# QCD, Effective theories and dark matter

RICHARD HILL

University of Chicago

INT, Seattle

2 October, 2015

*based on work with M.P. Solon: (Sakurai thesis award)*

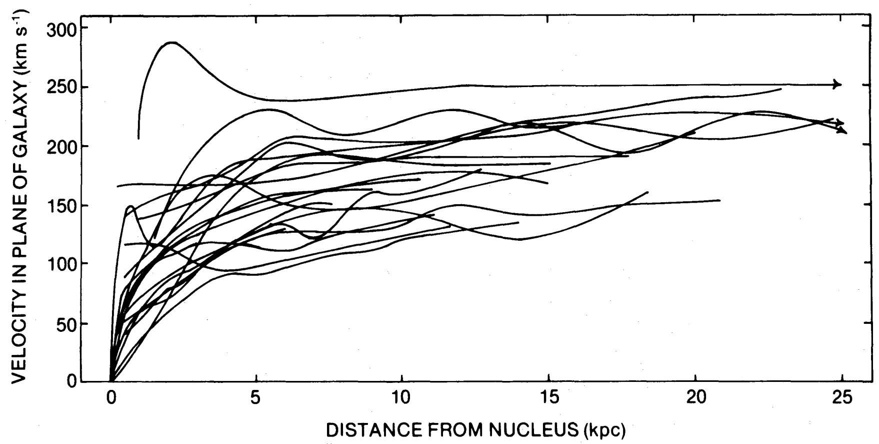
*Heavy WIMP Effective Theory 1111.0016, 1309.4092, PRL*

*Standard Model Anatomy of WIMP Direct Detection I, II 1401.3339, 1409.8290, PRD*

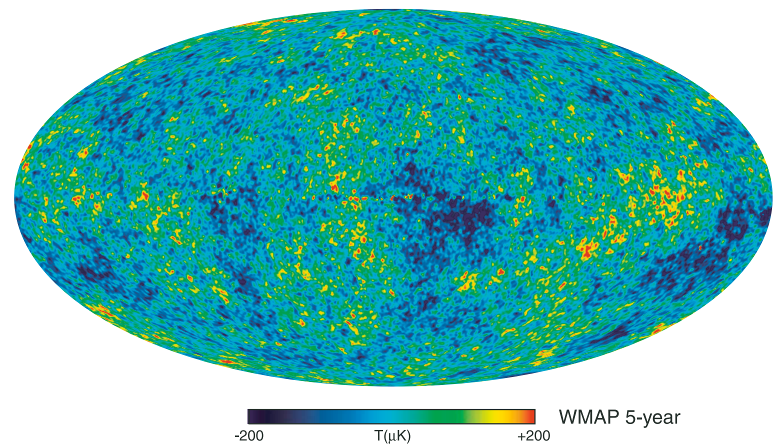
*Thanks to co-organizers and participants of MITP program "Effective Theories and Dark Matter", March 2015: https://indico.mitp.uni-mainz.de/conferenceDisplay.py?ovw=True&confId=25*

*See also INT workshop "Nuclear aspects of DM searches", December 2014: http://www.int.washington.edu/PROGRAMS/14-57w/*

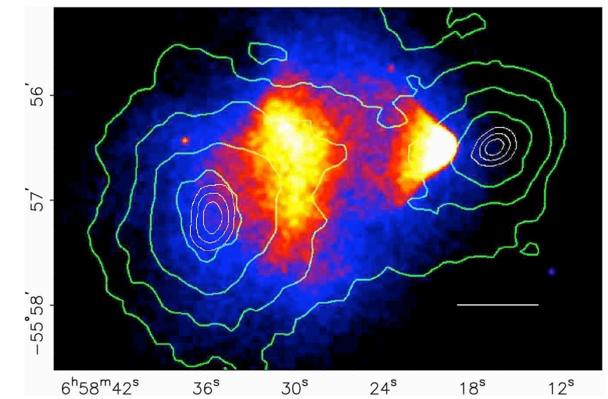
# ***The dark matter problem***




modification of galactic rotation curves

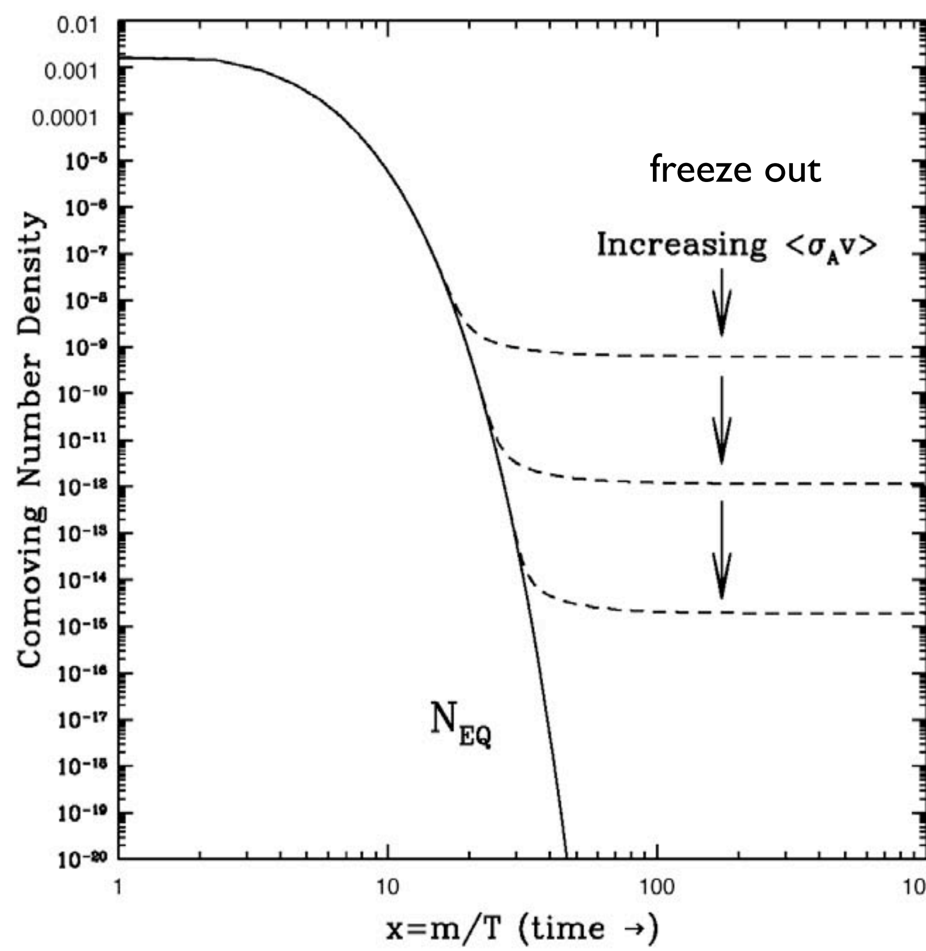



imprints on microwave background

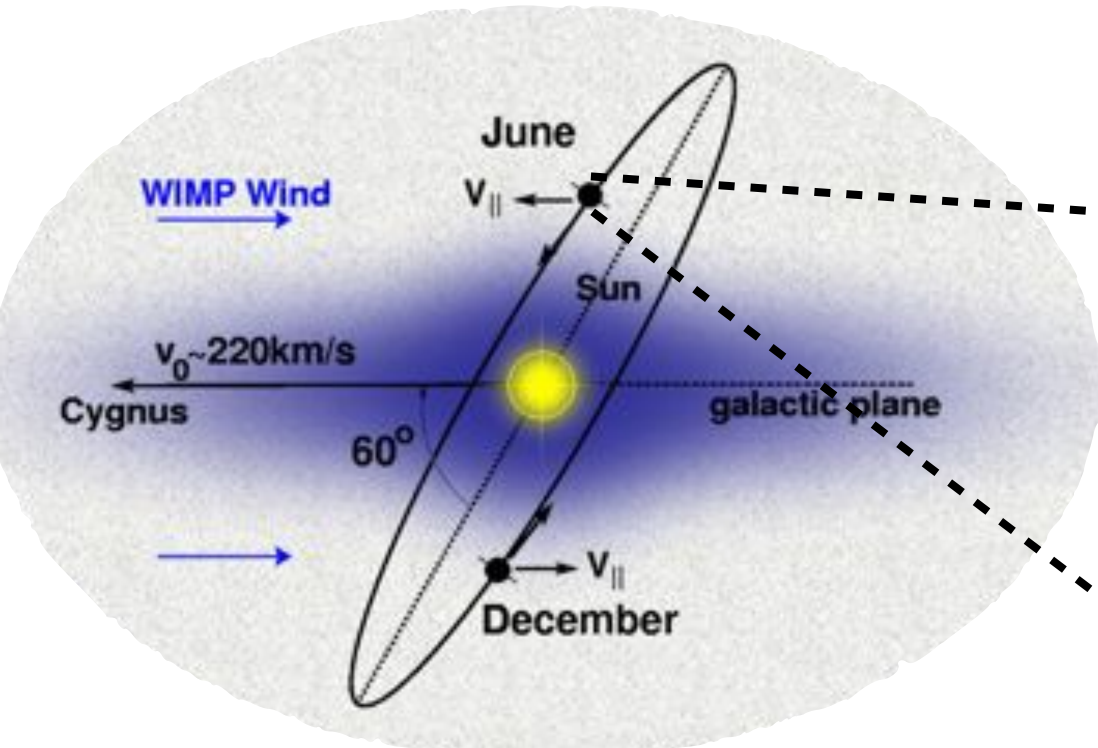


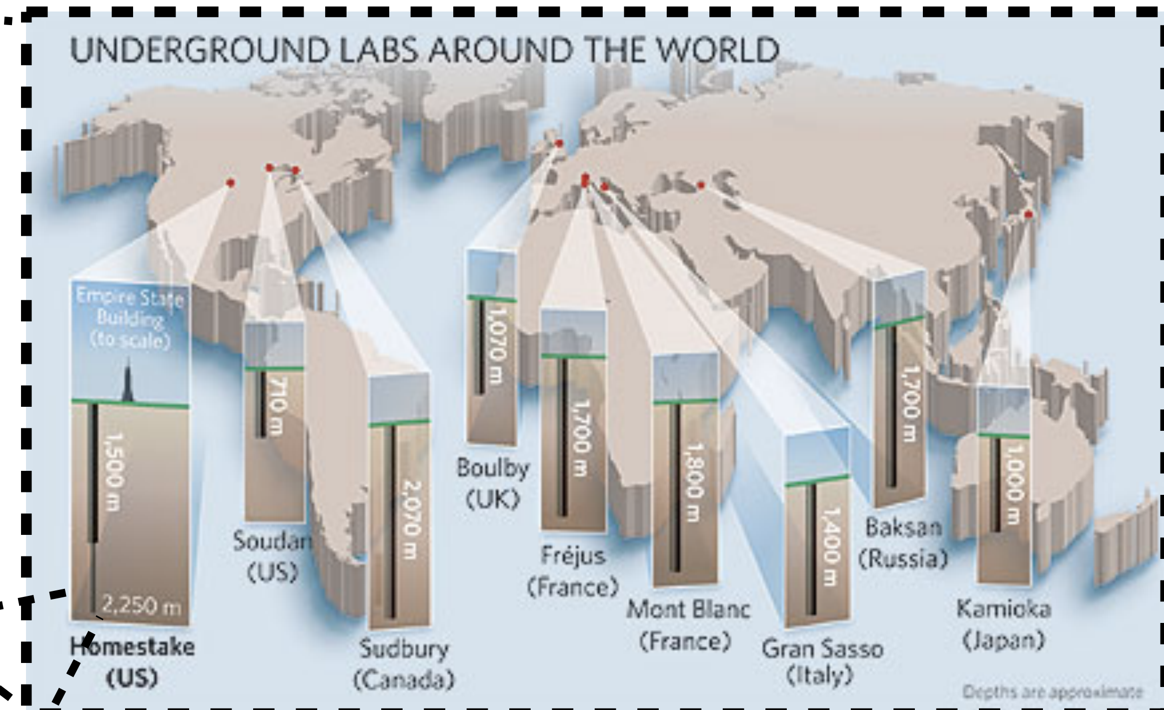

apparent extra collisionless matter from lensing measurements

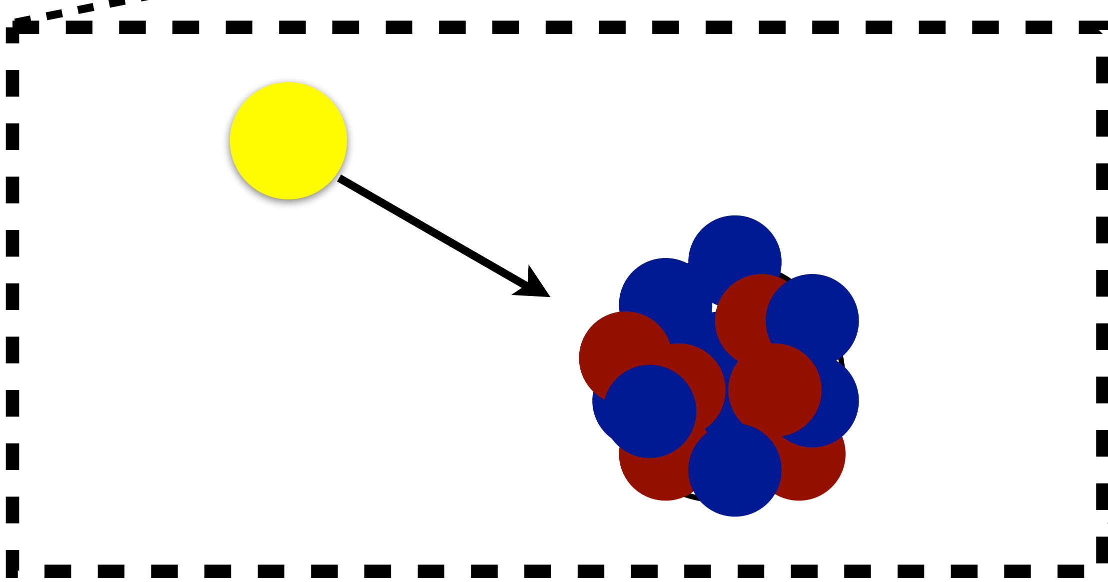
*perhaps a thermal relic Weakly Interacting Massive Particle (WIMP)*



# *The dark matter problem*



## *Three motivations for studying QCD & DM*

- important, sometimes dramatic, impact on discovery potential

- post-discovery interpretation and/or anomaly debunking

- new field theory tools

# Some themes in the contemporary particle physics:

- $\Lambda_{\text{New Physics}} > m_W$ (maybe $>> m_W$)

- *interplay of particle, astro, nuclear*

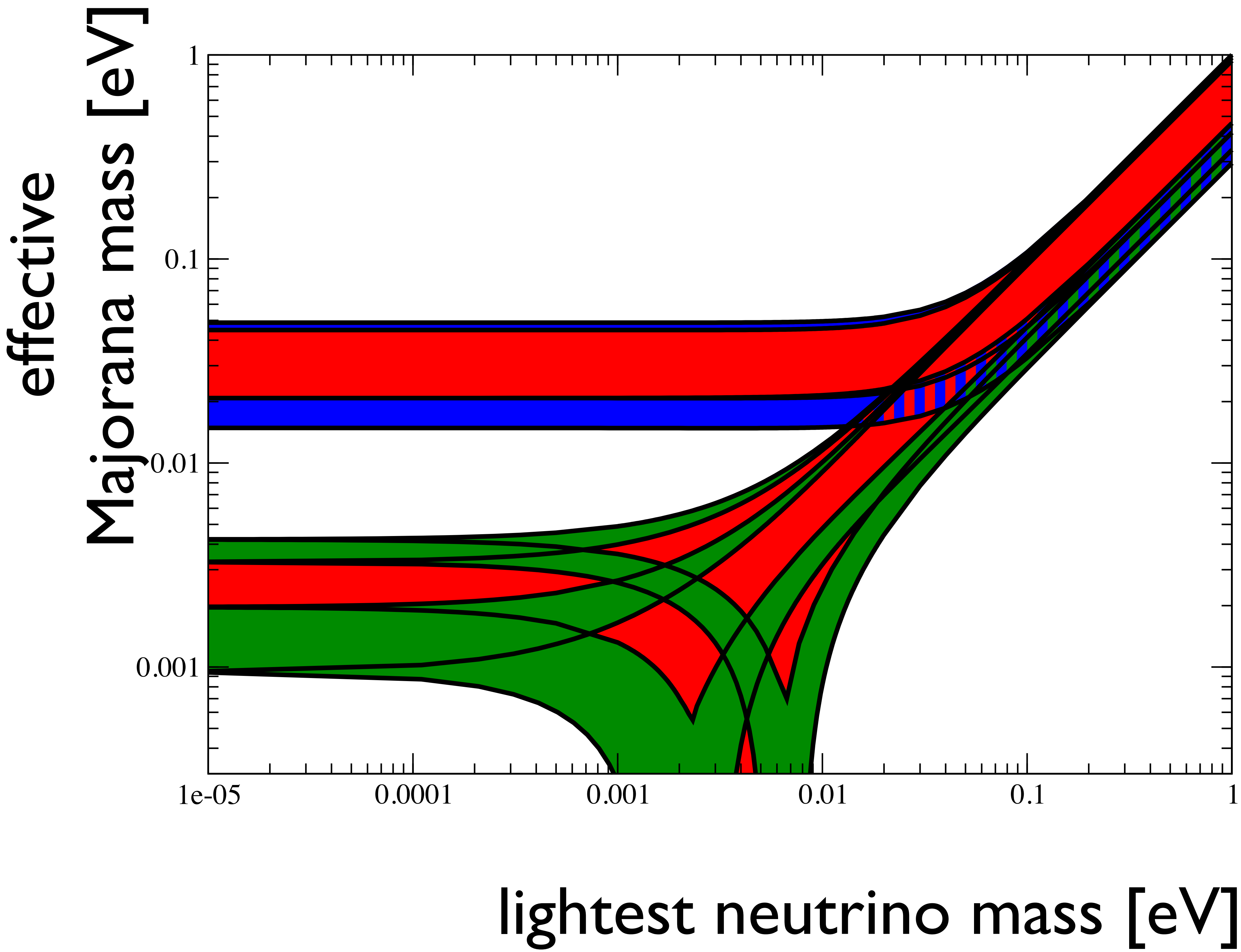
- *lattice QCD and baryon matrix elements*

- interplay of radiative corrections and hadronic structure


Compelling physics questions demand analysis outside the comfort zone of any one field.

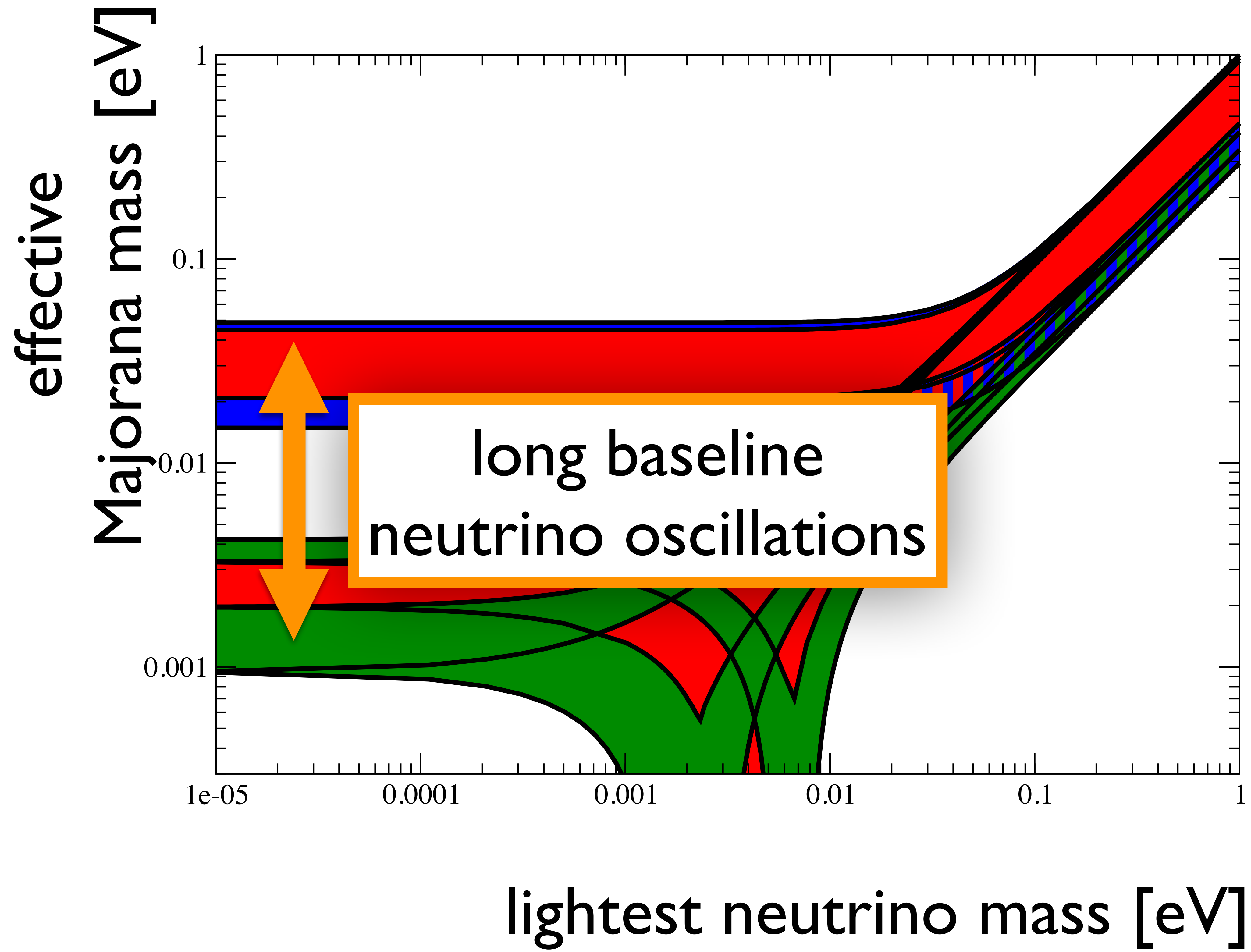
*Dark Matter applications a prime example*

*Interplay of particle-, nuclear-, astro-physics/cosmology*



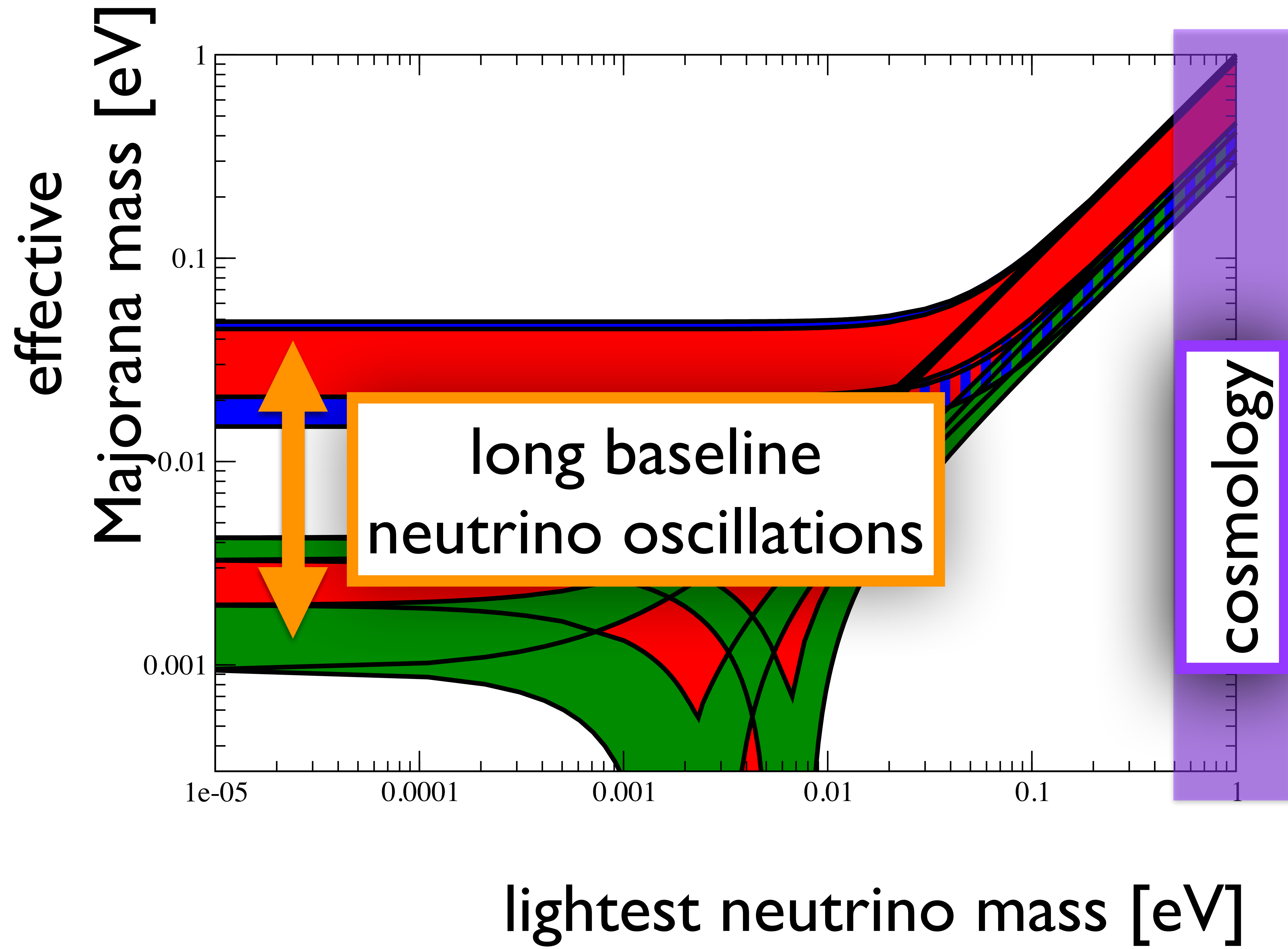

- Observability of lepton number violation depends on presently unknown neutrino mass ordering

*Interplay of particle-, nuclear-, astro-physics/cosmology*



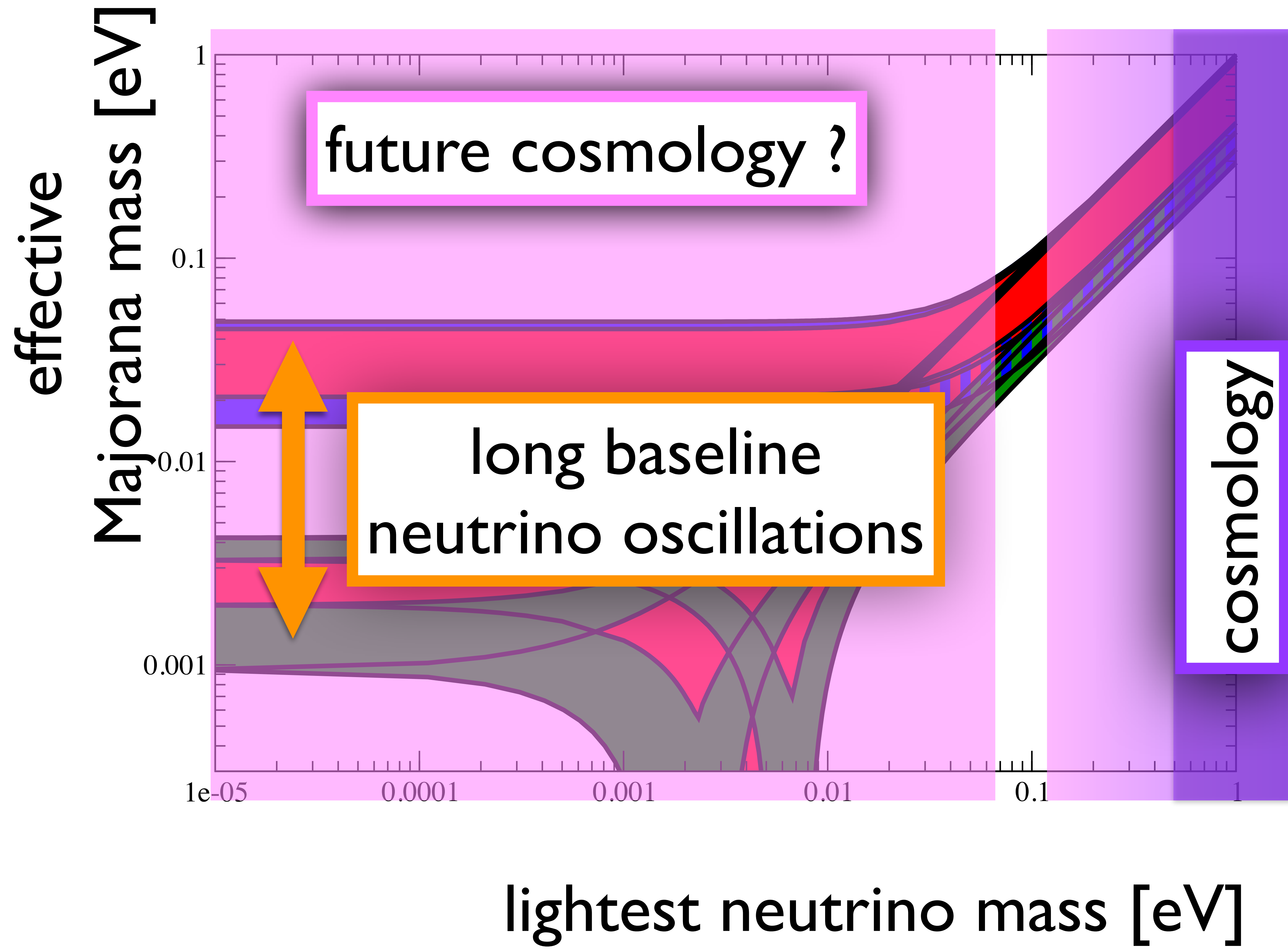

- Observability of lepton number violation depends on presently unknown neutrino mass ordering

## *Interplay of particle-, nuclear-, astro-physics/cosmology*



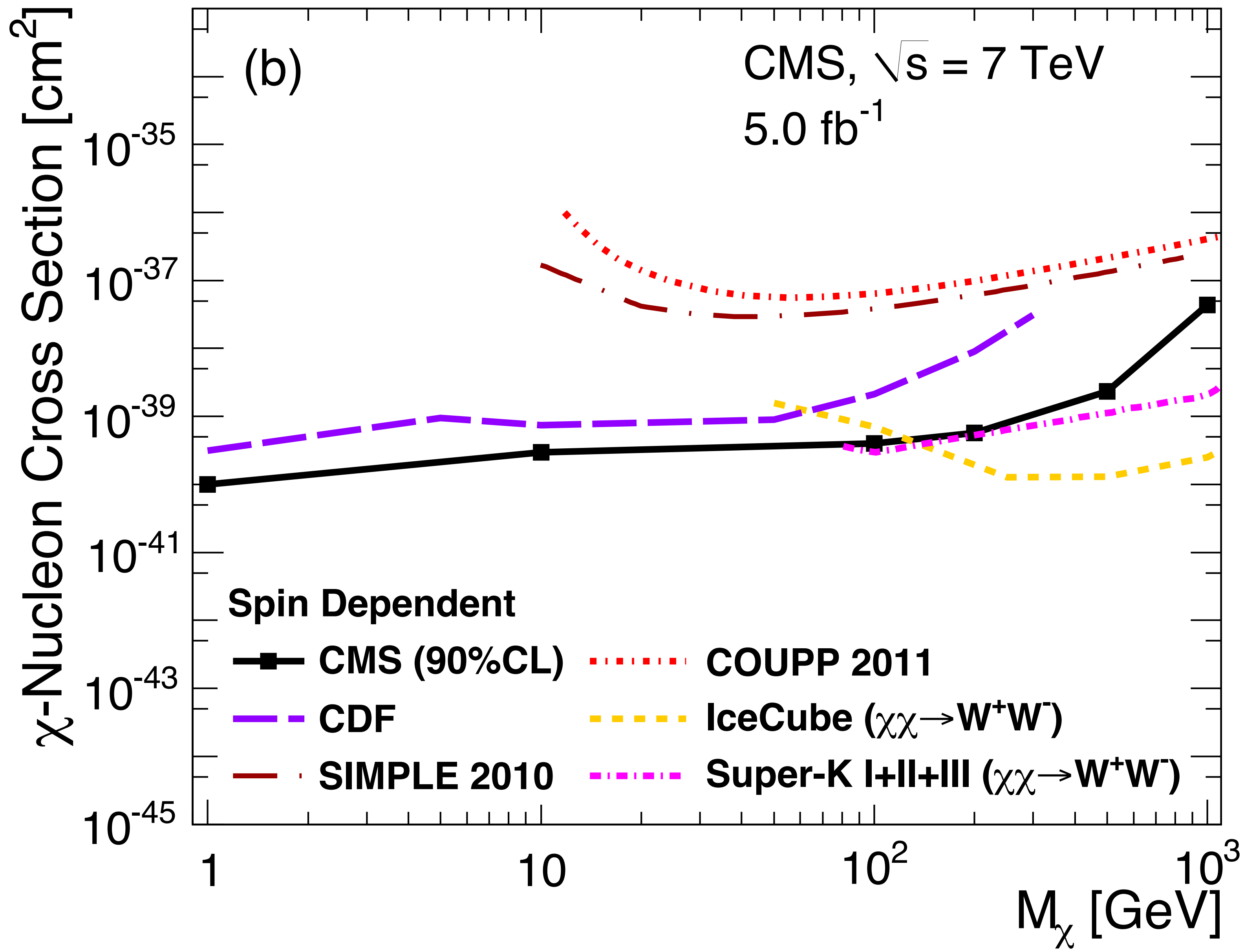

• Observability of lepton number violation depends on presently unknown neutrino mass ordering

*Interplay of particle-, nuclear-, astro-physics/cosmology*




- Observability of lepton number violation depends on presently unknown neutrino mass ordering

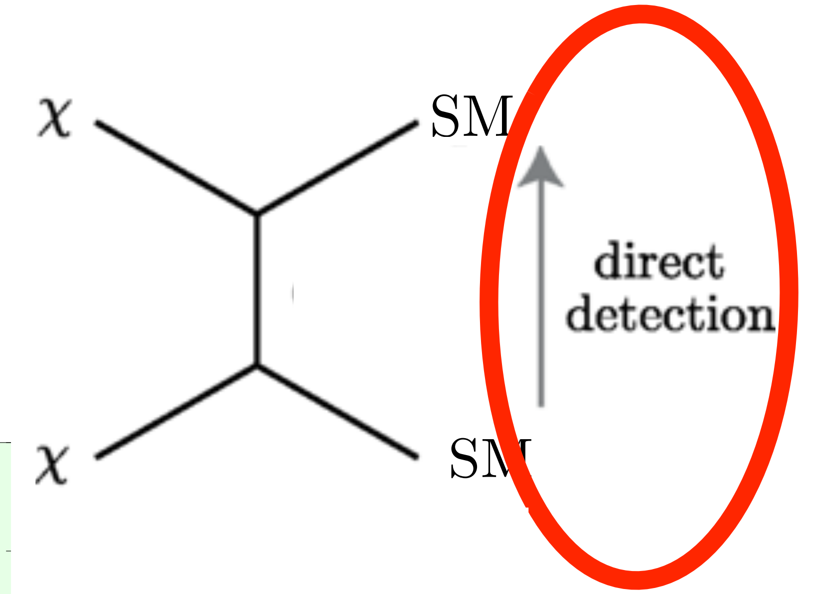
# *Interplay of particle-, nuclear-, astro-physics/cosmology*

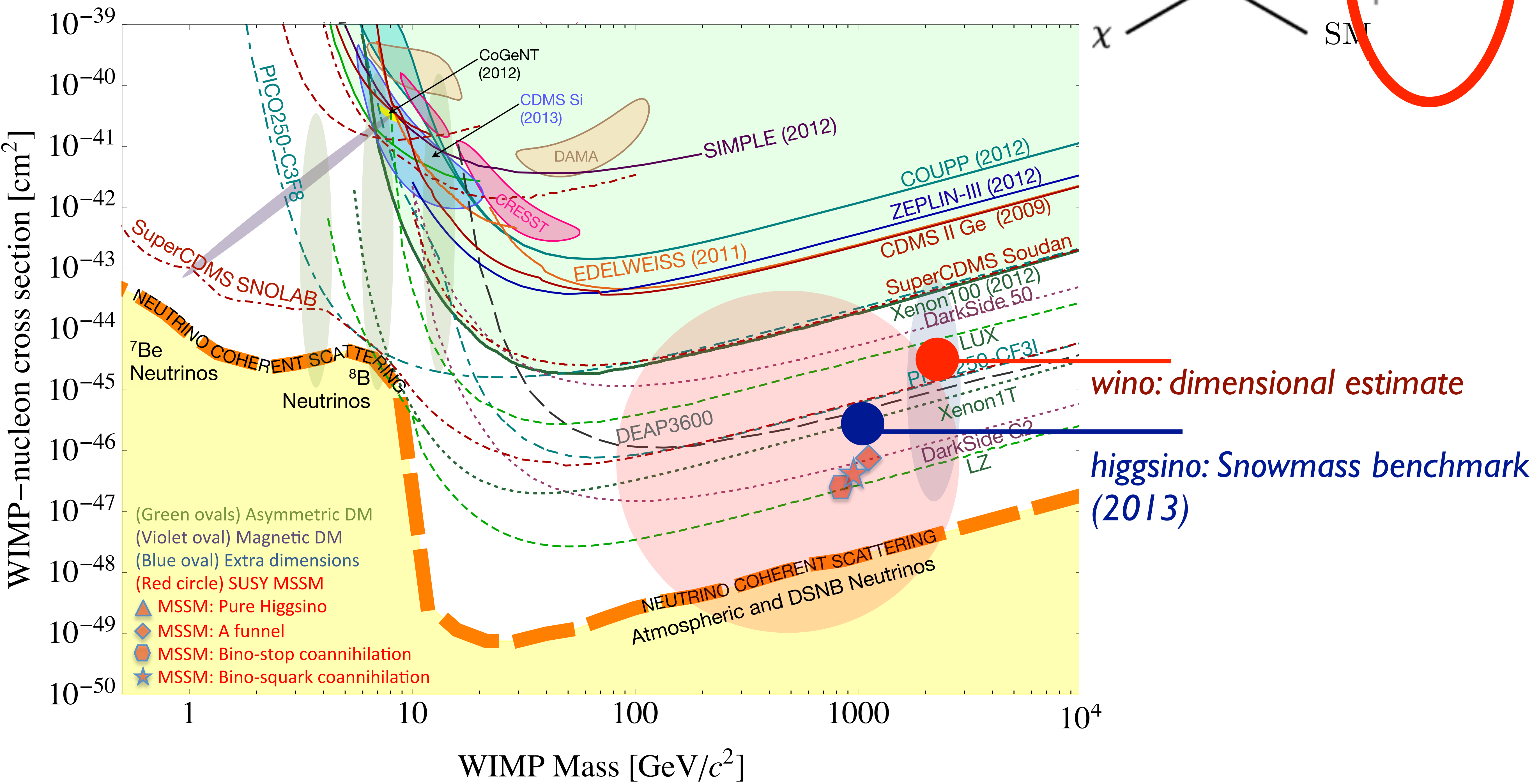



Axial-vector quark contact interaction with Dirac fermion WIMP

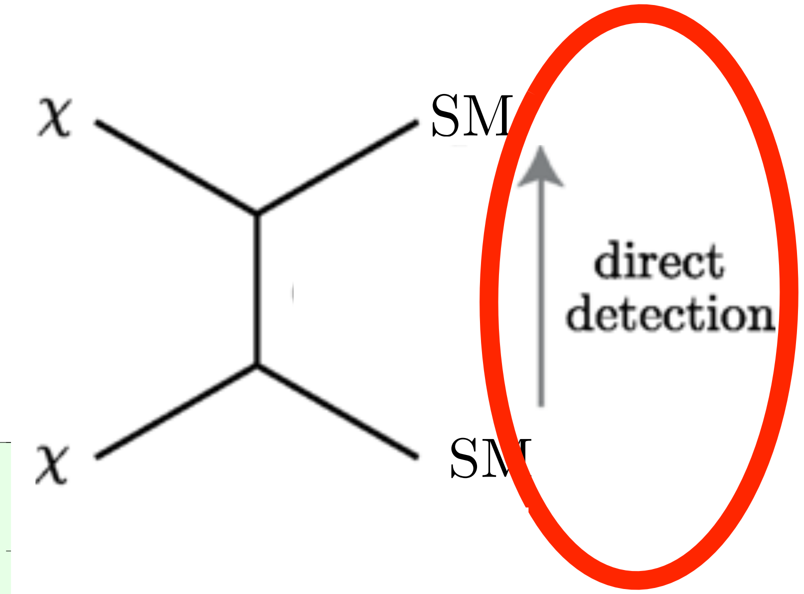
- Wide range of searches with overlapping constraints

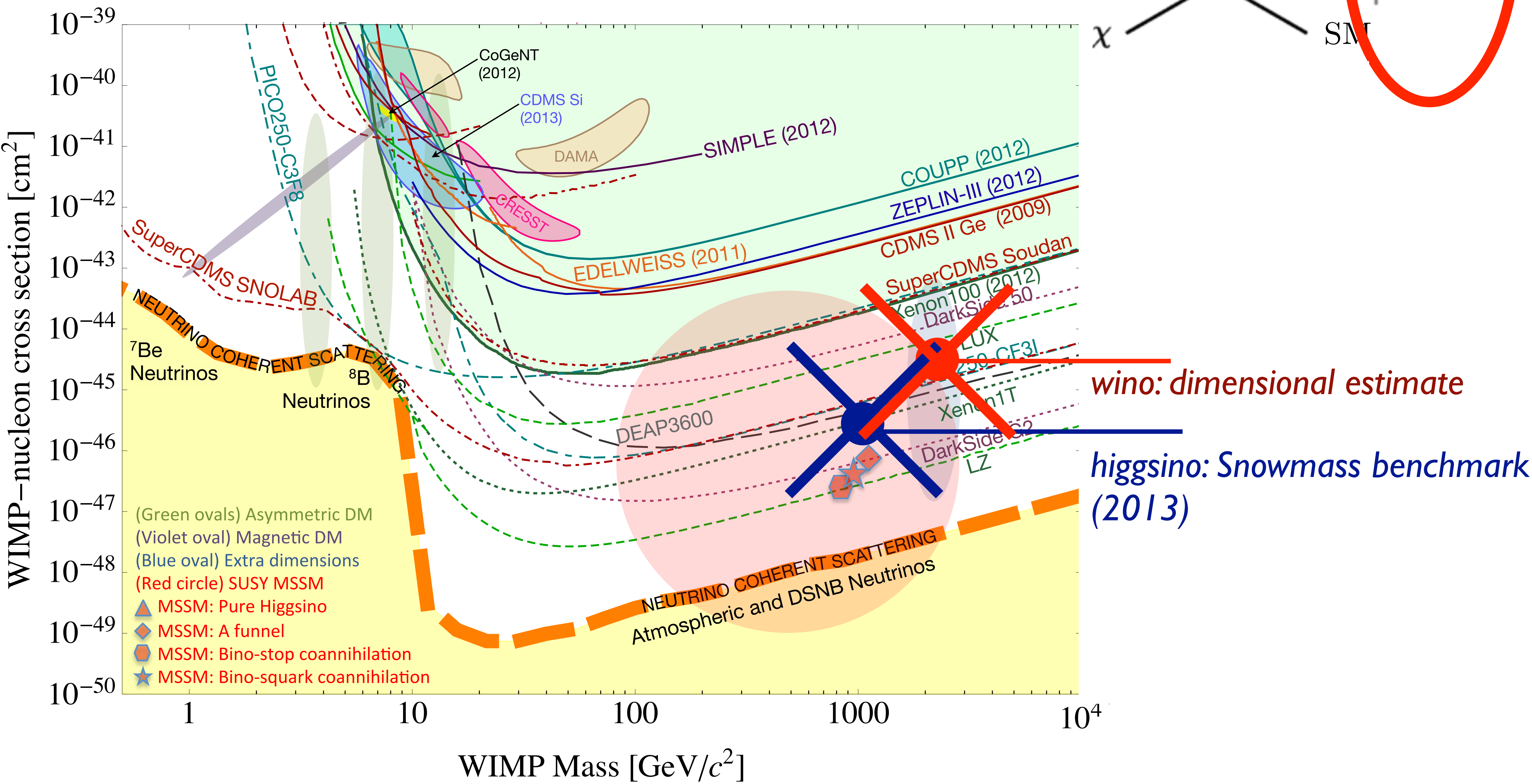
# Not quibbling about percents (example 1: heavy WIMP scattering)



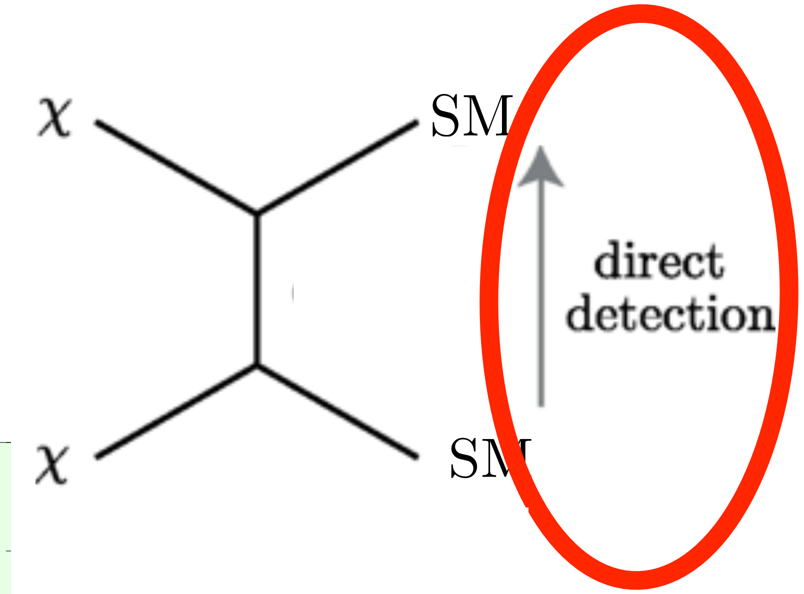



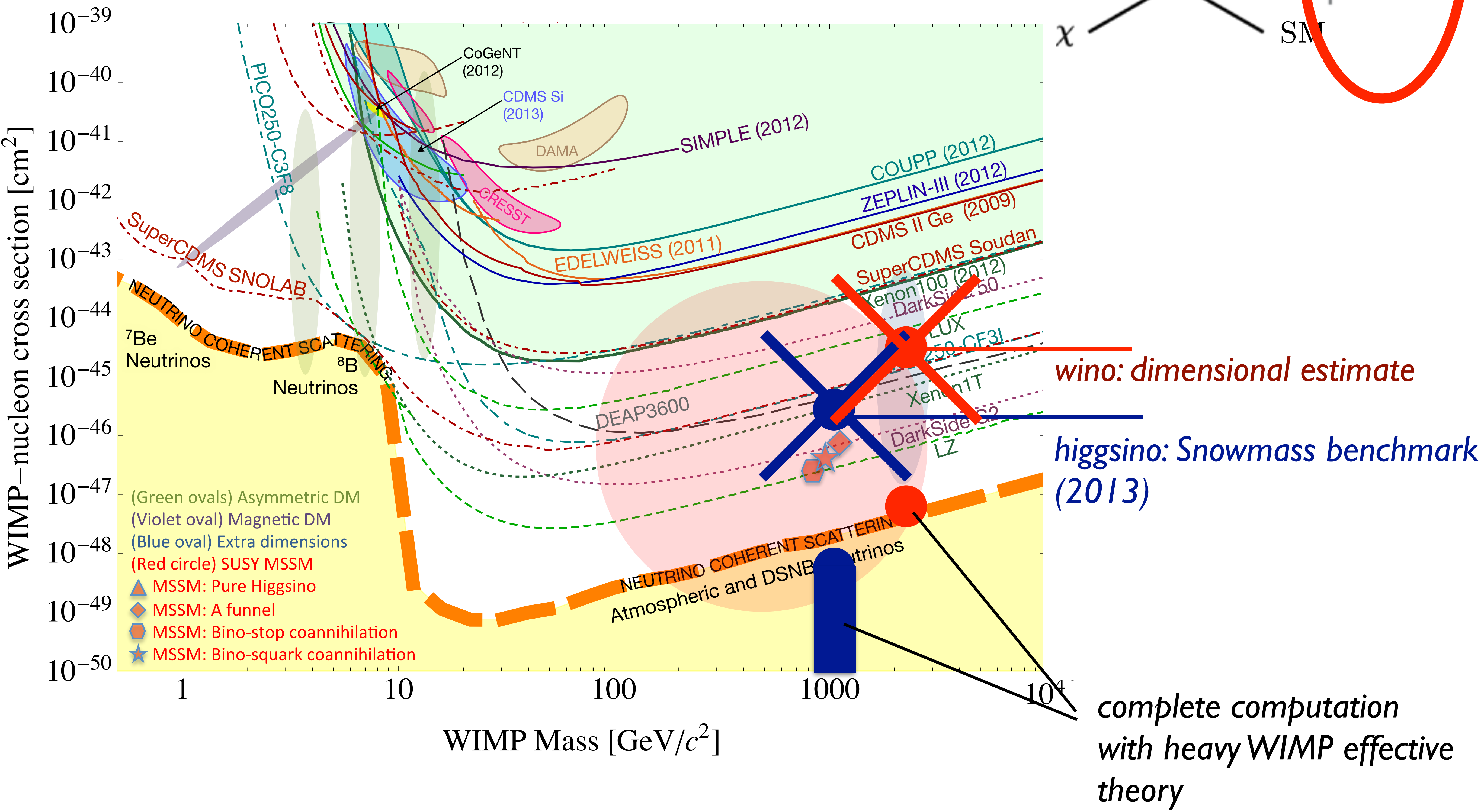
# Not quibbling about percents (example 1: heavy WIMP scattering)



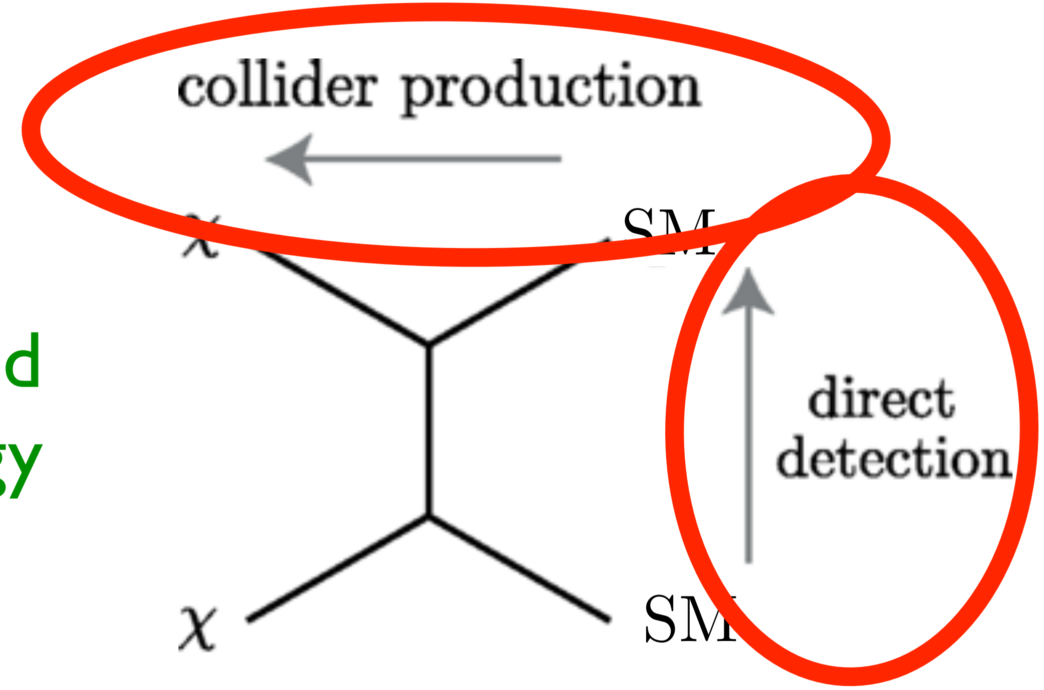



# Not quibbling about percents (example 1: heavy WIMP scattering)

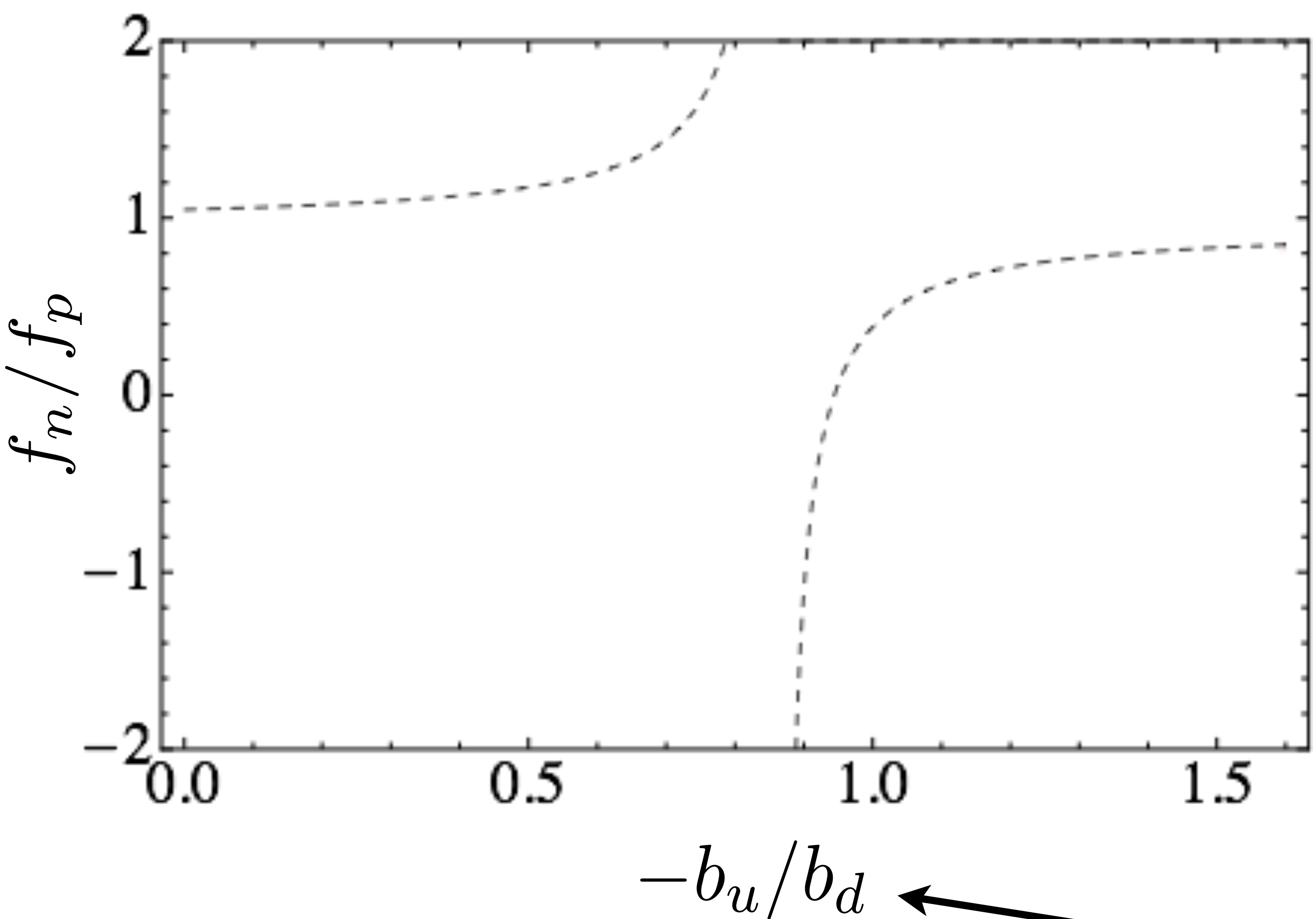


# Not quibbling about percents (example 2: light WIMPs)




DM complementarity: connect direct detection and collider phenomenology



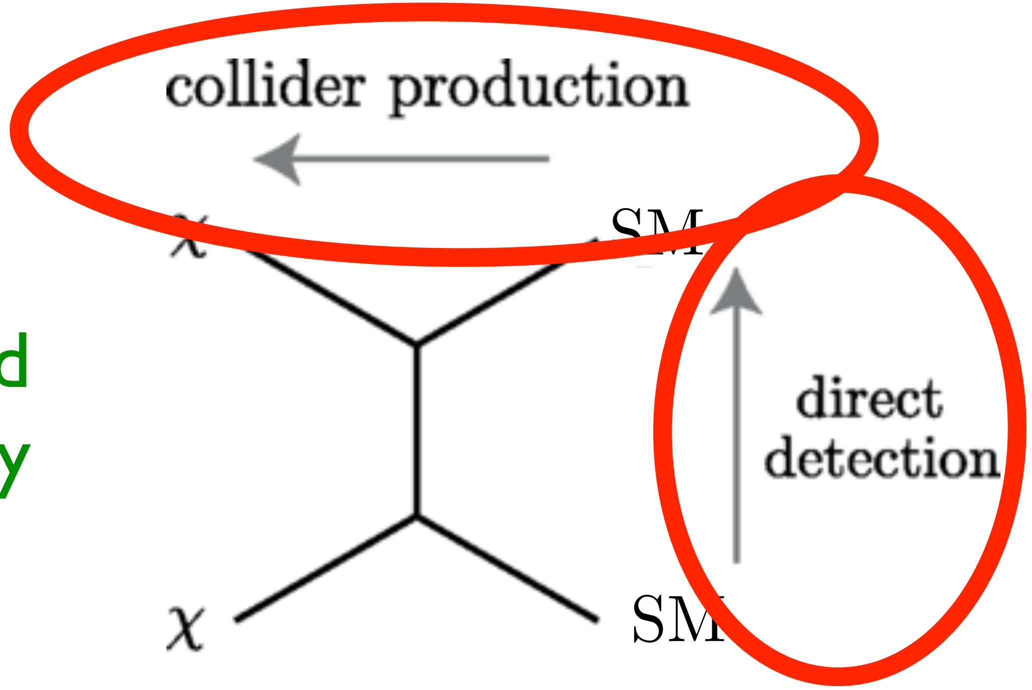

$f_n/f_p$ = ratio of SI nucleon amplitudes for WIMP-nucleon scattering

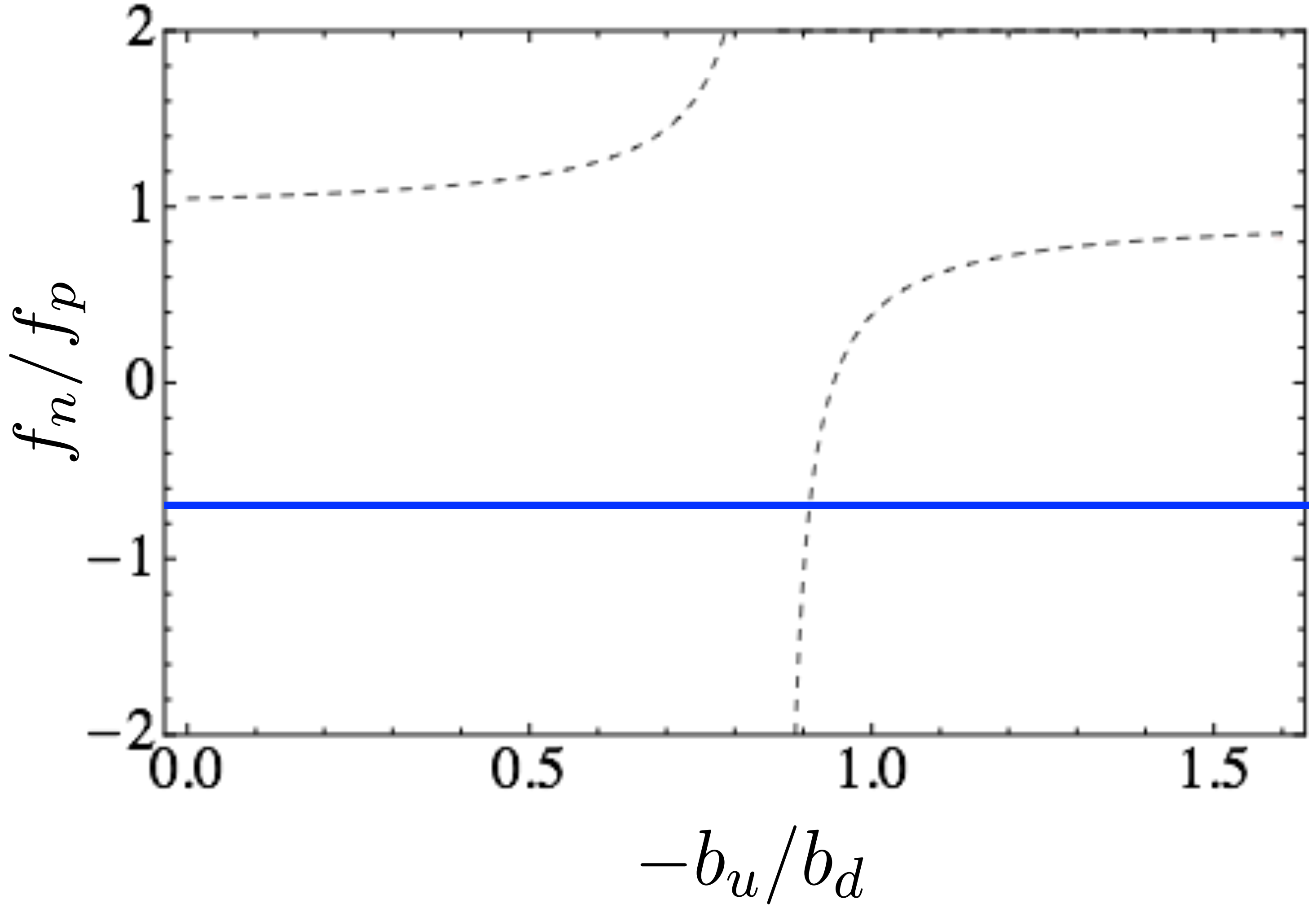
four-fermion interactions constrained by collider bounds on missing energy signatures

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

# Not quibbling about percents (example 2: light WIMPs)

DM complementarity: connect direct detection and collider phenomenology

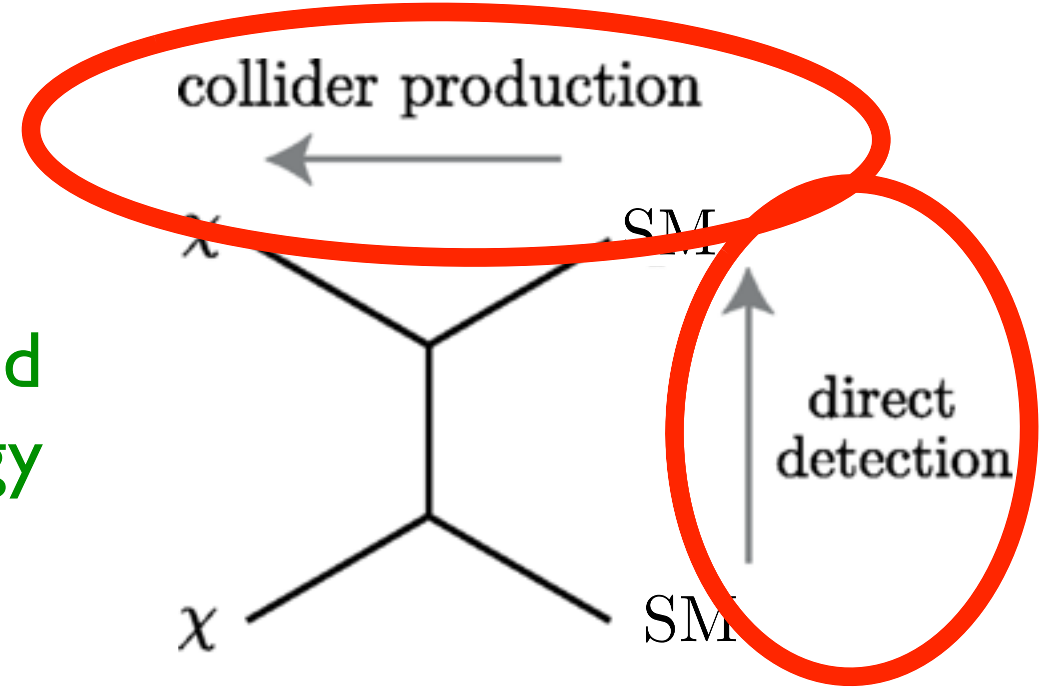


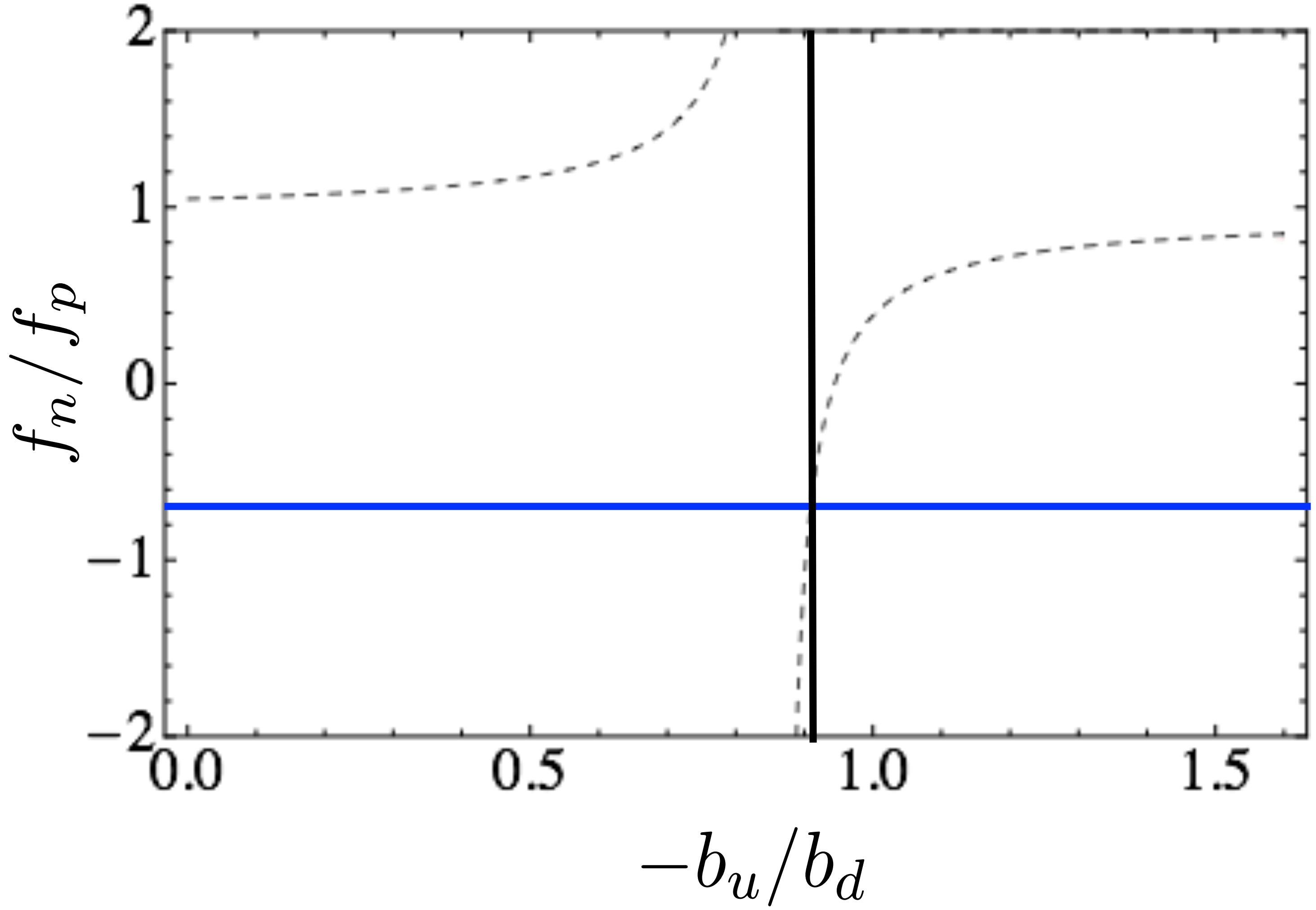

$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

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

# Not quibbling about percents (example 2: light WIMPs)




DM complementarity: connect direct detection and collider phenomenology

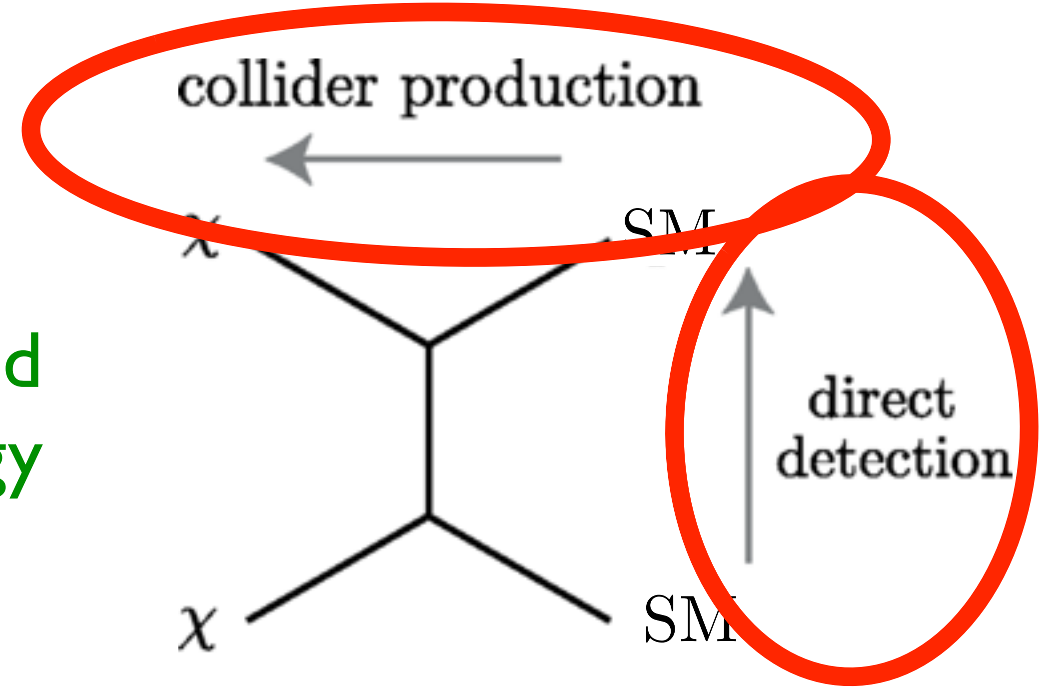



$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

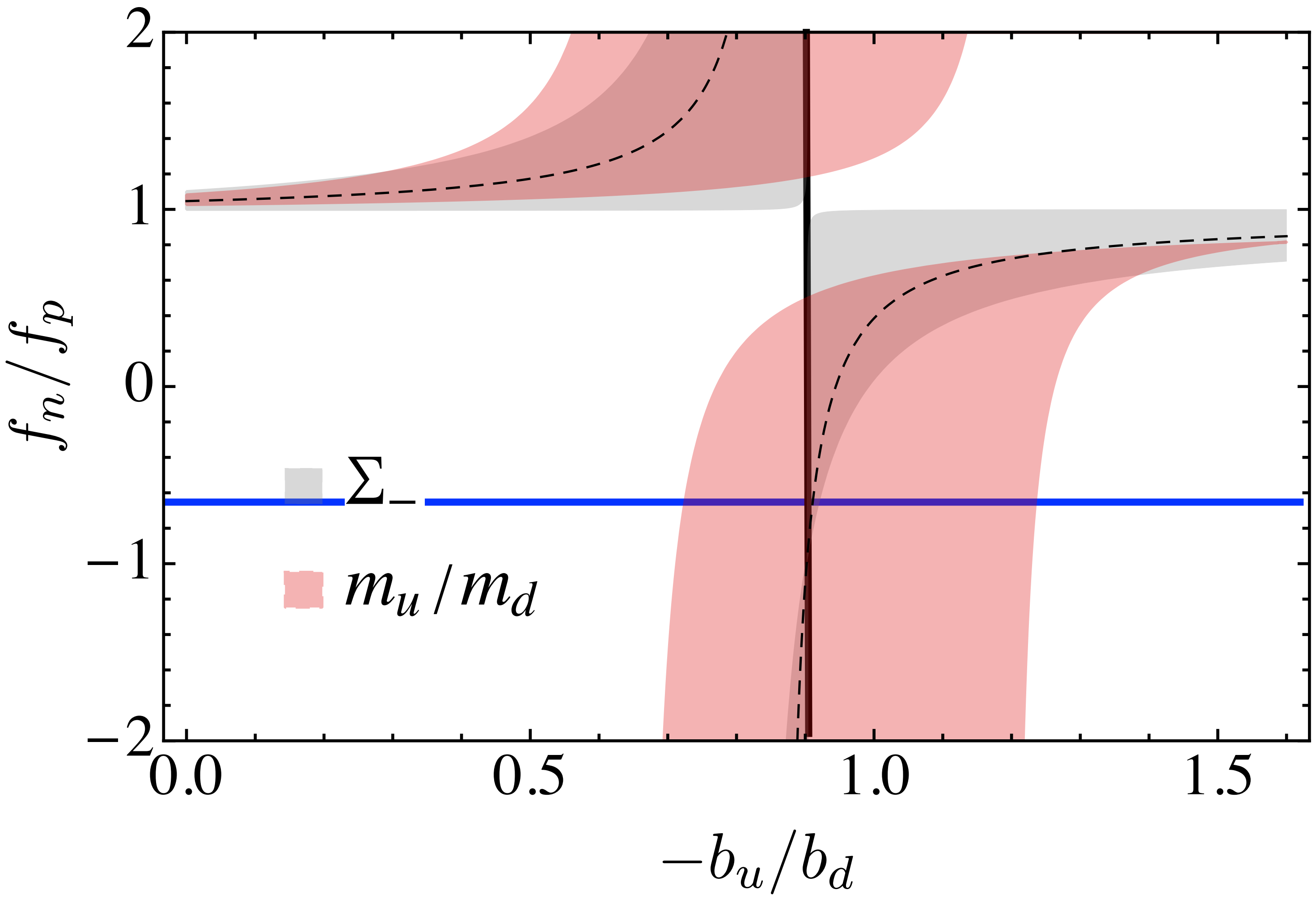
Solution: $b_u/b_d$=-0.9

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

# Not quibbling about percents (example 2: light WIMPs)




DM complementarity: connect direct detection and collider phenomenology

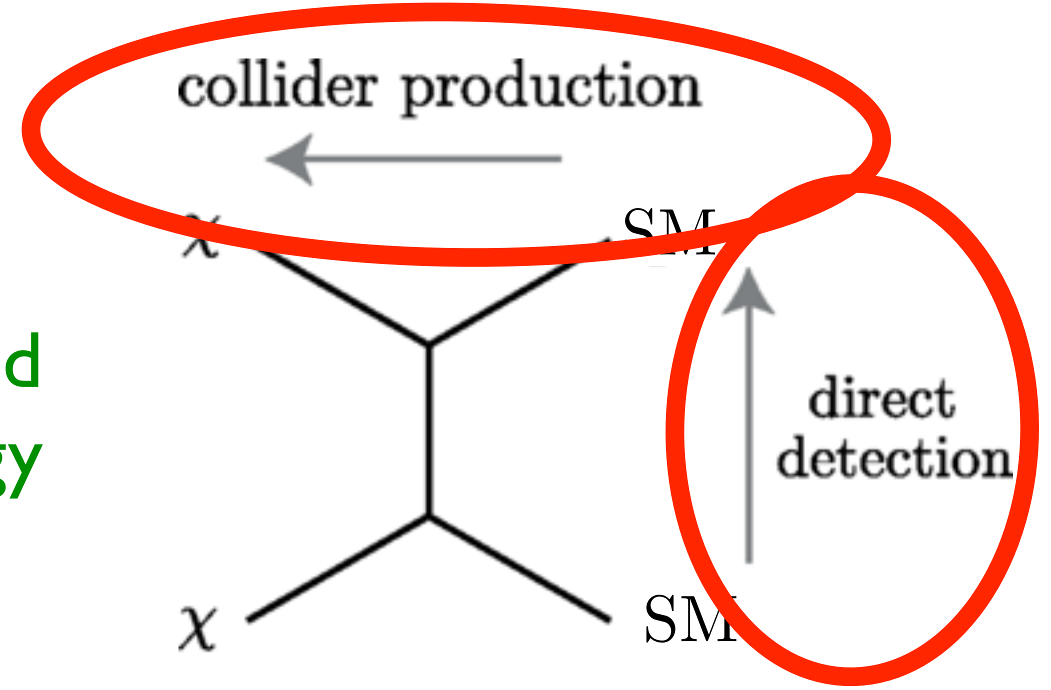



$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

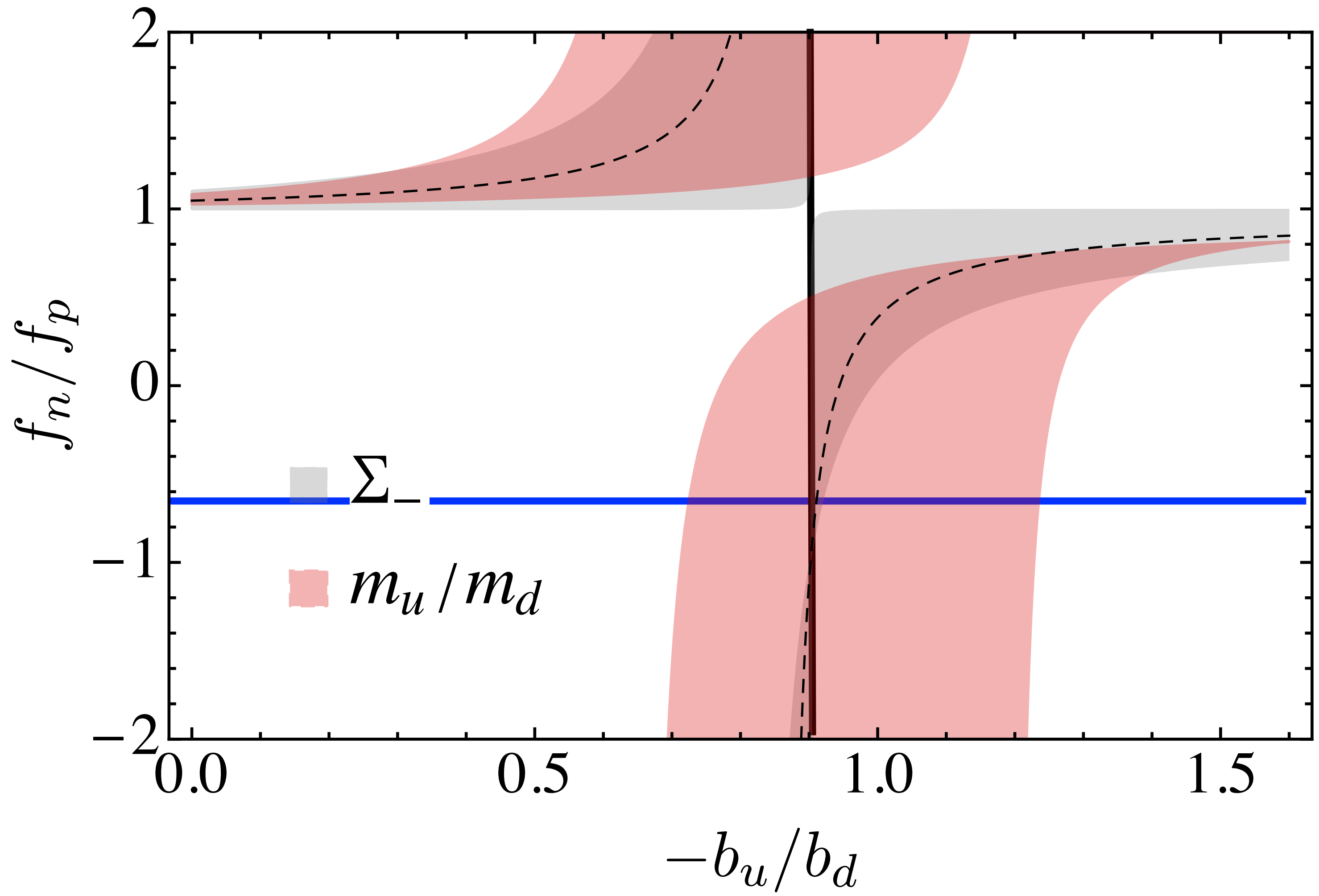
Solution: $b_u/b_d = -0.9$

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

# Not quibbling about percents (example 2: light WIMPs)




DM complementarity: connect direct detection and collider phenomenology



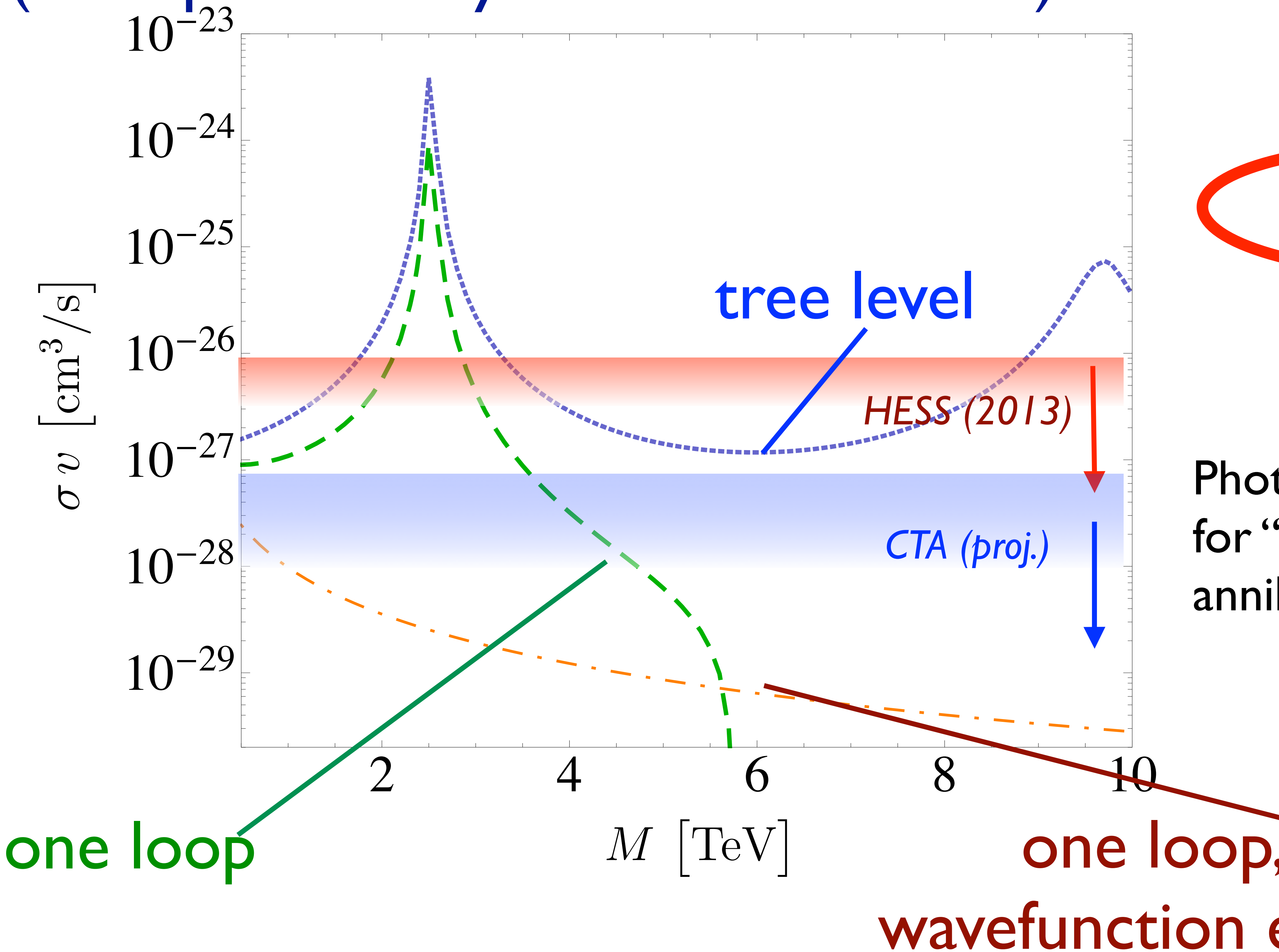

$f_n/f_p \approx -Z/(A-Z) \approx -0.7$ engineered to reconcile DAMA with results from Xe and other nuclei

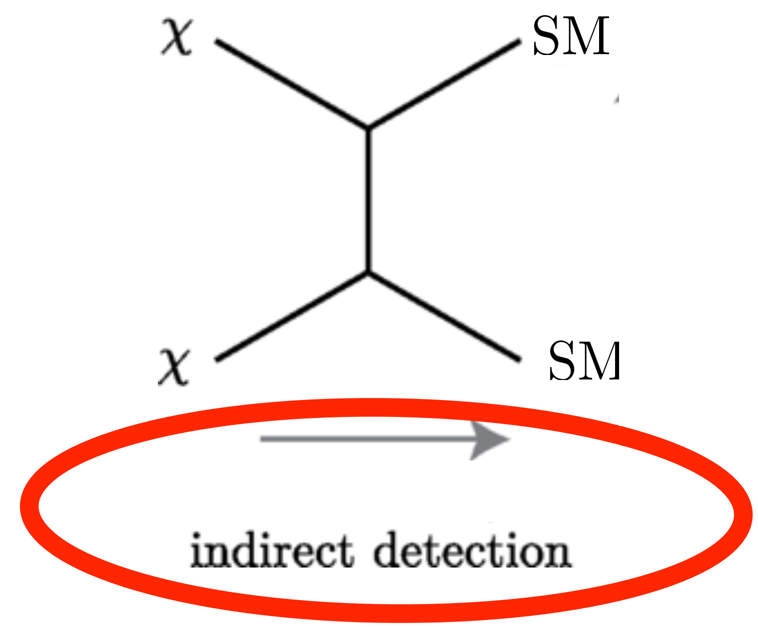
cf. $b_u/b_d$=-1.08 from "isospin-violating" DM

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 (example 3: heavy WIMP annihilation)

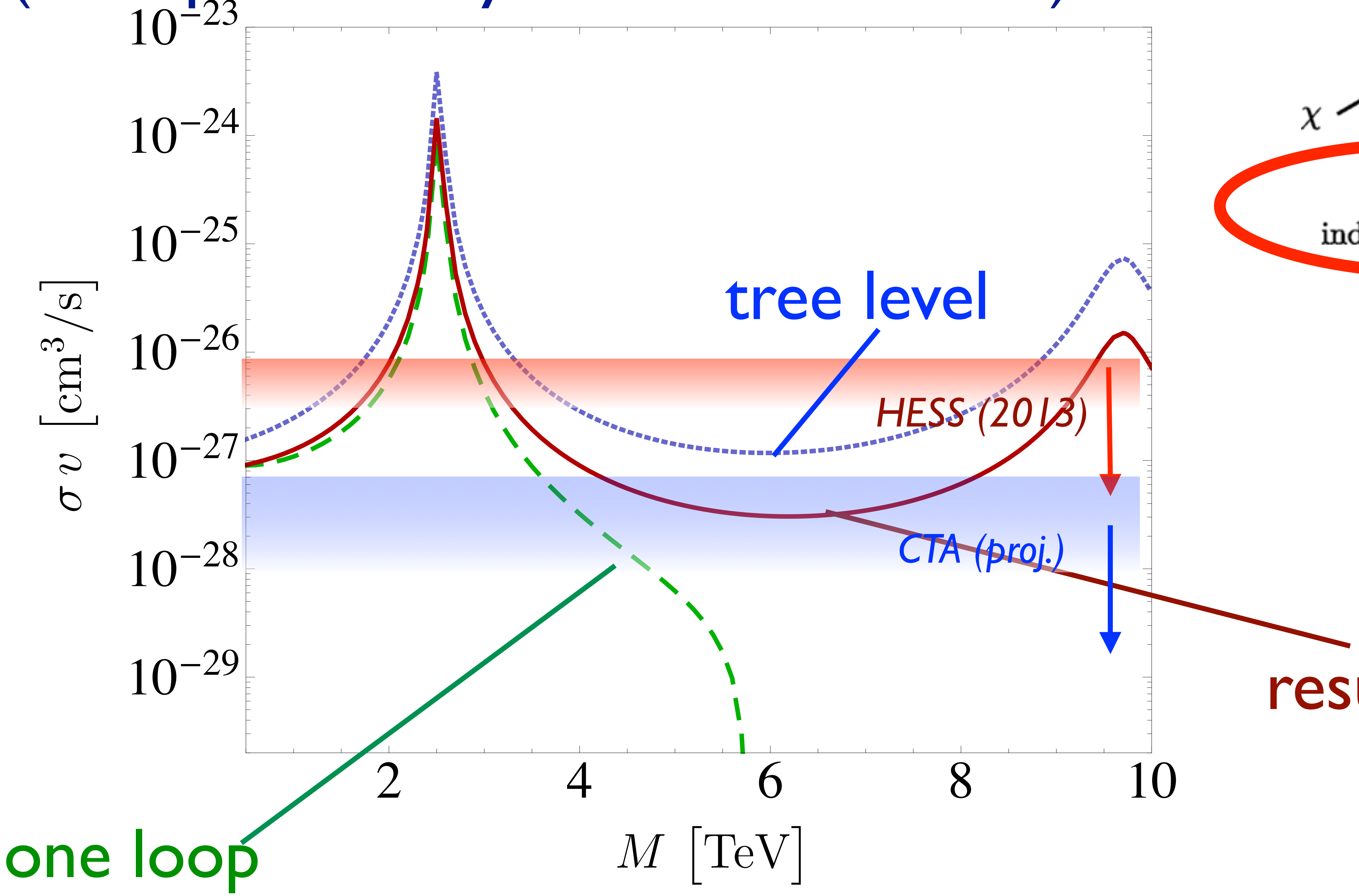


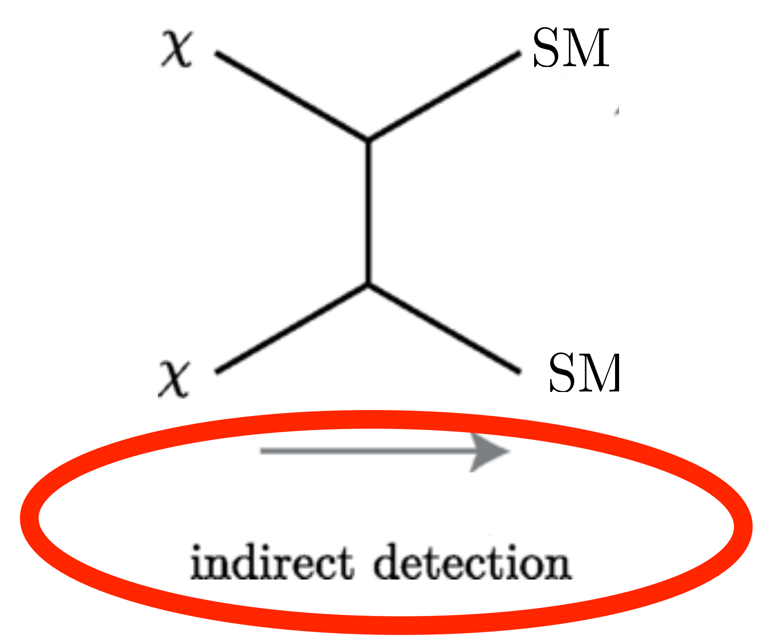




Photon line signal for “wino” annihilation

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

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



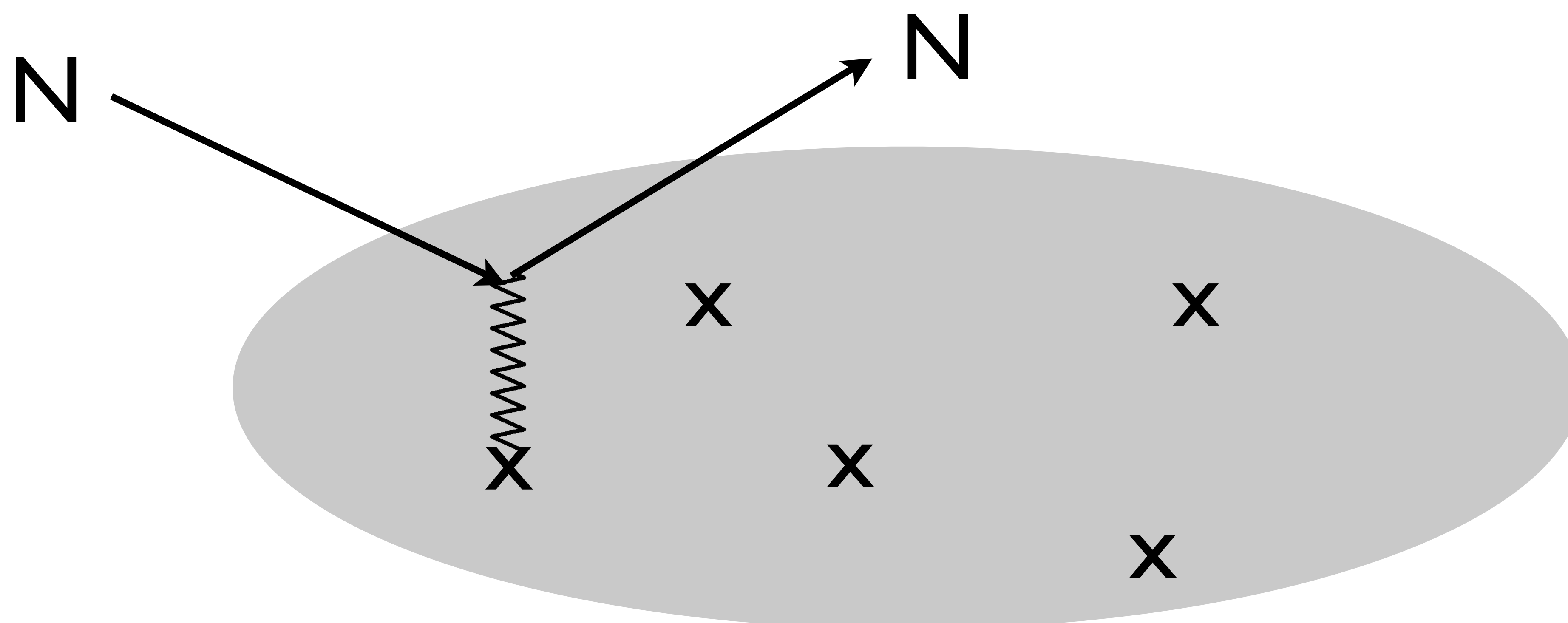




Multi-scale field theory problem, breakdown of naive perturbation theory

# Heavy WIMP effective theory

# Mechanisms versus models

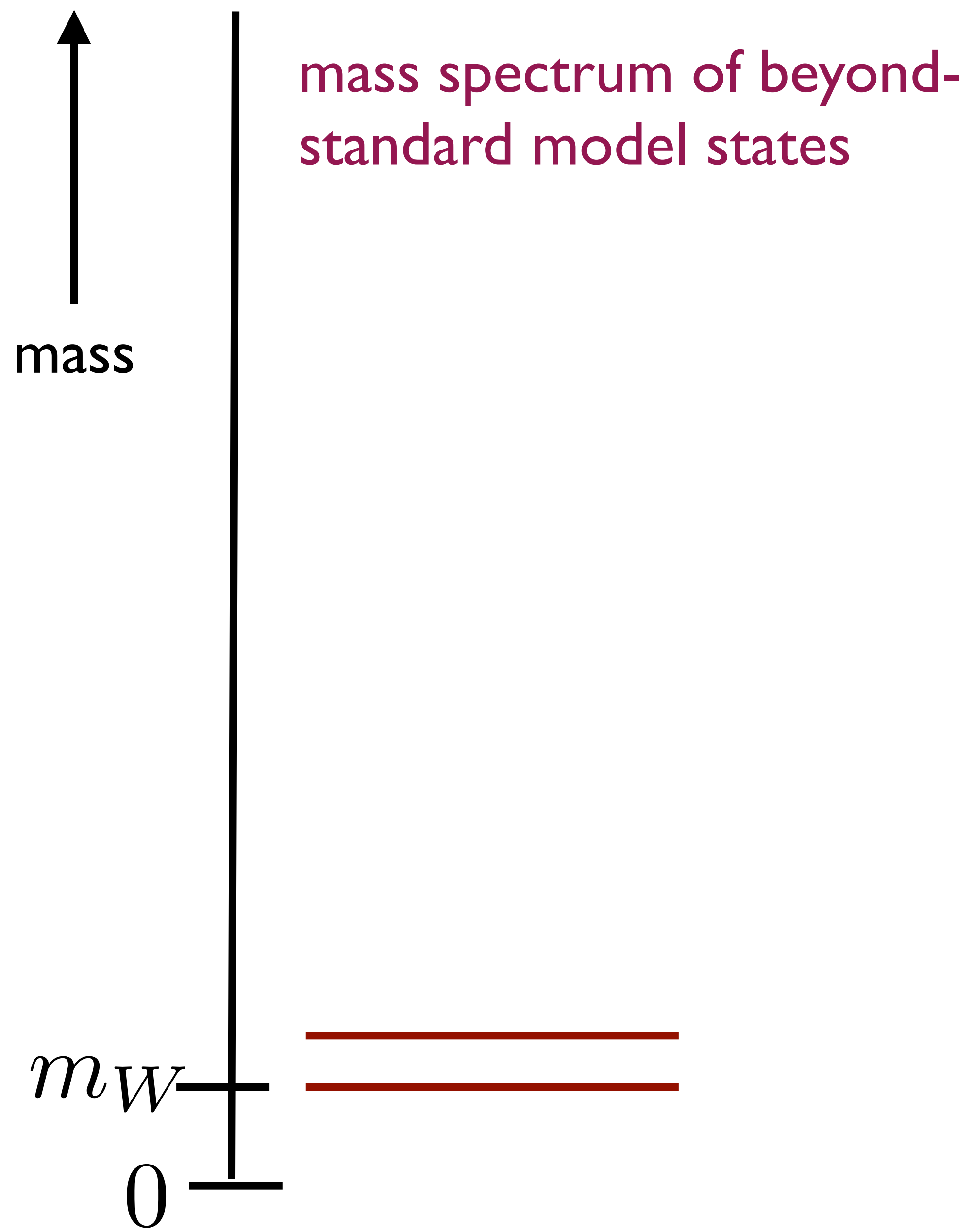
Electroweak charged WIMP Mechanism versus WIMP Model



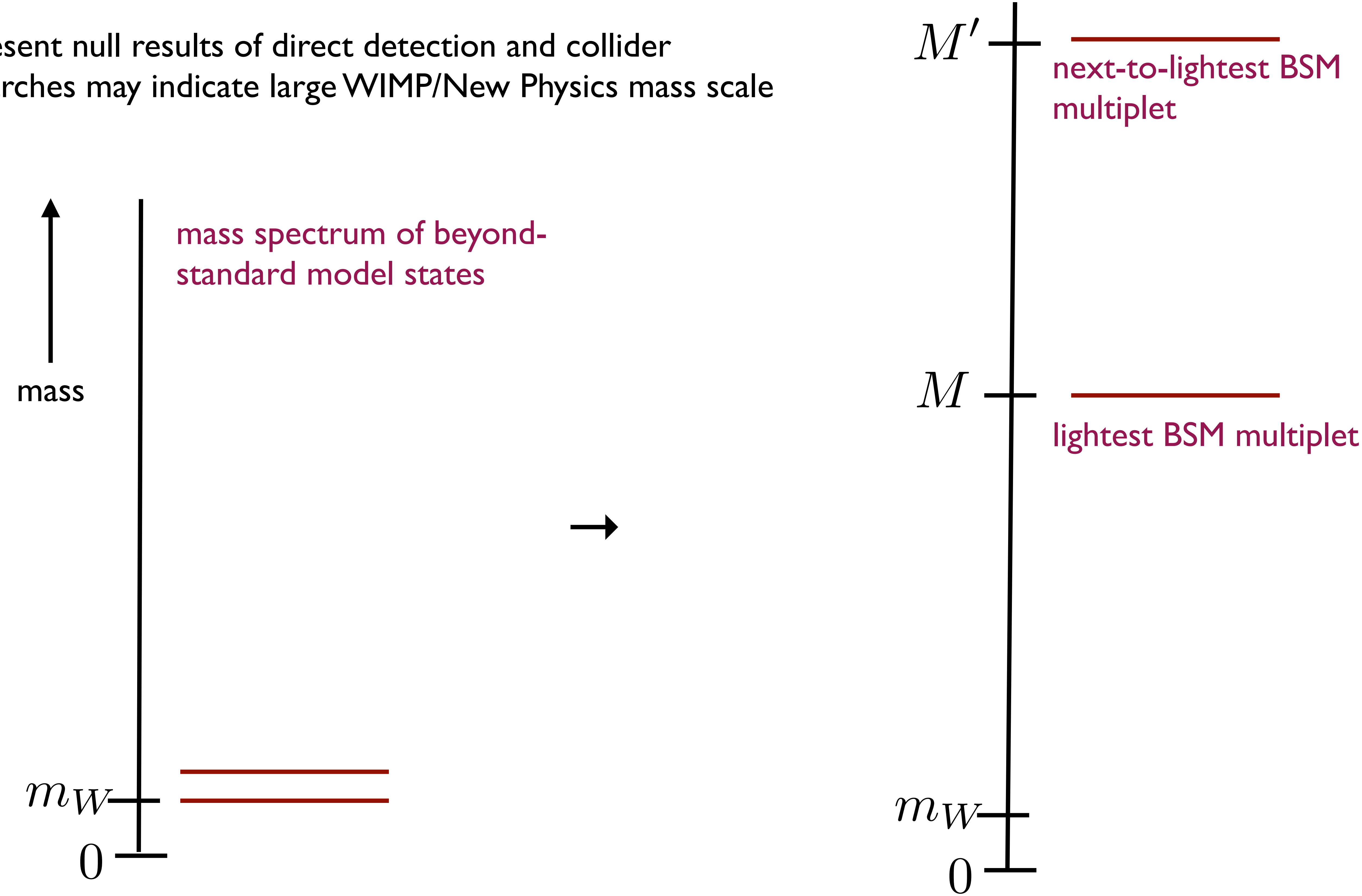

Focus on self-conjugate SU(2) triplet. Could be:

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

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



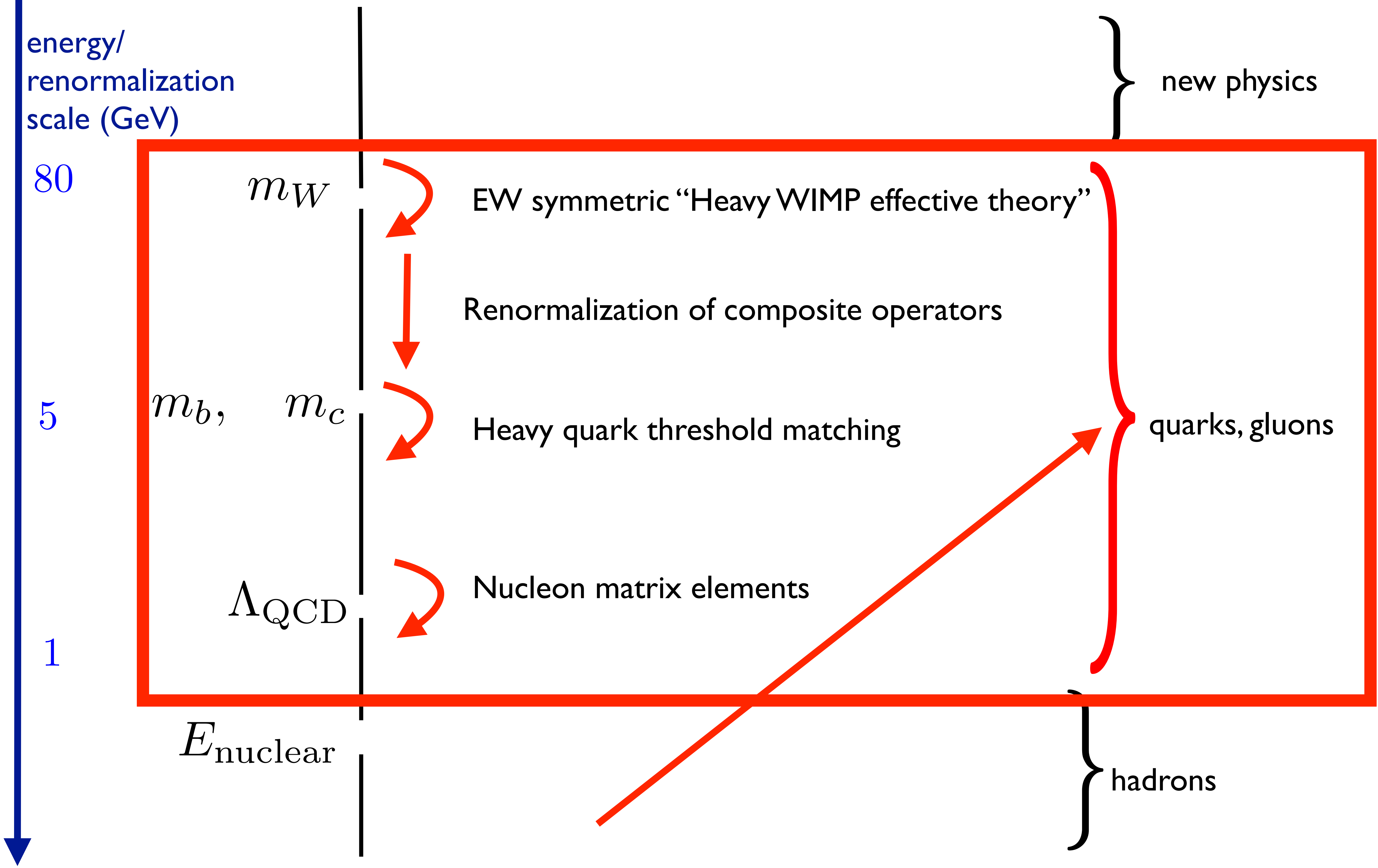
Present null results of direct detection and collider searches may indicate large WIMP/New Physics mass scale




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 scattering on nuclear targets

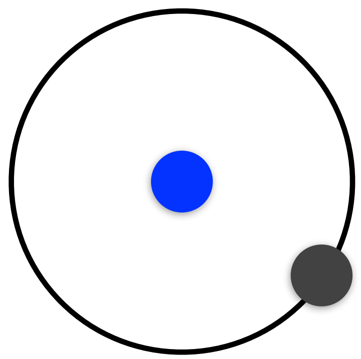



"SM anatomy" of interactions between weak and hadronic scales

| 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 |
| $m_W$ | $\chi_v^{(0)}$ | $u, d, s, c, b, A^a_\mu$ | 12 |
| $m_b, m_c$ | $\chi_v^{(0)}$ | $u, d, s, A^a_\mu$ | 8 |
| $\Lambda_{QCD}$ | $\chi_v^{(0)}$ | $N, \pi$ | 3 |
| $m_\pi$ | $\chi_v^{(0)}$ | $n, p$ | 2 |
| $1/R_{nucleus}$ | $\chi_v^{(0)}$ | $\mathcal{N}$ | 1 |

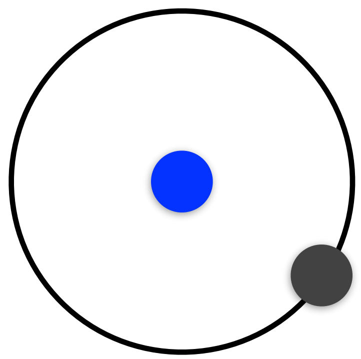
# Many manifestations of heavy particle symmetry:

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

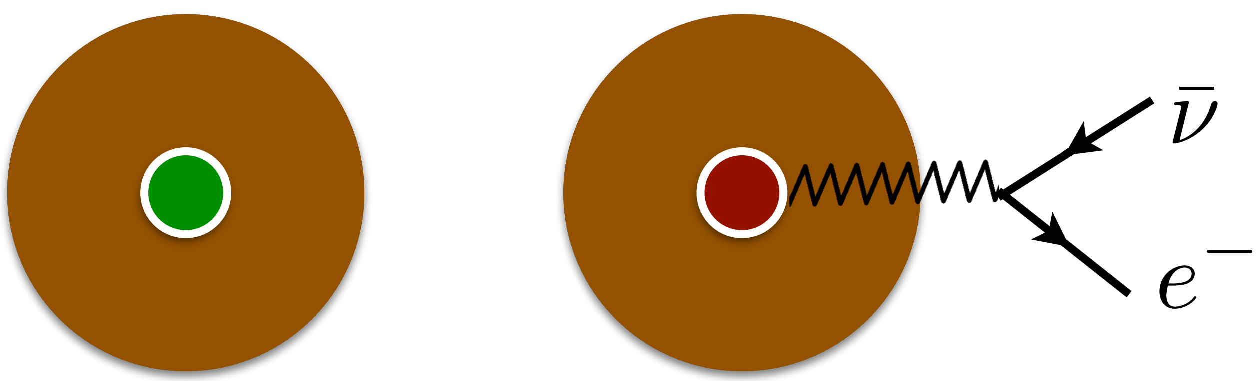


# Many manifestations of heavy particle symmetry:

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

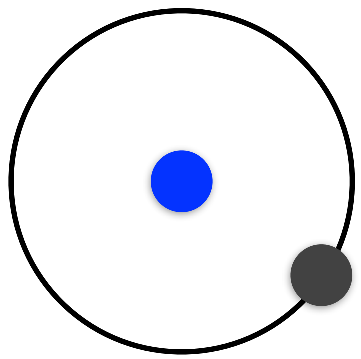


| | | |
|---|---|---|
| - heavy meson transitions | $F^{B\to D}(v' = v) = 1 + \dots$ | $\Lambda_{\rm QCD} \ll m_{b,c}$ |

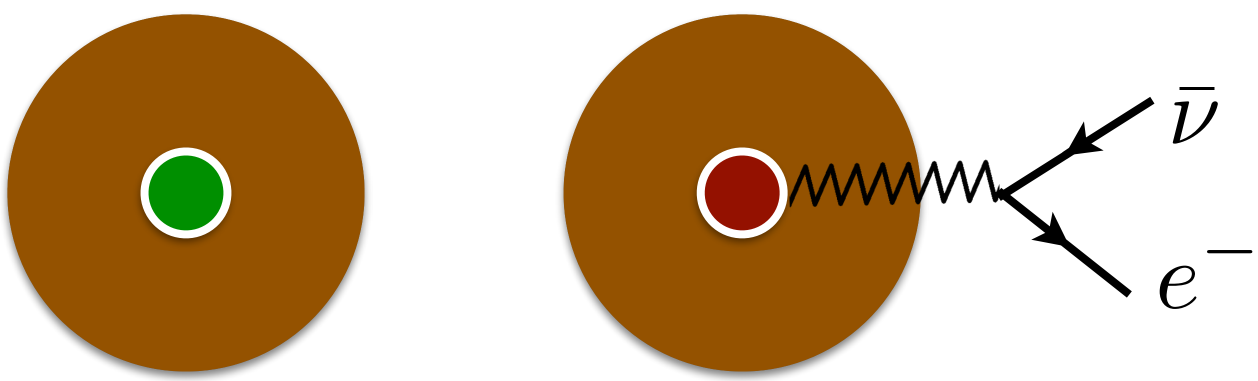


# Many manifestations of heavy particle symmetry:

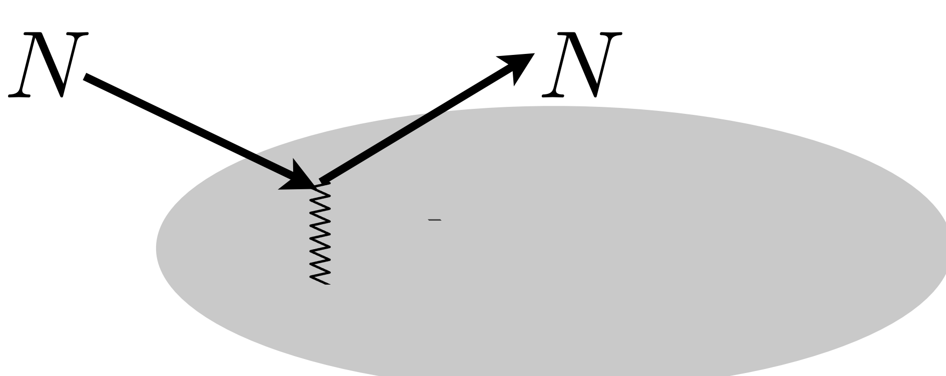
| | prediction: | small parameter: |
|---|---|---|
| - hydrogen/deuterium spectroscopy | $E_n(H) = -\frac{1}{2}m_e(Z\alpha)^2 + \ldots$ | $(m_e Z\alpha) \ll m_e$ |



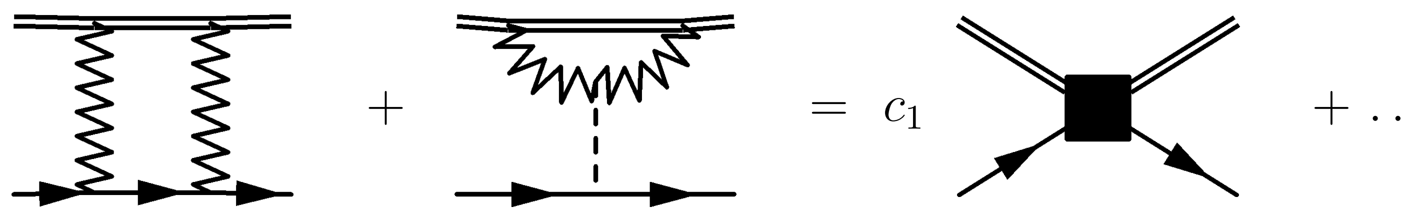
| | | |
|---|---|---|
| - heavy meson transitions | $F^{B\to D}(v' = v) = 1 + \ldots$ | $\Lambda_{\rm QCD} \ll m_{b,c}$ |



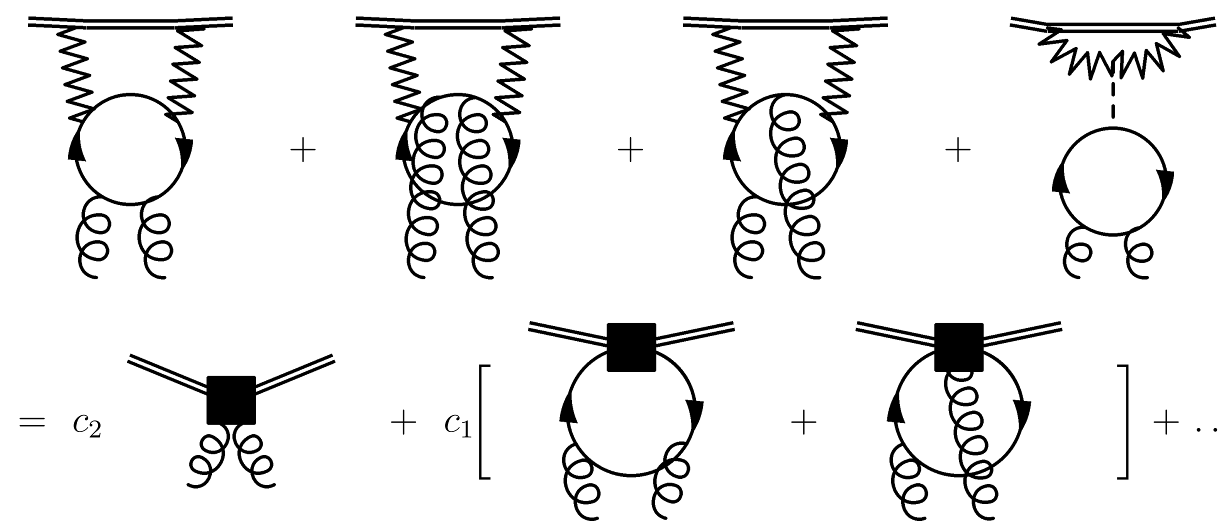

| | | |
|---|---|---|
| - DM interactions | $\sigma(\chi N \to \chi N) =?$ | $m_W \ll m_\chi$ |



| Scale separation: | dark sector d.o.f. | SM d.o.f. | # params. (beyond mass) |
|---|---|---|---|
| | $\chi^{(+,-,0)}$ | $Q, A_\mu^a, W_\mu^i, B_\mu$ | 0 |
| $M$ | | | |
| | $\chi_v^{(+,-,0)}$ | $Q, A_\mu^a, W_\mu^i, B_\mu$ | 0 |
| $m_W$ | | | |
| | $\chi_v^{(0)}$ | $u, d, s, c, b, A_\mu^a$ | 12 |
| $m_b, m_c$ | | | |
| | $\chi_v^{(0)}$ | $u, d, s, A_\mu^a$ | 8 |
| $\Lambda_{QCD}$ | | | |
| | $\chi_v^{(0)}$ | $N, \pi$ | 3 |
| $m_\pi$ | | | |
| | $\chi_v^{(0)}$ | $n, p$ | 2 |
| $1/R_{nucleus}$ | | | |
| | $\chi_v^{(0)}$ | $\mathcal{N}$ | 1 |

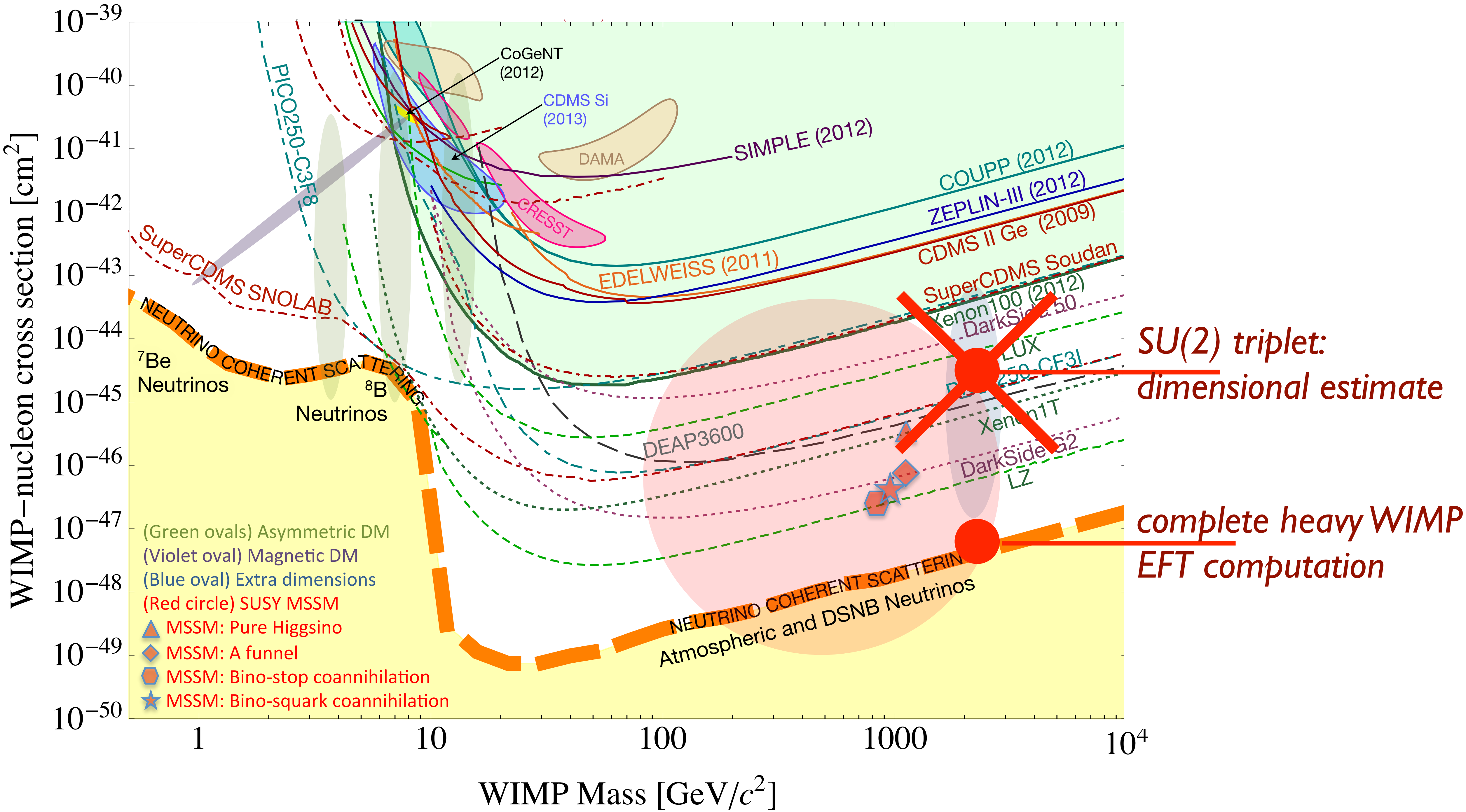


+
$= c_1$
$+ \dots$

+
+
+
$= c_2$
$+ c_1 [$
+
$] + \dots$

• the heavy lifting is necessary



# Perturbative QCD

| 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 |
| $m_W$ | | | |
| | $\chi_v^{(0)}$ | $u, d, s, c, b, A^a_\mu$ | 12 |
| $m_b, m_c$ | | | |
| | $\chi_v^{(0)}$ | $u, d, s, A^a_\mu$ | 8 |
| $\Lambda_{QCD}$ | | | |
| | $\chi_v^{(0)}$ | $N, \pi$ | 3 |
| $m_\pi$ | | | |
| | $\chi_v^{(0)}$ | $n, p$ | 2 |
| $1/R_{nucleus}$ | | | |
| | $\chi_v^{(0)}$ | $\mathcal{N}$ | 1 |

# Dark matter - Standard Model interactions

$$\mathcal{L} = \frac{1}{\Lambda^n} O_{\rm DM} \times O_{\rm SM}$$

| $d$ | Fermion |
|---|---|
| 3 | $\bar\psi[1\,,\ i\gamma_5\,,\ \gamma^\mu\gamma_5\,,\ \{\gamma^\mu\,,\ \sigma^{\mu\nu}\}]\psi$ |
| 4 | $\bar\psi[\{1\,,\ i\gamma_5\,,\ \gamma^\mu\gamma_5\}\,,\ \gamma^\mu\,,\ \sigma^{\mu\nu}]i\partial^\rho_-\psi$ |

| $d$ | Scalar |
|---|---|
| 2 | $\lvert\phi\rvert^2$ |
| 3 | $\{\phi^* i\partial^\mu_-\phi\}$ |

| $d$ | Heavy particle |
|---|---|
| 3 | $\bar\chi_v[1\,,\ \{\sigma_\perp^{\mu\nu}\}]\chi_v$ |
| 4 | $\bar\chi_v[\{1\}\,,\ \sigma_\perp^{\mu\nu}]i\partial^\rho_{\perp -}\chi_v$ |

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

complete QCD basis for d≤7

# 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

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

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

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)*

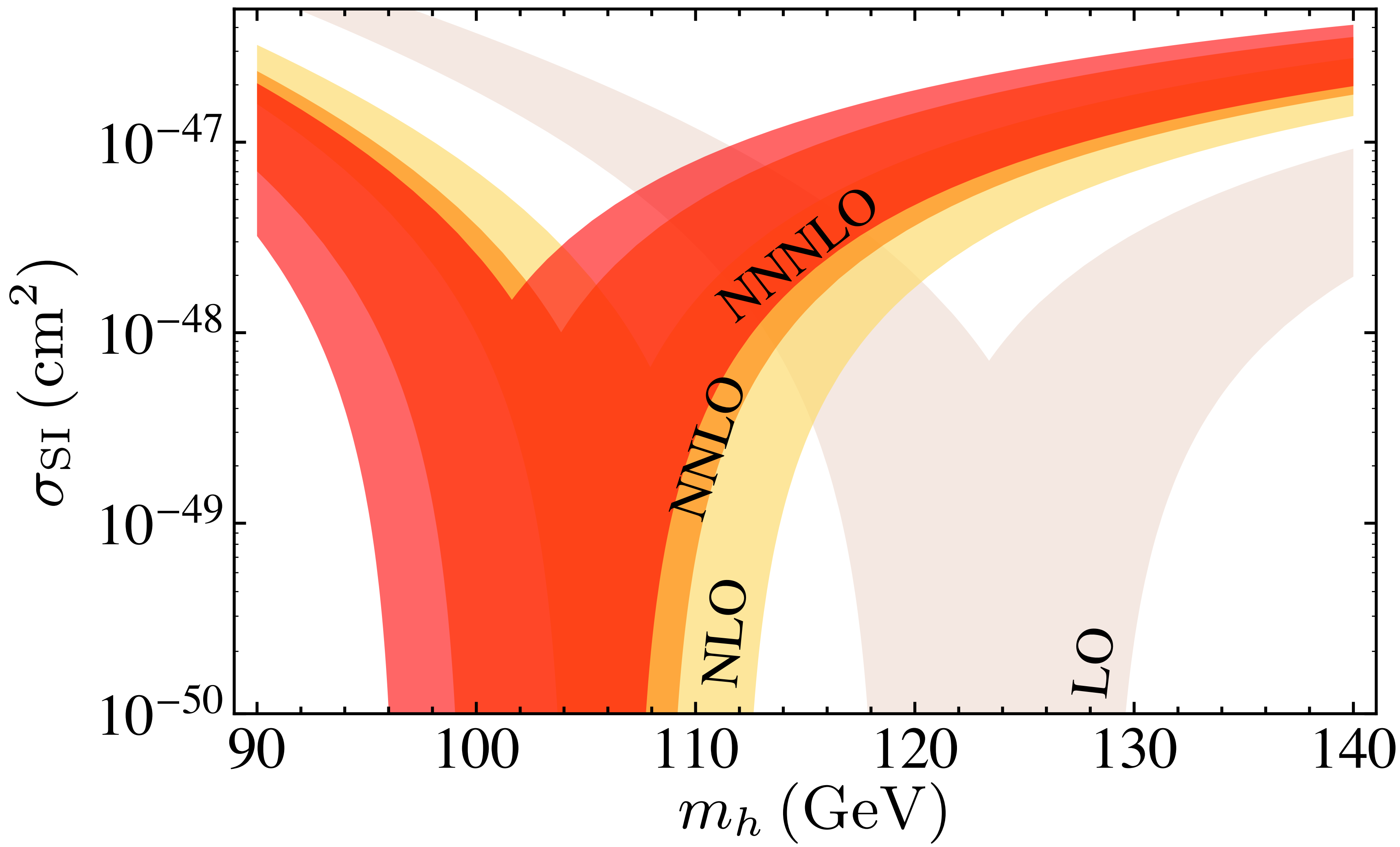
New results for gluon-induced decoupling relations

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

$$M_{gg}^{(3)} = \frac{564731}{41472} - \frac{2821}{288}\log\frac{\mu_Q}{m_Q} + \frac{3}{16}\log^2\frac{\mu_Q}{m_Q} - \frac{1}{27}\log^3\frac{\mu_Q}{m_Q} - \frac{82043}{9216}\zeta(3)$$
$$+ n_f\left[-\frac{2633}{10368} + \frac{67}{96}\log\frac{\mu_Q}{m_Q} - \frac{1}{3}\log^2\frac{\mu_Q}{m_Q}\right],$$
$$M_{qg}^{(2)} = -\frac{89}{54} + \frac{20}{9}\log\frac{\mu_Q}{m_Q} - \frac{8}{3}\log^2\frac{\mu_Q}{m_Q}.$$

*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) |
|---|---|---|---|
| $M$ | $\chi^{(+,-,0)}$ | $Q, A_\mu^a, W_\mu^i, B_\mu$ | 0 |
| | $\chi_v^{(+,-,0)}$ | $Q, A_\mu^a, W_\mu^i, B_\mu$ | 0 |
| $m_W$ | $\chi_v^{(0)}$ | $u, d, s, c, b, A_\mu^a$ | 12 |
| $m_b, m_c$ | $\chi_v^{(0)}$ | $u, d, s, A_\mu^a$ | 8 |
| $\Lambda_{QCD}$ | $\chi_v^{(0)}$ | $N, \pi$ | 3 |
| $m_\pi$ | $\chi_v^{(0)}$ | $n, p$ | 2 |
| $1/R_{nucleus}$ | $\chi_v^{(0)}$ | $\mathcal{N}$ | 1 |

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

complete QCD basis for d≤7

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

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

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

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

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

# • 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. 1109.4265*

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

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

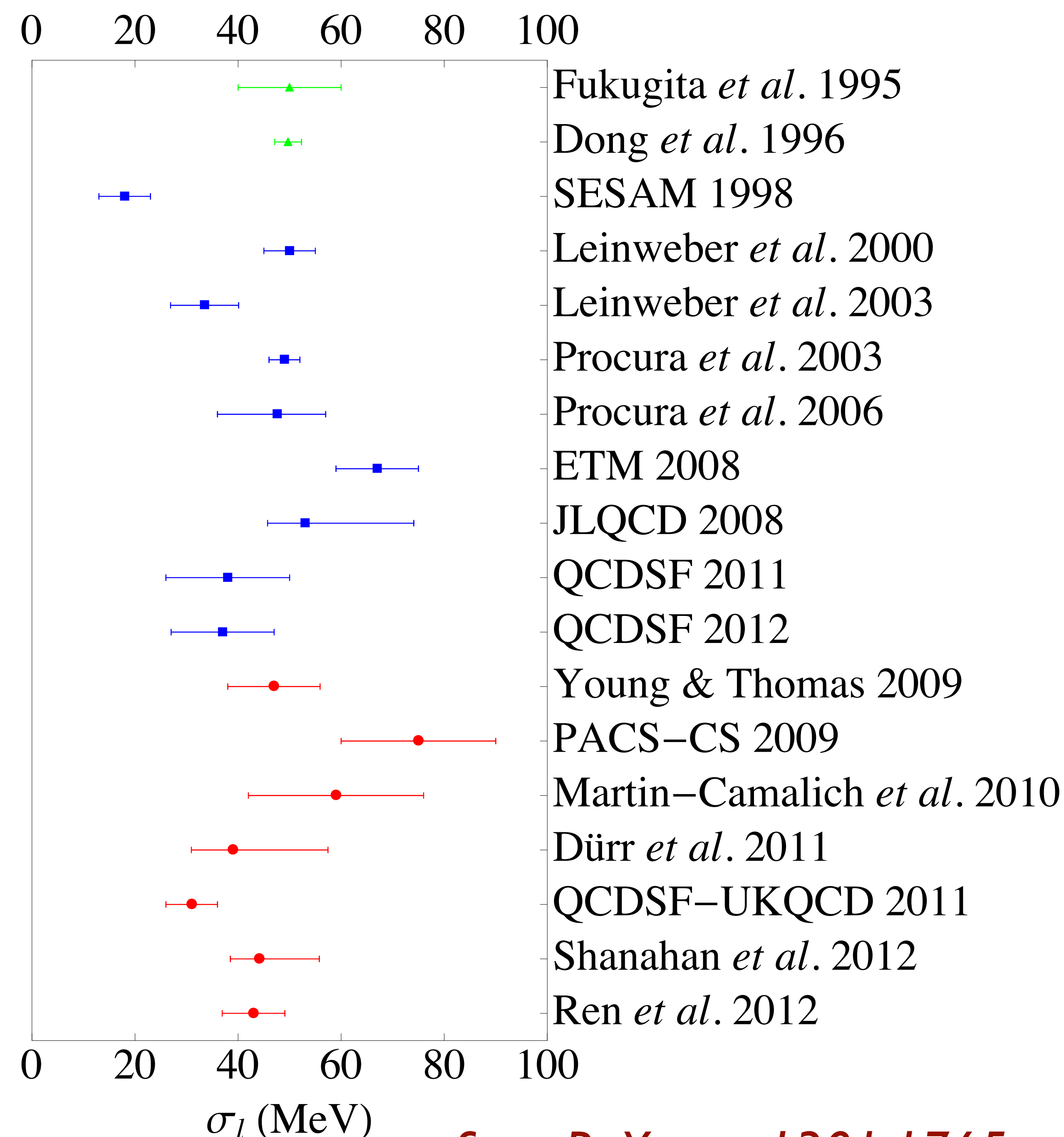
*Gasser, Leutwyler (1982)*

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

*Crivellin, Hoferichter, Procura (2014)*

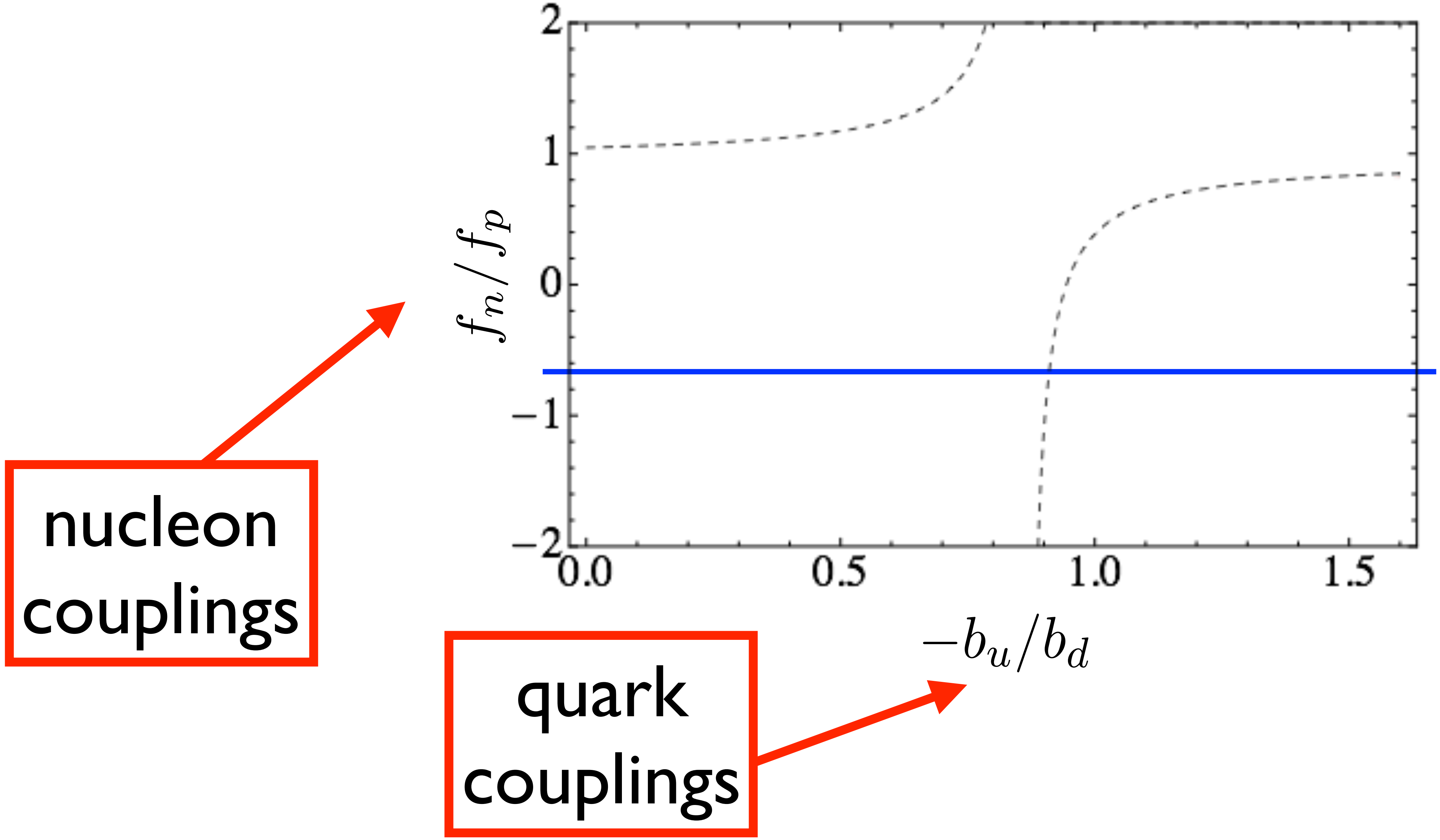
$$\frac{m_u}{m_d} = 0.49 \pm 0.13$$

*PDG*



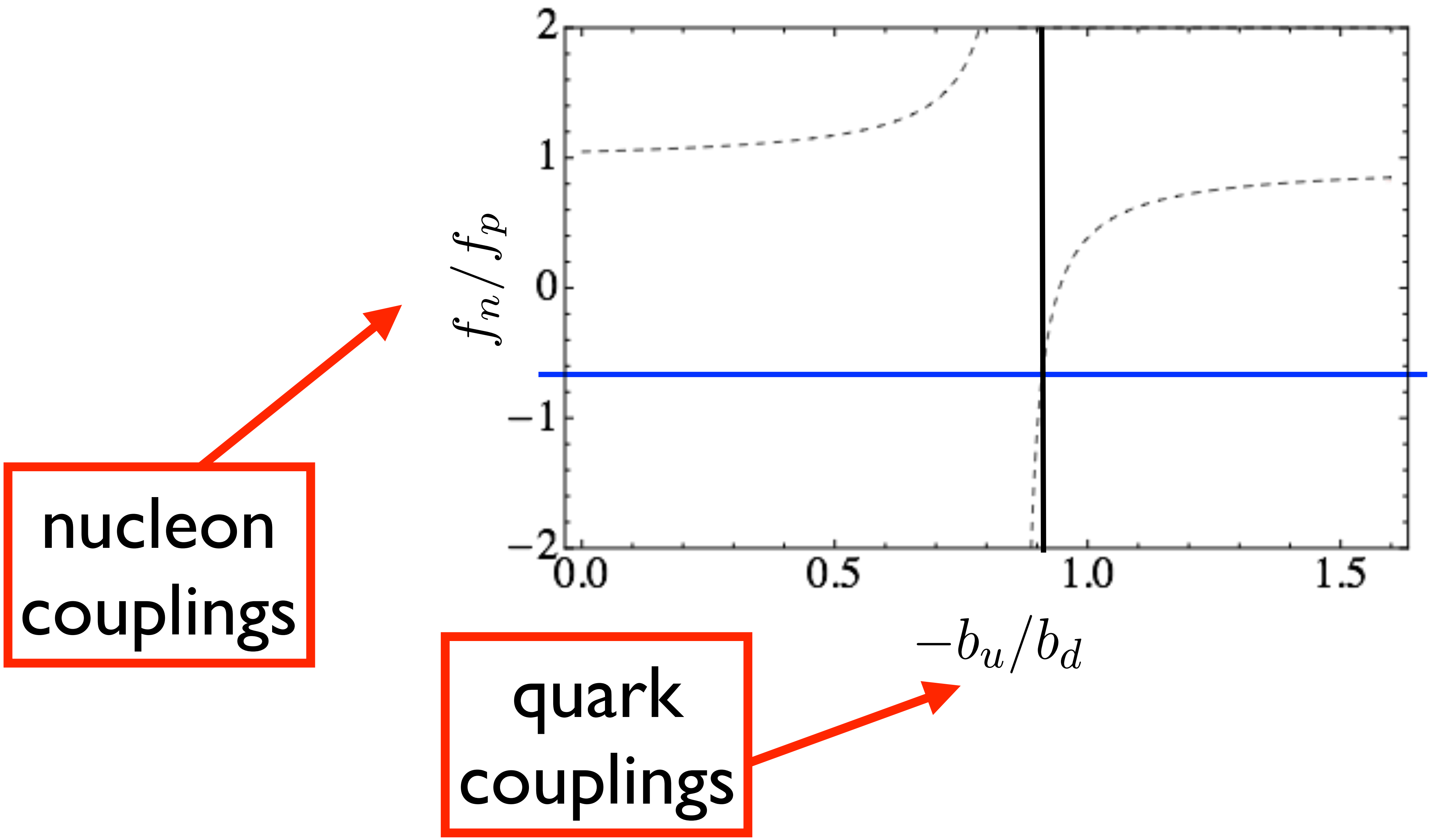

*from R. Young, 1301.1765*

- up, down quarks & isospin-violating dark matter



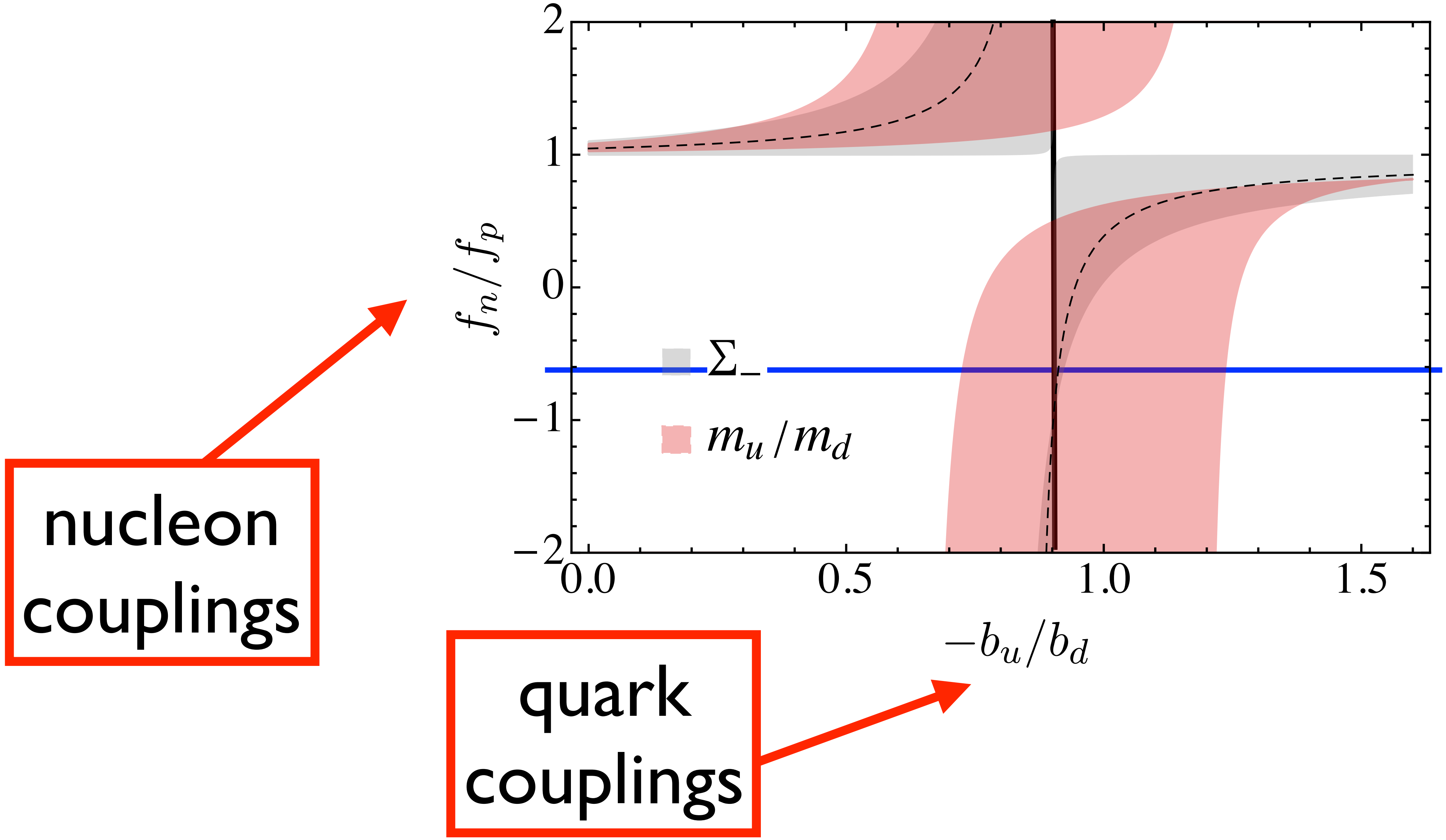

hadronic uncertainties important for determining viability of models for potential signals

• up, down quarks & isospin-violating dark matter




hadronic uncertainties important for determining viability of models for potential signals

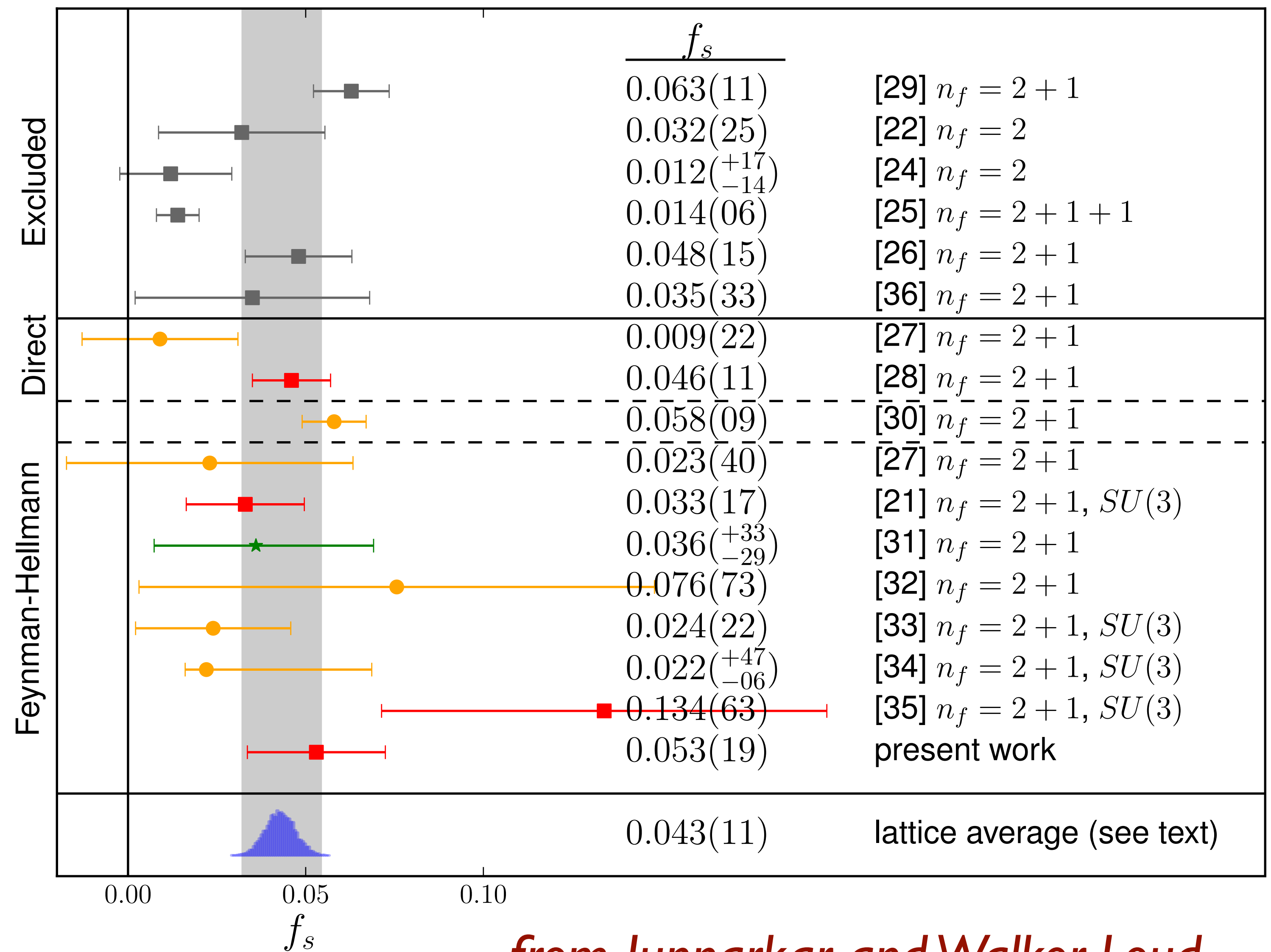
• up, down quarks & isospin-violating dark matter




hadronic uncertainties important for determining viability of models for potential signals

• strange quarks & heavy wino dark matter

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

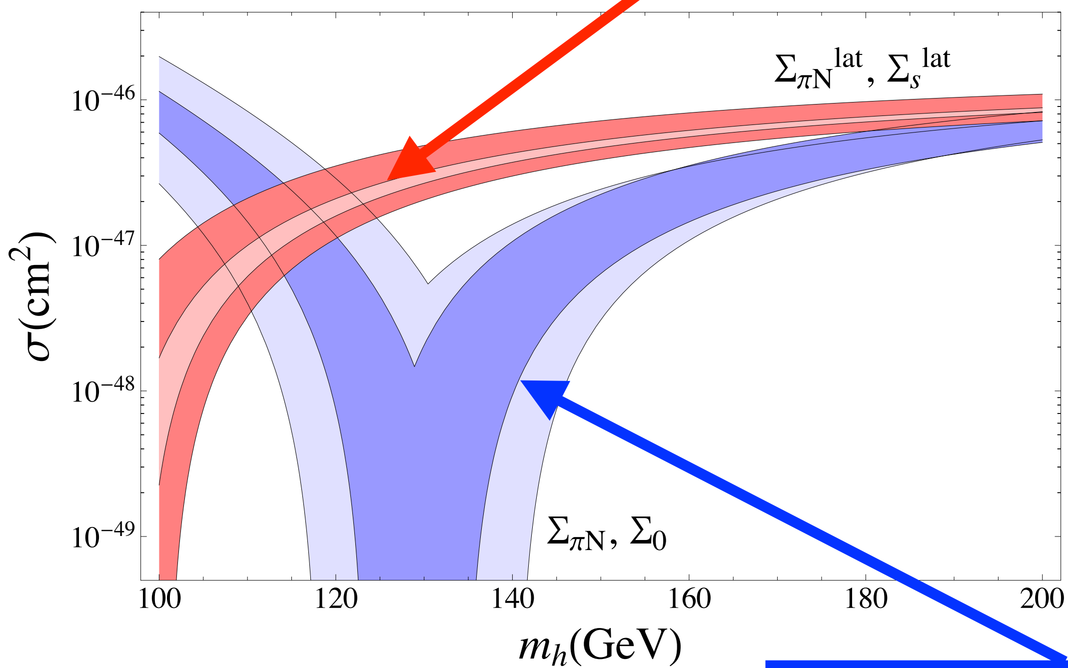



*from Junnarkar and Walker-Loud, 1301.1114*

- 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*

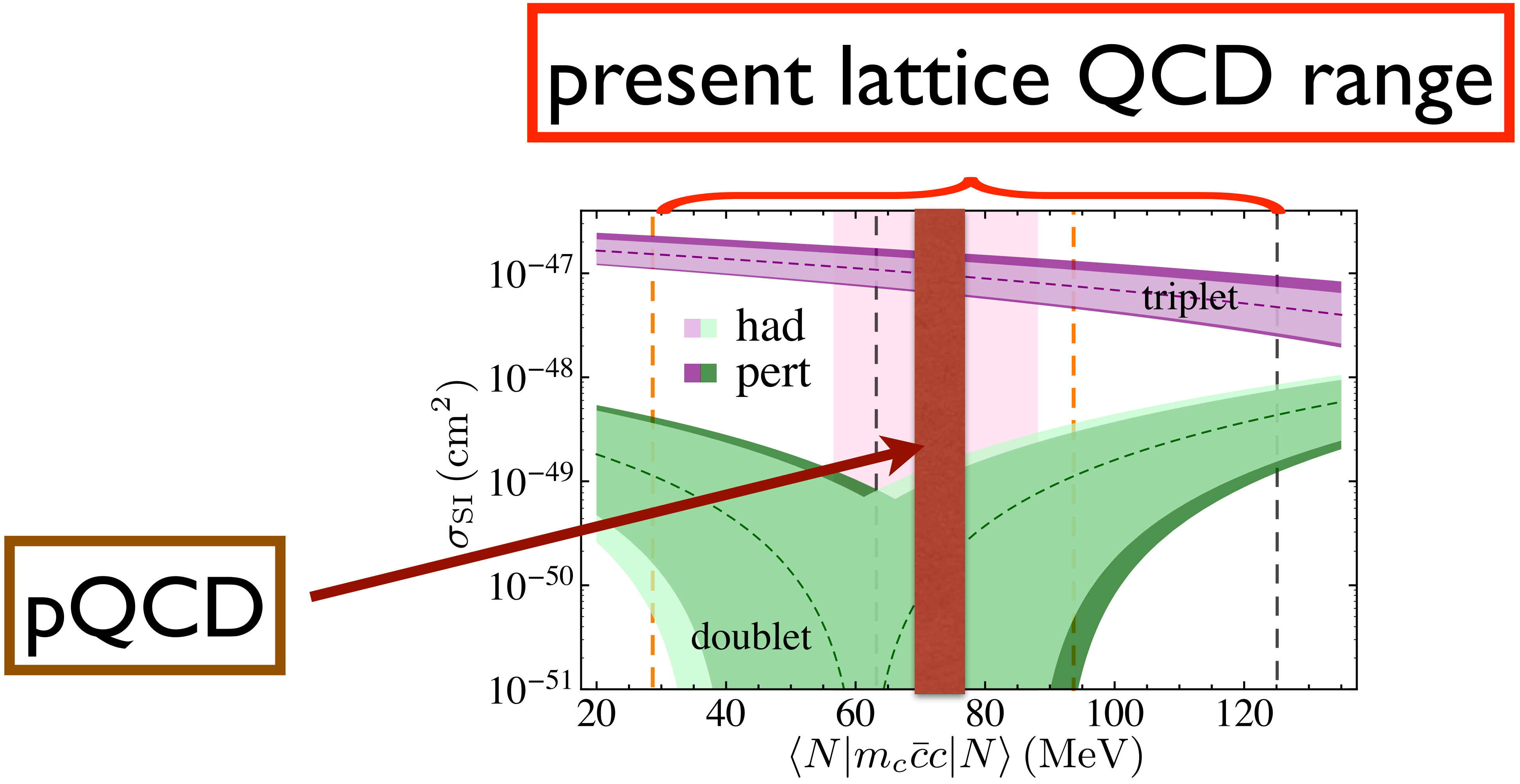
determines if cross section is above or below neutrino background for direct detection

- charm quarks & heavy higgsino dark matter

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

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

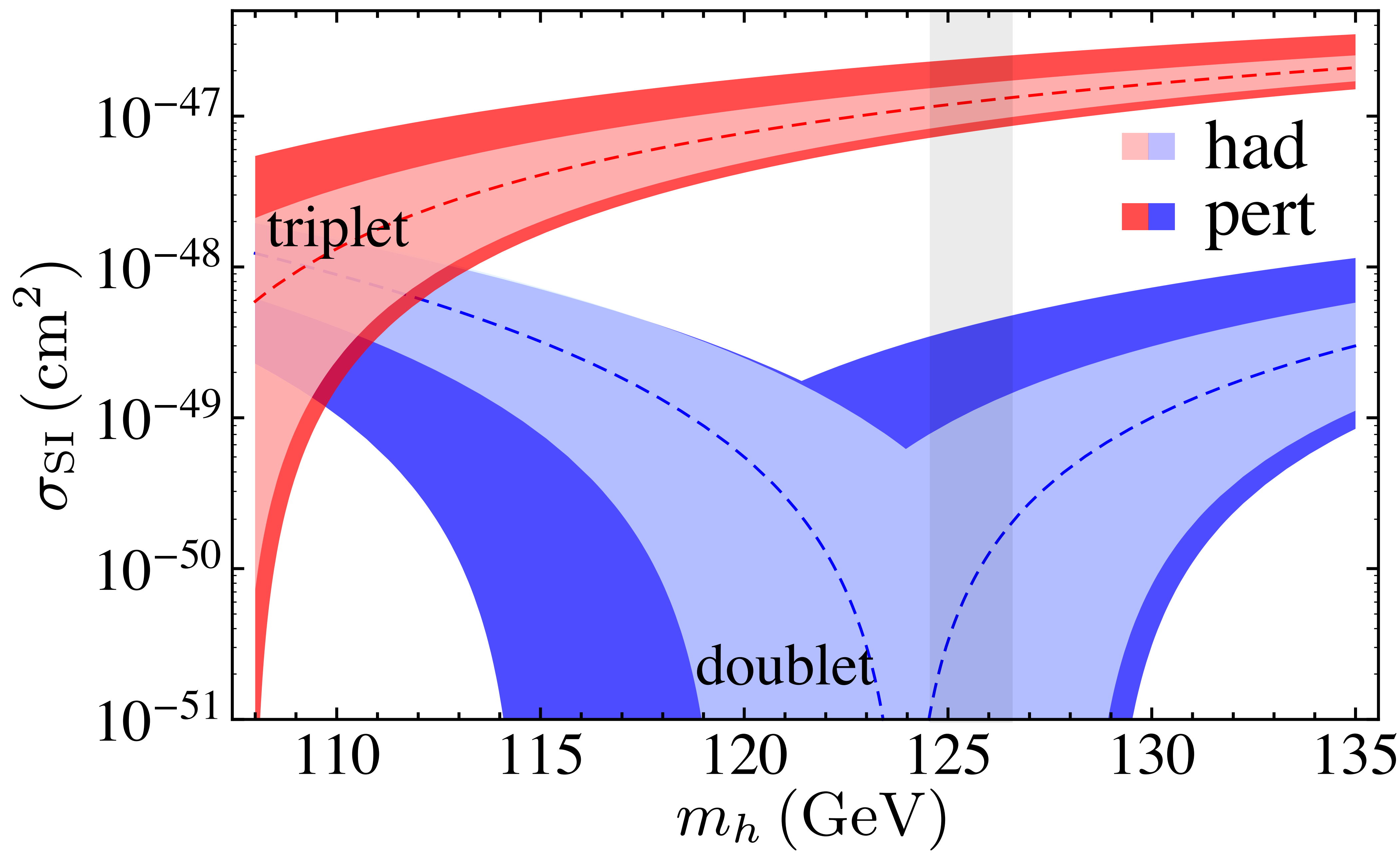
- charm quarks & heavy higgsino dark matter




$1/m_c$ could potentially shift cancellation region

# summary results for heavy electroweak charged WIMP scattering

*Solon, RJH, PRL 2014*




cross section per nucleon

Higgs boson mass

# other illustrative examples

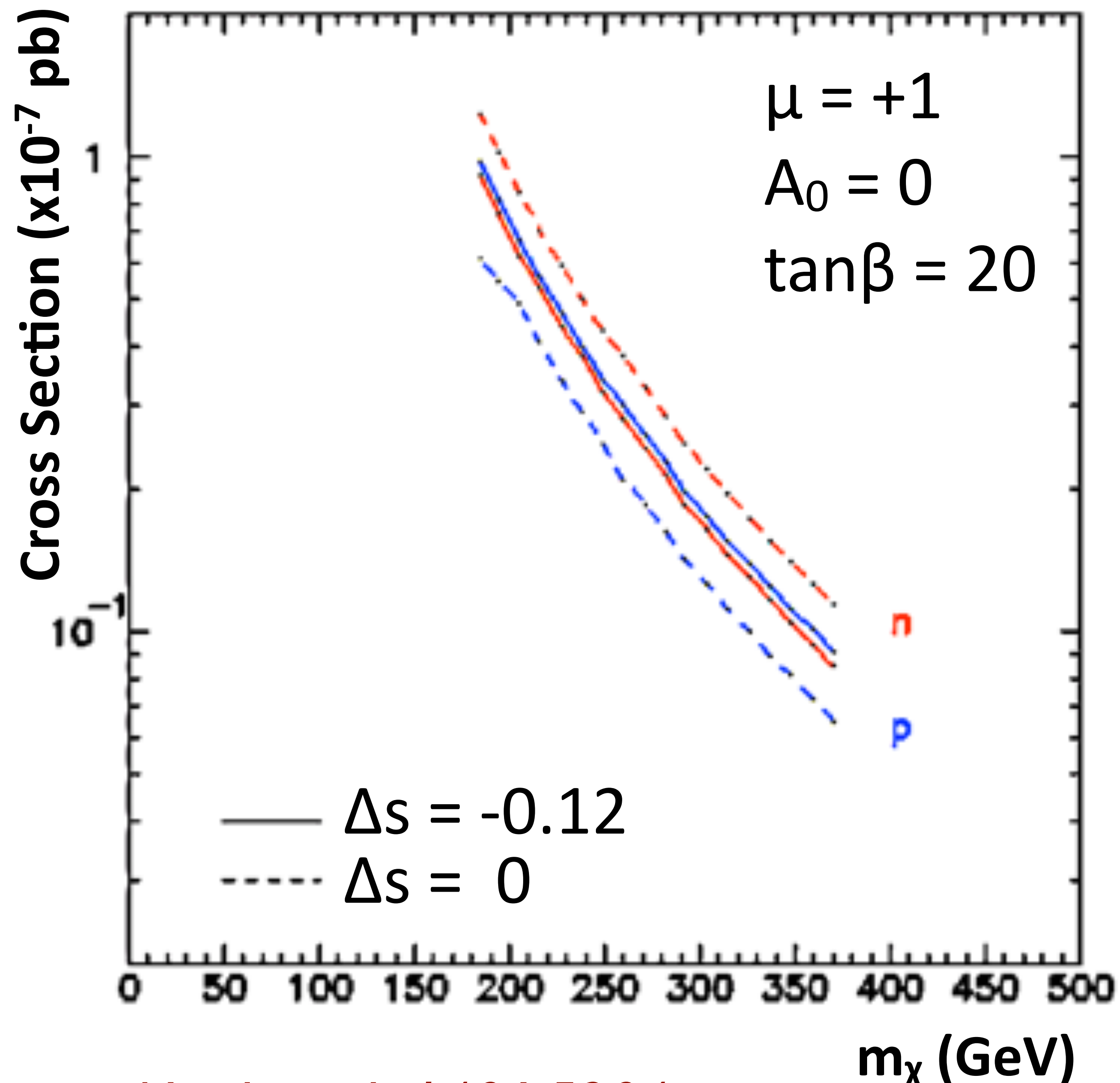
| $d$ | QCD operator basis |
|---|---|
| 3 | $V_q^\mu = \bar{q}\gamma^\mu q$ |
| | $A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$ |
| 4 | $T_q^{\mu\nu} = im_q\bar{q}\sigma^{\mu\nu}\gamma_5 q$ |
| | $O_q^{(0)} = m_q\bar{q}q\,, \quad O_g^{(0)} = G^A_{\mu\nu}G^{A\mu\nu}$ |
| | $O_{5q}^{(0)} = m_q\bar{q}i\gamma_5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

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

- flavor singlet pseudoscalar & low-mass WIMPs

- flavor singlet pseudoscalar & low-mass WIMPs

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

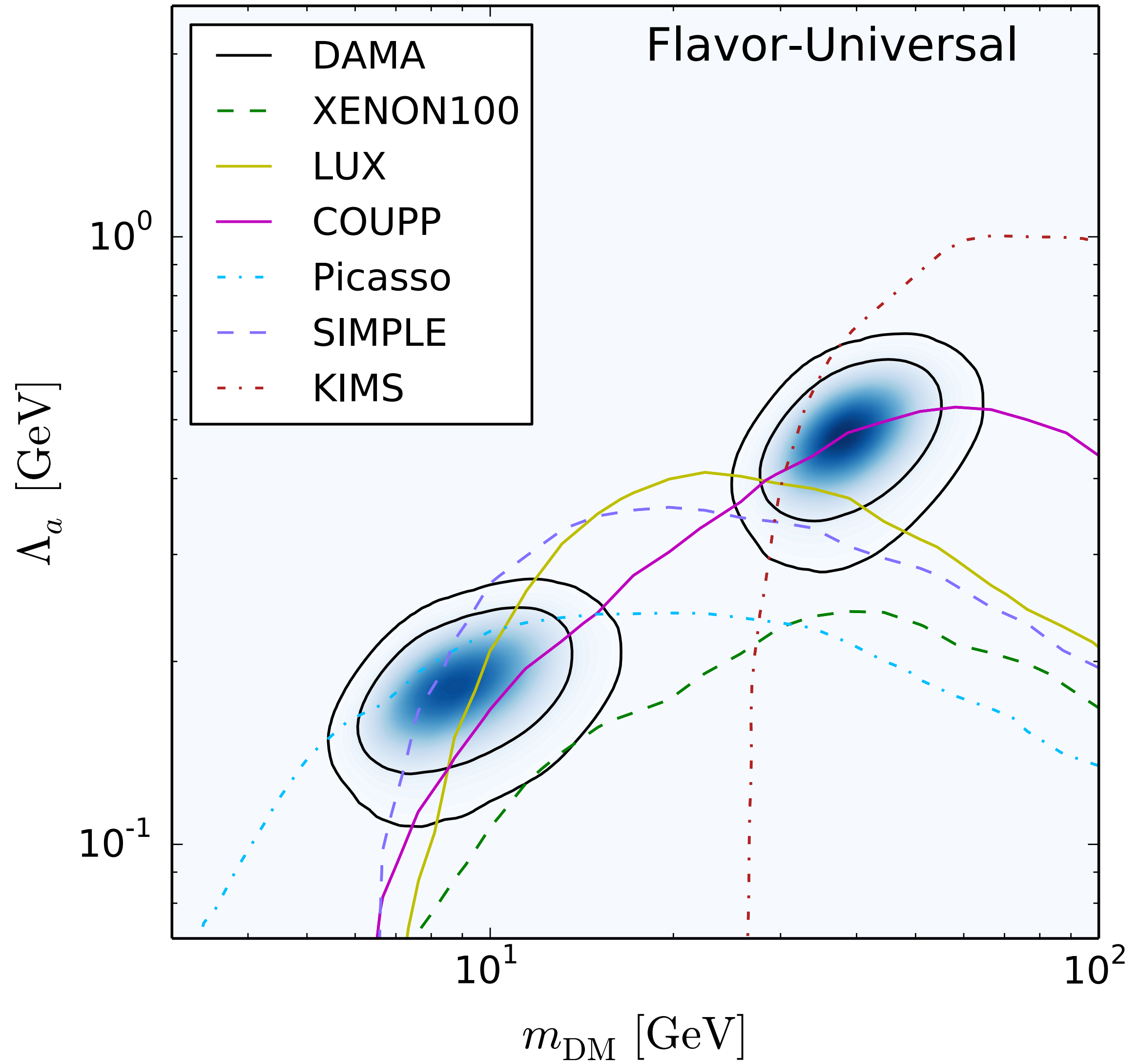
$$\kappa \sim 0?$$

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

$$\downarrow$$

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

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

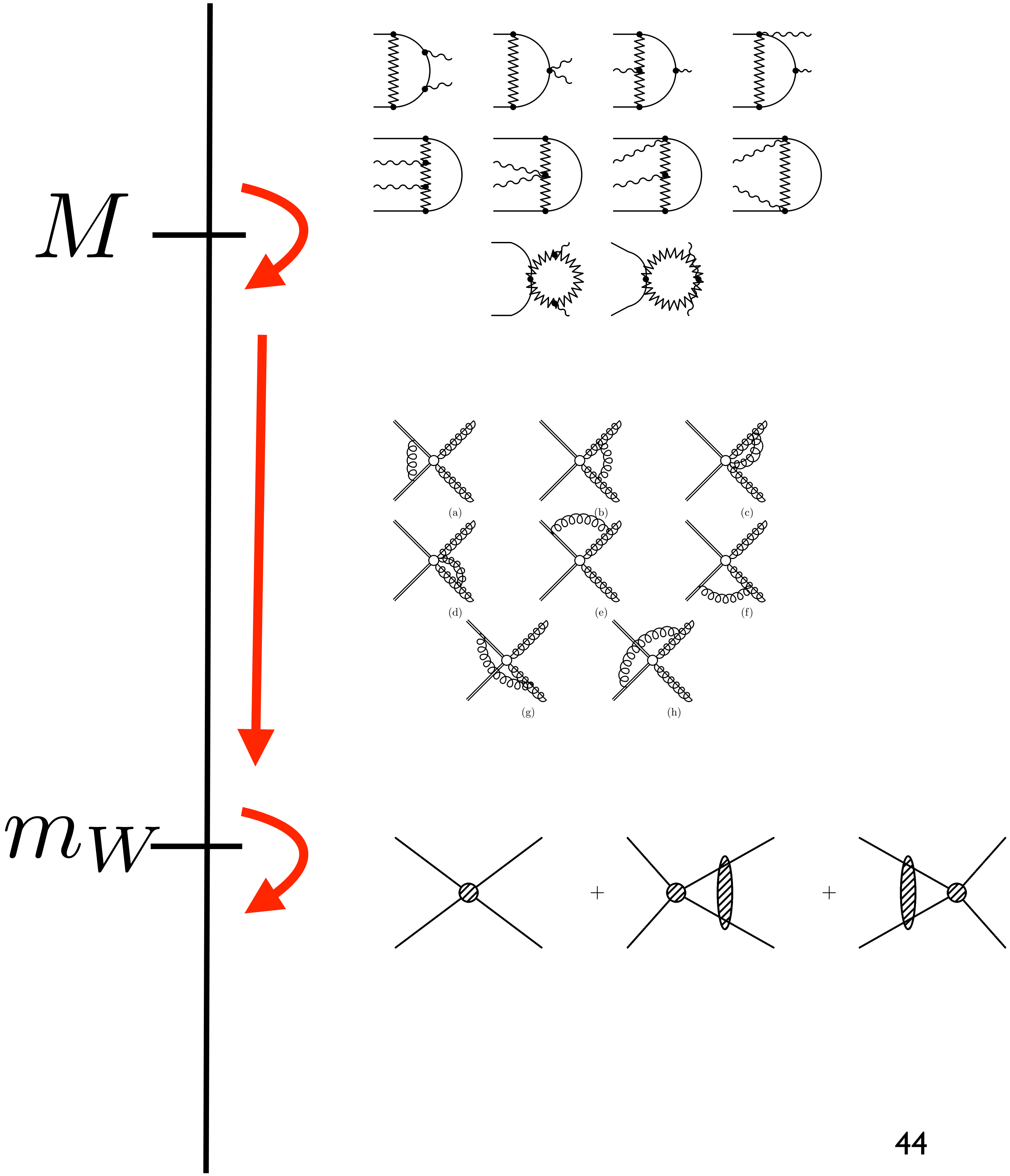



*Arina et al. 1406.5542*

Impacts tension between experiments

# Field theory tools

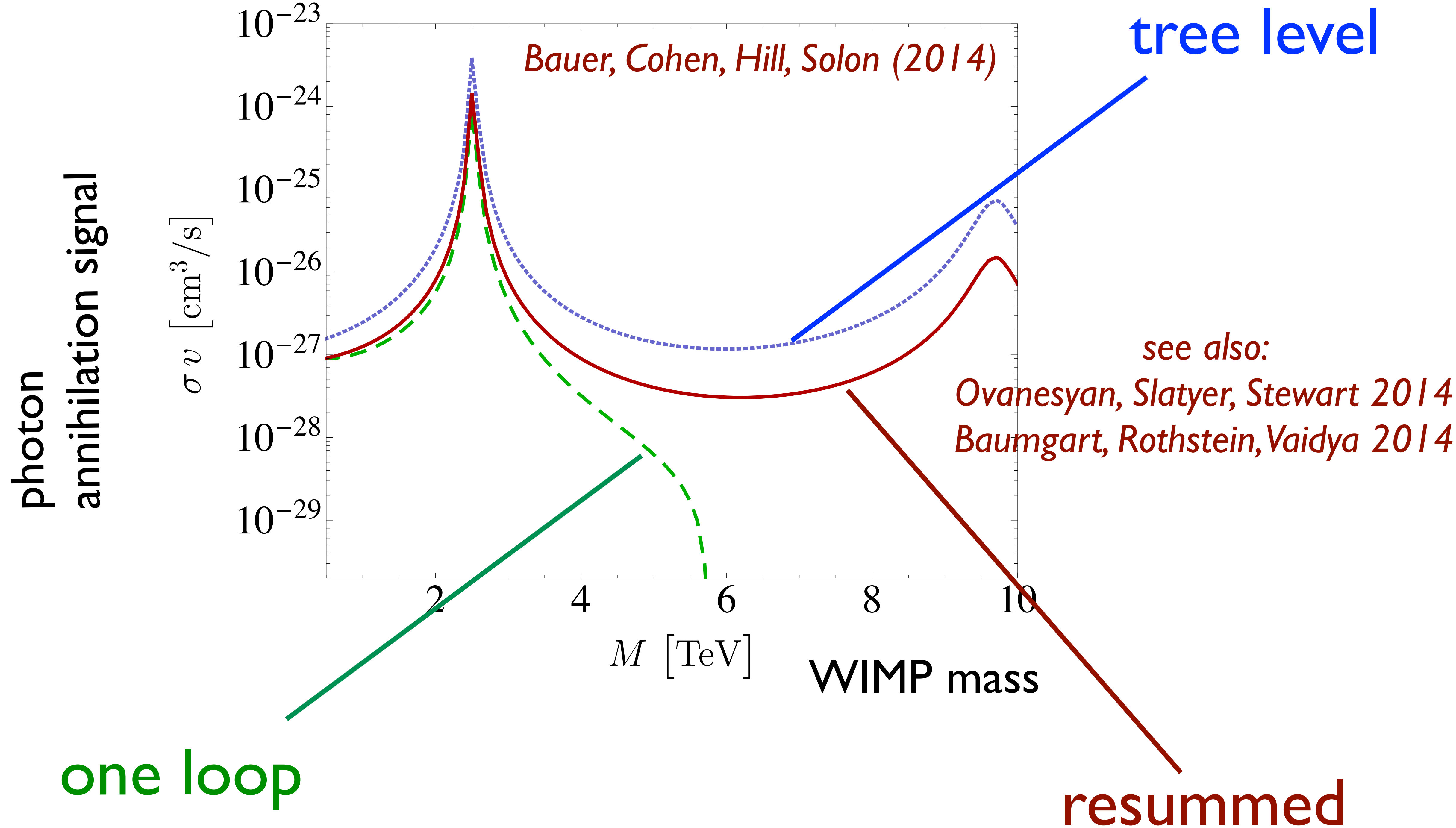
# Extend Heavy WIMP Effective Theory to describe annihilation. Worked example: SU(2) triplet annihilation to photons




hard annihilation
(makes it happen)

Sudakov suppression
(makes it slower)

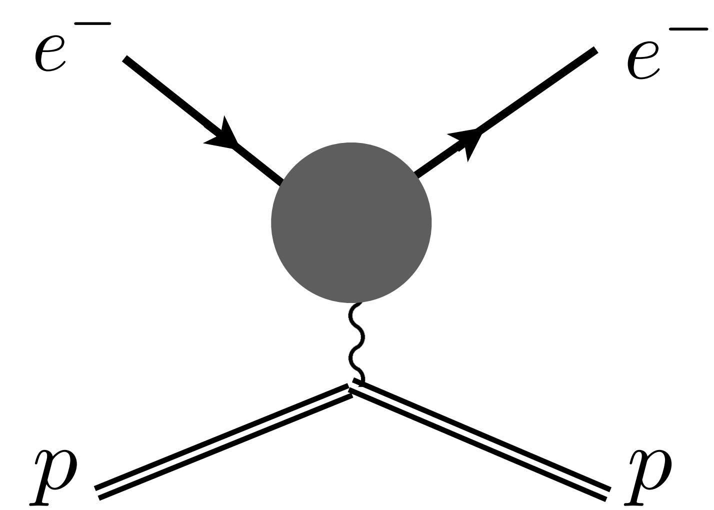
Sommerfeld enhancement
(makes it faster)




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

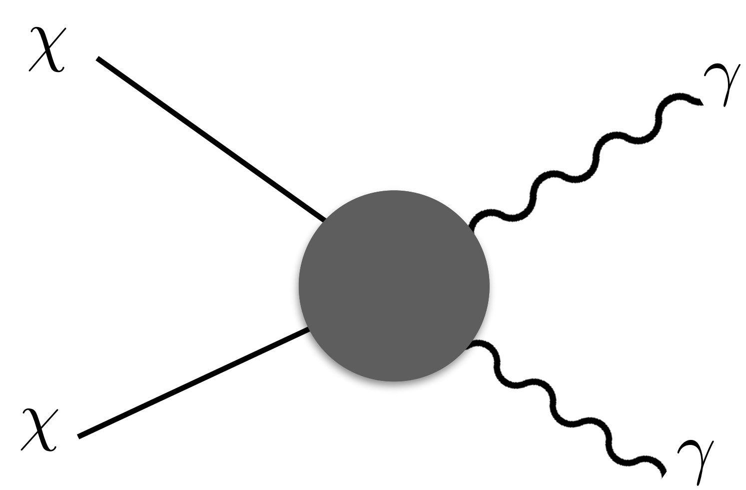
# Novel field theory tools for DM have broad application

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




radiative corrections to e-p scattering (proton radius puzzle)

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




heavy WIMP annihilation

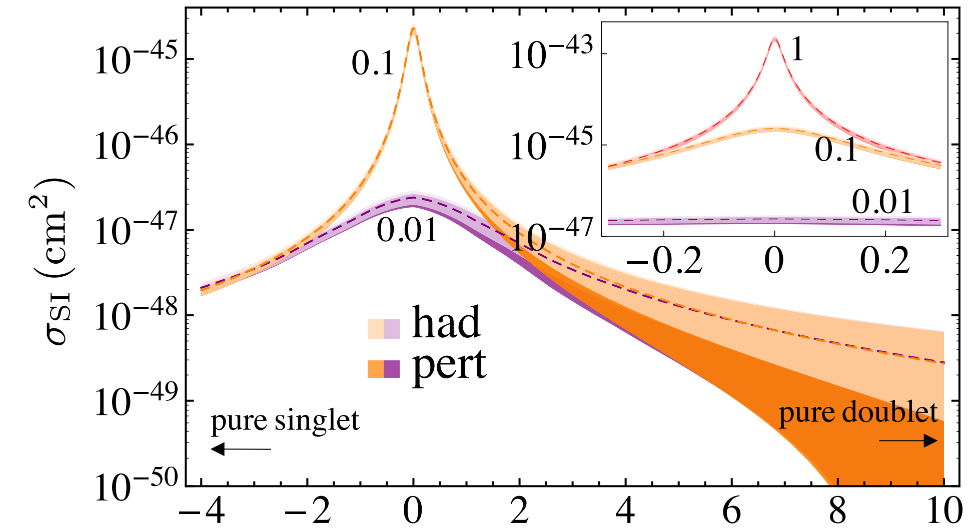
# Summary

- QCD corrections are important to dark matter searches
  - determine discovery potential (heavy wino)
  - determine compatibility of potential signals between experiments
- interplay with perturbative and nonperturbative QCD
  - lattice matrix elements
  - high-order decoupling relations
  - novel nuclear responses
- has motivated new field theory tools for particle and nuclear physics

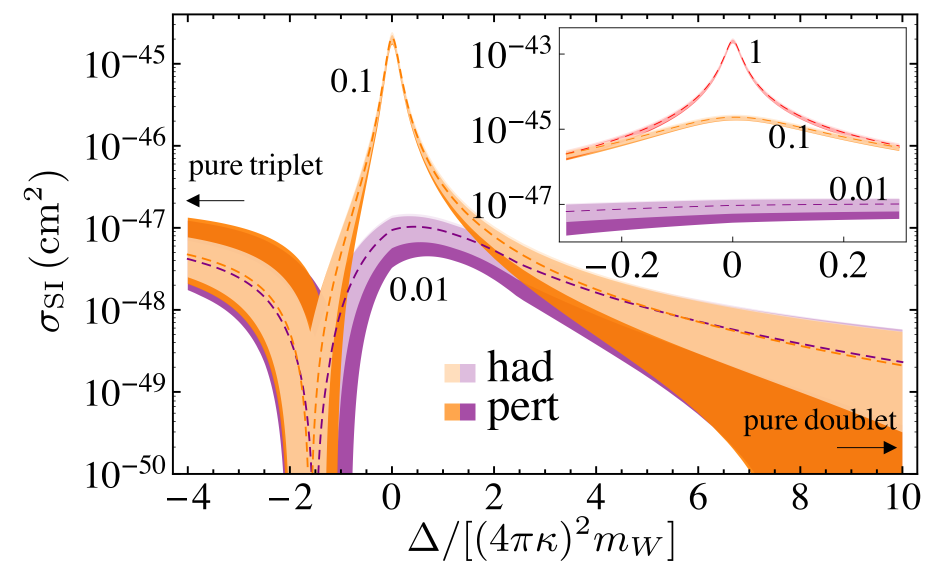
# back up

# 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

# 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

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

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

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

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

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

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

## Majorana:

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

# Heavy WIMP + SM

$$\mathcal{L}_{\chi_v,\mathrm{SM}} = \frac{c_{\chi 1}}{m_W}\bar{\chi}_v \sigma_\perp^{\mu\nu}\chi_v F_{\mu\nu} + \frac{c_{\chi 2}}{m_W}\bar{\chi}_v \sigma_\perp^{\mu\nu}\chi_v \tilde{F}_{\mu\nu} + \sum_{q=u,d,s,c,b}\Bigg\{ \frac{c_{\chi 3,q}}{m_W^2}\epsilon_{\mu\nu\rho\sigma}v^\mu \bar{\chi}_v \sigma_\perp^{\nu\rho}\chi_v \bar{q}\gamma^\sigma q$$

$$+ \frac{c_{\chi 4,q}}{m_W^2}\epsilon_{\mu\nu\rho\sigma}v^\mu \bar{\chi}_v \sigma_\perp^{\nu\rho}\chi_v \bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 5,q}}{m_W^2}\bar{\chi}_v\chi_v \bar{q}\not{v}\, q + \frac{c_{\chi 6,q}}{m_W^2}\bar{\chi}_v\chi_v \bar{q}\not{v}\,\gamma_5 q + \frac{c_{\chi 7,q}}{m_W^3}\bar{\chi}_v\chi_v m_q \bar{q}q$$

$$+ \frac{c_{\chi 8,q}}{m_W^3}\bar{\chi}_v\chi_v \bar{q}\not{v}\, iv\cdot D_- q + \frac{c_{\chi 9,q}}{m_W^3}\bar{\chi}_v\chi_v m_q \bar{q} i\gamma_5 q + \frac{c_{\chi 10,q}}{m_W^3}\bar{\chi}_v\chi_v \bar{q}\not{v}\,\gamma_5 iv\cdot D_- q$$

$$+ \frac{c_{\chi 11,q}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu} i\partial_{-\mu}^\perp \chi_v \bar{q}\gamma_\nu q + \frac{c_{\chi 12,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v \sigma_\perp^{\mu\nu} i\partial_-^{\perp\rho}\chi_v \bar{q}\gamma^\sigma q + \frac{c_{\chi 13,q}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu} i\partial_{-\mu}^\perp \chi_v \bar{q}\gamma_\nu\gamma_5 q$$

$$+ \frac{c_{\chi 14,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v \sigma_\perp^{\mu\nu} i\partial_-^{\perp\rho}\chi_v \bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 15,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}v^\mu \bar{\chi}_v \sigma_\perp^{\nu\rho}\chi_v\, \bar{q}(\not{v}\, iD_-^\sigma + \gamma^\sigma iv\cdot D_-)q$$

$$+ \frac{c_{\chi 16,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}v^\mu \bar{\chi}_v \sigma_\perp^{\nu\rho}\chi_v \bar{q}(\not{v}\, iD_-^\sigma + \gamma^\sigma iv\cdot D_-)\gamma_5 q + \frac{c_{\chi 17,q}}{m_W^3}\bar{\chi}_v i\partial_-^{\perp\mu}\chi_v \bar{q}\gamma_\mu q$$

$$+ \frac{c_{\chi 18,q}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu}\partial_{+\mu}^\perp \chi_v \bar{q}\gamma_\nu q + \frac{c_{\chi 18,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v \sigma_\perp^{\mu\nu}\partial_+^{\perp\rho}\chi_v \bar{q}\gamma^\sigma q + \frac{c_{\chi 20,q}}{m_W^3}\bar{\chi}_v i\partial_-^{\perp\mu}\chi_v \bar{q}\gamma_\mu\gamma_5 q$$

$$+ \frac{c_{\chi 21,q}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu}\partial_{+\mu}^\perp \chi_v \bar{q}\gamma_\nu\gamma_5 q + \frac{c_{\chi 22,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v \sigma_\perp^{\mu\nu}\partial_+^{\perp\rho}\chi_v \bar{q}\gamma^\sigma\gamma_5 q + \frac{c_{\chi 23,q}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu}\chi_v m_q \bar{q}\sigma_{\mu\nu} q$$

$$+ \frac{c_{\chi 24,q}}{m_W^3}\epsilon_{\mu\nu\rho\sigma}\bar{\chi}_v \sigma_\perp^{\mu\nu}\chi_v m_q \bar{q}\sigma^{\rho\sigma} q \Bigg\} + \frac{c_{\chi 25}}{m_W^3}\bar{\chi}_v\chi_v G^A_{\alpha\beta}G^{A\alpha\beta} + \frac{c_{\chi 26}}{m_W^3}\bar{\chi}_v\chi_v G^A_{\alpha\beta}\tilde{G}^{A\alpha\beta}$$

$$+ \frac{c_{\chi 27}}{m_W^3}\bar{\chi}_v\chi_v v_\mu v_\nu G^{A\mu}{}_\alpha G^{A\nu\alpha} + \frac{c_{\chi 28}}{m_W^3}\bar{\chi}_v \sigma_\perp^{\mu\nu}\chi_v \epsilon_{\mu\nu\alpha\beta}v^\alpha v^\gamma G^{A\beta\delta}G^A_{\gamma\delta} + \dots\,, \quad (7$$

# 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.