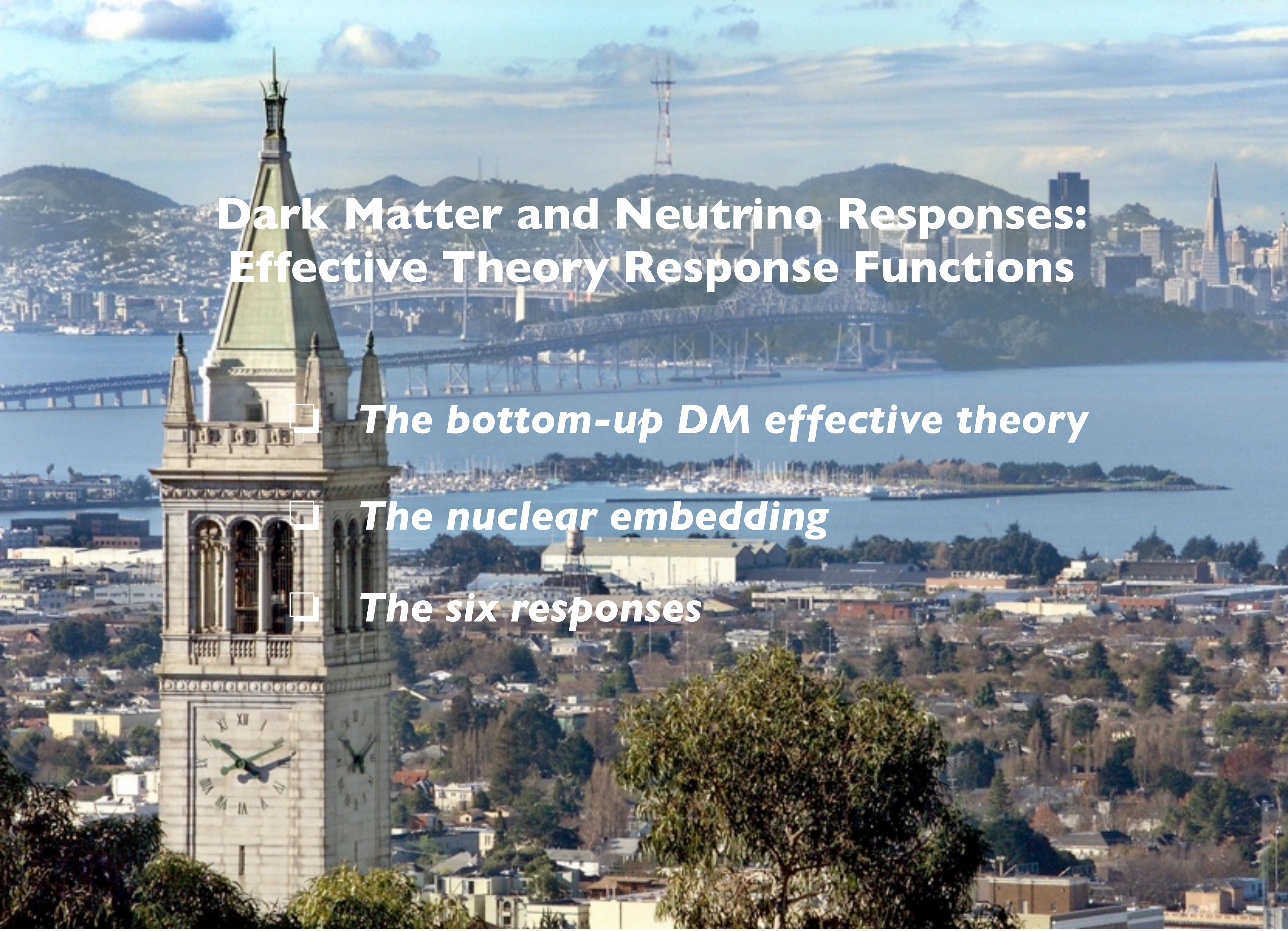


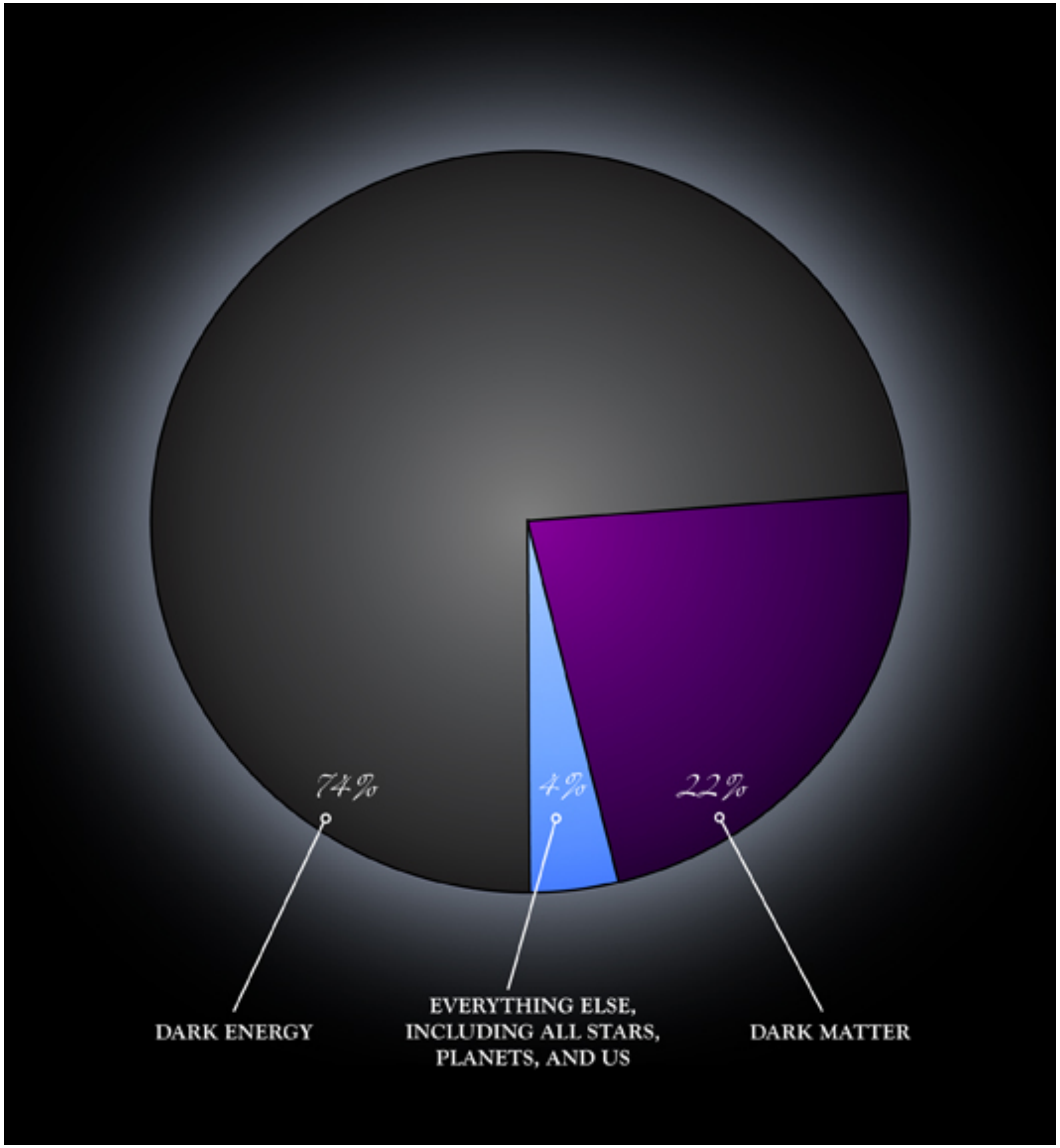
Dark Matter and Neutrino Responses: Effective Theory Response Functions

- ***The bottom-up DM effective theory***
- ***The nuclear embedding***
- ***The six responses***

Wick Haxton *Institute for Nuclear Theory* *July 24 2012*

I. Dark Matter Basics

- perhaps the most-likely-to-be-resolved new-physics problem
- closely linked to laboratory-based accelerator and underground experiments to probe for new particles beyond the standard model
- discovered in astrophysics, from the flat velocity rotation curves of galaxies
- must be long-lived or stable, cold or warm (so that it is slow enough to seed structure formation), gravitationally active, but without strong couplings to itself or to baryons
- leading candidates are weakly interactive massive particles (WIMPs - our focus) and axions (where the UW has the leading experiment)
- WIMPS connected to generic expectations that new particles might be found at the mass generation scale of the SM of 10 GeV - 10 TeV



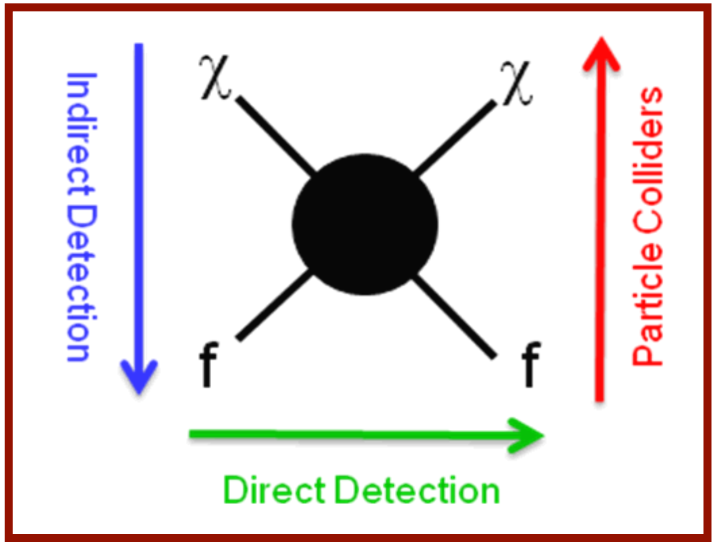
The inventory

There is a small, identified component from the standard model, massive neutrinos: using a conservative cosmological bound on the sum over light active species of 1 eV, the active neutrino contribution is less than 2% of the closure density

Thus the bulk of the DM must reside beyond the standard model

- "WIMP miracle:" G_F^2 annihilation cross sections imply $\Omega_{WIMP} \sim 0.1$

- their detection channels include
  - role in LSS formation
  - potential to annihilate into SM particles, a potential astrophysical signal
  - accelerator production in the collision of SM particles
  - scattering off SM particles, particularly heavy nuclear targets

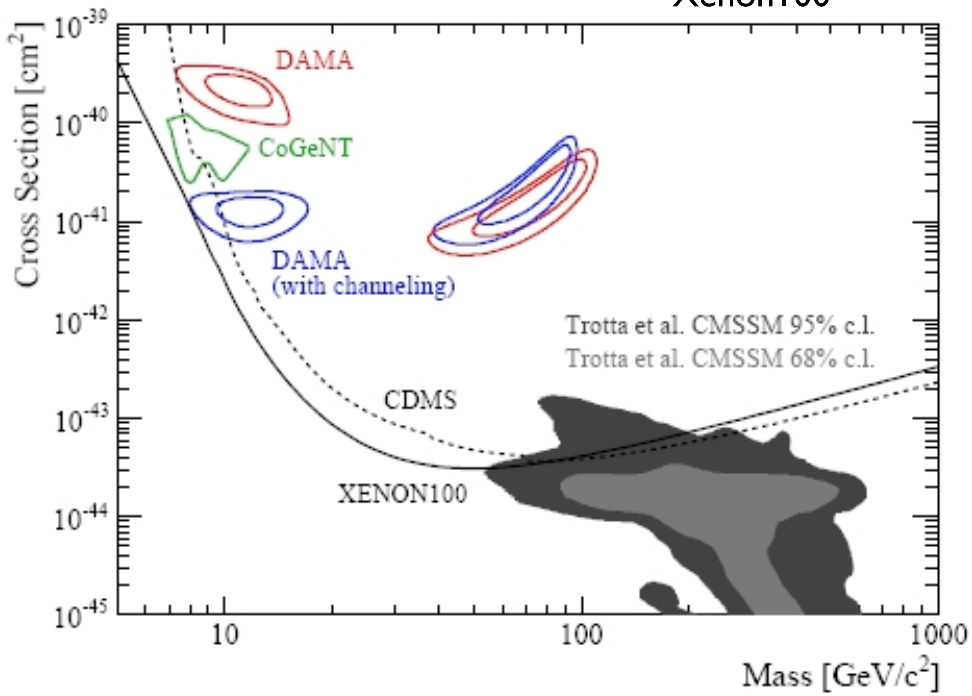


- conventionally nuclear description: spin-independent or spin-dependent nuclear scattering cross sections, depending on parameters

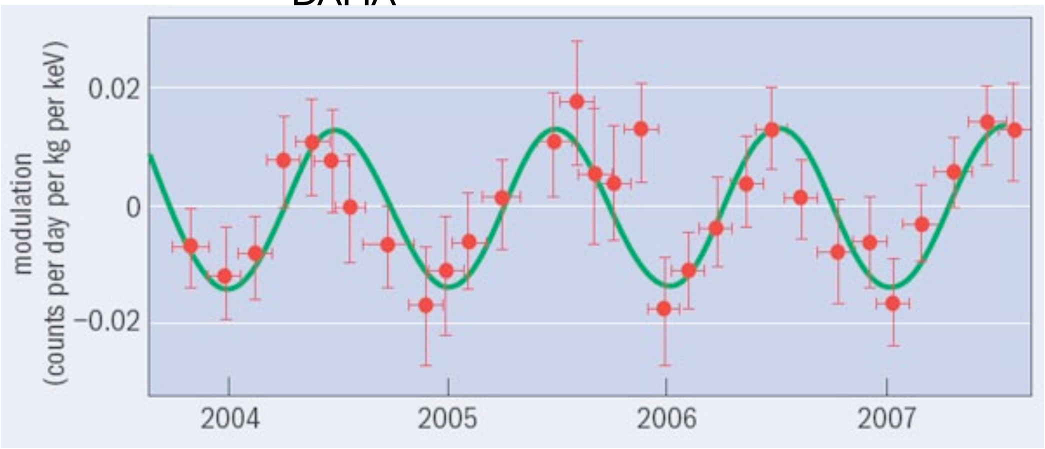
- searches focused on WIMP mass bounds of 10 GeV - TeV, with typical recoil momenta ~ 100 MeV (so form factors are important)

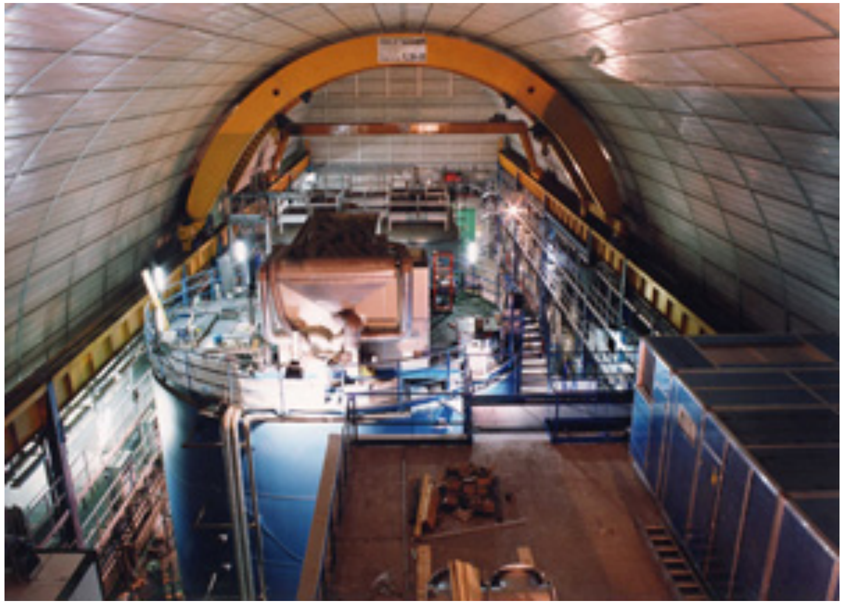
- detector masses have reached the 100 kg level

Xenon100



DAMA





controversy over DAMA, CoGeNT events at low energy vs. efficiency of Xenon100, CDMS to exclude such light-mass WIMPS

The field is not one for the timid! Lot's of infighting

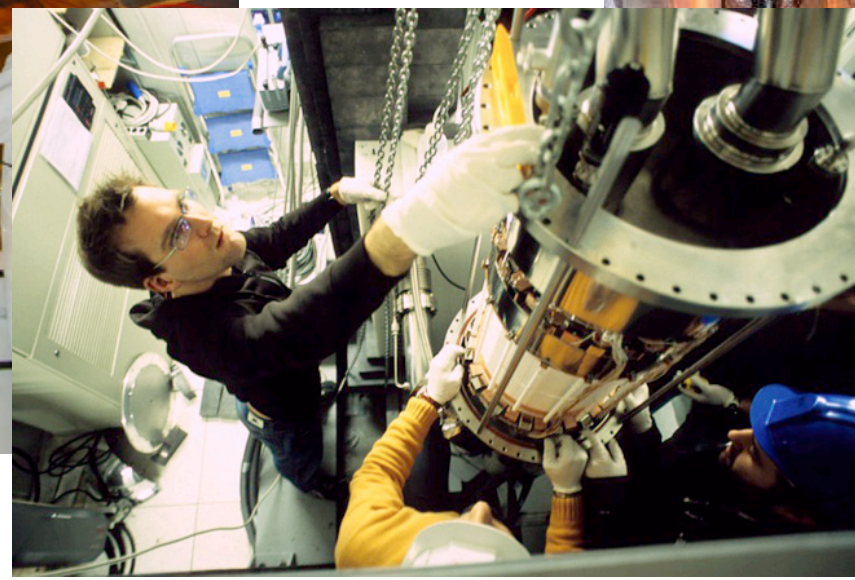
- e.g., the DAMA group's result for an annual modulation of nuclear recoil rate -- at 8.2 σ and climbing -- is close in magnitude and similar in phase to the annual variation in neutron backgrounds observed in Gran Sasso: Nygren observed that HE muon reactions in NaI(Tl) should produce delayed pulses similar to those seen

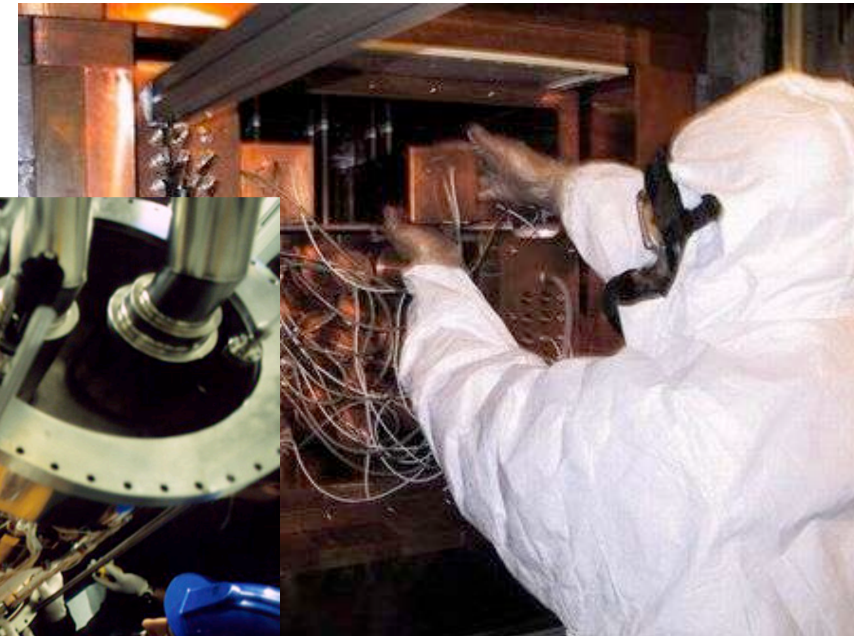
- negative results from CDMS (but two "events"), Xenon100; ambiguous results from Cogent; excess events above background seen by CREST II; Pamela positron/electron ratio growth with E argued to be an WIMP annihilation signal, versus conventional astro explanations; efforts to find an allowed WIMP "phase space" at < 10 GeV masses; Xenon100 latest results (July 19) push limits by x3.5

Our bottom line further complicates matters: a great deal more variability in detector responses theoretically than generally realized

II. The probe: nuclear recoil following elastic scattering

Xenon100





CDMS (Ge)

DAMA (NaI)

Among the experimentally favored isotopes:

$$^{19}\mathrm{F},\ \ ^{23}\mathrm{Na},\ \ ^{70,72,73,74,76}\mathrm{Ge},\ \ ^{127}\mathrm{I},\ \ ^{128,129,130,131,132,134,136}\mathrm{Xe}$$

Includes targets with vector (J >1/2) and tensor (J>1) responses

$$^{19}\mathrm{F}(1/2^+),^{129}\mathrm{Xe}(1/2^+); \quad ^{23}\mathrm{Na}(3/2^+),^{73}\mathrm{Ge}(9/2^+),^{127}\mathrm{I}(5/2^+),^{131}\mathrm{Xe}(3/2^+)$$

and thus in principle the WIMP can scatter off any scalar, vector, tensor static moment provided by the nucleus, consistent with angular momentum and with the assumption that the nuclear ground state is effectively parity- and time reversal-even

With few exceptions, the standard approach has been

1) "top-down" in which an ultraviolet theory motivates a specific nuclear coupling
2) which is then embedded in the nucleus assuming the nucleus is point-like and thus described by nuclear charges and spins
3) with possible form-factor corrections to account for the nonnegligible three-momentum transfer ~ 100 MeV

But nucleus is composite and the DM particle could also be complex

(So some inconsistencies here: point-like but not point-like, qR ~ 1)

Leads to the common terminology of cross sections characterized as

S.I. $\Rightarrow \quad \langle g.s.| \sum_{i=1}^{A} (a_0^F + a_1^F \tau_3(i)) \; |g.s.\rangle$

S.D. $\Rightarrow \quad \langle g.s.| \sum_{i=1}^{A} \vec{\sigma}(i) \; (a_0^{GT} + a_1^{GT} \tau_3(i)) \; |g.s.\rangle$

which has been the basis for most comparisons among experiments

Recent efforts to be more systematic:

- "bottom up" effective theory approach involving leading operators of Fan, Reece, and Wang arXiv: 1008:1591

$$\begin{aligned} \mathrm{S.I\ (scalar)} &\Leftrightarrow & A \\ \mathrm{WIMP\ edm} &\Leftrightarrow & Z \\ \mathrm{S.D} &\Leftrightarrow & \mathrm{GT\ strength} \\ \mathrm{S.D.} &\Leftrightarrow & \mathrm{Nuclear\ CP-odd\ dipole} \end{aligned}$$

- a more systematic "bottom up" expansion in which the most general Galilean-invariant effective interaction arising from exchange of particles of spin one or less was derived

+

embedding of that operator within the nucleus to determine the most general CP- and P-conserving scattering moments
Fitzpatrick, WH, Katz, Lubbers, Xu arXiv: 1203:3542

The nucleon-level effective interaction that arises from this treatment and that conserves CP has 11 invariants (x 2 for isospin)

$$\mathcal{L}_{EFT} = a_1 1 + a_2 \vec{v}^\perp \cdot \vec{v}^\perp + a_3 \vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp) + a_4 \vec{S}_\chi \cdot \vec{S}_N + i a_5 \vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp) + a_6 \vec{S}_\chi \cdot \vec{q} \vec{S}_N \cdot \vec{q}$$
$$+ a_7 \vec{S}_N \cdot \vec{v}^\perp + a_8 \vec{S}_\chi \cdot \vec{v}^\perp + i a_9 \vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}) + i a_{10} \vec{S}_N \cdot \vec{q} + i a_{11} \vec{S}_\chi \cdot \vec{q}$$

to quadratic order.
(Note to weak interaction experts: the Galilean invariance leads to a Hermitian velocity operator that is less easily obtained in standard treatments that begin with covariant interactions

Forces one to deal correctly with recoil currents

$$v^\perp \rightarrow \quad \frac{1}{2}(\vec{v}_{\chi,i} - \vec{v}_{Nuc,i} + \vec{v}_{\chi,f} - \vec{v}_{Nuc,f})$$
$$+ \quad \frac{1}{2}\left[\sum_{i=1}^{A} \frac{1}{2iM_N}\left(-\overleftarrow{\nabla}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\overrightarrow{\nabla}\right)\right]_{\text{intrinsic}})$$

The WIMP-nucleus Hamiltonian can be constructed (nucleon level)

$$\begin{aligned}\mathcal{H}_{ET}(\vec{x}) &= \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\ &+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right] \\ &+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i\times\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]\end{aligned}$$

All elements are familiar from past studies of electroweak interactions (including neutrino scattering)

The WIMP-nucleus Hamiltonian can be constructed

(generalized) vector charge

$$\mathcal{H}_{ET}(\vec{x}) = \boxed{\sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i)} + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i)+\delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right]$$
$$+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i)+\delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right]$$
$$+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i\times\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i)+\delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]$$

We will be interested generically in elastic channels

This is the vector charge density probed in elastic electron scattering or in coherent neutrino scattering

The WIMP-nucleus Hamiltonian can be constructed

axial-vector charge

$$\mathcal{H}_{ET}(\vec{x}) = \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i) \boxed{\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i \cdot \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right]}$$

$$+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right]$$

$$+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]$$

This is an operator density studied in beta decay, through $0^- \leftrightarrow 0^+$ inelastic transitions.

The WIMP-nucleus Hamiltonian can be constructed

axial-vector spin current

$$\mathcal{H}_{ET}(\vec{x}) = \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i \cdot \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right]$$

$$+ \sum_{i=1}^{A} \vec{l}_5(i) \boxed{\cdot\, \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i)} + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right]$$

$$+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]$$

This spin density dominates neutrino-nucleus inelastic scattering at solar and supernova neutrino energies. We know a lot about its elastic moments due to nuclear magnetic moments, etc.

The WIMP-nucleus Hamiltonian can be constructed

vector convection current

$$
\begin{aligned}
\mathcal{H}_{ET}(\vec{x}) &= \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i \cdot \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot \boxed{\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right]} \\
&+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]
\end{aligned}
$$

This is the vector convection-current response familiar from inelastic electron and neutrino scattering; elastic response known from back-angle magnetic electron scattering and from atomic hyperfine interactions

The WIMP-nucleus Hamiltonian can be constructed

$$\begin{aligned}
\mathcal{H}_{ET}(\vec{x}) \;=\; & \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i \cdot \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
+ & \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
+ & \sum_{i=1}^{A} \vec{l}_E(i)\cdot \boxed{\frac{1}{2M}\left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]}
\end{aligned}$$

vector spin-velocity current

The most exotic of the contributing densities: does not contribute in order(1/M) in neutrino physics due to the time-reversal properties of weak currents, but the associated inelastic response was discussed by Serot, who showed that this density arises in $1/M^2$, but accompanied by a q_0. Thus we have no elastic probe of this operator.

The WIMP-nucleus Hamiltonian can be constructed

$$
\begin{aligned}
\mathcal{H}_{ET}(\vec{x}) &= \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i \cdot \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i \times \vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]
\end{aligned}
$$

We see the nucleon-level effective theory has naturally mapped on to all of the possible charge and three-vector densities one can construct from $\{\ 1(i),\ \vec{\sigma}(i),\ \vec{\nabla}(i)\}$ consistent with our exchange assumption and hermiticity

The WIMP-nucleus Hamiltonian can be constructed

$$\begin{aligned}
\mathcal{H}_{ET}(\vec{x}) &= \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i\times\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]
\end{aligned}$$

These 5 nuclear densities are coupled to WIMP tensors that can project out in principle a total of 8 nuclear responses. These 8 responses should be viewed as one's available probes of DM. The WIMP tensors are themselves functions of 11 DM EFT couplings

$l_0(i)$	$l_0^A(i)$	$\vec{l}_5(i)\cdot\vec{q}$	$\vec{l}_5(i)\times\vec{q}$
$\vec{l}_M(i)\cdot\vec{q}$	$\vec{l}_M(i)\times\vec{q}$	$\vec{l}_E(i)\cdot\vec{q}$	$\vec{l}_E(i)\times\vec{q}$

The Galilean effective theory defines the candidate nuclear densities

Response constrained by good parity and time reversal of nuclear g.s.

charges:

	even	odd
vector	C_0	C_1
axial	C_0^5	C_1^5

currents:

	even	odd	even	odd	even	odd
axial spin	L_0^5	L_1^5	$T_2^{5\mathrm{el}}$	$T_1^{5\mathrm{el}}$	$T_2^{5\mathrm{mag}}$	$T_1^{5\mathrm{mag}}$
vector velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}
vector spin – velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}

where we list only the leading multipoles in J above

Response constrained by good parity and time reversal of nuclear g.s.

	even	odd
vector	C_0	~~C_1~~
axial	~~C_0^5~~	C_1^5

	even	odd	even	odd	even	odd
axial spin	~~L_0^5~~	L_1^5	~~$T_2^{5\mathrm{el}}$~~	$T_1^{5\mathrm{el}}$	$T_2^{5\mathrm{mag}}$	~~$T_1^{5\mathrm{mag}}$~~
vector velocity	L_0	~~L_1~~	T_2^{el}	~~T_1^{el}~~	~~T_2^{mag}~~	T_1^{mag}
vector spin – velocity	L_0	~~L_1~~	T_2^{el}	~~T_1^{el}~~	~~T_2^{mag}~~	T_1^{mag}

Response constrained by good parity and time reversal of nuclear g.s.

	even	odd
vector	C_0	C_1
axial	C_0^5	C_1^5

	even	odd	even	odd	even	odd
axial spin	L_0^5	L_1^5	$T_2^{5\mathrm{el}}$	$T_1^{5\mathrm{el}}$	$T_2^{5\mathrm{mag}}$	$T_1^{5\mathrm{mag}}$
vector velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}
vector spin − velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}

The Galilean effective theory defines the candidate densities

Response constrained by good parity and time reversal of nuclear g.s.

	even	odd
vector	C_0	
axial		

	even	odd	even	odd	even	odd
axial spin		L_1^5		$T_1^{5\mathrm{el}}$		
vector velocity						T_1^{mag}
vector spin − velocity	L_0		T_2^{el}			

6 (not 2!) independent responses based on symmetry of 4-current densities

(familiar to Cecilia!)

Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \lVert M_{JM} \rVert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}} 1(i)$	M_{JM} : Charge
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \Sigma''_{JM} \rVert J_i\rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}} \sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \Sigma'_{JM} \rVert J_i\rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}} \sigma_{1M}(i)$	T^{el5}_{JM} : Axial Transverse Electric
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \Delta_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Delta_{1M}(q\vec{x}_i)$	$-\frac{q}{2m_N\sqrt{6\pi}} \ell_{1M}(i)$	T^{mag}_{JM} : Transverse Magnetic
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \Phi''_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Phi''_{00}(q\vec{x}_i)$	$-\frac{q}{3m_N\sqrt{4\pi}} \vec{\sigma}(i)\cdot\vec{\ell}(i)$	L_{JM} : Longitudinal
	$\frac{q}{m_N}\Phi''_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{30\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	
$\sum_{J=2,4,\ldots}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \tilde{\Phi}'_{JM} \rVert J_i\rangle\rvert^2$	$\frac{q}{m_N}\tilde{\Phi}'_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{20\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	T^{el}_{JM} : Transverse Electric

Two scalar (one scalar/tensor) , three vector, one tensor

Calculate in SM the responses for the key isotopes...

theorist's analog of the experimentalist's photo of equipment...

$$\frac{1}{2J_i+1}\sum_{M_i,M_f}|\langle J_iM_f|\ H\ |J_iM_i\rangle|^2 = \frac{4\pi}{2J_i+1}\Bigg[\sum_{J=1,3,,...}^{\infty}|\langle J_i||\ \vec{l}_5\cdot\hat{q}\ \Sigma''_J(q)\ ||J_i\rangle|^2$$

$$+\quad \sum_{J=0,2,...}^{\infty}\Bigg\{|\langle J_i||\ l_0\ M_J(q)\ ||J_i\rangle|^2 + |\langle J_i||\ \vec{l}_E\cdot\hat{q}\ \frac{q}{m_N}\Phi''(q)\ ||J_i\rangle|^2$$

$$+\quad 2\mathrm{Re}\left[\langle J_i||\ \vec{l}_E\cdot\hat{q}\ \frac{q}{m_N}\Phi''(q)\ ||J_i\rangle\langle J_i||\ l_0\ M_J(q)\ ||J_i\rangle^*\right]\Bigg\}$$

$$+\quad \frac{q^2}{2m_N^2}\sum_{J=2,4,...}^{\infty}\left(\langle J_i||\ \vec{l}_E\ \tilde{\Phi}'_J(q)\ ||J_i\rangle\cdot\langle J_i||\ \vec{l}_E\ \tilde{\Phi}'_J(q)\ ||J_i\rangle^* - |\langle J_i||\ \vec{l}_E\cdot\hat{q}\ \tilde{\Phi}'_J(q)\ ||J_i\rangle|^2\right)$$

$$+\quad \sum_{J=1,3,...}^{\infty}\Bigg\{\frac{q^2}{2m_N^2}\left(\langle J_i||\ \vec{l}_M\ \Delta_J(q)\ ||J_i\rangle\cdot\langle J_i||\ \vec{l}_M\ \Delta_J(q)\ ||J_i\rangle^* - |\langle J_i||\ \vec{l}_M\cdot\hat{q}\ \Delta_J(q)\ ||J_i\rangle|^2\right)$$

$$+\quad \frac{1}{2}\left(\langle J_i||\ \vec{l}_5\ \Sigma'_J(q)\ ||J_i\rangle\cdot\langle J_i||\ \vec{l}_5\ \Sigma'_J(q)\ ||J_i\rangle^* - |\langle J_i||\ \vec{l}_5\cdot\hat{q}\ \Sigma'_J(q)\ ||J_i\rangle|^2\right)$$

$$+\quad 2\mathrm{Re}\left[i\hat{q}\cdot\langle J_i||\ \vec{l}_M\ \frac{q}{m_N}\Delta_J(q)\ ||J_i\rangle\times\langle J_i||\ \vec{l}_5\ \Sigma'_J(q)\ ||J_i\rangle^*\right]\Bigg\}\Bigg]$$

the general result for scattering probability

Shell model calculations performed (CENPA), modest bases < 0.65M after symmetries ⇒ could be substantially improved (shape transitions)

Purpose: quick survey to access target response variability as well as the systematic of these operators

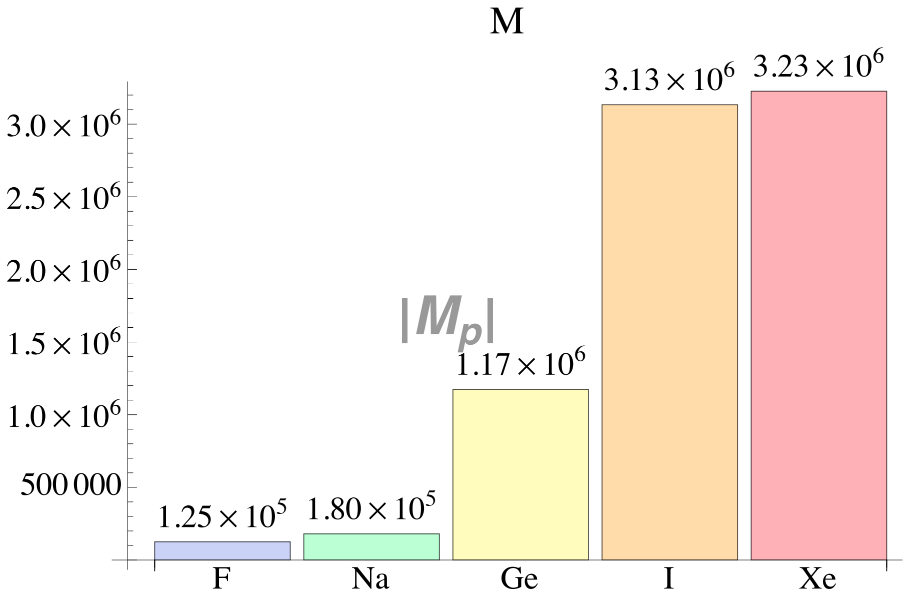
^{19}F, ^{23}Na standard $2s_{1/2}1d_{3/2}1d_{5/2}$ calculations, BW interaction

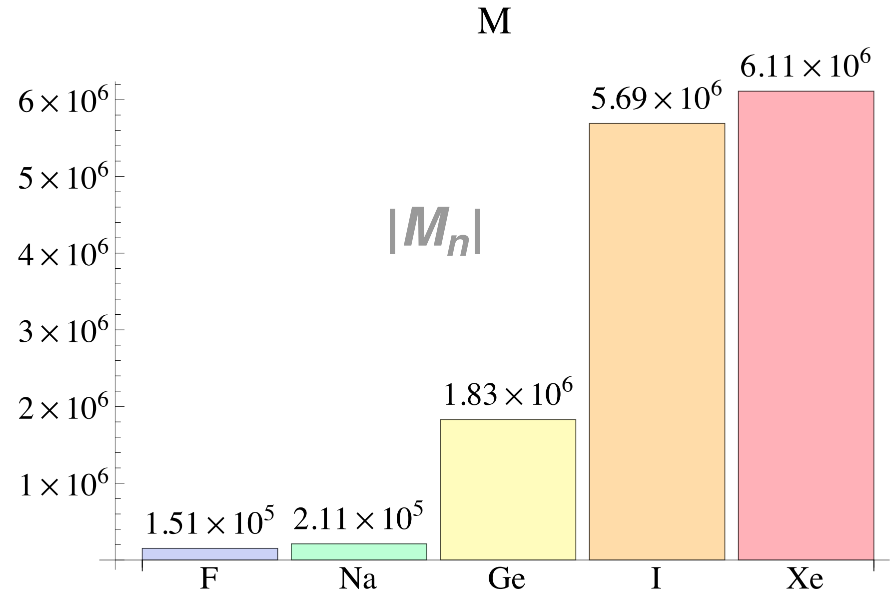
^{70,72,73,74,76}Ge $1f_{5/2}2p_{1/2}2p_{3/2}1g_{9/2}$ above ^{56}Ni core, truncated so that occupation of the $1g_{9/2}$ orbit is no more than minimum occupation + 2; potential from Madrid/Strasbourg group

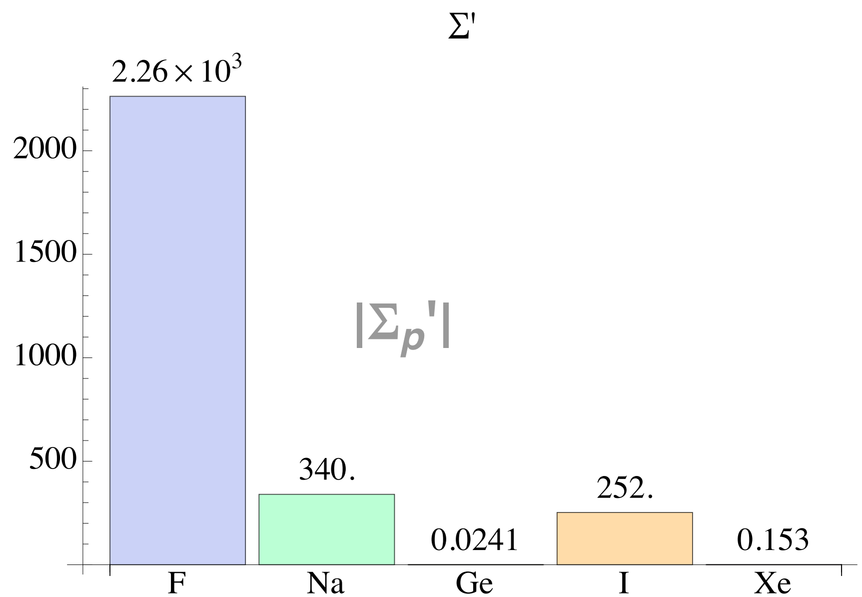
^{127}I, ^{128,129,130,131,132,134,136}Xe $3s_{1/2}2d_{3/2}2d_{5/2}1g_{7/2}1h_{11/2}$ above ^{100}Sn core, for most similar truncations involving $1h_{11/2}$ occupation; potential based on bare g-matrix as modified by Baldridge, Vary

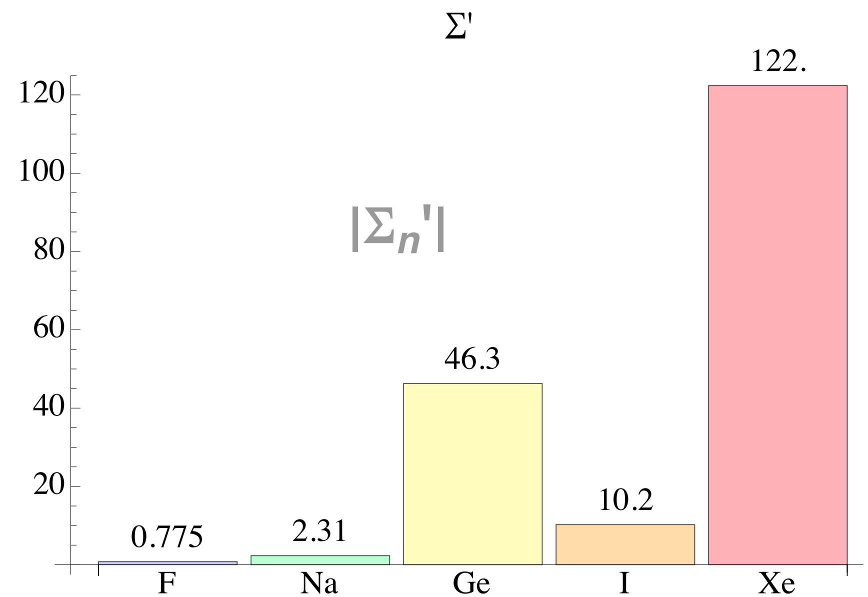
vector charge (amplitudes!)

(normalized to natural abundance)



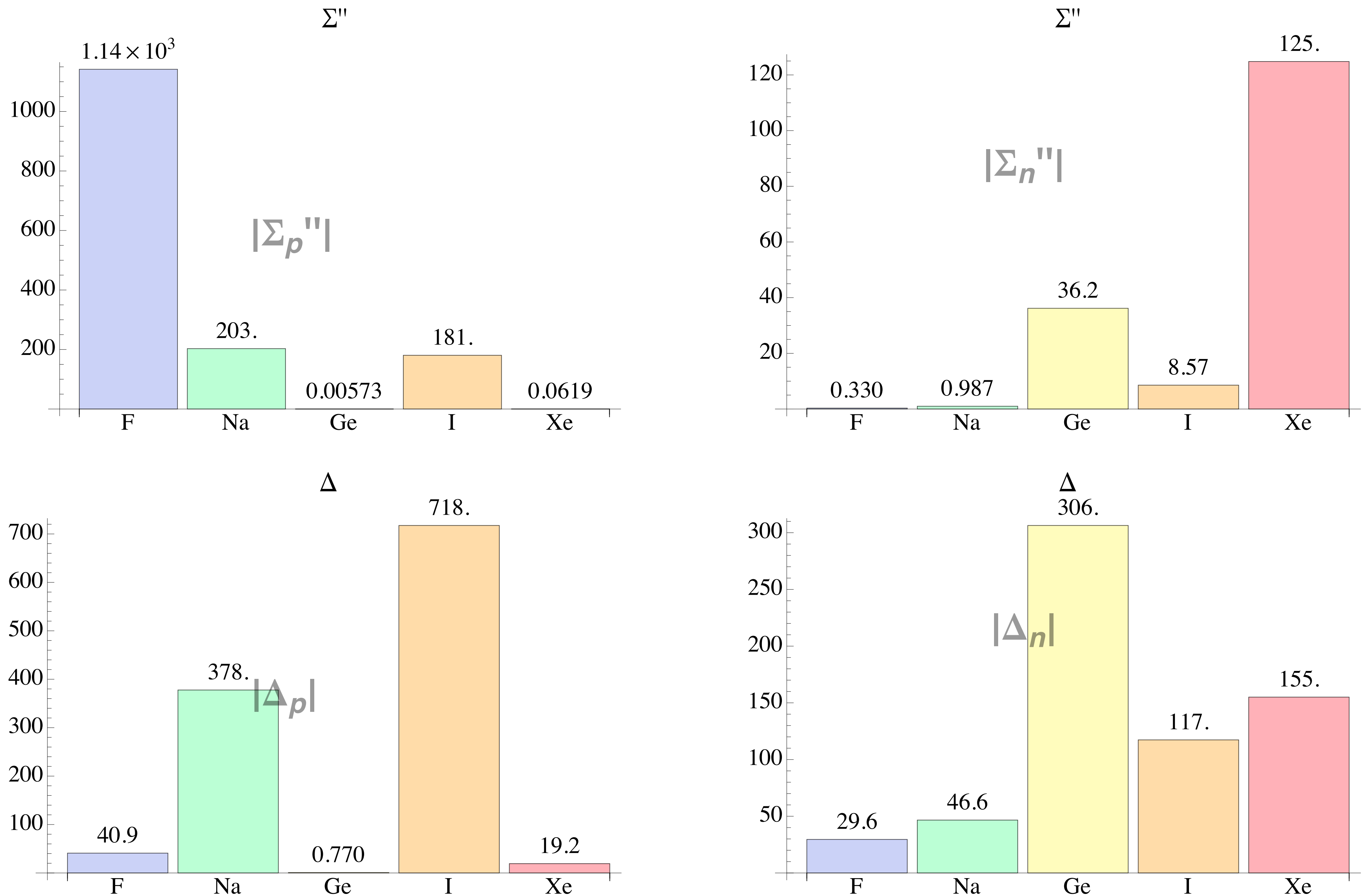




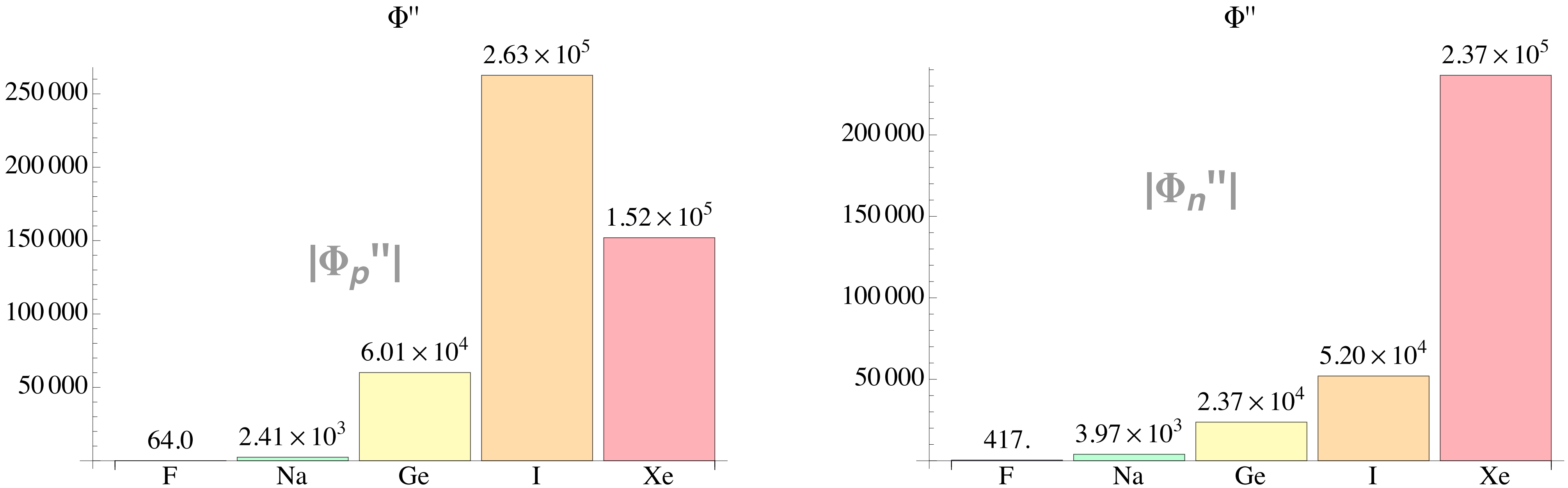


transverse electric axial (spin) response

longitudinal electric axial (spin) response



vector transverse magnetic (orbital angular momentum)



semi-coherent isoscalar $\vec{\sigma}(i) \cdot \vec{\ell}(i)$

note the absence of the nuclear-physics-allowed tensor response

cross sections arranged so the nucleus is the probe: operators map onto the unique nuclear densities with definite behavior under P,T

the coefficients map onto the EFT coefficients, and thus make the "hand shake" with ultraviolet theories

Bottom line: Adequate particle physics freedom in a CP-conserving, ≤(spin-1) ET to turn on or off any of the five nuclear responses

Conclusions

(Sixth response requires either CP violation or the inclusion of, say, a tensor-tensor contact interaction)

* The elastic response to DM is considerably richer than traditionally described: huge variations among experimental sensitivities possible

* The Galilean invariant ET is an elegant way to factor the nuclear and particle physics: the two communities have a simple meeting point

* Recommend a view of DM where the nuclear densities are viewed as the probe: Our "master formula" was constructed in this way

* Quite surprising to me that the field is this mature, yet previously lacked a straight-forward delineation of the response possibilities: nuclear physics is useful!

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