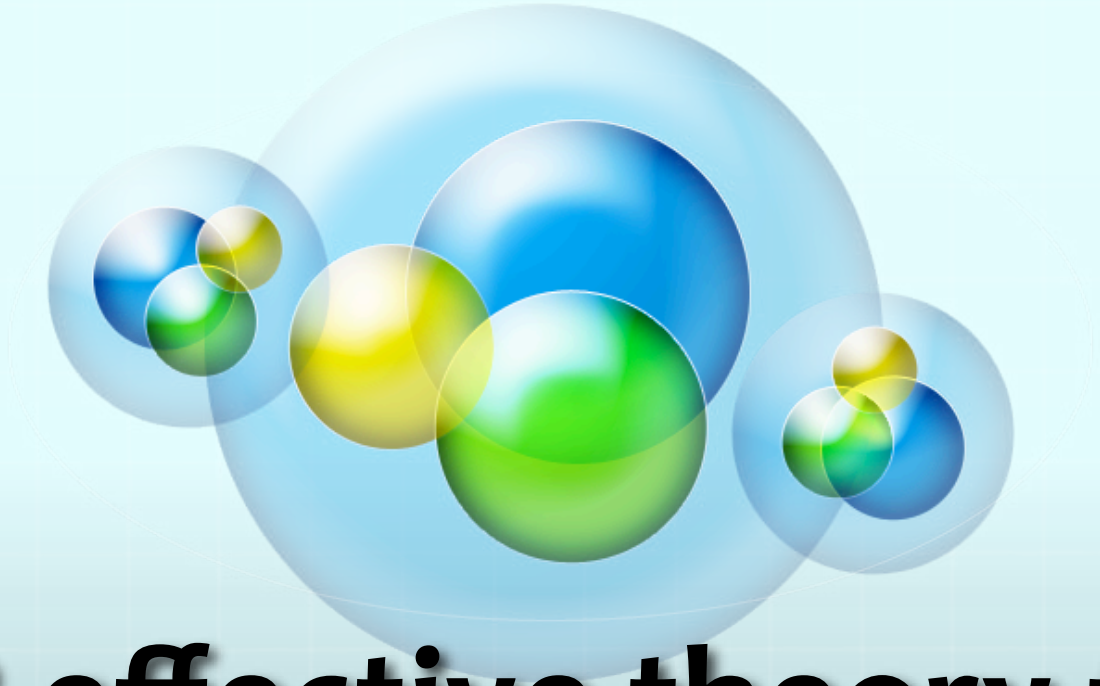

NR effective theory for DM direct detection

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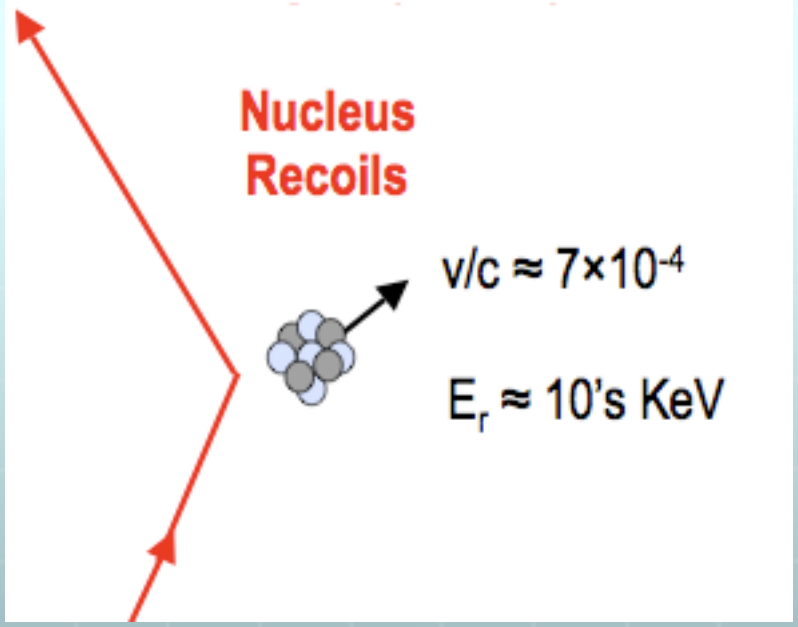
In progress

Outline

- Dark matter direct detection
- Motivation
- NR quantum mechanics theory of DM direct detection
  - --- Scales and power counting rules
  - --- Example
- Recoil spectrum
- Constraints from present direct detection experiments

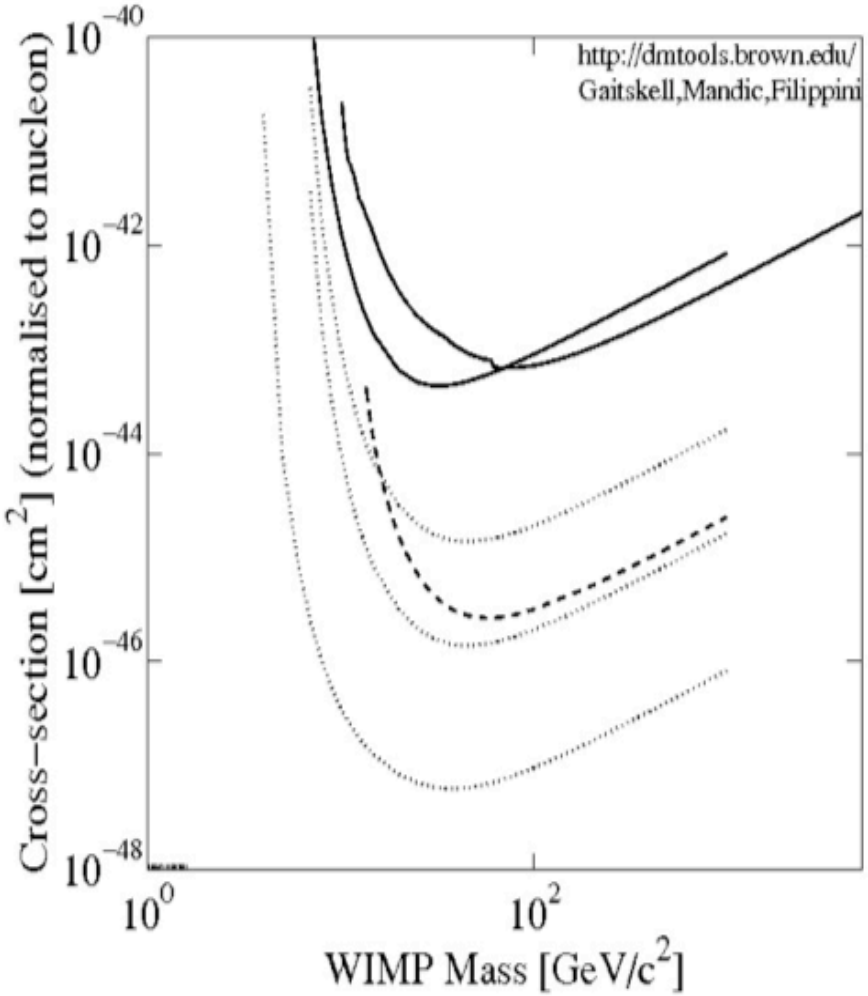
Direct detection signal

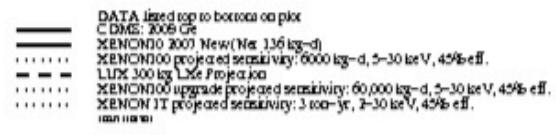
Direct detection looks for signals from DM scattering off nucleus.



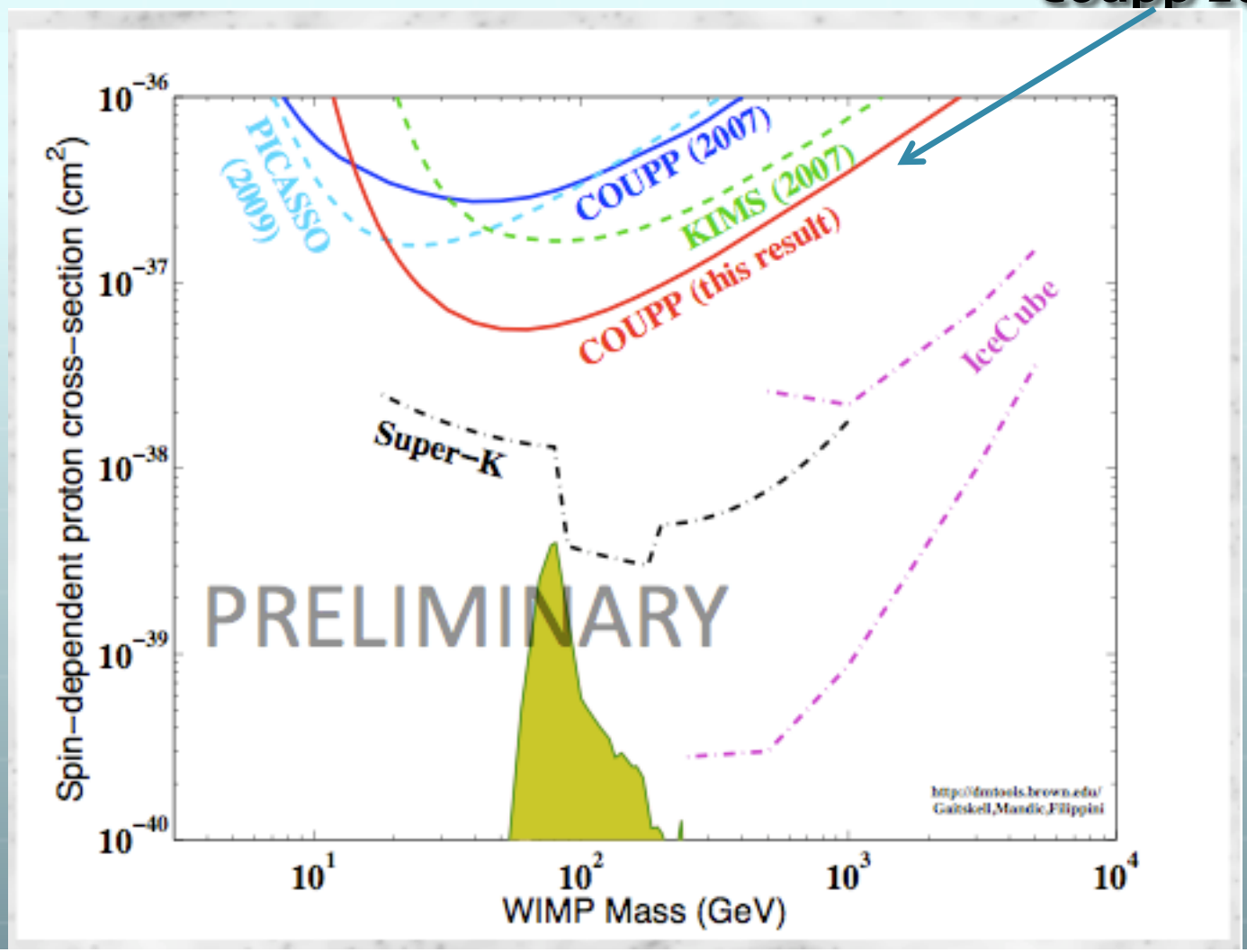
Dark matter

Current direct detection status (SI)





Continued: Direct detection (SD)



- **In direct detection,**

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

At the simplest level of theories, the scattering process is described by non-relativistic quantum mechanics modulo detailed nuclear physics.

- **We focus only on direct detection and do not make connections to indirect searches and relic abundance.**

Motivation

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

↓ NR limit

Non-relativistic quantum mechanics theory

Model independent analysis

- **From direct detection to theories:**

Direct detection constraints

non-relativistic quantum mechanics operators

Effective field theory operators

UV complete DM Models

- **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.

- **Recoiling rate directly bounds the coupling of contact interaction.**

Scales and power counting

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

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

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

Mediator mass: m_0 unfixed

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

DM with electromagnetic form factor

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

Continued

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

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

$$\frac{q}{m_0}, \quad \frac{q}{\Lambda}$$ **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**

  Also the nuclear form factor (nucleus finite size effect) factorize out of the microscopic cross section.

Assume all expansion paramters 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

$$
\begin{aligned}
V_{\rm eff} &= V_{\rm eff}^{\rm SI} + V_{\rm eff}^{\rm SD} \\
V_{\rm eff}^{\rm SI} &= c_{h1}\delta^3(\vec{r}) + i c_{h2}\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}) \\
&+ c_{l1}\frac{1}{4\pi r} - c_{l2}\frac{i\vec{s}_\chi \cdot \vec{r}}{4\pi r^3}, \\
V_{\rm eff}^{\rm SD} &= c'_{h1}\vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r}) + i c'_{h2}\vec{s}_N \cdot \vec{\nabla}\delta^3(\vec{r}) \\
&+ c'_{l1}\frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r} - c'_{l2}\frac{i\vec{s}_N \cdot \vec{r}}{4\pi r^3},
\end{aligned}
$$

contact interaction

long range interaction

Aside:

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

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

Only list static potential, or, v-independent potential;

v-dependent potential produce nearly identical recoil spectrum to the static one;

Only list potential leads to interaction suppressed by a single |q|;

The coefficients are dimensionful; direct detection bounds on combinations of couplings and scales.

Example: Femionic DM(SI)

- **SI NR operator complete set:** up to a scalar function $f(q^2, v^2)$

momentum space (w/o mediator)

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_2 = \vec{\sigma}_\chi \cdot \vec{q}$$
$$\mathcal{O}_3 = \vec{\sigma}_\chi \cdot \vec{v}$$
$$\mathcal{O}_4 = \vec{\sigma}_\chi \cdot (\vec{v} \times \vec{q})$$

position space

$$\mathcal{O}_1 = \delta^3(\vec{r}), \quad \frac{1}{r}$$
$$\mathcal{O}_2 = \vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}), \quad \frac{\vec{s}_\chi \cdot \vec{r}}{r^3}$$
$$\mathcal{O}_3 = \vec{s}_\chi \cdot \vec{v}\delta^3(\vec{r}), \quad \frac{\vec{s}_\chi \cdot \vec{v}}{r}$$
$$\mathcal{O}_4 = \vec{s}_\chi \cdot (\vec{v} \times \vec{\nabla})\delta^3(\vec{r}), \quad \frac{\vec{s}_\chi \cdot (\vec{v} \times \vec{r})}{r^3}$$

In general, four building block to construct rotational invariants

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

Effective field theory operators

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

$$\mathcal{O}_2 = \vec{\sigma}_\chi \cdot \vec{q} \qquad \bar{\chi}\gamma^5\chi\bar{q}q, \quad \bar{\chi}\gamma^5\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$\mathcal{O}_3 = \vec{\sigma}_\chi \cdot \vec{v} \qquad \bar{\chi}\gamma^5\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$\mathcal{O}_4 = \vec{\sigma}_\chi \cdot (\vec{v} \times \vec{q}) \qquad (\bar{\chi}\gamma^5 q)(\bar{q}\gamma^5\chi)$$

$$\sim \bar{\chi}\chi\bar{q}q - \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \ldots,$$

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

$\delta^3(\vec{r})$ **Higgs exchange**

$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r})$ **Majorana fermion w Z-exchange**

$\bar{\chi}\gamma^5\gamma^\mu\chi\bar{q}(\alpha+\beta\gamma^5)q$

$\frac{1}{r}$ **exchange of a light boson**

$\frac{\vec{s}_\chi \cdot \vec{r}}{r^3}$ **DM EDM off nucleus charge**

Recoil spectrum

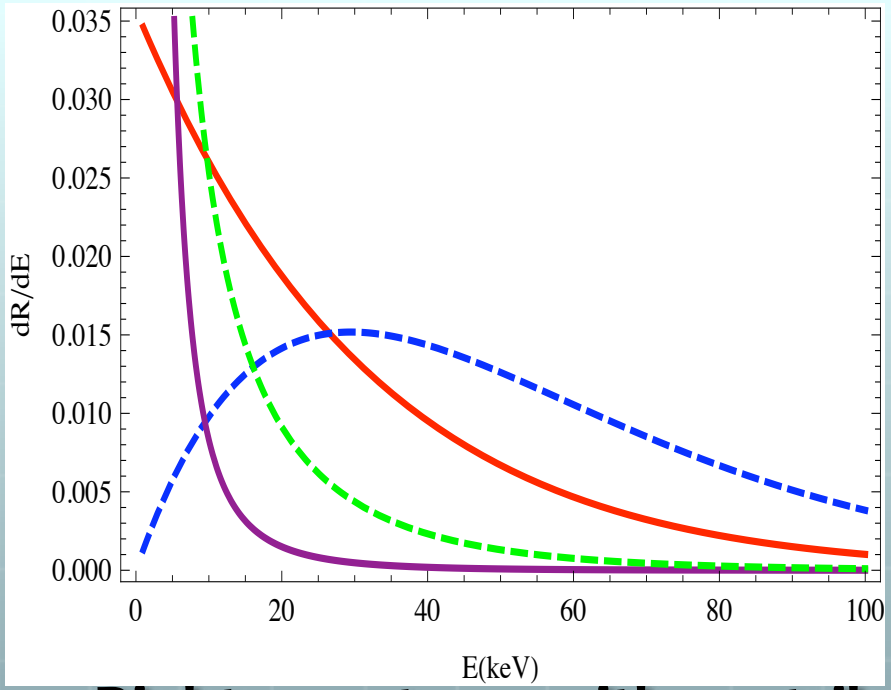
The NR theory highlights the possibility of having qualitatively different recoil energy spectrum.

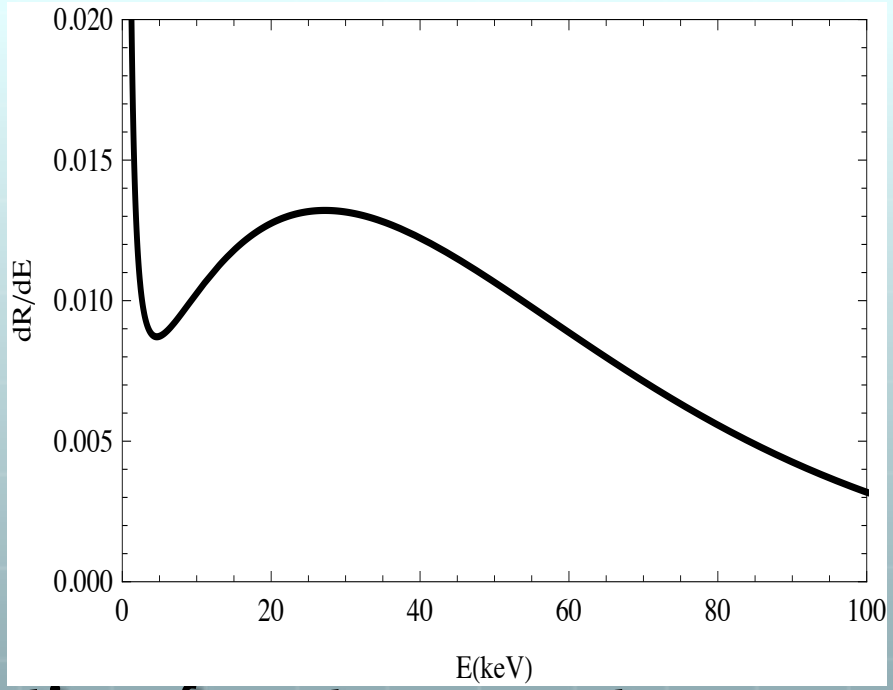
SI NR operators	SD NR operators	E_R
$\delta^3(\vec{r})$	$\vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r})$	1
$i\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r})$	$i\vec{s}_N \cdot \vec{\nabla}\delta^3(\vec{r})$	E_R
$\frac{1}{4\pi r}$	$\frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r}$	E_R^{-2}
$\frac{-i\vec{s}_\chi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

Sample Spectrum

- 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)

$$\delta^3(\vec{r}) \qquad c_{h1} \sim \left(10^{-8}\mathrm{GeV}^{-2}\right)\left(\frac{g}{10^{-4}}\right)\left(\frac{100\mathrm{GeV}}{\Lambda}\right)^2$$

$$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r}) \qquad c_{h2} \sim \left(10^{-7}\mathrm{GeV}^{-3}\right)\left(\frac{g}{0.1}\right)\left(\frac{100\mathrm{GeV}}{\Lambda}\right)^3$$

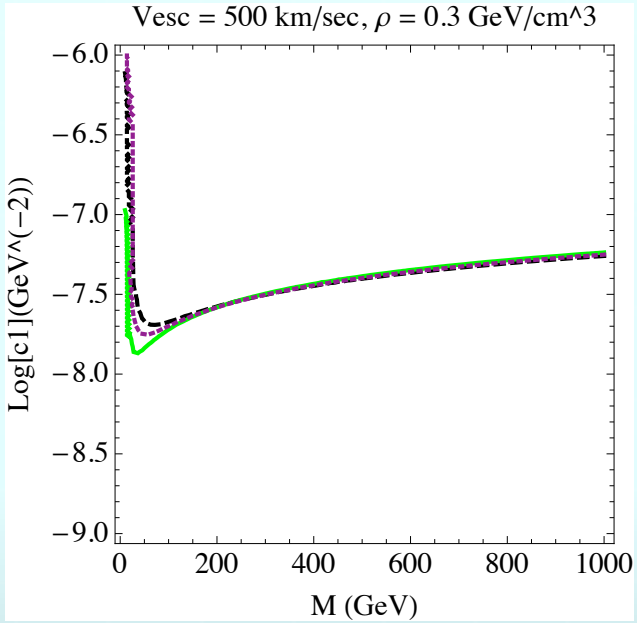
$$\frac{1}{r} \qquad c_{l1} \sim 10^{-10}$$

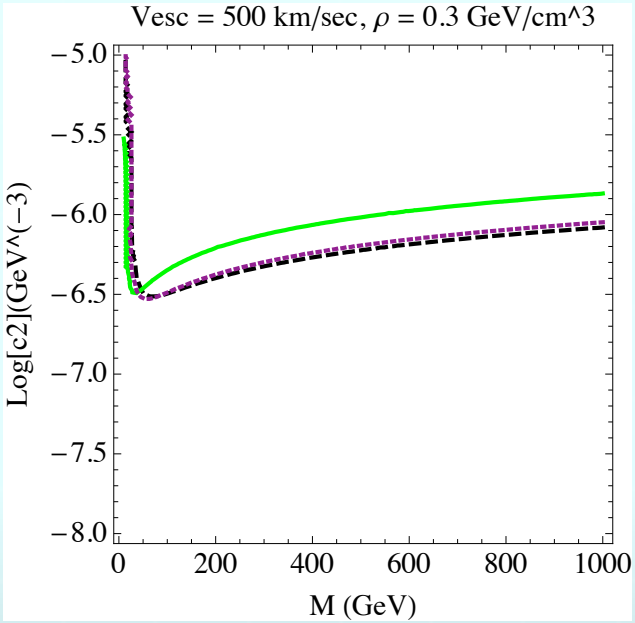
$$\frac{\vec{s}_\chi \cdot \vec{r}}{r^3} \qquad c_{l2} \sim \left(10^{-9}\mathrm{GeV}^{-1}\right)\left(\frac{g}{10^{-7}}\right)\left(\frac{100\mathrm{GeV}}{\Lambda}\right)$$

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.

Backup plots


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[c1](GeV^(−2))
M (GeV)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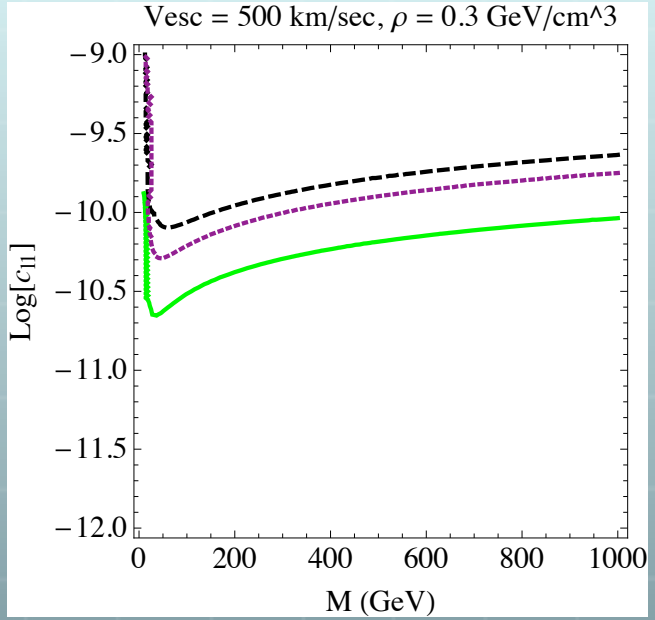
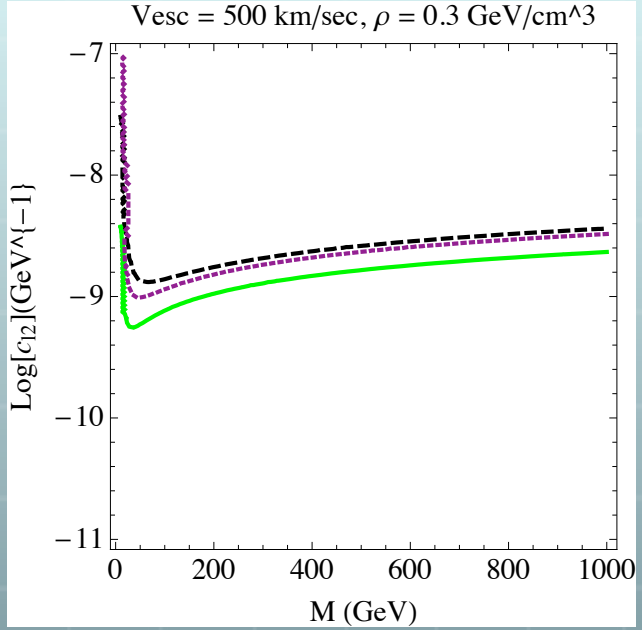
Log[c2](GeV^(−3)
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[c11]
M (GeV)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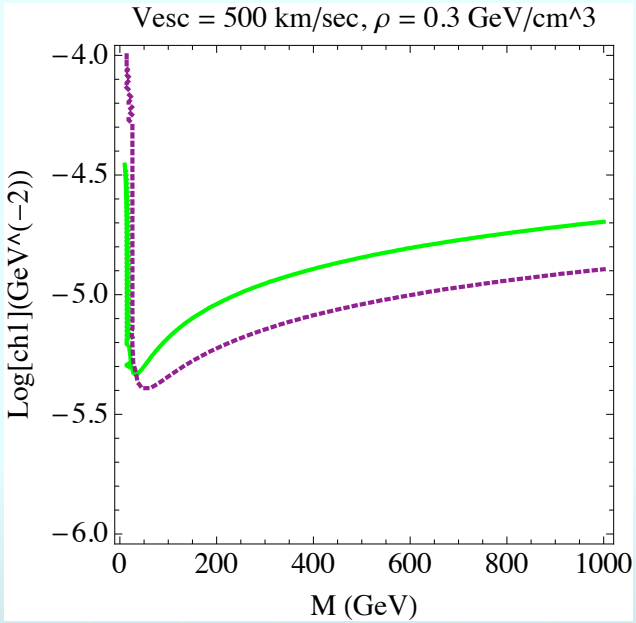
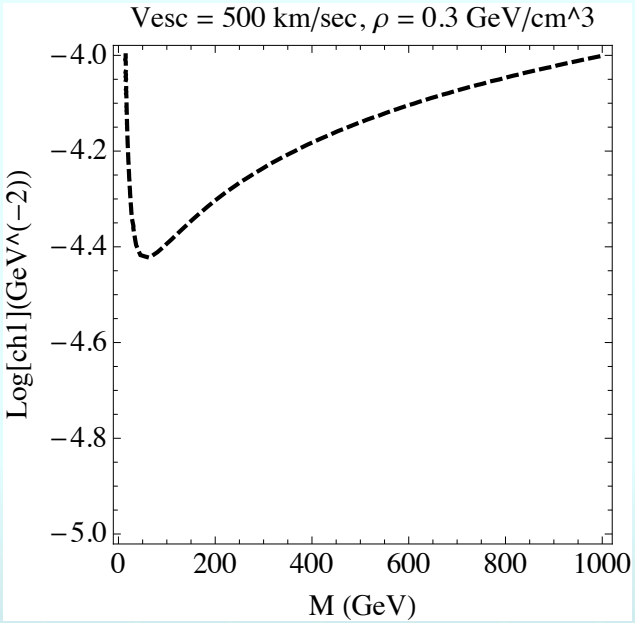
Log[c12](GeV^{−1}
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[ch1](GeV^(−2))
−4.0
−4.5
−5.0
−5.5
−6.0
0
200
400
600
800
1000
M (GeV)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Log[ch1](GeV^(−2))
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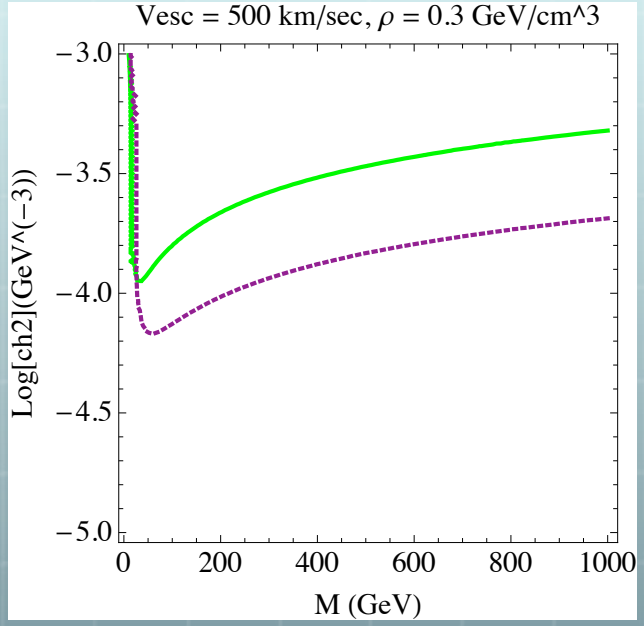
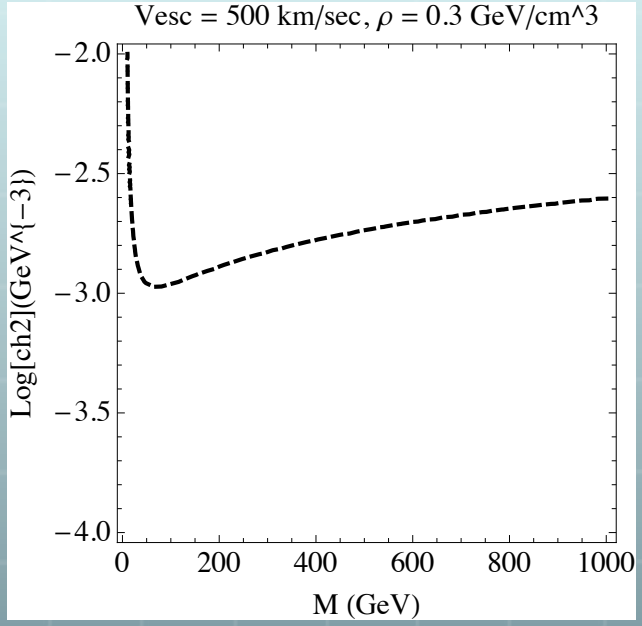
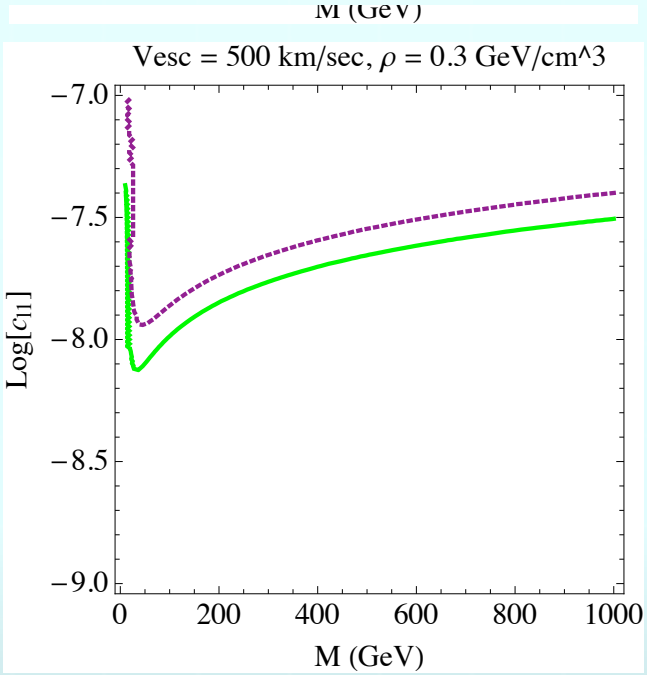
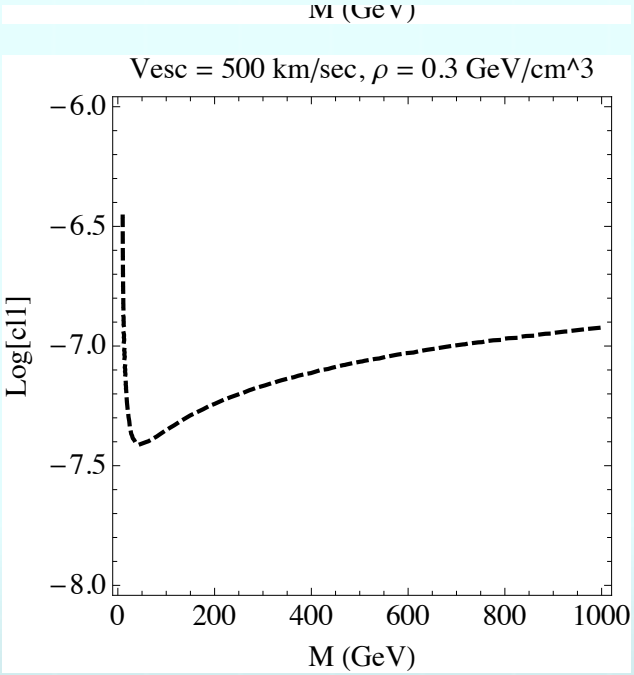
−4.2
−4.4
−4.6
−4.8
−5.0
0
200
400
600
800
1000
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[ch2](GeV^(−3))
−3.0
−3.5
−4.0
−4.5
−5.0
0
200
400
600
800
1000
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[ch2](GeV^{−3})
−2.0
−2.5
−3.0
−3.5
−4.0
0
200
400
600
800
1000
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[c11]
M (GeV)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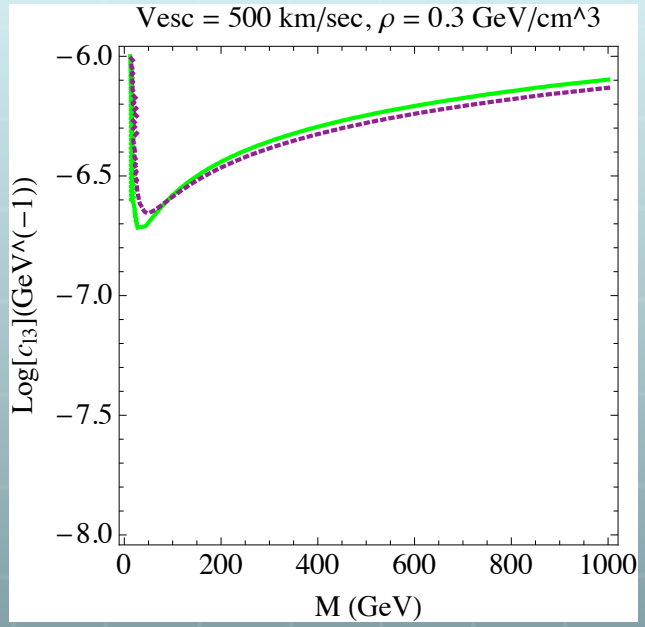
Log[cl1]
M (GeV)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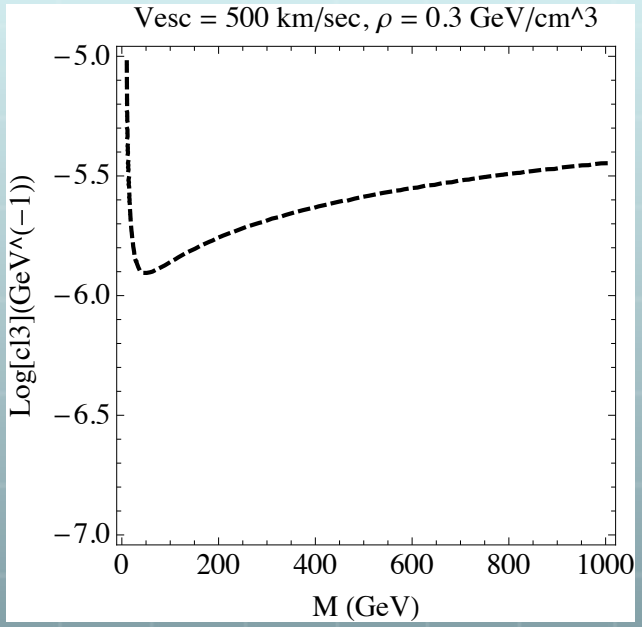
Log[c13](GeV^(−1))
M (GeV)


Vesc = 500 km/sec, ρ = 0.3 GeV/cm^3
Log[cl3](GeV^(−1))
M (GeV)