From DAMA/NaI to DAMA/LIBRA and beyond

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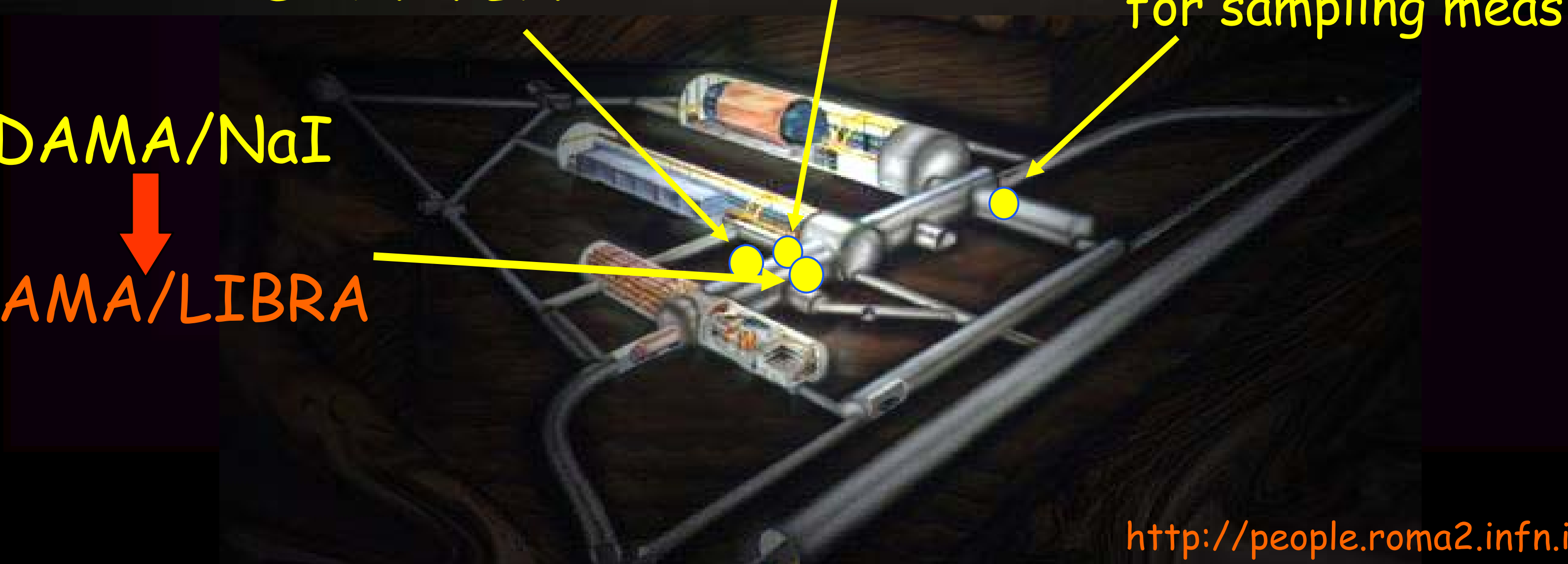
Roma2,Roma1,LNGS,IHEP/Beijing

DAMA: an observatory for rare processes @LNGS



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

DAMA/LXe: results on rare processes

NIMA482(2002)728

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering — PLB387(1996)222, NJP2(2000)15.1
- Neutron calibration — PLB436(1998)379, EPJdirectC11(2001)1
- ^{129}Xe *vs* ^{136}Xe by using PSD $\rightarrow$ SD *vs* SI signals to increase the sensitivity on the SD component — foreseen/in progress

Other rare processes:

- Electron decay into invisible channels — Astrop.Phys5(1996)217
- Nuclear level excitation of ^{129}Xe during CNC processes — PLB465(1999)315
- N, NN decay into invisible channels in ^{129}Xe — PLB493(2000)12
- Electron decay: $e^- \rightarrow \nu_e \gamma$ — PRD61(2000)117301
- 2β decay in ^{136}Xe — Xenon01
- 2β decay in ^{134}Xe — PLB527(2002)182
- Improved results on 2β in ^{134}Xe,^{136}Xe — PLB546(2002)23
- CNC decay ^{136}Xe $\rightarrow$ ^{136}Cs — Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe — EPJA27 s01 (2006) 35

DAMA/R&D set-up: results on rare processes

- Particle Dark Matter search with CaF_2(Eu) — NPB563(1999)97, Astrop.Phys.7(1997)73

- 2β decay in ^{136}Ce and in ^{142}Ce — Il Nuov.Cim.A110(1997)189
- $2EC2\nu$ ^{40}Ca decay — Astrop. Phys. 7(1999)73
- 2β decay in ^{46}Ca and in ^{40}Ca — NPB563(1999)97
- $2\beta^+$ decay in ^{106}Cd — Astrop.Phys.10(1999)115
- 2β and β decay in ^{48}Ca — NPA705(2002)29
- $2EC2\nu$ in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce — NIMA498(2003)352
- $2\beta^+ 0\nu$ and EC $\beta^+ 0\nu$ decay in ^{130}Ba — NIMA525(2004)535
- Cluster decay in $LaCl_3$(Ce) — NIMA555(2005)270
- CNC decay ^{139}La $\rightarrow$ ^{139}Ce — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15

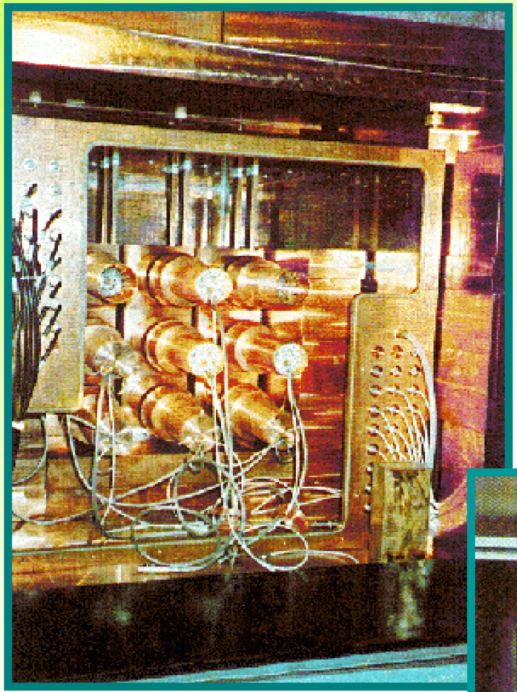
DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up;
- several RDs on low background PMTs;
- qualification of many materials
- measurements with a $Li_6Eu(BO_3)_3$ crystal (NIMA572(2007)734)
- measurements with ^{100}Mo sample investigating some double beta decay mode in progress in the 4π low-background HP Ge facility of LNGS (to appear on Nucl. Phys. and Atomic Energy)

+ Many other meas. already scheduled for near future

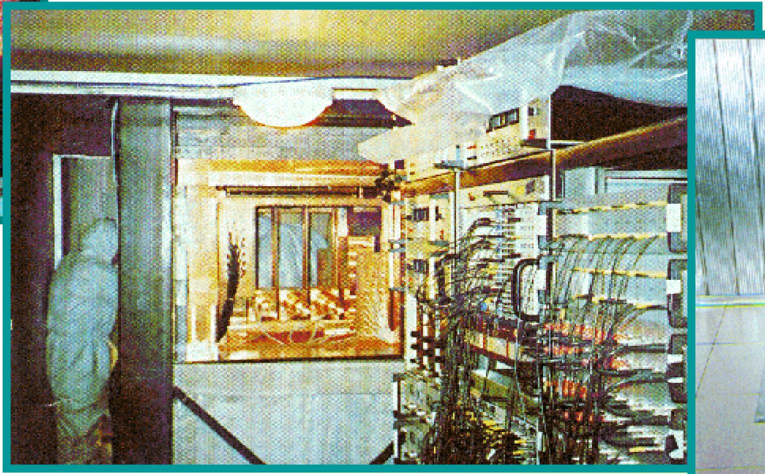
DAMA/NaI(Tl)~100 kg

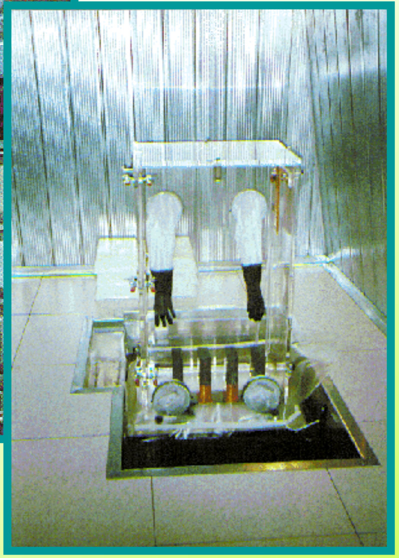
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127



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)

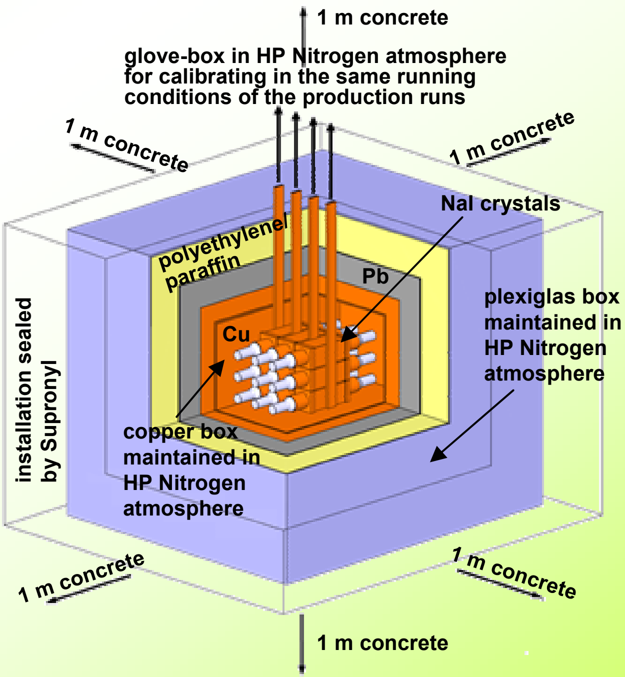
total exposure collected in 7 annual cycles 107731 kg×d

Main features of DAMA/NaI

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

- Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- PMTs: Each crystal coupled - through 10cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI9265B53/FL (special development) 3" diameter PMTs working in coincidence.
- Detectors inside a sealed highly radiopure Cu box maintained in HP Nitrogen atmosphere in slight overpressure
- Very low radioactive shields: 10 cm of highly radiopure Cu, 15 cm of highly radiopure Pb + shield from neutrons: Cd foils + 10-40 cm polyethylene/paraffin+ ~ 1 m concrete (from GS rock) moderator largely surrounding the set-up
- Installation sealed: A plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure. Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm^2/s permeability).Three levels of sealing from environmental air.
- Installation in air conditioning + huge heat capacity of shield
- Calibration in the same running conditions as the production runs down to keV region.
- Energy and threshold: Each PMT works at single photoelectron level. Energy threshold: 2 keV (from X-ray and Compton electron calibrations in the keV range and from the features of the noise rejection and efficiencies). Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
- Pulse shape recorded over 3250 ns by Transient Digitizers.
- Monitoring and alarm system continuously operating by self-controlled computer processes.

+ electronics and DAQ fully renewed in summer 2000



Simplified schema

Main procedures of the DAMA data taking for the DMp annual modulation signature

- data taking of each annual cycle starts from autumn/winter (when $\cos\omega(t-t_0)\approx0$) toward summer (maximum expected).
- routine calibrations for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration + periodical Compton calibrations, etc.
- continuous on-line monitoring of all the running parameters with automatic alarm to operator if any out of allowed range.

Competitiveness of NaI(Tl) set-up

- **High duty cycle**
- **Well known technology**
- **Large mass possible**
- ***"Ecological clean"* set-up; no safety problems**
- **Cheaper than every other considered technique**
- **Small underground space needed**
- **High radiopurity by selections, chem./phys. purifications, protocols reachable**
- **Well controlled operational condition feasible**
- **Routine calibrations feasible down to keV range in the same conditions as the production runs**
- **Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)**
- **Absence of microphonic noise + effective noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)**
- **High light response (5.5 -7.5 ph.e./keV)**
- **Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-nuclei**
- **Sensitive to both high (by Iodine target) and low mass (by Na target) candidates**
- **Effective investigation of the annual modulation signature feasible in all the needed aspects**
- **PSD feasible at reasonable level**
- **etc.**

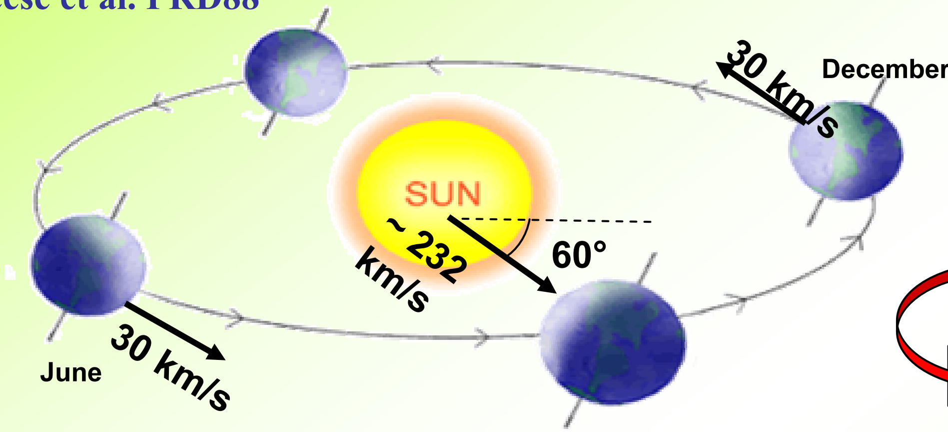
A low background NaI(Tl) also allows the study of several other rare processes such as: possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost

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

The model independent result

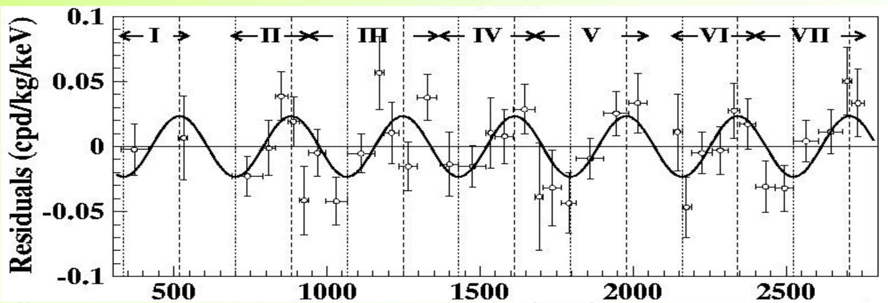
Riv. N. Cim. 26 n.1. (2003) 1-73
IJMPD13(2004)2127

DAMA/NaI 7 annual cycles: experimental single-hit residuals rate vs time and energy

107731 kg · d

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

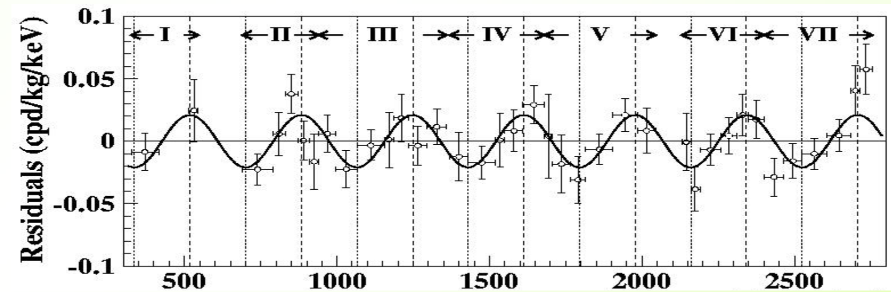
2-4 keV



fit: A=(0.0233 ± 0.0047) cpd/kg/keV

Time (day)

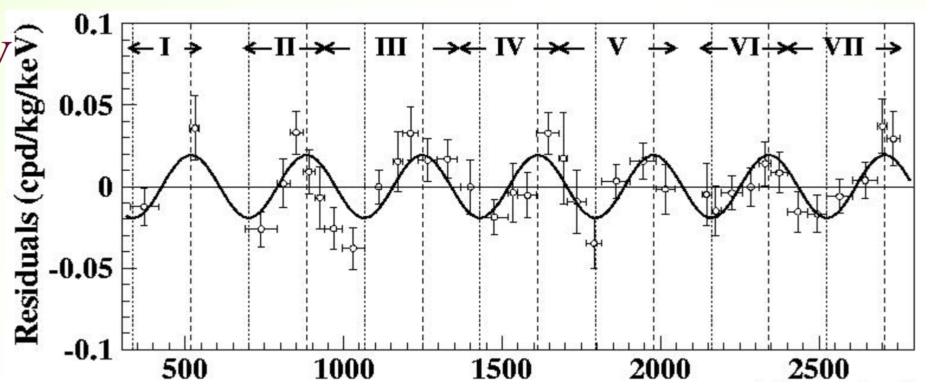
2-5 keV



fit: A = (0.0210 ± 0.0038) cpd/kg/keV

Time (day)

2-6 keV



Time (day)

Absence of modulation? No

χ^2/dof=71/37 → P(A=0)=$7\cdot10^{-4}$

fit: A = (0.0192 ± 0.0031) cpd/kg/keV

fit (all parameters free):

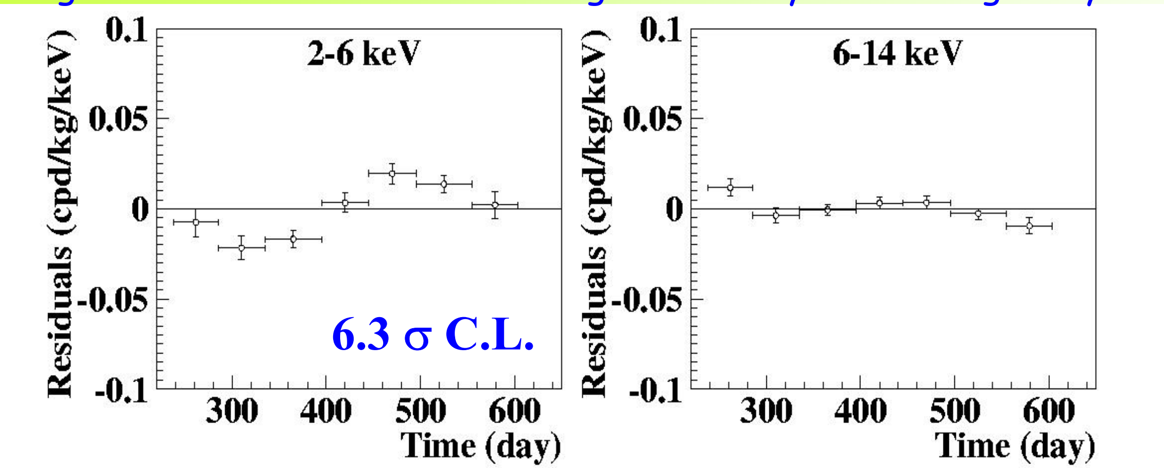
A = (0.0200 ± 0.0032) cpd/kg/keV;

t_0 = (140 ± 22) d ; T = (1.00 ± 0.01) y

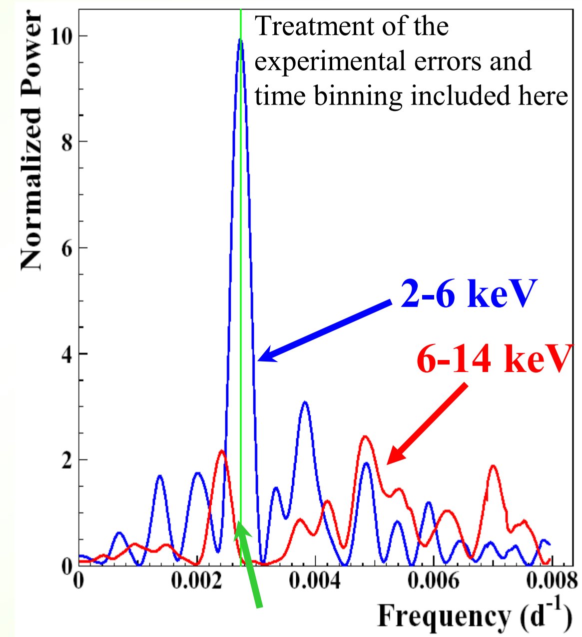
The data favor the presence of a modulated behavior with proper features at 6.3σ C.L.

Low energy vs higher energy

Single-hit residual rate as in a single annual cycle ≈ 10^5 kg × day



Power spectrum of single-hit residuals

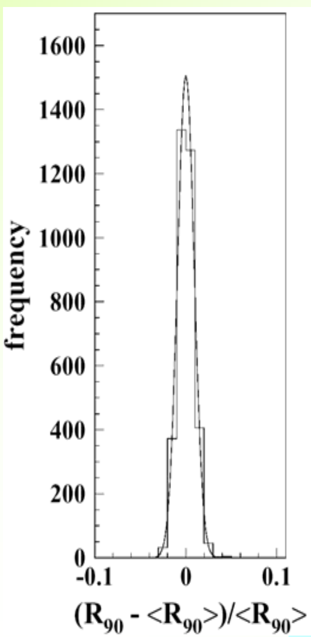


fixing t_0 = 152.5 day and T = 1.00 y, the modulation amplitude:

A=(0.0195 ± 0.0031) cpd/kg/keV   A= -(0.0009 ± 0.0019) cpd/kg/keV

Principal mode in the 2-6 keV region → $2.737 \cdot 10^{-3}$ d^{-1} ≈ 1 y^{-1}

Not present in the 6-14 keV region (only aliasing peaks)



- Clear modulation present in the lowest energy region: from the energy threshold, 2 keV, to 6 keV.
- No modulation found:
  - in the 6-14 keV energy regions
  - in other energy regions closer to that where the effect is observed e.g.: mod. ampl. (6-10 keV): -(0.0076 ±0.0065), (0.0012±0.0059) and (0.0035±0.0058) cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero
  - in the integral rate above 90 keV, e.g.: mod. ampl.: (0.09±0.32), (0.06±0.33) and -(0.03±0.32) cpd/kg for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

Multiple-hits events in the region of the signal

- In DAMA/NaI-6 and 7 each detector has its own TD (multiplexer system removed) → pulse profiles of multiple-hits events (multiplicity > 1) also acquired (total exposure: 33834 kg d).
- The same hardware and software procedures as the ones followed for single-hit events

→ just one difference: events induced by Dark Matter particles do not belong to this class of events, that is: multiple-hits events = Dark Matter particles events "switched off"

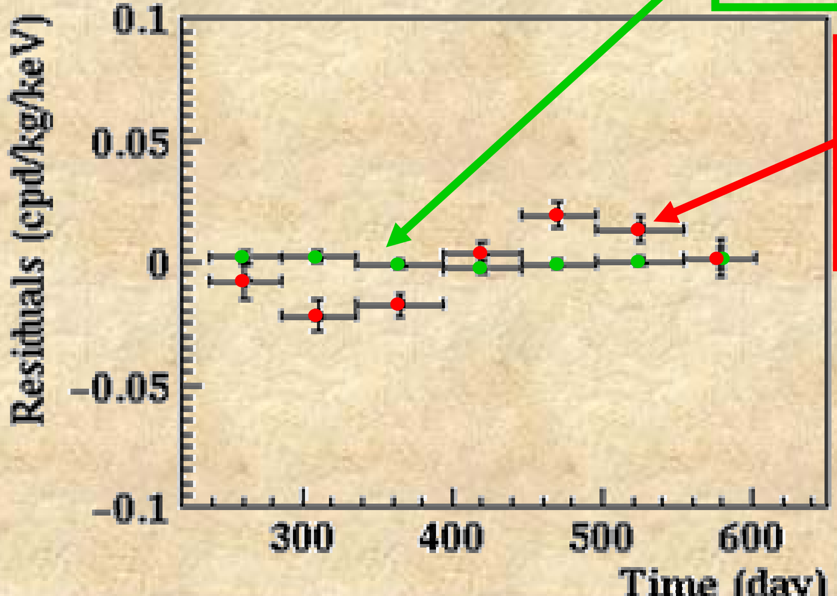
- **2-6 keV residuals**

Residuals for multiple-hits events (DAMA/NaI-6 and 7)

Mod ampl. = $-(3.9 \pm 7.9) \cdot 10^{-4}$ cpd/kg/keV

Residuals for single-hit events (DAMA/NaI 7 annual cycles)

Mod ampl. = (0.0195 ± 0.0031) cpd/kg/keV



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

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 $\rightarrow$ huge heat capacity + T continuously recorded + etc.	$<0.5\%\ S_m^{obs}$
NOISE	Effective noise rejection near threshold ($\tau_{noise}\sim$ tens ns, $\tau_{NaI}\sim$ 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

The positive and model independent result of DAMA/NaI

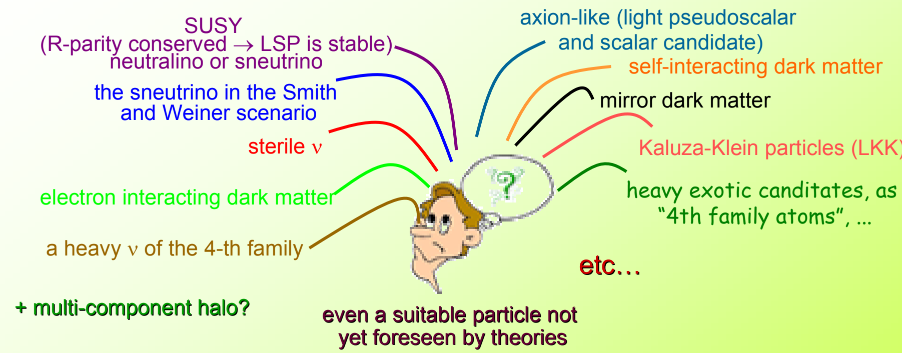
- Presence of modulation for 7 annual cycles at ~6.3σ C.L. with the proper distinctive features of the signature; all the features satisfied by the data over 7 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account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

Examples of uncertainties in models and scenarios

see for some details e.g.:
Riv.N.Cim.26 n.1 (2003) 1, IJMPD13(2004)2127, EPJC47 (2006)263, IJMPA21 (2006)1445

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic
+ e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirorror dark matter
- Heavy Exotic candidate
- …etc. etc.

Scaling law
of cross section for the case of recoiling nuclei

• Different scaling laws for different DM particle:

$\sigma_A \propto \mu^2 A^2 (1+\varepsilon_A)$

$\varepsilon_A = 0$ *generally assumed*

$\varepsilon_A \approx \pm 1$ *in some nuclei? even* for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ very simple but unphysical halo model
- Many consistent halo model with different density and velictiy distributions profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- …etc. …

Form Factors
for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factor: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factor for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depends on the nuclear potential models
- Large differences in the measured counting rate can be expected using:

  either SD not-sensitive isotopes

  or SD sensitive isotpes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Their dependence on energy
- …

Quenching Factor

- differences are present in different experimental determinations of *q* for the same nuclei in the same kind of detector depending on its specific features (e.g. in doped scintillators *q* depends on dopant and on the impurities/trace contaminants; in LXe e.g.on trace impurities, on initial UHV, on presence of degassing/releasing materials in the Xe, on thermodynamical conditions, on possibly applied electric field, etc)
- Sometime increases at low energy in scintillators (dL/dx)

  → energy dependence

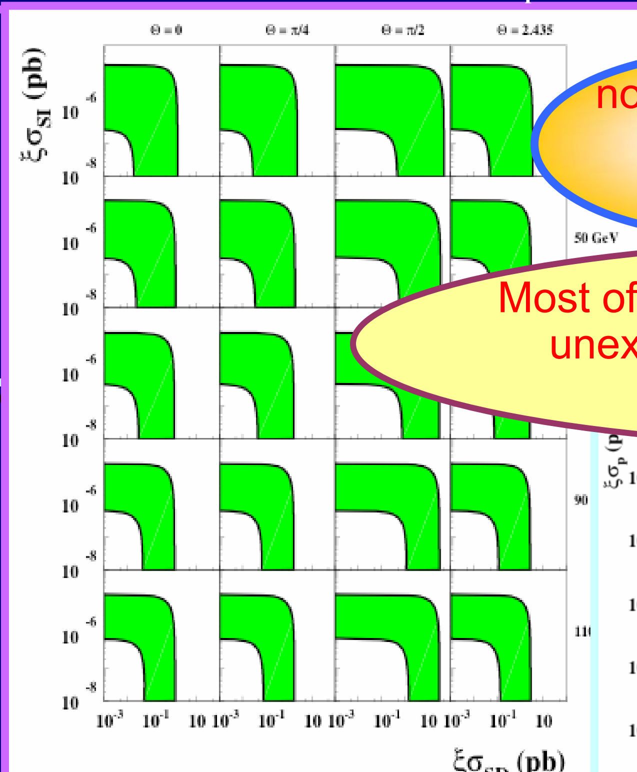
… and more …

Few examples of corollary quests for the WIMP class in given frameworks

(Riv. N.Cim. vol.26 n.1. (2003) 1-73, IJMPD13(2004)2127)

DM particle with elastic SI&SD interactions

(Na and I are fully sensitive to SD interaction, on the contrary of e.g. Ge and Si) 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

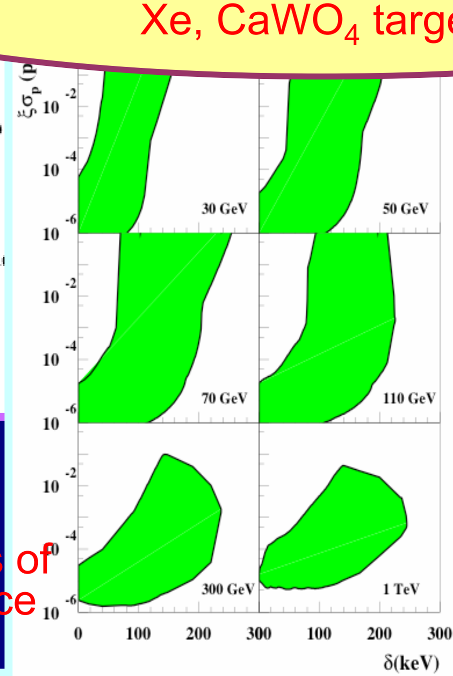


not exhaustive + different scenarios?

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

DM particle with preferred inelastic interaction:

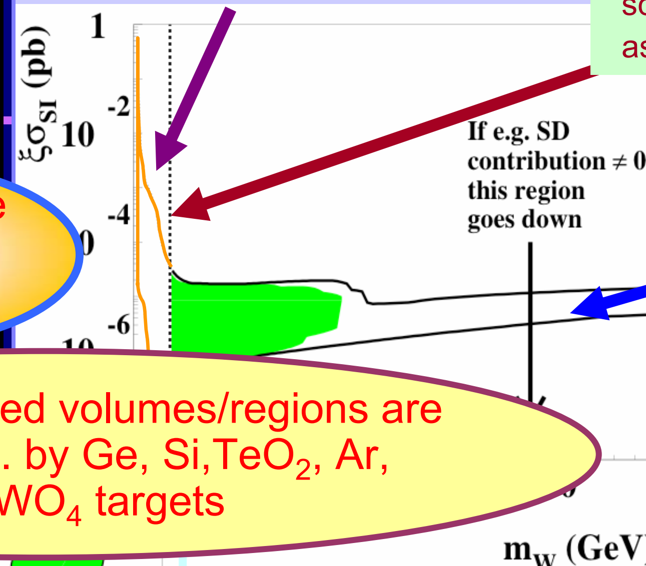
$W + N \rightarrow W^* + N$ (S_m/S_0 enhanced): examples of slices of the allowed volume in the space ($\xi\sigma_p$, m_W, δ) [e.g. Ge disfavoured]



DM particle with dominant SI coupling

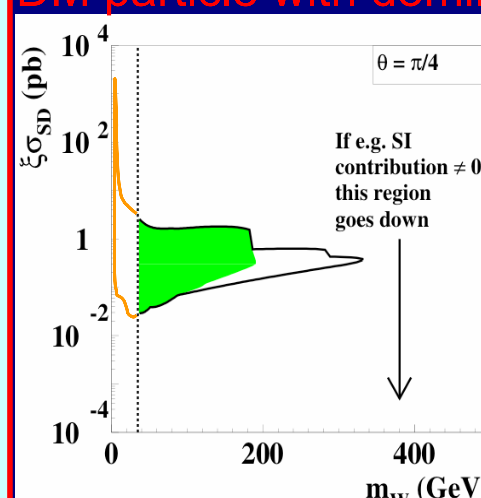
Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for "generic" DM particle

Model dependent lower bound on neutralino mass as derived from LEP data in supersymmetric schemes based on GUT assumptions (DPP2003)



higher mass region allowed for low v_0, every set of parameters' values and the halo models: Evans' logarithmic C1 and C2 co-rotating, triaxial D2 and D4 non-rotating, Evans power-law B3 in setA

DM particle with dominant SD coupling

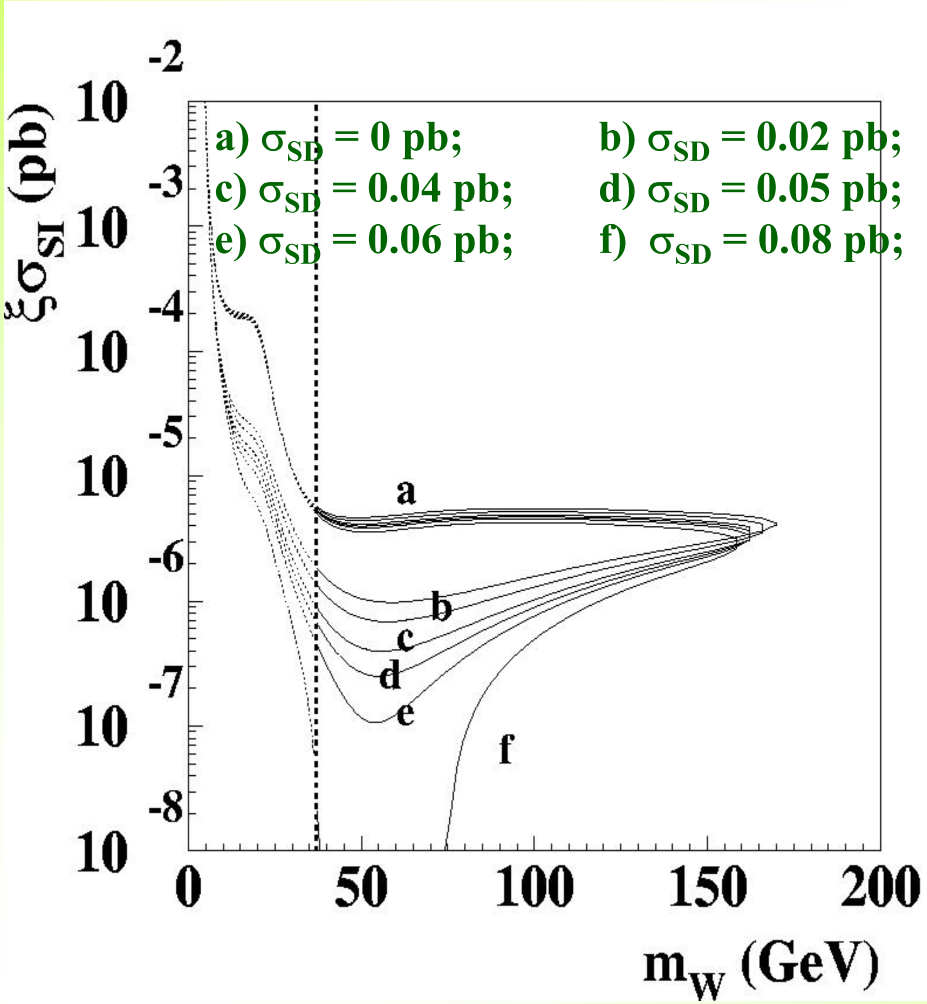


volume allowed in the space (m_W, $\xi\sigma_{SD}$, θ); here example of a slice for $\theta = \pi/4$ ($0 \le \theta < \pi$)

Regions above 200 GeV allowed for low v_0, for every set of parameters' values and for Evans' logarithmic C2 co-rotating halo models

An example of the effect induced by a non-zero SD component on the allowed SI regions

- Example obtained considering Evans' logarithmic axisymmetric C2 halo model with v_0 = 170 km/s, ρ_0 max at a given set of parameters
- The different regions refer to different SD contributions with θ=0



A small SD contribution ⇒ drastically moves the allowed region in the plane (m_W, $\xi\sigma_{SI}$) towards lower SI cross sections ($\xi\sigma_{SI} < 10^{-6}$ pb)

Similar effect for whatever considered model framework

- There is no meaning in bare comparison between regions allowed in experiments sensitive to SD coupling and exclusion plots achieved by experiments that are not.
- The same is when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron where $\theta \approx \mathbf{0}$ or $\theta \approx \pi$.

Example of comparison with Supersymmetric expectations in MSSM

- 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

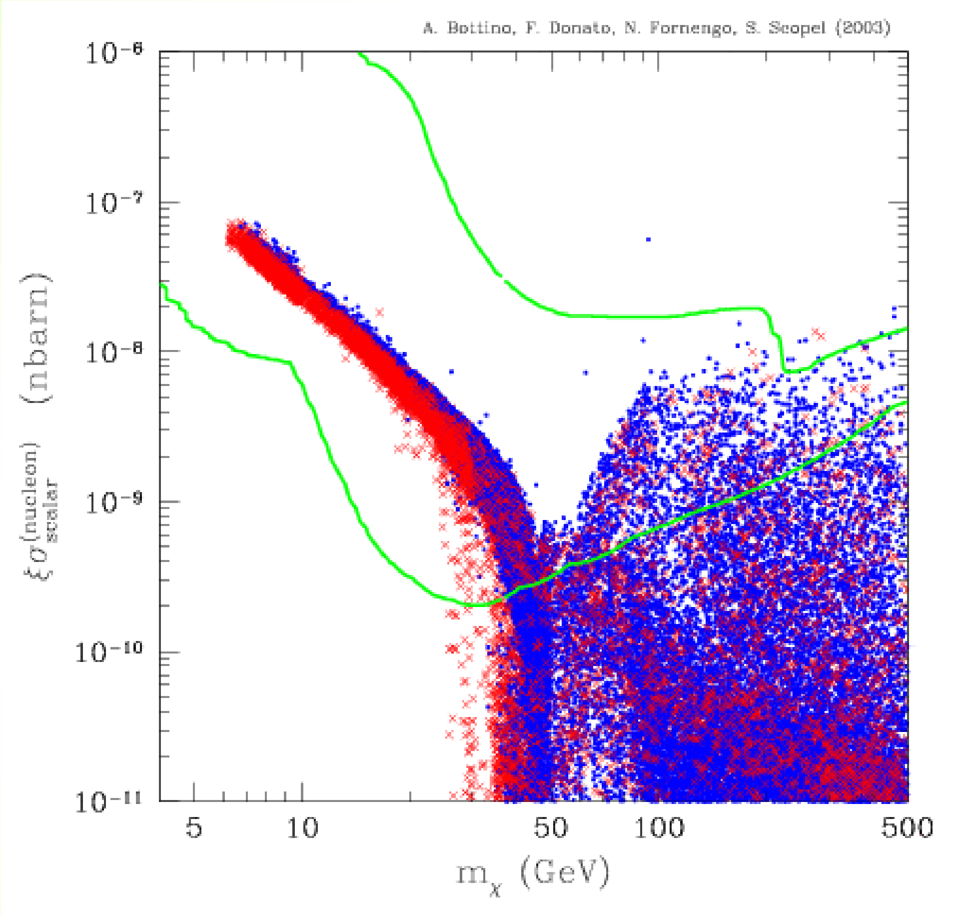


figure taken from PRD69(2004)037302

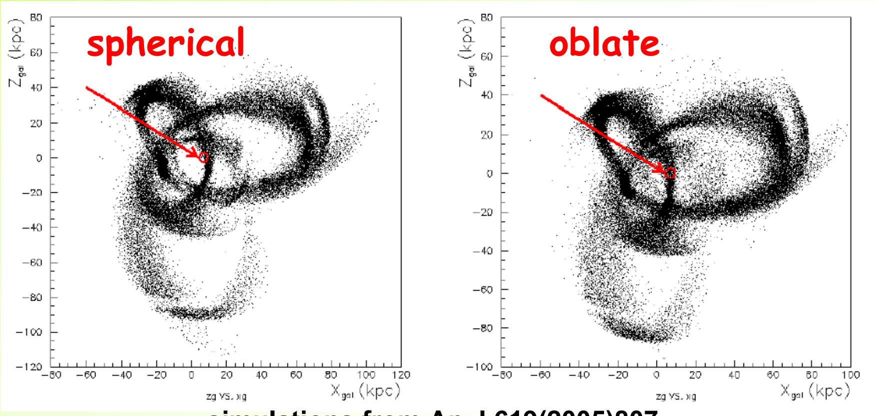
scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line);

(for previous DAMA/NaI partial exposure see PRD68(2003)043506)

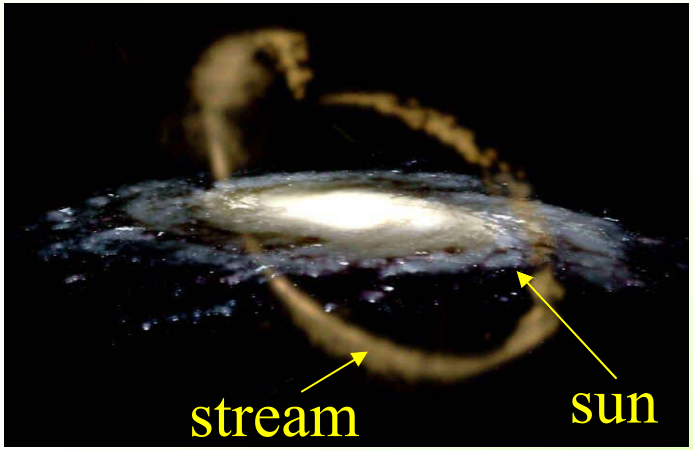
Investigating halo substructures by underground expt through annual modulation

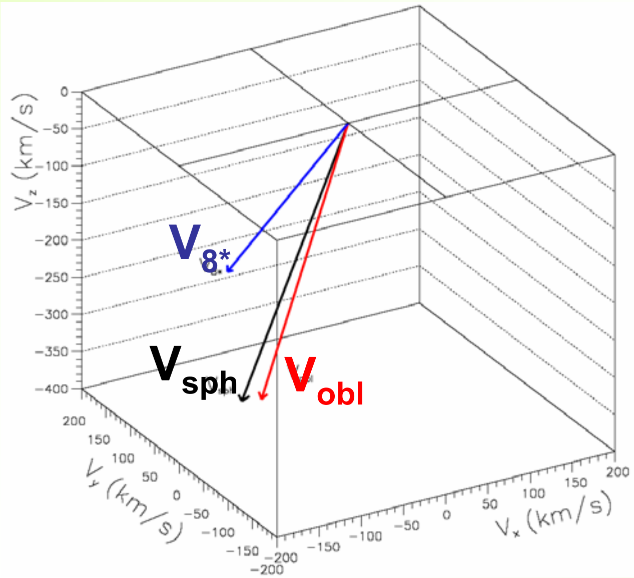
Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way

EPJC47(2006)263



simulations from Ap.J.619(2005)807





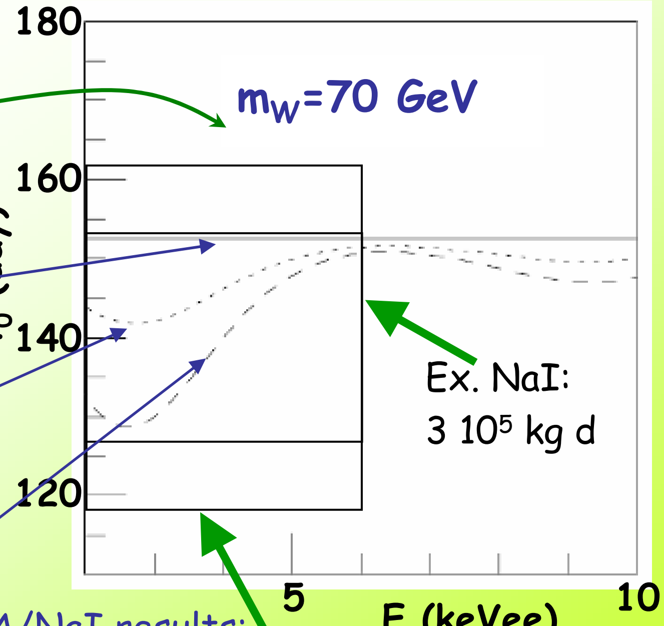
V_{8*} from 8 local stars: PRD71(2005)043516

Examples of the effect of SagDEG tail on the phase of the signal annual modulation

Expected phase in the absence of streams t_0 = 152.5 d (June 2nd)

NFW spherical isotropic non-rotating, v_0 = 220km/s, ρ_{0max} + 4% SagDEG

NFW spherical isotropic non-rotating, v_0 = 220km/s, ρ_{0min} + 4% SagDEG



DAMA/NaI results:
(2-6) keV t_0 = (140±22) d

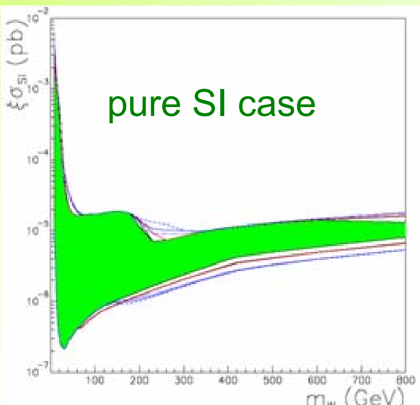
Investigating the effect of SagDEG for WIMPs and Constraining the SagDEG stream by DAMA/NaI

DAMA/NaI: seven annual cycles 107731 kg d for some SagDEG modelling

EPJC47 (2006) 263

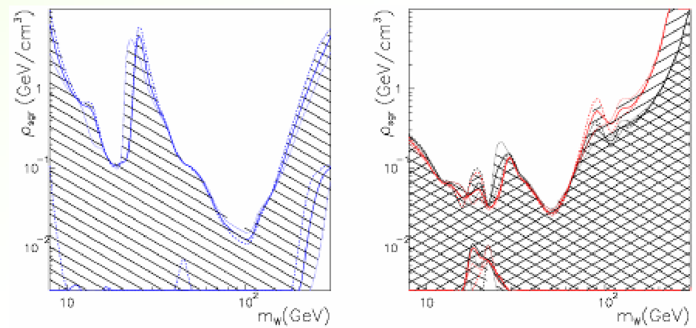
Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way

Investigating local halo features by annual modulation signature considering different SagDEG velocity dispersions (20-40-60 km/s)



Few examples

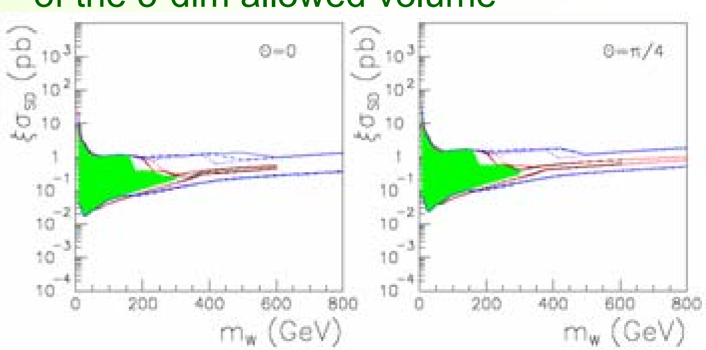
green areas: no SagDEG

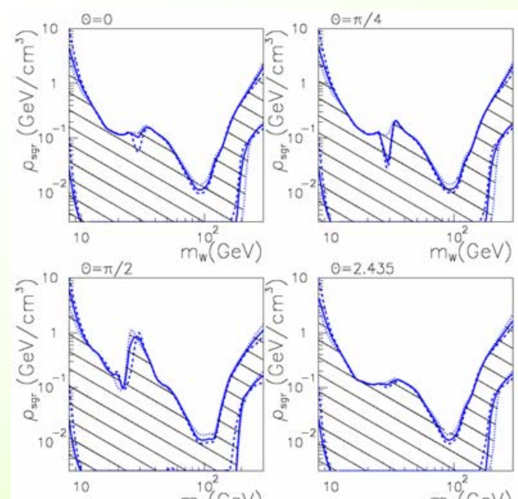


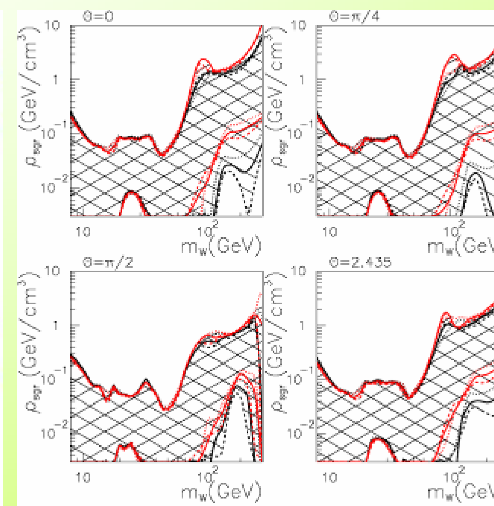
pure SI case

pure SD case

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





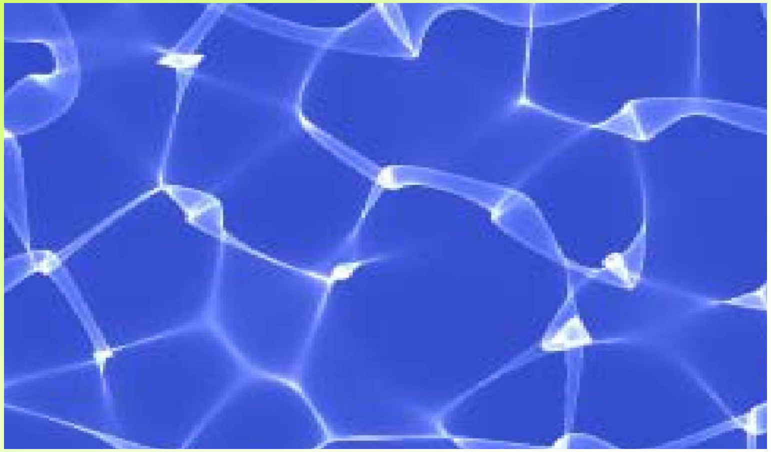


The higher sensitivity of DAMA/LIBRA will allow to more effectively investigate the presence and the contributions of streams in the galactic halo

… other astrophysical scenarios?

Possible other (beyond SagDEG) non-thermalized component in the galactic halo?

In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected :



Possible presence of caustic rings

$\Rightarrow$ streams of Dark Matter particles

Fu-Sin Ling et al. astro-ph/0405231

under investigation

Interesting scenarios for DAMA

Effect on $|S_m/S_o|$ respect to "usually" adopted halo models?

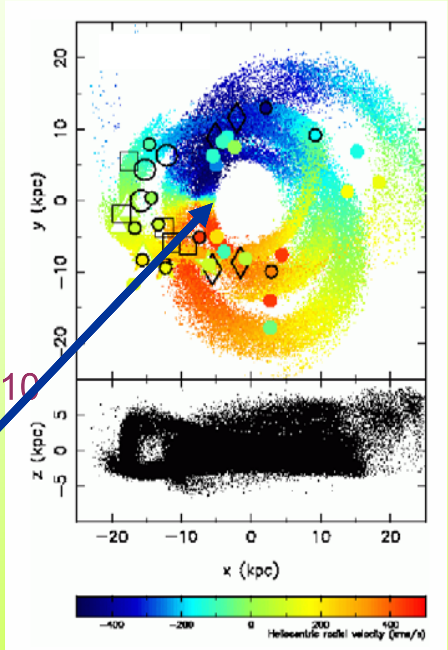
Effect on the phase of annual modulation signature?

Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

.....very likely....

Canis Major simulation:
astro-ph/0311010

Position of the Sun:
(-8,0,0) kpc



Can be guess that spiral galaxy like Milky Way have been formed capturing close satellite galaxy as Sgr, Canis Major, ecc…

Investigating electromagnetic contributions in searches for 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)

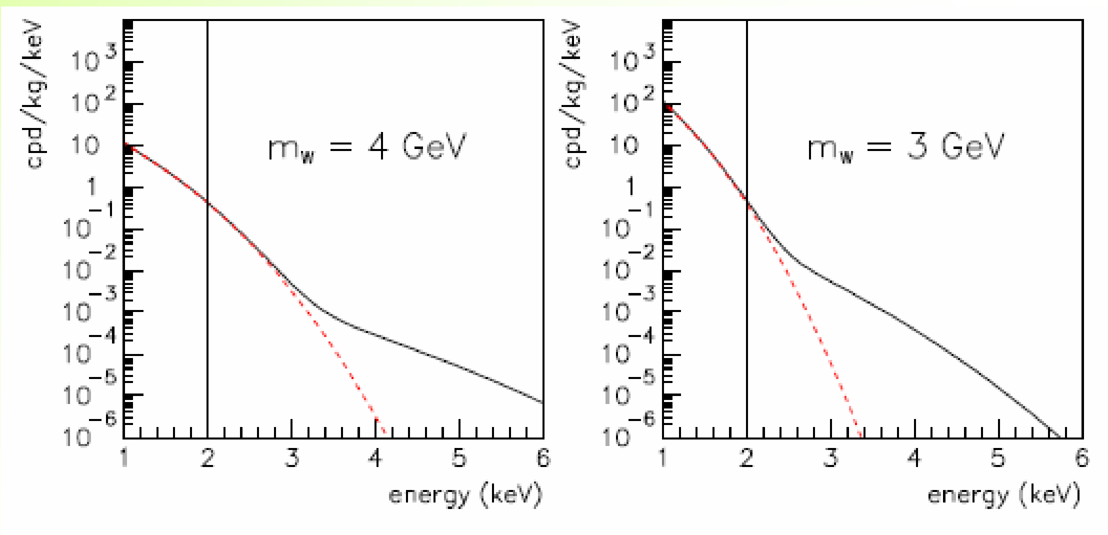
→ **the recoiling nucleus can "shake off" some of the atomic electrons**

→ **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

Example



accounting for Migdal effect

Without Migdal effect

Adopted assumptions in the examples:

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

ii) non-rotating Evanslogarithmic 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

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

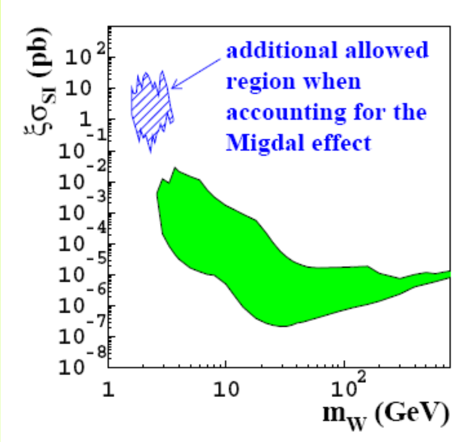
- **the unquenched nature of the e.m. contribution**
- **the behaviour of the energy distribution for nuclear recoils induced by WIMP-nucleus elastic scatterings**
- **etc.**

can give an appreciable impact at low WIMP masses

Examples of the impact of the accounting for the e.m. contribution to the detection of WIMP candidates

IJMPA 22 (2007) 3155

Example of a WIMP with dominant SI coupling

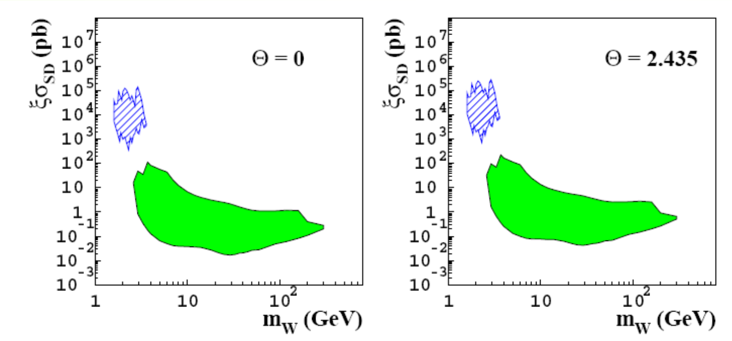


Region allowed in the ($\xi\sigma_{SI}$; m_W) plane in the considered model frameworks for pure SI coupling;

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

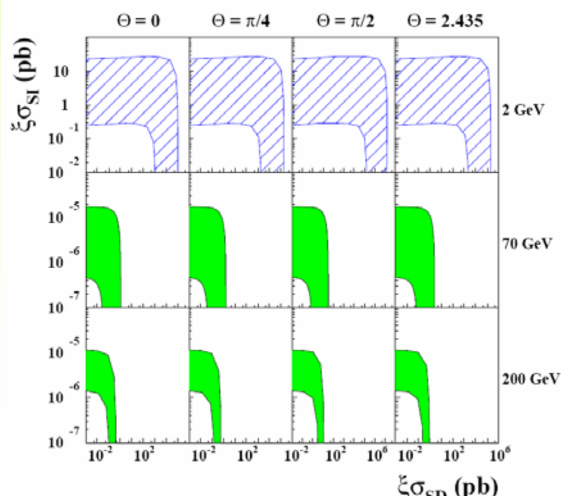
2) considered frameworks as in Riv.N.Cim 26 n1 (2003)1

Example of a WIMP with dominant SD coupling



Two slices of the 3-dimensional allowed volume ($\xi\sigma_{SI}$; m_W; θ) in the considered model frameworks for pure SD coupling

Example of a WIMP with SI&SD coupling



Examples of slices of the 4-dimensional allowed volume ($\xi\sigma_{SI}$; $\xi\sigma_{SD}$; m_W; θ) in the considered model frameworks

GeV mass DM particle candidates have been widely proposed in literature in order to account not only for the DM component of the Universe but also other cosmological and particle physics topics (Baryon Asymmetry, discrepancies between observations and LCDM model on the small scale structure, etc.)

Among DM GeV mass condidates: 1) H dibarion (predicted in Standard Model); 2) a real scalar field in extended Standard Model; 3) the light photino early proposed in models with low-energy supersimmetry; 4) the very light neutralino in Next-to-MSSM model; 5) the mirror deuterium in frameworks where mirror dark matter interations with ordinary matter are dominated by very heavy particles; …

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.

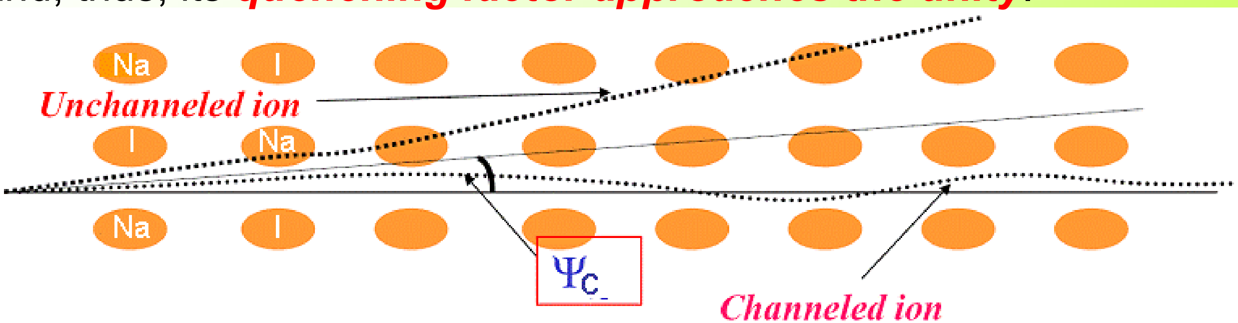
Well-known effect, discovered on 1957, when a deep penetration of $^{134}Cs^+$ ions into a Ge crystal to a depth $\lambda_c \approx 10^3$ Å was measured (according to SRIM, a 4 keV Cs^+ ion would penetrate into amorphous Ge to a depth $\lambda_a = 44$ Å, $S_n/S_e = 32$ and q=0.03). Within a channel,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

- 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***.

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

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

$$q(E) \approx 1$$



Modeling the channeling effect: critical angles for channeling

J. Lindhard, Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 34 (1965) 1.

Axial channeling. Lindhard's channeling theory treats channeling of low energy, high mass ions as a separate case from high energy, low mass ions. For low energy, high mass ions (recoiling nuclei) Lindhard's critical angle Ψ_c is given by:

$$\Psi_c = \sqrt{\frac{C a_{TF}}{d\sqrt{2}}\Psi_1}$$

$C^2=3$, d is the interatomic spacing in the crystal along the channeling direction. The characteristic angle Ψ_1 is defined as:

$$\Psi_1 = \sqrt{\frac{2Z_1Z_2e^2}{E_R d}}$$

Z_1 and Z_2 are the atomic numbers of the projectile (recoil nucleus) and target atoms, respectively, E_R is the recoiling nucleus energy, e is the electronic charge and a_{TF} the Thomas-Fermi radius

This equation is valid for $\Psi_1 > \Psi_{1,\lim} = \frac{a_{TF}}{d} \longrightarrow E_R < E_{\lim} = \frac{2\,Z_1\,Z_2\,e^2\,d}{a_{TF}^2}$ more than 150 keV for NaI(Tl)

The critical angles should not depend on the temperature

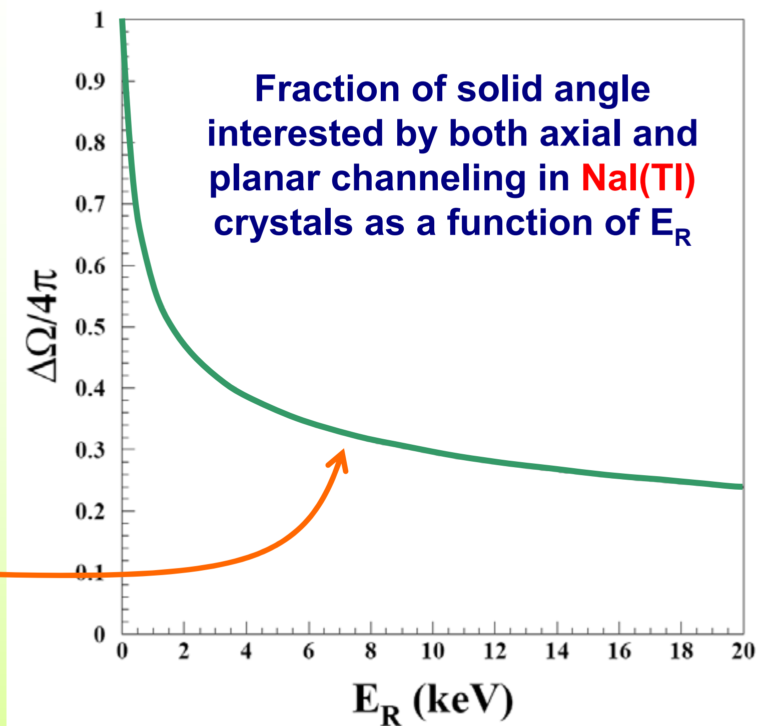
At higher energy, the critical angle is: $C\Psi_1$

Planar channeling. $\theta_{pl} = a_{TF}\cdot\sqrt{Nd_p}\cdot\left(\frac{Z_1Z_2e^2}{E\cdot a_{TF}}\right)^{1/3}$

N is the atomic number density, d_p is the inter-plane spacing.

At higher energy, the critical angle is: $\theta_{pl} = a_{TF}\cdot\sqrt{Nd_p}\cdot\left(\frac{2Z_1Z_2e^2C}{E\cdot a_{TF}}\right)^{1/2}$

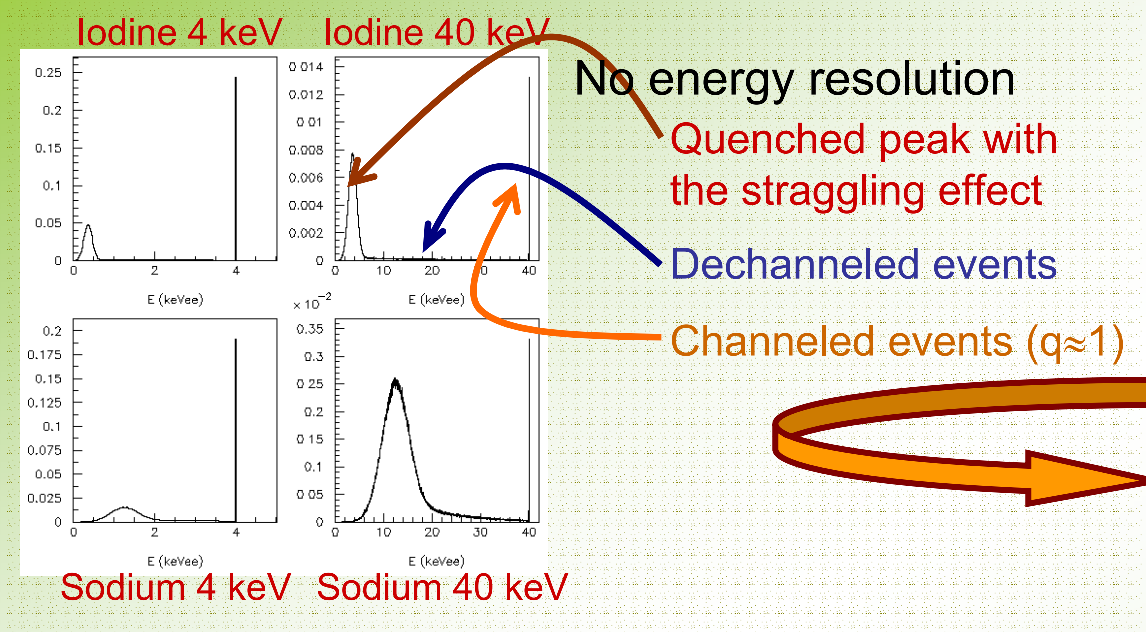
Axial channeling considering the lower index crystallographic axes: <100>, <110>, <111> and planes: {100}, {110}, {111}



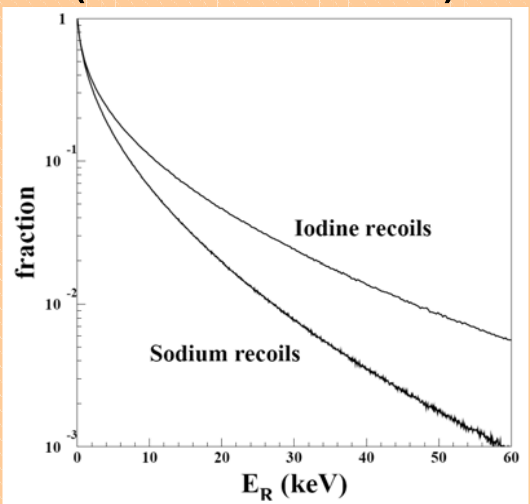
Modeling the channeling effect:

Examples of light responses

ROM2F/2007/15, to appear

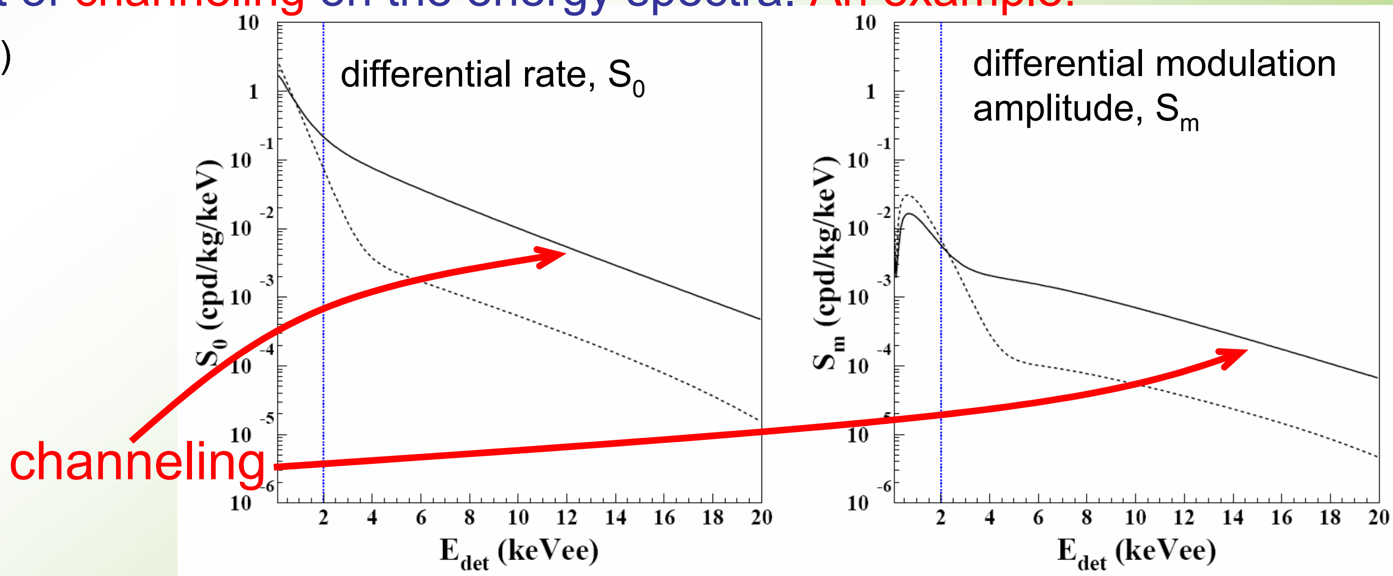


Fraction of events with q ~ 1 (channeled events)



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)

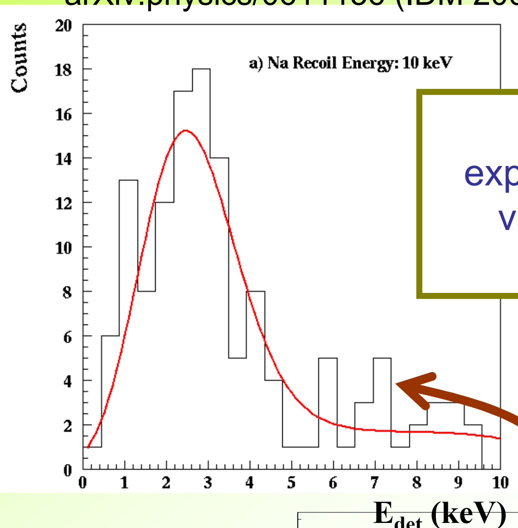


What about the neutron calibrations of NaI(Tl) detectors?

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

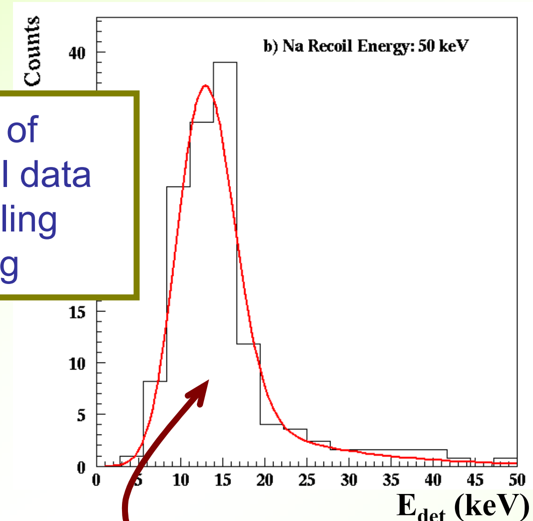
H. CHAGANI*, P. MAJEWSKI**, E. J. DAW, V. A. KUDRYAVTSEV, and N. J. C. SPOONER

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

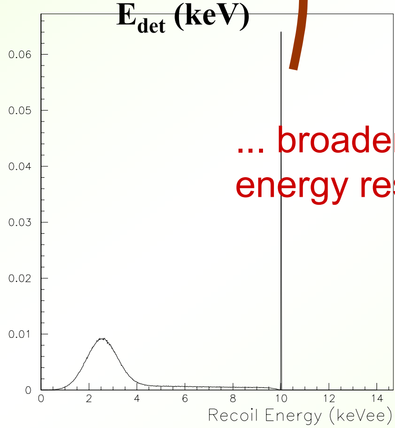


Example of experimental data vs channeling modeling

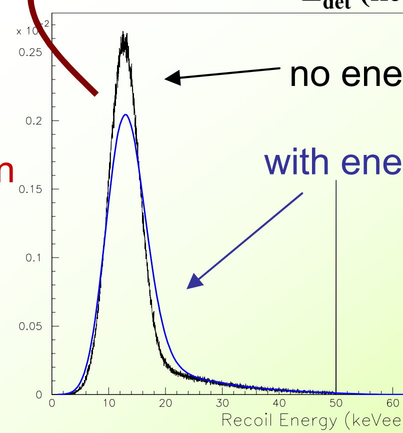
ROM2F/2007/15, to appear

- **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



no energy res.

with energy res.

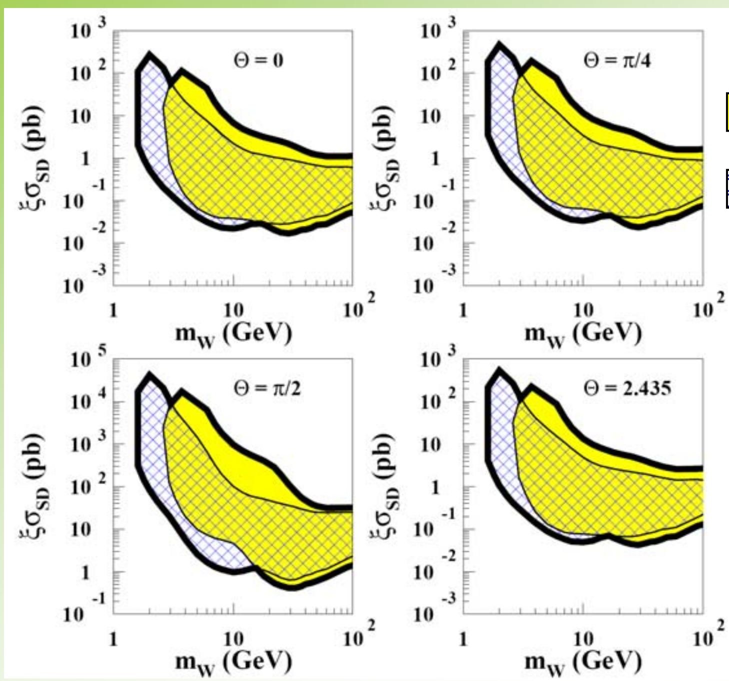
Therefore, there is no hope to identify the channeling effect in the already-collected neutron data on NaI(Tl)

the accounting for the channeling effect can give some impact in the sensitivities for WIMP or WIMP-like candidates with low masses

Some examples of accounting for channeling effect as modeled in some given frameworks

ROM2F/2007/15, to appear

purely SD WIMP

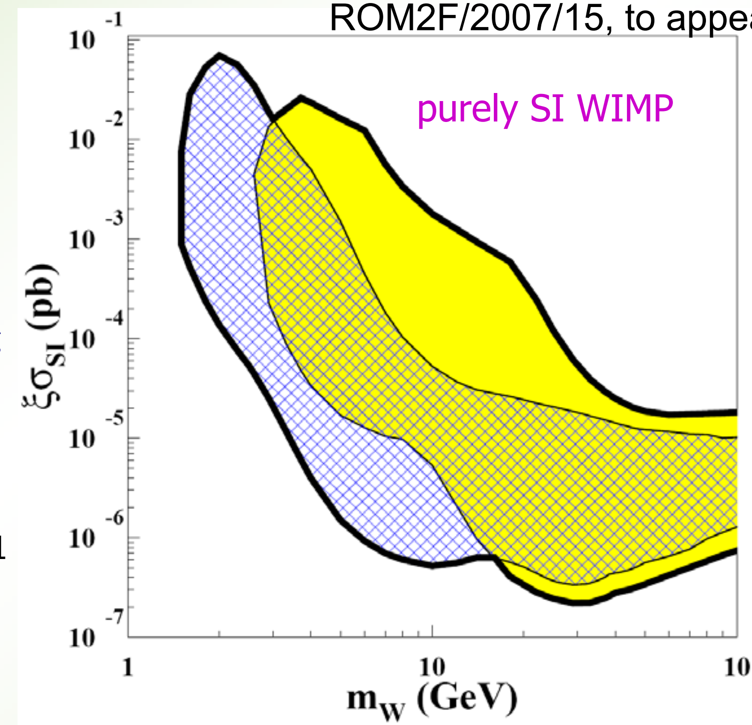


without channeling

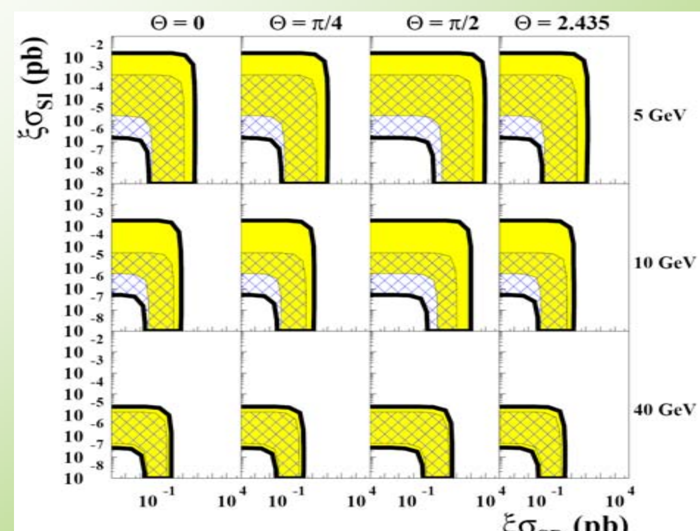
with (for modelling see before)

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

purely SI WIMP



SI & SD WIMP

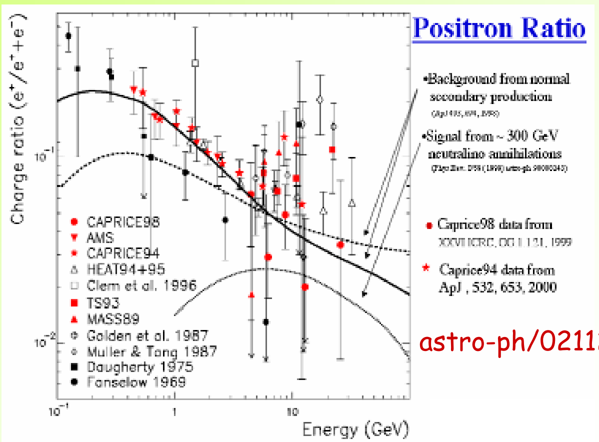


to point out just the impact of the channeling effect the SagDEG contribution and the Migdal effect have not been included here

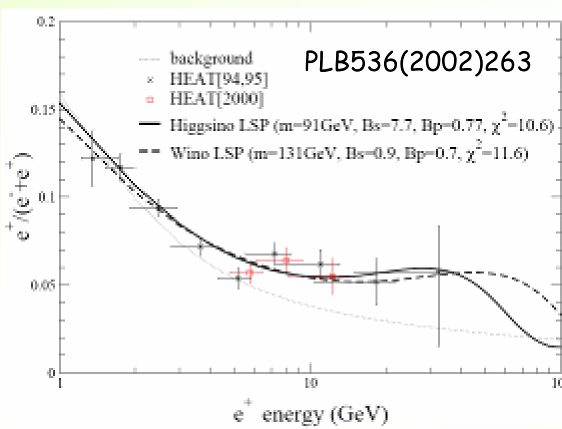
What about the indirect searches of DM particles in the space?

It was already noticed in 1997 that the EGRET data showed an excess of gamma ray fluxes for energies above 1 GeV in the galactic disk and for all sky directions.

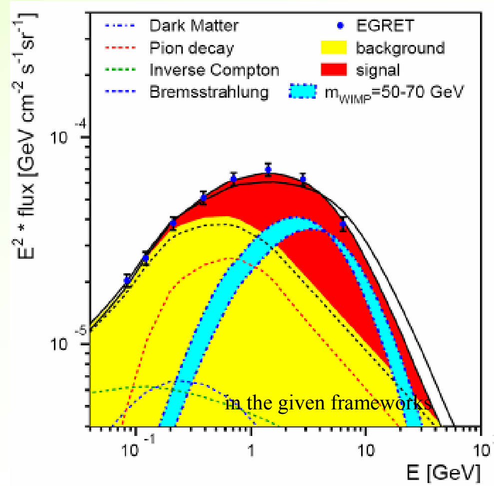
The EGRET Excess of Diffuse Galactic Gamma Rays



astro-ph/021128

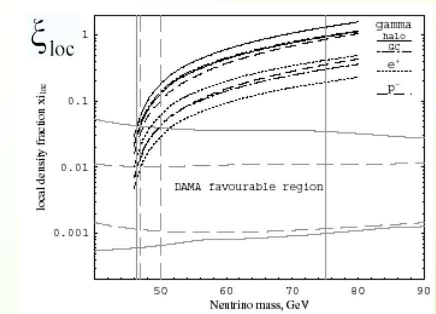


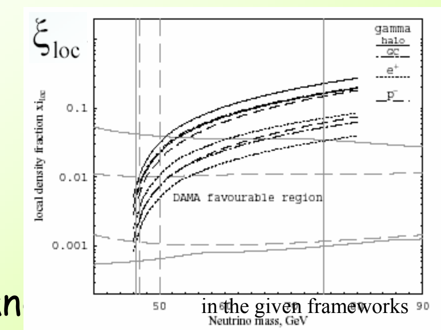
PLB536(2002)263



EGRET data, W.de Boer, hep-ph/0508108

hep-ph/041109





interpretation, evidence itself, derived m_W an
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

In next years new data from DAMA/LIBRA (direct detection) and from Agile, Glast, Ams2, Pamela, ... (indirect detections)

Another class of DM candidates:

light bosonic particles

IJMPA21(2006)1445

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

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, as CDMS, Edelweiss,CRESST, WARP, Xenon,...)

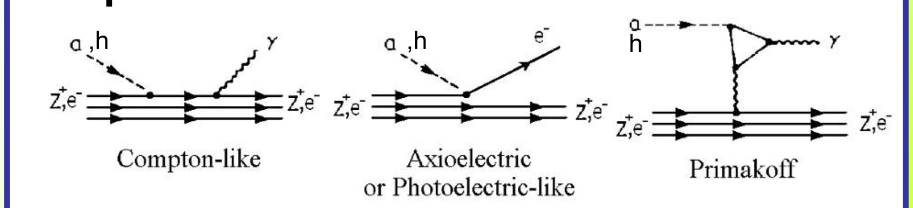
Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants allowed.

A wide literature is available and various candidate particles have been and can be considered + similar candidate can explain several astrophysical observations (AP23(2003)145)

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.

They can account for the DAMA/NaI observed effect as well as candidates belonging to the WIMPs class

Main processes involved in the detection:



a	S_0	S_0, S_m	S_0, S_m
h	S_0, S_m	S_0	S_0, S_m

Light bosons additional solutions for the annual modulation data of DAMA/NaI

IJMP A21(2006)1445

The pseudoscalar case (*a*)

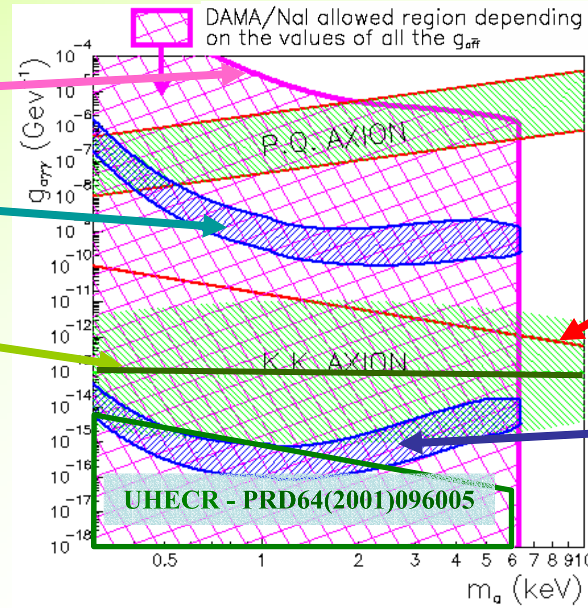
Maximum allowed photon coupling

only electron coupling

Di Lella, Zioutas AP19(2003)145

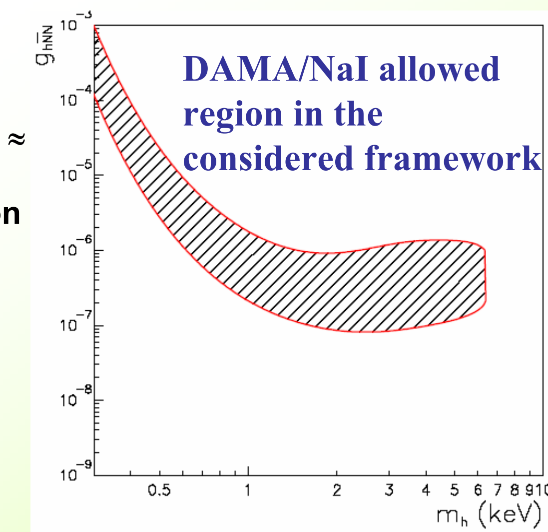
cosmological interest: at least below

Majoron as in PLB99(1981)411

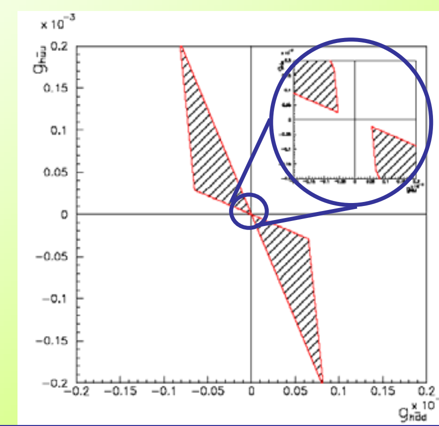


The scalar case (*h*)

1) electron coupling does not provide modulation
2) from measured rate: $g_{hee} < 3\ 10^{-16}$ to 10^{-14} for $m_h \approx$ 0.5 to 10 keV
3) coupling only to hadronic matter: allowed region in $g_{h\bar{N}N}$ vs. m_h (3σ C.L.)

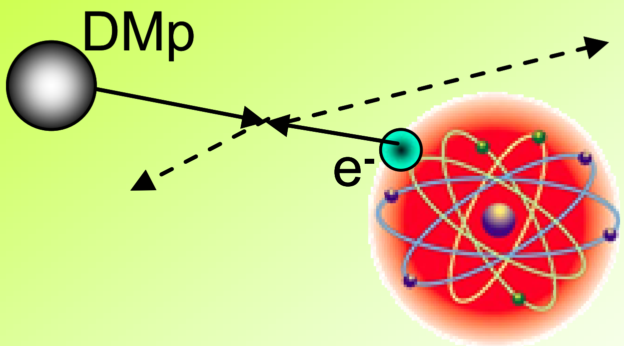


Many configurations of cosmological interest are possible depending on the values of the couplings to other quarks and to gluons….

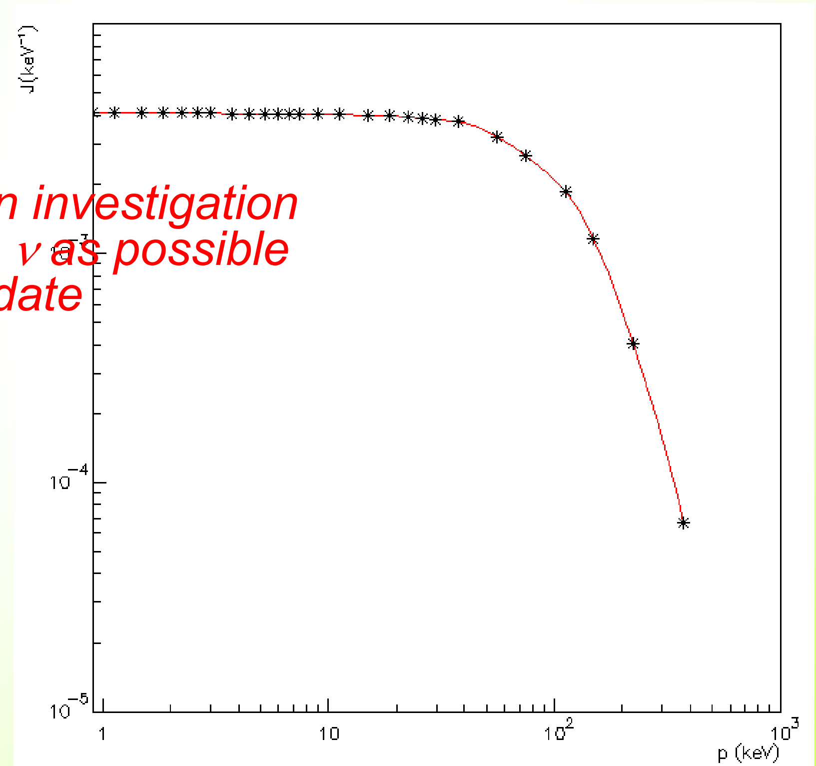


h configurations of cosmological interest in $g_{h\bar{u}u}$ vs $g_{h\bar{d}d}$ plane

In advanced phase of investigation: electron interacting DM



- The electron in the atom is not at rest.
- There is a very-small but not-zero probability to have electrons with momenta of ≈ MeV/c.
- Ex.: Compton profile for the 1s electron of Iodine:



For relativistic electrons:

$$E_{\max} \approx \beta_{DM}\, p$$

→ towards an investigation on the sterile ν as possible further candidate

where, β_{DM}~10^{-3} is the DM velocity and *p* is the electron momentum. Thus, when *p* is of order of MeV/c, scattered electrons with keV energy can be produced

→ They can be detectable.

→ The modulation is expected, due to β_{DM} dependence.

Although the probability of interacting with a ≈MeV momentum atomic electrons is very tiny, this process can be the **only detection method when the interaction with the nucleus is absent**.

This is the case, for example, of DM models from theory that foreseen leptonic colour interactions: $SU(3)_l$ x $SU(3)_c$ x $SU(2)_L$ x $U(1)$ broken at low energy.

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

OBVIOUSLY NO

They give a single model dependent result using other targets
DAMA/NaI gives a model independent result using ^{23}Na and ^{127}I targets

No direct model independent comparison possible

Even 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; they release orders of magnitude lower exposures, etc.

The new DAMA/LIBRA set-up (~250 kg NaI(Tl))

As a result of a second generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques

improving installation and environment

PMT + HV divider

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

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

(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

view at end of detectors' installation in the Cu box

DAMA/LIBRA in data taking since March 2003.

First data release foreseen at end of 2008

DAMA/LIBRA

- Data collected up to March 2007:

exposure: of order of 1.5×10^5 kg × d

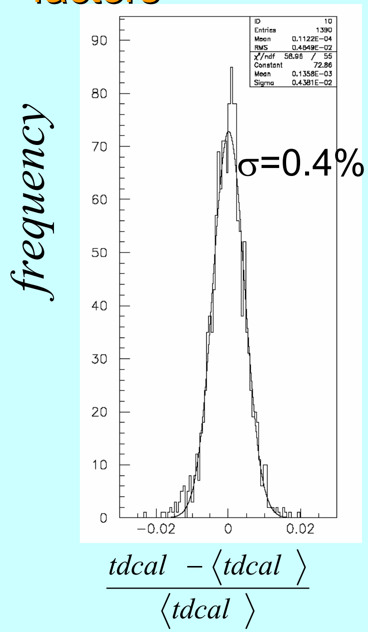
calibrations: acquired ≈ 40 M events of sources

acceptance window eff: acquired ≈ 2 M ev/keV

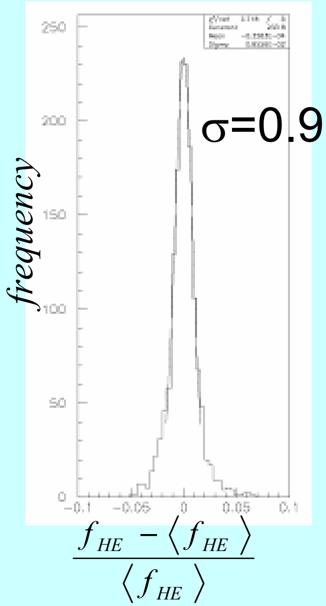
continuously running

Examples: here from March 2003 to August 2005

Stability of the low energy calibration factors



Stability of the high energy calibration factors



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

- Model independent analysis already concluded almost in all the aspects on an exposure of

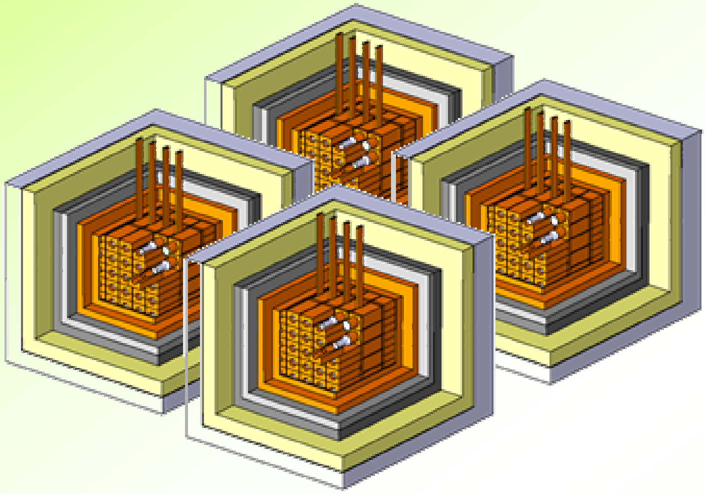
≈ 0.40 ton × year [$(\alpha-\beta^2) = 0.537$]

+ in progress

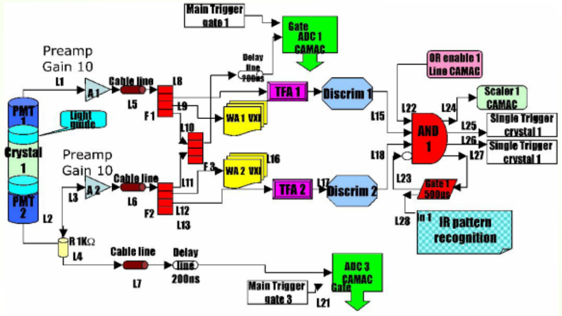
Towards possible DAMA/1ton

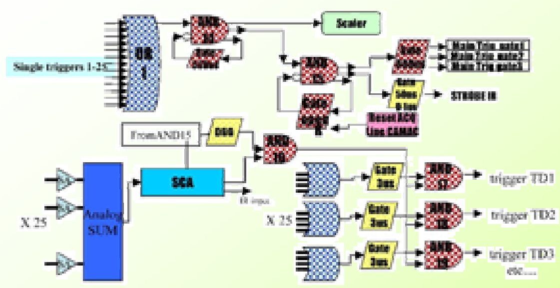
1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand (large experiences and fruitful collaborations among INFN and companies/industries)
3) Still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, 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





Electronic chain and example of the trigger system

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

Aims of possible DAMA/1 ton for Dark Matter

We proposed in 1996

Goals of 1 ton NaI detector:

- Extremely high C.L. for the model independent signal
- Model independent investigation on other peculiarities of the signal
- High exposure for the investigation and test of different astrophysical, nuclear and particle physics models

Improved sensitivity and competitiveness in DM investigation with respect to DAMA/LIBRA

- Further investigation on Dark Matter candidates (further on neutralino, bosonic DM, mirror DM, inelastic DM, neutrino of 4th family, etc.):

✓ high exposure can allow to disantangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, particle conversion processes, …, form factors, spin-factors and more on new scenarios)

✓ scaling laws and cross sections

✓ multi-componente DM particles halo?

+

- Further investigation on astrophysical models:

✓ velocity and position distribution of DM particles in the galactic halo

✓ effects due to:

i) satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal “streams”;

ii) caustics in the halo;

iii) gravitational focusing effect of the Sun enhancing the DM flow (“spike“ and “skirt”);

iv) possible structures as clumpiness with small scale size;

+ second-order effects

Conclusion

→ Dark Matter investigation is a crucial challenge for cosmology and for physics beyond the standard model

→ DAMA/NaI observed the first model independent evidence for the presence of a Dark Matter component in the galactic halo at 6.3σ C.L. with a total exposure 107731 kg$\cdot$d

→ DAMA/LIBRA the 2nd generation NaI(Tl) detector (~250 kg) is in measurement

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

to deep investigate Dark Matter phenomenology at galactic scale