Dark Matter III

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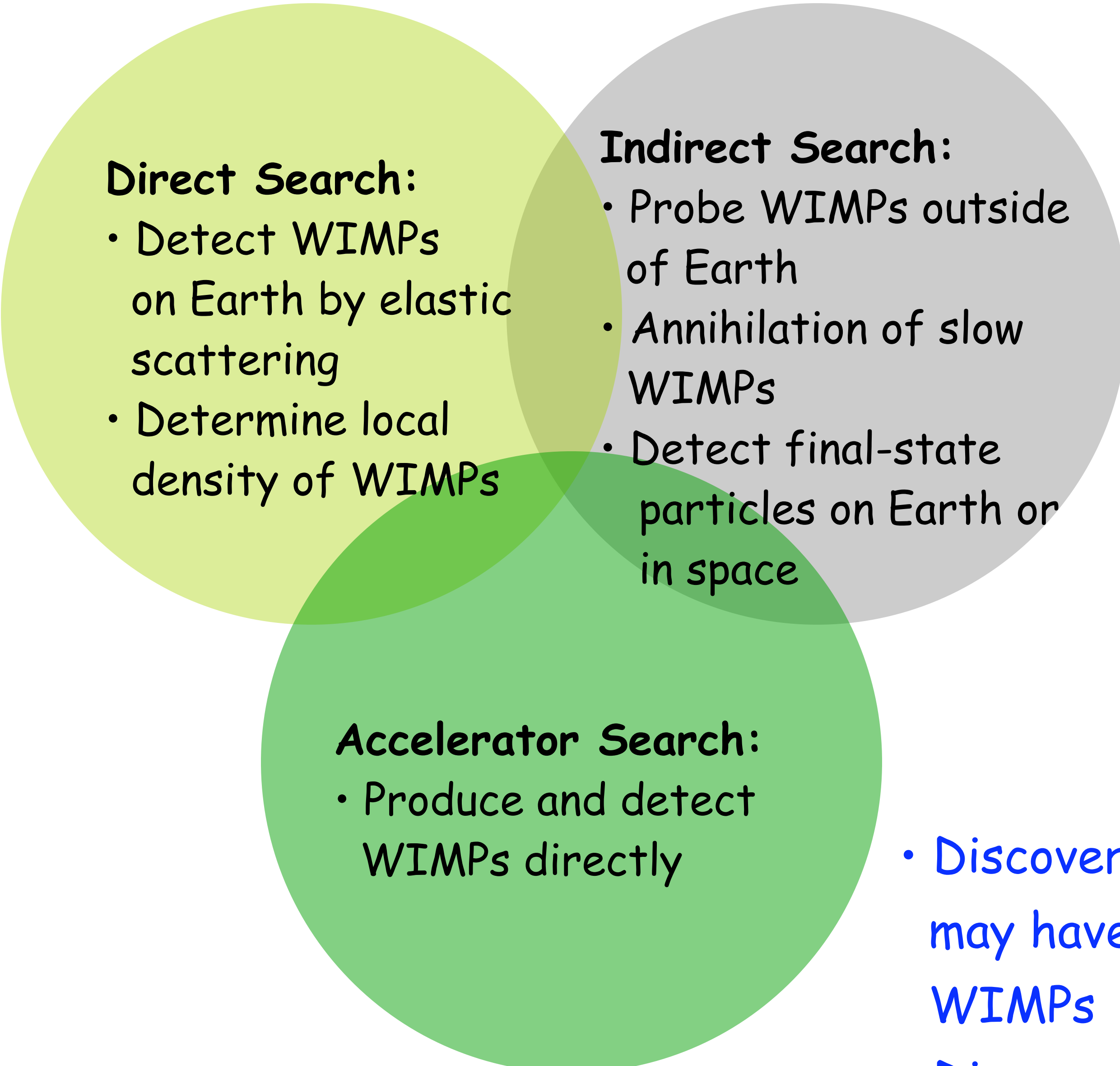
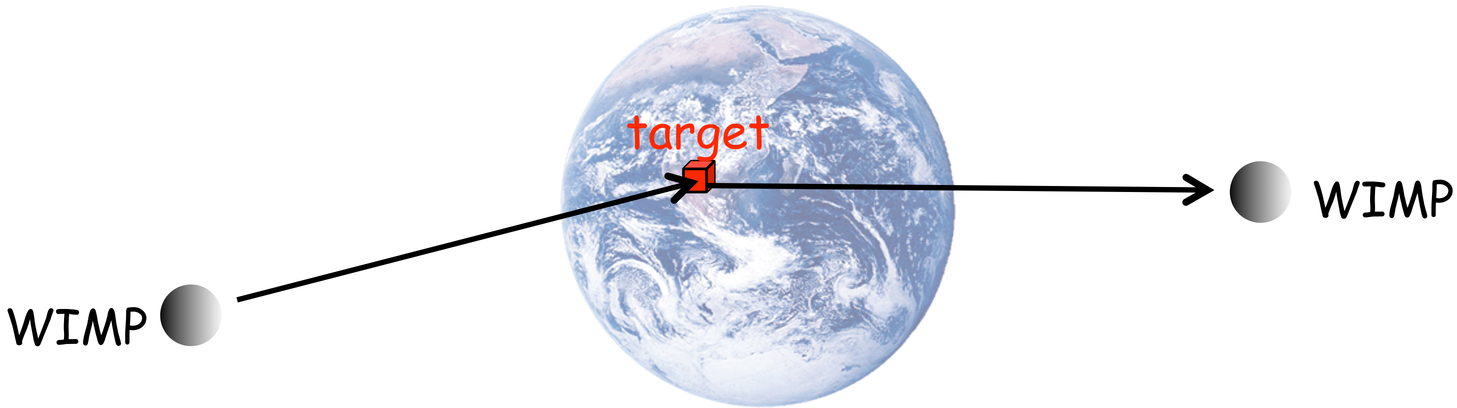
Unveiling Dark Matter



- Discovery with accelerators may have nothing to do with WIMPs
- Discovery of direct search may

Direct Search: Estimate Rates



For a perfect detector, the rate of collision is:

$$R = \frac{dN_{\mathrm{det}}}{dt} = \sigma_{xN} N_{tgt} \phi_x = \sigma_{xN} N_{tgt} \frac{\rho_x}{m_x} v_x \approx \langle \sigma_{xN} \rangle N_{tgt} \frac{\langle \rho_x \rangle}{m_x} \langle v_x \rangle$$

ϕ_x = flux of WIMP

N_{tgt} = number of nuclei in the target

m_x = mass of the WIMP, input from particle physics

σ_{xN} = cross section of elastic scattering of WIMP with a nucleus

ρ_x = local mass density of WIMP

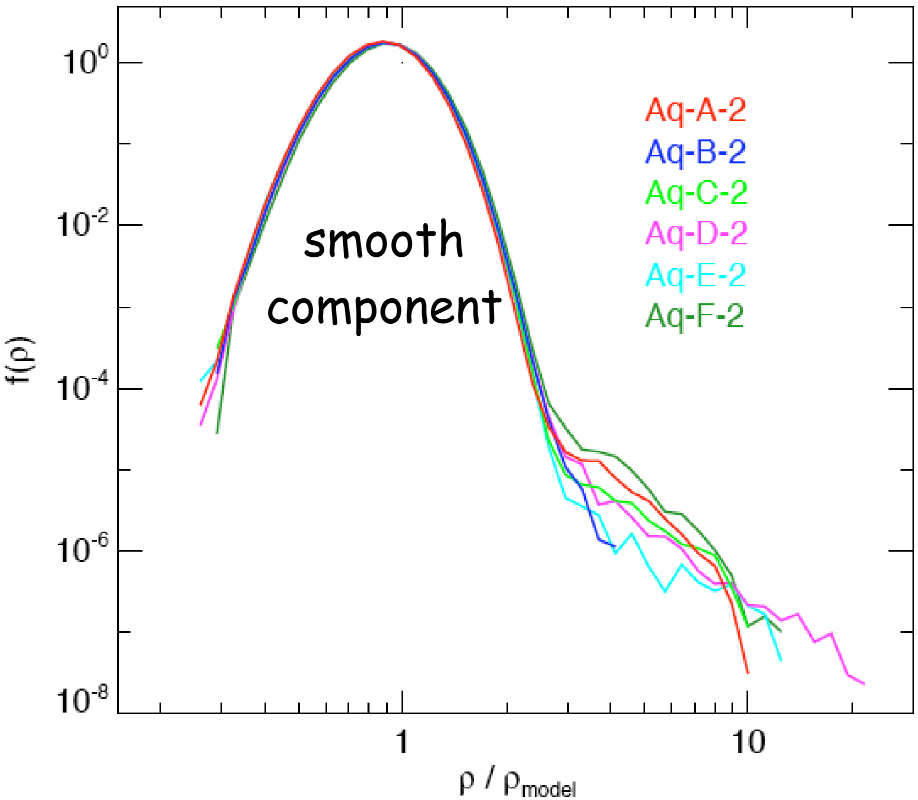
Local Density of WIMPs

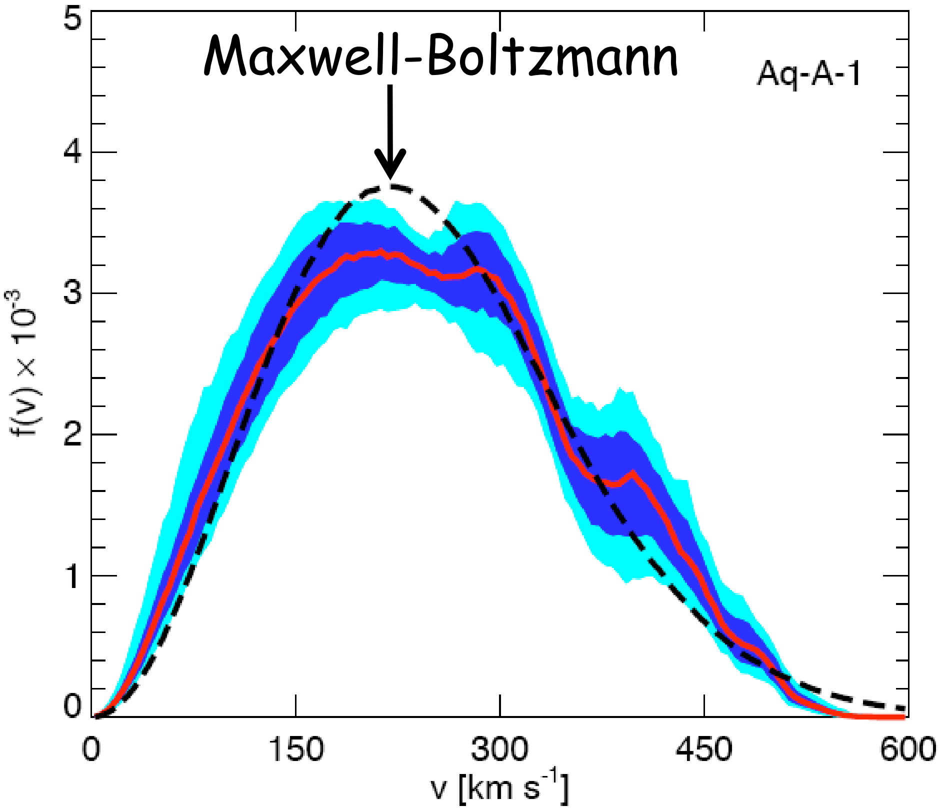
- From Particle Data Group: ρ_{halo} = 0.1-0.7 GeV/cm^3
- Taking M_{WIMP} = 100 GeV:

  ρ_{WIMP} = 10^{-2}-10^{-3} WIMPs/cm^3

Local Mass and Speed Distributions

- Based on simulation without ordinary matter:





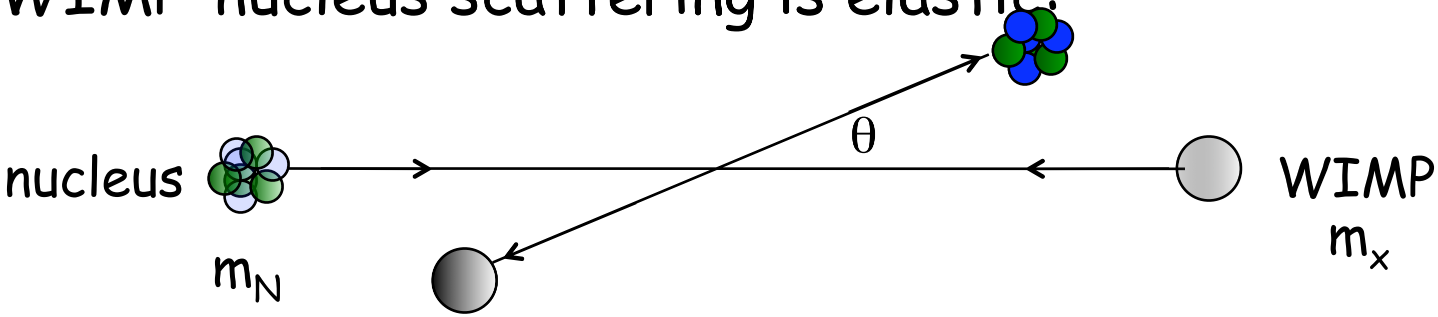
arXiv: 0812.0362

- Local mass density is in the smooth component (smooth to < 15% from the mean).

- Speed distribution is close to a Maxwellian distribution in the vicinity of the Sun.

Kinematics of Elastic Scattering

- For local dark matter: $v_{WIMP} \sim 10^{-3}c$, non-relativistic.
- WIMP-nucleus scattering is elastic:



Momentum transfer to the recoiled nucleus:

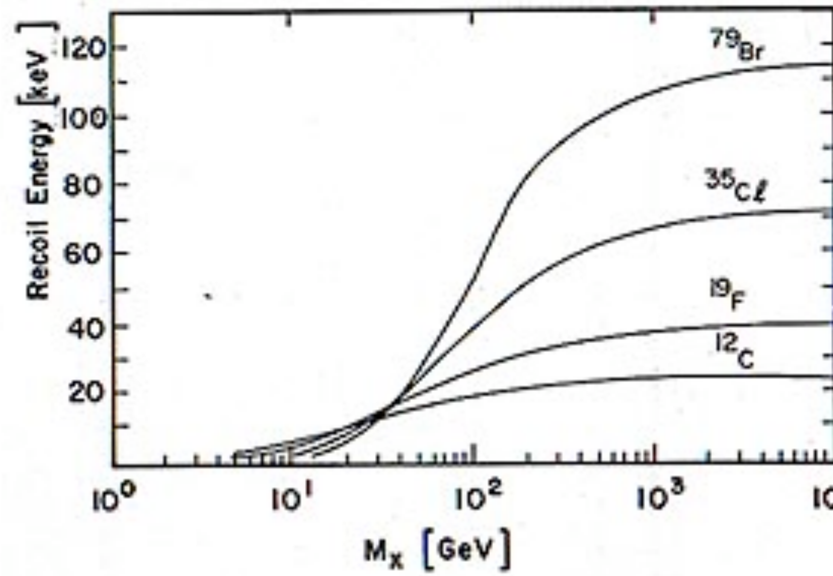
$$q^2 = 2\mu^2 v_x^2 (1 - \cos\theta)$$

μ is the reduced mass.

Kinetic energy of recoiled nucleus:

$$E_r = \frac{q^2}{2m_N} = \frac{\mu^2 v_x^2}{m_N}(1 - \cos\theta)$$

$$\frac{dR}{dE_r} \propto e^{-\frac{E_r}{\langle E_r \rangle}}$$



Elastic Scattering Cross Sections

- Since the spin of WIMP can be 0, 1, 1/2…
  - The most general Lorentz-invariant Lagrangian density has scalar (S), pseudo-scalar (P), vector (V), axial-vector (A), and tensor (T) interactions.
- The elastic scattering processes of WIMP with nucleus can be classified as:

(1) Scalar interactions (spin-independent, coupled to nuclear mass)

$$\sigma_A^{SI} = \frac{4}{\pi}\frac{m_x^2 m_N^2}{(m_x+m_N)^2}\left[Zf_p+(A-Z)f_n\right]^2 F(q^2)$$

f_p, f_n = effective couplings to p and n.

$F(q^2)$ = nuclear form factor

(2) Spin-spin interactions (from the axial interactions)

$$\sigma_A^{SD} = \frac{32}{\pi}G_F^2\frac{m_x^2 m_N^2}{(m_x+m_N)^2}\frac{J_N+1}{J_N}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 F(q^2)$$

J_N = spin of nucleus

a_p, a_n = effective couplings to p and n.

$\langle S_{p,n}\rangle$ = average values of the spin of p, n in the nucleus

Spin-dependent Enhancement

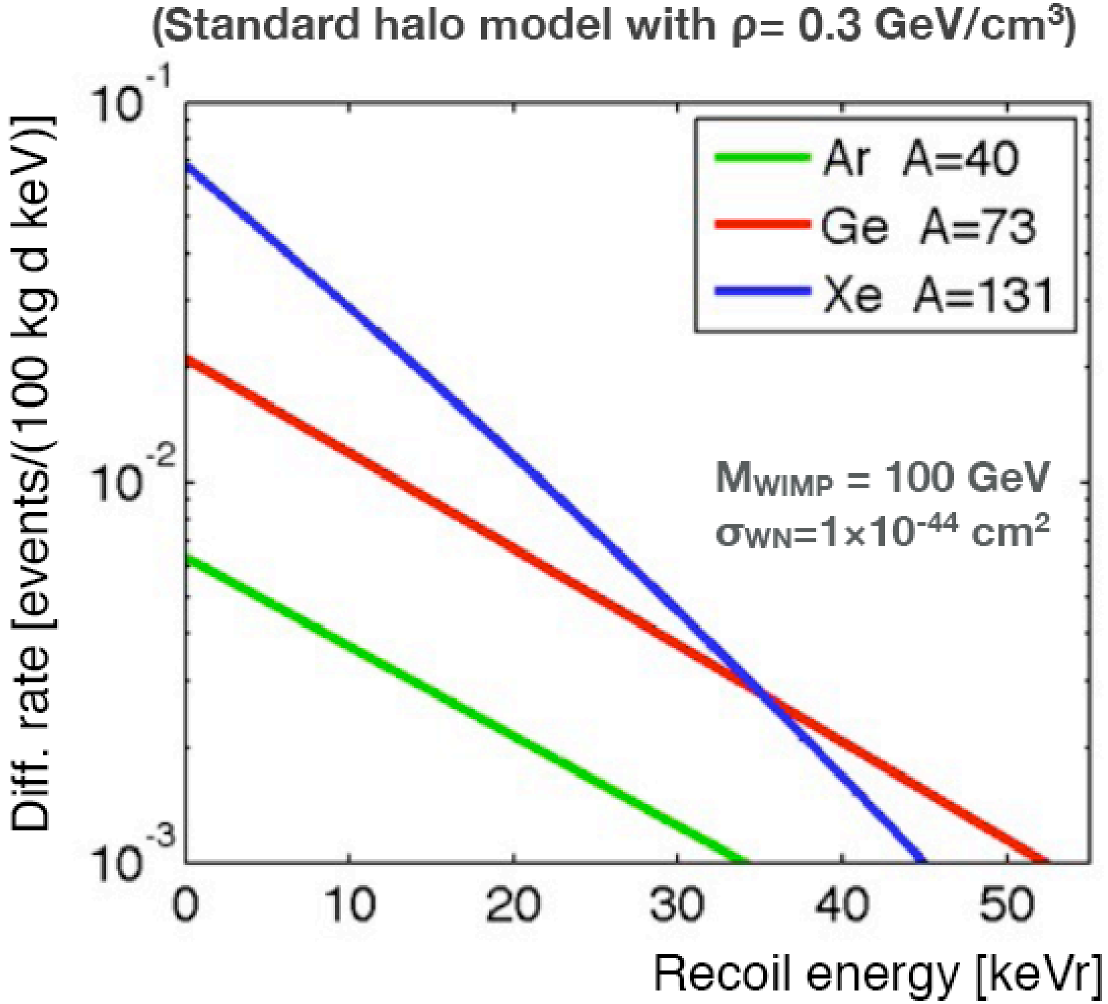
$$\sigma_A^{SD} \propto \gamma^2 J_N \left(J_N + 1\right)$$

Isotope	J_N	Unpaired	γ^2
^{1}H	1/2	p	1
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

^{19}F is the target of choice for spin-dependent scattering.

Estimated Rates

- After integrating over the Maxwellian velocity distribution, the estimated rate of scattering is:

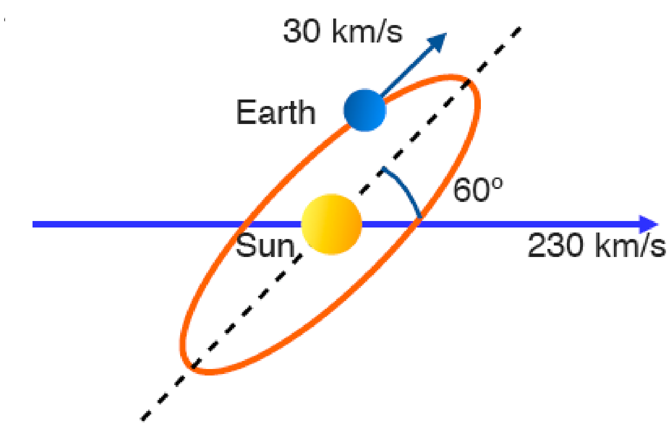


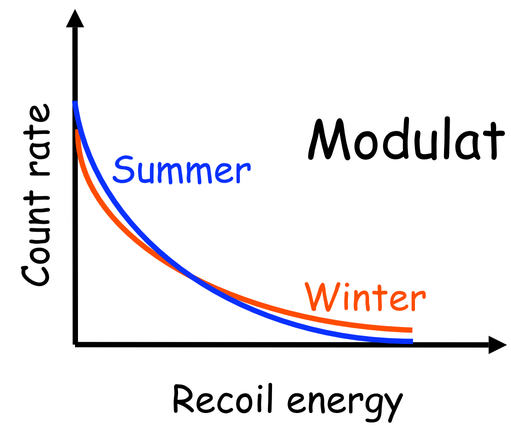
Experimental Requirements

- Large target mass
  - At least 100 kg
- Need extremely low background: < 0.1 counts/kg/d
  - Reduce intrinsic background: use ultra radio-pure materials
  - Suppress gamma/neutron background
    - Go deep underground to cut down spallation neutrons
    - Shield detector against ambient radiation
- Capable of discriminating signal from background
  - Pixelize target
  - Energy and tracking
- Very low energy threshold
  - At the keV level
- Extremely stable operation

Signature of WIMP Signal

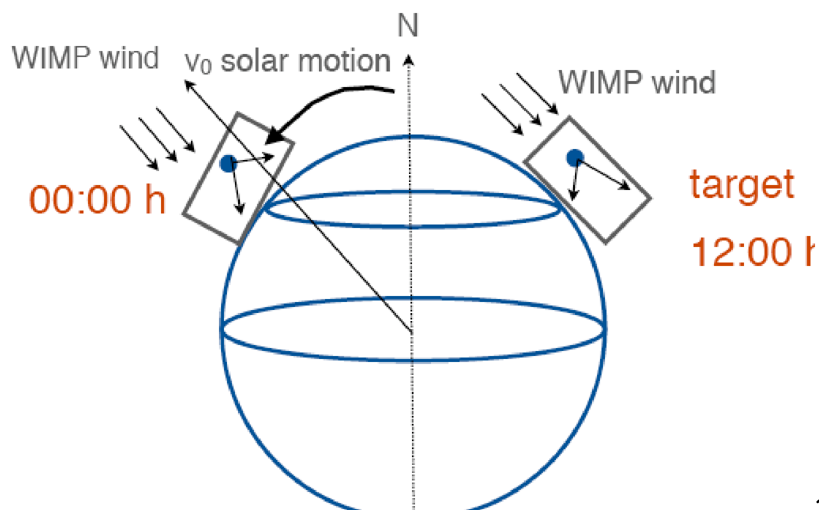
- Single scatters
  - Uniform throughout the fidiucial volume of the target.
- A^2-dependence of the target material.
-





Modulation ~(3-7)%

- Day-night variation
  - (7-17)%
  - tracking capability is needed.

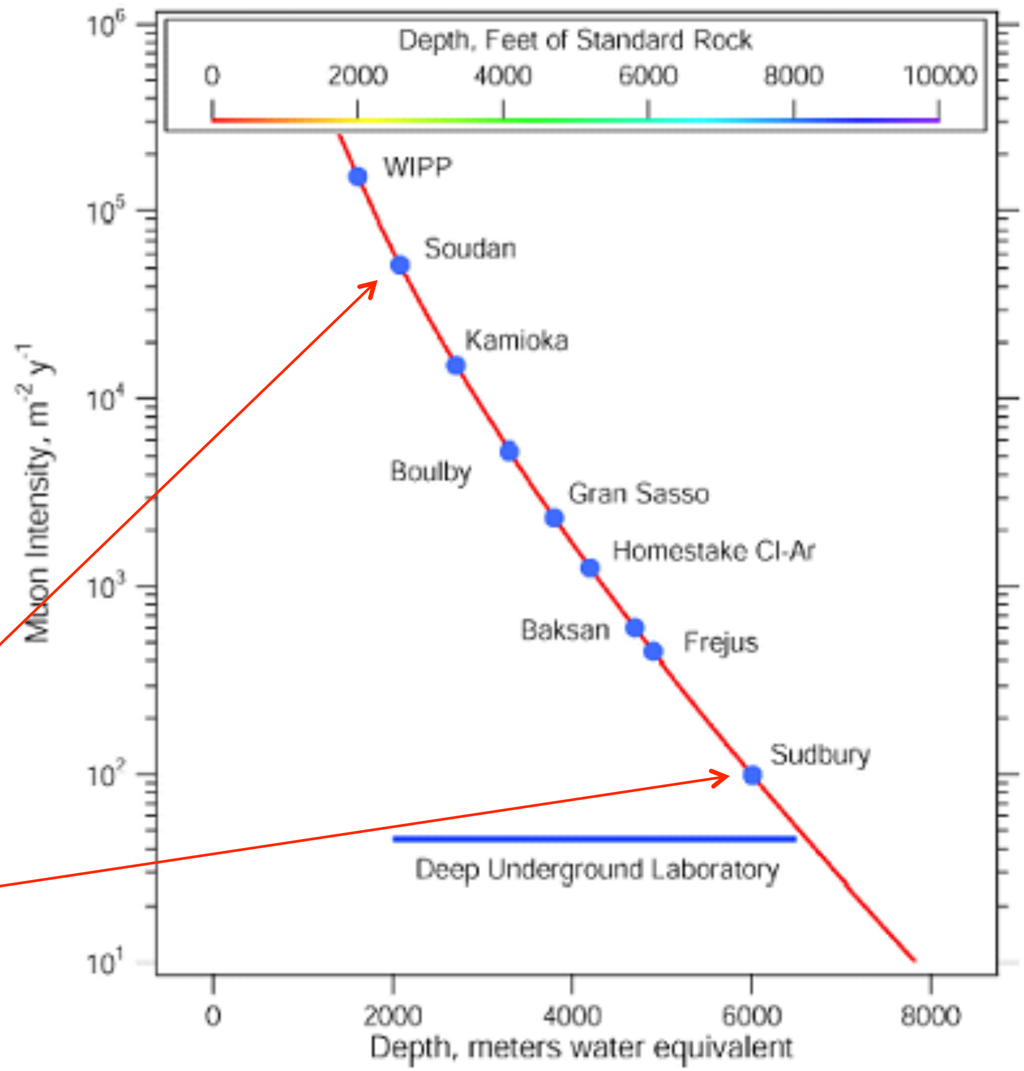


Neutron Background

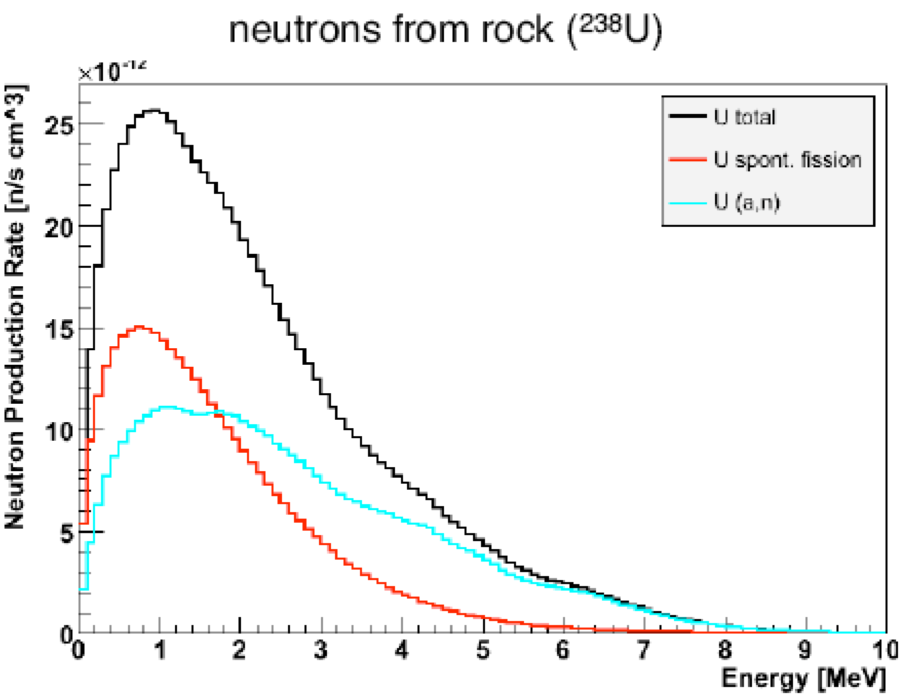
- From natural radioactivity
  - (α,n) reactions
  - fission
- From muon-induced reactions
  - inside the target
  - in the shielding
  - in the surrounding rock

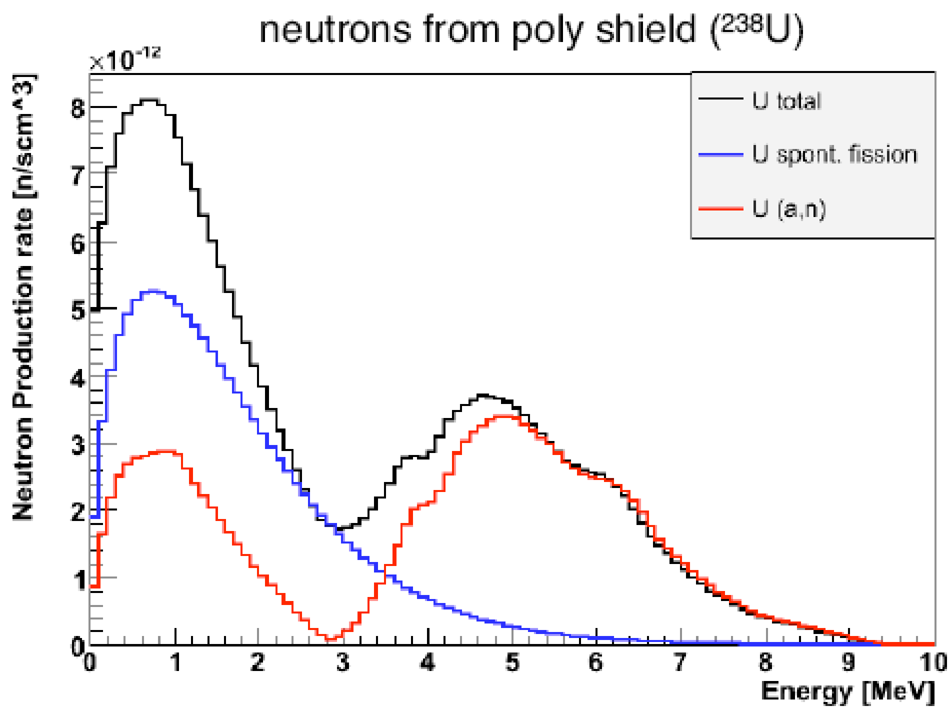
SOUDAN: 0.05 n/kg/d

SNOLAB: 0.2 n/ton/y



Energy Spectrum Of Neutron Background

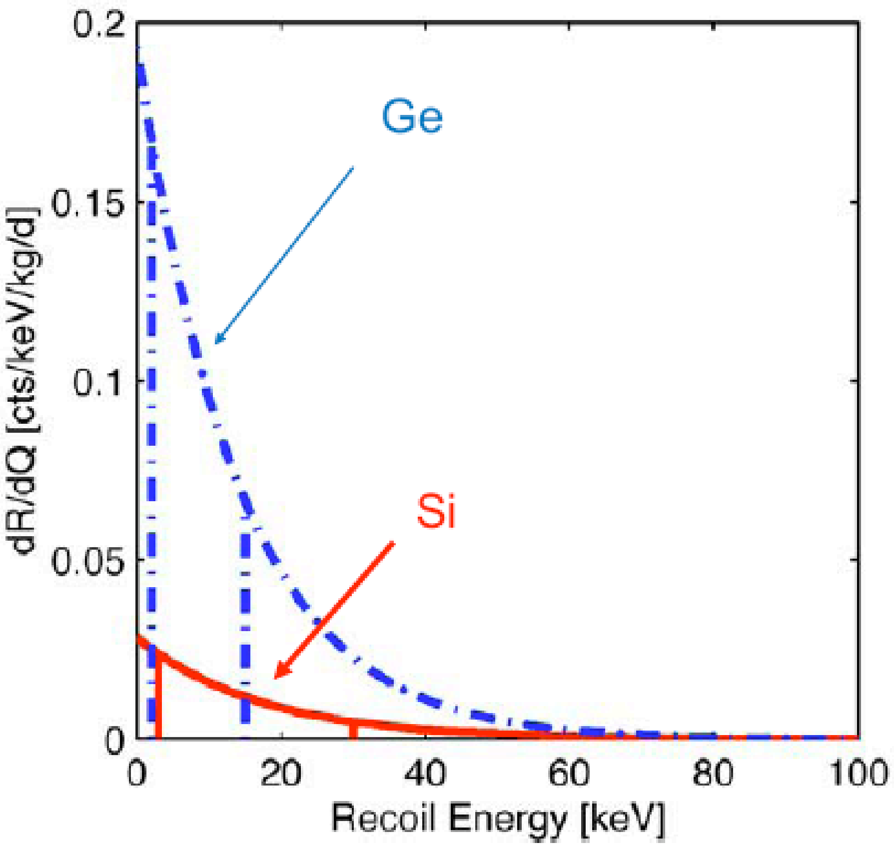




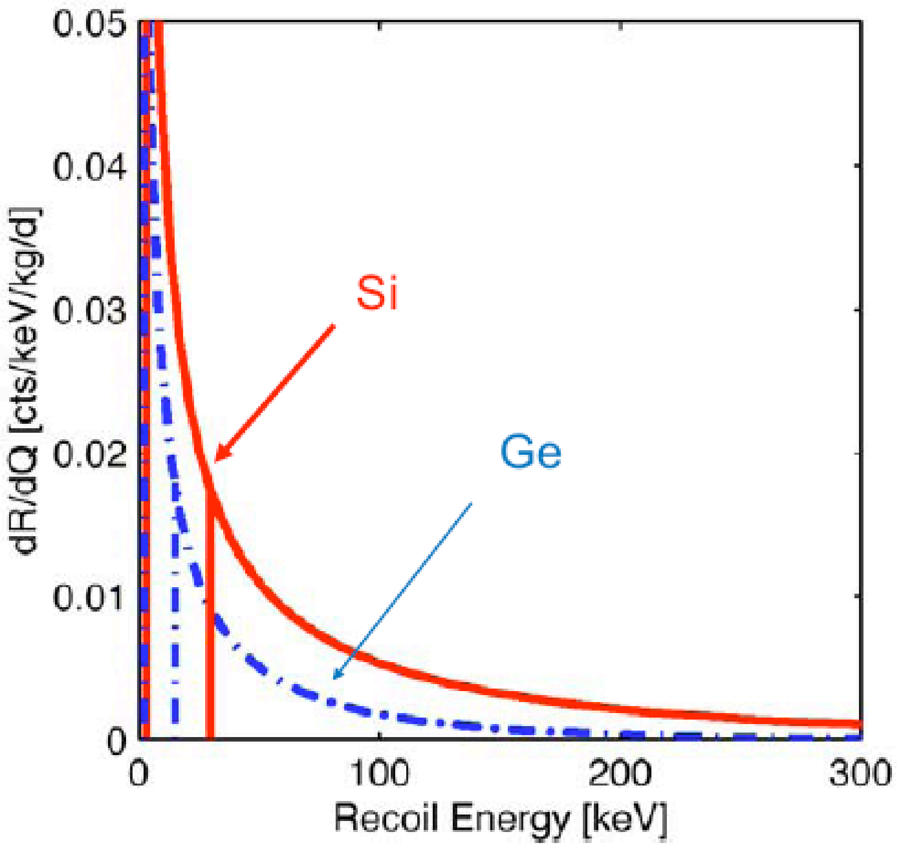
E. Tziaferi

Distinguishing Neutron From WIMP

- Neutrons have mean-free path of few cm in the target
- Different A-dependence for the E_r spectrum



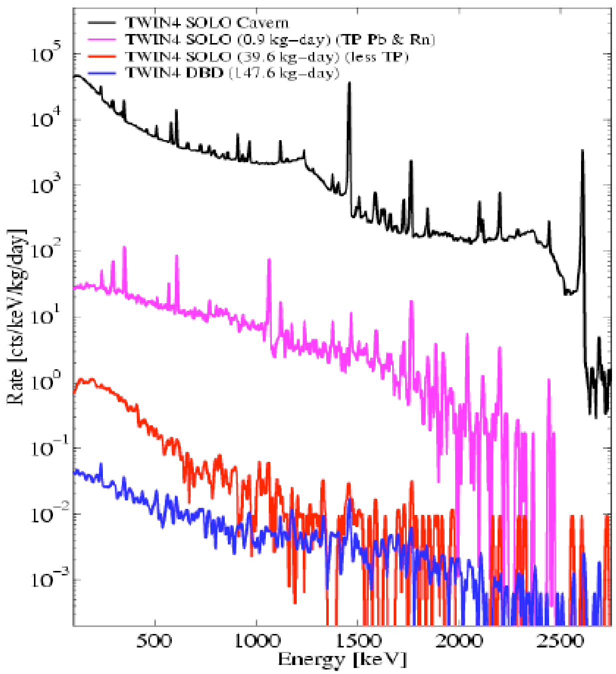
WIMP, m_x = 40 GeV



neutron

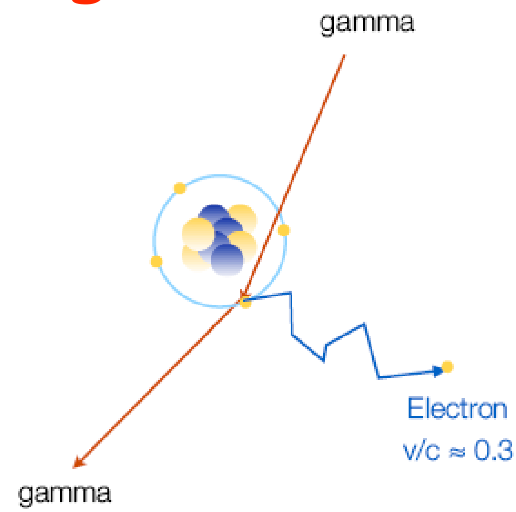
Gamma-ray background

- From natural radioactivity
- From radon decays

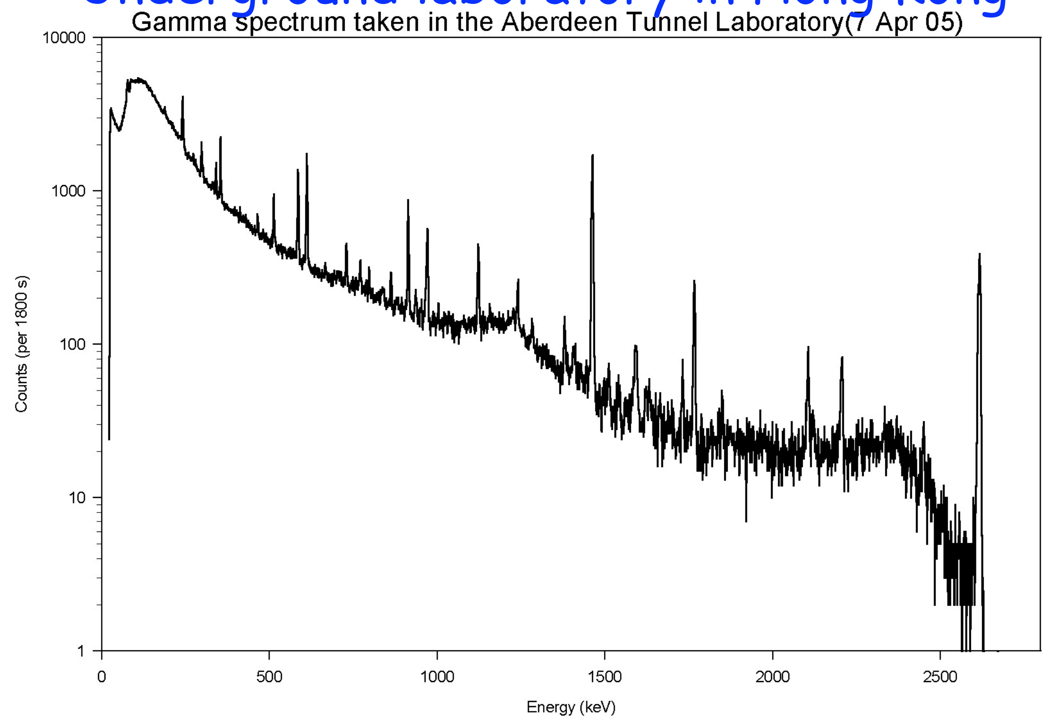


Ge detector underground, no shield

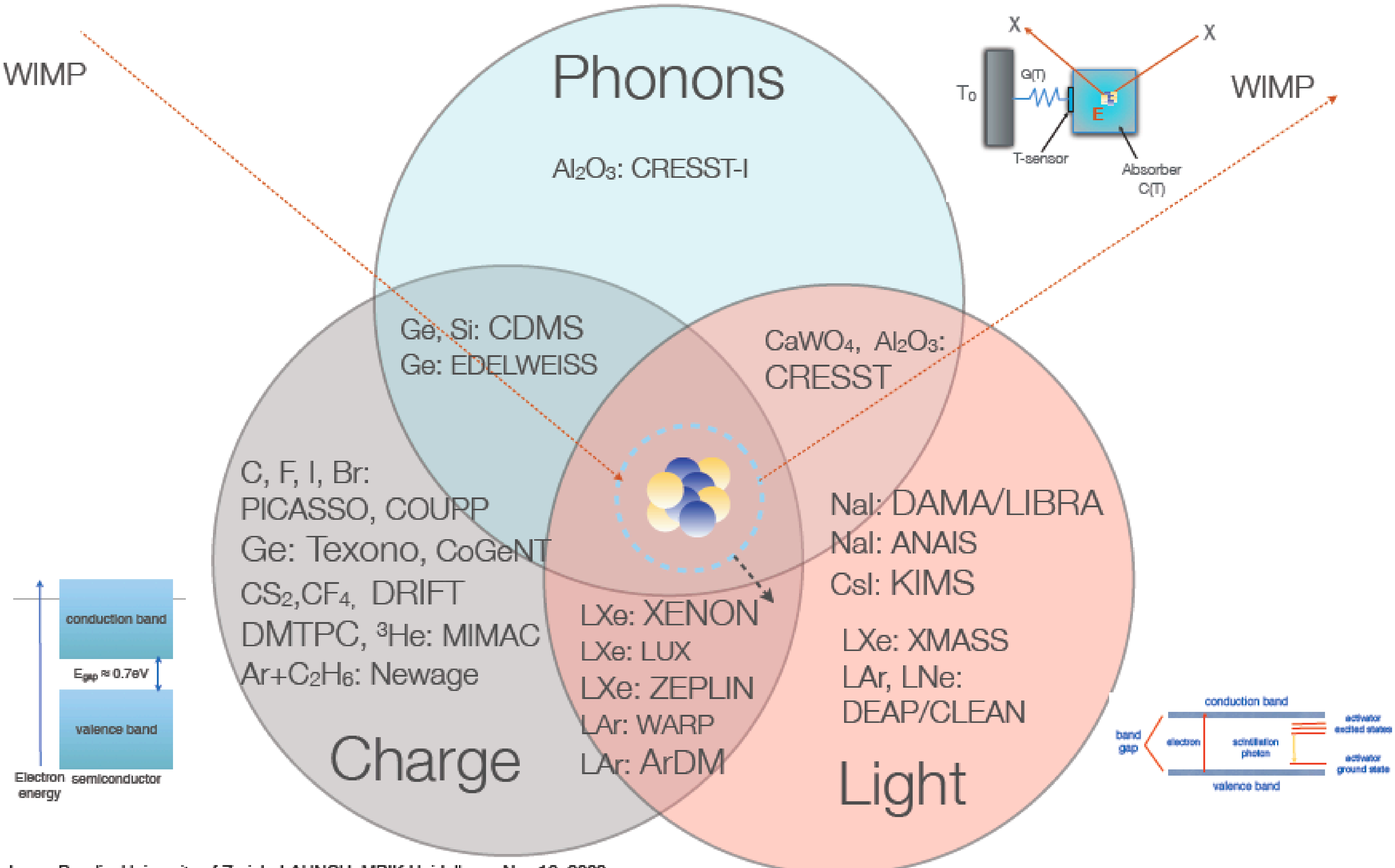
Ge detector underground, Pb shield and purge for Rn



Underground laboratory in Hong Kong

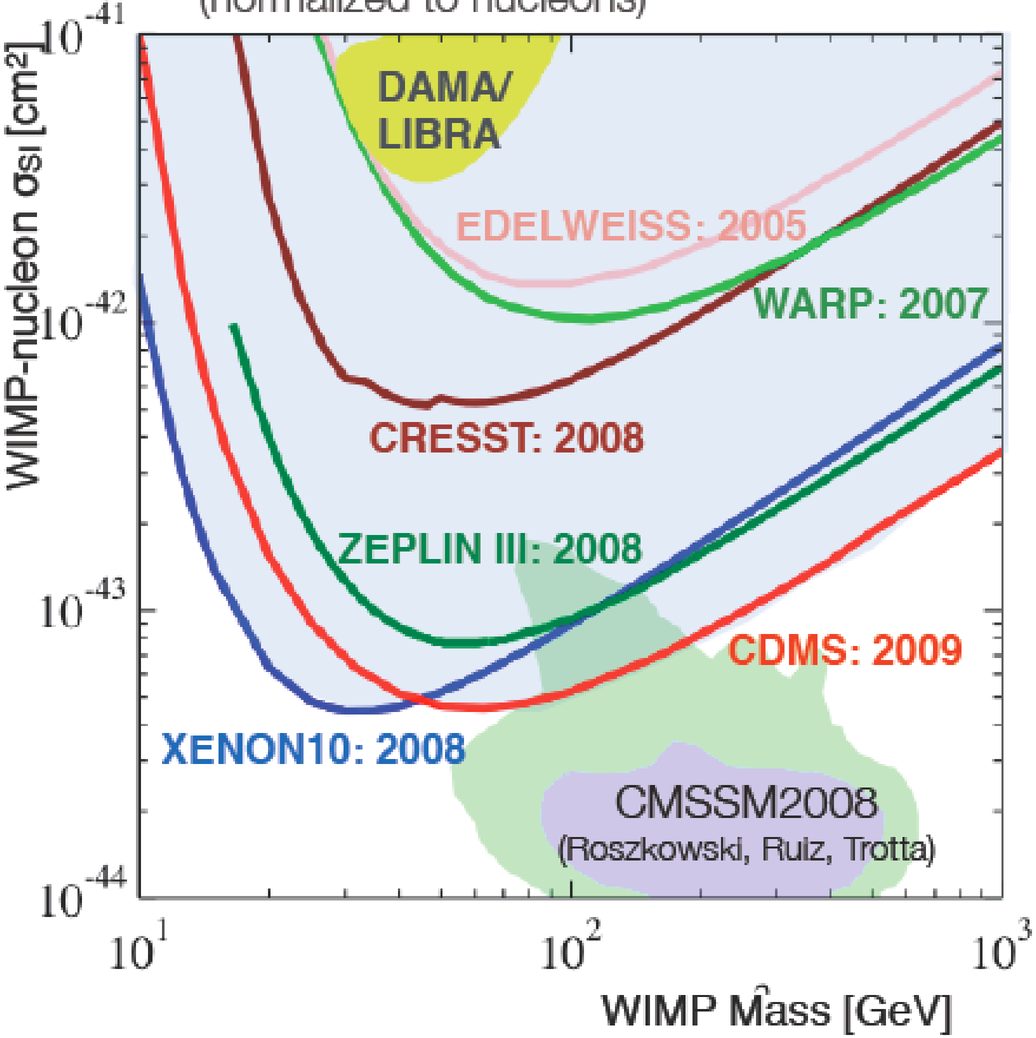


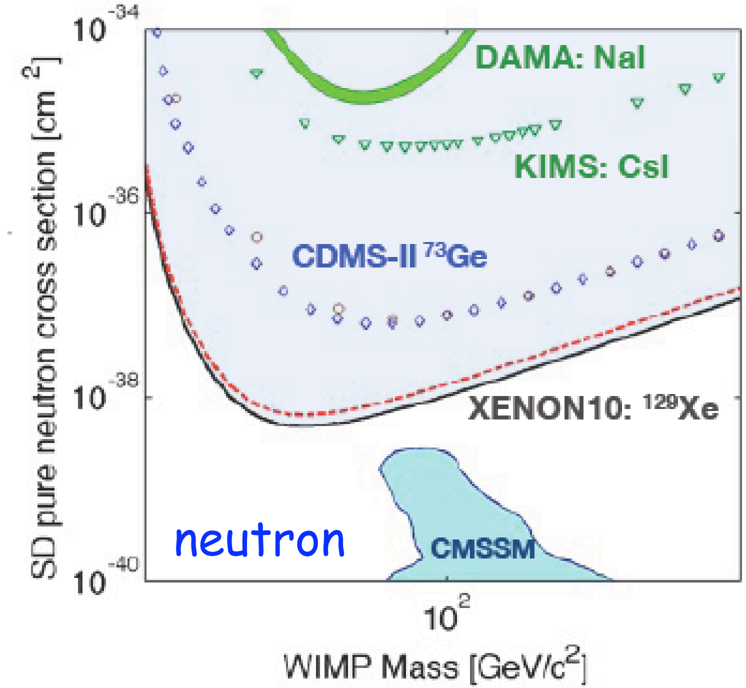
Techniques For Direct Search



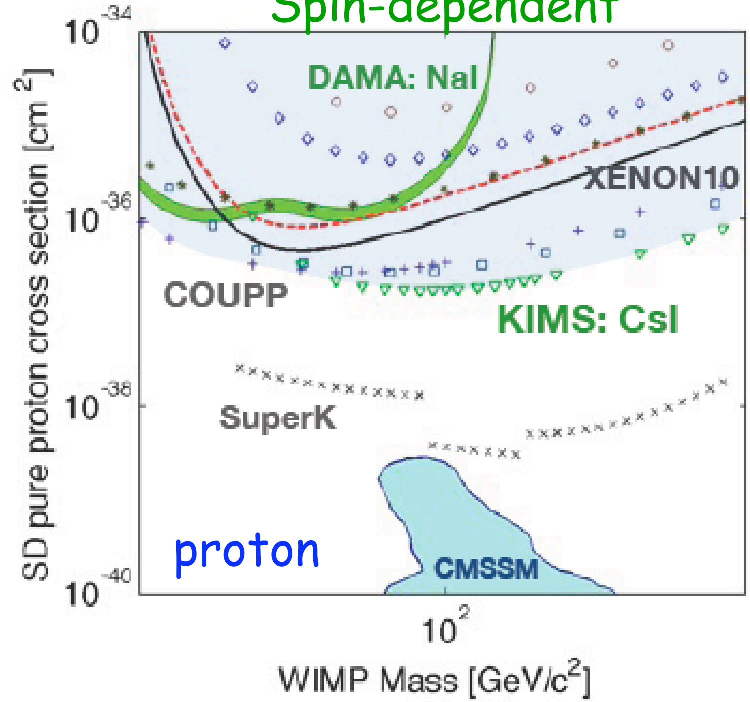
Experimental Results

Spin-independent cross section
(normalized to nucleons)

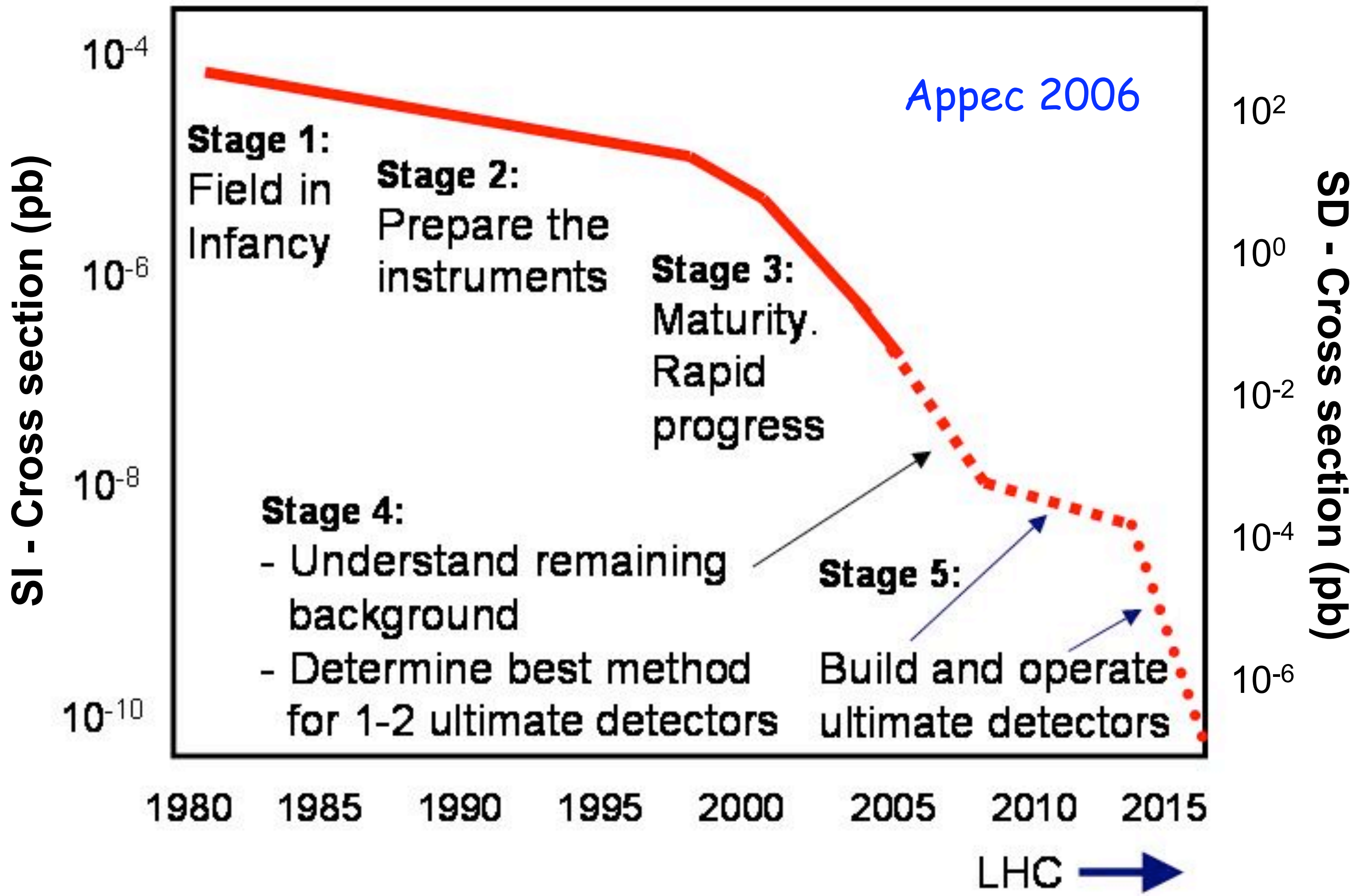




Spin-dependent



Evolution of Dark-matter Experiments



Summary

- There are compelling evidences that ~20% of the Universe is made up of something that we can't identify and is called 'dark matter'.

- Assuming dark matter is particle-like, its interactions with ordinary matter are weak with cross sections comparable or smaller than those of neutrinos at low energies.

- The open question is:

  Are we making the right assumption to account for the ~20% of the Universe ?