Recent DAMA activity on Dark Matter investigation at LNGS

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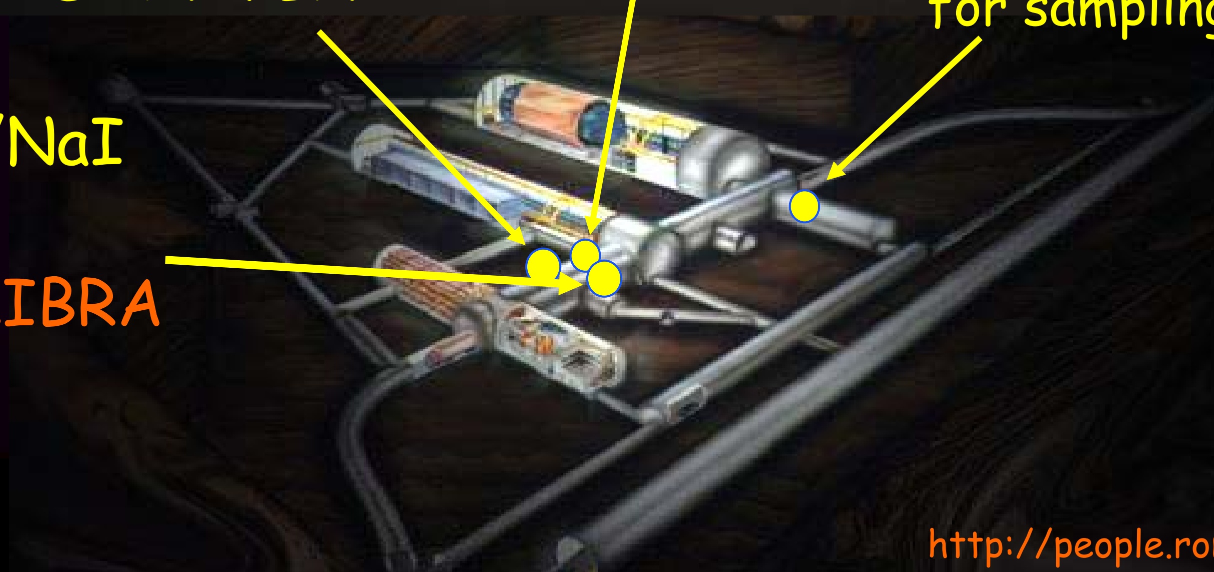
Roma2,Roma1,LNGS,IHEP/Beijing

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 → 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 → ^{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
- 2EC2ν ^{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
- 2EC2ν 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 → ^{139}Ce — UJP51(2006)1037

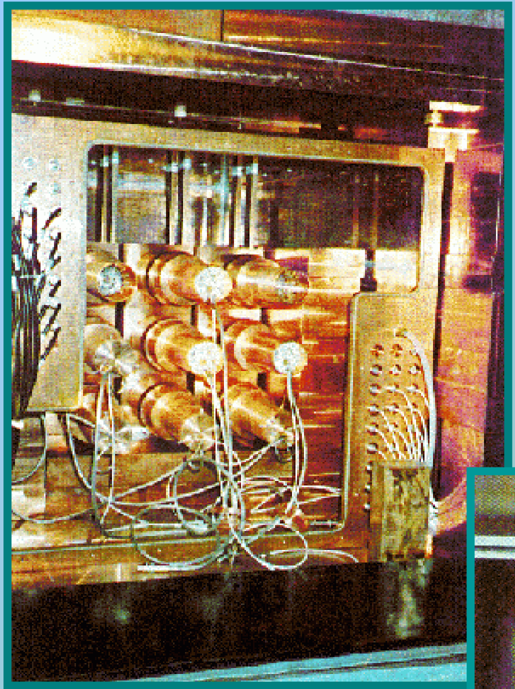
DAMA/Ge & LNGS Ge facility

- 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

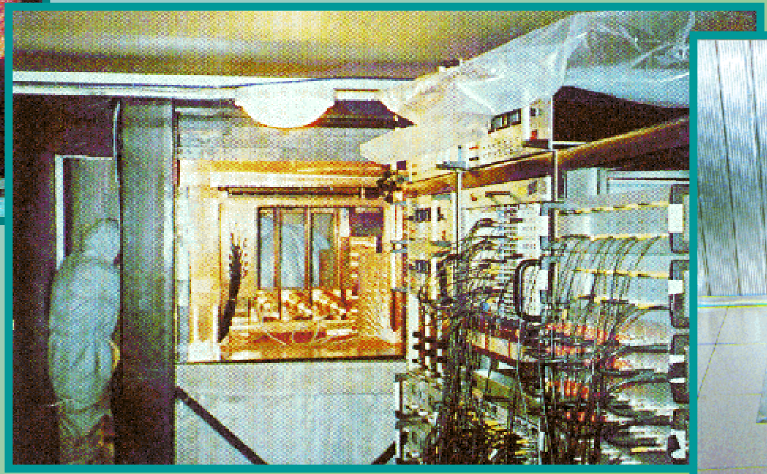
DAMA/NaI(Tl)~100 kg

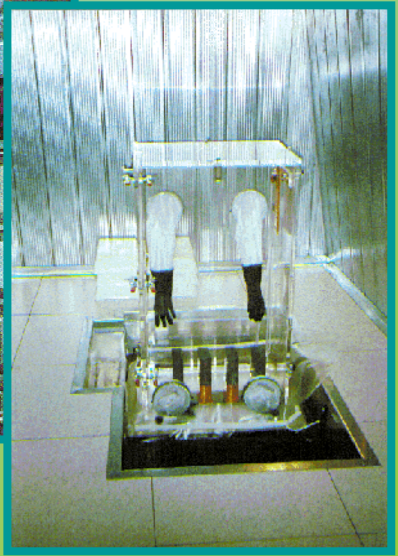
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127



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:

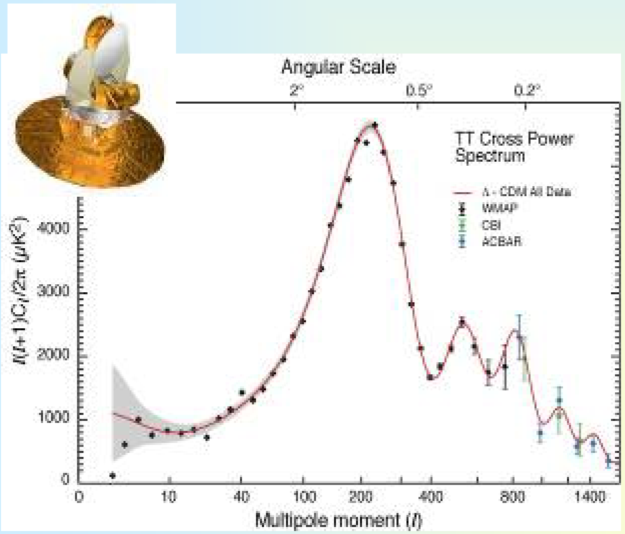
- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- Annual Modulation Signature
  PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23,EPJ C18(2000)283, PLB509(2001)197, EPJ C23 (2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1-73, IJMPD13(2004)2127, IJMPA21(2006)1445), EPJC47(2006)263 + other works in progress....

data taking completed on July 2002
(still producing results)

total exposure collected in 7 annual cycles 107731 kg×d

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

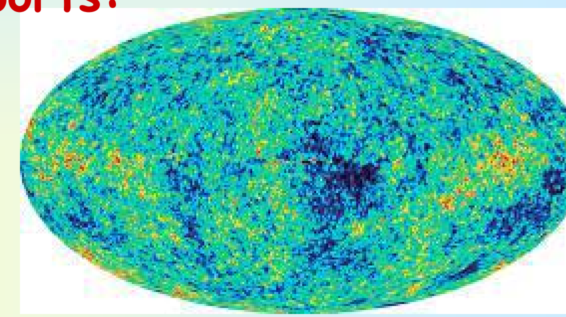
From larger scale ...



"Precision" cosmology supports:

Flat Universe:

$\Omega = 1.02 \pm 0.02$



"Concordance" model:

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

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

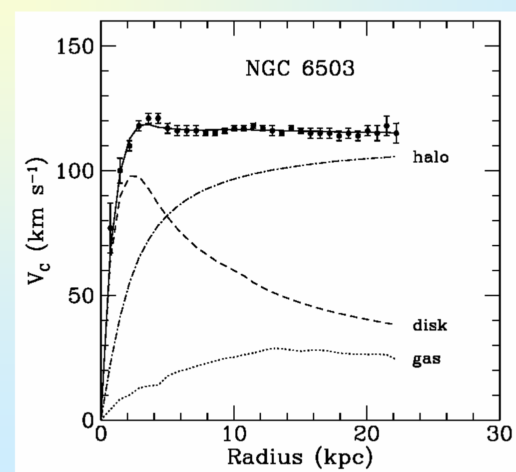
$\Omega_b \sim 4\%$

$\Omega_\nu < 1\ \%$

Evidence for dark matter at large and small scales since 70 years (luminous matter less than 1%)

... to galaxy scale

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

axion-like (light pseudoscalar and scalar candidates)

the sneutrino in the Smith and Weiner scenario

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

a heavy ν of the 4-th family

&

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

even a suitable particle not yet foreseen by theories

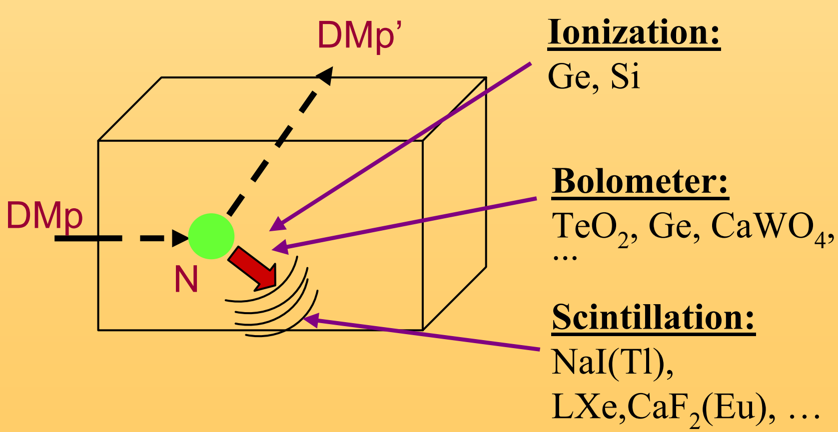
etc…

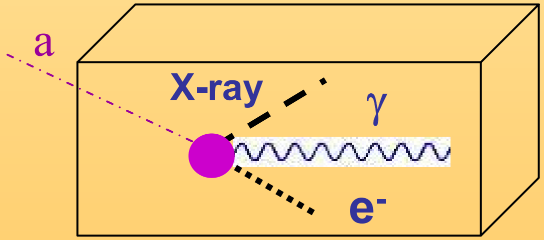
Direct detection of Dark Matter particles in the galactic halo

- Various approaches and techniques (many still at R&D stage)
- Various different target nuclei
- Various different experimental site depths
- well different sensitivities to various candidates, interactions, etc.

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^-



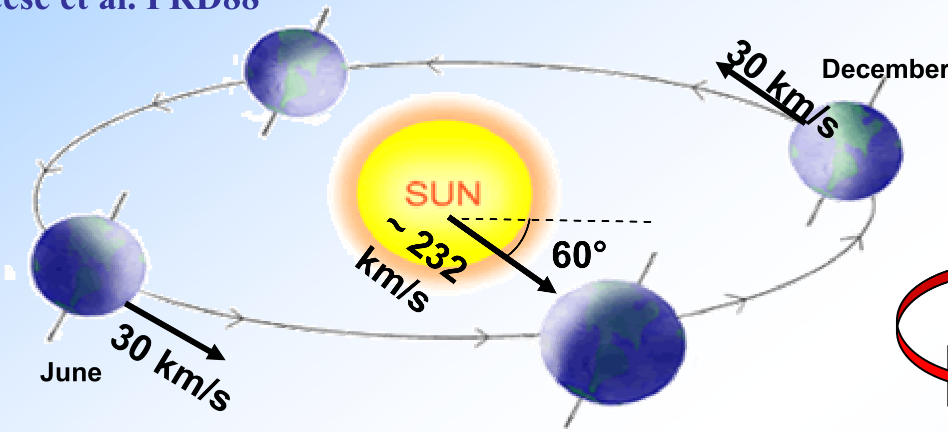


NOTE: these signals are lost in experiments based on rejection procedures of the electromagnetic events

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.

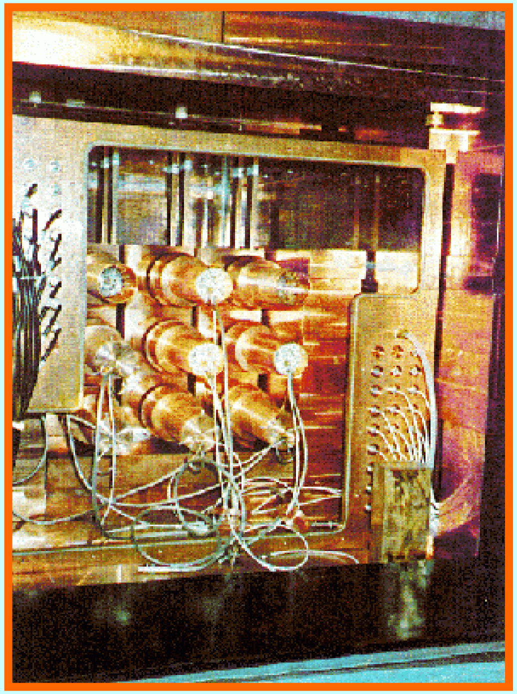
A low background NaI(Tl) also allows the study of several other rare processes such as: possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar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

High benefits/cost

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 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 + polyethylene/paraffin+ ~ 1 m concrete 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 using the upper glove-box (equipped with compensation chamber) in HP Nitrogen atmosphere in slight overpressure calibration $\rightarrow$ in the same running conditions as the production runs.
- 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

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

- data taking of each annual cycle starts from autumn/winter (when $\cos\omega(t-t_0)\approx 0$) 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 from ^{210}Pb (~ 7 days periods) + 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

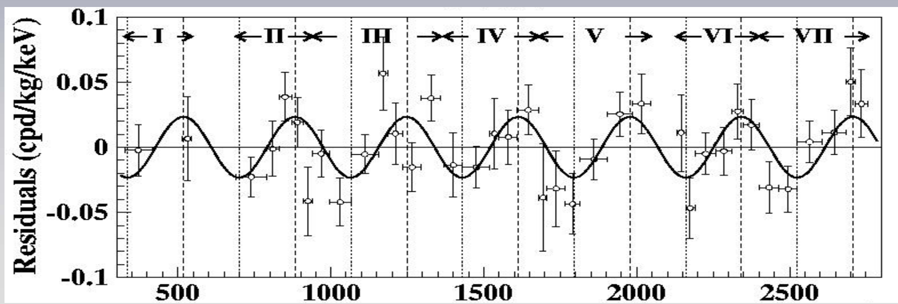
Riv. N. Cim. 26 n.1. (2003) 1-73
IJMPD13(2004)2127

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

107731 kg · d

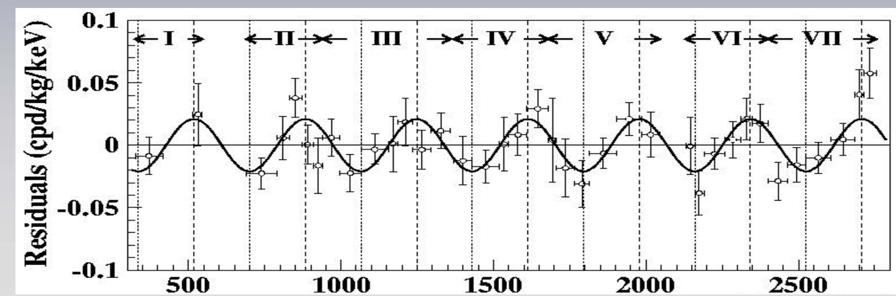
$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV



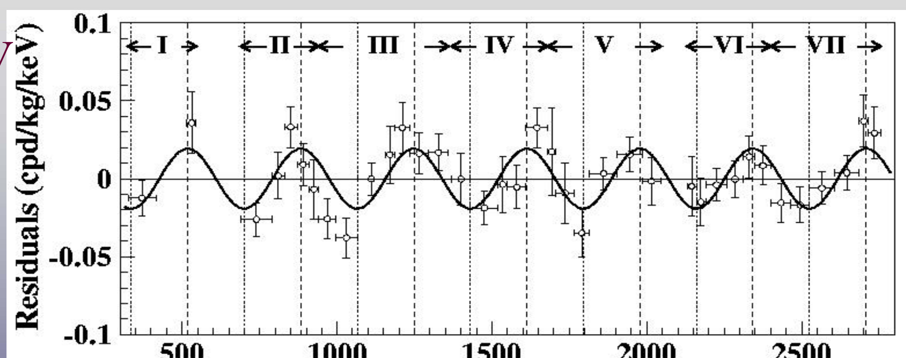
fit: A=(0.0233 ± 0.0047) cpd/kg/keV Time (day)

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)=$7\cdot10^{-4}$

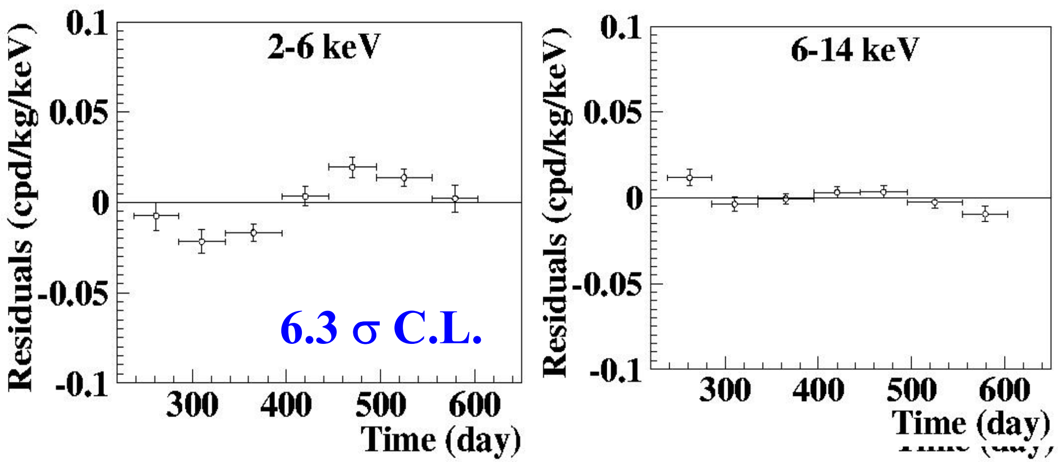
fit: A = (0.0192 ± 0.0031) cpd/kg/keV

fit (all parameters free):
A = (0.0200 ± 0.0032) cpd/kg/keV;
t_0 = (140 ± 22) d ; T = (1.00 ± 0.01) y

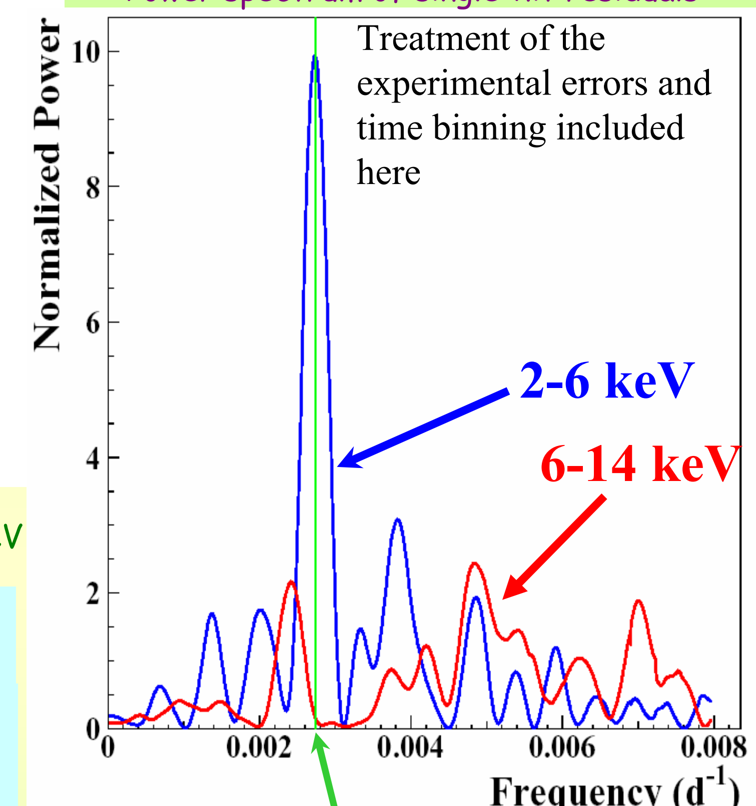
The data favor the presence of a modulated behavior with proper features at 6.3σ C.L.

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



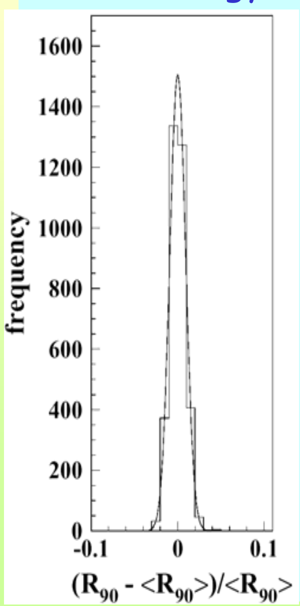
fixing t_0 = 152.5 day and T = 1.00 y, the modulation amplitude:

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 · 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:

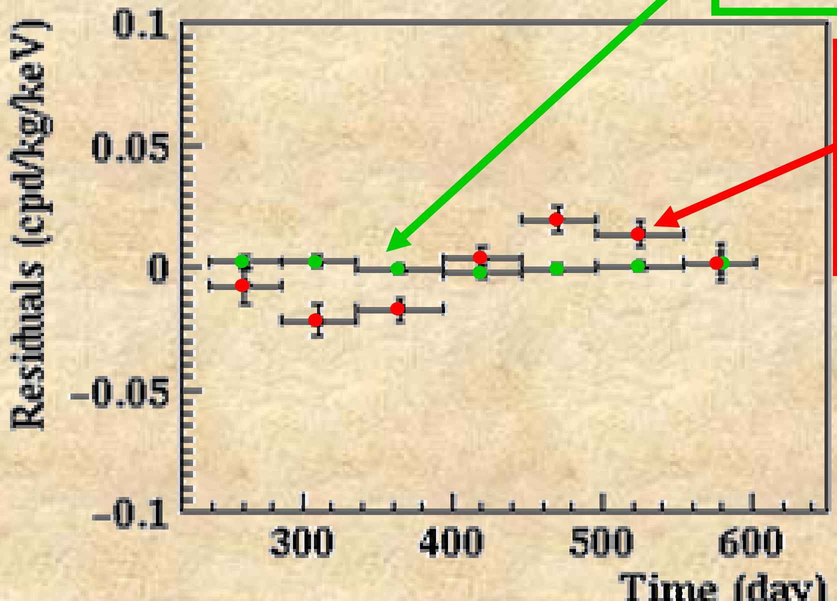
- in the 6-14 keV energy regions
- in other energy regions closer to that where the effect is observed e.g.: mod. ampl. (6-10 keV): -(0.0076 ±0.0065), (0.0012±0.0059) and (0.0035±0.0058) cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero
- in the integral rate above 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±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 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	Sealed Cu box 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	$<0.5\%\ S_m^{obs}$
NOISE	Effective noise rejection	$<1\%\ S_m^{obs}$
ENERGY SCALE	Periodical calibrations + 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 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 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

\+ multi-component?

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

First case: the case of DM particle scatterings on target-nuclei, considering only the recoil energy

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

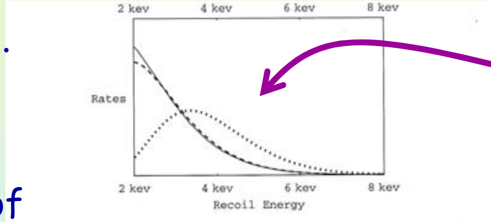
Note: not universal description. Scaling laws assumed to define point-like cross sections from nuclear ones. Four free parameters: m_W, σ_{SI}, σ_{SD}, $tg\theta = \frac{a_n}{a_p}$

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

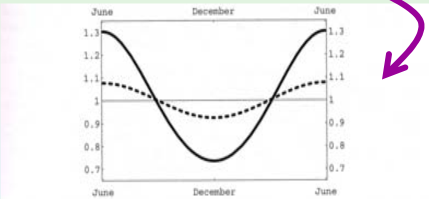


Normalized modulation (S_m) as a function of energy for ordinary WIMP scenario (solid), inelastic WIMP scenario with δ = 100keV (dashed), and inelastic WIMP scenario with δ = 150keV (dotted), all with m_χ = 60GeV.

S_m/S_0 enhanced with respect to the elastic scattering case

Ex. m_W = 100 GeV

m_N	μ
70	41
130	57



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

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, ...)

On results on model dependent analyses

Results given in terms of allowed regions have been obtained as superposition of the configurations in the space parameters of the considered candidate corresponding to likelihood function values distant more than 4σ from the null hypothesis (absence of modulation) in each of the several (but still a limited number of the possible) model frameworks

The best fit values obtained for all the considered model frameworks range over some orders of magnitude; for example, for the case of WIMP candidate with SI coupling, the best fit values of the mass range between few GeV to TeV scale, and the best fit values of the SI cross section range on orders of magnitude

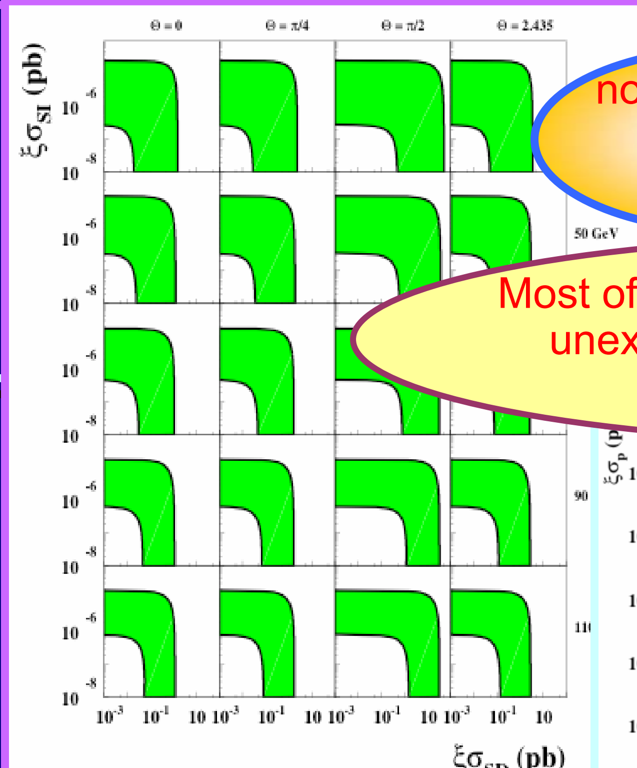
Allowed regions take into account the time and energy behaviours of the experimental data

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

(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

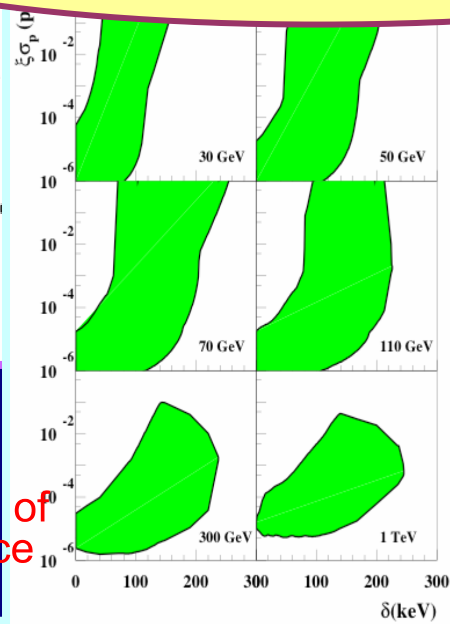


not exhaustive + different scenarios?

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:

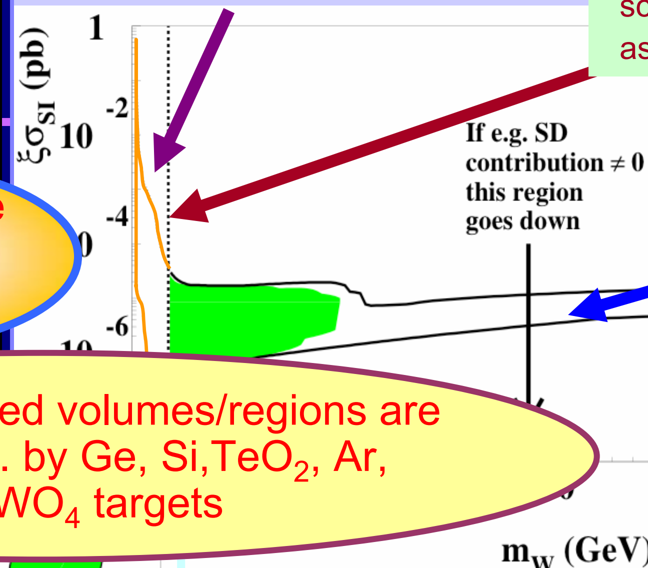
$W + N \rightarrow W^* + N$ (S_m/S_0 enhanced): examples of slices of the allowed volume in the space ($\xi\sigma_p$, m_W, δ) [e.g. Ge disfavoured]



DM particle with dominant SI coupling

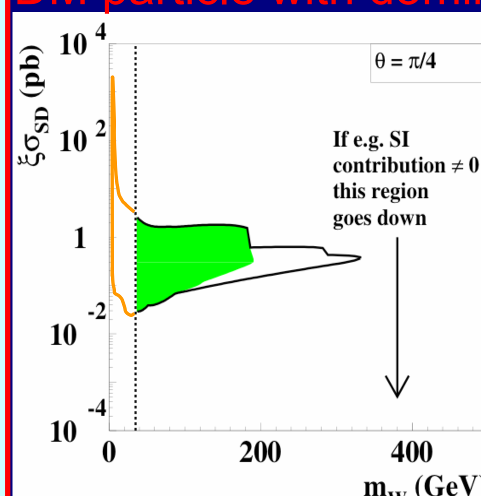
Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for "generic" DM particle

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

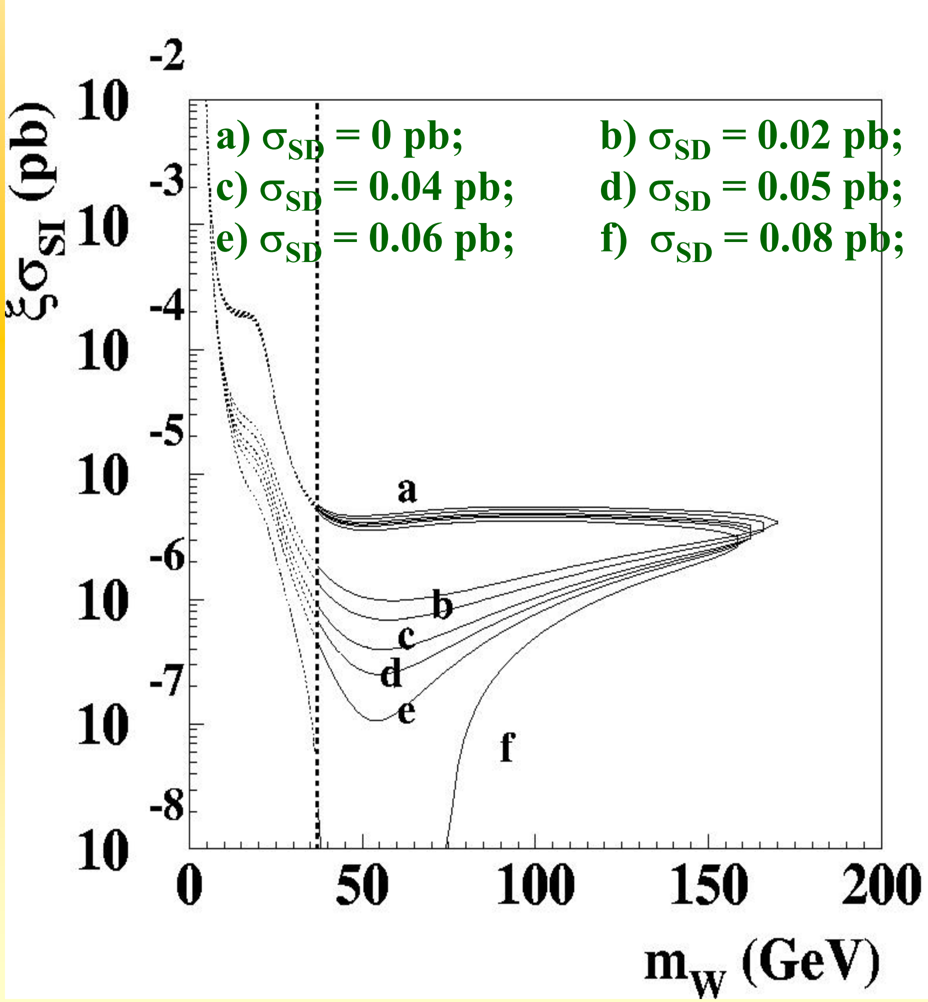


volume allowed in the space (m_W, $\xi\sigma_{SD}$, θ); here example of a slice for $\theta = \pi/4$ ($0 \le \theta < \pi$)

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 $\theta \approx 0$ 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

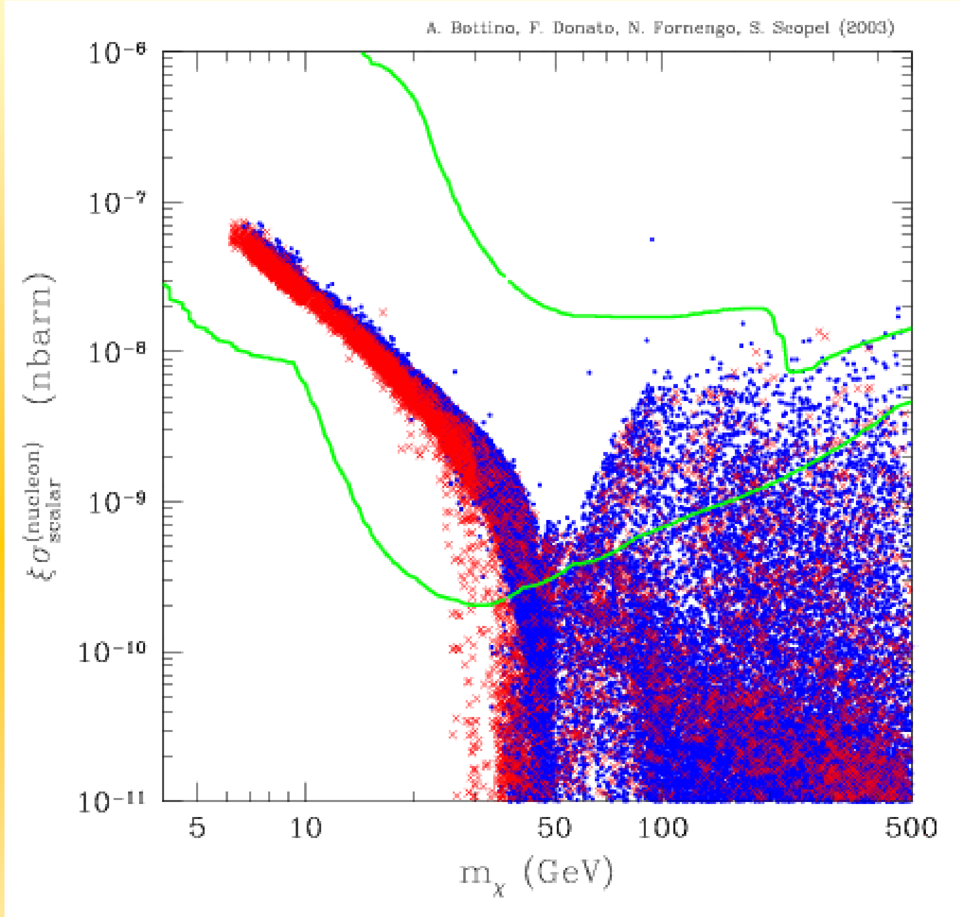
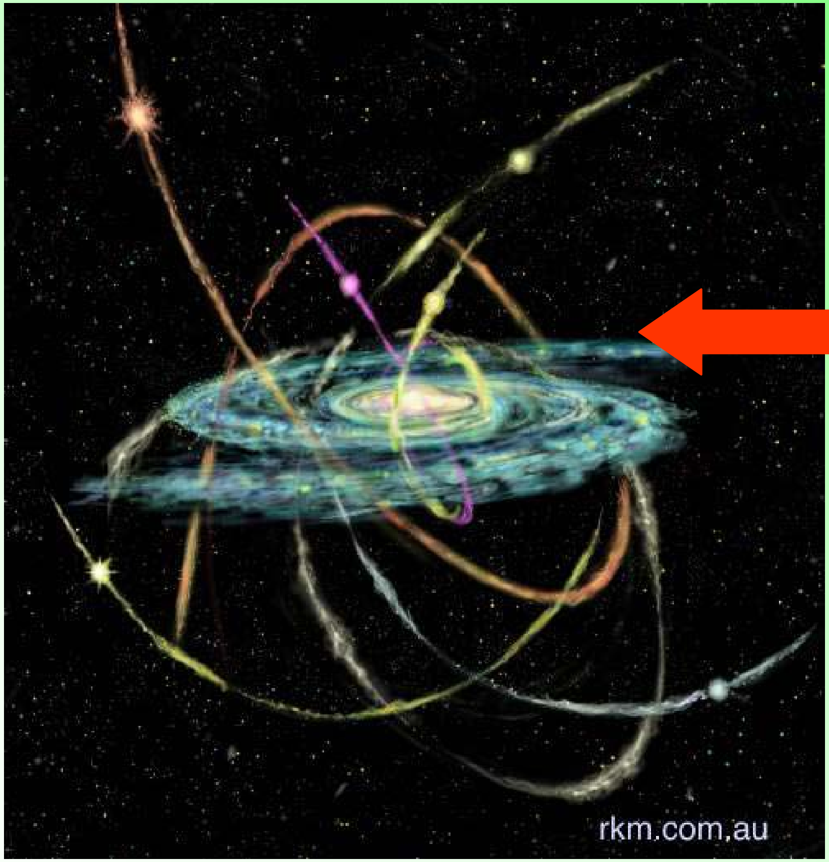


figure taken from PRD69(2004)037302

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);

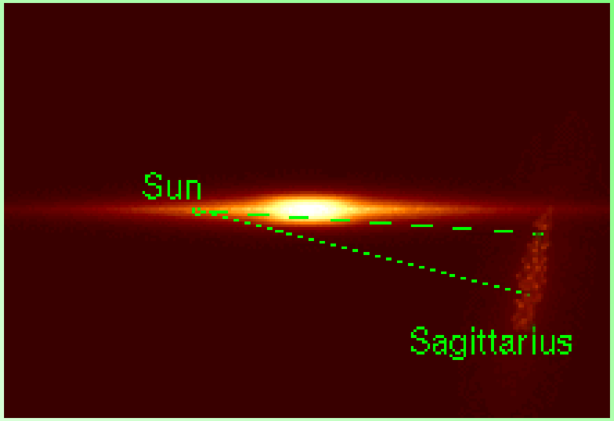
(for previous DAMA/NaI partial exposure see PRD68(2003)043506)

Some open scenarios on astrophysical aspects



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

some relics of the hierarchical assembly of the Milky Way are already observed in the visible: Sagittarius dwarf galaxy since 1994, Canis Major galaxy early discovered…

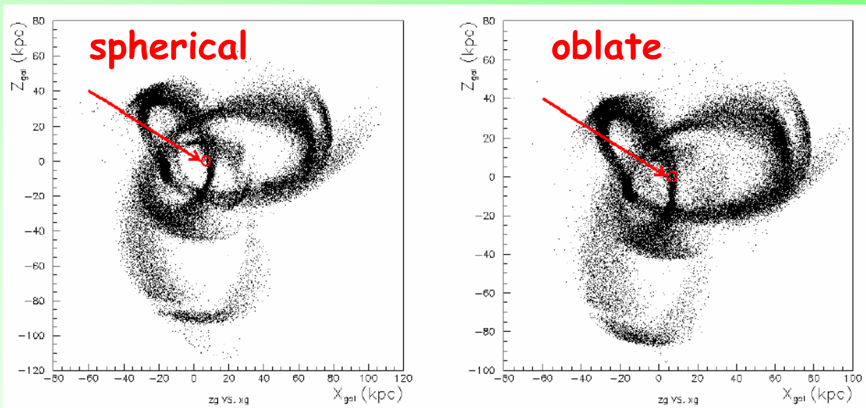


This scenario foreseen streams of Dark Matter particles with low velocity dispersion, very interesting for direct detection: S_m/S_0 enhanced in A.M., new signature for streams

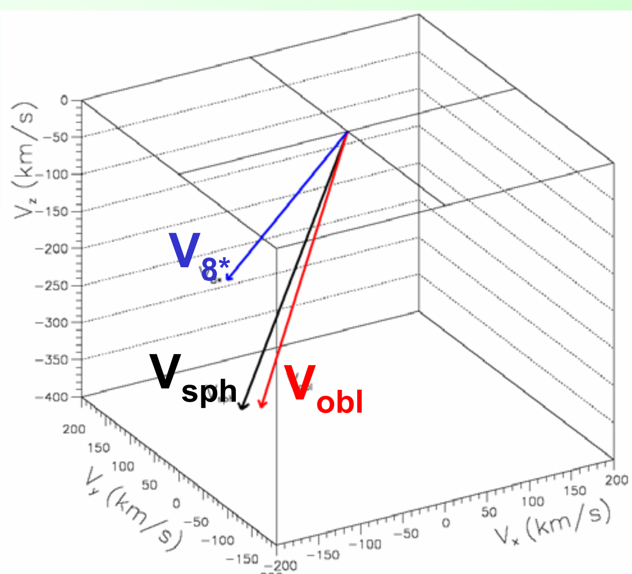
NEW: investigating halo substructures by underground expt through annual modulation

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



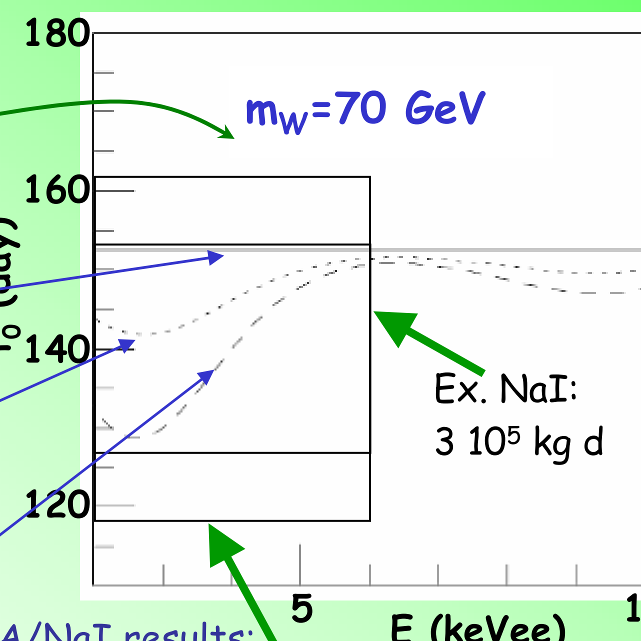
V_{8*} from 8 local stars: PRD71(2005)043516

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 2[nd])

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 Sagittarius Dwarf satellite galaxy (SagDEG) for WIMPs

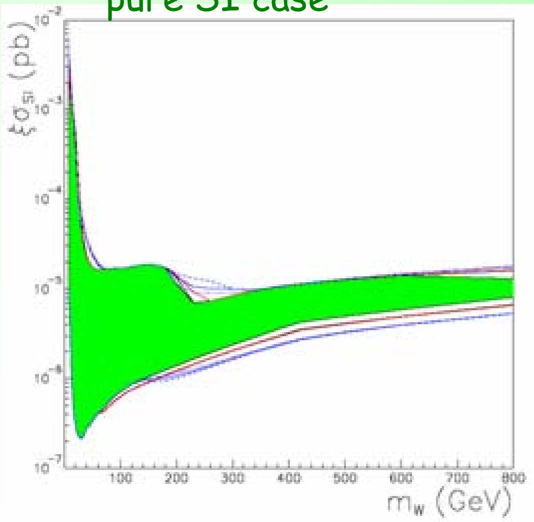
EPJC47 (2006) 263

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

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

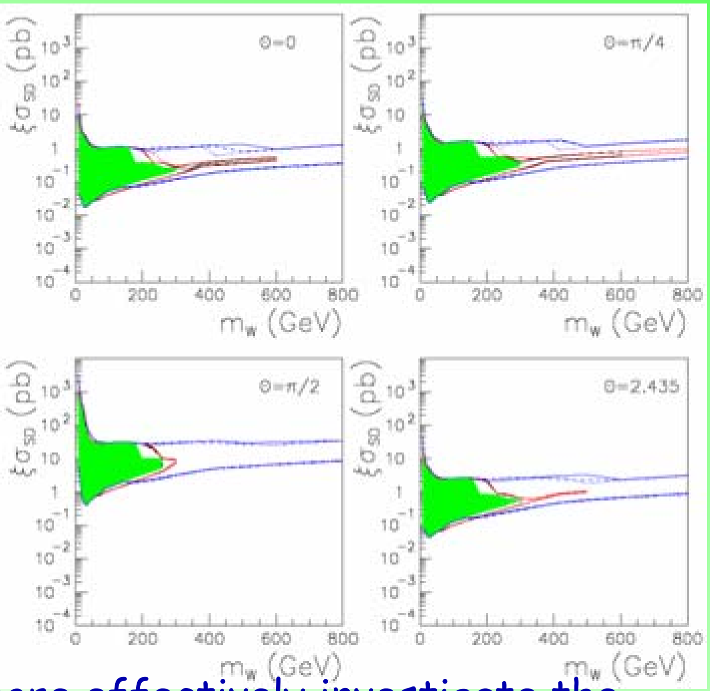
Few examples

pure SI case



green areas:
no SagDEG

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

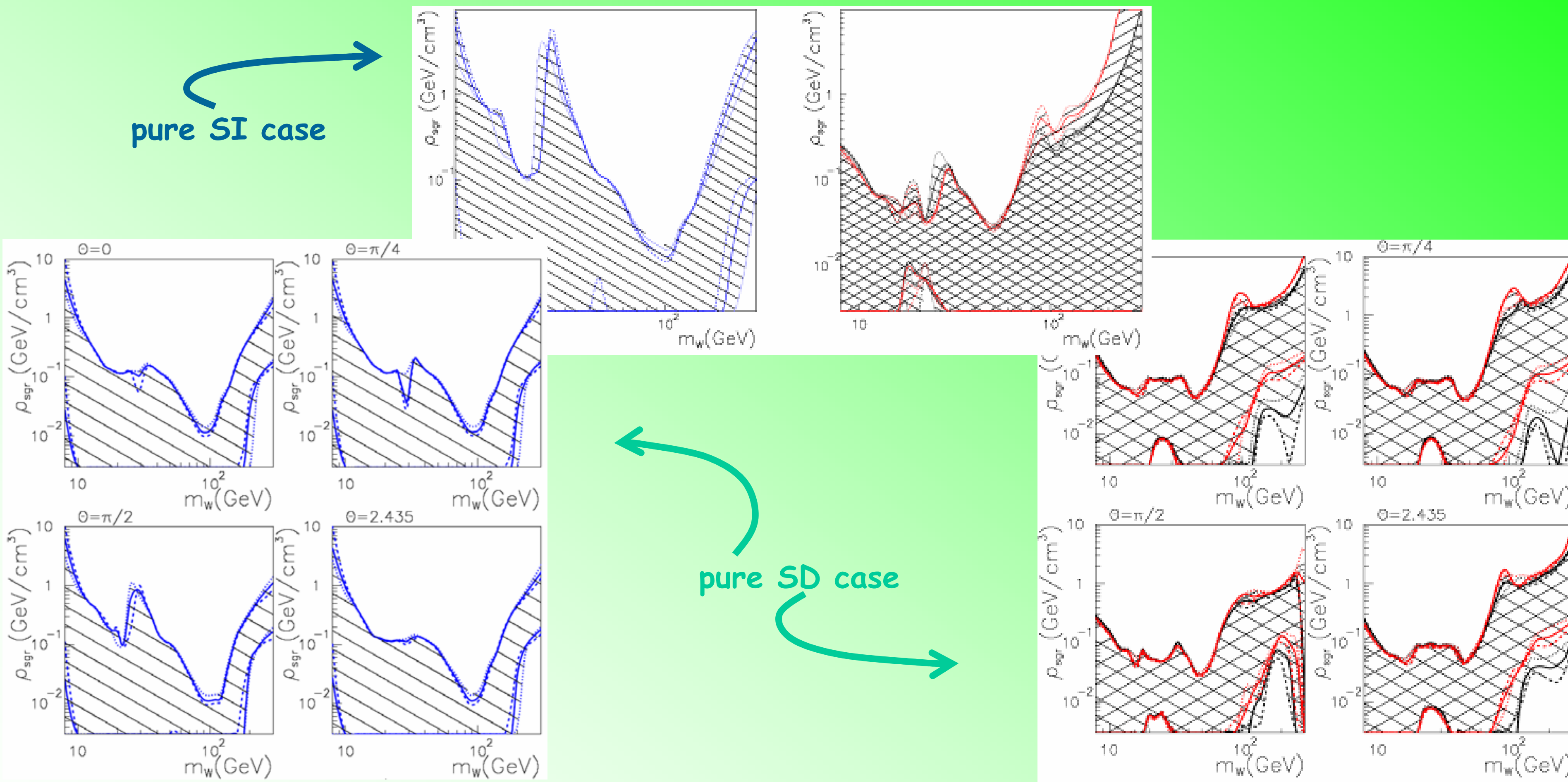


The higher sensitivity of DAMA/LIBRA will allow to more effectively investigate the presence and the contributions of streams in the galactic halo

Constraining the SagDEG stream by DAMA/NaI

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

EPJC47(2006)263



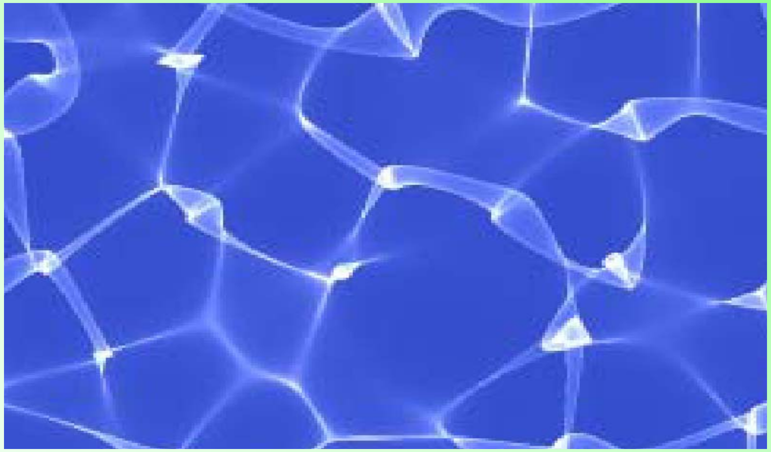
This analysis shows the possibility to investigate local halo features by annual modulation signature already at the level of sensitivity provided by DAMA/NaI, allowing to reach sensitivity to SagDEG density comparable with M/L evaluations.

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

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?

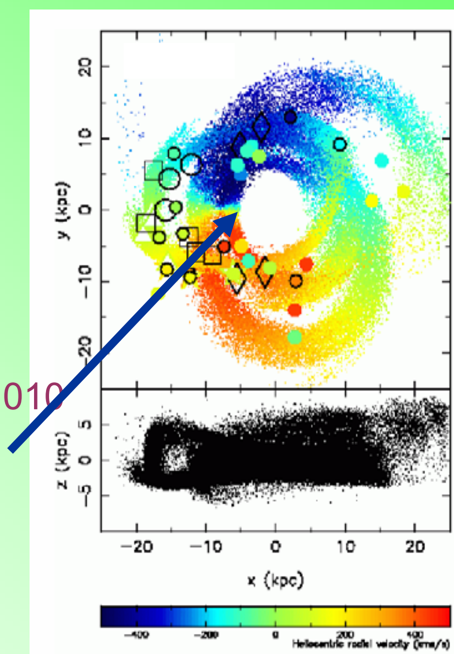
Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

.....very likely....

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

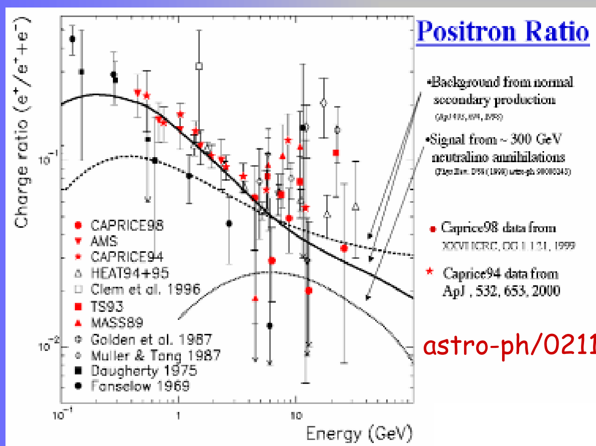
Canis Major simulation:
astro-ph/0311010

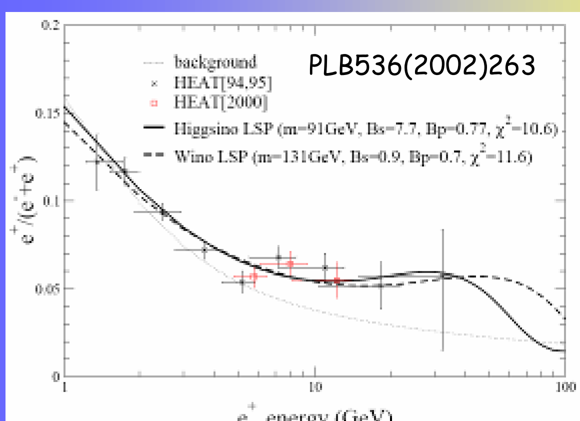
Position of the Sun:
(-8,0,0) kpc



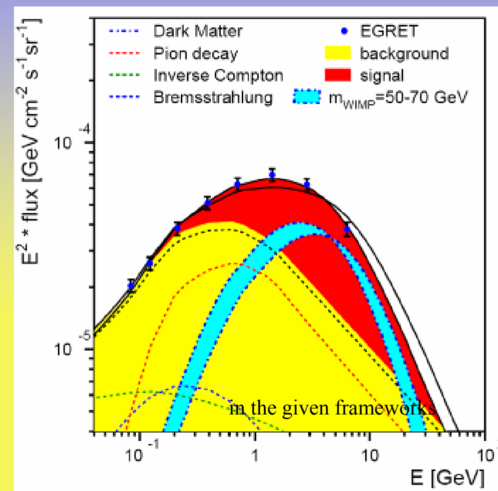
What about the indirect searches of DM particles in the space?

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.



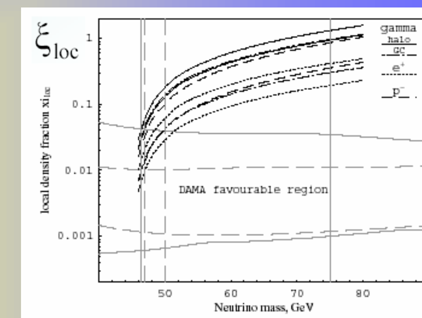


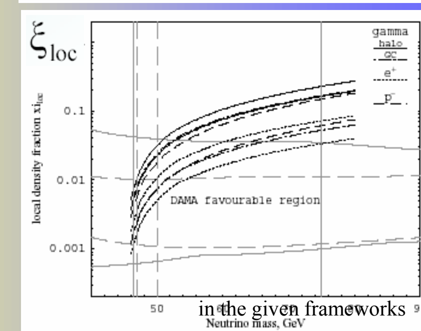
The EGRET Excess of Diffuse Galactic Gamma Rays



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

Example of joint analysis of DAMA/NaI and e^+/γ's excess in the space in the light of two DM particle components in the halo with the presence of a neutrino of 4th family hep-ph/0411093





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

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

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 bosonic 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)

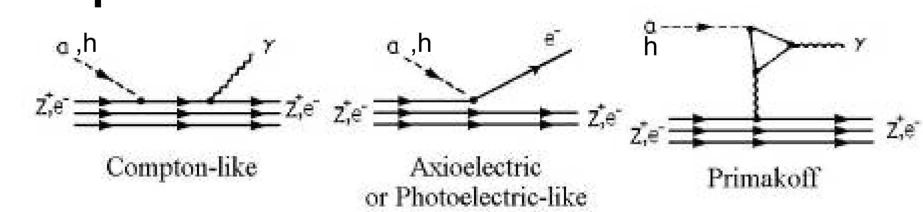
Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants allowed.

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

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

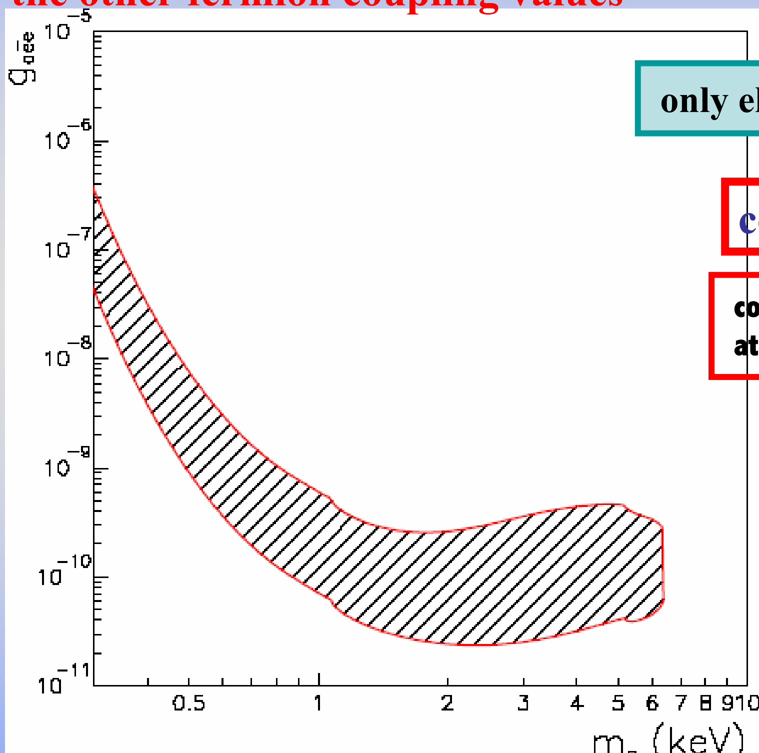
The pseudoscalar case

Analysis of 107731 kg day exposure from DAMA/NaI.

IJMPA21 (2006) 1445

Allowed multi-dimensional volume in the space defined by m_a and all coupling constants to charged fermions (3σ C.L.) in the given frameworks

Axioelectric contribution dominant in all "natural" cases → allowed region **almost independent on the other fermion coupling values**



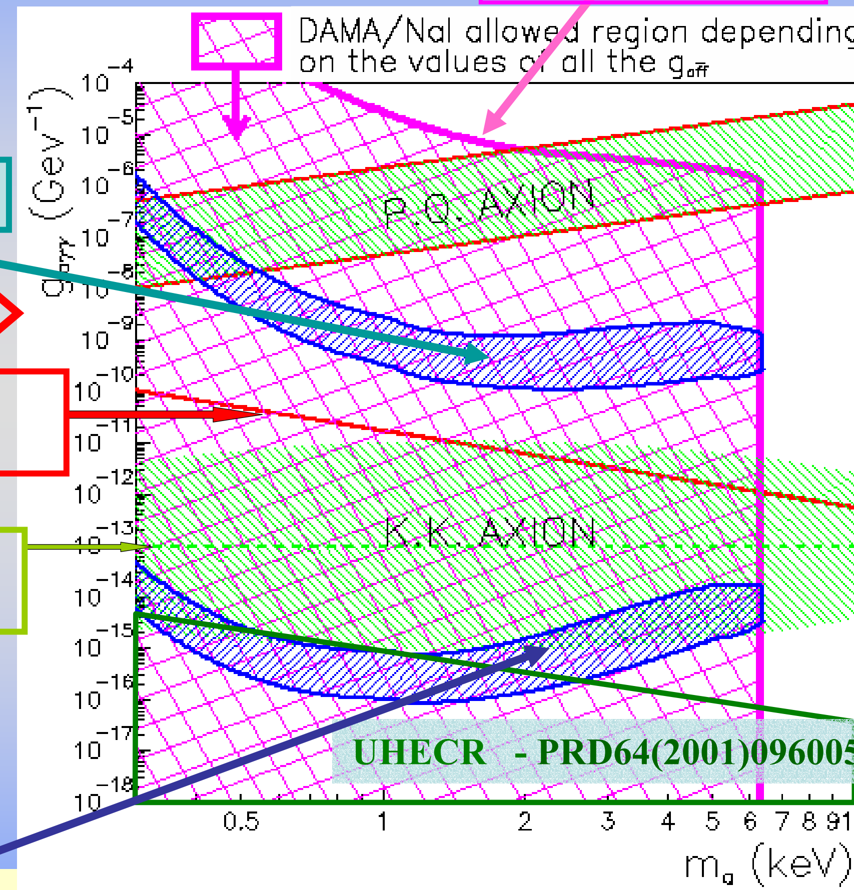
only electron coupling

coupling model

cosmological interest: at least below

Di Lella, Zioutas AP19(2003)145

Maximum allowed photon coupling



Majoron as in PLB99(1981)411; coupling to photons vanish at first order:

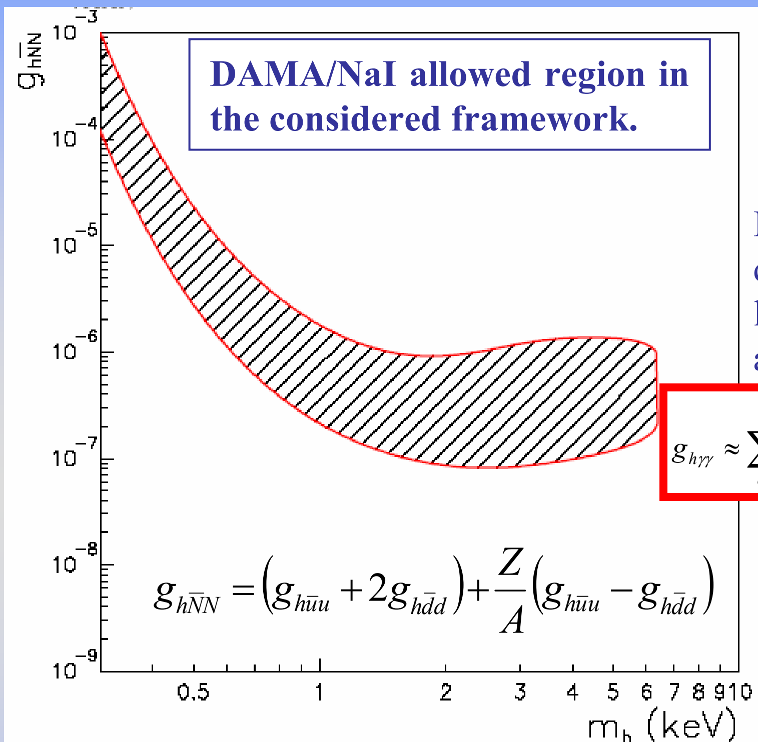
$$g_{a\gamma\gamma} \approx \frac{\alpha}{\pi}\left[\frac{g_{a\bar{e}e}}{m_e} + 3\frac{\frac{1}{9} g_{a\bar{d}d}}{m_d} + 3\frac{\frac{4}{9} g_{a\bar{u}u}}{m_u}\right] \approx 0 \quad \left(\frac{g_{a\bar{e}e}}{m_e} = \frac{g_{a\bar{d}d}}{m_d} = -\frac{g_{a\bar{u}u}}{m_u}\right)$$

Also this can account for the DAMA/NaI observed effect

The scalar case

Allowed multi-dimensional volume in the space defined by m_h and all the coupling constants to charged fermions (3σ C.L.) in the given frameworks

IJMPA21(2006)1445

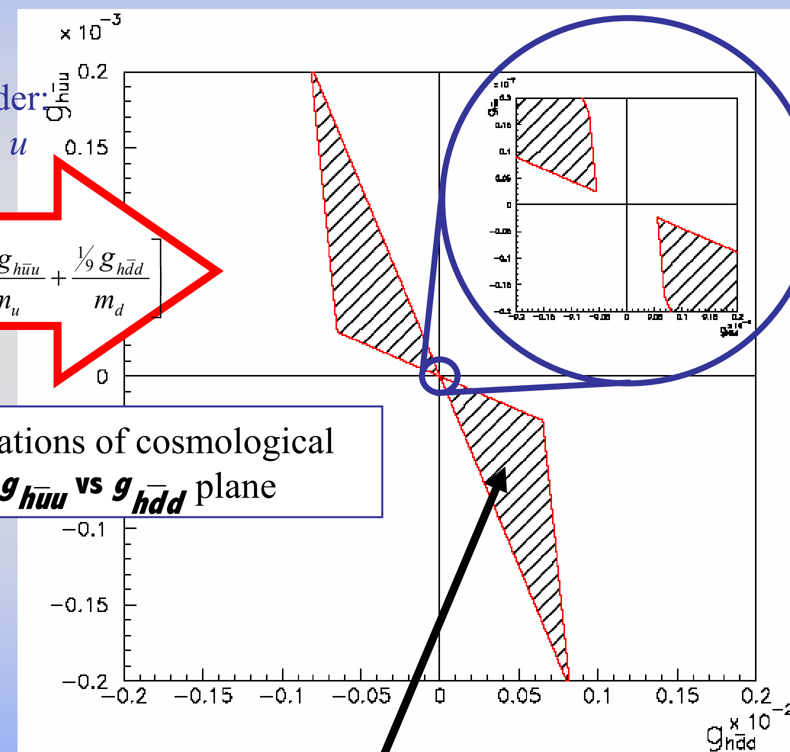


$$g_{h\bar N N} = \left(g_{h\bar u u} + 2 g_{h\bar d d}\right) + \frac{Z}{A}\left(g_{h\bar u u} - g_{h\bar d d}\right)$$

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.)

If all the couplings to quarks of the same order: lifetime dominated by *u* and *d* loops:

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



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

- **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**

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

- 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.

Also this can account for the DAMA/NaI observed effect

Some comparison

The DAMA/NaI result versus other experiments

- ✓ 6.3σ model independent evidence by investigating annual modulation signature with ~100 kg NaI(Tl) detector
- ✓ all the peculiarities of the signature satisfied in 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 modulation amplitude an to contemporaneusly satisfy the many peculiarities of the signature
- ✓ No background rejection procedures applied (sensitivity also to the e.m. radiation component, e.g. axion-like particle)
- ✓ Sensitivity to SI, SD, SI&SD, e.m. interactions + many other kind of interaction and candidate

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

- ✓ model dependent exclusion plots in a single simplified scenario without taking into account the uncertainties of the models in the calculation(isothermal halo model with parameter at fixed value, etc.)
- ✓ Assumptions on nuclear models (scaling laws, FFs, SF), particle physics models + theor. parameters assumed at fixed value
- ✓ Instrumental quantities can play a crucial rule (quenching factors, energy resolution, efficiency, energy threshold, stability of parameter and discimination windows with time, ...)
- ✓ marginal exposure
- ✓ Different target materials used i.e. different sensitivity to the various kinds of candidates, interactions (SI, SD, SI&SD, inlelastic DM, light boson ,...) and particle mass
- ✓ Consider that large differences in the measured counting rate can be expected, for example:

  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)
- ✓ When the e.m. component of the counting rate not accounted (discrimination, rejection, selection procedures), e.g.:

  Candidates producing e.m. radiation in the interaction completely lost (no sensitivity to candidates such as e.g. light bosons)

generally they present the DAMA/NaI implications in an uncorrect, not-updated and partial way

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 perspectives

DAMA/LIBRA (~250kg NaI(Tl)), running since 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

… wait for an exposure larger than DAMA/NaI

...and beyond?

- R&D-III approved and funded by INFN towards a possible multi-purpose NaI(Tl) ton set-up we proposed in 1996 → *work in progress*

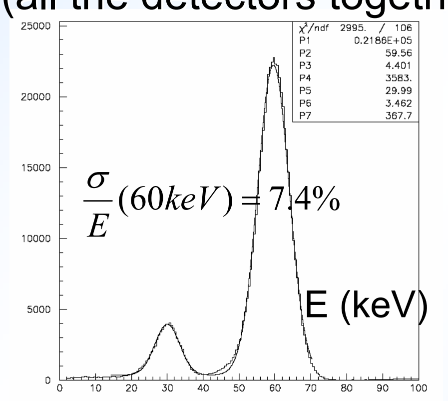
Some infos about DAMA/LIBRA data acquisition

DAMA/LIBRA in operation since March 2003

e.g. up to March 2006: exposure: of order of 10^5 kg x d
overall sources' data: of order of 4 x 10^7 events

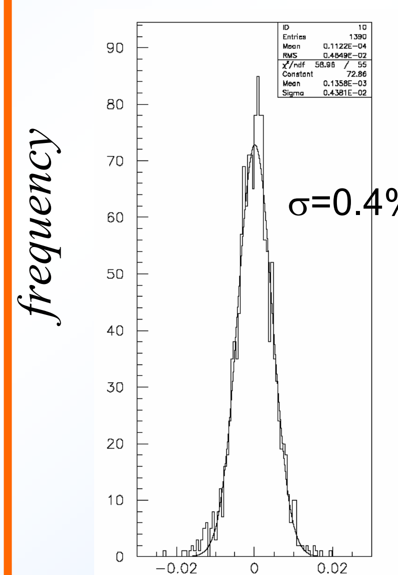
Few examples of operational features (here from March 2003 to August 2005):

^{241}Am routine calibrations (all the detectors together)

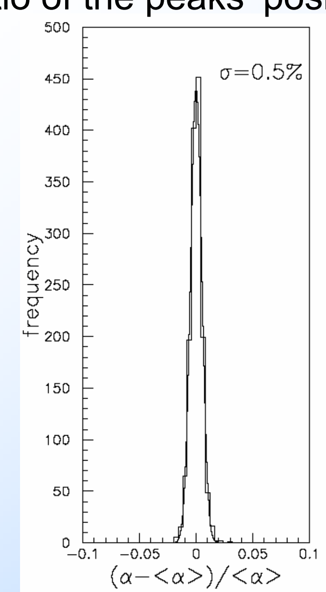


Stability of the low energy calibration factors

ratio of the peaks' positions

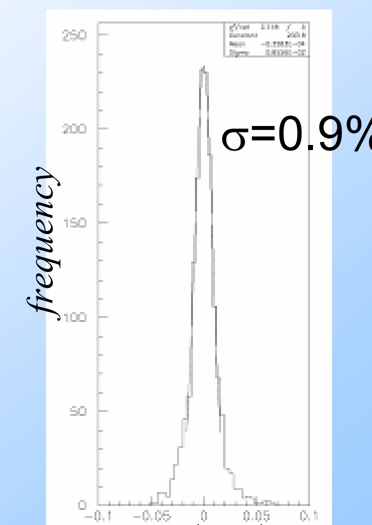


$$\frac{tdcal - \langle tdcal \rangle}{\langle tdcal \rangle}$$



$$\langle \alpha \rangle \approx 2$$

Stability of the high energy calibration factors



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

Summary

DAMA/NaI data show a 6.3σ C.L. model independent evidence for the presence of a Dark Matter particle component in the galactic halo

Corollary model dependent quests for the candidate particle:

- WIMP particles with m_W~ (few GeV to TeV) with coupling pure SI or pure SD or mixed SI/SD as well as particles with preferred inelastic scattering
  (Riv.N.Cim. 26 n.1. (2003) 1-73, IJMPD 13 (2004) 2127)
- several other particles suggested in literature by various authors
  (see literature)
- bosonic particles with m_a~ keV having pseudoscalar, scalar coupling
  (IJMPA21(2006)1445)
- halo substructures (SagDEG) effects (EPJC 47 (2006) 263)
- other possibilities given in literature

→ more in progress...

DAMA/LIBRA:

→ in data taking since March 2003 (collected more than 10^5 kg·d)
→ 1st data release foreseen not later than end of 2008
→ will further investigate the nature of the candidate and the phase space structure of the dark halo and the possible presence of multicomponents

... wait for more in the near future