

# Identifying the Theory of Dark Matter with Direct Detection

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TUI-3

*June 25, 2015*

based on work with K. Zurek [1311.2082, 1401.3739] as well as V. Gluscevic, A. Peter, and S. McDermott [1506.04454]





# Dark Matter

**(a subject that marries grand questions at  
disparate scales)**

**We know it exists, but we don't  
really know what it is.**



# What we do know about dark matter:

- **It's dark.** (It doesn't emit, absorb, or reflect light.)
- **It's matter.** (It gravitationally attracts other stuff as if it were matter.)
- **It's not *Standard Model* matter** (It's not composed of atomic nuclei and/or leptons.)
- **It outnumbers normal matter in our local universe by about five to one.**




electric  
weak  
strong

increasing mass →


$-\frac{1}{3}$	✓	✓
$+\frac{2}{3}$	✓	✓
0	✓	✗
-1	✓	✗

**QUARKS**


**UP QUARK**  
A teeny little point inside the proton and neutron, it is friends forever with the down quark.




**CHARM QUARK**  
A charming second generation quark.




**TOP QUARK**  
This heavyweight champion doesn't live long enough to make friends with anyone.




**DOWN QUARK**  
A tiny little point inside the proton and neutron, it is friends forever with the up quark.



**STRANGE QUARK**  
What's so strange about this second generation quark?




**BOTTOM QUARK**  
This third generation quark is puttin' on the pounds.




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**LEPTONS**


**ELECTRON-NEUTRINO**  
This minuscule bandit is so light, he is practically massless.




**MUON-NEUTRINO**  
Like the other 2 neutrinos, he's got an identity crisis from oscillation.




**TAU-NEUTRINO**  
He's a tau now, but what type of neutrino will he be next?




**ELECTRON**  
A familiar friend, this negatively charged, busy li'l guy likes to bond.



**MUON**  
A "heavy electron" who lives fast and dies young.



**TAU**  
A "heavy muon" who could stand to lose a little weight.



other?

✗	?	✗	?
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# Dark Matter

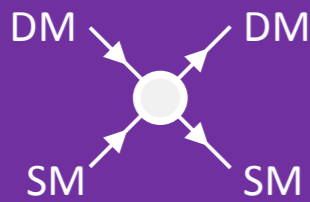
Nuclear Matter  
quarks, gluons

Leptons  
electrons, muons,  
taus, neutrinos

Photons,  
W, Z, h bosons

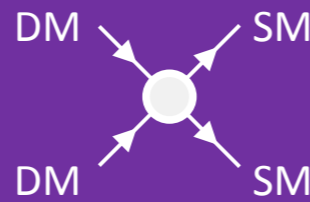
Other dark  
particles

Direct  
Detection



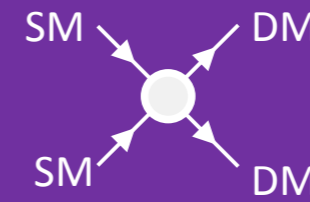
scattering

Indirect  
Detection



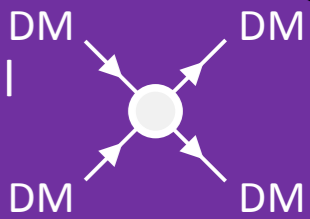
annihilation

Particle  
Colliders



production

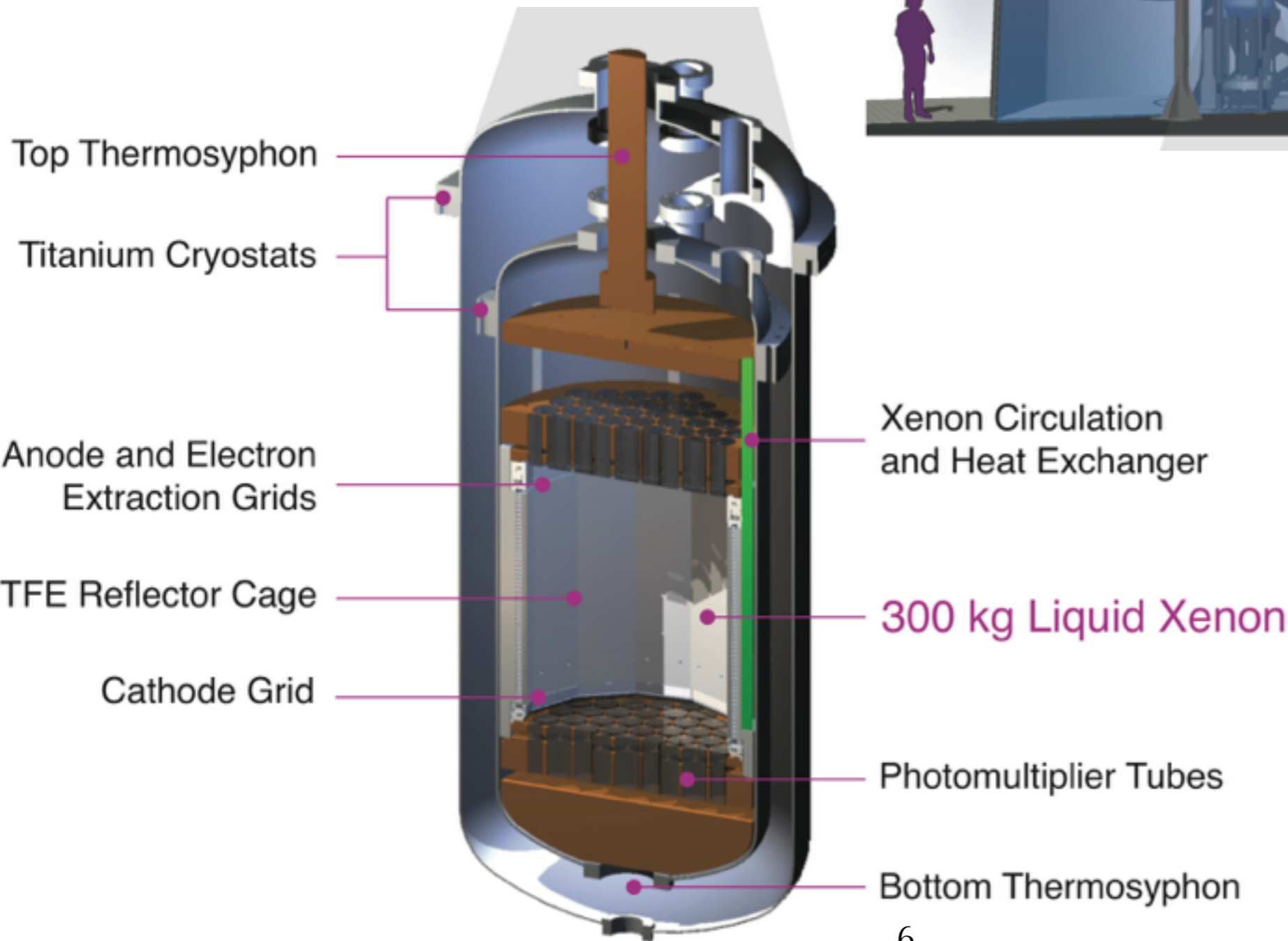
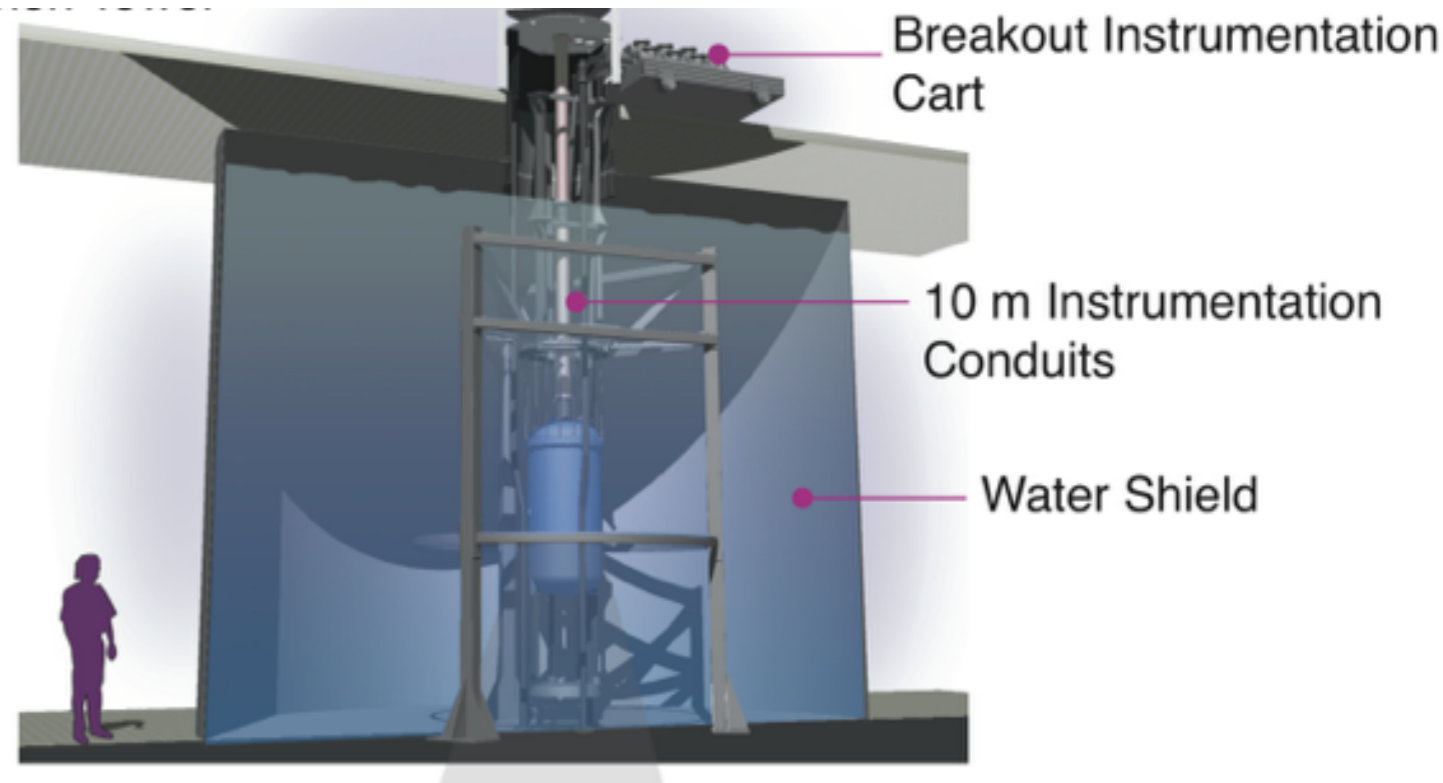
Astrophysical  
Probes



self-interaction

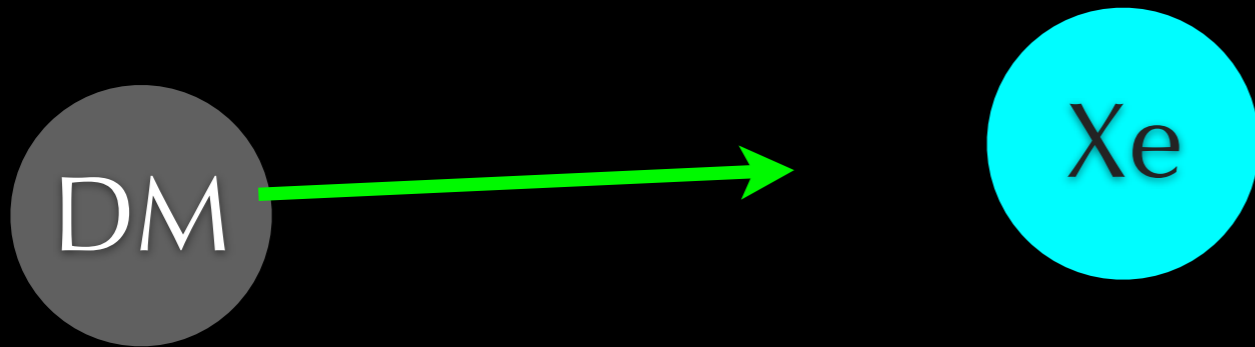






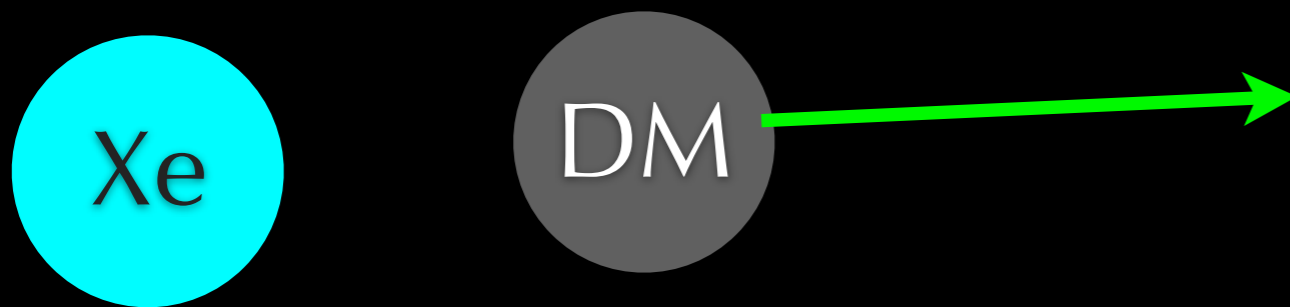
# Cartoon of Elastic Scattering

Before:



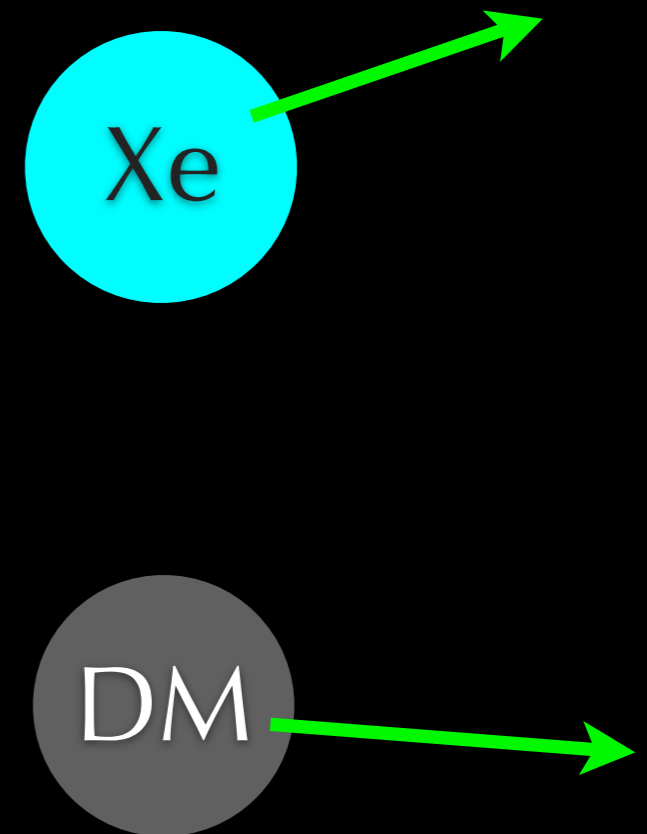
After:

[nothing happens]



[interaction occurs and we (indirectly) measure energy deposited]

OR



# What's the probability for the scattering to occur?

In principle it could depend on...

properties of the target (Xe, in this example)

- angular momentum
- mass
- # protons, # neutrons
- ...

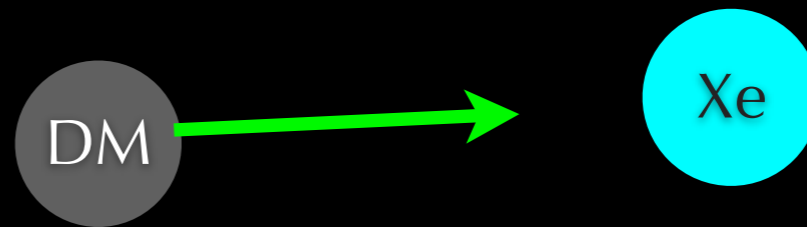
properties of the  
Dark Matter

- angular momentum
- mass

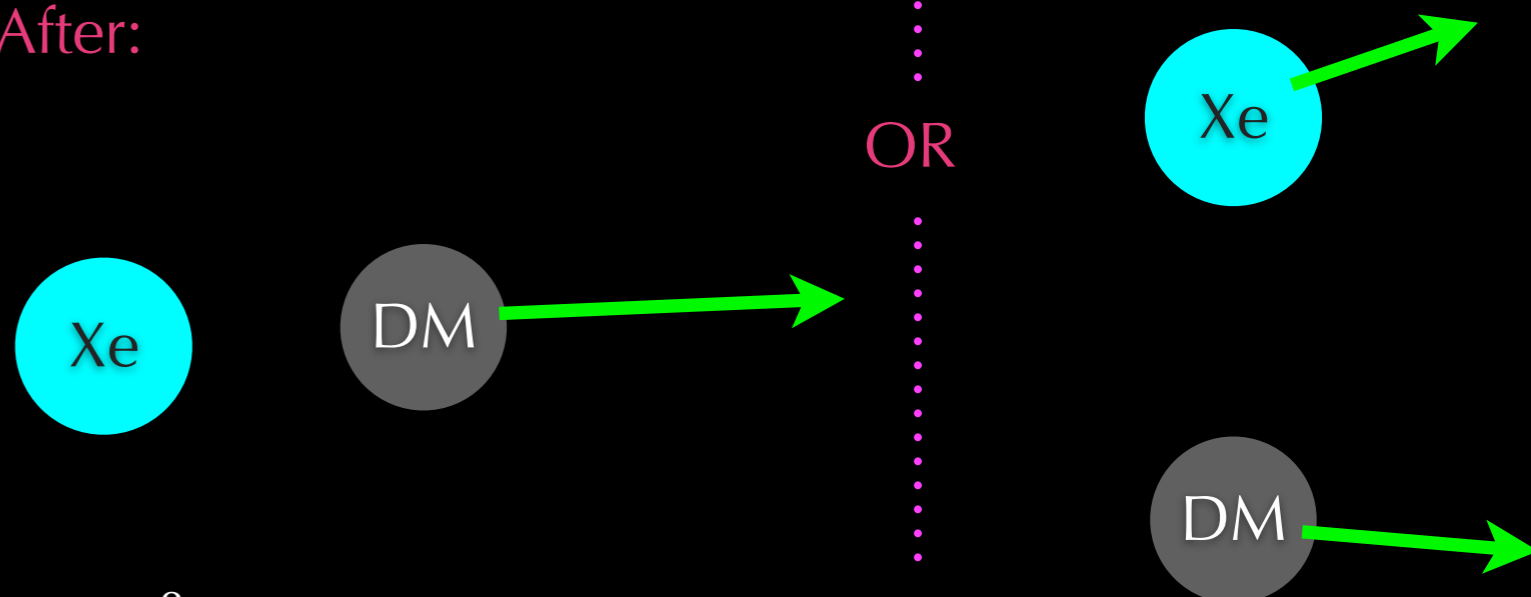
kinematic quantities

- DM velocity
- nuclear recoil energy

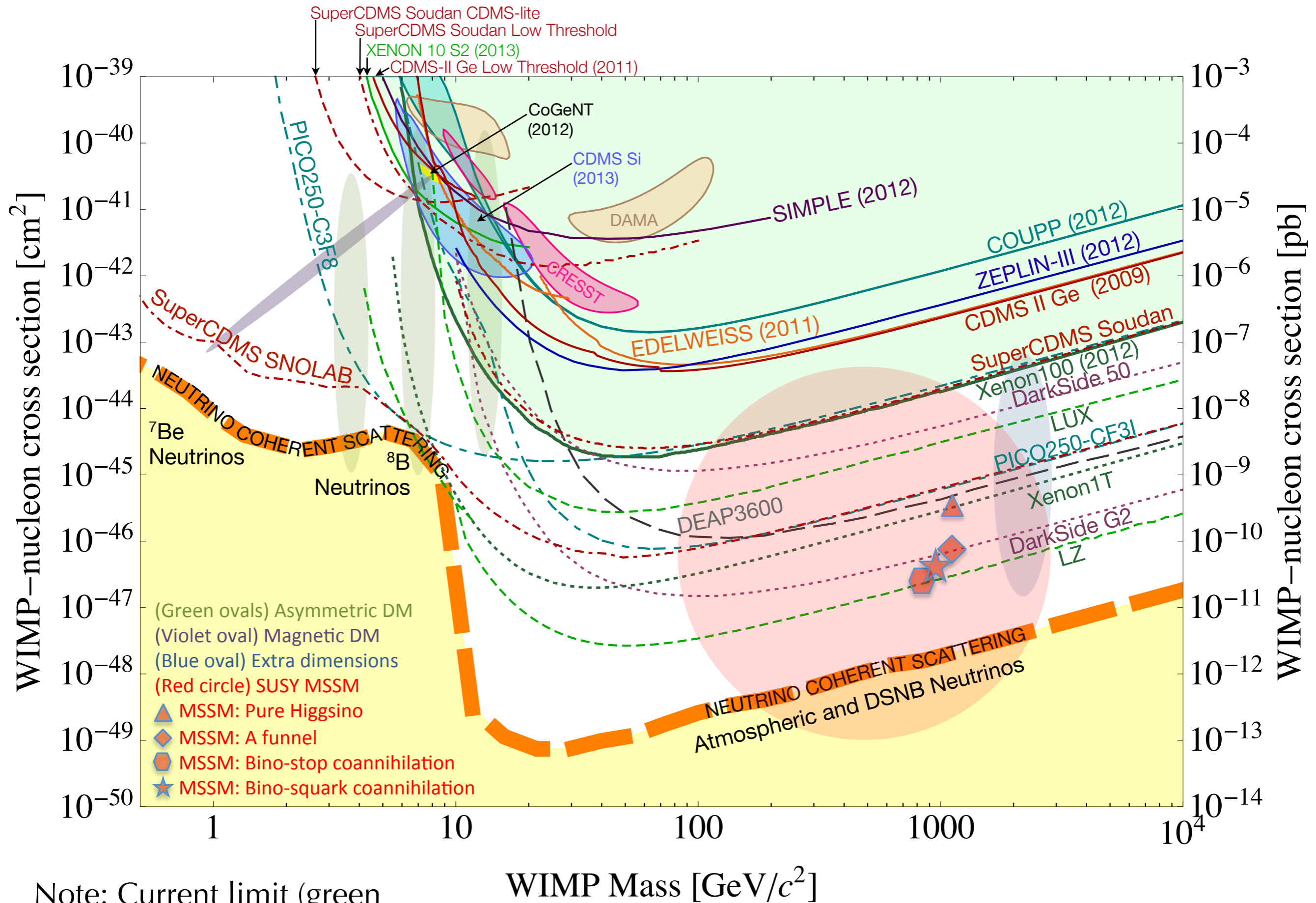
Before:



After:







Note: Current limit (green shaded) is slightly out of date.

(fig from Snowmass CF1 Summary, 1310.8327)

# Periodic Table of the Elements

1 1IA 11A <b>H</b> Hydrogen 1.0079	2 IIA 2A <b>He</b> Helium 4.00260											13 IIIA 3A <b>B</b> Boron 10.811	14 IVA 4A <b>C</b> Carbon 12.011	15 VA 5A <b>N</b> Nitrogen 14.00674	16 VIA 6A <b>O</b> Oxygen 15.9994	17 VIIA 7A <b>F</b> Fluorine 18.998403	18 VIIIA 8A <b>Ne</b> Neon 20.1797
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218											5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.00674	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.998403	10 <b>Ne</b> Neon 20.1797
11 <b>Na</b> Sodium 22.989768	12 <b>Mg</b> Magnesium 24.305	3 IIIB 3B <b>Al</b> Aluminum 26.981539	4 IVB 4B <b>Ti</b> Titanium 47.88	5 VB 5B <b>V</b> Vanadium 50.9415	6 VIB 6B <b>Cr</b> Chromium 51.9961	7 VIIB 7B <b>Mn</b> Manganese 54.938	8 VIII 8 <b>Fe</b> Iron 55.847	9 VIII 8 <b>Co</b> Cobalt 58.9332	10 VIII 8 <b>Ni</b> Nickel 58.6934	11 IB 1B <b>Cu</b> Copper 63.546	12 IIB 2B <b>Zn</b> Zinc 65.39	13 <b>Al</b> Aluminum 26.981539	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.4527	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.95591	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92159	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.9072	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.9055	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.90543	56 <b>Ba</b> Barium 137.327	57-71 Lanthanide Series	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.9479	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.9665	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98037	84 <b>Po</b> Polonium [209]	85 <b>At</b> Astatine 209	86 <b>Rn</b> Radon 222.0176
87 <b>Fr</b> Francium 223.0197	88 <b>Ra</b> Radium 226.0254	89-103 Actinide Series	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [285]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [289]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Uuq</b> Ununquadium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Uuh</b> Ununhexium [288]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown

Lanthanide Series

Actinide Series

57 <b>La</b> Lanthanum 138.9055	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.9127	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.9655	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
89 <b>Ac</b> Actinium 227.0278	90 <b>Th</b> Thorium 232.0381	91 <b>Pa</b> Protactinium 231.03589	92 <b>U</b> Uranium 238.0289	93 <b>Np</b> Neptunium 237.0482	94 <b>Pu</b> Plutonium 244.0642	95 <b>Am</b> Americium 243.0614	96 <b>Cm</b> Curium 247.0703	97 <b>Bk</b> Berkelium 247.0703	98 <b>Cf</b> Californium 251.0796	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.0951	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.1009	103 <b>Lr</b> Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides
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Motivation & basics

Effective theory of dark matter direct detection

How well can we reconstruct the theory of dark matter with direct detection?

Motivation & basics

Effective theory of dark matter direct detection

How well can we reconstruct the theory of dark matter with direct detection?



# Scattering probability, more precisely

$$\frac{dR}{dE_R} = \frac{1}{m_T} \left[ \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \int_{v_{\text{min}}(E_R)}^{\infty} d^3\vec{v} v f(\vec{v}) \right] \left[ \frac{d\sigma_T}{dE_R}(\vec{v}, E_R) \right]$$

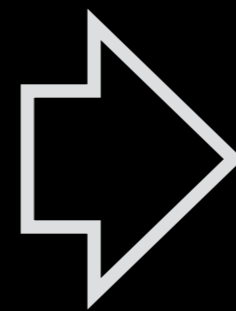
astrophysics

particle &  
nuclear physics

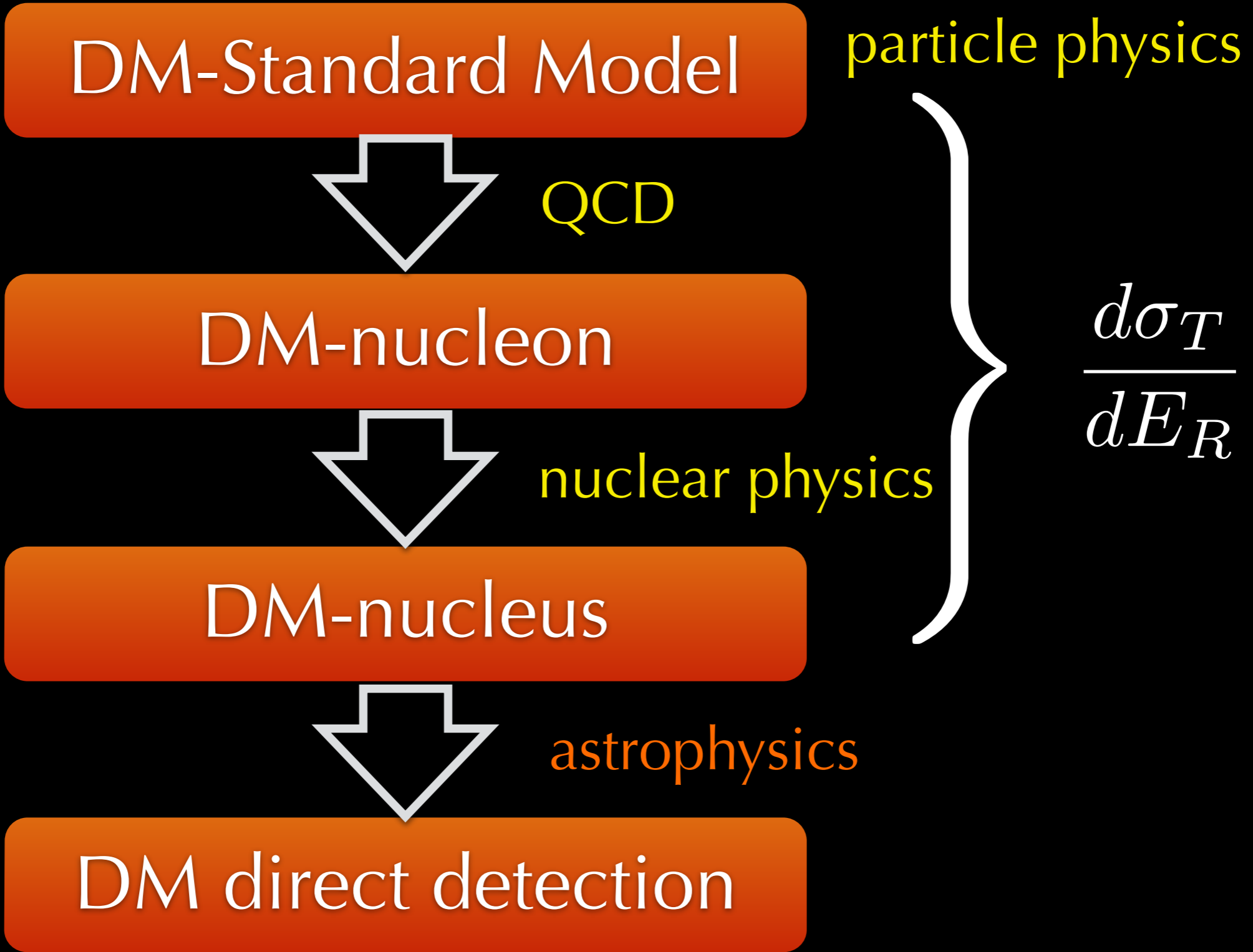
$R$  = probability of scattering  
per time, per target mass

typical  $v \sim 200 \text{ km/s} \ll c$

typical  $E_R \ll m_{\text{nucleon}}, m_{\text{DM}}$



*work in non-relativistic limit*



$$\frac{dR}{dE_R} = \frac{1}{m_T} \left[ \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \int_{v_{\min}(E_R)}^{\infty} d^3\vec{v} v f(\vec{v}) \right] \left[ \frac{d\sigma_T}{dE_R}(\vec{v}, E_R) \right]$$



# DM-Standard Model

$$\mathcal{L}_{\text{int}} \sim \bar{\chi}\chi\phi + \bar{q}q\phi \quad \text{or} \quad \sim \bar{\chi}\gamma^\mu\chi A_\mu + \bar{q}\gamma^\mu q A_\mu$$

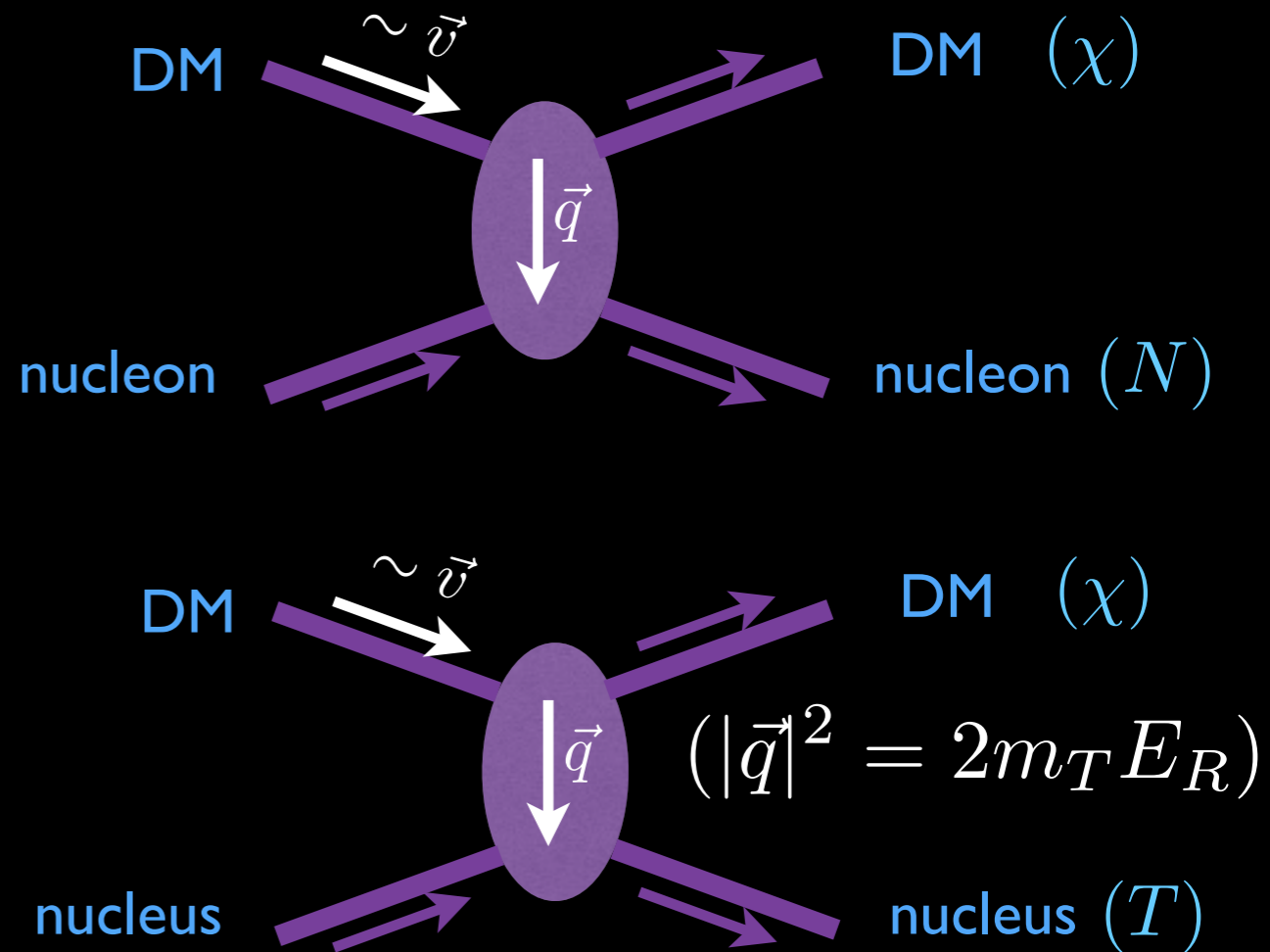
EXAMPLE (standard spin-independent case)

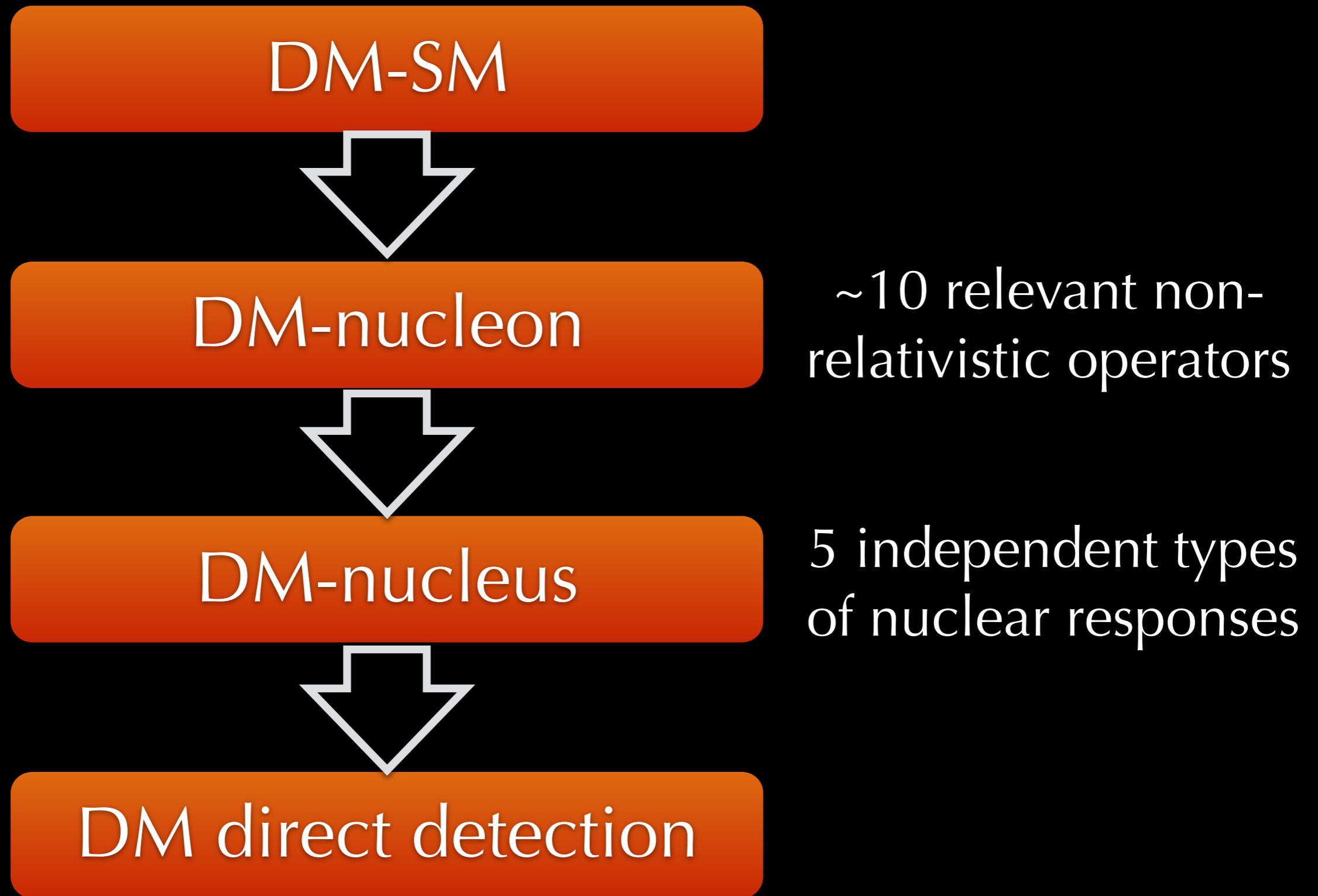
## DM-nucleon

$$\mathcal{L}_{\text{int, eff}} = \sum_{N=n,p} \frac{f_N}{\Lambda^2} \bar{\chi}\chi \bar{N}N$$

## DM-nucleus

$$\frac{d\sigma_T}{dE_R} = \frac{m_T}{2\mu_T^2 v^2} \sigma_p \left( Z + (A - Z) \frac{f_n}{f_p} \right)^2 F^2(E_R)$$





(Fitzpatrick, Haxton, Katz, Lubbers, Xu 1203.3542)

DM-SM



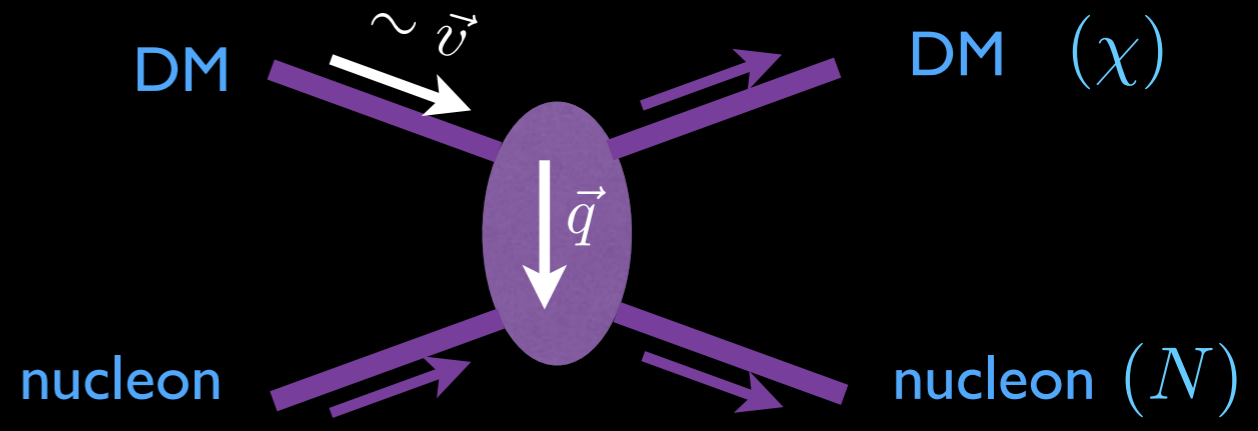
DM-nucleon



DM



DM direct detection



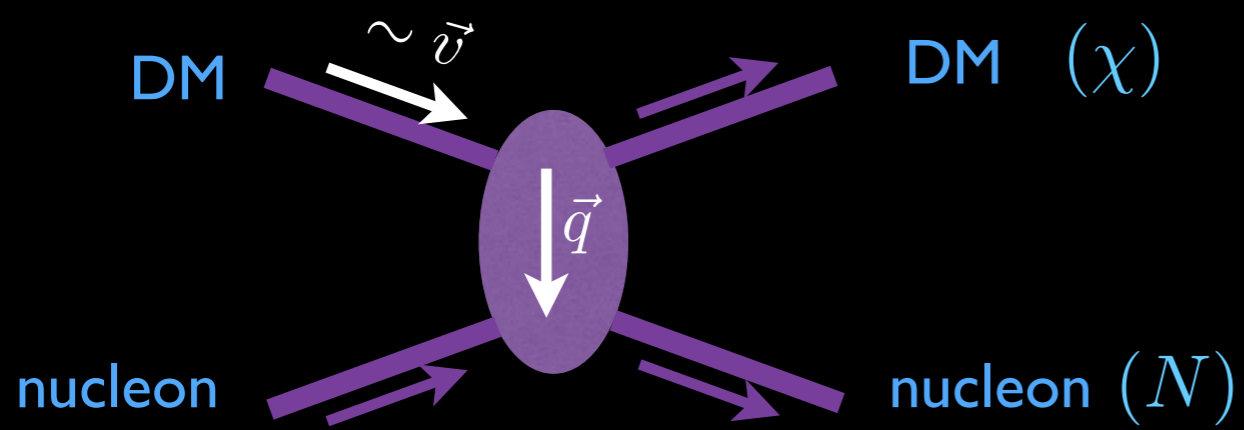
non-rel operator building blocks

$$i \frac{\vec{q}}{m_N} \quad \vec{S}_\chi$$

$$\vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N} \quad \vec{S}_N$$

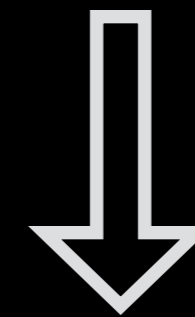
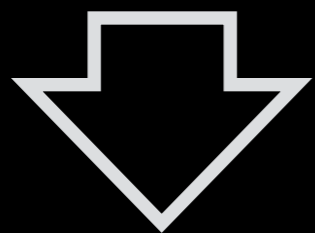
$$\mathcal{L}_{\text{int}} \sim \bar{\chi} \mathcal{O}_\chi \chi \bar{N} \mathcal{O}_N N$$





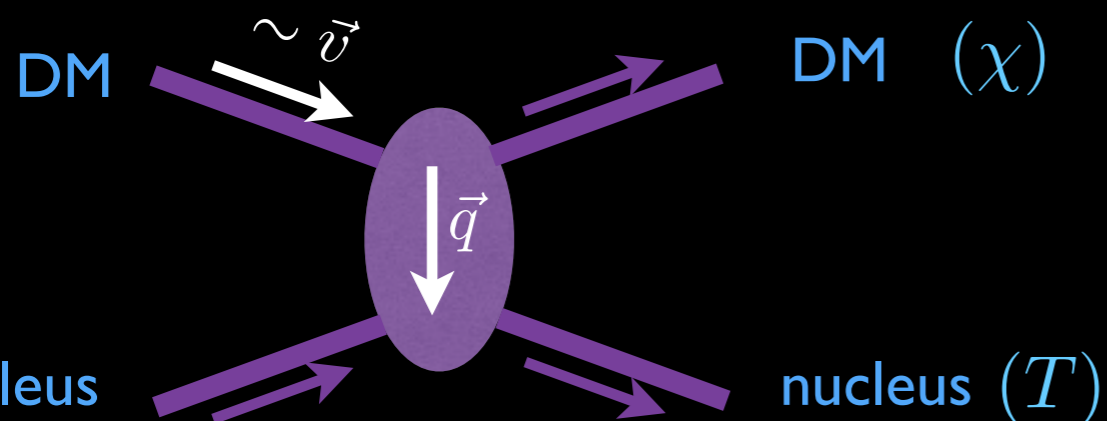
WIMP-nucleon

1



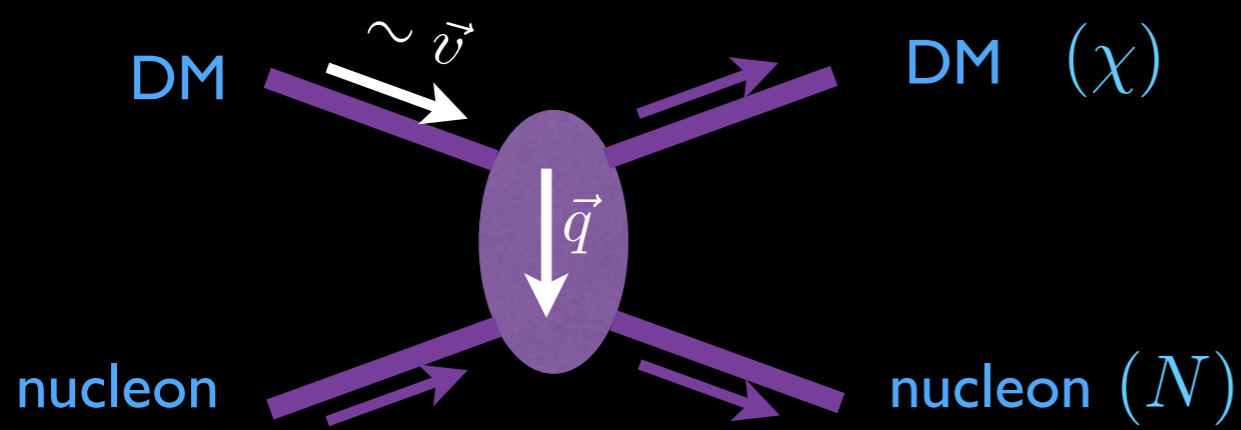
WIMP-nucleus

(usual) spin-independent response



$\sim Z$  for proton coupling

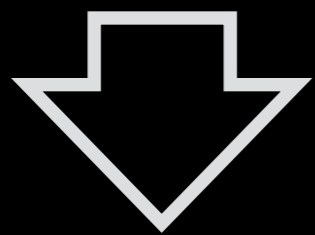
$\sim (A - Z)$  for neutron coupling



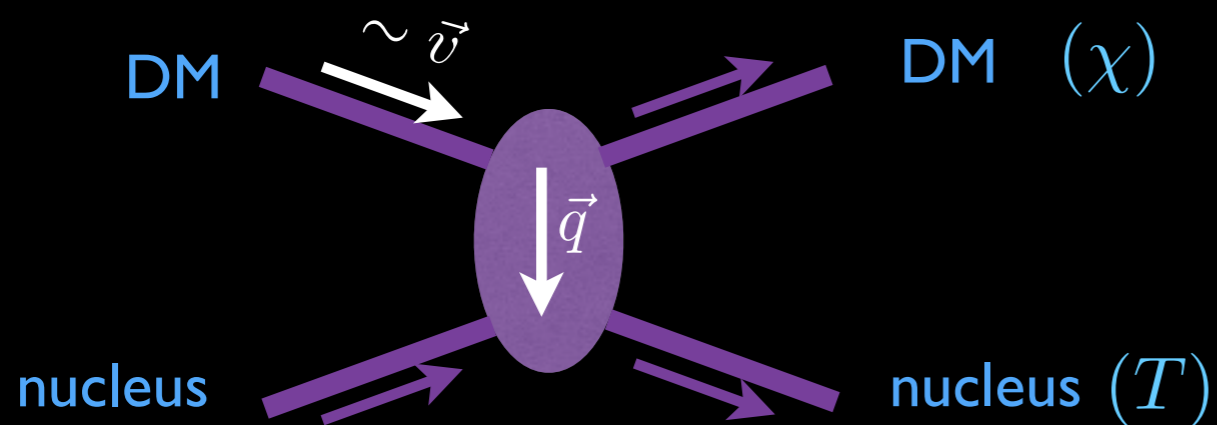
WIMP-nucleon

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

$$= (\vec{S}_\chi \cdot \hat{q})(\vec{S}_N \cdot \hat{q}) + (\vec{S}_\chi \times \hat{q}) \cdot (\vec{S}_N \times \hat{q})$$



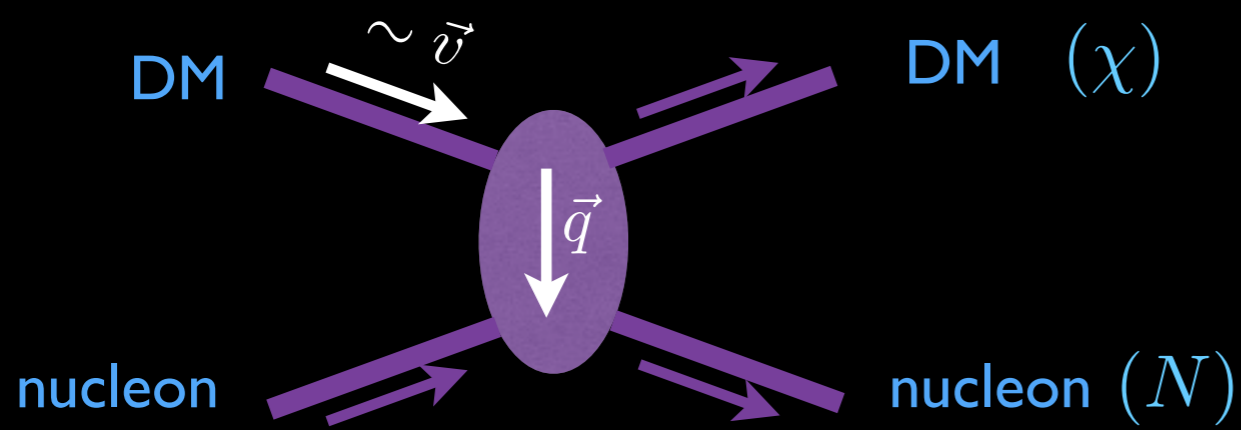
WIMP-nucleus



longitudinal  
spin-  
dependent  
response

+

transverse  
spin-  
dependent  
response

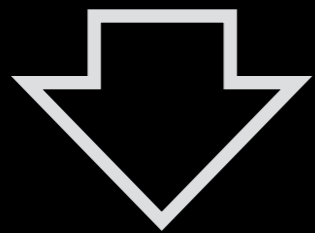


# WIMP-nucleon

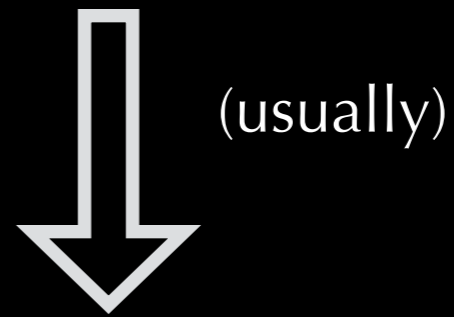
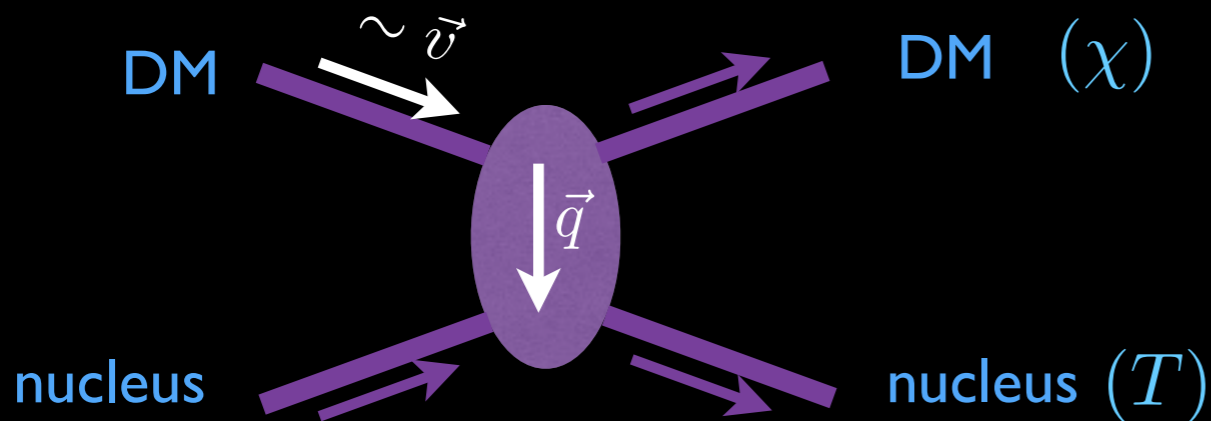
non-rel operator building blocks

$$\left\{ \begin{array}{ll} i \frac{\vec{q}}{m_N} & \vec{S}_\chi \\ \vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N} & \vec{S}_N \end{array} \right.$$

operators involving  $\vec{v}^\perp$



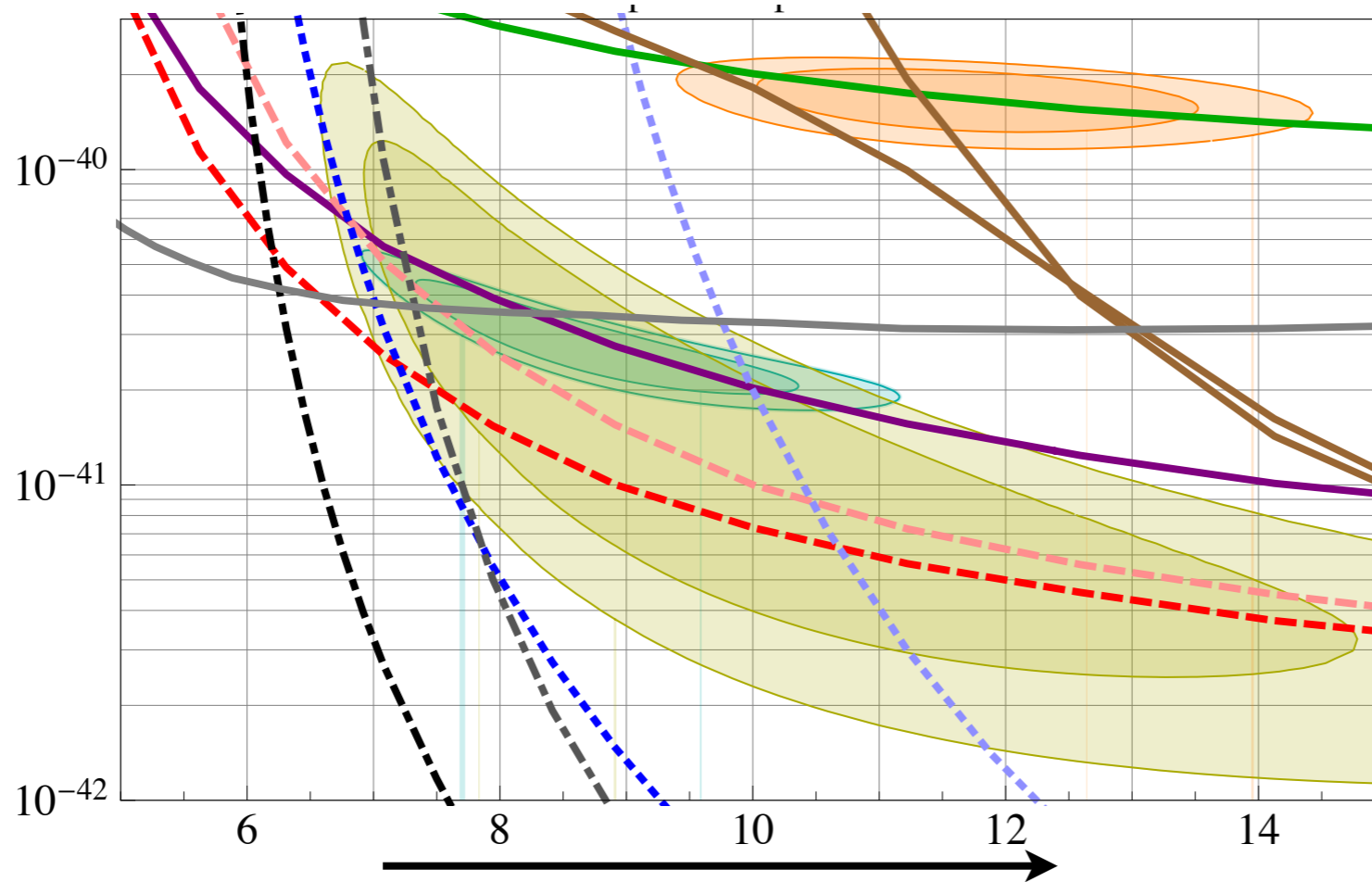
# WIMP-nucleus



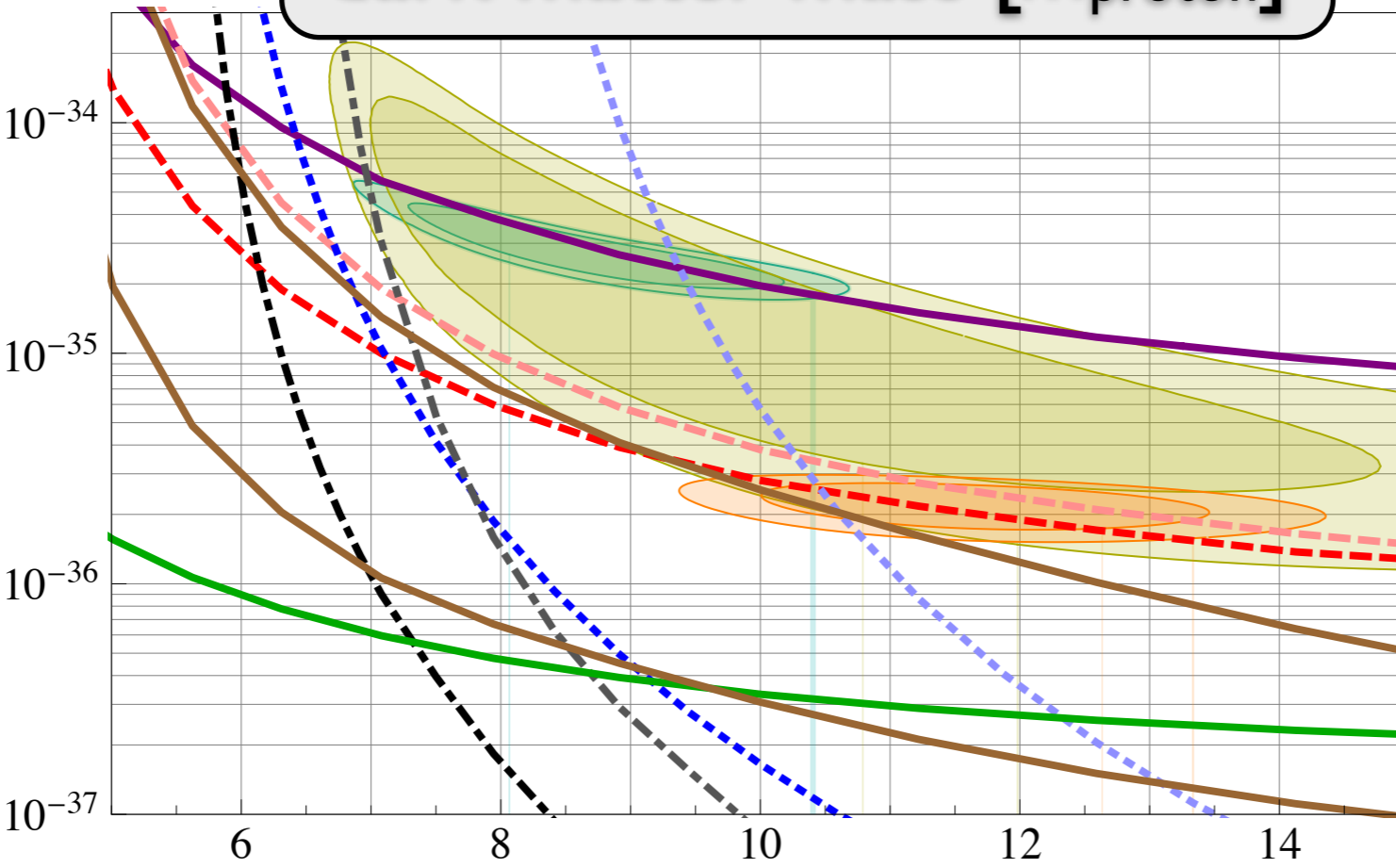
orbital  
angular  
momentum-  
dependent  
responses



DM-proton cross section [ $\text{cm}^2$ ]



dark matter mass [ $m_{\text{proton}}$ ]



spin-independent

- CoGeNT (90%, 99%)
- CDMS Si (68%, 90%)
- DAMA (90%, 99%)
- CDMS Ge L-E
- XENON10 (S2)
- XENON10 (S2), alt  $Q_y$
- XENON100
- XENON100, alt  $L_{\text{eff}}$
- LUX
- LUX, alt  $L_{\text{eff}}$
- PICASSO
- COUPP ( $\eta, \alpha$ )
- CDMSlite

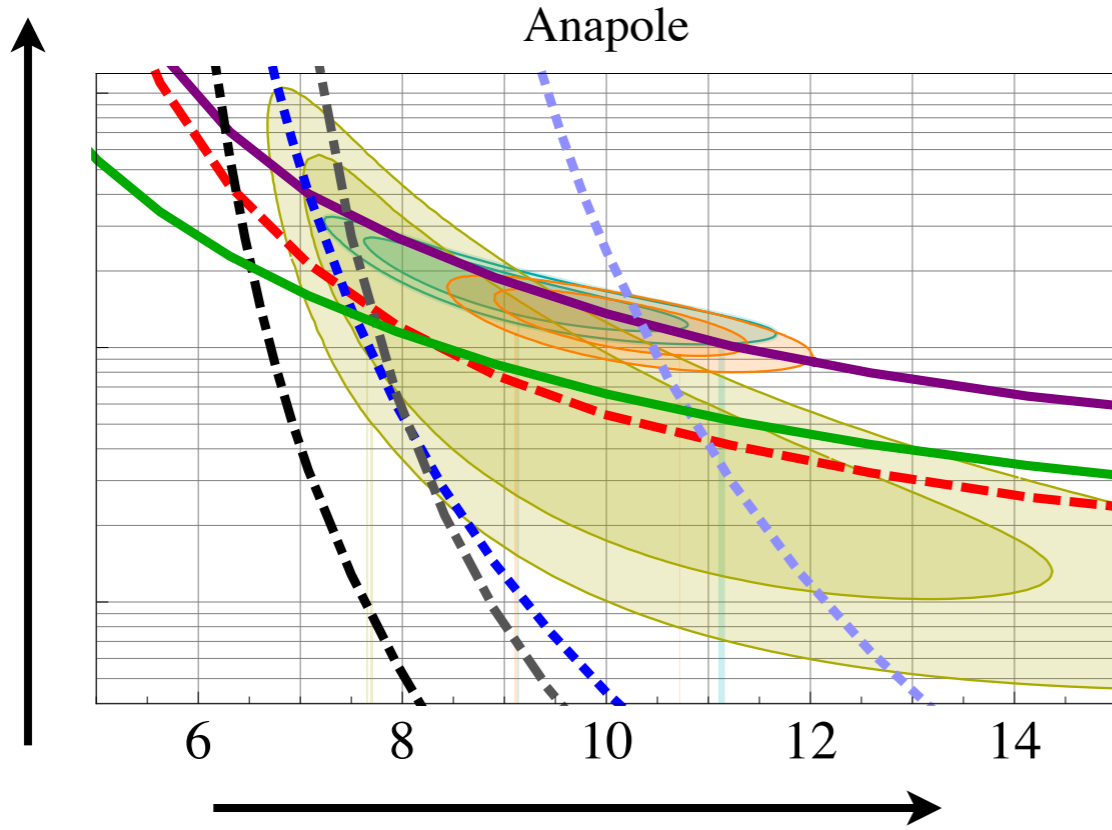
spin-dependent

(plots from 1311.2082)

$$\mathcal{L}_{\text{int}} \sim \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}$$

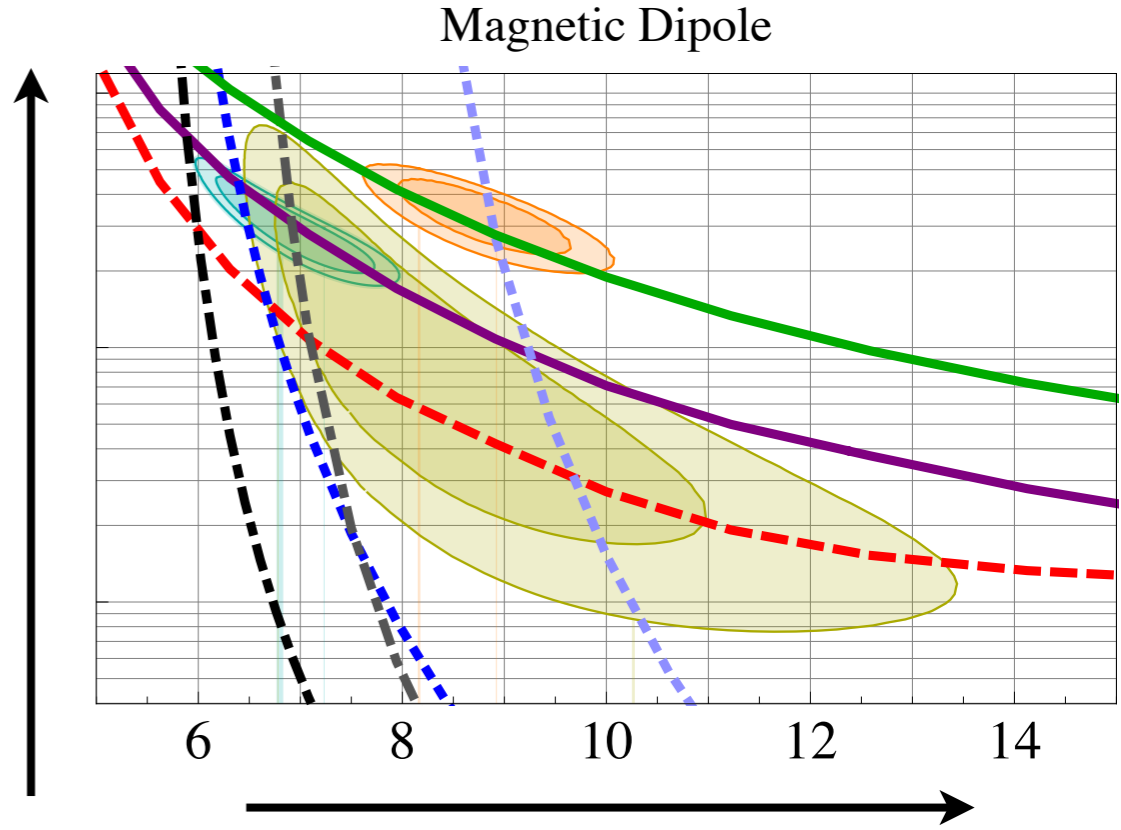
$$\mathcal{L}_{\text{int}} \sim \bar{\chi} \sigma^{\mu\nu} \chi F'_{\mu\nu}$$

interaction strength [cm<sup>2</sup>]



mass [ $m_{\text{proton}}$ ]

interaction strength [cm<sup>2</sup>]



mass [ $m_{\text{proton}}$ ]

Motivation & basics

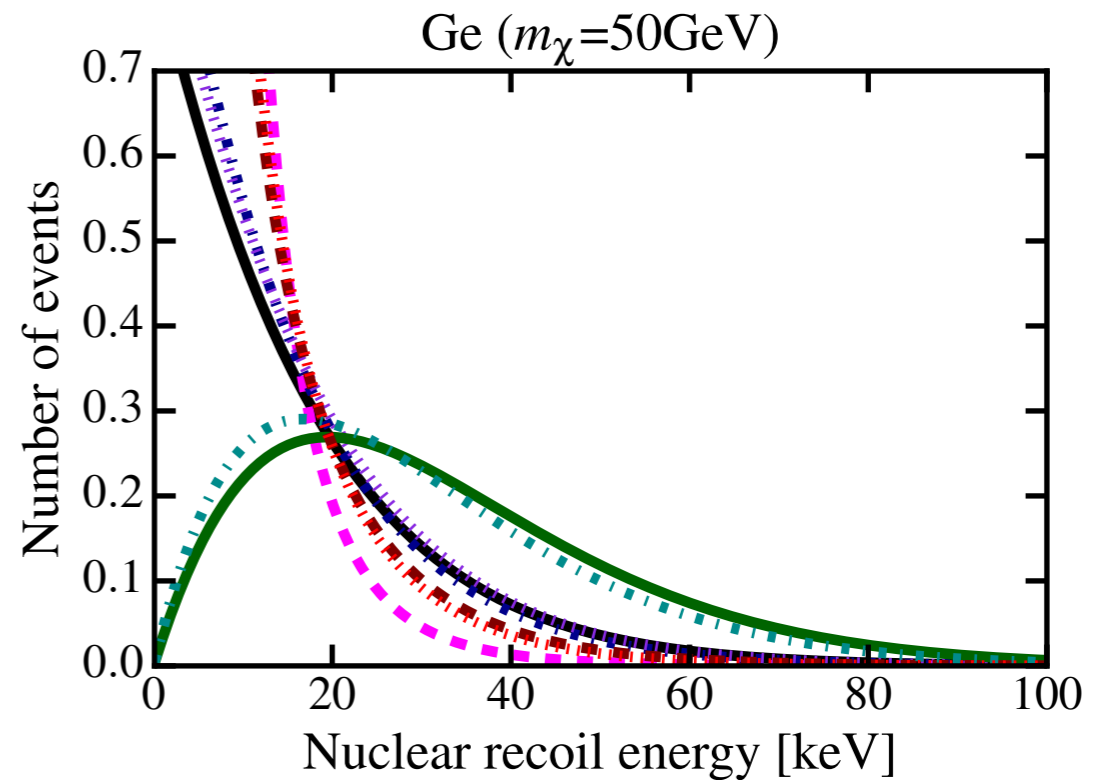
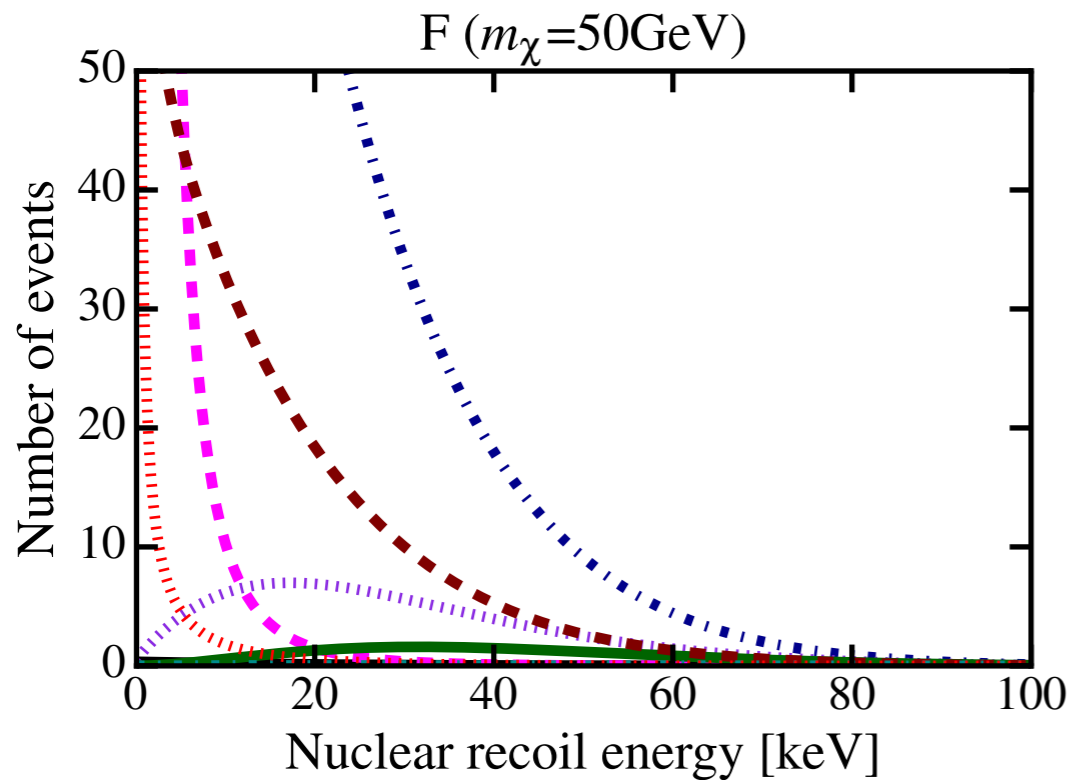
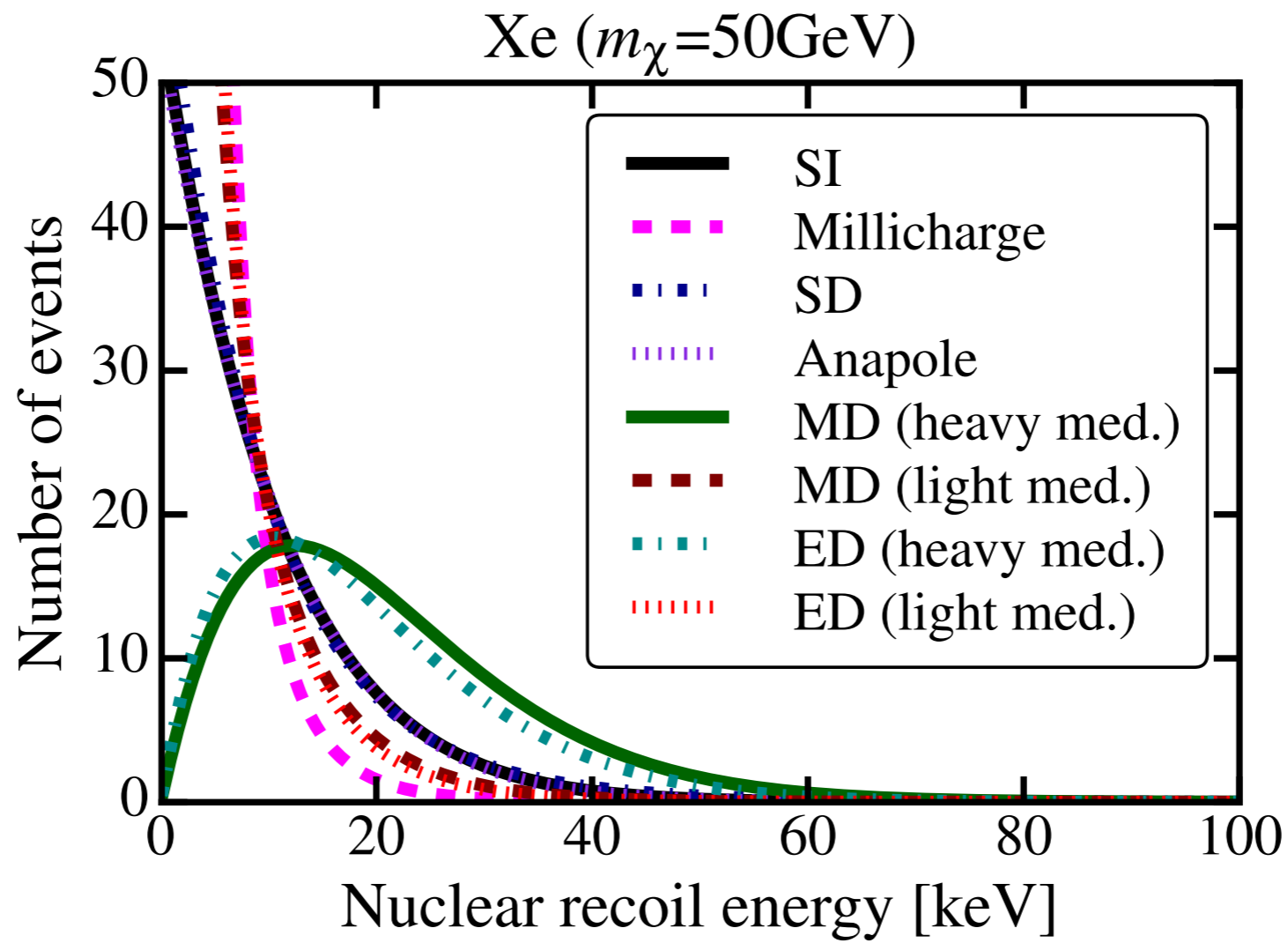
Effective theory of dark matter direct detection

How well can we reconstruct the theory of dark matter with direct detection?

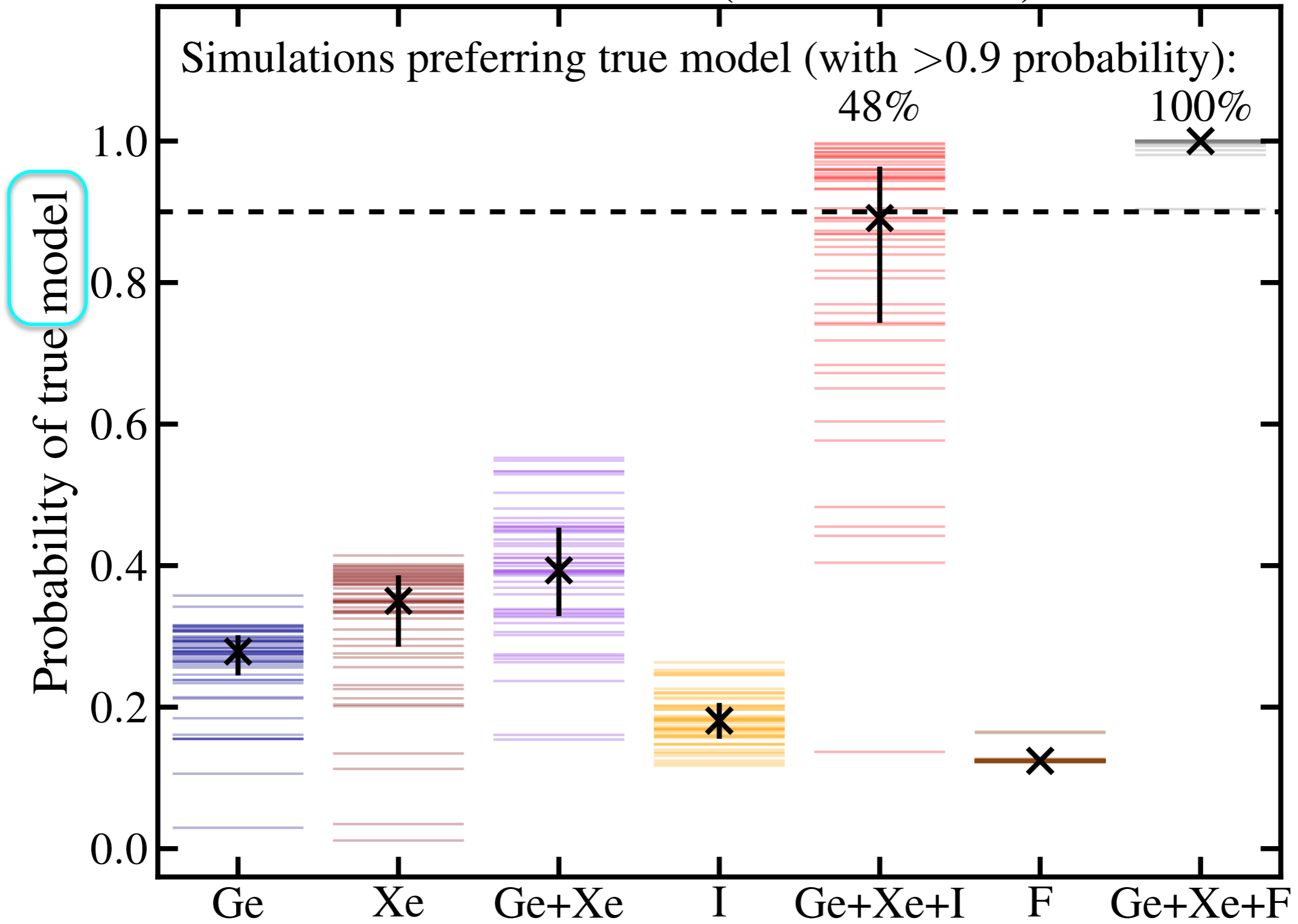


Simulate data for a variety of plausible underlying models with in-principle distinct direct detection phenomenology, assuming cross section at current upper limit. Then do model selection.

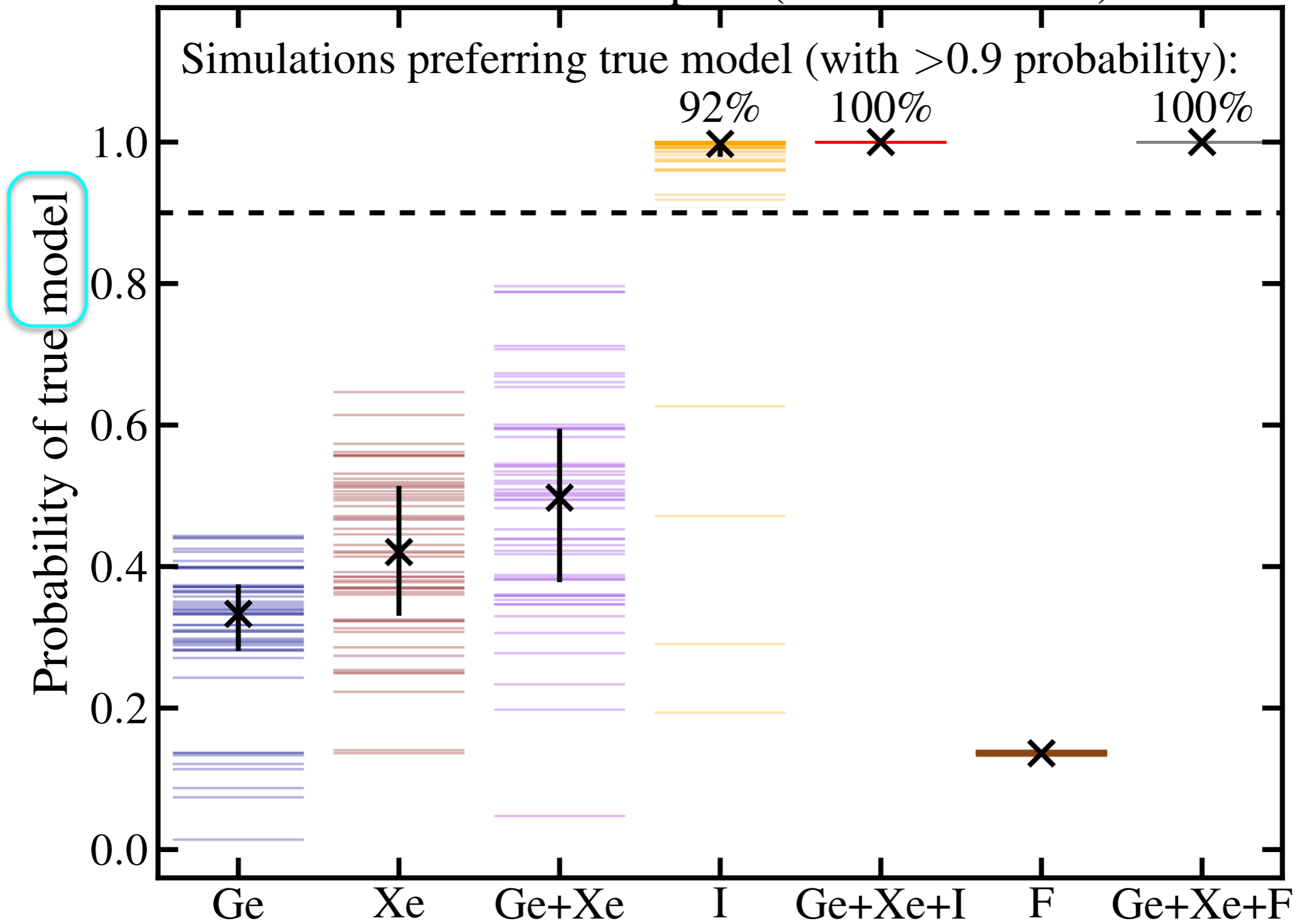
- include poisson noise
- assume perfect energy resolution
- 50 realizations for each model, on each target
- use Bayesian statistics for model selection.  
(Calculate evidence for model given data. Probability of model is its evidence divided by the sum of evidences for other models.)



True model: SI (mass: 50 GeV)

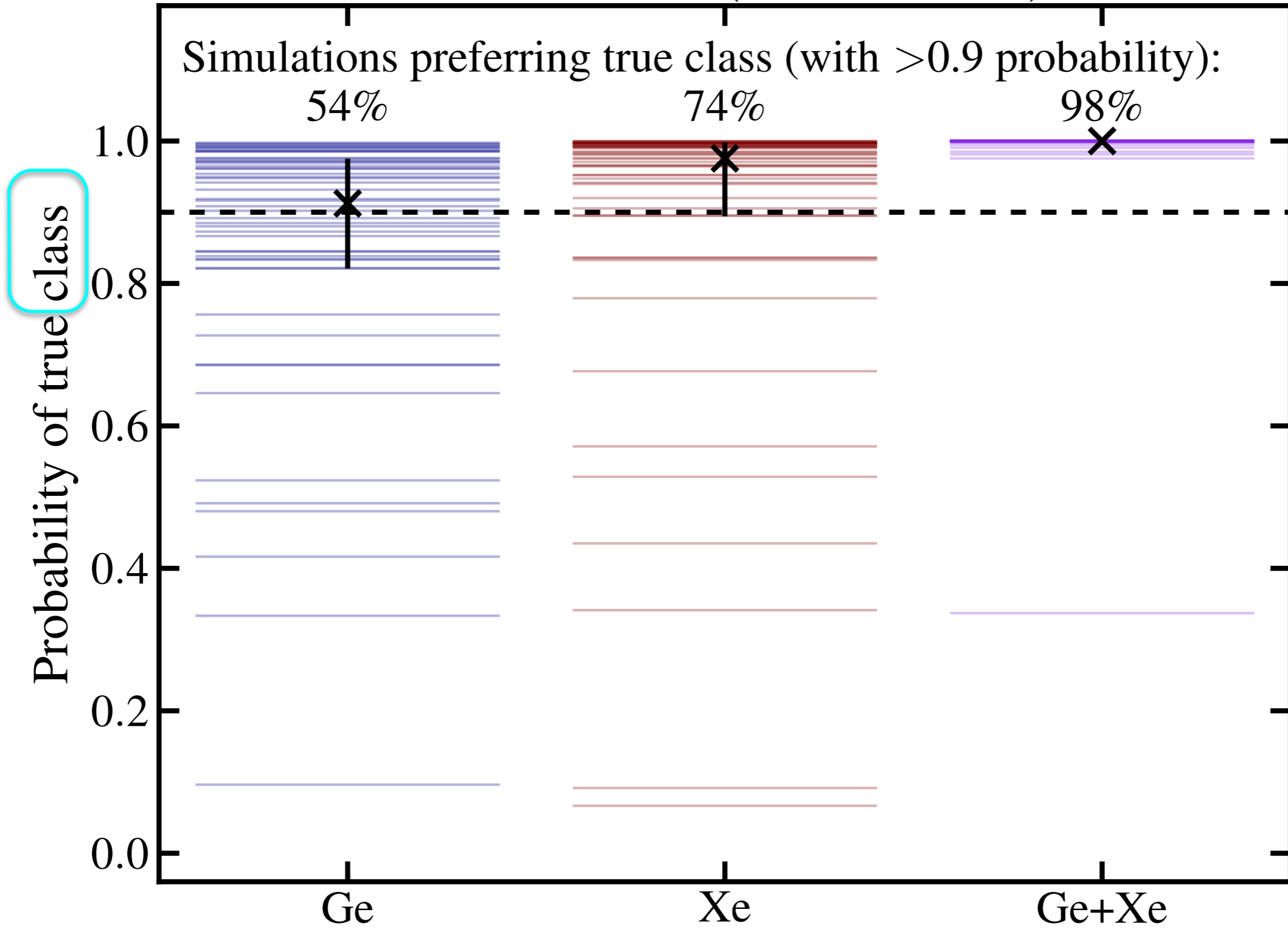


True model: Anapole (mass: 500 GeV)





True model: SI (mass: 50 GeV)



How much of the “theory” of dark matter can be reconstructed from direct detection?

- Because direct detection scattering events are inherently low energy, there’s degeneracy amongst “high energy” theories.
- Relevant effective interactions at the nucleon-DM level in the non-relativistic limit are well understood; therefore so are the high energy theory degeneracies.
- Including a diverse set of targets goes a long way in helping to distinguish between low energy effective theories.

# Identifying the Theory of Dark Matter with Direct Detection

Moira Gresham

Whitman College, Walla Walla, WA

TUI-3

*June 25, 2015*

based on work with K. Zurek [1311.2082, 1401.3739] as well as V. Gluscevic, A. Peter, and S. McDermott [1506.04454]