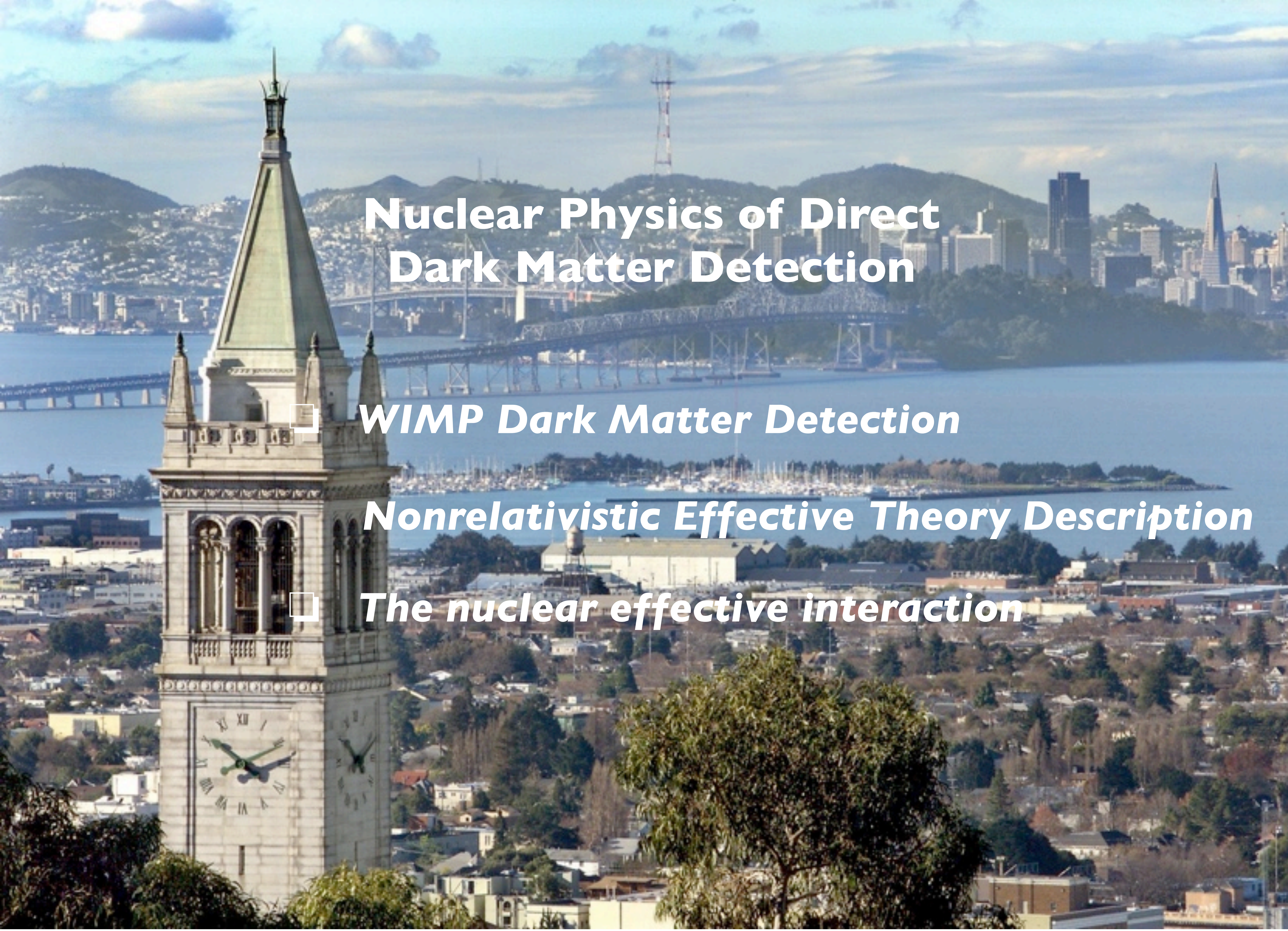


Nuclear Physics of Direct Dark Matter Detection

- ***WIMP Dark Matter Detection***

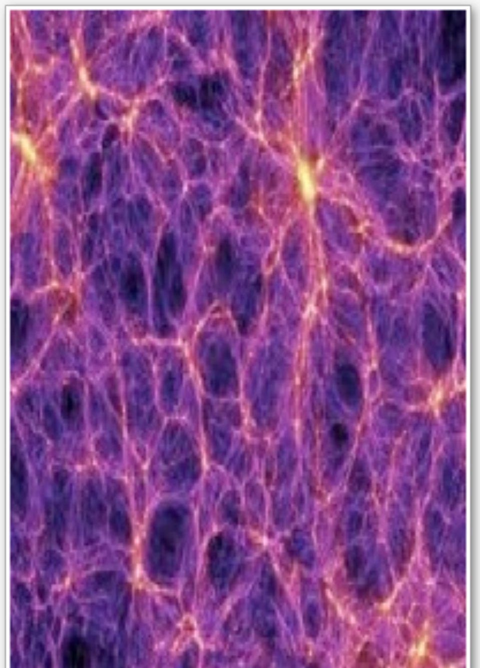
  Nonrelativistic Effective Theory Description

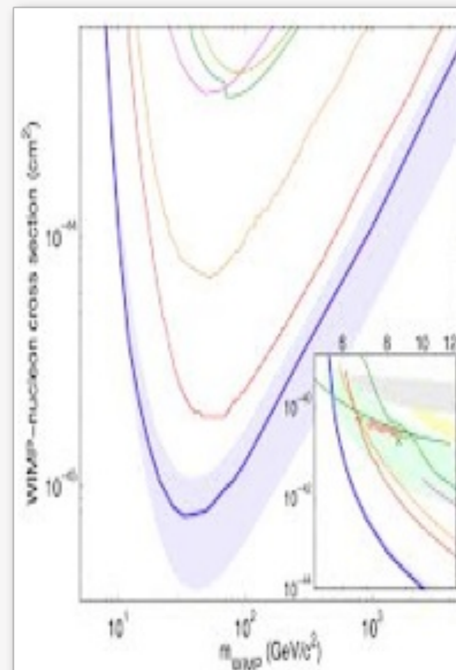
- ***The nuclear effective interaction***

New Perspectives on Dark Matter

Fermilab

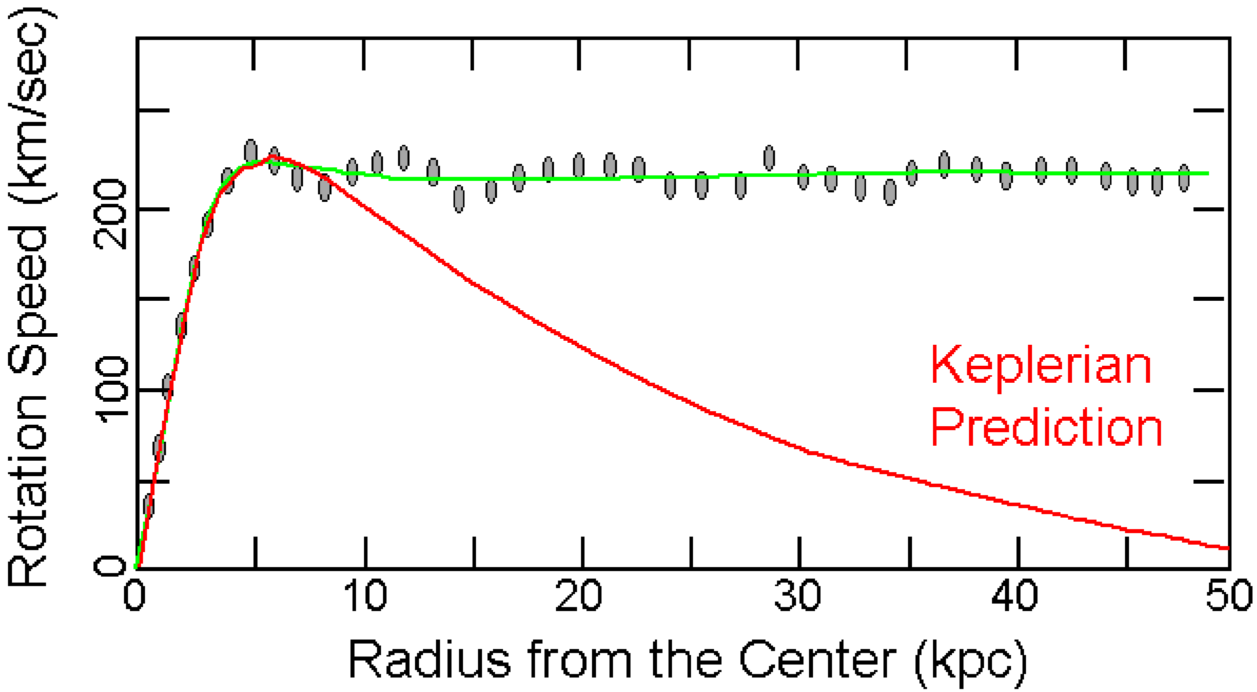
April 28 - May 2, 2014





Brian Batell (U Chicago)
Patrick Fox (FNAL)
Roni Harnik (FNAL)

DM gravitational signatures are by now quite varied...



$v \propto$ constant

$\longleftarrow$ $m(r) \propto r$

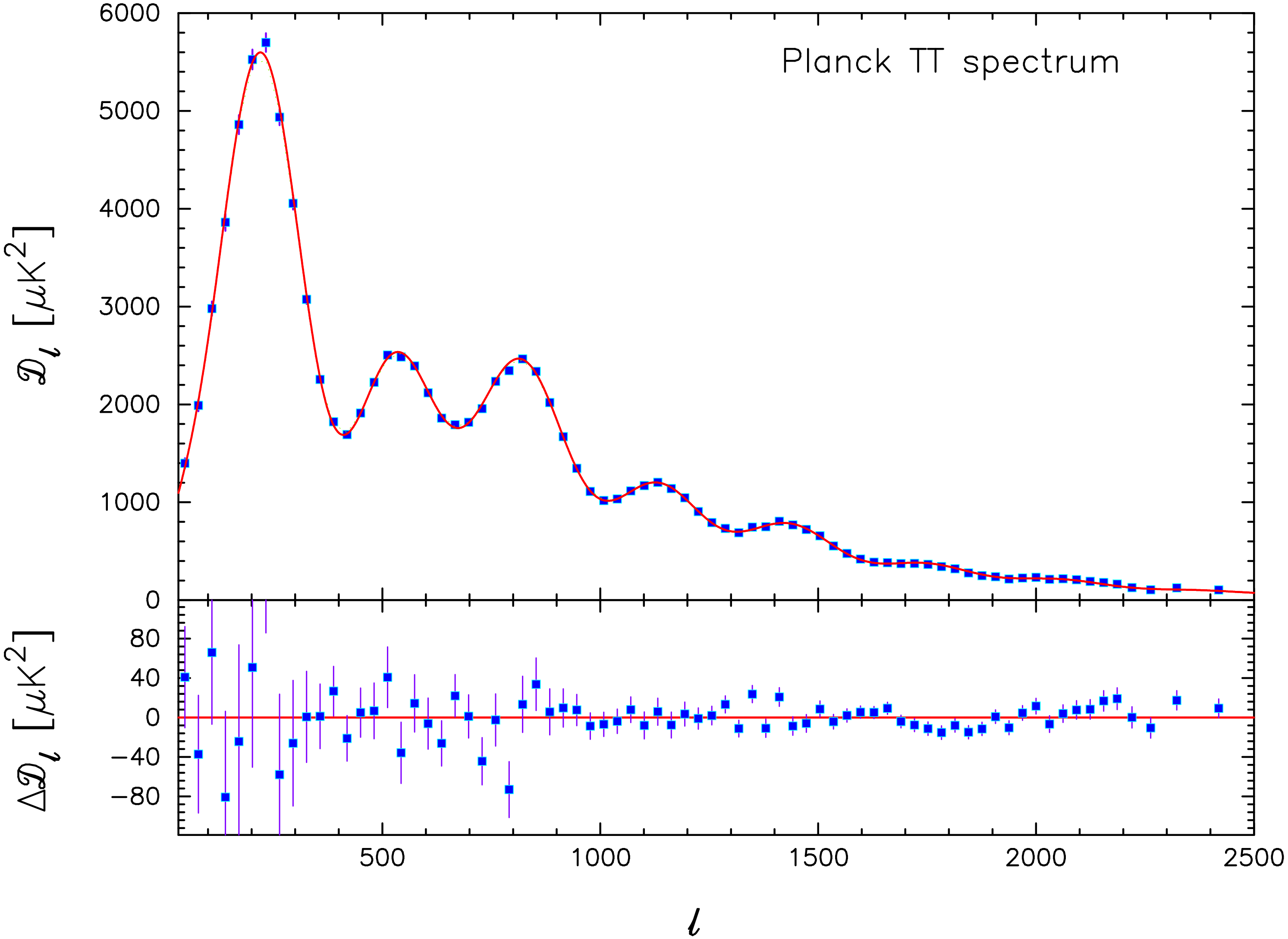
$\rho(r) \propto 1/r^2$

(flat rotation curve)

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

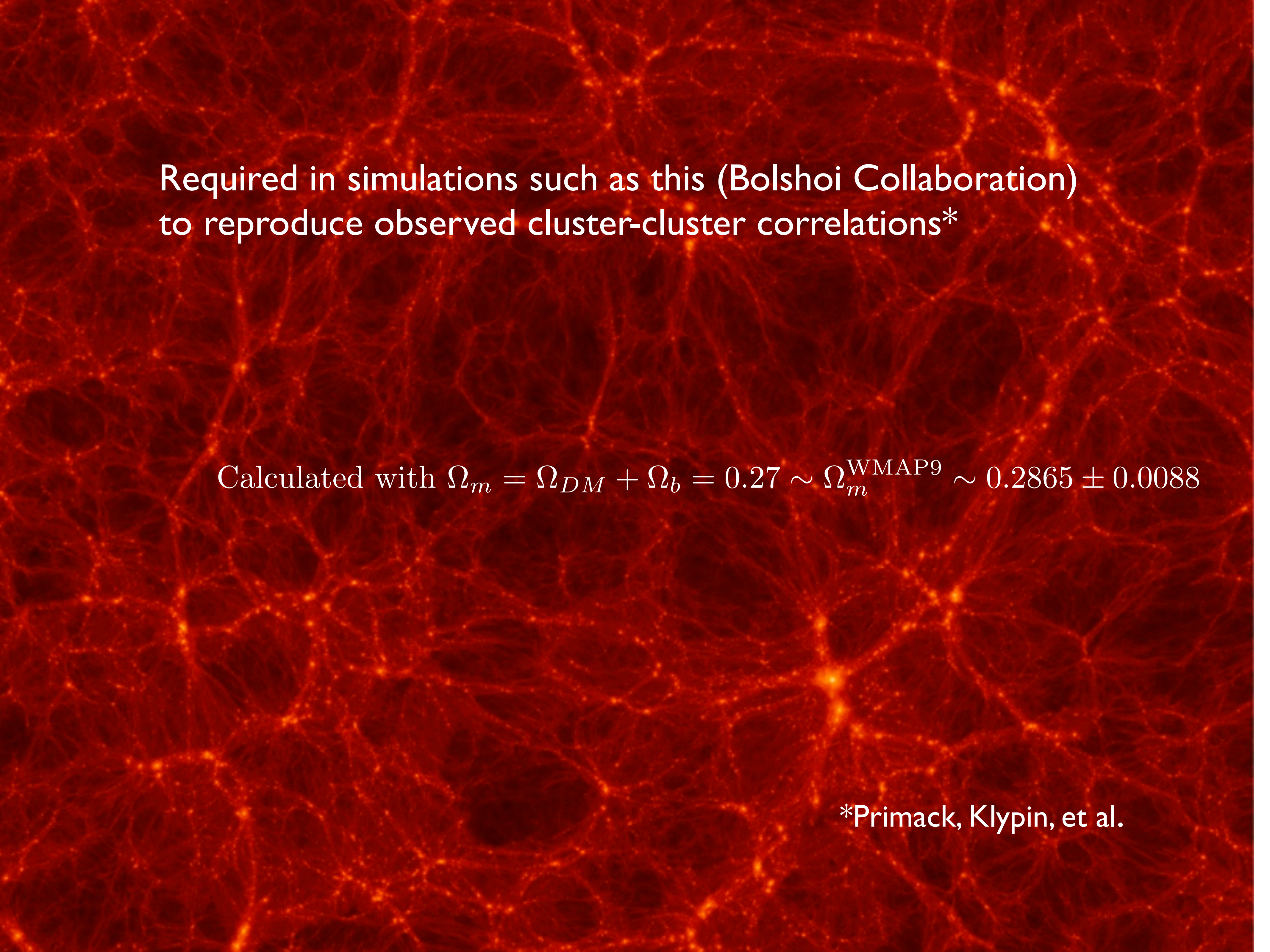
(gravitating central mass)

NGC-6384
(from HST)



ΛCDM comparison

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

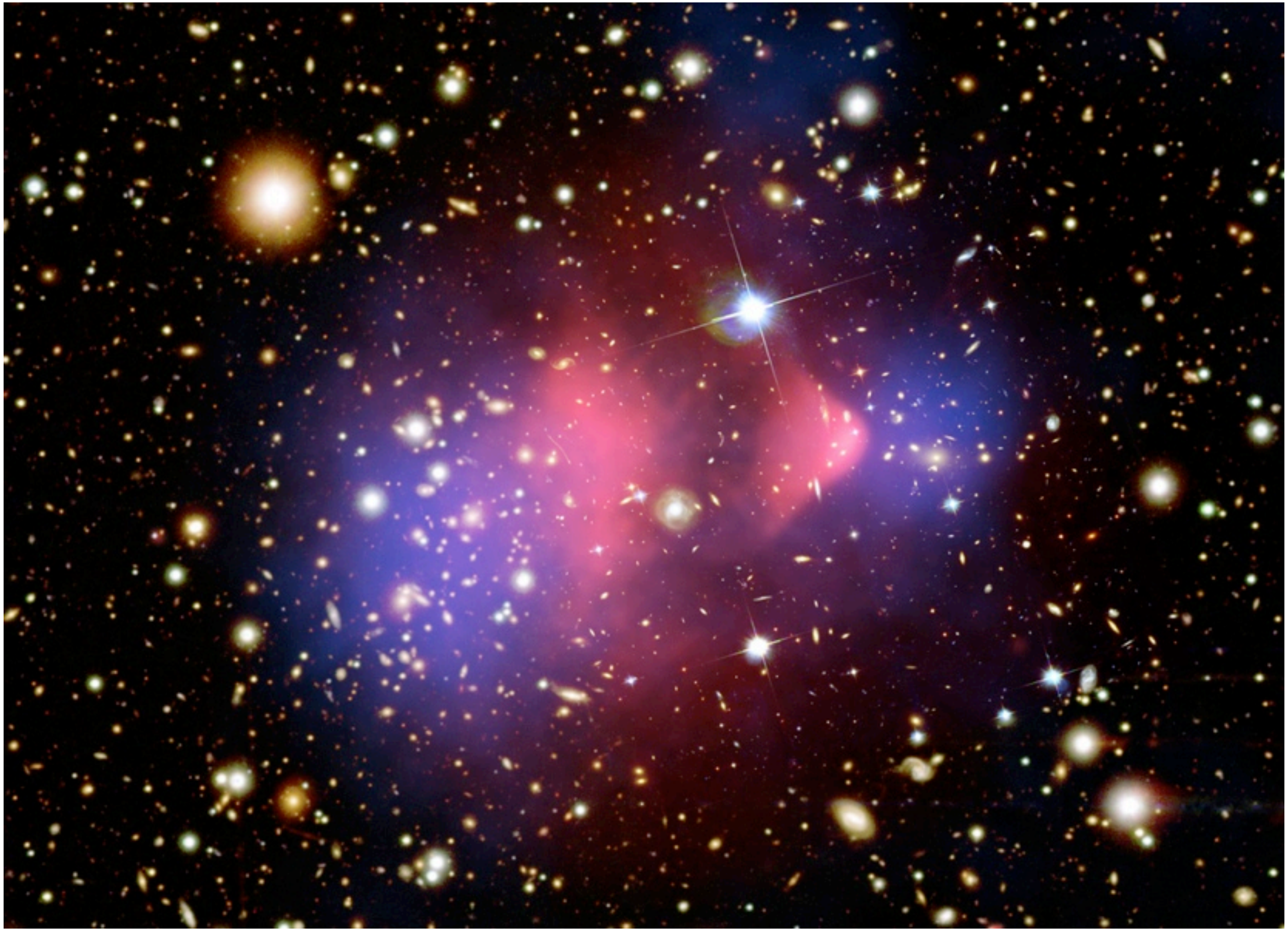


Required in simulations such as this (Bolshoi Collaboration) to reproduce observed cluster-cluster correlations*

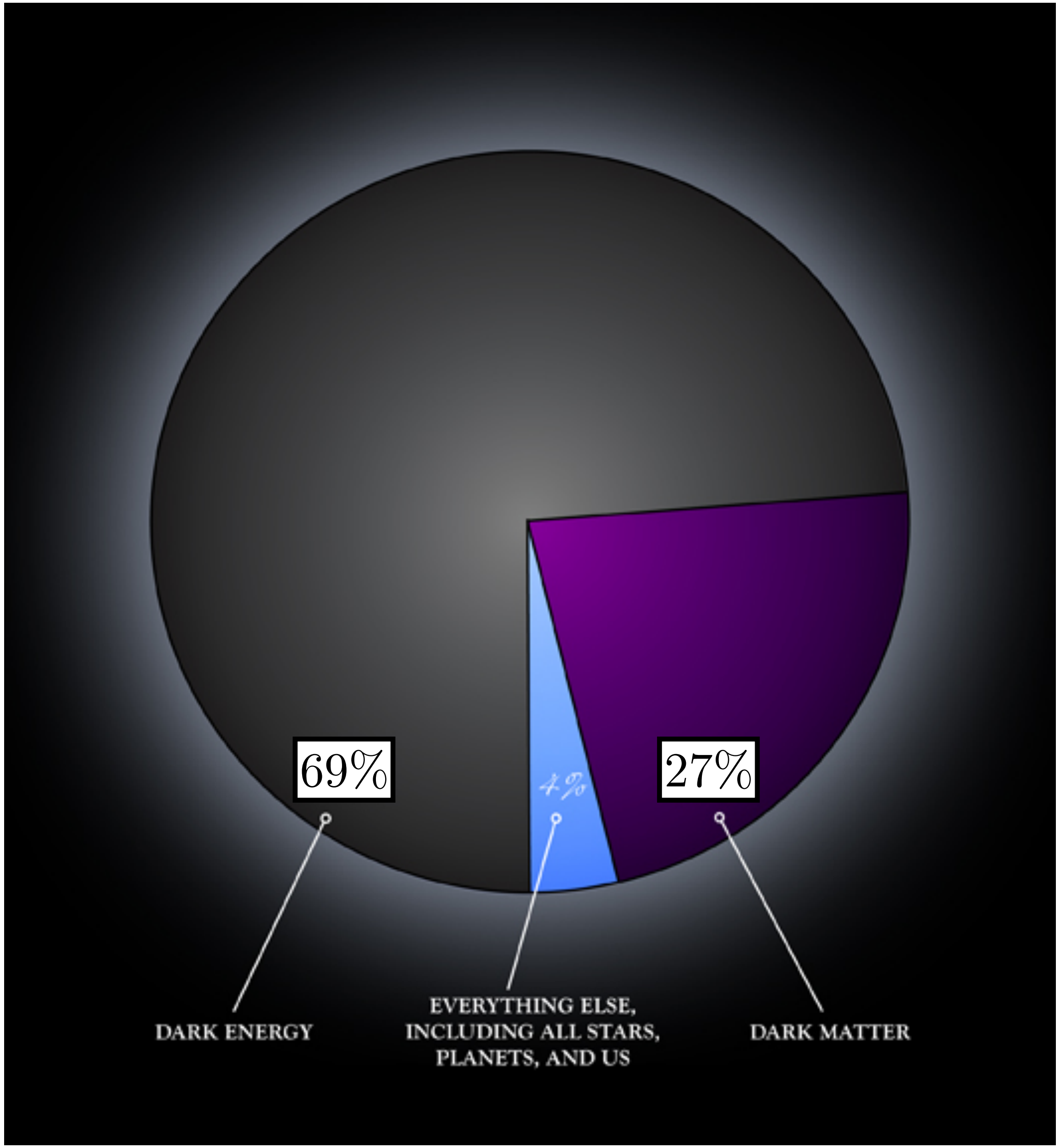
$$\text{Calculated with } \Omega_m = \Omega_{DM} + \Omega_b = 0.27 \sim \Omega_m^{\text{WMAP9}} \sim 0.2865 \pm 0.0088$$

*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



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

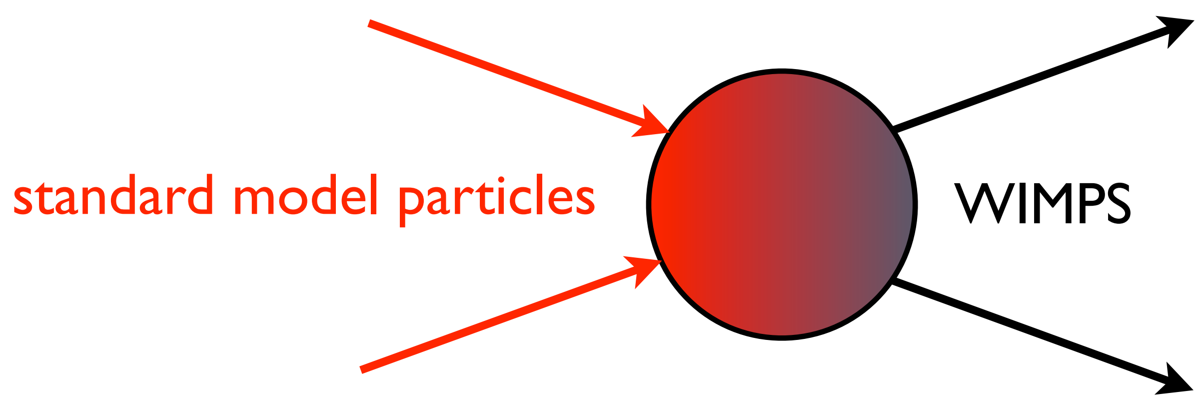
Leading candidates are weakly interacting massive particles (WIMPs) and axions

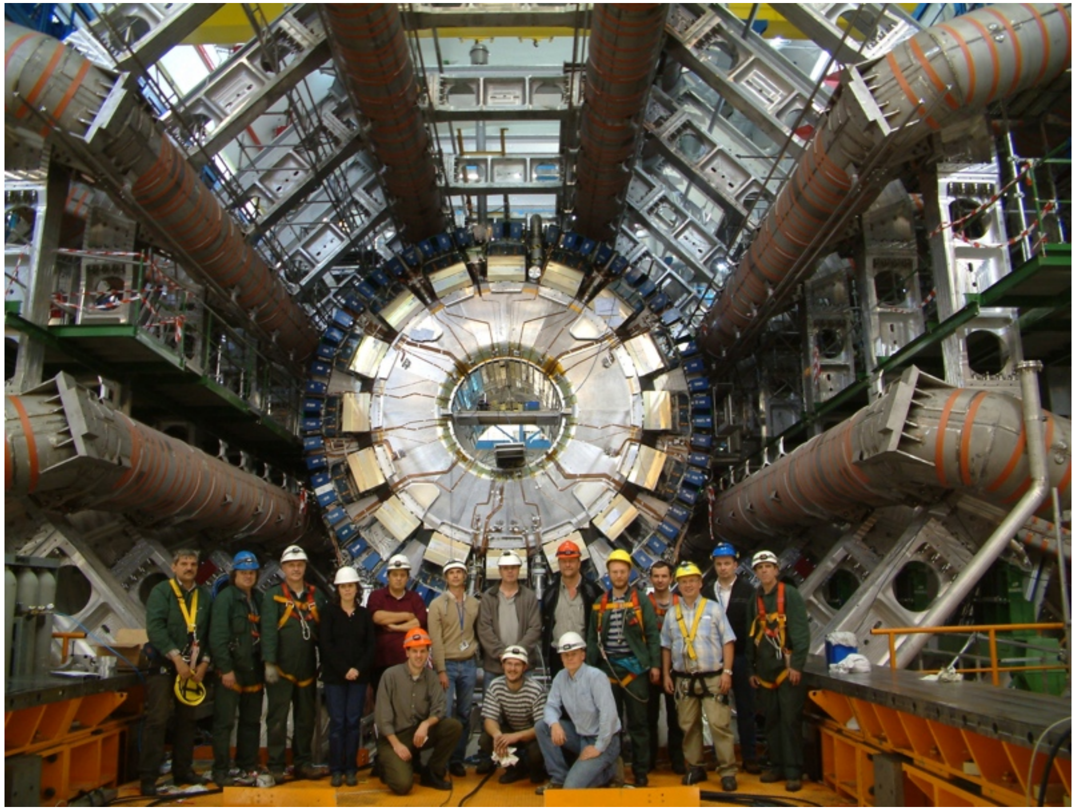
WIMPs motivated by the expectation that new physics might be found at the mass generation scale of the SM model: $M_{WIMP} \sim 10$ GeV - 10 TeV

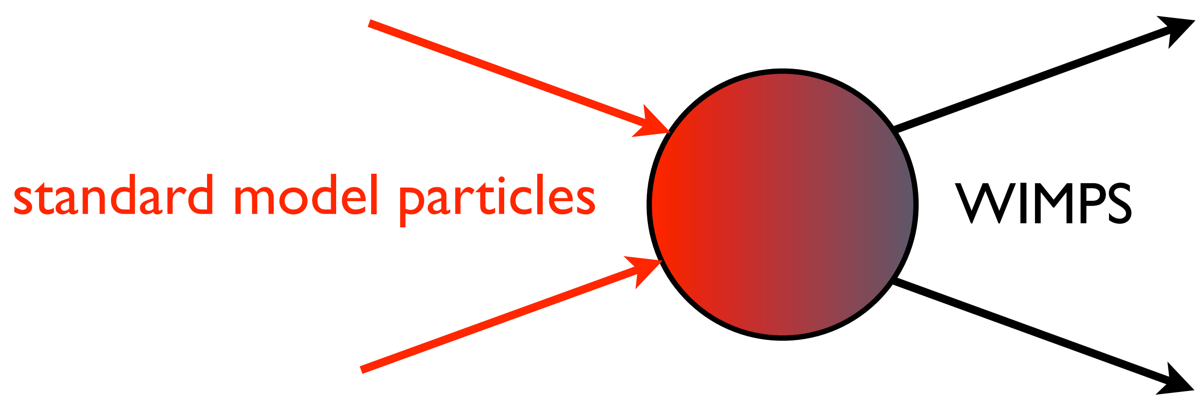
- "WIMP miracle:" G_F^2 annihilation cross sections imply $\Omega_{WIMP} \sim 0.1$

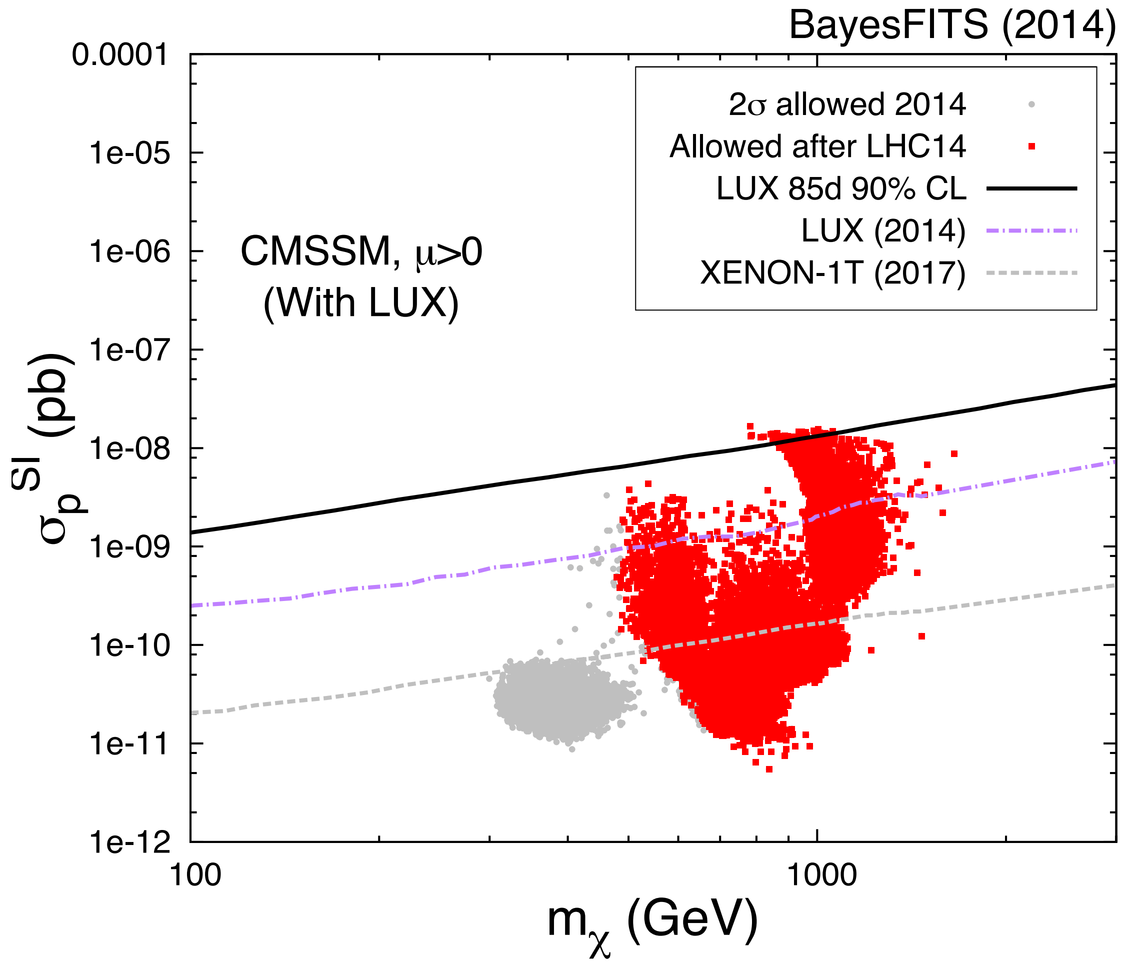
WIMP detection: the detection channels include (other than large scale structure)

- collider searches

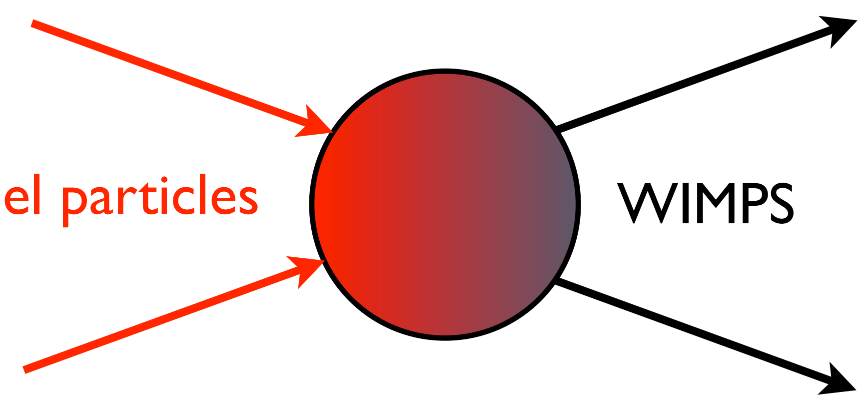





standard model particles
WIMPS



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



From L. Roszkowski, DM@UCLA 2014

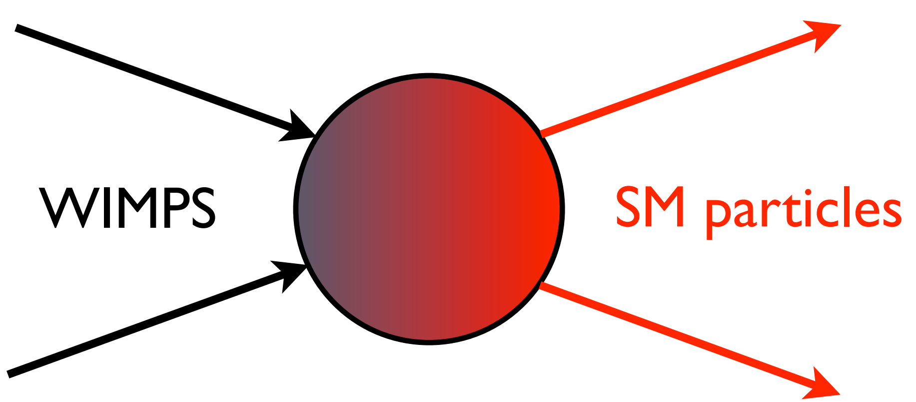
Detection: their detection channels include (other than large scale structure)

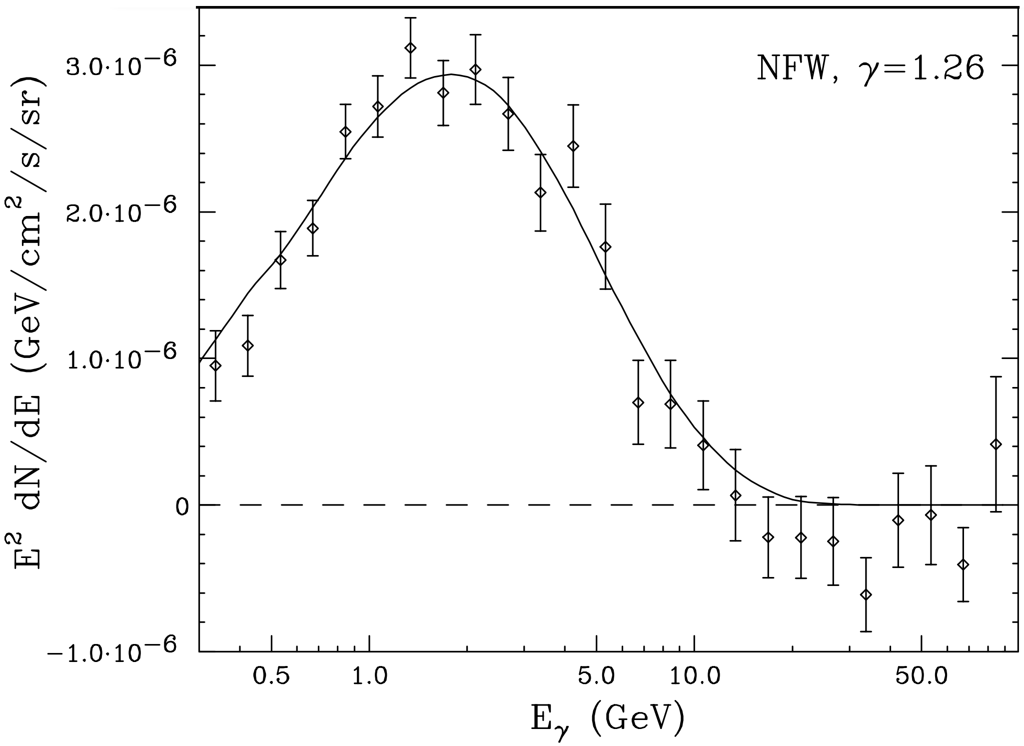
- collider searches
- indirect detection: astrophysical signals

Current focus is a possible dark-matter annihilation signal at the galactic center, consistent with a DM signal with

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

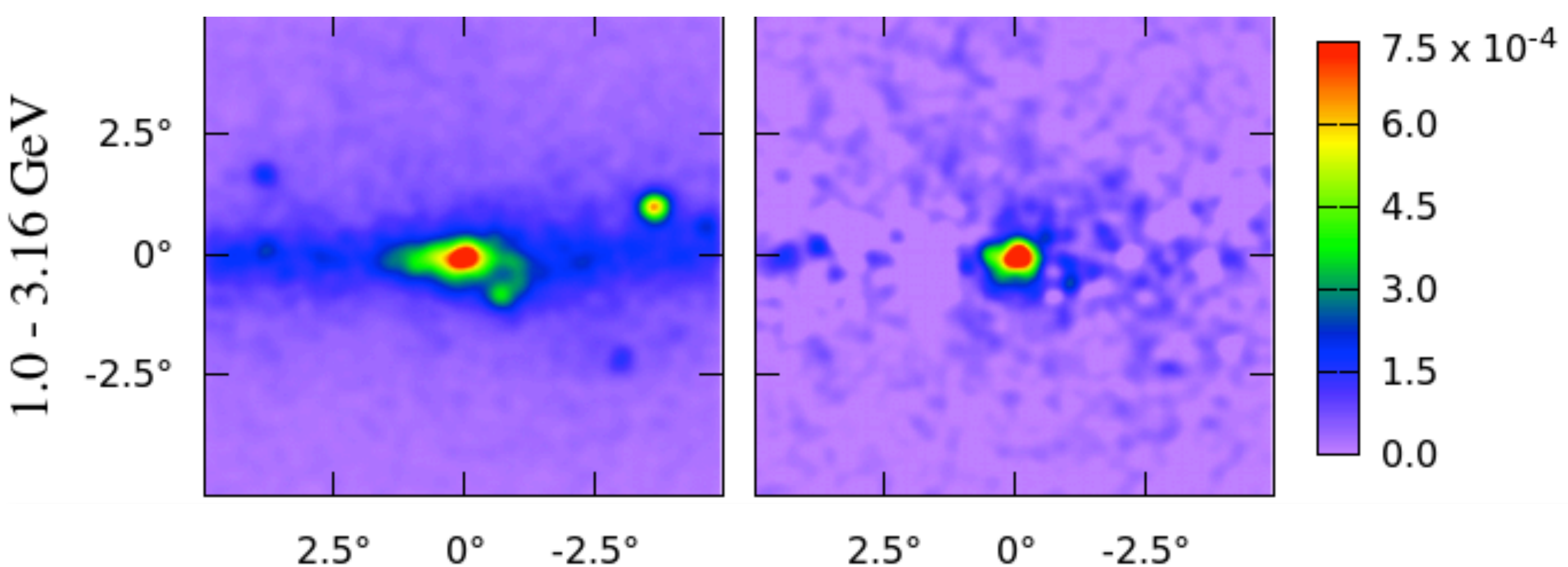
and consistent with a ~ 30-40 GeV WIMP annihilating to b quarks, producing ~ 5 GeV gammas





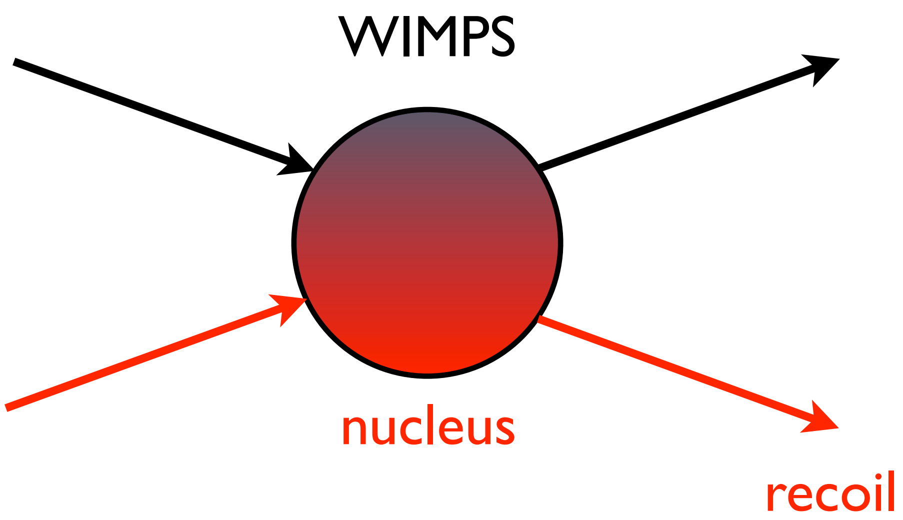
From D. Hooper,
UCLA DM Workshop

(Fermi collaboration has not yet made a claim)



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

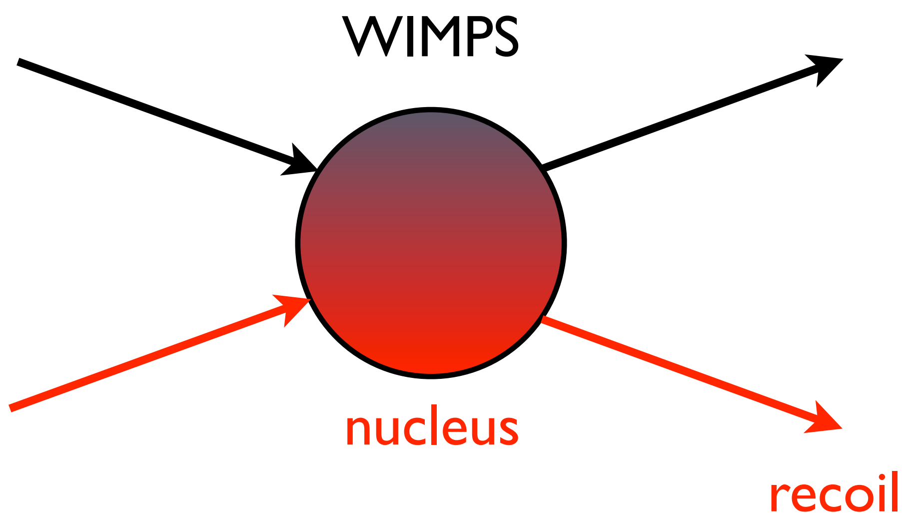
- collider searches
- indirect detection: astrophysical signals
- direct detection



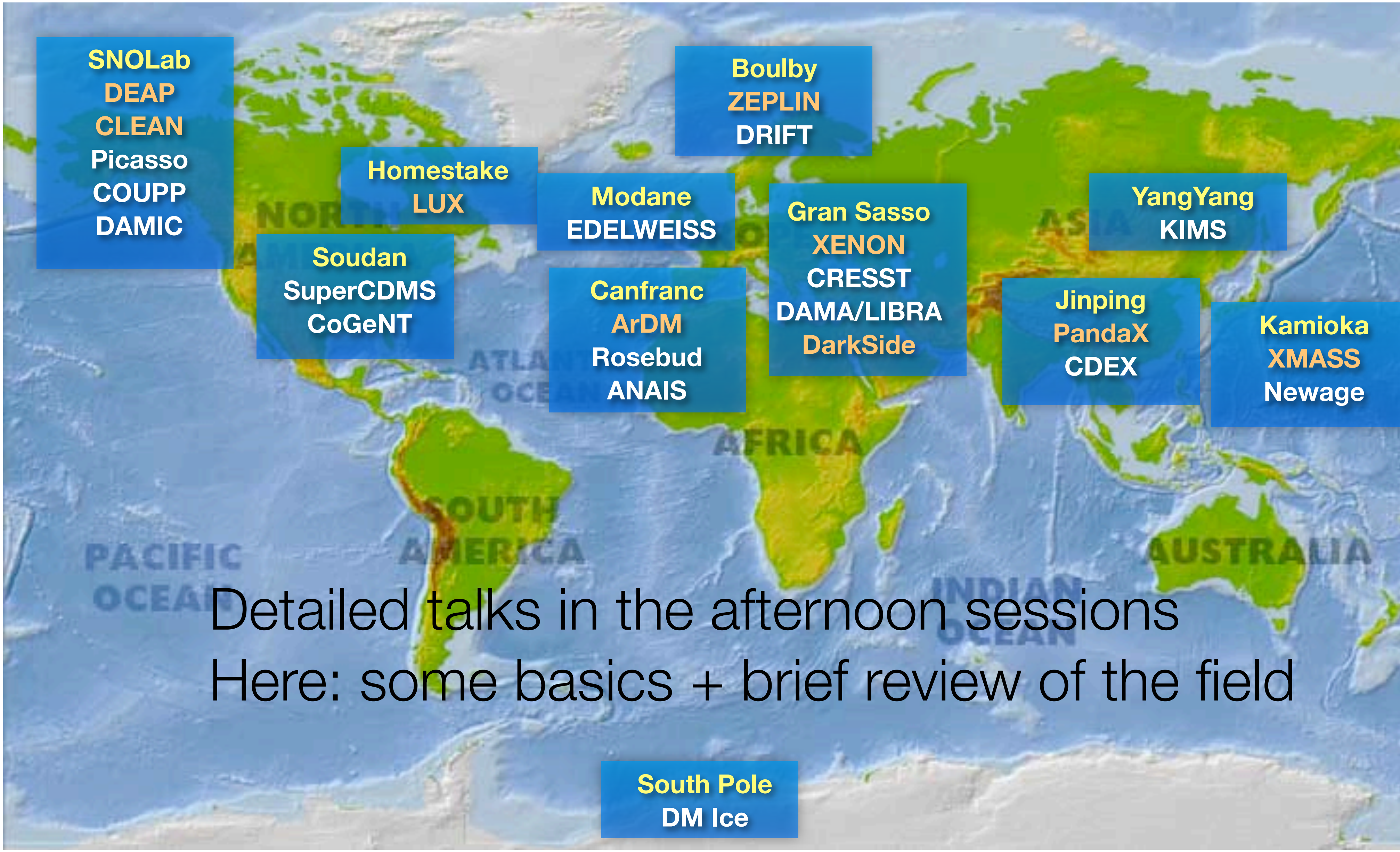
Detection: their detection channels include (other than large scale structure)

- 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
TeO2:	CUORE
CaWO4:	CRESST

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

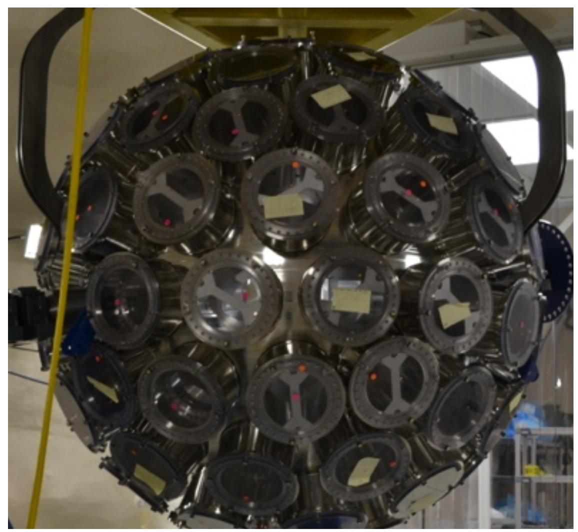
Noble Gasses

Single-phase detectors (scintillation light)

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

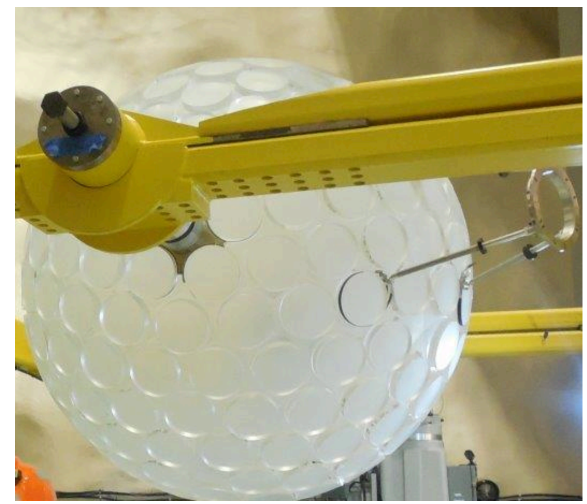
XMASS-RFB at Kamioka:

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



CLEAN at SNOLab:

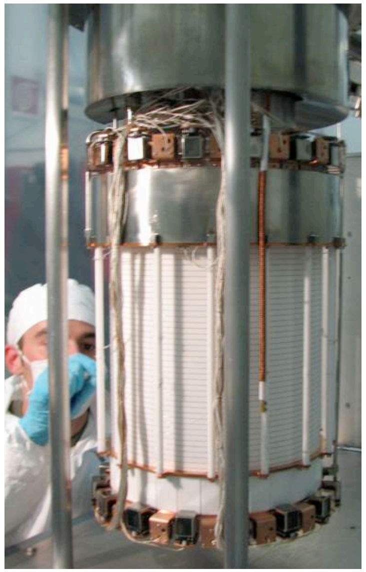
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014



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

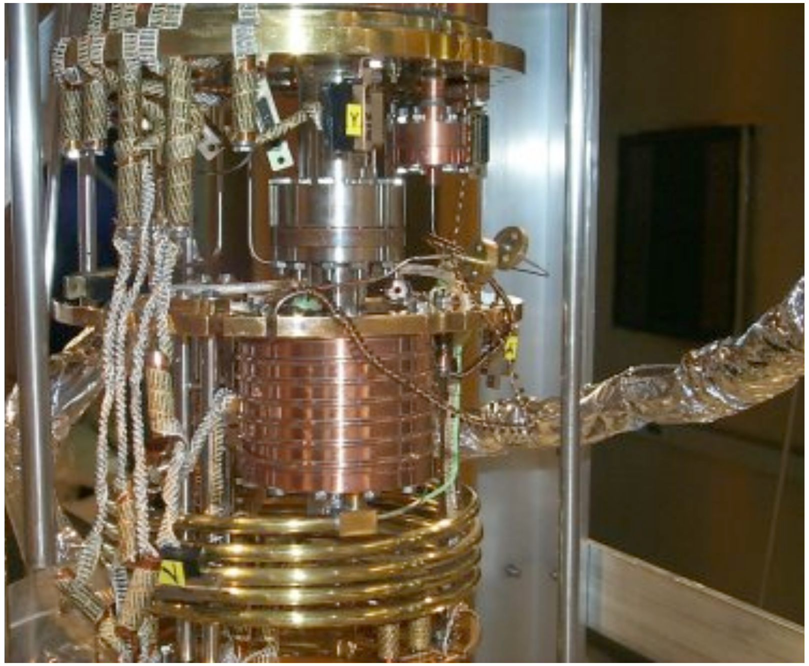
DarkSide at LNGS

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

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

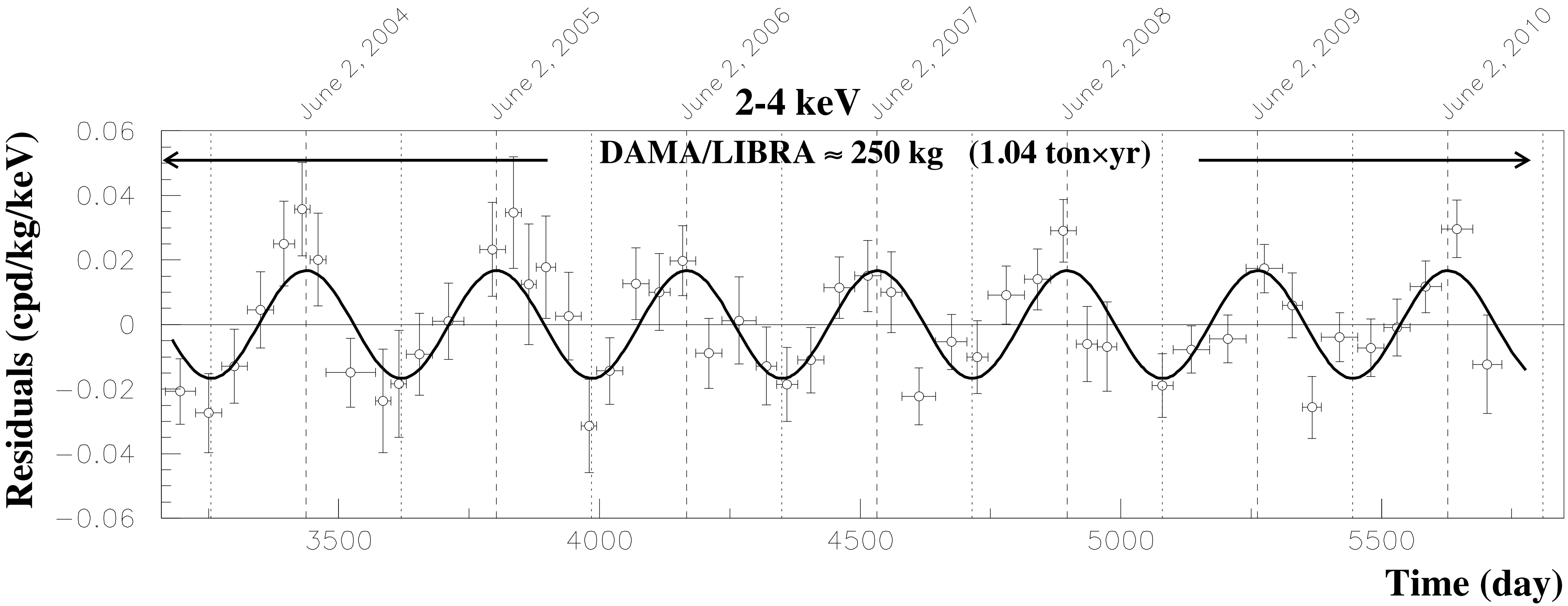
Crystals, Bubble Chambers, ...

DAMA/LIBRA NaI



CDMS Si, Ge
CoGENT Ge

Coup CF_3I

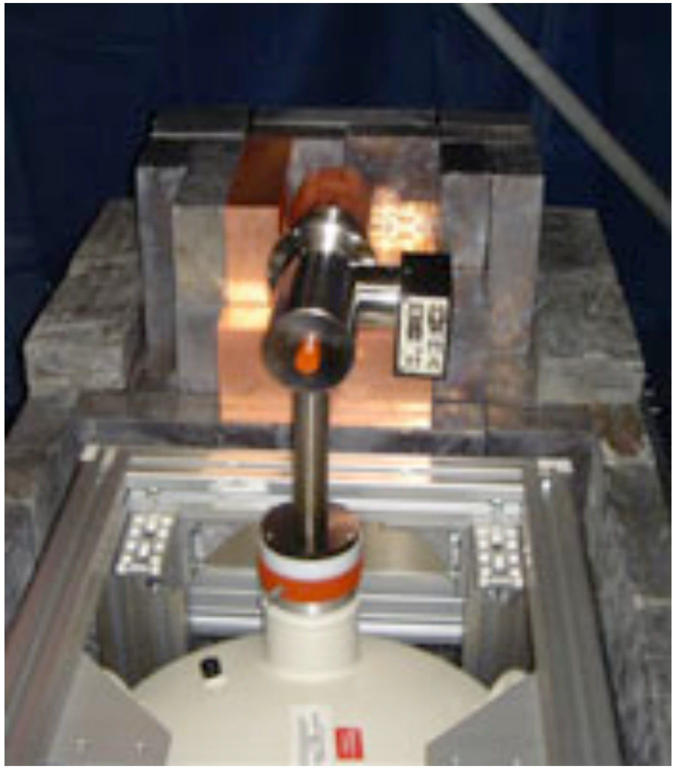


DAMA/LIBRA: 9.3σ variation of the signal over the year, attributed to the expected variation of a DM signal on the Earth's velocity due to rotation around the Sun

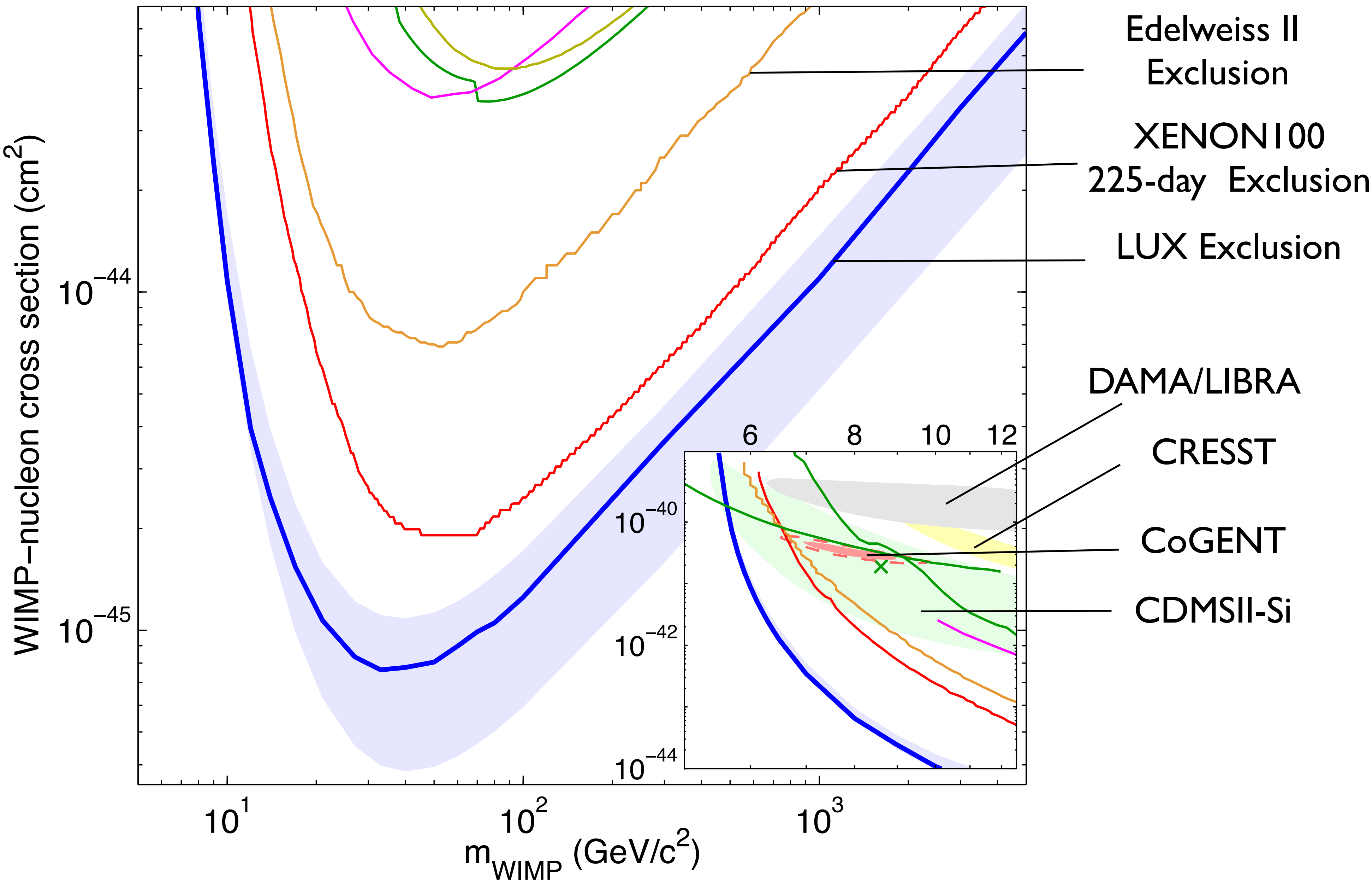
note 10 M_{WIMP} ~ 10 GeV → E_R^{max} ~10 keV

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

How are these comparisons among experiments done?

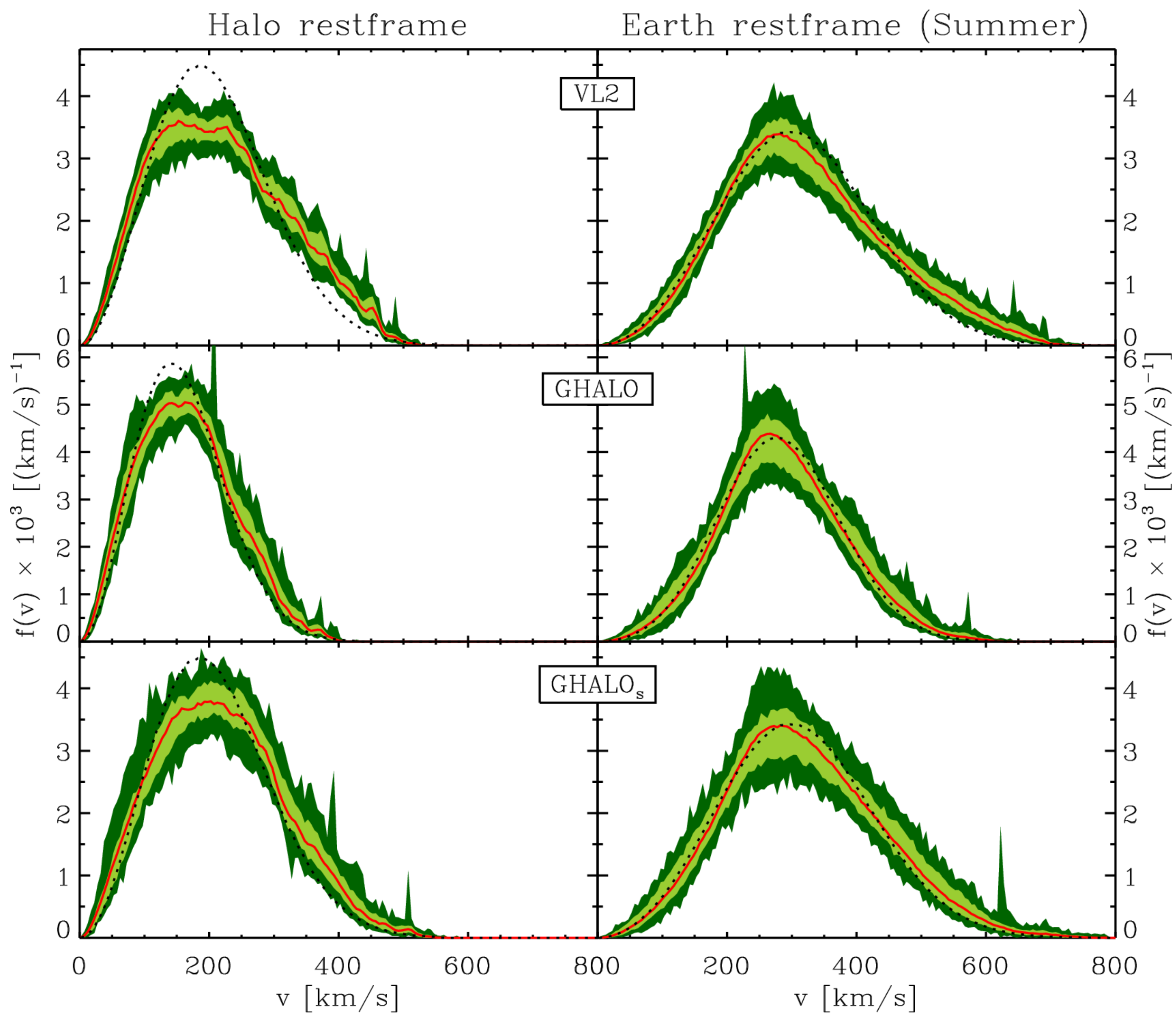
We know some basic parameters

- 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
- $R_{NUC} \sim 1.2\, A^{1/3}\, f \implies q_{max} R \sim 3.2 \Leftrightarrow 6.0$ for F $\Leftrightarrow$ Xe: the WIMP can "see" the structure of the nucleus

Our motion through the WIMP "wind" can be modeled

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

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



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

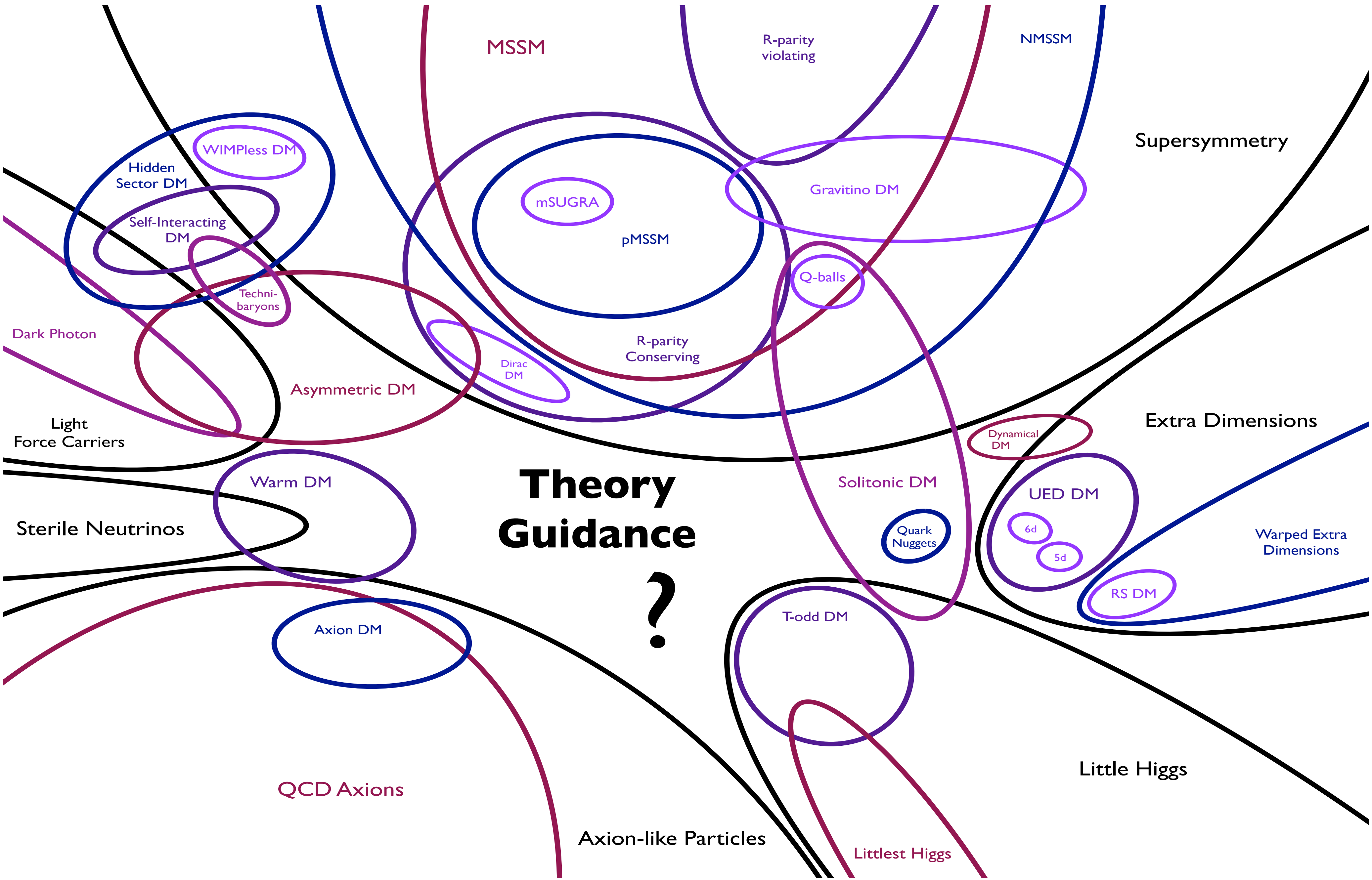
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

$N_N =$	number of target nuclei in detector
$\rho_0 =$	Milky Way dark matter density
$f(\mathrm{v}) =$	WIMP velocity distribution, Earth frame
$m_W =$	WIMP mass
$\sigma =$	WIMP – nucleus elastic scattering cross section

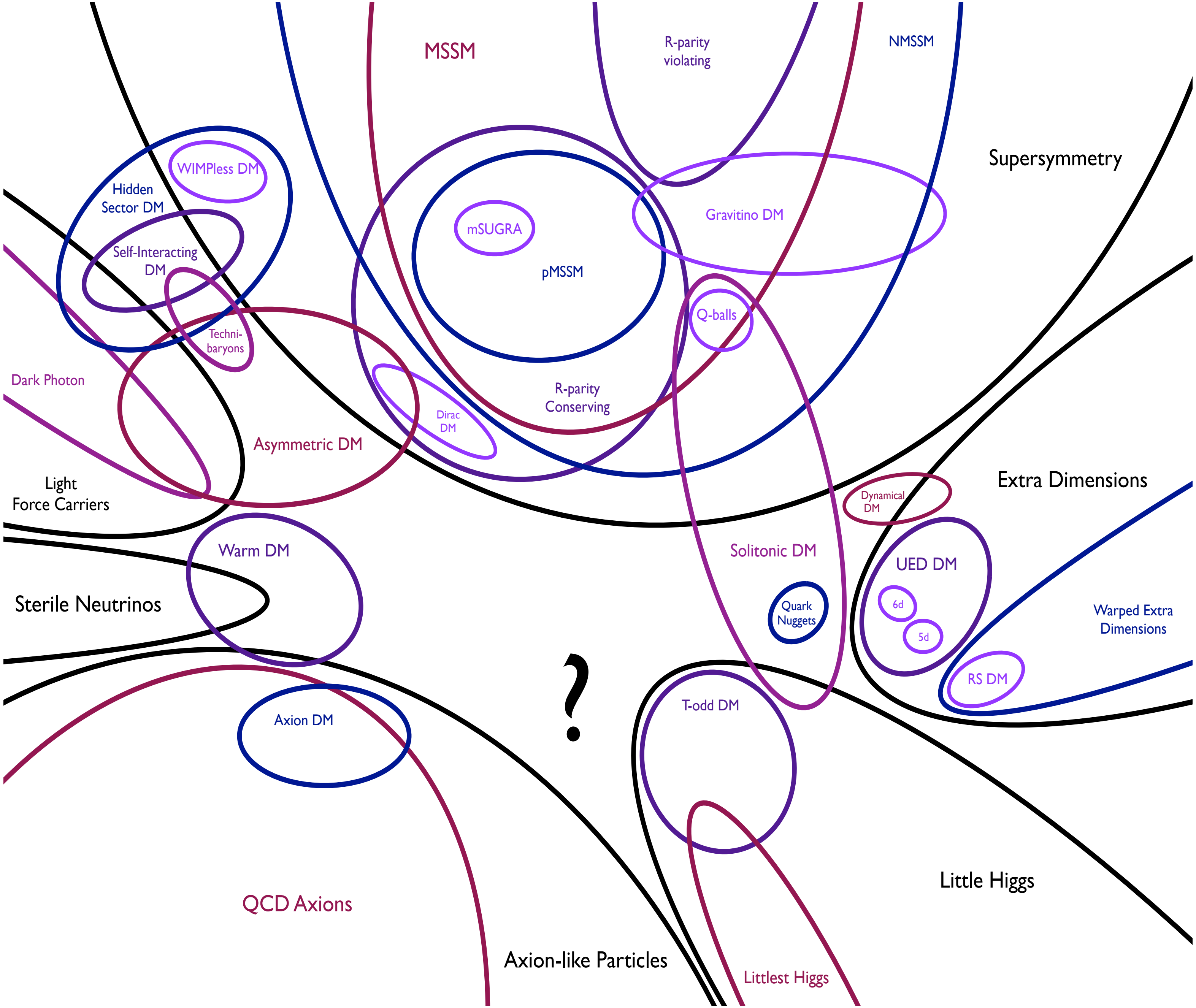
But where do we get the cross section -- the WIMP-nucleus interaction?

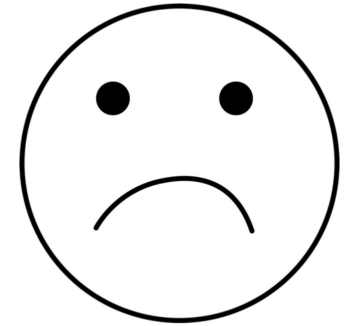
In fact, what can and cannot be learned about the WIMP-matter interaction from these low-energy elastic scattering experiments?

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

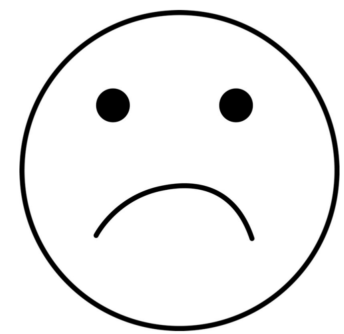


from Tim Tait

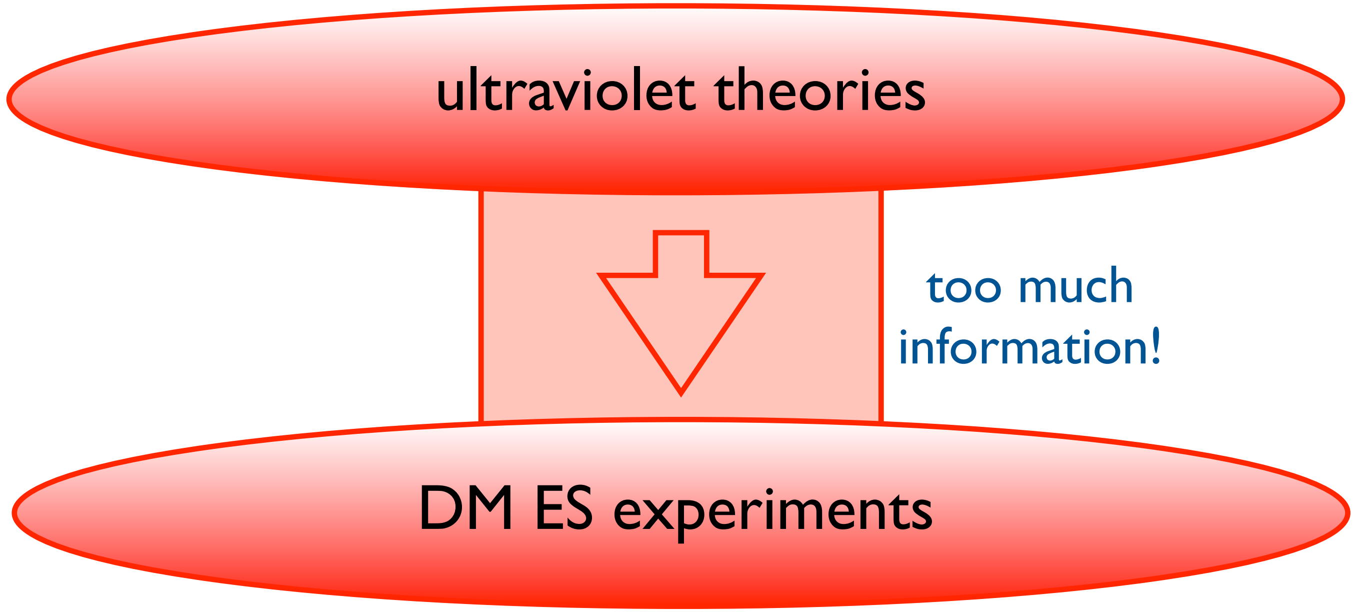




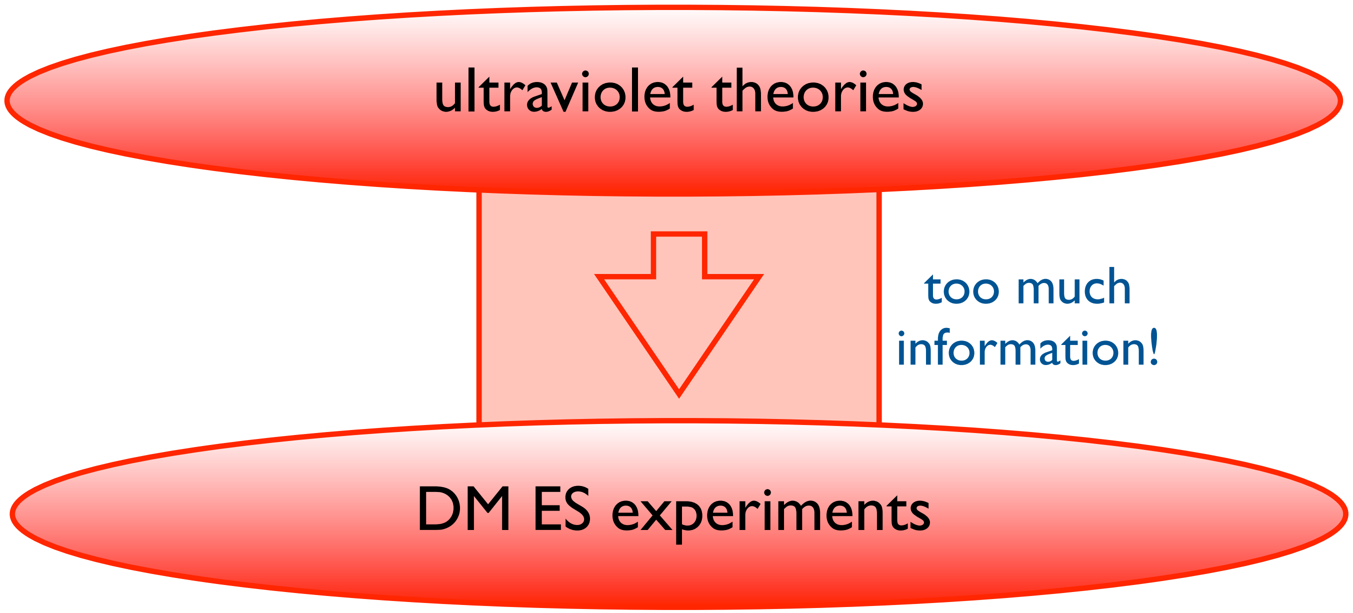
Nuclear theorist



DM experimentalist

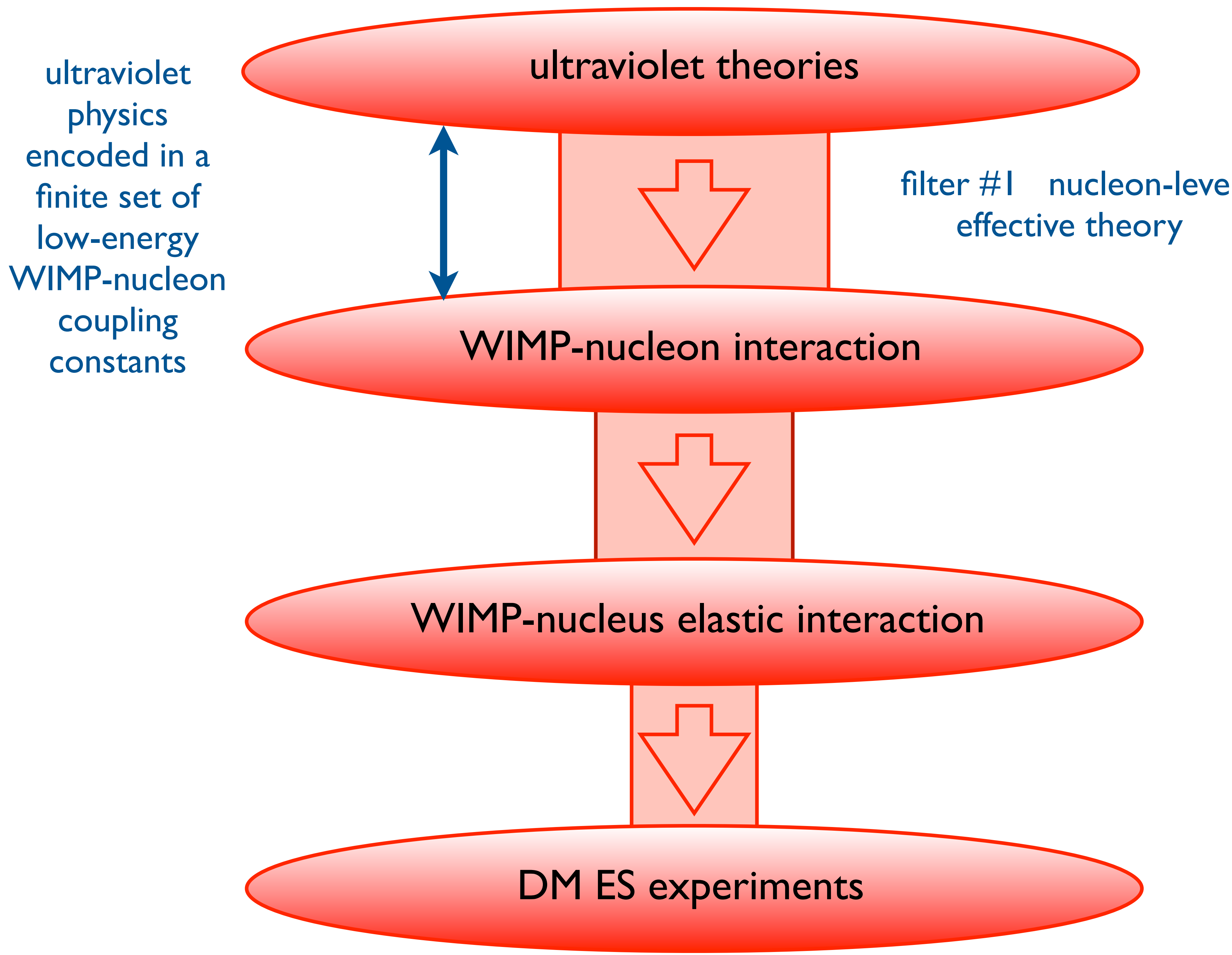


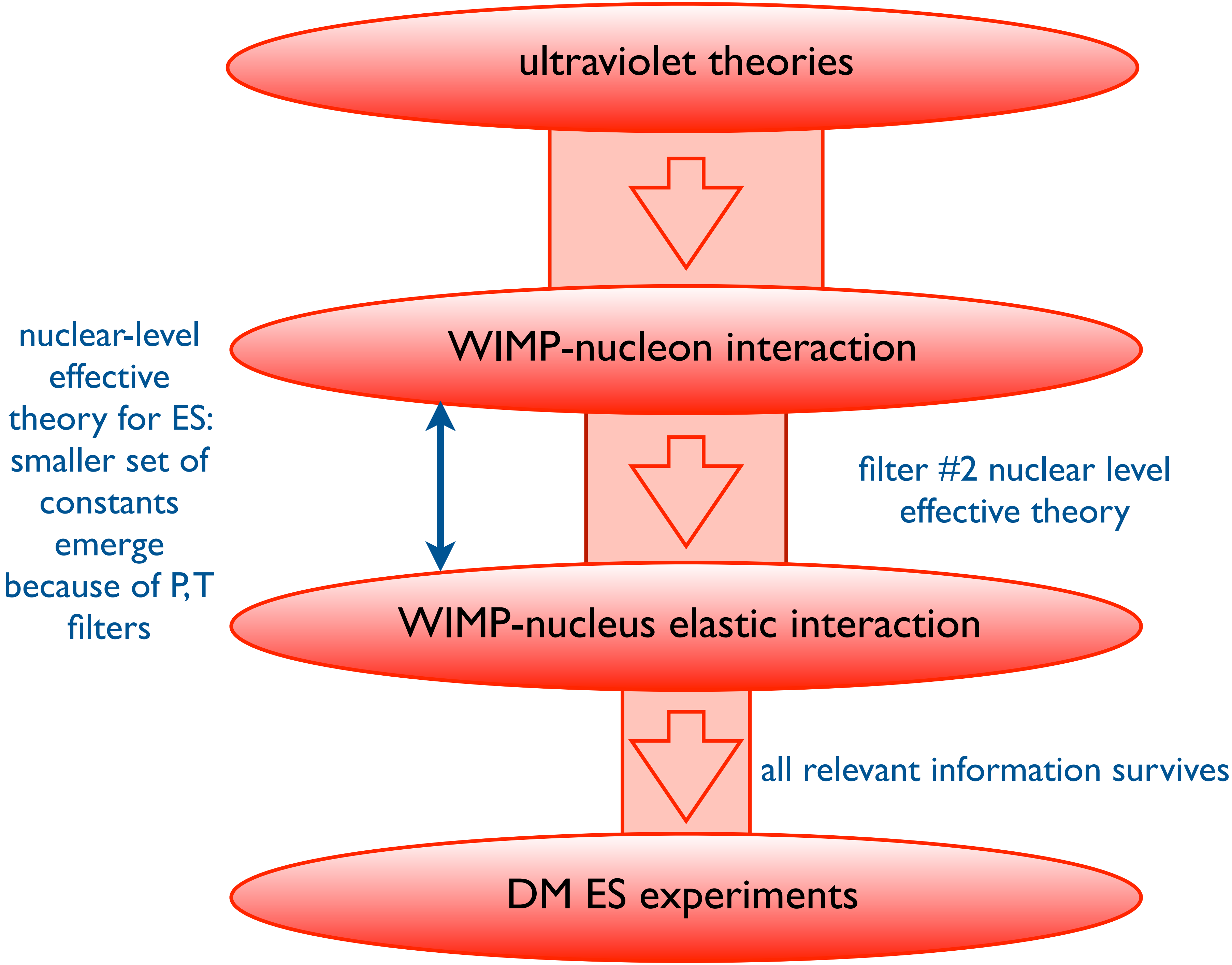
This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory



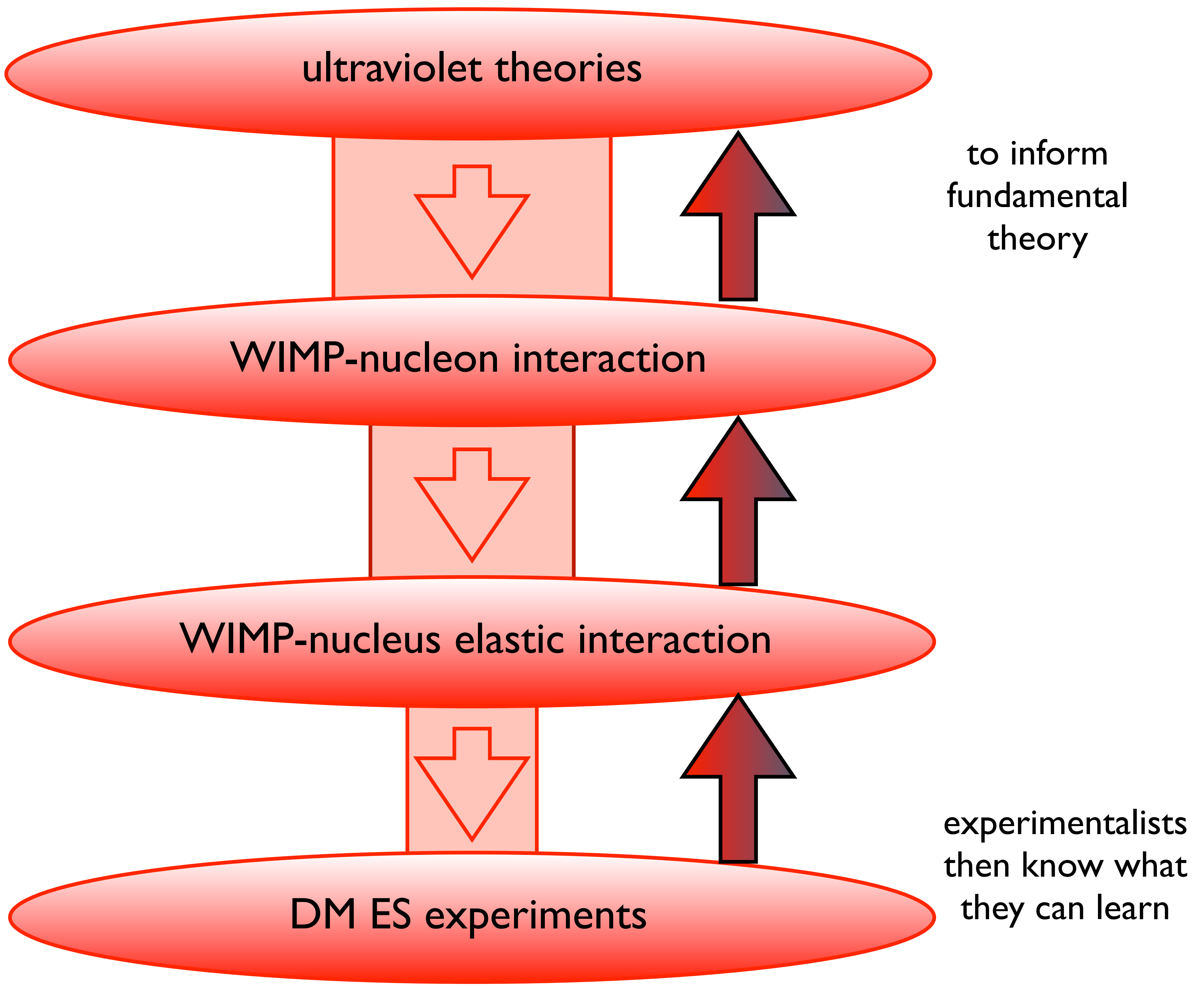
This is a very difficult step, and a tedious one as it must be taken for each candidate ultraviolet theory

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



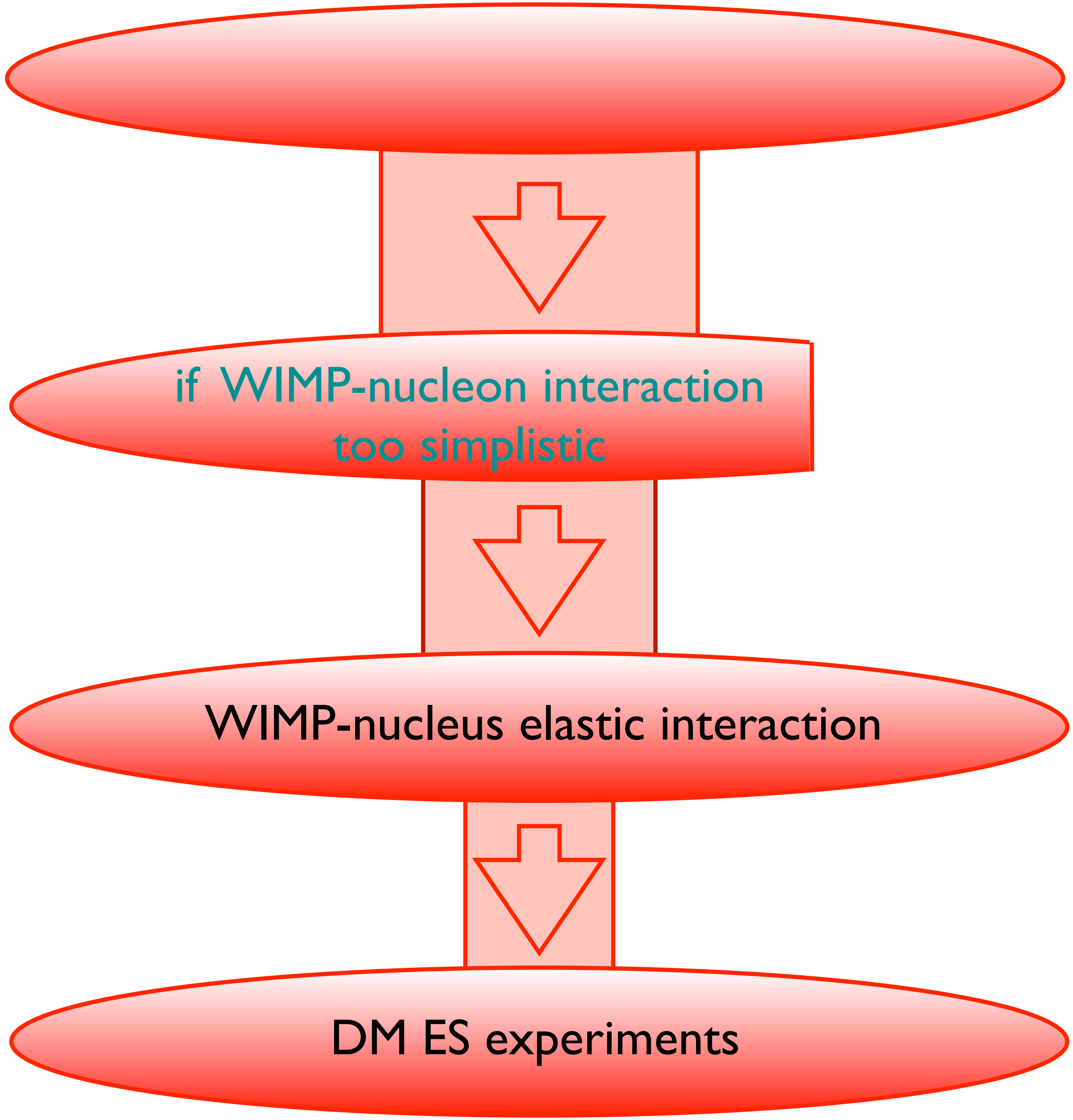
ultraviolet theories
WIMP-nucleon interaction
nuclear-level effective theory for ES: smaller set of constants emerge because of P,T filters
filter #2 nuclear level effective theory
WIMP-nucleus elastic interaction
all relevant information survives
DM ES experiments

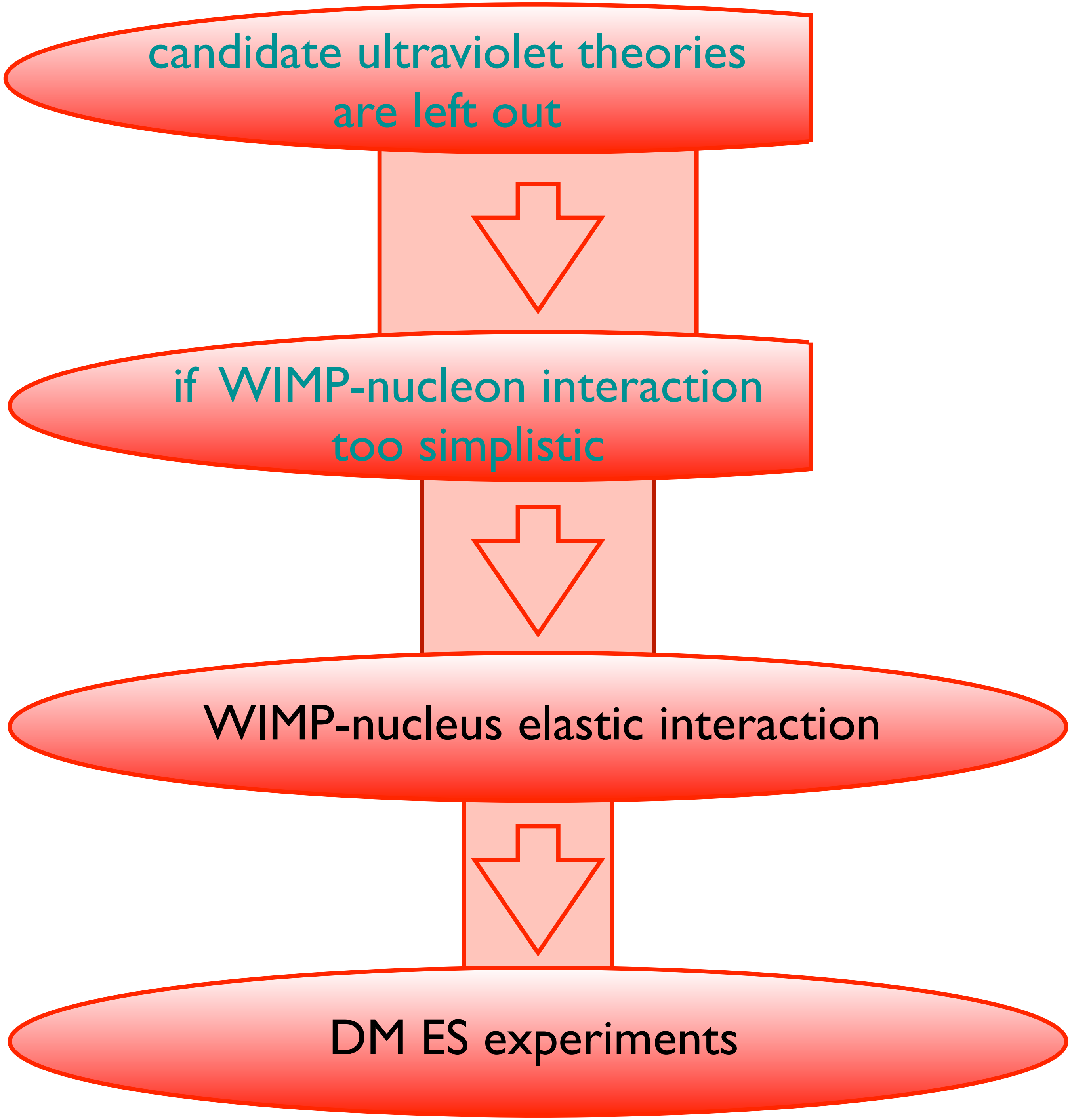

ultraviolet theories
to inform
fundamental
theory
WIMP-nucleon interaction
WIMP-nucleus elastic interaction
experimentalists
then know what
they can learn
DM ES experiments

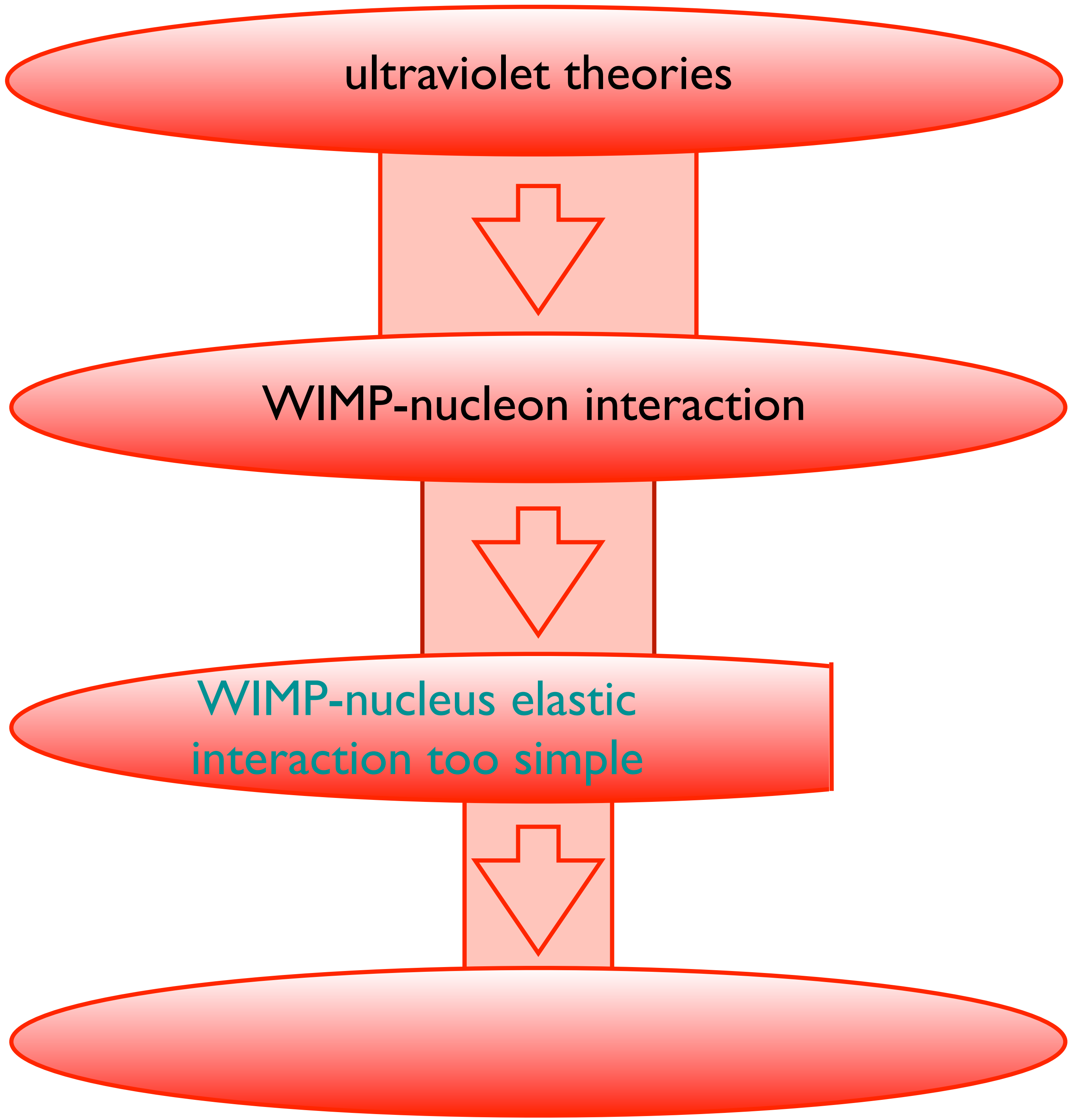
the effective theory process works only if each step is executed properly

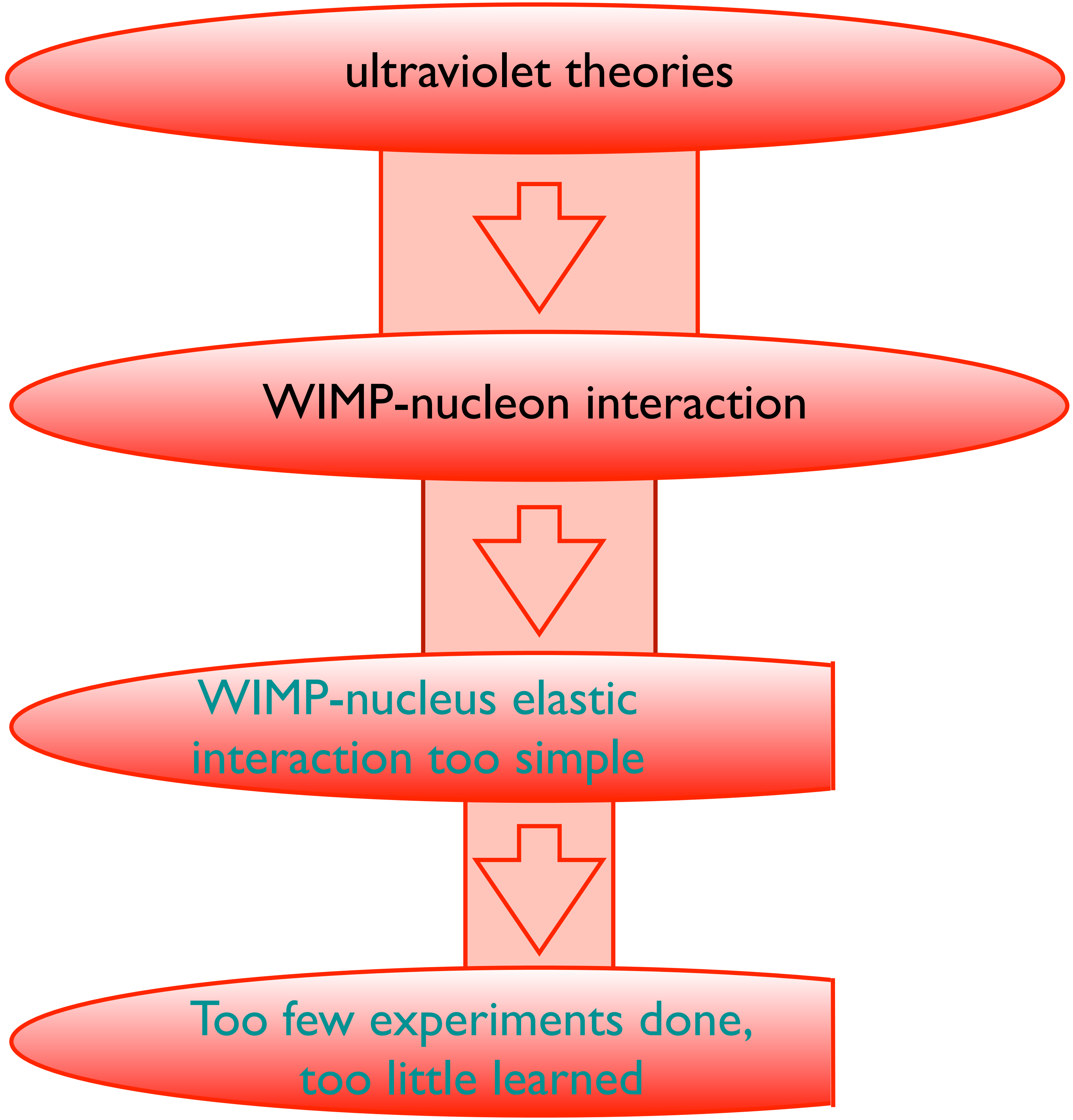
this

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	
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)

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? What are these additional responses?

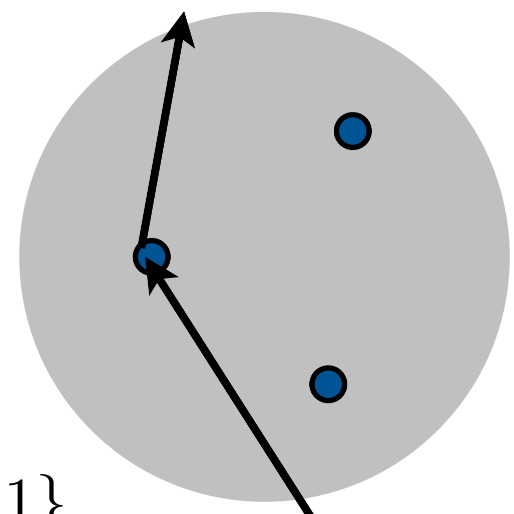
They are the responses connected with velocity-dependent interactions - that is, with theories that have derivative couplings

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 $\vec{S}_\chi \cdot \vec{v}_{\rm WIMP} \sum_{i=1}^{A} 1(i)$

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



- But in reality

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

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 $\vec{\dot{v}}(i)$ 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

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

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

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

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

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

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

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

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

WIMP tensor:
contains all of the DM particle physics

depends on two "velocities"

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

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

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

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?

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

$$\downarrow$$

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

take q → 0
suppress isospin

the S.I. response

contributes for J=0 nuclear targets

- What does the effective theory say about these responses?

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

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

take q → 0
suppress isospin

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

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?

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

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

take q → 0
suppress isospin

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?

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

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

take q → 0
suppress isospin

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?

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

take q → 0
suppress isospin

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

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

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

$$
\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}\Big[c_4^\tau c_4^{\tau'} + \\
&\quad \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'}\Big] \\
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}\Big[c_4^\tau c_4^{\tau'} + \\
&\quad \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'}\Big] \\
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}
$$

The point-nucleus world is a very simple one

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

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

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

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

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

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

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

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

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

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

- 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 another day but interesting: excited nuclear states

- ES almost blind to certain familiar interactions: axial charge $\vec{\sigma}(i) \cdot \vec{p}(i)$
  - signature would be a anomalous cross section for excited-state transitions, when compared to the elastic cross section

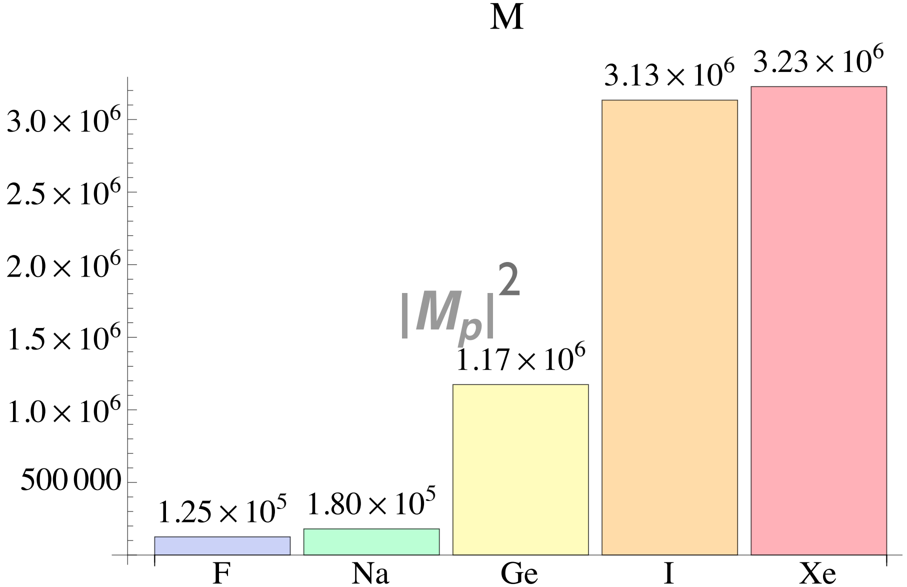
- gives one strategies for measuring the mass of a very heavy WIMP (hard to do with ES alone because $\mu(M_T, M_\chi) \rightarrow \mu(M_T)$)

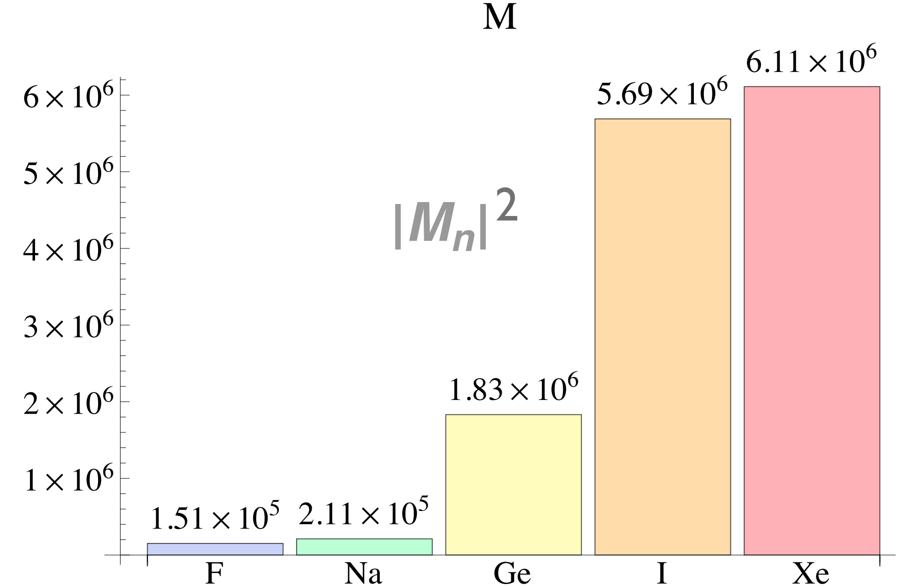
For illustration purposes only!

DAMA/LIBRA:	NaI
CoGENT:	Ge
LUX:	Xe

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

(normalized to natural abundance)

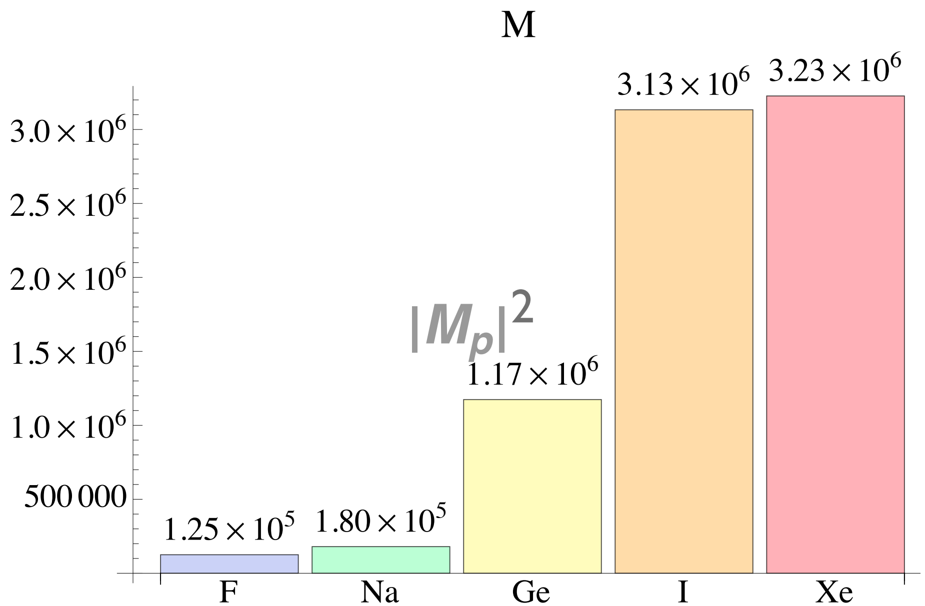


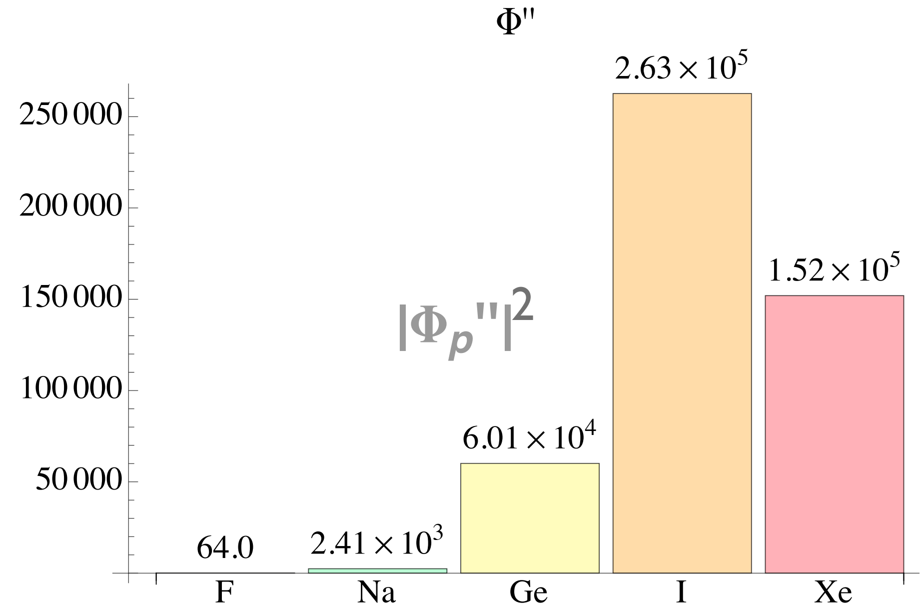


Standard SI sensitivities: LUX (Xe) > DAMA (NaI) > CDMS-Ge

Little sensitivity to isospin (unless tuned)

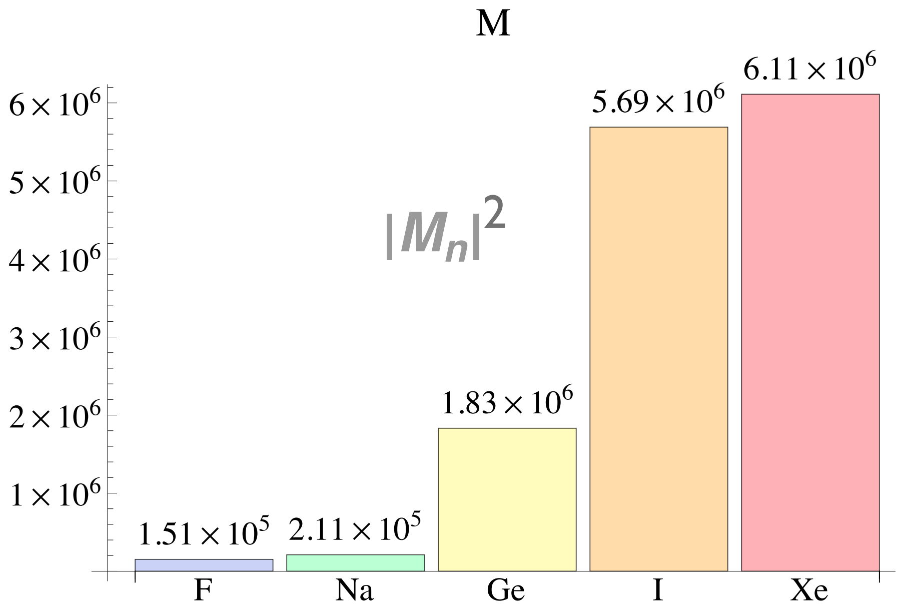
Scalar operators, p: $1(i)$ vs $\vec{\sigma}(i) \cdot \vec{\ell}(i)$

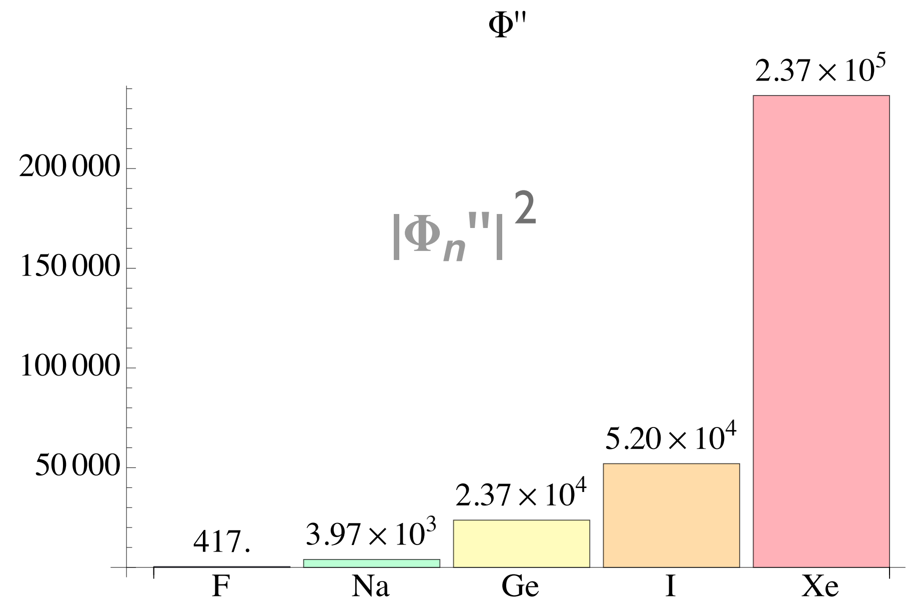




LUX (Xe) ~ DAMA (NaI) ⇒ DAMA > LUX

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

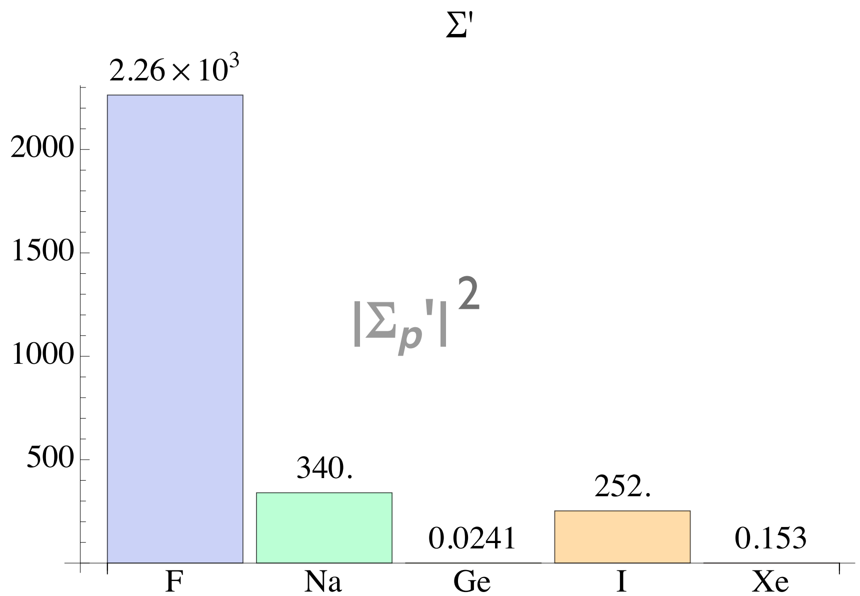


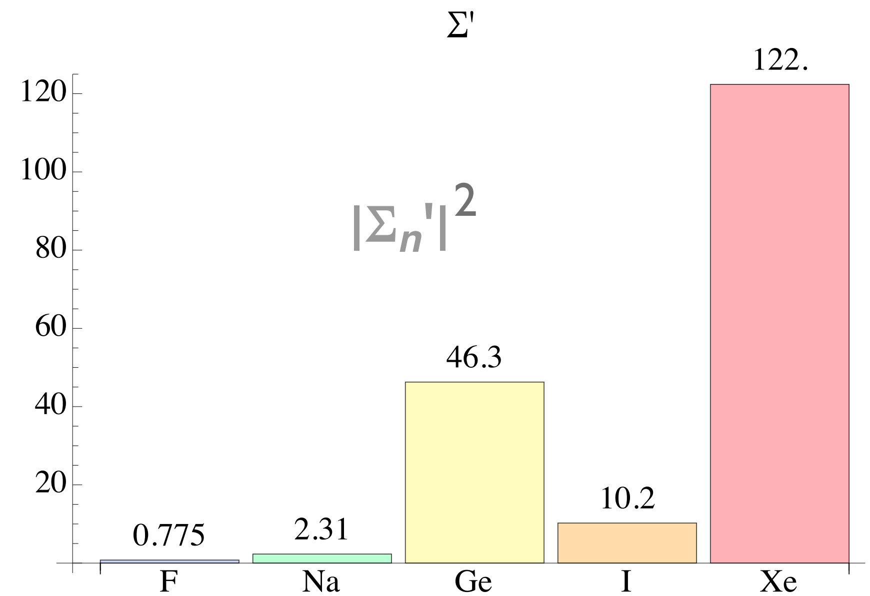


LUX (Xe) ~ DAMA (NaI) ⇒ DAMA < LUX

vector (transverse) spin response

(normalized to natural abundance)



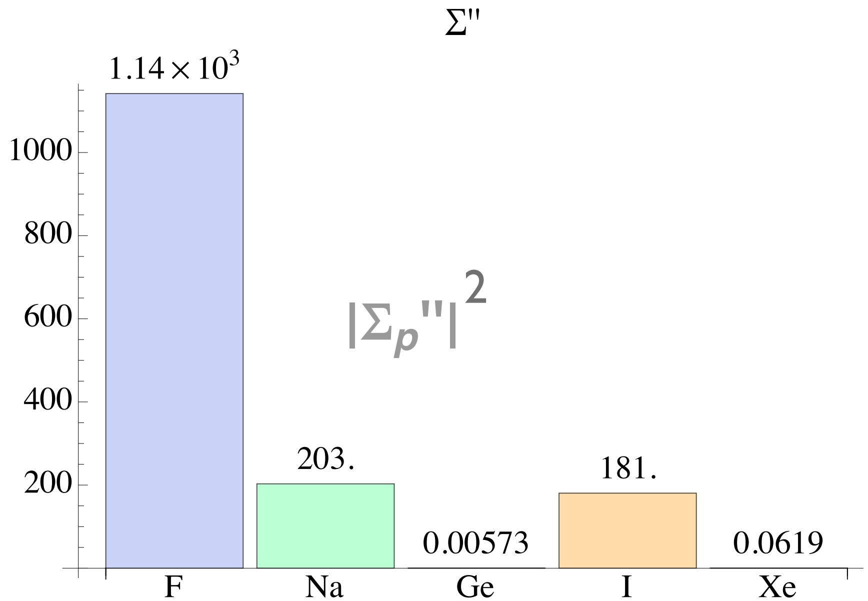


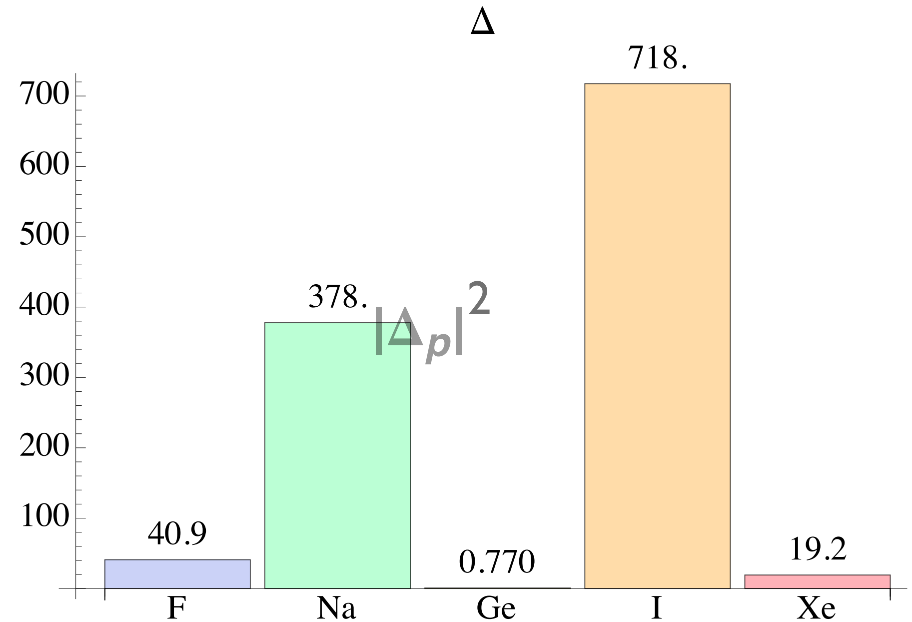
proton coupled: Picasso (F) > DAMA (NaI) ≫ CDMS-Ge & LUX

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

isospin

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



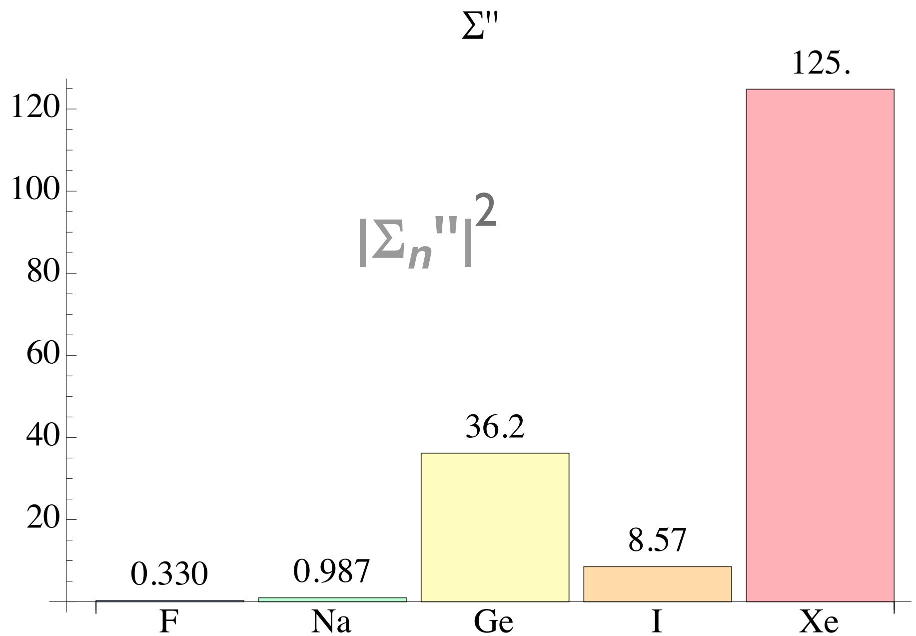


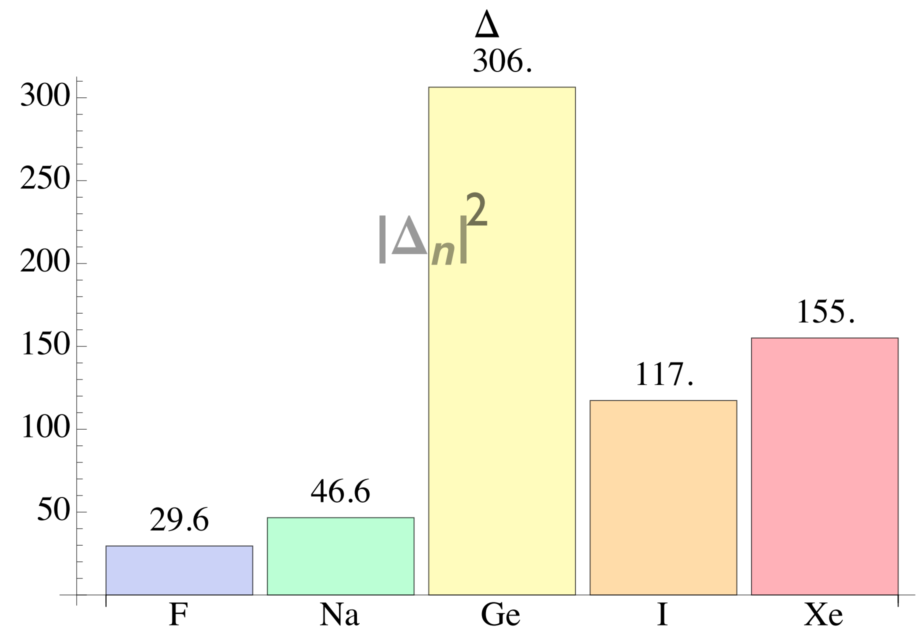
spin coupled: Picasso (F) > DAMA (NaI)

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

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