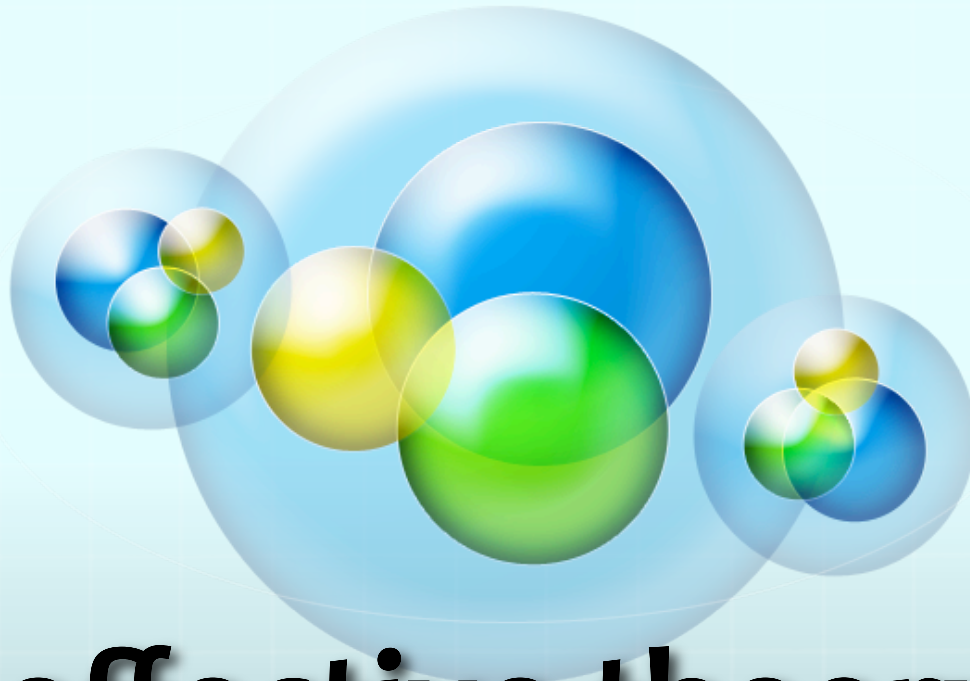

NR effective theory for DM direct detection

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Outline

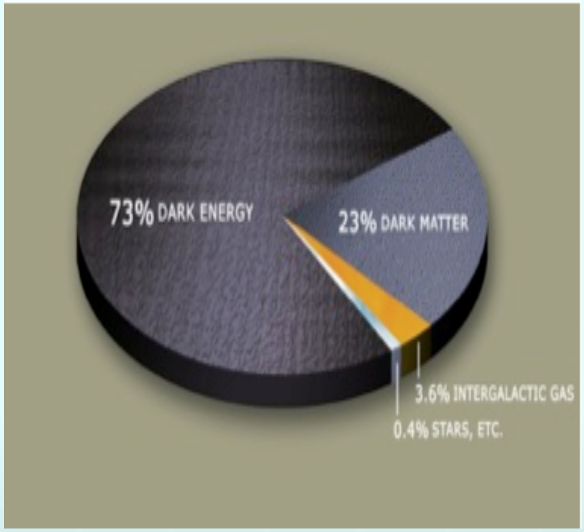
- Overview of dark matter detection
- Motivation
- NR effective theory of DM direct detection

  --- Scales and power counting rules

  --- Examples of matching
- Recoil spectra
- Constraints from current direct detection experiments
- Conclusion

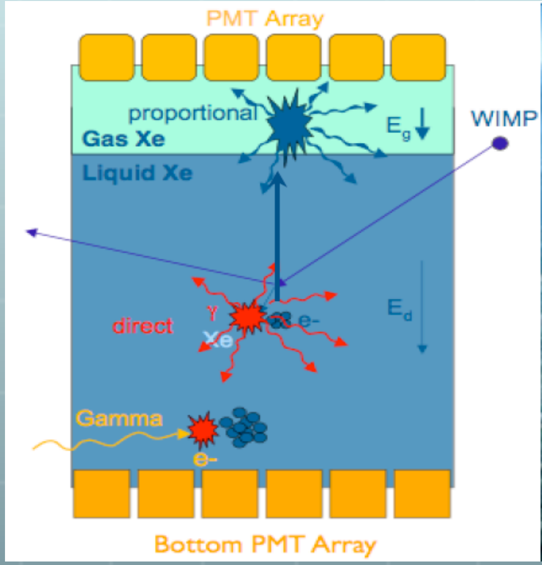
Overview

Measurement from CMB + supernovae +LSS indicates **23% of our universe is composed of DM;**

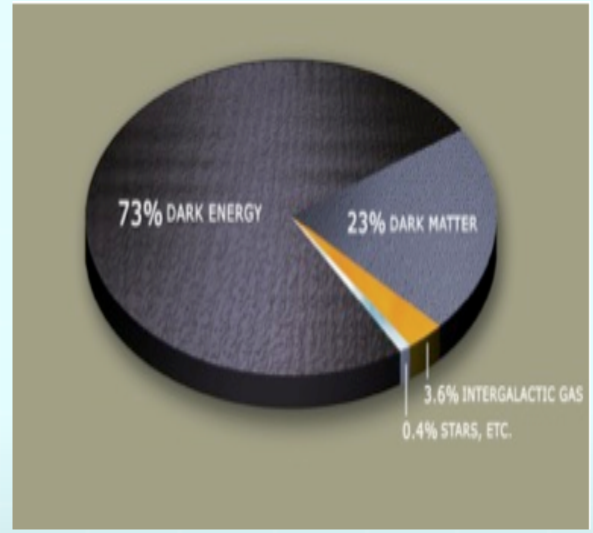


Three ways to detect DM:

Direct detection **Collider production** **Indirect detection**



Overview



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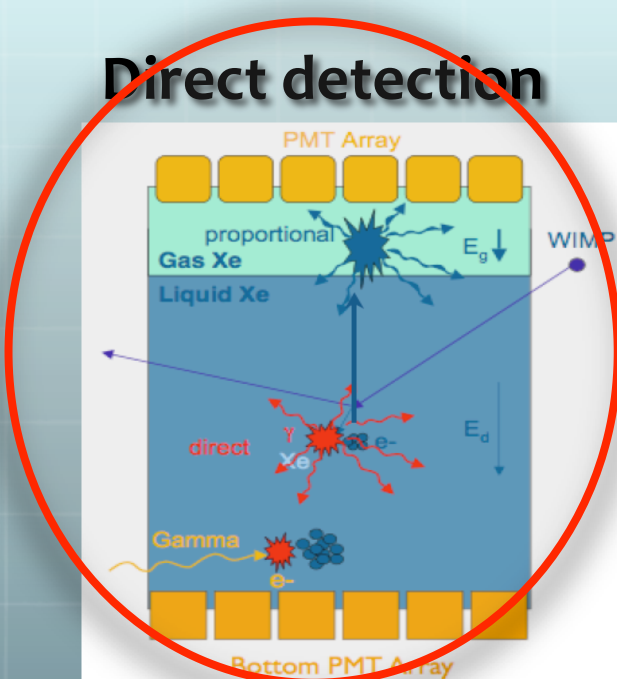
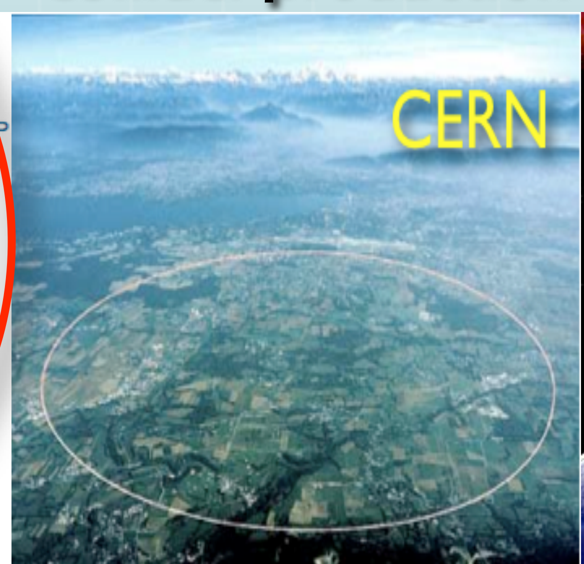
Three ways to detect DM:

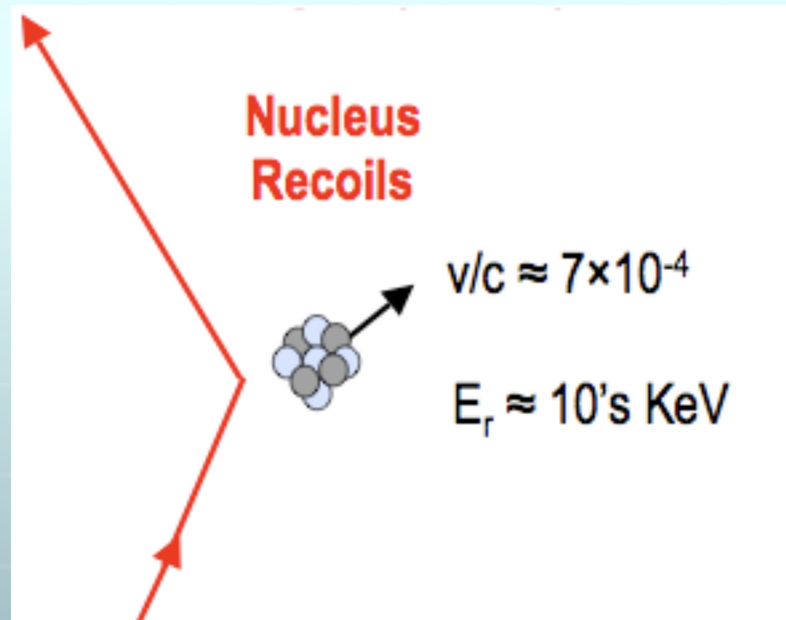
Direct detection | **Collider production** | **Indirect detection**





Direct detection

Direct detection looks for signals from DM scattering off nucleus in the underground detector.



Dark matter

- **Direct detection kinematic regime**

$$E_{kin} \sim \mathcal{O}(10\,keV)$$
$$E_R \sim \mathcal{O}(1 - 10\,keV)$$

The scattering against the whole nucleus is described by non-relativistic quantum mechanics.

Current direct detection status

- **Direct detection rate**

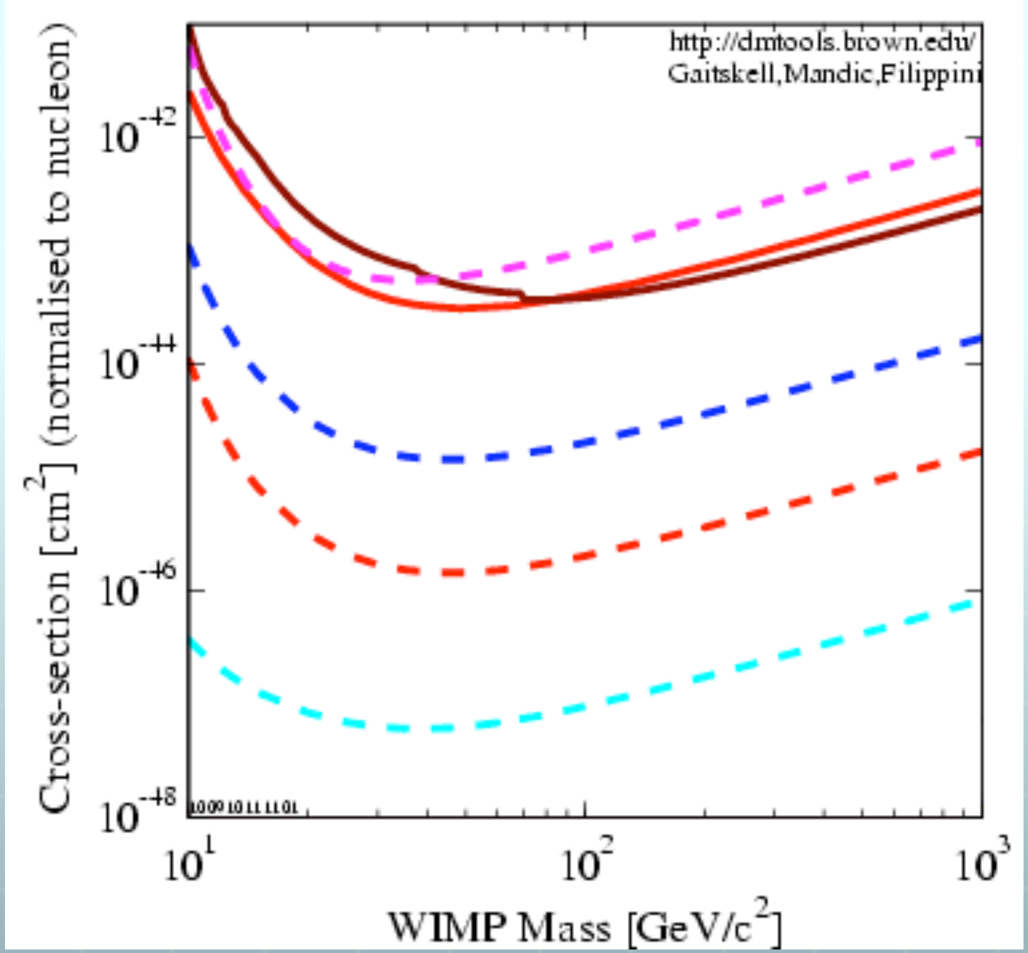
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_E} d^3v \, v f(v, v_E) \frac{d\sigma}{dE_R}$$

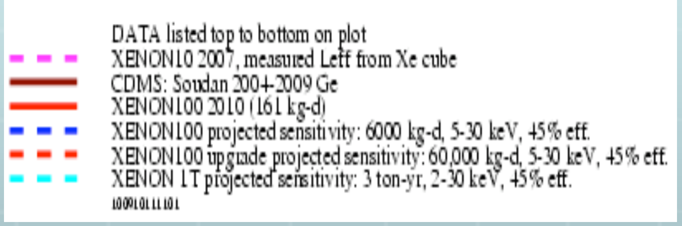
Traditionally, signals are assumed to come from contact interactions independent of momentum transfer. For instance, for SI scattering,

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2} \frac{\sigma_n}{\mu_n^2} A^2 F^2(E_R)$$

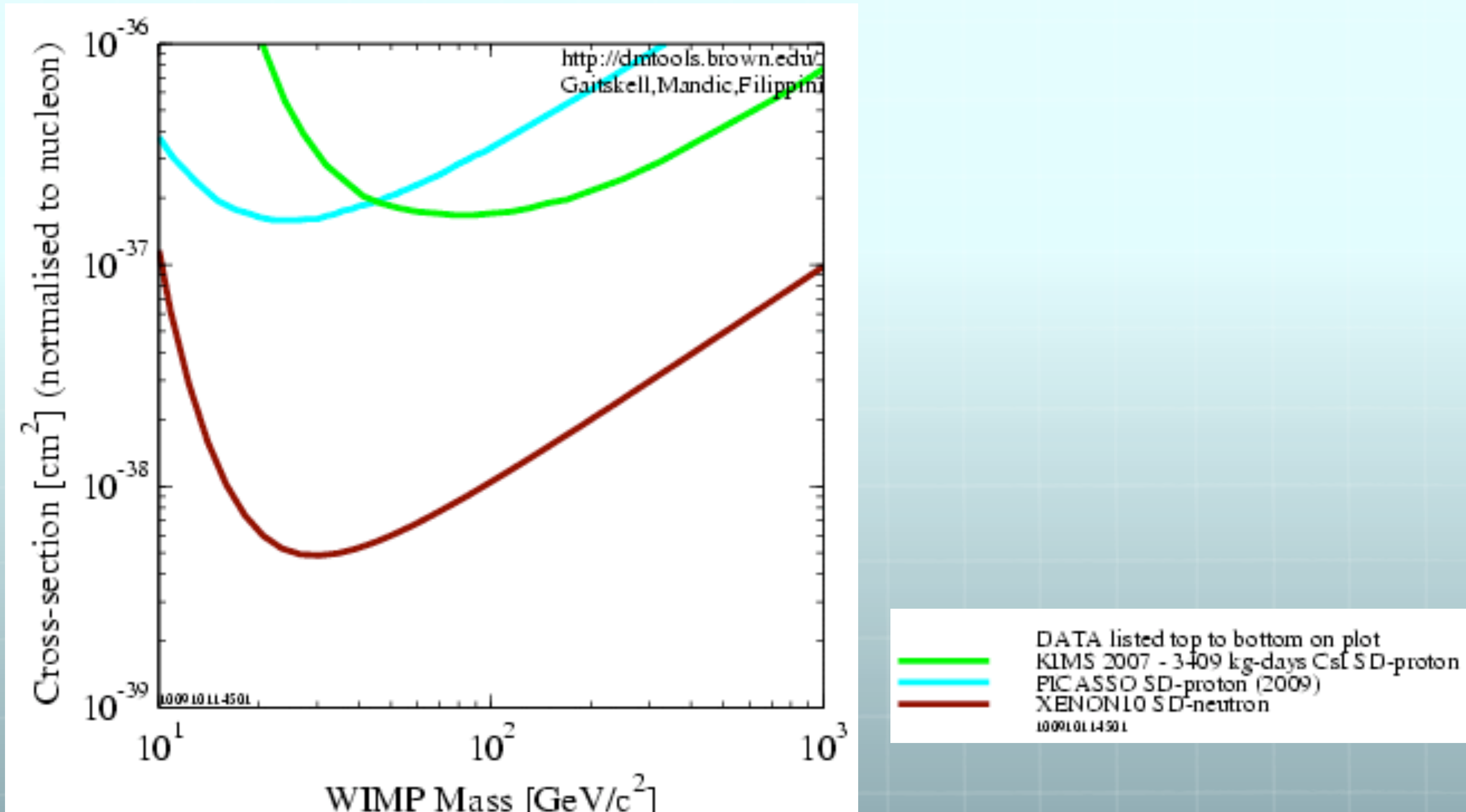
Experimental results are presented as bounds on σ_n **as a function of DM mass**

Spin-independent elastic scattering





Continued: spin-dependent scattering



Summary

- **The current bounds on xsec per nucleon are**

SI scattering: $(10^{-43} - 10^{-44})cm^2$

SD scattering: $(10^{-37} - 10^{-38})cm^2$

Motivation

- **How to extract more information about the underlying dark dynamics from the experimental data?**
- **The simple assumption of contact interaction between DM with nucleons overlooks direct detection's sensitivity to more general DM scenarios.**

E.g: Momentum-dependent DM (Chang, Pierce and Weiner; Feldstein, Fitzpatrick and Katz 2009);

Dark electromagnetic moments (Chang, Weiner and Yavin; Barger, Keung and Marfatia; Fitzpatrick and Zurek; Banks, Fortin and Thomas 2010)

Top-down view: (from theory to direct detection experiment)

UV complete DM Models predict relic abundance, direct detection signals in terms of specific model parameters

Effective field theory operators (Kurylov and Kamionkowski 2003; Agrawal, Chacko, Kilic and Mishra 2010)

NR limit

Model independent analysis

Non-relativistic quantum mechanics theory

- Different models/effective ops lead to the same NR interaction for direct detection.

E.g: Higgs exchange: $\bar{\chi}\chi\bar{q}q$

Z exchange: $\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$

gives the contact interaction in the NR limit.

- Measured recoiling rate directly bounds the coupling of contact interaction.

- From direct detection experiments to theories:

Direct detection

↓

Non-relativistic effective potential

↓

Effective field theory operators

UV complete DM Models

NR effective potential

- **Scales and simple power counting**

Transferred momentum: $|q| \sim 100$ MeV

Nucleus mass: $m_N \sim 10$ -100 GeV

DM mass: $m_\chi \sim 100$ GeV – 1 TeV

Mediator mass: m_0 unfixed

Other scales: e.g. DM-mediator interaction arises at nonrenormalizable level

DM with electric dipole moment

$$\frac{\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi F^{\mu\nu}}{\Lambda}$$

Continued

Expansion parameters:

$$v \sim 10^{-3}$$

$$\frac{q}{m_N} \sim \frac{q}{m_\chi} \sim 10^{-3}$$

$\frac{q}{m_0}, \quad \frac{q}{\Lambda}$ **unfixed, can be as large as 0.1**

- **SI experimental bounds**

$$\sigma \sim 10^{-44} cm^2$$

- **SD experimental bounds**

$$\sigma \sim 10^{-38} cm^2$$

compared to a typical weak process xsec

$$\sigma_W \sim 10^{-36} cm^2$$

|q| suppressed operator can still be relevant if they are the leading operator for direct detection.

- Consider two limits of mediator masses m_0:

  a. $m_0 \gg |q|$ Contact interaction

  b. $m_0 \ll |q|$ Long-range interaction

Assume all expansion parameters of order 10^{-3}

a. Contact interaction: Operators suppressed by a single $|q|$

b. Long-range interaction: Operators suppressed by $|q|^3$

   may still be relevant for direct detection if they are the leading operator.

Effective NR potential

$$
\begin{aligned}
V_{\mathrm{eff}} &= V_{\mathrm{eff}}^{\mathrm{SI}} + V_{\mathrm{eff}}^{\mathrm{SD}} \\
V_{\mathrm{eff}}^{\mathrm{SI}} &= h_1 \delta^3(\vec{r}) - h_2 \vec{s}_\chi \cdot \vec{\nabla} \delta^3(\vec{r}) \\
&+ l_1 \frac{1}{4\pi r} + l_2 \frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3} , \\
V_{\mathrm{eff}}^{\mathrm{SD}} &= h_1' \vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r}) - h_2' \vec{s}_N \cdot \vec{\nabla} \delta^3(\vec{r}) \\
&+ l_1' \frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r} + l_2' \frac{\vec{s}_N \cdot \vec{r}}{4\pi r^3} ,
\end{aligned}
$$

contact interaction

long range interaction

- **In the Born approximation, the matrix element of the scattering is**

$$\mathcal{M}(\vec{q},\vec{v}) = -\int d^3\vec{r} e^{i\vec{q}\cdot\vec{r}} V_{eff}(\vec{r},\vec{v})$$

- **For the numerical studies, we only consider elastic scattering;**
- **Only list static potential, or, v-independent potential;**

v-dependent potential produces nearly identical recoil spectrum to the static one for the elastic scattering;

- **Only list potential leads to interaction suppressed by a single |q|;**
- **The coefficients are dimensionful; direct detection bounds on combinations of couplings and scales.**
- **We factor out the nuclear form factor and suppress the spin indices.**

Example of matching: Femionic DM(SI)

- **SI NR operator complete set:** up to a scalar function f(q², v²)

In general, four building blocks to construct rotational invariants

$$\vec{q}, \vec{v}, \vec{s}_\chi, \vec{s}_N \qquad\qquad \vec{r}, \vec{v}, \vec{s}_\chi, \vec{s}_N$$

momentum space (w/o mediator)

PC

$$\mathcal{O}_1^{(++)} = 1$$

$$\mathcal{O}_2^{(-+)} = i\vec{s}_\chi \cdot \vec{q}$$

$$\mathcal{O}_3^{(--)} = \vec{s}_\chi \cdot \vec{P}$$

$$\mathcal{O}_4^{(++)} = i\vec{s}_\chi \cdot (\vec{P} \times \vec{q})$$

$(\vec{P} = \mu_N \vec{v} + \vec{q}/2)$

position space

$$\mathcal{O}_1 = \delta^3(\vec{r}), \quad \frac{1}{4\pi r}$$

$$\mathcal{O}_2 = \vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}), \quad \frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3}$$

$$\mathcal{O}_3 = \vec{s}_\chi \cdot \vec{P}\delta^3(\vec{r}), \quad \frac{\vec{s}_\chi \cdot \vec{P}}{4\pi r}$$

$$\mathcal{O}_4 = (\vec{s}_\chi \times \vec{v}) \cdot \delta^3(\vec{r}), \quad \frac{(\vec{s}_\chi \times \vec{v}) \cdot \vec{r}}{4\pi r^3}$$

- **Mapping of effective field theory operators to the NR potential**

$$\mathcal{O}_1^{(++)} = 1 \qquad \bar{\chi}\chi\bar{q}q, \quad \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

$$\mathcal{O}_2^{(-+)} = i\vec{s}_{\chi}\cdot\vec{q} \qquad \bar{\chi}\gamma^{5}\chi\bar{q}q \quad \bar{\chi}\sigma^{\mu\nu}\gamma^{5}D_{\mu}\chi\bar{q}\gamma_{\nu}q$$

$$\mathcal{O}_3^{(--)} = \vec{s}_{\chi}\cdot\vec{P} \quad \longleftarrow \quad \bar{\chi}\gamma^{5}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

$$\mathcal{O}_4^{(++)} = i\vec{s}_{\chi}\cdot(\vec{P}\times\vec{q}) \qquad \bar{\chi}\sigma^{\mu\nu}D_{\mu}\chi\bar{q}\gamma_{\nu}q$$

- **Examples of simple theories for each potential**

$\delta^3(\vec{r})$	**Higgs exchange**
$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r})$	**DM dark EDM off nucleus charge**
$\frac{1}{r}$	**exchange of a light boson**
$\frac{\vec{s}_\chi \cdot \vec{r}}{r^3}$	**DM EDM off nucleus charge**

Recoil spectrum

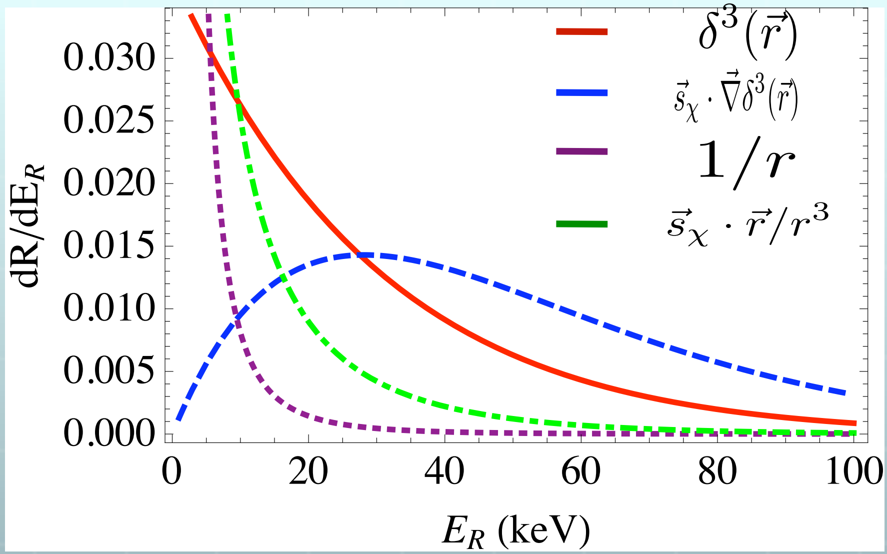
The NR theory highlights the possibility of having qualitatively different recoil energy spectrum.

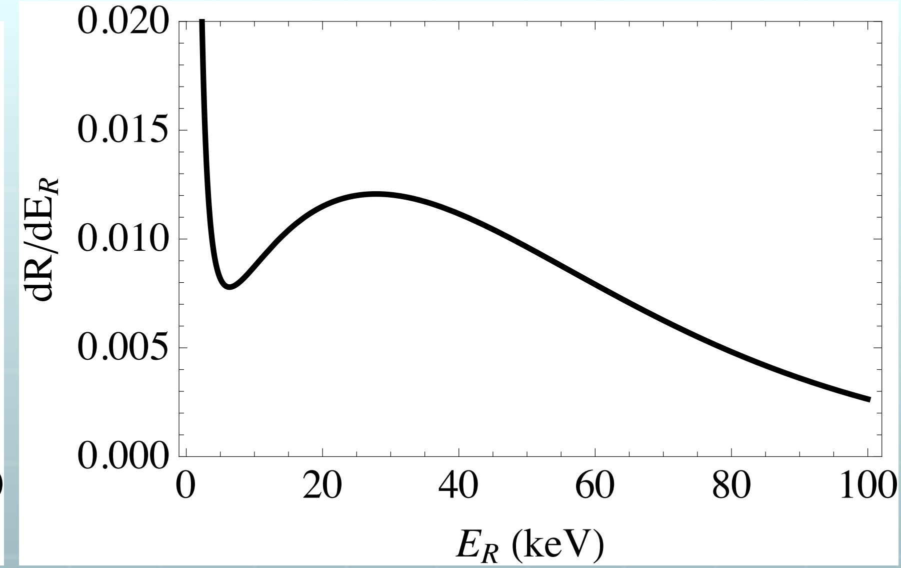
SI NR operators	SD NR operators	E_R
$\delta^3(\vec{r})$	$\vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r})$	1
$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r})$	$\vec{s}_N \cdot \vec{\nabla}\delta^3(\vec{r})$	E_R
$\frac{1}{4\pi r}$	$\frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r}$	E_R^{-2}
$\frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3}$	$\frac{\vec{s}_N \cdot \vec{r}}{4\pi r^3}$	E_R^{-1}

Sample Spectra

- **Sample spectrum for Germanium.**

Left: spectrum with contribution from one operator;





Right: spectrum with contributions from two operators;

Constraints from direct detection (CDMS, Xenon10, Xenon100 for SI direct detection)

$$\delta^3(\vec{r}) \qquad h_1 \lesssim 10^{-8}\,\mathrm{GeV}^{-2} = \frac{10^{-4}}{(100\,\mathrm{GeV})^2}$$

$$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}) \qquad h_2 \lesssim 10^{-7}\,\mathrm{GeV}^{-3} = \frac{10^{-1}}{(100\,\mathrm{GeV})^3}$$

$$\frac{1}{r} \qquad l_1 \lesssim 10^{-11}$$

$$\frac{\vec{s}_\chi \cdot \vec{r}}{r^3} \qquad l_2 \lesssim 10^{-9}\,\mathrm{GeV}^{-1} = \frac{10^{-7}}{(100\,\mathrm{GeV})}.$$

- **Example 1** $\delta^3(\vec{r}) \quad h_1 \lesssim 10^{-8}\,\mathrm{GeV}^{-2} = \frac{10^{-4}}{(100\,\mathrm{GeV})^2}$

Higgs exchange: $y_s \sim 10^{-4}$

Z exchange: $\bar{\chi}\gamma^\mu \chi h^\dagger D_\mu h \quad (v_{EW}/\Lambda)^2 \sim 10^{-4}$

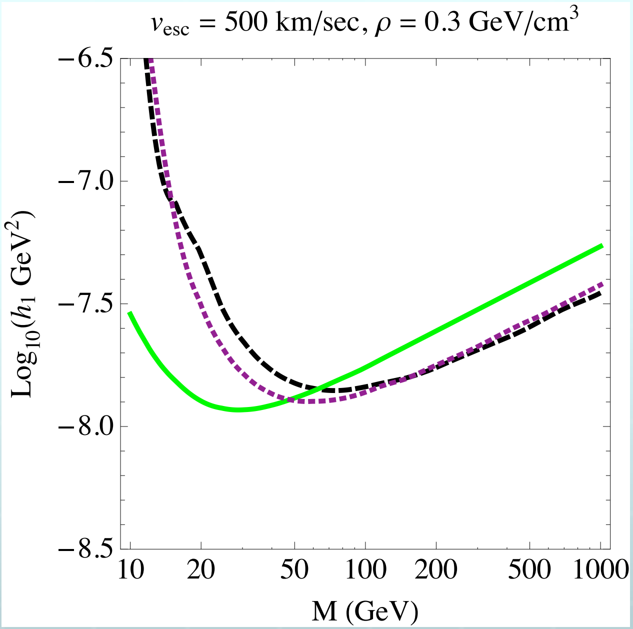
- **Example 2** $\vec{s}_\chi \cdot \vec{r}/r^3 \quad l_2 \lesssim 10^{-9}\,\mathrm{GeV}^{-1} = \frac{10^{-7}}{(100\,\mathrm{GeV})}$

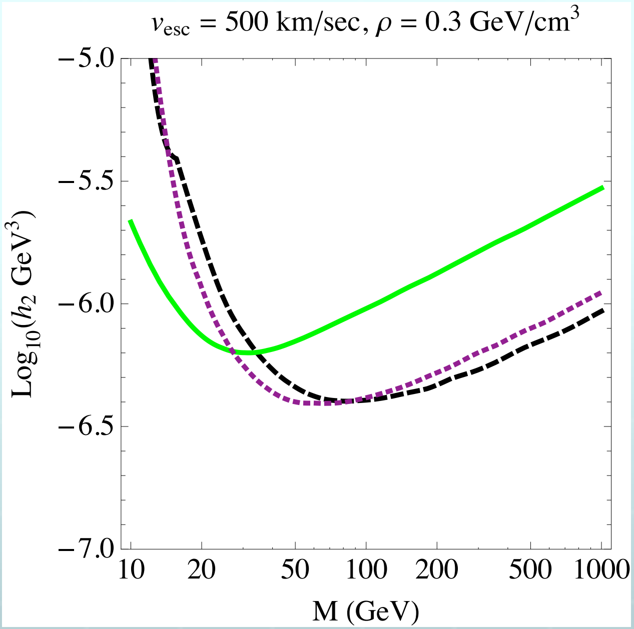
(Pseudo)scalar exchange: $l_2 \sim g/m_\chi \quad g \lesssim 10^{-7}$

DM dipole moment: $l_2 = d \quad d \lesssim 10^{-23}(e \cdot cm)$

- **Bound on contact interaction**

momentum independent **momentum dependent**

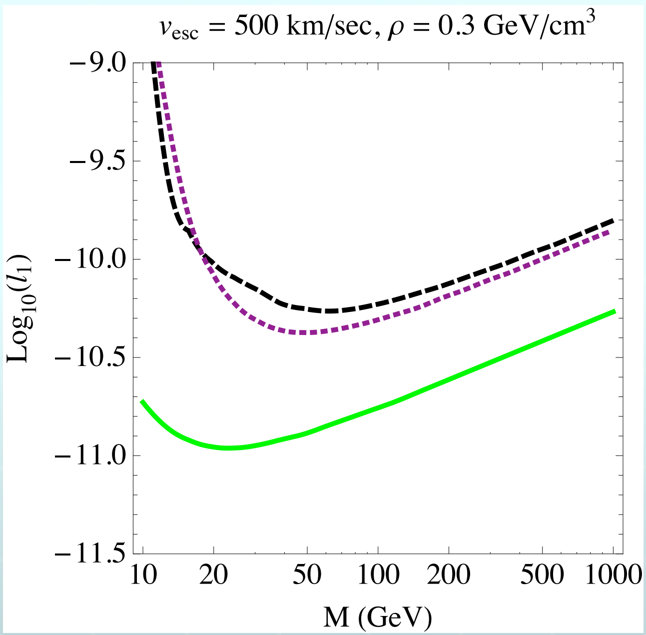




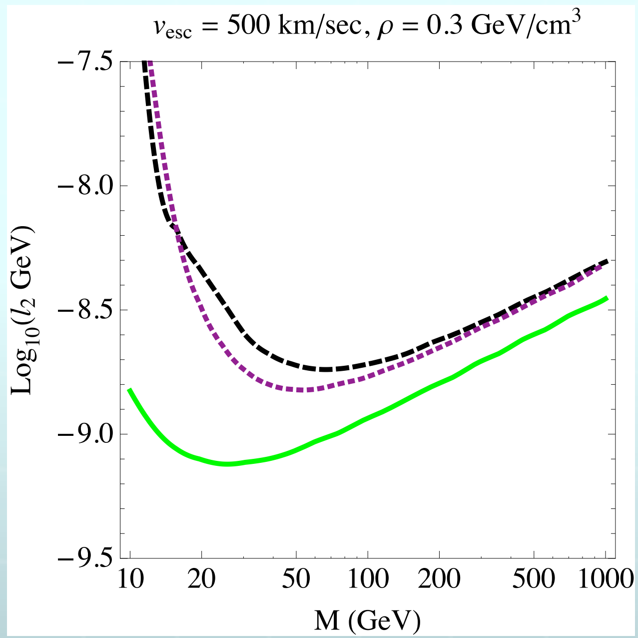
Black: CDMS; Green: Xenon 10; Purple: Xenon100

Bound on long range interaction

coloumb potential



dipole potential



Xenon 10 has strongest bound as it has the lowest energy threshold;

Threshold calibration is crucial for not only light DM but also long range interaction mediated by light bosons.

Conclusion

- **We present a model-independent framework based on NR operators to analyze data from direct detection.**
- **If near future direct detection sees DM, it will not only shed information on DM mass, overall scattering cross section but also DM interaction from recoiling spectrum.**

Thank you!