Mass or Model:
New ways to quantify the Signal Diversity in Dark Matter Searches

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1 Introduction

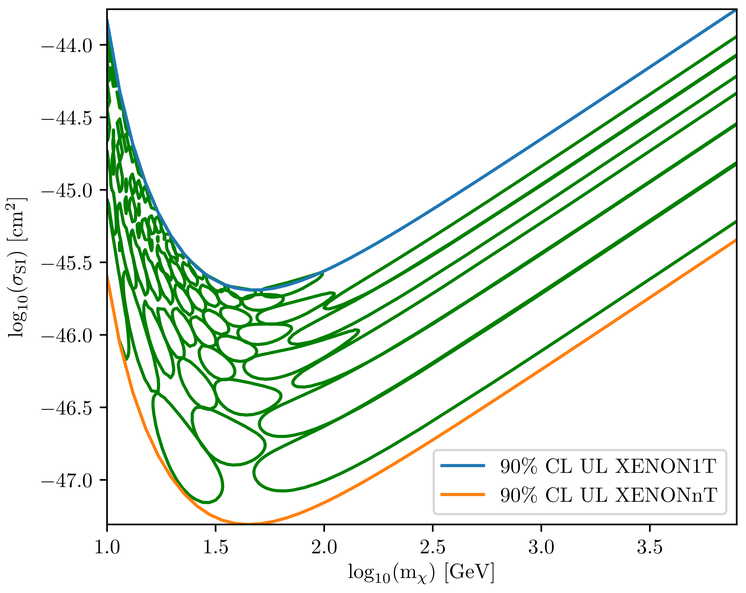
Dark Matter Problem

- A non-gravitational signature of Dark Matter (DM) has eluded physicists for several decades. The majority of search tactics involve counting experiments looking for a **signal above a *known* background**. The motivation for a theory to be realized at a particular point in the parameter space is quite sparse.
- Forecasting the sensitivity of experiments is a **ubiquitous task performed by theorists and experimentalists alike**. Characterizing potential signals of a theory or establishing the optimal observation pattern are just two of the necessary jobs undertaken by physicists.
- Here we establish a new method for characterizing the sensitivity of new experiments which is fundamentally benchmark-free. We try to answer the question: **With the lack of a theoretical prior, what experiments can we build today that will optimally constrain DM once discovered?**

$$\mathrm{TS}(\theta')_{\mathcal{D}(\theta)} \equiv -2\ln\frac{\mathcal{L}(\mathcal{D}(\theta)|\theta')}{\max_{\theta''}\mathcal{L}(\mathcal{D}(\theta)|\theta'')} \simeq (\theta-\theta')^T\,\mathcal{I}\,(\theta-\theta') \simeq \|x(\theta)-x(\theta')\|^2$$

Maximum Likelihood Ratio (MLR) Test and Benchmarking

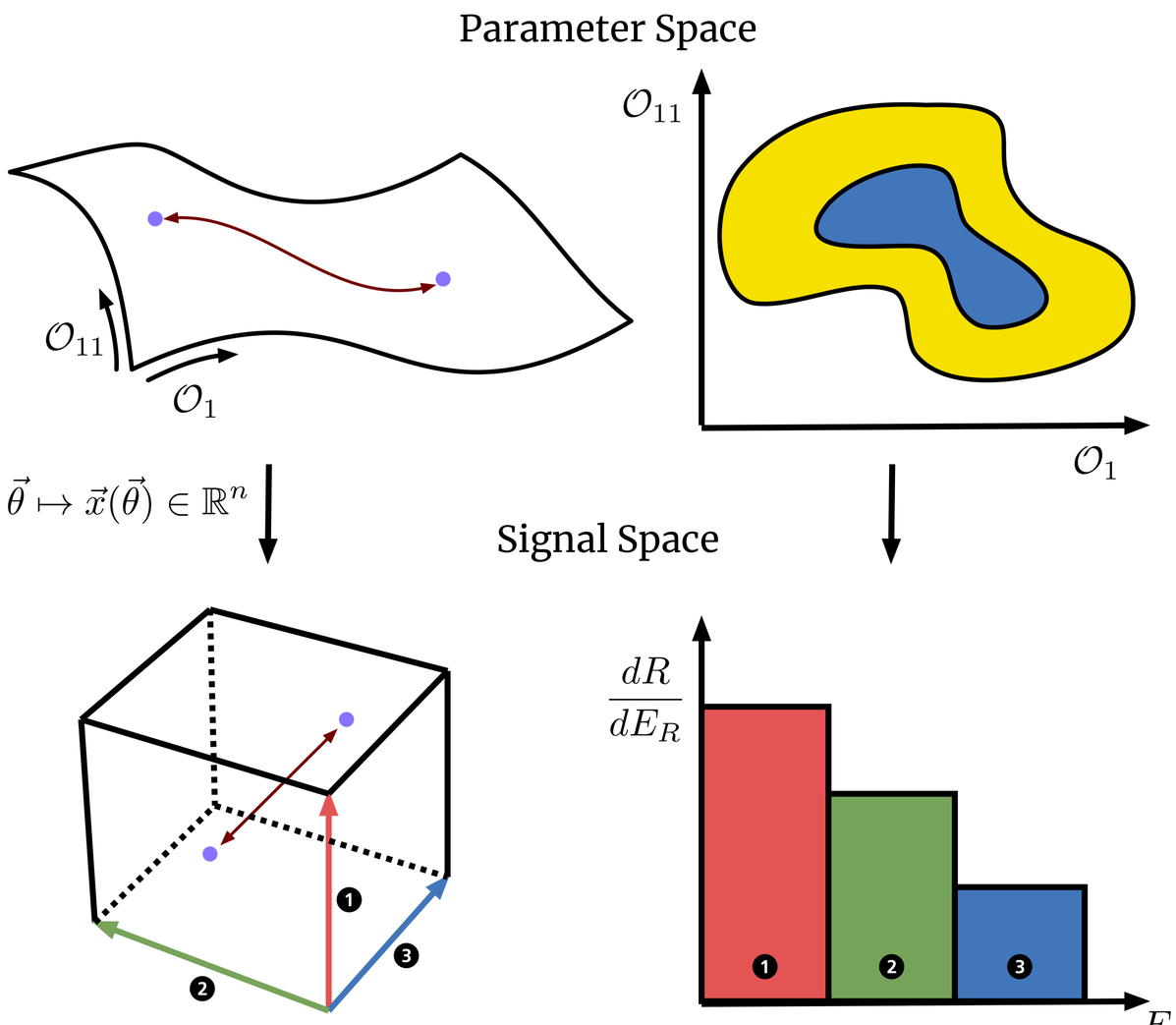
- The **standard test statistic chosen for model comparison in physics is the maximum likelihood ratio**. It can be **computationally intractable** for theories with many parameters OR when we wish to consider many benchmark scenarios.
- Typically a set of **benchmark scenarios** are chosen to assess if two theories can be discriminated from one another or against the background only hypothesis. Unfortunately this does not give an overall view of the parameter space.

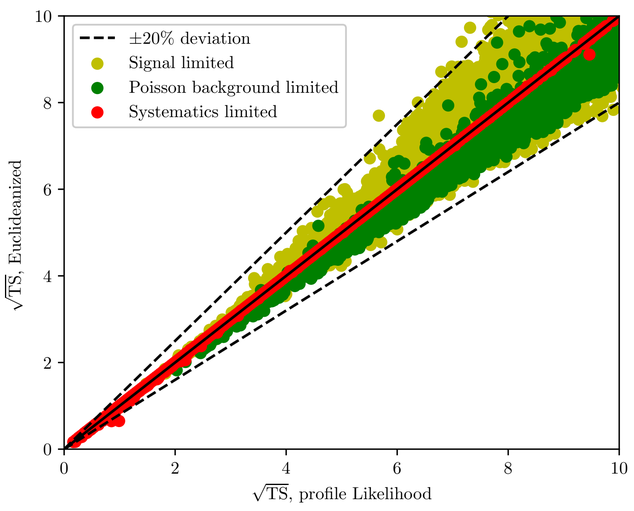


2 Techniques

Euclideanized Signals

- The MLR gives a description of the **statistical distance between two points in the parameter space**. We developed a technique to map points in the parameter space to a higher dimensional space where the MLR distance is instead given by the Euclidean distance.
- The statistical distance between two points of the parameter space is a characterization of the ability of an experiment to **distinguish between the signals produced by the points** i.e. points that produce similar signals for a given detector are defined to be close by the MLR. Points that produce vastly different signatures have a large statistical separation.
- We therefore propose that the most natural space to examine statistical distinctness is the **signal space, not the parameter space**. The mapping works for all Poisson likelihoods covering the majority of DM experiments and is accurate to 20% up to 5σ.





$$x_i \equiv \left(\sum_j (D^{-1/2})_{ij} S_j E_j\right)\left(1+\frac{R\cdot S_i}{R\cdot S_i + B_i + K_{ii}E_i}\right)$$

D_{ij} • Signal and background covariance matrix

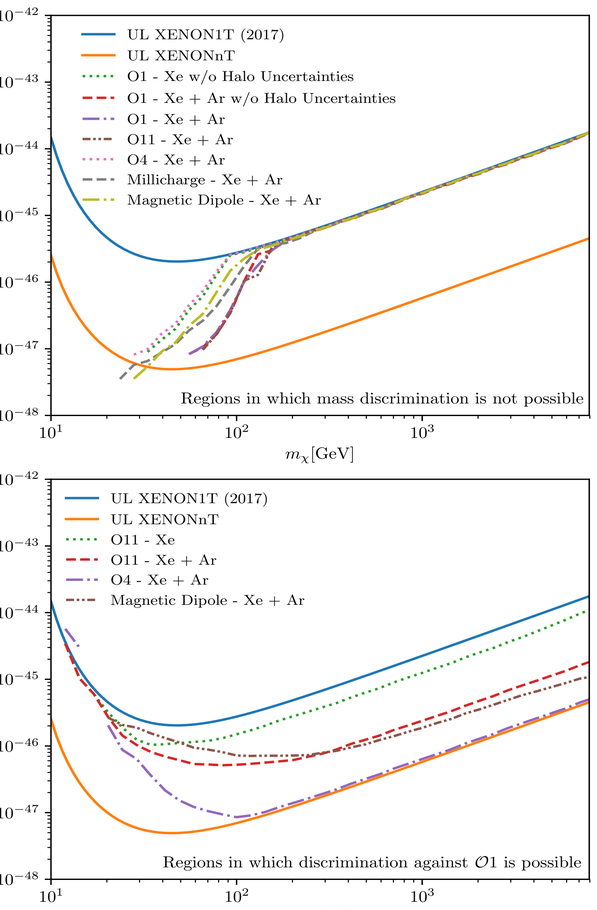
R • 0.1 Fudge factor

S_i • Signal in the ith bin

E_i • Exposure in the ith bin

Non-Relativistic Effective Field Theory and Considered Detectors

- The non-relativistic effective field theory framework allows for the characterization of **all possible** signals in direct detection (DD) experiments
- We primarily consider operators 1 and 11 which correspond to the standard **spin-independent and spin-independent with an additional E_R squared scaling interactions** (see below).
- Xenon-1T is the most sensitive DD experiment to date. We implement a **XENON-nT** like experiment along with the complementary (and similar scale) Argon experiment ***Darkside20k*.**



3 Results

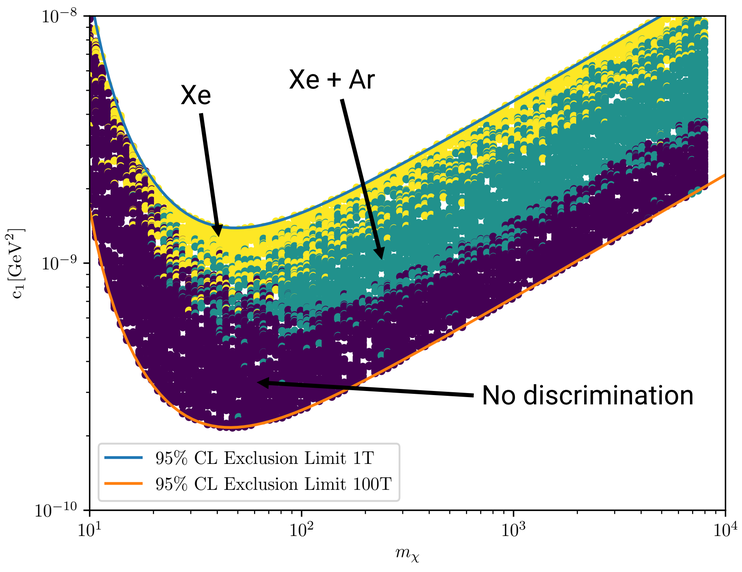
Methods

- At high masses the recoil spectrum is invariant to changes in the DM mass. At low masses the spectra appear similar extremely similar.
- Here is a step by step guide to performing a benchmark-free forecasting analysis:

1. **Sample the parameter space of M, calculating signals for each point**. For the problem at hand, we found that one obtains stable results if there are more than around **10 points within every 1σ (68% CL) confidence contour**. In the case of DD, the global model M may correspond to the non- relativistic effective field theory operators O1 and O11. We then have a three-parameter model i.e. the mass of the dark matter particle and the two individual DM-nucleon couplings to each operator. The sub-models A and B then correspond to two boundaries of M where one or the other of the DM-nucleon couplings is set to zero.
2. **Euclideanize the signals** using experimental parameters such that each parameter point has an associated new vector x_i. This step can be done using **swordfish**.
3. **For each point i in model A (i.e. points with model parameters θ_i corresponding to model A), find all points within $r_{0.046}(M)$.** We denote the set of model parameters for these neighboring points as {θ(i)}. The number of degrees of freedom used to calculate $r_{0.046}(M)$ for model comparison is equal to the difference in the dimensionality of the models of interest.
4. **Each point i is then defined as discriminable or not according to the list of parameter points $\{\theta_j\}$.** If $\{\theta_j\}$ contains a point from model B then i is not discriminable and vice versa.

Conclusions and take home messages

- Mass discrimination is not possible above roughly 100-200 GeV. Characterization of the DM-nucleon interaction is only possible below 100-200 GeV for regions just below the current limit. **Therefore only in a small part of the parameter space can both the mass and DM-nucleon interaction be constrained.** Inelastic signals may help break this tension when many events are measured.
- The **Euclideanized signals allow for an efficient exploration of the signal phenomenology** of complex models, and hence allow us to make 'benchmark-free' statements like those shown to the right that would otherwise require a large number of gridded Monte Carlo simulations that become **computationally unfeasible** in higher dimensions.



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- github.com/bradkav/WIMpy_NREFT

Acknowledgements:

This work was carried out on the Dutch national e-infrastructure with the support of SURF Co- operative. This research is funded by NWO through the Vidi research grant 680-47-532

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