Universität Heidelberg

Carl Zeiss Stiftung

INTRODUCTION TO DARK MATTER

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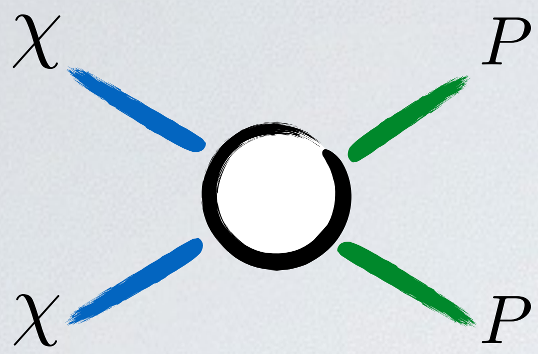
PART II
DARK MATTER NUCLEON SCATTERING

- Dark matter interactions with the standard model
- Direct detection by nucleon scattering
- Interpretation of experimental null results

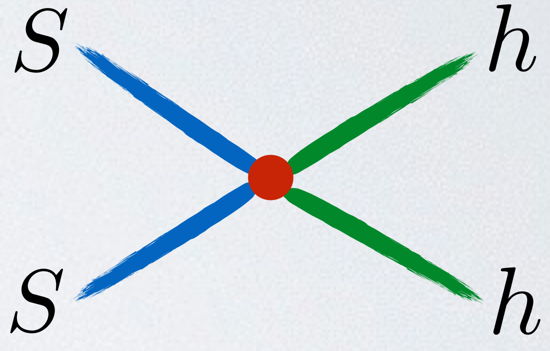
PORTALS TO A DARK SECTOR



How can dark matter possibly interact with standard-model particles?

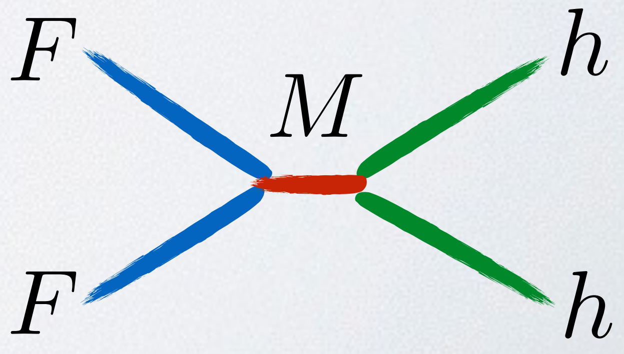
fundamental interactions:

neutrino portal	$\lambda_N \overline{L} \widetilde{H} N + h.c.$
scalar Higgs portal	$\lambda_S (H^\dagger H)(SS)$
kinetic mixing	$\epsilon\, F^{\mu\nu} F'_{\mu\nu}$



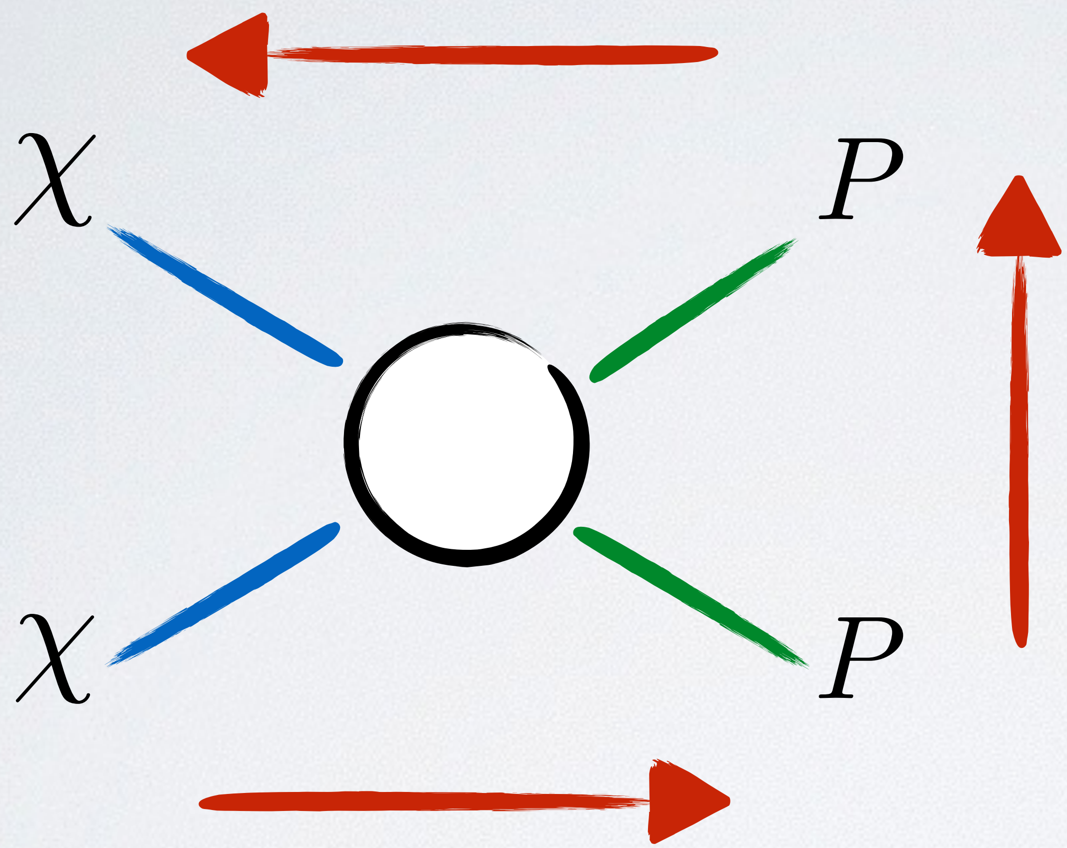
effective interactions through mediator M:

fermion Higgs portal	$\frac{\lambda_F}{\Lambda}(H^\dagger H)(\overline{F}F)$
4-fermion interaction	$\frac{C_f}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{F}\gamma^\mu F)$



LAB PROBES OF DARK MATTER

production at colliders
(missing energy and mediator searches)

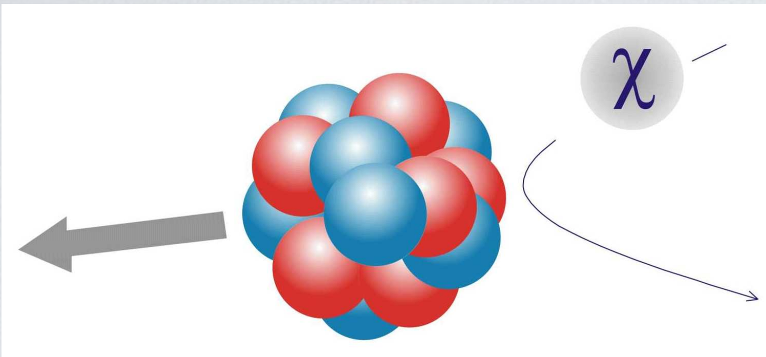


DM-nucleon scattering
(direct detection)

annihilation in DM-rich regions
(indirect detection)

Caution: very different kinematic regimes!

DARK MATTER-NUCLEON SCATTERING



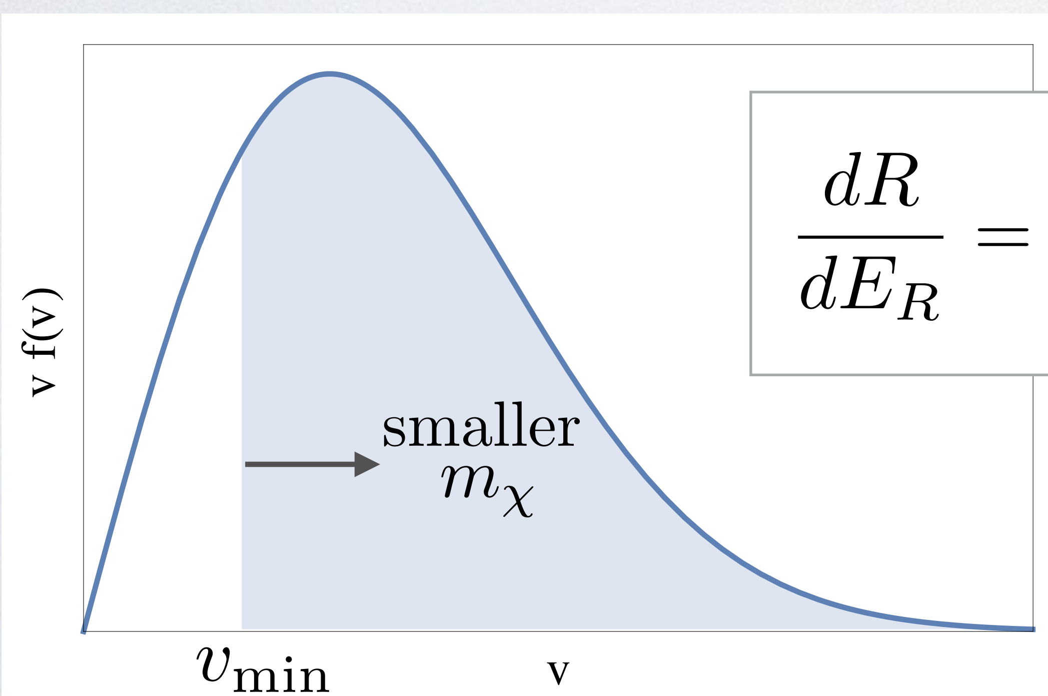
Dark matter velocity: $v \approx 10^{-3} c$

Mass of Xenon nucleus: $m_N \approx 120\,\mathrm{GeV}$

Recoil energy of nucleus:

$$E_R = \frac{(m_\chi v)^2}{2 m_N} \approx 50\,\mathrm{keV} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_N}\right)$$

Scattering rate:



$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{\min}}^{v_{\max}} d^3v\, v\, f(\mathbf{v} + \mathbf{v}_{\mathrm{sun}}(t)) \frac{d\sigma}{dE_R}$$

$$v_{\min}^2 = \frac{m_N E_R}{2\mu^2}$$

[Lisanti, TASI 2016]

SPIN-INDEPENDENT SCATTERING

Differential cross section for DM-**nucleus** scattering:

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}|Zf_p + (A-Z)f_n|^2 F^2(E_R)$$

For fermion DM with isospin-conserving interactions: $f_p = f_n$

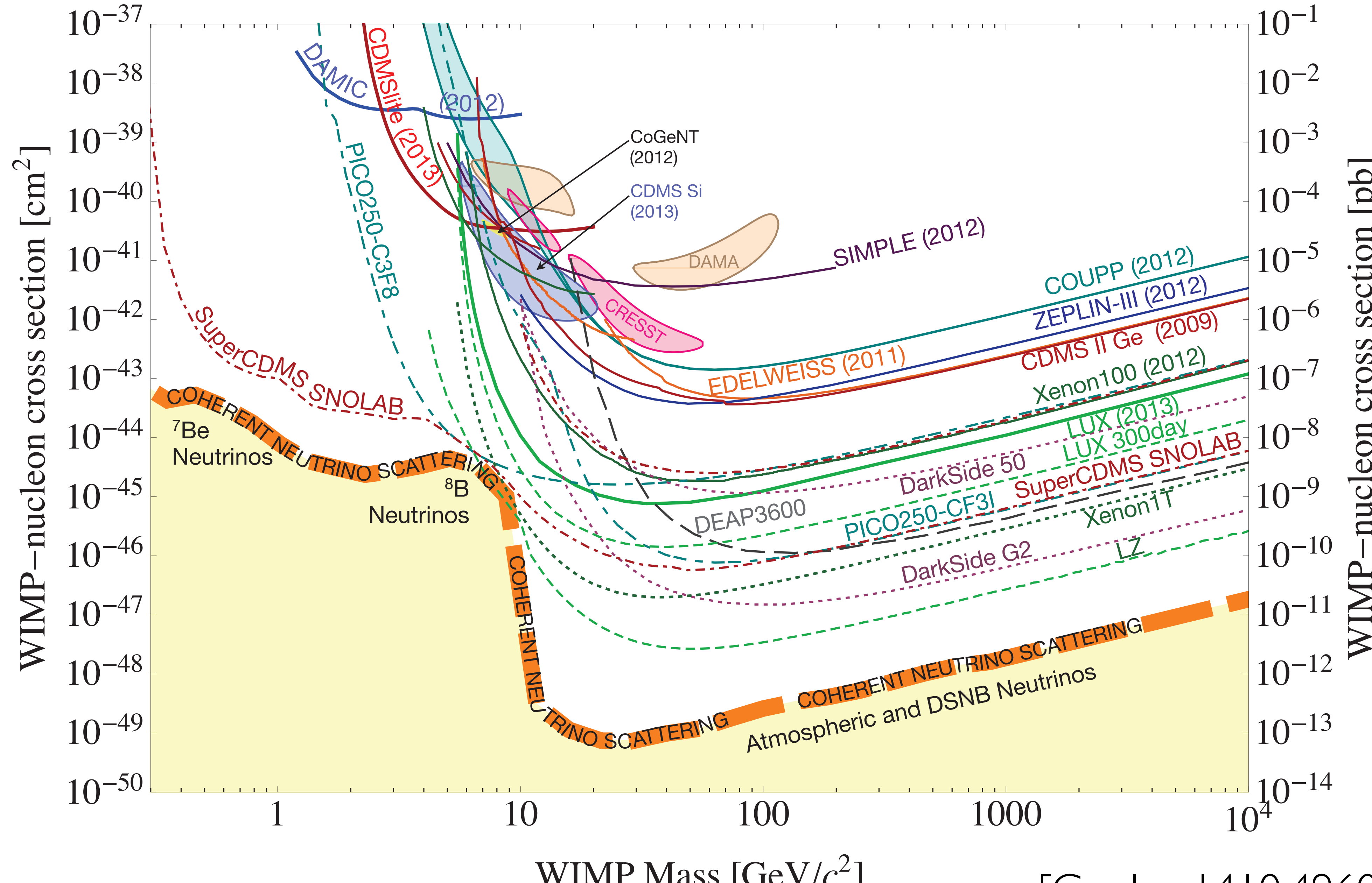
$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\kappa \mu_n^2 v^2}\sigma_n A^2 F^2(E_R)$$

Cross section for **nucleon** scattering: $\sigma_n = \kappa \frac{\mu_n^2 f_n^2}{\pi}$ $\quad \kappa = 1(4)$

Majorana (Dirac)

In **spin-independent** interactions, dark matter scatters **coherently** off the nucleus.

EXPERIMENTAL SENSITIVITY

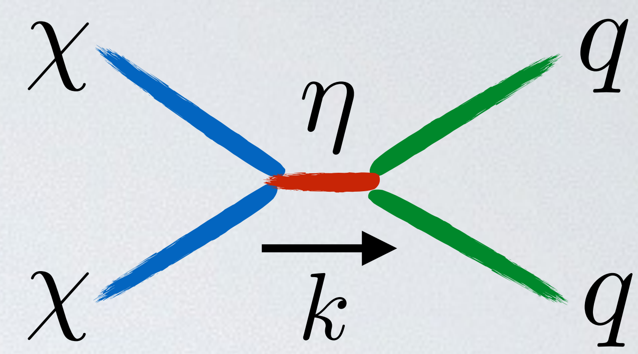


[Cooley, 1410.4960]

Xenon 1T: $\sigma_n(m_\chi = 35\,\mathrm{GeV}) < 7.7 \times 10^{-47}\,\mathrm{cm}^2$ (90%CL)

FUNDAMENTAL INTERACTIONS

Effective DM-quark interaction:



$$\mathcal{L}_{\text{eff}} = g_{\text{eff}}(\overline{\chi}\,\Gamma_\chi \chi)(\overline{q}\,\Gamma_q q)$$

$$\Gamma_i = \{1, \gamma_5, \gamma_\mu, \ldots\}$$

For a scalar interaction, the nucleon form factor is:

$$f_n = \sum_{q=u,d,s} m_n \frac{g_{\text{eff}}}{m_q} f^n_{T_q} + \frac{2}{27} f^n_{TG} \sum_{q=c,b,t} m_n \frac{g_{\text{eff}}}{m_q} \qquad m_n f^n_{T_q} = \langle n | m_q \overline{q} q | n \rangle$$

The matrix element for coherent nucleus scattering is then:

$$\mathcal{M} = [Z f_p + (A - Z) f_n](\overline{\chi}\chi)(\overline{N}N)F(k)$$

In the non-relativistic limit: $\dfrac{d\sigma}{dE_R} = \dfrac{2m_N}{\pi v^2}\langle|\mathcal{M}_{\text{NR}}|^2\rangle$

RELEVANCE OF NUCLEAR SPIN

Spin-independent interactions:

$$\mathcal{L}_{SI} \sim (\overline{\chi}\chi)(\overline{q}q) + (\overline{\chi}\gamma^{\mu}\chi)(\overline{q}\gamma_{\mu}q)$$

Pseudo-scalar interactions vanish in NR limit.

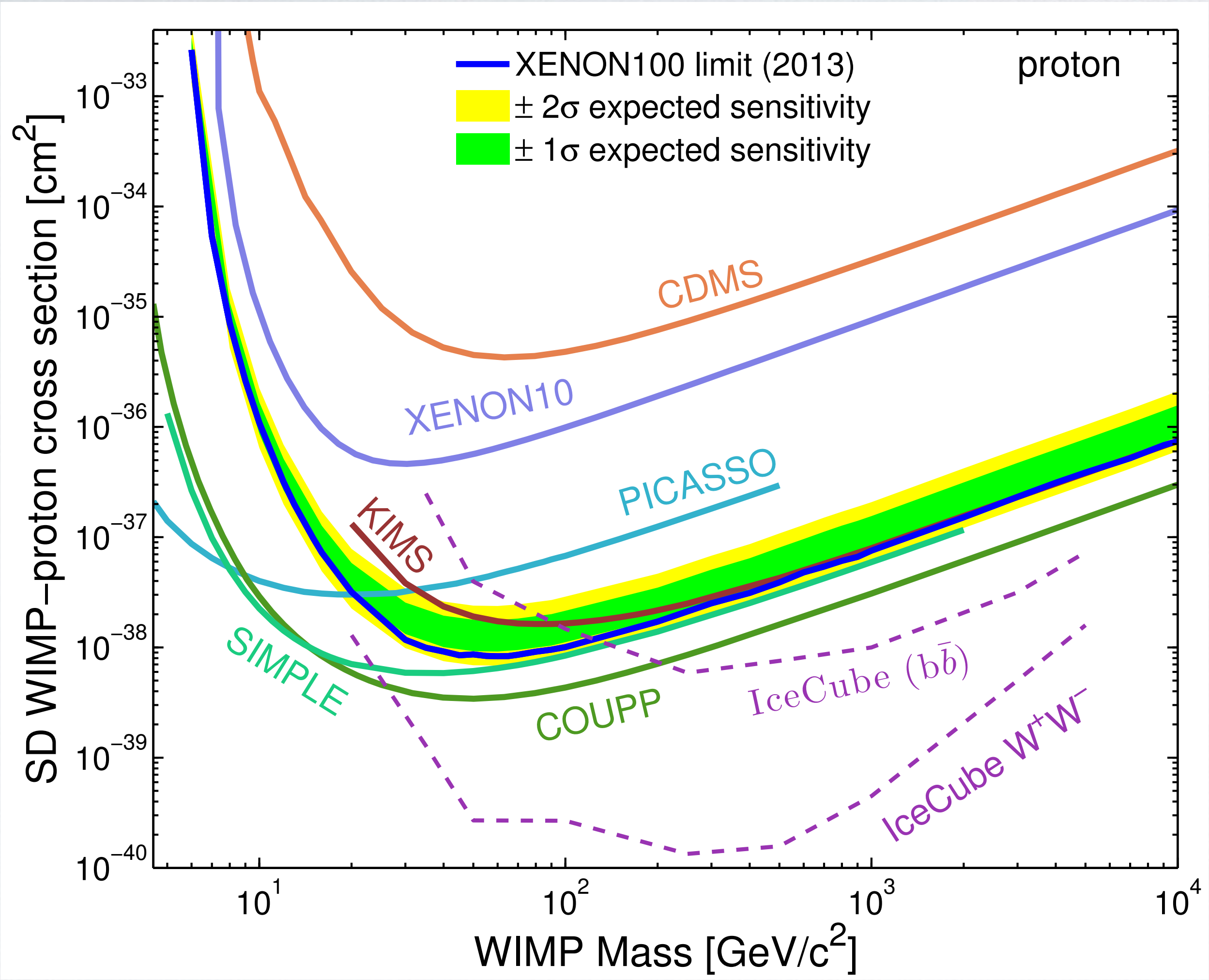
Spin-dependent interactions:

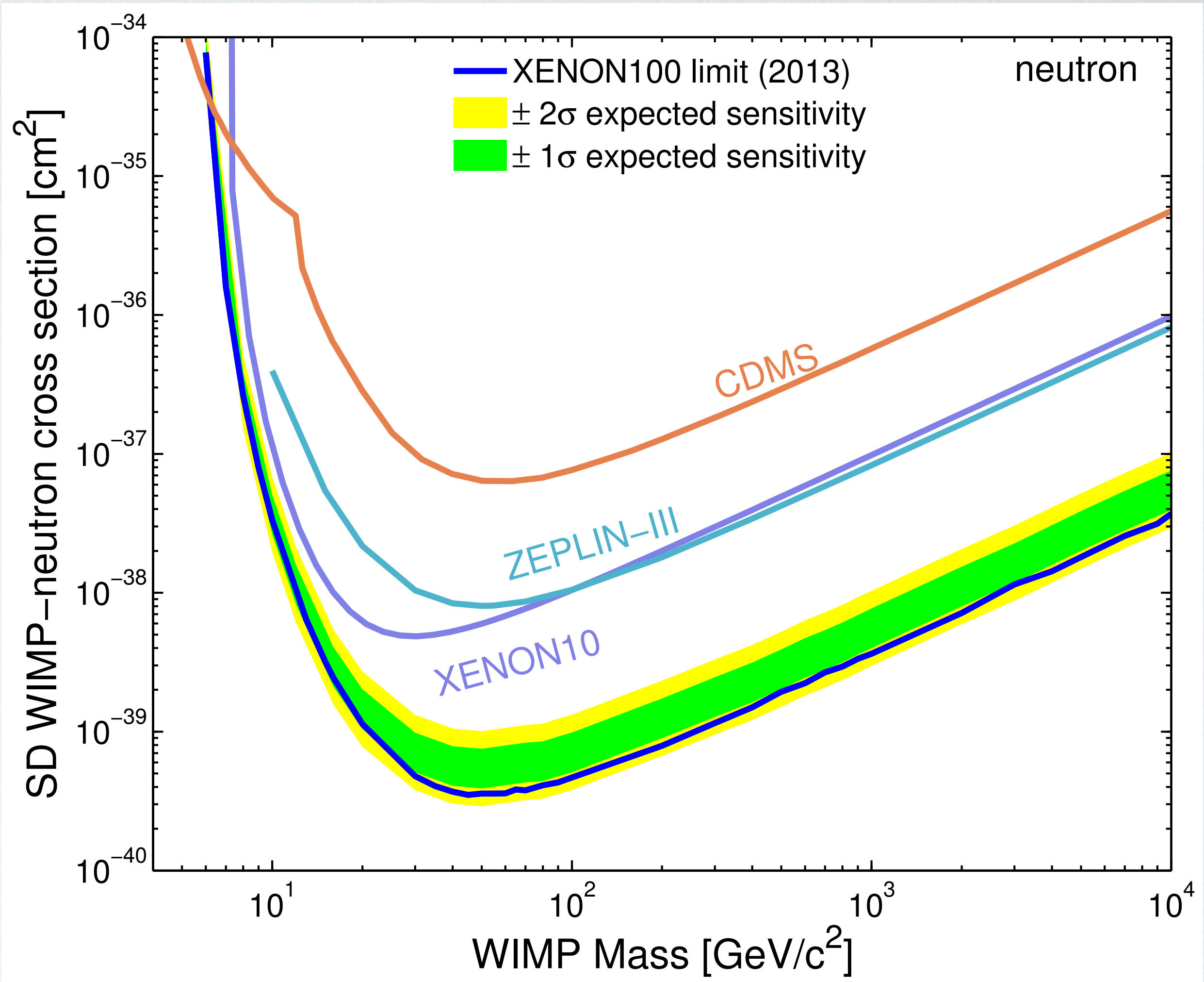
$$\mathcal{L}_{SD} \sim (\overline{\chi}\gamma^{\mu}\gamma_5\chi)(\overline{q}\gamma_{\mu}\gamma_5 q) + (\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)$$

Spin-dependent scattering off nucleus:

$$\frac{d\sigma}{dE_R} = \frac{16 m_N}{\pi v^2} G_F^2 J(J+1) \frac{(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2}{J^2} F_{SD}^2(E_R)$$

SPIN-DEPENDENT SCATTERING





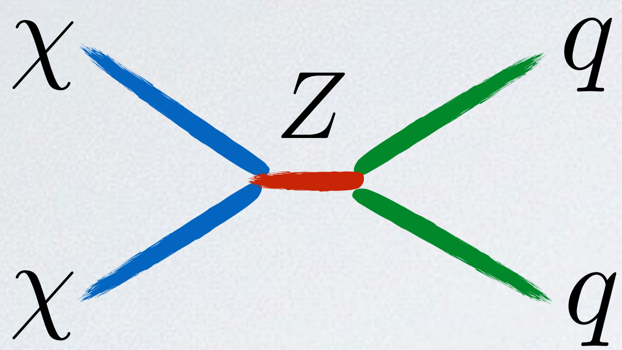
[Xenon 100 coll., 1301.6620]

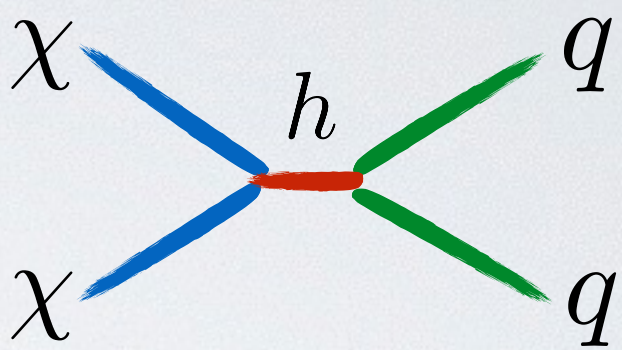
Xenon 100: bound on pure neutron interactions

$$\sigma_n(m_\chi = 45\,\mathrm{GeV}) < 3.5 \times 10^{-40}\,\mathrm{cm}^2\ \ (90\%\mathrm{CL})$$

MODEL BUILDING

Standard-model mediators: spin-independent scattering





$$\frac{g^2}{M_Z^2}(\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q) \qquad \frac{y_\chi y_q}{M_h^2}(\overline{\chi}\chi)(\overline{q}q)$$

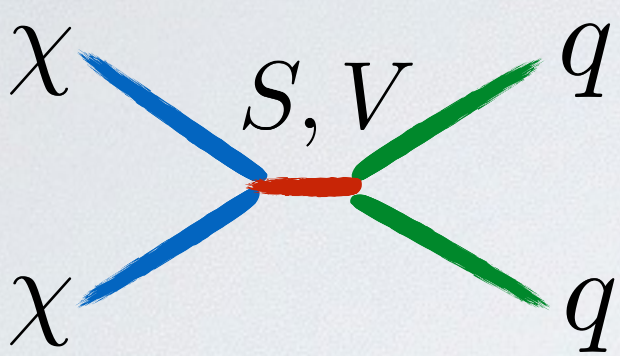
Null results in direct detection: $y_\chi \lesssim 10^{-2}$

Direct-detection proof candidates:

- **Majorana** dark matter (no vector coupling)
- **Pseudo-scalar** mediator (no scattering at tree level)

INTERPLAY WITH RELIC ABUNDANCE

scalar/vector interaction:

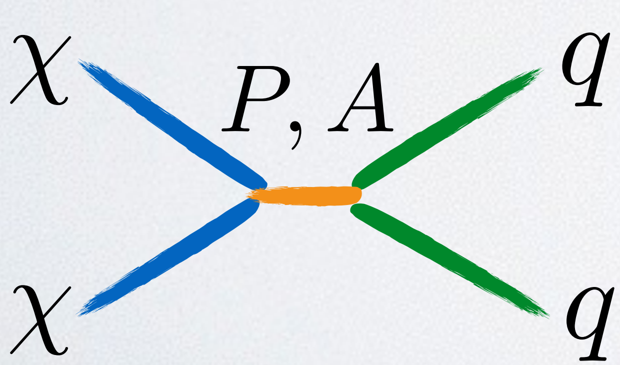


SI scattering active ⟶ suppress coupling

⟶ overabundance

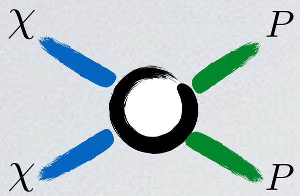
Co-annihilation or other channels can prevent overabundance.

pseudo-scalar/axial-vector interaction:

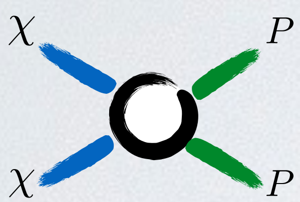


SI scattering absent ⟶ coupling set by observed abundance

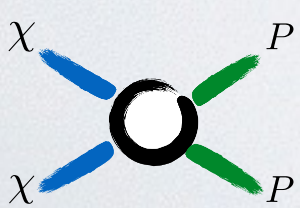
SUMMARY PART II



Dark matter-nucleon scattering can be tested in well shielded direct detection experiments.



Spin-independent scattering happens coherently and probes scalar and vector couplings.



Spin-dependent scattering leads to lower rates and probes axial-vector interactions.

LITERATURE

M. Lisanti: *Lectures on Dark Matter Physics,* 1603.03797

T. Marrodan and L. Rauch, *Dark matter direct detection experiments,* 1509.08767

Agrawal et al., *A classification of dark matter candidates with primarily spin-dependent interactions with matter*; 1003.1912