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Xe
XENON
Dark Matter Project

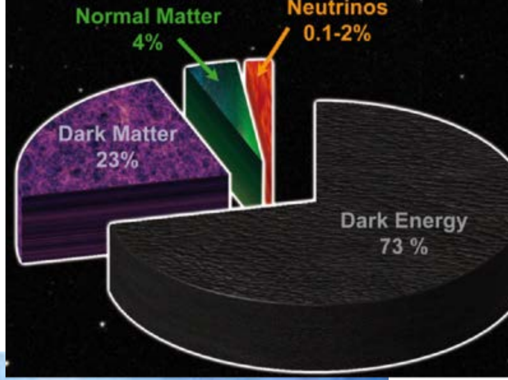
Status of the XENON Dark Matter Search Experiment

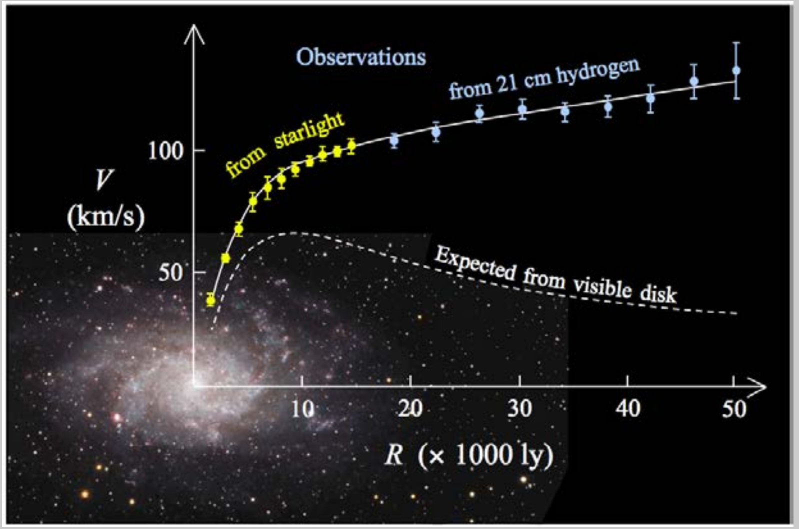
Fei Gao
Columbia University

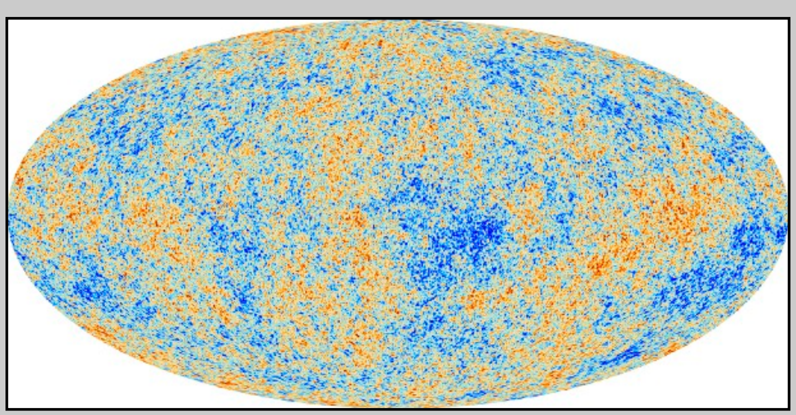
On behalf of the
XENON Collaboration

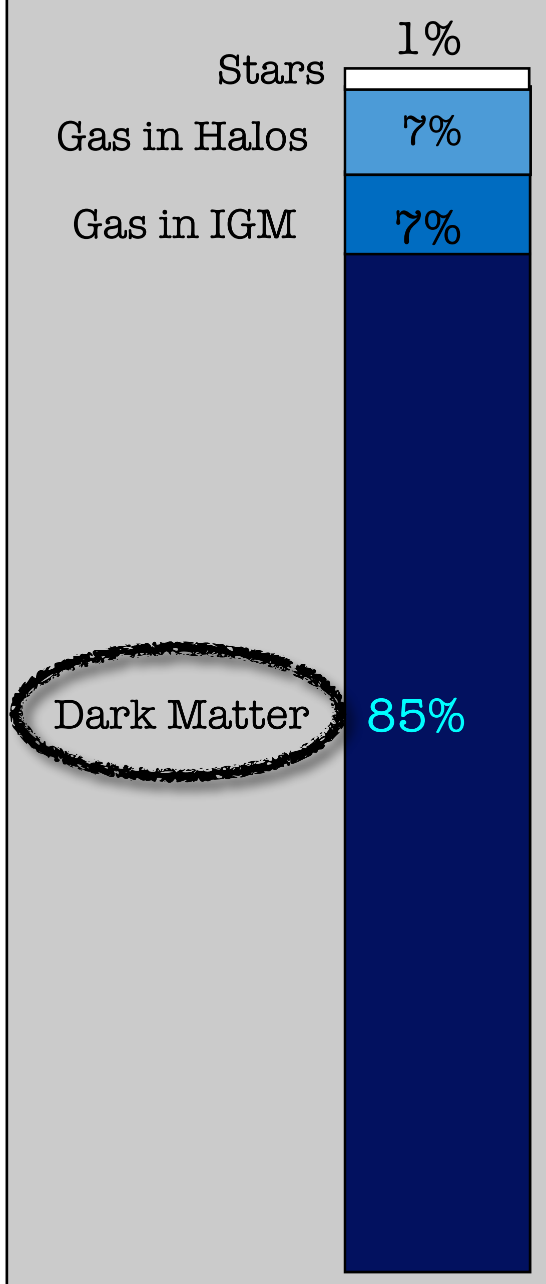
LNGS Seminar
Oct 10, 2019

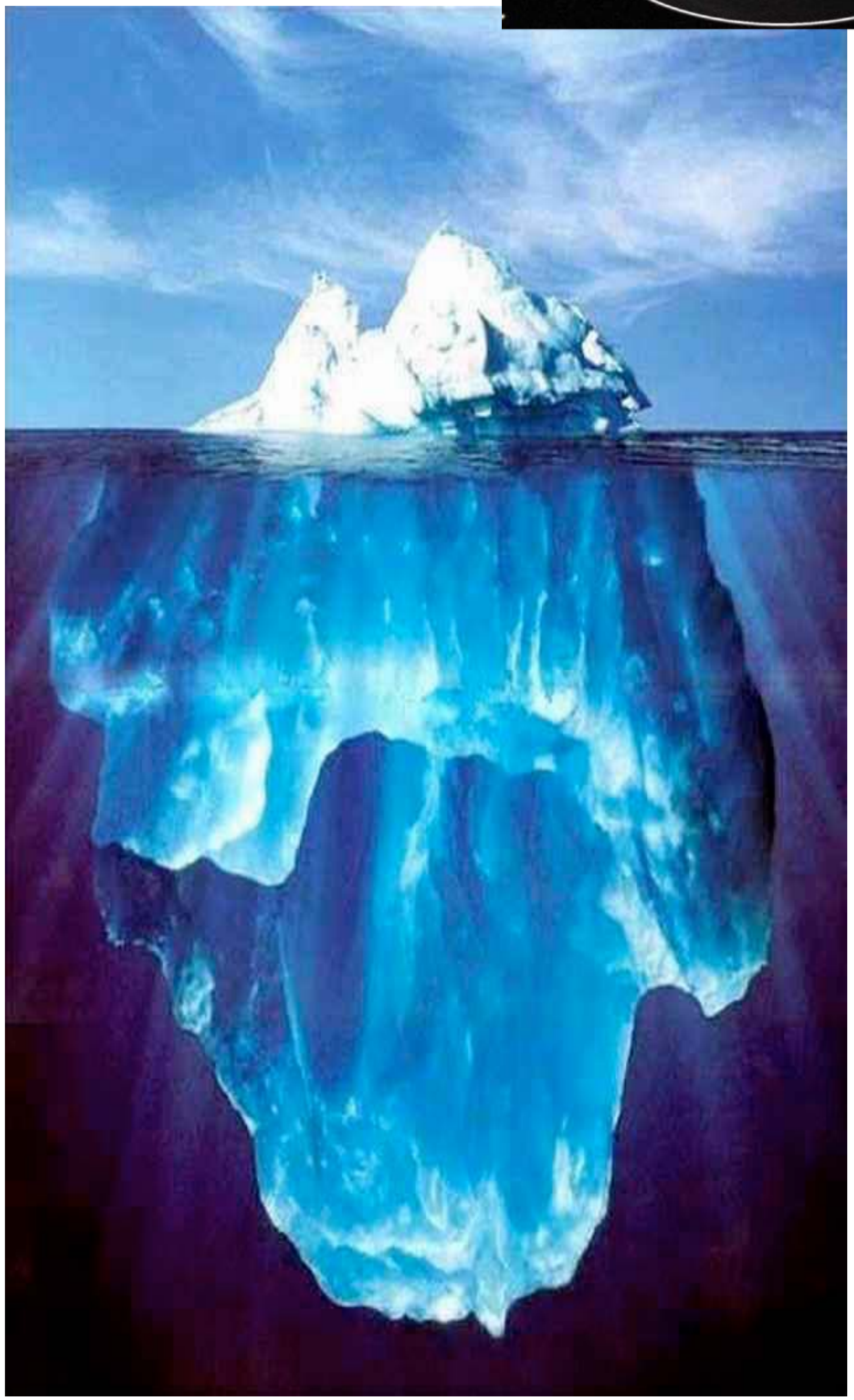
The Universe is Dark!





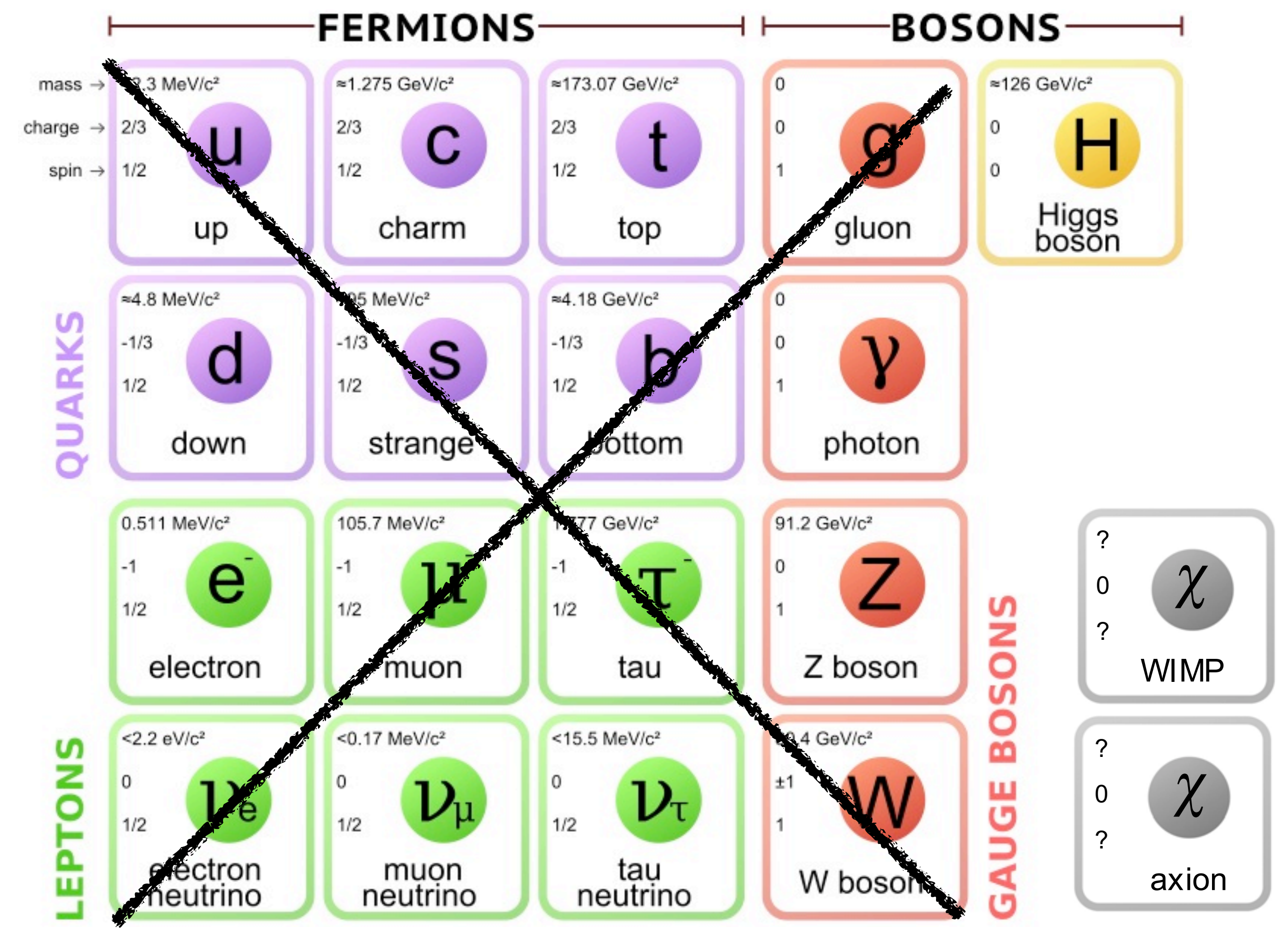


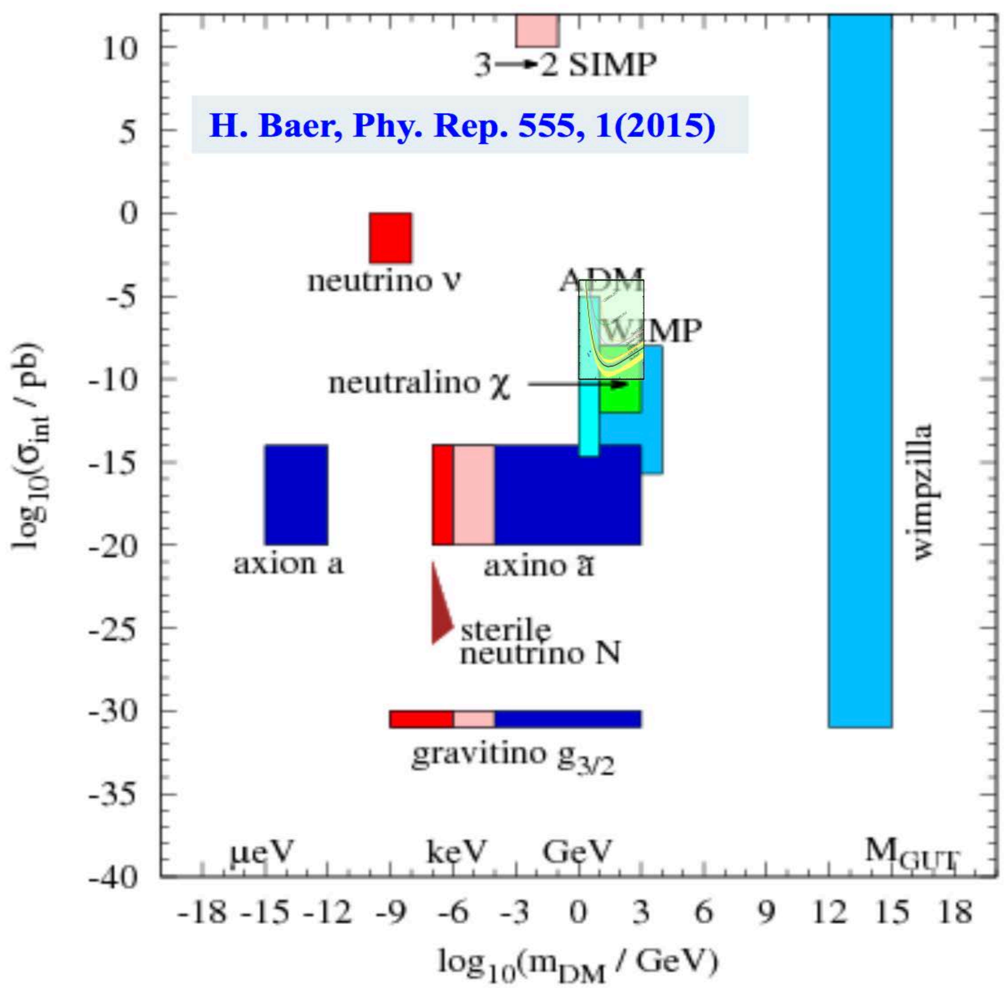


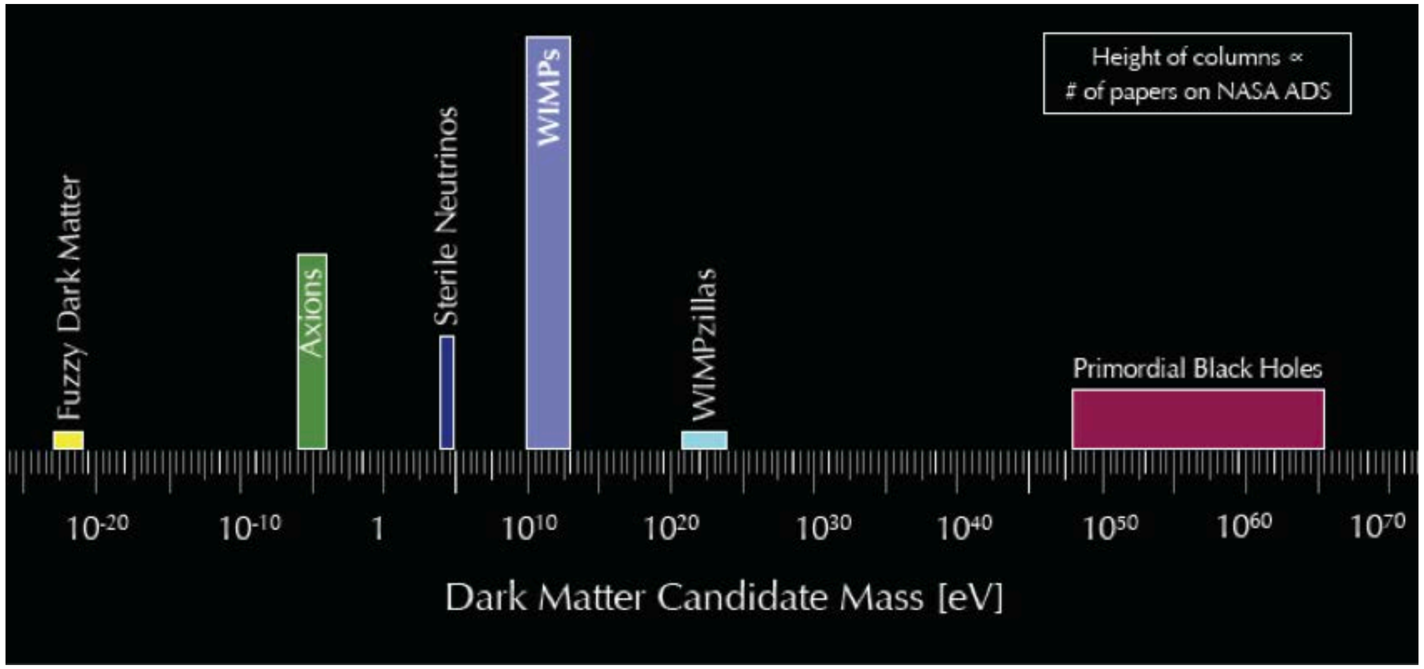


What is Dark Matter?

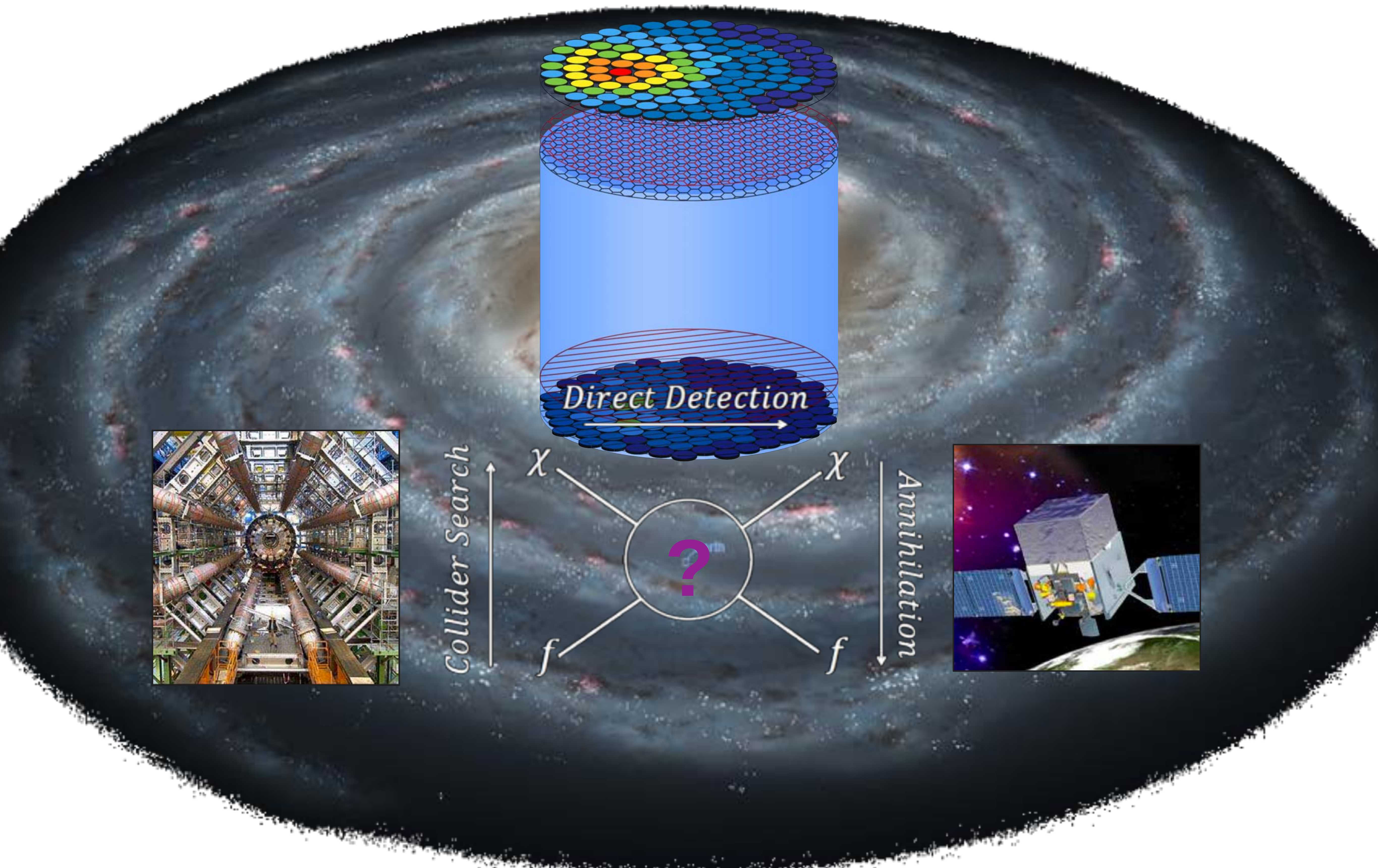
- Neutral: no EM interaction
- Stable: Lifetime larger than age of the Universe
- Massive: for structure formation
- Interaction besides Gravity ??





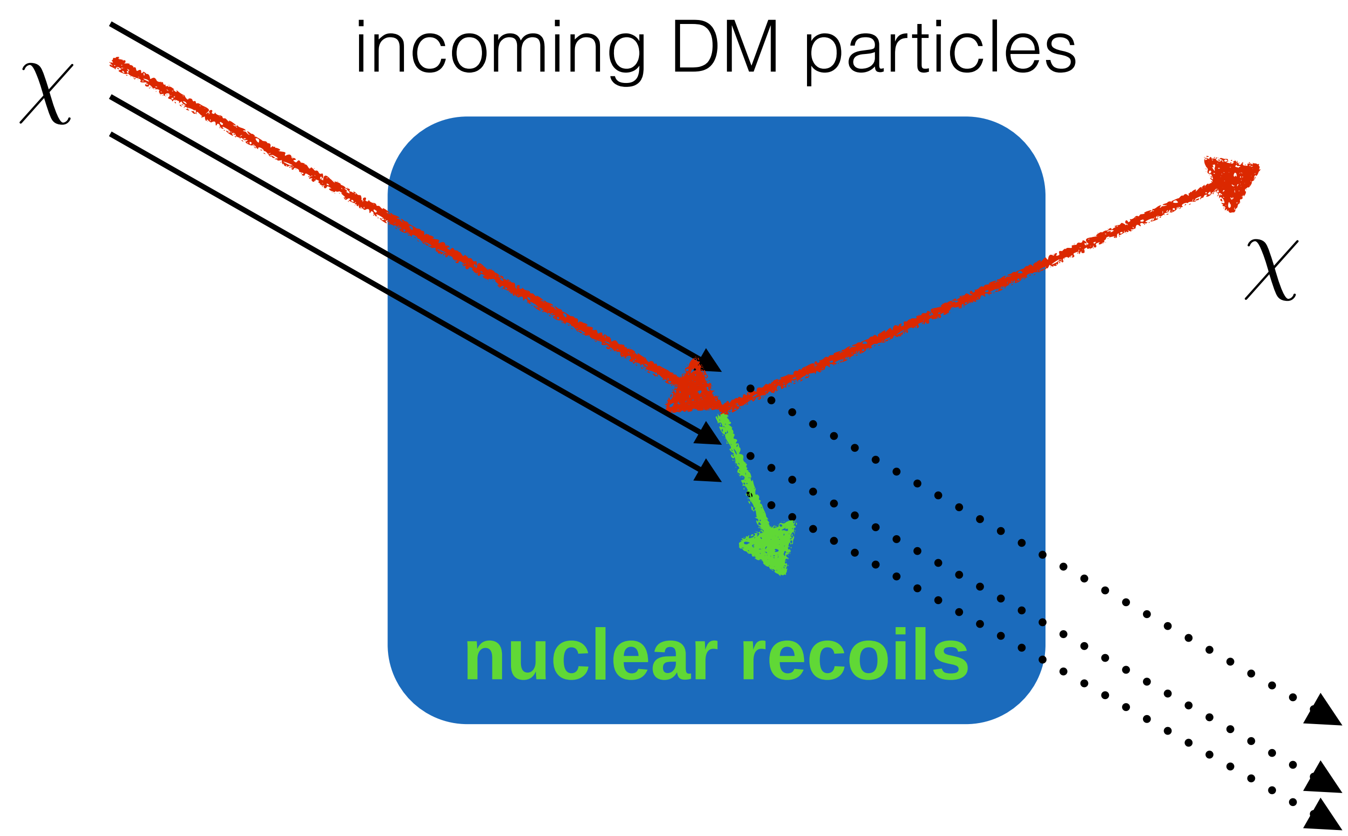


Search for WIMPs



Standard Assumptions for WIMPs Direct Detection

- DM mass range: GeV~TeV
- local WIMP density: 0.3 GeV/cm^3
- Isothermal velocity distribution: v_0~220 km/s
- WIMP escape velocity ~544 km/s



WIMPs density

interaction cross section

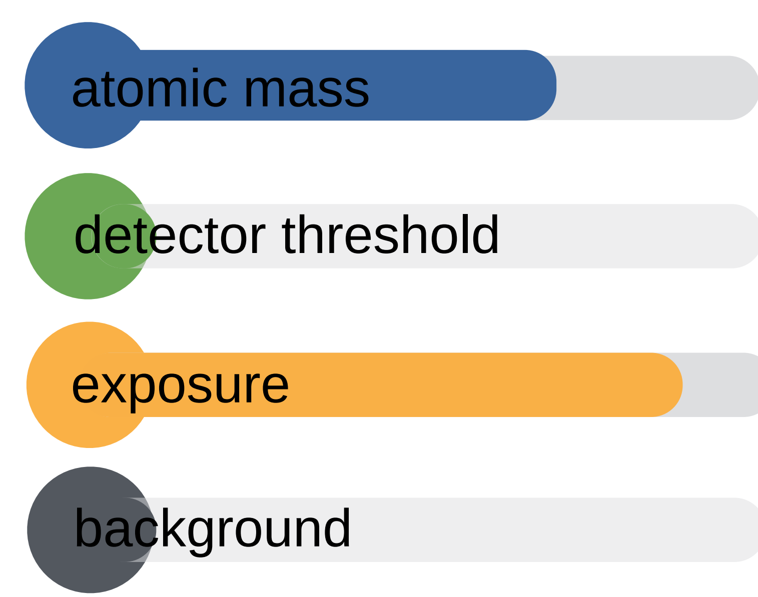
$$\frac{dR}{dE_{nr}} \propto N \frac{\rho_\chi}{2m_\chi m_r^2} \sigma_N \left|F^2(E_{nr})\right| \int_{v_{\min}}^{v_{esc}} \frac{f(v)}{v} d^3v$$

number of targets

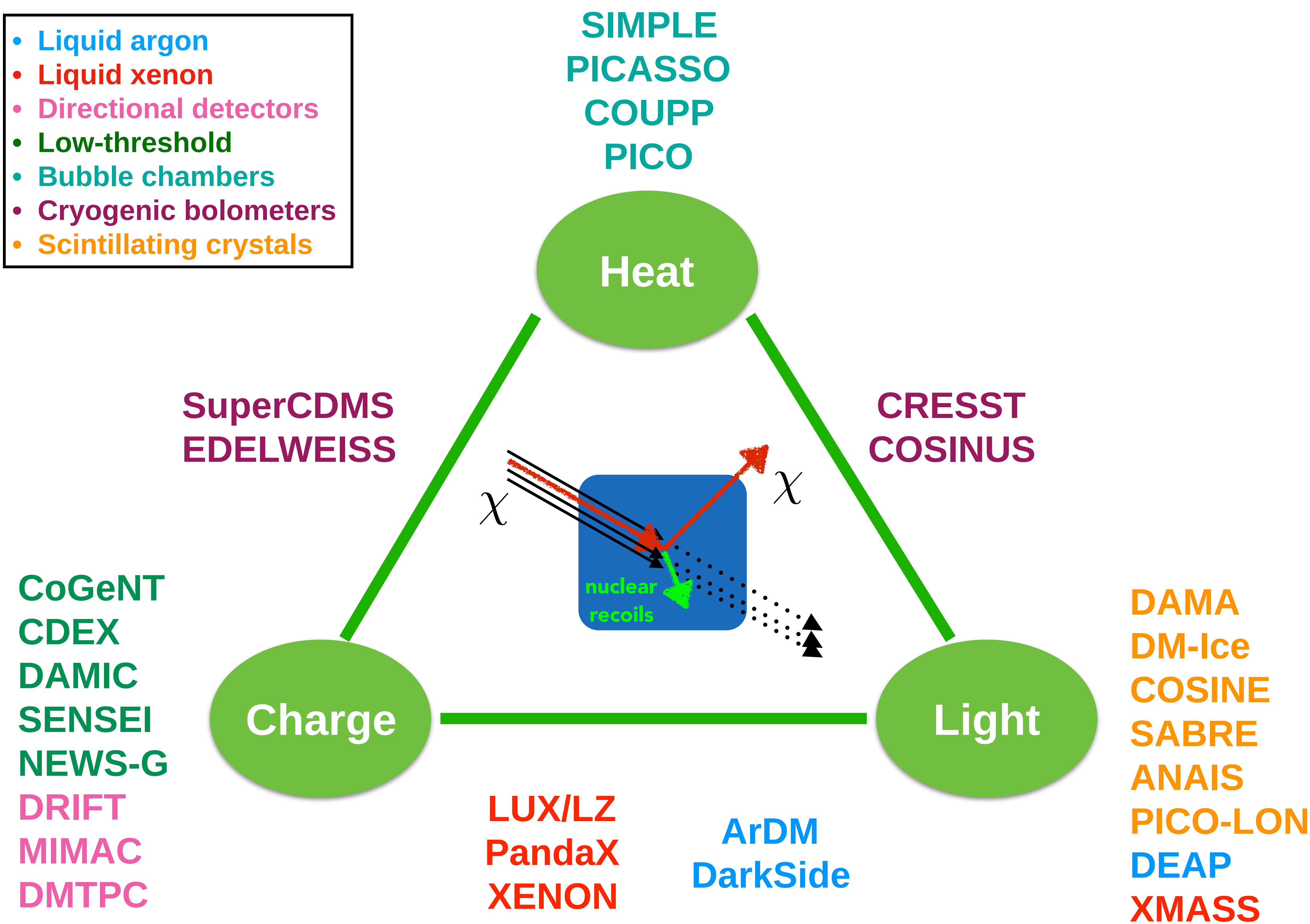
WIMP mass

nuclear effects

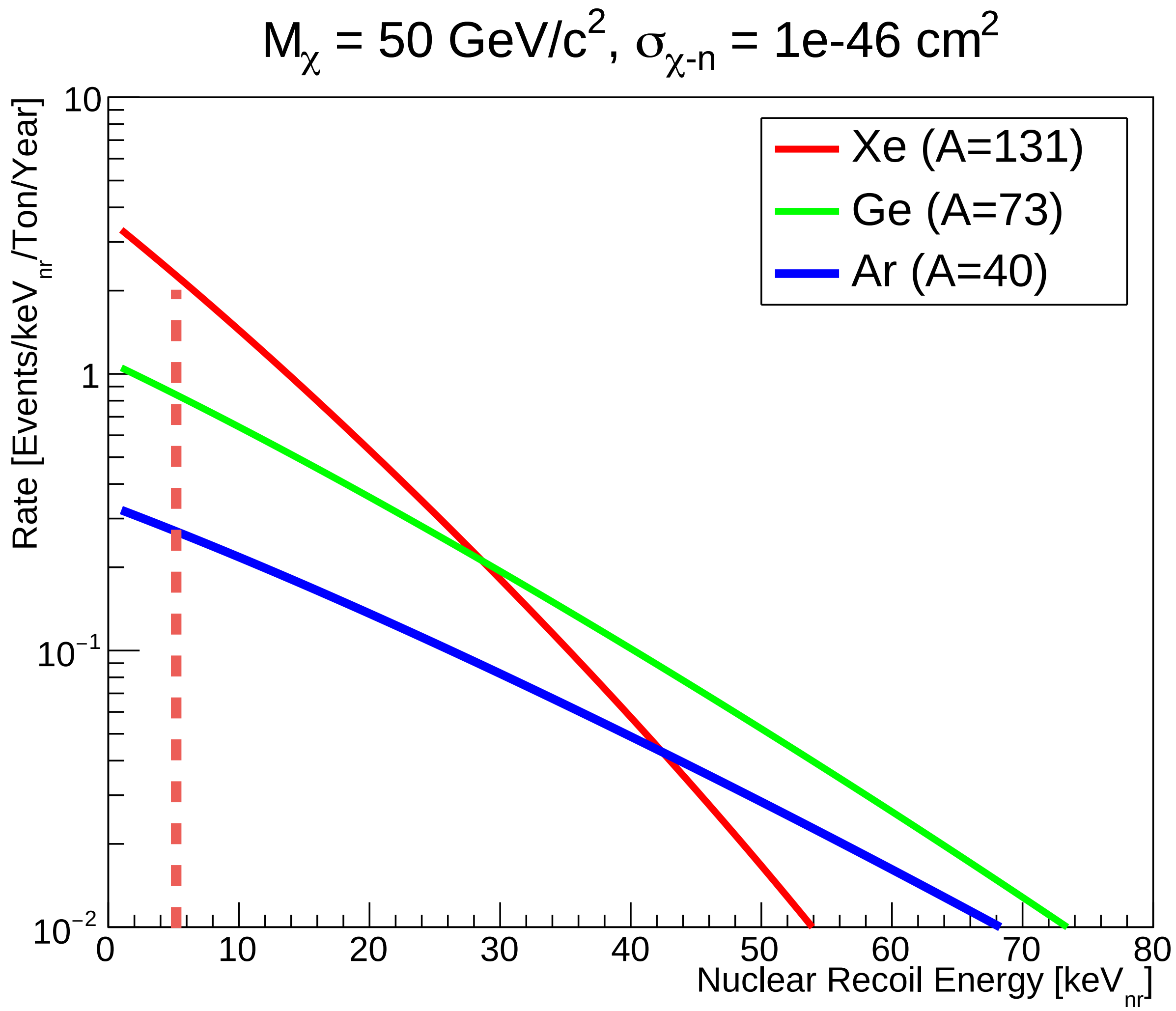
WIMP velocity distribution

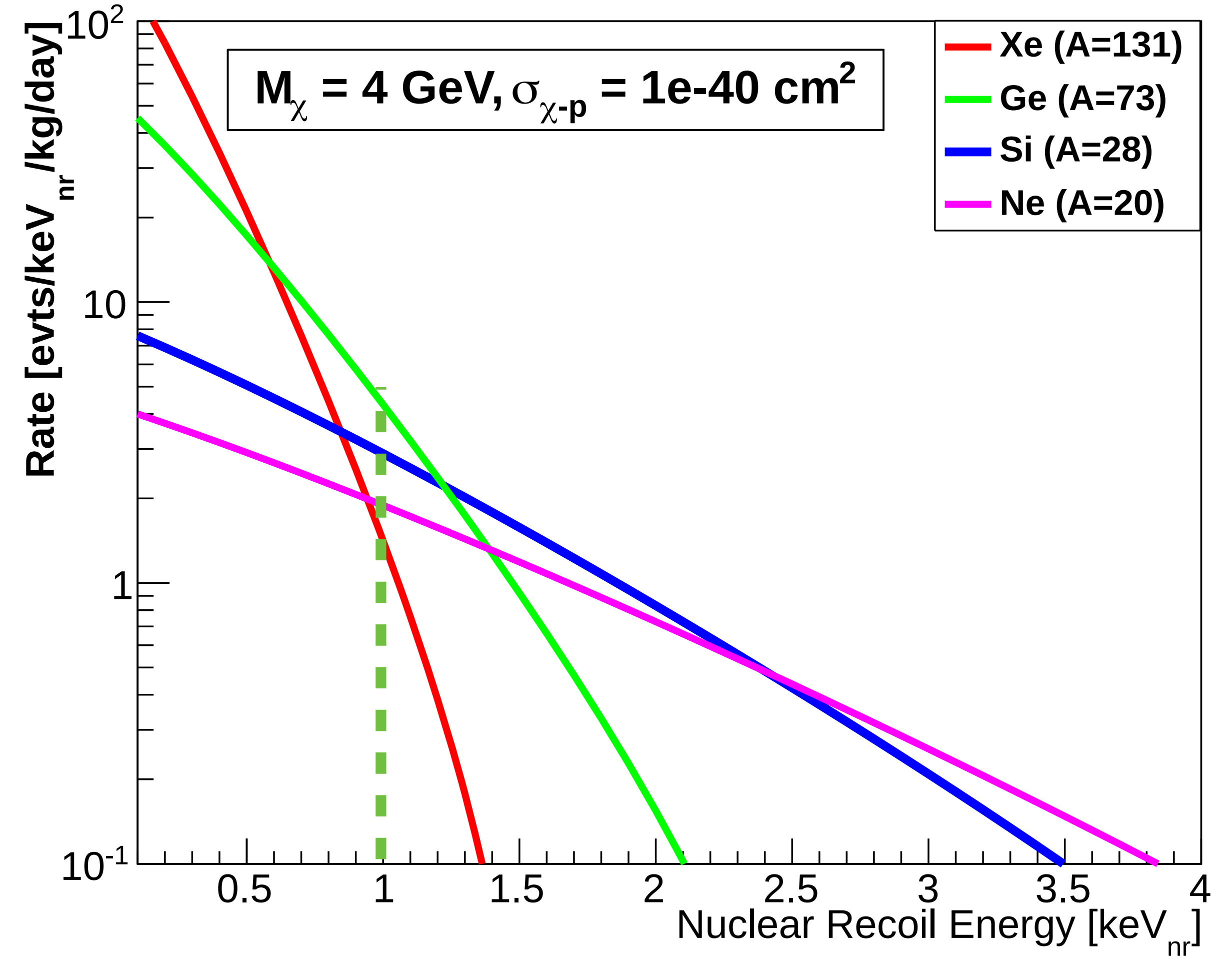


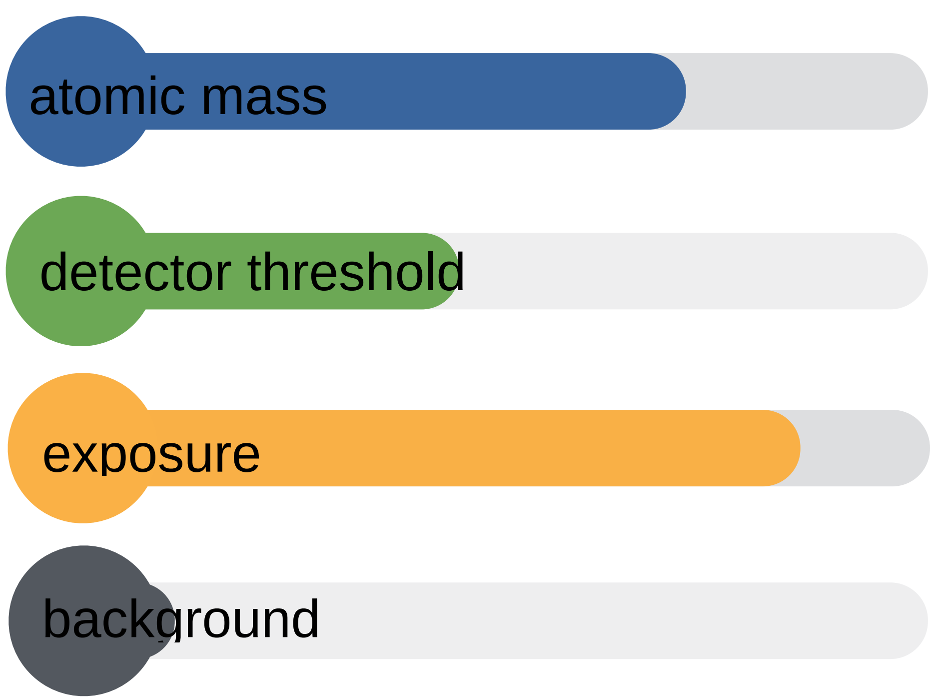
Direct Detection Techniques

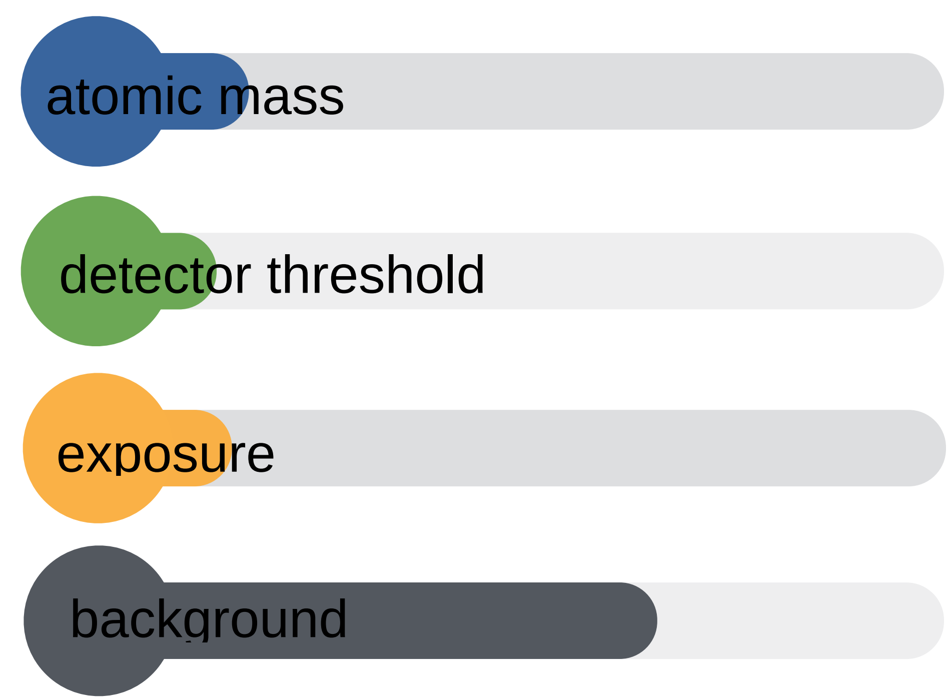


Heavy vs light WIMPs



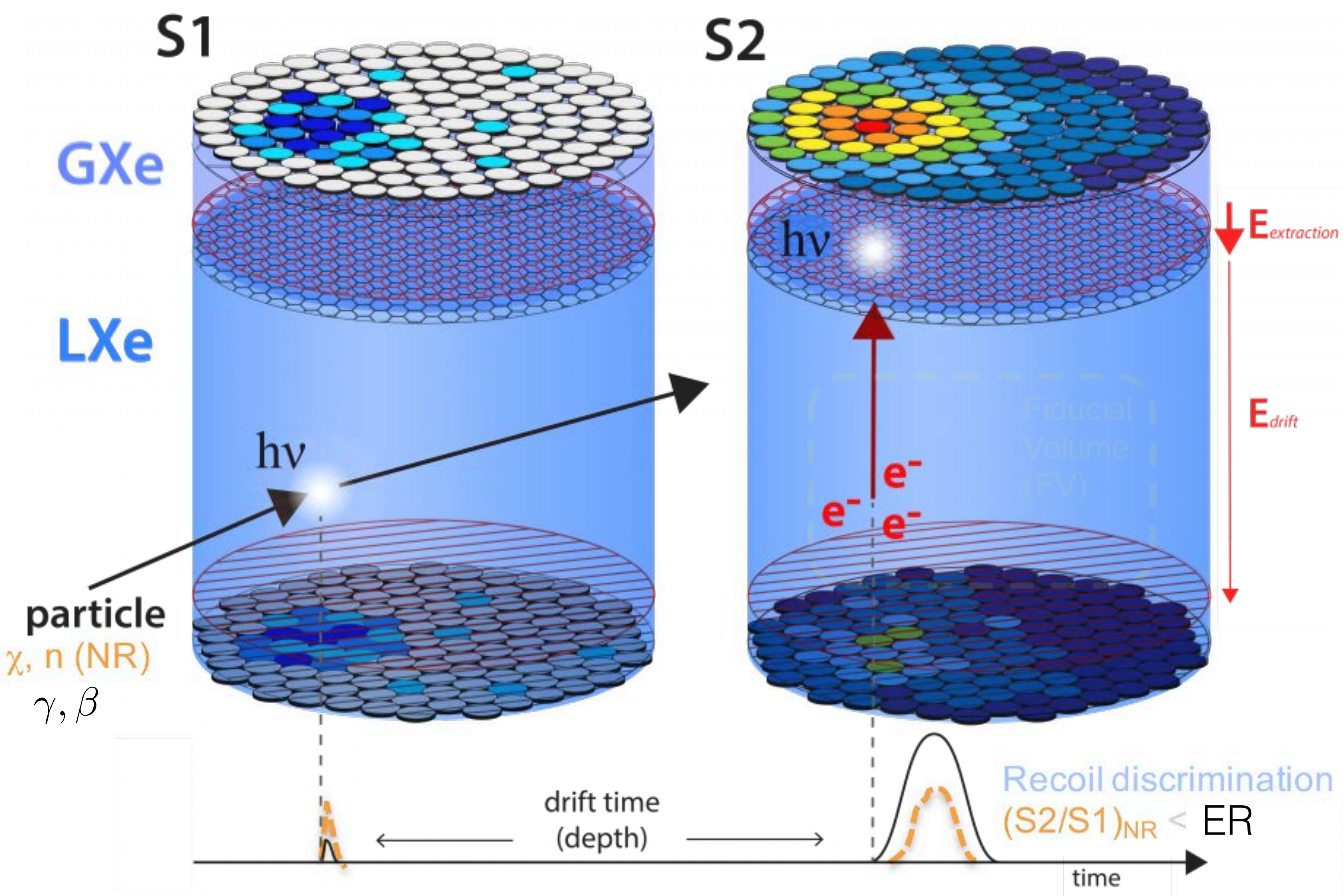






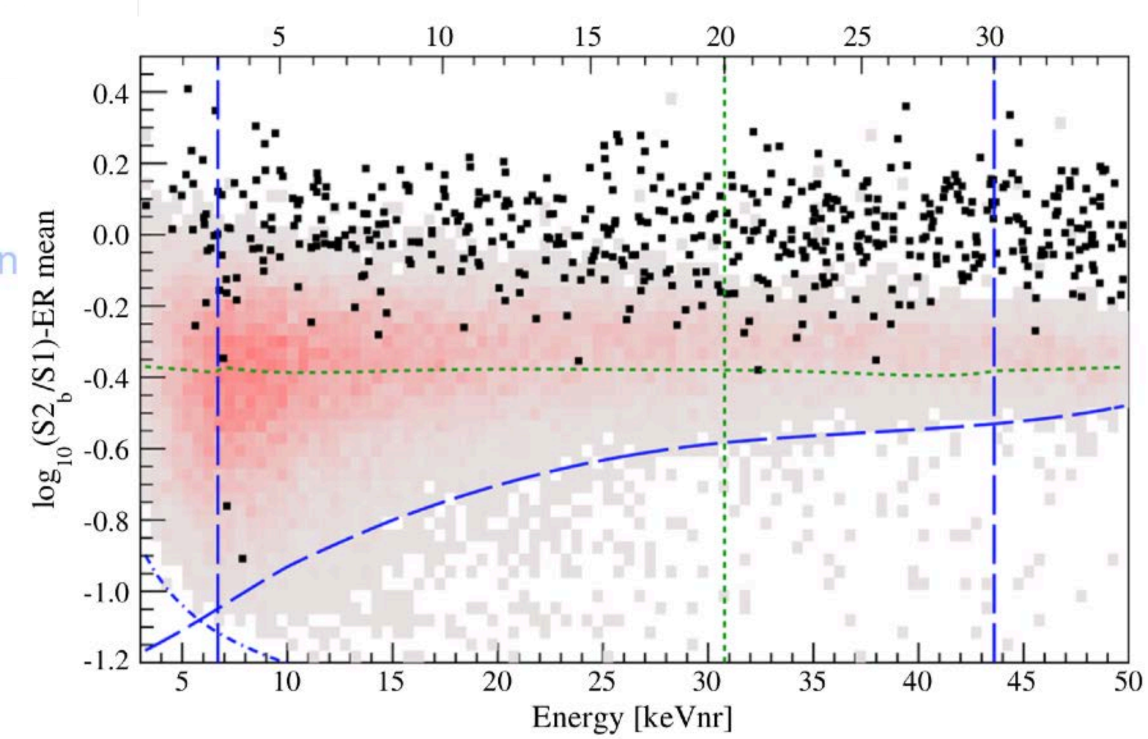
Two-phase Xe Time Projection Chamber as WIMP detector

- **Scintillation light - S1**
- **Ionization electron -S2**



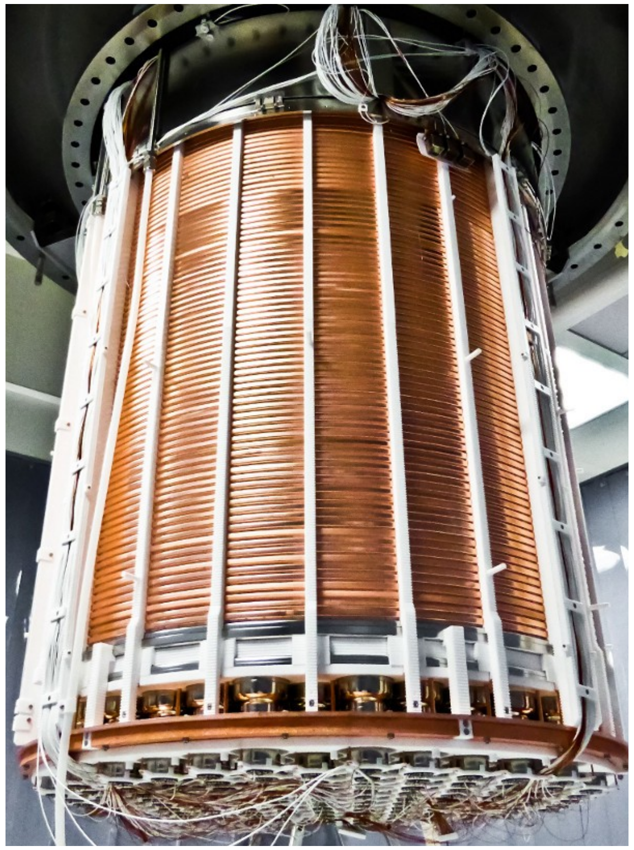
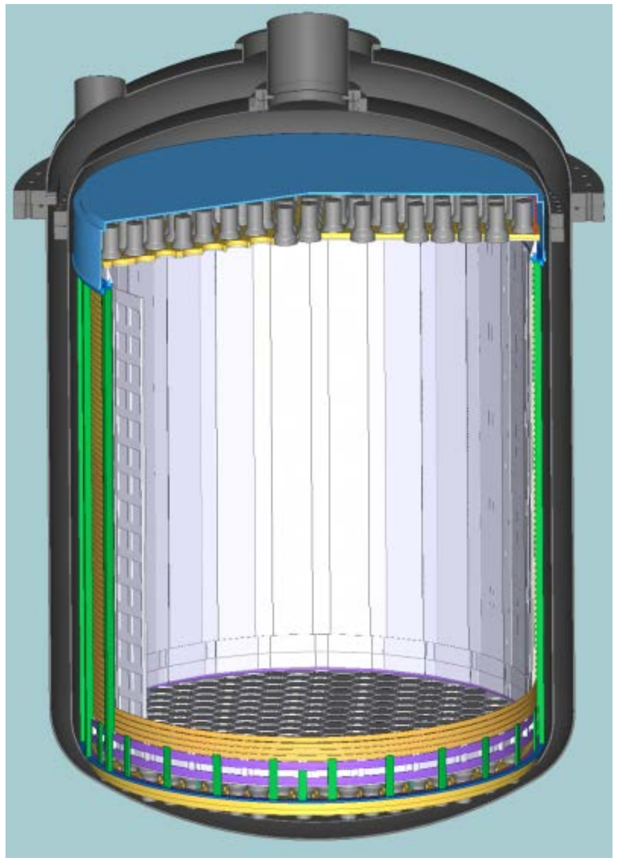
- two signals for each event:
  - Energy from S1 and S2 area
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
- Recoil type discrimination from ratio of charge (S2) to light (S1)

XENON100



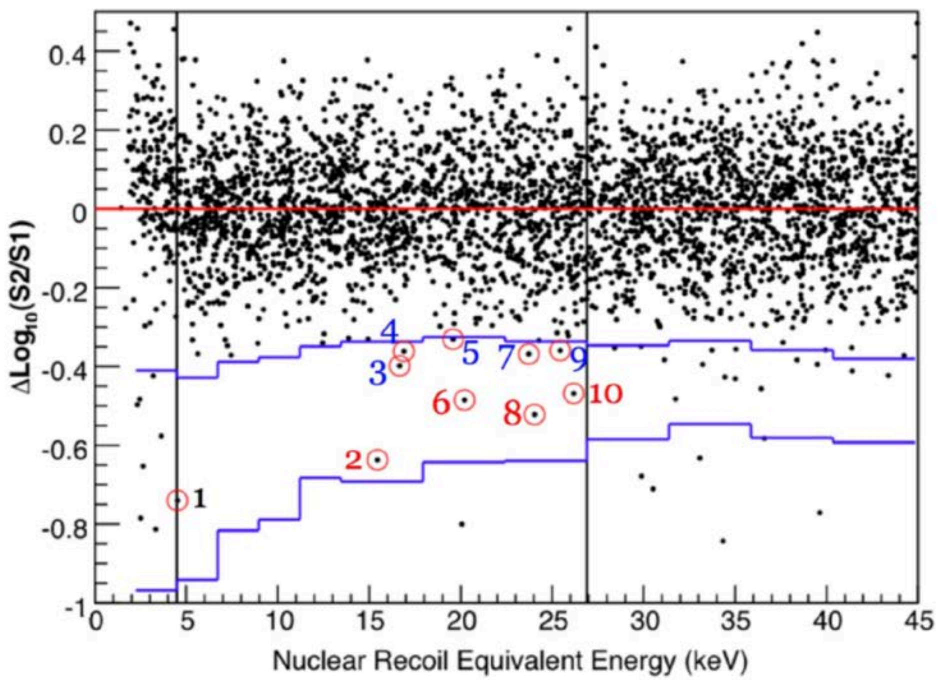
The XENON Collaboration: ~170 scientists

Development of XENON Program

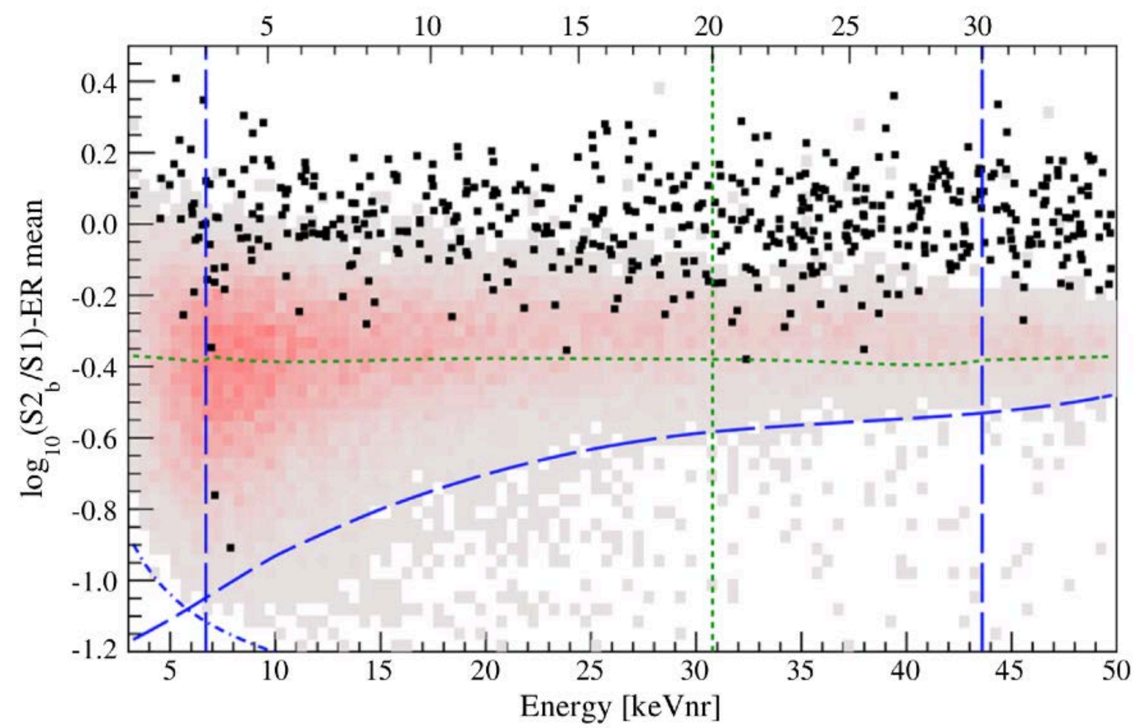
XENON10	XENON100	XENON1T	XENONnT
			
2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

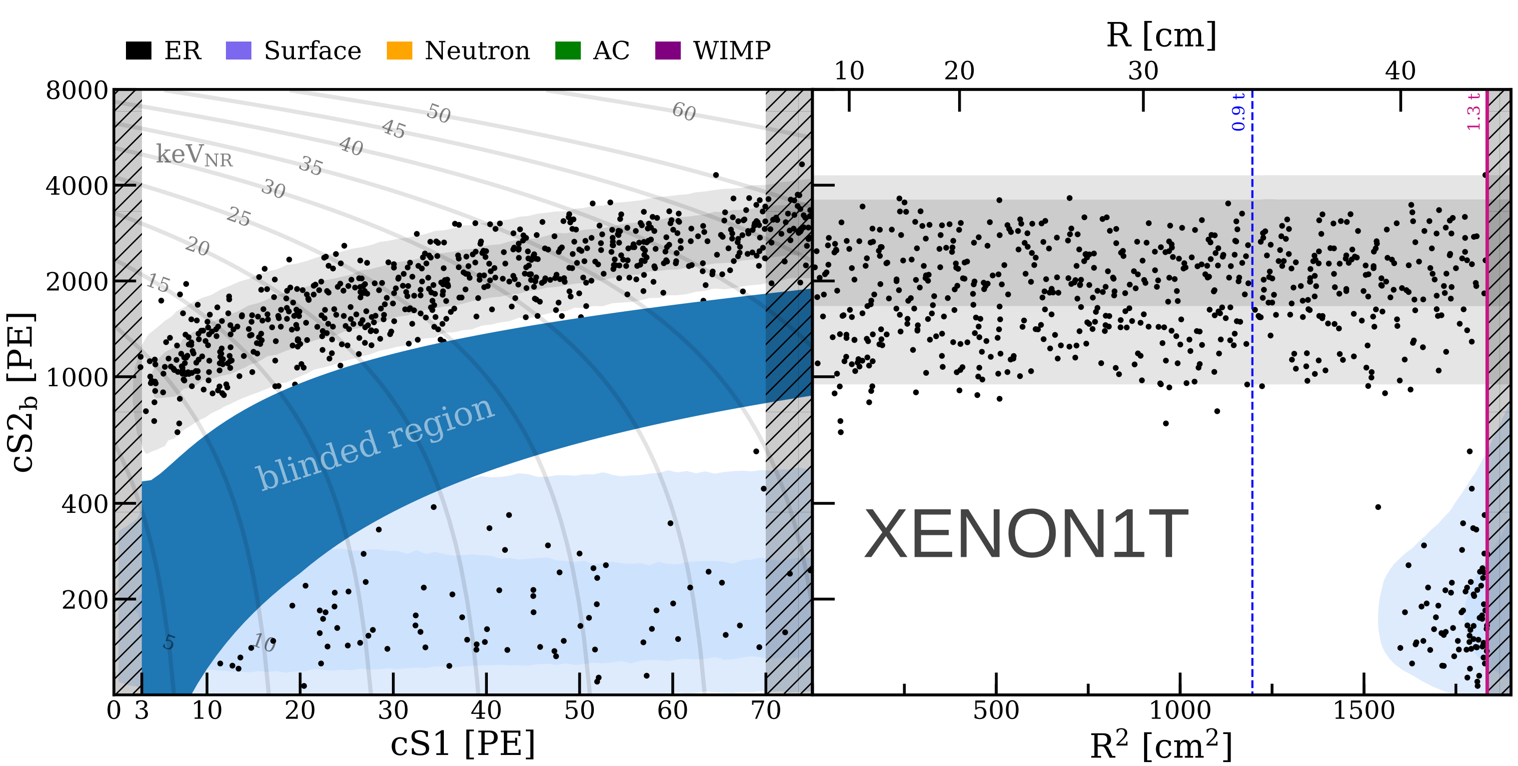
Background Tolerance

XENON10



XENON100

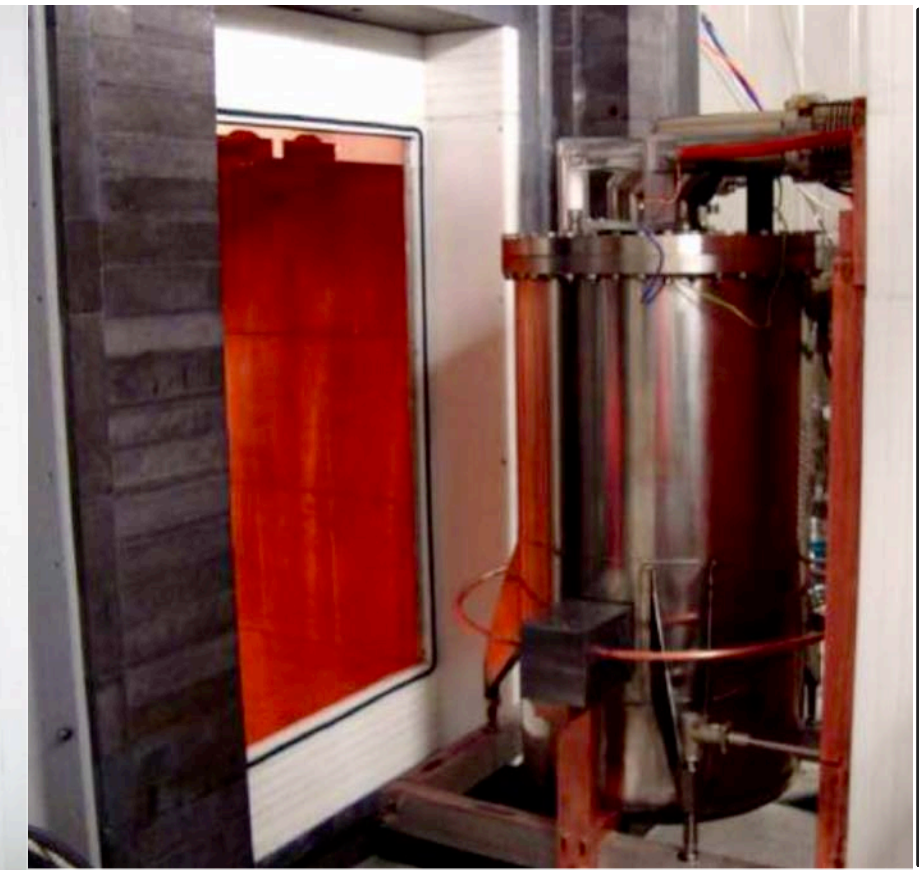




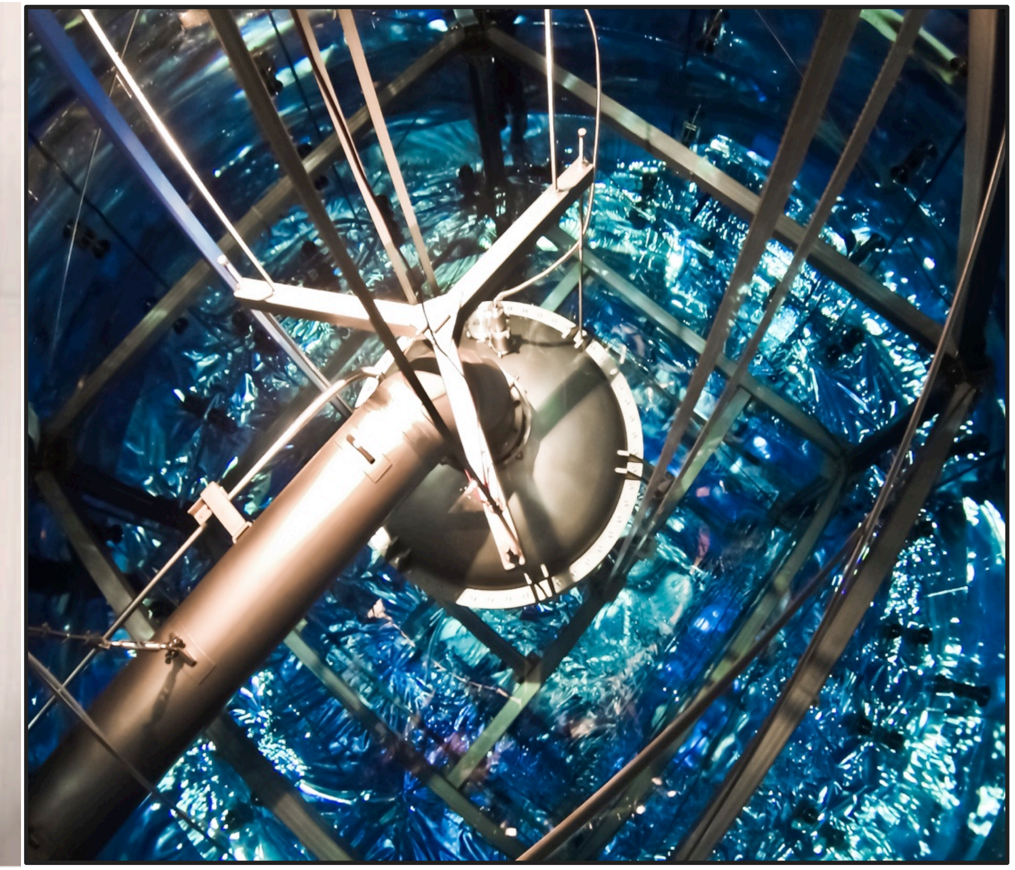
- O(100) ER events before discrimination
- O(1) NR background
- O(1) Other anomalous backgrounds
- Key is to get lower background rate for larger detectors

Shield: From XENON10 to XENON1T/nT

XENON10



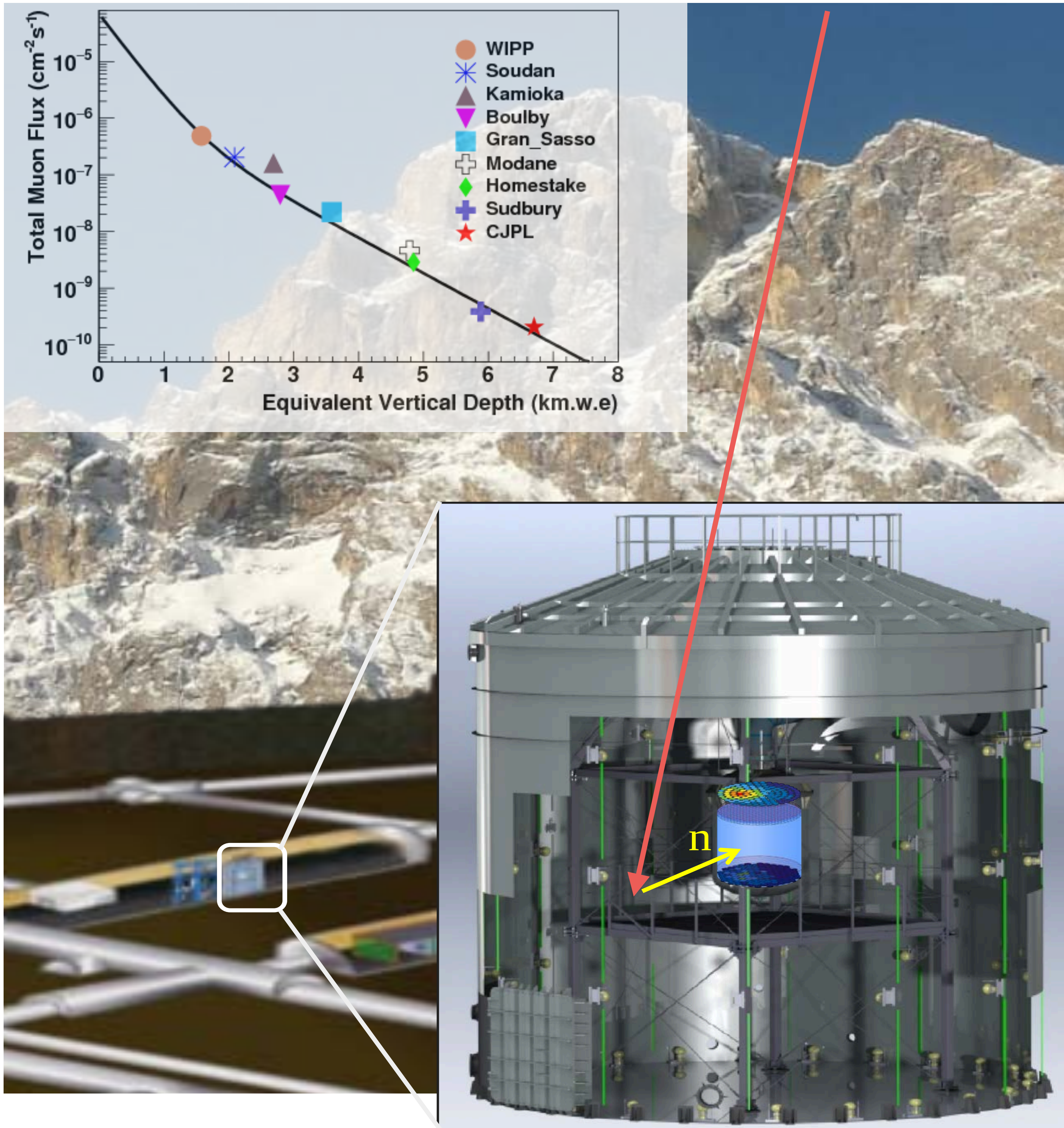
XENON100

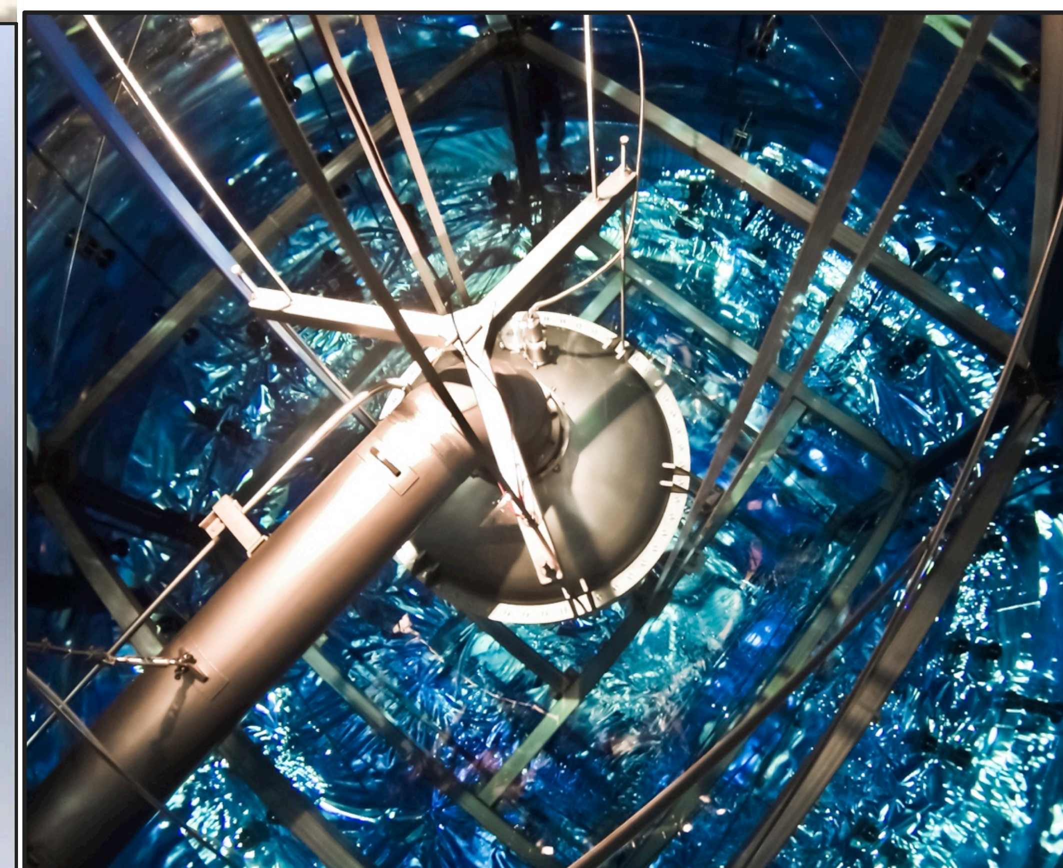


XENON1T/nT

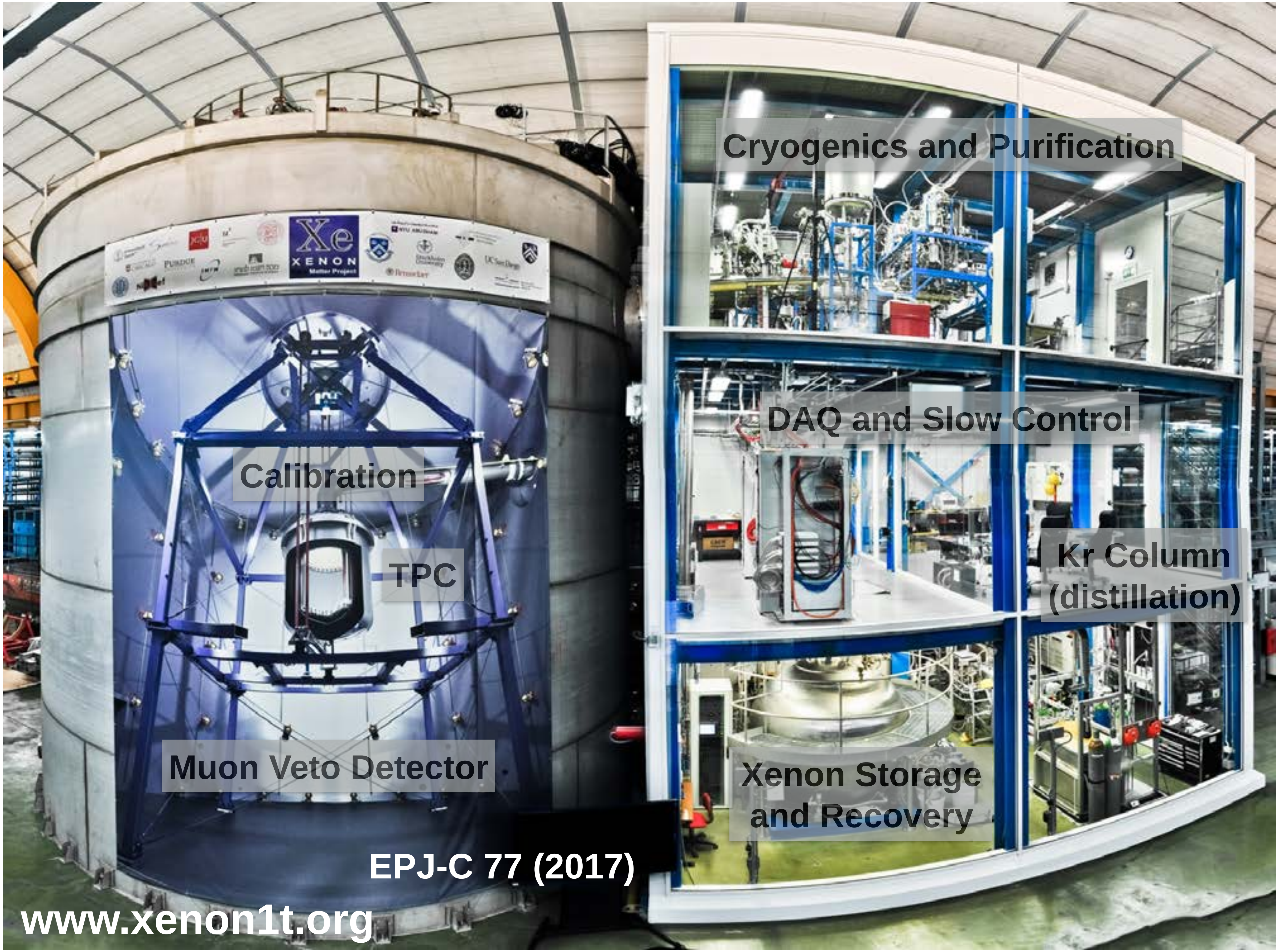
- XENON10, XENON100: conventional **passive** shield, onion-like structure
- XENON1T, XENONnT: large water Cherenkov **active** shield, necessary to remove muon induced backgrounds

Gran Sasso — The XENON Shield

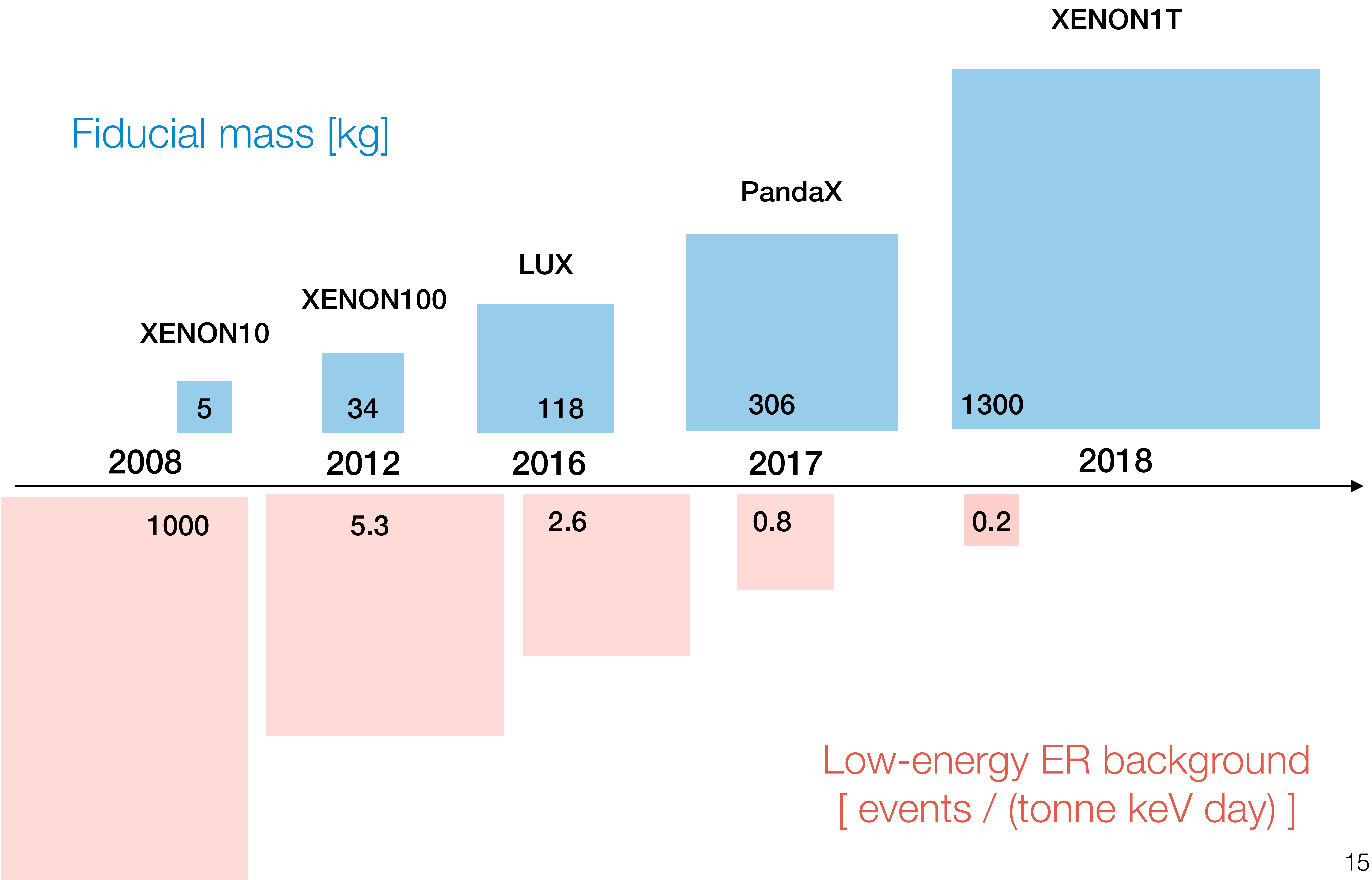




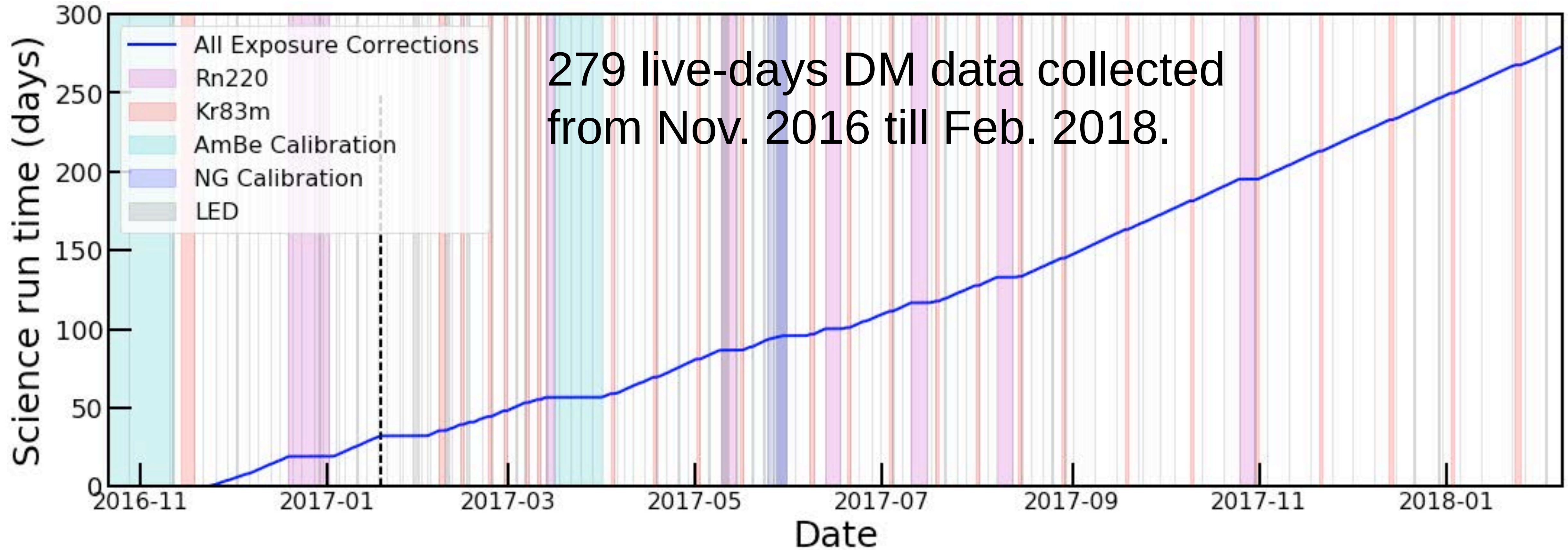
XENON1T: All Systems

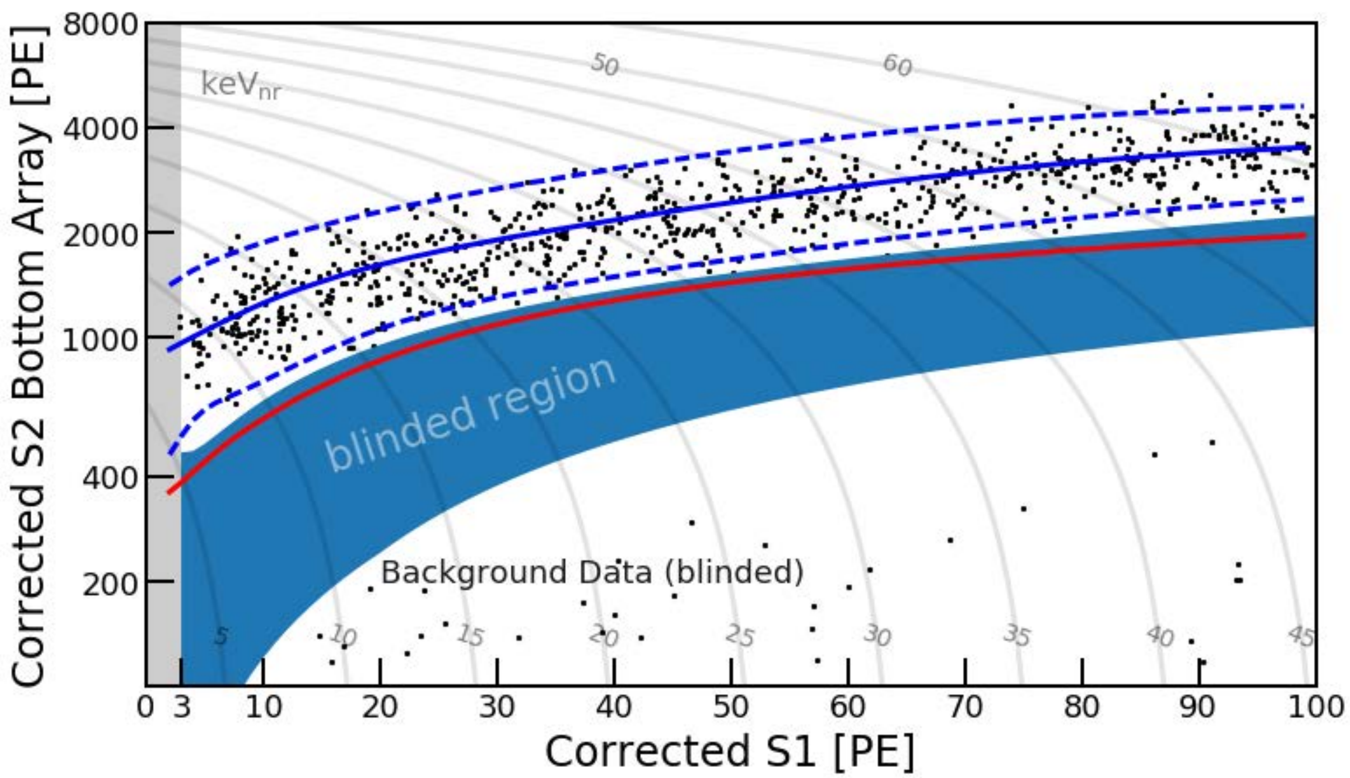


Evolution of LXeTPCs as WIMP detectors



1 ton-year of WIMPs Search

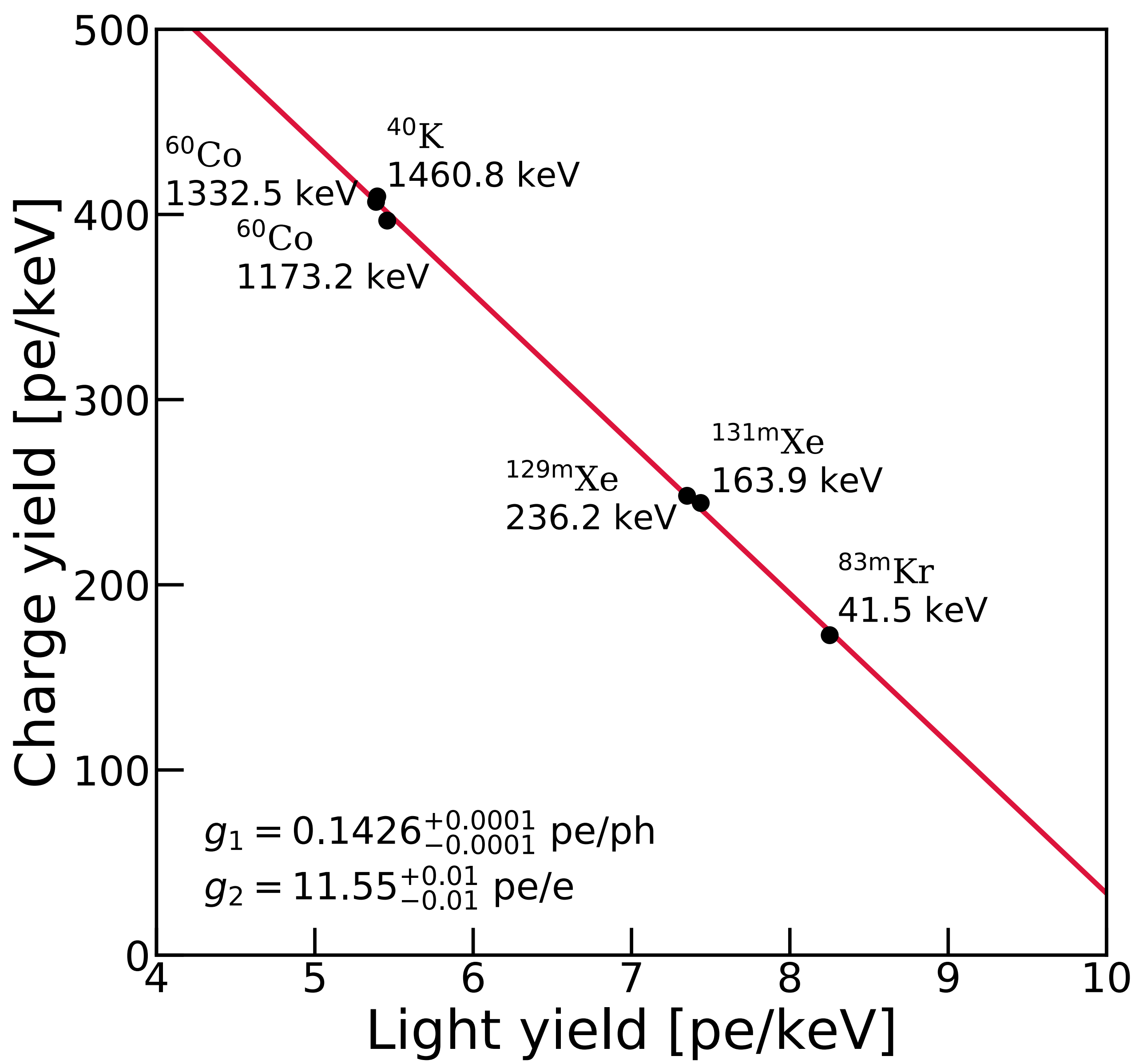




- **1.3t fiducial mass, resulting in 1 t-yr exposure for WIMPs search**
- **Blinding: to avoid potential bias in event selection and the signal/ background modeling**
- **Position dependent likelihood for the statistical inference**

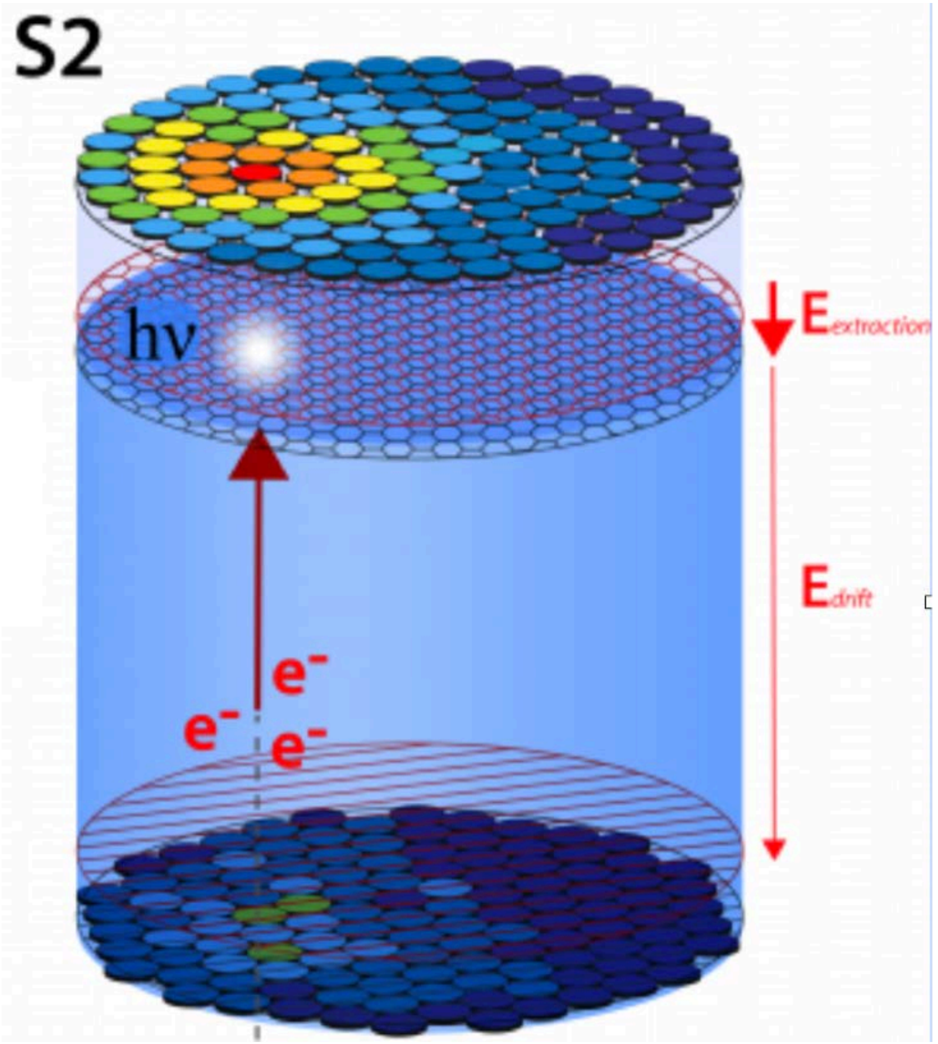
Energy Reconstruction

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



- exploit anti-correlation of charge and light for a more precise energy scale: excellent linearity with electronic recoil energy from ~ keV to ~ MeV
- g1 = 0.143 ± 0.007 (sys) PE/photon corresponds to a photon detection efficiency of 12.5 ± 0.6% (taking into account double PE emission). MC projected efficiency is12.1%.
- g2: the amplification of charge signal corresponds to near full extraction of charges from the liquid.

Position Reconstruction



x-y reconstruction via **neural network**:

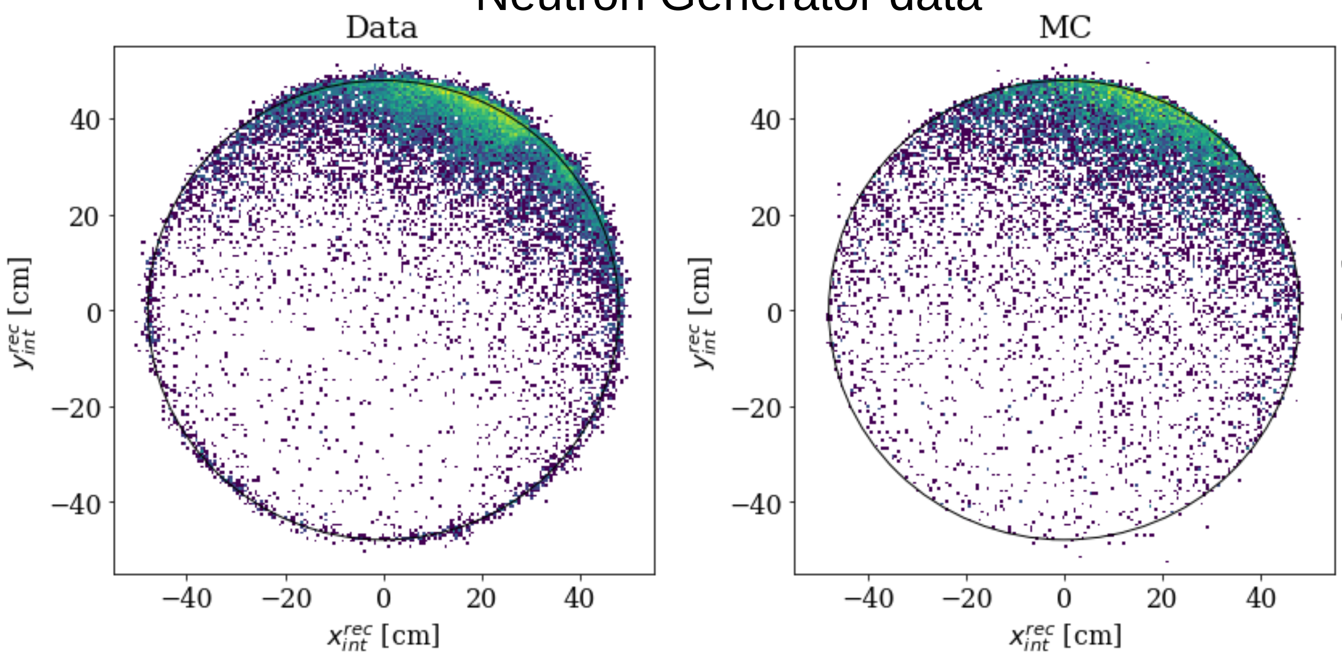
- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation
- TensorFlow framework implemented
- Pattern likelihood fit for cross-check

Position resolution

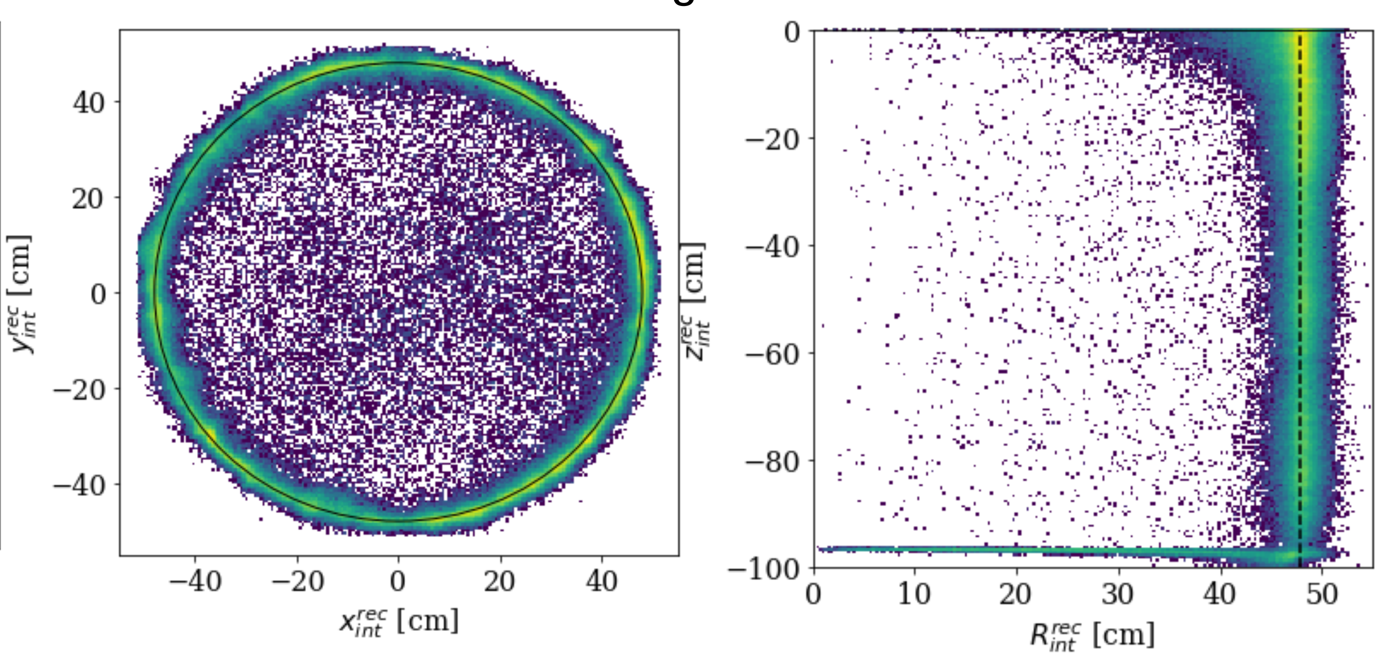
- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

PRD 100, 052014 (2019)

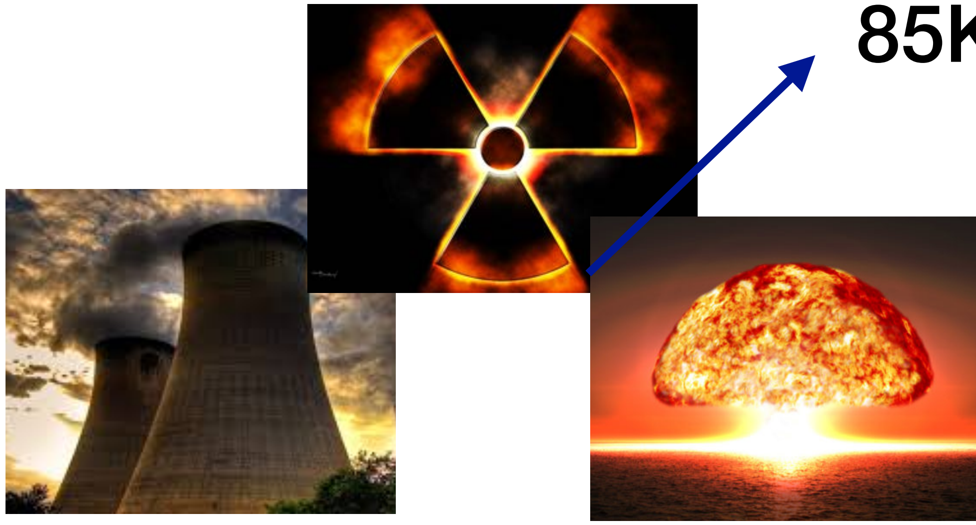
Neutron Generator data



Background data



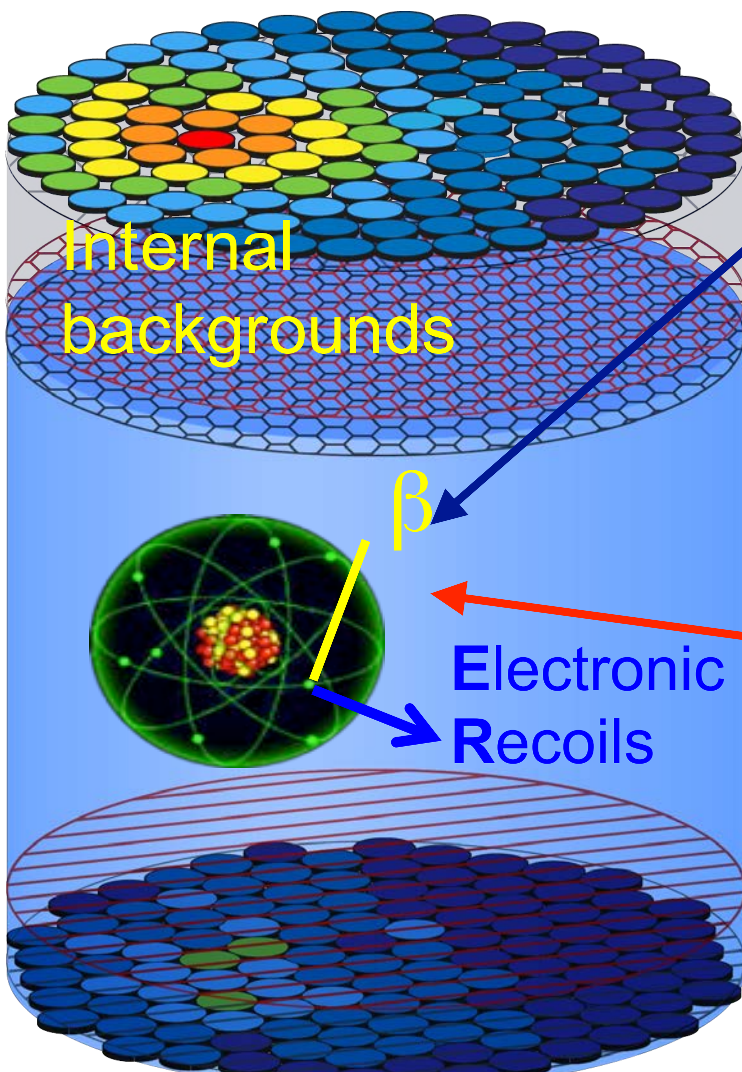
ER Background

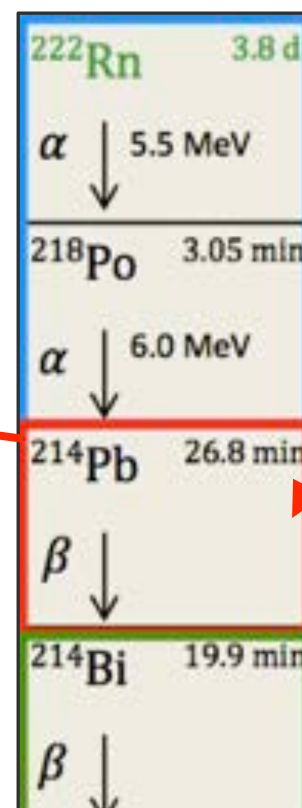


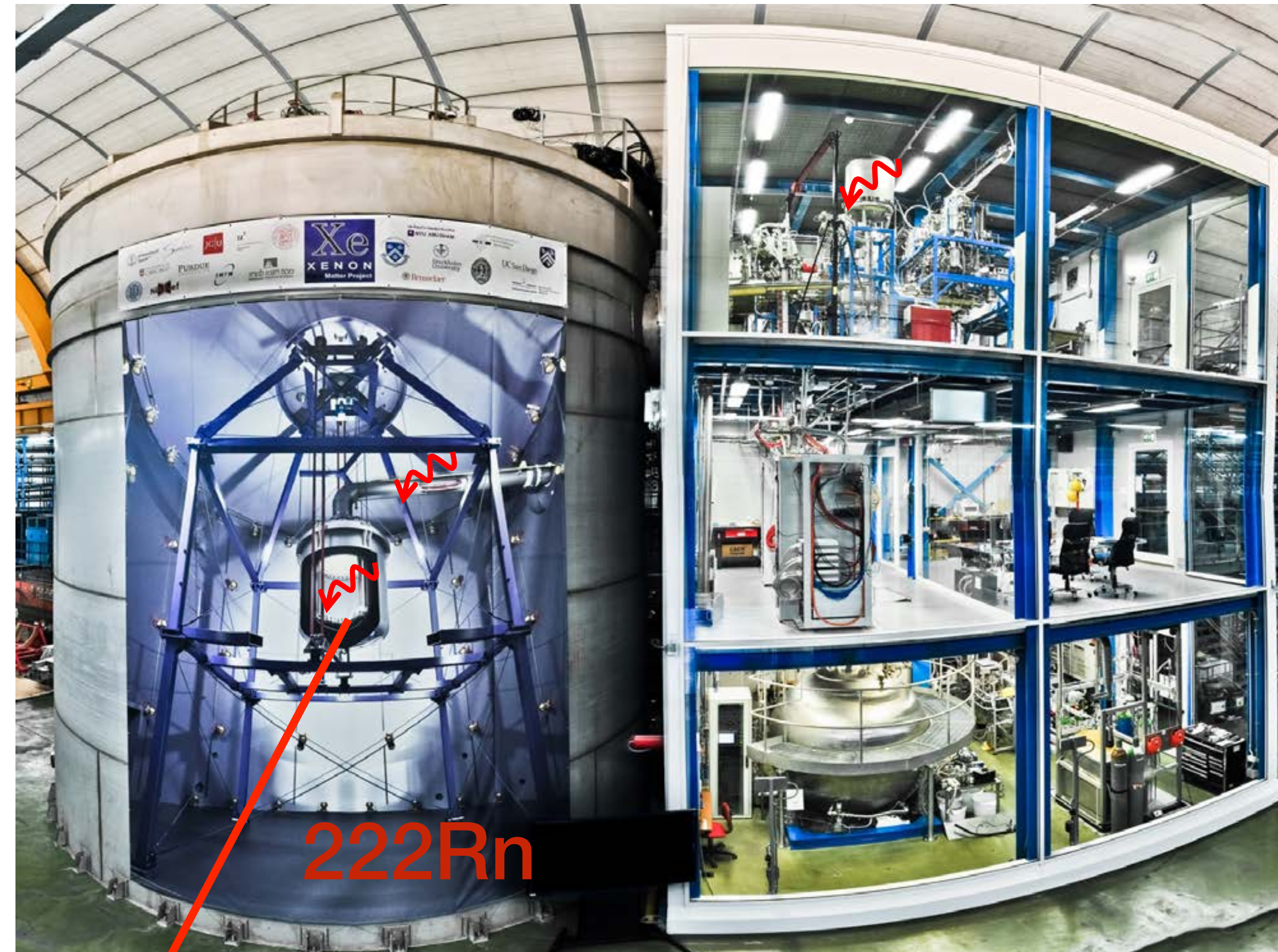
85Kr

Air

Xenon







PRD 99, 112009 (2019)

Source	Rate [t^{-1} y^{-1} keV^{-1}]	Fraction [%]
222Rn	56 ± 6	75.0
85Kr	7.7±1.3	10.3
Solar ν	2.5±0.1	3.3
Materials	8±1	10.7
136Xe	0.8±0.1	1.1
Total	75±8	
Measured	82±5	

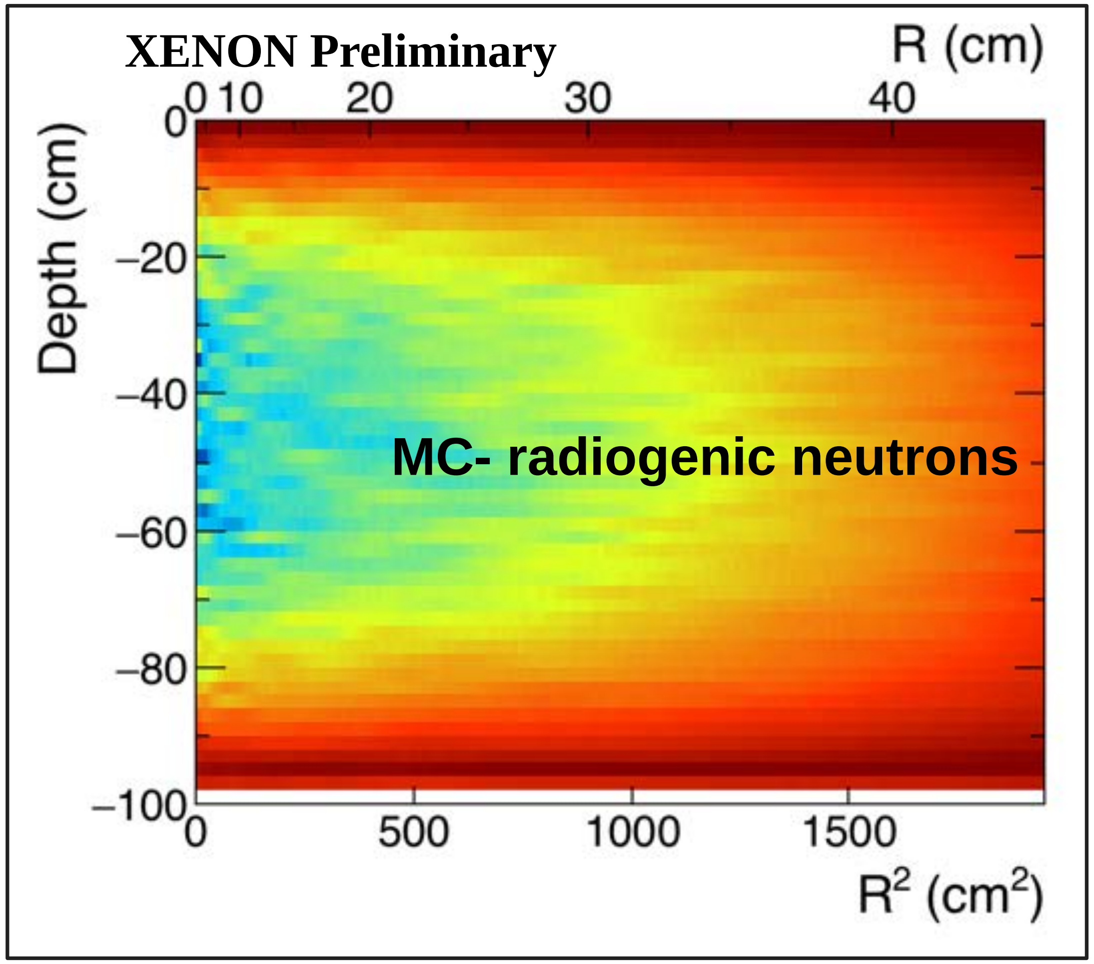
NR Background

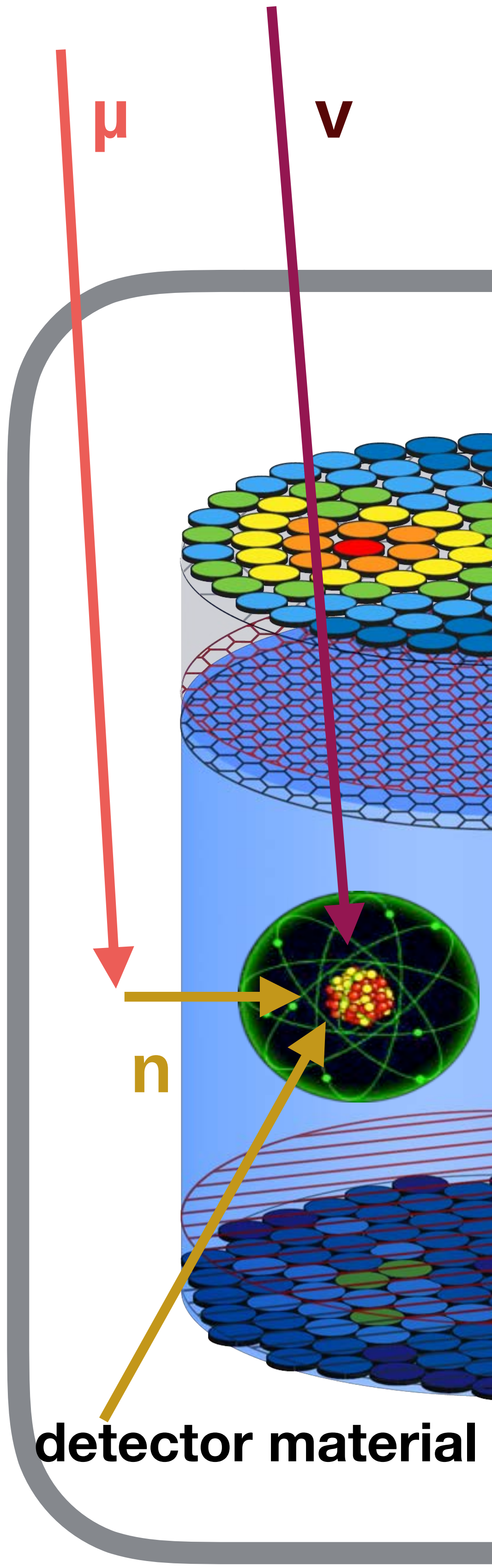
- Cosmogenic μ-induced neutrons, significantly reduced by muon veto detector
- Coherent elastic ν-nucleus scattering irreducible background (sun, atmosphere)
- Radiogenic neutrons from (α, n) reactions and fission from ^{238}U and ^{232}Th chains and spontaneous fission
  - reduced via careful material selection
  - non-homogeneous event distribution

Source	Rate [t^{-1} y^{-1}]	Fraction [%]
Radiogenic n	0.6 ± 0.1	96.5
CEνNS	0.012	2
Cosmogenic	< 0.01	< 2.0

(Expectations in 4-50 keV search window, 1t FV, single scatters)

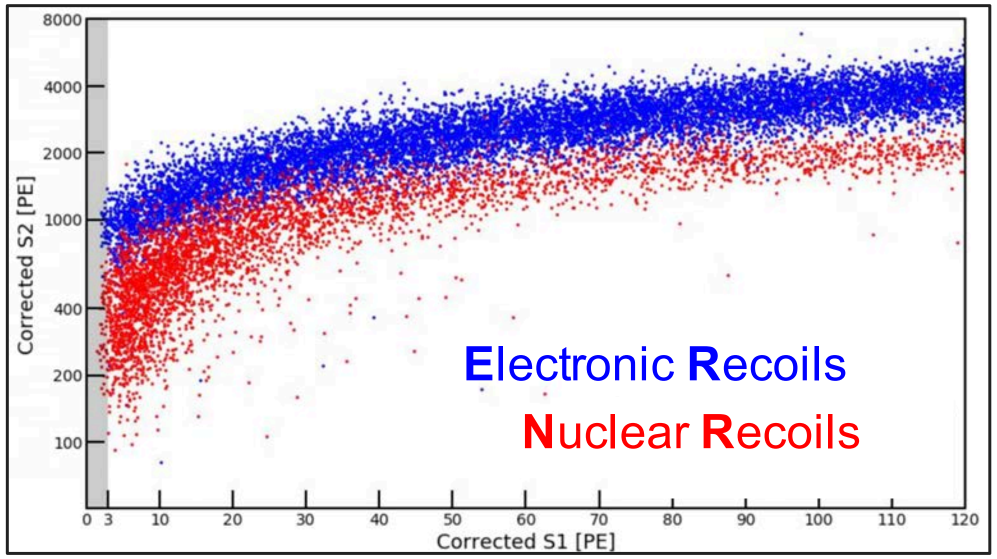
JCAP04 (2016) 027

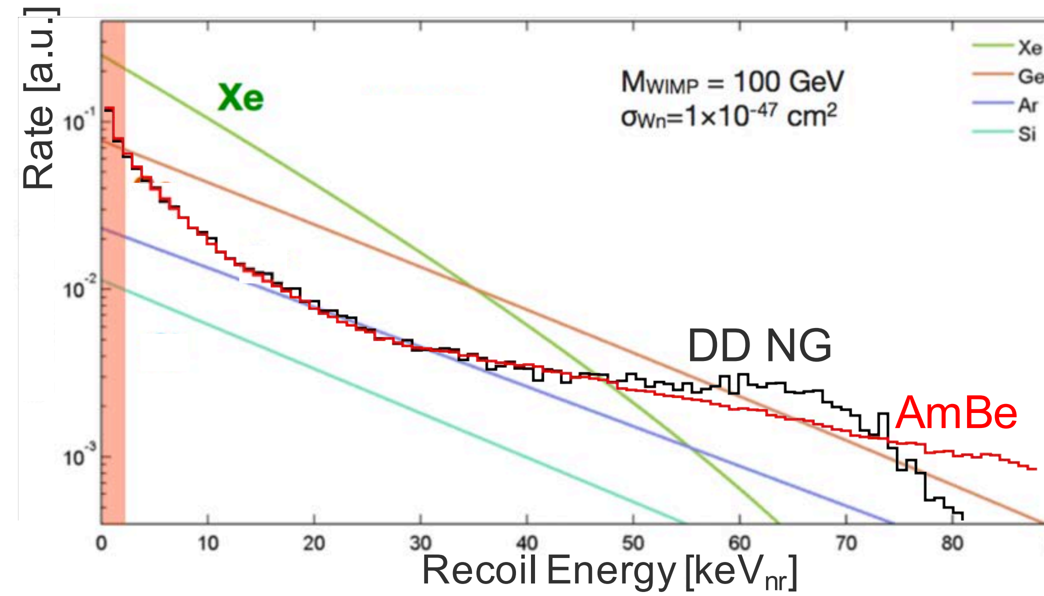




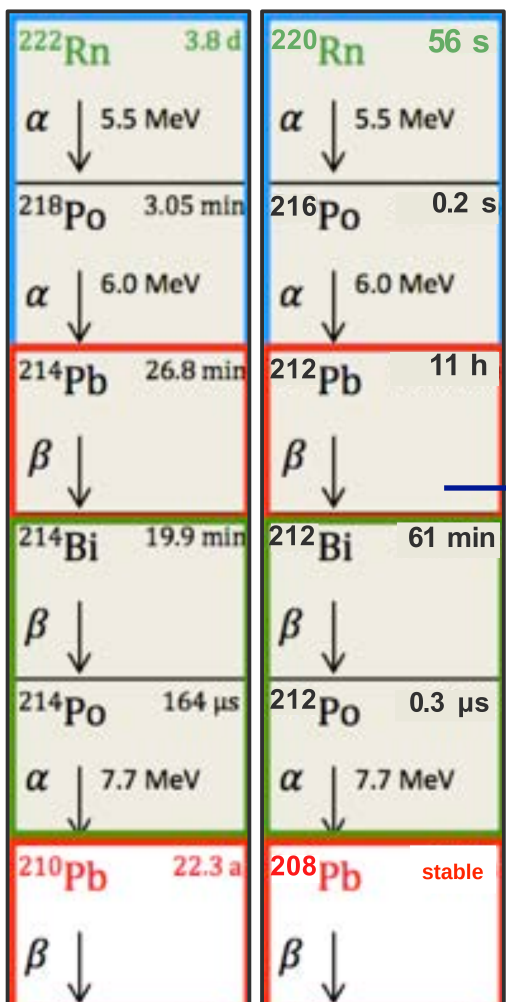
PRD 99, 112009 (2019)

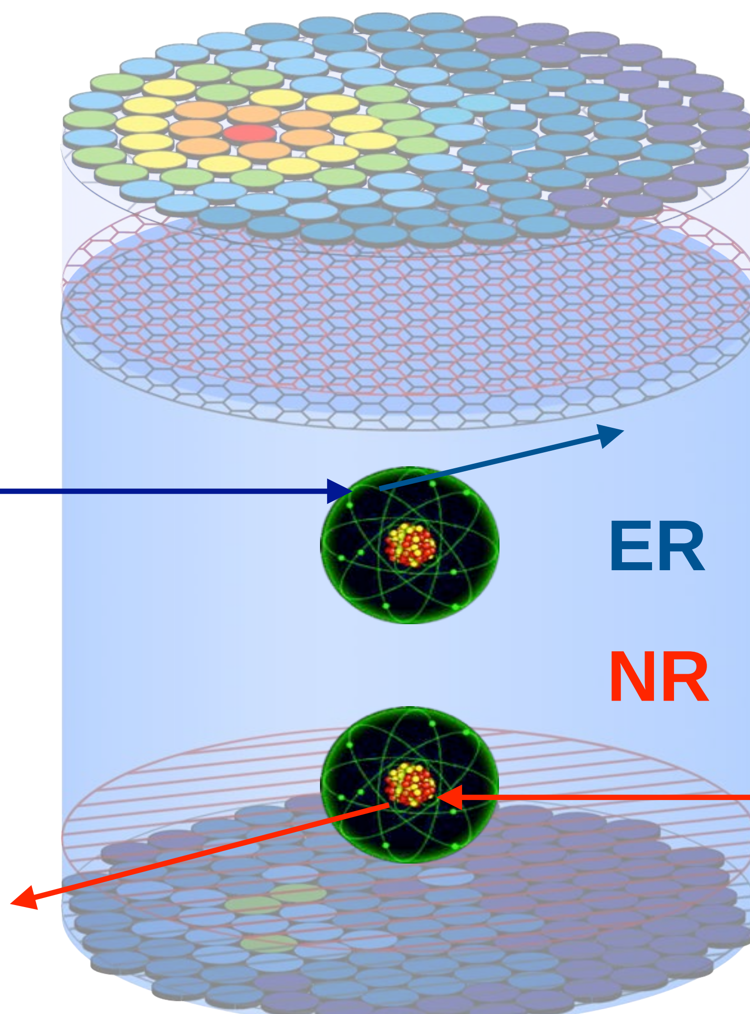
Calibrating ERs and NRs

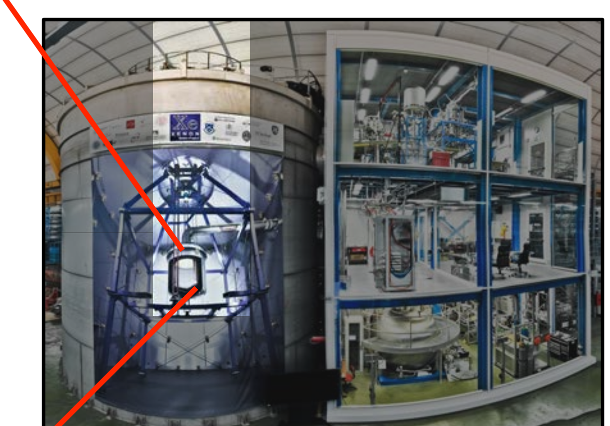




1), DD fusion neutron generator



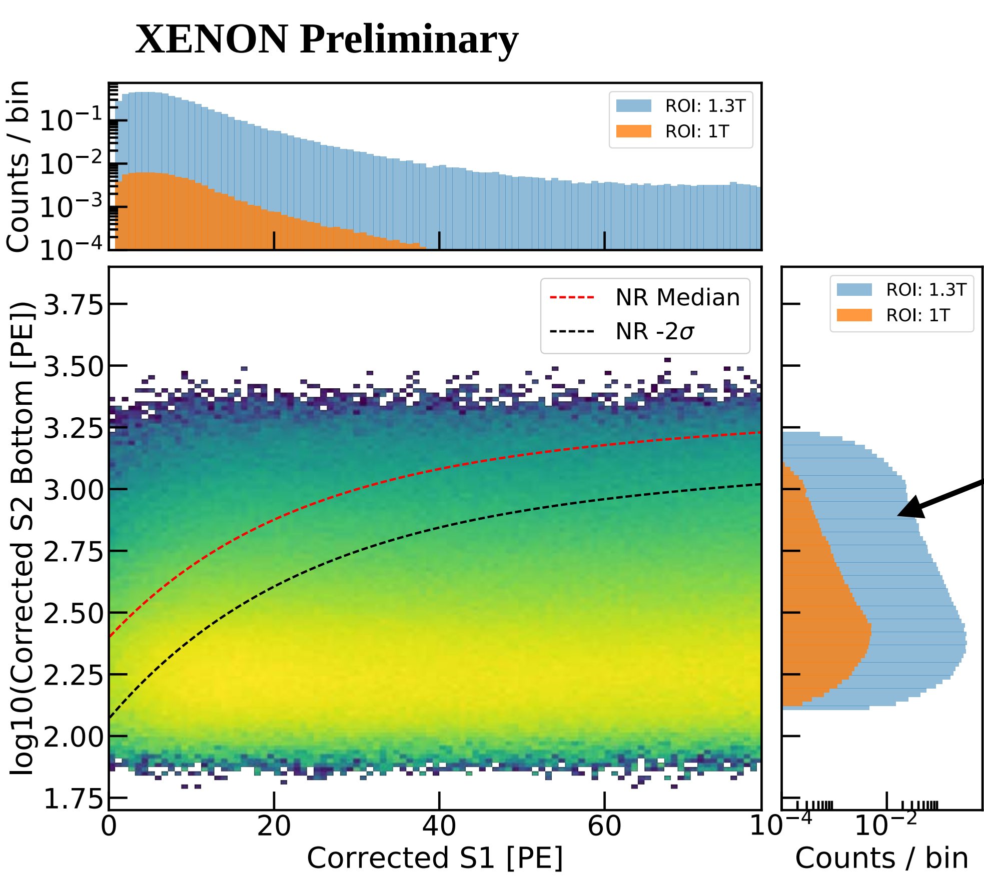


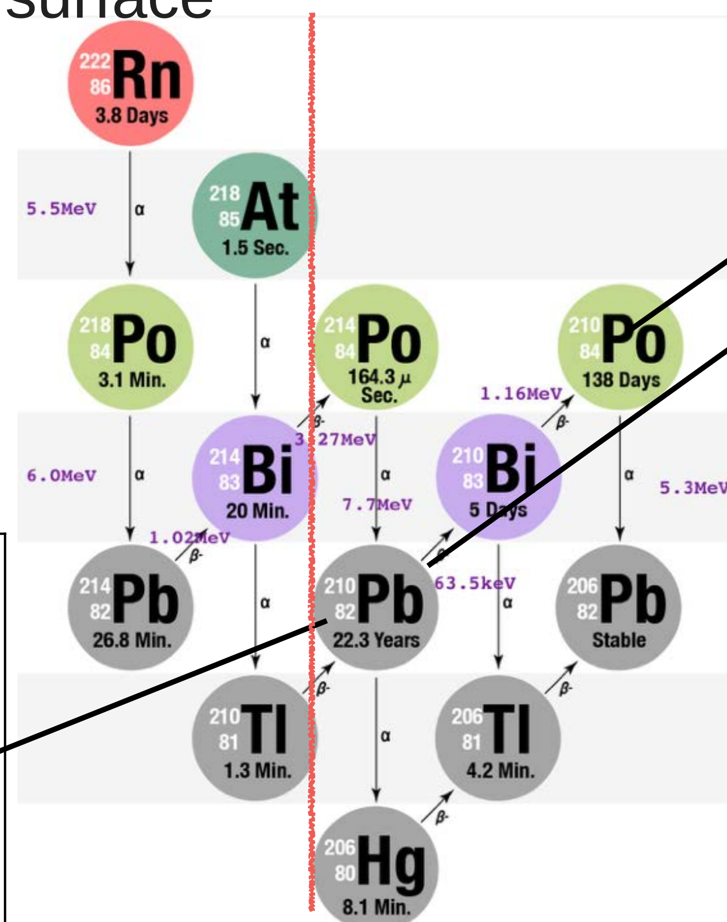


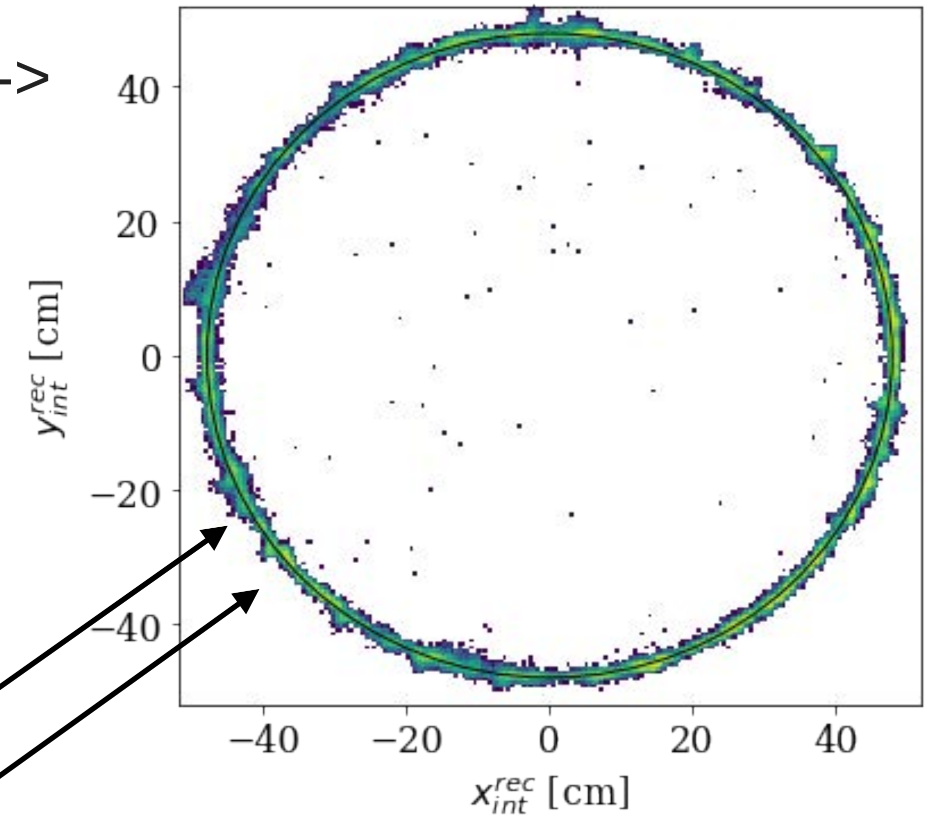
2), AmBe radioactive source

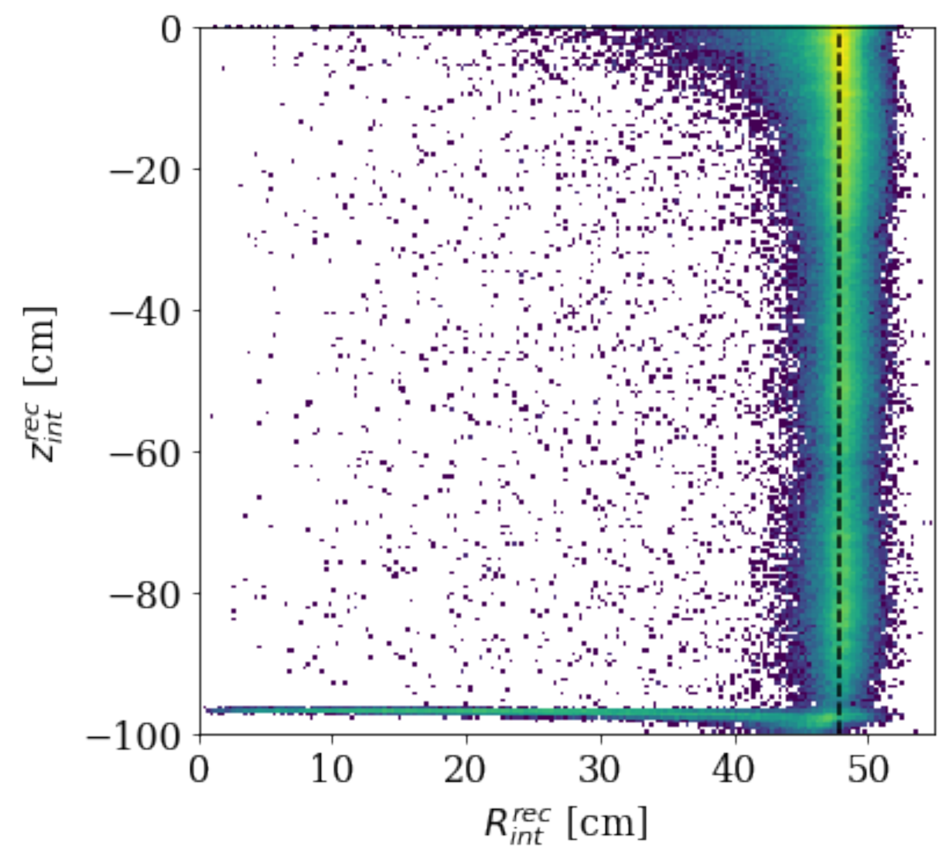
Surface Background

- ^{210}Pb and ^{210}Po plate-out on PTFE surface lose S2 charge -> can be mis-reconstructed into NR signal region
- Suppressed by fiducialization of volume
- Data-driven model derived from surface event control samples







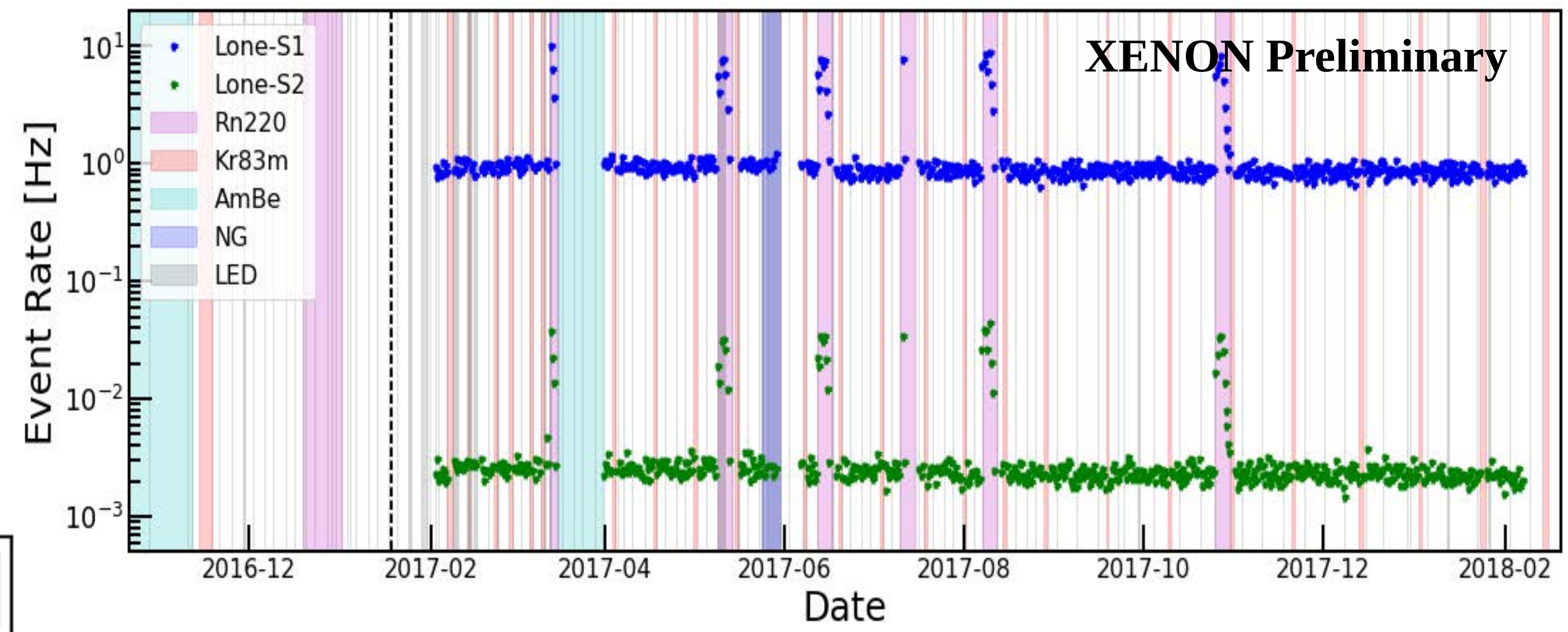


PRD 99, 112009 (2019)

Accidental Coincidence Background

"Lone" s1 and s2 accidental coincidences

- S1 from eg. below cathode
- S2 from eg. near field grids



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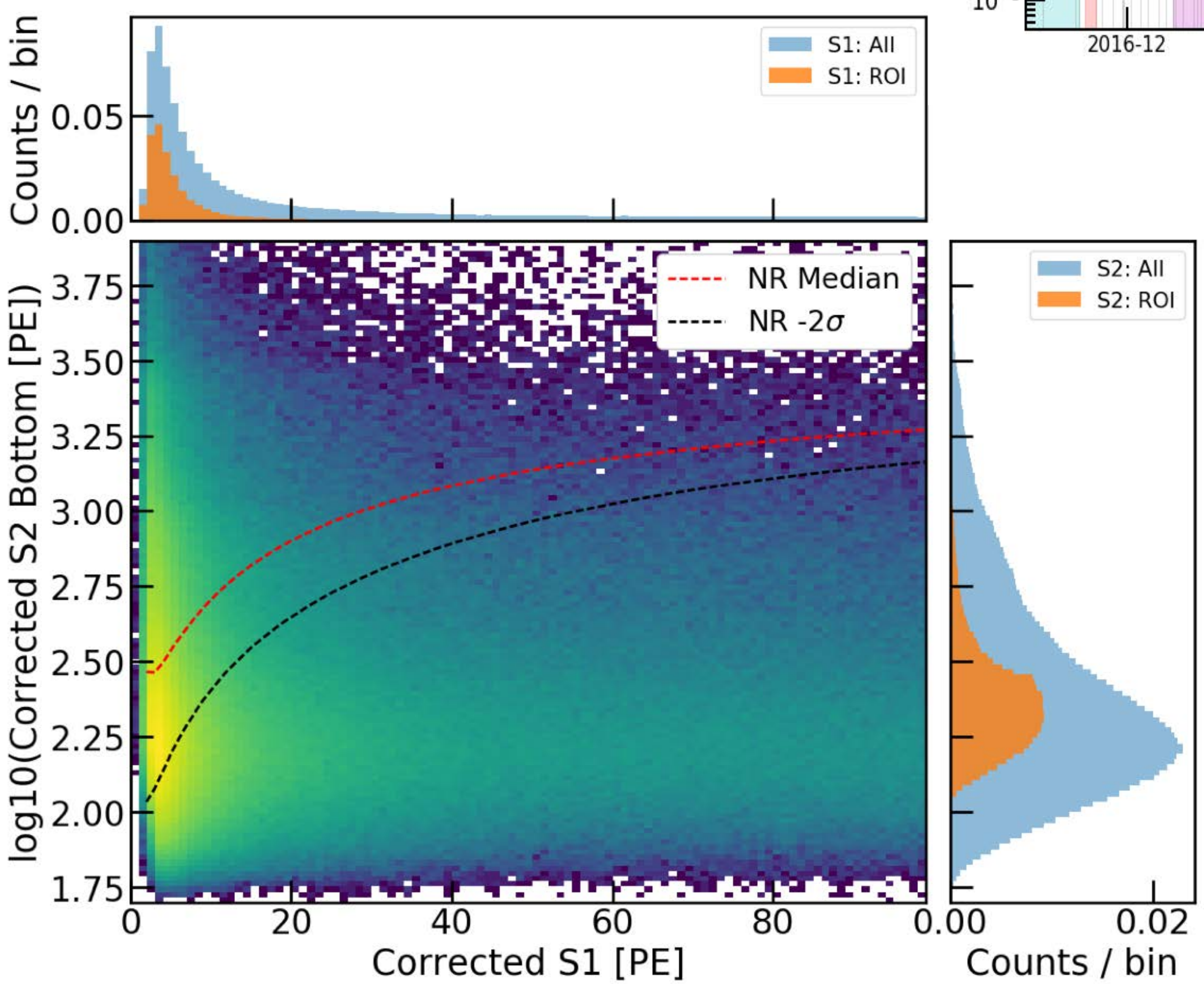


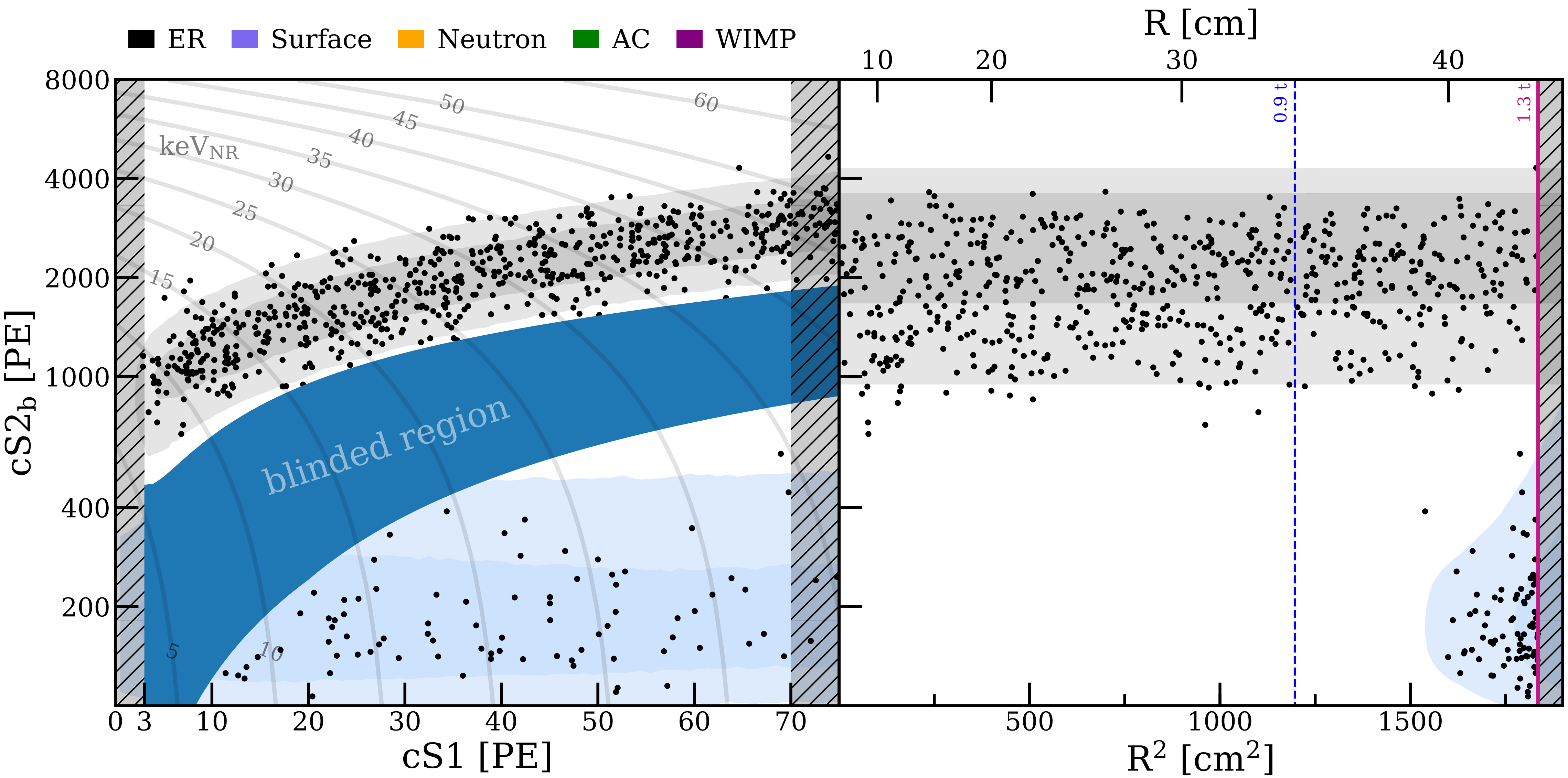
Model Procedure:

- Randomly pair S1/S2 to form events
- Suppressed with Machine Learning technique
- Performance verified in ^{220}Rn data and background sidebands

Background Prediction

All models derived in 3D space: (S1, S2, R, Z) including rate predictions while DM search data is blinded

Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02
Accidental	$0.5^{+0.3}_{-0.0}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4	0.02
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2



Unblinding and Results

Pie charts indicate fractions of the PDF from the best-fit of assuming 200 GeV/c² WIMPs with a cross-section of 4.7 x 10^{-47} cm²

Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
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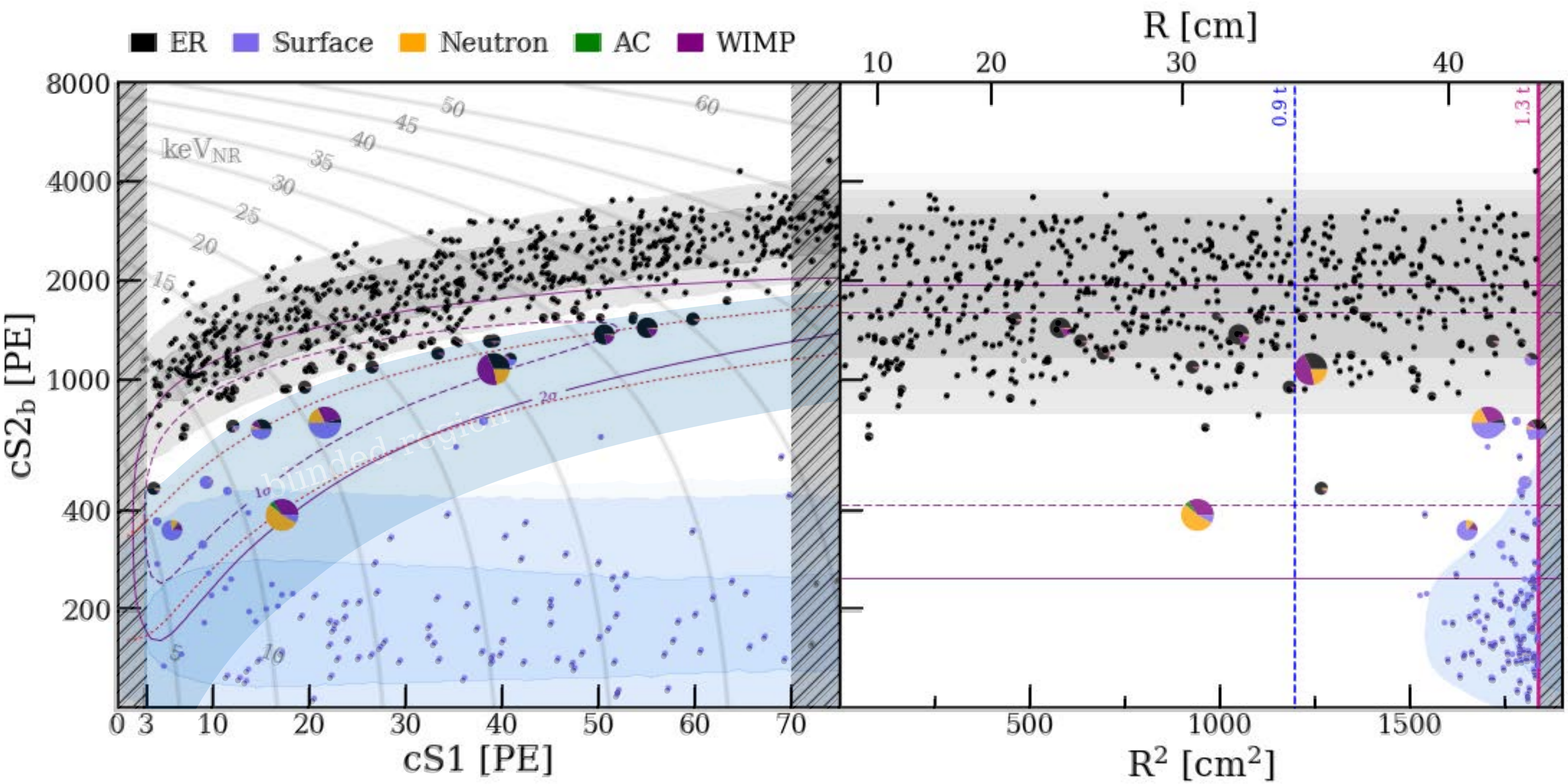
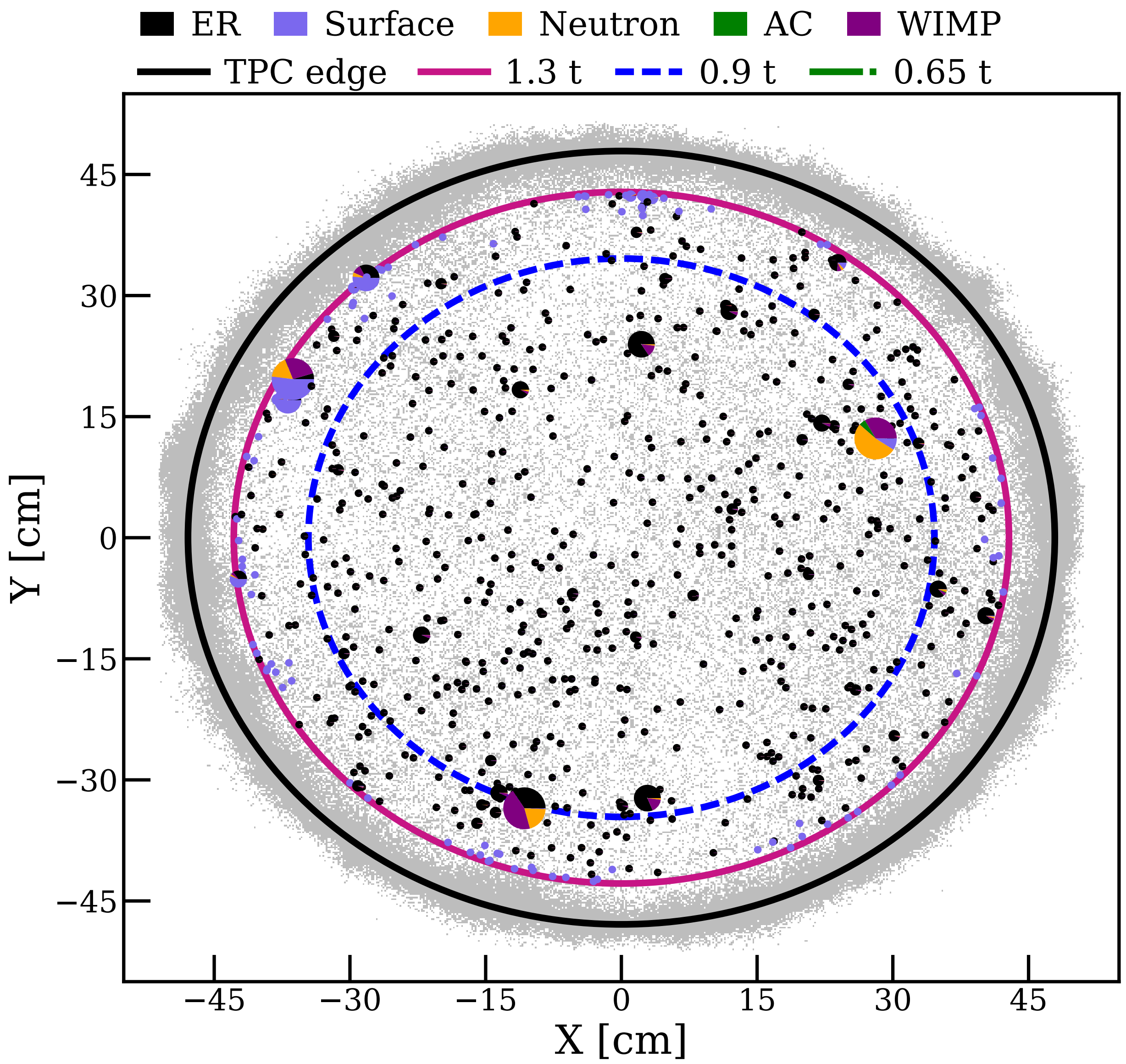
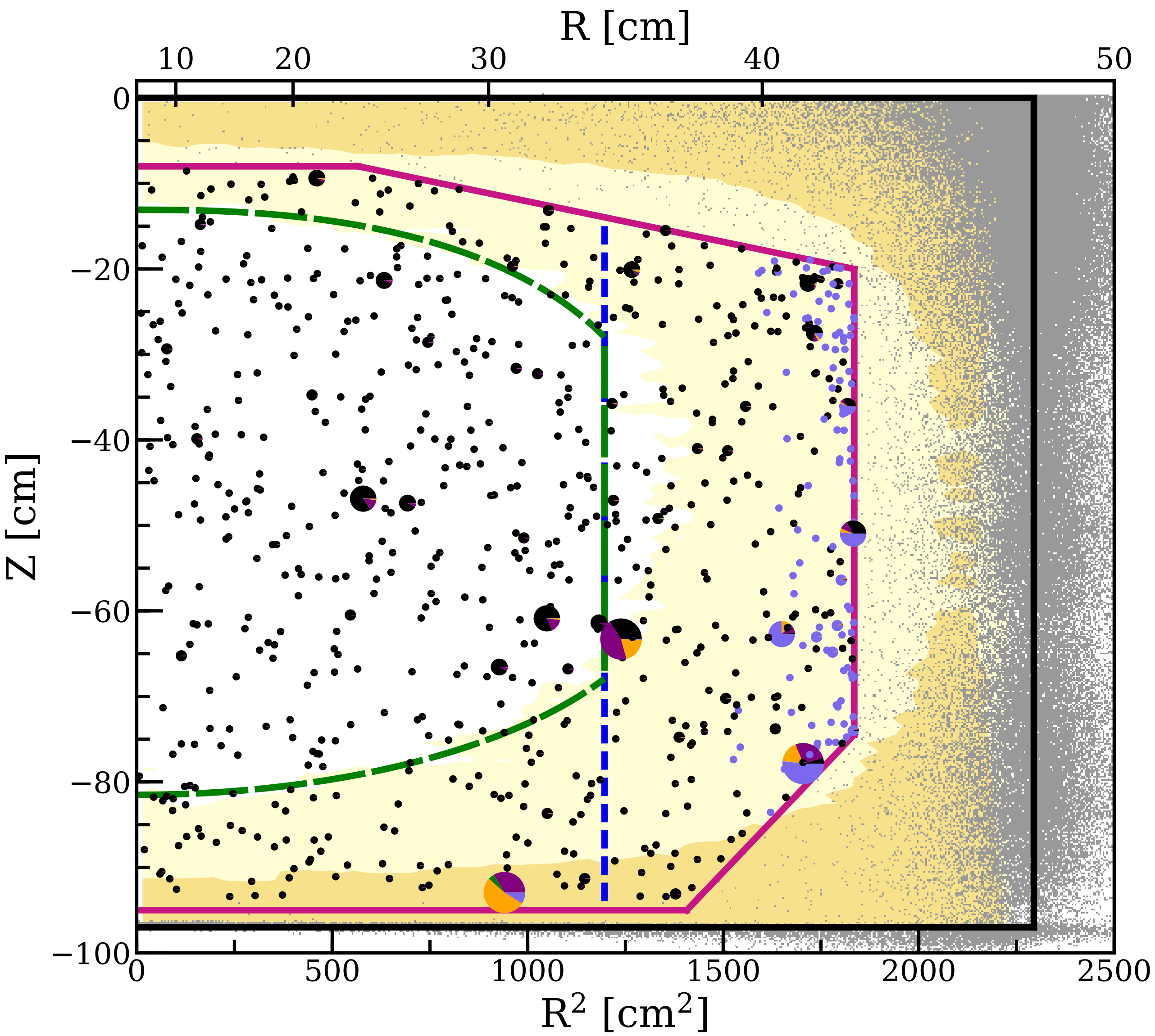
Surface	106 ± 8	4.8 ± 0.4	0.02
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2
Data	**739**	**14**	**2**



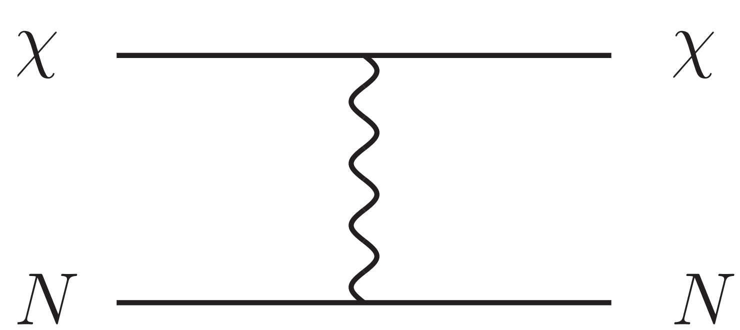
Spatial Distribution of Dark Matter Search Data

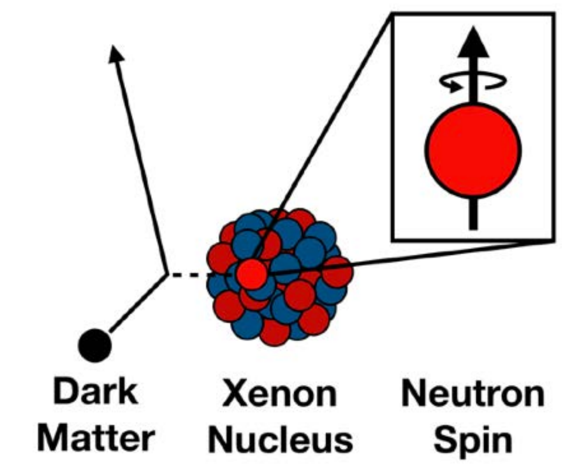
- Results interpreted with unbinned profile likelihood analysis in cS1, cS2, r space
- **Core volume** to distinguish WIMPs over neutron background



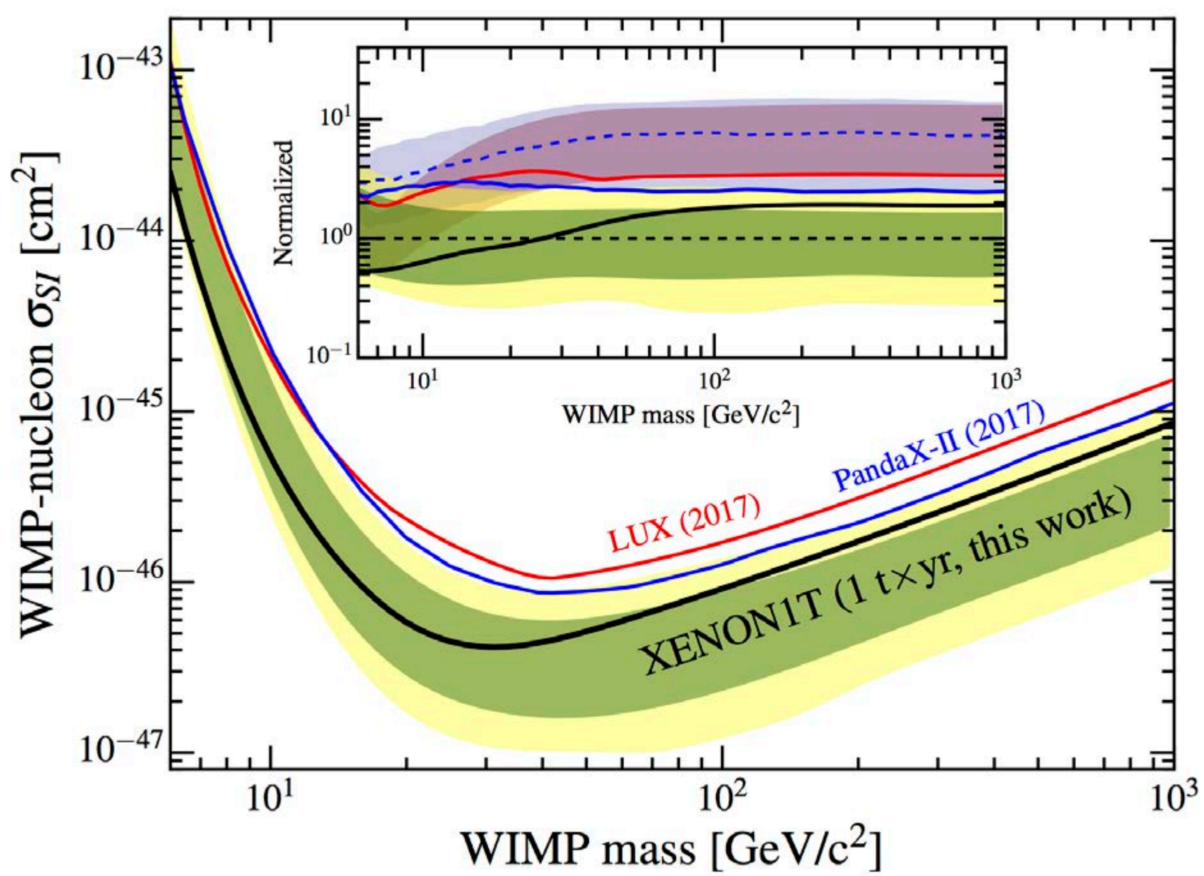


Constraints on WIMP interactions



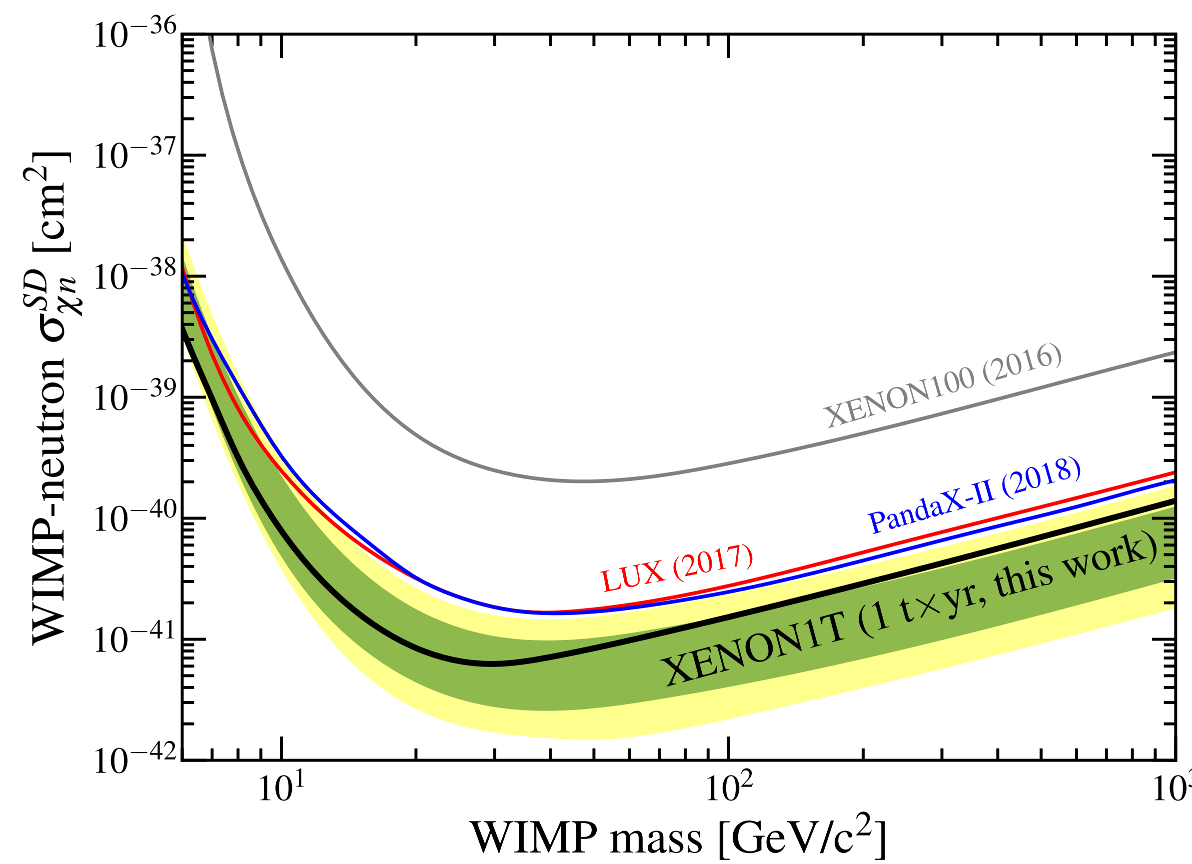


Phys. Rev. Lett. 121, 111302 (2018)



σ < 4.1 x 10^{-47} cm^2 at 30 GeV/c^2

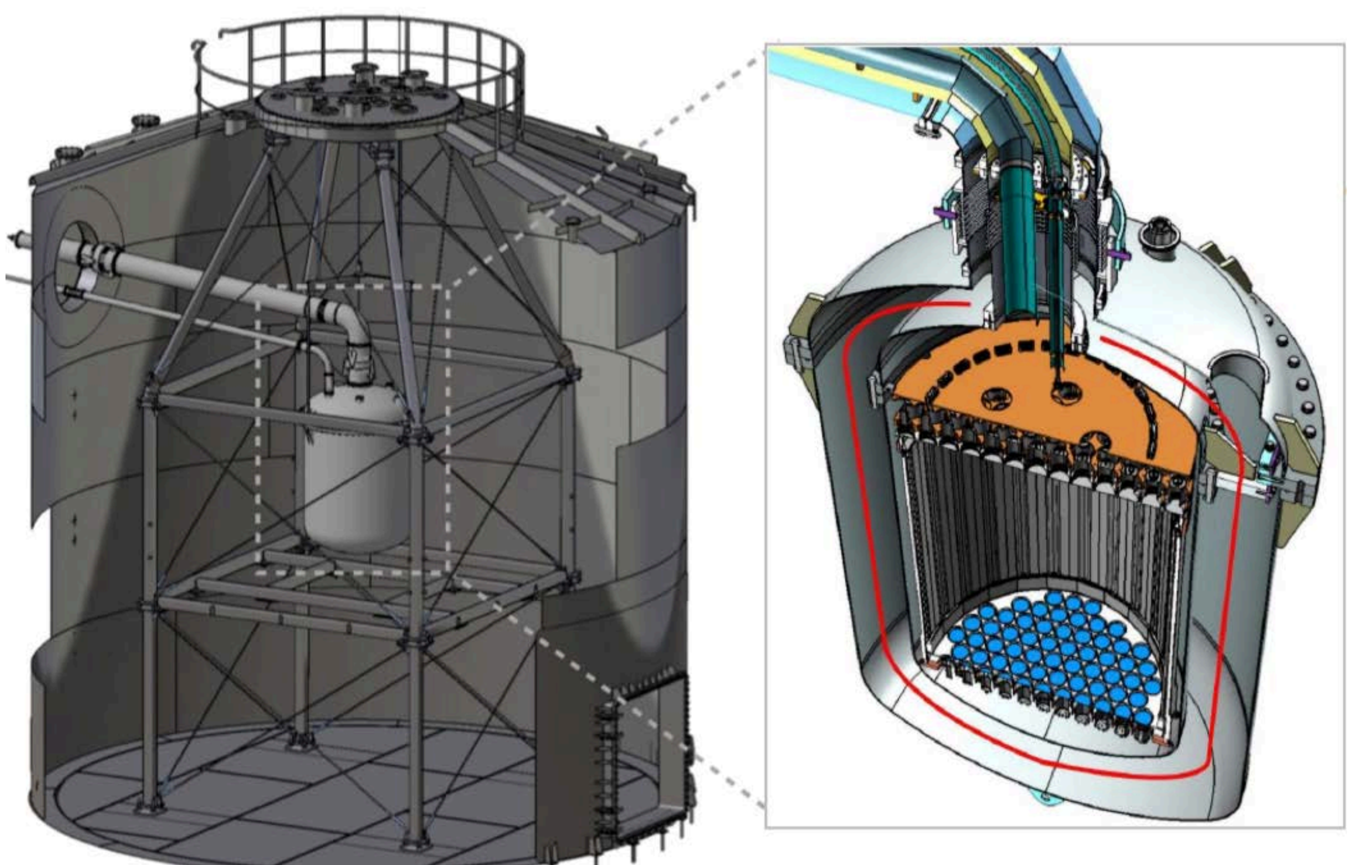
Phys. Rev. Lett. 122, 141301 (2019)

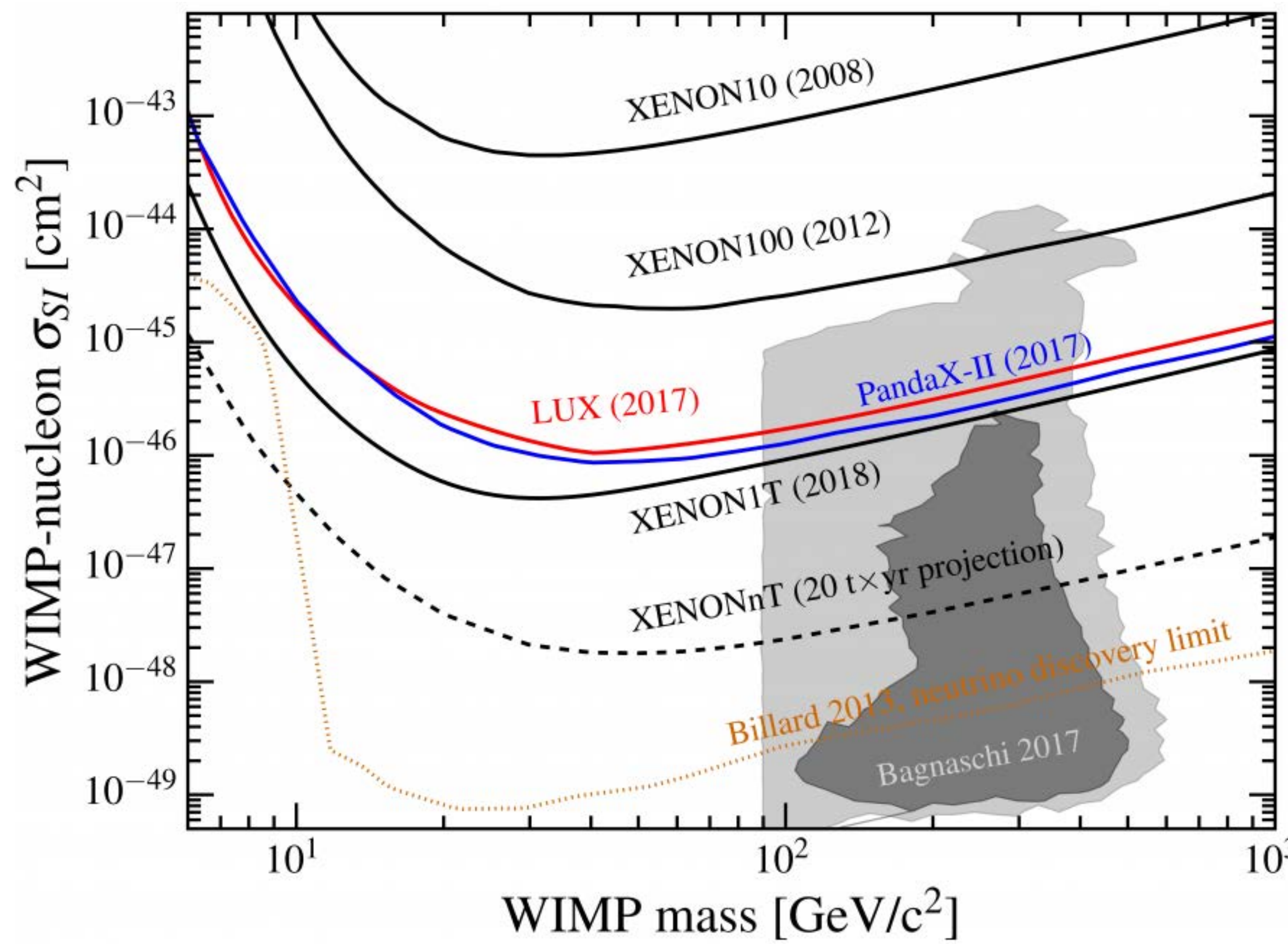


σ< 46.3 x 10^{-42} cm^2 at 30 GeV/c^2

The Next Step - XENONnT

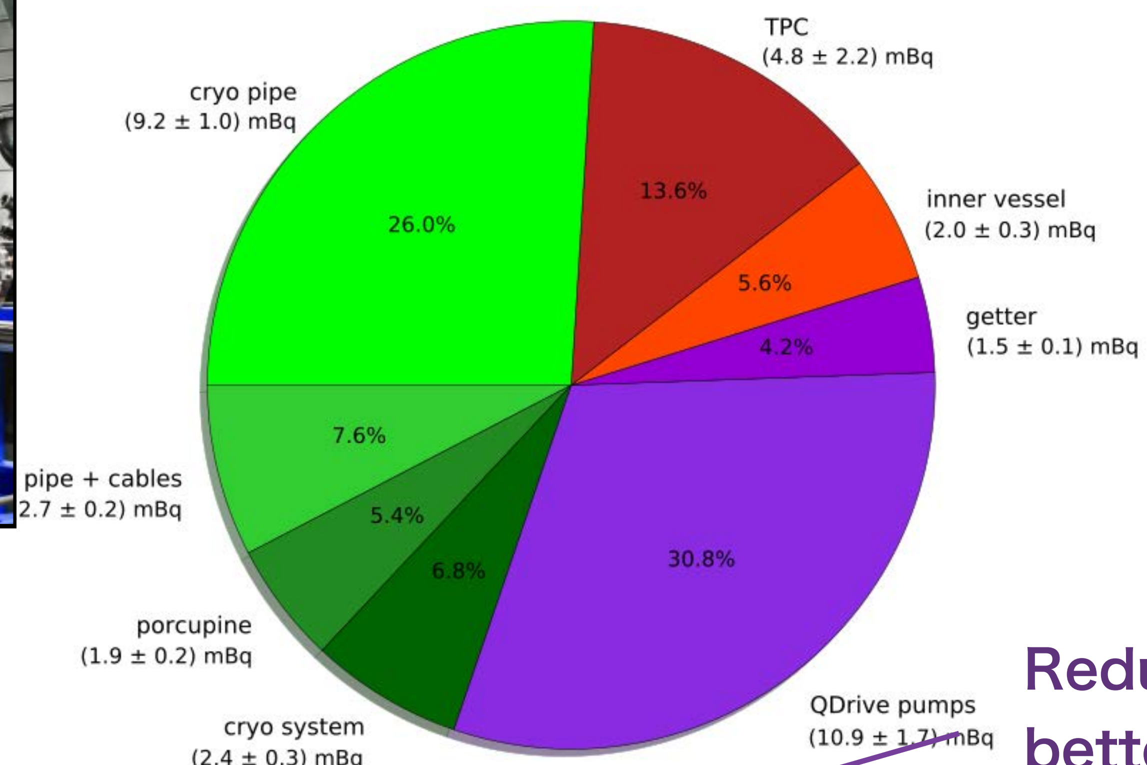
- 6t of LXe as sensitive WIMPs target, fiducial mass of > 4t
- ^{222}Rn background reduction of 10
- Neutron tagging with active neutron veto system
- Cryogenic liquid purification to reach > ms electron lifetime “promptly”
- Start commissioning in 2019, science data in 2020





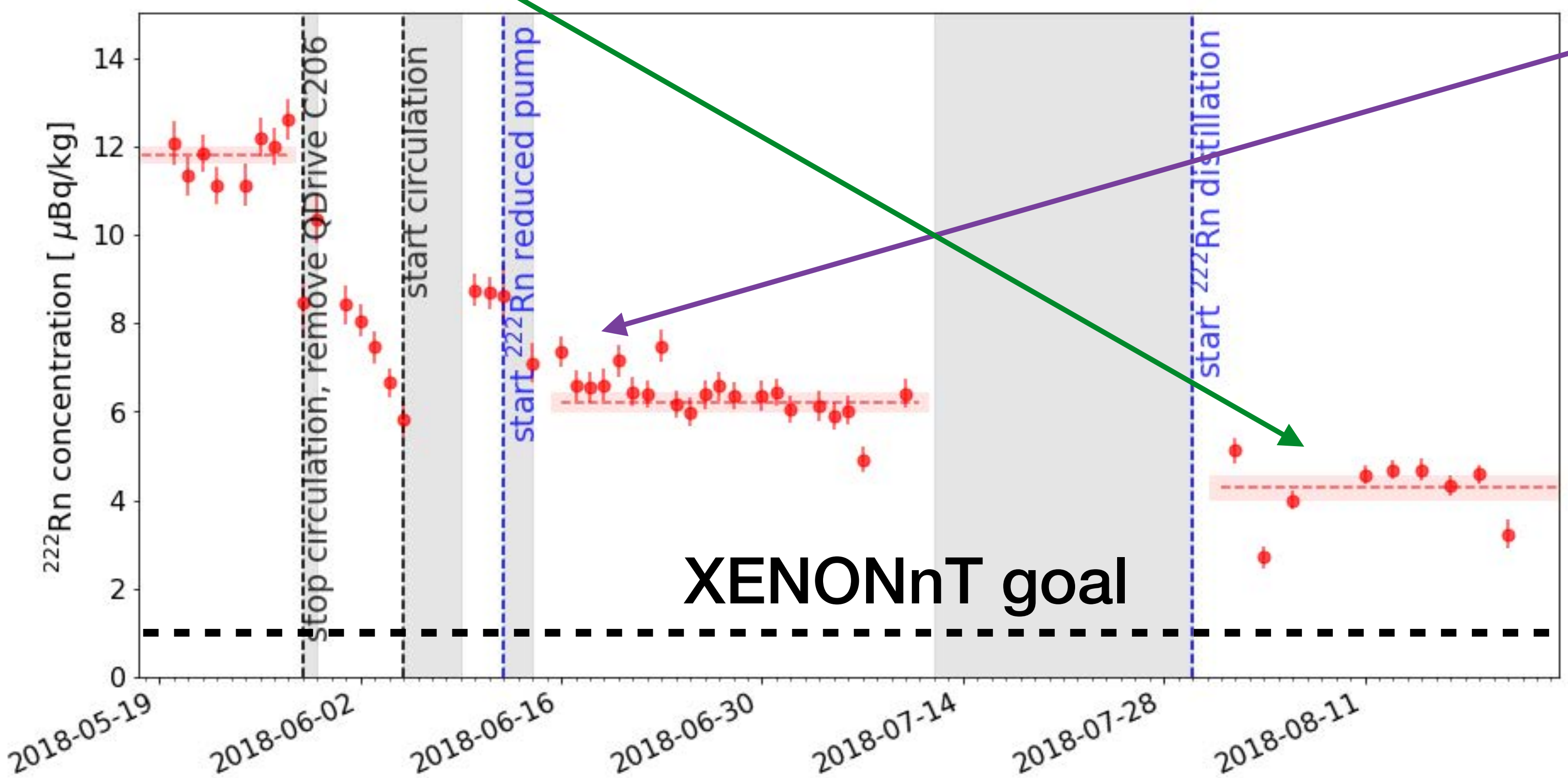
Radon Reduction in XENON1T/nT

Rn budget in XENON1T

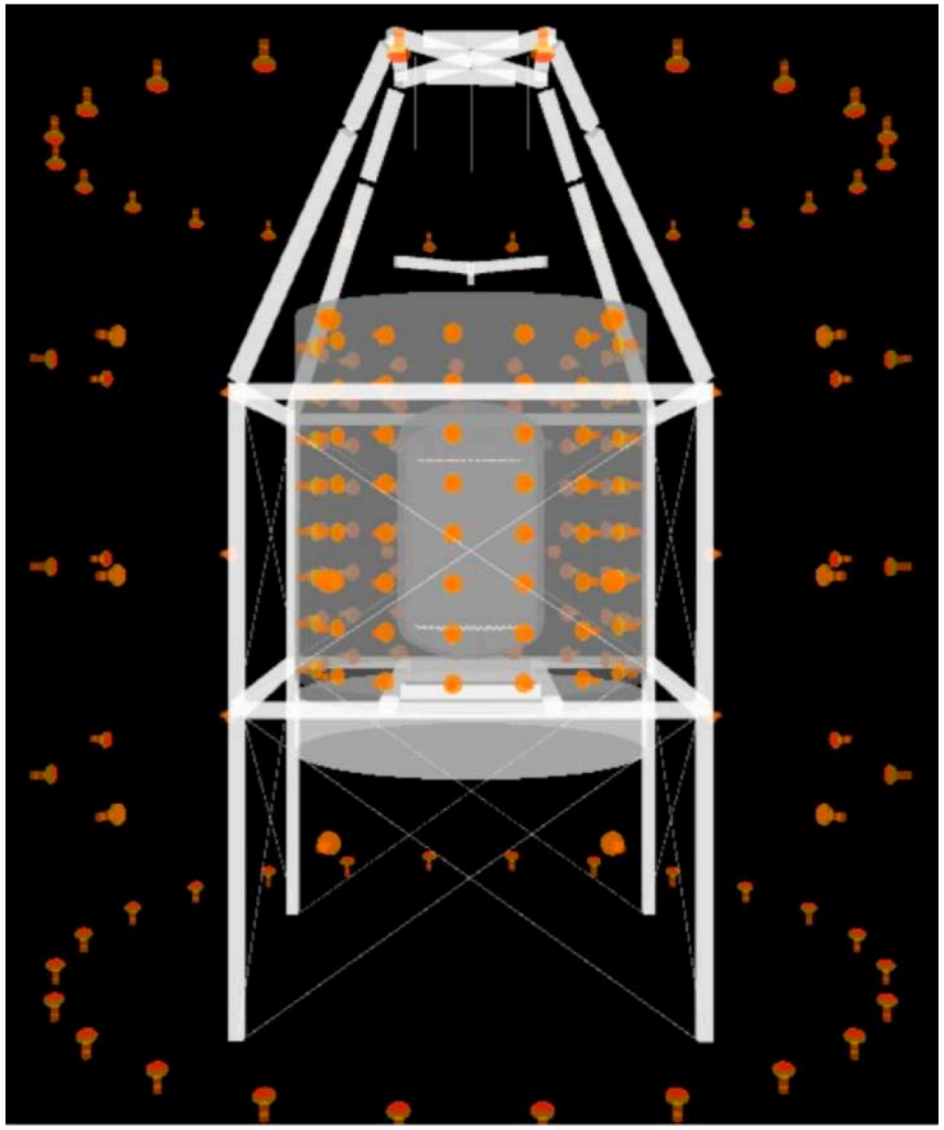


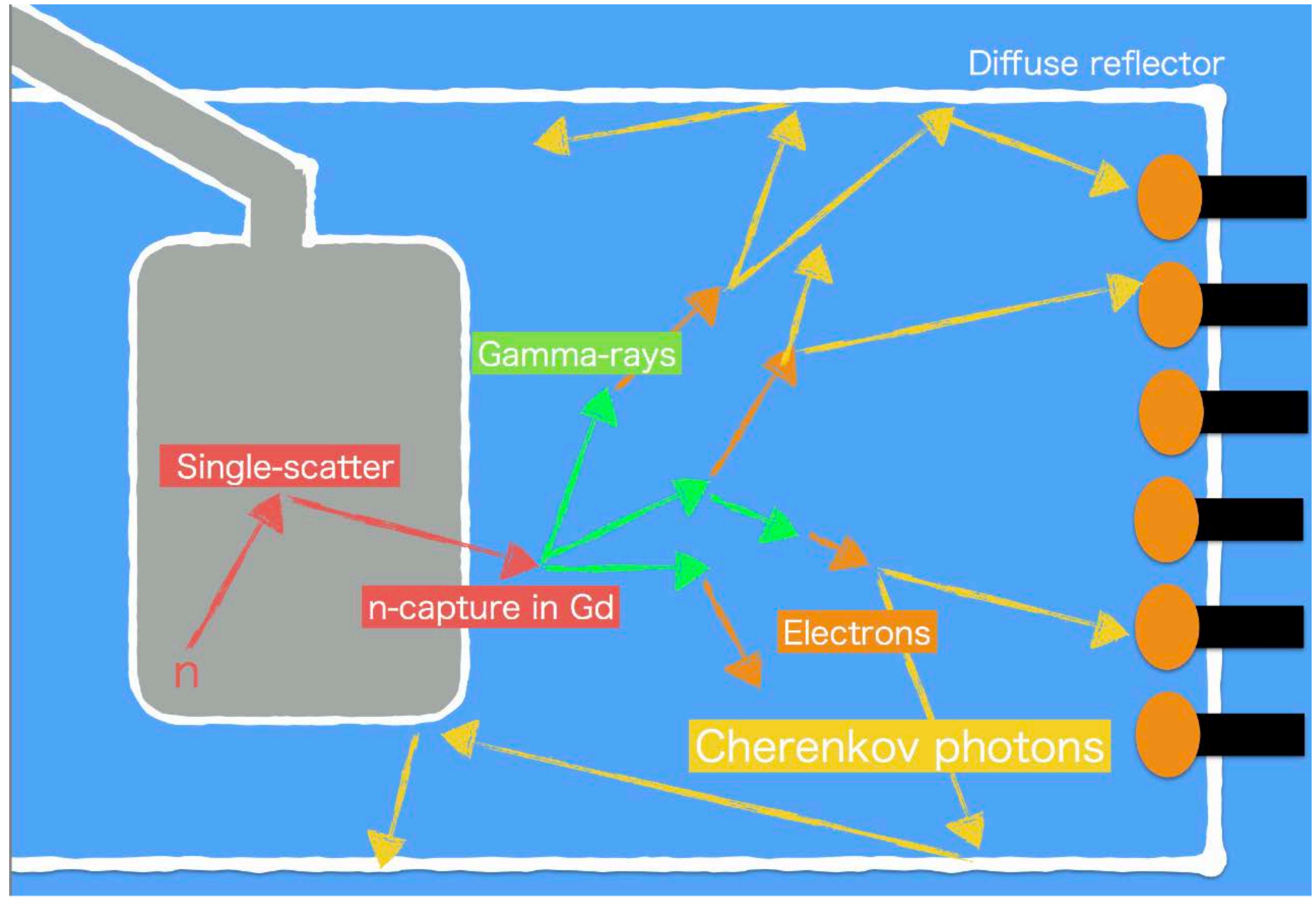
Reduced with online distillation

Reduced with better pump



XENONnT Neutron Veto





- Gd-Water Cherenkov veto detection is going to be deployed as neutron veto
- >85% tagging efficiency is expected.
- Reduce neutron background to be < 1 events / (20 tonne year)

Other physics opportunities in XENON1T/nT

- **light (< 6GeV) Dark Matter Searches**
  - **S2-only analysis**
  - **Electronic recoils (Migdal effect)**

- **Annual modulation**

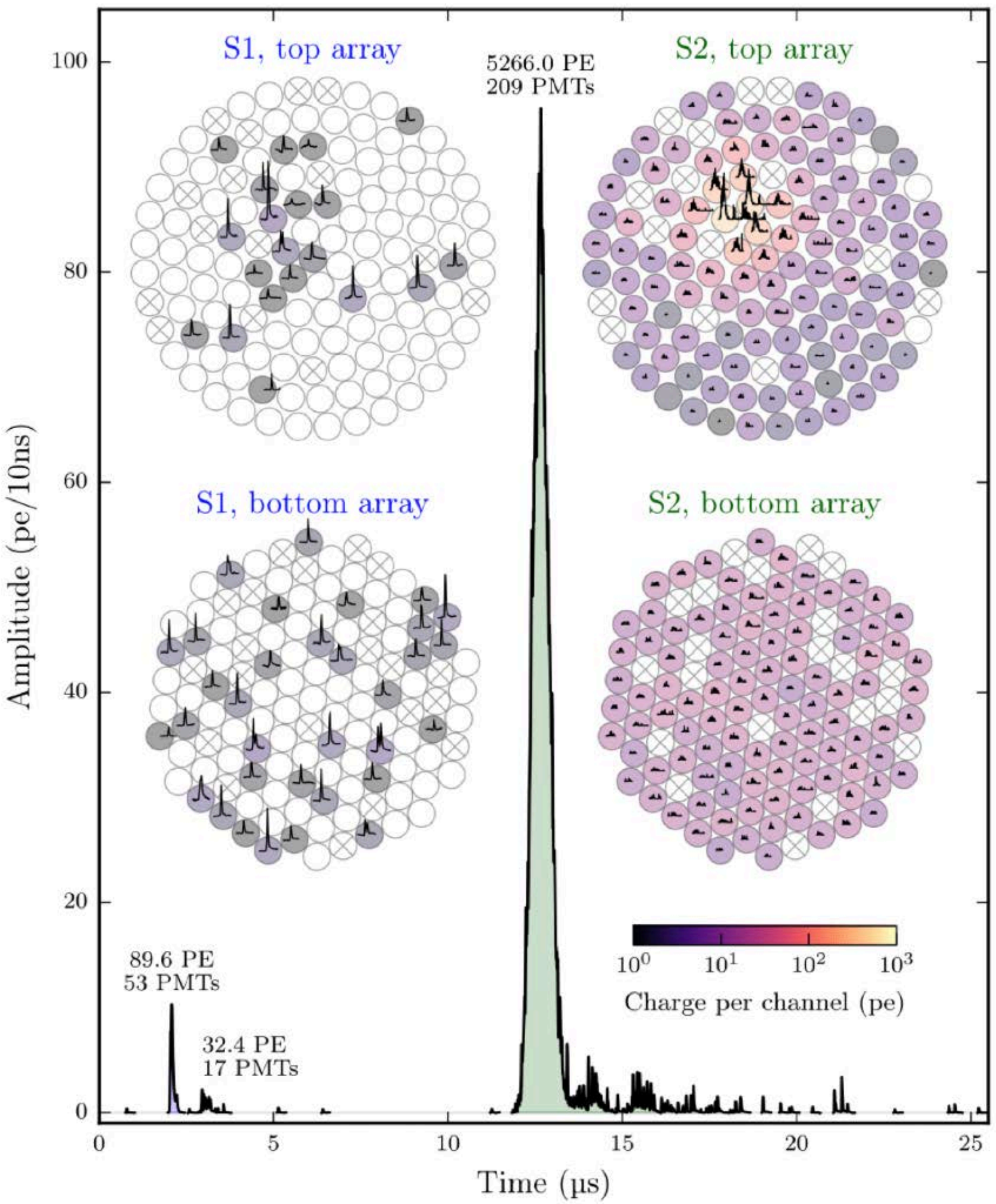
- **Double beta decay searches**
  - **2-neutrino double electron capture of Xe124**
  - **0-neutrino double beta decay of Xe136**

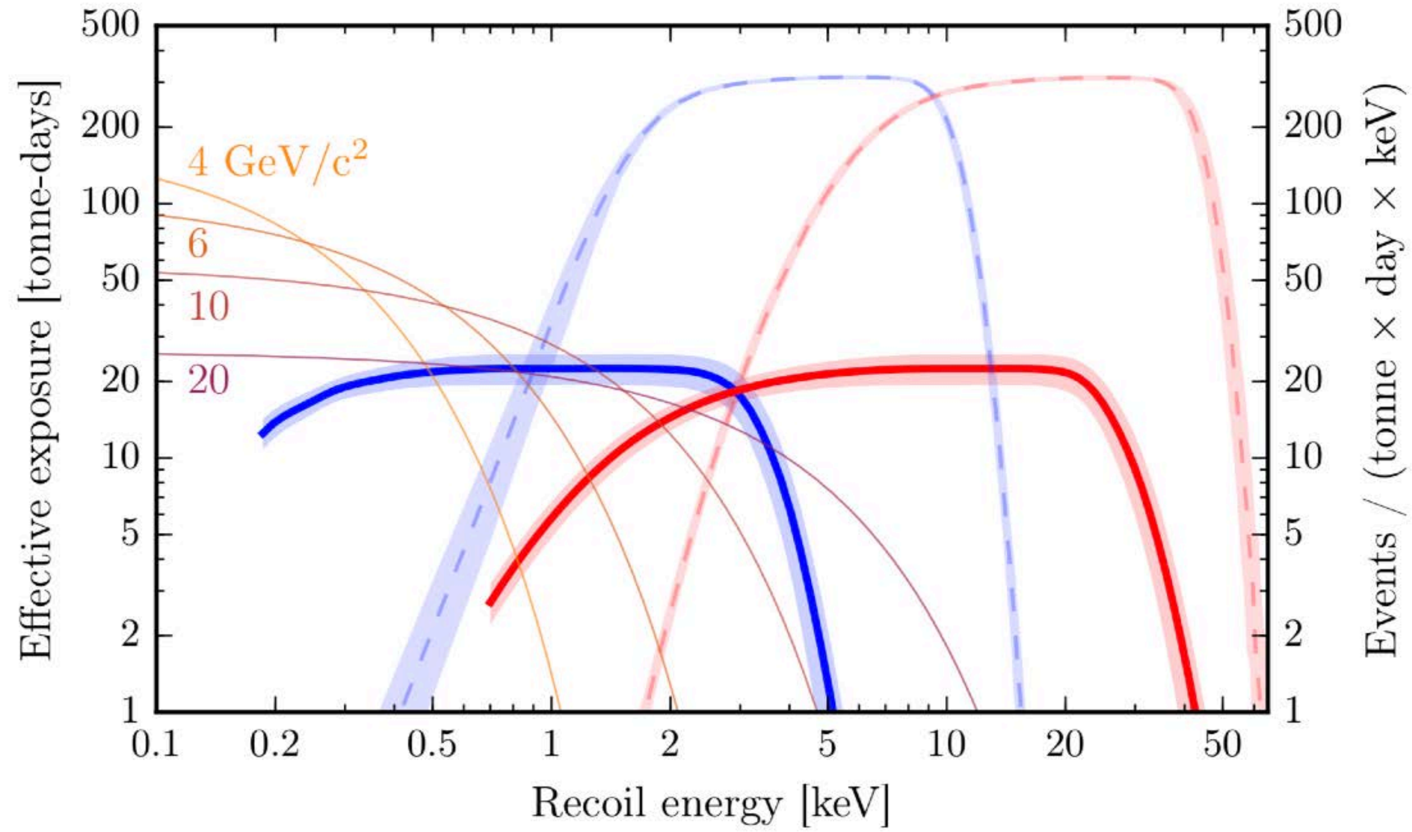
- **Search for Axion, Dark Photons**
  - Mono-Energetic lines from Axions, DP
  - Solar Axion, solar DP…

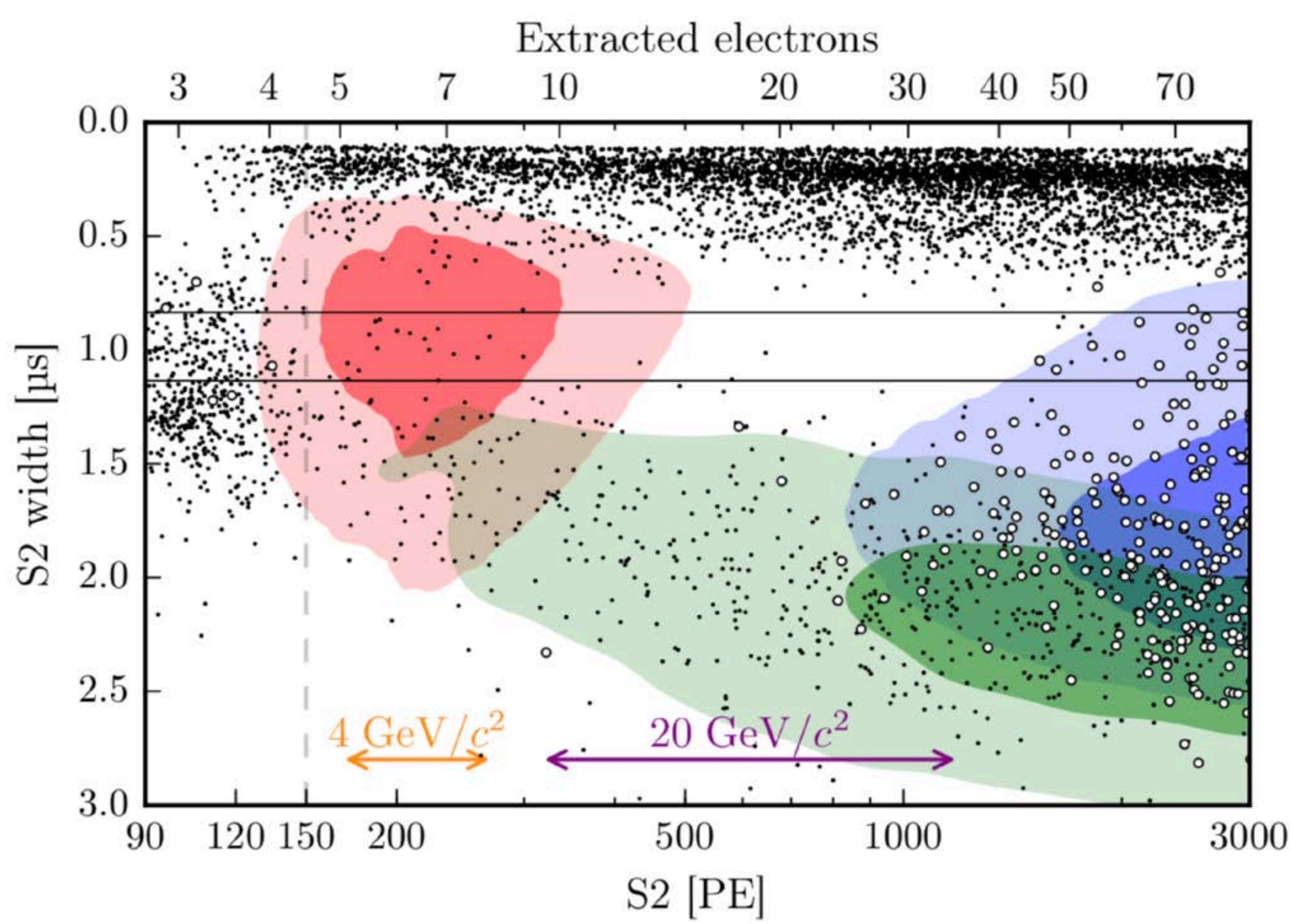
………

Lower the energy threshold: S2-only

Fig. credits to J. Aalber

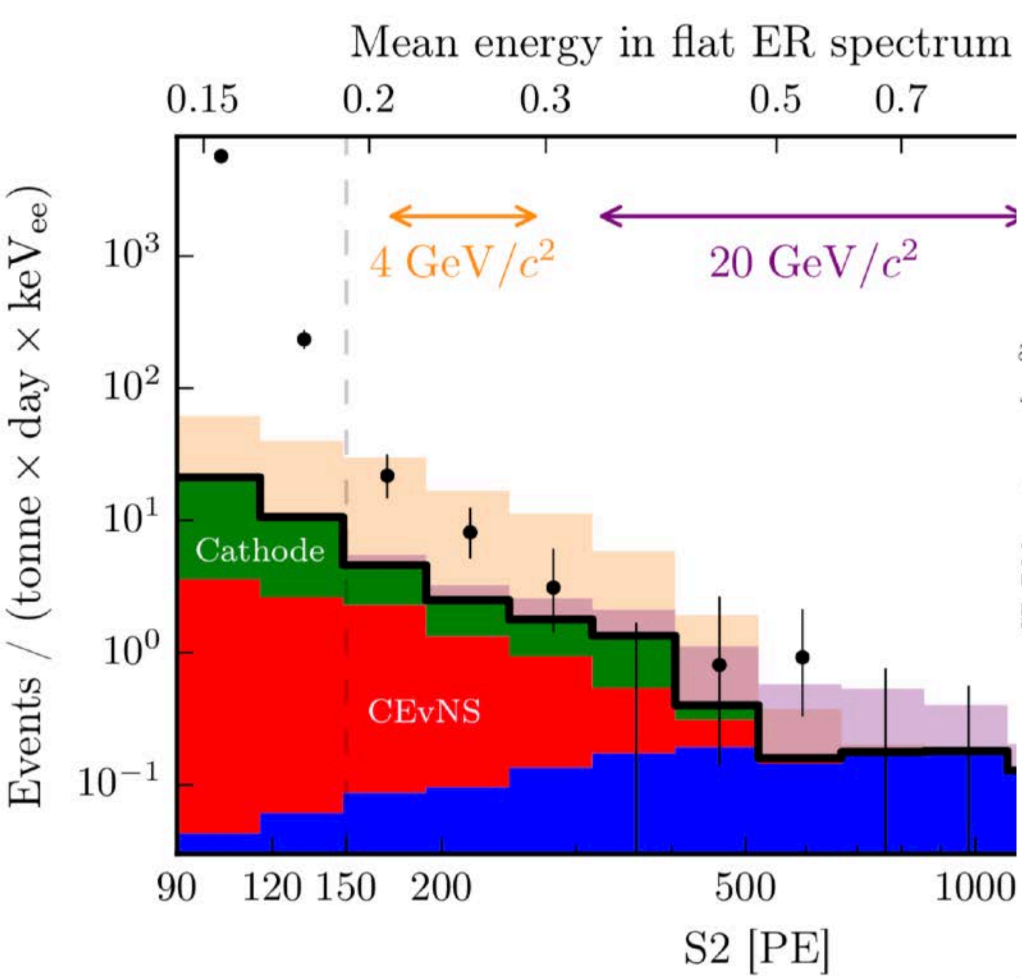


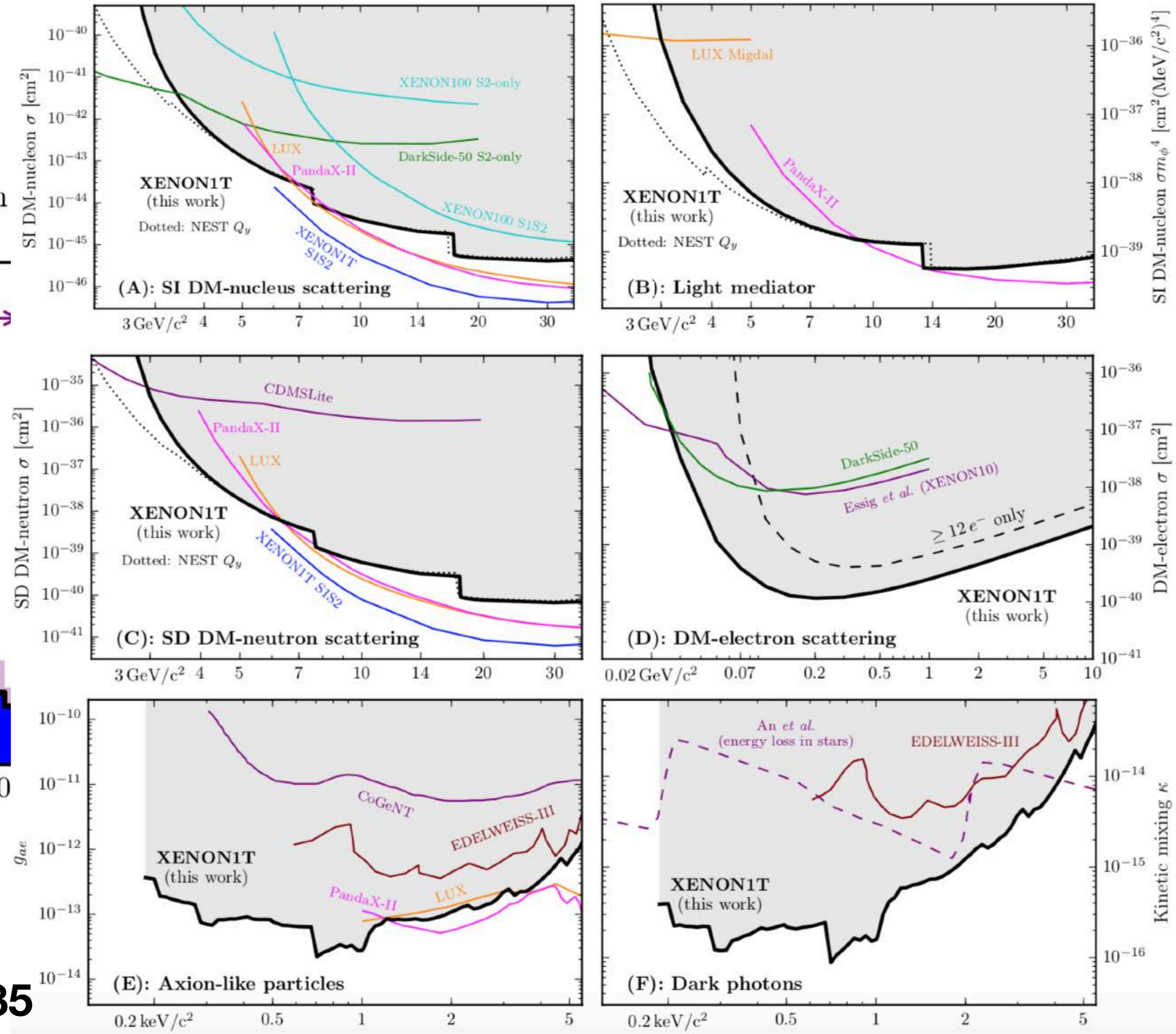




XENON1T, arXiv:1907.11485

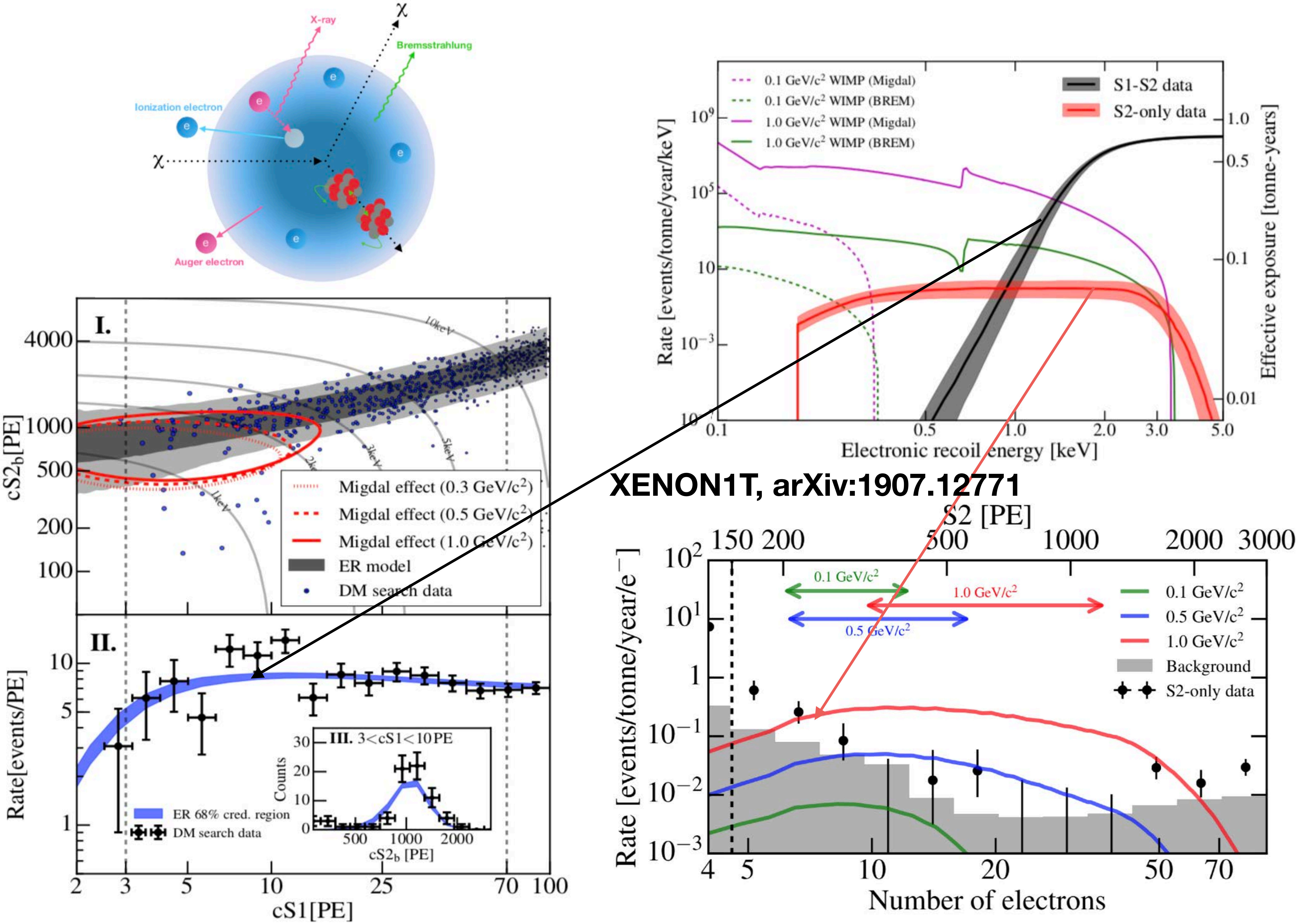
Lower the energy threshold: S2-only





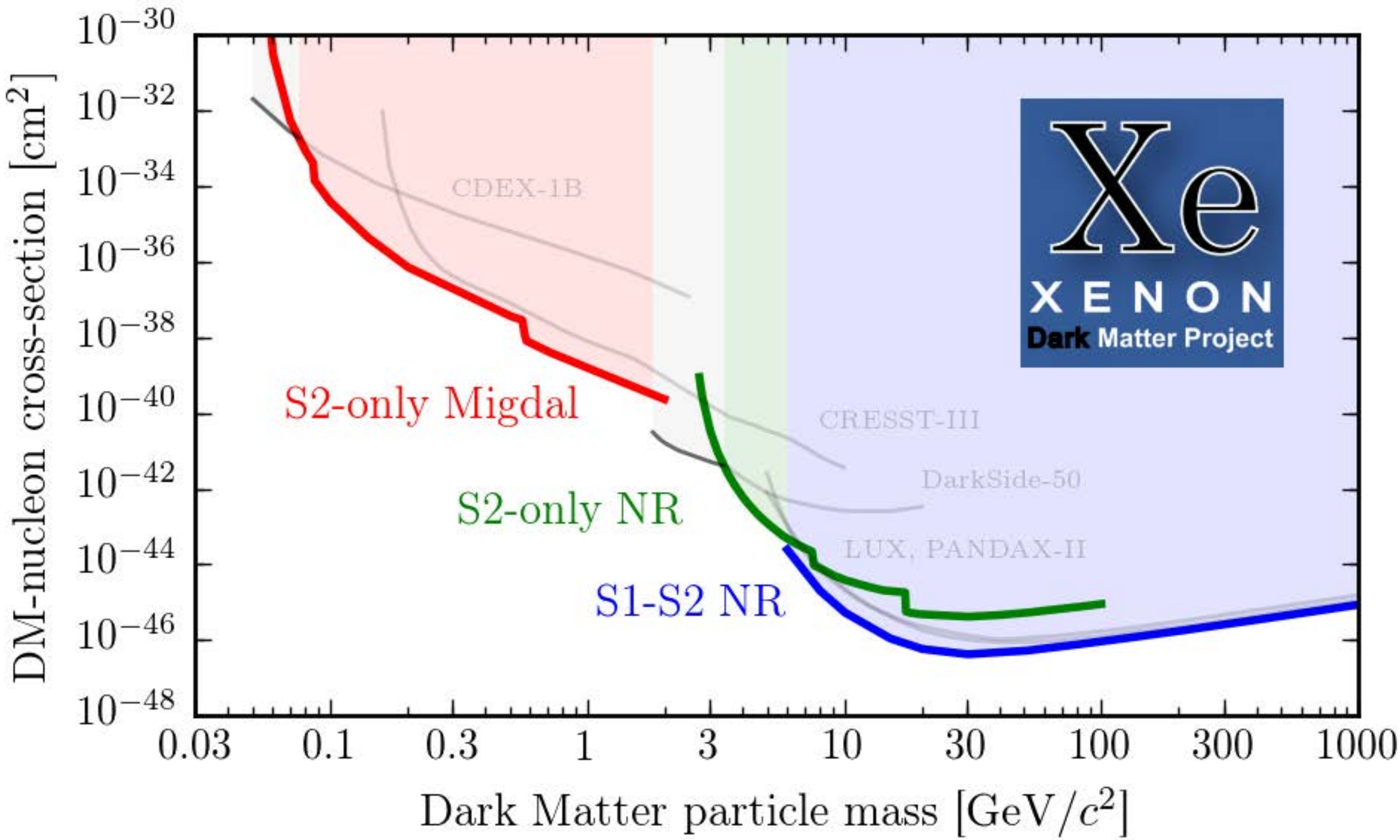
XENON1T, arXiv:1907.11485

Even lighter? — Migdal / Bremsstrahlung Effect



XENON1T, arXiv:1907.12771

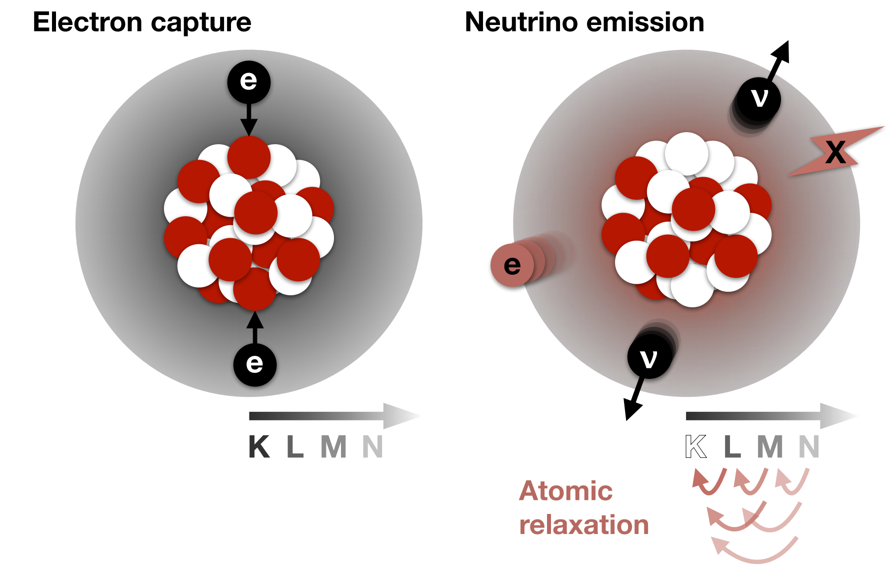
The current WIMPs landscape



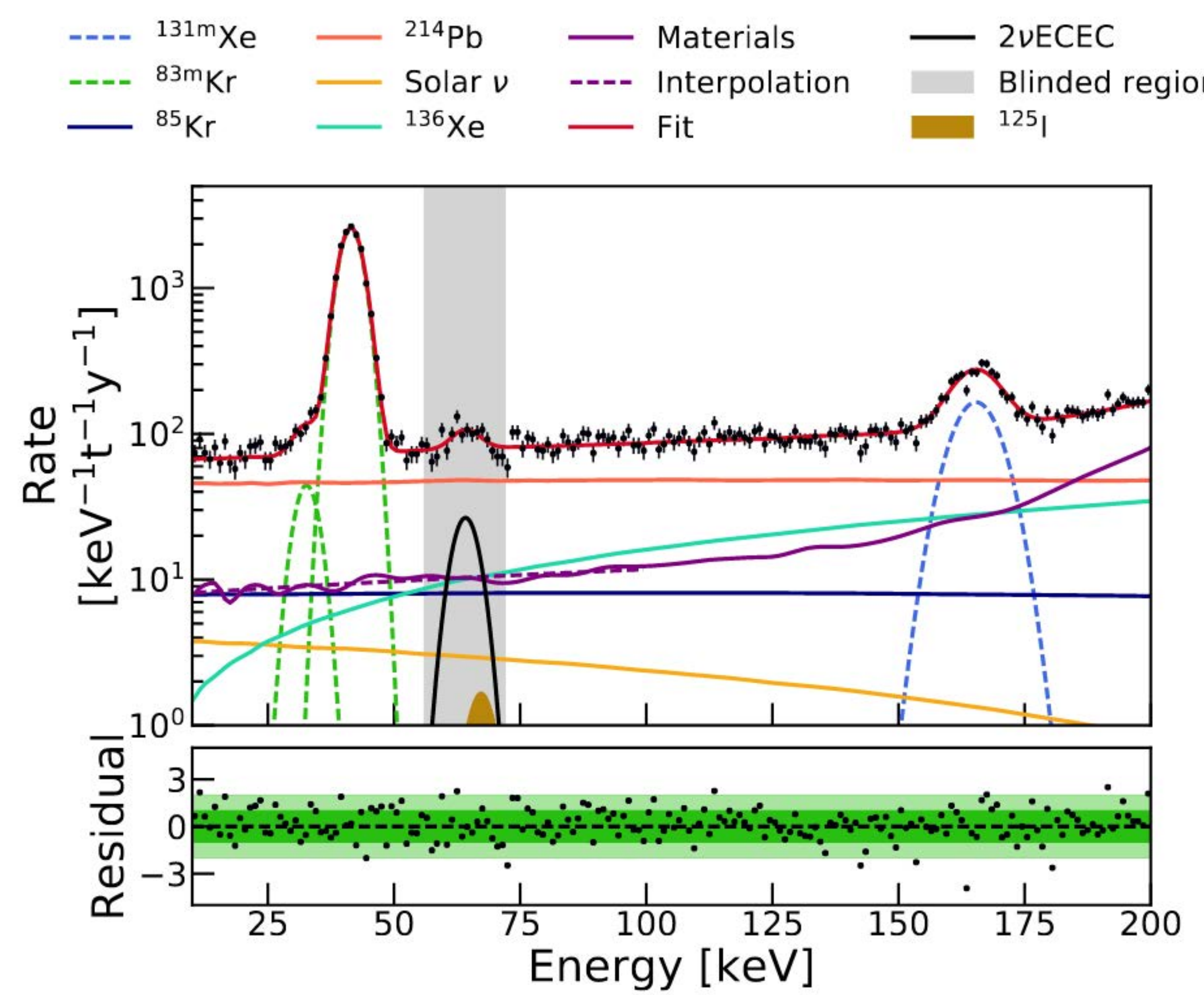
XENON1T, arXiv:1907.11485, arXiv:1907.12771

Observation of two-neutrino double electron capture in Xe-124 with XENON1T

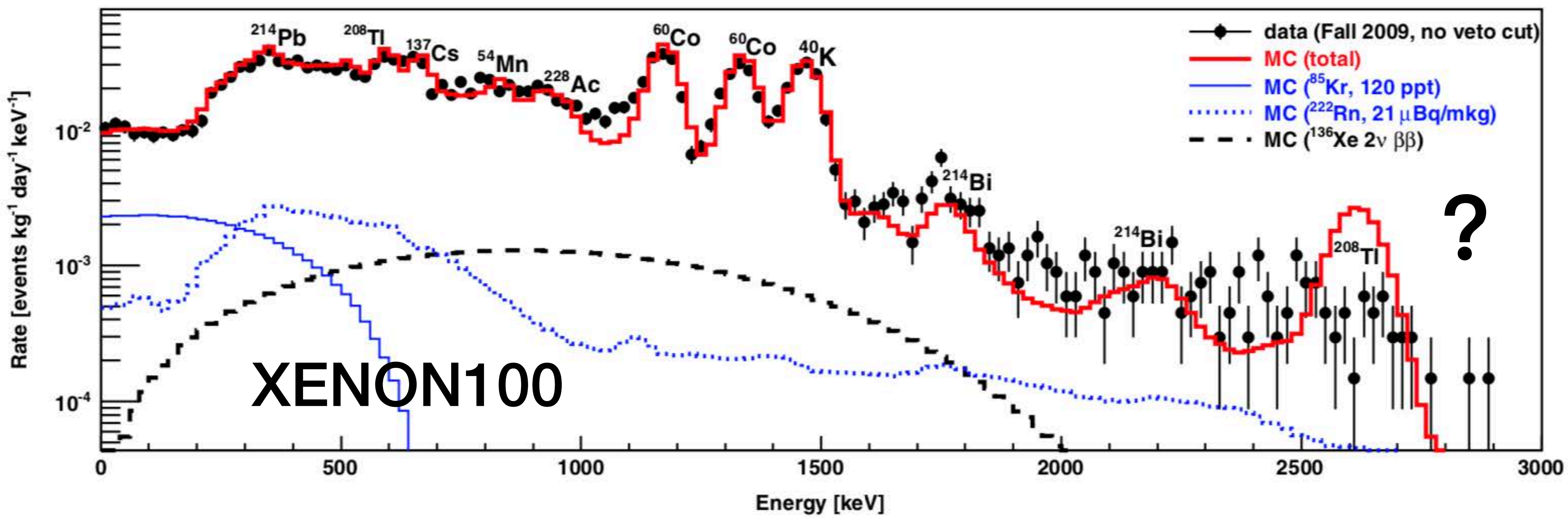
Half-life $T_{1/2}^{2\nu ECEC} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y



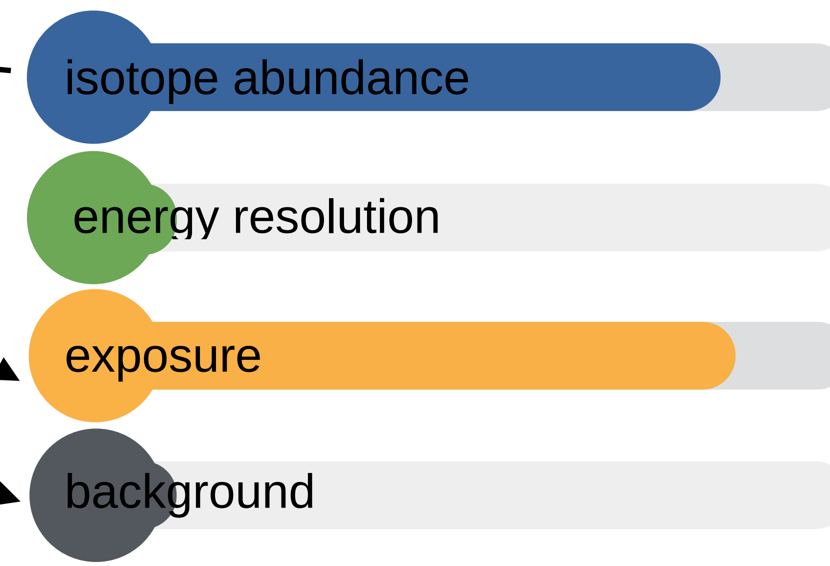
$^{124}Xe + 2e^{-} \rightarrow {}^{124}Te + 2\nu_e$



Challenge for a simultaneous 0vbb search

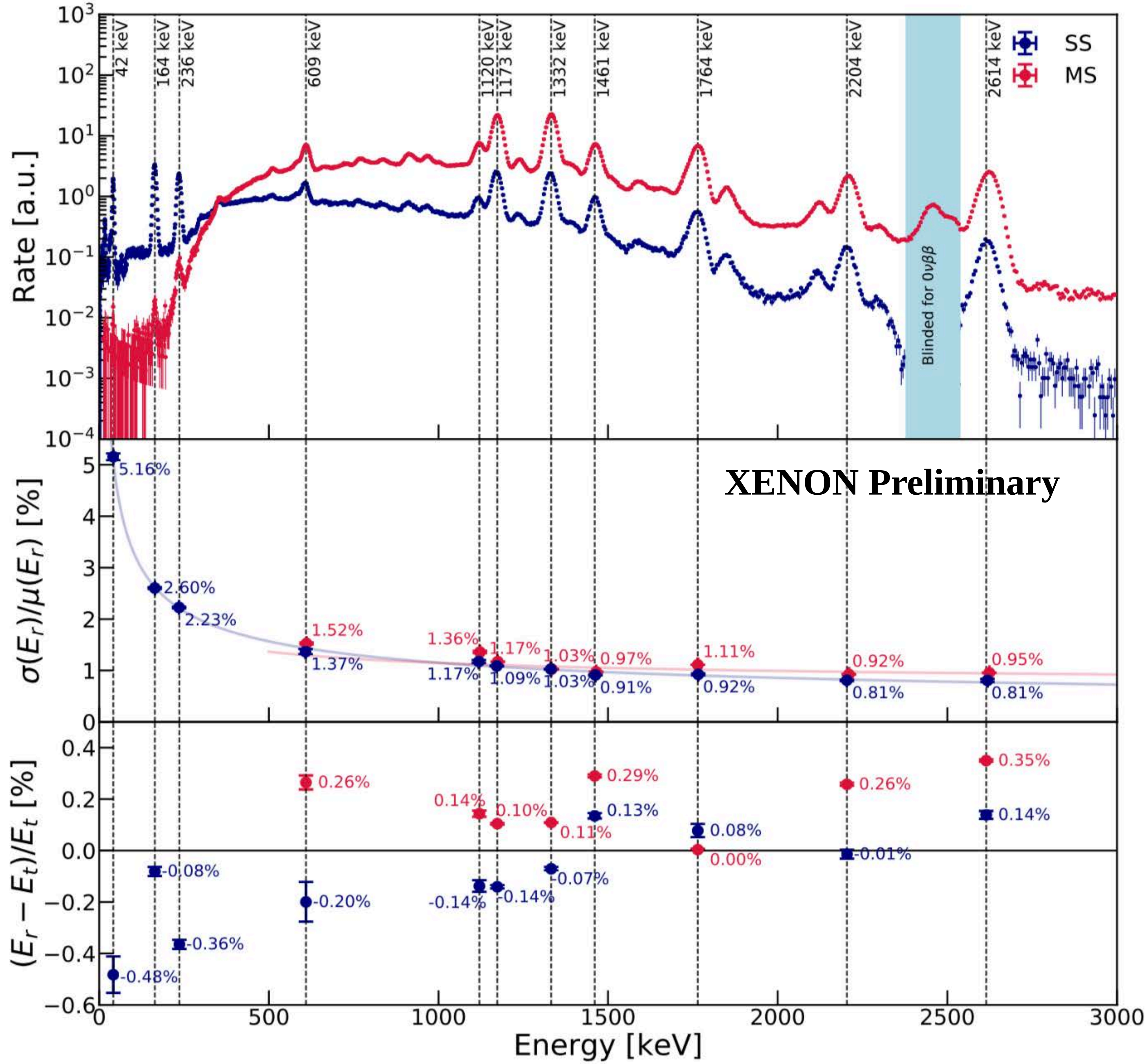


$$T^{0\nu}_{1/2} \propto \epsilon \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

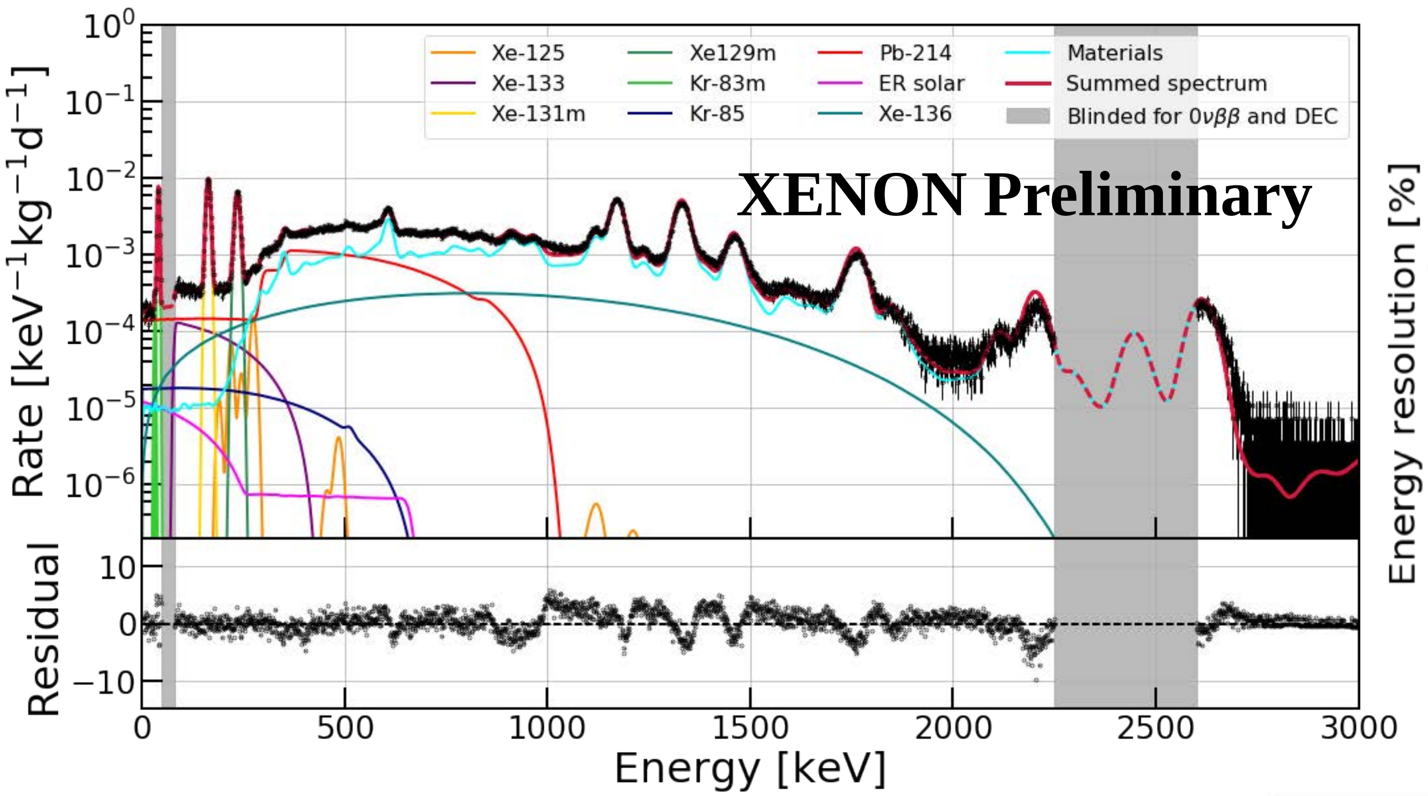


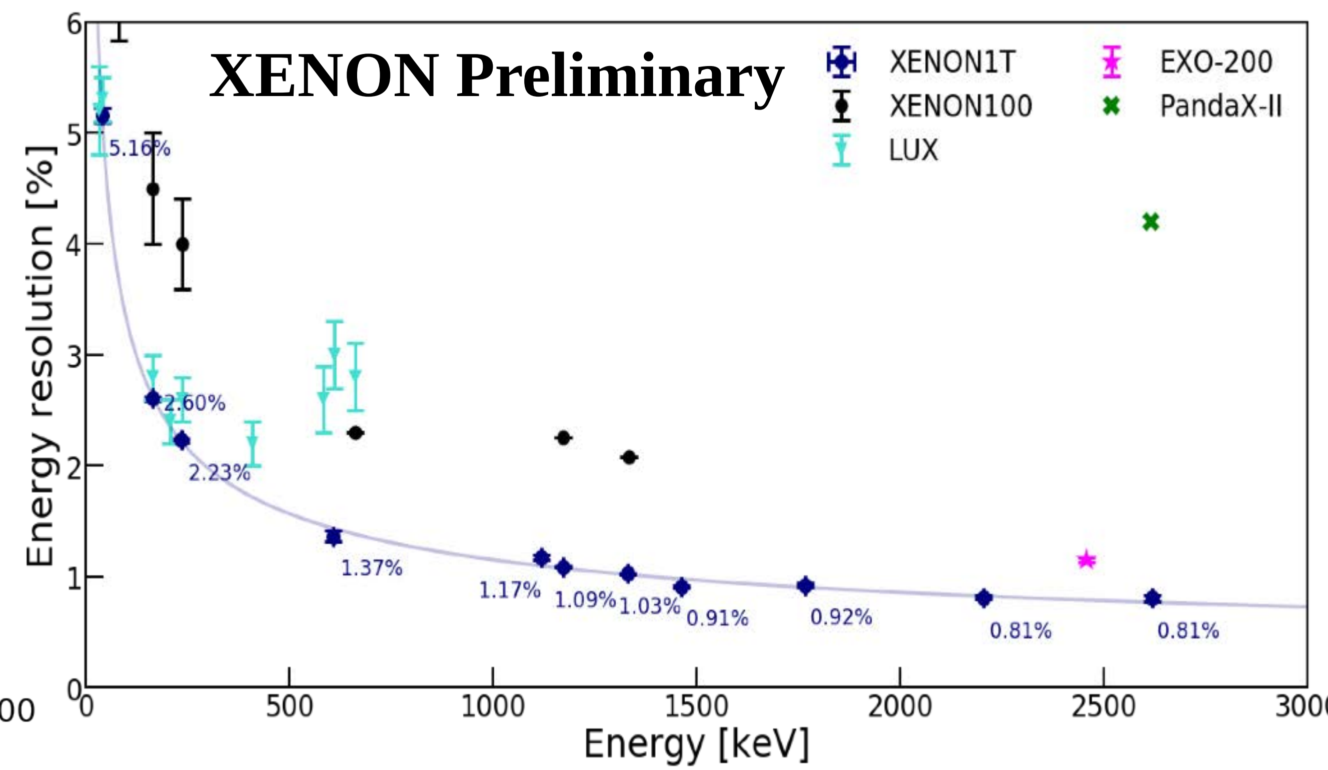
- Major problems and solutions:
  - Poor energy resolution at MeV region
    - Not an issue as demonstrated in XENON1T !!
  - Large background due to material radioactivity (PMTs, Cryostat)
    - improved in future large detectors (XENONnT/LZ, DARWIN)

XENON1T: spectrum and resolution



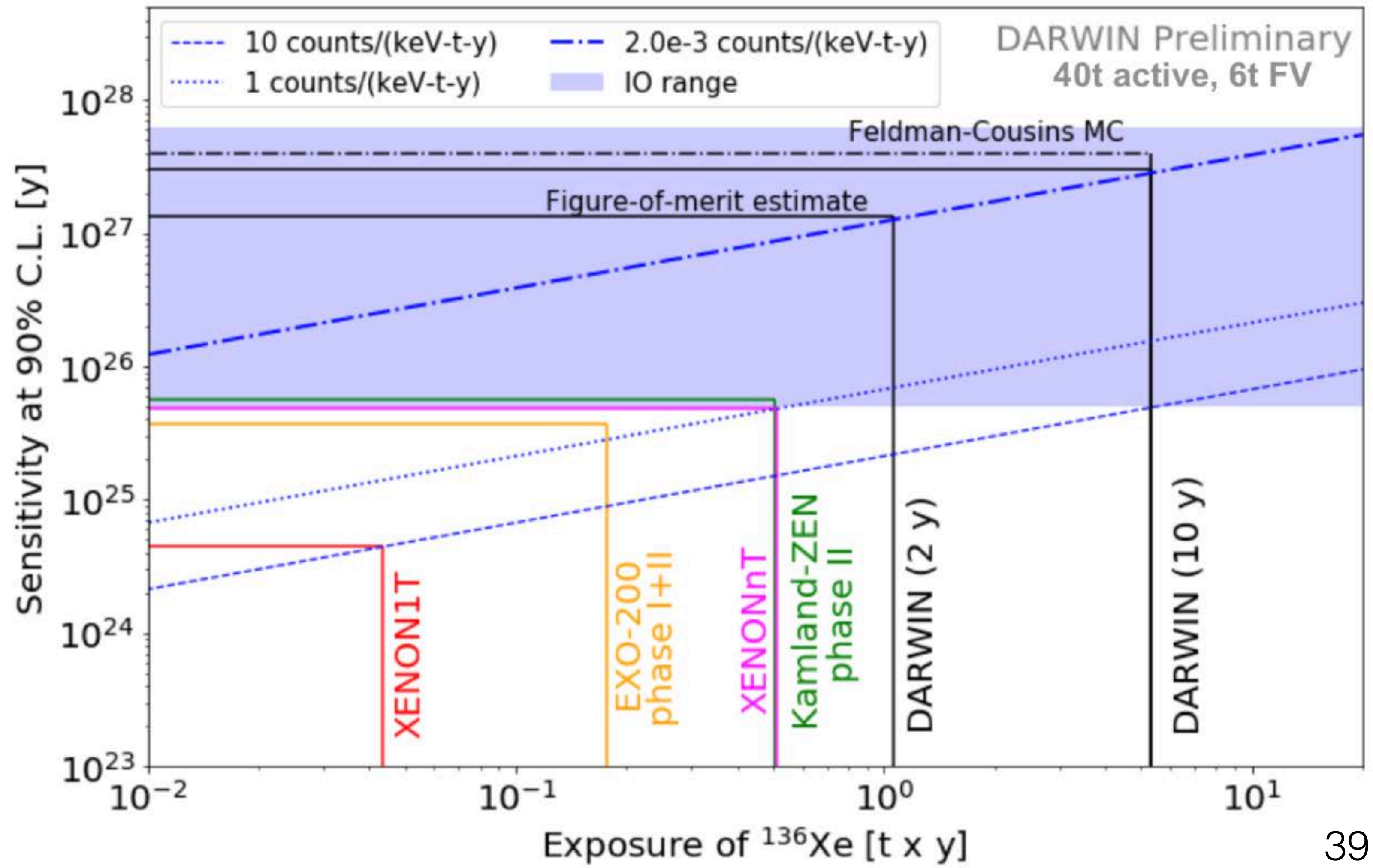
Outlook: Search for 0vbb in future LXeTPCs





A new world-record energy resolution in a LXeTPC

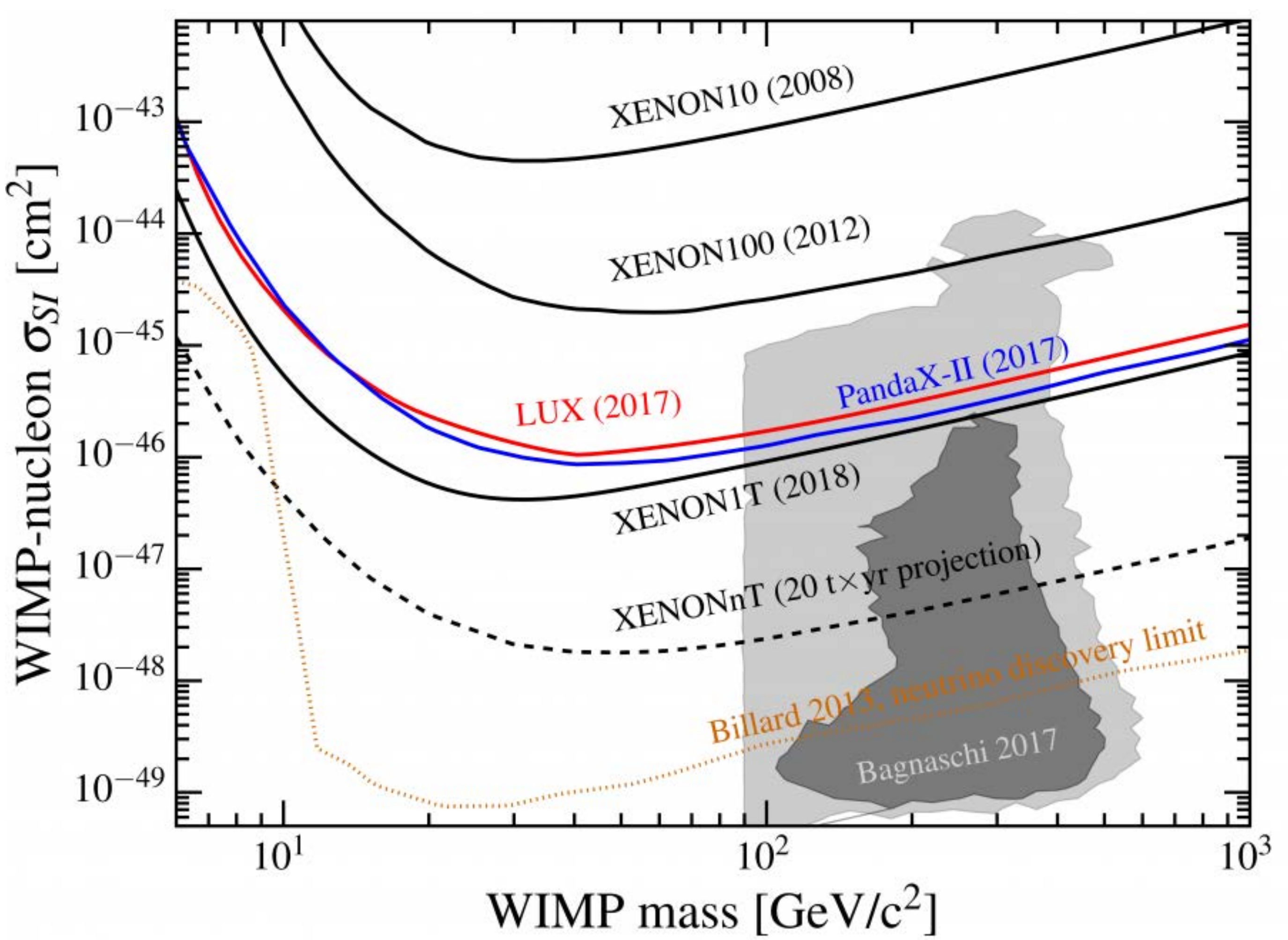
Future detectors like XENONnT, DARWIN will boost sensitivity to 0vbb



DARWIN plot from L. Baudis' slides Massive neutrino workshop

Summary and outlook

- XENON1T had finished dark matter search with 1 ton-year exposure, and produced world-leading sensitivity in large mass range
- XENONnT is being constructed and commissioning at LNGS, first science data to come in 2020.
- XENON1T detector demonstrated the power of LXeTPC for many different rare event searches. More exciting news to come from XENONnT



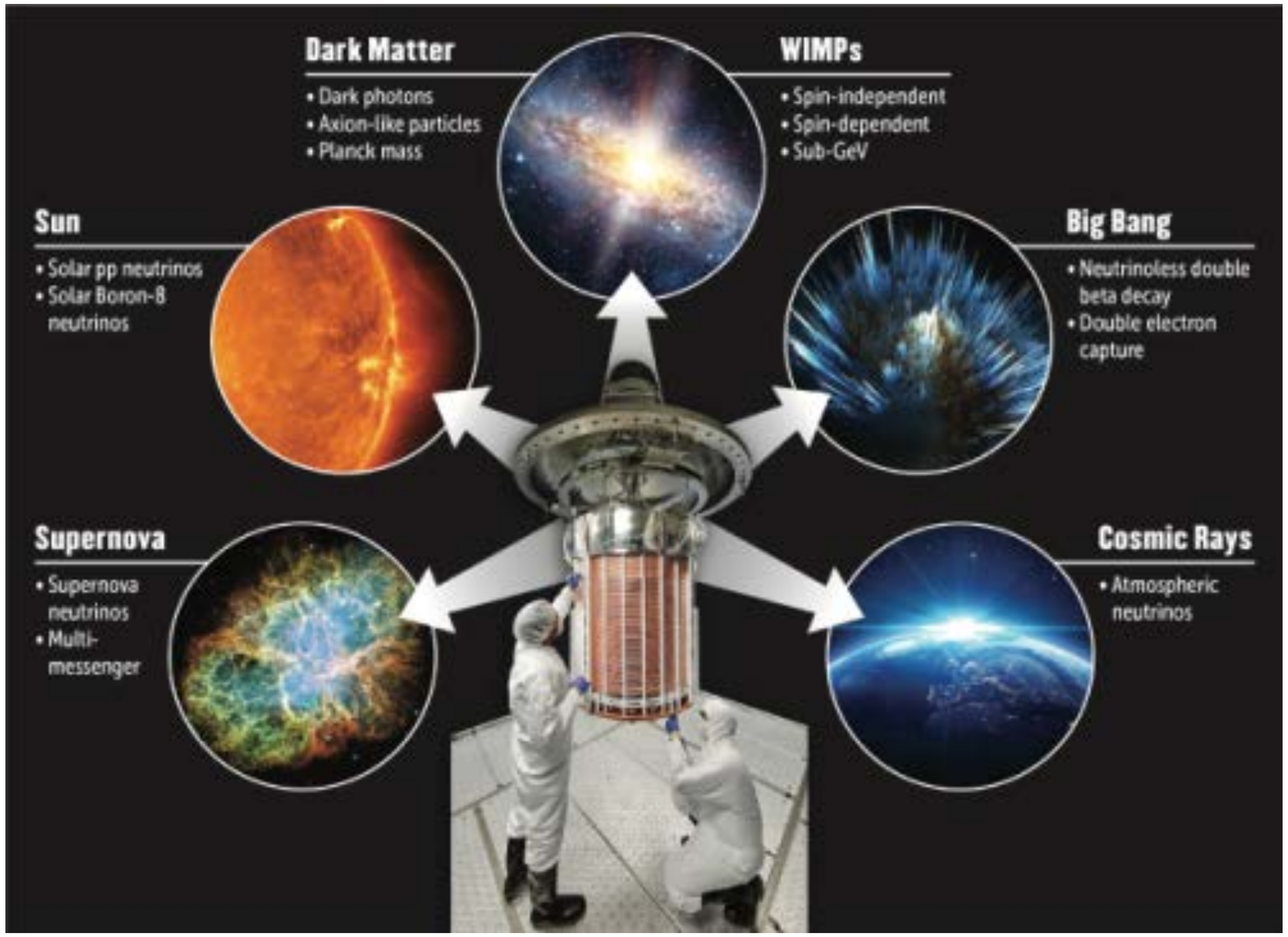


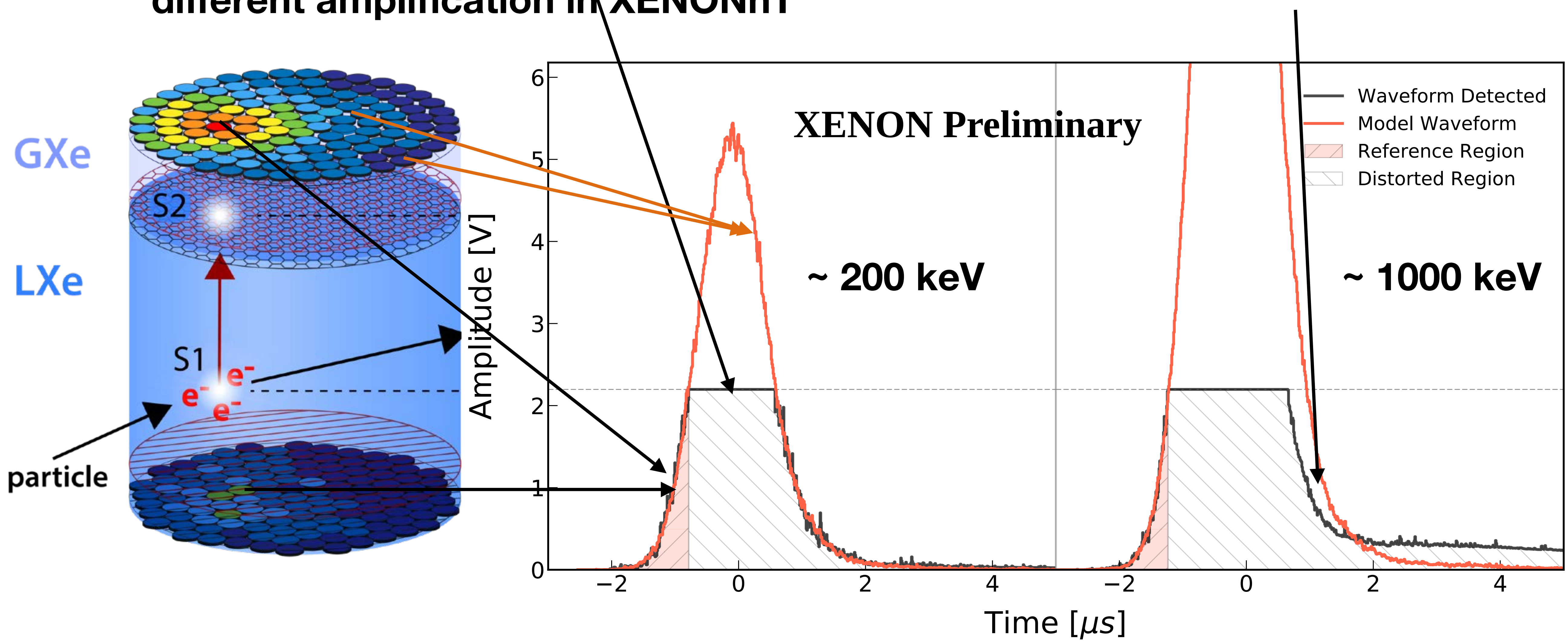
Fig. credits to R. Lang

More info

Corrections to the "saturated" S2s

Type I: Amplitude exceed FADC's dynamic range
Will be solved by "dual readout" with different amplification in XENONnT

Type II: PMT readout circuit is not responding linearly for S2>1e4PE (per PMT)



Study shows FADC saturation is happening before PMT "base" nonlinearity

Spatial and time distribution of S2 signal motivate this "desaturation" algorithm