# Results from the 1 tonne × year Dark Matter Search with XENON1T

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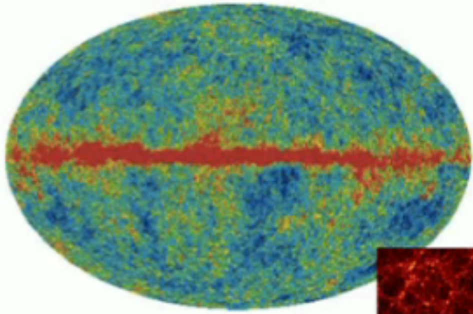
on behalf of the XENON Collaboration

Xe XENON Dark Matter Project

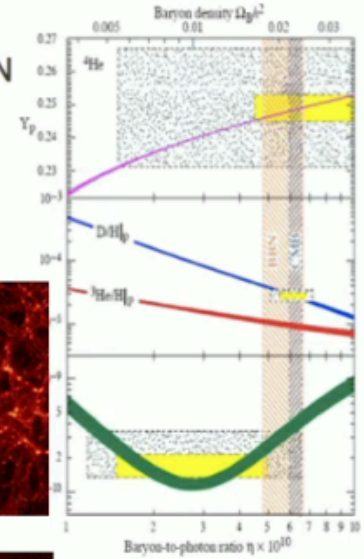
# A long List of Evidences for Dark Matter…

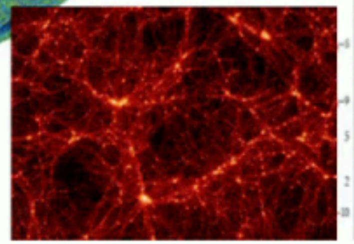
- Galactic rotation curves
- Galaxy clusters & GR lensing
- Bullet Cluster
- Gravitational lensing
- Velocity dispersions of galaxies
- Cosmic microwave background
- Sky Surveys and Baryon Acoustic Oscillations
- Type Ia supernovae distance measurements
- Big Bang Nucleosynthesis (BBN)
- Lyman-alpha forest
- Structure formation
- …

CMB (WMAP)

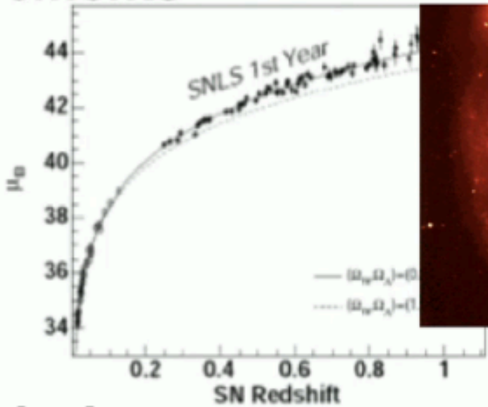


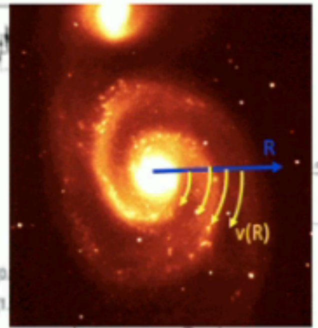
BBN



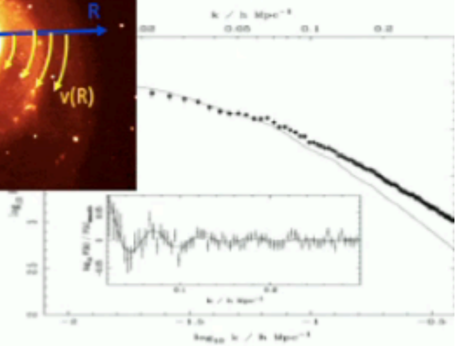



SN 1a




BAO



➔ strong evidence for a dominant dark sector

➔ synergy of evidences: GR-dynamics, radiation, …

➔ cannot be explained by ordinary matter

➔ two known components:
ν's (0.6%, hot) and black holes (?) ➔ what else ?

# Competing Dark Matter Directions

## Gravity

### MOND
a simple one scale modification
→ fails badly

### Other
new GR modifications

or

a suitable population (mass, number) of black holes

## Particles

### BSM physics motivated by SM problems
- WIMPs (neutralinos)
- axions
- sterile $\nu$'s
- …

### Models with correct abundance
- WIMP miracle
- dark photons
- ALPs
- other new particles

**WIMPs combine both aspects in an attractive way: BSM + abundance**

# Generic WIMP Cross Section

Wavelength $\lambda \sim 1/\text{mass}$ ➔ "size": $\simeq \pi\lambda^2 = \pi/m^2$

➔ cross section: area × coupling strength

$\sigma \sim O(0.001\text{-}1.0)^2 \quad g_2^2 \quad \pi/m^2$

model parameters — some weak coupling — area

or tuning, symmetry, …

↔ abundance

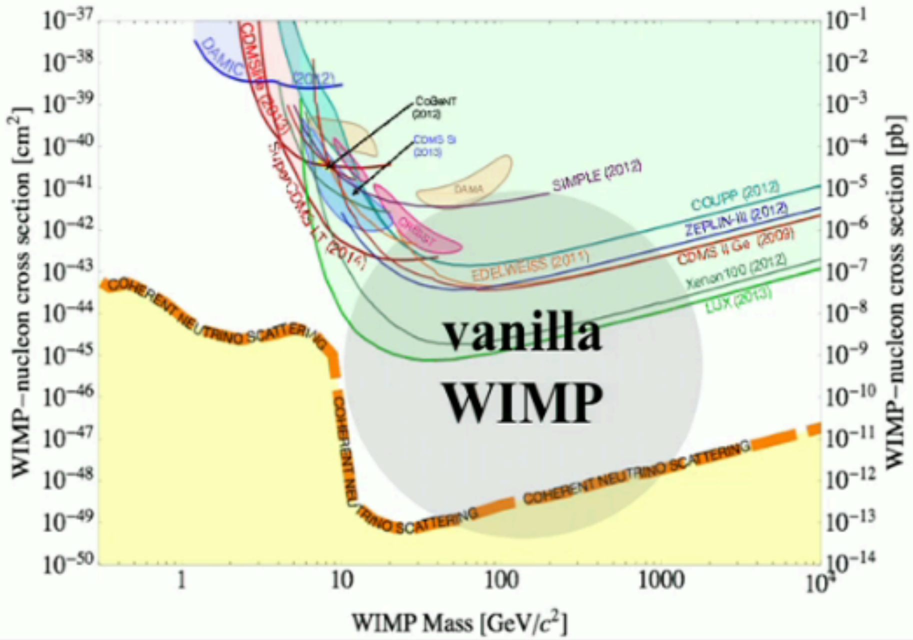
➔ natural range for a 50GeV WIMP: $\sigma \sim 10^{-42} - 10^{-49}\ \text{cm}^2$

known amount of DM

➔ abundance ➔ WIMP flux

➔ rate@direct detection

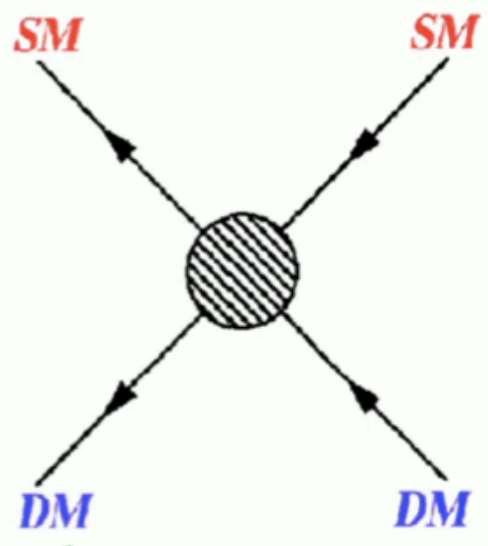
➔ required size/sensitivity of a detector which can cover the most interesting natural WIMP space




How much is left? …linear…

# Hunting WIMPS in different Ways

**known Standard Model (SM) particles interact with WIMPs: assumptions…**



# Hunting WIMPS in different Ways

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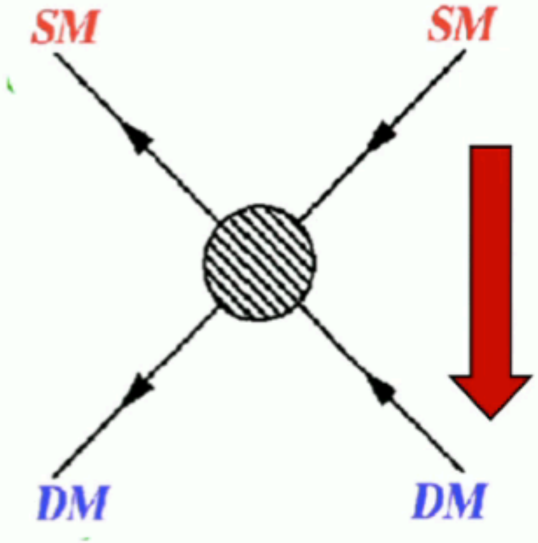
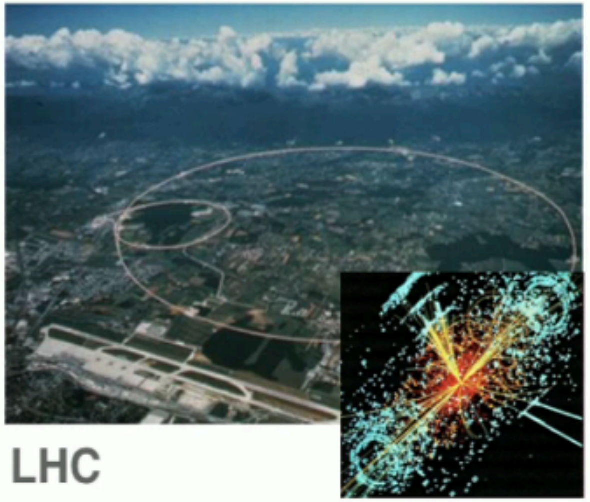



colliders



LHC

**may detect new particles, but is it DM (lifetime, abundance)?**

So far no new physics…

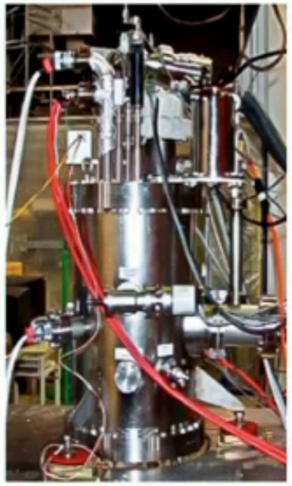
→ impact on theory…

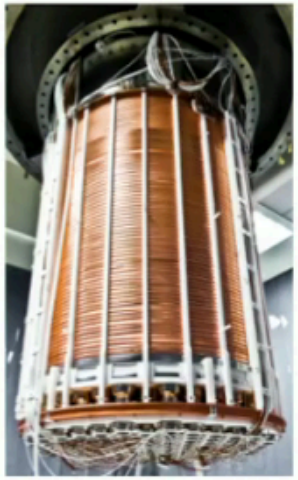
→ SUSY → higher scale

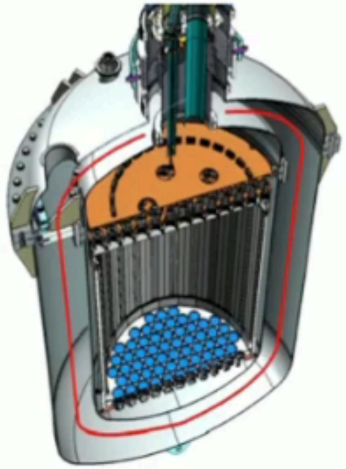
→ larger WIMP mass...

# The XENON Dark Matter Program

**The XENON program at Gran Sasso, Italy (3600 mwe)**



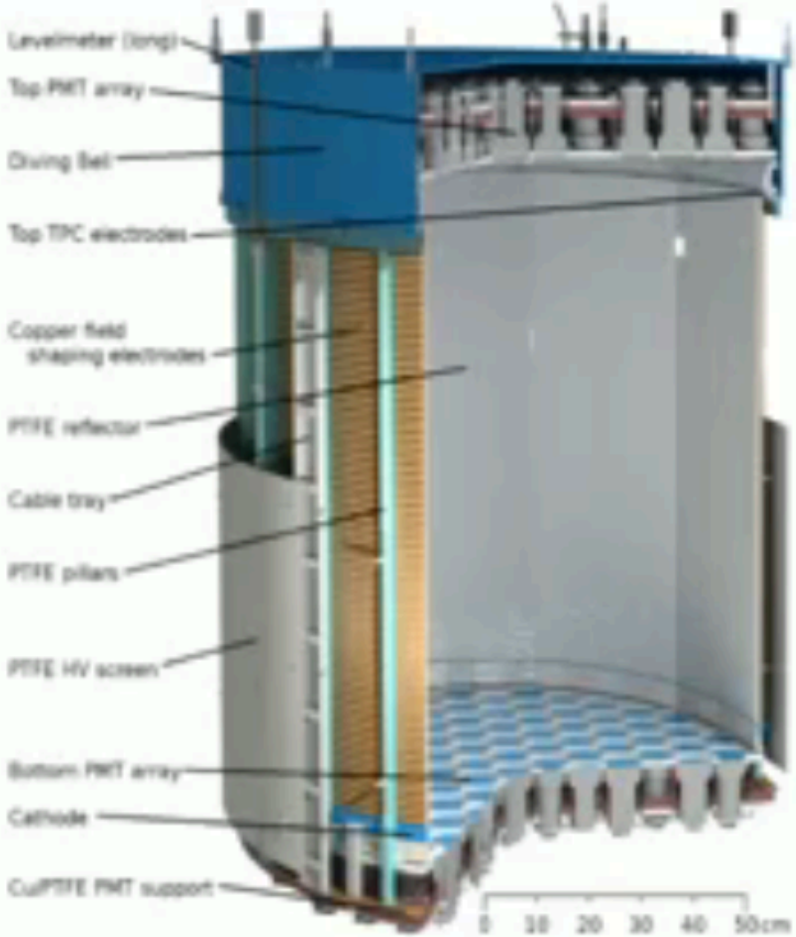


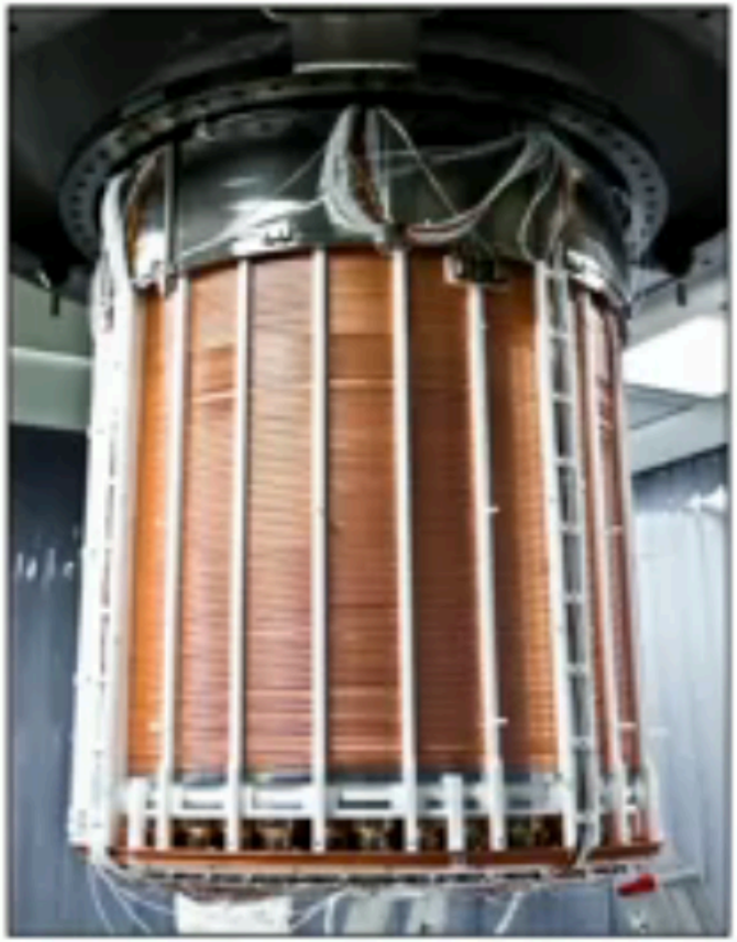
| | XENON10 | XENON100 | XENON1T | XENONnT |
|---|---|---|---|---|
| **Period** | **2005-2007** | **2008-2016** | **2012-2018** → | **2019-2023** |
| **Total mass** | 25 kg | 161 kg | 3200 kg | ~8000 kg |
| **Drift length** | 15 cm | 30 cm | 100 cm | 150 cm |
| **Status** | Completed (2007) | Completed (2016) | Running | Construction |
| **$\sigma_{SI}$ limit** (@50 GeV/c$^2$) | $8.8 \times 10^{-44}$ cm$^2$ | $1.1 \times 10^{-45}$ cm$^2$ | $1.6 \times 10^{-47}$ cm$^2$ (2018) | $1.6\times10^{-48}$ cm$^2$ (2023) |

**XENON1T running**

**XENONnT → switching gears 2019**

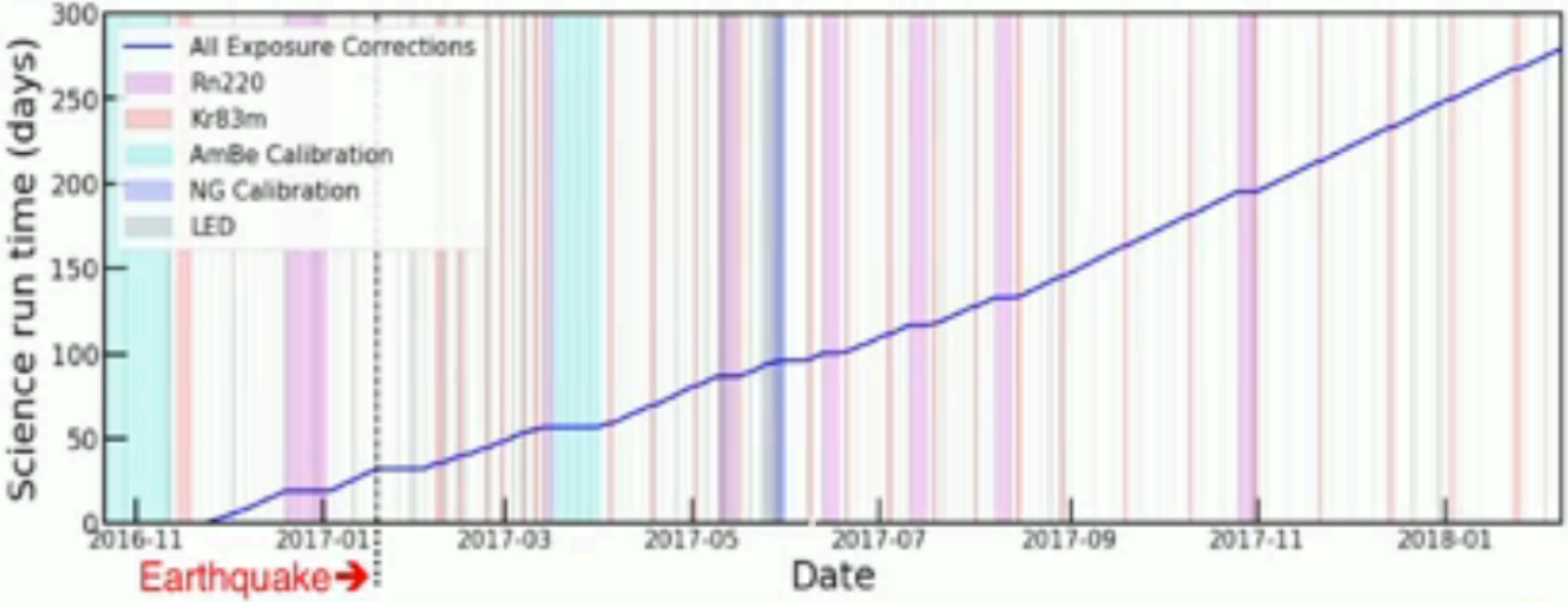
# The Time Projection Chamber (TPC)



- 248 3” low-background PMTs
- 1 m drift × ø1 m
  - 2 tons active LXe
  - largest LXe TPC built
- filled and functional since May 2016

# XENON1T Data Taking



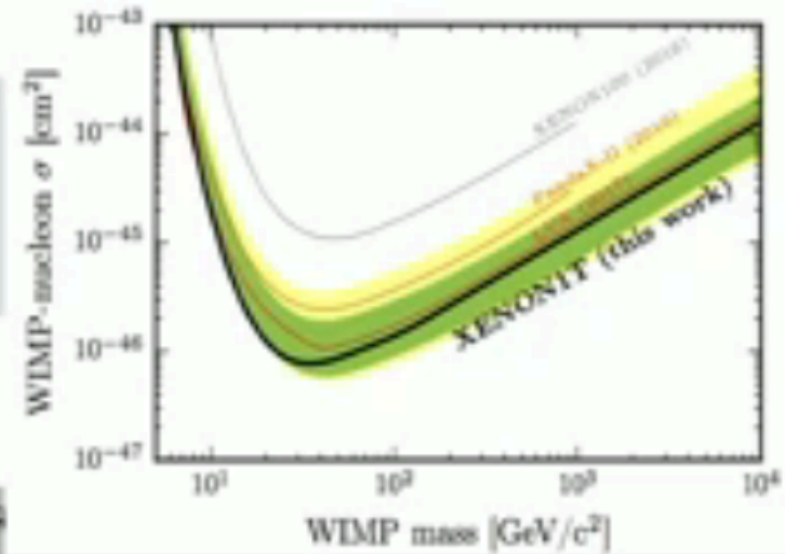

SR0: 32.1 live days

SR1: 246.7 live days → combined: 278.9 days

**1st result: SI limit**

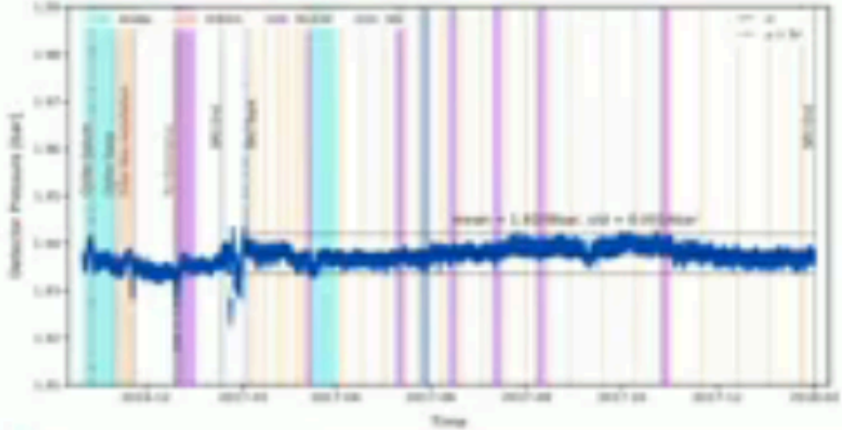
**PRL 119, 181301(2017)**

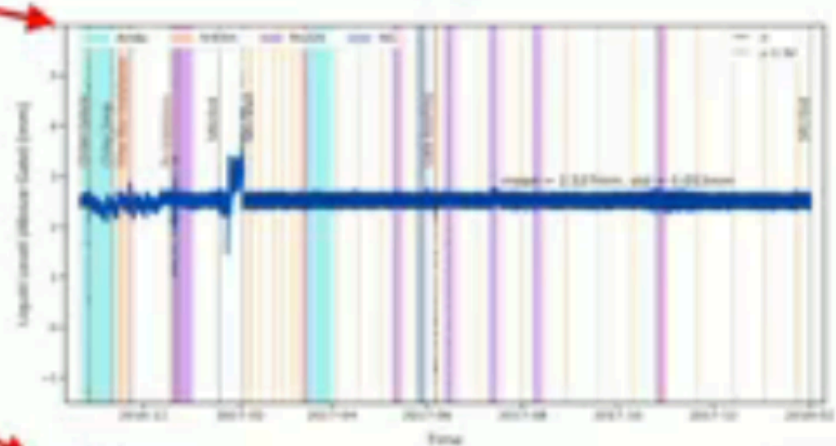
**Same range as other LXe TPCs**

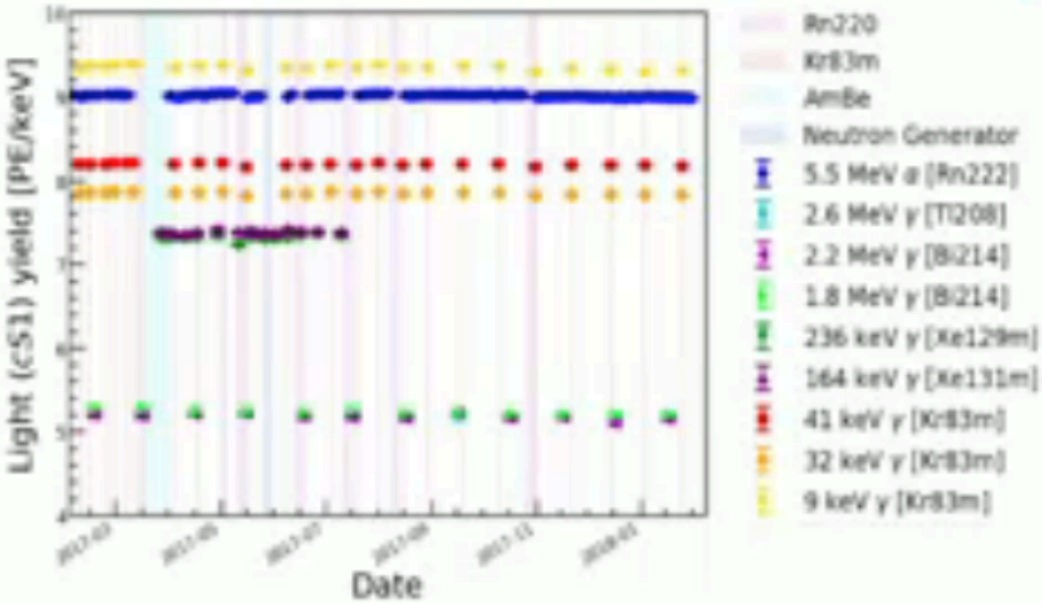


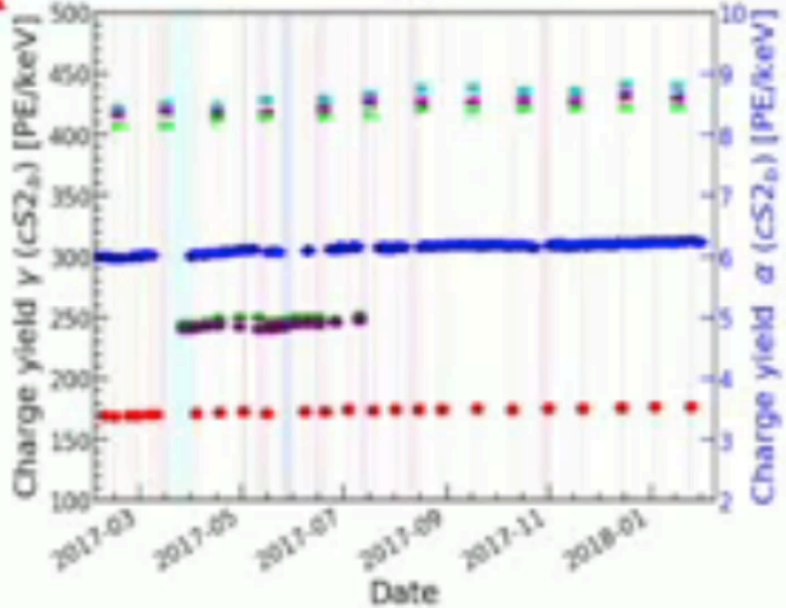
# Detector Stability

- Pressure: < 0.02% RMS
- Temperature: < 0.02% RMS
- Liquid level: < 2%
- Homogeneous drift field:
  SR0: 120V/m, SR1: 81V/m
  position dep. variations < 2.3V/cm
- Charge yield: < 1.5%
- Light yield: < 0.2%







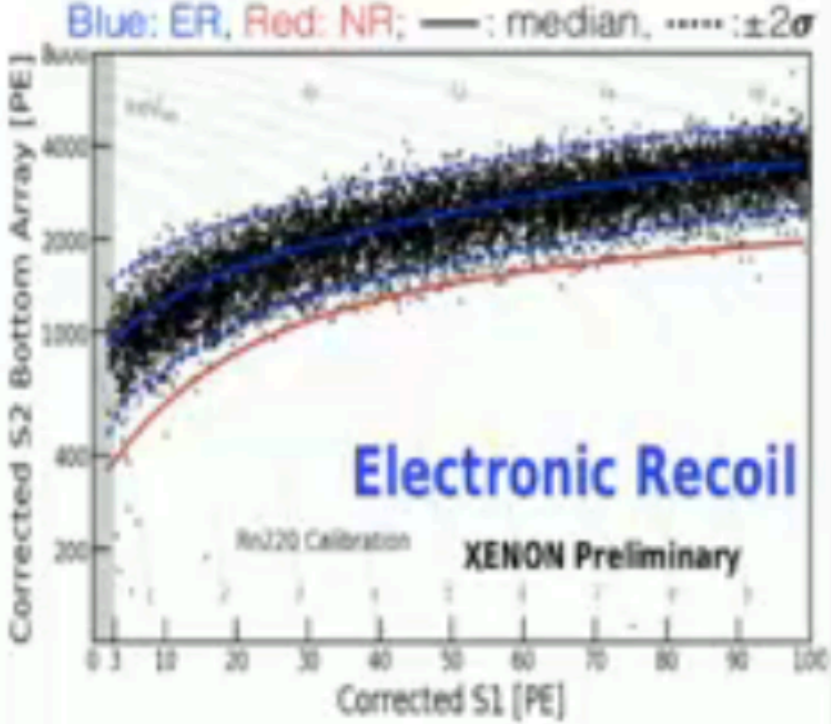



# Electronic and Nuclear Recoil Calibration

## Electronic Recoils (ER)

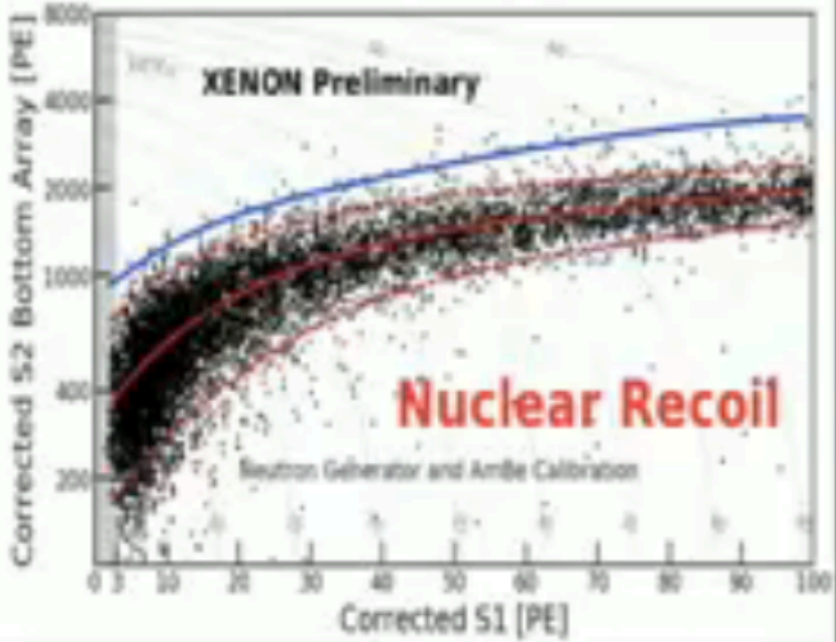
- $^{228}Th$ source emanates $^{220}Rn$ into LXe
- β-decay of $^{212}Pb$ to $^{212}Bi$ low energy events (2-20 keV)

**Phys. Rev. D 95, 072008 (2017)**




## Nuclear Recoils (NR)

- external $^{241}AmBe$ source mounted on a belt (α particles from Am-decay collide with Be → fast n)
- Neutron generator NIM Phys. Res. A, 879 (2017)



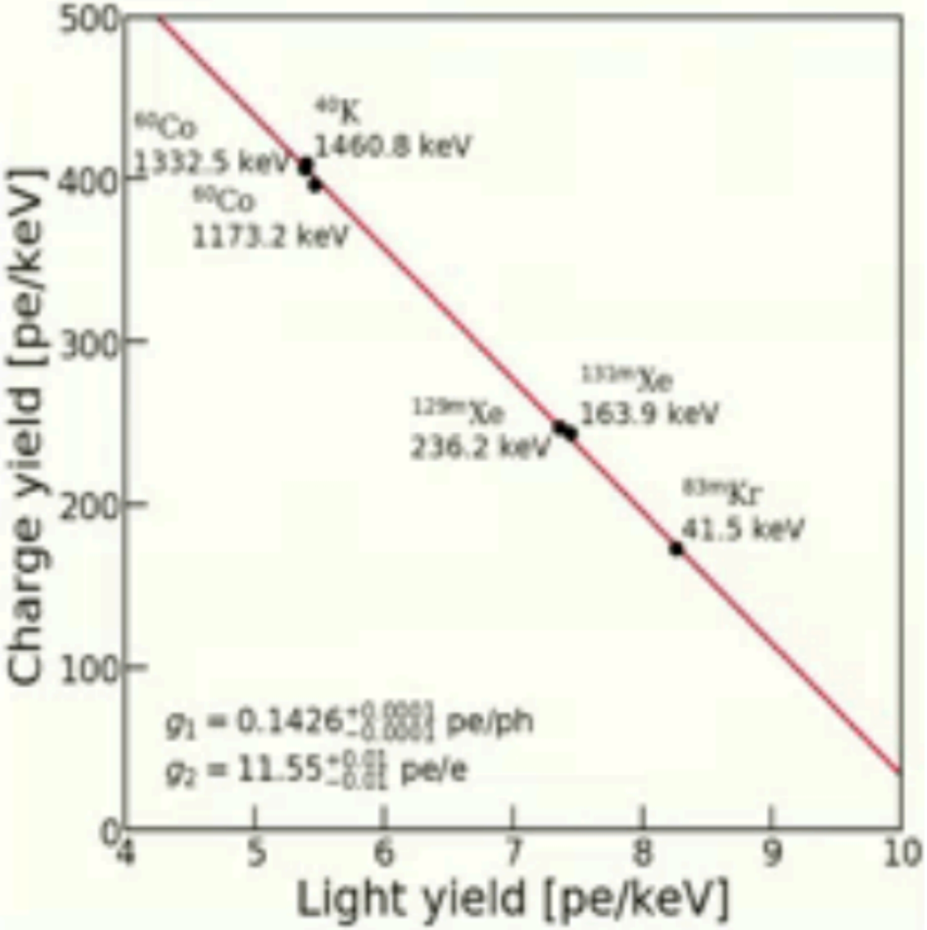
# Energy Scale Calibration

## calibration sources:

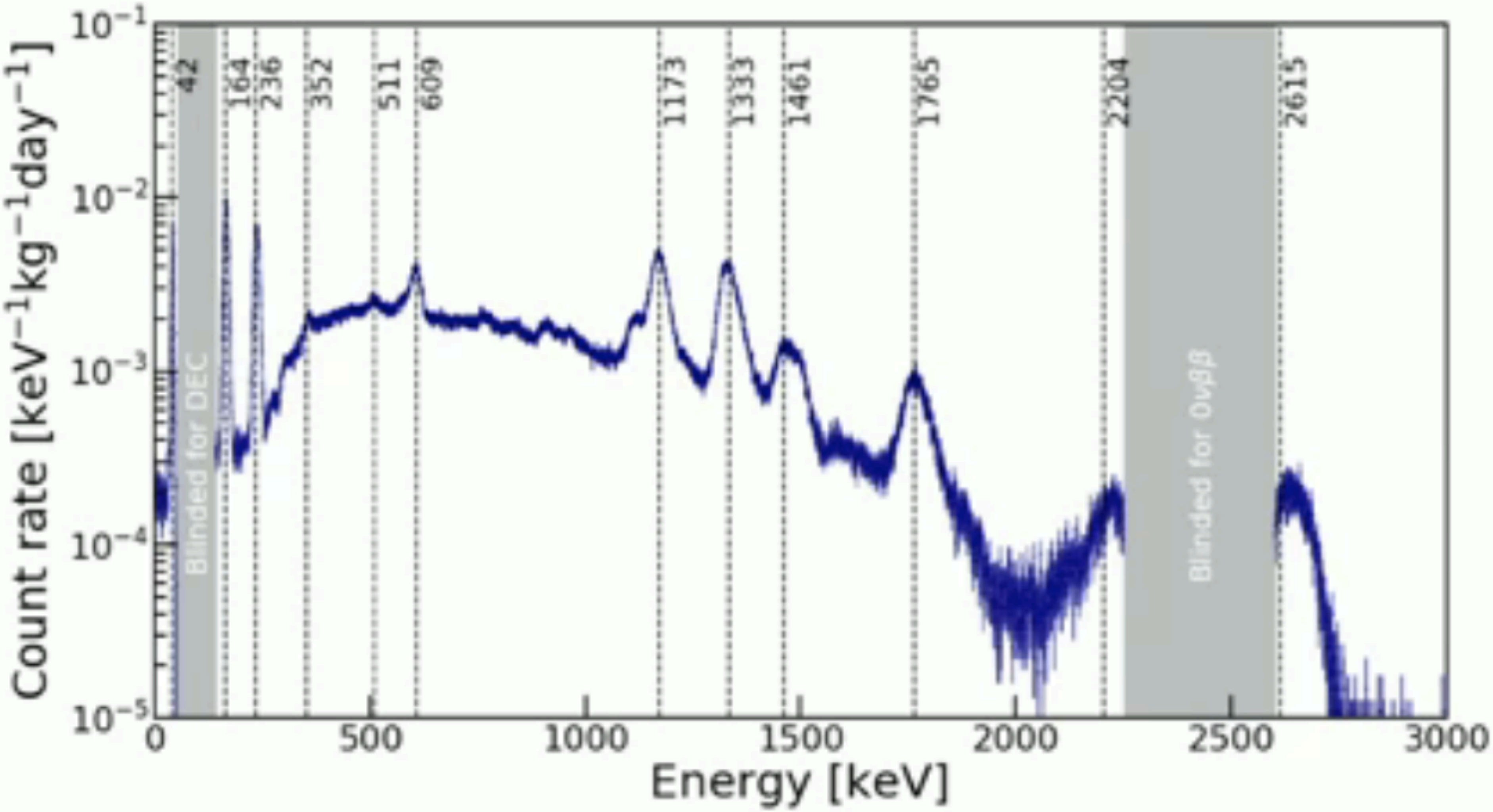
- $^{83m}$Kr, $^{241}$AmBe ($^{129m}$Xe, $^{131m}$Xe, $^{2}$H)
- background from detector material ($^{60}$Co)

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

- linearity from 40 keV to 2.2 MeV
- photon gain
  g1 = 0.1426 ± 0.0017 (sys) PE/ph
- electron gain
  g2 = 11.55 ± 0.24 (sys) PE/e
  - corresponds to ~100% extraction of ionization charges from LXe



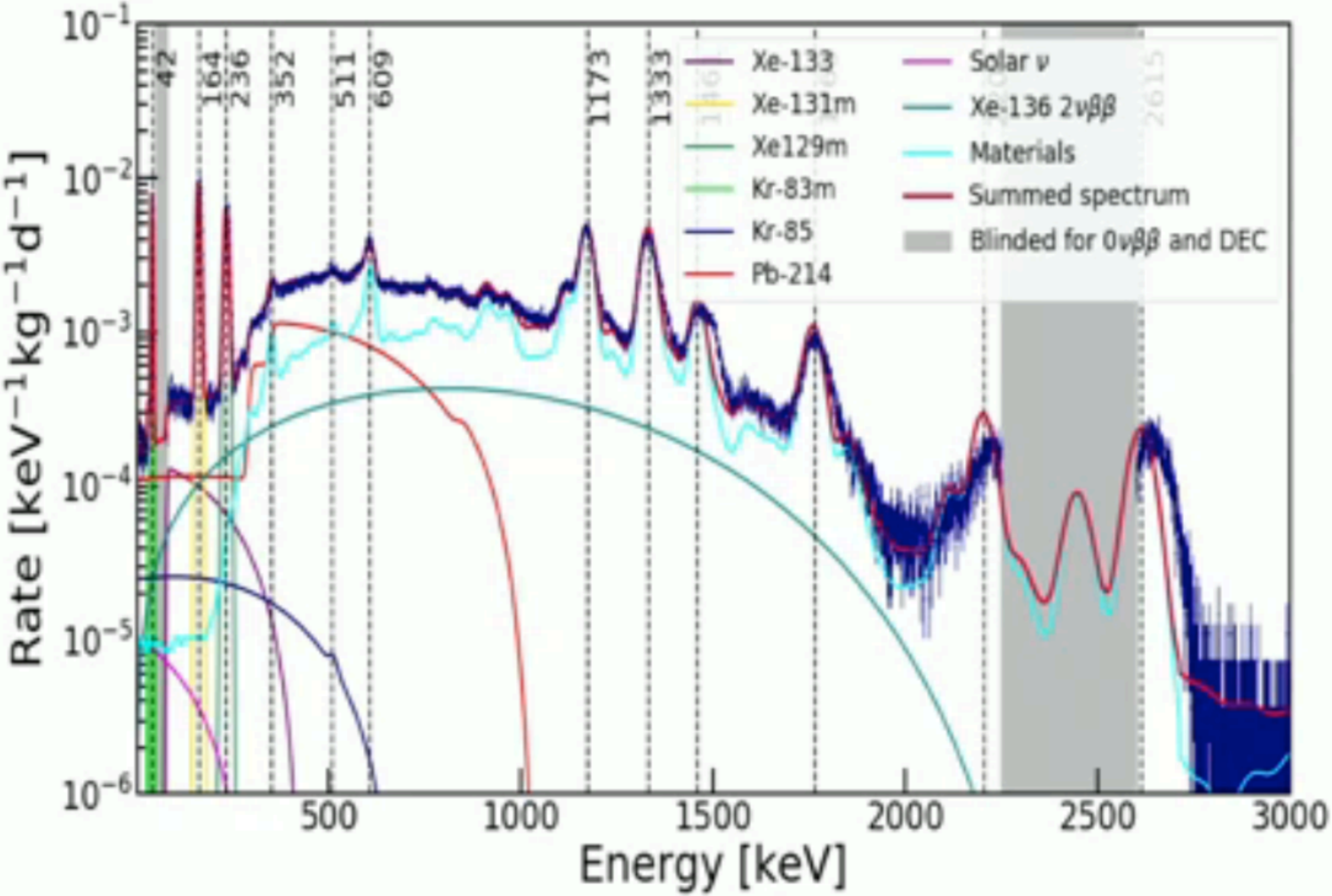
# Excellent Energy Resolution




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

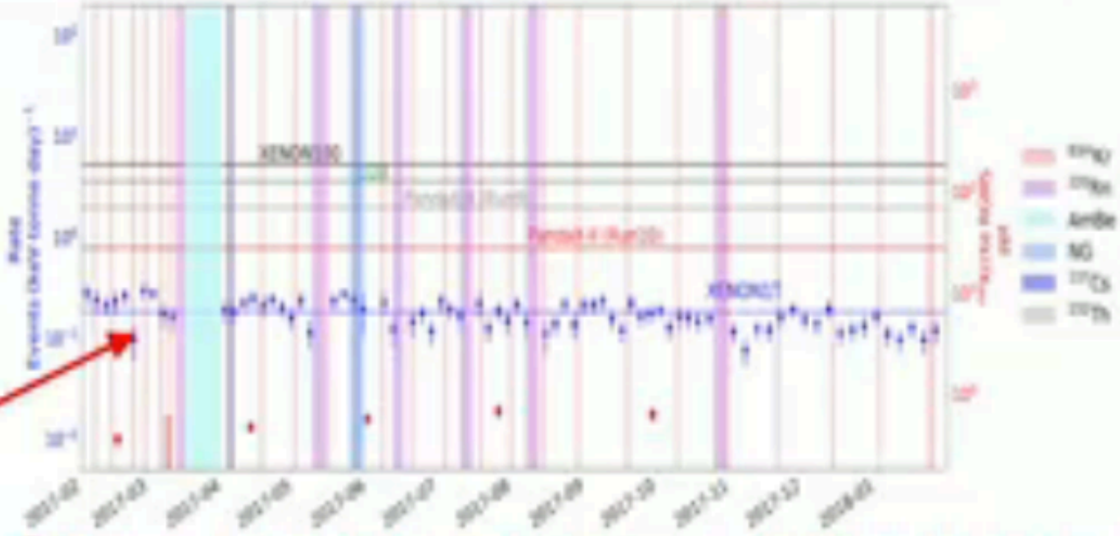
~ 1.5% energy resolution
@2.5 MeV

# MC Matching of Energy Spectrum



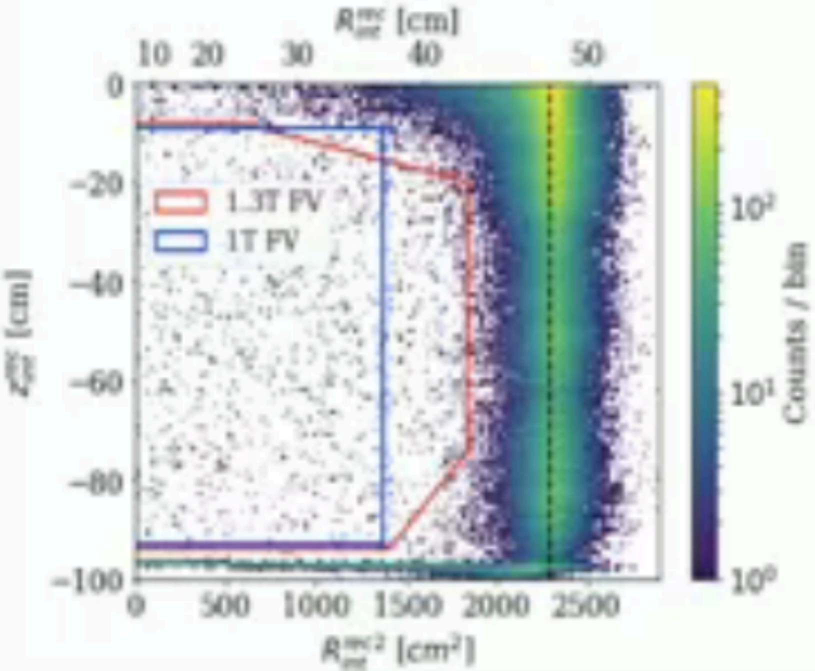
# Electronic Recoil Background

- Material γ - screening and selection during construction
- $^{222}Rn$ emanation measurements and selection of materials
  ➔ achieved 10 μBq/kg for $^{222}Rn$
- online cryogenic distillation
  ➔ $^{85}Kr$ removal
  ➔ ca. 720 evts/(t*yr)



➔ lowest ER background ever @ DM detectors

- Select fiducial volume in the TPC

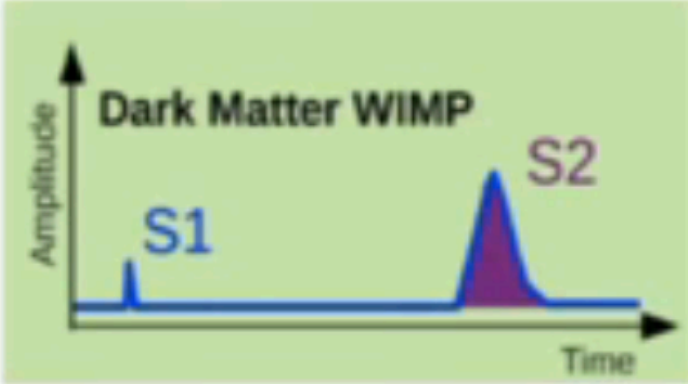


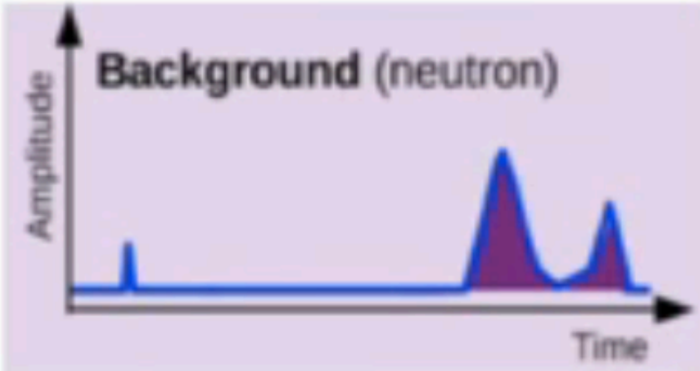

| Source | Rate [t $^{-1}$ yr $^{-1}$] | Fraction of ER [%] in 1t FV (1-12 keV) |
|---|---|---|
| $^{222}Rn$ | 620 ± 60 | 84.5 |
| $^{85}Kr$ | 31 ± 6 | 4.3 |
| solar neutrinos | 36 ± 1 | 4.9 |
| materials | 30 ± 3 | 4.1 |
| $^{136}Xe$ | 9 ± 1 | 1.4 |
| total | 720 ± 60 | |

# Nuclear Recoil Backgrounds

- 3600 mwe overburden (LNGS)
- water Cherenkov muon veto
- material screening
- fiducial volume seelction
- Single scatter requirement

➔ Total expected rate: ~ 1 event /(t*yr)

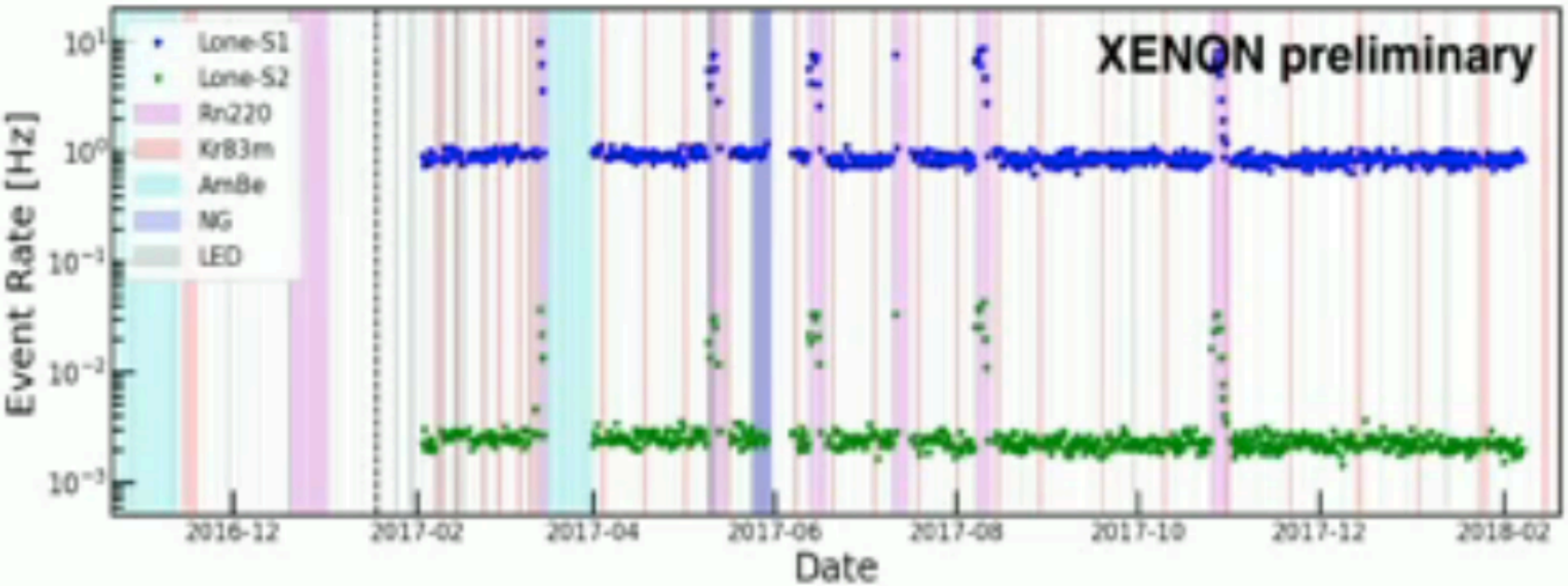



| Source | Rate [$t^{-1}$ $yr^{-1}$] | Fraction of NR [%] in 1t FV (4-50 keV) |
|---|---|---|
| radiogenic neutrons | 0.6 ± 0.1 | 96.5 |
| coherent neutrino scattering | 0.012 | 2.0 |
| muon induced neutrons | < 0.01 | < 2.0 |

# Accidential Coincidences

- lone S1 and lone S2 signals
  ➔ from interactions in regions with poor light/charge collection
  ➔ lone signals close in time get paired to fake events
- Background modeled by searching for randomly paired lone S1/S2



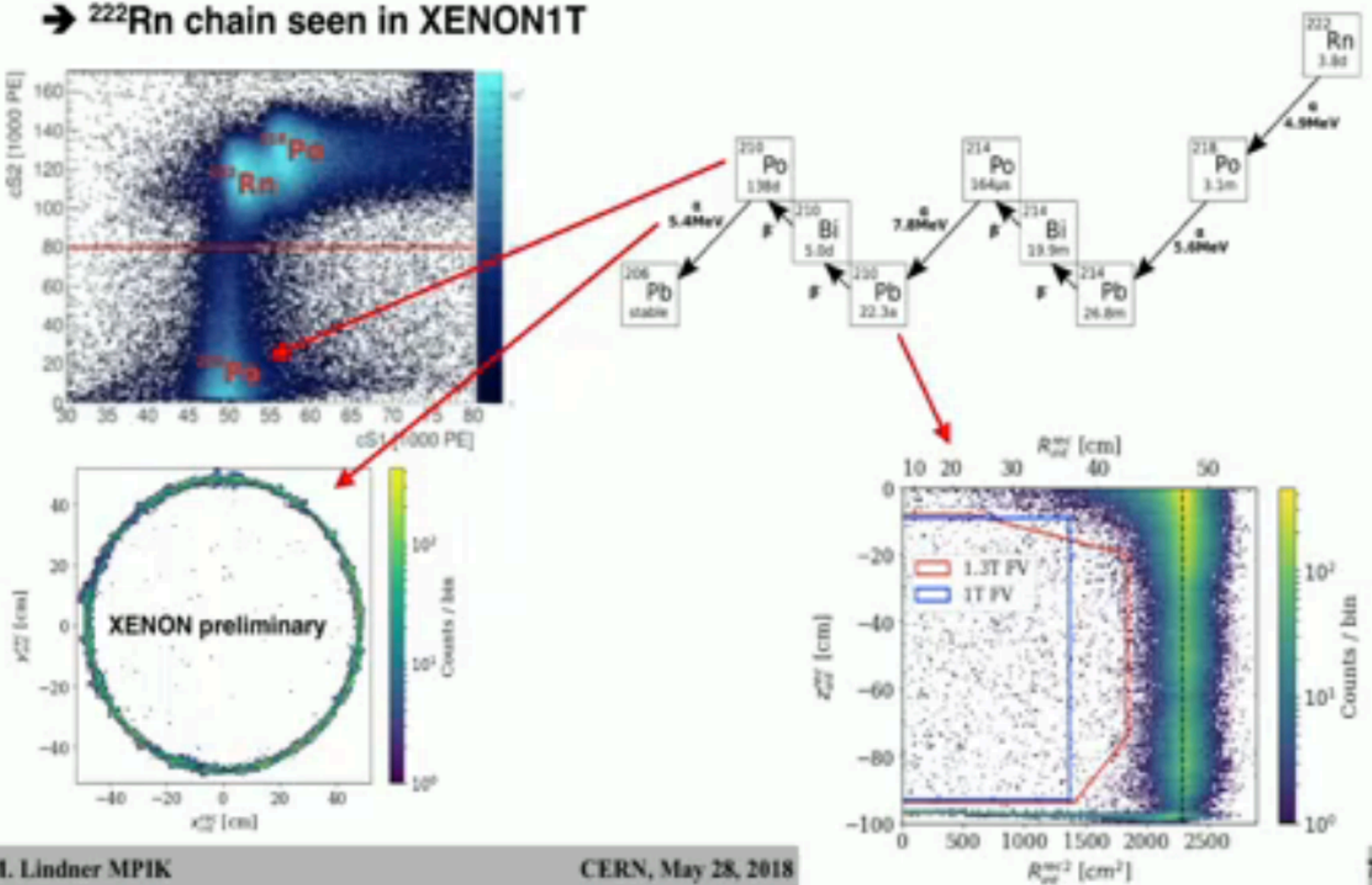

**Isolated S1 and S2 signals analyzed dataset by dataset**
**➔ time evolution of lone-S1 and lone-S2 rate**
**➔ apply selection conditions to suppress ACs**

# PTFE Surface Background

Plate-out of $^{222}$Rn daughters on PTFE surface during construction

➔ attenuated S2 due to charge loss

➔ $^{222}$Rn chain seen in XENON1T



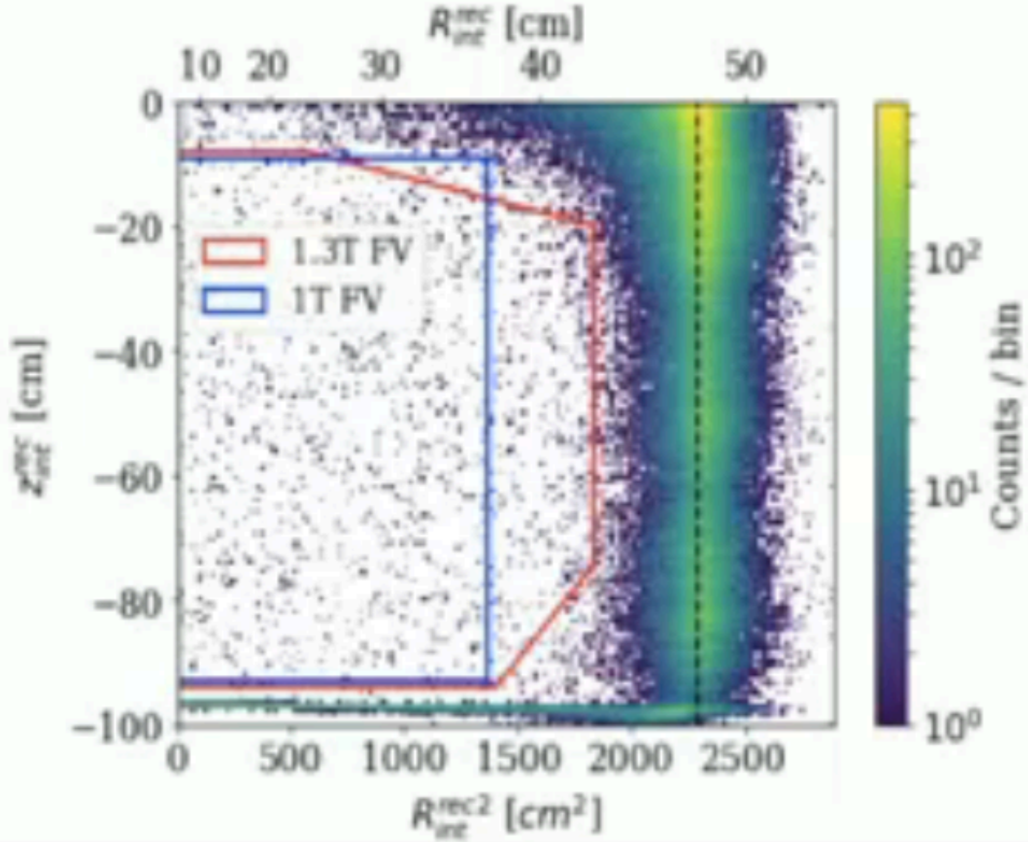
# Optimized Fiducial Volume

**Optimize fiducial volume before unblinding by using improved understanding:**

- **position reconstruction**
- **detector response**
- **correlations between spectral and spacial distribution**
- **include knowledge on background distributions in statistical framework**
- **MC simulations**

➔ **aim at optimal S/B:**

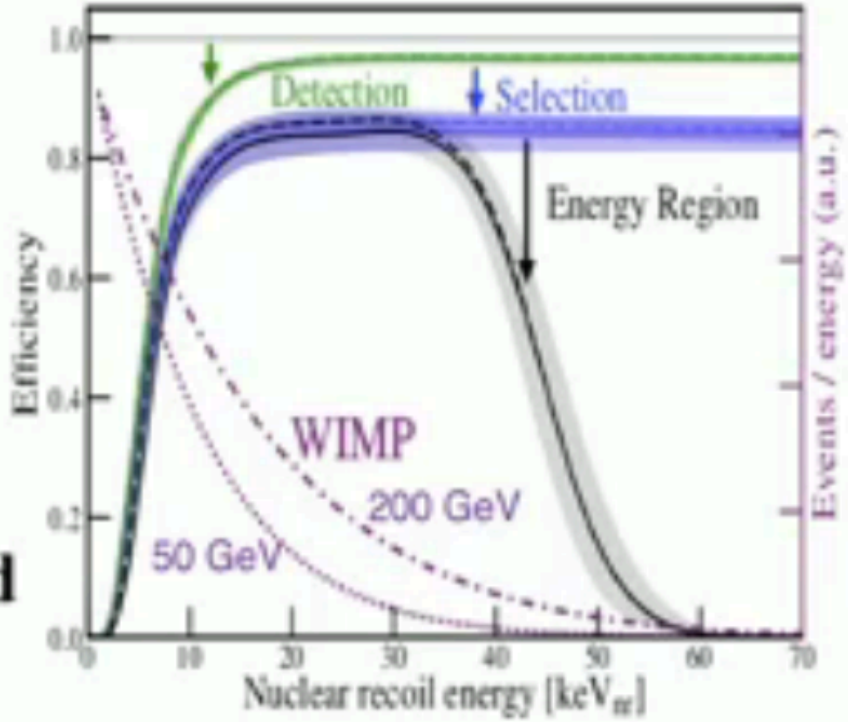
- **larger FV: 1 ton ➔ 1.3 tons**



# Event Selection

- **Blind analysis to avoid selection biases**
- **In addition "salting" (addition of fake signal events)**
  ➔ method allows to test statistical interpretation after unblinding

- **NR detection efficiency:**
  - selection criteria (well reconstructed events only), suppress backgrounds
  - impacted by small detection efficiency for small S1
  - restriction to [3-70] pe in S1



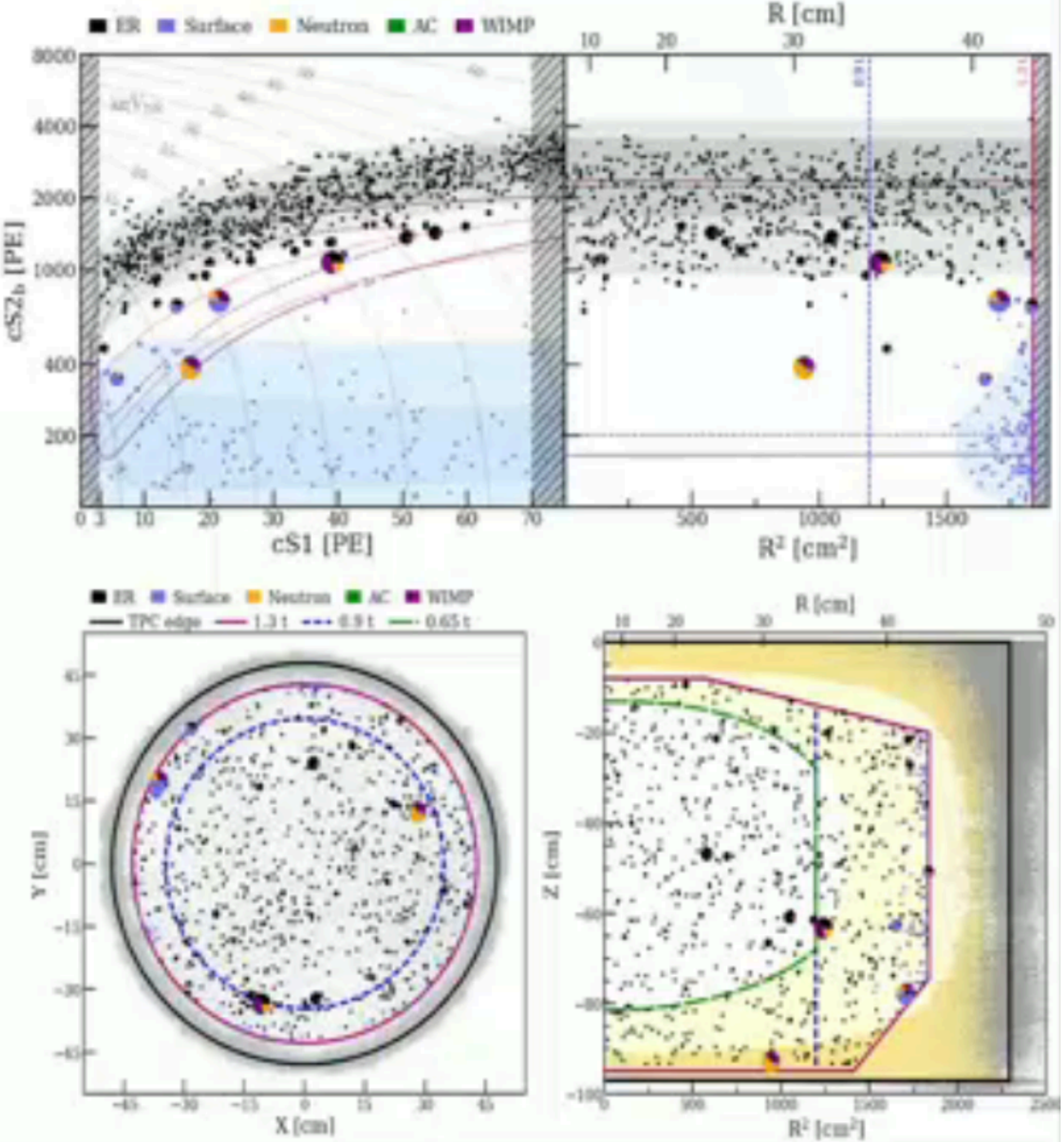

- **Extended unbinned profile likelihood analysis in (S1, S2, position) space**

  ➔ **Opening the box:**
  1) **Unblinding**
  2) **Removal of salt events**

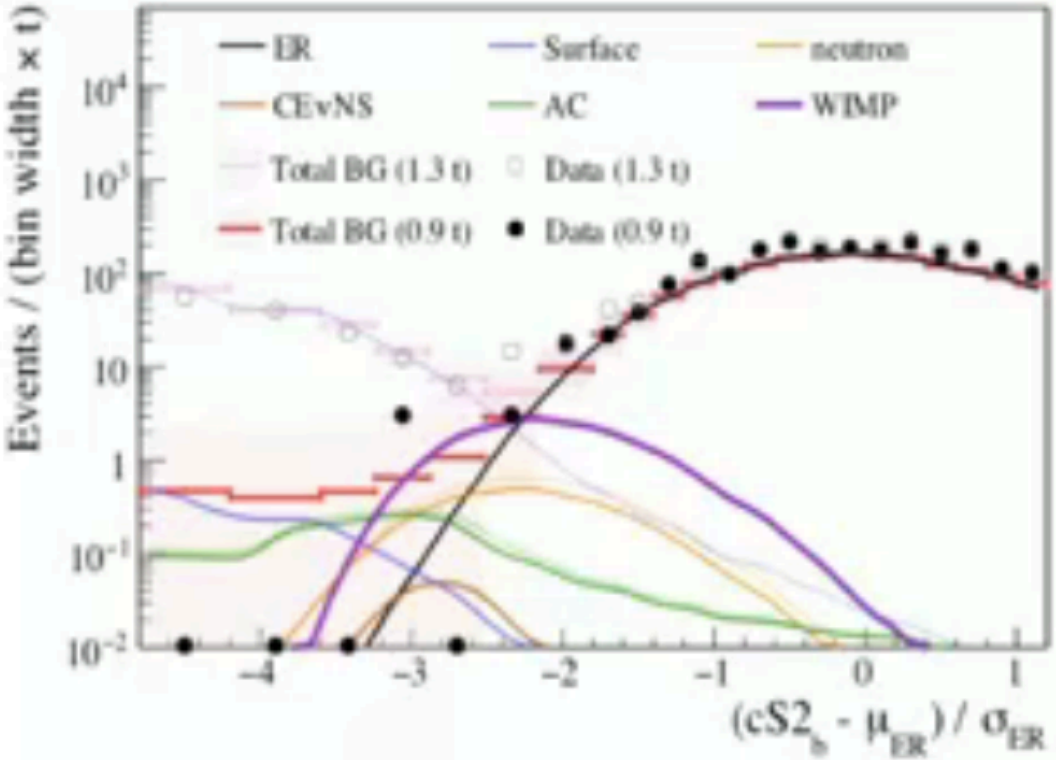
unbinned profile likelihood analysis in cs1, cs2, r space

1 σ, 2 σ for a 200 GeV/$c^2$ WIMP

pie charts show relative probabilities of this event to be of a certain class for a best fit to a 200 GeV WIMP



# Observations versus Expectations




**Best fit expected event rates for 278.8 life days and 1.3t or 0.9t**

**``WIMP" ≙ 200 GeV/c² prediction assuming $\sigma_{SI} = 2.9 \times 10^{-48}$ cm²**

| Mass | 1.3 t | 0.9 t |
|---|---|---|
| ($cS2_b$, cS1) | Reference | Reference |
| ER | 2.17±0.09 | 1.53±0.06 |
| neutron | 0.75±0.30 | 0.42±0.18 |
| CEνNS | 0.02±0.01 | 0.02±0.01 |
| AC | $0.10^{+0.06}_{-0.00}$ | 0.05±0.02 |
| Surface | 5.36±0.54 | 0.02 |
| BG | 8.40±0.63 | 2.05±0.18 |
| Data | 11 | 0 |
| $\mathrm{WIMP}_{\text{best-fit}}$ | 1.55 | 1.09 |

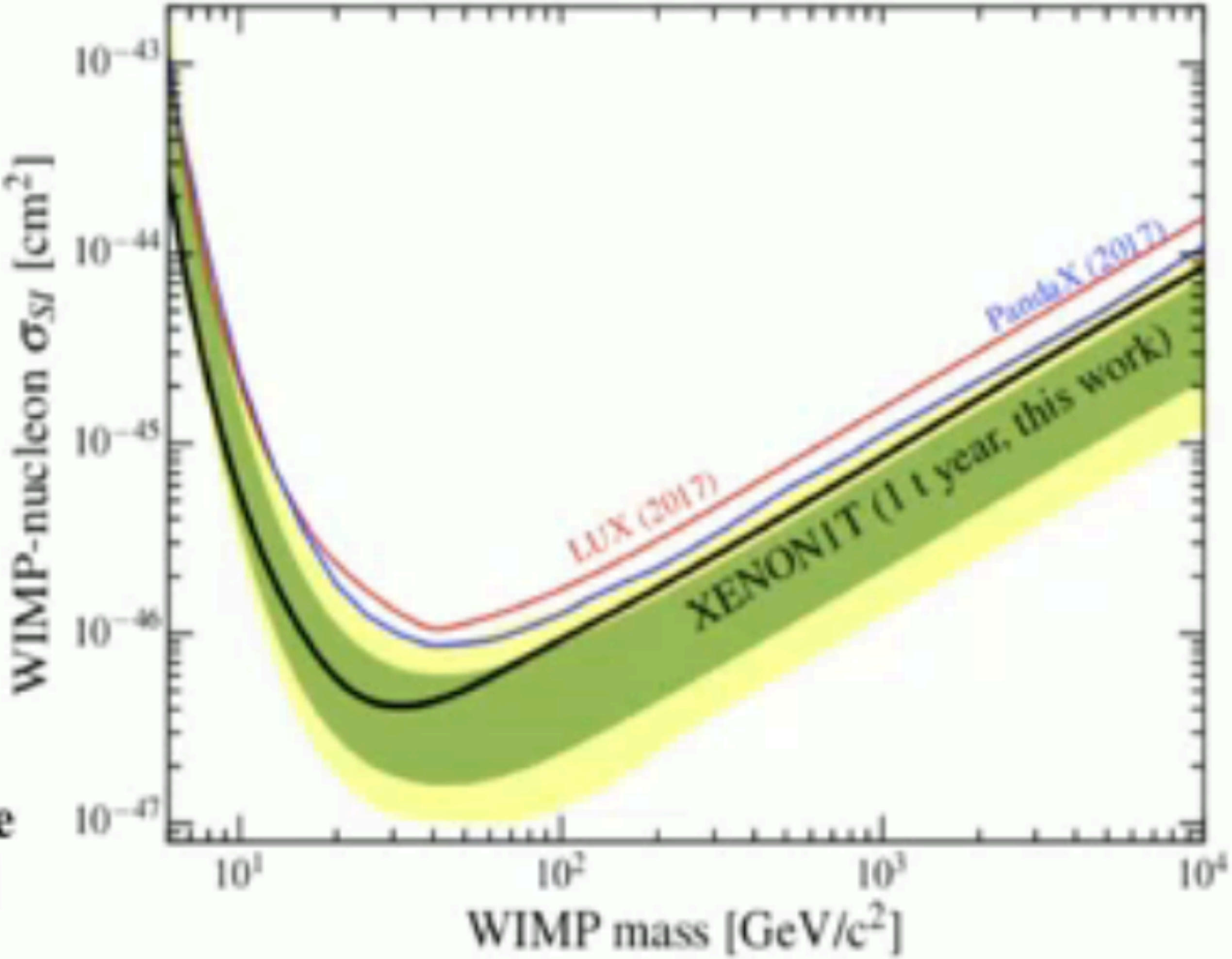
- ``profile construction" analysis (Feldman & Cousins with profile likelihood)
- background & WIMP signal predictions compared to DM for 0.9t and 1.3t
- x-axis: projection along the ER mean ($\mu_{ER}$) normalized to the ER 1σ quantile ($\sigma_{ER}$)
- shaded: 68% region for total expected BG

# The Result: New leading SI WIMP Limits

**Most stringent upper limit on WIMP-nucleon cross section at all masses above 6 GeV**

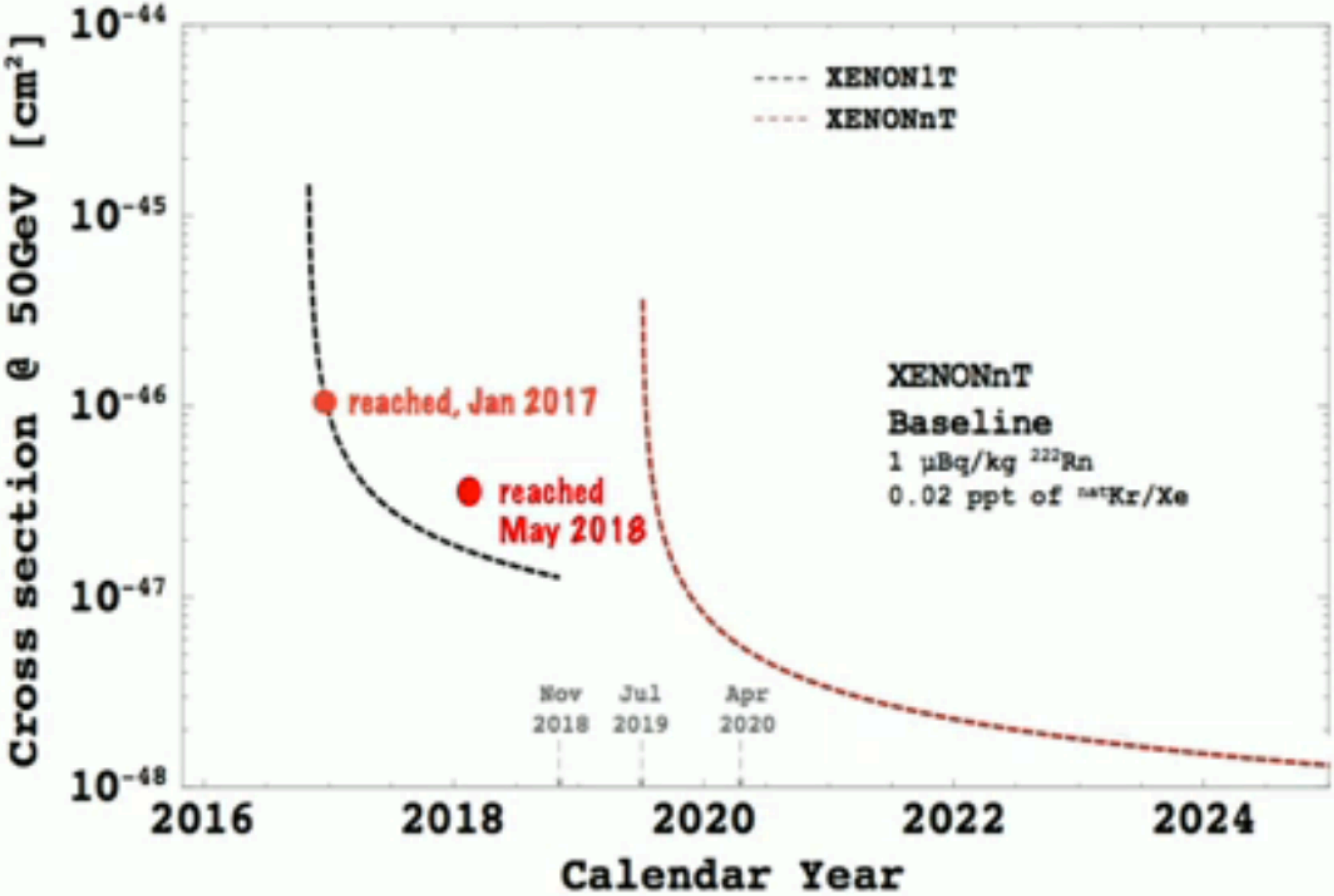
**Factor of 7 improvement compared to previous experiments (LUX, PandaX-II)**

**~ 1σ upper fluctuation at high WIMP masses, could be due to background or signal**




90% CL upper limit
1σ (green), 2σ (yellow) sensitivity bands

# XENONnT Sensitivity Reach & Schedule



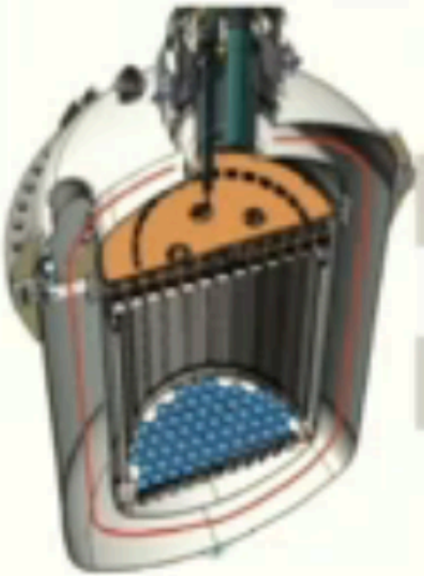
# Summary

- demonstrated >1 year stable operation with the first multi-ton scale LXe TPC ➔ accumulated 1 tonne-year exposure
- achieved lowest background in a DM detector: 0.2 evts/ (t keV d)
- surpassed the original XENON1T sensitivity goal, but found no statistically significant sign of WIMPs
- blind analysis of 1 tonne x year
  ➔ improved WIMP-nucleon SI interaction limit
  ➔ minimum: $4.1 \times 10^{-47}$ $cm^2$ at 30 $GeV/c^2$ (90% CL)
- upcoming analyses: DEC, annual modulation.
  low WIMP masses, $0\nu\beta\beta$ of $^{136}Xe$, ...

# Summary

- **search with XENON1T continues until the even larger and better upgrade, XENONnT, will further boost the sensitivity (fully funded, under construction ➔ 2019)**

## XENONnT



2019-2023

~8000 kg

144 cm

Construction

$1.6\times10^{-48}$ cm$^2$
(2023)