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INFN-Roma Tor Vergata

TAUP 2007,
Sendai, September 2007

Direct searches for WIMPs

(above LN_2 temperature)

Relic DM particles from primordial Universe

Heavy candidates:

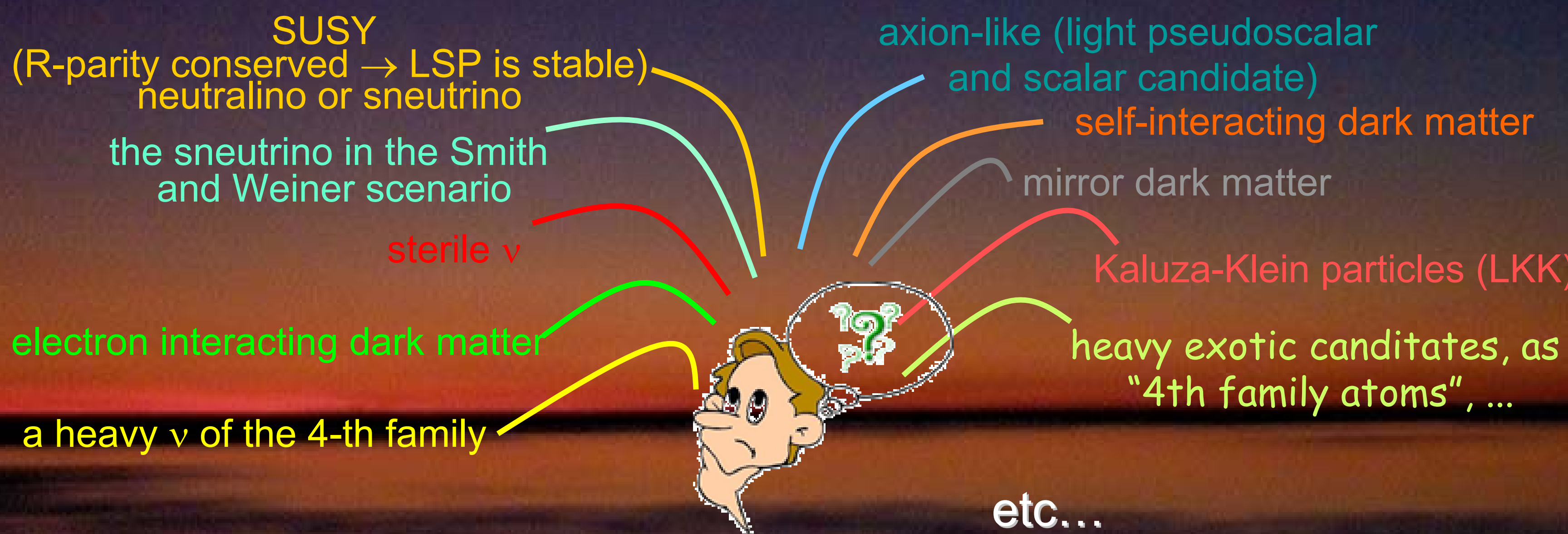
- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time:

  $<\sigma_{ann} \cdot v> \sim 10^{-26}/\Omega_{WIMP}h^2 \ cm^3 s^{-1} \ \rightarrow \ \sigma_{ordinary\ matter} \sim \sigma_{weak}$
- 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:

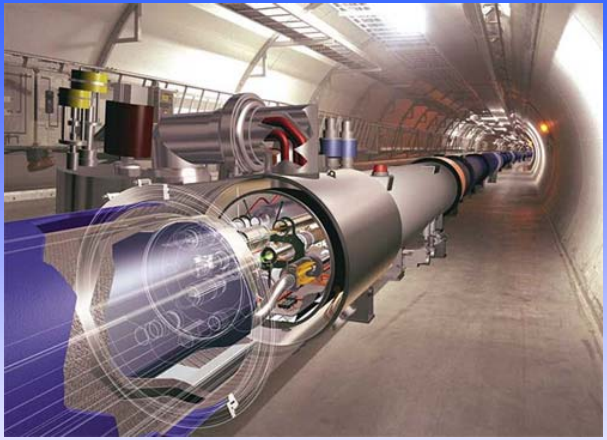
axion, sterile neutrino, axion-like particles cold or warm DM

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



+ multi-component halo?

even a suitable particle not yet foreseen by theories



What accelerators can do:

to demostrate the existence of some of the possible DM candidates

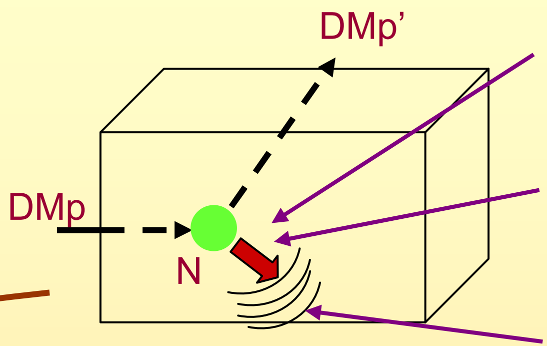
What accelerators cannot do:

to credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution…

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

DM direct detection method using a model independent approach

Some direct detection processes:



Ionization:
Ge, Si

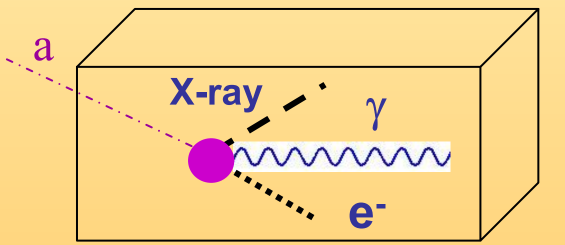
Bolometer:
TeO_2, Ge, $CaWO_4$, …

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

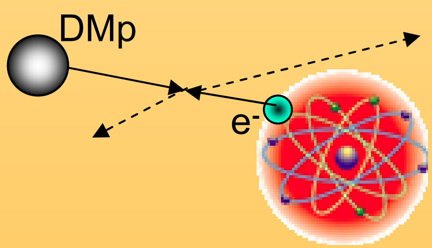
- Scatterings on nuclei
  → detection of nuclear recoil energy

- Excitation of bound electrons in scatterings on nuclei
  → detection of recoil nuclei + e.m. radiation

- Conversion of particle into electromagnetic radiation
  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons
  → detection of e.m. radiation



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**

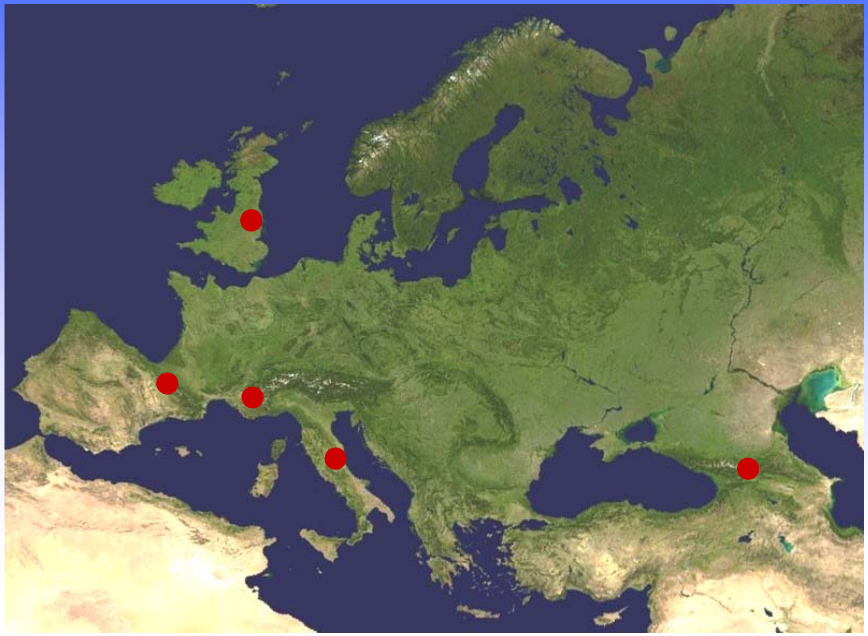
Dark Matter direct detection activities in underground labs

✓ Various approaches and techniques (many still at R&D stage)

✓ Various different target materials

✓ Various different experimental site depths

✓ Different radiopurity levels, etc.



- Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, Xenon10
- Boulby (depth ~ 3000 m.w.e.): Drift, Zeplin, NAIAD
- Modane (depth ~ 4800 m.w.e.): Edelweiss
- Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM

- Snolab (depth ~ 6000 m.w.e.): Picasso, DEAP, CLEAN
- Stanford (depth ~10 m): CDMS I
- Soudan (depth ~ 2000 m.w.e.): CDMS II

- Y2L (depth ~ 700 m): KIMS
- Oto (depth ~ 1400 m.w.e.): PICO-LON
- Kamioka (depth ~2700 m.w.e.): XMASS

DIRECT DETECTION EXPERIMENTS

Experiment	Target	Type	Status	Site
ANAIS	NaI	annual modulation	construction	Canfranc
DAMA/NaI	**NaI**	**annual modulation**	**concluded**	**LNGS**
DAMA/LIBRA	**NaI**	**annual modulation**	**running**	**LNGS**
DAMA/1 ton	NaI	annual modulation	R&D	LNGS
NAIAD	NaI	PSD	concluded	Boulby
HDMS	Ge	ionization	concluded	LNGS
KIMS	**CsI**	**PSD**	**R&D**	**Y2L (Korea)**
Caf$_2$-Kamioka	CaF_2	PSD	running	Kamioka
DAMA/LXe	LXe	PSD	running	LNGS
WARP	**LAr**	**2 phase**	**running**	**LNGS**
XENON 10	**LXe**	**2 phase**	**running**	**LNGS**
Zeplin II	**LXe**	**2 phase**	**running**	**Boulby**
Zeplin III	LXe	2 phase	installation	Boulby
ArDM	LAr	2 phase	R&D	Canfranc
LUX	LXe	2 phase	R&D	Dusel
CLEAN	LNe	PSD	R&D	
DEAP	LAr	PSD	R&D	SNOLAB
XMASS	LXe	PSD	construction	Kamioka
CDMS	Ge	bolometer	running	Soudan
CRESST	$CaWO_4$	bolometer	running	LNGS
EDELWEISS	Ge	bolometer	running	Frejus
ROSEBUD	Ge, sap,tung	bolometer	R&D	Canfranc
COUPP	F	SH droplet	R&D	
PICASSO	F	SH droplet	running + R&D	SNOLAB
SIMPLE	F	SH droplet	running + R&D	Bas Bruit
Drift	**CS_2 gas**	**TPC**	**R&D**	**Boulby**
MIMAC	^{3}He gas	TPC	R&D	

Experiments using liquid noble gases

- Single phase: LXe,LAr, LNe $\rightarrow$ scintillation, ionization
- Dual phase liquid /gas $\rightarrow$ scintillation + scintillation

Background rejection

in single phase detector:

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

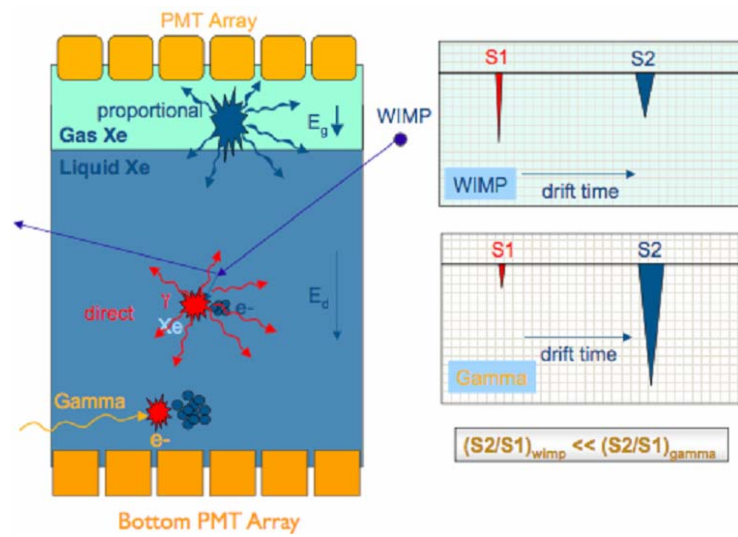
DAMA/LXe

ZEPLIN-I

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

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

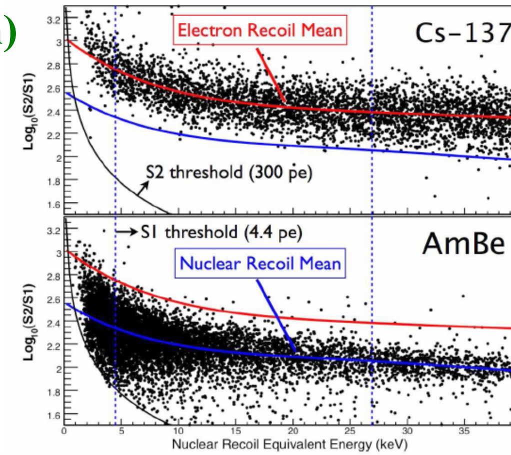


XENON10, WARP, ZEPLIN-II

Recent results of a liquid noble gas experiment: XENON10

(arXiv:0706.0039)

Experimental site:	**Gran Sasso (1400 m depth)**
Target material:	**^{nat}Xe**
Target mass:	**≈5.4 kg (tot: 15 kg)**
Used exposure:	**136 kg × day**



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.

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

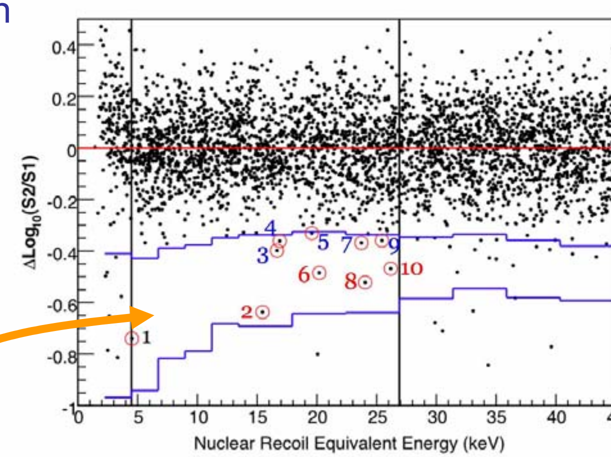
QC2: High level cuts

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

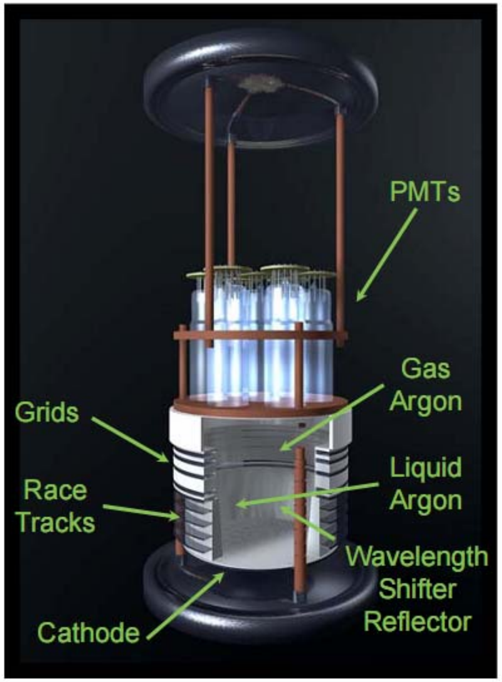


50% efficiency

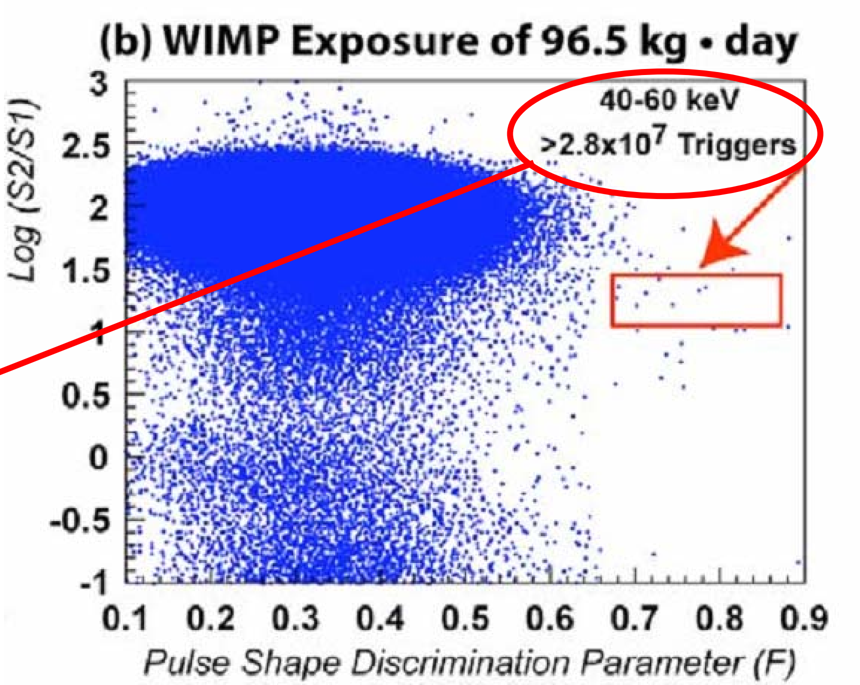
- **Ten events survives the many cuts.**
- **Some speculations about their nature.**
- **Has the (intrinsic) limitations of the method been reached?**

Recent results of a liquid noble gas experiment: WARP

(arXiv:0701286)



Experimental site: Gran Sasso (1400 m depth)
Target material: ^{nat}Ar
Target volume: ≈2.3 liters
Used exposure: 96.5 kg × day



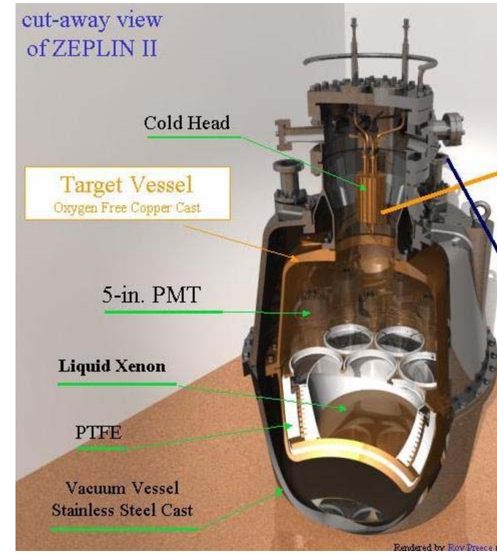
Integral Rate = 3×10^5 cpd/kg

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 ?

- **Eight events survives the many cuts.**
- **Some speculations about their nature.**
- **Has the (intrinsic) limitations of the method been reached?**

ZEPLIN-II



Experimental site: Boulby mine
Detector: 7.2 kg (tot: 31 kg) two phase Xenon
Exposure: 225 kg x day

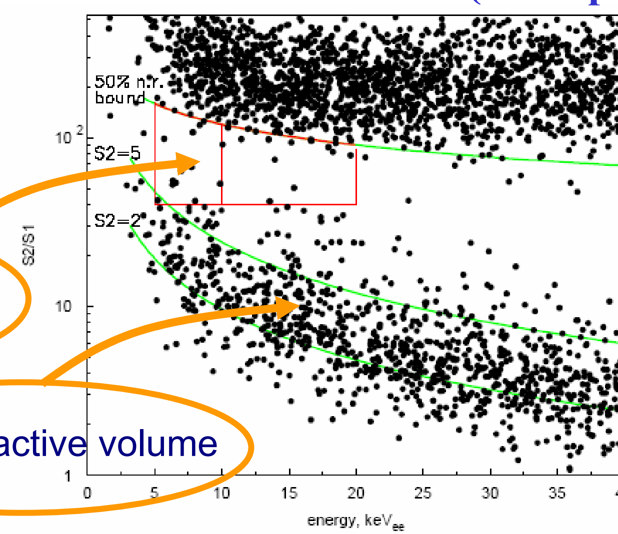
Discrimination between nuclear recoils and background electron recoils by recording scintillation and ionisation signals generated within the liquid xenon

(astro-ph/0701858)

Cuts

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 ?

Selection cut	Efficiency	Description
S2 Cut-0	≈100% (exp)	Requirement that a WIMP-like event has one and only one primary and secondary
S2 Cut-1	f(E): 100% >10 keV	Selection of S2 candidates with area>1 Vns
		(smaller pulses due to extraneous single electron extraction are ignored)
S2 Cut-2	90.2%	Removal of events by S2 pulse shape cut (photon mean arrival time)
S2 Cut-3	≈100%	Removal of events with non-physical S2 arrival times relative to trigge[r]
S2 Cut-4	≈100%	Removal of events with multiple S2 candidates (multiple scattering)
S1 Cut-1	f(E): 100%	Selection of S1 candidates with ≥3-fold coincidence at 2/5 photoelectron amplitude
	(5 keV:43% 10 keV:92%)	
S1 Cut-2	≈100%	Removal of events with non-physical drift times relative to S2
S1 Cut-3	≈100%	Removal of events by S1 pulse shape cut (photon arrival time distribution)
S1 Cut-4	98.7%	Removal of events with multiple S1 candidates
S1 Cut-5	99.7%	Tagging of <3-fold S1 signals with cathode drift time (event removed by S1-4)
DAQ Cut-1	f(E): 100% <30 keV	Digitiser saturation cut
DAQ Cut-2	90%	DAQ dead-time correction for science run (trigger rate dependent)
DAQ Cut-3	99.2%	Coincidental events in veto (trigger rate dependent)
DAQ Cut-4	99.7%	Requirement that a valid S1 or S2 trigger the DAQ



- In the acceptance region registered 29 events
- Some speculations about their nature: interpreted as γ and radon progeny induced background
- Has the (intrinsic) limitations of the method been reached?

... some warnings, comments, ... on dual phase detectors

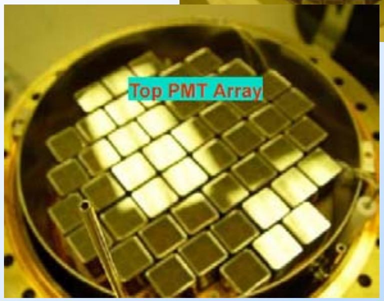
- Physical energy threshold unproved by source calibrations
- Disuniformity of detector: intrinsic limit? corrections applied: which systematics?
- The used gas is natural xenon and argon, that is with an unavoidable content of Kripton and ^{39}Ar, respectively
- Duty cycles
- Small light responses (e.g. 2.2 and ≈0.5÷1 ph.e./keVee for XENON10 and for WARP, respectively)
- Poor energy resolutions (e.g. $\sigma/E \approx$ 13% and 16% @ 122 keV for WARP and ZEPLIN, respectively)

WARP:

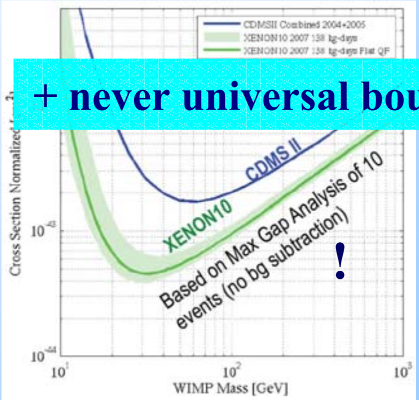
- for γ: σ/E=13% @ 122 keV (they quote 2.9 ph.e./keV)
- for recoils: they quote Y_{Ar}≈1.6 ph.e./keV
  → quenching factor for recoils: >0.6 ?

- Despite of the small light response an energy threshold of 2 keVee is claimed (XENON10)
- What about the energy resolution at 2 keV (XENON10)?
- It is quite hard to justify low levels of bckg taking into account all the materials involved in the core of the experiment.

- Case of XENON10: 89 PMTs (with photocathodes of Rb-Cs-Sb), all the materials for the electric field, the stainless steel containers, ...

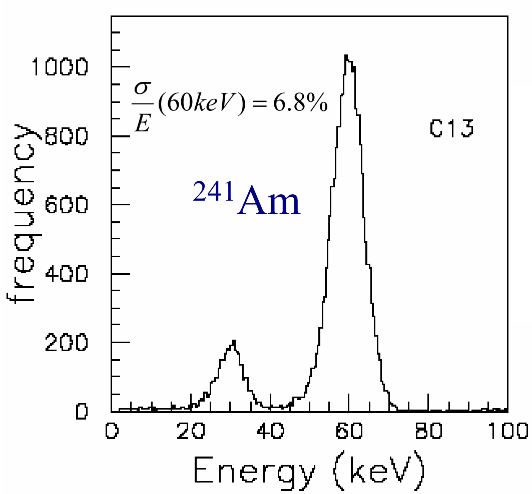


- Notwithstanding the larger A of Xenon than that of Germanium, much lower WIMP masses are reported as reached in sensitivity in an exclusion plot under the single set of used expt and theo assumptions.
- How is it robust? It depends on all the assumptions about the energy thresholds, energy resolutions, ...
- How does the exclusion plot depend on the used parametrization for the energy resolution? for the light correction ...



Examples of energy resolutions: comparison with NaI(Tl)

NaI(Tl)



astro-ph/0603131, Jan 2007

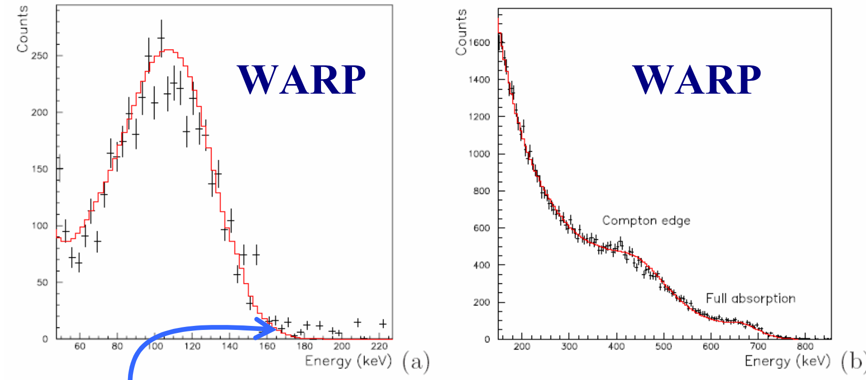


Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source (E = 122 keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source (E = 662 keV).

subtraction of the spectrum ?

ZEPLIN-II

arXiv:astro-ph/0701858v2

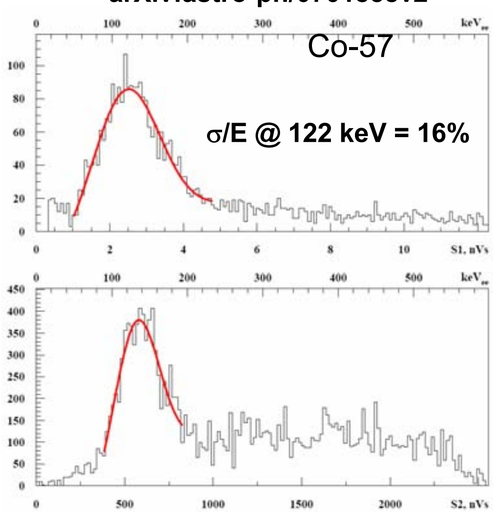


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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

XENON10

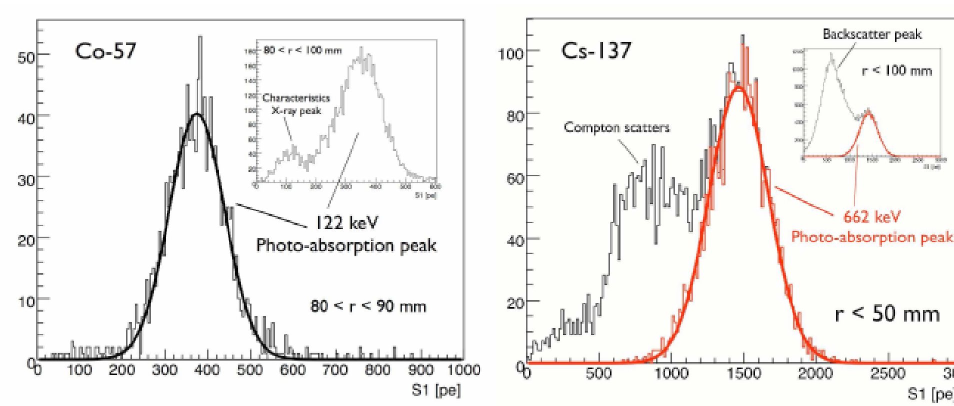
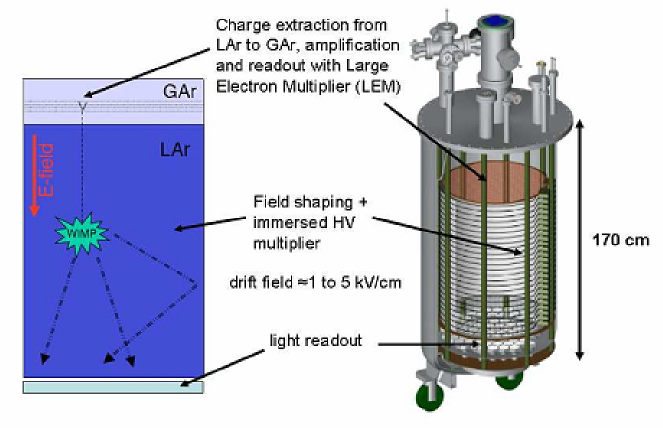


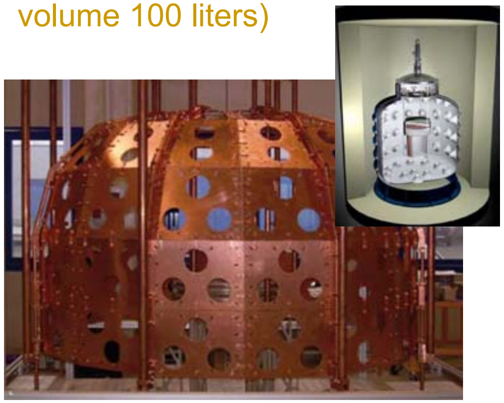
Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

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

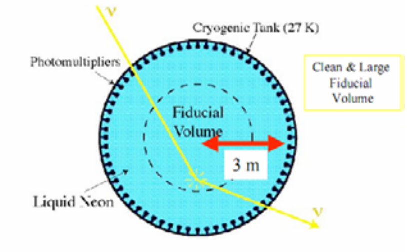
ArDM: ton scale dual-phase Argon detector



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

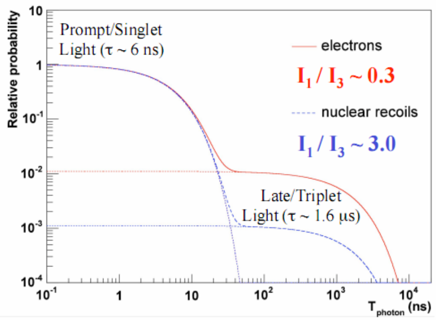


CLEAN: Cryogenic Low Energy Astrophysics with Neon

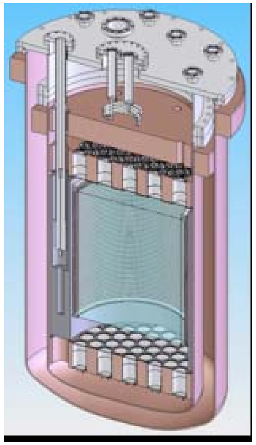


Single phase liquid Neon detector of tens of tons

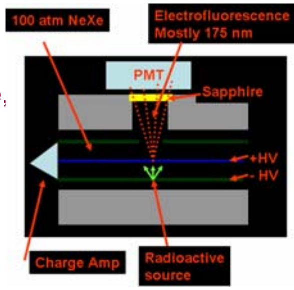
DEAP (SNOLAB): scintillation light in LAr at 85K → PSD studying different lifetimes in singlet/ triplet states for electrons and nuclear recoil (ton scale)



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

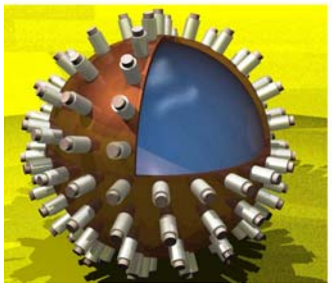


SIGN: A High-Pressure, Room-Temperature, Gaseous-Neon-Based Underground Physics Detector (100 kg @ 100 atm towards 10 tons)



XMASS

Solar ν : Xenon MASsive detector for Solar neutrinos
Dark M: Xenon detector for weakly interacting MASSive Particles
ββ : Xenon neutrino MASS detector



- 10 ton liquid Xe
- 1350 3-in PMTs
- solar neutrinos by $\nu + e \rightarrow \nu + e$
- $0\nu\beta\beta \sim 3.3\times10^{26}$ 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"

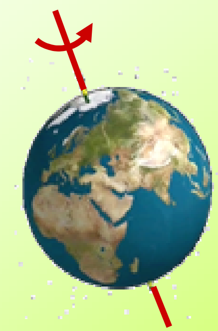
A model independent signature is needed

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

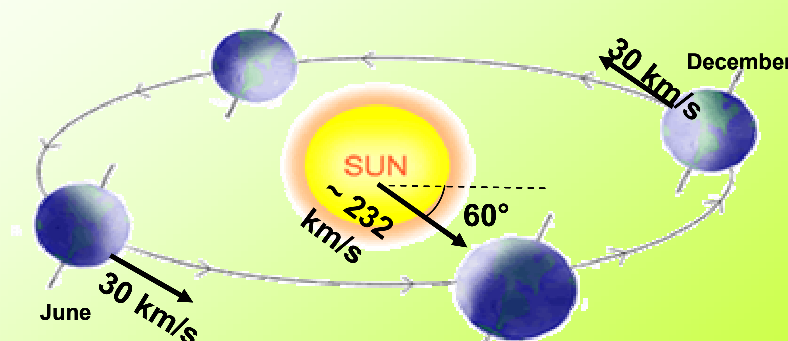
Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high σ



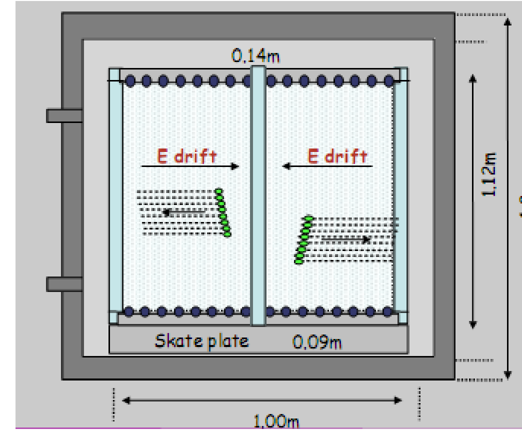
Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun

at present the only feasible one



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 m³ 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

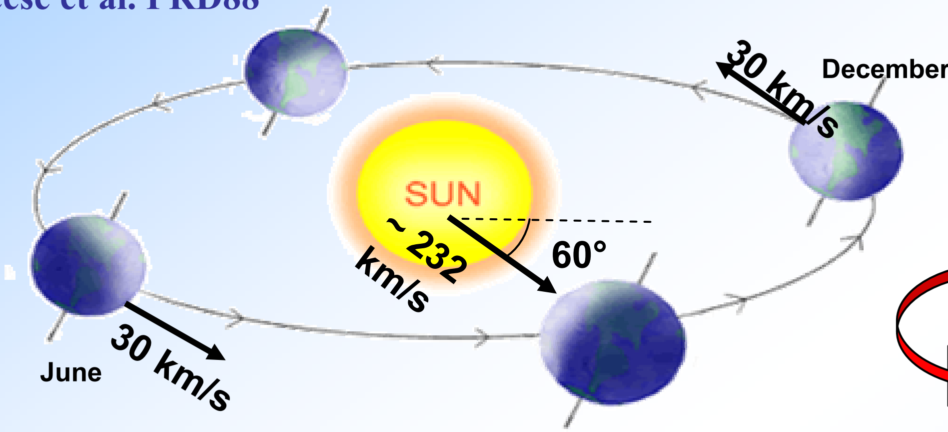
After an exposure of 10.2 kg x days a population of nuclear recoils (interpreted as due to the decay of unexpected ^{222}Rn daughter nuclei, present in the chamber) has been observed.

Not yet results on Dark Matter particle

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

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 the annual motion of the Earth around the Sun moving in the Galaxy

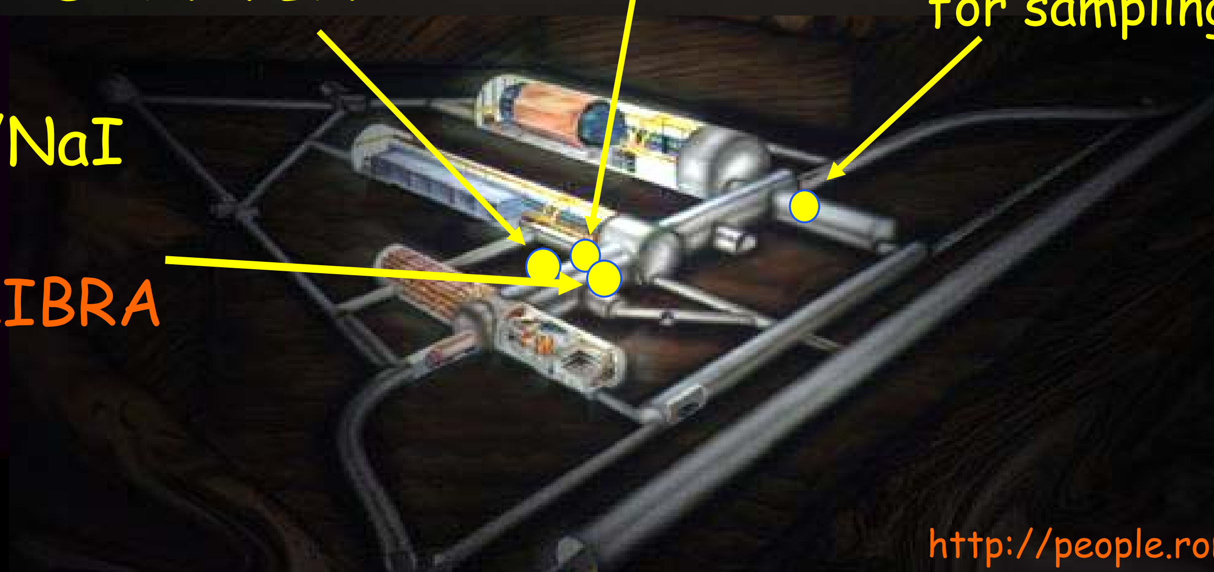
Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <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 - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Roma2,Roma1,LNGS,IHEP/Beijing

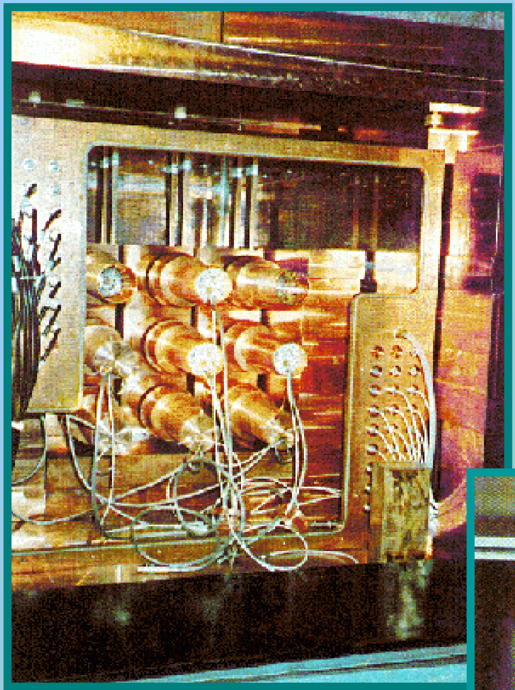
DAMA: an observatory for rare processes @LNGS



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

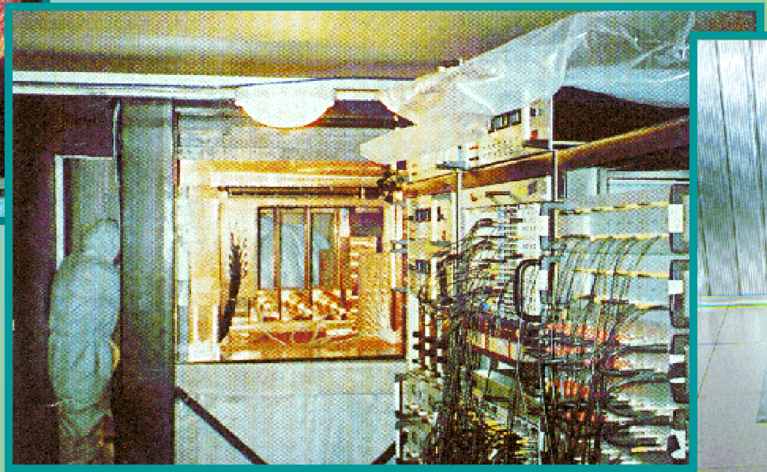
DAMA/NaI(Tl)~100 kg

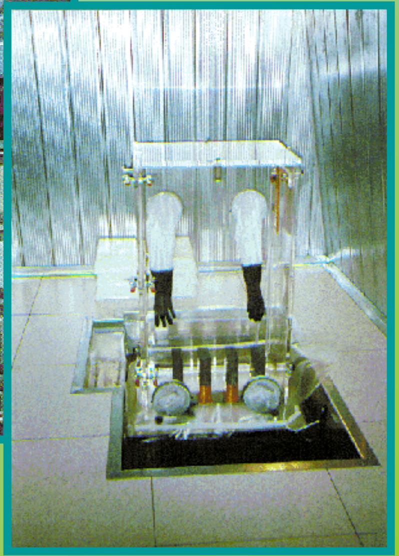
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127



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)1-73, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155 + other works in progress ...

data taking completed on July 2002 (still producing results)

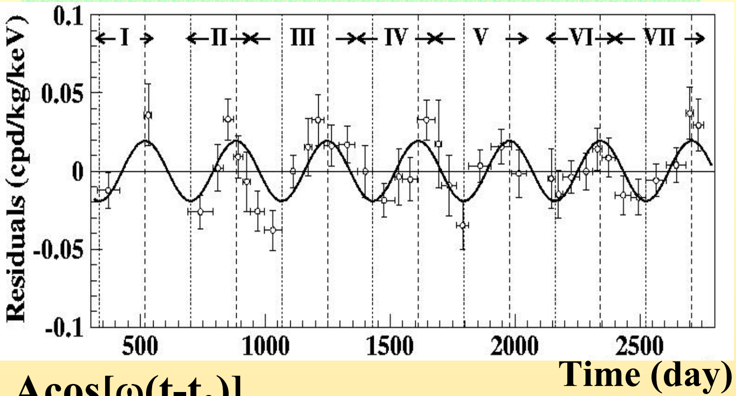
total exposure collected in 7 annual cycles 107731 kg×d

The final model independent result by DAMA/NaI

7 annual cycles: total exposure ~ 1.1 x 10^5 kg×d

Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD 13 (2004) 2127

Experimental residual rate of the single hit events in 2-6 keV over 7 annual cycles



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

$P(A=0) = 7\cdot10^{-4}$

Solid line: t_0 = 152.5 days, T = 1.00 years

from the fit:

$A = (0.0192 \pm 0.0031)$ cpd/kg/keV

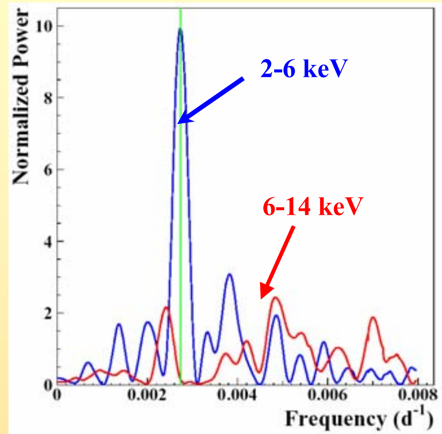
from the fit with all the parameters free:

$A = (0.0200 \pm 0.0032)$ cpd/kg/keV

$t_0 = (140 \pm 22)$ d

$T = (1.00 \pm 0.01)$ y

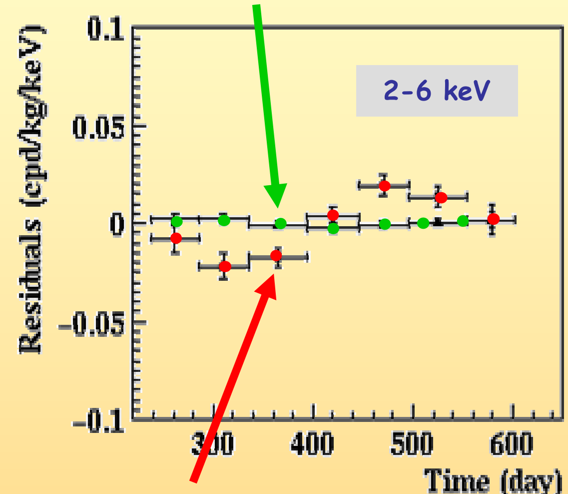
Power spectrum



Principal mode

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

experimental residual rate of the multiple hit events (DAMA/NaI-6 and 7) in the 2-6 keV energy interval: $A = -(3.9\pm7.9)\cdot10^{-4}$ cpd/kg/keV



experimental residual rate of the single hit events (DAMA/NaI-1 to 7) in the 2-6 keV energy interval: $A = (0.0195\pm0.0031)$ cpd/kg/keV

Multiple hits events = Dark Matter particle "switched off"

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

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

All the peculiarities of the signature satisfied

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

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

(see for details Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD13(2004)2127 and references therein)

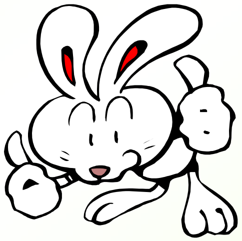
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	installation excluded by external Rn + 3 levels of sealing in HP Nitrogen atmosphere, etc	$<0.2\%\ S_m^{obs}$
TEMPERATURE	Installation is air conditioned + detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded + etc.	$<0.5\%\ S_m^{obs}$
NOISE	Effective noise rejection near threshold (τ_{noise}~ tens ns, τ_{NaI} ~ hundreds ns)	$<1\%\ S_m^{obs}$
ENERGY SCALE	X-rays + periodical calibrations in the same running conditions + continuous monitoring of ^{210}Pb peak	$<1\%\ S_m^{obs}$
EFFICIENCIES	Regularly measured by dedicated calibrations	$<1\%\ S_m^{obs}$
BACKGROUND	No modulation observed above 6 keV + this limit includes possible effect of thermal and fast neutrons + no modulation observed in the multiple-hits events in 2-6 keV region	$<0.5\%\ S_m^{obs}$
SIDE REACTIONS	Muon flux variation measured by MACRO	$<0.3\%\ S_m^{obs}$

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

Thus, they can not mimic the observed annual modulation effect

... about the interpretation of the direct DM experimental results

The positive and model independent result of DAMA/NaI



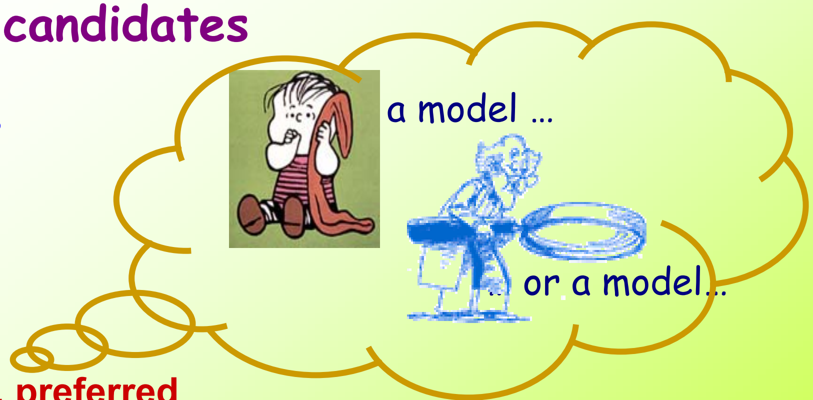
- Presence of modulation for 7 annual cycles at ~6.3σ C.L. with the proper distinctive features of the signature; all the features satisfied by the data over 7 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed effect and to contemporaneously satisfy the many peculiarities of the signature

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

To investigate the nature and coupling with ordinary matter of the possible DM candidate(s), effective energy and time correlation analysis of the events has to be performed within given model frameworks

Corollary *quests* for candidates

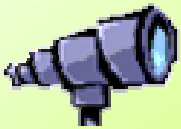
- **astrophysical models: ρ_{DM}, velocity distribution and its parameters**
- **nuclear and particle Physics models**
- **experimental parameters**



e.g. for WIMP class particles: SI, SD, mixed SI&SD, preferred inelastic, scaling laws on cross sections, form factors and related parameters, spin factors, halo models, etc.

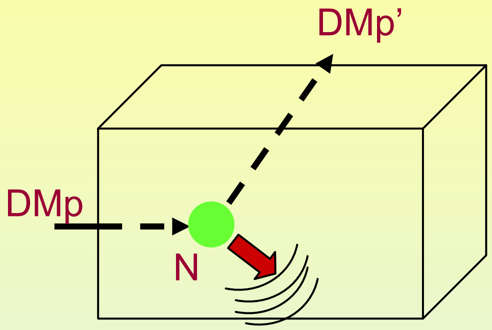
+ different scenarios

+ multi-component halo?



THUS uncertainties on models and comparisons

First case: the case of DM particle scatterings on target-nuclei. When just the recoil energy is the detected quantity



- DM particle-nucleus elastic scattering (SI, SD, SI&SD coupling)
- Preferred inelastic DM particle-nucleus scattering (S_m/S_0 enhanced with respect to the elastic scattering case)

The differential energy distribution depends:

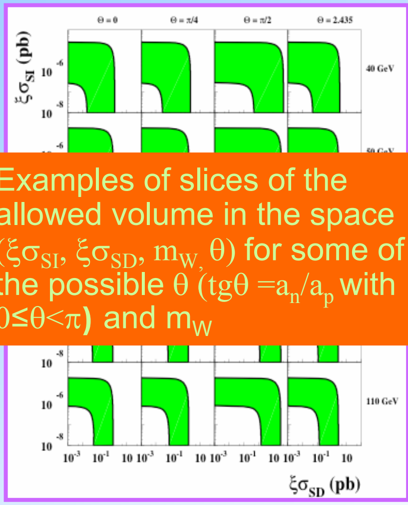
- on the assumed scaling laws, nuclear form factors, spin factors, free parameters ($\rightarrow$ kind of coupling, mixed SI&SD, pure SI, pure SD, pure SD through Z_0 exchange, pure SD with dominant coupling on proton, pure SD with dominant coupling on neutron, preferred inelastic, ...),
- on the assumed astrophysical model (halo model, presence of non-thermalized components, particle velocity distribution, particle density in the halo, ...)
- on instrumental quantities (quenching factors, energy resolution, efficiency, ...)

Few examples of corollary quests for the WIMP class - DAMA/NaI

WIMP class: examples of allowed volumes/regions

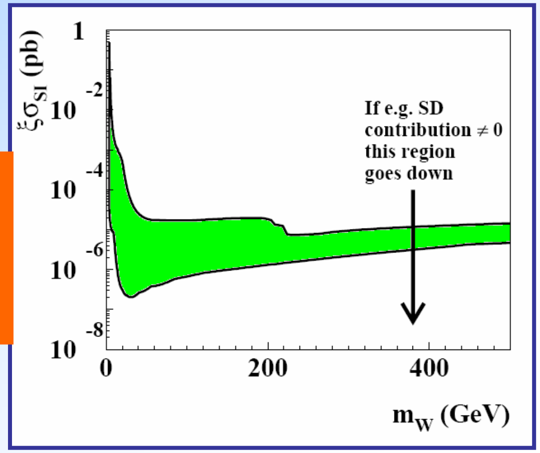
in given scenarios (Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD 13 (2004) 2127)

DM particle with elastic SI&SD interactions

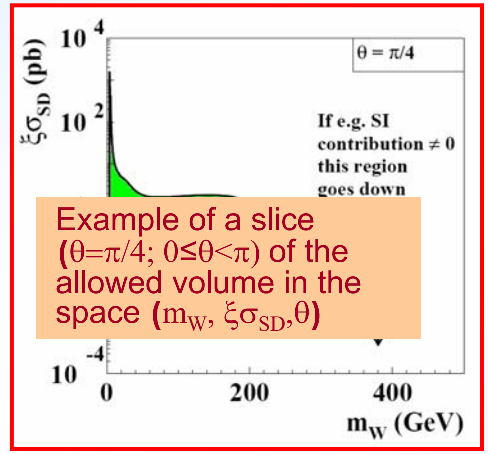


Examples of slices of the allowed volume in the space ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$, m_W, θ) for some of the possible θ ($tg\theta = a_n/a_p$ with $0 \le \theta < \pi$) and m_W

DM particle with dominant SI coupling

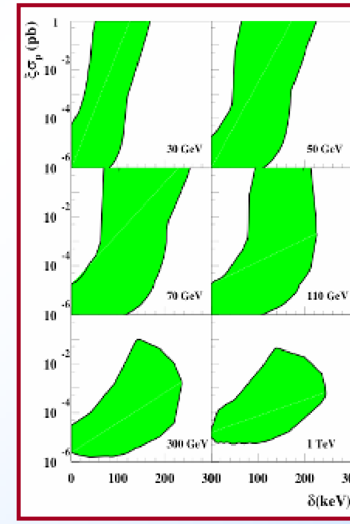


DM particle with dominant SD coupling



Example of a slice ($\theta=\pi/4$; $0 \le \theta < \pi$) of the allowed volume in the space (m_W, $\xi\sigma_{SD}$, θ)

DM particle with preferred inelastic interaction



Most of these allowed volumes/regions are unexplorable e.g. by Ge, Si, TeO_2, Ar, Xe, $CaWO_4$ targets

not exhaustive + different scenarios? + different halo features?

Example: Investigating the effect of Sagittarius Dwarf satellite galaxy (SagDEG)

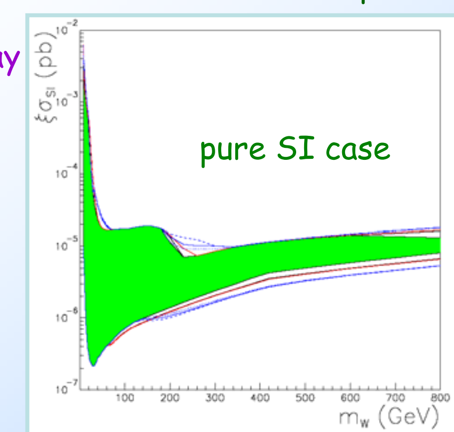
Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way

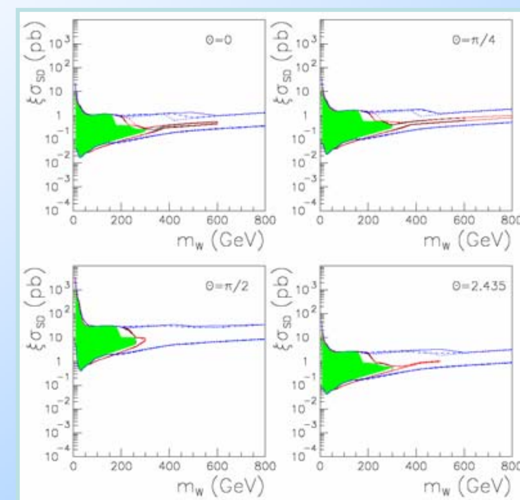
signature: SagDEG tail affects the phase of the annual modulation signal

green areas: no SagDEG

EPJC47(2006)263

few examples





pure SD case: examples of slices of the 3-dim allowed volume

Other contributions and effects involved in the DM particle scatterings on target-nuclei ?

Investigating electromagnetic contributions in the detection of WIMP candidates

IJMPA 22 (2007) 3155

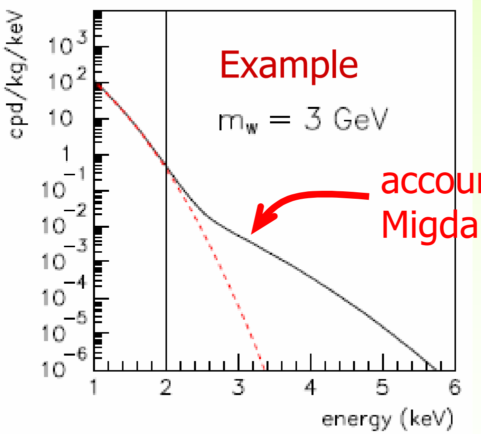
Ionization and the excitation of bound atomic electrons induced by the presence of a recoiling atomic nucleus in the case of the WIMP-nucleus elastic scattering (named hereafter Migdal effect)

→ the recoiling nucleus can "shake off" some of the atomic electrons

→ recoil signal + e.m. contribution made of the escaping electron, X-rays, Auger electrons arising from the rearrangement of the atomic shells

→ e.m. radiation fully contained in a detector of suitable size

The effect is well known since long time



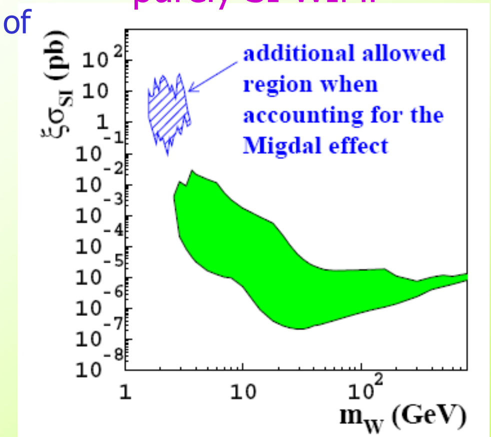
Adopted assumptions in the examples:

i) WIMP with dominant SI coupling and with $\sigma \propto A^2$;

ii) non-rotating Evans logarithmic galactic halo model with R_c=5kpc, v_0=170 km/s, ρ_0= 0,42 GeV cm^{-3}

iii) form factors and q of ^{23}Na and ^{127}I as in case C of Riv.N.Cim 26 n1 (2003)1

Example of a purely SI WIMP

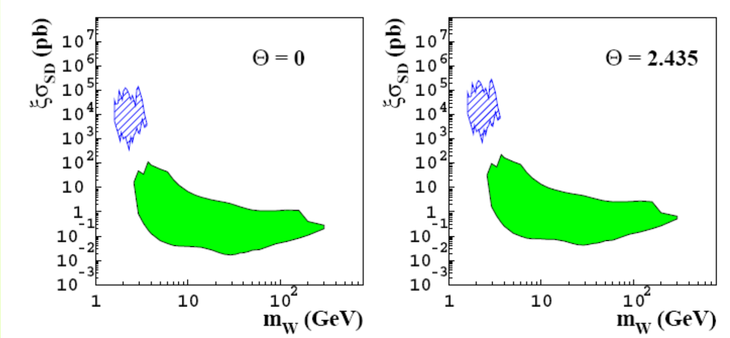


Although the effect of the inclusion of the Migdal effect appears quite small:

- the unquenched nature of the e.m. contribution
- the behaviour of the energy distribution for nuclear recoils induced by WIMP-nucleus elastic scatterings
- etc.

can give an appreciable impact at low WIMP masses

Example of a purely SD WIMP



WARNING:
1) to point out just the impact of the Migdal effect the SagDEG contribution has not been included here.

2) considered frameworks as in Riv.N.Cim 26 n1 (2003)1

Further uncertainties in the quest for WIMPs: the case of the recoils' quenching

ROM2F/2007/15, to appear

arXiv:0706.3095

- ***In crystals, ions move in a different manner than that in amorphous materials.***
- In the case of motion along crystallographic axes and planes, a channeling effect is possible, which is manifested in an anomalously deep penetration of ions into the target.

Channeling effect in crystals

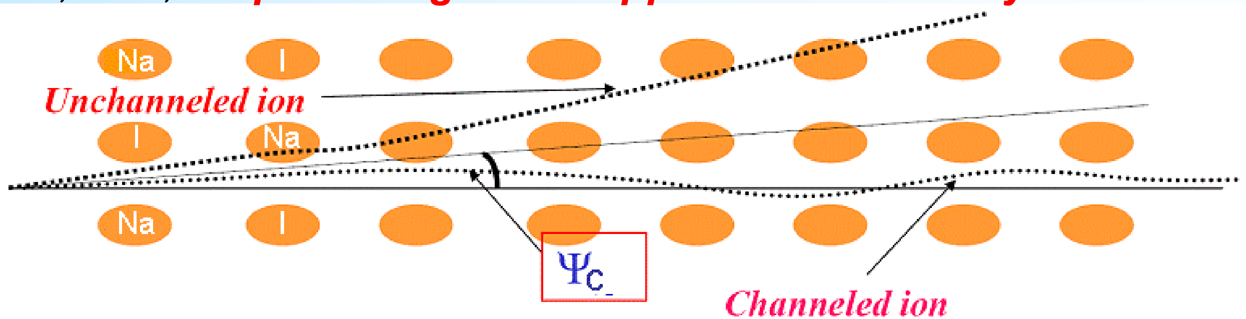
- Occurs in **crystalline** materials due to correlated collisions of ions with target atoms.
- Steering of the ions through the open channels can result in **ranges several times the maximum range** in no-steering directions or in **amorphous materials**.
- **Electronic losses** determine the range and there is very little straggling.
- When a low-energy ion goes into a channel, its energy losses are mainly due to the electronic contributions. This implies that a channeled ion transfers its energy mainly to electrons rather than to the nuclei in the lattice and, thus, its ***quenching factor approaches the unity***.

Well-known effect, discovered on 1957, when a deep penetration of $^{134}Cs^+$ ions into a Ge crystal to a depth $\lambda_c \approx 10^3$ Å was measured (according to SRIM, a 4 keV Cs^+ ion would penetrate into amorphous Ge to a depth λ_a = 44 Å, S_n/S_e = 32 and q=0.03). Within a channel, mostly electronic stopping takes place (in the given example, $\lambda_c \approx \lambda_a/q \approx$ 1450 Å).

$$R_{ion}(E) \approx R_{el.}(E)$$

$$L_{ion} \approx L_{el}$$

$$q(E) \approx 1$$

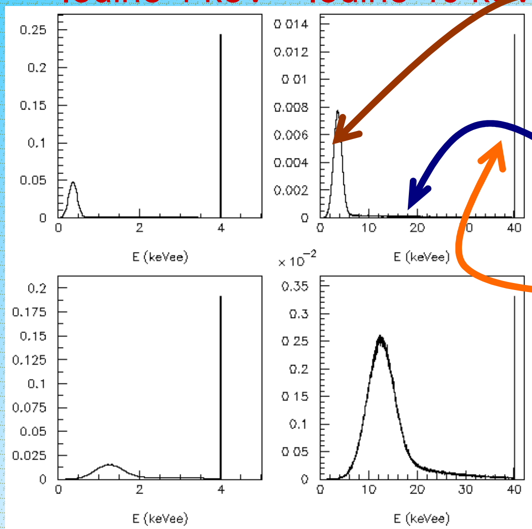


Modeling the channeling effect:

Examples of light responses

ROM2F/2007/15, to appear

Iodine 4 keV Iodine 40 keV



Sodium 4 keV Sodium 40 keV

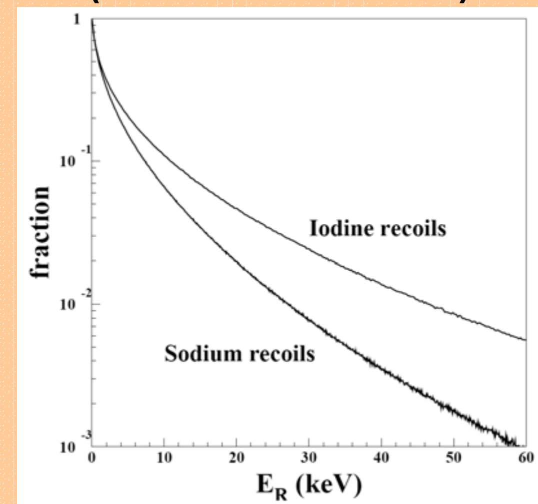
No energy resolution

Quenched peak with the straggling effect

Dechanneled events

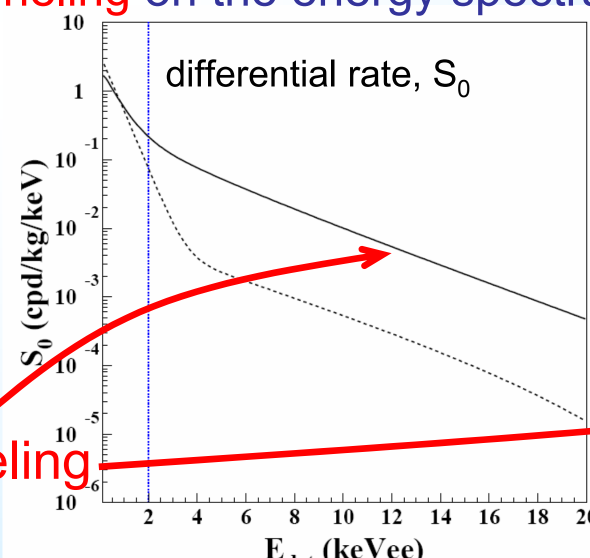
Channeled events (q≈1)

Fraction of events with q ~ 1 (channeled events)

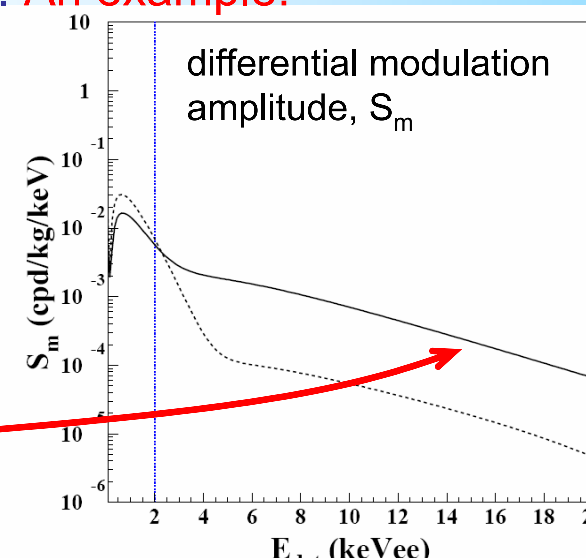


The effect of channeling on the energy spectra. An example:

- NaI(Tl) (as those of DAMA)
- m_W=20 GeV
- pure SI
- $\sigma_{SI}=10^{-6}$ pb
- halo model A5
- NFW, v_0=220 km/s, ρ_{max}
- FF parameters and q factors at the mean values (case A in RNC26(2003)1)



channeling



What about the neutron calibrations of NaI(Tl) detectors?

MEASUREMENT OF THE SCINTILLATION EFFICIENCY OF Na RECOILS IN NaI(Tl) DOWN TO 10 keV NUCLEAR RECOIL ENERGY RELEVANT TO DARK MATTER SEARCHES

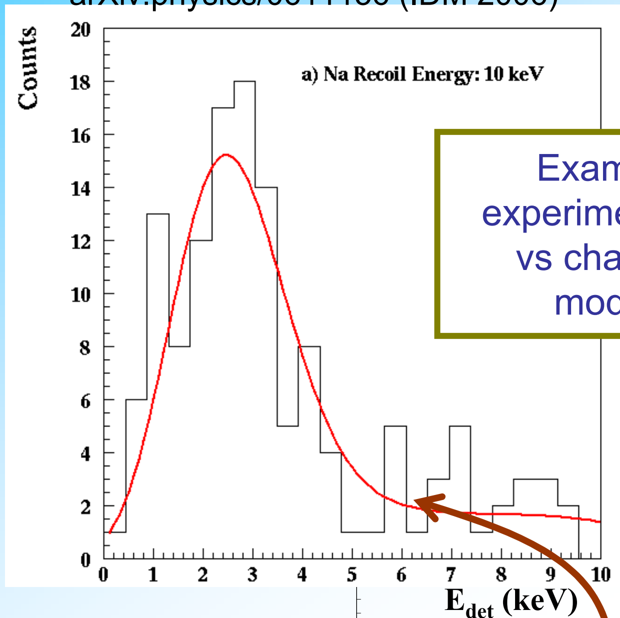
H. CHAGANI*, P. MAJEWSKI**, E. J. DAW, V. A. KUDRYAVTSEV, and N. J. C. SPOONER

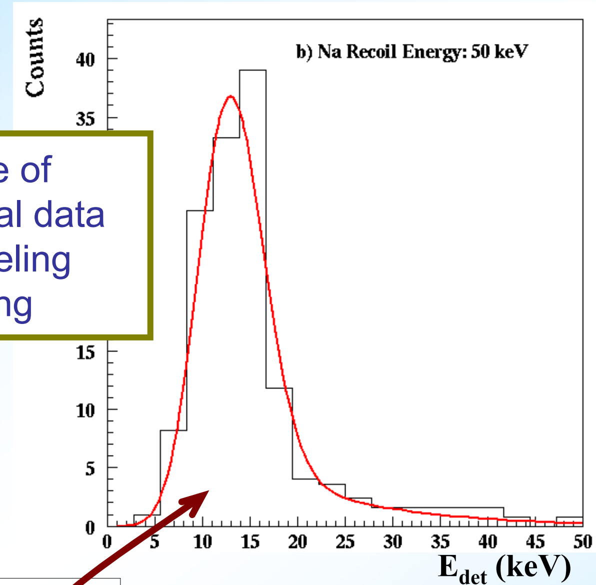
arXiv:physics/0611156 (IDM 2006)

SICANE: a Detector Array for the Measurement of Nuclear Recoil Quenching Factors using a Monoenergetic Neutron Beam

NIMA 507 (2003) 643

ROM2F/2007/15, to appear

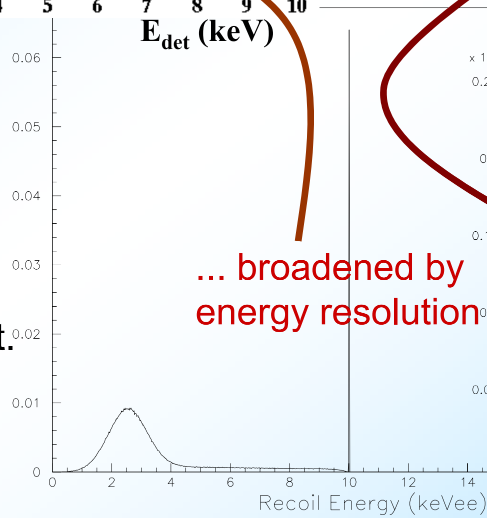




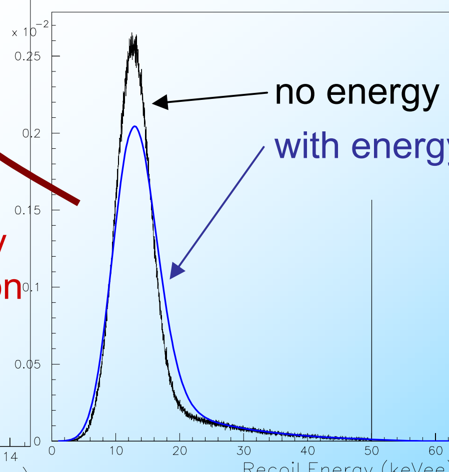
Example of experimental data vs channeling modeling

- **neutron data can contain channeled events**
- **but – owing to the low-statistics of these measurements and to the small effect looked for – they cannot be identified**
- **At higher energy and for Iodine recoils the channeling effect becomes less important and gives more suppressed contributions in the neutron scattering data**

Detector responses to 10keV and 50keV Na recoils in NaI(Tl) taking into account the channeling effect.

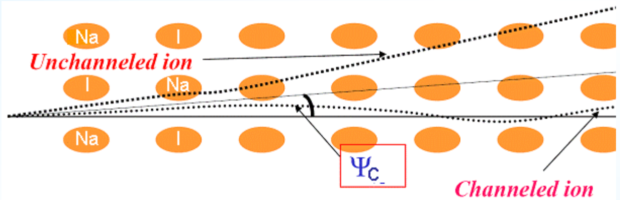


... broadened by energy resolution



Therefore, there is no hope to identify the channeling effect in the already-collected neutron data on NaI(Tl)

... while the accounting of the channeling effect can give a significant impact in the sensitivities of the Dark Matter direct detection methods when WIMP (or WIMP-like) candidates are considered.



Effect for DM direct detection experiments

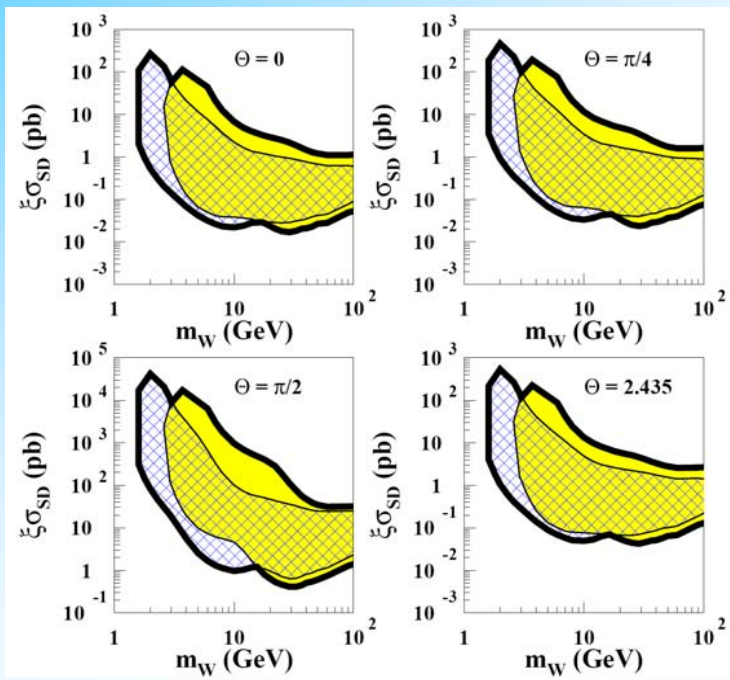
- Lower cross sections explorable for WIMP and WIMP-like candidates by crystal scintillators, such as ***NaI(Tl)*** (up to more than a factor 10 in some mass range), lower recoil energy thresholds, lower mass thresholds, ...
- The same holds for purely ionization detectors, as ***Ge*** (HD-Moscow – like).
- Loss of sensitivity when PSD is used in crystal scintillators (***KIMS***); in fact, the channeled events ($q \approx 1$) are probably lost.
- No enhancement on ***liquid noble gas*** expts (DAMA/LXe, WARP, XENON10, ZEPLIN, ...).
- No enhancement for ***bolometer double read-out*** expts; on the contrary some loss of sensitivity is expected since events (those with $q_{ion} \approx 1$) are lost by applying the discrimination procedures based on $q_{ion} \ll 1$.

Some examples of accounting for the channeling effect on the DAMA/NaI allowed regions

- the modeling in some given frameworks

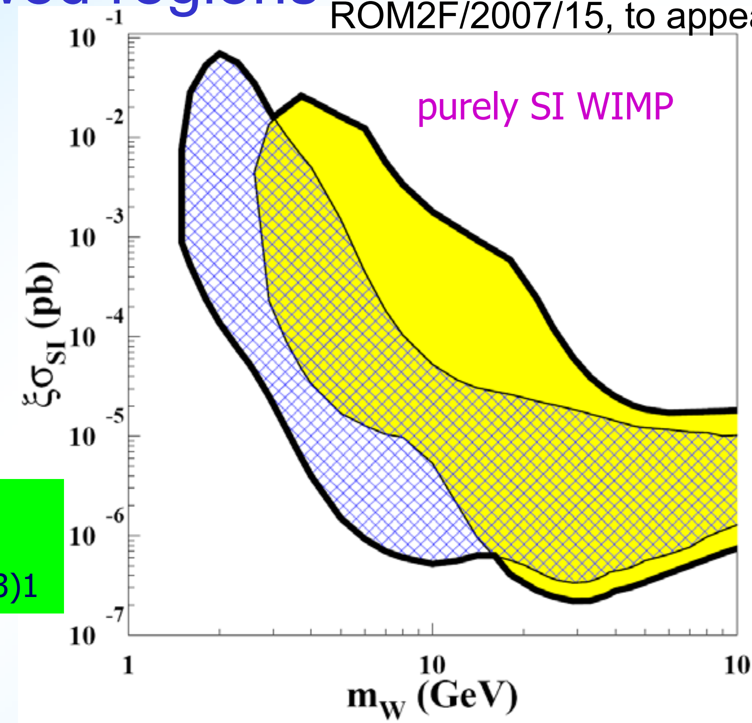
ROM2F/2007/15, to appear

purely SD WIMP



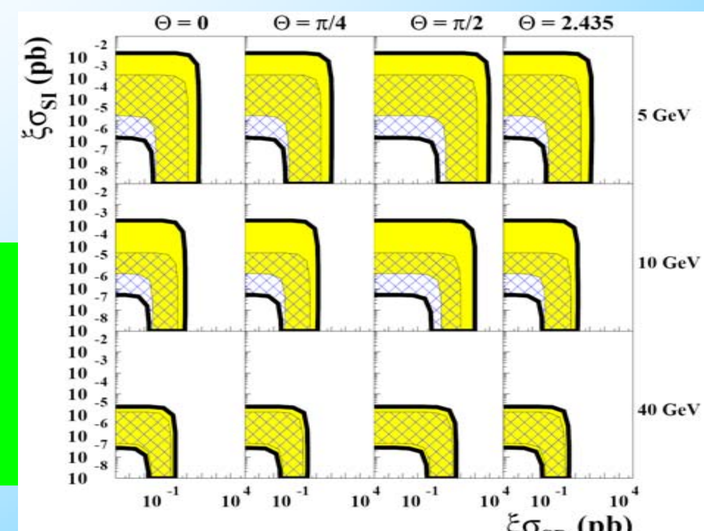
with

without channeling



for details on model frameworks see Riv.N.Cim 26 n1 (2003)1

SI & SD WIMP



WARNING:

- to point out just the impact of the channeling effect the Migdal and SagDEG contributions have not been included here.
- the slices of the volumes shown here are focused just in the low mass region where the channeling effect is more effective

Other kind of interactions involved in the DM particle interactions on a detector ?

Another class of DM candidates:
light bosonic particles

IJMPA21 (2006) 1445

Light bosons: Axion-like particles, similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants are allowed.

A wide literature is available and various candidate particles have been and can be considered.

A complete data analysis of the total 107731 kgxday exposure from DAMA/NaI has been performed for pseudoscalar (a) and scalar (h) candidates in some of the possible scenarios.

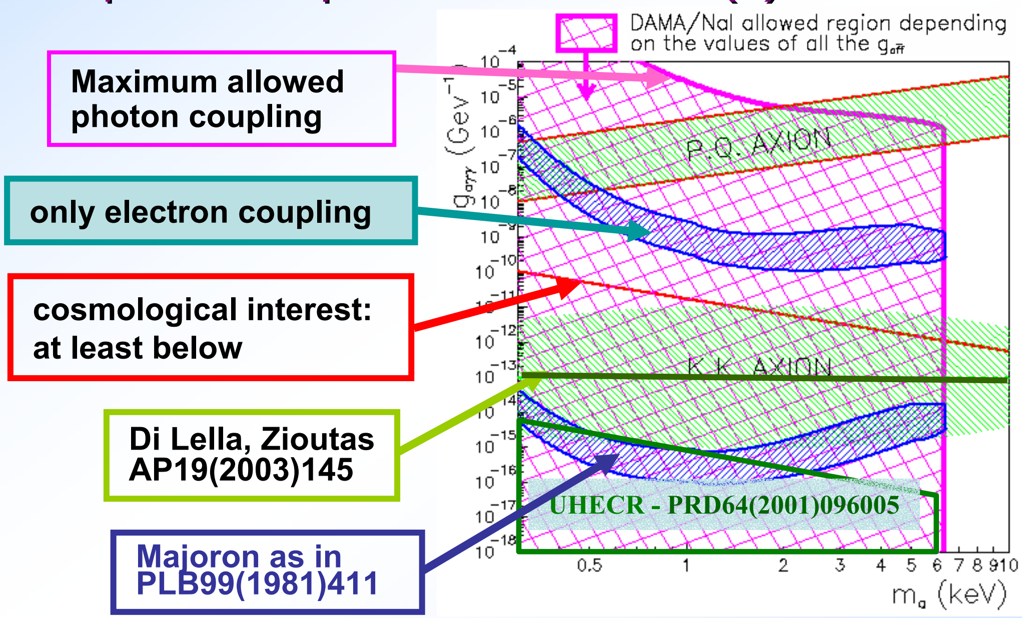
The detection is based on the total conversion of the absorbed bosonic mass into electromagnetic radiation.

Axion-like, some astrophysical hints:
- solar corona problem — Di Lella & Zioutas
- X-ray from dark side of the Moon
- soft X-ray background radiation
- "diffuse" soft X-ray excess

Hypothesis: ~ keV axion-like (K.K. axion) trapped in the Sun neighborhood and $\gamma\gamma$ decay

Allowed multi-dimensional volume

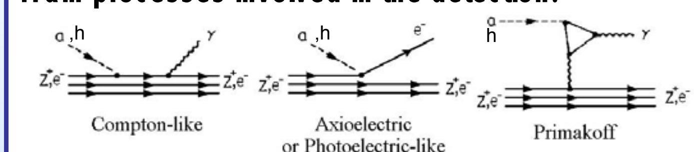
Example of the pseudoscalar case (*a*)



The scalar case is interesting as well

In these processes the target nuclear recoil is negligible and not involved in the detection process (i.e. signals from these candidates are lost in experiments applying rejection procedures of the electromagnetic contribution)

Main processes involved in the detection:



	Compton-like	Axioelectric or Photoelectric-like	Primakoff
a	S_0	S_0, S_m	S_0, S_m
h	S_0, S_m	S_0	S_0, S_m

Many configurations are of cosmological interest

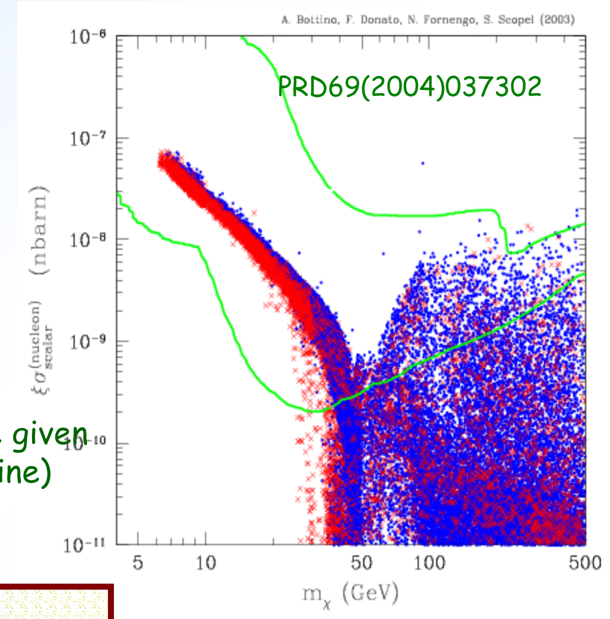
DAMA/NaI vs ...

... supersymmetric expectations in MSSM

The result is consistent with the most popular candidate, the neutralino, over a large range of mass and cross sections (see the Scopel's talk)

- *Assuming for the neutralino a dominant purely SI coupling*
- *when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (<); (where M_1 and M_2 U(1) and SU(2) gaugino masses) low mass configurations are obtained*

scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line)



... other DM candidate particles, as (see literature)

the sneutrino in the Smith and Weiner scenario

a heavy ν of the 4-th family

+

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

... and more; even a suitable particle not yet foreseen by theories

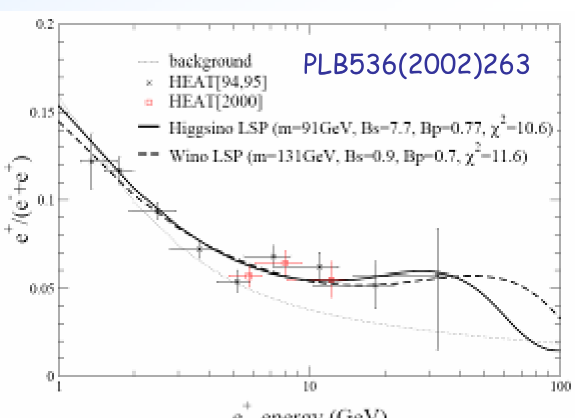
heavy exotic canditates, as "4th family atoms", ...

light bosons

... and more

compatibility

... indirect searches of DM particles in the space



- Positron excess (see e.g. HEAT)
- Excess of Diffuse Galactic Gamma Rays for energies above 1 GeV in the galactic disk and for all sky directions (see EGRET).

interpretation, evidence itself, derived m_W and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.

Hints from indirect searches are not in conflict with DAMA/NaI for the WIMP class candidate

FAQ: ... DAMA/NaI "excluded" by others ?

Obviously No

They give a single model dependent result
DAMA/NaI gives a model independent result

} No direct model independent comparison possible

Assuming their expt. results as they quote:

Case of DM particle scatterings on target-nuclei

•**In general:** OBVIOUSLY NO

The results are fully "decoupled" either because of the different sensitivities to the various kinds of candidates, interactions and particle mass, or simply taking into account the large uncertainties in the astrophysical (realistic and consistent halo models, presence of non-thermalized components, particle velocity distribution, particle density in the halo, ...), nuclear (scaling laws, FFs, SF) and particle physics assumptions and in all the instrumental quantities (quenching factors, energy resolution, efficiency, ...) and theor. parameters.

•**At least in the purely SI coupling they only consider:** OBVIOUSLY NO

Still room for compatibility either at low DM particle mass or simply accounting for the large uncertainties in the astrophysical, nuclear and particle physics assumptions and in all the expt. and theor. parameters.

Case of bosonic candidate (full conversion into electromagnetic radiation) and of whatever e.m. component

•**These candidates are lost by these expts.** OBVIOUSLY NO

+ they usually quote in an uncorrect, partial and unupdated way
the implications of the DAMA/NaI model independent result

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

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)

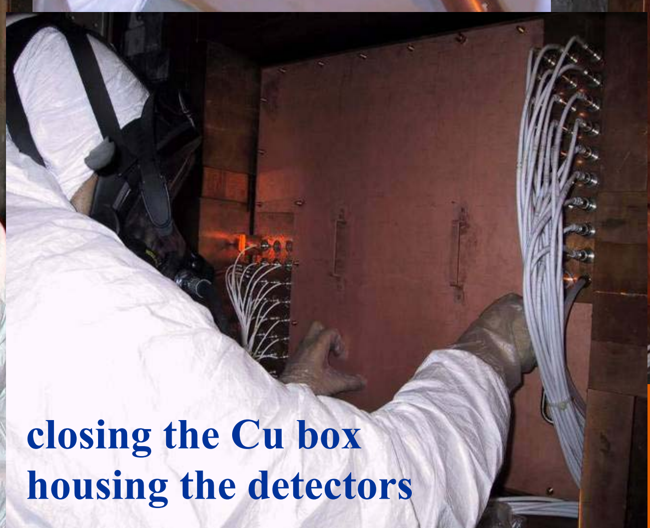
installing DAMA/LIBRA detectors

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

DAMA/LIBRA started operations on March 2003

filling the inner Cu box wi
further shield



closing the Cu box
housing the detectors

view at end of detectors' installation in the Cu box

DAMA/LIBRA

- <u>Data collected up to March 2007:</u>

  exposure: of order of 1.5 x 10^5 kg x d

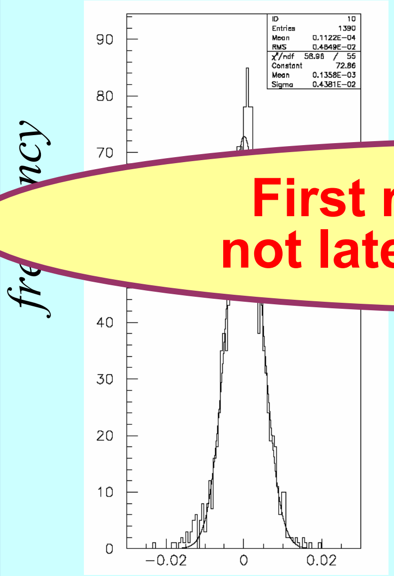
  calibrations: acquired ≈ 40 M events of sources

  acceptance window eff: acquired ≈ 2 M ev/keV

  continuously running

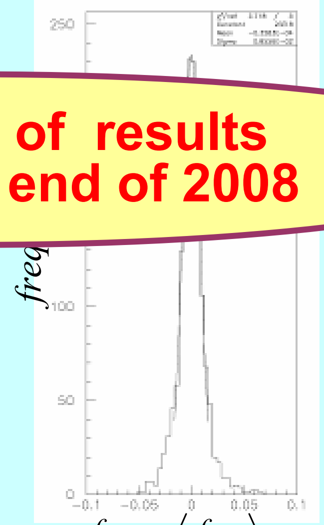
Examples:
here from
March 2003
to August 2005

Stability of the low energy calibration factors



$$\frac{tdcal - \langle tdcal \rangle}{\langle tdcal \rangle}$$

Stability of the high energy calibration factors



$$\frac{f_{HE} - \langle f_{HE} \rangle}{\langle f_{HE} \rangle}$$

First release of results not later than end of 2008

all operations involving crystals and PMTs -including photos- in HP N_2 atmosphere

- <u>Model independent analysis already concluded almost in all the aspects on an exposure of</u>

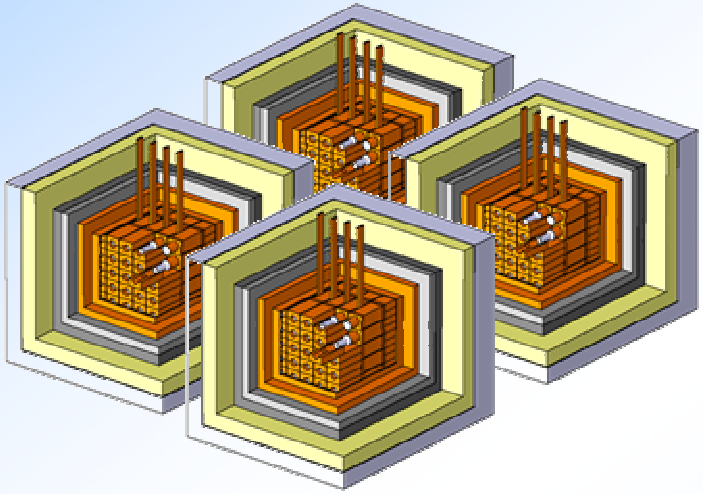
  ≈ 0.40 ton × year **[(α−β²) = 0.537]**

+ in progress

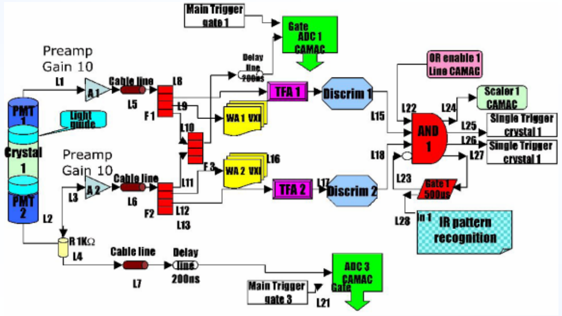
Towards possible DAMA/1ton: now at R&D stage

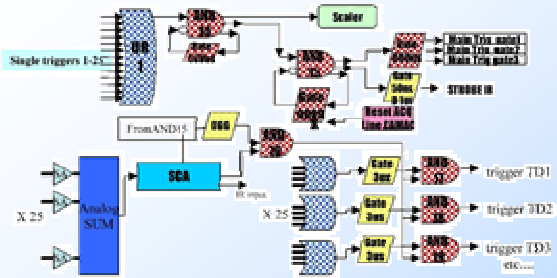
1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand (large experiences and fruitful collaborations among INFN and companies/industries)
3) Still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, etc.)
4) 1 ton detector: the cheapest, the highest duty cycle, the clear signature, the fast realization in few years

A possible design: DAMA/1 ton can be realized by four replicas of DAMA/LIBRA:



- the detectors could be of similar size than those already used
- the features of low-radioactivity of the set-up and of all the used materials would be assured by many years of experience in the field
- electronic chain and controls would profit by the previous experience and by the use of compact devices already developpped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA





- R&Ds on PMTs and crystals in progress
- 1st detector prototype ready for measurements

Electronic chain and example of the trigger system

Some scintillation detector experiments either in preparation or at R&D stage

KIMS:

Experimental site:	Yangyang und. lab. (depth 700m)
Detector:	4 CsI(Tl) scintillators of 8.7 kg mantained at 0°C
Exposure:	3409 kg x day

(arXiv:0704.0423v2)

PSD to discriminate γ,e^- / nuclear recoils

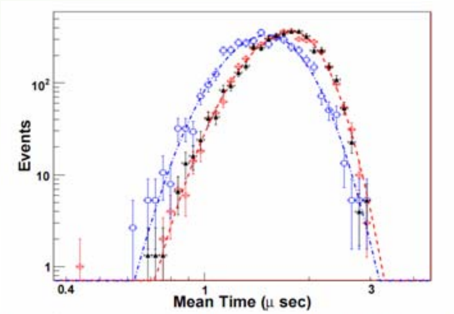
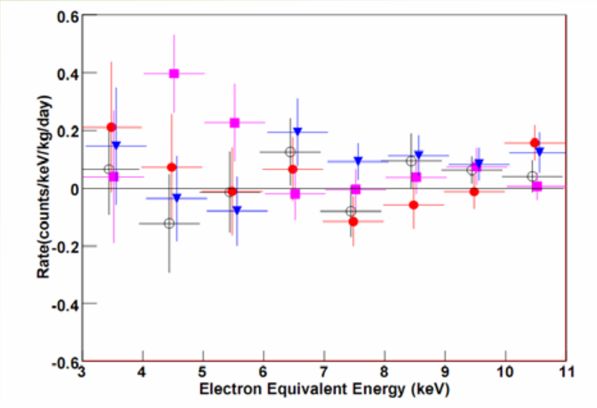


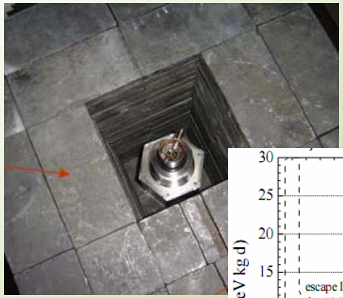
FIG. 1: (color online). MT distribution of NR events (open squares), ER events (open circles) and WIMP search data (filled triangles) of S0501A crystal in the 5-6 keV range. Fitted PDF functions are overlayed. χ^2/DOF =0.8 and 1.3 with DOF=38 and 35 for NR and ER events respectively.

Extracted Nuclear Recoils event rates of the CsI(Tl) crystals



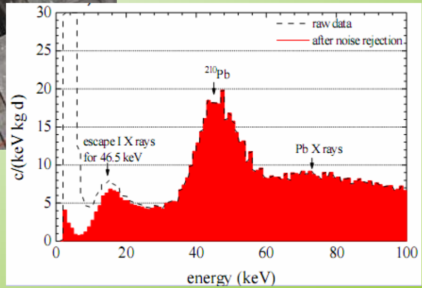
- **Energy spectra after data handling and cuts: about 10 cpd/kg/keV at 3 keV.**
- **Level of background still high. Cesium presence.**

ANAIS: NaI(Tl) scintillator for studying annual modulation signature in Canfranc laboratory



Home-made efforts to improve old detectors.

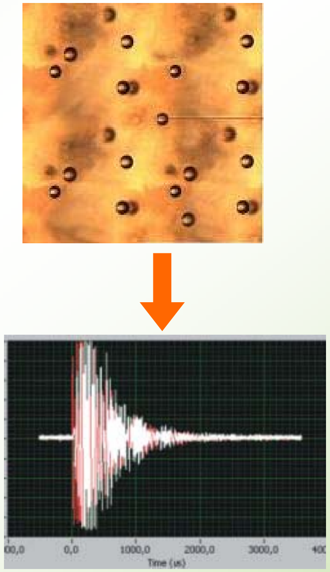
Example of a prototype:



Some alternative techniques for direct detection experiments

PICASSO 3 kg

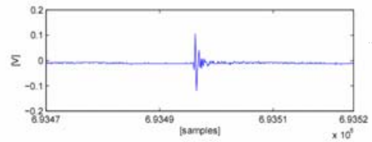
fluorine loaded active superheated liquid C_4F_{10} dispersed in the form of 50-100 μm diameter droplets in a polymerized or viscous medium



- 32 detectors, 3 kg of C_4F_{10}
- 288 acoustic channels
- First detectors installed at SNOLAB
- Data taking ongoing

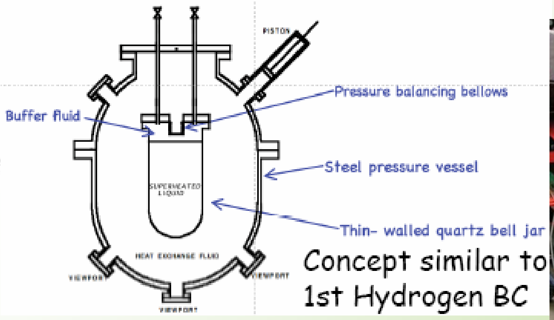
the superheated droplet detectors

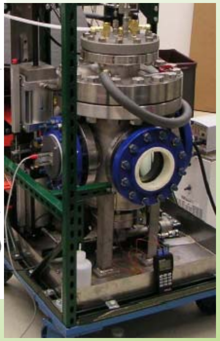
SIMPLE: a freon-loaded superheated droplet detector (CF_3I)



First results from a prototype submitted on april 2007

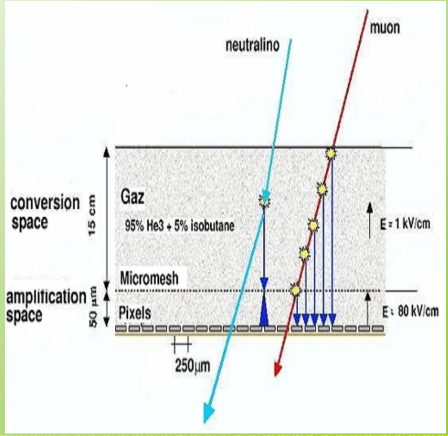
COUPP (NUMI TUNNEL)





- 2 kg CF_3I Bubble chamber
- until Sept. 06 running
- sensitive to SD and SI interactions

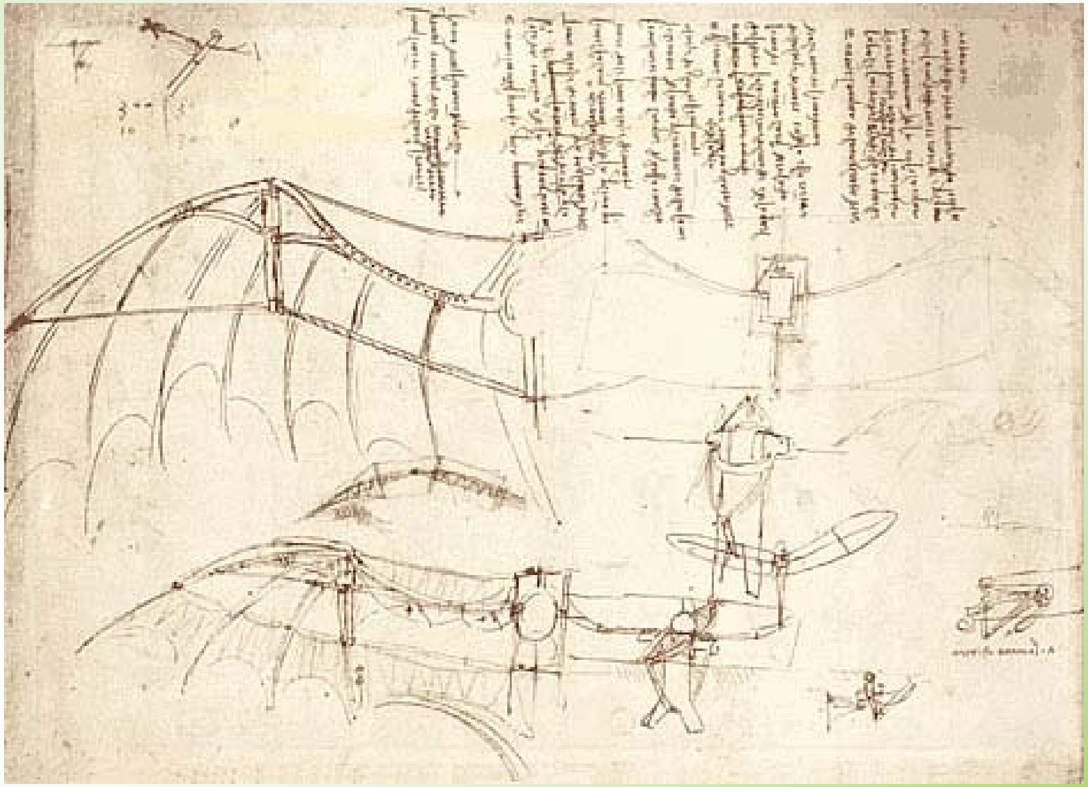
MIMAC: MIcro-tpc Matrix of Chambers of He3



also DMTPC, see Dujmic

Conclusions

- Different techniques can give complementary results
- Some further efforts to demonstrate the solidity of some techniques are desirable
- The model independent signature is the definite strategy to investigate the Dark Matter particles
- Solid experimental results obtained by considering different detectors, target materials, techniques, etc., can – at least at some extent – constrain the dark matter particle nature and disentangle among the different astrophysical scenarios, nuclear and particle physics models



Felix qui potuit rerum cognoscere causas *(Virgilio, Georgiche, II, 489)*