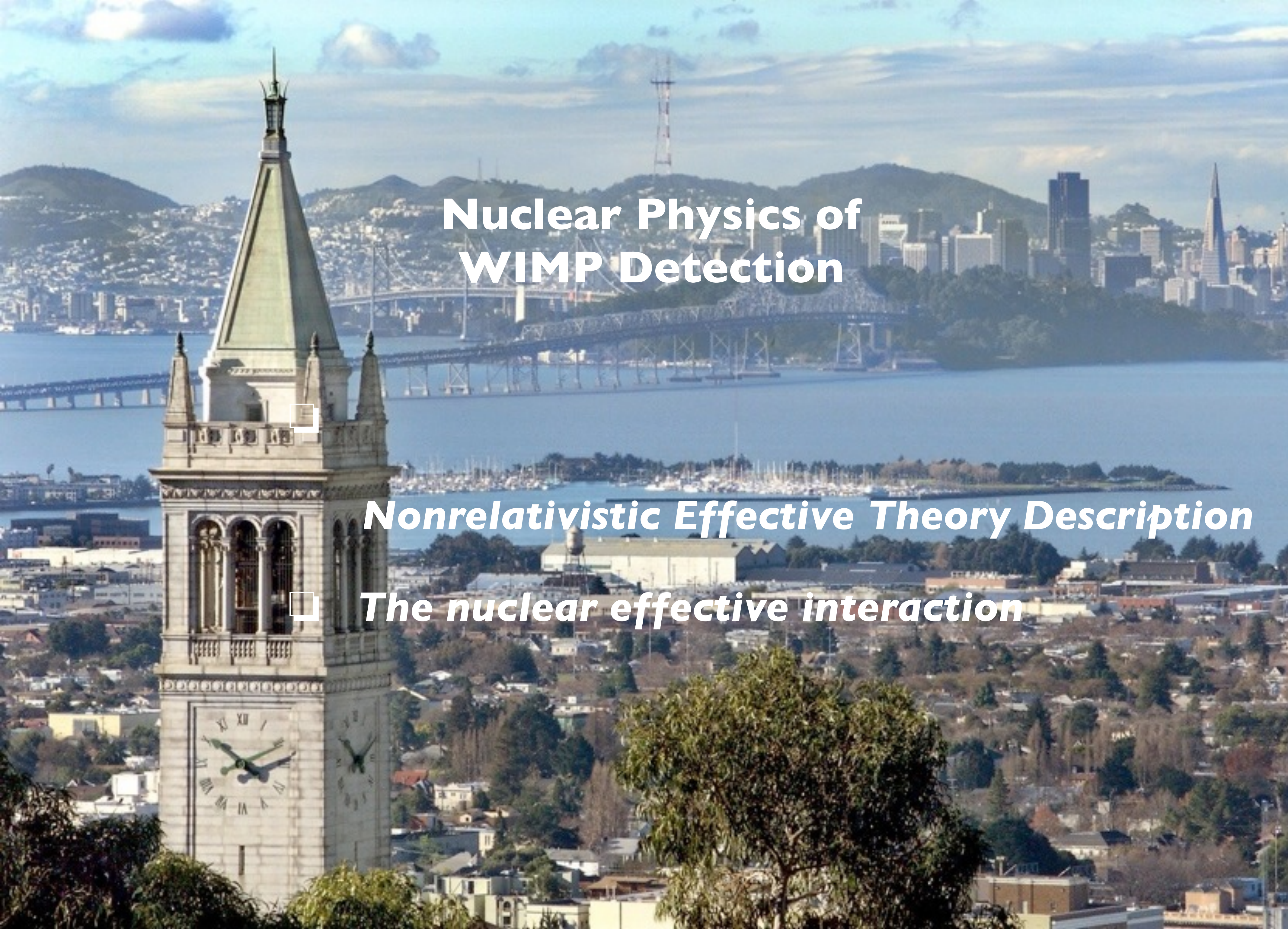
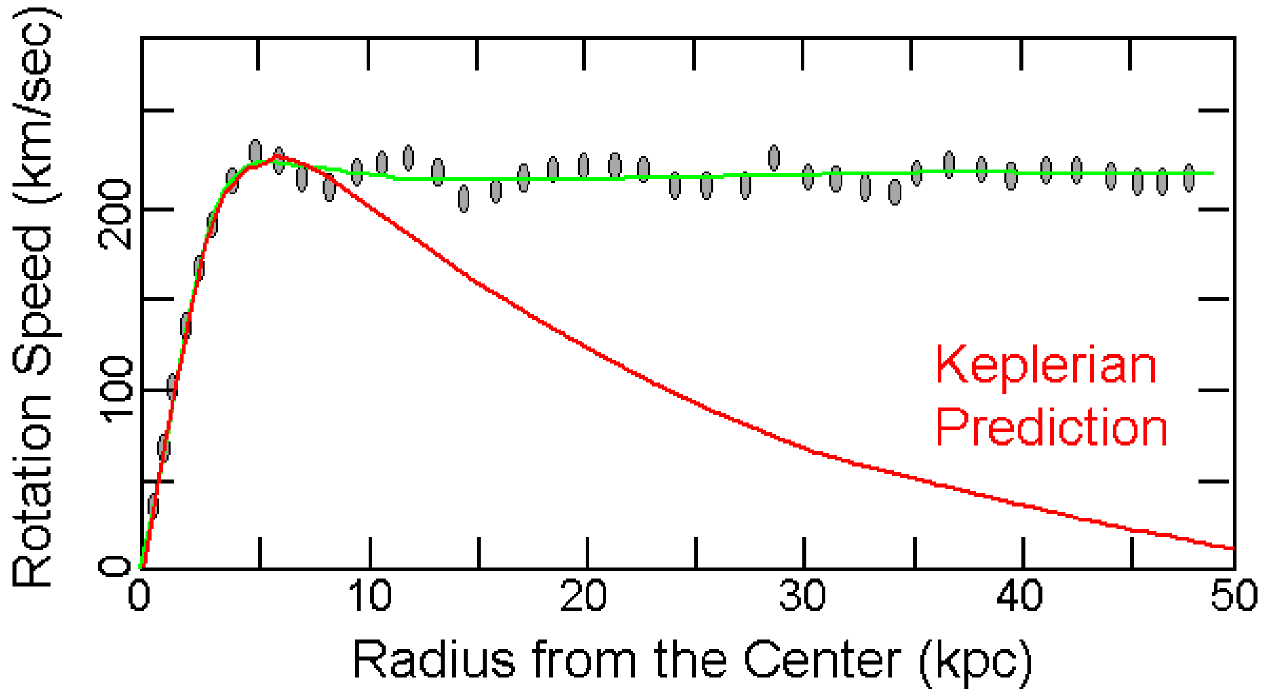


Nuclear Physics of WIMP Detection

- *Nonrelativistic Effective Theory Description*
- *The nuclear effective interaction*

Wick Haxton *INPA Workshop* *Bike-to-work Day, 2014*

Astrophysical Results



$v \propto$ constant

$\leftarrow$ $m(r) \propto r$

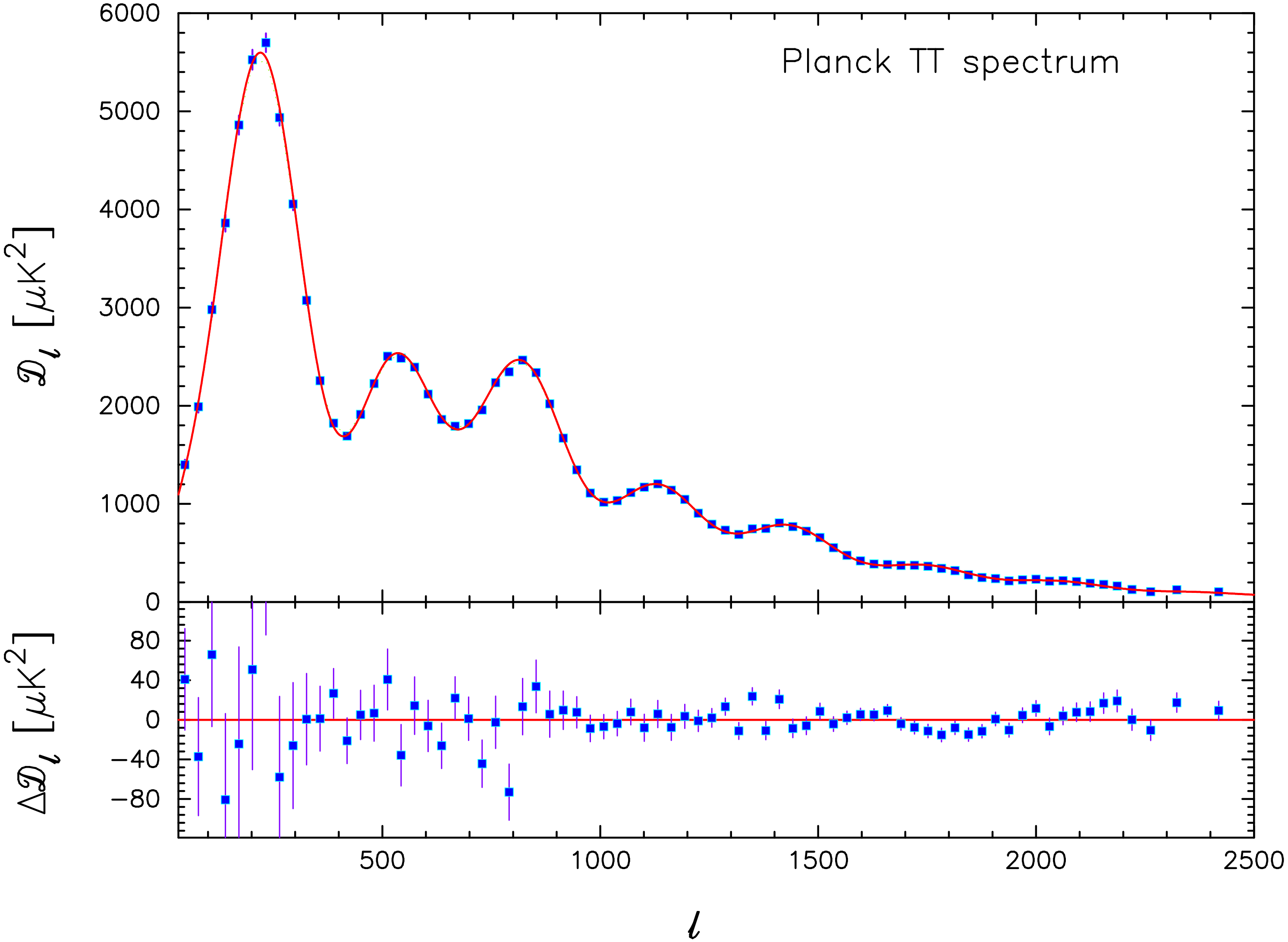
$\rho(r) \propto 1/r^2$

(flat rotation curve)

$\leftarrow v \propto 1/\sqrt{r}$

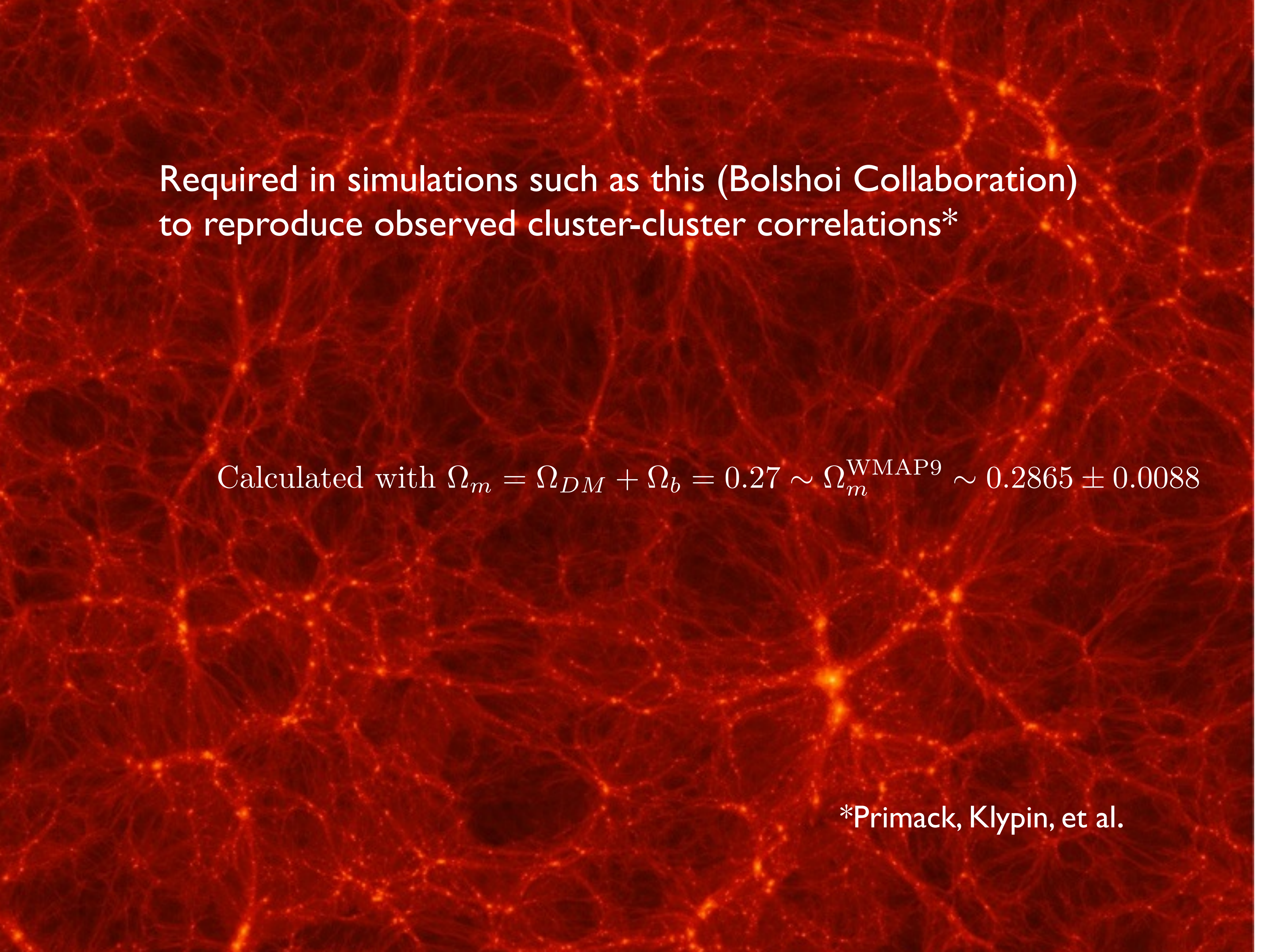
(gravitating central mass)

NGC-6384
(from HST)



ΛCDM comparison

Planck XVI $\Omega_m \sim 0.315 \pm 0.017$



Required in simulations such as this (Bolshoi Collaboration) to reproduce observed cluster-cluster correlations*

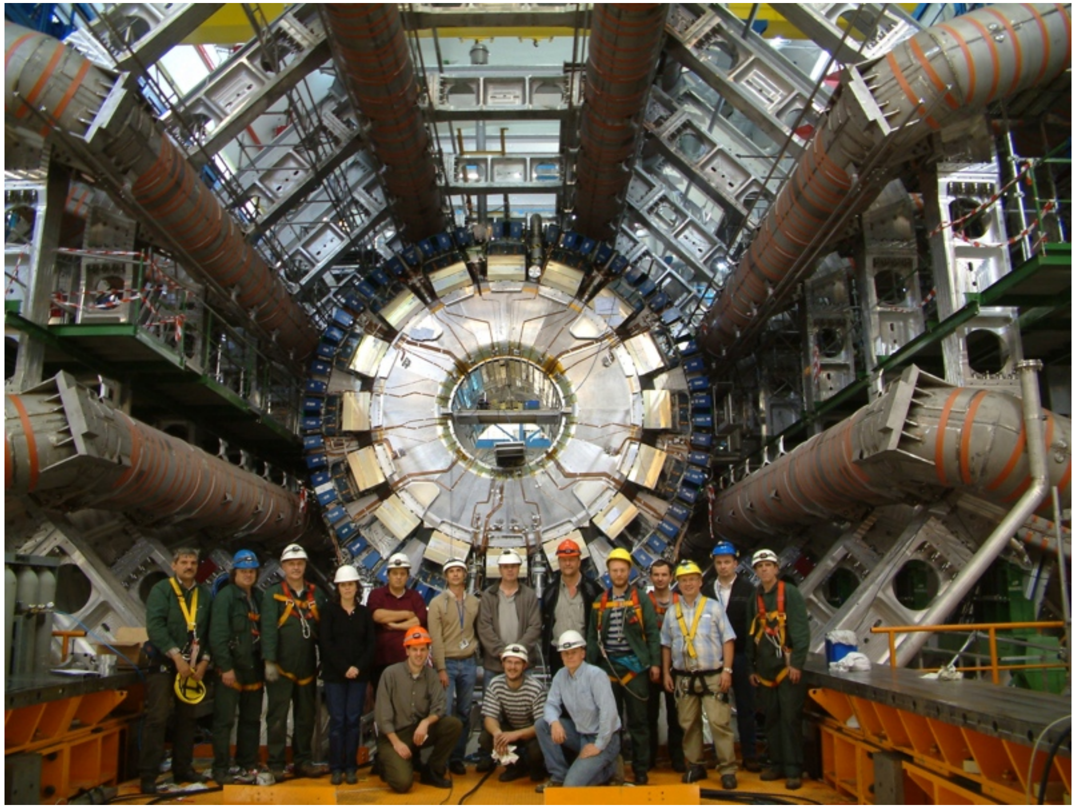
$$\text{Calculated with } \Omega_m = \Omega_{DM} + \Omega_b = 0.27 \sim \Omega_m^{\text{WMAP9}} \sim 0.2865 \pm 0.0088$$

*Primack, Klypin, et al.

Bullet Cluster

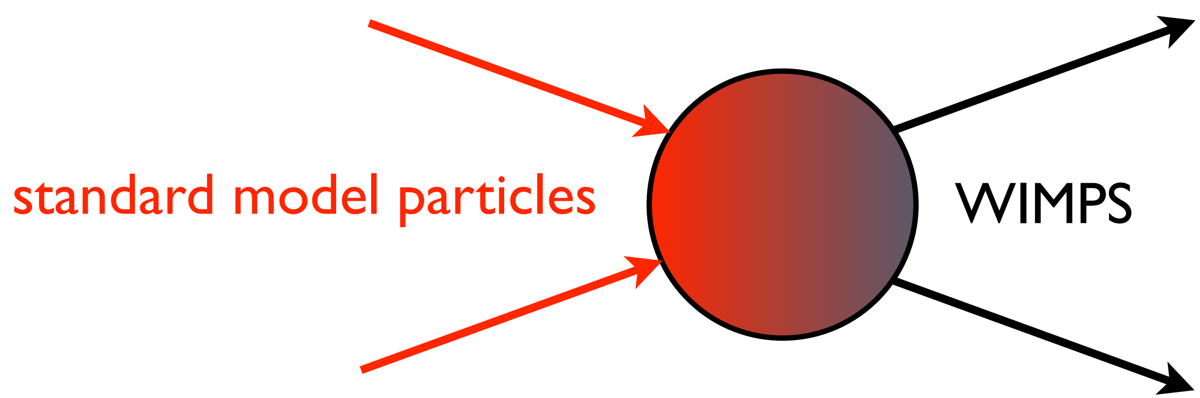
A collision between two clusters of galaxies, imaged by gravitational lensing, showing a separation of visible (pink) and dark (blue) matter

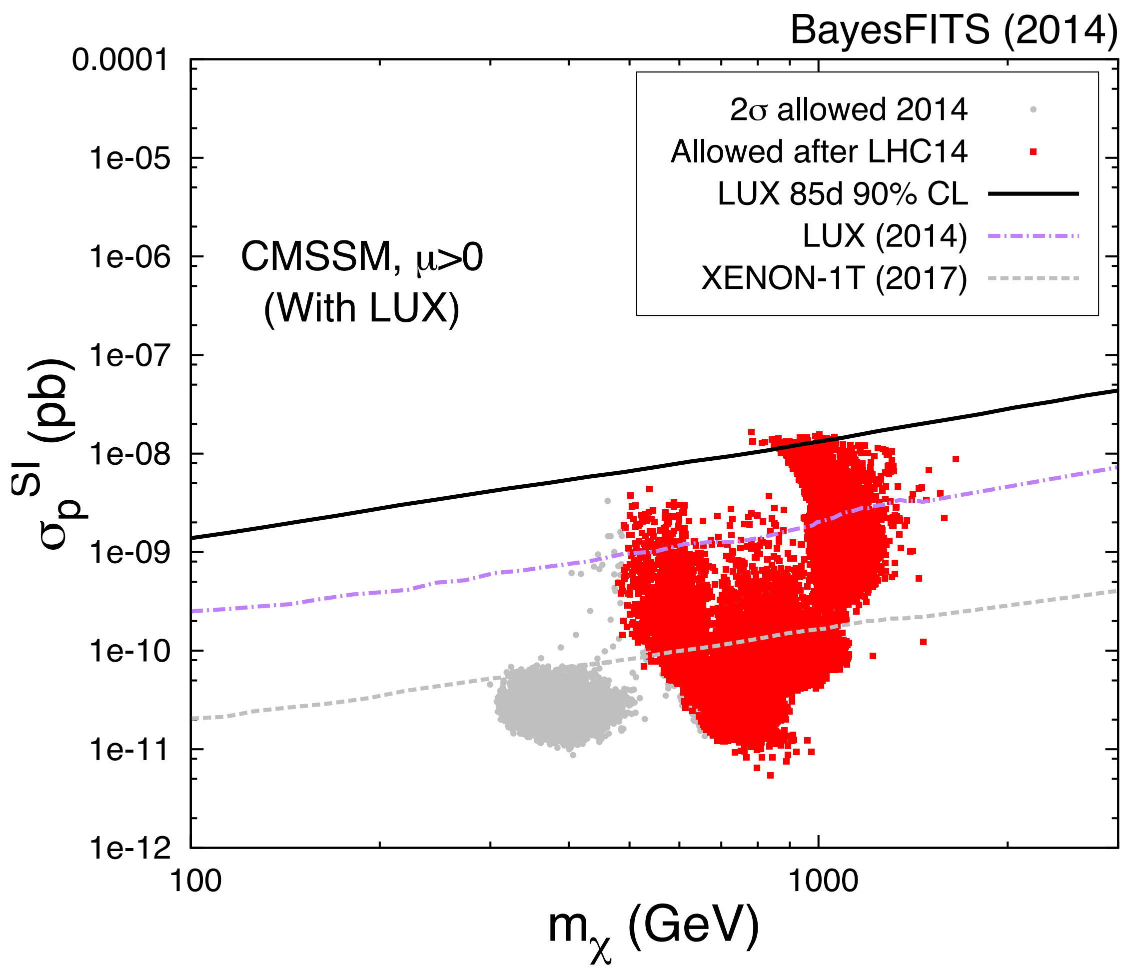
Nongravitational Evidence?



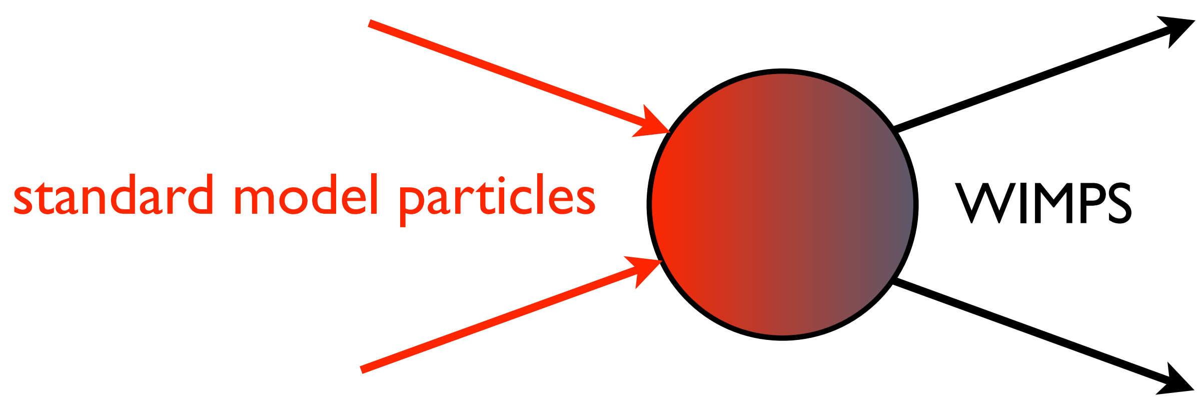
WIMP detection:

- collider searches



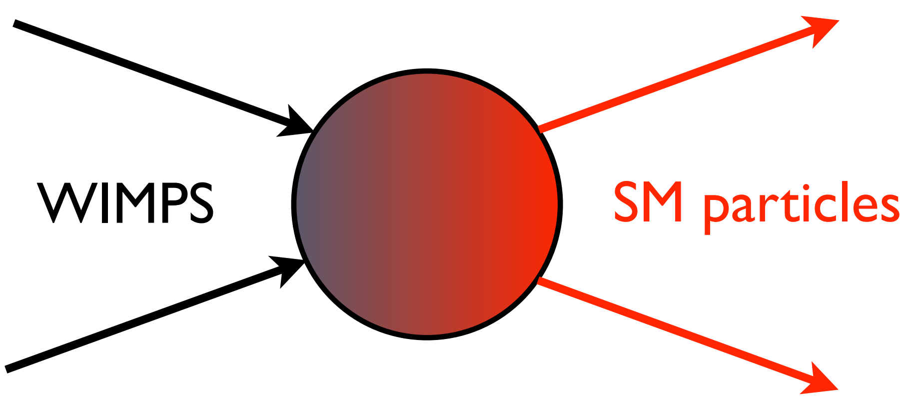


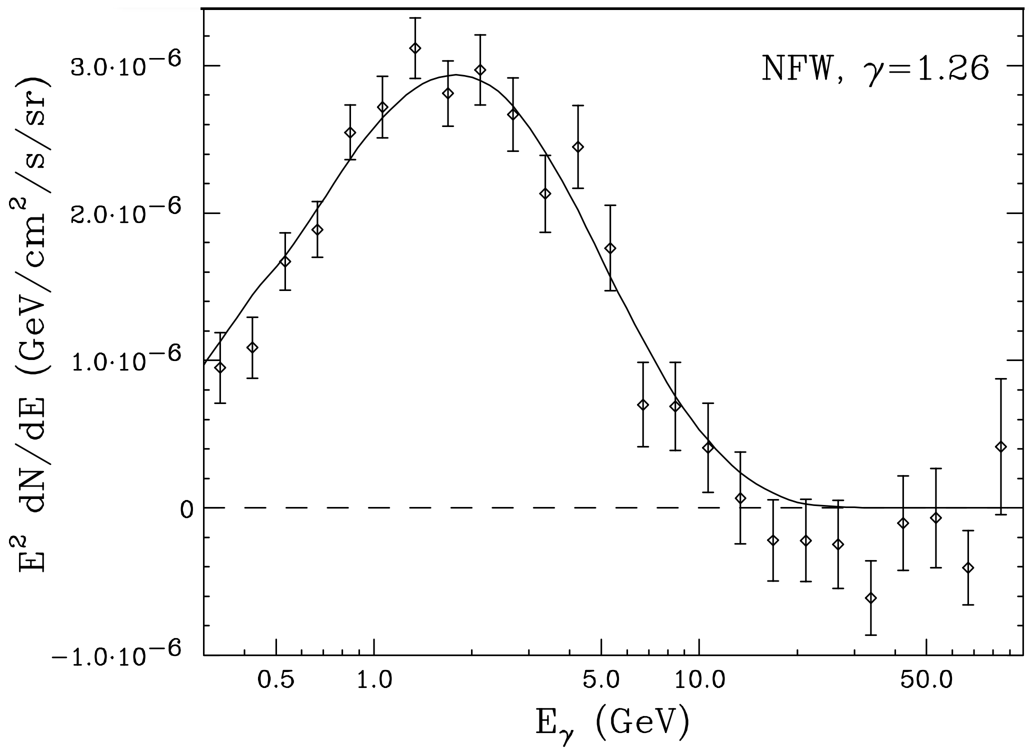
LHC second run starting in 2015 will extend collision energies to 14 TeV and probe WIMP masses up to about 600 GeV



From L. Roszkowski, DM@UCLA 2014

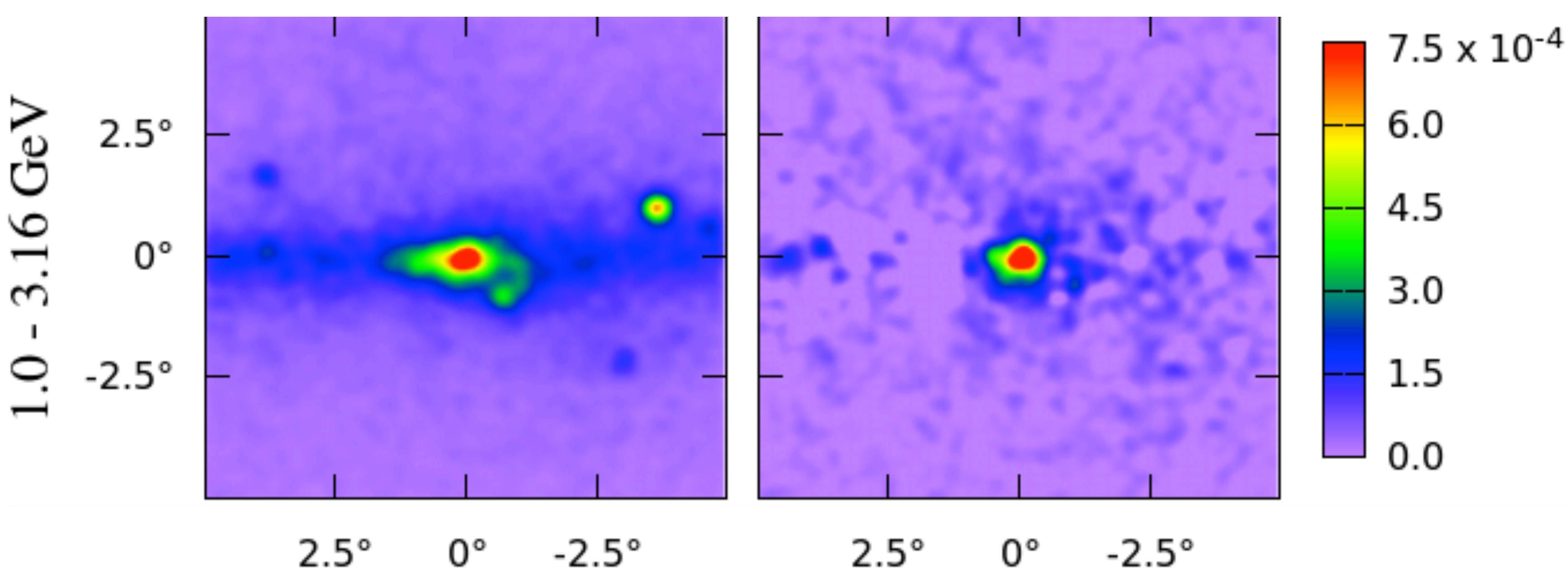
- collider searches
- indirect detection: astrophysical signals





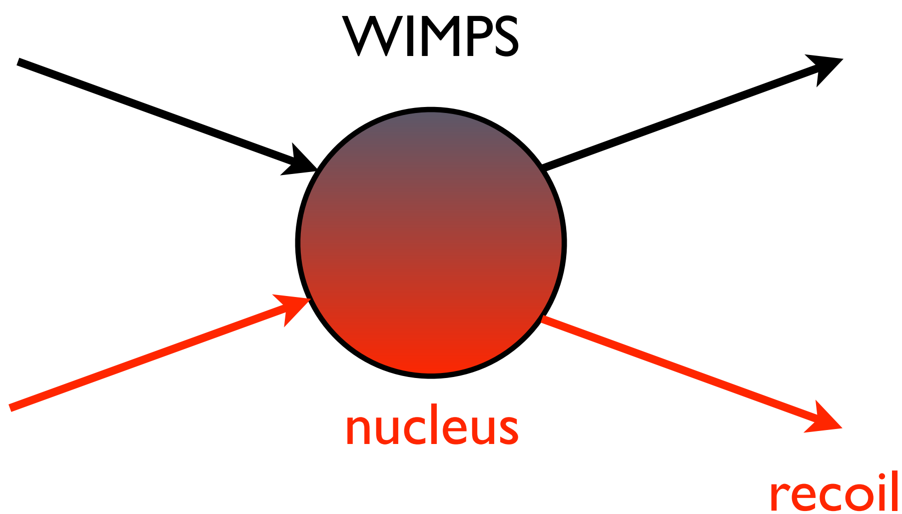
Some claims:
From D. Hooper,
UCLA DM Workshop

One interpretation: ~ 30-40 GeV WIMPs annihilating to b quarks, producing ~ 5 GeV gammas



Detection: their detection channels include (other than large scale structure)

- collider searches
- indirect detection: astrophysical signals
- direct detection: large variety of experiments, some claims...



Essentially every underground lab has experiments

Xe:	Xenon 100/1T; LUX/LZ; XMASS; Zeplin; NEXT
Si:	CDMS; DAMIC
Ge:	COGENT; Edelweiss; SuperCDMS; TEXONO; CDEX; GERDA; Majorana
NaI:	DAMA/LIBRA; ANAIS; DM-ice; SABRE; KamLAND-PICO
CsI:	KIMS
Ar:	DEAP/CLEAN; ArDM; Darkside
Ne:	CLEAN
C/F-based:	PICO; DRIFT; DM-TPC
CF_3I:	COUP
Cs2:	DRIFT
TeO2:	CUORE
CaWO4:	CRESST

A large variety of nuclei with different spins, isospin, masses

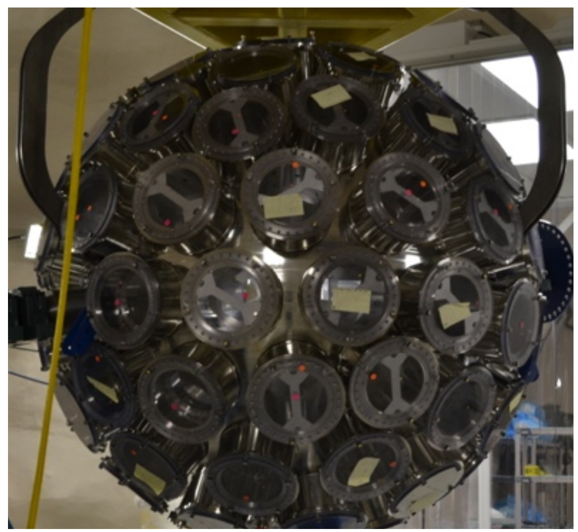
Noble Gasses

Single-phase detectors (scintillation light)

- Challenge: ultra-low absolute backgrounds
- LAr: pulse shape discrimination, factor 10^9-10^{10} for gammas/betas

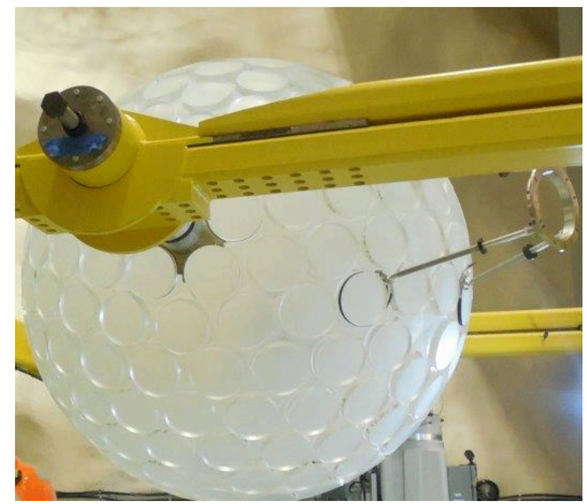
XMASS-RFB at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished (RFB)
new run this fall -> 2013



CLEAN at SNOLab:

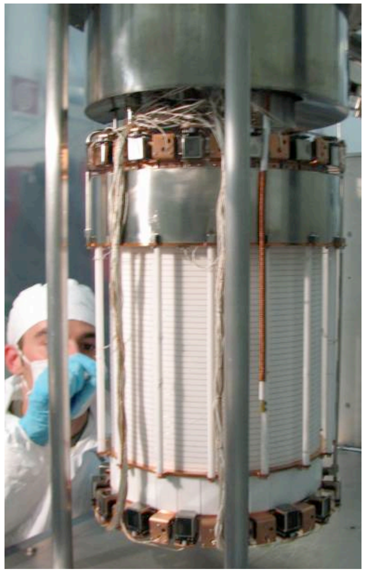
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014



DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

Time projection chambers (scintillation & ionization)



XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
taking new science data

LUX at SURF:

350 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run since spring 2013

PandaX at CJPL:

125 kg LXe
(25 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
started in 2013

ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

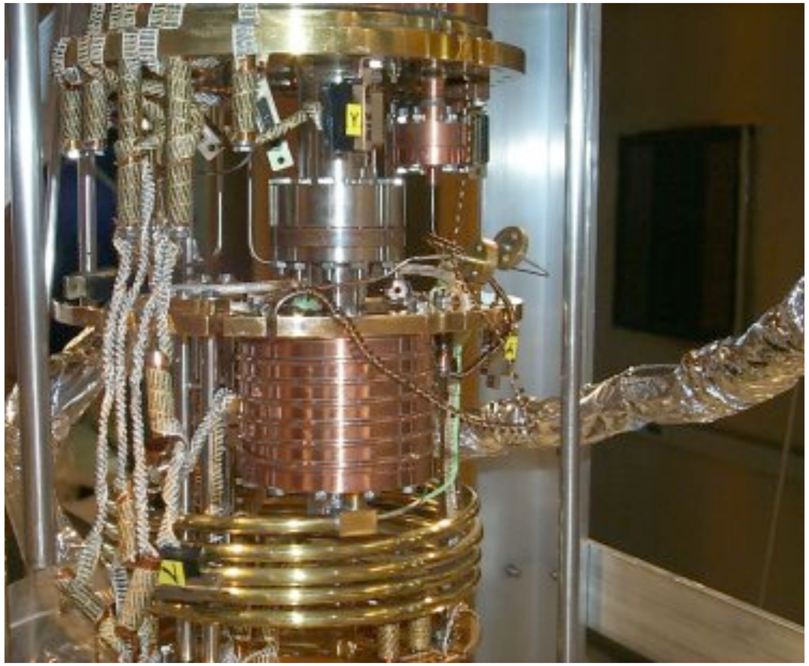
DarkSide at LNGS

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

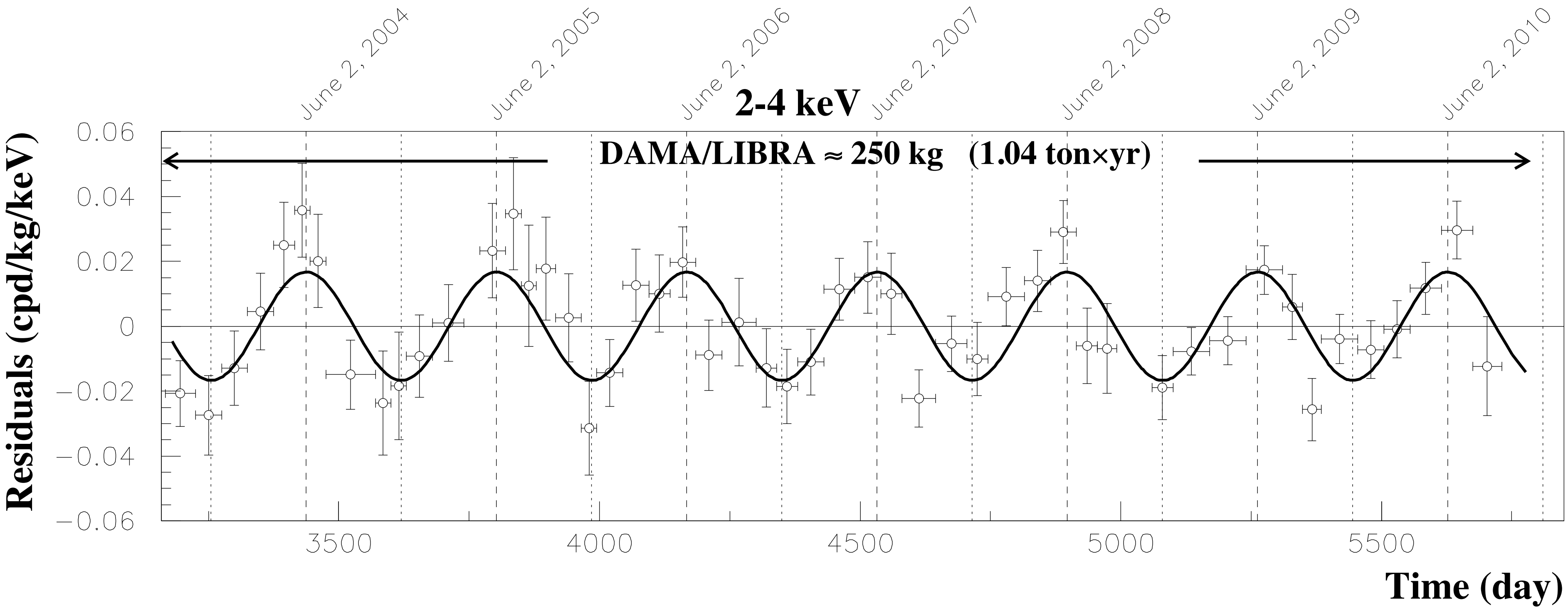
Crystals, Bubble Chambers, ...

DAMA/LIBRA NaI



CDMS Si, Ge
CoGENT Ge

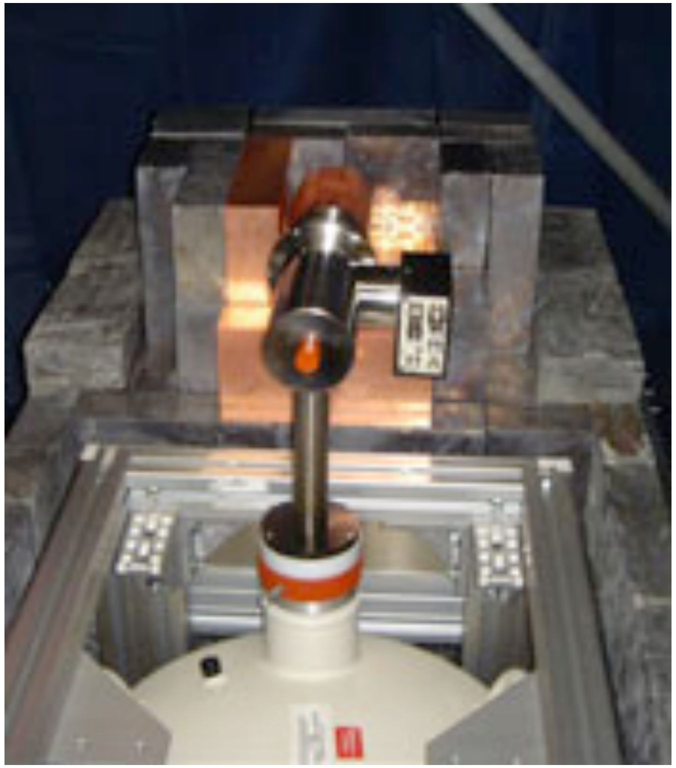
Coup CF_3I



DAMA/LIBRA: 9.3σ variation of the signal over the year, attributed to the expected variation of a DM signal on the Earth's velocity due to rotation around the Sun

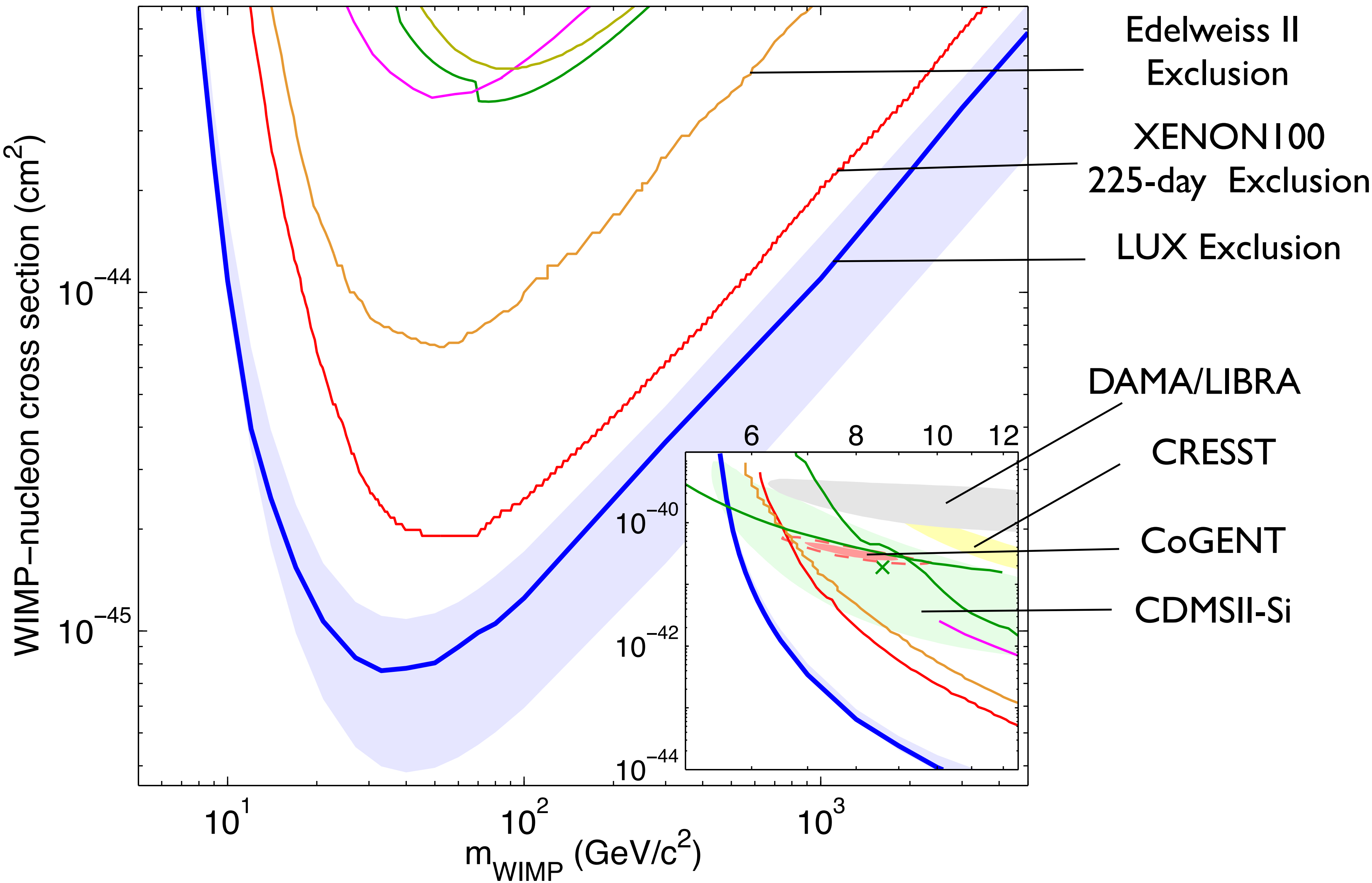
note 10 M_{WIMP} ~ 10 GeV → E_R^{max} ~10 keV

CoGENT: Ge detector in which a similar seasonal variation was seen at 2.8σ, consistent with a light 7 GeV WIMP

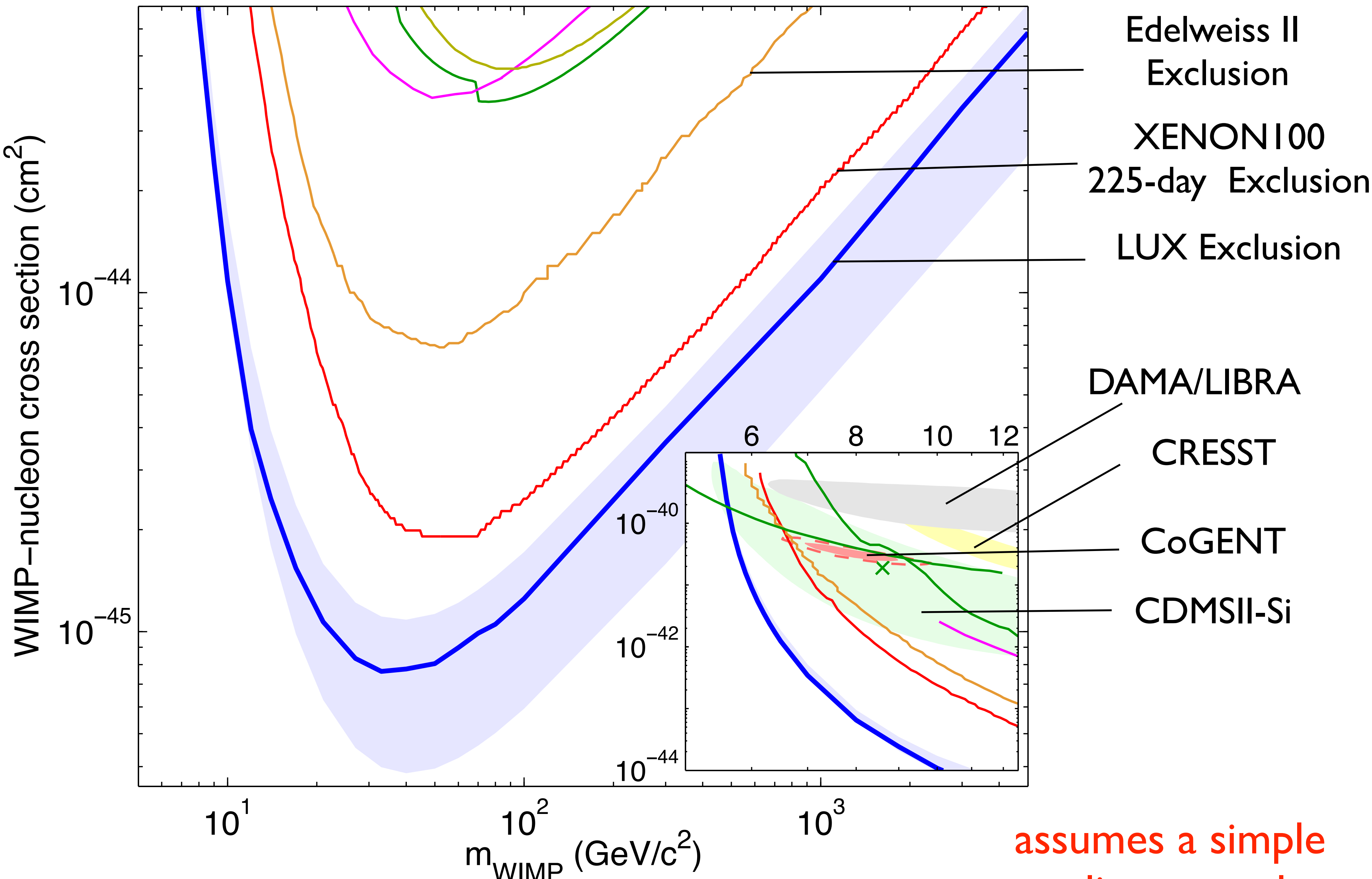


No such signal found by the MALBEK Ge detector group

CDSM II-Si: upper bound established, but found three low-mass events vs. an expected background signal of ~ 0.41 events. If interpreted as DM, implies M_{WIMP} ~ 10 GeV



LUX (Xe): arXiv:1310.8214



LUX (Xe): arXiv:1310.8214

assumes a simple coupling to nuclear "charge"

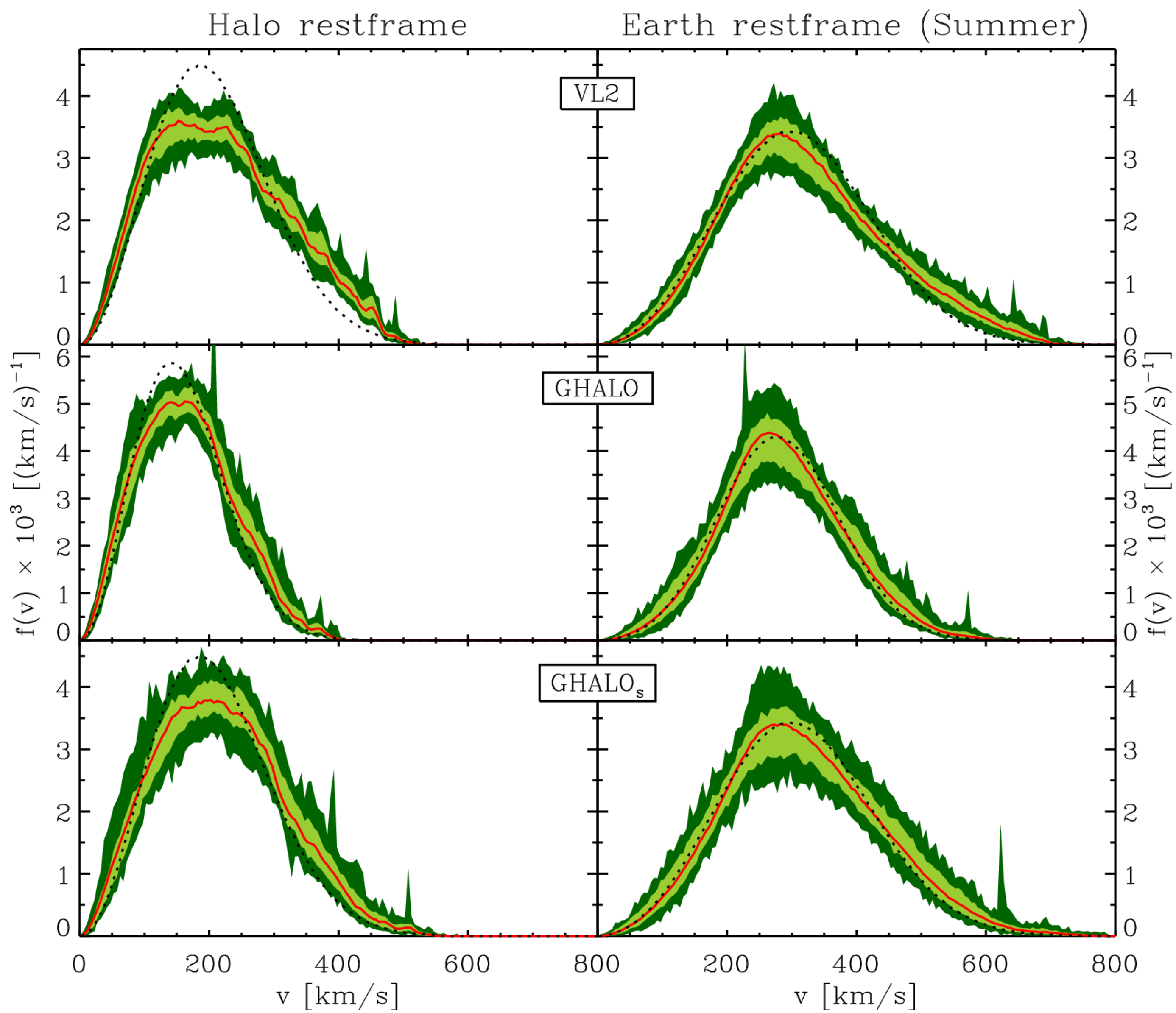
How are these comparisons among experiments done?

We know some basic parameters

- WIMP velocity relative to our rest frame $\sim 10^{-3}$
- if mass is on the weak scale, WIMP momentum transfers in elastic scattering can range to $q_{max} \sim 2 v_{\rm WIMP} \mu_T \sim$ 200 MeV/c
- WIMP kinetic energy ~ 30 keV: nuclear excitation (in most cases) not posible
- $R_{NUC} \sim 1.2\, A^{1/3}$ f $\Longrightarrow$ $q_{max} R \sim 3.2 \Leftrightarrow 6.0$ for F ⇔ Xe: the WIMP can “see” the structure of the nucleus

Our motion through the WIMP "wind" can be modeled

$$\rho_{\rm local} \sim 0.3\ {\rm GeV/cm^3} \Rightarrow$$
$$\phi_{\rm WIMP} \sim 10^5/\ {\rm cm^2 s}$$



M. Kuhlen et al, JCAP02 (2010) 030

An expression can be written for the rate as a function of nuclear recoil energy E_R

Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}} d\mathbf{v} f(\mathbf{v}) v \frac{d\sigma}{dE_R}$$

Particle+nuclear physics

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

$N_N =$ number of target nuclei in detector

$\rho_0 =$ Milky Way dark matter density

$f(\text{v}) =$ WIMP velocity distribution, Earth frame

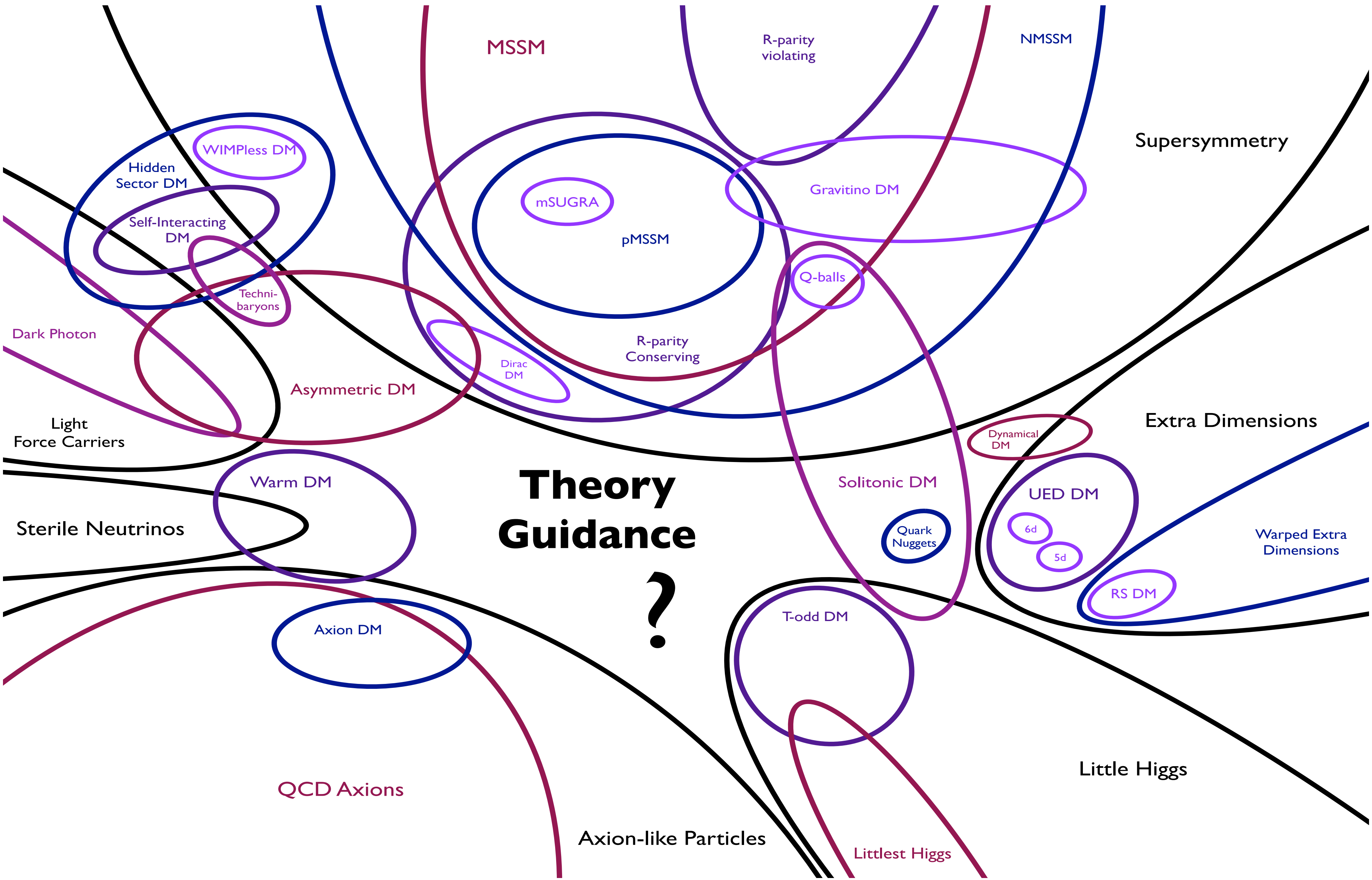
$m_W =$ WIMP mass

$\sigma =$ WIMP – nucleus elastic scattering cross section

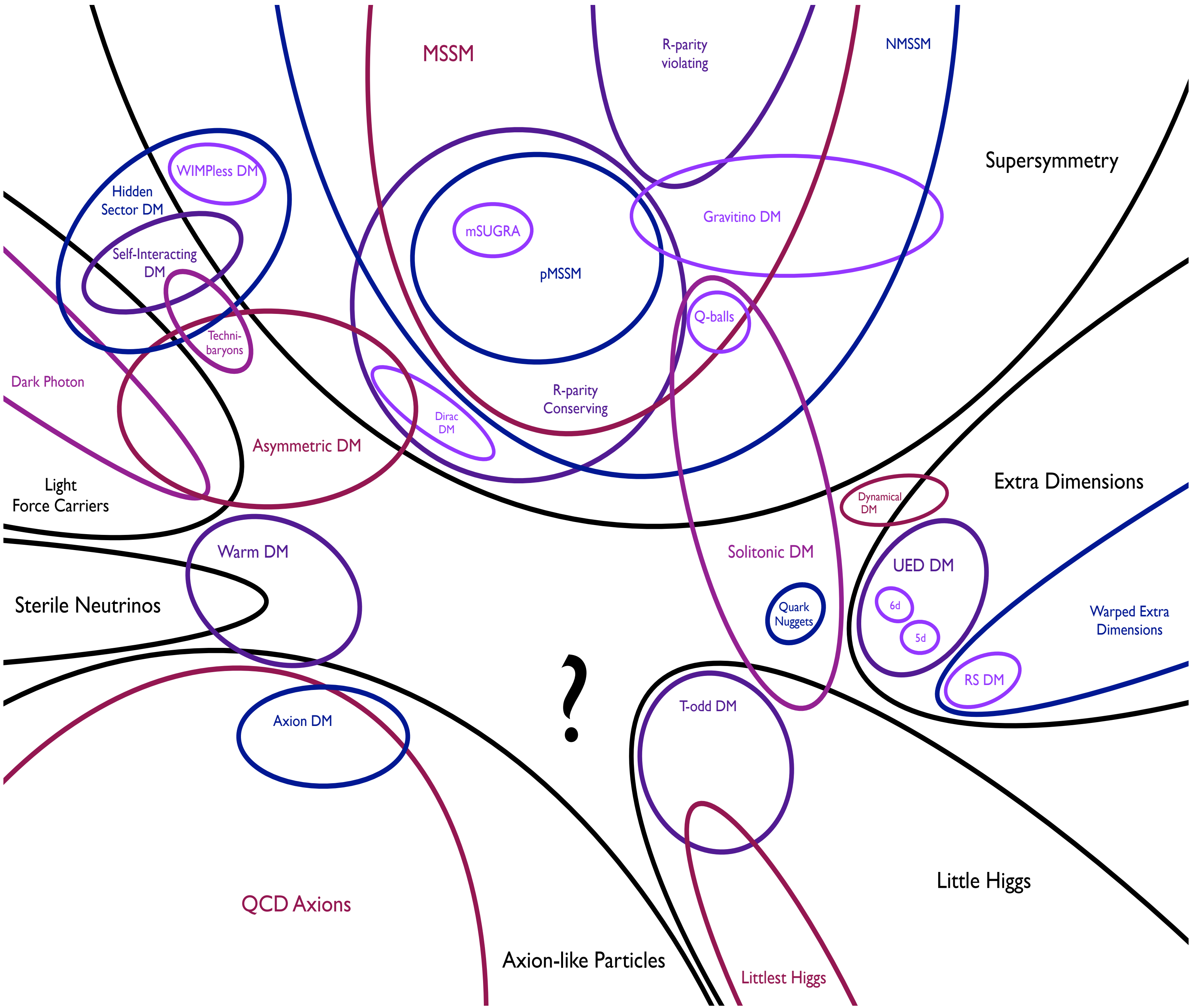
But where do we get the cross section -- the WIMP-nucleus interaction?

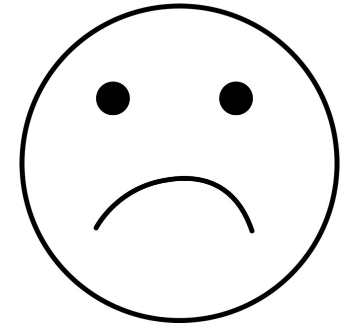
In fact, what can and cannot be learned about the WIMP-matter interaction from these low-energy elastic scattering experiments?

so just ask a particle theorist (or several)...

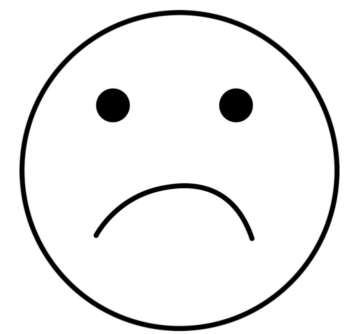


from Tim Tait

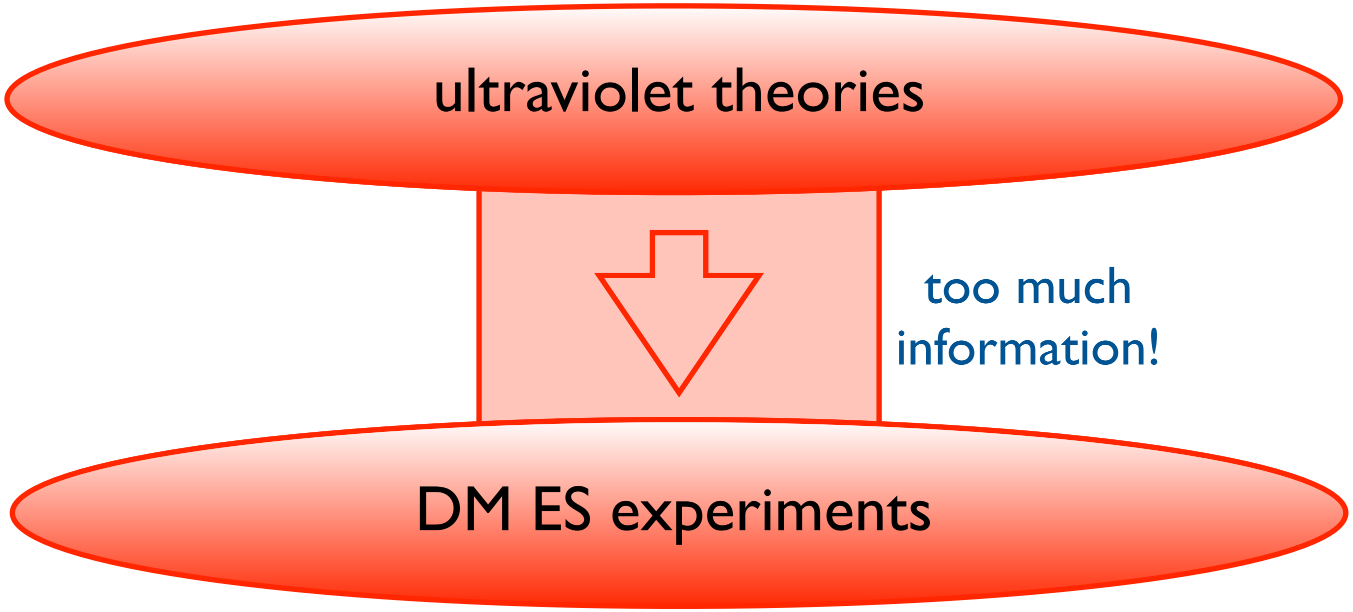




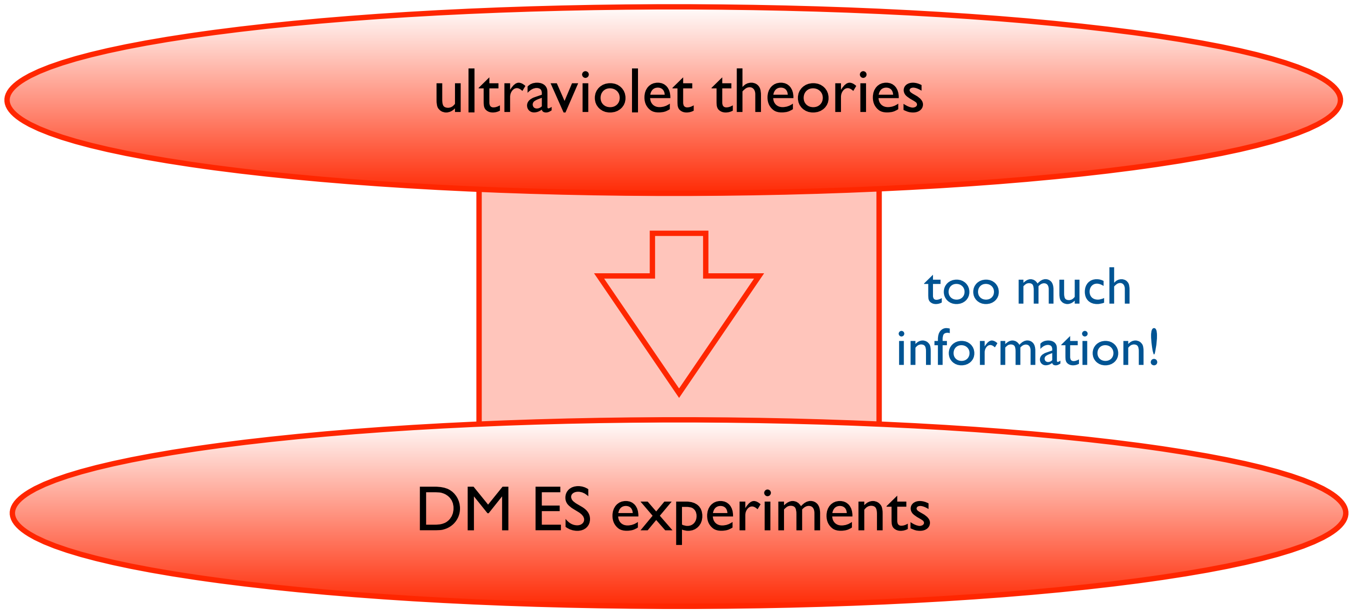
Nuclear theorist



DM experimentalist

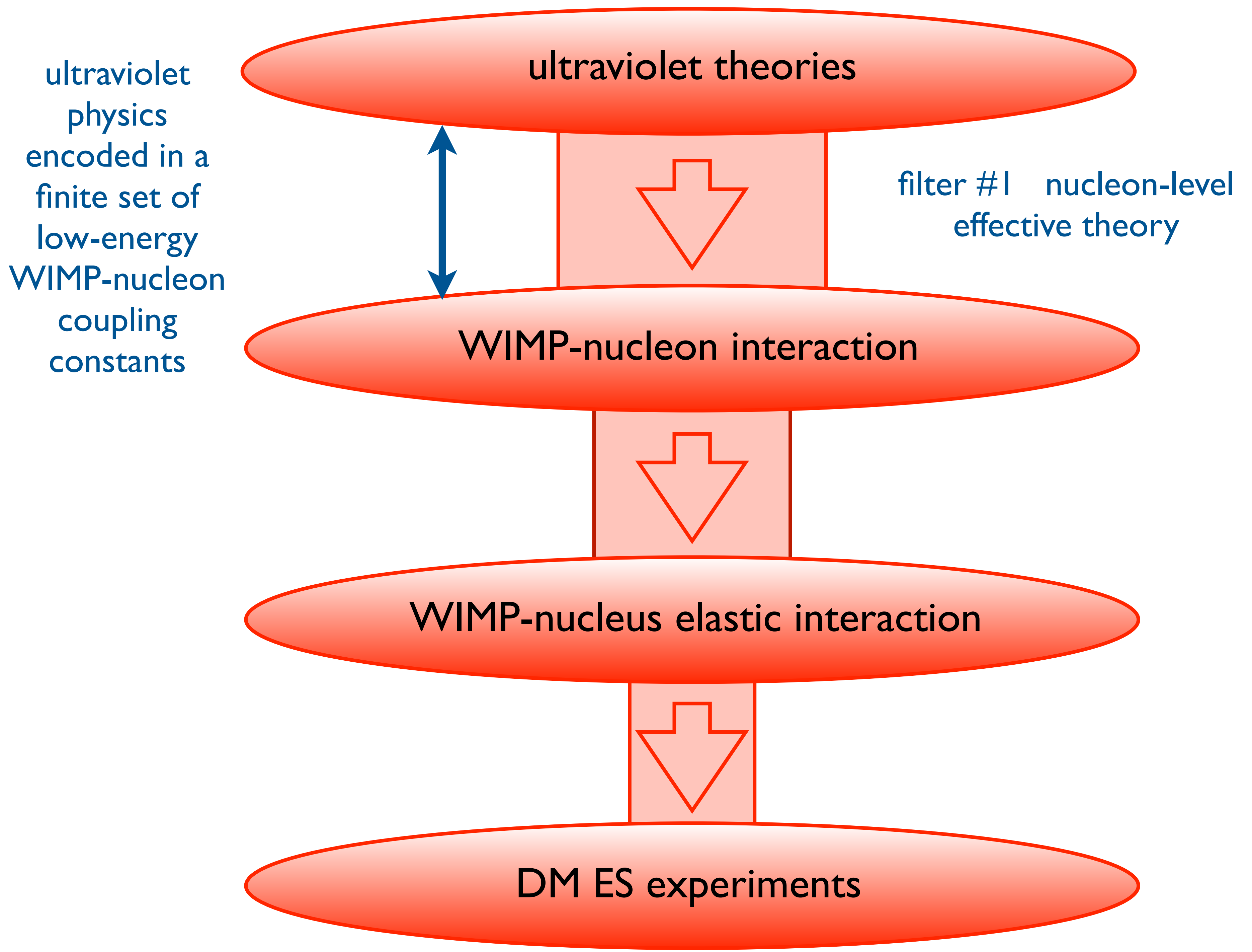


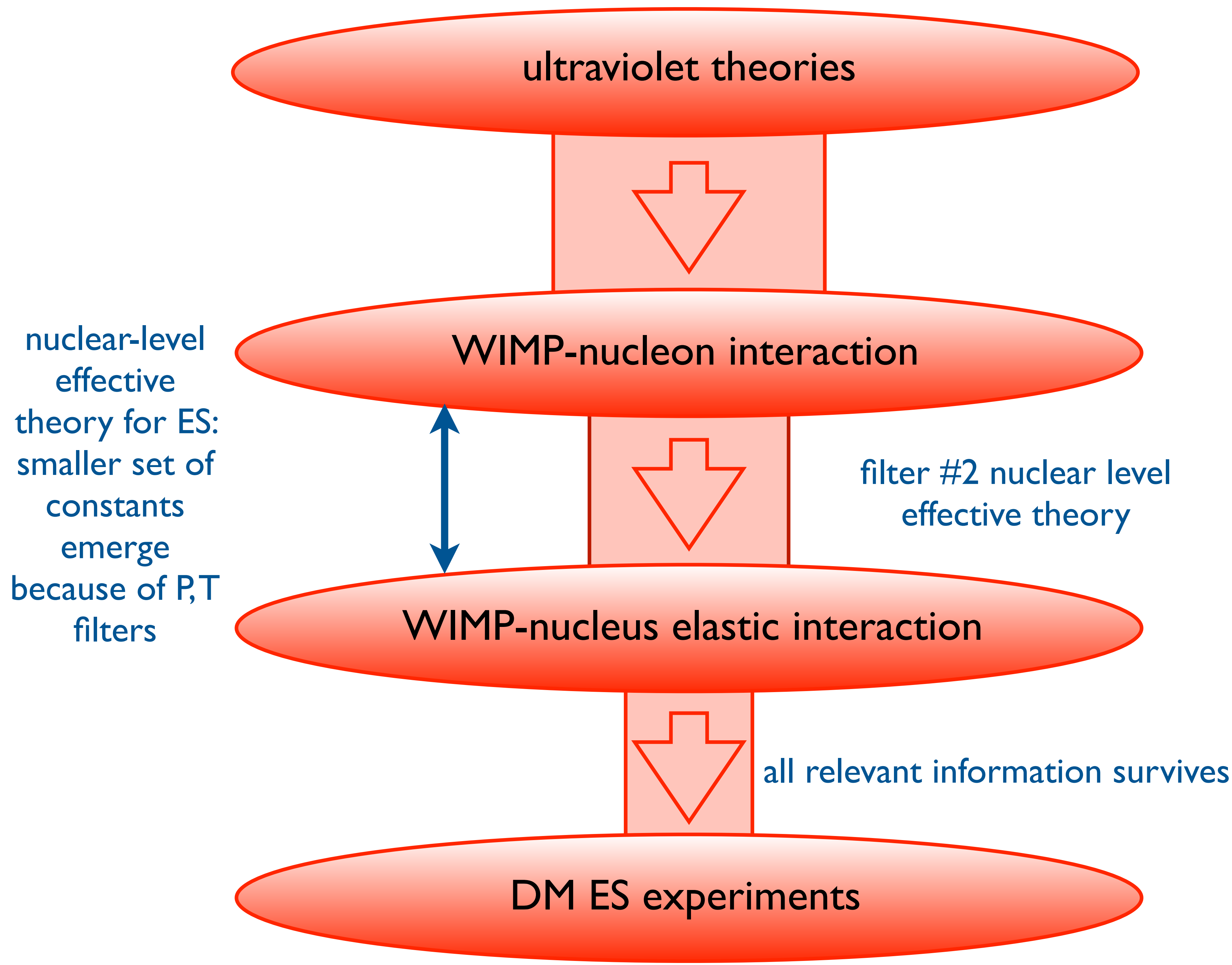
This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory

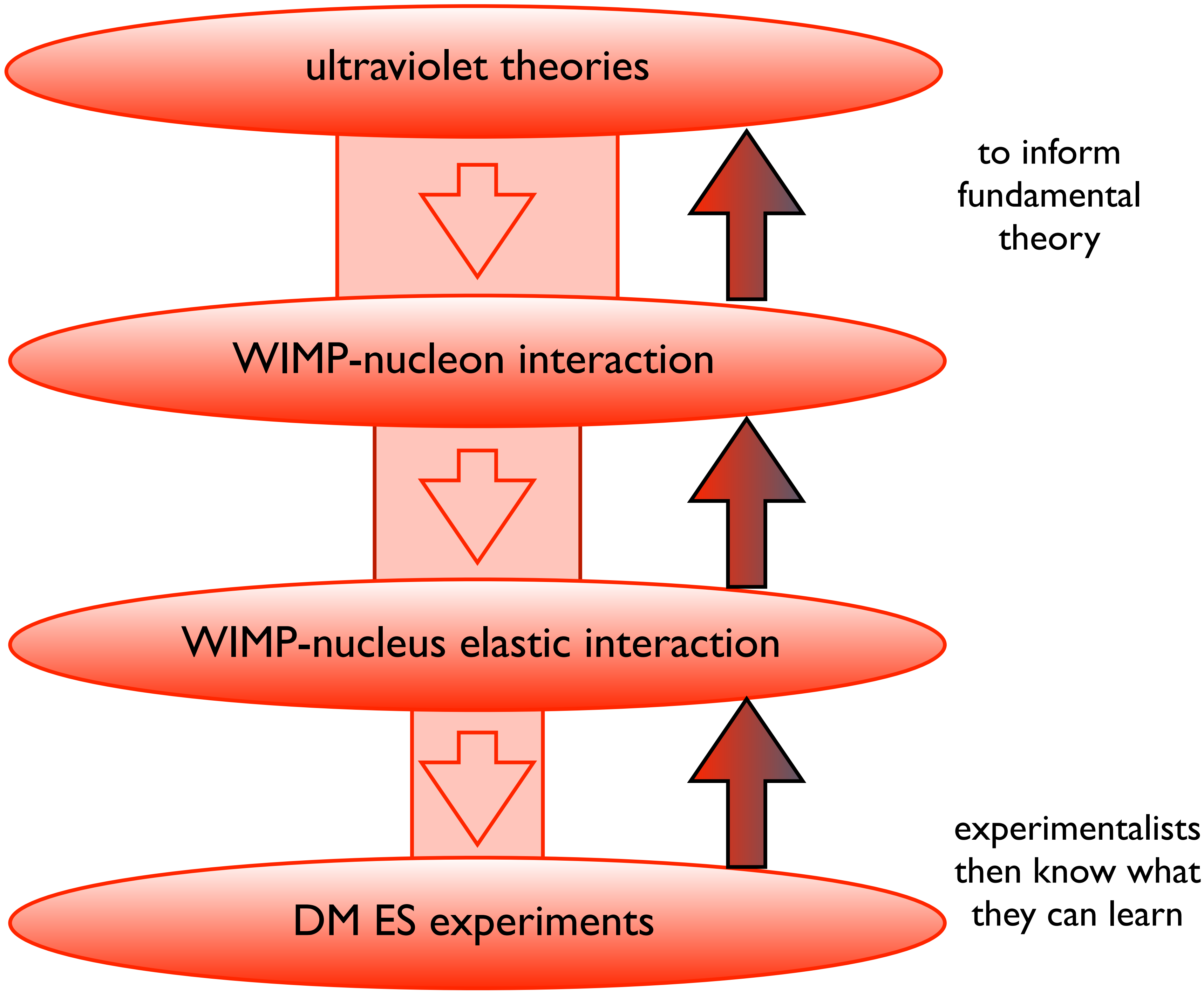


This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory

An alternative is provided by effective field theory


ultraviolet theories
ultraviolet physics encoded in a finite set of low-energy WIMP-nucleon coupling constants
filter #1 nucleon-level effective theory
WIMP-nucleon interaction
WIMP-nucleus elastic interaction
DM ES experiments

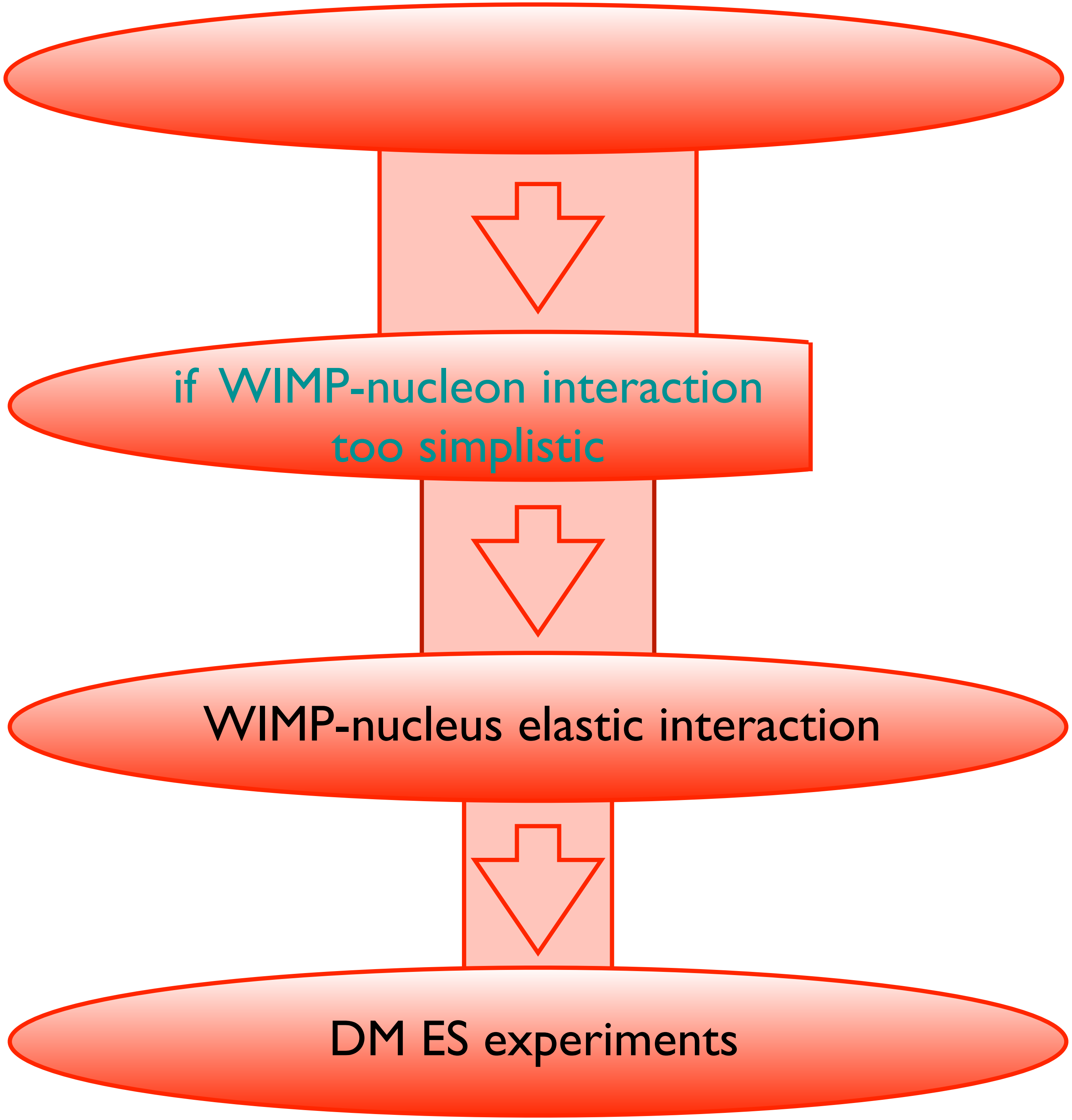

ultraviolet theories
WIMP-nucleon interaction
nuclear-level effective theory for ES: smaller set of constants emerge because of P,T filters
filter #2 nuclear level effective theory
WIMP-nucleus elastic interaction
all relevant information survives
DM ES experiments


ultraviolet theories
to inform fundamental theory
WIMP-nucleon interaction
WIMP-nucleus elastic interaction
DM ES experiments
experimentalists then know what they can learn

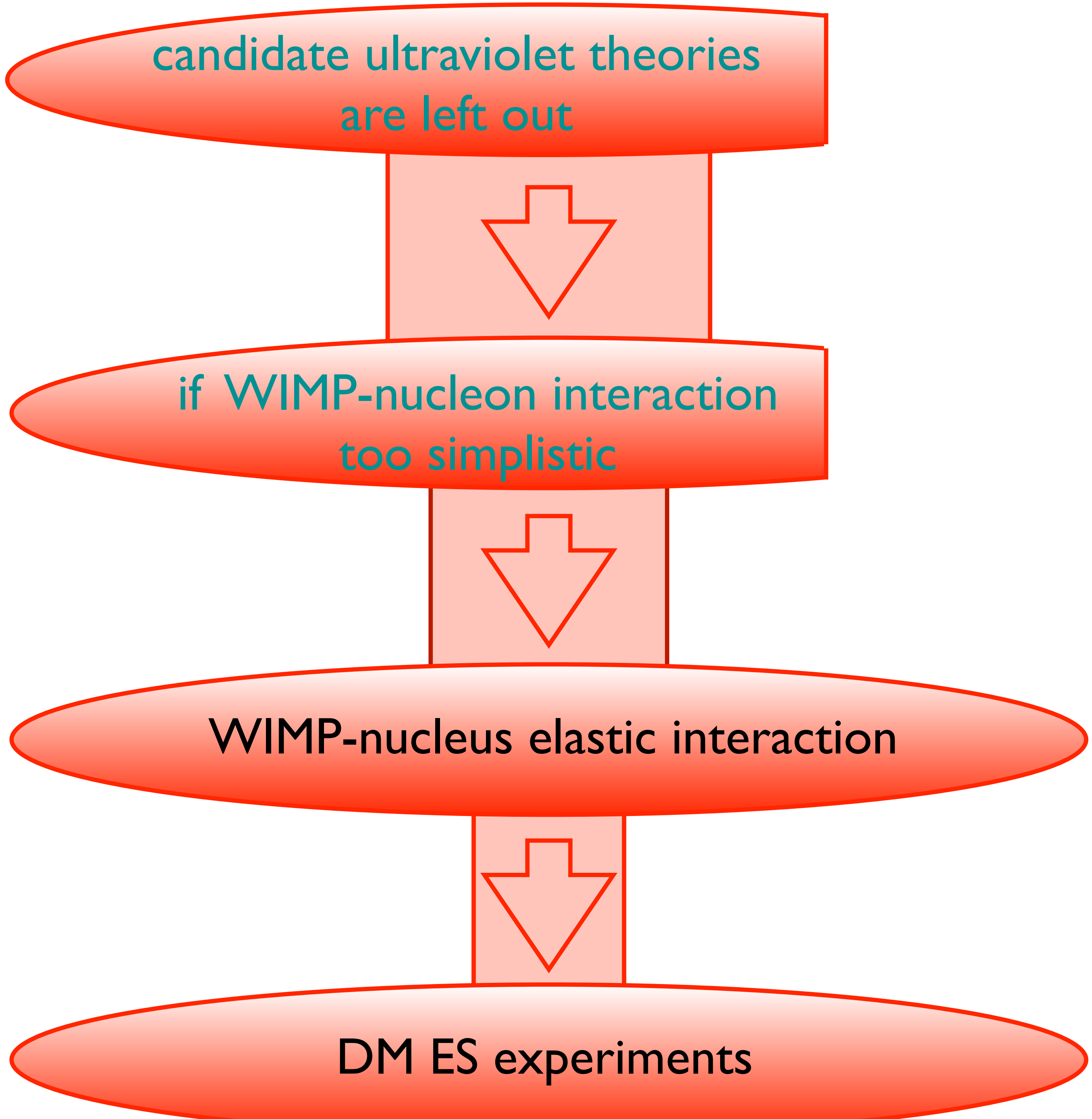
the effective theory process works only if each step is executed properly

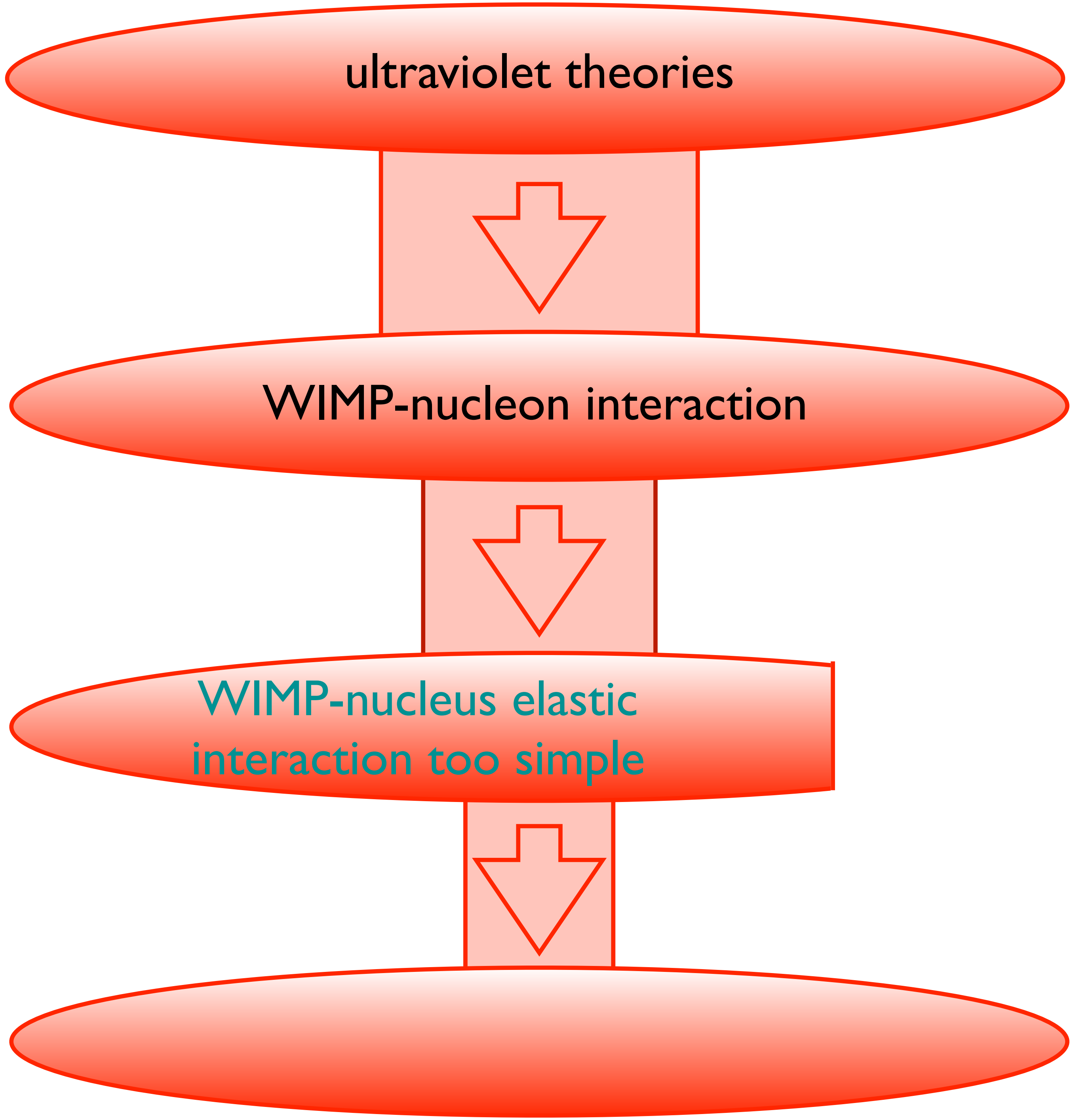
this

not this

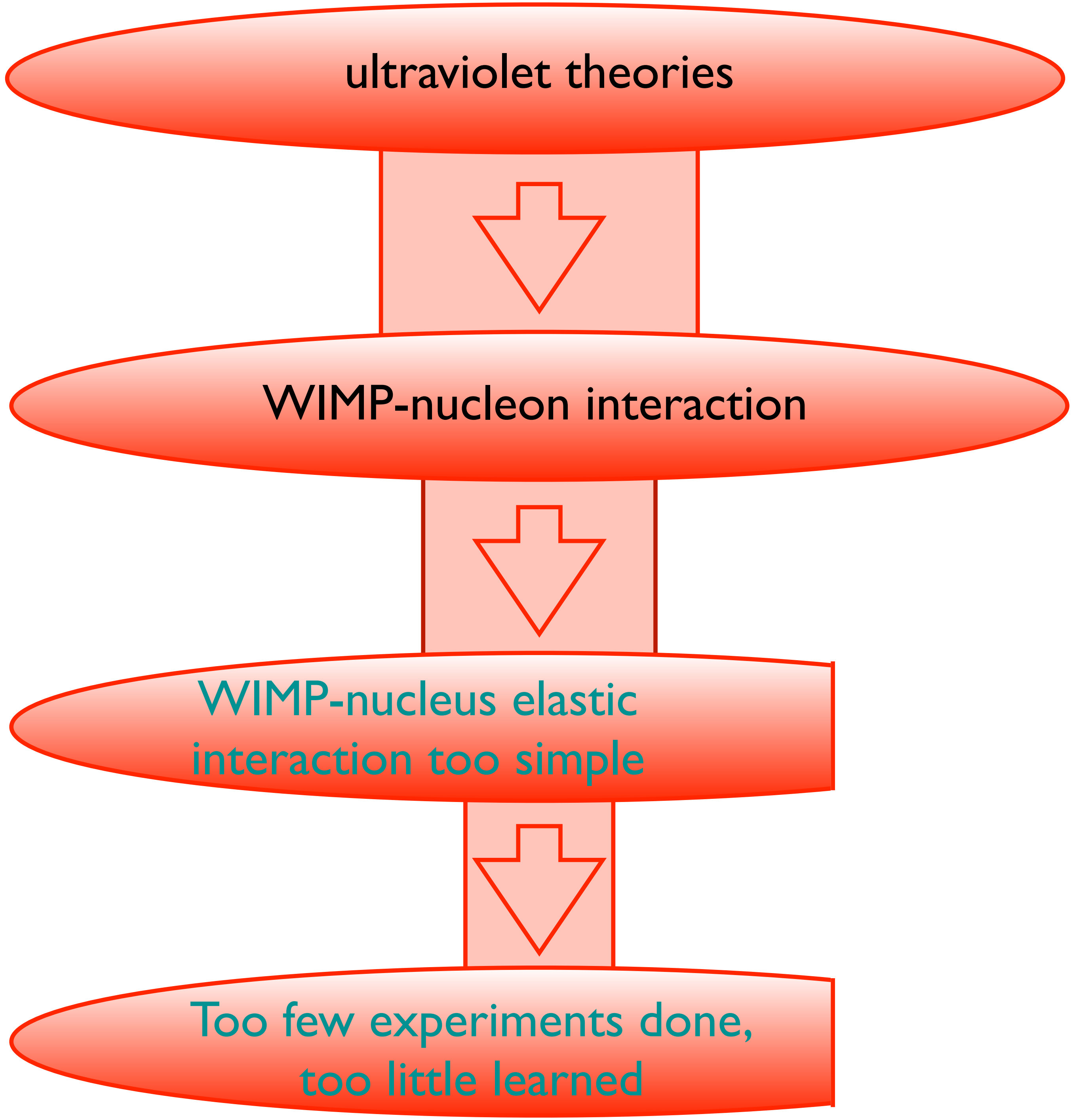


if WIMP-nucleon interaction
too simplistic
WIMP-nucleus elastic interaction
DM ES experiments


candidate ultraviolet theories
are left out
if WIMP-nucleon interaction
too simplistic
WIMP-nucleus elastic interaction
DM ES experiments



ultraviolet theories
WIMP-nucleon interaction
WIMP-nucleus elastic
interaction too simple


ultraviolet theories
WIMP-nucleon interaction
WIMP-nucleus elastic
interaction too simple
Too few experiments done,
too little learned

- Experiments are frequently analyzed and compared in a formalism in which the nucleus is treated as a point particle

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

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

- Is this treatment sufficiently general, to ensure a discovery strategy that will lead to the right result? Is it some lowest order ET?

- Reminiscent of an old weak interactions problem: we knew a lot more -- four fermions, contact interaction,... Constructed the low energy effective theory

$$S + V + A + P + T$$

- Yet took a lot of effort to determine V-A, including eliminating wrong experiments in favor of correct ones

- We can attack this problem with similar techniques: What is the form of the elastic response for a nonrelativistic theory with charges and current at most linear in velocities?

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	$T_2^{5\text{el}}$	$T_1^{5\text{el}}$	$T_2^{5\text{mag}}$	$T_1^{5\text{mag}}$
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)

- We can attack this problem with similar techniques: What is the form of the elastic response for a nonrelativistic theory with charges and current at most linear in velocities?

charges:

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

symmetry arguments ⇒ form of the nuclear ET

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	
axial		C_1^5

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

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}			

The resulting table of allowed responses has six entries (not two): just determined by the symmetries, not yet related to WIMP couplings to the nucleon/nucleus

One of the union rules for theorists:
Interactions allow by symmetries must be (and will be) included in a proper effective theory

- This suggests more can be learned about ultraviolet theories from ES than is generally assumed - that's good

- But what quantum mechanics are we missing? How do these responses from interactions?
  - to answer this in full, we need to construct the Galilean-invariant ET at the nucleon level (the ladder to HE)

- Helpful to first understand the quantum mechanics that is missing in the standard treatment -- which assumes the nucleus behaves as a point particle, and is thus characterized by just its charge and spin...

  (this helps us define the ET construction)

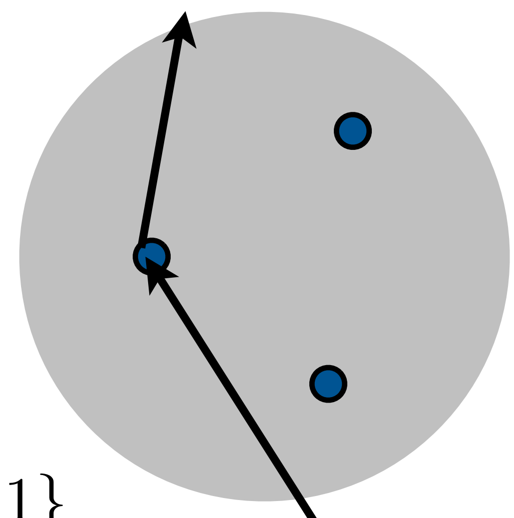
The new responses are connected with velocity-dependent interactions - that is, with theories that have derivative couplings

Let's take an example: consider $\sum_{i=1}^{A} \vec{S}_\chi \cdot \vec{v}^\perp(i)$

the velocity is defined by Galilean invariance $\vec{v}^\perp(i) = \vec{v}_\chi - \vec{v}_N(i)$

- In the point-nucleus limit $\vec{S}_\chi \cdot \vec{v}_{\mathrm{WIMP}} \sum_{i=1}^{A} 1(i)$

where $\vec{v}_{\mathrm{WIMP}} \sim 10^{-3}$.



- But in reality

$\{\vec{v}^\perp(i), i = 1, ...A\} \to \{\vec{v}_{\mathrm{WIMP}}; \;\; \dot{\vec{v}}(i), i = 1, ..., A-1\}$

and $\dot{\vec{v}}(i) \sim 10^{-1}$: SI/SD retains the least important term

Parameter counting in the effective theory

- These velocities hide: the $\dot{\vec{v}}(i)$ carry odd parity and cannot contribute by themselves to elastic nuclear matrix elements.

- But in elastic scattering, momentum transfers are significant. The full velocity operator is

$$e^{i\vec{q}\cdot\vec{r}(i)}\dot{\vec{v}}(i) \quad \text{where} \quad \vec{q}\cdot\vec{r}(i) \sim 1$$

- We can combine the two vector nuclear operators $\vec{r}(i),\ \dot{\vec{v}}$ to form a scalar, vector, and tensor. To first order in $\vec{q}$ for the new "SD" case

$$-\frac{1}{i}q\vec{r}\times\dot{\vec{v}} = -\frac{1}{i}\frac{q}{m_N}\vec{r}\times\dot{\vec{p}} = -\frac{q}{m_N}\vec{\ell}(i)$$

$\vec{\ell}(i)$ is a new dimensionless operator. And we deduce an instruction for the ET that is not obvious. Internal nucleon velocities are encoded

$$\dot{v} \sim 10^{-1} \sim \frac{q}{m_N}$$

Galilean invariant effective theory

- The most general Hermitian WIMP-nucleon interaction can be constructed from the for variables

$$\vec{S}_\chi \quad \vec{S}_N \quad \vec{v}^\perp \quad \frac{q}{m_N}$$

- This interaction (filter #1) can be constructed to 2nd in velocities

$$
\begin{aligned}
H_{ET} = & \left[a_1 + a_2\, \vec{v}^\perp \cdot \vec{v}^\perp + a_5\, i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)\right] + \vec{S}_N \cdot \left[a_3\, i\frac{\vec{q}}{m_N} \times \vec{v}^\perp + a_4\, \vec{S}_\chi + a_6\, \frac{\vec{q}}{m_N}\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \\
+ & \left[a_8\, \vec{S}_\chi \cdot \vec{v}^\perp\right] + \vec{S}_N \cdot \left[a_7\, \vec{v}^\perp + a_9\, i\frac{\vec{q}}{m_N} \times \vec{S}_\chi\right] \qquad \text{(parity odd)} \\
+ & \left[a_{11}\, i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] + \vec{S}_N \cdot \left[a_{10}\, i\frac{\vec{q}}{m_N} + a_{12}\, \vec{v}^\perp \times \vec{S}_\chi\right] \qquad \text{(time and parity odd)} \\
+ & \vec{S}_N \cdot \left[a_{13}\, i\frac{\vec{q}}{m_N}\vec{S}_\chi \cdot \vec{v}^\perp + a_{14}\, i\vec{v}^\perp\, \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \qquad \text{(time odd)}
\end{aligned}
$$

The coefficients represent the information that survive at low energy from a semi-infinite set of high-energy theories

Galilean invariant effective theory

- The most general Hermitian WIMP-nucleon interaction can be constructed from the for variables

$$\vec{S}_\chi \quad \vec{S}_N \quad \vec{v}^\perp \quad \frac{q}{m_N}$$

(previous physics argument defines this dimensionless parameter)

- This interaction (filter #1) can be constructed to 2nd in velocities

$$\begin{aligned}
H_{ET} = \; & \left[a_1 + a_2\, \vec{v}^\perp \cdot \vec{v}^\perp + a_5\, i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)\right] + \vec{S}_N \cdot \left[a_3\, i\frac{\vec{q}}{m_N} \times \vec{v}^\perp + a_4\, \vec{S}_\chi + a_6\, \frac{\vec{q}}{m_N}\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \\
+ \; & \left[a_8\, \vec{S}_\chi \cdot \vec{v}^\perp\right] + \vec{S}_N \cdot \left[a_7\, \vec{v}^\perp + a_9\, i\frac{\vec{q}}{m_N} \times \vec{S}_\chi\right] \qquad \text{(parity odd)} \\
+ \; & \left[a_{11}\, i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] + \vec{S}_N \cdot \left[a_{10}\, i\frac{\vec{q}}{m_N} + a_{12}\, \vec{v}^\perp \times \vec{S}_\chi\right] \qquad \text{(time and parity odd)} \\
+ \; & \vec{S}_N \cdot \left[a_{13}\, i\frac{\vec{q}}{m_N}\vec{S}_\chi \cdot \vec{v}^\perp + a_{14}\, i\vec{v}^\perp\, \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \qquad \text{(time odd)}
\end{aligned}$$

The coefficients represent the information that survive at low energy from a semi-infinite set of high-energy theories

- We can then embed this in the nucleus (filter #2) to find what information survives, accessible to experiment.

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2})\; W_i(q^2 b^2)$$

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WIMP tensor:
contains all of the DM particle physics

depends on two "velocities"

$$\vec{v}^{\perp\,2} \sim 10^{-6} \qquad \frac{\vec{q}}{m_N}^{2} \sim \langle v_{\rm internucleon}\rangle^2 \sim 10^{-2}$$

- We can then embed this in the nucleus (filter #2) to find what information survives, accessible to experiment.

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2}) \, W_i(q^2 b^2)$$

Nuclear tensor:
"nuclear knob" that can be turned by the experimentalists to deconstruct dark matter

Game - vary the W_i to determine the R_i: change the nuclear charge, spin, isospin, and any other relevant nuclear properties that can help

- What does the effective theory say about these responses?

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\, 2}, \frac{\vec{q}^{\,2}}{m_N^2})\; W_i(q^2 b^2)$$

$$W_1 \sim \langle J| \; \sum_{i=1}^{A} 1(i) \; |J\rangle^2$$

take q→0,
suppress isospin

the S.I. response

contributes for J=0 nuclear targets

- What does the effective theory say about these responses?

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2})\ W_i(q^2 b^2)$$

take q→0,
suppress isospin

$$W_2 \sim \langle J|\ \sum_{i=1}^{A} \hat{q}\cdot\vec{\sigma}(i)\ |J\rangle^2$$

$$W_3 \sim \langle J|\ \sum_{i=1}^{A} \hat{q}\times\vec{\sigma}(i)\ |J\rangle^2$$

the S.D. response (J>0) ....
but split into two components, as the longitudinal and transverse responses are independent, coupled to different particle physics

- What does the effective theory say about these responses?

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2}) \, W_i(q^2 b^2)$$

take q→0,
suppress isospin

$$W_4 \sim \frac{q^2}{m_N^2} \langle J| \sum_{i=1}^{A} \vec{\ell}(i) \; |J\rangle^2$$

A second type of vector (requires J>0) response, with selection rules very different from the spin response

- What does the effective theory say about these responses?

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2}) \; W_i(q^2 b^2)$$

take q→0,
suppress isospin

$$W_5 \sim \frac{q^2}{m_N^2} \langle J | \;\sum_{i=1}^{A} \vec{\sigma}(i) \cdot \vec{\ell}(i)\; | J \rangle^2$$

A second type of scalar response, with coherence properties very different from the simple charge operator

- What does the effective theory say about these responses?

$$\frac{d\sigma}{dE_R} \sim G_F^2 \sum_i R_i(\vec{v}^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2})\, W_i(q^2 b^2)$$

$$W_6 \sim \frac{q^2}{m_N^2} \langle J|\ \sum_{i=1}^{A} \left[\vec{r}(i) \otimes \left(\vec{\sigma}(i) \times \frac{1}{i} \vec{\nabla}(i) \right)_1 \right]_2\ |J\rangle^2$$

A exotic tensor response: in principle interactions can be constructed where no elastic scattering occurs unless J is at least 1

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

↑ Full responses: operators familiar from standard semileptonic weak interactions

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

↑ consistent with our symmetry arguments ↑

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

Two interference terms: M - L

T^{el5} - T^{mag} just as in neutrino scattering

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} \sim \frac{4\pi}{2J_i+1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \Bigg\{ & R_C^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i || \, M_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, M_{J;\tau'}(q) \, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_L^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i || \, \Phi''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Phi''_{J;\tau'}(q) \, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{L/C}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i || \, \Phi''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, M_{J;\tau'}(q) \, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{el}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=2,4,\ldots}^{\infty} \langle J_i || \, \tilde{\Phi}'_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \tilde{\Phi}'_{J;\tau'}(q) \, || J_i \rangle \\
& + R_{L^5}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i || \, \Sigma''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma''_{J;\tau'}(q) \, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i || \, \Delta_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Delta_{J;\tau'}(q) \, || J_i \rangle \\
& + R_{T^{el5}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i || \, \Sigma'_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma'_{J;\tau'}(q) \, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}/T^{el5}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i || \, \Delta_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma'_{J;\tau'}(q) \, || J_i \rangle \Bigg\}
\end{aligned}
$$

experimentalists have all of these nuclear “knobs” to turn

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} \sim \frac{4\pi}{2J_i+1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \Bigg\{ & R_C^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i ||\, M_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, M_{J;\tau'}(q)\, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_L^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i ||\, \Phi''_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \Phi''_{J;\tau'}(q)\, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{L/C}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=0,2,\ldots}^{\infty} \langle J_i ||\, \Phi''_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, M_{J;\tau'}(q)\, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{el}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=2,4,\ldots}^{\infty} \langle J_i ||\, \tilde{\Phi}'_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \tilde{\Phi}'_{J;\tau'}(q)\, || J_i \rangle \\
& + R_{L^5}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i ||\, \Sigma''_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \Sigma''_{J;\tau'}(q)\, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i ||\, \Delta_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \Delta_{J;\tau'}(q)\, || J_i \rangle \\
& + R_{T^{el5}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i ||\, \Sigma'_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \Sigma'_{J;\tau'}(q)\, || J_i \rangle \\
& + \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}/T^{el5}}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) \sum_{J=1,3,\ldots}^{\infty} \langle J_i ||\, \Delta_{J;\tau}(q)\, || J_i \rangle \langle J_i ||\, \Sigma'_{J;\tau'}(q)\, || J_i \rangle \Bigg\}
\end{aligned}
$$

to extract the low-energy DM information embedded in the DM responses

The coefficients are what one "measures." They define the particle physics that can be mapped back to high energies, to constrain models

$$R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

$$R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{\vec{q}^{\,2}}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right)$$

$$R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'}$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{\vec{q}^{\,2}}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^{\,4}}{m_N^4} c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{1}{8}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^{\,2}}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right]$$

$$R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right]$$

$$R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].$$

The point-nucleus world is a very simple one

Generally any derivative coupling is seen most easily in the new responses

$$
\begin{aligned}
R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right] \\
R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{\vec{q}^{\,2}}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right) \\
R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'} \\
R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{\vec{q}^{\,2}}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^{\,2}}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^{\,4}}{m_N^4} c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{1}{8}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^{\,2}}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^{\,2}}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right] \\
R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right] \\
R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].
\end{aligned}
$$

Observations:

- The set of operators found here map on to the ones necessary in describing *known* SM electroweak interactions

- ES can in principle give us 8 constraints on DM interactions

- This argues for a variety of detectors - or at least, continued development of a variety of detector technologies: G2???

- There are a significant number of relativistic operators that reduce in leading order to the new operators

- Power counting -- e.g., $1 \text{ vs } q/m_N$ -- does not always work as the associated dimensionless operator matrix elements differ widely
    - examples can be given

- As noted before velocity-dependent interactions will generate a SI or SD coupling, but proportional to $\vec{v}^{\perp 2}$ and misleading
    - the predicted strength is 10^{-4} the actual strength
    - the associated SI/SD operator will have the wrong rank, e.g., predicted small SI when the dominant contribution is "spin"-dependent (e.g., governed by $\vec{\ell}(i)$)

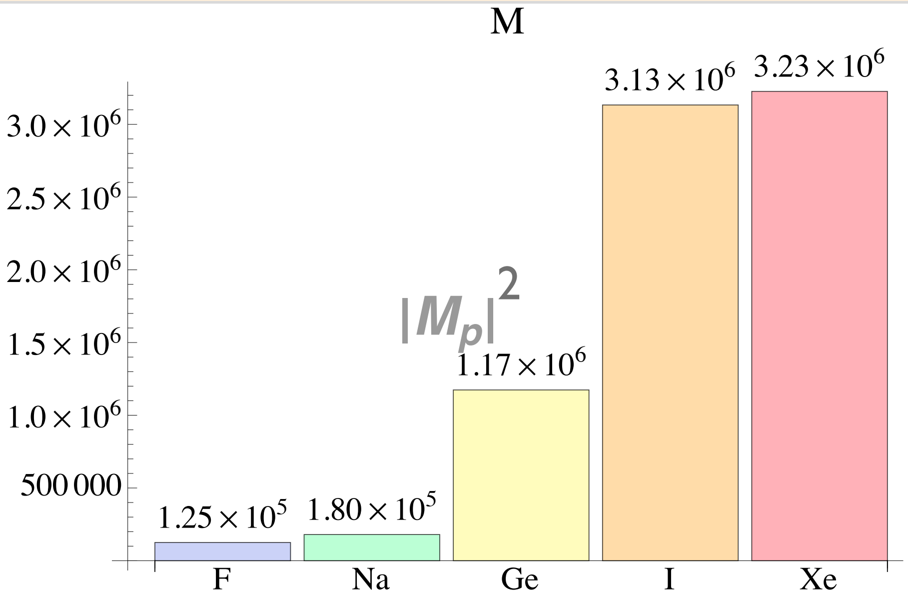
Could be really confusing!

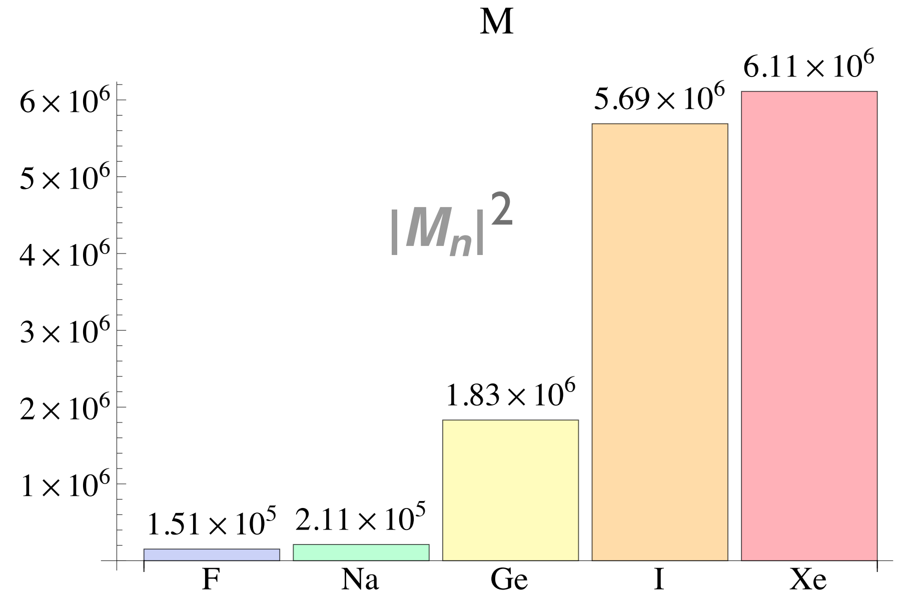
For illustration purposes only!

DAMA/LIBRA:	NaI
CoGENT:	Ge
LUX:	Xe

scalar charge responses: p vs. n S.I.

(normalized to natural abundance)

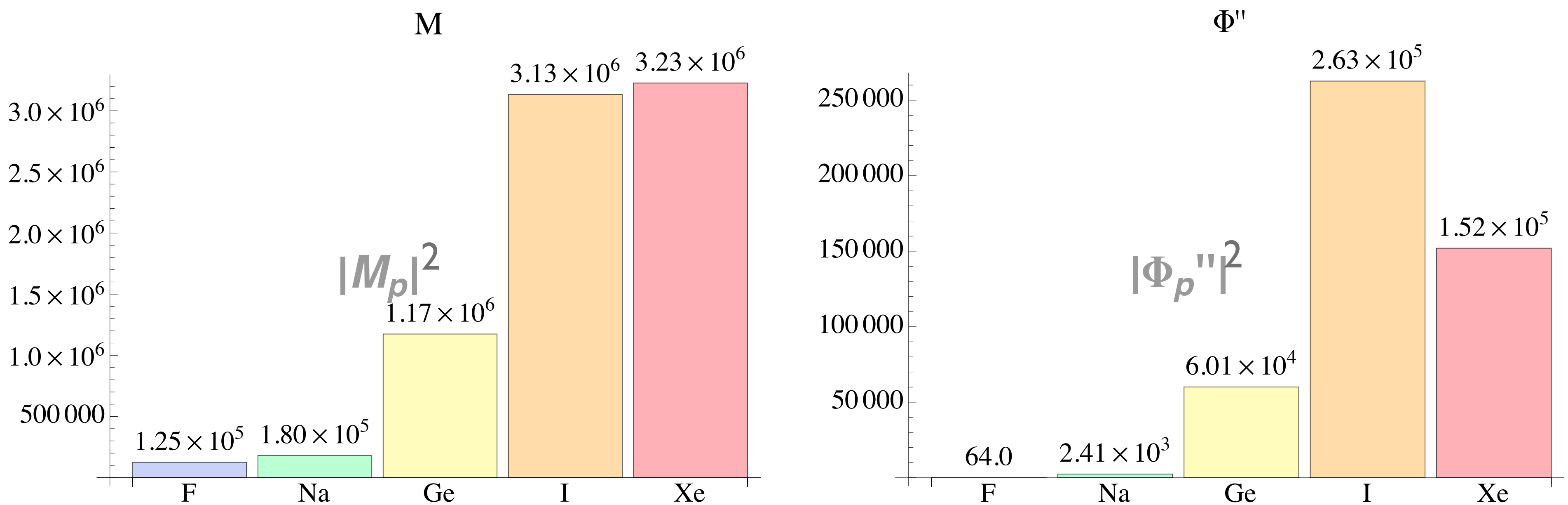




Standard SI sensitivities: LUX (Xe) > DAMA (NaI) > CDMS-Ge

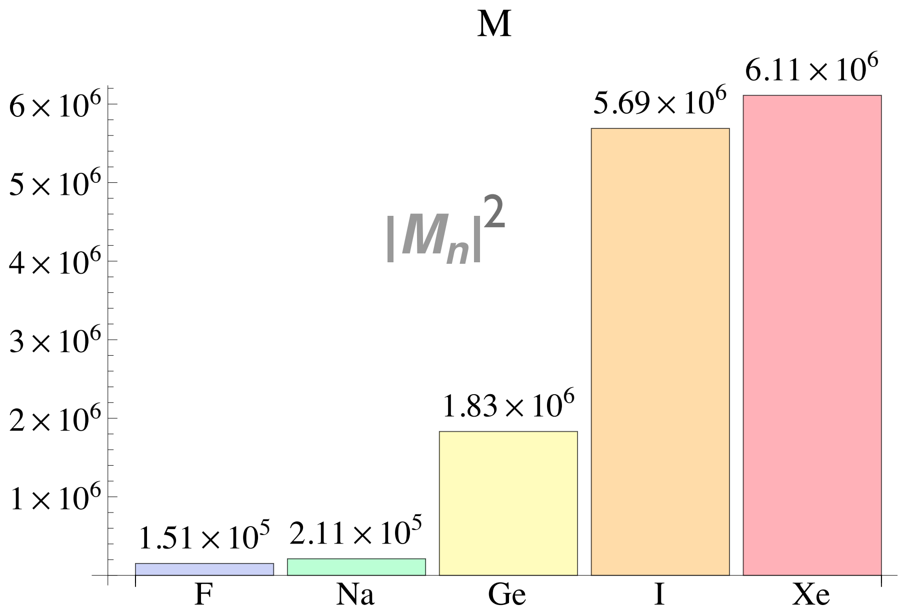
Little sensitivity to isospin (unless tuned)

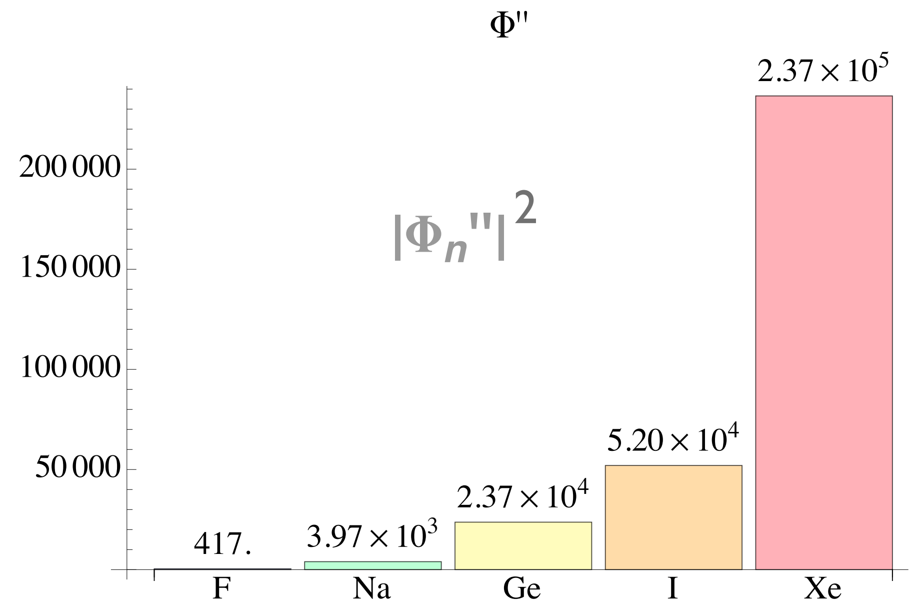
Scalar operators, p: $1(i)$ vs $\vec{\sigma}(i) \cdot \vec{\ell}(i)$



LUX (Xe) ~ DAMA (NaI) ⇒ DAMA > LUX

Scalar operators, n: $1(i)$ vs $\vec{\sigma}(i) \cdot \vec{\ell}(i)$

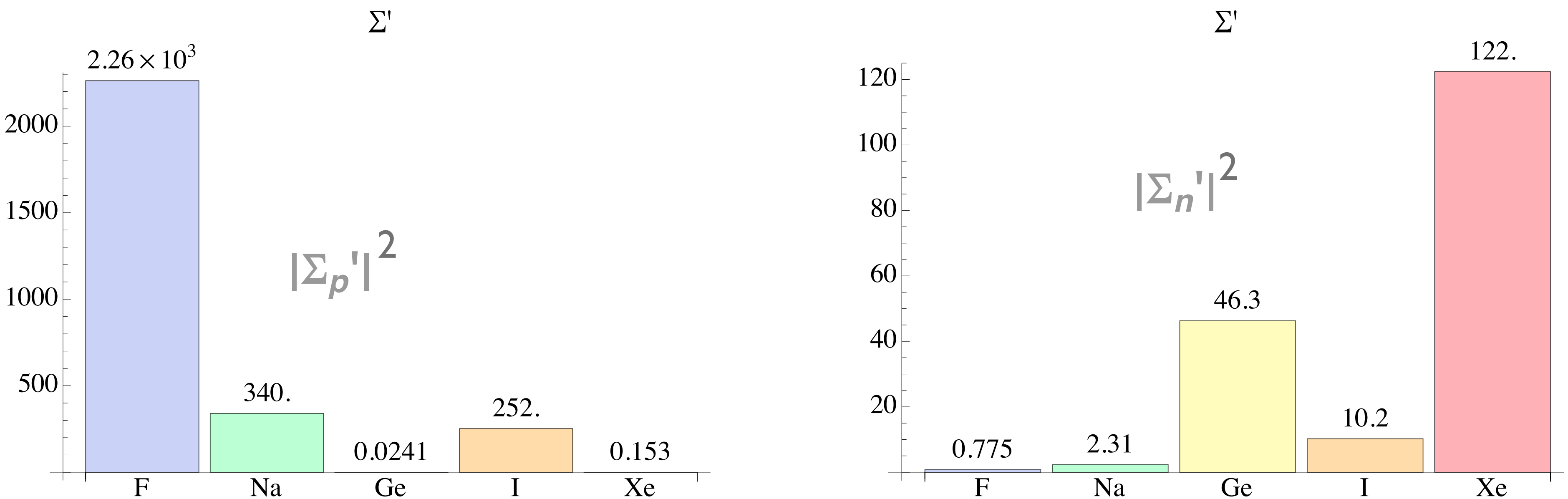




LUX (Xe) ~ DAMA (NaI) ⇒ DAMA < LUX

vector (transverse) spin response

(normalized to natural abundance)

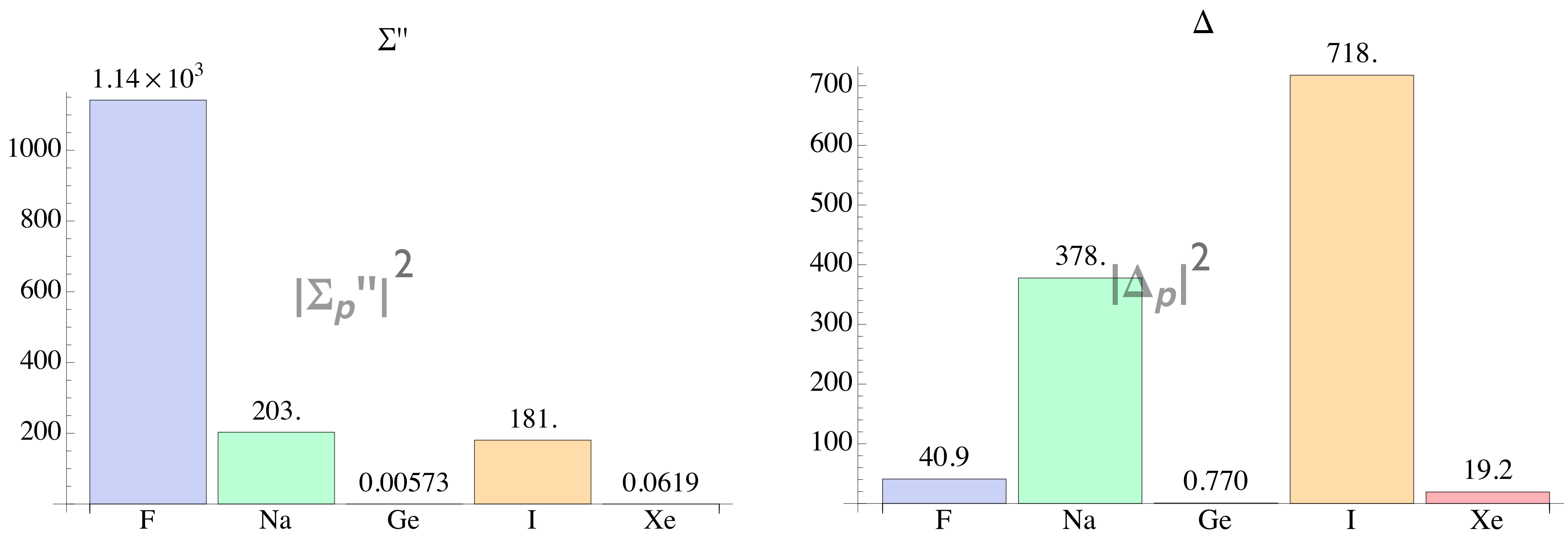


proton coupled: Picasso (F) > DAMA (NaI) ≫ CDMS-Ge & LUX

neutron coupled: LUX & CDMS-Ge ≫ DAMA ≫ Picasso

isospin

Vector, proton coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$

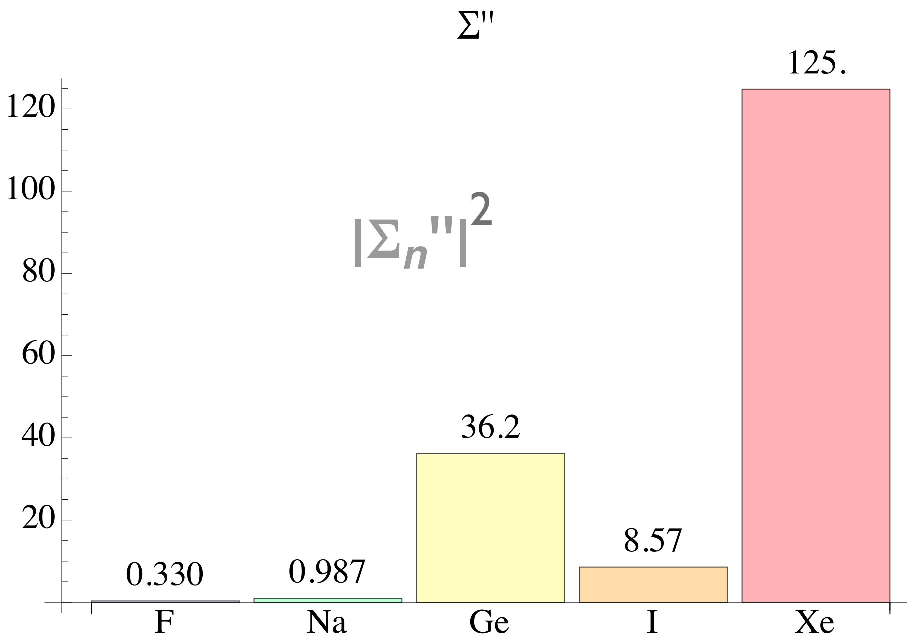


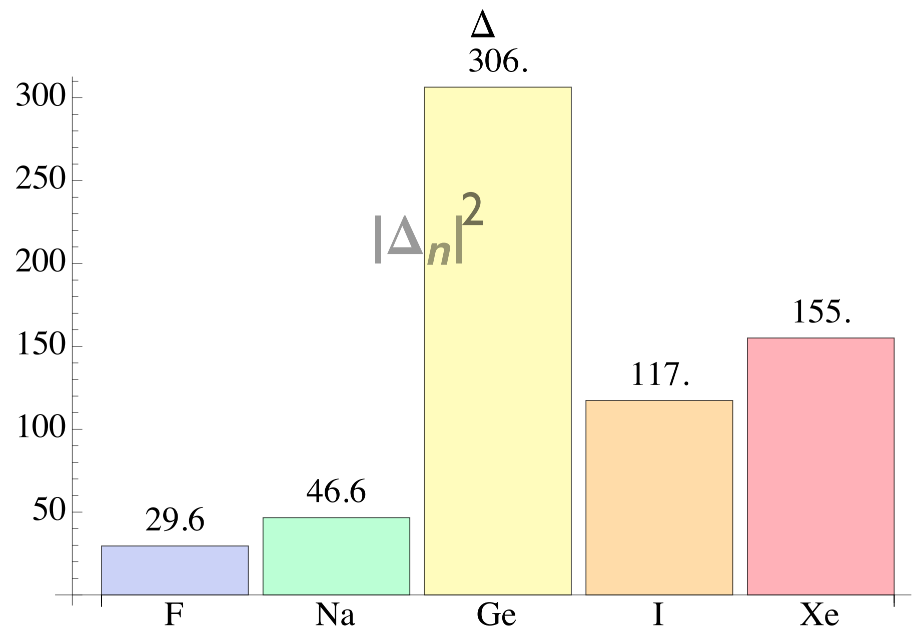
spin coupled: Picasso (F) > DAMA (NaI)

l-coupled coupled: DAMA (NaI) ≫ Picasso (F) F: $2s_{1/2}$

orbital vs. spin ambiguity

Vector, neutron coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$





spin coupled: LUX > CDMS-Ge ≫ DAMA

l-coupled coupled: CDMS-Ge > LUX ~ DAMA

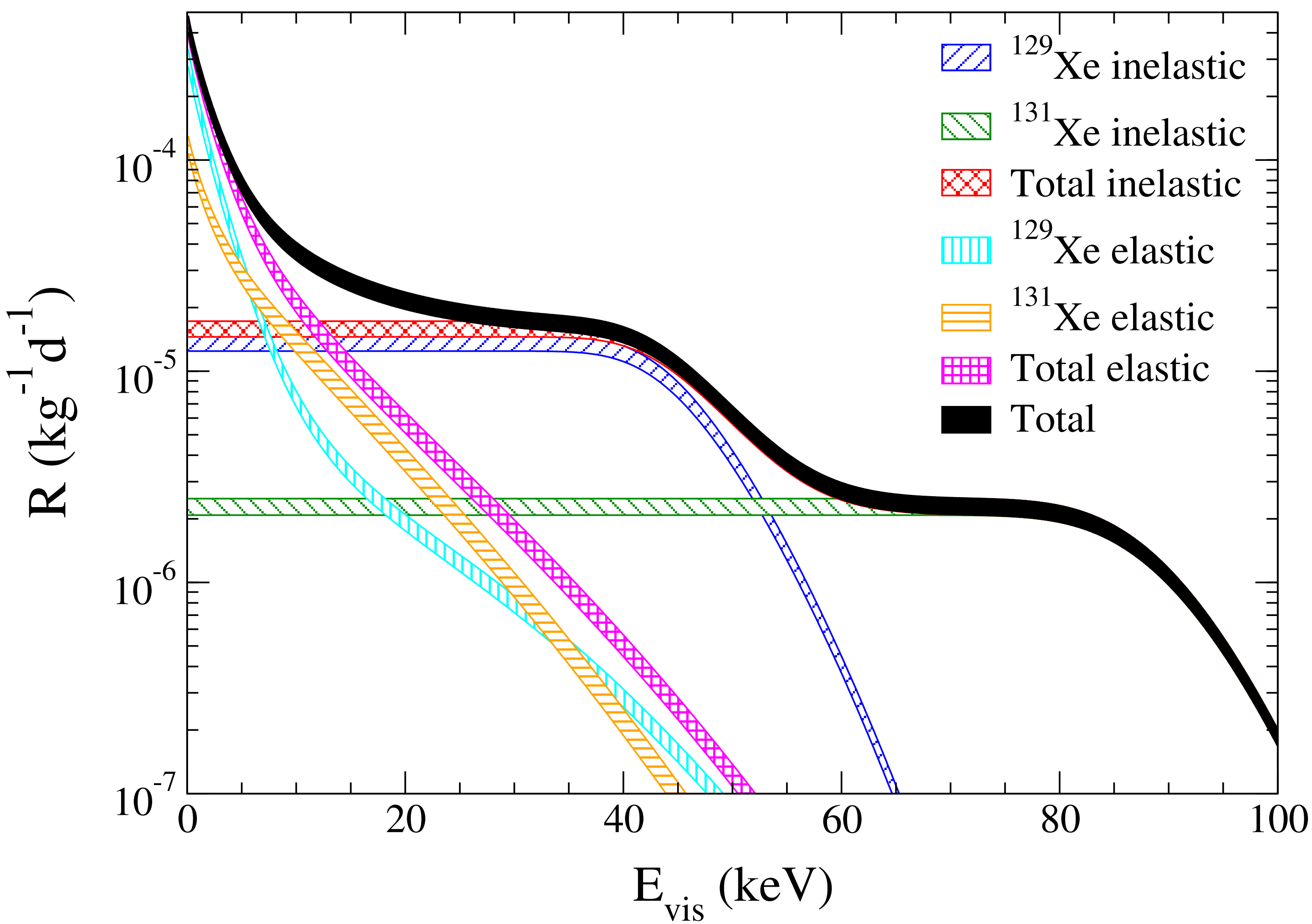
orbital vs. spin ambiguity

Note on inelastic excitations:

- Fortunate that key targets like Xe and Ge have unusual low-lying states: transitions can be inelastic

$^{129}Xe(1/2^+) \rightarrow {}^{129}Xe(3/2^+)$ 39.6 keV

$^{131}Xe(3/2^+) \rightarrow {}^{131}Xe(1/2^+)$ 80.2 keV



Baudis et al.

- Important because recoil energies for 100 GeV WIMP $\lesssim$ 250 keV

- Analyses again treated only in the SI/SD framework

- But we have seen that the elastic scattering "filter" is imposed by symmetry constraints of P and T: T does not constrain inelastic transitions

- There are familiar operators that effectively cannot contribute to elastic scattering, but can have large inelastic cross sections

  most familiar of these is the axial charge operator $\vec{\sigma}(i) \cdot \vec{p}(i)$

Summary

- There is a lot of variability that can be introduced between detector responses by altering operators (and their isospins)
- Pairwise exclusion of experiments in general difficult
- But the bottom line is a favorable one: there is a lot more that can be learned from elastic scattering experiments than is apparent in conventional analysis
- This suggests we should do more experiments, not fewer
- When the first signals are seen, things will get very interesting: those nuclei that do not show a signal may be as important as those that do

Thanks to my collaborators: Liam Fitzpatrick, Nikhil Anand, Ami Katz