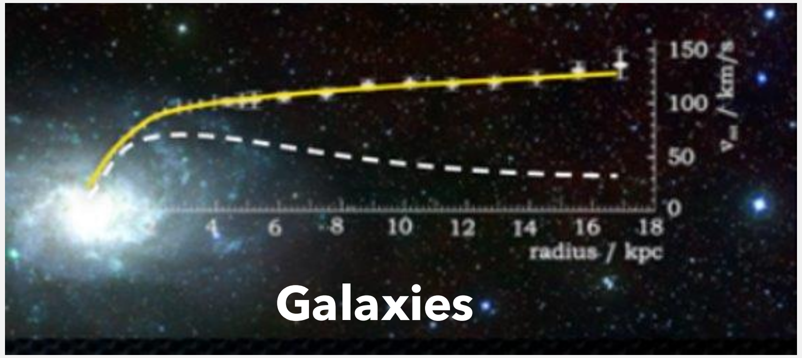
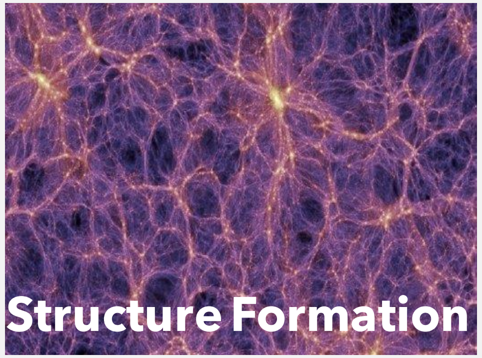
Hunting For Dark Matter

Jacques Pienaar
University of Chicago

14 November 2022

Evidence for Missing Mass





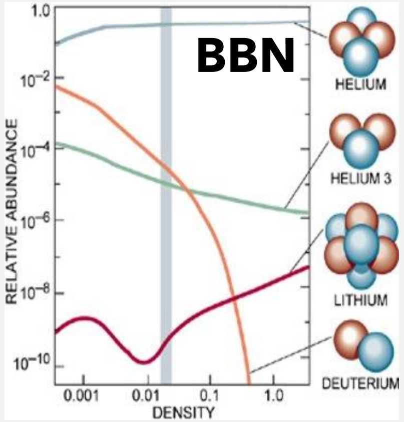
Evidence for Dark Matter

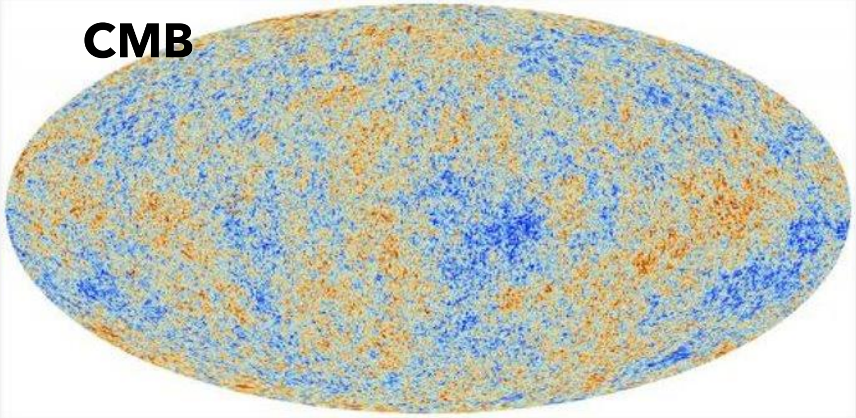
- At various length scales
- Throughout the lifetime of the universe

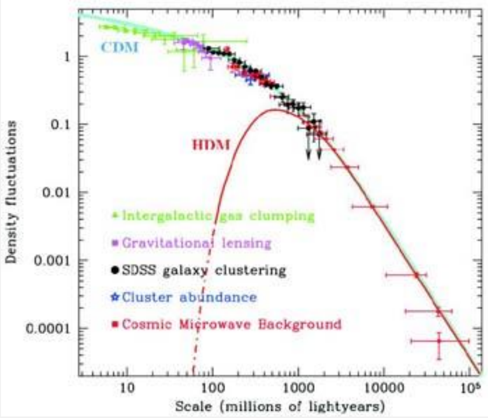
Motivates terrestrial based search via direct detection

Dark Matter Candidates are

- Massive
- Non-baryonic
- Neutral

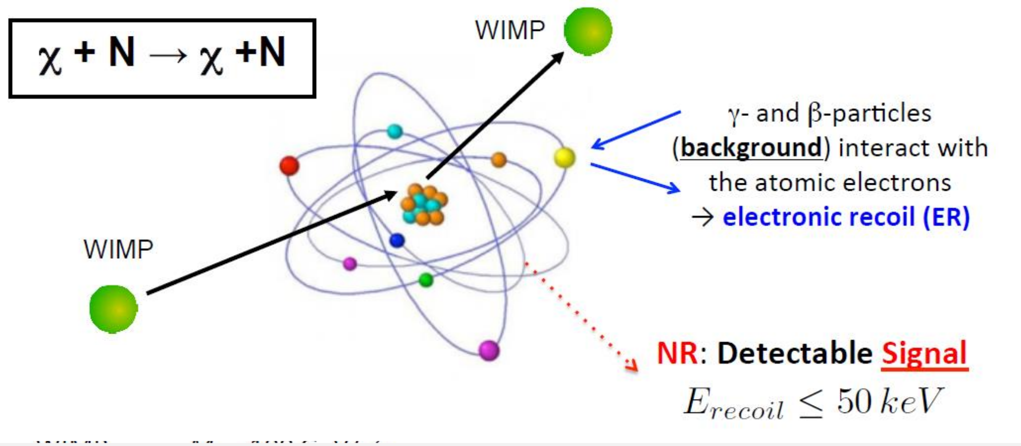






arXiv:astro-ph/0409280

Scattering off Atoms



$$\frac{dR}{dE_R}(t) = \frac{\rho}{m \times m_N} \int_{v_{min}}^{v_{esc}} d^3v\, f(v,t)\, v\, \frac{d\sigma_{WN}}{dE_R}(E_R)$$

ASTROPHYSICS | PARTICLE PHYSICS

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma^{SI}}{dE_R}(E_R) + \frac{d\sigma^{SD}}{dE_R}(E_R)\right)$$

$$\frac{d\sigma^{SI}}{dE_R}(E_R) \propto A^2 \times F_{SI}^2(E_R)$$

Detector independent

- DM density
- Galactic escape velocity
- Earth/Sun velocity

Accord in:

- **Baxter et al** *Eur. Phys. J. C* 81, 907 (2021)

Elastic Collisions

- GeV scale WIMPS
- Recoil energy < 50 keV

Detection Channels

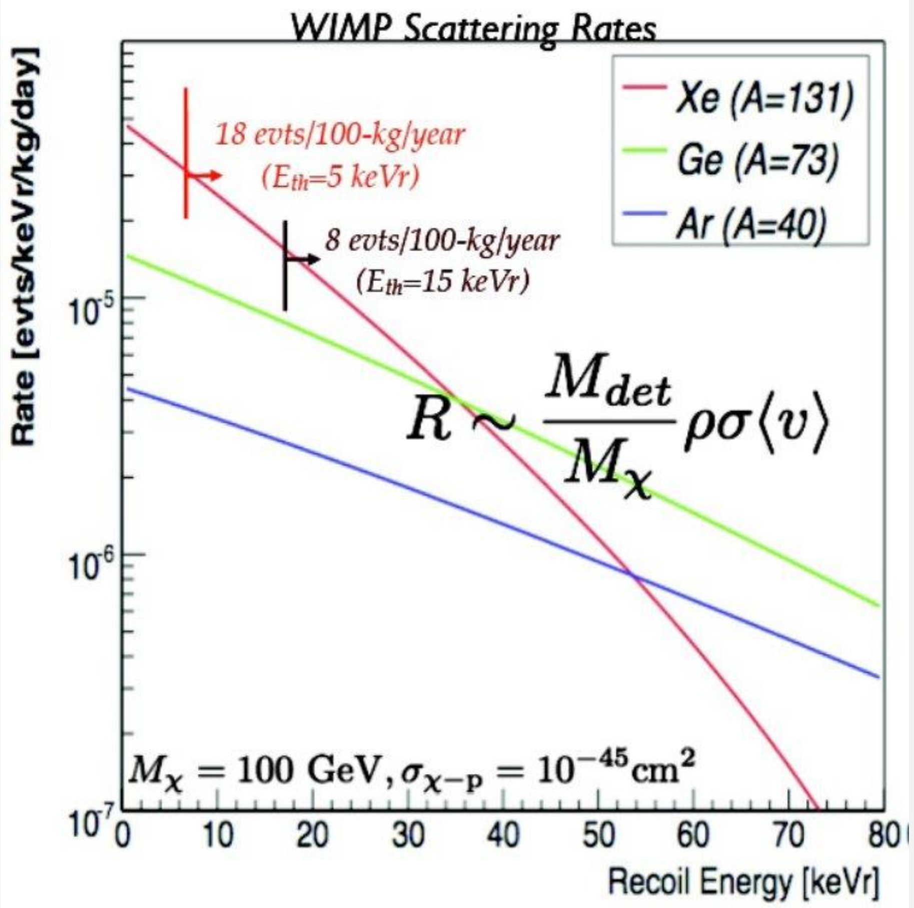
- Scintillation
- Ionization
- Heat

Choice of Target

XENON

Xenon is a desirable target

- Heavy Nucleus (A~131), large number of SI interactions
- 50% of Xenon comprises odd isotopes, useful for spin independent interactions
- High nuclear charge (Z=54) and density (ρ=2.83 kg/l) provide self-shielding properties
- Ultra-clean, as no long lived isotope except ^{136}Xe.
- Scintillation wavelength of 178nm means no wavelength shifters are needed.
- Charge and light yield highest amongst noble liquids
- Scalability



XENONnT

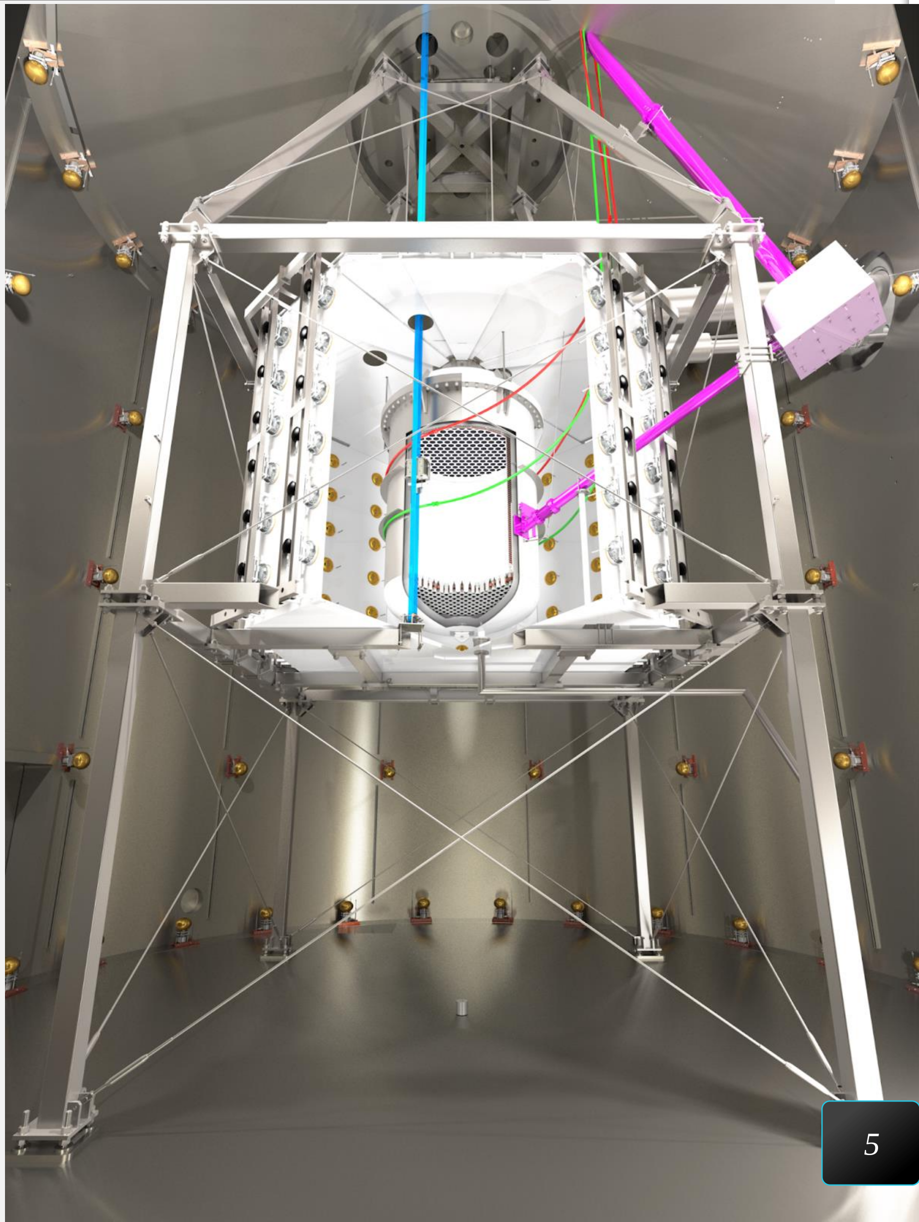
XENON

Consists of 3 nested detectors

- Water Cherenkov Muon Veto (retained from XENON1T)
- Gd-loaded water-based Neutron Veto (NV)
- Time Projection Chamber (TPC)

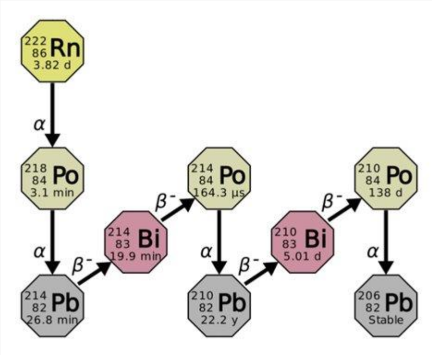
Essential Performance Goals

- High electron lifetime in TPC
- Reduced ^{222}Rn background
- <1 neutron event in target exposure requiring NV



Searching for a needle in a haystack

XENON



DM searches are rare event searches

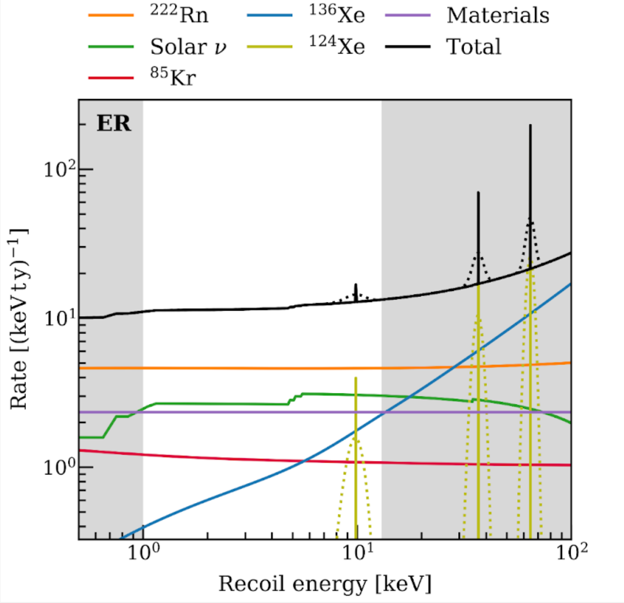
Require detailed understanding of backgrounds

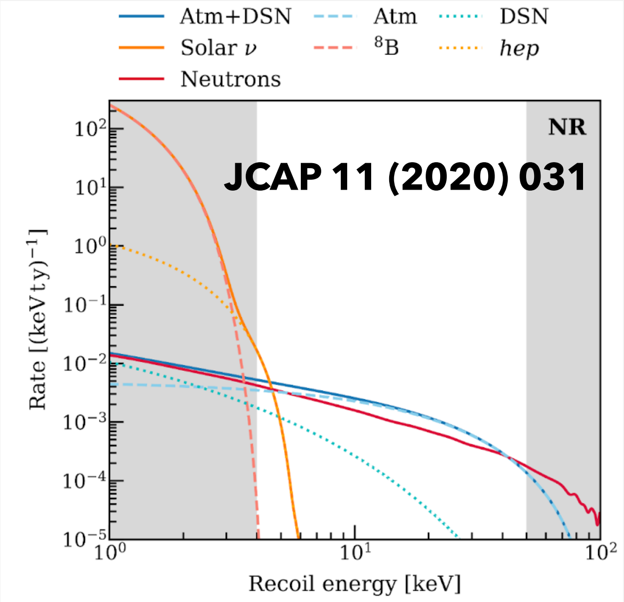
Electronic recoil backgrounds

- ^{222}Rn and ^{85}Kr are intrinisc, reduced via distillation
- Material backgrounds minimized through fiducialization
- Xe isotopes and solar neutrinos are irreducible

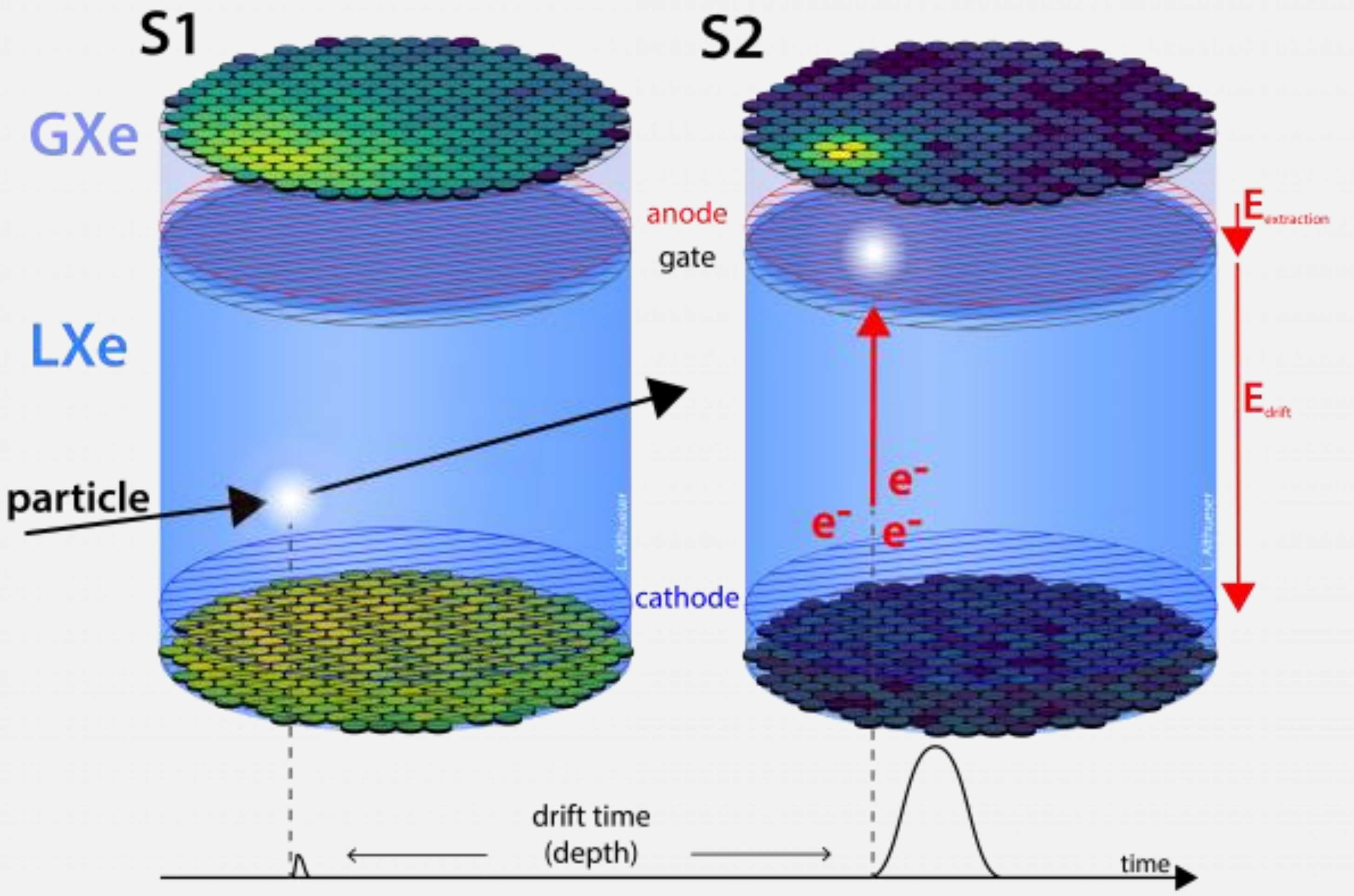
NR recoil backgrounds

- Neutron and Muon detectors veto neutron events
- Neutrinos (via CEvNS) represent irreducible background to future detectors





Two-phase Time Projection Chamber



Signal Detection after particle interaction

- Prompt scintillation light (S1)
- Delayed signal from charge extracted into gas phase (S2)

Full 3D position reconstruction

- x-y from PMT response to S2
- Depth (z) from S1-S2 delay

Electronic vs nuclear recoil discrimination possible through S1/S2 parameter space

Signal Dsicrimination

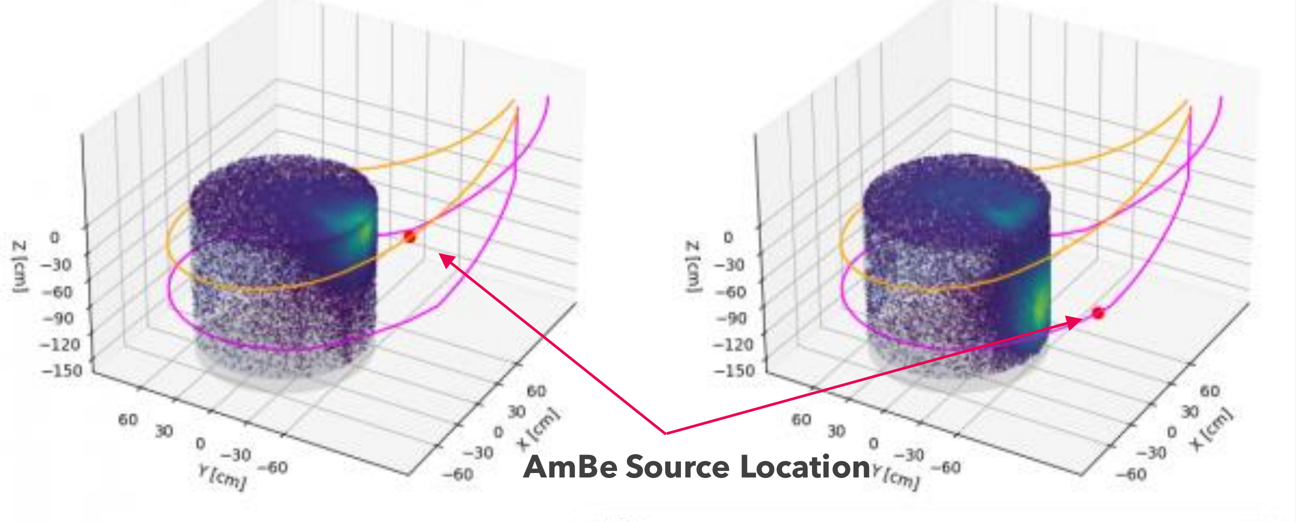
XENON

ER and NR responses calibrated using radioactive sources

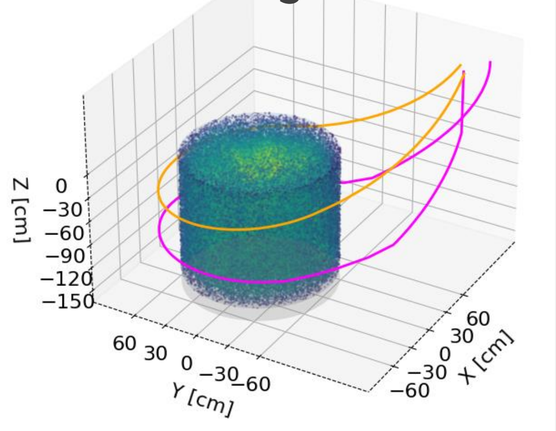
- Calibration of position dependent TPC response using ^{83m}Kr.
- Low energy NR and ER bands being modelled from AmBe and ^{220}Rn data

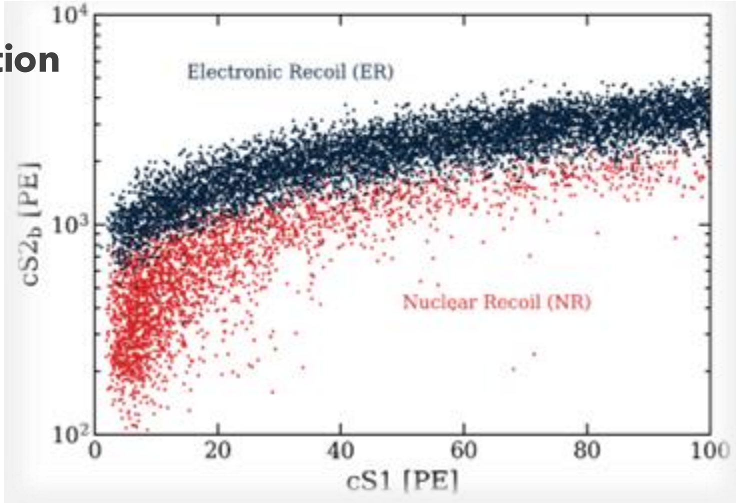
Signal discrimination using S1/S2 ratio is crucial to traditional WIMP searches

TPC data during AmBe calibration in XENONnT



TPC data during ^{83m}Kr calibration



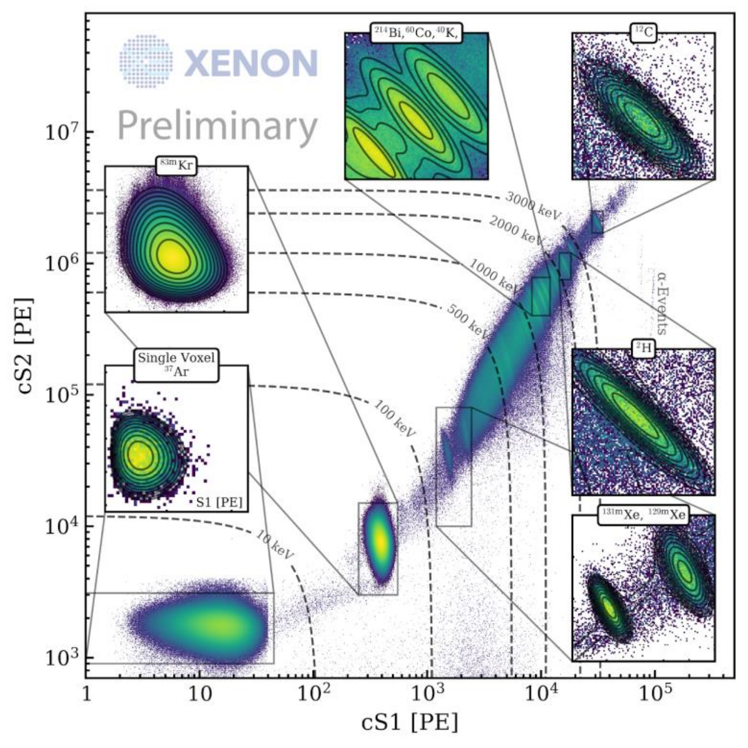


XENON1T calibration data

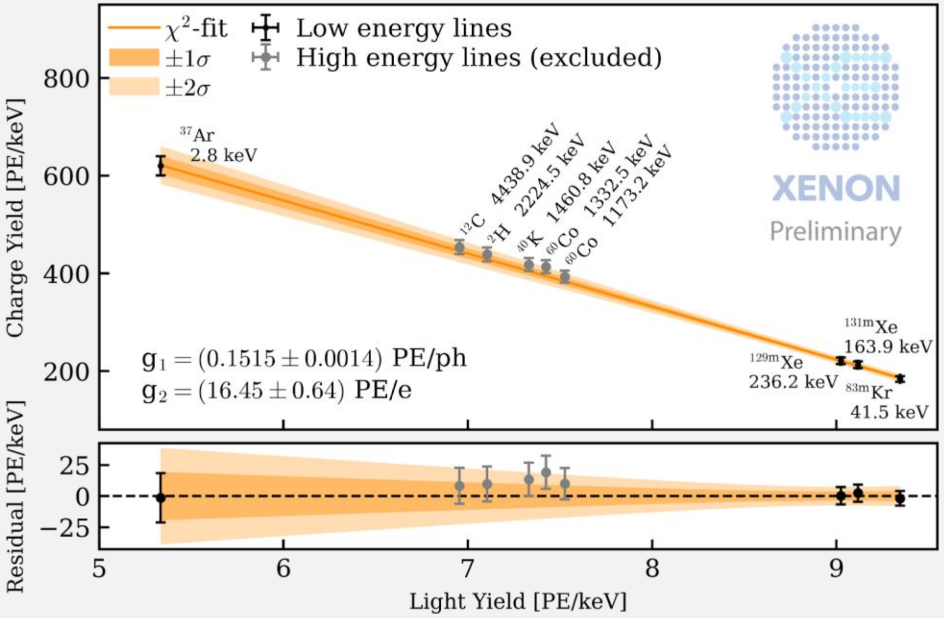
Energy Reconstruction

Use multiple mono-energetic signals to reconstruct recoil energy

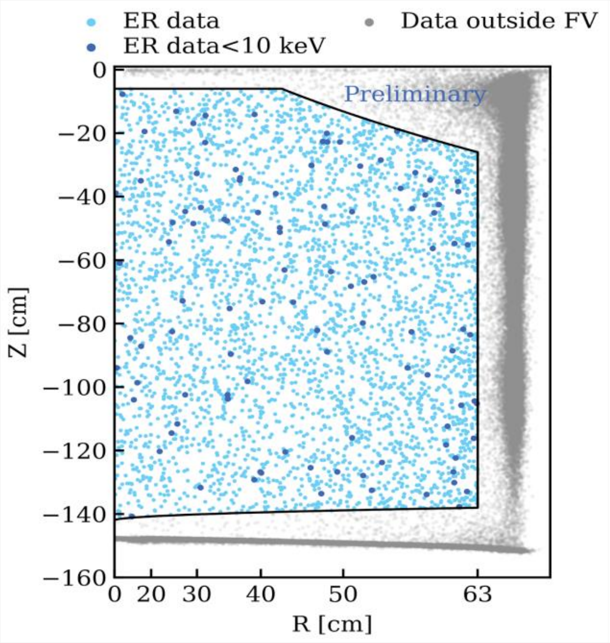
- Four low-energy calibration points: ^{37}Ar, ^{83m}Kr, ^{129m}Xe and ^{131m}Xe
- Observed 1-2% bias in reconstructed energy used as systematic uncertainty in modeling in XENONnT

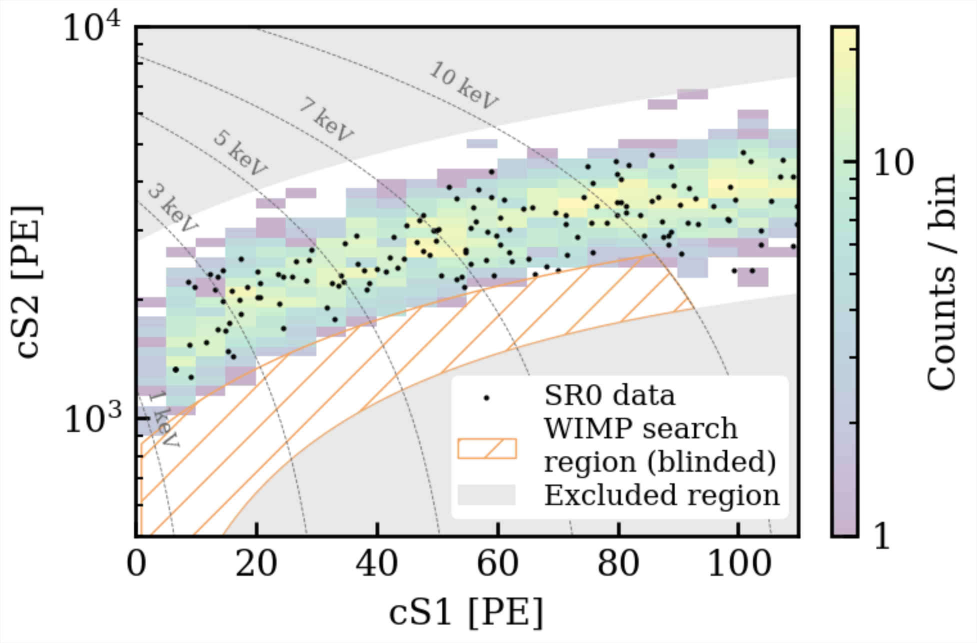


$$E = 13.7\text{eV}\left(\frac{cS1}{g_1} + \frac{cS2}{g_2}\right)$$



Defining Search Region





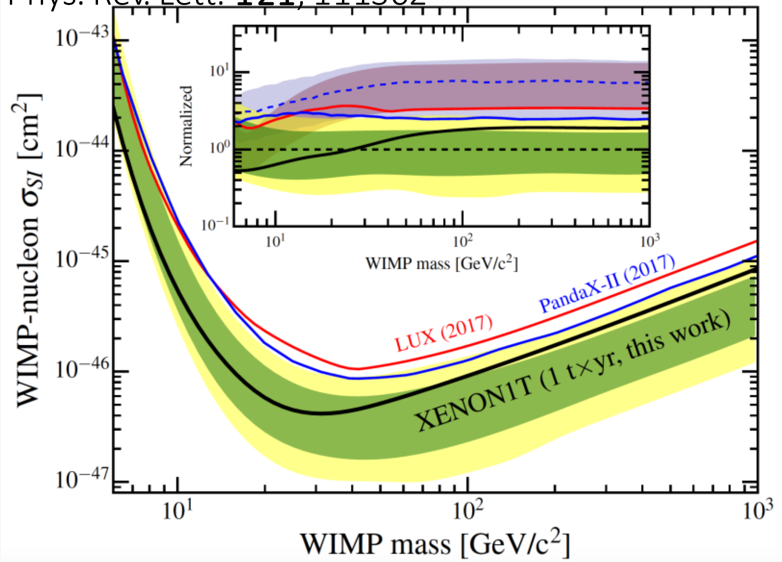
Searching for NR DM models

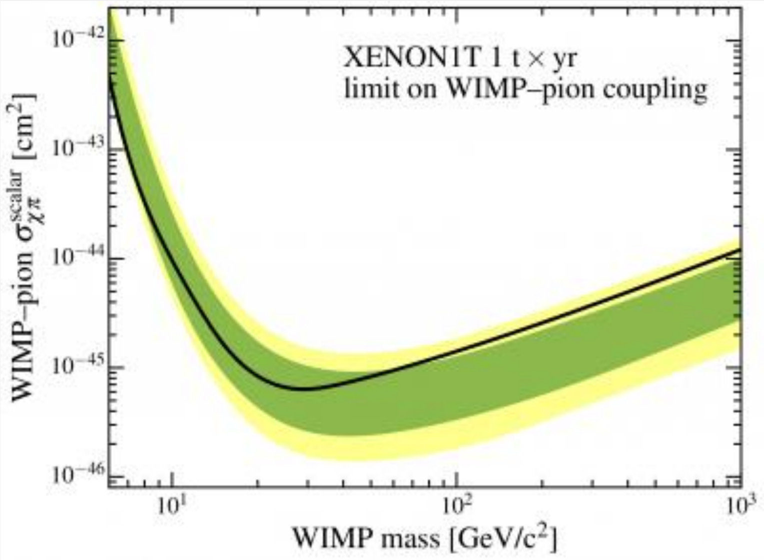
- Define blinded region in cS1/cS2 space
- Background models constructed in cS1, cS2, r and Z space
- Perform unbinned profile likelihood in analysis space

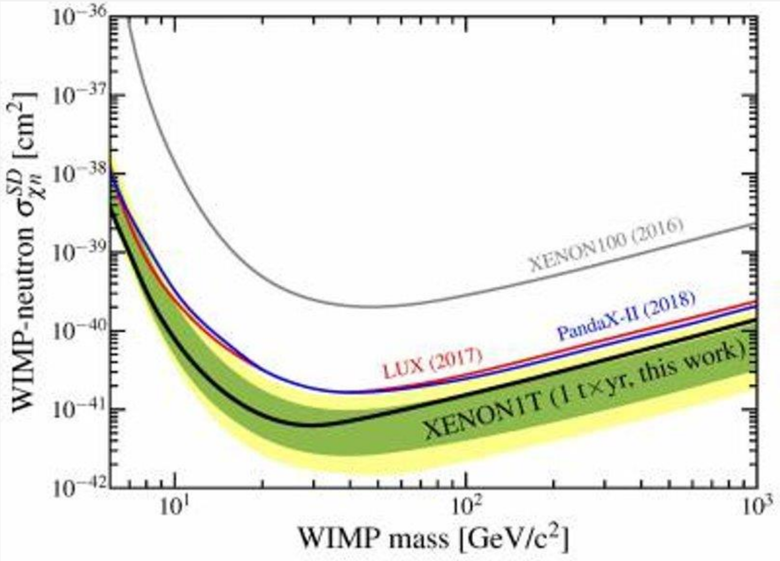
XENON

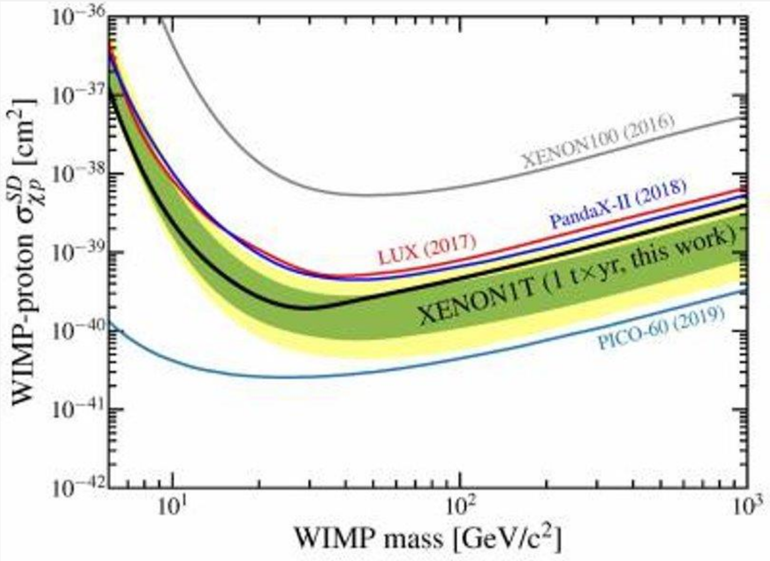
Spin Independent/Depenant WIMP and WIMP-Pion

Phys. Rev. Lett. **121**, 111302









Making results accesible

XENON

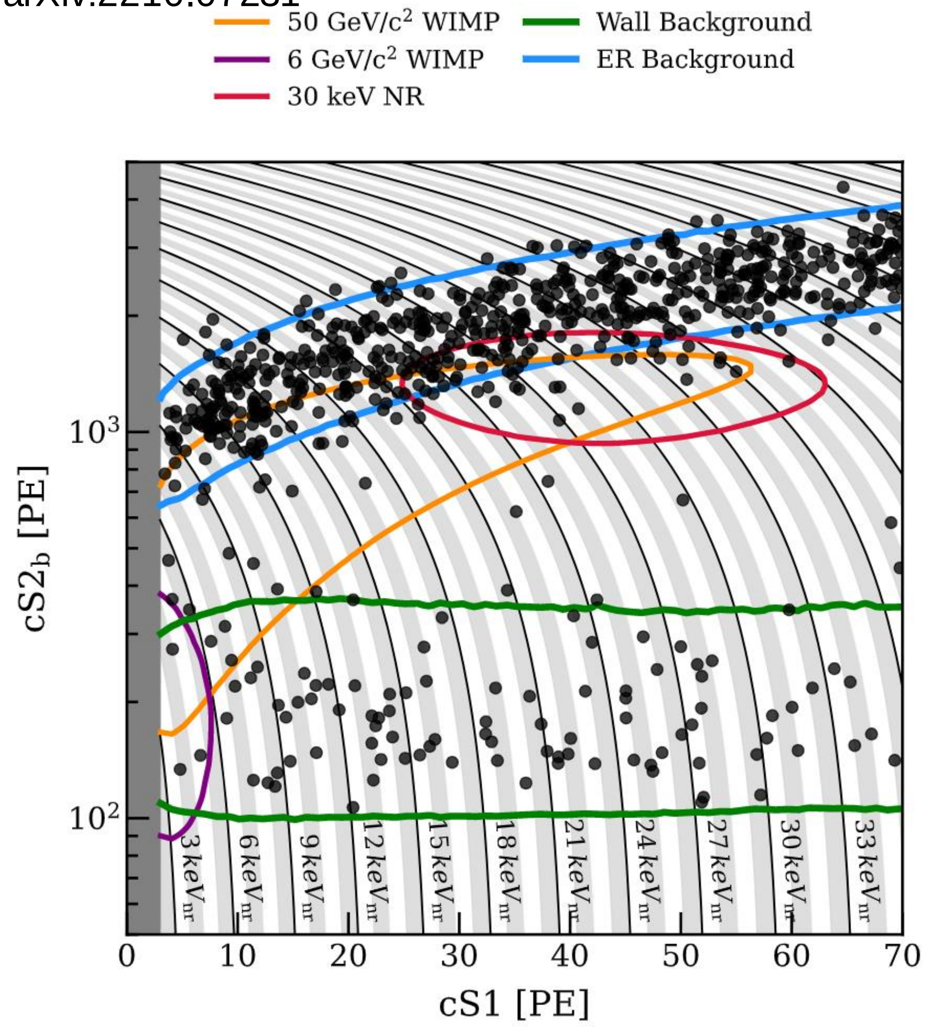
In order to test XENON data against an NR model require

- Knowledge of detector response
- Selection efficiencies
- Background models
- Science data

Modelling response

- Detector observable are photons and electrons
- Number of quanta produced dependent on original recoil
- Number of photons and electrons anticorrelated
- Thus for a given cS1 energy, cS2 response is dependent on NR energy

arXiv:2210.07231



XENON1T science data

Transforming analysis space

Reconstructed energy space is unique

- $E_{\mathrm{recER}}(\mathrm{cS1}, \mathrm{cS2_b}) \equiv W \cdot [\mathrm{cS1}/g_1 + \mathrm{cS2_b}/g_2],$

Require other analysis space to be independent of E_{rec}

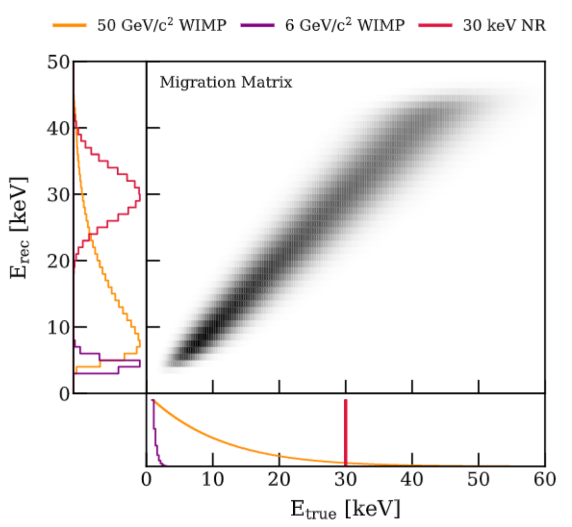
- $E^{\perp}_{\mathrm{rec}}(\mathrm{cS1}, \mathrm{cS2_b}) \equiv W \cdot [\mathrm{cS1}/g_2 - \mathrm{cS2_b}/g_1],$

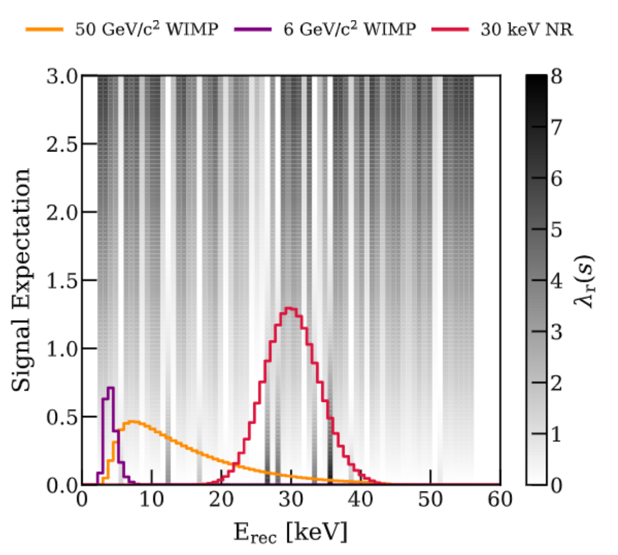
Provide migration matrix

- Measured XENON detector response accounted for
- Converts input spectrum in true energy to reconstructed energy

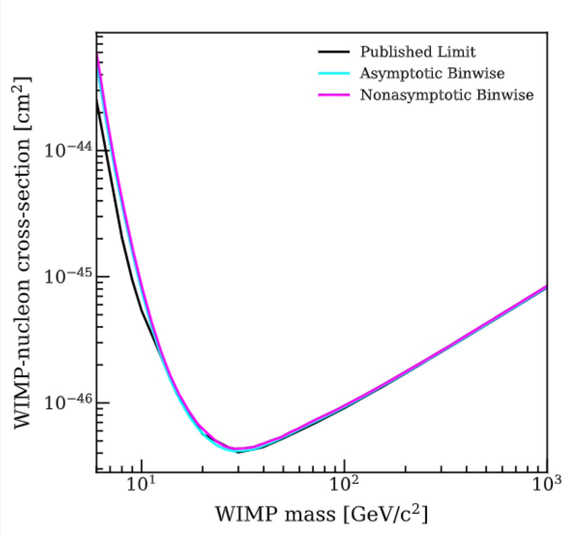
Science likelihood per bin can be expressed as:

$$\mathscr{L}^{\mathrm{sci}\prime}_{\mathrm{r,SR}}(s, \boldsymbol{\theta}) = Poisson(N_r \mid \mu^{\mathrm{tot}}_r(s, \boldsymbol{\theta})) \times \prod_{i \in S_r} f^{\mathrm{tot}\prime}(E_{\mathrm{rec},i}, E^{\perp}_{\mathrm{rec},i}, R_i \mid s, \boldsymbol{\theta})$$

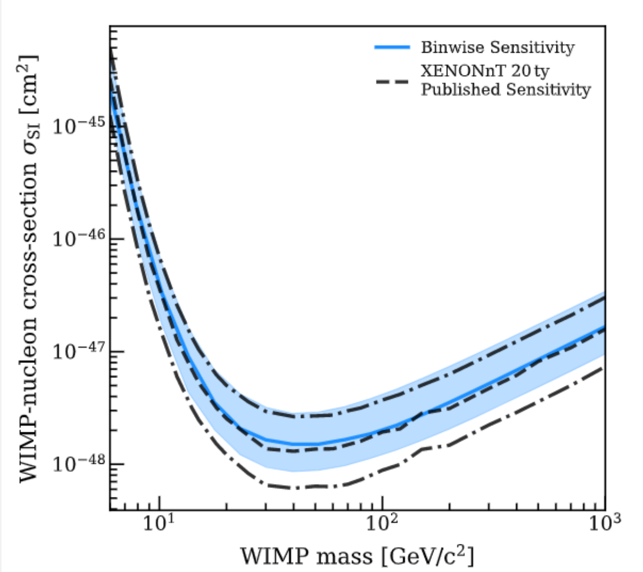


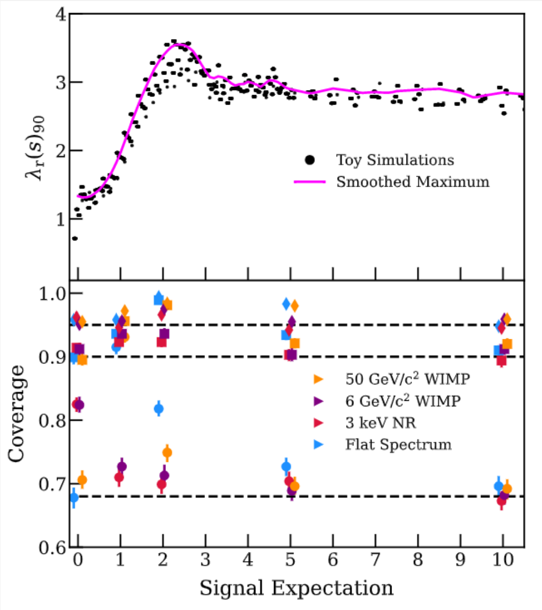


An Approximate Likelihood



(a) Spin-independent WIMP-nucleon





	$n = 60$ Bins	$n = 80$ Bins	$n = 120$ Bins
Flat Spectrum	$1.01^{+0.08}_{-0.06}$	$1.01^{+0.07}_{-0.05}$	$1.01^{+0.07}_{-0.04}$
NR Lines			
3 keV	$1.06^{+0.33}_{-0.16}$	$1.04^{+0.29}_{-0.15}$	$1.03^{+0.23}_{-0.15}$
5 keV	$1.13^{+0.24}_{-0.14}$	$1.11^{+0.19}_{-0.13}$	$1.11^{+0.17}_{-0.12}$
7 keV	$1.14^{+0.19}_{-0.14}$	$1.13^{+0.16}_{-0.12}$	$1.13^{+0.15}_{-0.12}$
10 keV	$1.11^{+0.15}_{-0.12}$	$1.11^{+0.14}_{-0.11}$	$1.11^{+0.12}_{-0.10}$
20 keV	$1.05^{+0.14}_{-0.09}$	$1.04^{+0.12}_{-0.08}$	$1.05^{+0.12}_{-0.08}$
30 keV	$1.04^{+0.11}_{-0.09}$	$1.03^{+0.10}_{-0.08}$	$1.04^{+0.10}_{-0.08}$
SI WIMP signals			
6 GeV/c^2	$1.07^{+0.40}_{-0.21}$	$1.02^{+0.31}_{-0.19}$	$1.01^{+0.25}_{-0.17}$
10 GeV/c^2	$1.08^{+0.24}_{-0.14}$	$1.06^{+0.19}_{-0.14}$	$1.05^{+0.17}_{-0.13}$
50 GeV/c^2	$1.07^{+0.10}_{-0.08}$	$1.06^{+0.09}_{-0.07}$	$1.07^{+0.07}_{-0.07}$
100 GeV/c^2	$1.06^{+0.10}_{-0.08}$	$1.06^{+0.09}_{-0.06}$	$1.06^{+0.07}_{-0.06}$

Table 1 Table of bias and spread, defined as the median and 1-sigma spread of the ratio between binwise and full likelihood upper limits using 1000 toy-MC simulations.

Approximate likelihoods

- Calculated on XENON1T science data
- 1000 no-signal MC simulations of XENONnT
- Available at https://zenodo.org/record/7255651

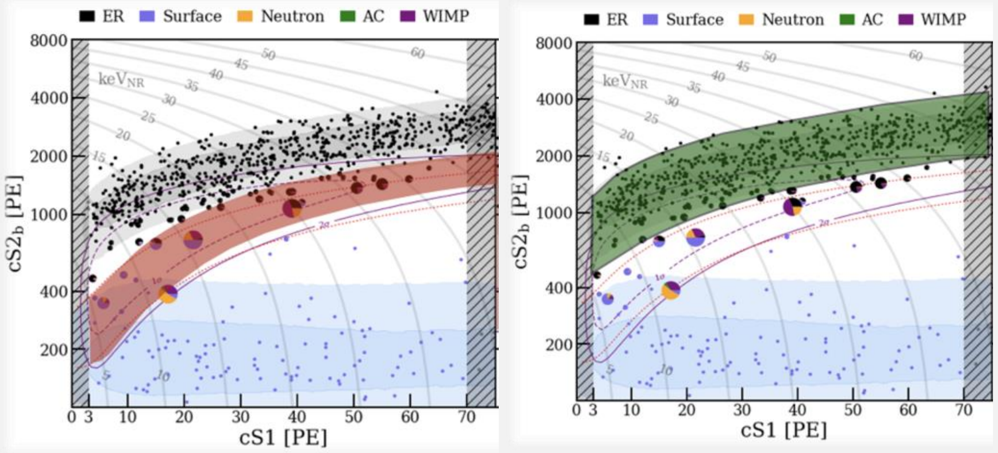
Extending the Search for Dark Matter in XENON1T

Alternate models can be investigated using ERs

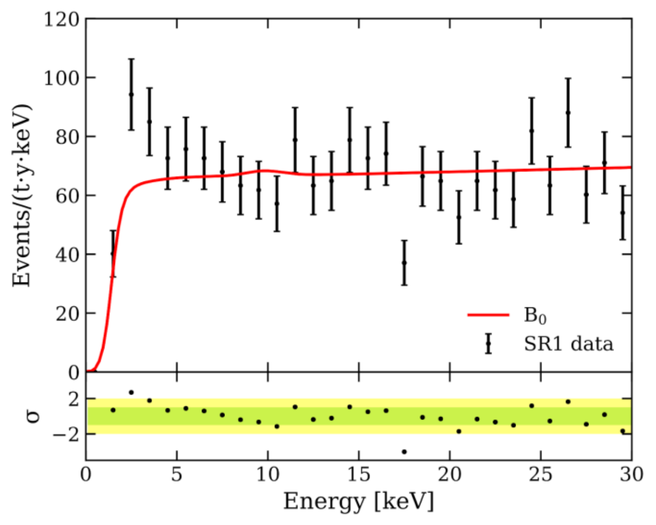
- Dark photons
- Solar Axions,
- Axion like particles.
- Neutrino magnetic moment

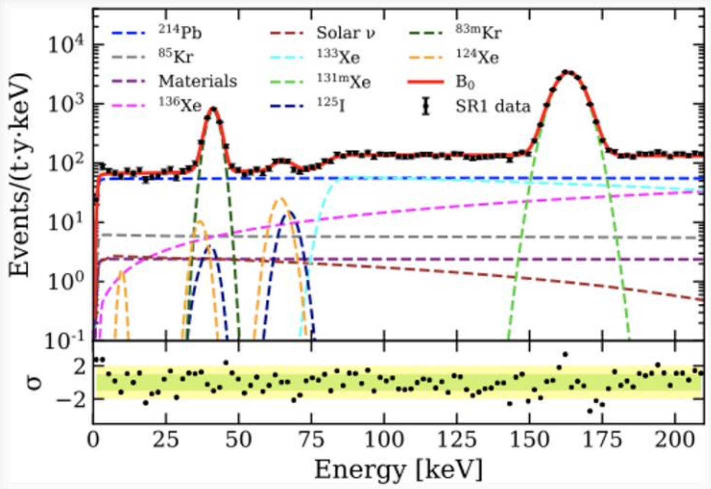
XENON1T observed an excess in ER events

- 285 events (232 +/- 15 expected), 3.3 sigma
- Excess consistent with several beyond SM models
- However couldn't exclude potential tritium background



PRD 102, 072004 (2020)





Low energy ER search in XENONnT

Detection efficiency validated with simulations

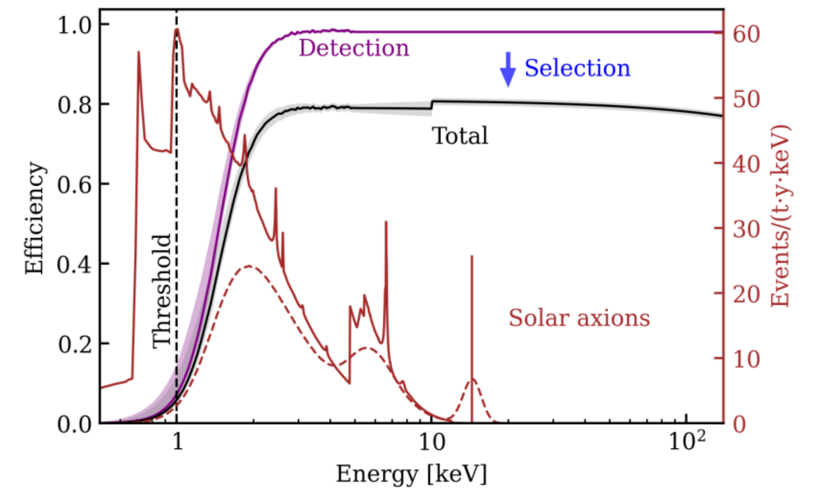
- Dominated by 3-fold PMT coincidence requirement on S1 signals
- Data selection cuts applied to events
- Fiducial volume cut results in 4.37 tonne search region

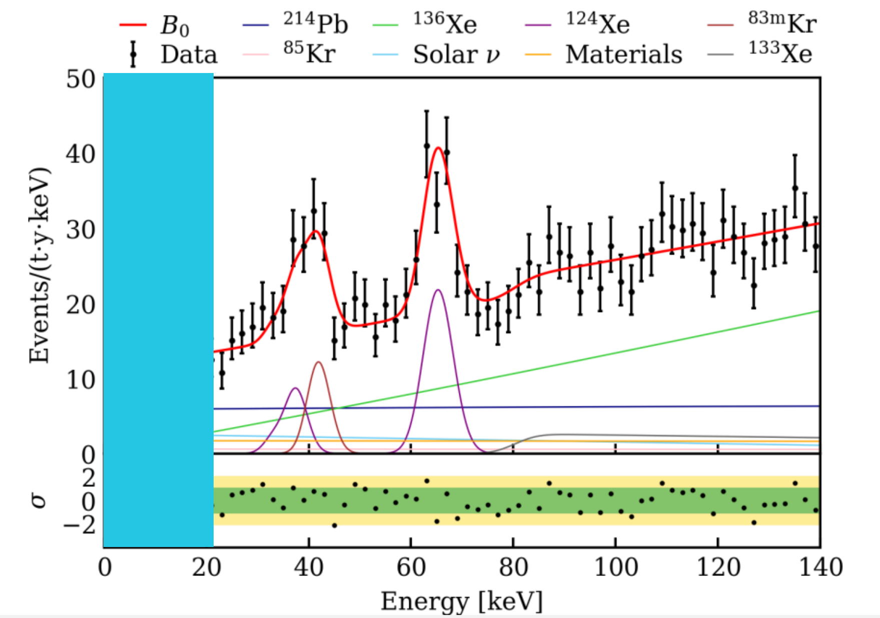
Science Data

- 1-140 keV
- 1.16 t.y exposure
- Both NR and ER data blinded below 20 keV

Background Estimates

- Constraints by external measurements
- Data-driven accidental coincidence model
- Verification in side band before unblinding
- Double weak processes 2vECEC (^{124}Xe) and 2vββ (^{136}Xe) dominate background

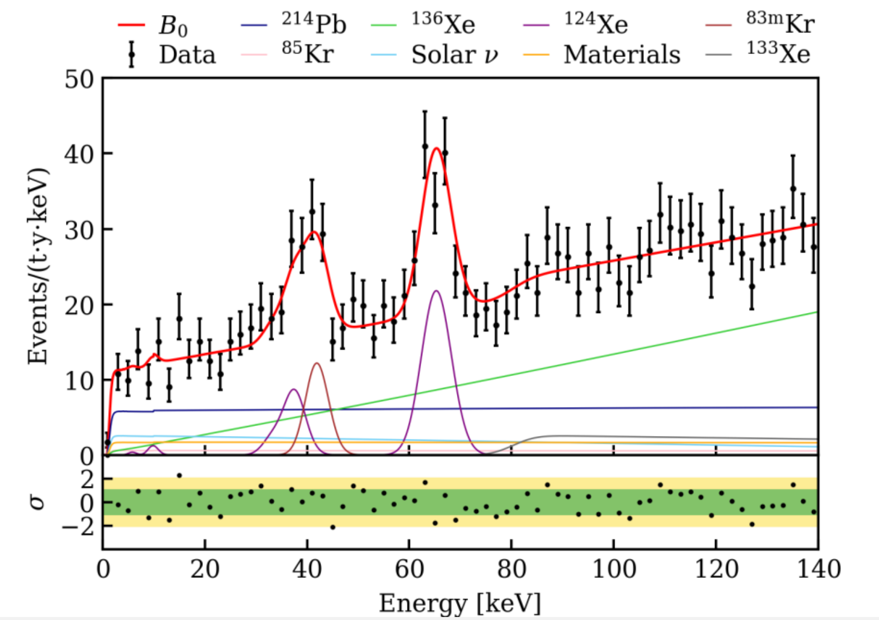




Electronic Recoil Unblinding

TABLE I. The background model B_0 with fit constraint and best-fit number of events for each component in (1, 140) keV.

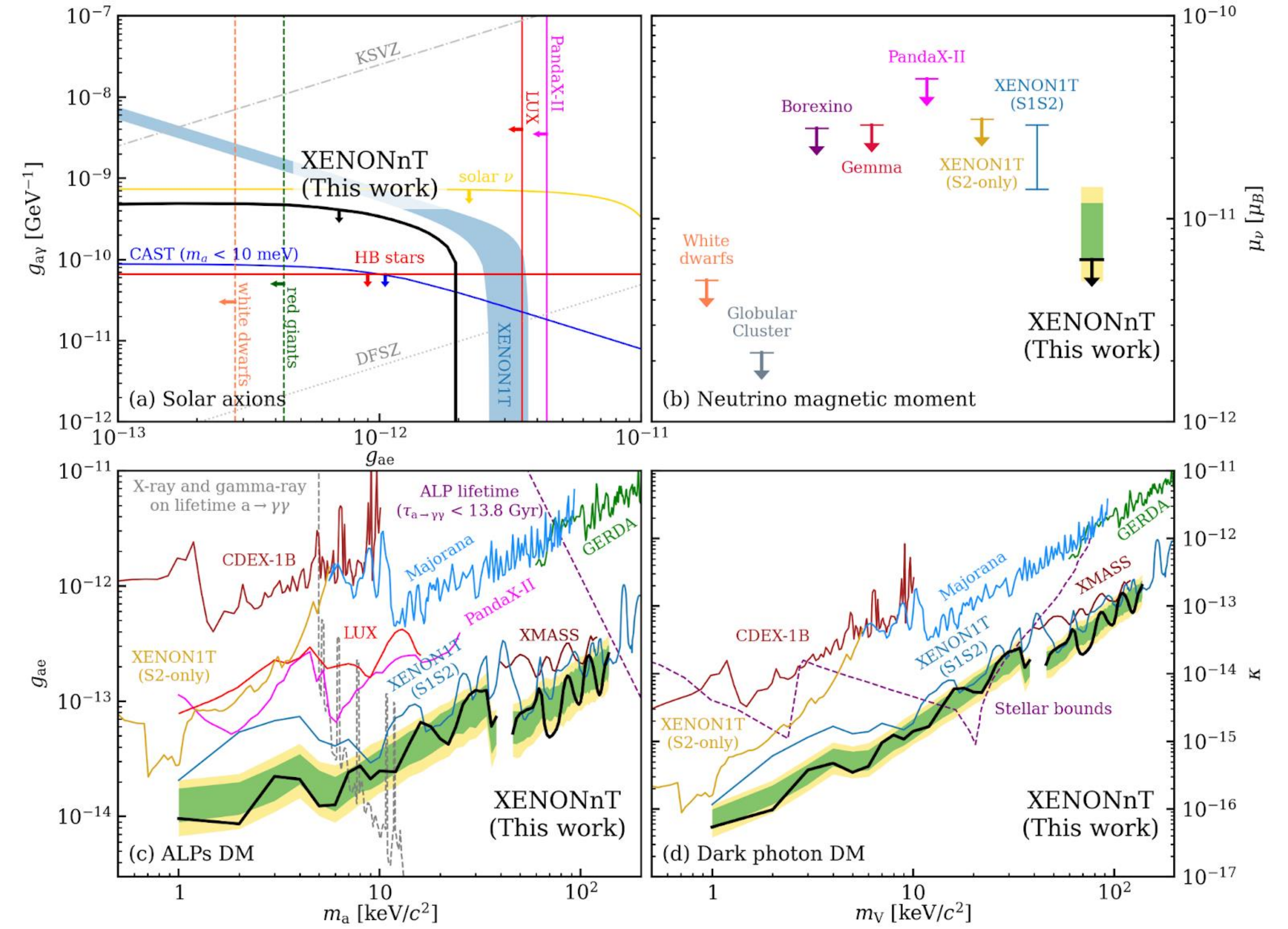
Component	Constraint	Fit
^{214}Pb	(584, 1273)	980 ± 120
^{85}Kr	90 ± 59	91 ± 58
Materials	266 ± 51	267 ± 51
^{136}Xe	1537 ± 56	1523 ± 54
Solar neutrino	297 ± 30	298 ± 29
^{124}Xe	-	256 ± 28
AC	0.70 ± 0.04	0.71 ± 0.03
^{133}Xe	-	163 ± 63
^{83m}Kr	-	80 ± 16



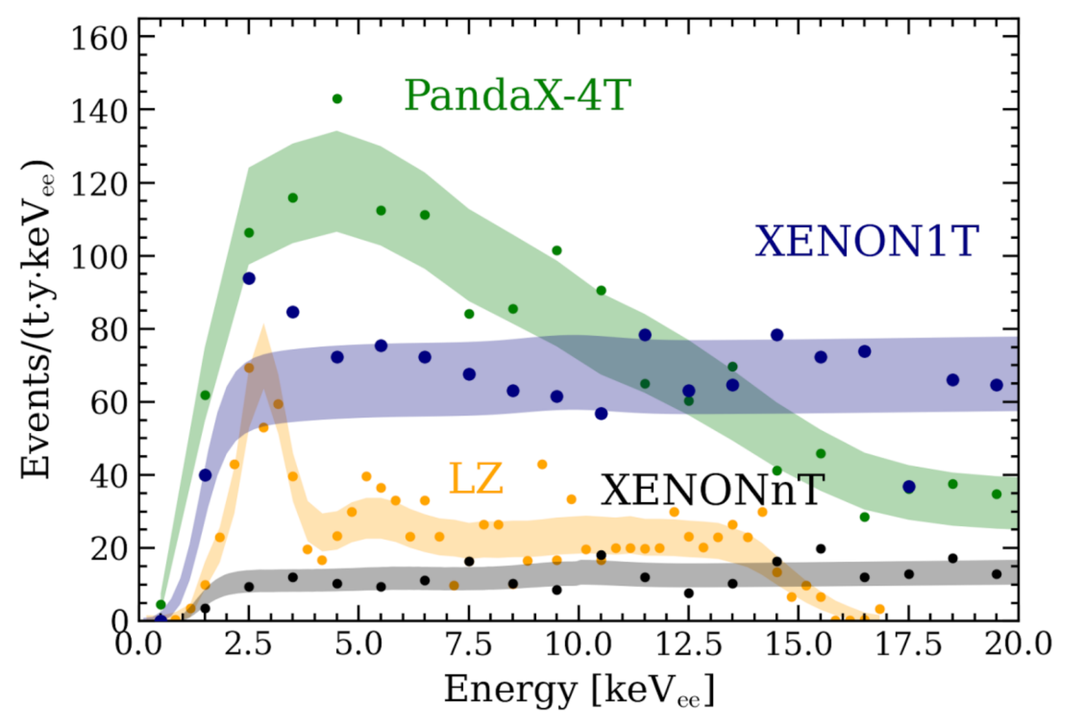
No excess observed

A small tritium contamination is most likely origin of XENON1T excess

First results from XENONnT



XENONnT low energy ER rate in context



PRL 129, 161804 (2022)
PRD 102, 072004 (2020)
arXiv:2207.03764
PRL 129, 161805 (2022)

- Factor five background reduction with respect to XENON1T
- No excess below 5 keV found: 8.6σ exclusion on XENON1T excess