Direct Dark Matter Searches

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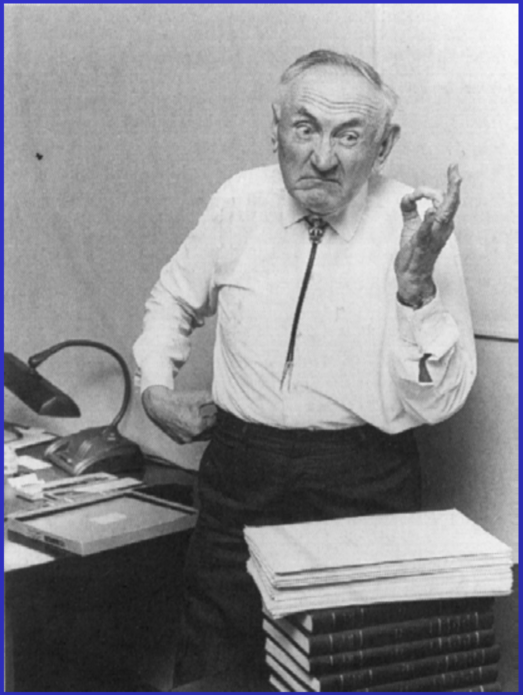


discovered in 1933

by Fritz Zwicky

Dark matter

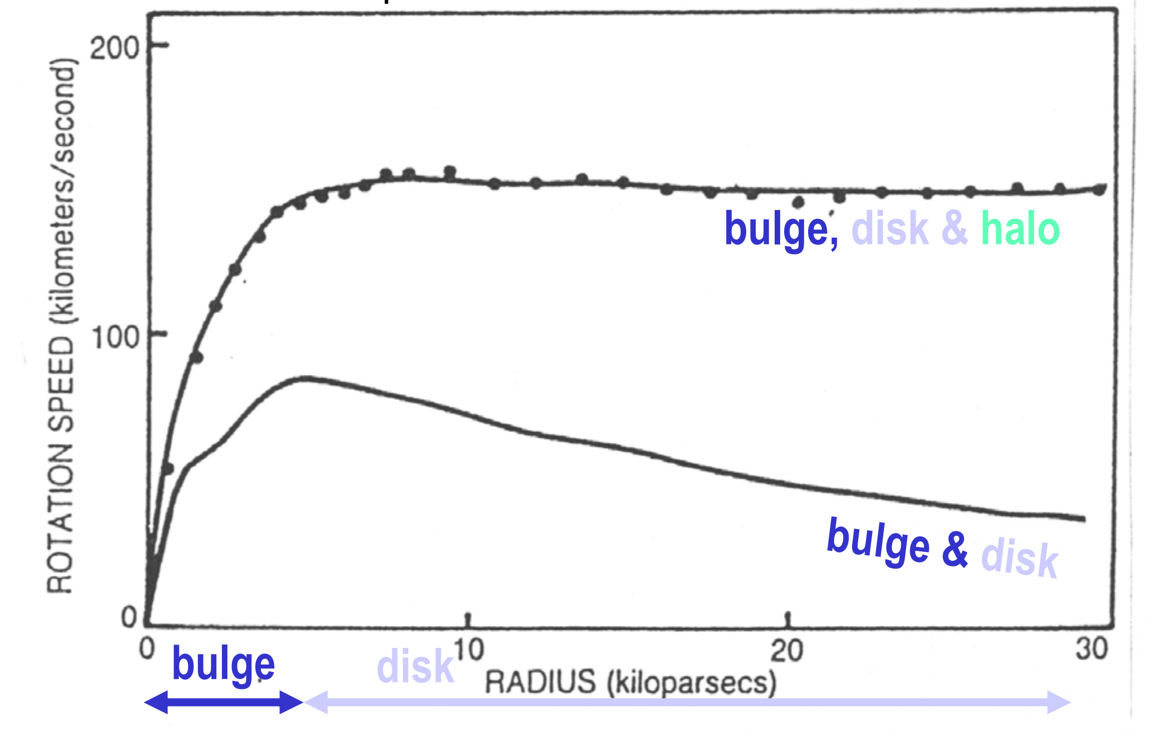
shows up by its gravitation

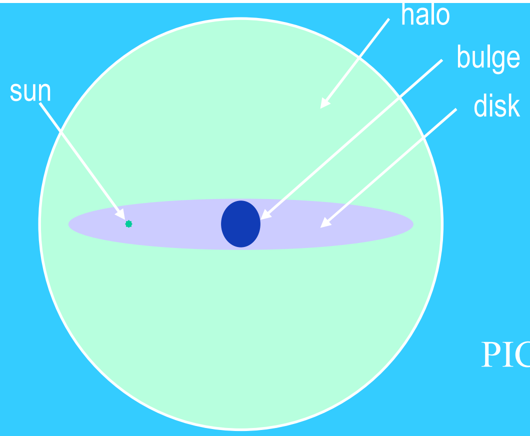
and does not emit or absorb electromagnetic radiation

favoured candidate: WIMP

Dynamical Evidence: Galactic Halos

Galaxies – 10-100 kpc





$$F_{\text{centripetal}} = F_{\text{gravity}}$$

$$\frac{mV_r^2}{r} = \frac{GmM_{\text{total}}(r)}{r^2}$$

$$\Rightarrow \quad V_r = \sqrt{\frac{GM_{\text{total}}(r)}{r}}$$

$$\rho_{\text{dark}}(r) \propto \frac{1}{1 + (r/r_c)^2}$$

$$\Omega_{\text{dark}} \geq 10\Omega_{\text{stars}}$$

Density : 0.3 GeV /cm^3

Velocity: 270 Km/s

WIMP mass: GeV

How to detect them?

Indirect methods

Looking for annihilation products : → in space : GLAST, AMS, ...
→ on Earth : Amanda, Antares, Nestor, HESS, HEAT, SuperK, MAGIC...

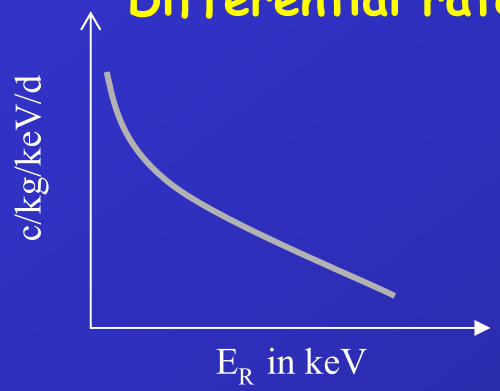
Direct detection

Elastic scattering of WIMPs at nuclei

Signal: nuclear recoil (some 10 keV)

Rates and Energy Spectrum

Differential rate :



Exponentially shaped recoil spectrum

Particle physics

$$\frac{dR}{dE_R} = N_T \frac{\sigma \rho}{2\, m_N\, m_W} F^2(E_R) \int \frac{f(v)}{v}\, dv$$

Detector properties

Astrophysics

Nuclear physics

Depending on its composition, neutralinos can have
spin dependent and/or spin independent interactions

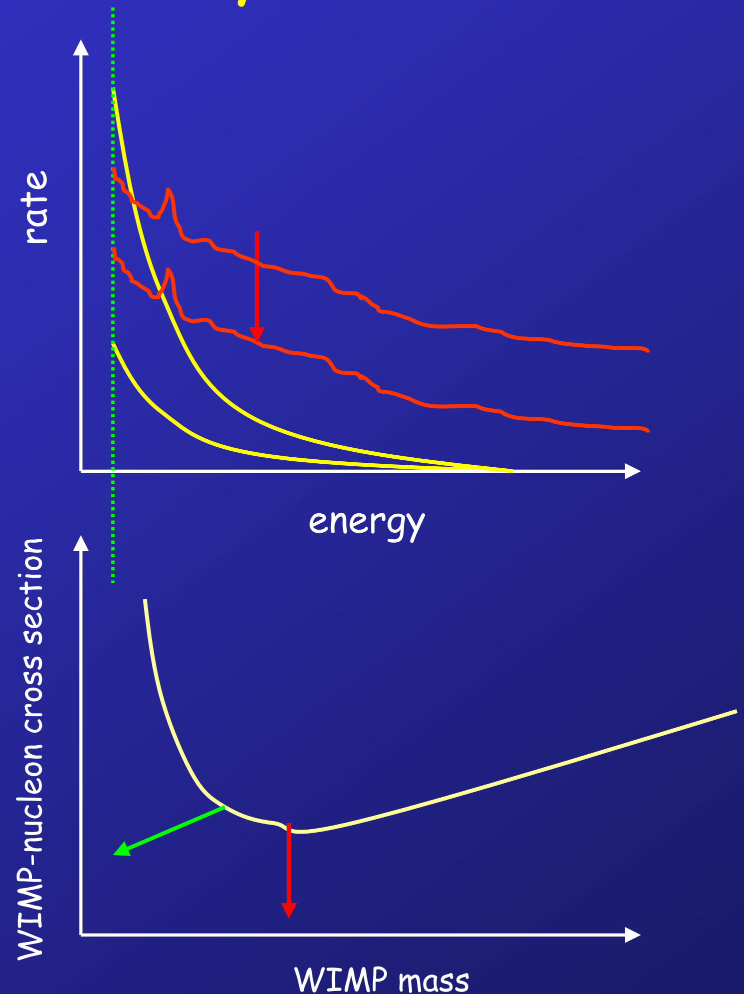
$\sigma_{sd} \propto \lambda^2\ J(J+1)$ spin dependent (favoures nuclei with spin) F, Al

$\sigma_{sid} \propto A^2$ spin independent (favoures heavy nuclei) Ge, I, W

Sensitivity

In reality one has background

Sensitivity is given by
the maximum amount of
WIMP contribution which is
compatible with the measured spectrum



Exclusion plot

Influence of detector properties

Energy threshold

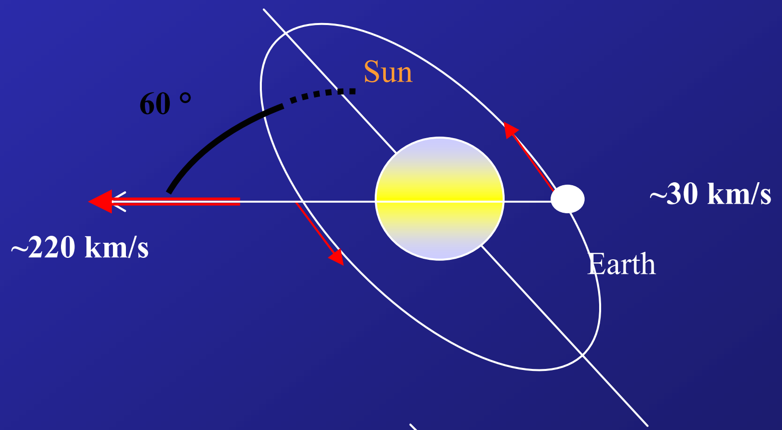
Background

How to Identify a WIMP Signal ?

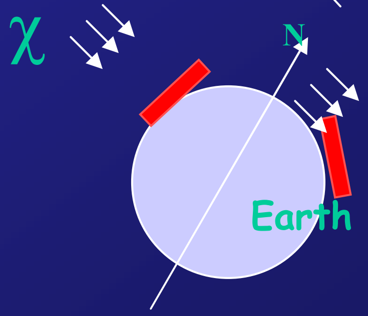
Shape of the recoil spectrum

Dependence of recoil spectrum on target nucleus (spin and mass)

Annual variation of rate and spectrum



Diurnal variation in directionality

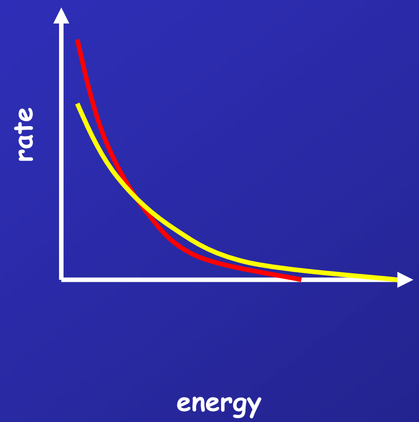


How to use the annual modulation

Look for modulation of rate

control of systematic errors
monitoring of the detector stability
very good understanding of the background

Look for modulation of rate and spectral shape



good E-resolution
low threshold
low background

Combine with use of different target nuclei

What is the Background ?

Photons and electrons coming from radioactive impurities in the detector and ist surrounding

Neutrons from surrounding

Detector specific „imperfections“

Background is everything !!

Shield well (underground, lead, copper, PE)

work cleanly

discriminate

Detector mass has to follow background

Experimental demands

Low background

Low threshold

Different target nuclei

Reasonable energy resolution

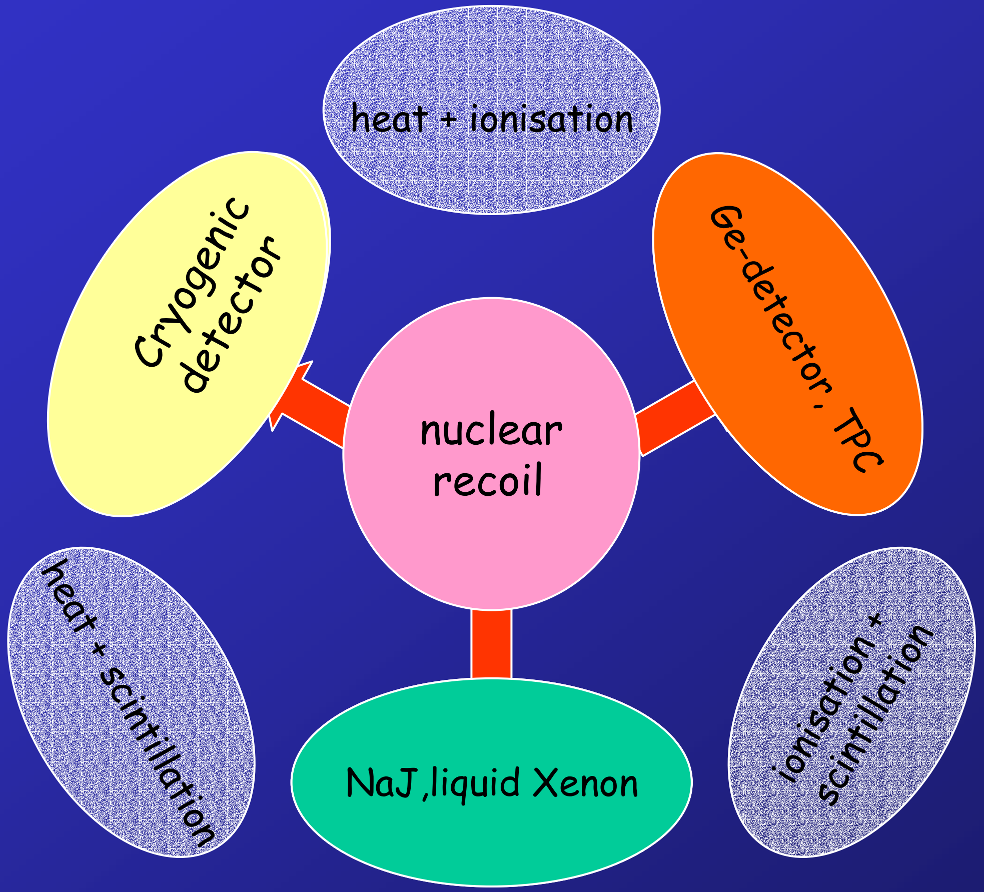
Long term stability

Continuous monitoring of detector sensitivity and trigger efficiency

Dark matter search is the physics of the first bin

Detector Types

For good photon and electron background suppression combine different detection channels



Ge-Detectors

The classical low background detector

Used to look for neutrinoless ββ- decay

Quenching factor Q =4

$$Q = \text{Signal}_{\text{Photon}} / \text{Signal}_{\text{Recoil}}$$

Standart technology

Can be made very clean

Recoils spectrum squeezed by a factor Q

Final limitation will be intrinsic impurities

Threshold has to be low enough to see recoils

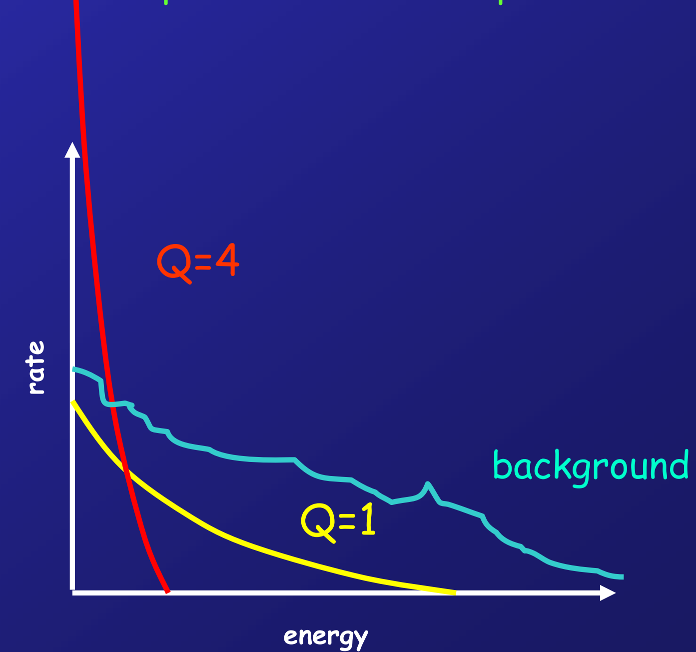
Signal to background ratio improved by factor Q

Experiments:

Spectral information reduced by factor Q

Heidelberg-Moscow, HDMS, COSME, IGEX.....

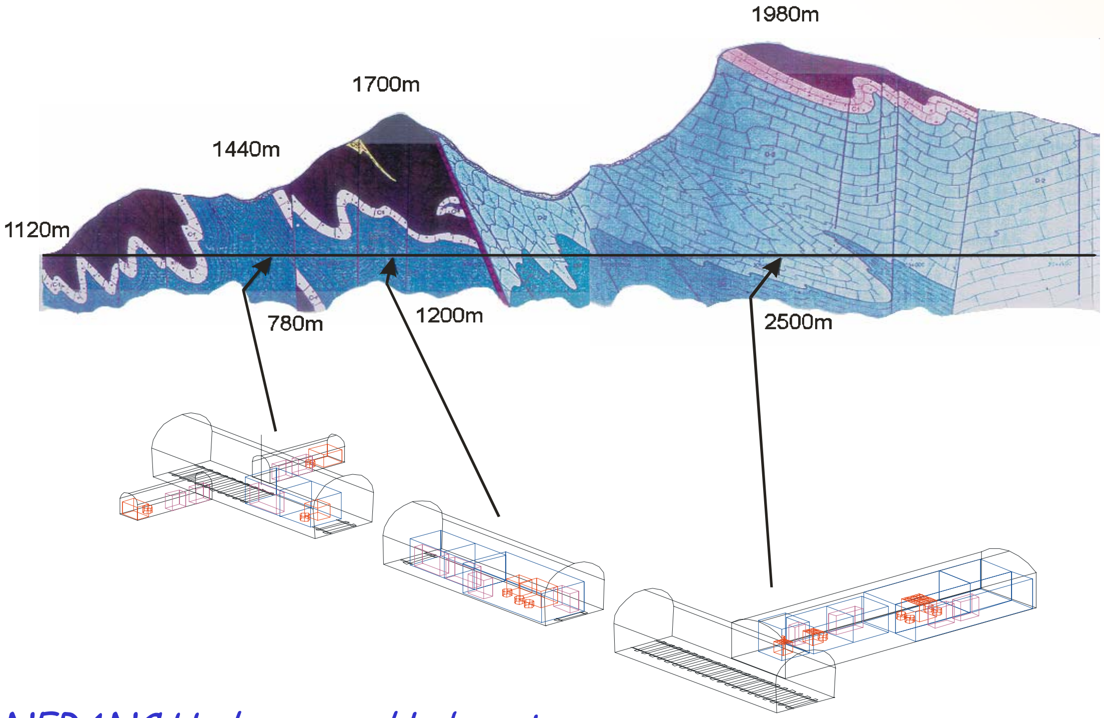
For example: in Ge a 40keV recoil shows up at 10 keV in the spectrum



IGEX-DM EXPERIMENT

IGEX detectors:

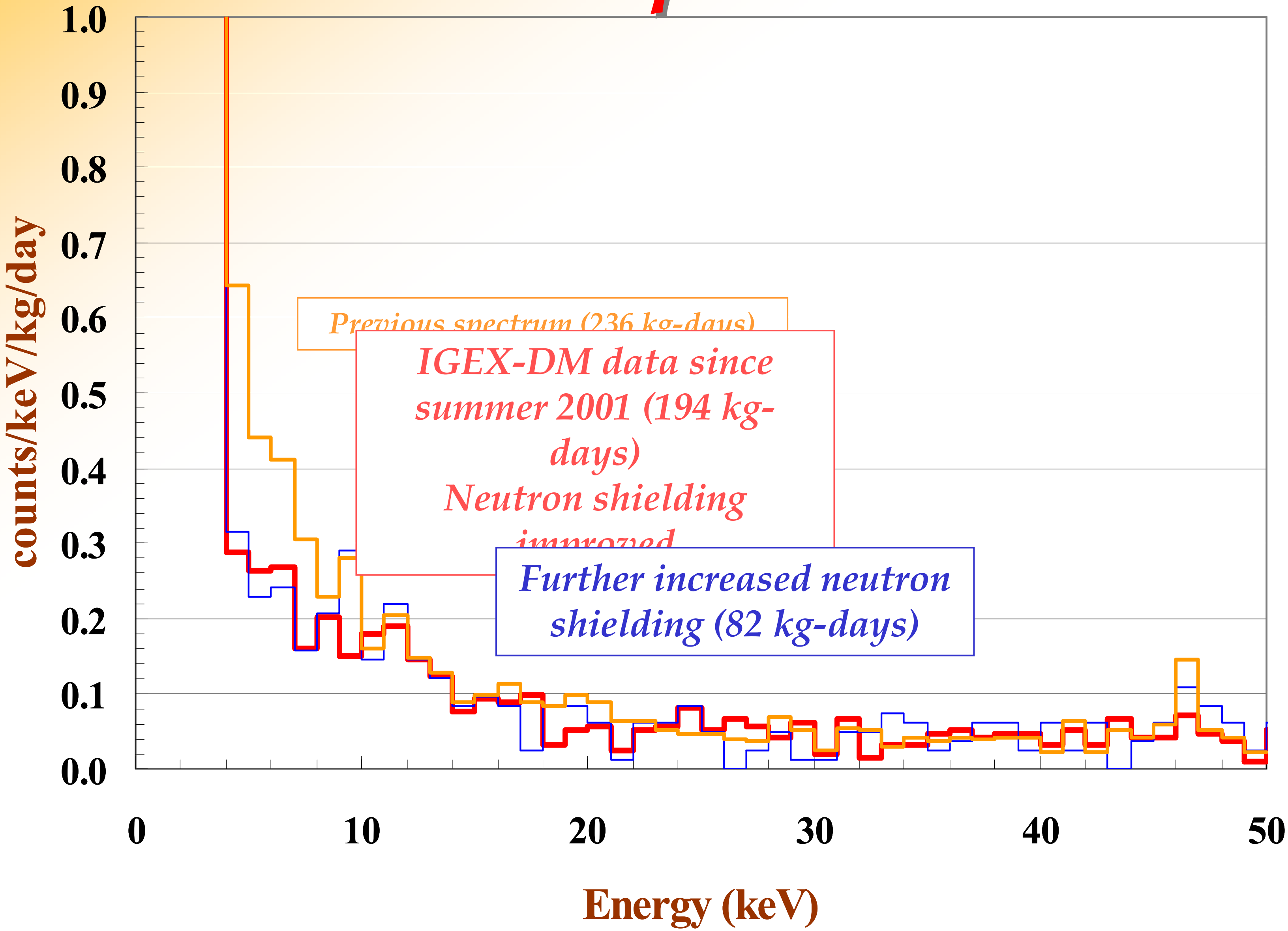
3 germanium detectors of 2 kg total mass each, enriched to 86% in ^{76}Ge.



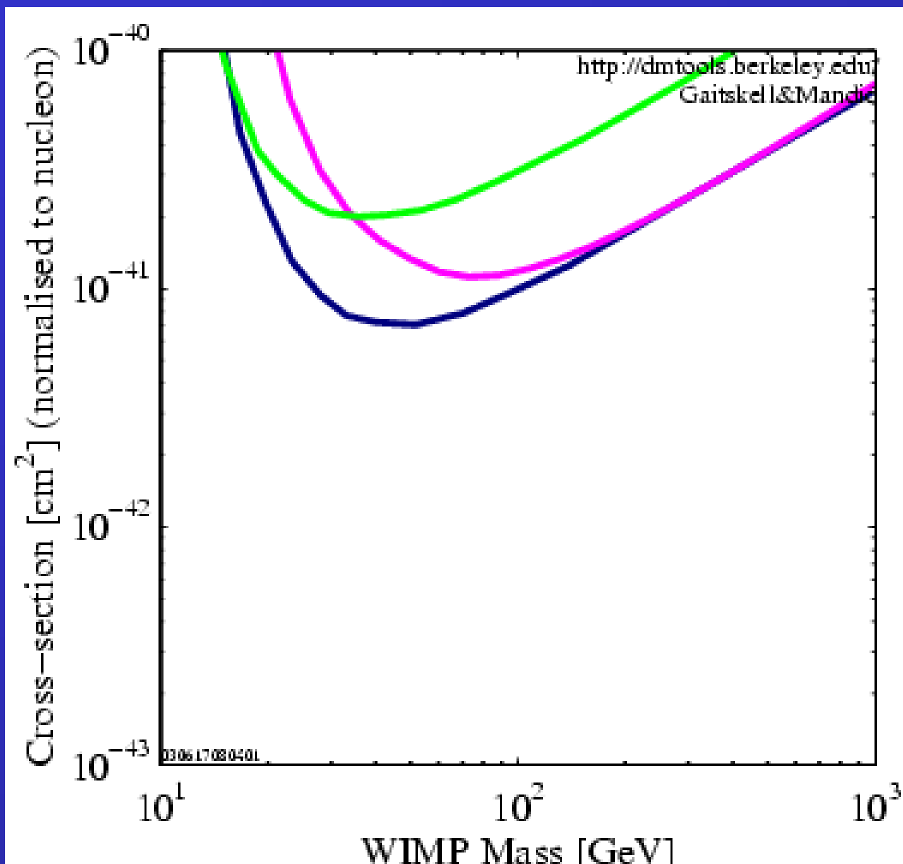
CANFRANC Underground Laboratory

One IGEX detector opened in clean atmosphere

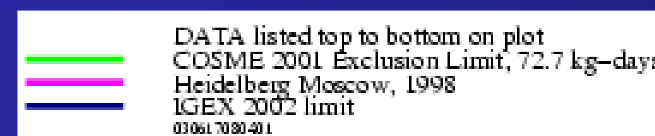
IGEX-DM last spectra



Ge-Limits

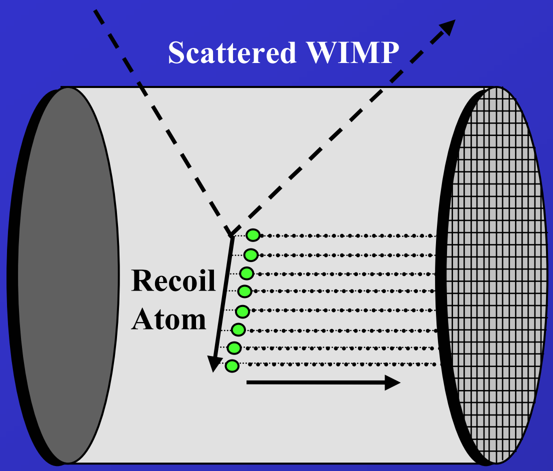


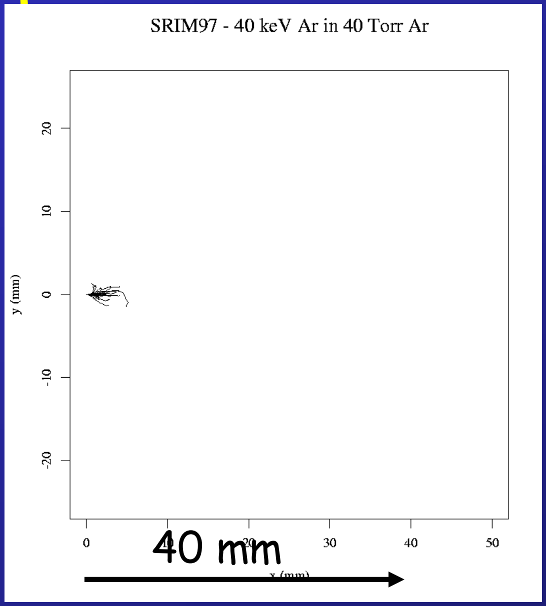
http://dmtools.berkeley.edu/
Gaitskell&Mandic
Cross-section [cm^2] (normalised to nucleon)
WIMP Mass [GeV]
10^-40
10^-41
10^-42
10^-43
10^1
10^2
10^3

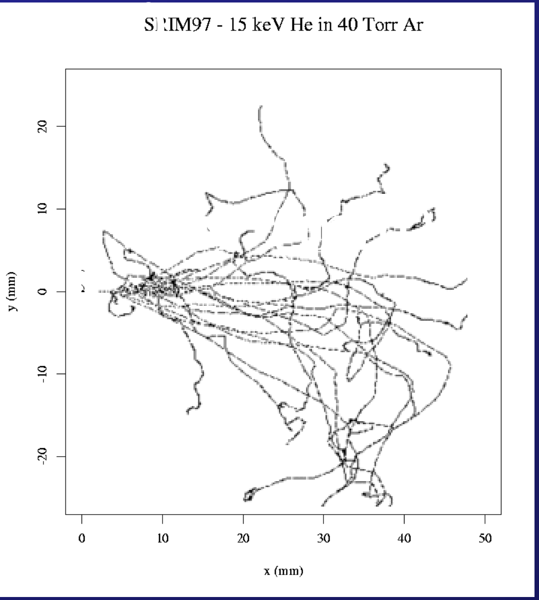


DATA listed top to bottom on plot
COSME 2001 Exclusion Limit, 72.7 kg-days
Heidelberg Moscow, 1998
IGEX 2002 limit
030617080401

UKDM
Directional: DRIFT







Sensitive to direction of recoiling nucleus

Diurnal modulation signal

Electron recoils rejected via dE/dx

DRIFT I

Cubic meter in Boulby since 2001

Engineering runs completed

DRIFT II extension to 10 kg module proposed

Scintillation Detectors
NaJ

Iodine as heavy target nucleus   A=127

Q = 11

low threshold needed

well known and available technique

„bad" spectral resolution

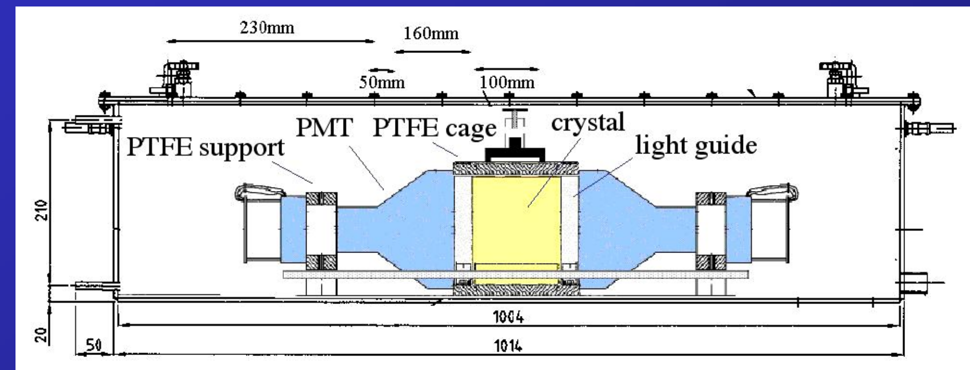
Pulse shape discrimination possible ?!

Experiments:

DAMA, UKDM-NaIAD, ELEGANT V

NaIAD

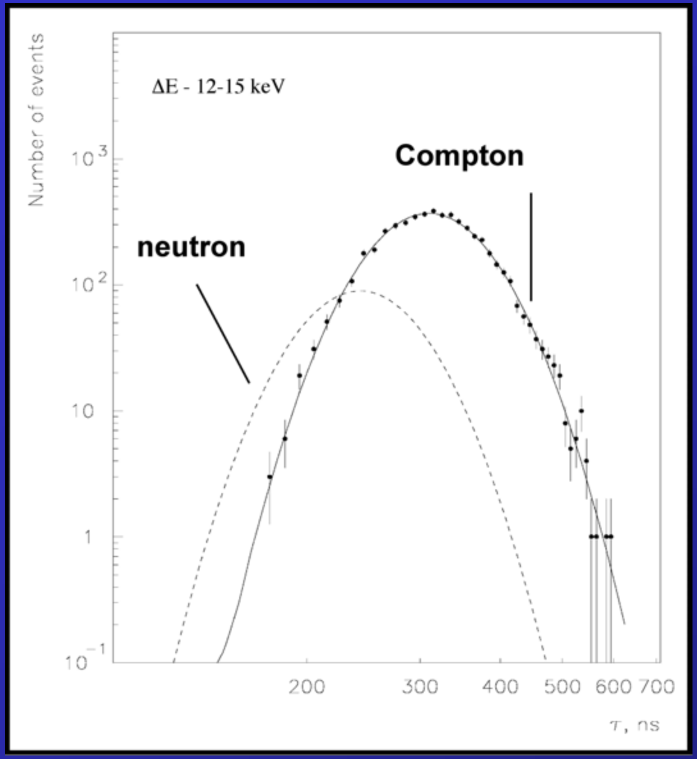
UK –Dark Matter
Collaboration
Located at Boulby

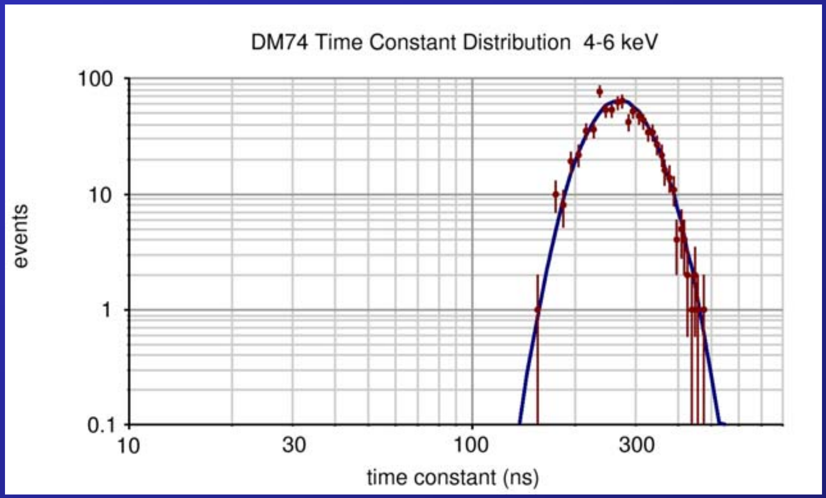


- NaIAD: 8 NaI(Tl) crystals totalling 65kg, pulse shape discrimination
  - –6 unencapsulated, 2 encapsulated
  - –Light yield 5 - 9 p.e./keV, temperature stabilised to 0.1˚C
- Unencapsulated crystals
  - –Removal of fast anomalous events (radon induced low energy alphas)
  - –Operated in dry nitrogen, 1cm PTFE cage, quartz light guides

Statistical pulse shape discrimination

Nuclear recoil pulses have a slightly faster decay time





Fit time distribution spectrum of data with Time distribution spectrum of background and see how much nuclear recoils can be hidden in the statistics.

Sensitive points of this analysis

Systematics

How does one know the decay time distribution of the background?

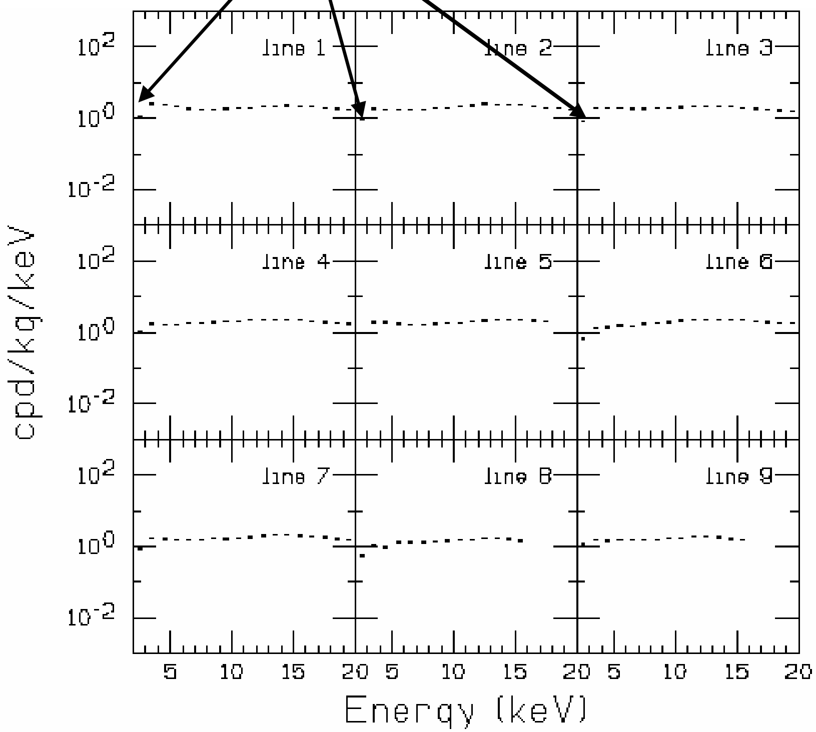
Decay time distributions may differ for different background components!

This type of an analysis is an implicit background subtraction.
One has to understand the background extremely well if one wants to subtract it

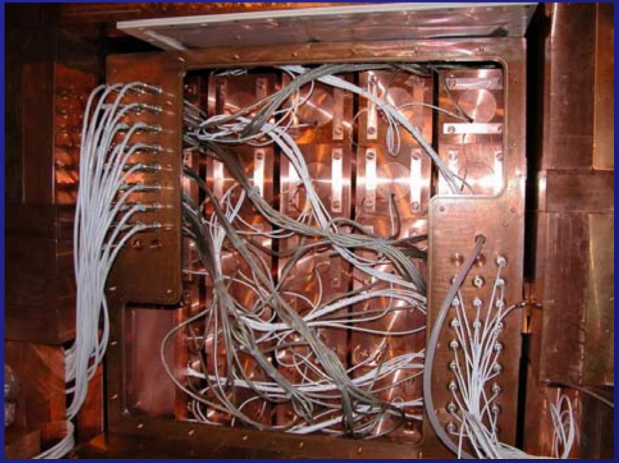
DAMA

100 kg NaI with extremely low threshold of 2 keV

First bin is most important for sensitivity

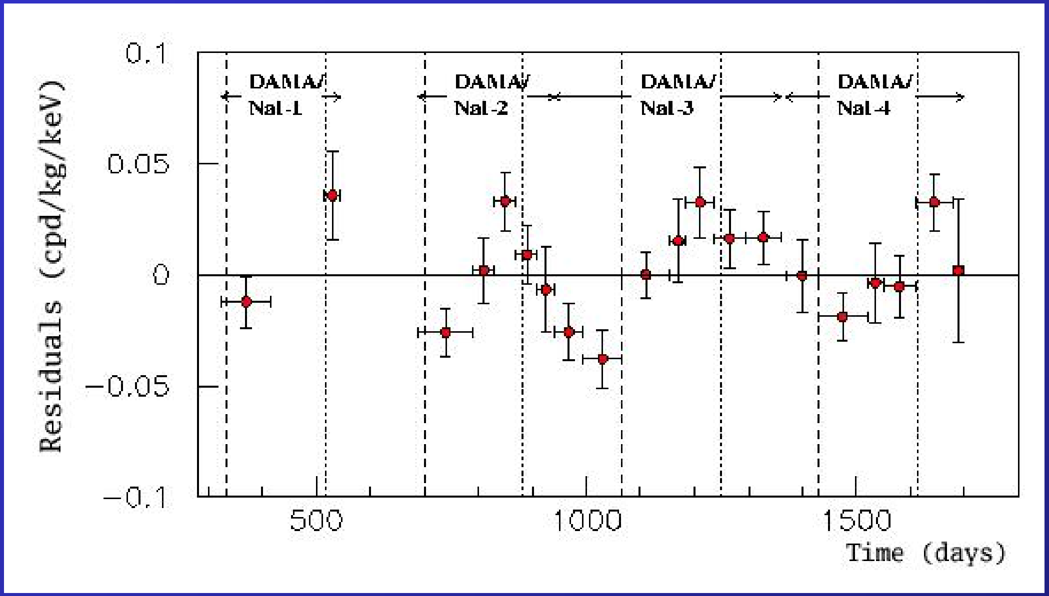


tributions measured by the 9 detectors in the prese
sual the data have been already corrected for the n
nge is shown for the detectors on lines 5,8,9 to c



DAMA-Evidence

evidence for WIMPs in galactic halo by annual modulation signature

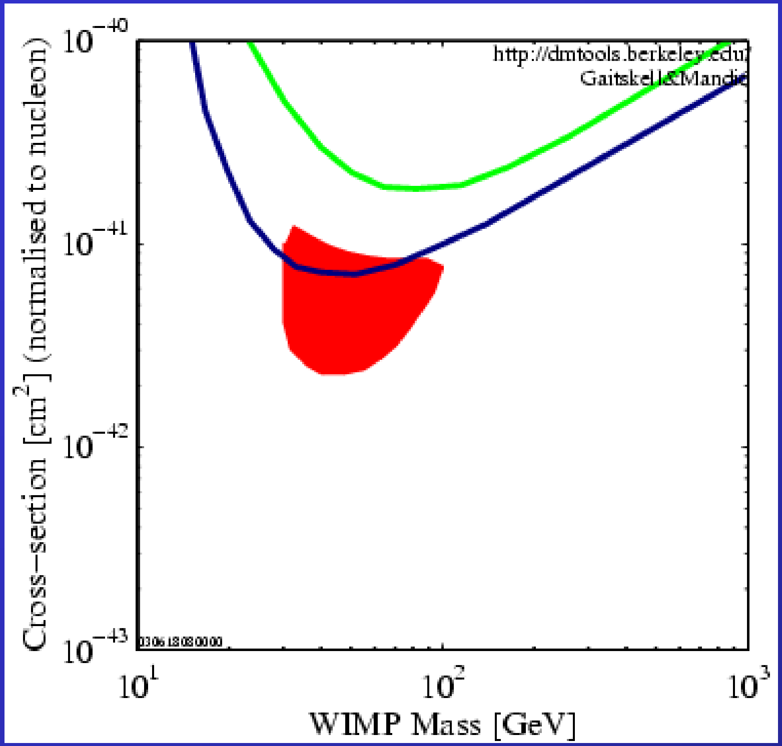


Systematics:

Detector stability

„background stability"

About 60000 kg d of data



http://dmtools.berkeley.edu/
Gaitskell&Mandic
Cross−section [cm^2] (normalised to nucleon)
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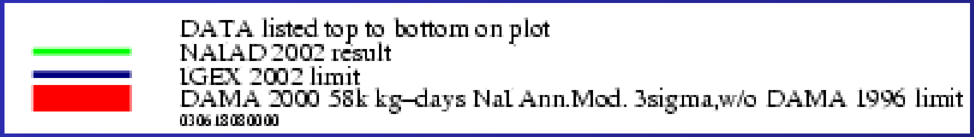


DATA listed top to bottom on plot
NAIAD 2002 result
IGEX 2002 limit
DAMA 2000 58k kg-days NaI Ann.Mod. 3sigma,w/o DAMA 1996 limit
030618080000

Scintillation Detectors
Liquid Xenon

Heavy target nucleus A = 131

Q = 2-3

Pulse shape discrimination (background suppression on statistical basis)

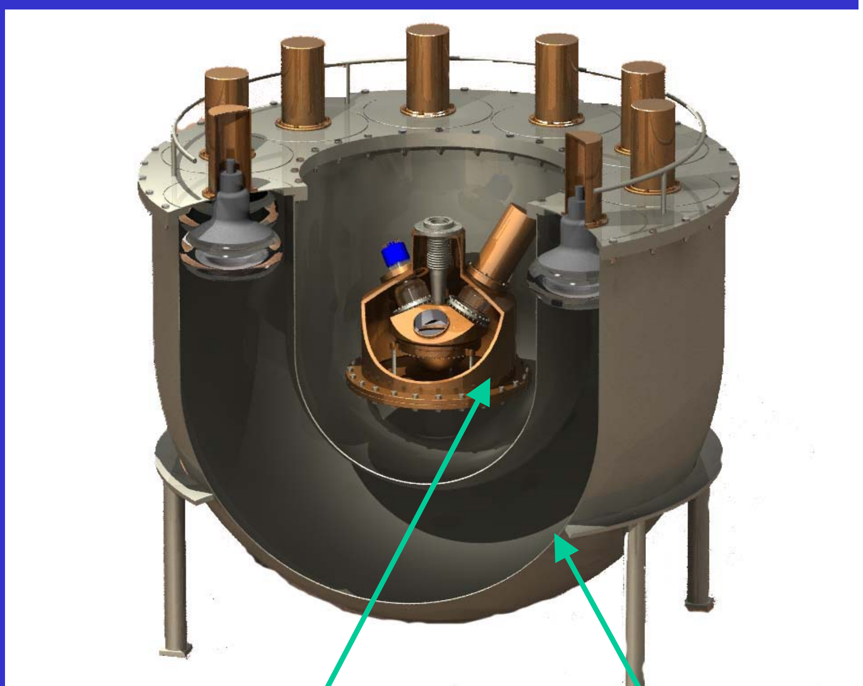
Very moderate energy resolution

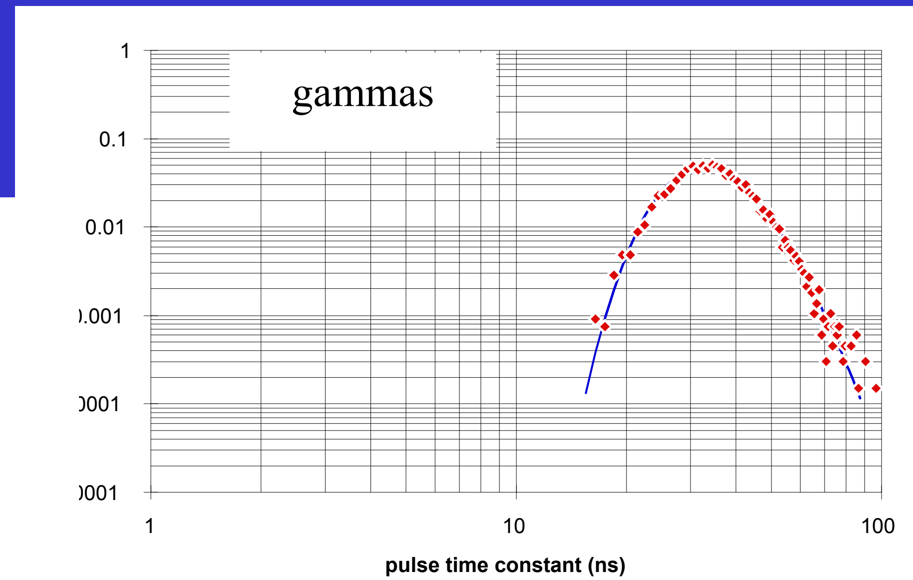
Experiments: DAMA, ZEPLIN I ......

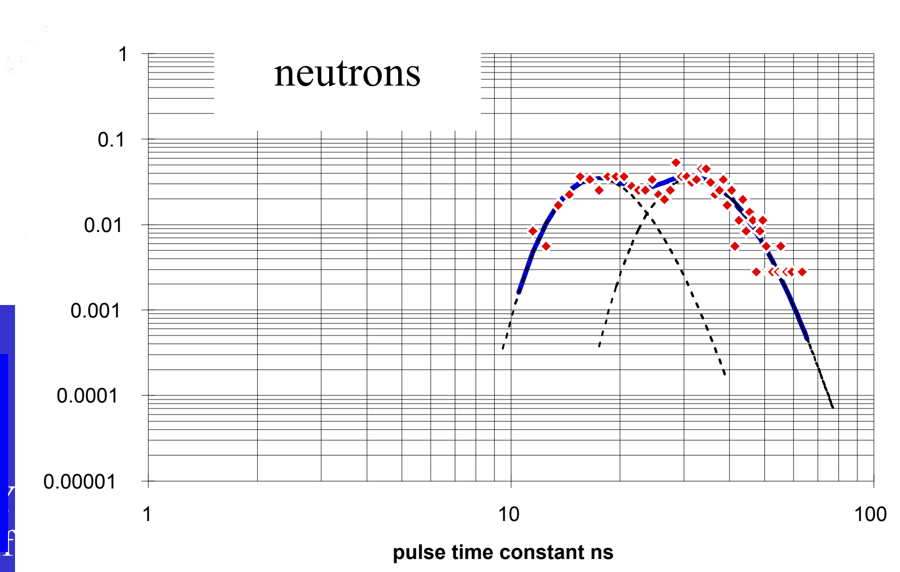
UKDM Collaboration: Zeplin I

Pulse time constant

- Pulse shape discrimination
- Measure primary scintillation



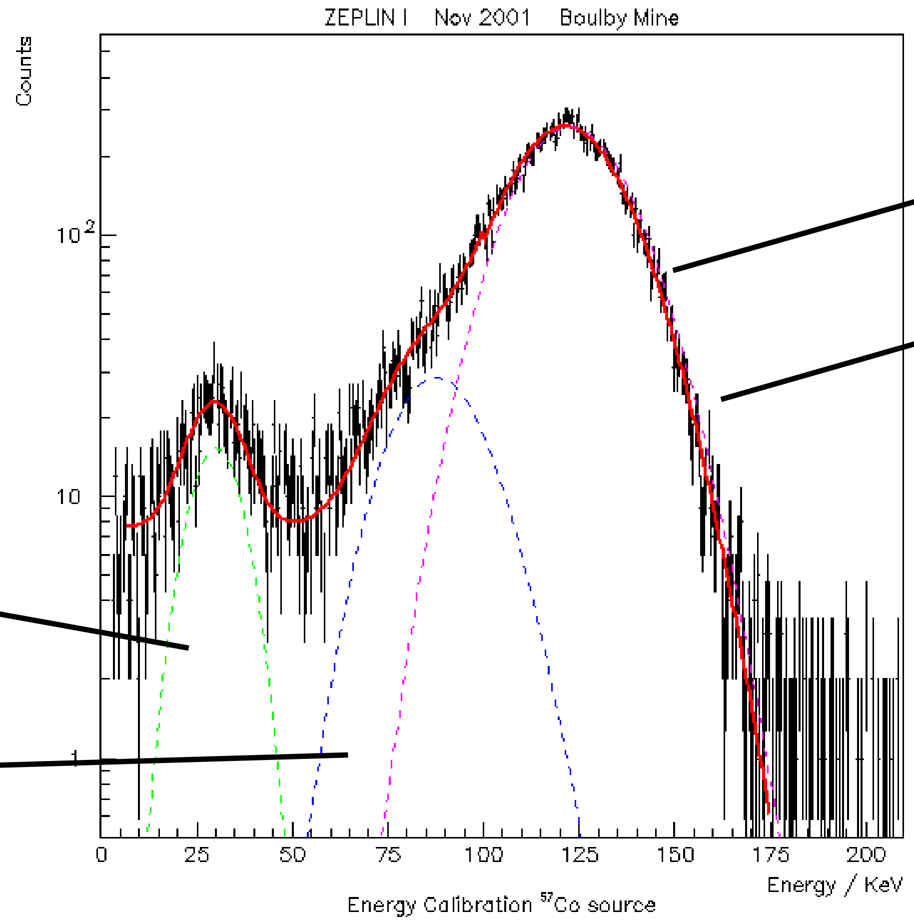




5kg LXe target (3.1kg fid)
3 PMTs
Cu construction

1 t Compton veto
PMT background tag
Gamma calibration
Neutron monitor

ZEPLIN I Energy Calibration



122 keV peak

136 keV peak (10%)

30 keV X-ray

90 keV recoil e-

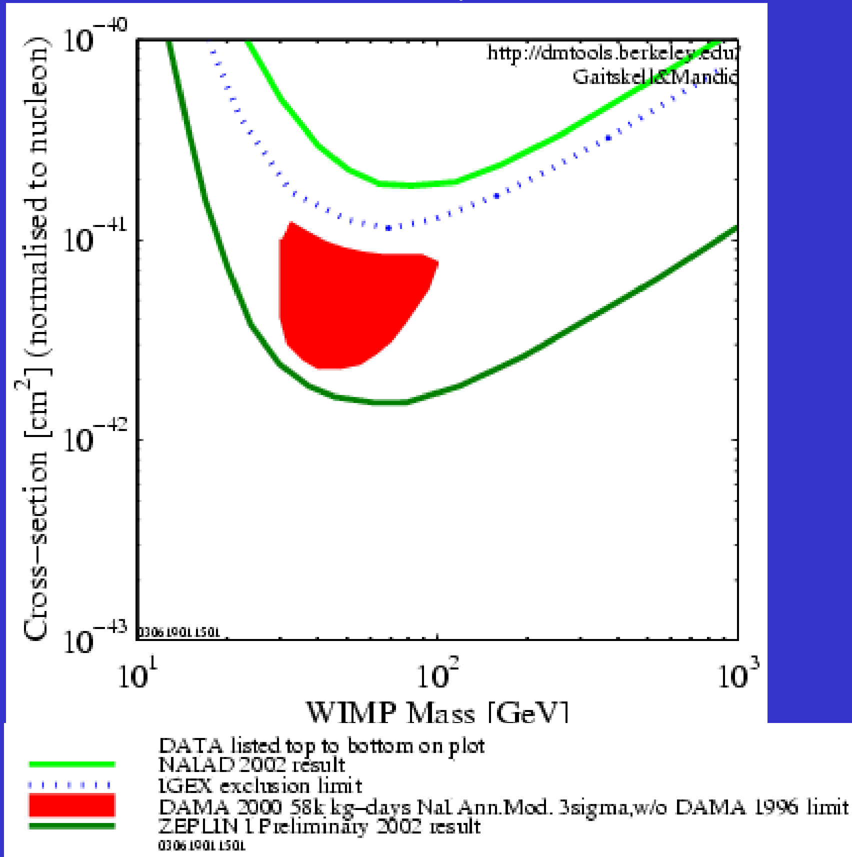
Linear response
1.5 p.e./keV
Resolution

$$\sigma(E) = 1.24\sqrt{E}$$

ZEPLIN I limit

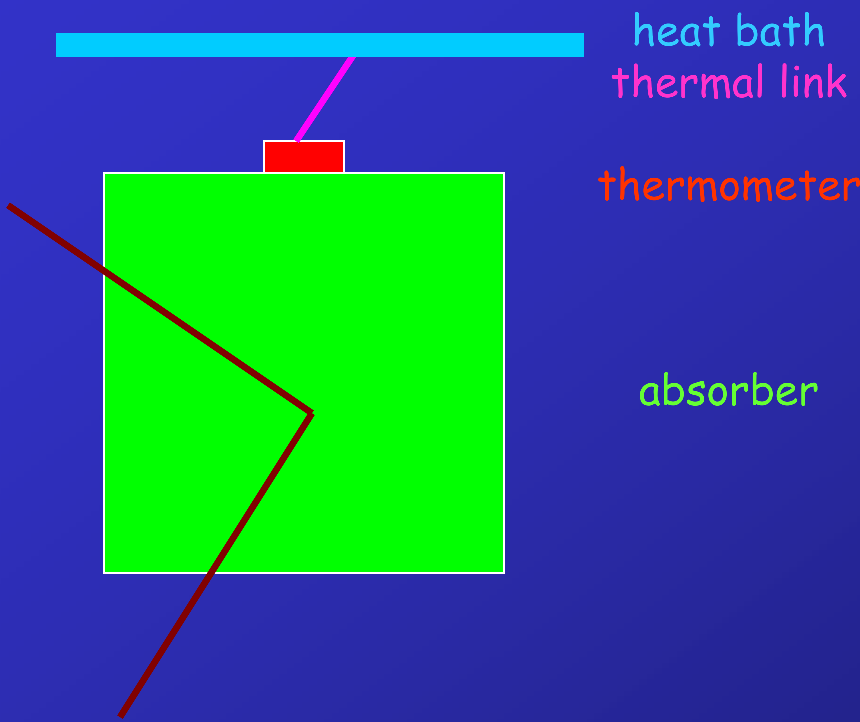
preliminary !!!

- Based on lab neutron discrimination (source and ambient)
- Efficiencies incorporated
  - Poisson trigger efficiency (analytically)
  - Light collection response matrix
  - S3 volume efficiency
  - Compton veto
  - Dead-time
- 'Standard' DM model
- Nuclear physics
  - Quenching
  - Form factor



heat

Cryogenic calorimeters



A particle interaction creates phonons which lead to a temperature rise of the thermometer

Operating temperature: 10-100 mK

wide choice of absorber materials

Low threshold

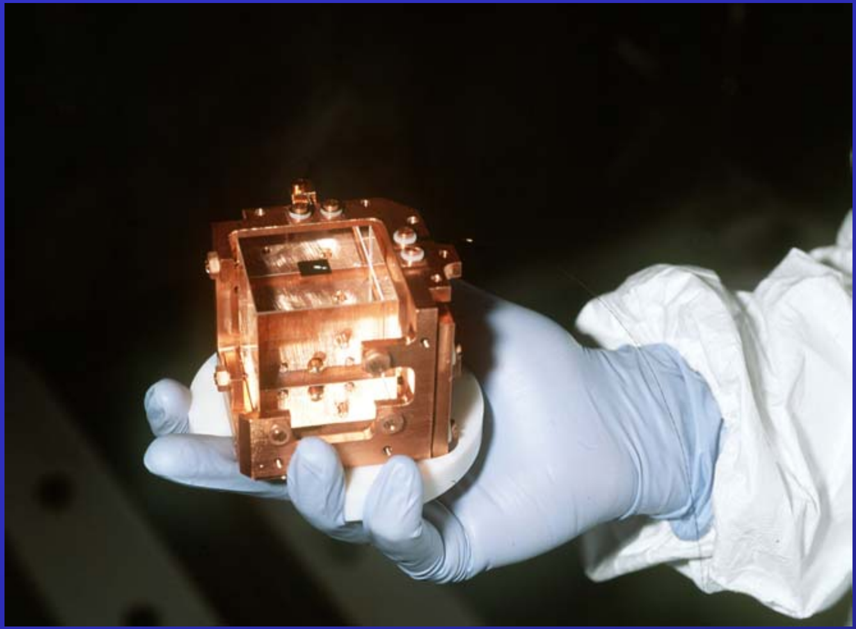
Excellent energy resolution

Q=1

Different experiments use different thermometers

CRESST I

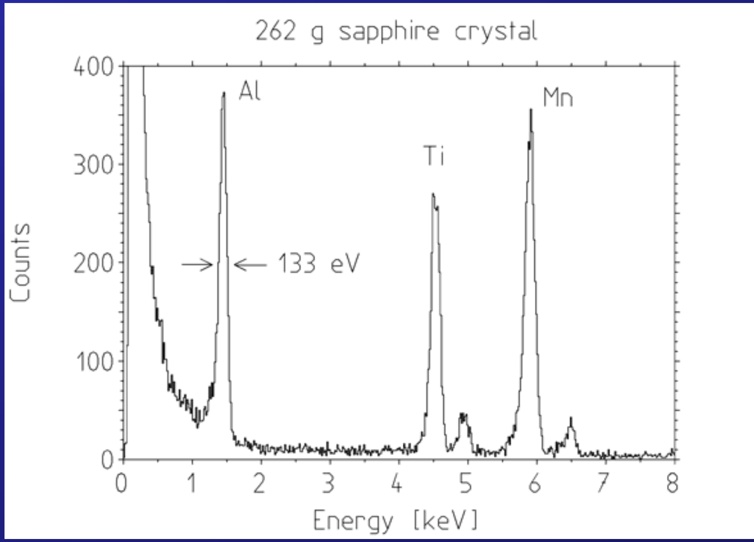
Located at the LNGS



$4x4x4\ cm^3$ sapphire crystal
262g

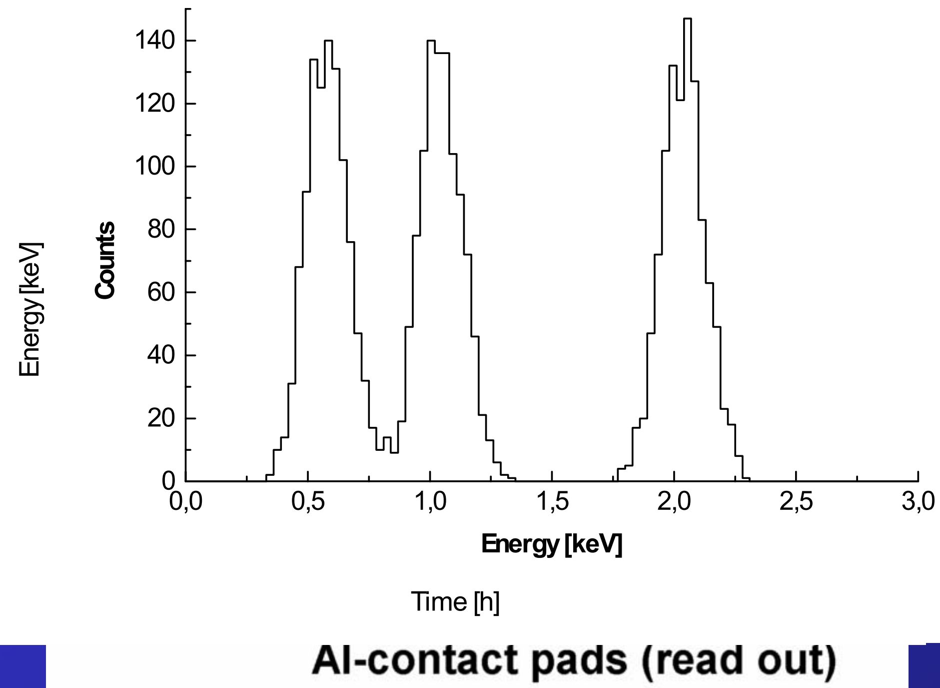
with a W-thermometer on

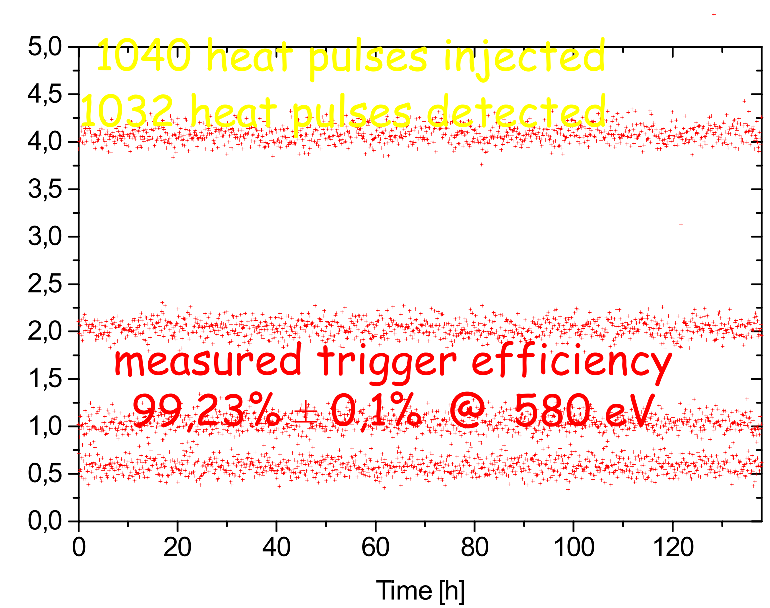
Operating temperature: 12 mK



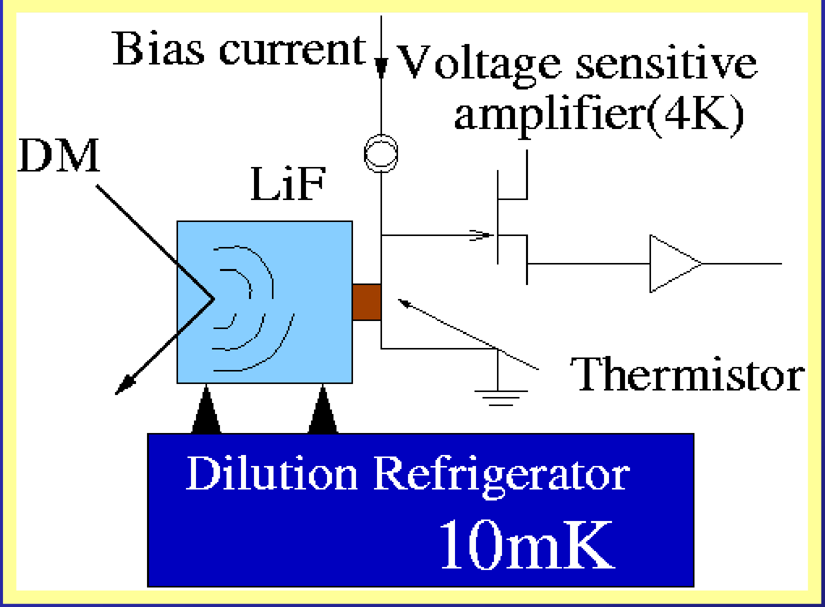
energy resolution: 133eV @ 1.5 keV

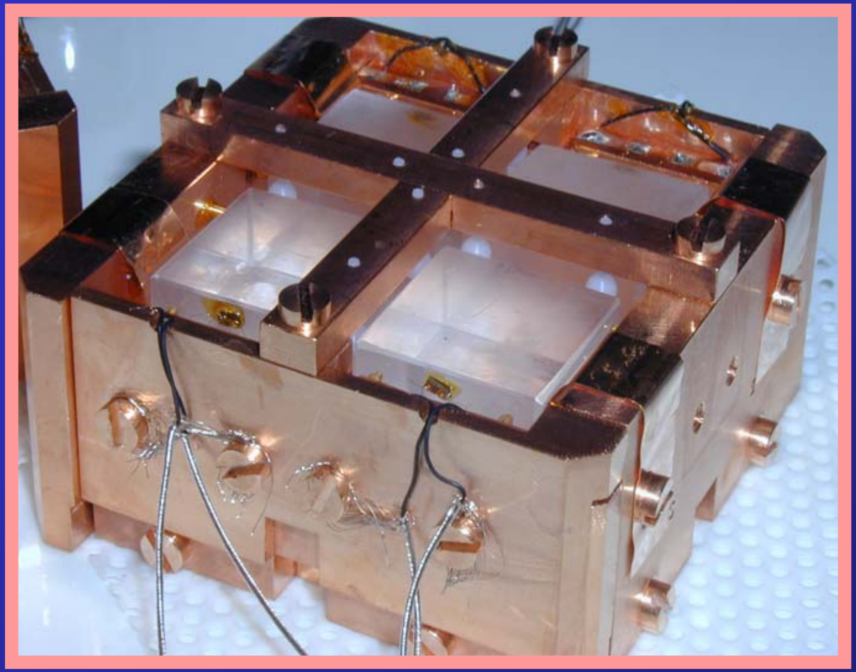
Sensitivity and trigger efficiency monitoring





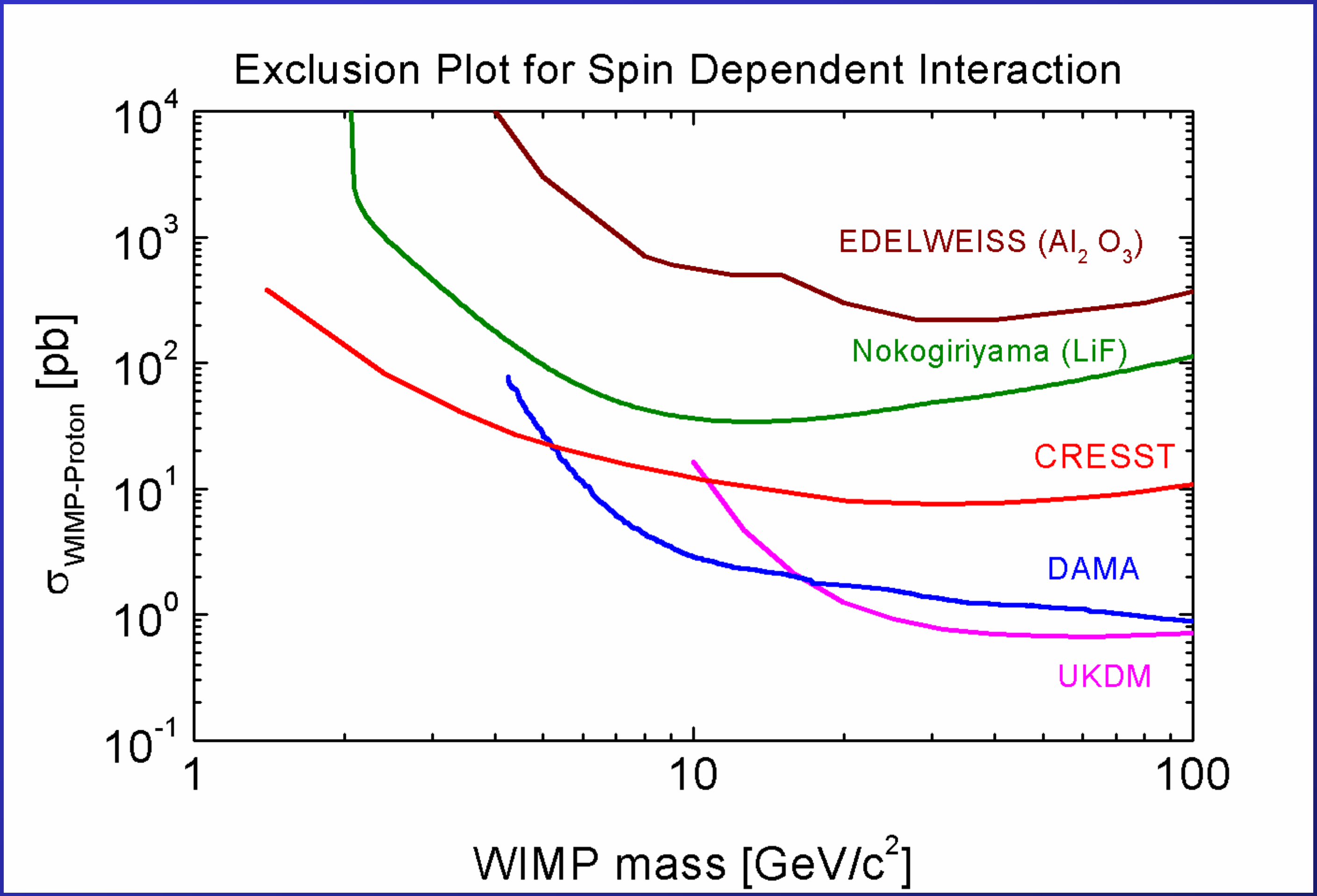
LiF Calorimeters at Kamioka





LiF calorimeter array
8pcs×21g LiF crystals
($2\times2\times2cm^3$)

Spin dependent limits



Heat + Ionisation

Especially developed for excellent background discimination
on a event by event basis

Works with Ge and Si as target nucleus

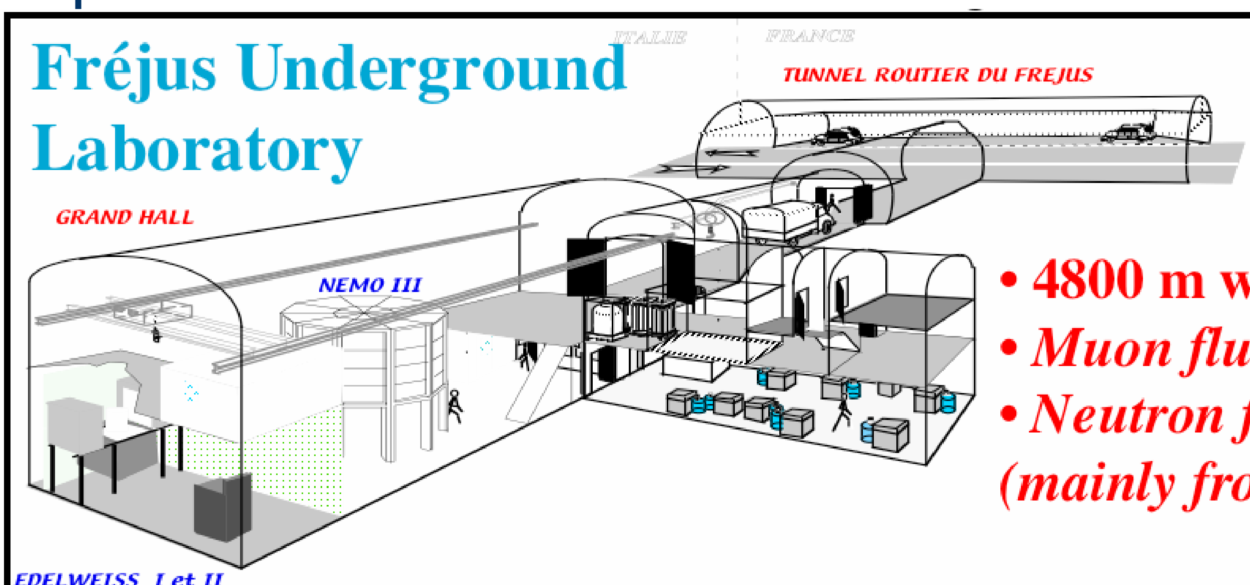
Excellent discrimination
Low threshold
Excellent energy resolution

Experiments: CDMS, EDELWEISS

Edelweiss

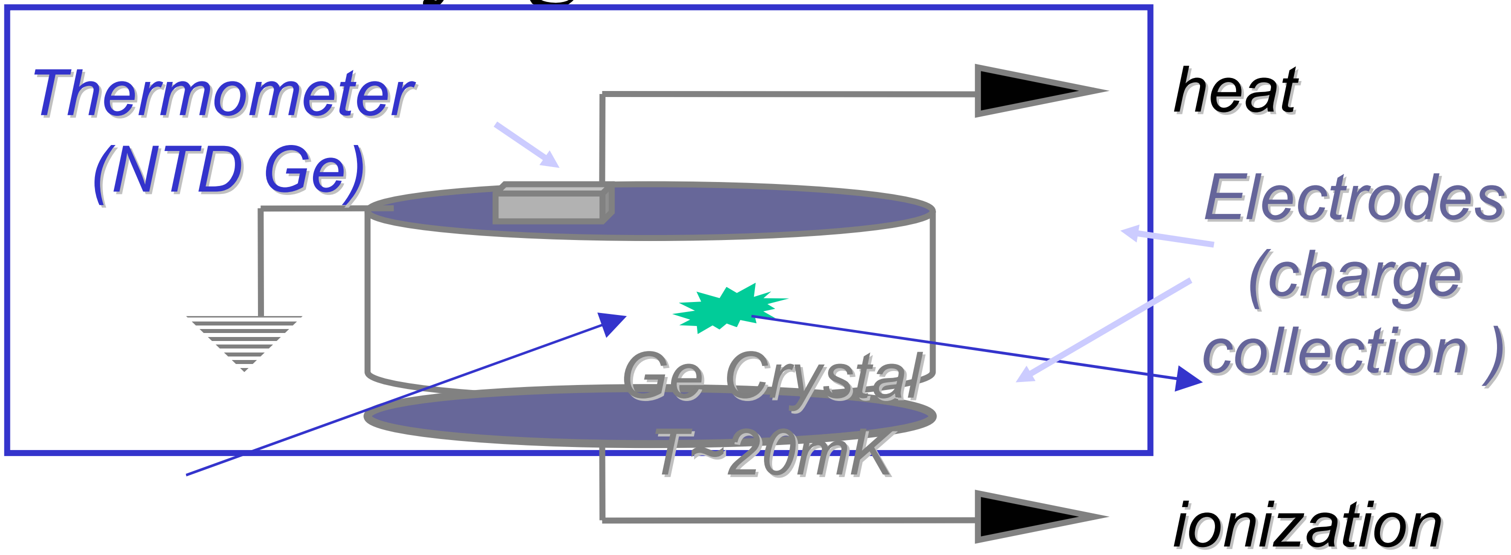
-Dark Matter Search -

CEA-Saclay DAPNIA and DRECAM
CRTBT Grenoble
CSNSM Orsay
IAP Paris
IPN Lyon
Laboratoire souterrain de Modane (Fréjus)
FZ-Karlsruhe and Univ. Karlsruhe



- 4800 m water eq.
- *Muon flux ≈ 4 muons/m²/day*
- *Neutron flux ≈ 1.5 10^{-6} s^{-1} cm^{-2} (mainly from rock radioactivity)*

Ionization-heat cryogenic detectors

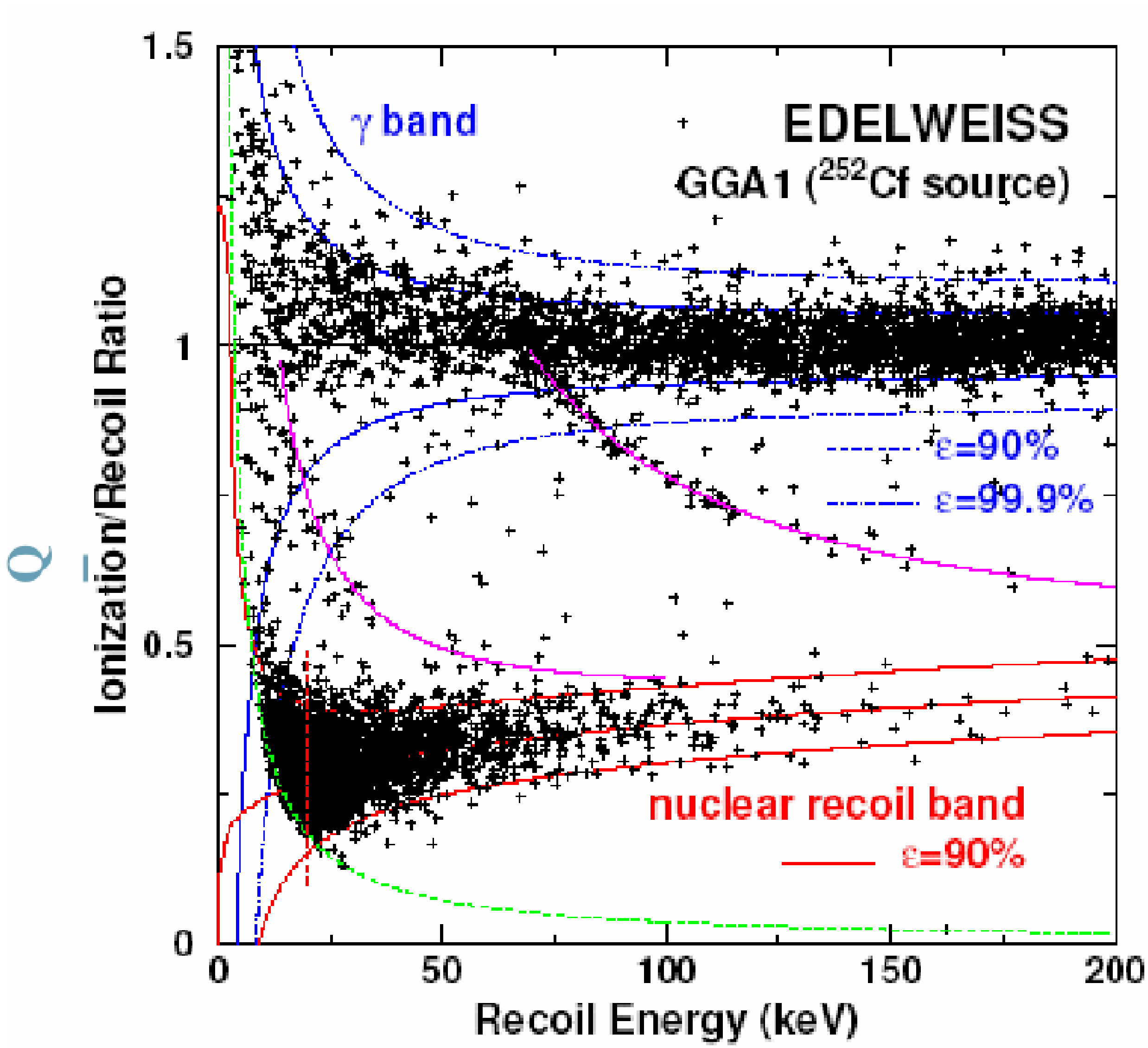


Simultaneous measurement of charge and heat signals for each interaction.

Different charge/heat ratio for nuclear recoils and electronic recoils

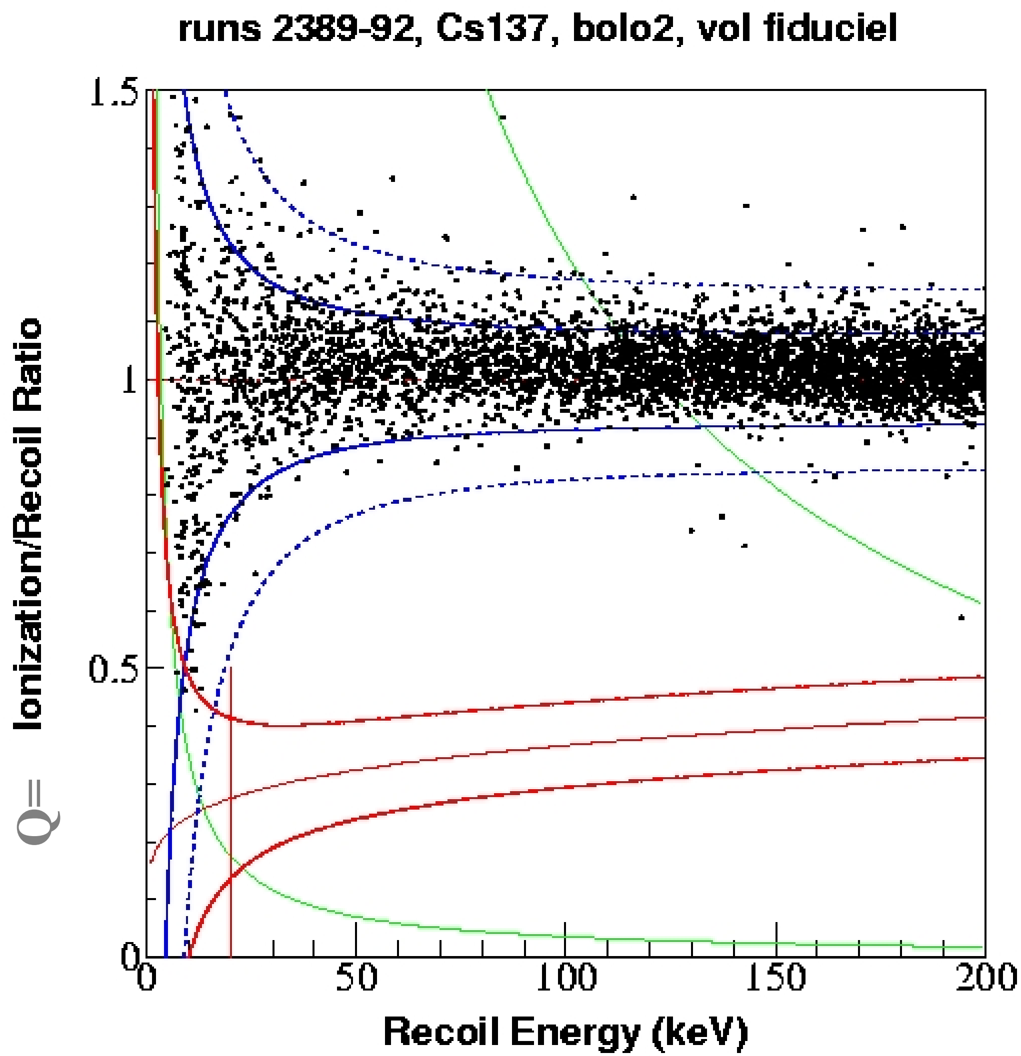
➲ **event by event discrimination**

GGA1 neutron calibration



Event-by-event discrimination down to threshold energy

GGA1 gamma calibration

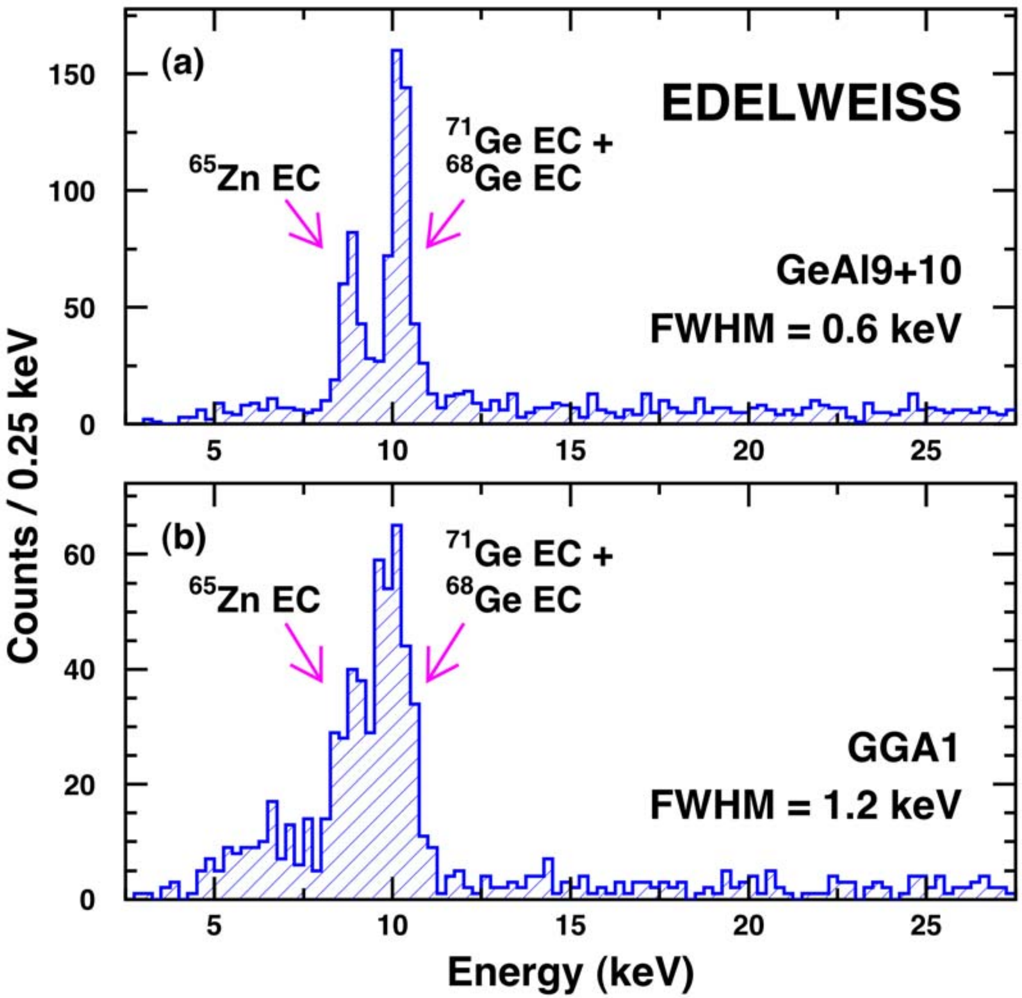


Present EDELWEISS detectors: excellent energy resolution

Sub-keV energy resolution on phonon channels (300 eV FWHM on GGA3)

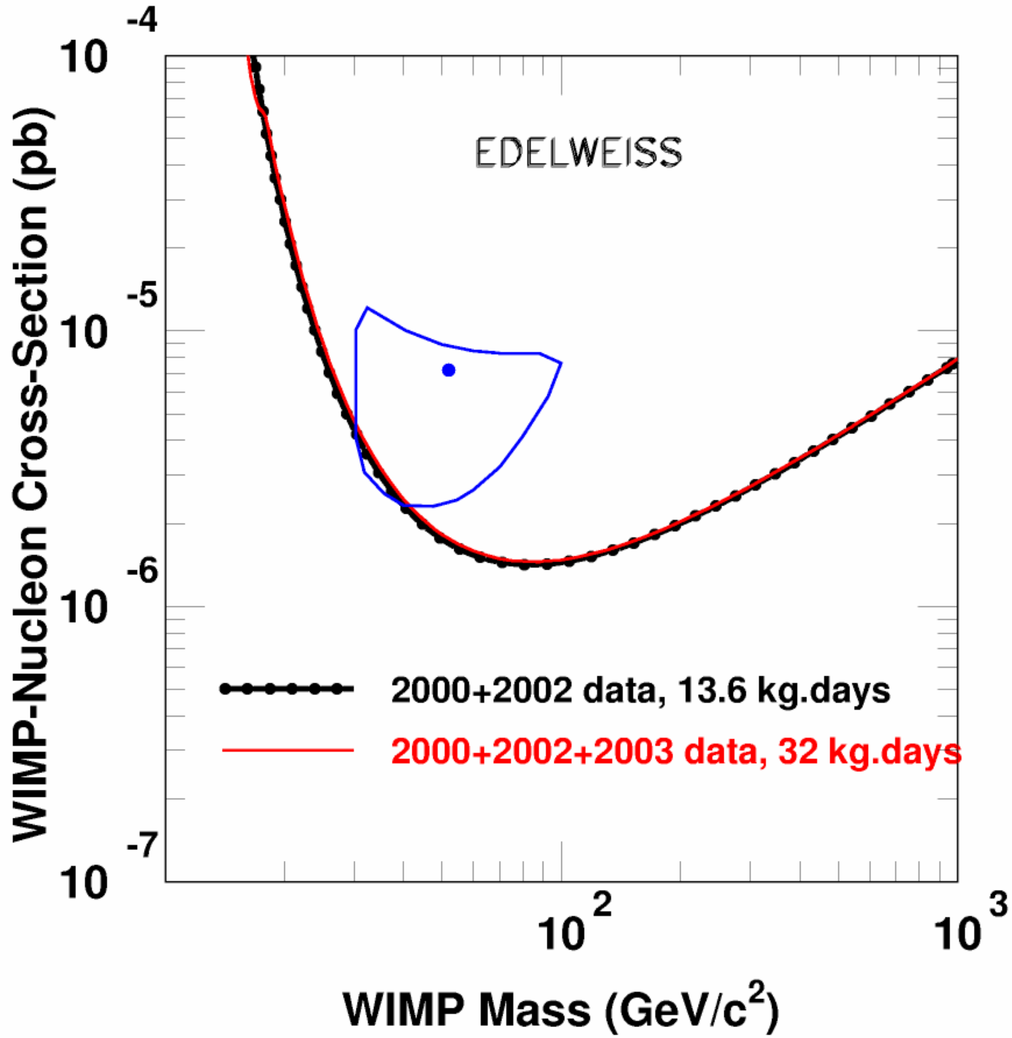
- ≈1 keV FWHM on charge channels

- **Background comprehension down to a few keV e.e.**



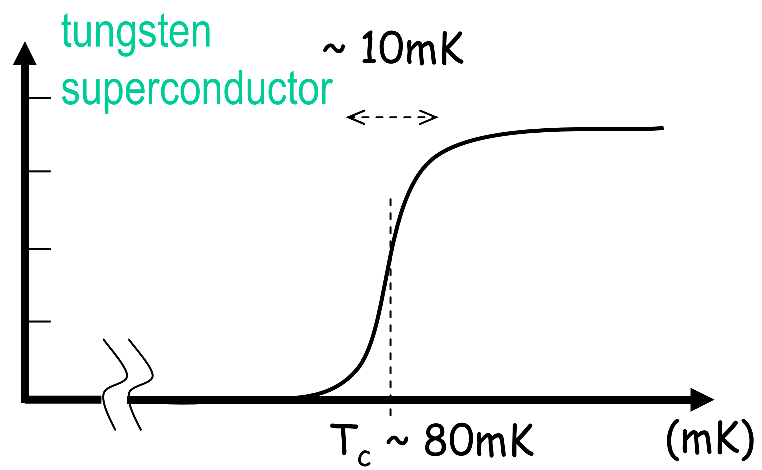
EDELWEISS limits

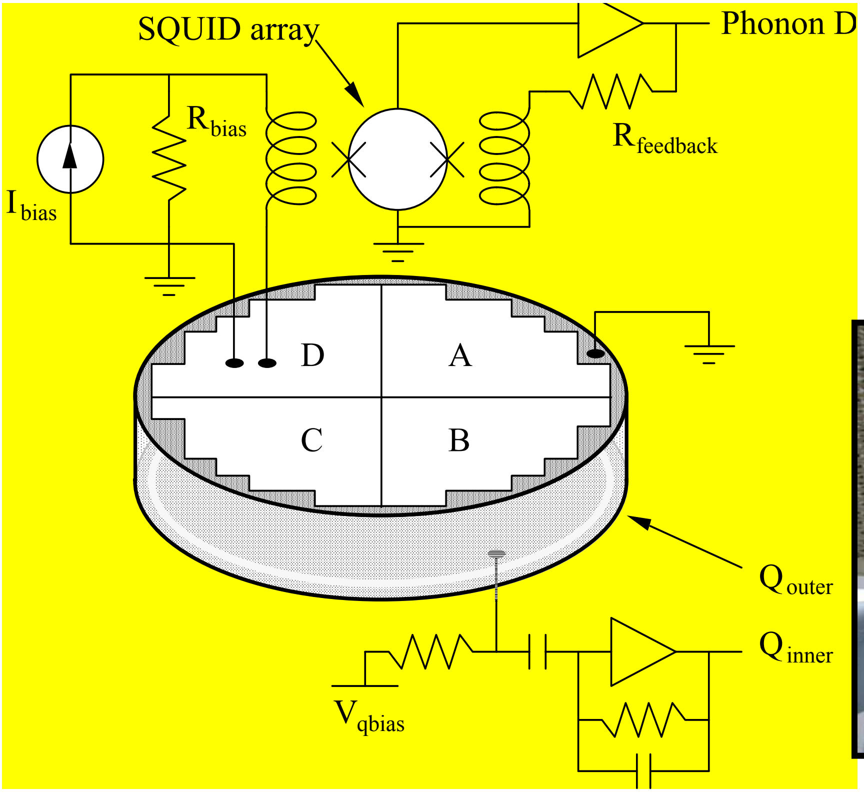
- No background subtraction

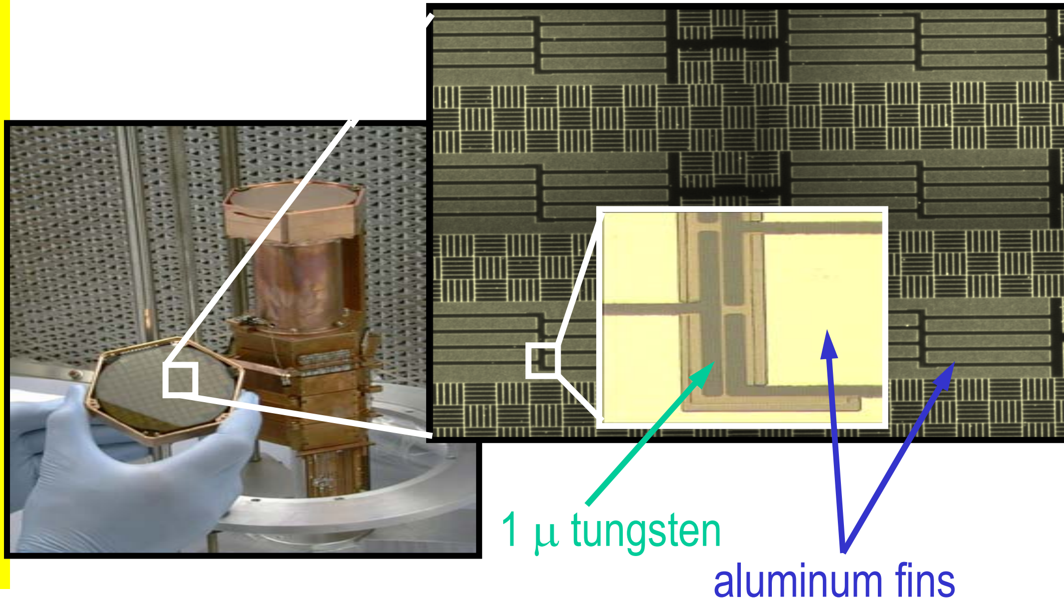


CDMS ZIP Ionization & Phonon Detectors

Fast athermal phonon technology
- Superconducting thin films of W, Al
- Stable Electrothermal Feedback
- Aluminum Quasiparticle Traps give area coverage

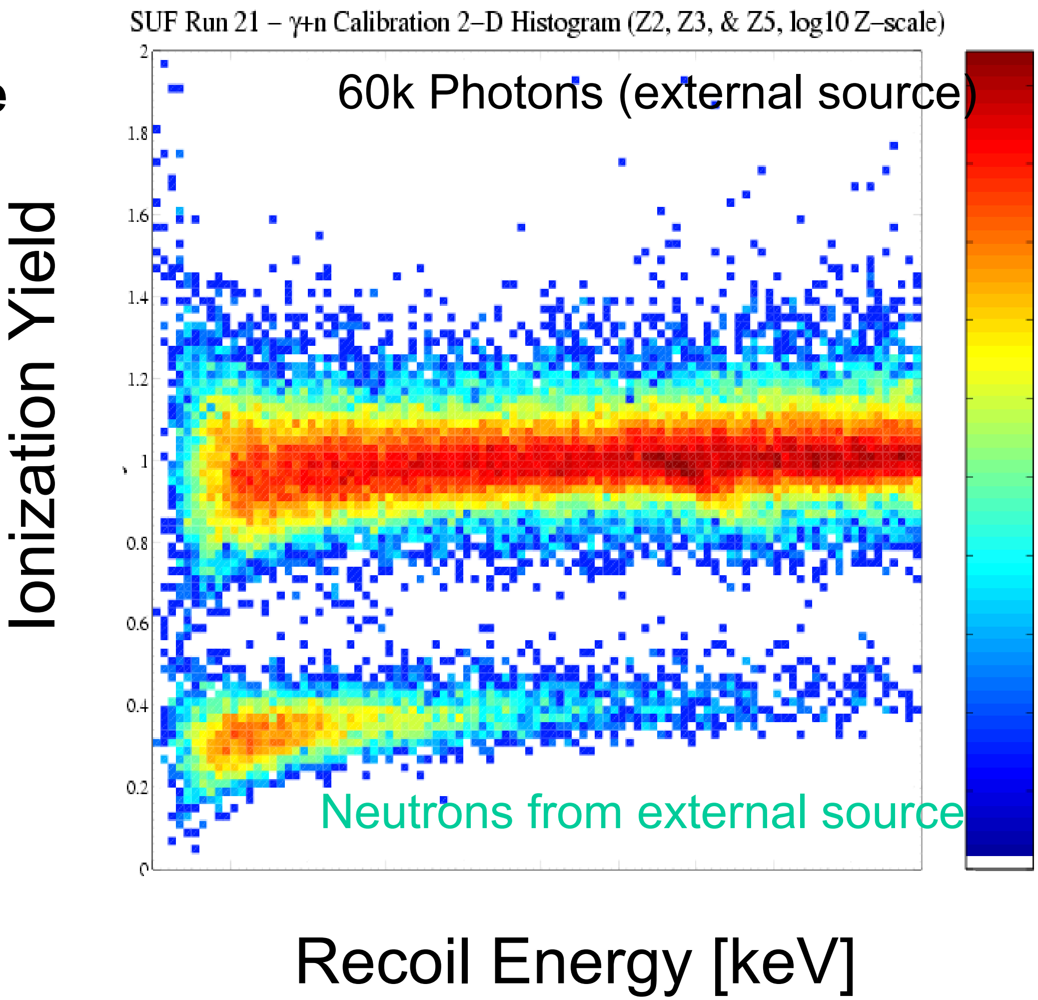






Photon Rejection with ZIPs

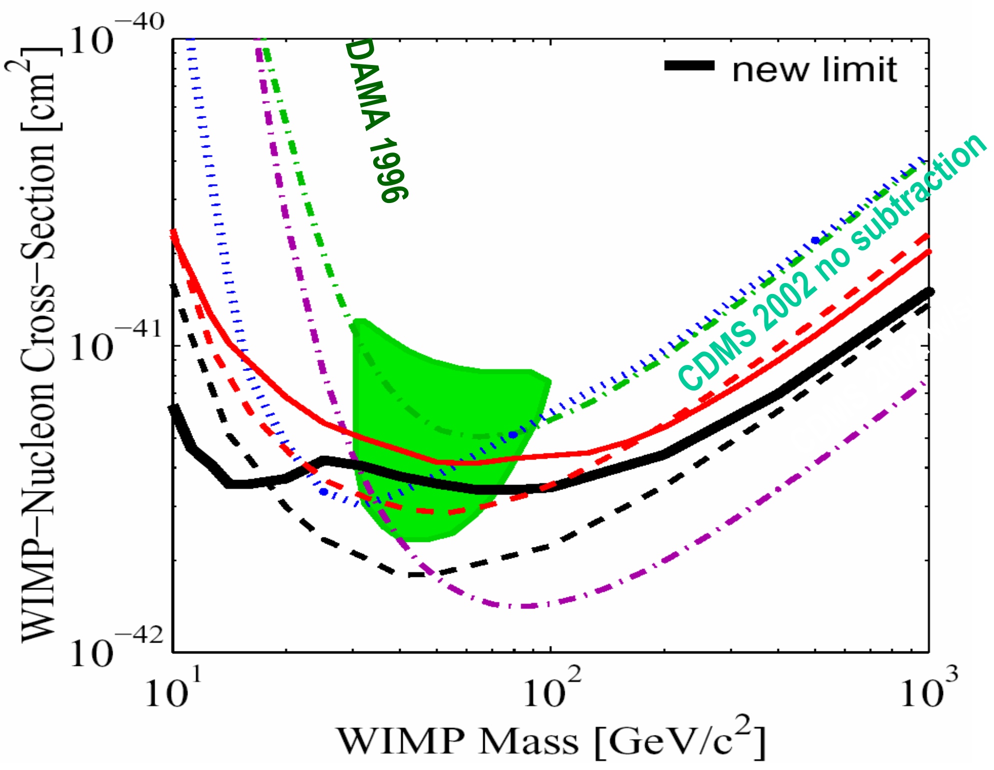
- Photon rejection > 99.99% (2/60500) for 5-100 keV range in Ge detectors
  - Equivalent to 5 years of background operation at 0.8 events/keV/kg/day
  - >5x better performance than specified in CDMS II proposal
- Rejection in Si detectors almost as good
- Results from *in-situ* photon and neutron calibrations at Stanford Underground Facility



Tower 1 at 17 mwe depth

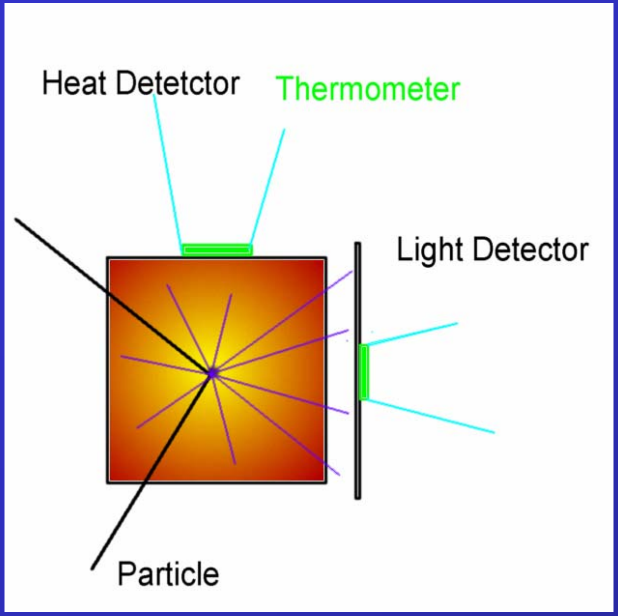
NEW 28 kg days exposure

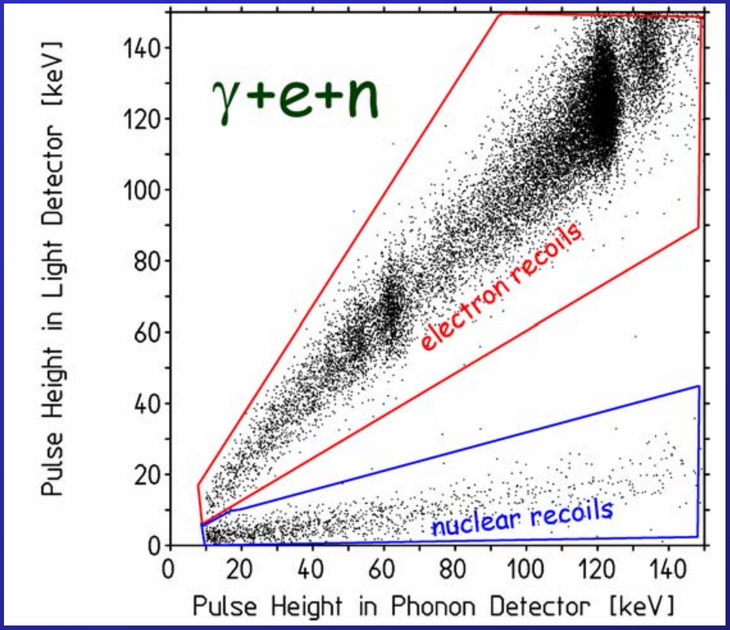
- Neutron rate consistent with
  - 16 kg-d 'BLIP' run (same site)
  - 2.3x predicted reduction (increase poly shielding)
- Derive upper limit on WIMP-nucleon cross section:
  - Apply background 'subtraction' from 'gold plated' multiples
  - Standard halo
  - A^2 scaling
- Work continues on characterizing electron background
  - 3V vs 6V charge bias



Heat+scintillation, CRESST II

Background discrimination by simultaneous detection of phonons and light





Works with many absorber materials
$CaWO_4$,$PbWO_4$,BaF,BGO
(other tungstates and molybdates)

light detector is a cryo-detector of CRESST type

no surface effects

space charges ....

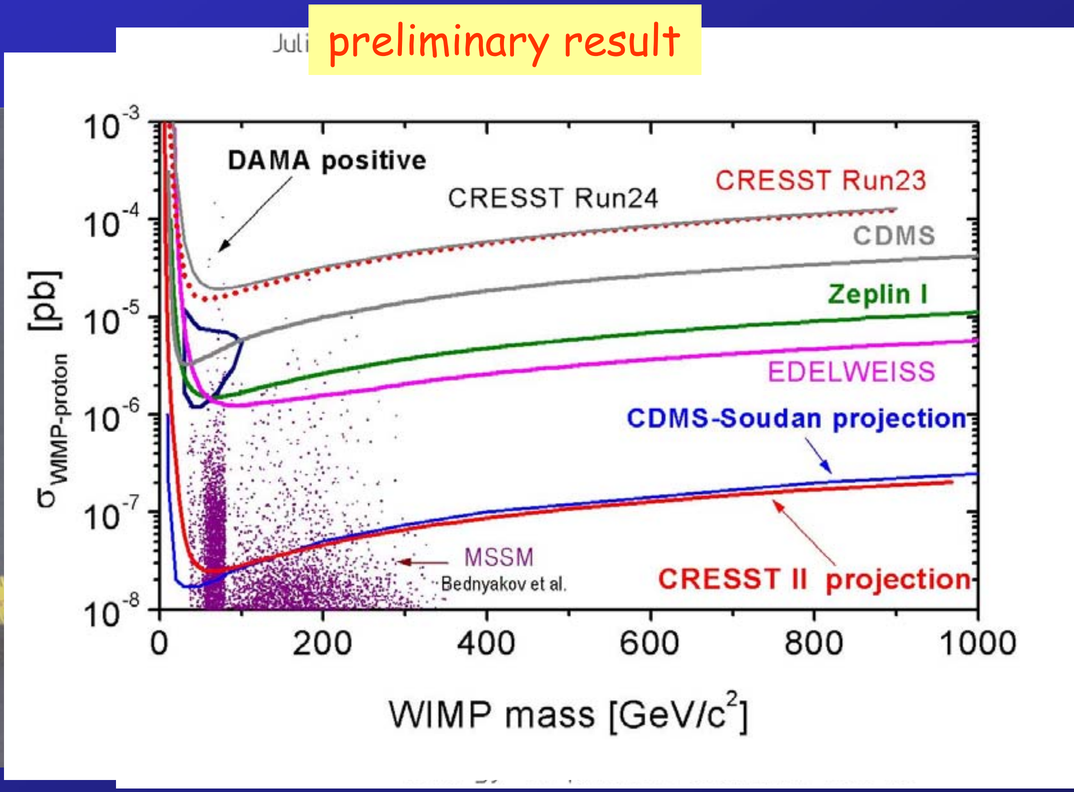
but less energy in light

High rejection:

99.7% E > 15 keV

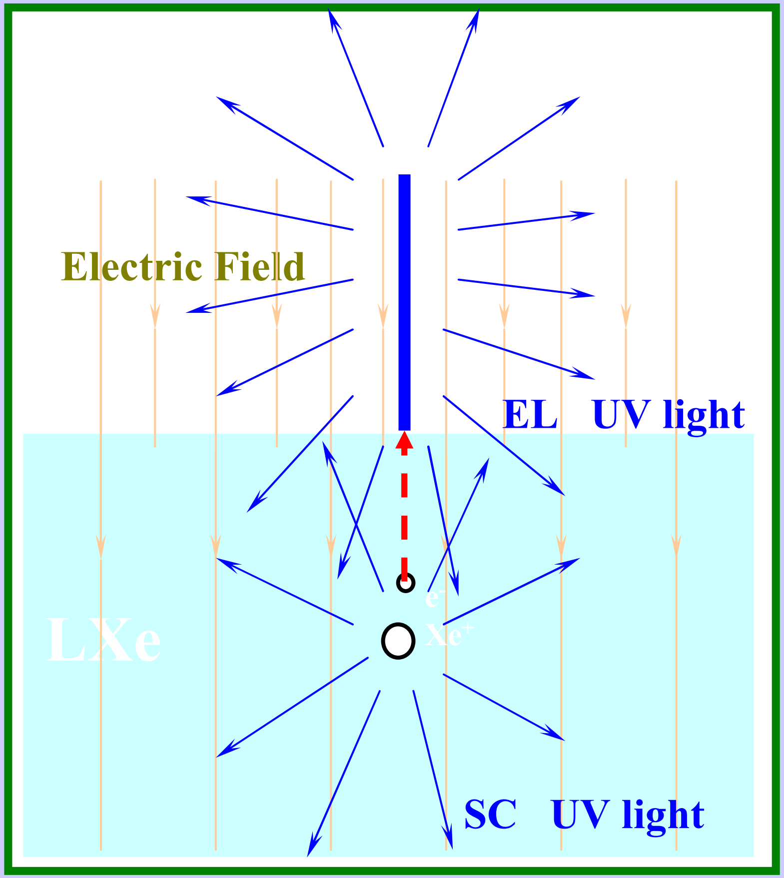
99.9% E > 20 keV

CRESST II will have 33 300g modules (total mass about 10 kg)



Scintillation+ Ionisation

Particle produces excitation (Xe^*) and ionisation (Xe^+, e)



Zeplin II........

Particle detection and background discrimination with two-phase Xe

Both SC and EL are detected by the same photodetector

Discrimination of background is based on analysis of EL/SC

Background (mostly γ and e) produces high EL/SC

Xe recoils (WIMPs and neutrons) produce low EL/SC due to much stronger recombination

Conclusions

Direct dark matter search is a experimentally challenging field

Background discrimination is a important issue

Background discrimination on an event by event basis is taking over.

Near future experiments expect an improvement of sensitivity of about 2 orders of magnitude