Direct Dark Matter Searches

0- Context

1- Elastic scattering rates

2- Detection principle: signal and backgrounds

3- Review of current experiments

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Recommended reading

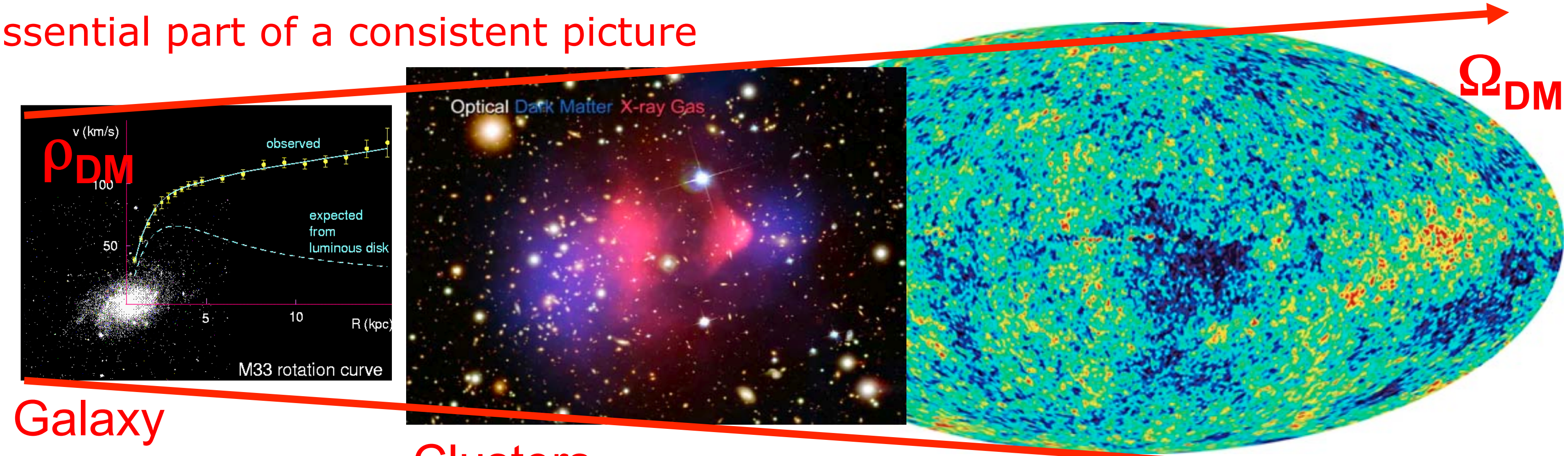
- *Particle Dark Matter : observations, models and searches*, G. Bertone (dir.), Cambridge University Press, 2010.
  - *Recent and complete review of direct dark matter searches*
- *Supersymmetric Dark Matter*, G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267**, 195 (1996).
  - *First comprehensive reviews on all aspects of supersymmetric dark matter and its detection*
- *Particle Dark Matter: Evidence, Candidates and Constraints*, G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005).
  - *A more recent reviews on dark matter and its detection*
- *Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoils*, J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).
  - *Complete – and easy to follow – presentation of all ingredients needed to calculate experimental recoil spectra in a given detector for a given WIMP model. Must-read for all.*
- Particle Data Group: sections *Cosmology*, *Dark Matter* et *Detectors for non-accelerators physics*
  - http://pdg.lbl.gov/

0- DIRECT SEARCH: CONTEXT

Cold Dark Matter in the Universe

- Cold Dark Matter present at all scales in the Universe…

Essential part of a consistent picture



Galaxy

Clusters

CMB

- Searched as a new particle at LHC
- Searched via the remains of its decay in cosmic rays (γ, ν, e+, antimatter)
- *… Direct seach: collision of WIMPs from our galactic halo on target nuclei I a laboratory on Earth*
  - Proof that Dark Matter is present in our environment
  - After discovery: observatory for WIMP velocity distribution in our environment?
  - Sensitive to local WIMP density ρ_{DM} (not to the cosmological density Ω_{DM})

Can we detect WIMPs?

- Cosmology: $\Omega_{DarkMatter}$ ~ 0.268 +- 0.02 **(1.3 M_{proton} /m^3)**
- Astrophysics: Localy, ρ_{DM} ~ 0.4 GeV/cm^3 **(0.3 M_{proton} /cm^3)**

Hypothesis: thermal production in the Big Bang

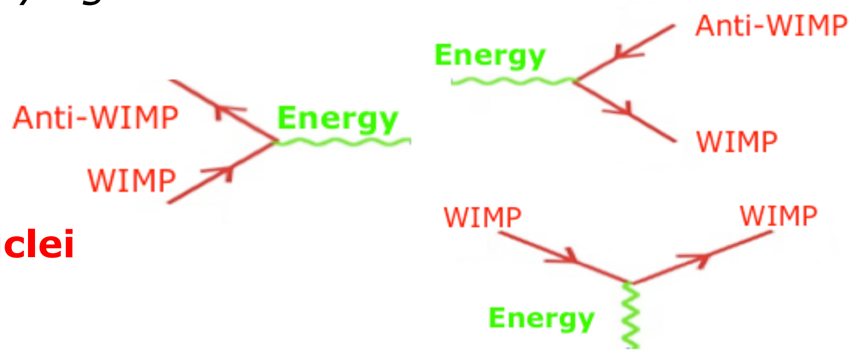
- *Particle physics*: pair production (and annihilation)
- *Big Bang Thermodynamics*: $\Omega_{DarkMatter}$ proportional to $\sigma_{annihilation}$:

$$<\sigma_{annihilation} v> / (\Omega_{DM} h^2) \sim 0.3 \times 10^{-27}\ cm^3/s$$

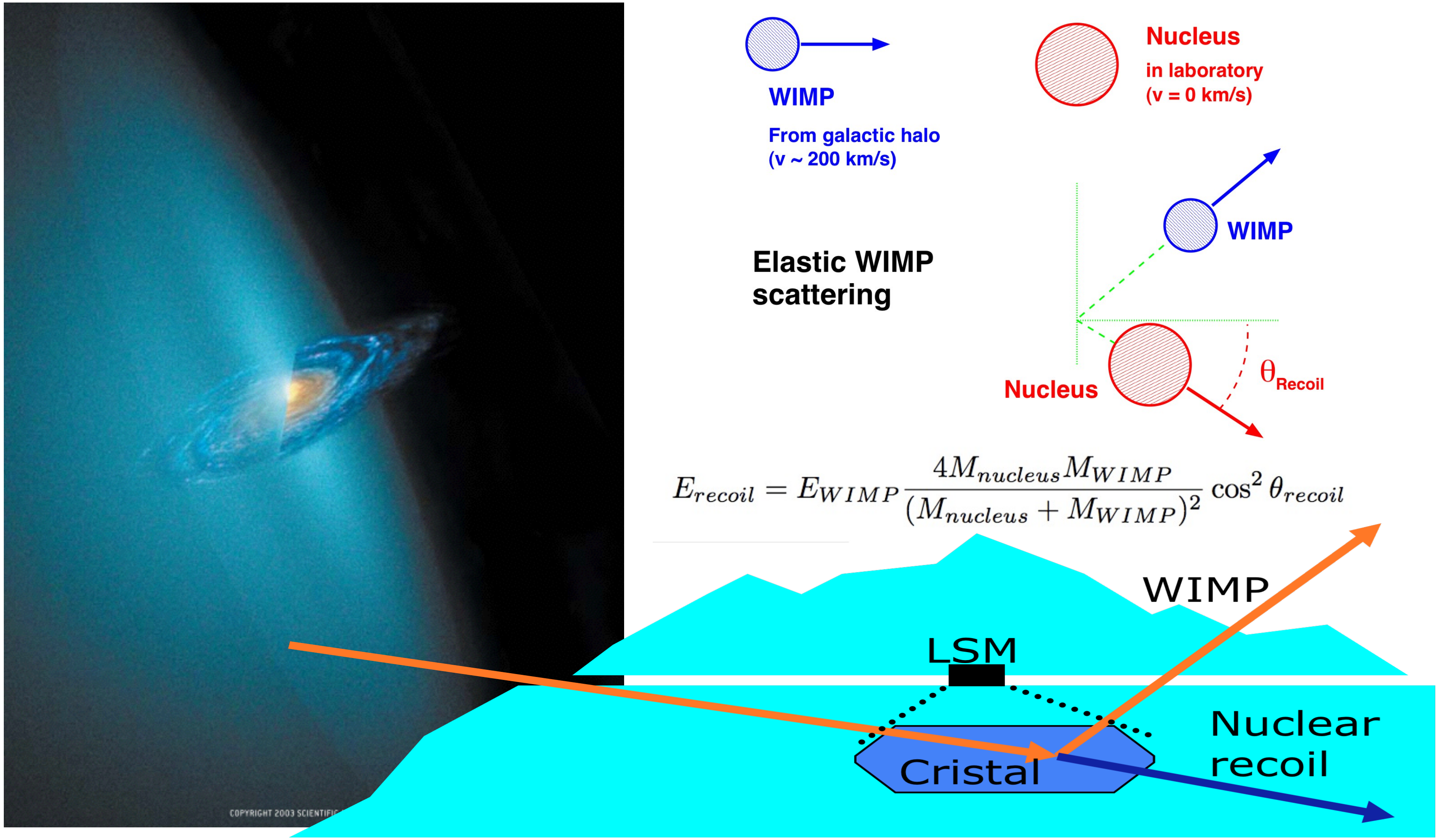
- *Miracle WIMP*: For Ω = 0.27, $\sigma_{annihilation}$ ~ Weak Nuclear Force.
- *Big Bang Thermodynamics +Weak Force*: M_{WIMP} ~ 10 – 10 000 GeV/c^2

➔ *Predictions are possible for identifying WIMPs in 3 channels* :

1. **Creation at LHC ($\sigma_{creation}$)**
2. **Annihilation producs in cosmic rays ($\sigma_{annihilation}$)**
3. **Elastic Scattering on target nuclei ($\sigma_{scattering}$)**



Direct search schematics



$$E_{recoil} = E_{WIMP} \frac{4 M_{nucleus} M_{WIMP}}{(M_{nucleus} + M_{WIMP})^2} \cos^2 \theta_{recoil}$$

Observables: Event rate, E_{recoil} , θ_{recoil} (recoil range is related to E_{recoil})

Risk Analysis

- One, two or three of the detection methods can fail:
  - *Dark matter may not exist as a particle*
  - *Dark matter particles may have decayed since the Big Bang*
  - *By accident, the local Dark Matter density is very small*
  - *Dark matter particle exists, but their non-gravitational interaction with normal matter is strongly suppressed (e.g.: the "WIMP miracle" is a fluke: there was no thermal production …)*

- Given the uncertainties on WIMPs, positive or negative results are needed on the three search methods. Each method has advantages and drawbacks

- LHC and indirect searches are performed in experiments dedicated to other physics anyways (particle physics, cosmic rays). Direct Searches are on dedicated instruments (although some can perform other type of rare event searches)

- New "proof" of absence/presence of Dark Matter per ~month: should we wait before investing in a Direct Search experiment? No, too many clues are pointing to that direction… and it takes decades to develop proper experimental techniques

Historical notes

PHYSICAL REVIEW D — VOLUME 31, NUMBER 12 — 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Method suggested in 1985 (28 years ago!) by Goodman + Witten

- Predict rates between 4 and 1400 events/kg/day for heavy ν.
  M_ν = 100 TeV ↵ ↳ M_ν = 100 GeV

- As early as 1987, first significant constraints (*exclusion of a heavy ν*) with ionization Ge and Si detectors: sensitivity to ~ few evts/kg/day
  - Ge: S. P. Ahlen, et al., Phys. Lett. B 195 (1987) 603
  - Ge: D. O. Caldwell, et al., Phys. Rev. Lett., 61 (1988) 510
  - Si: D. O. Caldwell, et al., Phys. Rev. Lett. 65 (1990) 1305

- To do better, need better rejection of radioactive backgrounds
  - Competition between techniques: Pulse-shape discrimination in NaI? Phonon+ Ionization detectors *[Shutt et al, PRL 69 (1992) 3531]*? CsI? Liquid Ar? 2-phase Xenon? Bubbles? Etc …

Basic questions

- Direct Dark Matter searches are simple: just look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision with a WIMP, but…
- How many such events can we expect per unit time and per number of target nuclei?
- How big is the kinetic energy involved in such collisions?
- What is the fake rate and how can we reject it?

Let's now follow Lewin and Smith to calculate…

1- SCATTERING RATES

Scattering probability

- Collision rate (per unit time) R:

$$R = \varphi\, \sigma_A\, N_{target}$$

φ = WIMP flux (WIMP/cm^2/s) = $(\rho_W/M_W)\, v$

σ_A = cross-section for the elastic scattering of a WIMP on a nucleus (cm^2, barn or picobarn) 1 pb = 10^{-36} cm^2

N_{target} = number of target nuclei exposed to the flux φ

➔ Need massive detectors (N_{target})

Scattering probability

- Collision rate (per unit time) R:

$$\mathbf{R = \varphi\, \sigma_A\, N_{target}}$$

Astrophysics

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- Collision rate (per unit time) R:

Particle Physics
Nuclear Physics

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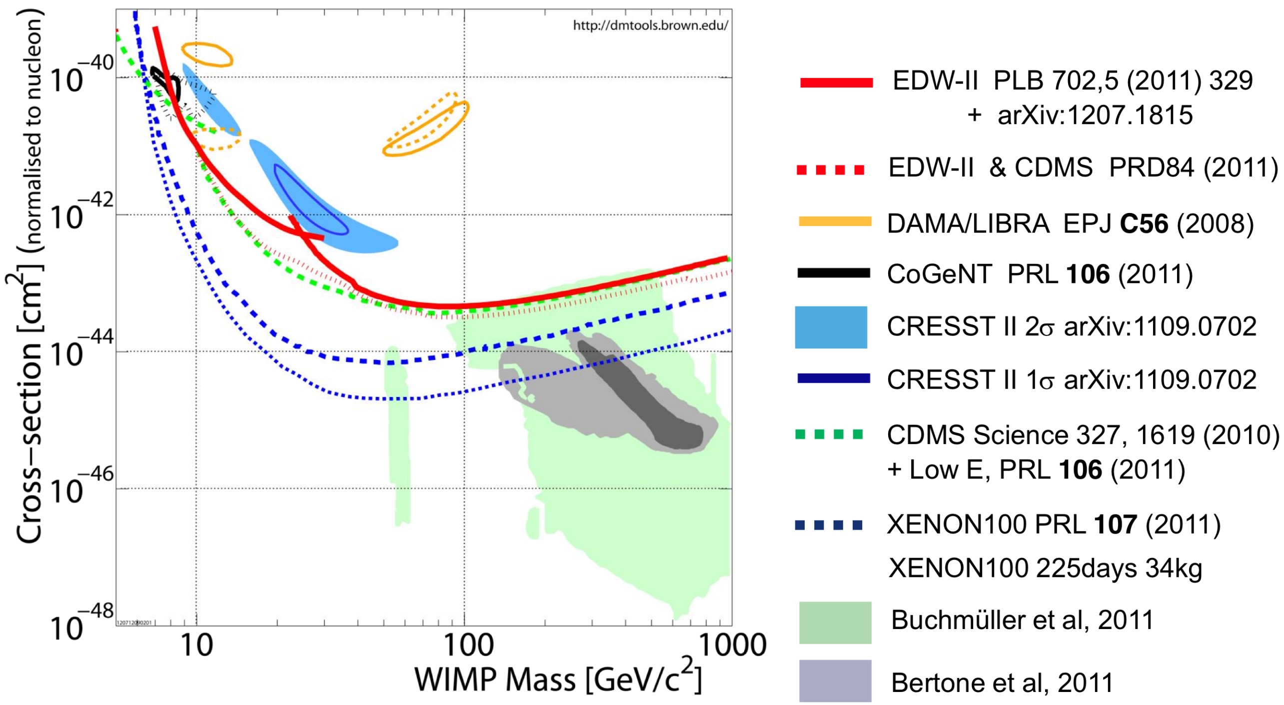
N_{target} = number of target nuclei exposed to the flux φ

➔ Need massive detectors (N_{target})

The search domain

- We don't know (yet) what is the mass of the WIMPs
- We don't know (yet) what is the cross-section for WIMP-nucleus scattering
- Generic searches for ALL WIMPs masses M_W and ALL cross-section σ.
- A given experiment will be able to probe a certain region of (M_W, σ):

"exclusion plots"



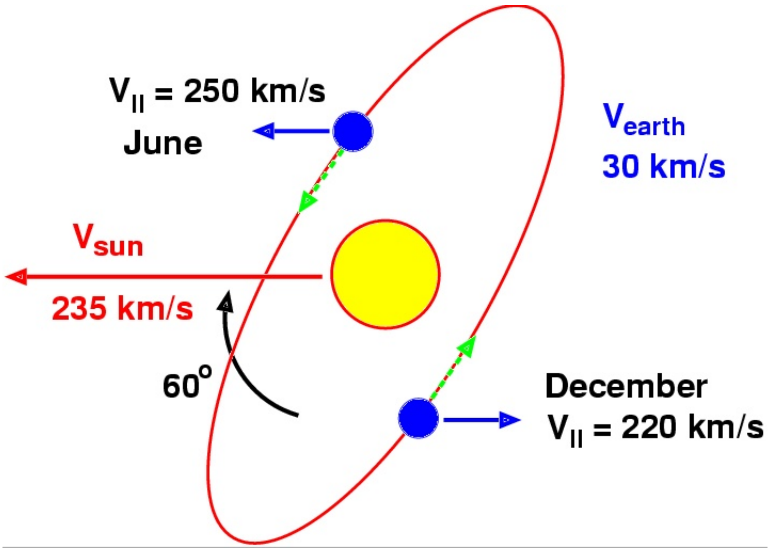
Let’s now follow Lewin and Smith to calculate…

1.1- RATES: WIMP FLUX

Flux: WIMP velocity distributions

- Exact calculation extremely difficult
  - N-body calculation, N=∞, Gravity range = ∞
  - No dissipation: WIMPs don't "stick" together as ordinary matter
- Equilibrium: Kinetic energy ~ -Potential energy/2
- Simplest (crudest) case: spherical isothermal halo
  - Maxwellian velocity distribution: $$\frac{dP(v)}{v^2 dv} = \frac{1}{(\pi v_0^2)^{3/2}} \exp(-\frac{v^2}{v_0^2})$$
  - v_0 ~ 220 km/s (v_{rms} = sqrt(3/2)v_0 = 270 km/s)
  - Truncated to escape velocity from Galaxy (v_{esc} ~ 544 km/s)
- More realistic halo model: heated debate
  - Central cusp? clumps? triaxial? caustics? tidal flows? Comoving?
  - Direct search mostly sensitive to *average* v^2 (if not too clumpy)

- Sun around the galaxy: ~235 km/s
- $\exp(-v^2/v_0^2) \rightarrow \exp(-|\vec{v}+\vec{v}_{||}|^2/v_0^2)$ (energy boost)
- Earth around the sun: 30 km/s (~60° to Galactic plane)



f (v) =

f (v; v_o, v_{escape}, v_{sun}, v_{earth})

- Annual modulation of ± 7% of $v_{||}$ → ~ ± 3% on WIMP flux
- Modulation more sensitive to detailed halo model

Kinematics

- For $M_{WIMP} \sim 100$ GeV/c^2 and $v_{WIMP} \sim 200$ km/s:
- $(v_{WIMP}/c) = 0.7$ %

Good news #1: non relativistics! Use Newtonian kinematics…

- $M_{WIMP} = 10^{+8}$ keV/c^2
- $E_{kinetic} = ½\ M_{WIMP}\ (v/c)^2 = 22$ keV

Good news #2: a single 22 keV deposit is detectable in (good) conventional detectors used in nuclear physics

- Momentum = pc = sqrt(2 M_{WIMP} v_{WIMP} c) ~ 66 MeV
- Associated wavelenght λ = h/p ~ 20 fm : larger but comparable to nuclear radii (2-7 fm)

~Good news #3: we can first consider the whole nucleus as a "point-like" particle but will need to consider quantum physics corrections

Dealing with the velocity distribution f(v)

- If $v_{Sun+Earth} = 0$, and v_{ESCAPE} = infinity, the probability to have a velocity would be given by the Maxwellian distribution:

  $$dP(v) = v^2\, dv * \exp(-v^2/v_0^2) / [\pi v_0^2]^{3/2}$$

- If we shift this distribution by $v_E = v_{Sun+Earth}$, the normalization remains the same:

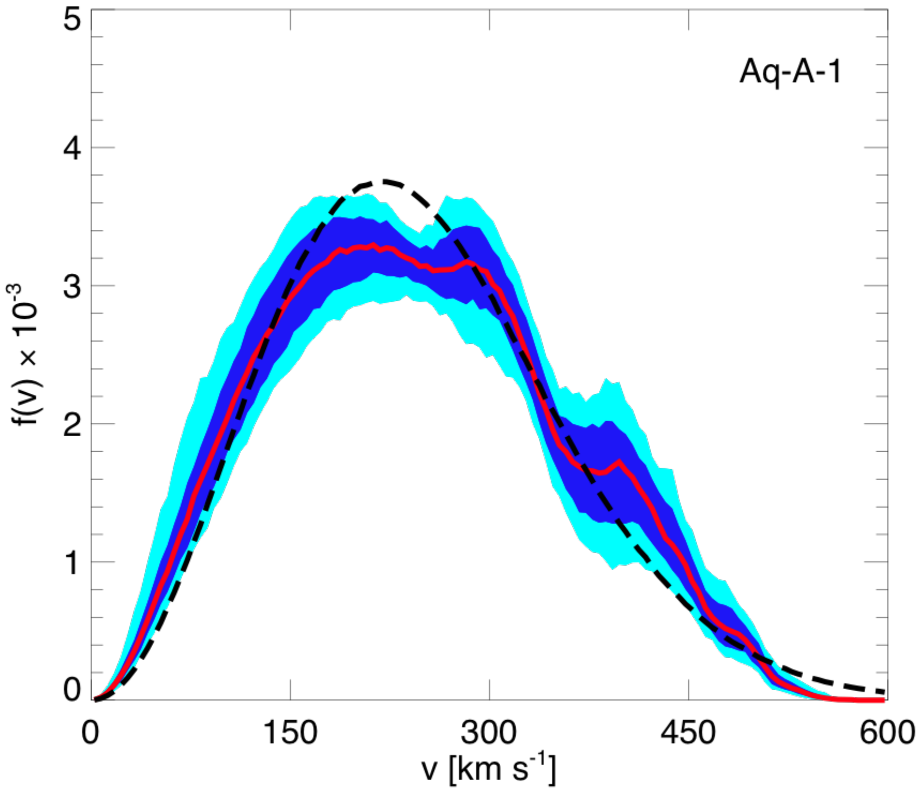
  $$dP(v) = v^2\, dv * \exp(-(|\vec{v}+\vec{v}_E|)^2/v_0^2) / [\pi v_0^2]^{3/2}$$

- The normalization constant becomes a bit more involved if we truncate the velocity distribution to exclude $v>v_{ESCAPE}$

  $$[\pi v_0^2]^{3/2} \to [\pi v_0^2]^{3/2} * \left[\operatorname{erf}\left(\frac{v_{\rm esc}}{v_0}\right) - \frac{2}{\pi^{1/2}}\frac{v_{\rm esc}}{v_0}\, e^{-v_{\rm esc}^2/v_0^2}\right]$$

- But we'll come back later to the problem of the escape velocity…

More realistic velocity distributions?



- Triaxial halo? Clumps?
- May use results of many-body DM simulations [e.g. Vogelsberger et al, astro-ph/0812.0362]: some deviations wrt simple Maxwel distribution
- So far, using a very simple halo model is advantageous to compare experiments between themselves…
- Will be another story when a signal is found…

Total scattering rate (1)

- We want a rate R per unit time and per kilograms, for a target of atomic mass A (in a.m.u.=g/mol).

$$R = (\ 1000\ N_0/A\ )\ \sigma_0\ \phi \qquad\qquad (N_0 = 6.022 \times 10^{23})$$

- The flux is due to n_0 WIMP per volume, $n_0 = \rho_{WIMP}/M_{WIMP}$
- σ_0 = scattering cross-section on a *nucleus*:.

- Must integrate over the velocity distribution. Contribution *d*R from the flux $n_0\ v\ dP(v)$ of WIMPs with velocity v:

$$dR = (\ N_0/A\ )\ \sigma_0\ n_0\ v\ dP(v)$$

- Total rate is thus obtained by averaging v over P(v)

$$R = (\ N_0/A\ )\ \sigma_0\ n_0\ \langle v \rangle$$

Total scattering rate (2)

- For v_E=0 and infinite V_{ESCAPE}, <v> = 2/sqrt(π) v0, so L&S define a reference rate R_0:

  R_0 = 2/sqrt(π) (N_0/A) σ_0 n_0 v_0

- The numerical value is:

  R_0 = 540 * σ * (ρ_{WIMP}/0.4) * (v_0/230) / A / M_{WIMP}

  … in events per kg of target and per day, for σ in pb, ρ_{WIMP} in GeV/cm^3, v_0 in km/s, A in a.m.u. and M_{WIMP} in GeV/c^2.

- The rates R(v_E, V_{ESCAPE}) for $v_E \neq 0$ and finite V_{ESCAPE} are:

$$\frac{R(0, v_{\mathrm{esc}})}{R_0} = \frac{k_0}{k_1}\left[1 - \left(1 + \frac{v_{\mathrm{esc}}^2}{v_0^2}\right) e^{-v_{\mathrm{esc}}^2/v_0^2}\right];$$

~1 in most cases

$$\frac{R(v_E, \infty)}{R_0} = \frac{1}{2}\left[\pi^{1/2}\left(\frac{v_E}{v_0} + \frac{1}{2}\frac{v_0}{v_E}\right)\mathrm{erf}\left(\frac{v_E}{v_0}\right) + e^{-v_E^2/v_0^2}\right];$$

~1.30 for $v_E \sim v_0$

$$\frac{R(v_E, v_{\mathrm{esc}})}{R_0} = \frac{k_0}{k_1}\left[\frac{R(v_E, \infty)}{R_0} - \left(\frac{v_{\mathrm{esc}}^2}{v_0^2} + \frac{1}{3}\frac{v_E^2}{v_0^2} + 1\right) e^{-v_{\mathrm{esc}}^2/v_0^2}\right].$$

Differential scattering rate

- In practice, we don't measure the rate R but the number of events where the recoil energy of the target is larger than some threshold value

- We need the differential rate dR/dT_A, where T_A is the kinetic energy of the recoil

- We can then integrate dR/dT_A above the threshold T_{min}

Collision in centre-of-mass frame (1)

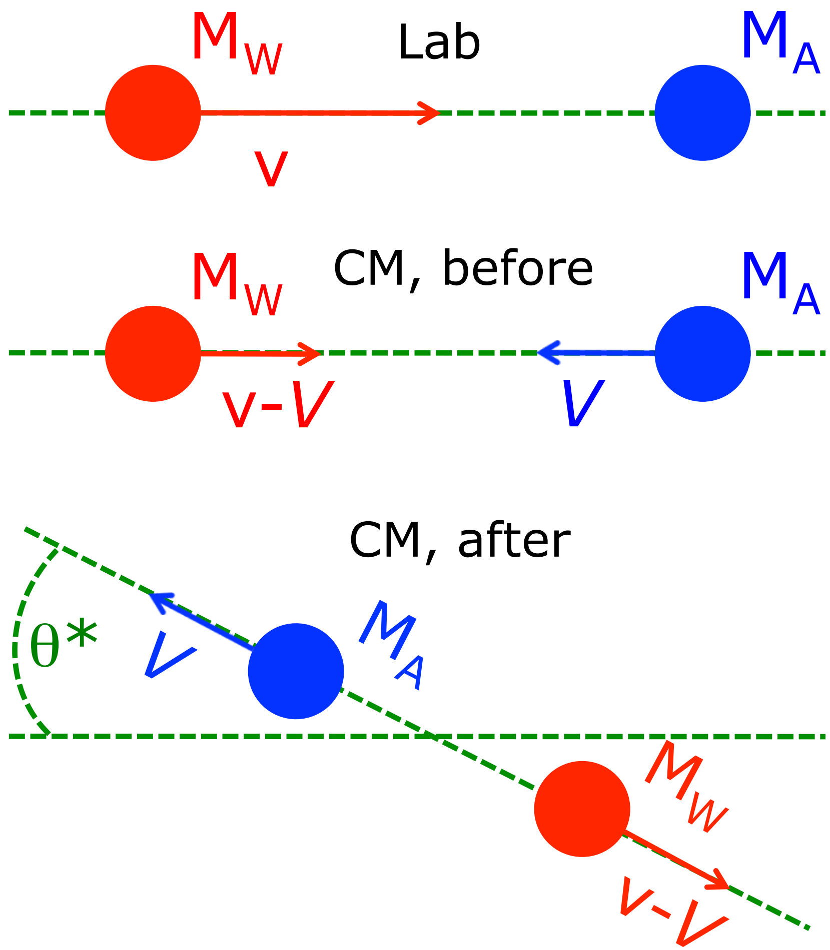
- Lab frame
  - M_A mass of target
  - M_W mass of WIMP
- C.M. frame

  $M_W(v-V) = M_A V$
- CM velocity:

  $V = v * M_W/(M_A+M_W)$
- Scattering angle in CM: θ^*
- Nucleus velocity after collision in LAB, v_A:

  $V * \mathrm{sqrt}[(1-\cos\theta^*)^2+(-\sin\theta^*)^2]$

  (if $\theta^*=0$, $v_A=0$)



Collision in centre-of-mass frame (2)

- v_A = V*sqrt[2(1-cosθ*)]
- T_A = $\frac{1}{2} M_A (v_A)^2$ = kinetic energy of recoil in lab

$= \frac{1}{2} M_A\, 2\, V^2\, (1-\cos\theta^*)$

$= \frac{1}{2} M_A\, 2\, v^{2} * M_W^{2}/(M_A+M_W)^2\, (1-\cos\theta^*)$

$= T * [\, M_A M_W / (M_A+M_W)^2\,] * 2(1-\cos\theta^*)$

where $T = \frac{1}{2} M_W v^2$ is the initial WIMP kinetic energy

and L&S call $r = 4[\, M_A M_W / (M_A+M_W)^2\,]$ for simplicity

1. T_{RECOIL} *goes from 0 (grazing collision) to rT (max impact)*
2. *Maximal energy transfer when r is maximum, and that happens for $M_A=M_W$ when r=1… the target can then fully stop the WIMP, like in the game of pool!*

Note: T_{WIMP} after the collision can't be measured, so we don't care about it

- If no axis is preferred (evidently the case for spin-independent interactions), all solid angles $d(\cos\theta^*)d\phi^*$ are populated equally, so the probability to scatter at a given angle is:

$$dP(\theta^*,\phi^*)/d\Omega^* \quad = \quad 1 / (4\pi)$$

$$dP(\cos\theta^*)/d\cos\theta^* \quad = \quad 1 / 2$$

- If there is a uniform distribution of $\cos\theta^*$, then it will be the same for $T_A = 2\, r\, (1-\cos\theta^*)\, T$:

$$dP(T_A;T)/dT_A \quad = \quad ½ / (dT_A/d\cos\theta^*)$$

$$= \quad 1 / (rT)$$

… and the integral of $dP(T_A)$ for T_A between 0 and rT is indeed 1

Differential cross-sections (1)

- The differential rate of recoils with energy T_A is the sum of the contributions of the WIMPs with velocity able to give as much kinetic energy to a recoil.
- For v_E=0 and infinite V_{ESCAPE}, the kinetic energy of the WIMP must be above $E_{min} = T_A/r$.
- The integration we did for the total rates

$$R = (N_0/A)\ \sigma_0\ n_0 \int v\ dP(v)$$

… has a new integration range and we take into account the probability of having a recoil TA for a given recoil T:

$$dR/dT_A = (N_0/A)\ \sigma_0\ n_0 \int v\ dP(v)\ dP(T_A;T)/dT_A$$

Differential cross-sections (2)

$$dR/dT_A = (N_0/A)\ \sigma_0\ n_0 \int v\ dP(v)\ dP(T_A;T)/dT_A$$

- $v\,dP(v)$ is proportional to $v^3 dv = T\,dT$ and the term $\exp(-v^2/v_0^2)$ is $\exp(-T/T_0)$ where $T_0 = ½\ M_W v_0^2$.
- $dP(T_A;T)/dT_A$ is simply $1/(rT)$, so it comes to integrate $\exp(-T/T_0)$ between E_{min} and infinity ($v_E=0$ and infinite V_{ESCAPE}).

$$dR/dT_A \quad = \quad R_0 \exp[-T_A/(rE_0)] \, / \, (rE_0) \quad = \quad dR(0,\infty)/dT_A$$

- For $v_E > 0$ the integral is not as simple:

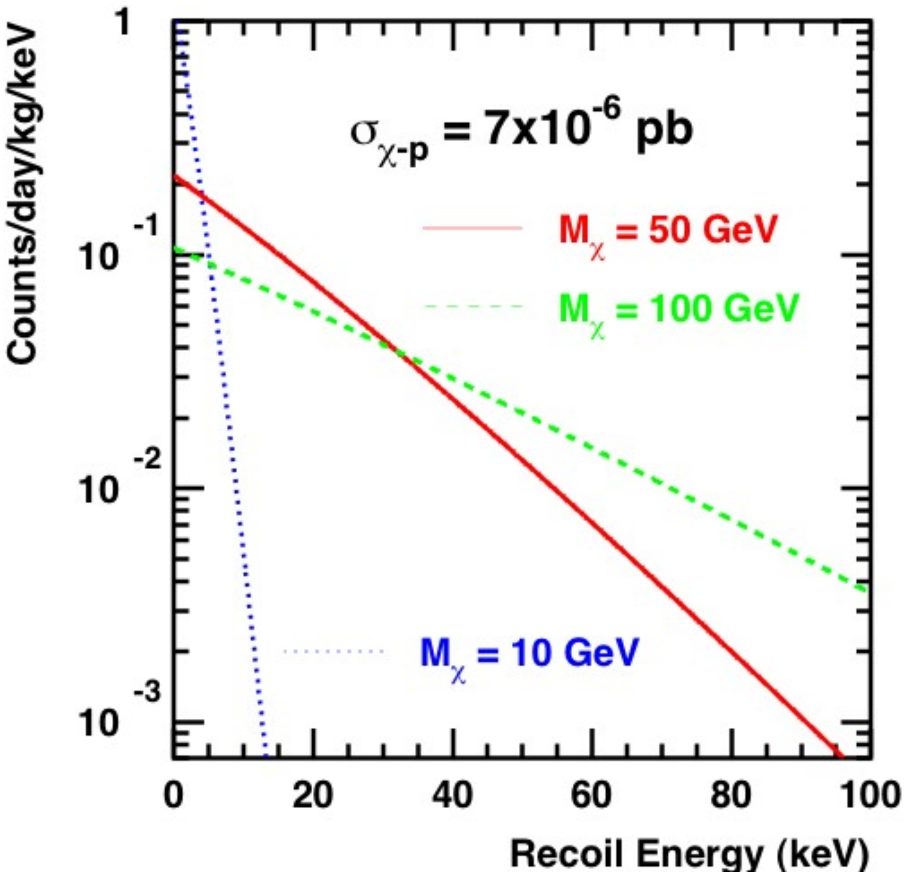
$$\frac{dR(v_E,\infty)}{dE_R} = \frac{R_0}{E_0 r} \frac{\pi^{1/2}}{4} \frac{v_0}{v_E} \left[\mathrm{erf}\left(\frac{v_{\min}+v_E}{v_0}\right) - \mathrm{erf}\left(\frac{v_{\min}-v_E}{v_0}\right) \right]$$

- For finite V_{ESCAPE}, the L&S truncation is a bit too approximate, it’s better to use Gondolo, hep-ph/0209110

Example of recoil energy spectra

- Reminder: E_{recoil} was our T_A
- $<E_{recoil}> \sim ½\ rT = ¼\ M_W\ v^2$
- ~Exponential distribution of $v^2 \rightarrow$

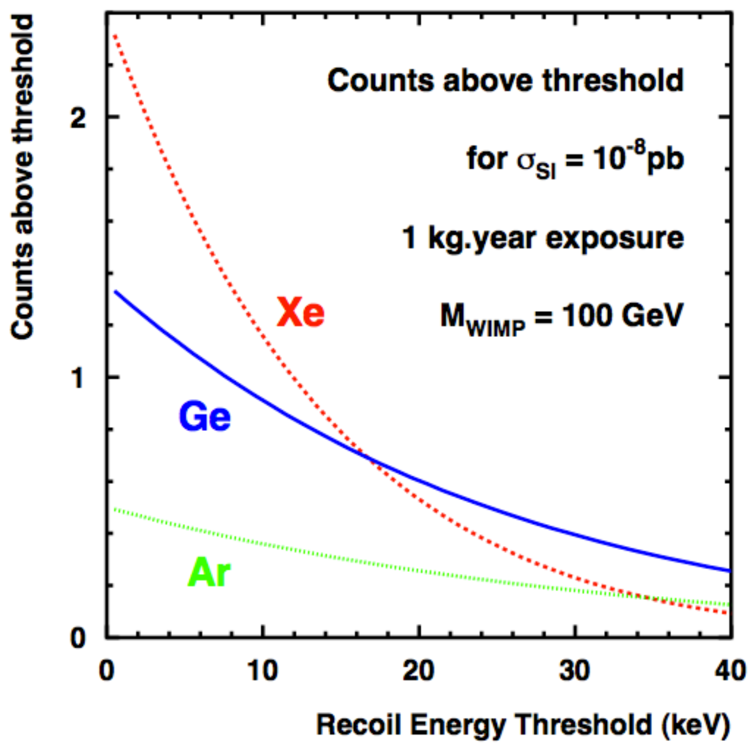
  ~Exponential distribution of E_{WIMP}
- Flat distribution of $\cos\theta^*$ $\rightarrow$ flat distribution of E_{recoil}/E_{WIMP}

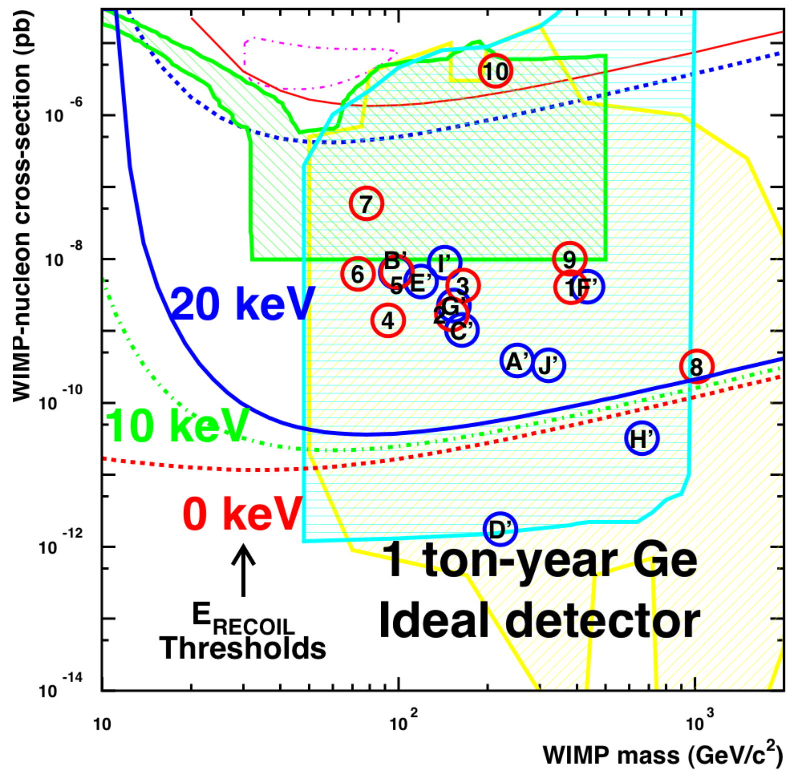


- $\rightarrow$ Exponential distribution of E_{recoil}

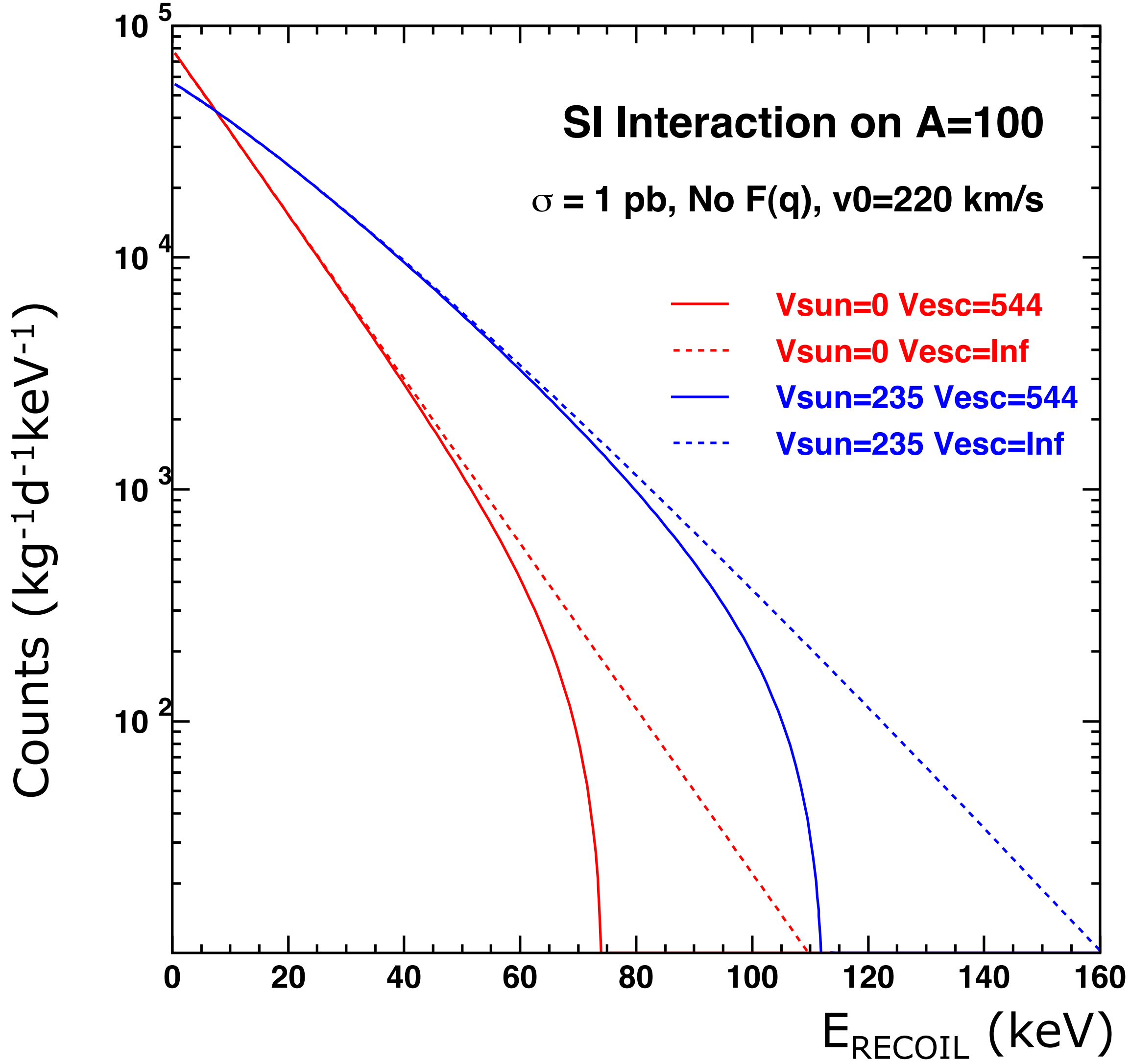
Influence of Recoil Energy Thresholds

- The integrated rate above a given threshold varies rapidly with that threshold!
- The effect is very strong for low-mass WIMPs





Influence of velocities



Let's now follow Lewin and Smith to calculate…

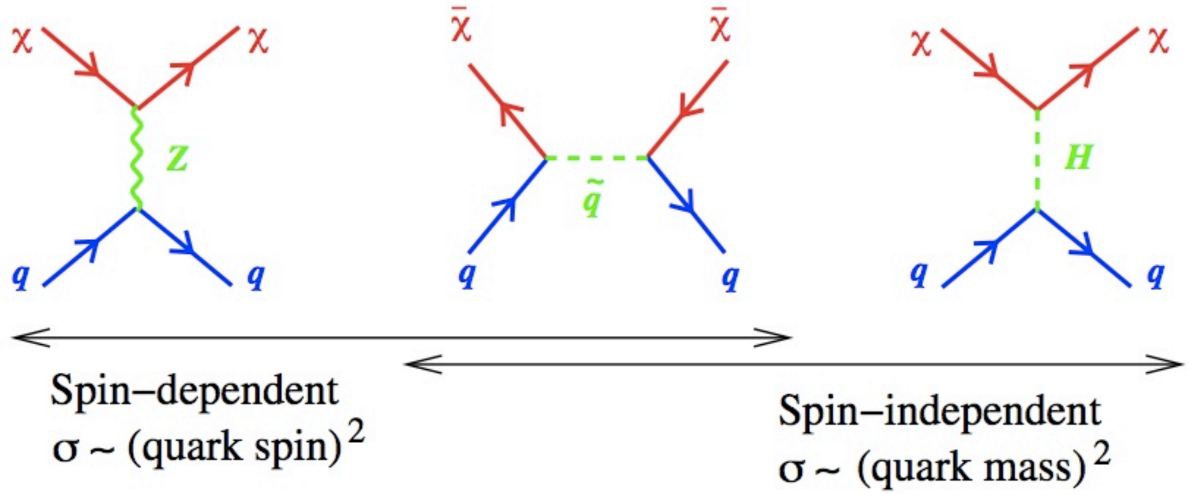
1.2- RATES: CROSS-SECTION

Cross-sections

- Now that we know how to hande the WIMP flux in our calculation, let's turn to the cross-section
- So far σ_0 was a cross-section for the scattering on a *nucleus* with A nucleons, of radius $r \ll h/p_{WIMP}$
- Fundamental particle physics theories (for example: the WIMP is a neutralino χ) begin with a prediction for a scattering cross-section on a *quark*
  - *Hadronic physics* will give what is the relation between this cross-section and the cross-section on a *nucleon* (n or p)
  - *Nuclear physics* will give what is the relation of this second cross-section with the one for a nucleus containing Z protons and (A-Z) neutrons

From the quark to a nucleon (1)

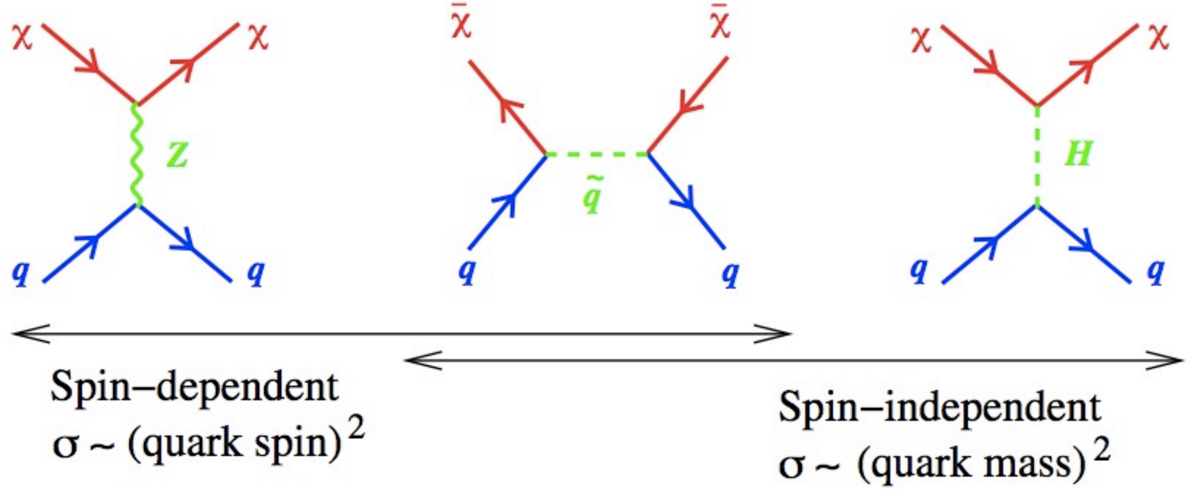
- χ-nucleon scattering cross-section can be calculated within SUSY



- Separation spin dependent (SD) / independent (SI): most general expression for most types of interactions, even beyond SUSY
- In a nucleus, spin of quarks add incoherently
  - Spin of most nucleons cancels out in most nucleus: incoherent sum
  - In a nucleus, quark masses add coherently
  - Strange quark content dominates! (ok, known to some precision)
  - Expect large coherence effects for SI (Good,that will help!)

From the quark to a nucleon (2)

- χ-nucleon scattering cross-section can be calculated within SUSY



- The spin-independent cross-section depends on massive virtual particles… Neutralinos tend to couple to the heaviest quarks in nucleons: the strange quarks from the sea.
    - The quark-to-nucleon scaling depends a lot on the strangeness content of the nucleons: see e.g. Ellis et al, astro-ph/0110225, discussing factor ~3 variations in cross-section depending on the choice of parameters

Nucleon-to-nucleus scaling (1)

- Centre-of-mass effect: the scattering cross-section is related to the matrix element of the interaction M_{if} via (see e.g. Perkins, chap. 4)

  $$\sigma(a+b \rightarrow a+b) = |M_{if}|^2 \, p_f^2 / v_i / v_f$$

  p_f = final momentum in CM frame

  $v_i = v_f$ = relative velocities in CM frame (equal for elastic case)

- Hence $\sigma(a+b \rightarrow a+b) = |M_{if}|^2 \, \mu_{ab}^2$
  - $\sigma_{nucleus}/\sigma_{nucleon} = \mu_A^2/\mu_n^2$ with reduced mass (for both SI and SD):

    $$\mu_A = M_{WIMP} M_A / (M_{WIMP} + M_A)$$

    $$\mu_n = M_{WIMP} M_{nucleon} / (M_{WIMP} + M_{nucleon})$$

- First coherence effect, favoring large M_A.

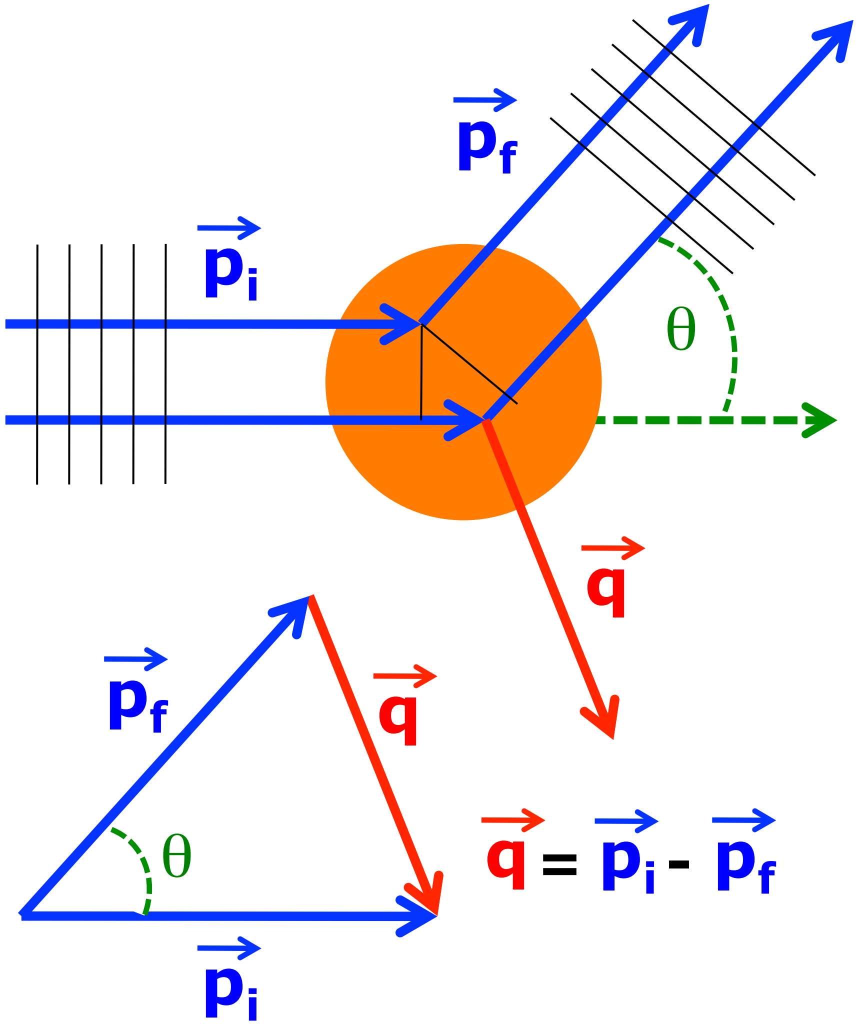
Nucleon-to-nucleus scaling (2)

- For SI interactions, $\sigma(a+b \rightarrow a+b) = |M_{if}|^2 \mu^2$ implies that for h/p>>r the amplitudes M_{if} of each the A nucleons will add coherently
- Second coherence effect: $\sigma_A/\sigma_n = A^2$ *for spin-independent interactions*
  - Coherent sum of scattering amplitude on each nucleon ($\propto A x M_{if}$)
  - $\sigma \propto (A\mu)^2$ (… but since rate/kg/d $\propto \sigma/A$, then rate/kg/d $\propto A\mu^2$)
  - Huge gain relative to spin-dependent terms for A > ~ 20

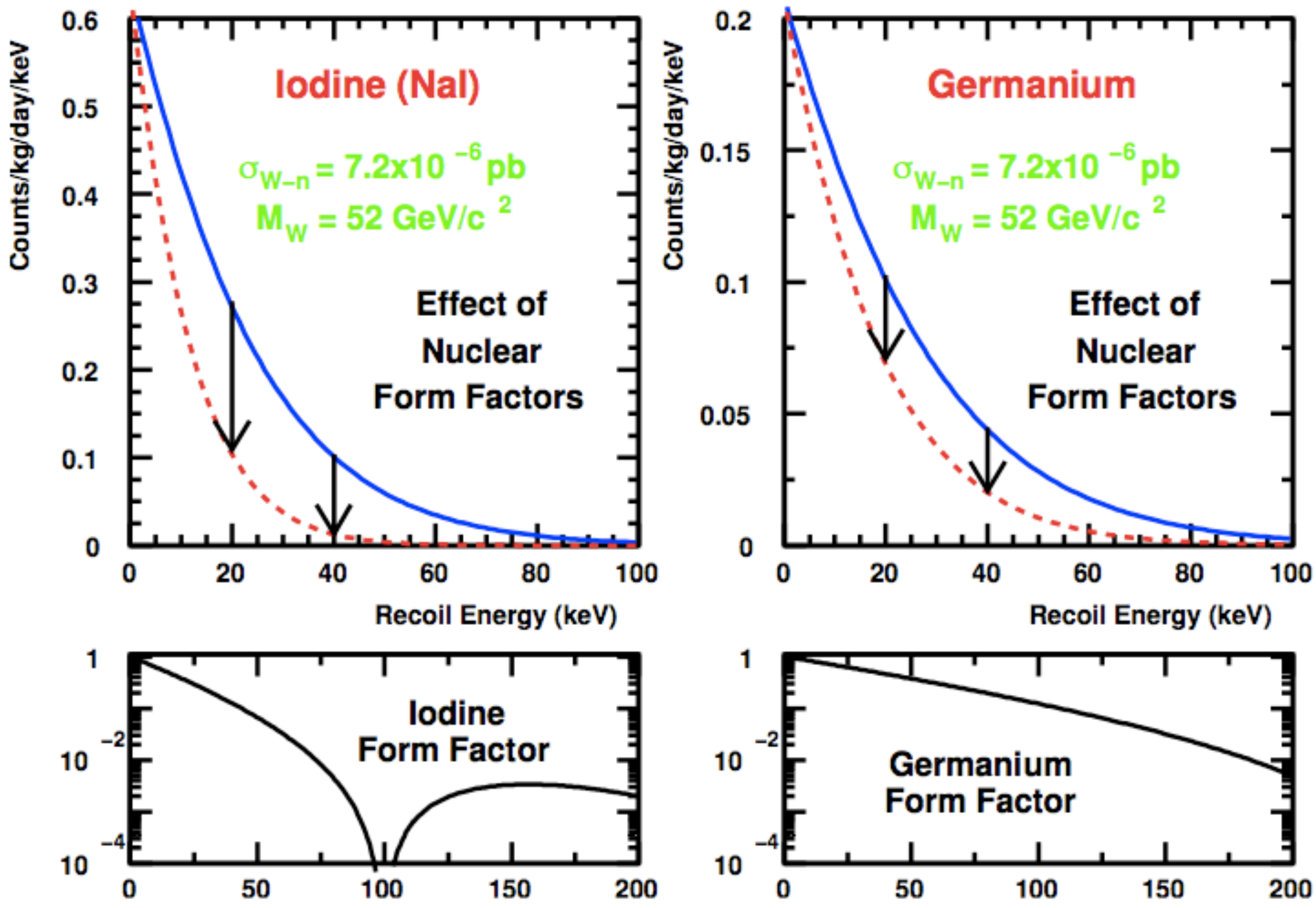
- Nuclear form factor $F^2(E_{recoil})$:
  - Coherent scattering reduced by diffraction effects if the transferred momentum is not small compared to hbar/R (R = nuclear radius).
- Rates scales as $\mu_A^2 A^2 F^2(E_{recoil})$

Nuclear form factors (semiclassical picture)

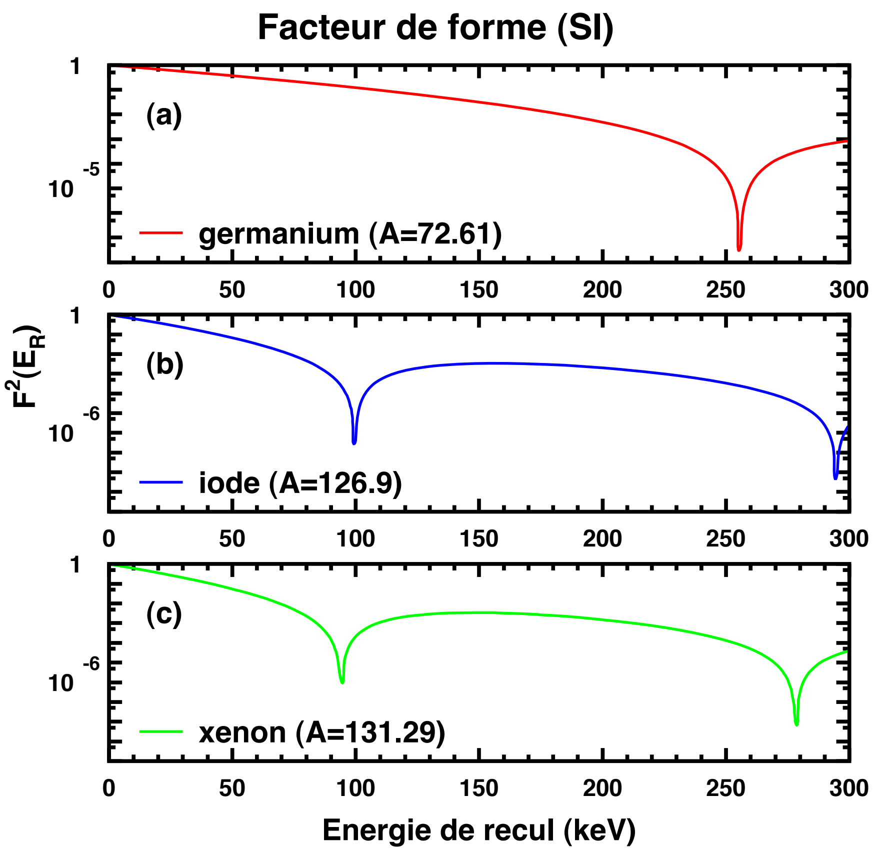
- Nucleons inside sphere of radius
  $R \sim 1.2\ A^{1/3}$ fm
- Diffraction: Interference between outgoing scattered waves coming from different scattering centers inside that sphere
- Integrated effect (~Fourier transform of nuclear density) depends on the transferred momentum
  $q = M_A v_A = \mathrm{sqrt}(2 M_A T_A)$
  (but not of nature of probe: can use μ scattering to evaluate F(q))
- SI: Sphere of constant density:
  $F_{SI}(q) = 3(\sin x - x\cos x)/x^3$
  with $x = q\ R$ / hbar
- SD: use other, appropriate, F(q)

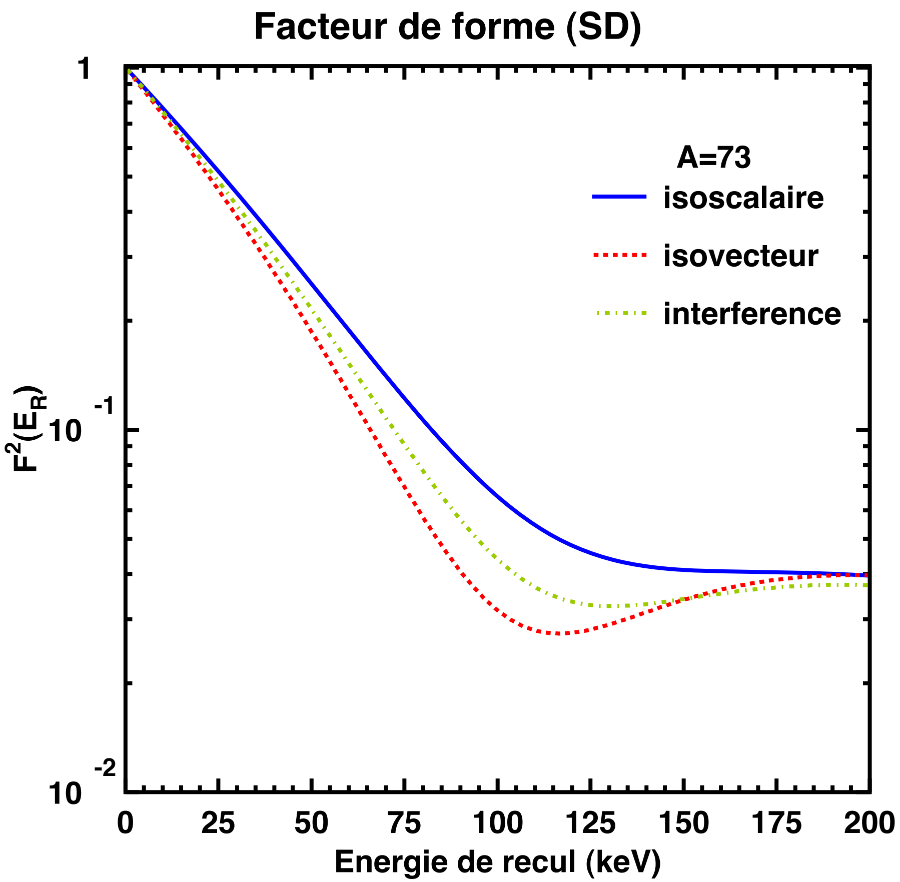


Nuclear form factors

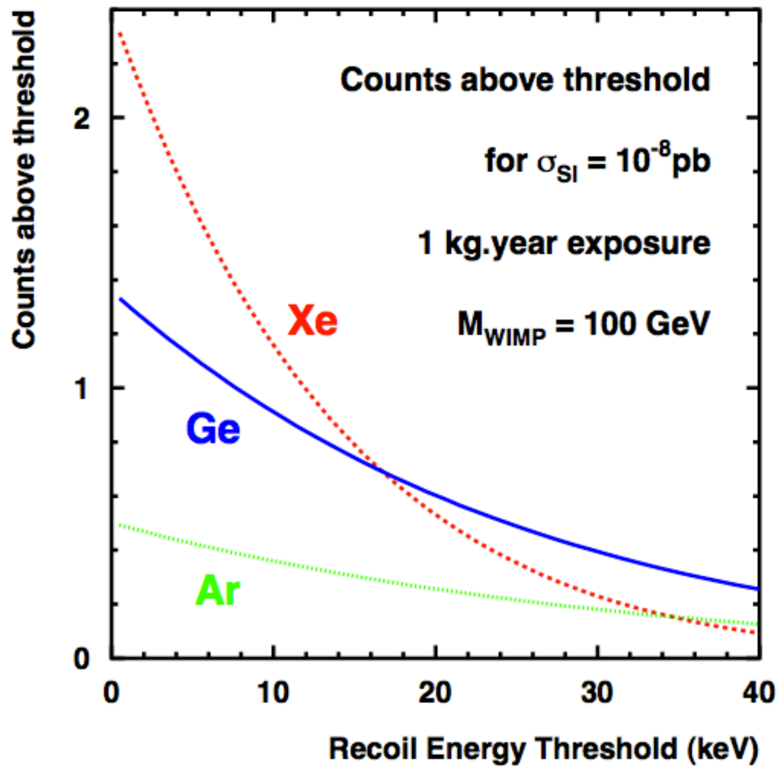


Form Factors



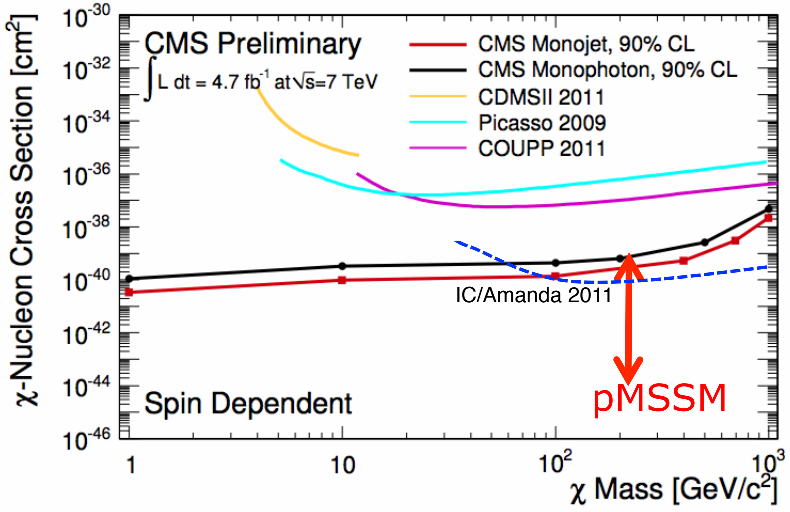


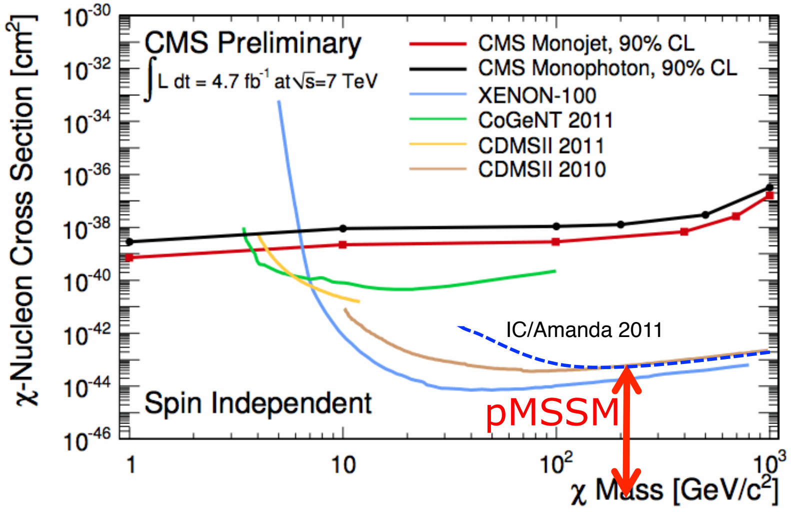
- As A increases, the A^2 boost is slowly eaten away by the form factor ($R \sim 1.2\ A^{1/3}$ fm)
- Example M_W=100 GeV:
- $A_{Ge} = 73$, $\mu_{W\text{-}Ge} = 43$
- $A_{Xe} = 131$, $\mu_{W\text{-}Ge} = 59$
- $(131/73)^2 = 3.22$
  - But rate/kg goes as 1/A… and we should not forget μ^2.
- $(A_{Xe}/A_{ge})(\mu_{Xe}/\mu_{Ge})^2 = 3.31$
- With form factors: rate ratio = 1.8 only



Spin-dependent (SD) vs spin-independent (SI)

- In many models, like SUSY, the SD is already excluded or mixed with some SI (and SI then dominates because of supplementary A^2 factor).
- SD is probed more efficiently by indirect searches (e.g. IceCube) or even LHC, because the direct search do not gain via the A^2 boost.
- SI direct search favored (-> high-A targets favored instead of high-spin ones), … but that remains a search bias

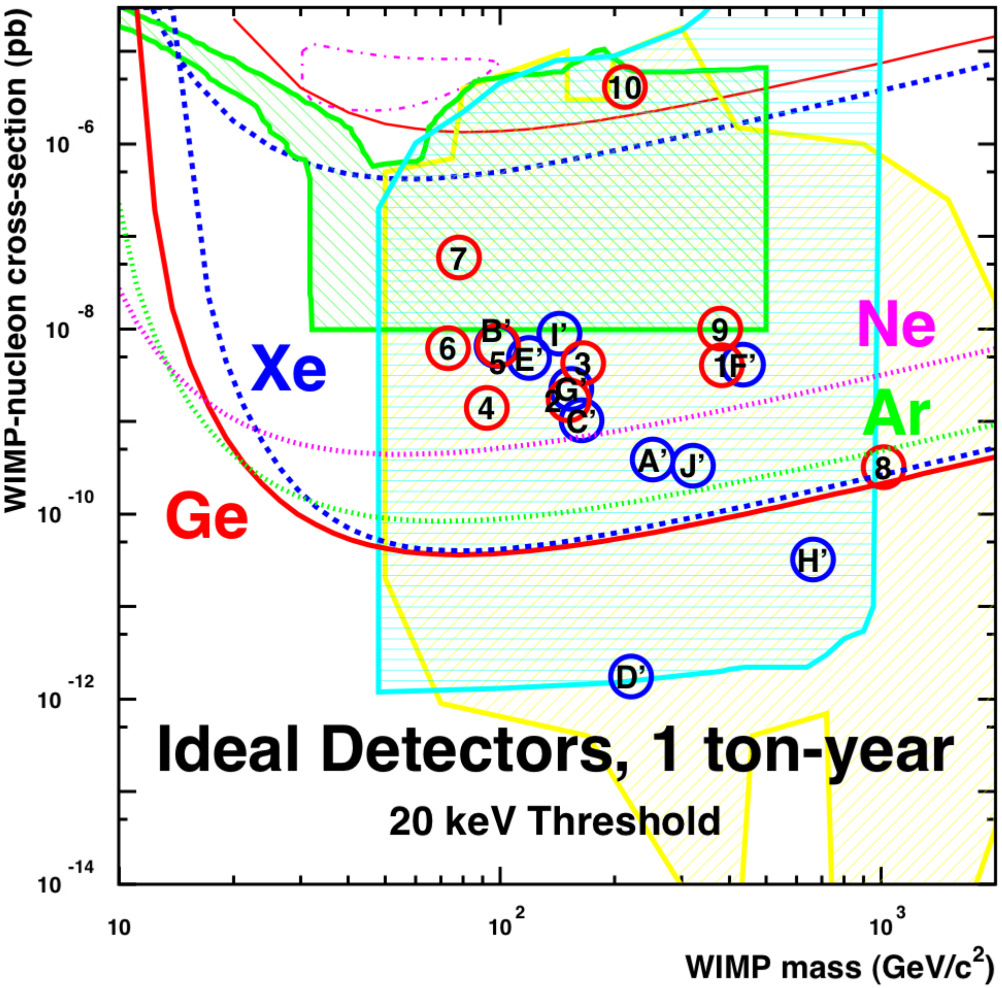




CMS Moriond EW 2012 + PRD85 (2012) 042002

Choice of target atomic mass

- Coherence favors large atomic masses A
- … until form factor takes its bite
- *Thresholds* may vary
- A>~40 is ok
- Costs per kg may vary
- Lower A is ok if detector size is ok
- **Variety of targets essential to check A dependency and systematics control**



Summary of ingredients (1)

First three ingredients usually taken from the Lewin and Smith's prescriptions for comparing experiments.

- ρ_W , WIMP density in the laboratory
  - Local measurements suggests ~0.4 GeV/cm^3 but adopted reference is 0.3
  - Observed rate $\propto \sigma_n \times \rho_W$
- f(v), WIMP velocity distribution
  - Dependence on average v_{rms}, not much on f(v) details (except: modulation)
  - Adopted reference: Isothermal halo, v_{rms} = 270 km/s (v_0 = 220 km/s), v_{escape} = 544 km/s, + sun (235 km/s) and earth (0±15 km/s) velocities.
- σ_A/σ_n , nucleon-to-nucleus scaling of scattering cross-section
  - Nuclear form factors matter (from ~0.2 to 1).
  - A^2 μ^2 scaling (spin-indep. case) dominates for A > 30 in MSSM.
  - A < 30, non-MSSM WIMPs: spin-dependent may dominate. No large gains from scaling, more model-dependence, poor rates.

Summary of ingredients (2)

- Last two ingredients usually left as free parameters of the searches:
- M_W , WIMP mass
  - Taken from SUperSYmmetric (or other) Model prediction
  - Method works from a few GeV/c^2 to >10 TeV/c^2
  - Typical SUSY range: from 50 GeV/c^2 to 1 TeV/c^2
- σ_n, WIMP-nucleon cross-section
  - Taken from SUperSYmmetric (or other) prediction
  - Method *could maybe* work down to 10^{-11} pb
  - Typical SUSY range: 10^{-6} to 10^{-11} pb (kg.day -> ton.year)
- Generic search: test all values of (M_W , σ_n)

How we share the world

The agreed division of tasks
for presenting Direct Dark Matter search results and predictions

Astrophysics

ρ = 0.3 GeV/cm^3
Maxwell: v_0=220 km/s
V_{sun}=235, V_{escape}=544

Theoretical Particle physics

Predict $\sigma_{nucleon}(M_W)$

Correct for $\sigma_{nucleon}/\sigma_{quark}$

Experiments

Measure $\sigma_{nucleon}(M_W)$

Evaluate efficiencies

Correct for F(q) $\sigma_{nucleus}/\sigma_{nucleon}$

Use agreed-upon numbers and corrections, even if we know these are not the most correct choices

Quick rate calculation

- Rate calculation per 1 kg Germanium target (A(Ge) = 0.073 kg/mol, $N_A = 6 \times 10^{23}$ atoms/mol)

$$N_{target}/\text{kg} = N_A/A = 8 \times 10^{24} \text{ atoms/kg}$$

- Recall:
  - WIMP local density $\rho \sim 3000/\text{m}^3 = 3 \times 10^{-3}/\text{cm}^3$
  - WIMP velocity $v \sim 200$ km/s $= 2 \times 10^7$ cm/s
  - WIMP flux $\phi = \rho v \sim 6 \times 10^4$ WIMP/cm²/s (5×10^9 /cm²/day)
- for $\sigma_A = 10^{-6}$ pb, let's calculate $\phi \sigma_A N_{target}$

$$R = 5 \times 10^9 \text{ /cm}^2\text{/day} \times (10^{-6} \times 10^{-12} \times 10^{-24} \text{ cm}^2) \times (8 \times 10^{24} \text{ /kg})$$

$$R = 4 \times 10^{-8} \text{ collision/kg/day}$$

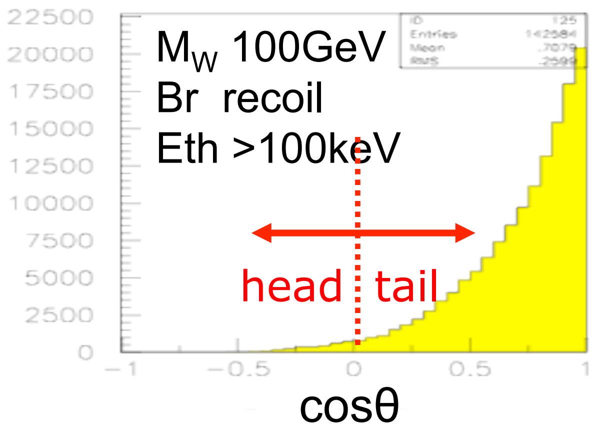
- ... with $\mu^2 A^2$ enhancement: R = 0.4 collision/kg/day

Some notes on…

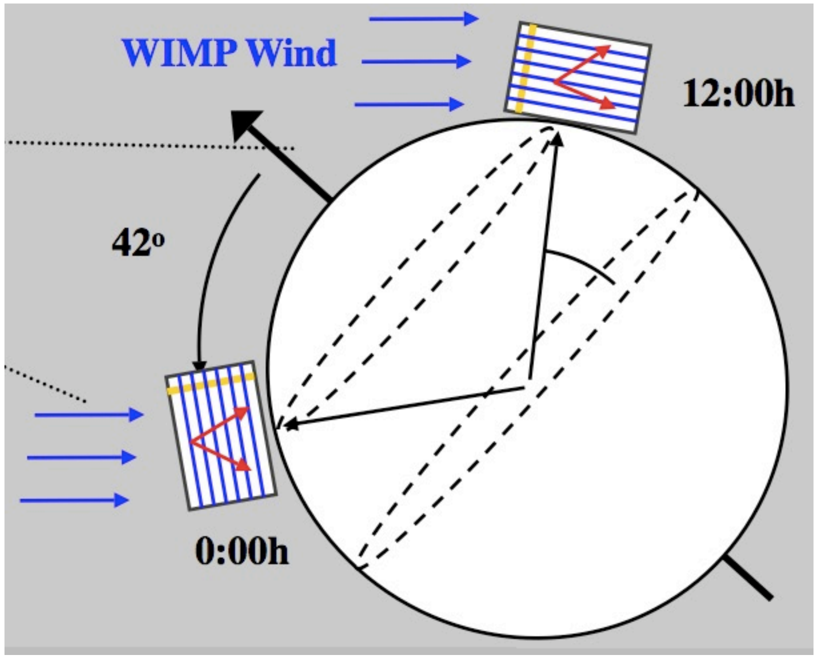
1.3- DIRECTIONALITY

Directionality: use v_{Earth} to detect WIMP wind

- Average WIMP wind direction due to v_E
- $\theta_{RECOIL} \neq \theta_{WIMP}$
  but $<\theta_{RECOIL}> = <\theta_{WIMP}>$



Naka, IDM2008

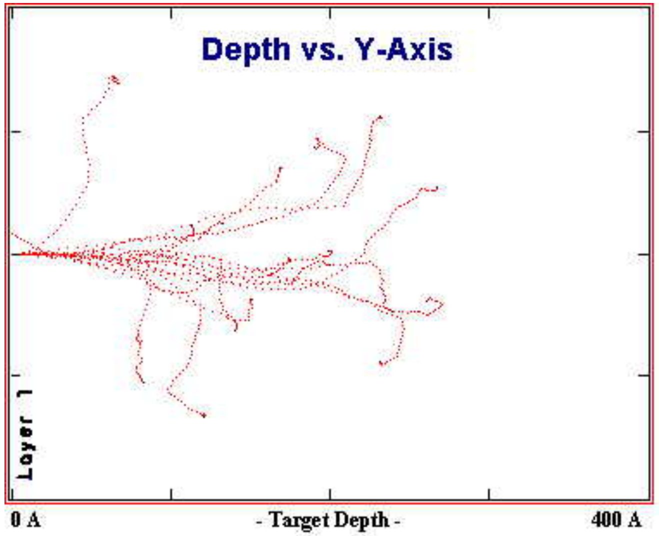


Spooner, IDM2008

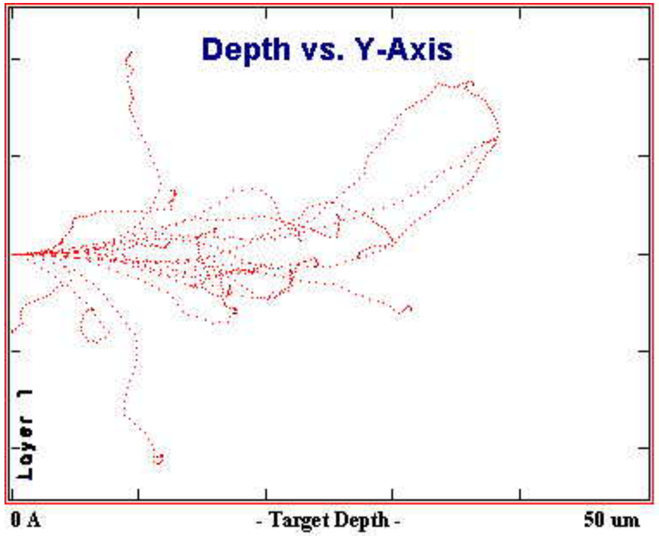
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

- *Difficult to observe θ_{recoil} and Range*

20 keV Ge recoils
in crystal Ge:
Range ~20 nm



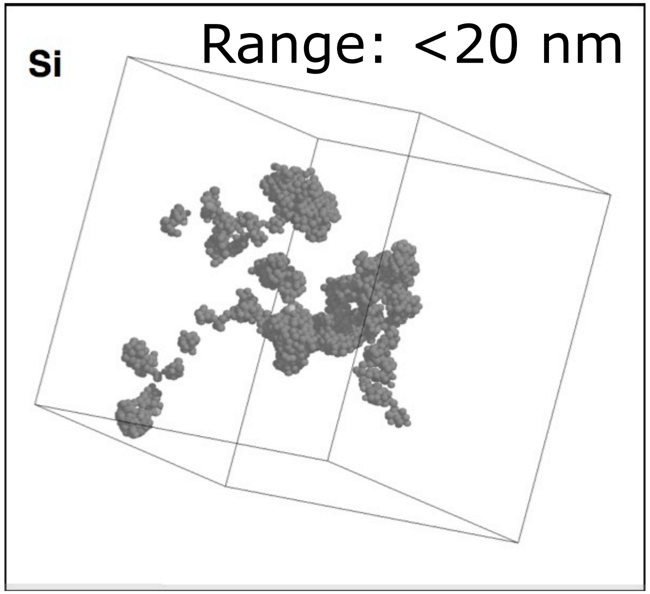
20 keV Kr recoils
in gaseous Kr:
Range ~30 μm

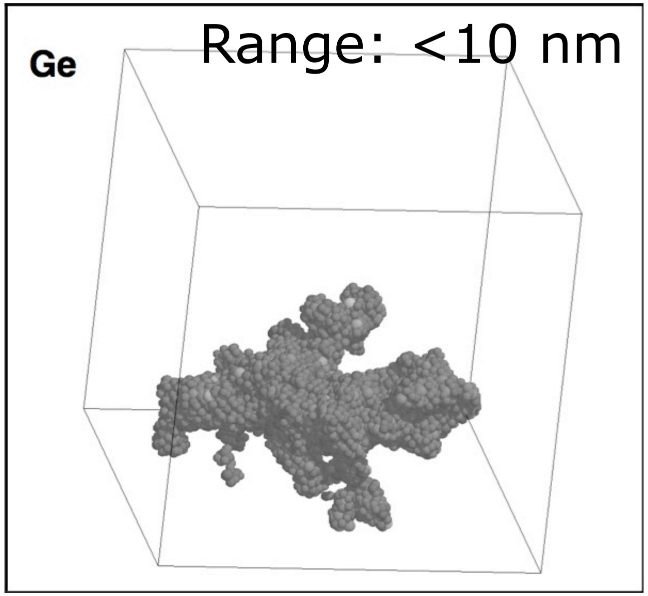


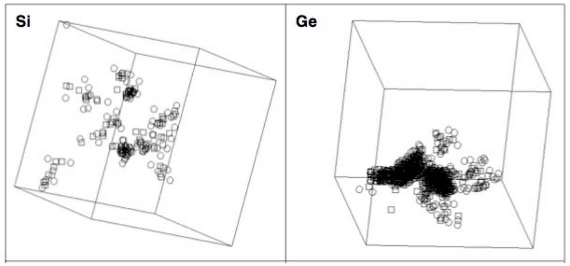
SRIM

Directionality of nuclear recoils

- Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)







Permanent damages due to this « femtoGray » dose (negligible in metals, but maybe not in semiconductors?)

Directionality

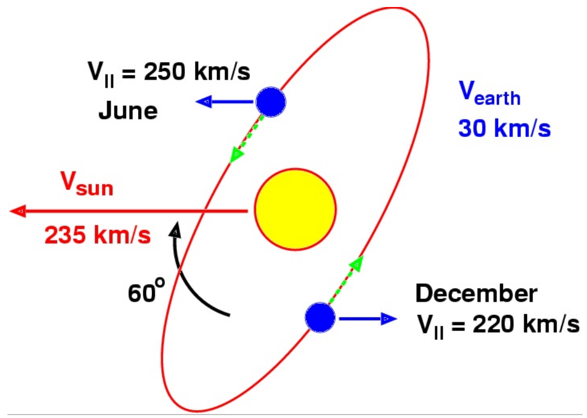
- Idea: check for recoil tracks in ancient mica, $\theta_{recoil} \sim -v_{sun}$
  - *Problem: direction of v_{sun}, v_{earth} changes constantly, continental drift...*
- Idea: low-pressure gas TPC detector (DRIFT+MIMAC project)
  - *Problems: "expand" track length to ~cm (low-density target), keep e−/ion diffusion low (negative CS_2 ions instead of e−), target density...*
- Idea: use emulsions
  - *Not trivial to scan short tracks in >> kg-year exposure with known velocity direction*
- **Observe E_{recoil} instead, use detector mass as target.**
  - **Count events with "unexplained" energy deposited in a detector**
  - **Need differential Rate vs E_{recoil}**

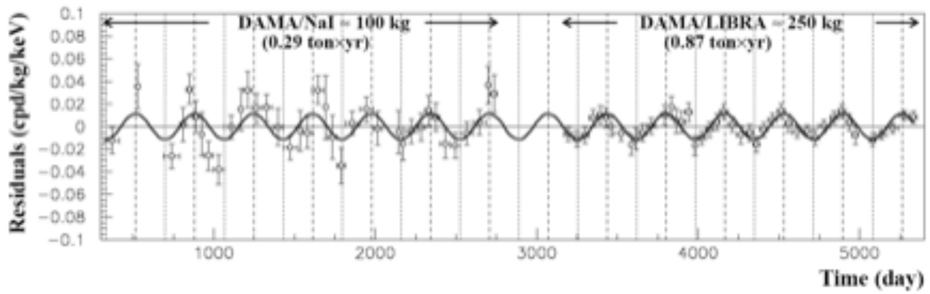
Annual modulation

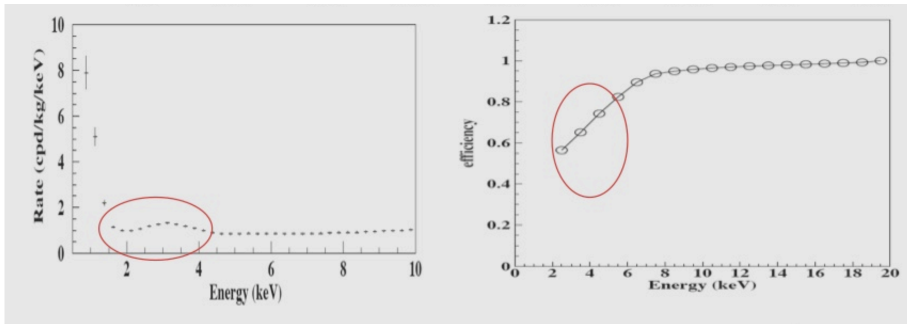
- Need large statistics: flux modulation is ~½ (±15/235) = ±3%, or less when considering experimental thresholds

- Claimed to be observed (~±2%) at low-energy in NaI (DAMA)

- Non-modulating component (~1 evt/kg/day) is ~total rate in NaI, but not observed in Ge, Xenon, $CaWO_4$ and CsI.
- Signal in low-efficiency, near-threshold region
- No "source off" expt. possible







1.4 CONCLUSIONS ON RATES

Direct searches Domain

Apply to any particle able to scatter elasticaly on an atomic nucleus *(Neutralino χ, Kaluza-Klein, mirror, scalar...)*

- *... If the kinetic energy of the WIMP* E_{WIMP} *is not too small*
  - $M_{WIMP} \sim 100$ GeV/c^2 (supersymmetry) and v ~ 200 km/s correspond to an average $E_{WIMP} \sim 20$ keV (hard X ray).
- *… If* $M_{WIMP} \sim M_{nucleus}$
  - Optimal momentum transfer for $M_{WIMP} = M_{nucleus} \sim 100$ GeV/c^2 corresponding to an atomic weight of A ~ 100 g/mol
- *... If the scattering probability is not zero*
  - It's small, otherwise we would have already seen it
  - Quantum field theory suggest a relationship between the probability of creating, annihilation or scattering these particles, depending on the interaction. Weak force, supersummetry : kilo.day… or ton.year.