Low-mass dark matter searches with XENON1T

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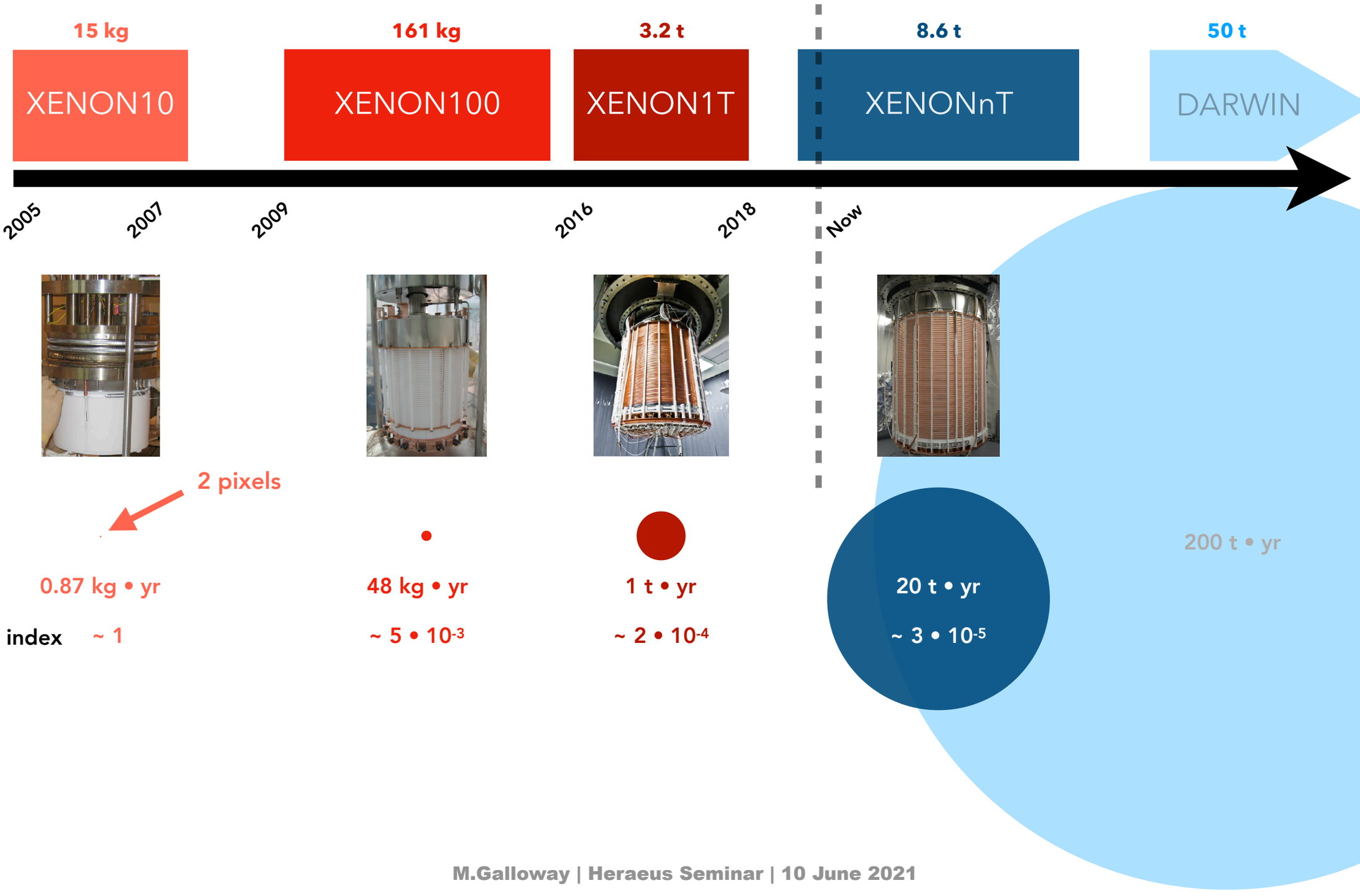
Heraeus Seminar, 10 June 2021

Outline

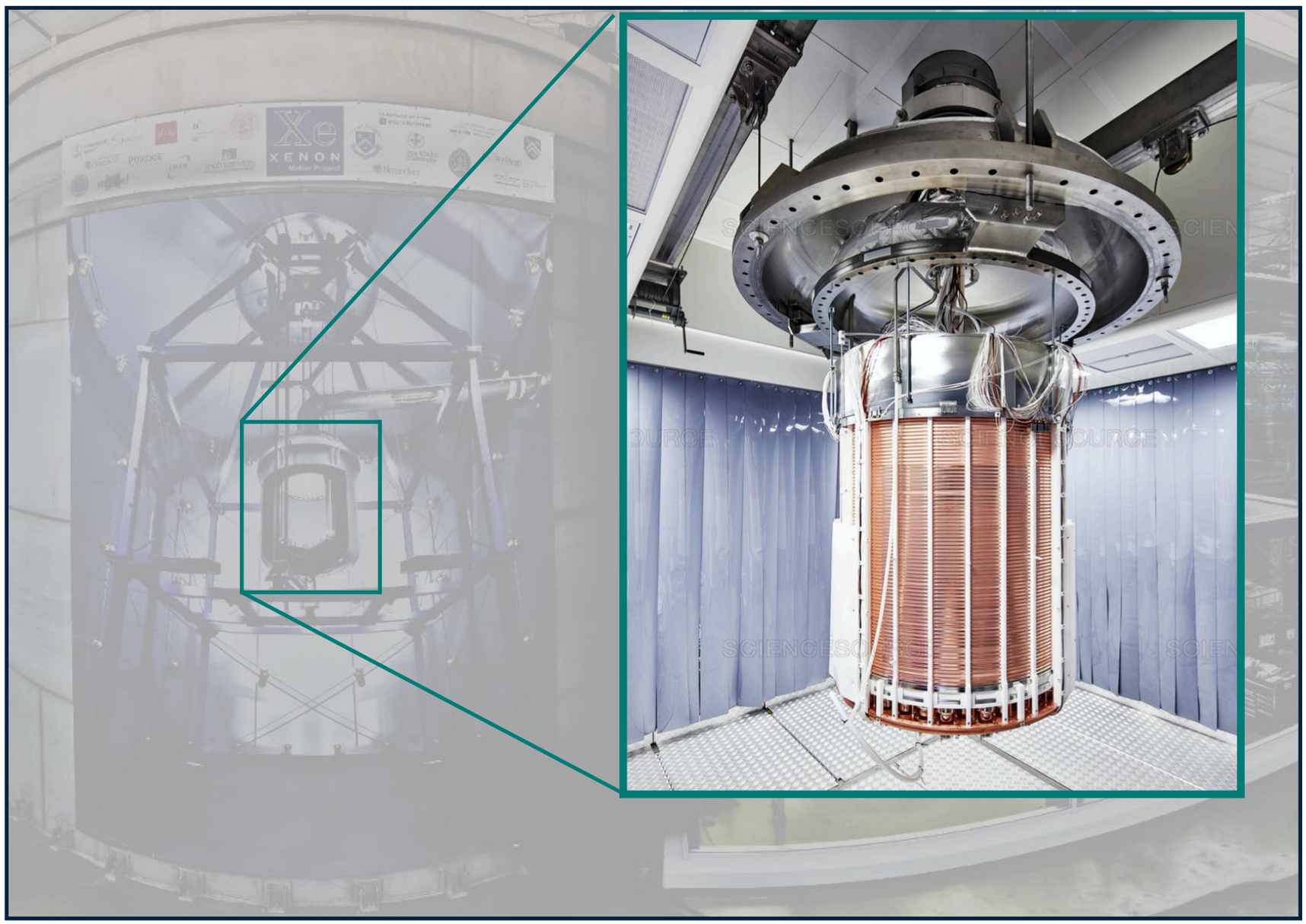
- The XENON program and detection method
- lowering the threshold
- reaching light DM via electronic recoils
- detection of an excess
- the next steps: XENONnT

The XENON experiment

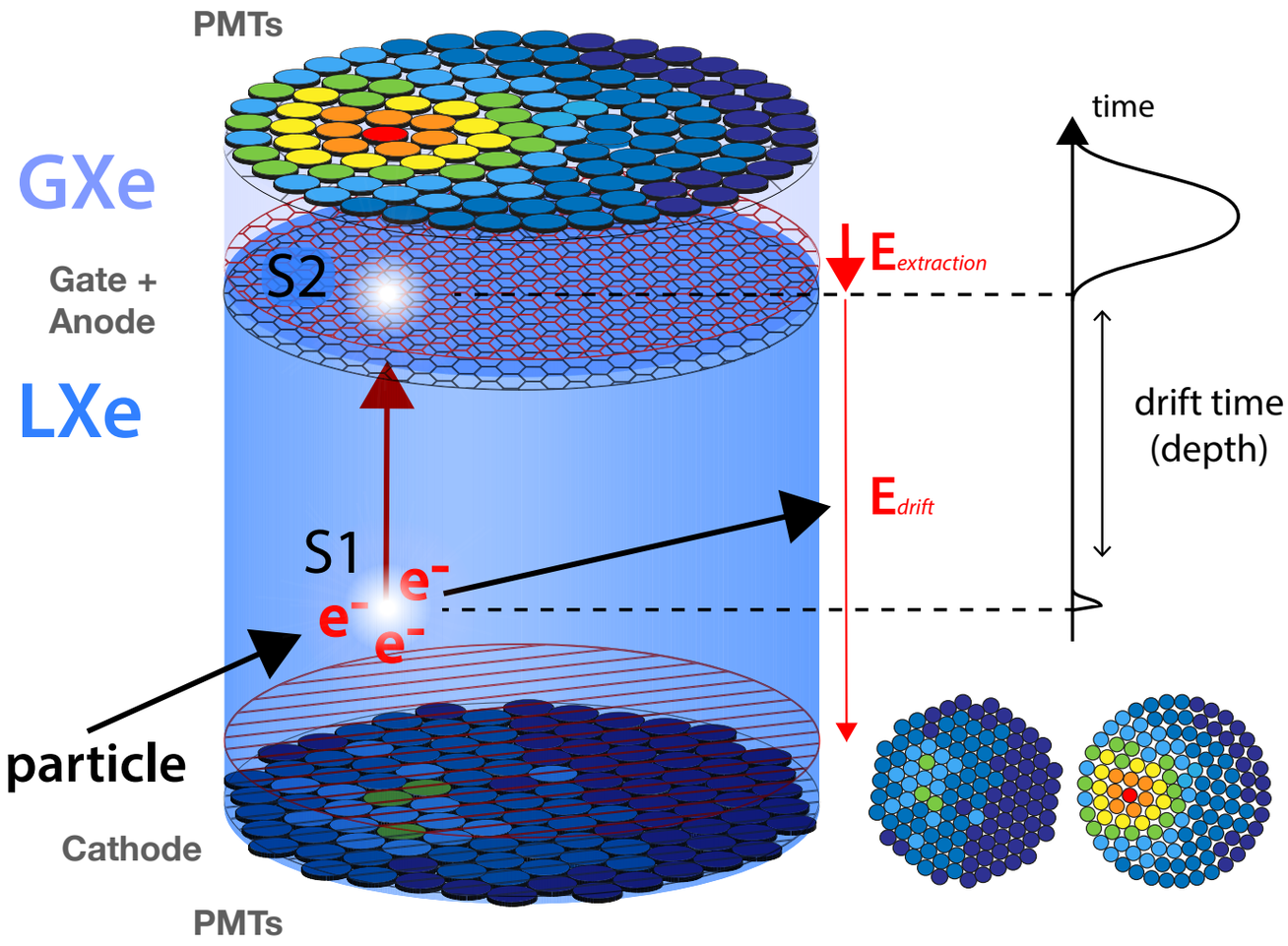


The XENON experiment

Laboratori Nazionali del Gran Sasso



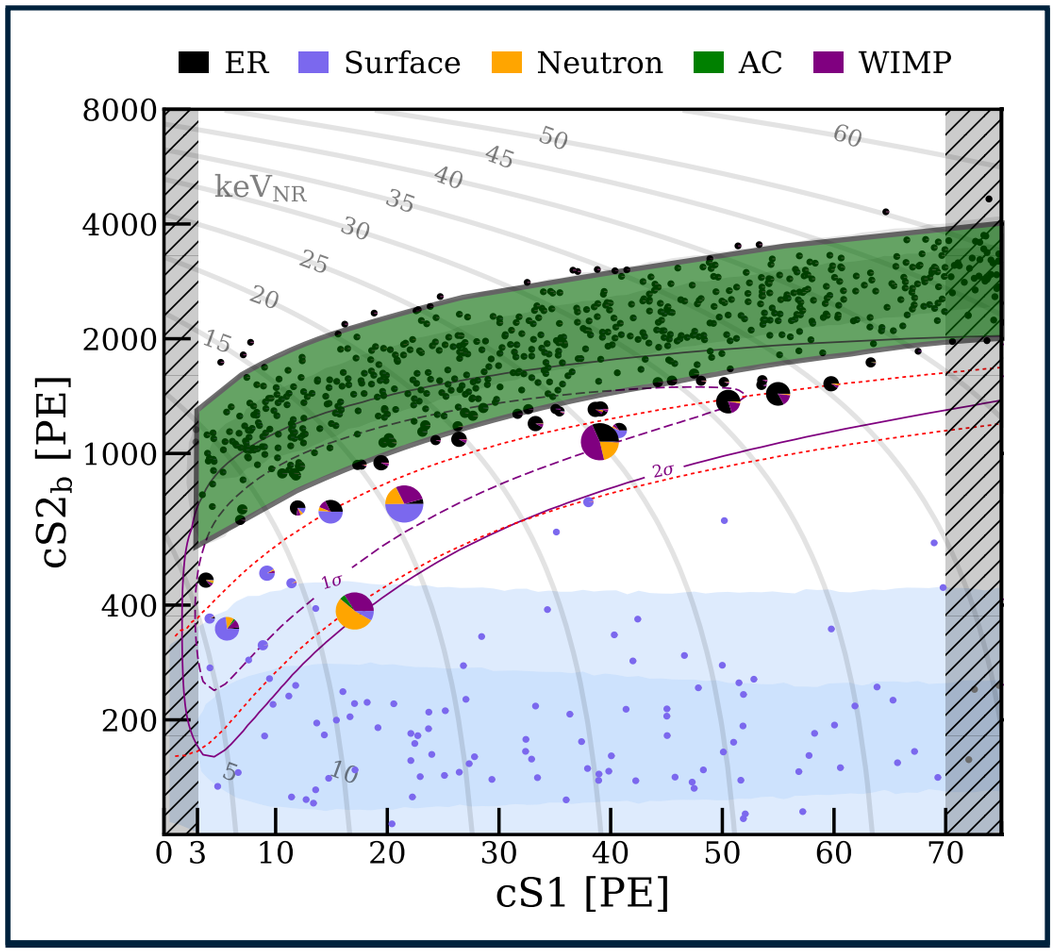
Time Projection Chamber



Scintillation and **ionization:**

- Prompt light signal (**S1**)
- Secondary light in GXe from drifted charges (**S2**)
- Position reconstruction (**x, y, z**), calorimetry (**E**) and interaction type (Response difference between Electronic Recoil (**ER**) and Nuclear Recoil (**NR**) events

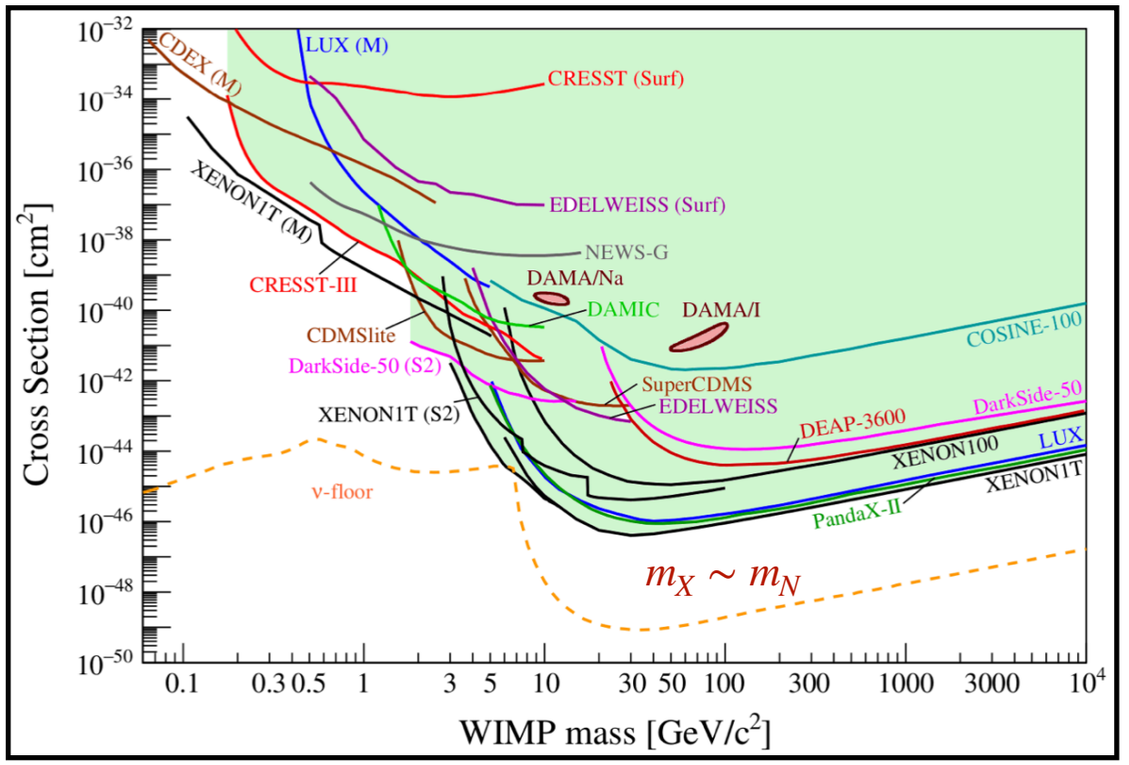
Towards light DM



Electronic Recoils (ER)

(gammas, betas, light DM)

< 100 events/(t/yr/keV$_{ee}$)



arXiv:2104.07634

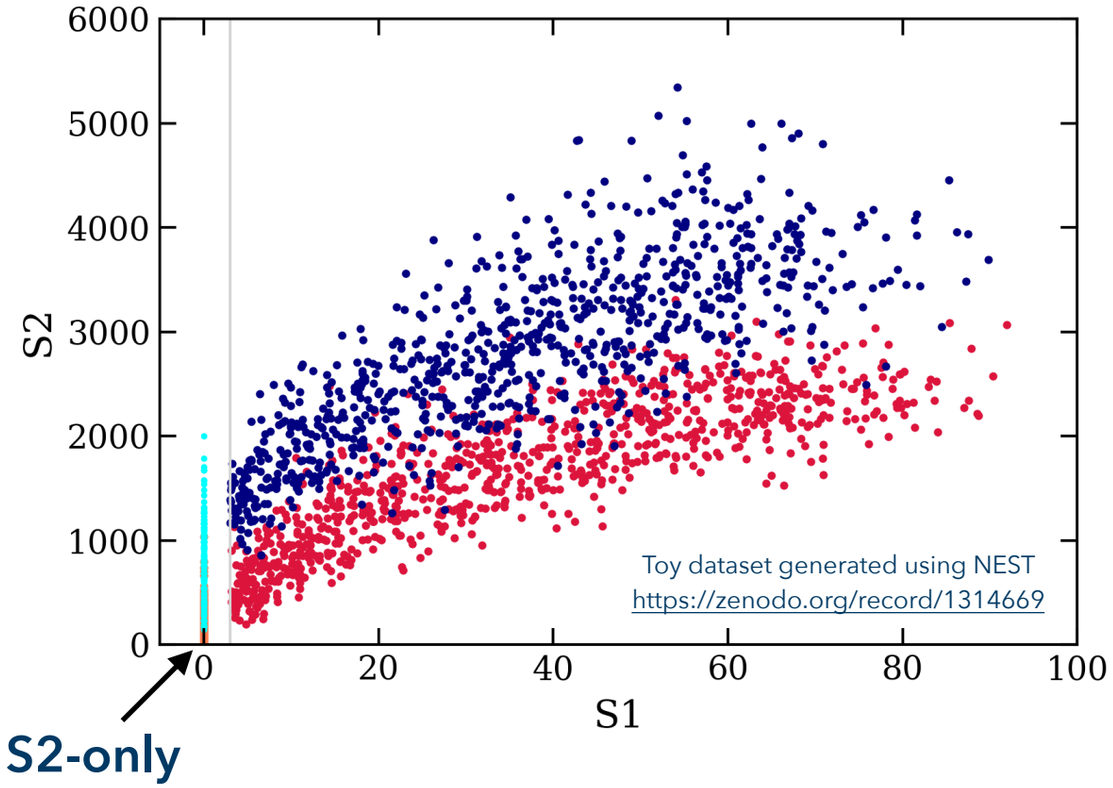
Current status of spin-independent direct searches

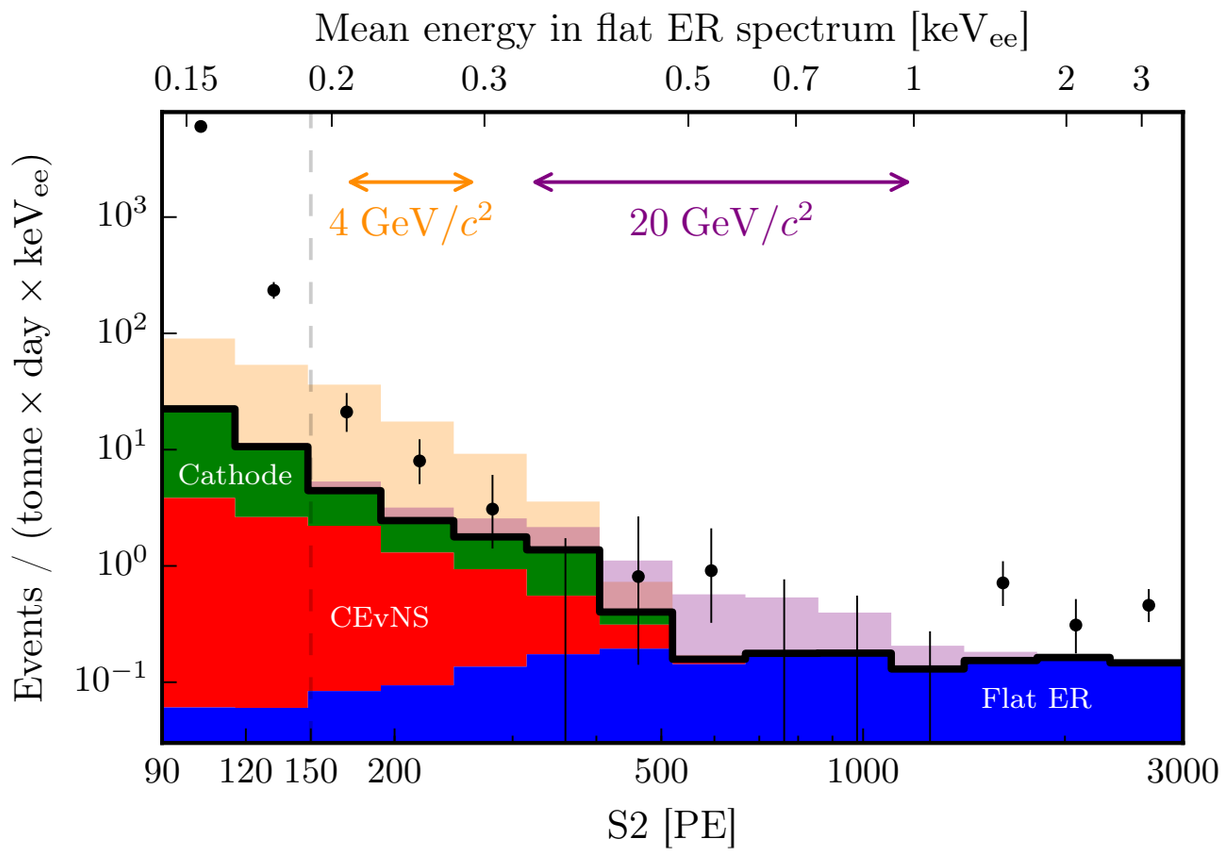
XENON1T result on WIMP DM down to 3 GeV

- Lower the coincidence (threshold) requirement
- "S2-only" (drop the S1 requirement - no Particle ID)
- "S2-only" with Migdal effect
- Other (e.g. Xe doping – possibly in the future)

Search for excess above known ER backgrounds.

S2-only

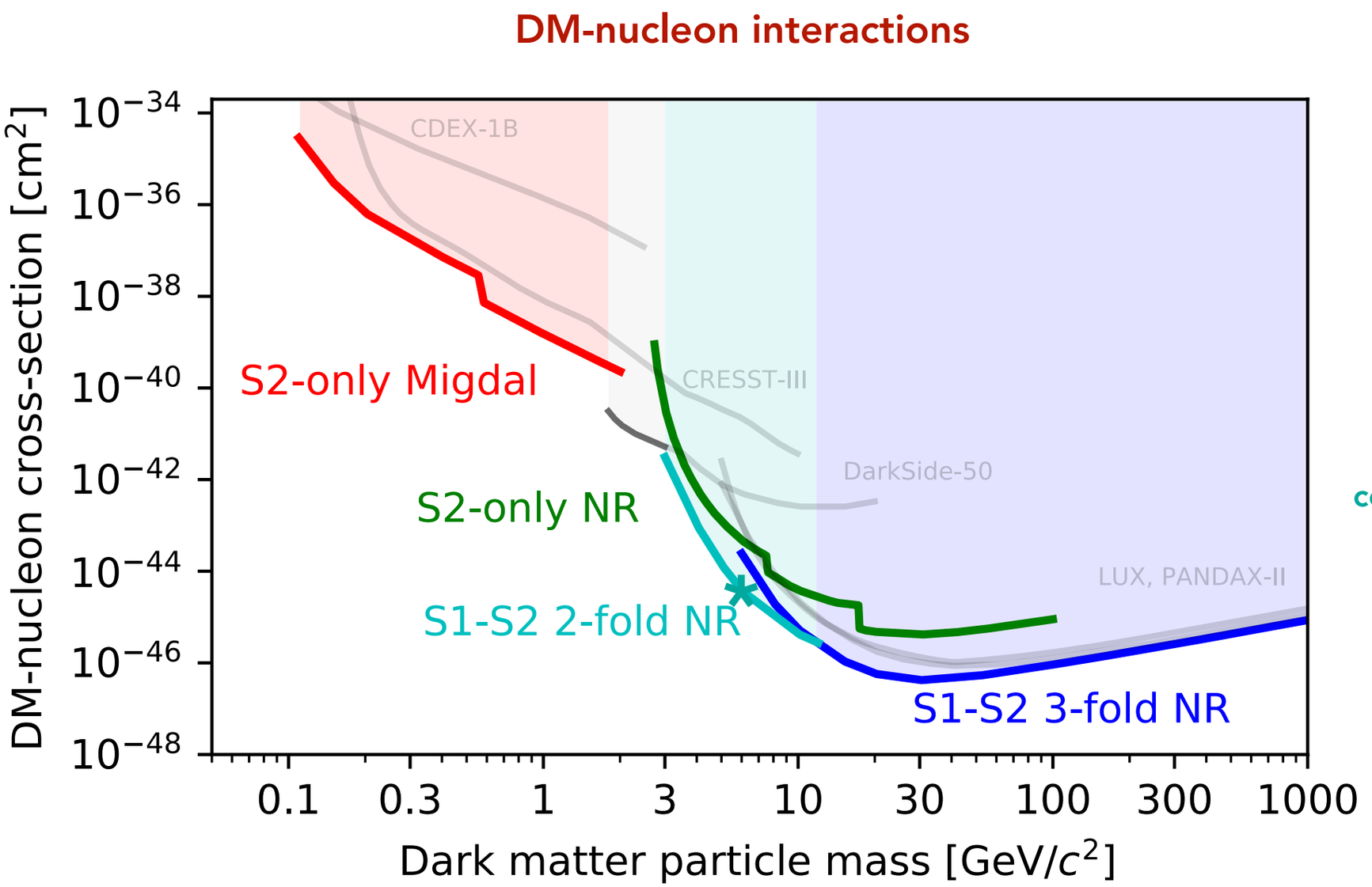




Phys. Rev. Lett. 123 (2019) 251801

- Only ionisation channel is used
- O(100 eV) energy threshold
- **Limit-setting only** (no PID)
- More systematic, unmodelled and/or **unknown backgrounds** (particularly single and few electrons)
- 30% training data + cuts on S2-width

Full reach

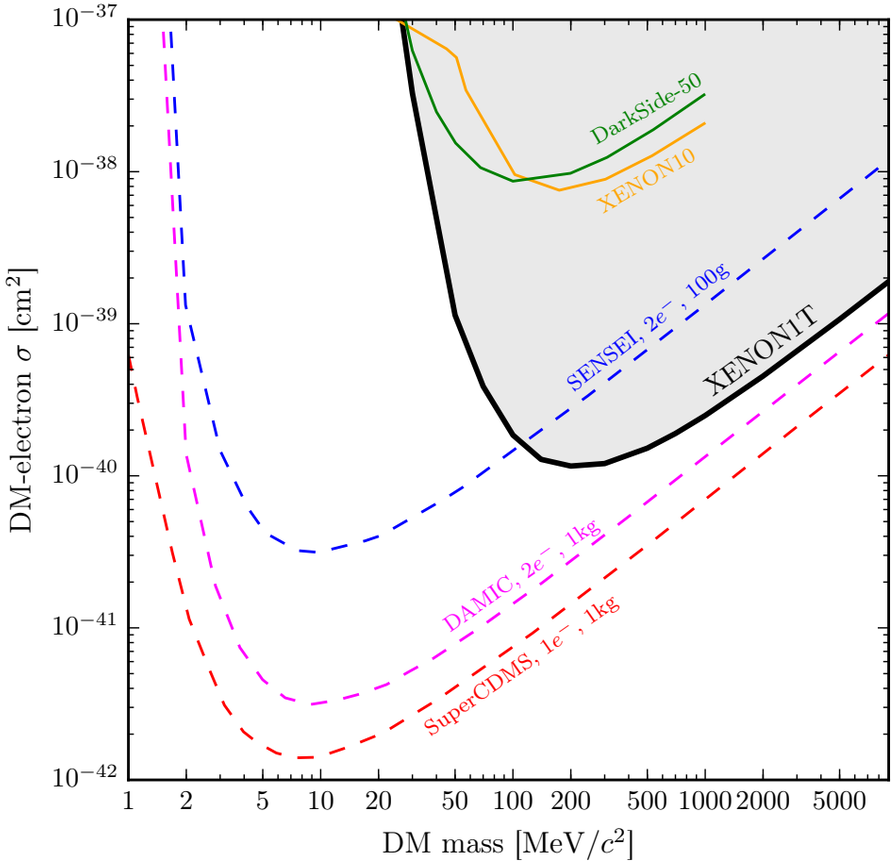


*drop 3-fold PMT coincidence requirement (discovery potential)

Phys. Rev. Lett. 126 (2021) 091301

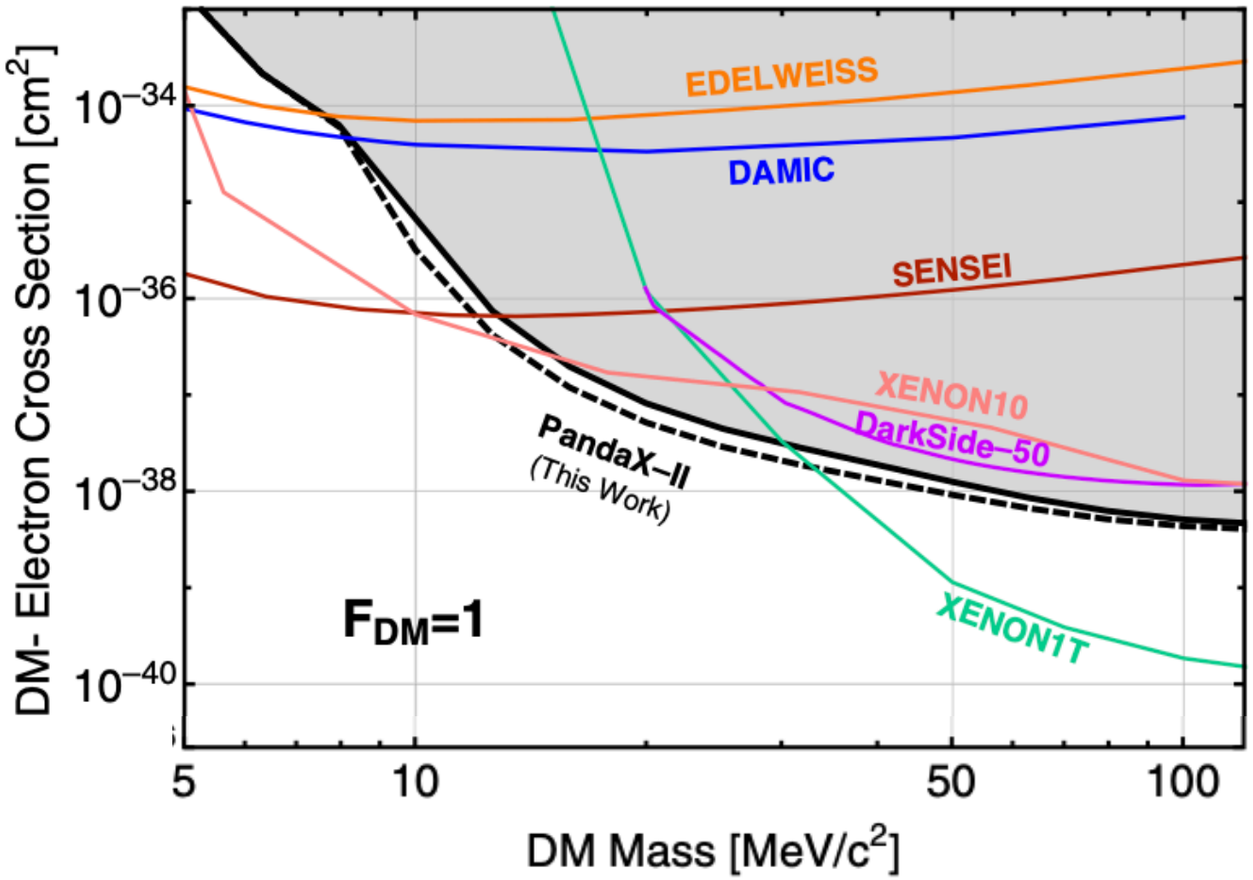
S2-only

DM-electron interactions (limits only)



XENON

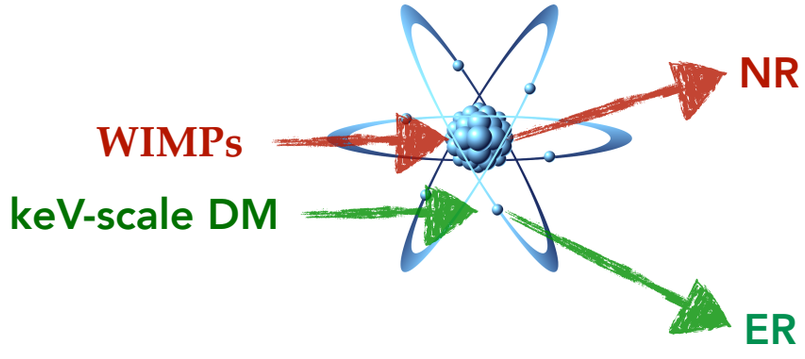
Phys. Rev. Lett. 123 (2019) 251801



PandaX-II

Phys. Rev. Lett. 126 (2021) 211803

Electronic recoils with discovery potential

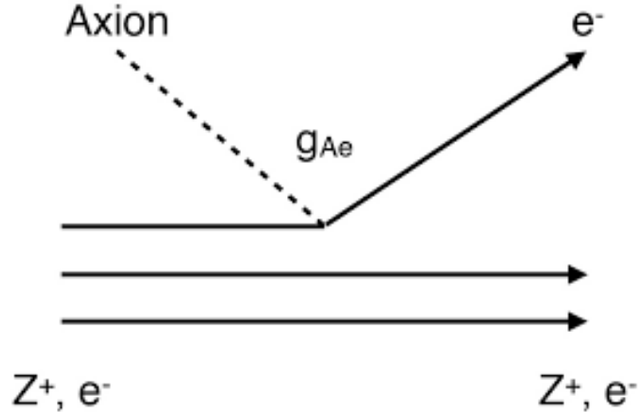


Bosonic dark matter

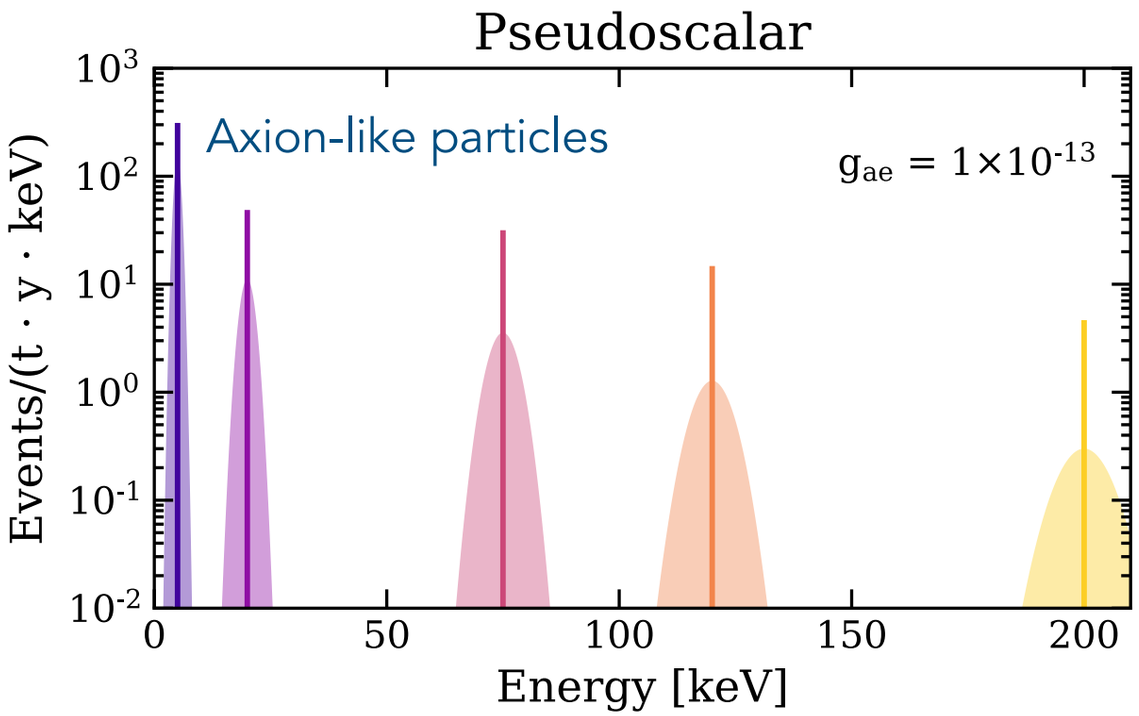
- Can constitute all galactic DM (0.3 GeV/cm^3)
- Non-relativistic (v~10^{-3}c)
- Deposited energy is rest mass of particle

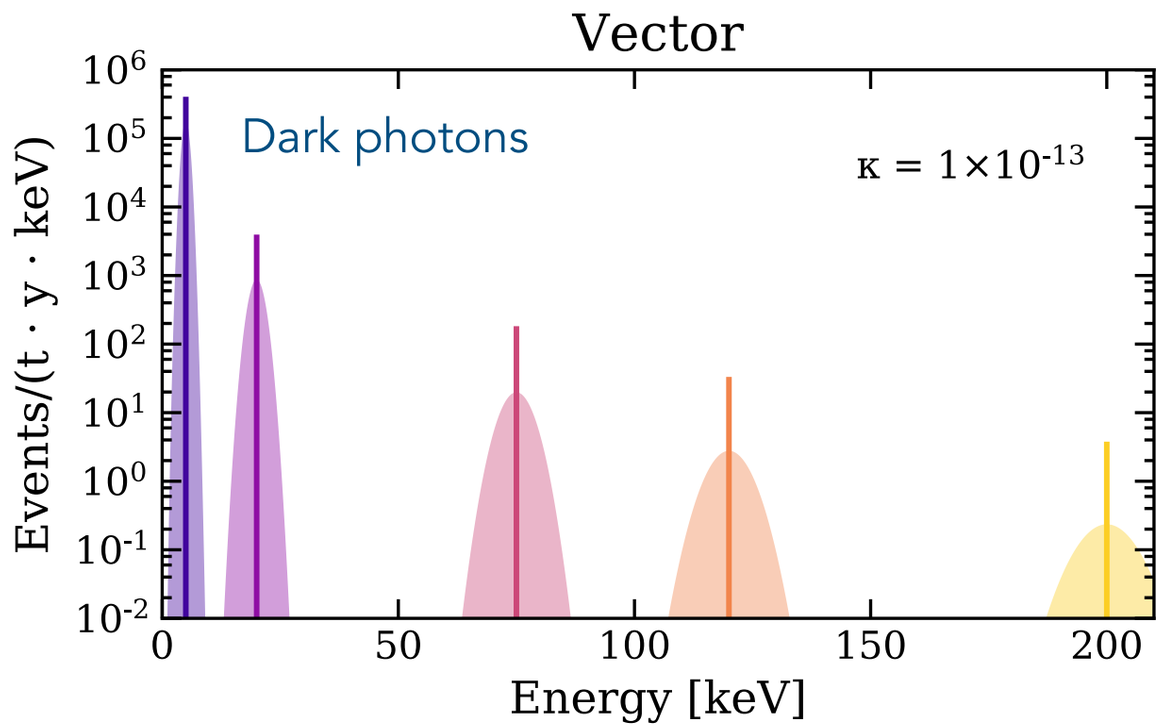
- Pseudoscalar DM couples to SM axial current
- Vector DM couples to SM photons via kinetic mixing
- Absorption cross section is proportional to photoelectric cross section

Detection via axioelectric effect



Bosonic dark matter





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

Axioelectric cross section

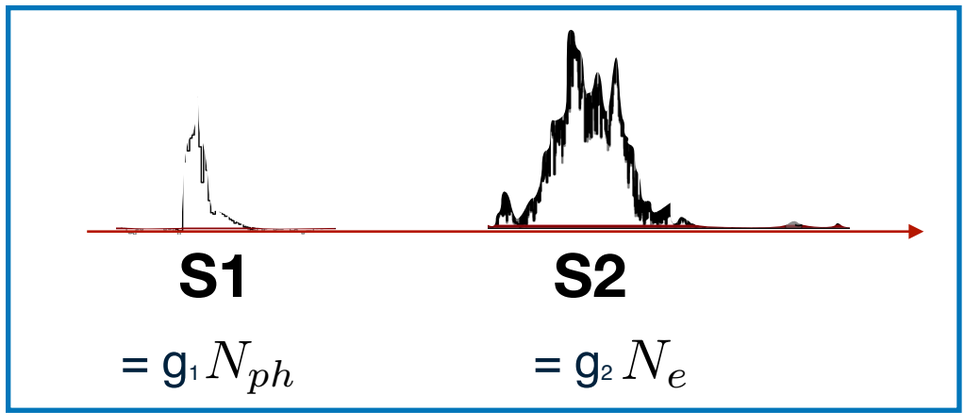
$$\sigma_{\mathrm{ae}} = \sigma_{\mathrm{pe}}\frac{g_{\mathrm{ae}}^2}{\beta}\frac{3E_{\mathrm{a}}^2}{16\pi\alpha m_{\mathrm{e}}^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

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

Kinetic mixing with SM photons

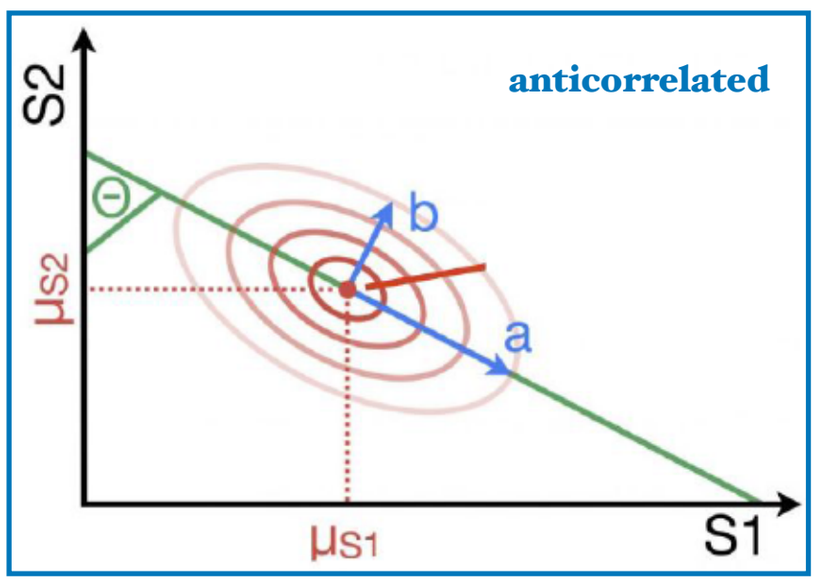
$$\sigma_{\mathrm{V}} \simeq \frac{\sigma_{\mathrm{pe}}}{\beta}\kappa^2$$

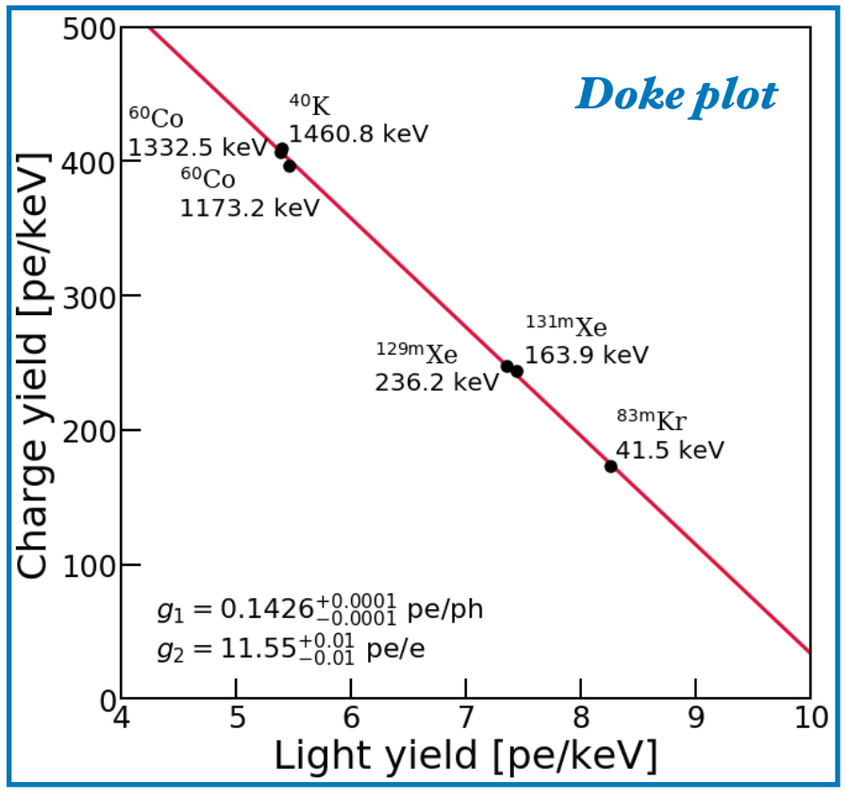
Combined energy scale



$$E = (N_{ph} + N_e) \cdot W$$

with *W*-value = 13.7 eV/quanta for xenon





$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

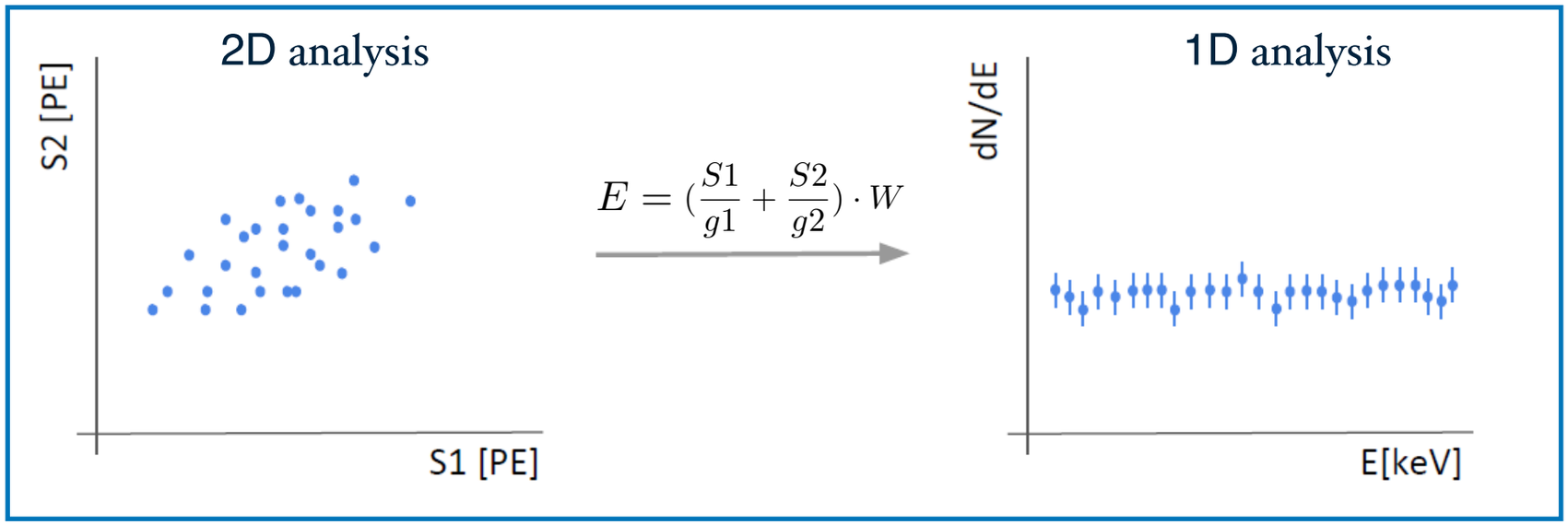
g₁ and **g₂**:

detector-specific gain constants

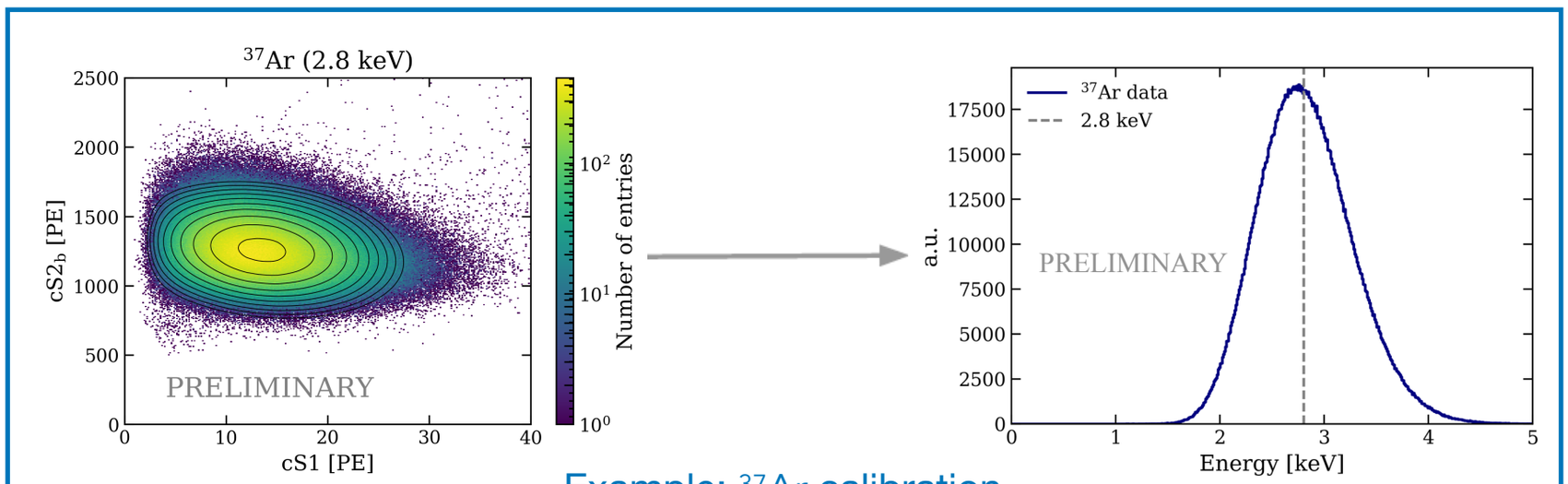
extract g_1/g_2 from calibration data

can reconstruct energy of each event

Energy reconstruction

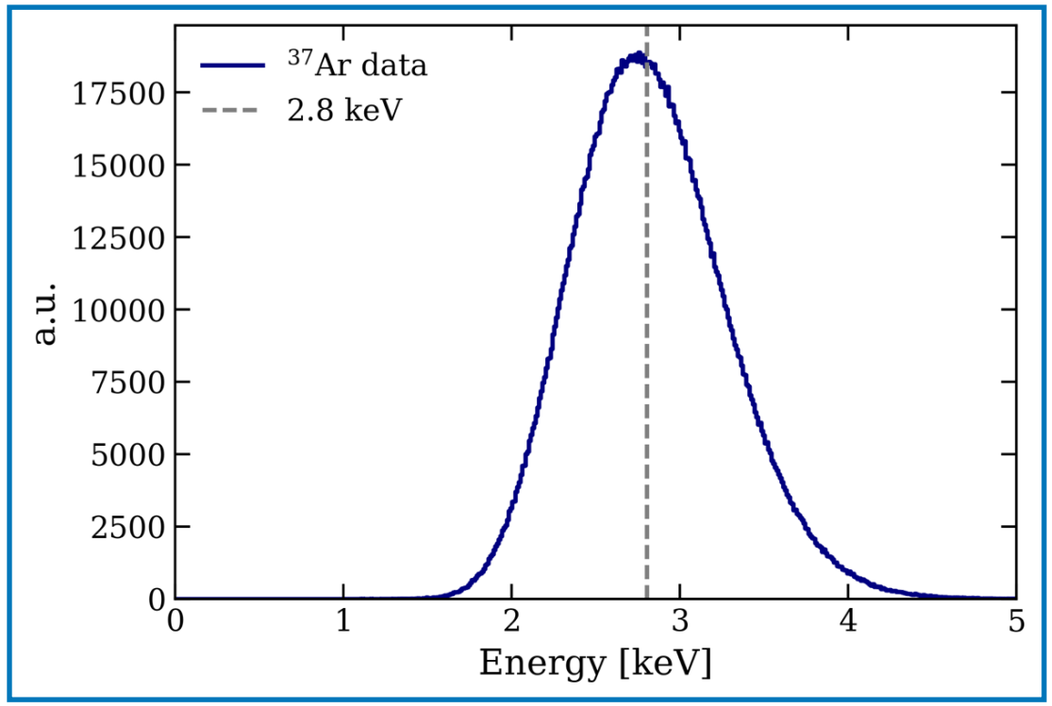


S2/S1 space | **Combined Energy Scale**



Example: ^{37}Ar calibration

Energy resolution

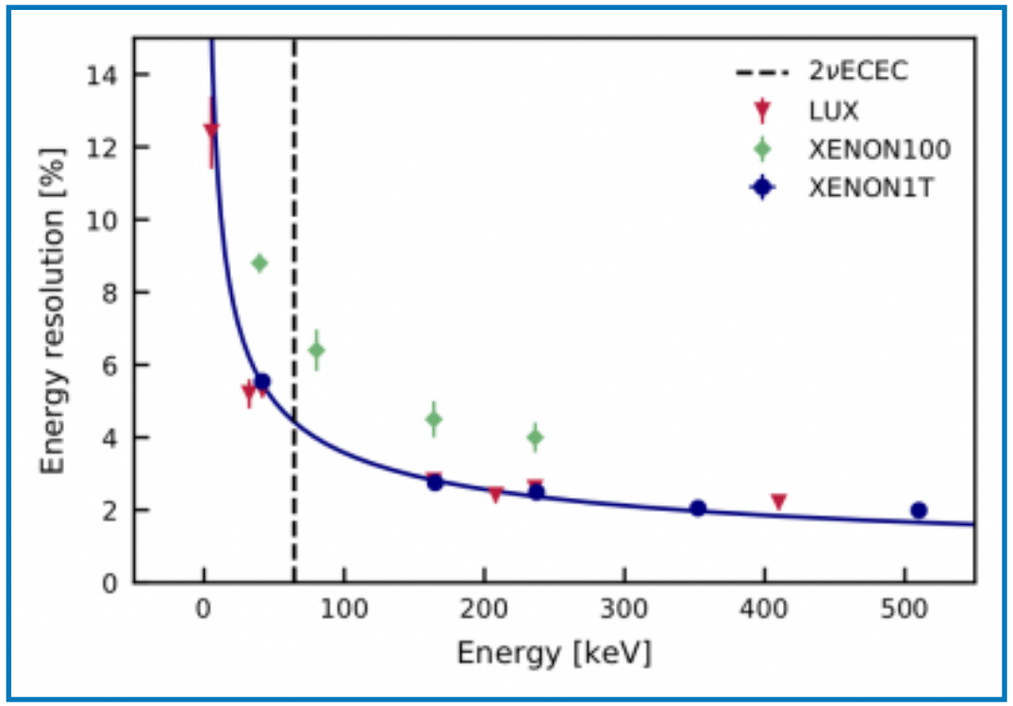


^{37}Ar 2.8 keV reconstructed peak

Mean energy

Observed: 2.827 keV

Model: 2.834 keV



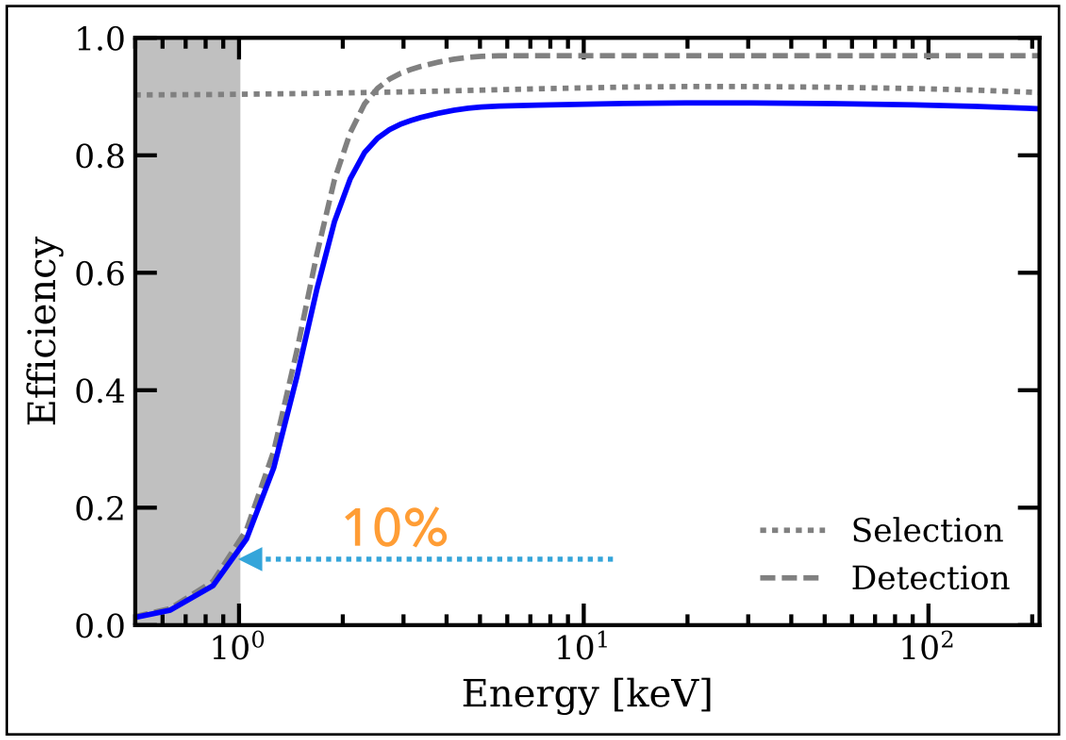
Energy Resolution

^{37}Ar Resolution

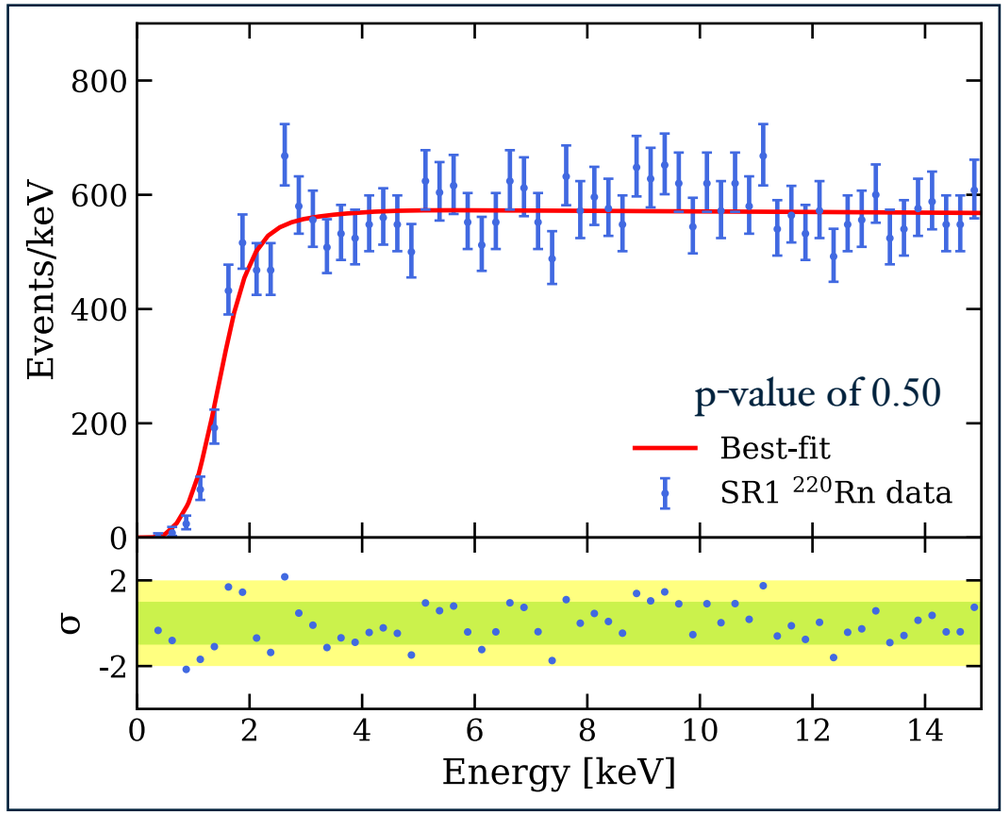
Observed: 18.12%

Model: 18.88%

Threshold and efficiency



- S1: 3-fold PMT coincidence; S2 500 pe threshold
- single-scatter (rare) events only
- **1 keV** threshold at **10%** efficiency
- uncertainty on efficiency added as nuisance parameter

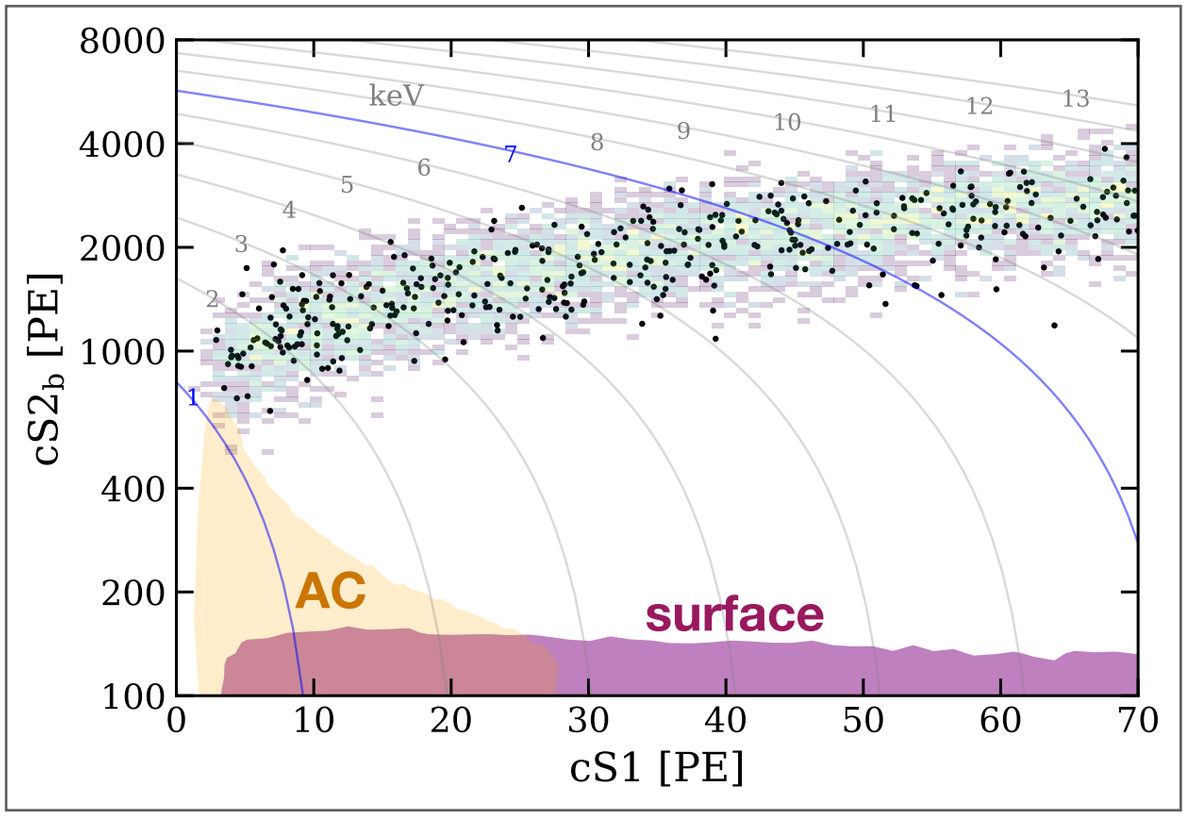


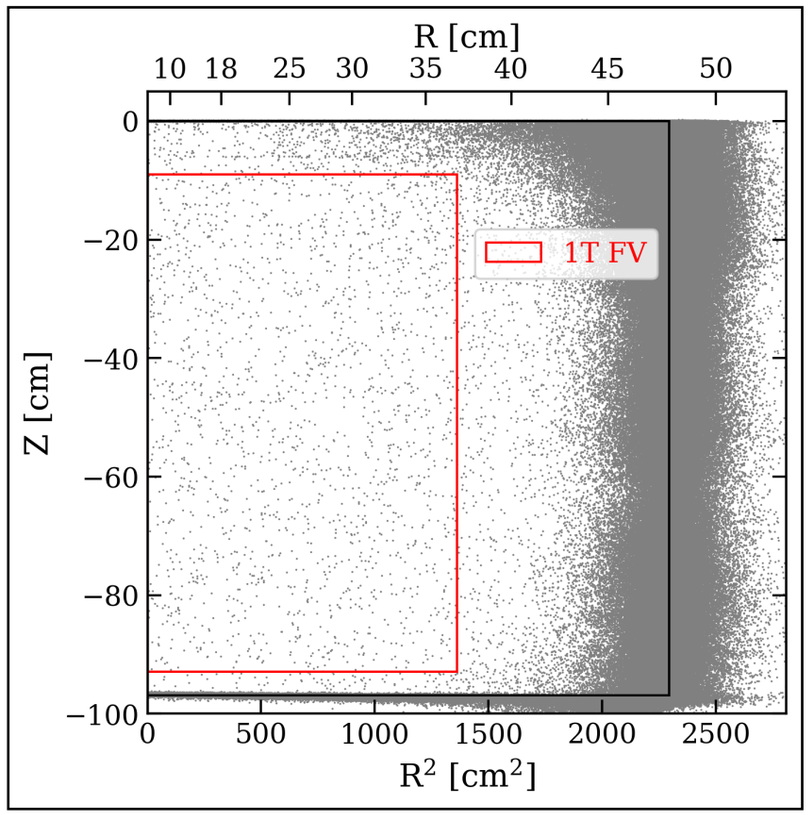
Fit to ^{220}Rn calibration data

All signal and background models are convolved with efficiency and energy resolution.

Fits use unbinned profile likelihood method.

Data selection





Instrumental backgrounds → **Fiducial volume 1042 kg**

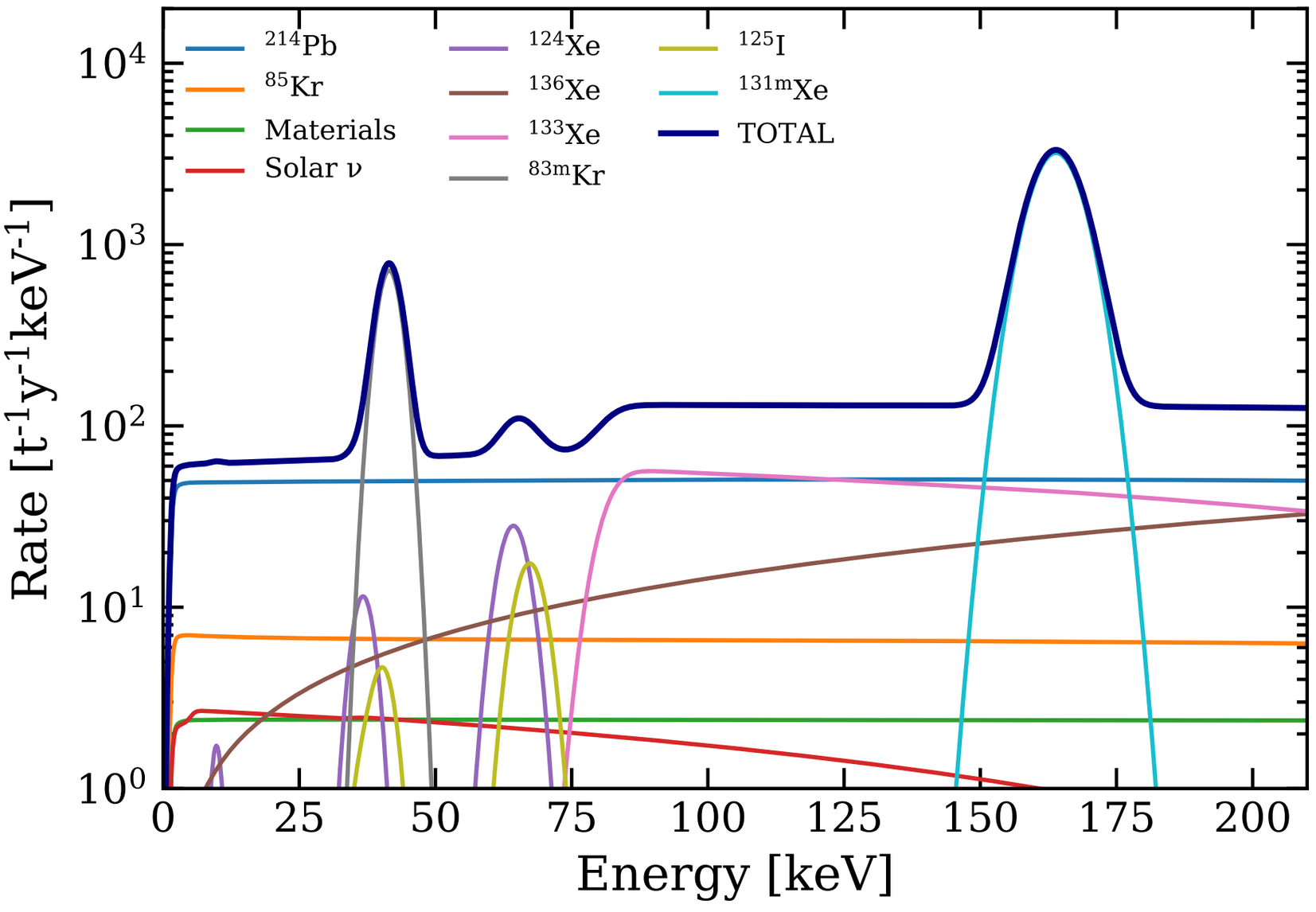
Accidental coincidences (AC) and surface backgrounds removed with fiducial volume cut

Science Run 1 (SR1)

226.9 days

0.65 tonne-yr exposure

ER background model



Intrinsic

^{214}Pb ^{136}Xe

^{85}Kr ^{124}Xe

Neutron activated

^{131m}Xe ($T_{1/2}$ = 11.9 d)

^{133}Xe ($T_{1/2}$ = 5.3 d)

^{125}I ($T_{1/2}$ = 60 d)

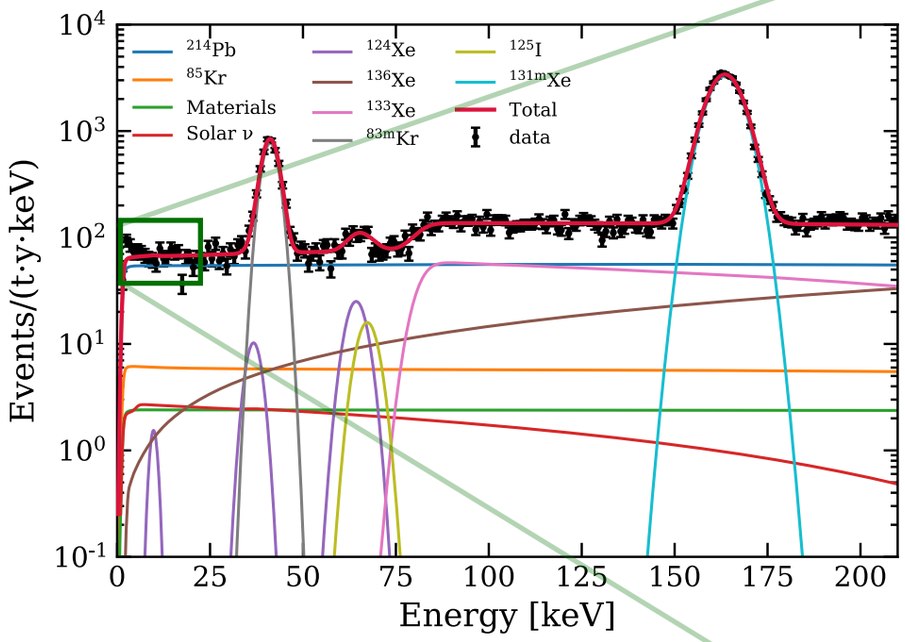
Materials

Solar neutrinos

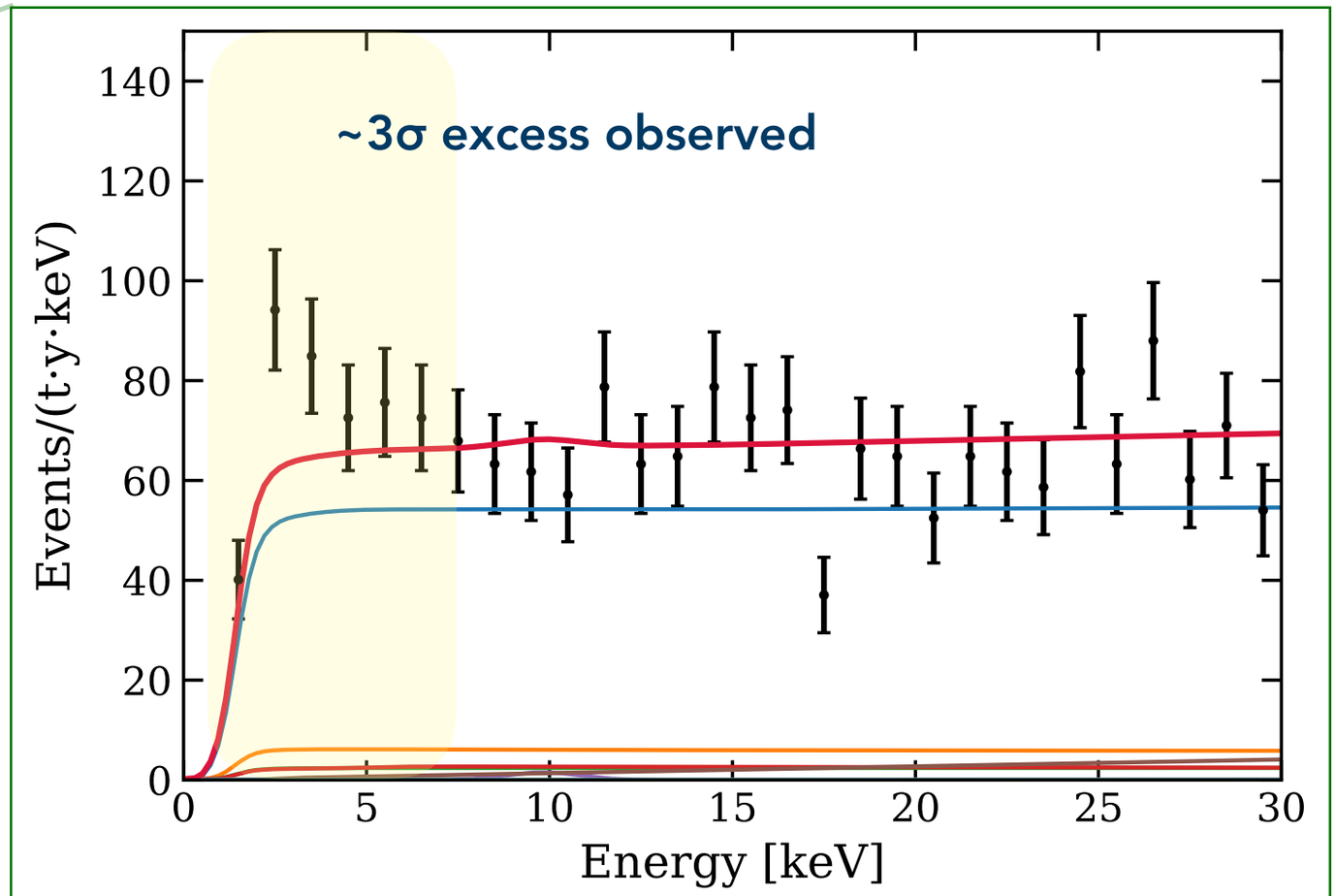
Predicted energy spectra based on detailed modeling of each background component.

Rates constrained by measurements and/or time dependence, except ^{214}Pb and ^{124}Xe.

Background fit



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



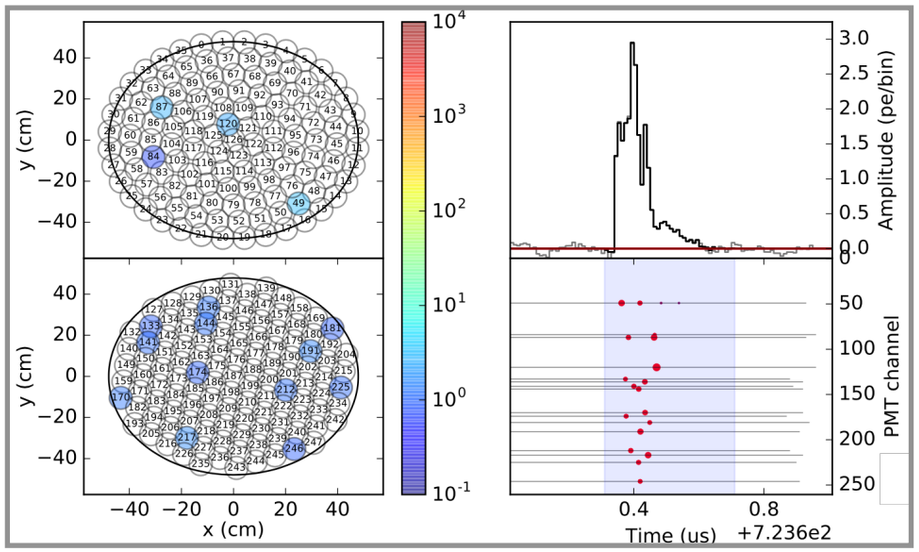
Excess between 1-7 keV

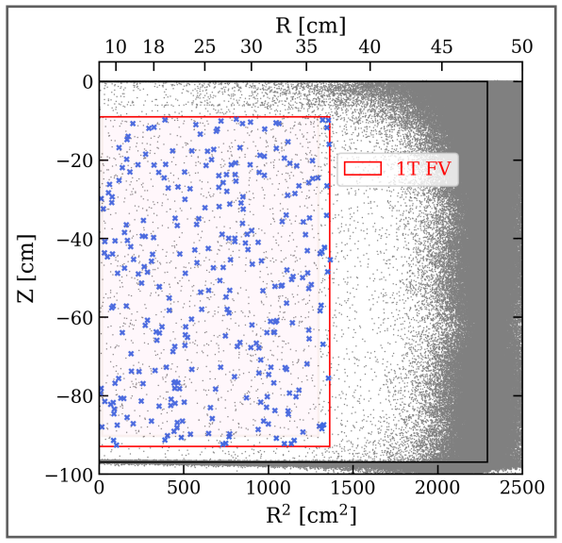
285 events observed

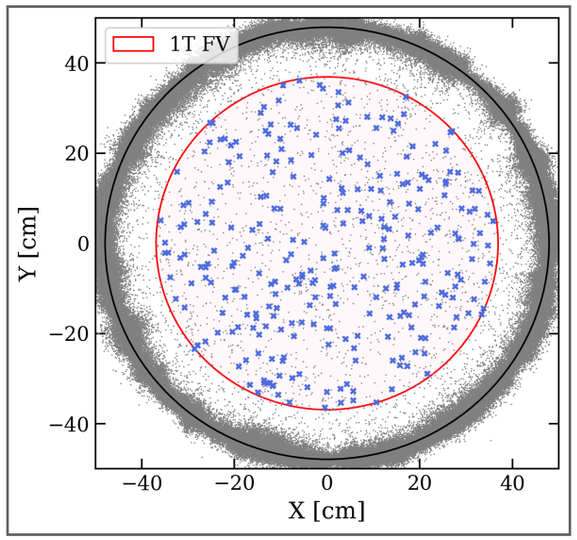
vs.

232 events expected (from best-fit)

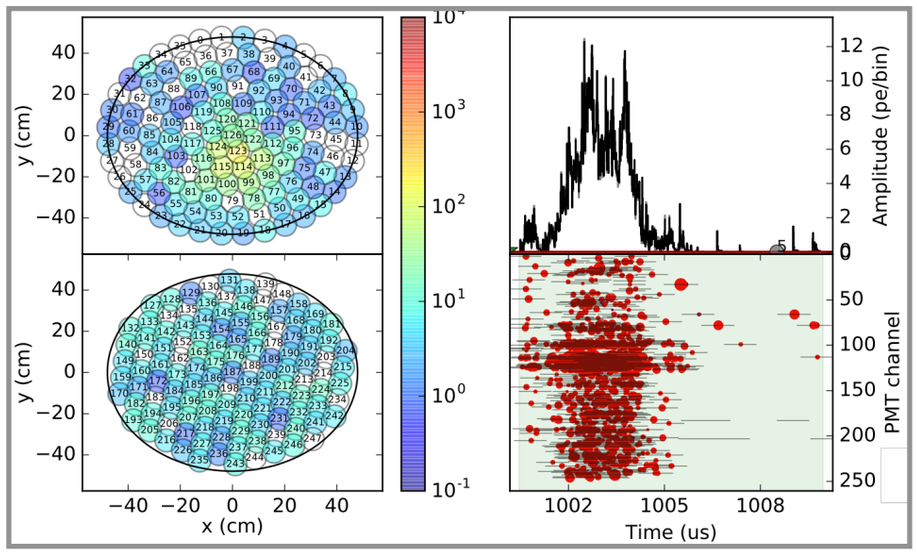
Further checks



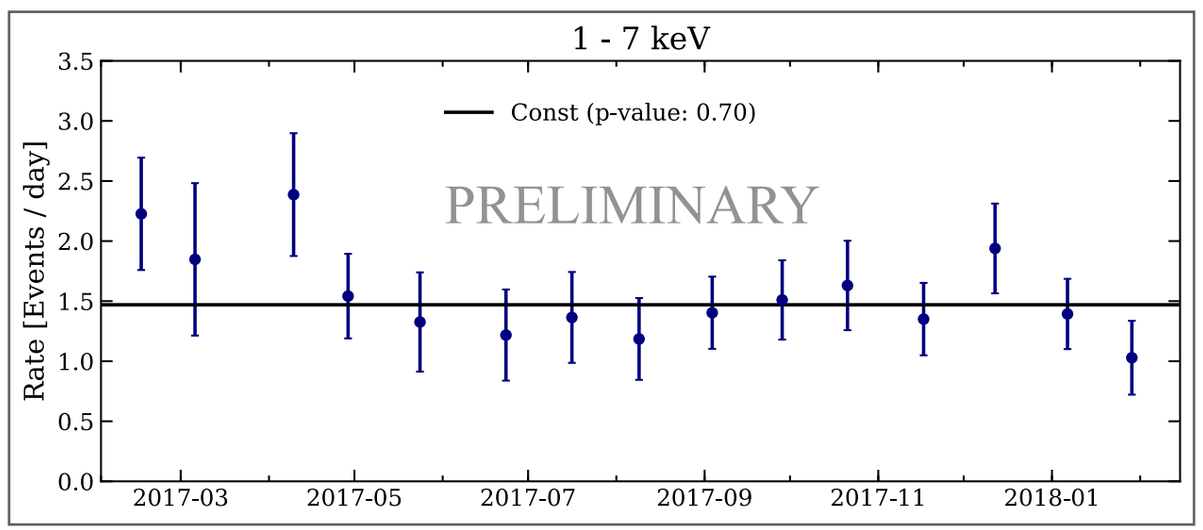




Events uniformly distributed within fiducial volume



All passed event classification checks and waveform inspection

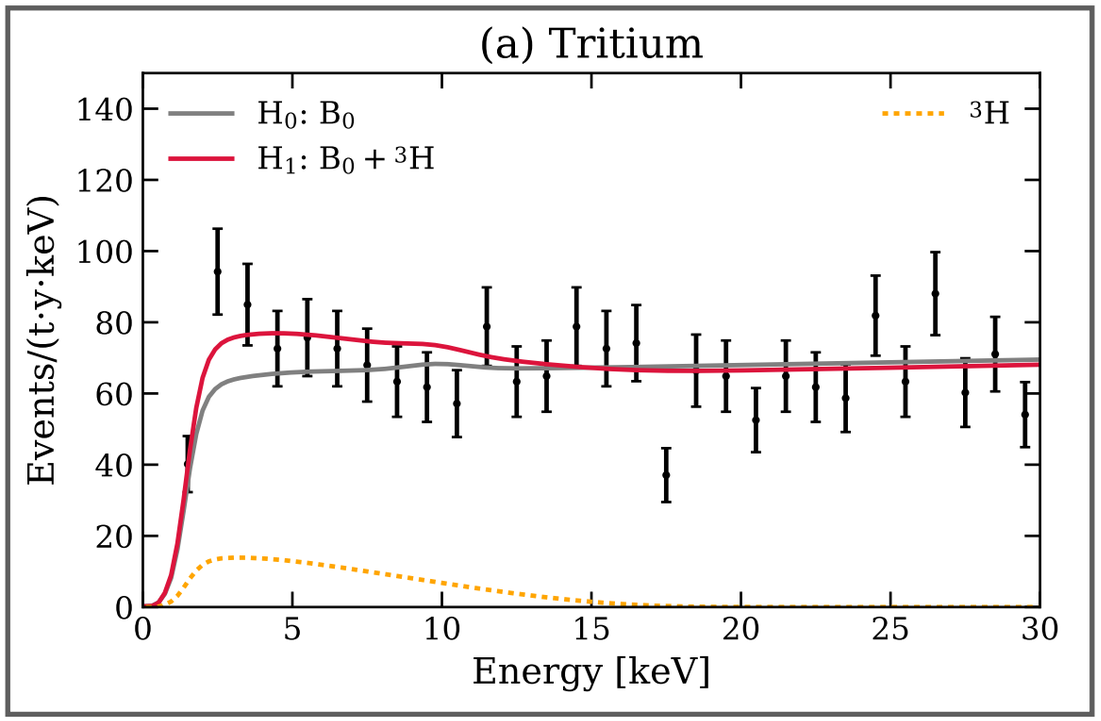


Consistent with constant in time, but with very low statistics!

(dedicated annual modulation analysis in progress)

New backgrounds?

Tritium

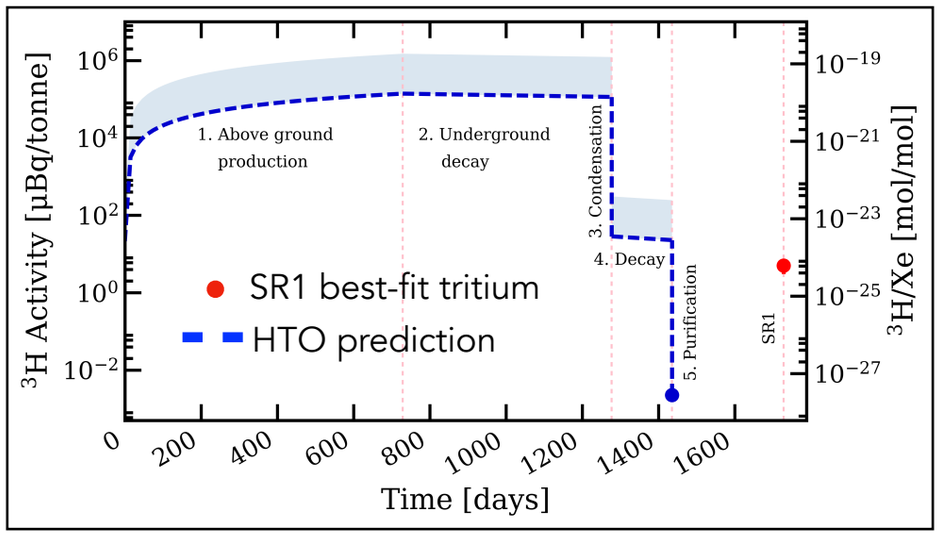


Tritium favored over background-only at 3.2**σ**

Best-fit tritium rate: 159 ± 51 events/(t · y)

^{3}H:Xe concentration: $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol

< 3 tritium atoms per kg of xenon!



- cosmogenic HTO (purification, distillation) and emanation (optical transparency) ruled out
- emanation of HT more difficult (no direct measurements - would need to be 100 x that of electronegative impurities)

can neither confirm nor exclude it (possible HT emanation from materials)

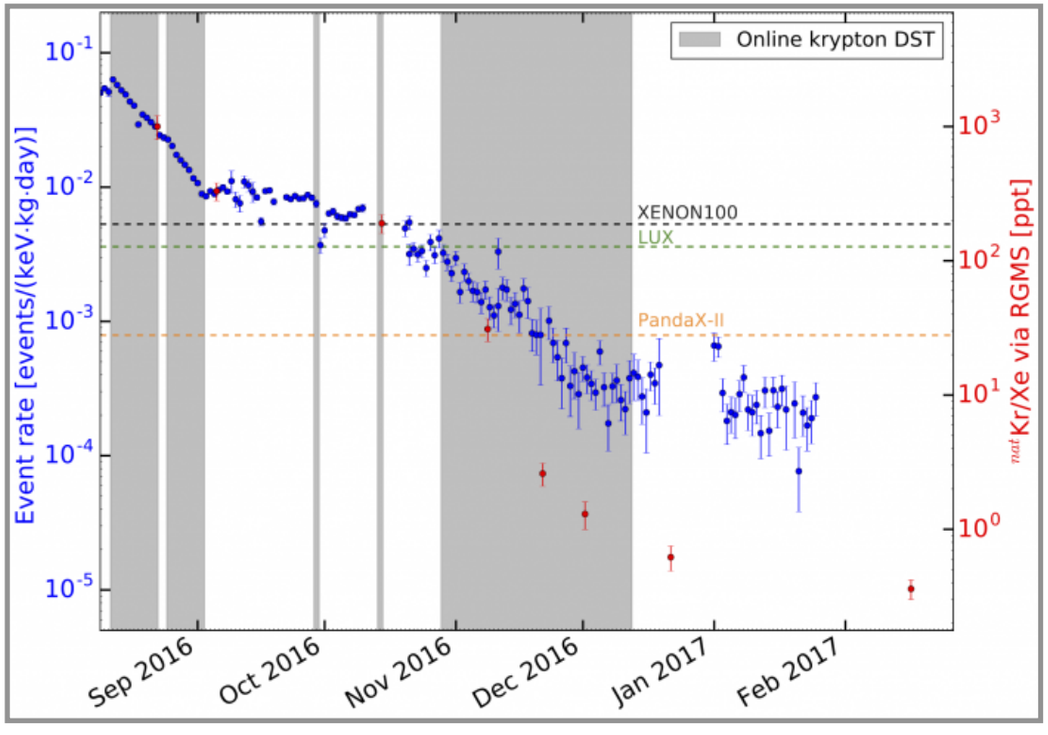
New backgrounds?

^{37}Ar: 2.8 keV peak from electron capture

35 day half-life plus removal through cryogenic distillation

Negligible by the start of XENON1T

Krypton residual gas measurements



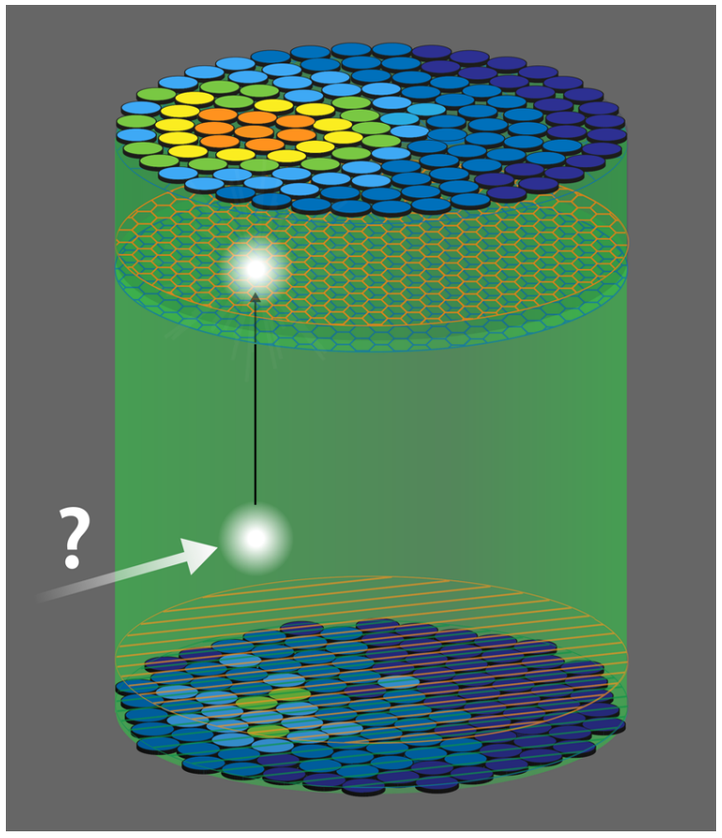
From estimated air leak via regular Kr-85 measurements and direct measurements of Ar37 in the lab air:

< 5.2 events/tonne/yr

(~65 events/tonne/y needed for excess at 2.8 keV)

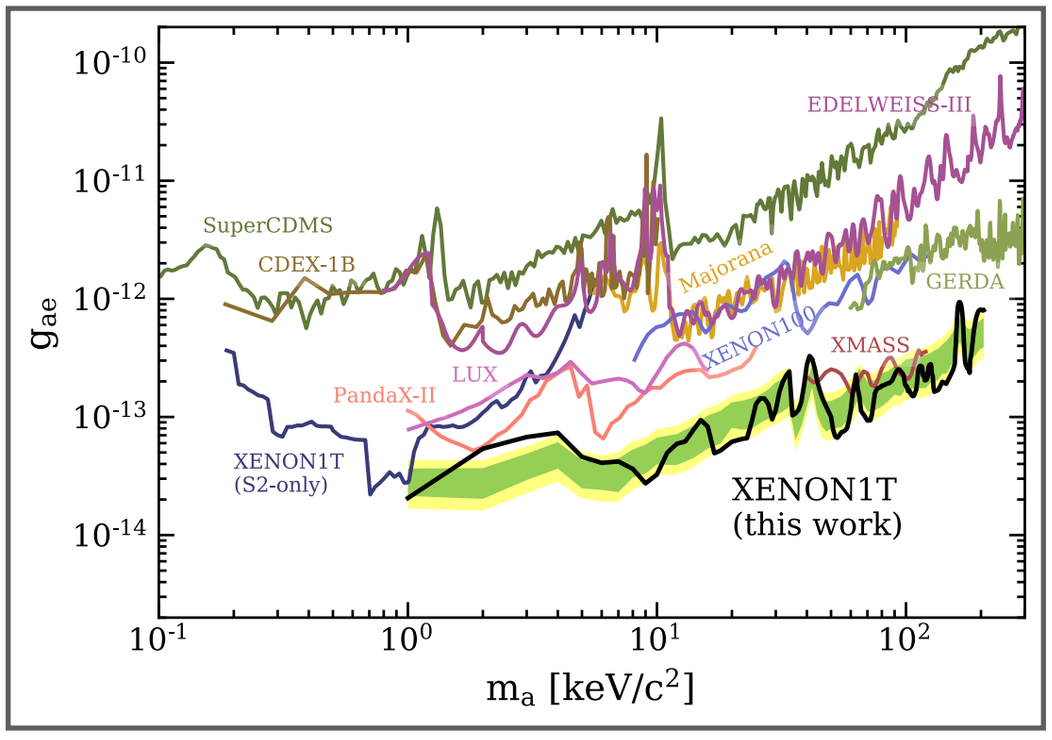
Ruled out.

Interpretations

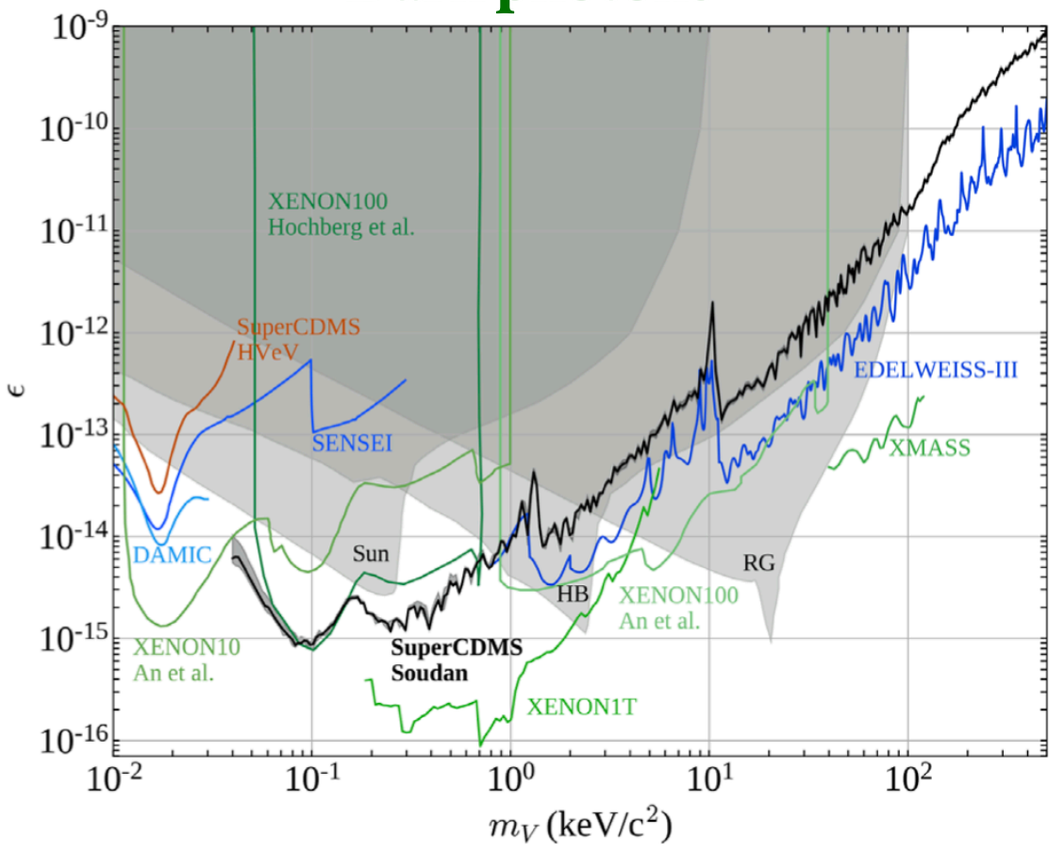


Bosonic DM

Axion-like particles



Dark photons



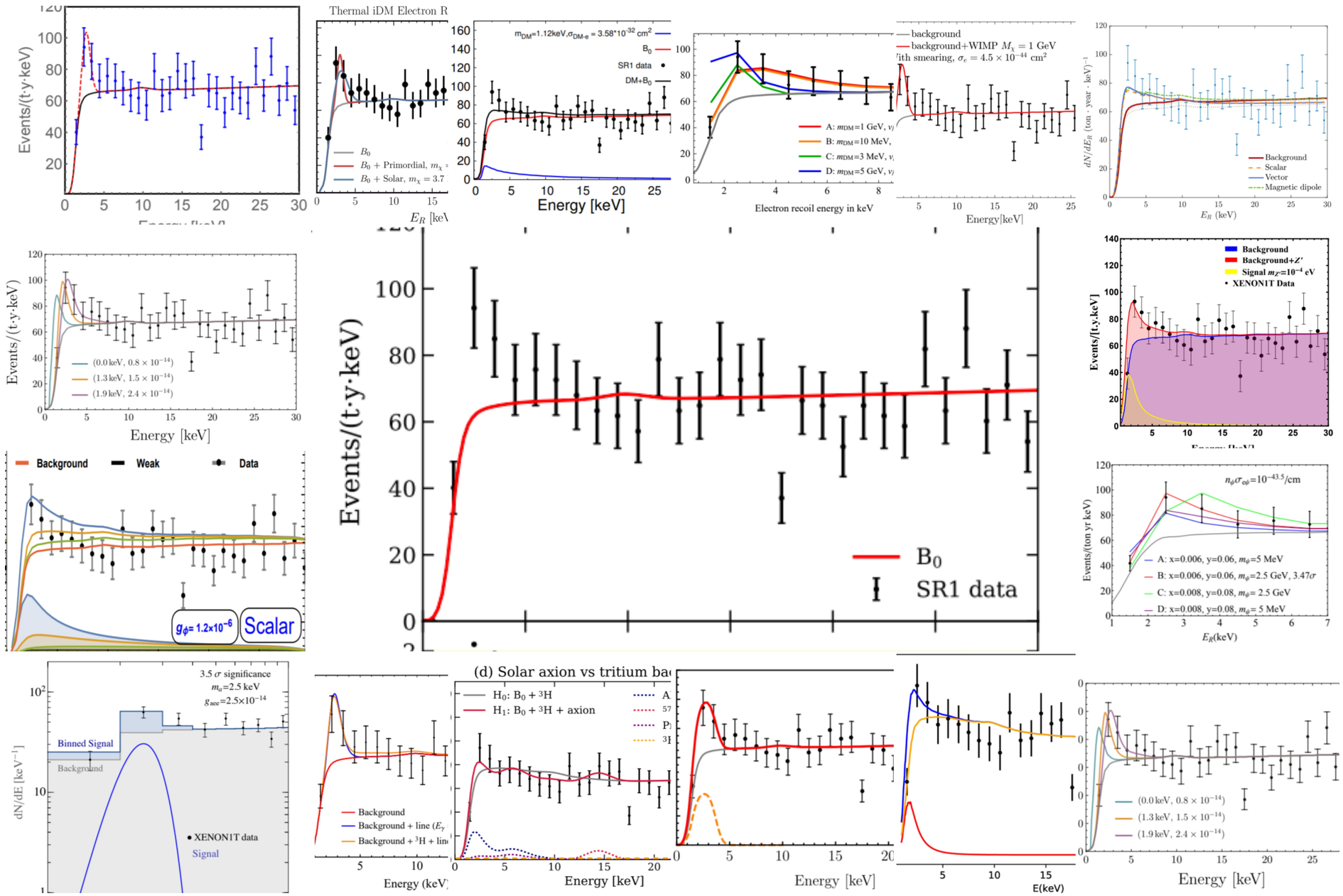
most stringent limits over most of 1 - 210 keV mass range

90% CL upper limits and sensitivities

arXiv:2006.09721 (PRD 2020)

SuperCDMS: PHYSICAL REVIEW D 101, 052008 (**2020**)

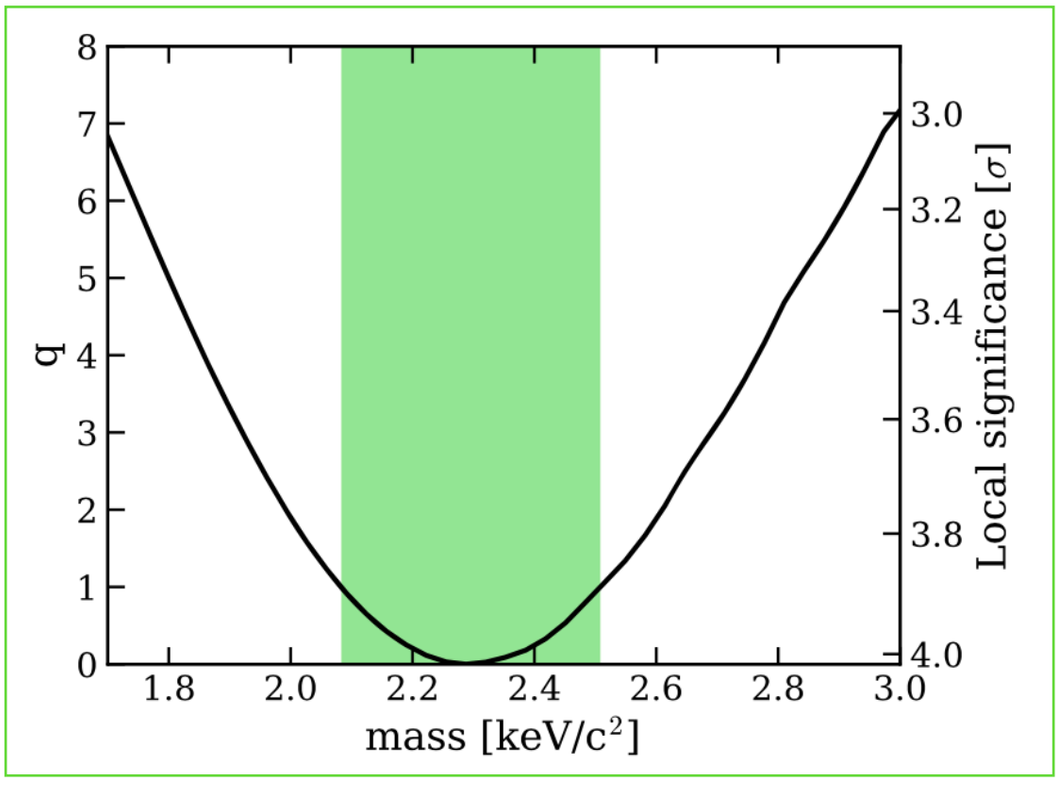
Community fits



Fits to the binned data within first 2 weeks after arXiv release.

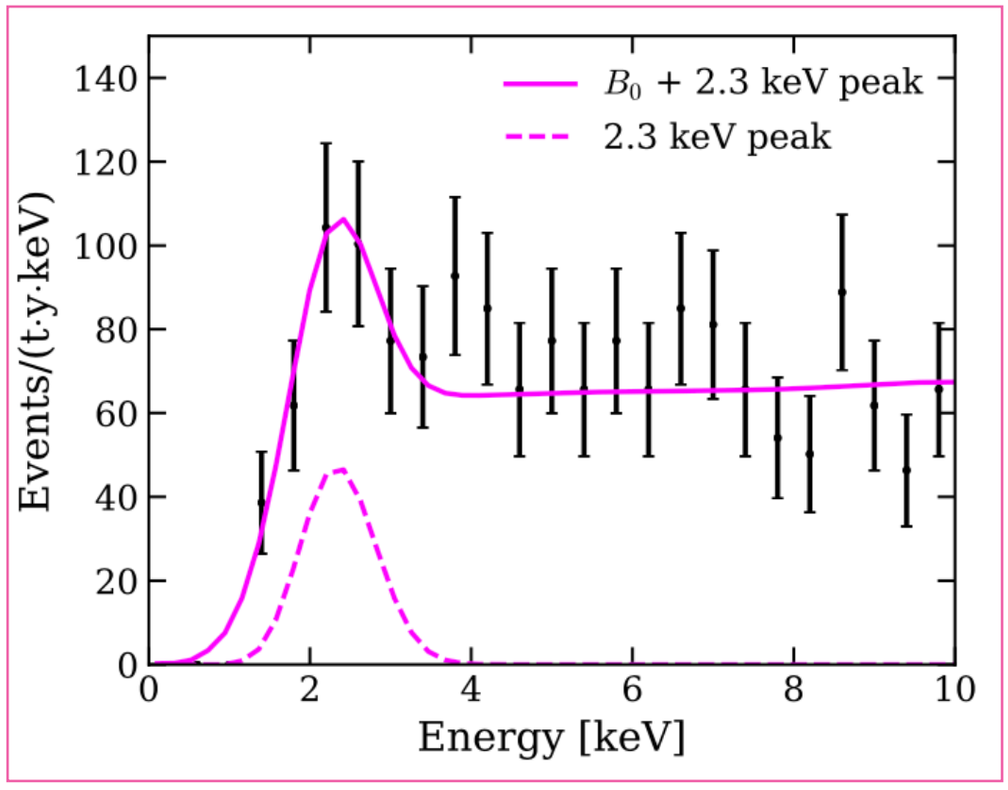
Source: Oz Amram

XENON1T fit



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

arXiv:2006.09721 (PRD 2020)

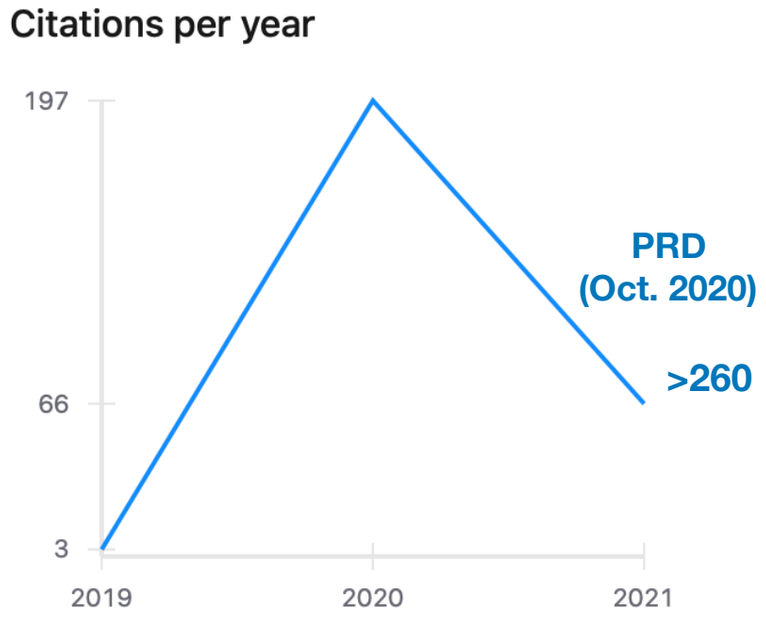
Experimental checks and theoretical interpretations

A few examples:

- **experimental checks:** 2006.13278 (tritium), 2006.16220 (reconstruction), 2007.00528 (Ar37), 2007.13686 (beta decay), 2008.06485 (PandaX-II)

- more on **bosonic dark matter:** 2006.10035, 2006.11243, 2006.12488, 2006.13159, 2006.13929, 2006.14521, 2007.00874, 2008.08594

- **strongly interacting dark matter**: 2002.04038
- luminous dark matter: 2006.12461
- mirror dark matter: 2006.14577
- plasma dark matter: 2007.15191
- pico-charged particles: 2007.14421
- shining dark matter: 2006.12462
- **sterile neutrinos**: 2008.05029, 2008.03150
- decaying dark matter: 2006.12348, 2008.03150, 2008.09615
- **boosted dark matter:** 2006.10735, 2006.11837, 2006.11264 (GC, or sun), 2006.12447 (Sun-heated), 2006.12529 (Migdal+boosted), 2006.12767 (CR-boosted), 2006.13910 (CR boosted), 2006.16078, 2007.15006, 2008.07116 (CR-boosted)
- **inelastic dark matter:** 2006.11938, 2006.13918, 2006.14089, 2006.15672, 2007.04963, 2008.12137
- mediator and Z' models: 2006.11949, 2006.13183, 2007.02898

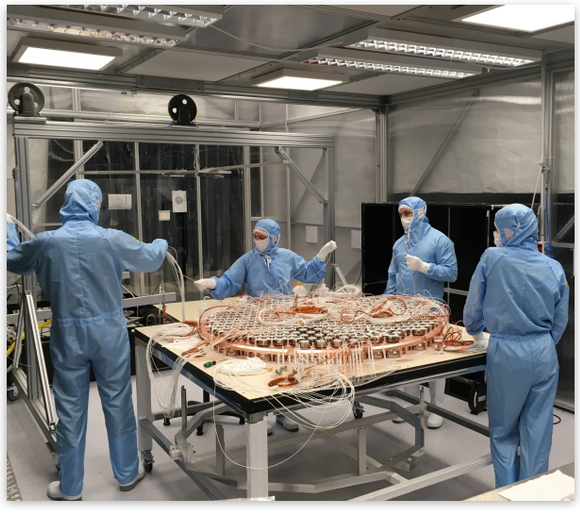


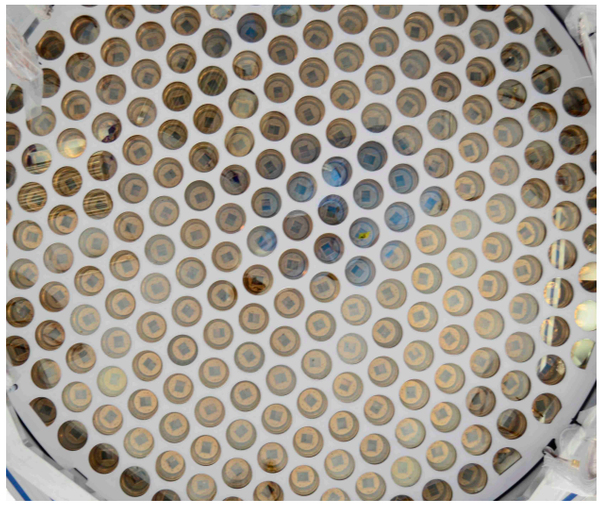
- more on **solar axions:** 2006.12487, 2006.14598, 2006.15112, 2006.15118, 2006.14568, 2006.16931
- more on **solar neutrino** interactions: 2006.11225, 2006.11919, 2006.11250, 2006.12457, 2006.12887, 2006.15112, 2006.16069, 2006.16192, 2007.01765, 2007.05513, 2007.15563, 2008.05080

XENONnT

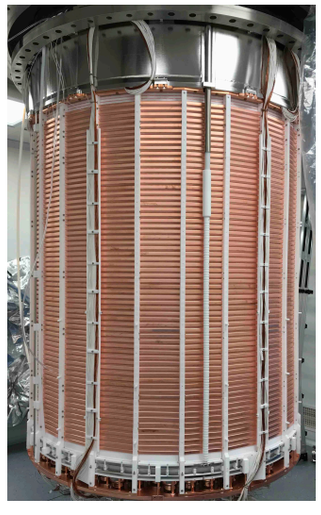
3x larger active xenon target

TPC (5.9 t LXe, 4 t fiducial)



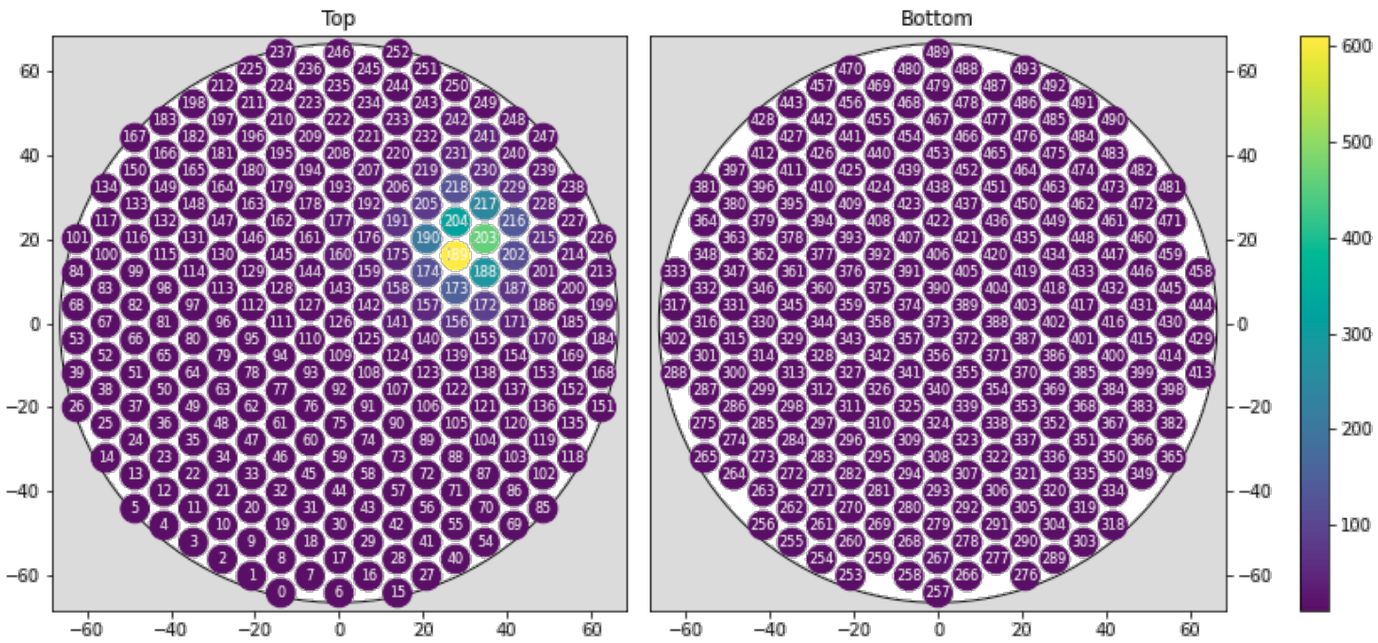


PMT array (494 PMTs in total, in 2 arrays)



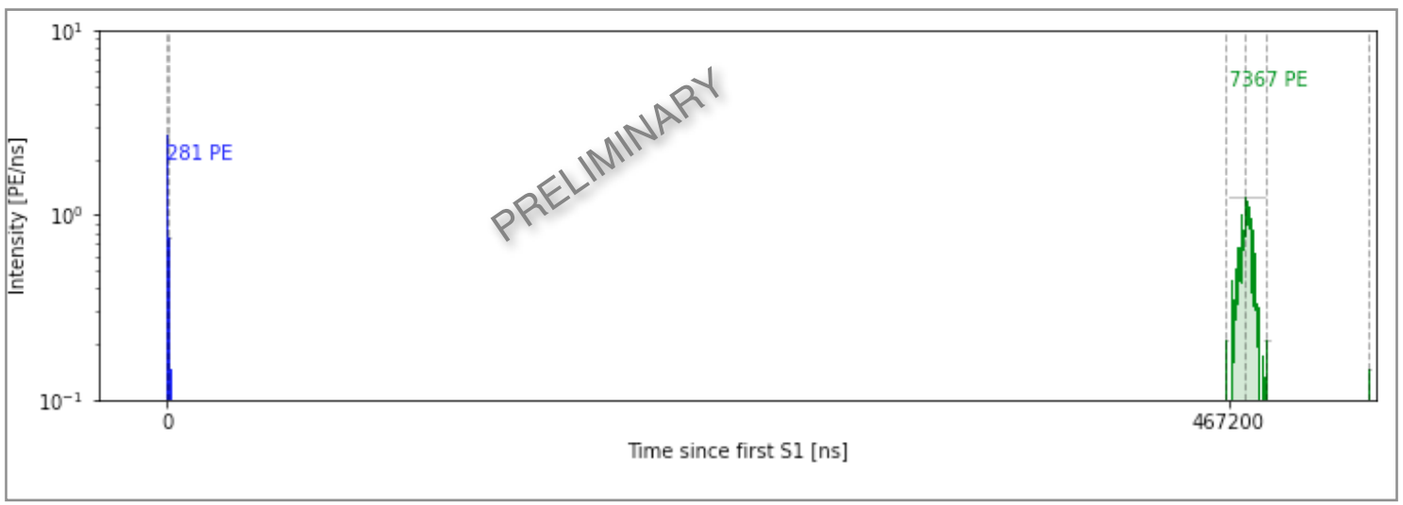
1.5 m drift length

XENONnT

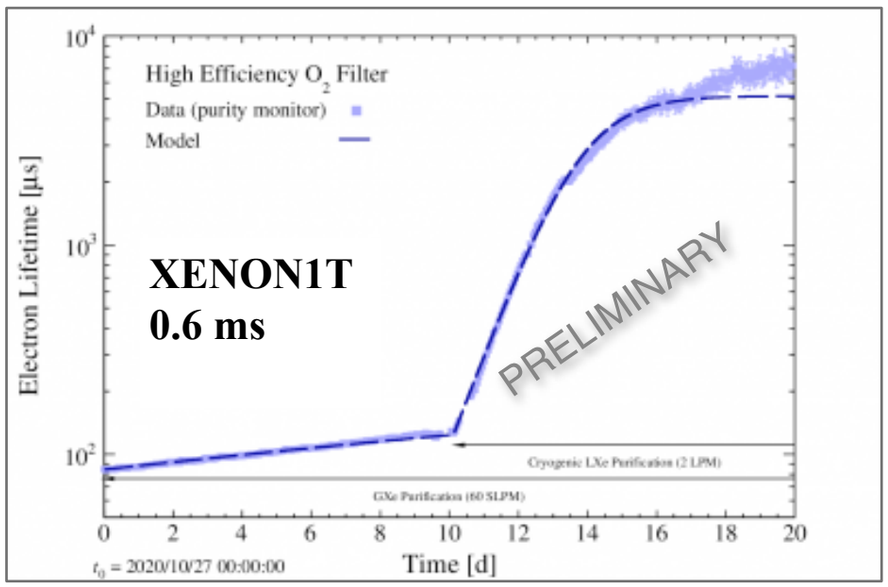


PMT hit pattern for event below

Commissioning ongoing



Paired S1 + S2 waveform



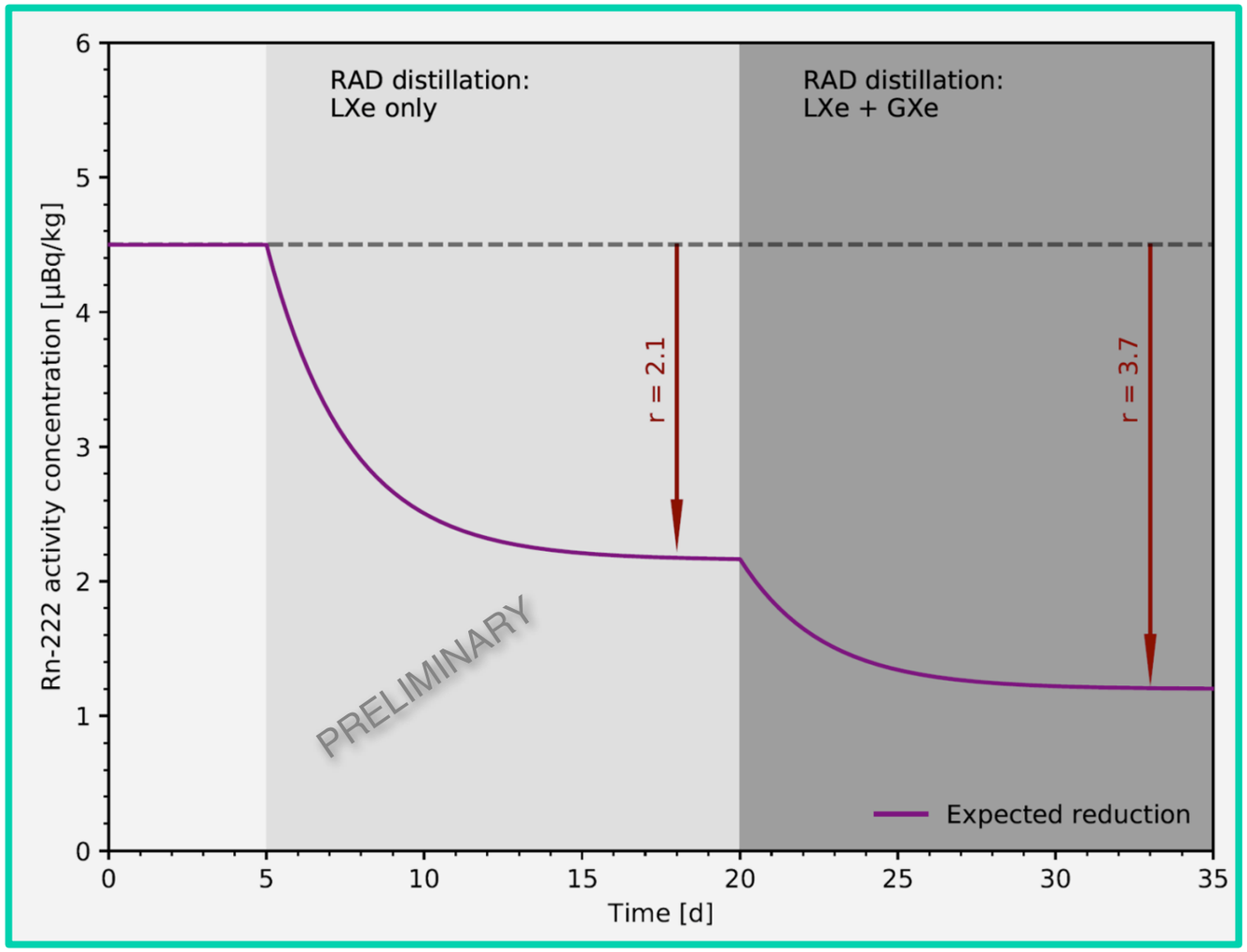
Electron lifetime: new LXe purification

XENONnT

Distillation column to reduce ^{222}Rn (^{214}Pb)

- 1 μBq/kg ^{222}Rn level (goal)
- In XENON1T was
  13 μBq/kg (science run)
  4.5 μBq/kg (latest R&D run)

Reduced background level



Summary

XENON1T dual-phase TPC

- Methods to go lower with NRs and also ERs for standard (and also light mediator) WIMPs, but mostly limit-setting.
- Extremely low ER background allows for sensitive searches with discovery potential in the keV range.
- An excess was found with mono energetic peak at 2.3 keV, but with limited statistics.

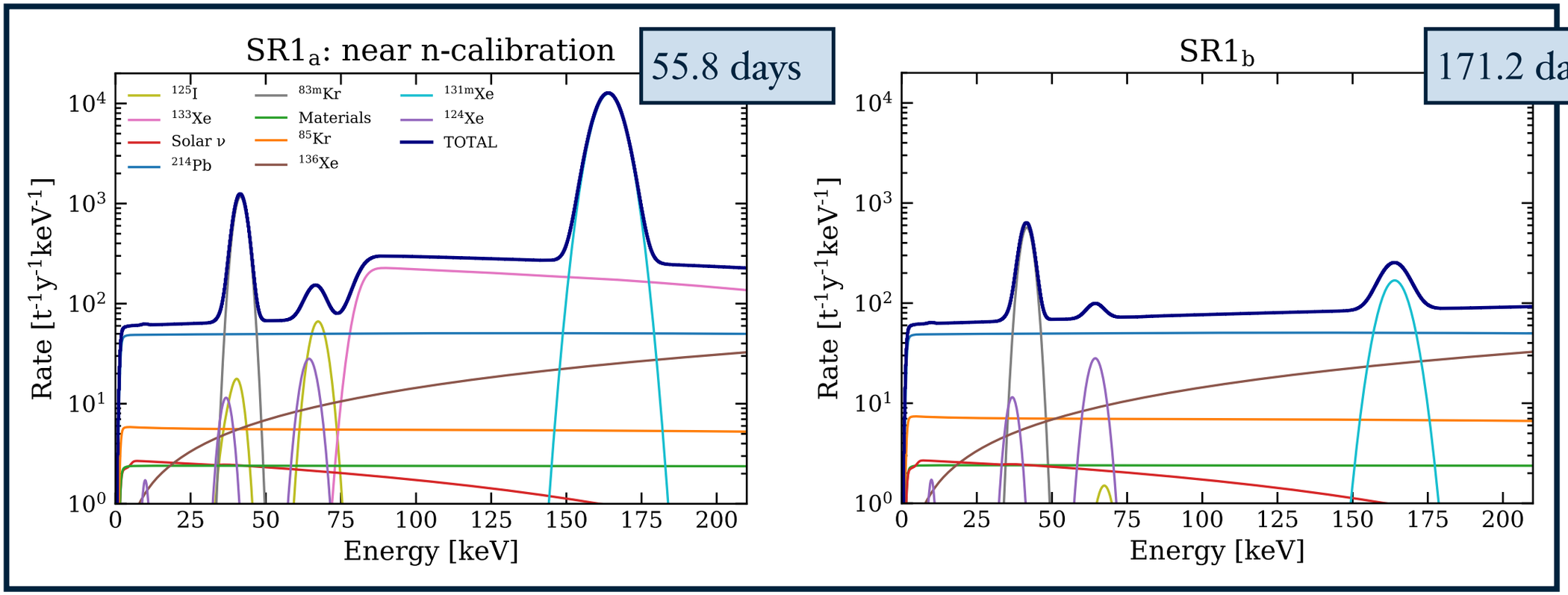
XENONnT online and will soon provide more information.

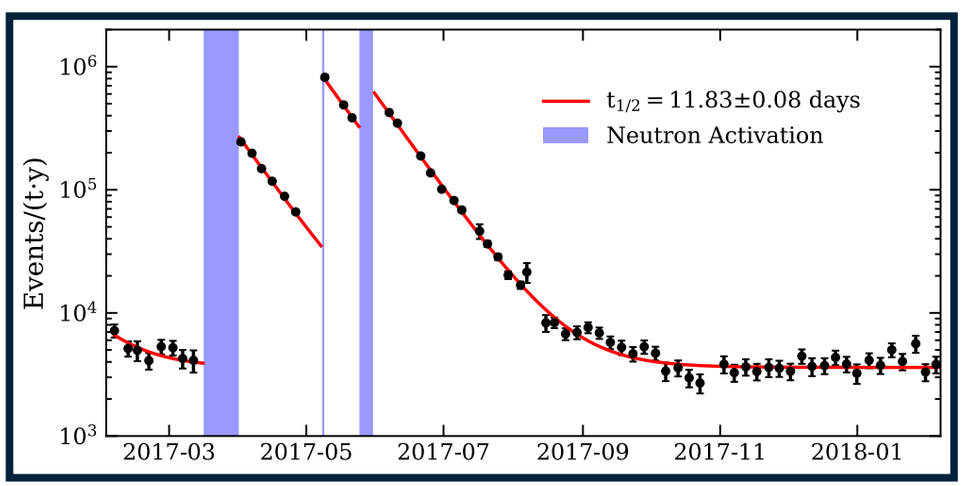
Bosonic dark matter results: XENON collaboration, Phys. Rev. D 102, 072004, October 12, 2020

Data available on zenodo:
https://zenodo.org/record/4273099
(Link available on arxiv: 2006.09721)

Backup

ER background model





Time-evolution and model of ^{131m}Xe

Background model B_0

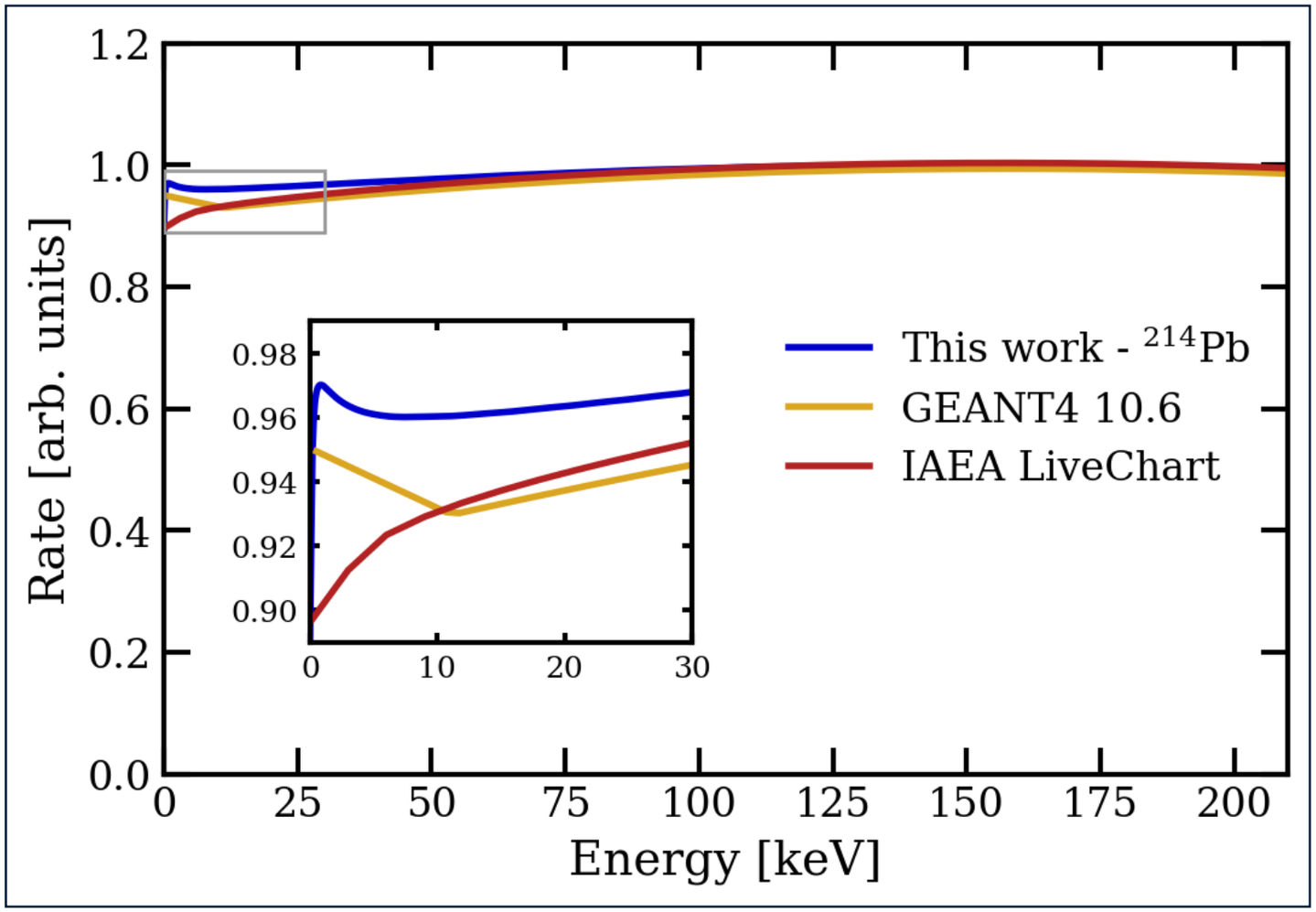
Partitioned into two datasets and fit simultaneously

$SR1_a$: activated backgrounds, peaks

$SR1_b$: allows to constrain ^{214}Pb background

Model checks

^{214}Pb dominant background component



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

~6% uncertainty on the shape

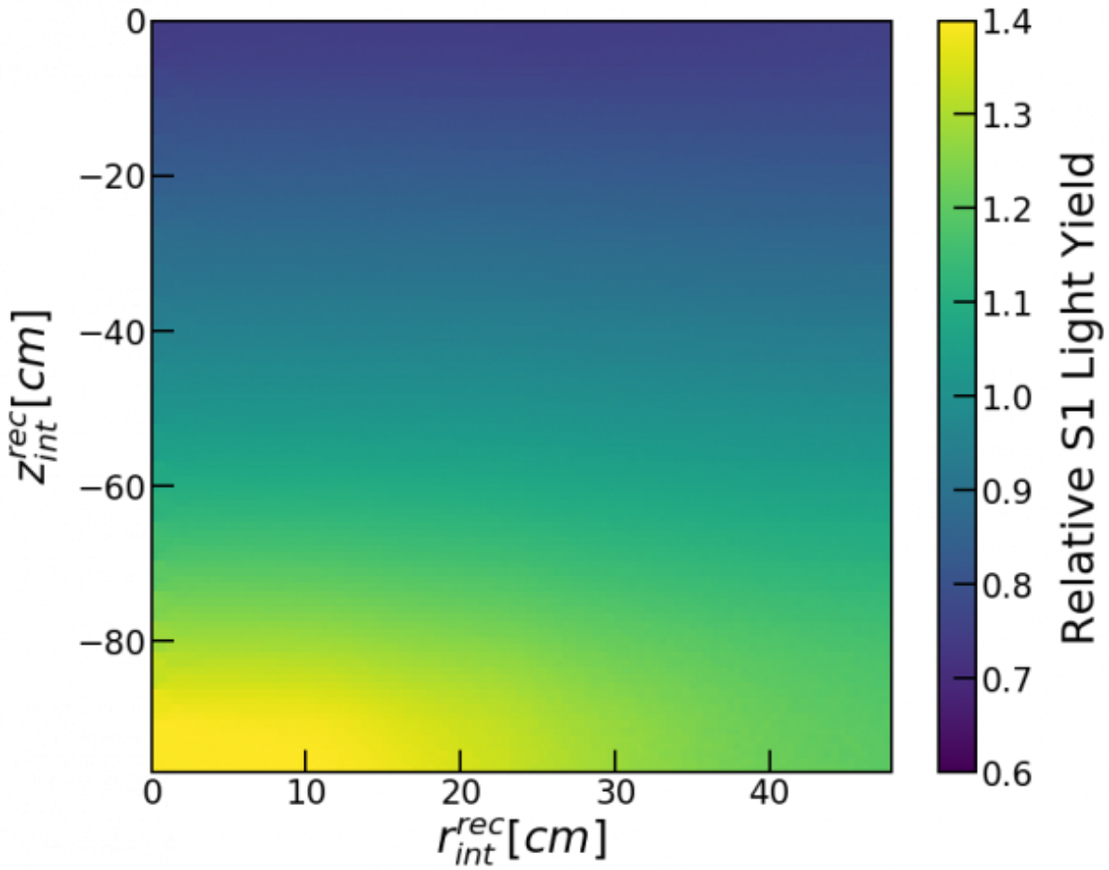
~50% needed to account for excess

^{212}Pb, ^{85}Kr also calculated and recently updated.

Signal corrections

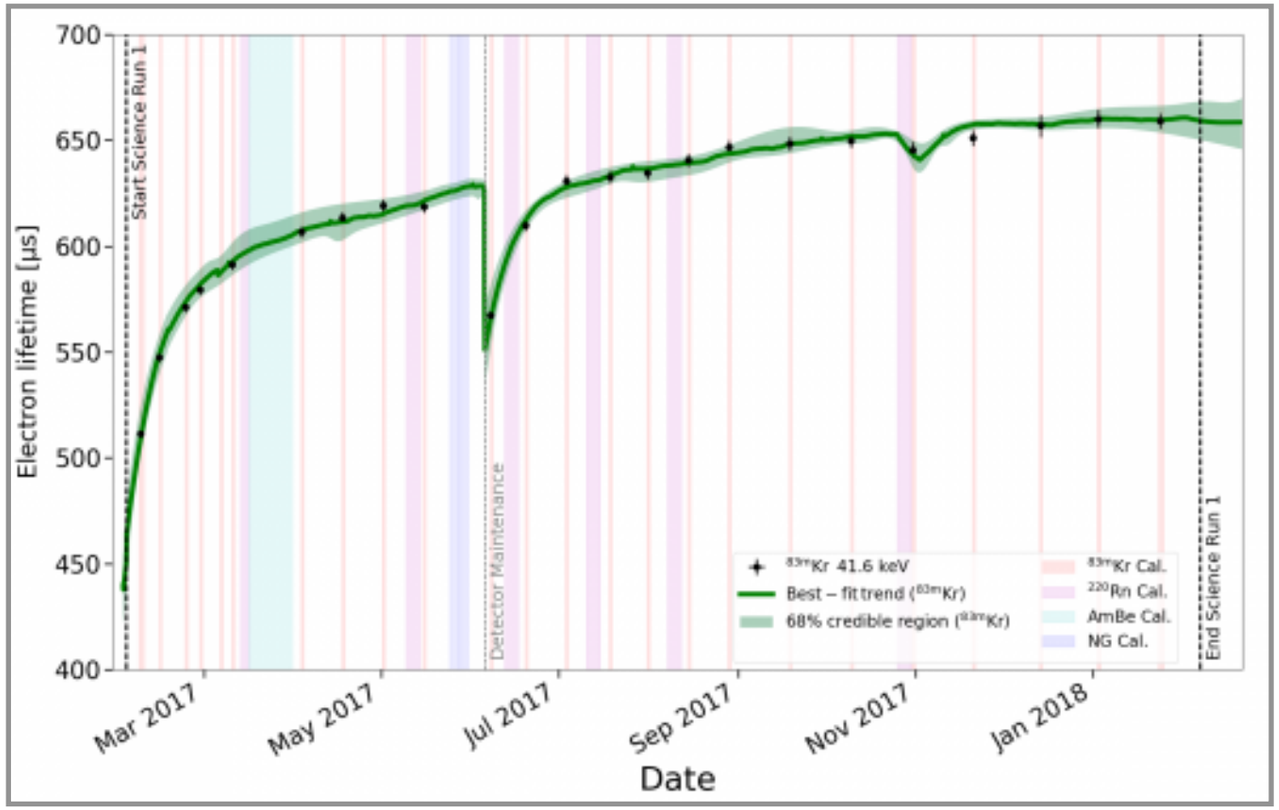
Depth-dependent corrections of signal areas based on calibration data

S1: Light collection efficiency map



Depends on H2O impurity concentration

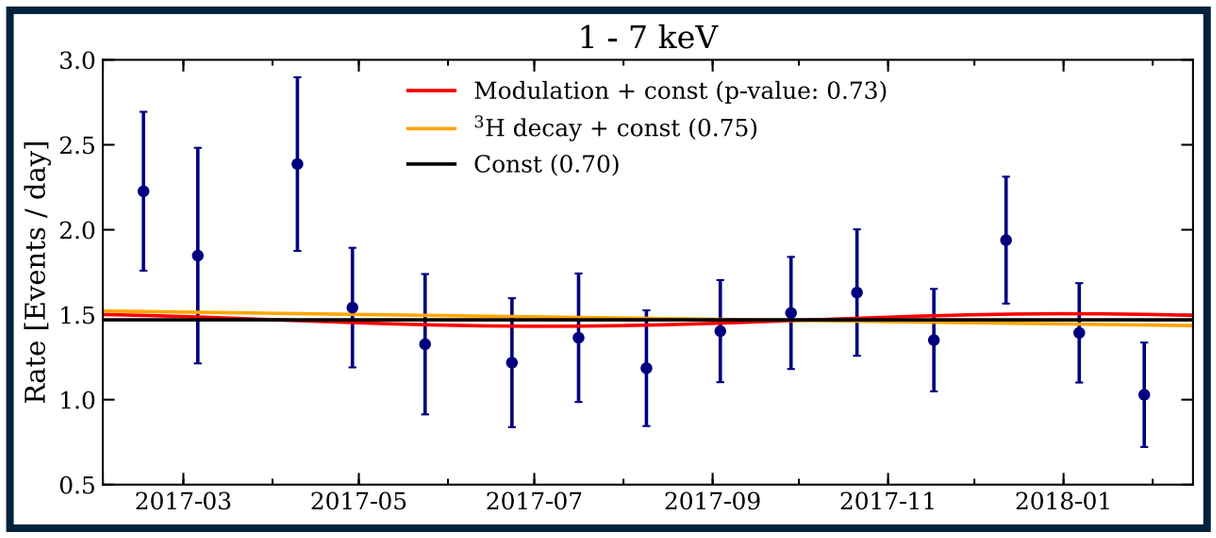
S2: Electron lifetime



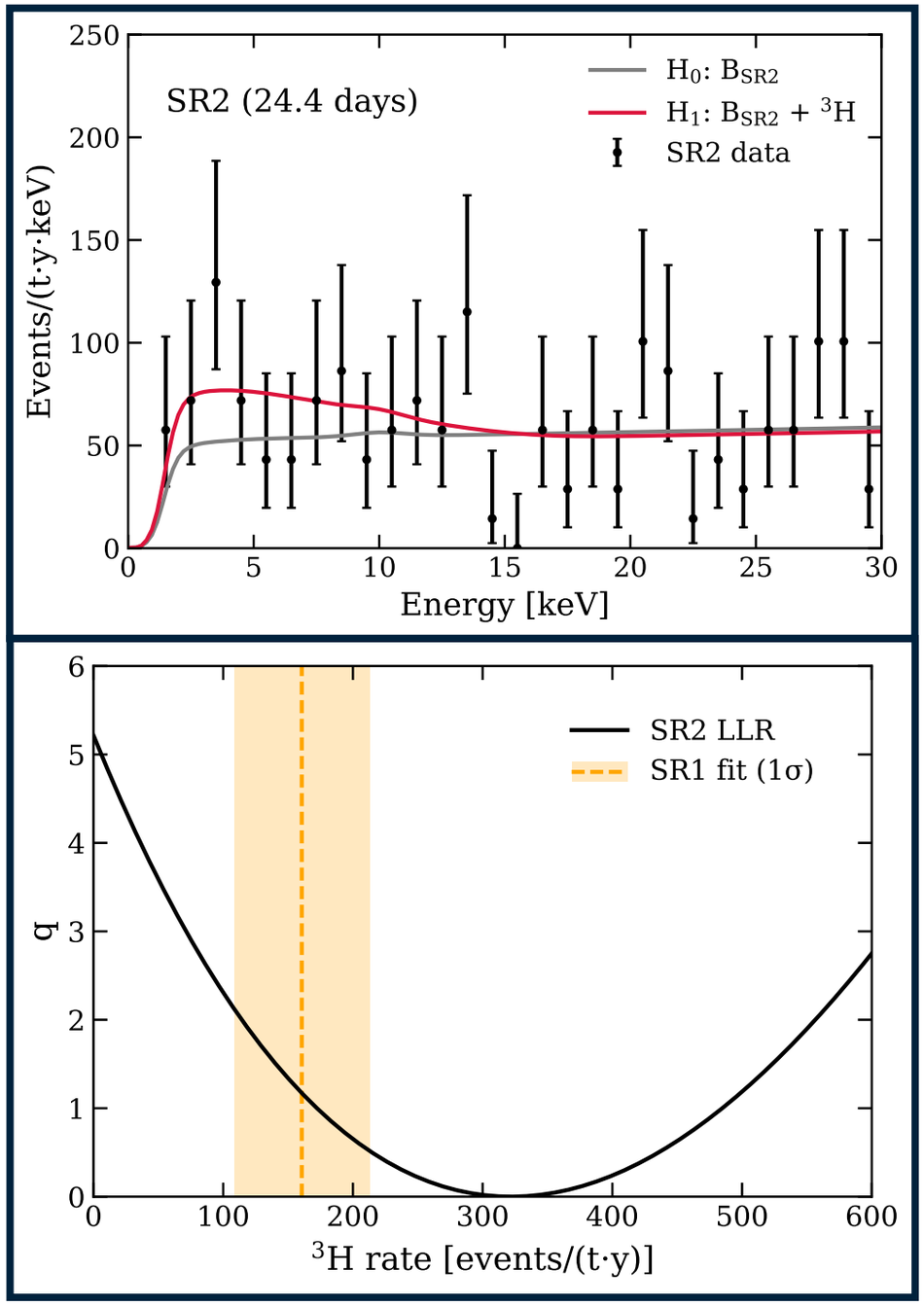
Depends on O2-equivalent electronegative impurity concentration

Additional checks

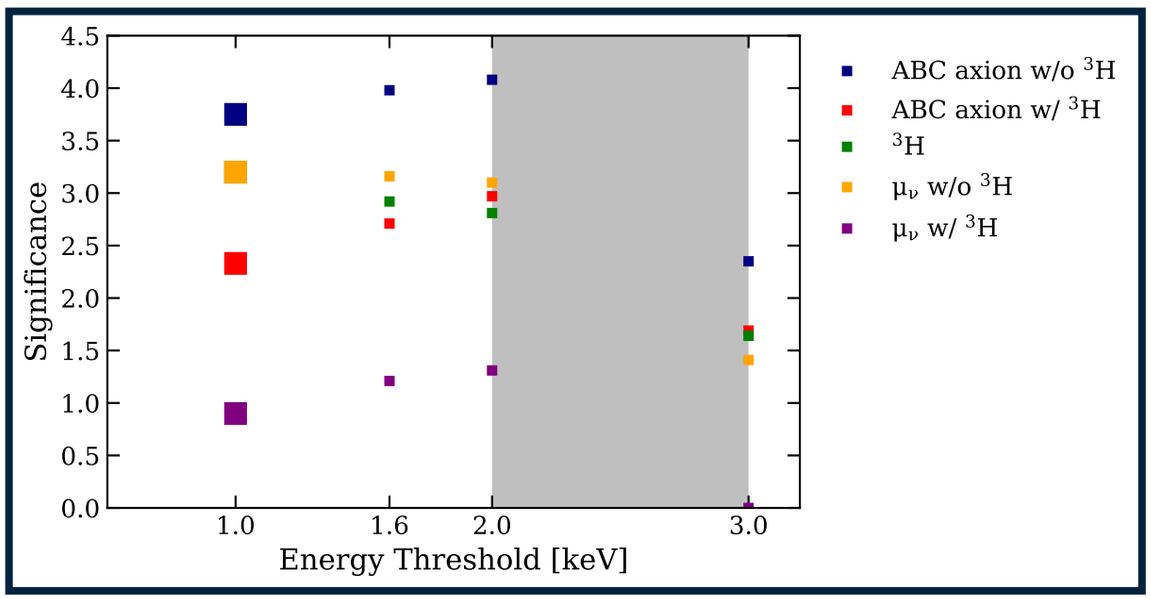
Time dependence



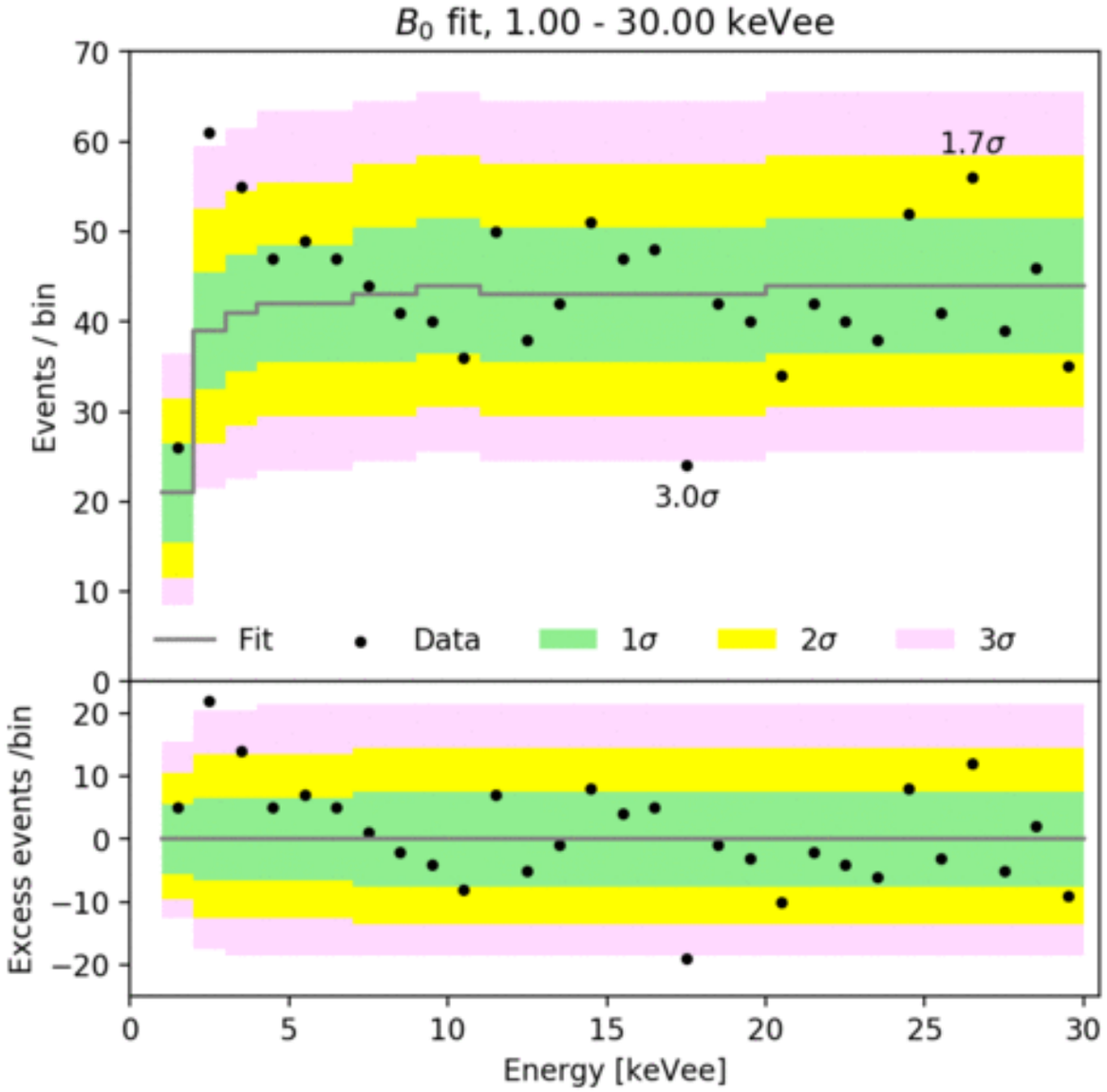
Additional data

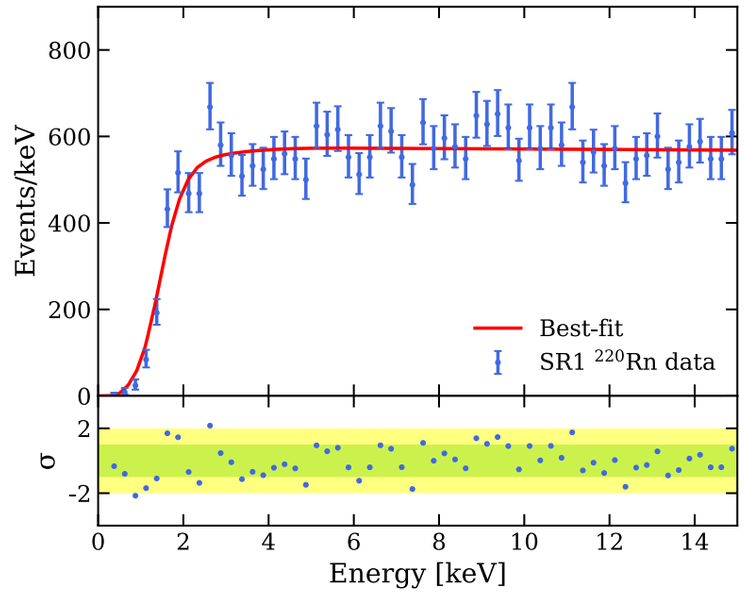


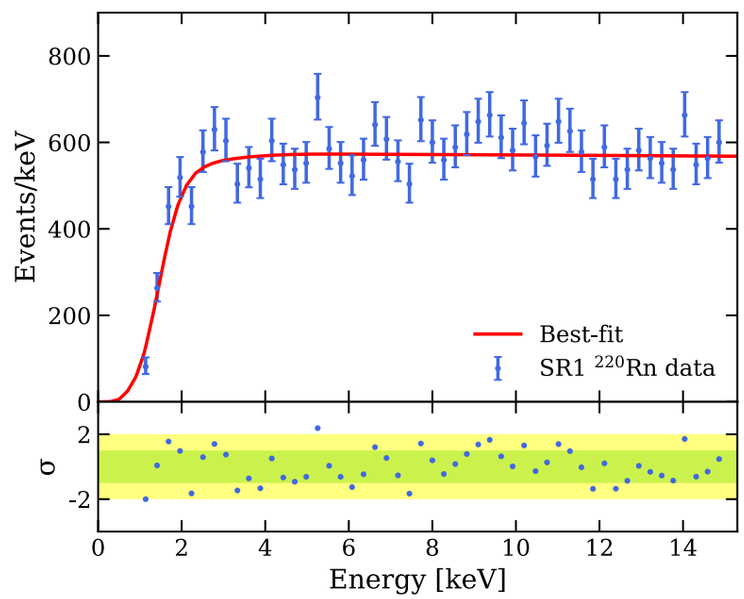
Threshold effects



Binning effects







Rn-220 rebinned

Analysis framework

Unbinned profile likelihood analysis

- Profile over the nuisance parameters (background components, efficiency)

expected total signal events

expected total background events

i - over all observed events, N = 42251

background PDF

signal PDF

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

$$\mu_{\text{tot}} \equiv \sum_j \mu_{b_j} + \mu_s$$

μ_b, θ : nuisance parameters

θ = includes shape parameters for the eff. spectral uncertainty & peak location

constraints on the expected nr of background (m) events and shape parameters (n=6)

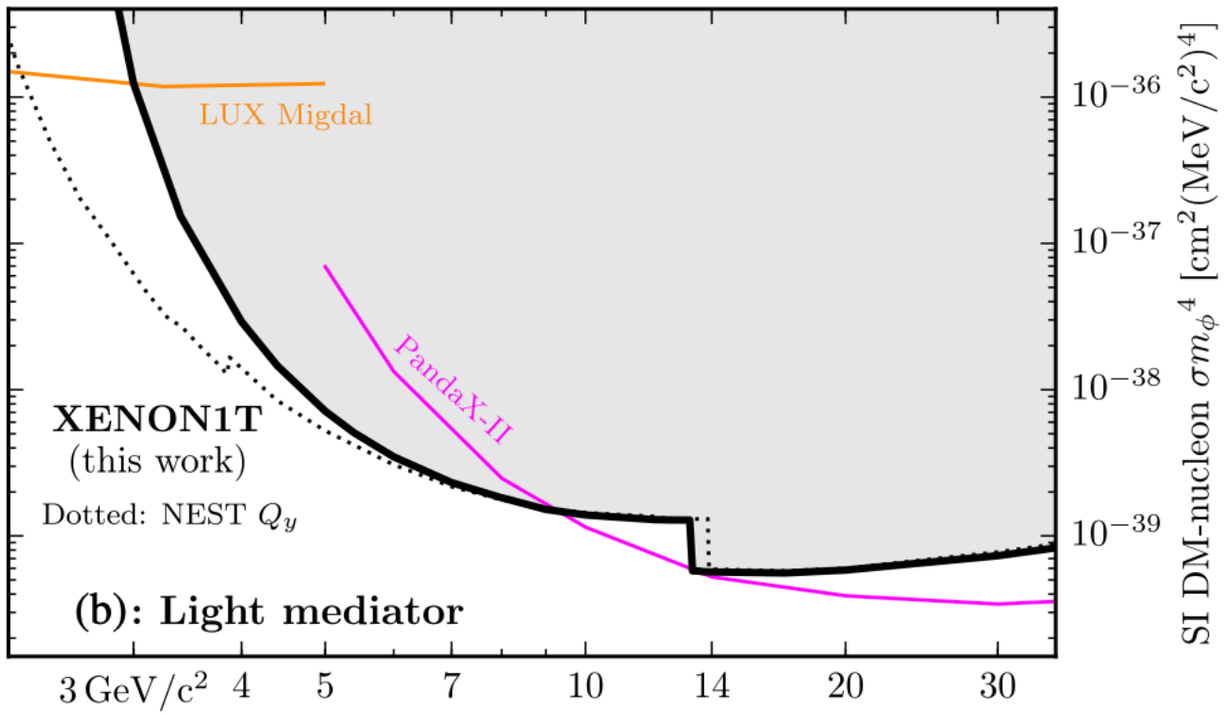
- Test statistic q for inference

$$q(\mu_s) = -2\ln \frac{\mathcal{L}(\mu_s, \hat{\hat{\boldsymbol{\mu}}}_b, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}_s, \hat{\boldsymbol{\mu}}_b, \hat{\boldsymbol{\theta}})}$$

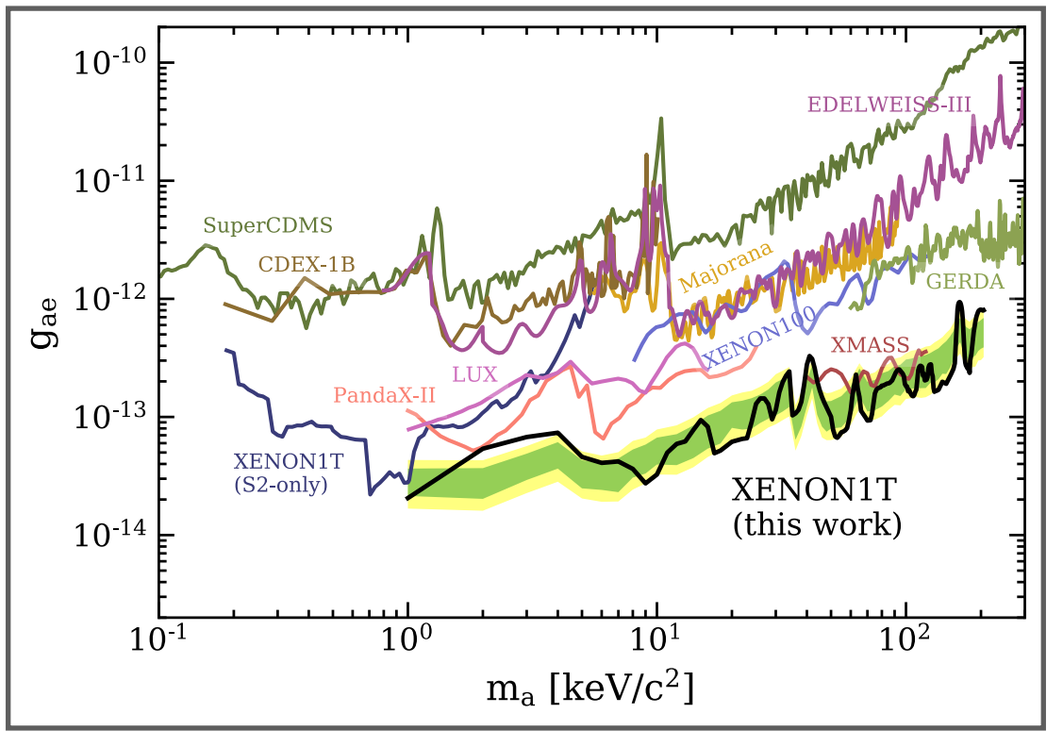
max. L with specified signal parameter μ_s

nuisance parameters that maximise L

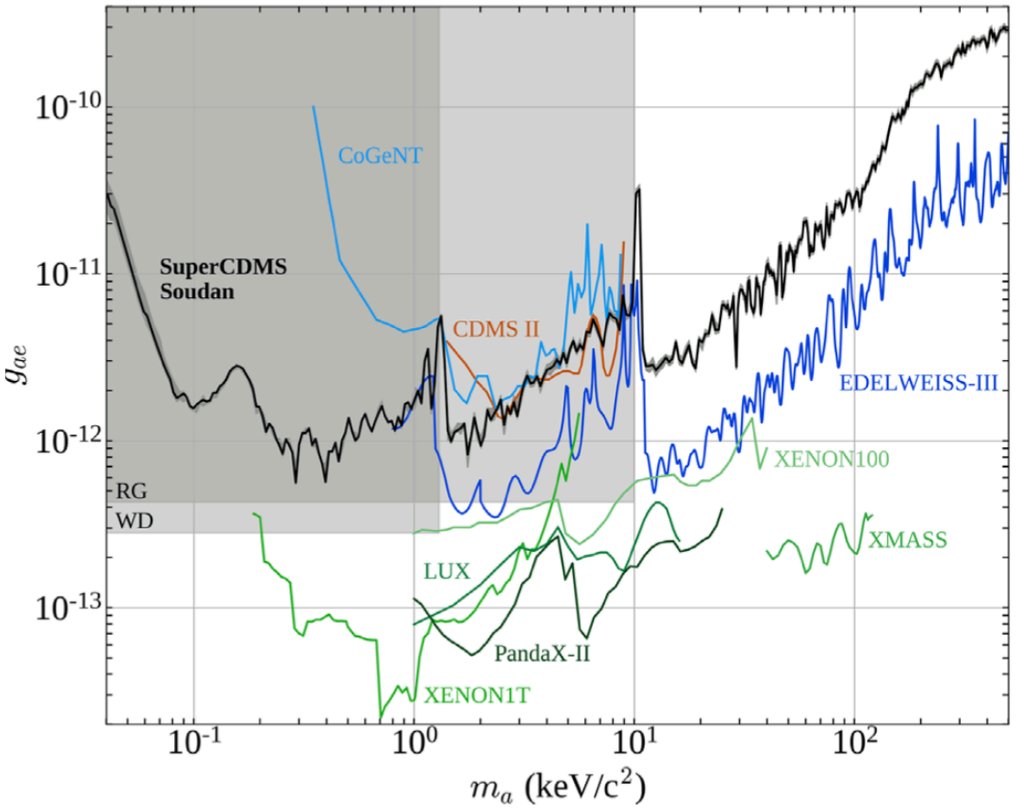
Light mediators



ALPs limits?



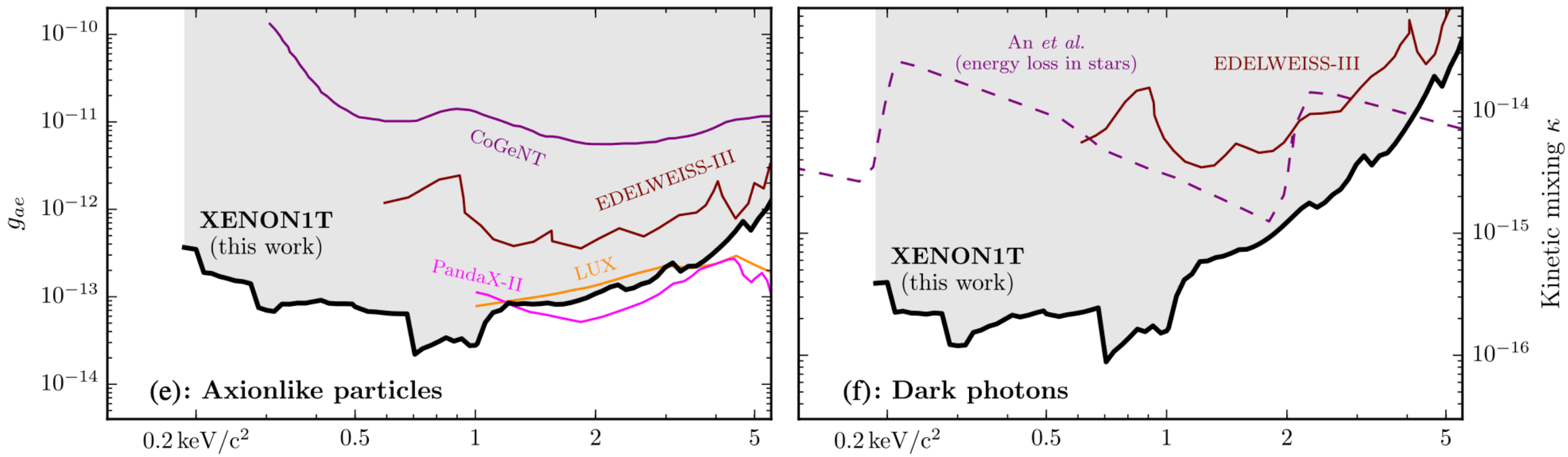
arXiv:2006.09721 (PRD 2020)



SuperCDMS: PHYSICAL REVIEW D 101, 052008 (**2020**)

I think this is mistakenly the XENON dark photon limit overlaid with ALPs results.

S2-only



arXiv:2006.09721 (PRD 2020)