Inelastic Dark Matter Nucleus Scattering

Christian Döring

based on: arXiv:1906.10466

In cooperation with:
Giorgio Arcadi, Constanze Hasterok and Stefan Vogl

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

26.9.2019 @Hamburg
DESY Theory Workshop

Content

- Introduction
- Non-relativistic effective field theory (NREFT)
- Inelastic DM-nucleus scattering
- Discovery reach for inelastic scattering
- Discriminating DM-nucleus interactions
- Conclusion

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Hints for Dark Matter

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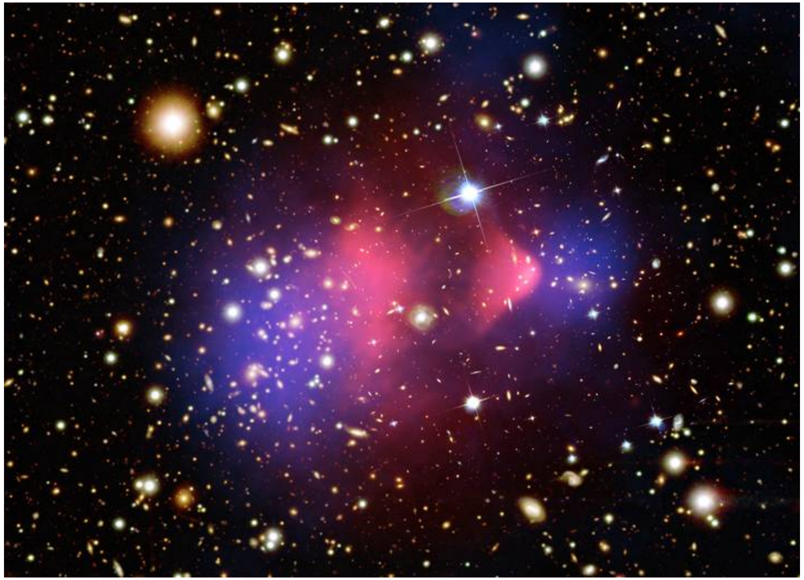
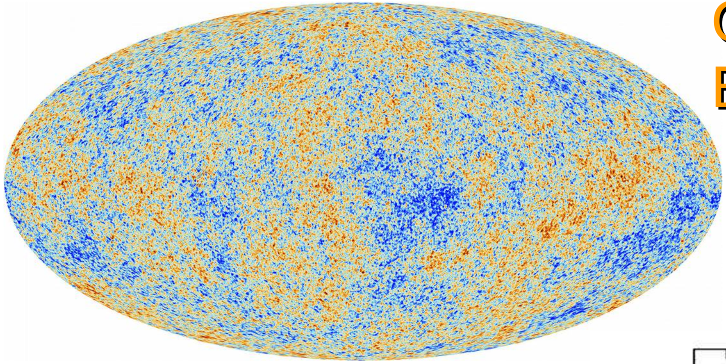
Bullet Cluster



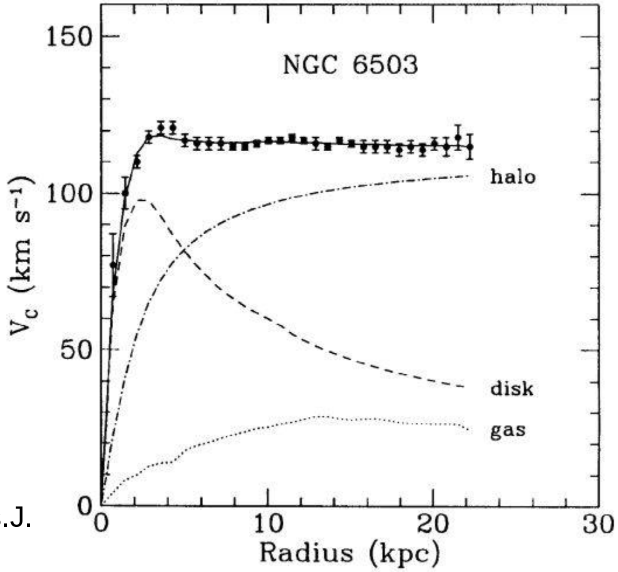
NASA/CXC/CfA/M.Markevitch et al.



www.esa.int.spaceimages

Cosmic Microwave Backgrond

Galaxy Rotationcurve



Van Albada et al. [Astrophys.J. 295 (1985) 305-313]

XENON-like Direct Detection Exp.

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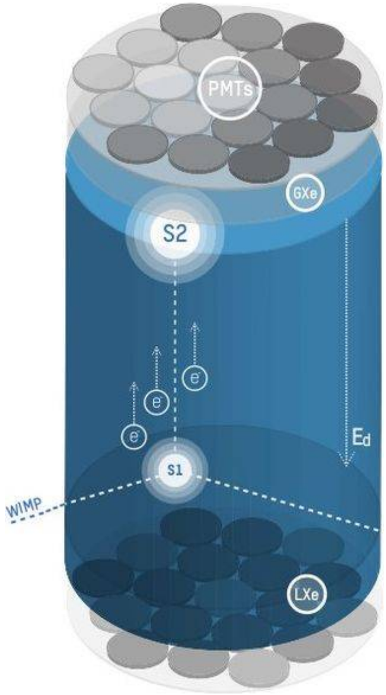

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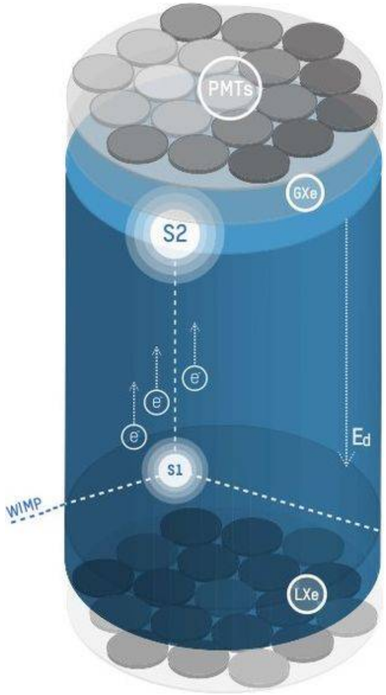

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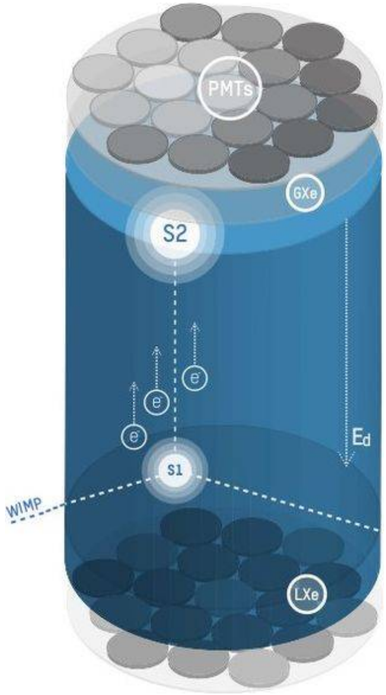

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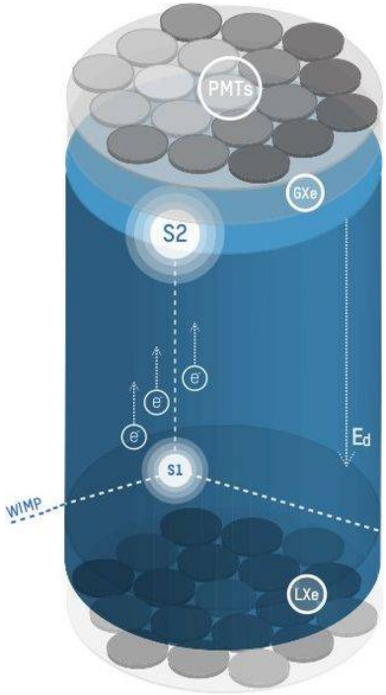

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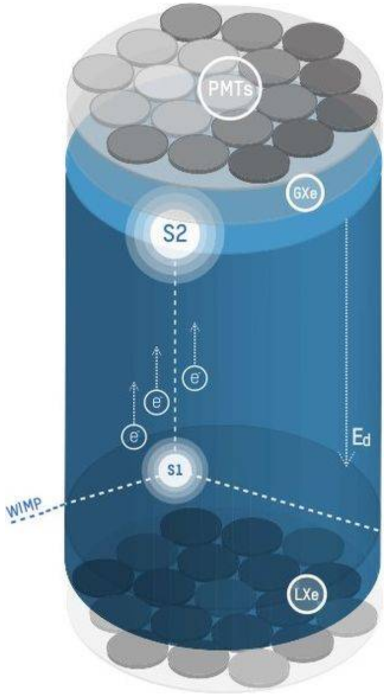

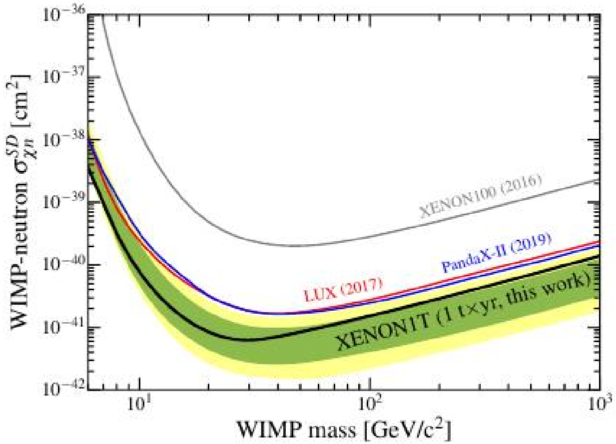

E.Aprile et al. [ArXiv:1902.03234]

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Inelastic Scattering

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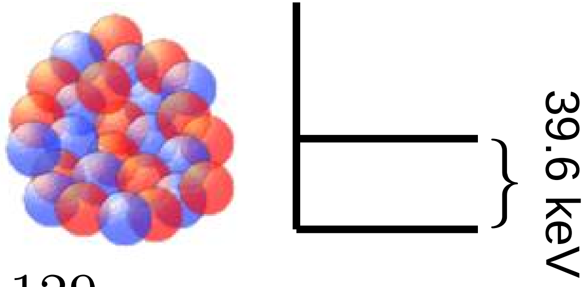
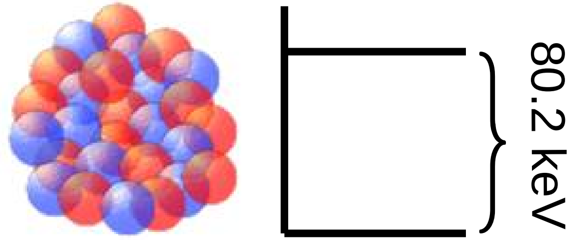
Heidelberg

- In xenon the two isotops ^{129}Xe and ^{131}Xe have high natural abundance (20%–26%)



$^{129}\mathrm{Xe}$



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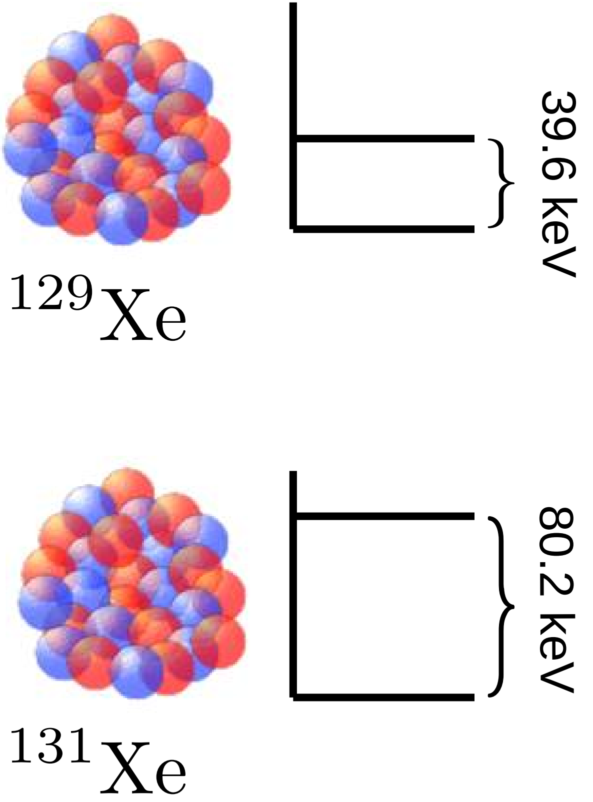

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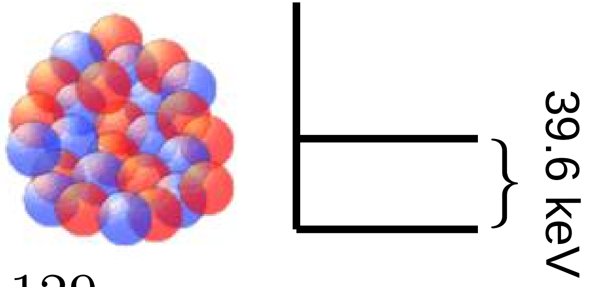

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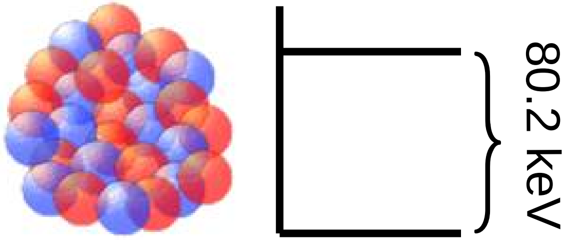

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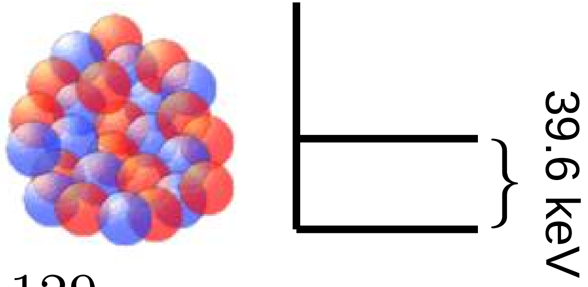

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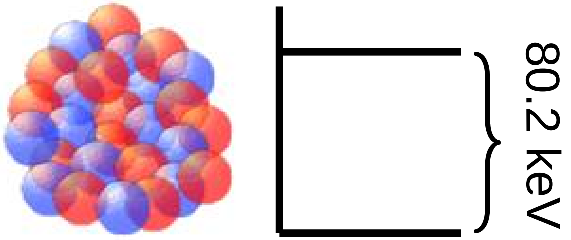

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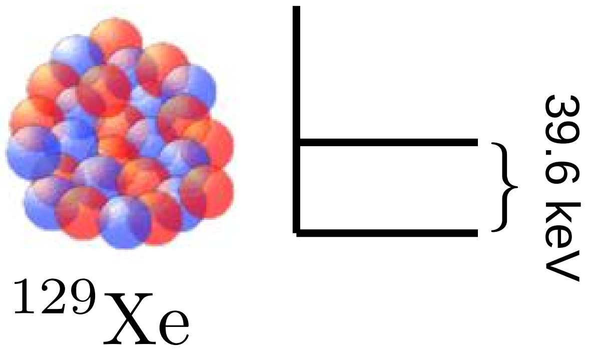

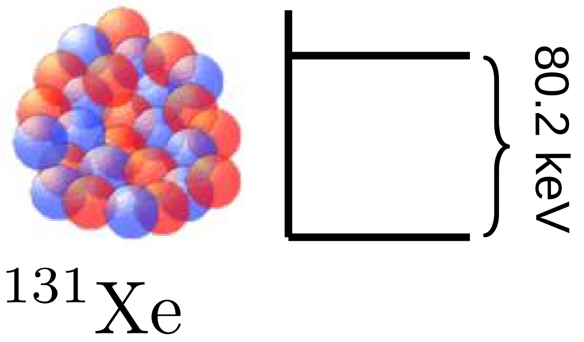

J.R. Ellis et al. [Phys. Lett. B212]

L. Baudis et al. [ArXiv:1309.0825]

C. McCabe [ArXiv:1512.00460]

DM-Nucleus Scattering
Non-relativistic effective field theory

- Maximal DM-velocity $v_{\rm esc} \approx 550\,{\rm km/s} \;=>\; E_R^{\rm max} \approx 300\,{\rm keV}$
  => direct detection tests non-relativistic regime

A.L.Fitzpatrick et al.
[ArXiv:1203.3542]

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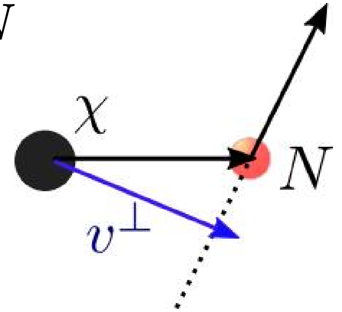
$$1_{\chi\, N} \qquad \vec{S}_\chi \qquad \vec{S}_N \qquad i\vec{q} \qquad \vec{v}^{\perp} := \vec{v} + \frac{\vec{q}}{2\mu_N}$$



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NREFT Operators

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- Fund. Operators combine to a set of DM–Nucleon interaction operators

SI

SD

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
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Set of linear ind. one-body DM–nucleon interaction operators, that are at most linear in the fundamental ops.

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New Physics scale

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$$\boxed{\frac{\mathrm{d}\sigma_T(v^2, E_R)}{\mathrm{d}E_R} = \frac{m_T}{2\pi v^2}\langle|\mathcal{M}_{\text{eff}}|^2\rangle}$$

Differential recoil cross section DM–Nucleus

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SI $\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
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SD $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Set of linear ind. one-body DM–nucleon interaction operators, that are at most linear in the fundamental ops.

$$\mathcal{H} = \sum_{\tau=0,1} \sum_{k=1}^{15} c_k^\tau \mathcal{O}_k t^\tau$$

with $\quad c_k^i = \frac{1}{\Lambda^2}$

New Physics scale

$$\boxed{\frac{d\sigma_T(v^2, E_R)}{dE_R} = \frac{m_T}{2\pi v^2}\langle|\mathcal{M}_{\text{eff}}|^2\rangle}$$

Differential recoil cross section DM–Nucleus

NREFT Matrix Element

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$$
\begin{aligned}
\langle|\mathcal{M}_{\text{eff}}|^2\rangle = \frac{4\pi}{2J+1}\sum_{\tau,\tau'}\sum_{L}\Big[& R_M^{\tau\tau'}\langle j_i||M_{L;\tau}|j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + R_{\Sigma''}^{\tau\tau'}\langle j_i||\Sigma''_{L;\tau}||j_f\rangle\langle j_f||\Sigma''_{L;\tau'}||j_i\rangle + R_{\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}|j_f\rangle\langle j_f||\Sigma'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||\Phi''_{L;\tau'}||j_i\rangle + 2\frac{q^2}{m_N^2}R_{M\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}'_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}'_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta}^{\tau\tau'}\langle j_i||\Delta_{L;\tau}||j_f\rangle\langle j_f||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Delta\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_i||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Sigma}^{\tau\tau'}\langle j_i||\Sigma_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Delta'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Omega}}^{\tau\tau'}\langle j_i||\tilde{\Omega}_{L;\tau}|j_f\rangle\langle j_f||\tilde{\Omega}_{L;\tau'}|j_i\rangle + \frac{q^2}{m_N^2}R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Delta}''}^{\tau\tau'}\langle j_i||\tilde{\Delta}''_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Delta}''_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'\Sigma}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle\Big] ,
\end{aligned} \tag{1}
$$

NREFT Matrix Element

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$$\langle|\mathcal{M}_{\rm eff}|^2\rangle = \frac{4\pi}{2J+1}\sum_{\tau,\tau'}\sum_L \Big[R_M^{\tau\tau'} \langle j_i||M_{L;\tau}|j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle$$
$$+ R_{\Sigma''}^{\tau\tau'}\langle j_i||\Sigma''_{L;\tau}||j_f\rangle\langle j_f||\Sigma''_{L;\tau'}||j_i\rangle + R_{\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}|j_f\rangle\langle j_f||\Sigma'_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||\Phi''_{L;\tau'}||j_i\rangle + 2\frac{q^2}{m_N^2} R_{M\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}'_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}'_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2} R_{\Delta}^{\tau\tau'}\langle j_i||\Delta_{L;\tau}||j_f\rangle\langle j_f||\Delta_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\Delta\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_i||\Delta_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\Sigma}^{\tau\tau'}\langle j_i||\Sigma_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2} R_{\Delta'}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Delta'_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\tilde{\Omega}}^{\tau\tau'}\langle j_i||\tilde{\Omega}_{L;\tau}|j_f\rangle\langle j_f||\tilde{\Omega}_{L;\tau'}|j_i\rangle + \frac{q^2}{m_N^2} R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}_{L;\tau'}||j_i\rangle$$
$$+ \frac{q^2}{m_N^2} R_{\tilde{\Delta}''}^{\tau\tau'}\langle j_i||\tilde{\Delta}''_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Delta}''_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2} R_{\Delta'\Sigma}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle\Big], \tag{1}$$

- DM response functions
- Here is where the effective operators enter
- Caclulated analytically

NREFT Matrix Element

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$$
\begin{aligned}
\langle|\mathcal{M}_{\rm eff}|^2\rangle = \frac{4\pi}{2J+1}\sum_{\tau,\tau'}\sum_{L}\Big[& R_M^{\tau\tau'}\langle j_i||M_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + R_{\Sigma''}^{\tau\tau'}\langle j_i||\Sigma''_{L;\tau}||j_f\rangle\langle j_f||\Sigma''_{L;\tau'}||j_i\rangle + R_{\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_f||\Sigma'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||\Phi''_{L;\tau'}||j_i\rangle + 2\frac{q^2}{m_N^2}R_{M\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}'_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}'_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta}^{\tau\tau'}\langle j_i||\Delta_{L;\tau}||j_f\rangle\langle j_f||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Delta\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_i||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Sigma}^{\tau\tau'}\langle j_i||\Sigma_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Delta'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Omega}}^{\tau\tau'}\langle j_i||\tilde{\Omega}_{L;\tau}|j_f\rangle\langle j_f||\tilde{\Omega}_{L;\tau'}|j_i\rangle + \frac{q^2}{m_N^2}R_{\tilde{\Phi}}^{\tau\tau'}\langle j_i||\tilde{\Phi}_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Delta}''}^{\tau\tau'}\langle j_i||\tilde{\Delta}''_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Delta}''_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'\Sigma}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle \ ,
\end{aligned}
\tag{1}
$$

- Nuclear response functions
- Need to be calculated numerically (Nutshell package)

NREFT Matrix Element

$$
\begin{aligned}
\langle|\mathcal{M}_{\text{eff}}|^2\rangle = \frac{4\pi}{2J+1}\sum_{\tau,\tau'}\sum_{L}\Bigg[& R_M^{\tau\tau'}\langle j_i||M_{L;\tau}|j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + R_{\Sigma''}^{\tau\tau'}\langle j_i||\Sigma''_{L;\tau}||j_f\rangle\langle j_f||\Sigma''_{L;\tau'}||j_i\rangle + R_{\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}|j_f\rangle\langle j_f||\Sigma'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||\Phi''_{L;\tau'}||j_i\rangle + 2\frac{q^2}{m_N^2}R_{M\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}'_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}'_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta}^{\tau\tau'}\langle j_i||\Delta_{L;\tau}||j_f\rangle\langle j_f||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Delta\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_i||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Sigma}^{\tau\tau'}\langle j_i||\Sigma_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Delta'_{L;\tau'}||j_i\rangle \\
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\end{aligned}
\tag{1}
$$

Elastic & Inelastic Scattering

NREFT Matrix Element

$$
\begin{aligned}
\langle|\mathcal{M}_{\mathrm{eff}}|^2\rangle = \frac{4\pi}{2J+1}\sum_{\tau,\tau'}\sum_{L}\Big[& R_M^{\tau\tau'}\langle j_i||M_{L;\tau}|j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + R_{\Sigma''}^{\tau\tau'}\langle j_i||\Sigma''_{L;\tau}||j_f\rangle\langle j_f||\Sigma''_{L;\tau'}||j_i\rangle + R_{\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}|j_f\rangle\langle j_f||\Sigma'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||\Phi''_{L;\tau'}||j_i\rangle + 2\frac{q^2}{m_N^2}R_{M\Phi''}^{\tau\tau'}\langle j_i||\Phi''_{L;\tau}||j_f\rangle\langle j_f||M_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Phi}'}^{\tau\tau'}\langle j_i||\tilde{\Phi}'_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}'_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta}^{\tau\tau'}\langle j_i||\Delta_{L;\tau}||j_f\rangle\langle j_f||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Delta\Sigma'}^{\tau\tau'}\langle j_i||\Sigma'_{L;\tau}||j_f\rangle\langle j_i||\Delta_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\Sigma}^{\tau\tau'}\langle j_i||\Sigma_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Delta'_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Omega}}^{\tau\tau'}\langle j_i||\tilde{\Omega}_{L;\tau}|j_f\rangle\langle j_f||\tilde{\Omega}_{L;\tau'}|j_i\rangle + \frac{q^2}{m_N^2}R_{\tilde{\Phi}}^{\tau\tau'}\langle j_i||\tilde{\Phi}_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Phi}_{L;\tau'}||j_i\rangle \\
& + \frac{q^2}{m_N^2}R_{\tilde{\Delta}''}^{\tau\tau'}\langle j_i||\tilde{\Delta}''_{L;\tau}||j_f\rangle\langle j_f||\tilde{\Delta}''_{L;\tau'}||j_i\rangle + \frac{q^2}{m_N^2}R_{\Delta'\Sigma}^{\tau\tau'}\langle j_i||\Delta'_{L;\tau}||j_f\rangle\langle j_f||\Sigma_{L;\tau'}||j_i\rangle\Big] ,
\end{aligned}
\tag{1}
$$

Elastic & Inelastic Scattering

Inelastic Scattering only

Inelastic Rates

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_T E_R}}$$

Inelastic Rates

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\,\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

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Astrophysics

Max-Planck-Institut für Kernphysik Heidelberg

Inelastic Rates

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v \geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_T E_R}}$$

Particle Physics

Astrophysics

Inelastic Rates

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_T E_R}}$$

Particle Physics

Inelastic Rates

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$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

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Inelastic Rates

Max-Planck-Institut für Kernphysik Heidelberg

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- Ratios of eventrates between inelastic and elastic rates for 14 Operators

Operator	1	3	4	5	6	7	8	9	10	11	12	13	14	15
R_{in}/R_{el}	–	–	0.13	0.04	0.06	62.	0.009	0.07	0.11	–	–	27.	–	–

$m_\chi = 300\,\mathrm{GeV}$

Inelastic Rates

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$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

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$m_\chi = 300\,\mathrm{GeV}$

- 6 Operators (SI) with rate-ratios <<10^{-3}.
  Understand from O_1: elastic rate is coherently enhanced in SI interaction (A^2)

Inelastic Rates

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_T E_R}}$$

- Ratios of eventrates between inelastic and elastic rates for 14 Operators

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$m_\chi = 300\,\mathrm{GeV}$

- 6 Operators (SI) with rate-ratios <<10^{-3}.
  Understand from O_1: elastic rate is coherently enhanced in SI interaction (A^2)
- 6 Operators (SD) with rate-ratios of O(0.01-0.1).
  Reason: Leads to spin-flip => incoherent process. Only higher momentum transfer

Inelastic Rates

$$\frac{dR}{\mathrm{d}E_R} = \frac{1}{m_T}\frac{\rho_\chi}{m_\chi}\int_{v\geq v_{\min}} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_E)\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}} + \frac{E^*}{\sqrt{2 m_T E_R}}$$

- Ratios of eventrates between inelastic and elastic rates for 14 Operators

Operator	1	3	4	5	6	7	8	9	10	11	12	13	14	15
R_{in}/R_{el}	–	–	0.13	0.04	0.06	62.	0.009	0.07	0.11	–	–	27.	–	–

$m_\chi = 300\,\mathrm{GeV}$

- 6 Operators (SI) with rate-ratios <<10^{-3}.
  Understand from O_1: elastic rate is coherently enhanced in SI interaction (A^2)
- 6 Operators (SD) with rate-ratios of O(0.01-0.1).
  Reason: Leads to spin-flip => incoherent process. Only higher momentum transfer
- 2 Opertors with rate ratios of O(10).
  Reason: Elastic rate is supressed by $v_T^\perp$ but does not supress inelastic rate

Discovery Prospects

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Two goals now:

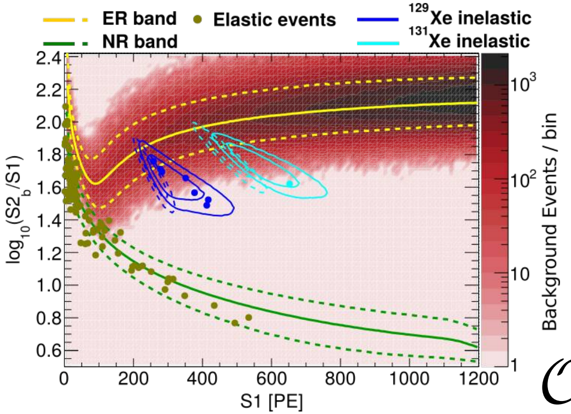
1. Derive a discovery reach for the inelastic signal and compare it to the elastic one.

2. Prospect of using the inelastic signal as discrimination tool.

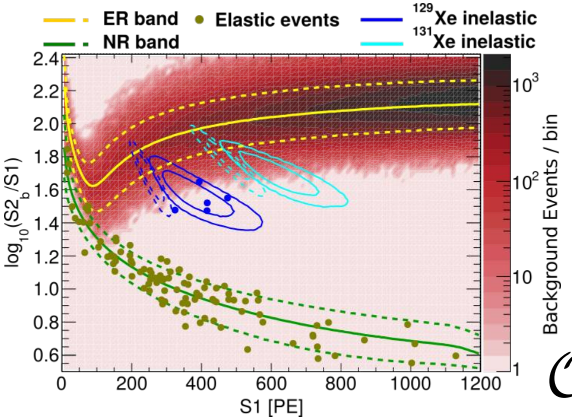
→ To do so we implement a likelihood analysis

Detectorsimulation XENON-like exp.

$$m_\chi = 300\,\mathrm{GeV}$$



$\mathcal{O}_4\ \Lambda = 1900\,\mathrm{GeV}$



$\mathcal{O}_6\ \Lambda = 230\,\mathrm{GeV}$

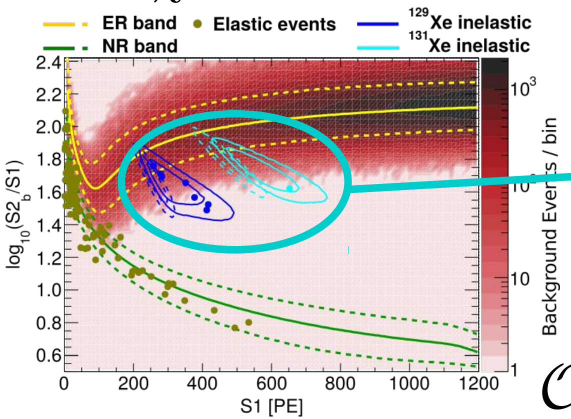
100 tonne x year exposure

Corresponds to 100 signal events

Detectorsimulation XENON-like exp.

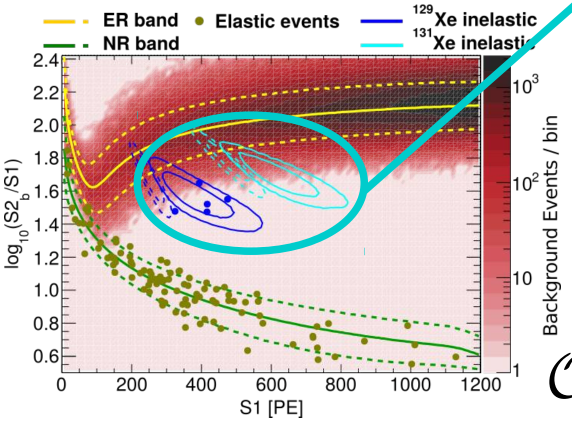
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

$m_\chi = 300\,\mathrm{GeV}$



$\mathcal{O}_4\ \Lambda = 1900\,\mathrm{GeV}$

Inelastic Events



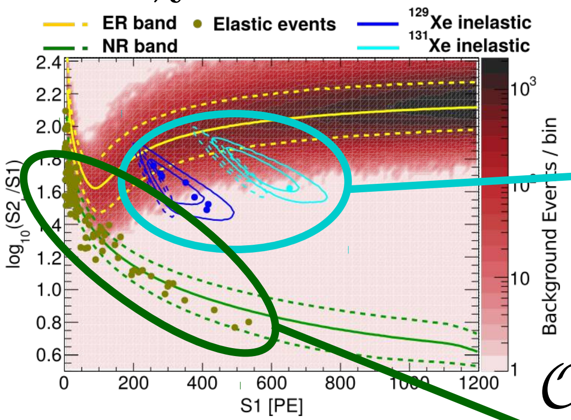
$\mathcal{O}_6\ \Lambda = 230\,\mathrm{GeV}$

100 tonne x year exposure

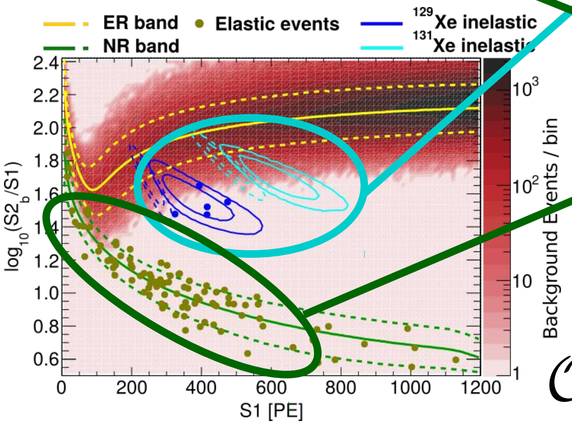
Corresponds to 100 signal events

Detectorsimulation XENON-like exp.

$m_\chi = 300\,\mathrm{GeV}$



$\mathcal{O}_4\ \Lambda = 1900\,\mathrm{GeV}$



$\mathcal{O}_6\ \Lambda = 230\,\mathrm{GeV}$

Inelastic Events

Elastic Events

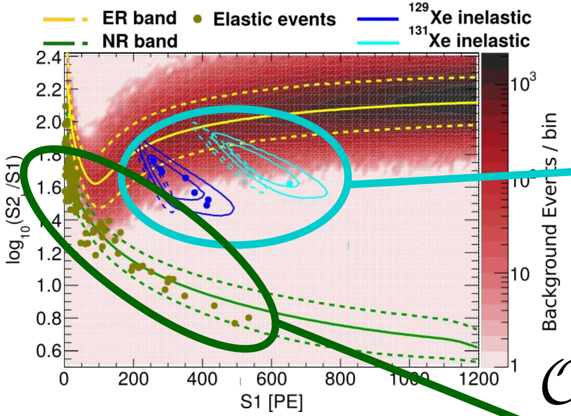
100 tonne x year exposure

Corresponds to 100 signal events

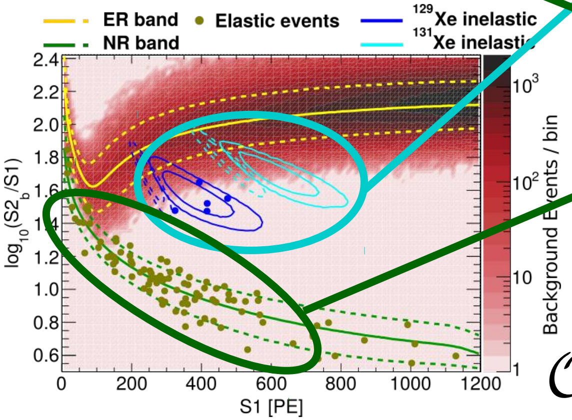
Detectorsimulation XENON-like exp.

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

$m_\chi = 300\,\mathrm{GeV}$



$\mathcal{O}_4\ \Lambda = 1900\,\mathrm{GeV}$

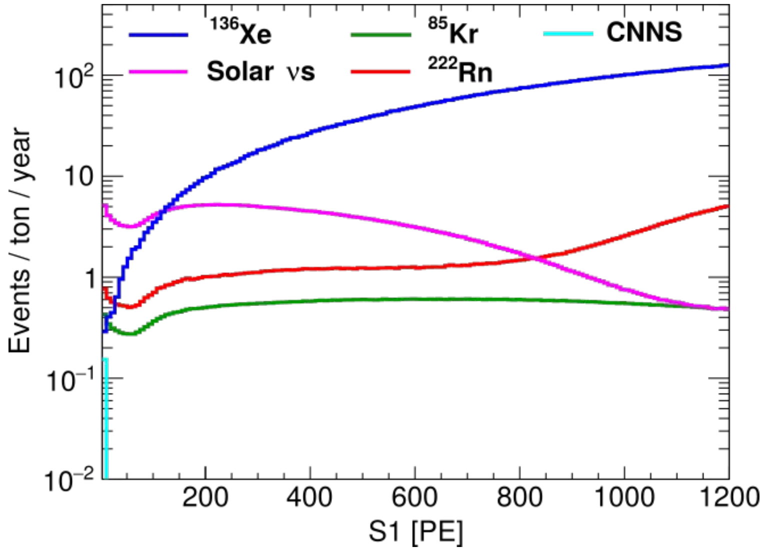


$\mathcal{O}_6\ \Lambda = 230\,\mathrm{GeV}$

Inelastic Events

Elastic Events

Backgrounds



100 tonne x year exposure

Corresponds to 100 signal events

Part I: Discovery Reach

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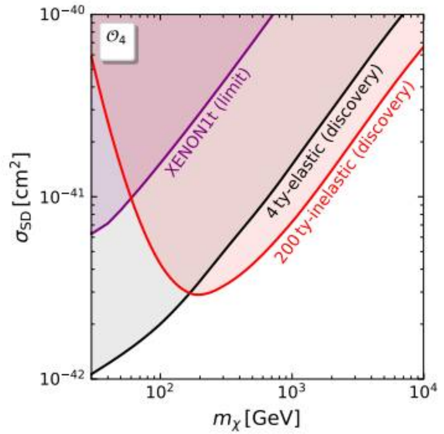
- Using likelihood ratio method to discriminate between:

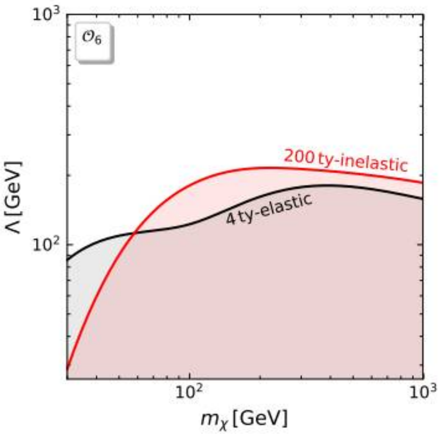
  a) Hypothesis of BG only
  b) Hypothesis of DM(E/I)+BG

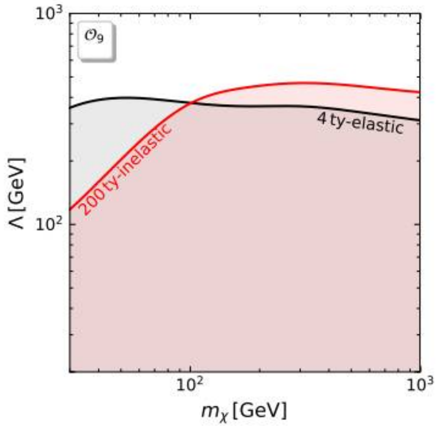
Definition (Discovery Reach):

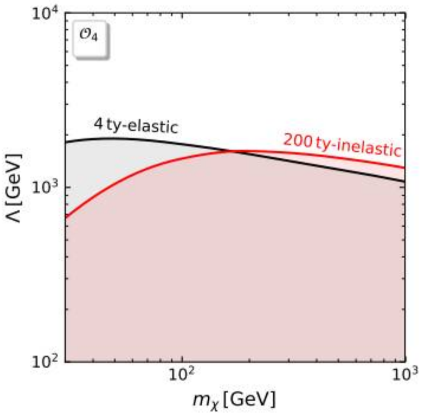
We define the discovery reach for each DM mass as the value of the DM rate $\overline{\mathcal{R}}_\chi$ for which 90% of experiments find a q_0–value with a statistical significance of at least 3 sigma ($\sqrt{q_0} \geq 3$).

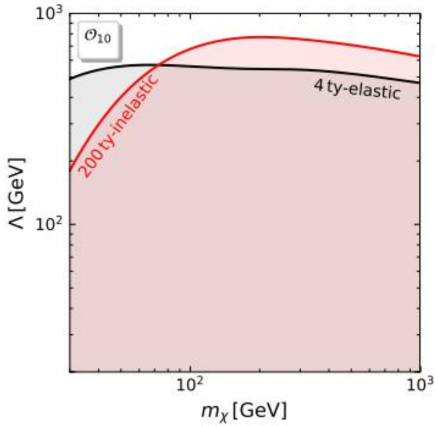
Results I


$\mathcal{O}_4$
XENON1t (limit)
4 ty-elastic (discovery)
200 ty-inelastic (discovery)
$\sigma_{SD}\,[\mathrm{cm}^2]$
$m_\chi\,[\mathrm{GeV}]$


$\mathcal{O}_6$
200 ty-inelastic
4 ty-elastic
$\Lambda\,[\mathrm{GeV}]$
$m_\chi\,[\mathrm{GeV}]$


$\mathcal{O}_9$
4 ty-elastic
200 ty-inelastic
$\Lambda\,[\mathrm{GeV}]$
$m_\chi\,[\mathrm{GeV}]$


$\mathcal{O}_4$
4 ty-elastic
200 ty-inelastic
$\Lambda\,[\mathrm{GeV}]$
$m_\chi\,[\mathrm{GeV}]$


$\mathcal{O}_{10}$
4 ty-elastic
200 ty-inelastic
$\Lambda\,[\mathrm{GeV}]$
$m_\chi\,[\mathrm{GeV}]$

Results I

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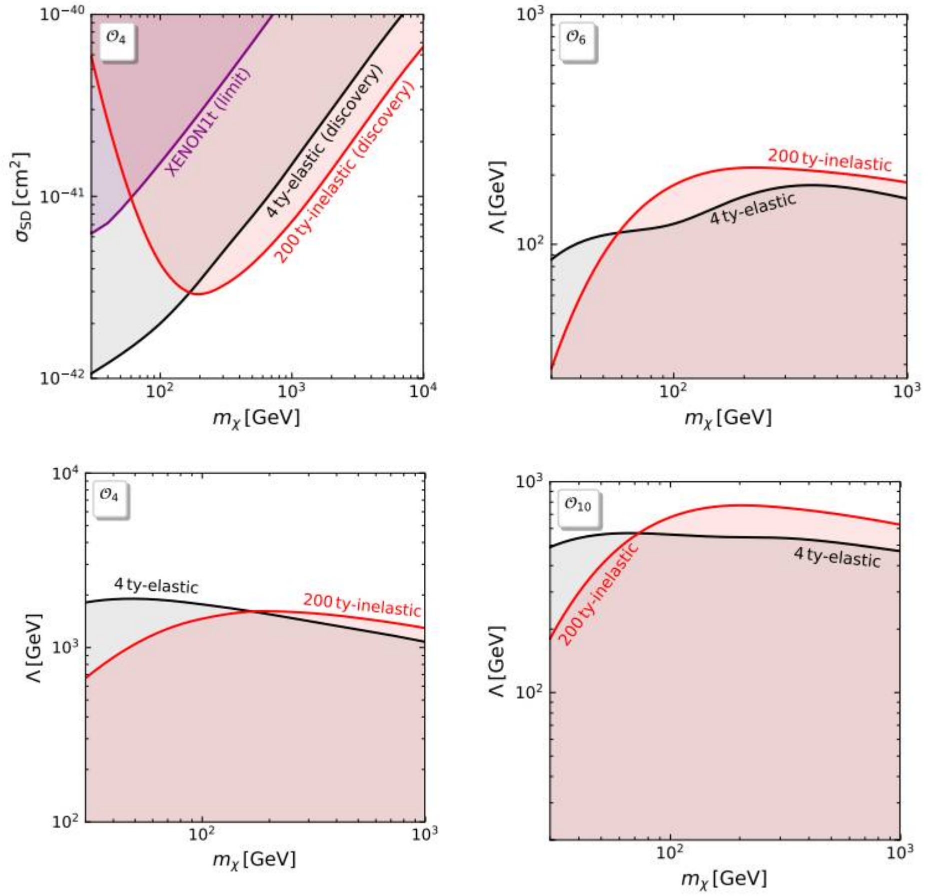
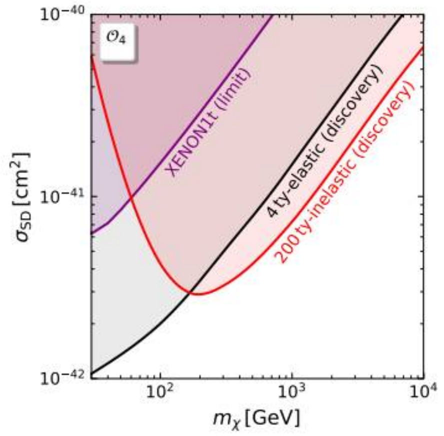
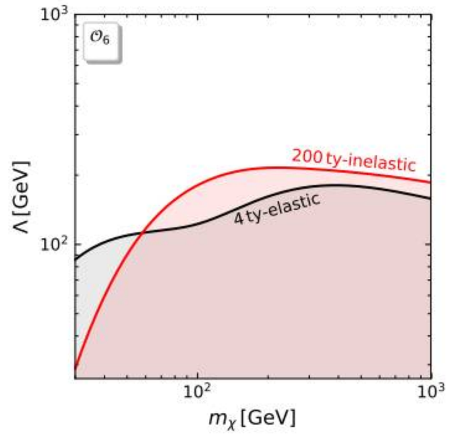


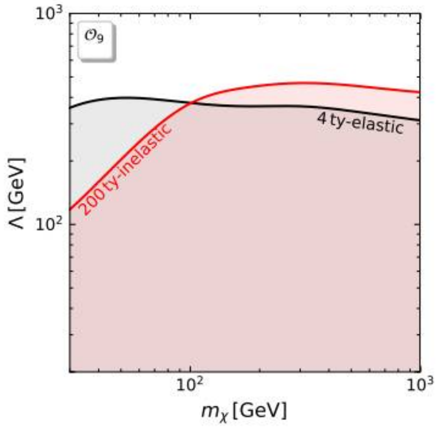
4ty
(XENONnT)

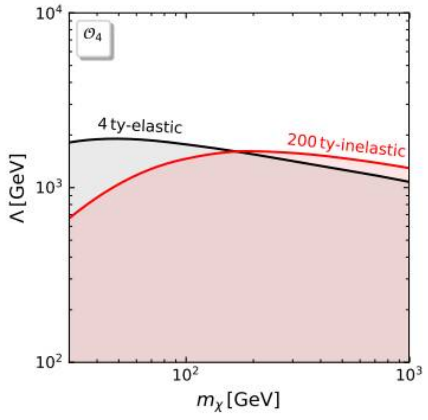
1. Discover elastic signal

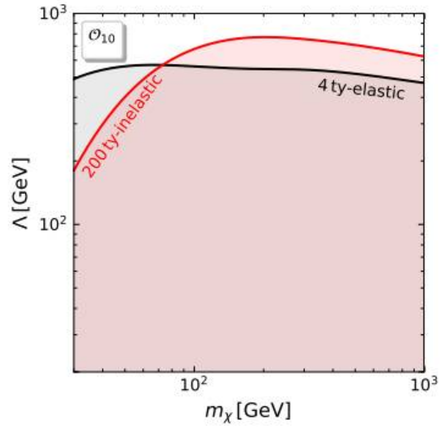
Results I





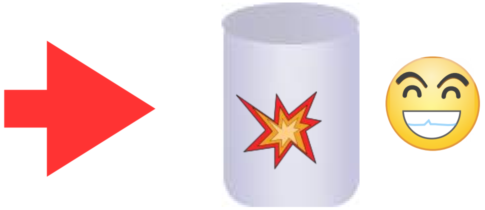






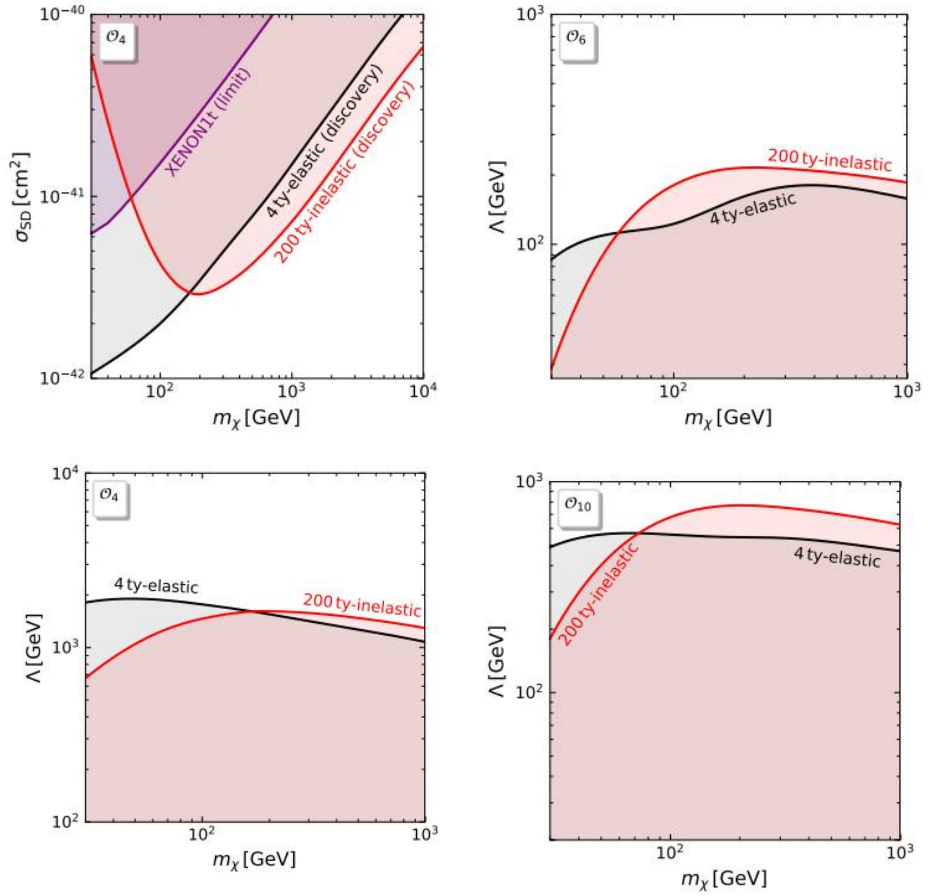
4ty

(XENONnT)



1. Discover elastic signal

Results I



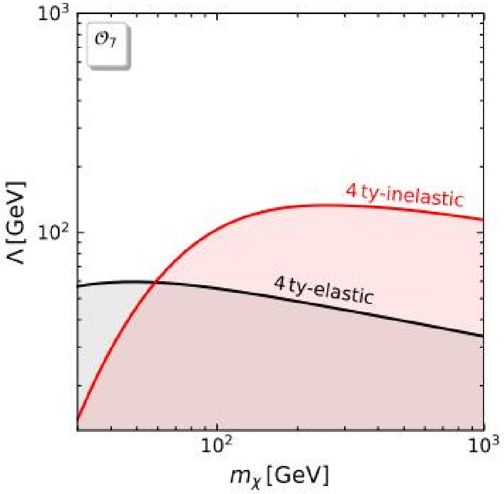
4ty (XENONnT)

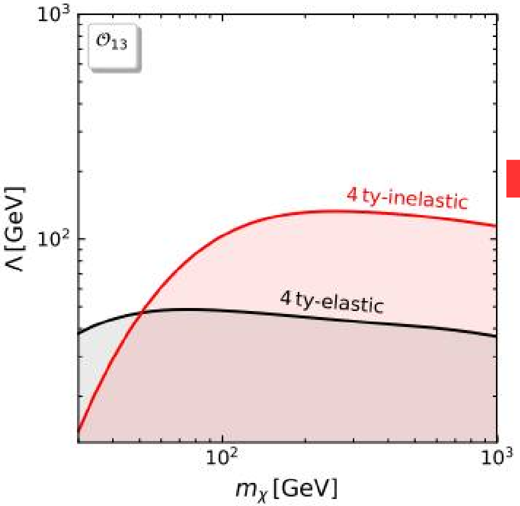
200ty (DARWIN)

1. Discover elastic signal

2. Discover inelastic signal

Results I

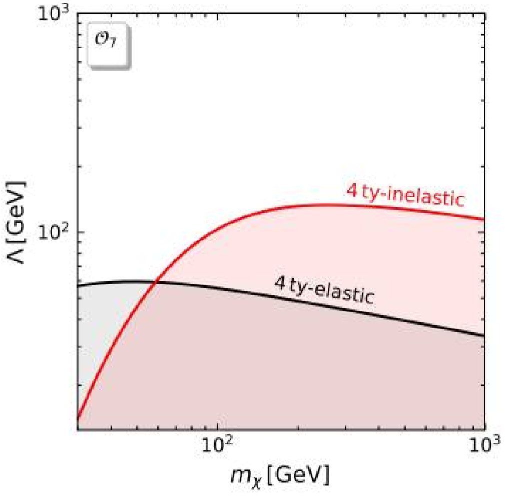


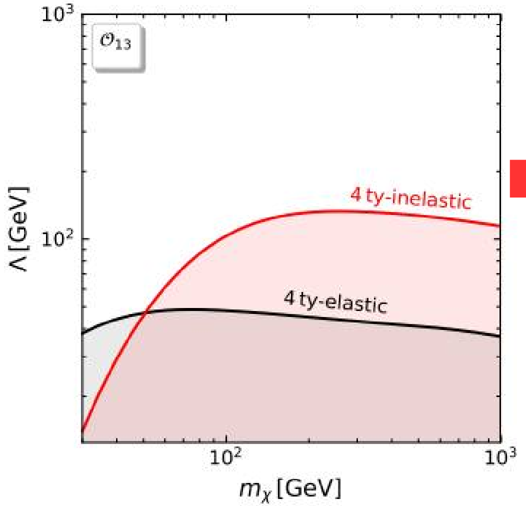


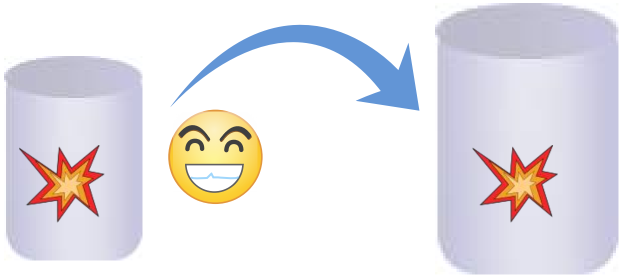
1. Discover inelastic signal

2. Discover elastic signal

Results I







1. Discover inelastic signal

2. Discover elastic signal

O_7 and O_{13} inelastic signals can be seen or excluded in the already existing data

Part II : Operator Discrimination

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- Likelihood ratio test between:

  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Part II : Operator Discrimination

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- Likelihood ratio test between:

  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Part II : Operator Discrimination

- Likelihood ratio test between:

  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Only elastic signals

Part II : Operator Discrimination

- Likelihood ratio test between:

  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Only elastic signals

Part II : Operator Discrimination

- Likelihood ratio test between:

  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Only elastic signals

Elastic+inelastic signals

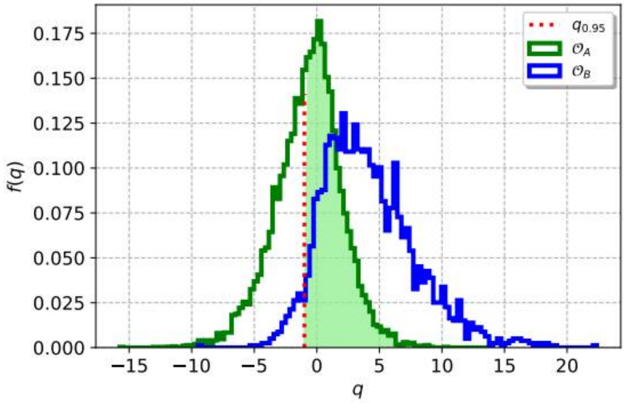
Part II : Operator Discrimination

- Likelihood ratio test between:

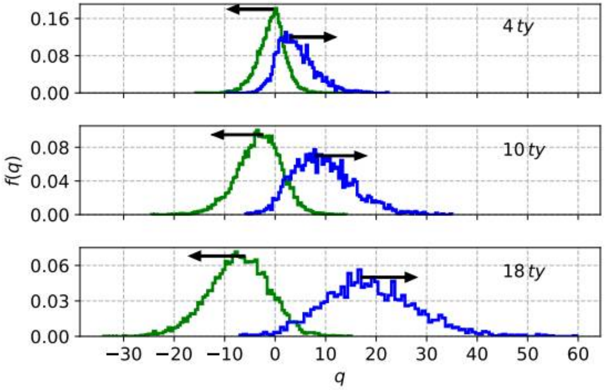
  a) Hypothesis of signal due to O_A
  b) Hypothesis of signal due to O_B

Only elastic signals

Elastic+inelastic signals

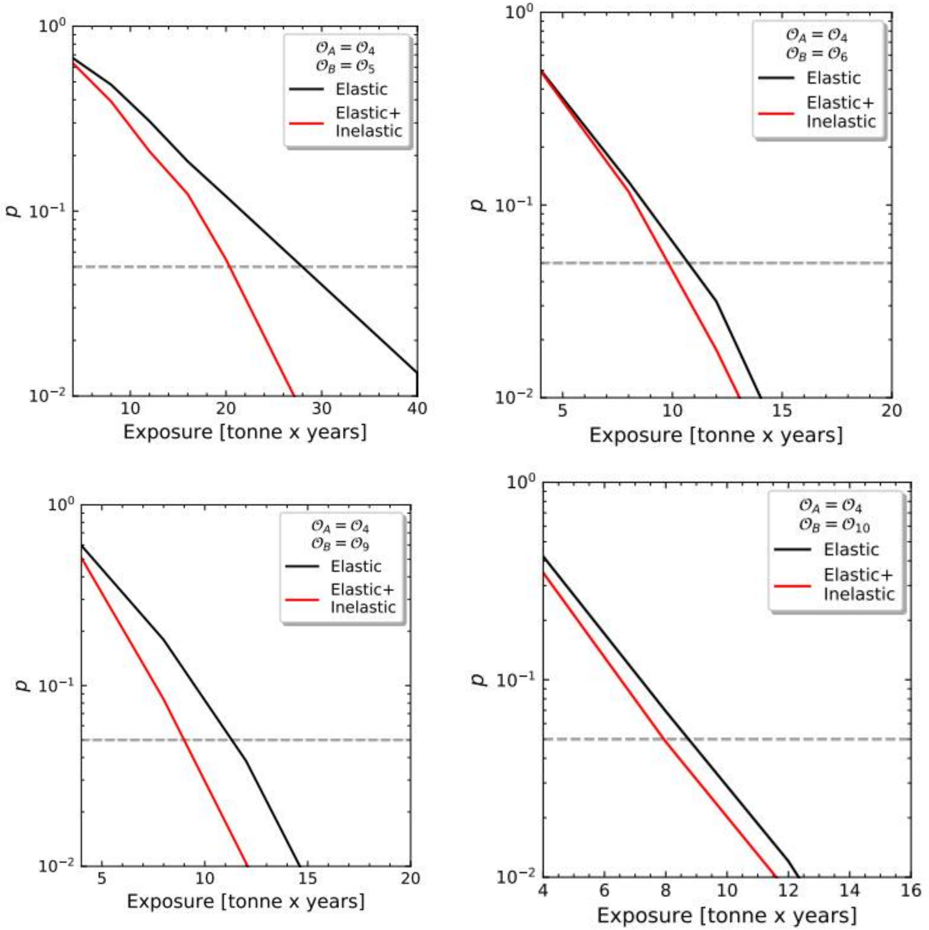


Derive p-value as a measure of distinctness



Increase exposure for better discrimination

Results II



- Inelastic signal **enhances** the discrimination potential for **O_4 and O_5**
- Only slight enhancement for O_4 and O_9
- Almost no improvement for O_4–O_6 and O_4–O_{10}

$m_\chi = 300\,\mathrm{GeV} \quad \overline{\mathcal{R}} \sim 10\,\mathrm{events}$

Conclusions

Part "0":

- Inelastic rates are for some operators 1%–10% of the respective elastic rates
- Inelastic rates of O_7 and O_{13} are significantly larger than their respective elastic rates

Part "1":

- For operators $O_{4,5,6,9,10}$ a discovery of the elastic signal would motivate the next generation direct detection experiment to detect the inelastic signal
- For operators O_7 and O_{13} an inelastic signal would be seen bevor the elastic signal and could be seen or excluded in the already existing data

Part "2":

- For 4 operators, the inelastic signal allows for a better discrimination between them and standard SD than the elastic signal does

Likelihood Method

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Goal: Discriminat between elastic/inelastic and background events

Binned likelihood function

$$L(\mathcal{D}|R_\chi, \boldsymbol{R}_{\rm BG}) := \prod_{i=1}^{N_{\rm bins}} \left[\frac{(\mu_i(R_\chi, \mathbf{R}_{\rm BG}))^{n_i(\mathcal{D})}}{n_i(\mathcal{D})!} \right] \cdot \prod_\beta L_\beta(R_\beta)$$

Theoretically expected number of events

Background uncertainties

Events from sim. detector

Likelihood ratio between the two hypotheses: DM(E/E+I)+BG signal / BG only

$$\lambda(0) := \frac{\max_{\mathbf{R}_{\rm BG}} L(\mathcal{D}|R_\chi = 0, \mathbf{R}_{\rm BG})}{\max_{R_\chi, \mathbf{R}_{\rm BG}} L(\mathcal{D}|R_\chi, \mathbf{R}_{\rm BG})}$$

$$q_0 := \begin{cases} -2\ln\lambda(0) & R_\chi \geq 0 \\ 0 & R_\chi < 0 \end{cases}.$$

Definition (Discovery Reach):

We define the discovery reach for each DM mass as the value of the DM rate $\overline{\mathcal{R}}_\chi$ for which 90% of experiments find a q_0-value with a statistical significance of 3 sigma ($\sqrt{q_0} \geq 3$).

C. McCabe[ArXiv:1512.00460]

Benchmark values and assumptions

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solar circular vel.	220 km/s
earth speed	232 km/s
galactic escp. vel	550 km/s

Xe-isotops deexcite	$1 \leq 1\,\mathrm{ns}$
scintillation light	$\lambda \sim 178\,\mathrm{nm}$
Drift field	500 V/cm