Conclusions

- **Direct search for WIMP: hot topic**
  - * Dama claim should soon be settled
  - * Improvements of "conventionnal" techniques
- **Bolometer technology**
  - * Breaking away from limitations of ionisation and scintillation detectors
  - * Sensitivity to full recoil energy, no "quenching"
  - * Very low threshold achievable
  - * Large freedom in absorber material
- **Double-component detectors**
  - * Heat and Scintillation in development
  - * Heat and ionisation giving best WIMP limits so far: >99% event-by-event rejection of γ,β
- **R&D meeting the challenge of the new problems**
  - * Particle identification accelerates the progress in the fight against the background
  - * Bad charge/light collection being addressed
  - * Improved understanding of basic detector physics
- **Steady improvements in WIMP sensitivity**
  - * Now: ~1 event/kg/day, at the edge of SUSY
  - * Moving towards ~1 event/kg/year
  - * Test of technolog(ies) for large arrays

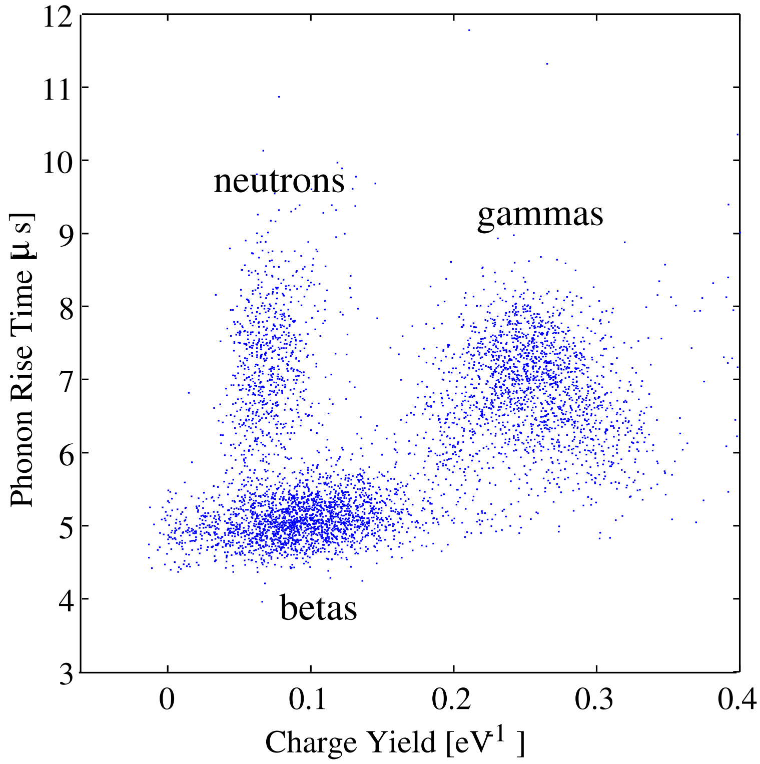
Surface events R&D

Active area of detector R&D to remove this potential limit.

Incomplete charge collection for surface events (mostly β) is observed to depend strongly on implantation scheme for electrodes (B, P implantation; Al vaporisation, presence of SI dead layer).

Bad charge collection of surface β can be tagged by faster risetime of (athermal) phonon signal

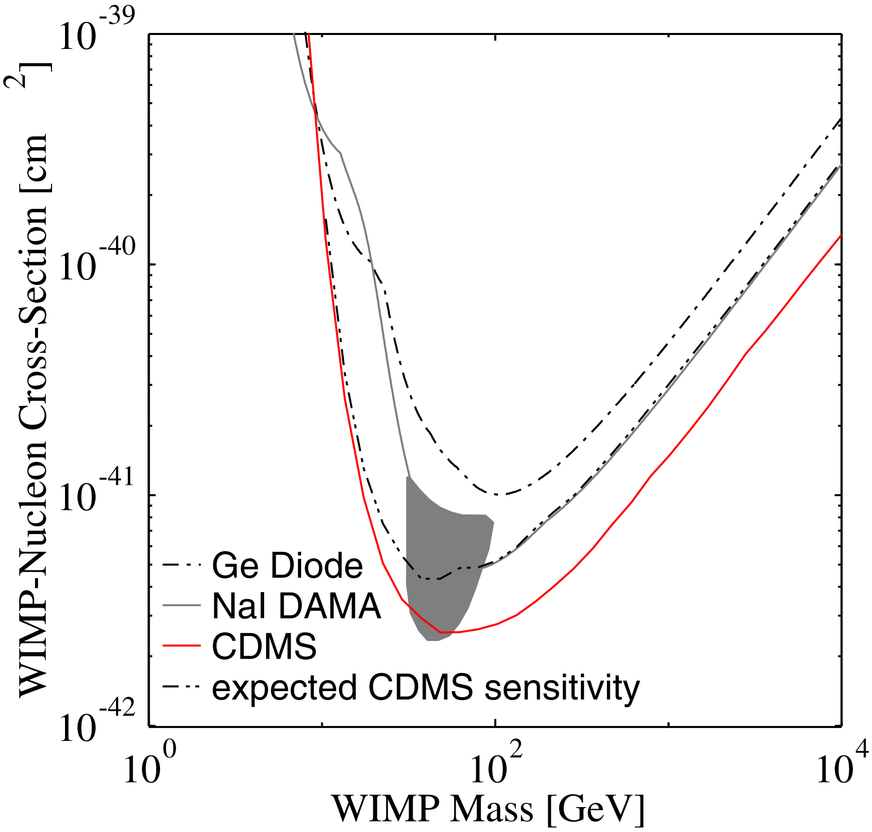
CDMS



Other R&D (Edelweiss) plans to discriminate against surface β using:

- **Amplitude of ballistic (fast) component in NbSi thin films**
- **Risetime of ionisation signal**

New CDMS limits



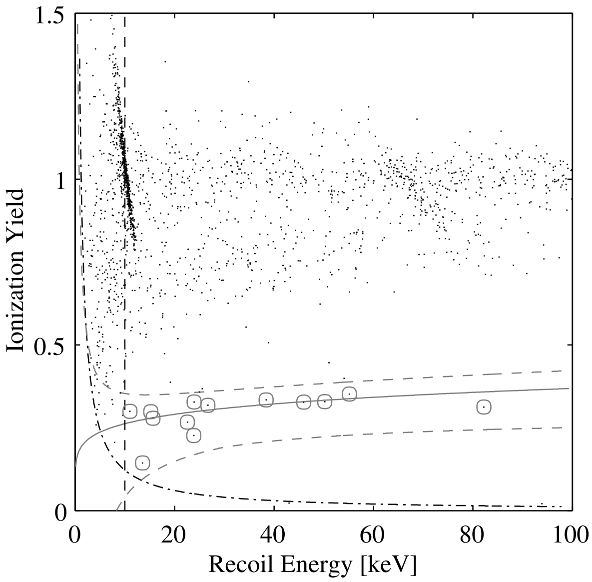
New CDMS limits incompatible with DAMA region

CDMS plans: increase statistics, and (June 2001) take data in SOUDAN mine

With increased statistics, the situation should become clearer.

CDMS

* Heat+ionis., still installed just below ground (μ veto).
* 3 X 165 g Ge and 1 X 100 g Si detector



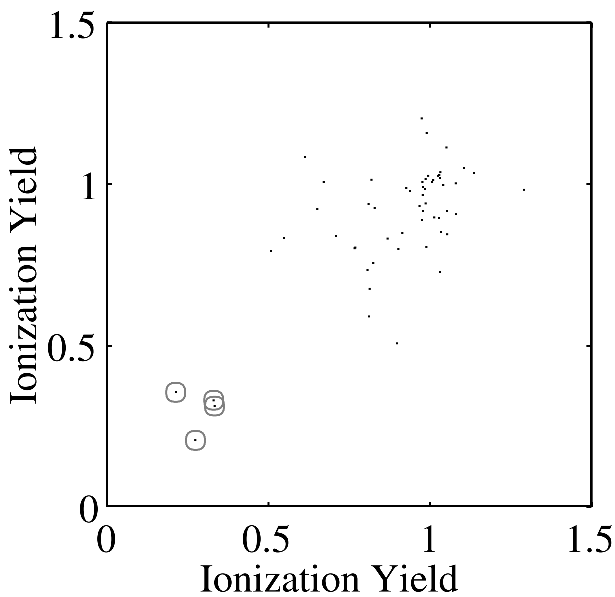
Total exposure 10.3 kg.d

Surface events:
* Guard electrode (reject ~50% of fiducial volume close to surface)
* amorphous Si deposit
* Ge shielding.

13 nuclear recoil events identified as (probably) neutrons:

* **shape of E_{recoil} spectra**
* **comparison of Ge / Si rates (n / WIMP ~ 12)**
* **comparison of single / double scatters**

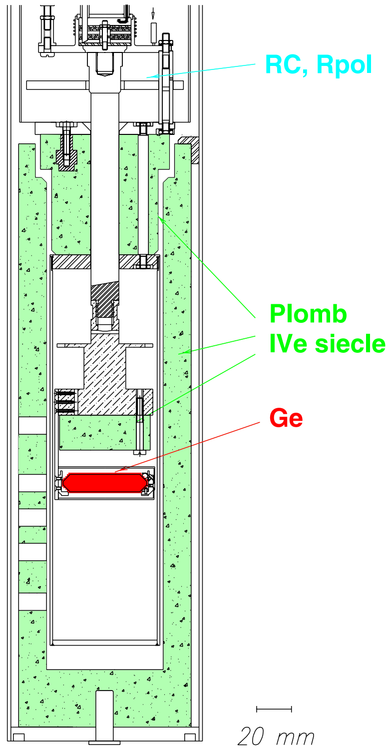
-> Subtract neutron background using maximum likelihood

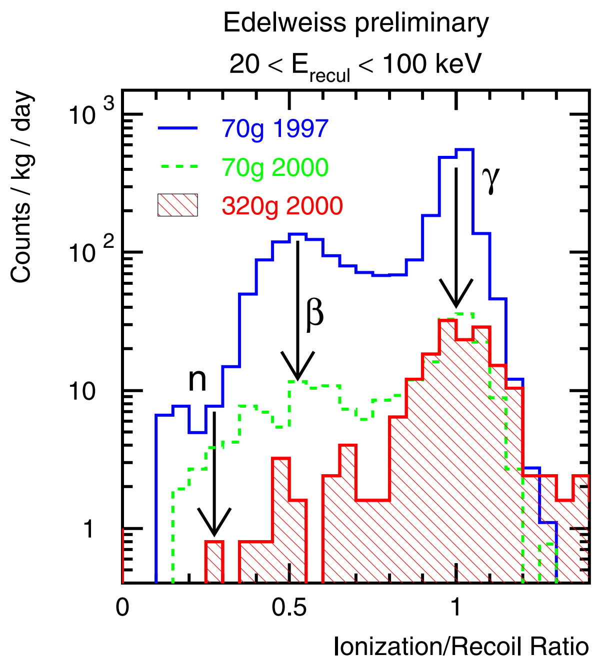


CDMS

Edelweiss Upgrades

- **Acoustical and electrical insulation**
- **Removable 30 cm paraffin shielding ($E_{neutron}$<10 MeV)**
- **Rigourous selection of material in the vicinity of the detector:**
  - **> Roman Lead shielding close to detector**
  - **> Front-end Electronics moved behind Roman lead shielding**
- **Nitrogen flushing against radon**
- **Test of new implantation scheme for the electrodes**





recent development:

First operation of 320 g detector

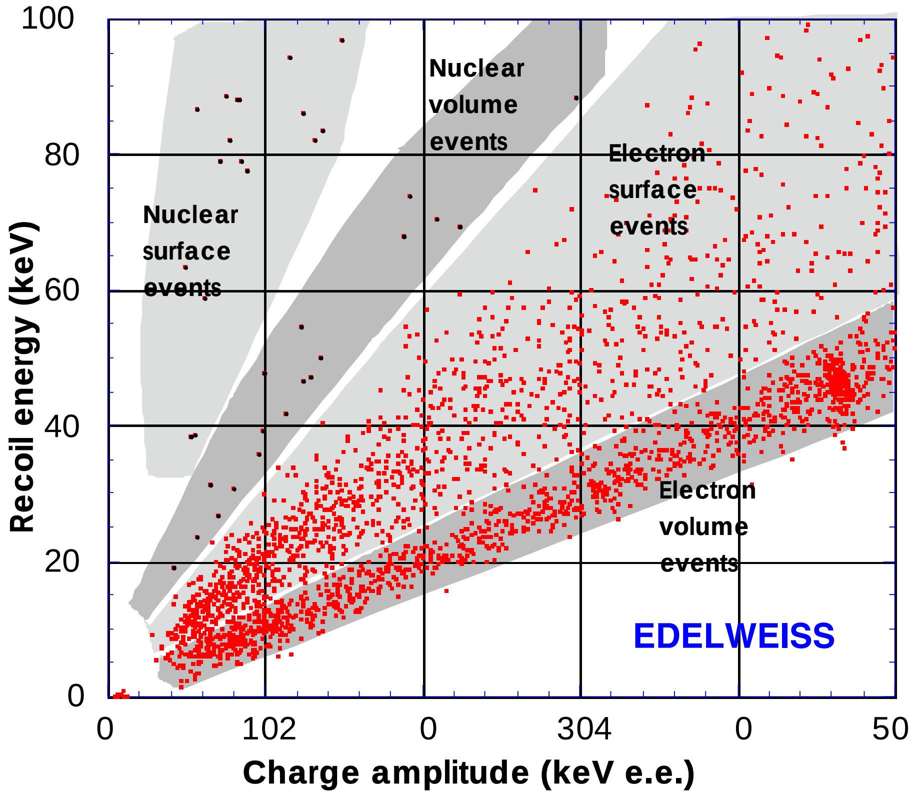
Improved volume/surface

Two-electrode detector to exclude most of the outer volume from fiducial volume

Steady improvements in background rates

Edelweiss results

* Underground (Frejus: 4 $\mu/m^2/d$, 0.4 $n/cm^2/d$).
* 70g Ge: nuclear recoils indentification (ionis. vs heat)
* Discrimination complicated by surface events (charge badly collected, may simulate nuclear recoil).
* Identifed an unsuspected population: nuclear surface events.



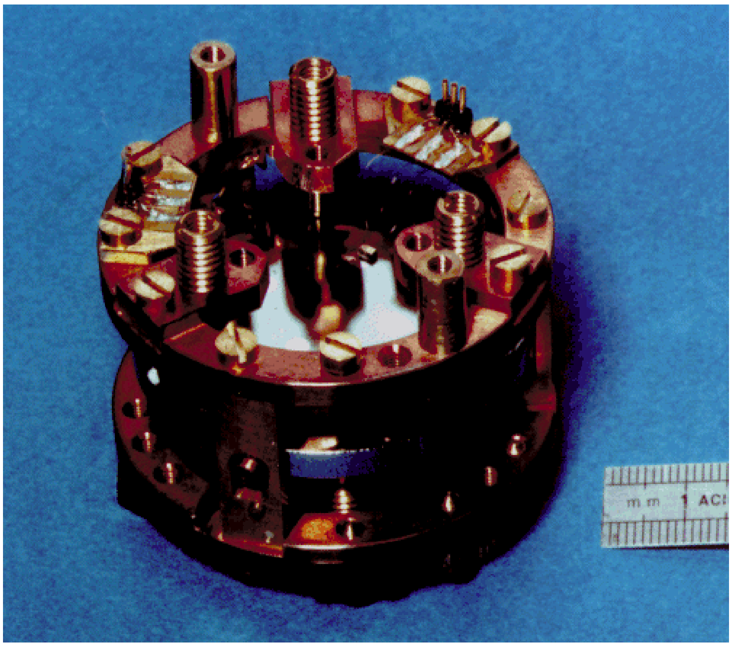
Progess in 1999: Overall Background reduced by ~10 (γ, neutron shielding, radiopurity). In 2000: 320 g detectors.

2001: Larger (100 l) cryostat, more (and more massive) detectors: Edelweiss-II.

The Edelweiss detectors

Ge4 (1997 data set): h = 8mm, Diameter = 48mm

70 g High-purity Ge crystal (here in its copper holder)



Ionisation measurement:

Electrodes by B and P implantation. p-i-n diode structure allows large fields (operated at 2-12 V)

~1 keV resolution FWHM for Eγ=122 keV.

Heat measurement:

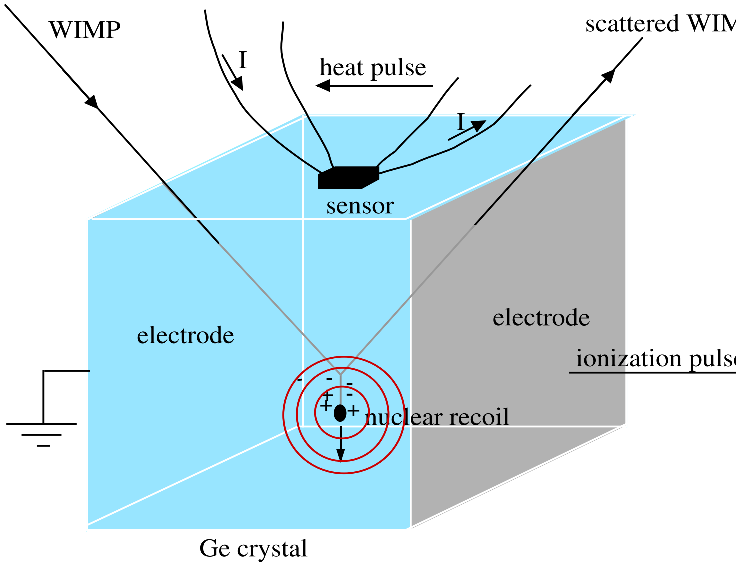
Neutron Transmutation Doped Ge Thermistor glued to the detector. Base temperature of the cryostat: 10-18 mK.

Heat signal: ΔT ~0.1 μK/keV -> ΔV ~0.2 μV/keV

~1 keV resolution FWHM for Eγ=122 keV.

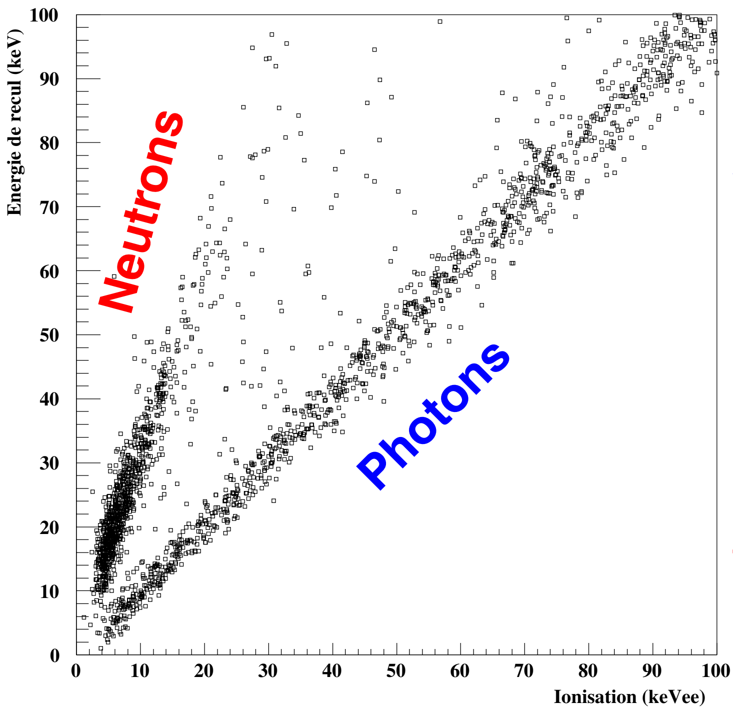
Heat-and-Ionisation Ge detectors

Ratio of ionisation/heat signal differs for nuclear recoils (<<1μm) and electron recoils (>>1μm, larger ionisation yield).



Direct measurement of recoil energy (Luke-Neganov effect):

Heat = Recoil + (V/3) Ionisation



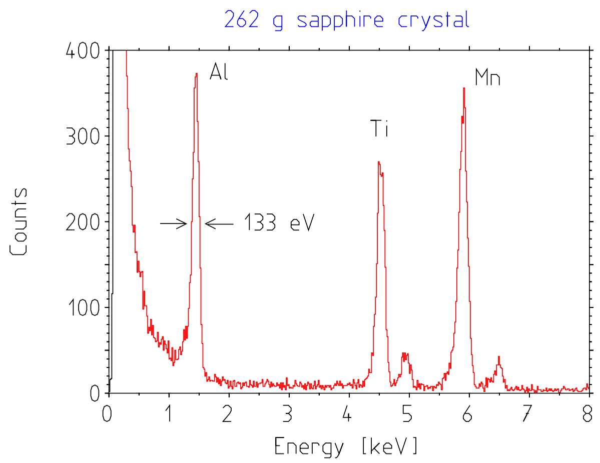
Recoil energy vs ionisation energy (Edelweiss 1997) with neutron and γ sources

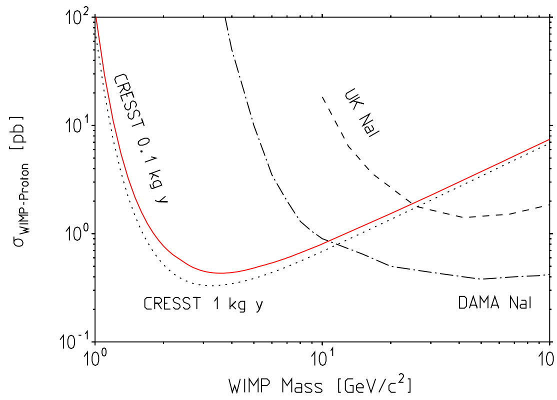
Nuclear recoils produce ~3.5 times less ionisation than photons (electron recoils)

Rejection > 99%

CRESST

* Currently use heat-only detectors, 4 x 262 g sapphire detectors
* E_{recoil} threshold: 500 eV, resolution 150 eV.
* Test low-mass region (1-10 GeV).



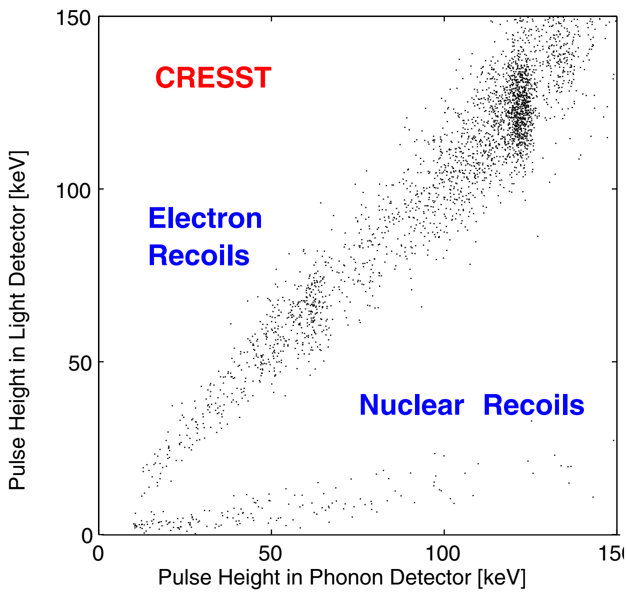


Developing heat-scintillation $CaWO_4$ detectors.

Light collected in an absorber detected with low-temperature thermometer

Results from a 6 g prototype

300 g under study



The advantages of bolometers

- **Measure directly the recoil energy, instead of (quenched) ionisation or scintillation yield**
- **Excellent energy resolution and low threshold achievable.**
- **Wide variety of target material (A,spin,radiopurity)**

Heat-only detectors: CRESST, CUORE, ROSEBUD

- **Event-by-event identification of nuclear recoils...**

... combining heat with ionisation or scintillation measurement. Achieving >99% rejection of (dominant) γ and β background, ~100 g detector competes with ~10 kg Ge or NaI.

Heat + Scintillation:

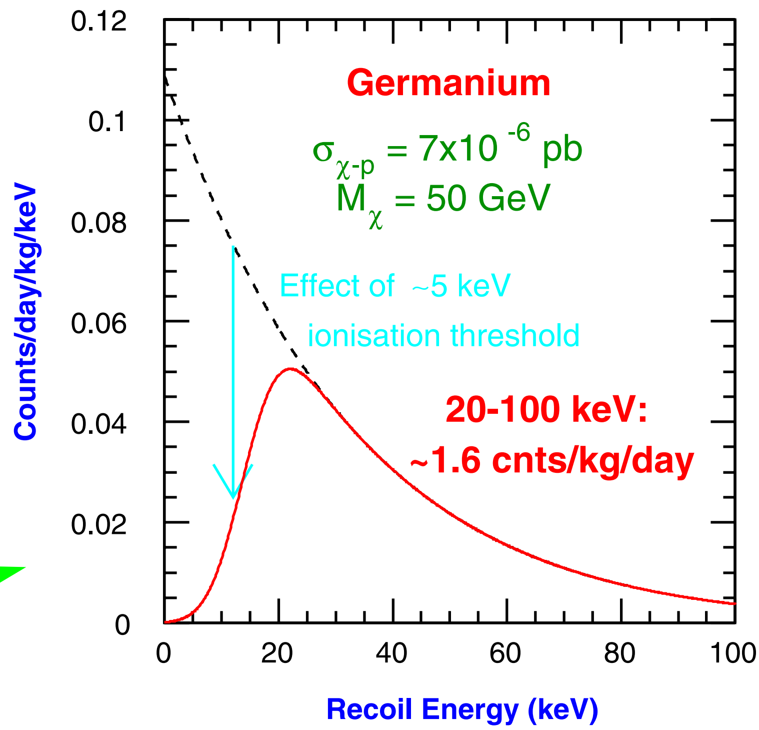
CRESST ($CaWO_4$)

Heat + Ionisation:

CDMS (Ge,Si),

EDELWEISS (Ge)

Simulated recoil signal in a Ge detector



Genius

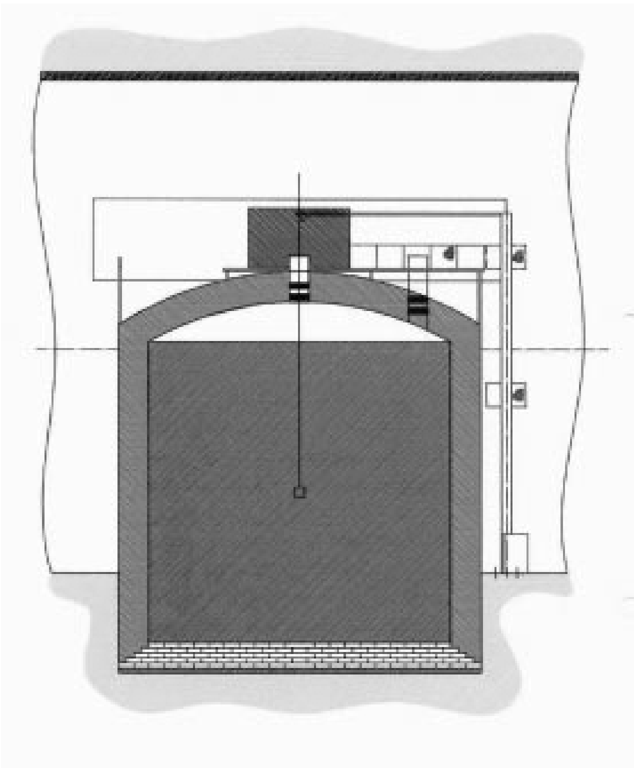
The ultimate all-Ge experiment?

*** large mass of Ge (100 kg Genino first stage) as self-shielding (Ge is extremely radiopure),**

*** surrounded by liquid Nitrogen (another material easy to purify) tank 12m x 12 m:**

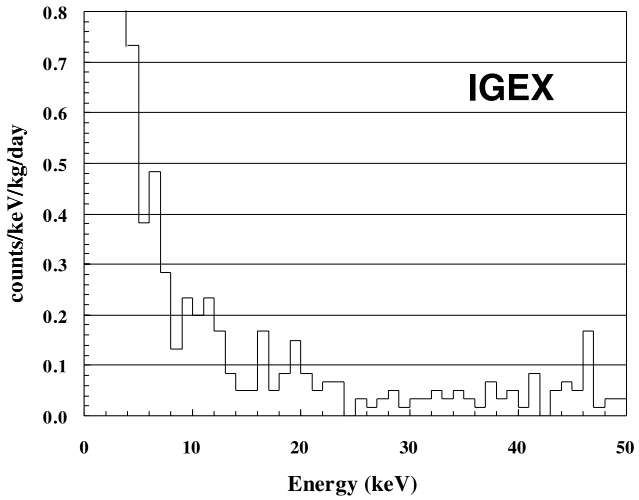
*** and almost nothing else (...kevlar wire suspension)!**

Proposal for Gran Sasso Genino, 5m x 5m tank:

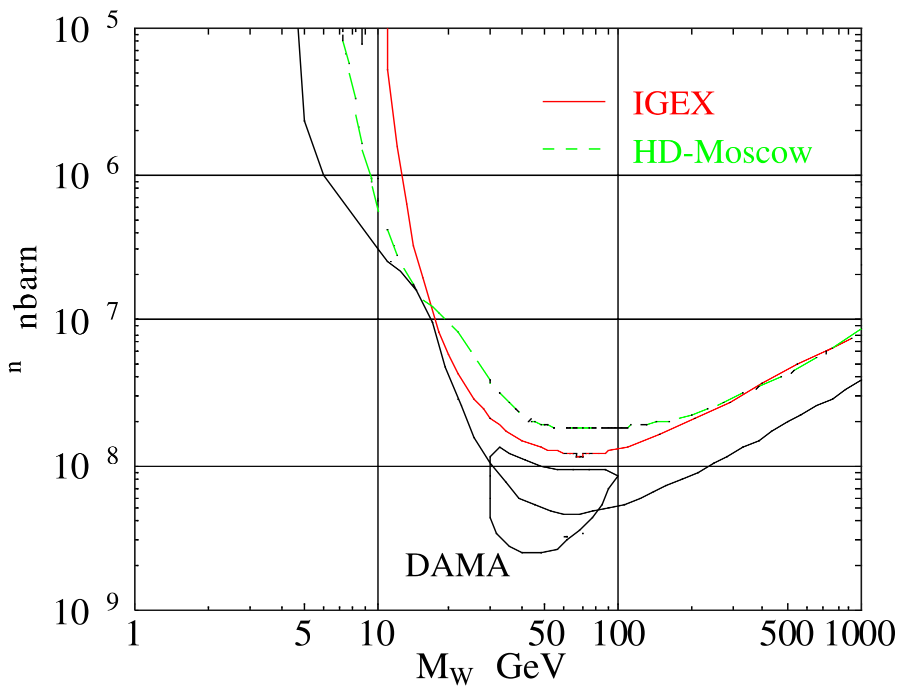


Ge experiments

HD-Moscow (hep-ex/9811045), IGEX(hep-ex/0002053)



Count rate below ~0.04 /kg/day, but not below ~9 keV (recoil ~30 keV)



Other NaI experiments

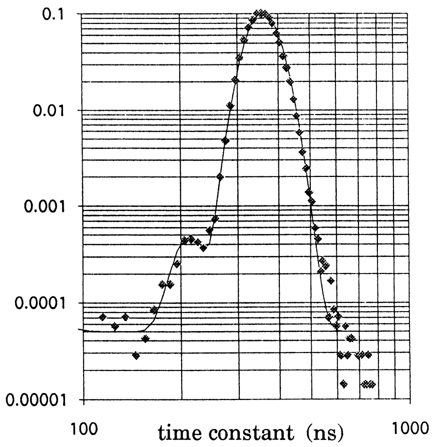
ELEGANT:

* use annual modulation: 2133 kg.d so far (1/30 DAMA), ~5 evt/kg/d around 5 keV.
* Also: inelastic collision on ^{127}I (recoil + 57.6 keV)

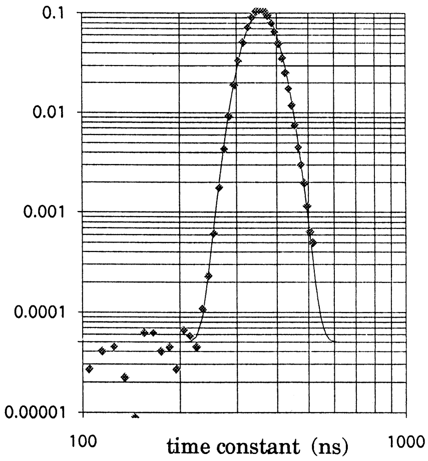
DAMA-0, UKDMC, Saclay-Lyon:

* statistical discrimination using time constant of scintillation pulses

Limitation: pulse shape discrimination on low-energy pulses



UKDMC, Saclay: unknown population with too short time constant to be nuclear recoil. Simple separation nuclear vs electronic recoils does not work.



DAMA: annual modulation

New data with 100 kg NaI array: 57986 kg.d in total since NaI-0

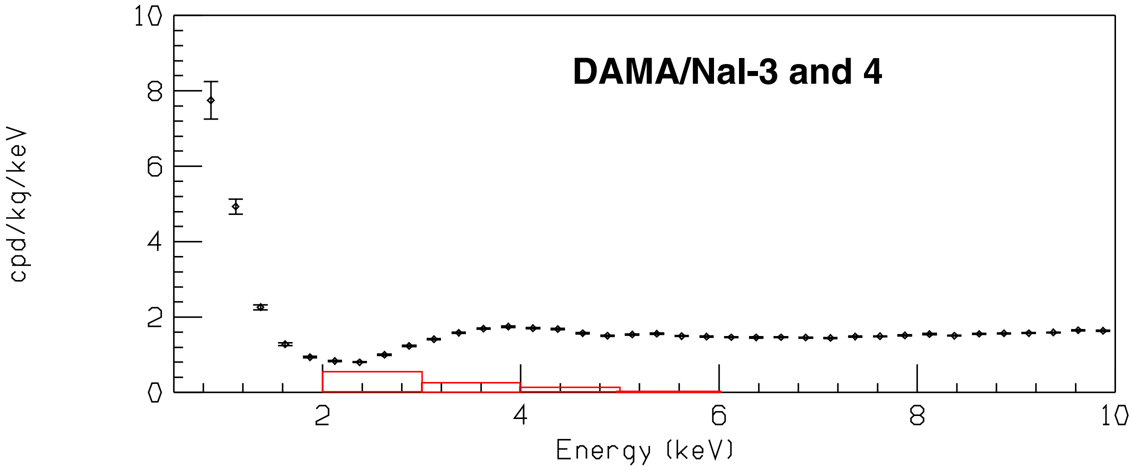
Assume background has no time dependence.

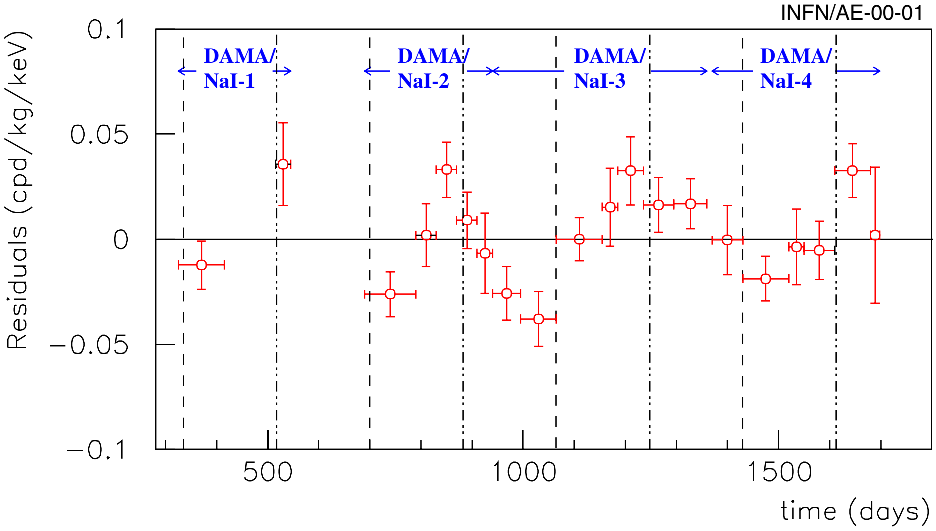
Finds $M_{WIMP} = 52^{+10}_{-8}$ GeV,

$\sigma_{WIMP\text{-}n} = 7.2^{+0.4}_{-0.9}\ 10^{-6}$ pb

at 4 σ C.L.

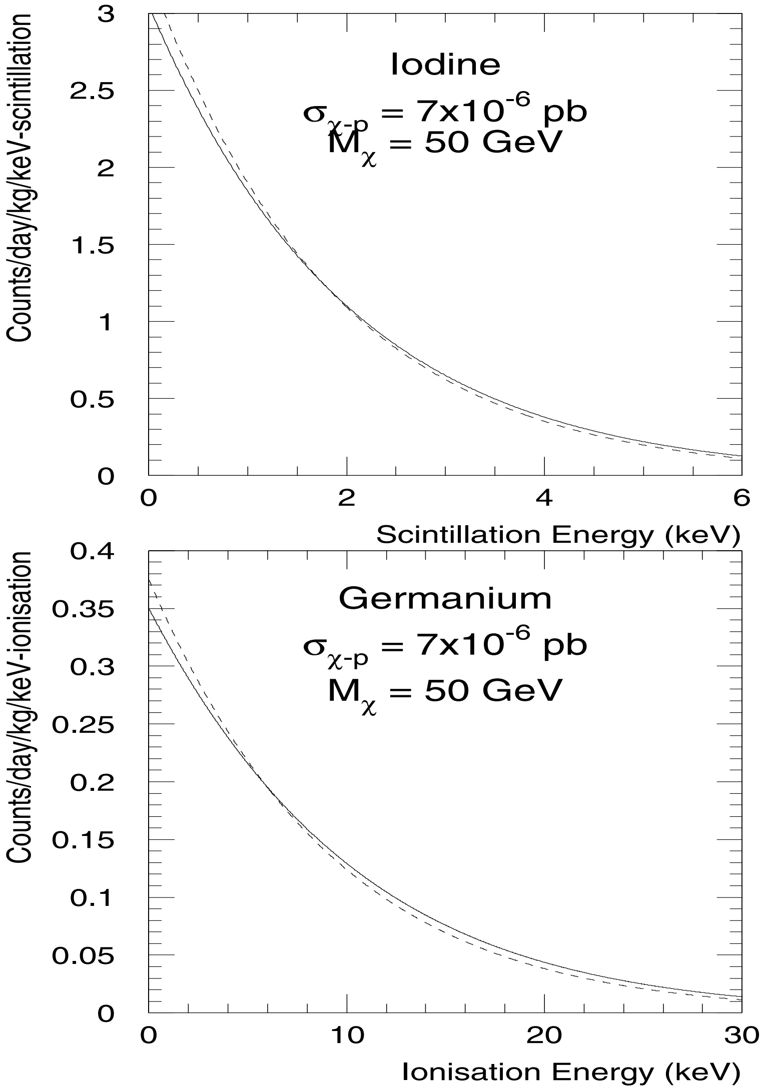
~ 0.5 counts/kg/day/keV in 2-3 keV $E_{scintillation}$ bin





Annual Modulation

$V_{EARTH} \sim 220 + 15 \cos [2\pi(\text{day - June},2^{nd})/365]$ km/s



Small (5-10%) effect on rate, slope of recoil distribution

Need large statistics

Modulation of background?

Different strategies...

1) Go to largest possible mass, using "standard" detectors (Ge, NaI). Best bounds: IGEX, HD-M, DAMA. To remove background

* go to even larger, self-shielding volume (GENIUS)
* or use statistical discrimination using annual modulation (DAMA, ELEGANT),
* or pulse shape discrimination (UKDMC, Saclay+Lyon)

2) Go to lowest possible threshold (explore low-mass, non-MSSM, WIMPS): heat measurement (CRESST, ROSEBUD, CUORE).

3) Develop event-by-event discrimination of nuclear/electronic recoils (gain in discrimination to compensate lack of mass),

* Heat and Ionisation (CDMS, EDELWEISS). Best bounds: CDMS, with ~1/5000 of DAMA exposure in kg.d.
* Heat and scintillation (CRESST)
* Superheated Droplets (SIMPLE, PICASSO)
* Scintillating grains (CASPAR)
* Scintillation lifetime in Liquid Xe (ZEPLIN-I)
* Superfluid 3He (MACHe3)

... and when technology is ready, go to large volume!

4) Directional sensitivity: reconstruct ionisation tracks (dE/dx, length) in low-pressure Ar/Xe TPC (DRIFT)

Removing the Background

Electronic recoils (Photons, electrons): **Dominating background**

- **Radiopurity**
- **Lead (+Cu) shielding**
- **Measure heat AND ionisation (CDMS,Edelweiss), or heat and scintillation (CRESST); event-by-event rejection.**
- **Detector sensitive only to large energy deposition in small volume (CaF2 grains, Superheated Droplet).**

Nuclear recoils from neutrons

- **Light-A shielding**
- **Coincidence between detectors (neutron interaction length ~ few cm)**
- **Compare rates in detectors with different A's**
  ($\sigma_{WIMP} \sim A^4$, $\sigma_{neutron} \sim A^{2/3}$)
- **Other concern: nuclear recoils from surface contamination?**

Cosmic-ray induced background (source of neutrons)

- **Underground site**
- **Coincidence with muon detector**

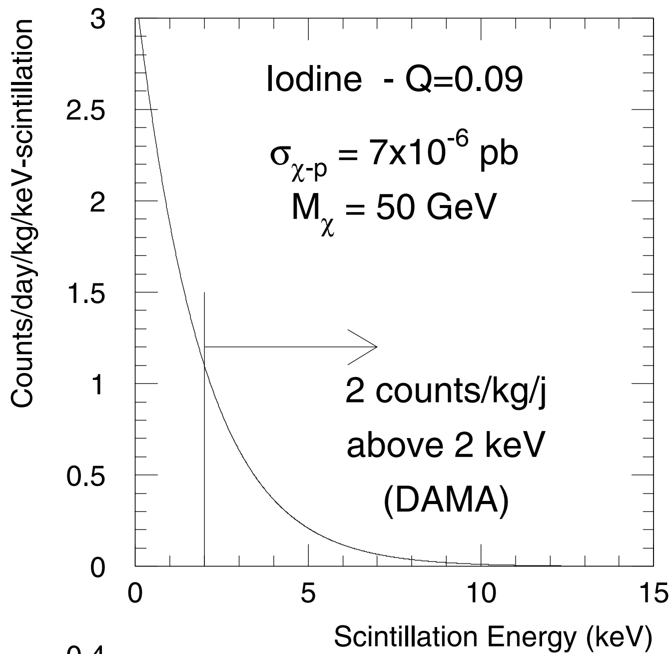
Annual Modulation (see DAMA)

WARNING: low background = tail of distributions
-> dealing with "exceptional" events: detector physics!

Quenching, Threshold, etc...

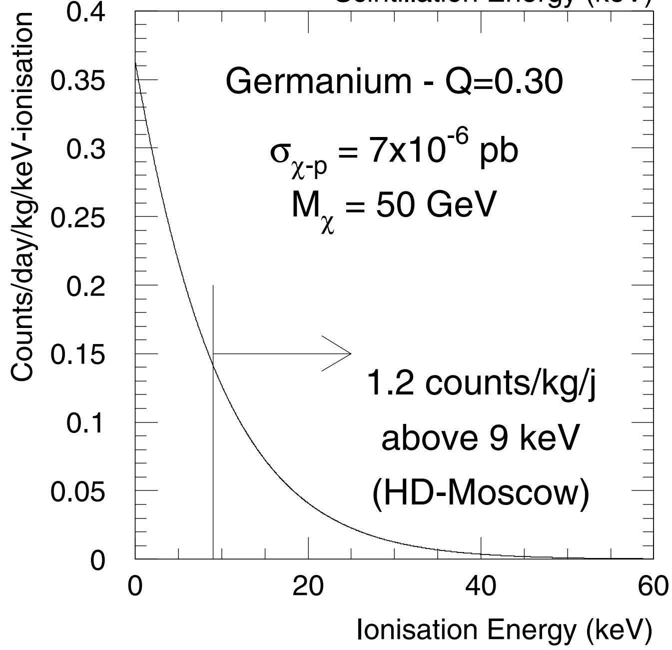
Comparison between experiments not trivial

Scintillation



Resolution ~5 keV
FWHM at 6 keV

Ionisation



Resolution ~2 keV
FWHM at 0 keV

2 c/kg/day above 5 keV

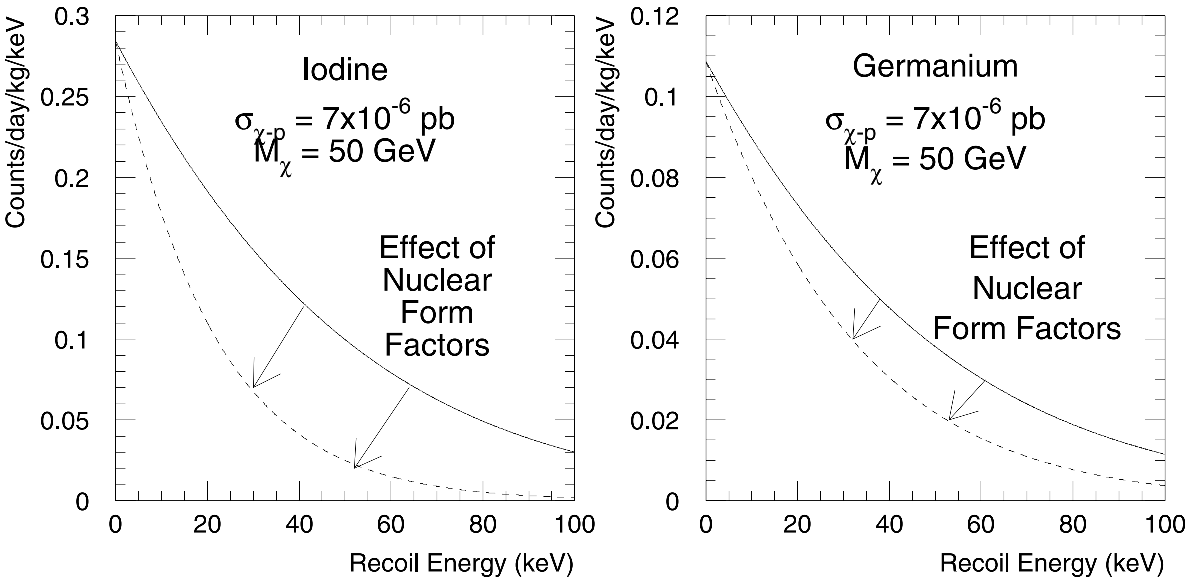
Form factors, ...

When wavelength of the momentum transfer comparable to nuclear radius:

$$\sigma \to \sigma F^2(q)$$

coherent scattering: $F^2(q) \sim \exp(-(qr/h)^2/5)$

Example: coherent scattering, ~gaussian distribution

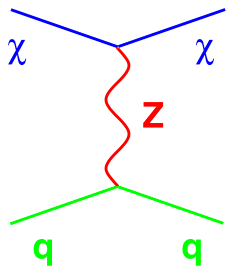


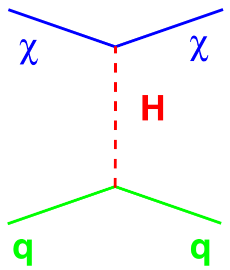
Counts / kg / day for $\sigma_{\chi\text{-}n} = 7\times10^{-6}$ pb

M_χ (GeV)	10	50	100
in Ge	2	3	2
in Iodine	5	6	4

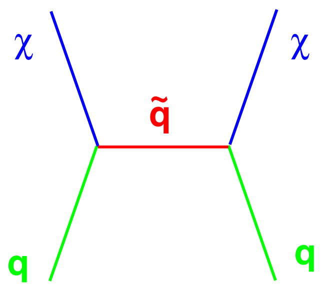
Temperates slightly A-dependence of rates

Cross-section





Neutralino interact with nuclear matter via Higgs, squarks and Z exchange.



For massive nuclei, the axial-axial part (prop. to the spin of the nucleus) can be neglected, the scalar-scalar part dominates (coherent scattering).

Relation between the wimp-nucleon and wimp-nucleus cross-sections (nucleus of atomic mass A, reduced mass μ):

$$\sigma_{\chi\text{-}A} = \sigma_{\chi\text{-}n} \, (A \, \mu(\chi,A))^2 / (\mu(n,A))^2$$

In the case of Ge, Iodine: factor ~ x10^5 on rates: MSSM favors large A detectors

Counts / kg / day for $\sigma_{\chi\text{-}n} = 7\times10^{-6}$ pb

Mχ (GeV)	10	50	100
in Ge	3	5	4
in Iodine	5	13	14

Note: MSSM cross-sections may be 10,000 smaller!

Recoil distributions

let's assume:

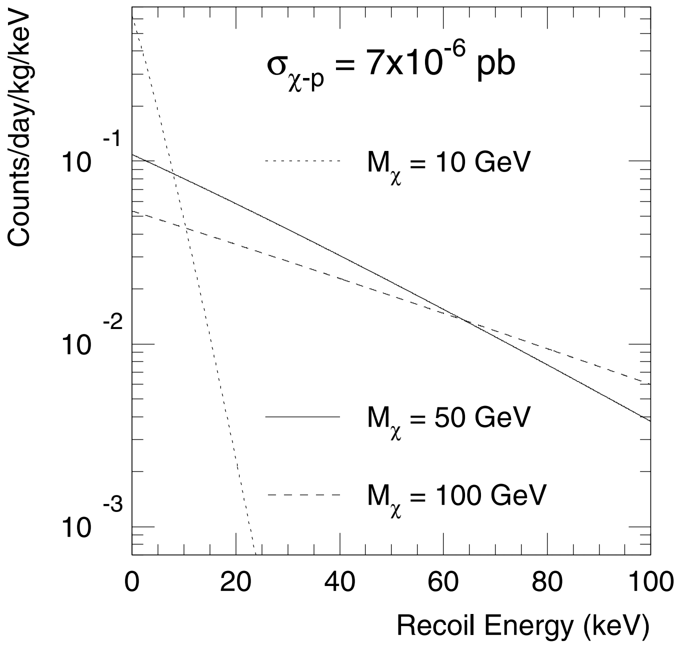
ρ_{DM} in our neighbourhood = 0.3 GeV/cm^3 (uniform)

Maxwellian velocity distribution $<v_{WIMP}>$ = 220 km/s

v_{SUN} = 220 km/s

-> Average WIMP kinetic energy, for M_{WIMP}=50 GeV: ~29 keV

Resulting recoil spectrum (in Ge): ~exponential



Average Recoil Energy in Ge

M_χ (GeV)	10	50	100
$<E_R>$ (keV)	4	29	43

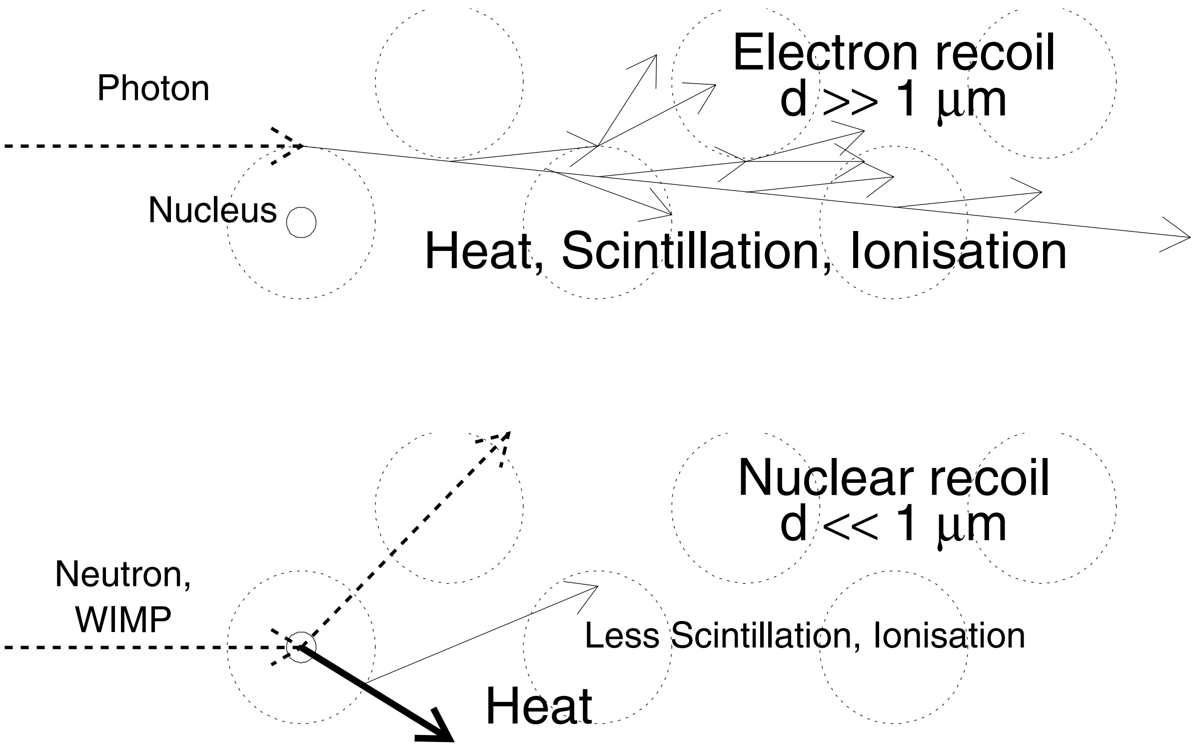
A WIMP collision

The kinetic energy of the nuclear recoil depends on:

* the WIMP mass
* the WIMP velocity (0 to +- ~500 km/s, avg. ~ 250 km/s)
* the vector sum of the sun's (220 km/s) and earth's velocities (30 km/s, at 60^{o} angle)
* the mass of the target nucleus

All of this energy is converted to heat;

* some of it (="Quenching factor") can be observed as scintillation or ionisation



The Case for WIMP Dark Matter

Astrophysics:

Rotation curves of galaxies, velocity distributions of clusters: large quantities of non-luminous mass. In our vicinity, $\rho \sim 0.3$ GeV/cm^3.

Cosmology: $\Omega = \rho/\rho_c$, $\rho_c \sim 10^{-5}$ GeV/cm^3.

Strong limits on total baryon density in universe (Ω_b~0.05). Structure formation requires large quantities of Cold Dark Matter -> heavy particle, decoupling from ordinary matter and radiation at early times:

$$\Omega_{CDM} \sim 0.3,\ \sigma_{annihilation} \sim 10^{-37}\ \text{cm}^2$$

Particle physics:

Weakly interacting particle a good candidate. Observation in laboratory of nuclear recoils from collisions with galactic halo WIMPs possible. Supersymmetry provides a natural candidate: the LSP neutralino.

The case for neutralino dark matter:

Other candidates exists (axions, axinos and more exotic...) however:

- **Predictions for rates (<1 event/kg/day or <1 /kg/year, or less...)**
- **Comparisons between target nucleus**
- **Comparison between direct and indirect (cosmic rays and neutrino observatories) searches.**
- **LEP constraint on neutralino mass (>32 GeV/c^2)**

Direct search of WIMP Dark Matter with bolometers

Direct Search: observing nuclear recoils induced by collisions with Weakly Interacting Massive Particles from the galactic halo.

- **What WIMPS are**
- **Their experimental signature**
- **Non-bolometric searches**
  - DAMA: NaI
  - Heidelberg-Moscow, GENIUS: Ge
- **Bolometer experiments**
  - Heat (ex.: CRESST)
  - Heat and scintillation (ex.: CRESST)
  - Heat and ionisation (EDELWEISS and CDMS)
- **Prospects**
- **Conclusions**