Simulation of the Directional Dark Matter Detector (D^3) and Directional Neutron Observer (DiNO)

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- **collaboration**
- **introduction**
- **simulation status (early stage of development)**
- **D^3 reach plots (highly preliminary)**
- **conclusion**

Collaboration

UNIVERSITY of HAWAI'I
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BERKELEY LAB
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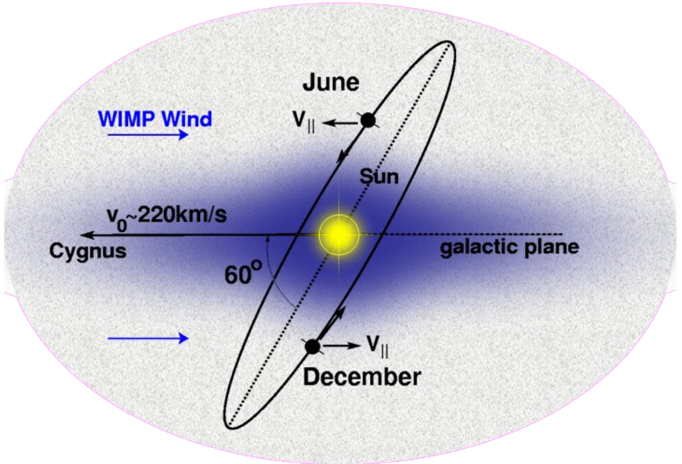
What do we want to detect ?

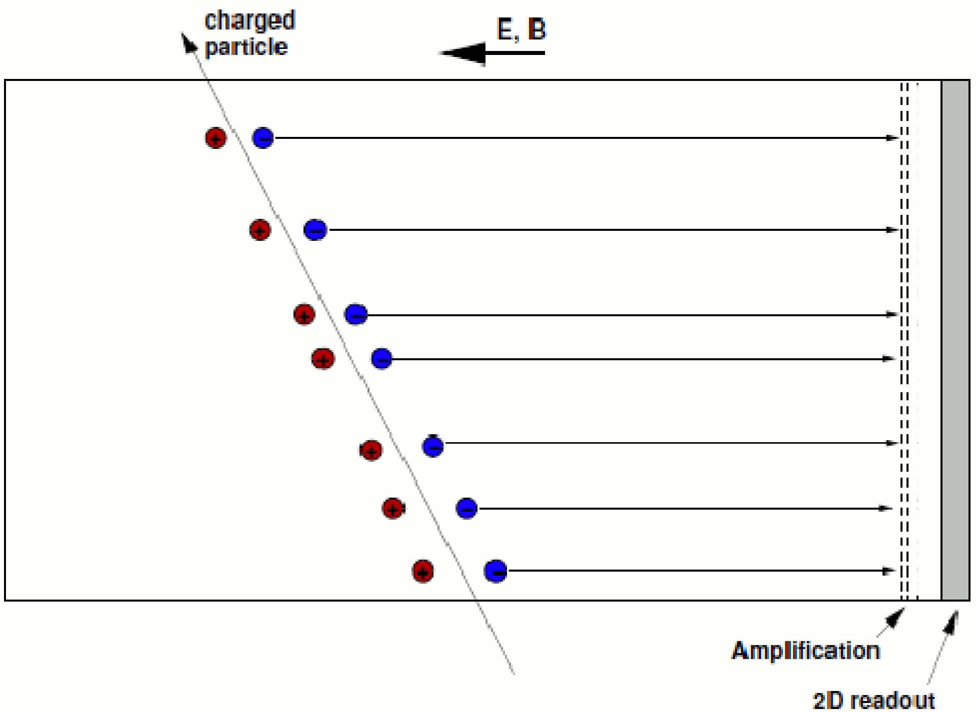
- **neutron emitted by Special Nuclear Materials e.g. plutonium**
  - **~ 1 GeV mass, few MeV in kinetic energy with a flux of several 100 $g^{-1}s^{-1}$**
  - **interact through strong force**

- **Weakly Interacting Massive Particle emitted by Cold Dark Matter**
  - **existence hypothetical**
  - **mass unknown, few keV in kinetic energy**
  - **interact through gravitational and weak forces**
  - **<u>hypothesis</u>: behaves as a slow moving heavy neutron**



Detection principle

- **detect the ionization produced when a particle scatters off nucleus of the gas material**
- **neutron: C_4H_{10} (iso-butane) gas – $m_{neutron} \sim m_H$**
- **WIMP: ^4He, CF_4, ^{40}Ar and ^{131}Xe gas – m_{WIMP} ?**



- **identifiable if elastic scattering occurs**

e.g. $n + H \rightarrow n + H$

- **amplification with GEMs enables detection of electrons produced by the nuclear recoil with nearly 100 % efficiency estimated**

Simulation steps

NB: a complete simulation is not yet implemented

- signal and background sources
- geometry and materials
- neutron/WIMP interaction with the detector
- creation of the ionization in the gas target
- electron transport from the primary ionization to the readout
- electronic readout

Signal and background sources

- **neutron**
  - **neutron sources (^{240}Pu or laboratory source ^{252}Ca)**
  - **background sources (alpha, beta etc ...)**

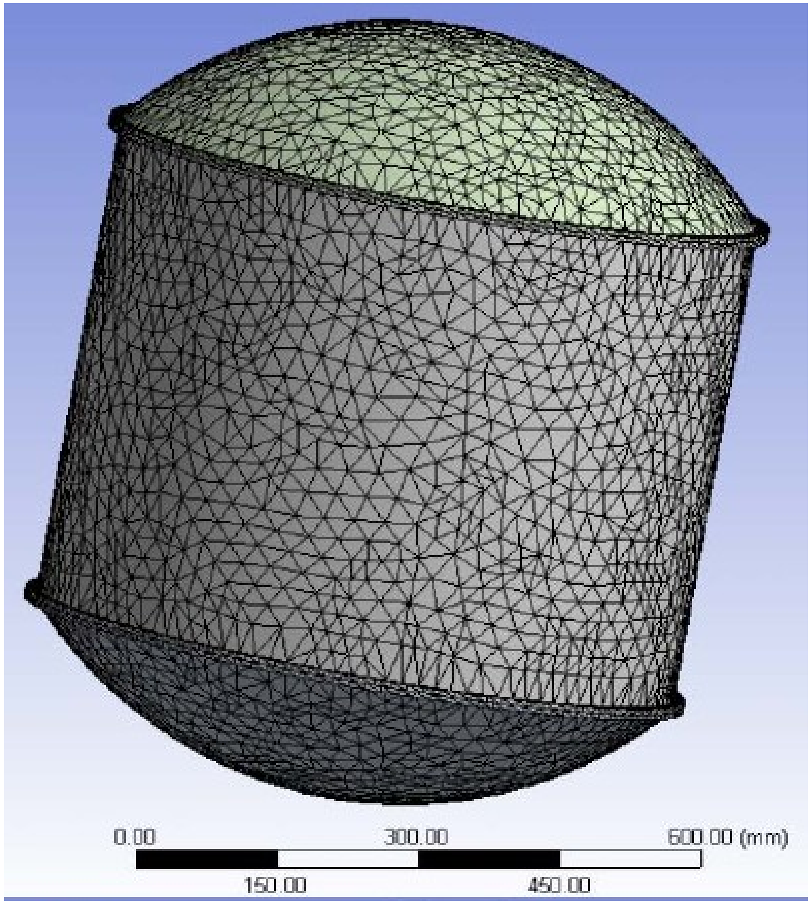
=> PLUTO, PYTHIA, EvtGen, MCPNX, GEANT3 and GEANT4

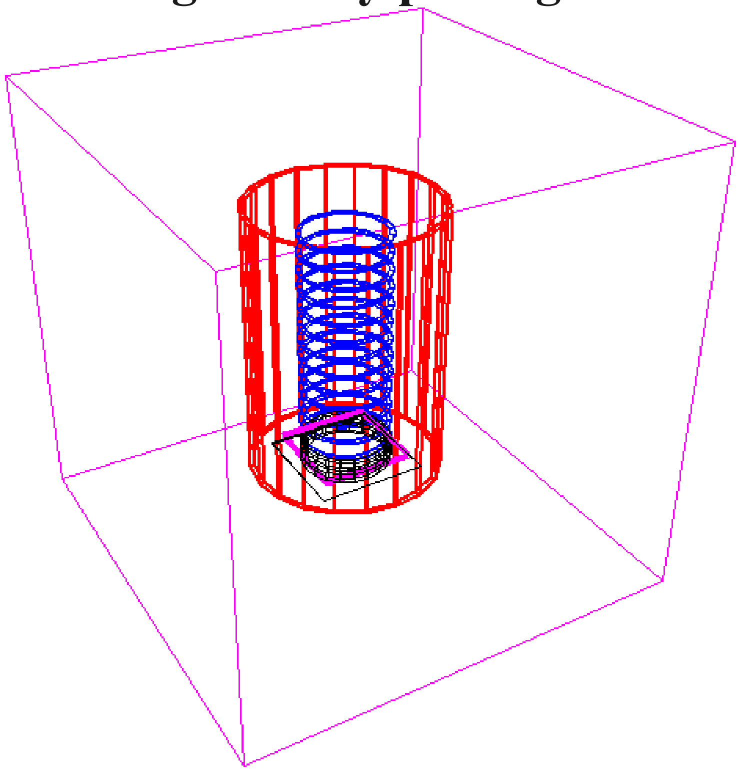
- **WIMP**
  - **WIMP sources**
  - **background sources (neutron, ^{222}Rn)**

=> PLUTO, PYTHIA, EvtGen, GEANT3 and GEANT4

Geometry and materials

- CAD can be transformed to GEANT3 and GEANT4 format
- shown: DiNO/D^3-micro model using CAD and ROOT geometry package





Probability of interaction

- $P = \sigma \cdot l \cdot \rho$
  - σ cross section [b] (barn = $1e^{-24}$ cm^2)
  - l target length [cm]
  - ρ density [cm^{-3}] = ρ_0 [g/cm^3] . $\mathcal{N}_A$[mol^{-1}] / $\mathcal{M}_A$[g/mol]
- between a neutron and a H belonging to C_4H_{10}

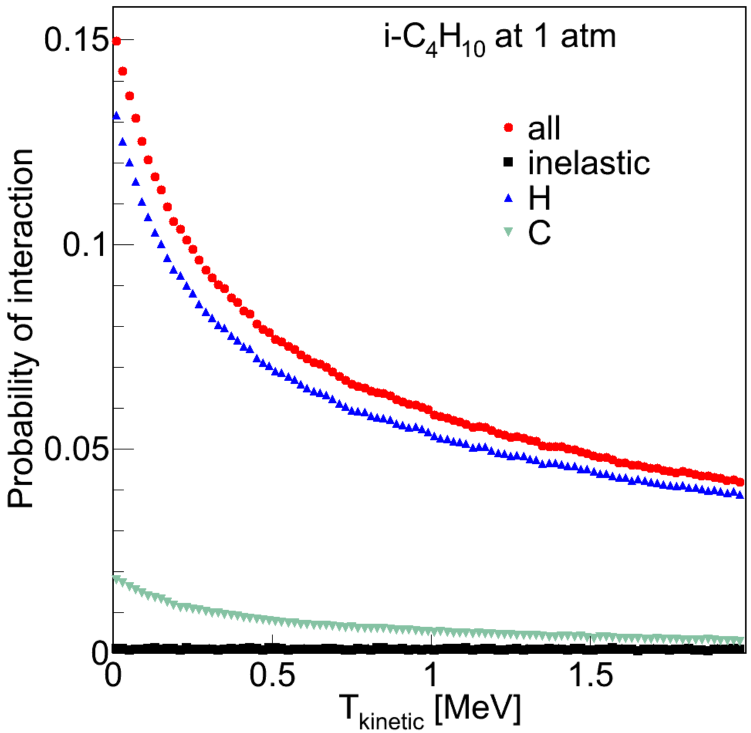
=> 0.11 % for 1 cm

- between a neutron and a F belonging to CF_4

=> 0.003 % for 1 cm

- GEANT4 results for DiNO

=> 50 cm^3, C_4H_{10} (1 atm) ~ 5 % efficiency at 1 MeV



=> good agreement between geant4 and analytical calculation

=> efficiency can be adjusted by varying size and pressure

Reach plot - general formula

J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

- **differential energy spectrum of nuclear recoils**

$$\frac{dR}{dT_R} = R_0 S(T_R) F^2(T_R) I$$

- **R is the event rate per unit mass**
- **T_R is the recoil energy**
- **R_0 is the total event rate**
- **S is the modified spectral function**
- **F is the form factor**
- **I is an interaction function**

Total cross section off nucleus and off nucleon

$$\frac{d\sigma^A(M_X)}{dT_R} = \frac{1}{V\,\rho\,\phi(M_X)\,\Delta t\,\epsilon(M_X)}\frac{dN(M_X)}{dT_R} \text{ and } \frac{d\sigma^N(M_X)}{dT_R} = \frac{\mu_N^2(M_X)}{\mu_A^2(M_X)}\Gamma^N \frac{d}{dT_R}\frac{\sigma^A(M_X)}{\Gamma^A(T_R)}$$

- **N event number if N = 2.3 CL = 90 %, in this work N = 1**
- **V detector volume [cm^3]**
- **ρ target density [cm^{-3}] = ρ_0 [g/cm^3] . $\mathcal{N}_A$[mol^{-1}] / $\mathcal{M}_A$[g/mol]**
- **φ WIMP flux [$cm^{-2}s^{-1}$] – <u>model dependent</u>**
- **Δt exposure time [s]**
- **ε detection efficiency**

  $M_X + A \rightarrow M_X + A$
- **$\Gamma^{N,A}$ "interaction" between the WIMP and the nucleon/nucleus: $\Gamma^A = F^2\ I$**

  <u>model dependent</u>

- **μ_N nucleon reduced mass**
- **μ_A nucleus reduced mass**

- **I = A^2 for SI or I = $C^2\lambda^2 J(J+1)$ for SD**
- **F^2 (qr_n) is the form factor**

WIMP flux

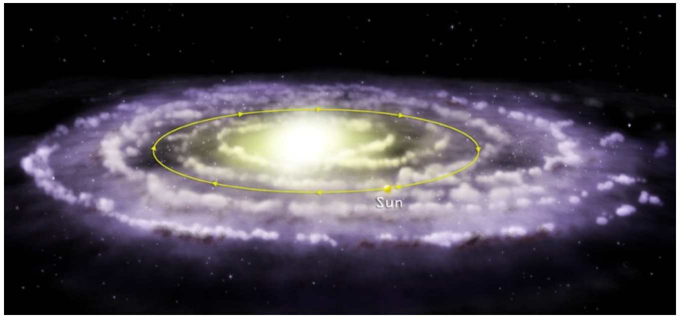
J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

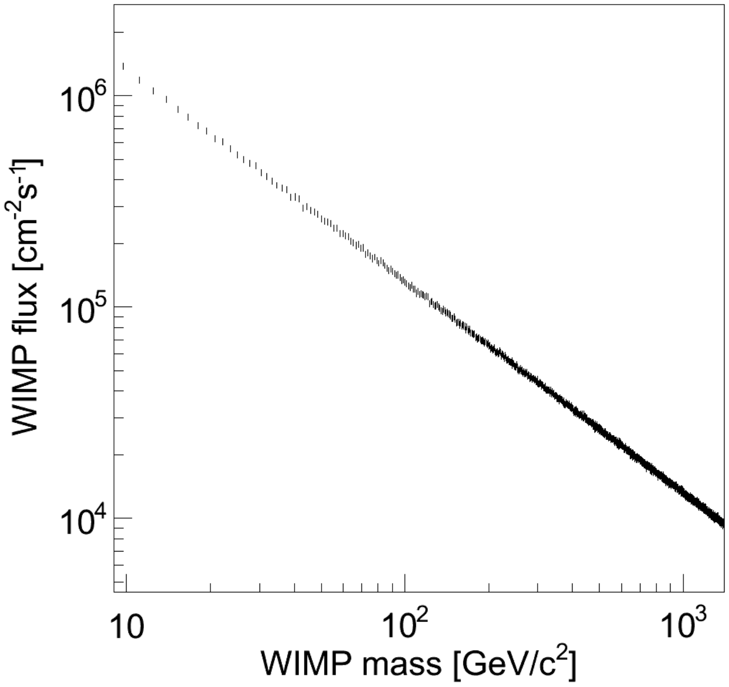
- $\Phi = \rho_D v_D / M_D$ [$cm^{-2}s^{-1}$]
- $\rho_D = 0.3$ [$GeV/c^2/cm^3$]
- v_D depends on WIMP velocity distribution choice

- **Gaussian velocity distribution**

$$f(v) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{|v|^2}{2\sigma^2}\right)$$

- σ is the speed dispersion = $(3/2)^{1/2} v_c$, v_c local circular speed (= 220 km/s)
- $v_{detector} = v_{galaxy} + v_{sun} + v_{earth}$, v_{escape} = 530 km/s



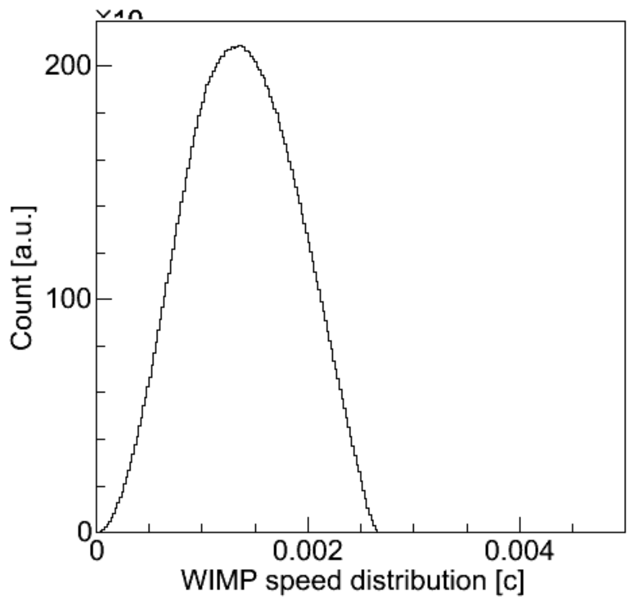


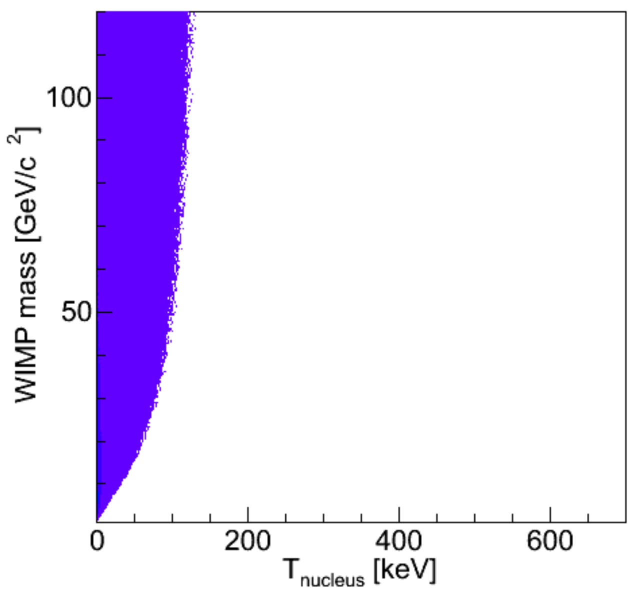
Elastic scattering

$$T^{cm}_{nucleus} = \frac{M_D^2}{(M_T+M_D)^2}\frac{M_T}{2}v^2$$

- **T nucleus kinetic energy in CMS**
- **M_D and M_T respectively WIMP and nucleus masses**
- **v WIMP velocity in CMS**

in LAB.





Interaction function

J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

- **SI : σ α |A|^2**
- **SD : σ α J^2**
- **I = C^{2}λ^{2}J(J+1)**
- **C related to the quark spin**
- **λ^{2}J(J+1) related to nuclear magnetic moment and the unpaired nucleon spin**

Isotope	J	$\lambda^2 J(J+1)$	
		single particle	odd group
^{1}H	1/2	0.75	0.75
^{19}F	1/2	0.75	0.647
^{23}Na	3/2	0.15	0.041
^{27}Al	5/2	0.35	0.087
^{43}Ca	7/2	0.321	0.152
^{73}Ge	9/2	0.306	0.065
^{93}Nb	9/2	0.306	0.162
^{127}I	5/2	0.35	0.007
^{129}Xe	1/2	0.75	0.124
^{131}Xe	3/2	0.15	0.055

Table 3: Values of $\lambda^2 J(J+1)$ for various isotopes

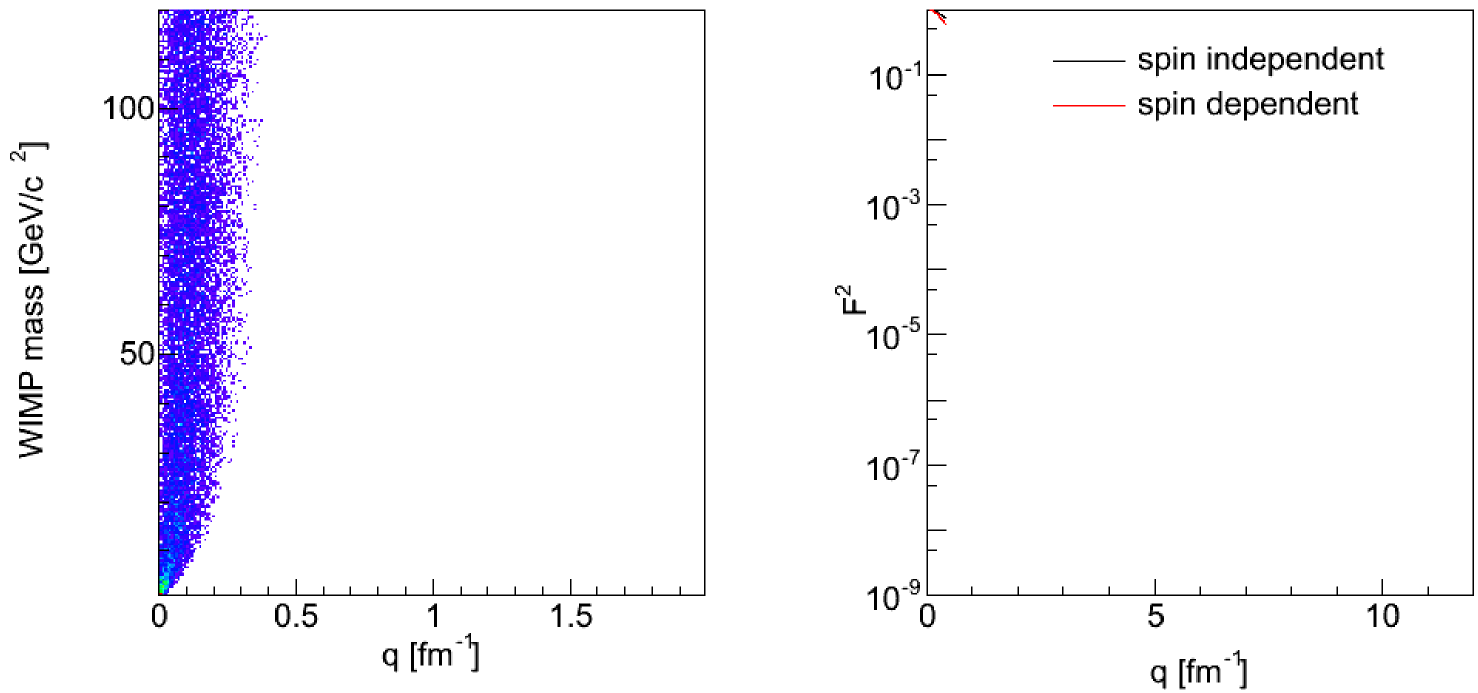
WN	C^2_{WN}			$\frac{\sigma_{WN}\vert_{spin}}{\mu^2 I_s}$	$\frac{\sigma_{WN}\vert_{spin}}{\sigma_{\nu_M N}}$
	NQM	EMC [36]	EMC [4]		
$\tilde{\gamma}p$	0.14 ± 0.01	0.096 ± 0.009	0.06 ± 0.02	$\frac{4}{\pi}\left(\frac{e}{m_{\tilde{q}}c}\right)^4$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4$
$\tilde{\gamma}n$	0.002 ± 0.001	0.012 ± 0.003	0.03 ± 0.01		
$\tilde{H}p$	0.40 ± 0.02	0.46 ± 0.04	0.55 ± 0.10	$\frac{8G_F^2}{\pi\hbar^4}\cos^2 2\beta$	$4\cos^2 2\beta$
$\tilde{H}n$	0.40 ± 0.02	0.34 ± 0.03	0.26 ± 0.07		
$\tilde{B}p$	0.16 ± 0.01	0.10 ± 0.01	0.06 ± 0.02	$\frac{1}{\pi}\left(\frac{e}{m_{\tilde{q}}c}\right)^4 \frac{1}{\cos^2\theta_W}$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4 \frac{1}{4\cos^2\theta_W}$
$\tilde{B}n$	$(7 \pm 5) \times 10^{-4}$	0.010 ± 0.003	0.03 ± 0.01		
$\tilde{Z}p$	1.9 ± 0.1	0.9 ± 0.1	0.3 ± 0.2	$\frac{4}{\pi}\left(\frac{e}{m_{\tilde{q}}c}\right)^4 \tan^4\theta_W$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4 \tan^4\theta_W$
$\tilde{Z}n$	0.21 ± 0.04	0.002 ± 0.006	0.1 ± 0.1		

Table 4: Values of WIMP-nucleon spin factors; $M_F = \sqrt{8}\,M_W \sin\theta_W \simeq 109\ \mathrm{GeV c^{-2}}$

Nuclear Form Factor

J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

- **one nuclear form factor per nucleus**
- **momentum transfer $q = | p_{\text{nucleus at rest}} - p_{\text{nucleus after elastic scattering}} |$**
- **spin dependent**
- **spin independent**



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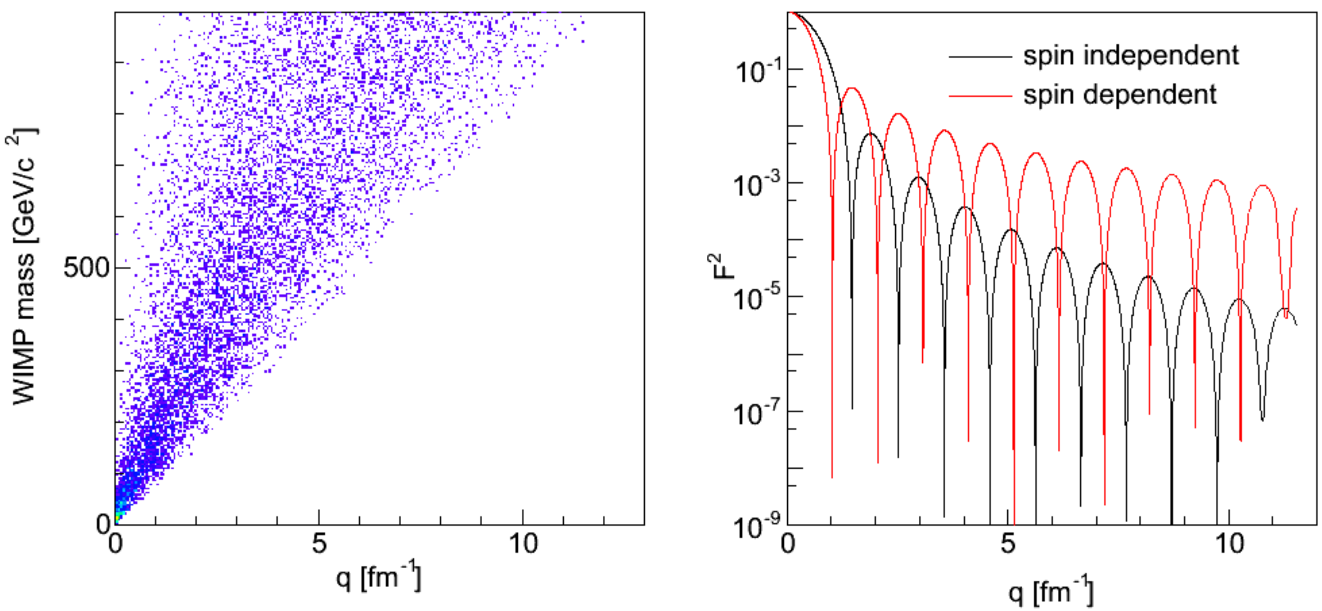
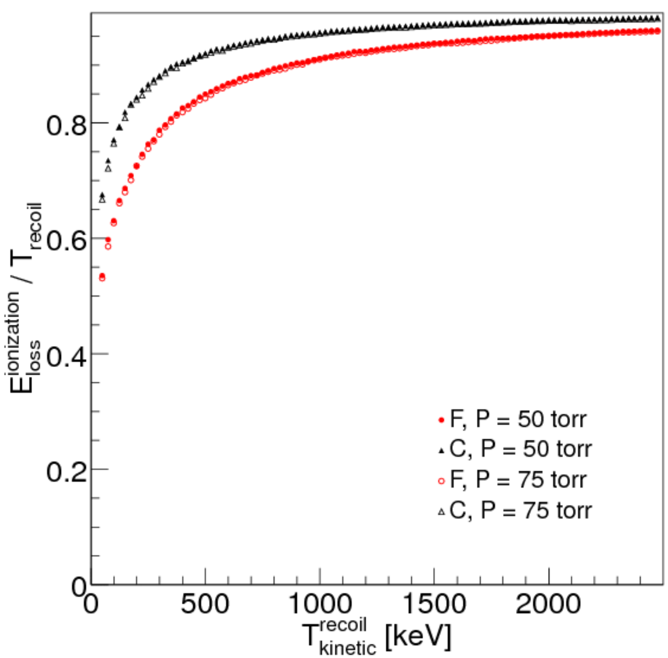


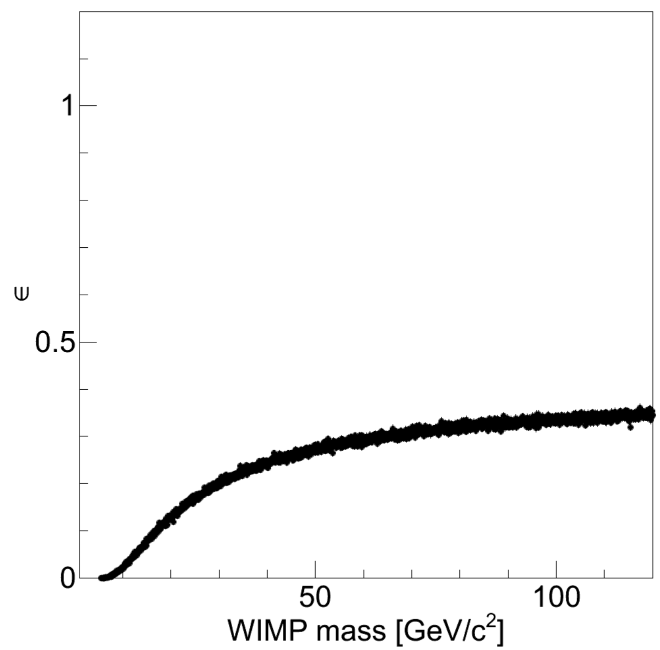
- **remark: if enough energy is transferred one can deduce from the position of the minima what kind of interaction did occur**

Detection efficiency

- depends on the thresholds and WIMP velocity distribution
- energy deposited eg through ionization

$$X + p \rightarrow X^{+} + p + e^{-}$$





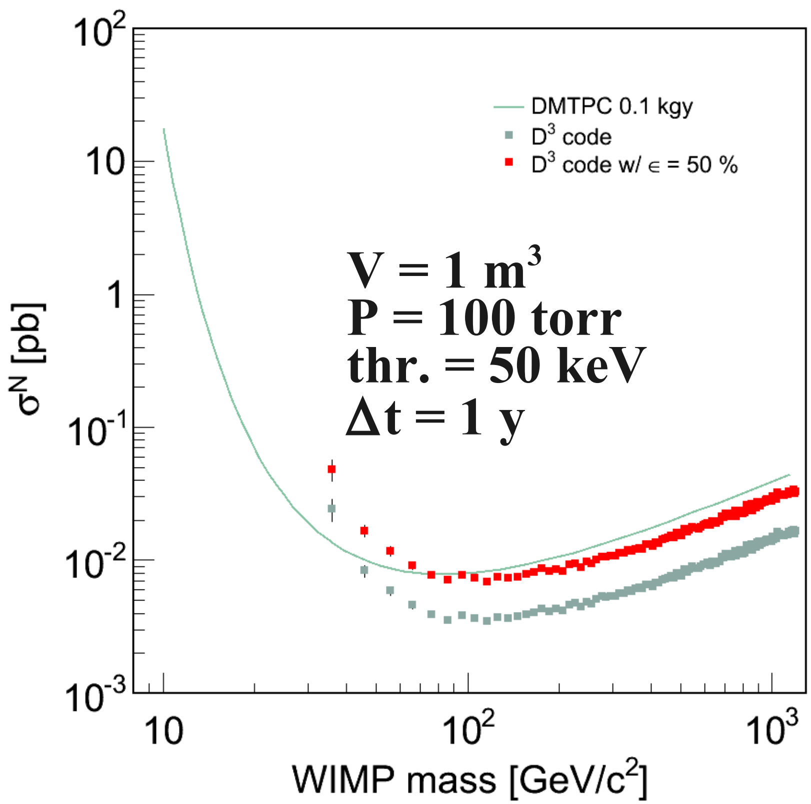
thresholds:

- energy threshold
- minimum track length measurable
  - GEM: at least 3 holes covered
- directionality
  - L / σ > 3

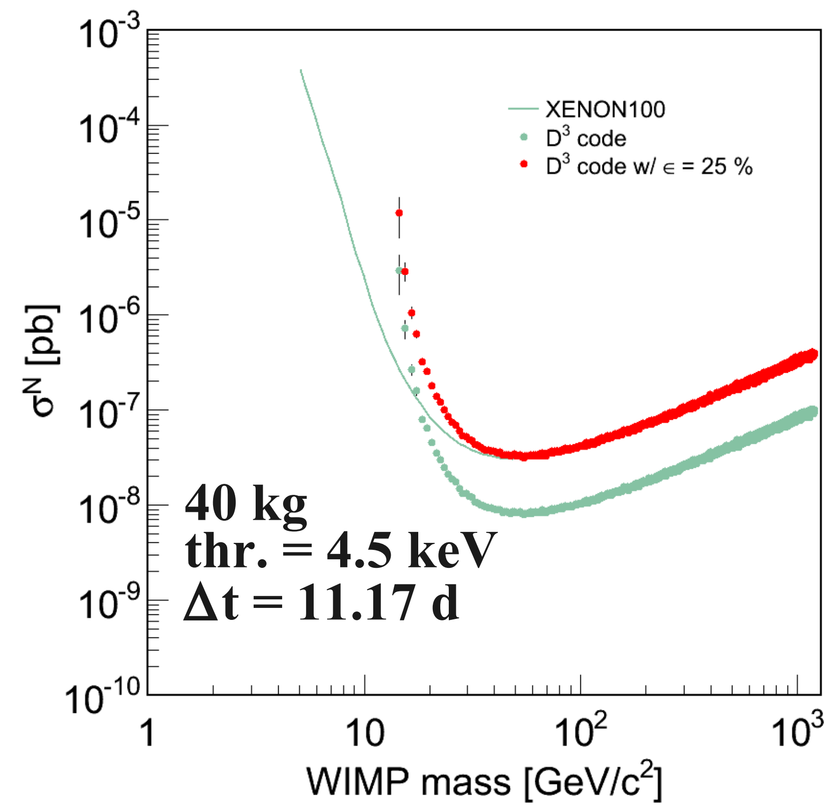
- SRIM simulation and quenching factor

Code validation

- code tested by putting the input parameters corresponding to DMTPC and XENON100
- detection efficiency approximated by a constant value



quenching factor determined from SRIM

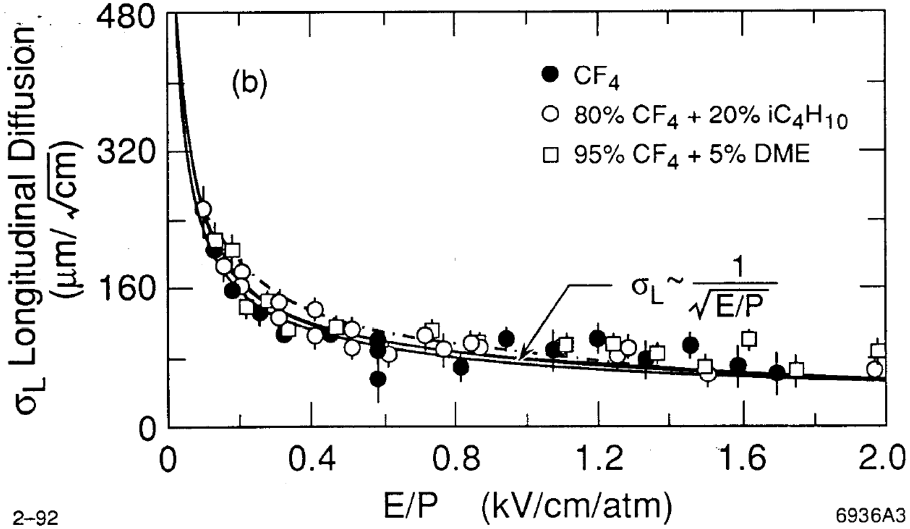


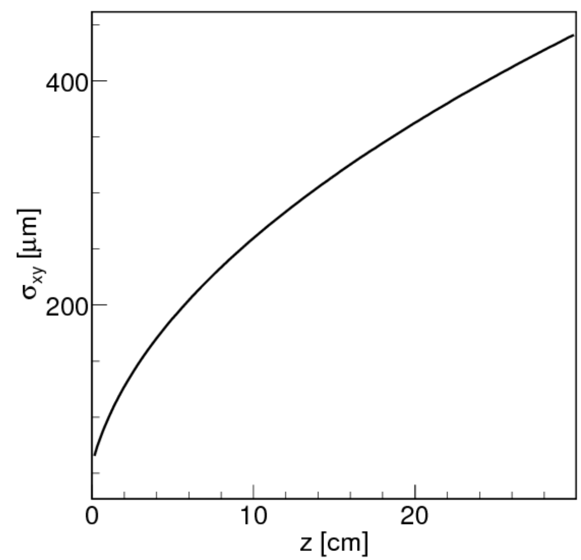
constant quenching factor 25 %

Design optimization

- 1 m^3 divided into 3 detectors of drift length of 33.33 cm
- other key ingredients
  - energy threshold 1 keV
  - spacing between GEM holes 0.140 mm
  - pad size 0.2 mm
  - transverse diffusion

$$\frac{C_D}{\sqrt{N_{eff}}} = 80\ \mu m/\sqrt{cm}$$





$$\sigma_{xy} = \sqrt{\left(\frac{pad}{\sqrt{12}}\right)^2 + \frac{C_D^2}{N_{eff}} z}$$

- pad: pad size
- C_D transversal diffusion constant
- N_{eff} effective number of primary electrons

S. Biagi, Nucl. Instr. & Meth. A283 (1989) 716.
S. Biagi, Nucl. Instr. & Meth. A310 (1991) 133.
J. Va'vra, P. Coyle, J. Kadyk, and J. Wise, SLAC-PUB-5728 (1992).

Design optimization

- 1 m^3 divided into 3 detectors of drift length of 33.33 cm
- other key ingredients
  - energy threshold 1 keV
  - spacing between GEM holes 0.140 mm
  - pad size 0.2 mm
- transverse diffusion

$$\sigma_{xy} = \frac{1}{\sqrt{P}} f\left(\frac{E}{P}\right)$$

- by changing only the pressure

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Design optimization

- 1 m^3 divided into 3 detectors of drift length of 33.33 cm
- other key ingredients
  - energy threshold 1 keV
  - spacing between GEM holes 0.140 mm
  - pad size 0.2 mm
- transverse diffusion **if E changed accordingly σ remains the same for all pressure**

$$\sigma_{xy} = \frac{1}{\sqrt{P}} f\left(\frac{E}{P}\right)$$

- **by changing only the pressure**

S. Biagi, Nucl. Instr. & Meth. A283 (1989) 716.
S. Biagi, Nucl. Instr. & Meth. A310 (1991) 133.
J. Va'vra, P. Coyle, J. Kadyk, and J. Wise, SLAC-PUB-5728 (1992).

Pressure optimization

- **1 m^3 of CF_4 divided into 3 detectors of drift length of 33.33 cm**

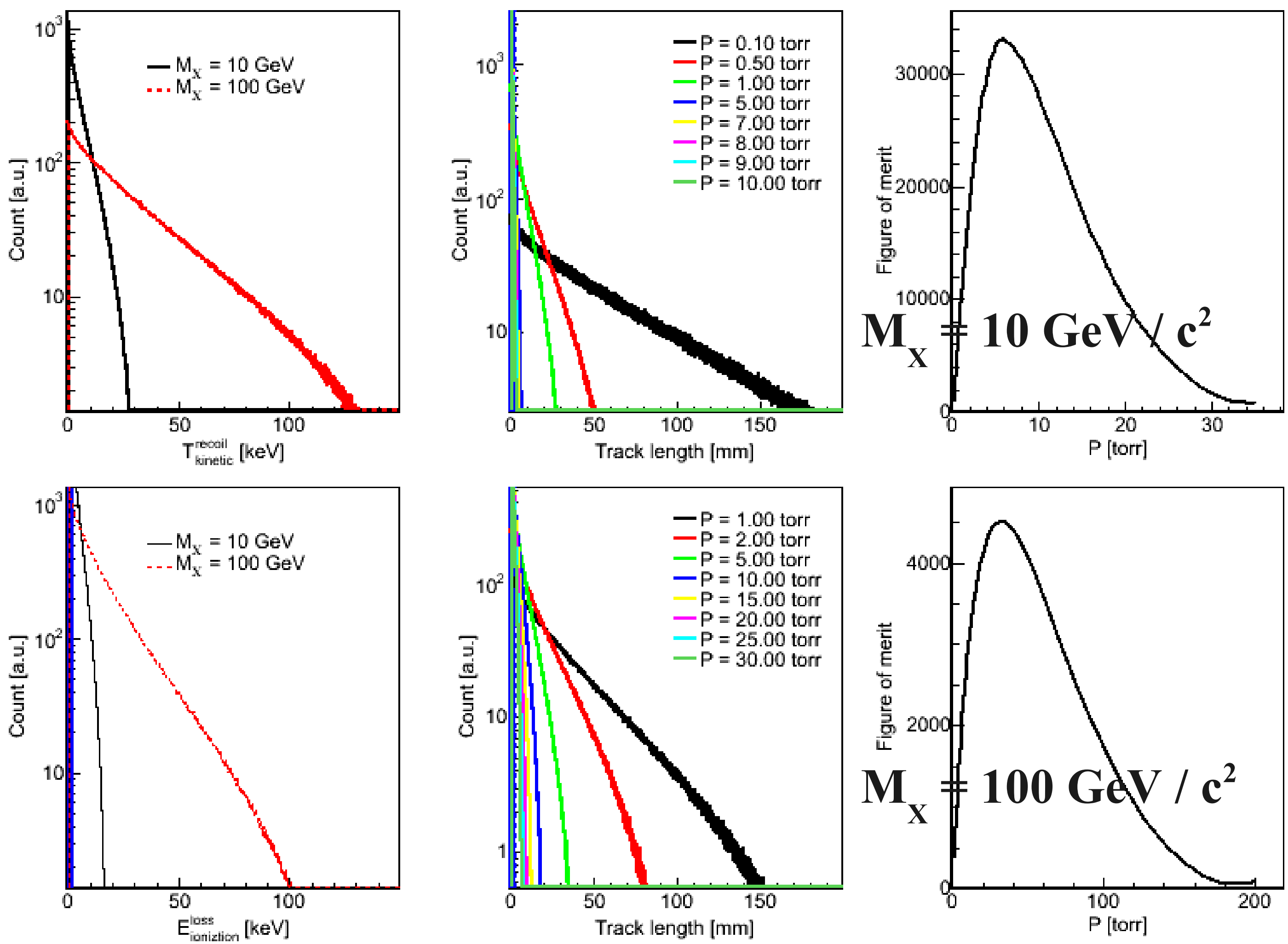
- **other key ingredients**
  - **energy threshold 1 keV**
  - **3 GEM holes covered L > 0.7 mm**
  - **$L / \sigma > 3$**

- **figure of merit calculated for two WIMP masses 10 GeV / c^2 and 100 GeV / c^2**

Pressure optimization

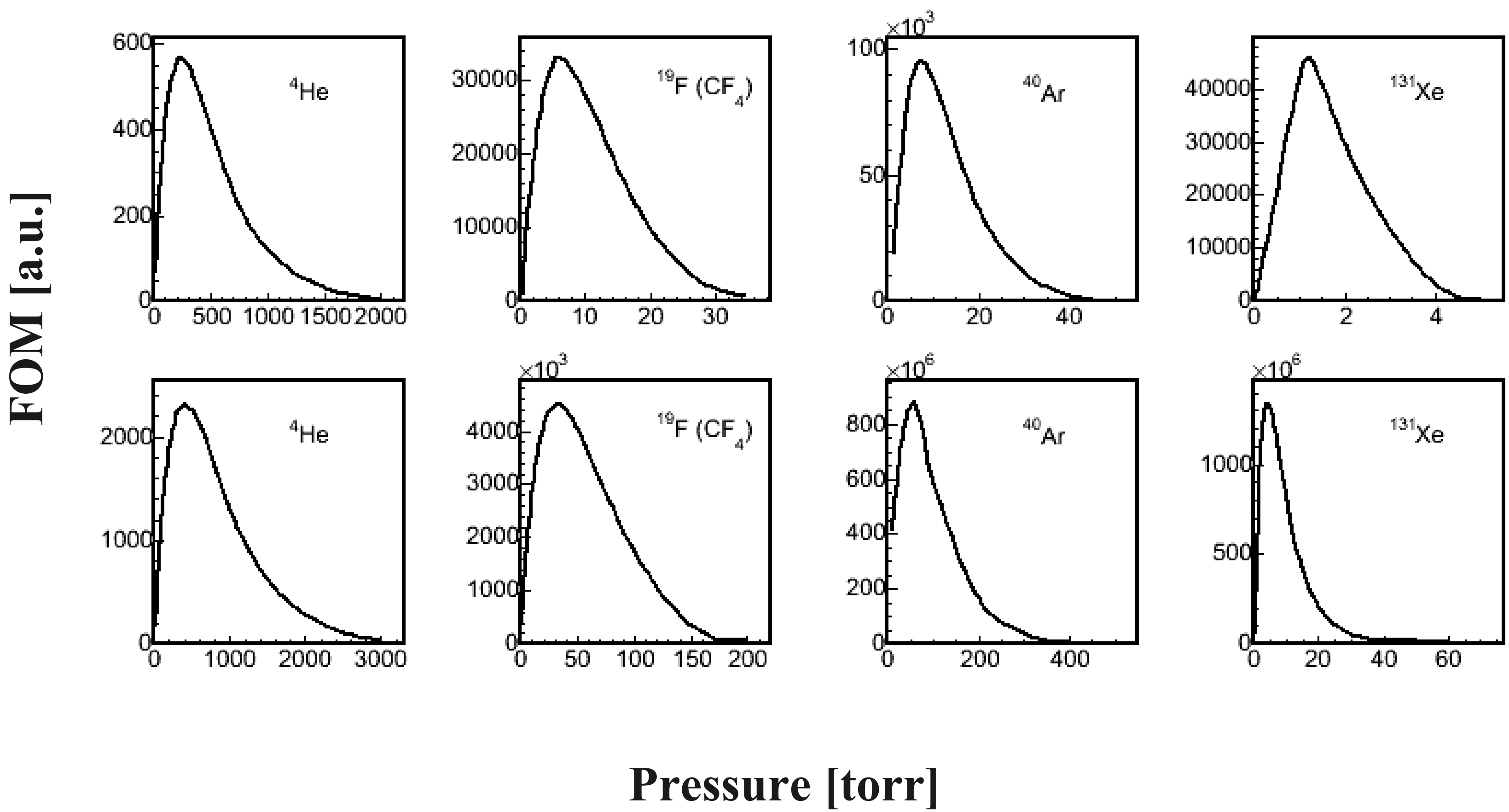
- figure of merit for SI

$$\frac{d\,FOM(P)}{dT_R} = \frac{\mu_A^2}{\mu_N^2} \cdot \rho(P)\,V \cdot A^2 \cdot \frac{d}{dT_R} F^2(qr_n) \cdot \int_0^z \frac{L(T_R,P)\text{ above thres}}{L(T_R,P)}\,dz$$



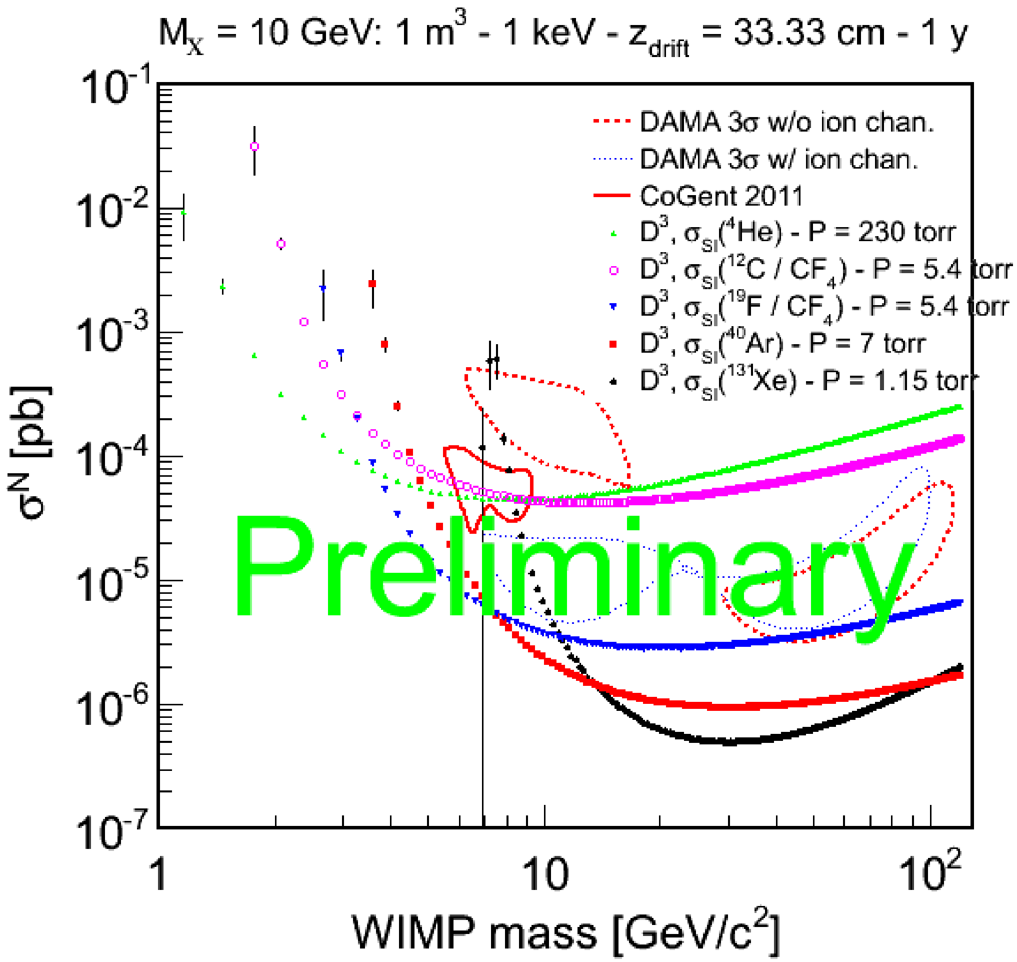
Pressure optimization

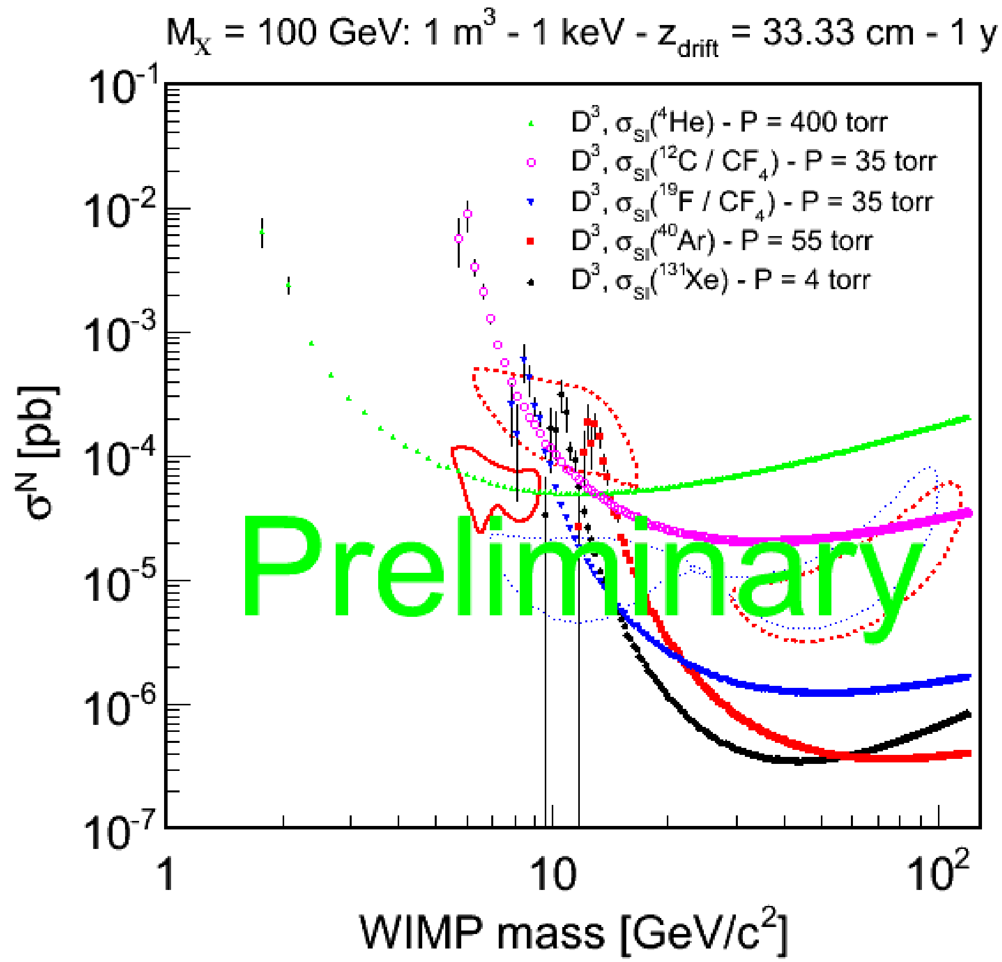
- **figure of merit for SI** $$\frac{d\,FOM(P)}{dT_R} = \frac{\mu_A^2}{\mu_N^2} \cdot \rho(P)\,V \cdot A^2 \cdot \frac{d}{dT_R} F^2(qr_n) \cdot \int_0^z \frac{L(T_R,P)\text{ above thres}}{L(T_R,P)}\,dz$$



D^3 reach plot
HIGHLY PRELIMINARY

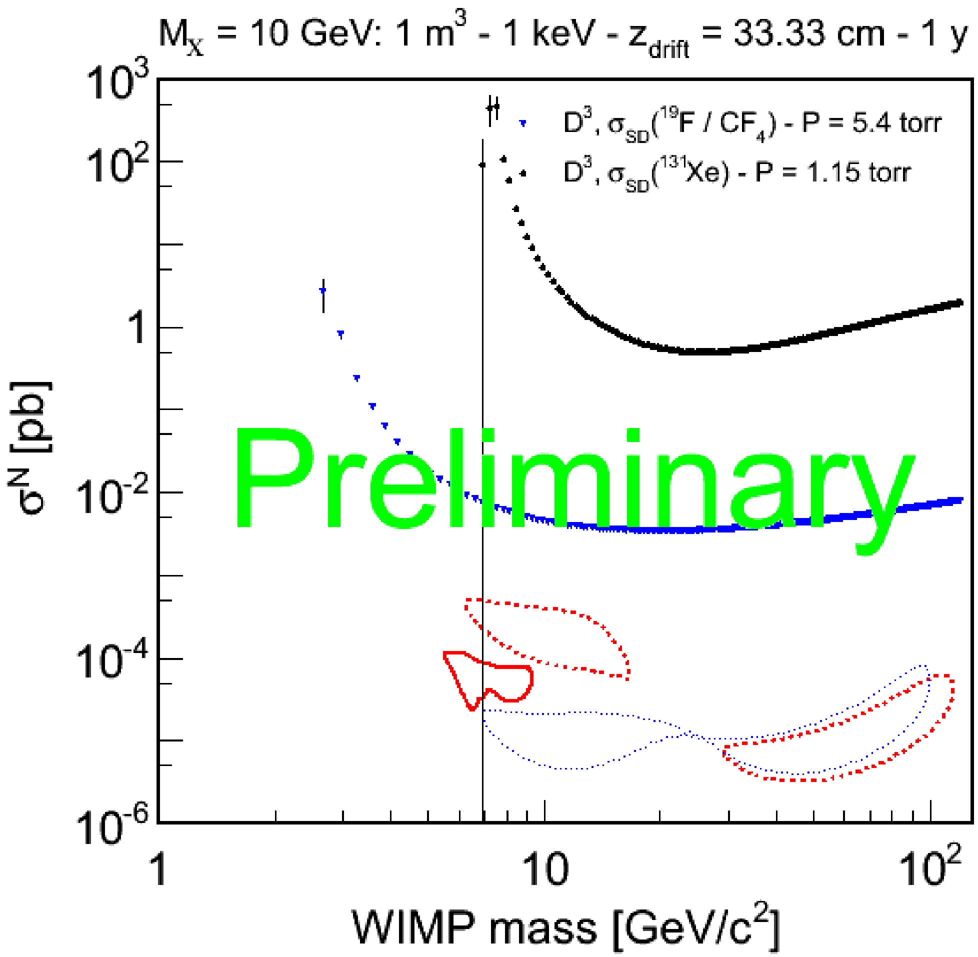
- **SI case**
- **by lowering the pressure the directional sensitivity increases for low mass WIMP**

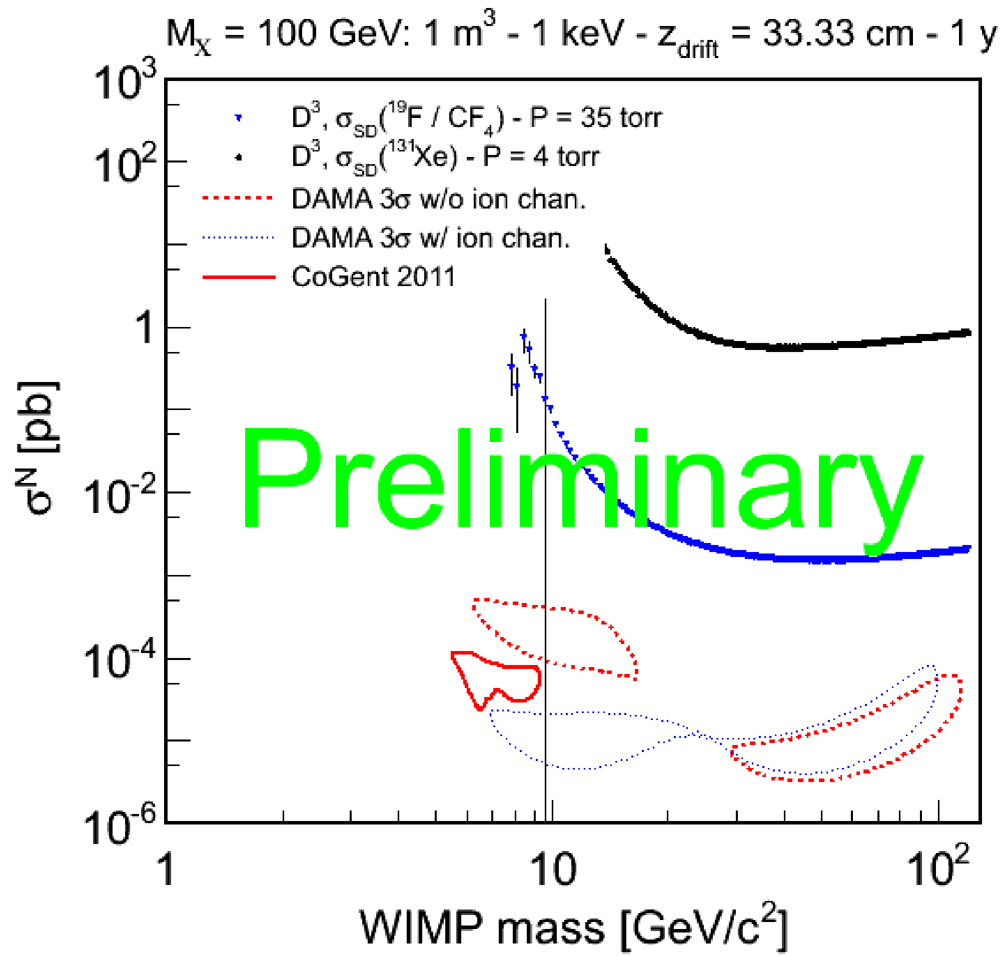




D^3 reach plot
HIGHLY PRELIMINARY

- **SD case**
- **by lowering the pressure the directional sensitivity increases for low mass WIMP**





Conclusion

- **currently integrating different simulation programs on a single platform**

- **geant4 and analytical calculation for the interaction probability are in good agreements**

- **preliminary design optimization of directional dark matter detector, D^3**
  - **by lowering the pressure the directional sensitivity increases for low mass WIMP**
  - **still room for improvements**

- **validation against measurements of DiNO/D^3-micro this year**

Thanks for your attention

Neutron interaction with matter depend on the neutron kinetic energy

- **<u>elastic scattering</u> from nuclei: n+A->n+A => dominant in the MeV region**
- **<u>inelastic scattering</u>: n+A->n'+A*, A* excited state of the nucleus A*-> A + γ**

=> > 1 MeV neutron enough to excite the nucleus

=> hydrogen has no excited state

- **<u>radiative neutron capture</u>: n+(Z,A) $\rightarrow$ γ+(Z,A+1)**

=> since $\sigma \sim 1 / v$, the neutron is most likely absorbed when it is slow

- **<u>other nuclear reactions</u>: (n,p),(n,d),(n,α) etc …**

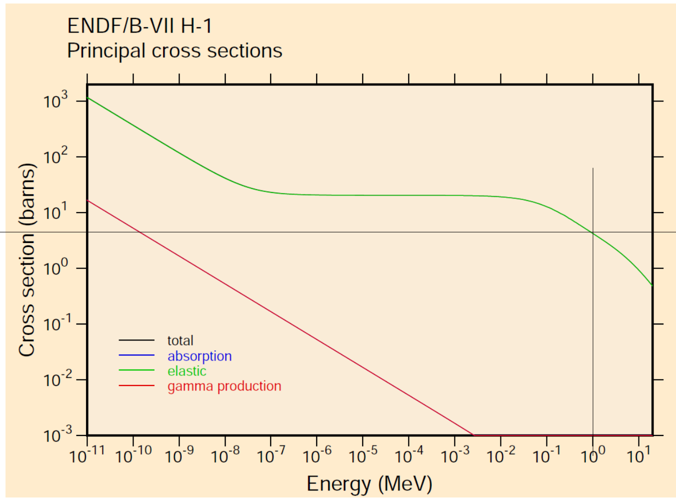
=> the neutron is captured and charged particles are emitted

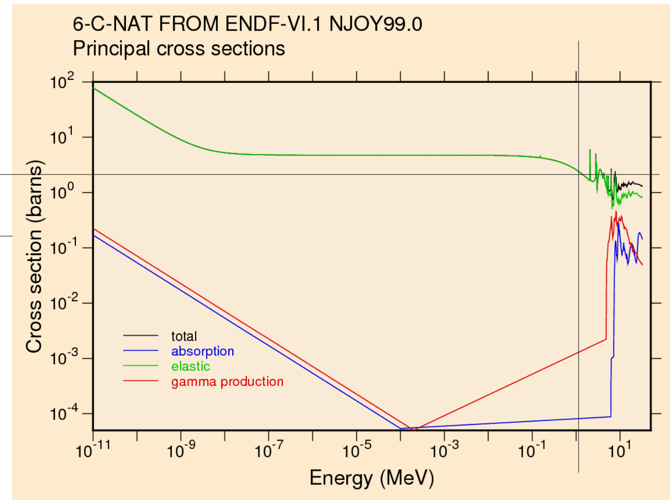
=> $\sigma \sim 1 / v$ i.e. eV to keV

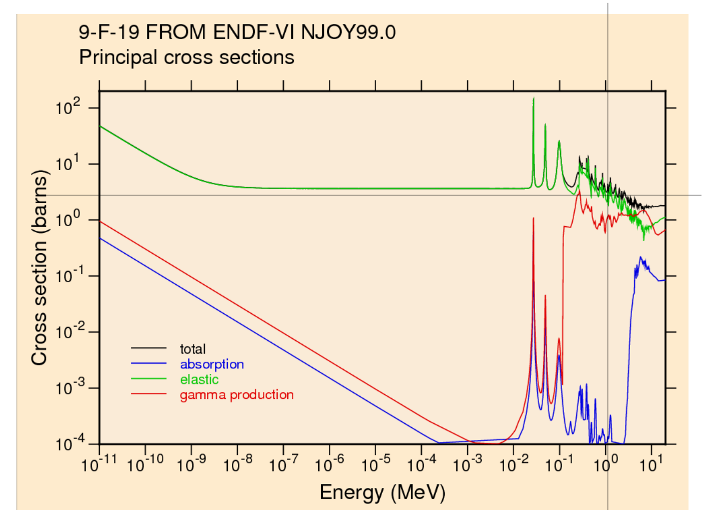
- **fission => thermal energies below eV**
- **high energy hadron shower > 100 MeV**

H, C and F cross sections

- generated by ACE-MCNP using ENDF/B-VI Cross Section Library 2006







ENDF/B-VI Cross Section Library 2006 combined

- **measured cross section (by Time-of-Flight technique)**
- **calculation from N-body physics**

- **elastic scattering is the dominant process (> 95 %) in all 3 cross sections**

- **σ(H at 1 MeV) ~ 4.5 b**
- **σ(C at 1 MeV) ~ 2 b**
- **σ(F at 1 MeV) ~ 3.2 b**