Nucleonic EFT for Direct Detection

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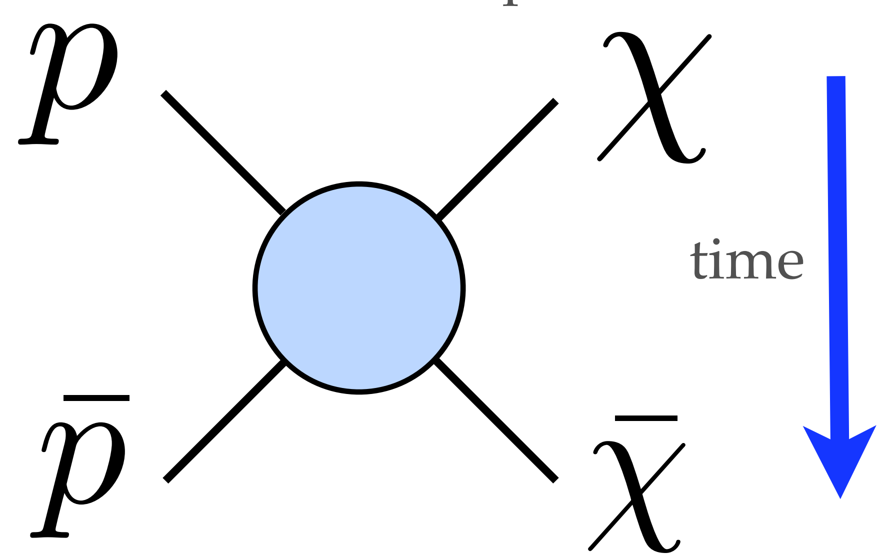
0908.2991, 0910.0007, 1007.5325
Feldstein, ALF, Katz, Tweedie, Zurek
1203.3542, 1211.2818, 1308.6288
Anand, Haxton, ALF, Katz, Lubbers, Xu

Detection

Direct Detection

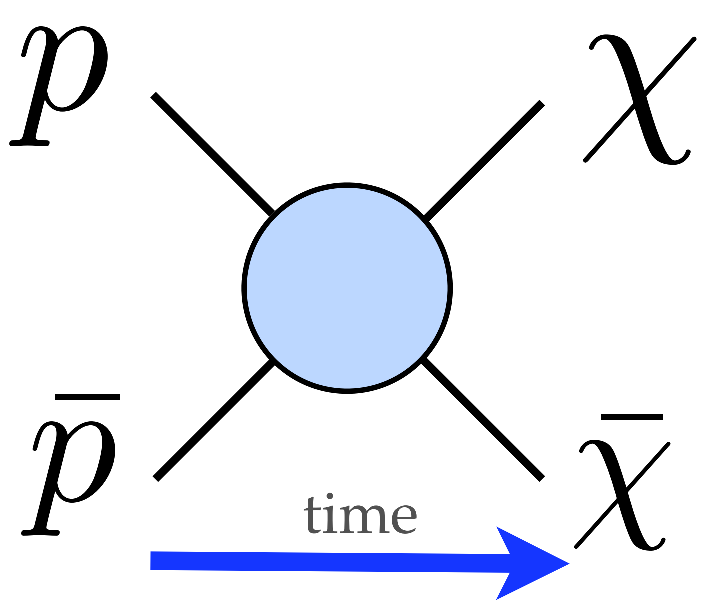
DM particle scatters off nuclei inside detector

Measure recoil spectrum



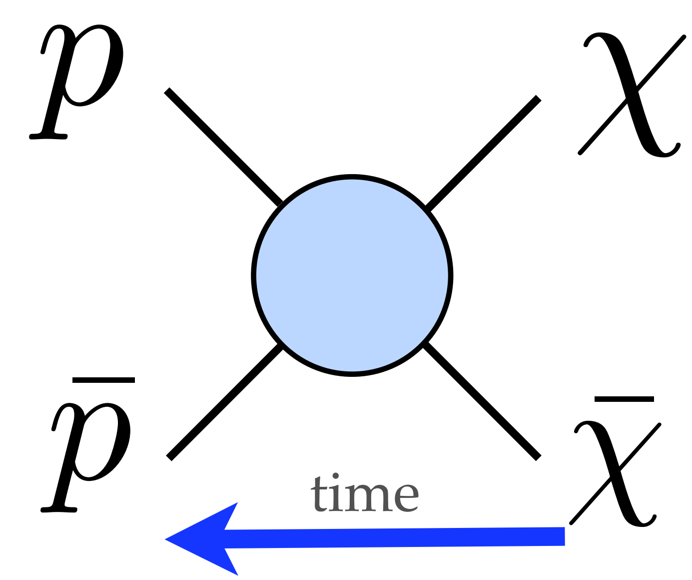
Colliders

Produce it

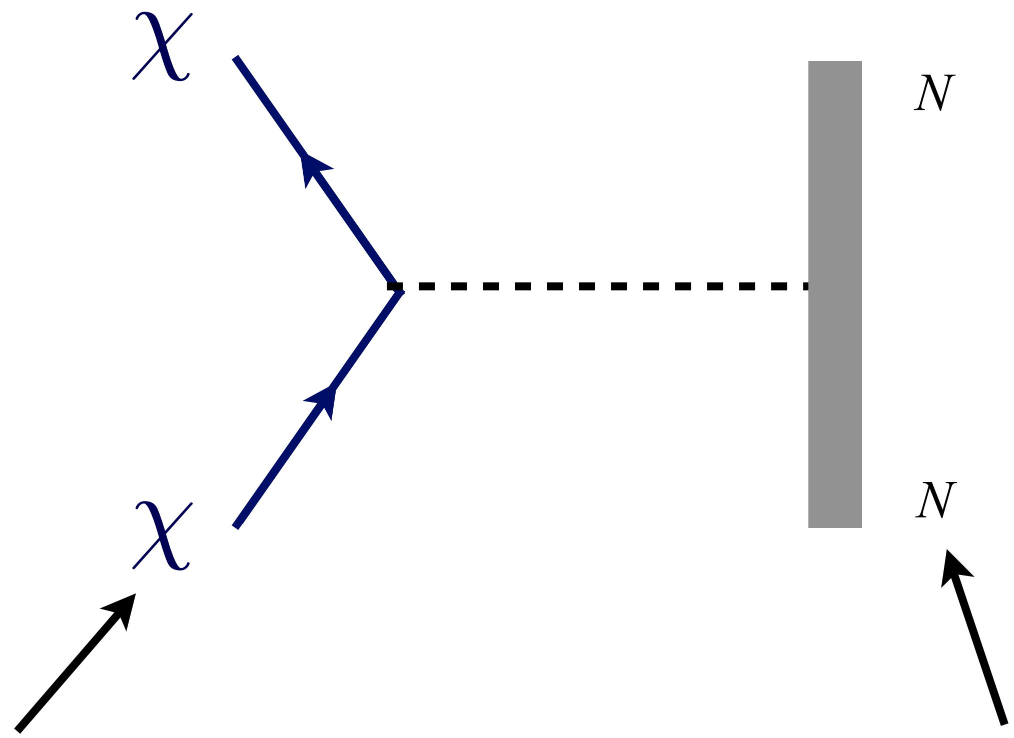


Indirect detection

Particle annihilates in galaxy



Direct Detection of Dark Matter



Dark matter particle scatters off nuclei in detectors

Measure nuclear recoil spectrum

[Counts/kg day/keV]

Multiply by exposure [kg day]

Event Rates

Local DM density ~ 0.3 GeV/cm³

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

Nuclei per detector mass

Kinematic lower limit

$$v_{\rm min} = \frac{q}{2\mu} + \frac{\delta}{q}$$

Halo velocity distribution

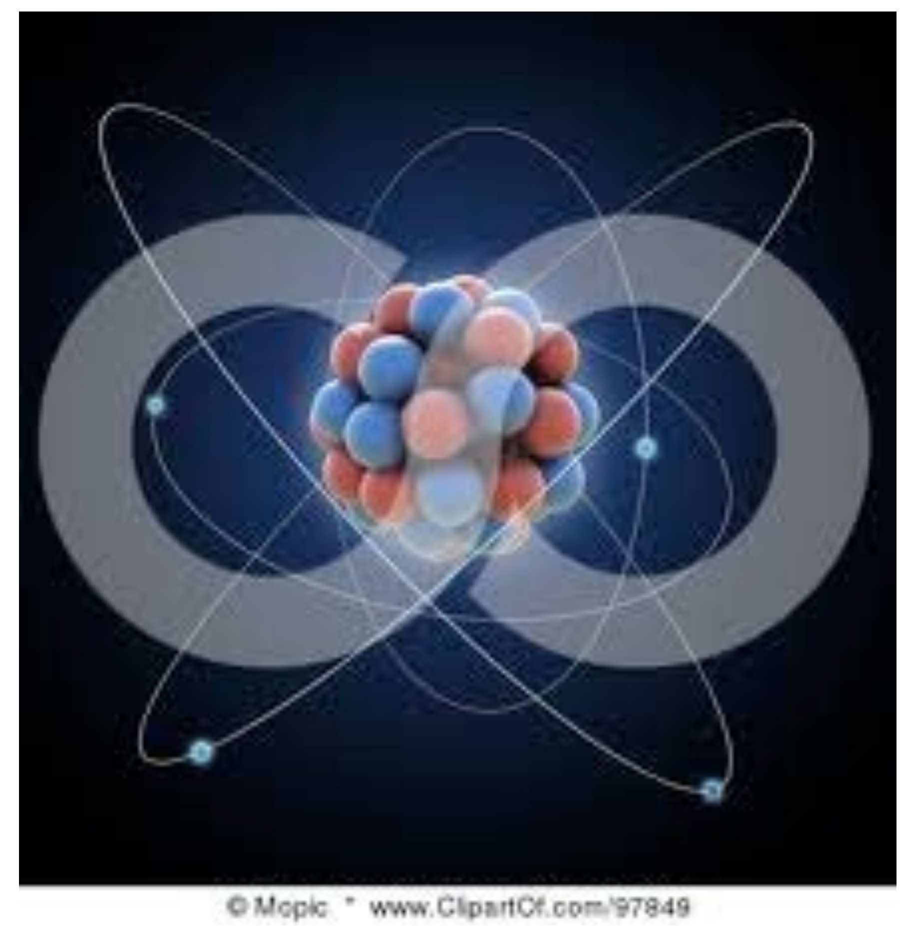
$$f(v) \sim e^{-v^2/\bar{v}^2}$$

Scattering cross-section

“Dark Sector” Picture of WIMPs

Visible matter is complex.
Why shouldn’t dark matter be?

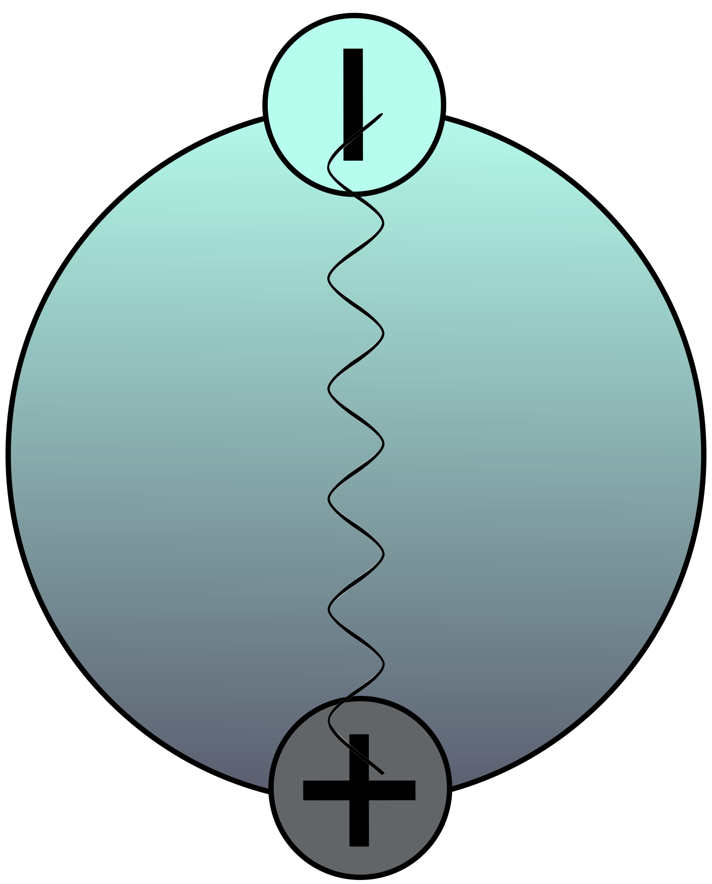
Dark
Sector



Dark Atoms

Simple Example

Dark matter could be a neutral bound object, with charged constituents



Interacts through a “charge radius” interaction

At low momentum: interaction shuts off

Remember, (almost) all of your mass is in neutral bound states!

Momentum-Dependence

Recoil energy uniquely tells us the momentum transfer

$$E_R = \frac{q^2}{2m_T}$$

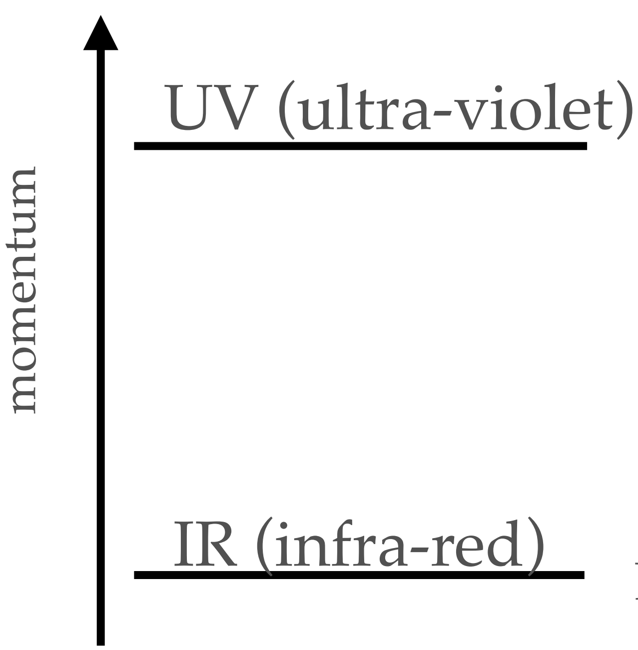
Range relevant for direction detection experiments is

$q \sim$ 15 MeV - 150 MeV

A Gap in Energy Scales

We usually think about models in a "top-down" approach, based on UV models.

But it is equally important to take a complementary "bottom-up" approach where we just ask what is consistent within the low-energy theory.



Theory: TeV scale (electroweak)

Experiment: $\lesssim$ 100 MeV

A) We can never know if we have missed important classes of UV theories.

B) Once/if dark matter is detected, the first step in characterizing its interactions will be to constrain the low-energy EFT.

Goal of EFT approach

- Ignore UV model prejudice
- Parameterize theory in terms of IR quantities, with direct connection to experimental observables
- Constrain these low-energy parameters directly

Some important previous approaches:

Pospelov, Veldhuis (2000)

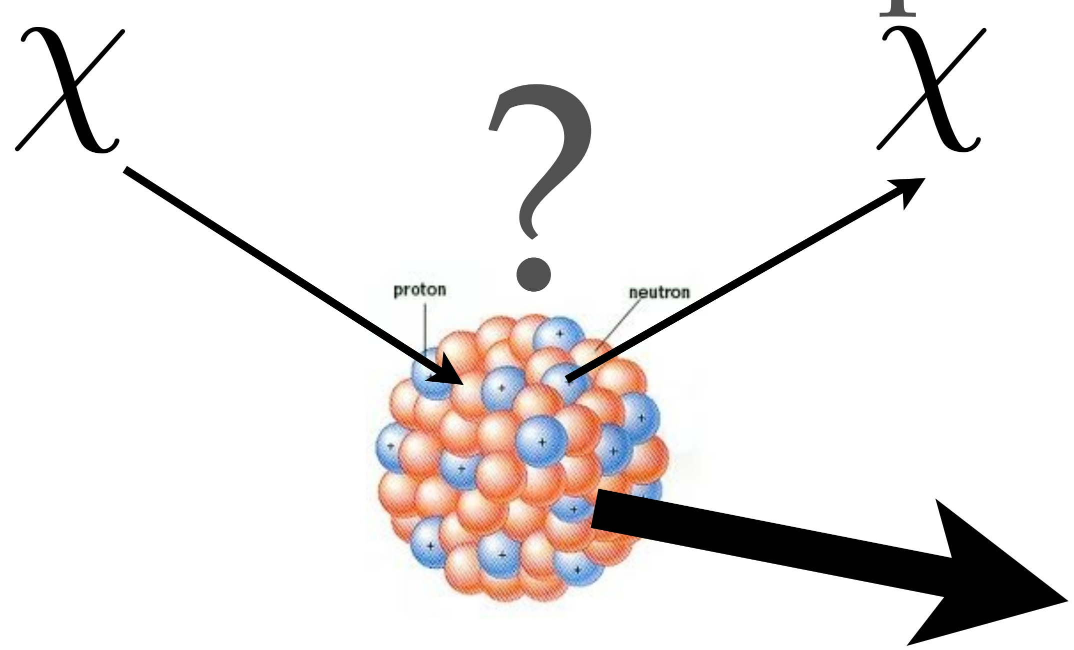
Fan, Reece, Wang (2010)

Our Goal

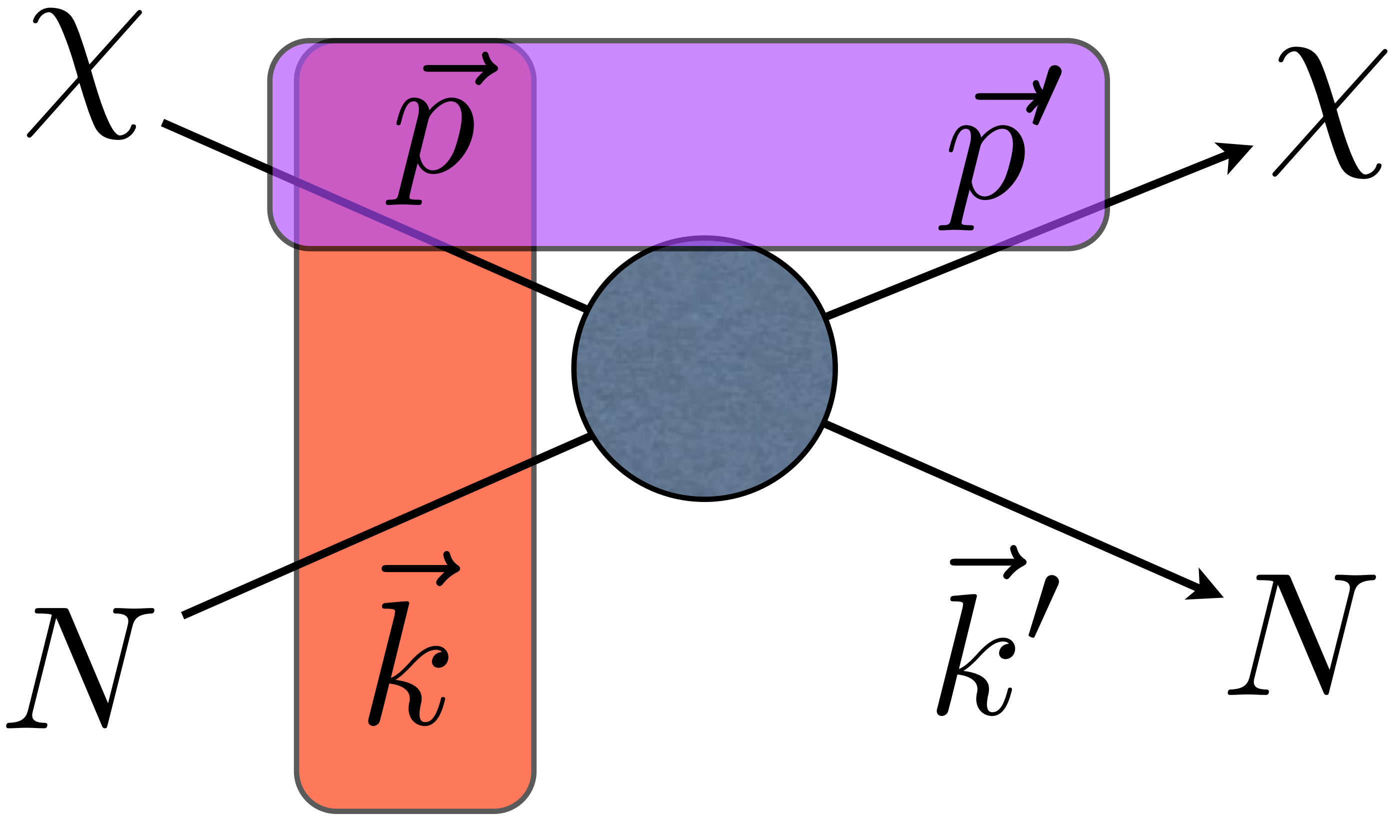
Once we write theory this way, we can answer two important questions:

1) What are all possible WIMP-nucleon interactions?

2) What are all the ways different elements can respond?



Basics of the WIMP-nucleon Effective Theory



By momentum-conservation and inertial-frame-independence: only two independent momenta

$$\vec{q} = \vec{p} - \vec{p}'$$

$$\vec{v} = \vec{v}_{\chi,\mathrm{in}} - \vec{v}_{N,\mathrm{in}}$$

Basics of the Effective Theory: Hermiticity

Haxton, ALF, Katz, Lubbers, Xu

So, all interactions should be built out of

$(\vec{v}^{\perp} \cdot \vec{q} = 0)$

$$i\vec{q}, \vec{v}^{\perp}, \vec{S}_{\chi}, \vec{S}_N$$

Momentum-dependence is crucial! Without $i\vec{q}$ and $\vec{v}^{\perp}$, only allowed interactions are

$\mathbf{1}$ and $\vec{S}_{\chi} \cdot \vec{S}_N$

"contact", or "SI" "spin-spin", or "SD"

The Effective Theory

All possible operators in the effective theory: just put the four building blocks together in all ways possible

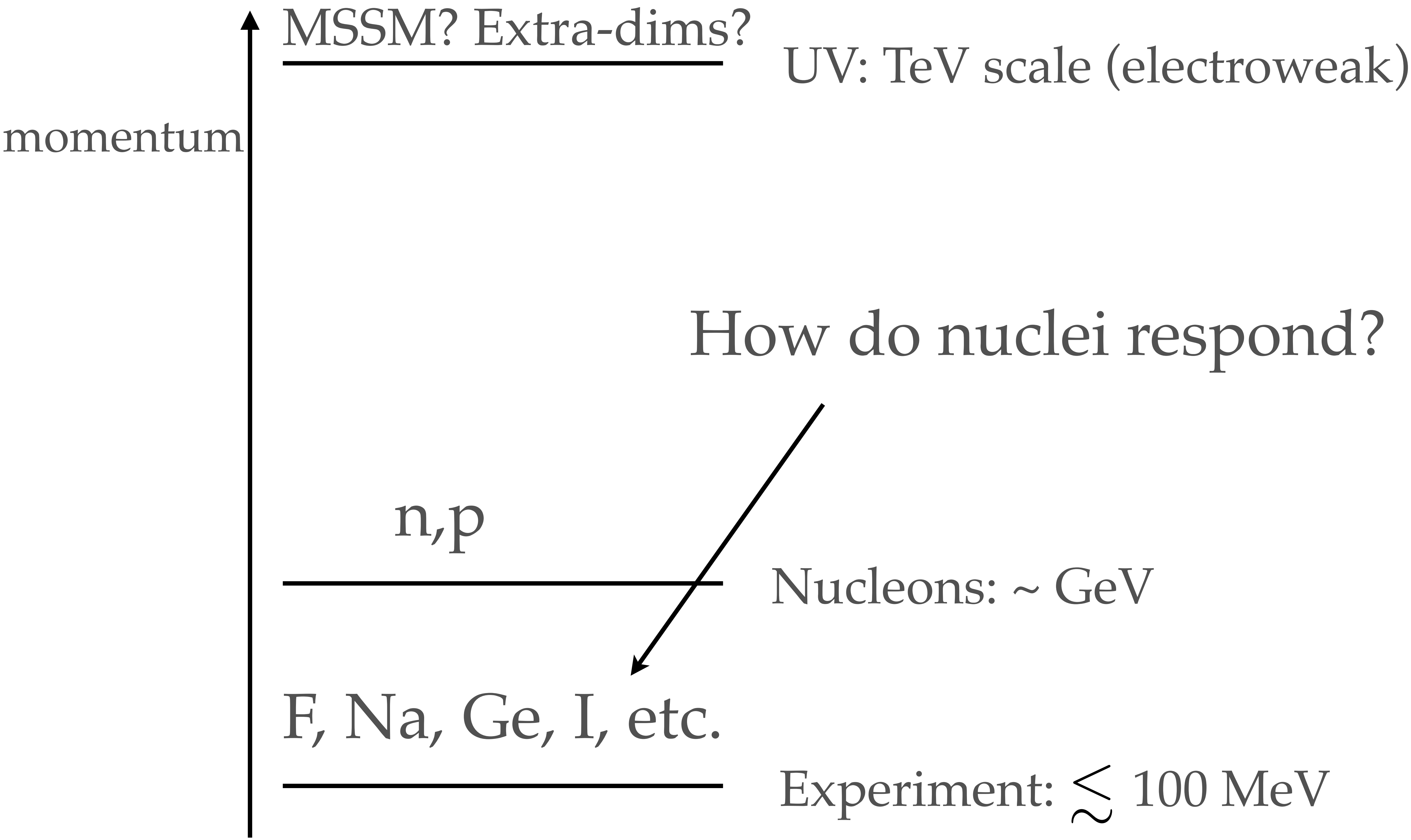
There are many such combinations.
However there are basically only six different macroscopic responses

$$1 \qquad \vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)$$

$$\vec{S}_N \cdot \vec{q} \qquad \vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

$$\vec{S}_\chi \cdot \vec{v}^\perp \qquad \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

Nucleons vs. Nuclei

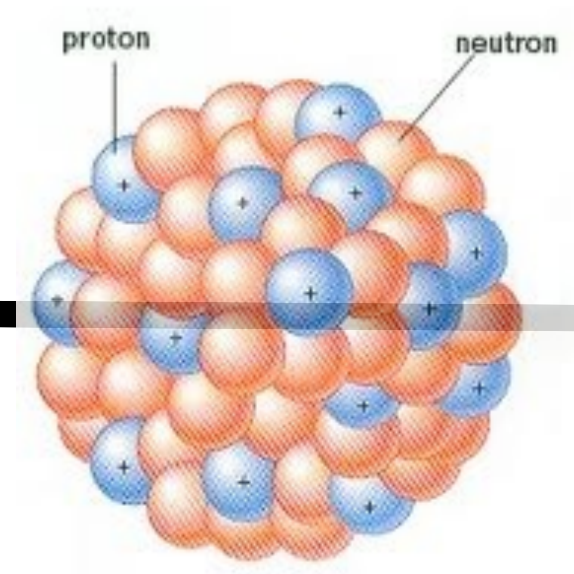


Nuclear responses

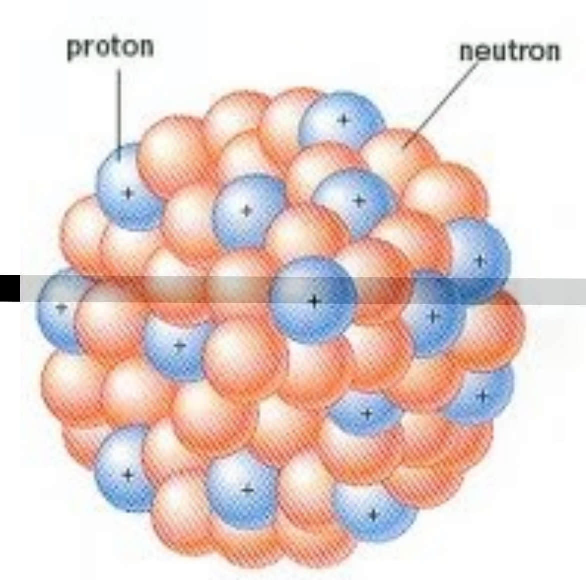
This is a concrete problem for nuclear physics - what are the form factors for all interactions?

Nuclear form factor

$$\vec{S}_\chi \cdot \vec{S}_N \longrightarrow F_N(q^2)$$



$$\vec{S}_\chi \cdot \vec{v}^\perp \longrightarrow ?$$



Additional Form Factors

Input internal structure of the nucleus to calculate cross-sections for all operators in the effective theory.

Additional Form Factors

Velocity operator acting inside the nucleus produces angular-momentum-dependence

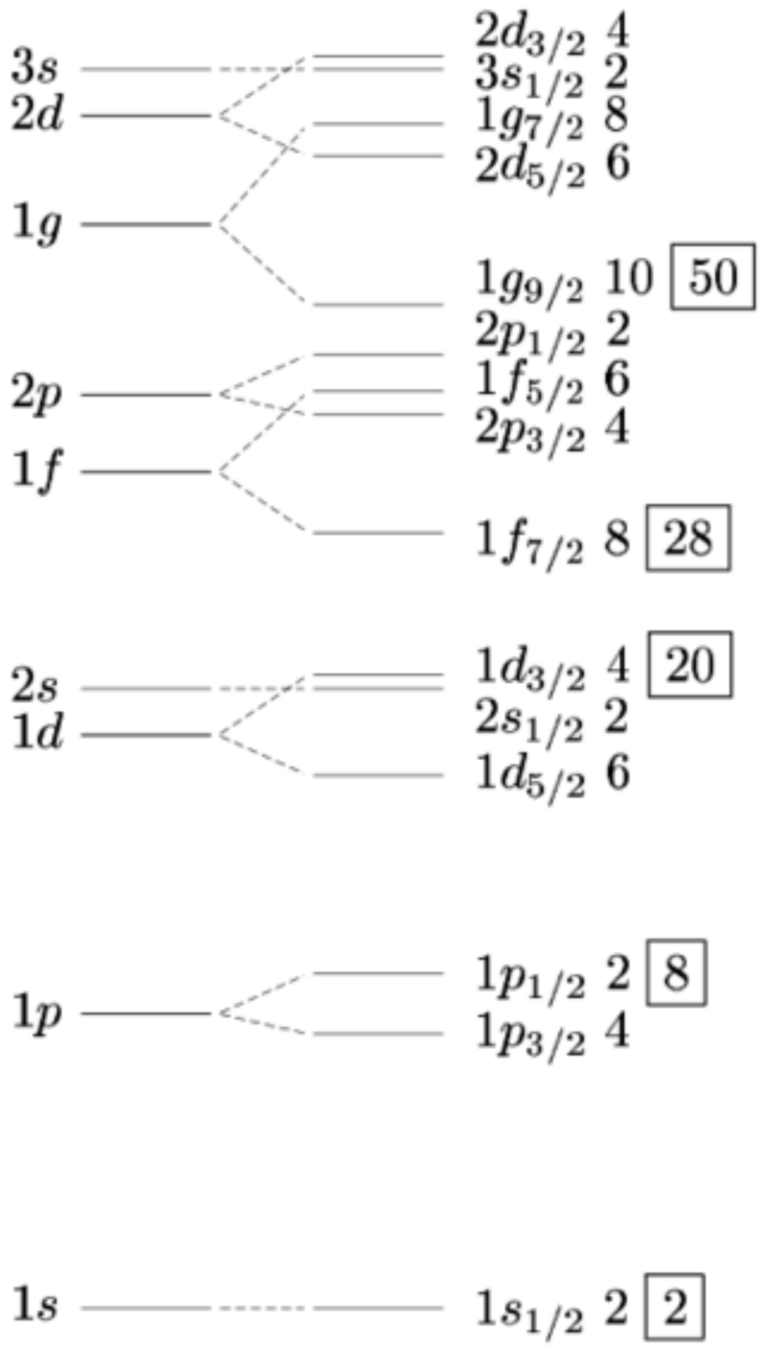
$$\int d^3r e^{iq\cdot r}\psi^\dagger(r)(\vec{v}^\perp)^i\psi(r)$$

$r \times P \sim L$

$$\sim \int d^3r\psi^\dagger(r)\big(iq^j r^j \frac{P^i}{m}\big)\psi(r)$$

$$\sim \frac{\vec{q}}{m} \times \int d^3r\psi^\dagger(r)\vec{L}\psi(r)$$

Some Nuclear Structure



$$\langle L \cdot S \rangle = \frac{j(j+1) - \ell(\ell+1) - s(s+1)}{2}$$

	$j = \ell + \frac{1}{2}$	$j = \ell - \frac{1}{2}$
$\langle L \cdot S \rangle_{\text{nucleon}}$	$\frac{\ell}{2}$	$-\frac{\ell+1}{2}$
$n_{\text{orb}} = 2j+1$	$2(\ell+1)$	2ℓ
$\langle L \cdot S \rangle_{\text{orb}}$	$\ell(\ell+1)$	$-\ell(\ell+1)$

Additional Form Factors

All possible cross-sections can be worked out in terms of a few response functions:

$$M \sim 1$$

$$\Sigma \sim \langle \vec{S} \rangle$$

$$\Phi \sim \langle \vec{S} \cdot \vec{L} \rangle$$

$$\tilde{\Delta} \sim \langle \vec{L} \rangle$$

Additional Form Factors

All possible cross-sections can be worked out in terms of a few response functions:

$M \sim 1$

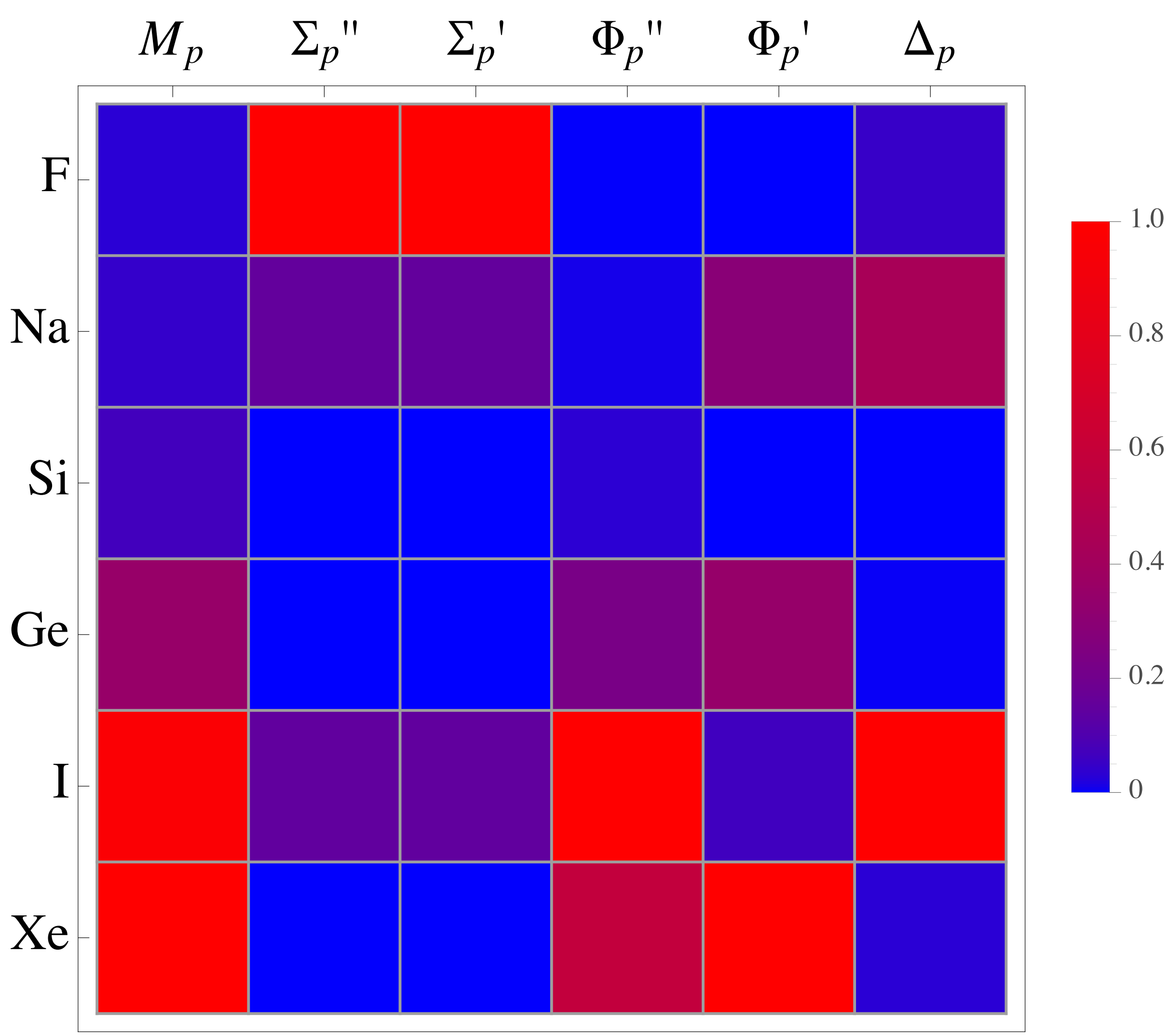
$\Sigma \sim \langle \vec{S} \rangle$ → $\Sigma' \sim \langle \vec{S} \rangle |_{\text{trans.}}$ and $\Sigma'' \sim \langle \vec{S} \rangle |_{\text{long.}}$

$\Phi \sim \langle \vec{S} \cdot \vec{L} \rangle$ → $\tilde{\Phi}' \sim \langle \vec{S} \cdot \vec{L} \rangle$ and $\Phi'' \sim \vec{q} \langle \vec{S} \cdot \vec{L} \rangle - \langle \vec{L} (\vec{S} \cdot \vec{q}) \rangle$

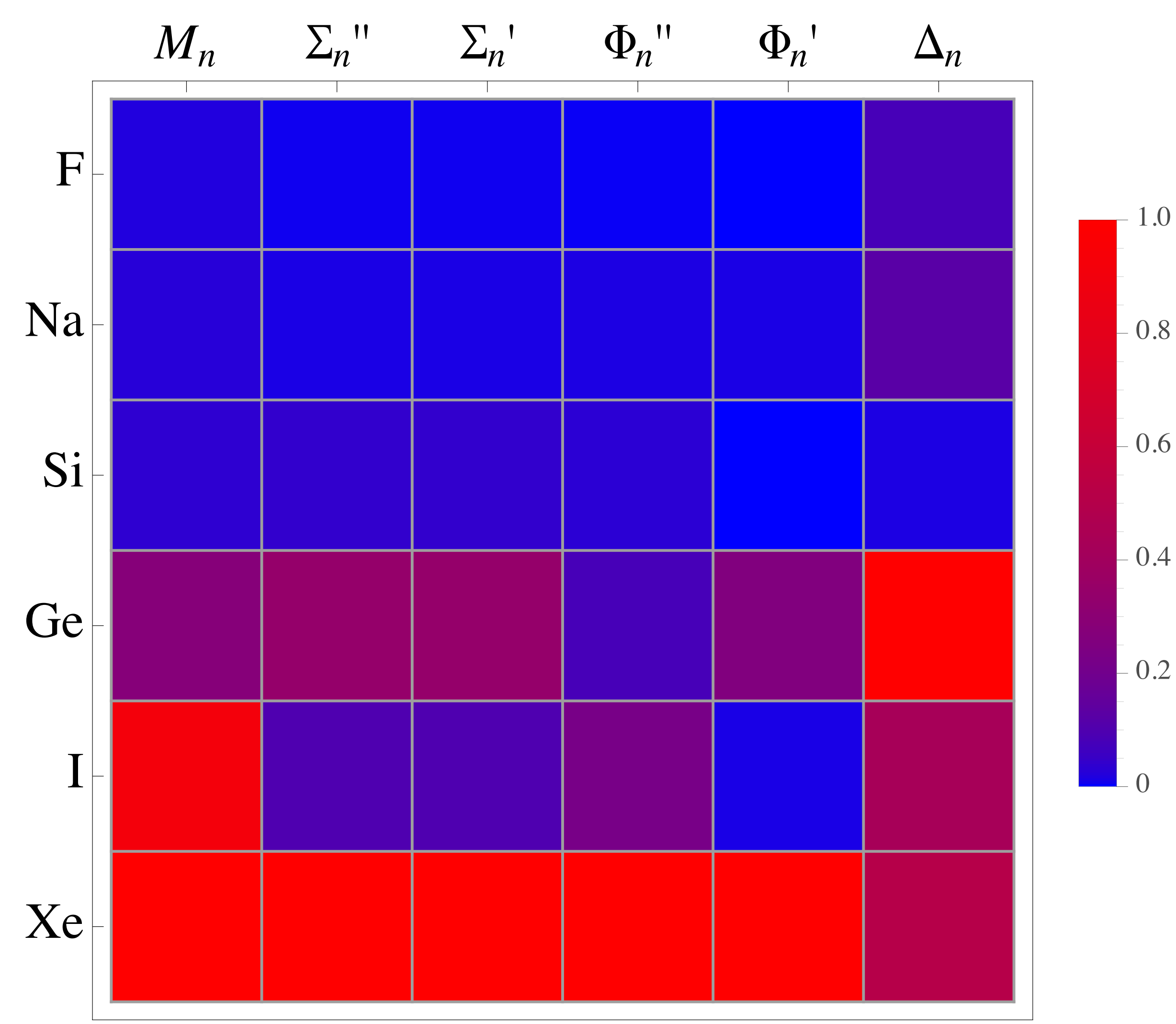
$\tilde{\Delta} \sim \langle \vec{L} \rangle_{\text{trans.}}$

Different Responses Favor Different Elements!

Protons



Neutrons



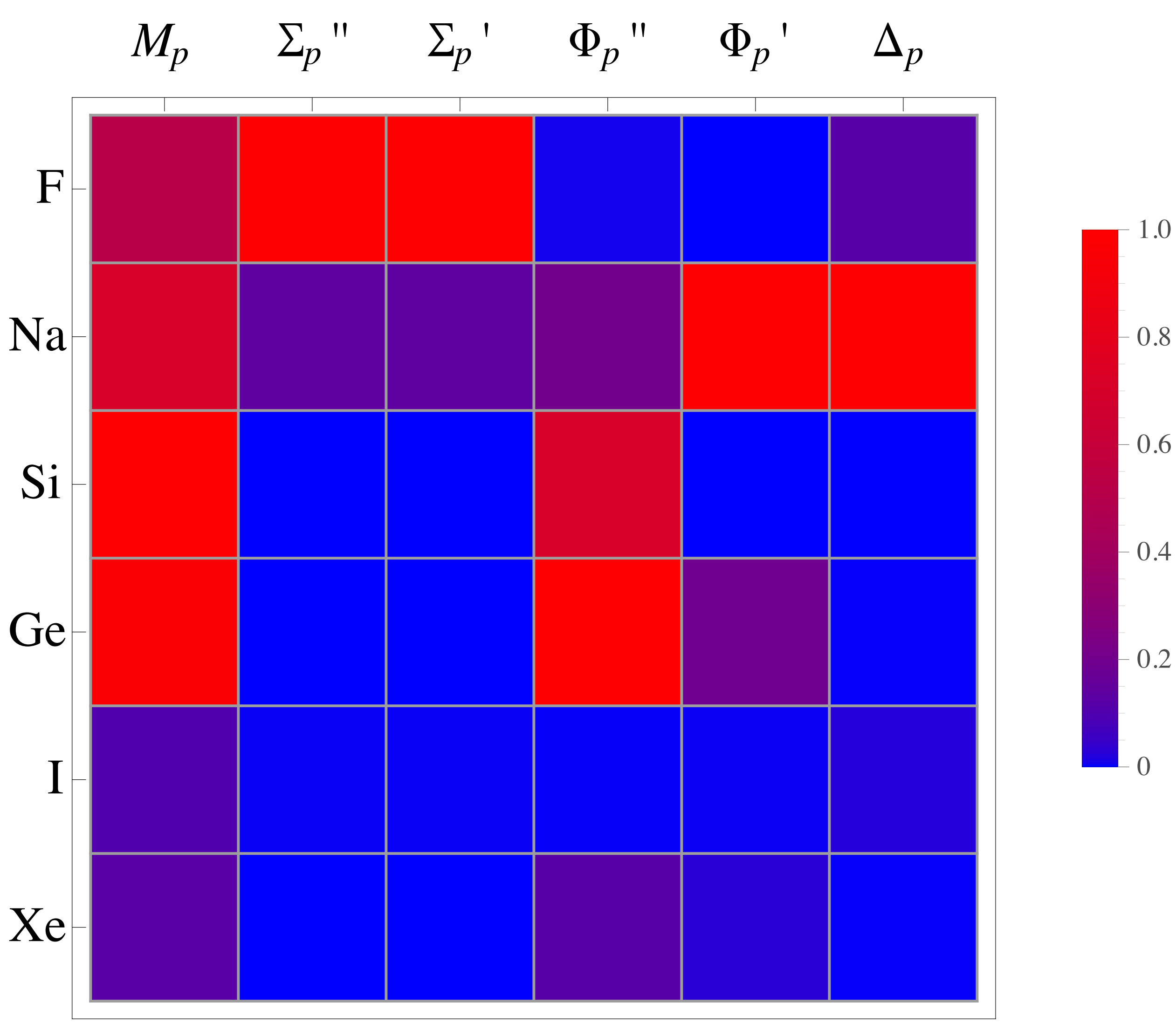
Kinematics also matter: Light Dark Matter

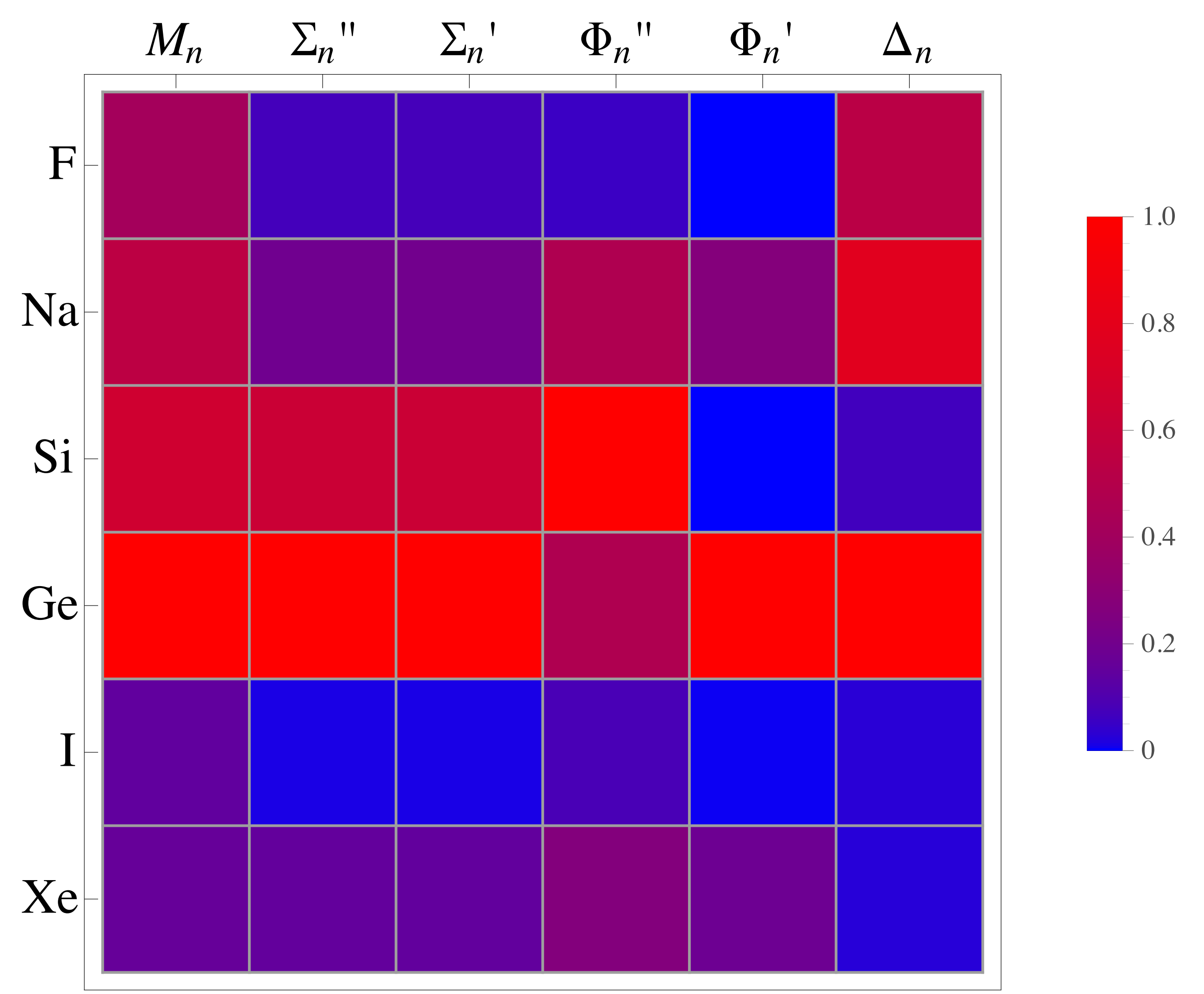
Protons

mDM=4GeV

$E_{min} = 1$ keV

Neutrons





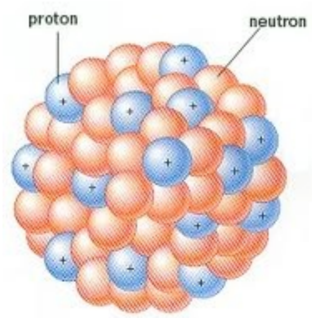
Different Responses Favor Different Elements!

Much of this variation can be captured by two "generalized SI" and two "generalized SD" interactions

$$\left.\begin{array}{l} M \sim \mathbf{1} \\ \Phi \sim \langle \vec{S} \cdot \vec{L} \rangle \end{array}\right\} \text{generalized SI}$$

$$\left.\begin{array}{l} \Sigma' \sim \langle \vec{S} \rangle\big|_{\text{trans.}} \\ \tilde{\Delta} \sim \langle \vec{L} \rangle_{\text{trans.}} \end{array}\right\} \text{generalized SD}$$

DMFormFactor: A Mathematica Package



$$\frac{dR_D}{dE_R} = N_T \frac{\rho_\chi m_T}{32\pi m_\chi^3 m_N^2} \times \left\langle \frac{1}{v} \sum_{ij} \sum_{N,N'=p,n} c_i^{(N)} c_j^{(N')} F_{ij}^{(N,N')}(v^2, q^2) \right\rangle$$

$\texttt{EventRate}[N_T, \rho_\chi, q, b, v_e, v_0 (, v_{\text{esc}})]$

Conclusions

Attention has been focused on a very small piece of all possible WIMP scattering

$$\mathbf{1} \quad \vec{S}_\chi \cdot \vec{S}_N \quad \text{vs.}$$

$$\mathbf{1}$$

$$\vec{S}_\chi \cdot \vec{S}_N$$

$$(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$

$$i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

$$i\vec{S}_N \cdot (\vec{q} \times \vec{v})$$

$$\vec{S}_N \cdot \vec{v}^\perp$$

$$i\vec{S}_\chi \cdot (\vec{q} \times \vec{v})$$

$$\vec{S}_\chi \cdot \vec{v}^\perp$$

...

Write theory in terms of IR quantities- this makes it much clearer what all possible interactions are.

Gives a concrete set of physical quantities that we need nuclear physics input to calculate.

The End