Investigating the Dark halo

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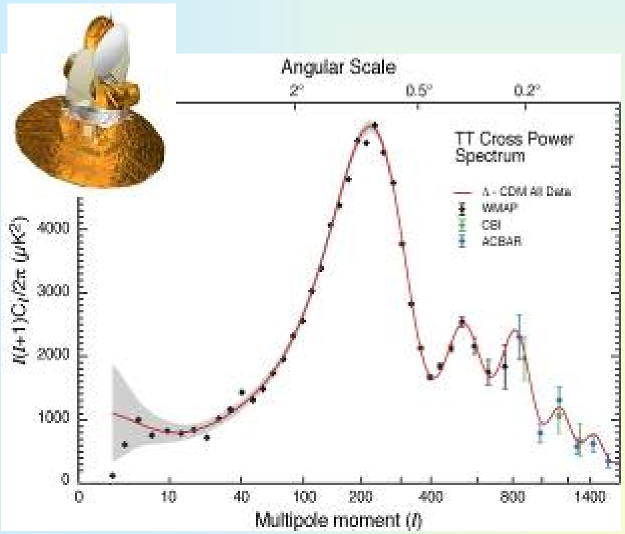
The Dark Side of the Universe: experimental evidences ...

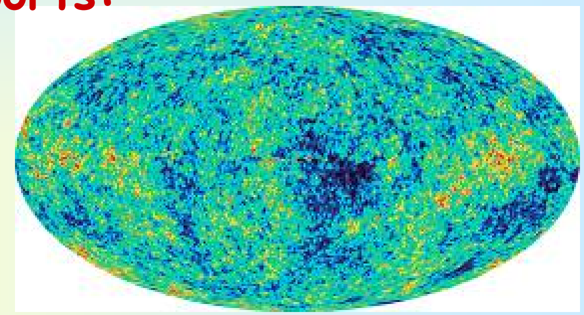
From larger scale ...



"Precision" cosmology supports:

Flat Universe:

$$\Omega = 1.02 \pm 0.02$$



"Concordance" model:

$\Omega_\Lambda \sim 73\%$ from SN1A

$\Omega_{CDM} \sim 23\%$

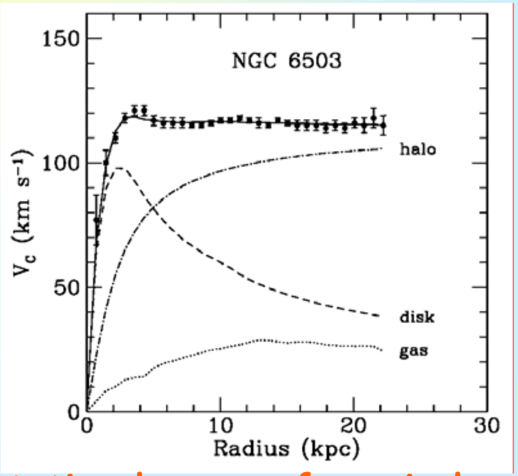
$\Omega_b \sim 4\%$

$\Omega_\nu < 1\ \%$

... to galaxy scale

Open questions:

- Composition?
- Right halo model and parameters?
- Multicomponent also in the particle part?
- Related nuclear and particle physics?
- Non thermalized components?
- Caustics and clumpiness?
- ....



Rotational curve of a spiral galaxy

Relic DM particles from primordial Universe

Light candidates: axion, sterile neutrino, axion-like particles cold or warm DM

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

Heavy candidates:

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

the sneutrino in the Smith and Weiner scenario

SUSY (R-parity conserved $\rightarrow$ LSP is stable) neutralino or sneutrino

a heavy ν of the 4-th family

even a suitable particle not yet foreseen by theories

&

self-interacting dark matter

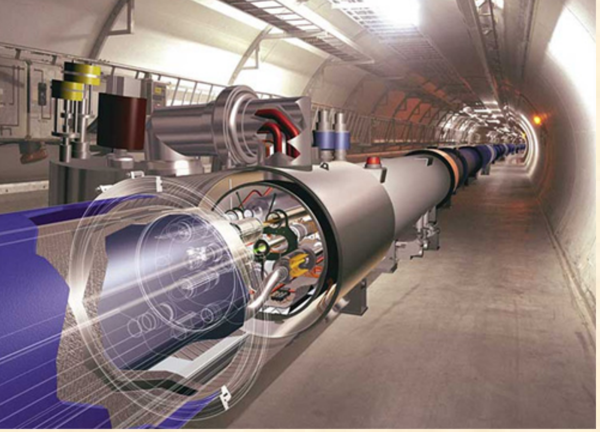
mirror dark matter

Kaluza-Klein particles (LKK)

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

axion-like (light pseudoscalar and scalar candidate)

etc…

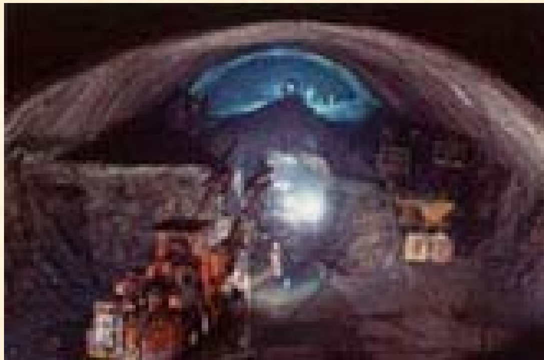


What accelerators can do:
to demostrate the existence of some of the possible DM candidates

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

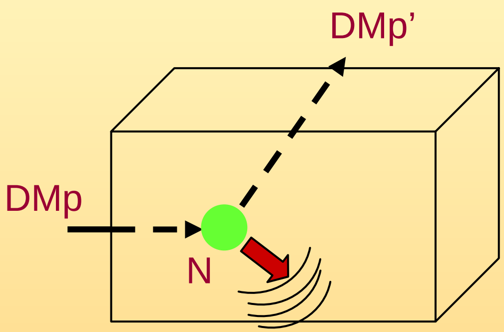
DM direct detection method using a model independent approach



Some direct detection processes:

- scatterings on nuclei

  → detection of nuclear recoil energy

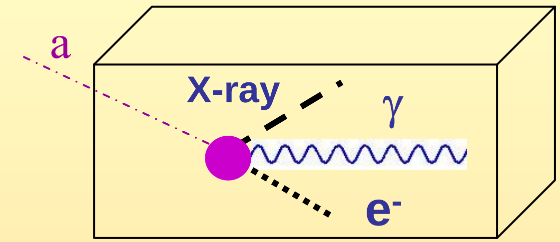


- excitation of bound electrons in scatterings on nuclei

  → 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

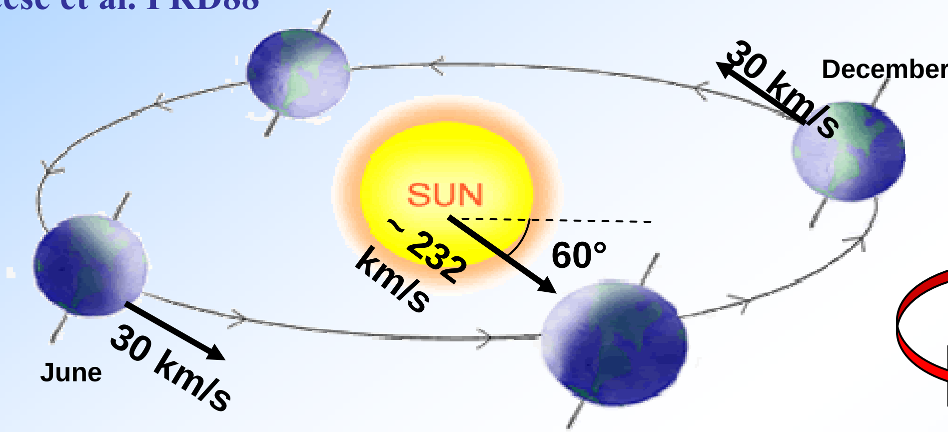
e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the electromagnetic component of their counting rate

- … and more

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

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.

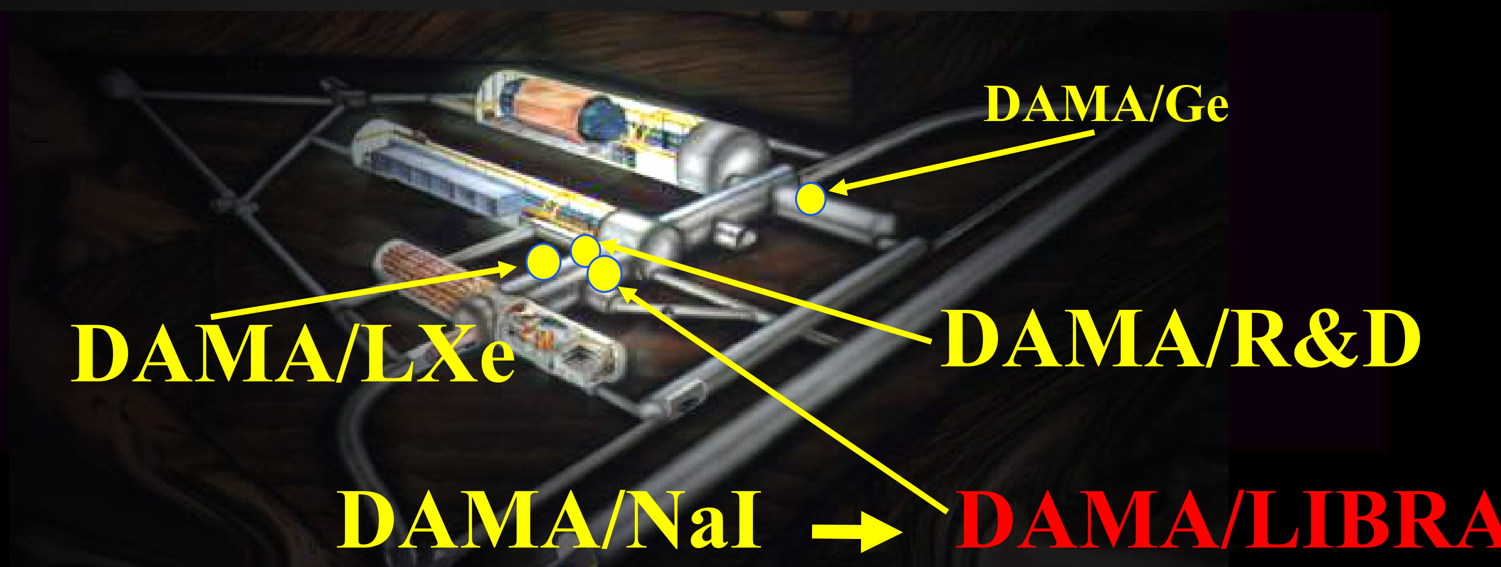
<u>A low background NaI(Tl) also allows the study of several other rare processes :</u>
possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar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

High benefits/cost

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

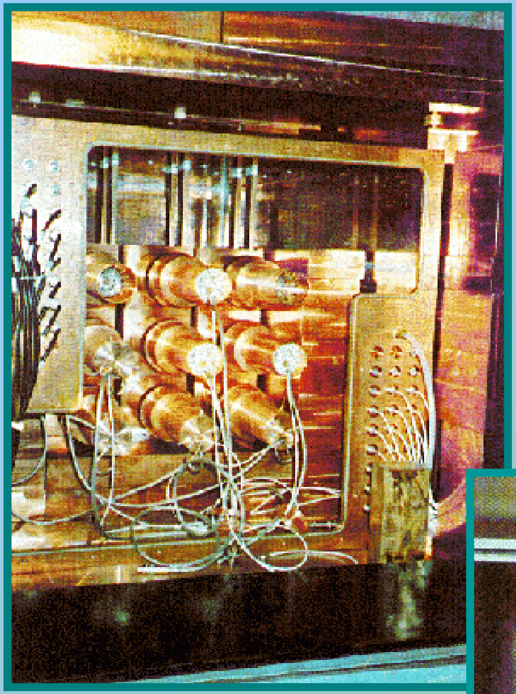
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati

& in some studies on $\beta\beta$ decays (DST-MAE project):
IIT Kharagpur, India



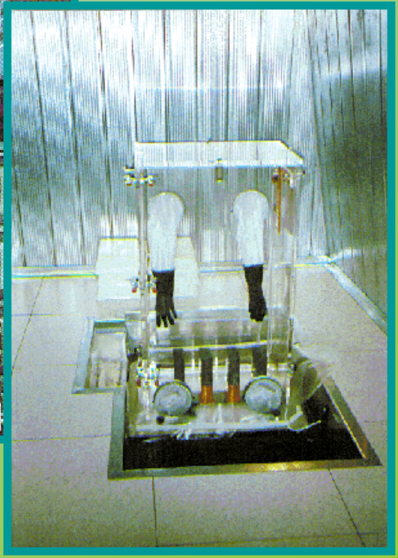
DAMA/NaI(Tl)~100 kg

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,EPJ C18(2000)283, PLB509(2001)197, EPJ C23 (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)

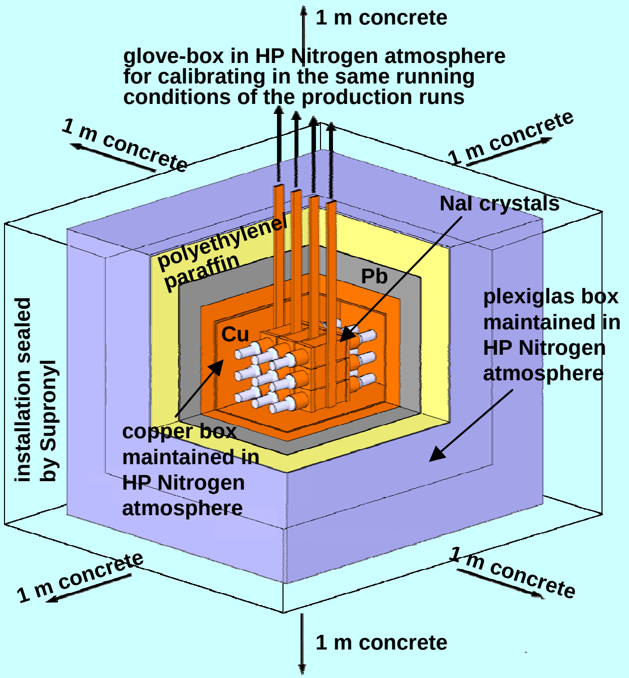
total exposure collected in 7 annual cycles 107731 kg×d

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.

The model independent result

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

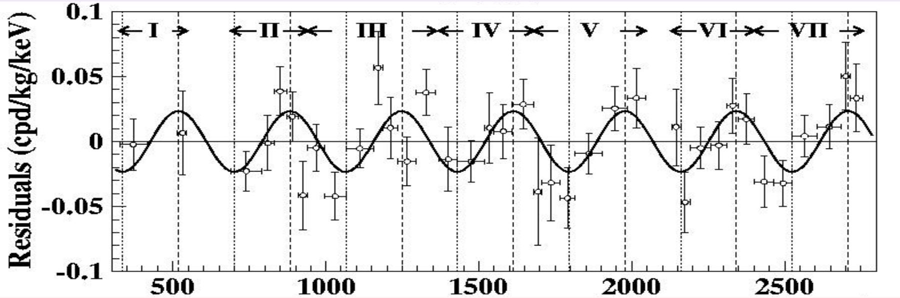
Annual modulation of the rate: DAMA/NaI 7 annual cycles

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

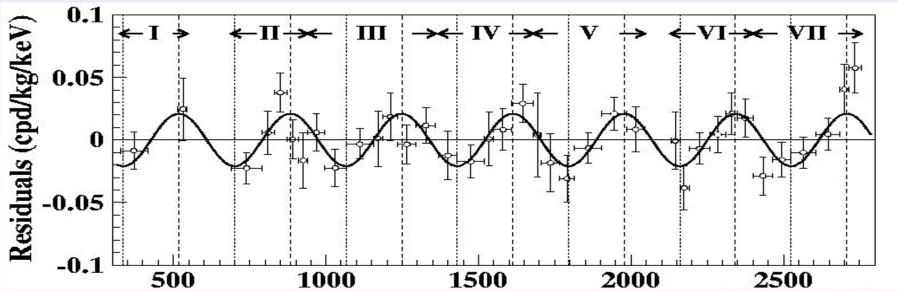
2-4 keV



fit: A=(0.0233 ± 0.0047) cpd/kg/keV

Time (day)

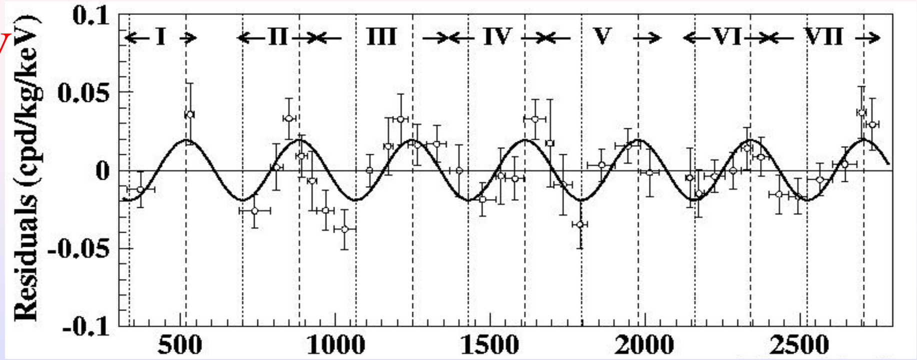
2-5 keV



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):

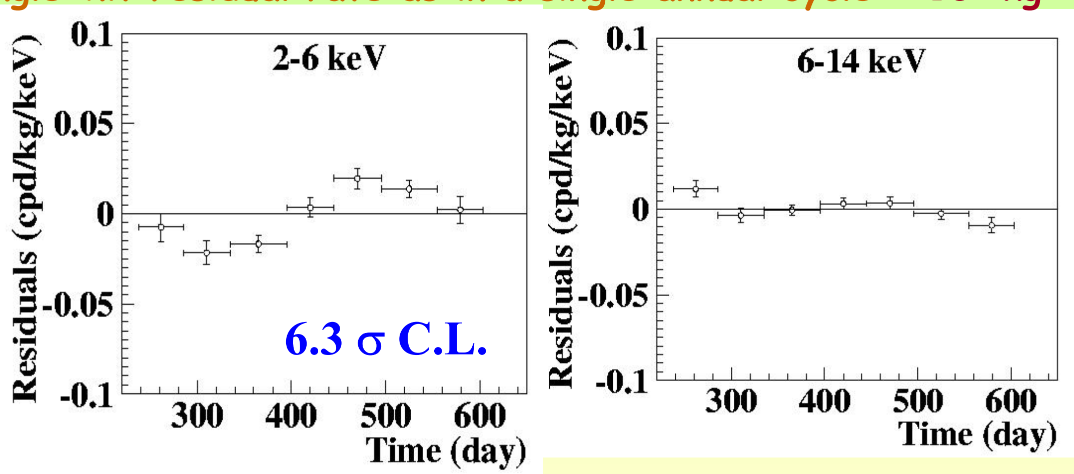
A = (0.0200 ± 0.0032) cpd/kg/keV;

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

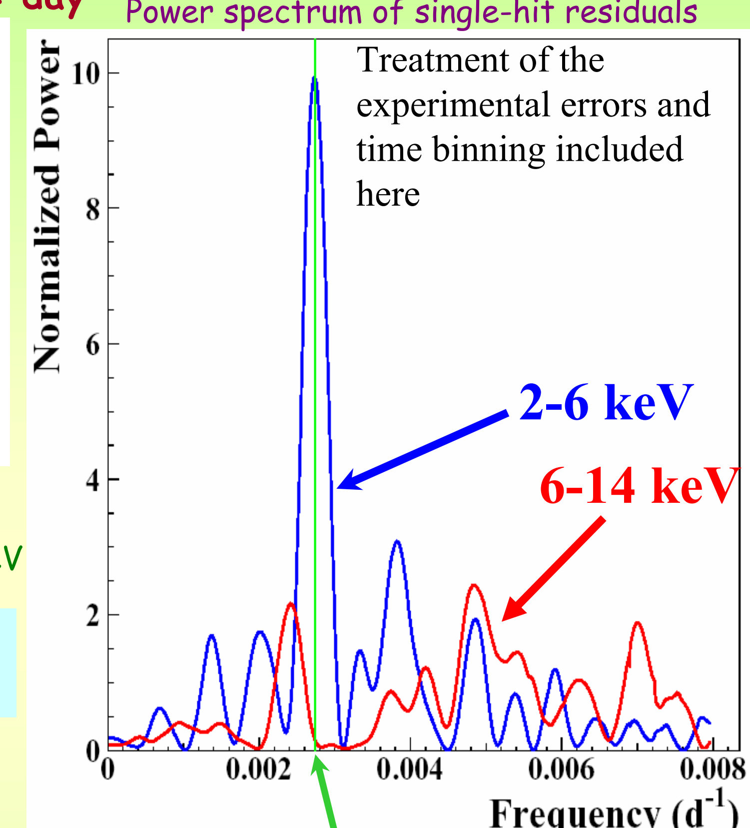
Single-hit residual rate as in a single annual cycle ≈ 10^5 kg × day



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

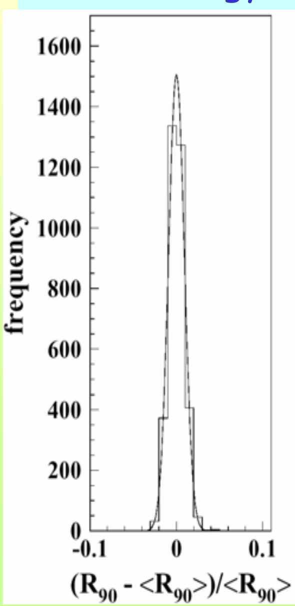
Power spectrum of single-hit residuals



Principal mode in the 2-6 keV region → 2.737 · 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

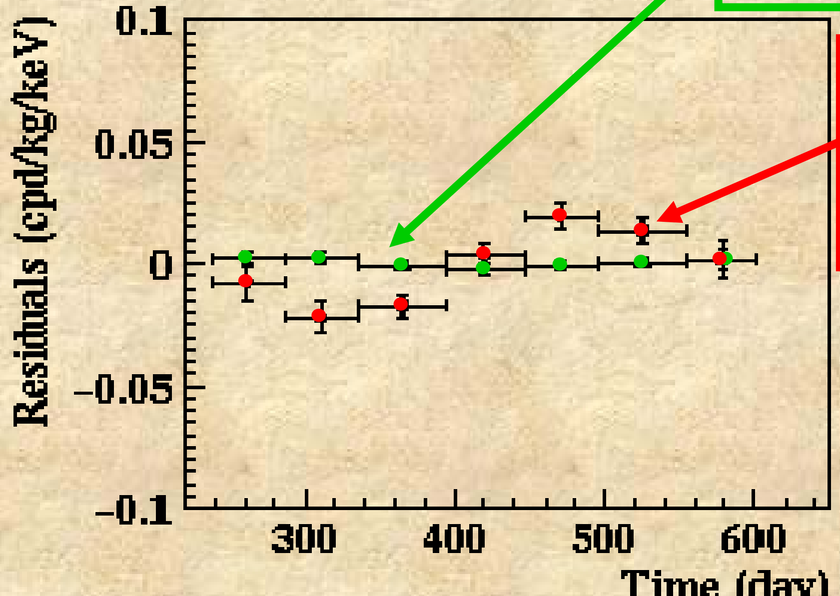
- In DAMA/NaI-6 and 7 each detector has its own TD (multiplexer system removed) → pulse profiles of multiple-hits events (multiplicity > 1) also acquired (total exposure: 33834 kg d).
- The same hardware and software procedures as the ones followed for single-hit events

→ 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

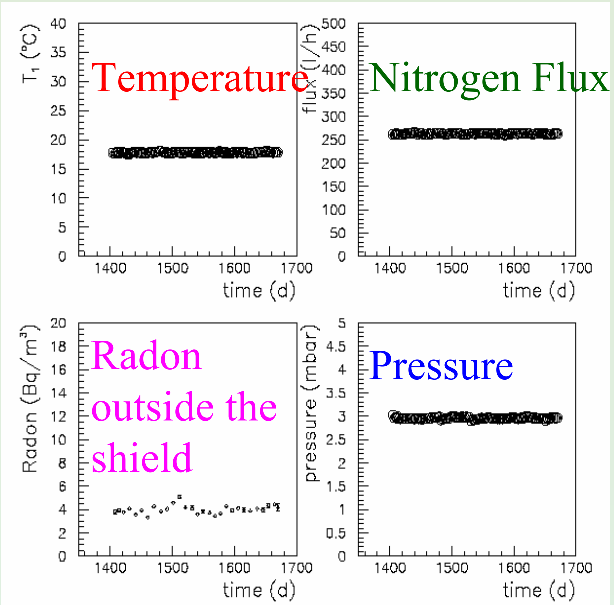


Residuals for single-hit events (DAMA/NaI 7 annual cycles)

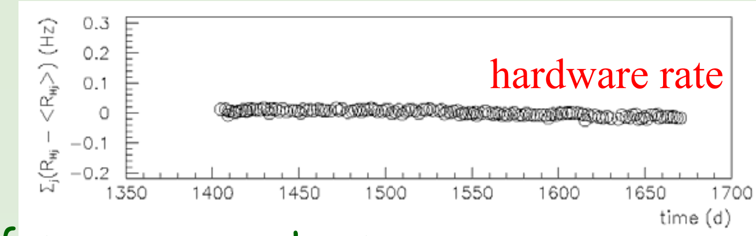
Mod ampl. = (0.0195 ± 0.0031) cpd/kg/keV

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

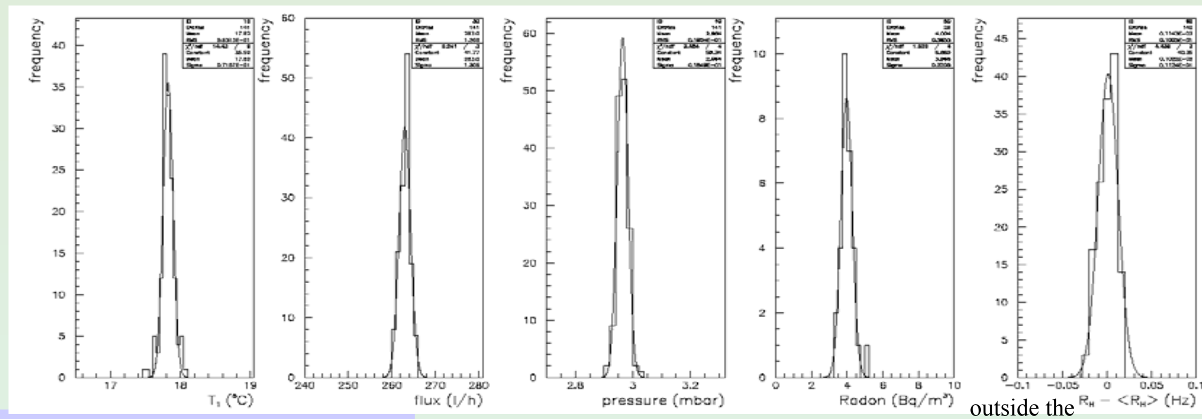
Running conditions



an example:
DAMA/NaI-6



Distribution of some parameters



Running conditions stable at level < 1%

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a modulation term as in the Dark Matter particles case.

	DAMA/NaI-5	DAMA/NaI-6	DAMA/NaI-7
Temperature	$-(0.033 \pm 0.050)°C$	$(0.021 \pm 0.055)°C$	$-(0.030 \pm 0.056)°C$
Flux	(0.03 ± 0.08) l/h	(0.05 ± 0.14) l/h	(0.07 ± 0.14) l/h
Pressure	$-(0.6 \pm 1.7)10^{-3}$ mbar	$(0.5 \pm 2.5)10^{-3}$ mbar	$(0.2 \pm 2.8)10^{-3}$ mbar
Radon	$-(0.09 \pm 0.17)$ Bq/m^3	(0.06 ± 0.14) Bq/m^3	$-(0.02 \pm 0.03)$ Bq/m^3
Hardware rate	$(0.10 \pm 0.17)10^{-2}$ Hz	$-(0.09 \pm 0.19)10^{-2}$ Hz	$-(0.22 \pm 0.19)10^{-2}$ Hz

All the measured amplitudes well compatible with zero
+ none can account for the observed effect

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

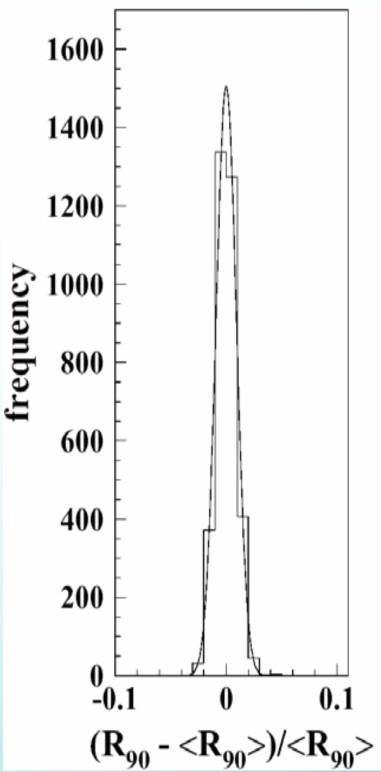
[for details and for the other annual cycles see for example: PLB424(1998)195, PLB450(1999)448, PLB480(2000)23, RNC26(2003)1-73, EPJC18(2000)283, IJMPD13(2004)2127]

Can a hypothetical background modulation account for the observed effect?

Integral rate at higher energy (above 90 keV), R_{90}

- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/NaI-5,6,7 running periods

→ cumulative gaussian behaviour with $\sigma \approx 0.9\%$, fully accounted by statistical considerations



- Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles:

Period	Mod. Ampl.
DAMA/NaI-5	(0.09±0.32) cpd/kg
DAMA/NaI-6	(0.06±0.33) cpd/kg
DAMA/NaI-7	-(0.03±0.32) cpd/kg

→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

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; → they can be considered statistically consistent with zero

In the same energy region where the effect is observed:

no modulation of the multiple-hits events (see elsewhere)

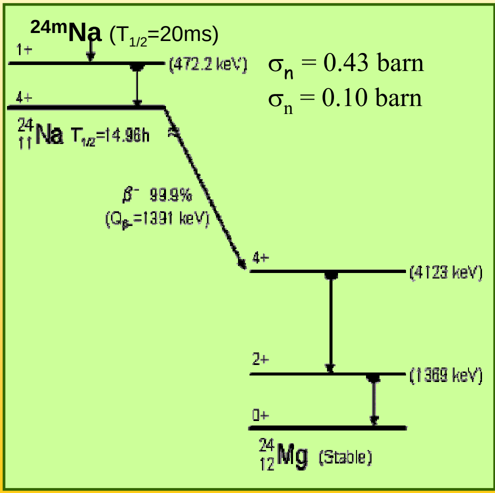
No modulation in the background:
these results also account for the bckg component due to neutrons

Can a possible thermal neutron modulation account for the observed effect?

NO

• Thermal neutrons flux measured at LNGS :

$\Phi_n = 1.08\ 10^{-6}$ n cm^{-2} s^{-1} (N.Cim.A101(1989)959)
(cautiously adopted here and in all the DAMA calculations)



- Experimental limit on the neutrons flux "*surviving*" the neutron shield in the DAMA/NaI set-up:
  - less sensitive approach: studying some neutron activation channels (N.Cim.A112(1999)545):

    $\Phi_n < 5.9\ 10^{-6}$ n cm^{-2} s^{-1}
  - more sensitive approach: studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation (derivable from EPJA24(2005)51):

    $\Phi_n < 4.0\ 10^{-7}$ n cm^{-2} s^{-1}

Evaluation of the expected effect:

- Capture rate = $\Phi_n\ \sigma_n\ N_T$ = 0.17 capture/d/kg • $\Phi_n/(10^{-6}$ n cm^{-2} s$^{-1})$
- For ex., neutron capture in ^{23}Na: ^{23}Na(n,γ)^{24}Na; ^{23}Na(n,γ)^{24m}Na

HYPOTHESIS: assuming very cautiously $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1} and a 10% thermal neutron modulation:

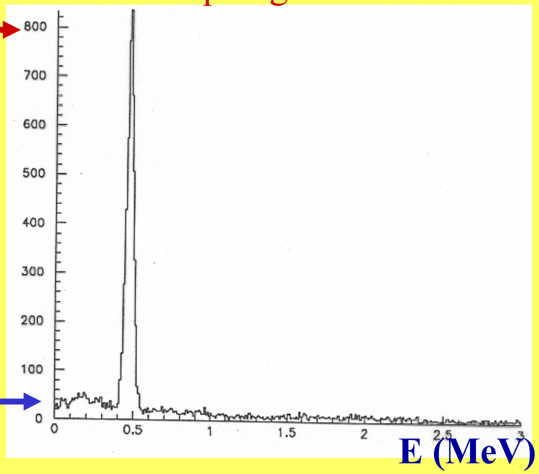
⟹ $S_m^{(\text{thermal n})} < 10^{-5}$ cpd/kg/keV (< 0.05% S_m^{observed}) ⟸

MC simulation of the process

When $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1}:

$7 \cdot 10^{-5}$ cpd/kg/keV

$1.4 \cdot 10^{-3}$ cpd/kg/keV

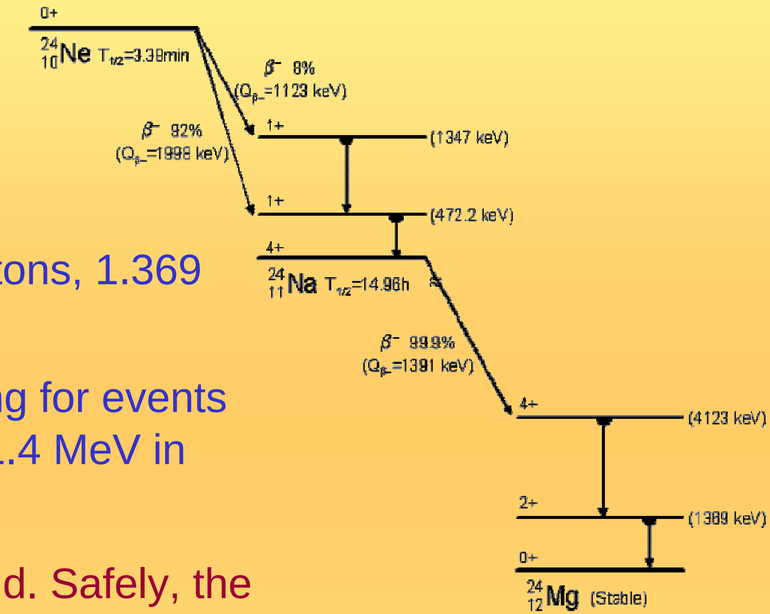


In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

Already excluded also by R_{90} analysis

Experimental limit of neutron flux surviving the DAMA/NaI neutron shield

- Thermal neutrons may activate ^{23}Na to ^{24}Na (direct measurement of neutron flux).
- The possible presence of ^{24}Na in a steady state inside the NaI(Tl) detectors can give information about _two_ physical processes:
  - neutron capture of ^{23}Na
  - cluster decay of ^{127}I : $^{127}_{53}I \rightarrow ^{24}_{10}Ne + ^{103}_{43}Tc$



- ^{24}Na nuclide β decays emitting two characteristic photons, 1.369 MeV and 2.754 MeV.
- The presence of ^{24}Na has been investigated by looking for events with multiplicity of 3 induced by a β with end-point at 1.4 MeV in one detector and the two γ's in two adjacent ones.

Three events with the required features have been found. Safely, the presence of ^{24}Na: **< *0.9 μBq/kg* (90% C.L.).**

- If ascribed to cluster decay: $\tau(^{127}_{53}I \rightarrow ^{24}_{10}Ne + ^{103}_{43}Tc) > 1.4 \times 10^{23}\ y \quad (90\% C.L.)$ **EPJ A24 (2005) 51**
- If ascribed to neutron capture:

$$\sigma_c(^{24}Na + ^{24m}Na) = 0.53\, barn$$

$$\varphi_n(thermal) < 4 \cdot 10^{-7}\ n\, cm^{-2}\ s^{-1}\ (90\%\, C.L.)$$

- Thermal neutron flux @ LNGS (very cautiously used in all the evaluations made by DAMA):

  $\Phi_n = 1.08\ 10^{-6}$ n cm^{-2} s^{-1} (N.Cim.A101(1989)959)
- Moreover, another less-sensitive determination in the DAMA set-up from some neutron activation channels:

  $\Phi_n < 5.9\ 10^{-6}$ n cm^{-2} s^{-1} (N.Cim.A112(1999)545)

Can a possible fast neutron modulation account for the observed effect?

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9\ 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995),23)

By MC: differential counting rate above 2 keV $\approx 10^{-3}$ cpd/kg/keV

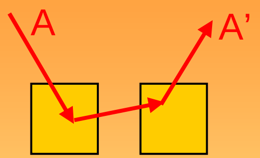
HYPOTHESIS: Assuming - very cautiously - a 10% neutron modulation: ⇒ $S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

Moreover, a possible fast n modulation would induce:

- a variation in all the energy spectrum (steady environmental fast neutrons always accompained by thermalized component)
  - already excluded also by R_{90}
- a modulation amplitude for multiple-hit events different from zero
  - already excluded by the multiple-hit events (see also elsewhere)

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

What we can also learn from the multiple/single hit rates. A toy model



$$R_{\rm mult} = R_{\rm single} \cdot \left\langle \frac{N_T \sigma_T}{4\pi r^2} \right\rangle$$

What about the nuclear cross sections of the particle (*A*) responsible of the modulation in the single-hit rate and not in the multiple-hit rate?

$$N_T \sigma_T = N_{Na}\sigma_{Na} + N_I \sigma_I = N \cdot (\sigma_{Na} + \sigma_I)$$

The 8 NaI(Tl) detectors in (anti-)coincidence have 3.1×10^{26} nuclei of Na and 3.1×10^{26} nuclei of Iodine. $N = 3.1\times10^{26}$

$$R_{\rm mult} \approx R_{\rm single} \cdot \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{med}^2}$$

$r_{med} \sim$ *10-15 cm*

Therefore, the ratio of the modulation amplitudes is:

$$\frac{A_{mult}}{A_{\rm single}} \approx \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{med}^2}$$

From the experimental data: $A_{mult} \approx -(4 \pm 8)\cdot 10^{-4}$ cpd/kg/keV $< 10^{-3}$ cpd/kg/keV;

$$A_{\rm single} \approx 2 \cdot 10^{-2} \text{ cpd/kg/keV;}$$

Hence: $\frac{A_{mult}}{A_{\rm single}} < 5 \cdot 10^{-2}$

In conclusion, the particle (*A*) responsible of the modulation in the single-hit rate and not in the multiple-hit rate must have:

$$\sigma_{Na} + \sigma_I < 0.2 \text{ barn}$$

Since for fast neutrons the sum of the two cross sections (weighted by 1/E, ENDF/B-VI) is about 4 barns:

It (*A*) cannot be a fast neutron

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; etc.)	**<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

Summary of the DAMA/NaI Model Independent result

Presence of modulation over 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 candidate(s)

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

+ multicomponent?

THUS uncertainties on models and comparisons

A model ......

or a model ......

DM particle scatterings on target-nuclei - I

DM particle-nucleus elastic scattering

$$\frac{d\sigma}{dE_R}(v,E_R) = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD} =$$

$$\frac{2G_F^2 m_N}{\pi v^2}\left\{\left[Zg_p + (A-Z)g_n\right]^2 F_{SI}^2(E_R) + 8\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 F_{SD}^2(E_R)\right\}$$

SI+SD differential cross sections:

- $g_{p,n}(a_{p,n})$ effective DM particle-nucleon couplings
- $\langle S_{p,n}\rangle$ nucleon spin in the nucleus
- $F^2(E_R)$ nuclear form factors
- m_{Wp} reduced DM particle-nucleon mass

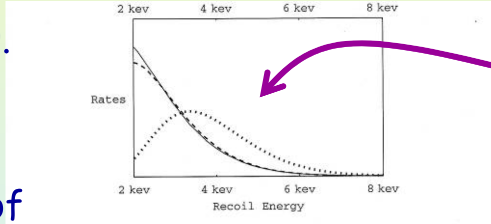
Note: not universal description. Scaling laws assumed to define point-like cross sections from nuclear ones. Four free parameters: m_W, σ_{SI}, σ_{SD}, $tg\theta = \frac{a_n}{a_p}$

Preferred inelastic DM particle-nucleus scattering: $\chi_- + N \rightarrow \chi_+ + N$

- DM particle candidate suggested by D. Smith and N. Weiner (PRD64(2001)043502)
- Two mass states χ_+, χ_- with δ mass splitting
- Kinematical constraint for the inelastic scattering of χ_- on a nucleus with mass m_N becomes increasingly severe for low m_N

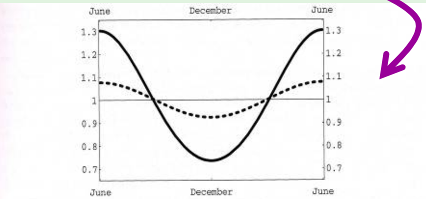
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

Three free parameters: m_W, σ_p, δ



Normalized modulation (S_m) as a function of energy for ordinary WIMP scenario (solid), inelastic WIMP scenario with $\delta = 100$keV (dashed), and inelastic WIMP scenario with $\delta = 150$keV (dotted), all with $m_\chi = 60$GeV.

S_m/S_0 enhanced with respect to the elastic scattering case



Annual modulation of event rate with average normalized to one in the inelastic WIMP scenario (solid line) and standard WIMP scenario (dashed), with $\delta = 100$keV and $m_\chi = 50$GeV.

Ex. m_W = 100 GeV

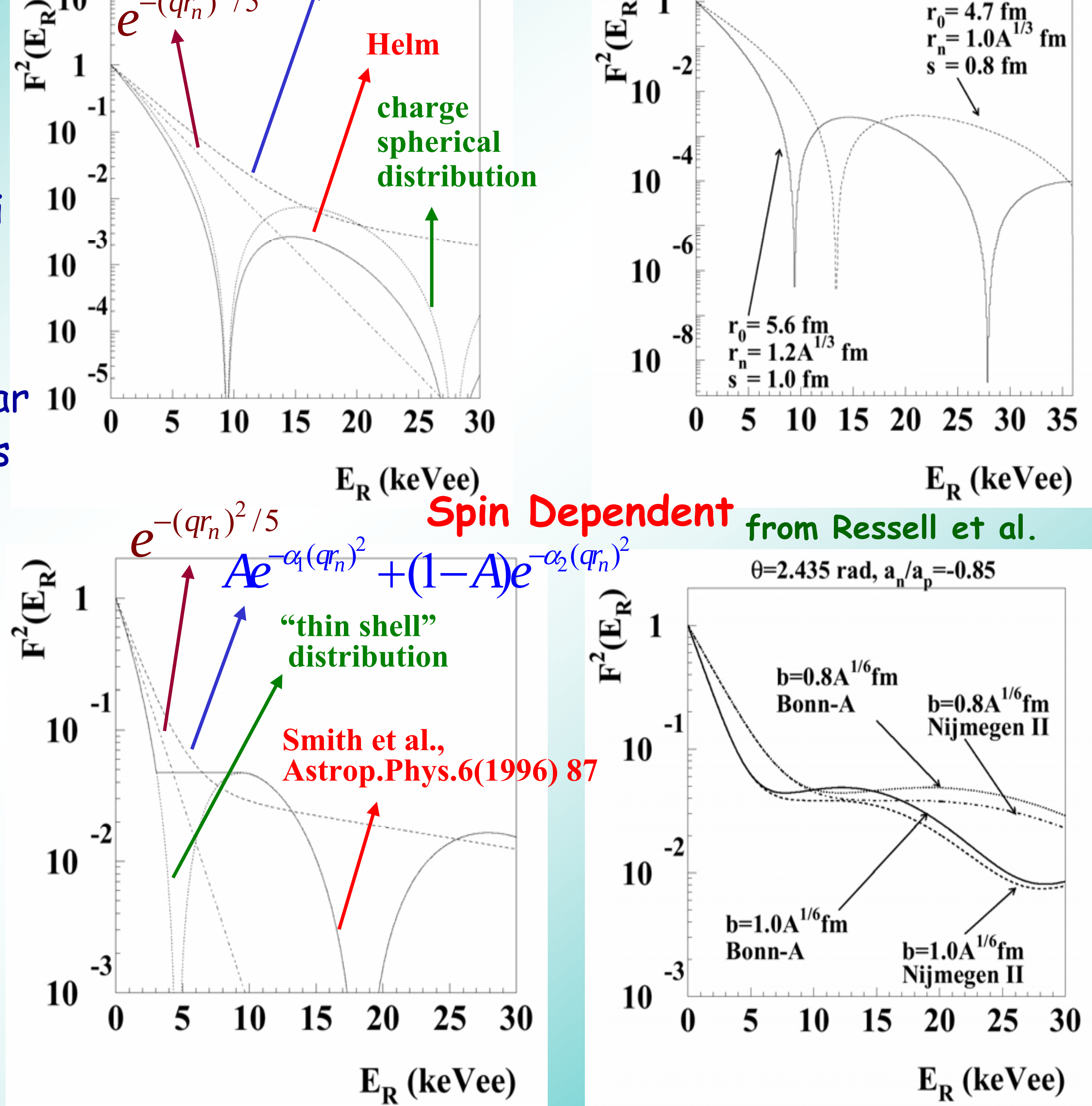
m_N	μ
70	41
130	57

Differential energy distribution depends on the assumed scaling laws, nuclear form factors, spin factors, free parameters (→ 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, ...) and on instrumental quantities (quenching factors, energy resolution, efficiency, ...)

Examples of different Form Factor for ^{127}I available in literature

- Take into account the structure of target nuclei
- In SD form factor: no decoupling between nuclear and Dark Matter particles degrees of freedom; dependence on nuclear potential.

Similar situation for all the target nuclei considered in the field



The Spin Factor

Spin Factors for some target-nuclei calculated in simple different models

Target-Nucleus	single particle	odd group	Comment
^{29}Si	0.750	0.063	Neutron is the unpaired nucleon
^{73}Ge	0.306	0.065	
^{129}Xe	0.750	0.124	
^{131}Xe	0.150	0.055	
^{1}H	0.750	0.750	Proton is the unpaired nucleon
^{19}F	0.750	0.647	
^{23}Na	0.350	0.041	
^{27}Al	0.350	0.087	
^{69}Ga	0.417	0.021	
^{71}Ga	0.417	0.089	
^{75}As	0.417	0.000	
^{127}I	0.250	0.023	

Spin factor $= \Lambda^2 J(J+1)/a_x^2$

($a_x = a_n$ or a_p *depending on the unpaired nucleon*)

Spin Factors calculated on the basis of Ressell et al. for some of the possible θ values considering some target nuclei and two different nuclear potentials

Target-Nucleus / nuclear potential	θ=0	$\theta=\pi/4$	$\theta=\pi/2$	θ=2.435 (pure Z_0 coupling)
^{23}Na	0.102	0.060	0.001	0.051
^{127}I/Bonn A	0.134	0.103	0.008	0.049
^{127}I/Nijmegen II	0.175	0.122	0.006	0.073
^{129}Xe/Bonn A	0.002	0.225	0.387	0.135
^{129}Xe/Nijmegen II	0.001	0.145	0.270	0.103
^{131}Xe/Bonn A	0.000	0.046	0.086	0.033
^{131}Xe/Nijmegen II	0.000	0.044	0.078	0.029
^{125}Te/Bonn A	0.000	0.124	0.247	0.103
^{125}Te/Nijmegen II	0.000	0.156	0.313	0.132

Spin factor $= \Lambda^2 J(J+1)/\bar{a}^2$

$$tg\theta = \frac{a_n}{a_p} \qquad (0 \le \theta < \pi)$$

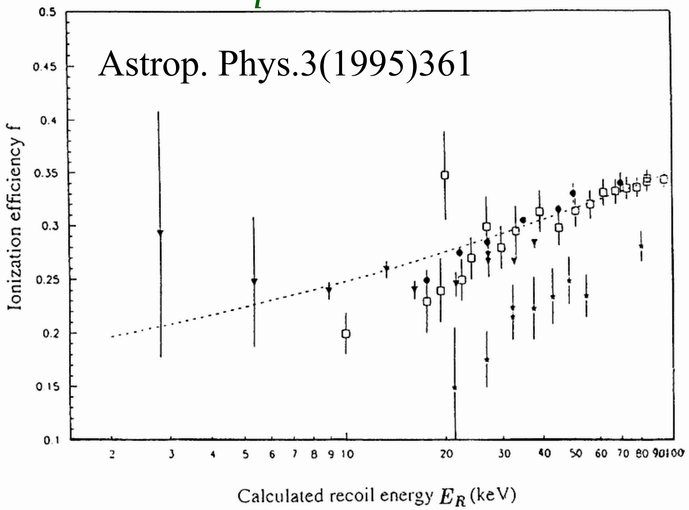
Large differences in the measured counting rate can be expected:

- **when using target nuclei sensitive to the SD component of the interaction (such as e.g. ^{23}Na and ^{127}I) with the respect to those largely insensitive to such a coupling (such as e.g. ^{nat}Ge, ^{nat}Si, ^{nat}Ar, ^{nat}Ca, ^{nat}W, ^{nat}O);**
- **when using different target nuclei although all – in principle – sensitive to such a coupling, 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).**

Quenching factor

Quenching factors, q, measured by neutron sources or by neutron beams for some detectors and nuclei

Ex. of different q determinations for Ge



- differences are often present in different experimental determinations of q for the same nuclei in the same kind of detector
- 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.
- Some time increases at low energy in scintillators (dL/dx)

... and more

recoil/electron response ratio measured with a neutron source or at a neutron generator

Nucleus/Detector	Recoil Energy (keV)	q	Reference
NaI(Tl)	(6.5-97)	(0.30 ± 0.01) for Na	[46]
	(22-330)	(0.09 ± 0.01) for I	[46]
	(20-80)	(0.25 ± 0.03) for Na	[119]
	(40-100)	(0.08 ± 0.02) for I	[119]
	(4-252)	(0.275 ± 0.018) for Na	[120]
	(10-71)	(0.086 ± 0.007) for I	[120]
	(5-100)	(0.4 ± 0.2) for Na	[121]
	(40-300)	(0.05 ± 0.02) for I	[121]
CaF_2(Eu)	(30-100)	(0.06-0.11) for Ca	[120]
	(10-100)	(0.08-0.17) for F	[120]
	(90-130)	(0.049 ± 0.005) for Ca	[45]
	(75-270)	(0.069 ± 0.005) for F	[45]
	(53-192)	(0.11-0.20) for F	[122]
	(25-91)	(0.09-0.23) for Ca	[122]
CsI(Tl)	(25-150)	(0.15-0.07)	[123]
	(10-65)	(0.17-0.12)	[124]
	(10-65)	(0.22-0.12)	[125]
CsI(Na)	(10-40)	(0.10-0.07)	[125]
Ge	(3-18)	(0.29-0.23)	[126]
	(21-50)	(0.14-0.24)	[127]
	(10-80)	(0.18-0.34)	[128]
	(20-70)	(0.24-0.33)	[129]
Si	(5-22)	(0.23-0.42)	[130]
	22	(0.32 ± 0.10)	[131]
Liquid Xe	(30-70)	(0.46 ± 0.10)	[72]
	(40-70)	(0.18 ± 0.03)	[132]
	(40-70)	(0.22 ± 0.01)	[133]
Bolometers	-	**assumed** 1 (see also NIMA507(2003)643))	

Consistent Halo Models

- **Isothermal sphere ⇒ very simple but unphysical halo model; generally not considered**
- **Several approaches different from the isothermal sphere model: Vergados PR83(1998)3597, PRD62(2000)023519; Belli et al. PRD61(2000)023512; PRD66(2002)043503; Ullio & Kamionkowski JHEP03(2001)049; Green PRD63(2001) 043005, Vergados & Owen astroph/0203293, etc.**

Models accounted in the following

(Riv. N. Cim. 26 n.1 (2003)1-73 and previously in PRD66(2002)043503)

- **Needed quantities**
  - → DM local density $\rho_0 = \rho_{DM}(R_0 = 8.5\text{ kpc})$
  - → local velocity $v_0 = v_{rot}(R_0 = 8.5\text{kpc})$
  - → velocity distribution $f(\vec{v})$

- **Allowed ranges of ρ_0 (GeV/cm^3) have been evaluated for v_0=170,220,270 km/s, for each considered halo density profile and taking into account the astrophysical constraints:**

$$v_0 = (220 \pm 50) km \cdot s^{-1}$$

$$1 \cdot 10^{10} M_\oplus \le M_{vis} \le 6 \cdot 10^{10} M_\oplus$$

$$0.8 \cdot v_0 \le v_{rot}(r = 100kpc) \le 1.2 \cdot v_0$$

NOT YET EXHAUSTIVE AT ALL

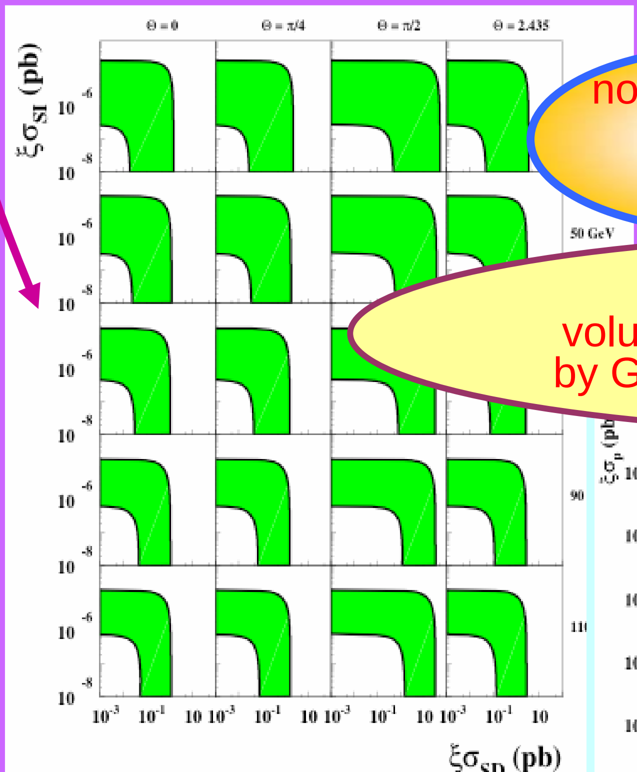
Class A: spherical ρ_{DM}, isotropic velocity dispersion		
A0	Isothermal Sphere	
A1	Evans' logarithmic [101]	$R_c = 5$ kpc
A2	Evans' power-law [102]	$R_c = 16$ kpc, $\beta = 0.7$
A3	Evans' power-law [102]	$R_c = 2$ kpc, $\beta = -0.1$
A4	Jaffe [103]	$\alpha = 1, \beta = 4, \gamma = 2, a = 160$ kpc
A5	NFW [104]	$\alpha = 1, \beta = 3, \gamma = 1, a = 20$ kpc
A6	Moore et al. [105]	$\alpha = 1.5, \beta = 3, \gamma = 1.5, a = 28$ kpc
A7	Kravtsov et al. [106]	$\alpha = 2, \beta = 3, \gamma = 0.4, a = 10$ kpc
Class B: spherical ρ_{DM}, non–isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)		
B1	Evans' logarithmic	$R_c = 5$ kpc
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$
B4	Jaffe	$\alpha = 1, \beta = 4, \gamma = 2, a = 160$ kpc
B5	NFW	$\alpha = 1, \beta = 3, \gamma = 1, a = 20$ kpc
B6	Moore et al.	$\alpha = 1.5, \beta = 3, \gamma = 1.5, a = 28$ kpc
B7	Kravtsov et al.	$\alpha = 2, \beta = 3, \gamma = 0.4, a = 10$ kpc
Class C: Axisymmetric ρ_{DM}		
C1	Evans' logarithmic	$R_c = 0, q = 1/\sqrt{2}$
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95, \beta = 0.9$
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2}, \beta = -0.1$
Class D: Triaxial ρ_{DM} [107] (q = 0.8, p = 0.9)		
D1	Earth on maj. axis, rad. anis.	$\delta = -1.78$
D2	Earth on maj. axis, tang. anis.	$\delta = 16$
D3	Earth on interm. axis, rad. anis.	$\delta = -1.78$
D4	Earth on interm. axis, tang. anis.	$\delta = 16$

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

(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

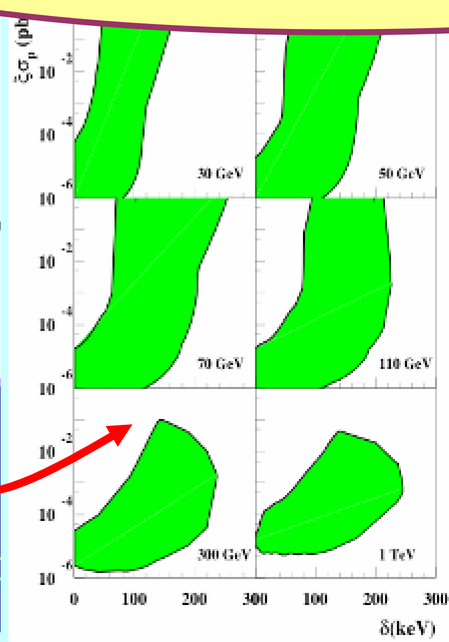


not exhaustive + different scenarios

Already 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:

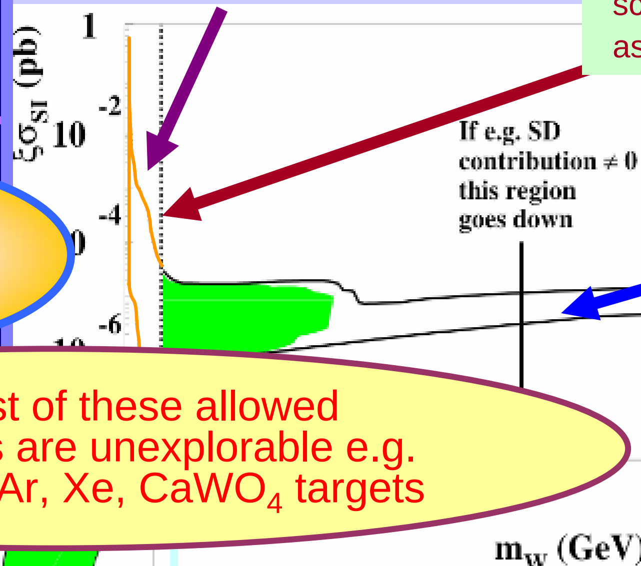
$W + N \rightarrow W^* + N$ (S_m/S_0 enhanced): examples of slices of the allowed volume in the spac[e] ($\xi\sigma_p$, m_W, δ) **[e.g. Ge disfavoured]**



DM particle with dominant SI coupling

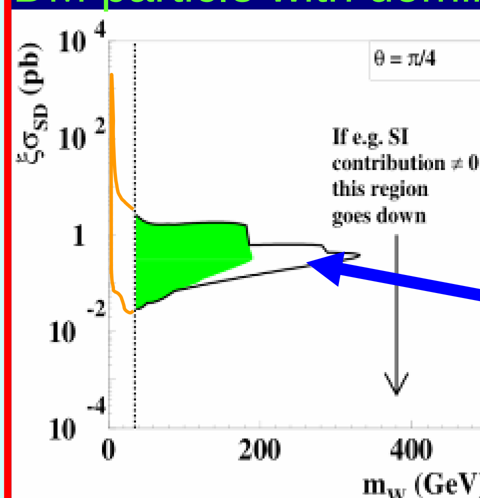
Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for "generic" DM particle

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

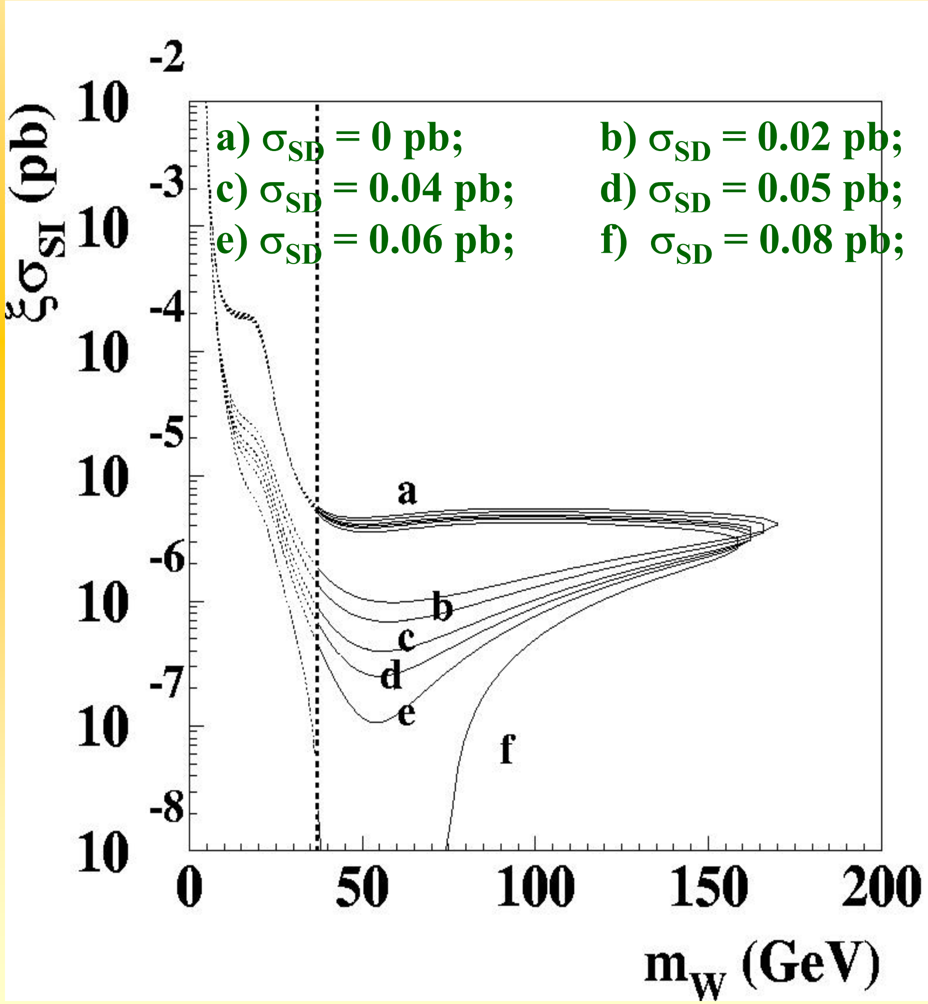


volume allowed in the space (m_W, $\xi\sigma_{SD}$, θ); here example of a slice for $\theta = \pi/4$ ($0 \le \theta < \pi$)

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 $\theta \approx 0$ or $\theta \approx \pi$.

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

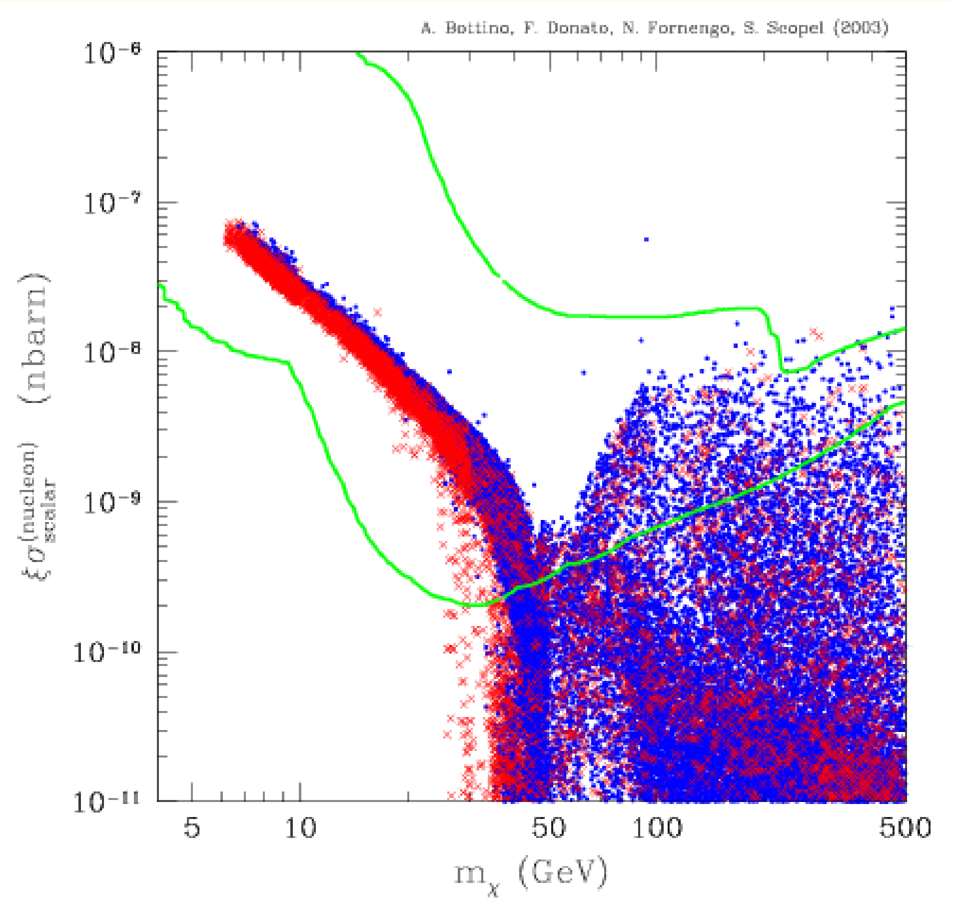


figure taken from PRD69(2004)037302

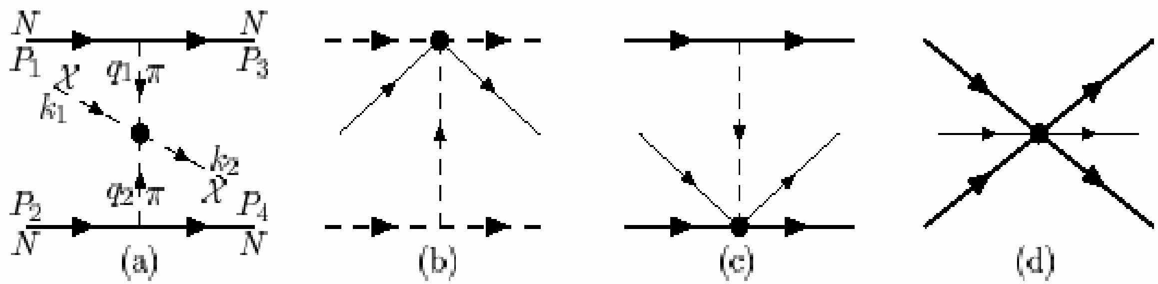
scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line);

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

... either other uncertainties or new models?

Two-nucleon currents from pion exchange in the nucleus:

FIG. 1: Two-nucleon diagrams that contribute to WIMP-nucleus scattering where the WIMP is generally denoted by $\mathcal{X}$. Graph (a) is of $\mathcal{O}(1/q^2)$, graphs (b) and (c) are of $\mathcal{O}(1/q)$ while the contact term of graph (d) is of $\mathcal{O}(1)$. The exchange diagrams are not included. The filled circles represent the non-standard model vertices.



"In supersymmetric models, the one-nucleon current generically produces roughly equal SI couplings to the proton and neutron [5], which results in a SI amplitude that is proportional to the atomic number of the nucleus. Inclusion of the two-nucleon contributions could change this picture since such contributions might cancel against the one-nucleon contributions. If the ratio of the two-nucleon matrix element to the atomic number varies from one nucleus to the next so will the degree of the cancellation. Thus, when the two-current contribution is taken into account, a dark-matter candidate that appears in DAMA but not in other searches [14] is conceivable for a WIMP with SI interactions even within the framework of the MSSM…"

Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301

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

$\varepsilon_A = 0$ "usually"

$\varepsilon_A \approx \pm 1$ here in some nuclei?

Different scaling laws for a DM particle with SI interactions even within the framework of the MSSM?

+

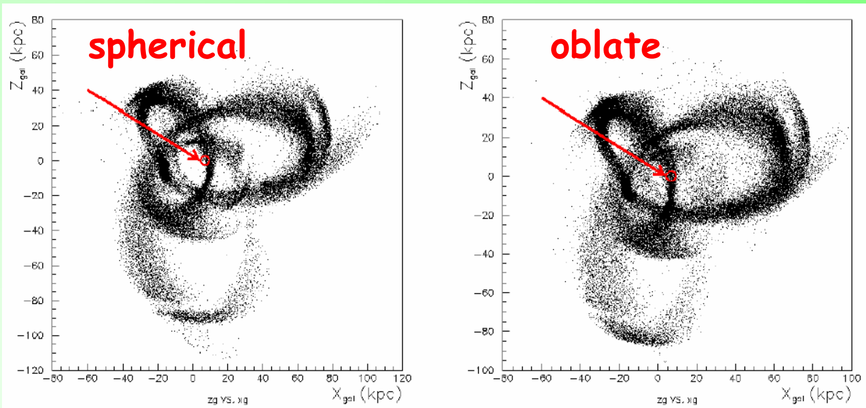
Different Form Factors, e.g. the recently proposed by Gondolo et al. hep-ph/0608035

Investigating halo substructures by underground expt

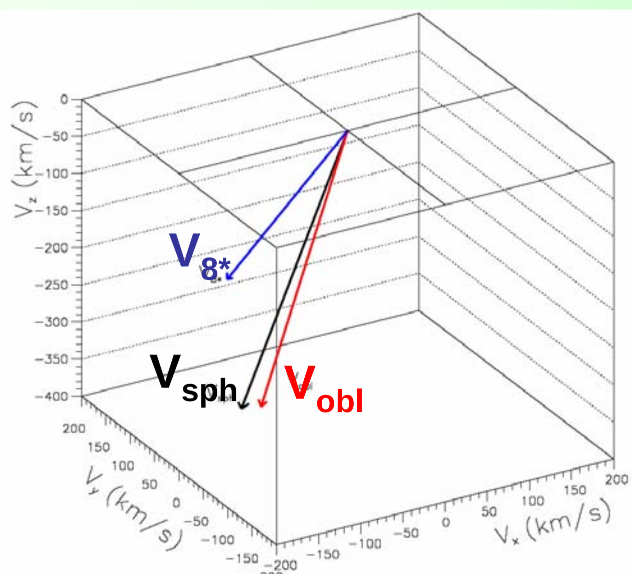
through annual modulation signature

EPJC47(2006)263

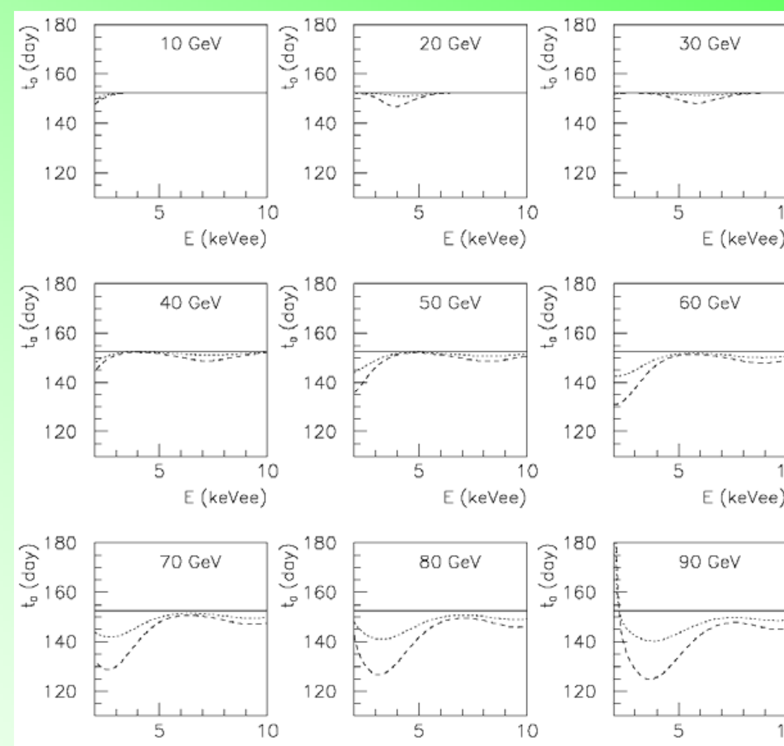
Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way



simulations from Ap.J.619(2005)807



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



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

Investigating the effect of SagDEG contribution for WIMPs

EPJC47(2006)263

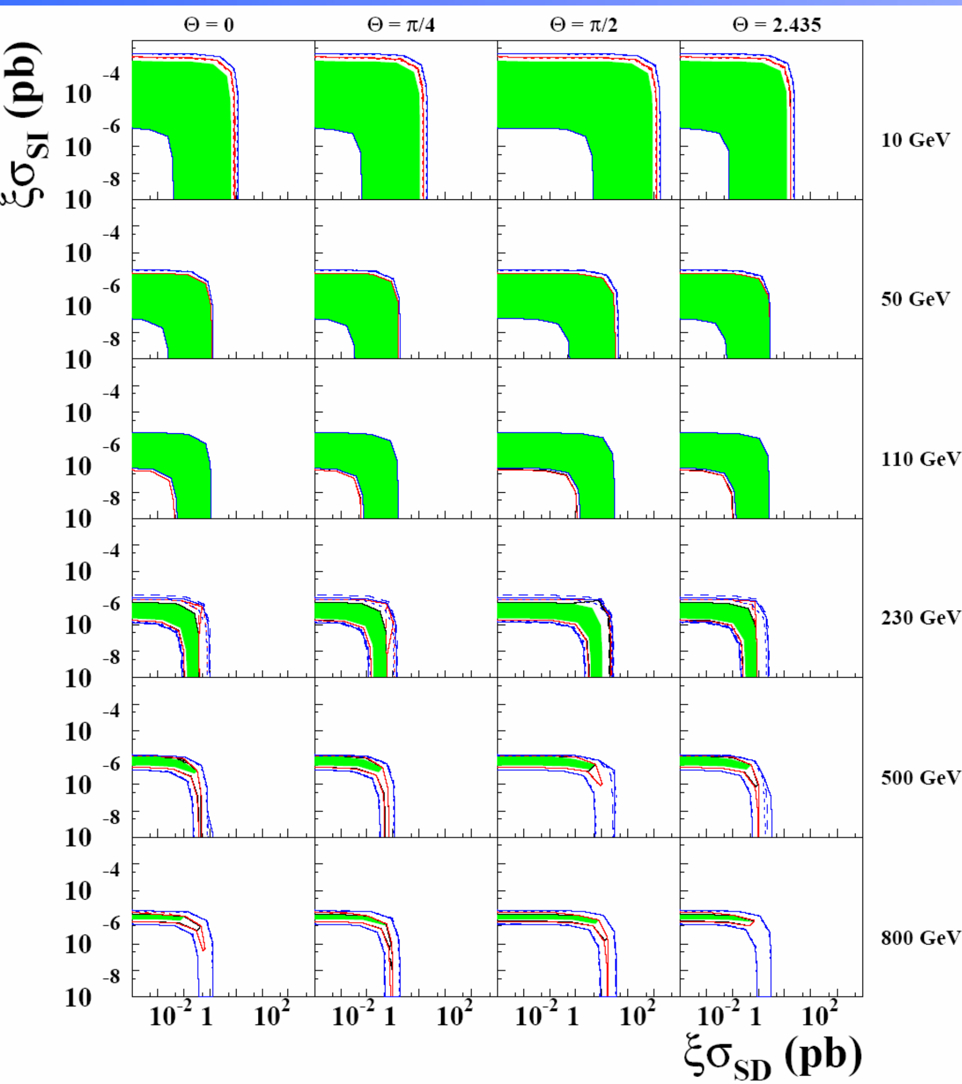
DAMA/NaI: seven annual cycles 107731 kg d

for different SagDEG velocity dispersions (20-40-60 km/s)

ρ_{SagDEG} < 0.1 GeV cm^{-3} (bound by M/L ratio considerations)

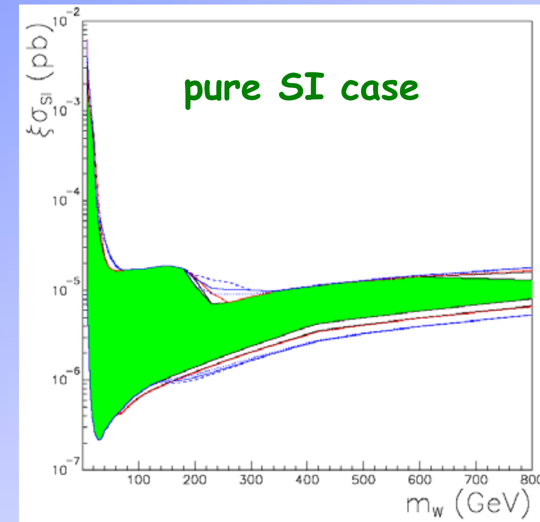
SOME EXAMPLES

mixed SI&SD case

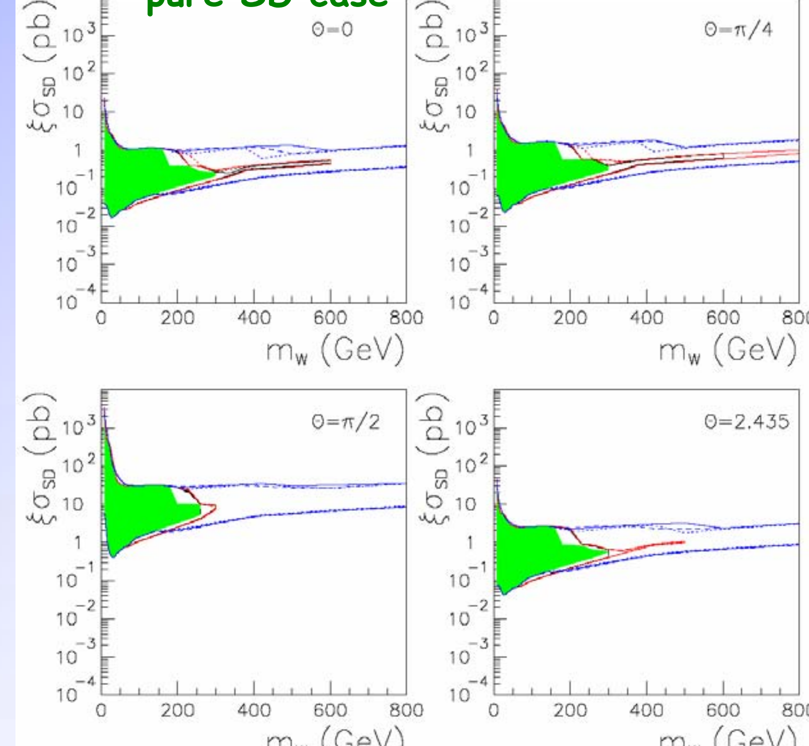


green area: no SagDEG

pure SI case



pure SD case

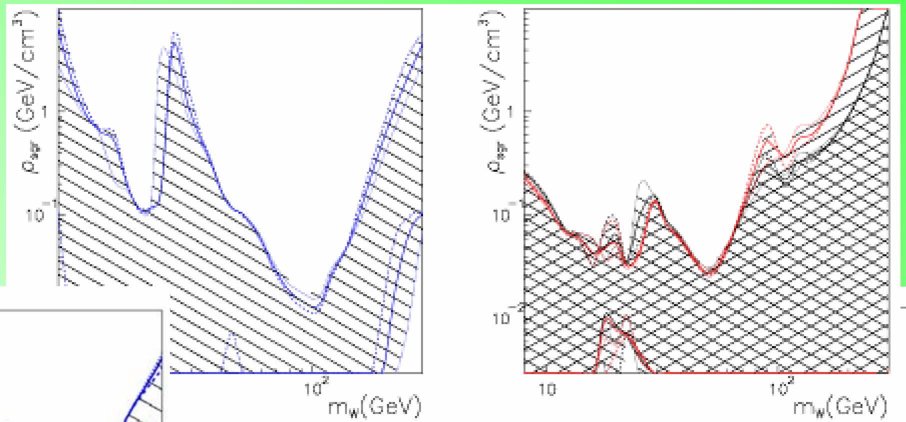


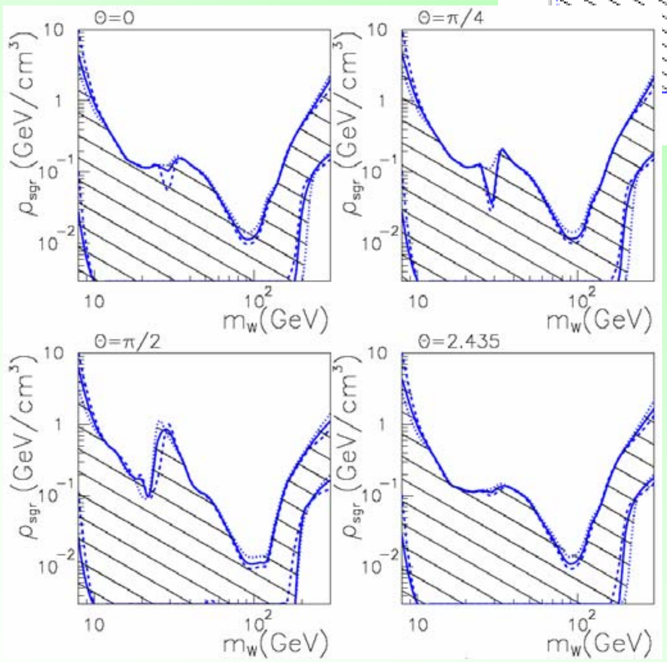
Constraining the SagDEG stream by DAMA/NaI

for different SagDEG velocity dispersions (20-40-60 km/s)

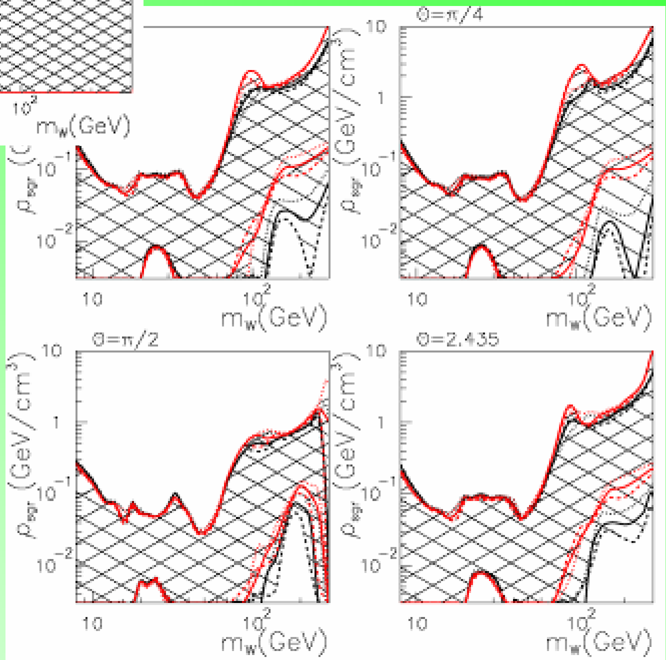
EPJC47(2006)263

pure SI case





pure SD case



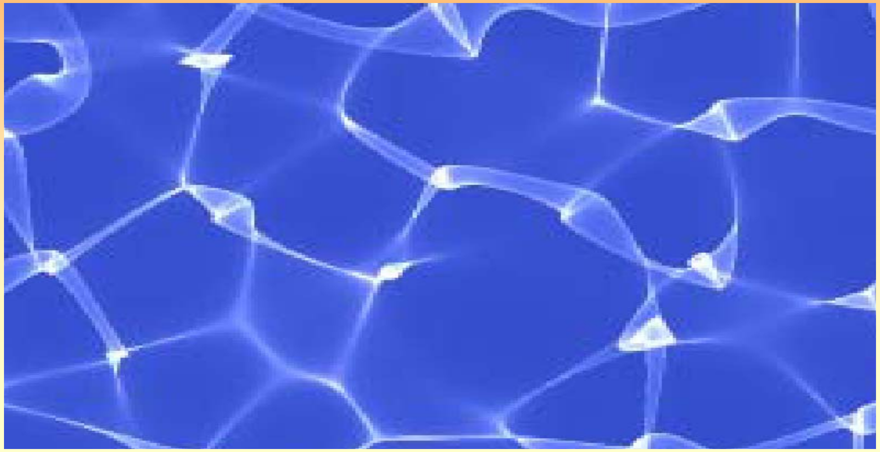
This analysis shows the possibility to investigate local halo features by annual modulation signature already at the level of sensitivity provided by DAMA/NaI, allowing to reach sensitivity to SagDEG density comparable with M/L evaluations.

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

⇒ streams of Dark Matter particles

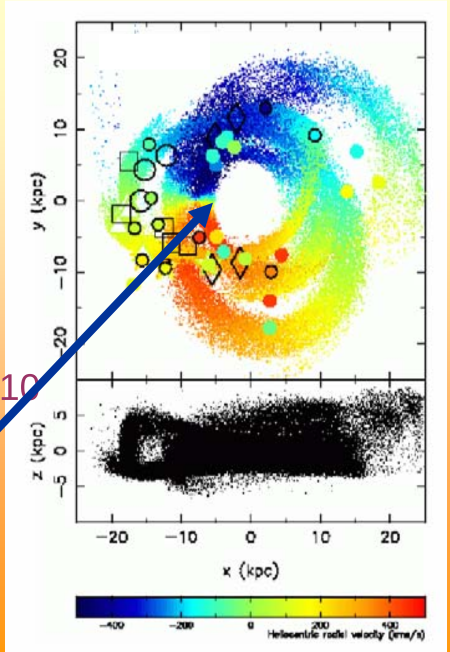
P. Sikivie, Fu-Sin Ling et al. astro-ph/0405231

Interesting scenarios for DAMA

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

Effect on the phase of annual modulation signature?

Canis Major simulation:
astro-ph/0311010



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

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

.....very likely....

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 quests 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)

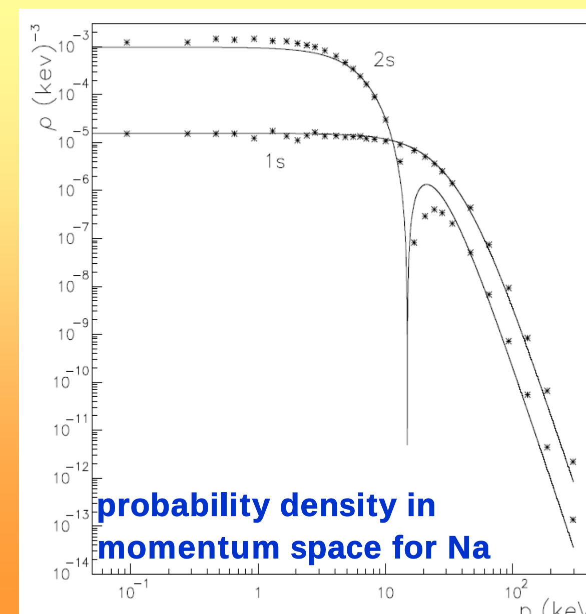
→ **the recoiling nucleus can "shake off" some of the atomic electrons**

→ **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: A.B. Migdal, J. Phys. USSR 4 (1941) 449;

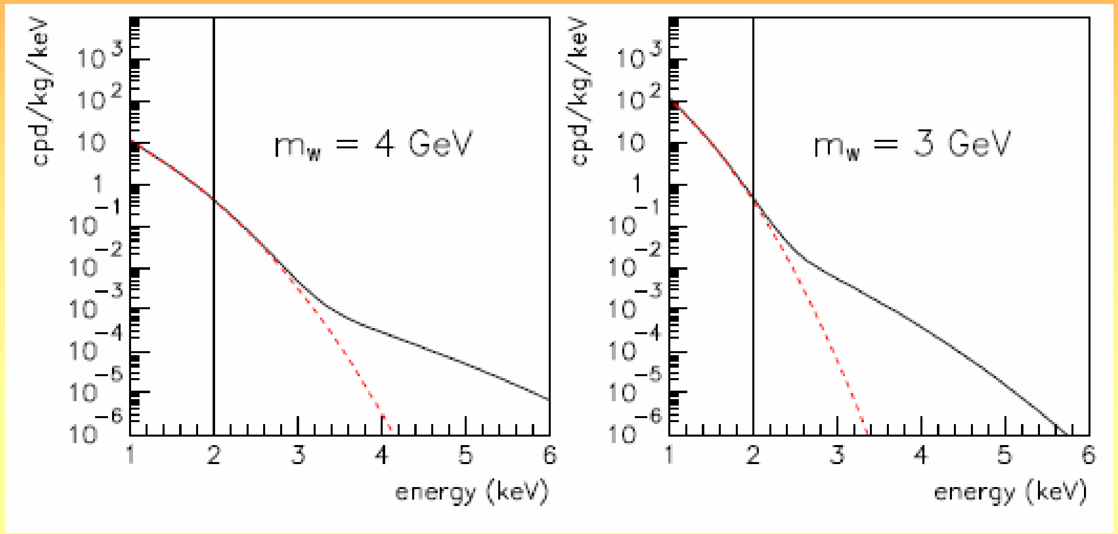
and described in many textbooks, e.g. : A.B. Migdal Qual. Meth. in Quantum Mechanics 1977
L. D. Landau and E. M. Lifshits Quantum Mechanics, Non- Relativistic Theory 1977 p 149.



probability density in momentum space for Na

IJMPA 22 (2007) 3155

Examples



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:

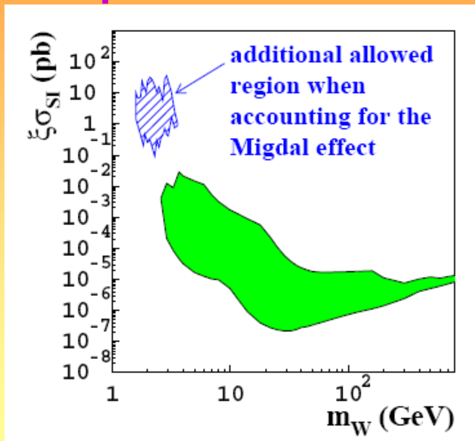
- **the unquenched nature of the e.m. contribution**
- **the behaviour of the energy distribution for nuclear recoils induced by WIMP-nucleus elastic scatterings**
- **etc.**

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

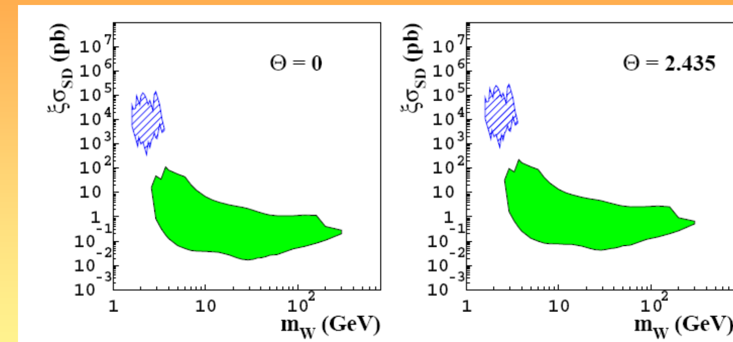


Region allowed in the ($\xi\sigma_{SI}$;m_W) plane in the considered model frameworks for pure SI coupling;

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

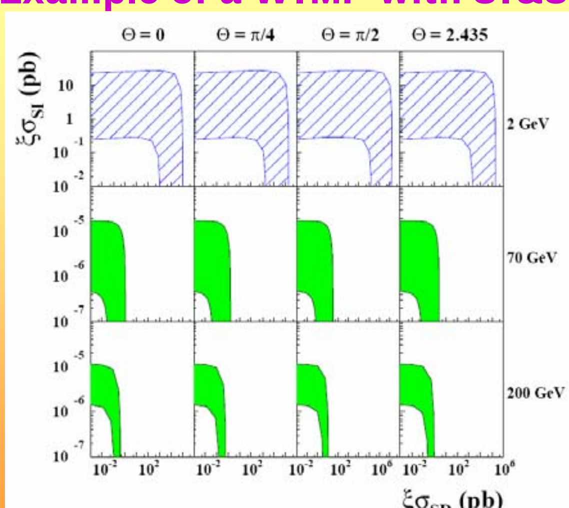
Example of a WIMP with dominant SD coupling



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

GeV mass DM particle candidate 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.)

Example of a WIMP with SI&SD coupling

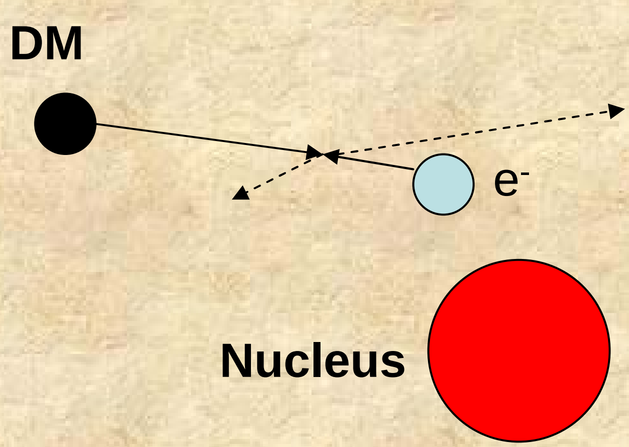


Examples of slices of the 4-dimensional allowed volume ($\xi\sigma_{SI}$; $\xi\sigma_{SD}$; m_W; θ) in the considered model frameworks

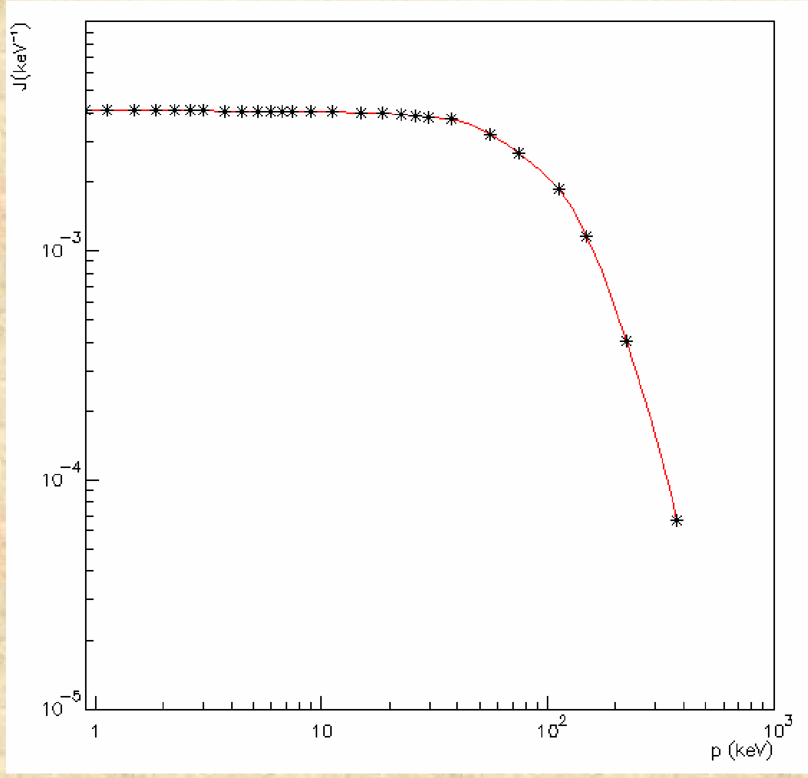
Among DM GeV mass condidates: 1) H dibarion (predicted in Standard Model); 2) a real scalar field in extended Standard Model; 3) the light photino early proposed in models with low-energy supersimmetry; 4) the very light neutralino in Next-to-MSSM model; 5) the mirror deuterium in frameworks where mirror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

→ working on other possible e.m. contributions

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:

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

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: $SU(3)_\ell \times SU(3)_c \times SU(2)_L \times U(1)$ broken at low energy.

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,...)

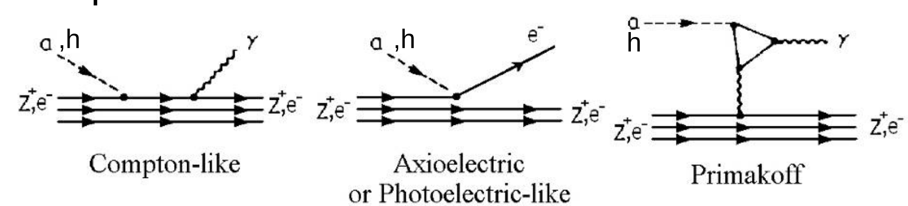
Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants allowed.

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:

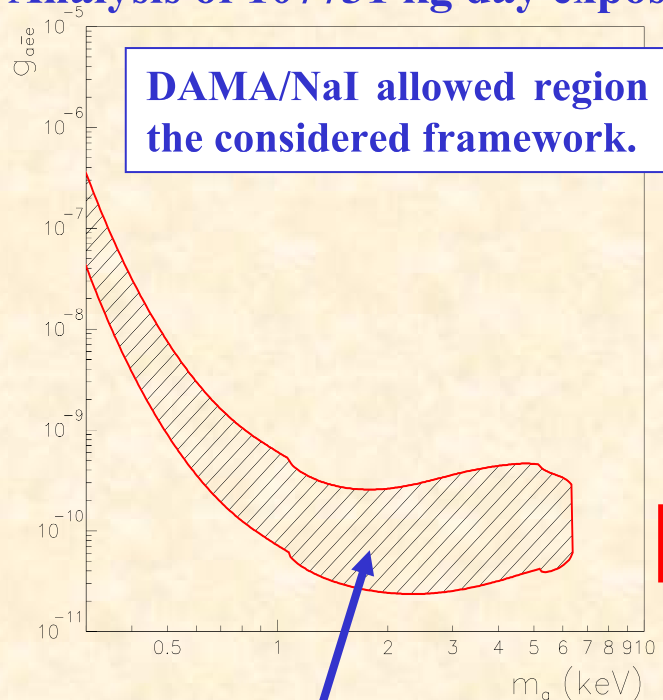


a	S_0	S_0,S_m	S_0,S_m
h	S_0,S_m	S_0	S_0,S_m

Pseudoscalar case:

IJMPA21(2006)1445

Analysis of 107731 kg day exposure from DAMA/NaI.



DAMA/NaI allowed region in the considered framework.

region almost indipendent on other fermion coupling values.

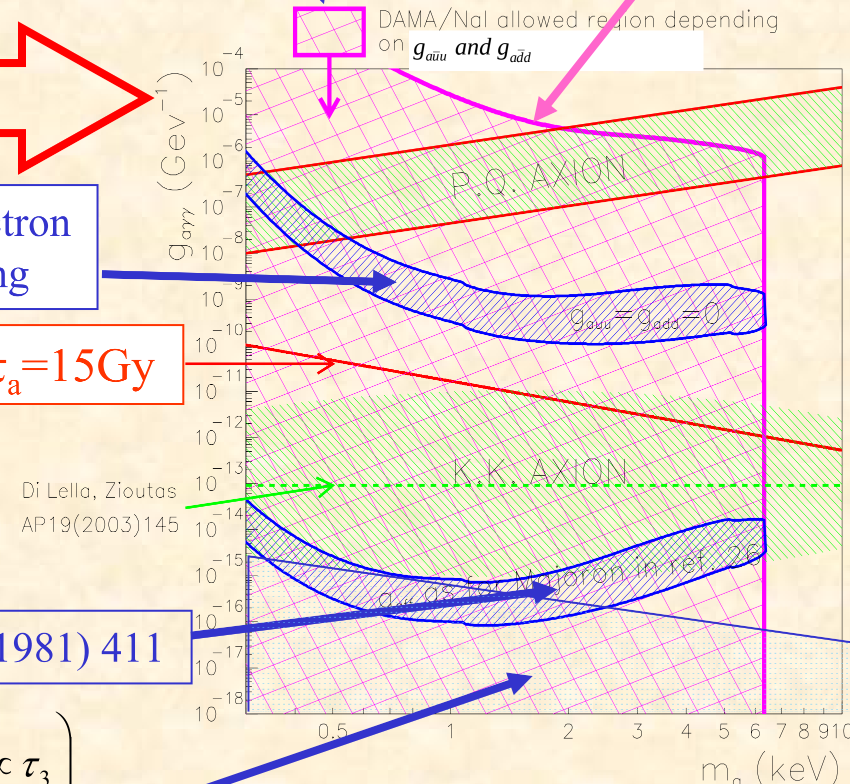
All these configurations are allowed by DAMA/NaI depending on the relative contributions of charged fermion couplings

coupling model

Considered dark halo models as in refs.:

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

Maximum allowed photon coupling



Only electron coupling

τ_a=15Gy

Also this can account for the DAMA/NaI observed effect

coupling to photons vanish at first order:

majoron as in PLB 99 (1981) 411

$$g_{a\gamma\gamma} \approx \frac{\alpha}{\pi}\left[\frac{g_{a\bar{e}e}}{m_e} + 3\frac{1/9\, g_{a\bar{d}d}}{m_d} + 3\frac{4/9\, g_{a\bar{u}u}}{m_u}\right] \approx 0 \qquad \left(\frac{g_{a\bar{e}e}}{m_e} = \frac{g_{a\bar{d}d}}{m_d} = -\frac{g_{a\bar{u}u}}{m_u} \propto \tau_3\right)$$

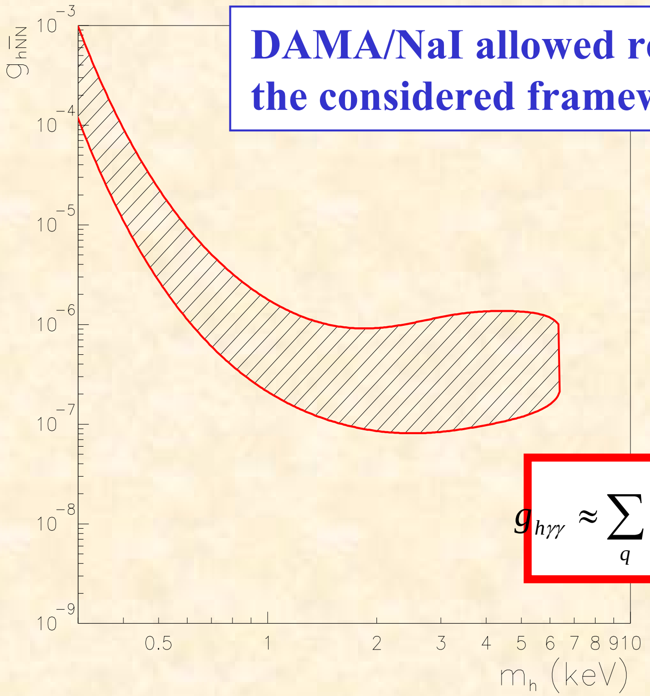
UHECR [3] **PRD64(2001)096005**

h

Scalar case:

IJMPA21(2006)1445

Analysis of 107731 kg day exposure from DAMA/NaI.



DAMA/NaI allowed region in the considered framework.

$$g_{h\bar{N}N} = \left(g_{h\bar{u}u} + 2g_{h\bar{d}d}\right) + \frac{Z}{A}\left(g_{h\bar{u}u} - g_{h\bar{d}d}\right)$$

Just an example: all the couplings to quarks of the same order ↔ lifetime dominated by u & d loops:

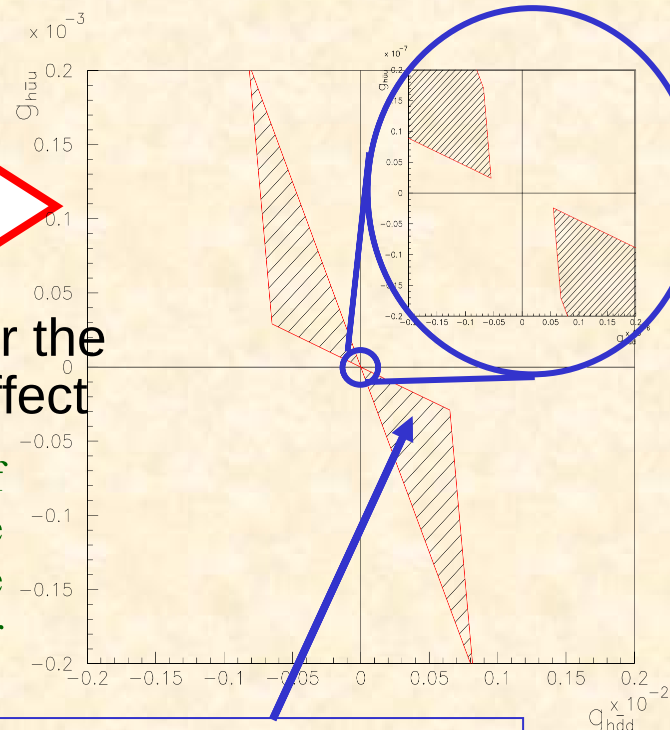
$$g_{h\gamma\gamma} \approx \sum_q -\frac{2}{3}\frac{\alpha\, Q_q^2 g_{h\bar{q}q}}{\pi\, m_q} \approx -2\frac{\alpha}{\pi}\left[\frac{4/9\, g_{h\bar{u}u}}{m_u} + \frac{1/9\, g_{h\bar{d}d}}{m_d}\right]$$

Also this can account for the DAMA/NaI observed effect

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

Considered dark halo models as in ref:

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



- **Annual modulation signature present for a scalar particle with pure coupling to hadronic matter (possible gluon coupling at tree level?).**
- **Compton-like to nucleus conversion is the dominant process for particle with cosmological lifetime.**

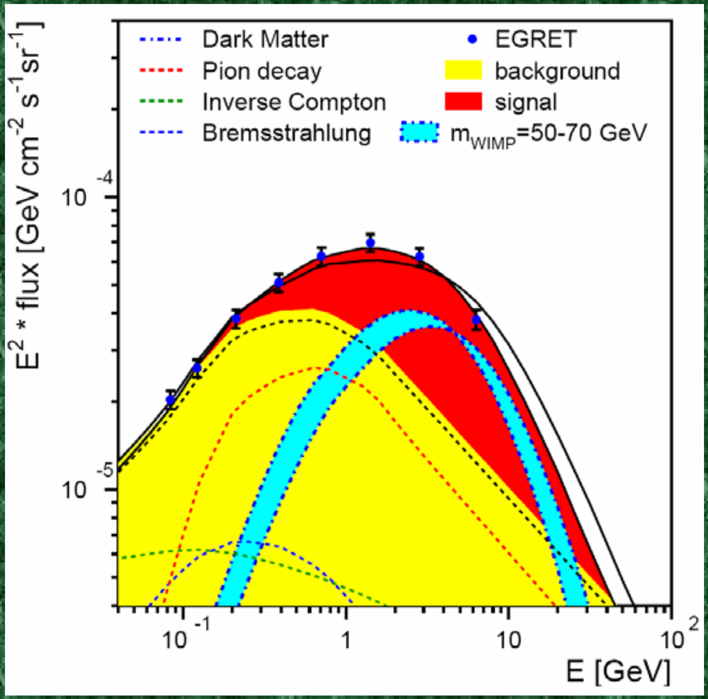
- **Allowed by DAMA/NaI (for m_h > 0.3 keV)**
- **τ_h > 15 Gy (lifetime of cosmological interest)**
- **m_u = 3.0 ± 1.5 MeV m_d = 6.0 ± 2.0 MeV**

h

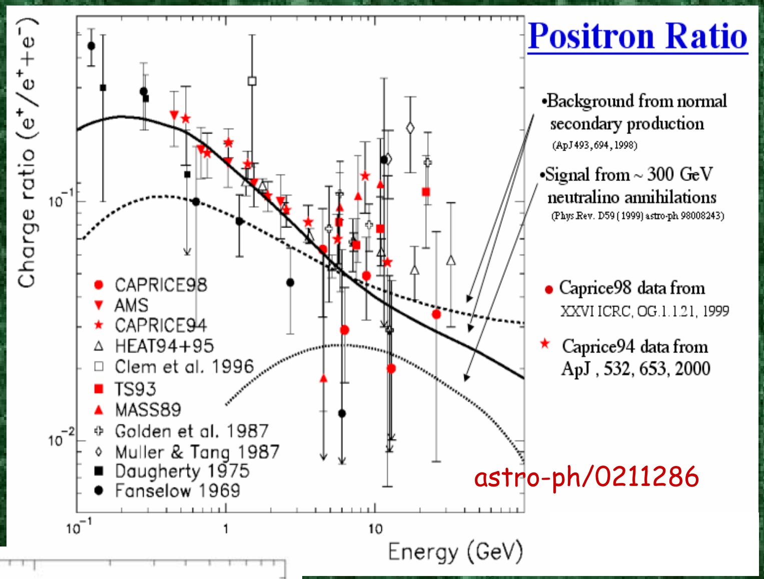
What about the indirect searches of DM particles in the space?

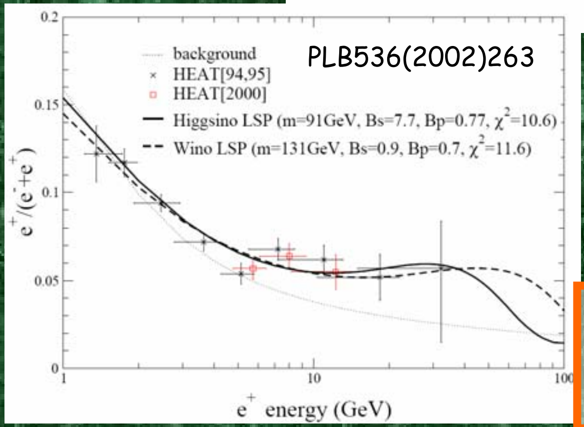
It was noticed that the EGRET data show an excess of gamma ray fluxes for energies above 1 GeV in the galactic disk and for all sky directions.

The EGRET Excess of Diffuse Galactic Gamma Rays



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





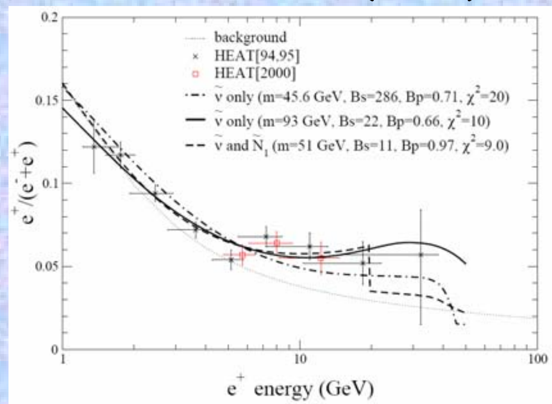
interpretation, evidence itself, derived m_W and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.

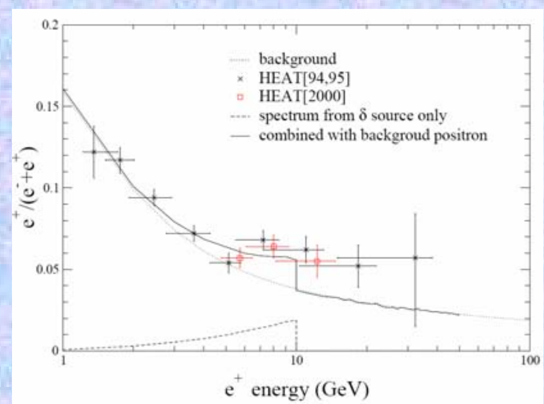
Hints from indirect searches are not in conflict with DAMA/NaI

... not only neutralino, but also e.g. ...

... sneutrino, ...

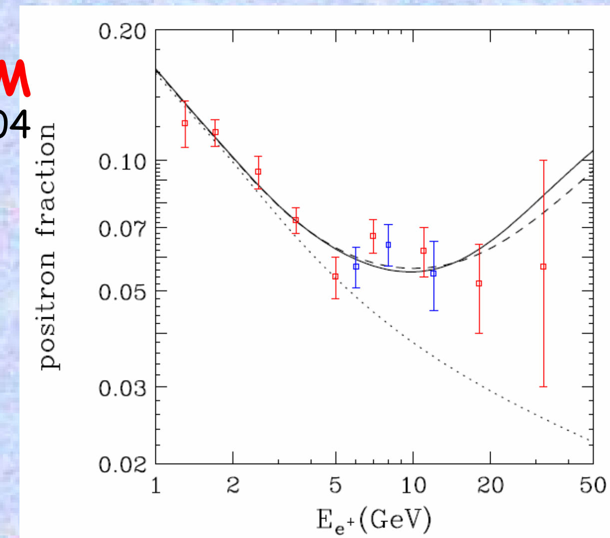
PLB536(2002)263





... or Kaluza-Klein DM

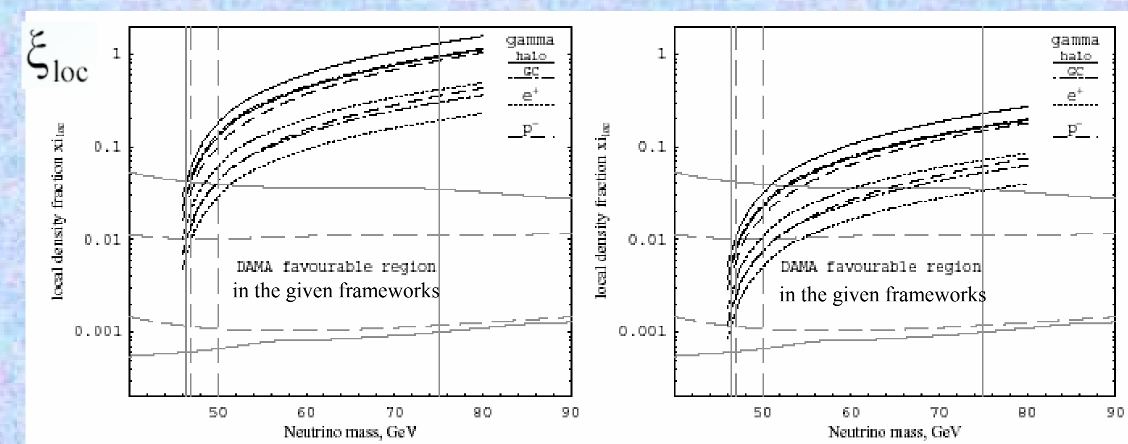
PRD70(2004)115004



... or neutrino of 4th family

hep-ph/0411093

Example of joint analysis of DAMA/NaI and positron/gamma's excess in the space in the light of two DM particle components in the halo



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

OBVIOUSLY NO

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

} No direct model independent comparison possible

Even "assuming" their expt. results as they claim ... e.g.:

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.

…and more

- 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; … and more

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

- These candidates are lost by these expts. OBVIOUSLY NO

….and more

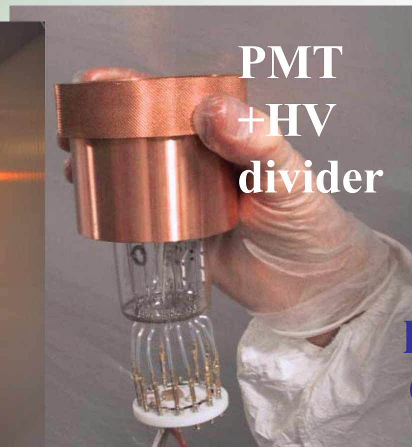
+ they usually quote in an uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent result; they release orders of magnitude lower exposures, etc.

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

improving installation and environment



PMT +HV divider

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

storing new crystals

etching staff at work in clean room

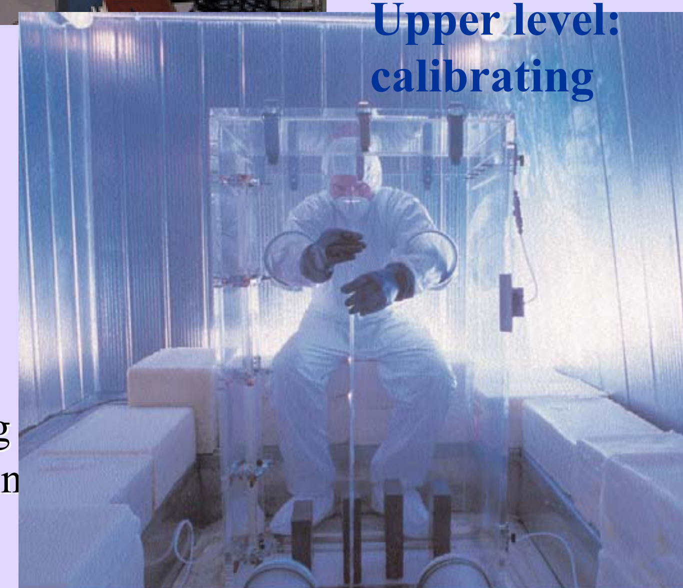
Further on DAMA/LIBRA installation

working under the passive shield before installing the paraffin

view with shielding completed

verifying Cd foils

installing DAMA/LIBRA electronics



Upper level: calibrating

Particular thanks to the Fire Department staff, inside LNGS, for having never left us alone during all the works on the installation performed in HP N_2 atmosphere.

An example: the Cu etching

- The Cu etching was performed in a clean room following a devoted protocol:

vessel I: pre-washing of the brick in iper-pure water
vessel II: washing in 1.5l of HCl 3M super-pure
vessel III: first rinse with iper-pure water (bath)
vessel IV: second rinse with iper-pure water (current)
vessel V: washing in 1.5l of HCl 0.5M ultra-pure
vessel VI: first rinse with iper-pure water (bath)
vessel VII: second rinse with iper-pure water (current)
vessel VIII: third rinse with iper-pure water (current)
bricks dried with selected clean towels and HP N_2 flux
bricks sealed in two envelopes (one inside the other) flowed and filled with HP N_2

- Very clean materials (teflon and high purity OFHC copper, selected vessels and gloves) were used. Special tools were also used to help managing the bricks to minimize the contact with gloves.
- The residual contaminants in HCl used in solution with iper-pure water are certified by the producer; in particular standard contaminants are quoted: 10 ppb for ^{nat}K and 1 ppb or U/Th for super-pure HCl and 100 ppt of ^{nat}K and 1 ppt for U/Th in case of ultra-pure HCl.
- For each brick the bath was changed and after each step the solution of the bath was analysed with ICP-MS technique.
- Residual contaminants were checked in order to optimize the choice of the materials (in particular for gloves) and the cleaning procedure. After cleaning, each brick was stored underground.


(all operations involving crystals and PMTs -including photos- in HP N_2 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
filling the inner Cu box with further shield
DAMA/LIBRA started operations on March 2003,
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

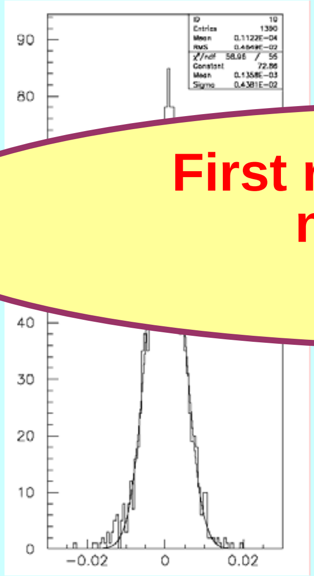
  calibrations: acquired ≈ 40 M events of sources

  acceptance window eff: acquired ≈ 2 M ev/keV

  continuously running

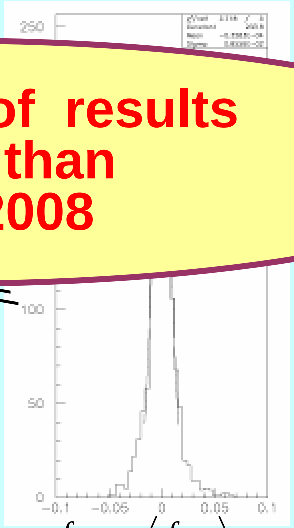
Examples: here from March 2003 to August 2005

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–β^2) = 0.537]

+ in progress

DAMA/LIBRA perspectives

DAMA/LIBRA (~250kg NaI(Tl)), start preliminary test run in March 2003, can allow to:

- **achieve higher C.L. for the annual modulation effect (model independent result)**
- **investigate many topics on the corollary model dependent quests for the candidate particle (continuing and improving past and present efforts on the data of the previous DAMA/NaI experiment):**

+ investigations e.g. on:

- **velocity and position distribution of DM particles in the galactic halo**
- **on more complete astrophysical scenarios: DM streams and/or caustics in the halo, effects due to clumpiness and possible distorsion due to the Sun gravitational field, etc.**
- **the nature of the candidate particles**
- **the phenomenology of the candidate particles and their interactions with ordinary matter**
- **scaling laws and cross sections.**
- **... and more**

- **competitive limits on many rare processes can also be obtained**

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");

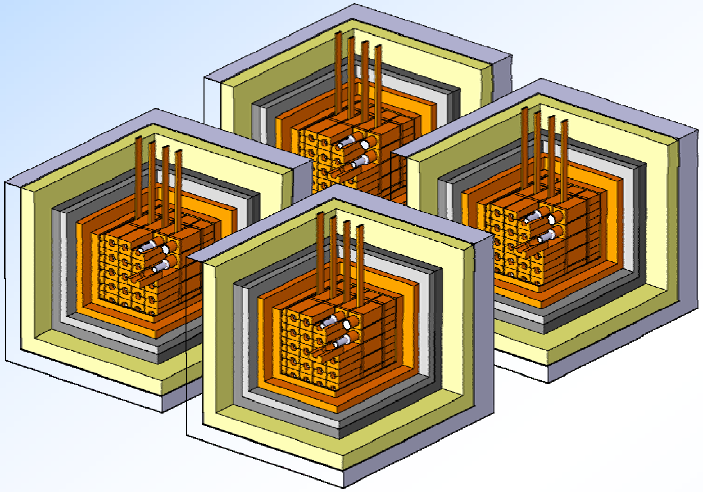
iv) possible structures as clumpiness with small scale size;

\+ second-order effects

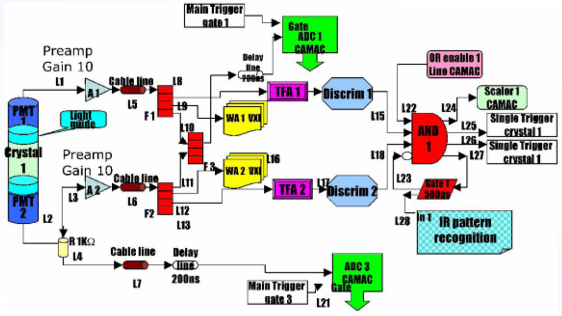
Towards possible DAMA/1ton

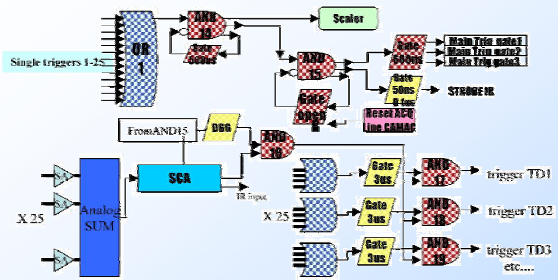
1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand (large experiences and fruitful collaborations among INFN and companies/industries)
3) Still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, 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 developped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA



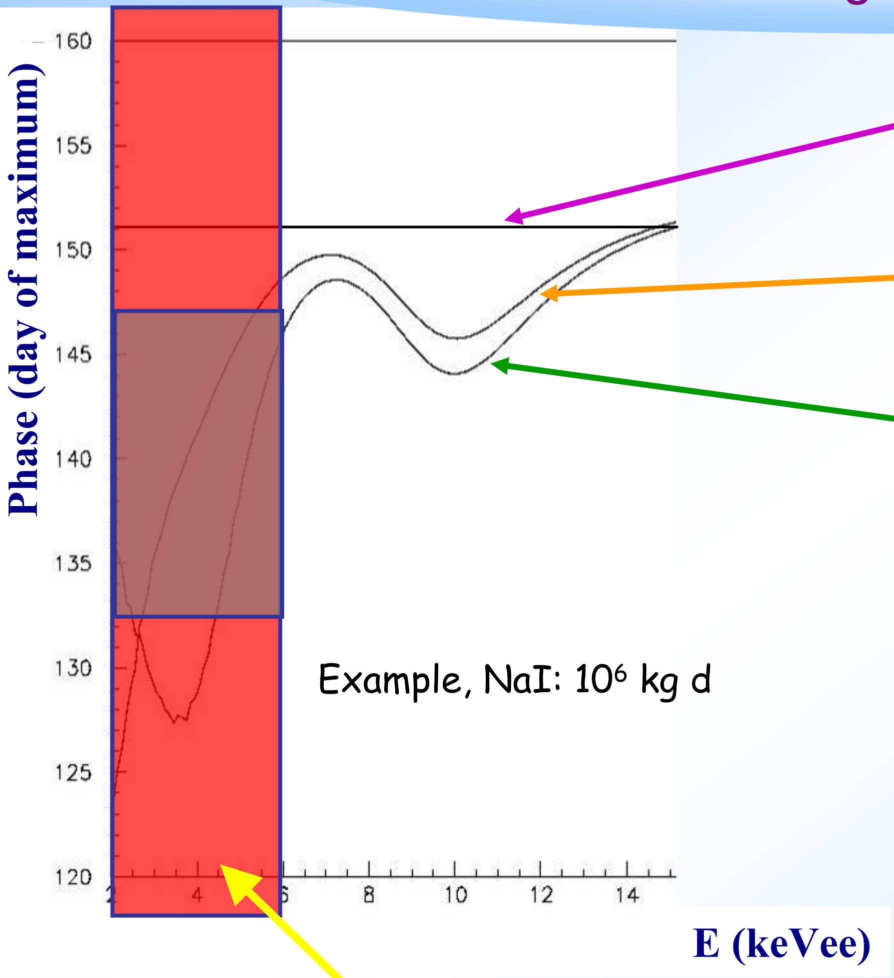


Electronic chain and example of the trigger system

DC270 Acqiris Digitizers

An example of possible signature for presence of Dark Matter streams in the Galactic halo

The streams effect on the phase depends also on the galactic halo model



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

Evans'log axisymmetric non-rotating, v_0=220km/s, R_c= 5kpc, ρ_0 max + 4% Sgr

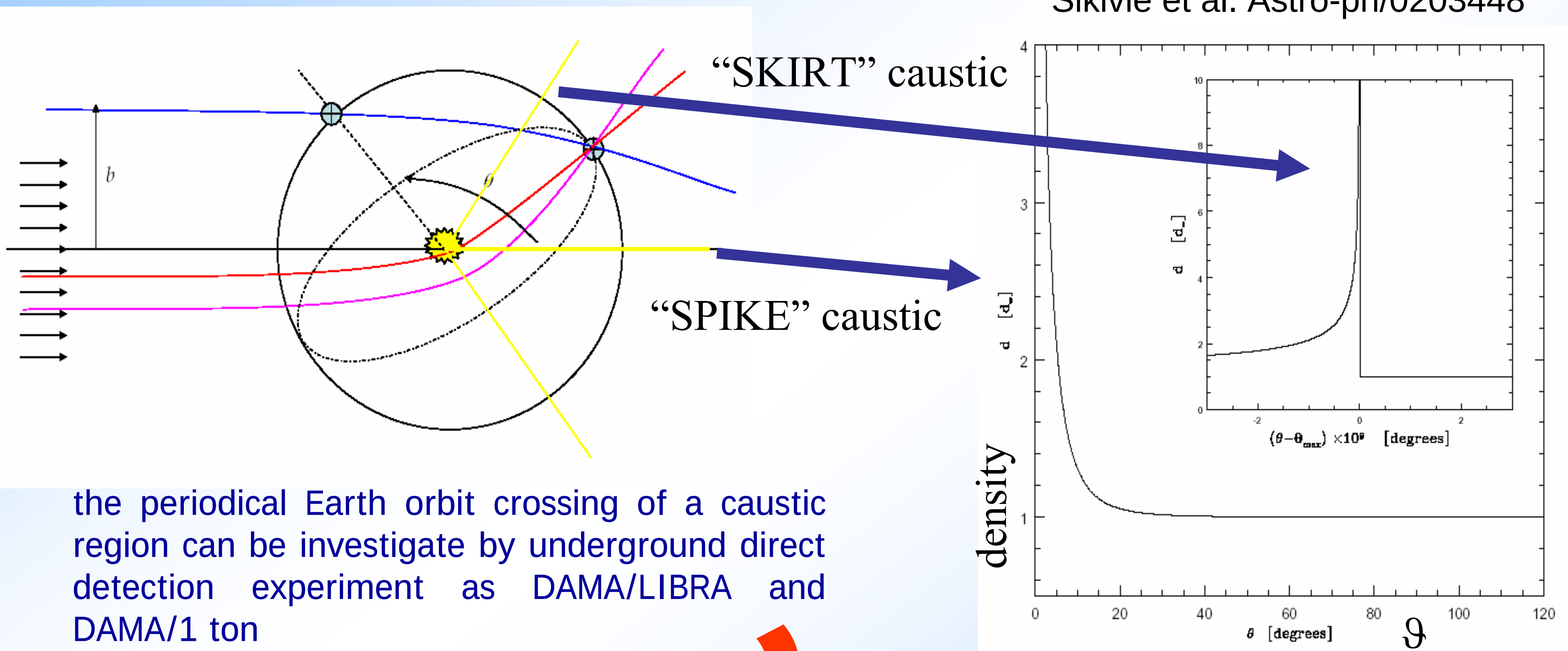
NFW sferical isotropic non-rotating, v_0=220km/s, ρ_0 max + 4% Sgr

The higher sensitivity of DAMA/1ton will allow a more effective investigation of streams contribution in the galactic halo

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

Example of a viable signature for DM streams in the solar neighborhood...

Sikivie et al. Astro-ph/0203448



the periodical Earth orbit crossing of a caustic region can be investigate by underground direct detection experiment as DAMA/LIBRA and DAMA/1 ton

an example:

$V_{flux} \sim 300$ km/s ; $\sigma_V \sim 70$km/s

Earth orbit within 10° from "spike"

sensibility to $\rho_{flux} >$ few % ρ_0

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·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