Heavy WIMP effective theory and anatomy of WIMP-nucleus interactions

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INT workshop on nuclear aspects of DM searches

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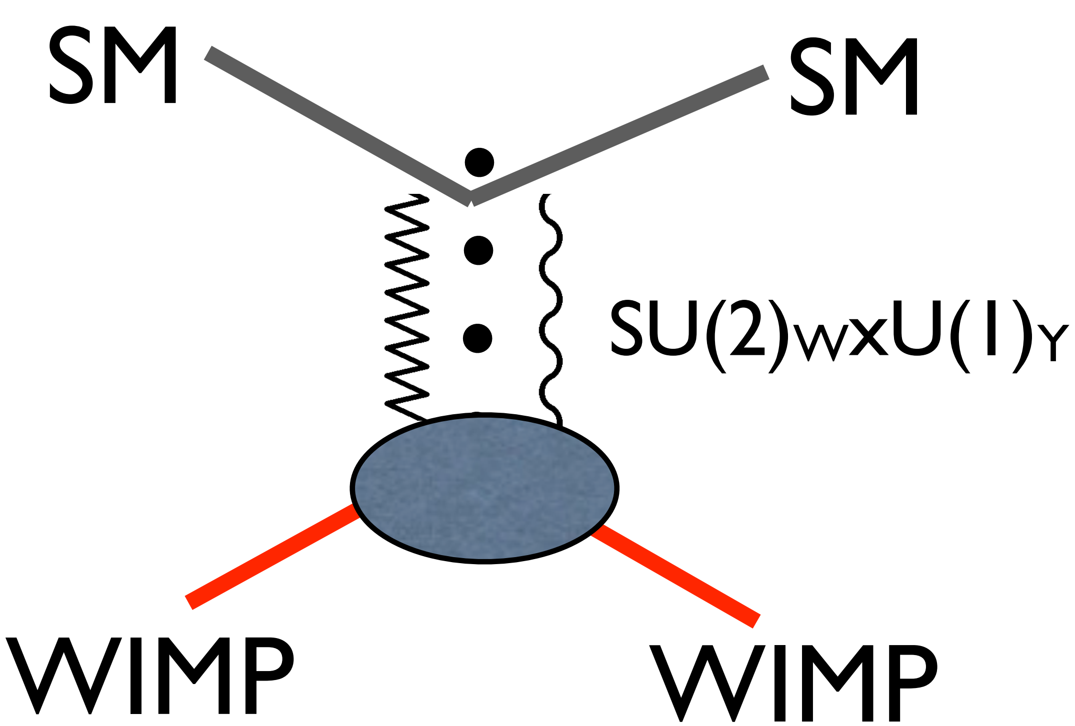
based on work with M.P. Solon: 1111.0016(PLB), 1309.4092(PRL), 1401.3339(PRD),1409.8290(PRD)

and with M.Bauer,T.Cohen and M.P.Solon: 1409.7392(JHEP)

What is Heavy WIMP Effective theory?

a manifestation of heavy particle symmetry:

- hydrogen/deuterium spectroscopy $E_n = -\frac{1}{2n^2} m_e (Z\alpha)^2 + \ldots$ $(m_e Z\alpha) \ll m_e$
- heavy meson B/B* transitions $F^{B\to D}(v' = v) = 1 + \ldots$ $\Lambda_{\rm QCD} \ll m_{b,c}$
- DM interactions $\sigma(\chi N \to \chi N) = ?$ $m_W \ll m_\chi$



universal interactions between a heavy WIMP and standard model particles, like nucleons

$\Rightarrow$ independent of WIMP spin or internal structure

What is it good for?

in addition to universality, the effective theory enables us to incorporate important effects:

- simplifies two loop matching (WIMP-nucleus scattering)
- enables large $\log(M_{DM}/m_W)$ resummation (WIMP annihilation)

in this talk, focus on WIMP-nucleus scattering.

Consider for definiteness a self-conjugate WIMP, odd under stabilizing parity symmetry (includes, but is not limited to SUSY neutralinos)

Low-velocity WIMP-nucleon cross section: a basic benchmark, but involves surprisingly intricate analysis

Other ingredients

To examine the implications of heavy WIMP symmetry, improvements to standard/simplified treatments are necessary:

- new results in high order perturbative QCD ($\alpha_s(m_c)$ expansion)
- systematic treatment of hadronic uncertainties

Aside: theoretical developments have implications beyond WIMPs

- *atomic physics*: Lorentz invariance and high order NRQED
- *collider physics*: Soft-collinear effective theory: interplay of soft-collinear singularities and electroweak symmetry breaking

In the remainder of the talk,

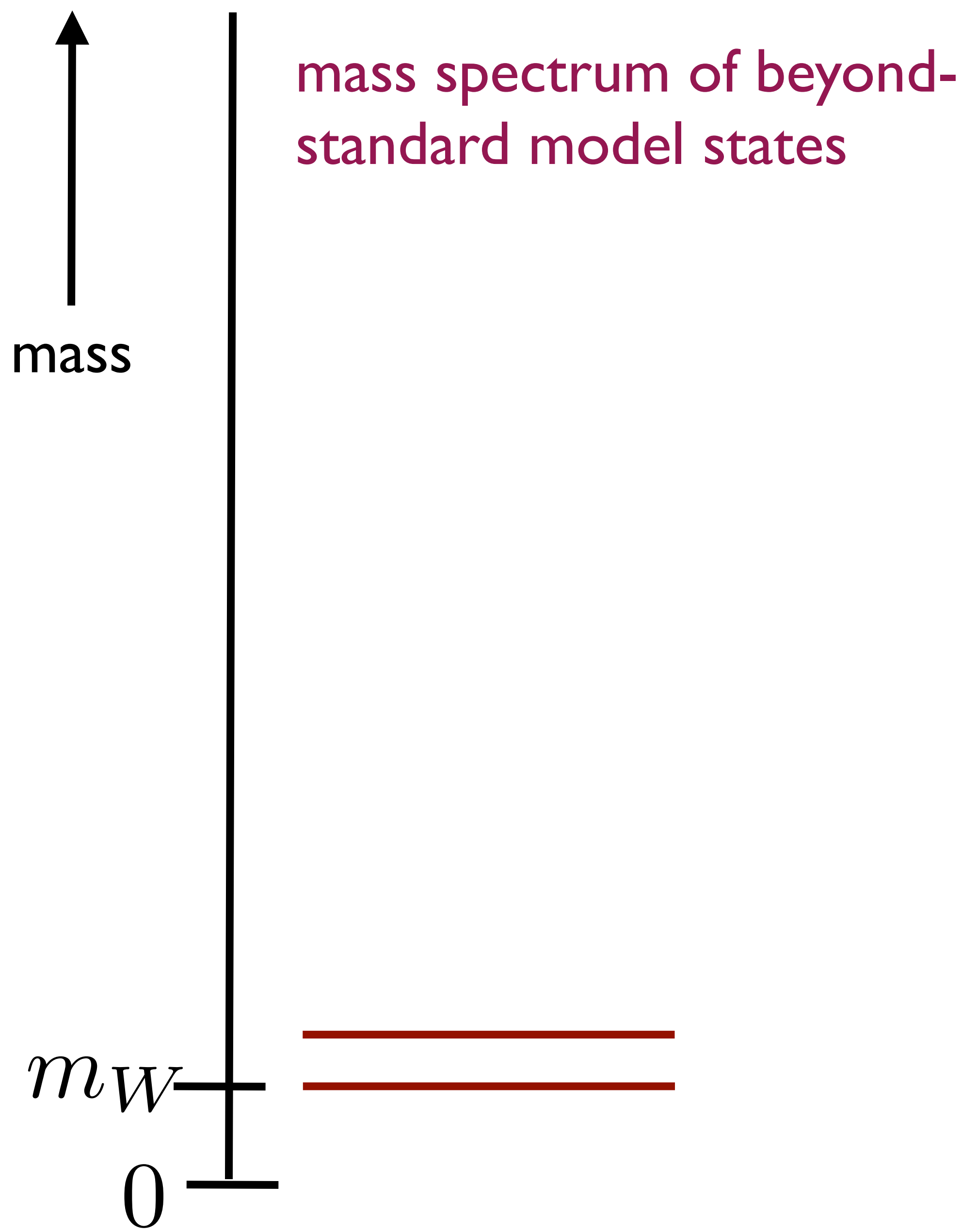
- motivate the study of heavy WIMP models

- describe "Standard Model anatomy" of WIMP-nucleus scattering process, necessary to determine the observable implications of heavy WIMP symmetry

- give (surprising) results for some simple examples

- discuss topics for further study

Present null results of direct detection and collider searches may indicate large WIMP mass scale



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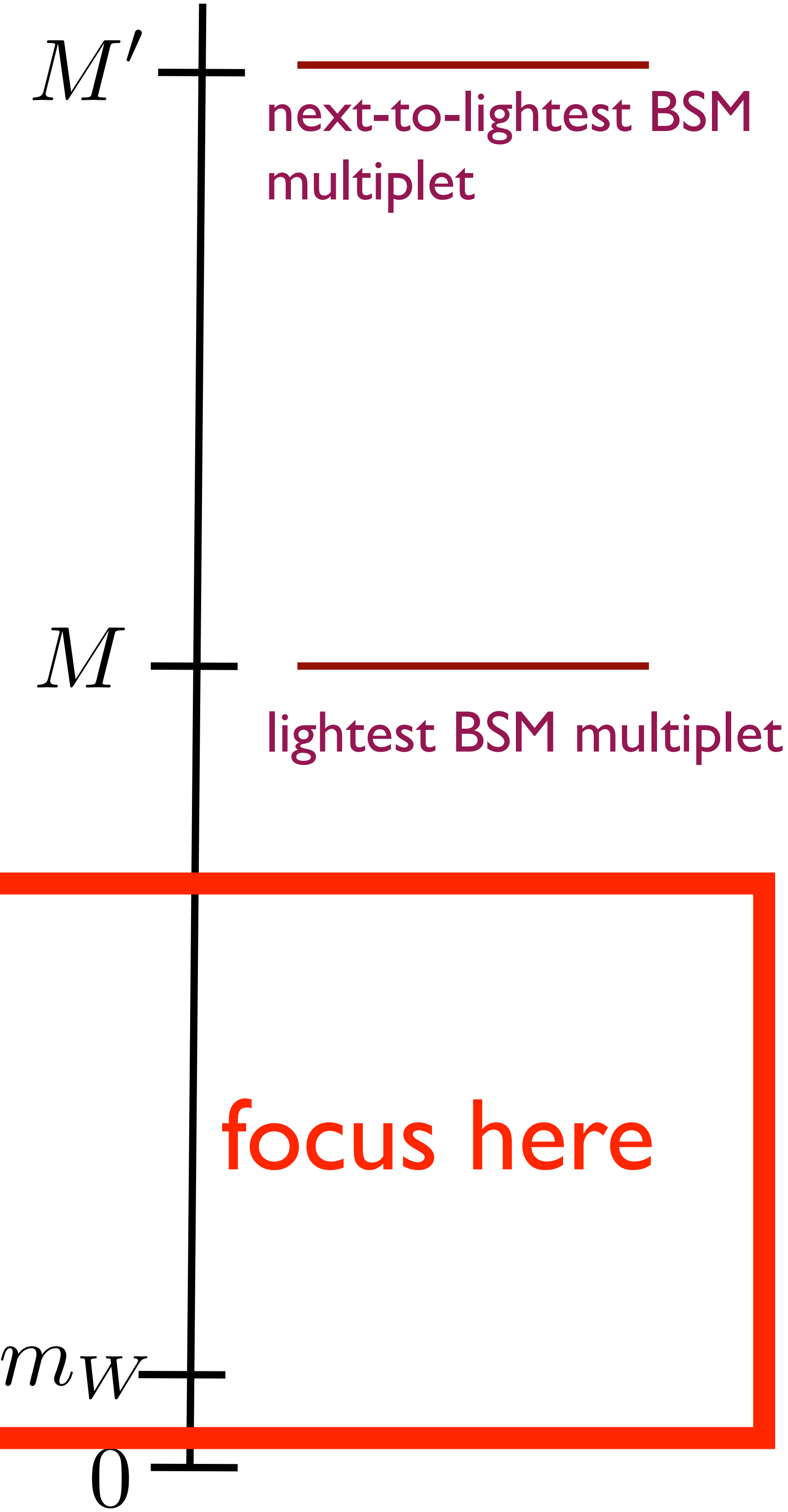
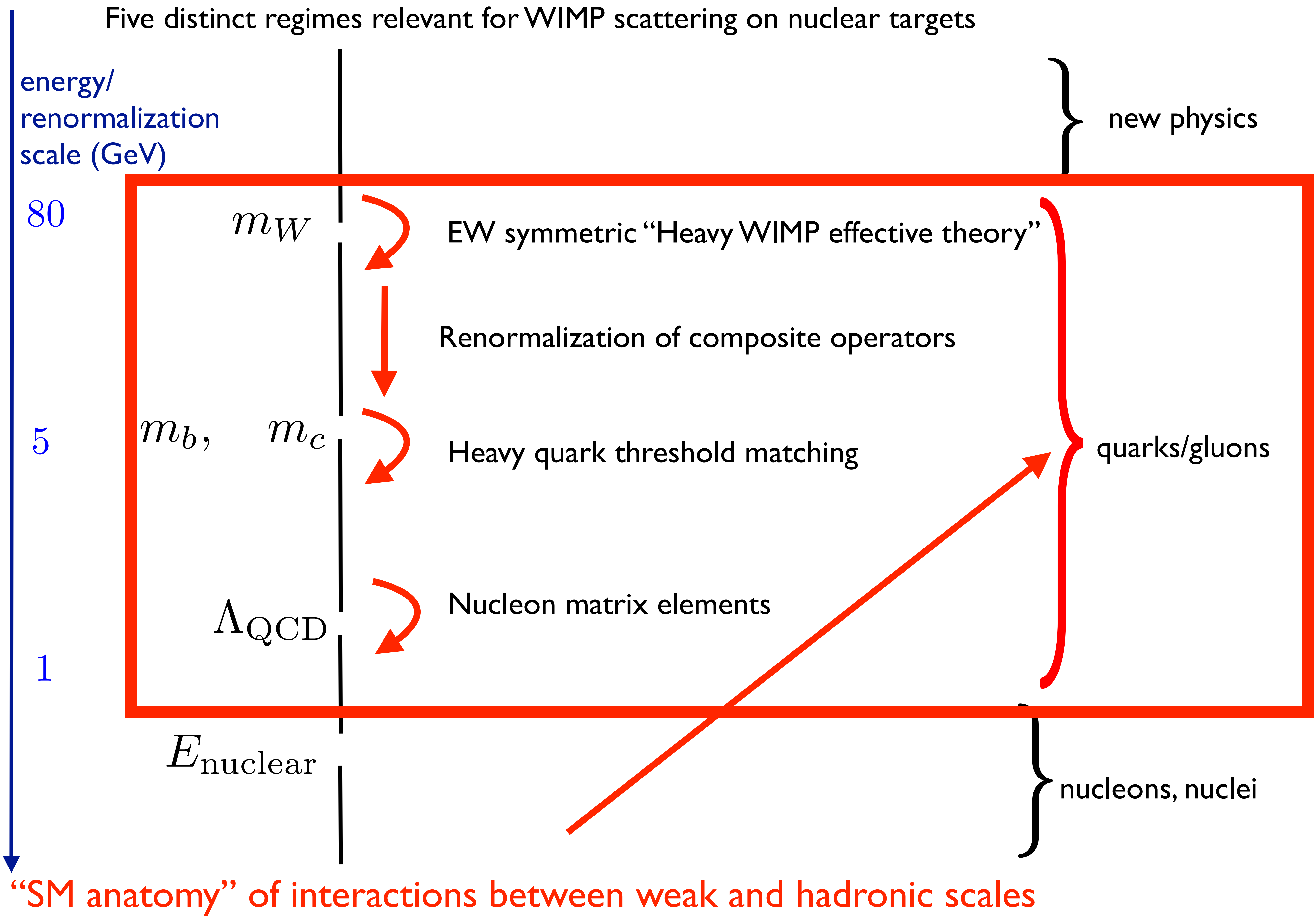


If WIMP mass M >> m_W , isolation (M'-M >> m_W) becomes generic.   Expand in m_W/M, m_W/(M'-M)

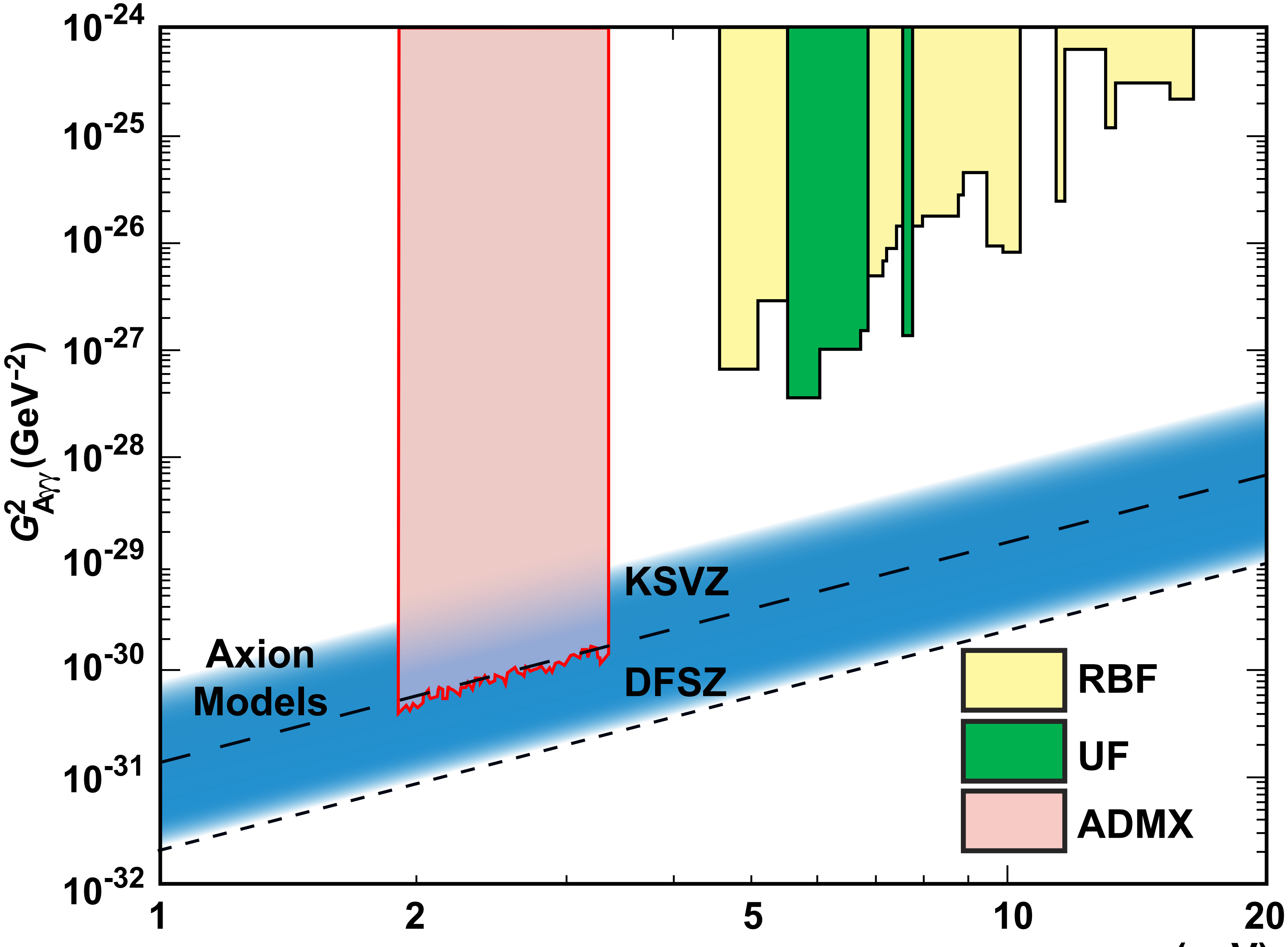
Large WIMP mass regime is a focus of future experiments in direct, indirect and collider probes


Five distinct regimes relevant for WIMP scattering on nuclear targets
energy/
renormalization
scale (GeV)
80
5
1
m_W
$m_b, \quad m_c$
$\Lambda_{\rm QCD}$
$E_{\rm nuclear}$
EW symmetric "Heavy WIMP effective theory"
Renormalization of composite operators
Heavy quark threshold matching
Nucleon matrix elements
new physics
quarks/gluons
nucleons, nuclei
"SM anatomy" of interactions between weak and hadronic scales

Mechanisms versus models

Effective theories allow us to make predictions independent of detailed models

E.g., PQ/axion mechanism versus specific axion model



electromagnetic anomaly

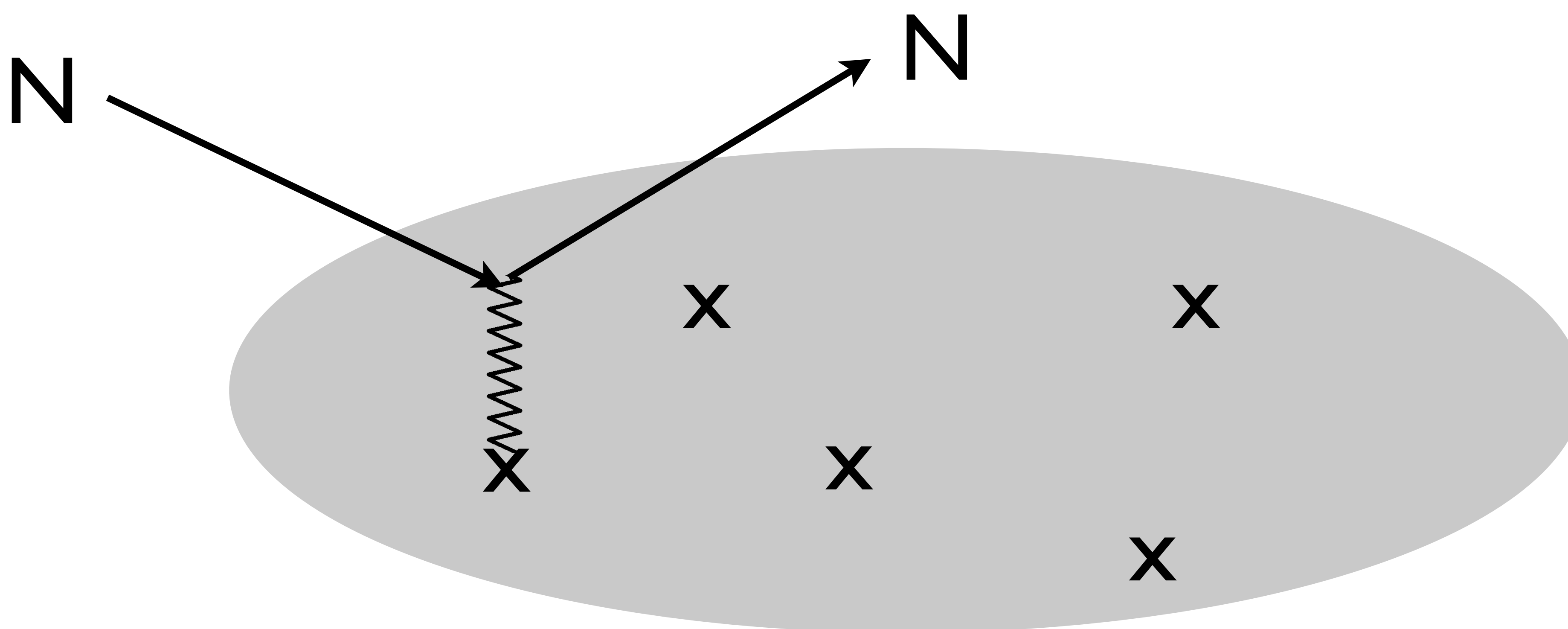
color anomaly

$$g_{a\gamma\gamma} \propto \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

$$= \frac{E}{N} - 2.01(13)$$

Mechanisms versus models

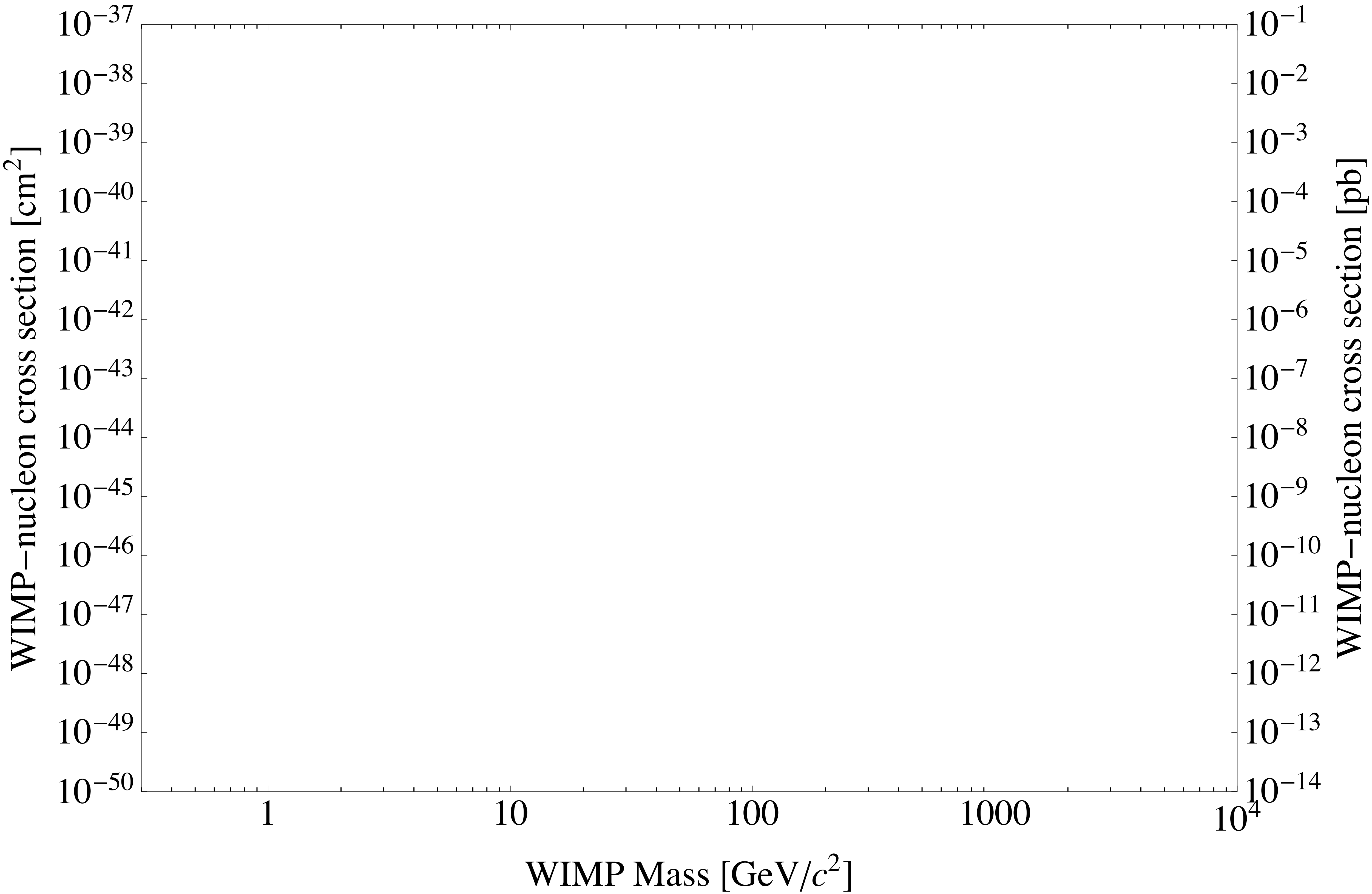
Electroweak charged WIMP Mechanism versus WIMP Model



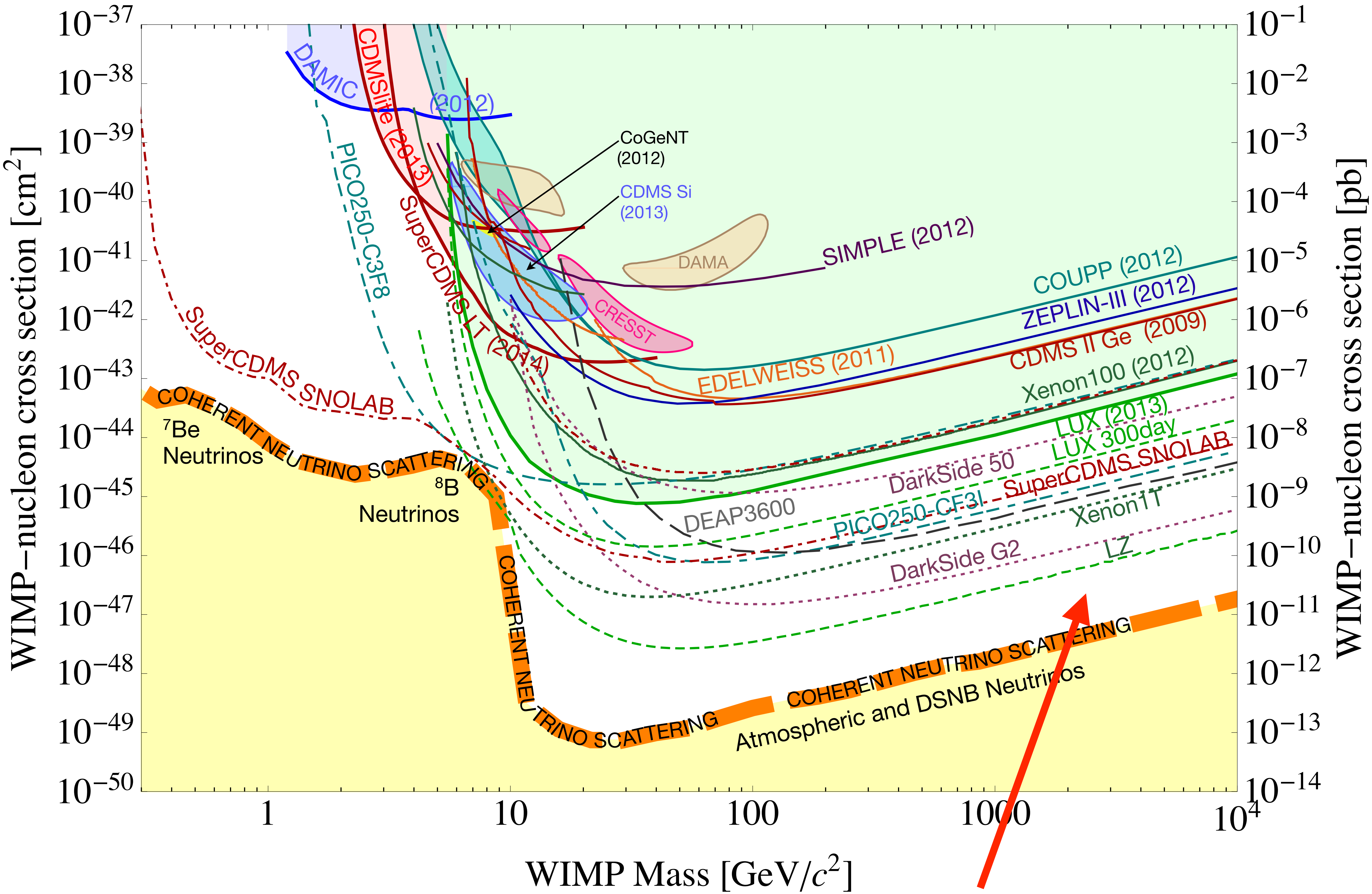
Focus on self-conjugate SU(2) triplet. Could be:

- SUSY wino
- Weakly Interacting Stable Pion
- Minimal Dark Matter
- ...

A lot of space...



A lot of space remaining...



we'll end up here

Start here: (e.g. fermion or composite boson UV completion)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\tilde{w}}(i\not{D} - M)\tilde{w} \qquad \mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}(\hat{A}^a_{\mu\nu})^2 + \bar{\psi}(i\not{\partial} + \hat{g}\not{\hat{A}} + g_2\not{W})\psi$$

Fill in here

End up here

$$\mathcal{L} = N^\dagger\left(i\partial_t + \frac{\boldsymbol{\partial}^2}{2m_N}\right)N + \chi^\dagger\left(i\partial_t + \frac{\boldsymbol{\partial}^2}{2M}\right)\chi + c_{\rm SI}N^\dagger N\chi^\dagger\chi + \dots$$

"SM anatomy" of interactions between weak and hadronic scales

Scale separation:

Scale	dark sector d.o.f.	SM d.o.f.	# params. (beyond mass)
	$\chi^{(+,-,0)}$	$Q, A^a_\mu, W^i_\mu, B_\mu$	0
M			
	$\chi_v^{(+,-,0)}$	$Q, A^a_\mu, W^i_\mu, B_\mu$	0
m_W			
	$\chi_v^{(0)}$	u, d, s, c, b, A^a_μ	12
m_b, m_c			
	$\chi_v^{(0)}$	u, d, s, A^a_μ	8
Λ_{QCD}			
	$\chi_v^{(0)}$	N, π	3
m_π			
	$\chi_v^{(0)}$	n, p	2
$1/R_{nucleus}$			
	$\chi_v^{(0)}$	$\mathcal{N}$	1

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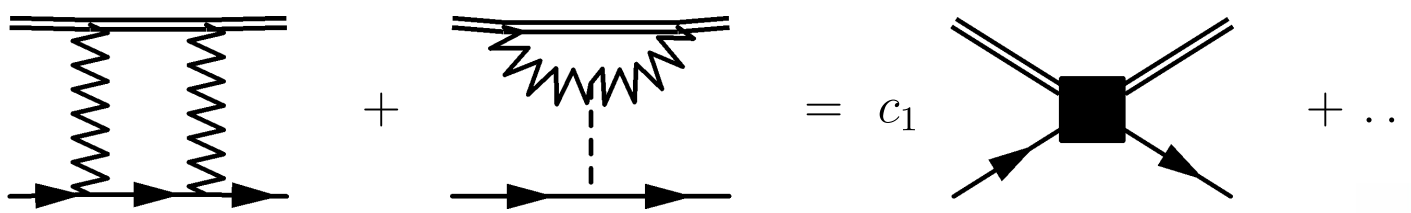
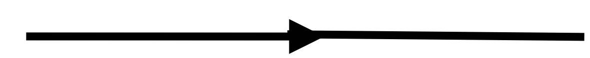
Heavy particle symmetry and weak-scale matching

12 operators (classified as spin-0 and spin-2) and 12 coefficients

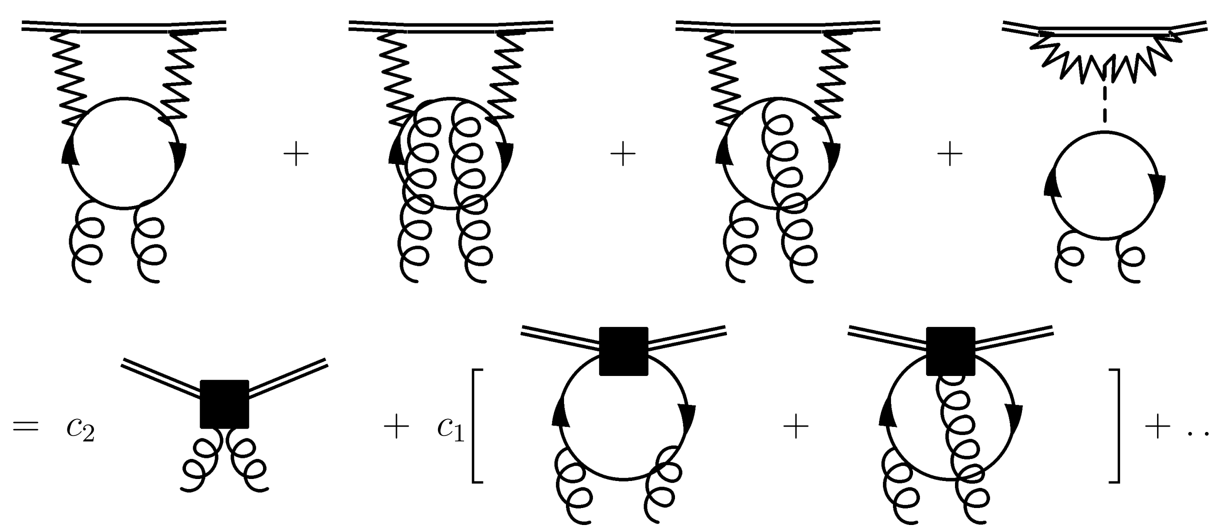
$$\mathcal{L}_{\phi_0,\mathrm{SM}} = \frac{1}{m_W^3}\phi_v^*\phi_v\left\{ \sum_q \left[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu} \right] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \right\} + \dots$$

Heavy WIMP Feynman rules drastically simplifiy integrals:

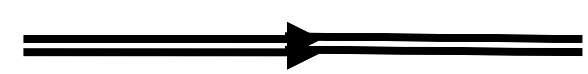




$$\frac{i}{L^2 - M^2 + i\epsilon}$$



vs.:



$$\frac{i}{v \cdot L + i\epsilon}$$

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Renormalization and heavy quark decoupling

$$\mathcal{L}_{\phi_0,\mathrm{SM}} = \frac{1}{m_W^3}\phi_v^*\phi_v\left\{ \sum_q \left[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu}\right] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \right\} + \dots$$

QCD operators are familiar: Lagrangian operators (spin-0) and components of QCD stress-energy (spin-2)

$$O_{1q}^{(0)} = m_q \bar{q} q \,, \qquad O_2^{(0)} = (G_{\mu\nu}^A)^2 \,,$$

$$O_{1q}^{(2)\mu\nu} = \bar{q}\left(\gamma^{\{\mu} i D^{\nu\}} - \frac{1}{d} g^{\mu\nu} i \not{D} \right) q \,, \qquad O_2^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_\lambda + \frac{1}{d} g^{\mu\nu} (G_{\alpha\beta}^A)^2 \,.$$

Anomalous dimensions known to high order

$$\frac{d}{d\log\mu} c_i^{(S)} = \sum_j \gamma_{ji}^{(S)} c_j^{(S)}$$

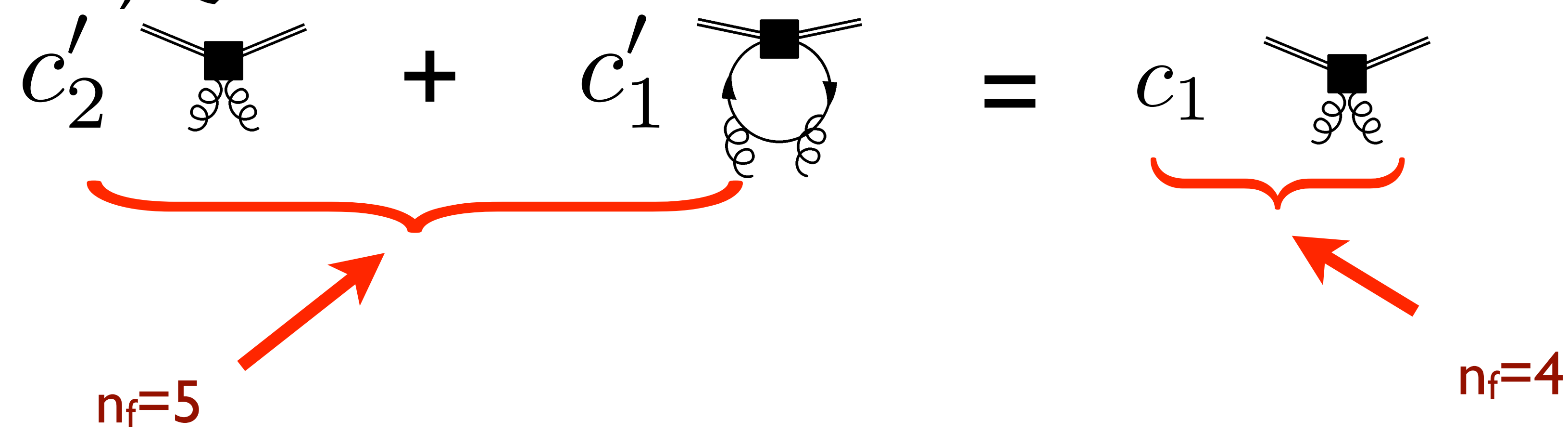
Determines coefficient solution (within theory of same n_f), e.g.

$$c_2^{(0)}(\mu) = c_2^{(0)}(\mu_t) \frac{\frac{\beta}{g}[\alpha_s(\mu)]}{\frac{\beta}{g}[\alpha_s(\mu_t)]}$$

$$c_1^{(0)}(\mu) = c_1^{(0)}(\mu_t) - 2[\gamma_m(\mu) - \gamma_m(\mu_t)] \frac{c_2^{(0)}(\mu_t)}{\frac{\beta}{g}[\alpha_s(\mu_t)]}$$

Heavy quark decoupling

In order to evaluate nucleon matrix elements, need to match onto 3-flavor (perhaps 4-flavor) QCD



Poor convergence of perturbation theory at charm mass leads to strong dependence on subleading corrections

$$\langle O_i'^{(S)} \rangle(\mu_b) = M_{ji}^{(S)}(\mu_b) \langle O_j^{(S)} \rangle(\mu_b) + \mathcal{O}(1/m_b)$$

$$M(\mu_Q) = \left(\begin{array}{ccc|c|c} & \mathbb{1}(M_{qq} - M_{qq'}) + \mathbb{J} M_{qq'} & & \begin{matrix} M_{qQ} \\ \vdots \\ M_{qQ} \end{matrix} & \begin{matrix} M_{qg} \\ \vdots \\ M_{qg} \end{matrix} \\ \hline M_{gq} & \cdots & M_{gq} & M_{gQ} & M_{gg} \end{array} \right)$$

Inami, Kubota, Okada (1983)

Chetyrkin, Kniehl, Steinhauser (1998)

NNNLO: Hill, Solon (2014)

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Nucleon matrix elements and hadronic uncertainty

Having evolved to 3-flavor QCD, appeal to lattice QCD or other nonperturbative methods for nucleon matrix elements

Gluon matrix elements determined by quark matrix elements + sum rules

spin-0: $\langle N|O_q^{(0)}|N\rangle \equiv m_N f_{q,N}^{(0)}$

$$m_N(f_{u,N}^{(0)} + f_{d,N}^{(0)}) \approx \Sigma_{\pi N}$$

$$m_N f_{s,N}^{(0)} = \frac{m_s}{m_u + m_d}(\Sigma_{\pi N} - \Sigma_0) = \Sigma_s$$

$$\Sigma_{\pi N} = \frac{m_u + m_d}{2}\langle p|(\bar{u}u + \bar{d}d)|p\rangle \qquad \Sigma_0 = \frac{m_u + m_d}{2}\langle p|(\bar{u}u + \bar{d}d - 2\bar{s}s)|p\rangle$$

spin-2: $\langle N(k)|O_q^{(2)\mu\nu}|N(k)\rangle = \frac{1}{m_N}\left(k^\mu k^\nu - \frac{g^{\mu\nu}}{4}m_N^2\right) f_{q,N}^{(2)}(\mu)$

$$f_{q,p}^{(2)}(\mu) = \int_0^1 dx\, x[q(x,\mu) + \bar{q}(x,\mu)]$$

Q: Why bother with naively subleading corrections?

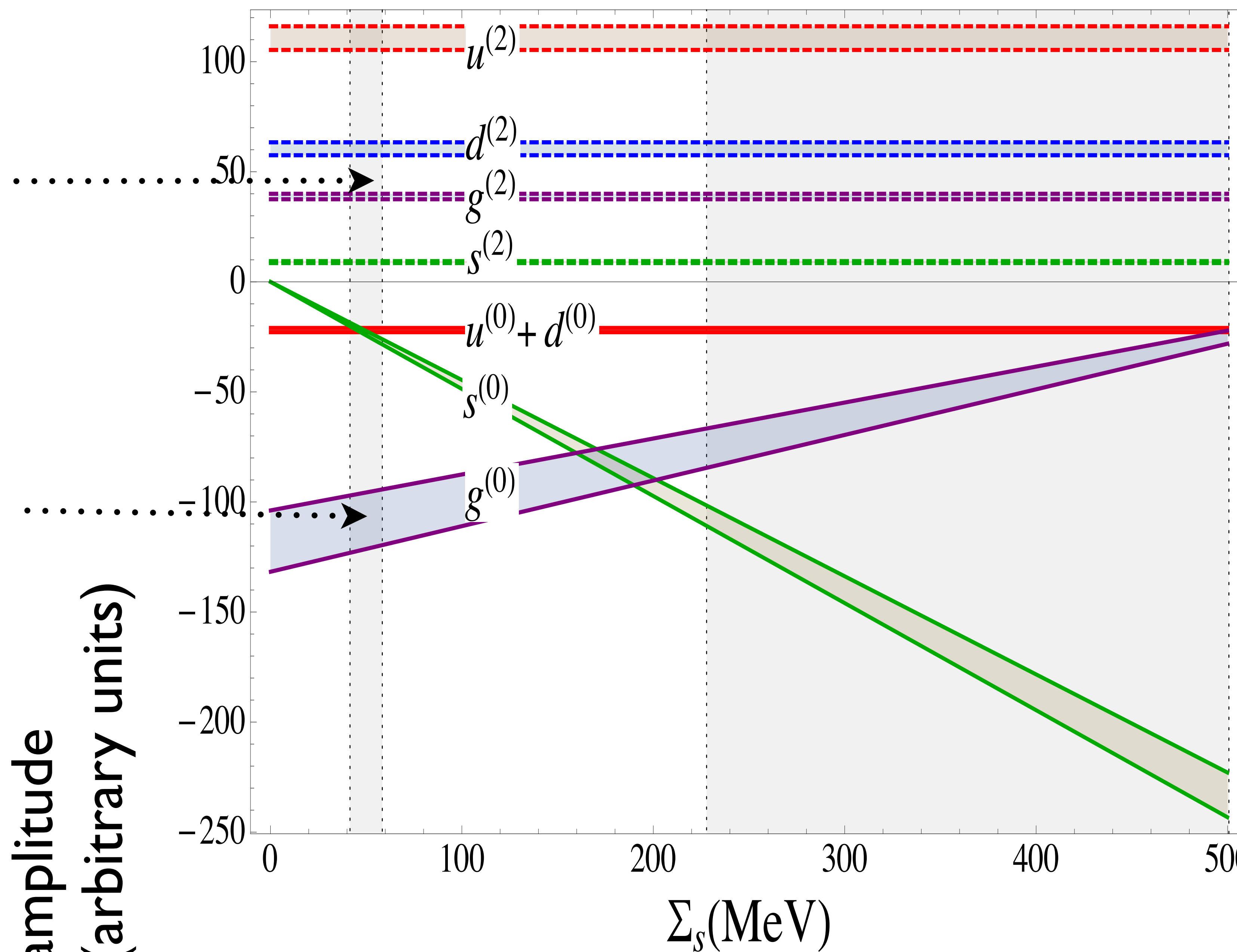
A: They matter, especially with amplitude-level cancellations

Illustrate with SU(2)W triplet (e.g. "wino")

$$\sigma \propto |M^{(0)} + M^{(2)}|^2$$

$$M^{(2)} = \sum_q M_q^{(2)} + M_g^{(2)} > 0$$

$$M^{(0)} = \sum_q M_q^{(0)} + M_g^{(0)} > 0$$



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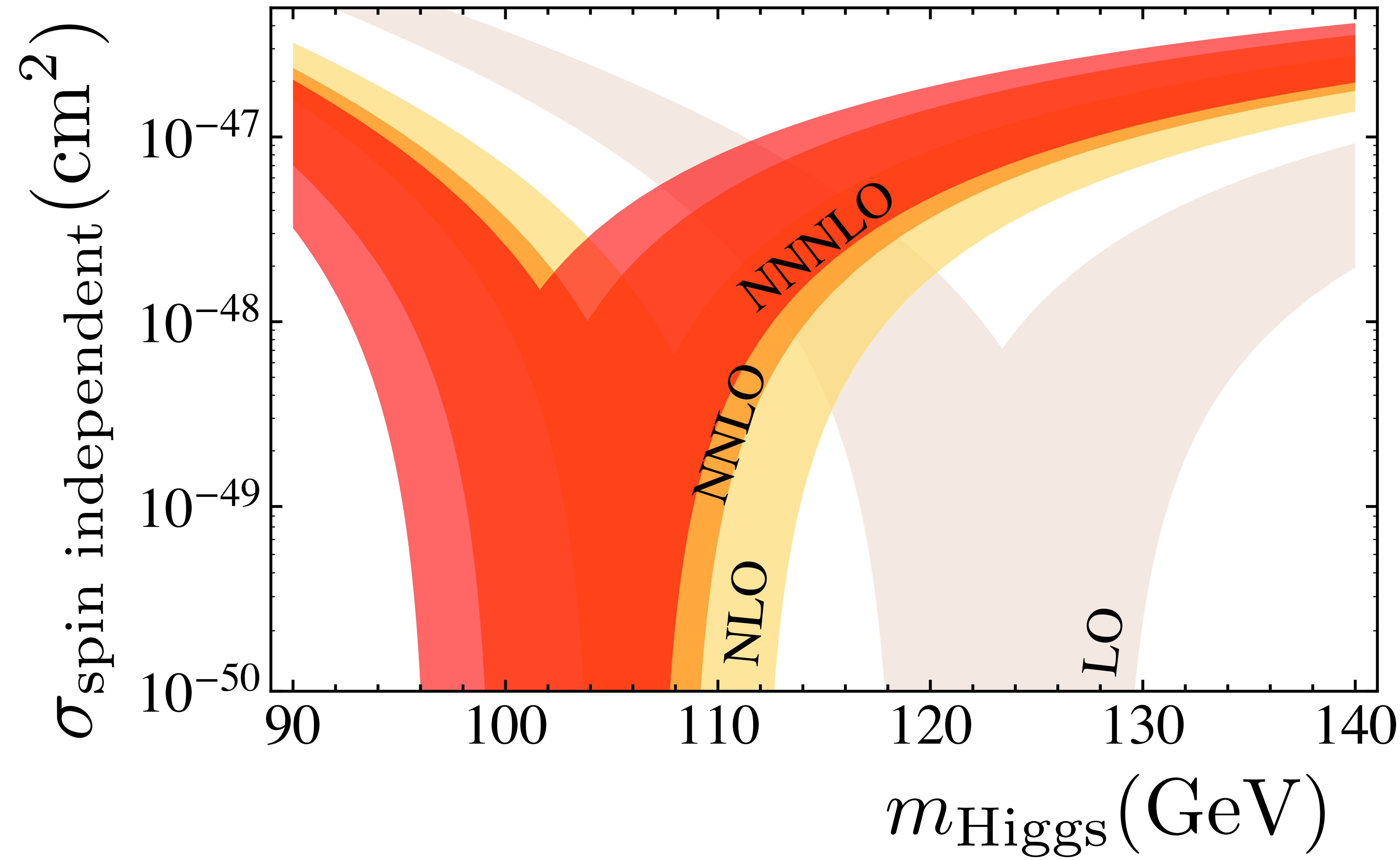
Strong dependence on both perturbative and hadronic corrections

Perturbative matching and renormalization corrections:



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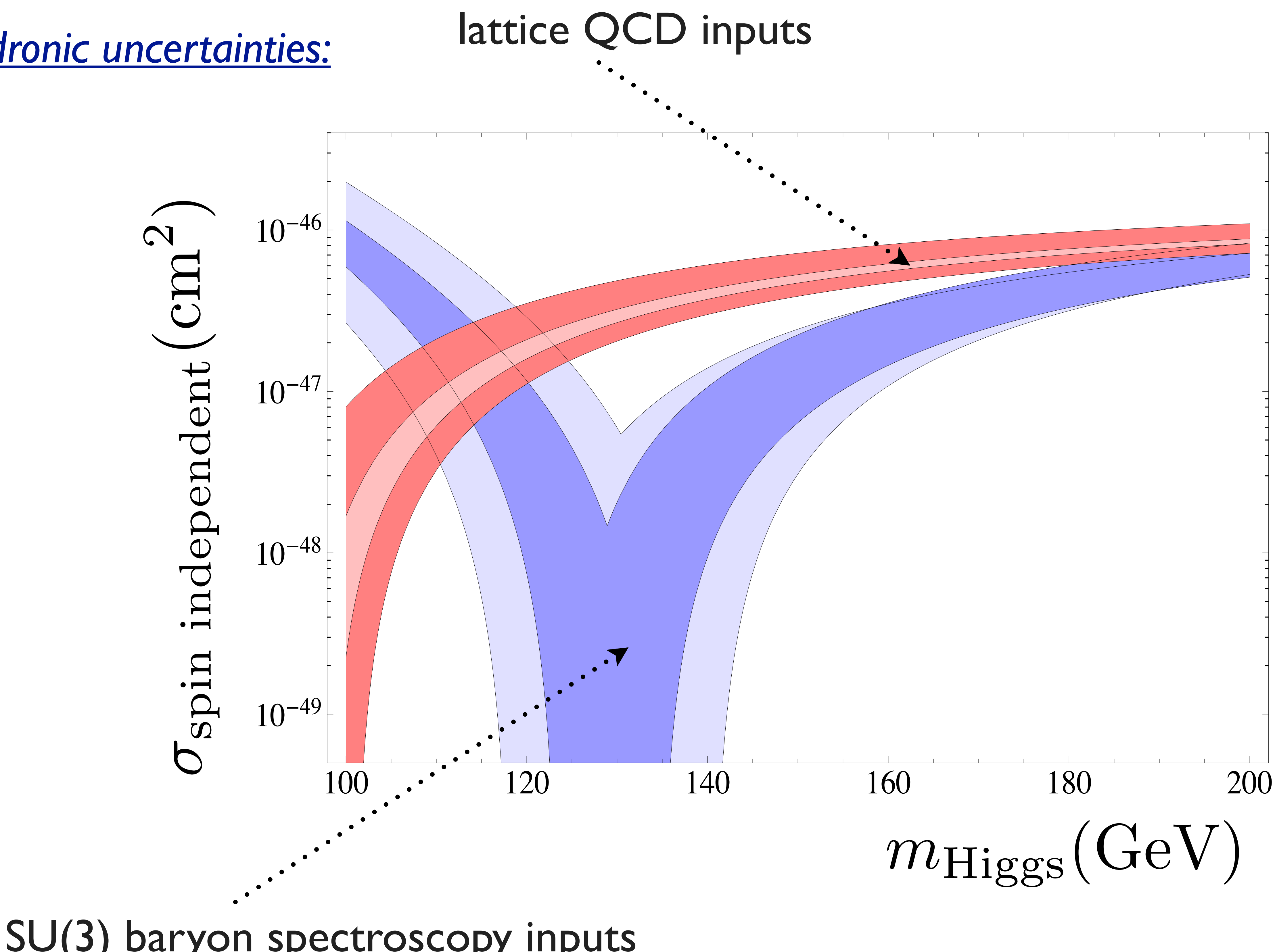
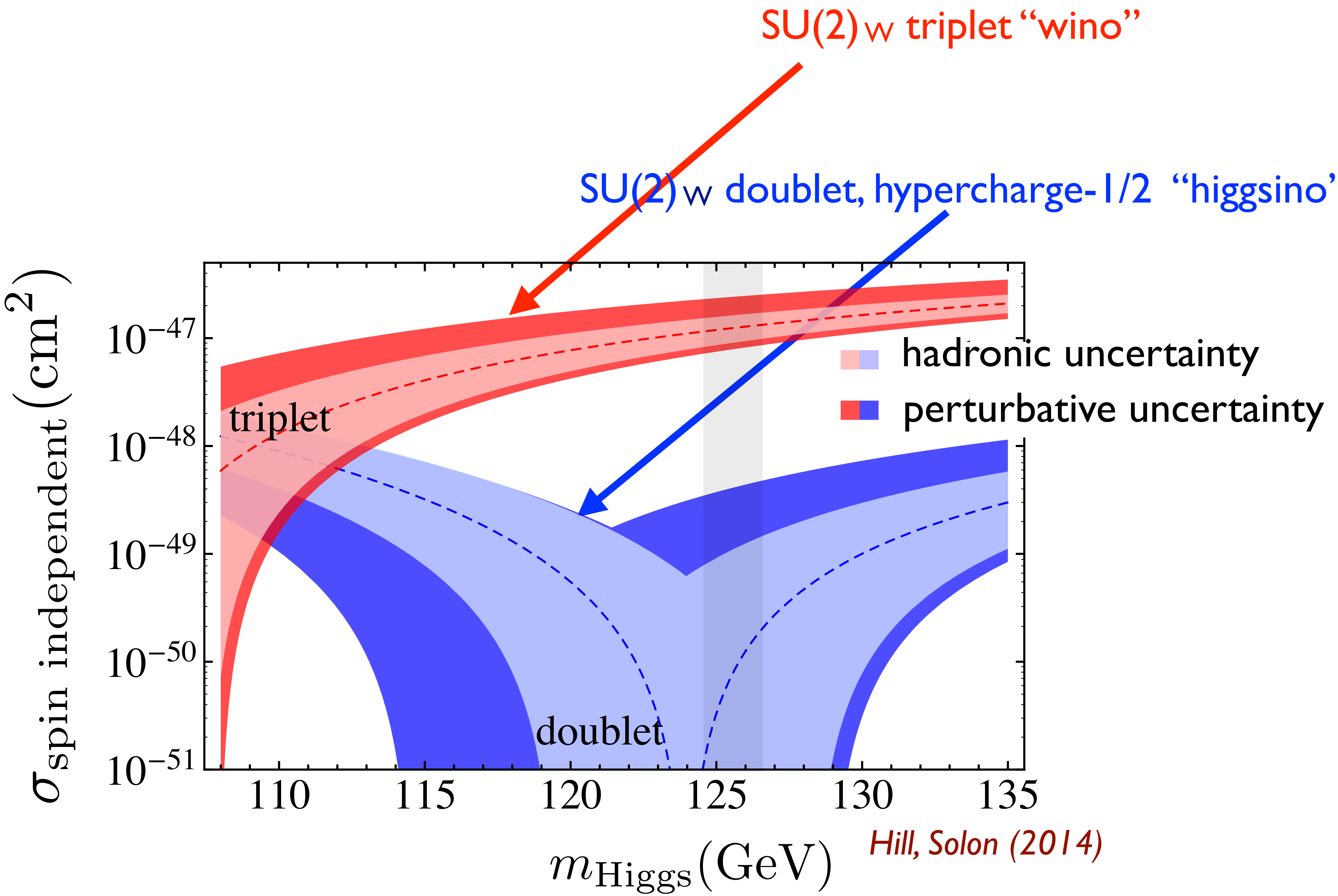
Strong dependence on both perturbative and hadronic corrections

Hadronic uncertainties:

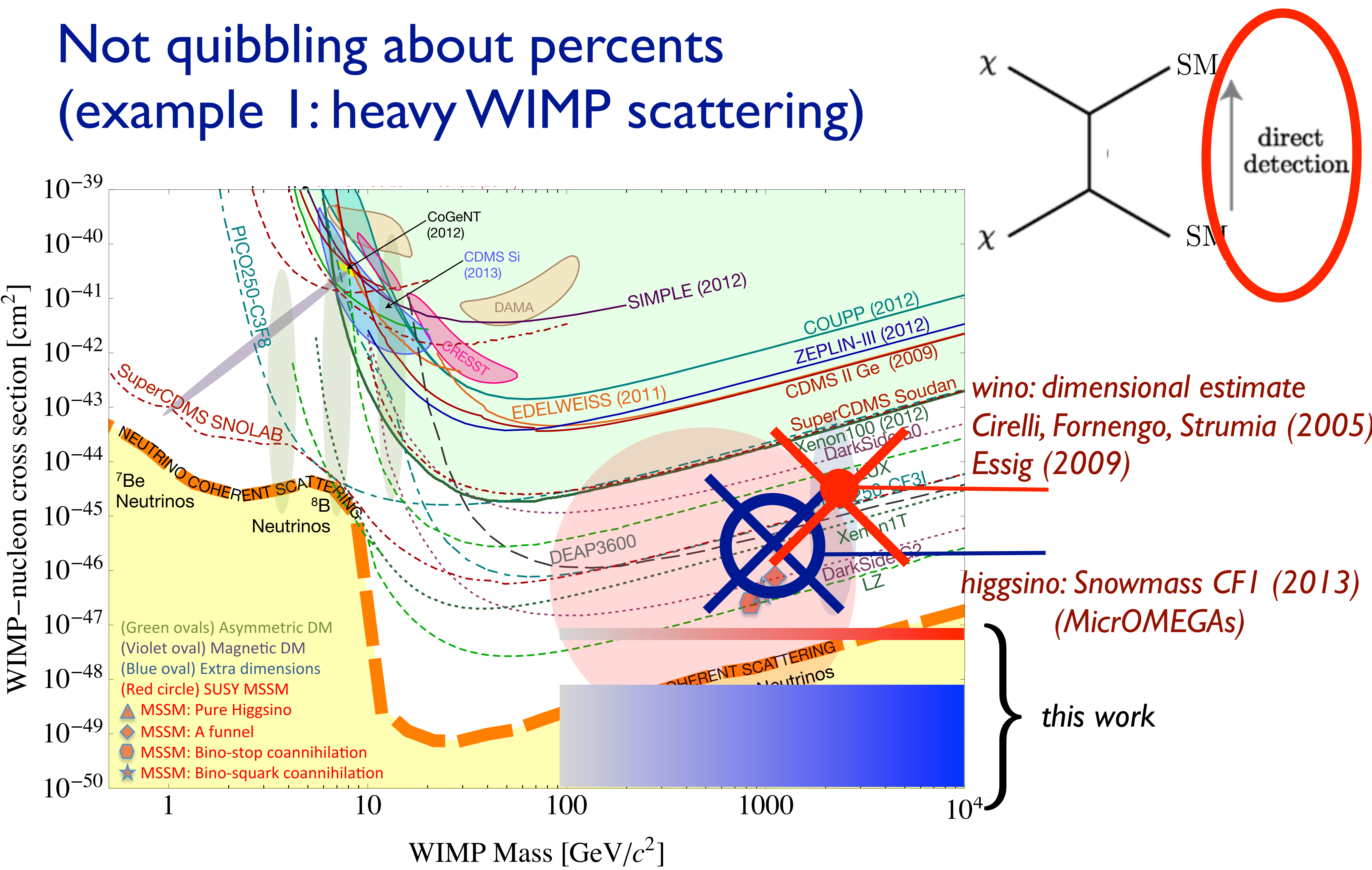


Summary for WIMP benchmarks:



Hill, Solon (2014)

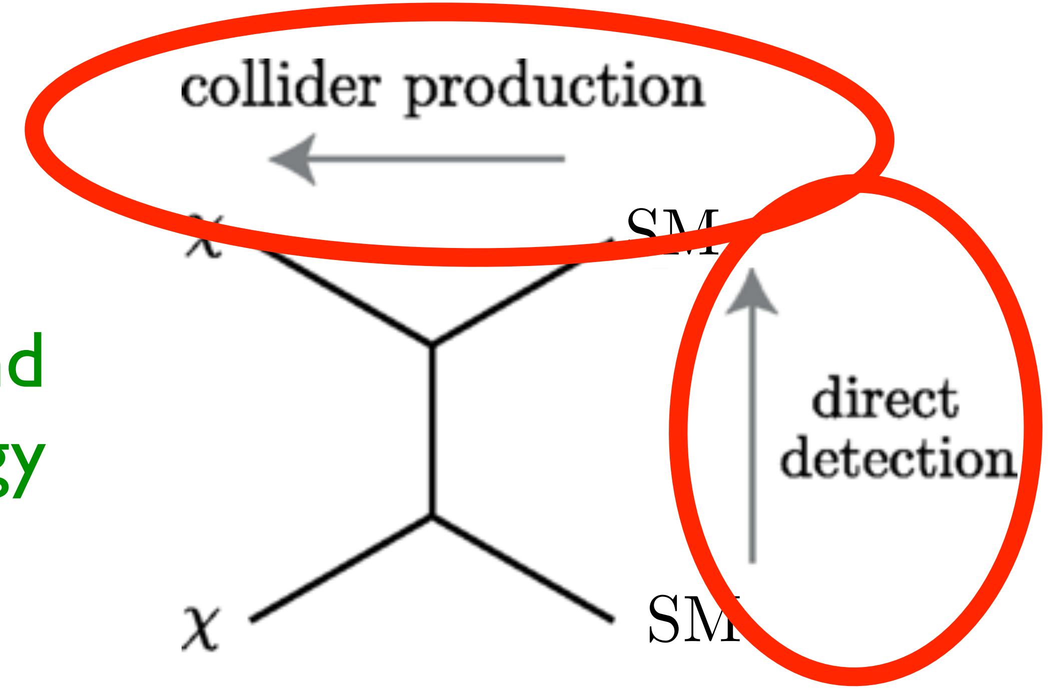
Not quibbling about percents (example 1: heavy WIMP scattering)



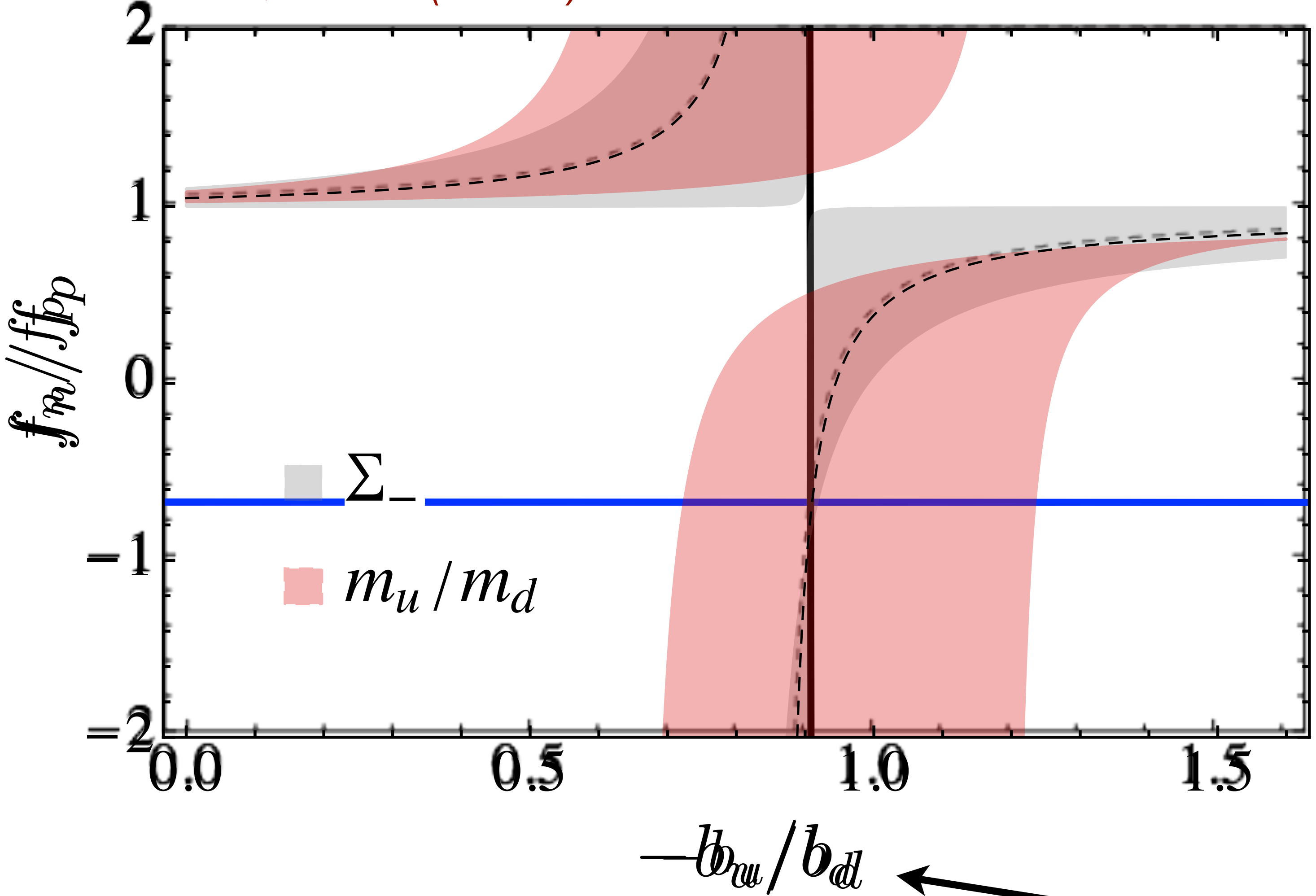
LHC pushing us into new regime: $M_{DM} \gg m_W$

Not quibbling about percents (example 2: light WIMPs)

DM complementarity: connect direct detection and collider phenomenology



Hill, Solon (2014)



f_n/f_p = ratio of SI nucleon amplitudes for WIMP-nucleon scattering

$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

four-fermion interactions constrained by collider bounds on missing energy signatures

$$\mathcal{L}_{\chi,\mathrm{SM}} = \bar{\chi}\chi\left[b_u \bar{u}u + b_d \bar{d}d\right]$$

cf. $b_u/b_d = -1.08$ from “isospin-violating” DM

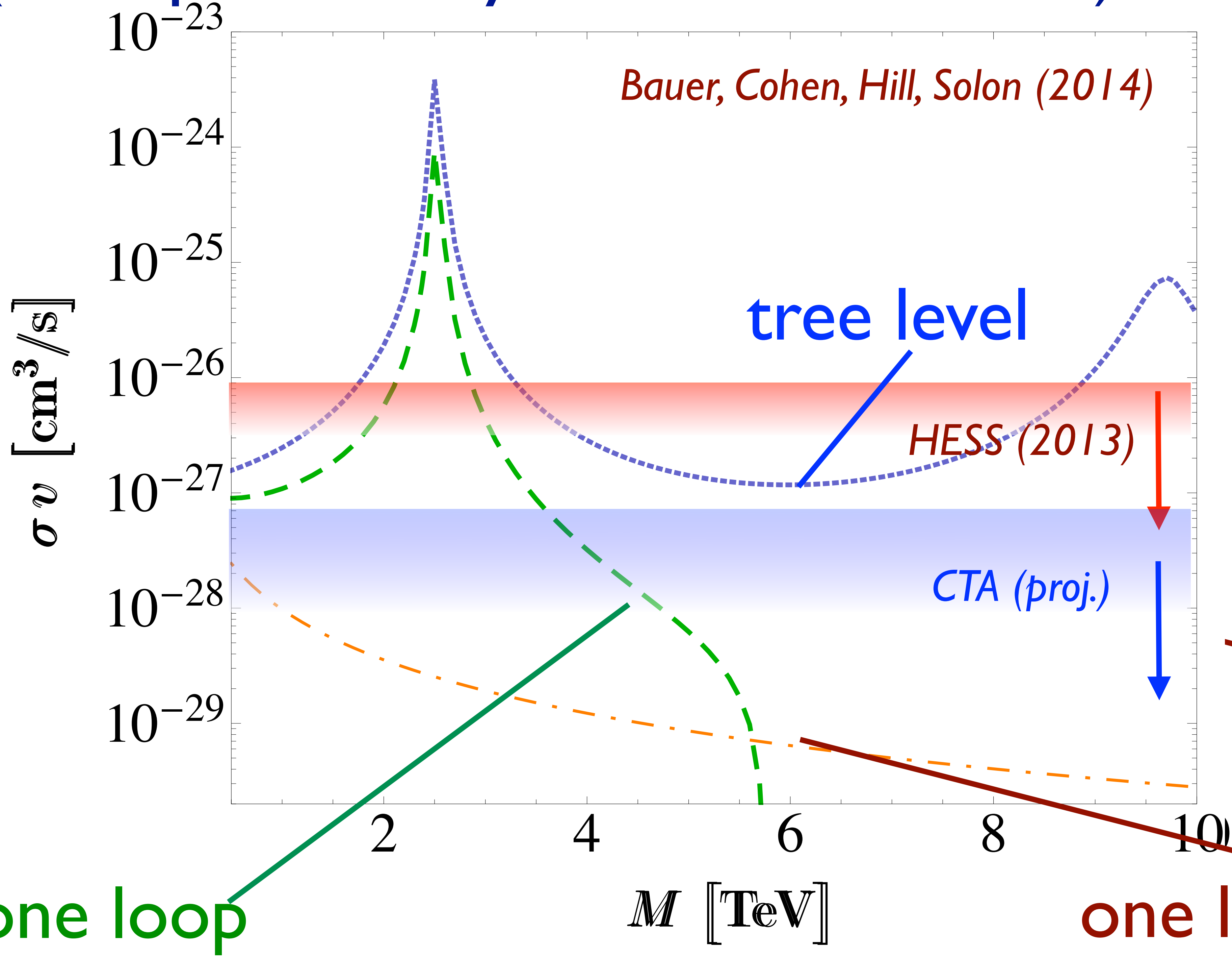
Solution: $b_u/b_d = -0.9$

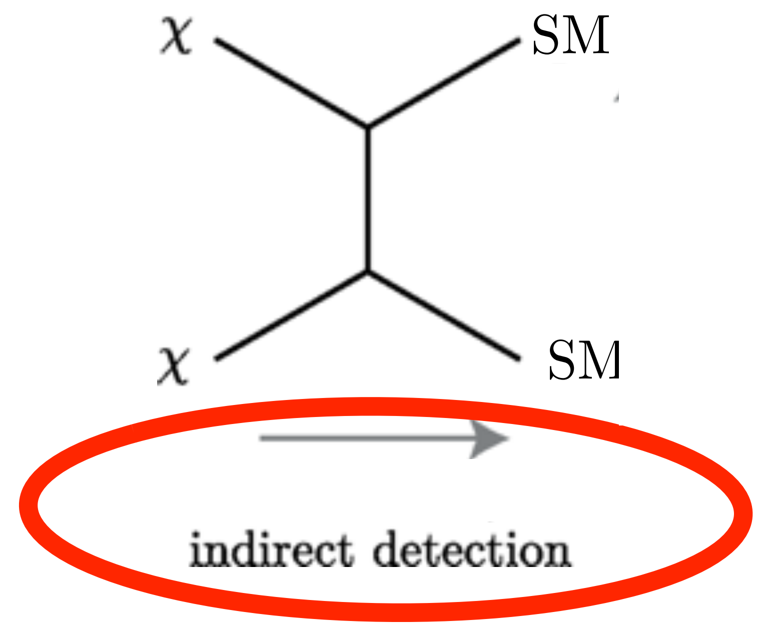
Assumed one-to-one mapping between b_u/b_d and f_n/f_p invalid

However, must account for uncertainties (hadronic and renormalization scale)

Nontrivial mapping from colliders to direct detection

Not quibbling about percents (example 3: heavy WIMP annihilation)





Photon line signal for "wino" annihilation

Multi-scale field theory problem, breakdown of naive perturbation theory

Topics for further study:

1) power corrections in m_W/M_{DM}

2) mass constraints: relic abundance, annihilation

3) multinucleon effects with tensor vs. scalar operators

4) systematic incorporation of running, matching in collider vs. direct detection

5) Lorentz vs. Galilean symmetry, total-momentum operators: leading spin-dep vs. subleading spin-indep

Summary

- LHC, direct detection constraints, relic abundance may point to heavy WIMP

- in this limit, observables become universal

- introduced heavy WIMP effective theory, and improvements to QCD analysis necessary to determine the observable implications of heavy WIMP symmetry

- sample results:

  - direct detection: generic cancellation shifts standard MSSM benchmarks ~order of magnitude (downward)

  - indirect detection: large perturbative logarithms in heavy WIMP annihilation must be resummed: factor ~3 Sudakov suppression relative to tree level

  - collider scale vs. hadronic scale: ~orders of magnitude shift in predicted f_n/f_p due to hadronic/scale uncertainties

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Discussion: Heavy WIMPs and quark and gluons vs. nucleons

1) MSSM vs. quarks and gluons vs. nucleon and pions vs. nuclei

2) scalar vs. tensor

3) Lorentz vs. Galilean invariance

4) connection between collider and direct detection?

5) connection to EFT for annihilation?