Observation of Low Energy Excess Events in XENON1T

PHYS. REV. D 102, 072004 (2020)
arXiv: 2006.09721

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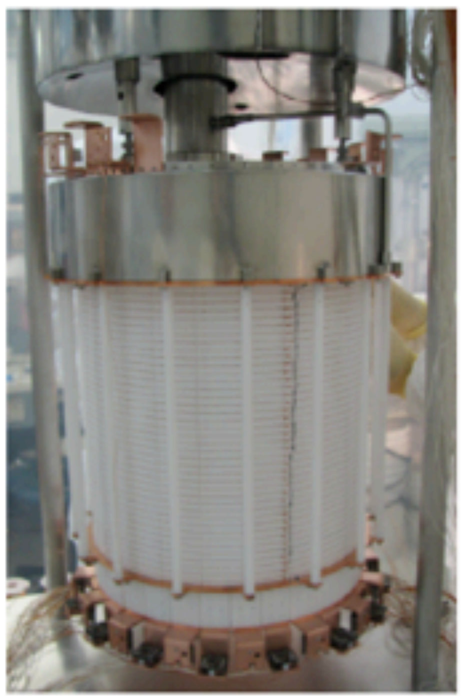
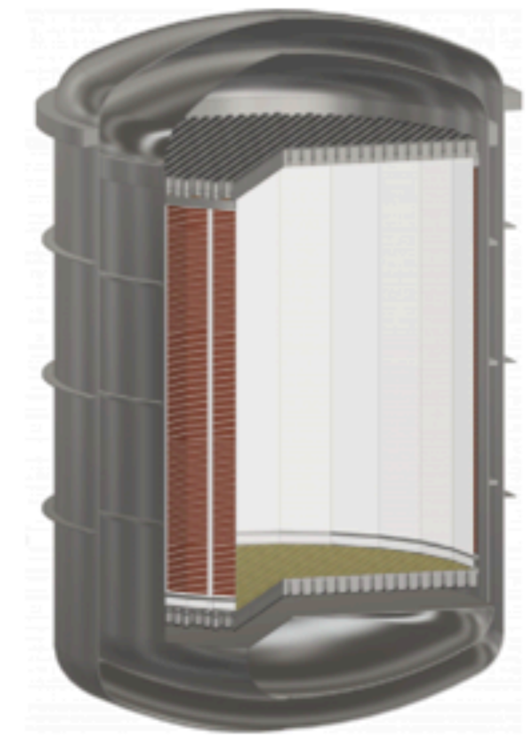
NCTS Annual Theory Meeting 2020

The Evolution of XENON Experiments for Dark Matter

Mission: build large-target-mass, low background and low threshold liquid xenon detectors to search for DM and other rare events at Gran Sasso Underground Laboratory

XENON10	XENON100	XENON1T	XENONnT	DARWIN
				
2005-2007	2008-2016	2012-2018	2020-2025	2027–
15 kg	161 kg	3200 kg	8400 kg	50 tonnes
15 cm	30 cm	96 cm	150 cm	260 cm
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

The XENON International Collaboration

- Founded: 2002
- Number of institutions: 28 from 12 countries
- Number of scientists: 170

Columbia, KIT, Nikhef, Muenster, Stockholm, Mainz, MPIK, Heidelberg, Freiburg, Zurich, Tsinghua

Chicago

UCSD

Rice

Purdue

Tokyo

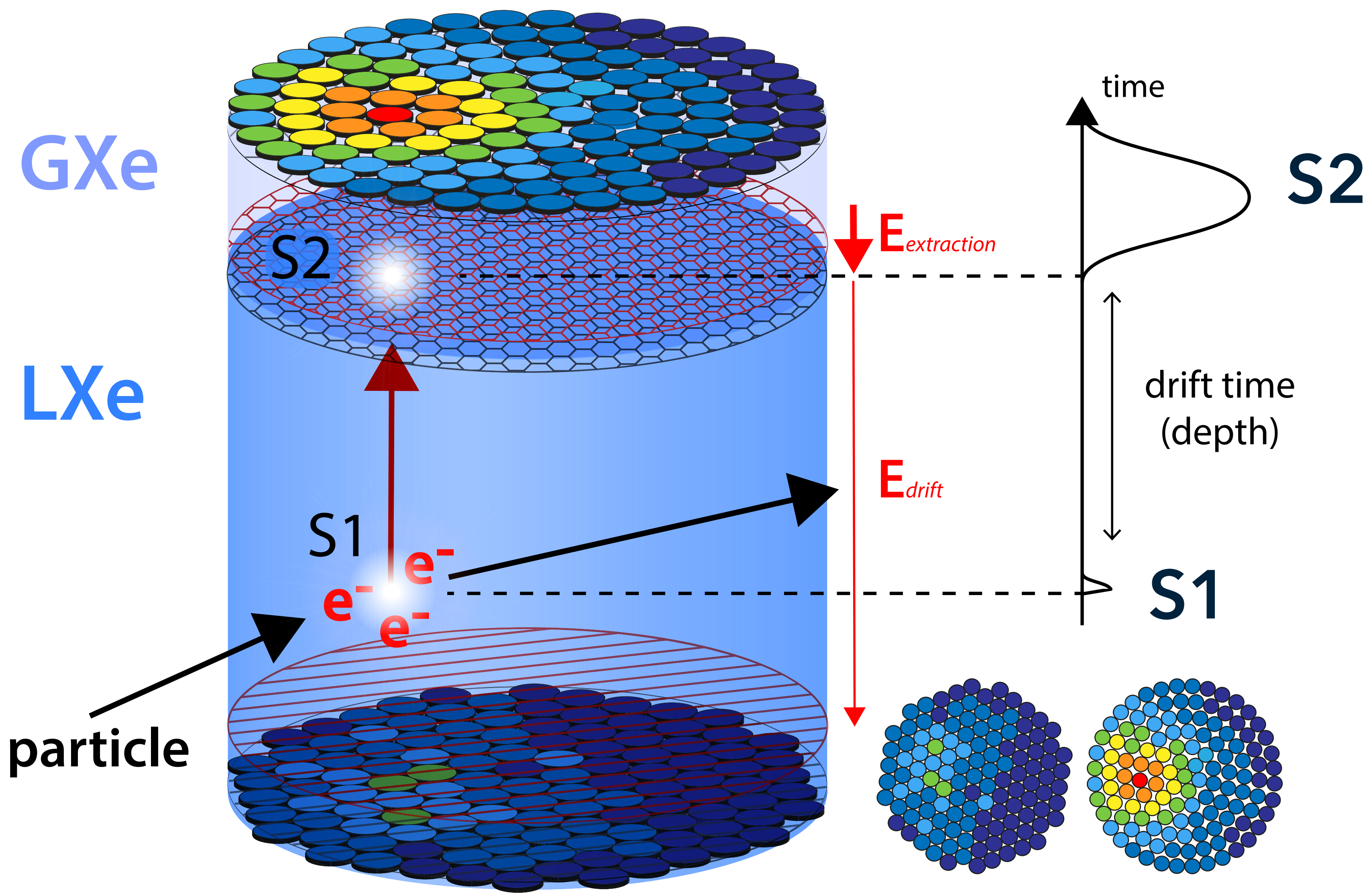
Nagoya

Kobe

NYUAD

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

Key Technology: Two-Phase Xenon Time Projection Chamber



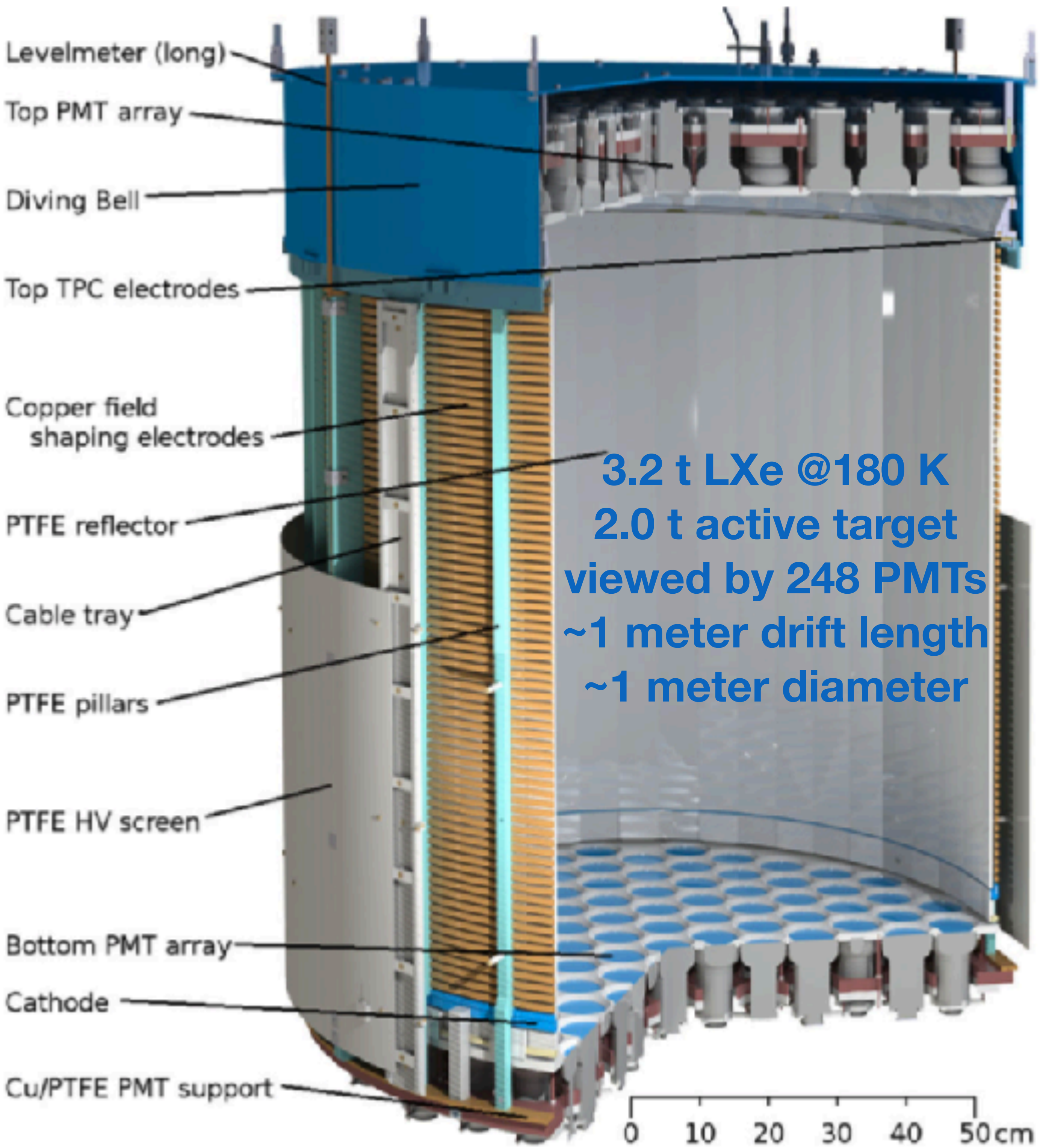
Why liquid xenon?

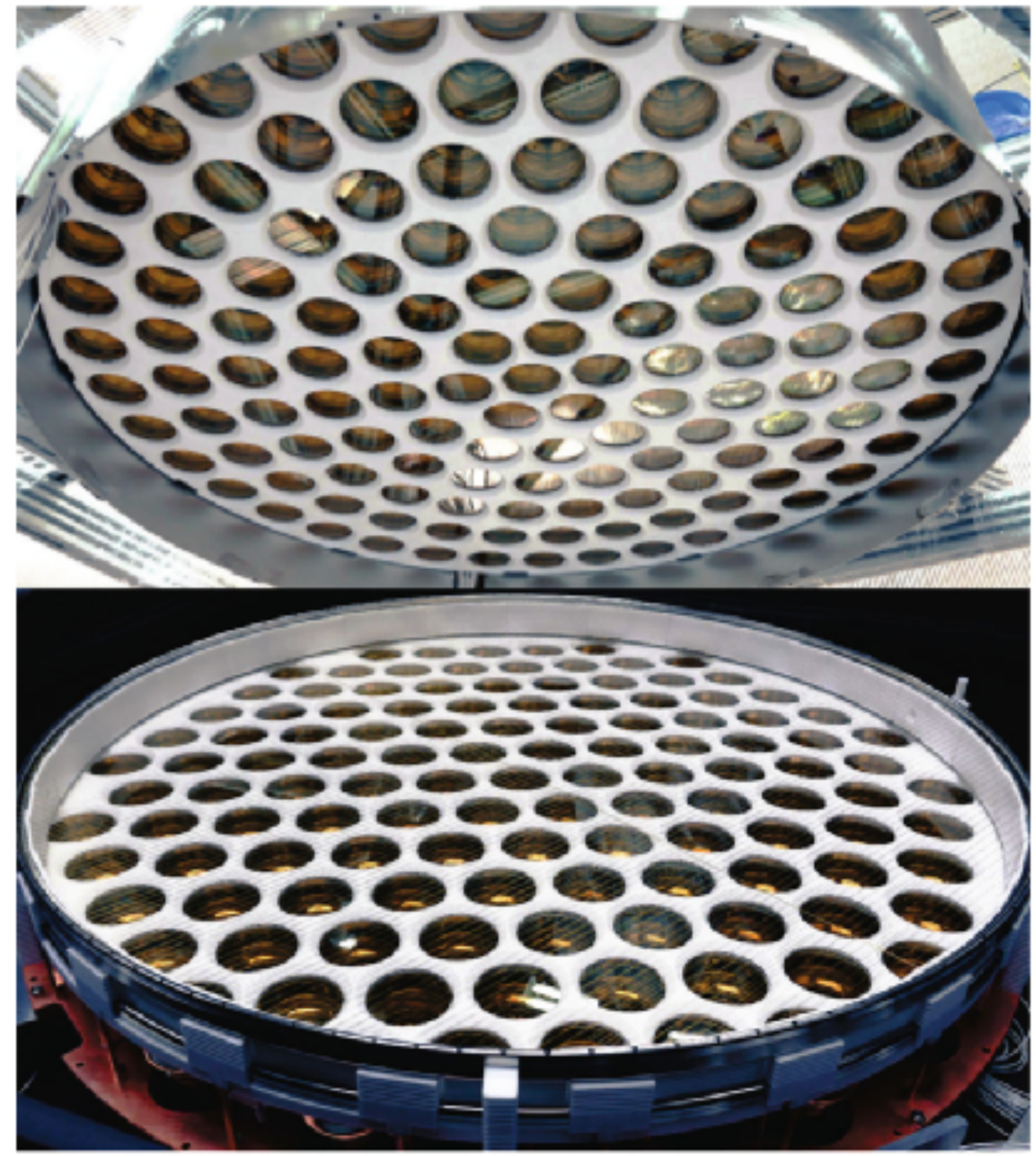
- large target feasible (cost, cryogenics)
- negligible intrinsic background
- fast and abundant scintillation
- sensitive to both SI and SD
- other physics (0vbb etc.)

Why two-phase TPC?

- 3D position sensitivity (fiducialization)
- electronic recoil (ER) and nuclear recoil (NR) discrimination
- low threshold (keV) with S1
- ultra-low threshold (sub-keV) with S2

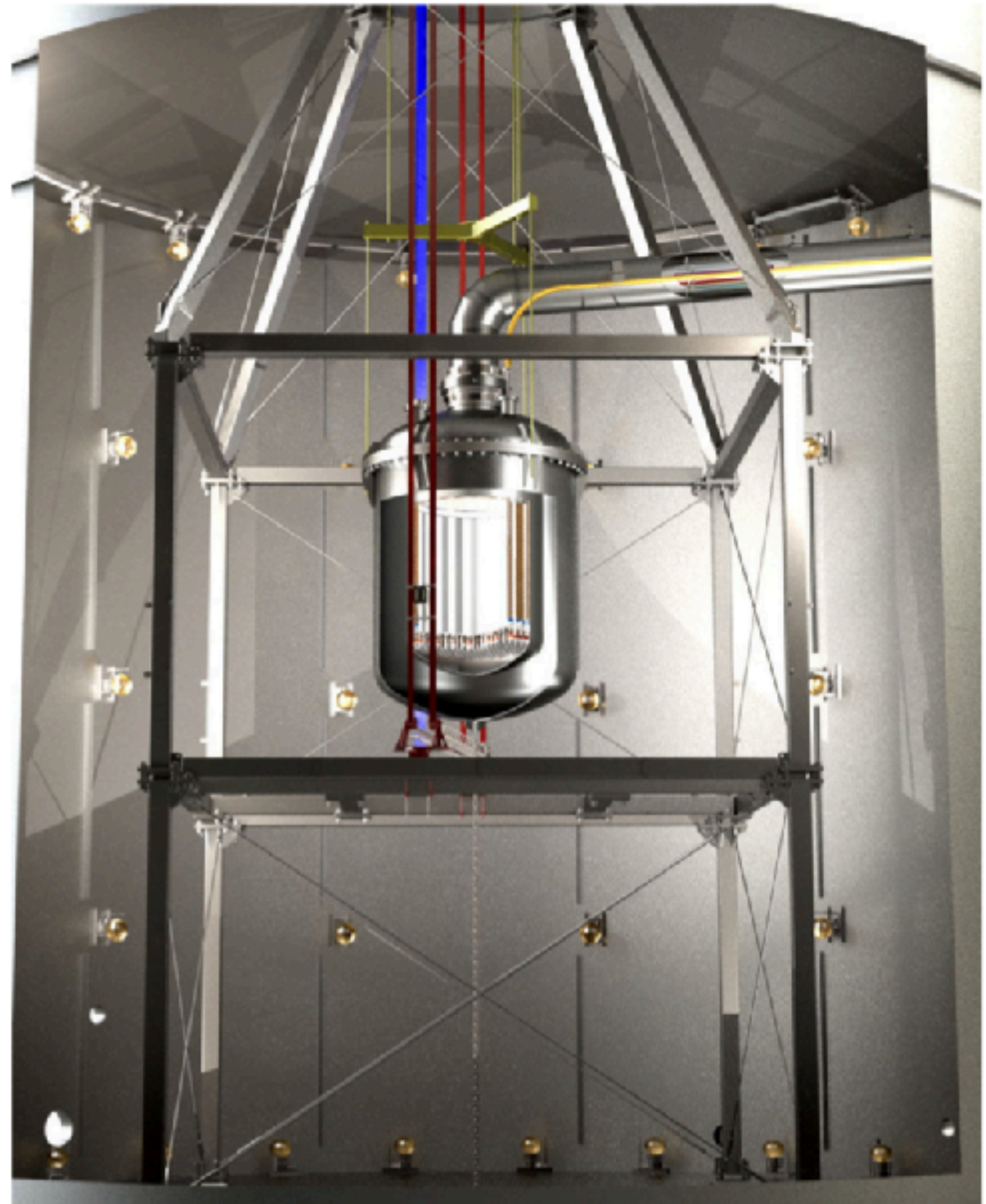
XENONIT Time Project Chamber





JCAP 04, 027 (2016)

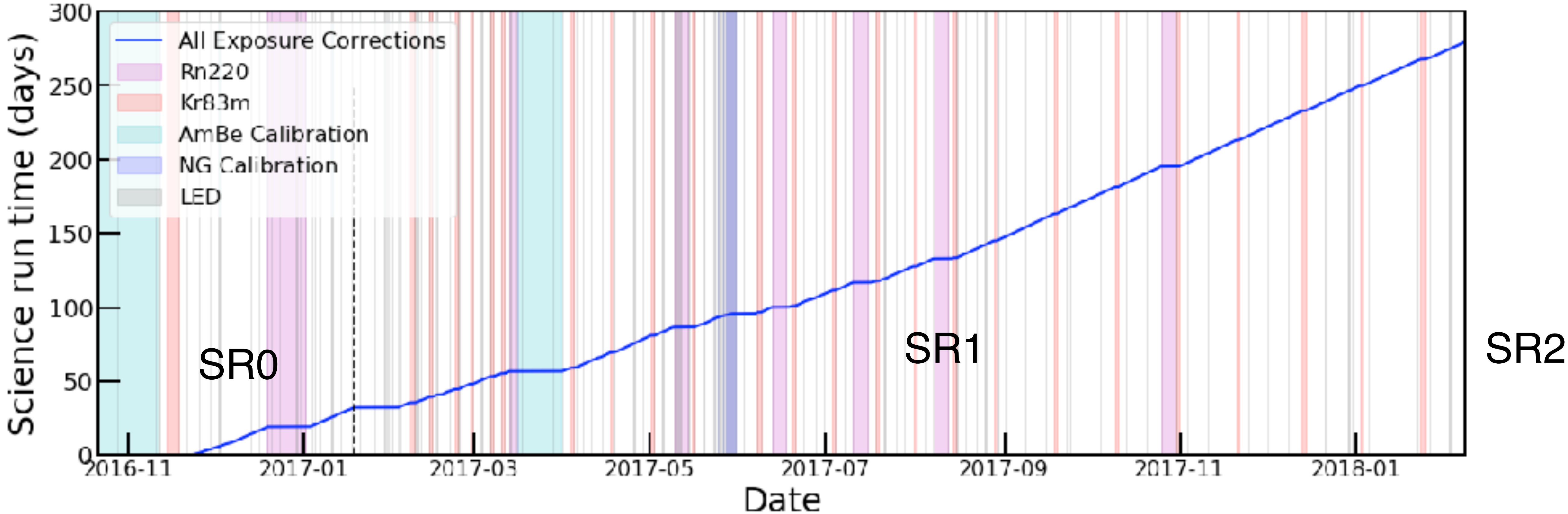
XENON1T Detector inside the Water Shield



XENON Experiment at Gran Sasso Underground Lab

XENON1T Science Runs (2016-2018)

- 279 live-days science run data (SR0 & SR1) collected between Nov. 2016 and Feb. 2018.

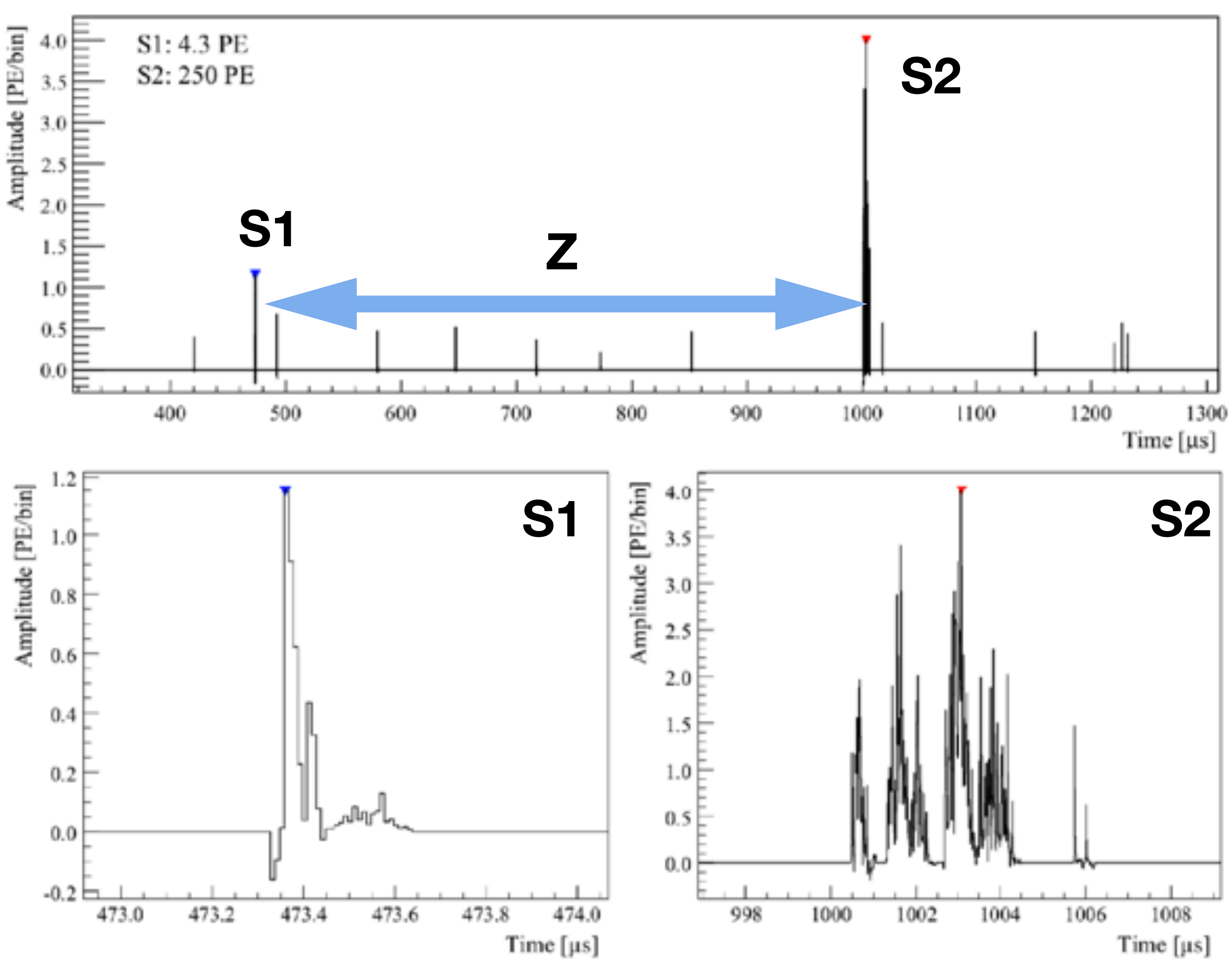


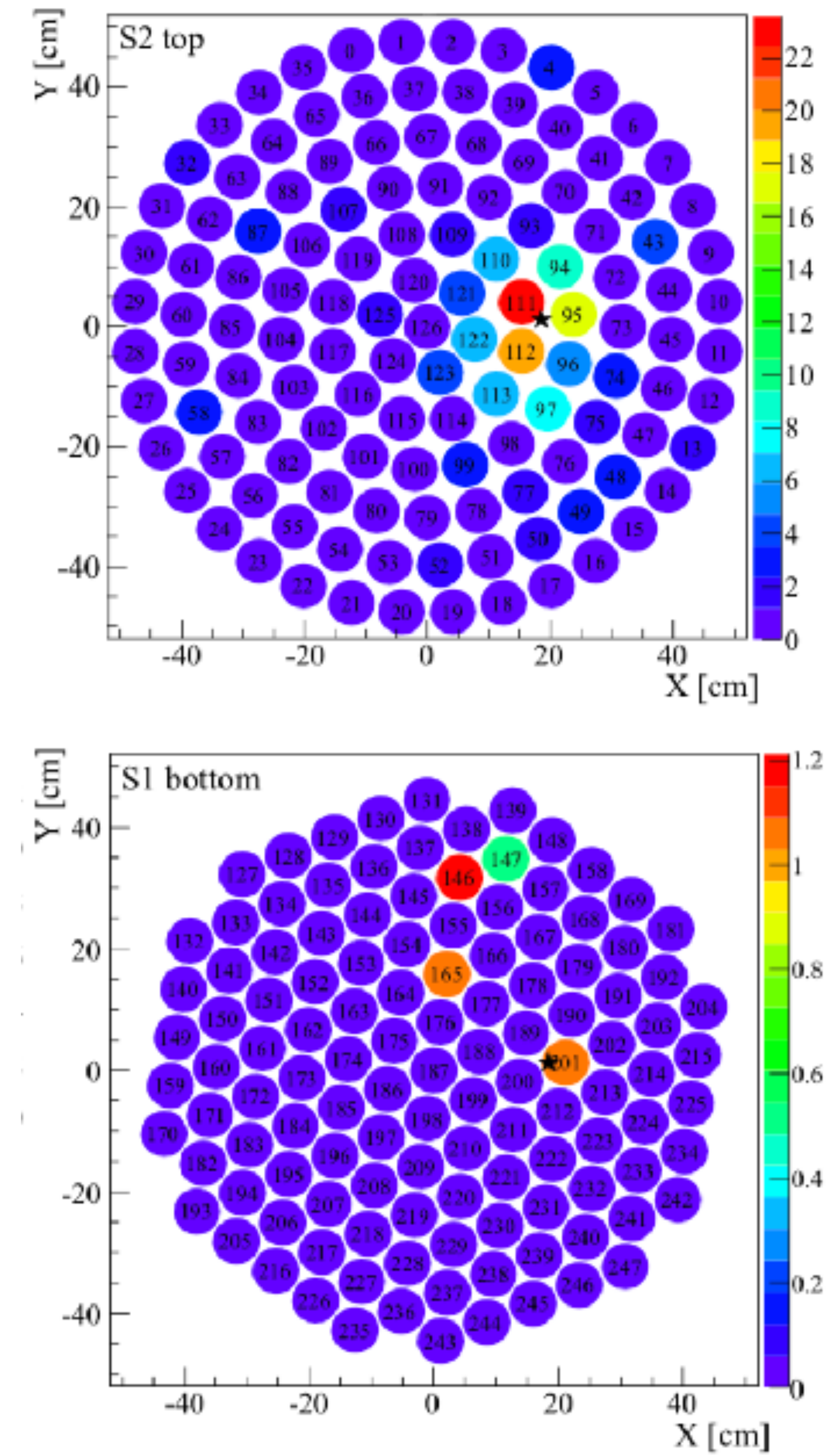
Instrument & Sensitivity & Analysis
JCAP 04, 027 (2016), 1512.07501
EPJ C 77, 881 (2017), 1708.07051
PRD 99, 112009 (2019), 1902.11297
PRD 100, 052014 (2019), 1906.04717
EPJ C 80, 785 (2020), 2003.03825

WIMP Search Results:
PRL 119,181301 (2017): first result
PRL 121, 111302 (2018): one ton-y SI
PRL 122, 071301 (2019): WIMP-pion
PRL 122, 141301 (2019): WIMP-SD
arXiv:2011.10431: inelastic scattering

Other search results:
Nature, 568, 532 (2019): Xe124 Double Electron Capture
PRL 123, 241803 (2019): light DM (Migdal effect)
PRL 123, 251801 (2019): light DM (S2-only)
PRD 102, 072004 (2020): low energy ER excess
(New) arXiv:2012.02846: search for CEvNS from ^{8}B solar neutrinos

A typical low energy event



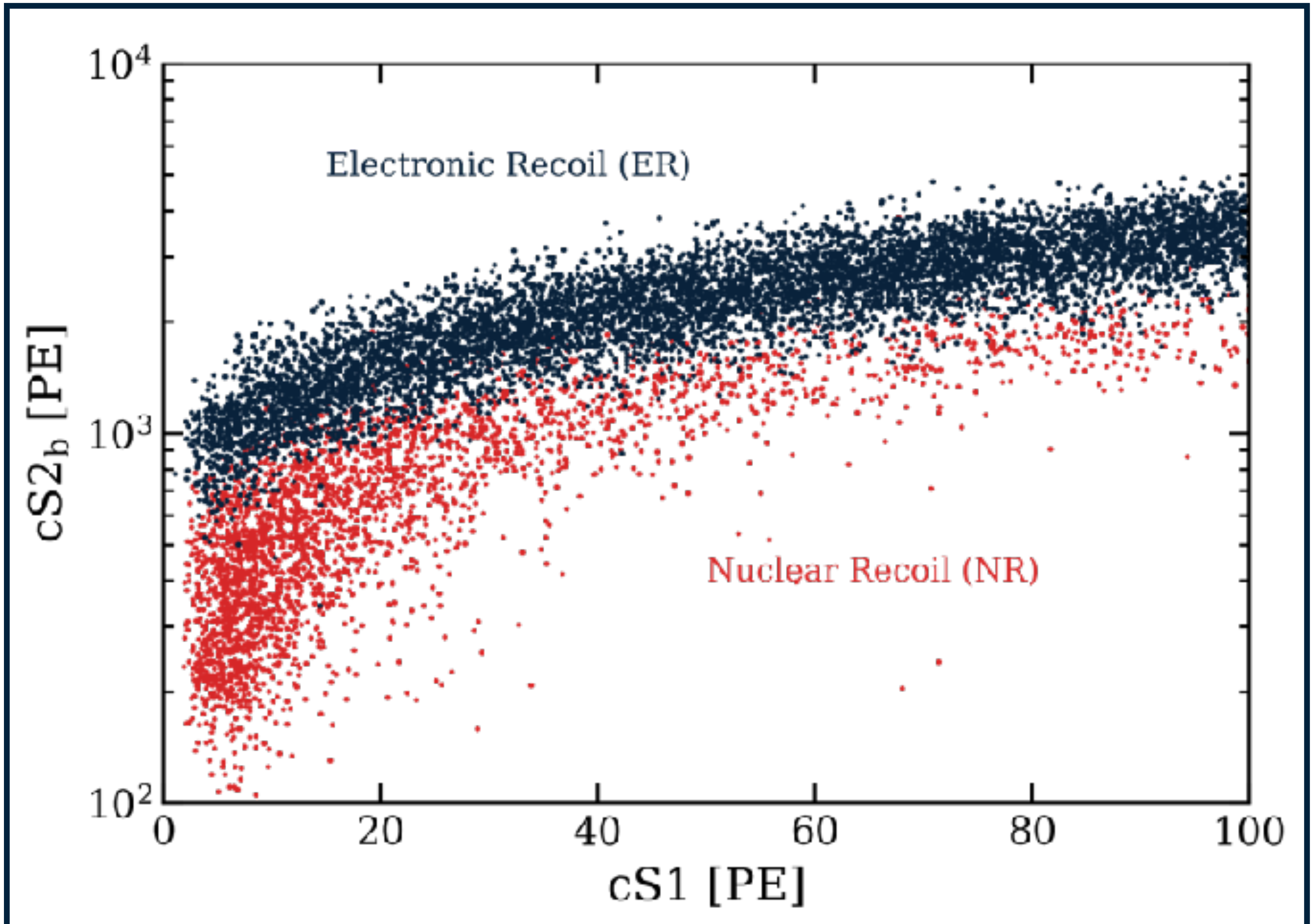


Parameters reconstructed from the waveforms:
S1, S2, XY positions, drift time (Z), etc.

PE: # of photoelectrons detected

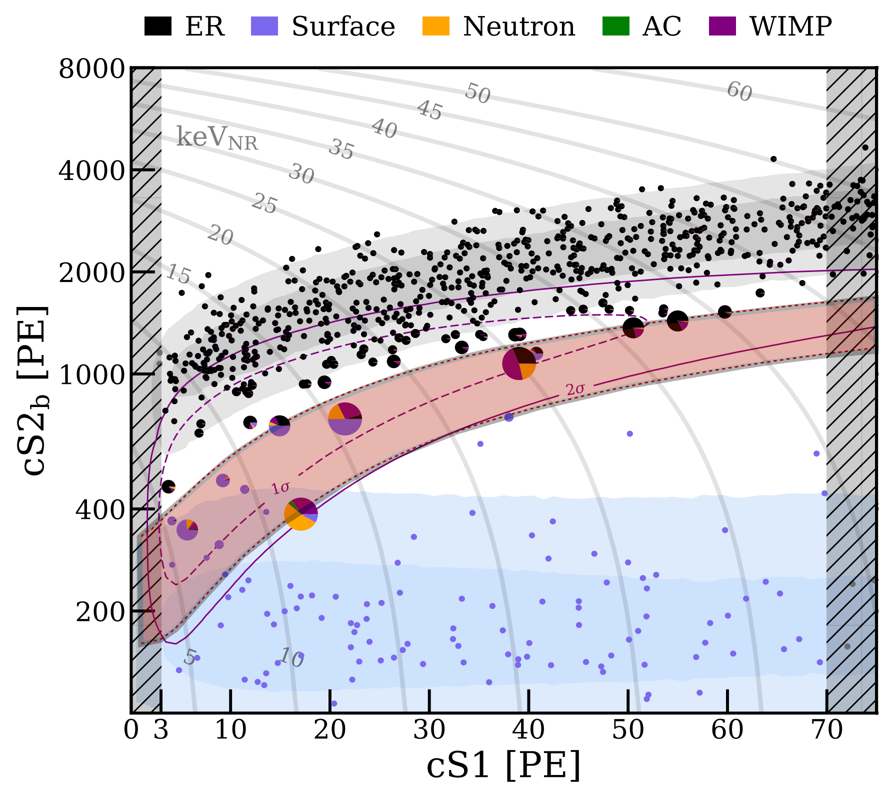
Event-type Discrimination in XENON1T

- **Electronic Recoils: gamma rays, beta decays, DM-electron scattering, neutrino-electron scattering…**
- **Nuclear Recoils: from WIMP dark matter, neutrino-nucleus coherent scattering, neutrons**

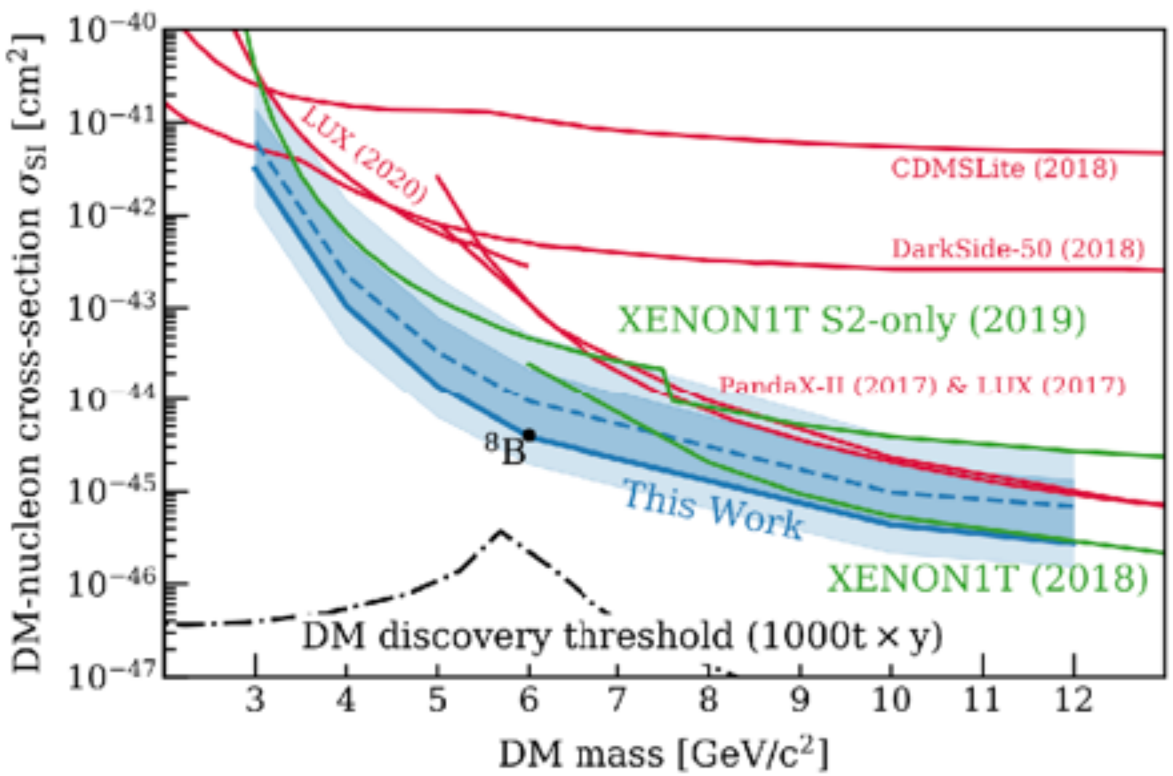


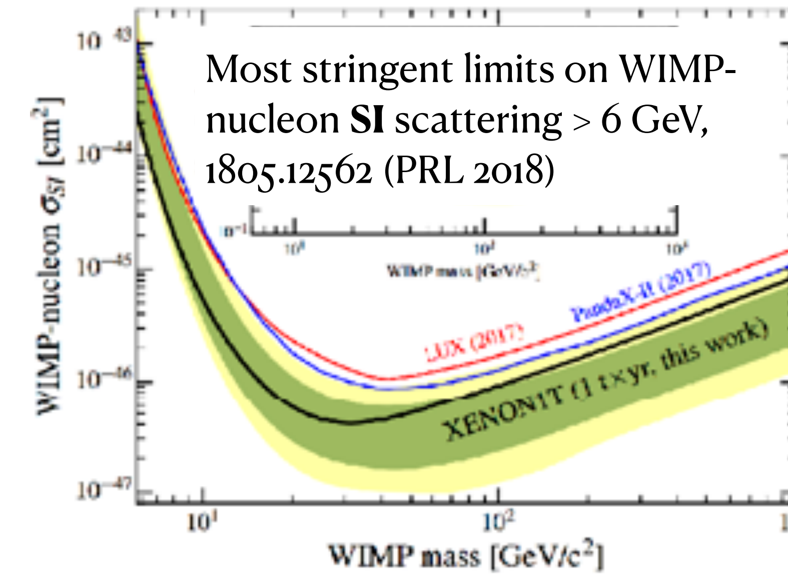
Plot from calibration sources (ER: beta decays; NR: neutrons)

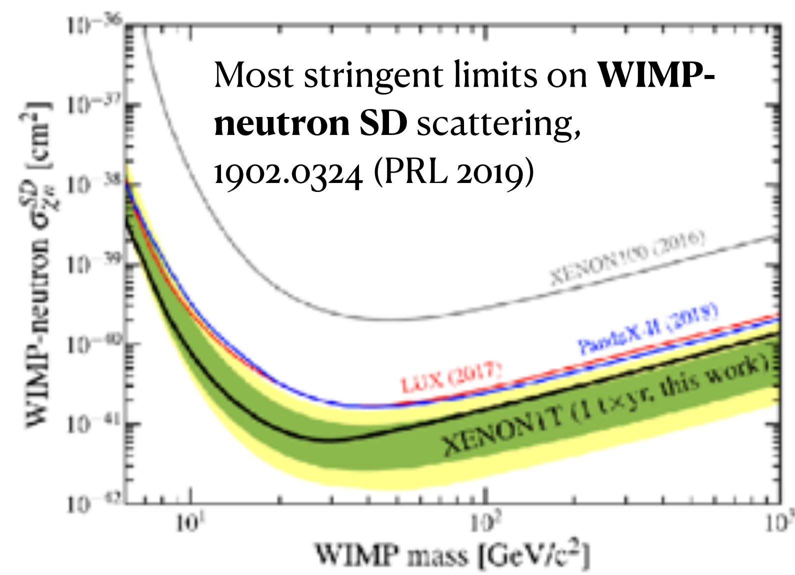
Search for WIMP Scattering in Nuclear Recoils

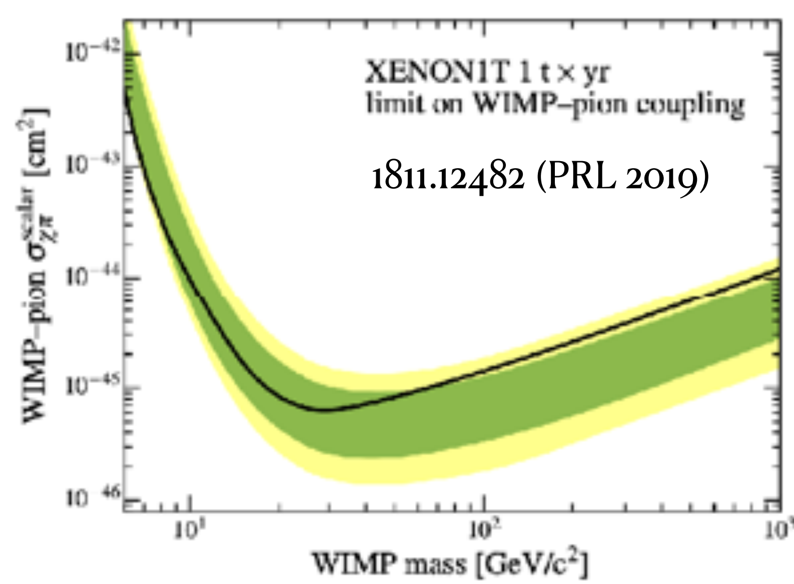


arXiv:2012.02846
Extending WIMP coverage down to 3 GeV



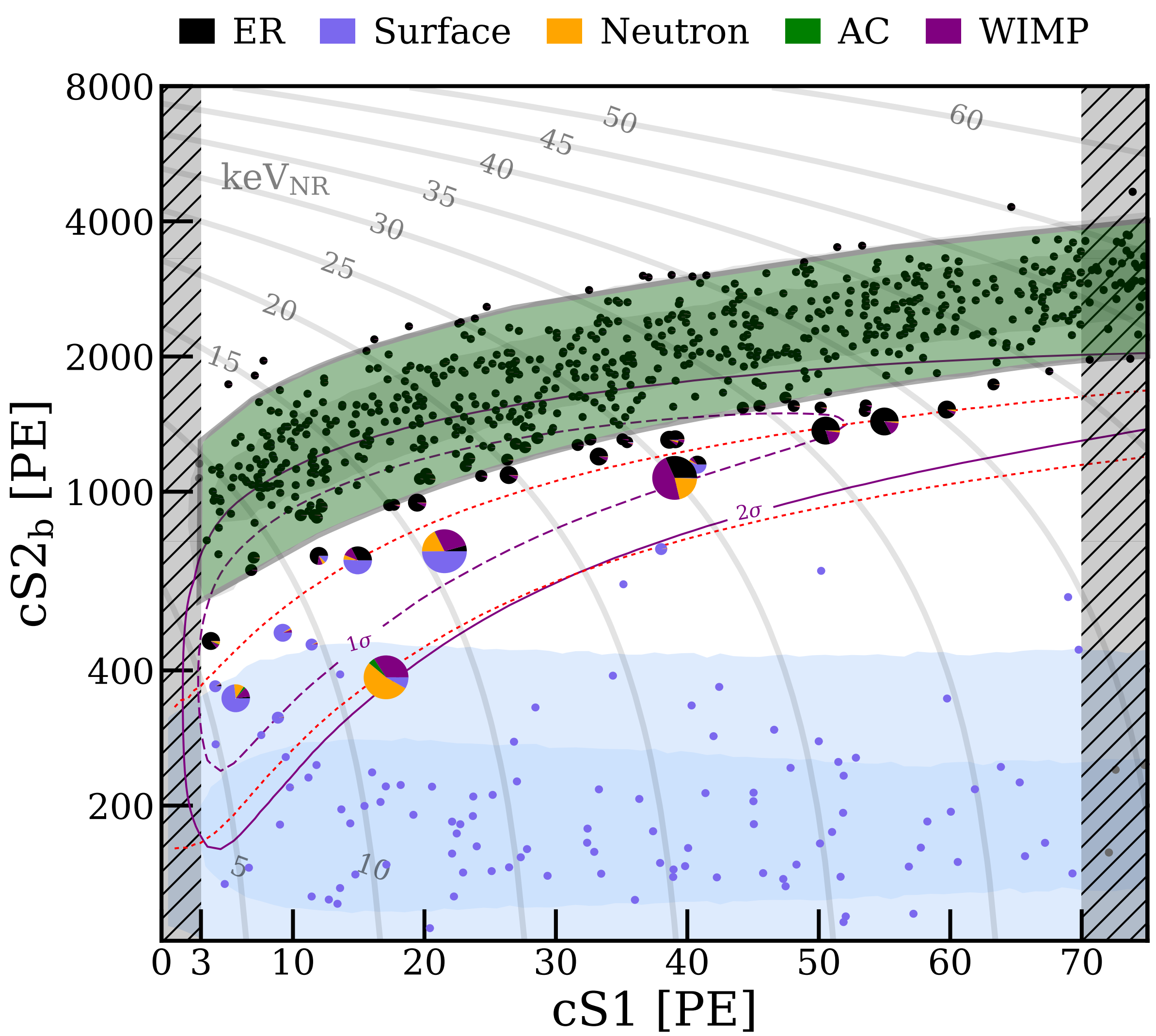


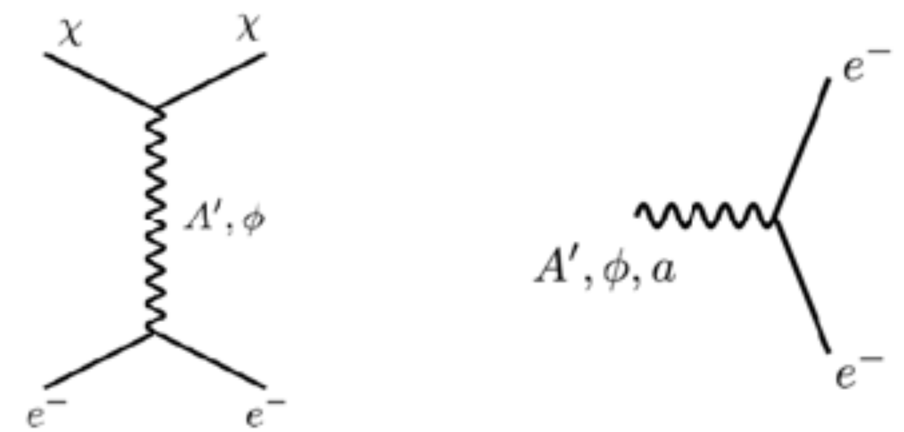




New Physics Searches with Electronic Recoils

Recent results reported: arXiv:2006.09721 (PRD 2020)



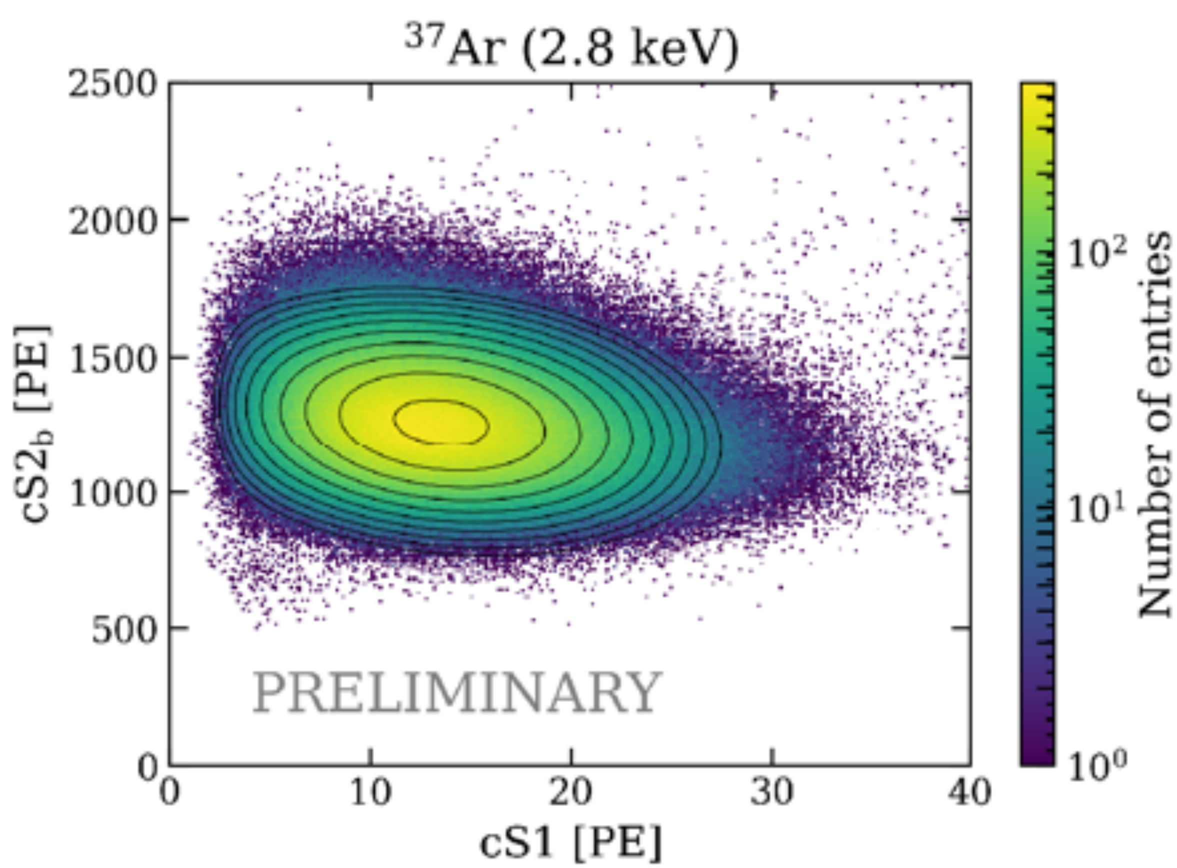


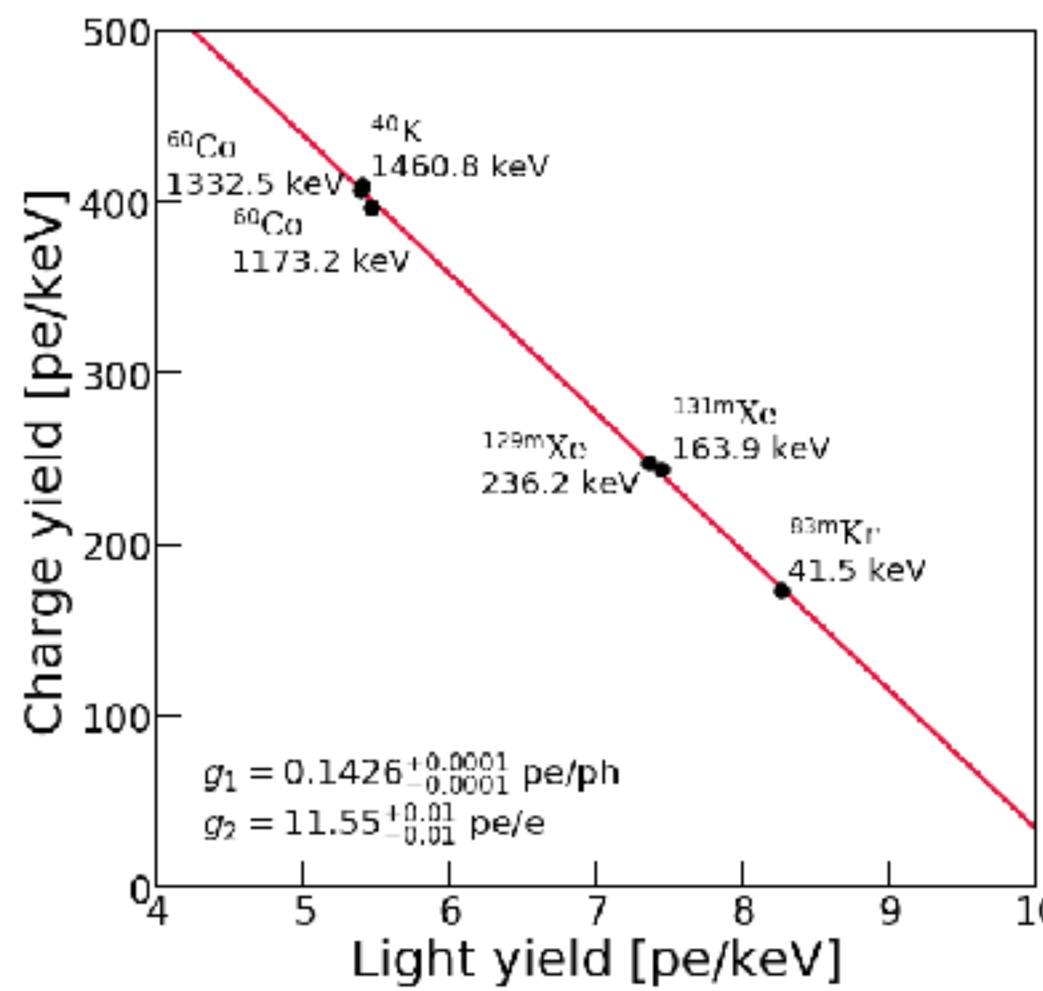
- Light dark matter scatters on electron
- **Solar neutrino - electron scattering**
- **Solar axion - electron interaction**
- Dark matter absorption and electron emission
    - **Axion-like particles (ALPs)**
    - **Dark photons**

Energy Reconstruction for Electron Recoils

- g_1, g_2 are detector-specific parameters, determined from all available calibration lines
- W = 13.7 eV is the average energy needed to produce a photon or electron in LXe
- energy reconstruction validated down to 2.8 keV (peak from ^{37}Ar calibration)

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

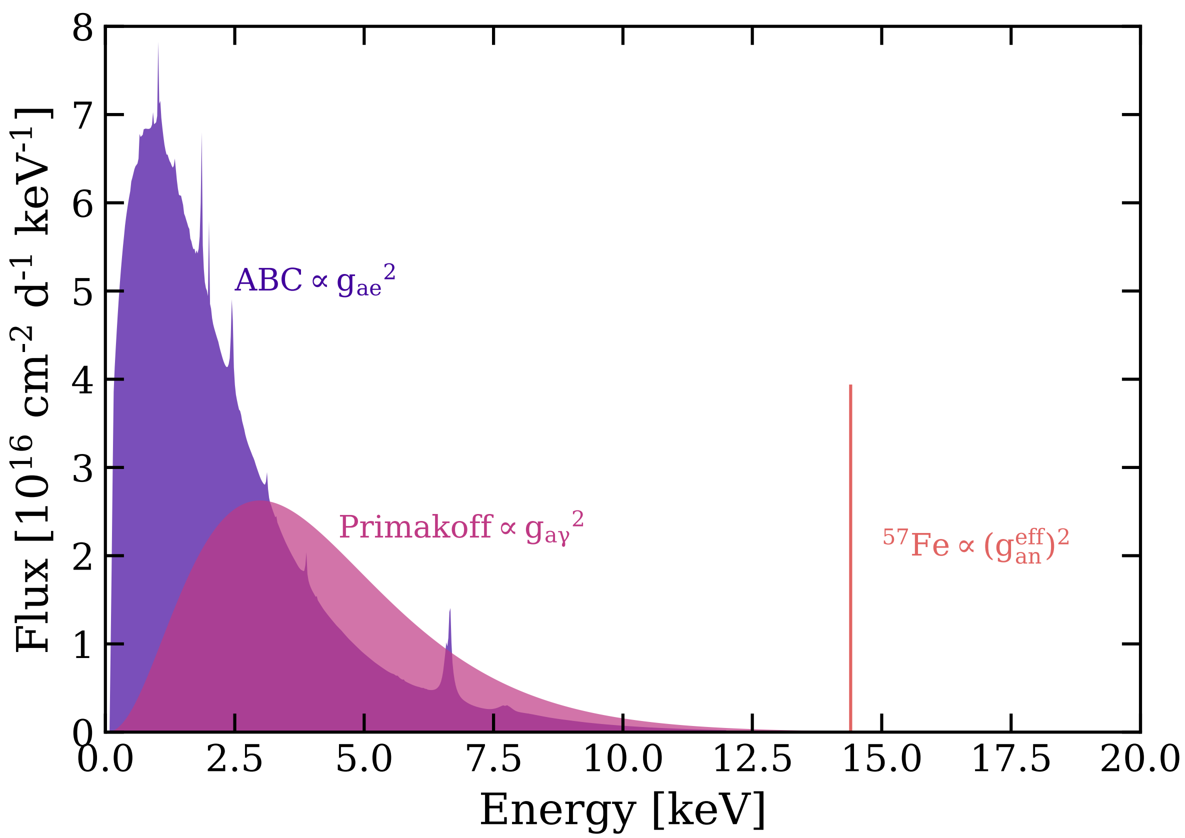




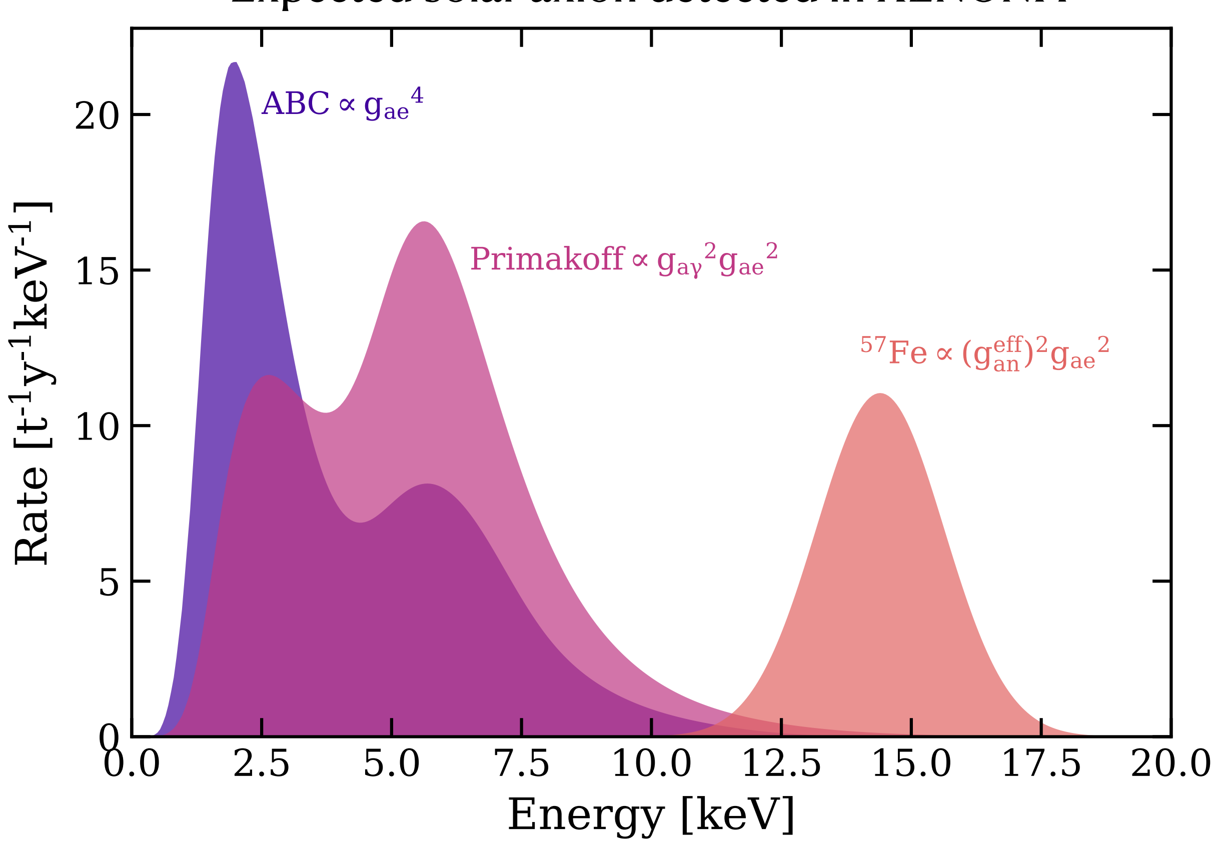
Solar axion search in XENON1T

- Axion is the theoretically-motivated new particle to solve the "strong CP problem"
- Axion could be the DM candidate particle to also solve the "dark matter problem", but the mass of DM axion would be too low to be detected by XENON1T
- **Axions could be produced in the Sun**
  - **via three model-dependent couplings:** $g_{ae}, g_{a\gamma}, g_{an}$
  - **detectable kinetic energy ~keV in XENON1T**
- **Solar axions are detected in XENON1T via axioelectric effect:** $\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$

Solar axion flux on earth



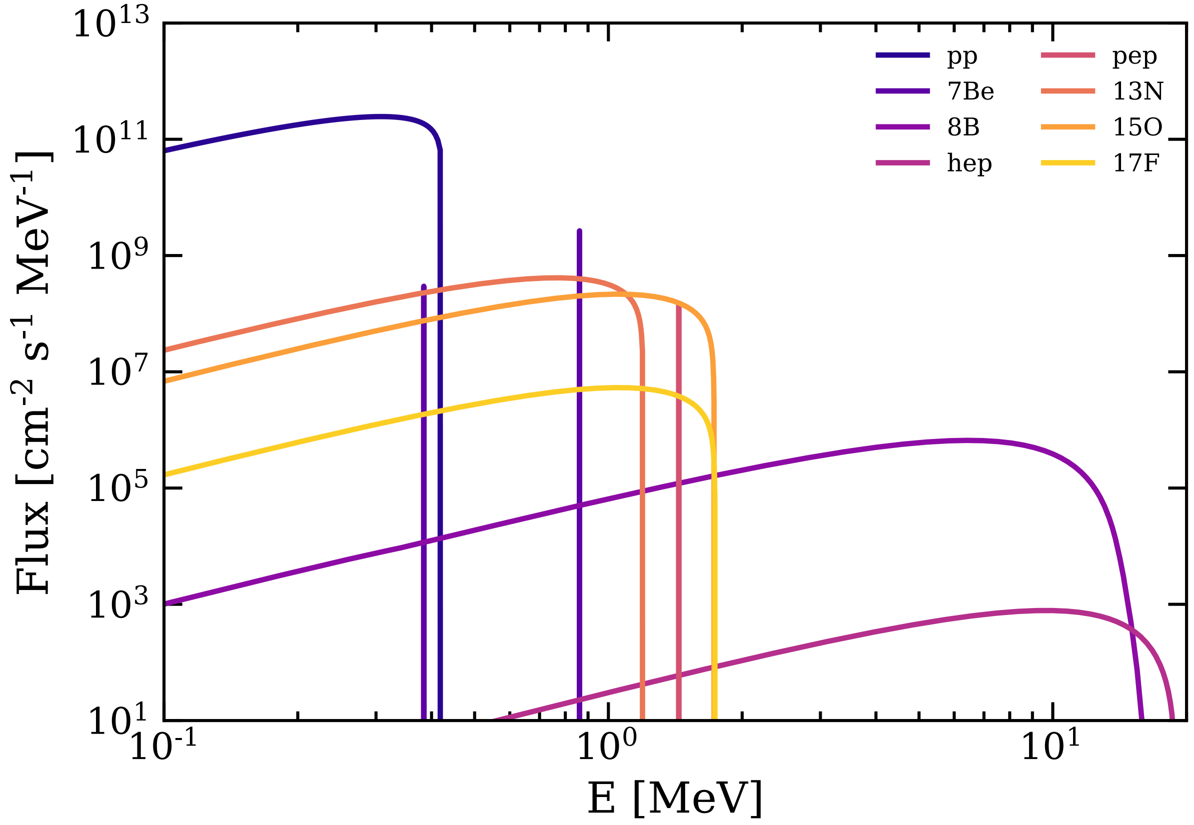
Expected solar axion detected in XENON1T



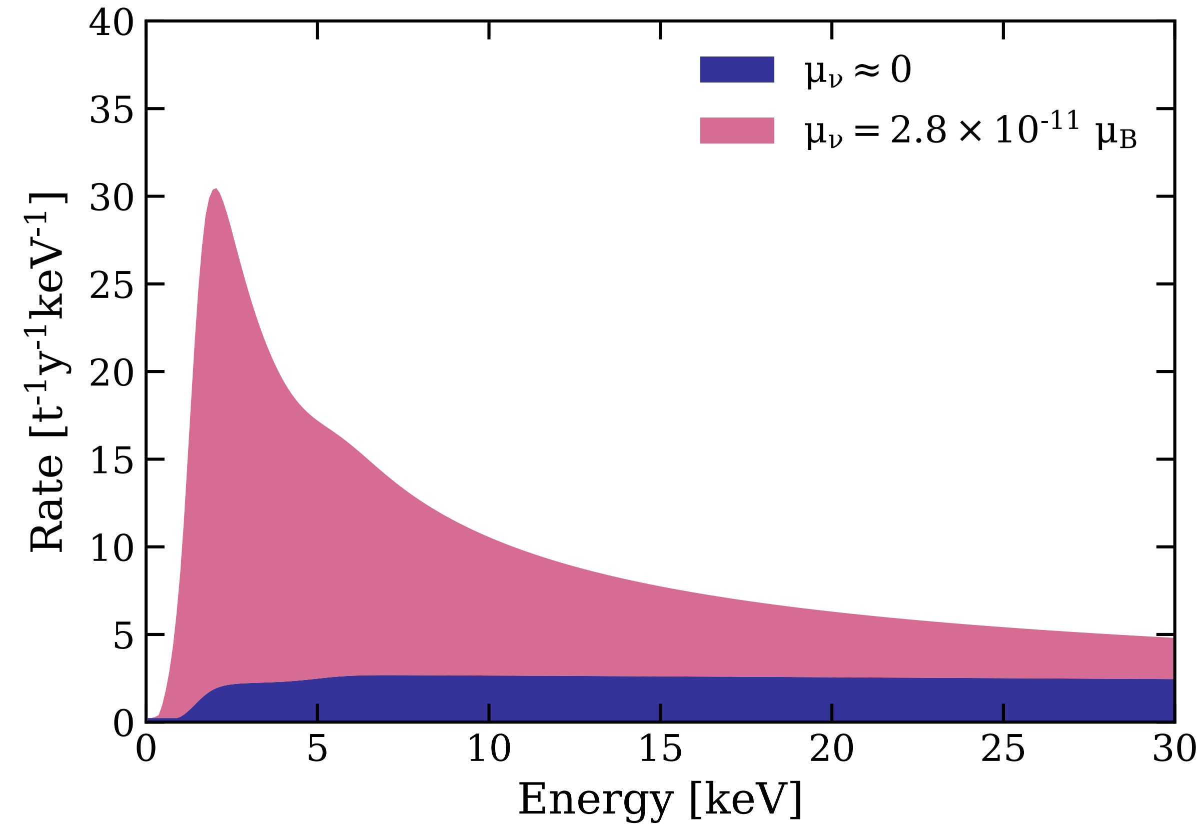
Solar neutrino detection in XENON1T

- Solar neutrinos would also be detected by XENON1T via elastic scattering on electron or nucleus.
- Solar neutrino electron scattering contributes a minor electronic recoil background
- **A large neutrino magnetic moment ($\mu_\nu \geq 10^{-15}\mu_B$) would enhance the solar neutrino electron scattering rate, a signature for new physics and indicate Majorana nature of neutrinos**

Solar neutrino flux



Expected solar neutrino in XENON1T
(with or without mag. moment)



Bosonic dark matter, ALPs, dark photon

- **Axion-like particle (ALPs), similar to QCD axions, are pseudoscalar bosons and viable DM candidates with mass higher than QCD axions.**

- **This class of models can be searched in XENON1T with mono-energetic electronic recoil peaks**

- **ALPs can be absorbed in Xe via axioelectric effect and produce mono-energetic peaks, with rate:**

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

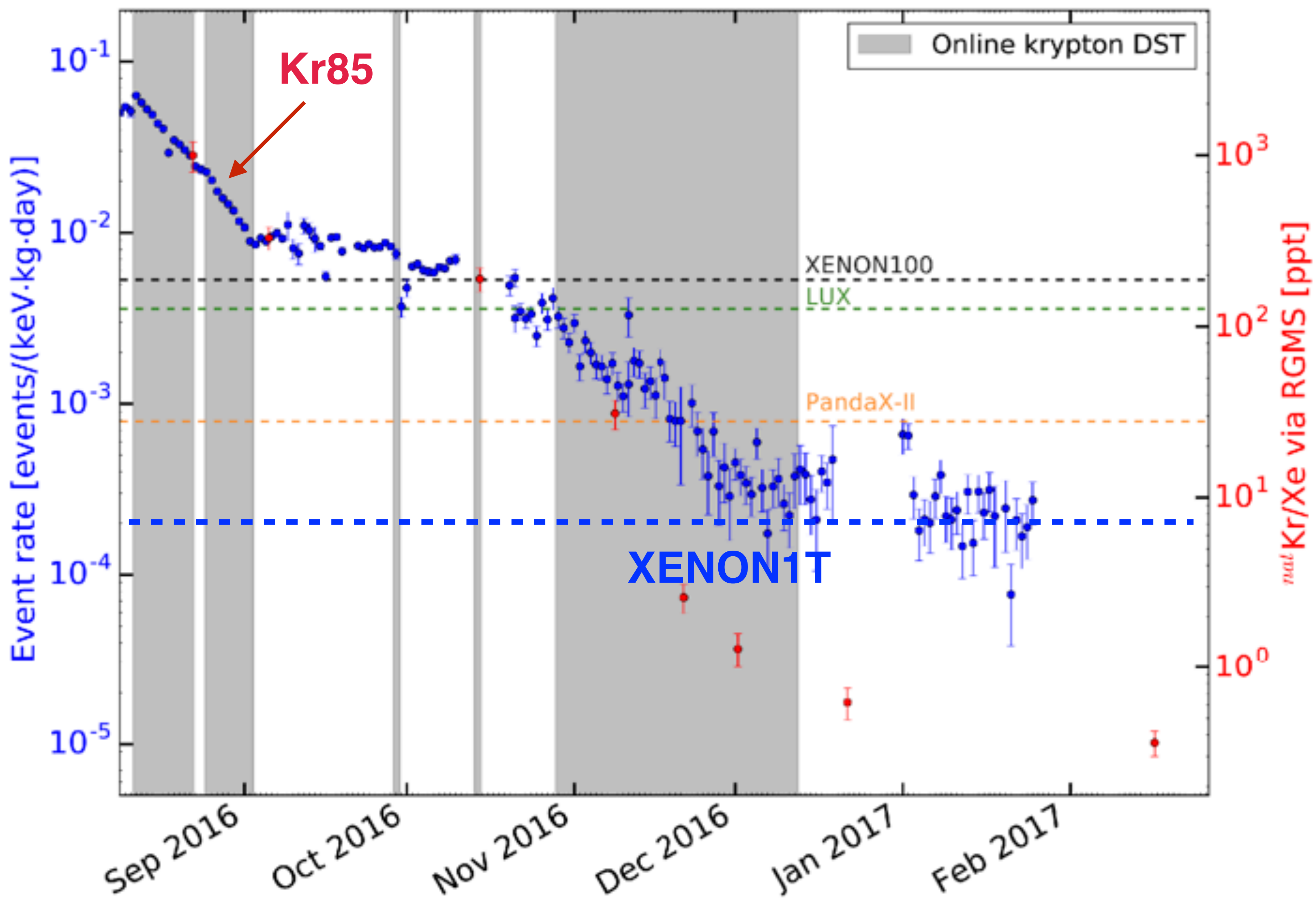
- **XENON1T is also sensitive to vector bosonic dark matter (eg. dark photon), coupled with SM photons via kinetic mixing term κ, with rate:**

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

➡ Looking for "peaks" above **known ER background**

Internal Electronic Recoil Background in XENON1T

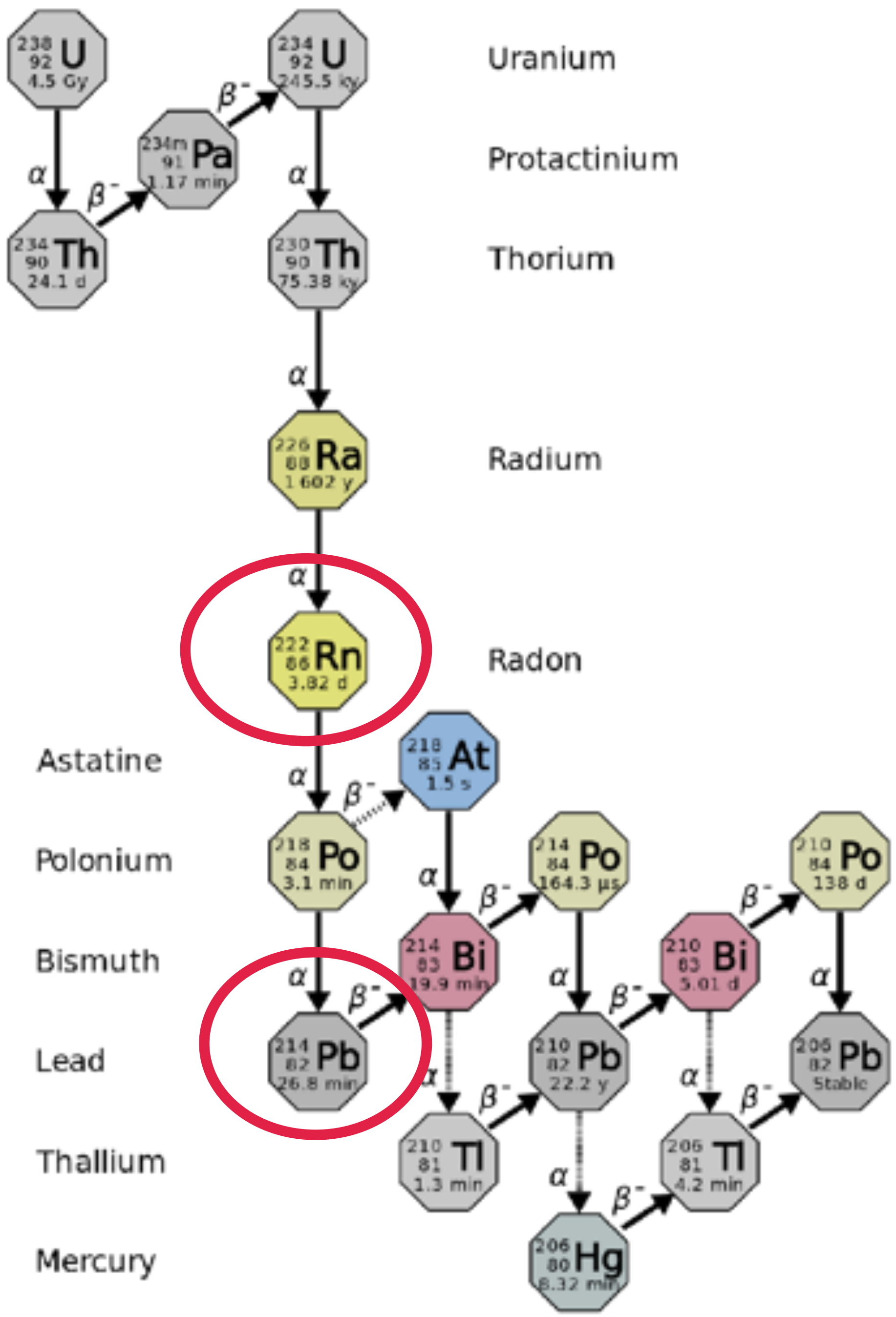
- Cryogenic distillation to reduce Kr/Xe from ~10 ppb (commercial) to sub-ppt to suppress ER background from **Kr85** beta decay
- Lowest ER background achieved in >1 tonne of DM-search target
- **Remaining ER background mainly comes from Radon-222**

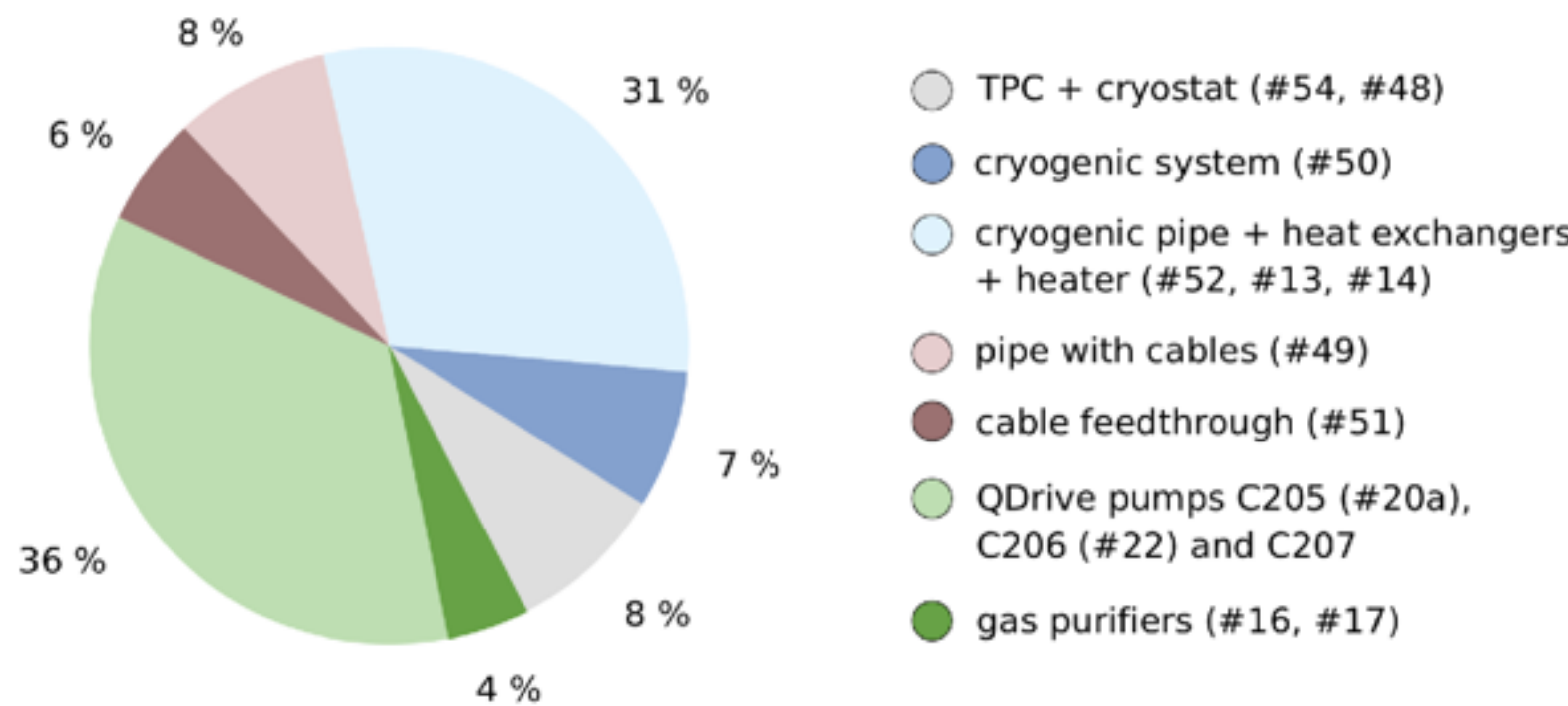


1612.04284 (EPJ 2017)

Radon-222

- Radon is a radioactive gas (half-life 3.8 d) from the breakdown of uranium in soil, rock, water and, in our case, detector materials
- Radon natural level in air: ~15 Bq/m^3
- Radon measured in the XENON1T target: ~10 μBq/kg of xenon



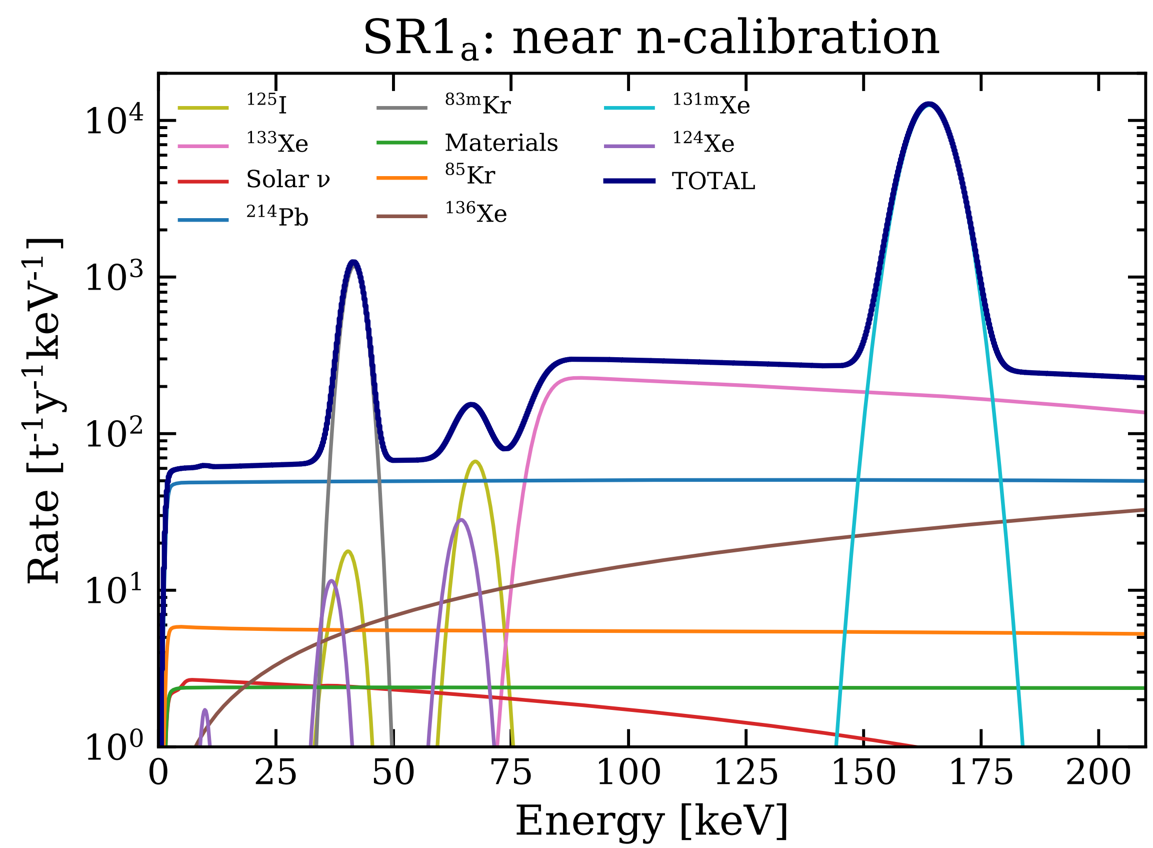


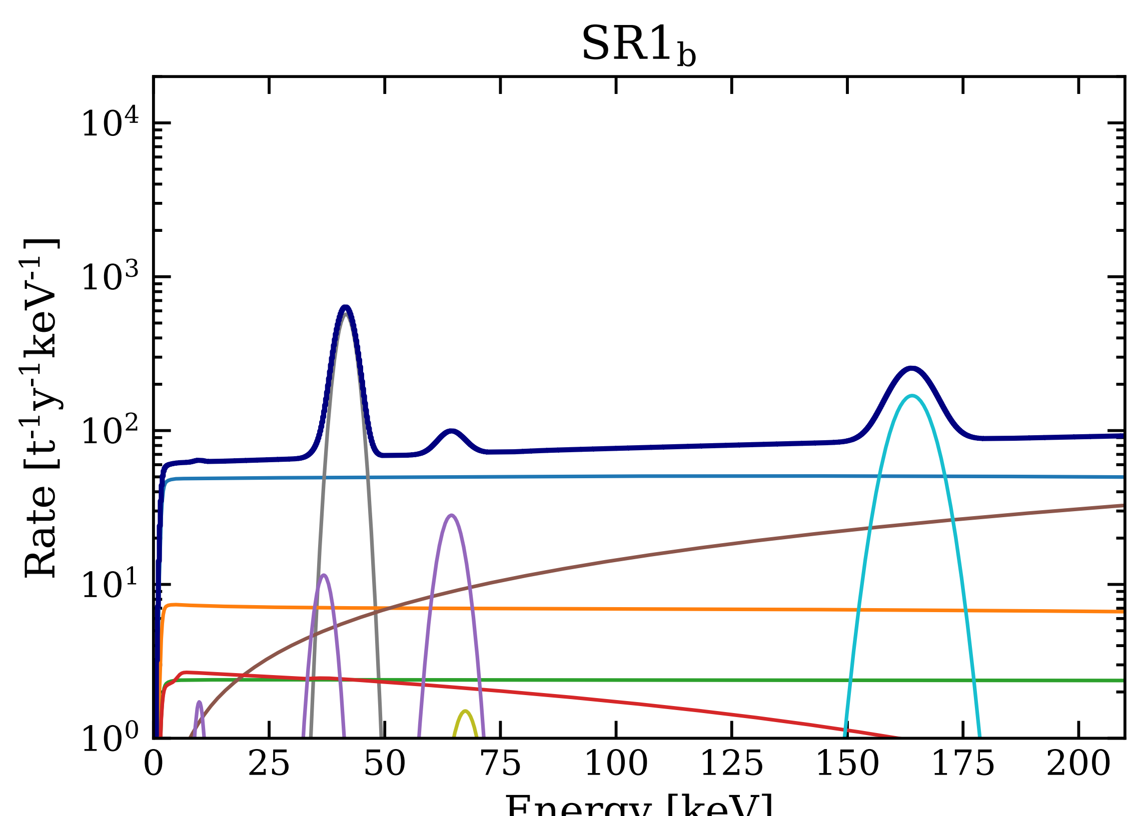
Radon-222 emanation measurements for XENON1T
arXiv:2009.13981

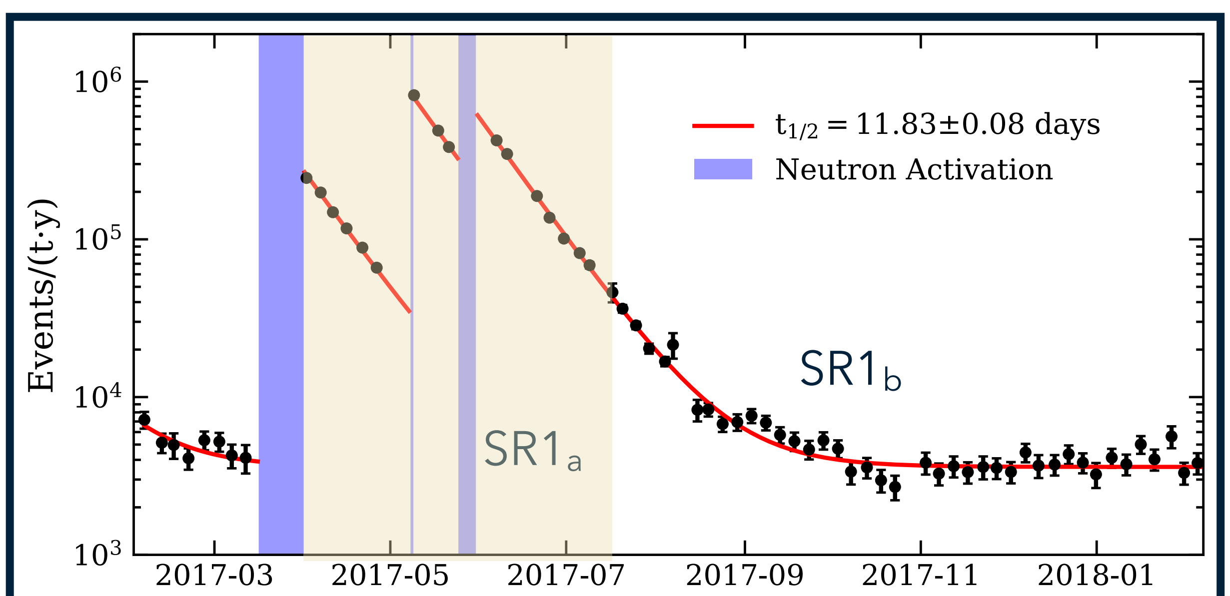
10-component of ER background in XENON1T

- **Internal background:**
  - Pb-214 from Radon, beta decay, dominant at low-energy
  - Kr-85, sub-ppt, beta decay
- **Intrinsic background:**
  - Xe-124, double electron capture peaks, first observed in XENON1T (1904.11002,Nature 2019)
  - Xe-136, double beta decay
- **Activated background**, following neutron calibration:
  - Xe-131m, 164-keV peak
  - Xe-133, beta+gamma, >80-keV
  - I-125, gamma+internal conversion electrons peaks
- **External**:
  - Gammas from surrounding materials: sub-dominant
  - solar neutrino - electron scattering (sub-dominant)
- **Contaminant**:
  - Kr-83m, 41.5 keV peak

Expected background spectrum in XENON1T

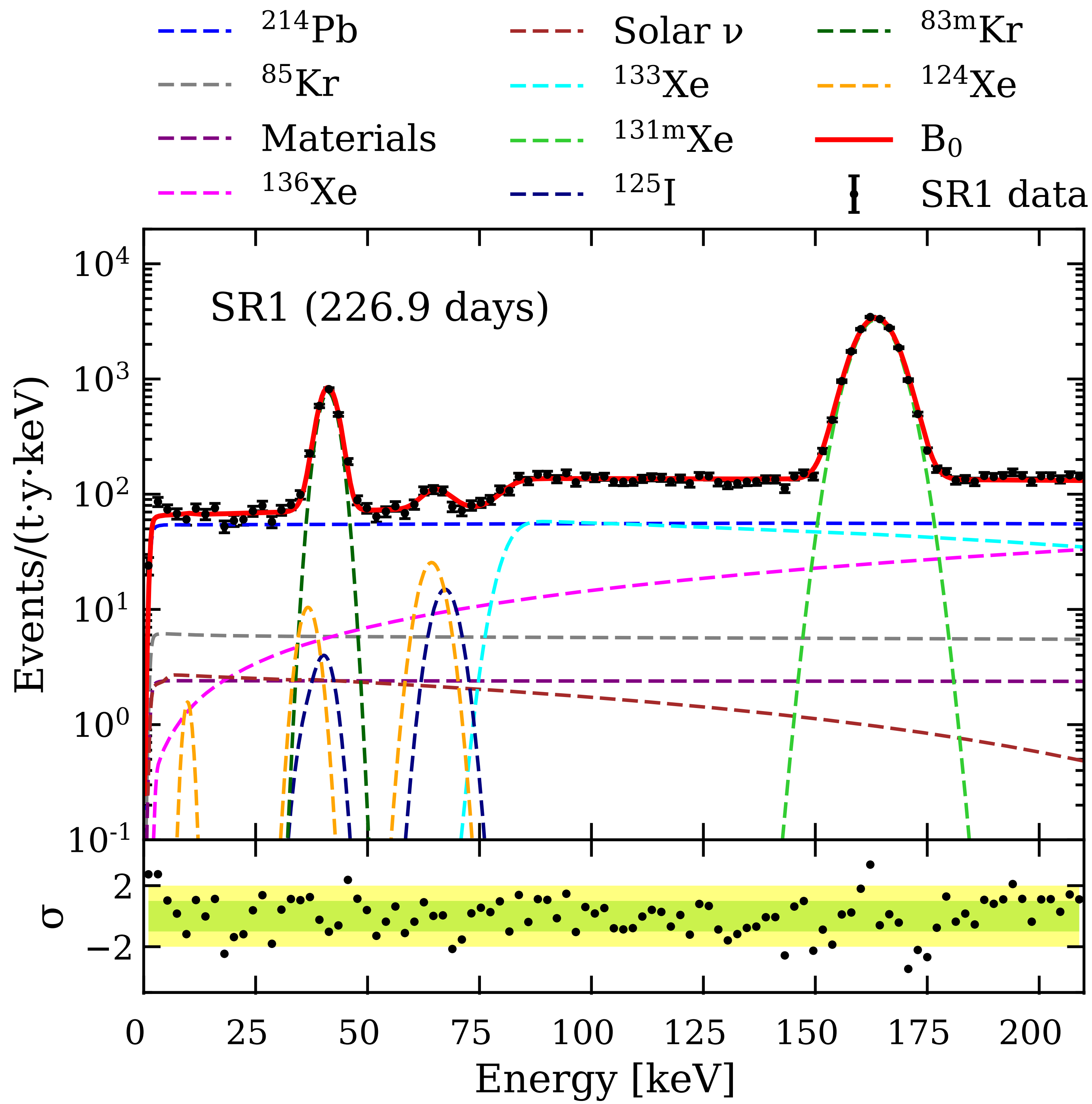






Time-evolution and model of ^{131m}Xe

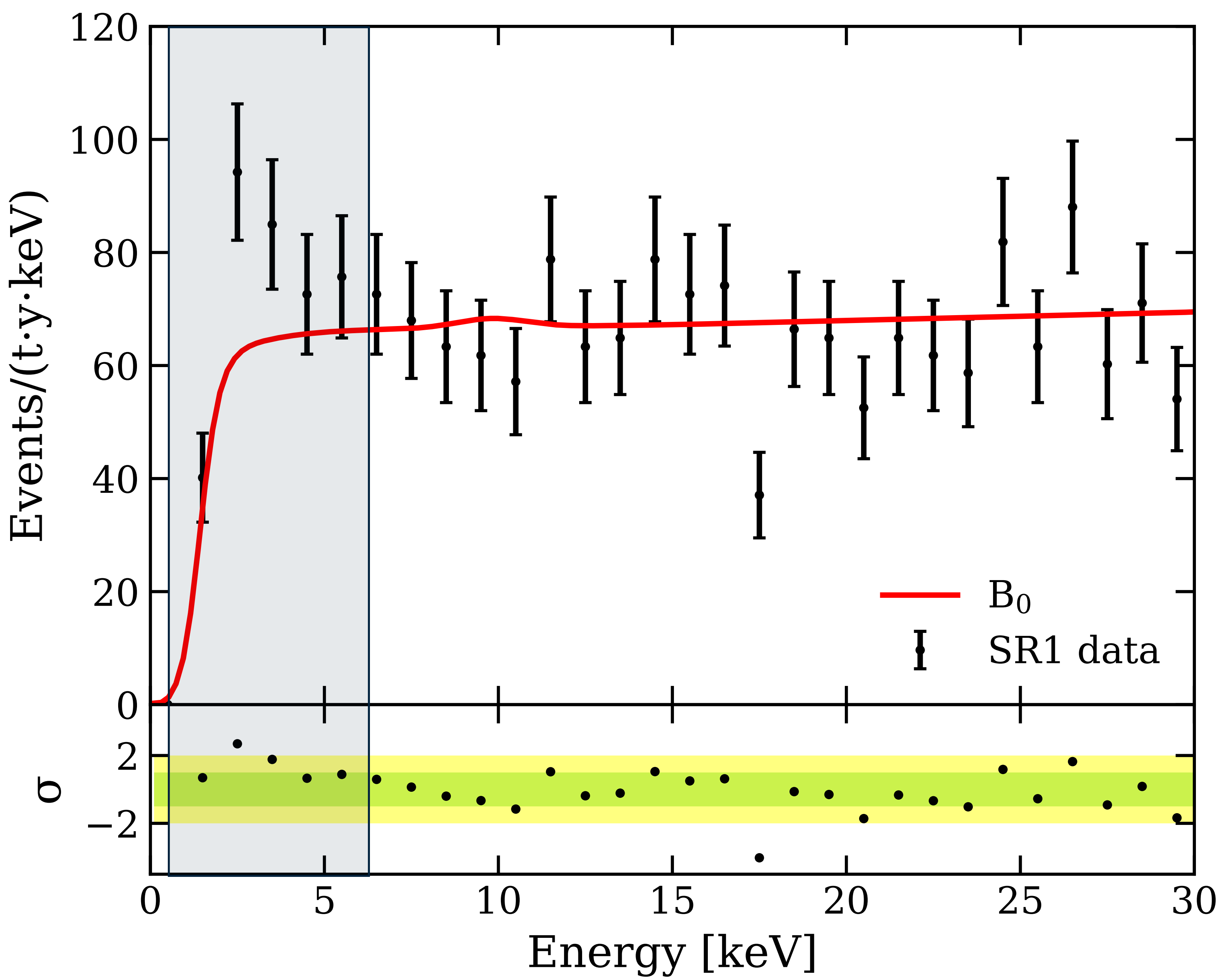
Compare observed data with the background model (B_0)



- Lowest background rate observed in any dark matter detector with one-ton target
- Observed rate consistent with expected background model, except at the lowest energy bins

Looking into the low energy region

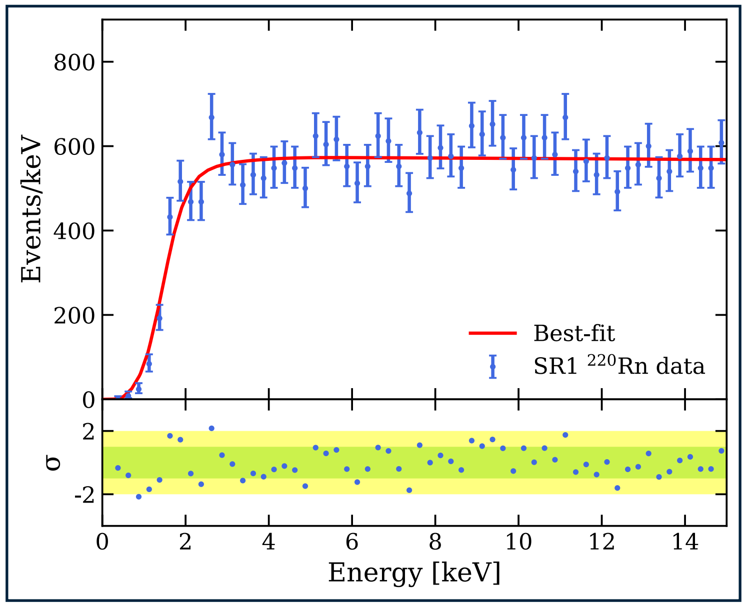
- Clear excess events between 1-7 keV
- 285 events observed vs. 232 ± 15 events expected from B_0 (3.3σ fluctuation)



unbinned data: https://doi.org/10.5281/zenodo.4273099

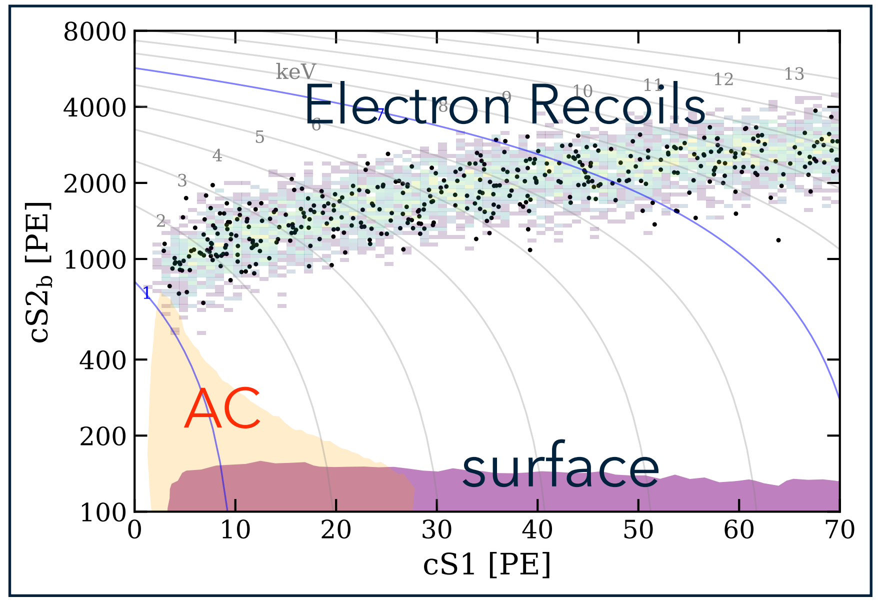
Possible energy misconstruction or instrument background?

validate energy reconstruction



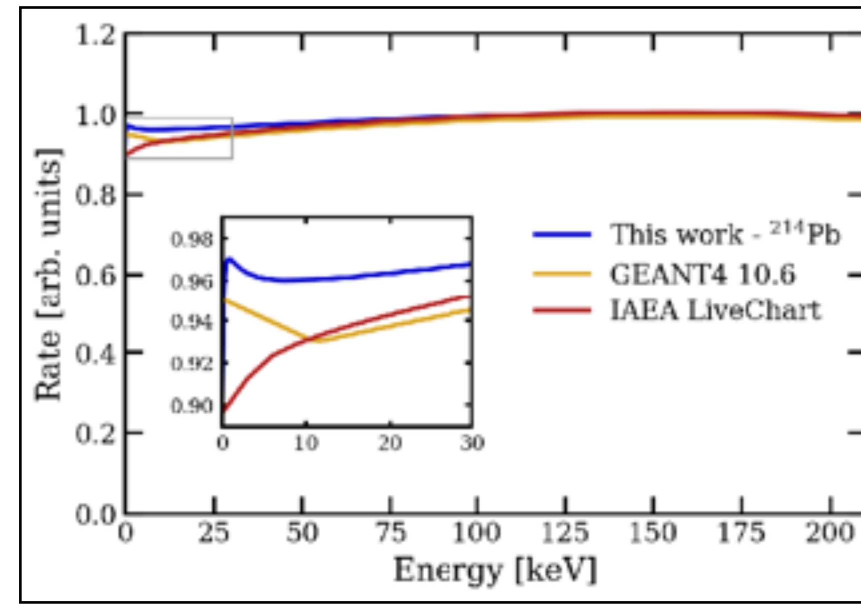
- same analysis framework used to fit ^{220}Rn (^{212}Pb) calibration data
- g.o.f p = 0.5
- validated efficiency and energy reconstruction

instrument background check



- accidental-coincidence (AC) and surface backgrounds not contribute to electron recoils, as expected

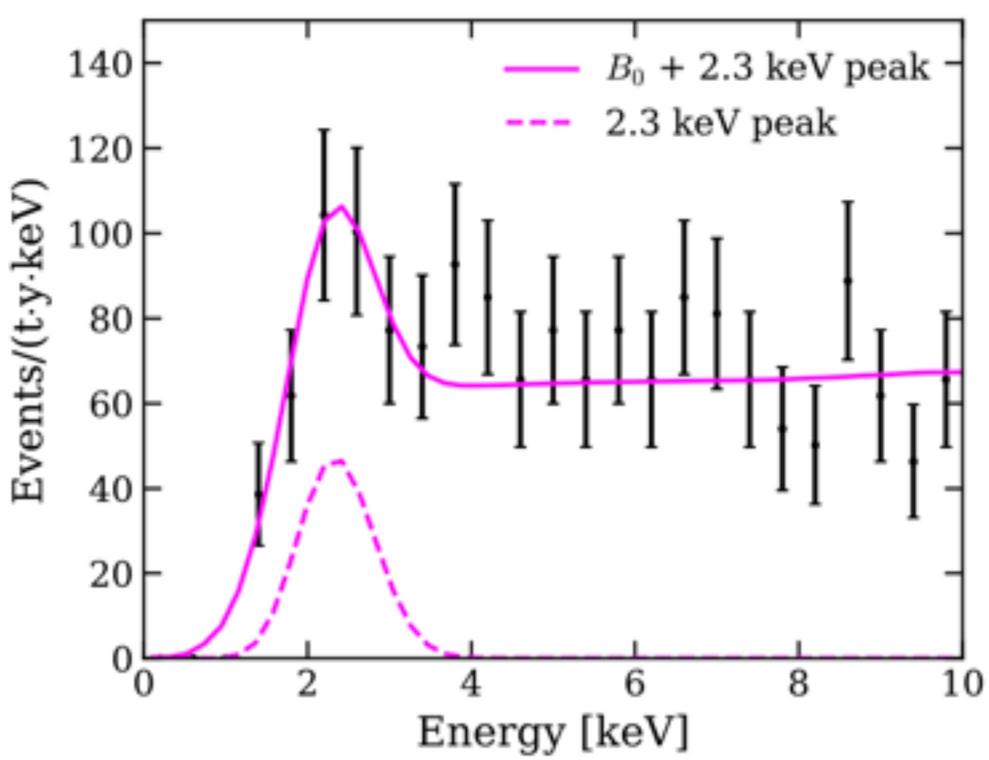
^{214}Pb beta decay spectrum



- atomic effects can increase rate at low energy
- teamed up with expert (X. Mougeot) on beta-decay spectrum
- ~6% uncertainty on shape
- ~50% needed to account for excess

Possible new background: Ar-37?

- Ar-37: decay via electron capture, emitting 2.8 keV x-ray (peak in ER)
- Ar-37 from initial concentration in xenon gas?
  - with natural abundance of 10^{-20} mol/mol in nat-Ar, would decay (half-life = 35 d) to a negligible level at the start of XENON1T
  - further removed by cryogenic distillation that removes Kr-85
- **Ar-37 in the air leaking into the detector during the run?**
  - maximum air leak rate constrained by Kr/Xe measurement: < 0.9 liter/year
  - measured Ar-37 concentration in air around XENON1T: < 3.2 mBq/m^3
  - **maximum event rate from Ar37 leaking into the detector: <5 events/t-y (vs. ~65 events/t-y observed excess)**
- In addition, the best-fit peak is 2.3+/-0.2 keV (not 2.8 keV)

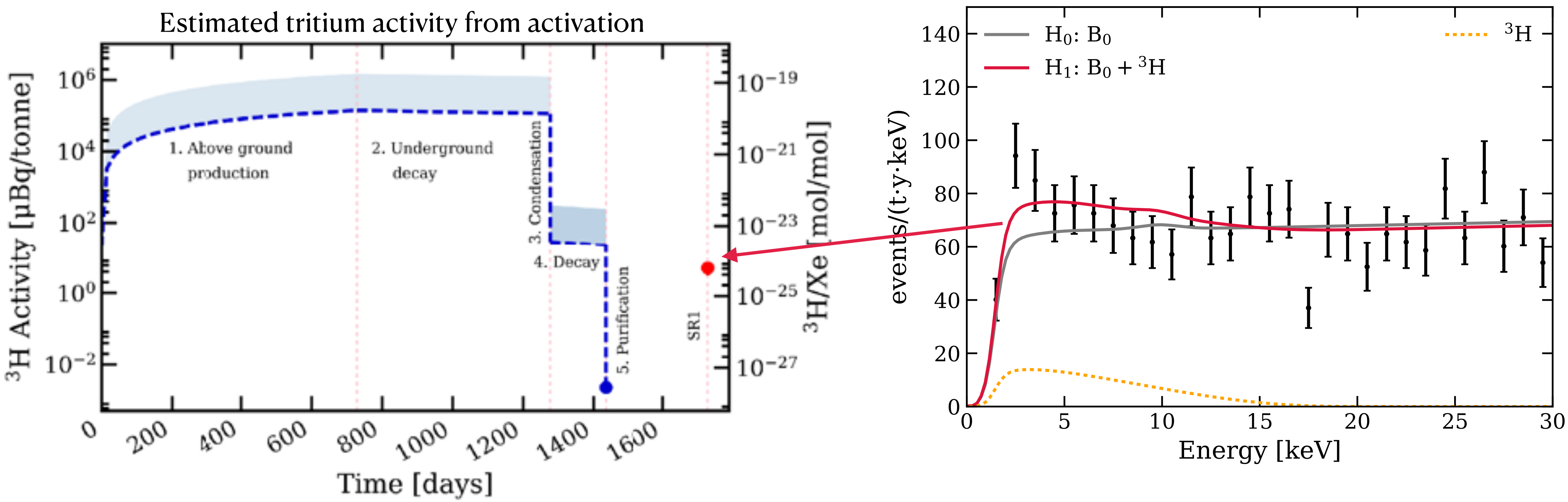


Ar-37 can't explain the observed excess

unbinned data: https://doi.org/10.5281/zenodo.4273099

Possible new background: Tritium?

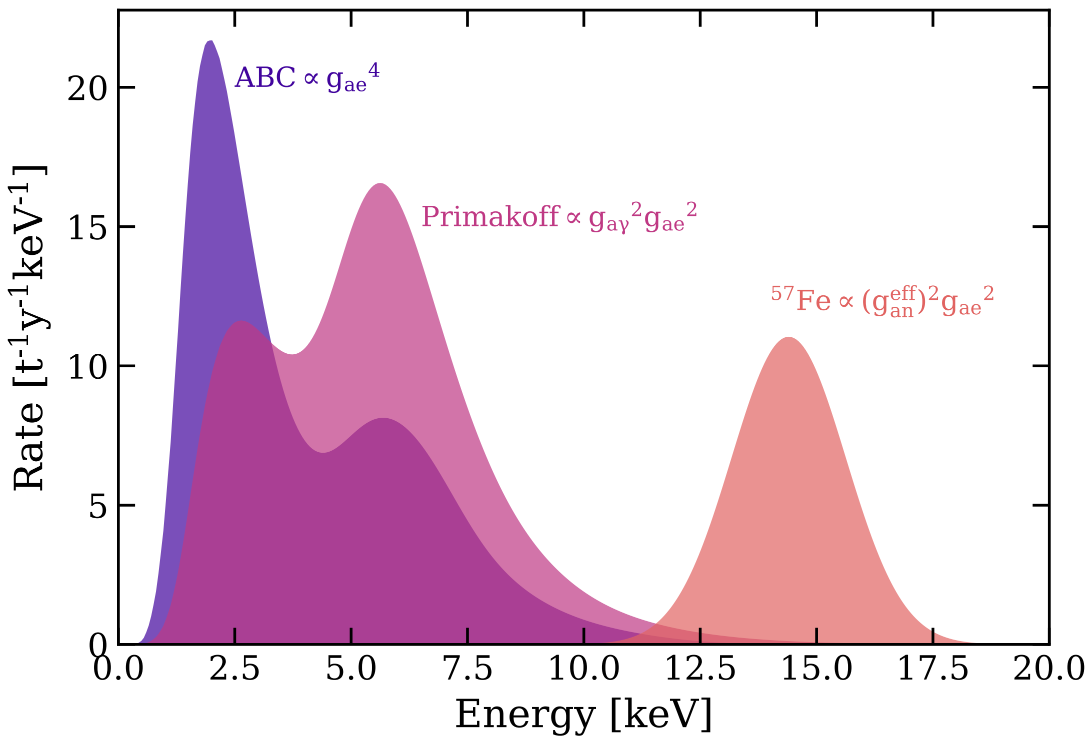
- Tritium: a beta emitter with 12.3 years half-life, Q value at 18.6 keV
- Exist in the atmosphere/water and can be produced cosmogenically in xenon
  - The purification system (getter) in XENON1T would remove tritium from activation
- How about tritium from H_2O in Xe?
  - H_2O/Xe is estimated at 1 ppb level based on light yield, while the excess rate requires ~100 ppb
- How about H_2 in Xe?
  - H_2/Xe not directly constrained but would require ~100 ppb
  - typically the purification getter would reduce it to <1 ppb (but not directly measured)



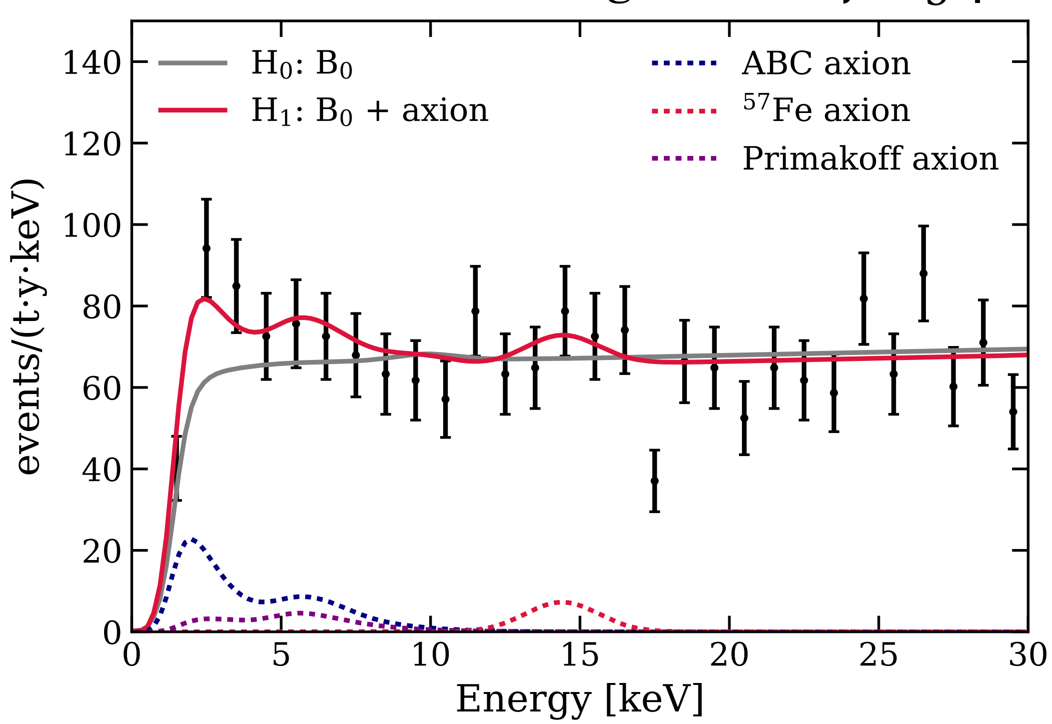
- A fit with tritium results 159 +/- 51 events/(t-yr-keV)
- favored over background-only hypothesis at 3.2σ, but difficult to explain where it's from
- would be ~3 tritium atoms per kg of xenon (concentration too low to measure directly)

New Physics: Solar Axion?

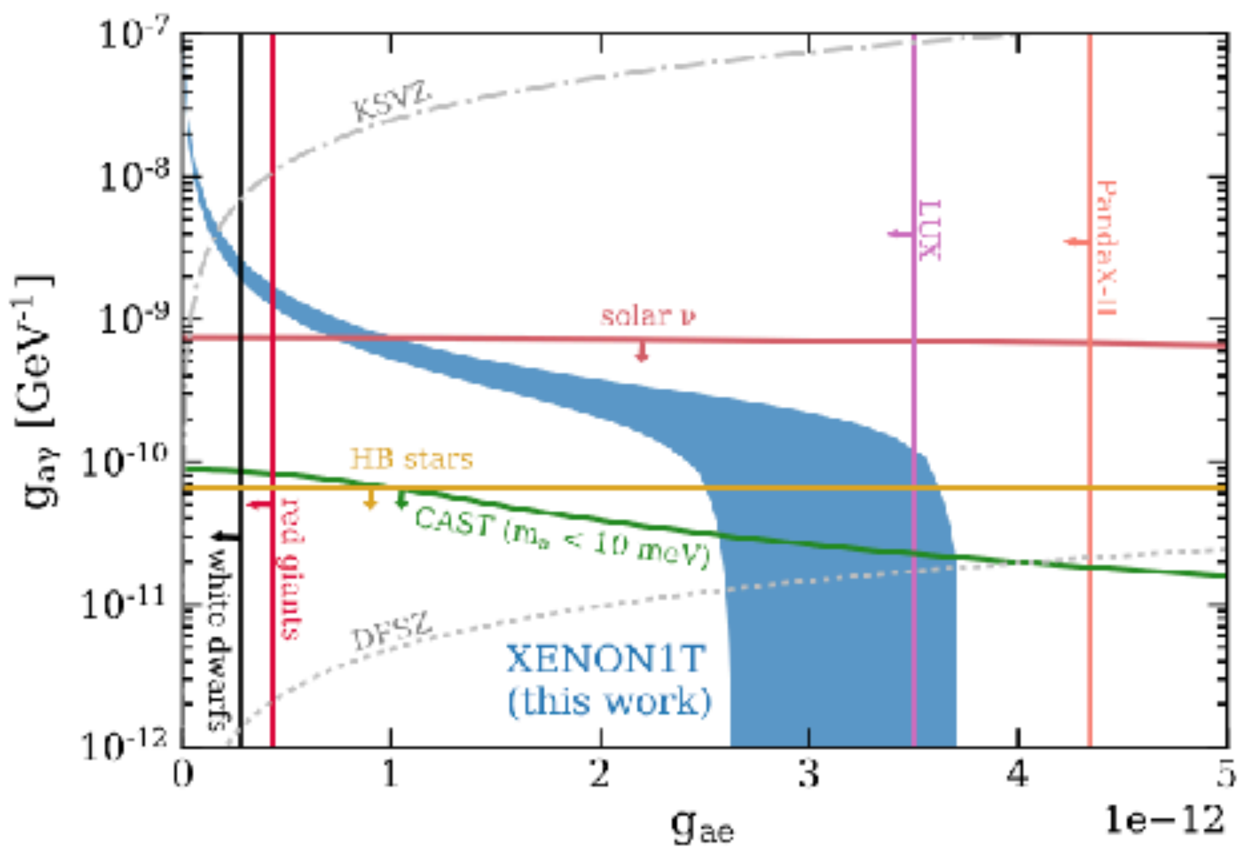
Expected **solar axion** spectrum in XENON1T



Axion favored over background-only at 3.4σ

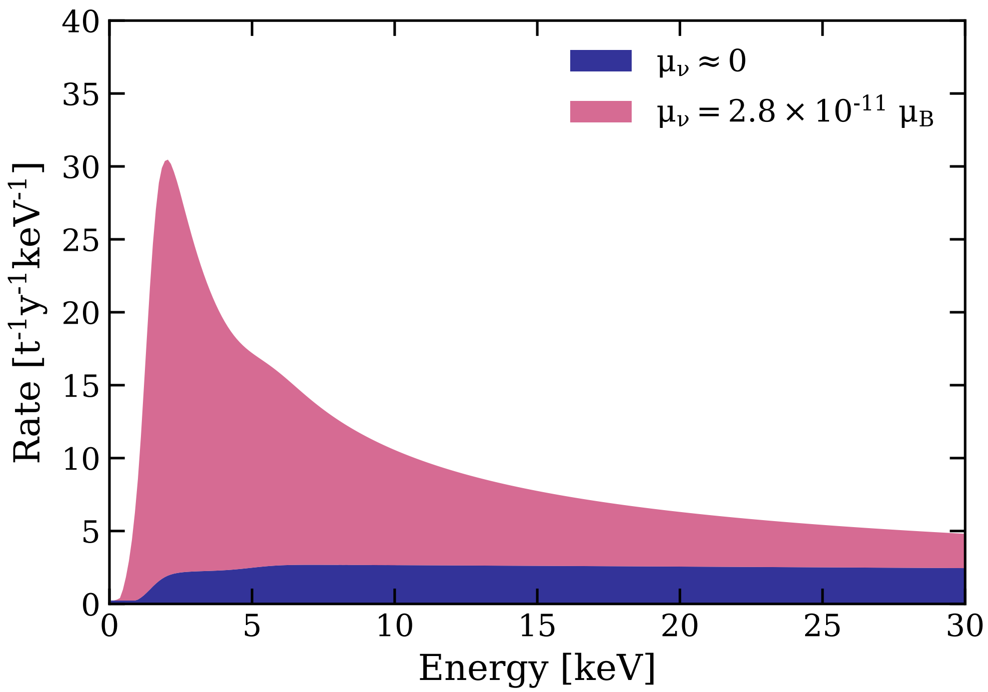


- Excludes $g_{ae} = 0$
- 90% CL surface inscribed in a cuboid with
  - $g_{ae} < 3.8 \times 10^{-12}$
  - $g_{ae} g_{an}^{eff} < 4.8 \times 10^{-18}$
  - $g_{ae} g_{a\gamma} < 7.7 \times 10^{-22}$ GeV^{-1}
- in strong tension with astrophysics constraints
  - include inverse Primakoff scattering (2006.14598, 2006.15118) would alleviate the tension

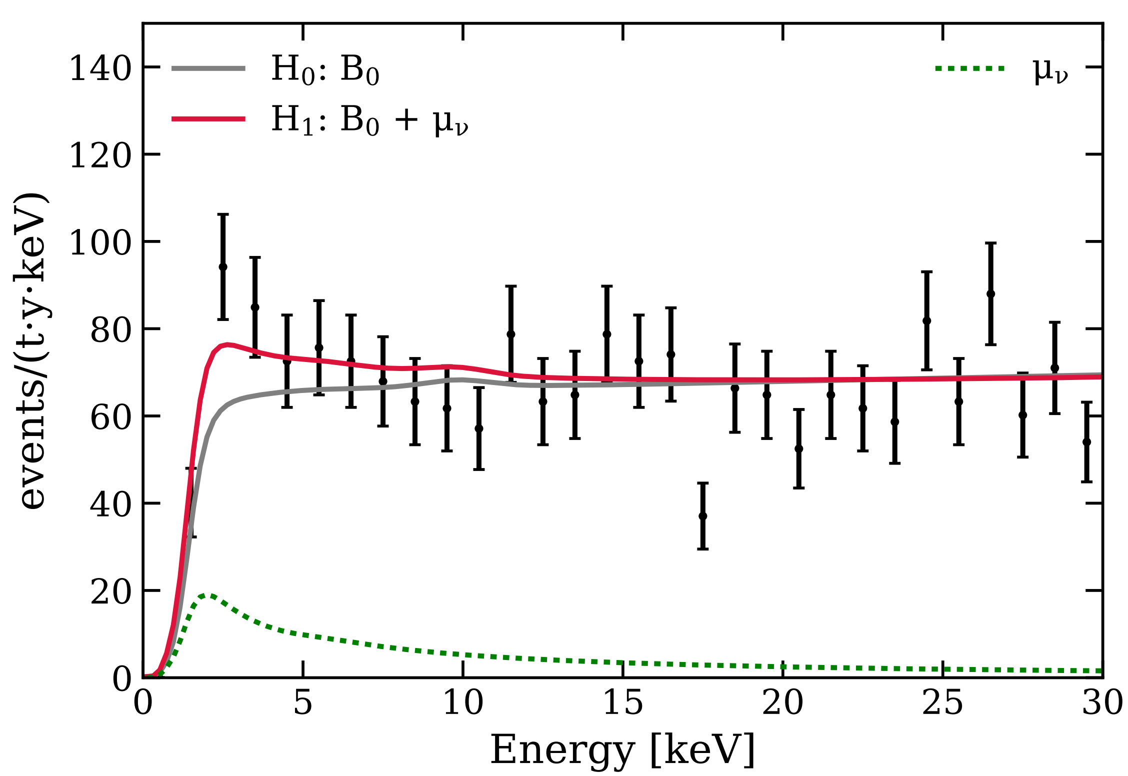


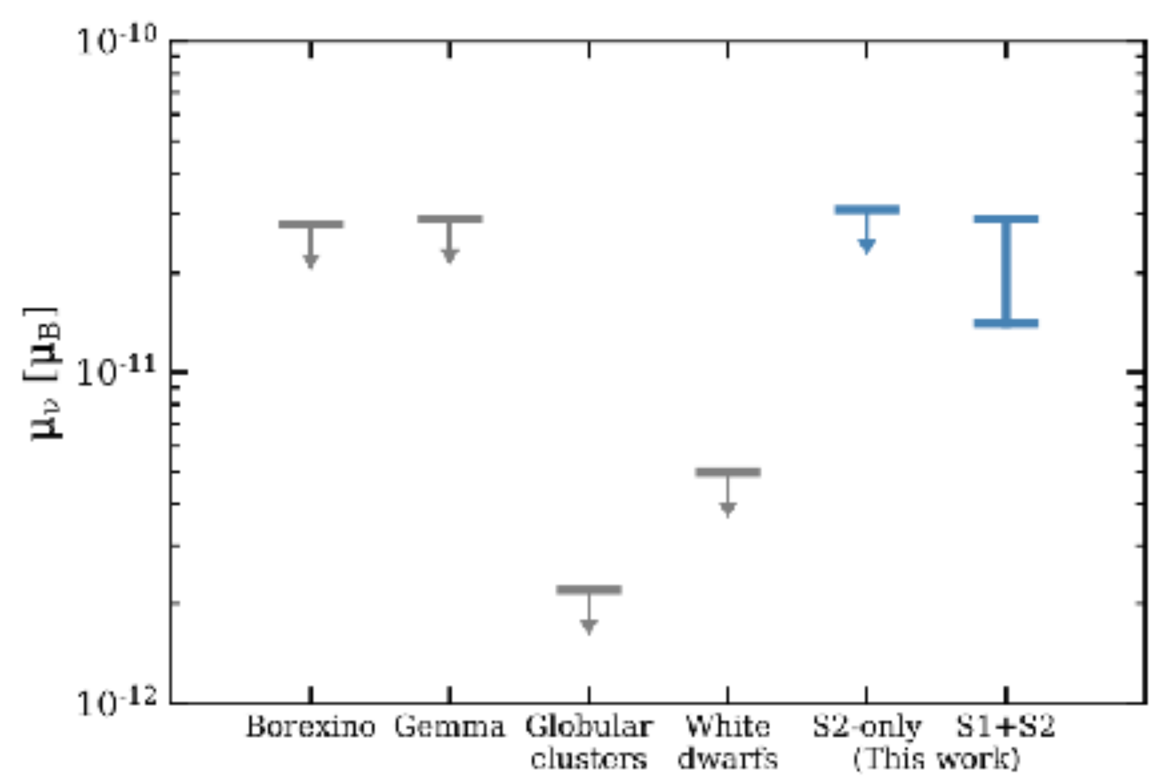
arXiv:2006.09721 (PRD 2020)

New Physics: Neutrino Magnetic Moment?



- neutrino magnetic moment favored over background-only at 3.2σ
- $\mu_\nu \in (1.4,\ 2.9) \times 10^{-11} \mu_B$ (90% CL)
- consistent with the most stringent direct constraints from solar/reactor neutrino experiments
- in strong tension (similar to the axion case) with astrophysics constraints





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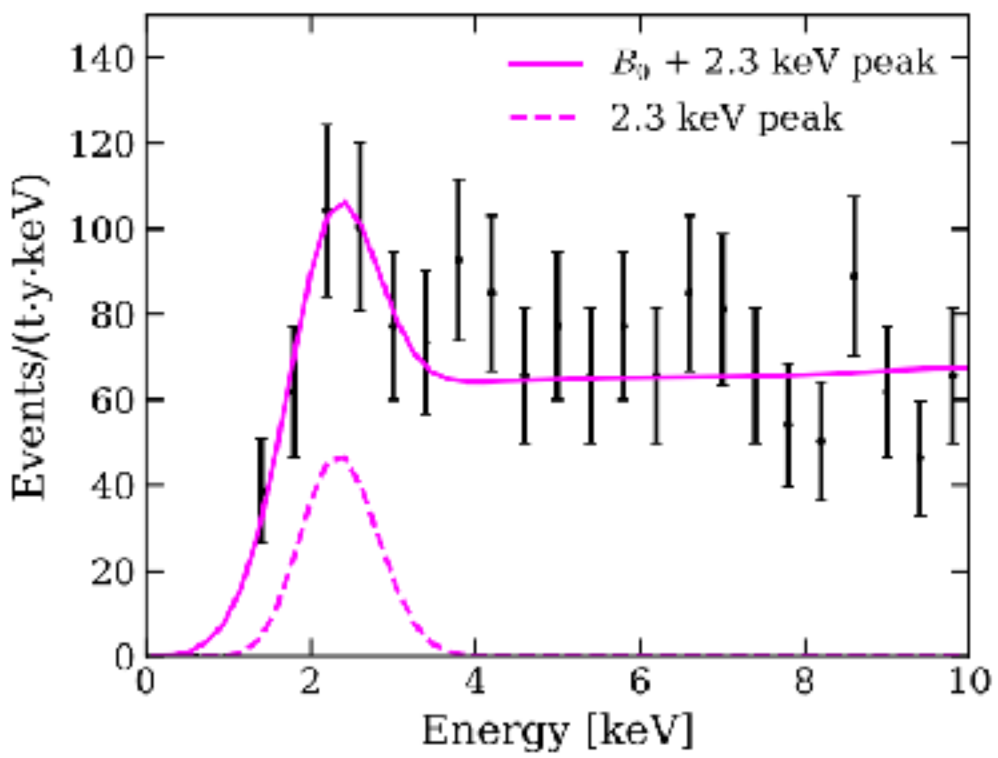
New Physics: Bosonic dark matter?

- searches for excess peaks over background from 1-210 keV
- the excess best-fit with mono-peak at 2.3 ± 0.2 keV (68% CL) with 3.0σ (4.0σ) global (local) significance
- sets the most stringent limits for bosonic dark matter (ALP, dark photon) between 1-210 keV/c^2



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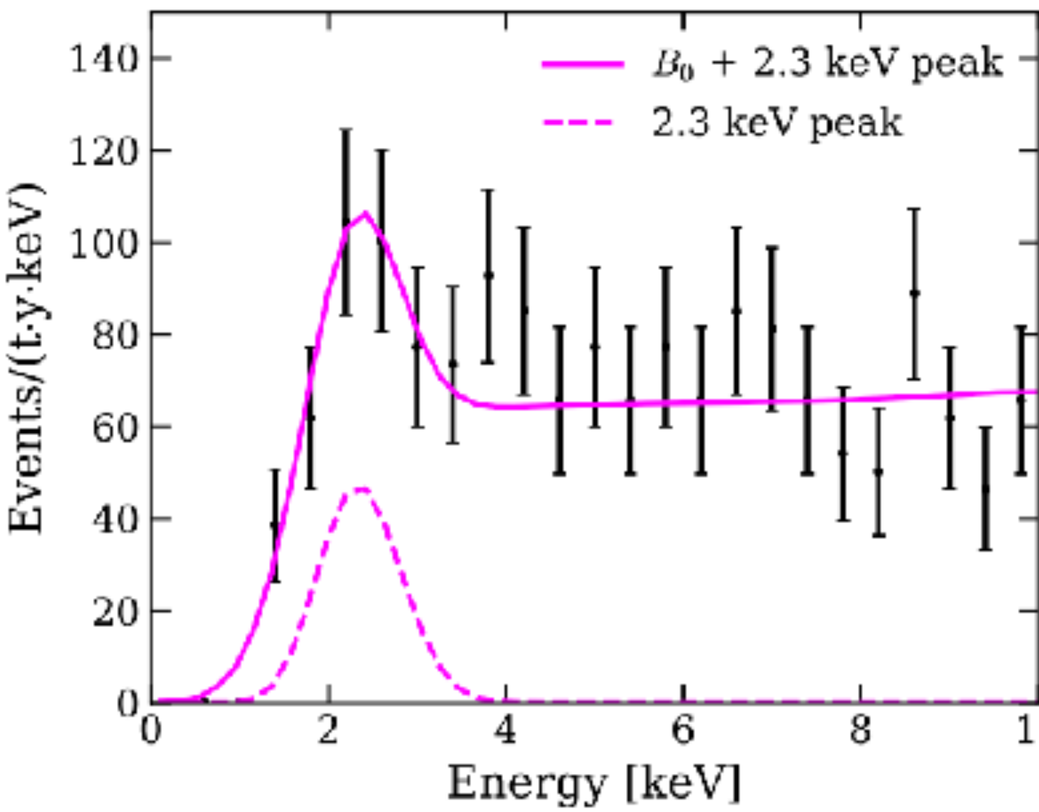
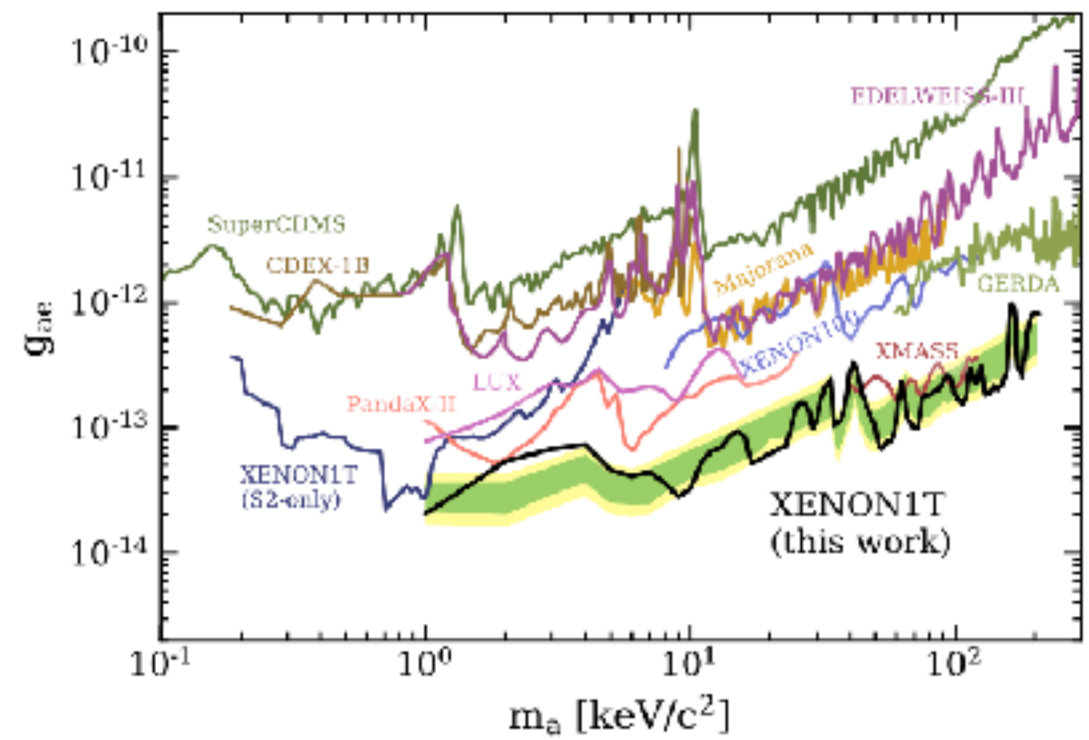
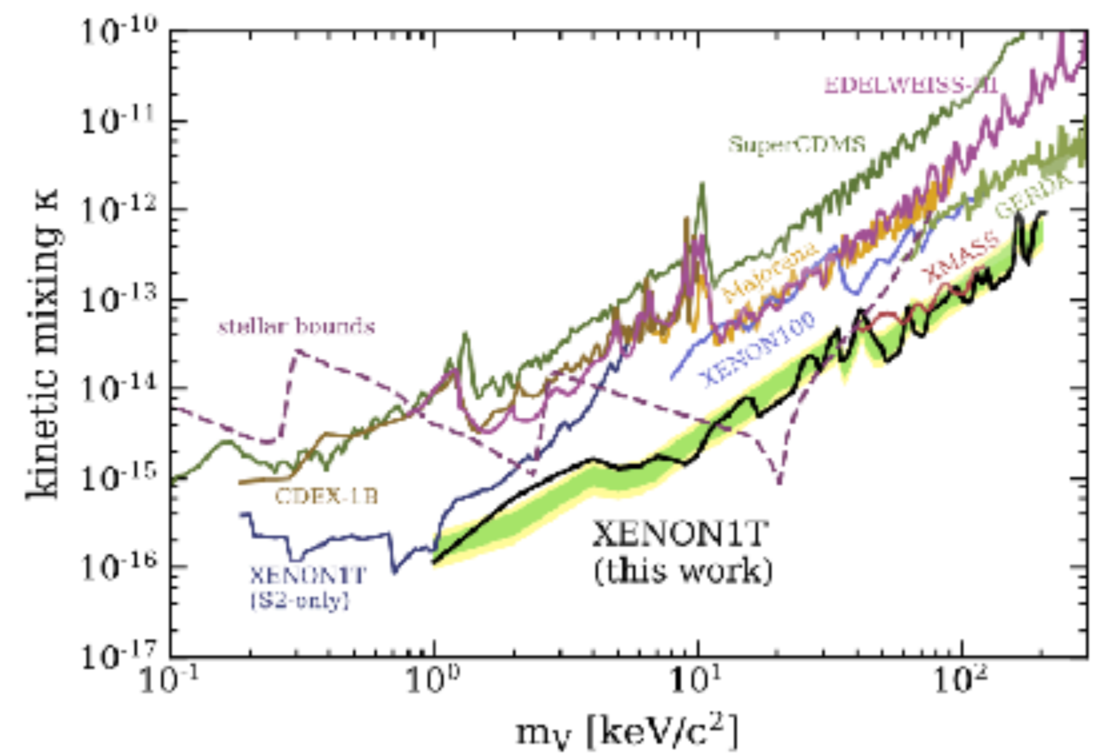
- the excess best-fit with mono-peak at 2.3 ± 0.2 keV (68% CL) with 3.0σ (4.0σ) global (local) significance
- sets the most stringent limits for bosonic dark matter (ALP, dark photon) between 1-210 keV/c²



arXiv:2006.09721 (PRD 2020)





Experimental Checks and Theoretical Interpretations

An incomplete look into >100 arXiv papers interpreting the XENON1T excess

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

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

- **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
- decaying dark matter: 2006.12348, 2008.03150, 2008.09615
- 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
- black holes: 2007.00650, 2009.02315
- hydrogen decay: 2006.15140

https://physics.aps.org/articles/v13/135 https://physics.aps.org/articles/v13/s132

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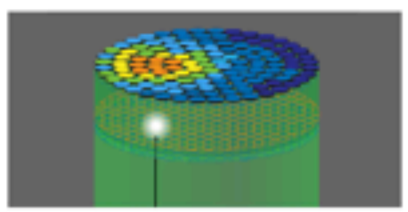
Physics

This Week in *Physics Magazine* — October 12

VIEWPOINT

Dark Matter Detector Delivers Enigmatic Signal

Tongyan Lin – October 12, 2020

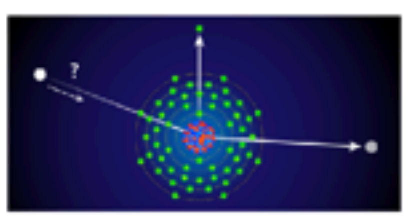


Are the excess events detected by the XENON1T experiment a harbinger of new physics or a mundane background?

SYNOPSIS

Theorists React to Potential Signal in Dark Matter Detector

October 12, 2020



A tantalizing signal reported by the XENON1T dark matter experiment has sparked theorists to investigate explanations involving new physics.

FOCUS

Nobel Prize: Facing the Reality of Black Holes

October 6, 2020

Three scientists were recognized for proving that gravitational collapse can lead to a black hole and for observing the supermassive black hole at the center of our Galaxy.

PDF Version

XENON1T Excess from Anomaly-Free Axionlike Dark Matter and Its Implications for Stellar Cooling Anomaly
Fuminobu Takahashi, Masaki Yamada, and Wen Yin
Phys. Rev. Lett. 125, 161801 (2020)
Published October 12, 2020

Neutrino Self-Interactions and XENON1T Electron Recoil Excess
Andreas Bally, Sudip Jana, and Andreas Trautner
Phys. Rev. Lett. 125, 161802 (2020)
Published October 12, 2020

Explaining the XENON1T Excess with Luminous Dark Matter
Nicole F. Bell, James B. Dent, Bhaskar Dutta, Sumit Ghosh, Jason Kumar, and Jayden L. Newstead
Phys. Rev. Lett. 125, 161803 (2020)
Published October 12, 2020

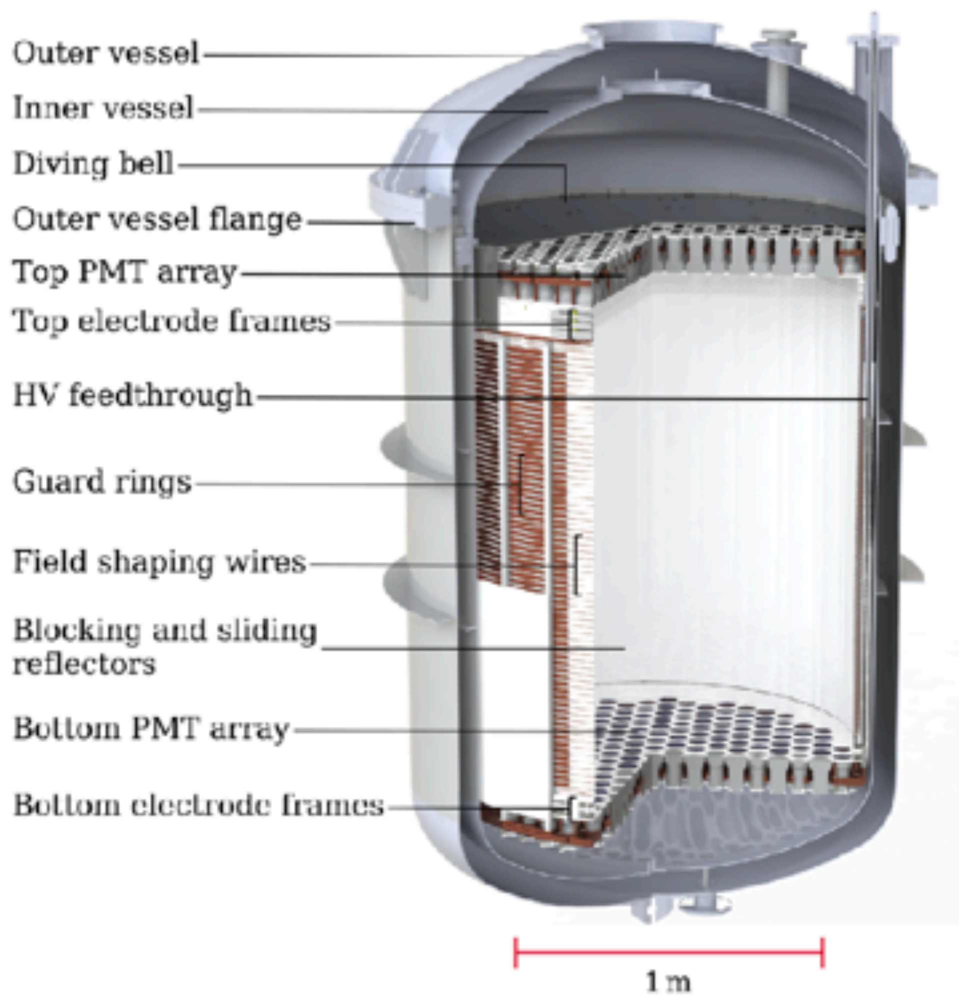
Boosted Dark Matter Interpretation of the XENON1T Excess
Bartosz Fornal, Pearl Sandick, Jing Shu, Meng Su, and Yue Zhao
Phys. Rev. Lett. 125, 161804 (2020)
Published October 12, 2020

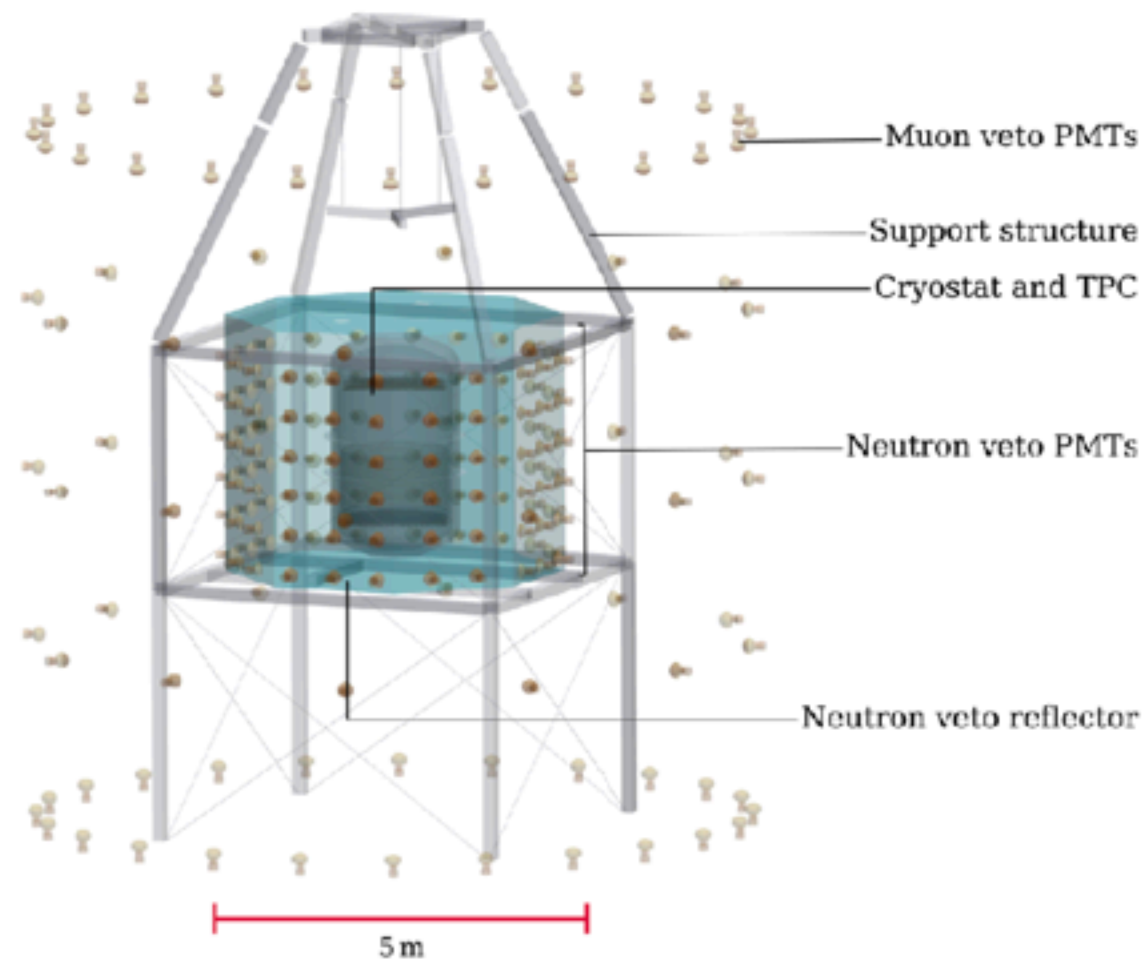
Electric But Not Eclectic: Thermal Relic Dark Matter for the XENON1T Excess
Joseph Bramante and Ningqiang Song
Phys. Rev. Lett. 125, 161805 (2020)
Published October 12, 2020

What's next? XENONnT

- Larger target mass: 5.9-tonne (x3 of XENON1T)
  - larger cryostat/TPC
  - more PMTs
- Reduce Nuclear Recoil Background
  - improve WIMP search sensitivity
  - Gd-loaded water as neutron-veto
- Reduce Electronic Recoil Background
  - improve new physics search in ER
  - Reduce Radon
- Improve signal detection
  - Liquid purification

arXiv:2007.08796 (JCAP)



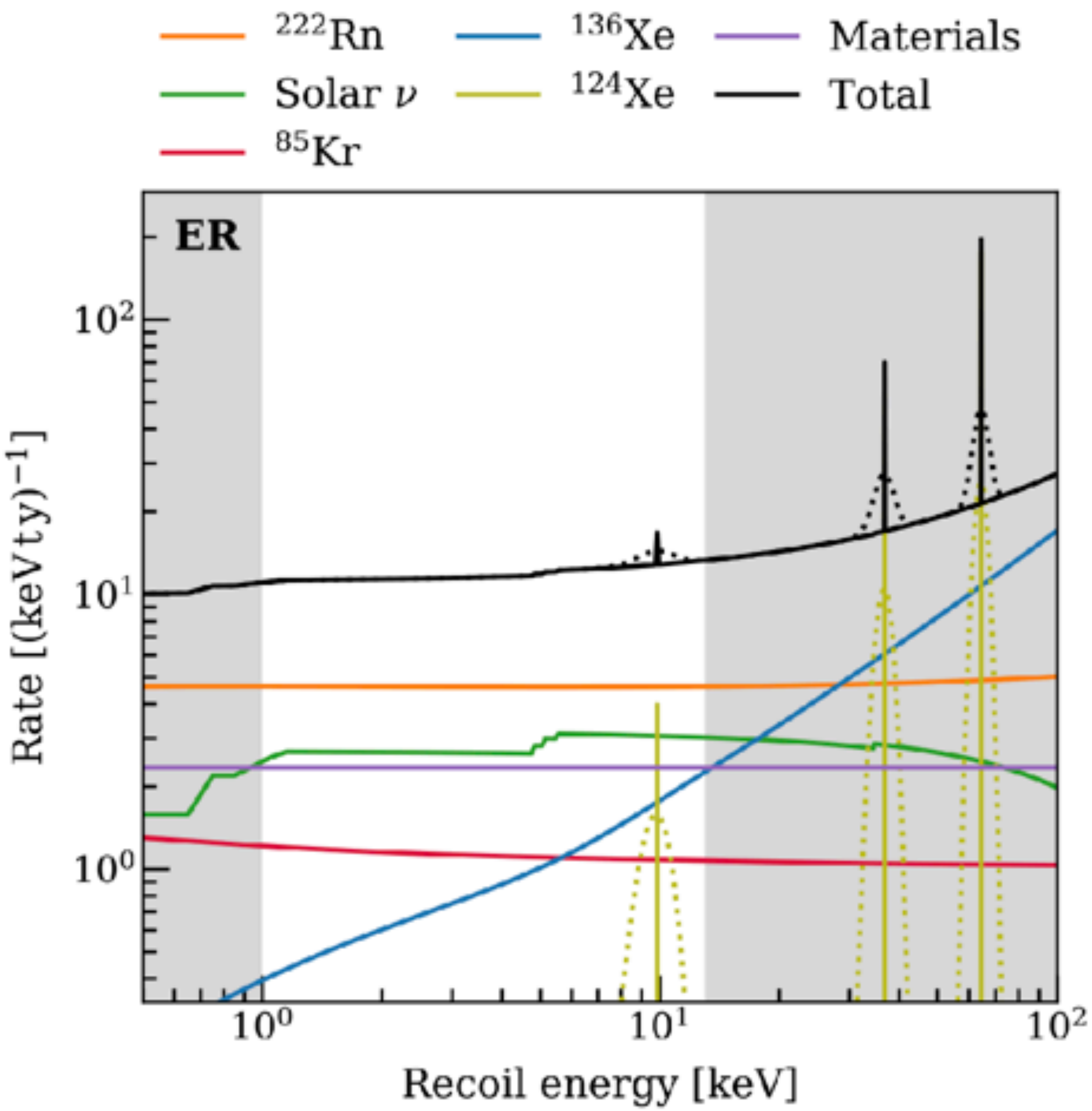


Commissioning ongoing...

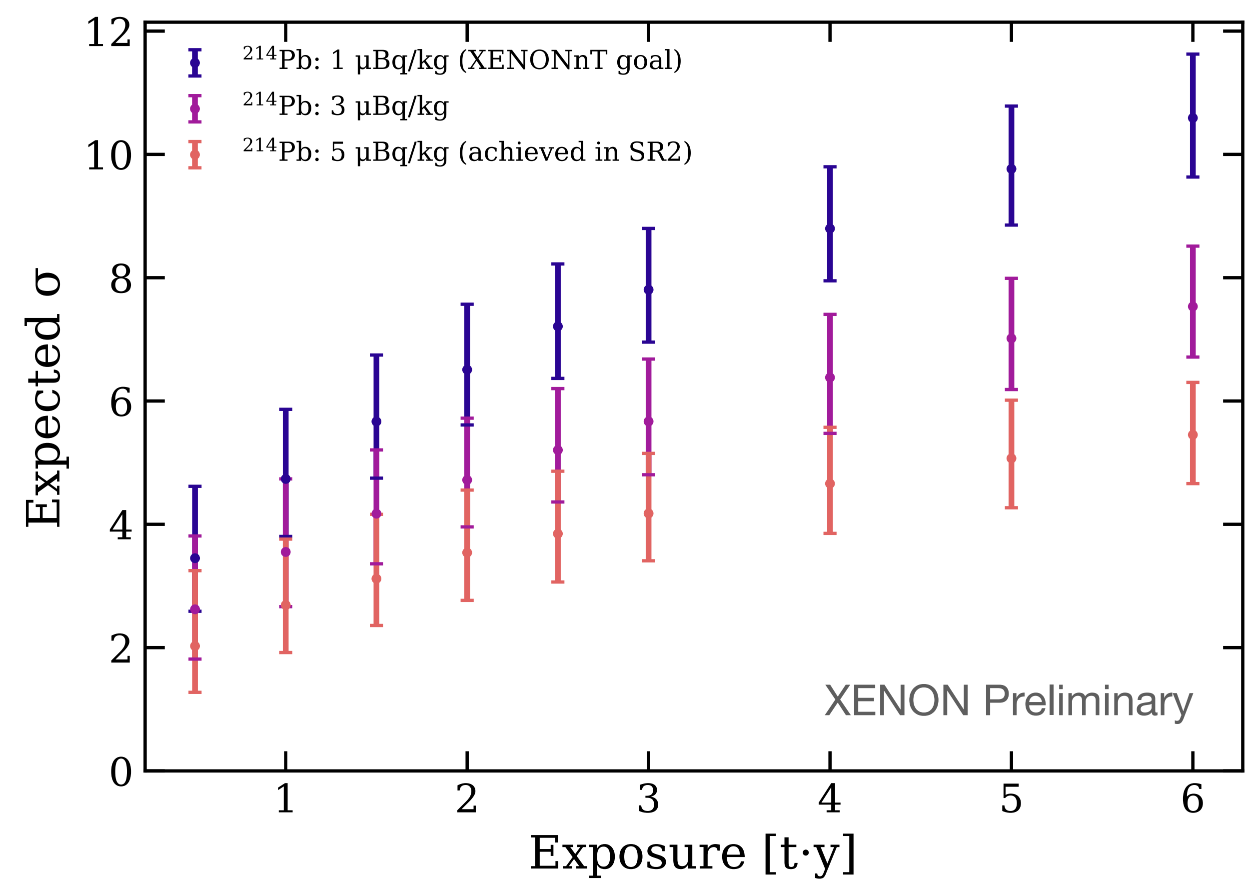
XENONnT: major upgrades to reduce the ER & NR backgrounds

XENONnT: Expected ER and NR background in 4-tonne fiducial mass

arXiv:2007.08796 (JCAP)

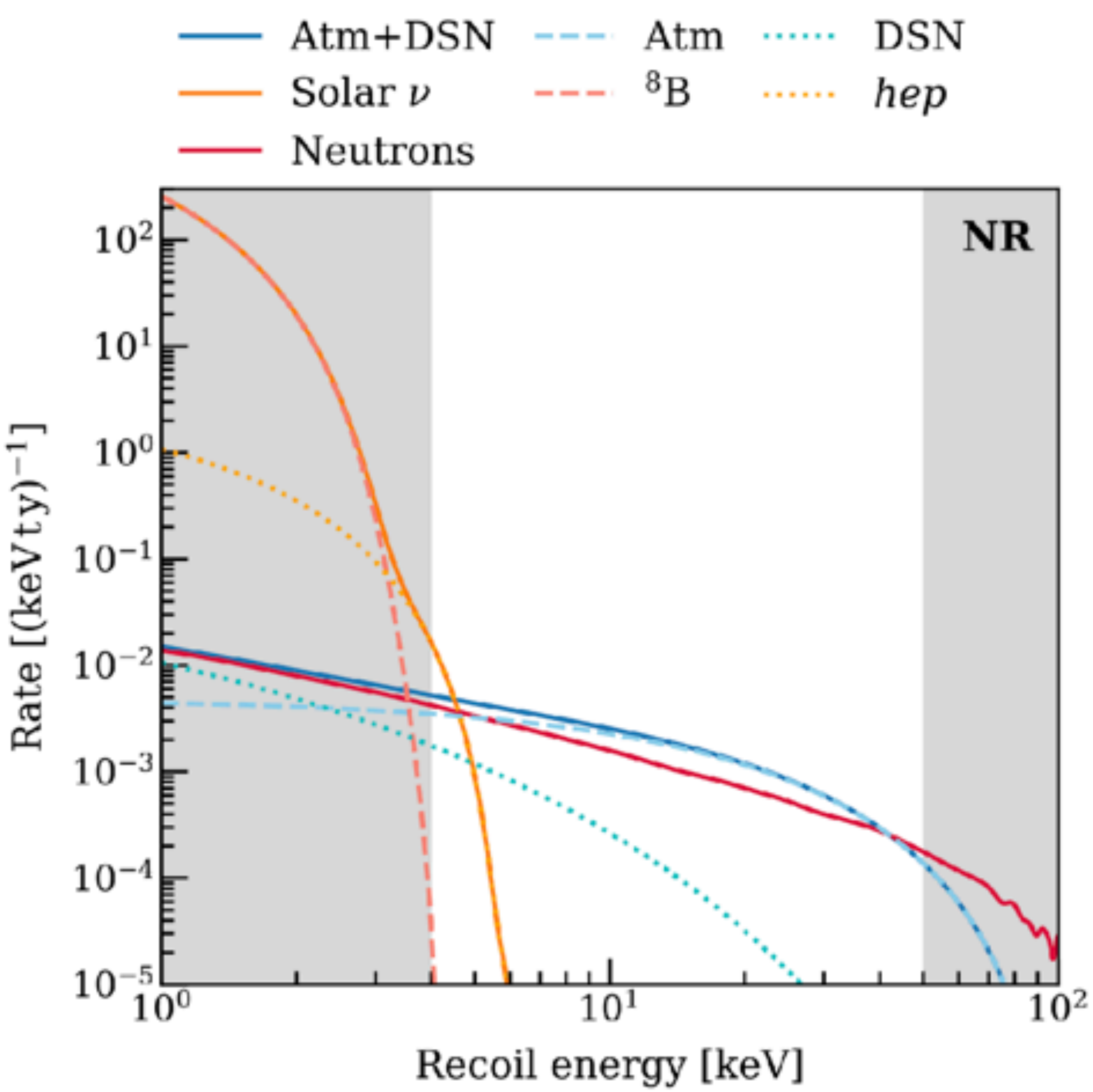


ER channel: XENONnT will discriminate between solar axions, NMM/tritium with a few months of data

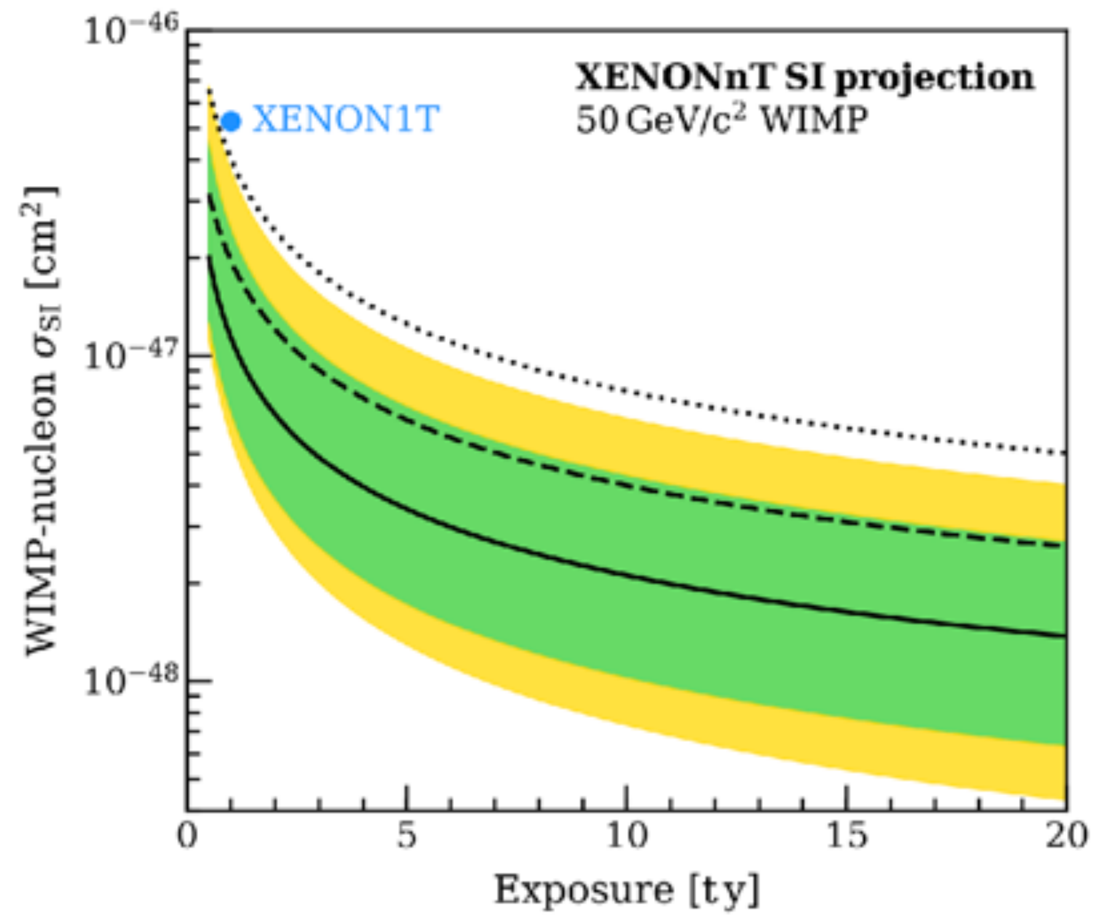


XENONnT: Searches for WIMP Dark Matter and Beyond

arXiv:2007.08796 (JCAP)



NR channel:
XENONnT improves WIMP detection sensitivity



Large liquid xenon detectors are expected to make contributions to many new physics topics in the next few years!