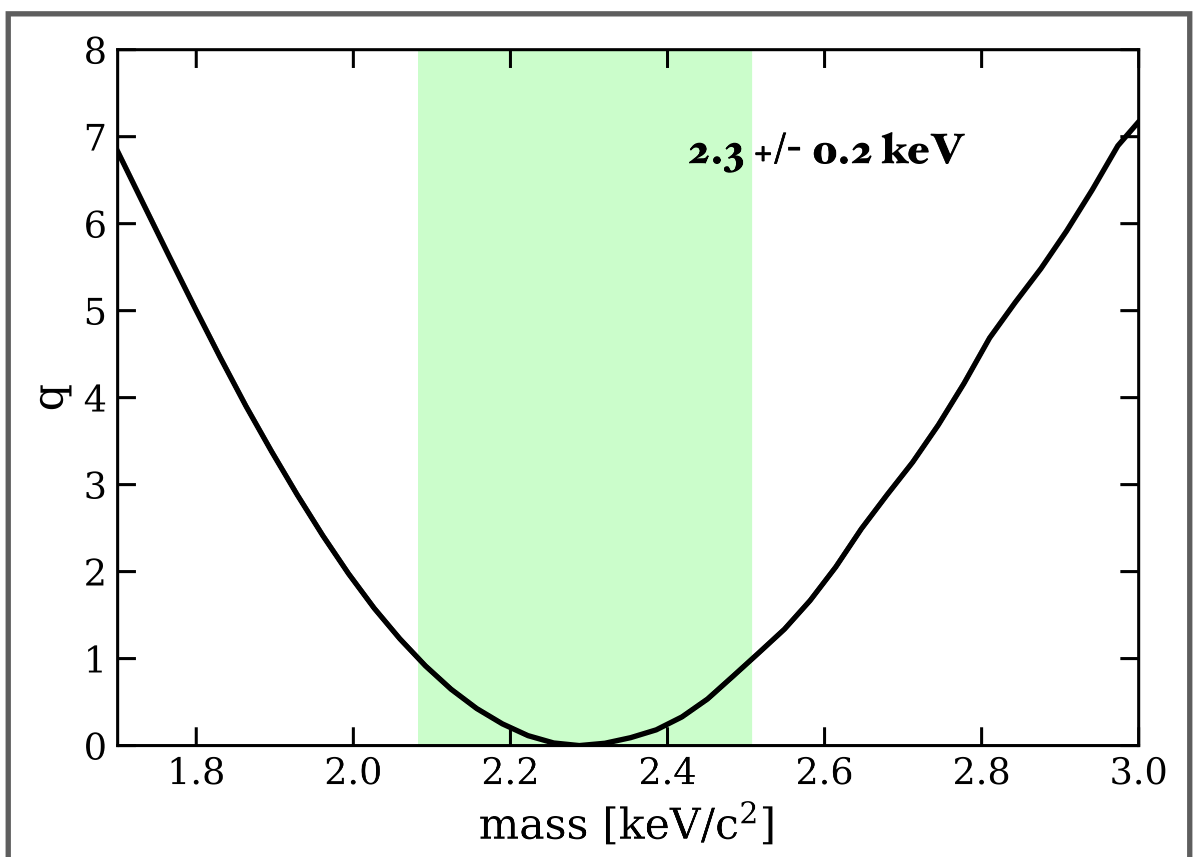
2. A possible air leak that could provide a constant source of argon.

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

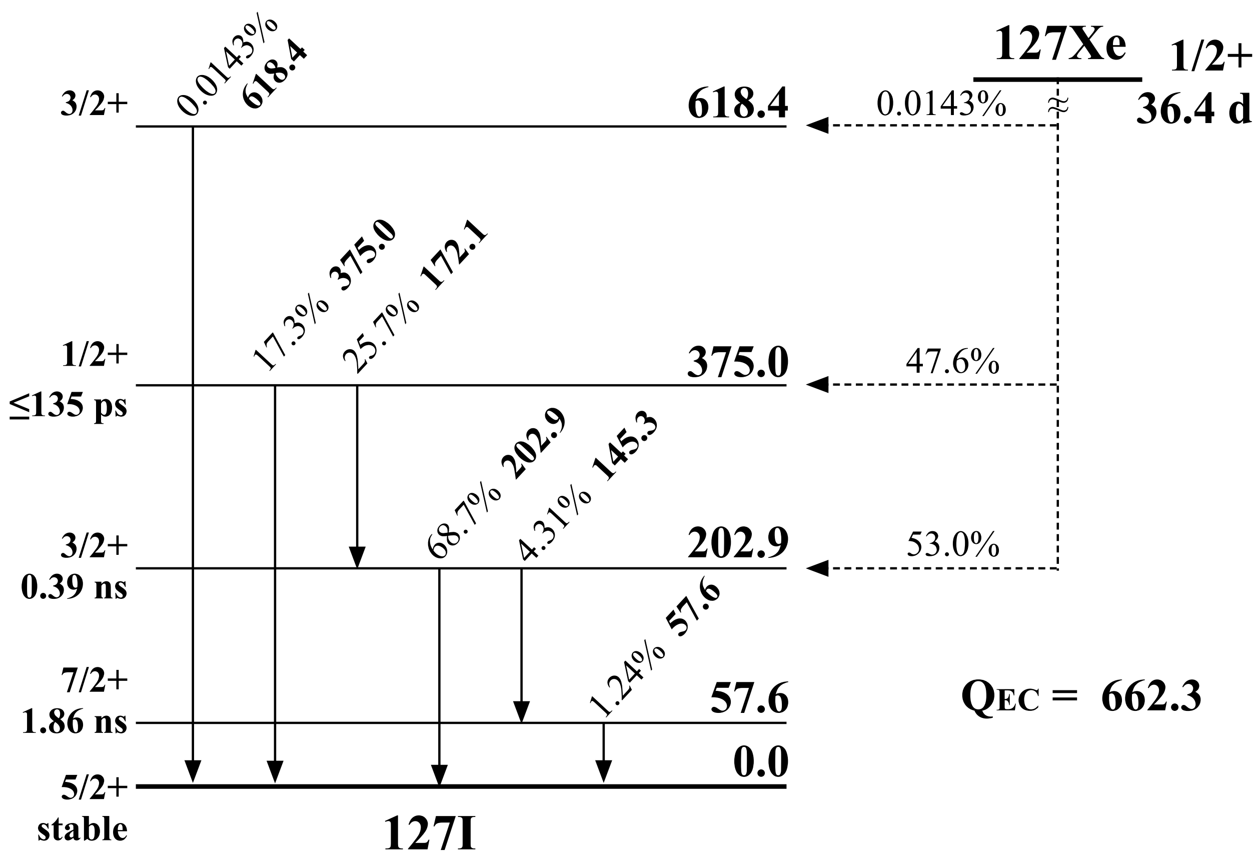
Xe127

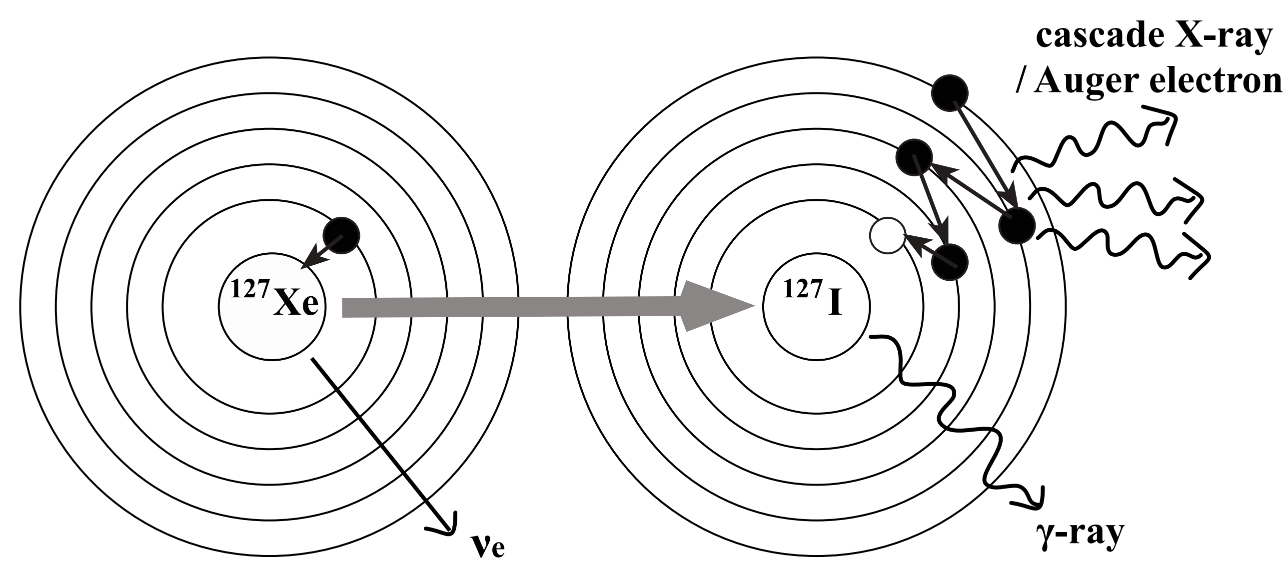
^{127}Xe can be produced from cosmogenic activation of Xe at sea level;

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

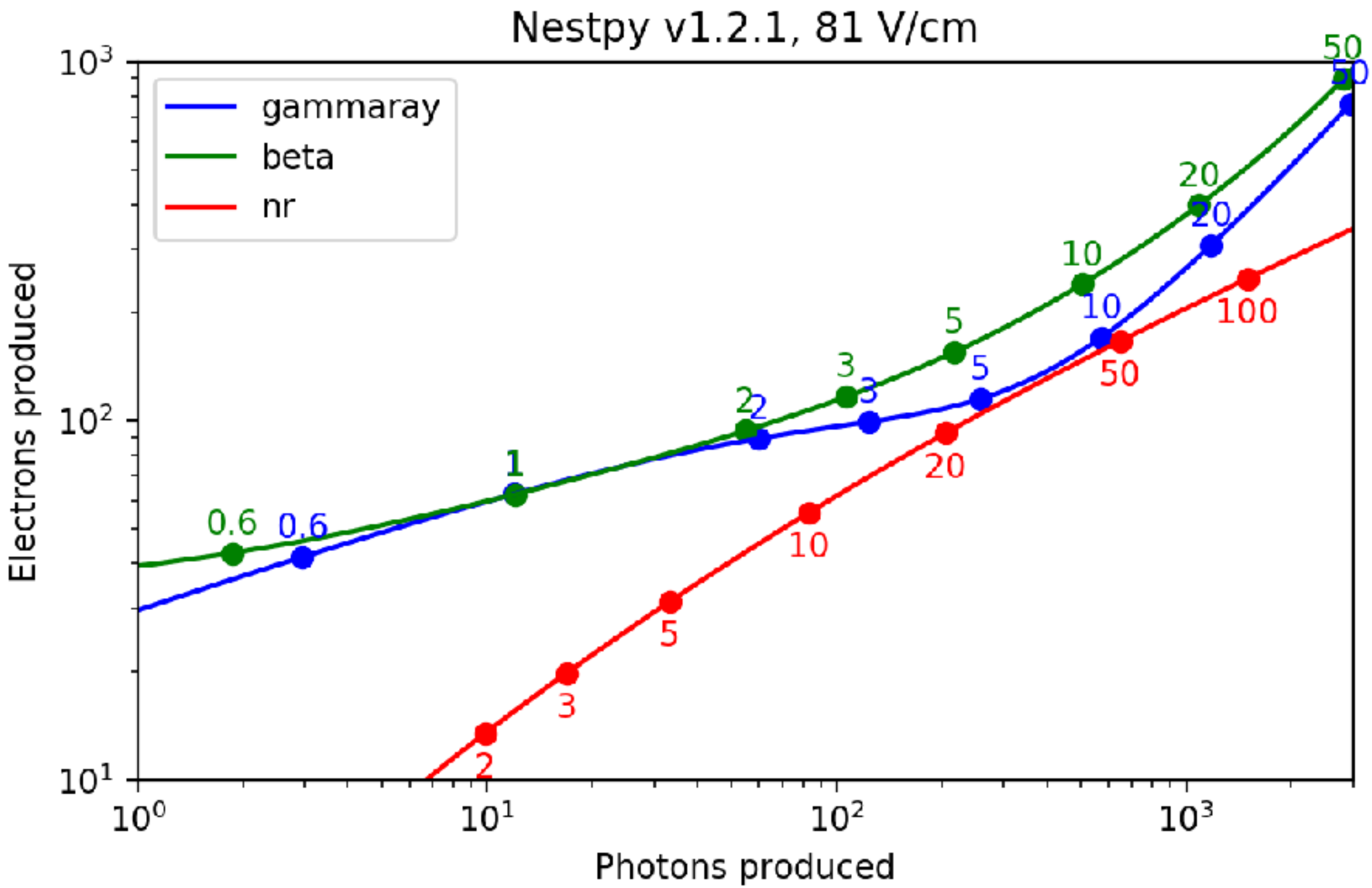
Phys. Rev. D 96, 112011 (2017)





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)

β/γ discrimination? NEST?



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

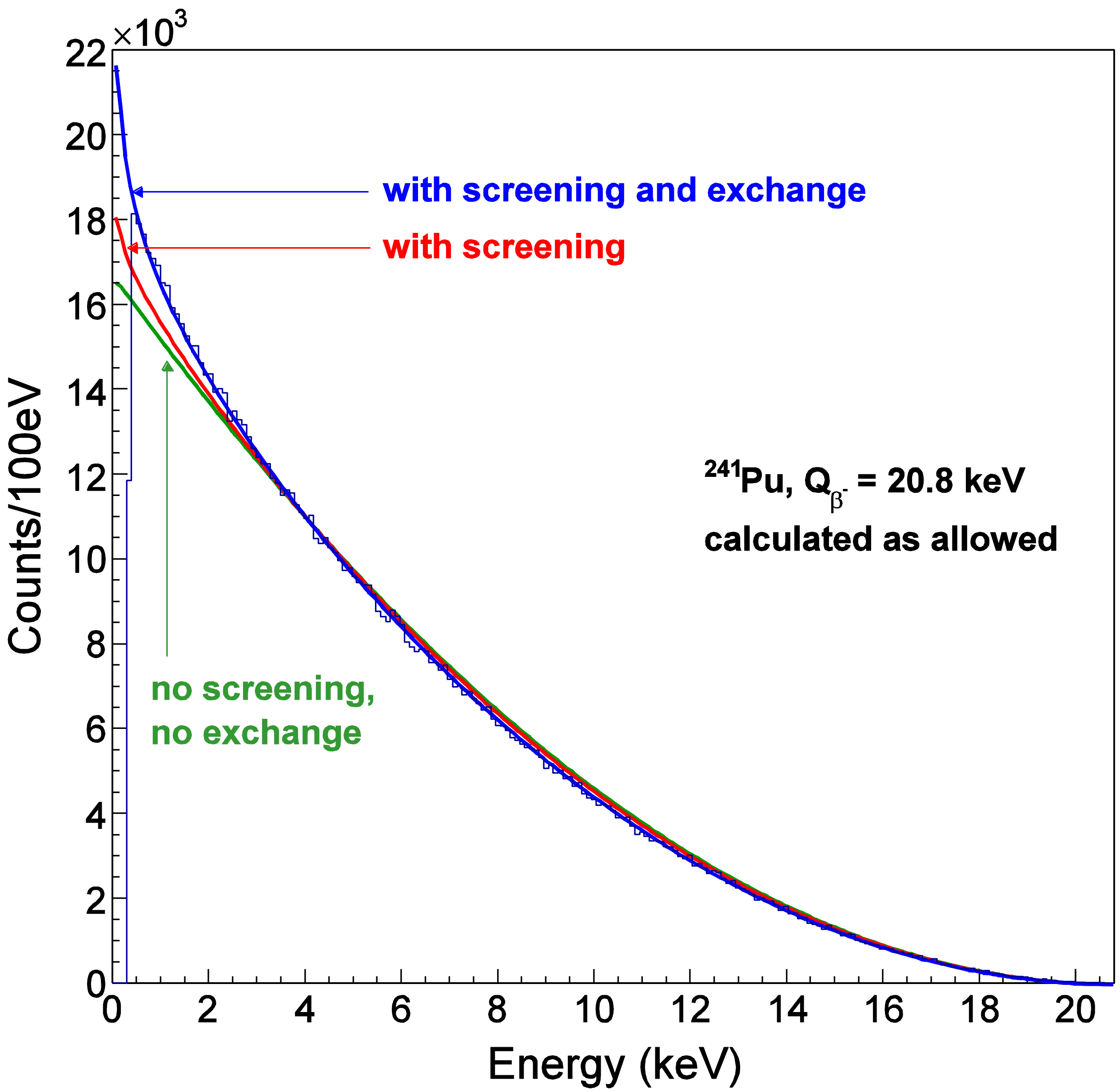
The electrons in bound states in the atom produce screening of the nuclear charge for the emitted beta particle. This change in electromagnetic field modifies the beta spectrum.

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

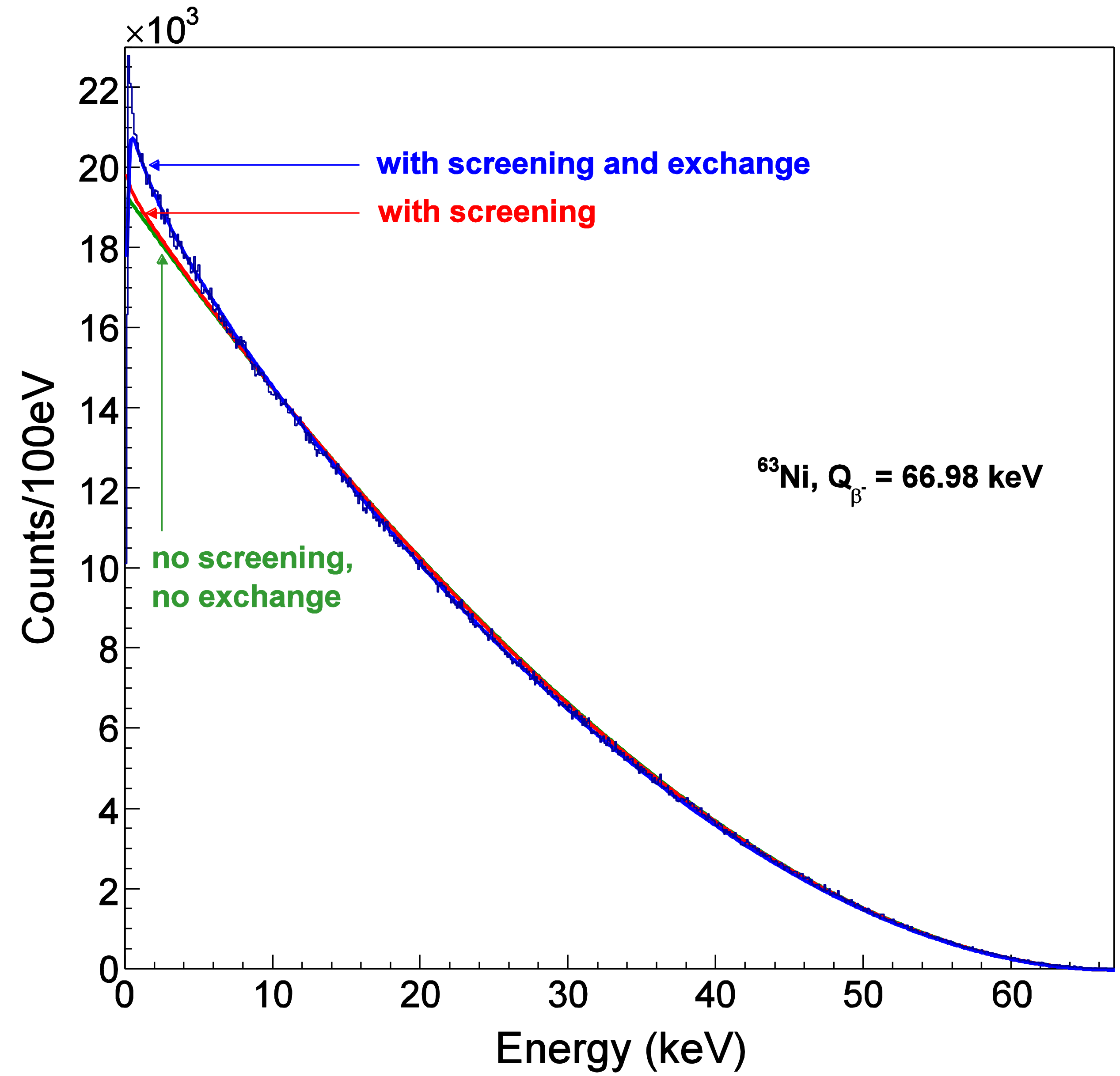
241Pu / 63 Ni beta-spectrum

From X. Mougeot

M. Loidl et al., App. Radiat. Isot. 68, 1454 (2010)

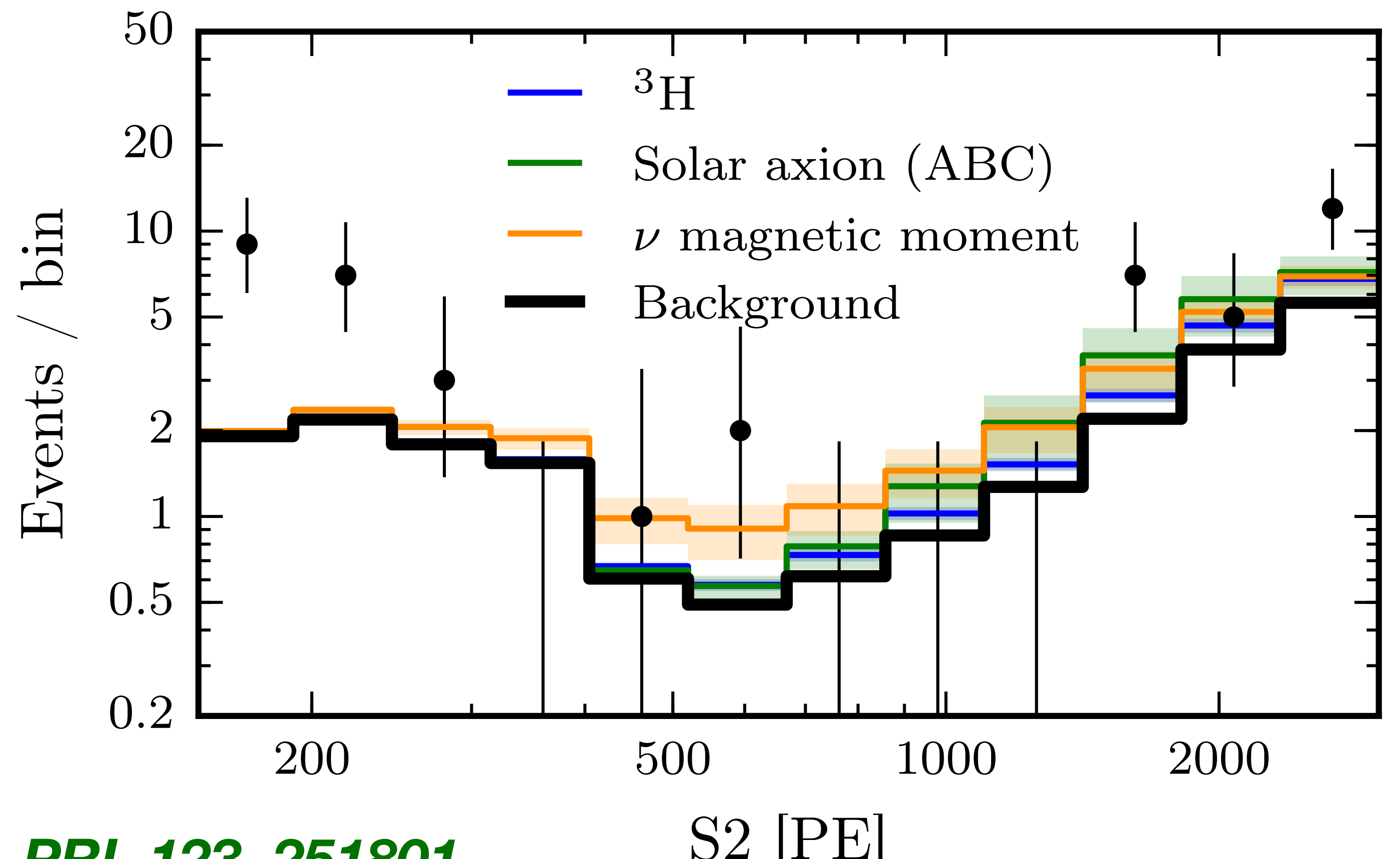


C. Le-Bret, PhD thesis, Université Paris 11 (2012)



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

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

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

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

consistent with this work for all 3 hypotheses

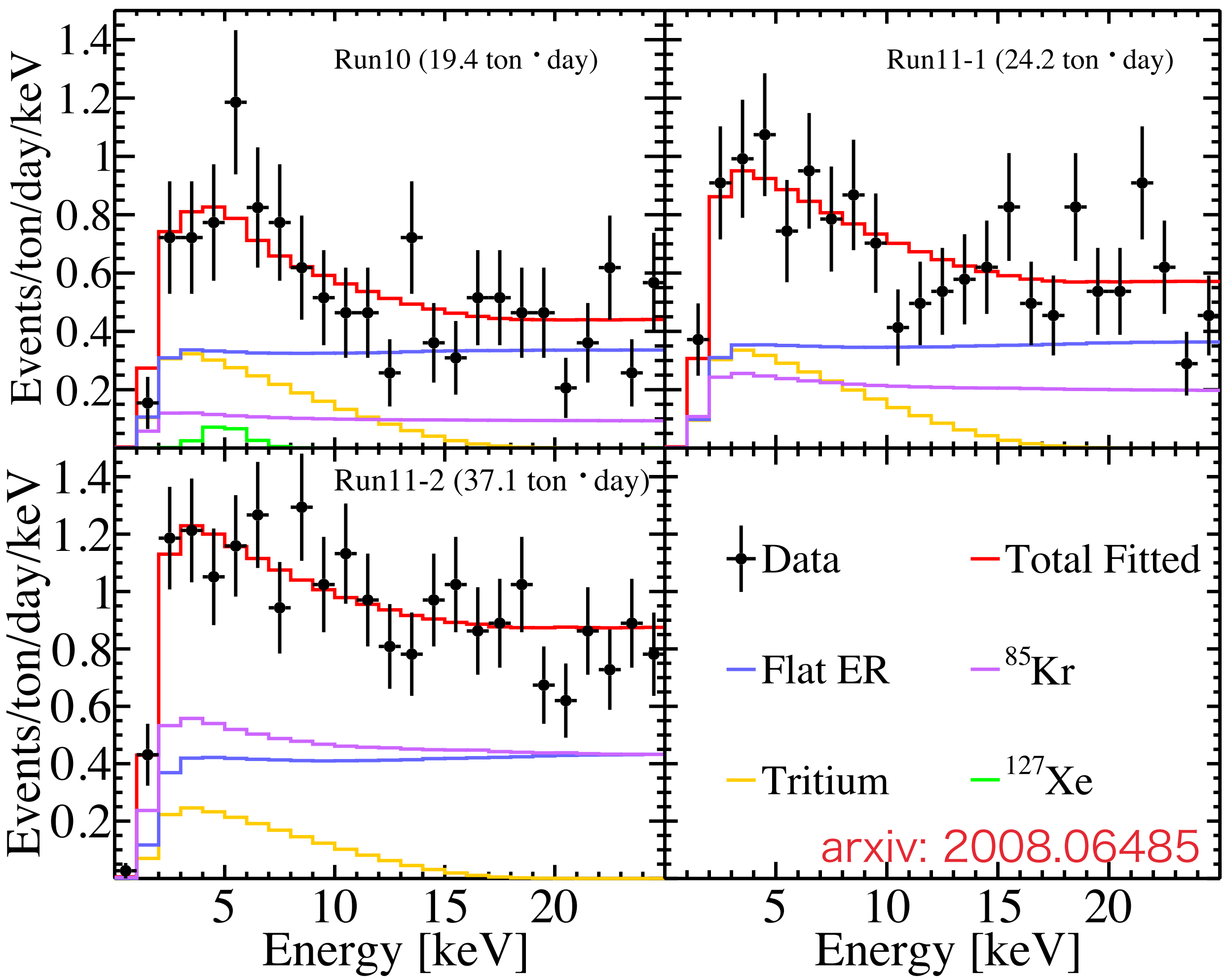
larger upper limits, S2-only analysis is not sensitive to the excesss we found

Other Experiments: PandaX?

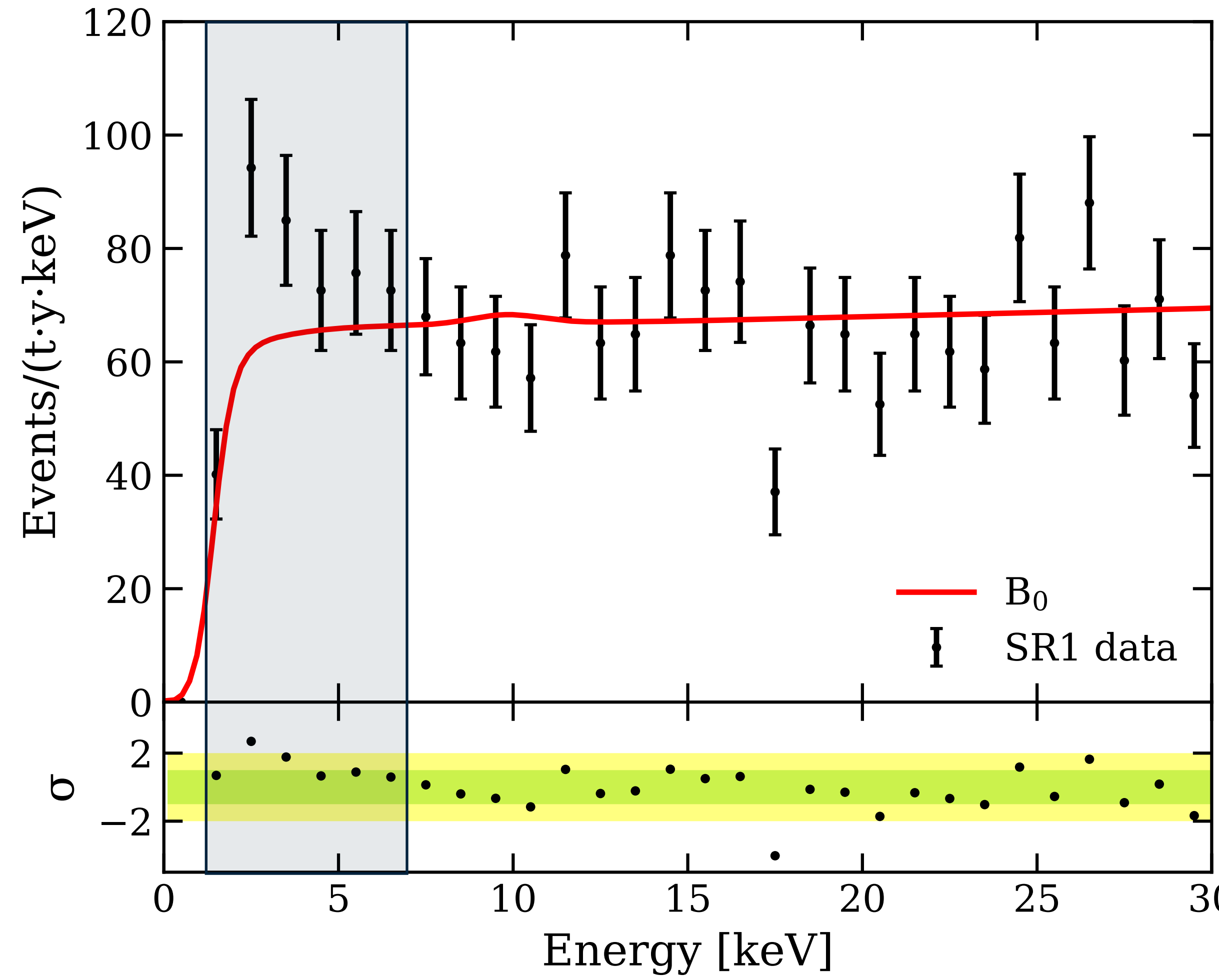
Exposure: 101 ton-days (XENON1T: 236 ton-days)

BG level: ~5 times higher BG than in XENON1T

PandaX



XENON1T



Note that PandaX experiment injected Tritiated Methane (CH3T) directly into the detector for low-E calibration, but they could not completely remove it with distillation.

Resulting tritium concentration is ~0.04 uBg/kg (~5×10^{-24} mol/mol in xenon)

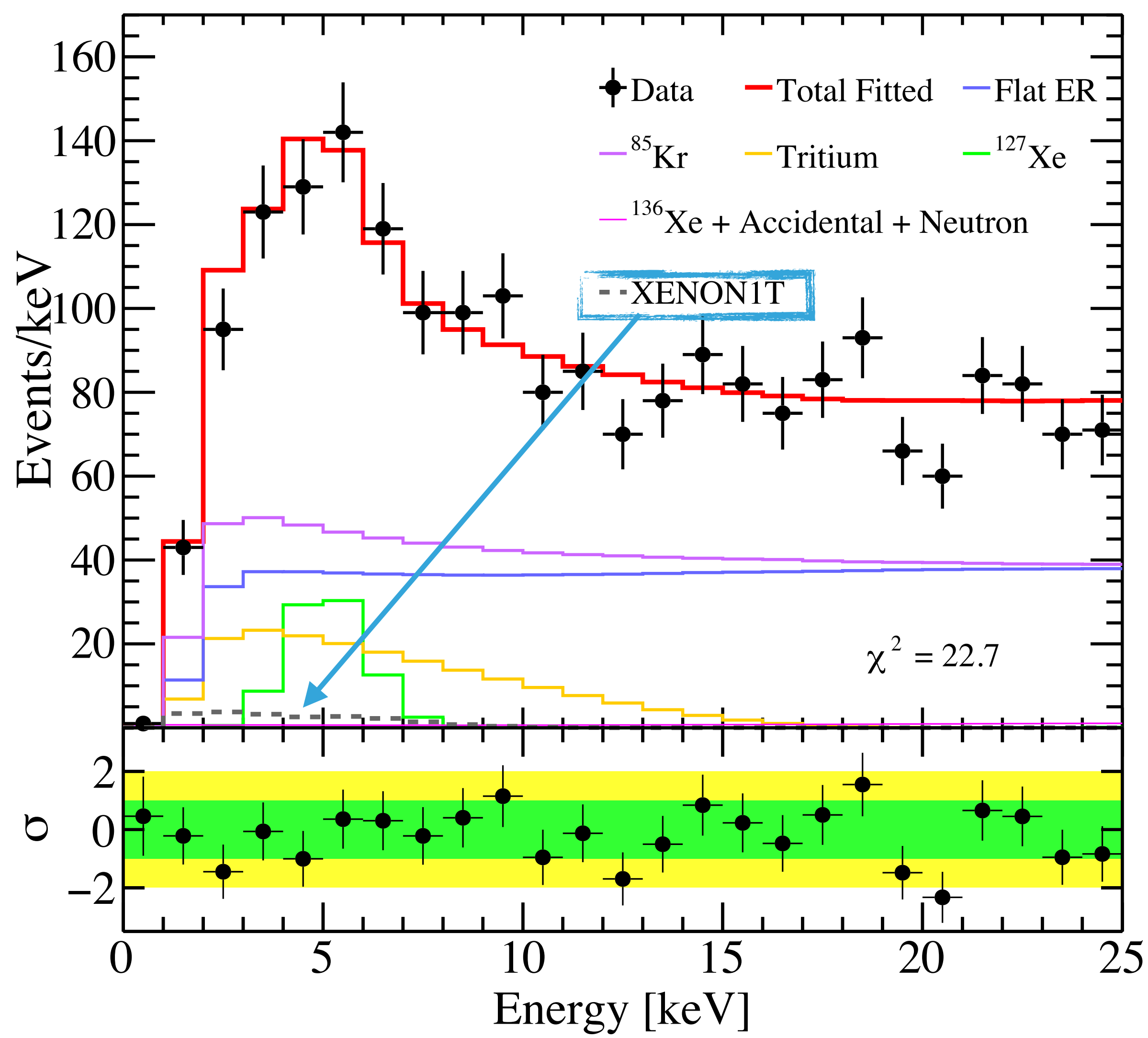
Best-fit for tritium hypothesis in XENON1T: ~6×10^{-25} mol/mol (we did not inject CH3T!)

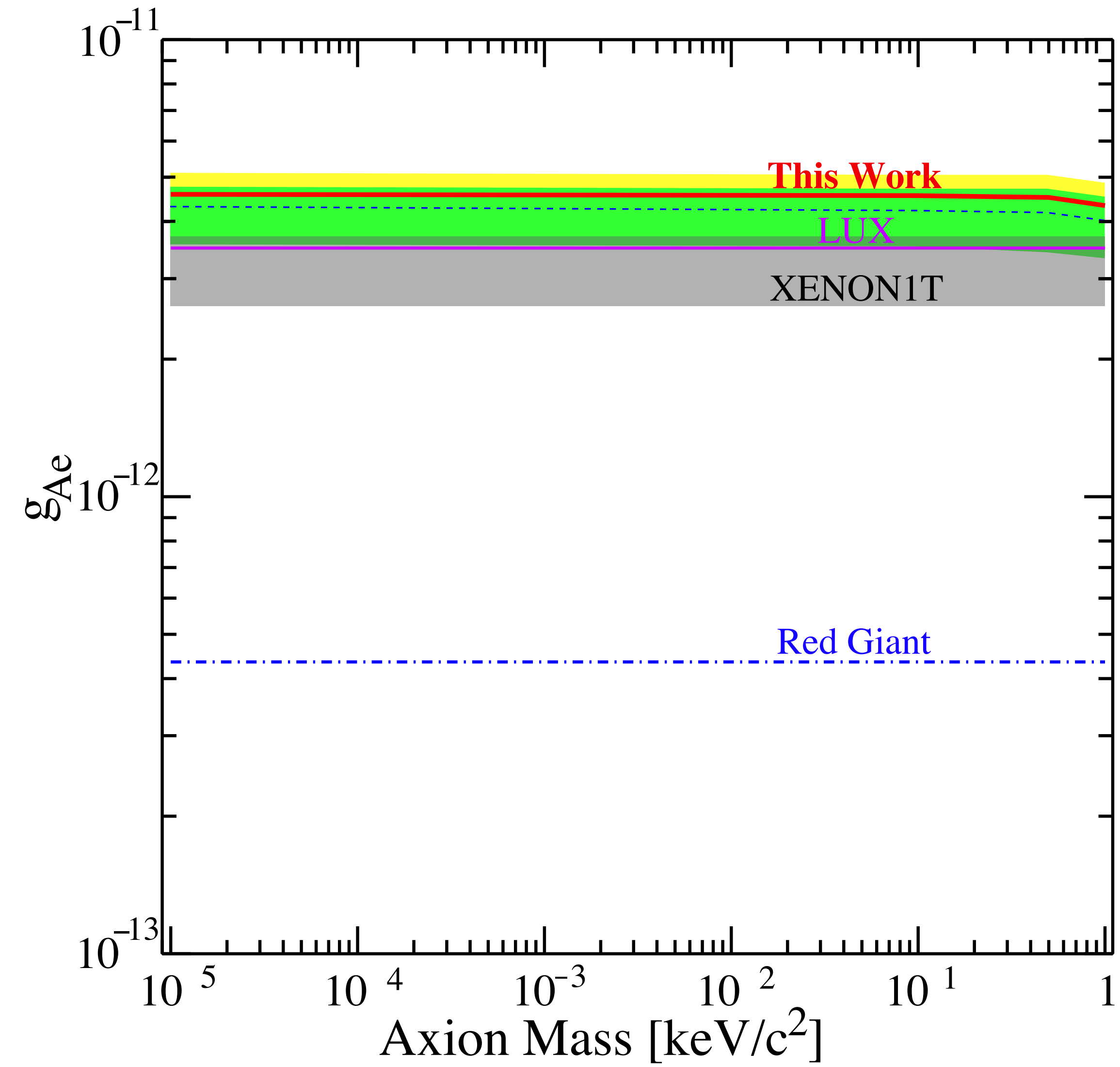
Other Experiments: PandaX?

arxiv: 2008.06485

Exposure: 101 ton-days (XENON1T: 236 ton-days)

BG level: ~5 times higher BG than in XENON1T

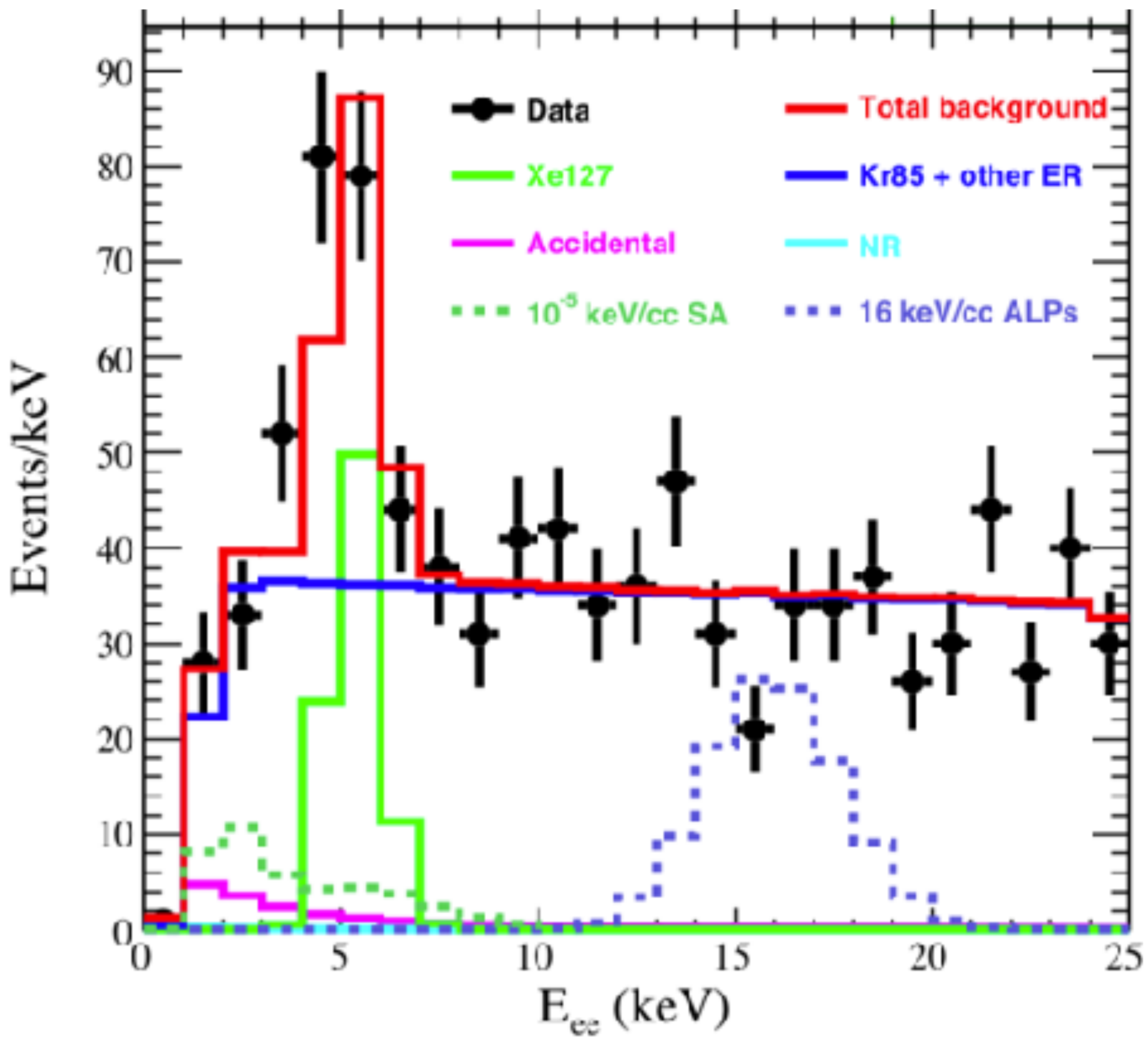


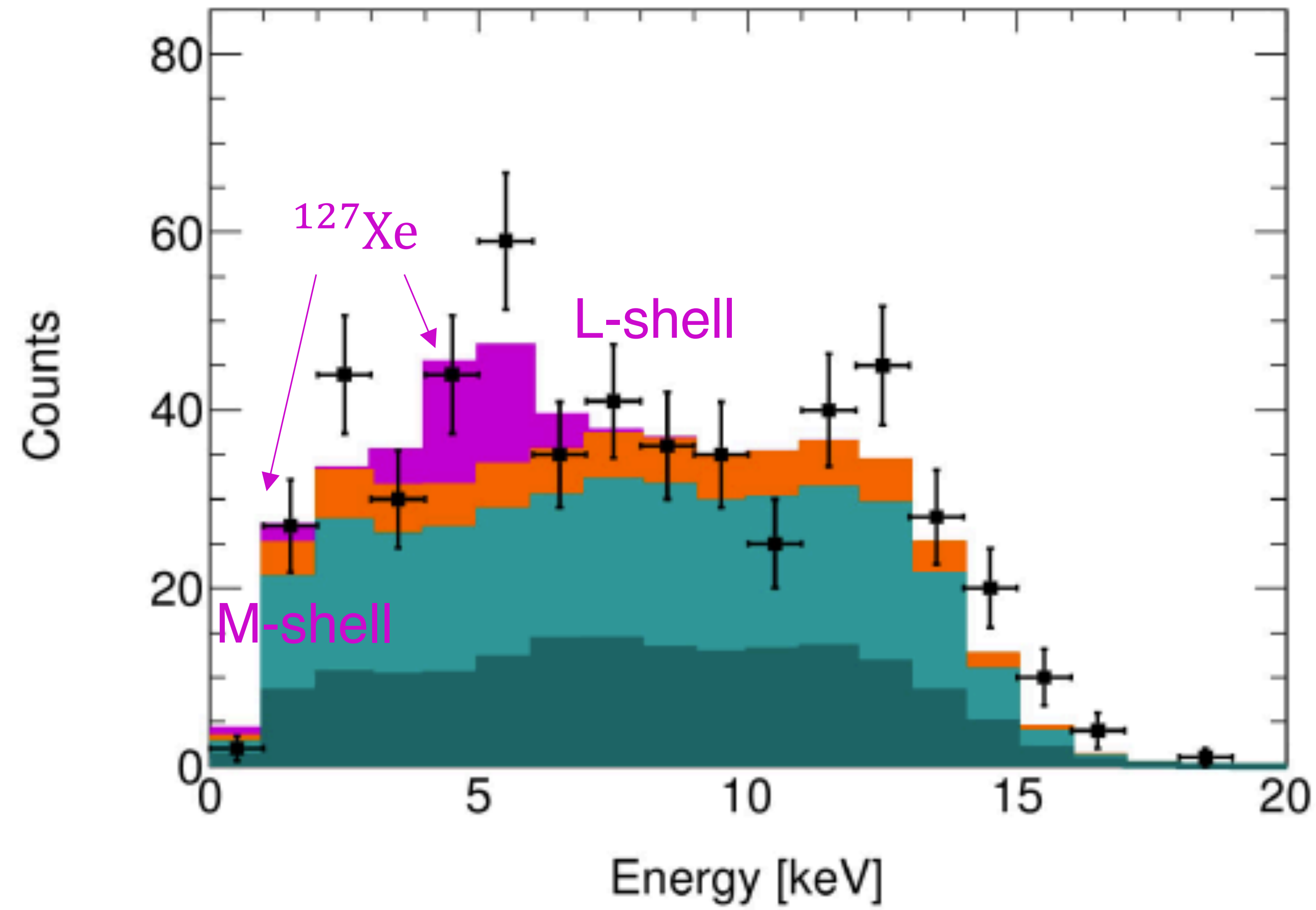


Expected excess assuming the best fit signal strength from XENON1T is compatible with their data within uncertainties, but their data are also consistent with background- only hypothesis

—> No conclusion because of lower statistics & higher BG

PandaX / LUX?





LUX Collaboration, PRL 118, 261301

low-z-origin γ rays (dark green),

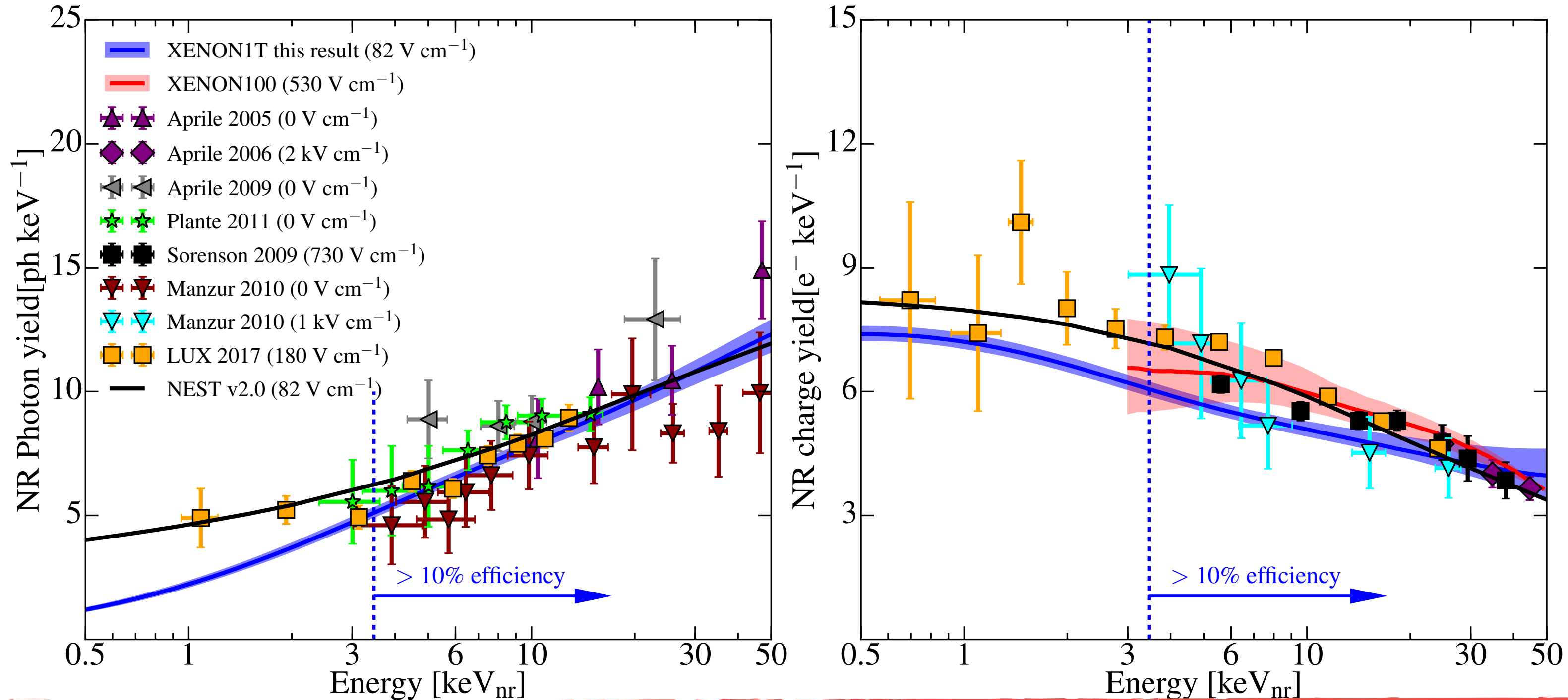
other γ rays (light green),

85Kr or Rn-daughter contaminants in the liquid xenon undergoing β decay (orange)

x rays due to 127Xe (purple).

PHOTON/CHARGE YIELD FOR ER / NR

NR

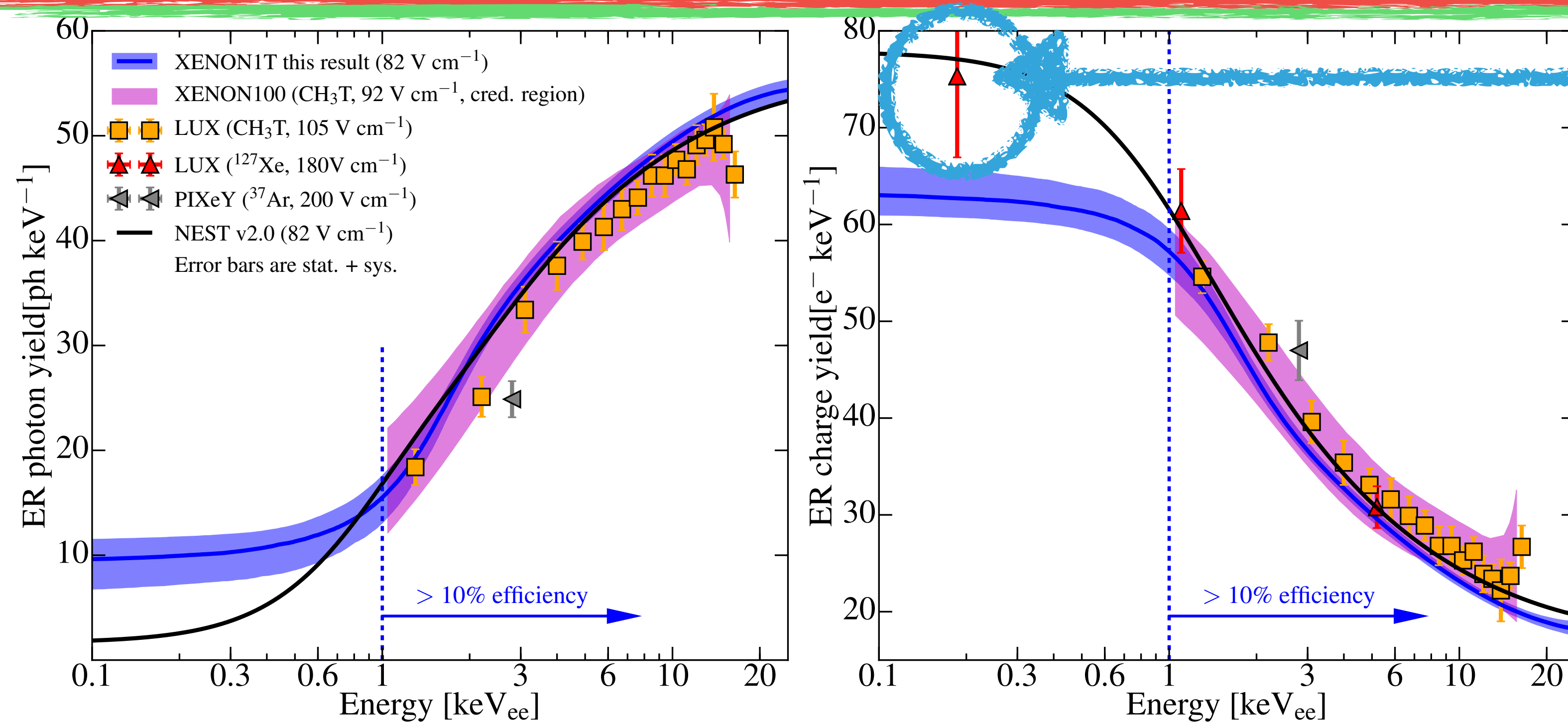


New results!

arXiv: 1902.11297

Estimated using ^{220}Rn (ER) and ^{241}Ambe / Neutron Generator (NR) calibration data.

ER



For charge yield, there is a 0.186 keVee (^{127}Xe) measurement from LUX

Phys. Rev. D **96**, 112011

1e- produces ~30 PEs.
Photo-detection eff ~ 10%

- 10% efficiency for S1&S2 analysis corresponds to energy deposit of ~1keV for ER and ~4 keV for NR
- ER signals can significantly enhance the detection efficiency —> higher sensitivity for low-mass WIMPs.
- Moreover, S2-only analysis can also decrease the threshold from 1 keVee to 0.186 keVee

QCD axion models

XENON Dark Matter Project

$$m_a \simeq \frac{6 \times 10^6 \text{ GeV}}{f_a} \text{ eV/c}^2$$

DFSZ: two Higgs doublets model
couplings to leptons at tree level

KSVZ: heavy quark model
couplings to leptons only at loop level

quarks/electrons related by Beta

photons/electrons related by E/N

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ)

Kim-Shifman-Vainshtein- Zhakharov (KSVZ)

axion-photon coupling same for both models

- relative contributions from each component can allow to distinguish between models (Primakoff dominates in KSVZ models); can also constrain β_{DFSZ}
- nuclear transition contribution always relatively small

the ABC flux is dominant in DFSZ models, while the Primakoff flux is dominant in KSVZ models.

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DFSZ: two Higgs doublets model
couplings to leptons at tree level
quarks/electrons related by Beta

$$g_{ae} = \frac{m_e}{3 f_a} \cos^2 \beta_{DFSZ}$$

$$\tan(\beta_{DFSZ}) = \left(\frac{X_u}{X_d} \right)^{1/2}$$

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ)

KSVZ: heavy quark model
couplings to leptons only at loop level
photons/electrons related by E/N

$$g_{ae} = \frac{3\alpha^2 N m_e}{2\pi f_a} \left(\frac{E}{N} \ln \frac{f_a}{m_e} - \frac{2}{3} \frac{4+z+w}{1+z+w} \ln \frac{\Lambda}{m_e} \right)$$

$$z = m_u/m_d, \quad m_{u/d}$$

$$w = m_u/m_s$$

Kim-Shifman-Vainshtein- Zhakharov (KSVZ)

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z} \right)$$

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Solar axion/ALP flux

ABC (Atomic recombination and deexcitation, Bremsstrahlung and Compton)

$$\frac{d\Phi_a}{d\omega} = \frac{1}{4\pi R_{\rm Earth}^2} \int_{\rm Sun} dV \frac{4\pi\omega^2}{(2\pi)^3} \Gamma_a^{\rm P}(\omega)$$

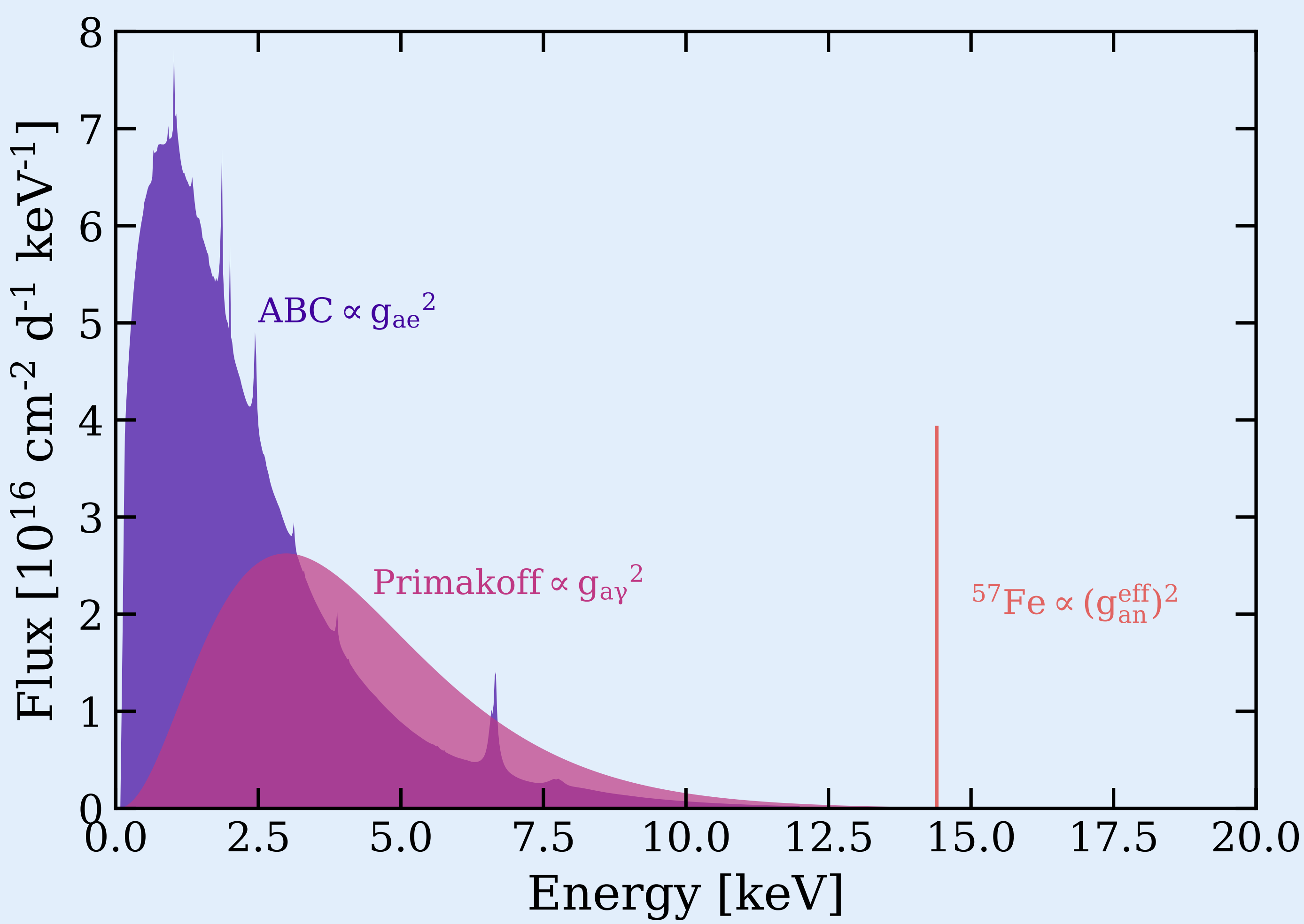
Primakoff:

$$\frac{d\Phi_a^{\rm Prim}}{dE} = \left(\frac{g_{a\gamma}}{\rm GeV^{-1}}\right)^2 \left(\frac{E_a}{\rm keV}\right)^{2.481} e^{-E_a/1.205/{\rm keV}} \times 6 \times 10^{30} \ {\rm cm^{-2}s^{-1}keV^{-1}}.$$

Fe-57 nuclear transition:

$$\Phi_a^{^{57}\rm Fe} = \left(\frac{k_a}{k_\gamma}\right)^3 \times 4.56 \times 10^{23} (g_{an}^{eff})^2 \ \ {\rm cm^{-2}s^{-1}}$$

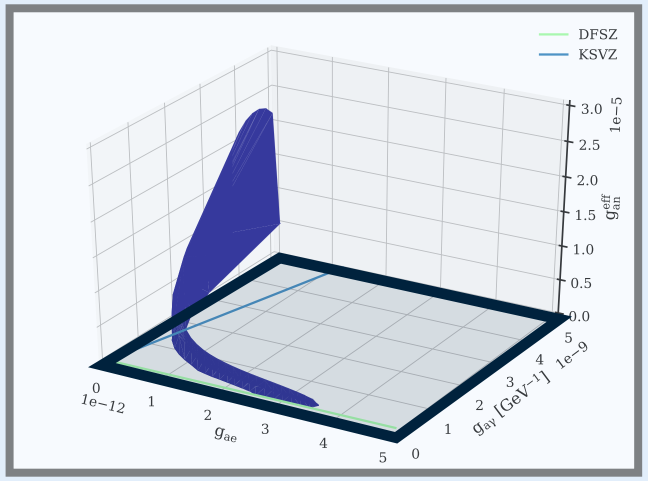
k: momenta of axion, photon



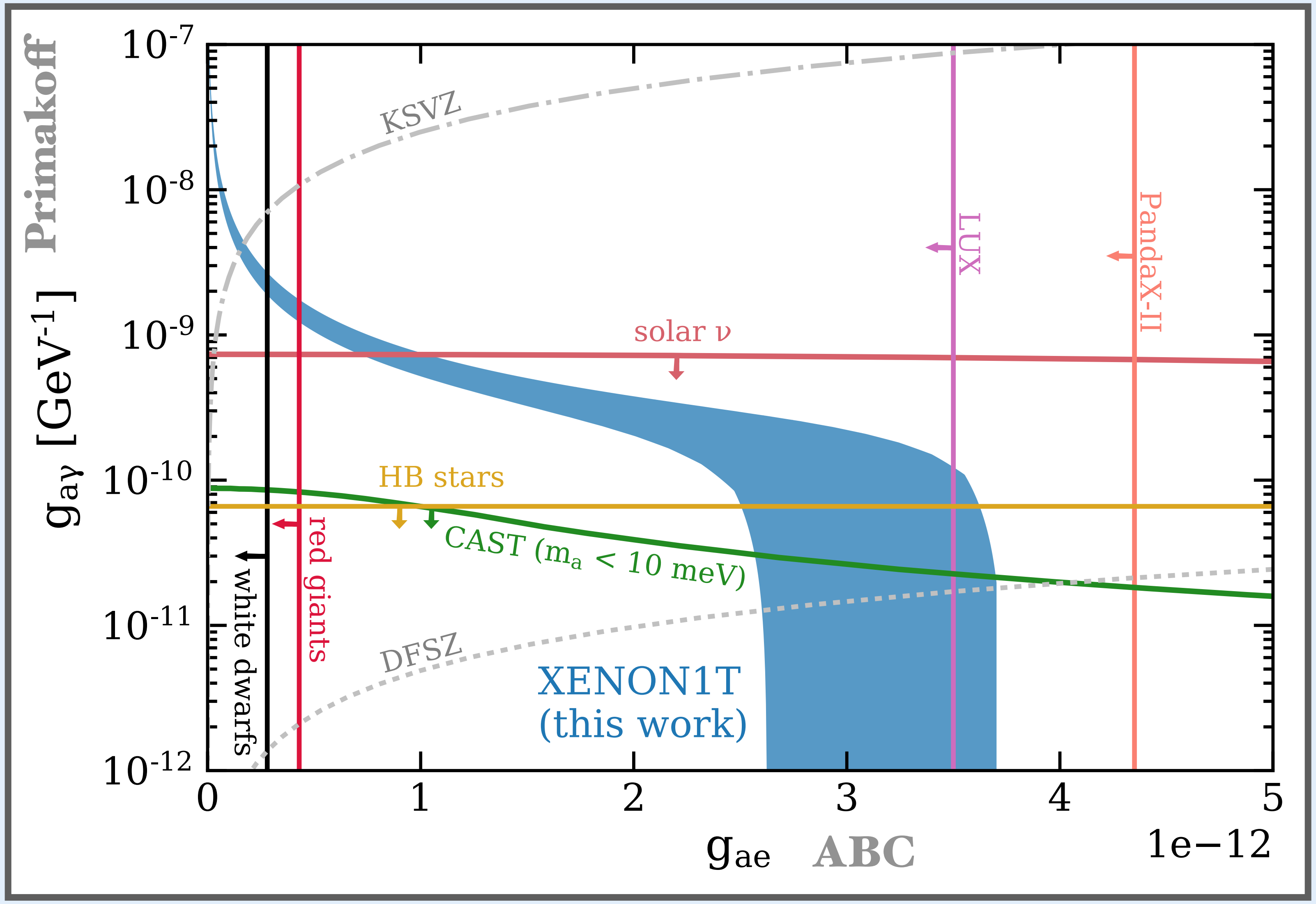
Statistical inference

3D confidence volume (90% C.L.)

Projected onto 2D regions



$$g_{ae} < 3.7 \times 10^{-12}$$
$$g_{ae} g_{an}^{eff} < 4.6 \times 10^{-18}$$
$$g_{ae} g_{a\gamma} < 7.6 \times 10^{-22}\ \text{GeV}^{-1}$$

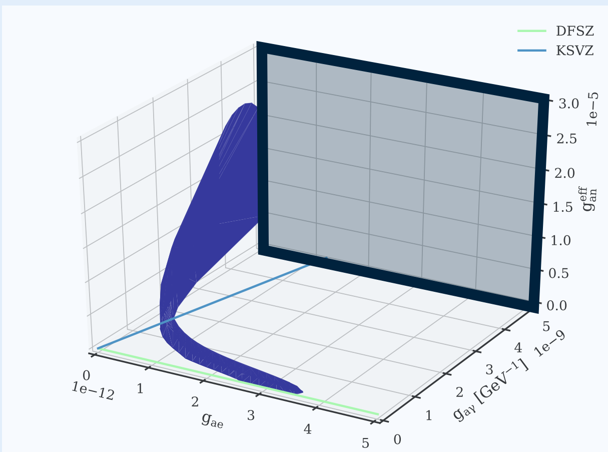


Discrepancy with astrophysical constraints from stellar cooling
(arXiv:2003.01100)

Statistical inference

Xe XENON Dark Matter Project

3D confidence volume (90% C.L.)



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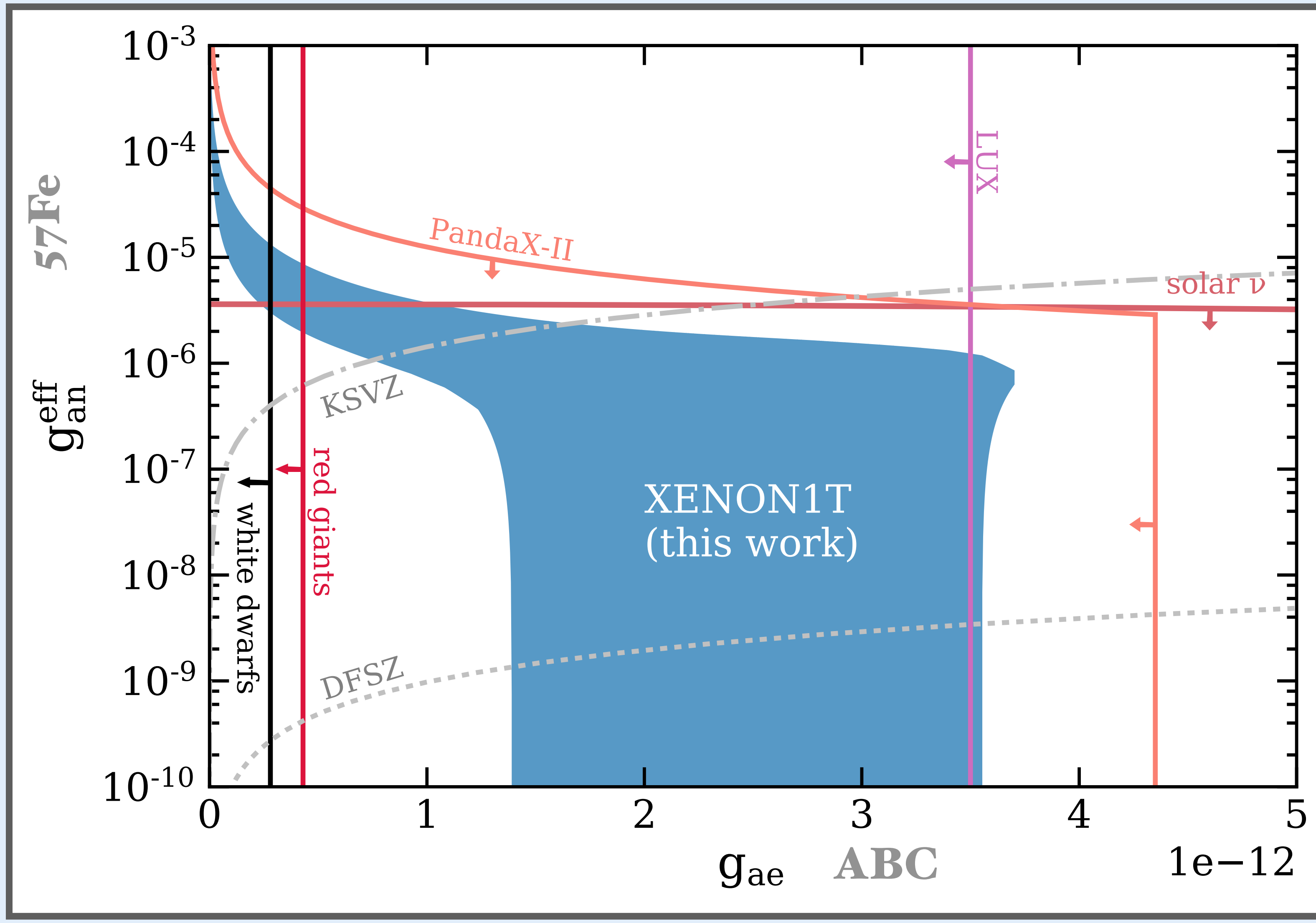
Poor fit for small ABC rate



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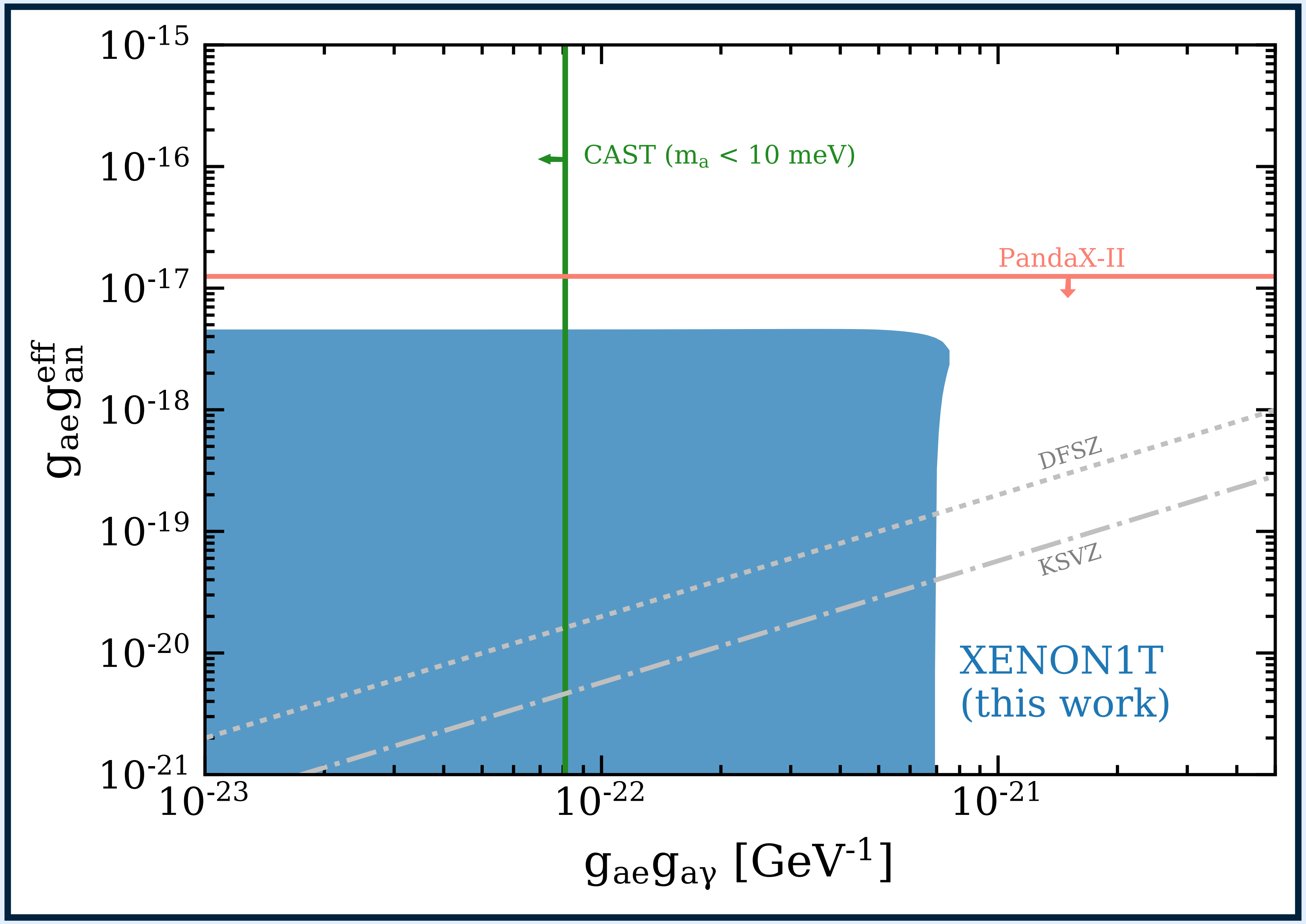
Solar axion/ALP

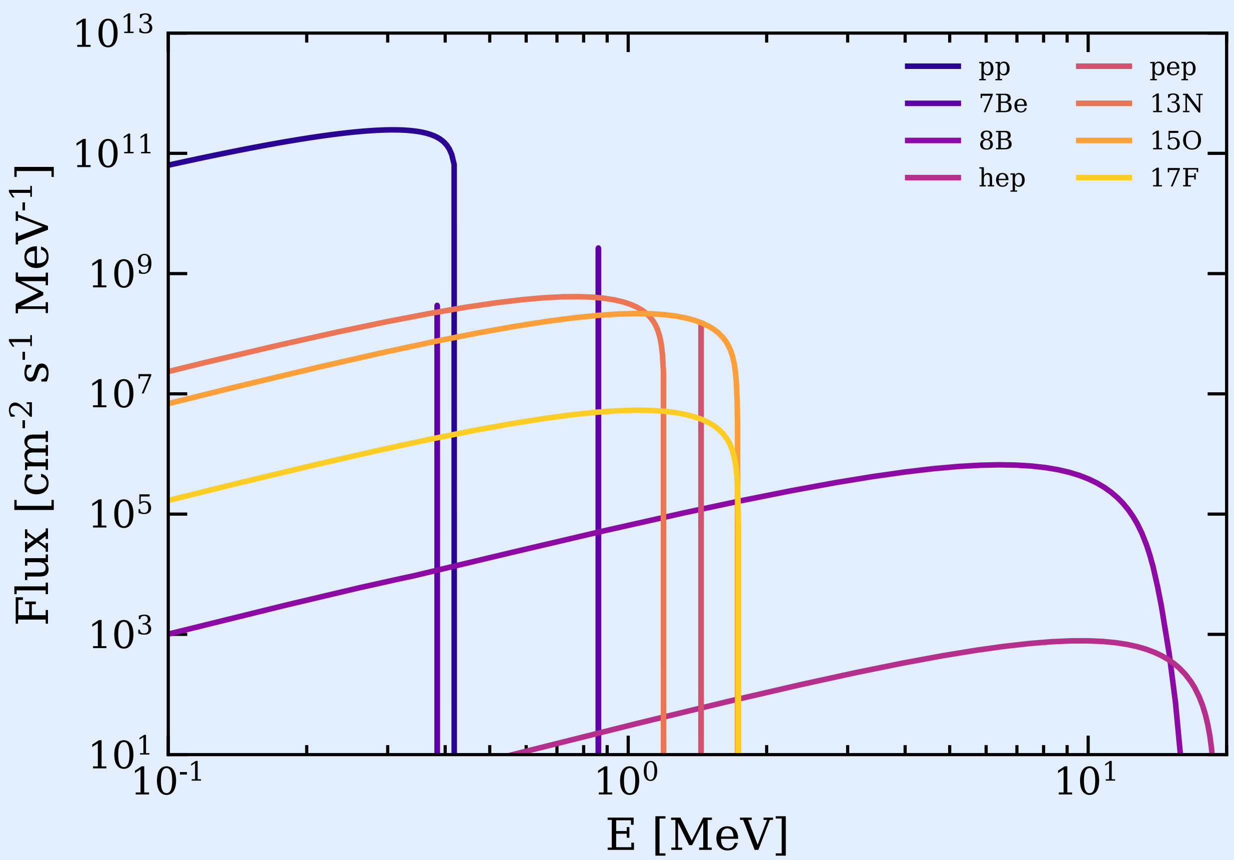
3D confidence volume (90% C.L.) Projected onto 2D regions

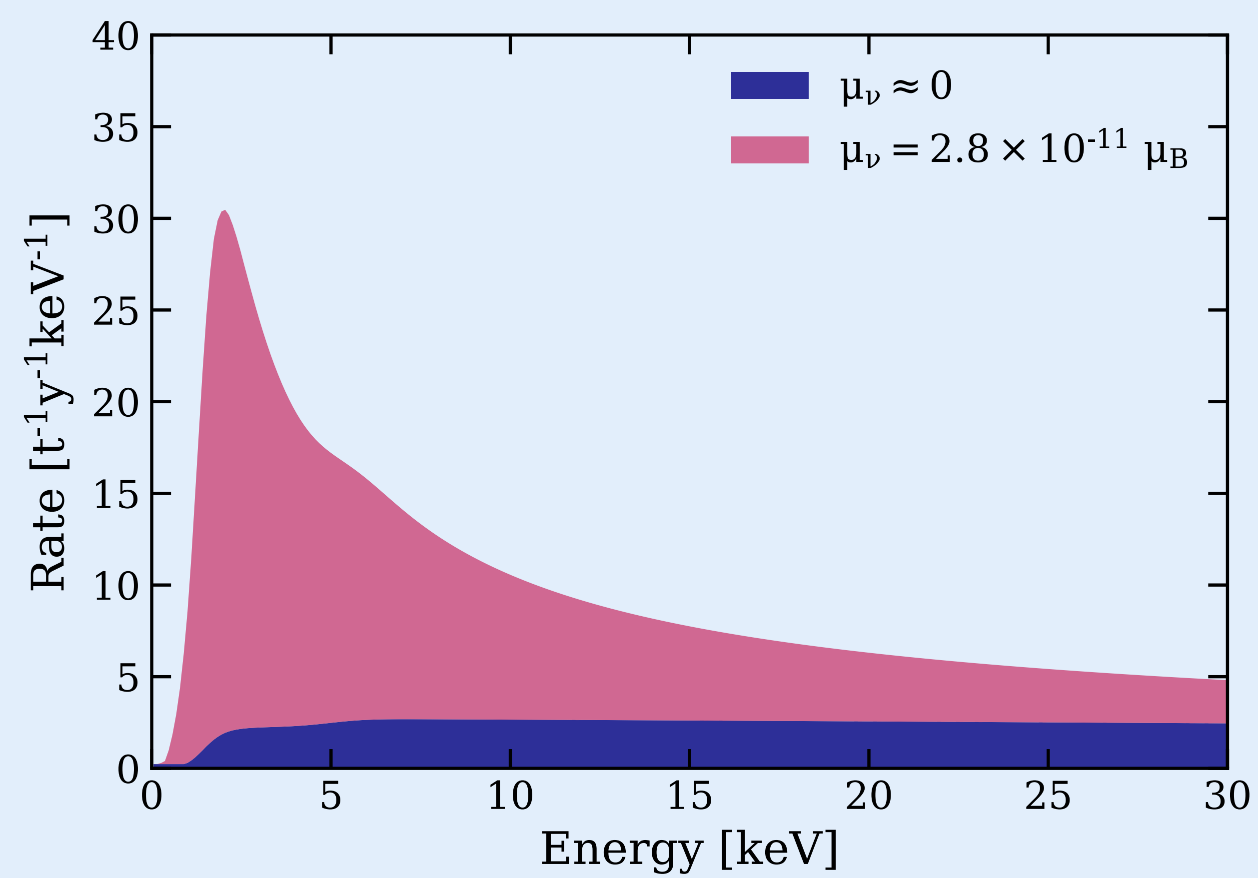


Primakoff and ^{57}Fe components can be absent *if* the ABC component is present

No statistical significance for Primakoff or ^{57}Fe on their own

Neutrino magnetic moment





$$\frac{d\sigma_\mu}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right)$$

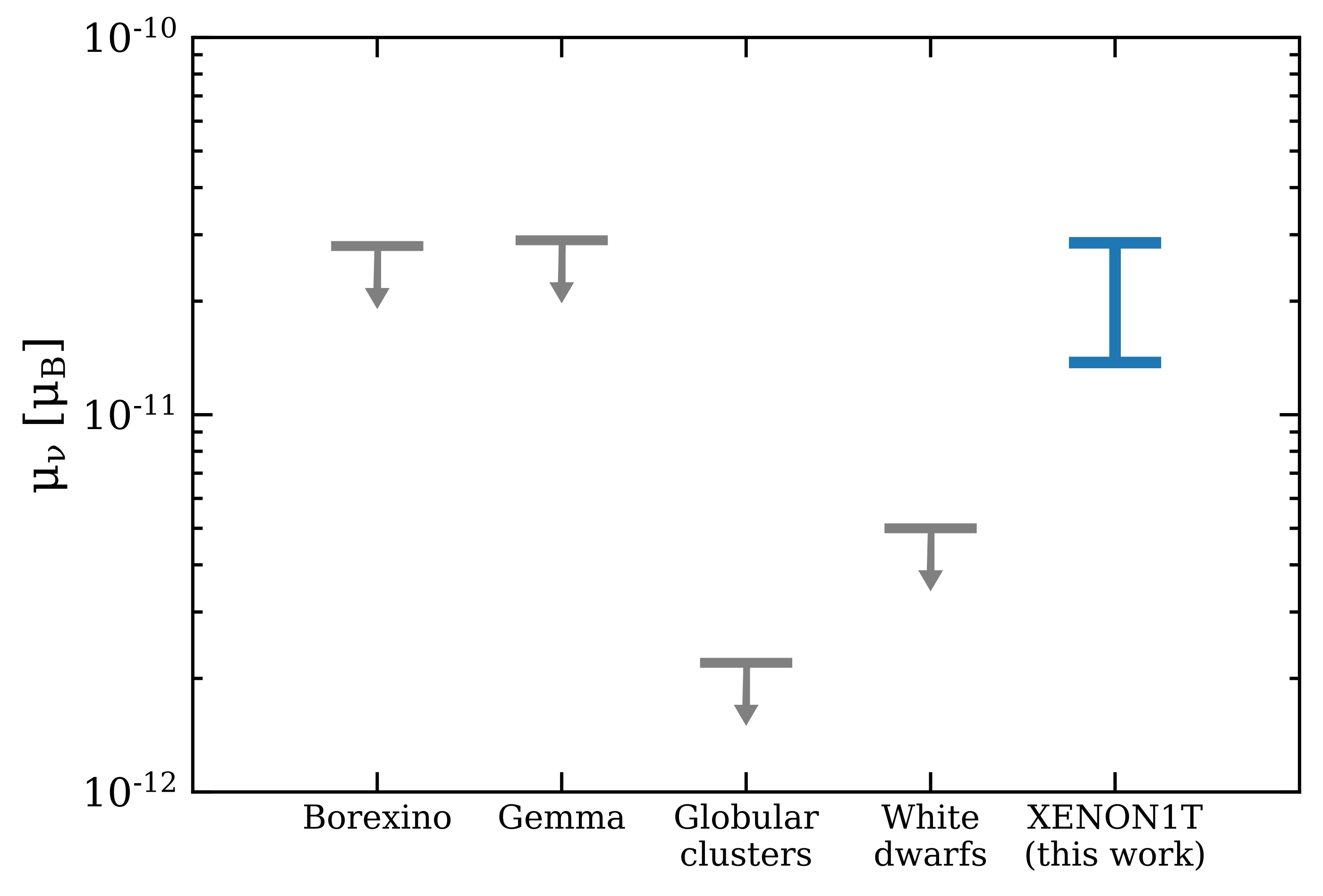
In the (extended) SM:

$$\mu_\nu \approx 3 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}} \right) \mu_B$$

A larger value would imply new physics, and possibly solve Dirac vs Majorana.

$$\mu_\nu \gtrsim 10^{-15}\ \mu_B \rightarrow$$ *Majorana fermion*

Neutrino magnetic moment



$$\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\ \mu_B$$

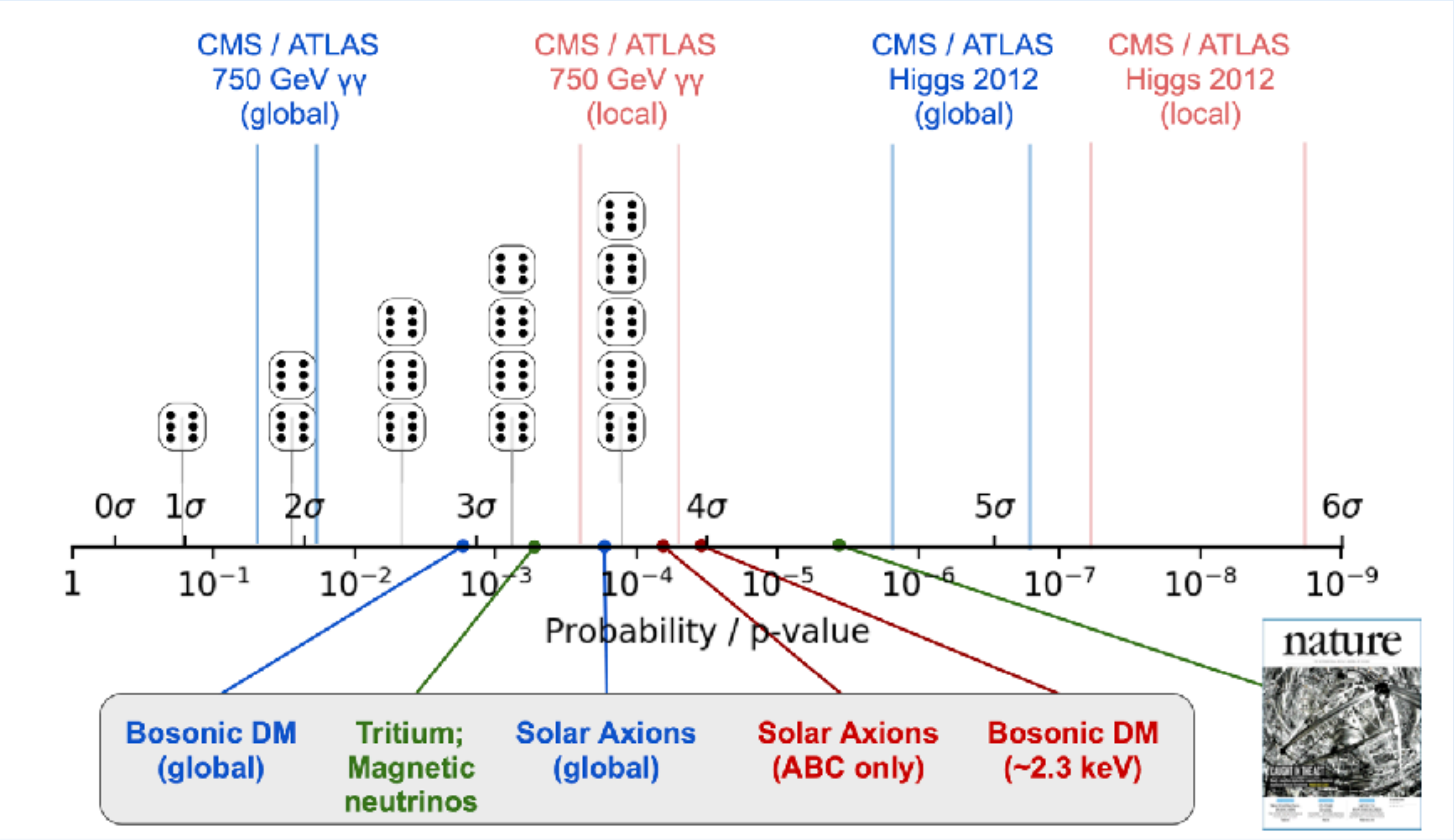
Background Fit

XENON Dark Matter Project

Component		Expected Events	Fitted Events	Constant in time? (shared across partitions)
^{214}Pb		(3450, 8530)	7480 +/- 160	YES
^{85}Kr		890 +/- 50	773 +/- 80	NO
^{136}Xe		2120 +/- 210	2150 +/- 120	YES
^{133}Xe		3900 +/- 410	4009 +/- 85	NO
^{131}Xe		23760 +/- 640	24270 +/- 150	NO
^{83m}Kr		2500 +/- 250	2671 +/- 53	NO
Materials		323 (fixed)	323 (fixed)	YES
Solar neutrino		220.7 +/- 6.6	220.8 +/- 4.7	YES
^{124}Xe	KK	125 +/- 50	113 +/- 24	YES
	KL	38 +/- 15	34.0 +/- 7.3	YES
	LL	2.8 +/- 1.1	2.56 +/- 0.55	YES
^{125}I	K	79 +/- 33	67 +/- 12	NO
	L	15.3 +/- 6.5	13.1 +/- 2.3	NO
	M	3.4 +/- 1.5	2.94 +/- 0.50	NO

unconstrained in the fit (dashed boxes: ^{214}Pb, ^{124}Xe)

Probabilities



slide credit: Jelle Aalbers