Dark Matter Interactions with Nucleons and Nuclei

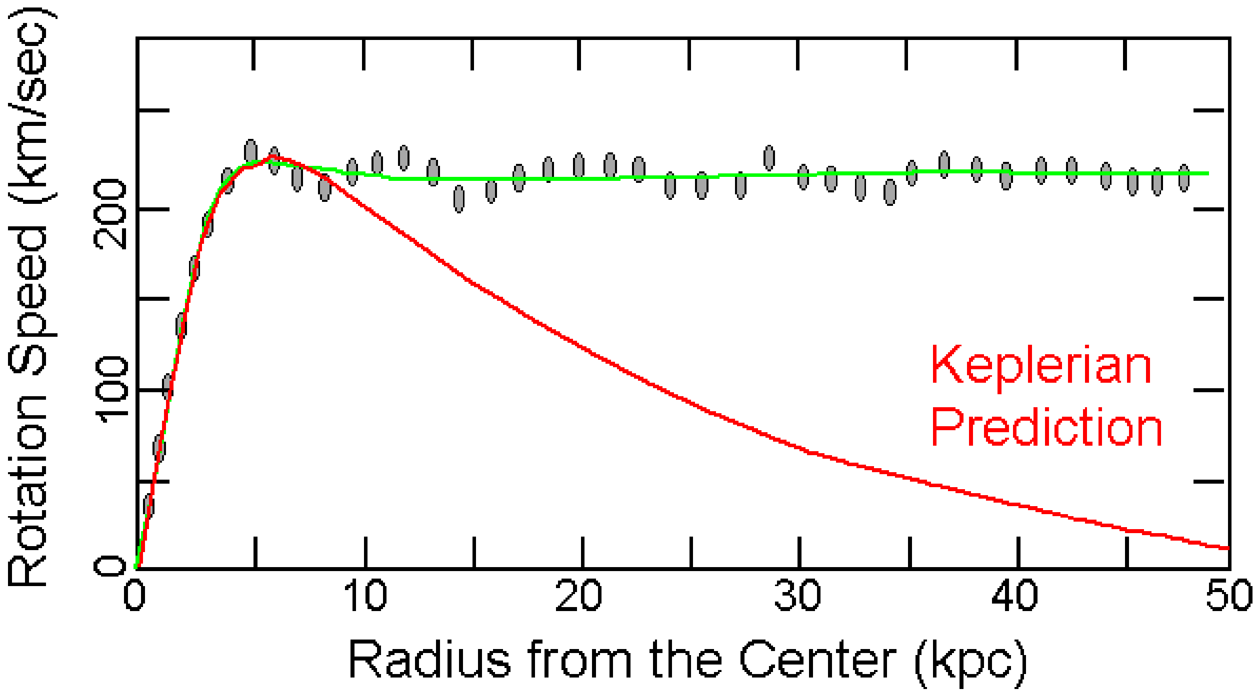
- *Dark Matter Basics*
- *Experimental status, post-LUX*
- *The nuclear effective interaction*

Wick Haxton *UCSC* *April 18, 2014*

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
- existence deduced from its dynamical effects in astrophysics
  - ▫ first discovered from the flat velocity rotation curves of galaxies
  - ▫ required in large-scale structure simulations, to produce the observed pattern of structure
  - ▫ baryon acoustic oscillations:

    Planck $\Omega_m = \Omega_B + \Omega_{DM} \sim 0.314 \pm 0.020$
  - ▫ in collisions of galaxy clusters, from the difference in the gravitating (lensing) and radiating matter distributions



$v \propto$ constant

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

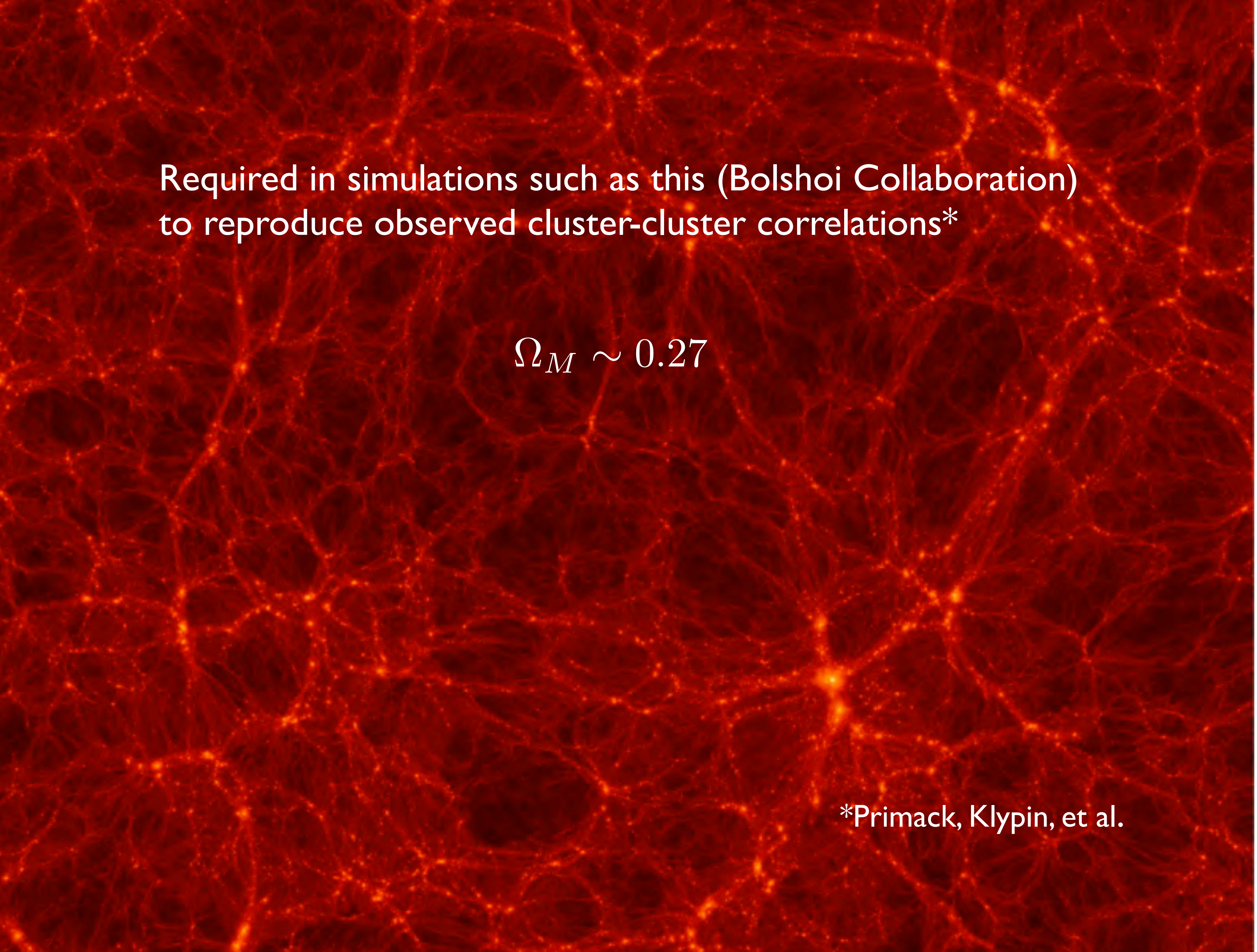
$\rho(r) \propto 1/r^2$

(flat rotation curve)

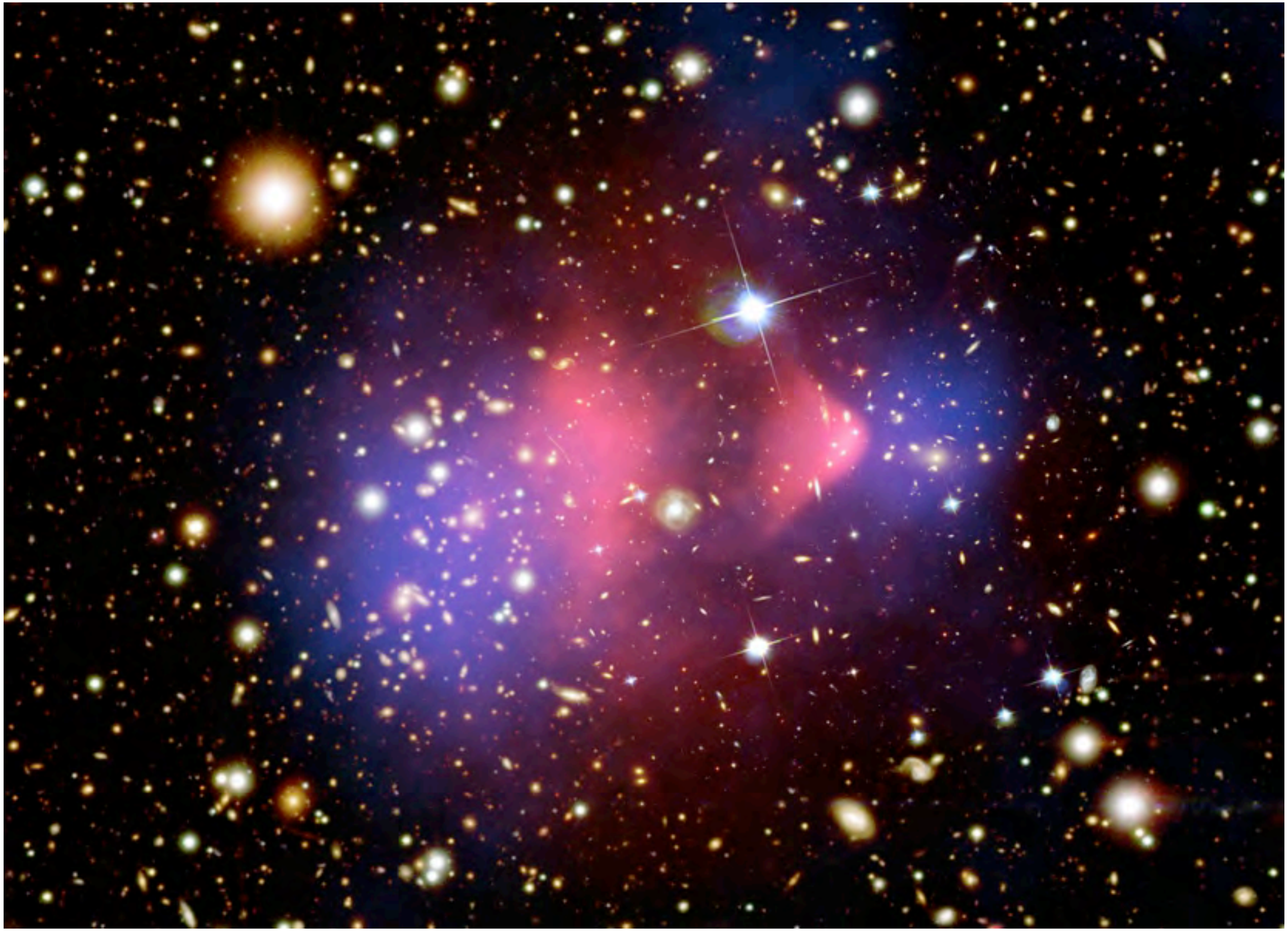
$\leftarrow v \propto 1/\sqrt{r}$

(gravitating central mass)

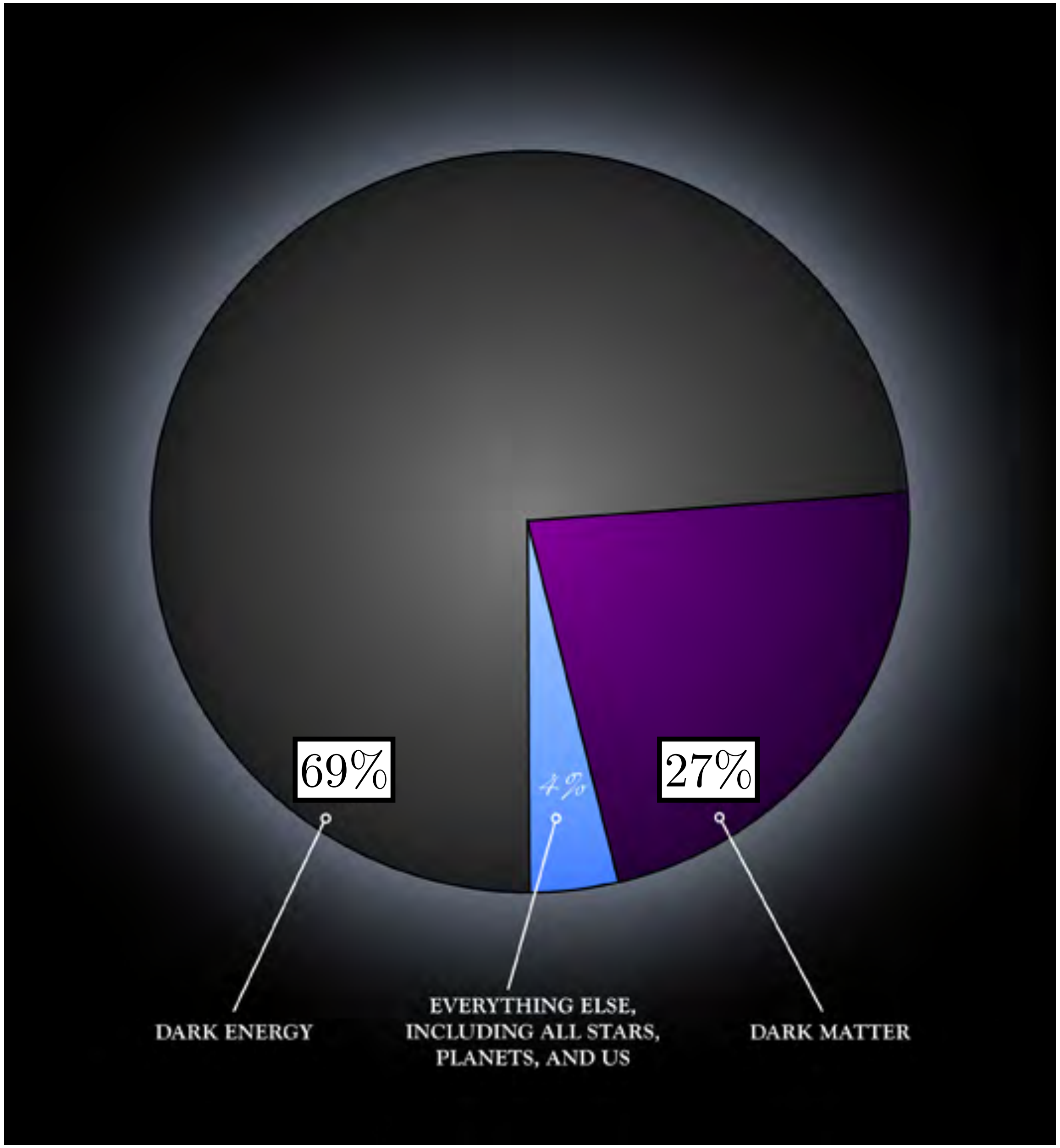
NGC-6384
(from HST)


Required in simulations such as this (Bolshoi Collaboration)
to reproduce observed cluster-cluster correlations*
$\Omega_M \sim 0.27$
*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



The inventory

There is a small, identified component from the standard model, massive neutrinos

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

Properties

- long-lived or stable
- cold or warm (slow enough to seed structure formation)
- gravitationally active
- lacks strong couplings to itself or to baryons

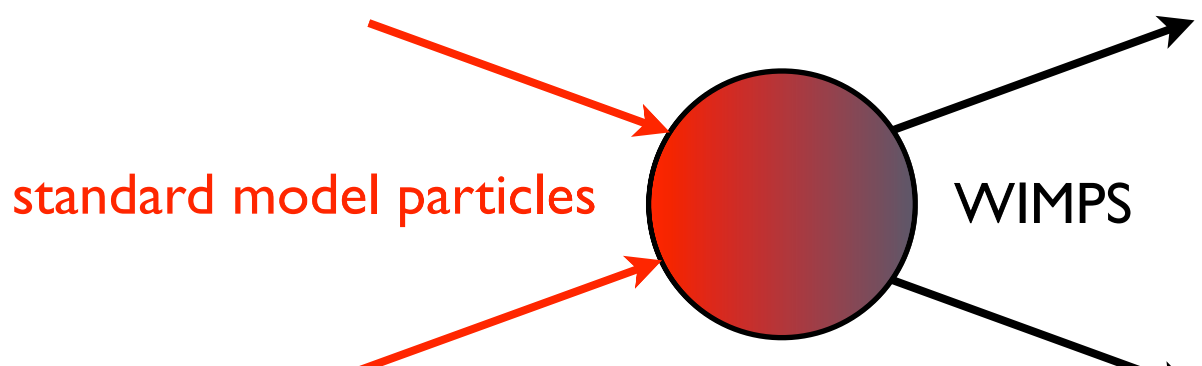
Leading candidates are weakly interacting massive particles (WIMPs) and axions

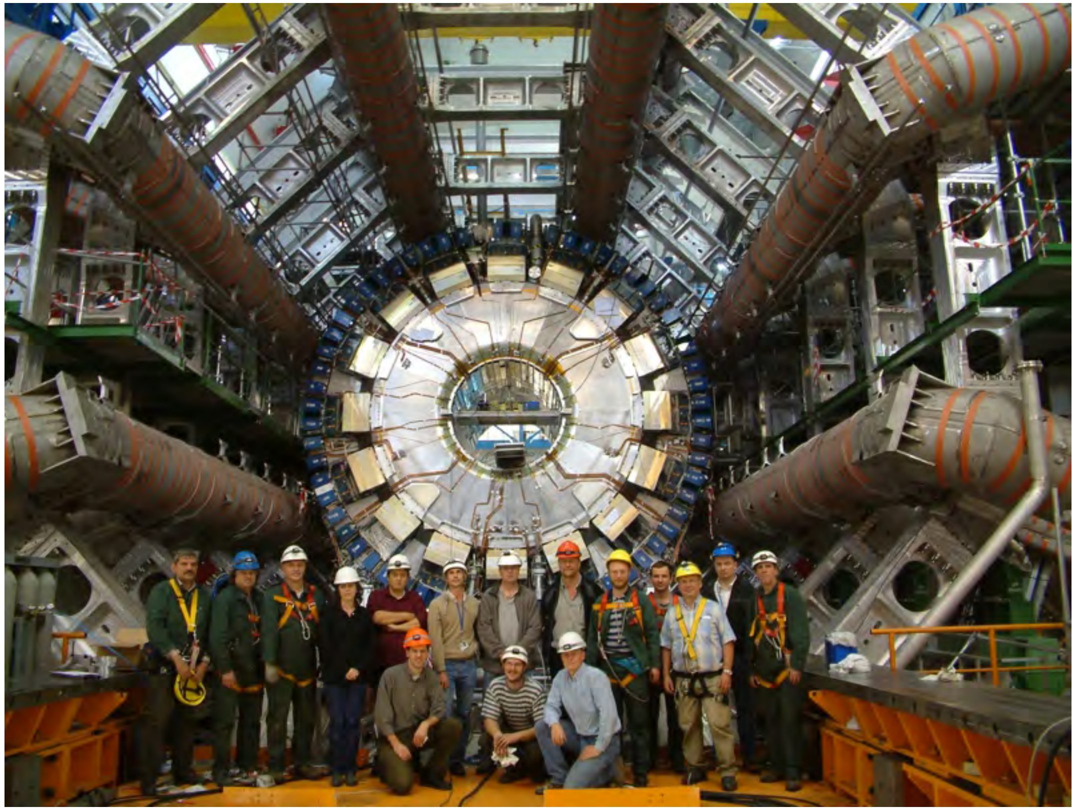
WIMPs motivated by the expectation that new physics might be found at the mass generation scale of the SM model: $M_{WIMP} \sim 10$ GeV - 10 TeV

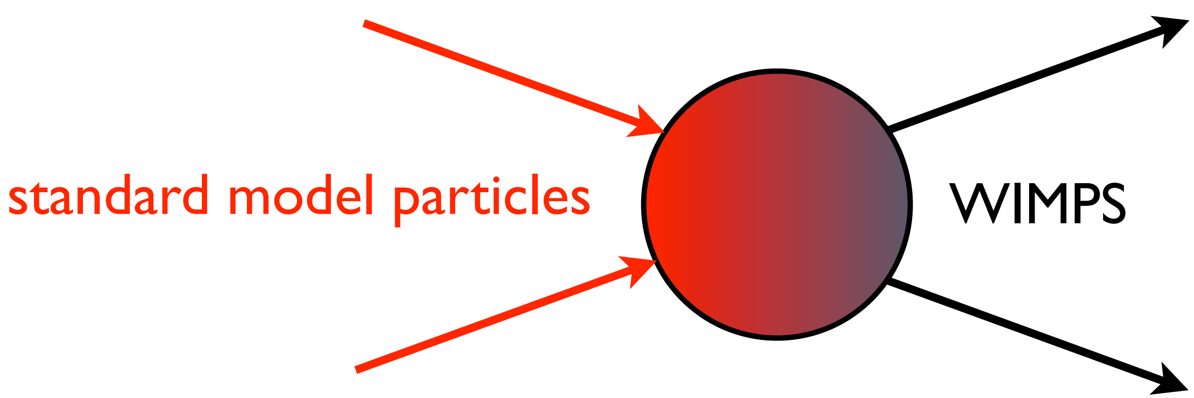
- "WIMP miracle:" G_F^2 annihilation cross sections imply $\Omega_{WIMP} \sim 0.1$

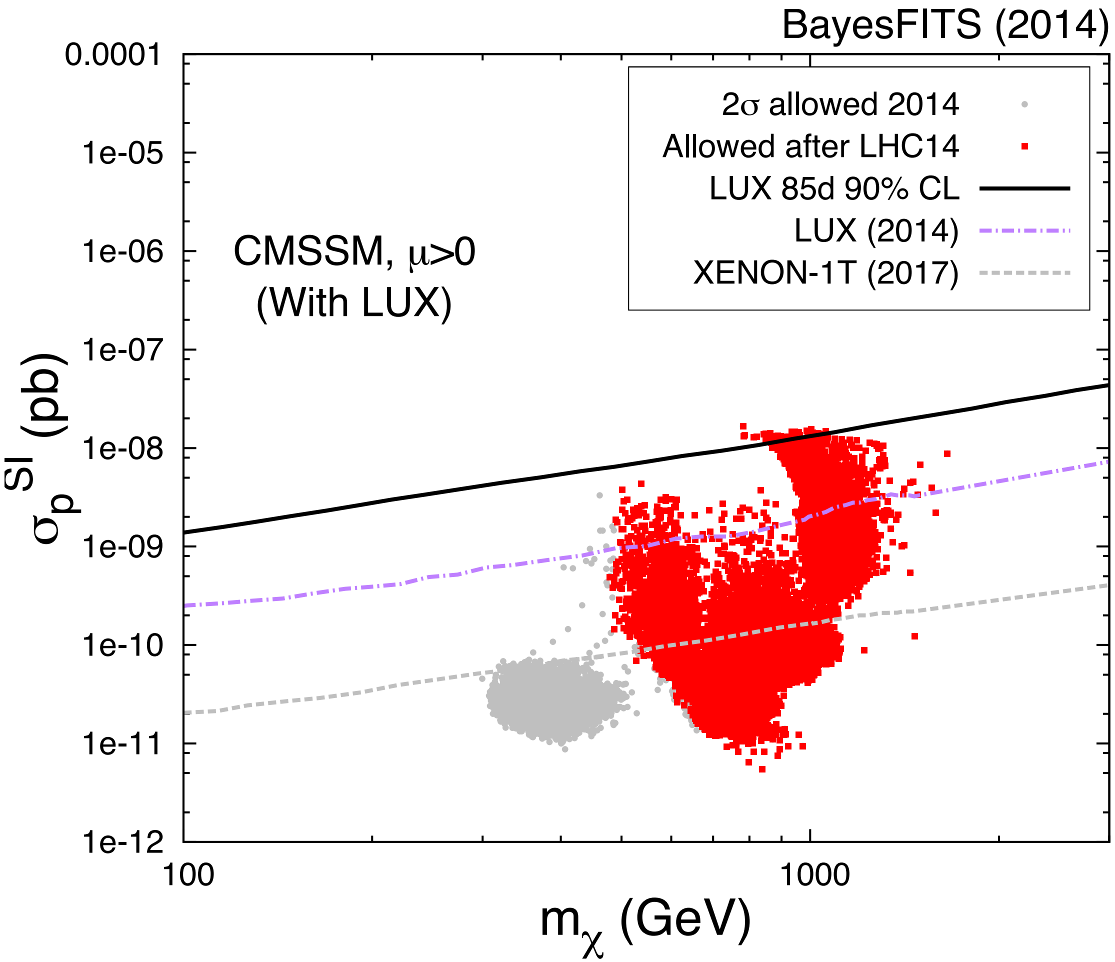
Detection: their detection channels include (other than large scale structure)

- collider searches

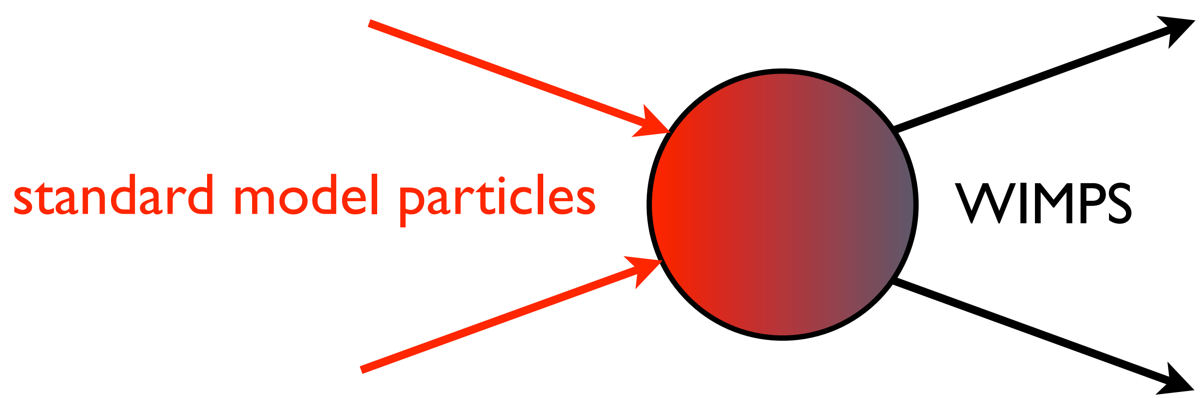





standard model particles
WIMPS



LHC second run starting in 2015 will extend collision energies to 14 TeV



From L. Roszkowski, DM@UCLA 2014

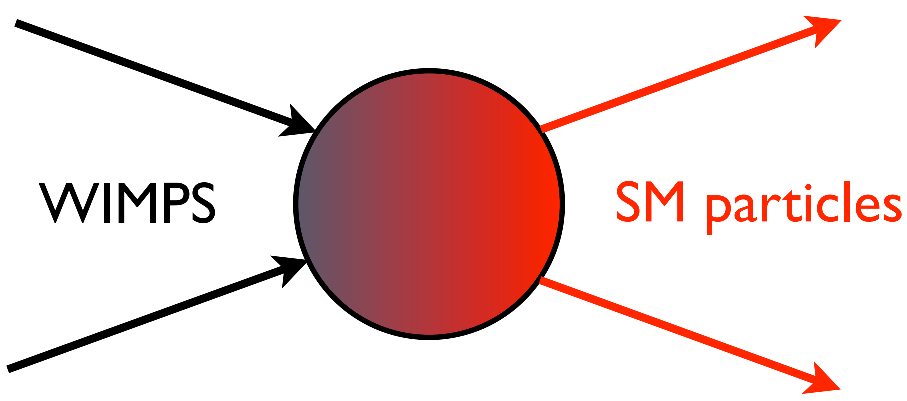
Detection: their detection channels include (other than large scale structure)

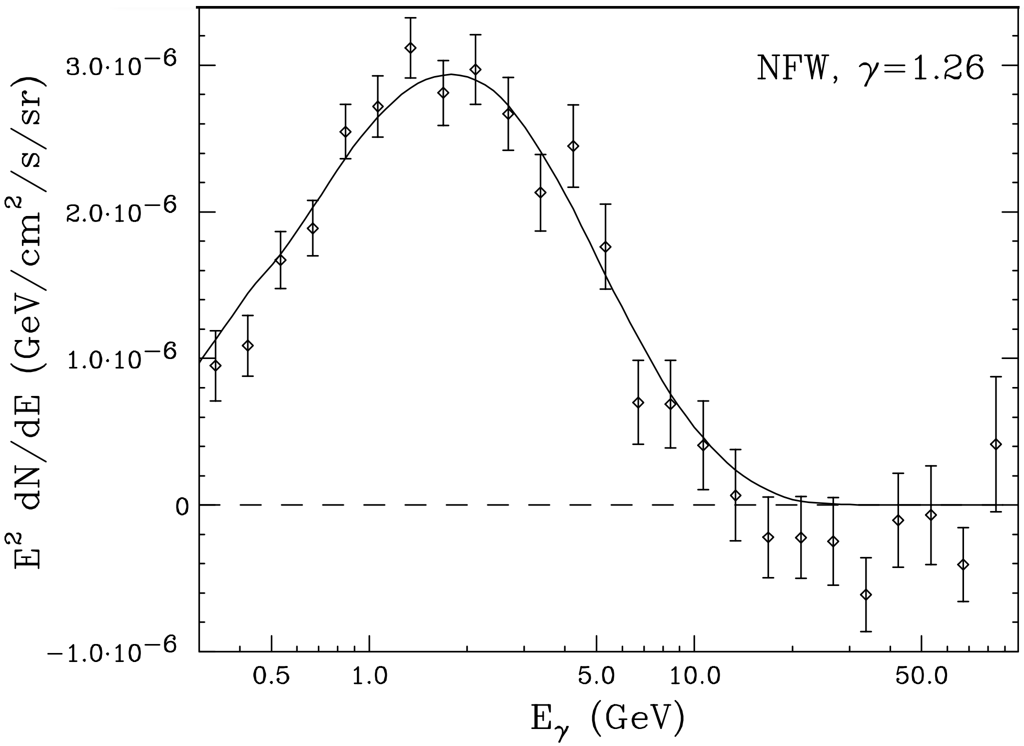
- collider searches
- indirect detection: astrophysical signals

Claim of a dark-matter annihilation signal at the galactic center, consistent with a DM signal with

$$\rho_{DM} \sim 1/r^{1.2}$$

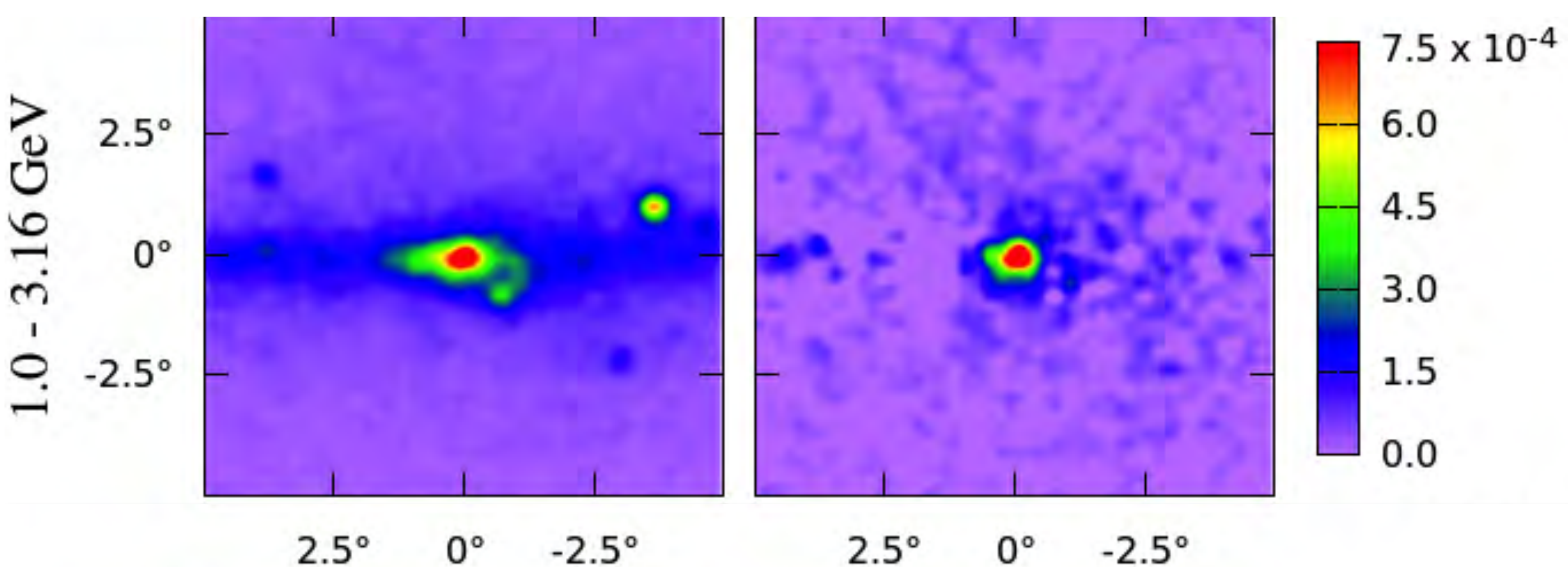
consistent with a ~ 30-40 GeV WIMP annihilating to b quarks, producing ~ 5 GeV gammas





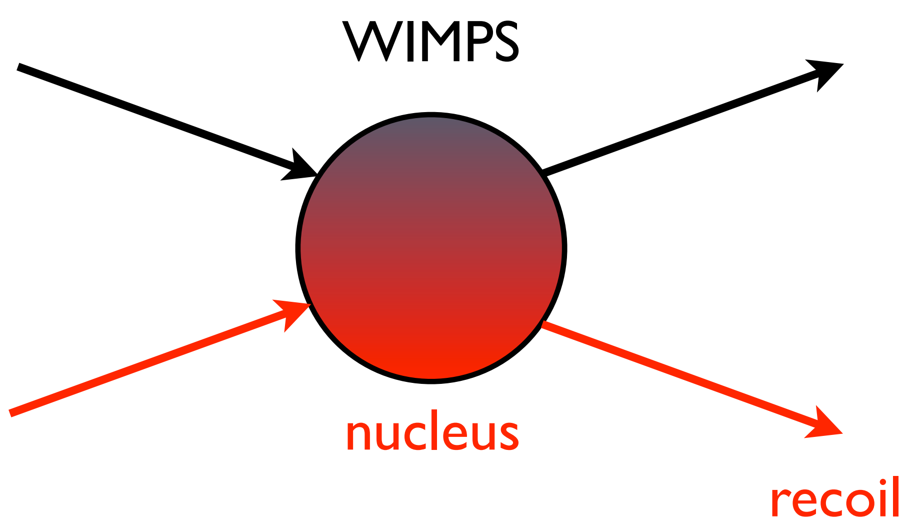
From D. Hooper, UCLA DM

(No such claim yet made by the Fermi collaboration)



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

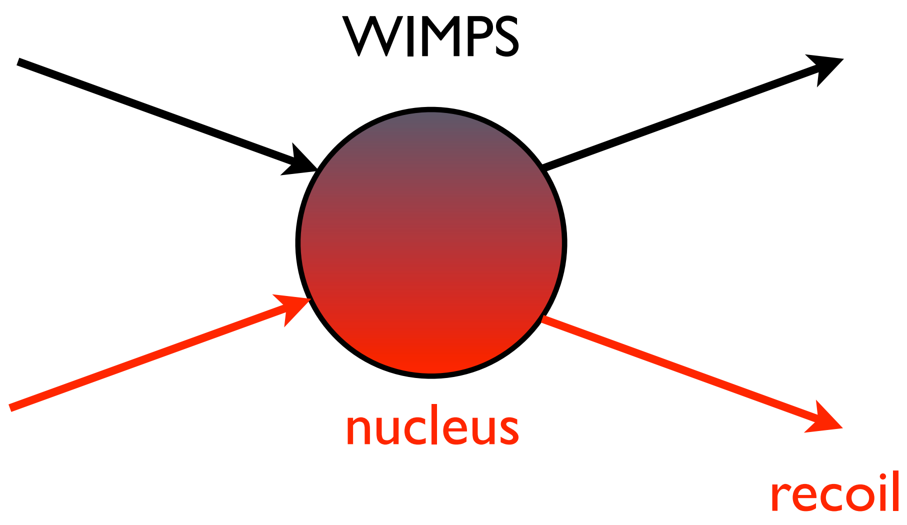
- collider searches
- indirect detection: astrophysical signals
- direct detection



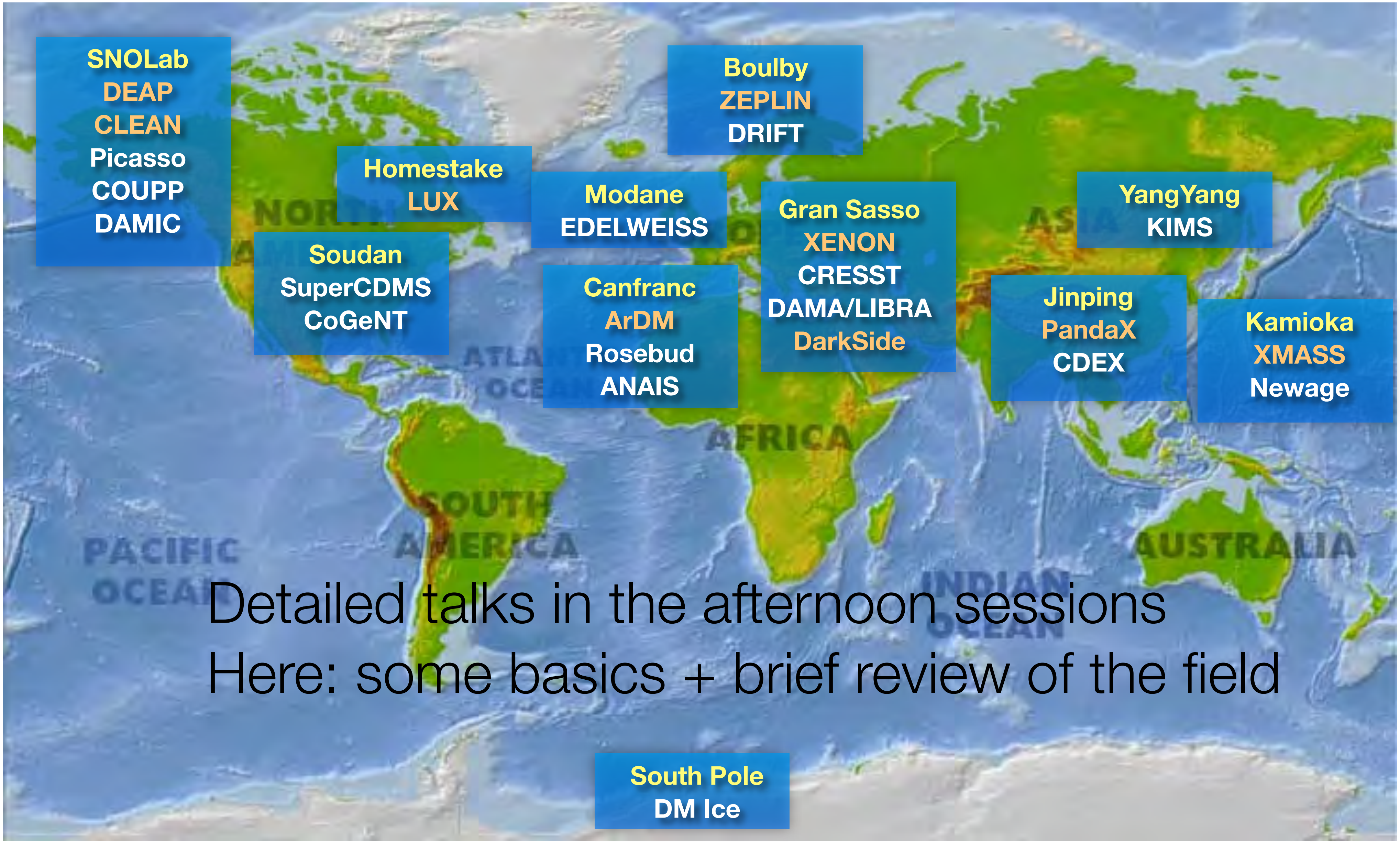
Detection: their detection channels include (other than large scale structure)

- collider searches
- indirect detection: astrophysical signals
- direct detection

Today's main topic



A world-wide effort to search for WIMPs



Detailed talks in the afternoon sessions

Here: some basics + brief review of the field

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
Te02:	CUORE
CaW04:	CRESST

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

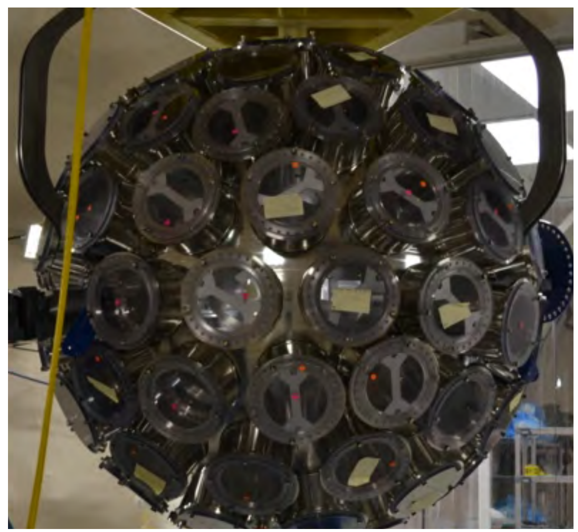
Noble Gasses

Single-phase detectors (scintillation light)

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

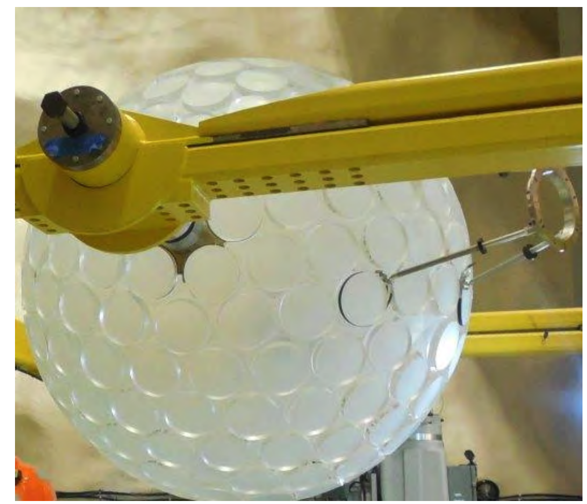
XMASS-RFB at Kamioka:

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



CLEAN at SNOLab:

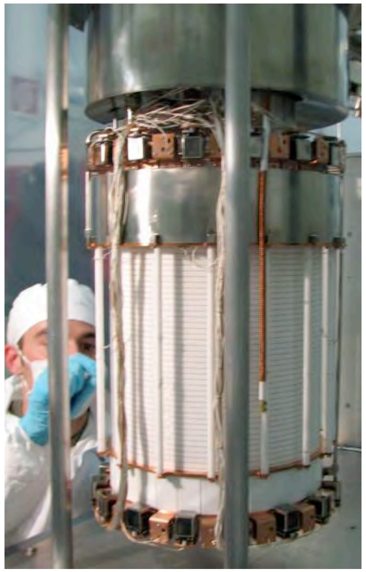
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014



DEAP at SNOLab:

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

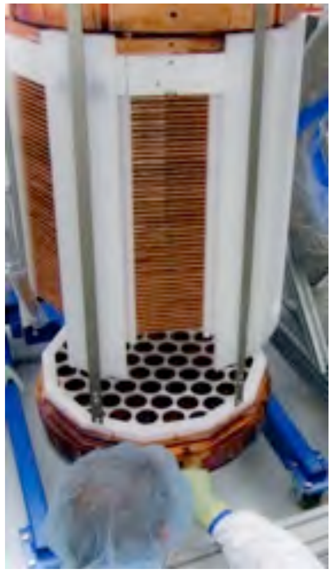
Time projection chambers (scintillation & ionization)



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)

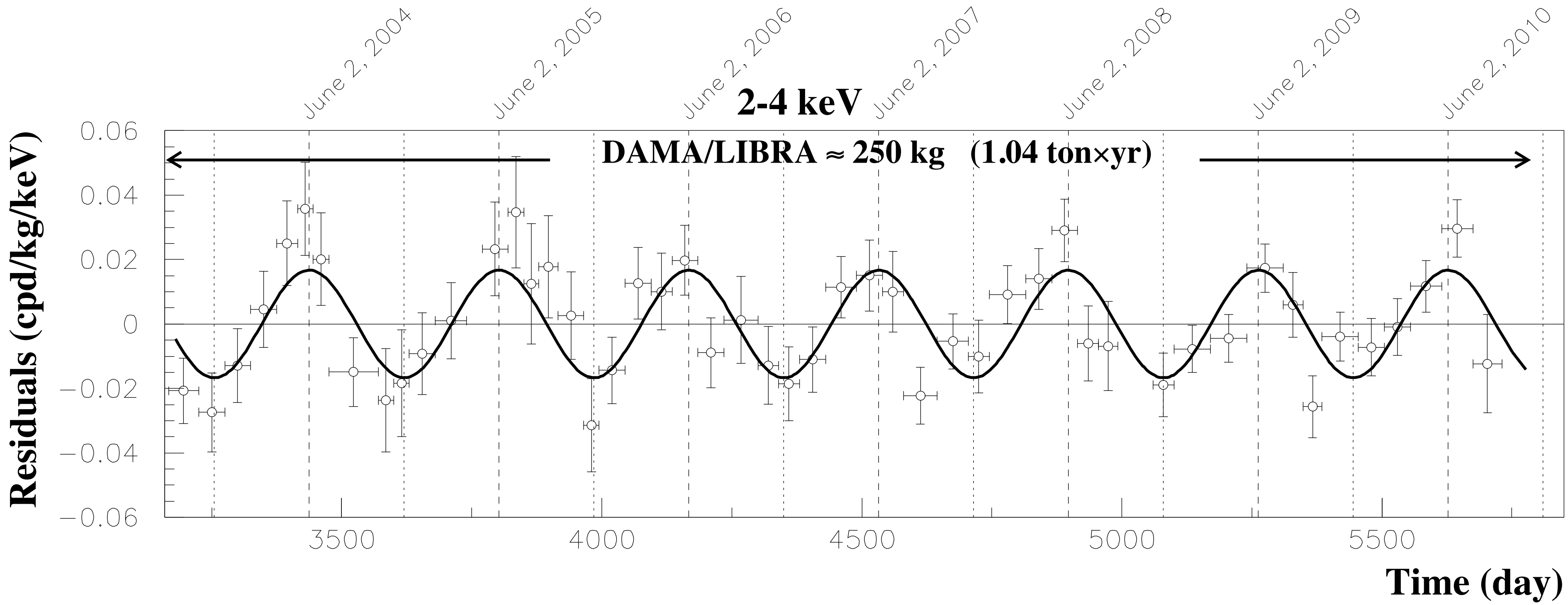
38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

Crystals, Bubble Chambers, ...

DAMA/LIBRA NaI

CDMS Si, Ge
CoGENT Ge

COUP CF_3I



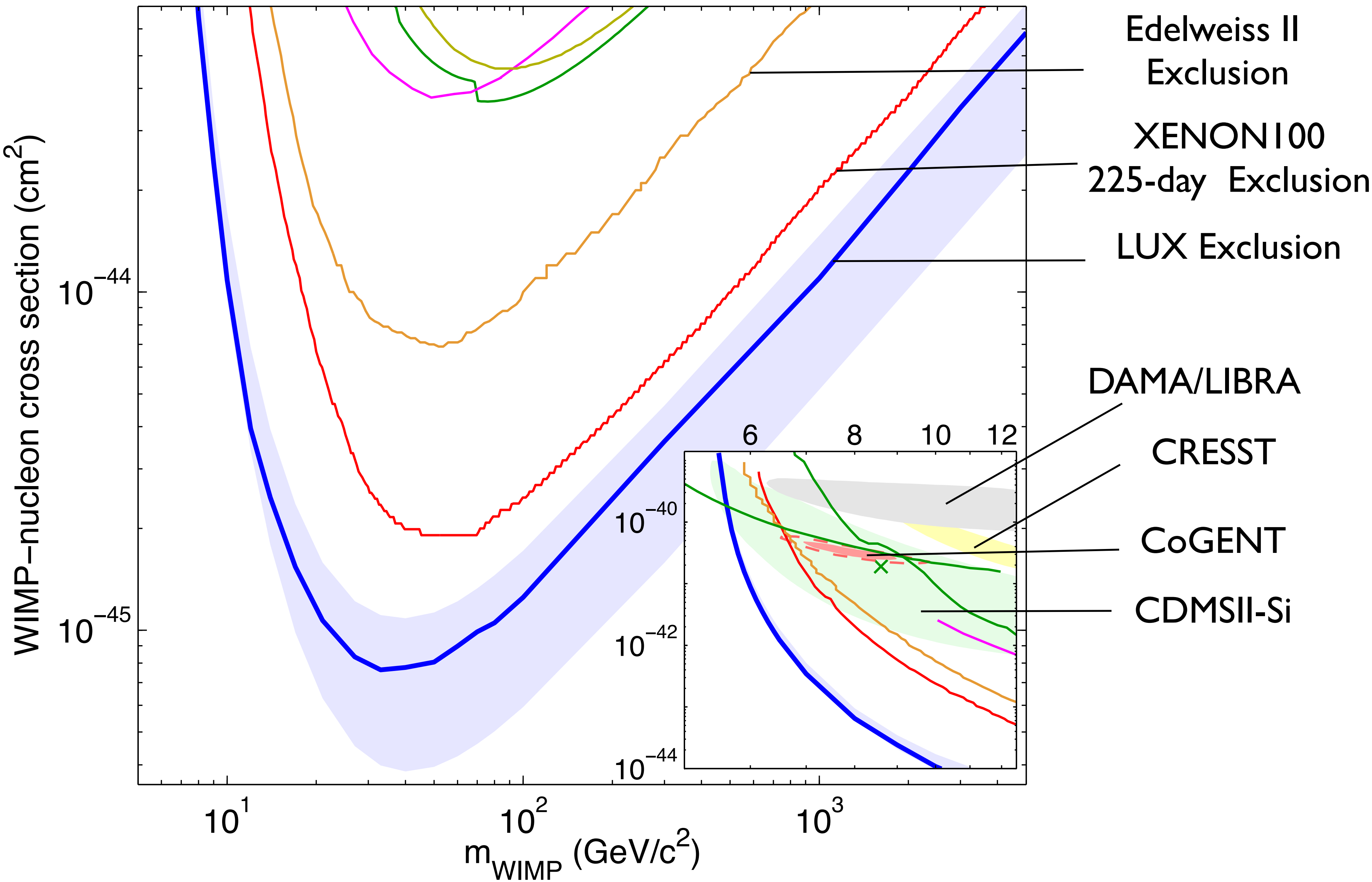
DAMA/LIBRA: 9.3σ variation of the signal over the year, attributed to the expected variation of a DM signal on the Earth's velocity due to rotation around the Sun

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

How are these comparisons among experiments done?

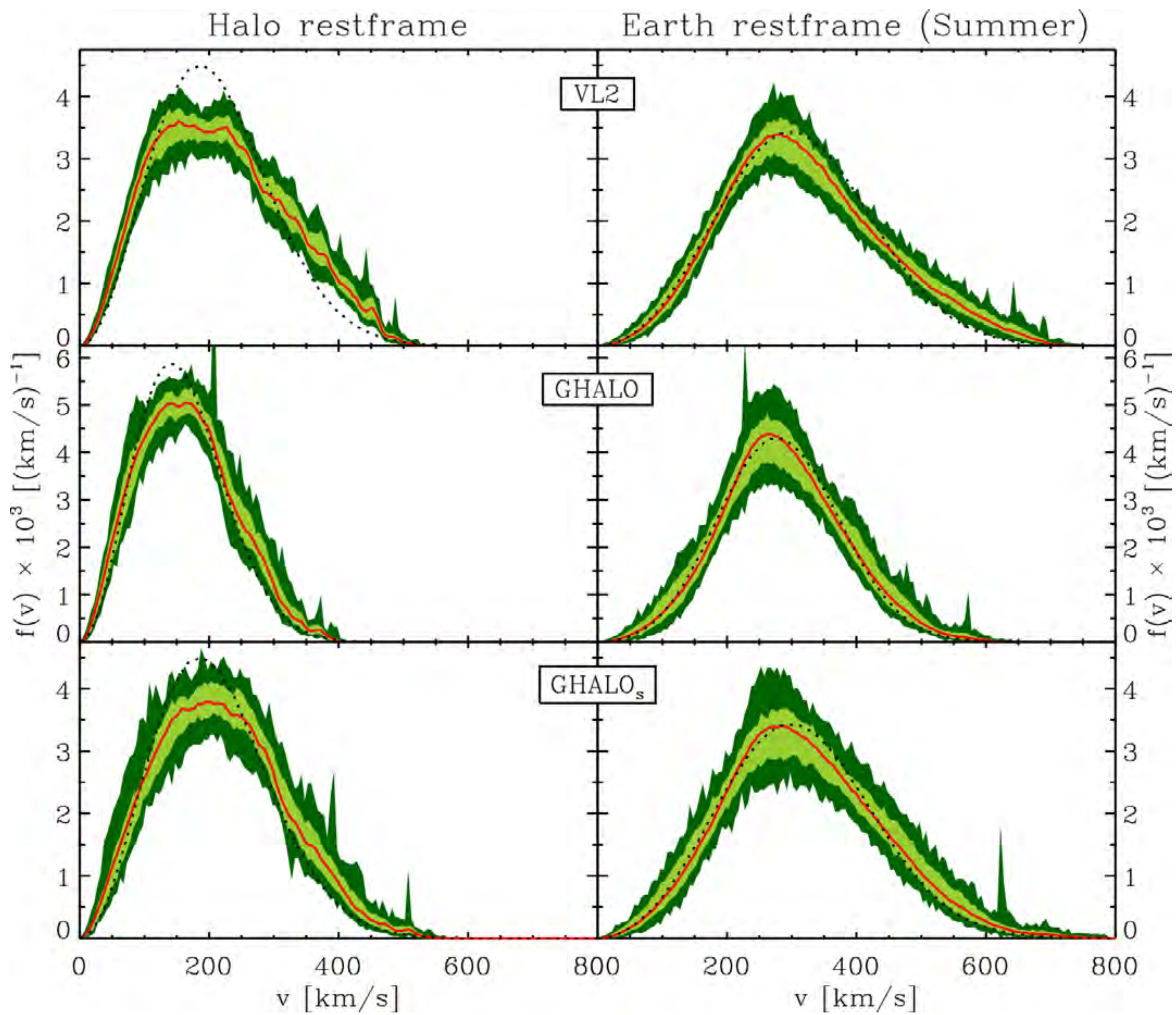
We know some basic parameters

- 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 $q_{max} \sim 2v_{\mathrm{WIMP}}\mu_T \sim$ 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 $\Leftrightarrow$ Xe: the WIMP can "see" the structure of the nucleus

Our motion through the WIMP "wind" can be modeled

$$\rho_{\rm local} \sim 0.3 \text{ GeV/cm}^3 \Rightarrow$$

$$\phi_{\rm WIMP} \sim 10^5 / \text{ cm}^2\text{s}$$



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

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

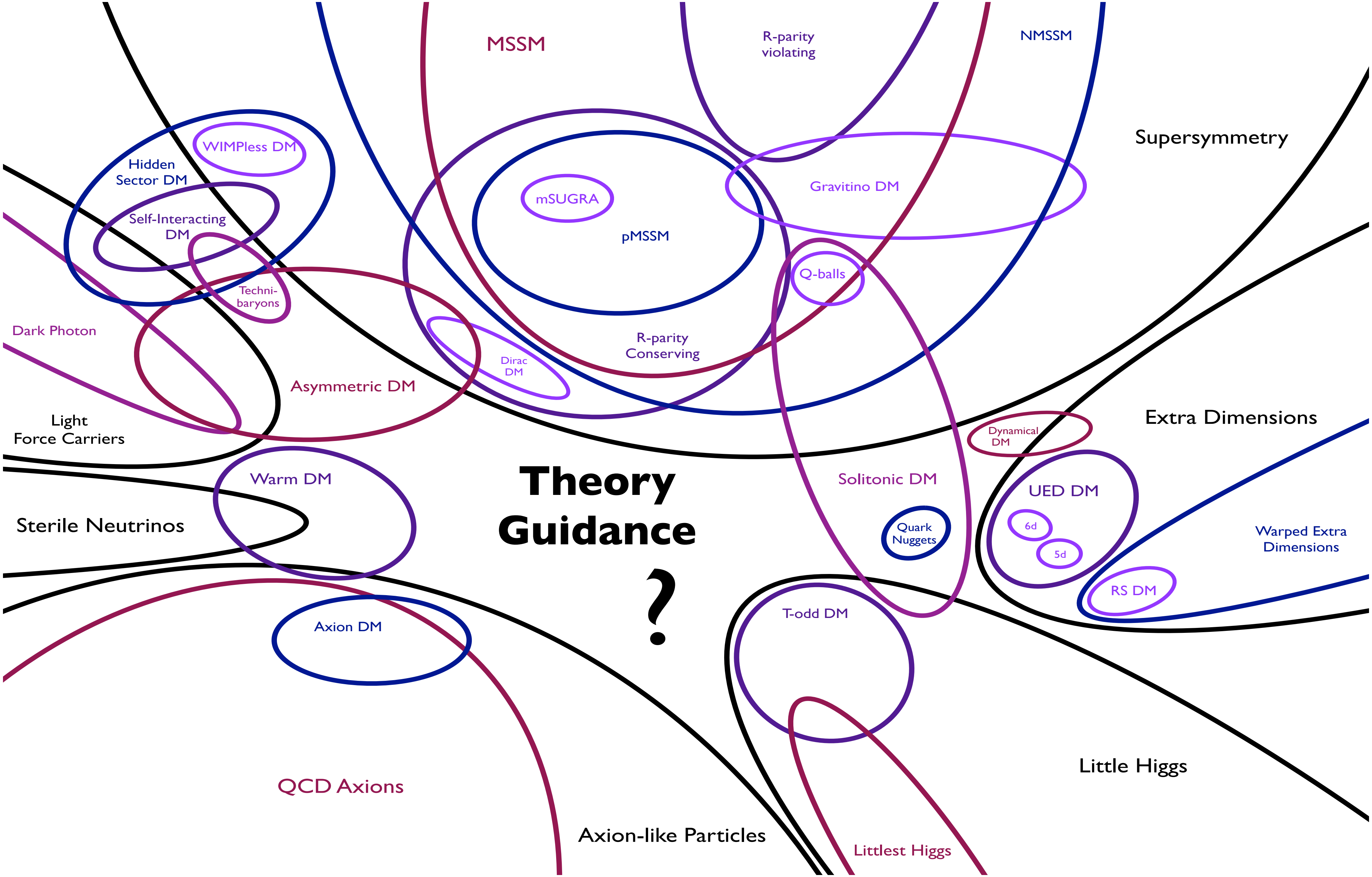
$m_W =$ WIMP mass

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

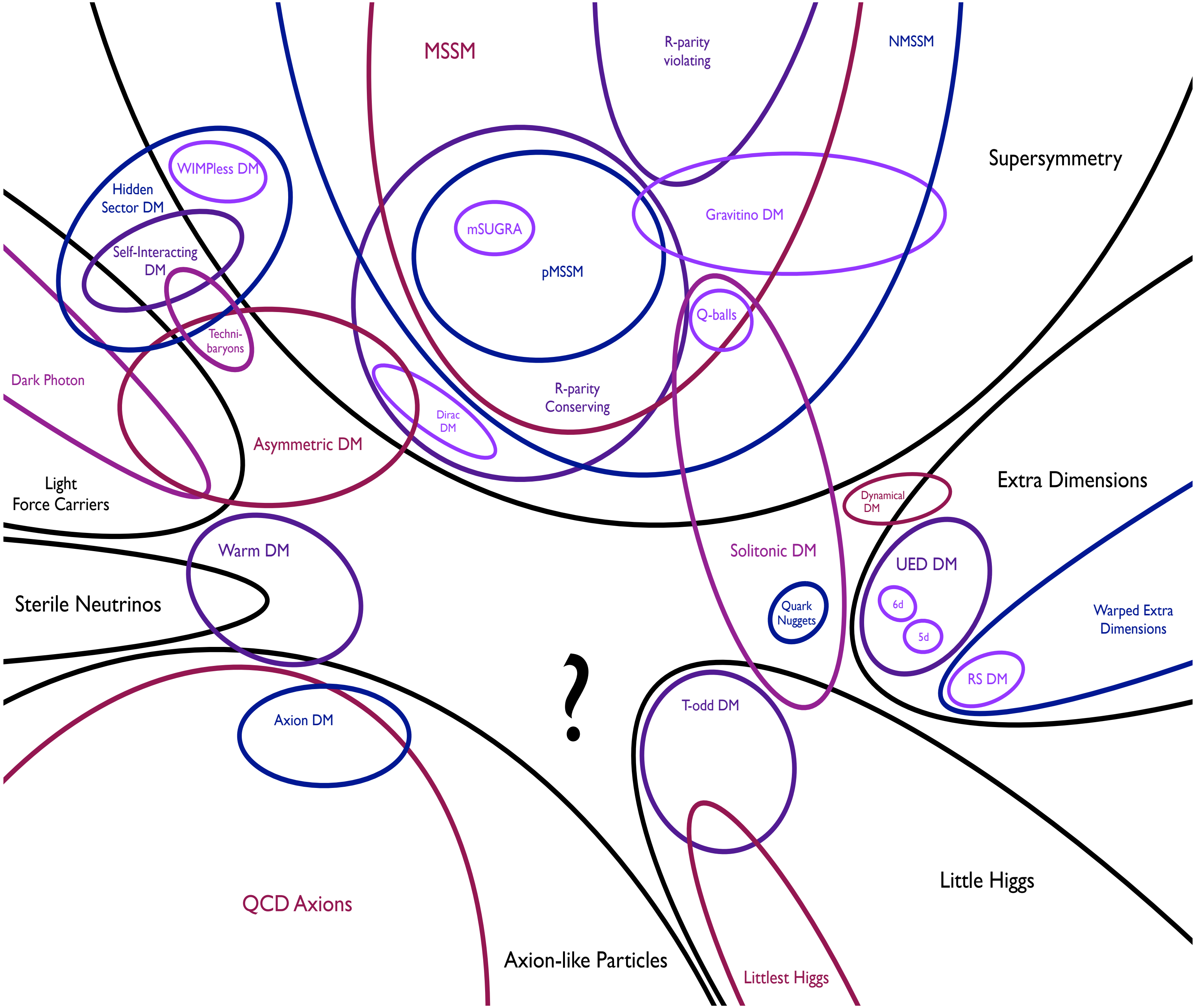
But where do we get the cross section -- the WIMP-nucleus interaction?

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)...

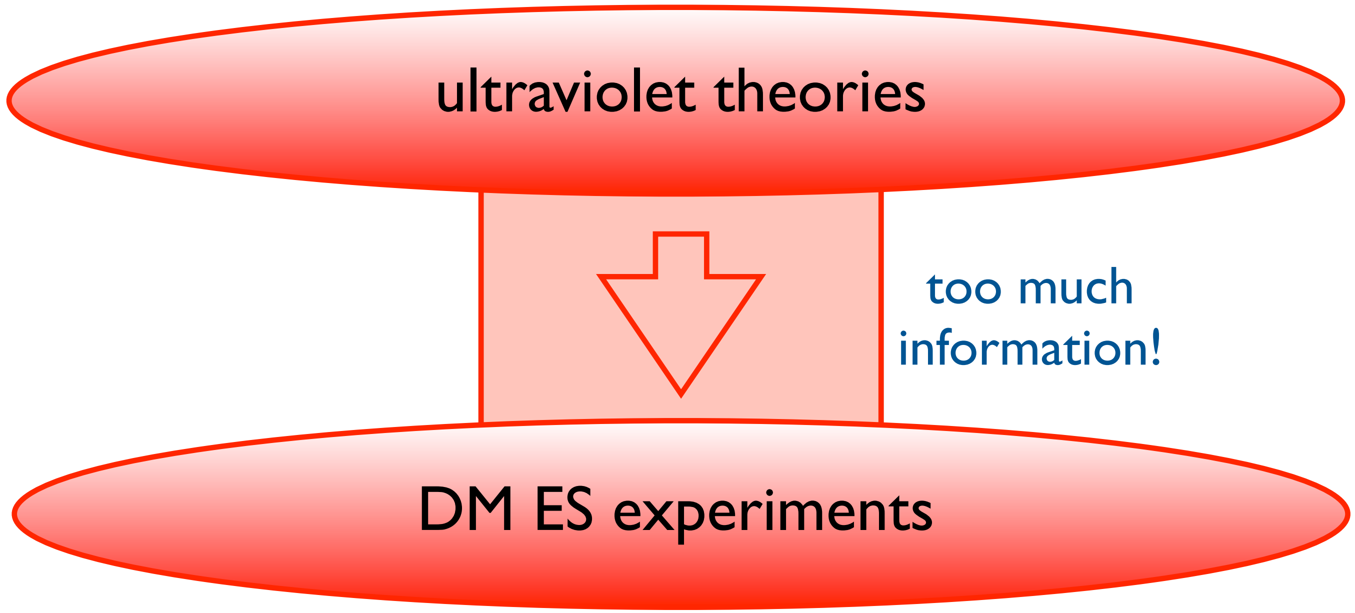


from Tim Tait

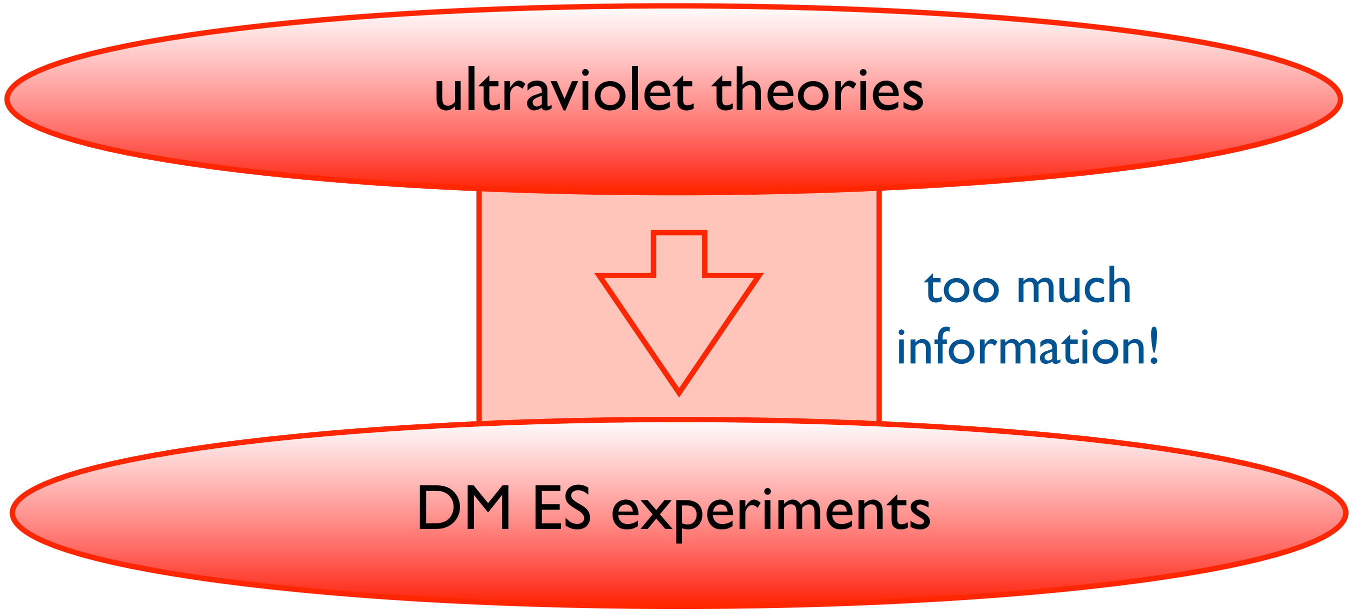


Nuclear theorist

DM experimentalist

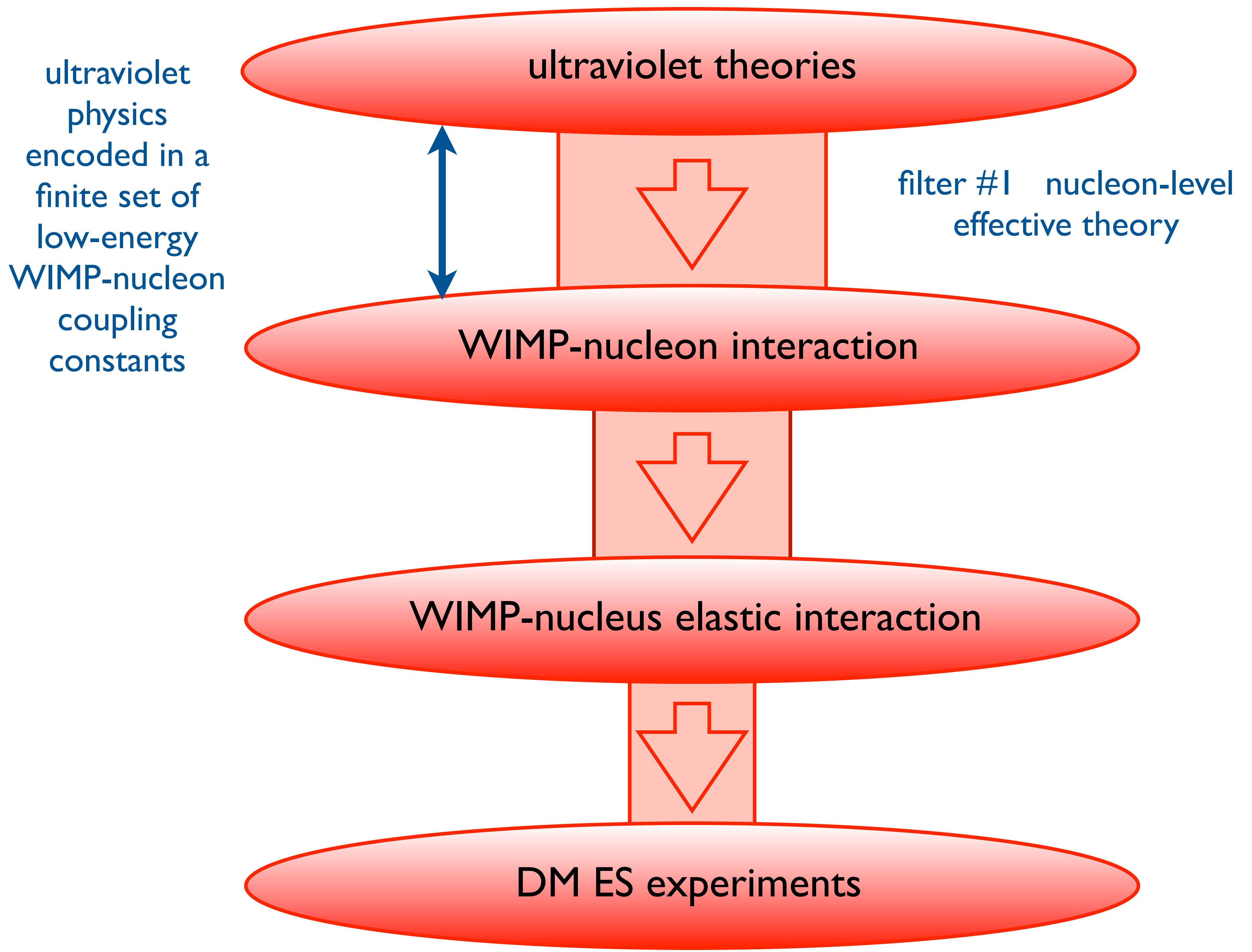


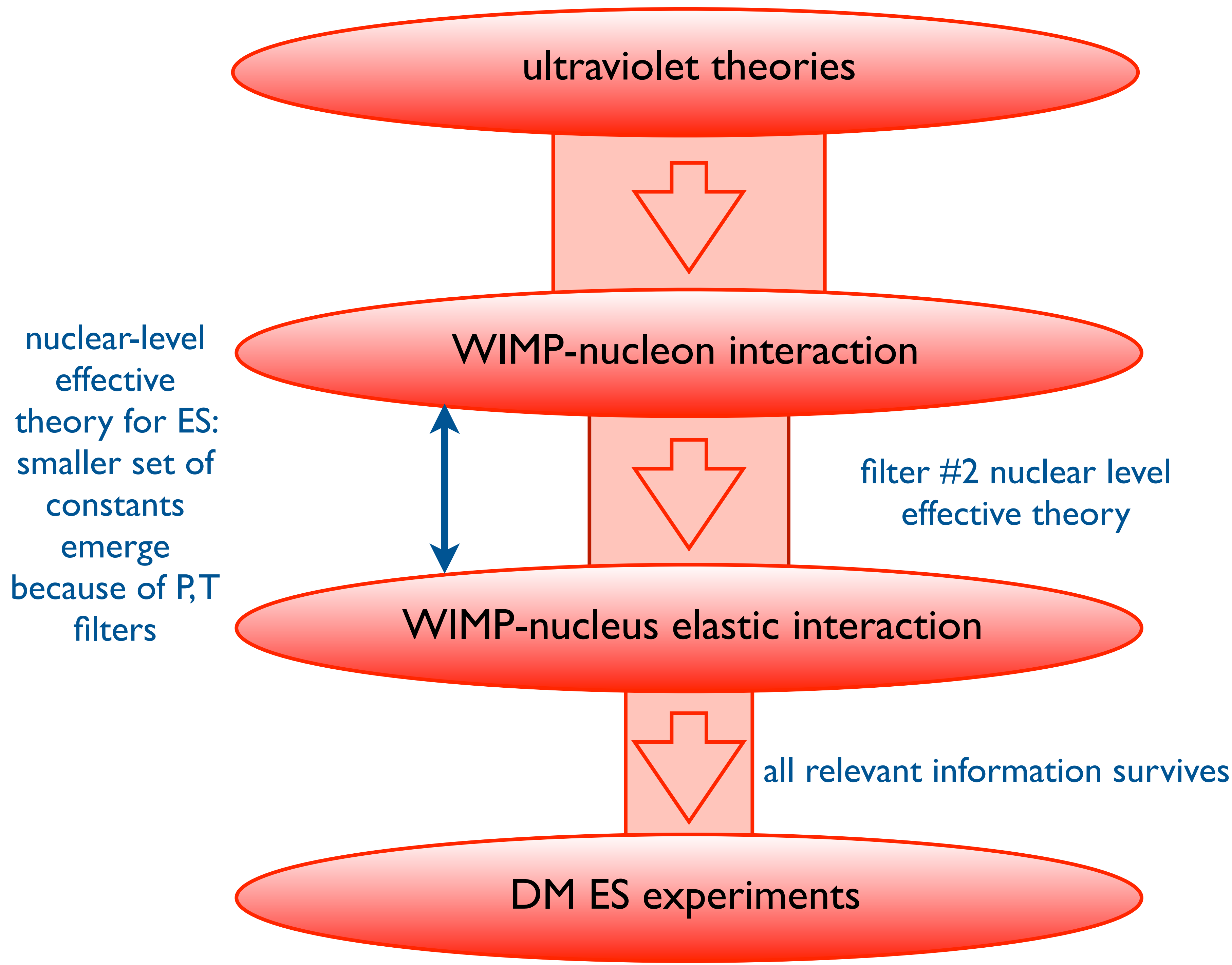
This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory

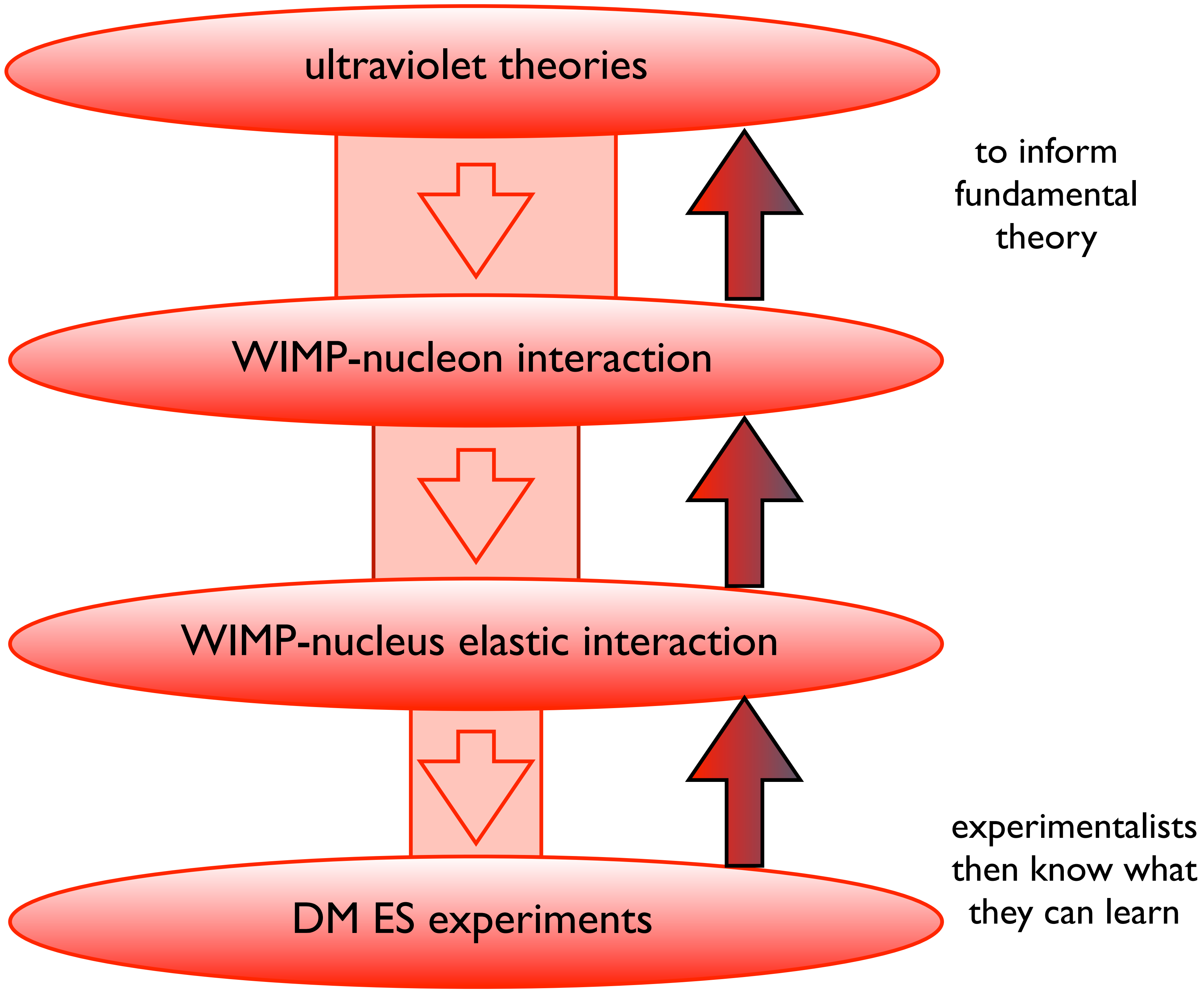


This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory

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

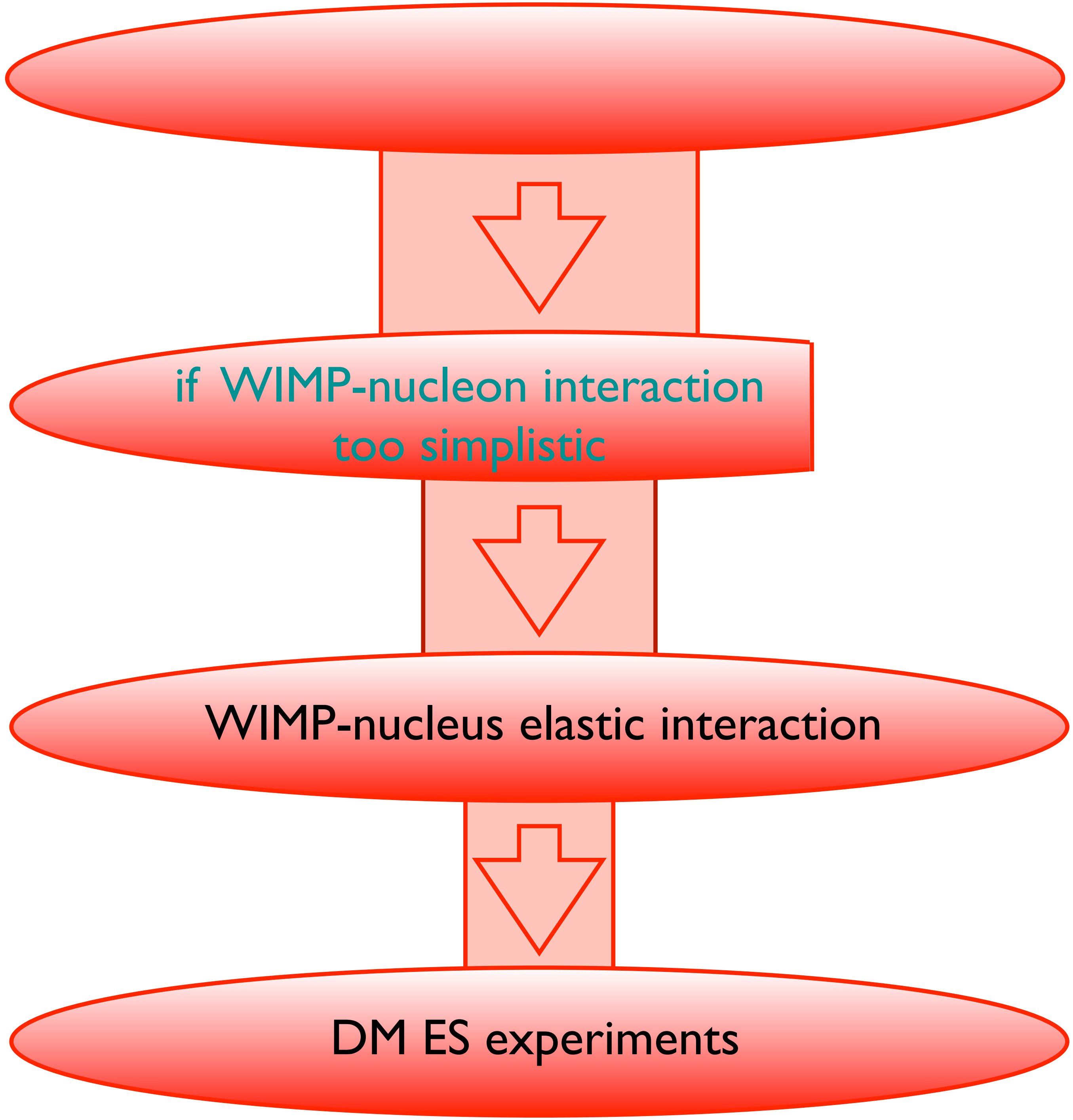

ultraviolet theories
WIMP-nucleon interaction
nuclear-level effective theory for ES: smaller set of constants emerge because of P,T filters
filter #2 nuclear level effective theory
WIMP-nucleus elastic interaction
all relevant information survives
DM ES experiments

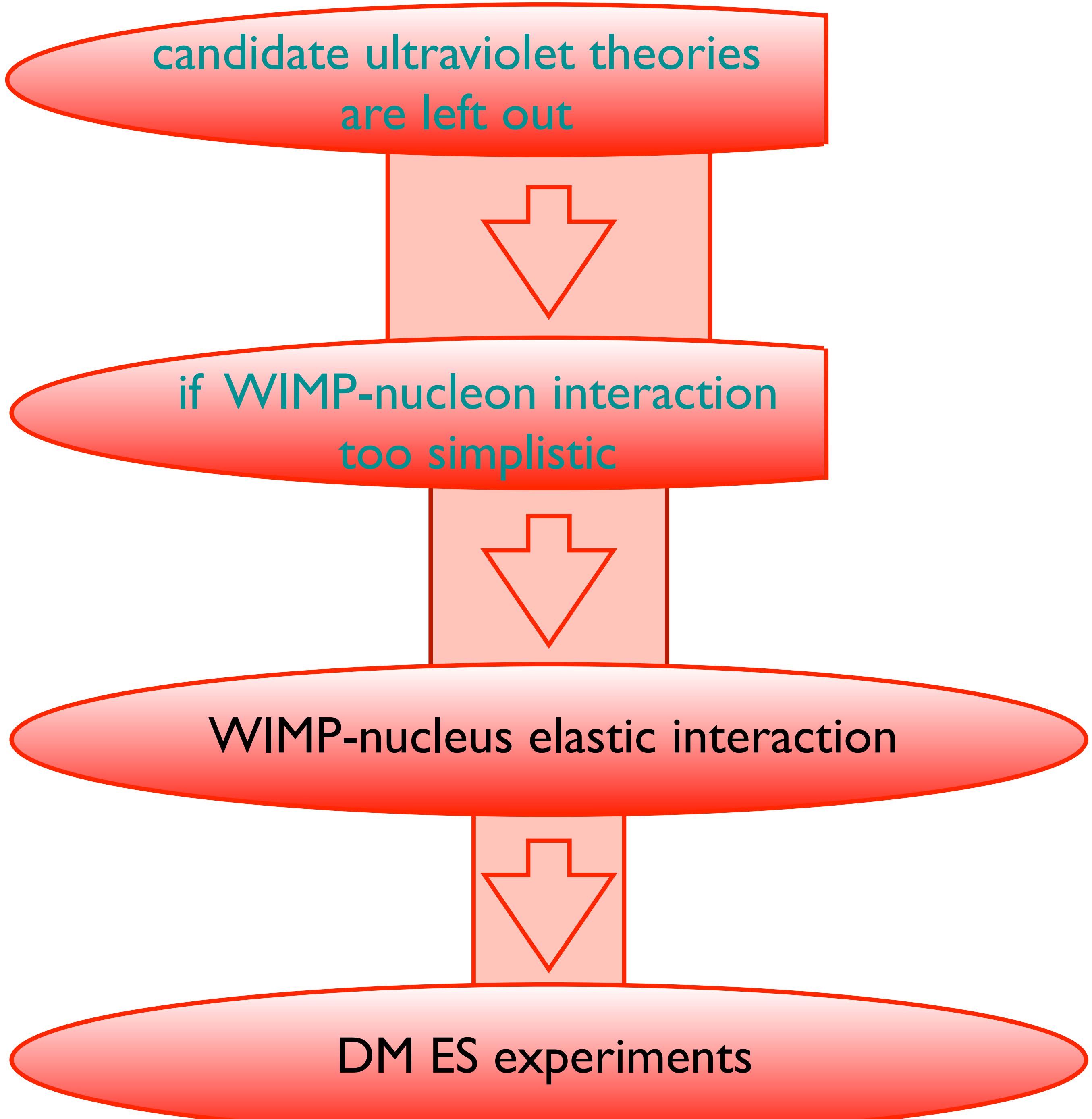

ultraviolet theories
to inform
fundamental
theory
WIMP-nucleon interaction
WIMP-nucleus elastic interaction
experimentalists
then know what
they can learn
DM ES experiments

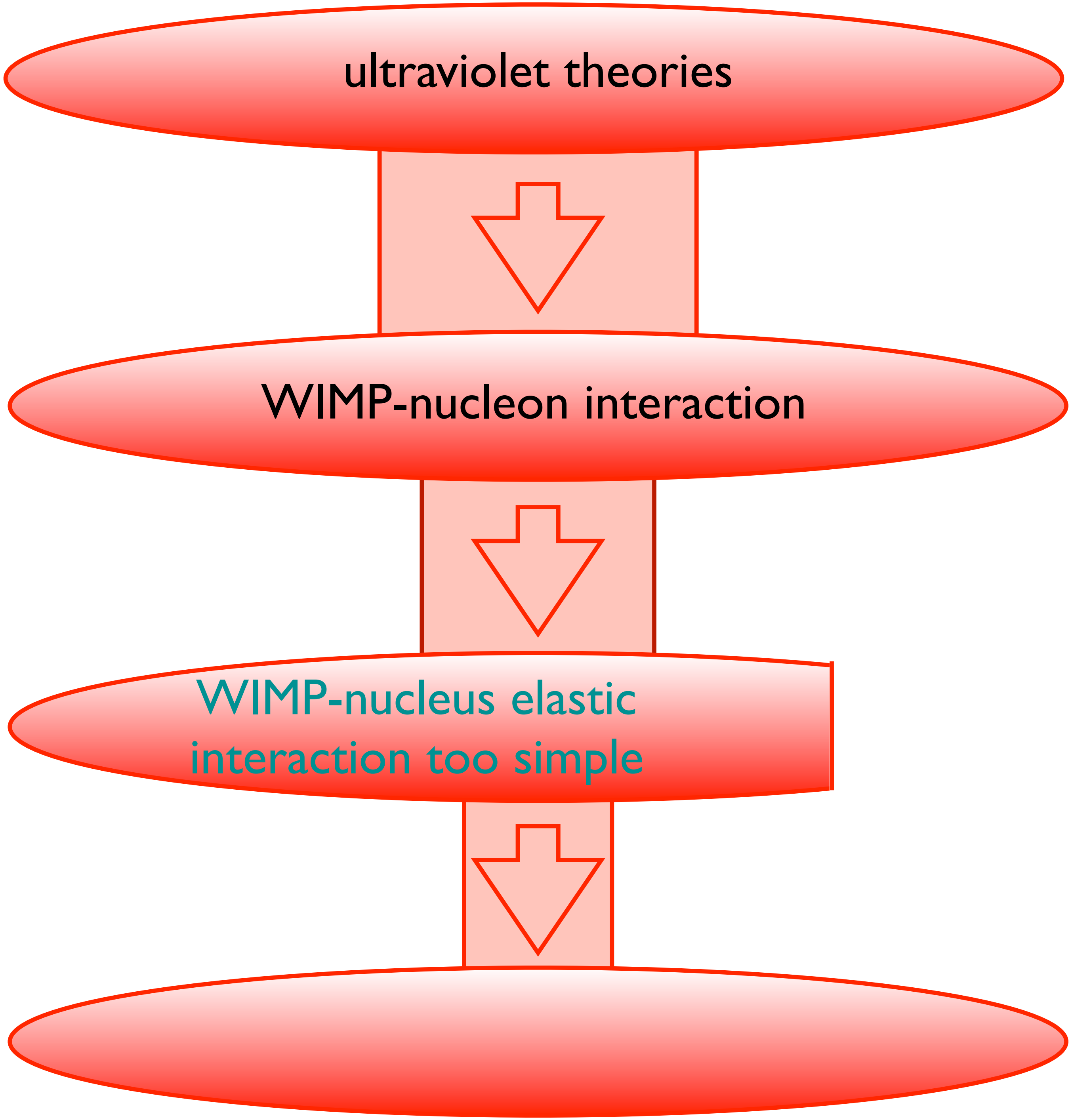
the effective theory process works only if each step is executed properly

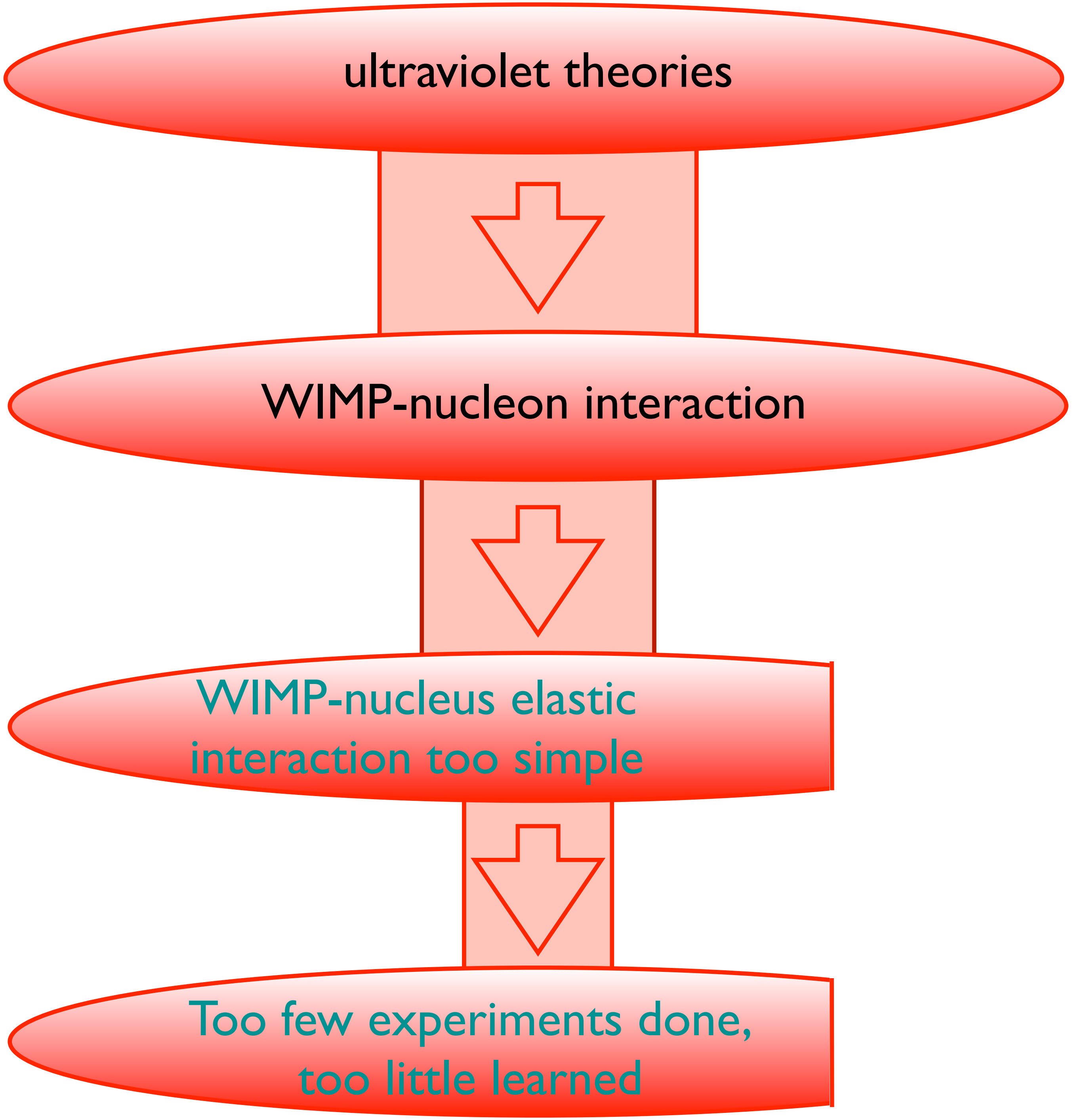
this

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?

(SI/SD is in fact the starting point of Fermi and Gamow&Teller...)

- A familiar electroweak interactions problem: What is the form of the elastic response for a nonrelativistic theory with vector and axial-vector interactions?

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	$\cancel{C_1}$
axial	$\cancel{C_0^5}$	C_1^5

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

Yielding the following table of allowed responses

	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}			

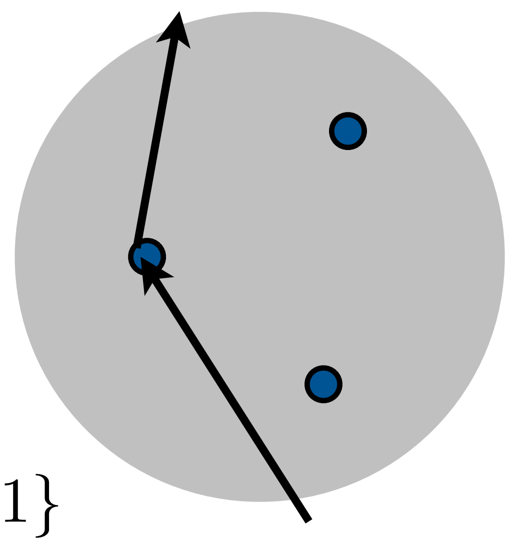
The union rules for theorists require:

Interactions allow by symmetries must be included in an effective theory

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

- What is the origin of the extra responses? They are the responses connected with velocity-dependent interactions:

e.g., $\sum_{i=1}^{A} \vec{S}_\chi \cdot \vec{v}^\perp(i)$ where by Galilean invariance $\vec{v}^\perp(i) = \vec{v}_\chi - \vec{v}_N(i)$



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

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

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

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

Parameter counting in DM effective theory

- These velocities hide: the $\vec{\dot{v}}(i)$ 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

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

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

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

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

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

That is, there are not only new operators, but these operators are parametrically of order $|\vec{\dot{v}}| \sim q/m_N \sim 10^{-1}$ not $|\vec{v}_{\rm WIMP}| \sim 10^{-3}$

In practice, one turns the ET crank, first deriving the nucleon-level H

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

Then one embeds this into the nucleus, imposing the constraints of P and T on the nuclear portion of these operator, and necessarily deriving the general WIMP-nucleus interaction

$$
\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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \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}
$$

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

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

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

$$
\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

$$\frac{d\sigma}{d\Omega} \sim \frac{4\pi}{2J_i+1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \Bigg\{ R_C^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=0,2,\dots}^{\infty} \langle J_i || \, M_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, M_{J;\tau'}(q) \, || J_i \rangle$$

$$+ \frac{\vec{q}^{\,2}}{m_N^2} R_L^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=0,2,\dots}^{\infty} \langle J_i || \, \Phi''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Phi''_{J;\tau'}(q) \, || J_i \rangle$$

$$+ \frac{\vec{q}^{\,2}}{m_N^2} R_{L/C}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=0,2,\dots}^{\infty} \langle J_i || \, \Phi''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, M_{J;\tau'}(q) \, || J_i \rangle$$

$$+ \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{el}}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=2,4,\dots}^{\infty} \langle J_i || \, \tilde{\Phi}'_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \tilde{\Phi}'_{J;\tau'}(q) \, || J_i \rangle$$

$$+ R_{L^5}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=1,3,\dots}^{\infty} \langle J_i || \, \Sigma''_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma''_{J;\tau'}(q) \, || J_i \rangle$$

$$+ \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=1,3,\dots}^{\infty} \langle J_i || \, \Delta_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Delta_{J;\tau'}(q) \, || J_i \rangle$$

$$+ R_{T^{el5}}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=1,3,\dots}^{\infty} \langle J_i || \, \Sigma'_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma'_{J;\tau'}(q) \, || J_i \rangle$$

$$+ \frac{\vec{q}^{\,2}}{m_N^2} R_{T^{mag}/T^{el5}}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \sum_{J=1,3,\dots}^{\infty} \langle J_i || \, \Delta_{J;\tau}(q) \, || J_i \rangle \langle J_i || \, \Sigma'_{J;\tau'}(q) \, || J_i \rangle \Bigg\}$$

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

More information is available from ES

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

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

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

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

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

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

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

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

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

- 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

- All interactions generate a SI/SD coupling, but for velocity-dependent interactions, the results are misleading
  - the predicted strength is 10^{-4} the actual strength
  - the associated sub-dominant operator will have the wrong rank, e.g., predict SD instead of SI

- ES is blind to certain familiar interactions: axial charge $\vec{\sigma}(i) \cdot \vec{p}(i)$
  - excited states important

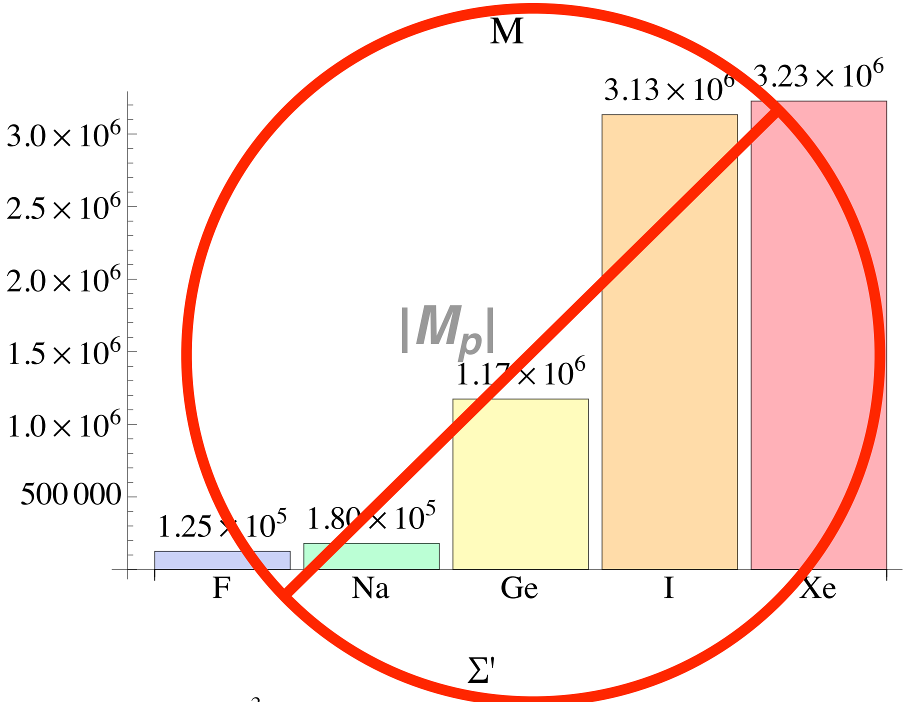
- The larger class of operators open up strategies for measuring the mass of a very heavy WIMP, where $\mu(M_T, M_\chi) \rightarrow \mu(M_T)$

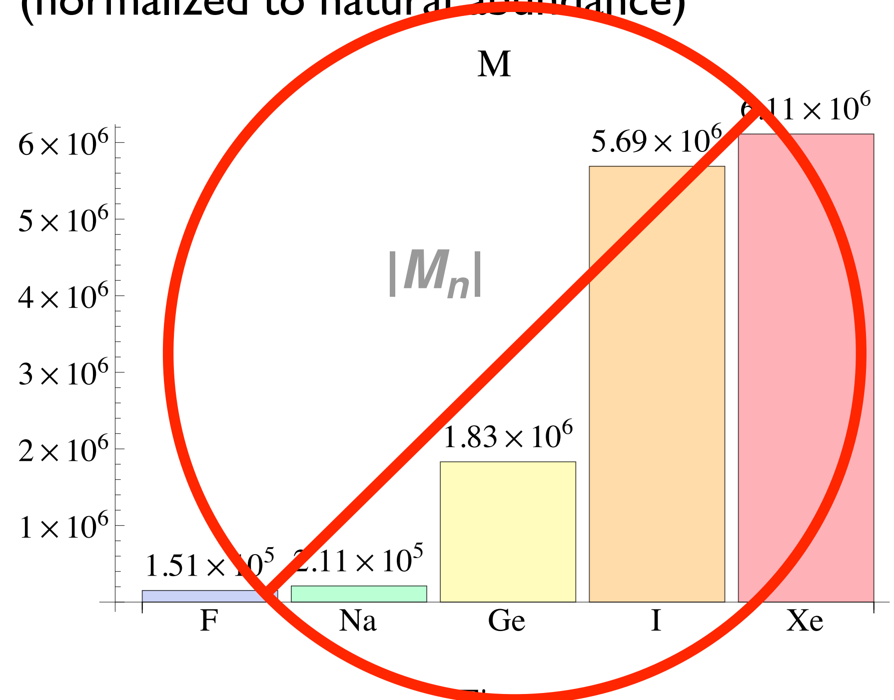
For illustration purposes only!

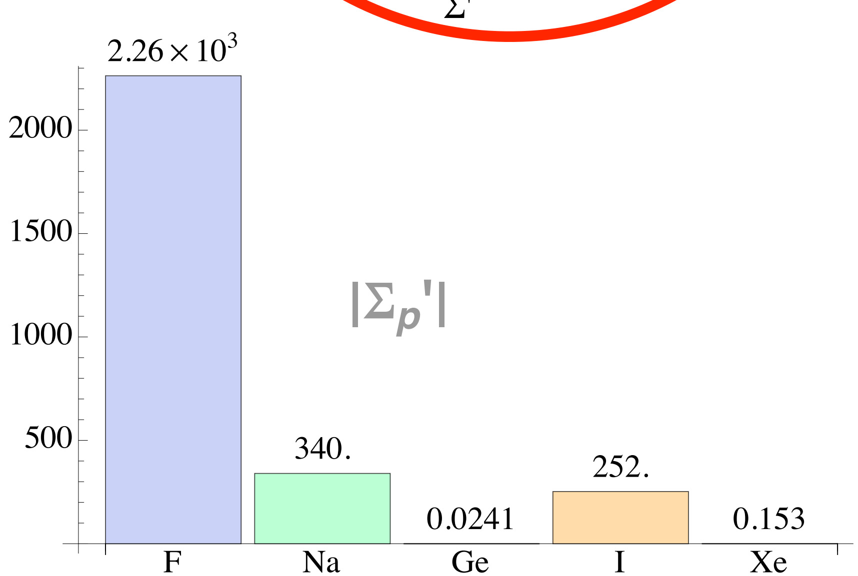
DAMA/LIBRA:	NaI
CoGENT:	Ge
LUX:	Xe

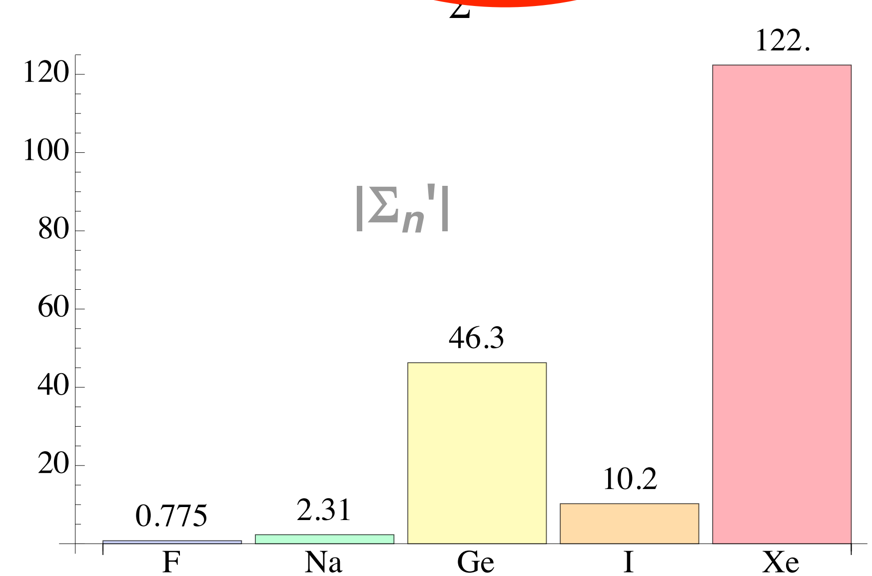
vector charge (amplitudes!)

(normalized to natural abundance)







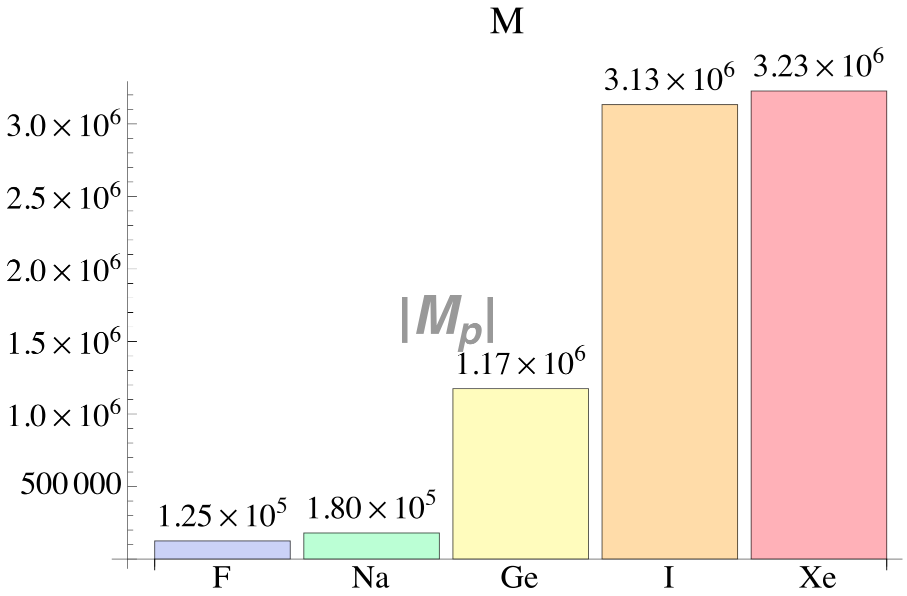


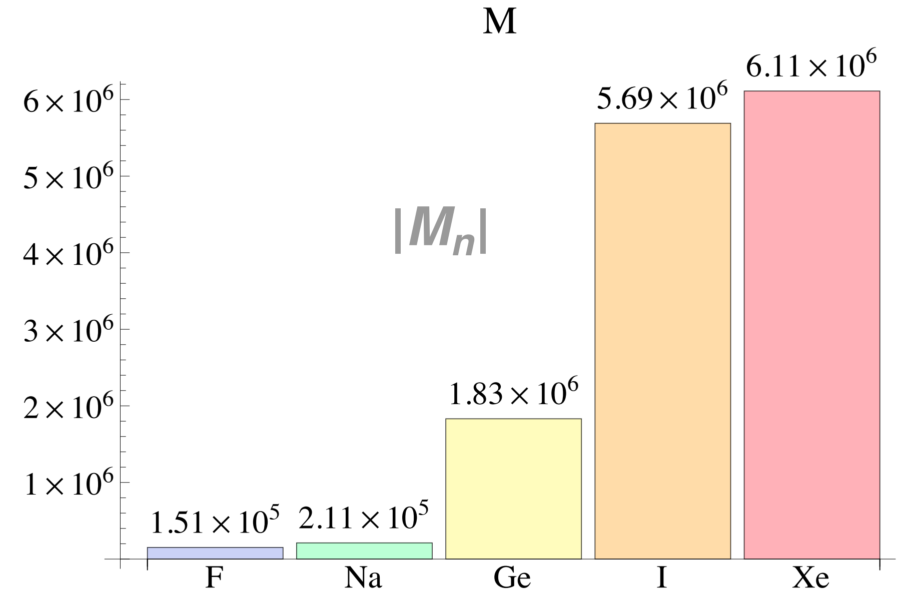
transverse electric axial (spin) response

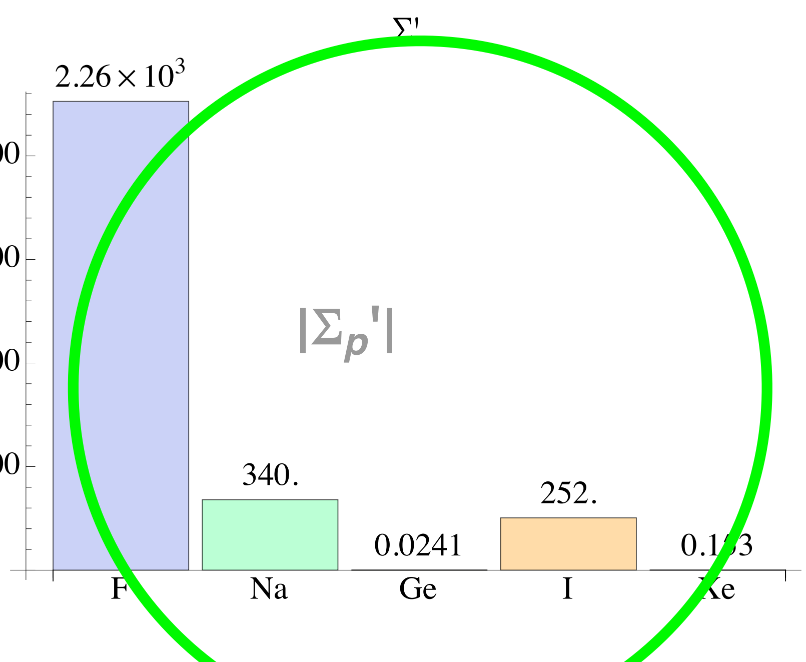
transverse nuclear spin

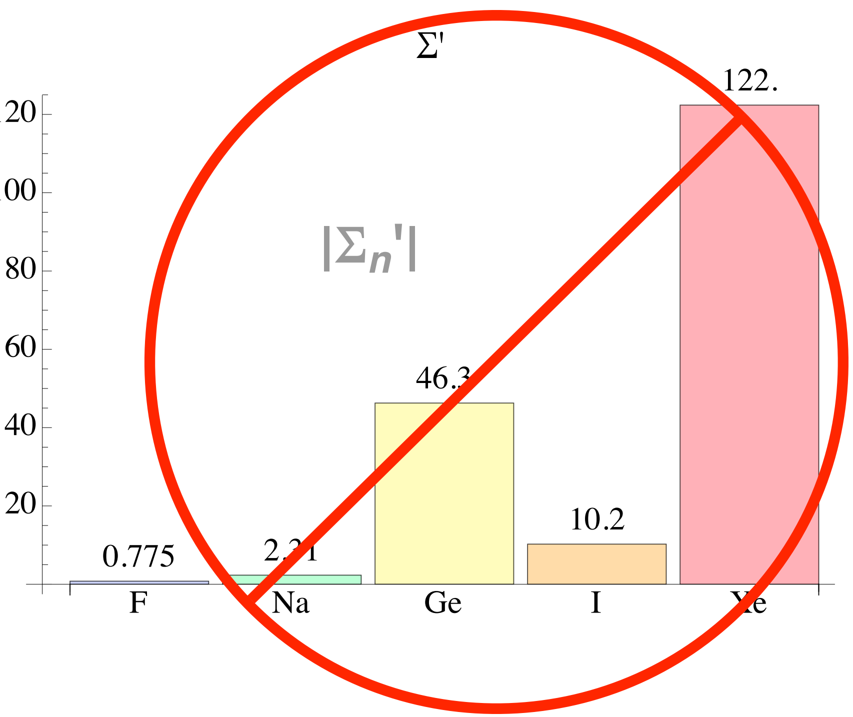
vector charge (amplitudes!)

(normalized to natural abundance)



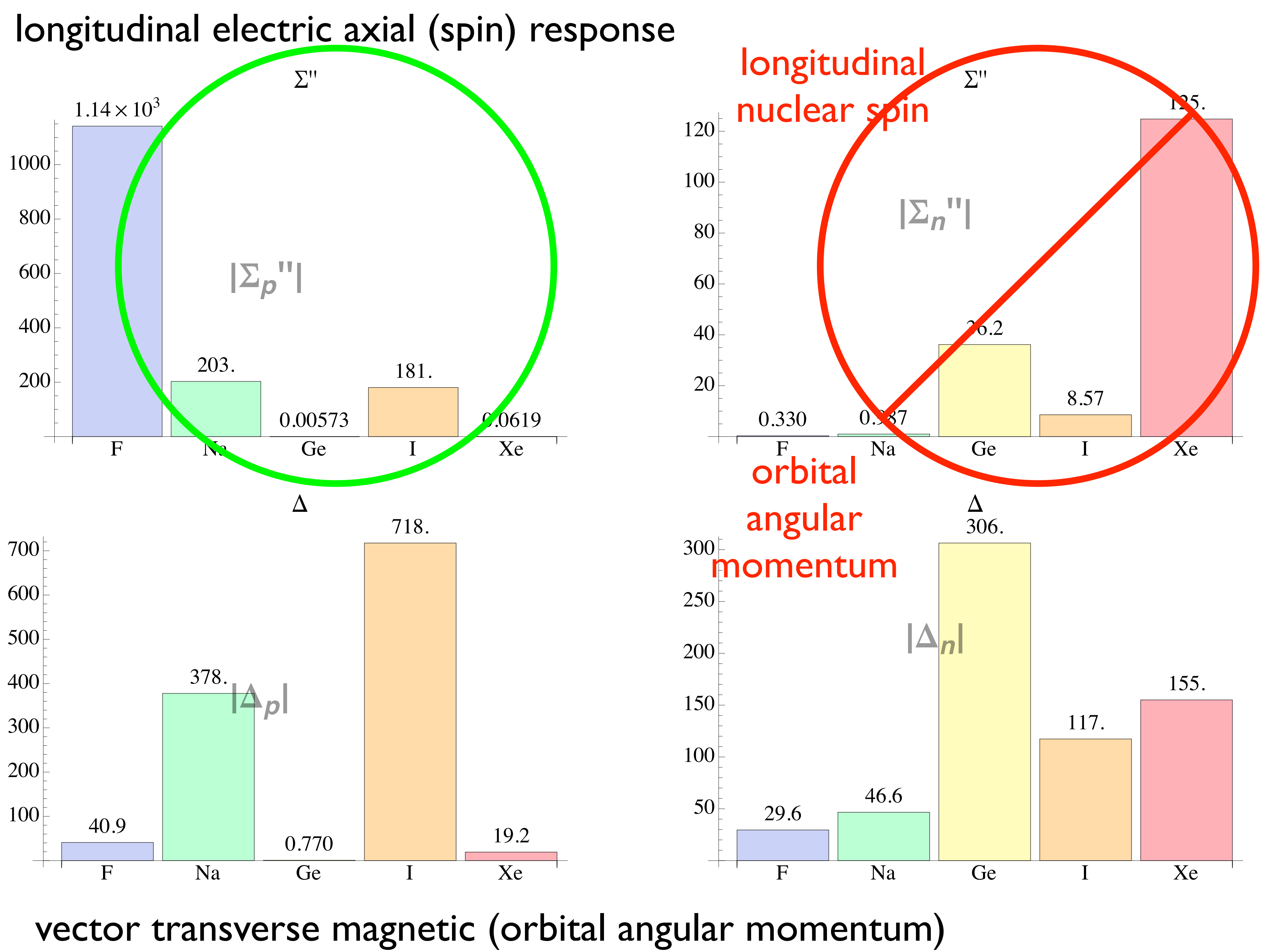




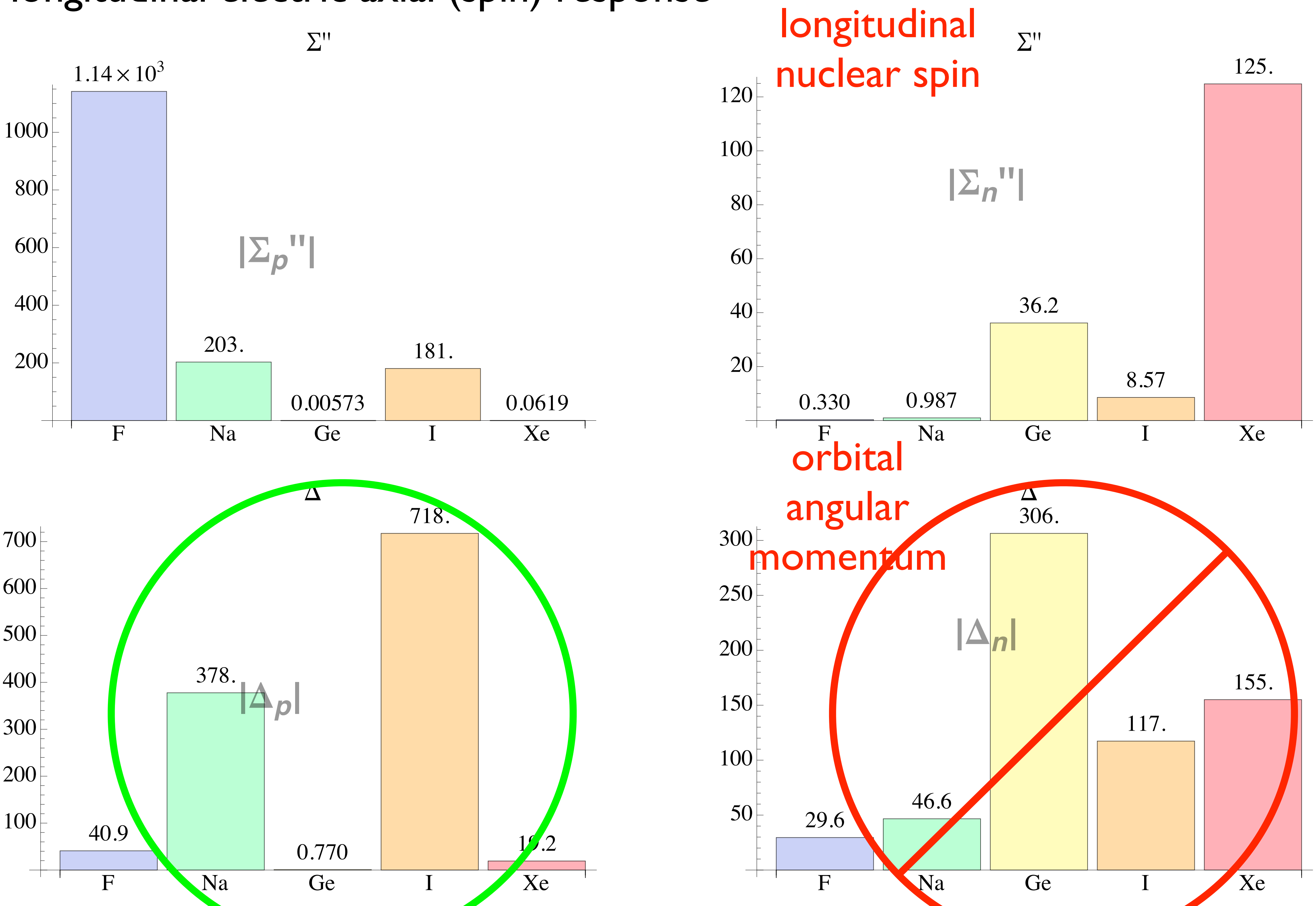


transverse electric axial (spin) response

transverse nuclear spin

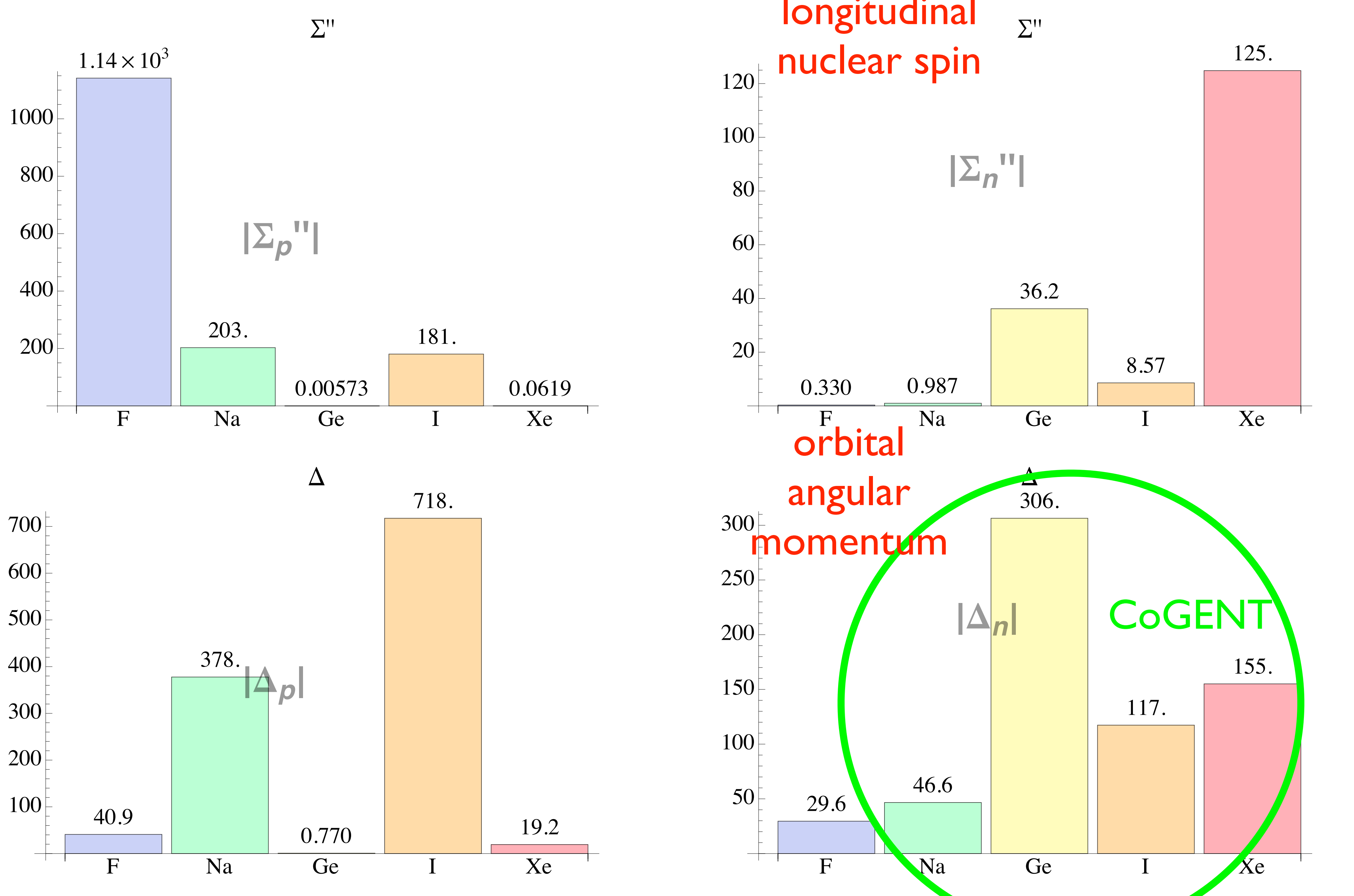

longitudinal electric axial (spin) response
Σ''
1.14 × 10^3
203.
0.00573
181.
0.0619
|Σ_p''|
F
Na
Ge
I
Xe
longitudinal
nuclear spin
|Σ_n''|
125.
36.2
0.330
8.57
orbital
angular
momentum
Δ
718.
378.
40.9
0.770
19.2
|Δ_p|
306.
155.
117.
46.6
29.6
|Δ_n|
vector transverse magnetic (orbital angular momentum)

longitudinal electric axial (spin) response



vector transverse magnetic (orbital angular momentum)

longitudinal electric axial (spin) response



vector transverse magnetic (orbital angular momentum)

Summary

- Reminds one of the early days of the weak interaction, SPVAT ↔ V-A (a simpler problem that was not easily sorted out)
- 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