Uncertainties of EFT coupling limits from dark matter direct detection experiments stemming from nuclear shell model calculations

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Dark matter direct detection

- **Dark matter** (**DM**) – a hypothesized beyond-the-Standard Model particle; accounts for the majority of matter in the universe by mass [4]
- Numerous proposed models for dark matter, such as axions and **weakly interacting massive particles** (**WIMPs**); we will focus on WIMPs [4]
- Many properties of WIMPs are still unknown, most importantly the **mass** m_χ, and **coupling** c_i^x **to Standard Model particles**
- DM direct detection – a class of dark matter detectors that look for **scattering off of nuclei** in a chamber [4]
  - Through non-detection, direct detectors can constrain the couplings c_i^x
- We analyze the uncertainty of these constraints due to uncertainties in nuclear physics

Effective field theory for WIMP-nucleon interactions

Total WIMP-nucleon interaction in a Galilean effective field theory (EFT) [2]:

$$\mathcal{H} = \sum_{x=\mathrm{p,n}} \sum_{i=1}^{15} c_i^x \mathcal{O}_i$$

c_i^x are the EFT couplings (a prior unknown) and $\mathcal{O}_i$ are the relevant operators constructed in the EFT.

WIMP-nucleon event rate given by [3]:

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{r}}(E_\mathrm{r}) = N_T n_\chi \int \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{r}} \tilde{f}(\vec{v})|\vec{v}|\, \mathrm{d}^3\vec{v} \quad .$$

Differential cross section $\mathrm{d}\sigma/\mathrm{d}E_\mathrm{r}$ dependent on nuclear response functions $W_i^{x,x'}$, which in turn are dependent on nuclear density matrices [3]

Monte Carlo modeling of nuclear uncertainties

We estimate uncertainties stemming from nuclear shell-model calculations using Monte Carlo sampling.

1. Take two nuclear shell-model interactions and calculate reduced one-body density matrices for both.
2. For each one-body matrix element $\rho_J^{fi}(a,b)$, calculate average and standard deviation between the two models.
3. Define Gaussian distribution for each matrix element $\rho_J^{fi}(a,b)$ using averages and standard deviations calculated in step 2.
4. Populate a new density matrix by drawing each element **randomly** from corresponding Gaussian distribution.
5. Repeat step 3 to create an ensemble of random density matrices.

Variation of density matrices in ensemble estimate statistical uncertainty of nuclear shell-model calculations. This uncertainty can be propagated through to other quantities of interest (see next column).

Determining uncertainty in experimental results

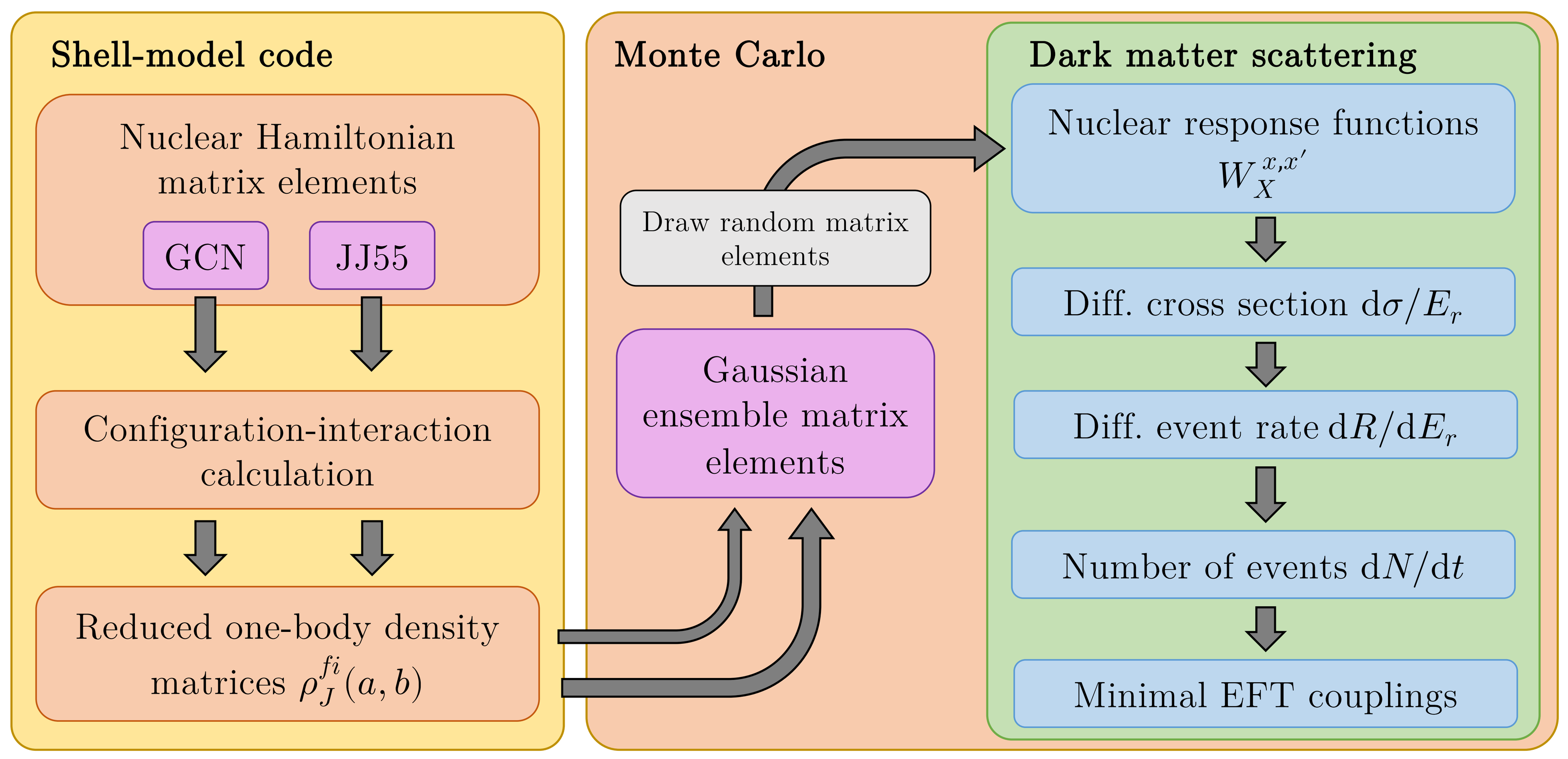

Figure 1. Outline of Monte Carlo uncertainty analysis process.

Constraining WIMP-nucleon EFT couplings

- DM direct detectors place limits on EFT couplings by determining **90% confidence level** (CL) limits (see [1])
- Calculating 90% CL as function of WIMP mass gives **exclusion curve** in m_χ-c_i^x plane
  - Exclusion curves show which m_χ, c_i^x combinations have been excluded as realistic scenarios through experimental non-detection

Example using XENON1T direct detection experiment

- Model detector as a mixture of the six most abundant isotopes of xenon (so multiple sources of nuclear uncertainty, from each isotope)
- XENON1T has near zero-background, so WIMP scattering rate can be modeled by Poisson distribution [1]
  - 90% CL limit on EFT couplings is then c_i^x value that yields **average of 2.3 events per unit exposure**
  - Number of events per effective exposure:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \int \varepsilon(E_\mathrm{r}) \frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{r}}(E_\mathrm{r})\mathrm{d}E_\mathrm{r}$$

- Calculate 90% CL limits of EFT couplings repeatedly **for each random density matrix**; **spread** of the resulting exclusion curves **is estimate of uncertainty**. Examples:

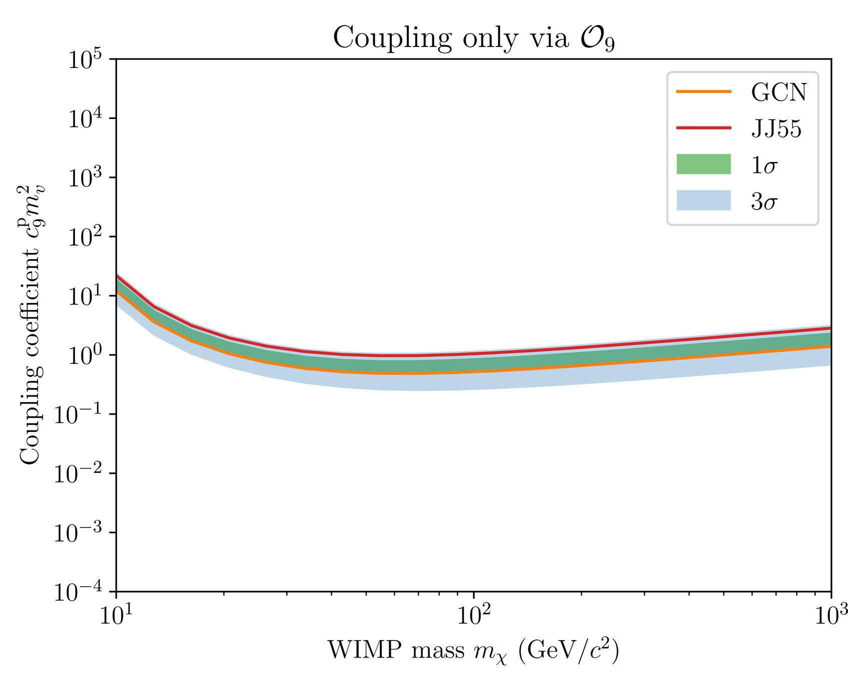

Figure 2. Exclusion plot for WIMP-proton coupling through $\mathcal{O}_9$.

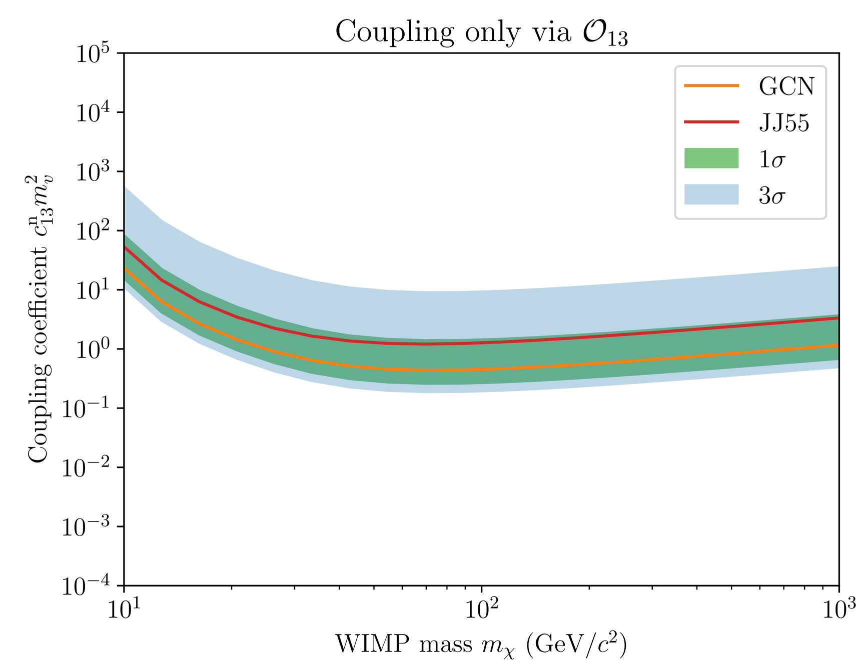

Figure 3. Exclusion plot for WIMP-neutron coupling through $\mathcal{O}_{13}$.

Discussion

- Non-zero uncertainty for many operator and nucleon combinations
- Coupling of DM to protons and neutrons through $\mathcal{O}_{13}$ has non-trivial uncertainty
  - Highly asymmetric uncertainty, could benefit from improved nuclear shell-model calculations
- Performing uncertainty analysis on **each xenon isotope individually reveals different responses and uncertainty** levels for each

Conclusions and future work

- We have presented a preliminary uncertainty analysis of the EFT coupling limits obtained from a general DM direct detection experiment.
  - Paper with full details to be published soon
  - Non-trivial uncertainty for the EFT couplings for certain operator and nucleon combinations
- Improved uncertainty quantification: start with uncertainty of nuclear Hamiltonian matrix elements and propagate error through
  - Calculations needed for this are much more computationally intensive and time-consuming
  - This is an area where **quantum computing** would excel
- Analysis presented here could easily be extended to other DM direct detection experiments (detectors using argon, germanium, etc.)

References

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