Ultraheavy Dark Matter Search in XENON1T

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Shengchao Li （李圣超）
lishengchao@westlake.edu.cn
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西湖大学 | 暗物质与中微子实验室

XENON

XENON

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

Chicago

UCSD

Rice

Purdue

Tsinghua

Tokyo

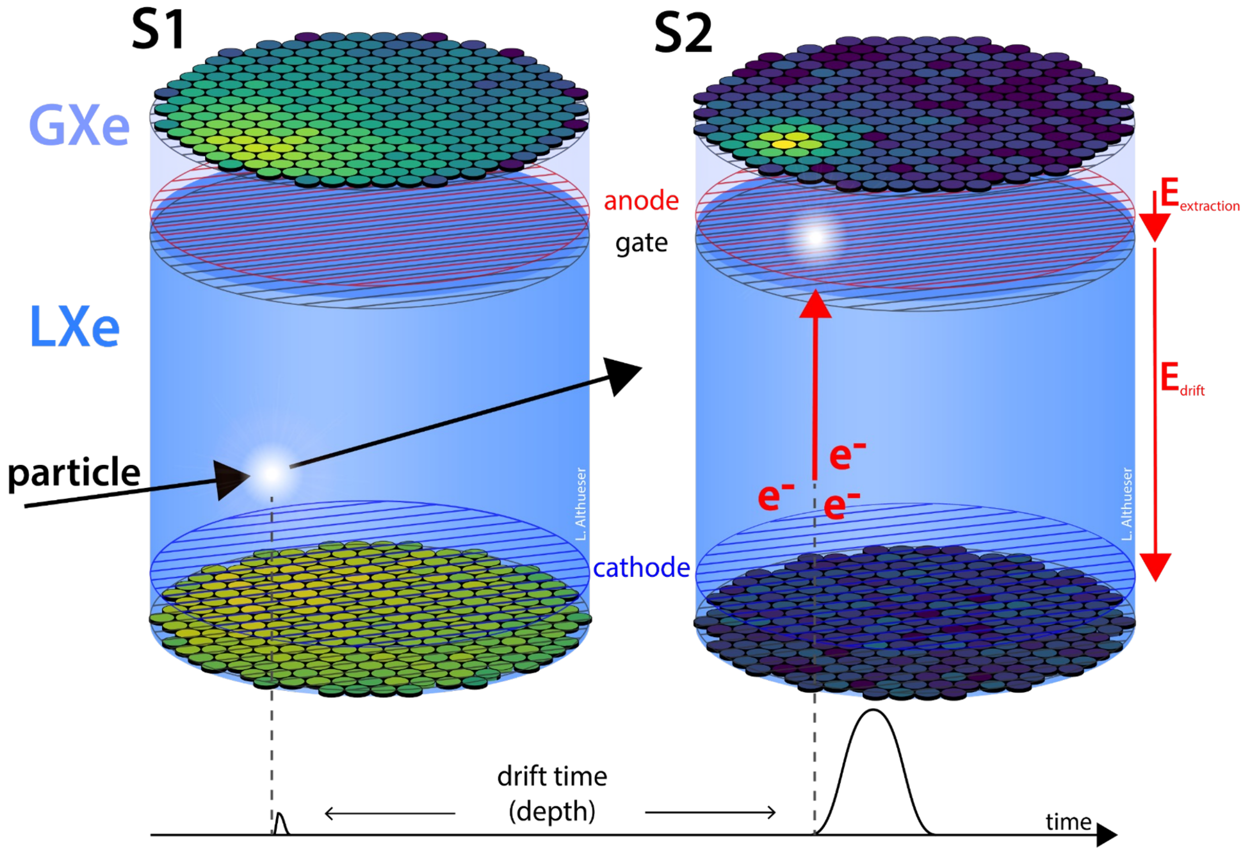
+1 Westlake University

Nagoya

Kobe

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

Dual-phase Time Projection Chamber (TPC)



Shengchao Li

Pairing two signals:

S1: prompt scintillation in **liquid**

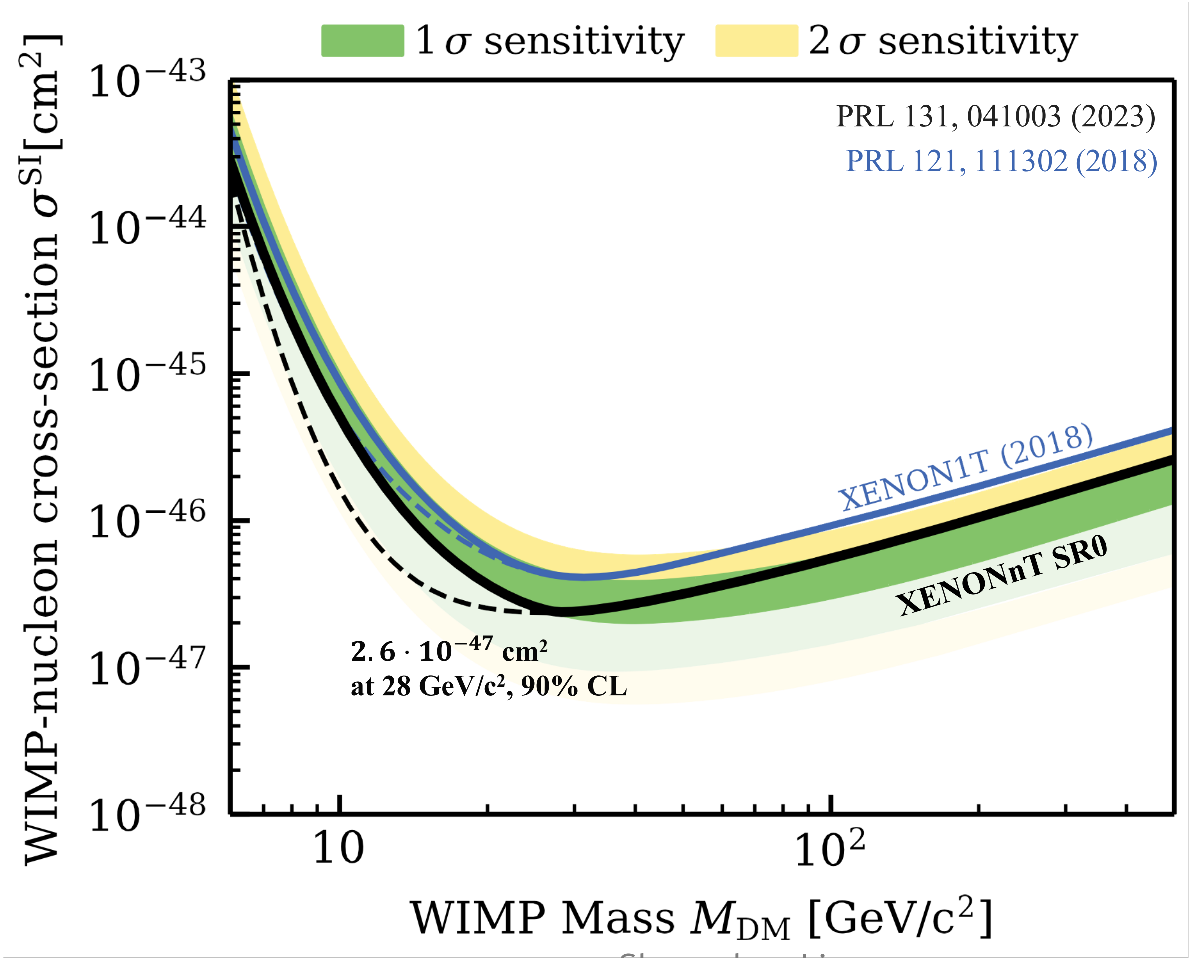
S2: delayed proportional scintillation in **gas**

3D information:

Hit pattern

+ drift time

WIMP Search in XENON



Weakly Interacting Massive Particle (WIMP):

- Most popular
- Thermal production valid up to the unitary limit (~10^4 GeV/c^2)
- High flux, low chance
  ⇒ single scatter

XENONnT SR0:

July 6 – Nov 10, 2021

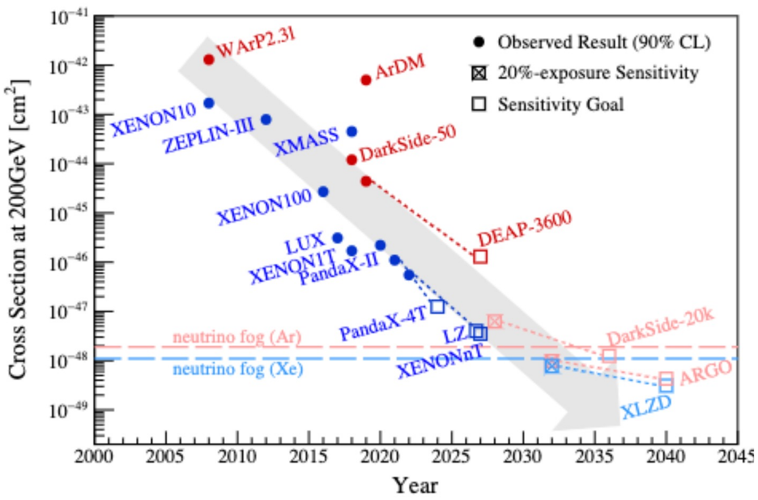
95.1 days lifetime corrected

(4.18 ± 0.13) t fiducial volume

1.1 tonne-year exposure

Delve Deep

10^5 in 20 years, will go below "neutrino floor/fog"



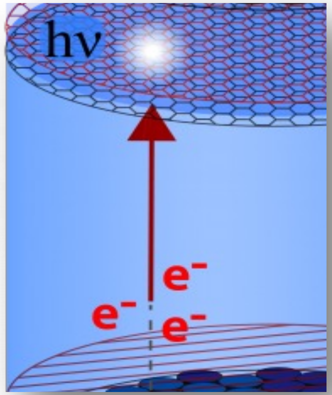
Single scatter
S1-S2 pair
"WIMP"

Search Wide

"fill the gap"

lower mass | higher mass

PRD 106 (2022) 2, 022001



S2-only

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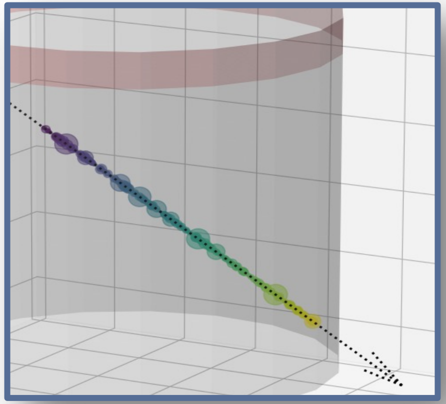
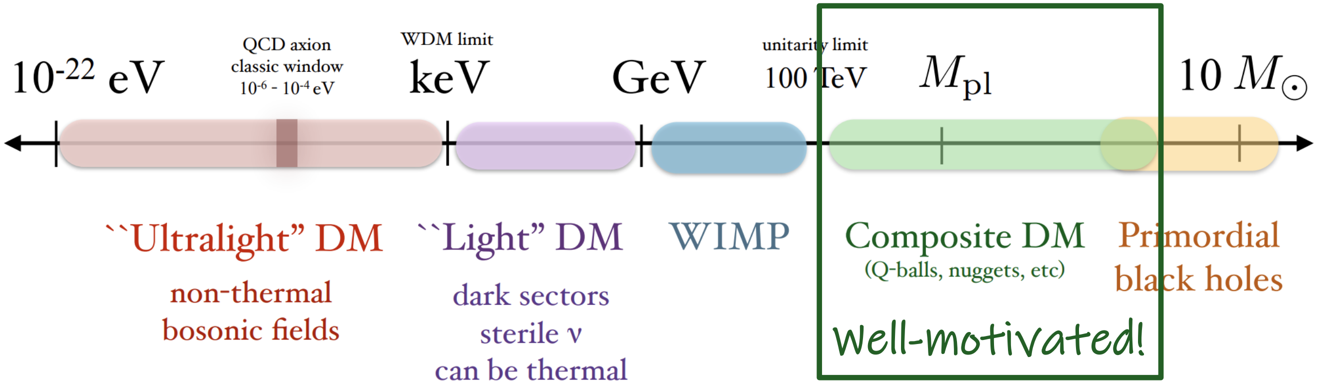


Multiple scatter

Dark Matter near the Planck Mass

Adapted from Lin 1904.07915



WIMP mass limited from GeV to 100 TeV, however:

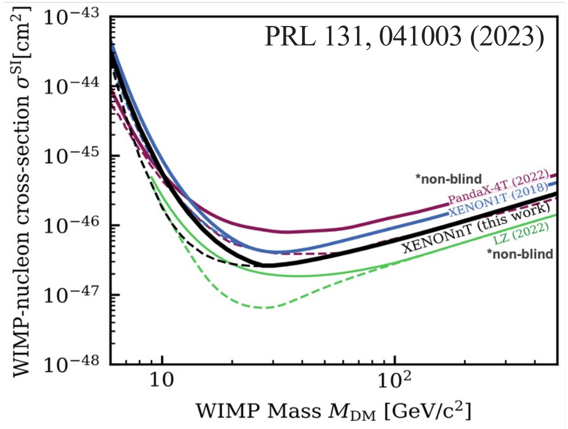
- Asymmetric annihilation can dominate relic abundance Kaplan+ 0901.4117

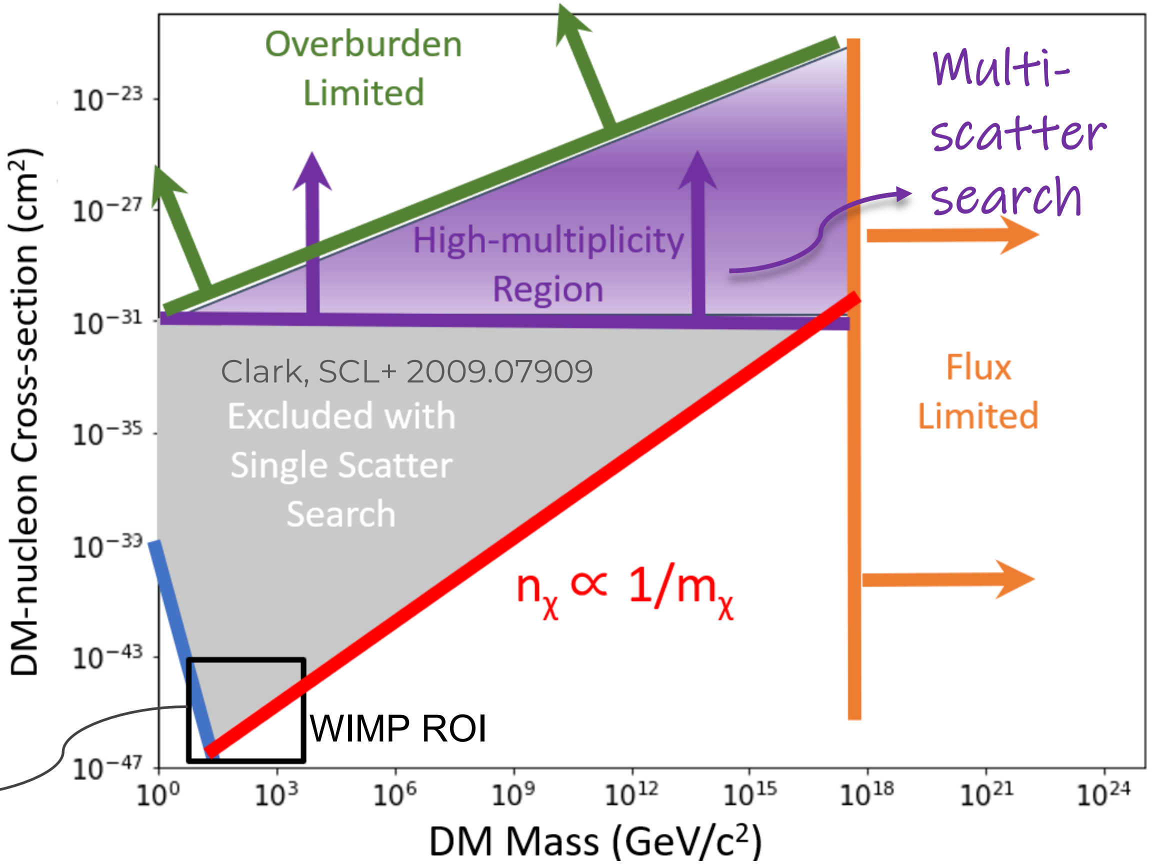
Non-thermal productions:

- Gravitational production MacGibbon 1987, Aharonov+ 1987
- Dark quark nuggets/composite states Detmold+ 1406.2276, Hardy+ 1504.05419
- Primordial black hole relics Detmold+ 1406.2276, Hardy+ 1504.05419
- Heavy dark monopoles Bai+ 2005.00503, Murayama+ 0905.1720

Filling up the Gap

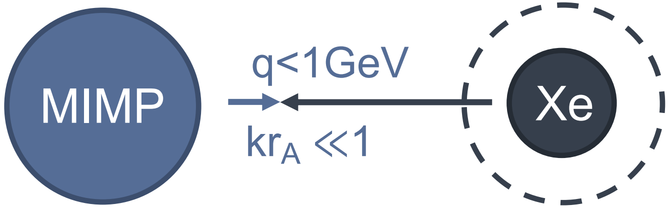
- $\rho_\chi \approx 0.3$ GeV/c² cm⁻³
- **Total flux limit**
  (1/m² · year)
- **Multiple scatters** dominate the high-mass DM signal
- Less constraint from **overburden** higher momentum





Introducing Multiply Interacting Massive Particles (MIMPs)

MIMP-Xe Kinematics



C.O.M. frame

r_A: characteristic nuclear radius

$$E_{max} = \frac{\mu^2 v^2}{m_A} \approx m_A v^2 \text{ (10 keV)} \ll \frac{1}{2} m_{MIMP} v^2 \text{ (>}10^9\text{ keV)}$$

Clark, SCL+, 2009.07909

$$\Omega_{max} \leq 1.7^\circ \left(\frac{m_A}{100GeV}\right)\left(\frac{10^{13}GeV}{m_{MIMP}}\right)\left(\frac{L_{det}}{1m}\right)\left(\frac{n_{det}}{10^{22}cm^3}\right)$$

Bramante+, 1803.08044

1st Born approx.: $f(k,\theta) \approx -2\mu_A \int_0^{r_A} V(r')r'^2 dr'$ for $kr_A<<1$

Digman+, 1907.10618

$$\Rightarrow \sigma_{\chi A} \propto \frac{\mu_A^2}{\mu_N^2} A^2 \sigma_{\chi N}$$

generic

*Consider $m_{MIMP}>10^{12}$GeV

- **Elastic scatter w/ negligible energy loss**
- **Colinear "track"**
- **A^4 enhancement?**

need: small effective potential area, i.e., elastic scattering cross-section

Magnetic Monopole as a DM Candidate

Bai+ 2005.00503

Dark t' Hooft-Polyakov monopoles:

$$\mathcal{L}_{\text{dark}} = \frac{1}{2}(D_\mu \Phi)^2 - \frac{1}{4}\text{Tr}(F_{\mu\nu}F^{\mu\nu}) - \frac{\lambda}{4}\left(|\Phi|^2 - f^2\right)^2$$

Production mechanism:

- Kibble-Zurek mechanism during a first or second order phase transition
- Inflation oscillations induce a parametric resonance during preheating

Monopole radius v.s. elastic scattering cross section:

$$\sigma^{\text{elastic}}_{N\textcircled{M}} \approx \frac{\sigma^{\text{elastic}}_{A\textcircled{M}}}{A^2} = 4\pi \frac{1}{A^2}\left|\frac{m_A}{q}\int_0^\infty dr\, r\, \sin(qr)\, V(r)\right|^2$$

$V(r) \rightarrow A\, y_{hNN}\,(h(r) - v)$ Higgs profile around the EW-symmetric monopole

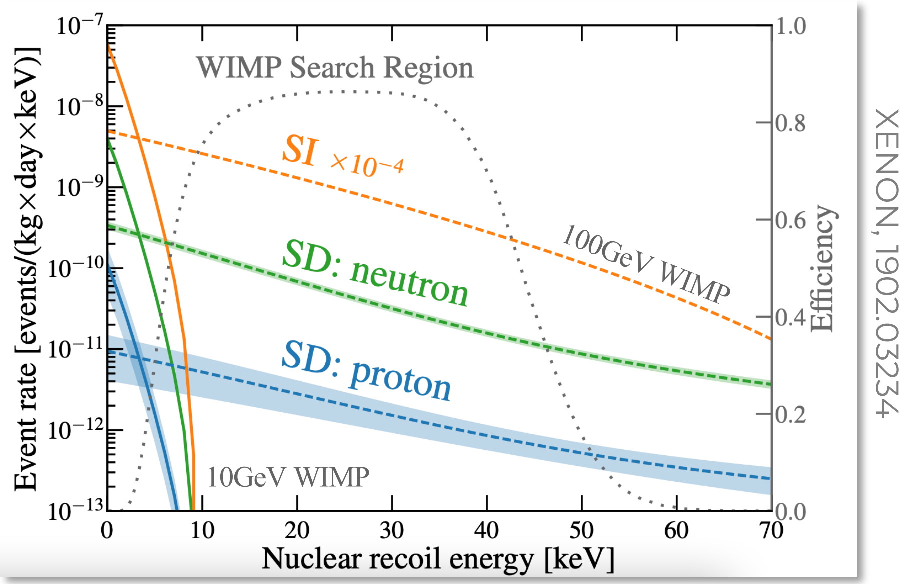
$$\approx \frac{16\pi}{9} m_N^2 A^2 y_{hNN}^2 v^2 R^6_{\textcircled{M}} \Rightarrow \sigma \sim R^6 \text{relation}$$

With larger radius, saturates at the geometric cross section $\sigma^{\text{elastic}}_{A\textcircled{M}} \approx 2\pi R^2_{\textcircled{M}}$

MIMP-Xe Scattering Cross-sections

$$\lambda = n_{\mathrm{Xe}} \int d\vec{v} \int dq^2 \frac{d\sigma_{A,\chi}}{dq^2} f(\vec{v})$$

$$\frac{d\sigma^{\mathrm{SI}}_{A,\chi}}{dq^2} = \frac{\mu^2_{A,\chi}}{\mu^2_{\mathrm{nucleon},\chi}} A^2 |F_A(q)|^2 \sigma^{\mathrm{SI}}_{\mathrm{nucleon},\chi} \qquad \frac{d\sigma^{\mathrm{SD}}_{A,\chi}}{dq^2} = \frac{4}{3}\frac{\pi}{2J+1}\frac{\mu^2_{A,\chi}}{\mu^2_{n/p,\chi}} S_A^{a_0=1,a_1=\mp1}(q)\sigma^{\mathrm{SD}}_{n/p,\chi}$$

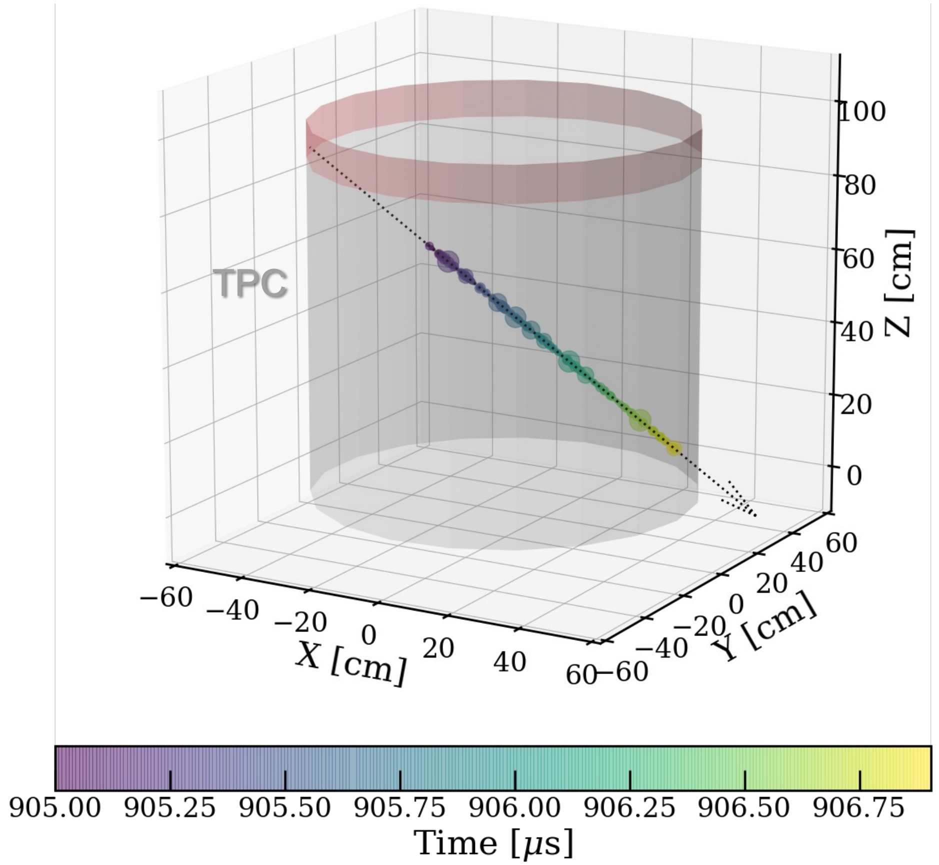


v is the lab-frame velocity of the isothermal DM halo

Max(q^2) of a 10^{18}GeV MIMP and a 1TeV WIMP differ by **20%**
⇒ Similar form factor integrals

Consider: spin-independent(SI) and spin-dependent(SD) cases (^{131}Xe, ^{129}Xe)

MIMP Track-like Signature



$$t = \left(\frac{L_{det}}{1m}\right)\left(\frac{10^{-3}c}{v_{MIMP}}\right) \cdot \mathbf{1\mu s}$$

$$0.2\mu s < \mathbf{1\mu s} < 100\mu s$$

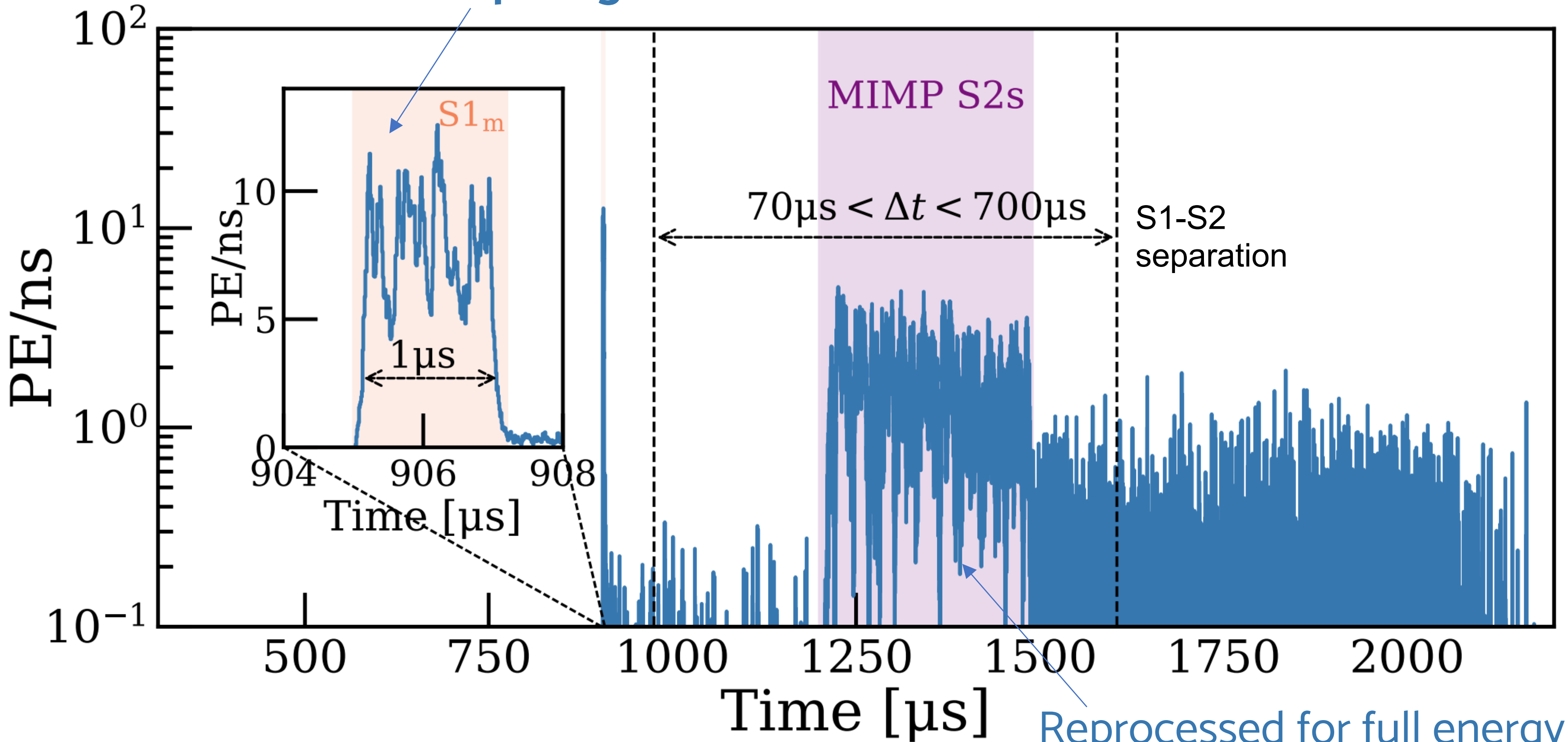
S1 S2

Prompt long-duration scintillation signal in liquid Xe
⇒ "Smoking gun" signature, *almost* background-free

Strong ionization signal to follow
⇒ Directional DM detection
(*future efforts)

Simulated MIMP Waveform

Unique signature of MIMP

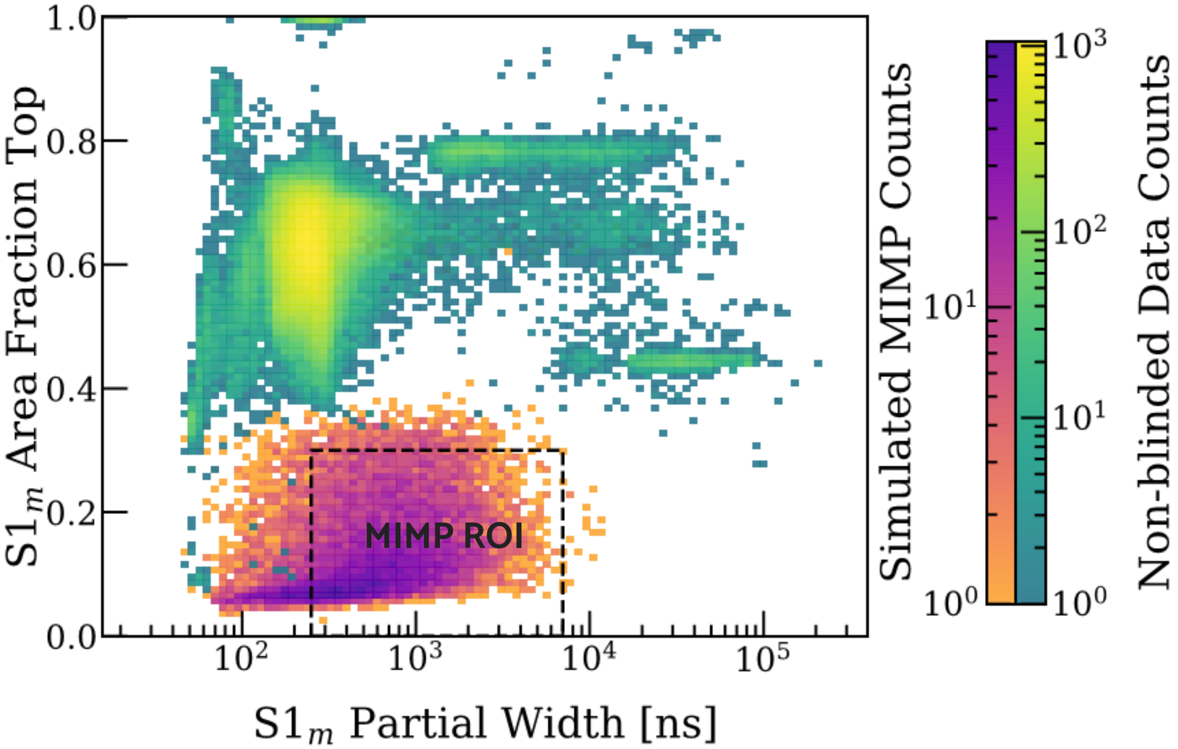


Reprocessed for full energy

MIMP Track-like Signature

*4% validation dataset, after quality cuts

Location in the TPC



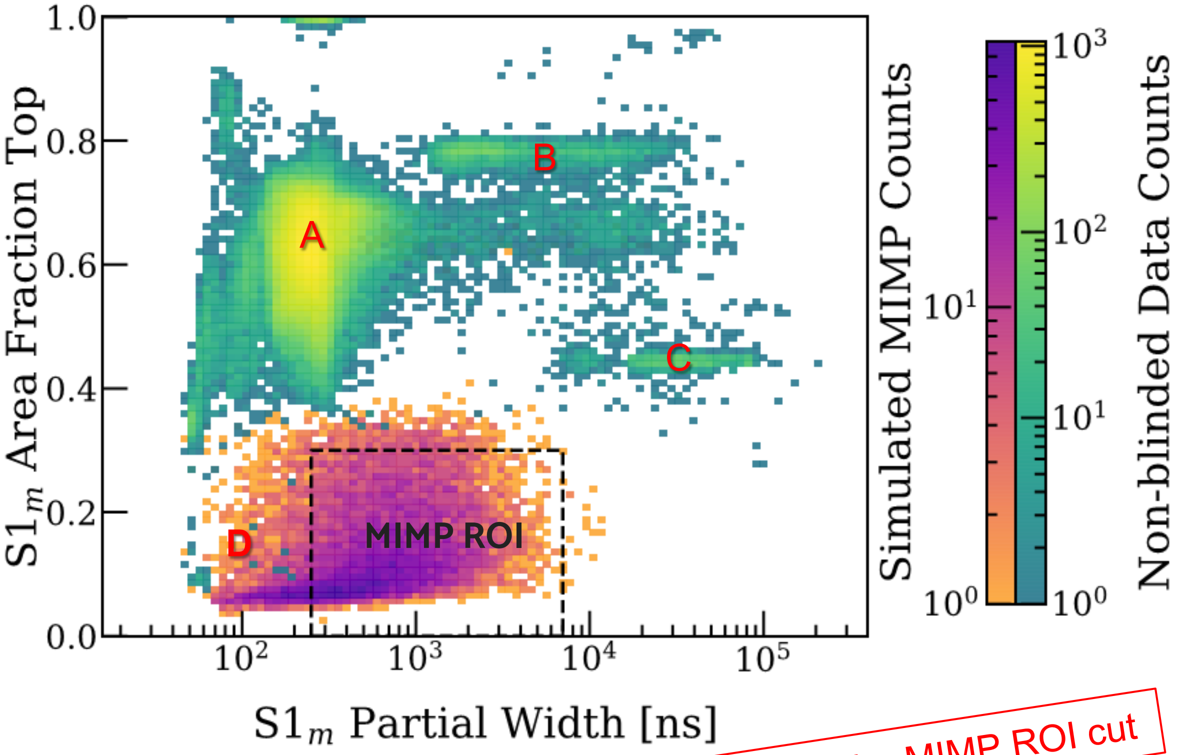
Time spent in the TPC

Here, MIMP tracks with various orientations and multiplicity are simulated, overlaid with pre-unblinded data

The **duration** and **location** of the light form a strong combination in selecting MIMP signals

Backgrounds of MIMP Search

*4% validation dataset, after quality cuts



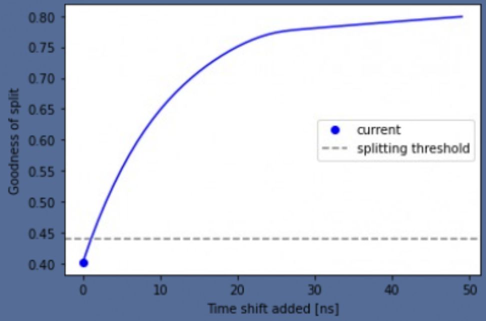
Excluded by the MIMP ROI cut

A: isolated S2 (gas, near-electrodes)

B: merged S1-S2 peak

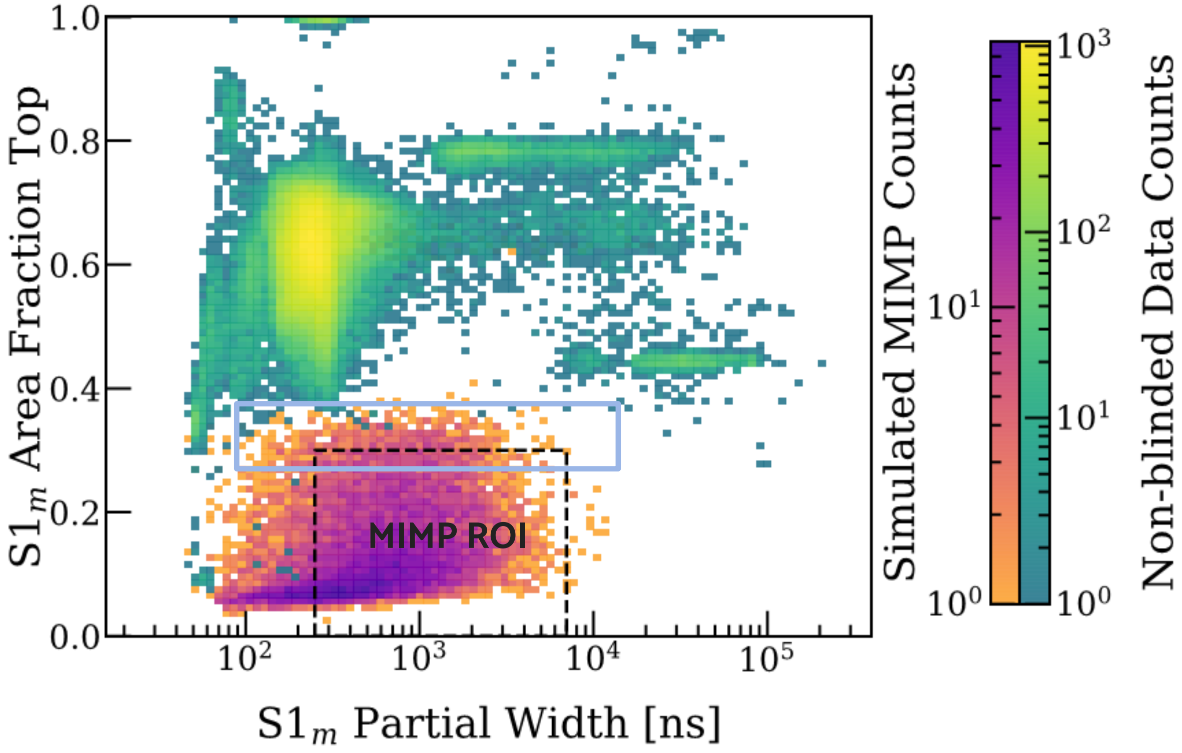
C: baseline fluctuation due to PMT flasher

D: merged S1-S1 peak from consecutive ^{212}BiPo or ^{214}BiPo decays, consistent with rate expectation



Muon Background

*4% validation dataset, after quality cuts



O(5000) cosmic muons crossed our TPC in LNGS

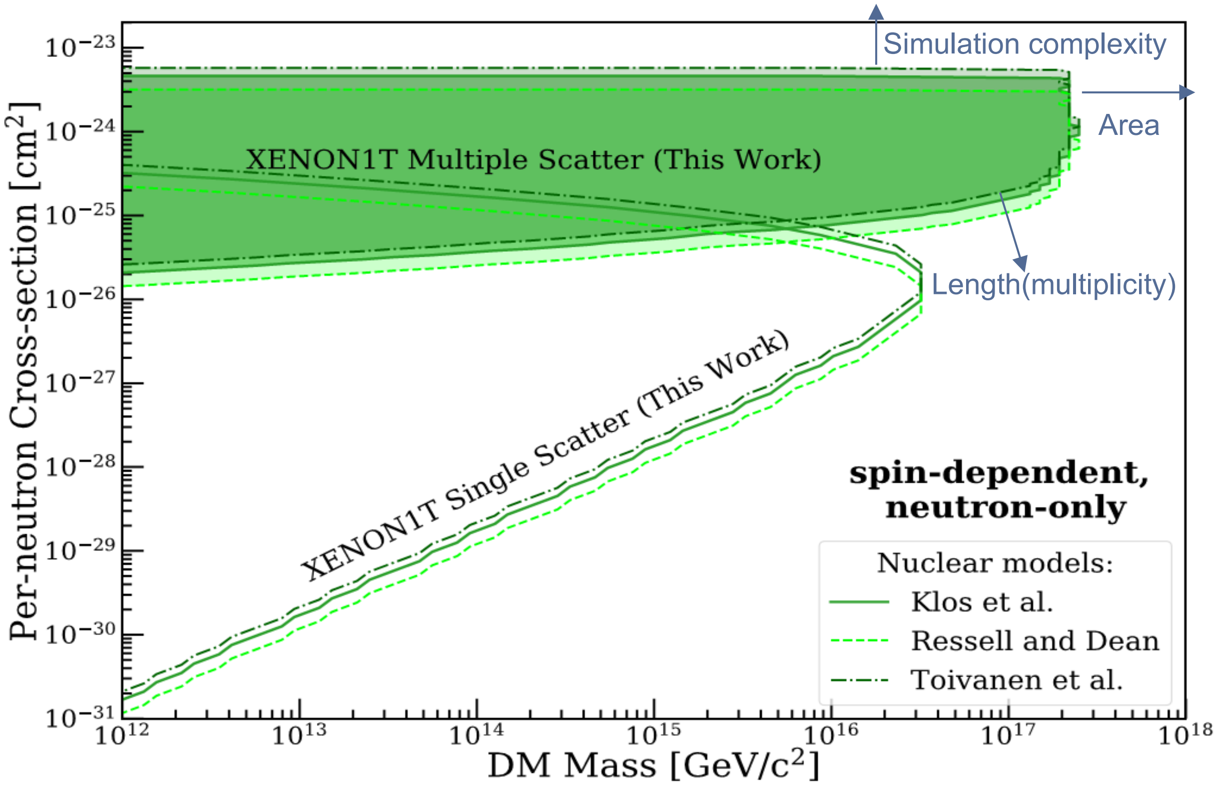
O(1)ns crossing time, but… vertical muons can *simultaneously* ionize the gas and liquid xenon, producing fake signals overlapping the MIMP ROI

This effect was studied with a “muon dataset” tagged by a water Cherenkov muon veto

XENON, 1406.2374 (2015)

0.5% leakage possibility gives **0.05 background**

Spin-dependent Limits (neutron)

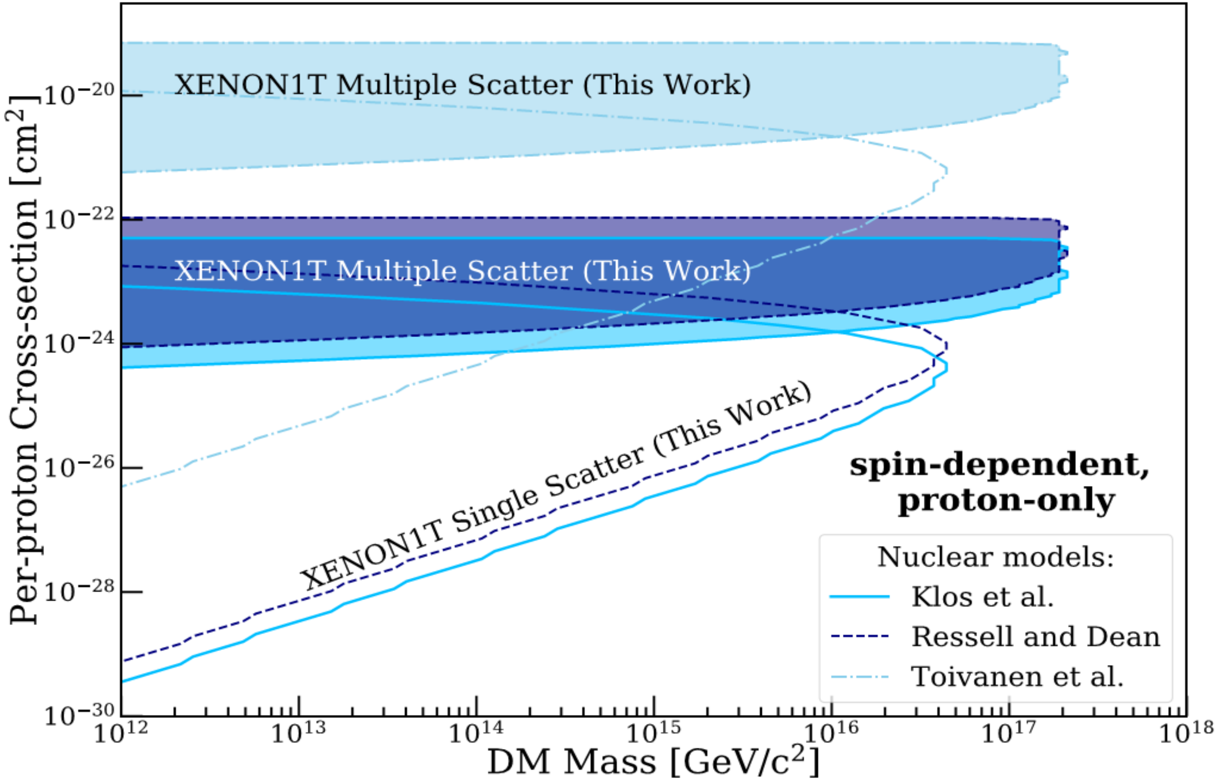


Zero MIMP candidates in 188.7 m²×day exposure

First spin-dependent constraint

Strong MIMP-neutron limit due to unpaired neutrons in xenon nuclei that are naturally abundant

Spin-dependent Limits (proton)

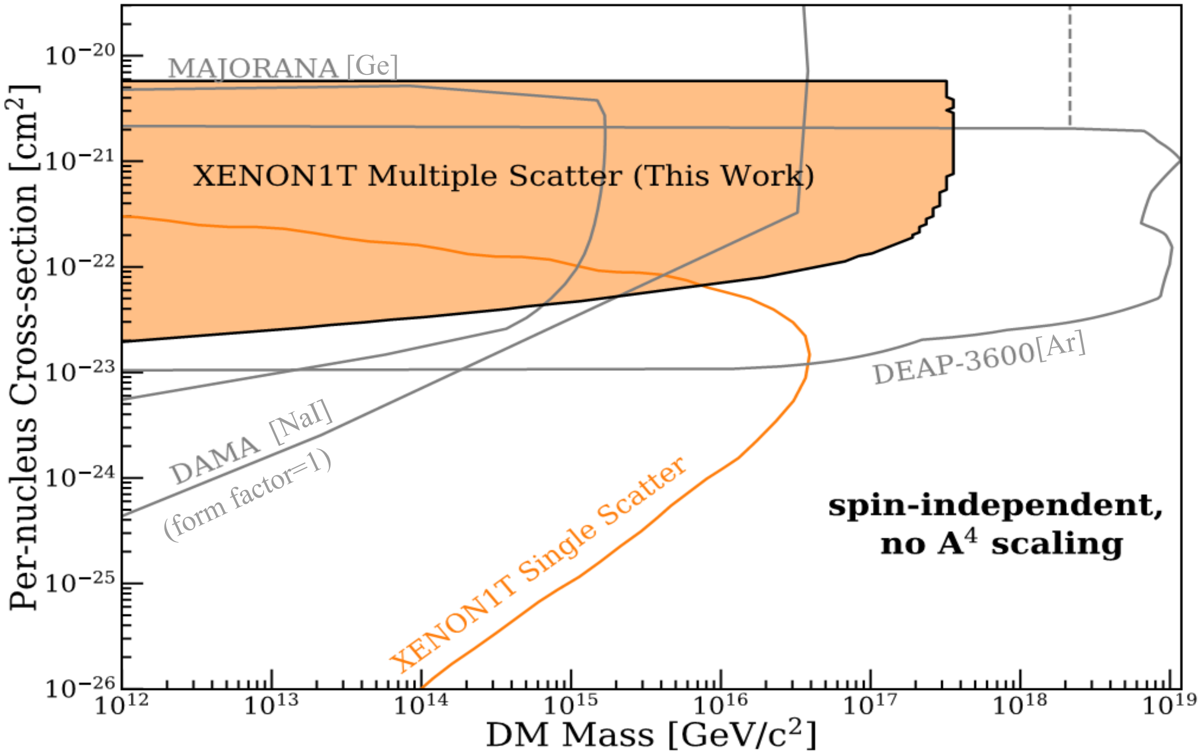


Zero MIMP candidates in 188.7 m^2×day exposure

First spin-dependent constraint

MIMP-proton scattering limit dominated by theoretical uncertainty

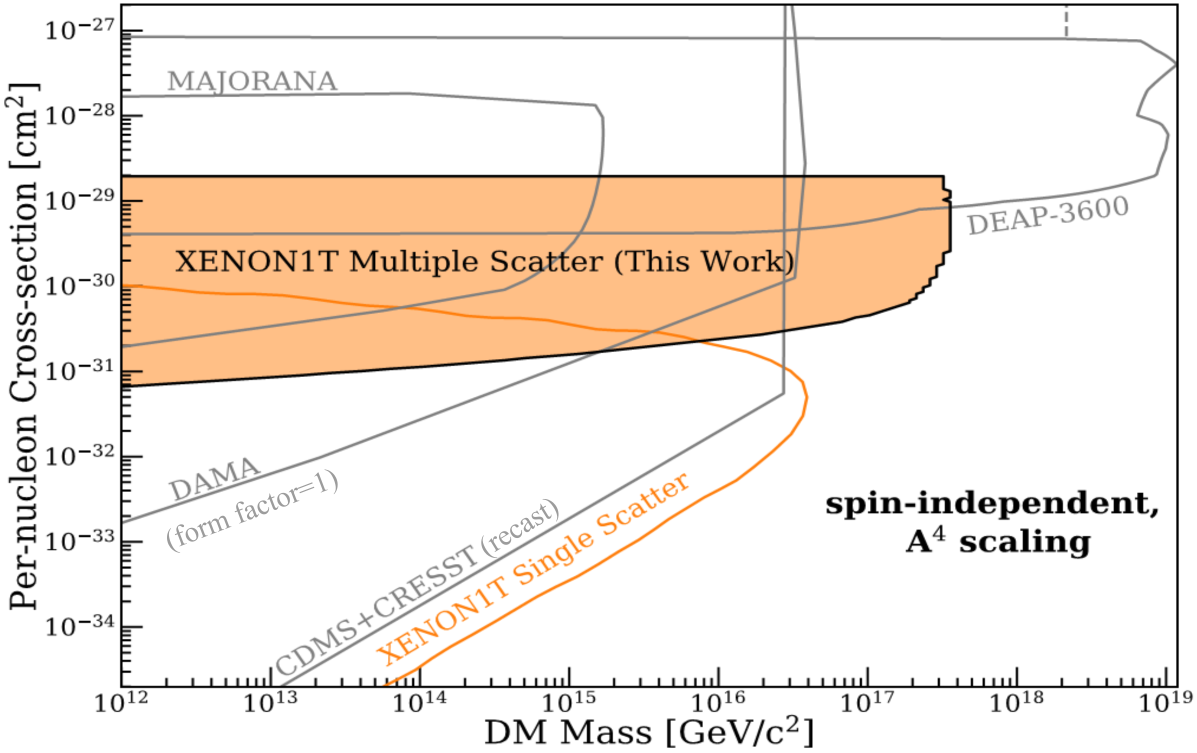
Spin-independent Limits (no scaling)



Zero MIMP candidates in 188.7 m^2×day exposure

Assume MIMP is opaque to the nucleus
⇒ per-nucleus basis to compare across different detector targets

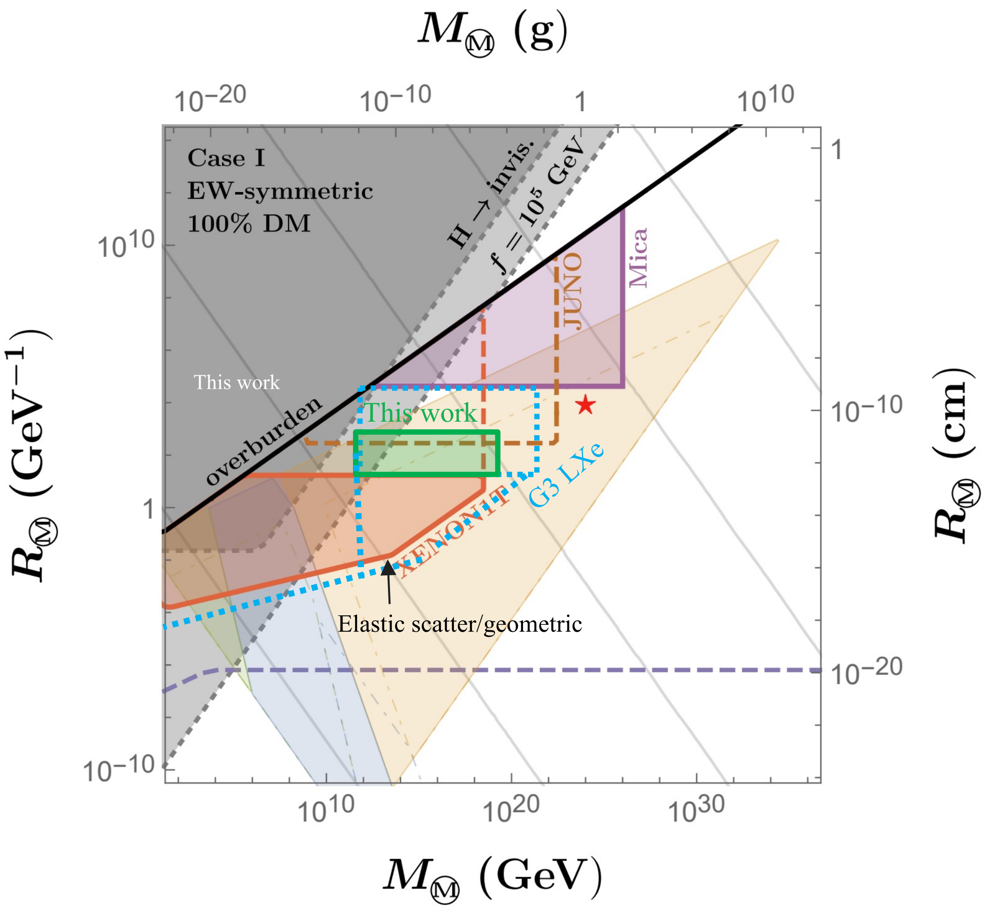
Spin-independent Limits (A^4 scaling)



Zero MIMP candidates in 188.7 m²×day exposure

Probed new DM parameter space in mass and cross-section by factors of 10~20

Limit on Dark Monopole



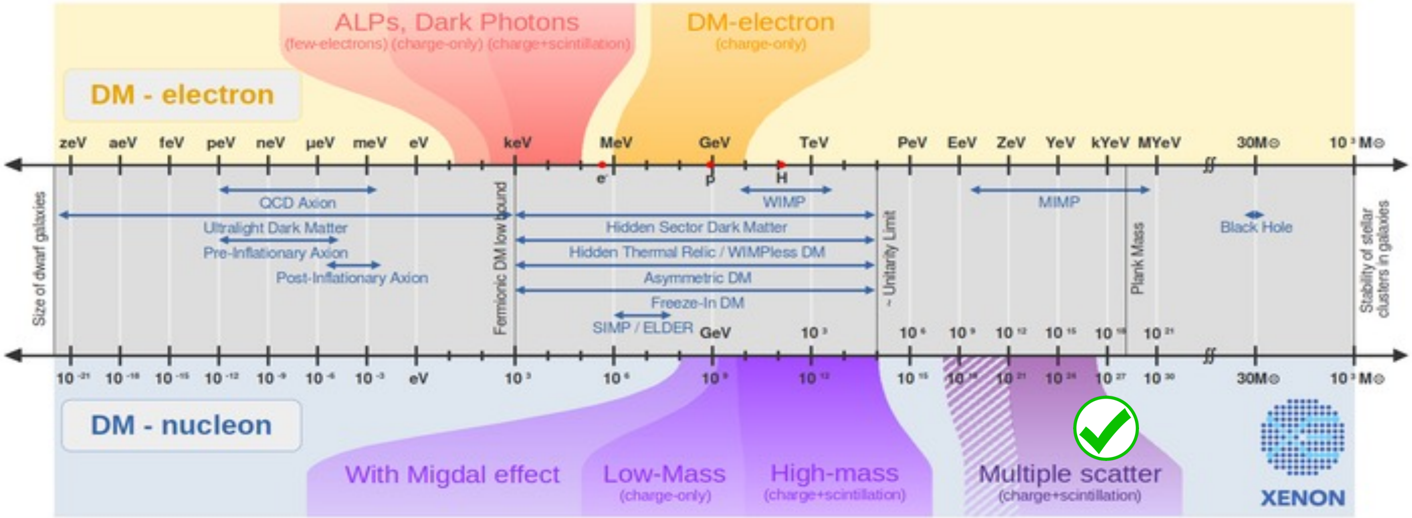
We adapted the Fig. 5 from *Bai+ 2005.00503* to show constraints on dark monopole mass and radius

Green box is our new multi-scatter limits adapted schematically from SI cross sections

Blue lines show the sensitivity prediction for the next generation LXe experiments

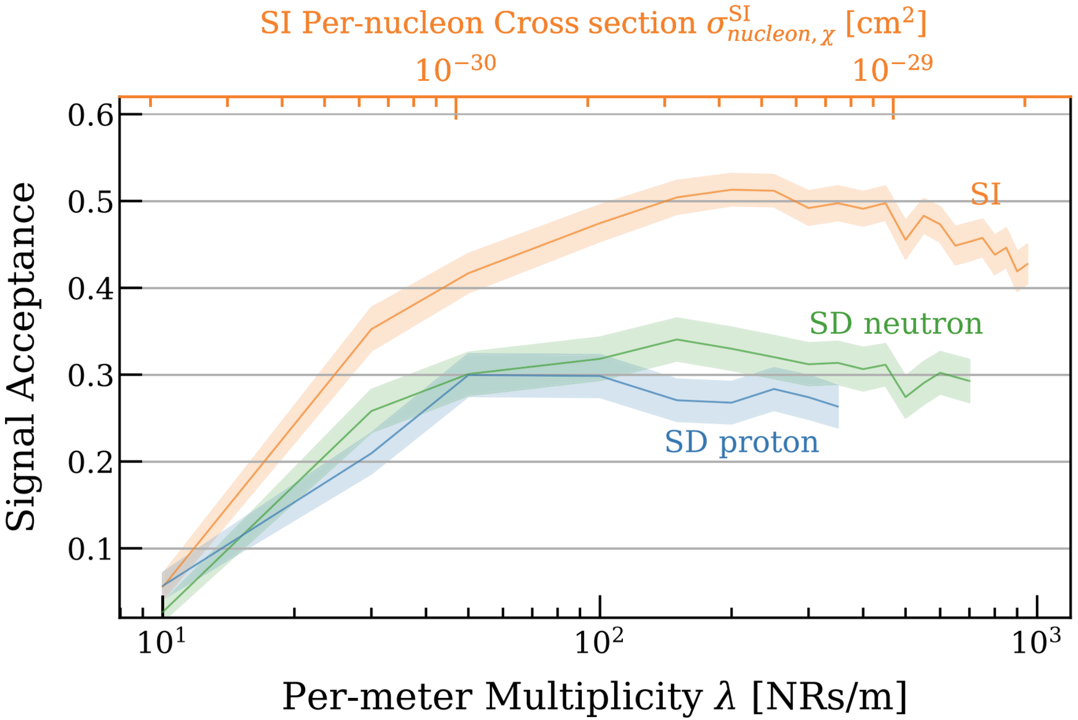
Takeaways

- **Ton-scale liquid xenon TPC** can be used for searching DM models with a much expanded mass range
- The idea of **ultraheavy DM** is theoretically motivated (e.g., dark monopoles) and experimentally accessible
- With a large total mass and heavy nucleus, a “track” search in XENON1T set **new constraints** on ultraheavy DM close to the Planck mass



Backups

Signal Acceptance



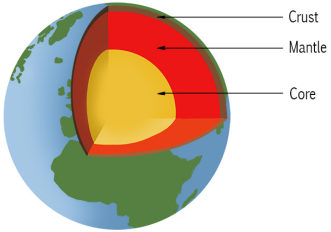
From the Monte Carlo simulation

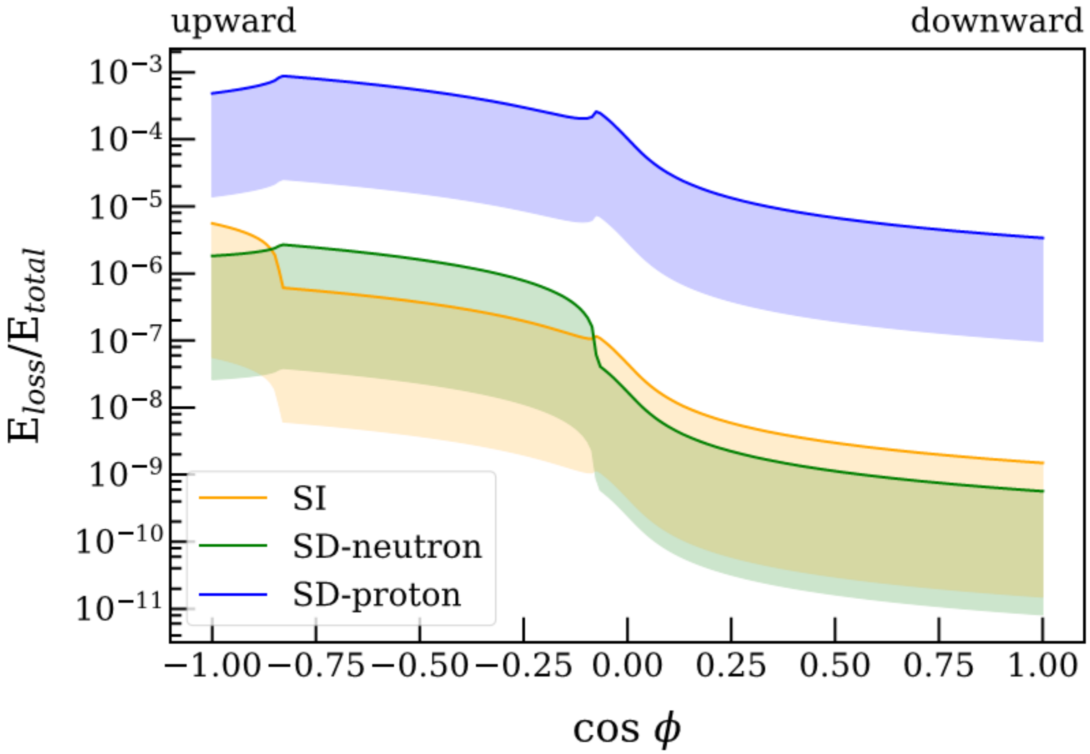
62% geometric acceptance included

SD w/ lower acceptance due to higher energy NR causing waveform fluctuation

Maximum cut-off due to computational complexity

Earth's Overburden





For heavy MIMP, its energy loss modeled as a continuous process along a straight trajectory across Earth

Effect is below 1% level for the cross-section simulated

DM-Xenon Interactions

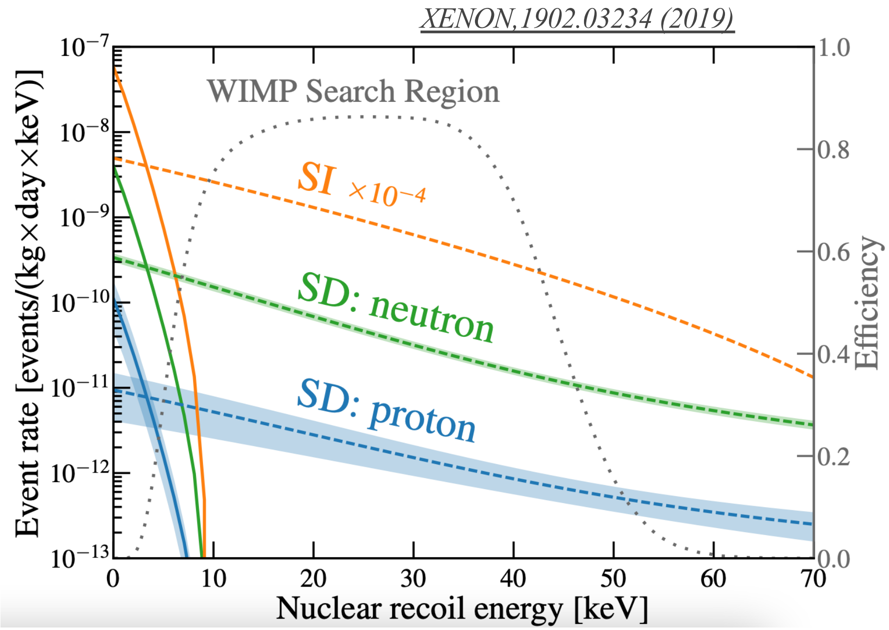
Spin-independent:

$$\frac{d\sigma^{\mathrm{SI}}_{A,\chi}}{dq^2} = \frac{\mu^2_{A,\chi}}{\mu^2_{\mathrm{nucleon},\chi}} A^2 |F_A(q)|^2 \sigma^{\mathrm{SI}}_{\mathrm{nucleon},\chi}$$

Spin-dependent:

$$\frac{d\sigma^{\mathrm{SD}}_{A,\chi}}{dq^2} = \frac{4}{3}\frac{\pi}{2J+1}\frac{\mu^2_{A,\chi}}{\mu^2_{n/p,\chi}} S_A^{a_0=1,a_1=\mp 1}(q)\sigma^{\mathrm{SD}}_{n/p,\chi}$$

$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J}|(a_0+a_1)\langle S_p\rangle + (a_0-a_1)\langle S_n\rangle|^2$$



LZ Preliminary Limits

- Focus on low multiplicity and collinearity
- Better in cross-section due to larger exposure
- Did not go into high multiplicity due to resolution