Heavy WIMP Effective Theory and direct detection of dark matter

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Symmetry Tests in Nuclei and Atoms

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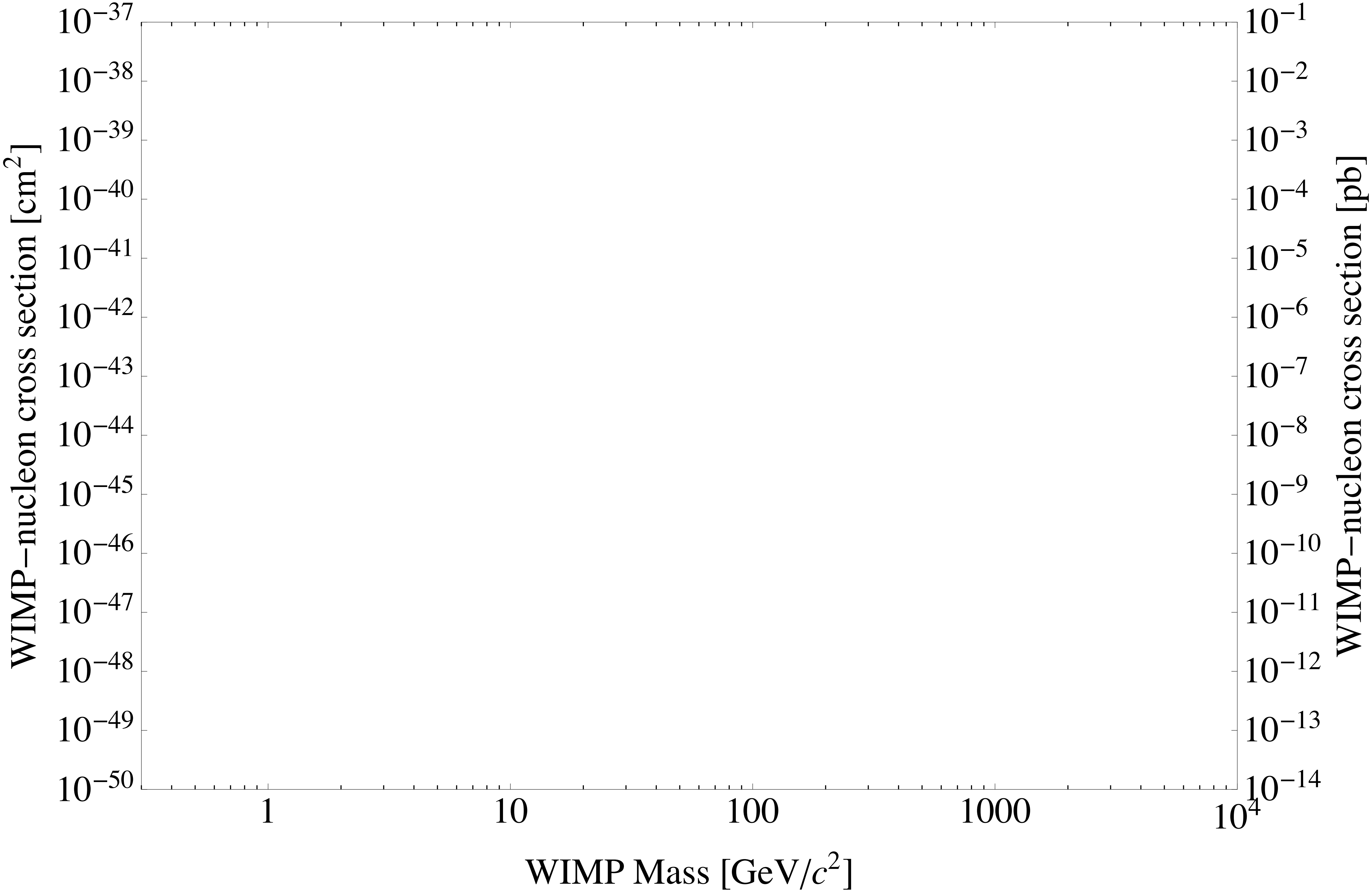
outline

- introduction
- Heavy WIMP Effective Theory
- perturbative QCD
- hadronic matrix elements
- summary

based largely on work with M.P. Solon (2015 Sakurai thesis prize):
Universal behavior 1111.0016, PLB
Heavy WIMP Effective Theory 1309.4092, PRL
Standard Model Anatomy of WIMP Direct Detection I, II 1401.3339, 1409.8290, PRD

thanks also C.-Y. Chen, A. Wijangco, A. Berlin, M. Hoferichter, A. Schwenk

Where should we look for WIMP dark matter?



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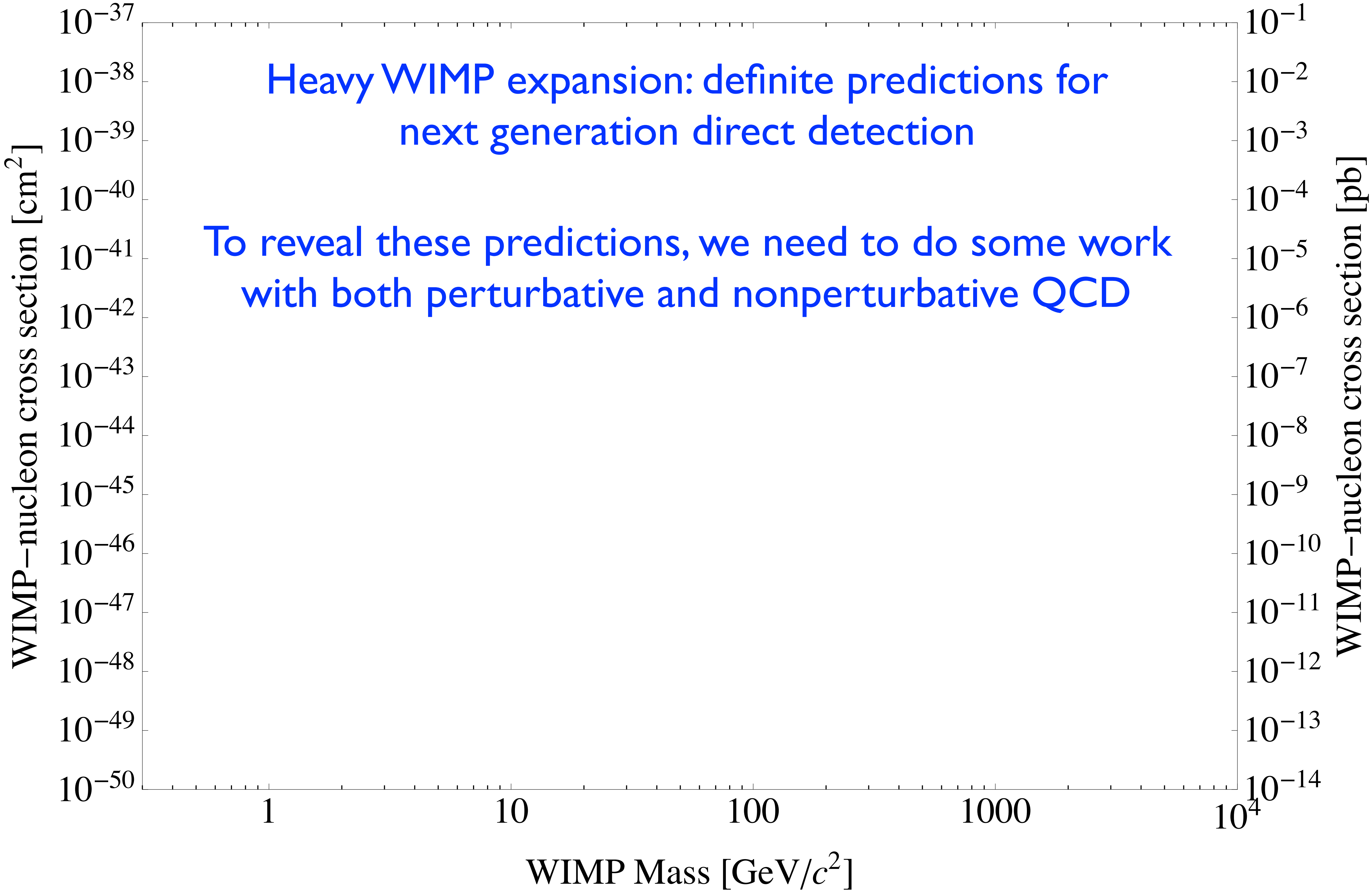


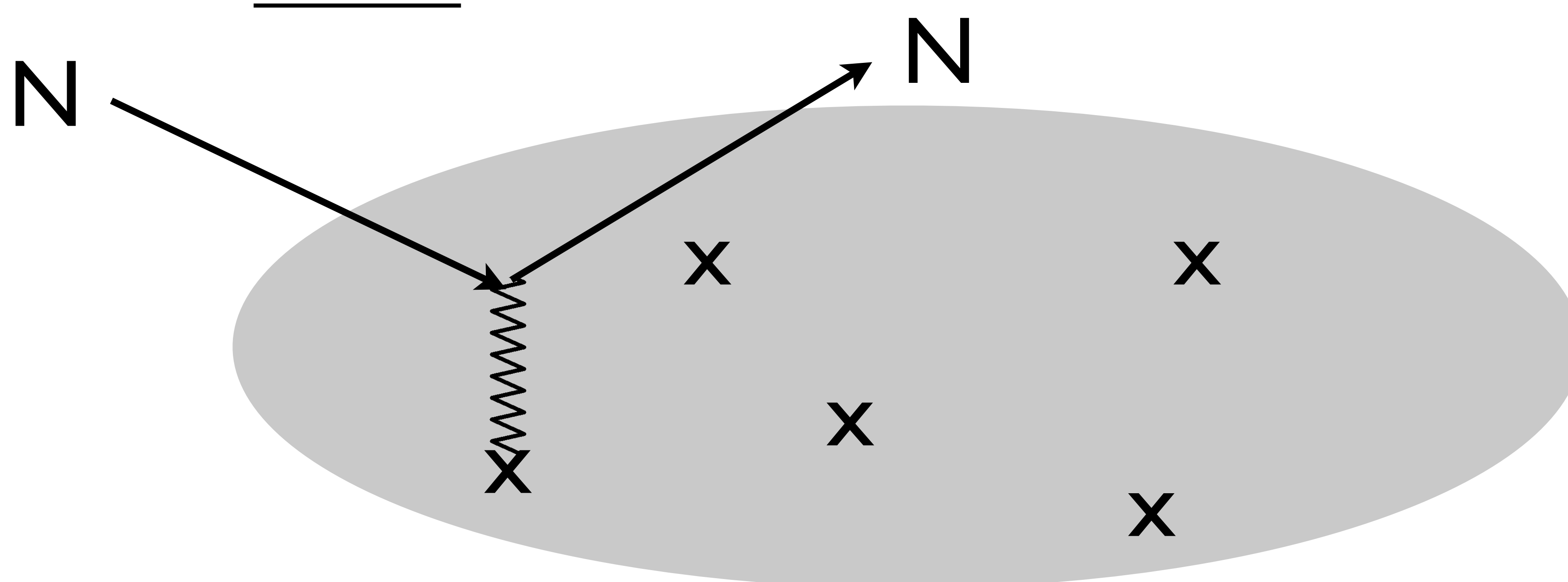
Heavy WIMP expansion: definite predictions for next generation direct detection

To reveal these predictions, we need to do some work with both perturbative and nonperturbative QCD

Mechanisms versus models

Effective theories: predictions without complete models

example 1 (this talk): Electroweak charged WIMP Mechanism versus WIMP Model



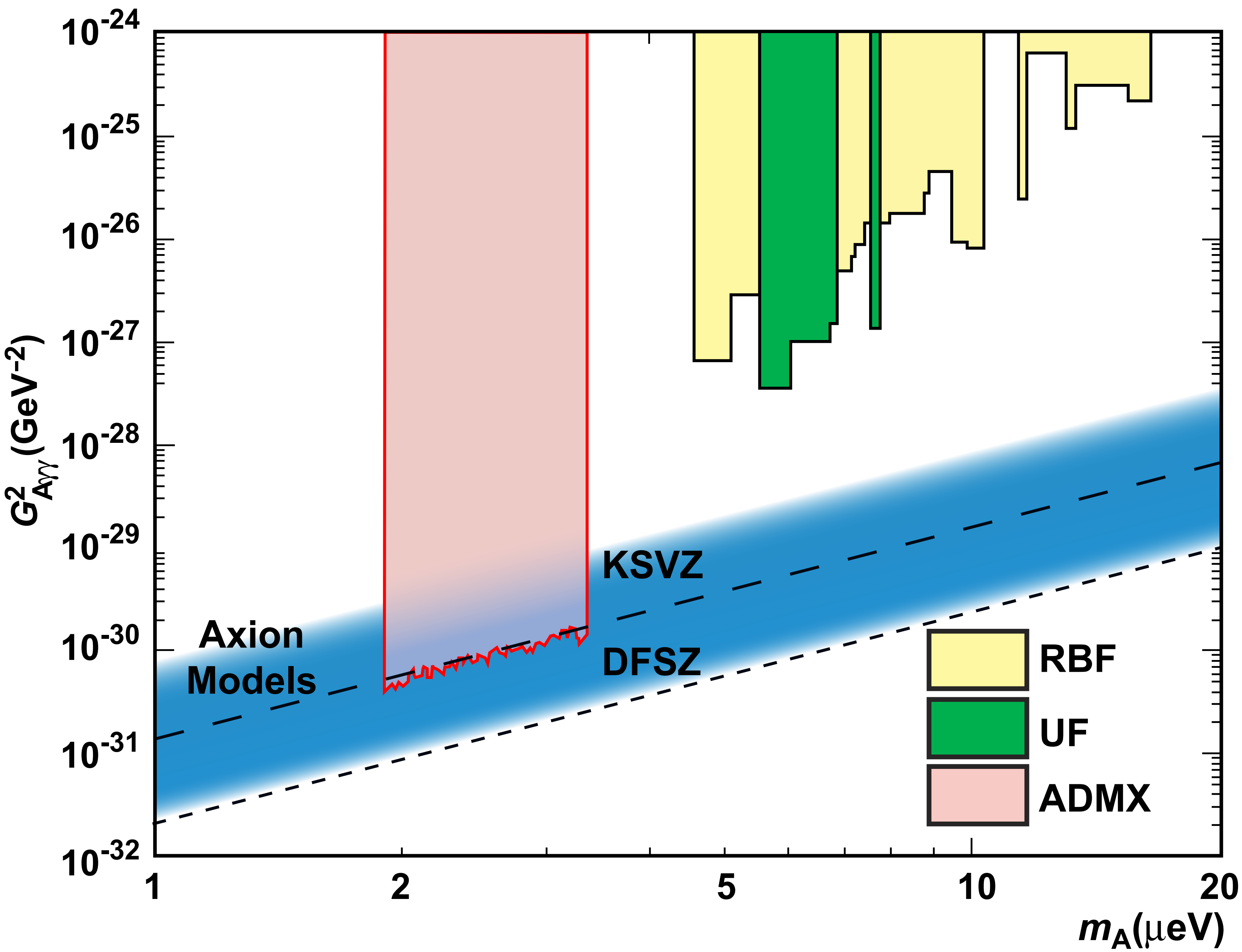
Focus on self-conjugate SU(2) triplet. Could be:

- Elementary fermion: SUSY wino
- Composite boson: Weakly Interacting Stable Pion
- ...

Mechanisms versus models

example 2: PQ mechanism versus specific axion model

$$\mathcal{L} \sim a(x) G\tilde{G}$$



electromagnetic anomaly

color anomaly

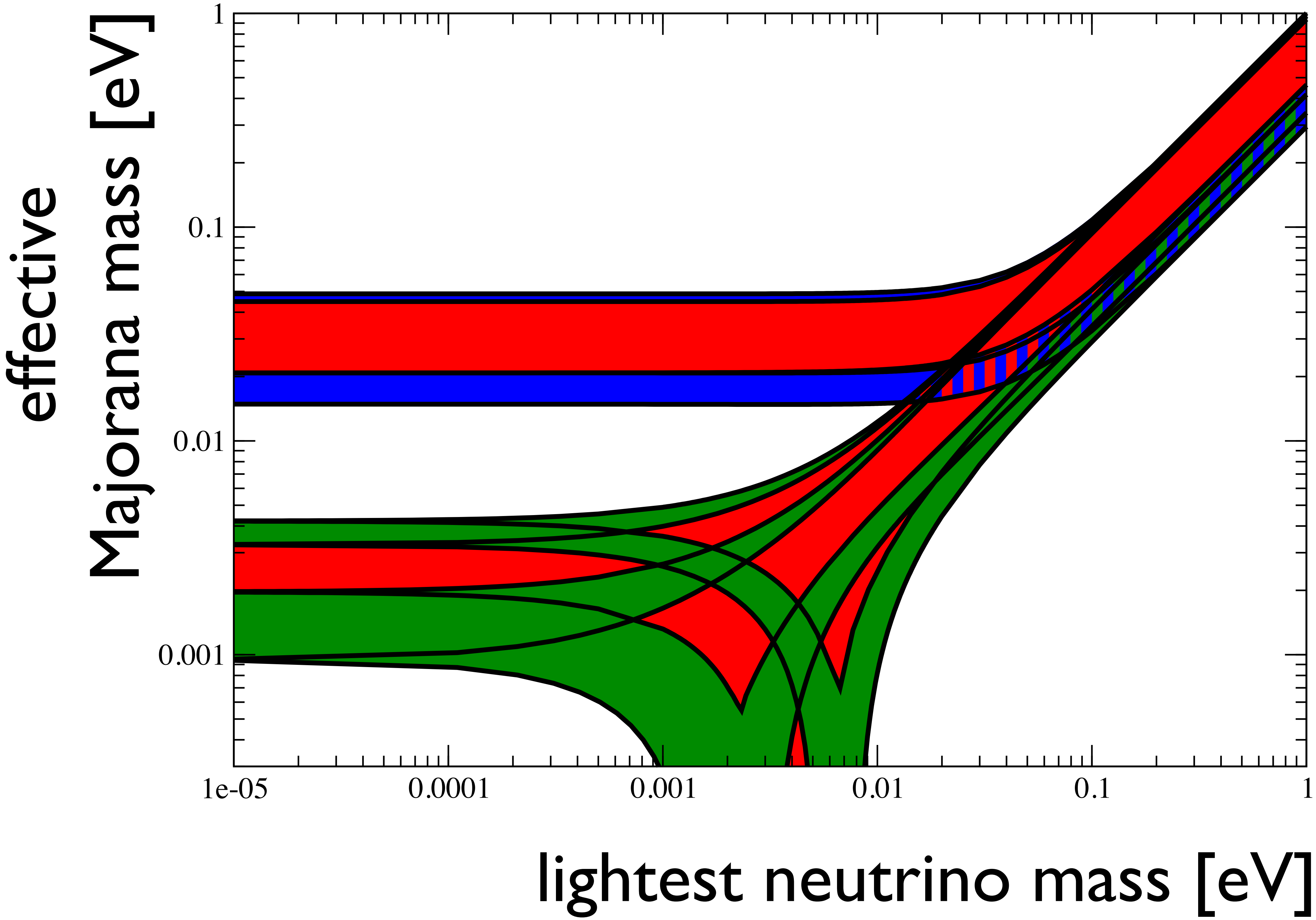
$$g_{a\gamma\gamma} \propto \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

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

Mechanisms versus models

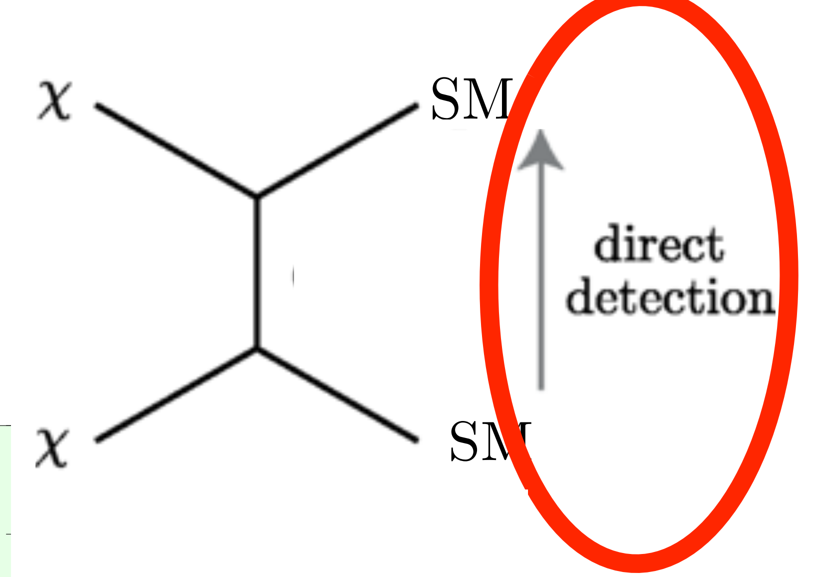
example 3: effective lepton-higgs mechanism for L-violation versus specific seesaw model

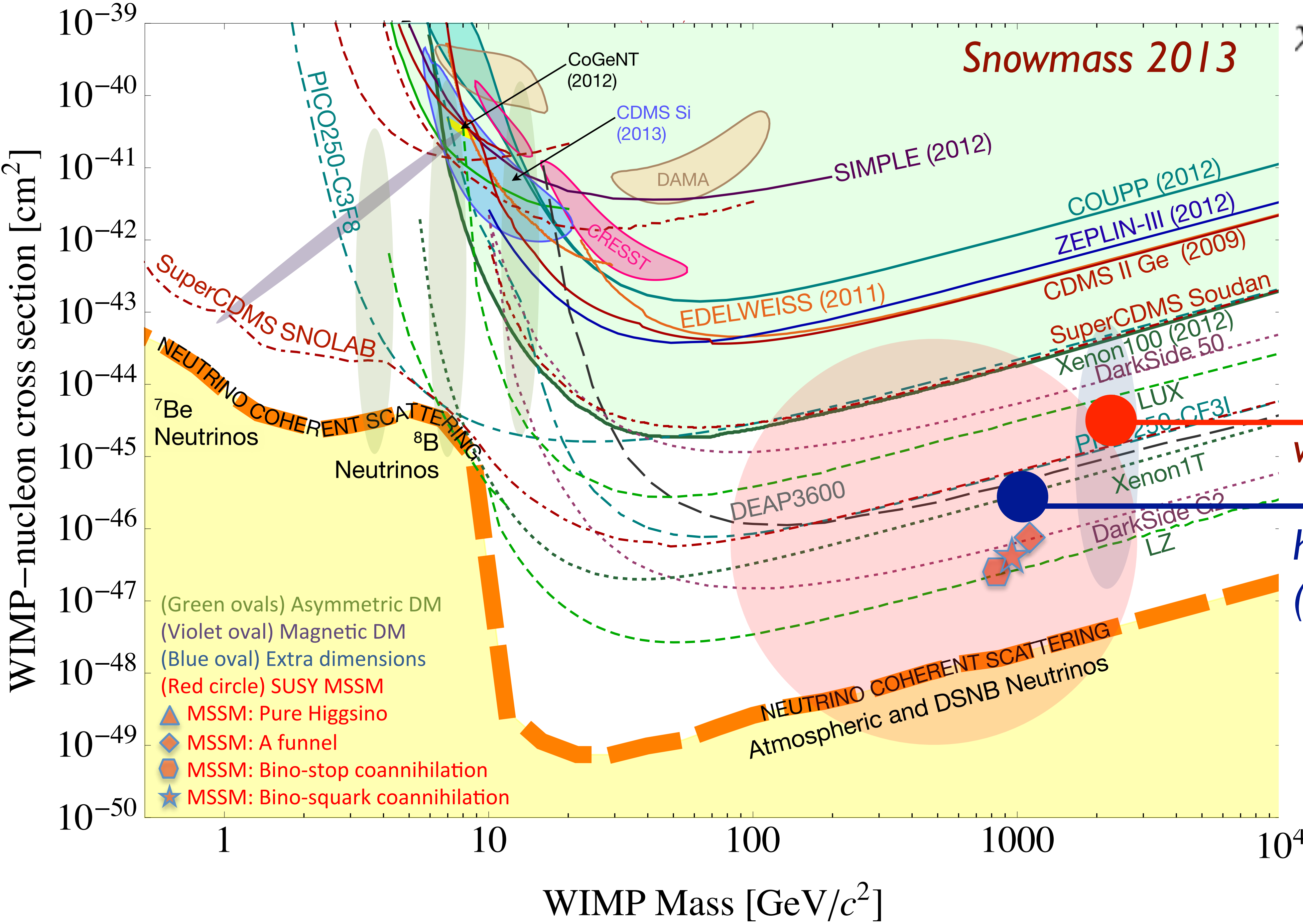
$$\mathcal{L} \sim \frac{1}{\Lambda} LLHH$$



Not quibbling about percents

(illustration 1: heavy WIMP scattering)





wino: dimensional estimate

higgsino: Snowmass benchmark (2013)

recent high-mass constraints (see backup): PandaX-II 1607.07400, LUX 1512.03506

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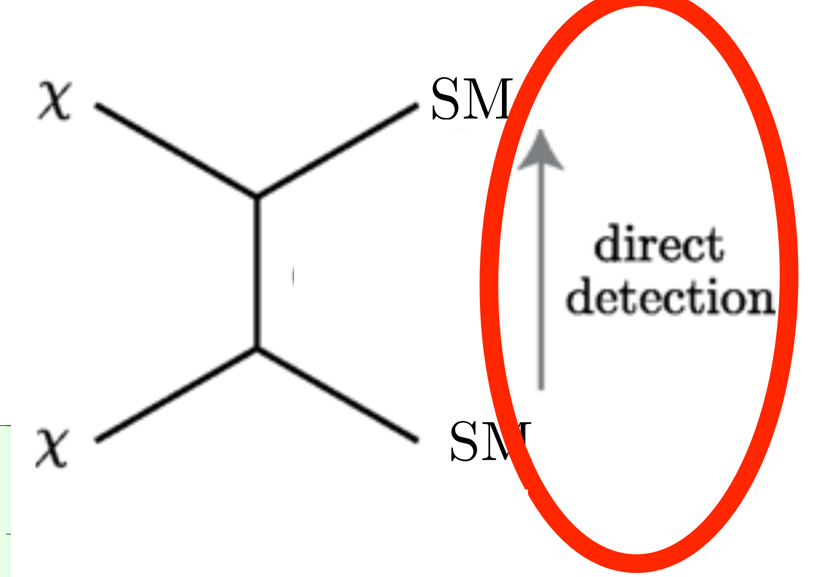

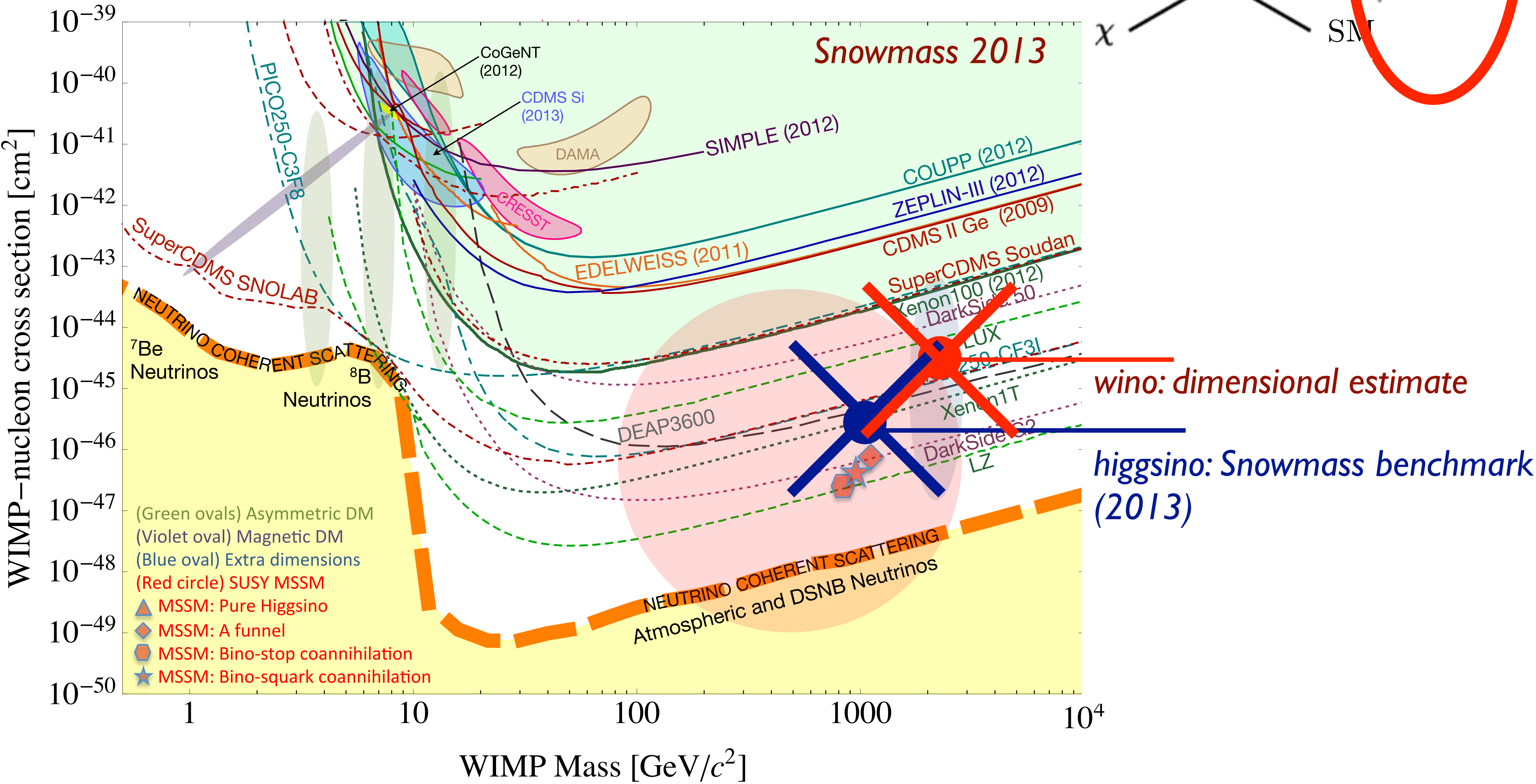

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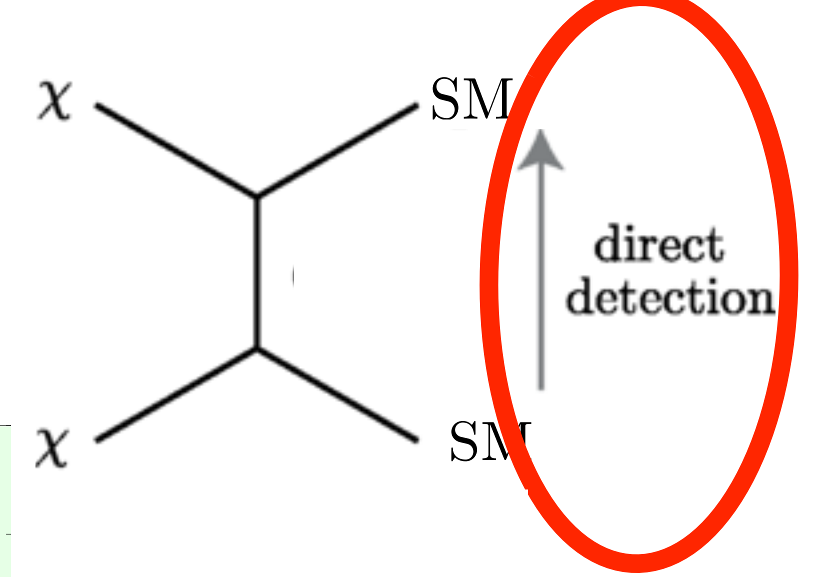

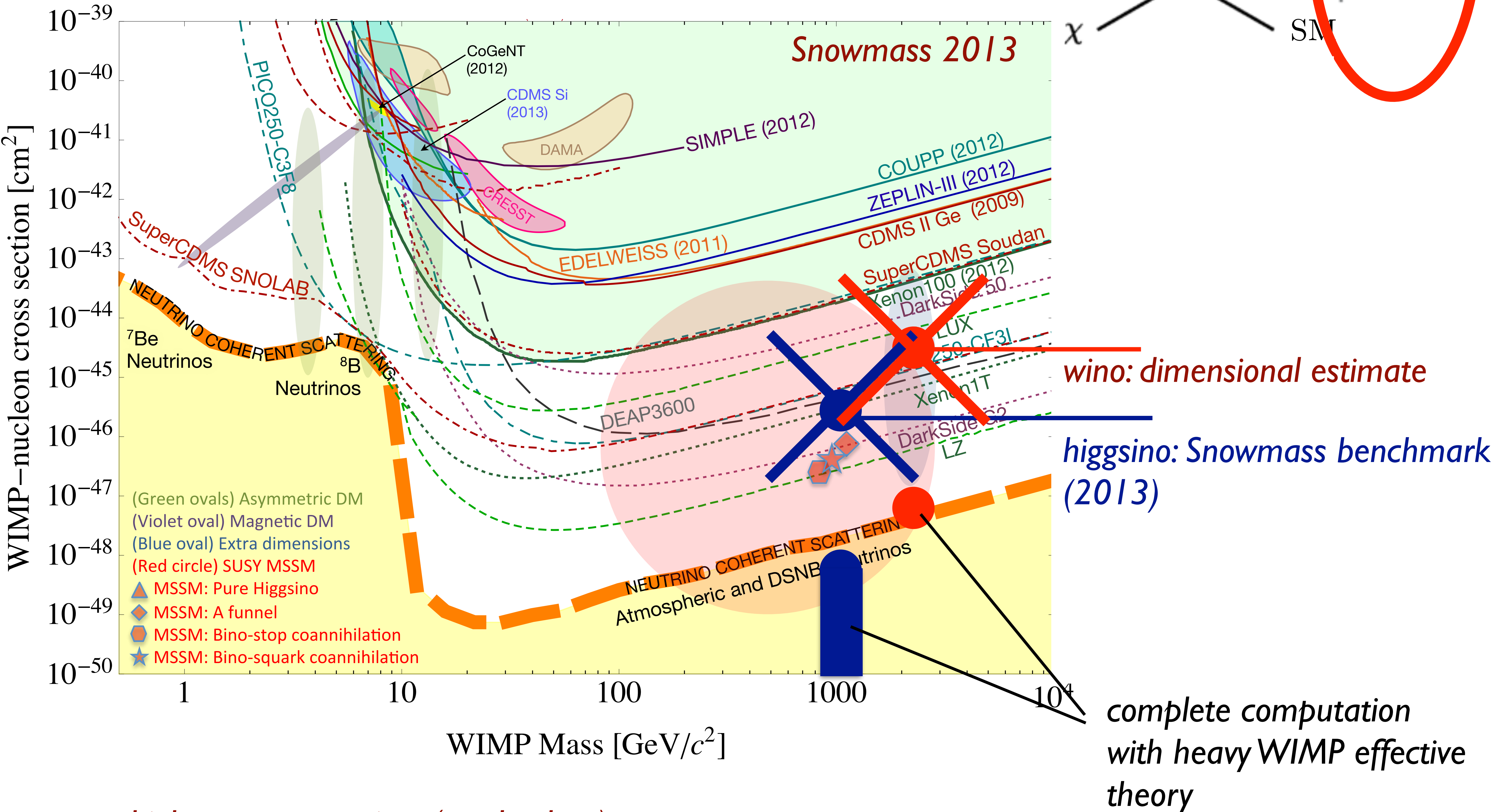

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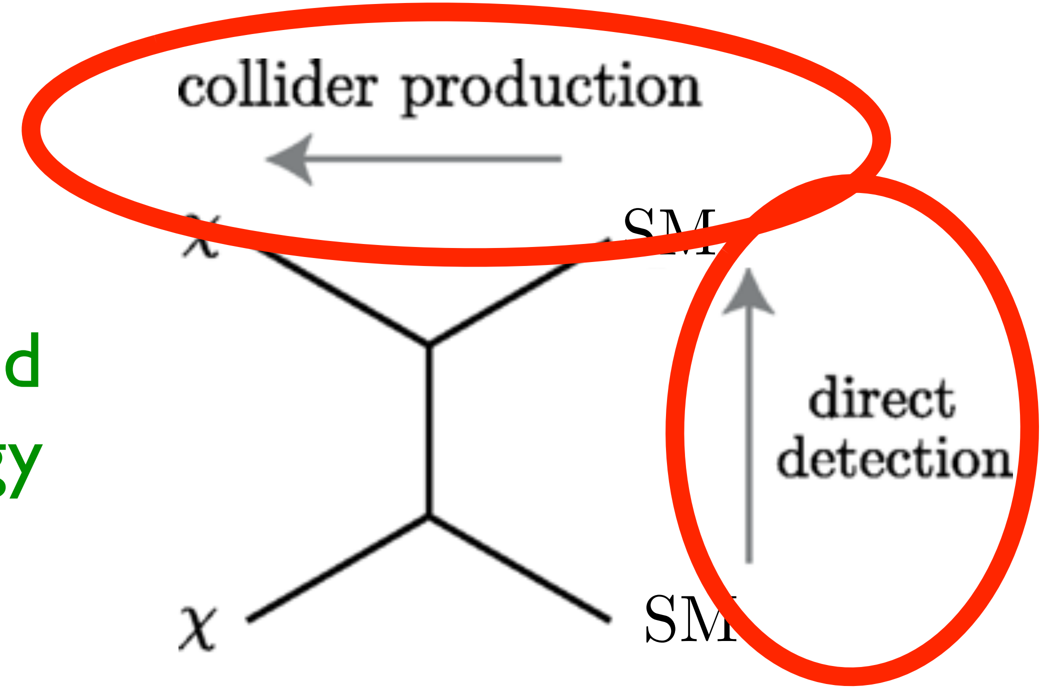
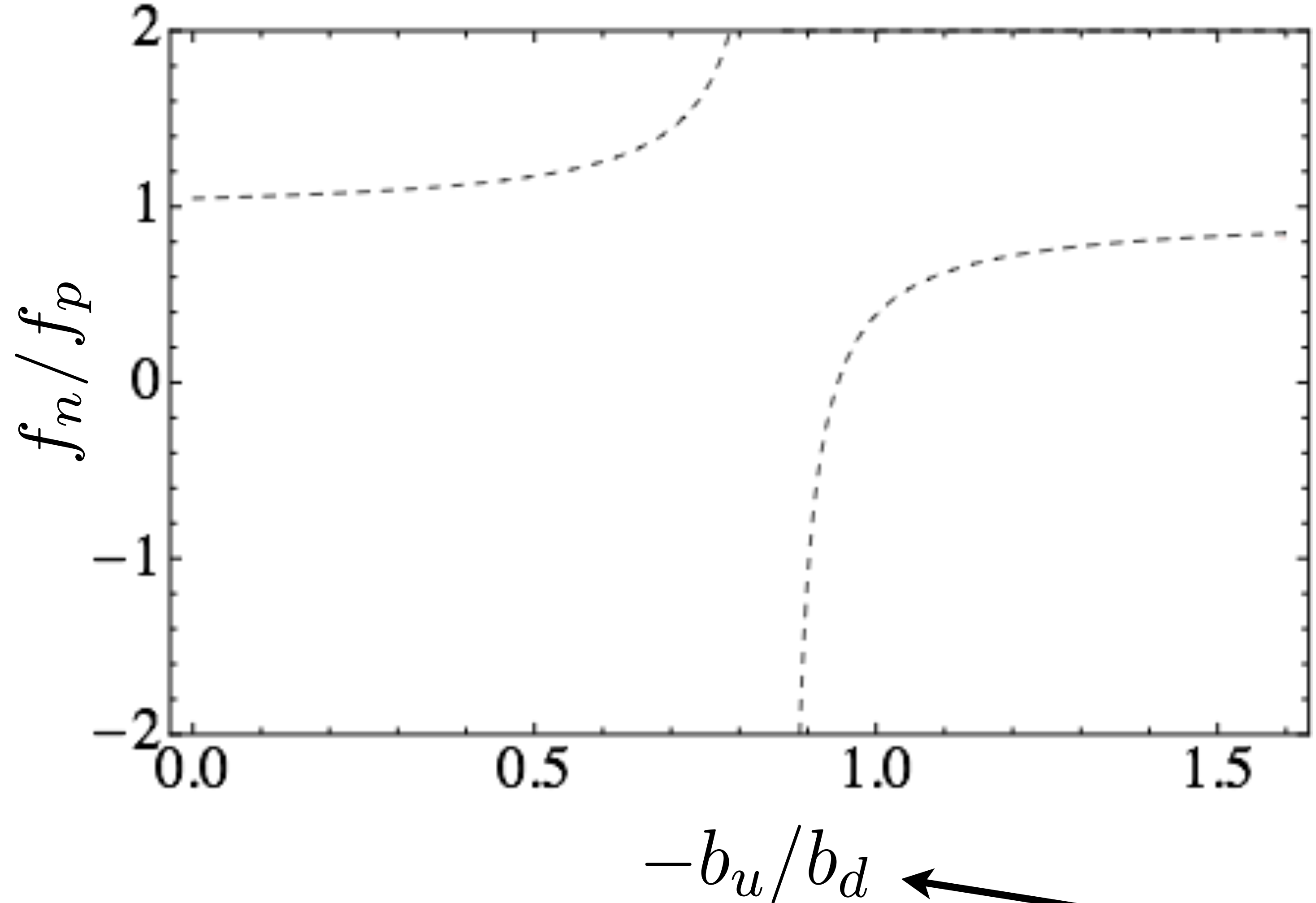


DM complementarity: connect direct detection and collider phenomenology

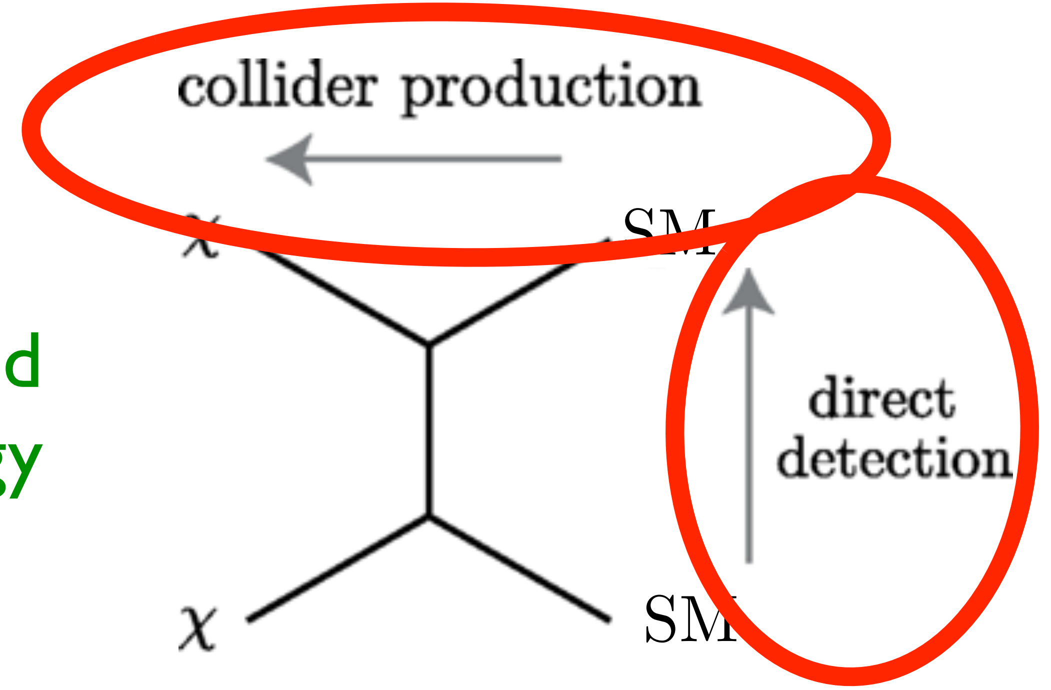


f_n/f_p = ratio of SI nucleon amplitudes for WIMP-nucleon scattering

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

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

Not quibbling about percents
(illustration 2: light WIMPs)



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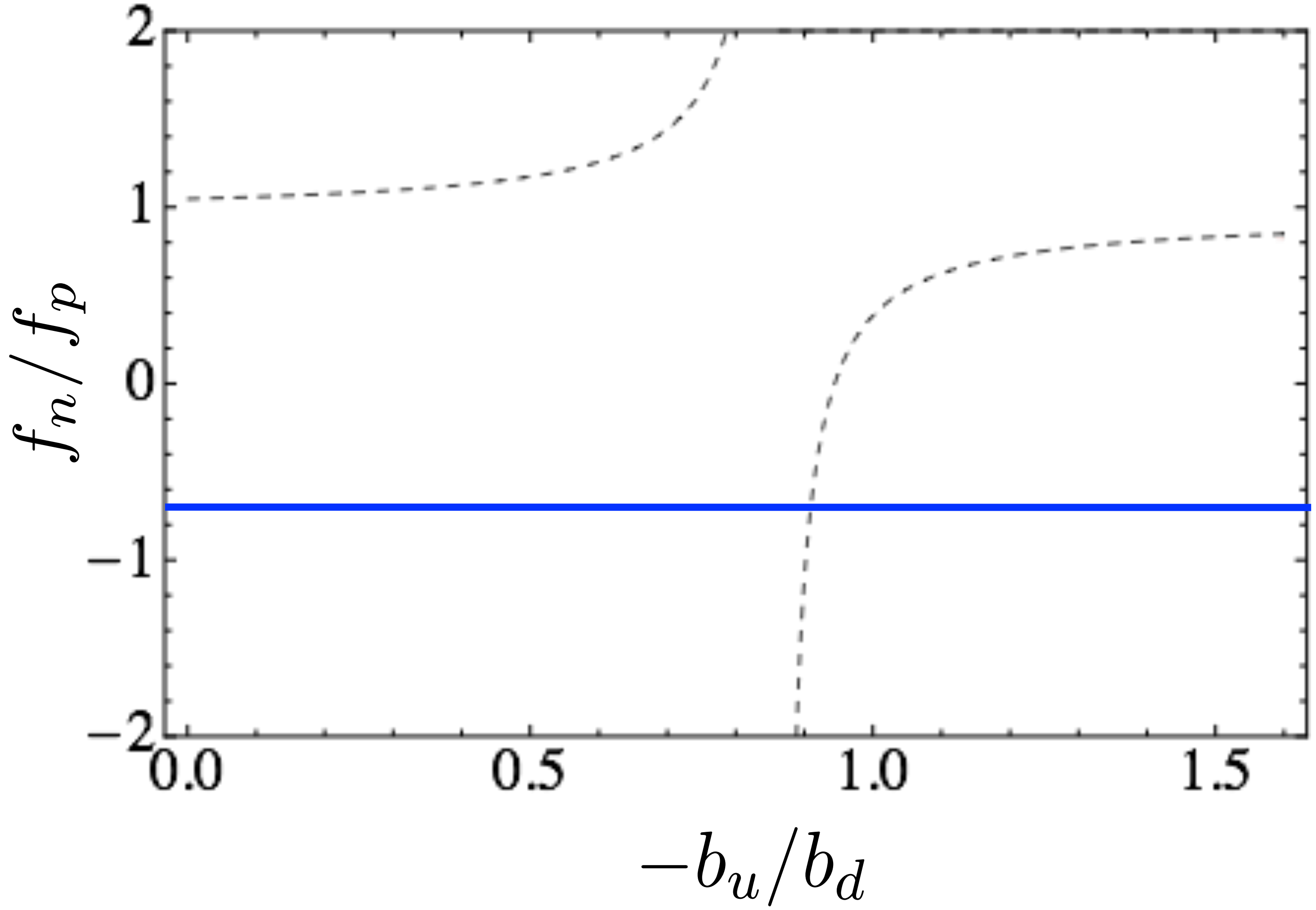

$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

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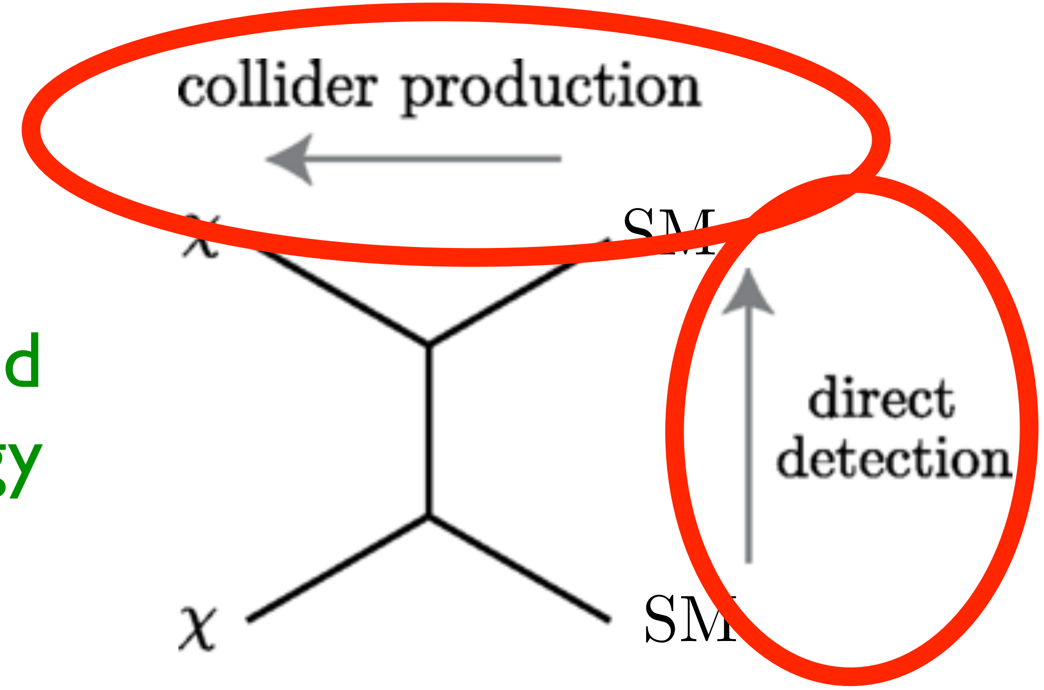

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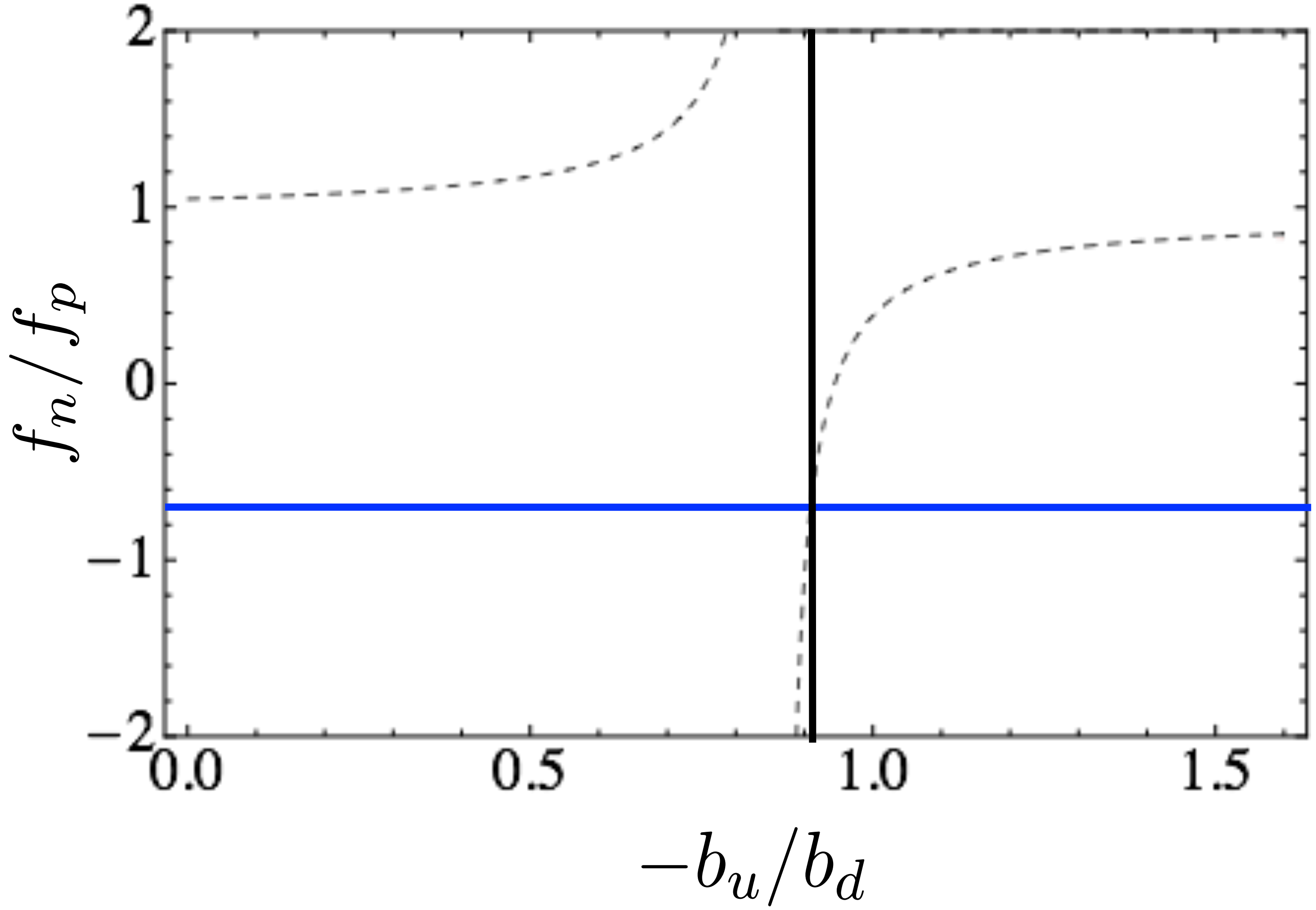

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Solution: $b_u/b_d = -0.9$

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

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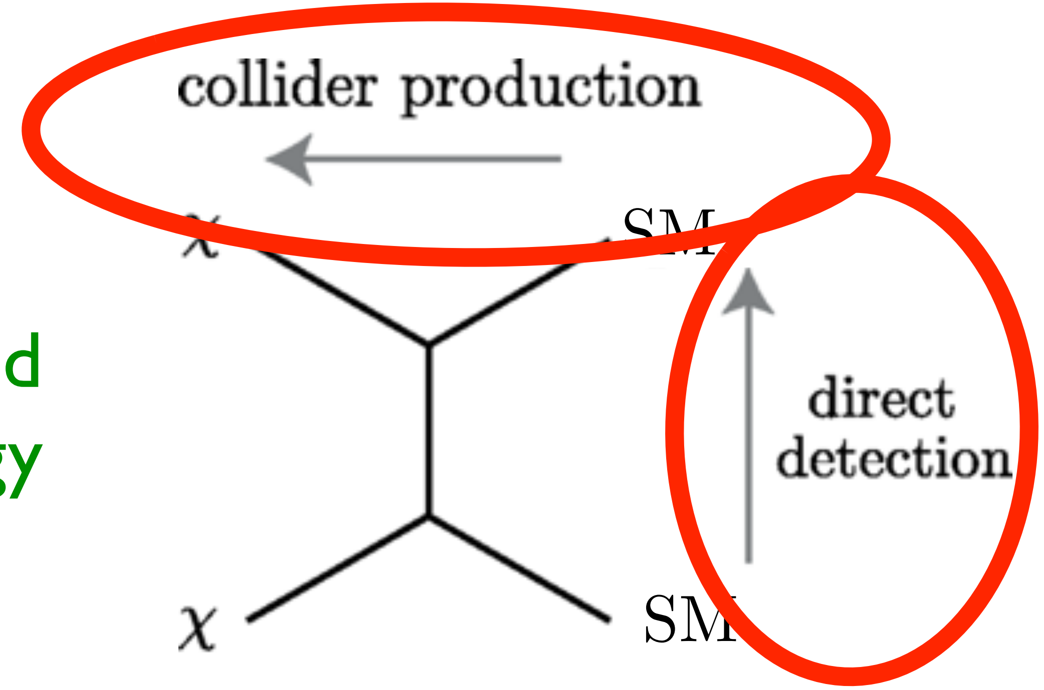

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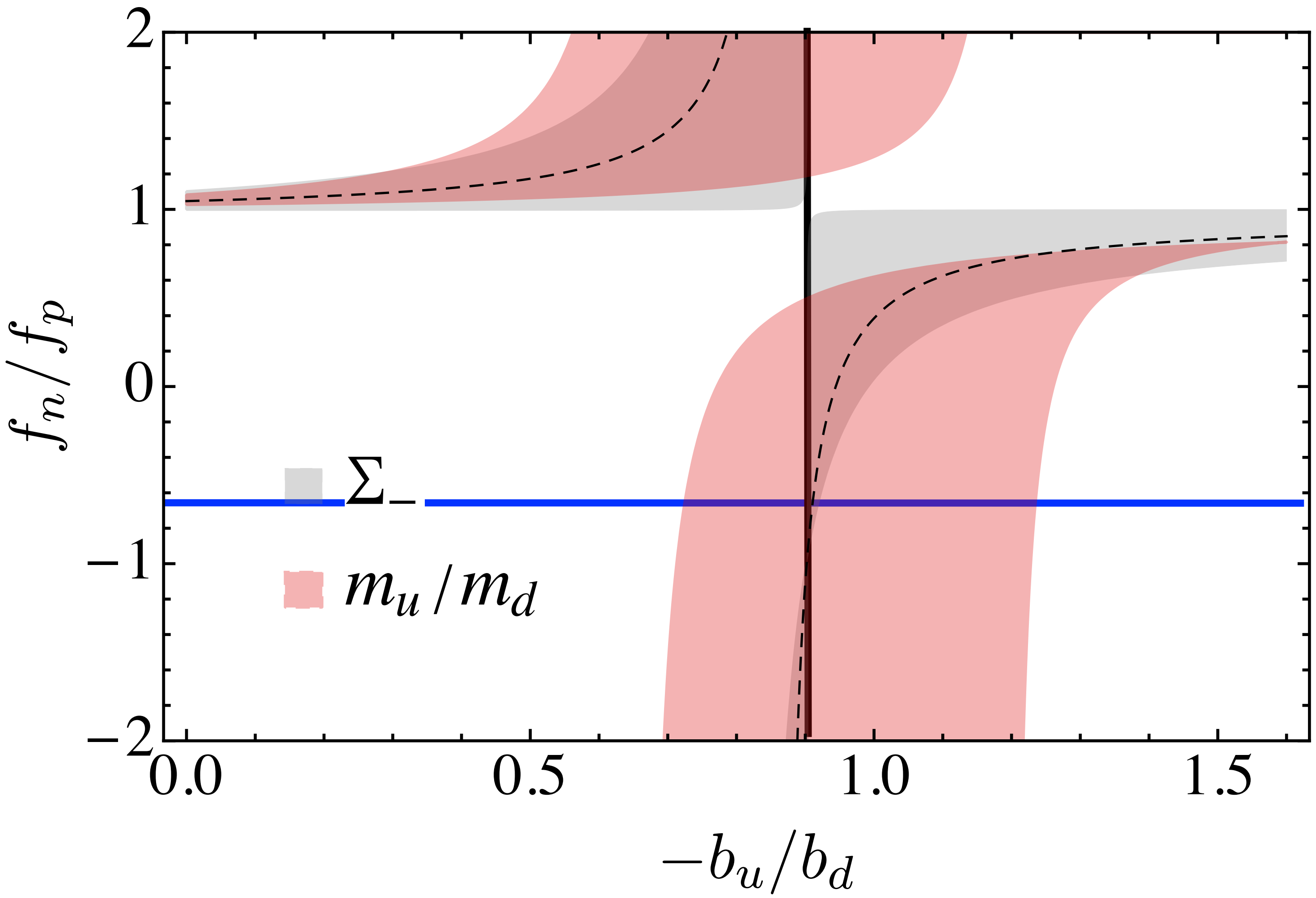

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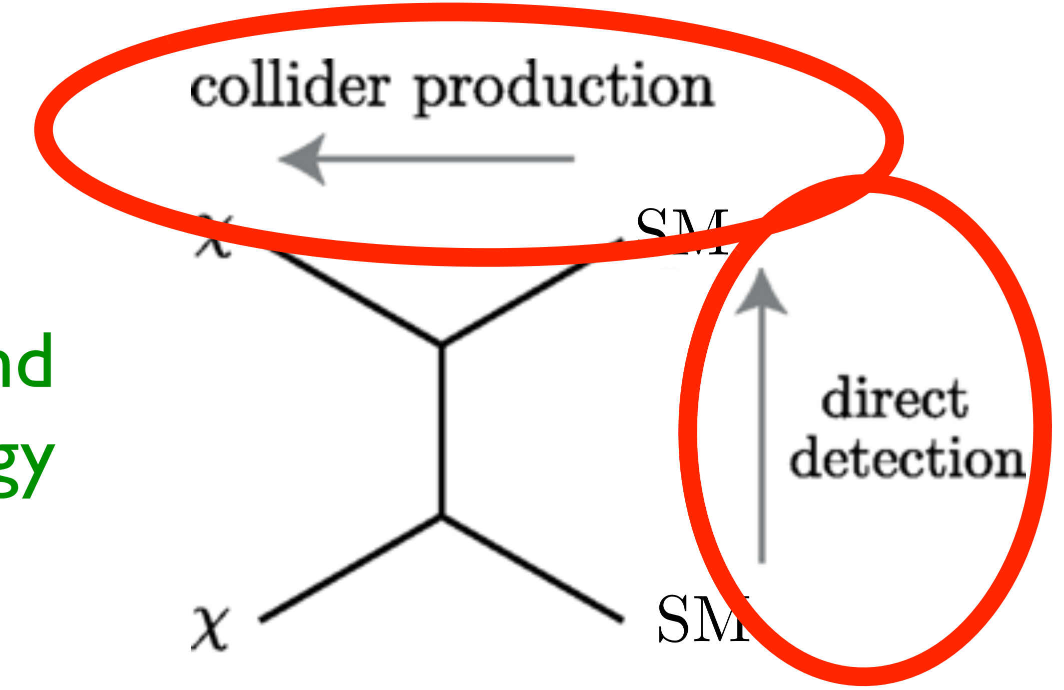

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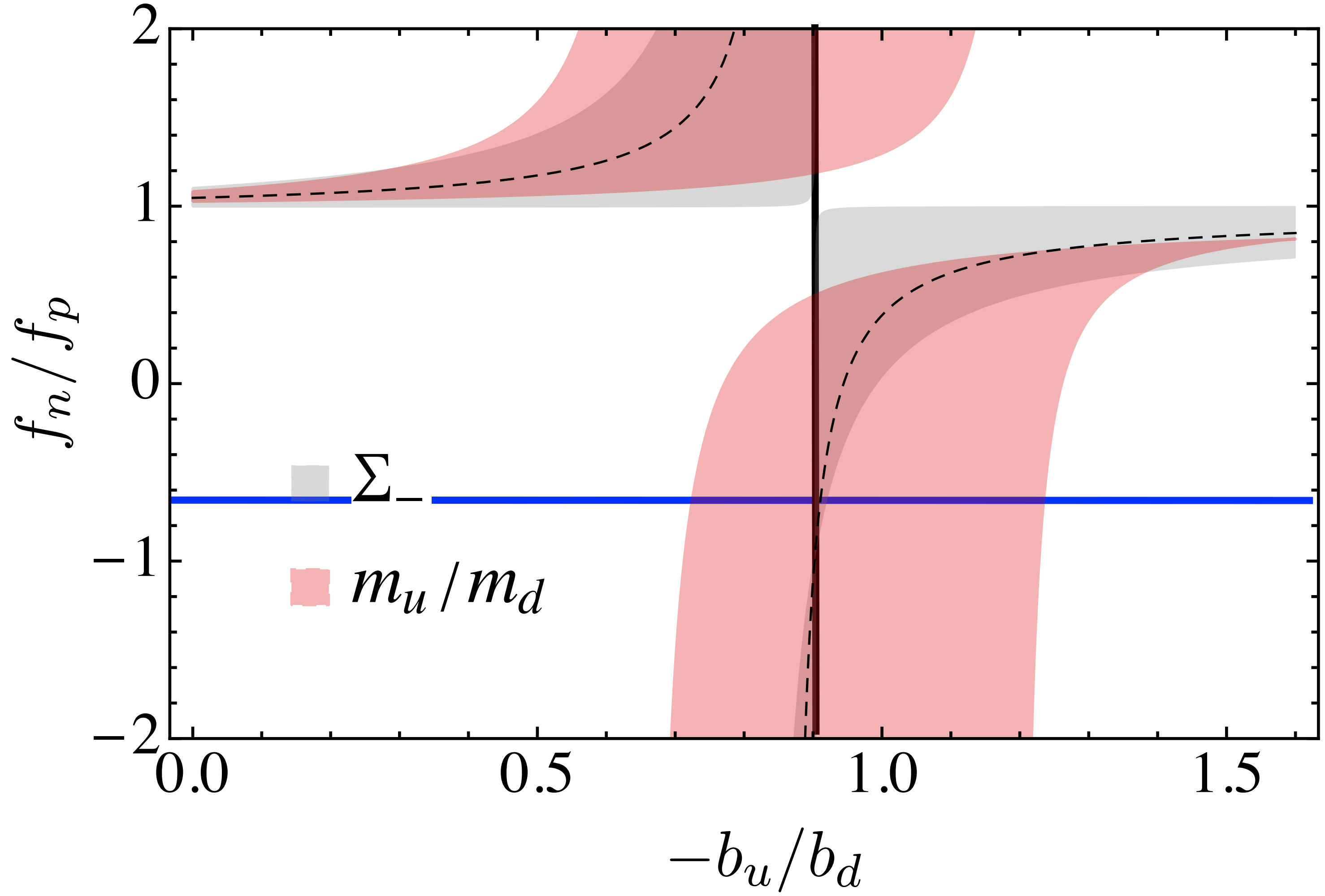

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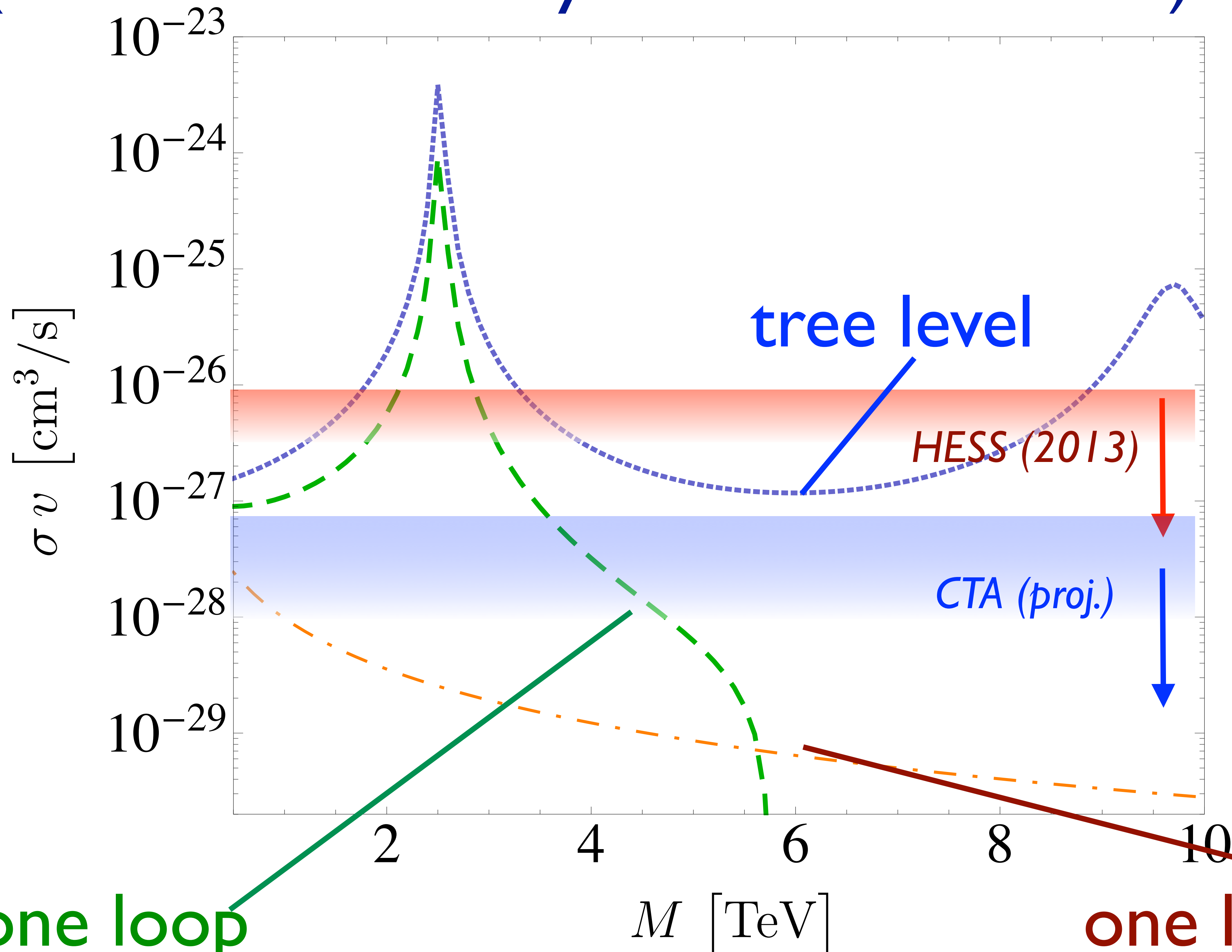
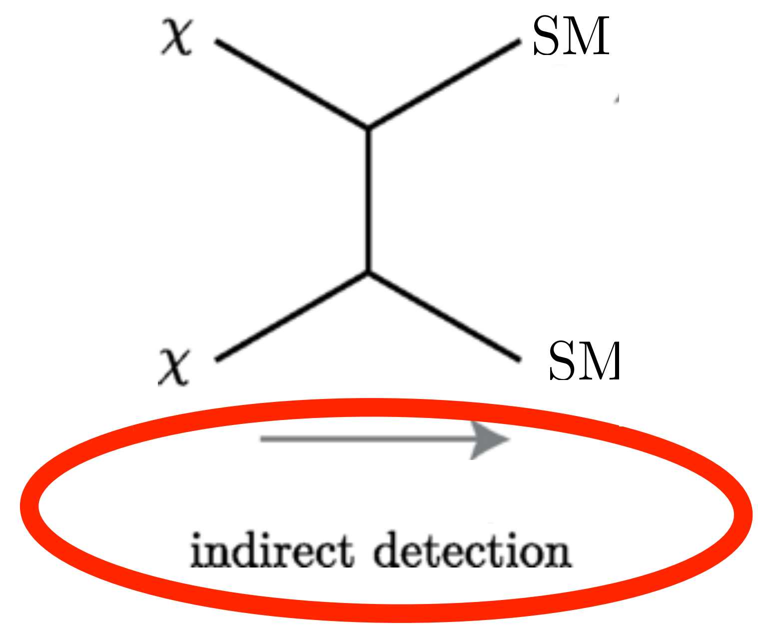
cf. b_u/b_d=-1.08 from “isospin-violating” DM

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

Nontrivial mapping from colliders to direct detection

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





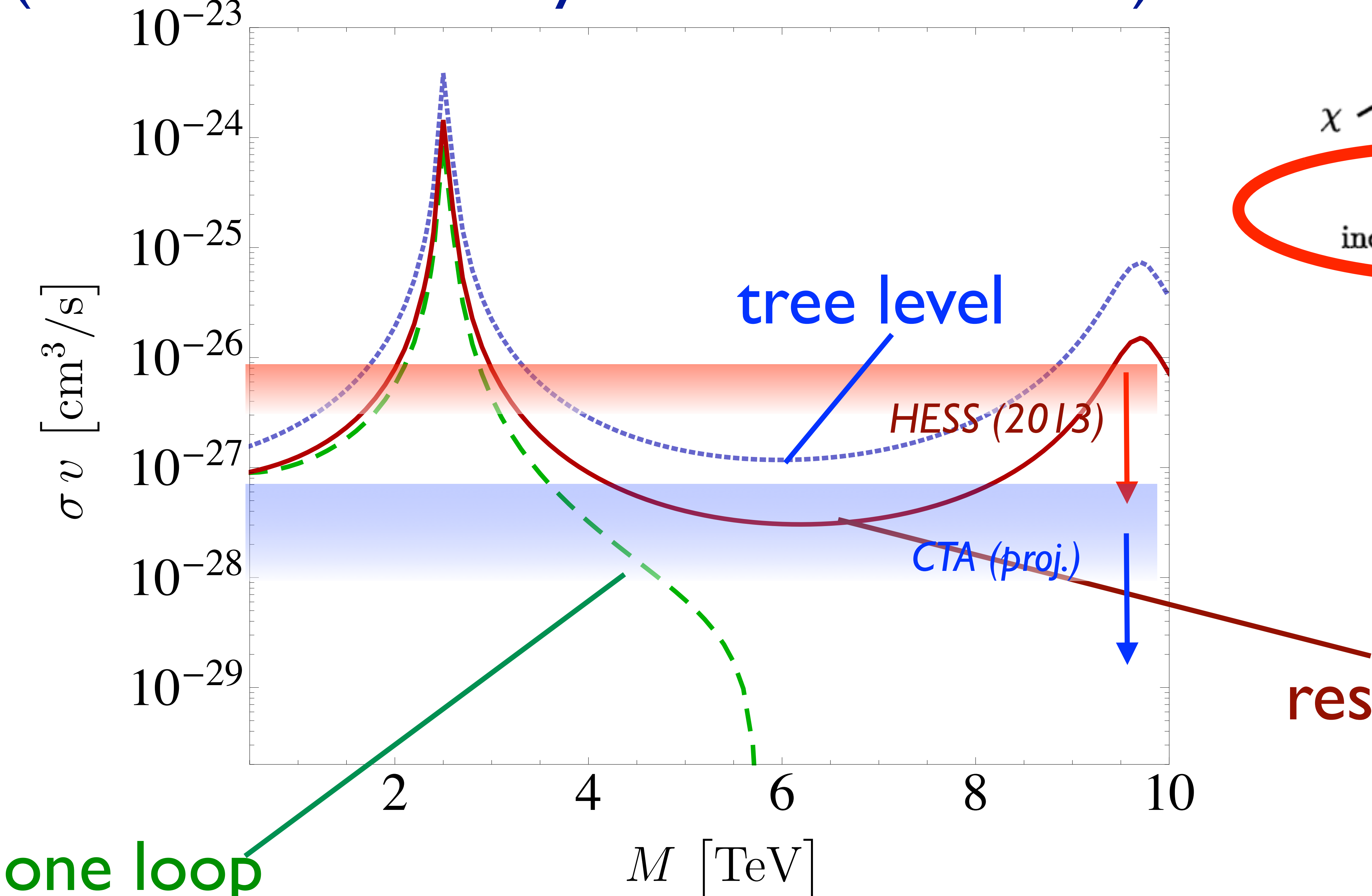
Photon line signal for "wino" annihilation

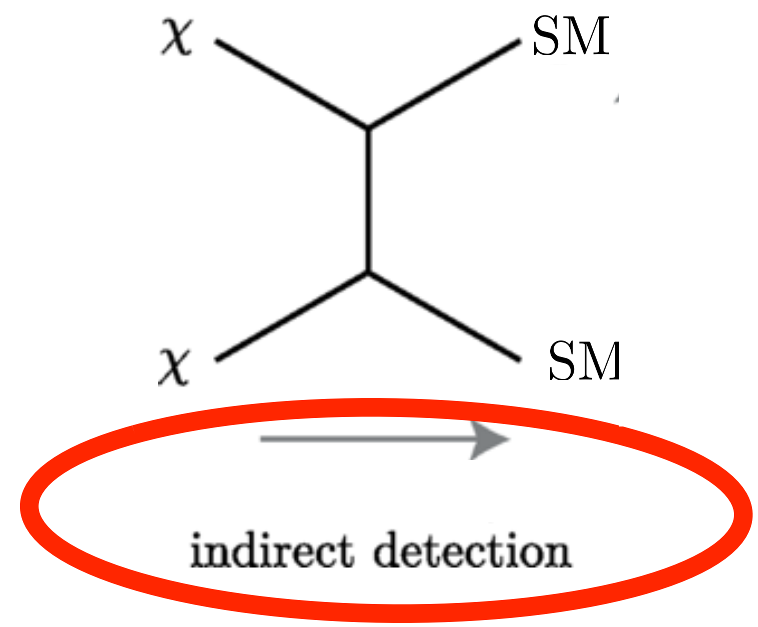
one loop

one loop, neglect wavefunction enhancement

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

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

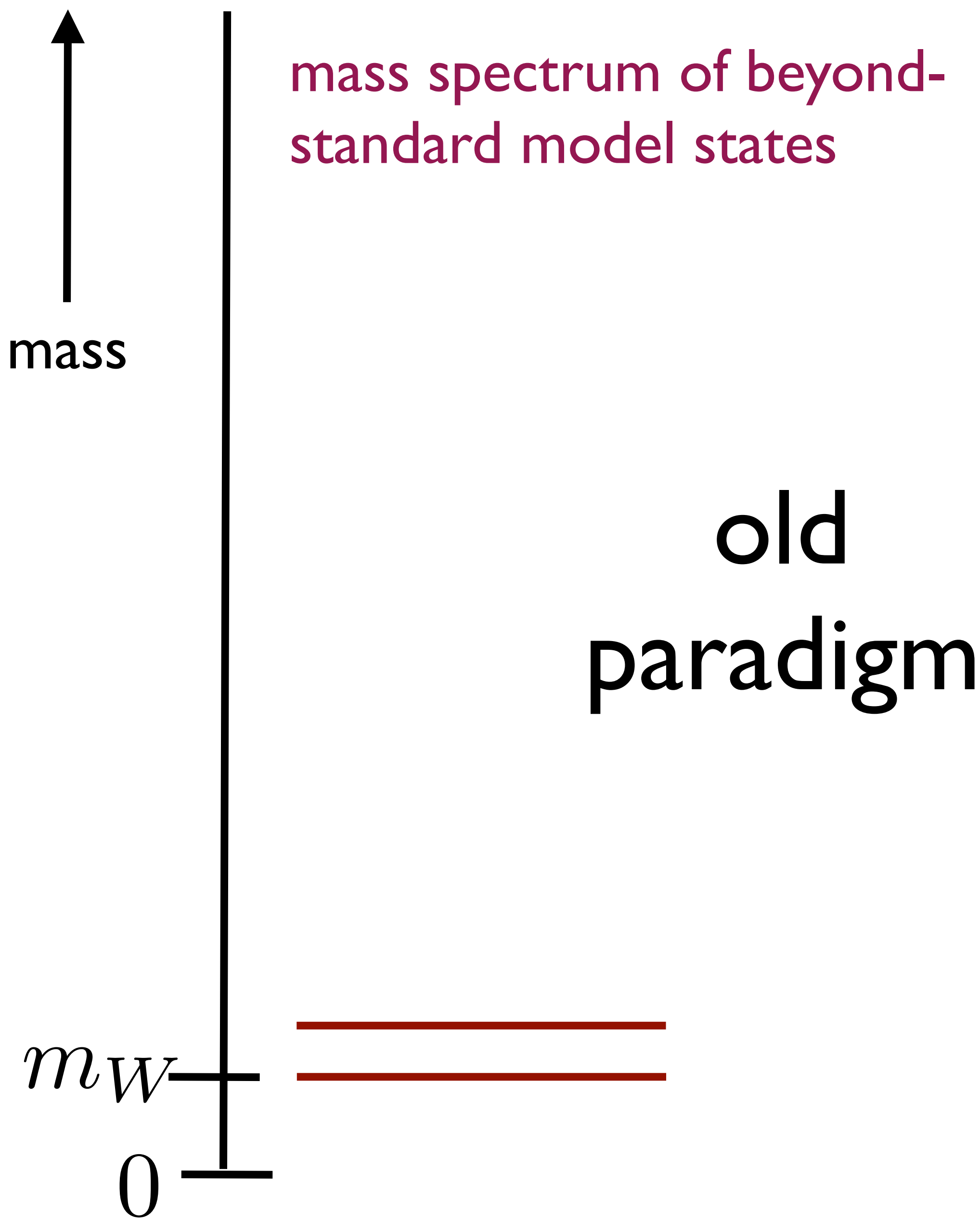




Multi-scale field theory problem, breakdown of naive perturbation theory

Heavy WIMP effective theory

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



old paradigm

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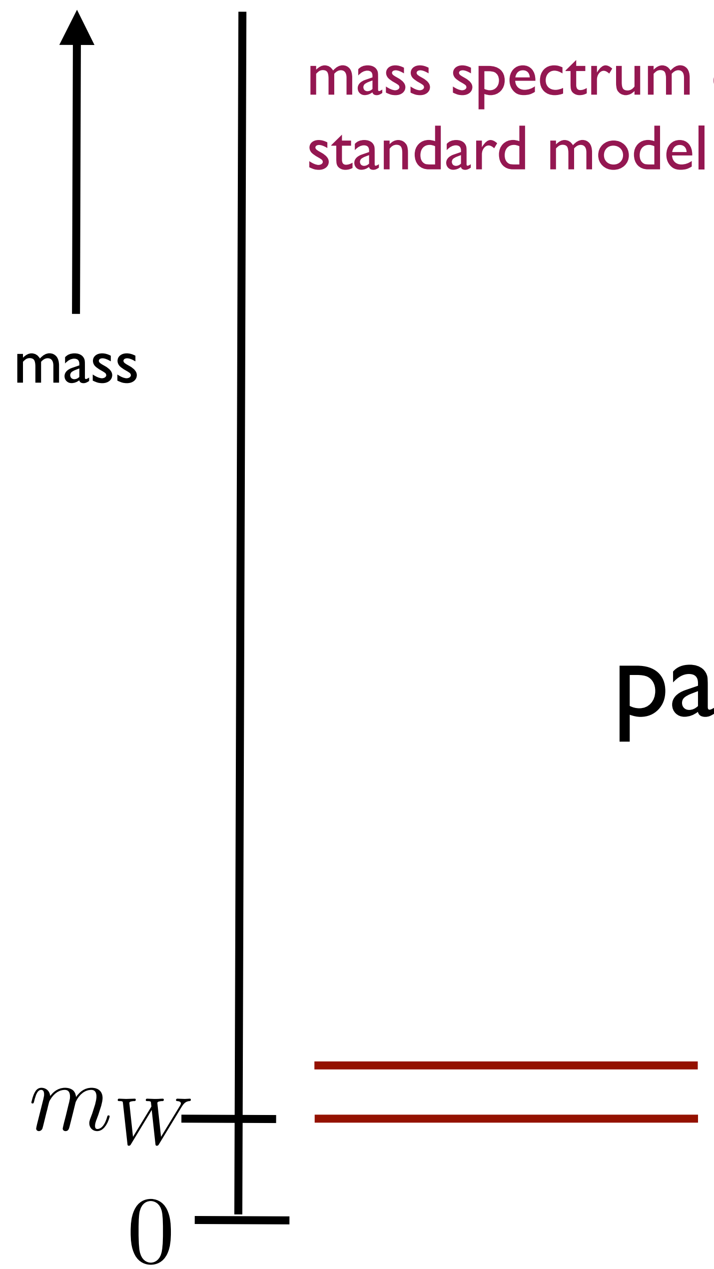
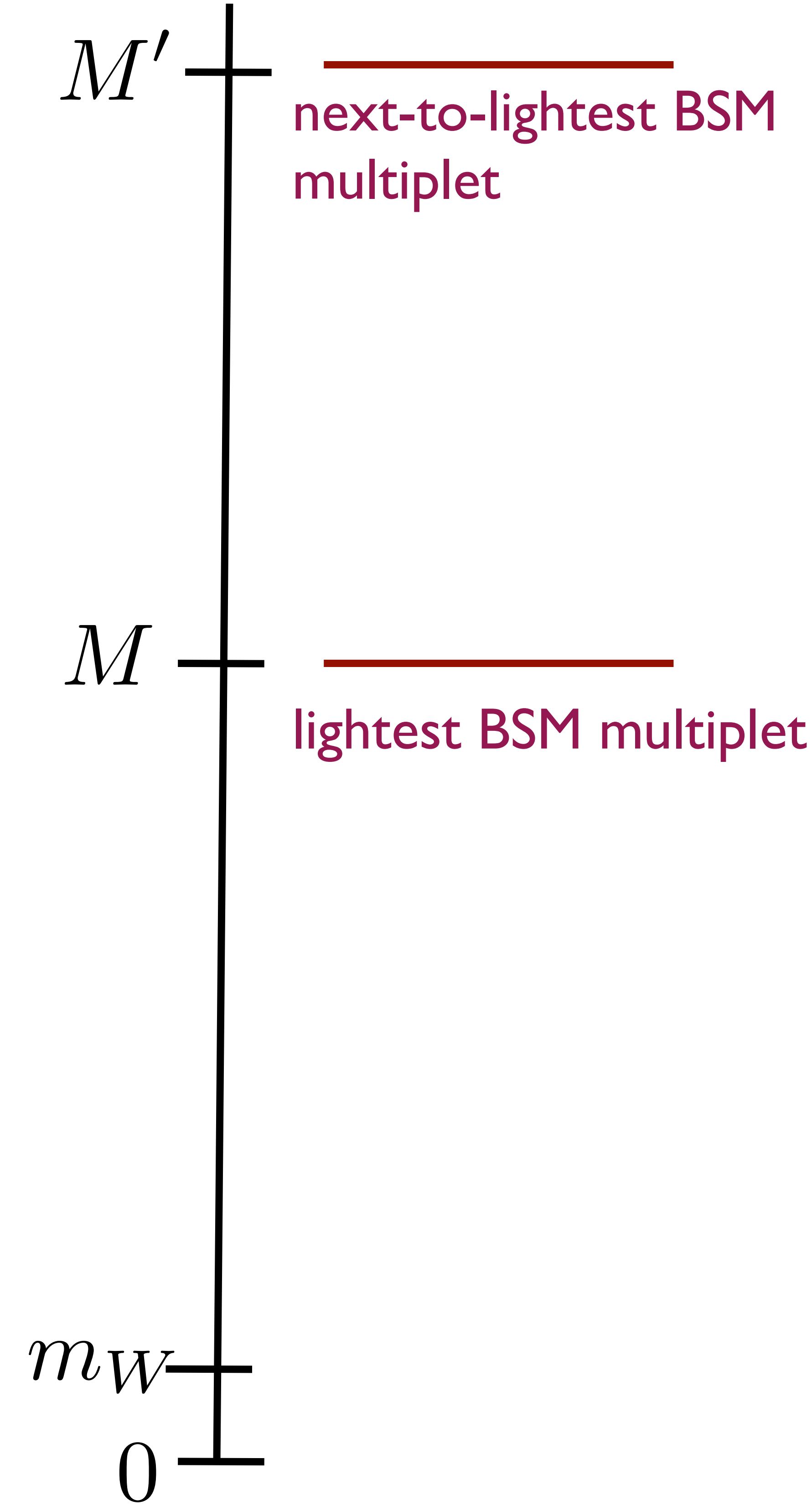
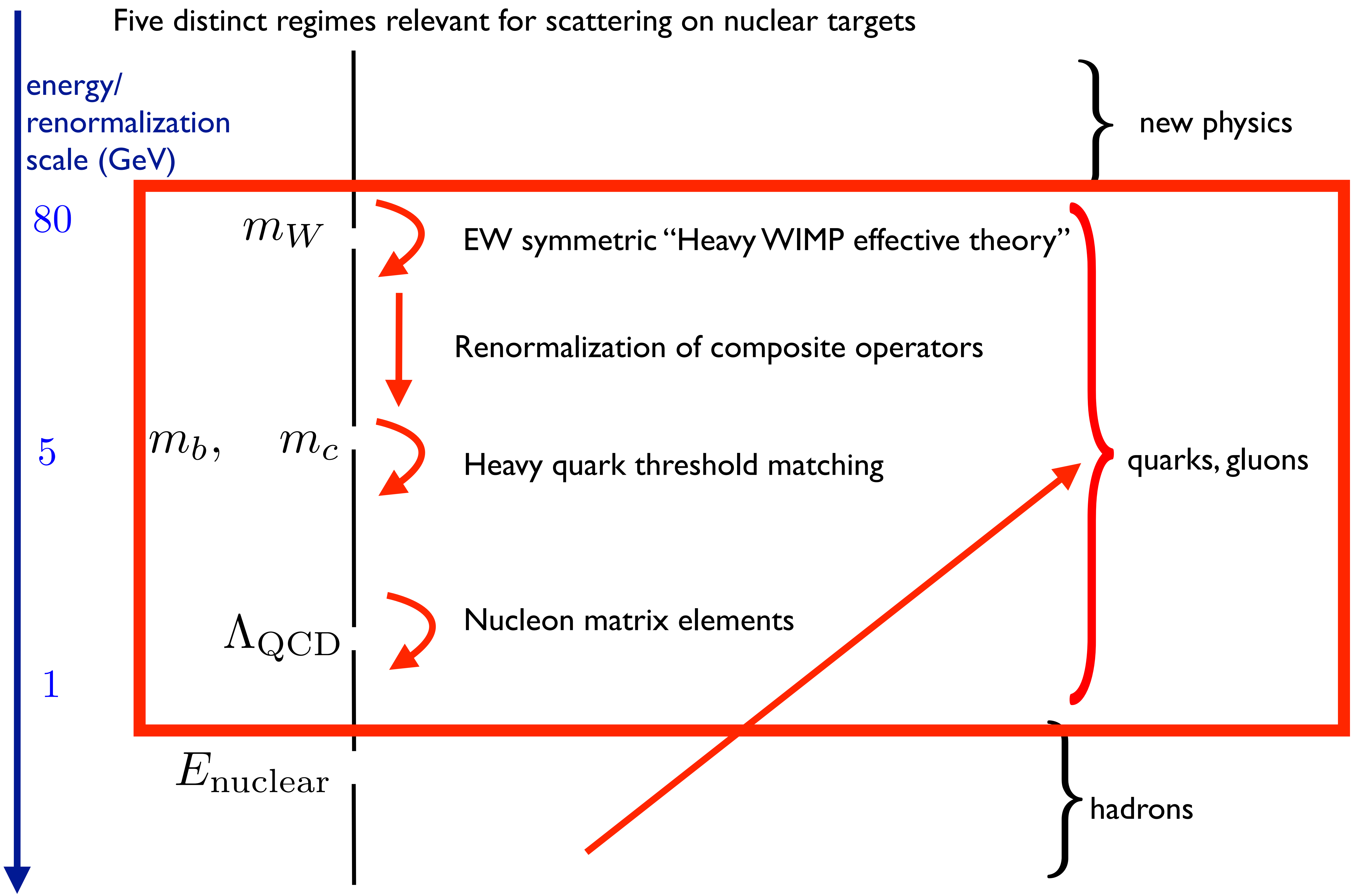


old paradigm → new paradigm



If WIMP mass $M \gg m_W$, isolation ($M' - M \gg m_W$) 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

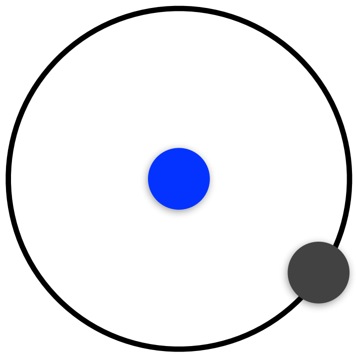


"SM anatomy" of interactions between weak and hadronic scales

Scale separation:	dark sector d.o.f.	SM d.o.f.	# params. (beyond mass)
M	$\chi^{(+,-,0)}$	$Q, A^a_\mu, W^i_\mu, B_\mu$	0
	$\chi_v^{(+,-,0)}$	$Q, A^a_\mu, W^i_\mu, B_\mu$	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

Many manifestations of heavy particle symmetry:

	prediction:	small parameter:
- hydrogen/deuterium spectroscopy	$E_n(H) = -\frac{1}{2} m_e (Z\alpha)^2 + \dots$	$(m_e Z\alpha) \ll m_e$



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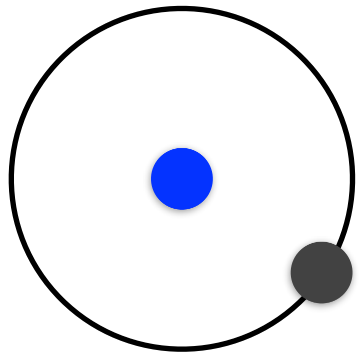
Many manifestations of heavy particle symmetry:

prediction: | **small parameter:**

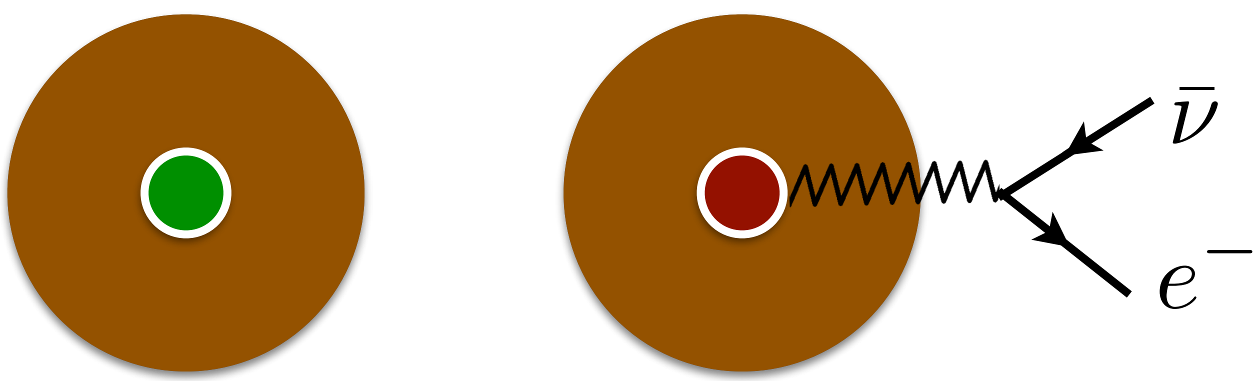
- hydrogen/deuterium spectroscopy

$$E_n(H) = -\frac{1}{2} m_e (Z\alpha)^2 + \ldots \qquad (m_e Z\alpha) \ll m_e$$



- heavy meson transitions

$$F^{B\to D}(v' = v) = 1 + \ldots \qquad \Lambda_{\rm QCD} \ll m_{b,c}$$



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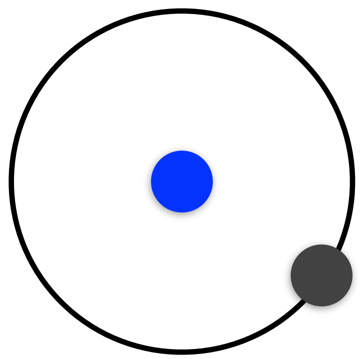
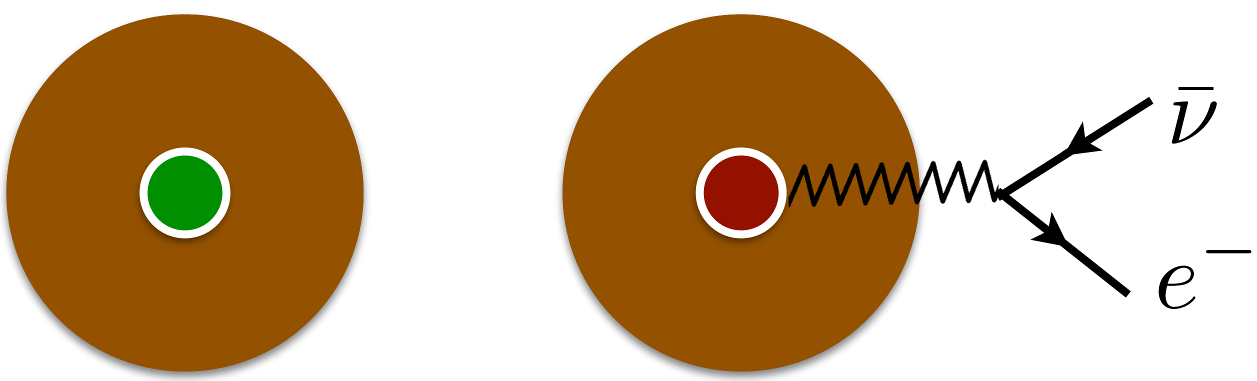
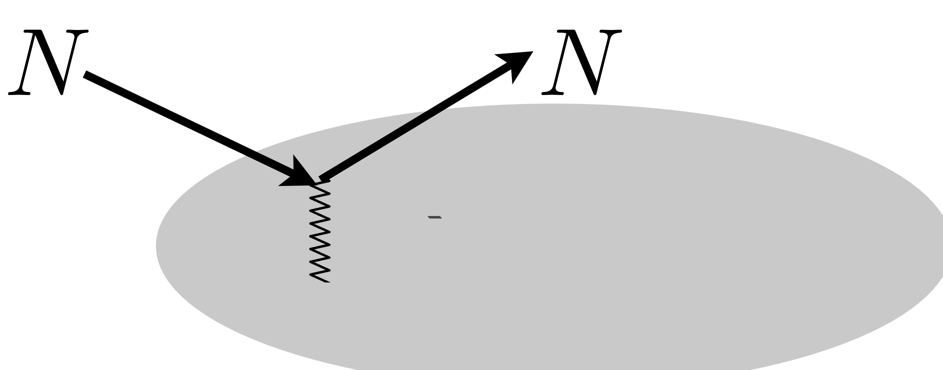
	prediction:	small parameter:
- hydrogen/deuterium spectroscopy	$E_n(H) = -\frac{1}{2} m_e (Z\alpha)^2 + \ldots$	$(m_e Z\alpha) \ll m_e$
- heavy meson transitions	$F^{B\to D}(v' = v) = 1 + \ldots$	$\Lambda_{\rm QCD} \ll m_{b,c}$
- DM interactions	$\sigma(\chi N \to \chi N) = ?$	$m_W \ll m_\chi$







Scale separation:	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			
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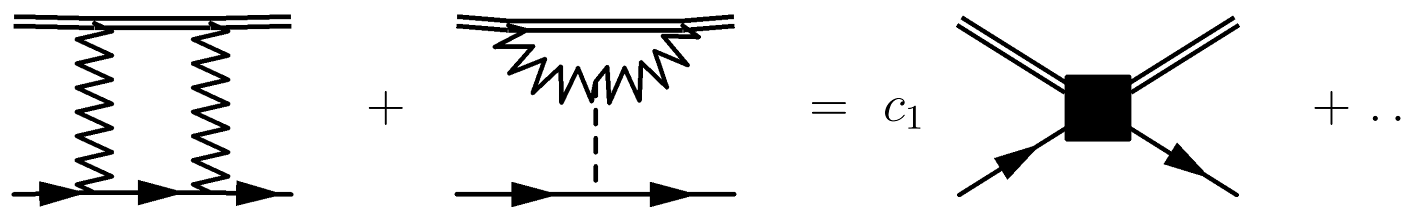
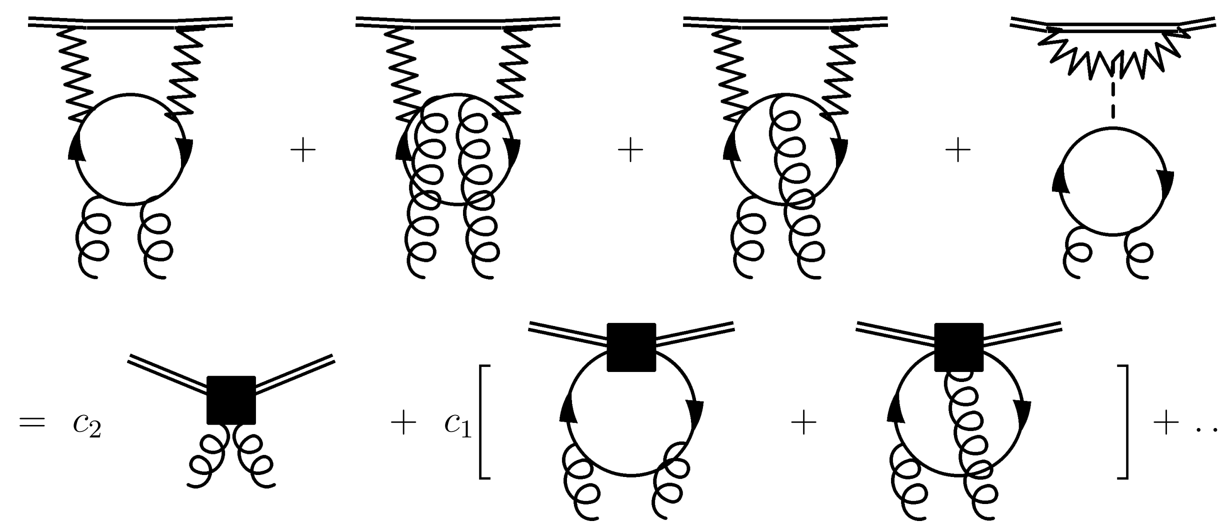
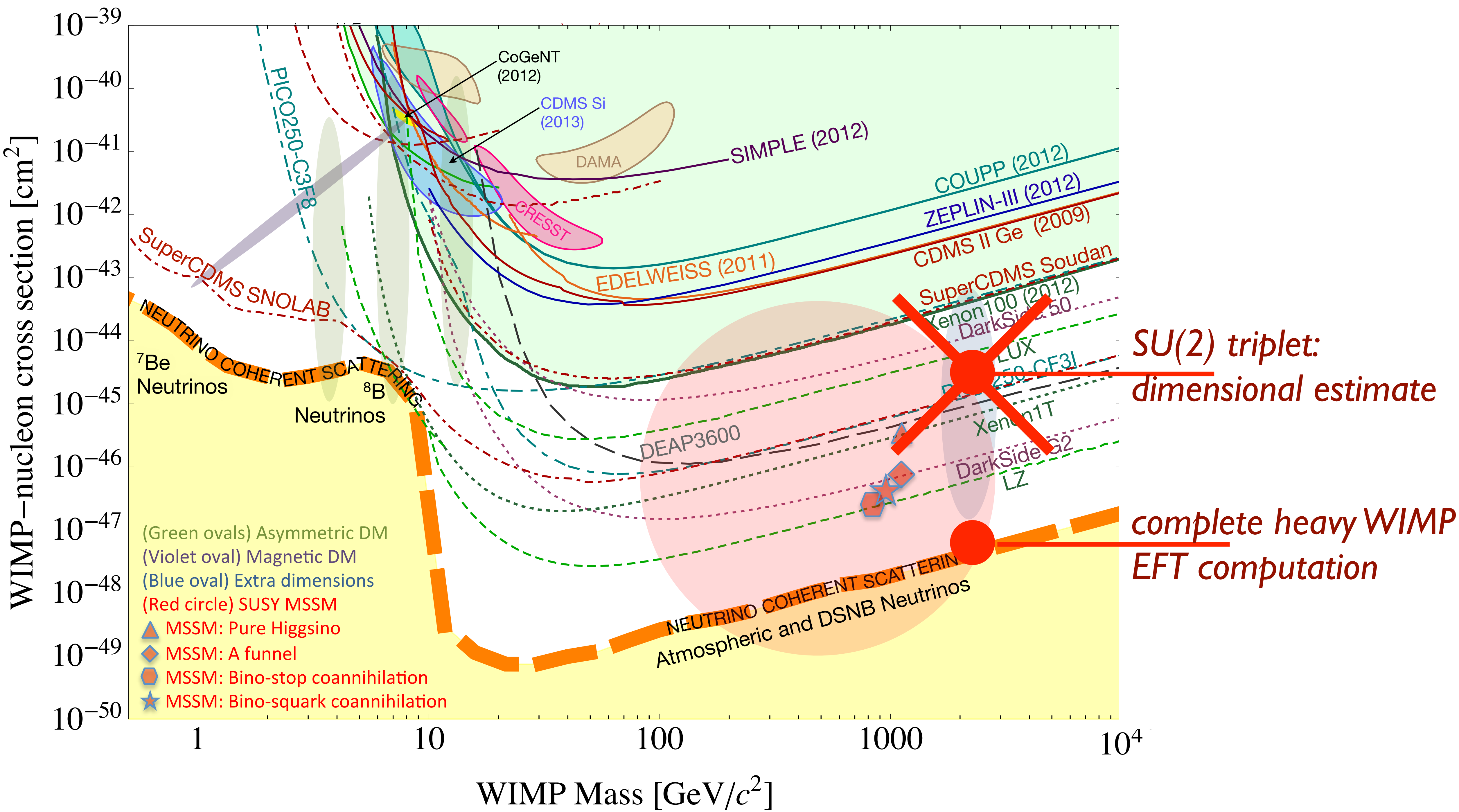
Λ_{QCD}			
	$\chi_v^{(0)}$	N, π	3
m_π			
	$\chi_v^{(0)}$	n, p	2
$E_{nuc.}$			
	$\chi_v^{(0)}$	$\mathcal{N}$	1

- the effective theory helps with the heavy lifting





• the heavy lifting is necessary



Perturbative QCD

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
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m_π			
	$\chi_v^{(0)}$	n, p	2
$1/R_{nucleus}$			
	$\chi_v^{(0)}$	$\mathcal{N}$	1

Renormalization and matching (sample):

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

$m_q\bar{q}q$ $\qquad$ $G^A_{\mu\nu}G^{A\mu\nu}$

focus on spin-0 (evaluate spin-2 at weak scale)

Renormalization group evolution from weak scale to hadronic scales, with perturbative corrections at heavy quark mass thresholds

$$c_i(\mu_Q) = M_{ij}(\mu_Q)c'_j(\mu_Q)\,.$$

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

Can show that:

$$M_{qq} \equiv 1\,, \quad M_{qq'} \equiv 0\,, \quad M_{gq} \equiv 0$$

M_{gQ} and M_{qQ} known through
3 loops:

Chetyrkin et al. (1997)

New results for gluon-induced decoupling relations

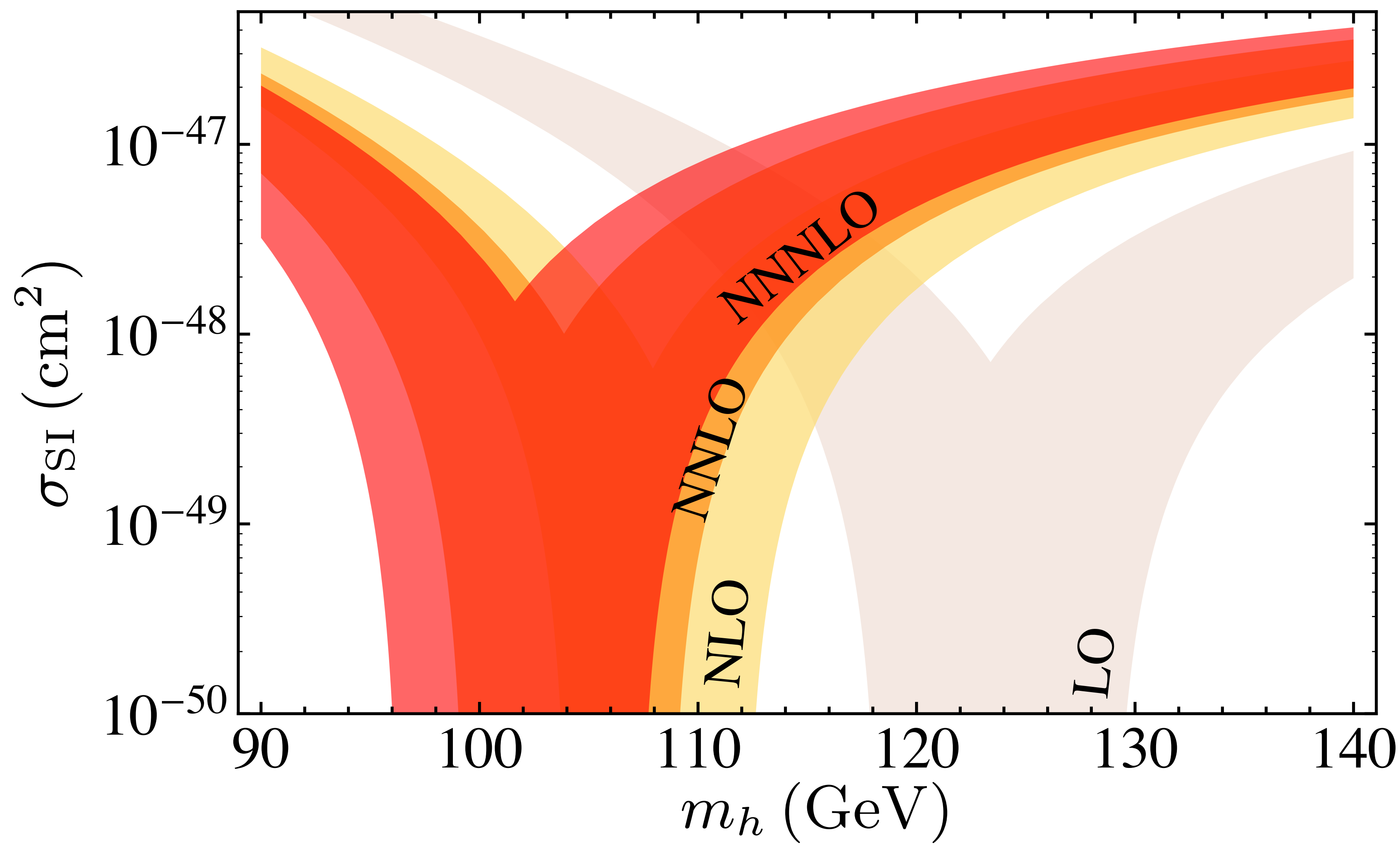
$$M_{gg}^{(2)} = \frac{11}{36} - \frac{11}{6}\log\frac{\mu_Q}{m_Q} + \frac{1}{9}\log^2\frac{\mu_Q}{m_Q}$$

$$M_{gg}^{(3)} = \frac{564731}{41472} - \frac{2821}{288}\log\frac{\mu_Q}{m_Q} + \frac{3}{16}\log^2\frac{\mu_Q}{m_Q} - \frac{1}{27}\log^3\frac{\mu_Q}{m_Q} - \frac{82043}{9216}\zeta(3)$$
$$+ n_f\left[-\frac{2633}{10368} + \frac{67}{96}\log\frac{\mu_Q}{m_Q} - \frac{1}{3}\log^2\frac{\mu_Q}{m_Q}\right],$$

$$M_{qg}^{(2)} = -\frac{89}{54} + \frac{20}{9}\log\frac{\mu_Q}{m_Q} - \frac{8}{3}\log^2\frac{\mu_Q}{m_Q}.$$

Hill, Solon (2014)

- the heavy lifting is necessary



Hadronic matrix elements

Scale separation:	dark sector d.o.f.	SM d.o.f.	# params. (beyond mass)
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nuclear studies: see talks of J. Menendez, M. Hoferichter

see also Cirigliano et al. 1205.2695, Haxton et al. 1203.3542 …

d	QCD operator basis
3	$V_q^\mu = \bar{q}\gamma^\mu q$
	$A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$
4	$T_q^{\mu\nu} = i m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q$
	$O_q^{(0)} = m_q \bar{q} q \,, \quad O_g^{(0)} = G^A_{\mu\nu} G^{A\mu\nu}$
	$O_{5q}^{(0)} = m_q \bar{q} i\gamma_5 q \,, \quad O_{5g}^{(0)} = \epsilon^{\mu\nu\rho\sigma} G^A_{\mu\nu} G^A_{\rho\sigma}$
	$O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu} i D_-^{\nu\}} - \frac{g^{\mu\nu}}{4} i \not{D}_-\right) q \,, \quad O_g^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_\lambda + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$
	$O_{5q}^{(2)\mu\nu} = \frac{1}{2}\bar{q}\gamma^{\{\mu} i D_-^{\nu\}}\gamma_5 q$

complete QCD basis for d≤7

- C-even spin-2: determined by PDF moments

$$\langle N | O^{(2)\mu\nu} | N \rangle = k^\mu k^\nu \int_0^1 dx\, x[q(x) + \bar{q}(x)]$$

d	QCD operator basis
3	$V^\mu_q = \bar{q}\gamma^\mu q$ $A^\mu_q = \bar{q}\gamma^\mu\gamma_5 q$
4	$T^{\mu\nu}_q = i m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q$ $O^{(0)}_q = m_q\bar{q}q\,, \quad O^{(0)}_g = G^A_{\mu\nu}G^{A\mu\nu}$ $O^{(0)}_{5q} = m_q\bar{q}i\gamma_5 q\,, \quad O^{(0)}_{5g} = \epsilon^{\mu\nu\rho\sigma}G^A_{\mu\nu}G^A_{\rho\sigma}$ $O^{(2)\mu\nu}_q = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu}iD^{\nu\}}_- - \frac{g^{\mu\nu}}{4}i\not{D}_-\right)q\,, \quad O^{(2)\mu\nu}_g = -G^{A\mu\lambda}G^{A\nu}{}_\lambda + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$ $O^{(2)\mu\nu}_{5q} = \frac{1}{2}\bar{q}\gamma^{\{\mu}iD^{\nu\}}_-\gamma_5 q$

- C-even spin-0: nucleon sigma terms (nucleon mass sum rule for gluon operator)

$$m_N = (1-\gamma_m)\sum_q \langle N|m_q\bar{q}q|N\rangle + \frac{1}{2}\beta\langle N|(G^a_{\mu\nu})^2|N\rangle$$

recent progress: see talks of H.-W. Lin, others at this conference, and updates at Lattice 2016

• up, down quarks & isospin-violating dark matter

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

$$= 44(13)\ \mathrm{MeV}$$

Durr et al. (2011)

$$= 59.1(3.5)\ \mathrm{MeV}$$

Hoferichter et al. (2015)

$$\Sigma_- = (m_d - m_u)\langle N|(\bar{u}u - \bar{d}d)|N\rangle$$

$$= \pm 2(2)\ \mathrm{MeV}$$

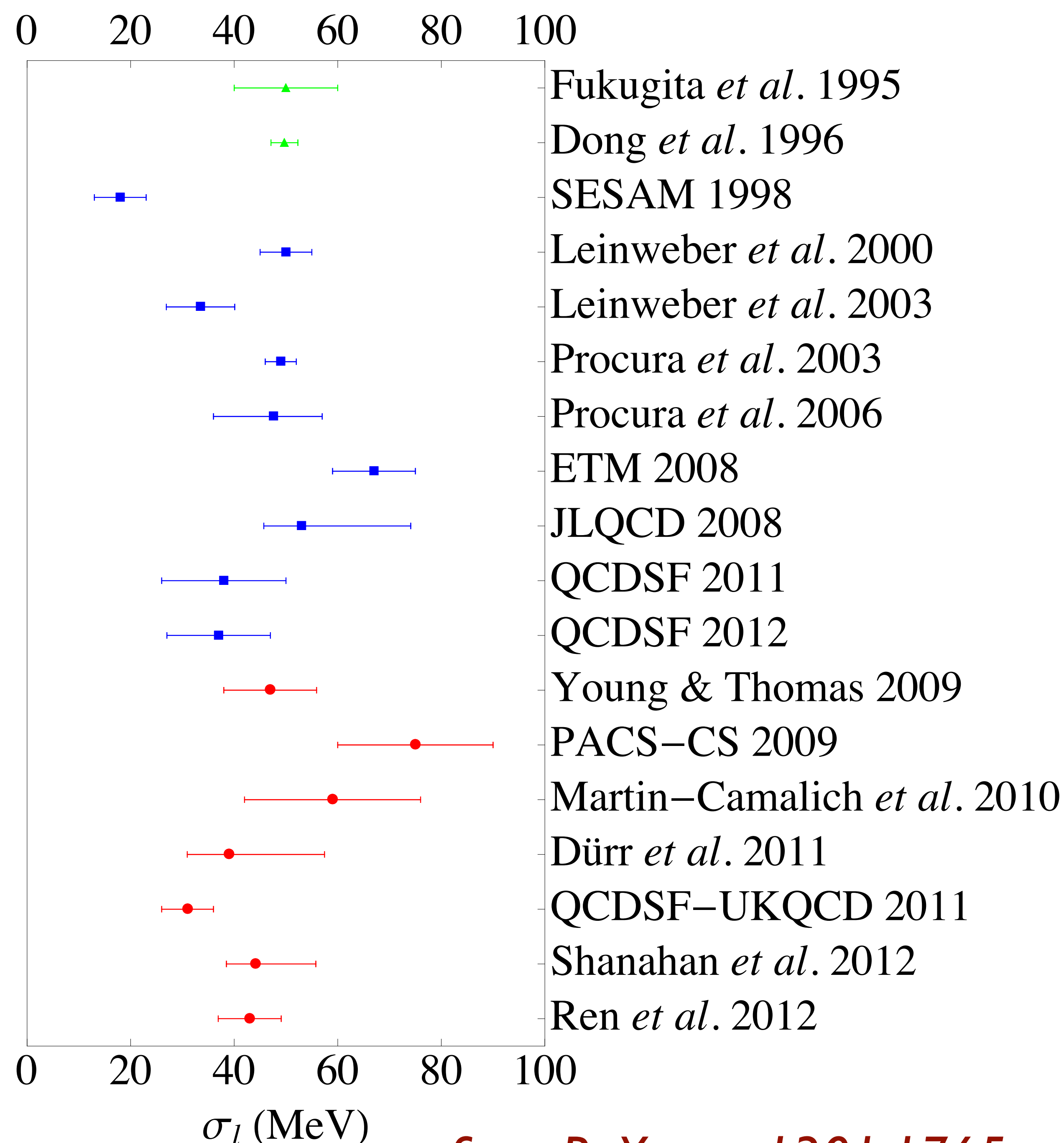
Gasser, Leutwyler (1982)

$$= \pm 2(1)\mathrm{MeV}$$

Crivellin, Hoferichter, Procura (2014)

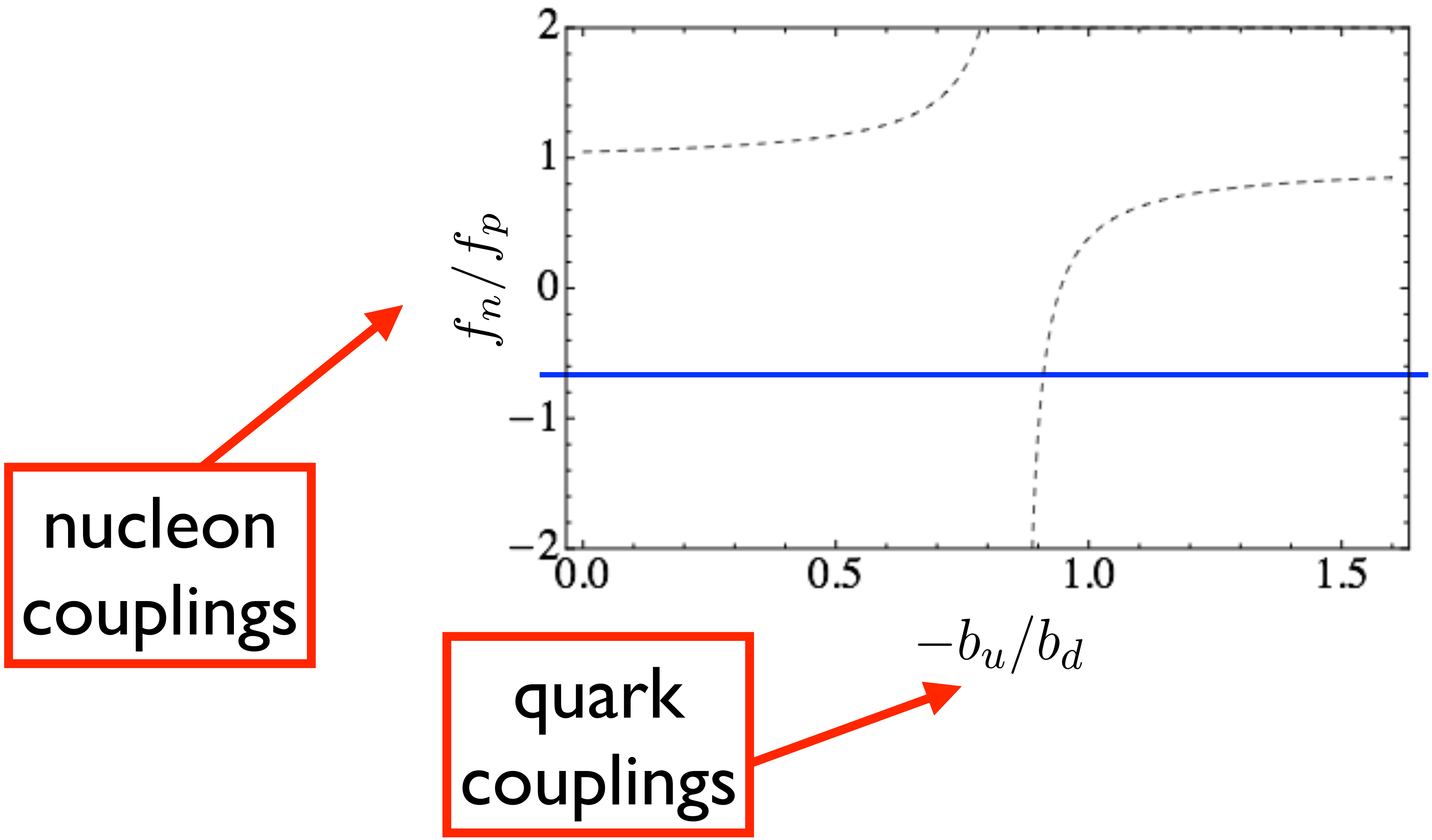
$$\frac{m_u}{m_d} = 0.49 \pm 0.13$$

PDG



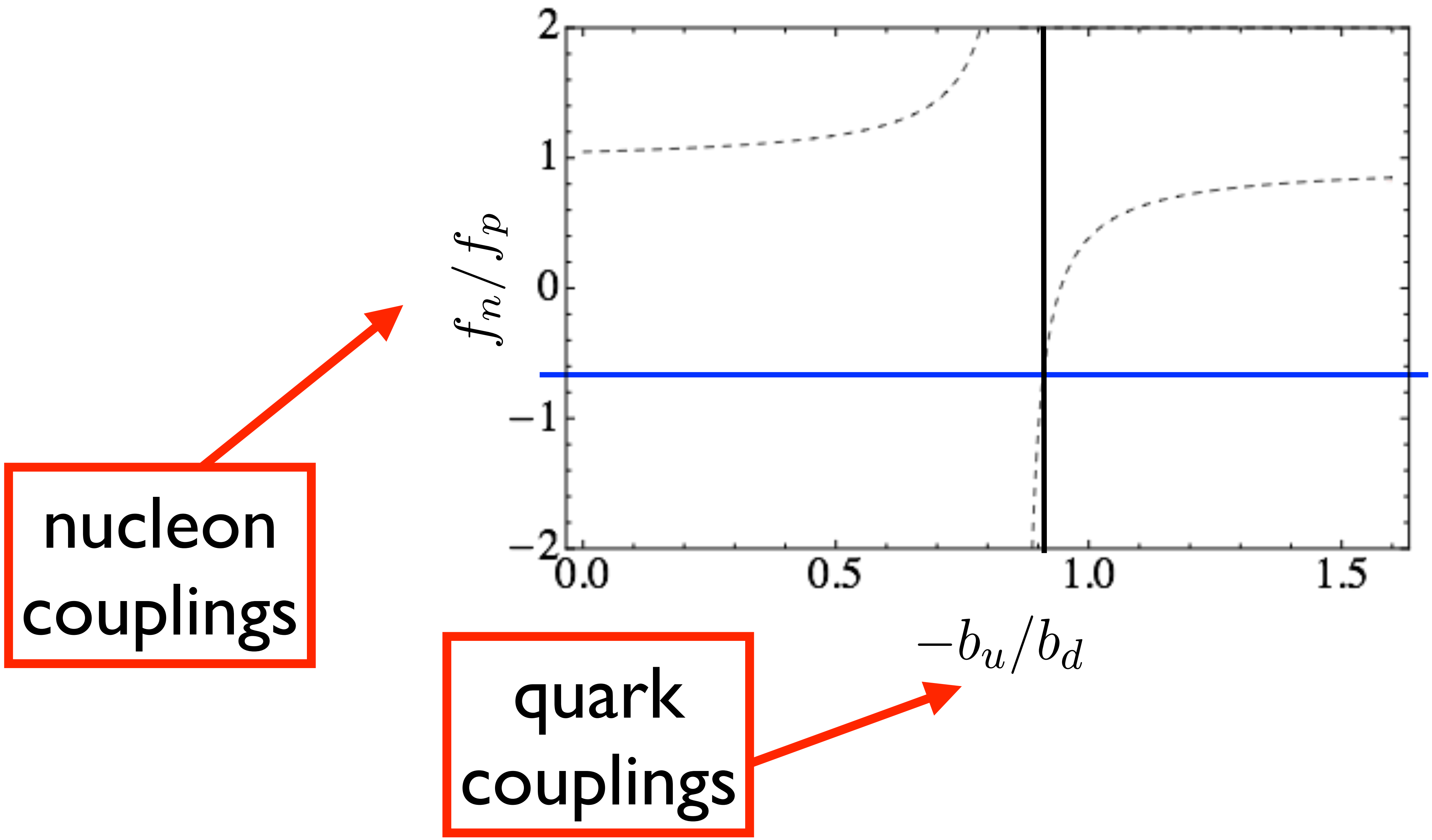
from R. Young, 1301.1765

- up, down quarks & isospin-violating dark matter



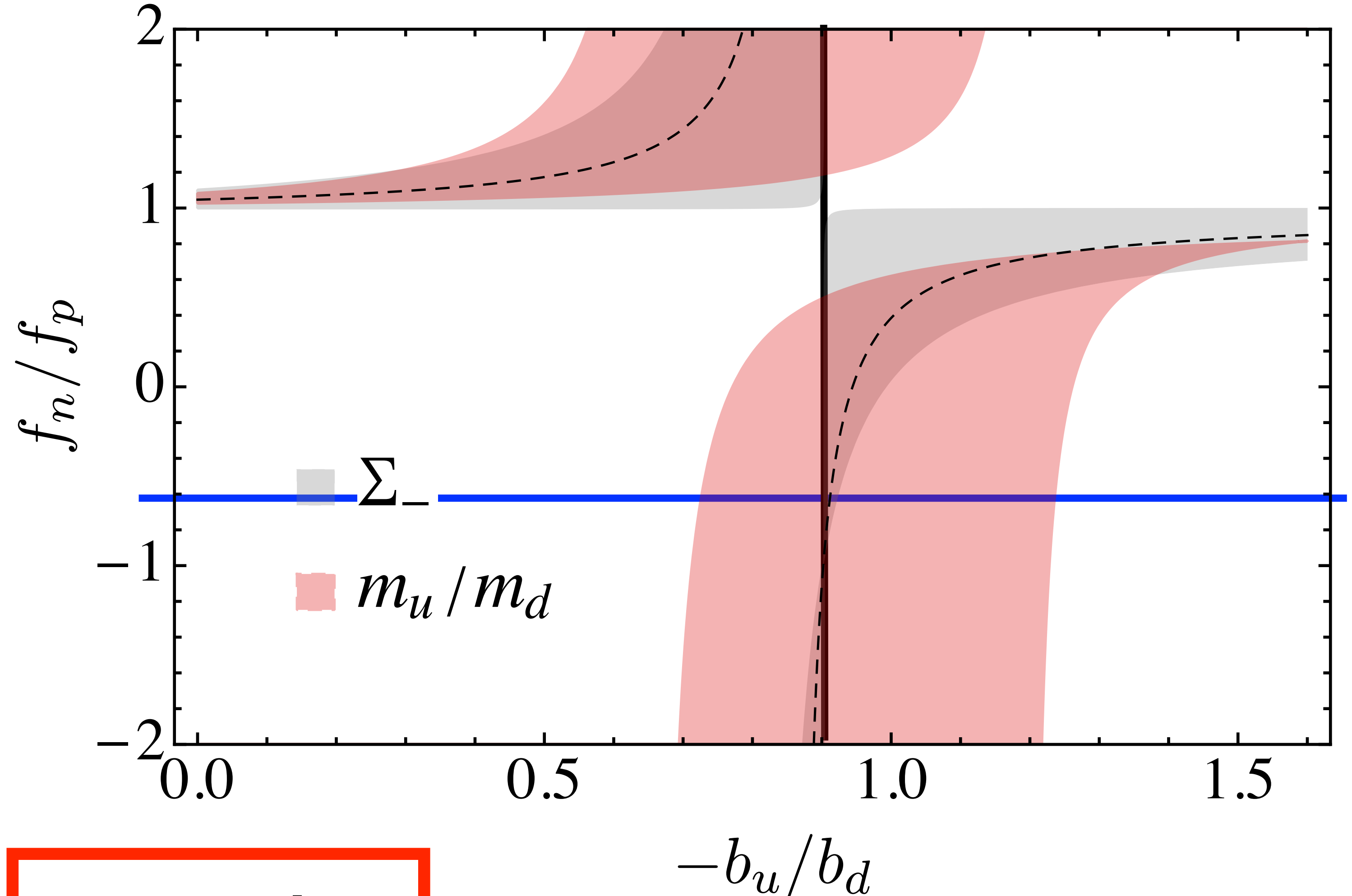
hadronic uncertainties important for determining viability of models for potential signals

- up, down quarks & isospin-violating dark matter



hadronic uncertainties important for determining viability of models for potential signals

• up, down quarks & isospin-violating dark matter



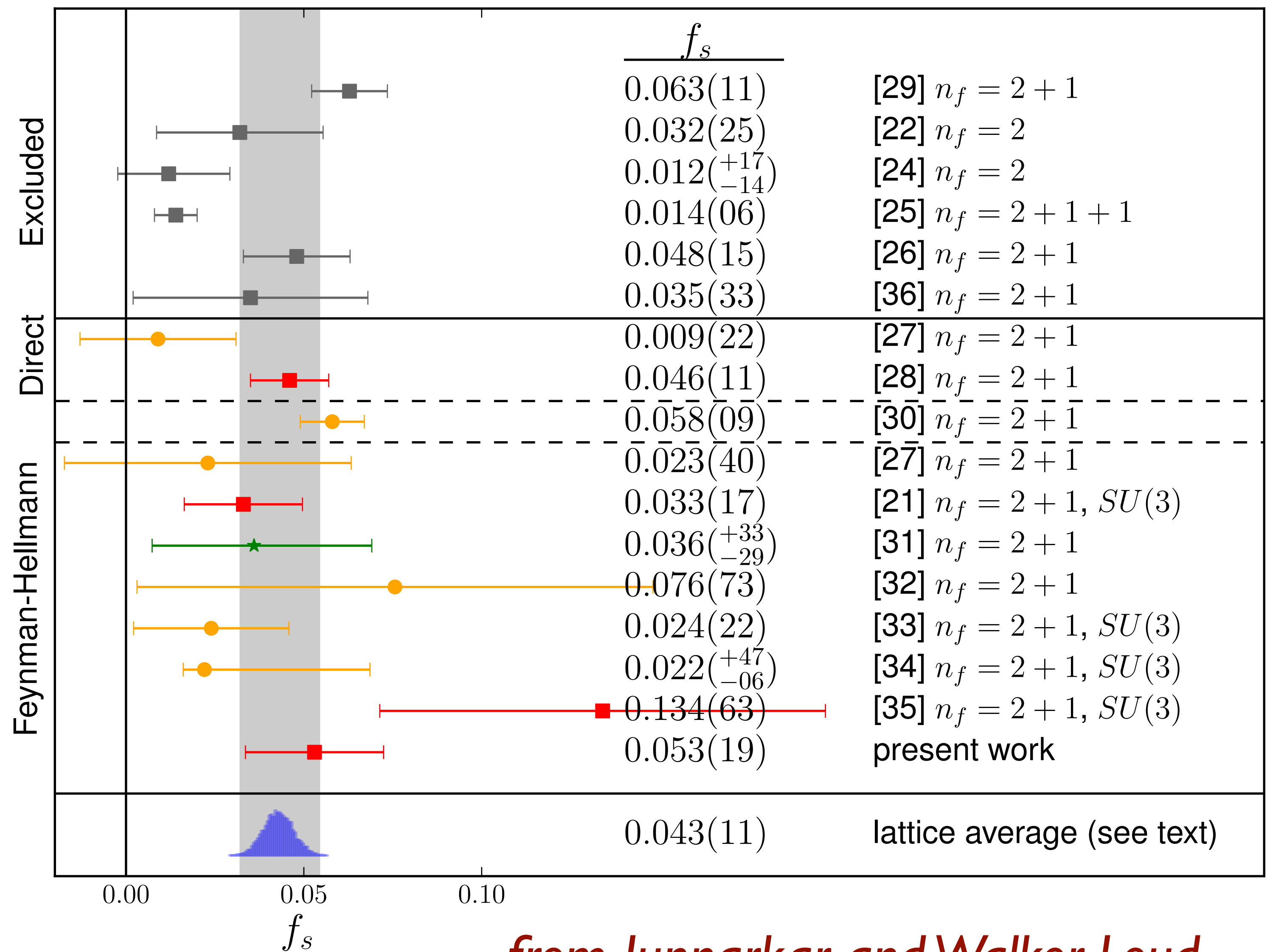
nucleon couplings

quark couplings

hadronic uncertainties important for determining viability of models for potential signals

- strange quarks & heavy wino dark matter

$$\Sigma_s = \langle N | m_s \bar{s} s | N \rangle$$
$$= 40 \pm 20\,\mathrm{MeV}$$

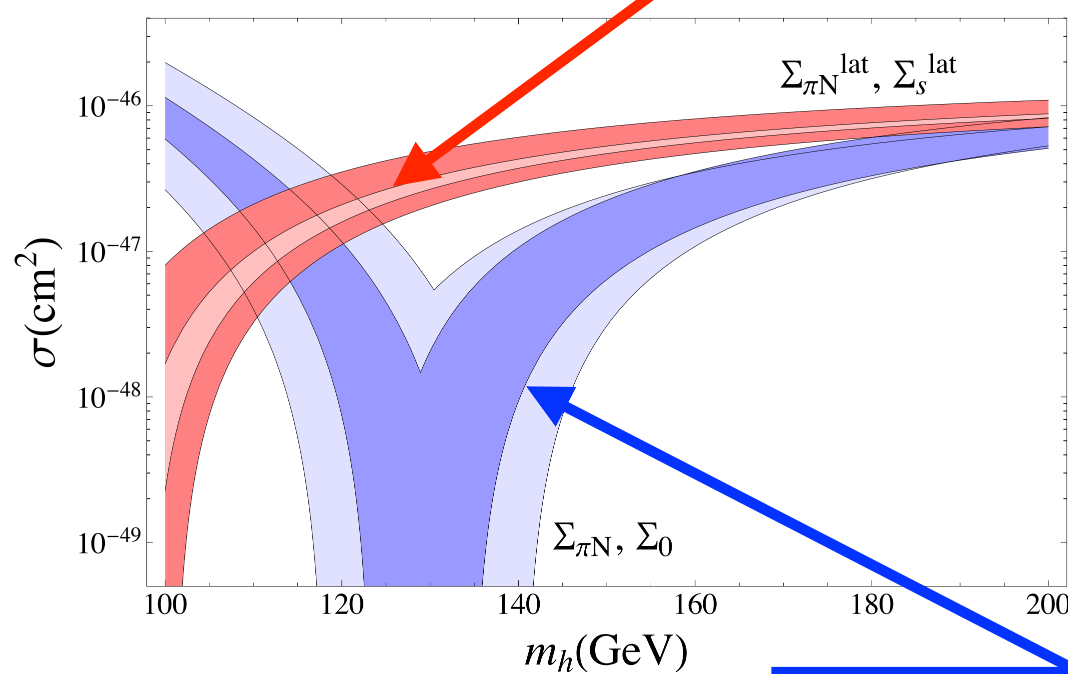


from Junnarkar and Walker-Loud, 1301.1114

- strange quarks & heavy wino dark matter

lattice QCD inputs

$$\Sigma_{\pi N} = 47(9)\ \mathrm{MeV}$$
$$\Sigma_s = 50(8)\ \mathrm{MeV}$$



baryon spectroscopy inputs

Pavan et al. hep-ph/0111066

Borasoy and Meissner, hep-ph/9607432

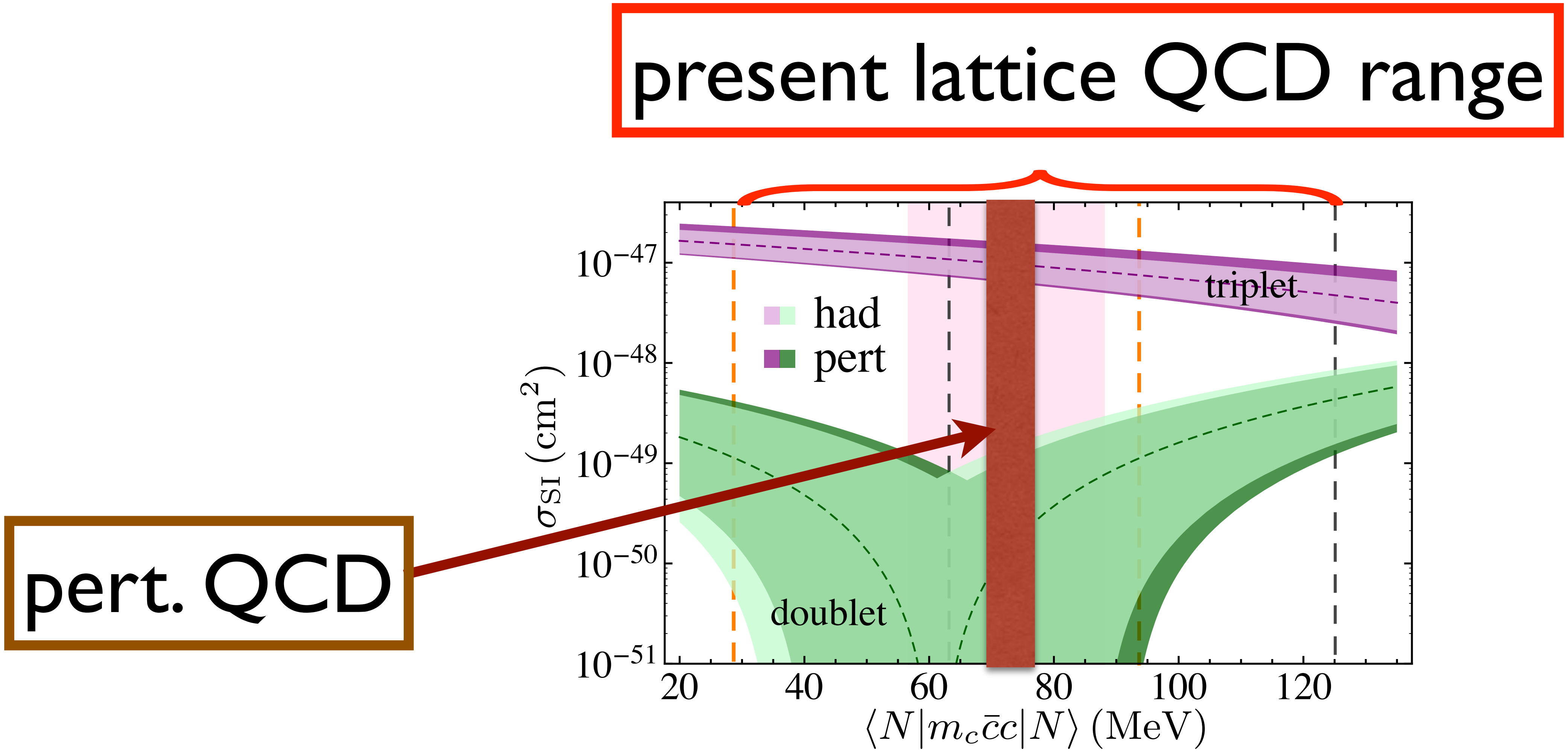
determines if cross section is above or below neutrino background for direct detection

- charm quarks & heavy higgsino dark matter

$$\Sigma_c = m_c \langle N | \bar{c} c | N \rangle$$

$$= m_N \begin{cases} 0.073(3) & \textit{pQCD RJH, Solon 2014} \\ 0.10(3) & \textit{Freeman et al. [MILC] 1204.3866} \\ 0.07(3) & \textit{Gong et al. [}\chi\textit{QCD] 1304.1194} \end{cases}$$

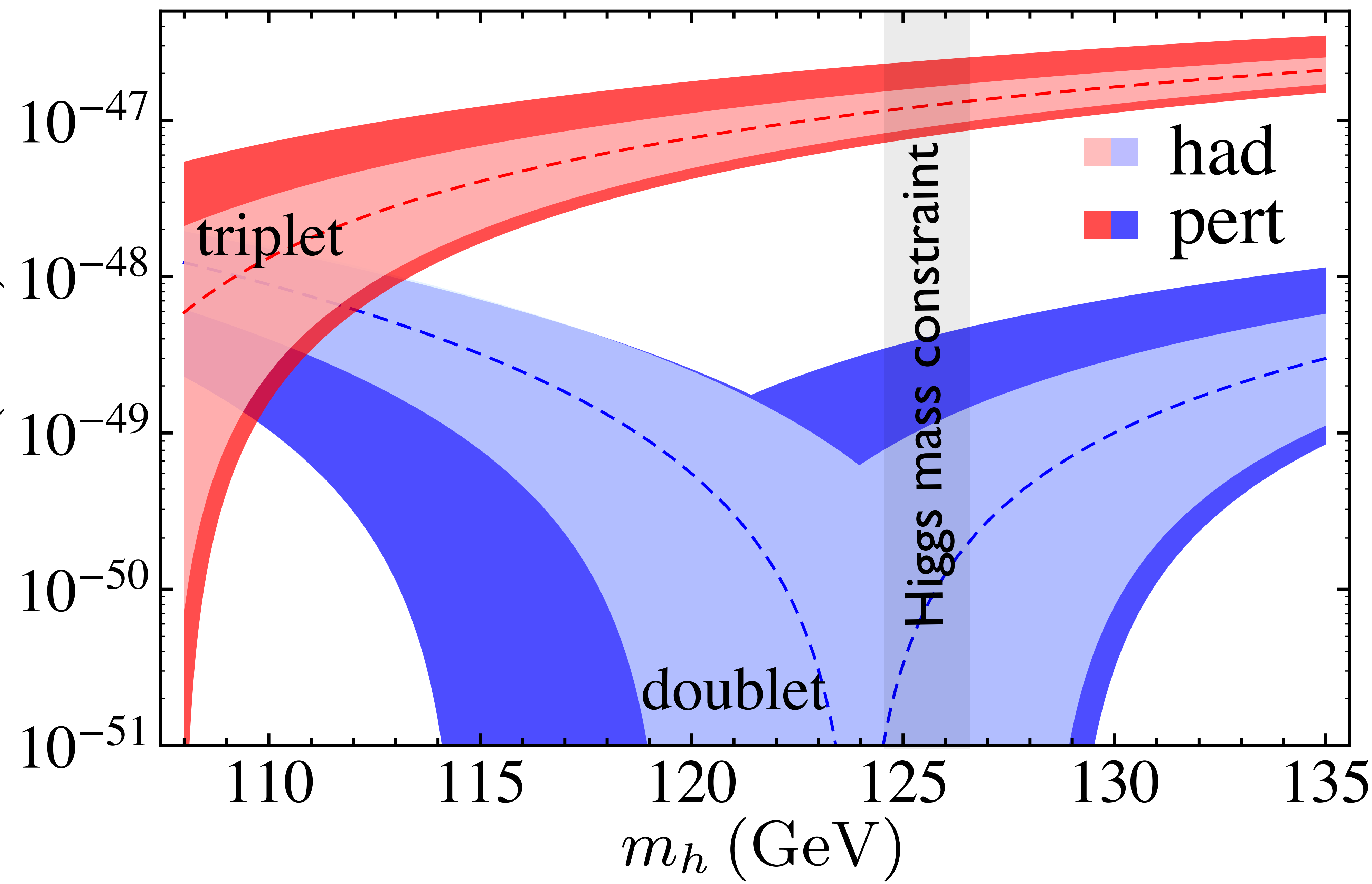
- charm quarks & heavy higgsino dark matter



$1/m_c$ could potentially shift cancellation region

summary results for heavy electroweak charged WIMP scattering

cross section per nucleon



Higgs boson mass

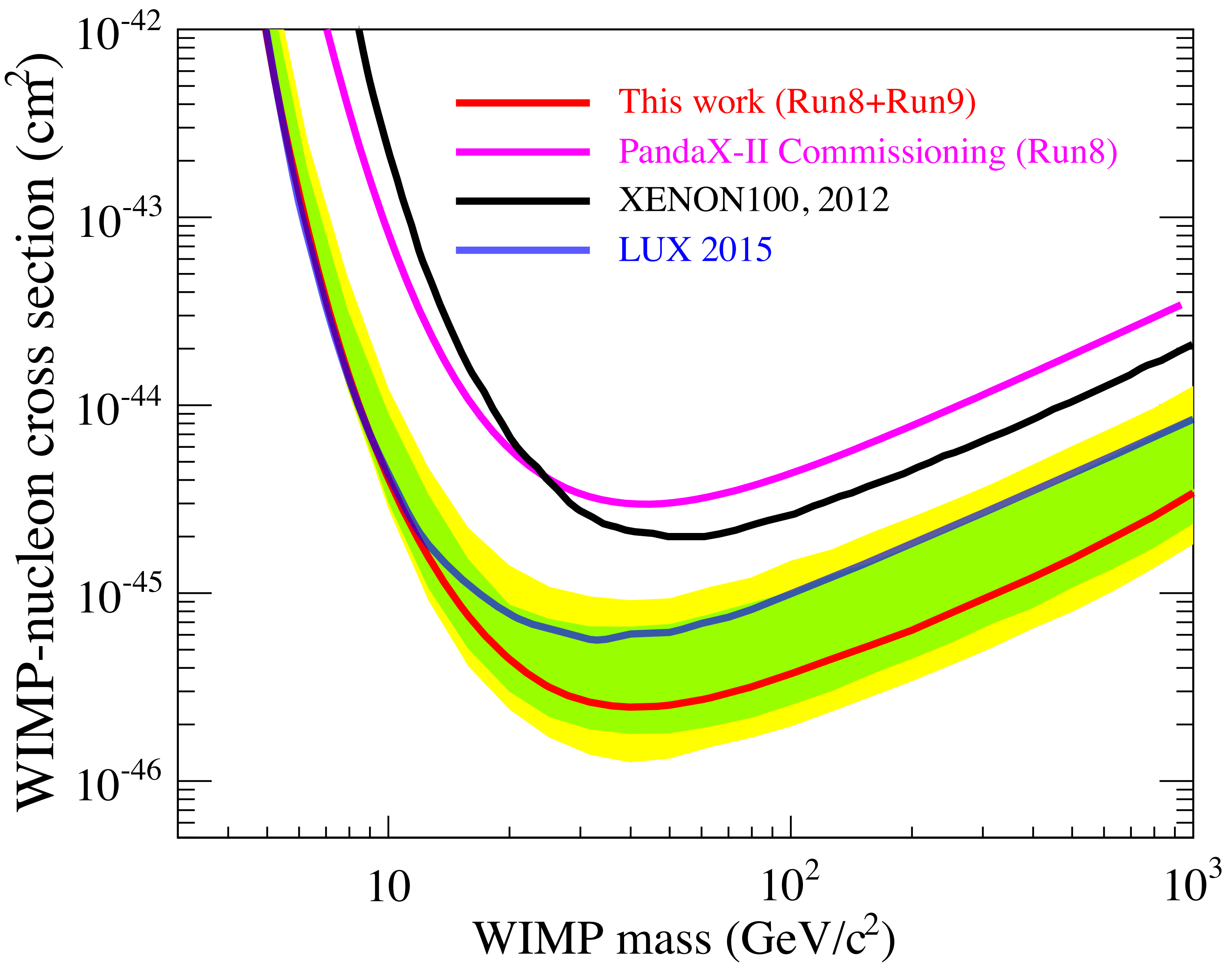
Summary

- Heavy WIMP effective theory: universal predictions for next generation searches

- Important QCD corrections
    - new high-order heavy quark decoupling relations
    - impact of strange, charm nucleon sigma terms

- Work remains
    - 1/M corrections in EFT
    - Improved nucleon matrix elements
    - Systematic nuclear corrections, especially impacting spin 0/ spin 2 cancellation
    - Interplay with annihilation observables

back up



PandaX-II 1607.07400, LUX 1512.03506, Xenon100 1301.6620

Three motivations for studying QCD & DM

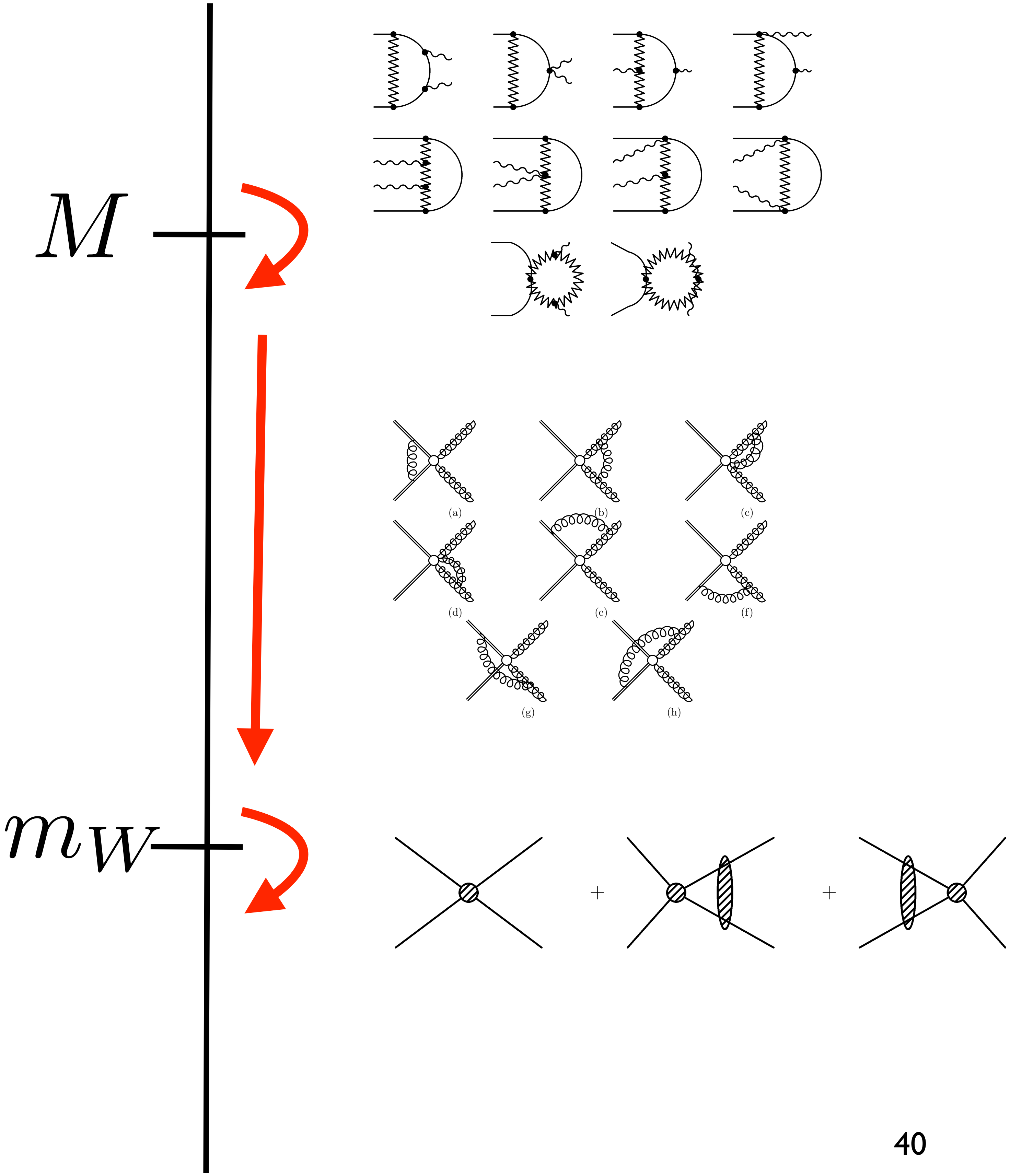
• important, sometimes dramatic, impact on discovery potential

• post-discovery interpretation and/or anomaly debunking

• new field theory tools (for DM and other applications)

Field theory tools

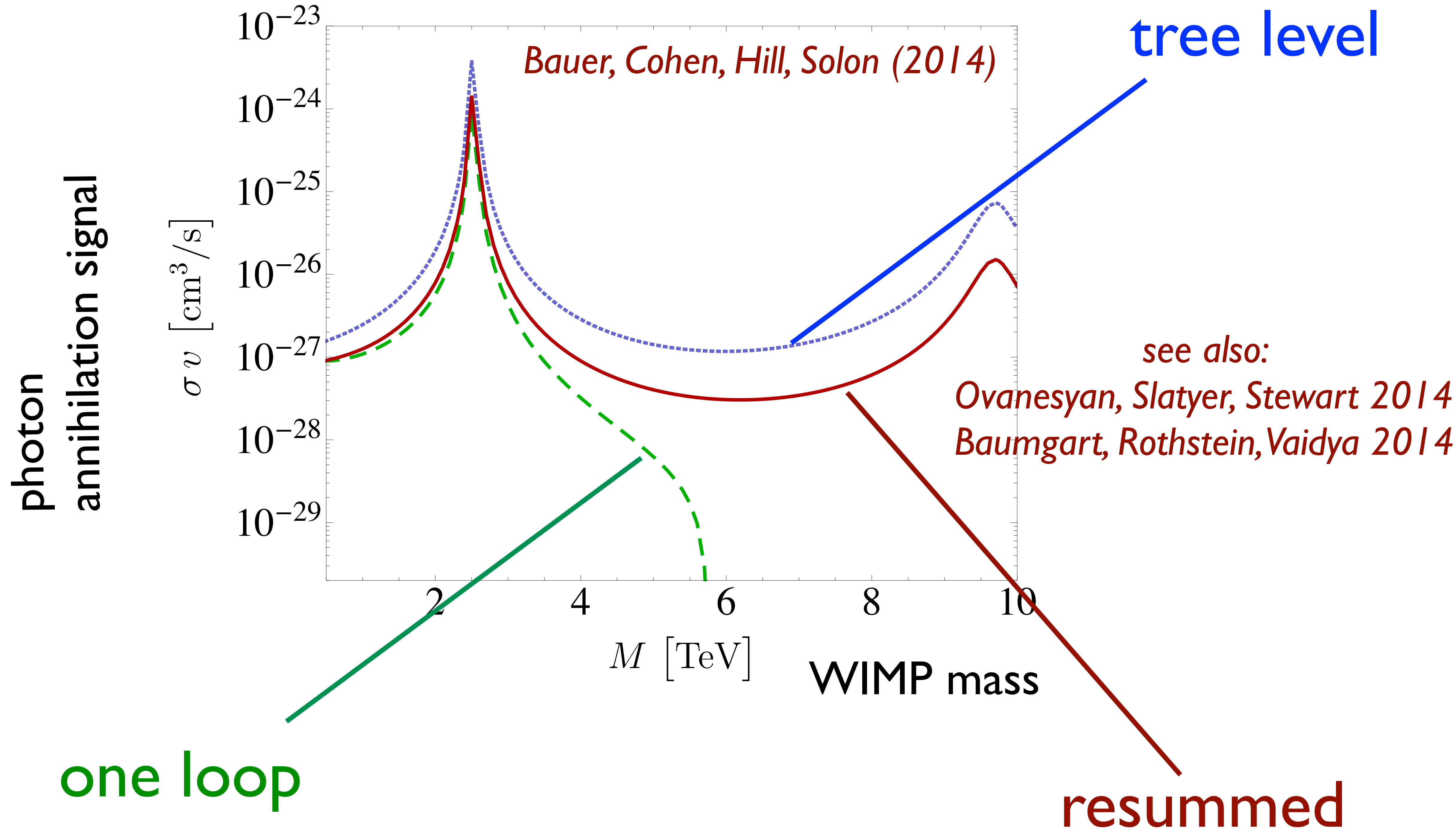
Extend Heavy WIMP Effective Theory to describe annihilation. Worked example: SU(2) triplet annihilation to photons



hard annihilation
(makes it happen)

Sudakov suppression
(makes it slower)

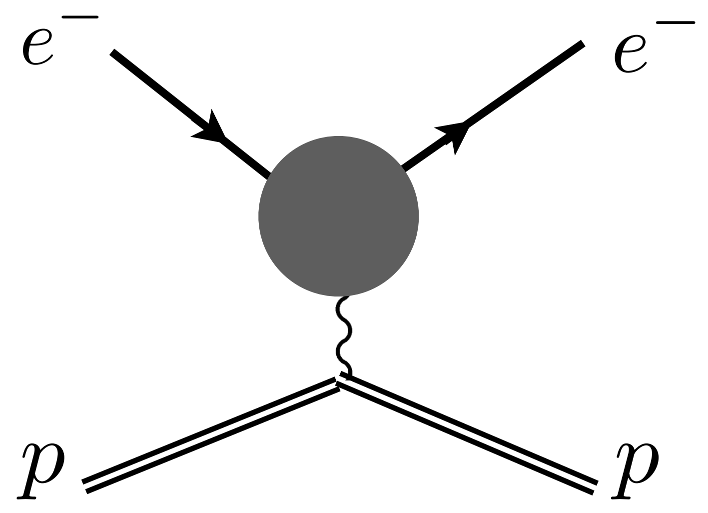
Sommerfeld enhancement
(makes it faster)



General framework in which to reliably compute annihilation signals for heavy WIMPs.

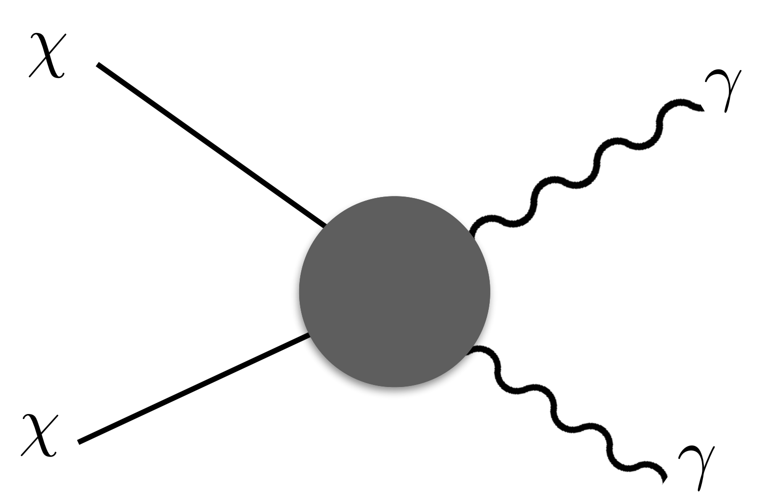
Novel field theory tools for DM have broad application

$$\alpha \log^2 \frac{Q^2}{m_e^2}\Big|_{Q^2=\mathrm{GeV}^2} \approx 1$$



radiative corrections to lepton-nucleon scattering (proton radius puzzle, neutrino oscillations)

$$\alpha_W \log^2 \frac{M_{\mathrm{DM}}^2}{m_W^2}\Big|_{M_{\mathrm{DM}}=\mathrm{TeV}} \approx 1$$



heavy WIMP annihilation

other illustrative examples

d	QCD operator basis
3	$V_q^\mu = \bar{q}\gamma^\mu q$ $A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$
4	$T_q^{\mu\nu} = i m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q$ $O_q^{(0)} = m_q \bar{q} q \,, \quad O_g^{(0)} = G^A_{\mu\nu} G^{A\mu\nu}$ $O_{5q}^{(0)} = m_q \bar{q} i\gamma_5 q \,, \quad O_{5g}^{(0)} = \epsilon^{\mu\nu\rho\sigma} G^A_{\mu\nu} G^A_{\rho\sigma}$ $O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu} iD_-^{\nu\}} - \frac{g^{\mu\nu}}{4} i\not{D}_-\right) q \,, \quad O_g^{(2)\mu\nu} = -G^{A\mu\lambda}G^{A\nu}{}_\lambda + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$ $O_{5q}^{(2)\mu\nu} = \frac{1}{2}\bar{q}\gamma^{\{\mu} iD_-^{\nu\}}\gamma_5 q$

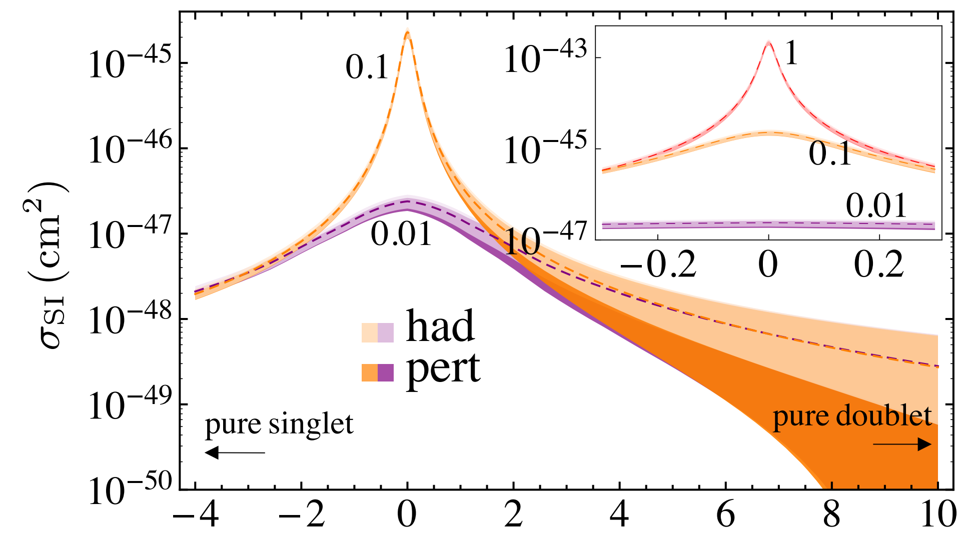
complete QCD basis for d≤7

- For canonical example (heavy electroweak multiplet), scalar operators

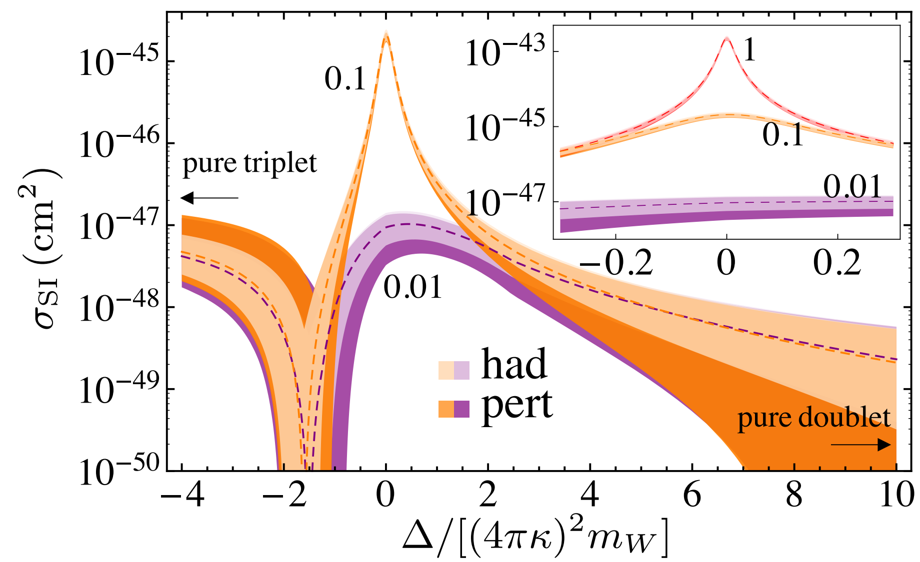
- Selected other examples

Additional states in the dark sector

singlet-doublet (e.g., bino-higgsino)



triplet-doublet (e.g., wino-higgsino)



Δ: mass splitting of multiplets, in units where tree/loop crossover occurs at ~1

interplay of mass-suppressed (tree level) and loop suppressed contributions

Hadronic matrix elements

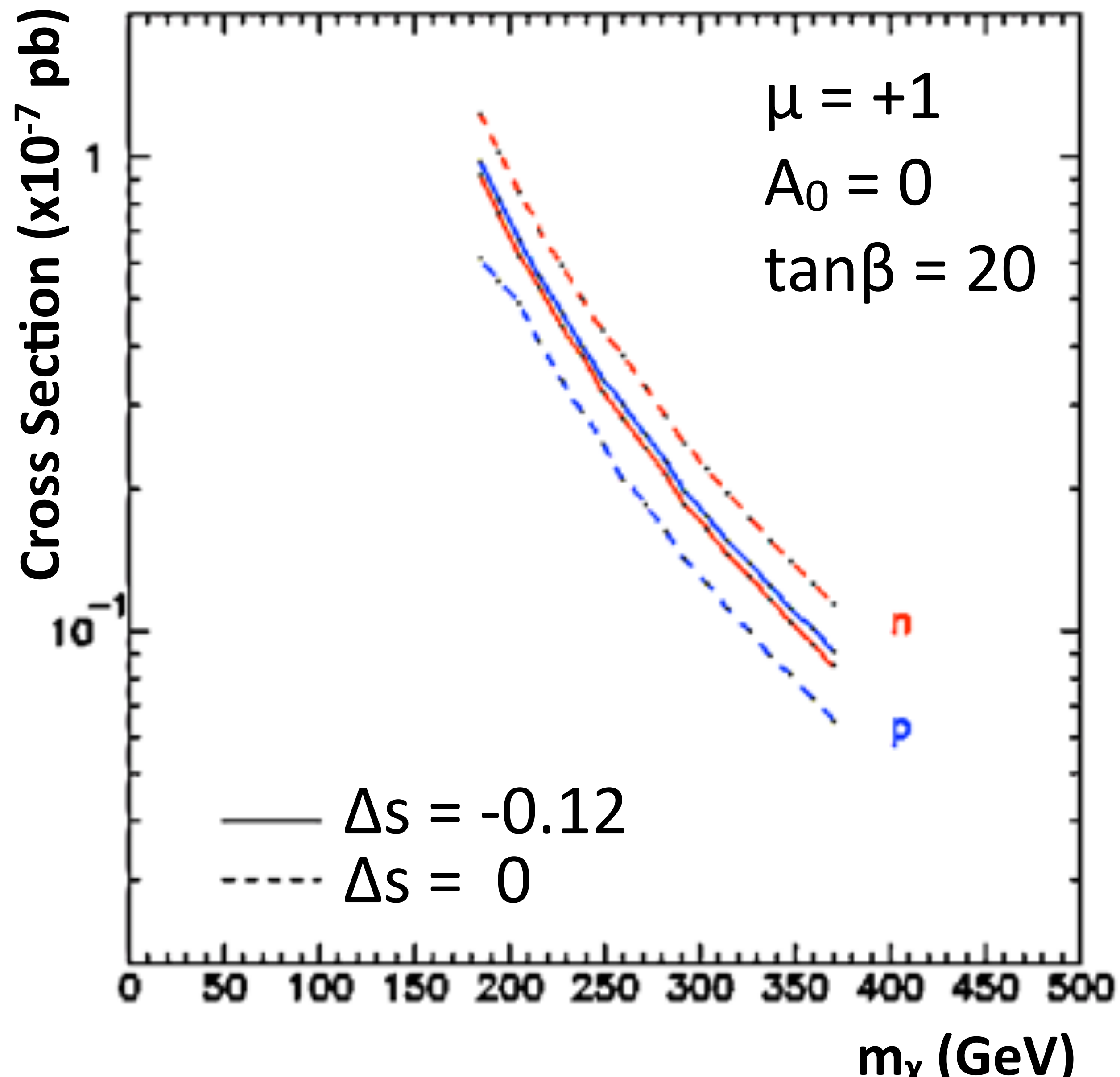
d	QCD operator basis
3	$V_q^\mu = \bar{q}\gamma^\mu q$
	$A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$
4	$T_q^{\mu\nu} = i m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q$
	$O_q^{(0)} = m_q \bar{q} q\,, \quad O_g^{(0)} = G^A_{\mu\nu} G^{A\mu\nu}$
	$O_{5q}^{(0)} = m_q \bar{q} i\gamma_5 q\,, \quad O_{5g}^{(0)} = \epsilon^{\mu\nu\rho\sigma} G^A_{\mu\nu} G^A_{\rho\sigma}$
	$O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu} i D_-^{\nu\}} - \frac{g^{\mu\nu}}{4} i \not{D}_-\right) q\,, \quad O_g^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_\lambda + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$
	$O_{5q}^{(2)\mu\nu} = \frac{1}{2}\bar{q}\gamma^{\{\mu} i D_-^{\nu\}}\gamma_5 q$

- strange component of nucleon spin & spin-dependent neutralino direct detection

• strange component of nucleon spin & spin-dependent neutralino direct detection

$$\langle N|\bar{s}\gamma^\mu\gamma_5 s|N\rangle$$

$$F_A^s(q^2=0)=\Delta s$$



Miceli et al., 1406.5204

Relevant, especially post-discovery for spin-dependent cross sections

d	QCD operator basis
3	$V_q^\mu = \bar{q}\gamma^\mu q$
	$A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$
4	$T_q^{\mu\nu} = i m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q$
	$O_q^{(0)} = m_q\bar{q}q\,, \quad O_g^{(0)} = G^A_{\mu\nu}G^{A\mu\nu}$
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	$O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu}iD_-^{\nu\}} - \frac{g^{\mu\nu}}{4}i\not{D}_-\right)q\,, \quad O_g^{(2)\mu\nu} = -G^{A\mu\lambda}G^{A\nu}{}_\lambda + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$
	$O_{5q}^{(2)\mu\nu} = \frac{1}{2}\bar{q}\gamma^{\{\mu}iD_-^{\nu\}}\gamma_5 q$

- flavor singlet pseudoscalar & low-mass WIMPs

- flavor singlet pseudoscalar & low-mass WIMPs

$$\sum_{q=u,d,s} \langle N(k')|\bar{q}i\gamma_5 q|N(k)\rangle \equiv \kappa(q^2,\mu)\bar{u}(k')i\gamma_5 u(k)$$

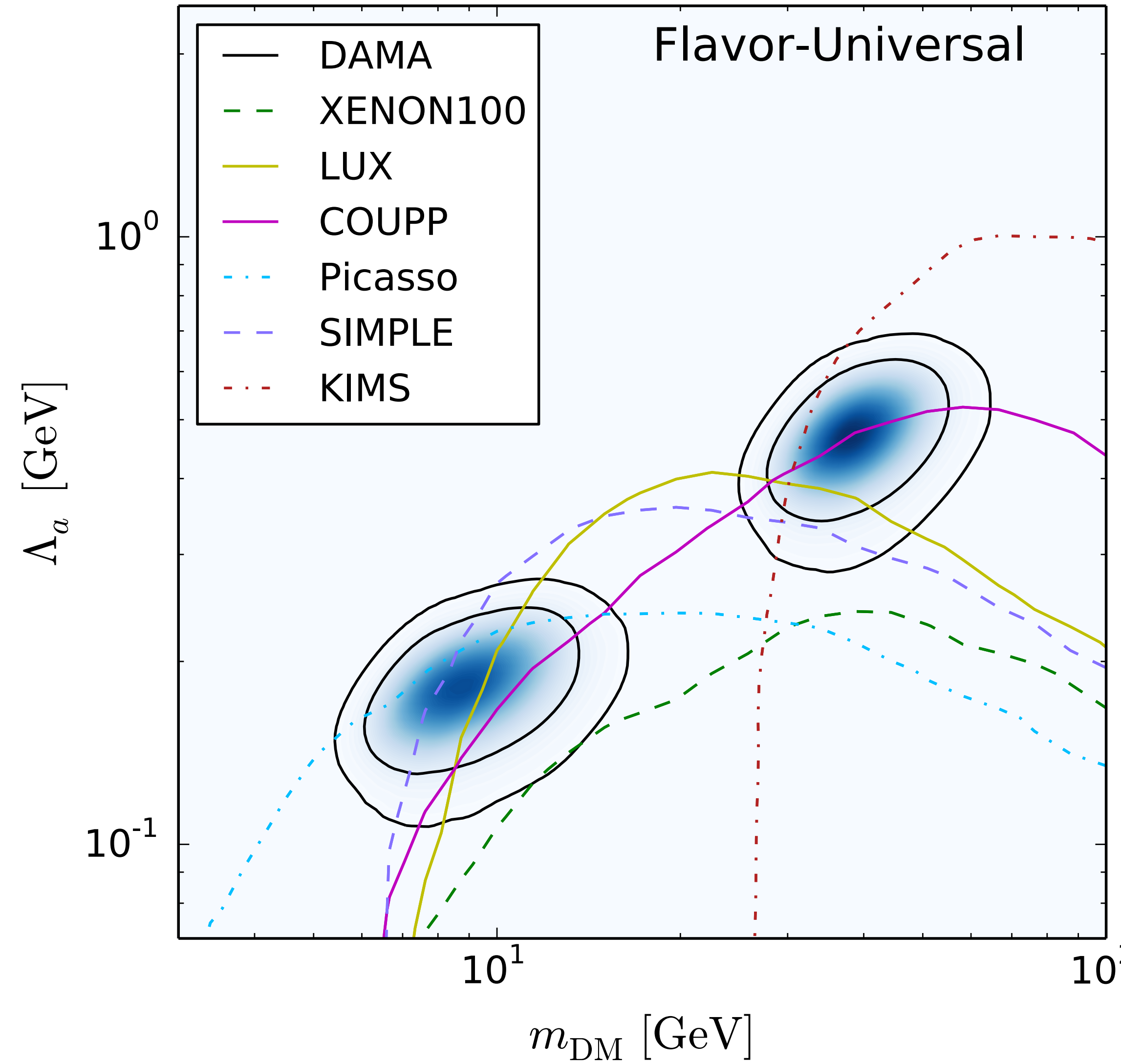
$$\kappa \sim 0?$$

$$\mathcal{L} = g_\chi a\bar{\chi}i\gamma_5\chi + \sum_q g_f a\bar{q}i\gamma_5 q$$

↓

$$\mathcal{L} \sim \frac{1}{\Lambda^2}\sum_{N=p,n} g_N\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$$

$$|g_p/g_n| \sim 15 - 45$$



Arina et al. 1406.5542

Impacts tension between experiments

Single-nucleon operators

$$\mathcal{L}_{N\chi,PT} = \frac{1}{m_N^2}\Big\{d_1 N^\dagger\sigma^i N\ \chi^\dagger\sigma^i\chi + d_2 N^\dagger N\ \chi^\dagger\chi\Big\} + \frac{1}{m_N^4}\Big\{d_3 N^\dagger\partial_+^i N\ \chi^\dagger\partial_+^i\chi + d_4 N^\dagger\partial_-^i N\ \chi^\dagger\partial_-^i\chi$$
$$+ d_5 N^\dagger(\boldsymbol{\partial}^2 + \overleftarrow{\boldsymbol{\partial}}^2)N\ \chi^\dagger\chi + d_6 N^\dagger N\ \chi^\dagger(\boldsymbol{\partial}^2 + \overleftarrow{\boldsymbol{\partial}}^2)\chi + id_8\epsilon^{ijk}N^\dagger\sigma^i\partial_-^j N\ \chi^\dagger\partial_+^k\chi$$
$$+ id_9\epsilon^{ijk}N^\dagger\sigma^i\partial_+^j N\ \chi^\dagger\partial_-^k\chi + id_{11}\epsilon^{ijk}N^\dagger\partial_+^k N\ \chi^\dagger\sigma^i\partial_-^j\chi + id_{12}\epsilon^{ijk}N^\dagger\partial_-^k N\ \chi^\dagger\sigma^i\partial_+^j\chi$$
$$+ d_{13}N^\dagger\sigma^i\partial_+^j N\ \chi^\dagger\sigma^i\partial_+^j\chi + d_{14}N^\dagger\sigma^i\partial_-^j N\ \chi^\dagger\sigma^i\partial_-^j\chi + d_{15}N^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\partial}_+ N\ \chi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\partial}_+\chi$$
$$+ d_{16}N^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\partial}_- N\ \chi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\partial}_-\chi + d_{17}N^\dagger\sigma^i\partial_-^j N\ \chi^\dagger\sigma^j\partial_-^i\chi$$
$$+ d_{18}N^\dagger\sigma^i(\boldsymbol{\partial}^2 + \overleftarrow{\boldsymbol{\partial}}^2)N\ \chi^\dagger\sigma^i\chi + d_{19}N^\dagger\sigma^i(\partial^i\partial^j + \overleftarrow{\partial}^j\overleftarrow{\partial}^i)N\ \chi^\dagger\sigma^j\chi$$
$$+ d_{20}N^\dagger\sigma^i N\ \chi^\dagger\sigma^i(\boldsymbol{\partial}^2 + \overleftarrow{\boldsymbol{\partial}}^2)\chi + d_{21}N^\dagger\sigma^i N\ \chi^\dagger\sigma^j(\partial^i\partial^j + \overleftarrow{\partial}^j\overleftarrow{\partial}^i)\chi\Big\} + \mathcal{O}(1/m_N^6)\,, \quad ('$$

Lorentz invariance:

$$rd_4 + d_5 = \frac{d_2}{4}\,, \quad d_5 = r^2 d_6\,, \quad 8r(d_8 + rd_9) = -rd_2 + d_1\,, \quad 8r(rd_{11} + d_{12}) = -d_2 + rd_1$$
$$rd_{14} + d_{18} = \frac{d_1}{4}\,, \quad d_{18} = r^2 d_{20}\,, \quad 2rd_{16} + d_{19} = \frac{d_1}{4}\,, \quad r(d_{16} + d_{17}) + d_{19} = 0\,, \quad d_{19} = r^2 d_{21}\,,$$

Light WIMP+ SM

$$\mathcal{L}_{\psi,\mathrm{SM}} = \frac{c_{\psi 1}}{m_W}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu} + \frac{c_{\psi 2}}{m_W}\bar{\psi}\sigma^{\mu\nu}\psi\tilde{F}_{\mu\nu} + \sum_{q=u,d,s,c,b}\Bigg\{\frac{c_{\psi 3,q}}{m_W^2}\bar{\psi}\gamma^\mu\gamma_5\psi\bar{q}\gamma_\mu q + \frac{c_{\psi 4,q}}{m_W^2}\bar{\psi}\gamma^\mu\gamma_5\psi\bar{q}\gamma_\mu\gamma_5 q$$

$$+ \frac{c_{\psi 5,q}}{m_W^2}\bar{\psi}\gamma^\mu\psi\bar{q}\gamma_\mu q + \frac{c_{\psi 6,q}}{m_W^2}\bar{\psi}\gamma^\mu\psi\bar{q}\gamma_\mu\gamma_5 q + \frac{c_{\psi 7,q}}{m_W^3}\bar{\psi}\psi m_q\bar{q}q + \frac{c_{\psi 8,q}}{m_W^3}\bar{\psi}i\gamma_5\psi m_q\bar{q}q$$

$$+ \frac{c_{\psi 9,q}}{m_W^3}\bar{\psi}\psi m_q\bar{q}i\gamma_5 q + \frac{c_{\psi 10,q}}{m_W^3}\bar{\psi}i\gamma_5\psi m_q\bar{q}i\gamma_5 q + \frac{c_{\psi 11,q}}{m_W^3}\bar{\psi}i\partial_-^\mu\psi\bar{q}\gamma_\mu q$$

$$+ \frac{c_{\psi 12,q}}{m_W^3}\bar{\psi}\gamma_5\partial_-^\mu\psi\bar{q}\gamma_\mu q + \frac{c_{\psi 13,q}}{m_W^3}\bar{\psi}i\partial_-^\mu\psi\bar{q}\gamma_\mu\gamma_5 q + \frac{c_{\psi 14,q}}{m_W^3}\bar{\psi}\gamma_5\partial_-^\mu\psi\bar{q}\gamma_\mu\gamma_5 q$$

$$+ \frac{c_{\psi 15,q}}{m_W^3}\bar{\psi}\sigma_{\mu\nu}\psi m_q\bar{q}\sigma^{\mu\nu}q + \frac{c_{\psi 16,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\psi}\sigma^{\mu\nu}\psi m_q\bar{q}\sigma^{\rho\sigma}q\Bigg\} + \frac{c_{\psi 17}}{m_W^3}\bar{\psi}\psi G^A_{\alpha\beta}G^{A\alpha\beta}$$

$$+ \frac{c_{\psi 18}}{m_W^3}\bar{\psi}i\gamma_5\psi G^A_{\alpha\beta}G^{A\alpha\beta} + \frac{c_{\psi 19}}{m_W^3}\bar{\psi}\psi G^A_{\alpha\beta}\tilde{G}^{A\alpha\beta} + \frac{c_{\psi 20}}{m_W^3}\bar{\psi}i\gamma_5\psi G^A_{\alpha\beta}\tilde{G}^{A\alpha\beta} + \dots,$$

Majorana:

$c_{\psi n}$ with $n = 1, 2, 5, 6, 11, 12, 13, 14, 15, 16$ vanish,

Heavy WIMP + SM

$$\mathcal{L}_{\chi_v,\mathrm{SM}} = \frac{c_{\chi 1}}{m_W}\bar{\chi}_v\sigma_\perp^{\mu\nu}\chi_v F_{\mu\nu} + \frac{c_{\chi 2}}{m_W}\bar{\chi}_v\sigma_\perp^{\mu\nu}\chi_v \tilde{F}_{\mu\nu} + \sum_{q=u,d,s,c,b}\Bigg\{\frac{c_{\chi 3,q}}{m_W^2}\epsilon_{\mu\nu\rho\sigma}v^\mu\bar{\chi}_v\sigma_\perp^{\nu\rho}\chi_v\bar{q}\gamma^\sigma q$$
$$+ \frac{c_{\chi 4,q}}{m_W^2}\epsilon_{\mu\nu\rho\sigma}v^\mu\bar{\chi}_v\sigma_\perp^{\nu\rho}\chi_v\bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 5,q}}{m_W^2}\bar{\chi}_v\chi_v\bar{q}\not{v}\, q + \frac{c_{\chi 6,q}}{m_W^2}\bar{\chi}_v\chi_v\bar{q}\not{v}\,\gamma_5 q + \frac{c_{\chi 7,q}}{m_W^3}\bar{\chi}_v\chi_v m_q\bar{q}q$$
$$+ \frac{c_{\chi 8,q}}{m_W^3}\bar{\chi}_v\chi_v\bar{q}\not{v}\, iv\cdot D_- q + \frac{c_{\chi 9,q}}{m_W^3}\bar{\chi}_v\chi_v m_q\bar{q}i\gamma_5 q + \frac{c_{\chi 10,q}}{m_W^3}\bar{\chi}_v\chi_v\bar{q}\not{v}\,\gamma_5 iv\cdot D_- q$$
$$+ \frac{c_{\chi 11,q}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}i\partial_{-\mu}^\perp\chi_v\bar{q}\gamma_\nu q + \frac{c_{\chi 12,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v\sigma_\perp^{\mu\nu}i\partial_-^{\perp\rho}\chi_v\bar{q}\gamma^\sigma q + \frac{c_{\chi 13,q}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}i\partial_{-\mu}^\perp\chi_v\bar{q}\gamma_\nu\gamma_5 q$$
$$+ \frac{c_{\chi 14,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v\sigma_\perp^{\mu\nu}i\partial_-^{\perp\rho}\chi_v\bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 15,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}v^\mu\bar{\chi}_v\sigma_\perp^{\nu\rho}\chi_v\,\bar{q}(\not{v}\, iD_-^\sigma + \gamma^\sigma iv\cdot D_-)q$$
$$+ \frac{c_{\chi 16,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}v^\mu\bar{\chi}_v\sigma_\perp^{\nu\rho}\chi_v\bar{q}(\not{v}\, iD_-^\sigma + \gamma^\sigma iv\cdot D_-)\gamma_5 q + \frac{c_{\chi 17,q}}{m_W^3}\bar{\chi}_v i\partial_-^{\perp\mu}\chi_v\bar{q}\gamma_\mu q$$
$$+ \frac{c_{\chi 18,q}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}\partial_{+\mu}^\perp\chi_v\bar{q}\gamma_\nu q + \frac{c_{\chi 18,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v\sigma_\perp^{\mu\nu}\partial_+^{\perp\rho}\chi_v\bar{q}\gamma^\sigma q + \frac{c_{\chi 20,q}}{m_W^3}\bar{\chi}_v i\partial_-^{\perp\mu}\chi_v\bar{q}\gamma_\mu\gamma_5 q$$
$$+ \frac{c_{\chi 21,q}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}\partial_{+\mu}^\perp\chi_v\bar{q}\gamma_\nu\gamma_5 q + \frac{c_{\chi 22,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v\sigma_\perp^{\mu\nu}\partial_+^{\perp\rho}\chi_v\bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 23,q}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}\chi_v m_q\bar{q}\sigma_{\mu\nu}q$$
$$+ \frac{c_{\chi 24,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v\sigma_\perp^{\mu\nu}\chi_v m_q\bar{q}\sigma^{\rho\sigma}q\Bigg\} + \frac{c_{\chi 25}}{m_W^3}\bar{\chi}_v\chi_v G_{\alpha\beta}^A G^{A\alpha\beta} + \frac{c_{\chi 26}}{m_W^3}\bar{\chi}_v\chi_v G_{\alpha\beta}^A\tilde{G}^{A\alpha\beta}$$
$$+ \frac{c_{\chi 27}}{m_W^3}\bar{\chi}_v\chi_v v_\mu v_\nu G^{A\mu}{}_\alpha G^{A\nu\alpha} + \frac{c_{\chi 28}}{m_W^3}\bar{\chi}_v\sigma_\perp^{\mu\nu}\chi_v\epsilon_{\mu\nu\alpha\beta}v^\alpha v^\gamma G^{A\beta\delta}G_{\gamma\delta}^A + \dots\,, \qquad (7$$

Lorentz:

$$\frac{m_W}{M}c_{\chi 3} + 2c_{\chi 12} = \frac{m_W}{M}c_{\chi 4} + 2c_{\chi 14} = \frac{m_W}{M}c_{\chi 5} - 2c_{\chi 17} = \frac{m_W}{M}c_{\chi 6} - 2c_{\chi 20} = c_{\chi 11} = c_{\chi 13} = 0\,,$$

Majorana:

$c_{\chi n}$ vanish for n=1, 2, 5, 6, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24.