La rivelazione diretta di particelle di materia oscura: stato e prospettive

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INFN sez. Roma
Roma, Maggio 2009

The Dark Side of the Universe: experimental evidences ...

COMA Cluster

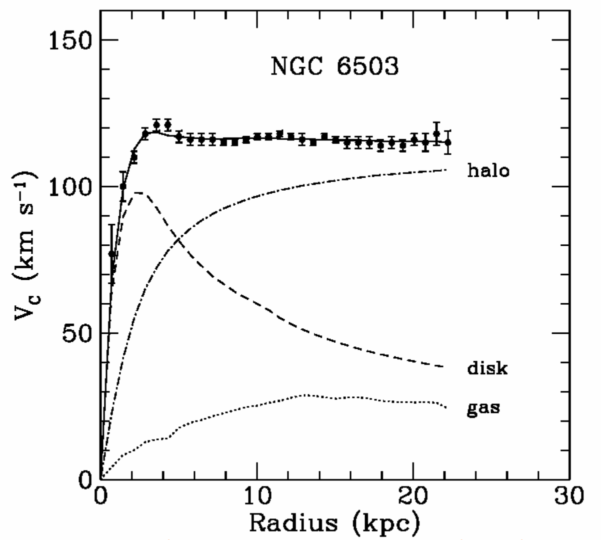
First evidence and confirmations:

1934 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

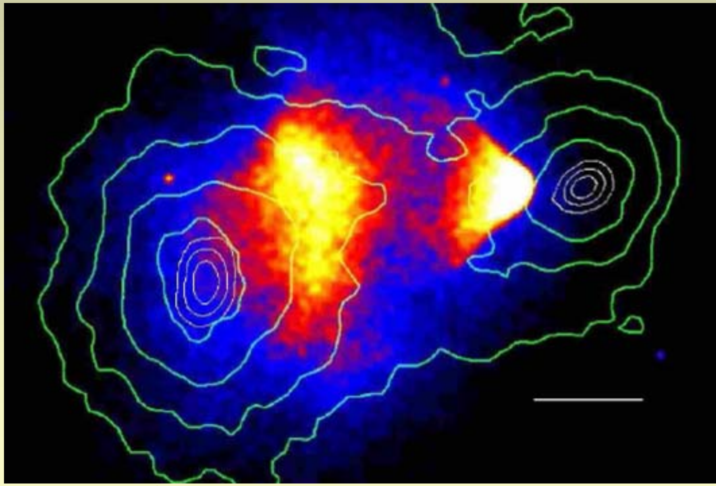
1974 two groups: systematical analysis of *mass* vs *distance from center* in many galaxies

Other experimental evidences



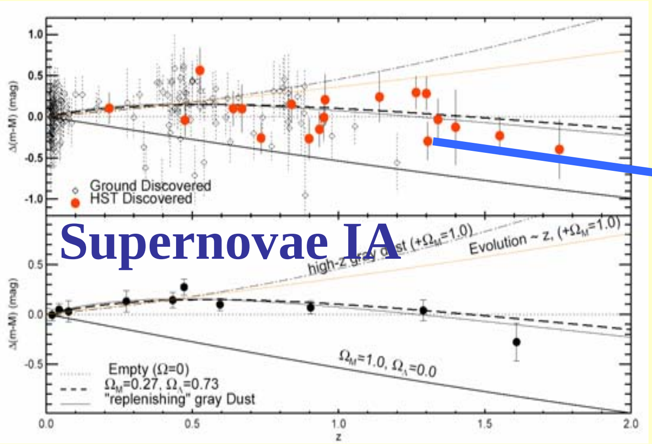
Rotational curve of a spiral galaxy

- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters
- ✓ ...
- ✓ bullet cluster 1E0657-558

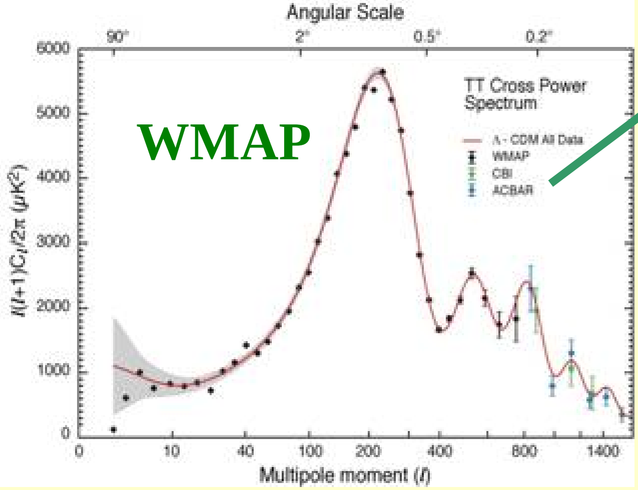


$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ ⇒ about 90% of the mass is DARK

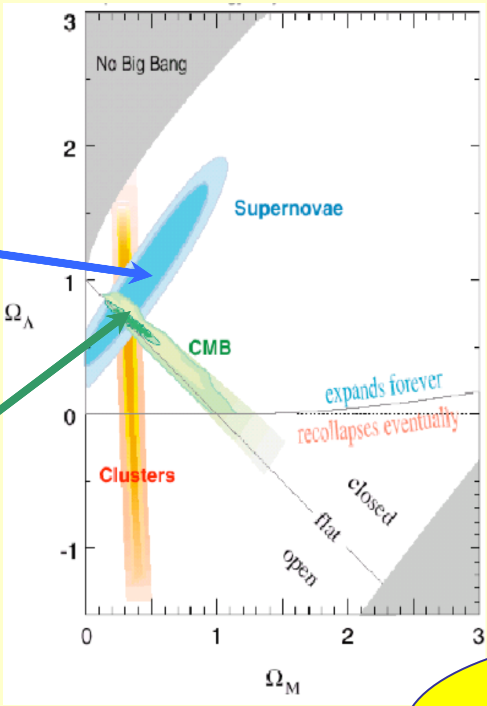
“Concordance model”



Supernovae IA



WMAP



$\Omega = \Omega_\Lambda + \Omega_M =$ close to 1

Ω = density/critical density

6 atoms of H/m³

$$\Omega_\Lambda \approx 0.74$$
$$\Omega_M \approx 0.26$$

The Universe is flat

Primordial Nucleosynthesis

Observations on:
- light nuclei abundance
- microlensings
- visible light.

Structure formation in the Universe

The baryons give “too small” contribution

$\Omega_b \sim 4\%$

Non baryonic **Cold Dark Matter** is dominant

$\Omega_{CDM} \sim 22\%,$
$\Omega_{HDM,\nu} < 1\ \%$

~ 90% of the matter in the Universe is non baryonic

A large part of the Universe is in form of non baryonic Cold Dark Matter particles

Relic DM particles from primordial Universe

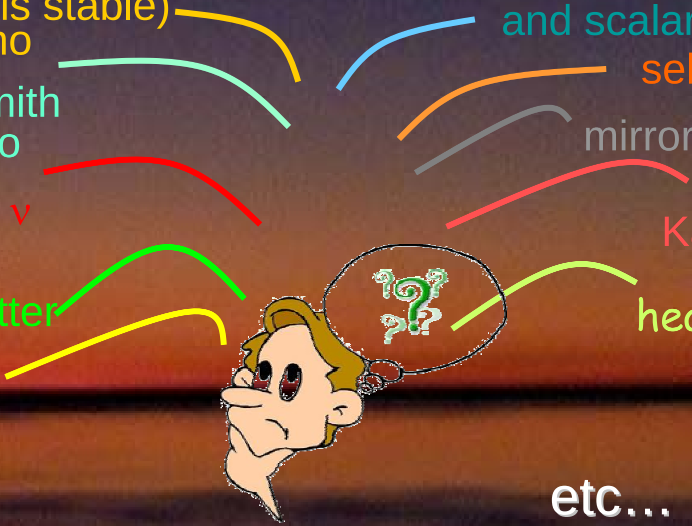
Heavy candidates:

- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time:
  $<\sigma_{ann} \cdot v> \sim 10^{-26}/\Omega_{WIMP}h^2 \ cm^3s^{-1} \rightarrow \sigma_{ordinary\ matter} \sim \sigma_{weak}$
- Expected flux: $\Phi \sim 10^7 \cdot (GeV/m_W)\ cm^{-2}\ s^{-1}$ $(0.2<\rho_{halo}<1.7\ GeV\ cm^{-3})$
- Form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}c$)
- Neutral, massive, stable (or with half life ~ age of Universe) and weakly interacting

Light candidates:

axion, sterile neutrino, axion-like particles cold or warm DM

(no positive results from direct searches for relic axions with resonant cavity)



SUSY
(R-parity conserved → LSP is stable)
neutralino or sneutrino

the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

axion-like (light pseudoscalar and scalar candidate)

self-interacting dark matter

mirror dark matter

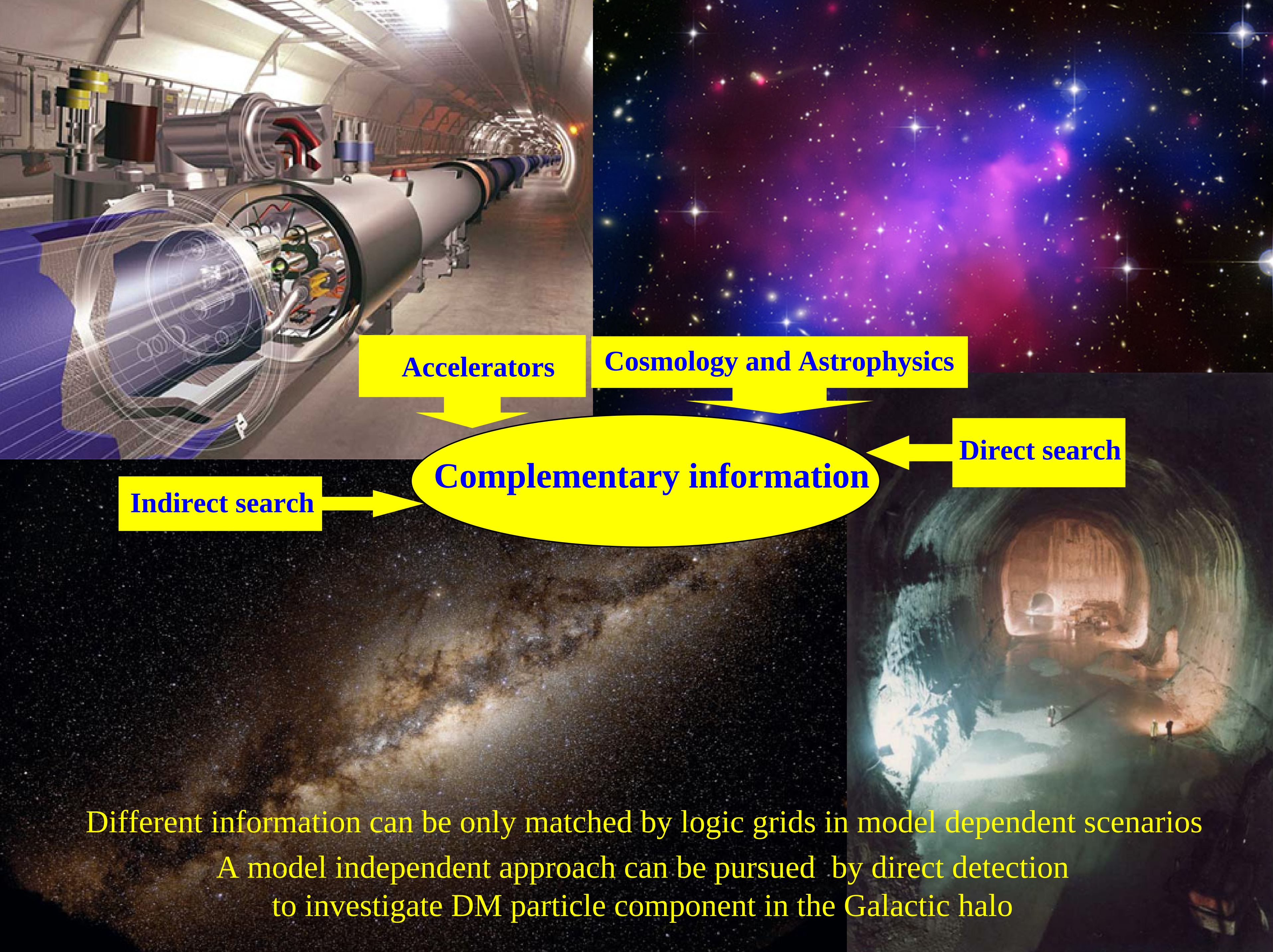
Kaluza-Klein particles (LKK)

heavy exotic canditates, as "4th family atoms", ...

etc…

+ multi-component halo?

even a suitable particle not yet foreseen by theories



Accelerators

Cosmology and Astrophysics

Direct search

Indirect search

Complementary information

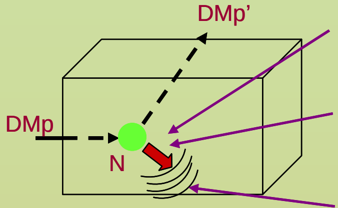
Different information can be only matched by logic grids in model dependent scenarios

A model independent approach can be pursued by direct detection
to investigate DM particle component in the Galactic halo

Some direct detection processes:

- Scattering on nuclei

  → detection of nuclear recoil energy



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl),
LXe,CaF_2(Eu), …

- Inelastic Dark Matter: **W + N → W* + N**

  → W has Two mass states χ+ , χ- with δ mass splitting

  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

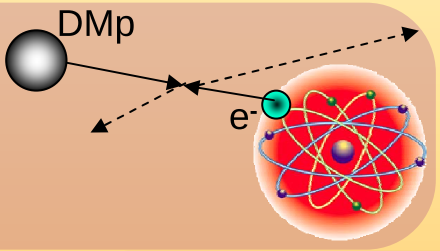
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

- Interaction only on atomic electrons

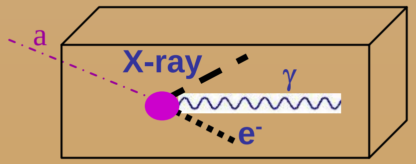
  → detection of e.m. radiation



… even WIMPs

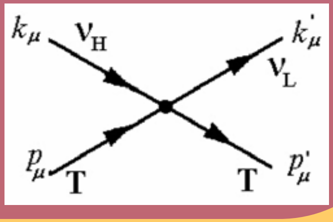
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy



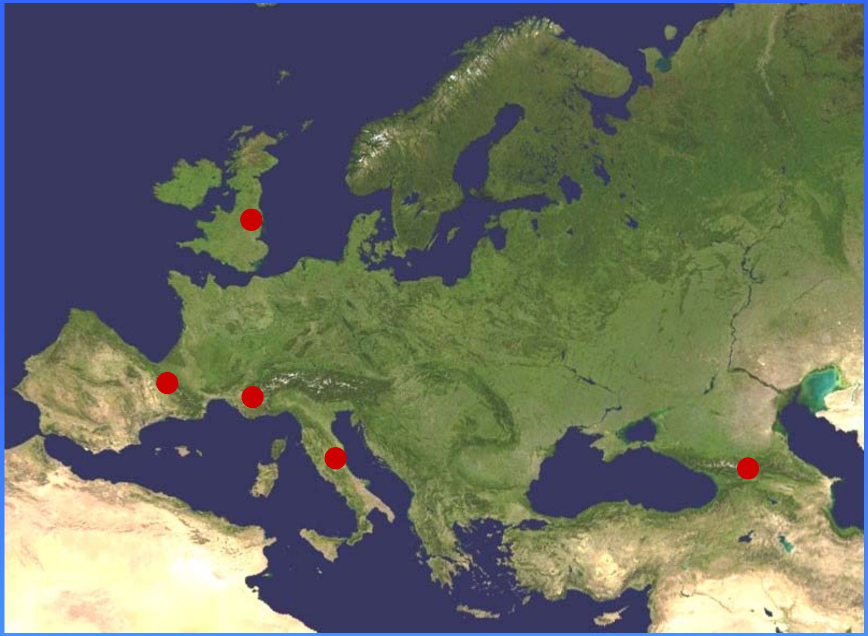
e.g. sterile ν

e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the electromagnetic component of their counting rate

- **… and more**

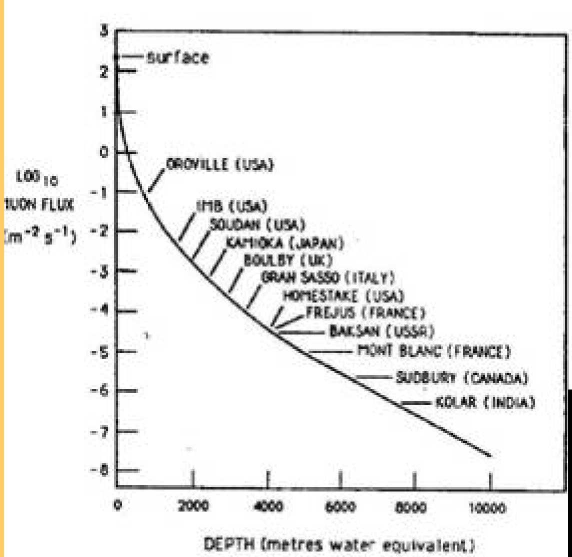
Dark Matter direct detection activities in underground labs

- ✓ Various approaches and techniques (many still at R&D stage)
- ✓ Various different target materials
- ✓ Various different experimental site depths
- ✓ Different radiopurity levels, etc.

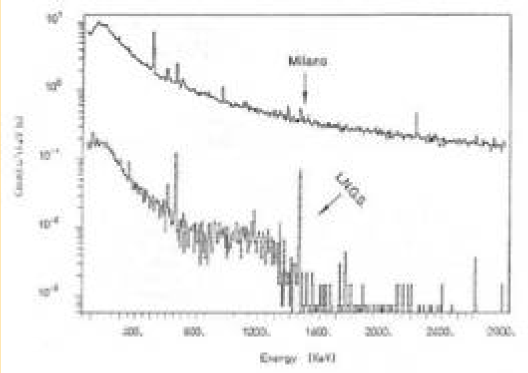


Main recipes for the Dark Matter particle direct detection

- Underground site
- Low bckg hard shields against γ's, neutrons
- Lowering bckg: selection of materials, purifications, growing techniques, ...
- Rn removal systems



Reduction from the underground site



Background sources

- LNGS:

muons → **0.6 μ/(m²h)**

neutrons → **$1.08 \cdot 10^{-6}$ n/(cm²s) thermal**

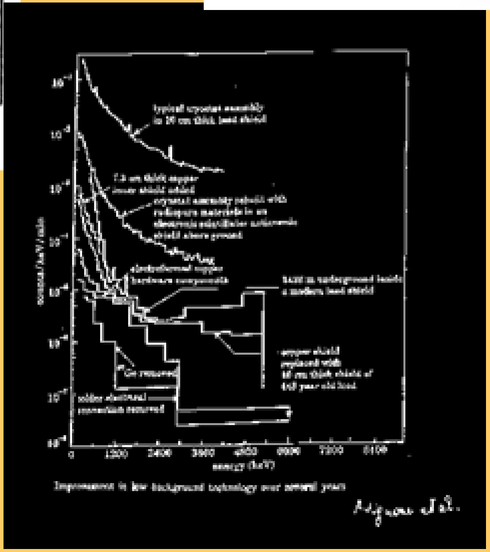
$1.98 \cdot 10^{-6}$ n/(cm²s) epithermal

$0.09 \cdot 10^{-6}$ n/(cm²s) fast (>2.5 MeV)

Radon in the hall → **≈30 Bq/m³**

- Internal Background:

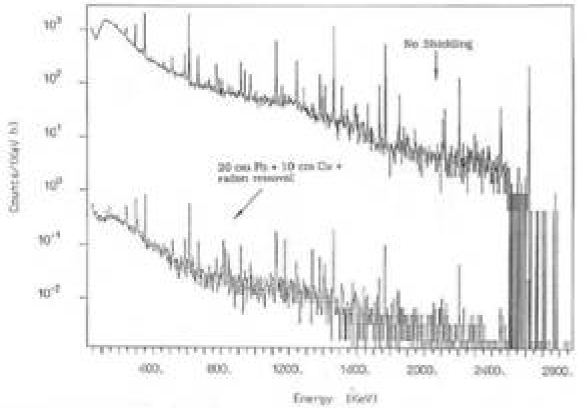
selected materials (Ge, NaI, AAS, MS, ...)



Improvement in low background technology over several years

Example of background reduction during many years of work

Example of the effect of a passive shield



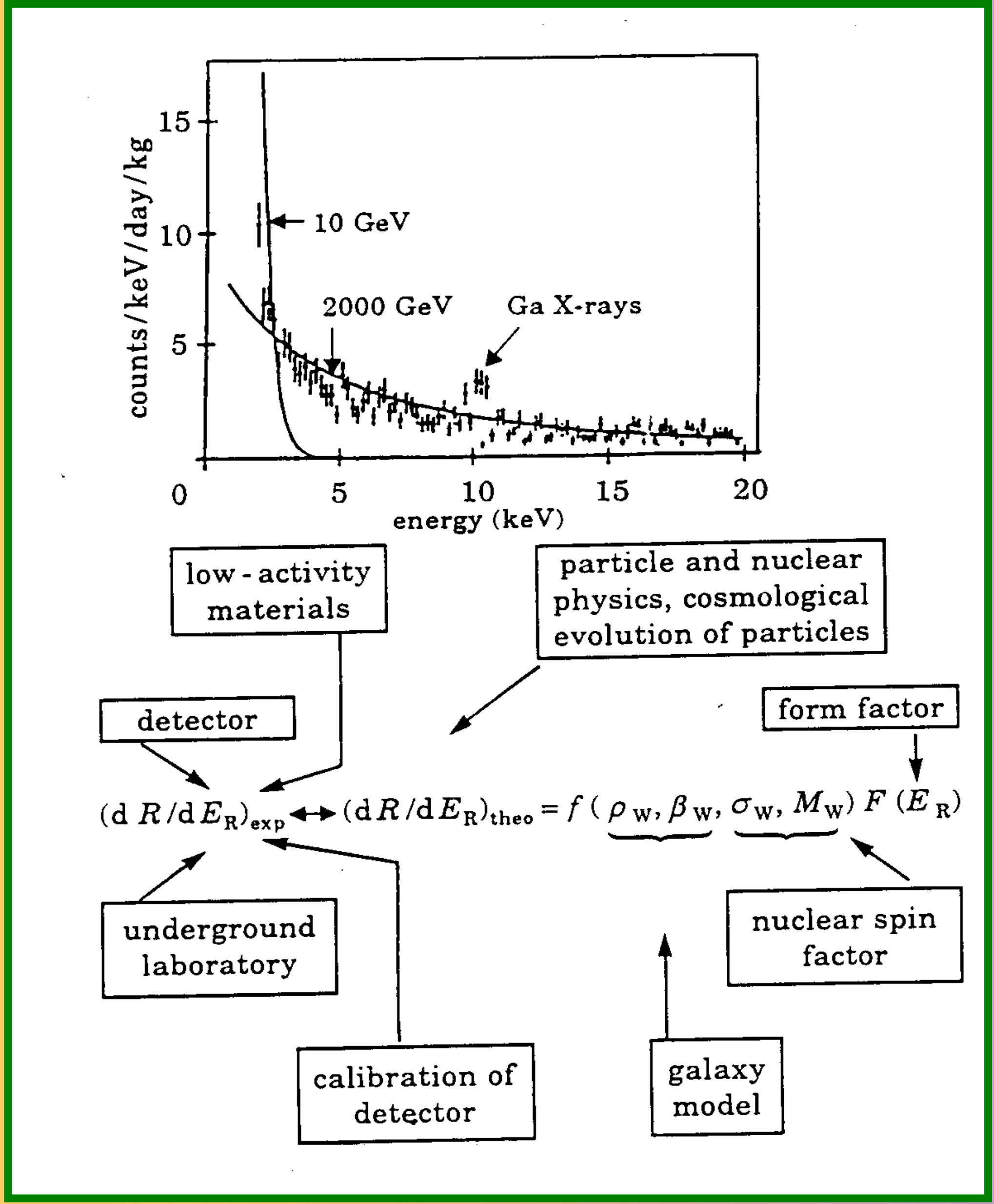
Shielding

Passive shield: Lead (Boliden [< 30 Bq/kg from ^{210}Pb], LC2 [<0.3 Bq/kg from ^{210}Pb], lead from old roman galena), OFHC Copper, Neutron shield (low A materials, n-absorber foils)

Active shield: Low radio-activity NaI(Tl) surrounding the detectors

The "traditional" approach

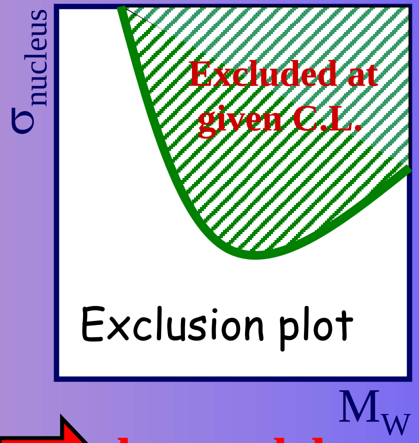
- Experimental vs Expected spectra (with or without bckg rejection)



several assumptions and modeling required

+

experimental and theoretical uncertainties generally not included in calculations

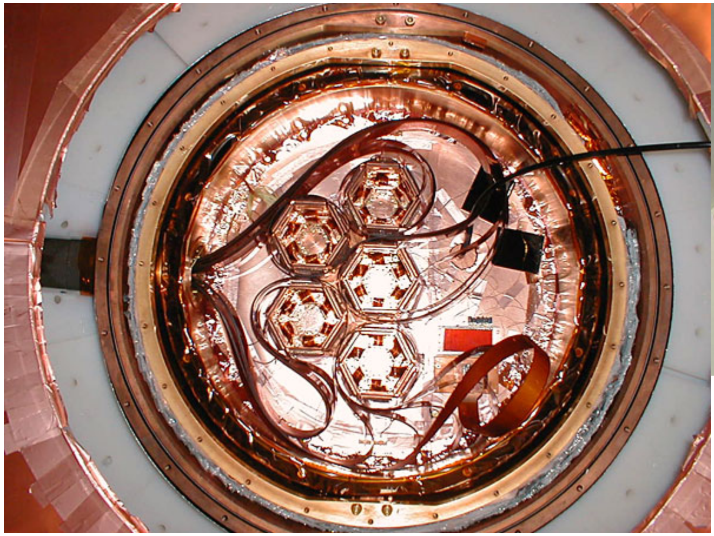


by model: σ_p

An exclusion plot is not an absolute limit

+ no potentiality of discovery

Bolometer/ionization bolometer/scintillation detectors



CDMSII (PRL102(2009)011301)

Experimental site: Soudan mine

Target material: ^{nat}Ge, ^{nat}Si

Target mass: 3.5 kg Ge depending on runs

Used exposure: 121.3 kg x day

(before cuts 397.8 kg x day)

EDELWEISS II

EDELWEISS I(PRD71(2005)122002)

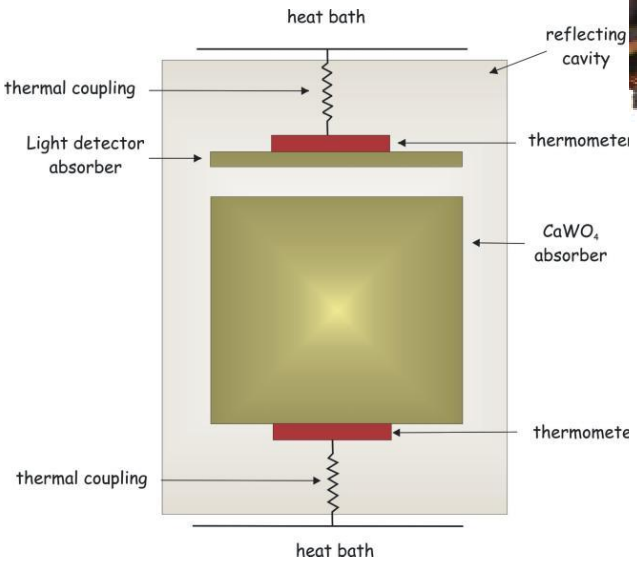
Experimental site: LSM

Target material: ^{nat}Ge

Target mass: 0.96 kg

Used exposure: 62 kg x day

See next slide for drawbacks



CRESST (AP23(2005)325, arXiv:0809.1829v2)

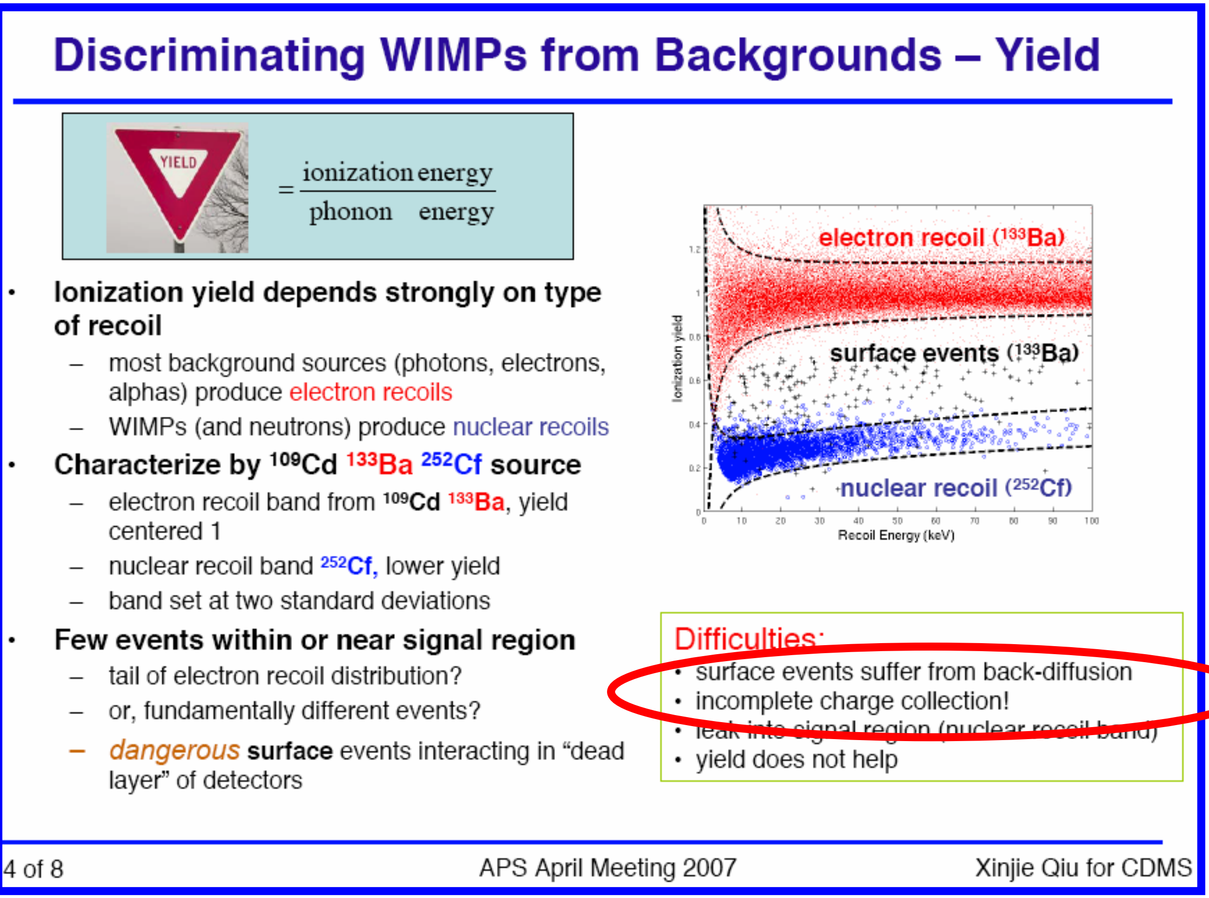
Experimental site: LNGS

Target material: CaWO$_4$

Target mass: 0.6 kg

Used exposure: 48 kg x day

Bolometer/ionization experiments, an example: CDMSII



Discriminating WIMPs from Backgrounds – Yield

$$= \frac{\text{ionization energy}}{\text{phonon energy}}$$

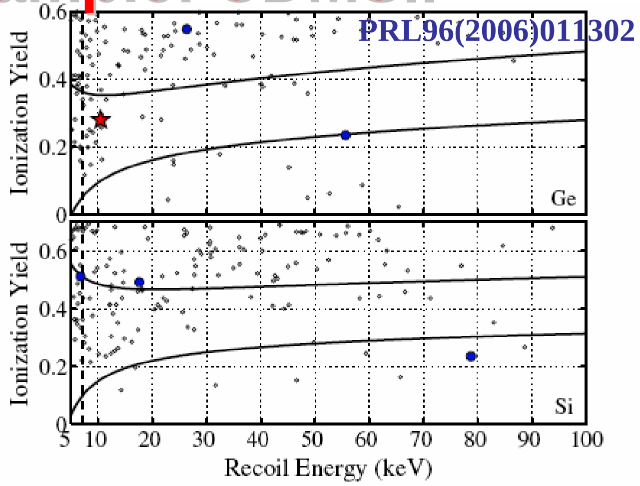
- **Ionization yield depends strongly on type of recoil**
  - most background sources (photons, electrons, alphas) produce electron recoils
  - WIMPs (and neutrons) produce nuclear recoils
- **Characterize by ^{109}Cd ^{133}Ba ^{252}Cf source**
  - electron recoil band from **^{109}Cd ^{133}Ba**, yield centered 1
  - nuclear recoil band **^{252}Cf,** lower yield
  - band set at two standard deviations
- **Few events within or near signal region**
  - tail of electron recoil distribution?
  - or, fundamentally different events?
  - *dangerous* **surface** events interacting in “dead layer” of detectors

Difficulties:

- surface events suffer from back-diffusion
- incomplete charge collection!
- leak into signal region (nuclear recoil band)
- yield does not help

4 of 8 APS April Meeting 2007 Xinjie Qiu for CDMS

“One Ge detector in tower 2, ZIP 5 [T2Z5(Ge)], had a spatial region of abnormal ionization response that was excluded from analysis. The Si detector T1Z6, known to be contaminated with ^{14}C, a beta emitter, was entirely excluded, as were detectors T1Z1(Ge) and T2Z1(Si) due to poor phonon sensor performance.” **PRL96(2006)011302**



PRL96(2006)011302

FIG. 3 (color online). Ionization yield versus recoil energy for events in all Ge detectors (upper) and all Si detectors (lower) passing initial data selection cuts prior to applying the surface electron recoil rejection cut. The signal region consists of recoil

COMMENTS:

•data “selection” and “handling”?(very small exposure released with respect to several years of the experiment)

• bckg rejection technique and associated uncertainties full under control?

•What about the needed continuous monitoring of rejection windows stability, energy scale and threshold, overall detection efficiency, calibration..?

•Are the two sensitive volumes (for ionization and bolometer signals) exactly identical?

•Bulk response, quenching factors, ….

•Starting from a high background level

Experiments using liquid noble gases (see arXiv: astro-ph/0806.0011)

- Single phase: LXe,LAr, LNe → scintillation, ionization
- Dual phase liquid /gas → scintillation + scintillation

Background rejection

in single phase detector:

- pulse shape discrimination γ/recoils from the UV scintillation photons

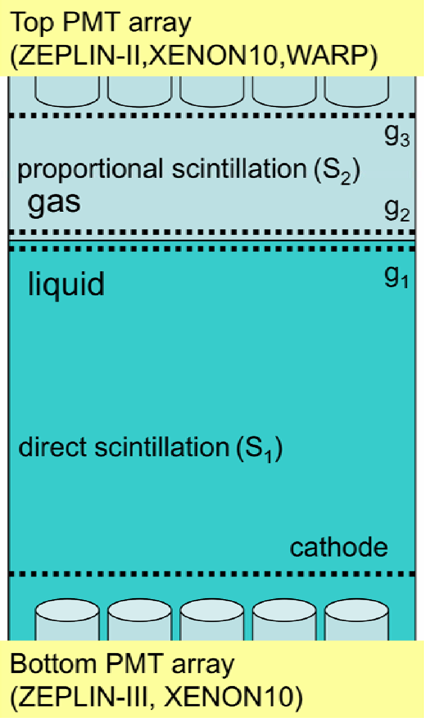
in dual phase detector:

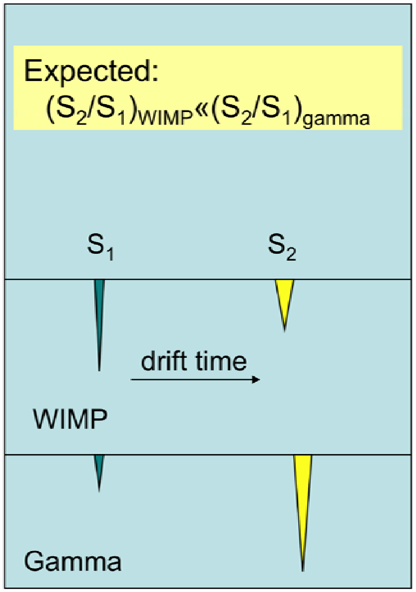
- prompt signal (S1): UV photons from excitation and ionisation
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field

DAMA/LXe

ZEPLIN-I

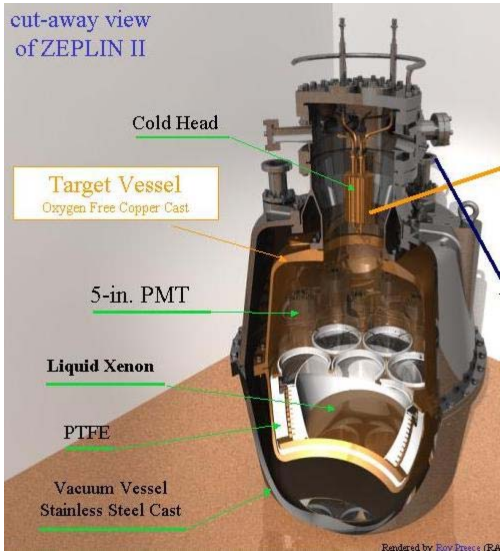
DAMA/LXe: low background developments and applications to dark matter investigation (since N.Cim. A 103 (1990) 767)





XENON, WARP, ZEPLIN

ZEPLIN-III (arXiv:astro-ph/0812.1150)
ZEPLIN-II(AP28(2007)287;PLB653(2007)161)



Experimental site: Boulby mine

Target material:^{nat}Xe

Target mass:7.2 kg (tot: 31 kg)

Used exposure: 225 kg x day

XENON10 (PRL100(2008)021303)

Experimental site: Gran Sasso (1400 m depth)

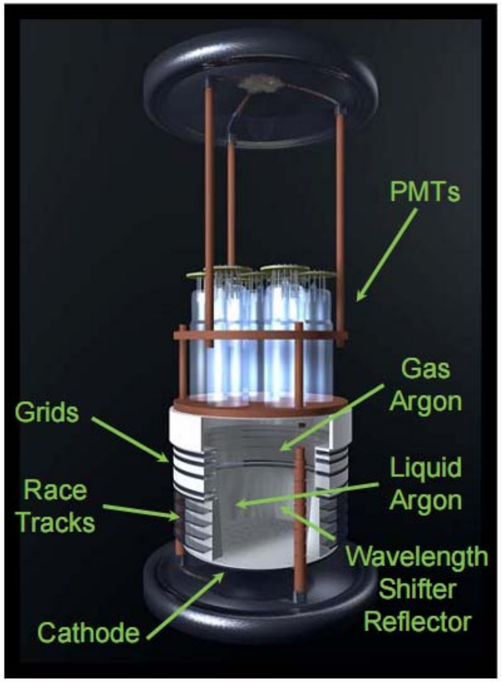
Target material:^{nat}Xe

Target mass:≈5.4 kg (tot: 15 kg)

Used exposure:136 kg × day

See next slide for drawbacks

WARP (AP28(2008)495)



Experimental site: Gran Sasso (1400 m depth)

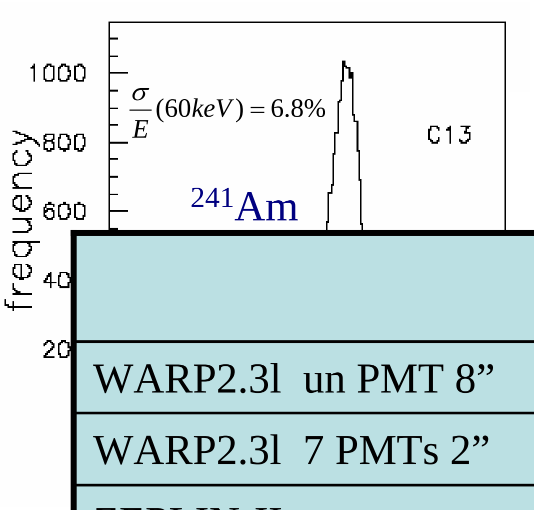
Target material:^{nat}Ar

Target mass:≈ 1.83 kg (tot: 2.6 kg)

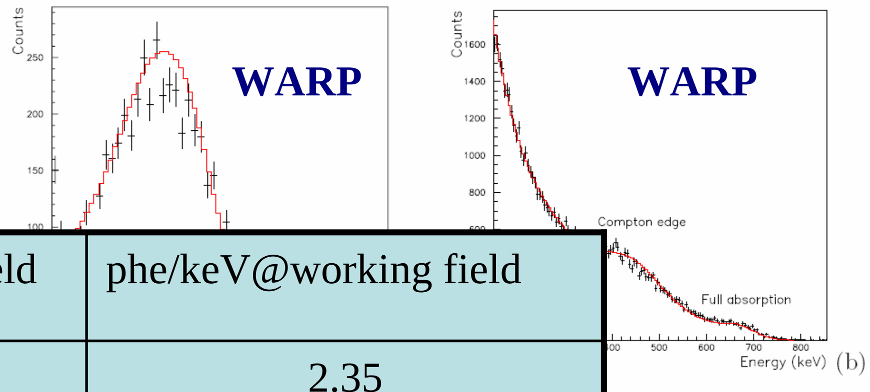
Used exposure:96.5 kg × day

Examples of energy resolutions: comparison with NaI(Tl)

NaI(Tl)



NIMA 574 (2007) 83



uperimposed with the
122 keV, B.R. 85.6%,

	phe/keV@zero field	phe/keV@working field
WARP2.3l un PMT 8”	--	2.35
WARP2.3l 7 PMTs 2”	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	--
Neon	0.93	field not foreseen

AP 28 (2007) 287

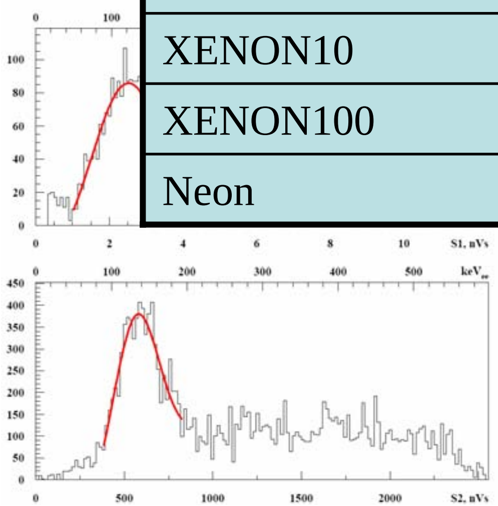


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

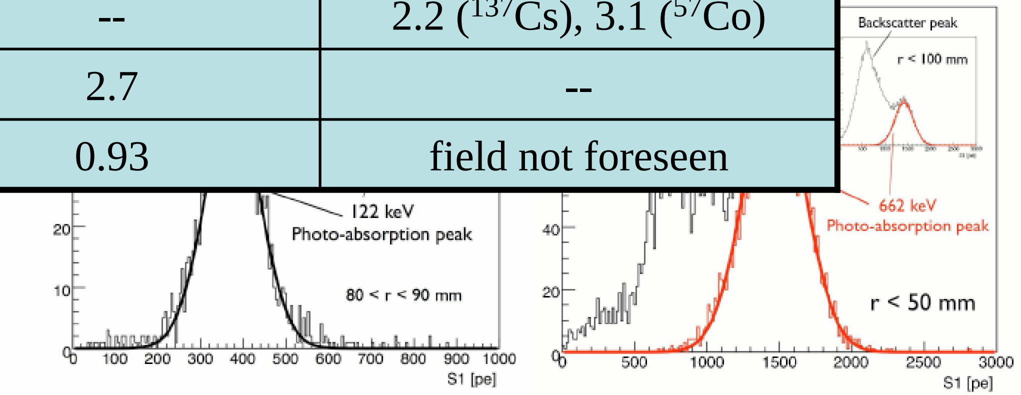
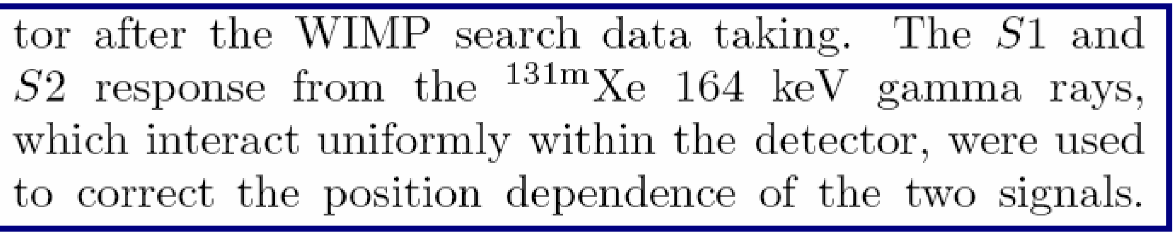


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

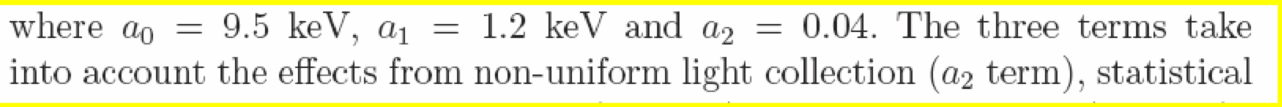
JoP: Conf. Ser. 65 (2007) 012015

… non-uniformity of the two-phase detectors: intrinsic limit



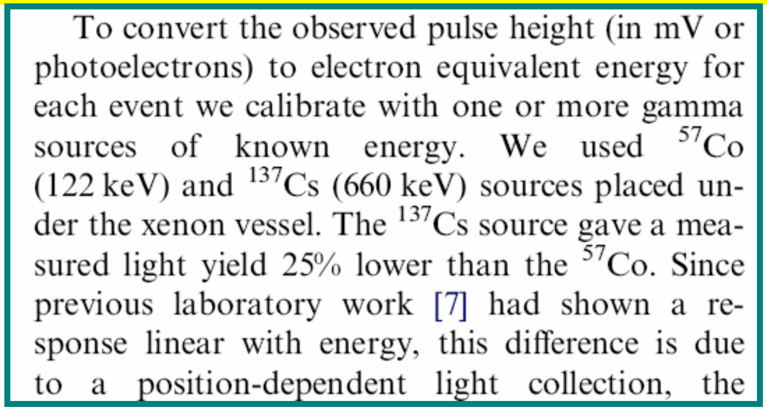
tor after the WIMP search data taking. The $S1$ and $S2$ response from the ^{131m}Xe 164 keV gamma rays, which interact uniformly within the detector, were used to correct the position dependence of the two signals.

position dependent correction on S1 and S2 signals with maps obtained from activated Xe XENON10 astro-ph0706.0039v1.



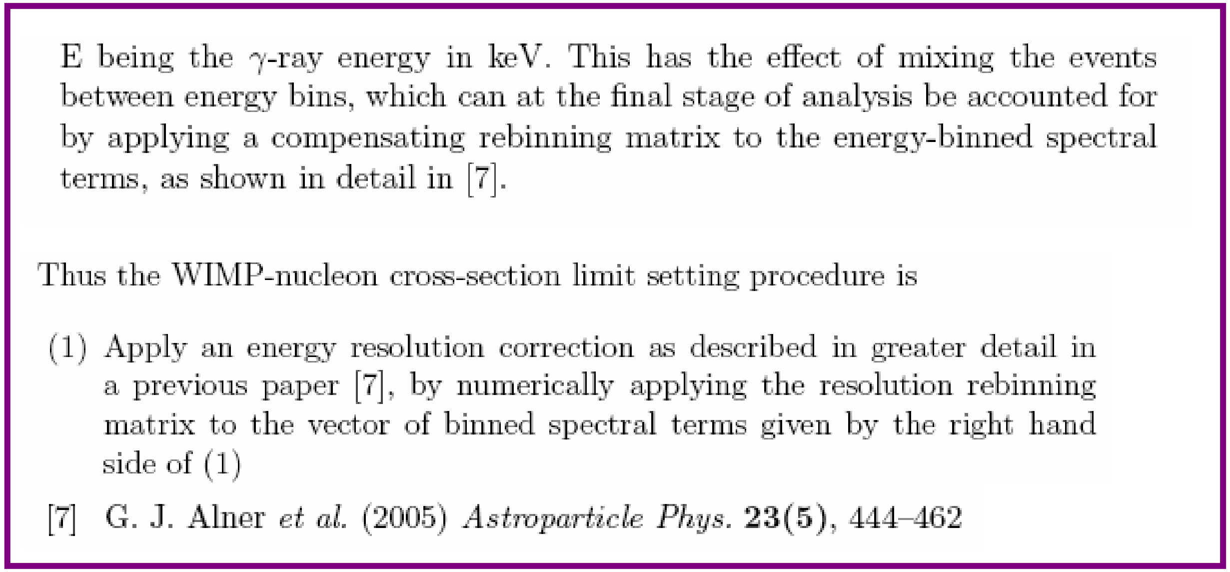
where $a_0 = 9.5$ keV, $a_1 = 1.2$ keV and $a_2 = 0.04$. The three terms take into account the effects from non-uniform light collection (a_2 term), statistical

effects of non-uniform light collection accounted in WARP (NIMA 574 (2007) 83)



To convert the observed pulse height (in mV or photoelectrons) to electron equivalent energy for each event we calibrate with one or more gamma sources of known energy. We used ^{57}Co (122 keV) and ^{137}Cs (660 keV) sources placed under the xenon vessel. The ^{137}Cs source gave a measured light yield 25% lower than the ^{57}Co. Since previous laboratory work [7] had shown a response linear with energy, this difference is due to a position-dependent light collection, the

A geometrical correction is performed via a "rebinning matrix" evaluated by MonteCarlo in ZEPLIN-I, AP 23(2005)444.



E being the γ-ray energy in keV. This has the effect of mixing the events between energy bins, which can at the final stage of analysis be accounted for by applying a compensating rebinning matrix to the energy-binned spectral terms, as shown in detail in [7].

Thus the WIMP-nucleon cross-section limit setting procedure is

(1) Apply an energy resolution correction as described in greater detail in a previous paper [7], by numerically applying the resolution rebinning matrix to the vector of binned spectral terms given by the right hand side of (1)

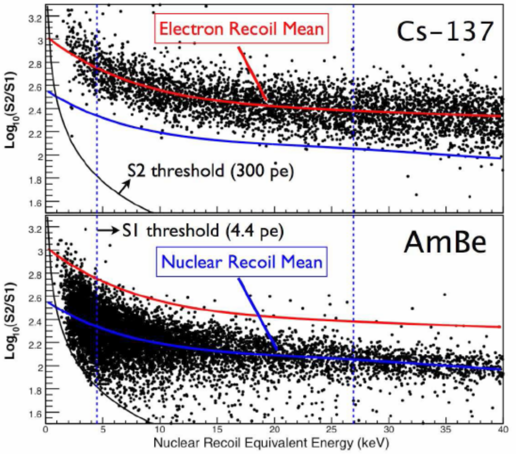
[7] G. J. Alner *et al.* (2005) *Astroparticle Phys.* **23(5)**, 444–462

the position dependent correction is still applied in ZEPLIN-II, AP 28 (2007) 287

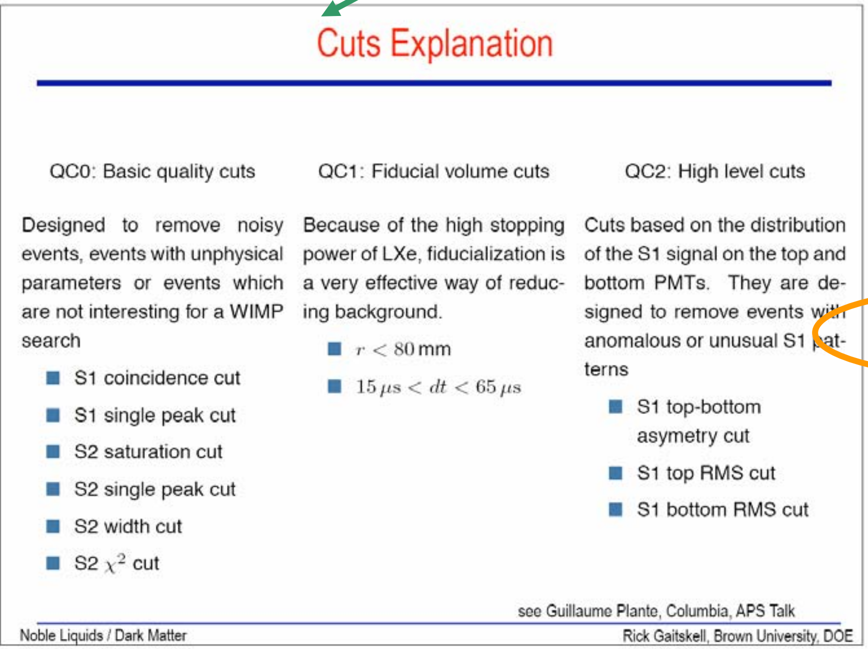
Liquid noble gas experiments, an example: XENON10

(PRL100(2008)021303)

Despite of the small light response an energy threshold of 2 keVee is claimed,
determination of the energy threshold @2keV without specific calibration,
the hardware threshold on the single PMTs is not given,
no information about energy resolution @2keV



But cautious actitude: Many cuts are applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration ?



Cuts Explanation

QC0: Basic quality cuts

Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search

- S1 coincidence cut
- S1 single peak cut
- S2 saturation cut
- S2 single peak cut
- S2 width cut
- S2 χ^2 cut

QC1: Fiducial volume cuts

Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.

- $r < 80\,\mathrm{mm}$
- $15\,\mu s < dt < 65\,\mu s$

QC2: High level cuts

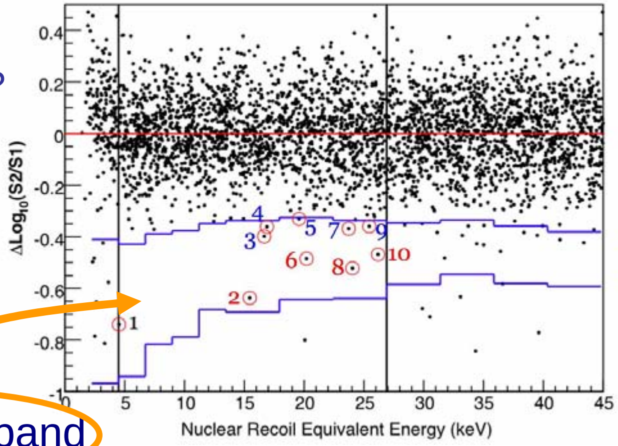
Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns

- S1 top-bottom asymmetry cut
- S1 top RMS cut
- S1 bottom RMS cut

see Guillaume Plante, Columbia, APS Talk

Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE

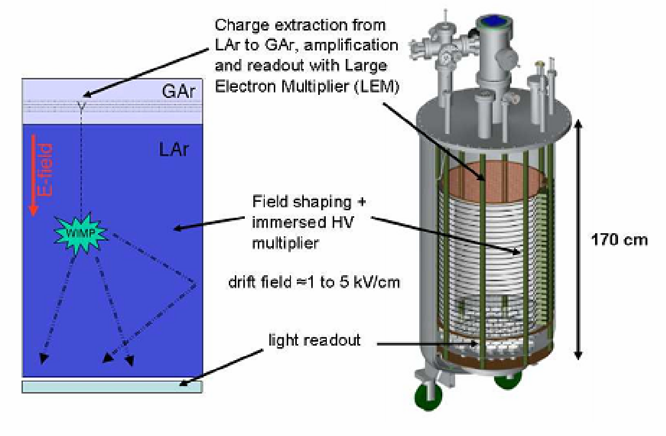


lower half band

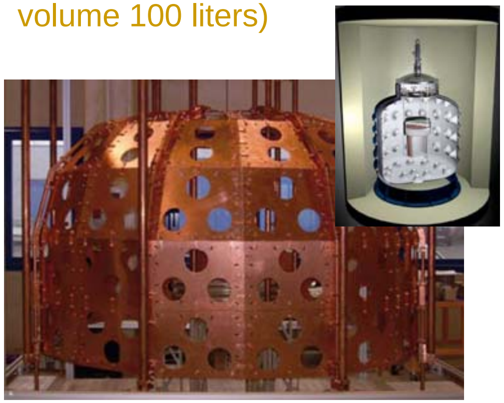
- **Ten events survive the many cuts**
- **Some speculations about their nature**
- **Stability?**
- **Intrinsic limitations of the method reached**

Some other direct detection activities either in preparation or at R&D stage

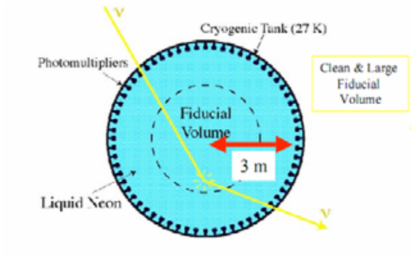
ArDM: ton scale dual-phase Argon detector



WARP: double phase Argon detector at LNGS (fiducial volume 100 liters)

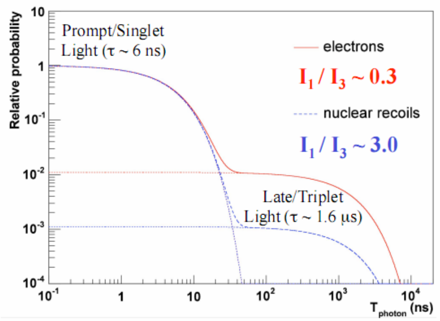


CLEAN: **Cryogenic Low Energy Astrophysics with Neon**

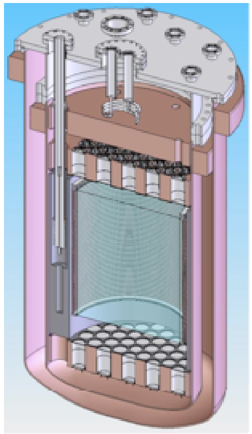


Single phase liquid Neon detector of tens of tons

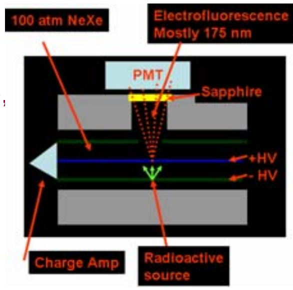
DEAP (SNOLAB): scintillation light in LAr at 85K → PSD studying different lifetimes in singlet/ triplet states for electrons and nuclear recoil (ton scale)

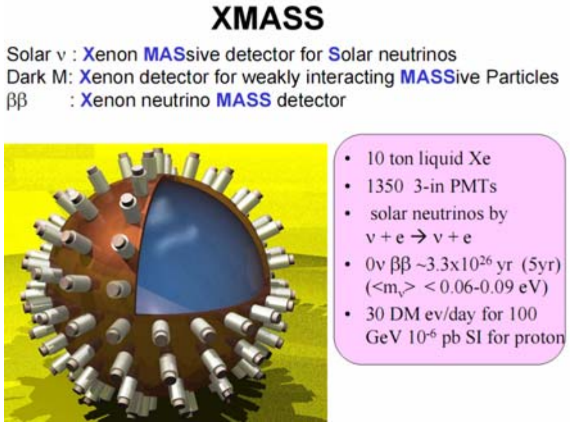


Lux: dual phase time projection chamber with 100 kg LXe (tot: 300 kg)



SIGN: A High-Pressure, Room-Temperature, Gaseous-Neon-Based Underground Physics Detector (100 kg @ 100 atm towards 10 tons)





XMASS

Solar ν : **X**enon **MAS**sive detector for **S**olar neutrinos
Dark M: **X**enon detector for weakly interacting **MASS**ive Particles
ββ : **X**enon neutrino **MASS** detector

- 10 ton liquid Xe
- 1350 3-in PMTs
- solar neutrinos by ν + e → ν + e
- 0ν ββ ~3.3×10^{26} yr (5yr) ($<m_\nu>$ < 0.06-0.09 eV)
- 30 DM ev/day for 100 GeV 10^{-6} pb SI for proton

… they should certainly profit by the previous experience to suitably improve the detectors' responses and performances a “discrimination on an event-by-event base” is possible just for zero systematics. Rejection procedures would require a much deeper and quantitative investigation than those done up to now at very small scale (from grams to few kg)

e.m. component of the rate can contain the signal or part of it

even assuming pure recoil case and ideal discrimination on an event-by-event base, the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well known existing recoil-like undistinguishable background

Therefore, even in the ideal case the “excellent background suppression” can not provide a “signal identification”

A model independent signature is needed

Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities

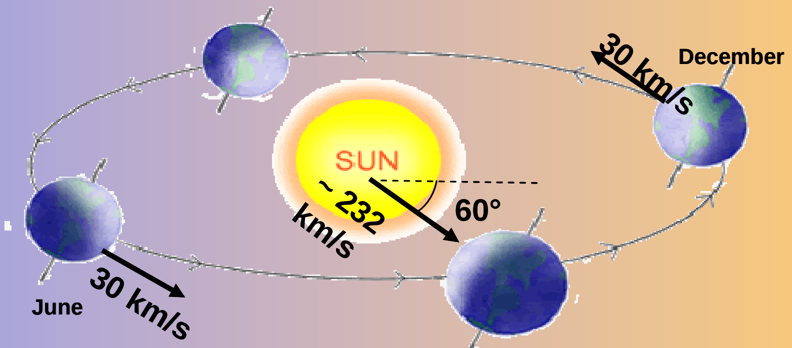
very hard to realize

Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high σ

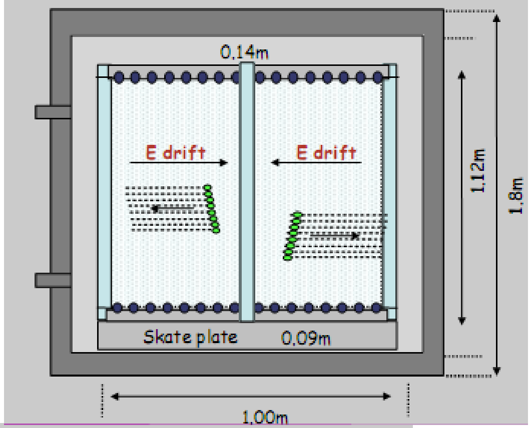
Annual modulation **Annual variation of the interaction rate due to Earth motion around the Sun**

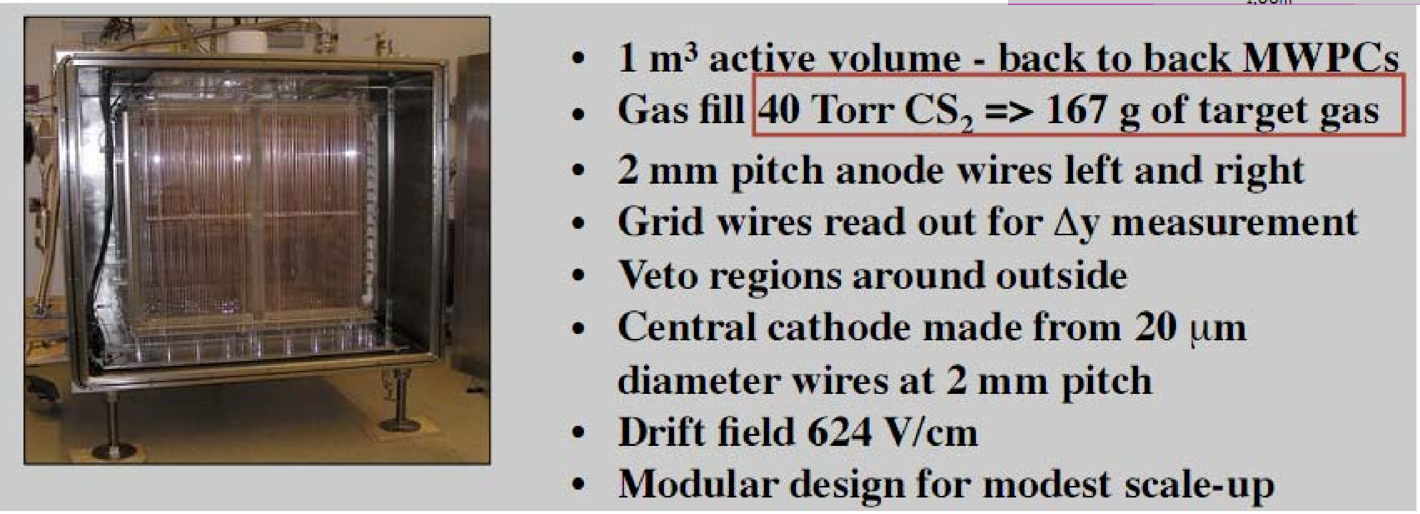
at present the only feasible one



Directionality, an example: DRIFT-IIa

- Experimental site: Boulby mine
- Identification of the Dark Matter particle by exploiting the non-isotropic recoil distribution correlated to the Earth position with to the Sun
- dE/dx discrimination between gammas and neutrons





- 1 m^3 active volume - back to back MWPCs
- Gas fill 40 Torr CS_2 => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design for modest scale-up

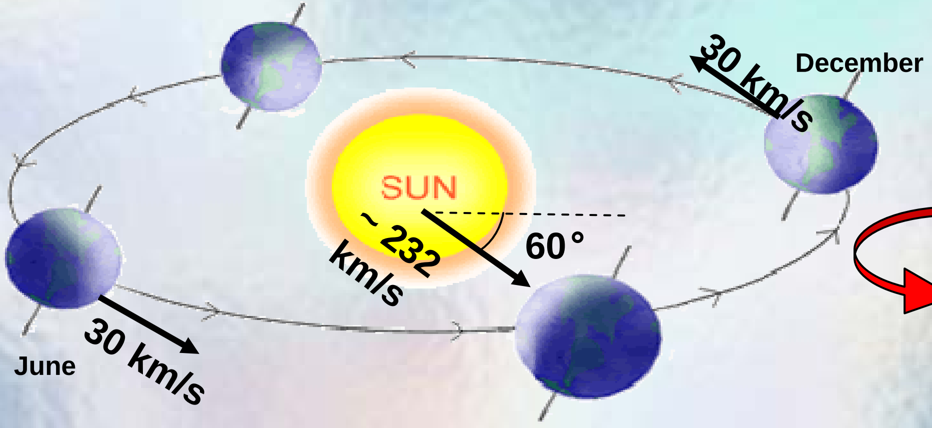
After an exposure of 10.2 kg x days a population of nuclear recoils (interpreted as due to the decay of unexpected ^{222}Rn daughter nuclei, present in the chamber) has been observed.

also R&D by: DMTPC -low pressure CF_4 TPC (optical readout)
MIMAC -2D (electronic readout with Micromegas)
NEWAge - low pressure CF_4 TPC (μpic 2D readout)

Still far from results on Dark Matter particle

Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R}\, dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because of the Earth's motion around the Sun moving in the Galaxy

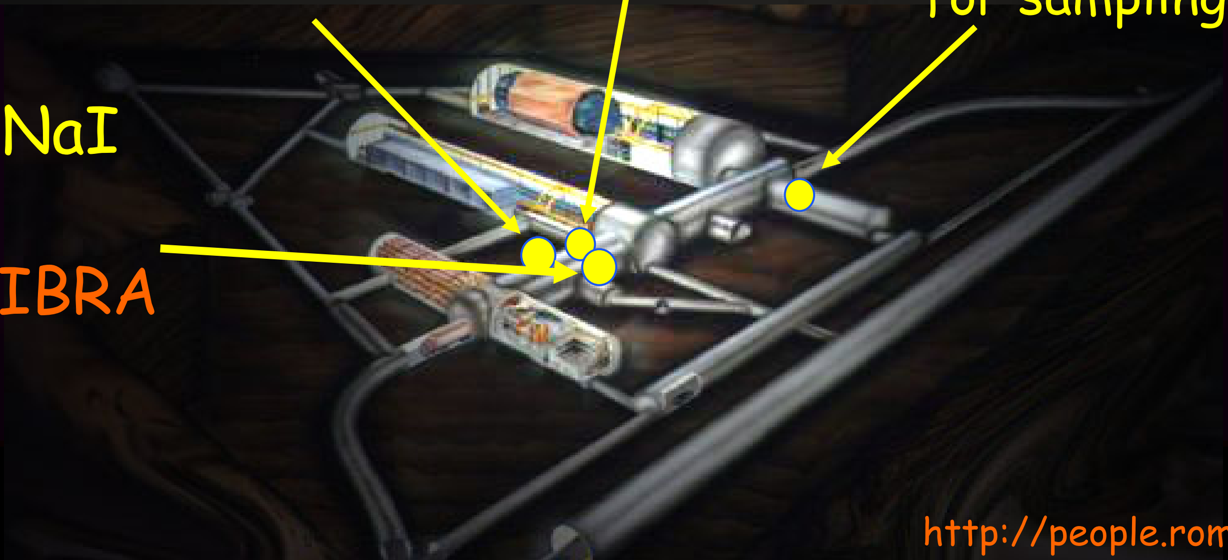
Requirements:

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2nd June)
5) For single hit in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7% (for usually adopted halo distributions, but it can be larger in case of some possible scenarios)

To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Roma2,Roma1,LNGS,IHEP/Beijing

DAMA: an observatory for rare processes @LNGS



DAMA/R&D

DAMA/LXe

low bckg DAMA/Ge
for sampling meas.

DAMA/NaI
↓
DAMA/LIBRA

http://people.roma2.infn.it/dama

DAMA/NaI : ≈100 kg NaI(Tl)

data taking completed on July 2002, last data release 2003: total exposure (7 annual cycles) 0.29 ton x yr

Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

Possible Pauli exclusion principle violation	PLB408(1997)439
CNC processes	PRC60(1999)065501
Electron stability and non-paulian transitions in Iodine atoms (by L-shell)	PLB460(1999)235
Search for solar axions	PLB515(2001)6
Exotic Matter search	EPJdirect C14(2002)1
Search for superdense nuclear matter	EPJA23(2005)7
Search for heavy clusters decays	EPJA24(2005)51

Results on DM particles:

PSD	PLB389(1996)757
Investigation on diurnal effect	N.Cim.A112(1999)1541
Exotic Dark Matter search	PRL83(1999)4918
Annual Modulation Signature	

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125, other works in progress ...

model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

DAMA/LIBRA ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

LIBRA
in DAMA

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

improving installation and environment

PMT +HV divider

storing new crystals

Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N_2

etching staff at work in clean room

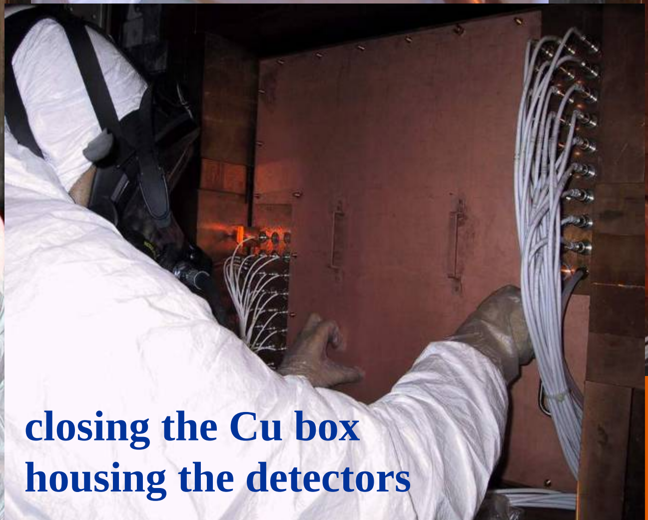
The new DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

filling the inner Cu box with further shield



closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

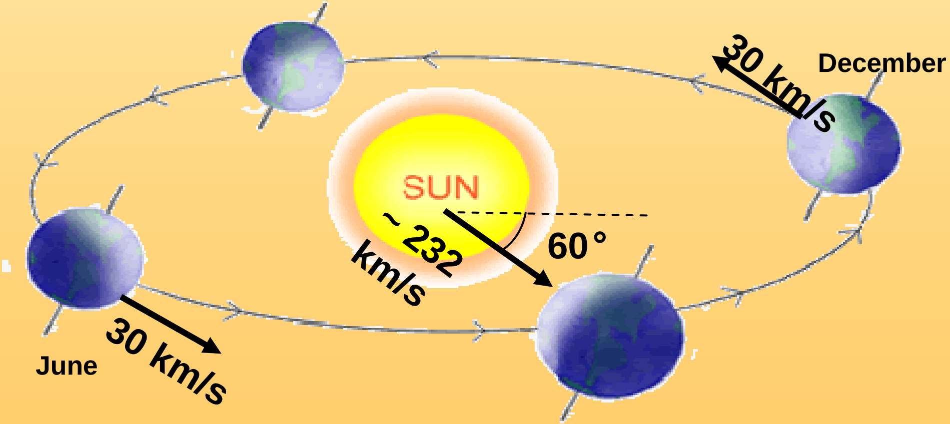
The calibration system

Experimental *single-hit* residuals rate vs time and energy

- Model-independent investigation of the annual modulation signature has been carried out by exploiting the time behaviour of the residual rates of the *single-hit* events in the lowest energy regions of the DAMA/LIBRA data.

- These residual rates are calculated from the measured rate of the *single-hit* events (obviously corrections for the overall efficiency and for the acquisition dead time are already applied) after subtracting the constant part:

$$\left\langle r_{ijk} - flat_{jk} \right\rangle_{jk}$$



- r_{ijk} is the rate in the considered *i-th* time interval for the *j-th* detector in the *k-th* energy bin

- $flat_{jk}$ is the rate of the *j-th* detector in the *k-th* energy bin averaged over the cycles.

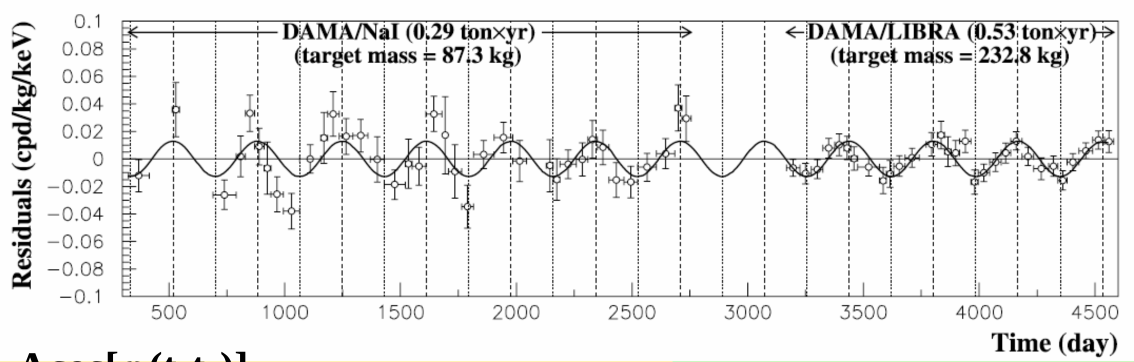
- The average is made on all the detectors (*j* index) and on all the energy bins (*k* index)

- The weighted mean of the residuals must obviously be zero over one cycle.

Model independent annual modulation result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

EPJC 56(2008)333



$A\cos[\omega(t-t_0)]$

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 8.2σ C.L.

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8´10-4

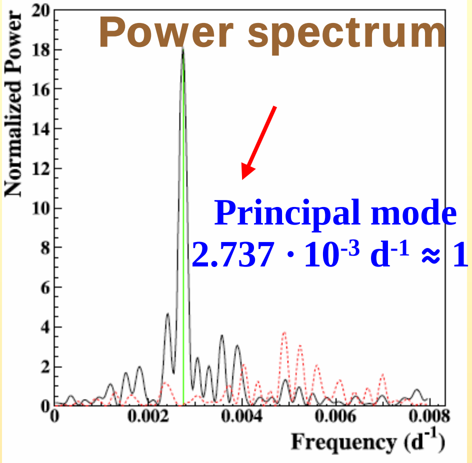
from the fit with all the parameters free:

A = (0.0131 ± 0.0016) cpd/kg/keV

t_0 = (144 ± 8) d

T = (0.998 ± 0.003) y

Experimental single-hit residuals rate vs time and energy in 2-6 keV over 11 annual cycles



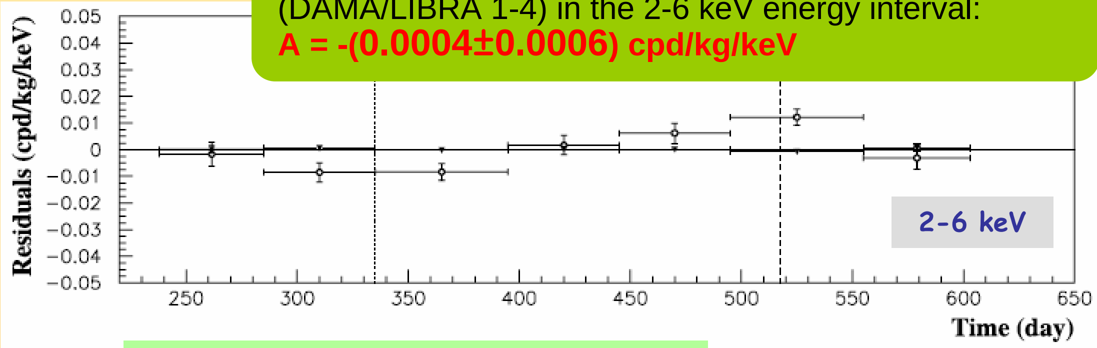
Power spectrum

Principal mode

$2.737 \cdot 10^{-3}$ $d^{-1} \approx 1$ y^{-1}

experimental residual rate of the multiple hit events (DAMA/LIBRA 1-4) in the 2-6 keV energy interval:

A = -(0.0004±0.0006) cpd/kg/keV



Multiple hits events = Dark Matter particle "switched off"

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

model independent evidence of a particle Dark Matter component in the galactic halo at 8.2σ C.L.

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

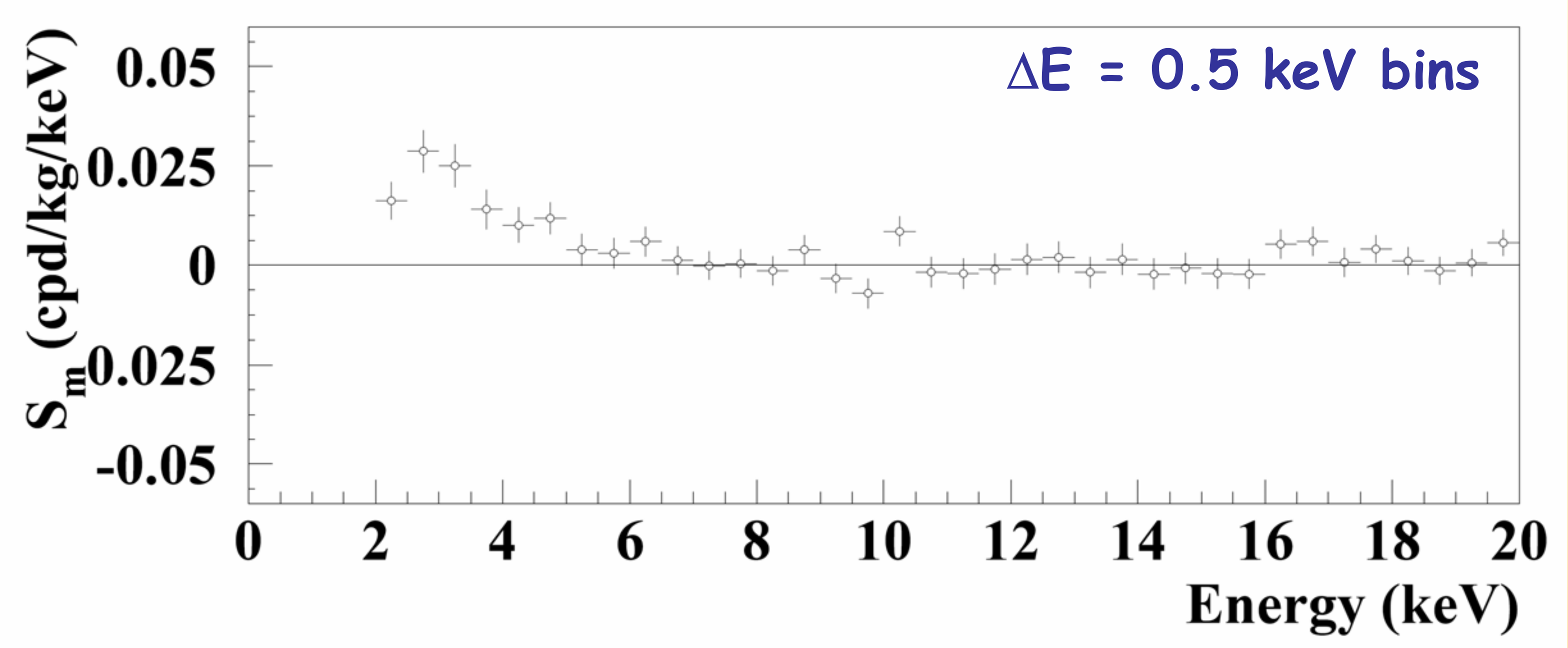
Energy distribution of the modulation amplitudes, S_m, for the total exposure

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

here $T=2\pi/\omega=1$ yr and $t_0= 152.5$ day

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr



A clear modulation is present in the (2-6) keV energy interval, while S_m values compatible with zero are present just above

In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 24.4 for 28 degrees of freedom

The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about S_m already exclude any sizeable presence of systematical effects.

Additional investigations on the stability parameters

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1%

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Temperature	-(0.0001 ± 0.0061) °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	-(0.07 ± 0.18) l/h	-(0.05 ± 0.24) l/h
Pressure	(0.015 ± 0.030) mbar	-(0.013 ± 0.025) mbar	(0.022 ± 0.027) mbar	(0.0018 ± 0.0074) mbar
Radon	-(0.029 ± 0.029) Bq/m^3	-(0.030 ± 0.027) Bq/m^3	(0.015 ± 0.029) Bq/m^3	-(0.052 ± 0.039) Bq/m^3
Hardware rate above single photoelectron	-(0.20 ± 0.18) × 10^{-2} Hz	(0.09 ± 0.17) × 10^{-2} Hz	-(0.03 ± 0.20) × 10^{-2} Hz	(0.15 ± 0.15) × 10^{-2} Hz

All the measured amplitudes well compatible with zero

+none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Summary of the results obtained in the additional investigations of possible systematics or side reactions

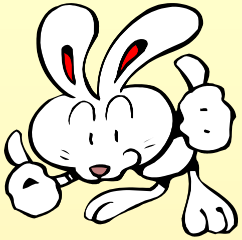
EPJC 56(2008)333

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured by MACRO	**$<3\times10^{-5}$ cpd/kg/keV**

+ even if larger they cannot satisfy all the requirements of annual modulation signature

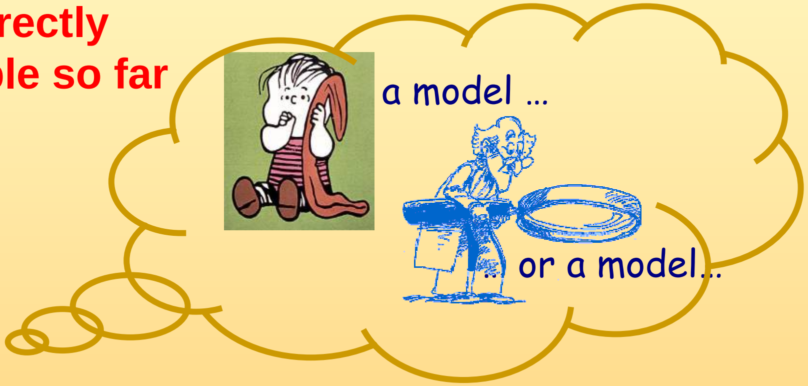
Thus, they can not mimic the observed annual modulation effect

The positive and model independent result by DAMA/NaI + DAMA/LIBRA



- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 11 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed modulation amplitude and to contemporaneously satisfy all the peculiarities of the signature

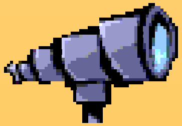
No other experiment whose result can be directly compared in model independent way is available so far



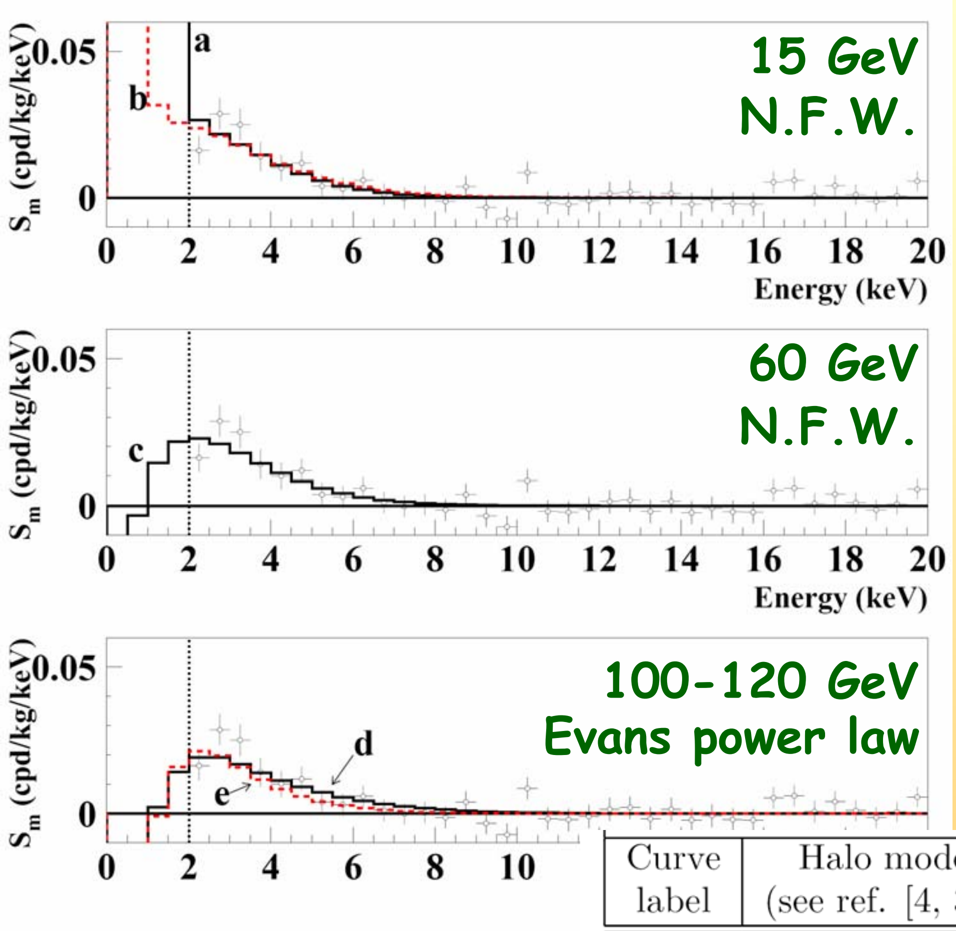
Corollary quests for candidates

•Just to offer some naive feeling on the complexity of the argument: experimental S_m values vs expected behaviours

for some DM candidates in few of the many possible astrophysical, nuclear and particle physics scenarios and parameters values



Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$

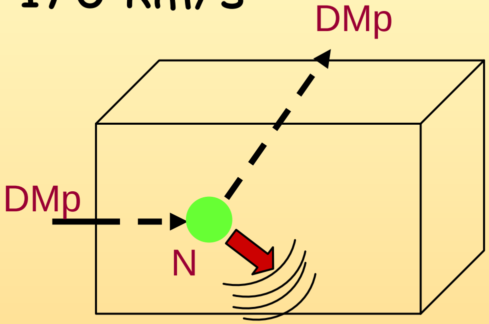


WIMP DM candidate (as in [4])

considering elastic scattering on nuclei

SI dominant coupling

v_0 = 170 km/s



About the same C.L.

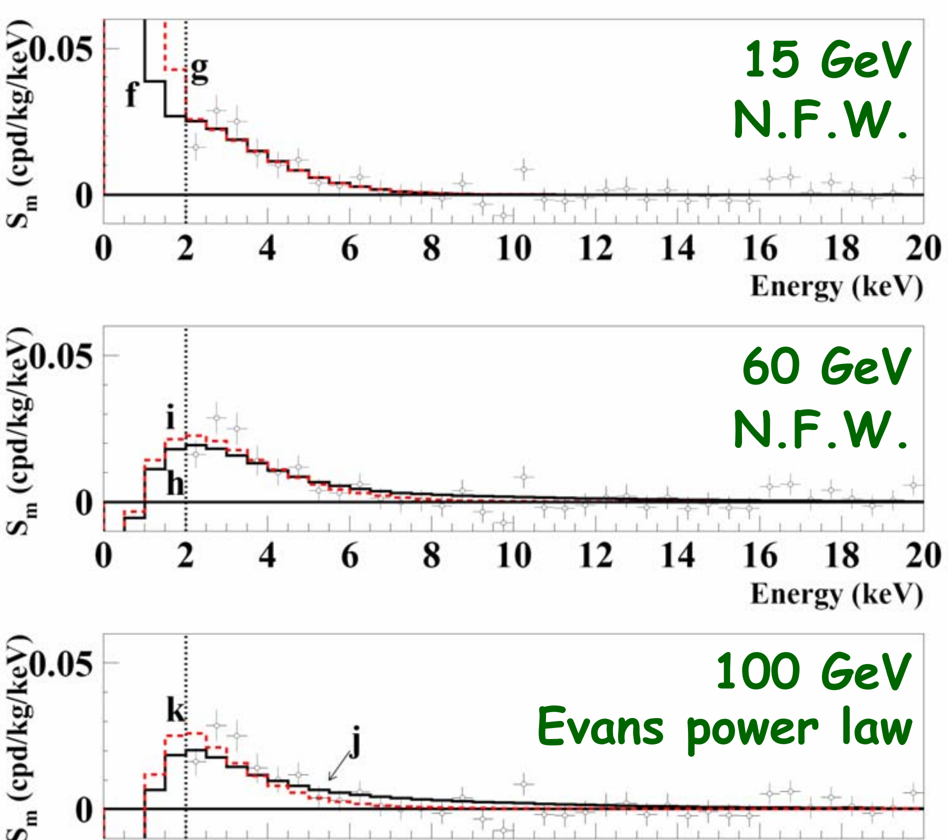
...scaling from NaI

channeling contribution as in EPJC53(2008)205 considered for curve *b*

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)	0.17	A	120 GeV	1.3×10^{-5}

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$

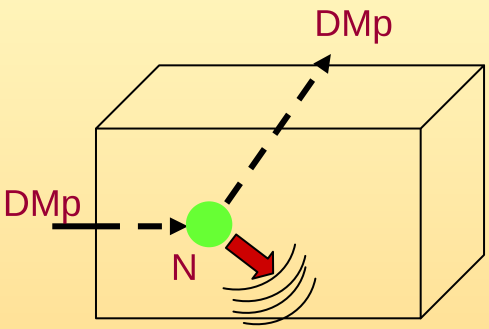


WIMP DM candidate (as in [4])

Elastic scattering on nuclei

SI & SD mixed coupling

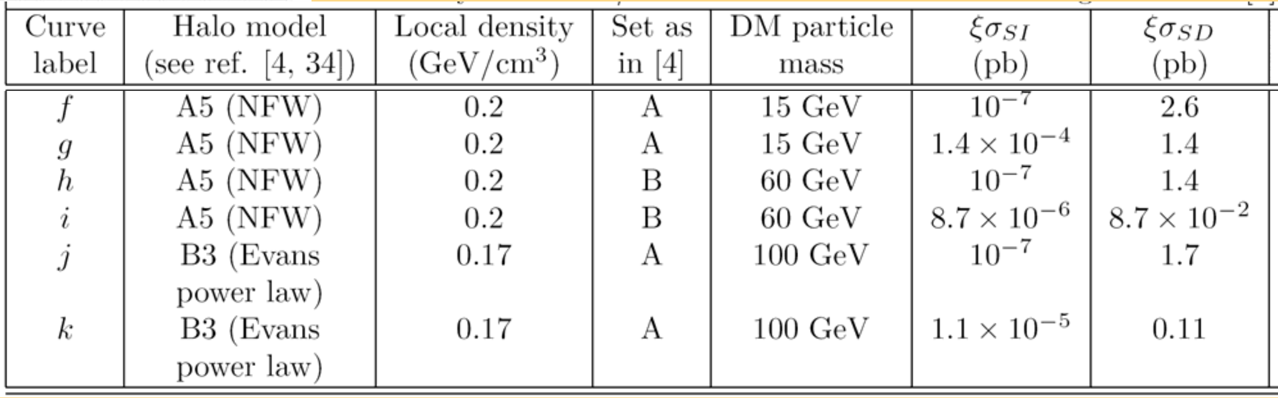
$v_0 = 170$ km/s



About the same C.L.

...scaling from NaI

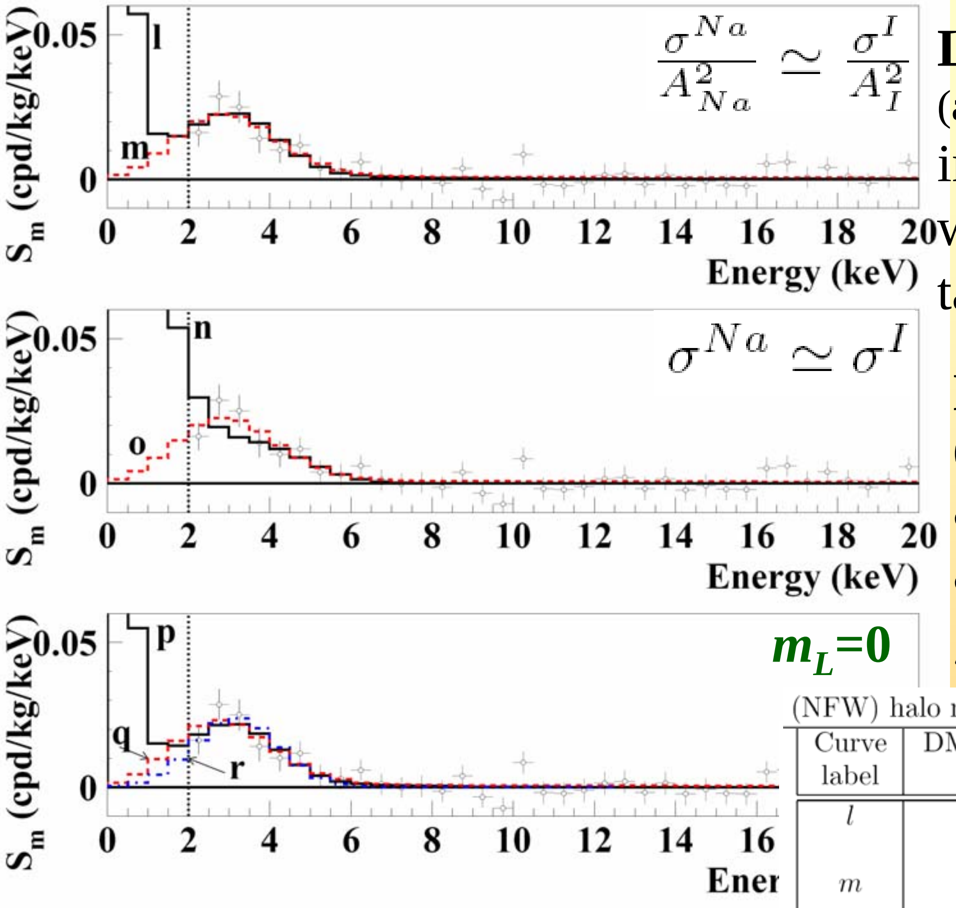
$\theta = 2.435$



Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}
j	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7
k	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11

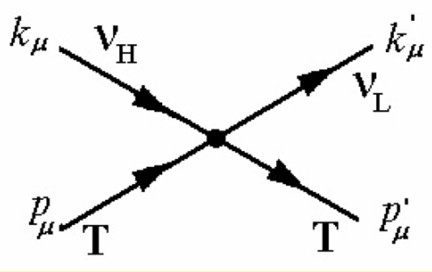
[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$



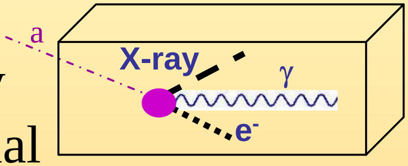
LDM candidate

(as in arXiv:0802.4336): inelastic interaction with electron or nucleus targets

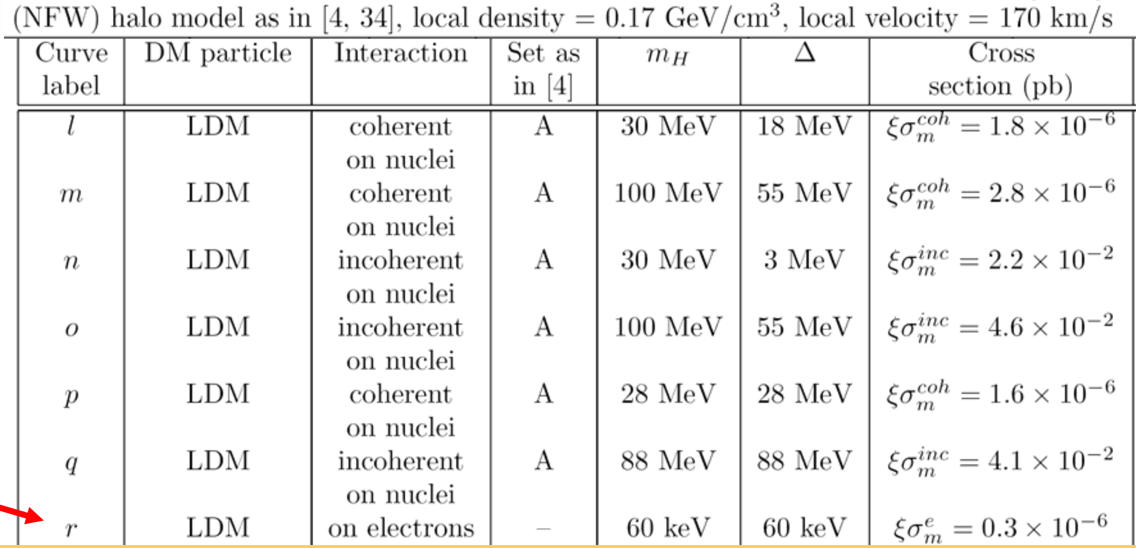


Light bosonic candidate

(as in IJMPA21(2006)1445): axion-like particles totally absorbed by target material



About the same C.L.



(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm³, local velocity = 170 km/s

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^{e} = 0.3 \times 10^{-6}$

curve *r*: also pseudoscalar axion-like candidates (e.g. majoron) m_a=3.2 keV g_{aee}= 3.9 10^{-11}

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates (in several of the many astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in SUSY theories

Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,… (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

heavy exotic canditates, as "4th family atoms", ...

Elementary Black holes such as the Daemons

Kaluza Klein particles

… and more

Possible model dependent positive hints from indir searches not in conflict with DAMA results
(but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

Available results from direct searches using different target materials and approaches do not give any robust conflict

where we are …

- DAMA/LIBRA over 4 annual cycles (0.53 ton×yr) confirms the results of DAMA/NaI (0.29 ton×yr)
- The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2 σ (total exposure 0.82 ton × yr)

- First upgrading of the experimental set-up in Sept. 2008

Phase 1

- Mounting of the "clean room" set-up in order to operate in HP N_2 atmosphere
- Opening of the shield of DAMA/LIBRA set-up in HP N_2 atmosphere
- Replacement of some PMTs in HP N_2 atmosphere
- Closing of the shield

Phase 2

- Dismounting of the Tektronix TDs (Digitizers + Crates)
- Mounting of the new Acqiris TD (Digitizers + Crate)
- Mounting of the new DAQ system with optical read-out
- Test of the new TDs (*hardware*) and of the new required DAQ system *(software)*

- *Since Oct. 2008 again in data taking*

...and where we are going

- *Continuing the data taking*
- *Updating of corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc. is in progress*
- *Next upgrading: replacement of all the PMTs with higher Q.E. ones*
- *Production of new Q.E. PMTs in progress. Goal: to study if it is possible to lower the energy threshold of the detectors*
- *Analyses/data taking to investigate other rare processes in progress/foreseen*

A possible highly radiopure NaI(Tl) multi-purpose set-up DAMA/1 ton (proposed by DAMA in 1996) is at present at R&D phase

Epilogo

Techniques

Results obtained with different target materials and/or different approaches cannot intrinsically be compared among them directly.

Models

It does not exist any approach (in direct and indirect DM investigation) which can offer information on the nature of the candidate independently on assumed astrophysical, nuclear and particle physics scenarios.

Methods

At the end, even in presence of an excess of nuclear recoil candidates, it is not guaranteed that these events are due neither to existing side processes nor to an instrumental effect. A model independent signature is needed.

Epistemology

“The question, then, is whether this flexibility generated by model-dependence can be mitigated by robustness - and here the answer is negative. Simply, because a model dependent is so burdened by assumptions, it follows that showing that the same result holds while varying a few parameters does little to lessen this dependence” ….. *“from the fact that it is pragmatically convenient for us to have multiple lines of support for the same result, it does not follow that possessing these alternate lines of support is epistemically valuable”*, R. Hudson, Found. Phys. 39 (2009) 174.

Implications

E.g. the sociological aspect: *“Sometimes detailed information is only needed for the outsiders, if you doubt the data or the analysis, but not needed, if an analysis is trusted.”*, an anonymous reviewer.

“Chi mira piu` alto, si differenzia piu` altamente; e ‘l volgersi al gran libro della natura, che e` ‘l proprio oggetto della filosofia, e` il modo per alzar gli occhi”, Dialogo dei massimi sistemi, G. Galilei

di

or!