QUANTIFYING THEORETICAL UNCERTAINTIES:

DARK MATTER DIRECT DETECTION OBSERVABLES

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See also ckoerber.github.io/vconf-21-dm-uncertainties for the slides (at best in Firefox).

CONTENT OF THIS TALK

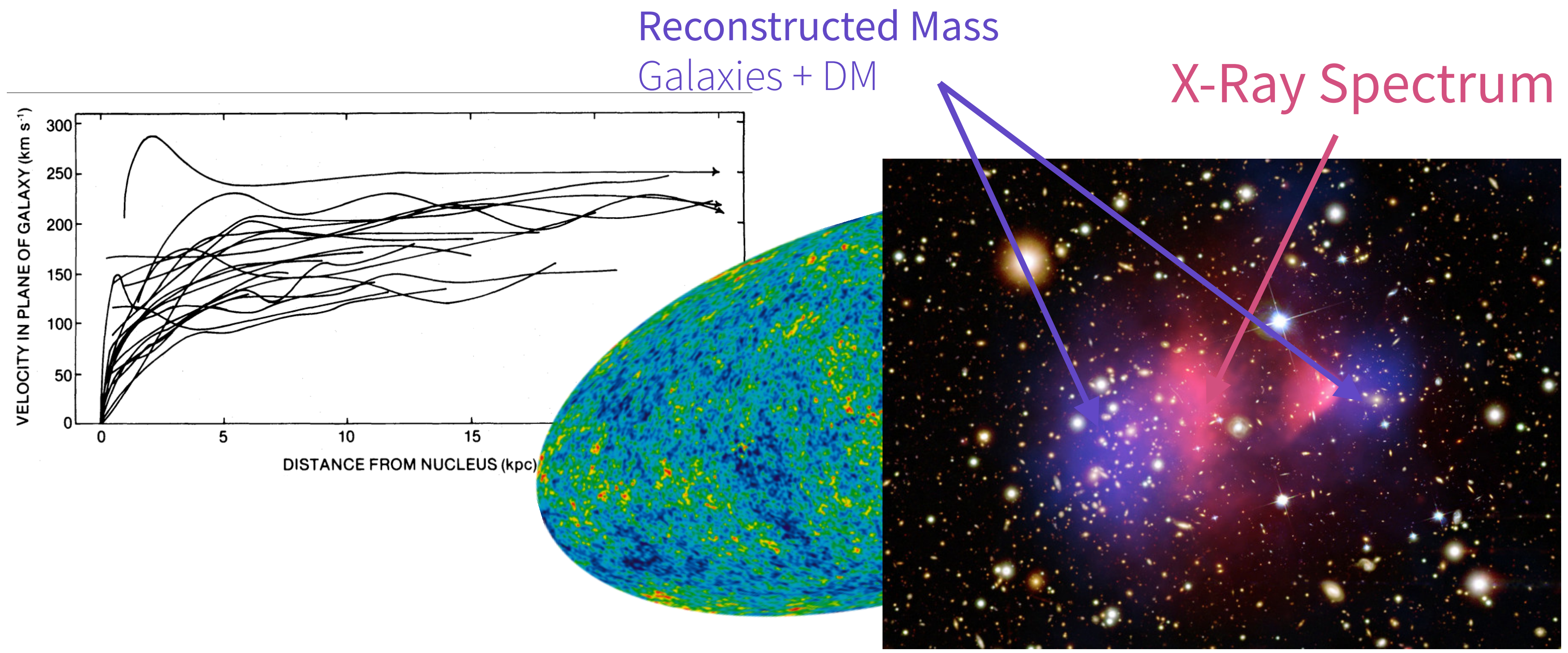
In this talk, you will see

- a brief introduction of the notion on how to disentangle different BSM theories *(and what this even means)*
- an examplifying study testing the sufficiency of nuclear computations to disentangle different theories, for a specific scenario *(spin-independent DM; light systems)*
- Technical details for ChPT practitioners related to this area

INTRO

WHAT IS DARK MATTER?

- We have evidence for gravitational interactions not yet observed by other means
  - Rotational velocity distributions within our Galaxy
  - Cosmological evidence provided by the ΛCDM model
  - Bullet cluster mass distributions
- A new particle is capable of explaining these observations
  - Requiring a minimal extension to the physics we know
    (at least to new parameters for the SM)
  - There is a multitude of ideas on how to introduce a new particle
  - This talk focuses on **WIMPs**
- WIMPs can potentially be measured through direct detection experiments
  - Nuclear physics is relevant for describing the target-DM interactions
  - Eventually, high-energy observables can be added to constrain the DM theory



Figures from: [doi.org/10.1086/158003] wikipedia.org/wiki/Lambda-CDM_model apod.nasa.gov | ap060824

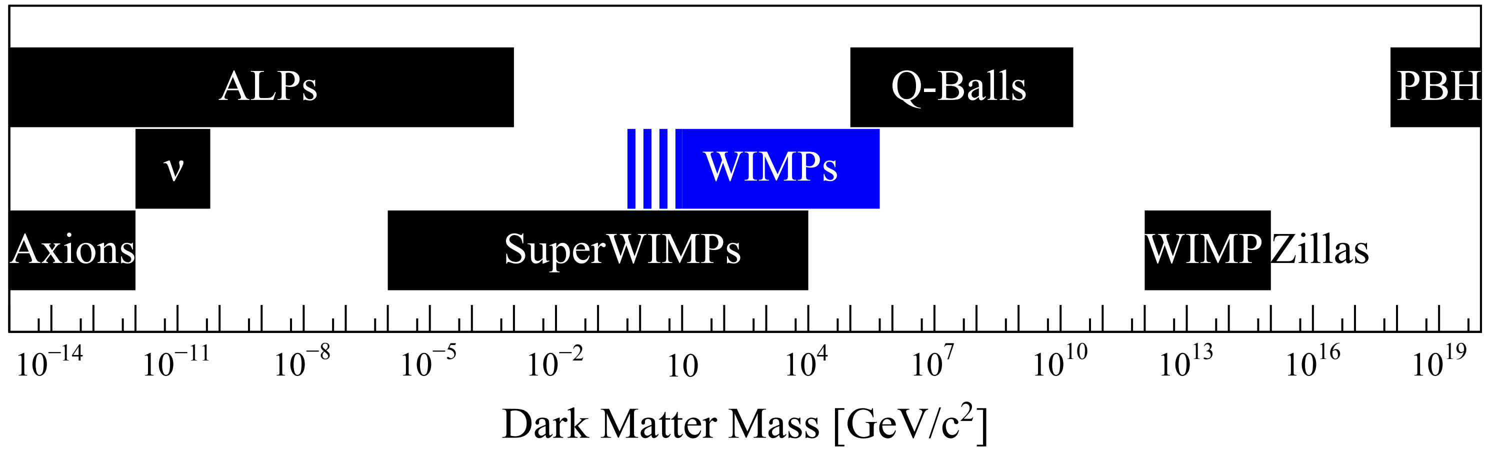


Figure from: [1903.03026]

TO DETERMINE THE NATURE OF PARTICLE DARK MATTER, WE NEED TO FIND PARTICLE DM SIGNALS!

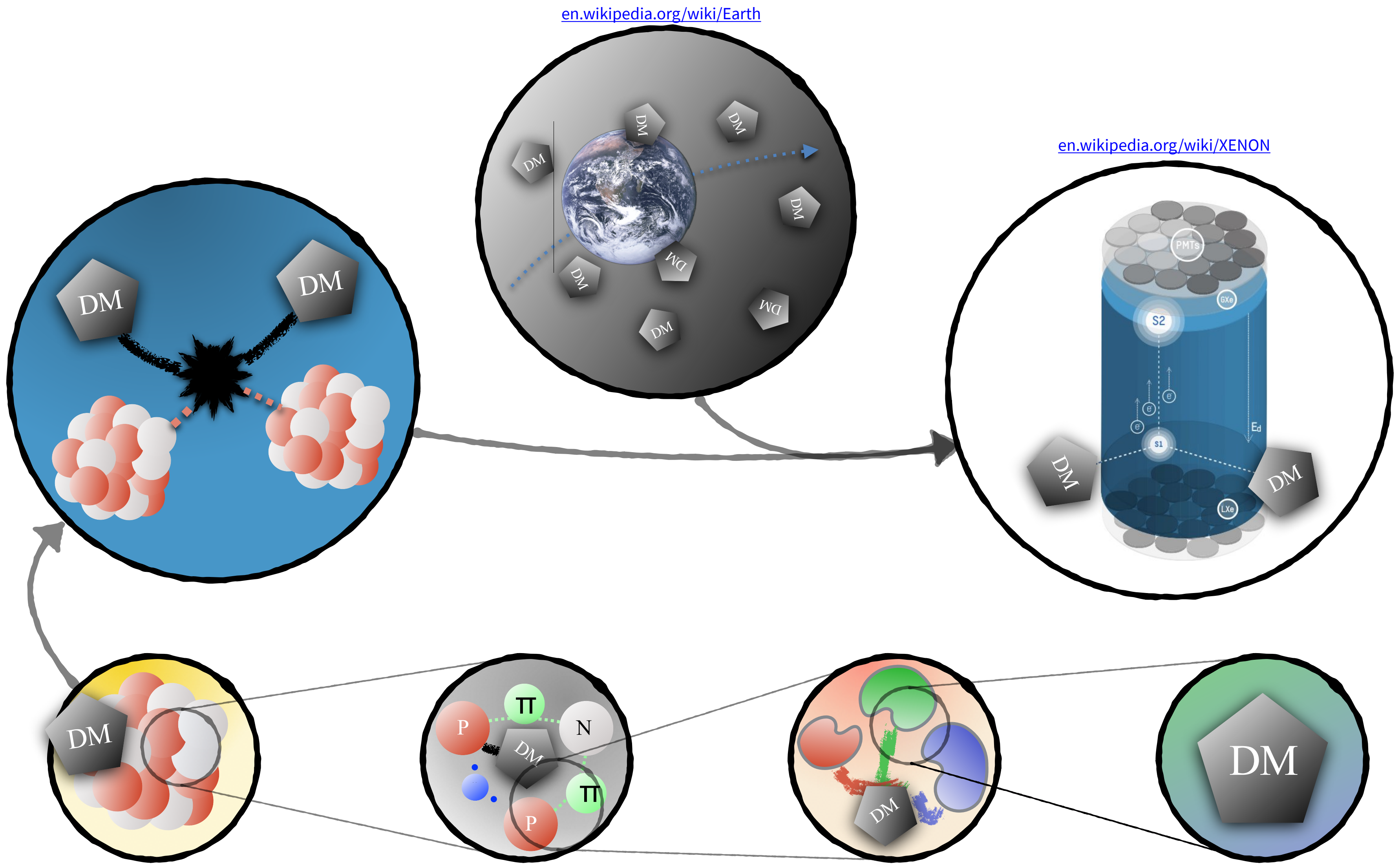
BRIDGING THE SCALES

To formulate constraints on DM theories, one has to compare

- detection rates
- using information about our local group
- to computations DM-nuclei cross-sections.

Such cross-sections require knowledge about

1. DM-nuclei interactions
2. DM-nucleon interactions
3. DM-QCD interactions
4. ...
5. Dark Matter



This talk will primarily address the theoretical framework in the few-nucleon regimes.

EXPERIMENTAL STATUS

Direct detection experiments *(Not all published results are shown)*

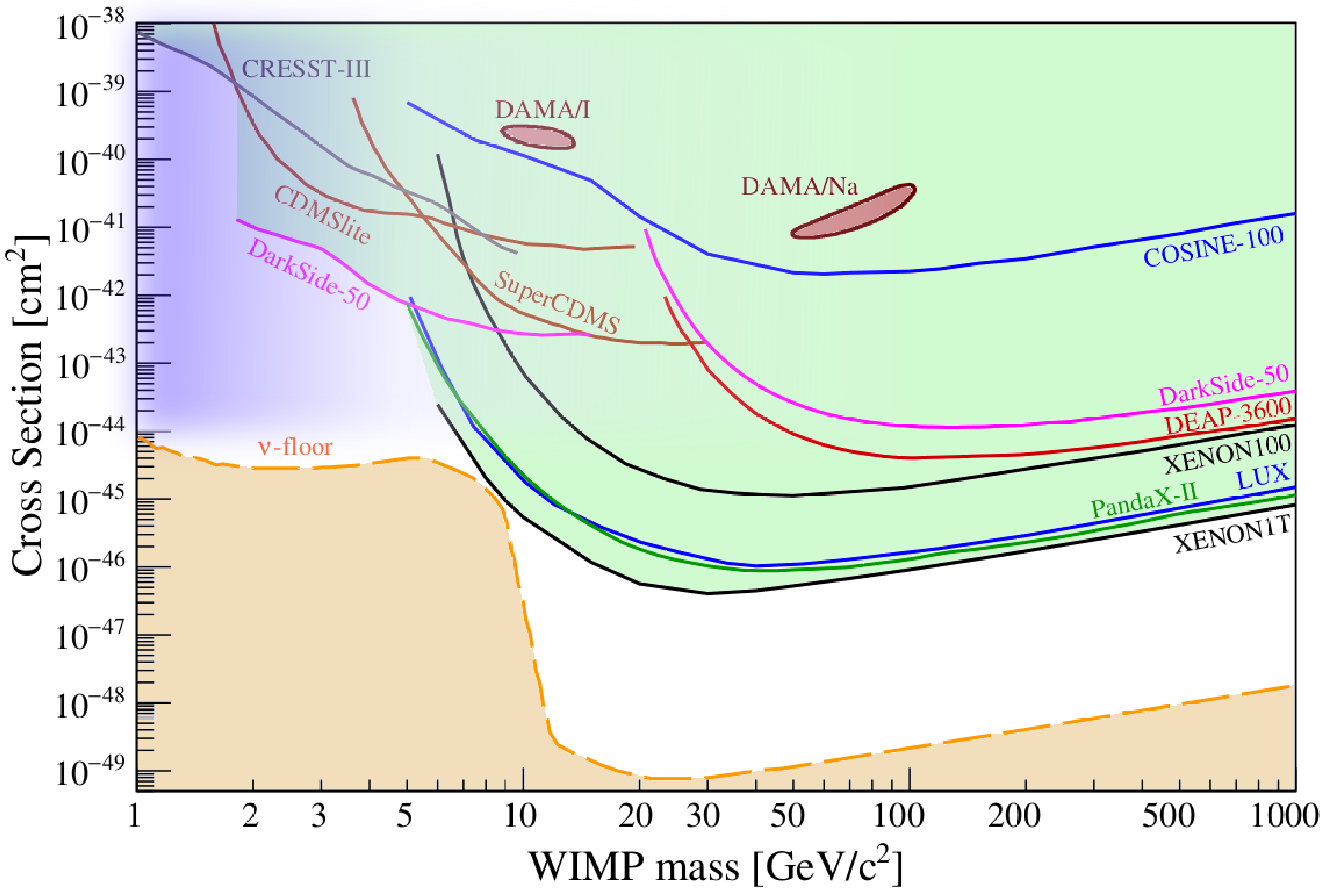


Figure taken from review [1903.03026]. *See also* [1907.11485]

- Direct detection bounds are functions of DM mass and interaction strength/cross-section
- Filled areas impose bounds
  - Green: Excluded region
  - Orange: Solar neutrino floor
  - Magenta: Positive signals
- Thus far, no consensus on a positive signal
- Sensitivity at low WIMP mass limited due to target lass mass (Xe)
- Notions for realizing lighter target experiments exist (Superfluid ^4He)

See also [1604.08206] [1910.10716]

RESOLVING DARK MATTER

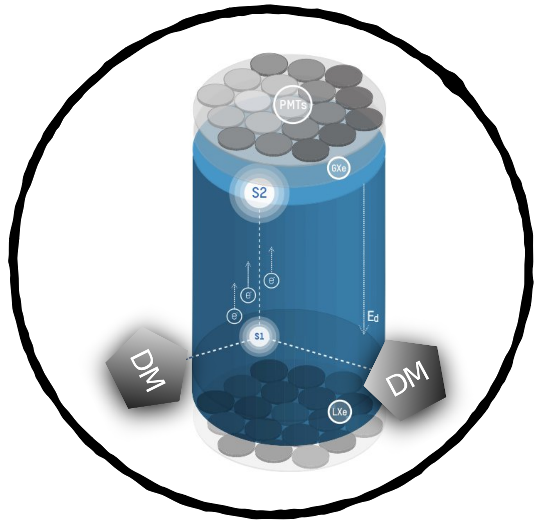
DIRECT DETECTION

See also [1903.03026]

Components for determining direct detection rates are

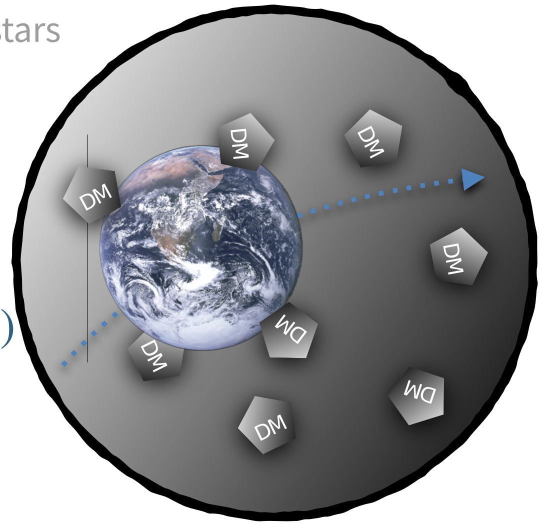
- detector dependent details,
  Efficiency and energy sensitivity, running time, …
- DM mass-velocity distributions at the location of the detector,
  Limited by kinematics (e.g., DM escape velocity)
- the Nuclear description of DM-target scattering.
  Characterized by an integral over response functions

en.wikipedia.org/wiki/XENON



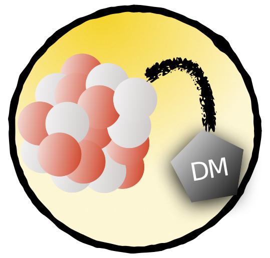
Escape velocity
$v_{esc} = 550(50)\,\mathrm{km/s}$
Observe escaping stars

en.wikipedia.org/wiki/Earth



$$N \sim \sigma_{\chi N} \int dE_R \left| \sum_i \alpha_i \mathcal{F}_i(E_R) \right|^2 \int_{v_{min}(E_R)}^{v_{esc}} dv_\chi$$

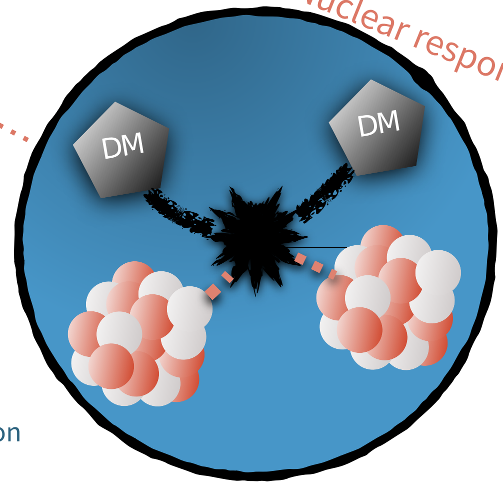
Nuclear response



Target nucleus
Total momentum

$$\mathcal{F}_i(\vec{q}) = \left\langle \psi\left(\vec{P} + \vec{q}\right), J, m_\tau \middle| O_i(\vec{q}) \middle| \psi\left(\vec{P}\right), J, m_\tau \right\rangle$$

Recoil momentum
DM Operator
Total spin
Isospin direction



Response functions are computed by evaluating nuclear matrix elements of different SM-BSM operators

Relevant momentum regions are fixed by kinematics (and masses).

EFFECTIVE FIELD THEORY ANSATZ

See also [1203.3542] [1205.2695] [1605.08043] [1707.06998]

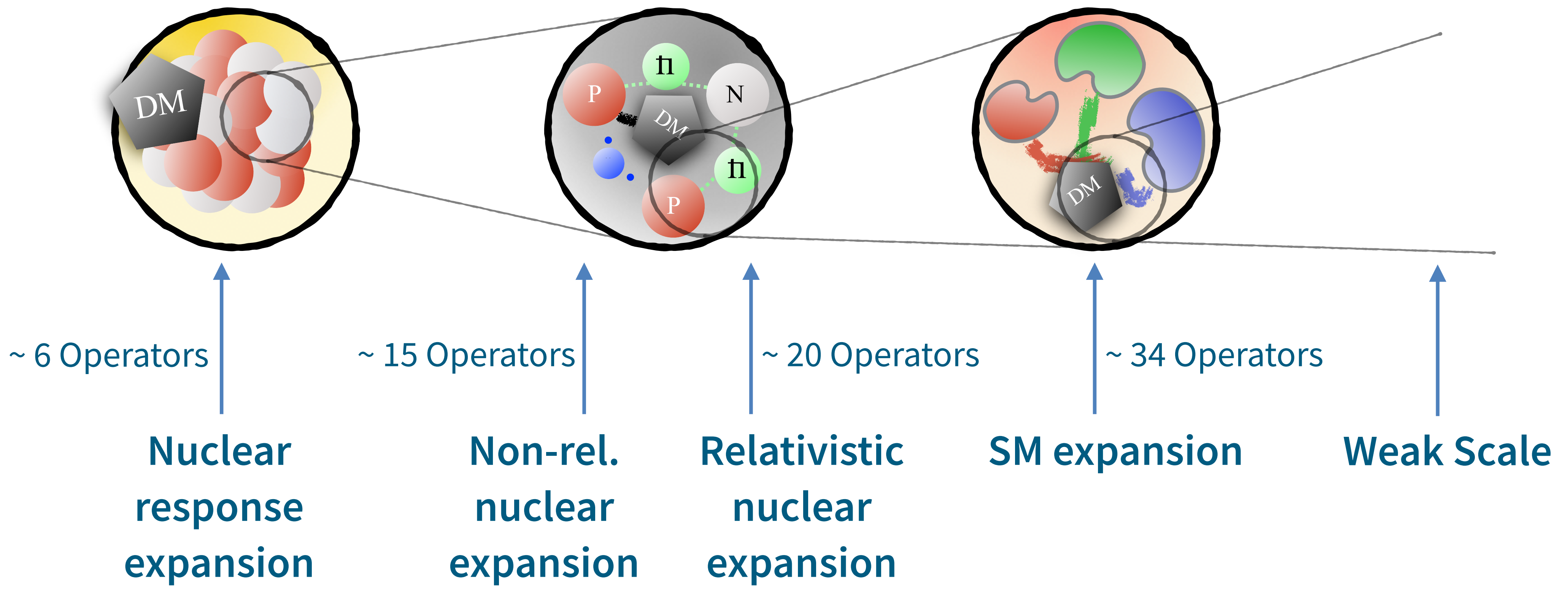
The SM-DM Hamiltonian is given as an expansion over all operators allowed by **symmetry** counted by **relevance**

$$\hat{H}_\chi = \sum_{i=1}^{N} c_\chi^{(i)} \bar{\chi}\Gamma_\chi^{(i)}\chi \cdot \bar{\psi}\Gamma_\psi^{(i)}\psi + \cdots$$

- The $c_\chi^{(i)}$ coefficient are unknown DM Wilson coefficient *(related to more fundamental coefficients at a higher scale)*
- The $\Gamma_Y^{(i)}$ structures are building blocks of the Lagrangian *(i.e., matrices or derivatives)*
- The $\cdots$ denote higher-order terms like *(non-coherent)* multi-particle interactions

What is a good starting point?

- Direct detection experiments *operators* correspond to distinct response functions
- Depending on scale specific counting *(ChPT, operator dimensions, ...)*, the number of allowed operators generally increases
- If done correctly, the eventual result is independent of the scale *(related to symmetries; but not one-to-one)*
- *Possibly, at an unknown, high enough scale, one only needs the DM mass and one Wilson coefficients*

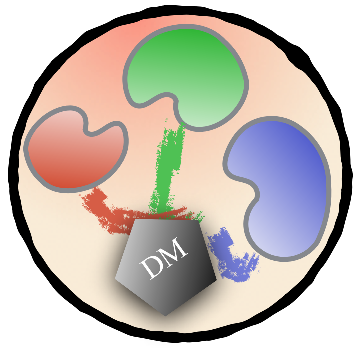


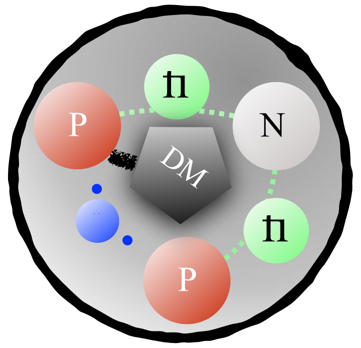
SCALE MATCHING

See also [1203.3542] [1205.2695] [1605.08043] [1707.06998]

An example of how the QCD-scale connects to the nucleon scale.

- Write down your initial Lagrangian *(e.g., scalar and vector quark-DM interactions).*
- Find nucleon-DM interactions with the same symmetries and match coefficients *(in this case, non-perturbative matching through, e.g., ChPT, LQCD, dispersive methods, …)*.
- DM-Wilson coefficients at nucleon scale are functions of DM-Wilson coefficients at QCD scale.
- Repeat this procedure to reach the non-relativistic effective theory (NRET).
- For similar lower scale dependence, different contributions can be compared.





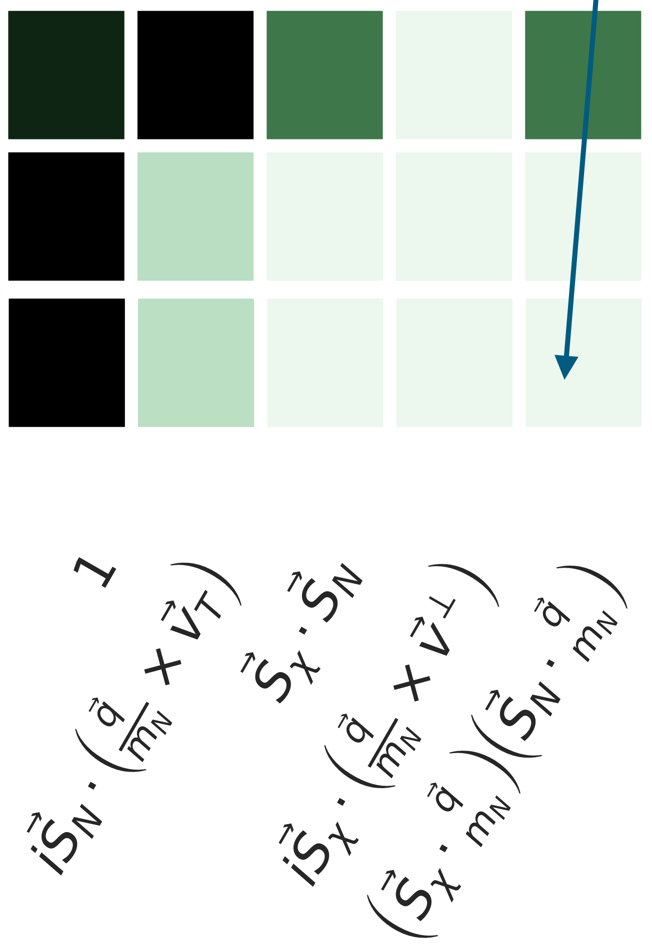
Relative weight

$$H_\chi = \sum_{i=1}^{N} c_\chi^{(i)}\, O^{(i)}$$

SM expansion | **Rel. nucleon expansion** | **NR nucleon expansion**

$$\frac{C_q^{VV}}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q \;\to\; \bar\chi\gamma^\mu\chi\bar N i\sigma^{\mu\nu}\frac{q_\nu}{m_N}N, \qquad \to\; \bar\chi\gamma^\mu\chi\bar N\gamma_\mu N$$

$$\frac{C_q^{SS}}{\Lambda^3}\bar\chi\chi m_q\bar q q \;\to\; \bar\chi\chi\bar N N$$



Matrix elements

Different coefficient for each quark

- Row-wise comparable if c_q unknown
- For fixed c_q comparable across different rows & sums

DISENTANGLING SPIN-INDEPENDENT DM CONTRIBUTIONS

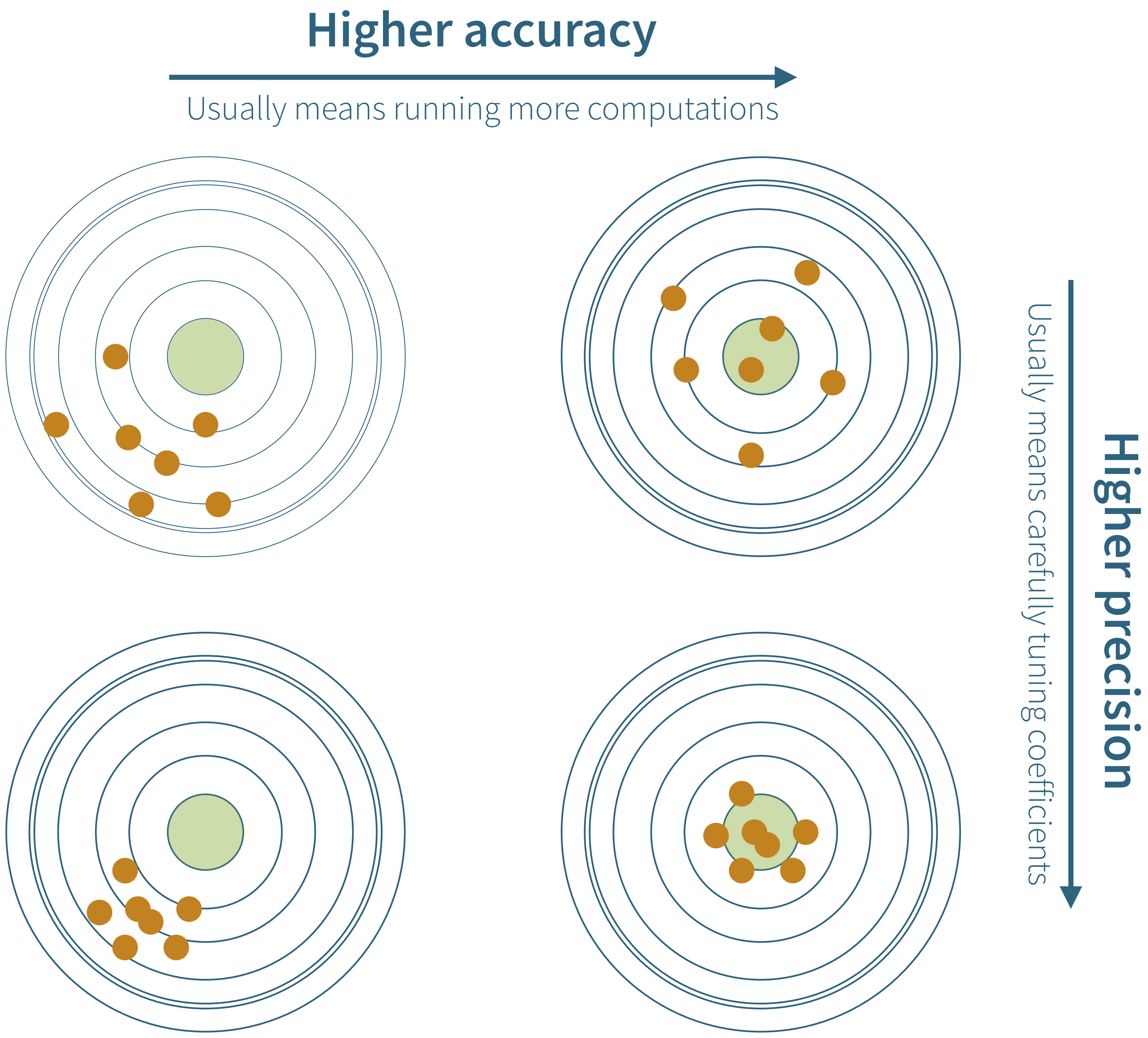
OBJECTIVE OF THIS STUDY

To remain in the spirit in Effective (Field) Theories, one must consider all interactions.

However, to test if our theoretical description is good enough for disentangling different DM-theories, we should start smaller…

With this work, we try to address two questions:

- At which point is the theoretical accuracy on the *(few)* nucleon level sufficient? *Can we trust results?*
- Given an accurate description, is our precision good enough to disentangle different sources for DM?



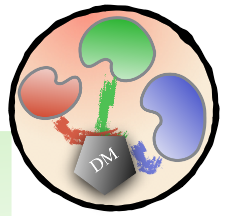
Choices in the following section *(to be expanded in future works…)*

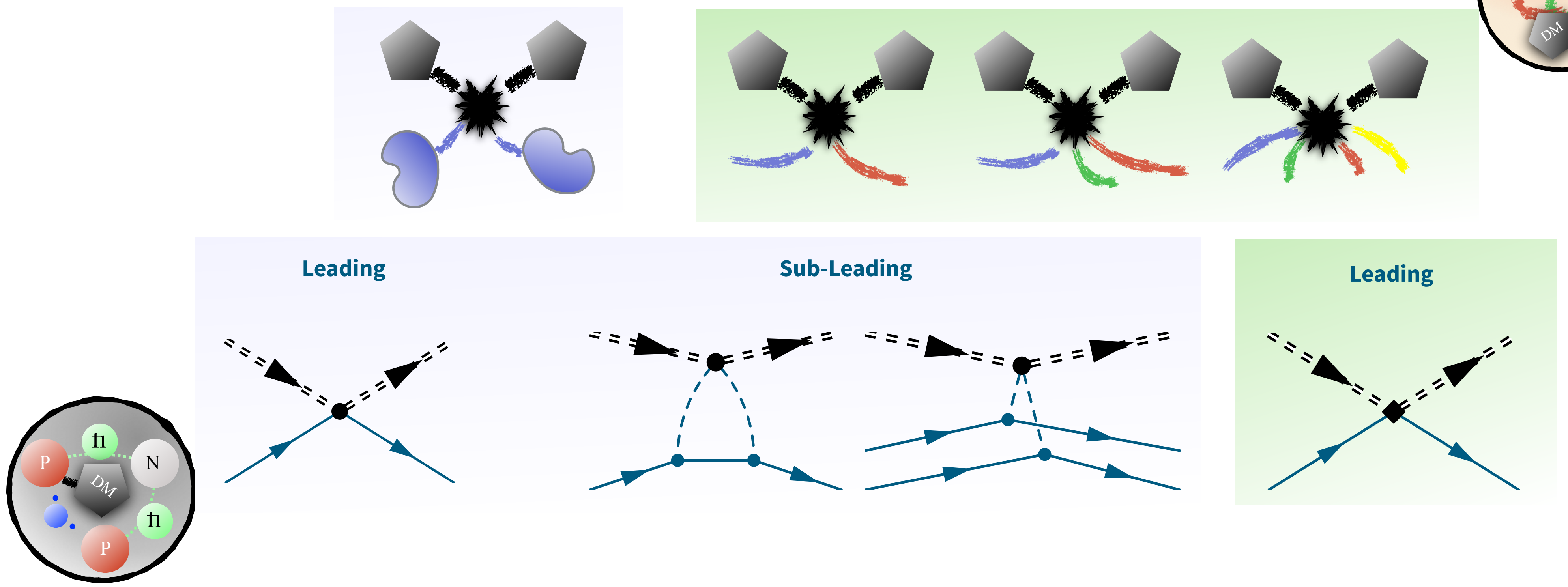
- Analyze **few-nucleon** targets $A = 2, 3, 4$ *(no experiment, yet)*
  - Possible to solve systems without many-body approximations *(i.e., minimal possible accuracy loss)*
  - Notions for superfluid ^{4}He experiment exist: [1604.08206] [1611.06228] [1902.02361]
- Focus on **scalar spin-independent** scalar interactions
  - This interaction is present in many BSM scenarios *(i.e., Higgs-Portal DM)*
  - Following power-counting analysis, this interaction may produce the strongest NLO contributions

LIGHT QUARK LAGRANGIAN

The spin-independent QCD-DM Lagrangian at leading order is given in terms of quark-DM and gluon-DM interactions

$$\mathscr{L}_{DM}^{(QCD)} = \bar{\chi}\chi \left[\sum_{f=u,d,s} \bar{c}_f m_f \bar{q}_f q_f + \bar{c}_g \alpha_s G^a_{\mu\nu} G^{\mu\nu a} \right]$$





At the nucleon level, *focussing on isospin-independent interactions*, one obtains

- nucleon-DM contact interactions at leading order from both the quark-DM and gluon-DM interactions
- nucleon-pion-DM interactions at next-to-leading order from the quark-DM interaction
  - a one-nucleon interaction mimicking a *radius correction* *(very small since ~q^2)*
  - a two-nucleon interaction caused by a **two-pion exchange**

See also [1605.08043] [1704.01150]

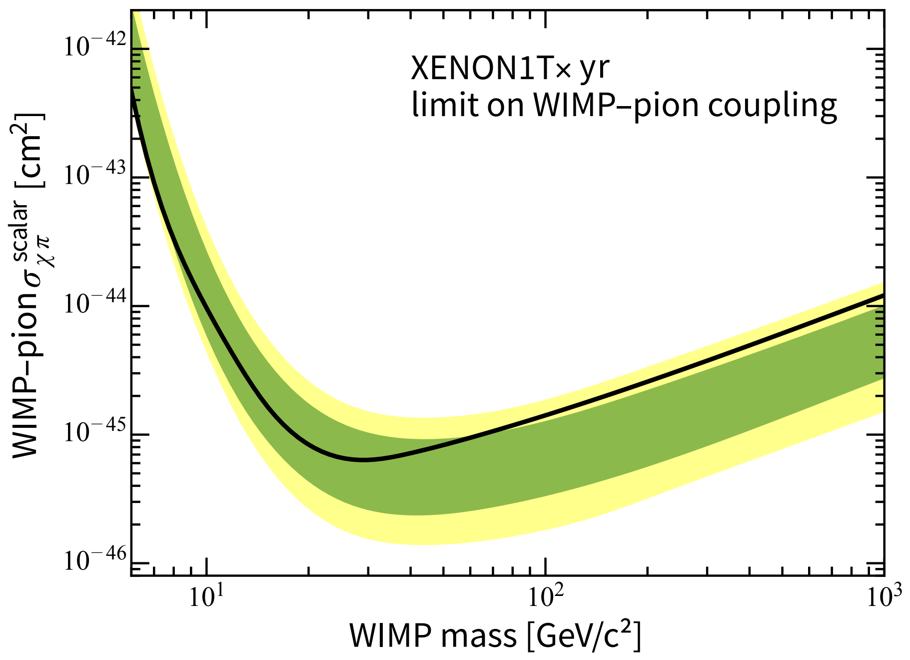


Figure taken from [1811.12482]

RESPONSE FUNCTIONS

For spin-independent iso-scalar (is) DM

The response function can be written as a perturbative expansion:

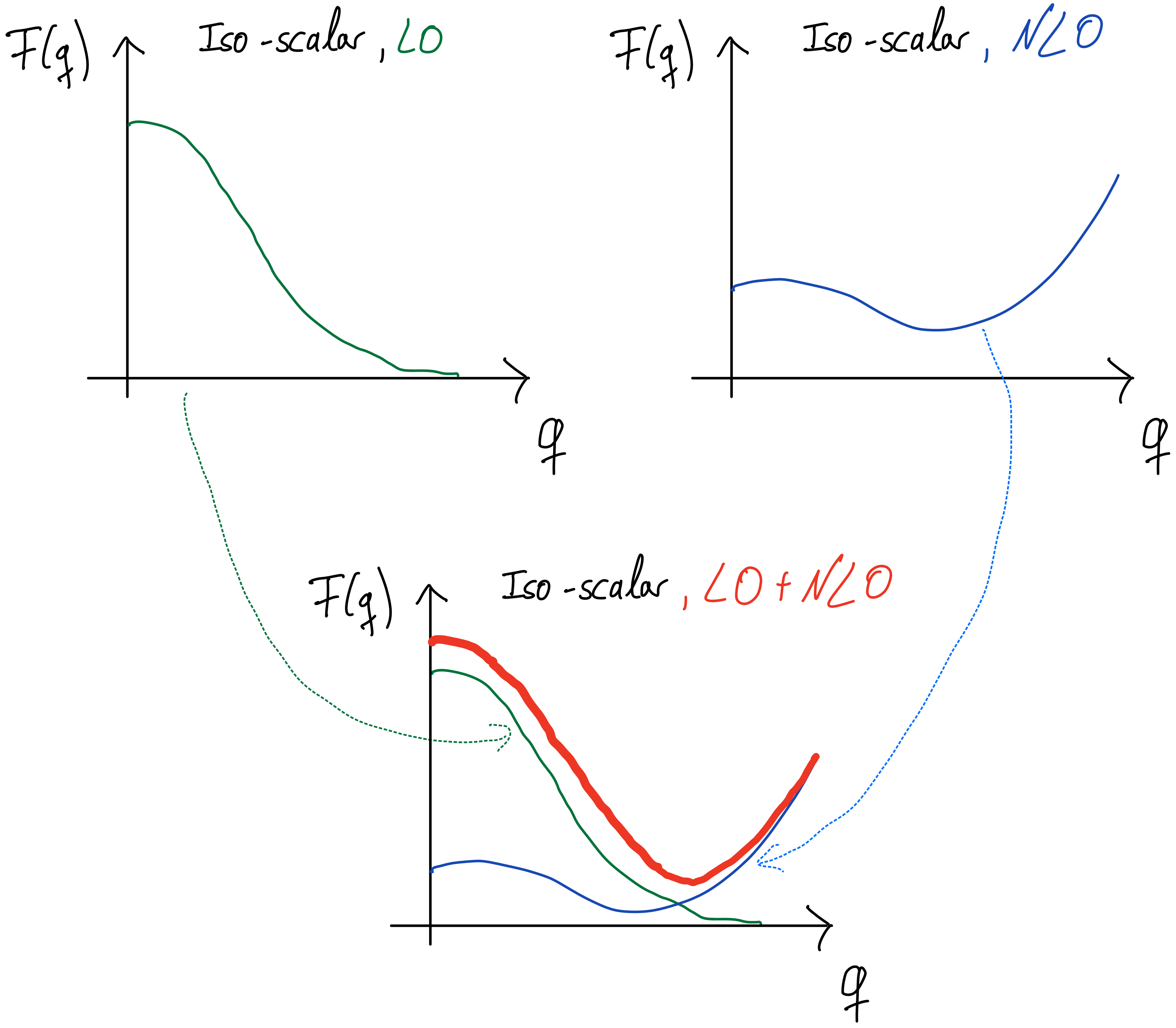
$$F_{\text{is}}(q) = (c_q + c_g)F_{\text{is}}^{(\text{LO})} + f(c_q)F_{\text{is}}^{(\text{NLO})} + \cdots$$

- BSM Wilson coefficients for quark-DM *(c_q)* and gluon-DM *(c_g)* interations.
- Response functions corresponding to operator structures at different chiral orders *(where $f(c_q)$ is a known function).*
- At the leading order, quark and gluon interactions produce the same response function.

Observations:

- The size of c_g relative to c_u changes the relevance of NLO contributions.
- To **disentangle** quark-DM and gluon-**DM interactions**, one must be able to distinguish LO and NLO contributions! *(Observables are related to $\int d^3q|F(q)|^2$; thus, there can be interference terms between different contributions.)*

Schematically

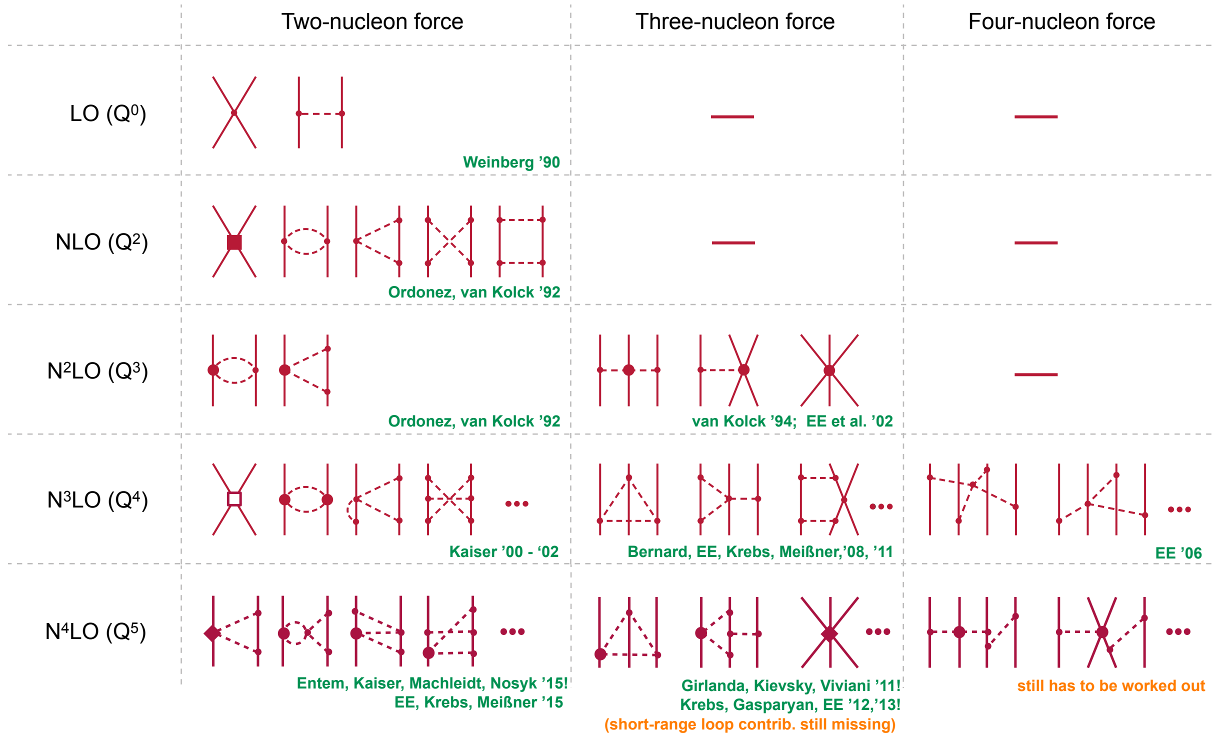


EMPLOYED METHODS

- To describe the target nucleus, we solve few-nucleon equations numerically exact *(i.e., no many-body approximations or extrapolations other than having a finite basis)*
- We utilize state of the art chiral interactions *(for different finite cutoffs at different chiral orders)* and phenomenological interactions *(cross-checks)* to characterize the target nucleus

  for A≤3 nuclei: [nucl-th/0006014] [nucl-th/9408016] [1412.4623]; *for 4He:* [1807.02848] [1911.11875]

  - Currently, results for chiral interactions do not utilize 3-nucleon forces; analysis on the way.



Courtesy of E. Epelbaum

- We utilize Bayesian inference frameworks to estimate truncation errors associated with wave function truncations at fixed BSM-operator orders [1704.01150] [1704.03308] [1904.10581] *(in particular* **gsum***)* [1907.03608] *(Differnt references use same Ansatz but different priors)*

$$X = X^{(0)} + \Delta X^{(2)} + \Delta X^{(3)} + \Delta X^{(4)} + \ldots$$
$$=: X_{\mathrm{ref}}\ \left(c_0 + c_2 Q^2 + c_3 Q^3 + c_4 Q^4 + \ldots\right)$$

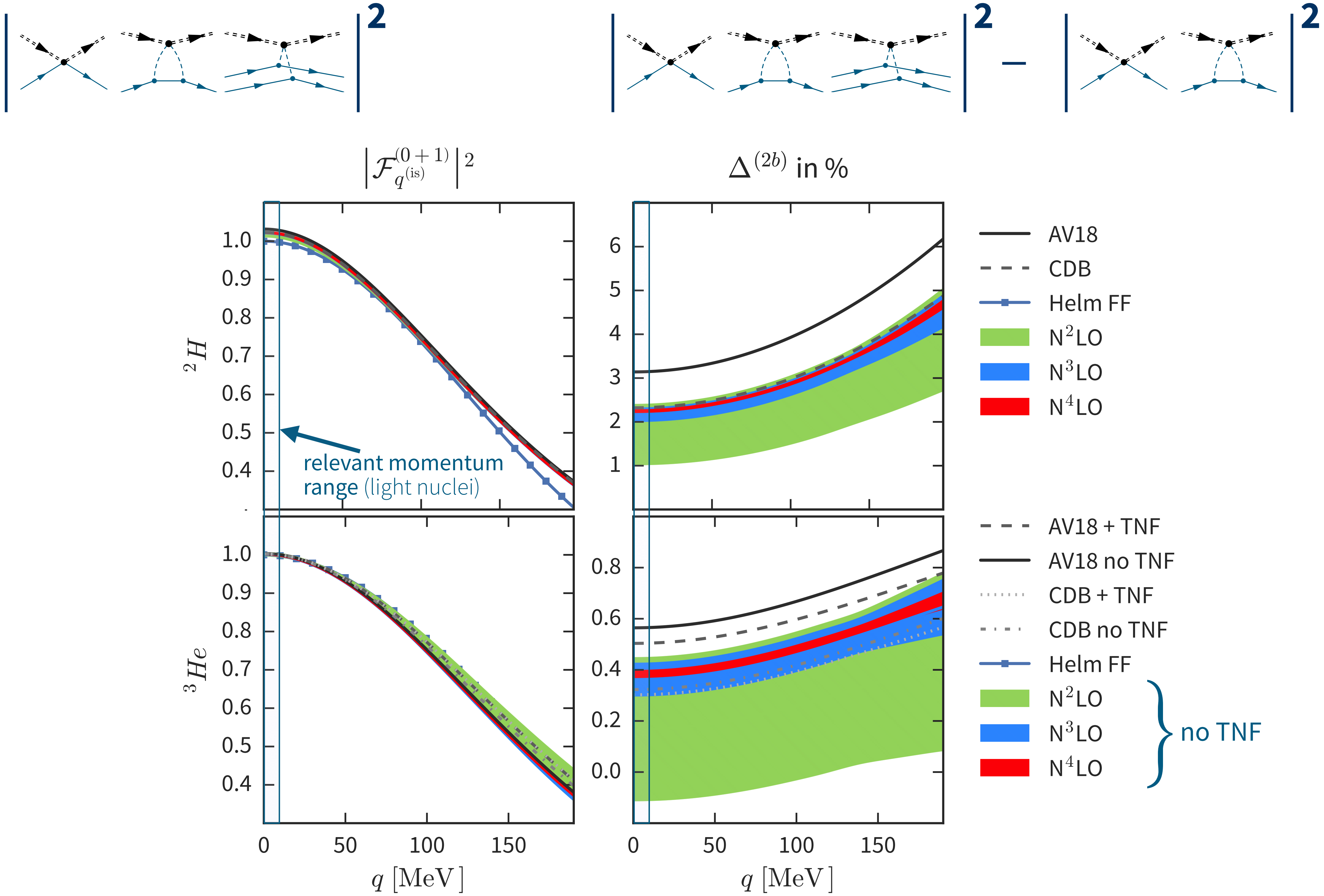
with $Q = \max\left(\frac{p}{\Lambda_b}, \frac{M_\pi^{\mathrm{eff}}}{\Lambda_b}\right)$, and expansion coefficients c_n following a to be inferred distribution parameterizing naturalness.

FEW-NUCLEON RESULTS

Exact A=2,3 analysis using ChPT operators and ChPT interactions: [1704.01150]

- *NCSM ³He,⁴He analysis using NREFT operators and ChPT interactions:* [1612.09165]
- *QMC A=2,3,4,6 analysis using ChPT operators and Phen. interactions:* [1811.01843]
- *SM A=19-132 analysis using ChPT operators and SM-ChEFT interactions:* [1812.05617]
- *...using* [1812.05617] *to match to XENON1T experiment:* [1811.12482]

- Set $c_q = 1$ and $c_g = 0$ in natural units and compute response function squared for different wave functions.
- For ^{2}H, 2-body contributions are at the 2% level and can be distinguished from zero.
- For ^{3}He, 2-body contributions are at the 0.5% level and can only be distinguished from zero for high-accuracy wave functions *(N3LO or higher; 3NForces seem to not affect results by much)*.
- Response function squared almost constant within uncertainties for relevant momentum range.



^{4}HE RESULTS

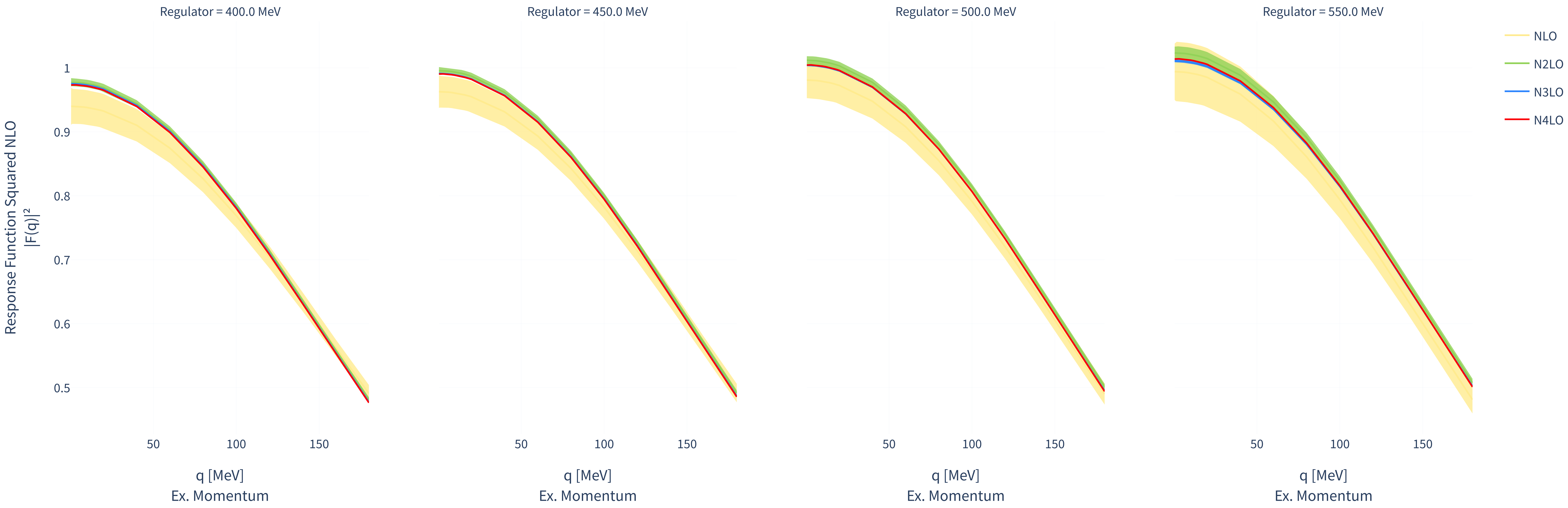
Preliminary results

A few cross-checks and analysis steps remain..

To be published soon...

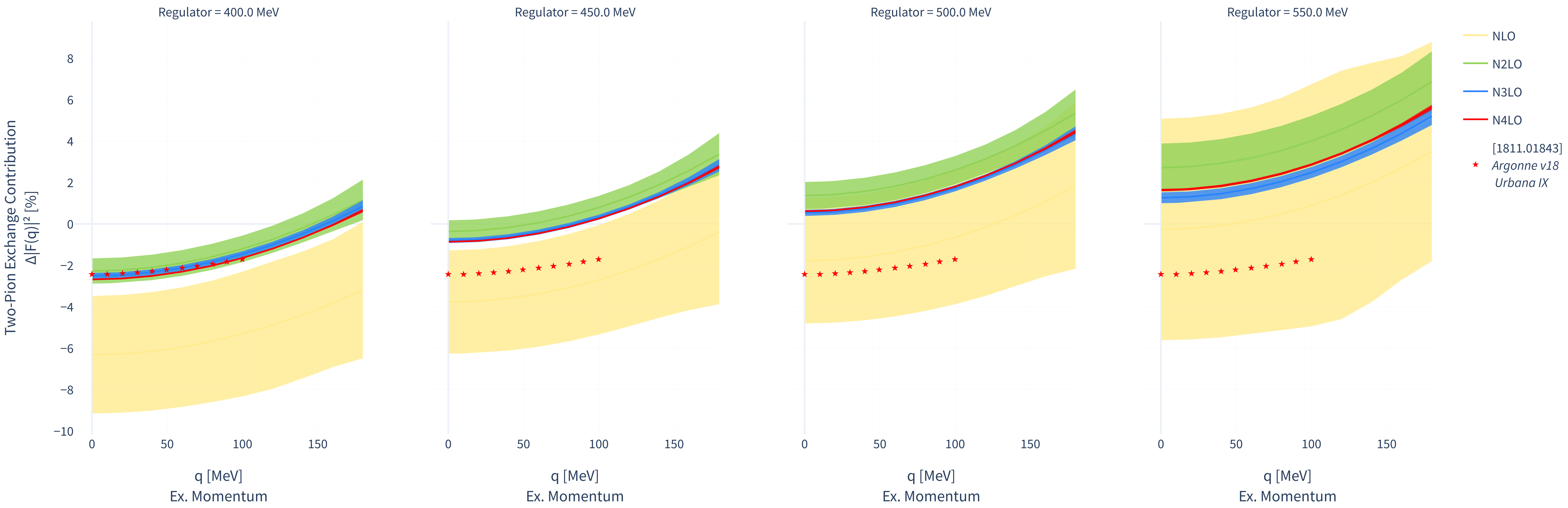
^{4}HE RESULTS

Response functions squared for NLO currents



^{4}HE RESULTS

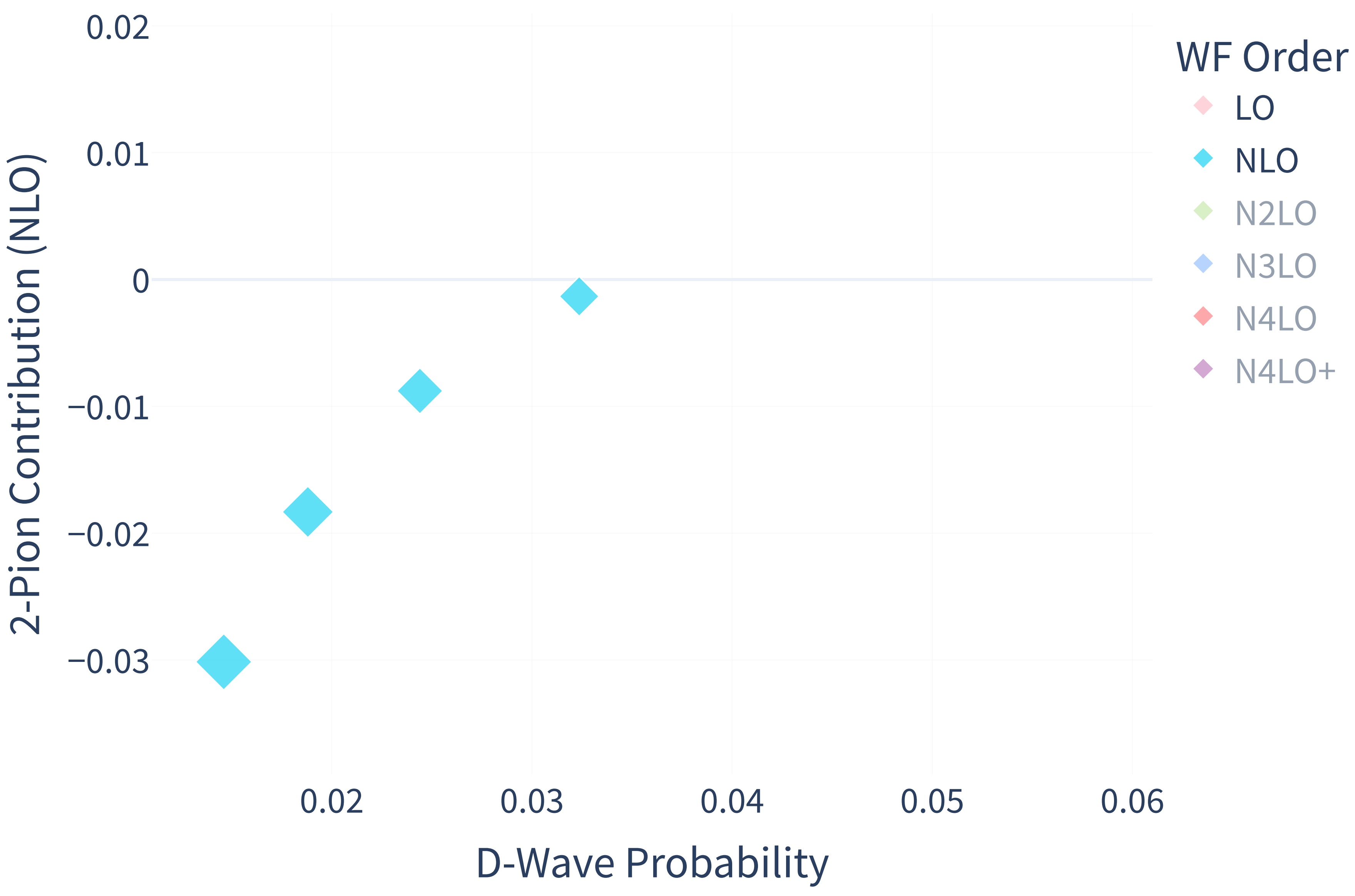
Two-pion exchange contributions to response functions squared



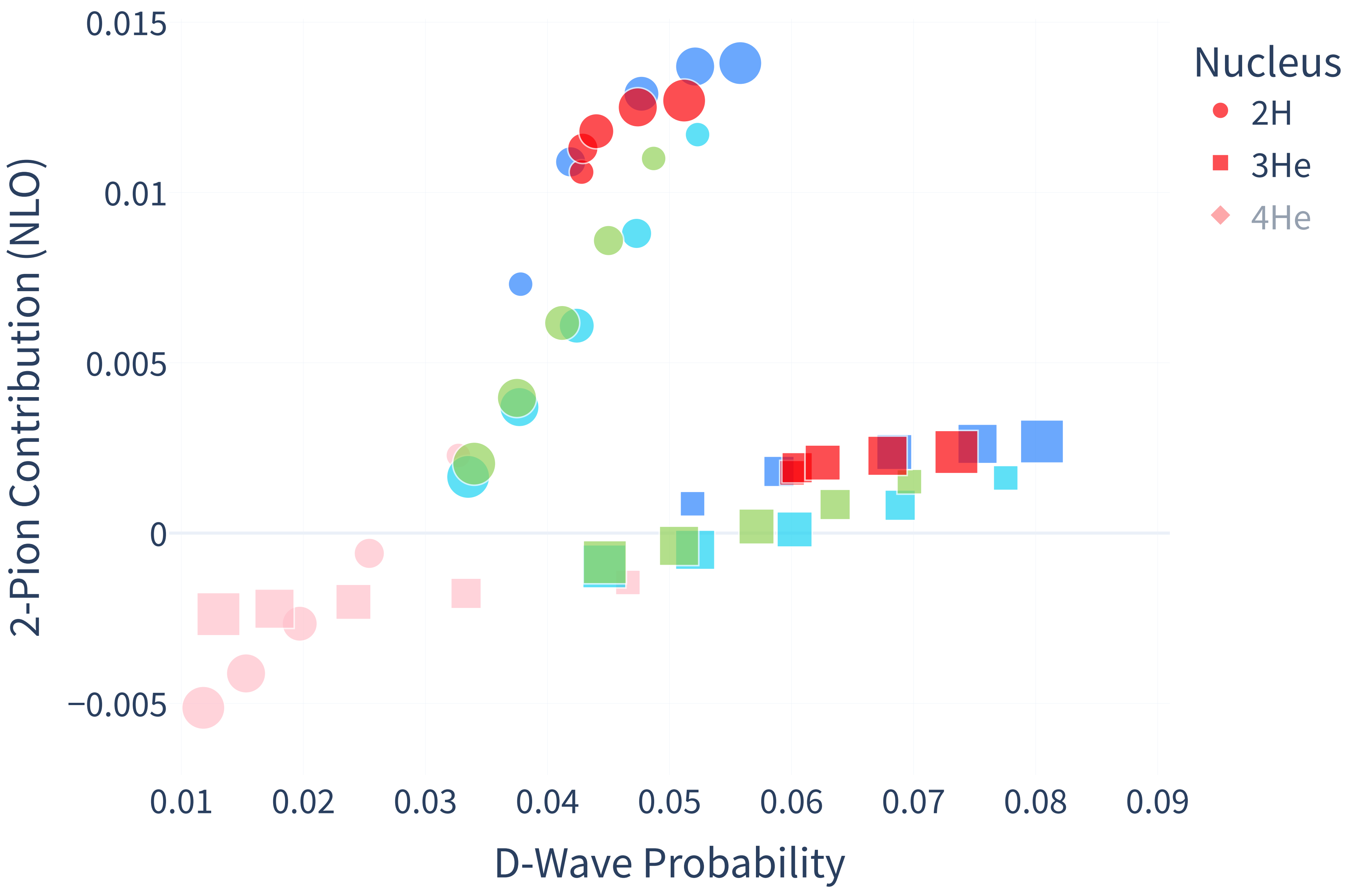
D-Wave correlation

The *unobservable (generalized)* D-wave probability correlates with the two-pion response function at $q = 0$.

4He



2H, 3He and 4He Results



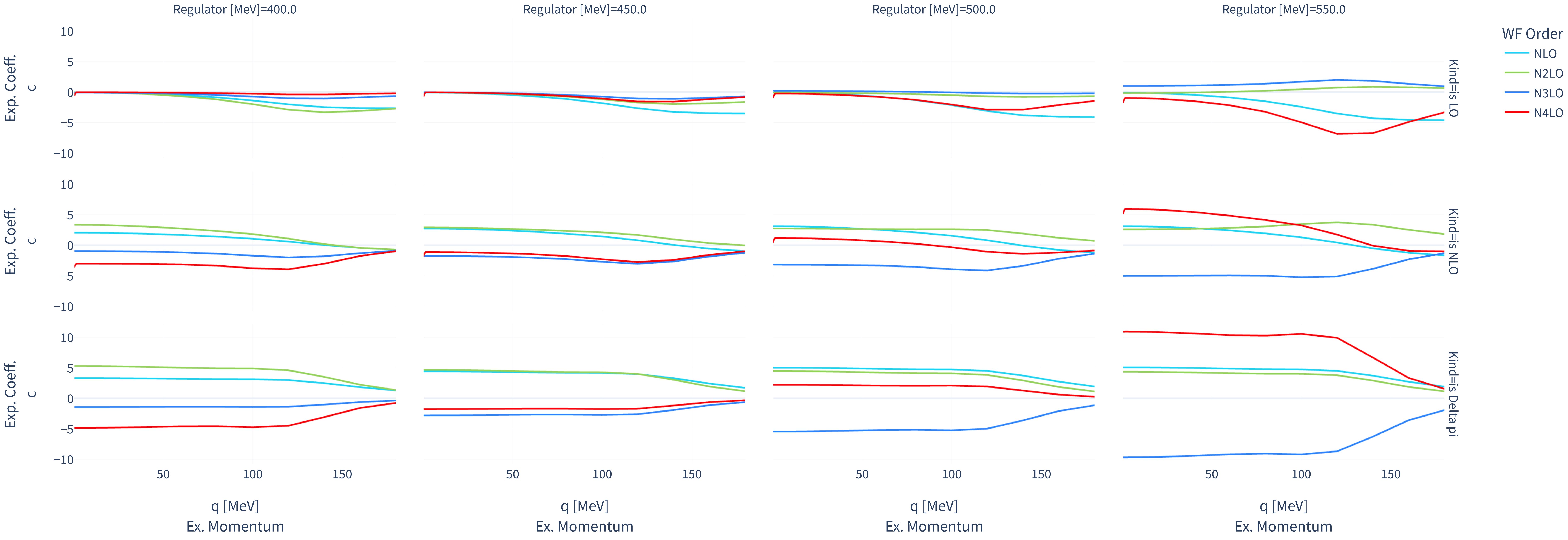
- Different marker sizes correspond to the cutoff size *(small makers mean small radii / large momenta)*
- Different colors correspond to chiral orders of the wave function
- Different symbols correspond to different nuclei

^{4}HE RESULTS

Chiral expansion coefficients

Reference scales for

- FFs: `LO` operator with `N4LO @ 500.0MeV` WF
- Pion contribution: `constant`



CONCLUSIONS

We need a non-zero DM signal measurement

(Preliminary as the analysis for ^{4}He is still ongoing)

- Scalar DM pion-contributions seem to be marginally relevant to light nuclear systems with $A \leq 3$ making it hard *but possible* to disentangle different spin-independent contributions

  At the level of a few percent for "natural" BSM coefficients and only distinguishable from zero for high-accuracy interactions.
- For ^{4}He, there seems to be a cutoff dependence surpassing estimated chiral uncertainties for high-accuracy interactions. Possible sources can be *(an investigation of these hypotheses is on the way)*
  - An incomplete power interaction counting (missing 3NForces).
  - Missing counterterms formally present at higher powers in the current counting.
  - Not utilizing a combined power counting simultaneously for currents and operators.
  - Not consistently deriving currents in the presence of regulators.

  See also contribution 116 and [2008.00974] for more details on the last two points.