

# First Directional Search for Magnetic Inelastic Dark Matter in XENONnT



David Ant3n-Martin

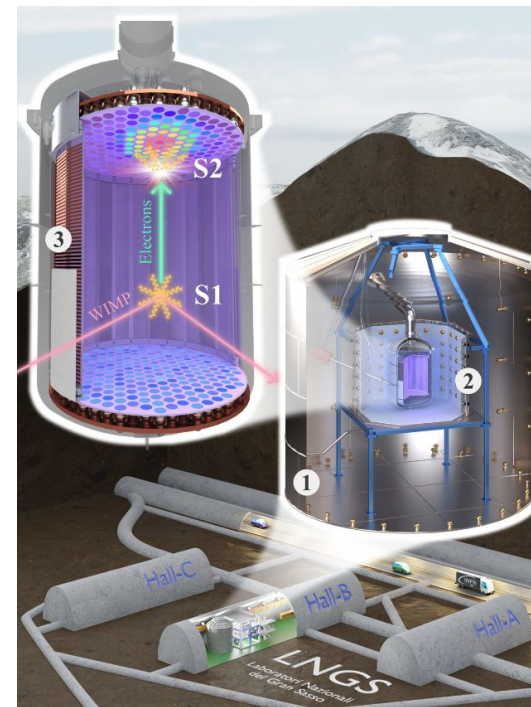
Les Rencontres de Noirmoutier  
June 1st 2026



# The XENONnT experiment

**XENONnT**: current iteration of the XENON program.

Located in the underground laboratories of LNGS, Italy.

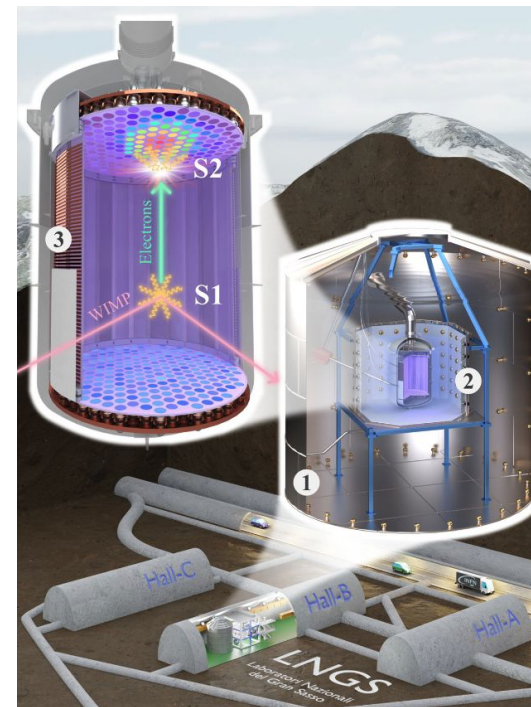


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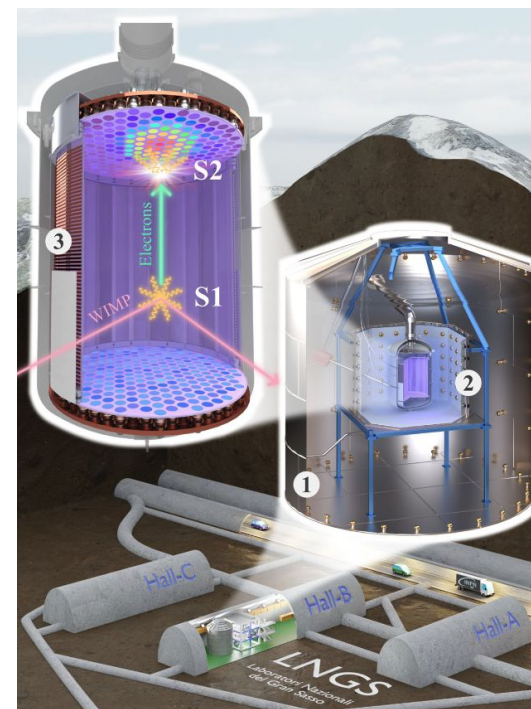
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**3-D position reconstruction** of energy depositions

- $(x, y)$  : from S2 hit patterns
- $z$  : from S1-S2 time delta



# The XENONnT experiment

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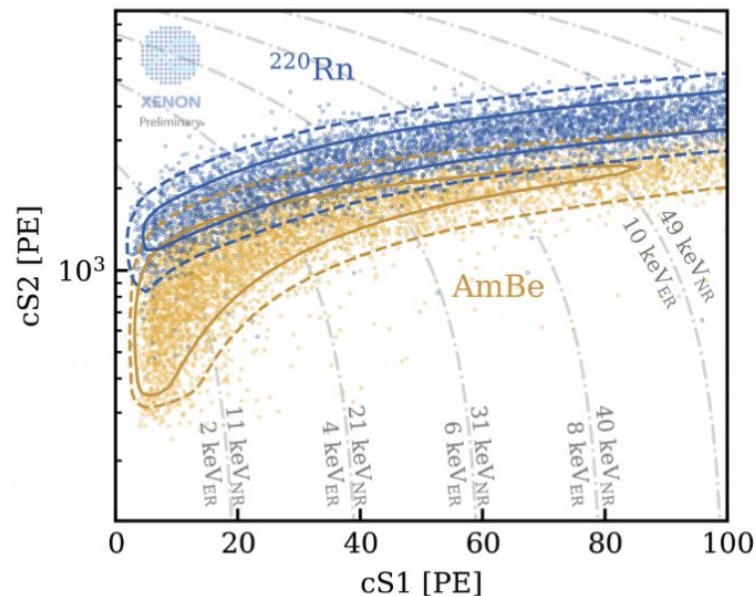
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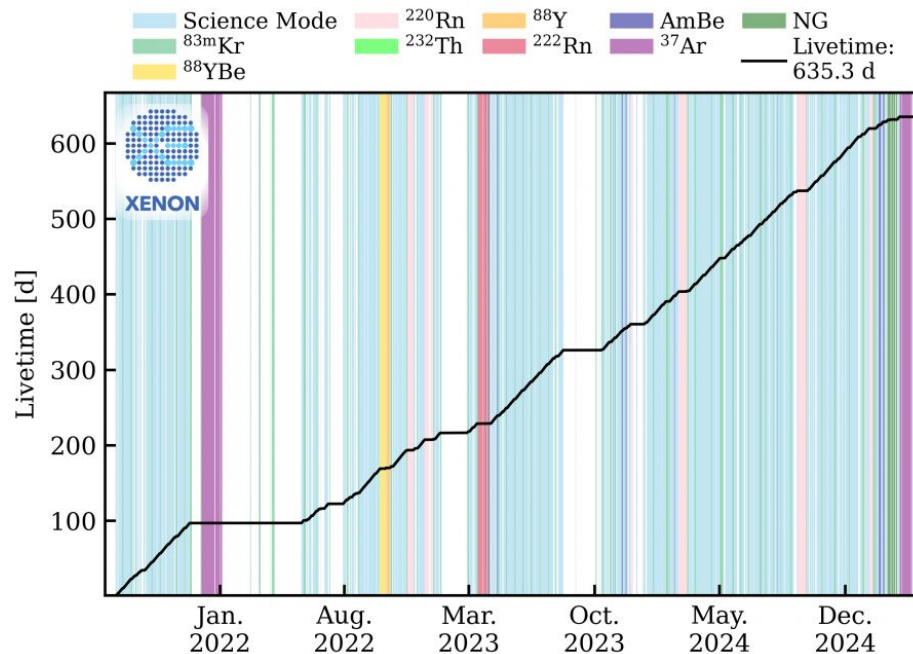
- $(x, y)$  : from S2 hit patterns
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**Discrimination of NRs from ERs**



# The XENONnT experiment

First **commissioned in 2020/21**, XENONnT underwent an upgrade campaign in 2025/26.

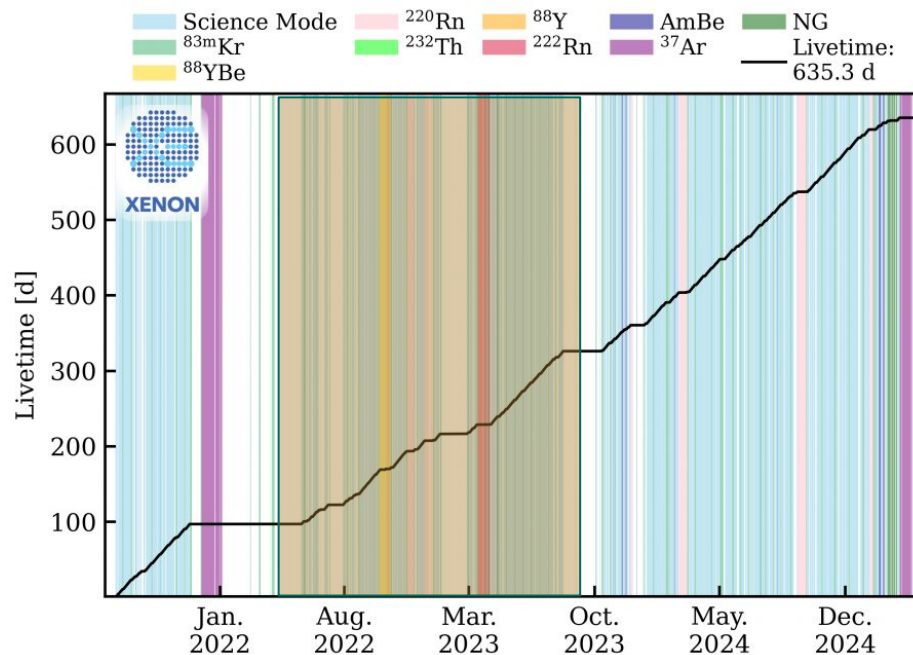


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Acquired 6.8 ton-years of exposure

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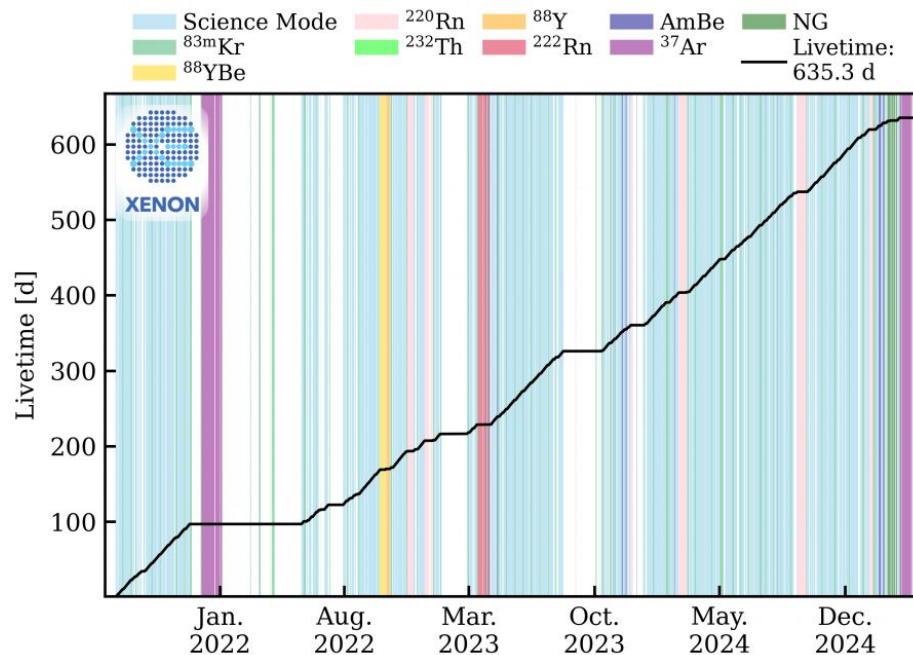
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## Blinded analysis & search:

- Signal and background modeling
- Event selection
- Statistical framework

All developed w/o access to the ROI data




# The MiDM model

MiDM features **2 finely split DM mass states**, mediated by a **magnetic dipole**  $\mu_\chi$

# The MiDM model

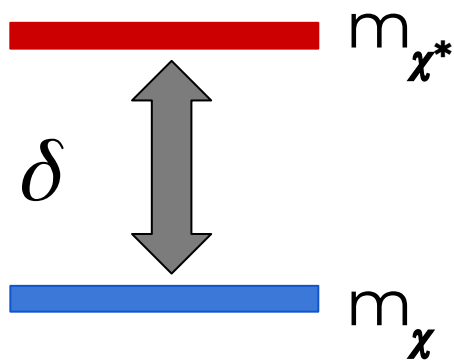
MiDM features **2 finely split DM mass states**, mediated by a **magnetic dipole**  $\mu_\chi$

Parameter	ROI for XENONnT
Mass of the ground state	$m_\chi \in (20 \text{ GeV}/c^2 \text{ to } 5 \text{ TeV}/c^2)$

  $m_\chi$

# The MiDM model

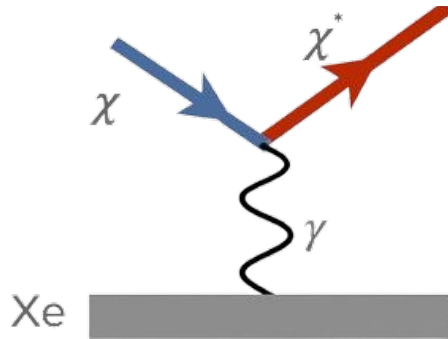
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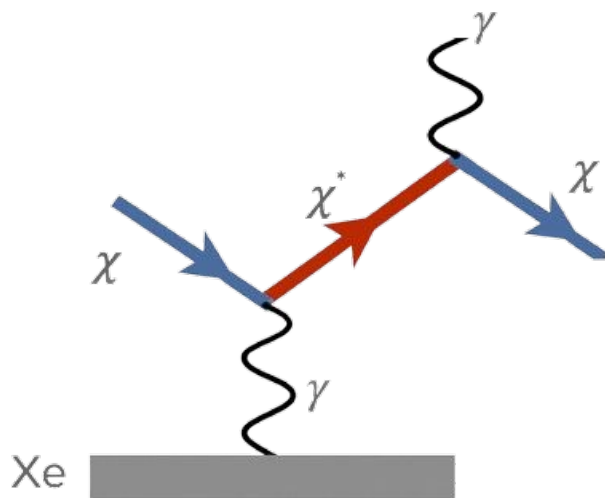
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Magnetic dipole moment	$\mu_\chi \in (0 \text{ to } 10 m\mu_N)$

# The MiDM model

MiDM features **2 finely split DM mass states**, mediated by a **magnetic dipole**  $\mu_\chi$



Spontaneous decay of the excited state by **photon emission**

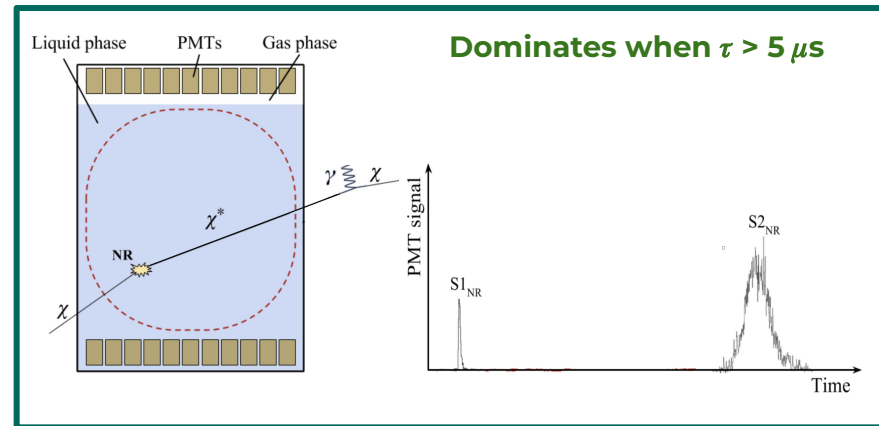
$$\tau = \frac{\pi}{\delta^3 \mu_\chi^2} = (79.3 \mu s) \left[ \frac{100 \text{ keV}}{\delta} \right]^3 \left[ \frac{10^{-3} \mu_N}{\mu_\chi} \right]^2$$

# MiDM signatures in XENONnT

The decay of  $\chi^*$  can take place:

**Outside the detector:** only the scatter is detected

→ Pure NR, with similarities to WIMP analysis

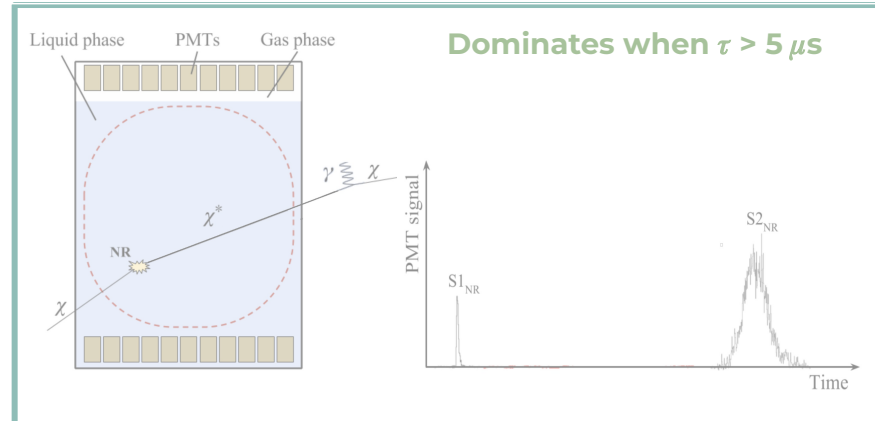


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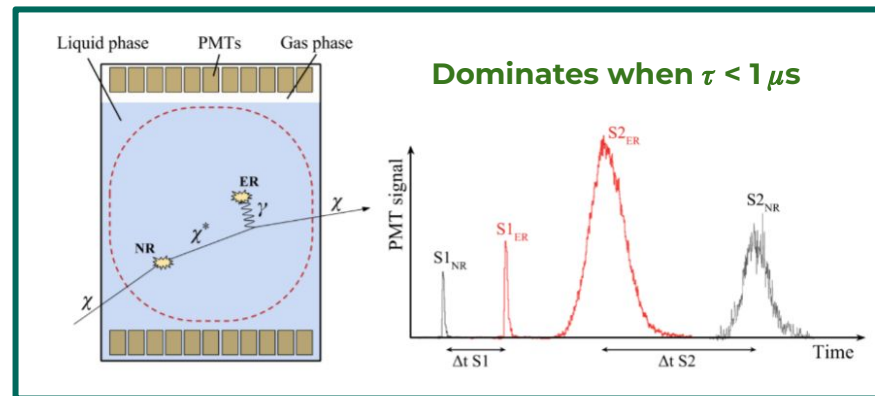
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**Inside the detector:** scatter and decay are detected

→ NR + ER, novel signal topology and analysis

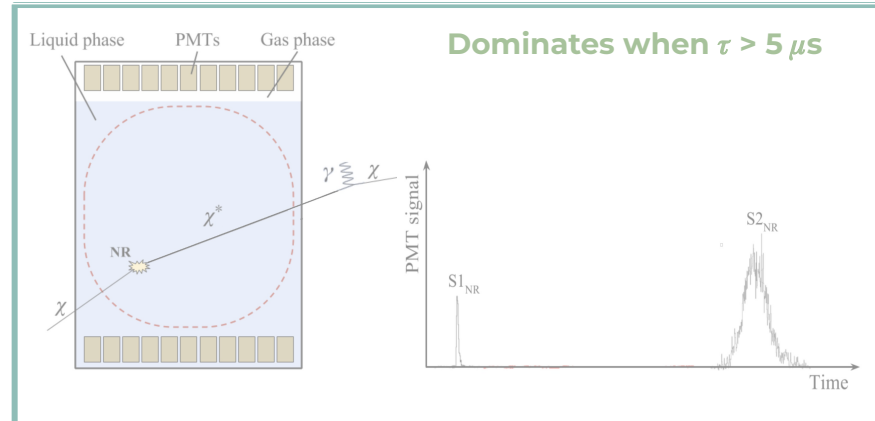


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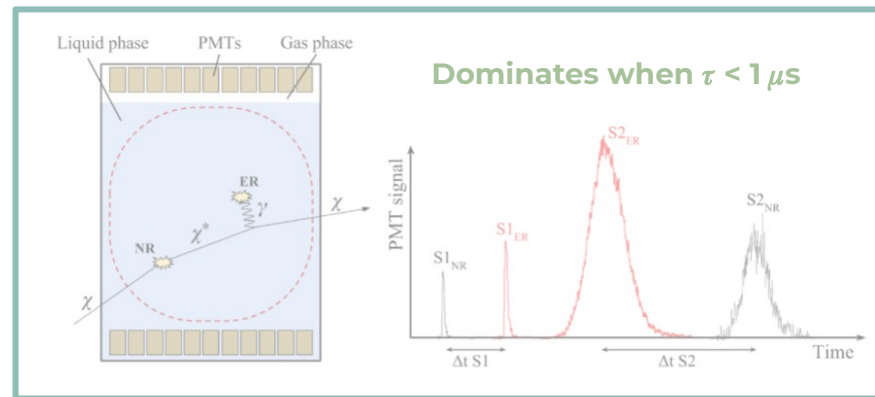
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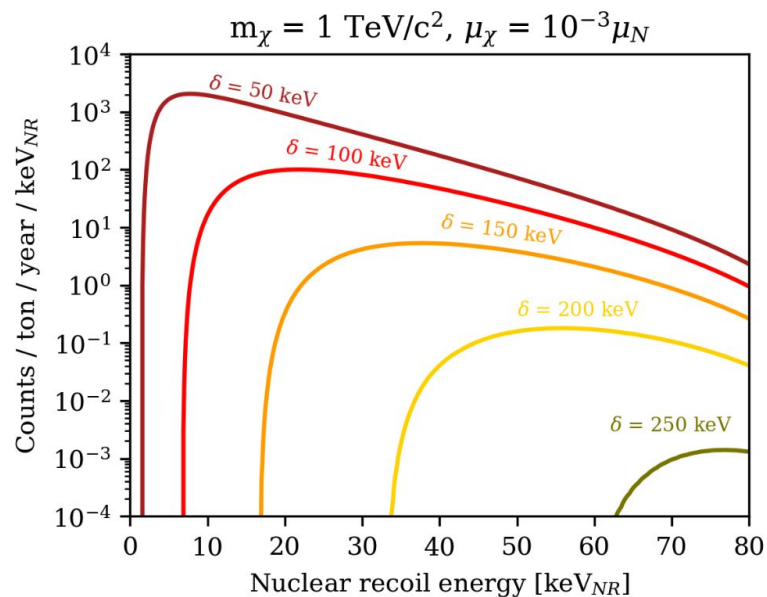
The search takes into account **both cases**.

Analyses are carried out separately and **merged at the statistical inference level**.

# MiDM signal modeling: nuclear recoils

Signal templates are obtained for all  $m_\chi$  and  $\delta$ .

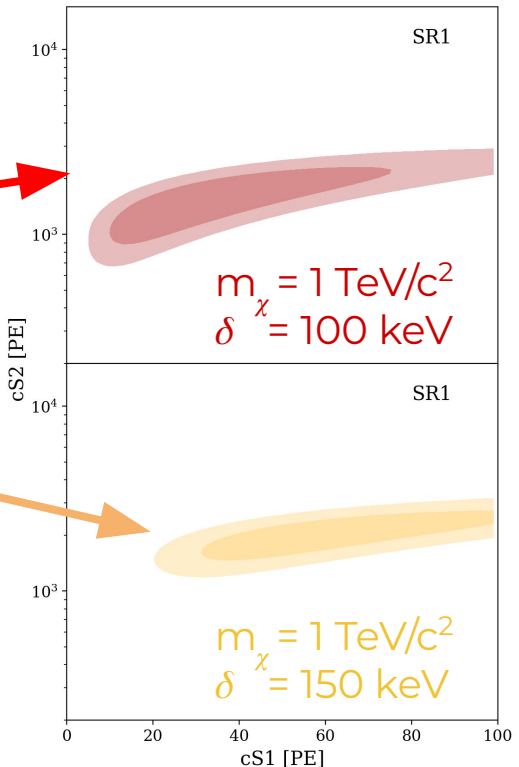
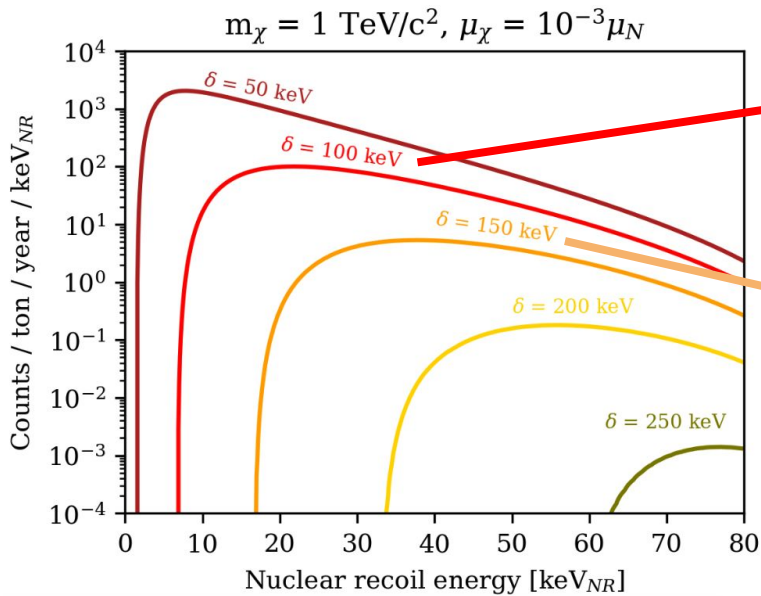
→ Obtained through response simulation from MiDM recoil energy spectrum.



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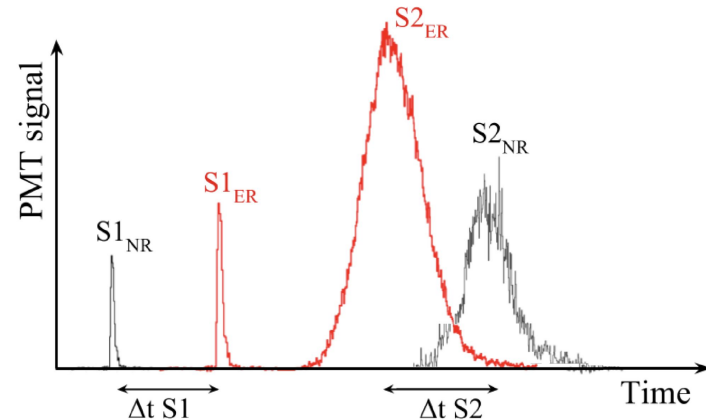
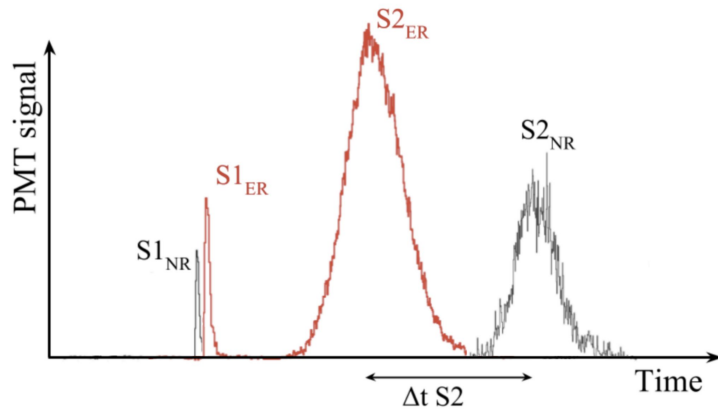


# MiDM signal modeling: full-chain simulations

Study	Description
<b>Reconstruction accuracies</b>	Signal size and positions, event velocities and directionality

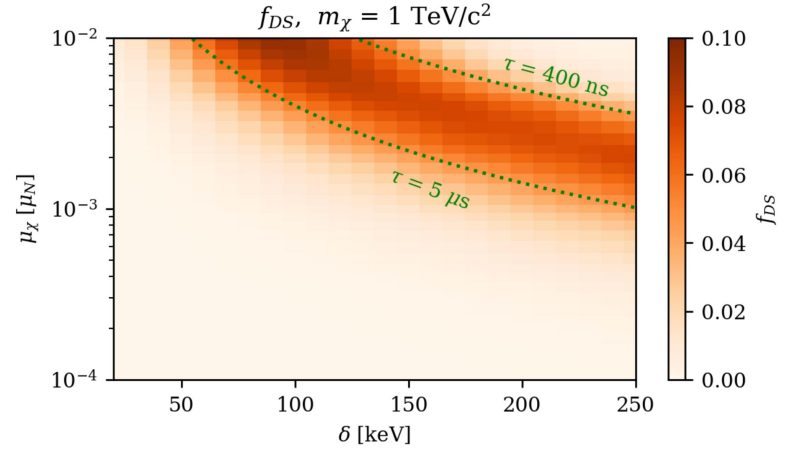
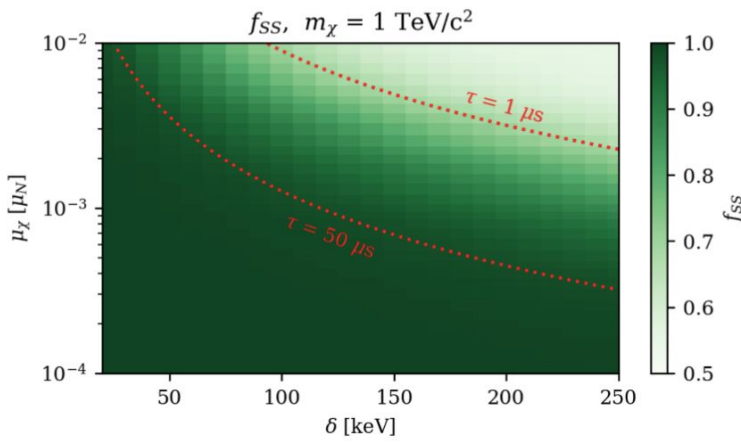
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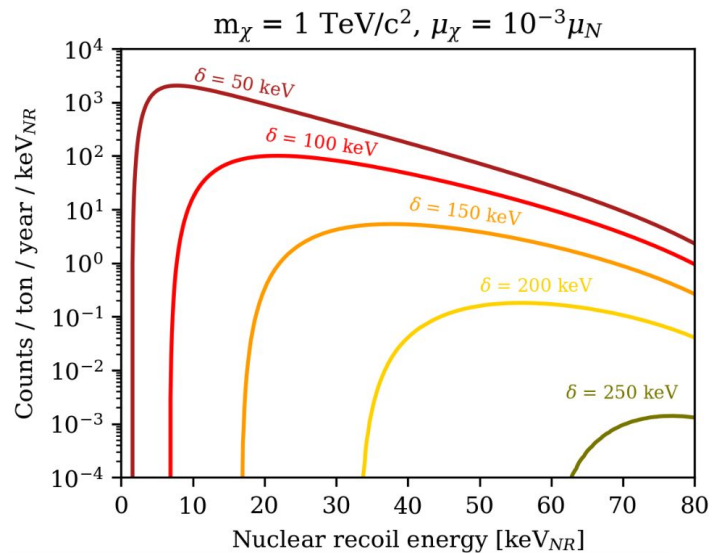
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<b>Signal topology split</b>	Fraction of NR-only vs. NR + ER signals.



# Double-site signals: kinematic and velocity selections

## Kinematic selection

MiDM-induced **NR and ER energies are correlated** by conservation of momentum.

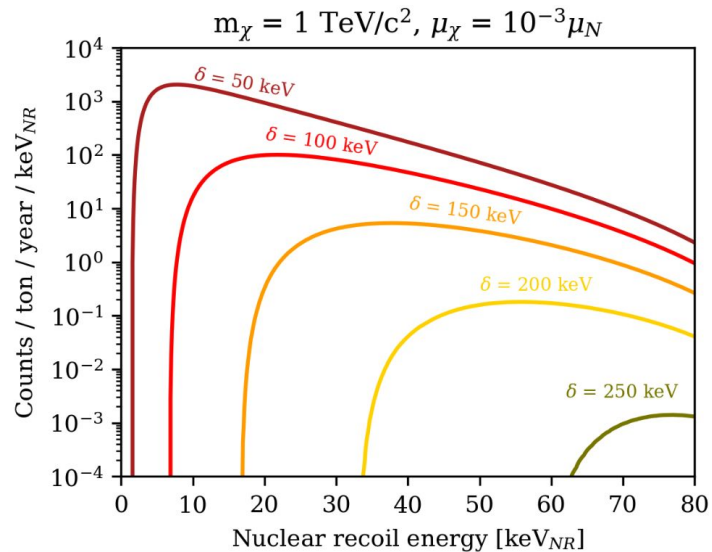


## Velocity selection

# Double-site signals: kinematic and velocity selections

## Kinematic selection

MiDM-induced **NR and ER energies are correlated** by conservation of momentum.



## Velocity selection

**Speed of  $\chi^*$  is bound** by the scatter kinematics

→ Reconstructed from NR-ER time and position.

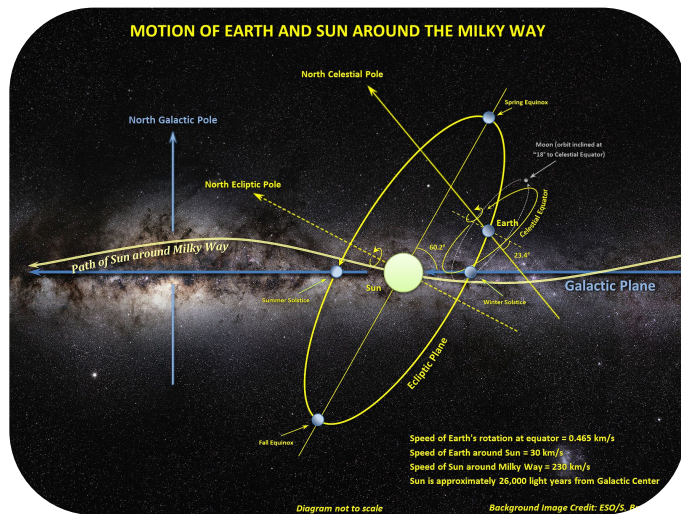
→ **Accuracy verified** through simulations

$$v_*^{max}(E_R) = \sqrt{(v_E + v_{esc})^2 - 2(E_R + \delta)/m_\chi},$$

$$v_*^{min}(E_R) = \left| \frac{E_R \left( \frac{m_N}{m_\chi} - 1 \right) - \delta}{\sqrt{2m_N E_R}} \right|$$

# Double-site signals: directional selection

DM particles move isotropically in the galactic frame, but Earth has a **net velocity**.

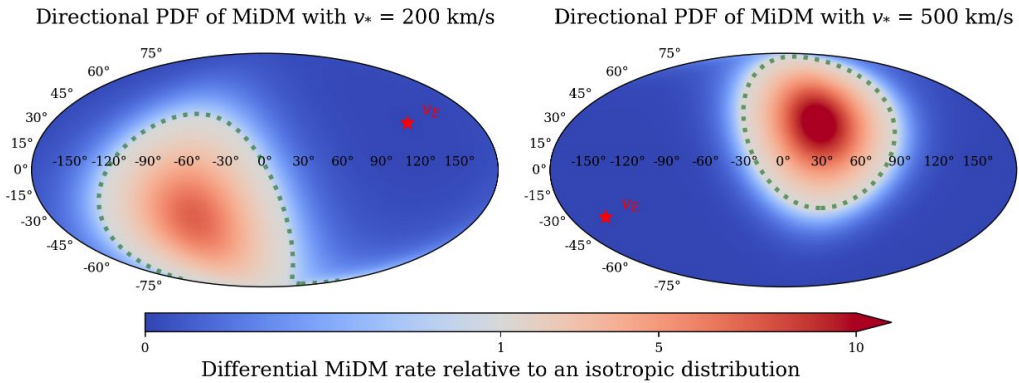
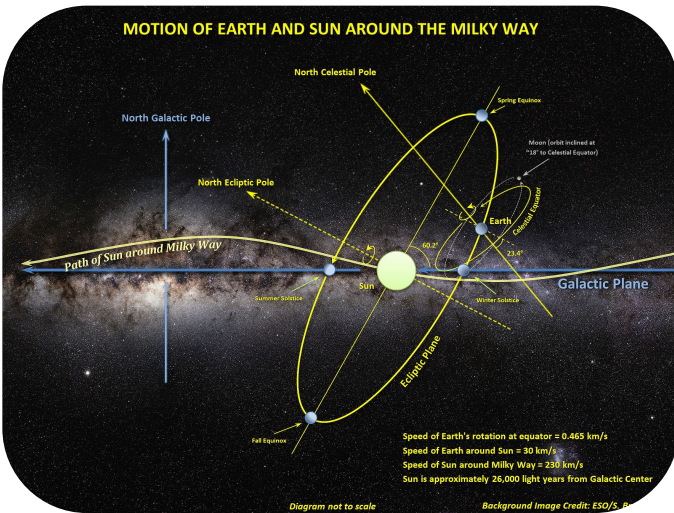


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DM particles move isotropically in the galactic frame, but Earth has a **net velocity**.

→ Directional clustering is **significant since  $\mathbf{v}_E \approx \mathbf{v}_\chi$**

→ Signal-to-background boosted by a factor  $\sim 5$



# Backgrounds in the search for MiDM

Single-site channel

Double-site channel

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Electronic recoils, accidental coincidences  
and surface events → same as WIMP search

Expectation of ~**800 background events**

Double-site channel

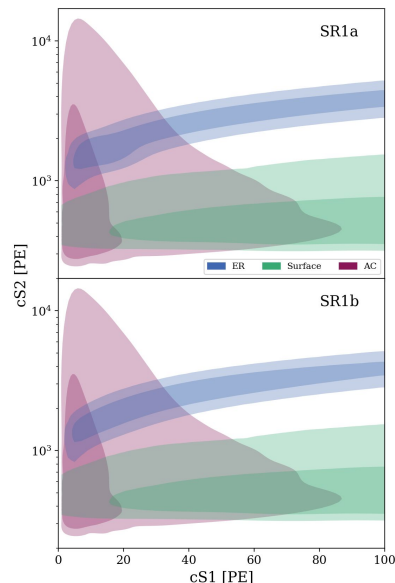
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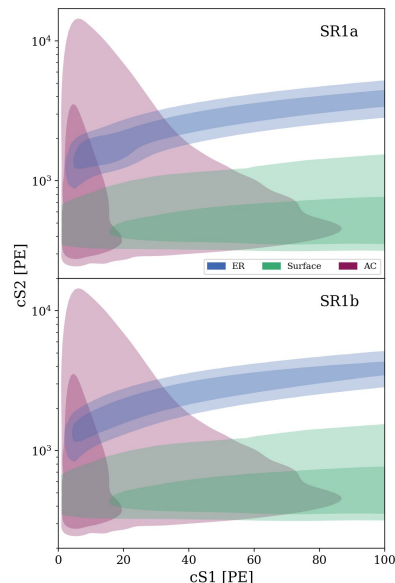
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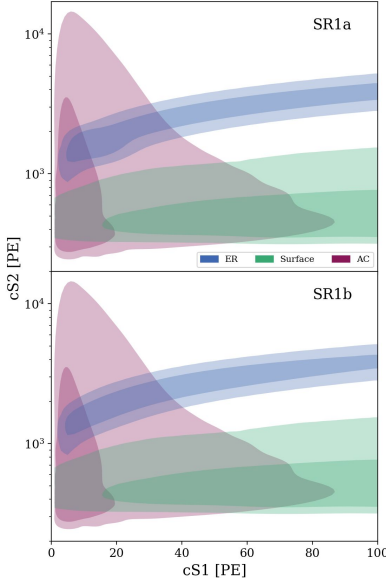
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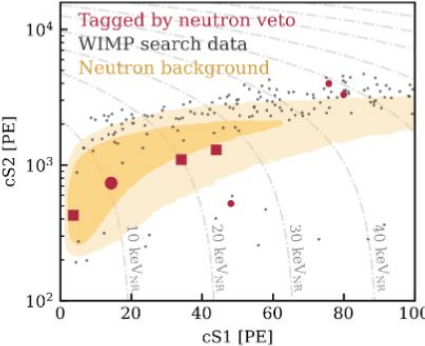
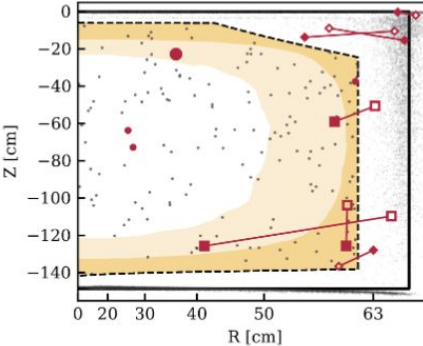
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Neutrons are emitted by radioactive impurities in the detector materials.



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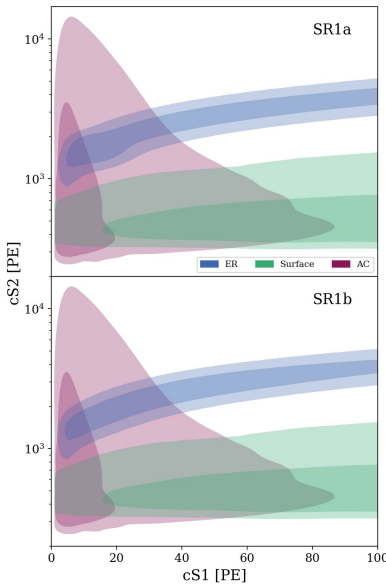
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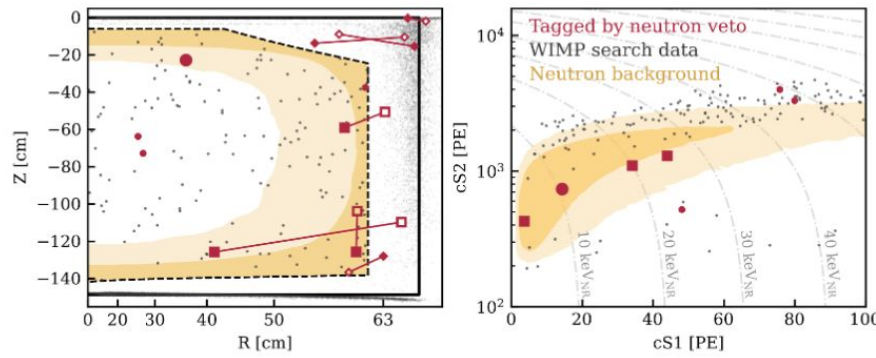
## Double-site channel

Neutrons are emitted by radioactive impurities in the detector materials.

Expectation of ~0.001 bkg events

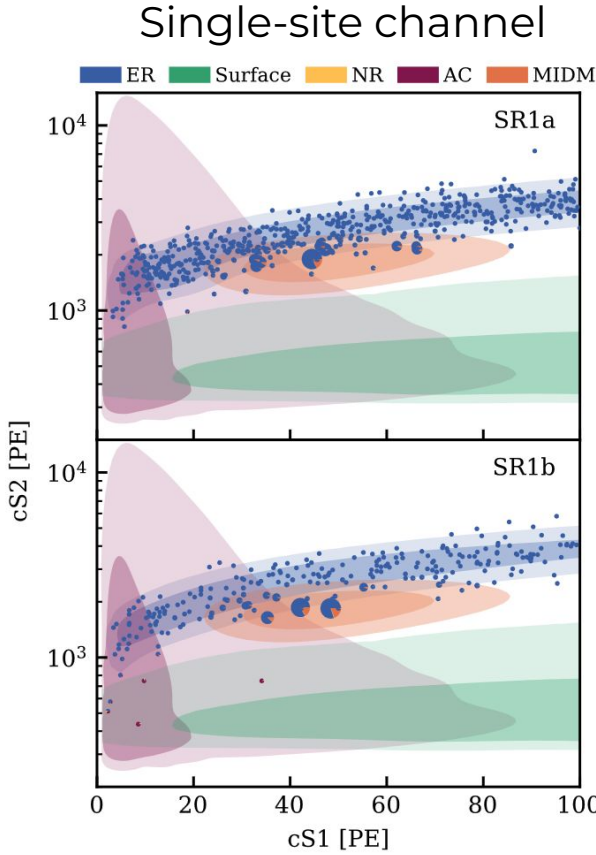
→ Thanks to MiDM-like cuts

→ 1 event is significant at 3σ level

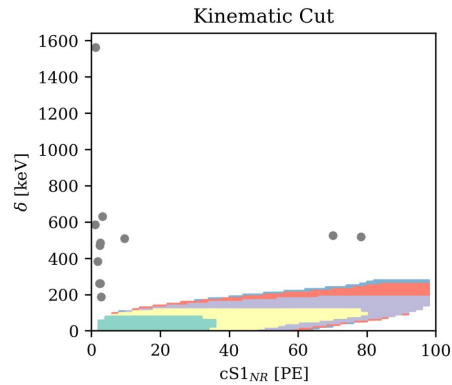
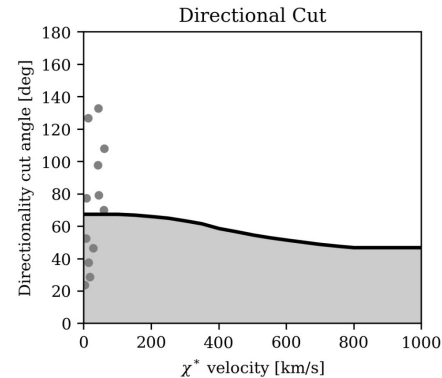


# Results and signal significances

After unblinding and event selection, we observe **810 single-site events** and **0 double-site events**



### Double-site channel

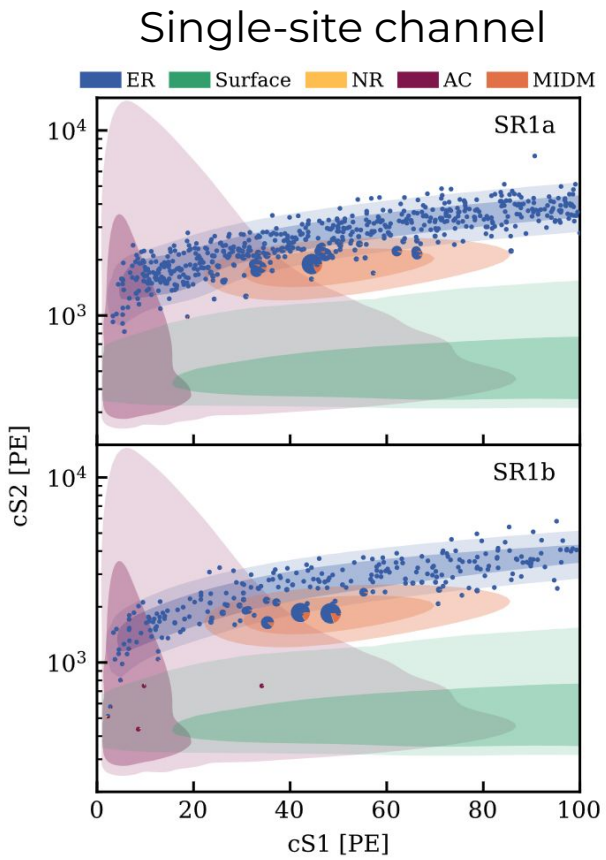


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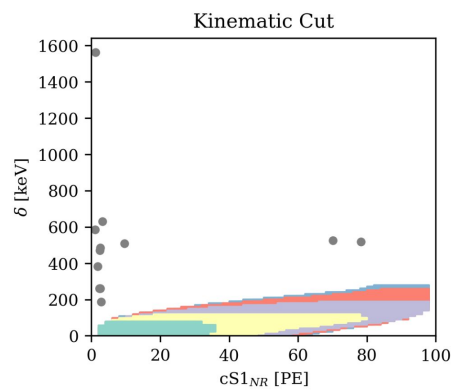
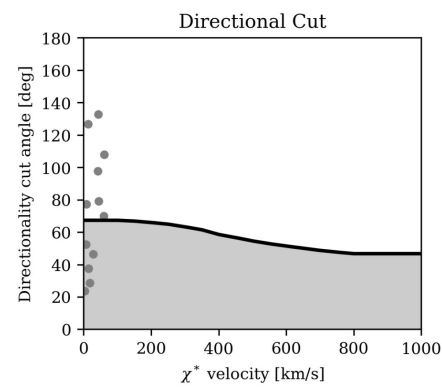
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We perform a **combined Log-Likelihood Ratio (LLR)** test comparing  $B_0$  to  $B_0+S$  hypotheses.

Fit parameter	Best fit
Ground state mass ( $m_\chi$ )	
Mass splitting ( $\delta$ )	
Magnetic dipole ( $\mu_\chi$ )	



## Double-site channel

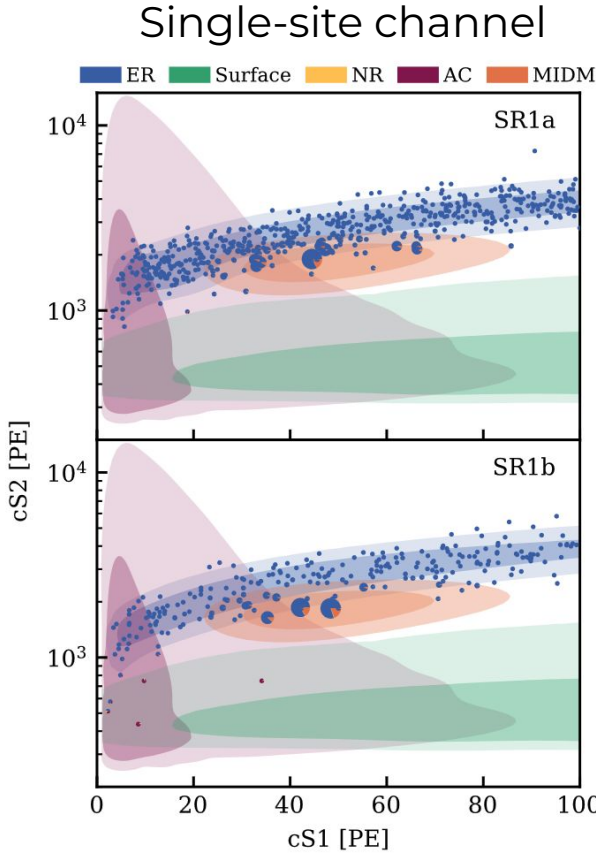


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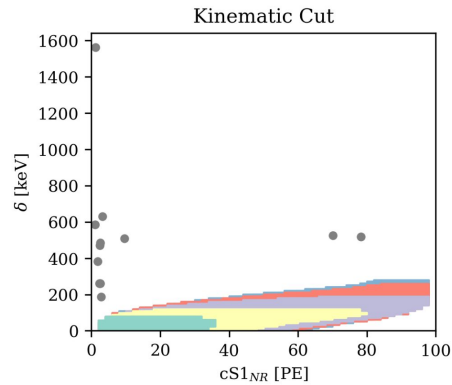
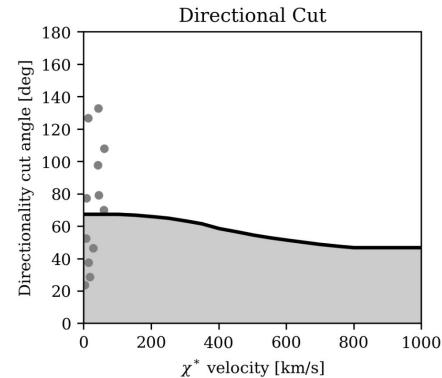
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Fit parameter	Best fit
Ground state mass ( $m_\chi$ )	50 GeV/ $c^2$
Mass splitting ( $\delta$ )	120 keV
Magnetic dipole ( $\mu_\chi$ )	$2.5 \times 10^{-4} \mu_N$



## Double-site channel



# Results and signal significances

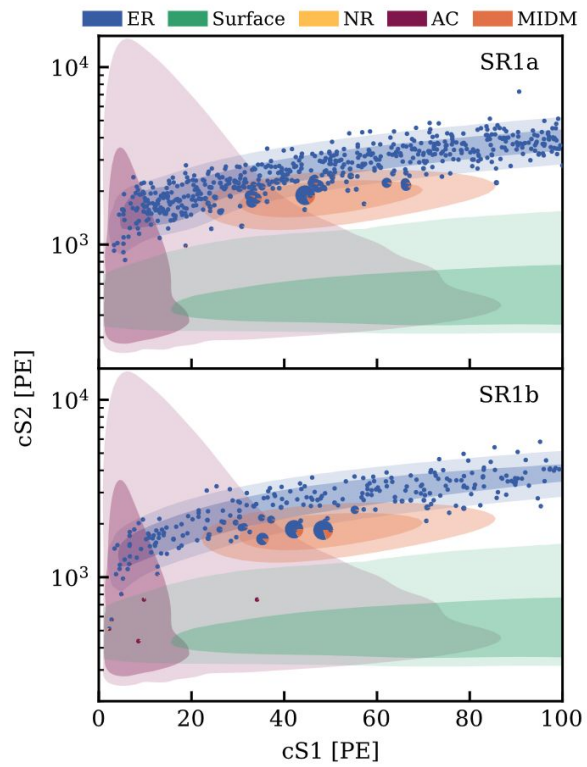
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Statistical significance	<b>1.6 <math>\sigma</math></b>

Significance < 3.0  $\sigma$

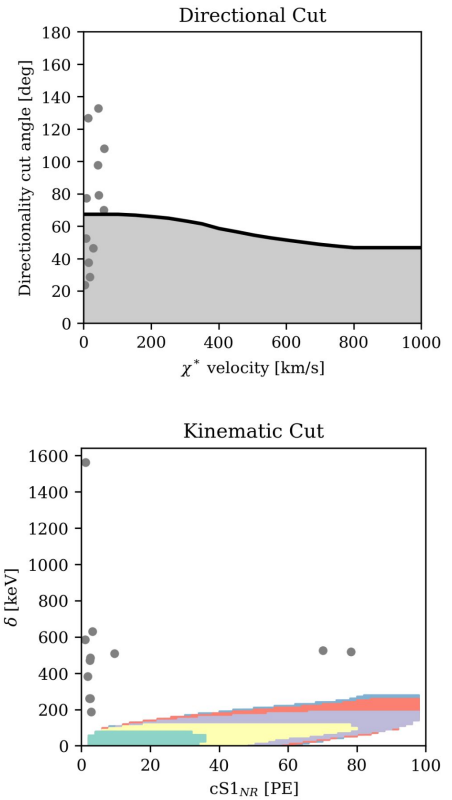
→ No statistical indication of an excess

→ We place **90% C.I. upper limits** on the value of  $\mu_\chi$ , over  $m_\chi$  and  $\delta$

Single-site channel



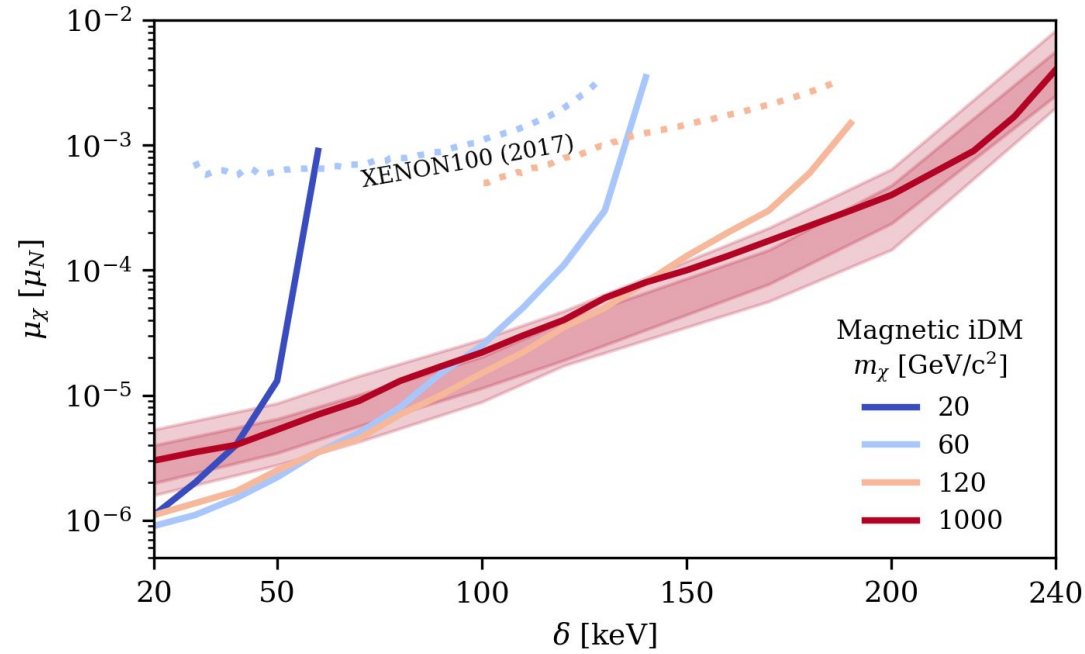
Double-site channel



# Limits from our combined dataset

We set world-leading constraints on the magnetic dipole moment of DM

Improvement of the sensitivity of  $10^5$  to  $10^6$  wrt. previous best



# The end!

Thank you for your time and attention.

Happy to hear any comments and answer questions.

# Best-fit and signal significances

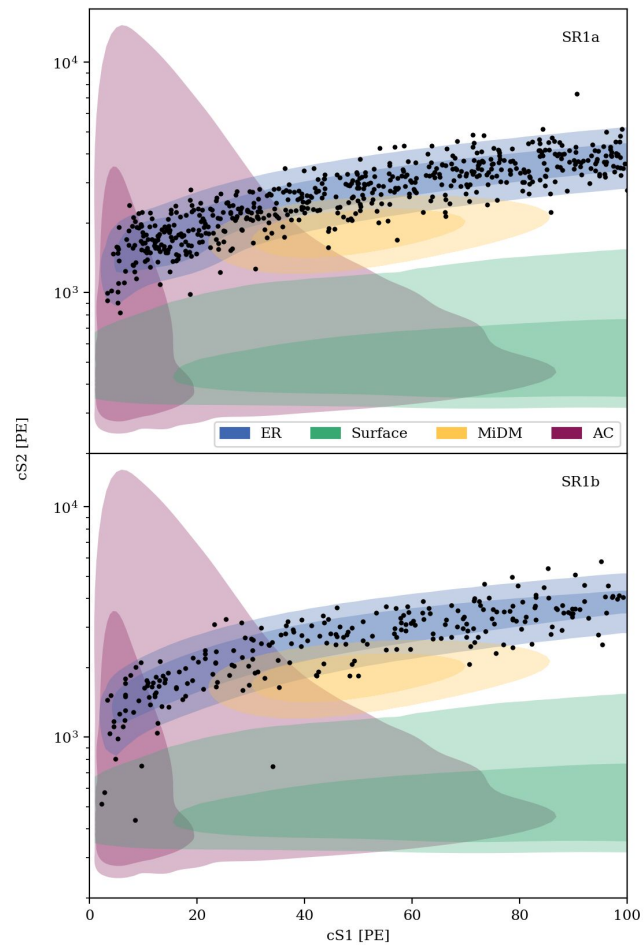
We search for the combination of  $(m_\chi, \delta, \mu_\chi)$  which best fits our combined dataset.

Ground state mass ( $m_\chi$ )	50 GeV/c <sup>2</sup>
Mass splitting ( $\delta$ )	120 keV
Magnetic dipole ( $\mu_\chi$ )	$2.5 \times 10^{-4} \mu_N$
$\chi^*$ lifetime ( $\tau$ )	735 $\mu$ s
Statistical significance	<b>1.6 <math>\sigma</math></b>

Very long,  
NR-only  
dominated



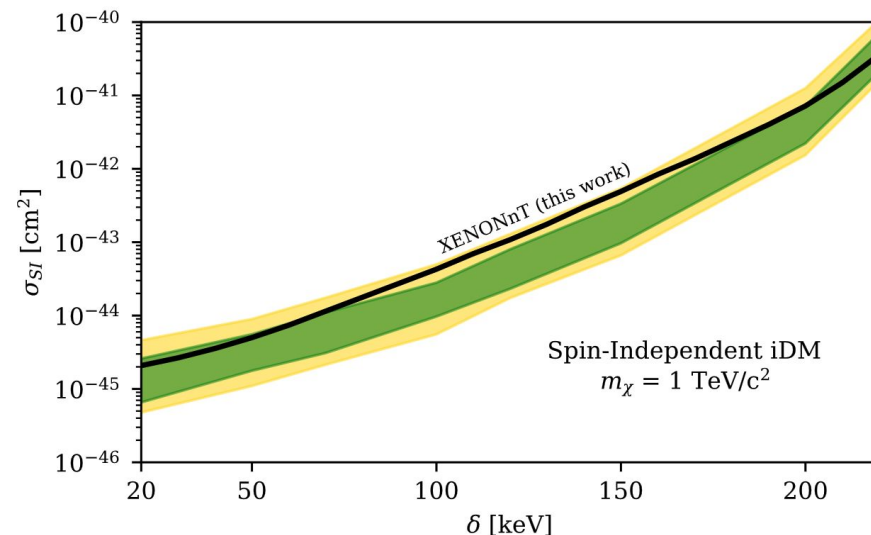
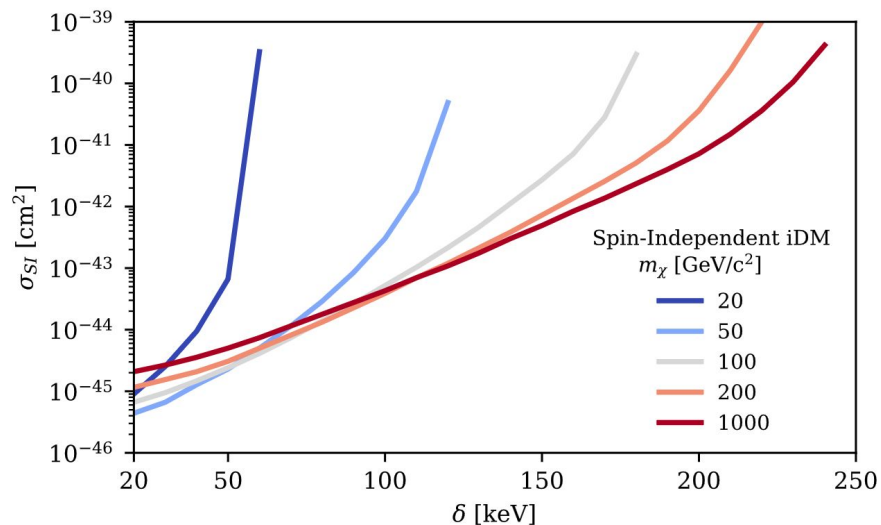
Number of events in best-fit			
<b>NR-only MiDM</b>	<b>7.0</b>	ER background	776
<b>NR+ER MiDM</b>	<b>0.01</b>	Surface background	1.2
Neutron Bkg	1.2	AC background	5.9



# Limits for Spin-Independent iDM

The NR-only channel alone allows us to search for decay-less iDM

We assume spin-independent cross-section between DM and nucleons



# Modeling of $^{124}\text{Xe}$ DEC

The (cS1, cS2) response of  $^{124}\text{Xe}$  DEC events is not well understood

→ DEC results in Auger cascades: many initial quanta

→ This could affect the ionization density, decreasing the charge yield

R&D measurements suggest charge yield 20% lower than ERs

