Identifying the Theory of Dark Matter with Direct Detection

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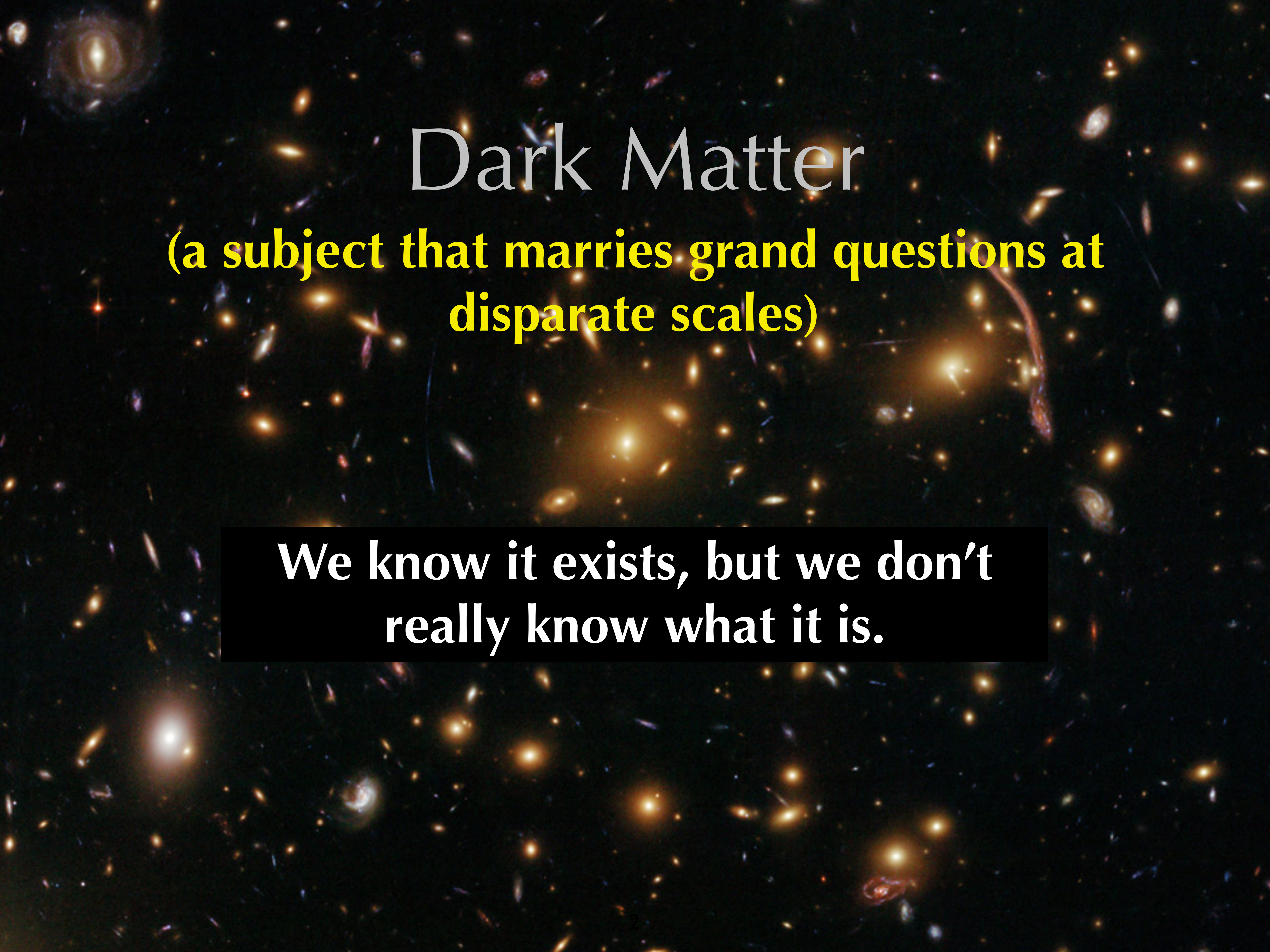
TUI-3

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]

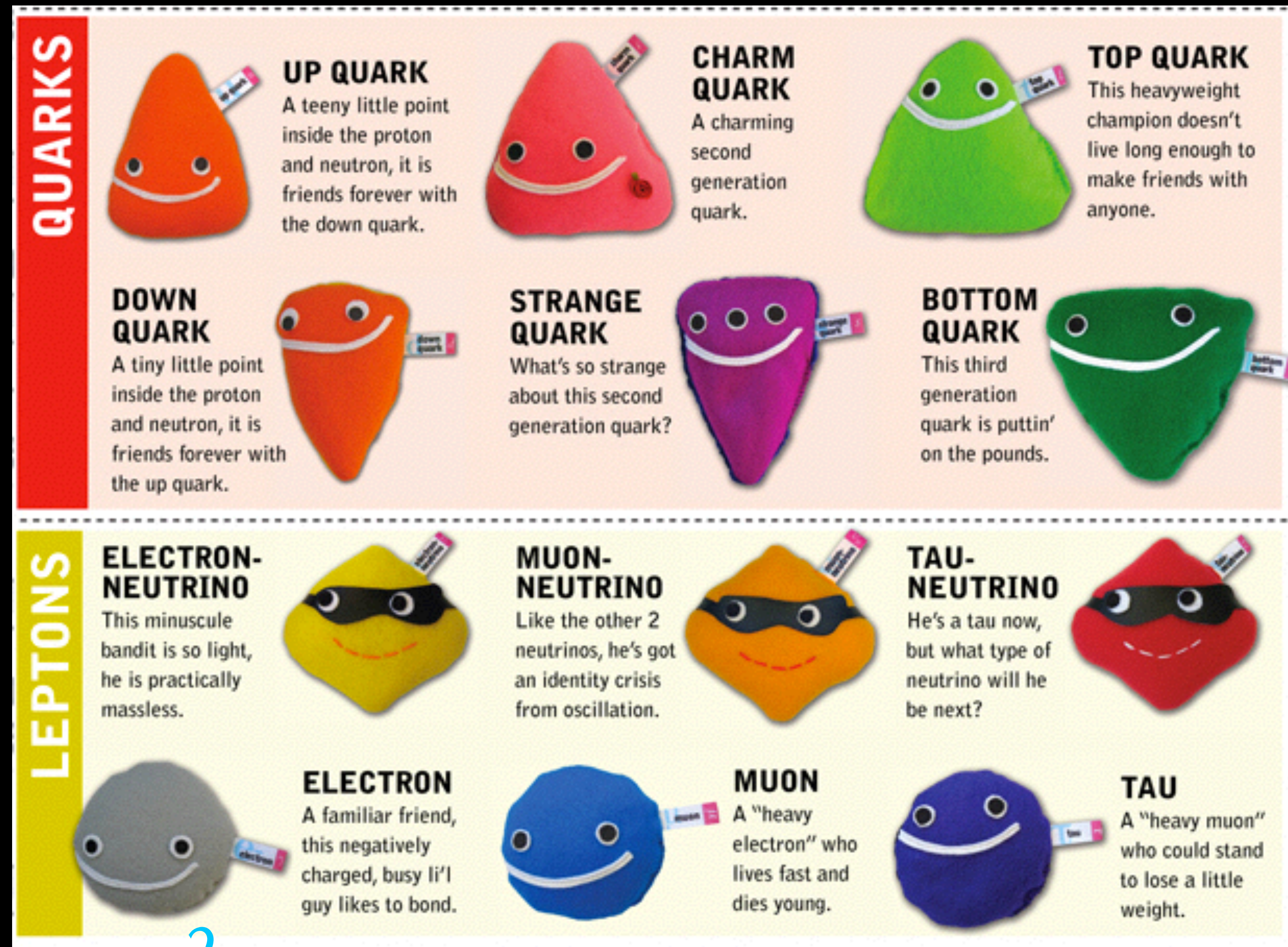

Dark Matter
(a subject that marries grand questions at disparate scales)
We know it exists, but we don't really know what it is.

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

increasing mass →



other?

×	?	×	?

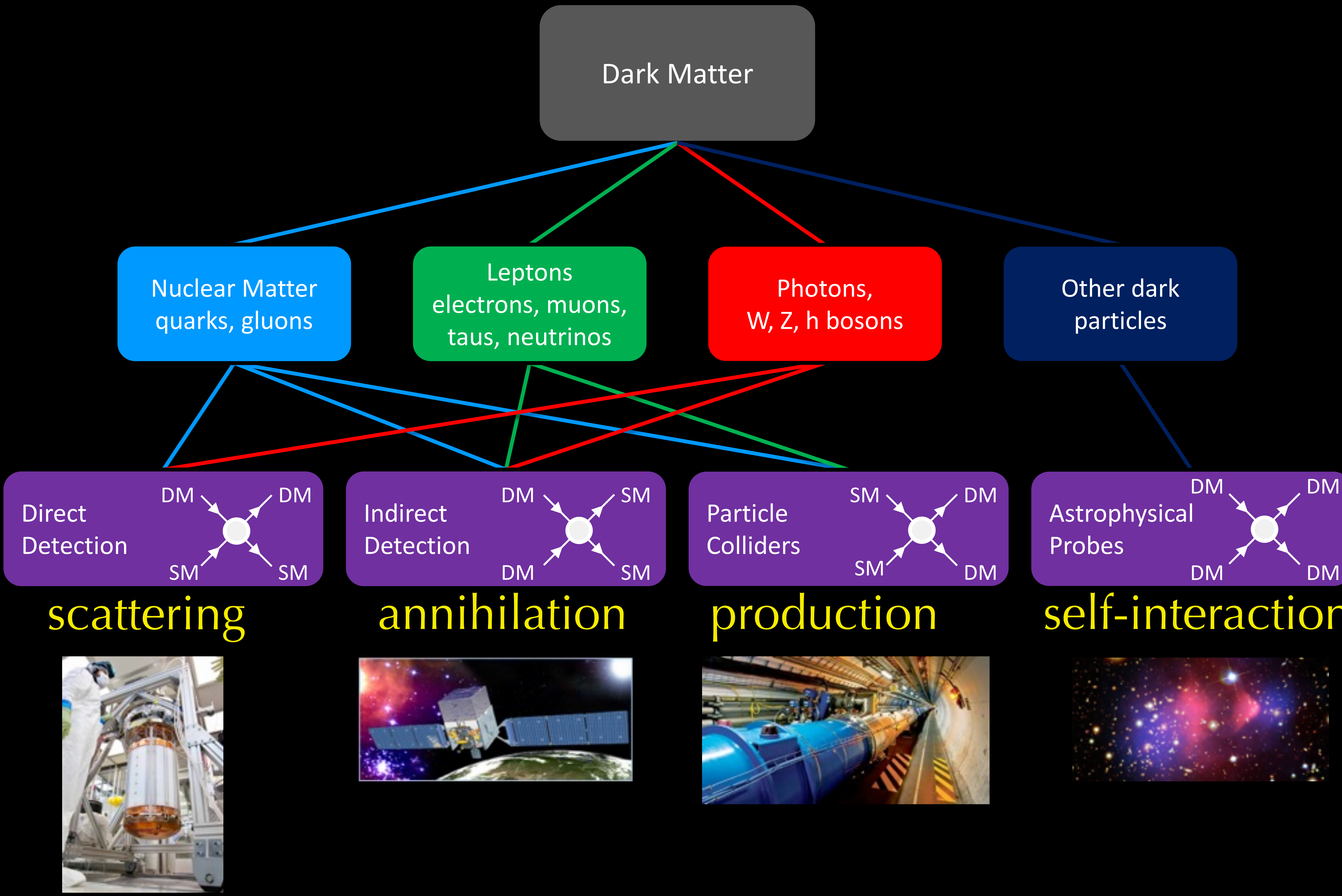
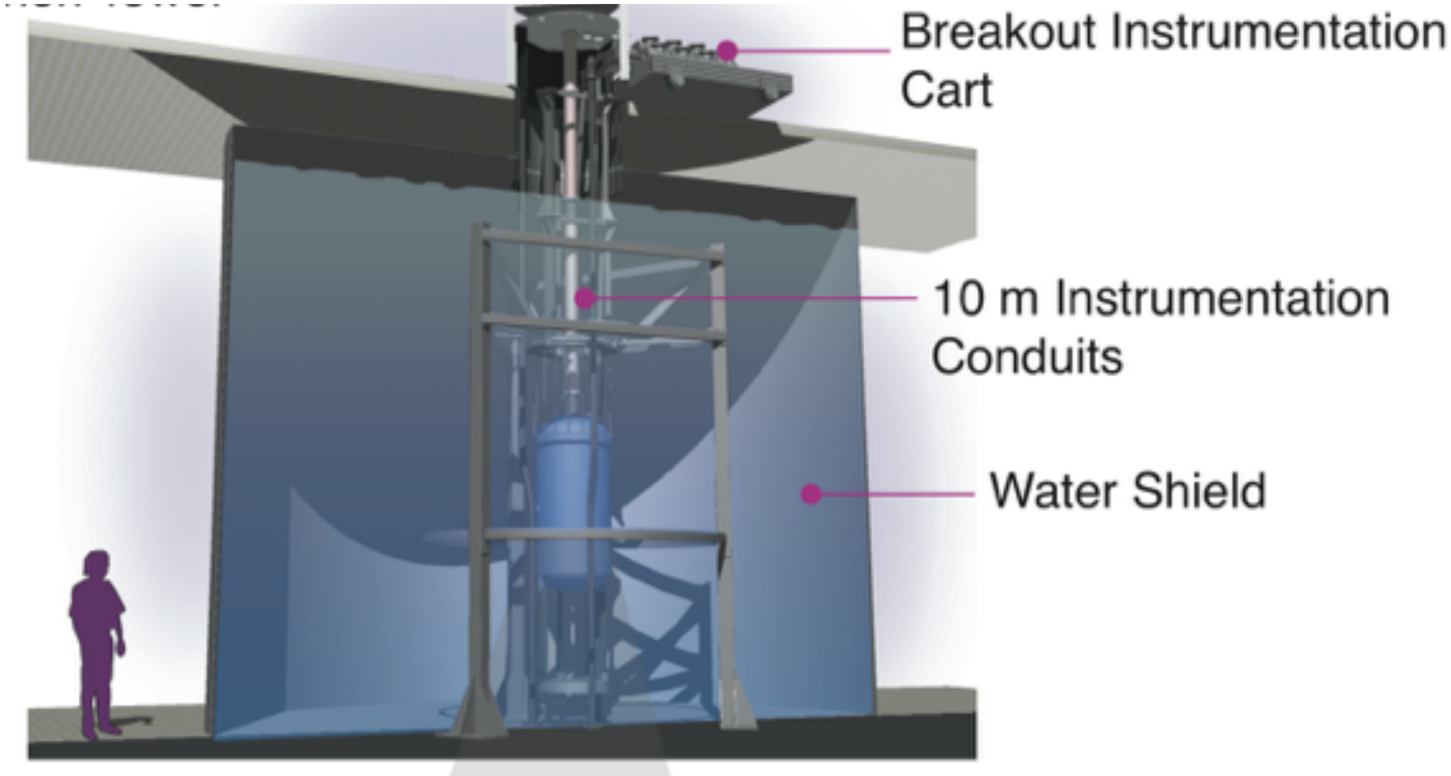
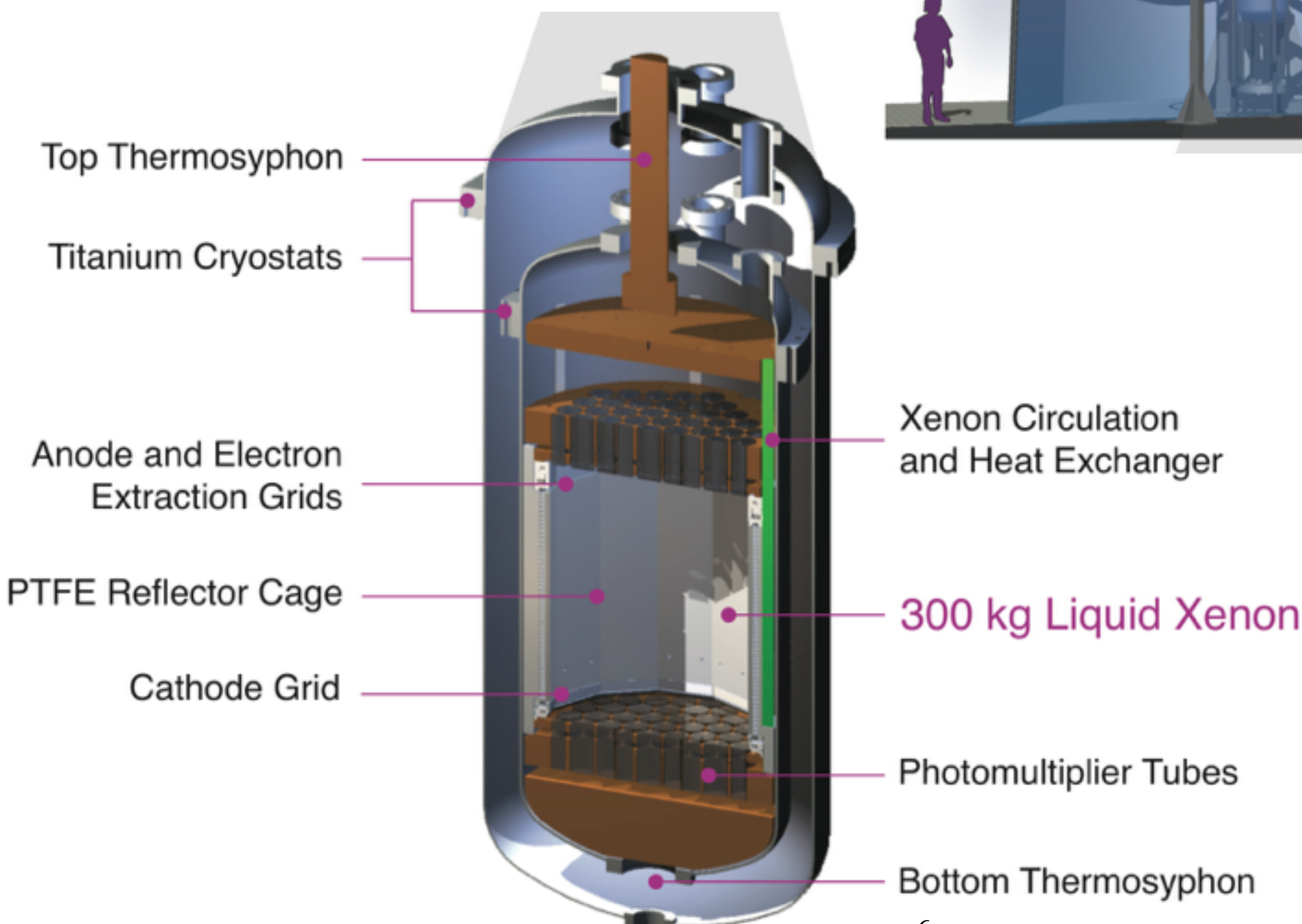
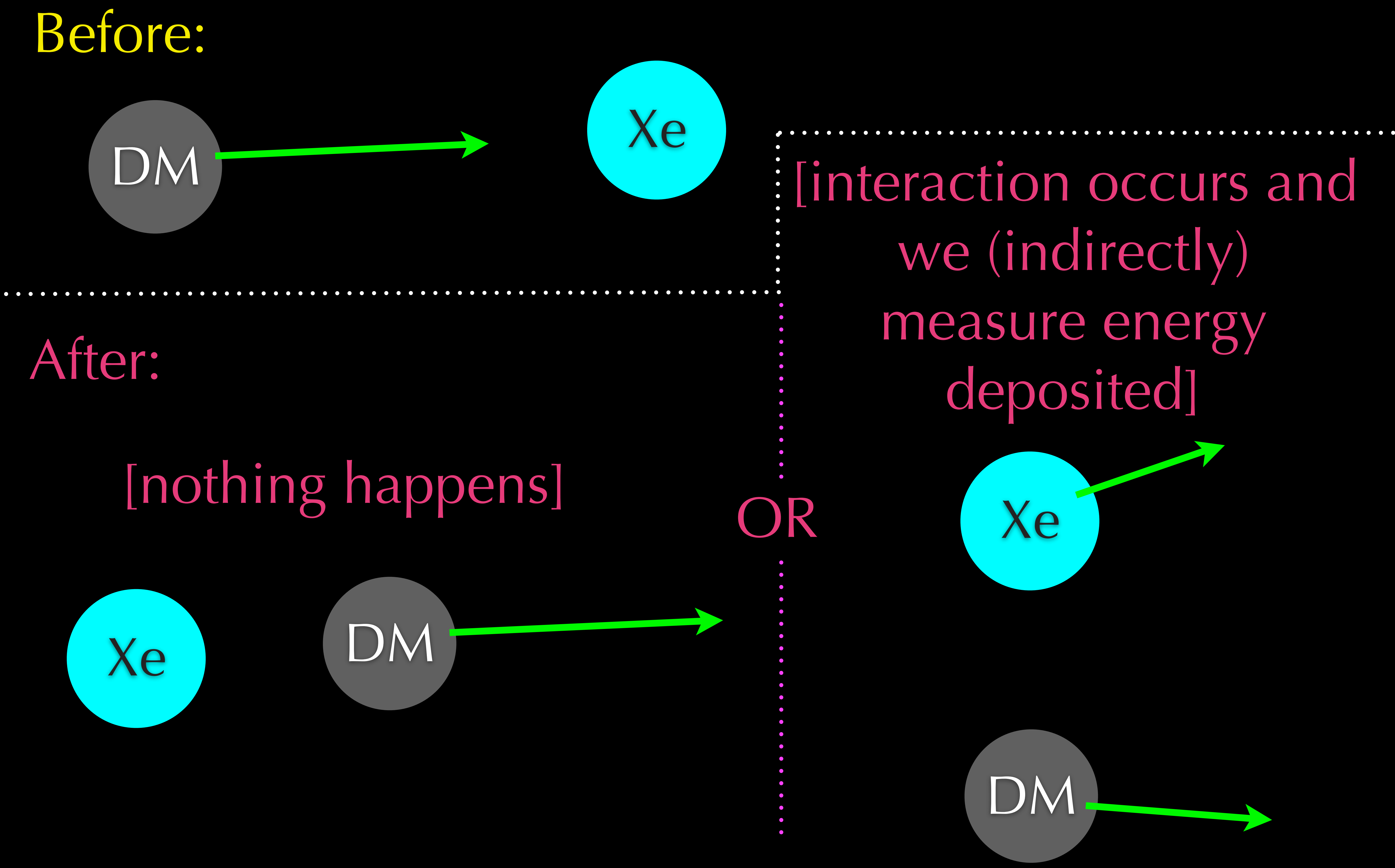


chart from Snowmass CF1 Summary 1310.8327


Breakout Instrumentation Cart
10 m Instrumentation Conduits
Water Shield


Top Thermosyphon
Titanium Cryostats
Anode and Electron Extraction Grids
PTFE Reflector Cage
Cathode Grid
Xenon Circulation and Heat Exchanger
300 kg Liquid Xenon
Photomultiplier Tubes
Bottom Thermosyphon

Cartoon of Elastic Scattering



What's the probability for the scattering to occur?

In principle it could depend on...

properties of the target (Xe, in this example)

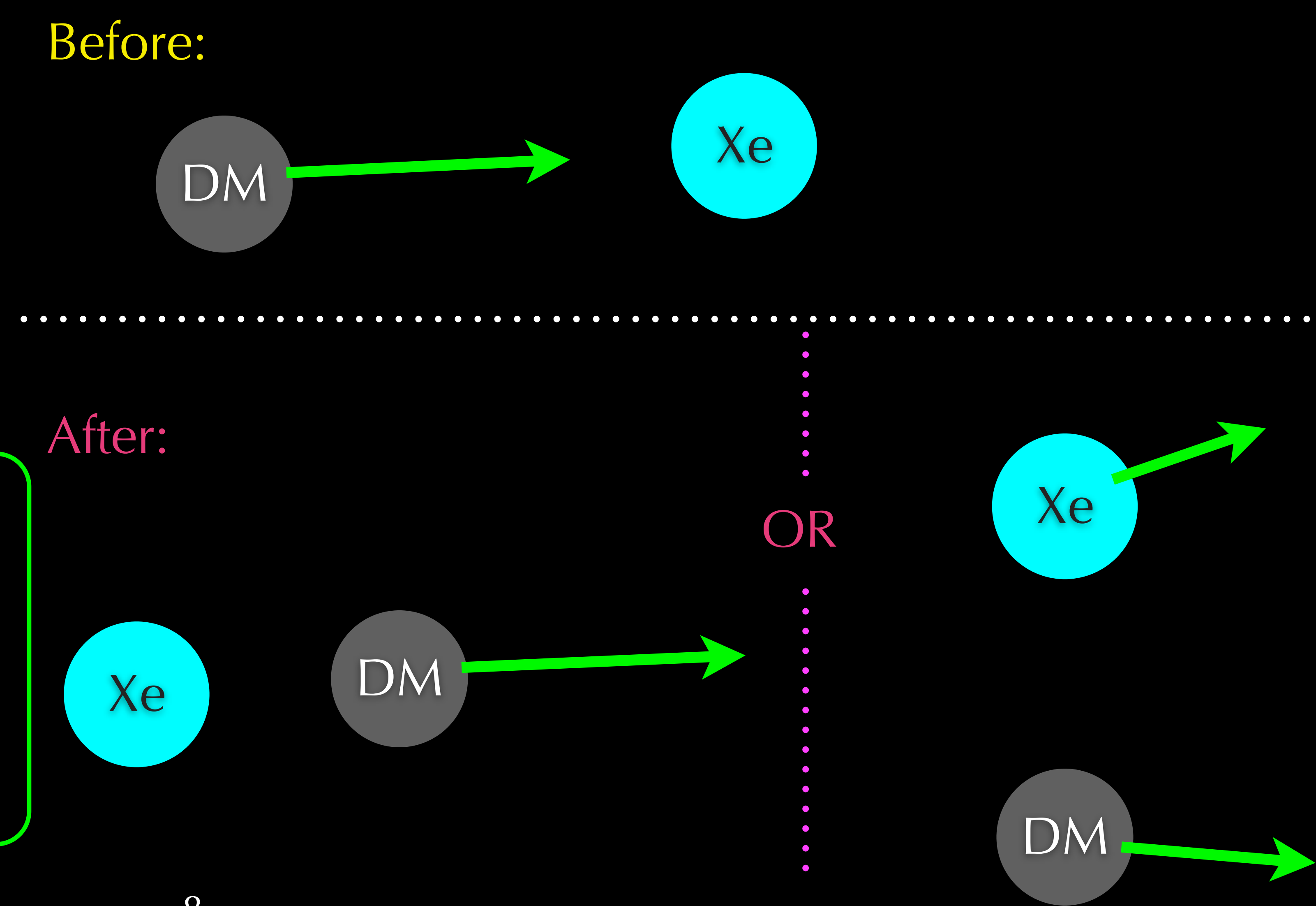
- angular momentum
- mass
- # protons, # neutrons
- ...

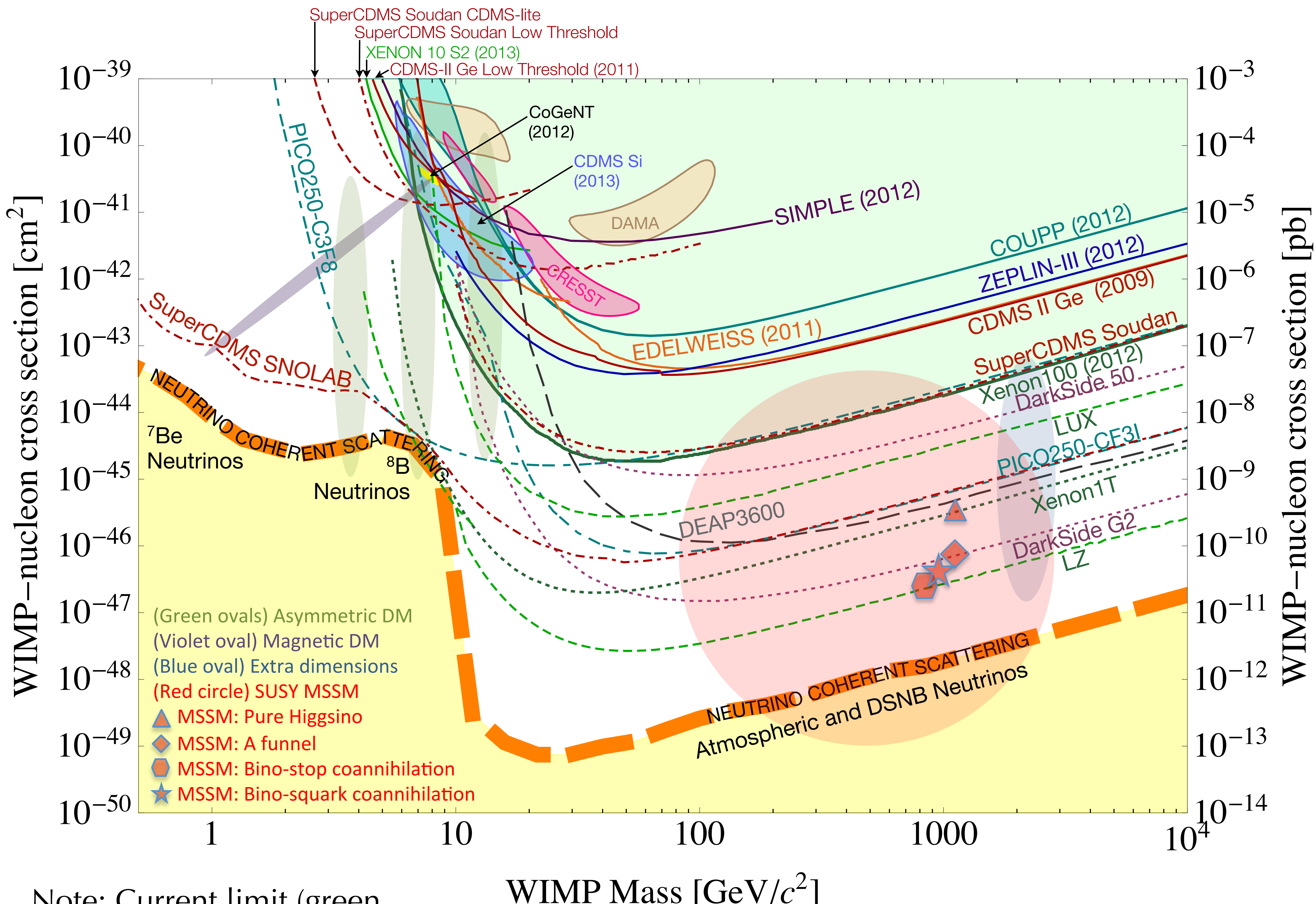
properties of the Dark Matter

- angular momentum
- mass

kinematic quantities

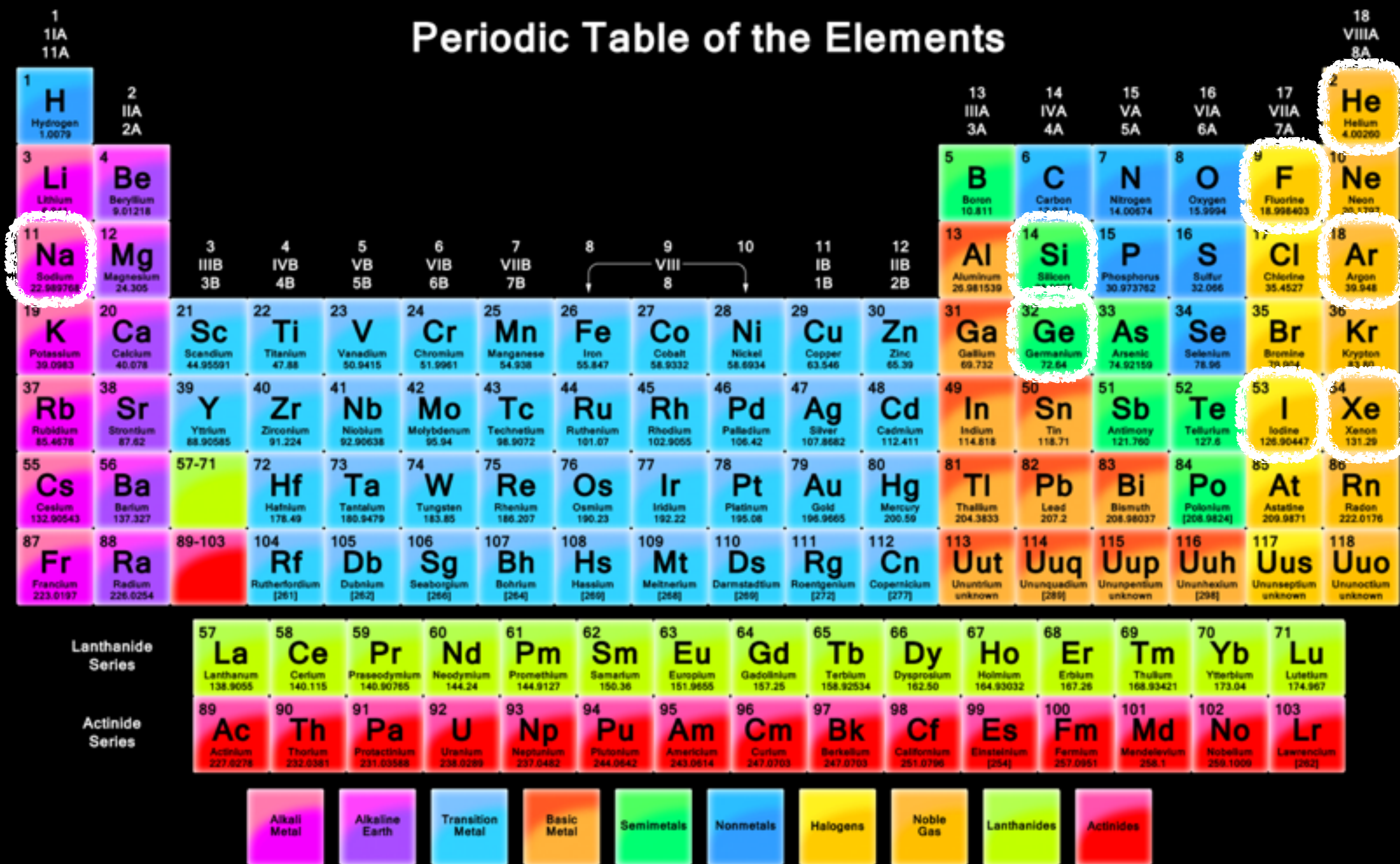
- DM velocity
- nuclear recoil energy





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

(fig from Snowmass CF1 Summary, 1310.8327)


Periodic Table of the Elements
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba 57-71 Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra 89-103 Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Uuq Uup Uuh Uus Uuo
Lanthanide Series
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Actinide Series
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

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

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

astrophysics

particle & nuclear physics

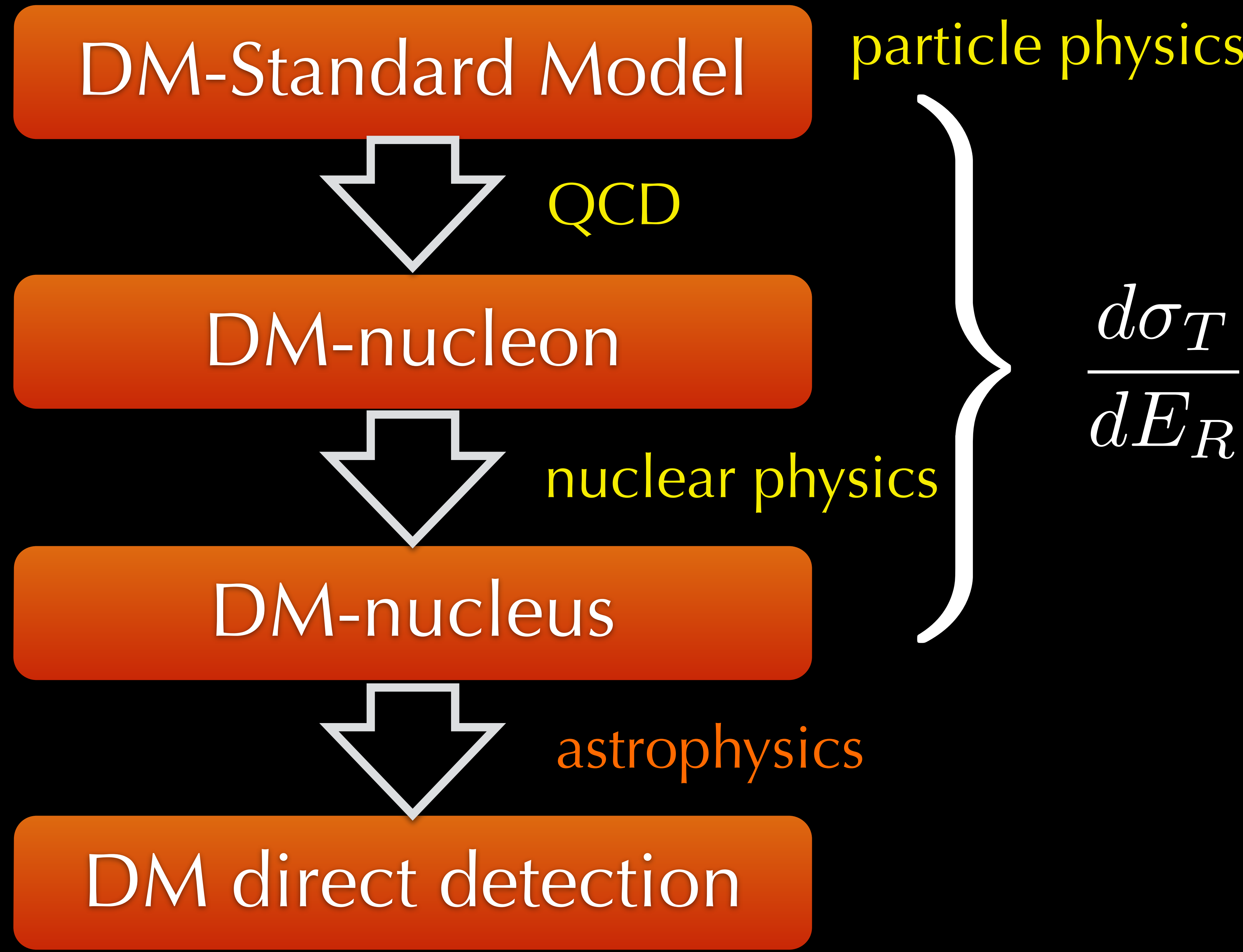
R = probability of scattering per time, per target mass

typical v ~ 200 km/s << c

typical E_R << m_{nucleon}, m_{DM}

⇒ *work in non-relativistic limit*

figure idea taken from W. Haxton, UCLA dark matter workshop slide



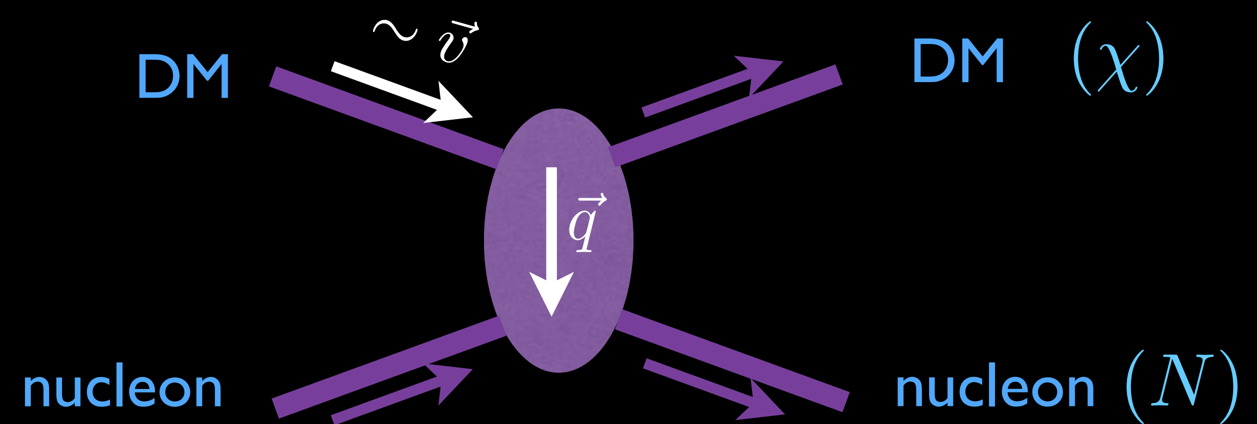
$$\frac{dR}{dE_R} = \frac{1}{m_T} \boxed{\frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v_{\rm min}(E_R)}^{\infty} d^3\vec{v}\, v\, f(\vec{v})} \boxed{\frac{d\sigma_T}{dE_R}(\vec{v}, E_R)}$$

DM-Standard Model

EXAMPLE (standard spin-independent case)

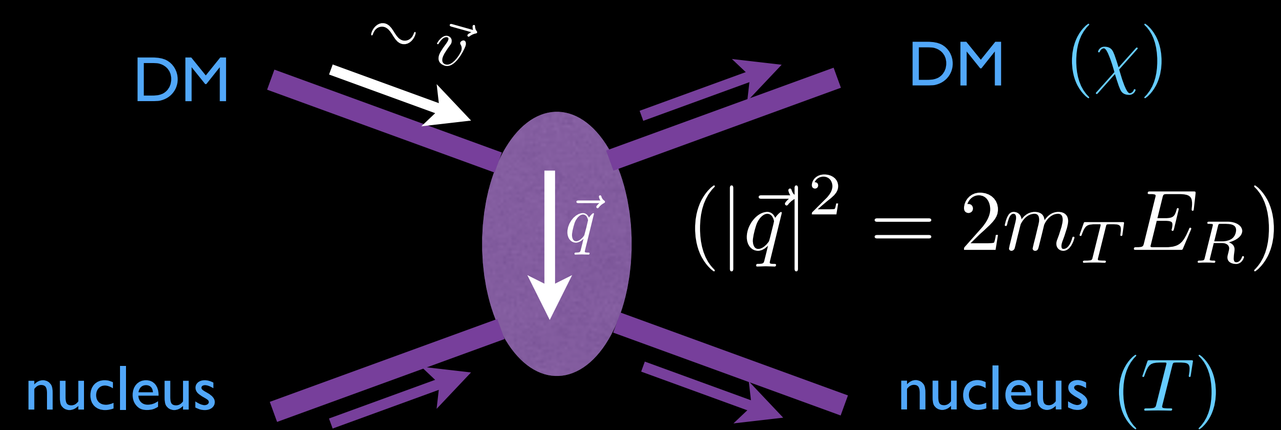
$$\mathcal{L}_{\rm int} \sim \bar{\chi}\chi\phi + \bar{q}q\phi \quad \text{or} \quad \sim \bar{\chi}\gamma^\mu\chi A_\mu + \bar{q}\gamma^\mu q A_\mu$$

DM-nucleon



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

DM-nucleus



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

DM-SM

↓

DM-nucleon

~10 relevant non-relativistic operators

↓

DM-nucleus

5 independent types of nuclear responses

↓

DM direct detection

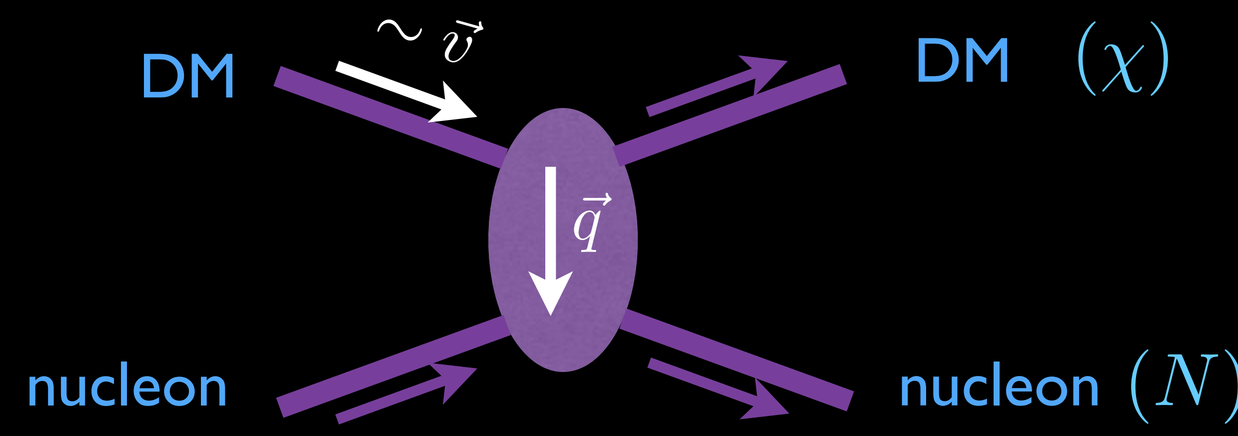
(Fitzpatrick, Haxton, Katz, Lubbers, Xu 1203.3542)

DM-SM

DM-nucleon

DM

DM direct detection



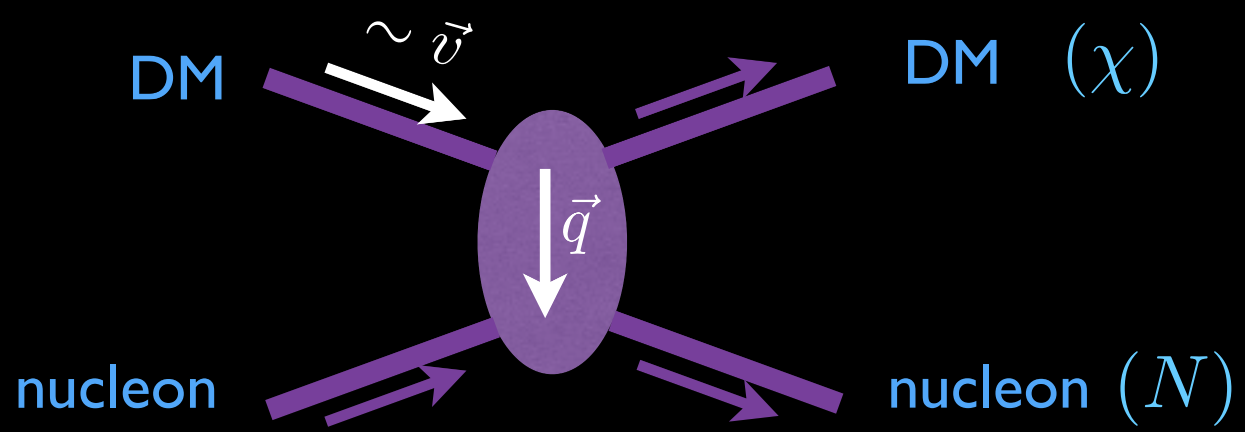
non-rel operator building blocks

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

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

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

(for more detail/precise definitions, see 1203.3542. See also 1211.2818, 1308.6288)

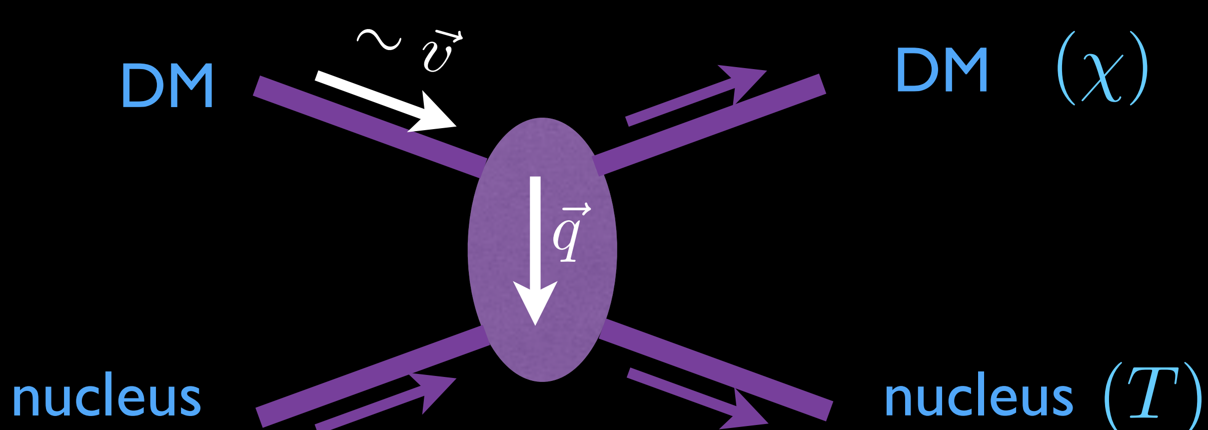


WIMP-nucleon

$$\mathbf{1}$$

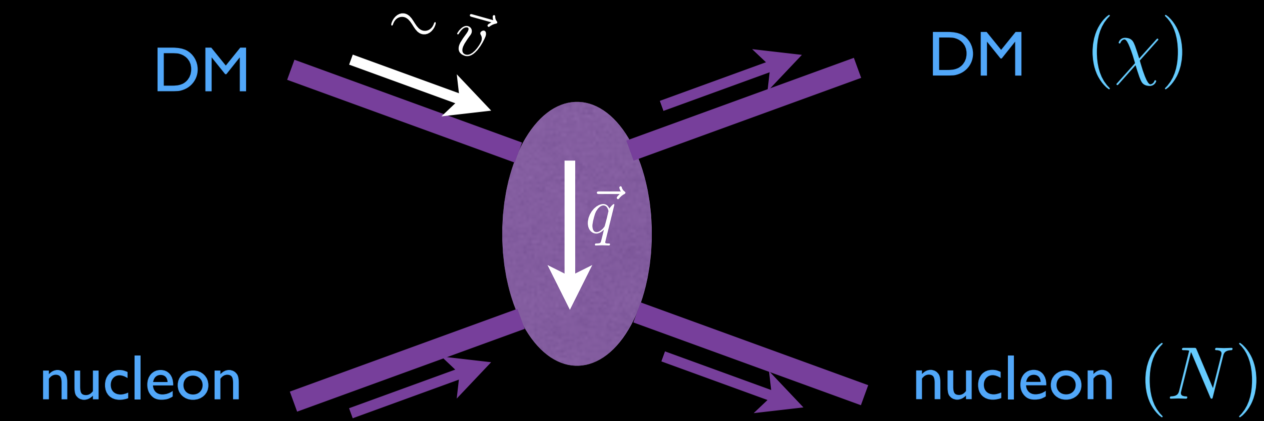
(usual) spin-independent response

WIMP-nucleus



$$\sim Z \quad \text{for proton coupling}$$

$$\sim (A - Z) \quad \text{for neutron coupling}$$



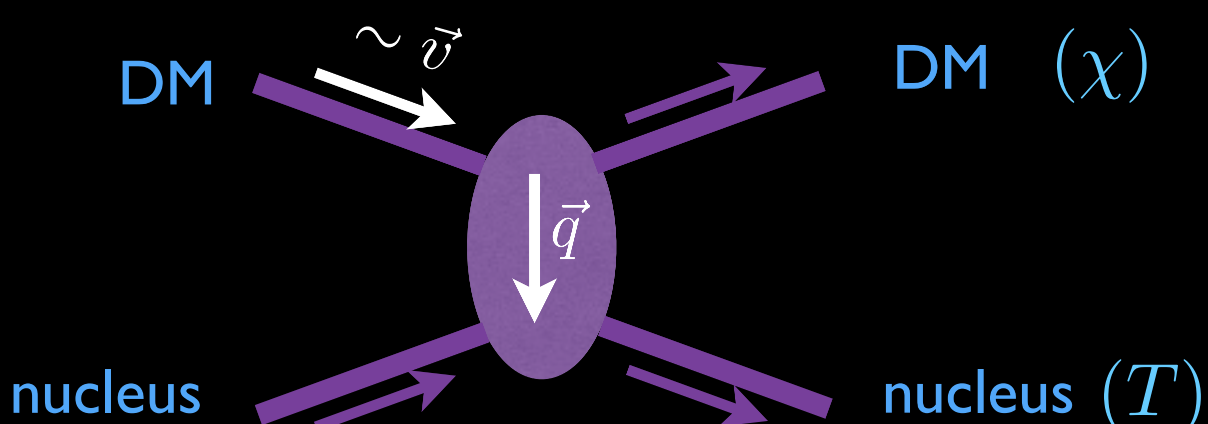
WIMP-nucleon

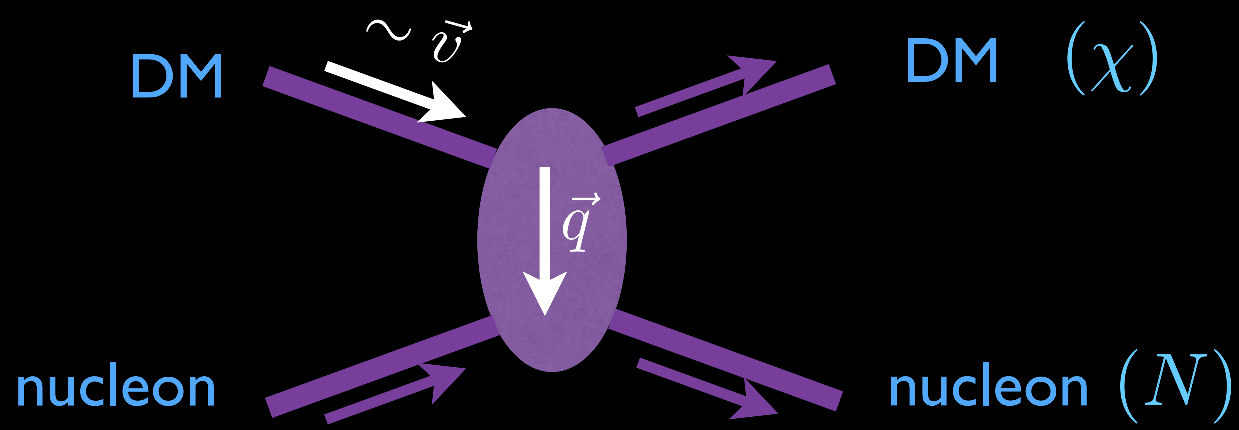
$$\vec{S}_\chi \cdot \vec{S}_N$$

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

longitudinal spin-dependent response + transverse spin-dependent response

WIMP-nucleus





non-rel operator building blocks

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

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

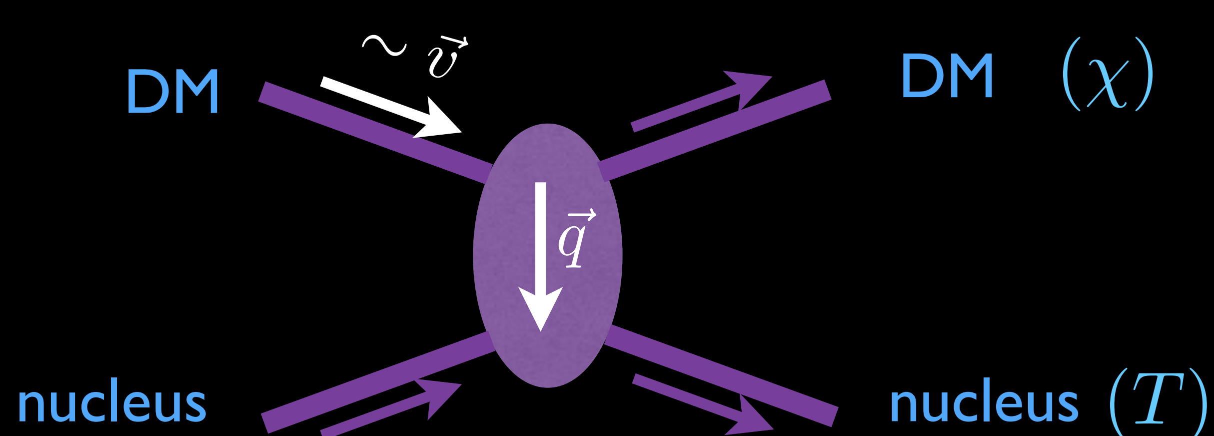
WIMP-nucleon

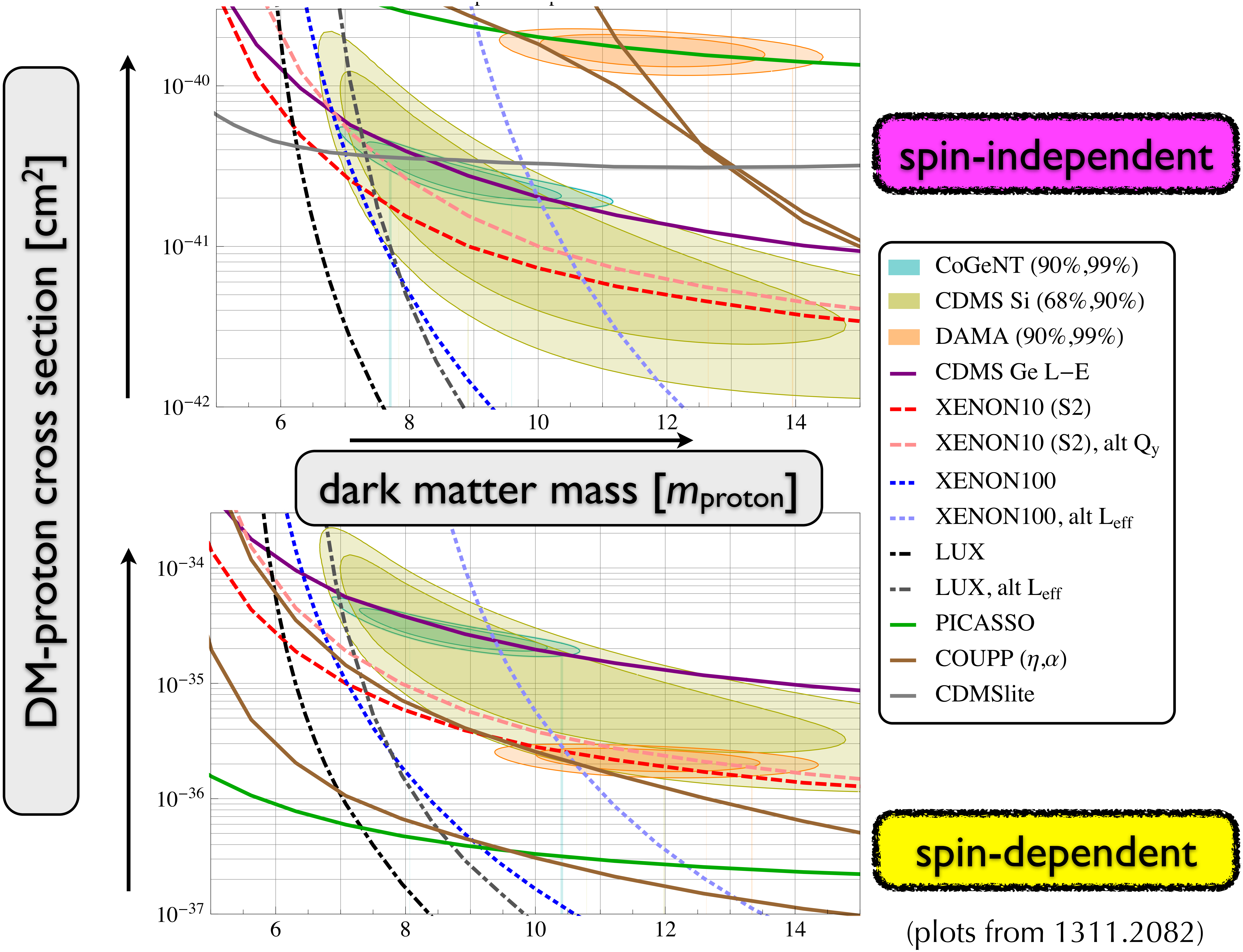
operators involving $\vec{v}^\perp$

(usually)

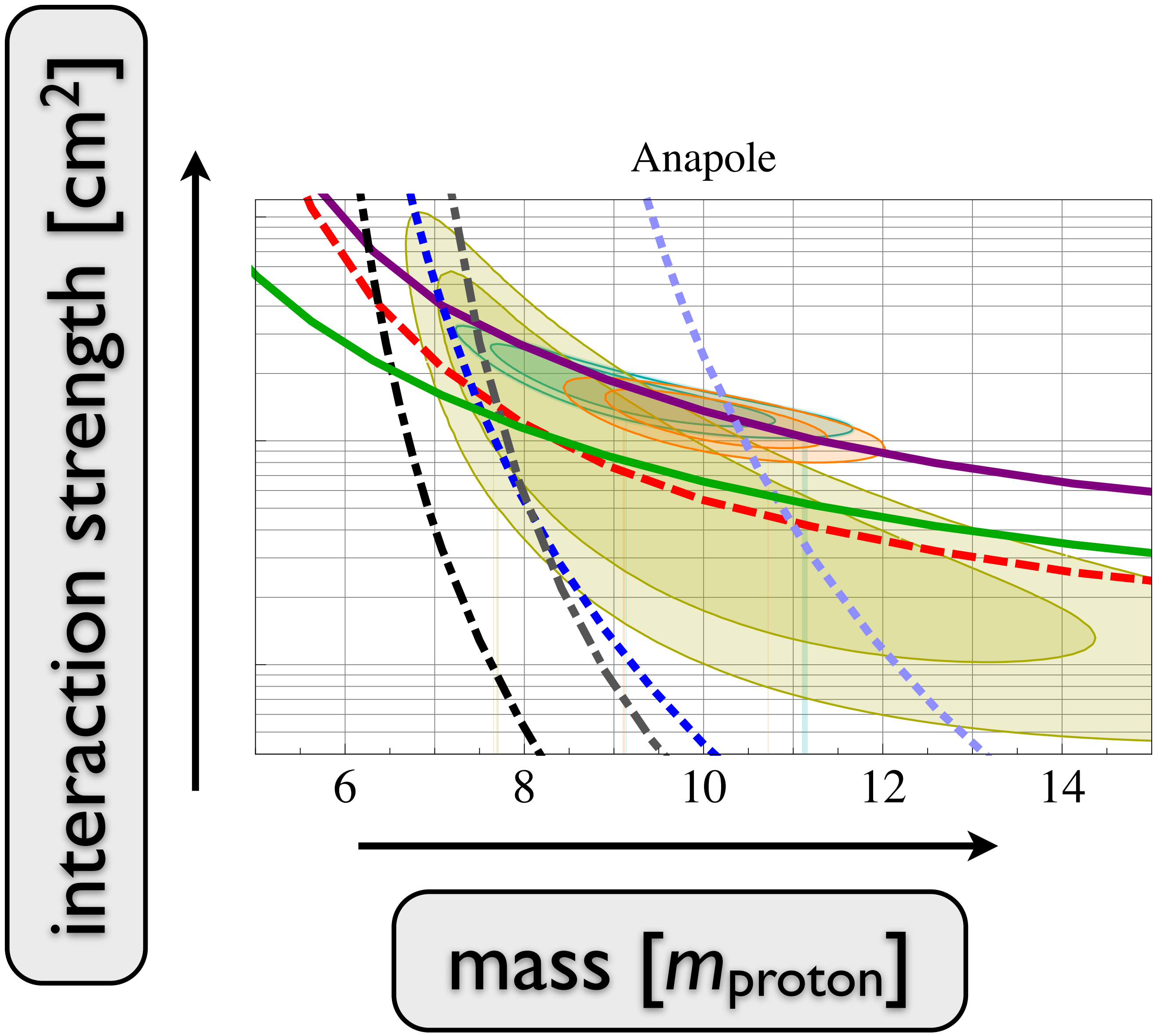
WIMP-nucleus

orbital angular momentum-dependent responses

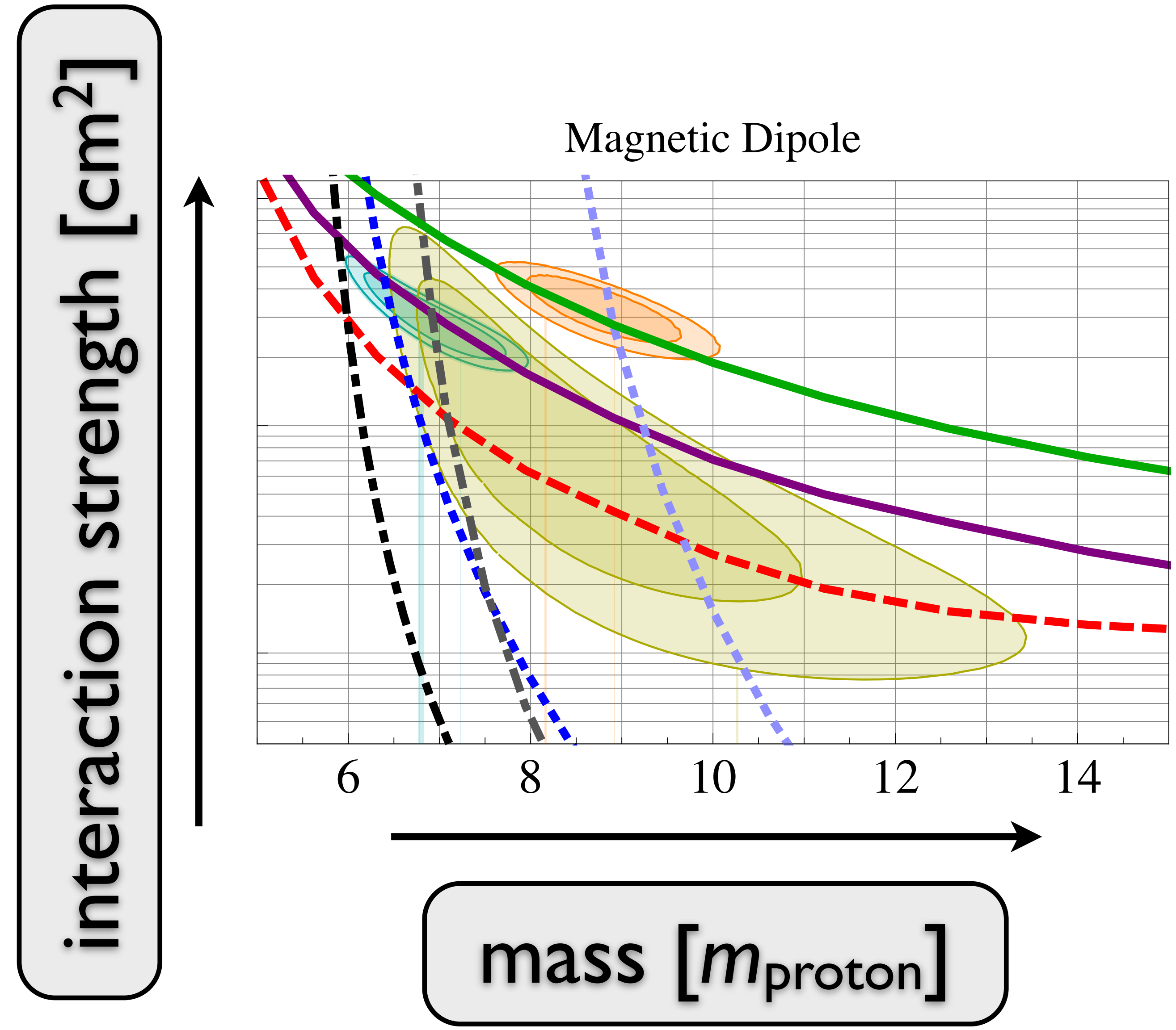



DM-proton cross section [cm^2]
dark matter mass [m_{proton}]
spin-independent
spin-dependent
CoGeNT (90%,99%)
CDMS Si (68%,90%)
DAMA (90%,99%)
CDMS Ge L−E
XENON10 (S2)
XENON10 (S2), alt Q_y
XENON100
XENON100, alt L_{eff}
LUX
LUX, alt L_{eff}
PICASSO
COUPP (η,α)
CDMSlite
10^{-40}
10^{-41}
10^{-42}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
6
8
10
12
14
(plots from 1311.2082)

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



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



(plots from 1311.2082)

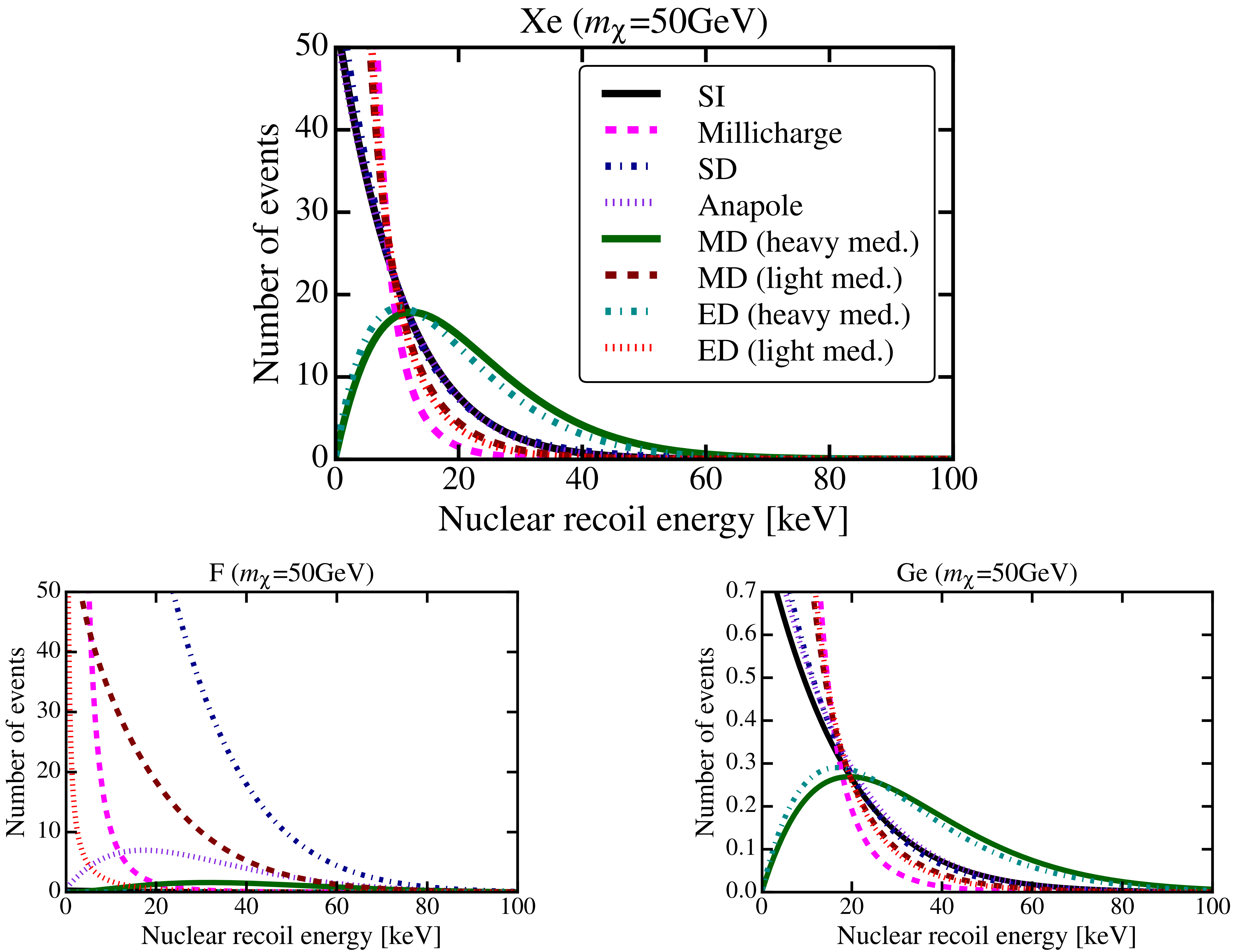
Motivation & basics

Effective theory of dark matter direct detection

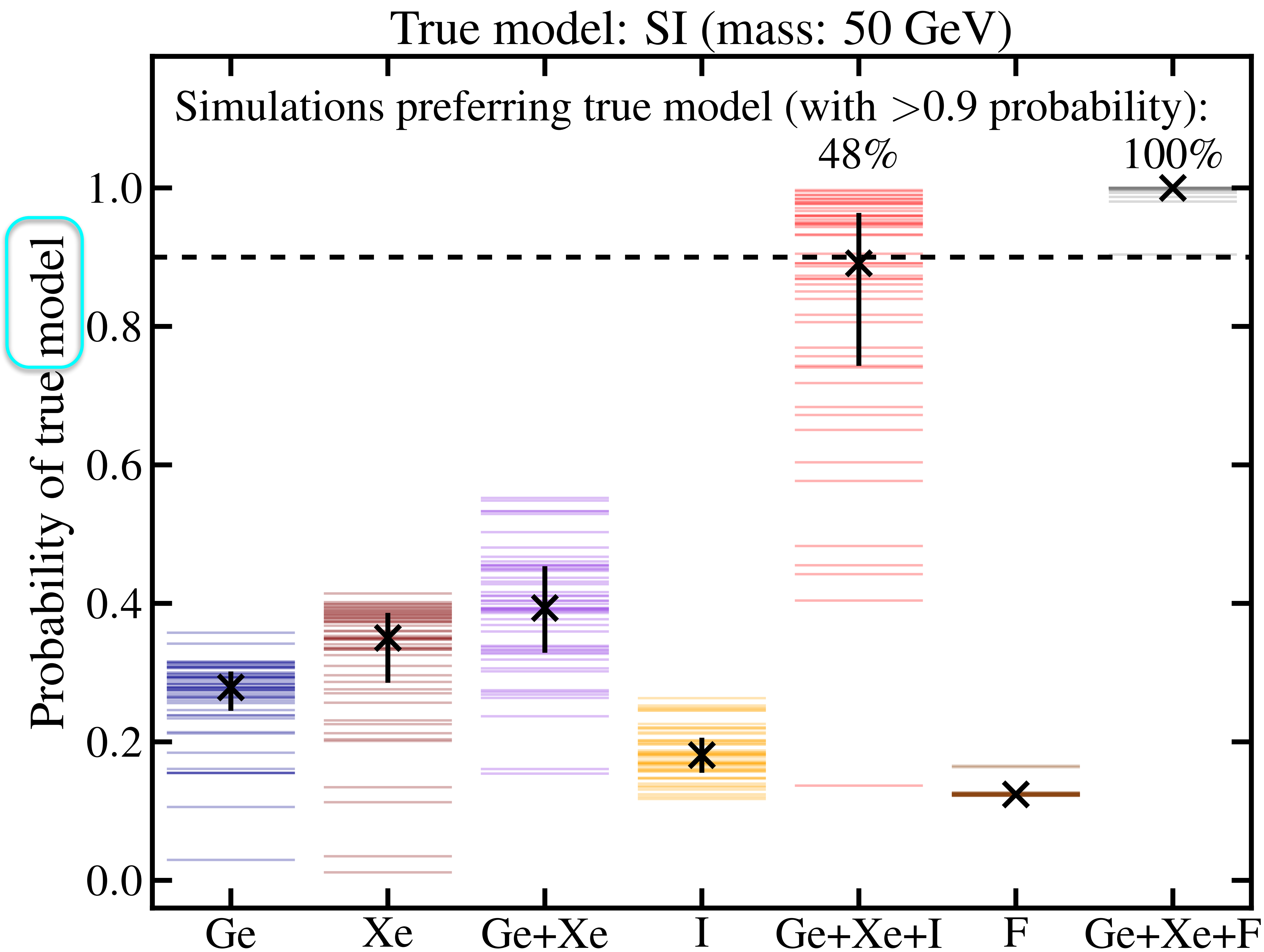
How well can we reconstruct the theory of dark matter with direct detection?

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.

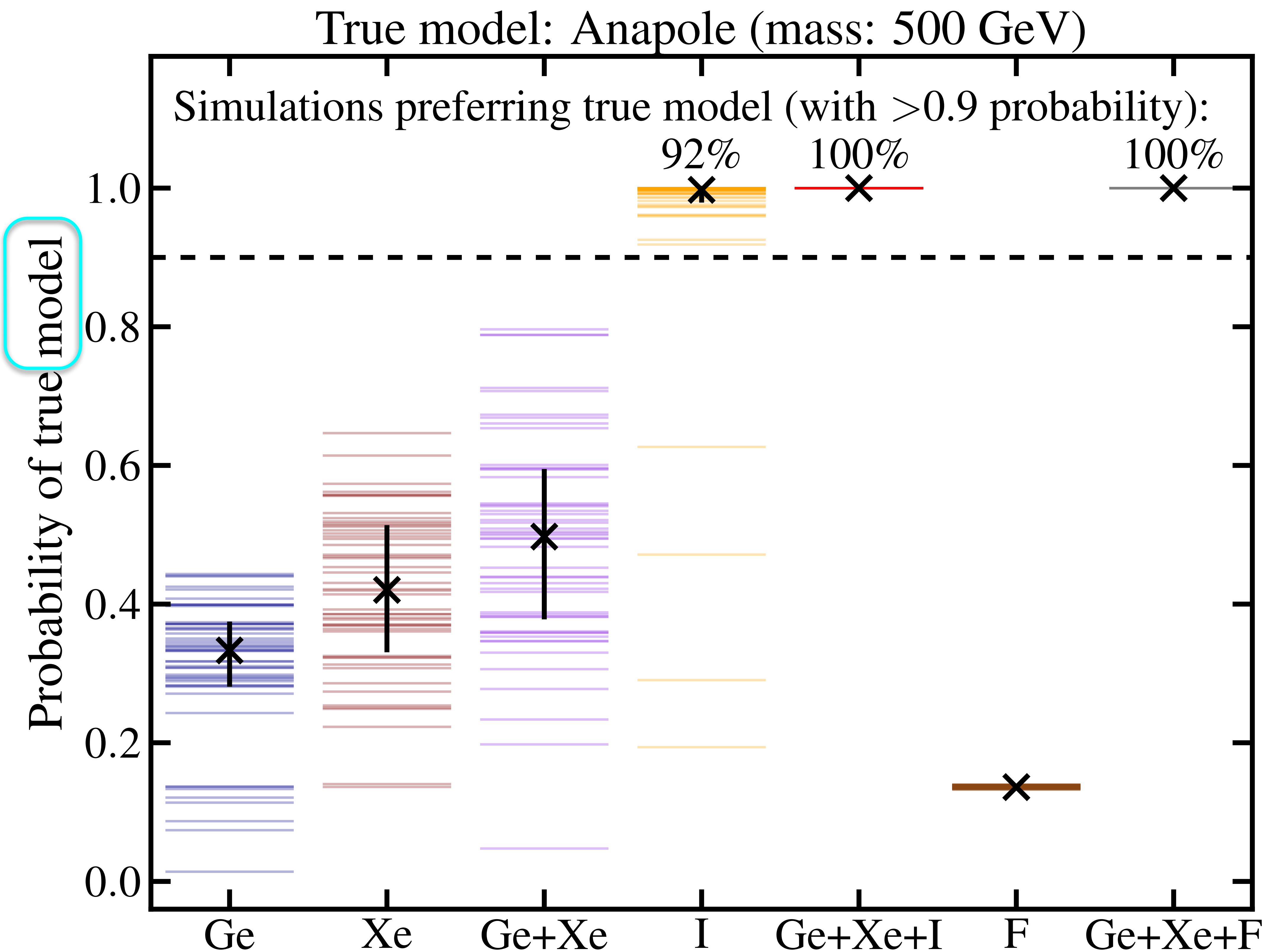
- include poisson noise
- assume perfect energy resolution
- 50 realizations for each model, on each target
- use Bayesian statistics for model selection. (Calculate evidence for model given data. Probability of model is its evidence divided by the sum of evidences for other models.)



(plots from 1506.04454)



(from 1506.04454)



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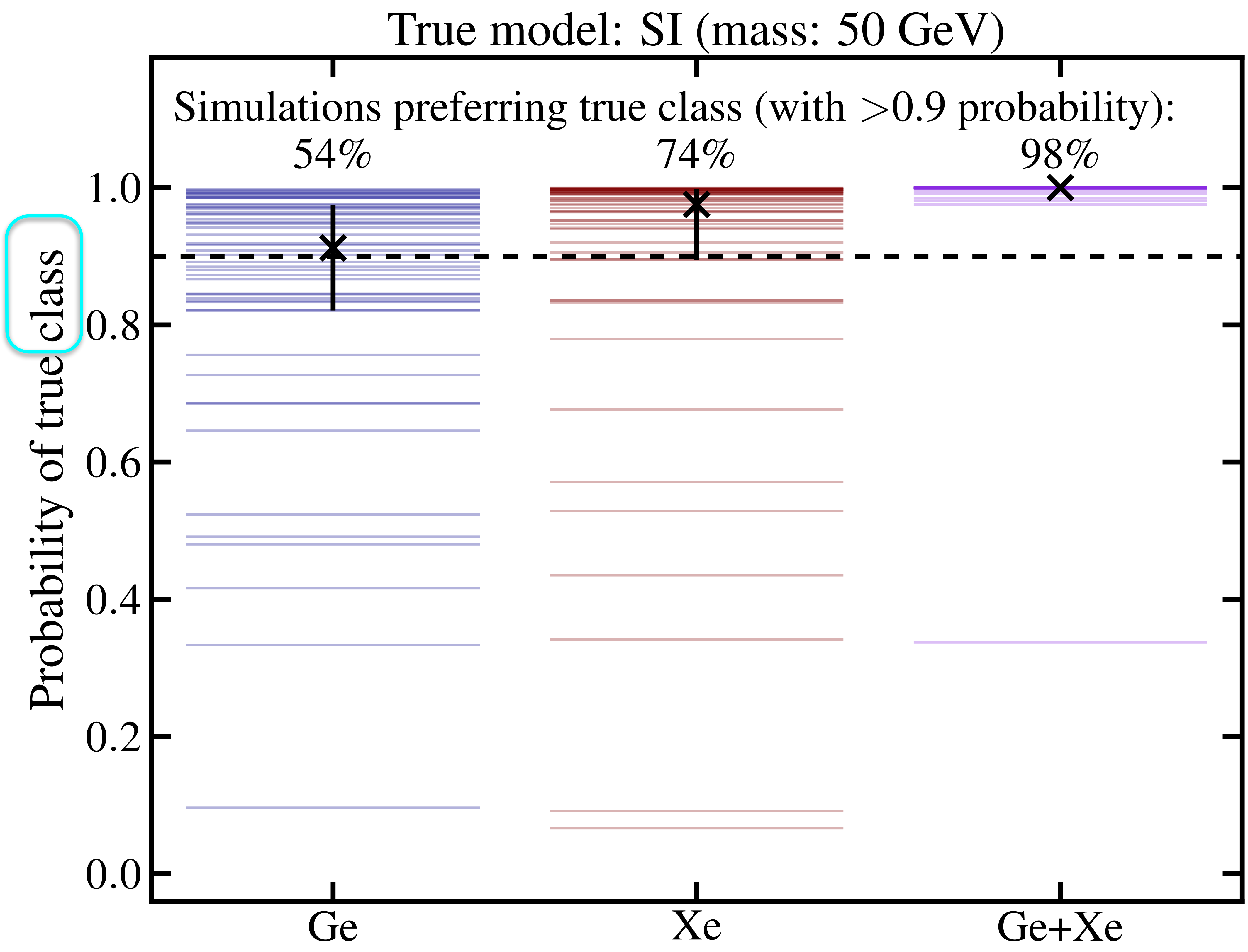

(from 1506.04454)

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.

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