

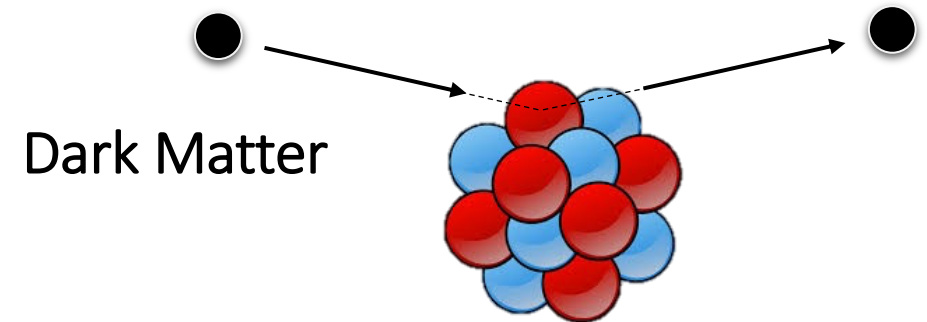
Impact of Nuclear Structure on WIMP-nucleus

Raghda Abdel Khaleq^{1,2}, Giorgio Busoni^{1,2}, Navneet Krishnan^{1,2},
Cedric Simenel^{1,2}, Andrew Stuchbery^{1,2}

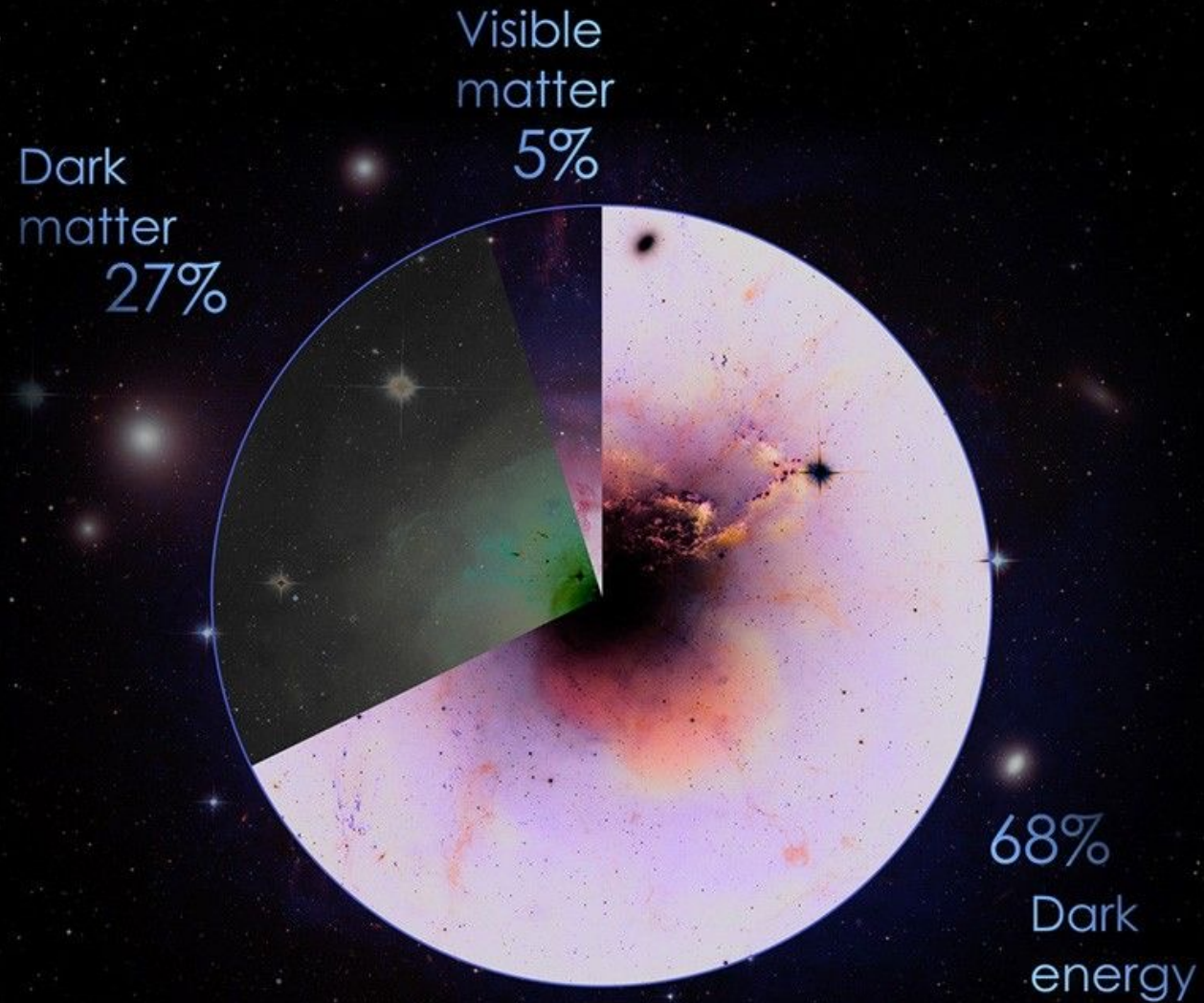
¹ *Centre of Excellence for Dark Matter Particle Physics*

² *The Australian National University*

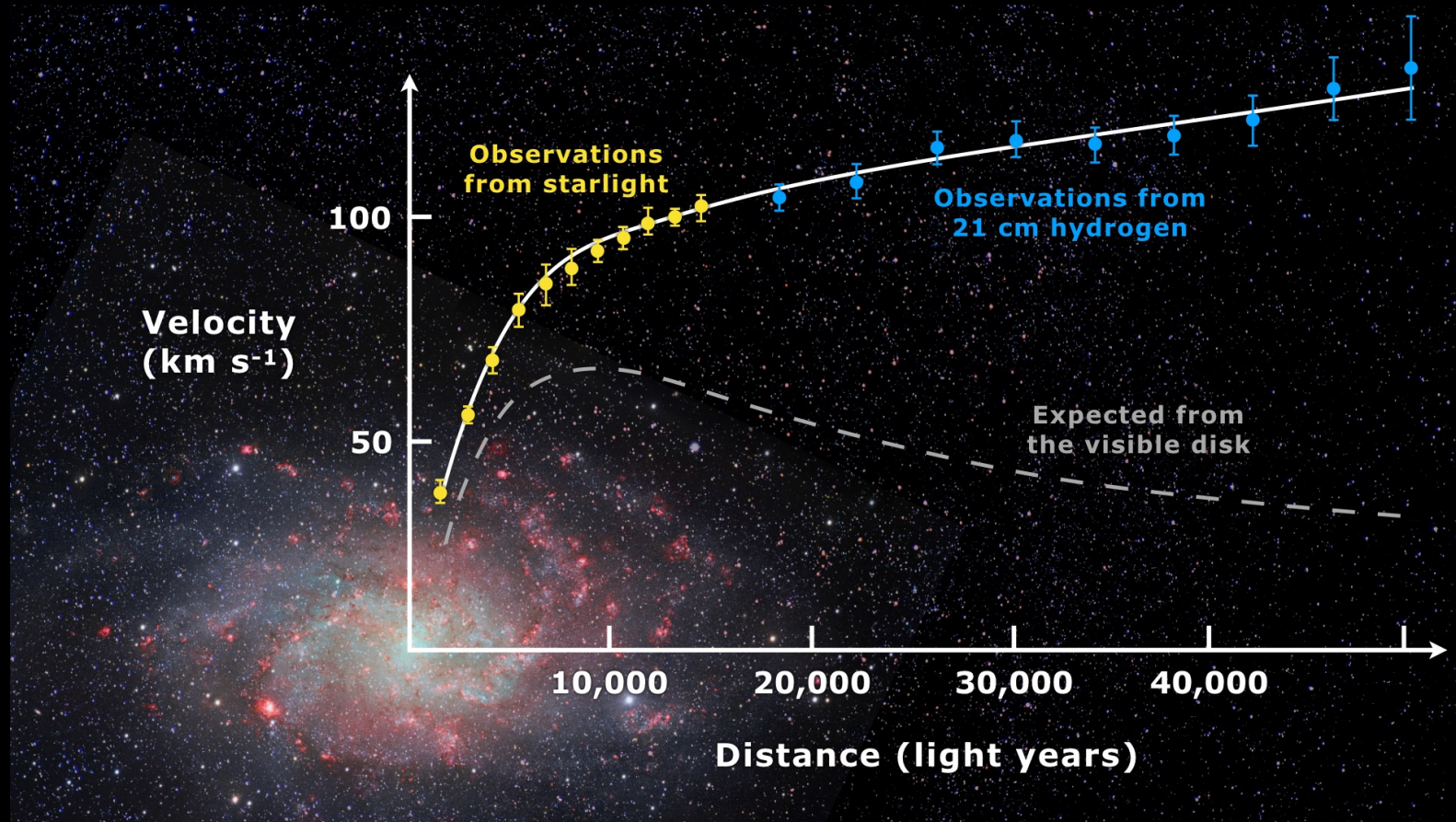
³ *University of Melbourne*



Evidence for Dark Matter



Evidence for Dark Matter



Astronomer Vera Rubin (1928-2016)
Pioneered work on galaxy rotation curves

Evidence for Dark Matter



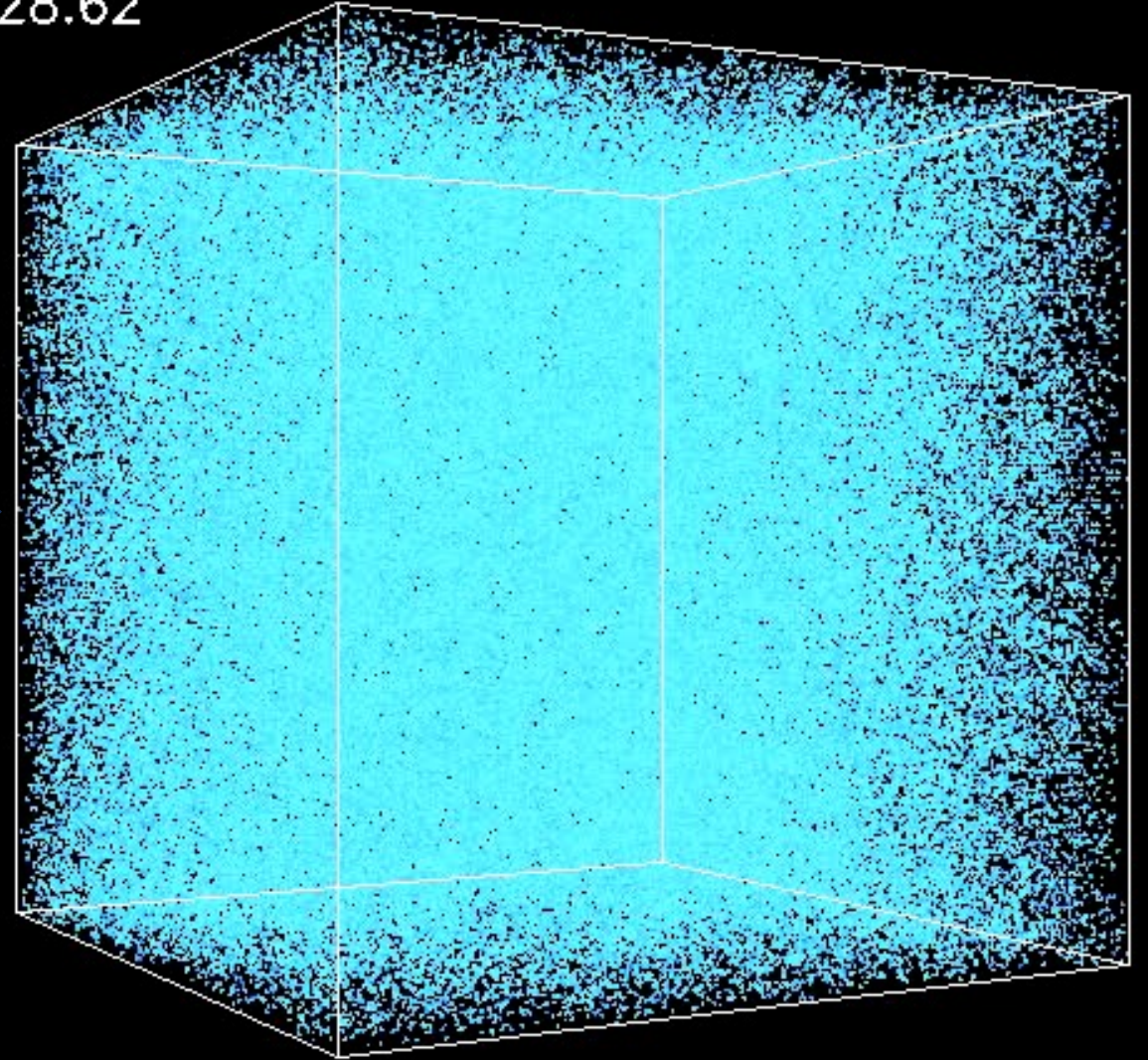
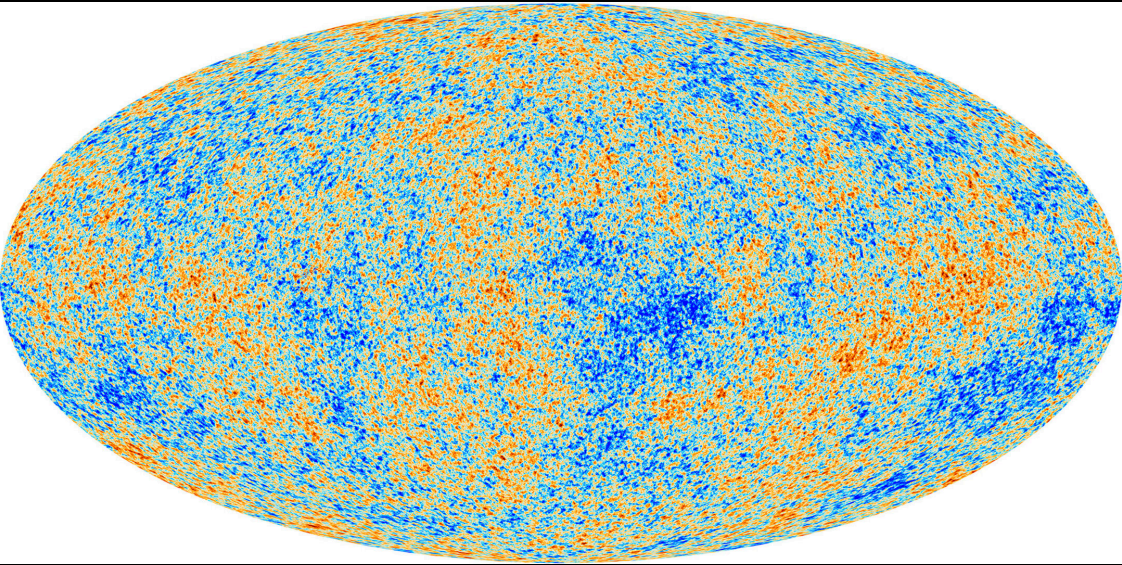
Evidence for Dark Matter

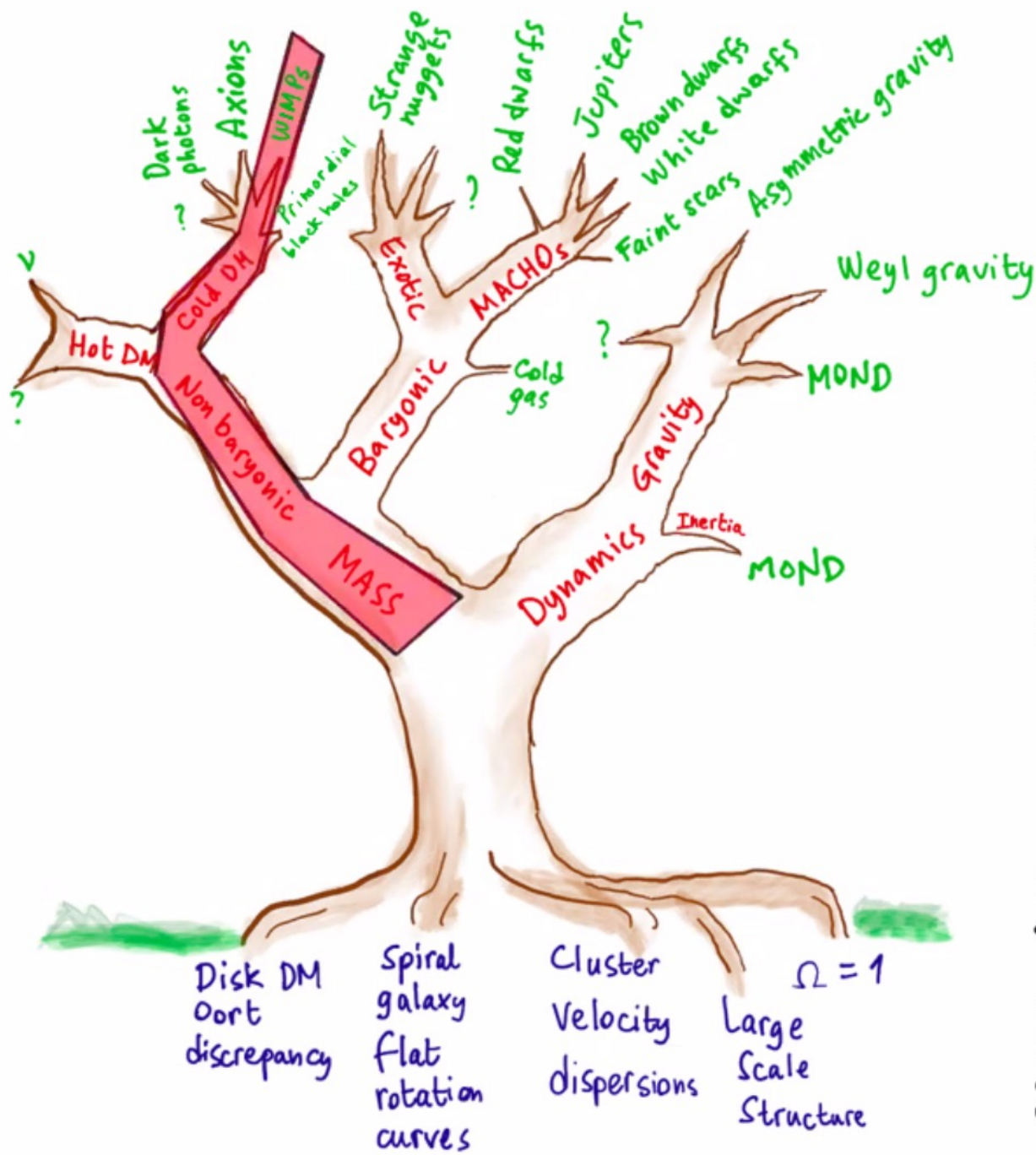
Evidence for Dark Matter

Evidence for Dark Matter

$z=28.62$

CMB

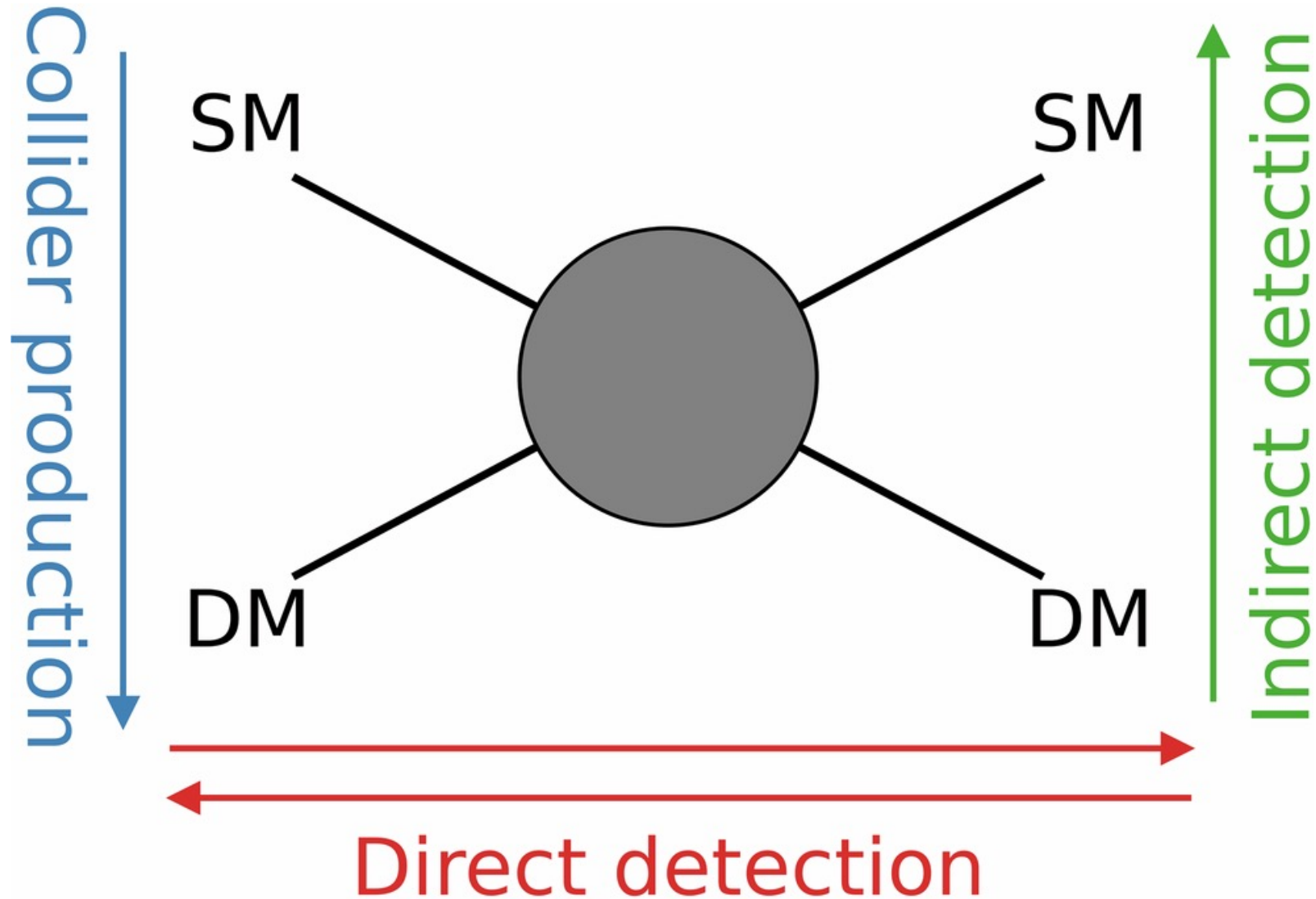




HYPOTHESIZED
SOLUTIONS

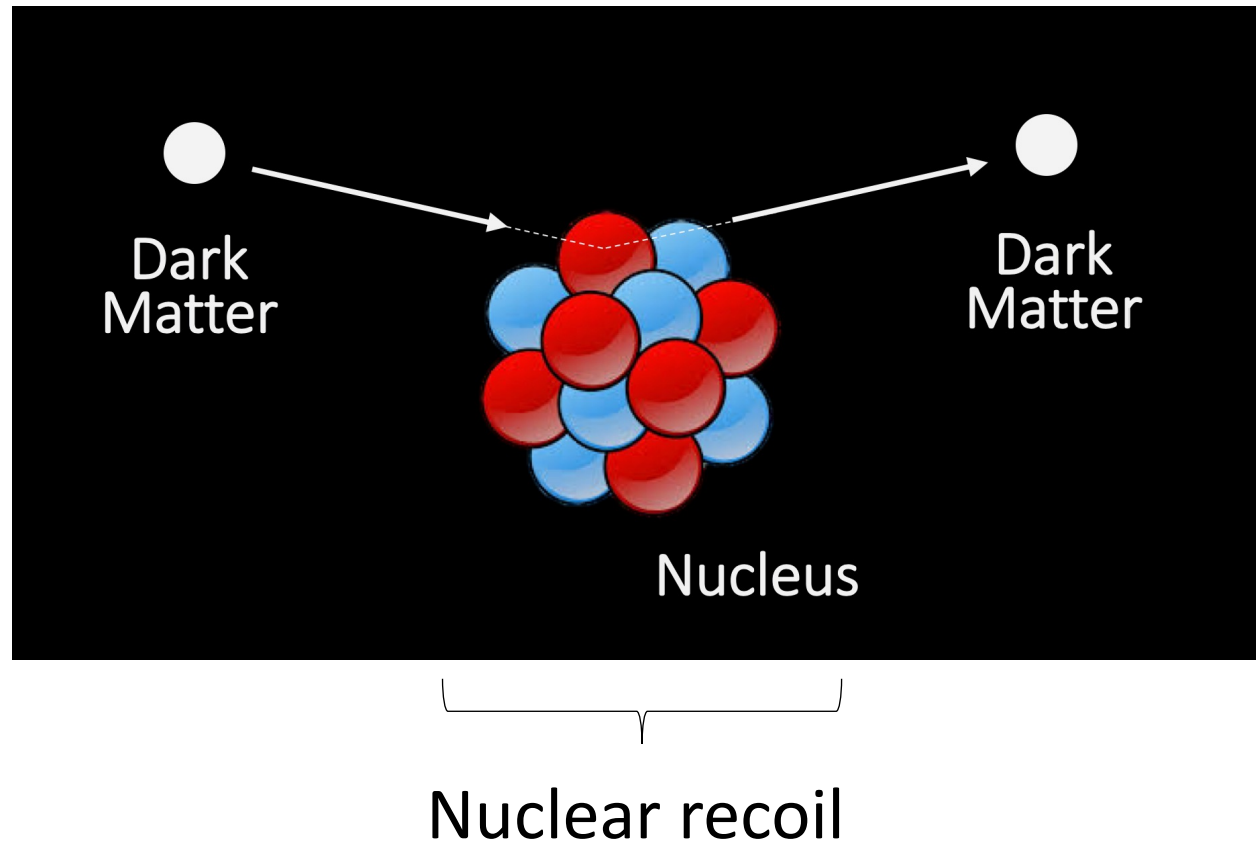
ROOTS of the
PROBLEM

WIMP detection



Direct Detection

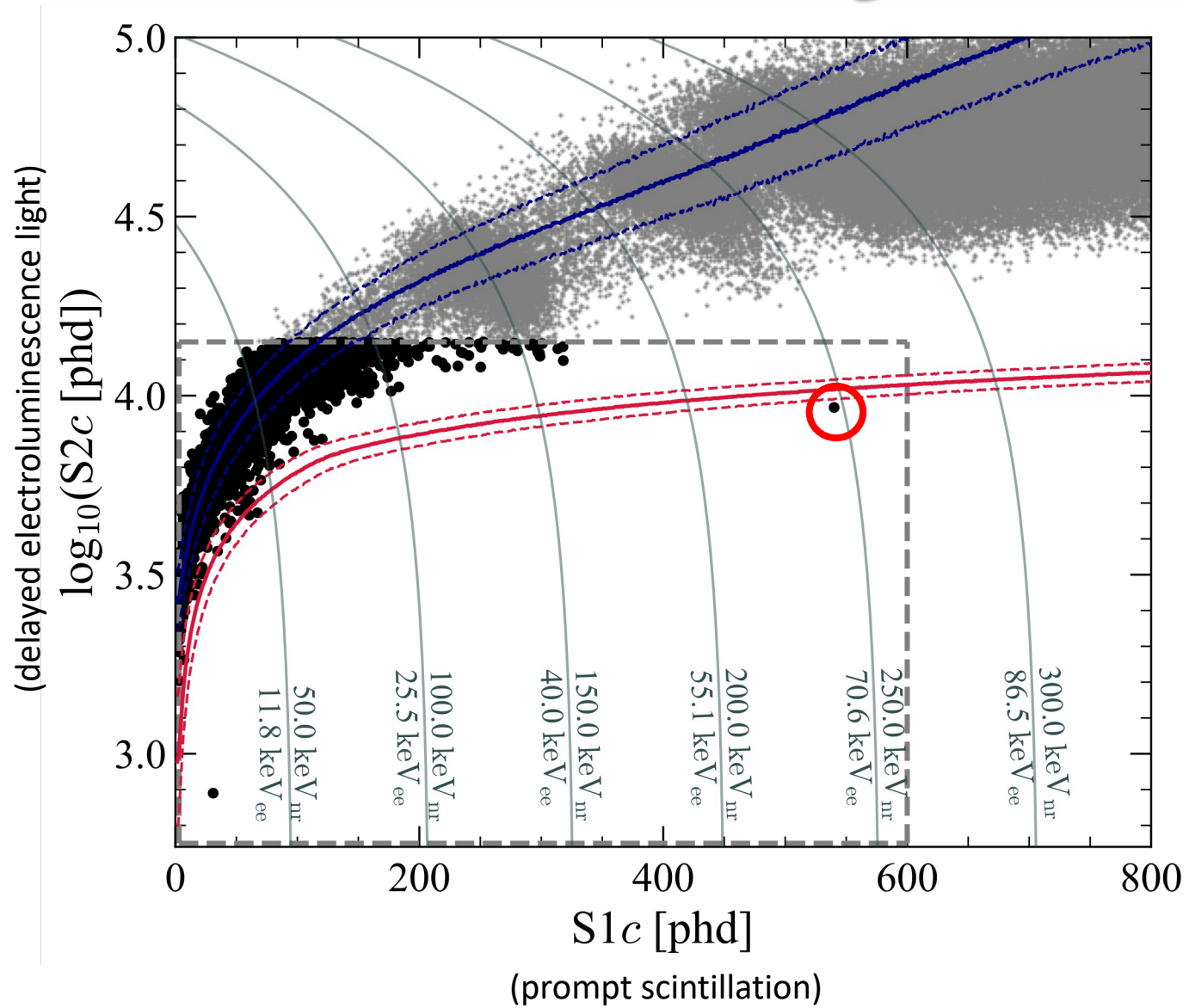
Dark Matter-Nucleus scattering



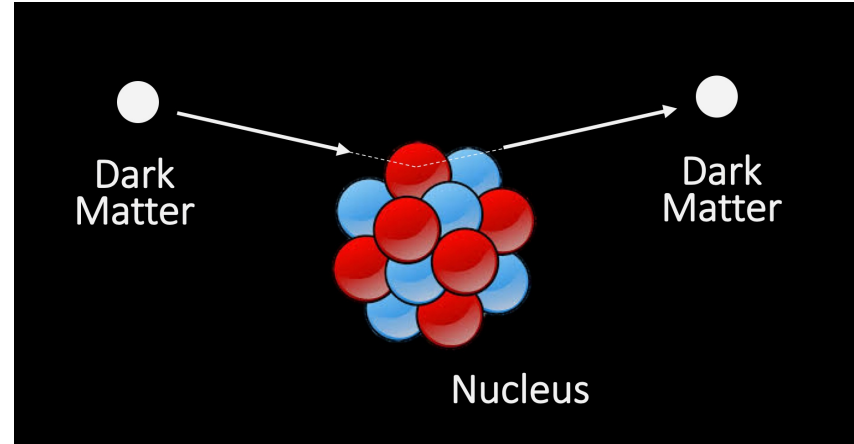
Direct Detection



$\mathcal{L}Z$ anomaly



WIMP-nucleus elastic scattering rate



$$\frac{dR}{dE_R} \propto \int v \, d^3v \sum_{ij} \sum_{N,N'=p,n} \quad \textcolor{red}{f_v(\vec{v})} \quad \textcolor{green}{R(\vec{v}, q)_{ij}^{(N,N')}} \quad \textcolor{blue}{F(q)_{ij}^{(N,N')}} \quad \textcolor{blue}{\text{Nuclear Structure}}$$

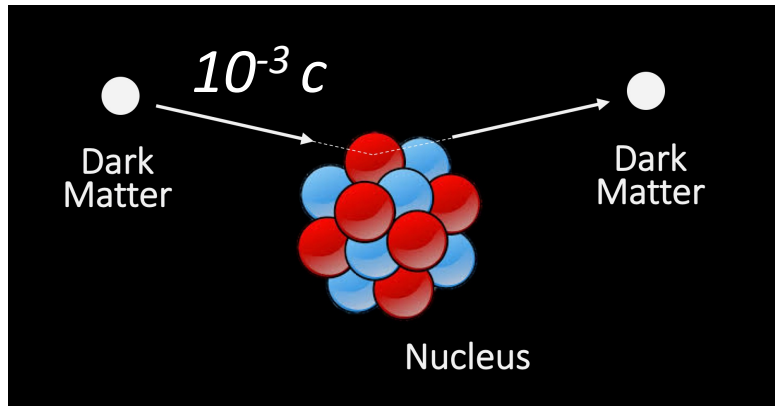
DM Velocity Distribution
Particle Physics
Nuclear Structure

Standard approach

Standard (momentum independent interaction) responses

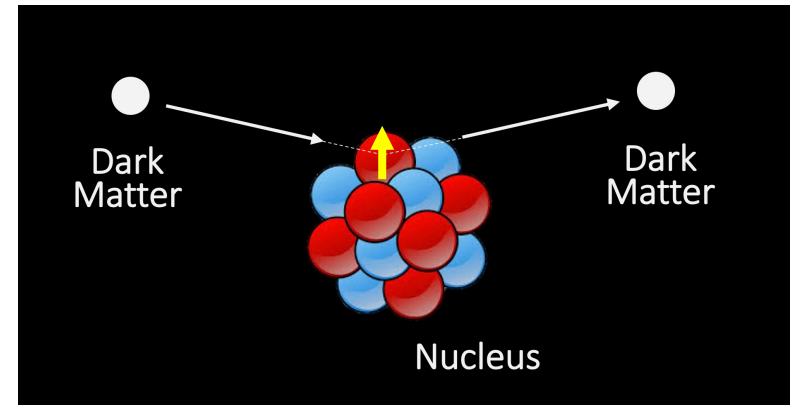
Spin-independent (SI)

*Takes into account
all nucleons*



Spin-dependent (SD)

*Sensitive to unpaired
nucleon spin*



Could the interaction depend on momentum?

○ Possible scenarios where standard SI and SD suppressed:

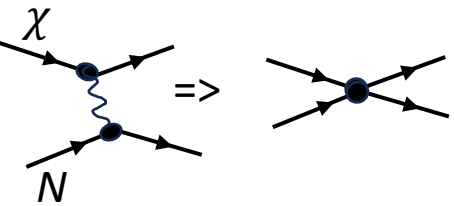
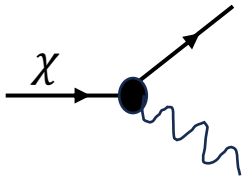
- Kinetic mixing $\mathcal{L}_{kin} = \epsilon F_{\mu\nu} F'^{\mu\nu}$ (Dark photon A'_μ) and Majorana WIMP χ

→ Charge interaction $g' \bar{\chi} \gamma^\mu \chi A'_\mu$ forbidden

→ Anapole interaction $ig' \bar{\chi} \gamma^\mu \gamma^5 \chi A'_\mu$ allowed (if A'_μ gauge symmetry broken)

→ 4-fermion operator after integrating out A'_μ : $\frac{eg'\epsilon}{m_A^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma_\mu N$

→ Non-relativistic limit: $\frac{eg'\epsilon}{m_N m_A^2} (\bar{\chi} \vec{S}_\chi \chi) \cdot (\bar{N} \vec{\sigma} N)$



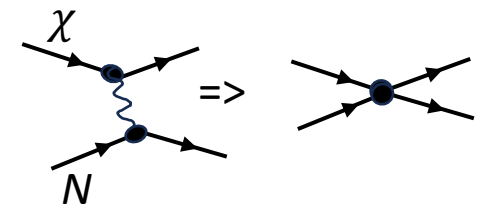
Could the interaction depend on momentum?

○ Possible scenarios where standard SI and SD suppressed:

- Kinetic mixing $\mathcal{L}_{kin} = \epsilon F_{\mu\nu} F'^{\mu\nu}$ (Dark photon A'_μ) and Majorana WIMP χ
- Dirac DM neutral and composite, size r , constituents with charge Q' under A'_μ



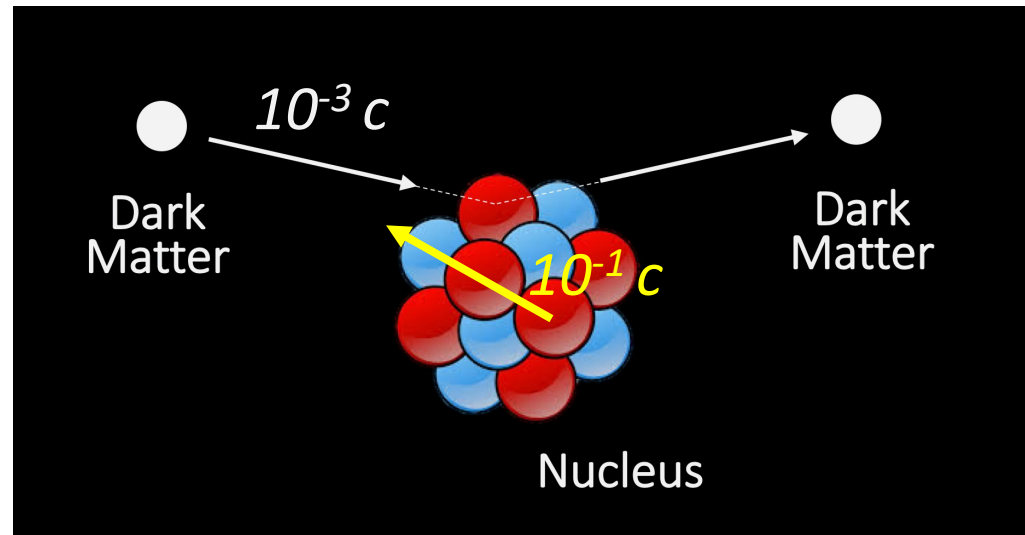
→ Magnetic dipole moment $\mathcal{L}_{DM} \sim g' Q' r \bar{\chi} \sigma^{\mu\nu} \chi F'_{\mu\nu}$



→ 4-fermion operator after integrating out A'_μ : $\frac{eg'\epsilon Q' r}{m_A^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{N} \gamma_\mu N$

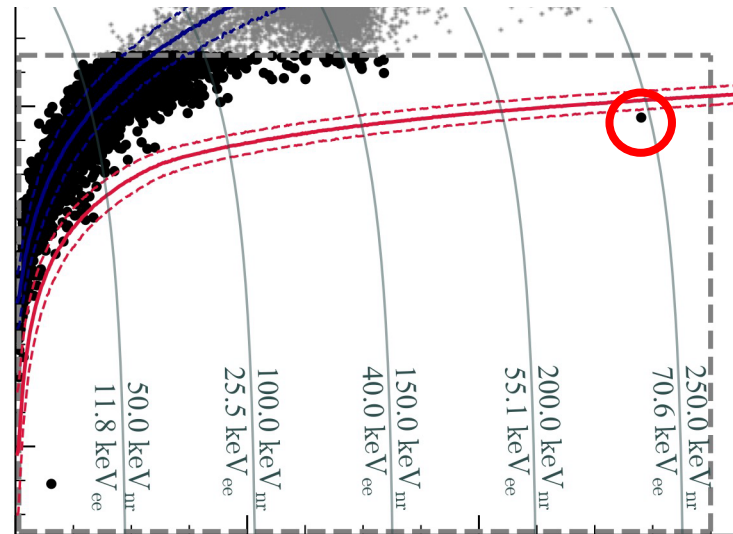
Could the interaction depend on momentum?

- Possible scenarios where standard SI and SD suppressed:
 - Kinetic mixing $\mathcal{L}_{kin} = \epsilon F_{\mu\nu} F'^{\mu\nu}$ (Dark photon A_μ') and Majorana WIMP χ
 - Dirac DM neutral and composite, size r , constituents with charge Q' under A_μ'
- WIMPs are slow but nucleons are not at rest!



Could the interaction depend on momentum?

- Possible scenarios where standard SI and SD suppressed:
 - Kinetic mixing $\mathcal{L}_{kin} = \epsilon F_{\mu\nu} F'^{\mu\nu}$ (Dark photon A_μ') and Majorana WIMP χ
 - Dirac DM neutral and composite, size r , constituents with charge Q' under A_μ'
- WIMPs are slow but nucleons are not at rest!
- LZ anomaly could be explained by momentum dependent interaction



Standard and momentum suppressed responses

Nuclear response function ($\sim$ form factor) $F(q)_{ij}^{(N,N')}$ decomposed into

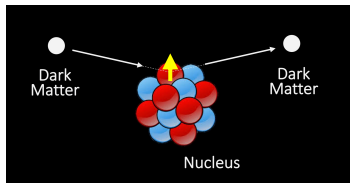
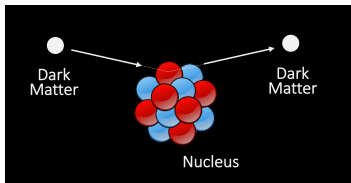
Standard

$$M_{JM}$$

$$\Sigma'_{JM}, \Sigma''_{JM}$$

Spin-independent (SI)

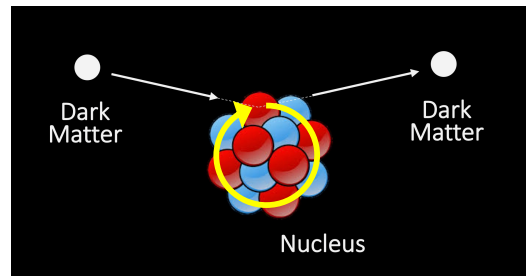
Spin-dependent (SD)



Momentum suppressed

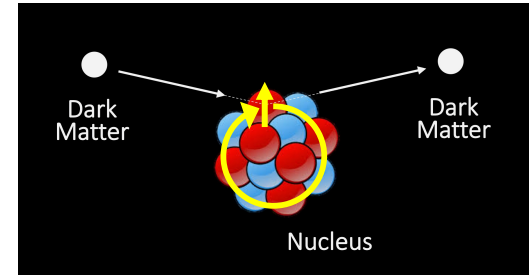
$$\Delta_{JM}$$

orbital angular momentum



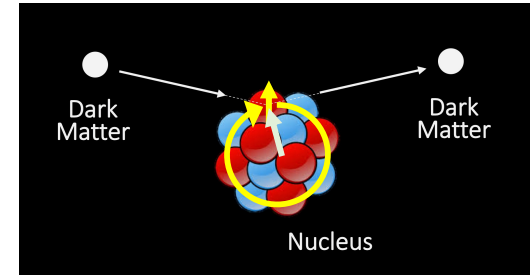
$$\Phi''_{JM}$$

Spin-orbit

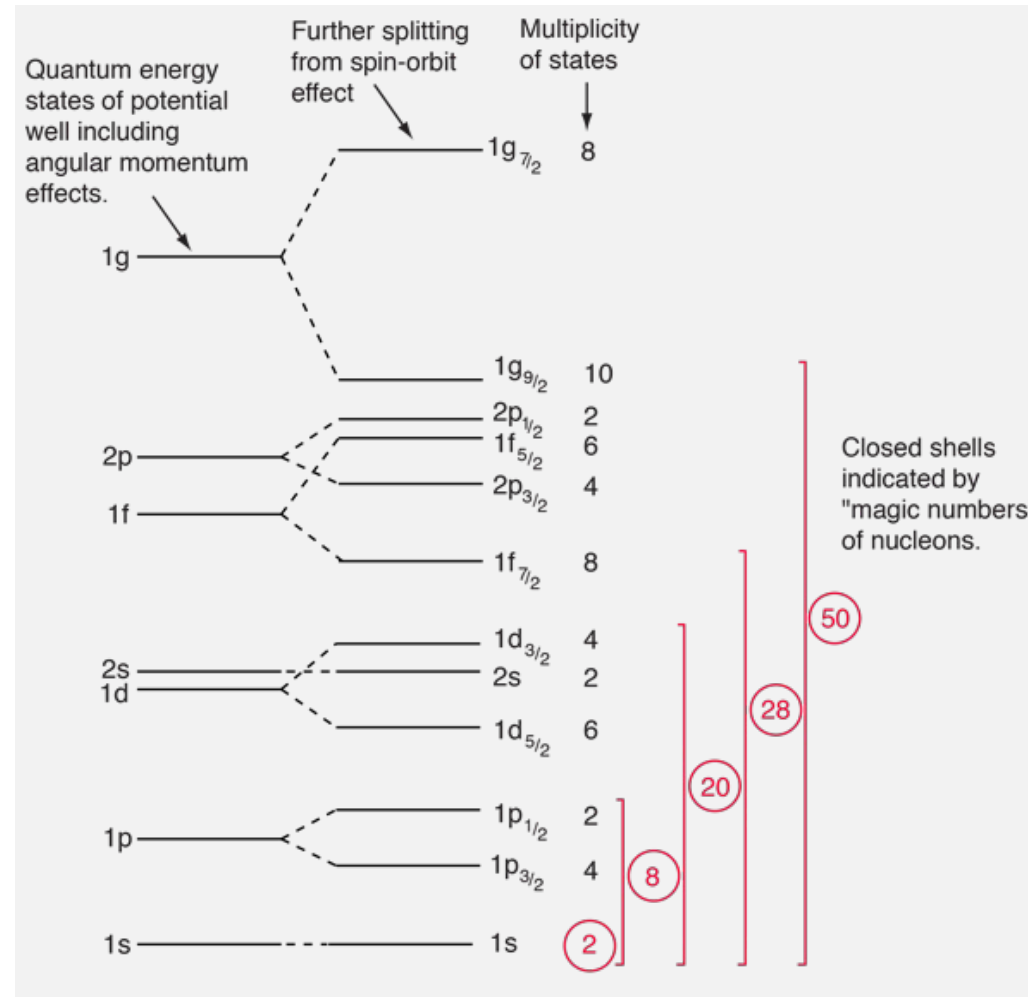


$$\tilde{\Phi}'_{JM}$$

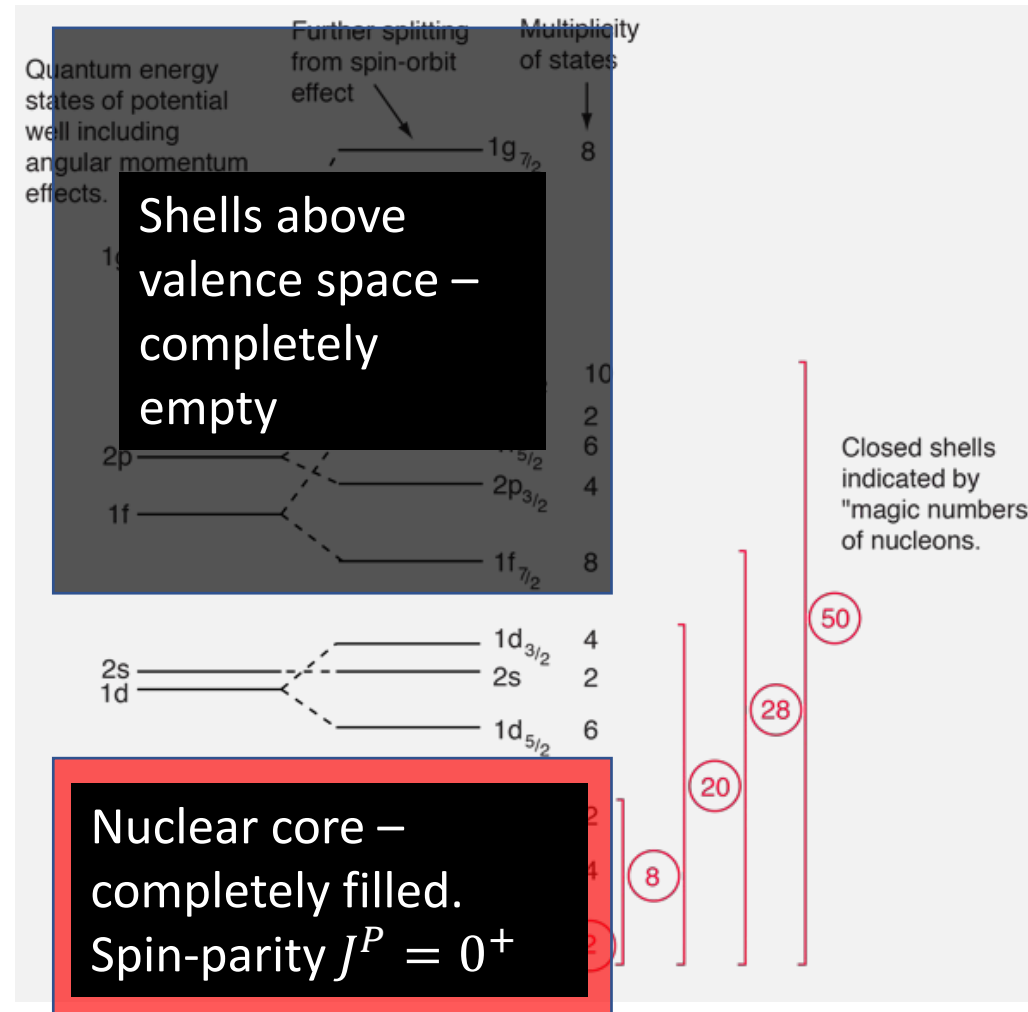
Tensor



Shell Model approach



Shell Model approach



Isotopes relevant for direct detection

^{19}F , ^{23}Na , $^{28,29,30}\text{Si}$, ^{40}Ar , $^{70,72,73,74,76}\text{Ge}$

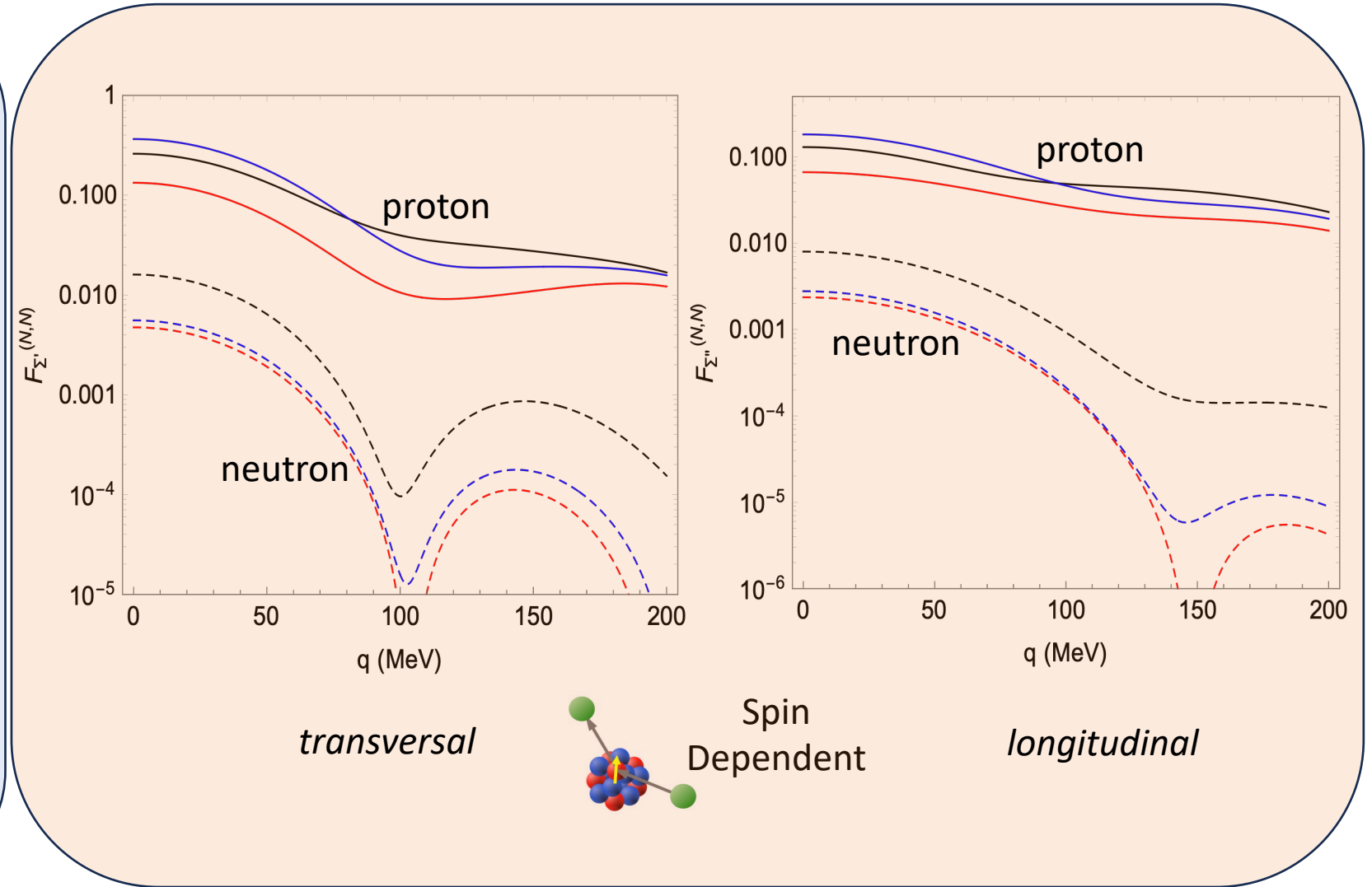
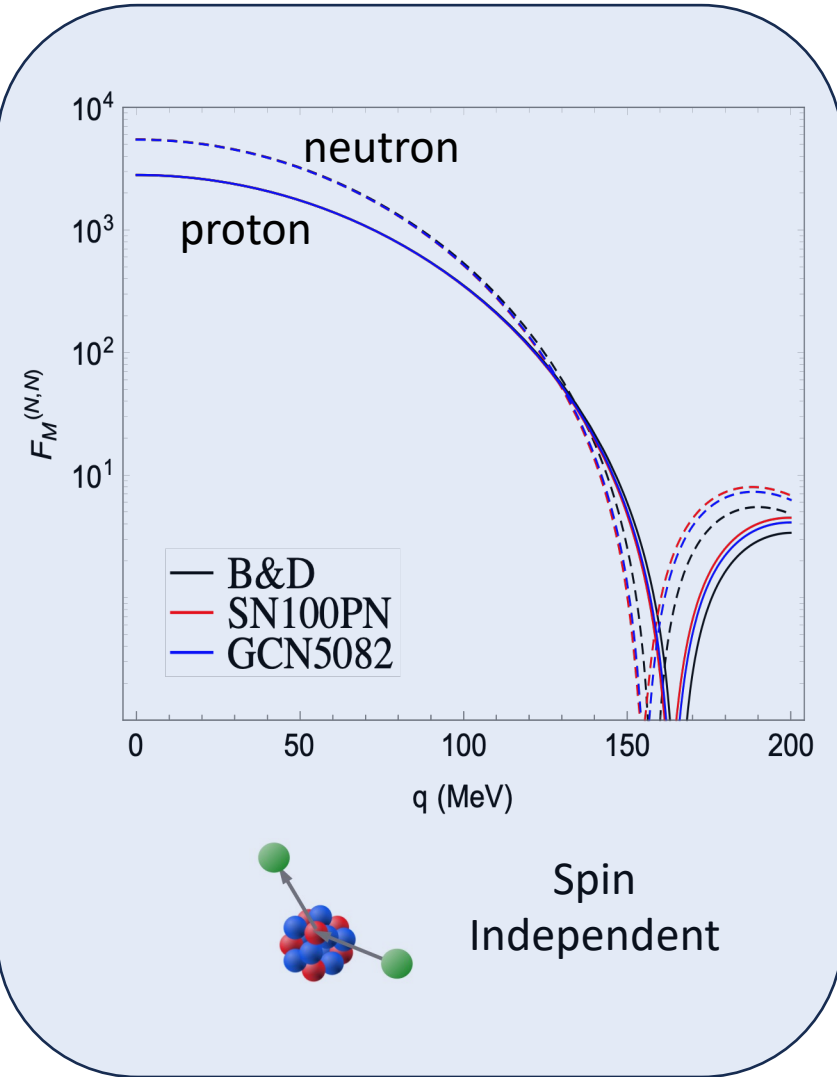
^{127}I $^{128,129,130,131,132,134,136}\text{Xe}$

PHYSICAL REVIEW D **109**, 075036 (2024)

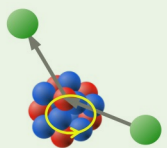
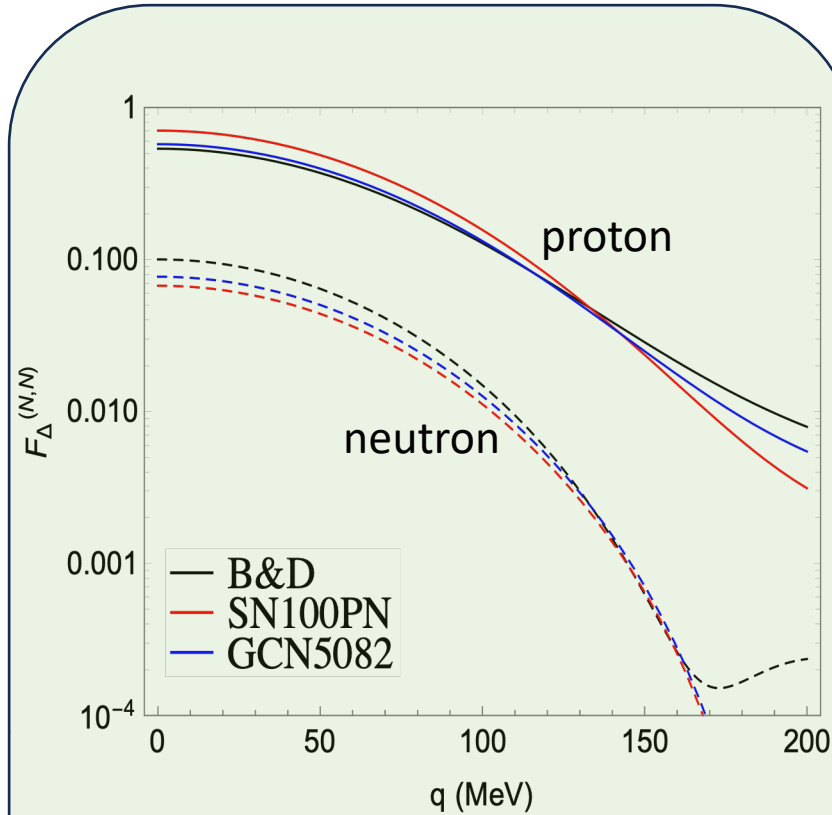
**Impact of shell model interactions on nuclear responses to
WIMP elastic scattering**

R. Abdel Khaleq^{1,2,3,*} G. Busoni^{1,3,†} C. Simenel^{1,2,3,‡} and A. E. Stuchbery^{2,3,§}

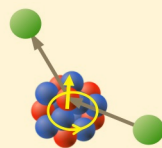
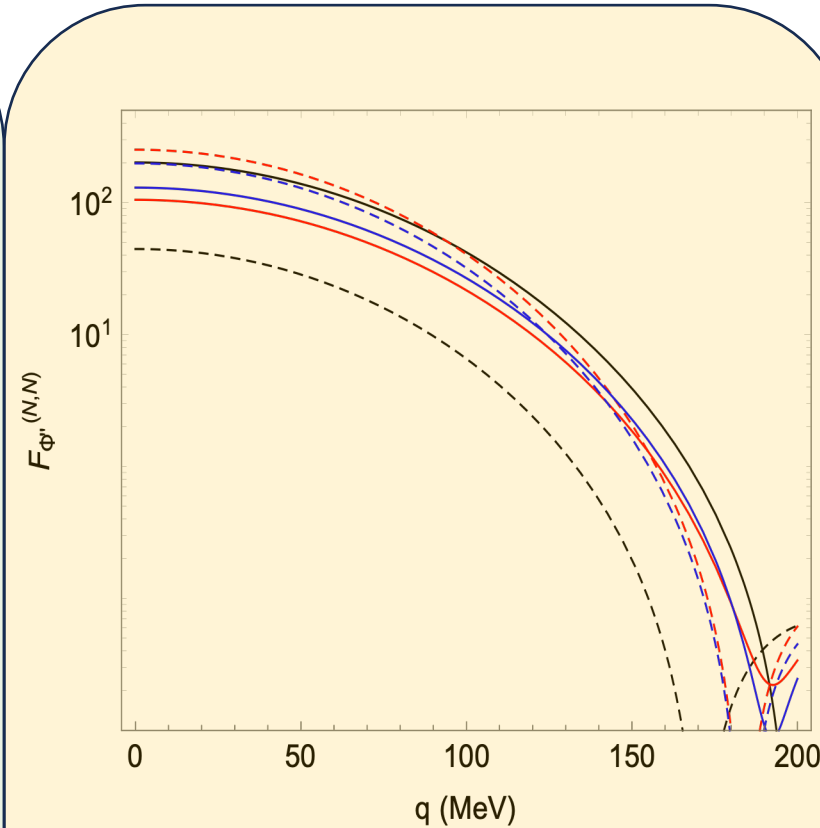
Form factors for ^{127}I – Standard response



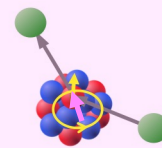
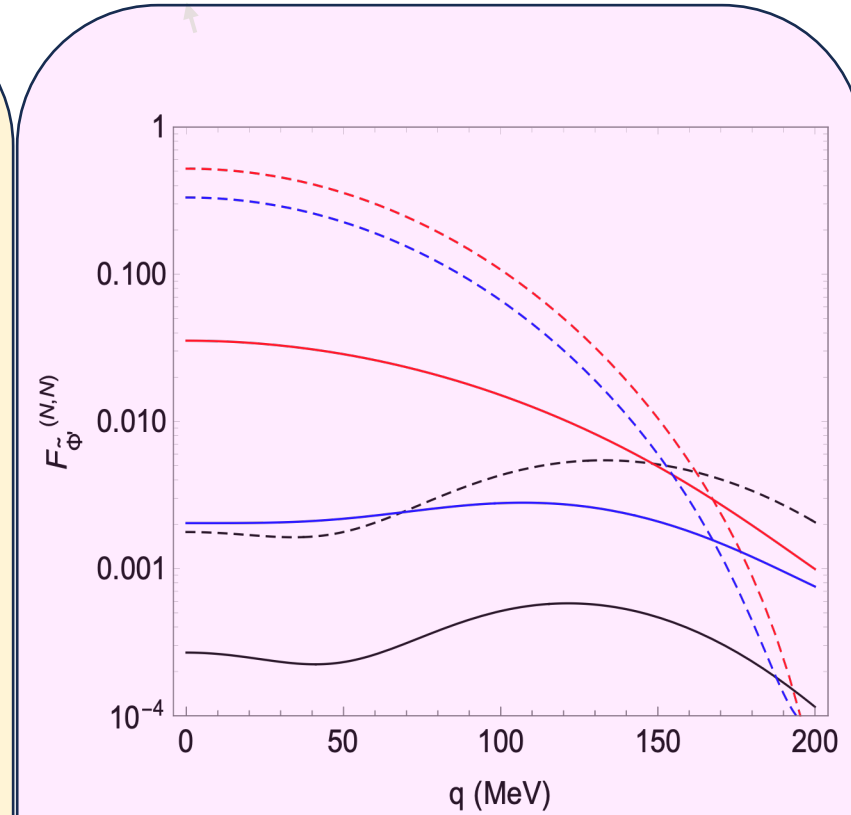
Form factors for ^{127}I – momentum dependent



Orbital angular momentum



Spin-orbit

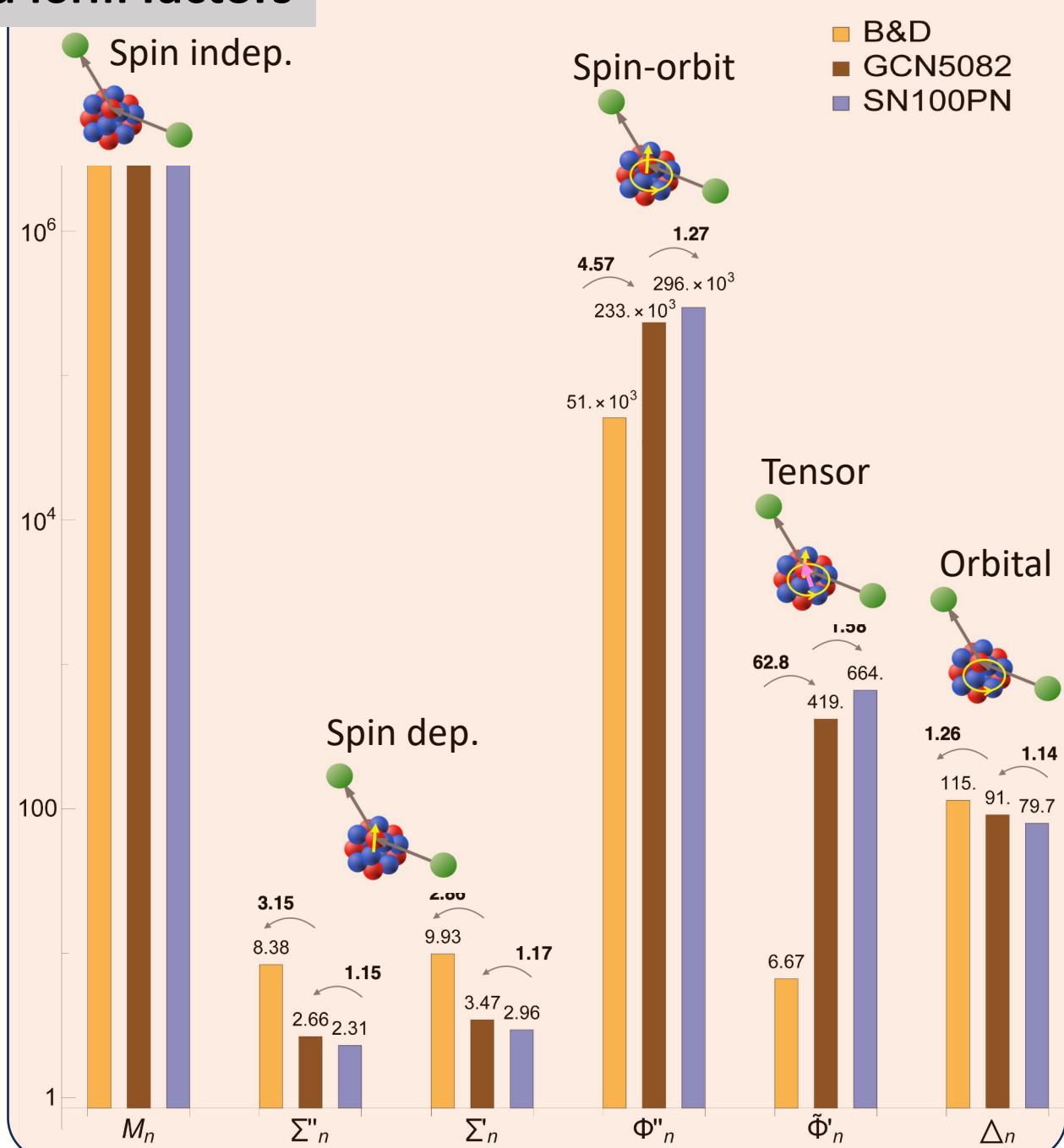
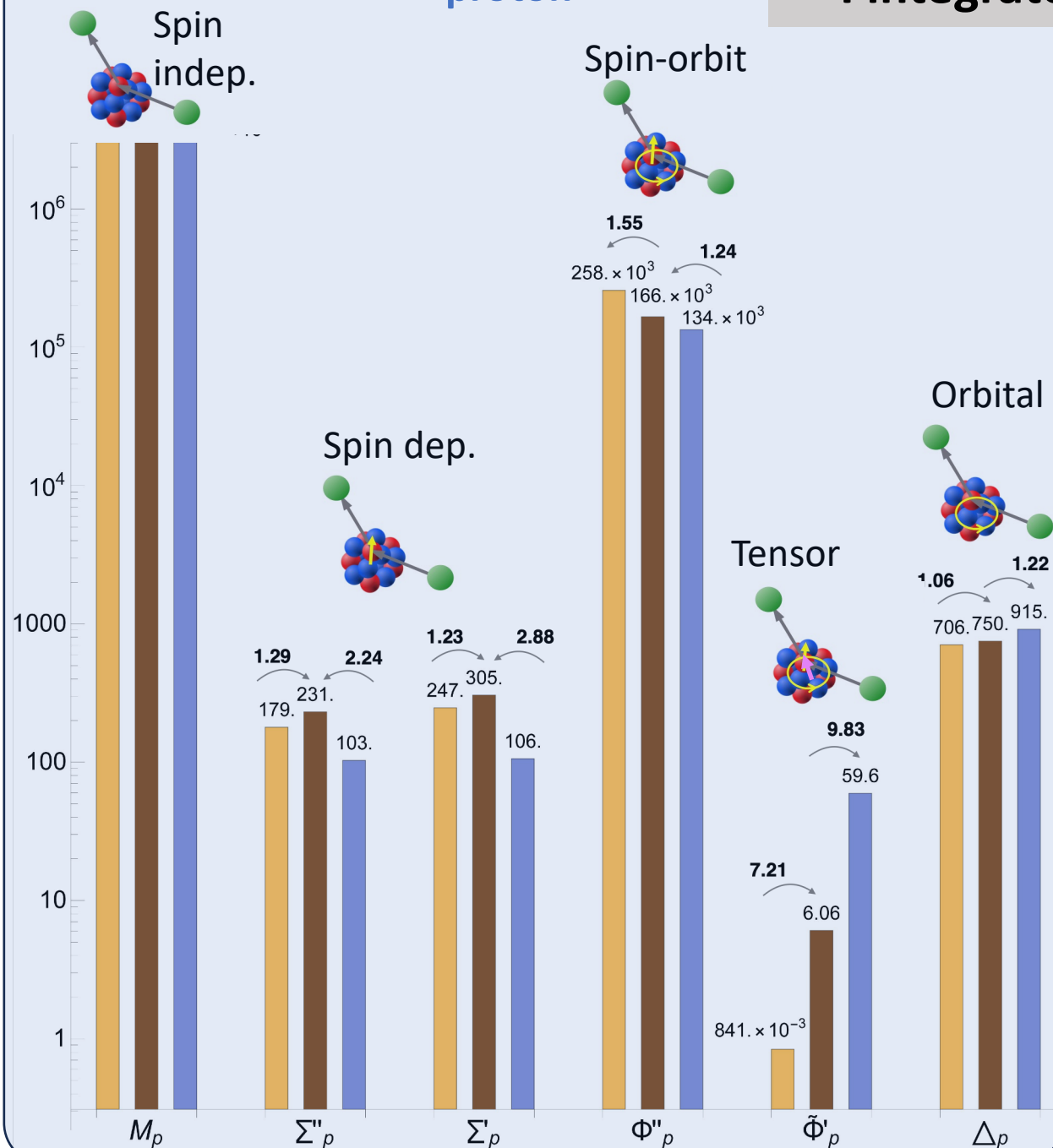


Tensor

proton

 ^{127}I integrated form factors

neutron

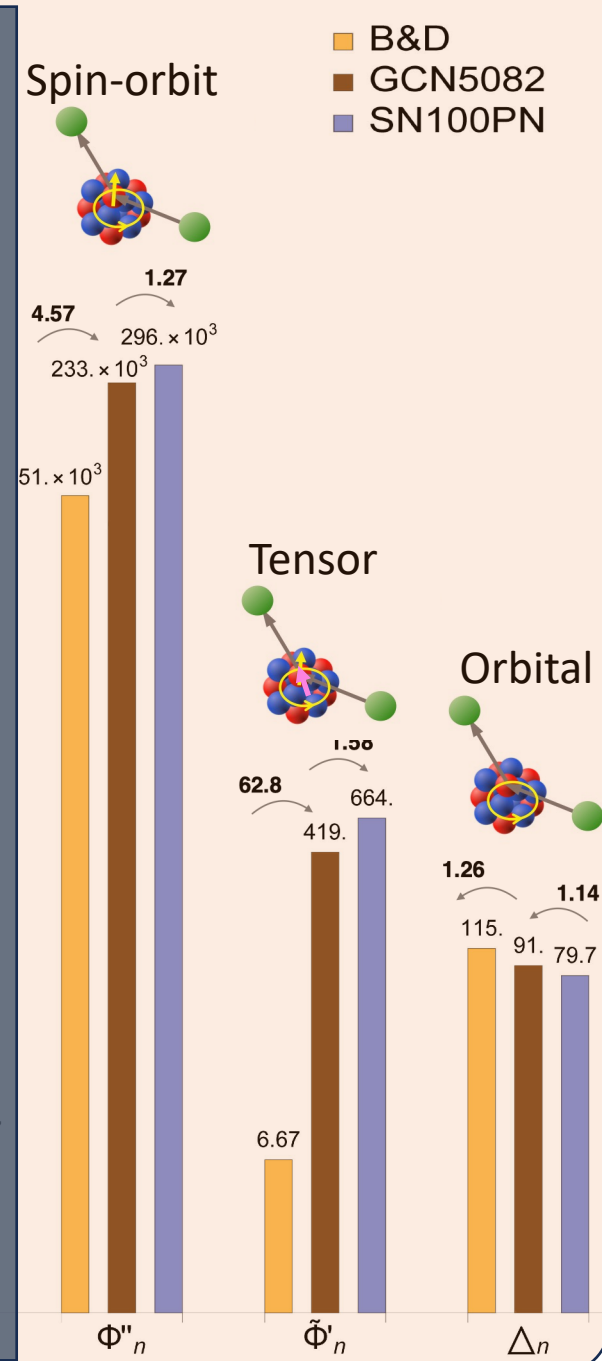
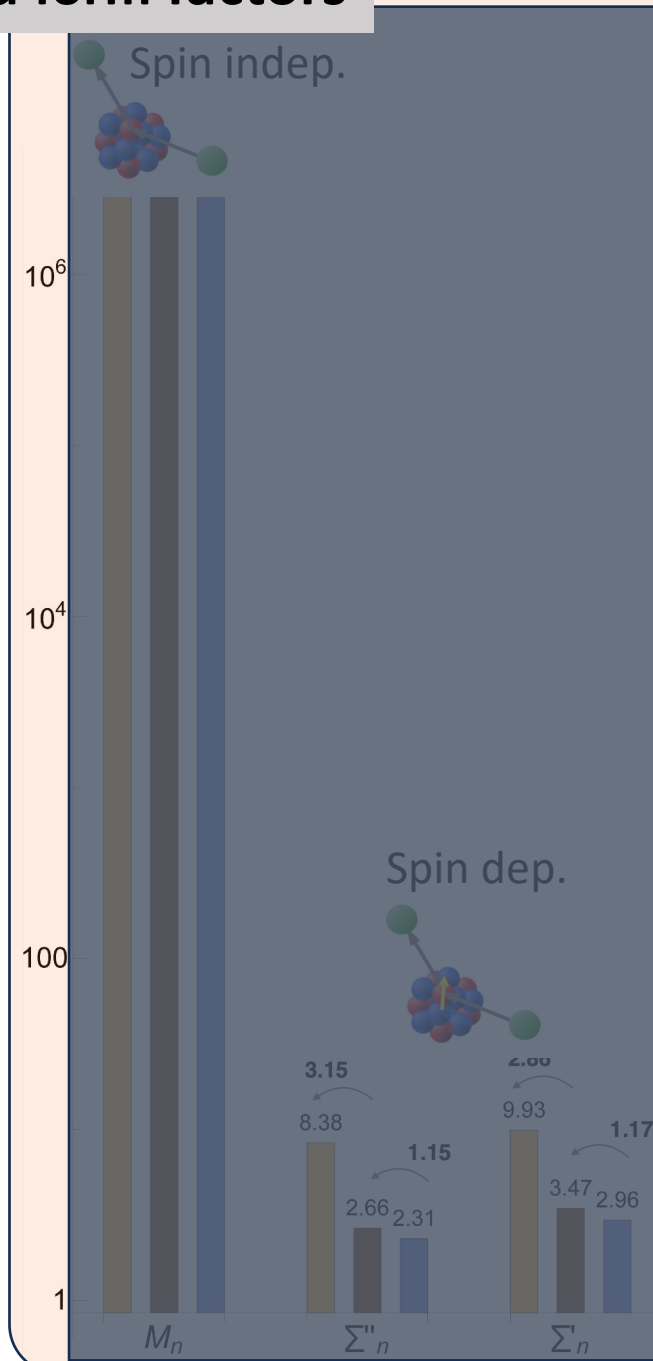
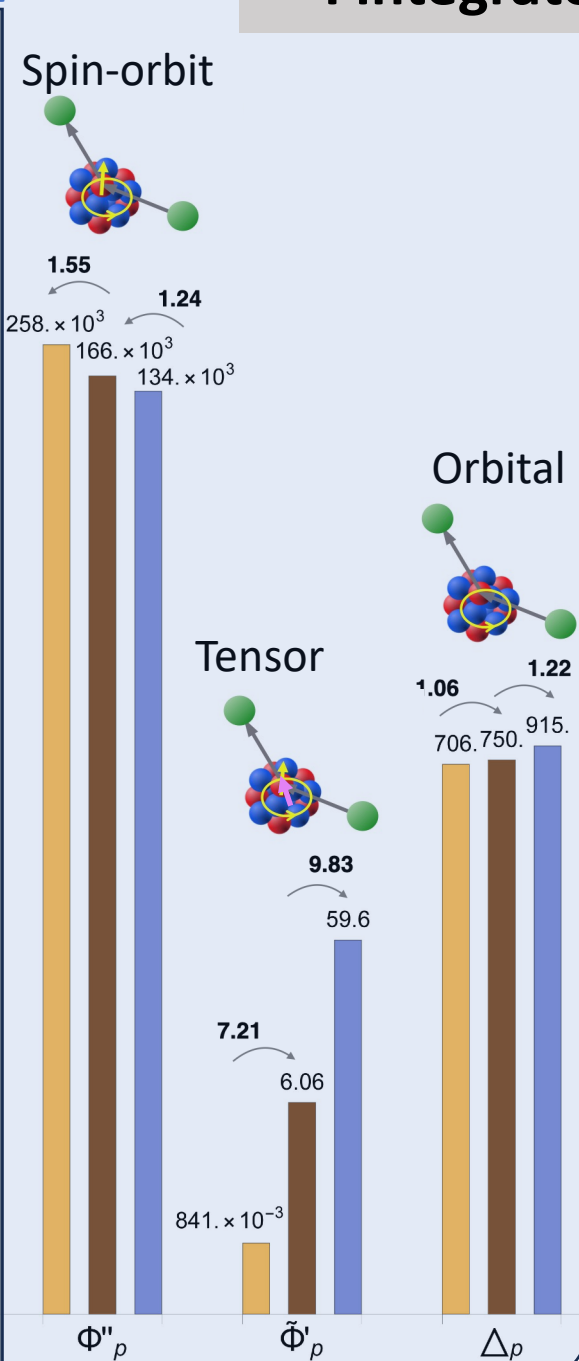
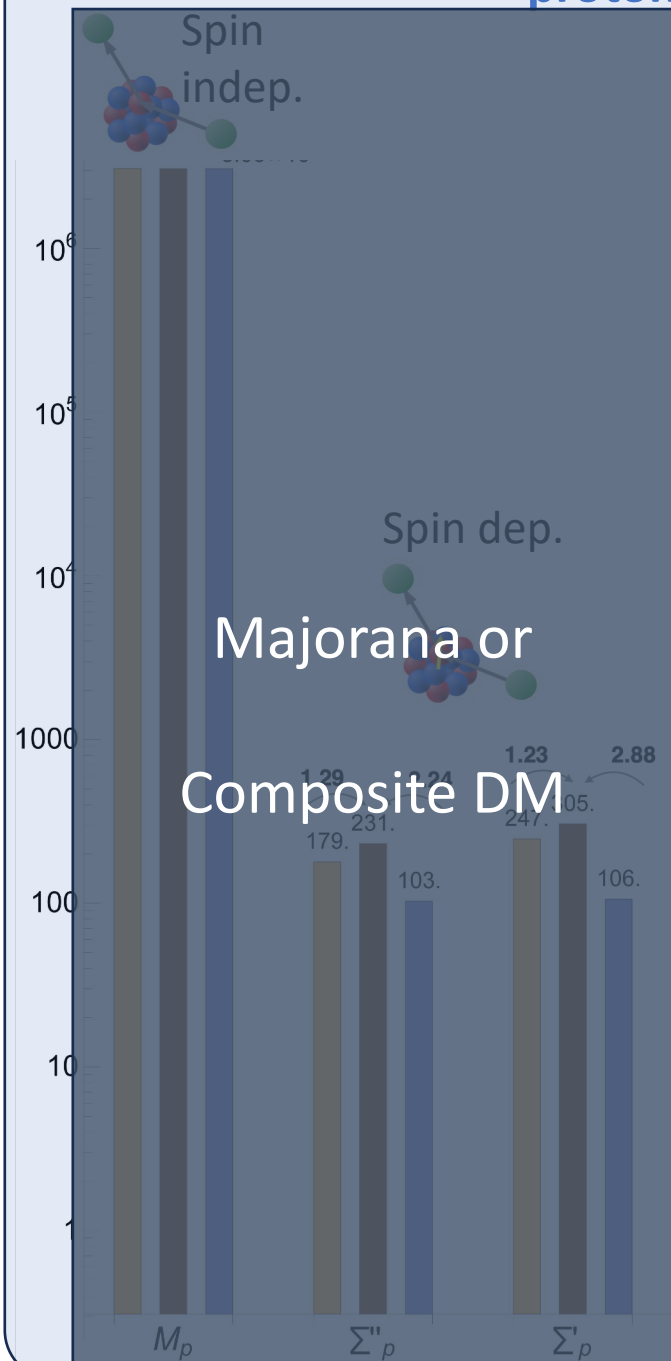


proton

¹²⁷I integrated form factors

neutron

B&D
 GCN5082
 SN100PN



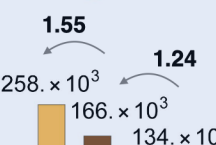
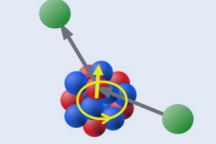
proton

¹²⁷I integrated form factors

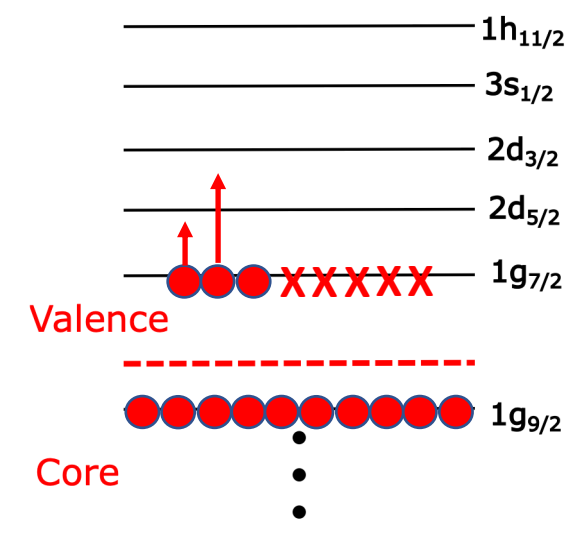
neutron

- B&D
- GCN5082
- SN100PN

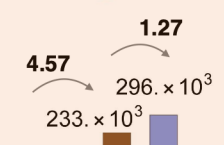
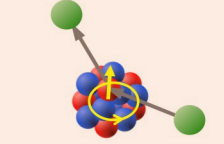
Spin-orbit



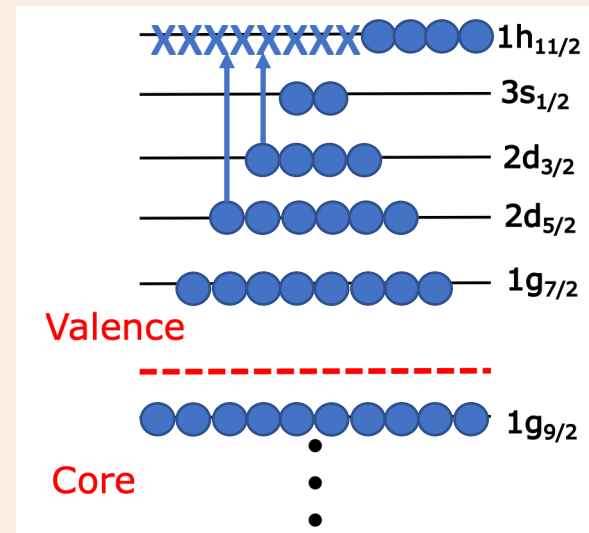
Φ''_p



Spin-orbit

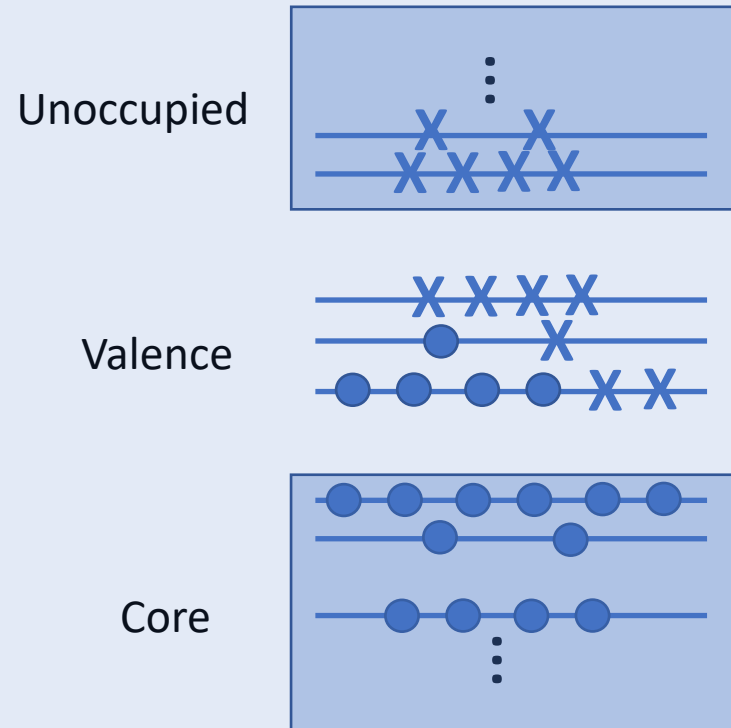


Φ''_n

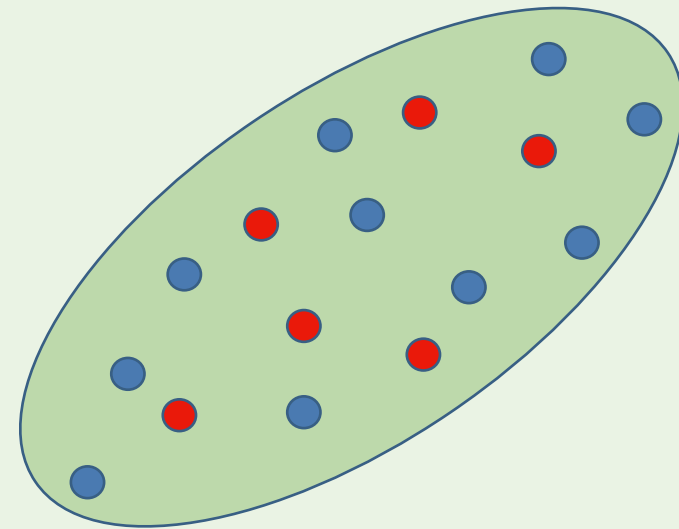


Mean field approach

Shell model

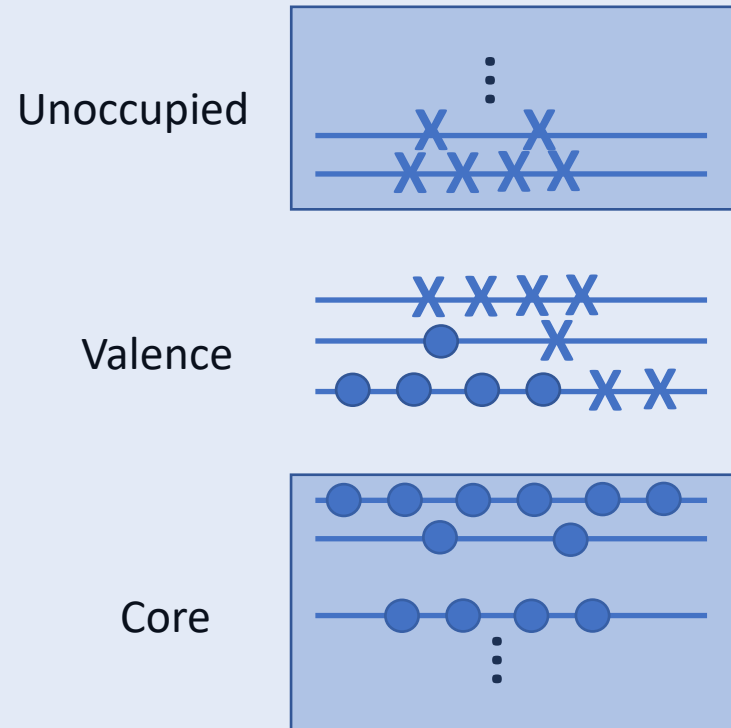


Hartree-Fock-Bogoliubov

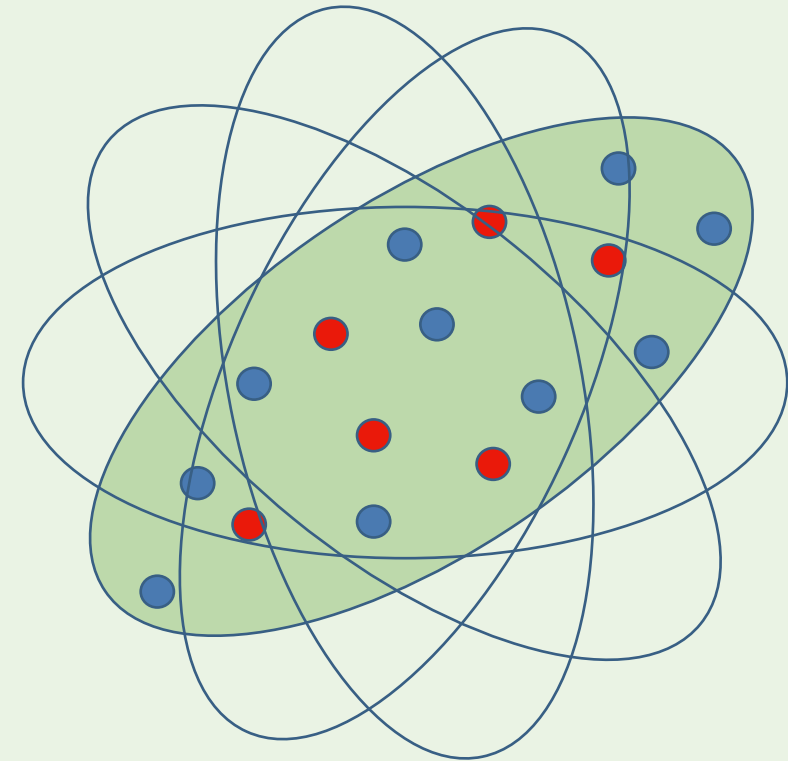


Mean field approach

Shell model



Beyond Mean-field



Proof of principle: ^{40}Ar

Application of the Skyrme Hartree-Fock-Bogoliubov Theory to WIMP-Nucleus Interactions in ^{40}Ar

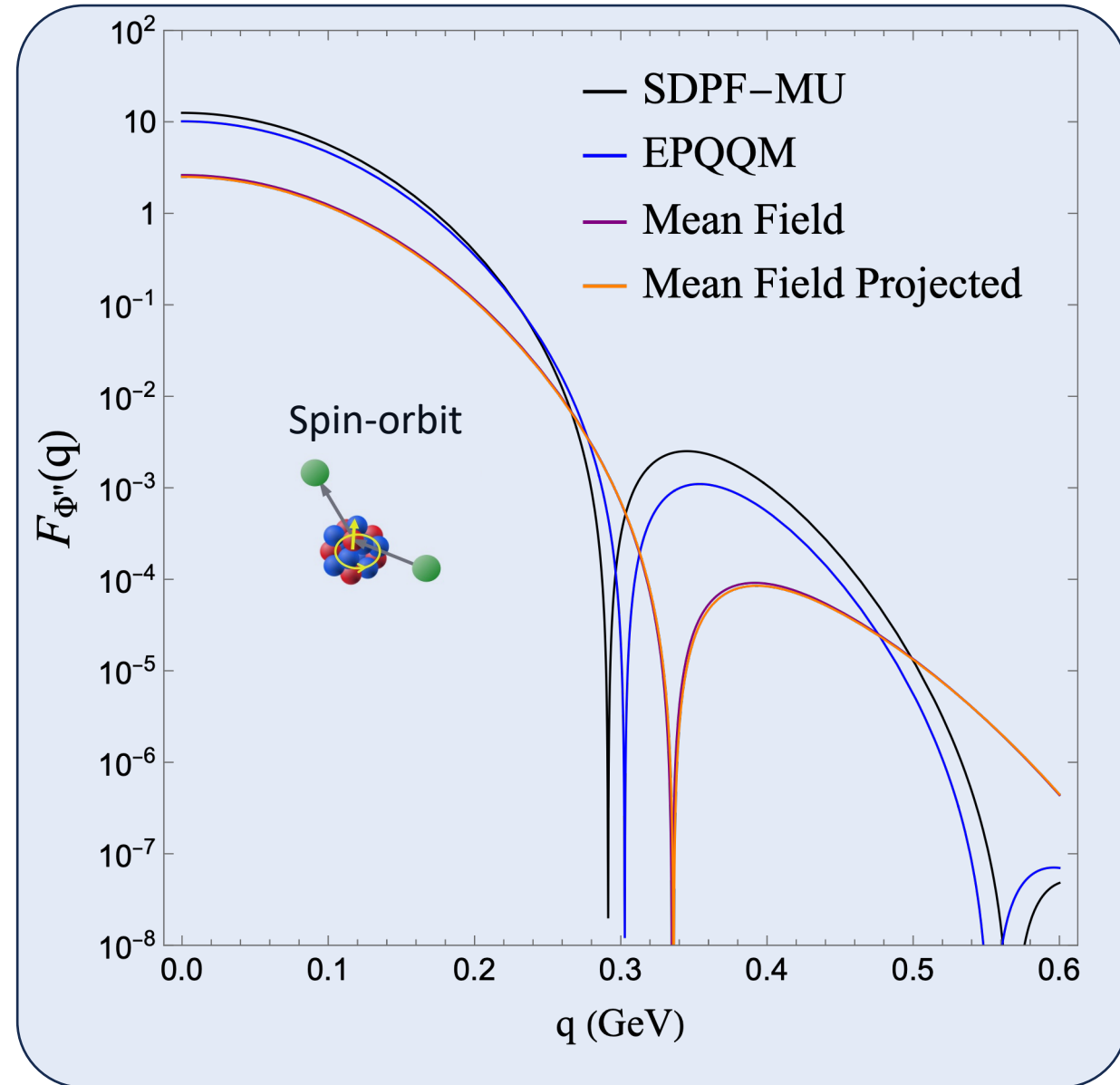
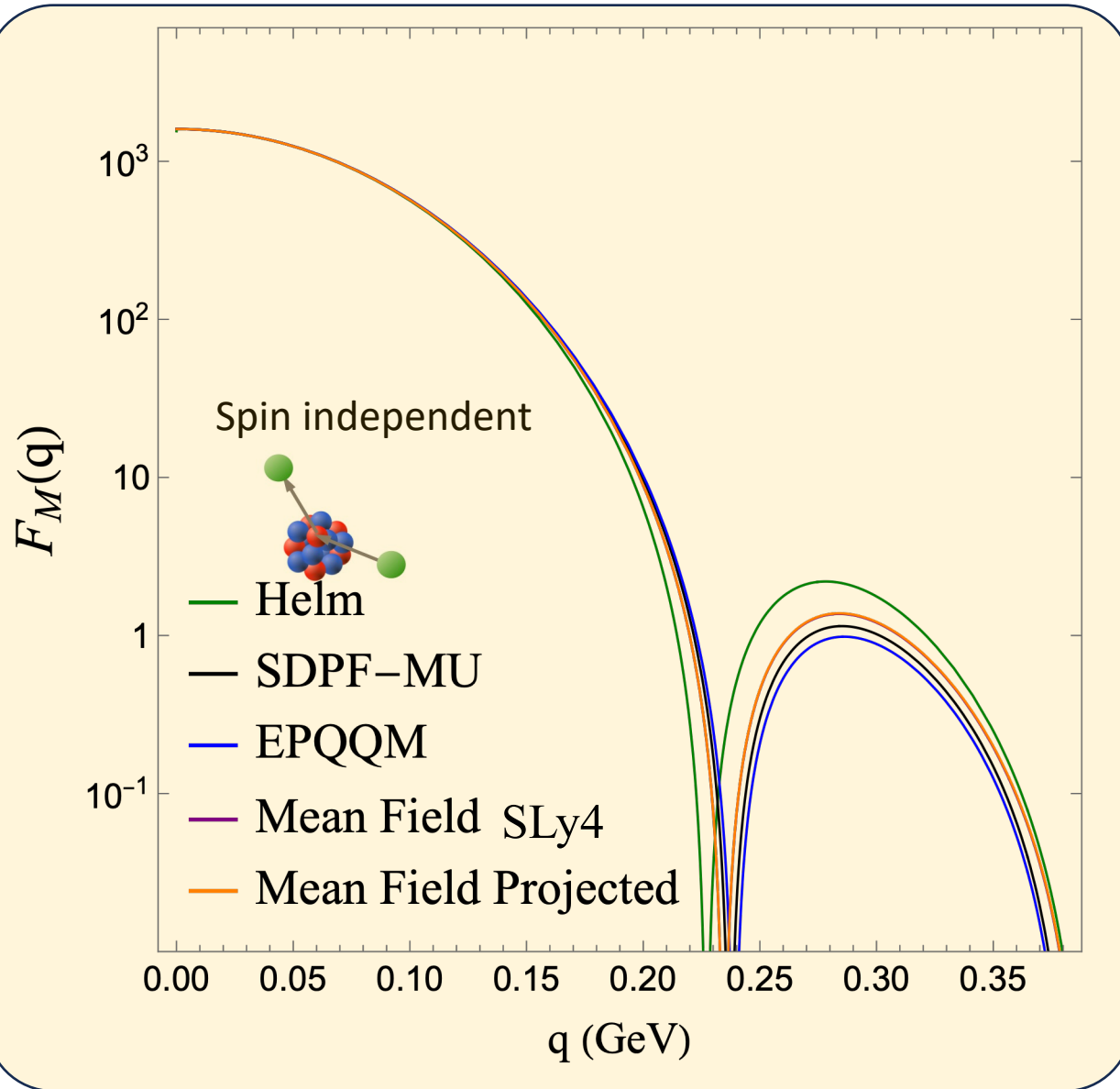
N. Krishnan,^{1,2,3,*} R. Abdel Khaleq,^{1,2,3,†} and C. Simenel^{1,2,3,‡}

arXiv:2606.11668

Technical details:

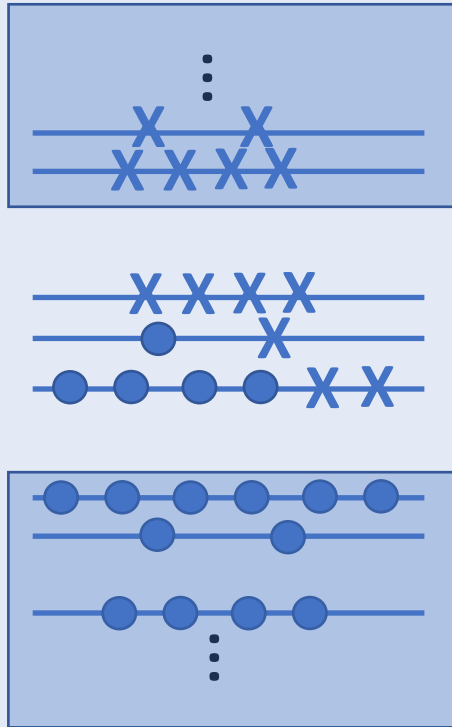
- HFBTHO solver
- Same spherical HO basis as shell model
- SLy4 Skyrme functional
- DDDI pairing, 60 MeV cutoff, adjusted on ^{120}Sn pairing gap
- Particle number projection (after variation)
- No angular momentum projection (spherical ground-state)

Proof of principle: ^{40}Ar



Proof of principle: 40Ar

Shell model



d5/2

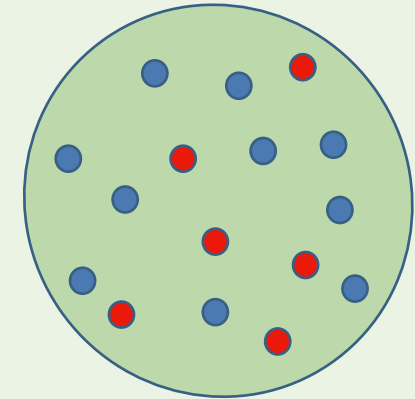
d3/2

f7/2

f5/2

n	l	j	SDPF-MU		MF	
			n_{nlj}^p	n_{nlj}^n	n_{nlj}^p	n_{nlj}^n
1	0	1/2	2	2	1.996303	1.997122
1	1	3/2	4	4	3.993052	3.992457
1	1	1/2	2	2	1.996871	1.996146
1	2	5/2	5.92	6	5.470287	5.9531
2	0	1/2	1.85	2	1.412168	1.972849
1	2	3/2	2.23	4	3.007262	3.946869
1	3	7/2	0	1.47	0.042784	1.334580
2	1	3/2	0	0.4	0.012501	0.325326
1	3	5/2	0	0.06	0.01514	0.348847
2	1	1/2	0	0.07	0.003123	0.055648
1	4	9/2	-	-	0.006957	0.01881
1	4	7/2	-	-	0.002955	0.011333
2	2	5/2	-	-	0.004916	0.007131
2	2	3/2	-	-	0.002364	0.006897
3	0	1/2	-	-	0.005933	0.002524
1	5	11/2	-	-	0.002309	0.005010
1	5	9/2	-	-	0.001011	0.004112
2	3	5/2	-	-	0.000845	0.002470
2	3	7/2	-	-	0.002087	0.002322
3	1	1/2	-	-	0.000930	0.000703
3	1	3/2	-	-	0.002212	0.001221
1	6	13/2	-	-	0.003186	0.003087
2	4	9/2	-	-	0.000709	0.001102
3	2	5/2	-	-	0.000931	0.001028
1	6	11/2	-	-	0.003513	0.003049
2	4	7/2	-	-	0.005132	0.003215
4	0	1/2	-	-	0.000629	0.000520
3	2	3/2	-	-	0.004096	0.002269

Hartree-Fock-Bogoliubov



Conclusions and Perspectives

- Direct detection of WIMP-nucleus elastic scattering
- Momentum dependent interactions for Majorana or composite DM
- Spin-orbit responses (larger in heavy nuclei)
- Uncertainties from interaction and nuclear model
- Future works:
 - More EDF (Skyrme, Gogny) and nuclei
 - Angular momentum projection for odd and deformed nuclei