R. Cerulli
Univ. Tor Vergata
and INFN-Roma2

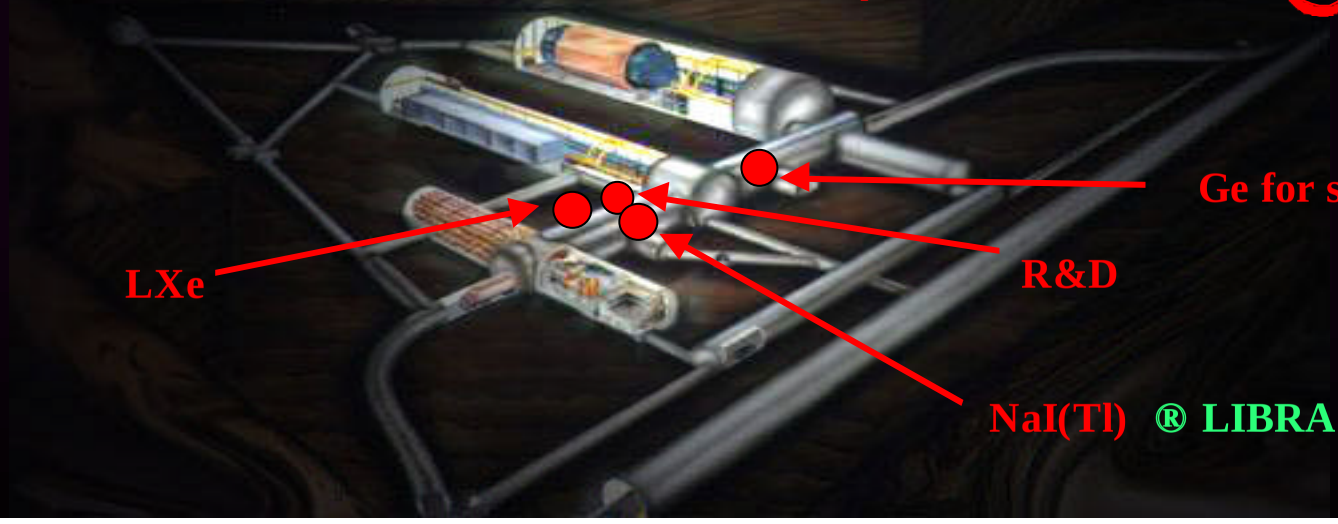
DAMA results and perspective for LIBRA

DAMA coll.
Roma2, Roma, IHEP/Beijing

see also DAMA site on: www.lngs.infn.it

COSMO-02
Chicago, Illinois, USA
September, 2002

DAMA: an observatory for rare processes @LNGS



Recent DAMA activities

Dark Matter

- Annual modulation see later
- Upper limits on recoils from PSD with NaI(Tl) PLB389(1996)757
- Upper limits on recoils from PSD with LXe PLB436(1998)379
- Investigation of diurnal variation of rate: N.Cim.A112(1999)1541
- New limits on SIMP search PRL83(1999)4918
- New limits on the flux of neutral nuclearites PRL83(1999)4918
- New limits on SD WIMPs with CaF_2(Eu) NPB563(1999)97
- New limits on inelastic scattering in LXe NJP2(2000)15.1
- New measurements of light response to recoils in LXe EPJdirect C11(2001)1

Other searches

new limits on:

- nuclear level excitation of ^{129}Xe during CNC processes PLB465(1999)315
- 2β in ^{40}Ca and ^{46}Ca using CaF_2(Eu) NPB563(1999)97
- nuclear level excitation of ^{127}I and ^{23}Na during CNC processes PRC60(1999)065501
- electron stability and non-paulian transitions in Iodine atoms PLB460(1999)235
- $2\beta^+$ in ^{106}Cd Astr.Phys.10 (1999), 115
- electron decay $e^- \rightarrow \nu_e \gamma$ using LXe PRD61(2000)117301
- nucleon and di-nucleon decay into invisible channels PLB493(2000)12
- solar axions in NaI crystals PLB515(2001)6
- 2β decay in ^{136}Xe ROM2F/2001/26
- 2β decay in ^{134}Xe PLB527(2002)182
- β and 2β decays in ^{48}Ca NPA705 (2002)29
- Q-balls search EPJdirect C14(2002)1

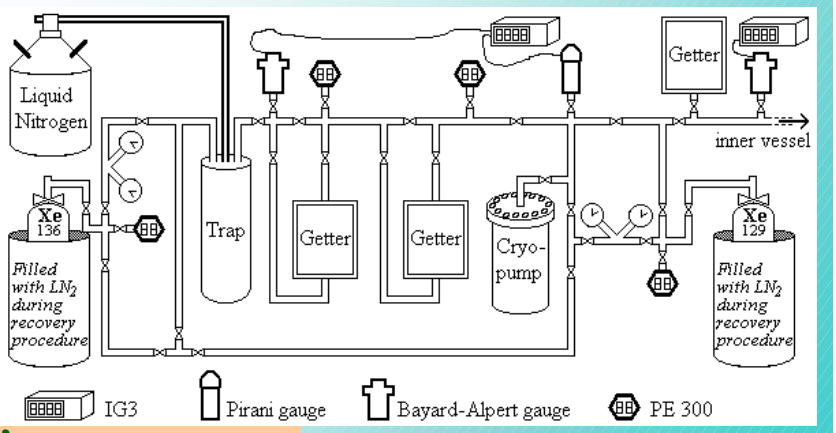
LXe set-up

Details on: NIM A 482 (2002) 728

- Detector specifically studied for low radioactive experiment
- ~6.5 kg LXe (≈ 2 l volume)
- Kr-free Xenon gas enriched in ^{129}Xe at 99.5% or, alternatively, in ^{136}Xe at 68.8%
- Inner vessel: OFHC low-radioactivity Copper ≤ 100 μBq/kg of U/Th and ≤ 310 μBq/kg of K.
- Three PMTs (Electron Tubes) with MgF_2 windows; quantum efficiency 18-32% @ 175 nm

- Windows in cultured crystal quartz (LXe UV light trasmission ≈ 80%)
- Low background shield: Cu in and outside the vacuum cell; 15 cm Pb; n-shield. Radon removal system: sealed plexiglas box.

vacuum/filling/purification/recovery line



Achieved results: **elastic scattering WIMP-^{129}Xe; PSD; inelastic scattering WIMP-^{129}Xe, charge non-conserving processes; nucleon and di-nucleon stability (new approach); search for bb decay in ^{136}Xe and in ^{134}Xe; measurement of quenching factor at ENEA neutron generator**

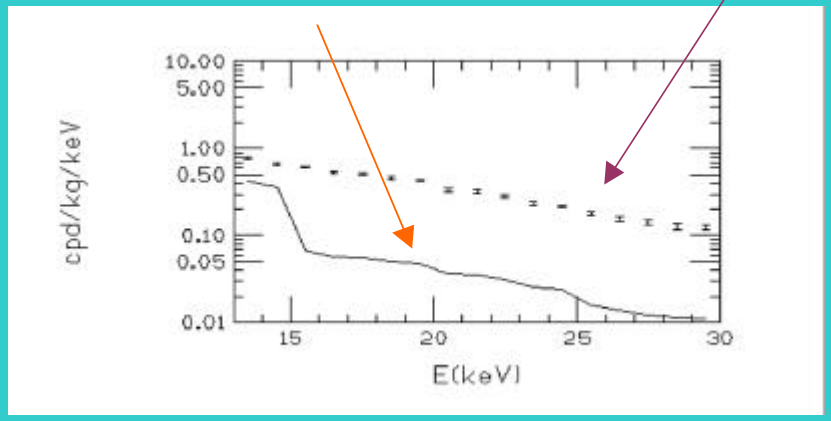
Now running with Kr-free Xe enriched in ^{136}Xe

LXe: DARK Matter search

A) Limits on recoils investigating the WIMP-^{129}Xe elastic scattering by means of Pulse Shape Discrimination

PLB436 (1998)379

measured upper limits on recoils — **total rate**

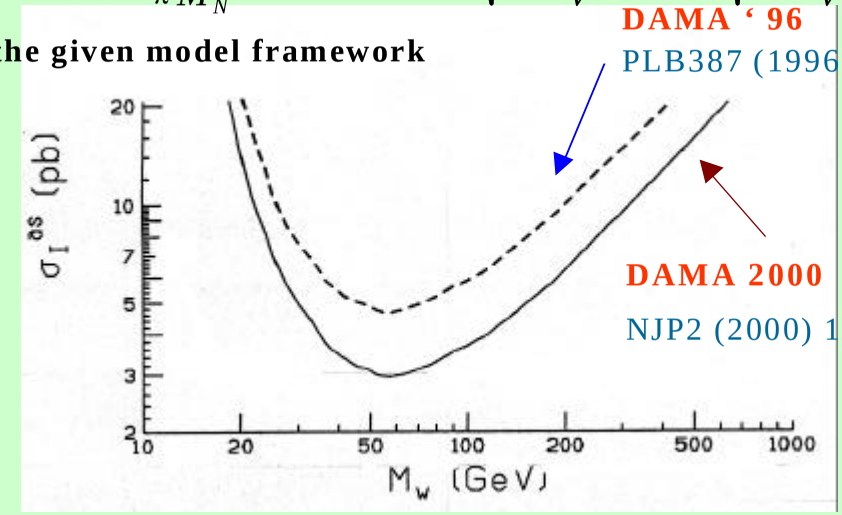


B) Limits on WIMP-^{129}Xe inelastic scattering

Search for characteristic peak (39.58 keV) in the measured energy spectrum as a result of emission of successive de-excitation g from the excited nuclear states.

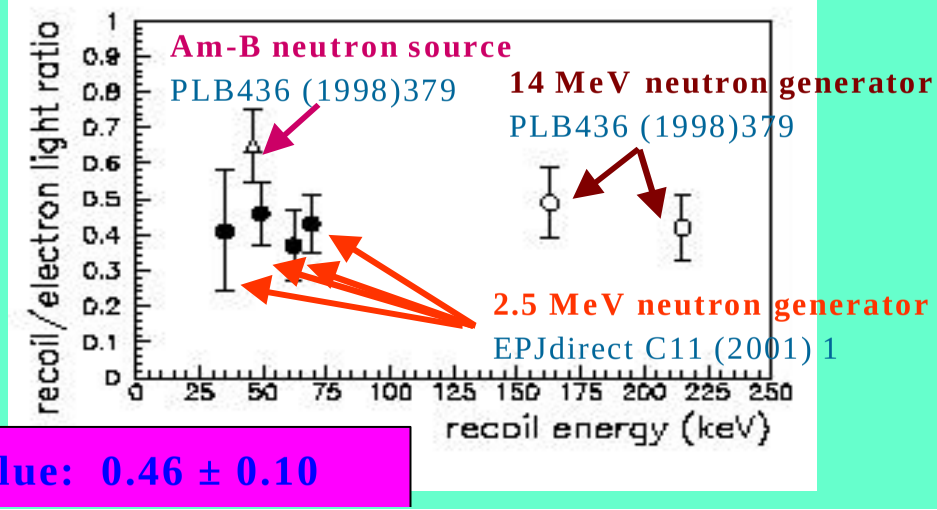
$$\sigma_I(v) = \frac{\mu^2}{\pi M_N} \langle N^* | M | N \rangle^2 \sqrt{1 - \frac{v_{thr}^2}{v^2}} = \sigma_I^{as} \sqrt{1 - \frac{v_{thr}^2}{v^2}}$$

for the given model framework

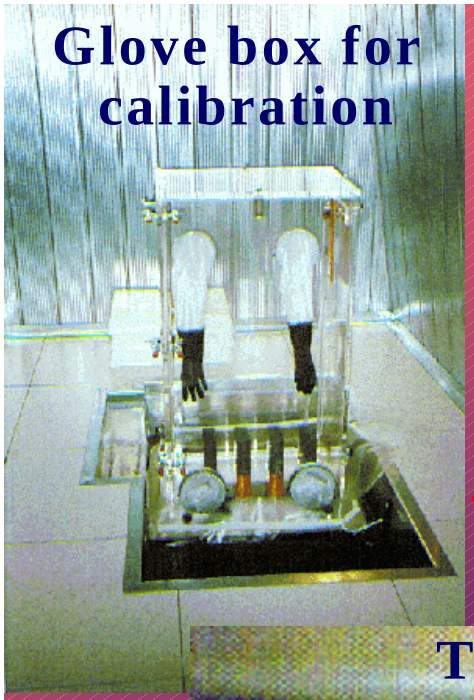


C) Neutron calibration

The ratio of the measured amount of light from a recoil nucleus to the amount of light from an electron of the same kinetic energy in a pure liquid Xenon scintillators as the one of DAMA experiment has been measured in 1998 both by using an Americium-Boron neutron source and by detecting scattered neutrons at fixed angles using the 14 MeV ENEA-Frascati neutron generator. In 2000/2001 measurements have been repeated at fixed scattering angles by using the 2.5 MeV ENEA-Frascati neutron generator.

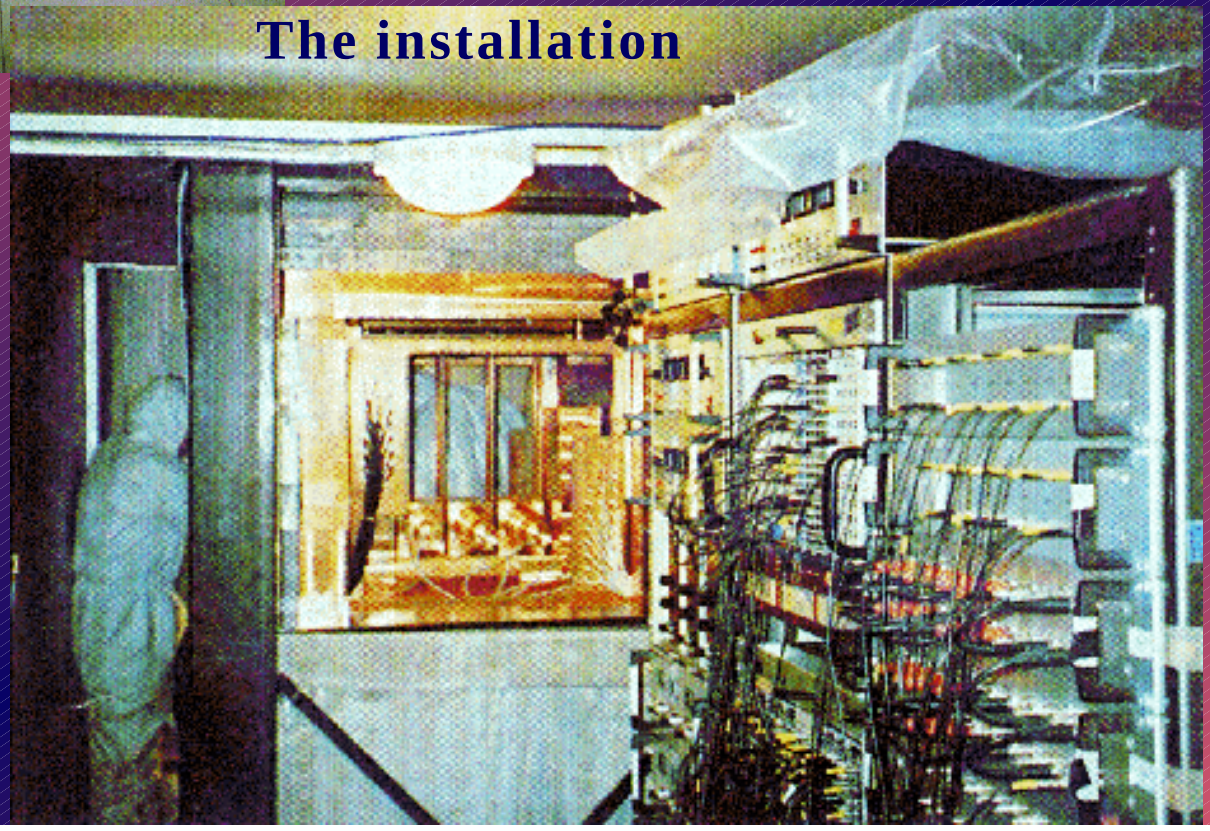


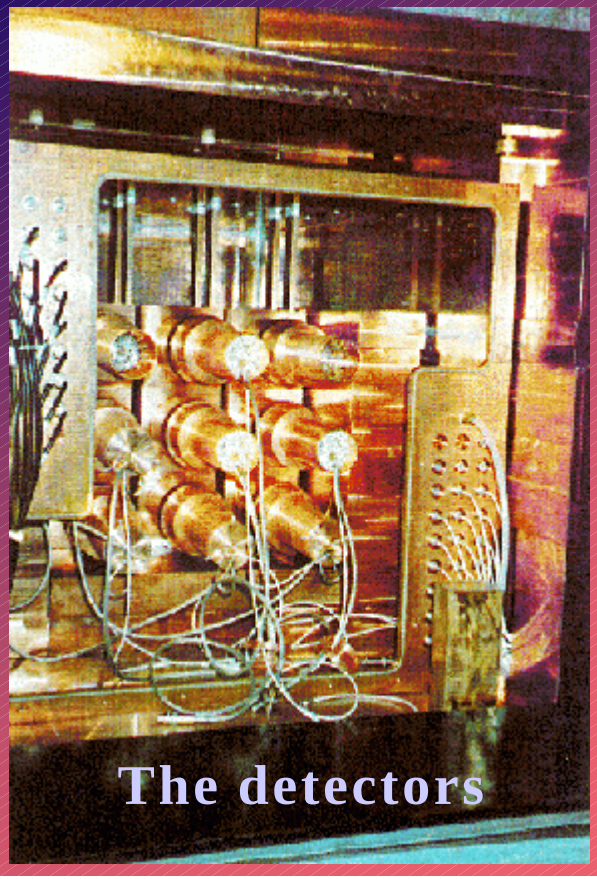
Overall averaged value: 0.46 ± 0.10



Experimental details on
Il N. Cim.A112(1999)545

The ~100 kg NaI(Tl) set-up

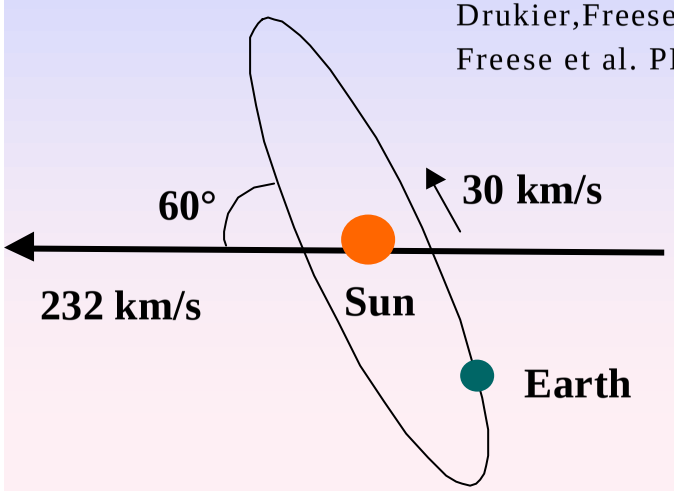




Identifying signal from the WIMP *wind*

Annual modulation of the rate

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)
- g = p/3
- w = 2p/T T = 1 year
- t_0 = 2nd June (when v_A is maximum)

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

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

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 in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7%

To mimic this signature, the spurious effects and side reactions must satisfy contemporaneously all these 6 requirements

The data released so far for the annual modulation search

PERIOD	STATISTICS (kg ·day)	REFERENCES
DAMA/NaI-1	3363.8 winter + 1185.2 summer	PLB424(1998)195
DAMA/NaI-2	14962 ~ November to end of July	PLB450(1999)440 + PRD61(1999)023512
DAMA/NaI-3	22455 ~middle August to end September	PLB480(2000) 23
DAMA/NaI-4	16020 ~middle October to second half August	idem
TOTAL STATISTICS	57986	idem + PLB509(2001) 197 EPJ C18 (2000)283 EPJ C 23 (2002)61 PRD66(2002)043503
+ DAMA/NaI-0 **(properly included in the cumulative result)**	limits on recoil fraction by PSD	PLB389(1996) 757

SI case v_{rms}=270 km/s

extension for uncertainties on velocities, also bulk halo rotation

SI + SD case
Invest. on syst.
Inelastic case
Halo models

The model independent result

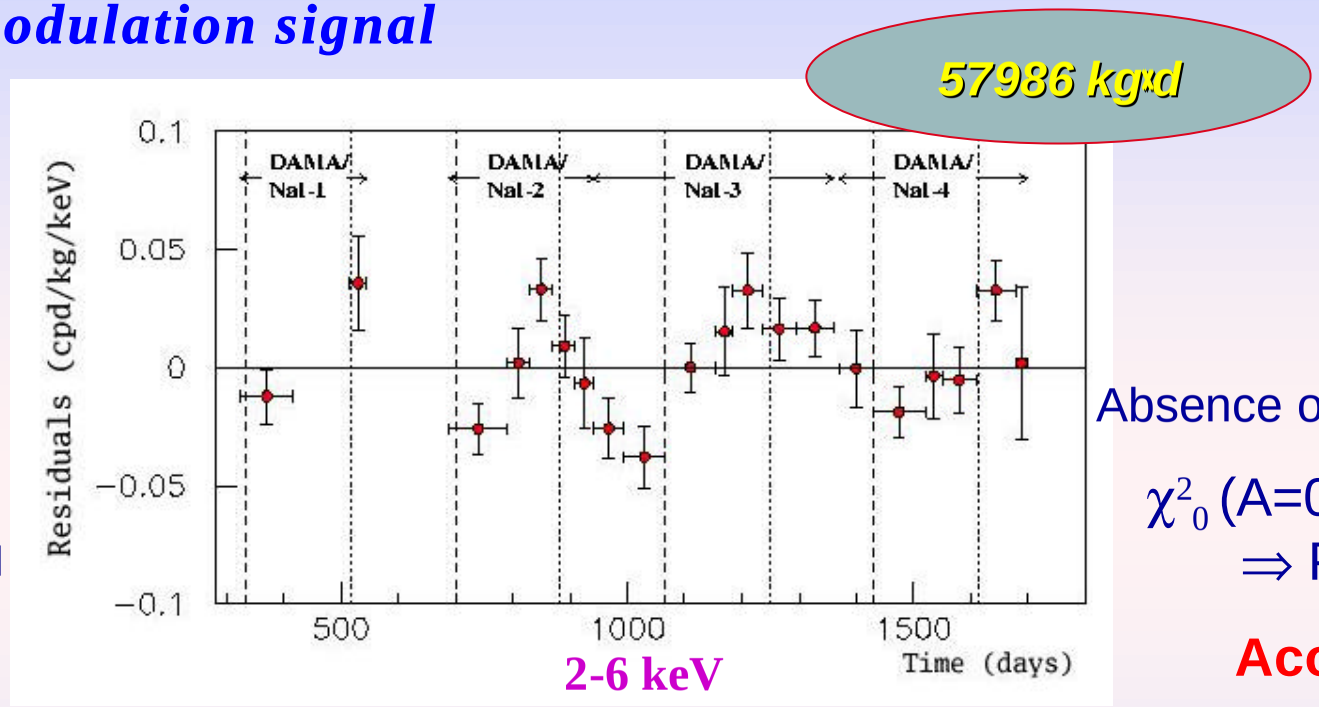
✓ **The quest for model independent signature:** ***evidence from WIMP annual modulation signal***

PLB424(1998)195
PLB450(1999)440
PRD61(1999)023512
PLB480(2000)23
PLB509(2001)197
EPJ C18(2000)283
EPJ C23 (2002)61
PRD66(2002)043503

--- **expected minimum**

… **expected maximum**

Experimental point



Absence of modulation:

χ^2_0 (A=0)/dof = 48/20

$\Rightarrow$ P = $4 \cdot 10^{-4}$

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

1) t_0 **= 152,5 days (fixed)**

A=(0.022±0.005) cpd/kg/keV

T=2p/w=(1.00± 0.01) years

c^2/dof= 23/18

2) T = 1 years (fixed)

A = (0.023 ± 0.005) cpd/kg/keV

t_0 = (144 ± 13) days

c^2/dof= 23/18

If all the 3 parameters kept free, similar values with slightly larger errors

- **All the peculiarities of the signature satisfied.**
- **Presence of the annual modulation signal with the proper distinctive features for a WIMP induced effect**
- **No systematic or side reaction able to mimic the signature found**

Presence of annual modulation with characteristics of a WIMP candidate

POSSIBLE SYSTEMATICS ? NO

Eur. Phys. J. C18 (2000), 283

RADON	Sealed Cu box in HP Nitrogen atmosphere	**<0.2% S_m^{obs}**
TEMPERATURE	The installation is air-conditioned	**<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 found in energy regions above 6keV	**<0.5% S_m^{obs}**
SIDE REACTIONS	Muon flux modulation by MACRO	**<0.3% S_m^{obs}**

+ even if larger they cannot satisfy all the 6 requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

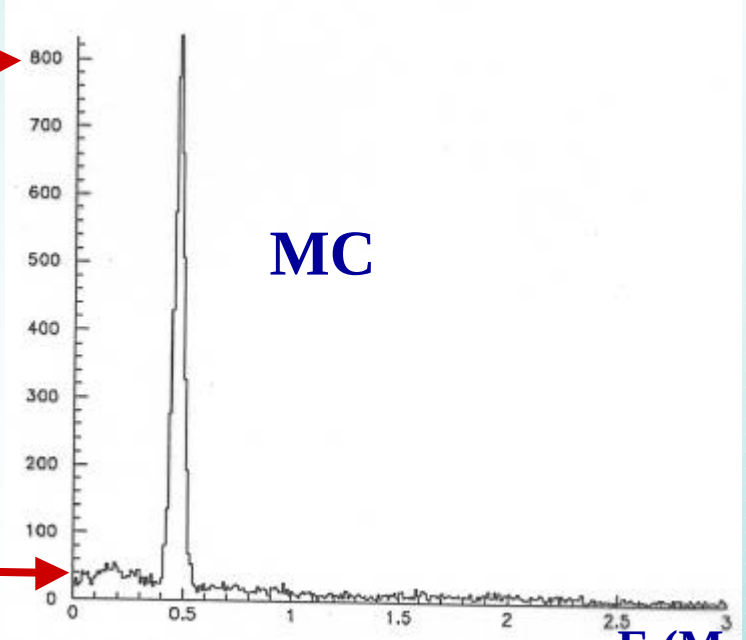
Can a possible thermal neutron modulation account for the observed effect?

Ex.: $^{23}Na(n,g)^{24}Na$; $^{23}Na(n,g)^{24m}Na$

capture rate = $\Phi_n\ \sigma_n\ N_T$ = 0.17 captures/d/kg $\Phi_n/(10^{-6}$ n cm^{-2} s$^{-1})$

$1.4\times10^{-3}\,cpd/kg/keV/\left(10^{-6}\,\frac{n}{cm^2 s}\right)$

$7.0\times10^{-5}\,cpd/kg/keV/\left(10^{-6}\,\frac{n}{cm^2 s}\right)$



E (MeV)

Thermal neutron flux @ LNGS:

F_n = 1.08 10^{-6} n cm^{-2} s^{-1} (N.Cim.A101(1989),959)

F_n < 5.9 10^{-6} n cm^{-2} s^{-1} (in the DAMA set-up from delayed coincidences see **N.Cim.A112(1999),545)**

Assuming - very cautiously - a 10% thermal neutron modulation:

⇓

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

NO

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

Excluded by R_{90} analysis

To investigate the nature and coupling with ordinary matter of the possible WIMP candidate, an effective energy and time correlation analysis has to be performed within given model frameworks

BUT

uncertainties on models and comparisons:

r_W

WIMP velocity distribution: $f(\vec{v})$

parameters of $f(\vec{v})$ (in the usual case: v_0 and v_{esc})

couplings: SI, SD, mixed, inelastic, ...

scaling laws on cross sections

SI and SD form factors

parameters of the form factors (in the usual case: r,s,b)

etc.

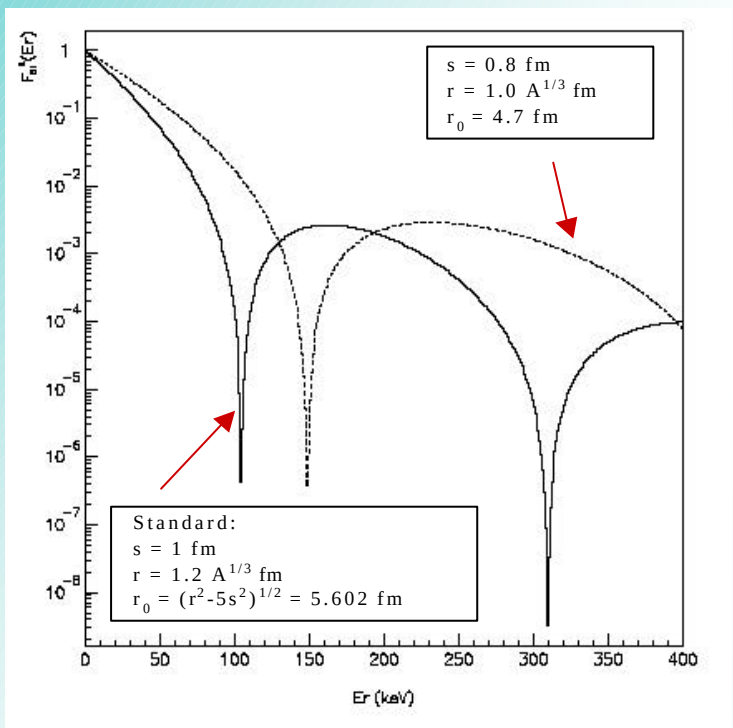
They can affect not only the annual modulation region but also the exclusion plots

experimental parameters (typical of each experiment)

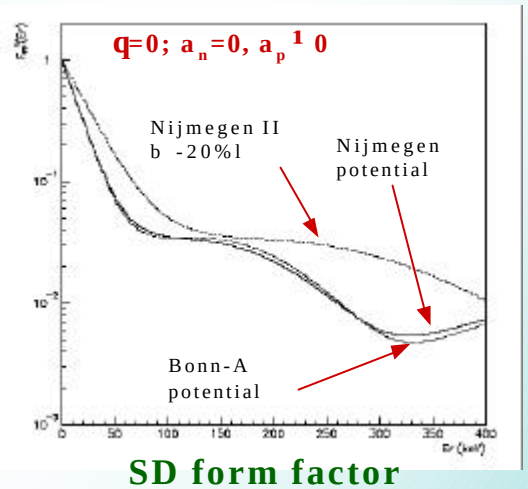
comparison within particle models

The Form Factors

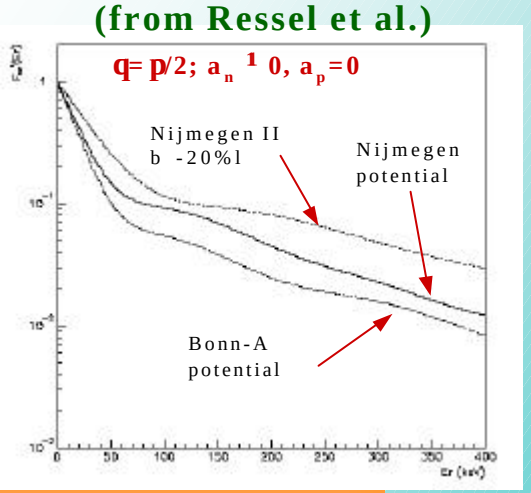
- **Take into account the structure of target nuclei**
- **In SD form factor: no decoupling between nuclear and WIMP degrees of freedom; dependence on nuclear potential.**
- **Example on ^{127}I nucleus:**



SI form factor (from Helm et al.)



SD form factor (from Ressel et al.)



Target-nucleus	$l^2J(J+1)$ single particle	$l^2J(J+1)$ odd group	$l^2J(J+1)$ from Ressel et al.	Comment
^{29}Si	0.750	0.063		Neutron is unpaired nucleon
^{73}Ge	0.306	0.065	0.103	
^{129}Xe	0.750	0.124	0.229 or 0.177	
^{131}Xe	0.150	0.055		
^{1}H	0.750	0.750		Proton is unpaired nucleon
^{19}F	0.750	0.647		
^{23}Na	0.350	0.041	0.089	
^{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	0.084 or 0.126	

1st Model Framework (improved with time)

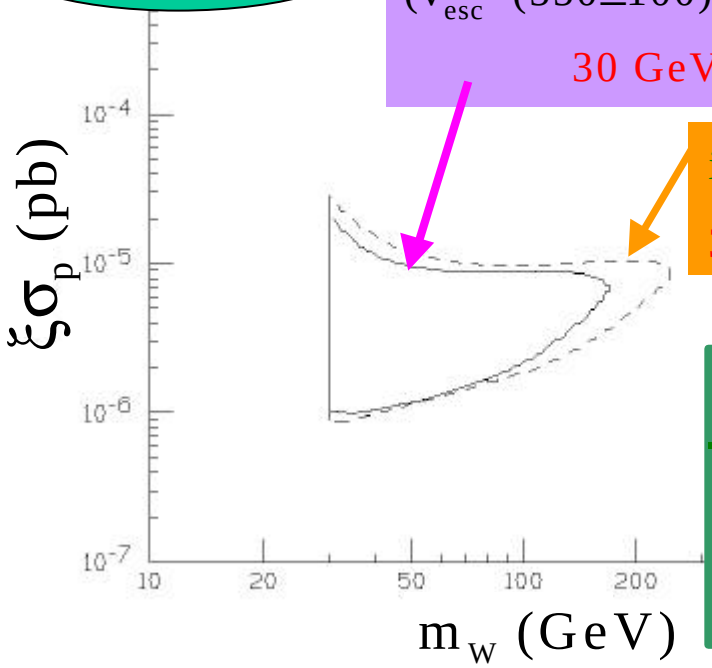
PLB480(2000) 23
PRD61(1999) 023512
PLB450(1999) 448
PLB424(1998) 195

- $x = r_W/(0.3\ \mathrm{GeV\ cm^{-3}})$
- isothermal, maxwellian WIMP velocity distribution
- v_0 = 220 km/s and v_{esc} = 650 km/s
  then accounting for v_0 and v_{esc} uncertainties
- only SI
- $s \mu m^2 A^2$
- Helm SI form factor with $r = 1.2\ A^{1/3}$fm, s = 1fm
- parameters at fixed values
- physical constraints: $m_W > 30$ GeV
  then accounting for limit on recoils from PSD

DAMA/NaI-0 to 4

$v_0 = (220 \pm 50)$ km/s (90% C.L.)
(v_{esc}=(550±100)km/s (90% C.L.) ←negligible effect)
30 GeV ≤ m_W ≤ 105 GeV (1σ C.L.)

including possible Dark halo rotation
30 GeV ≤ m_W ≤ 132 GeV (1σ C.L.)



v_0 (km/s)	m_W(GeV)	$\xi\sigma_p$(pb)
170	72^{+18}_{-15}	$(5.7\pm1.1)\cdot10^{-6}$
220	43^{+12}_{-9}	$(5.4\pm1.0)\cdot10^{-6}$
270	32^{+8}_{-7}	$(5.7^{+1.2}_{-1.1})\cdot10^{-6}$

Here other parameters, etc. at fixed values + assumptions ® larger allowed region

Furthermore: ***investigation of the effect of halo models, WIMP velocity distributions, uncertainties associated to all experimental and theoretical parameters.***

→ **see later + comment on FF in PLB480(2000)23 + etc.**

Consistent halo models

Interest on approaches different from the isothermal sphere model: Belli et al. PRD61(2000)023512; Vergados PR83(1998)3597, PRD62 (2000)023519; Ullio & Kamionkowski JHEP03(2001)049; Green PRD63(2001) 043005, Vergados & Owen astro-ph/0203293.

Quantitative approach on DAMA/NaI0-4 data:

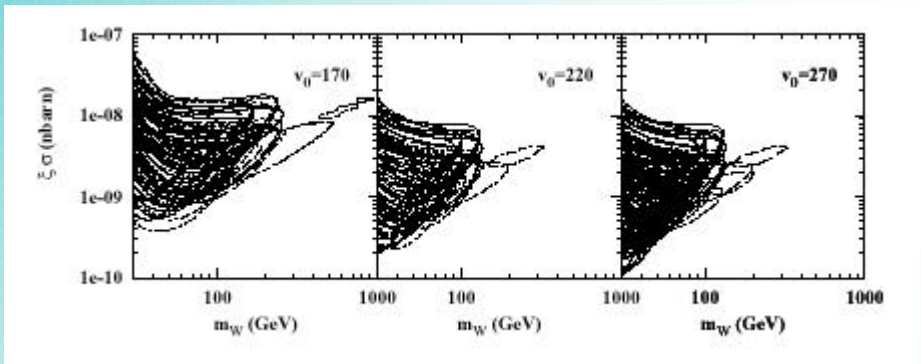
- purely SI coupling
- for the other assumptions see before

Belli,Cerulli,Fornengo,Scopel PRD66(2002)043503

Class A: Spherical ρ_{DM}, isotropic velocity dispersion		
A0	Isothermal sphere	
A1	Evans' logarithmic [15]	$R_c=5$ kpc
A2	Evans' power-law [16]	$R_c=16$ kpc, $\beta=0.7$
A3	Evans' power-law [16]	$R_c=2$ kpc, $\beta=-0.1$
A4	Jaffe [14]	$\alpha=1$ $\beta=4$ $\gamma=2$ a = 160 kpc
A5	NFW [18]	$\alpha=1$ $\beta=3$ $\gamma=1$ a = 20 kpc
A6	Moore *et al.* [19]	$\alpha=1.5$ $\beta=3$ $\gamma=1.5$ a = 28 kpc
A7	Kravtsov *et al.* [20]	$\alpha=2$ $\beta=3$ $\gamma=0.4$ 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} [17] (q=0.8, p=0.9)		
D1	Earth on major axis, radial anisotropy	$\delta=-1.78$
D2	Earth on major axis, tangential anis.	$\delta=16$
D3	Earth on intermediate axis, radial anis.	$\delta=-1.78$
D4	Earth on intermediate axis, tangential anis.	$\delta=16$

Summary of the results

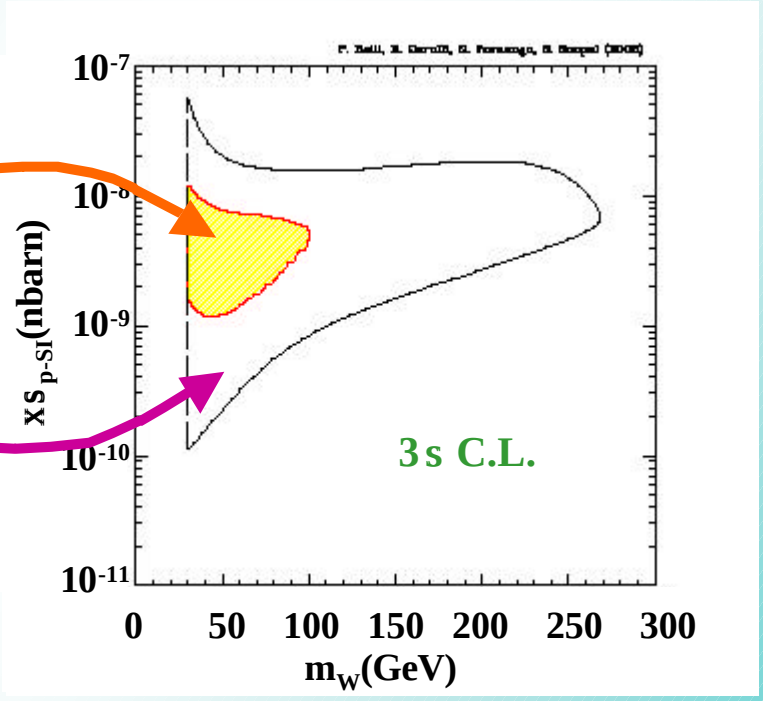
- 3-s modulation regions of all the models considered in the analysis plotted jointly



- Convolution of all the regions allowed obtained considering non-rotating models. The region is compared with the 3-s annual modulation region allowed by the DAMA experiment for an isothermal sphere halo with v_0=220 km/s

DAMA annual modulation region for an isothermal sphere halo with v_0=220 km/s

Convolution of all regions allowed for non rotating models



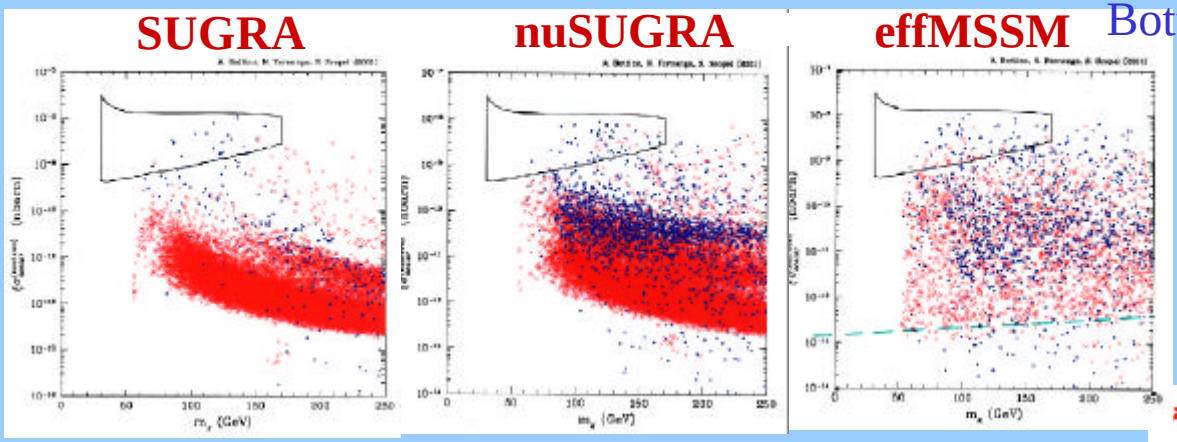
Allowed region:

- up to m_W @ 270 GeV
- few ´ 10^{-10} nbarn < $x s_p$ < 2 ´ 10^{-8} nbarn

If uncertainties on the parameters in the *model-dependent* analysis are considered, the allowed region is further enlarged

...and theories

Bottino et al.

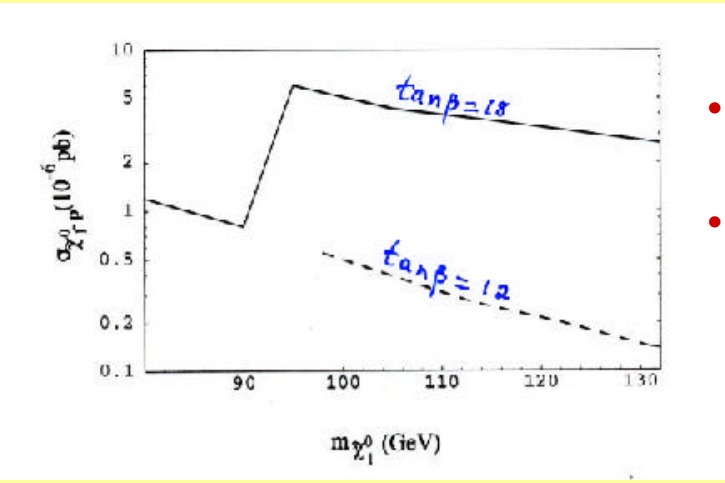


× $\Omega_\chi h^2 > 0.05$

• $\Omega_\chi h^2 < 0.05$

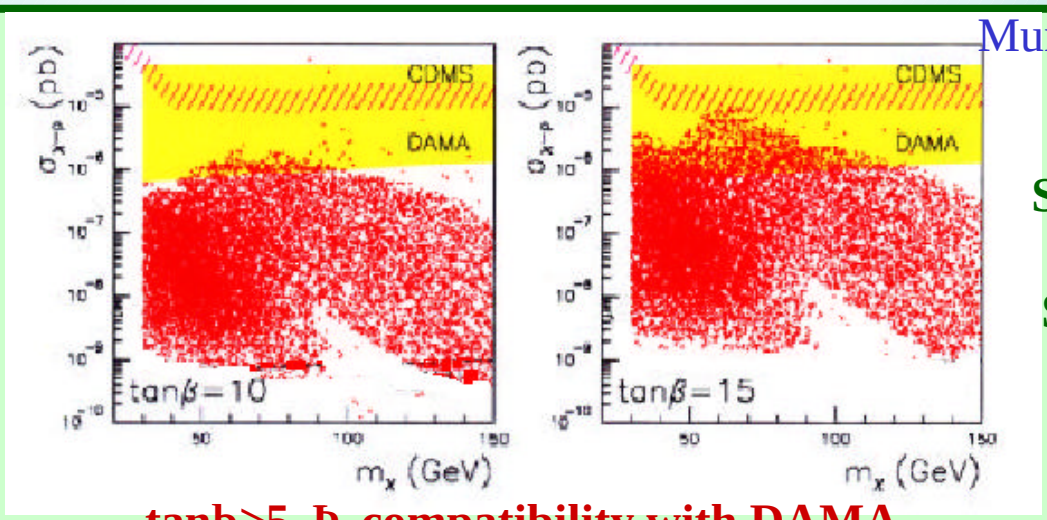
scatter plots do not represent the density of probability

Arnowitt, Cosmo01



- ***nuSUGRA*: tanb>15 Þ compatibility with DAMA**
- ***SUGRA*: tanb>50 Þ possible compatibility with DAMA (strongly dependence on m_t and m_b)**

Munoz, Cosmo01



Supergravity & Superstrings

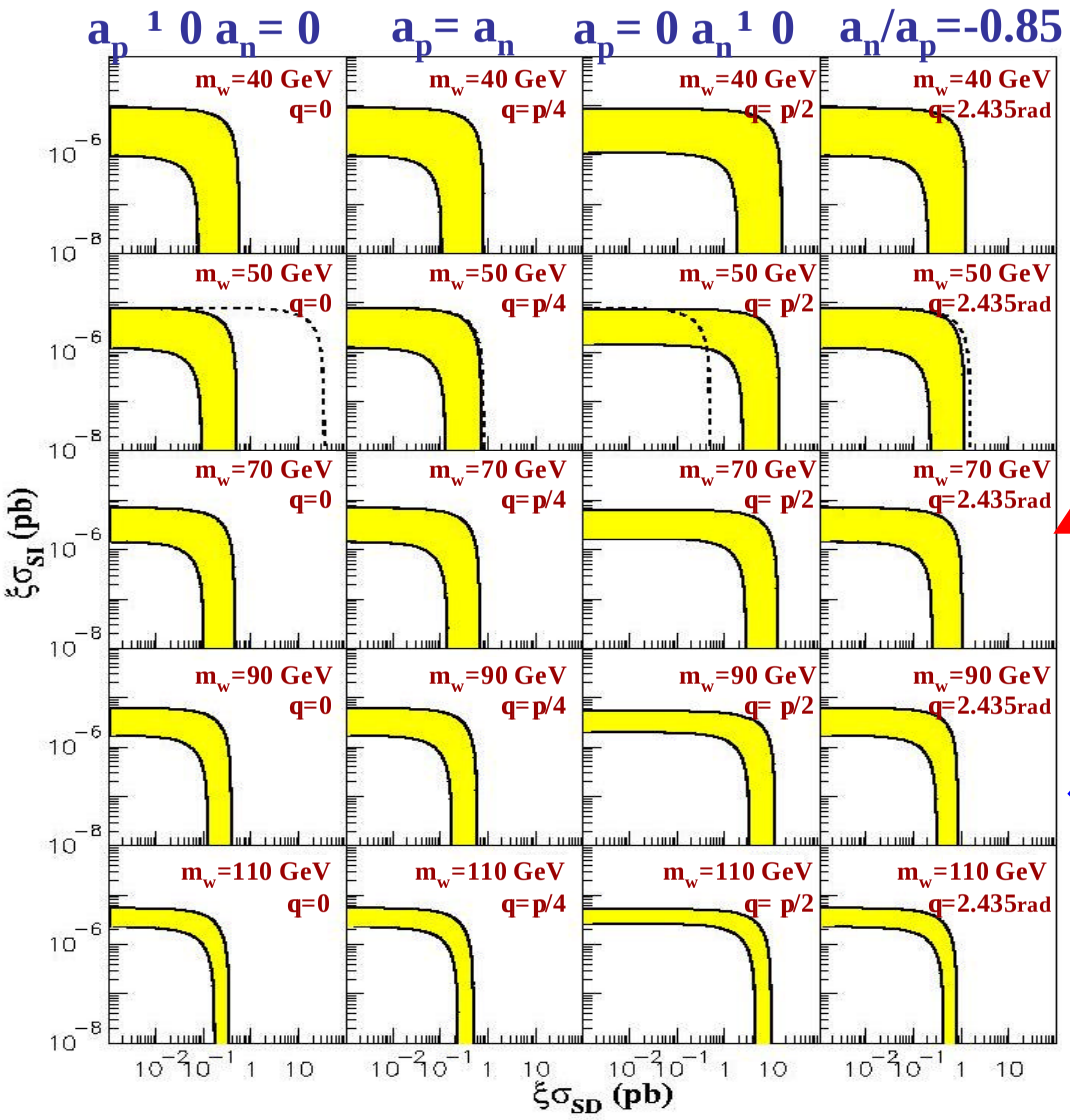
tanb>5 Þ compatibility with DAMA

+ halo modeling uncertainties + FF, etc.

® extend the allowed region

II Model Framework: Na and I (on the contrary of e.g. Ge, Si) fully sensitive to SD component → SI & SD mixed case

PLB509(2001)197



The result is an allowed volume in the space (m_W, x$s_{p\text{-}SI}$, x$s_{p\text{-}SD}$) for each possible q (tg q = a_n/a_p with 0 q<p)

Example of slices for given m_W and q (3 s C.L.)

including all the existing uncertainties much larger regions (and volumes) are obtained

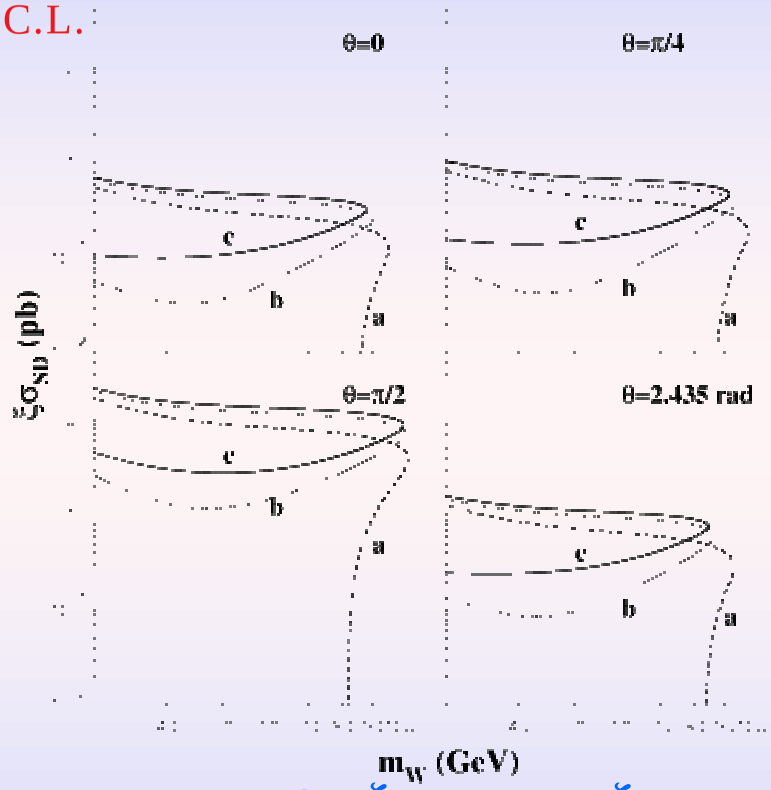
+ Several other possibilities for the SI &SD mixed model framework are open and to be investigated (different SD-FF (a_p & a_n), $g_n = g_p$?, different halo models, etc.)

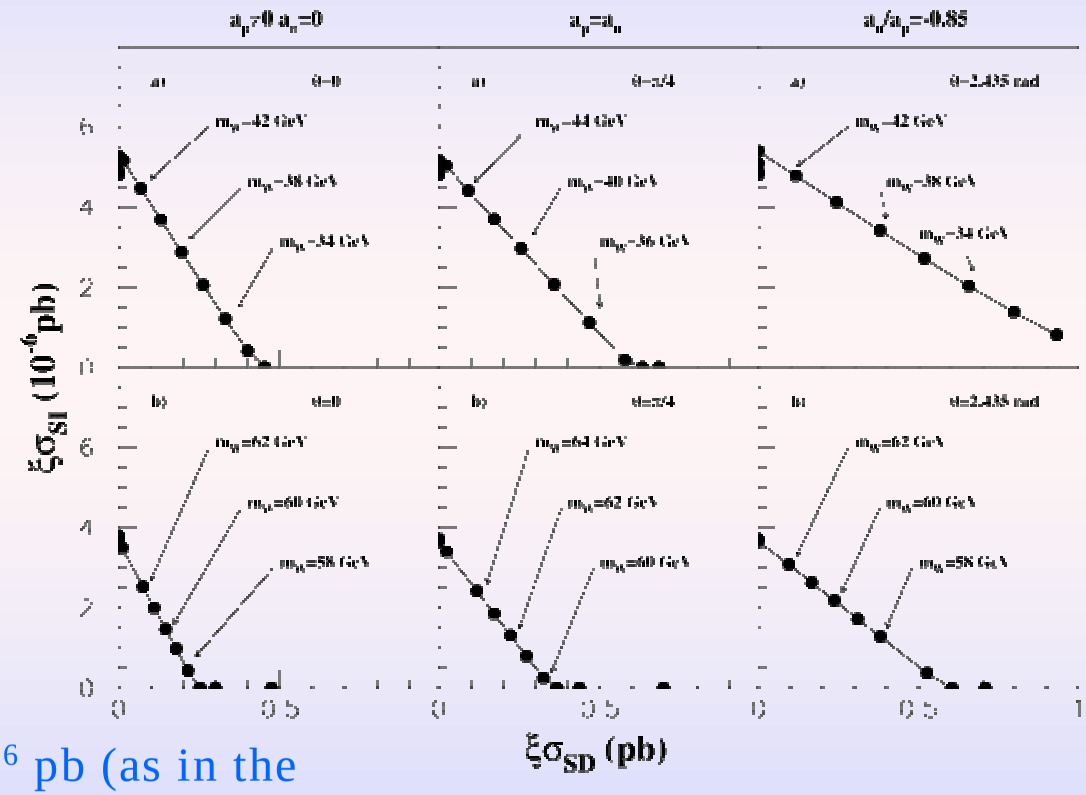
- If SD=0, interval not compatible with zero for $\xi\sigma_{SI}$
- If SI=0, interval not compatible with zero for $\xi\sigma_{SD}$
- Large regions allowed for mixed configurations also for $\xi\sigma_{SI} < 10^{-5}$ pb and $\xi\sigma_{SD} < 1$pb.

PLB509(2001)197

v_0=220km/s, fixed params

3σ C.L.





Allowed region for $\xi\sigma_{SD}$ when $\xi\sigma_{SI} \cong 3\cdot10^{-6}$ pb (as in the region allowed in the pure SI scenario) (contour a)

Allowed region for $\xi\sigma_{SD}$ when $\xi\sigma_{SI}$ much lower than those allowed in the pure SI scenario (contours b: $\xi\sigma_{SI} \cong 1\cdot10^{-6}$ pb , c: $\xi\sigma_{SI} \cong 5\cdot10^{-8}$ pb).

Minima of the *y* function in the plane ($\xi\sigma_{SI}$,$\xi\sigma_{SD}$) for some m_W and θ pairs (related C.L. ranges between 3 and 4 σ)

3rd Model Framework: WIMPs with "preferred" inelastic scattering

EPJC23(2002)61

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

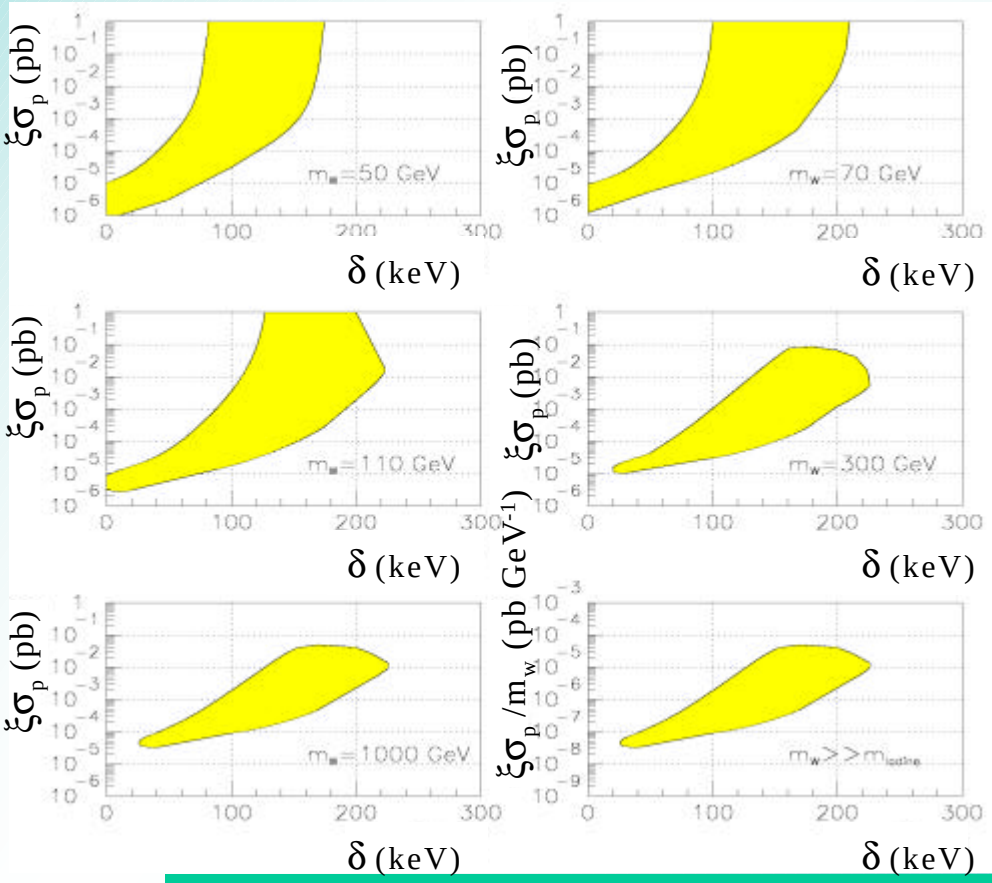
$$\frac{1}{2}mv^2 \geq d \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2d}{m}}$$

Ex. m_W =100 GeV

m_N	m
70	41
130	57

Energy-Time correlation analysis of the DAMA events gives an allowed volume in the space (m_W, $\xi\sigma_p$, δ)

Model framework: accounting for v_0 and v_{esc} uncertainties (v_0=170-270 km/s; v_{esc}=450-650 km/s) and for limit on recoils from PSD (DAMA/NaI-0) + for uncertainty on FF parameters



Example of slices for given m_W

best fit values for m_W=70 GeV

i) when v_0=170 km/s:

$x s_p$=2.5 10^{-2} pb and d=115 keV

ii) when v_0=220 km/s:

$x s_p$=6.3 10^{-4} pb and d=122 keV

+ proper inclusion of uncertainties will enlarge the allowed regions and move the best values

Large parts of these allowed regions are out of the sensitivity of low m_N detector (e.g. Ge, Si)

Reliable proofs and disproofs

Model independent comparisons

- No model independent comparison
- Proof in DAMA: 4 independent cycles give consistent results

NO DISPROOF

Model dependent comparisons

Direct detection:

- **Pure SI?**
  experiments not sensitive to annual modulation signature:
  Both existing Ge ionization/bolometers expts. → data "selection" and "handling", small statistics with respect to several years, bckg rejection technique and associated uncertainties, windows stability, sensitive volumes, not measured quenching factor, energy scale and threshold, overall detection efficiency, calibration, etc.
  UK-Zeplin I LXe expt. → *2 keV energy threshold claimed* but ~ 2 ph.e. (σ/E~100 %), high bckg level (~180 cpd/kg/keV@100keV), uncertainties on: noise rejection, fiducial volume cuts, veto, stability on the optical interfaces, effect on UV light collection, PSD, etc.
  +
  Other nuclei + Our data generally incorrectly quoted + Some comparison methodologically incorrect + Uncertainties effects ignored: on scaling laws, on different sensitivity to different interactions, on used values for theoretical and expt. parameters (eg. form factor), on astrophysical assumptions and model framework, etc..
- **Pure SD?**: no comparison available (only partial and/or uncorrect comparisons are available in literature)
- **Mixed coupling:** no comparison available
- **"inelastic" WIMPs:** no comparison available

NO DISPROOF + many other scenarios possible

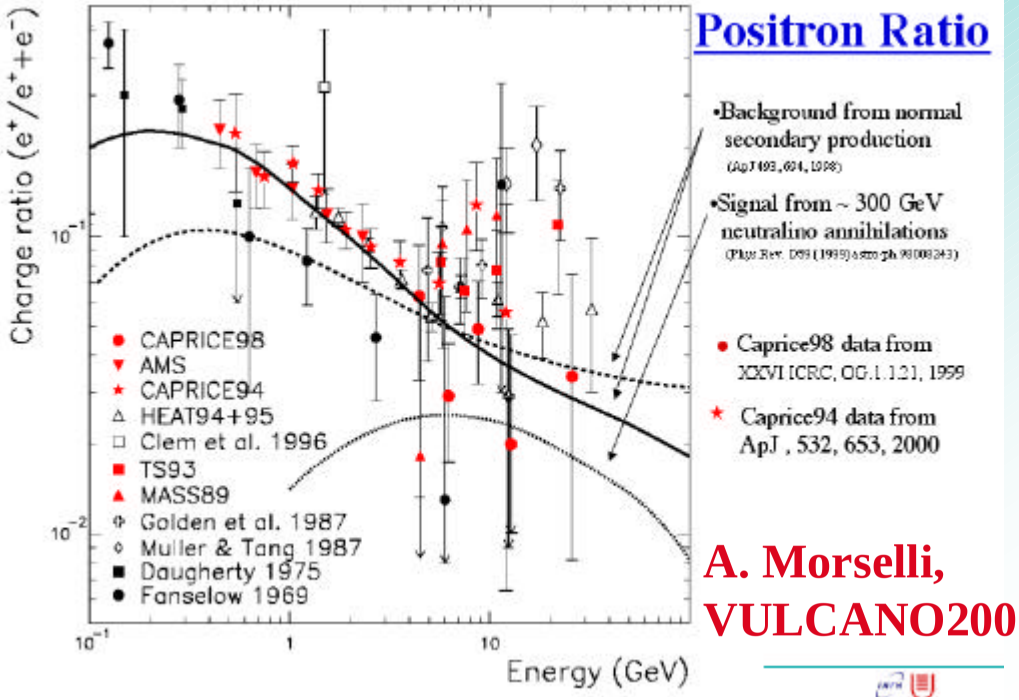
Indirect detection:

- No reliable quantitative comparison is possible, because it depends on assumptions and on the considered model framework.
- No biunivocal correspondence between the observables of direct/indirect detection (SI-SD cross sections / flux of secondary particles)
- Positron excess in cosmic rays? (see for example hep-ph/0108138, Morselli et al., Vulcano-2002)

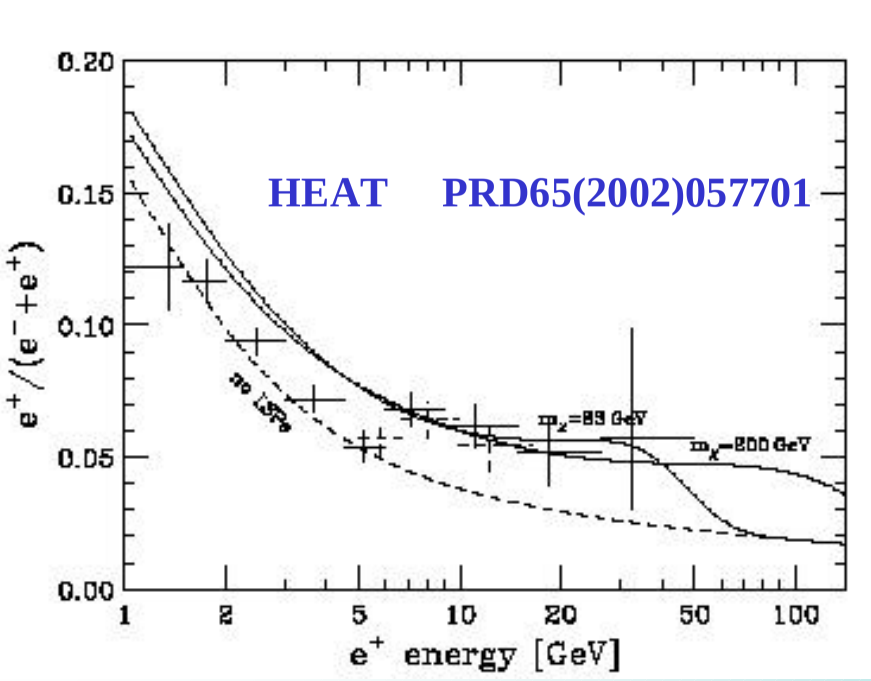
NO DISPROOF; PROOF?

... and theory?

DAMA model independent and model dependent results not based on the candidate nature.
If χ with dominant SI coupling → region compatible with MSSM. "Constrained" models possible, but ...?

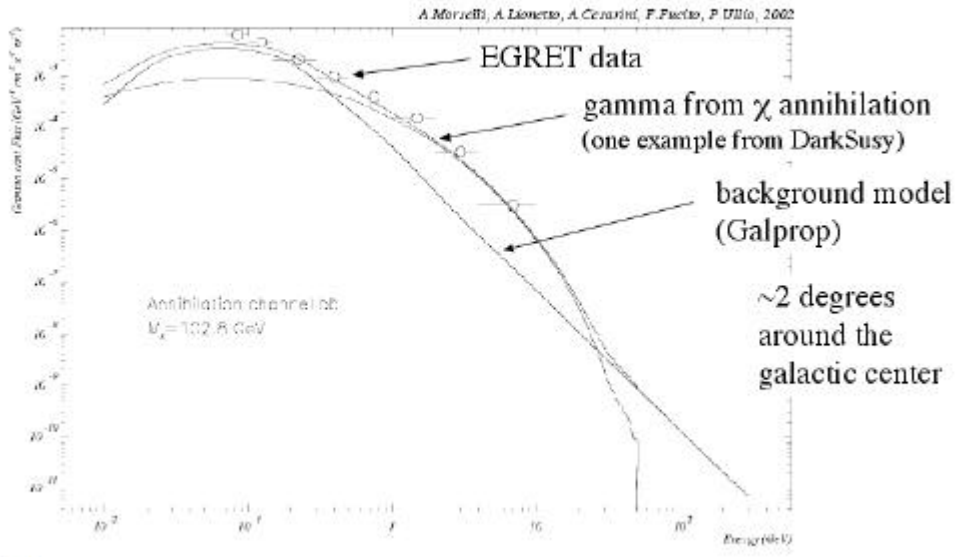


A. Morselli, VULCANO2002



Data set of 2000 (new and different instrument) confirms data set of 1994/95.

EGRET data & Susy models



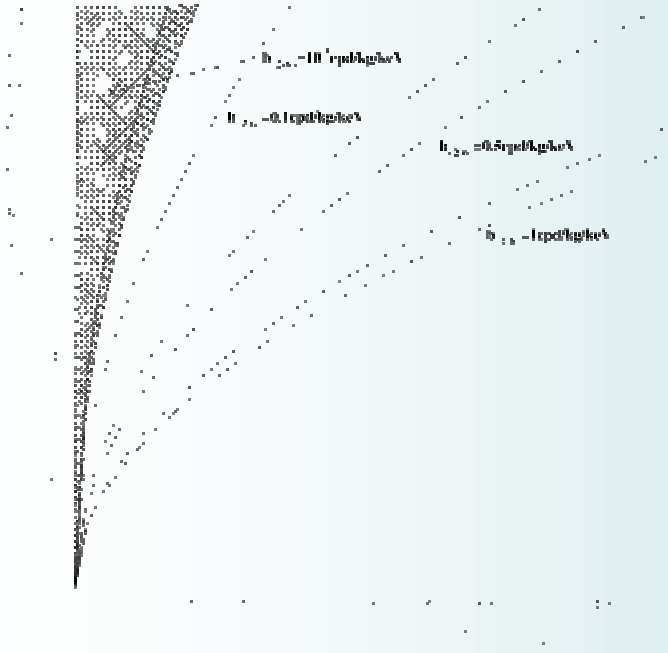
Some hints from indirect searches consistent with DAMA result

- **5th, 6th and 7th annual cycles at hand: data taking concluded and cumulative analyses in progress**

Now **LIBRA** set-up ~ 250 kg NaI(Tl)

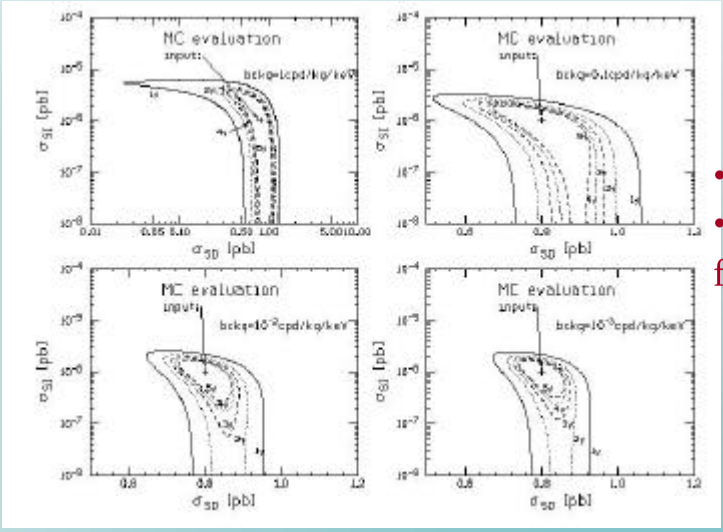
(**L**arge sodium **I**odine **B**ulk for **RA**re processes) in the **DAMA** experiment

Example of the reachable sensitivity with LIBRA



Reachable C.L. as function of running time and of the low energy bckg rate. The shaded regions account for several model frameworks.

Role of the increase of statistics and of the improvement in the bckg rate to identify a possible SI/SD coupled WIMP



- 1σ C.L.
- v_0=220km/s, fixed params

- Allowed regions evaluated by simulating the response of the ~250kg NaI(Tl) set-up to a WIMP having m_W=60GeV, $\sigma_{SI}=10^{-6}$ pb, σ_{SD}=0.8 pb and θ=2.435rad.
- Various exposure times are considered (from 1 to 5y).
- In each panel different bckg rate.

under installation

Summary

✓ **Successfully running ~100kg NaI(Tl), 6.5 kg LXe and R&D set-ups over many years**

✓ **Many rare processes significantly investigated with all the set-ups**

- **LXe** alternatively running with ^{129}Xe and ^{136}Xe
- **R&D** set-up running with small scale expts
- **100 kg NaI(Tl):**

  → **4 annual cycles released (~ 6´10^4 kg day) giving an evidence for an annual modulation effect**

  → **No known systematics or side reactions were found - or suggested by anyone - able to mimic the signature**

  → **Model independent analysis: presence of annual modulation with the proper features**

  → **Model dependent analyses up to 2002: pure SI coupling, pure SD, mixed SI/SD, WIMP with preferred inelastic scattering + studies on the uncertainties of the parameters and model frameworks + halo models + ...**

  → **5th, 6th and 7th annual cycles at hand: data taking concluded, cumulative analyses in progress**

- **Further investigations on model frameworks in progress**
- **From an improved R&D for radiopurity to improve the experimental sensitivity.**

  Installation in progress

LIBRA (~250 kg NaI(Tl))