ELECTRONIC-RECOIL EXCESS IN XENON1T

Sara Diglio – SUBATECH

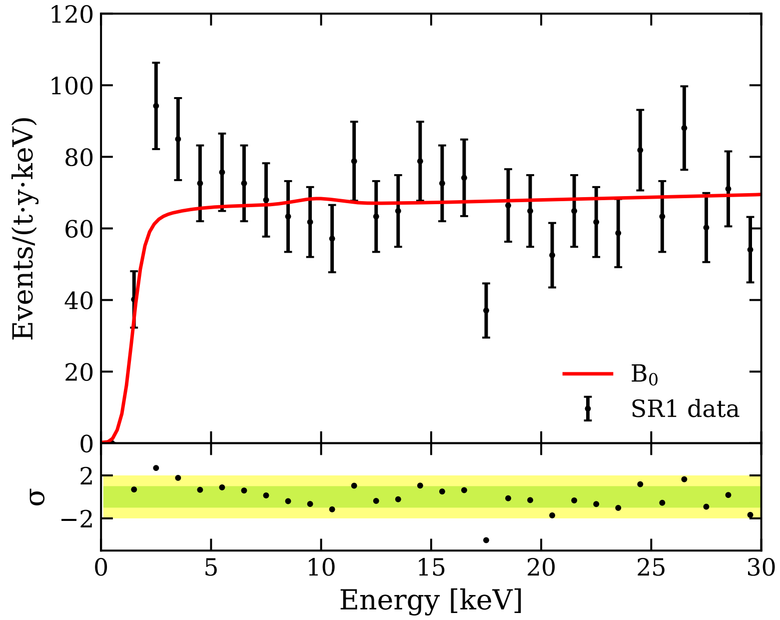
On behalf of

the XENON Collaboration + X. Mougeot

Online Seminar, 5 October 2020, CPPM, Marseille

XENON Dark Matter Project

arxiv: 2006.09721



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SCIENCES • PHYSIQUE

Partage

Physique des particules : des détections déroutantes en Italie

L'expérience Xenon1T, installée dans le laboratoire souterrain de Gran Sasso pour traquer la matière noire, a enregistré un signal inattendu. S'agit-il d'une particule encore jamais observée ou d'une contamination du dispositif ?

Par Nathaniel Herzberg · Publié le 19 juin 2020 à 14h23 · Mis à jour le 22 juin 2020 à 15h59

Lecture 1 min.

L'intérieur du château d'eau de Xenon1T, qui protège le détecteur contre les rayons cosmiques. © Enrico Sacchetti/XENON Collaboration

Une particule peut en cacher une autre. La collaboration

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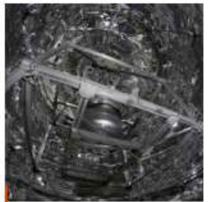
L'IN2P3 | Recherche | Technologies | International | Formation supérieure | Prix et distinctions



Le cryostat de XENON1T à l'intérieur du château d'eau qui le protège des rayons cosmiques. crédit : XENON collaboration

Accueil > Actualités

Observation d'un excès d'événements dans l'expérience de recherche directe de matière noire XENON1T

The New York Times

OUT THERE

Seeking Dark Matter, They Detected Another Mystery

Do signals from beneath an Italian mountain herald a revolution in physics?

Pour la Science

Expérience XENON1T : un signal anormal difficile à interpréter

Cette expérience de détection de matière noire a enregistré un signal inattendu. S'il n'est pas forcément lié à la matière noire, il permet de discuter de la détection éventuelle d'une nouvelle particule.

SCIENCES ET AVENIR

Espace | Santé | Nutrition | Nature | Animaux

Biologie cellulaire | Géologie | Mathématiques | Matériaux | Particules

Covid-19 | Médaille d'or CNRS | Nouveau mensuel Sciences et A

SCIENCES ET AVENIR > FONDAMENTAL > PARTICULES

PARTICULES

Signal inhabituel dans un détecteur de matière noire : bientôt une découverte majeure en physique ?

Par Marine Benoit le 19.06.2020 à 20h00 — ABONNÉS

La collaboration internationale Xenon 1T, qui traque depuis des années la matière noire, a fait savoir qu'elle pourrait avoir détecté des particules hypothétiques et jusqu'ici insaisissables : les axions. Nous avons interrogé l'une de ses membres, la physicienne Sara Diglio, pour faire le point sur cette annonce.

LUS · COMMENTÉS · PARTAGÉS SUR

Un gaz associé à la vie découvert sur Vénus

Où était située votre ville à l'époque des dinosaures ?

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la Repubblica

SPETTACOLI | TECNOLOGIA | MOTORI | TUTTE LE SEZIONI | REP TV

Gran Sasso, il mistero dei nuovi eventi rilevati dal cacciatore di materia oscura

Nuove particelle o una 'crepa' nel modello standard? Nello strumento Xenon1T dei Laboratori dell'Infn, l'elevato numero di interazioni potrebbe essere rivelatore dell'assione solare, teorizzato ma mai osservato, oppure un diverso valore del momento magnetico del neutrino, che potrebbe aprire a una nuova fisica. "Ma non è esclusa una fluttuazione statistica"

OUTLINE

- How did we find it?
  - → The XENON1T experiment
- What have we observed exactly?
  - → The Electronic-Recoil Excess
- Are we really sure?
  - → Cross-checks of the results
- What could it be?
  - → Standard Model & Beyond interpretations
- What next?
  - → the XENONnT experiment

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Xe
XENON
Dark Matter Project
XENON Technical Meeting, May 12-14, 2020
Manfred Lindner
Andrii Terliuk (MPIK/Uni He...
Alexey Elykov
Ethan Brown
Christopher Hils (JGU-Mai...
Michele Iacovacci

The XENON Collaboration

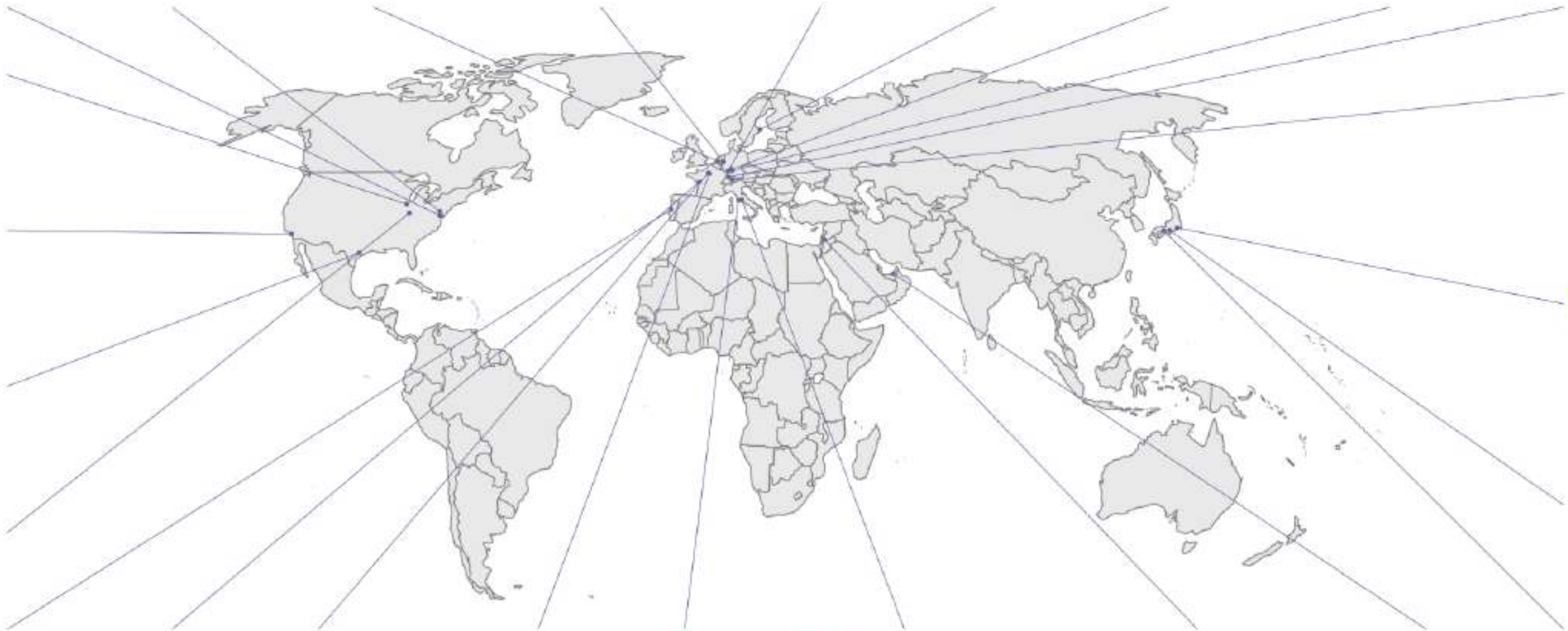
Columbia | RPI | Nikhef | Muenster | KIT | Stockholm | Mainz | MPIK, Heidelberg | Freiburg

Chicago

UCSD

Rice

Purdue



Zurich

Tokyo

Nagoya

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

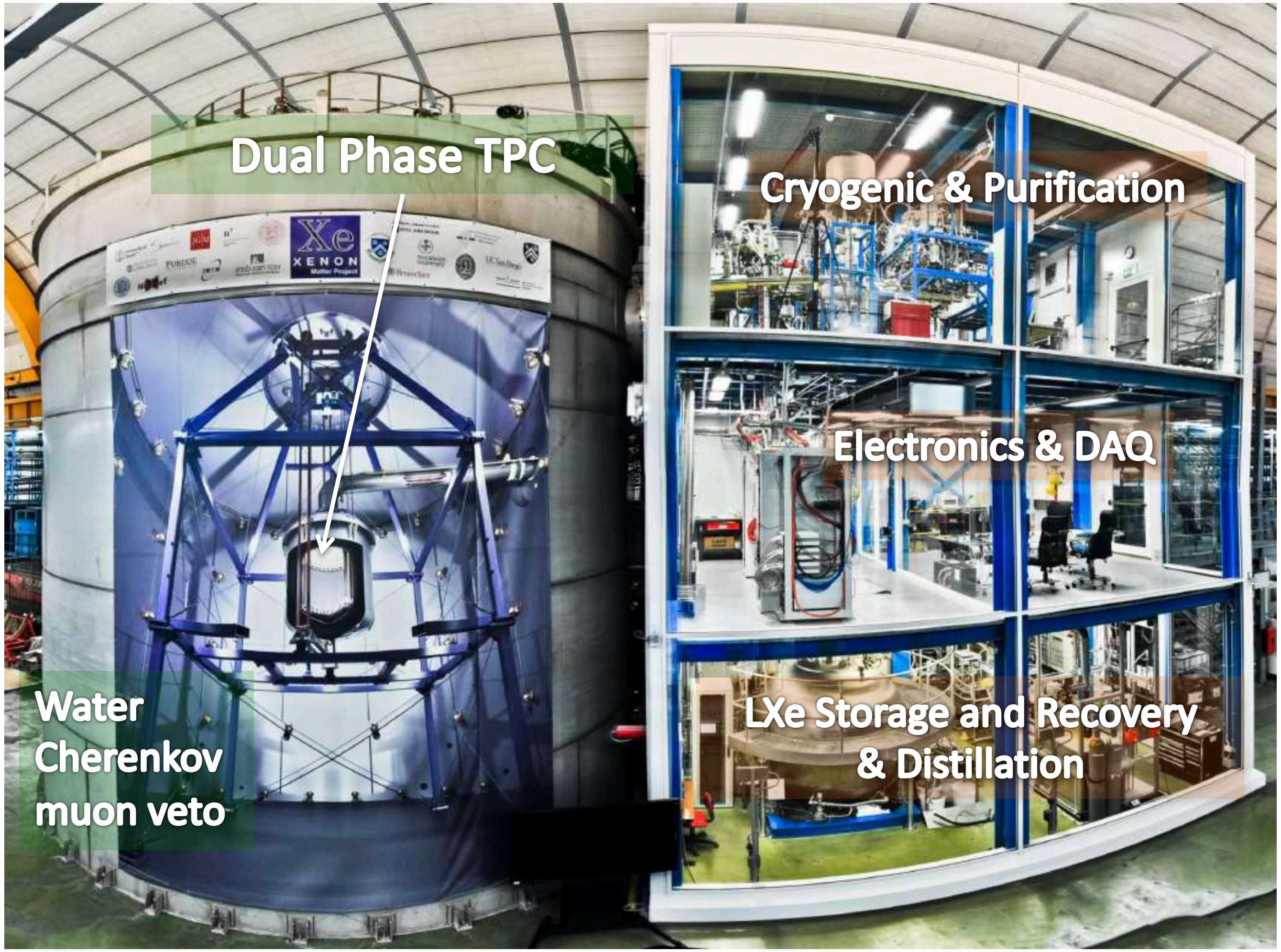
The XENON1T Experiment @ LNGS

Laboratori Nazionali del Gran Sasso

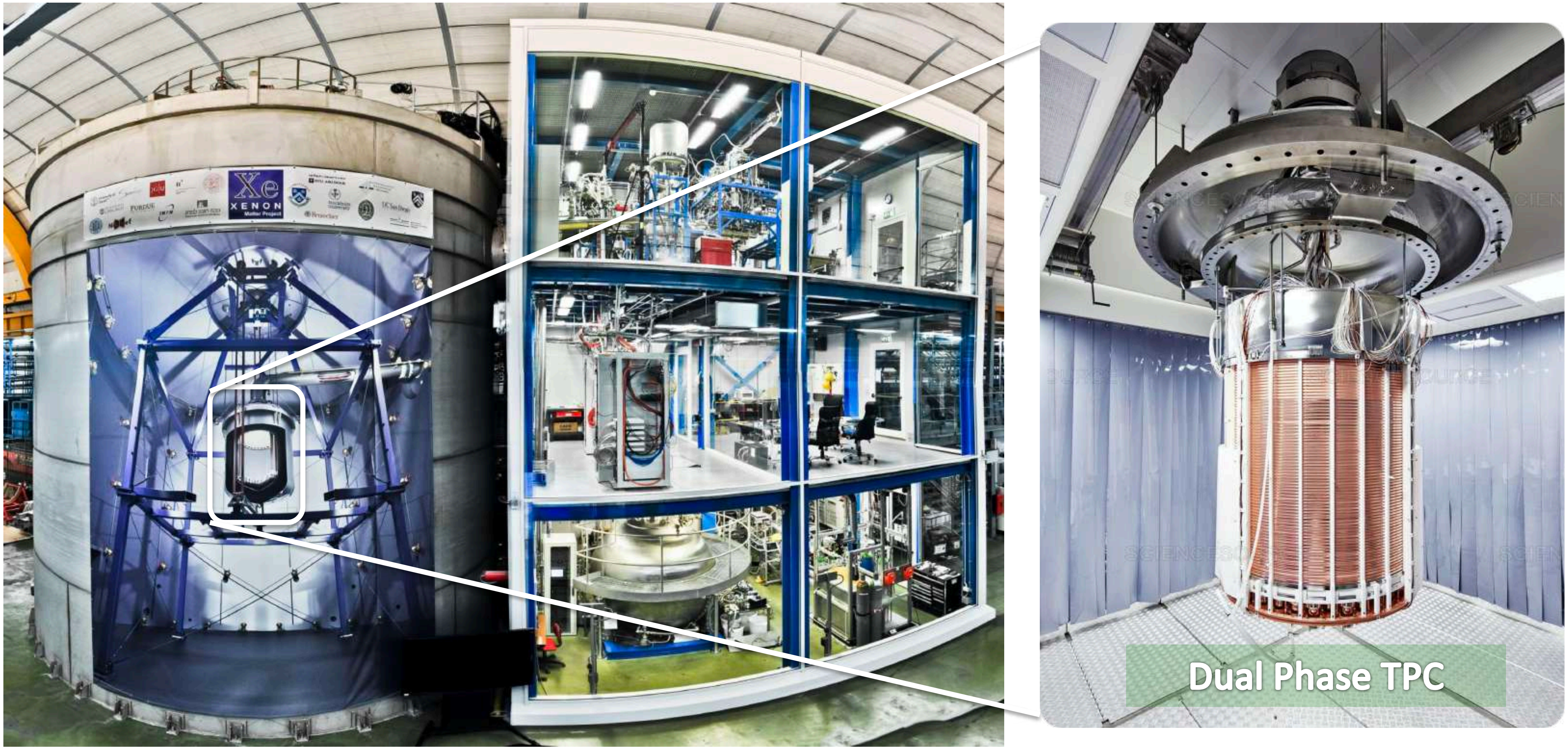
Below 1400 m of rock

(3.6 km water equivalent)

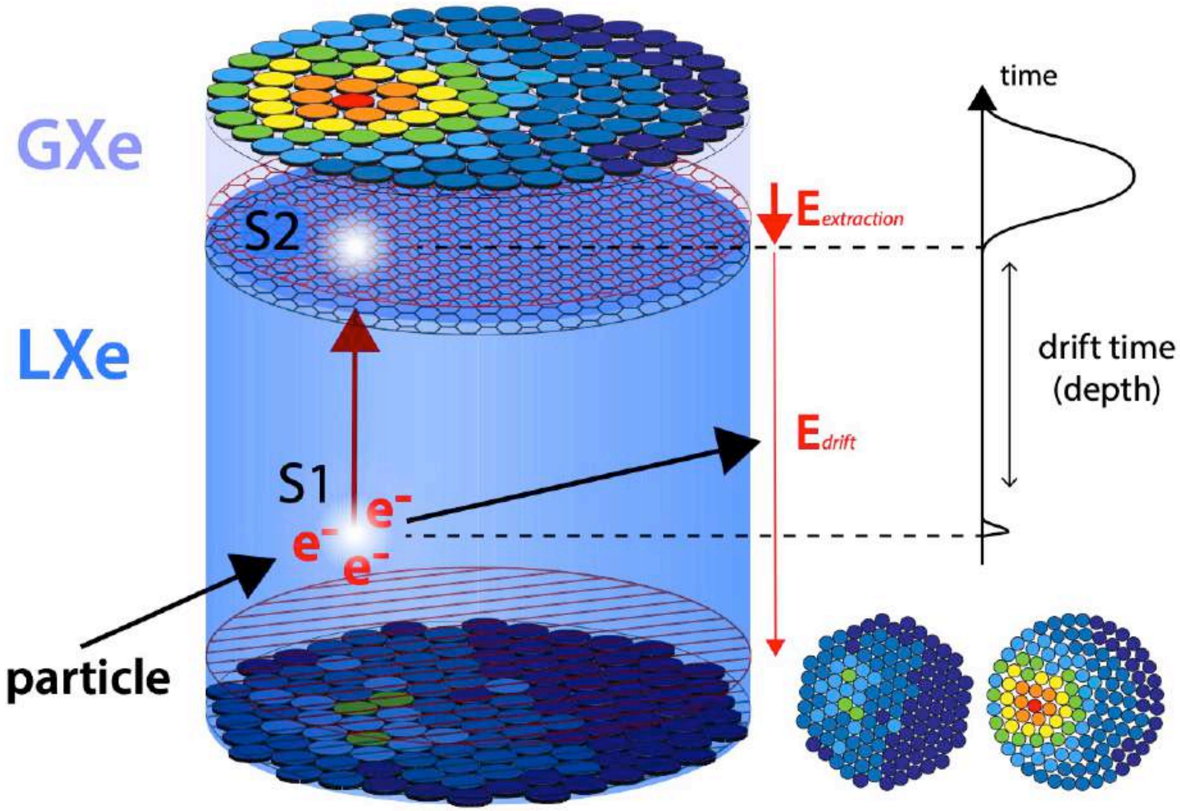
The XENON1T Experiment @ LNGS



THE XENON1T EXPERIMENT @ LNGS



LXe Dual Phase Time Projection Chamber



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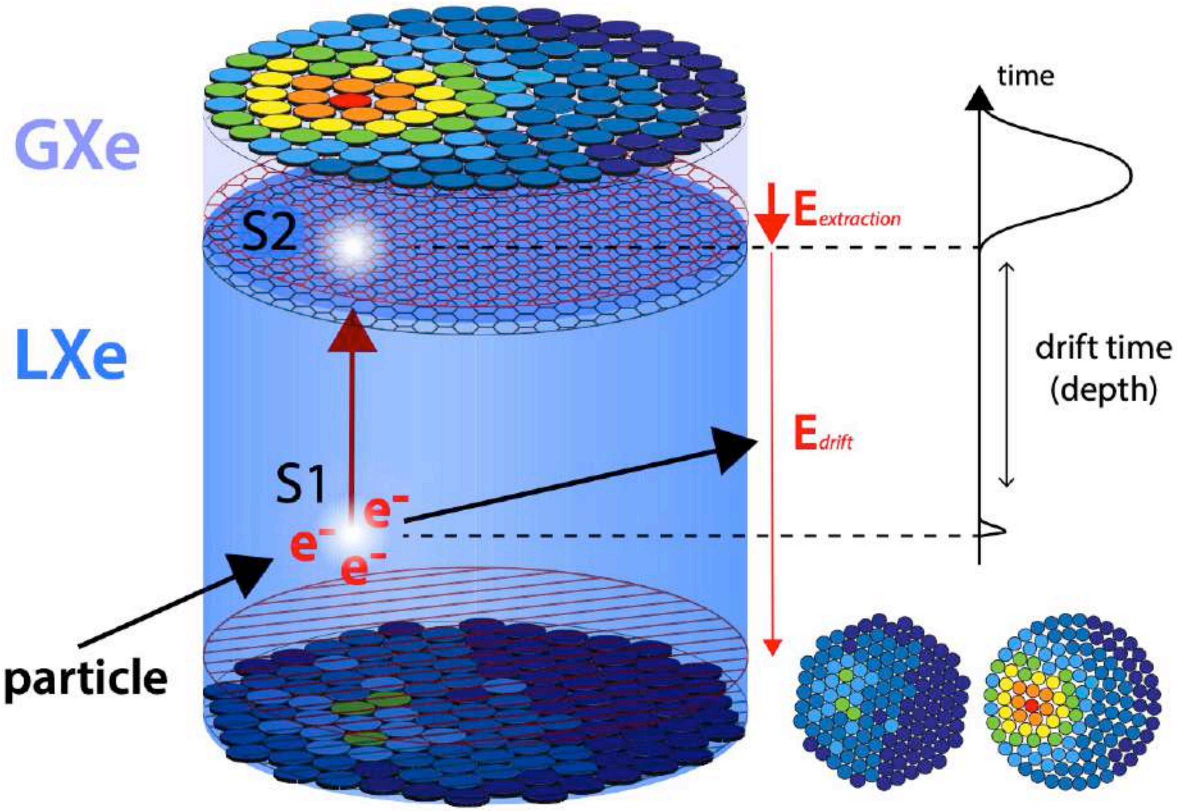
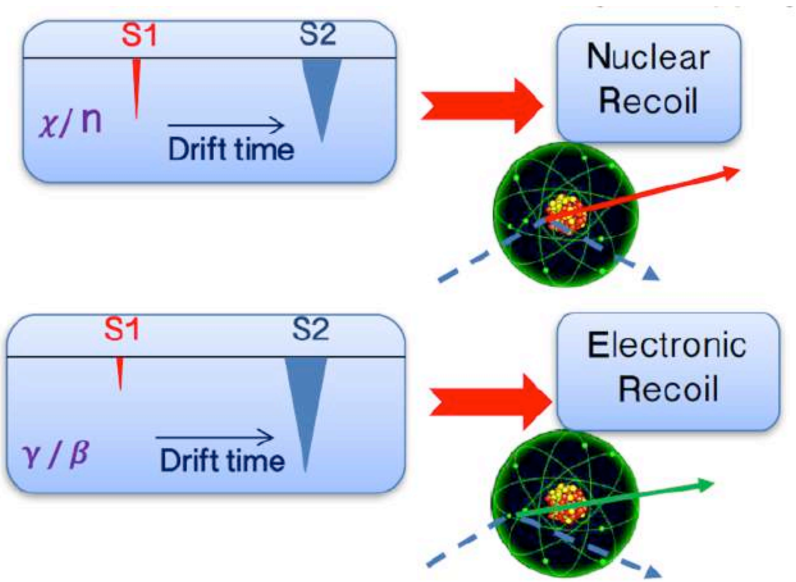


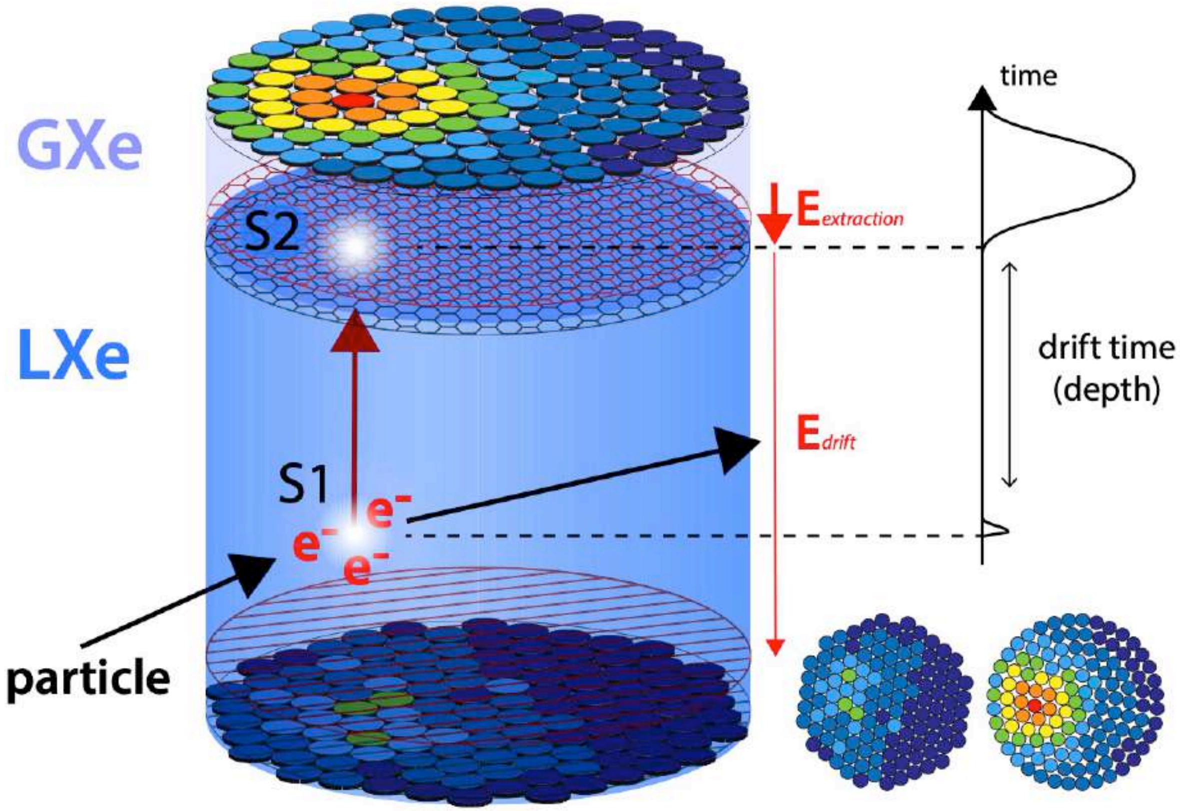
S1: Prompt Scintillation (light)

S2: Proportional scintillation following e^- drift and extraction into gas (charge)



$(S2/S1)_{NR} < (S2/S1)_{ER}$

LXE DUAL PHASE TIME PROJECTION CHAMBER



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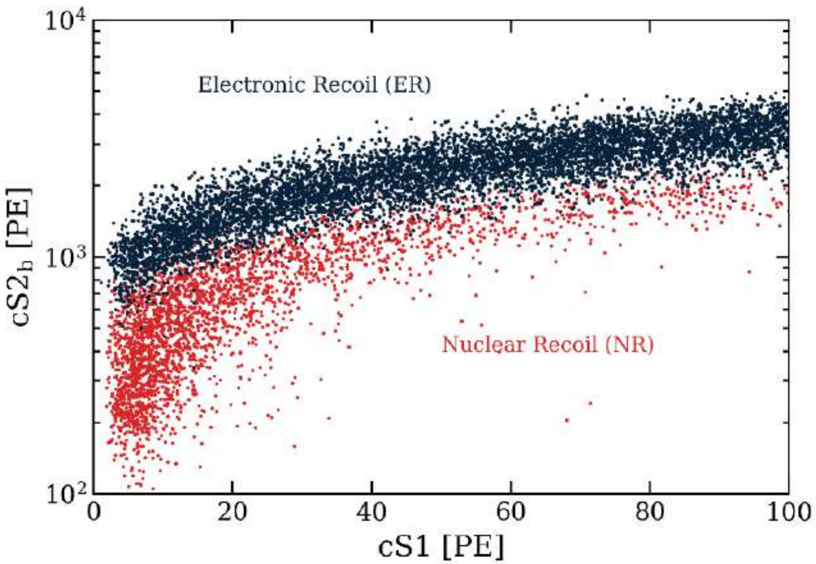

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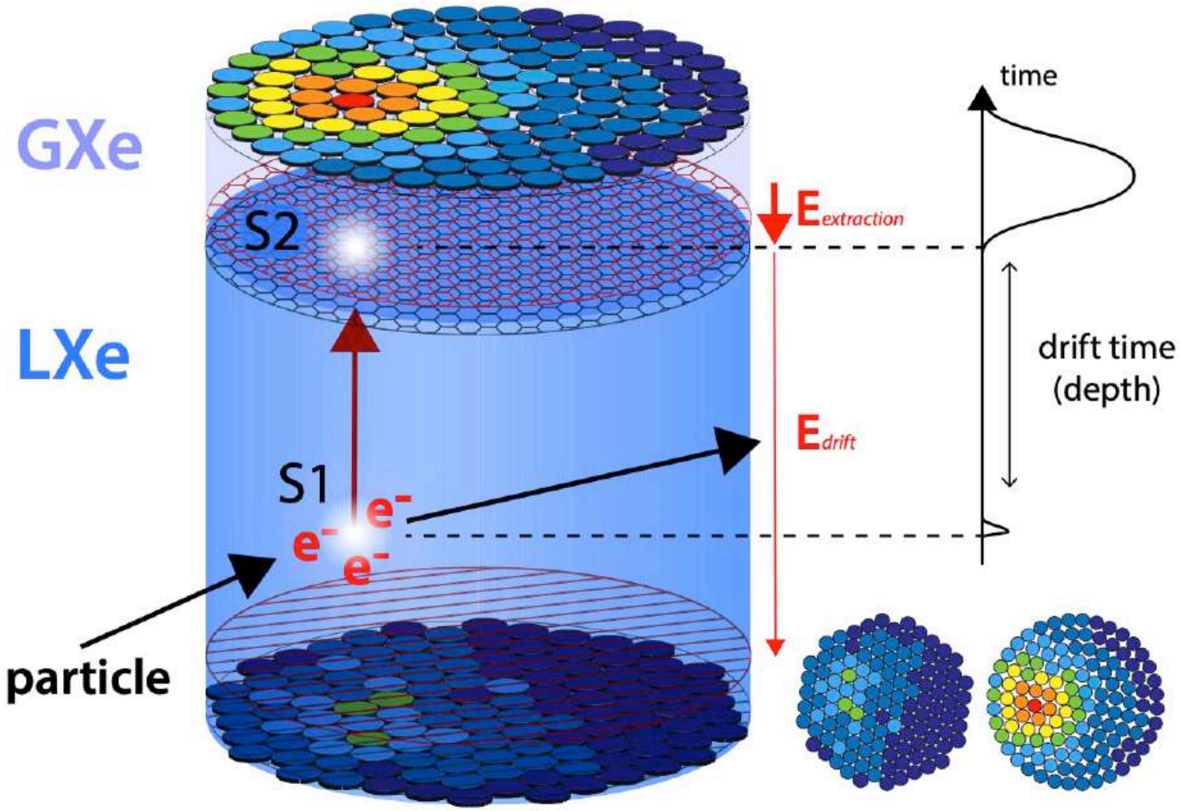
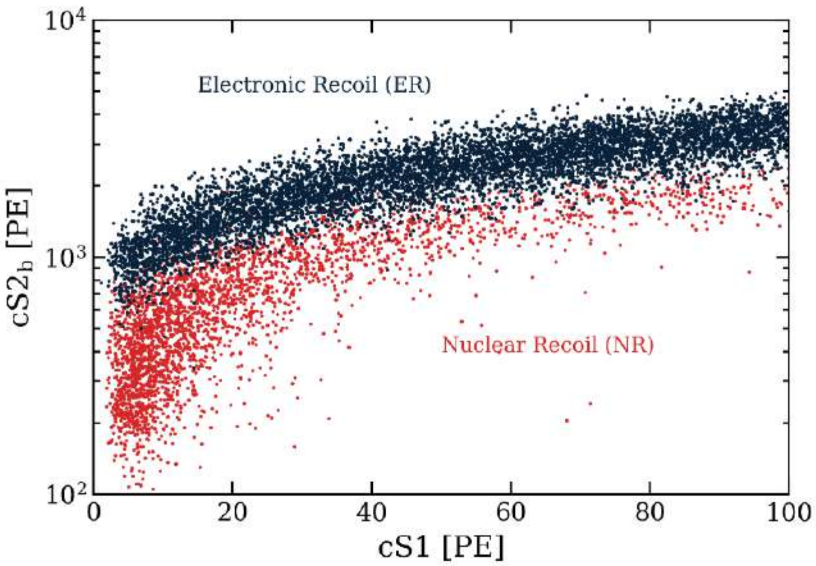
LXe Dual Phase Time Projection Chamber



- **Energy** from S1 and S2
- **3D** event **reconstruction**
  - X, Y from S2 hit pattern on top PMTs
  - Z from S2 – S1 time difference

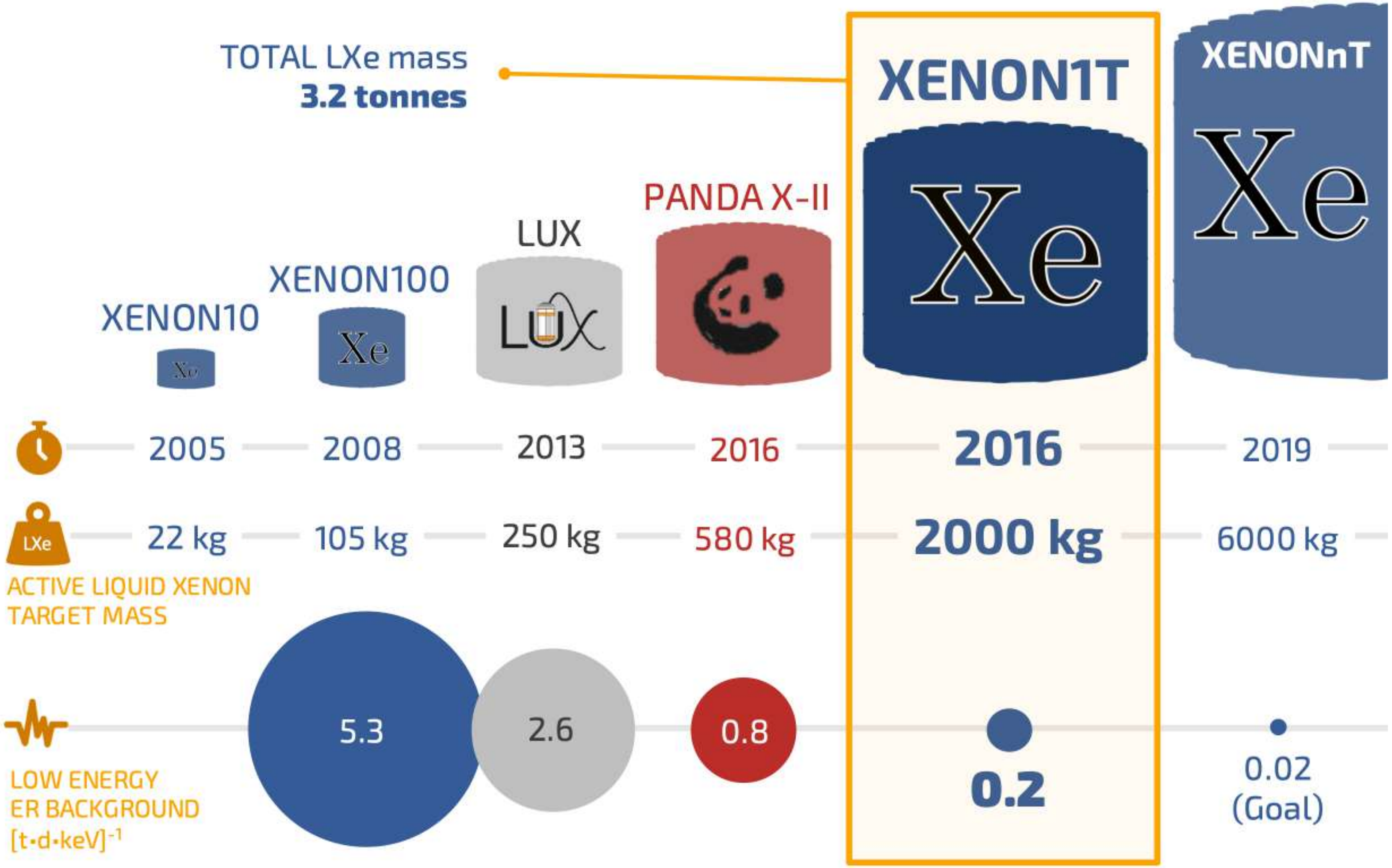


- **ER** vs **NR** discrimination

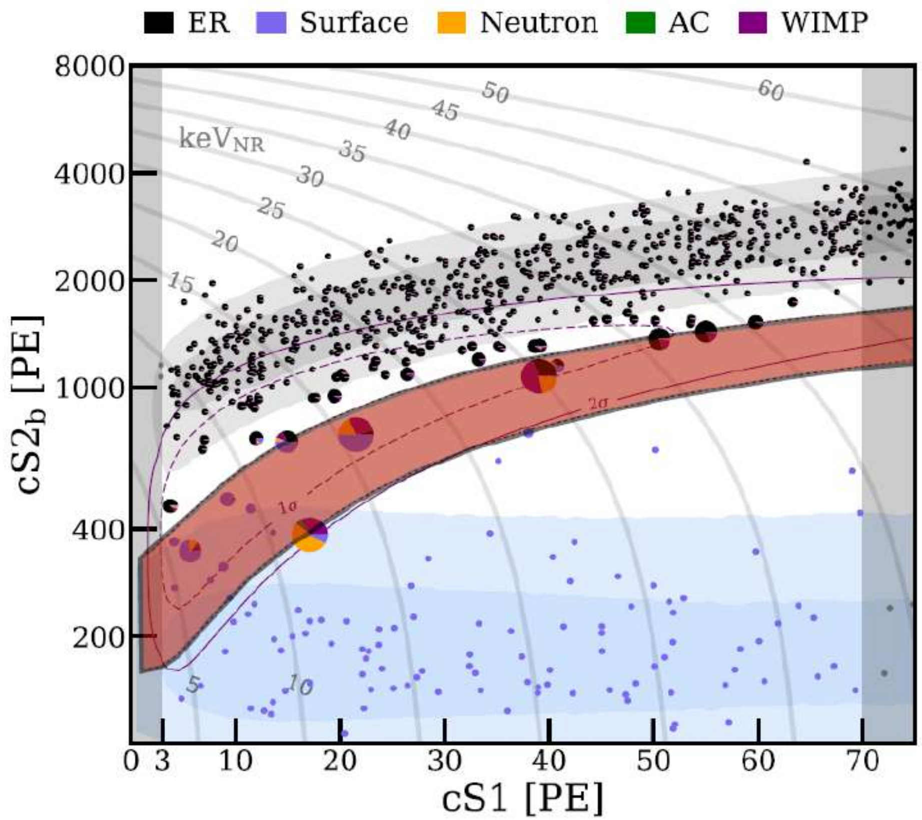
$(S2/S1)_{NR} < (S2/S1)_{ER}$

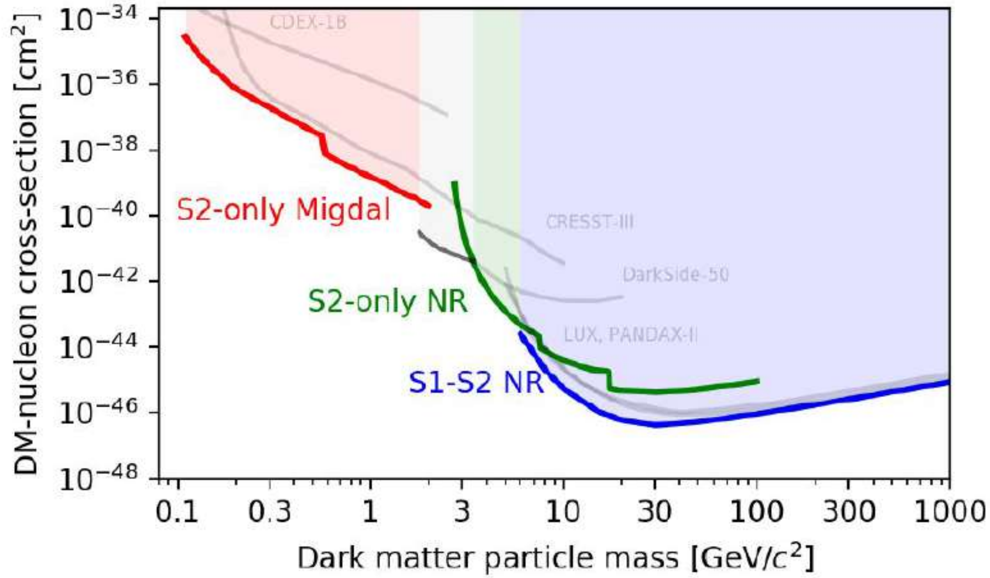
LXe Dual Phase Time Projection Chamber Evolution

Extremely difficult Dark Matter measurement requires large detectors with tiny electronic-recoil backgrounds



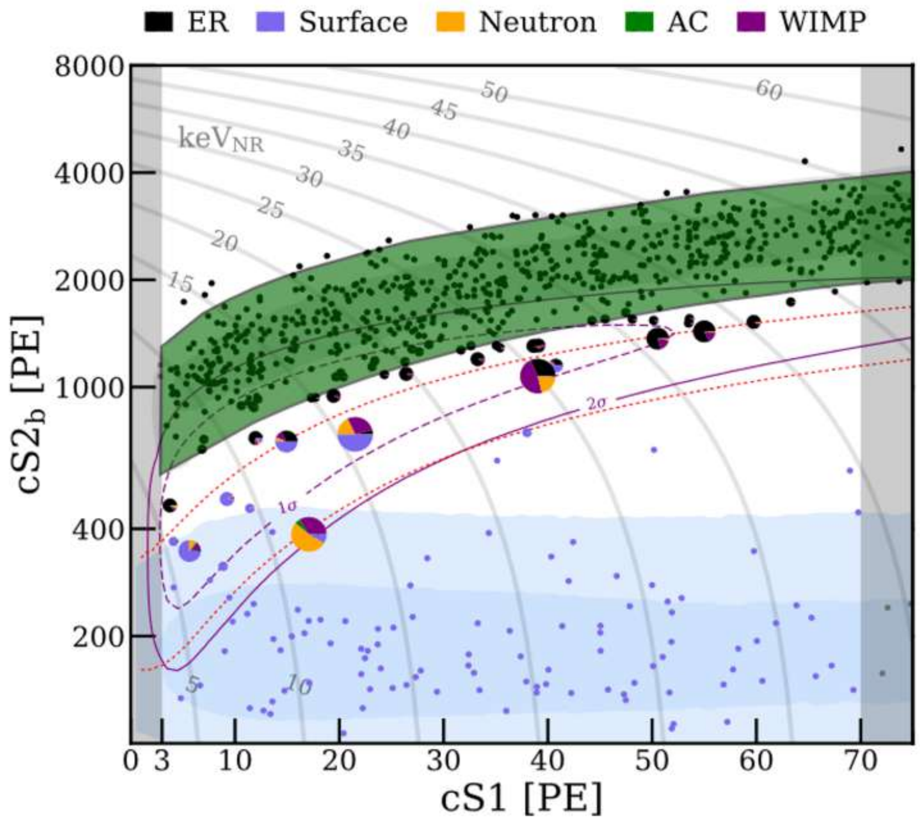
Nuclear Recoil Search in XENON1T





PRL 123, 241803 - Migdal effect
PRL 123, 251801 - Light dark matter
PRL 121, 111302 - Main WIMP search

WHAT ABOUT ELECTRONIC RECOILS ?



- This talk !

  → Search for excess events over known background in XENON1T

arxiv:2006.09721

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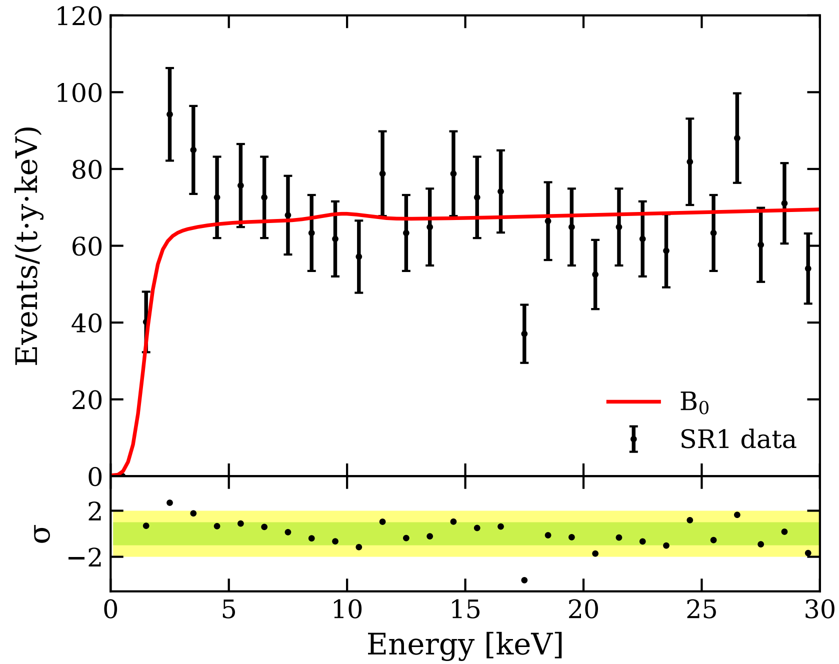
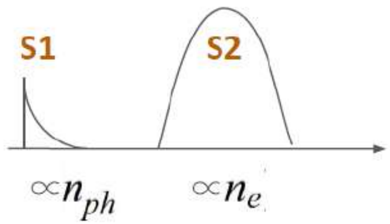
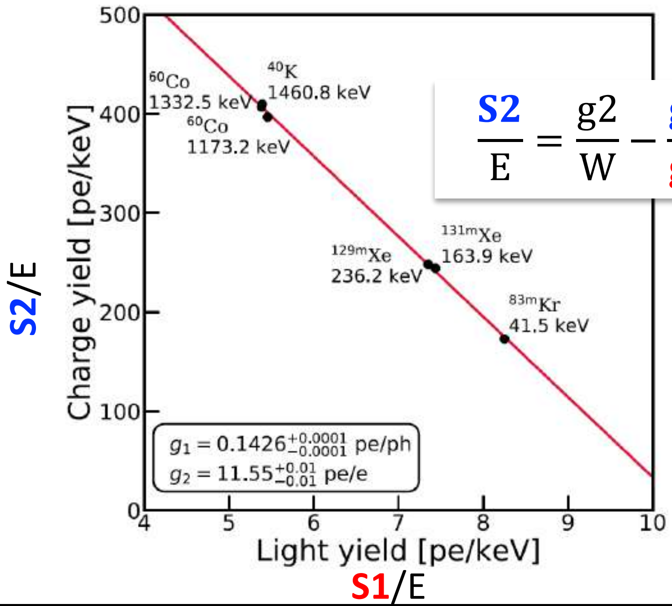


ENERGY RECONSTRUCTION

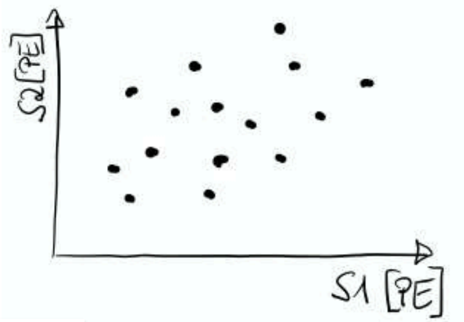


$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

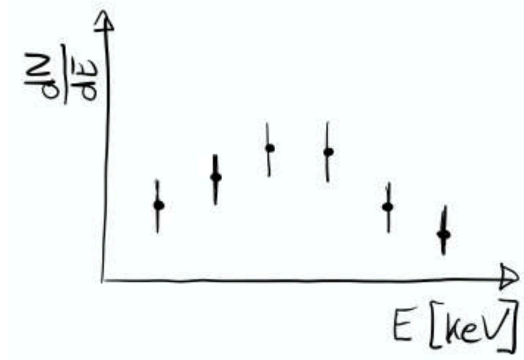


$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$

2D analysis



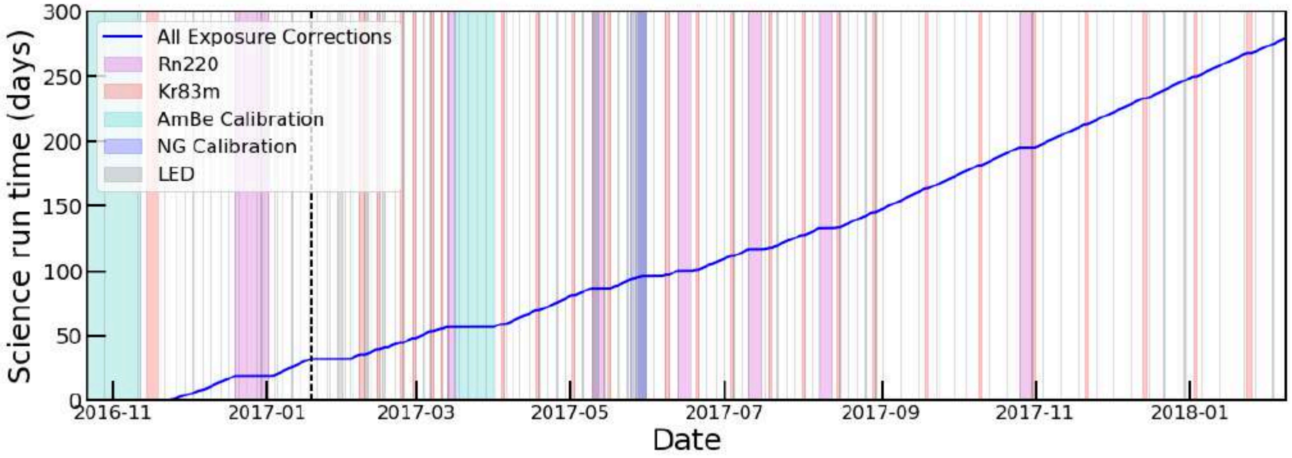
1D analysis



- **2D analysis** : use of both **S1** and **S2** signals
- Determination of scintillation (**g1**) and ionization (**g2**) gains with calibration data

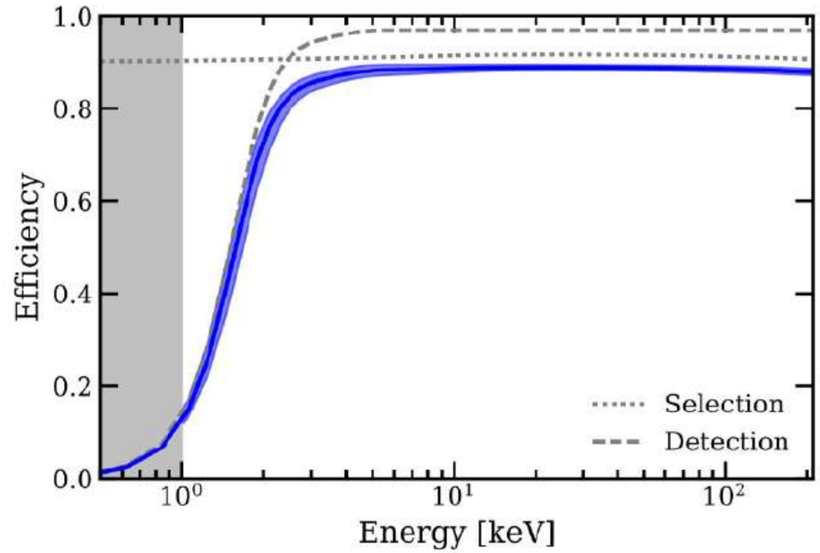
→ **1D analysis** : **Combined energy scale as analysis space**

DATA SELECTION

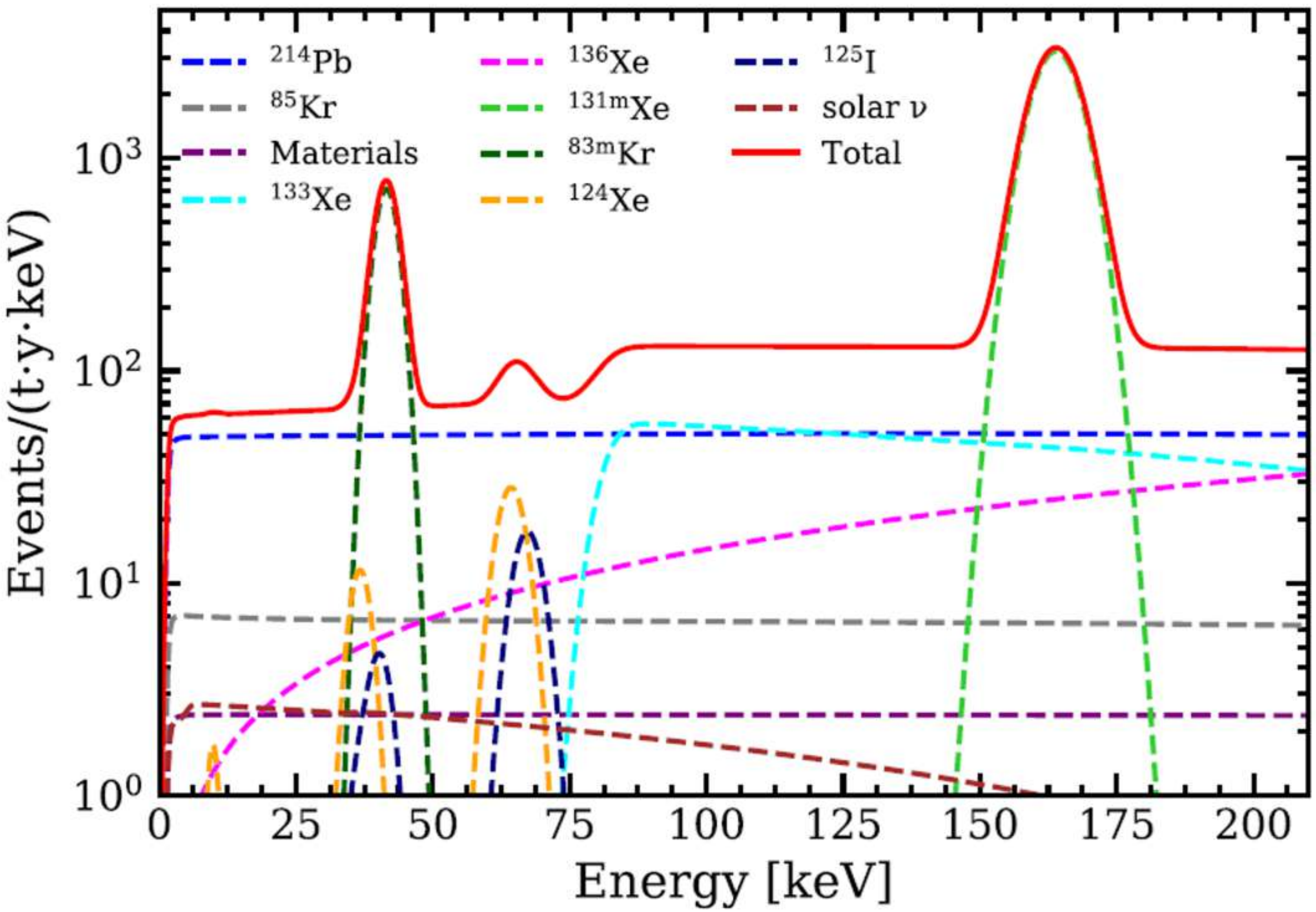


- Exposure 0.65 t * y
- Single-scatter events within [1, 210] keV_{ee}
- 3-fold PMT coincidence for S1 detection
- Standard quality cuts with higher S2 threshold
- 1 t Fiducial Volume

- **SCIENCE RUN 1 (SR1)**: from Feb 2017 to Feb 2018
  - Total of 226.9 live days
- SCIENCE RUN 2 (SR2): right after SR1 & until end of 2018
  - Several tests performed, 24.4 live days of stable data
  - 20% less background (new pumps, radon distillation)

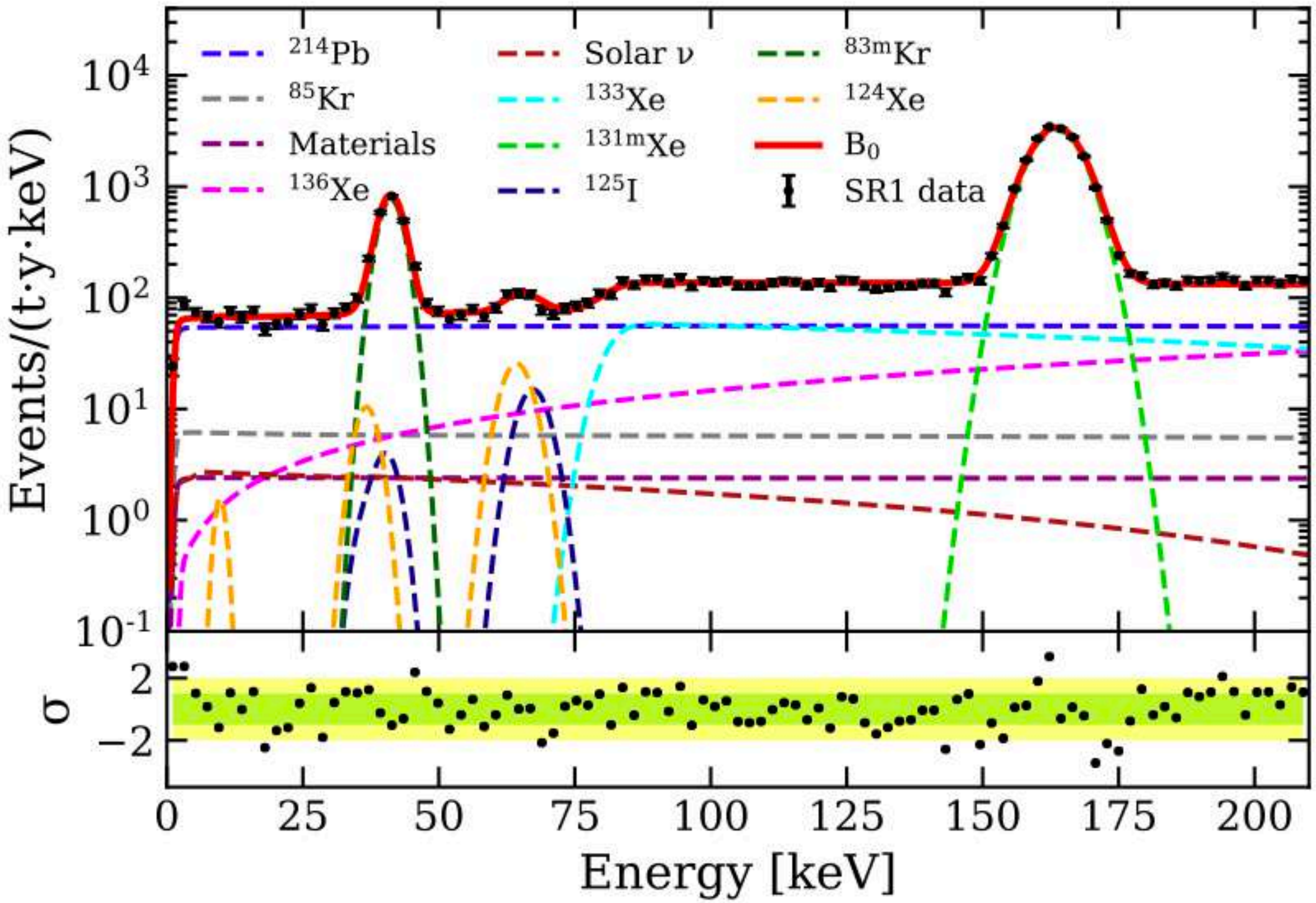


BACKGROUND MODEL



- **Intrinsic**
  - ^{214}Pb
  - ^{85}Kr
  - ^{136}Xe
  - ^{124}Xe
- **Neutron activated**
  - ^{131m}Xe
  - ^{133}Xe
  - ^{125}I
- **Materials**
- **Solar neutrinos**

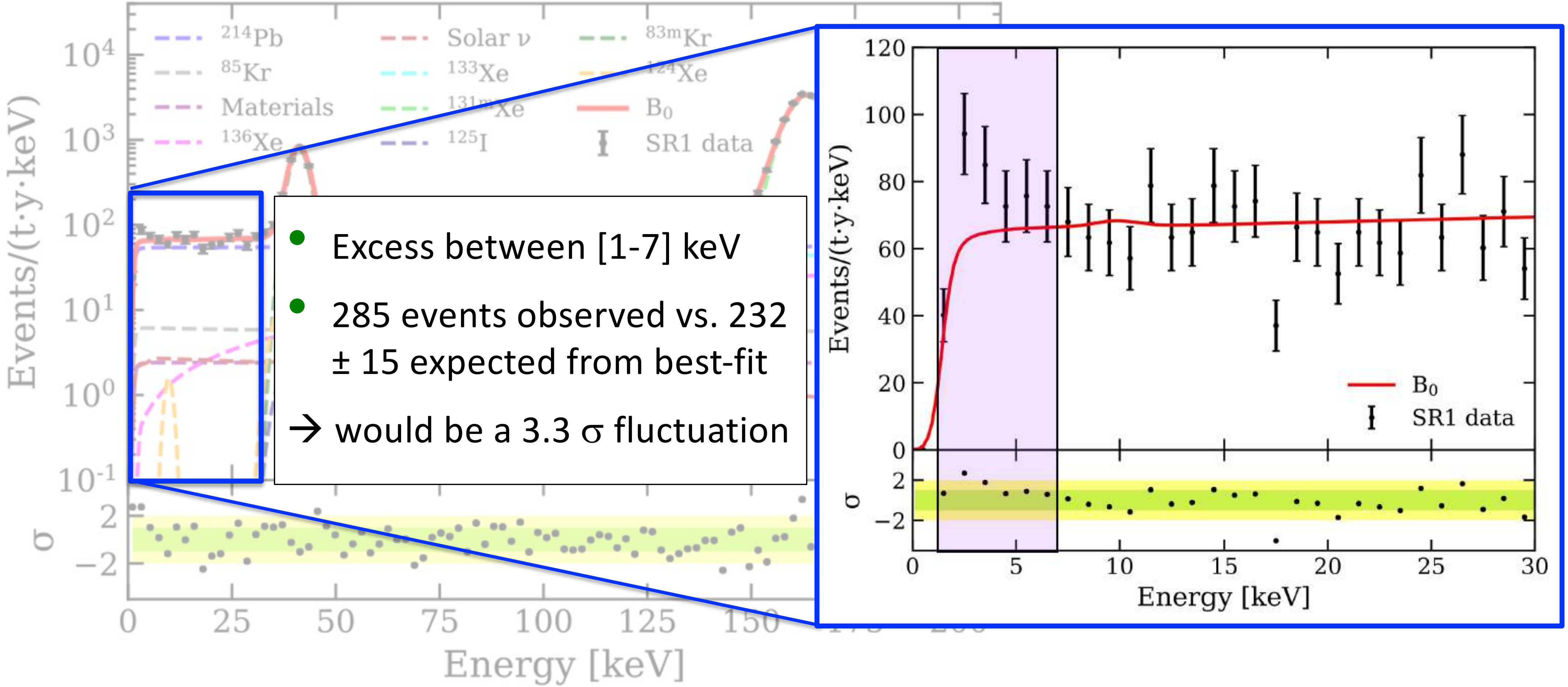
BACKGROUND MODEL & DATA



Lowest background rate ever achieved in this energy range!

- (76 ± 2) events/(t *y*keV) in [1, 30] keV
- Good fit observed over most of the energy range

THE EXCESS



- Excess between [1-7] keV
- 285 events observed vs. 232 ± 15 expected from best-fit

→ would be a 3.3 σ fluctuation

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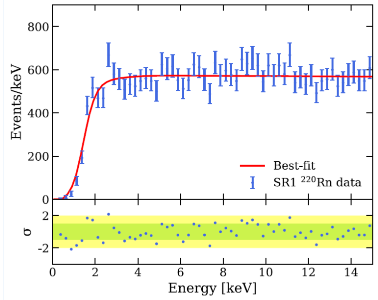
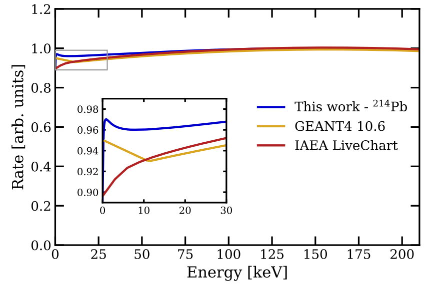
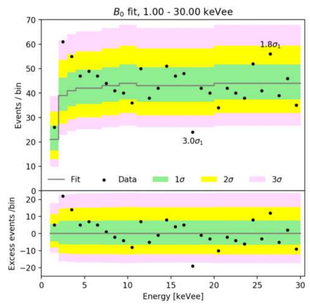
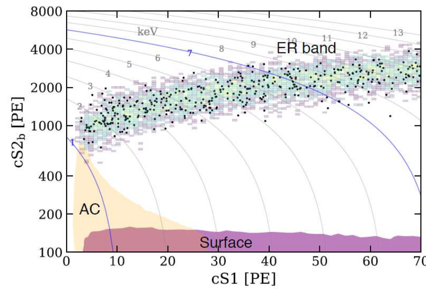
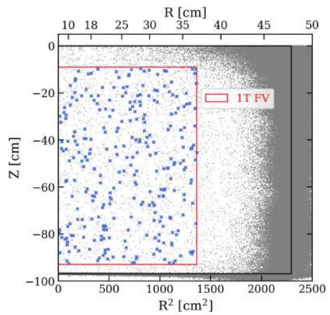
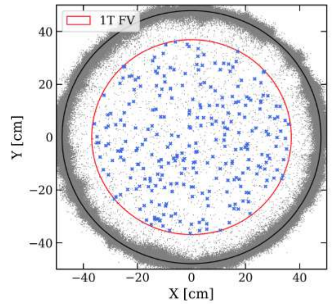










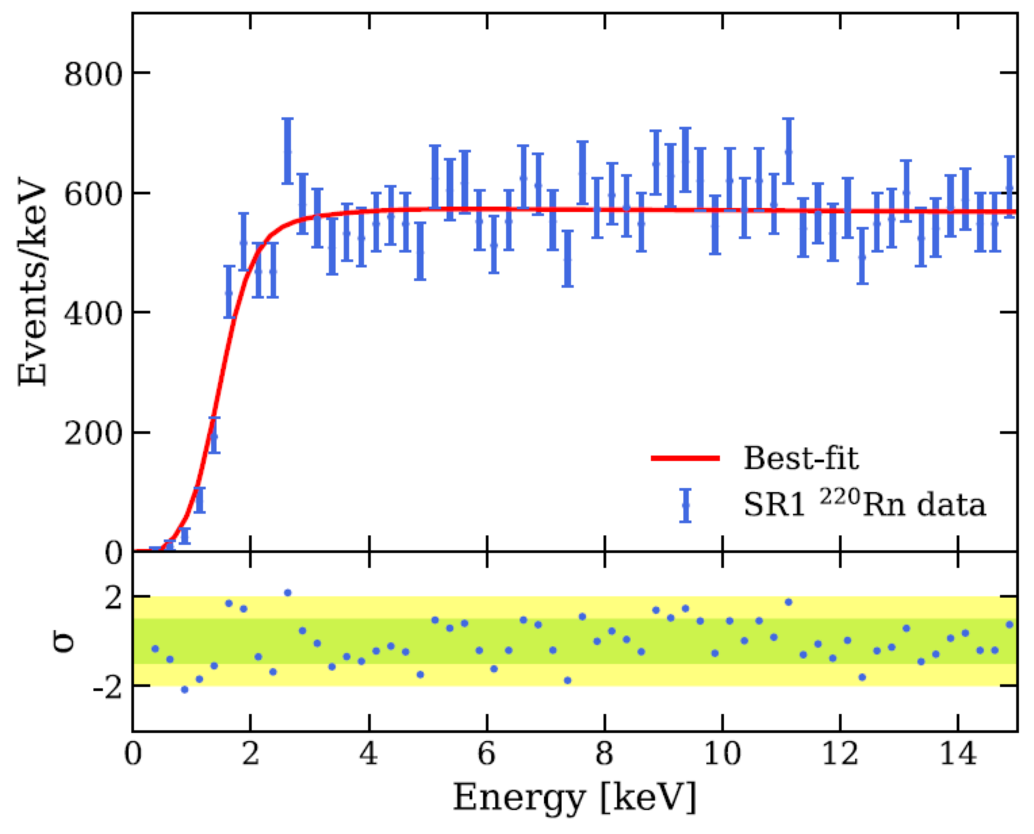


EFFICIENCY OR ENERGY RECONSTRUCTION ?

- High statistics ^{220}Rn calibration data validate our model

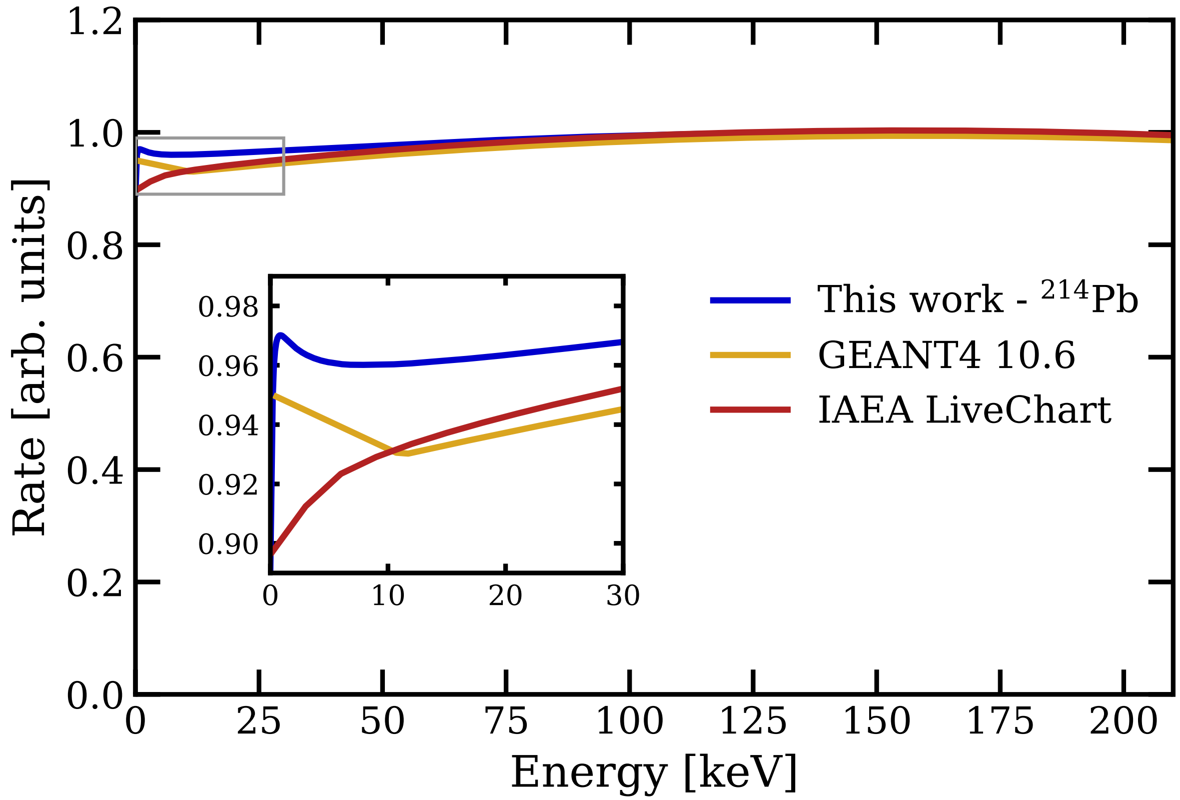
- The excess is **not at our threshold fall-off**. It persists:
  - if analysis threshold is doubled
  - with a profile likelihood in (S1, S2) space
  - if efficiencies are different within ±1 σ

- To explain the excess, you need:
  - a large systematic
  - that is absent when we calibrate



MIS-MODELING OF THE BACKGROUND SHAPE ?

- Atomic screening and exchange effects do lead to rate enhancement at very low energies
- Not properly considered in GEANT4 and IAEA
- We teamed up with X.Mougeot (CEA) to calculate the correct spectrum



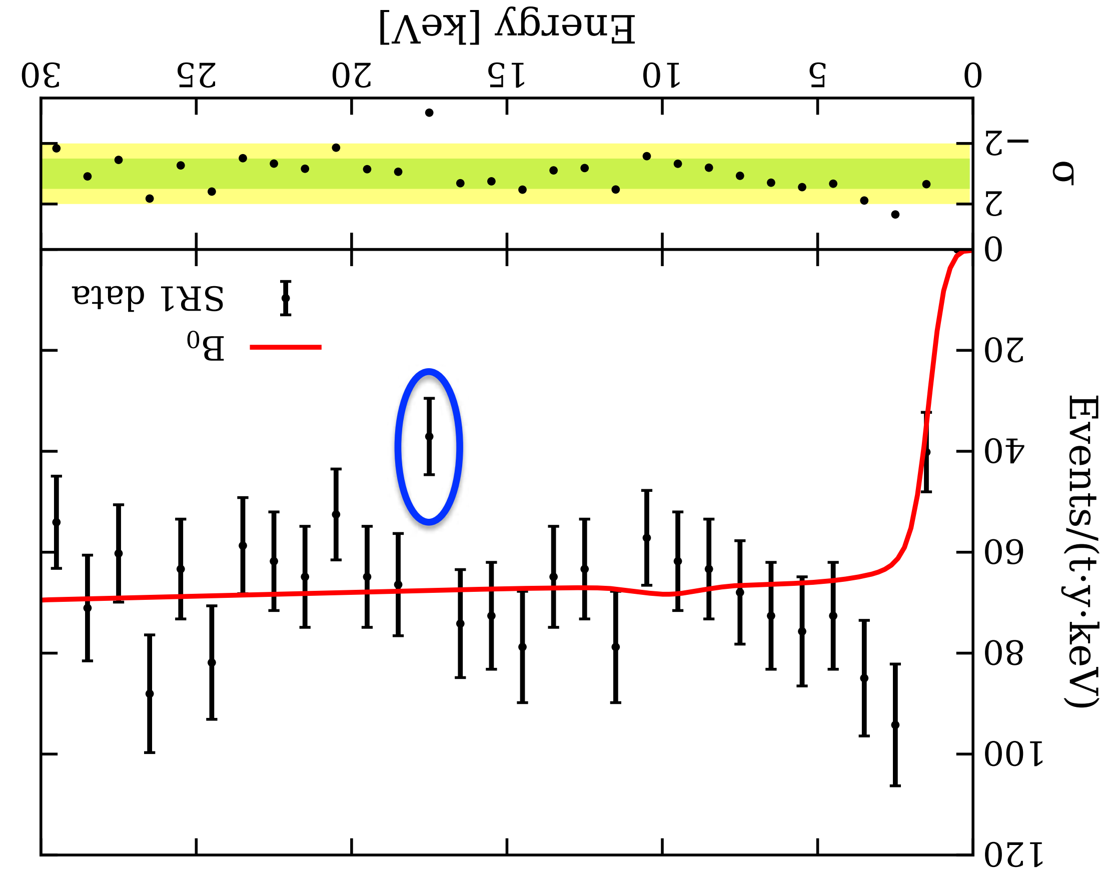
~ 6% uncertainty on the shape

~ 50% needed to account for the excess

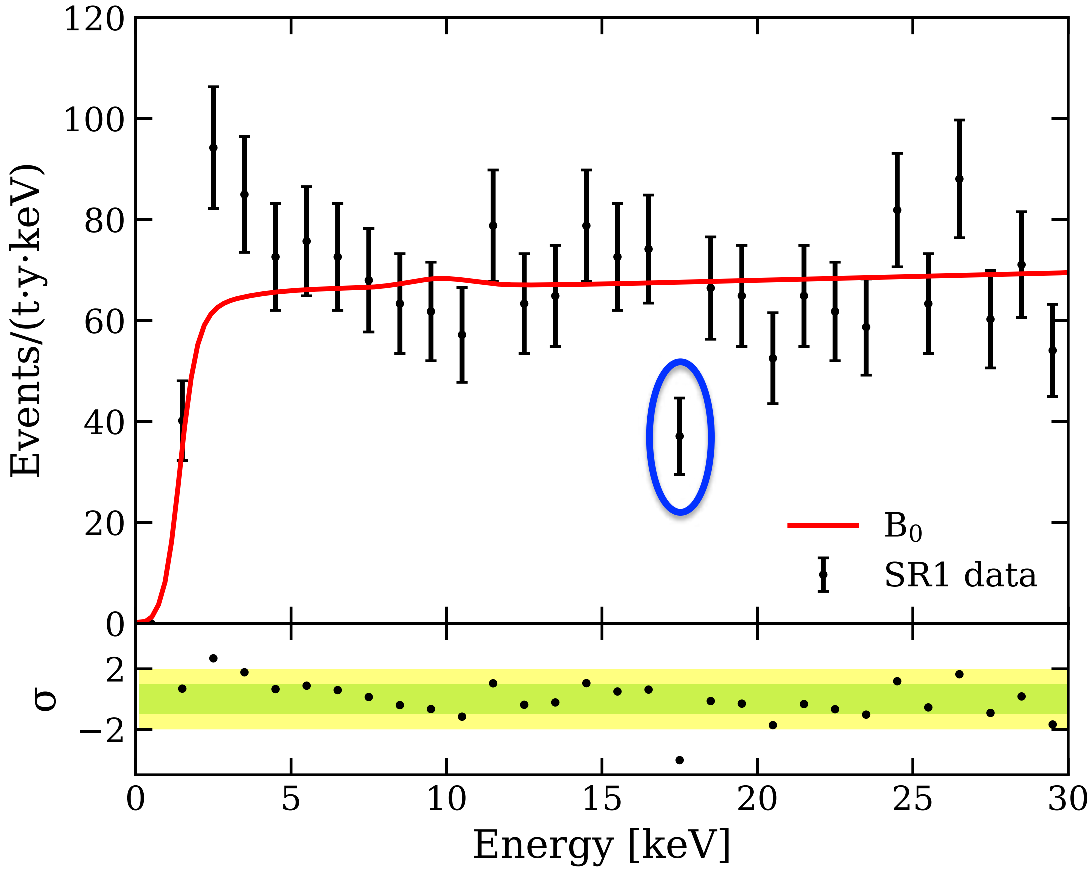
STATISTICAL FLUKE ?

Theorists' skepticism

Are we still excited if we rotate the plot by 180 degrees?

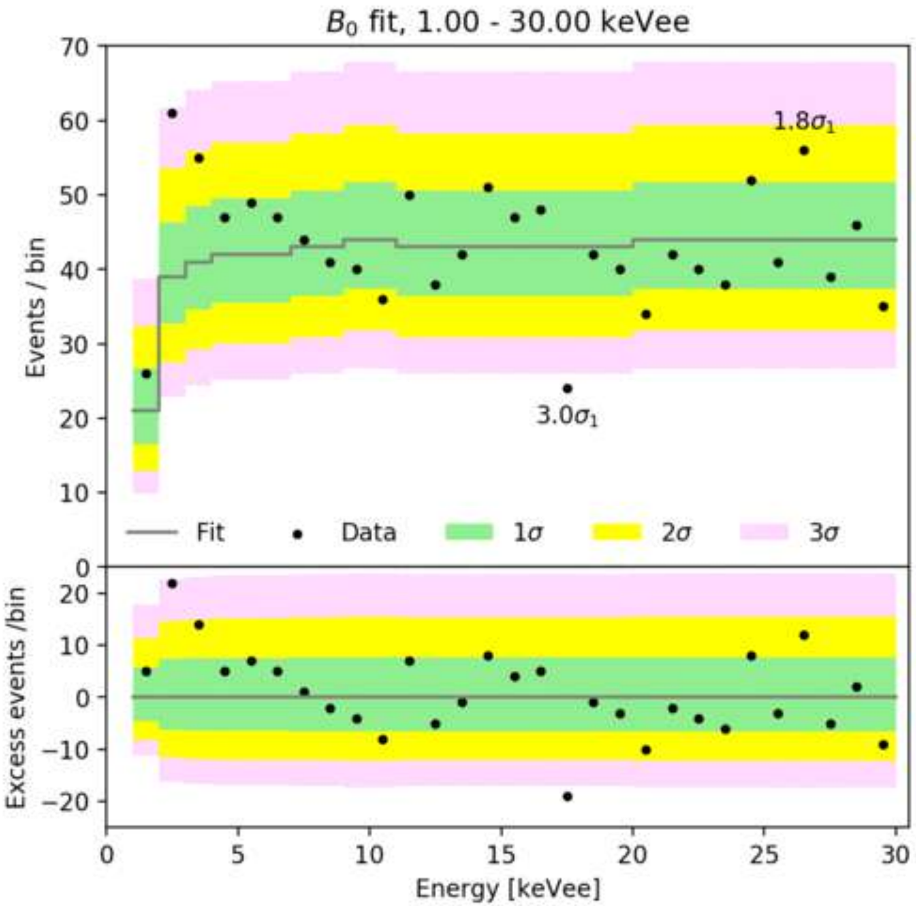


STATISTICAL FLUKE ?



We investigated the dip at ~ 17 keV

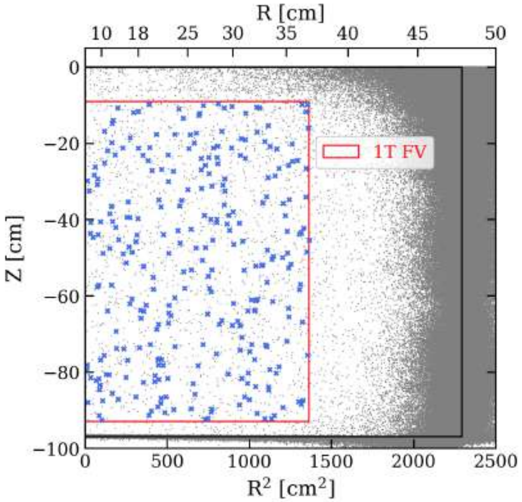
STATISTICAL FLUKE ?

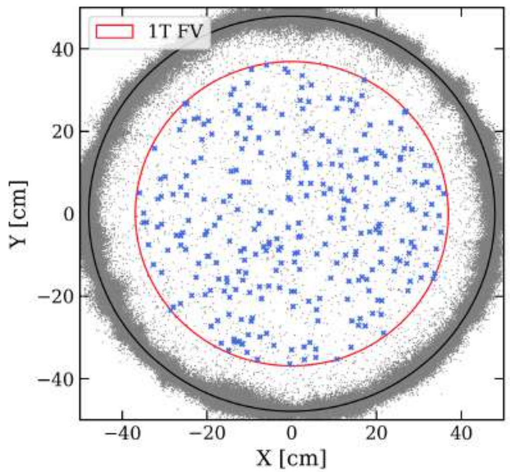


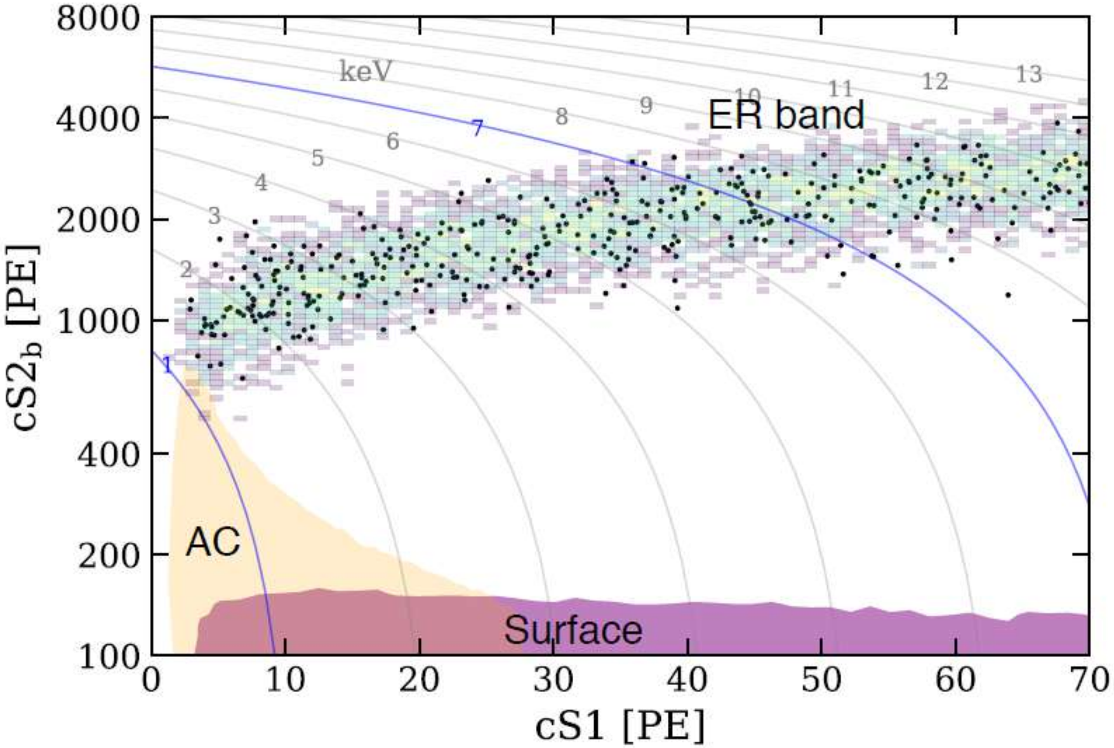
- Changing the display bins changes the apparent deviation
- Bins are for presentation only, we use an unbinned profile likelihood
- Bins are smaller than energy resolution → physics related phenomena should have bins correlated

The sub-7 keV excess is robustly visible across several bins

Event Location and Instrumental Backgrounds ?







- Spatially uniform
- Negligible amount of accidental coincidences (AC) in the ROI
- No surface background in the ROI

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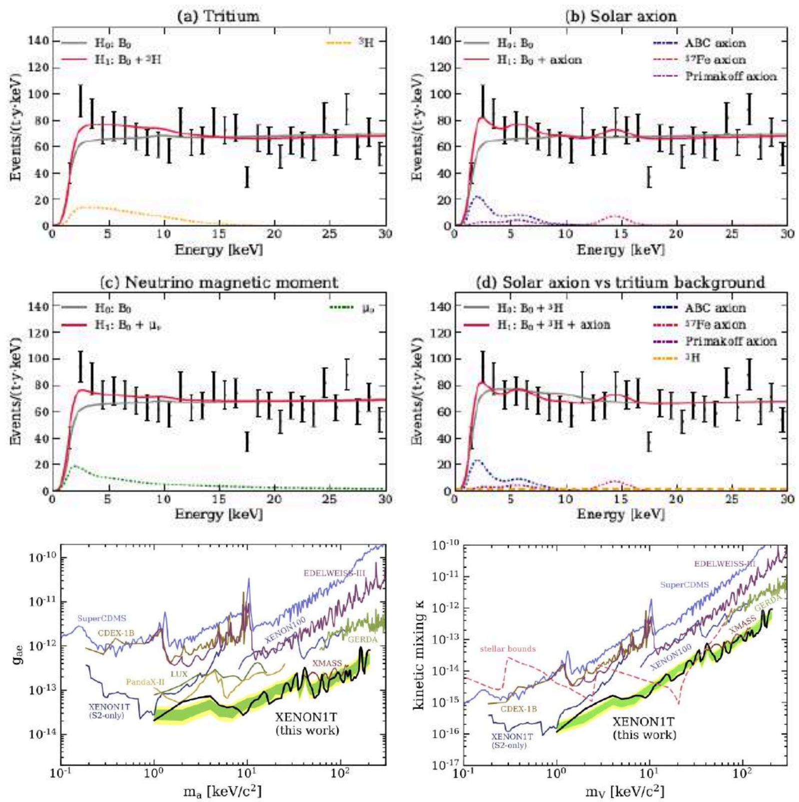


STANDARD MODEL & BEYOND INTERPRETATIONS

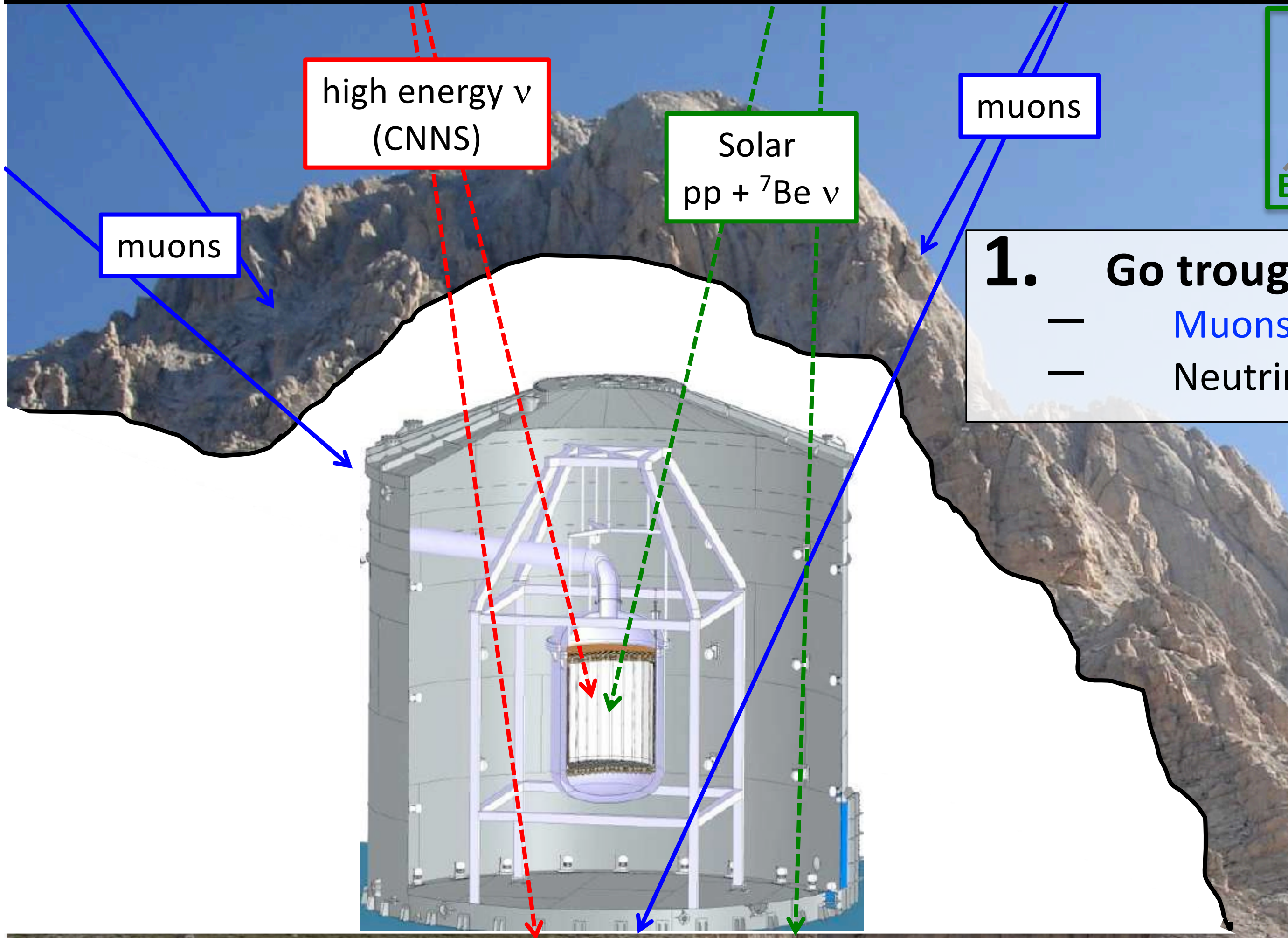
- **Standard Model**
  - Not considered backgrounds? → The **Tritium** hypothesis
- **Beyond the Standard Model**

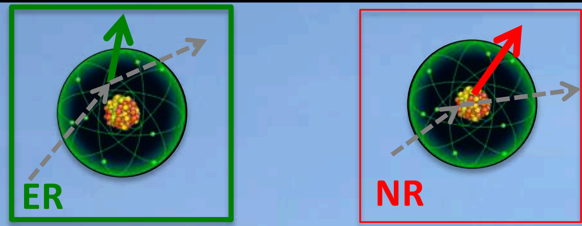
  We focus on 3 signals that are "traditional", but represent the variety of spectra
  - **Solar axions** : peaked around 1-2 keV, set by the Sun's core temperature
  - **Anomalous ν magnetic moment** : a continuous spectrum steeply rising towards low E
  - **Bosonic DM absorption** : a monoenergetic peak

Disclaimer

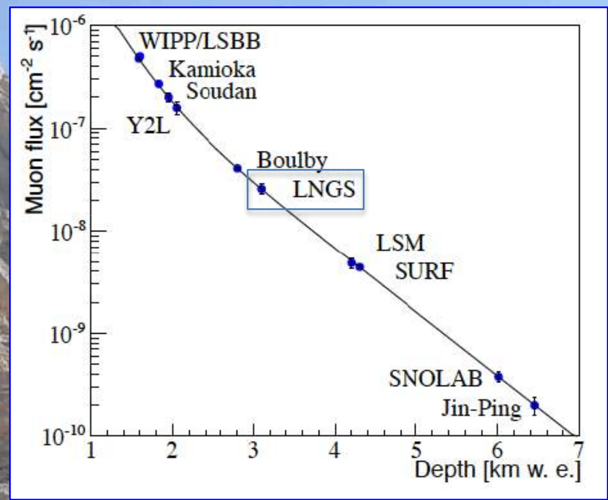
there are (many!) other possible models : I won't cover them today, sorry…

POTENTIAL BACKGROUND EVENTS IN XENON1T





1. Go trough > km of rock
- Muons : too high energy
- Neutrinos, dark particles



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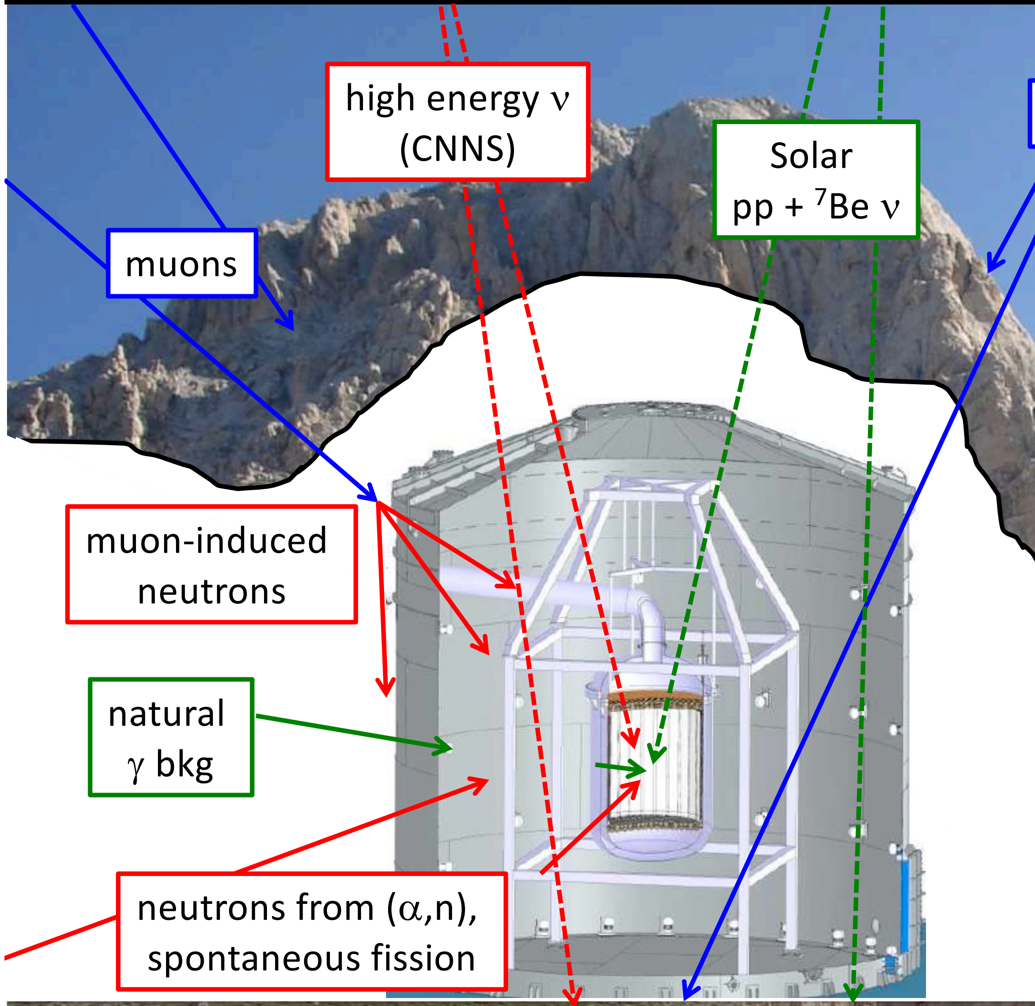
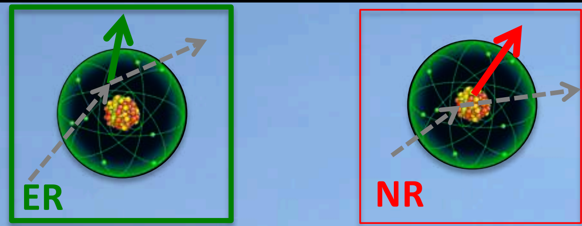
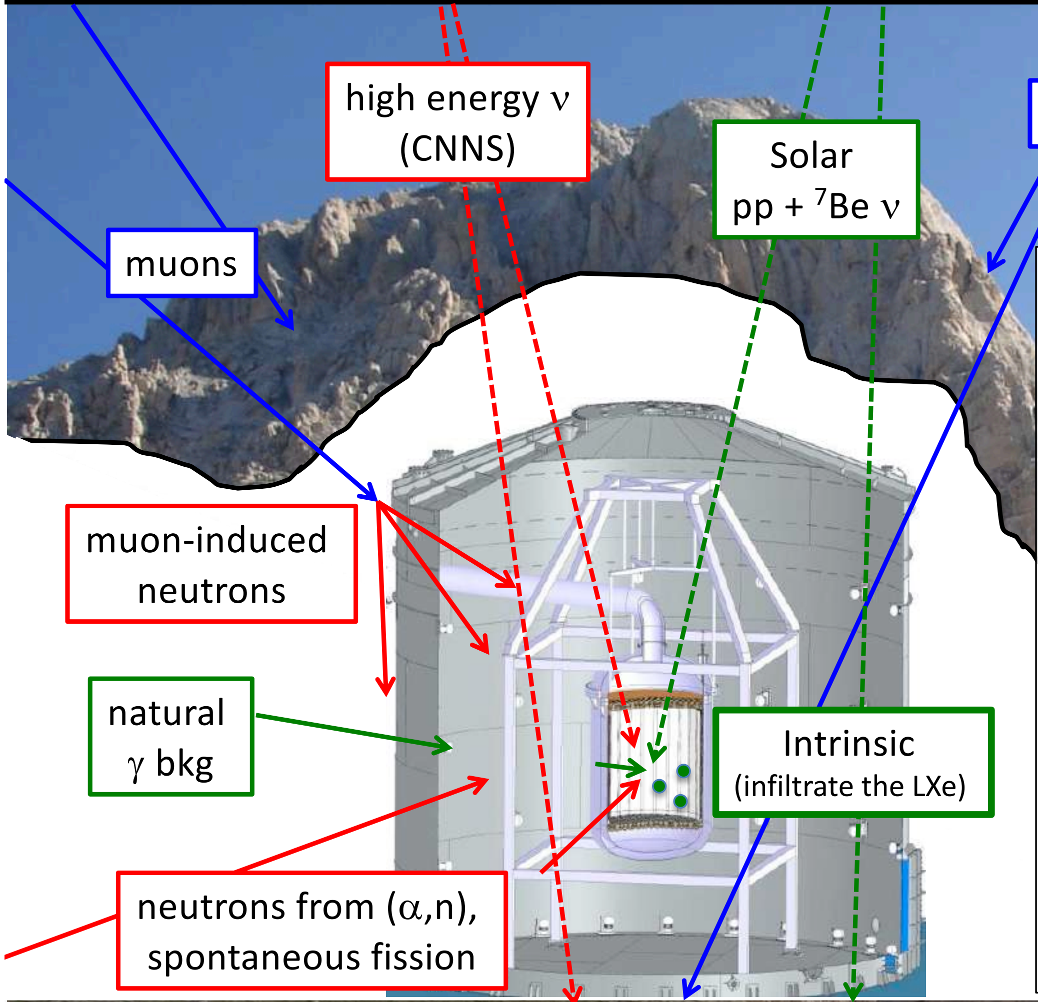
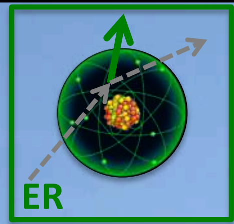


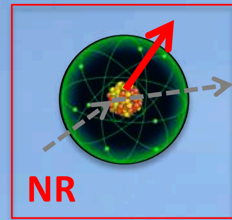


1. **Go trough > km of rock**
   - Muons : too high energy
   - Neutrinos, dark particles
2. **Go trough many cm of metal and Xe**
   - Neutrons (NR) : we can distinguish from ER
   - β and γ : too high energy, spectrum incompatible

POTENTIAL BACKGROUND EVENTS IN XENON1T







1. **Go trough > km of rock**
   - Muons : too high energy
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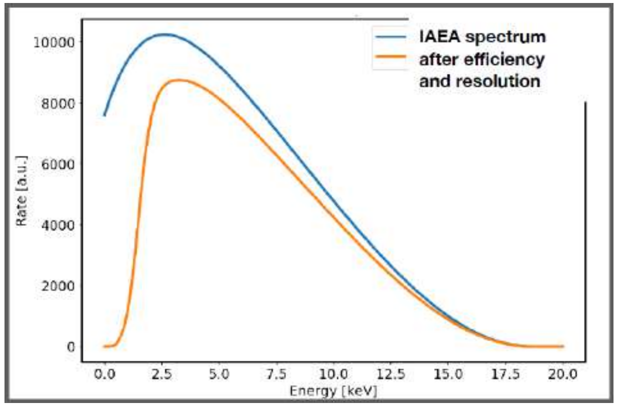
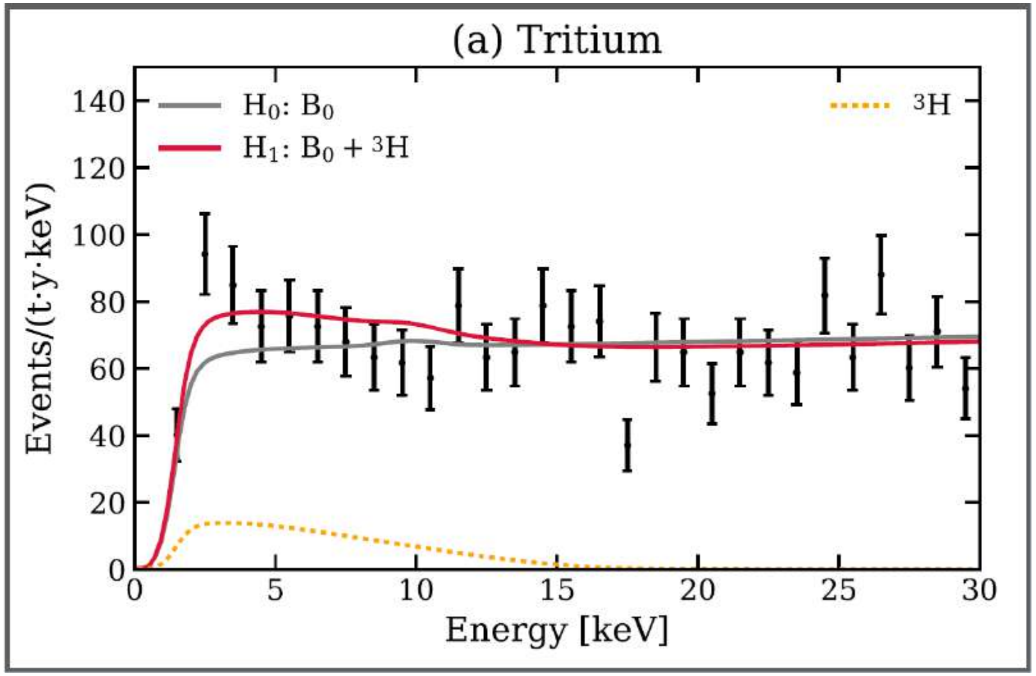
2. **Go trough many cm of metal and Xe**
   - Neutrons (NR) : we can distinguish from ER
   - β and γ : too high energy, spectrum incompatible
3. **Infiltrate the LXe**
   - ^{222}Rn → ^{214}Pb, ^{85}Kr, ^{136}Xe, ^{124}Xe : accounted for different energies
   - ^{127}Xe, ^{37}Ar :
     - $t_{1/2}$ ~ months : too short
     - > 6L day air leak ruled out by Kr measurements
   - **New bkg: Tritium? → see next slides**

TRITIUM

- Long-lived (12.3 y) low energy β emitter (Q-value 18.6 keV)
- **Cosmogenic activation** of xenon or **atmospheric abundance**?
- Favored over B_0 at 3.2σ





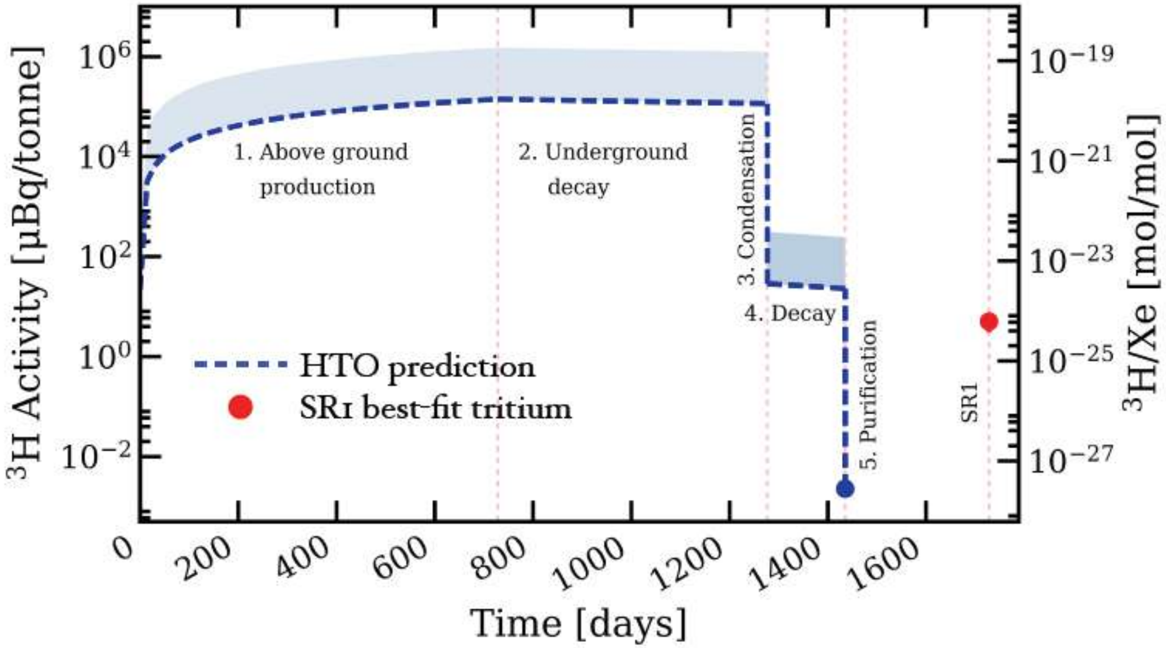
- Best fit rate (159 ± 51) evts/ (t·y·keV)
- ^{3}H/Xe concentration:
  (6.2 ± 2.0) × 10^{-25} mol/mol

Fewer than 3 tritium atoms per kg of xenon!

TRITIUM FROM COSMOGENIC ACTIVATION OF XENON

1. Xenon gas stored above ground
   - Cosmogenic activation of xenon produces ~32 tritium atoms / kg / day (Zhang, 2016)
   - 1 ppm of water in xenon bottles implies formation of HTO
2. Gas moved underground and decay
3. Xe filled into the cold ReStoX storage vessel (~ x4000 reduction)
   - Water (including HTO) condenses and remains on the vessel walls
4. Further decay until the detector is filled
5. Detector filling :efficient removal (99.99%) in dedicated hydrogen removal unit of the purification system

Tritiatited Water (HTO)



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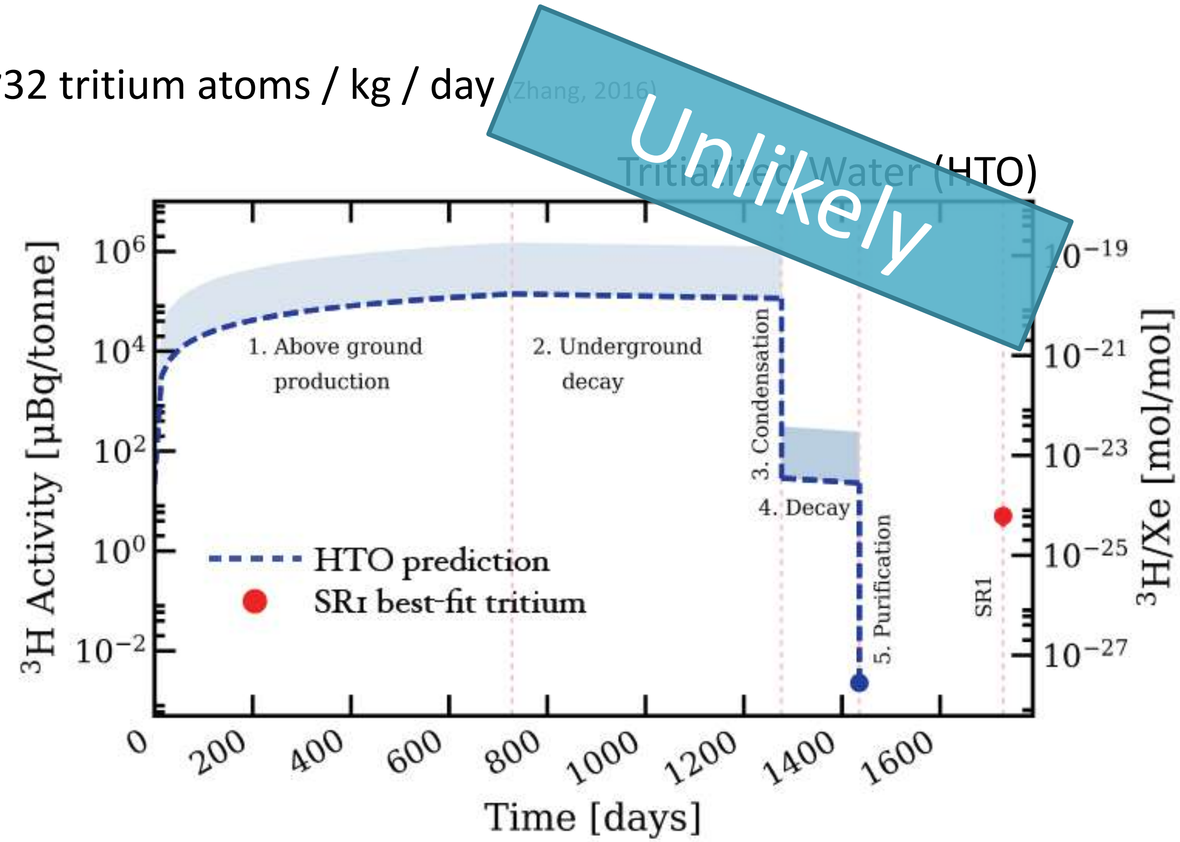


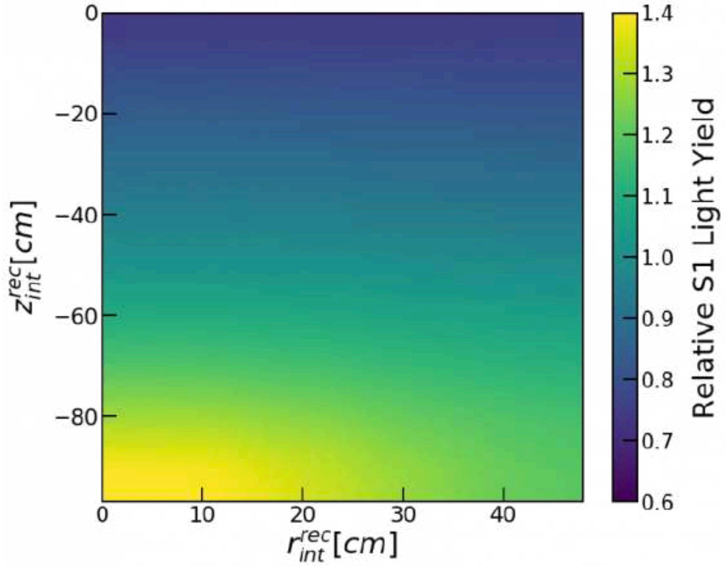
Predicted rate 100x lower than observation

TRITIUM FROM ATMOSPHERIC ABUNDANCE IN MATERIALS

HTO:H_2O concentration (*assume same for HT:H_2*)	**$(5—10)\times10^{-18}$ mol/mol** *
Required **$(H_2O + H_2)$:Xe** concentration to explain the excess	**60-120 ppb**

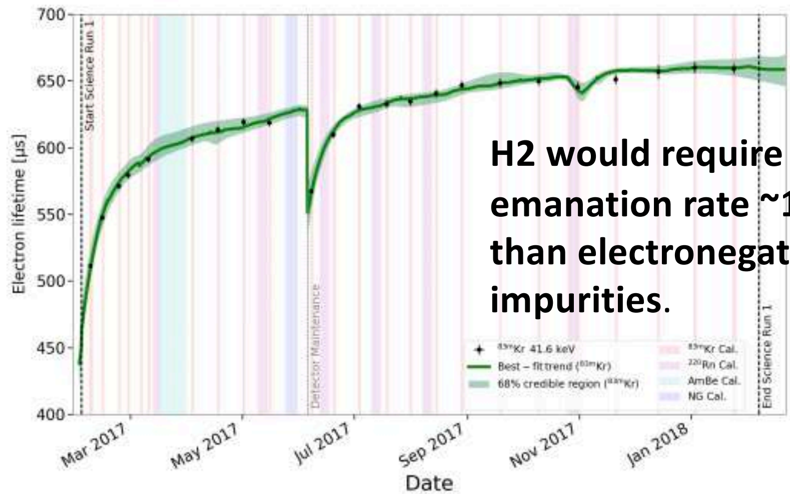
Tritiated Water (HTO)

Light yield ⟹ **O(1) ppb** H_2O:Xe



Triated Hydrogen (HT)

Electron lifetime ⟹ **< ppb** O_2-equivalent impurities



H2 would require equilibrium emanation rate ~100x higher than electronegative impurities.

*Hydrology measurements from IAEA nuclear database

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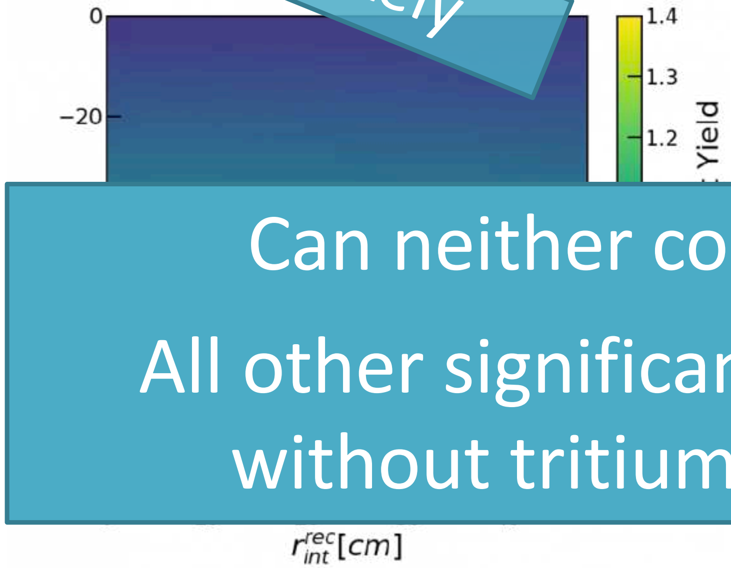
Required **(H_2O + H_2):Xe** concentration to explain the excess	**60-120 ppb**

Tritiated Water (HTO)

Light yield ⟹ … ppb H_2O:Xe

Unlikely



Tritiated Hydrogen (HT)

Electron lifetime ⟹ < … ppb O_2-equivalent impurities

Maybe ?

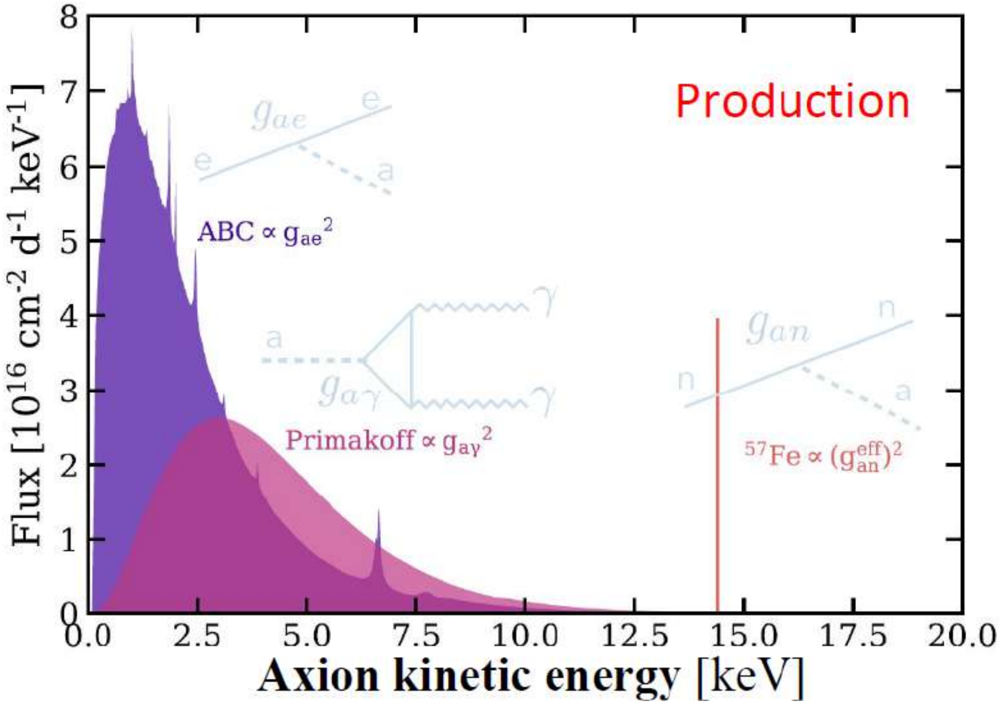
Can neither confirm nor rule out tritium

All other significances reported both with and without tritium in the background model

*Hydrology measurements from IAEA nuclear database

SOLAR AXIONS : PRODUCTION

Hypothetical axions proposed as a solution to the ’strong CP-problem’

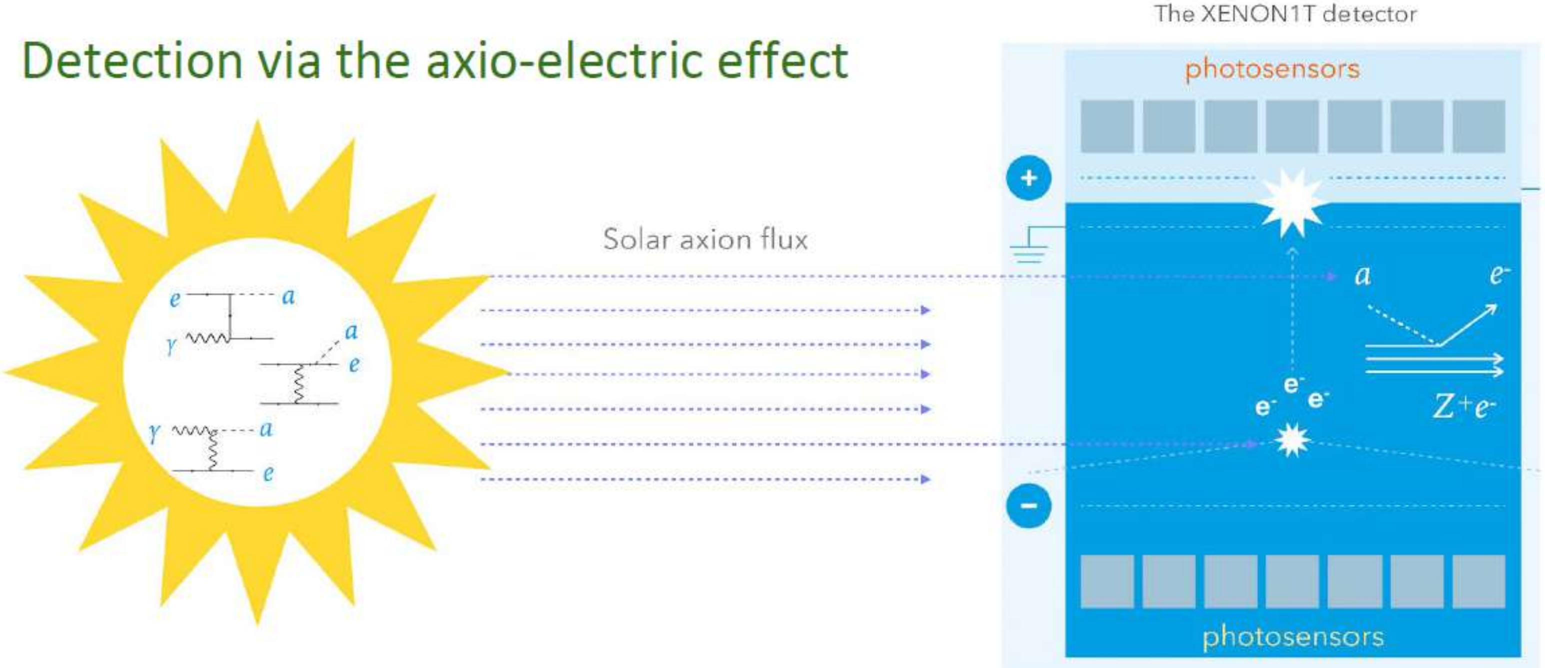


Solar axions would be produced in the Sun with keV energies:

- Atomic recombination and de-excitation, Bremsstrahlung and Compton: ABC
- Primakoff conversion of photons to axions
- A mono-energetic 14.4 keV nuclear transition of ^{57}Fe

SOLAR AXIONS : DETECTION

Hypothetical axions proposed as a solution to the ’strong CP-problem’

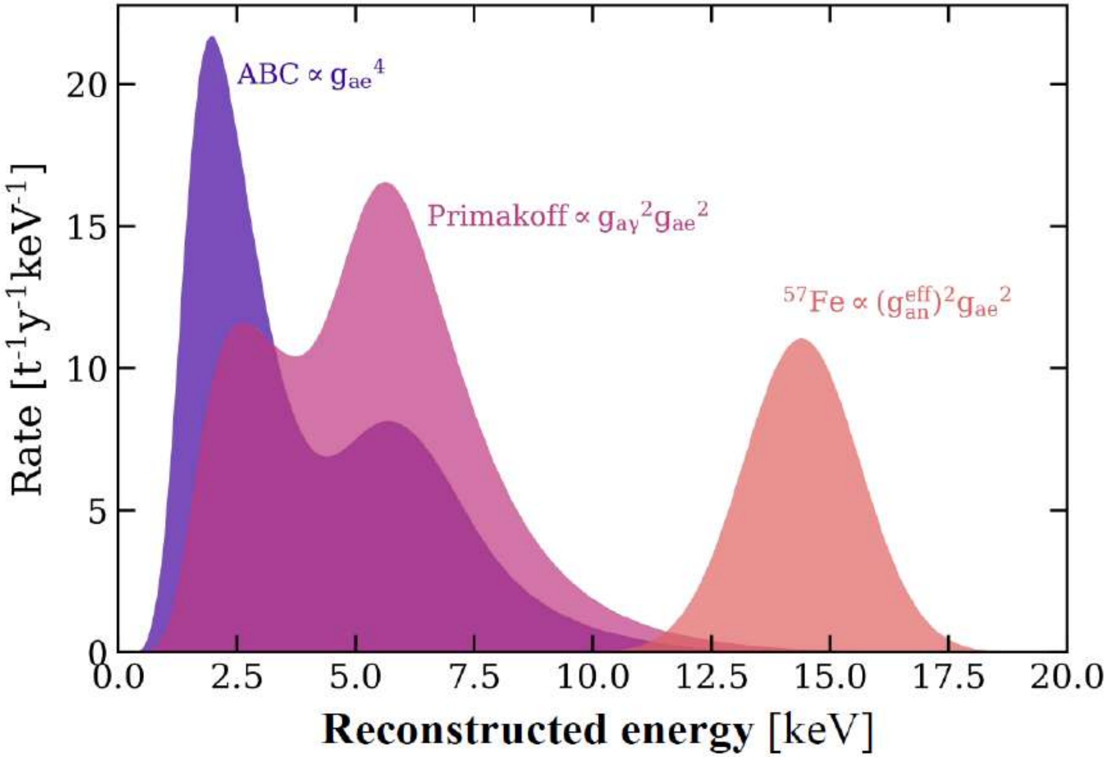


- Detection of axions via the axioelectric effect $\propto g^2_{ae}$
- Absorption of the axion similar to photoelectric effect

SOLAR AXIONS : RECONSTRUCTION

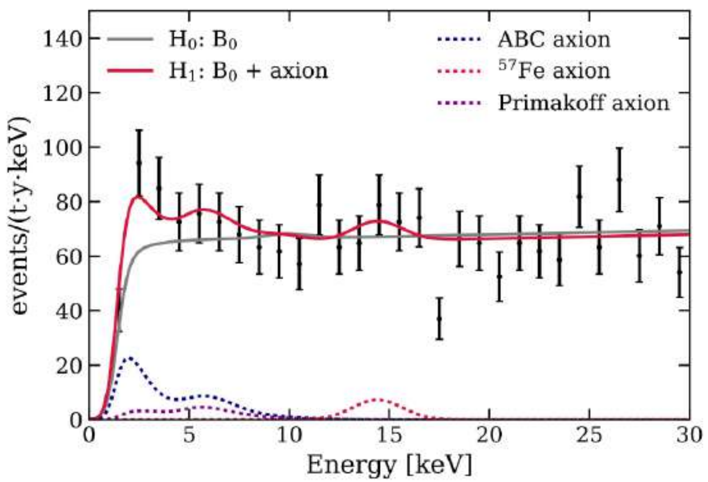
Hypothetical axions proposed as a solution to the ’strong CP-problem’

- Expected rate in xenon convolved with detector effects (resolution, efficiency)
- Energy resolution and shell structure affects the spectrum
- All three components left unconstrained in the fit

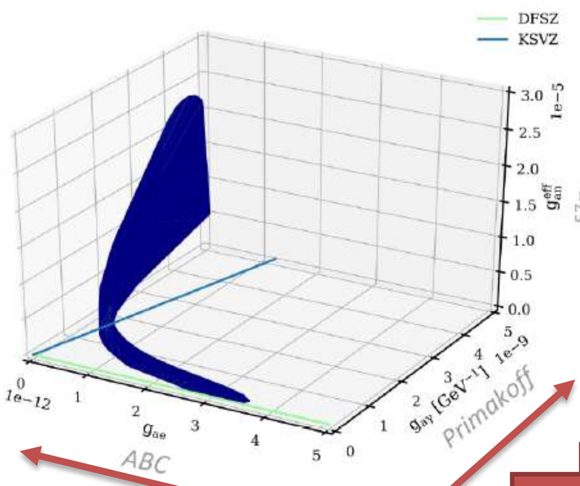


Favored over B_0 at 3.5 σ *

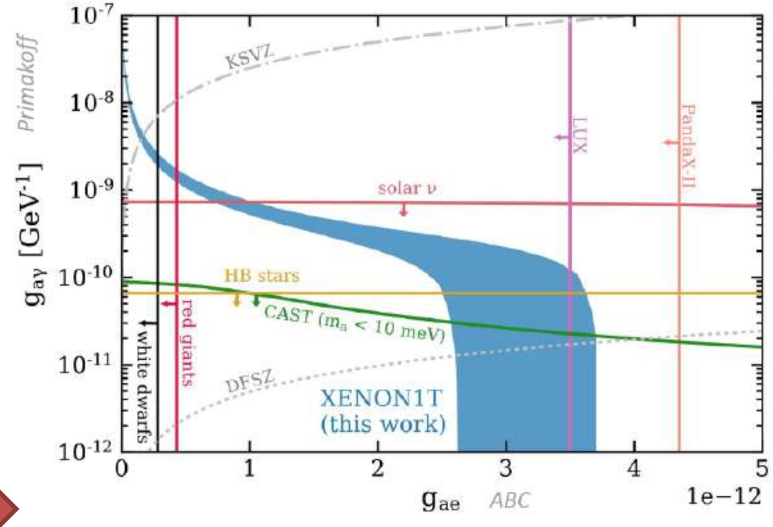
* Drop to 2.1 σ if H_0=B_0+^{3}H



90% C.L. 3D contour



90% C.L. contour projection



Results in tension with astrophysical constraints from stellar cooling

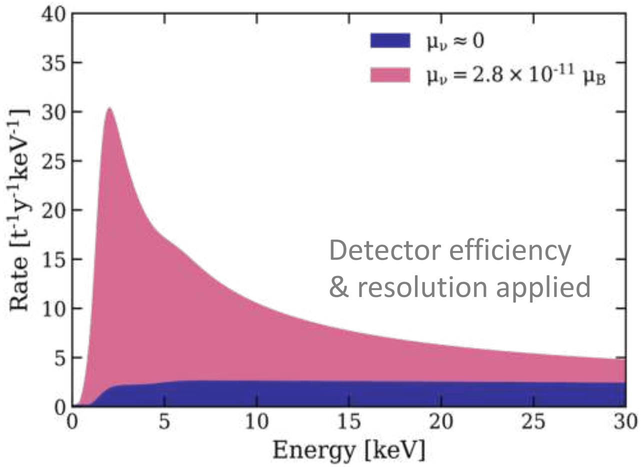
(tough in arXiv:2006.14598 Gao et al. shows that this is alleviated by taking into account the inverse Primakoff effect as detection process)

NEUTRINO MAGNETIC MOMENT

Neutrinos acquire magnetic moment in extensions of the SM

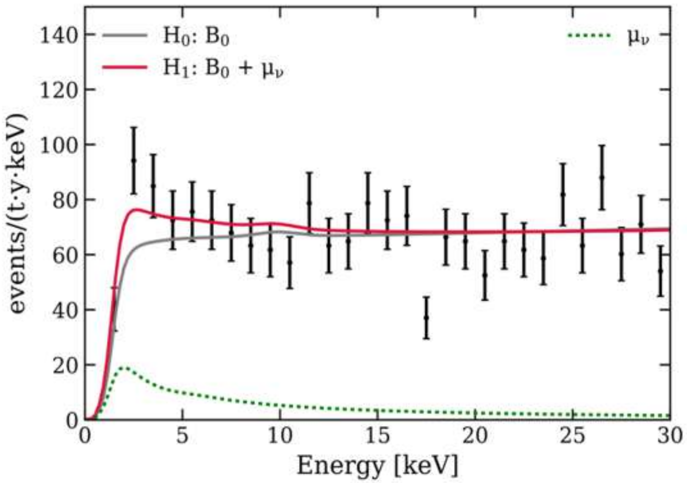
- Source: neutrinos from the Sun (mostly from pp-reactions)
- Reaction: elastic scattering off electrons
- Larger values implies new physics, $\mu_\nu > 10^{-15}\ \mu_B$ implies Majorana neutrinos

Would lead to enhanced neutrino-electron scattering cross-section

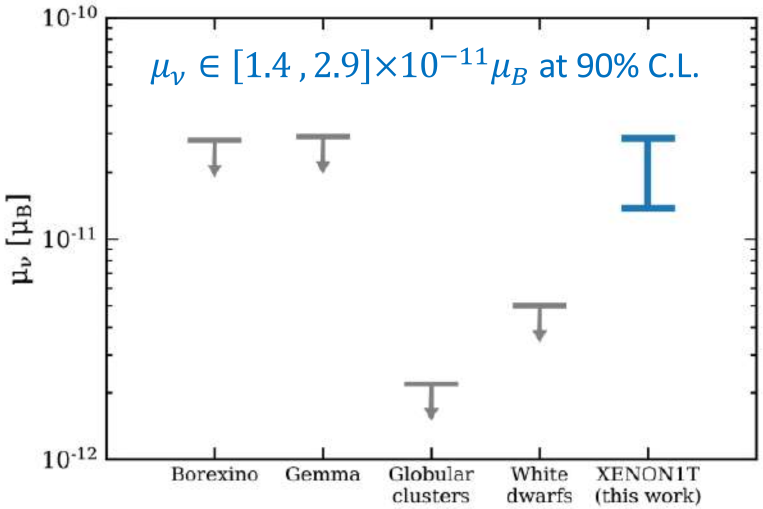


Neutrino magnetic moment hypothesis favoured at 3.2 σ *

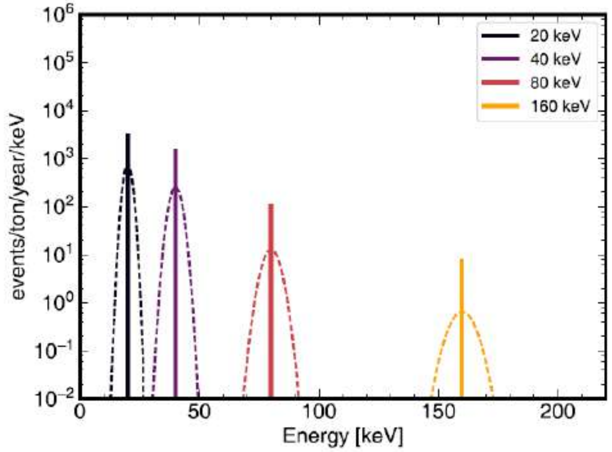
* Drop to 0.9 if $H_0=B_0+{}^3H$

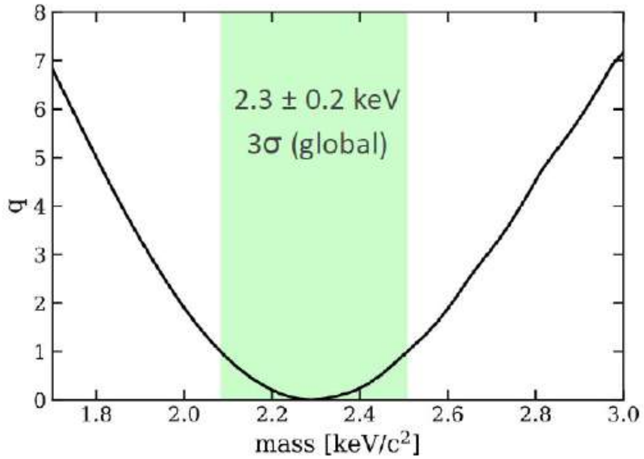


In tension with astrophysical observation

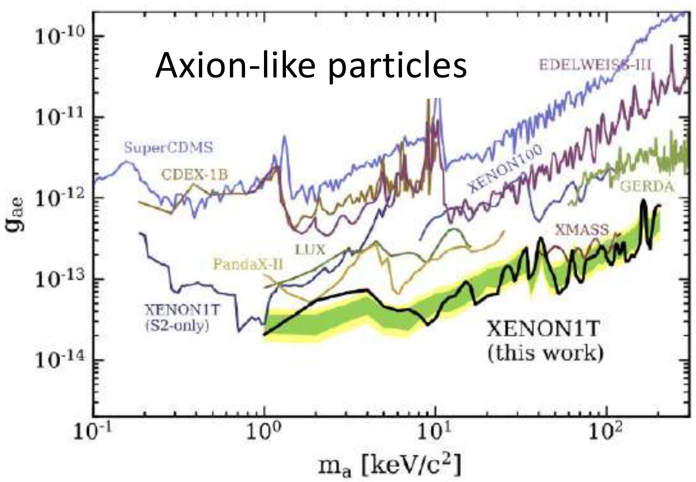


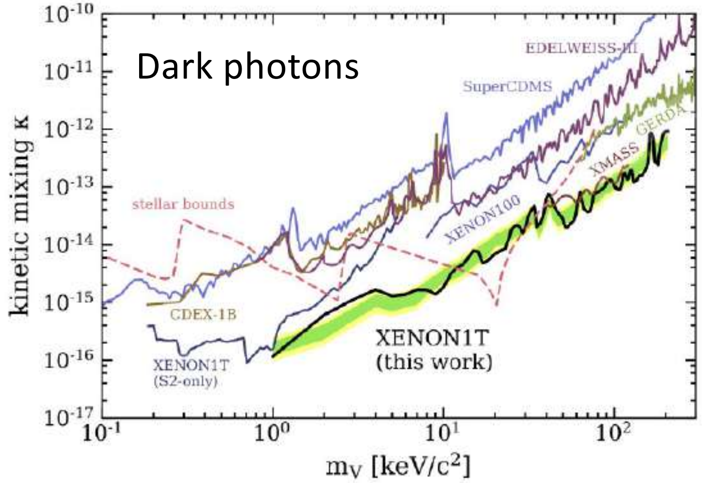
BOSONIC DARK MATTER





- Search for a mono-energetic peak
  - Could be dark matter, e.g. axion-like particle or dark photon



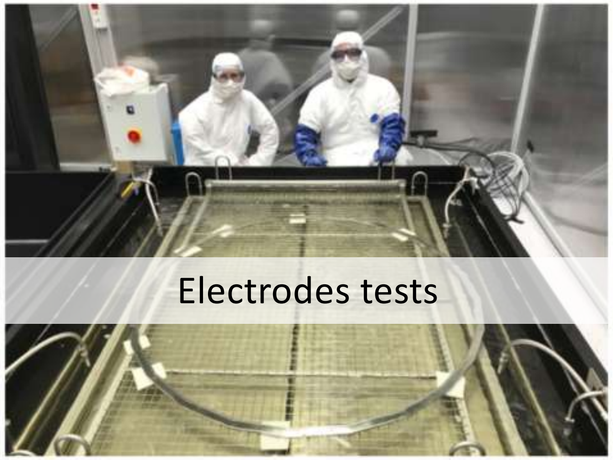


- Most significant at 2.3 ± 0.2 keV
- No > 3σ excess ⟹ only report limits

OUTLINE

- How did we find it?
  - →The XENON1T experiment
- What have we observed exactly?
  - →The Electronic-Recoil Excess
- Are we really sure?
  - →Cross-checks of the results
- What could it be?
  - →Standard Model & Beyond interpretations
- **What next?**
  - **→ the XENONnT experiment**

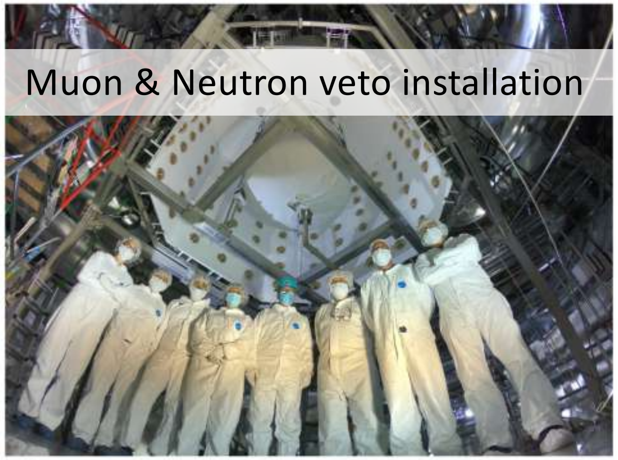
@LNGS: Despite COVID Pandemic …


Electrodes tests


PMTs assembly


TPC assembly


TPC transportation underground


Muon & Neutron veto installation


Cryostat Xe filling crew

Active volume — Background — Under commissioning

- **XENONnT is coming soon!!**
- XENONnT will discriminate axions from tritium with ~ few months of data