Particle Dark Matter

Results and perspectives
in particle Physics
La Thuile, Feb.- March 2005

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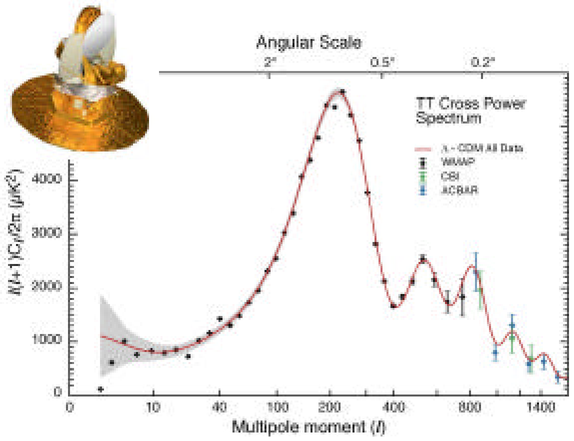
Dark Matter in the Universe

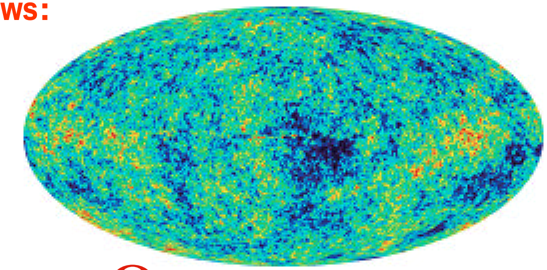
From larger scale ...

precision cosmology definitively shows:



Flat Universe:

$\Omega = 1.02 \pm 0.02$



$\Omega = \Omega_M + \Omega_\Lambda$

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

$W_{CDM} \sim 23\%$

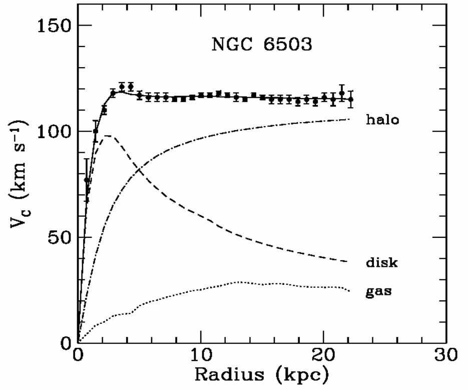
$\Omega_b \sim 4\%$

$\Omega_\nu < 1\ \%$

many evidence for dark matter since beginning of 1900 (luminous matter less than 1%)

... to galaxy scale

- Right halo model and parameters?
- Multicomponent also in the particle component?
- Non thermalized components?
- Caustics and clumpiness?
- ....



Rotational curve of a spiral galaxy

Relic CDM particles from primordial Universe

Light candidates: axion, axion-like produced at rest

(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**

$<s_{ann} \cdot v> \sim 10^{-26}/W_W h^2$ $cm^3 s^{-1}$ ® $s_{ordinary\ matter} \sim s_{weak}$

- **Expected flux:** $F \sim 10^7 \cdot (GeV/m_W)$ cm^{-2} s^{-1} $(0.2 < r_{halo} < 0.7$ 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 → LSP is stable)
neutralino or sneutrino

self-interacting dark matter

a heavy ν of the 4-th family

&

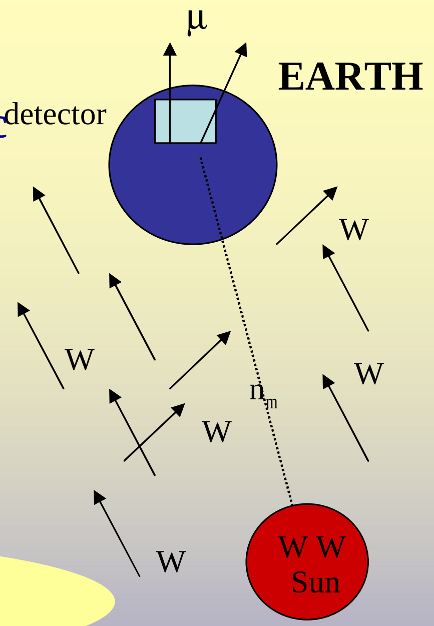
mirror dark matter

Kaluza-Klein particles

even a suitable particle not yet foreseen by theories

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

Indirect detection



Dark Matter particles may accumulate in Sun/Earth, in galactic halo

annihilate

high energy neutrinos, g's, anti-p and e^+

Search for an excess over a (not well known) background

antimatter signature

- **Search for antimatter excess in cosmic rays**
- **Space detectors**

n_m signature

- **Best signature from n_m producing up-ward going m**
- **Underground, underwater, underice detectors**

g signature

- **Search for quasi-monoenergetic g's in cosmic rays**
- **Space detectors**

See also next talk

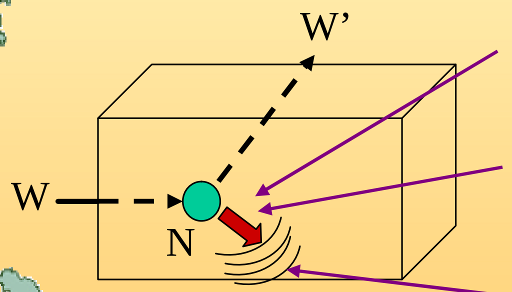
Similar searches can offer results which depend on the background modeling and on the astrophysical, particle and nuclear Physics assumptions

Direct detection:

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

Various different target nuclei

Various different experimental site depths



Ionization:
Ge, Si

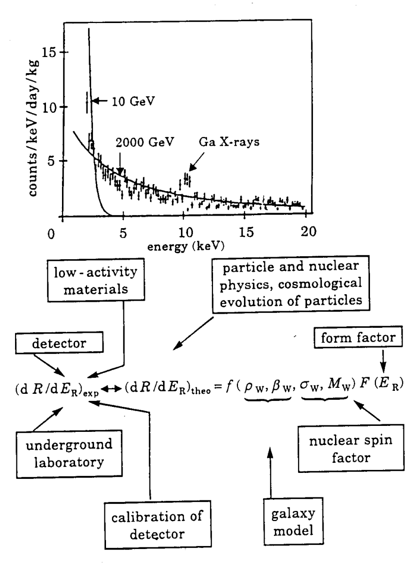
Scintillation:
NaI(Tl),
LXe,CaF_2(Eu),...

Bolometer:
TeO_2, Ge, ...

(Other possibilities?
... ionization/excitation not involving the nucleus?)

The “traditional” approach

- **Experimental vs Expected spectra (with or without bckg rejection)**



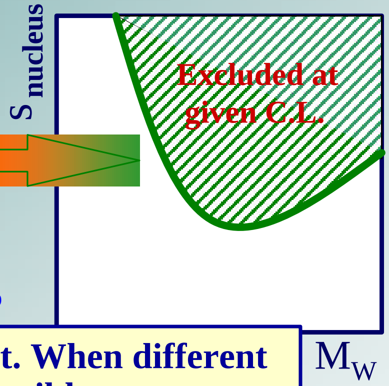
several assumptions and modeling required

+

experimental and theoretical uncertainties generally not included in calculations

Model dependent exclusion plot

by additional model (assuming scaling laws): s_p



An exclusion plot not an absolute limit. When different target nuclei, no direct comparison possible.

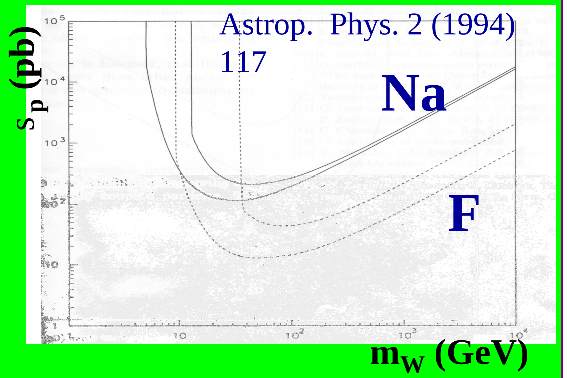
- **No discovery potentiality**
- Limitations in the recoil/background discrimination when applied
- Uncertainties in the exclusion plots and in comparisons (model dependent validity)

To have a potentiality of discovery a *model independent signature* is needed !

Example: effect on the exclusion plot when changing the value even of a single parameter (inside its allowed range) within the same model framework

- **Top curves: v_0=180 km/s; v_{esc}=500 km/s**
- **Lower curves: v_0=250 km/s; v_{esc}=1000 km/s**

- **v_0 affects mainly the overall rate**
- **v_{esc} affects mostly the lower mass region**



Similar effect found for every nucleus and interaction type changing assumptions and/or used expt/theoretical parameters values within existing uncertainties and possibilities ⇒ so far exclusion plots given under a single fixed set of assumptions and parameters values

No”universal” validity!

A model independent signature is needed

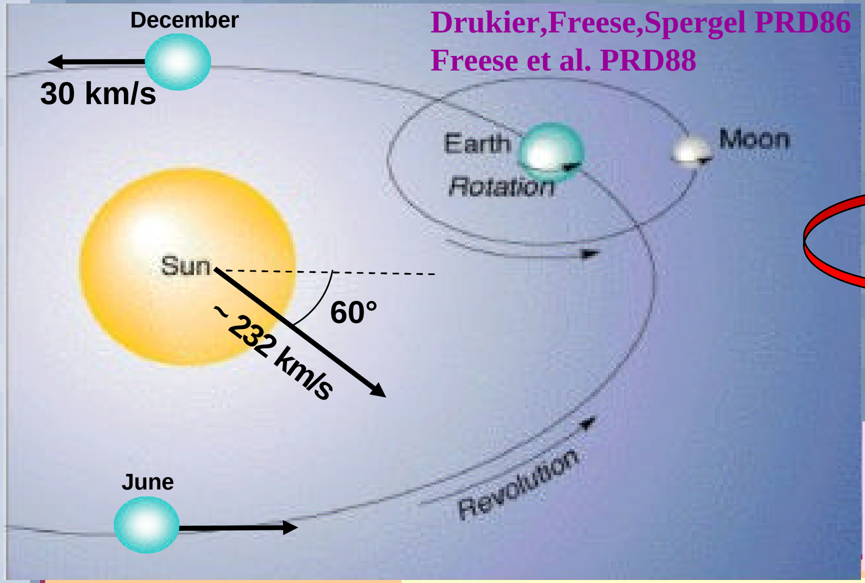
Directionality Correlation of nuclear recoil track with Earth's galactic motion due to the distribution of Dark Matter particles velocities very hard to realize

Nuclear-inelastic scattering Detection of γ's emitted by excited nucleus after a nuclear-inelastic scattering. very large exposure and very low counting rates hard to realize

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

Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun. at present the only feasible one

Investigating the presence of a Dark Matter particles component in the galactic halo by the model independent annual modulation signature



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 $v_Å$ 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

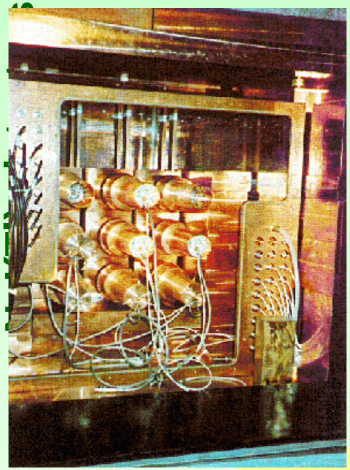
Requirements of the annual modulation

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 $\lesssim$7% (larger e.g. for Dark matter particles with preferred inelastic interaction, PRD64 (2001)043502, or if contributions from Sagittarius, astro-ph/0309279)

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

DAMA/NaI (~100 kg highly radiopure NaI(Tl) set-up) @ LNGS:

data taking completed on July 2002

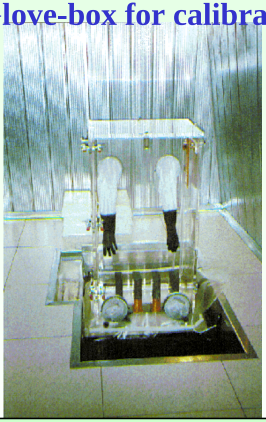


Performances: **N.Cim.A112(1999)545-575, EPJ C18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73**

Results on rare processes:

Possible Pauli exclusion principle violation	PLB408(1997)439
Nuclear level excitation of ^{127}I and ^{23}Na during CNC processes	PRC60(1999)065501
Electron stability and non-paulian transitions in Iodine atoms (by L-shell)	PLB460(1999)235
Exotic Dark Matter search	PRL83(1999)4918
Search for solar axions by Primakoff effect in NaI(Tl) crystals	PLB515(2001)6
Exotic Matter search	EPJdirect C14(2002)1
Search for superdense nuclear matter	EPJA23(2005)7
Search for heavy clusters decays	EPJA to appear

Glove-box for calibration



Results on Dark Matter particles:

- **PSD:** **PLB389(1996)757**
- **Investigation on diurnal effect** **N.Cim.A112(1999)1541**

- **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, IJMPD (astro-ph/0501412) to appear**

during installation

total exposure collected during 7 annual cycles released: **107731 kg×d**

(Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403)

The model independent result

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

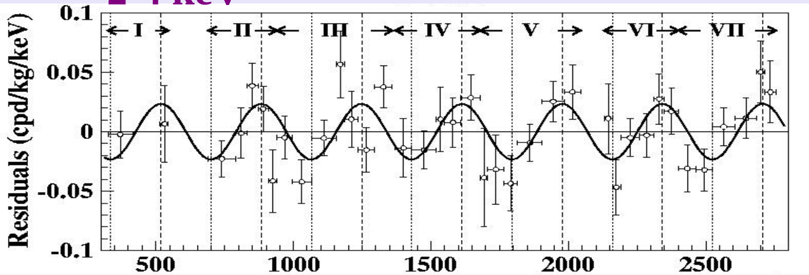
Riv. N. Cim. 26 n.1. (2003) 1-73
(astro-ph/0307403)

experimental single-hit residuals rate vs time and energy

107731 kg · d

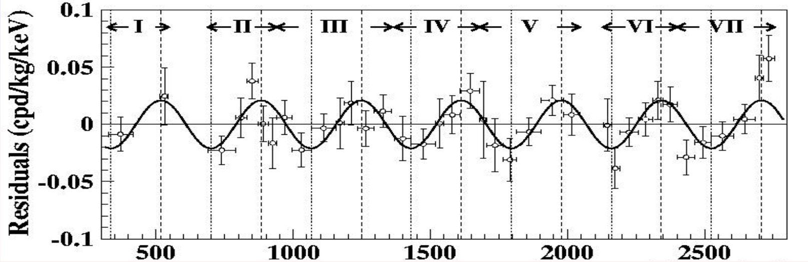
Acos[w(t-t_0)] ; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV



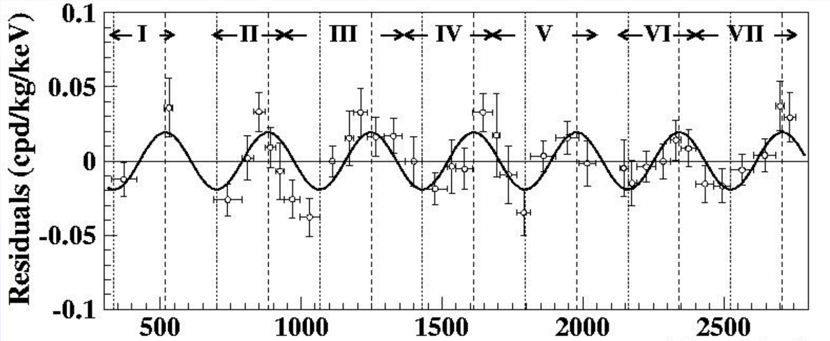
fit: A=(0.0233 ± 0.0047) cpd/kg/keV Time (day)

2-5 keV



fit: A = (0.0210 ± 0.0038) cpd/kg/keV Time (day)

2-6 keV



Time (day)

Absence of modulation? No

c^2/dof=71/37 ® P(A=0)=7×10^{-4}

fit: A = (0.0192 ± 0.0031) cpd/kg/keV

fit (all parameters free):

A = (0.0200 ± 0.0032) cpd/kg/keV;

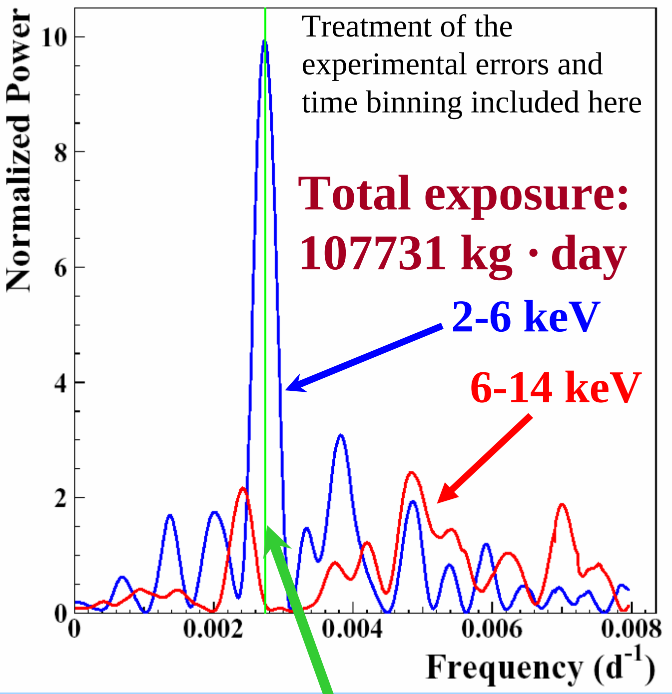
t_0 = (140 ± 22) d ; T = (1.00 ± 0.01) y

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

Power spectrum of single-hit residuals

(according to Ap.J.263(1982)835; Ap.J.338(1989)277)

2-6 keV vs 6-14 keV



Treatment of the experimental errors and time binning included here

Total exposure: 107731 kg · day

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

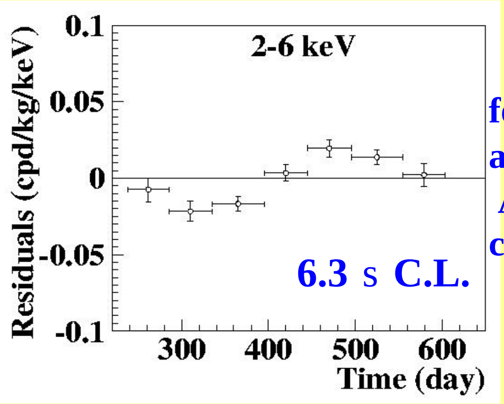
+

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

Single-hit residual rate as in a single annual cycle

DAMA/NaI 7 annual cycles: 107731 kg · day

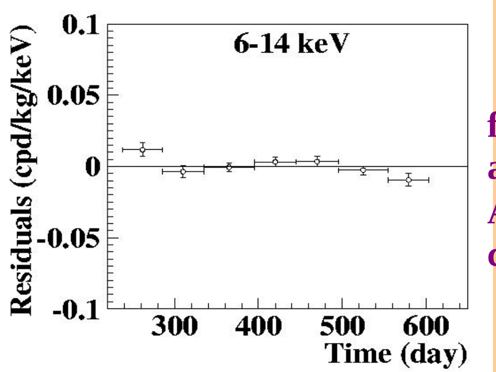
Initial time 7th August



6.3 s C.L.

for t_0 = 152.5 d and T = 1.00 y: A=(0.0195 ± 0.0031) cpd/kg/keV

Initial time 7th August



for t_0 = 152.5 d and T = 1.00 y: A= -(0.0009 ± 0.0019) cpd/kg/keV

A clear modulation is present in the lowest energy region, while it is absent just above

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

(see Riv. N. Cim. 26 n. 1 (2003) 1-73 [astro-ph/0307403] and references therein for details)

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

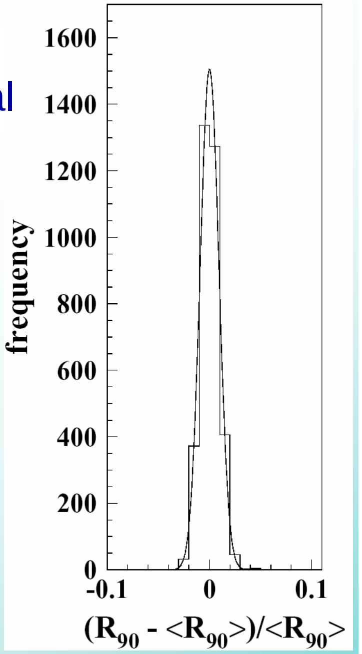
Thus, they can not mimic the observed annual modulation effect

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 s 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 fast neutron modulation account for the observed effect?

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

Elastic scatterings: recoil nuclei

capture rate = $\Phi_n \sigma_n N_T$

Measured fast neutron flux @ LNGS:

$F_n = 0.9\ 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995),23)

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

Assuming - very cautiously - a 10% neutron modulation:

$S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

NO

Moreover, a possible fast n modulation induces a variation in all the energy spectrum

Excluded by R_{90} analysis

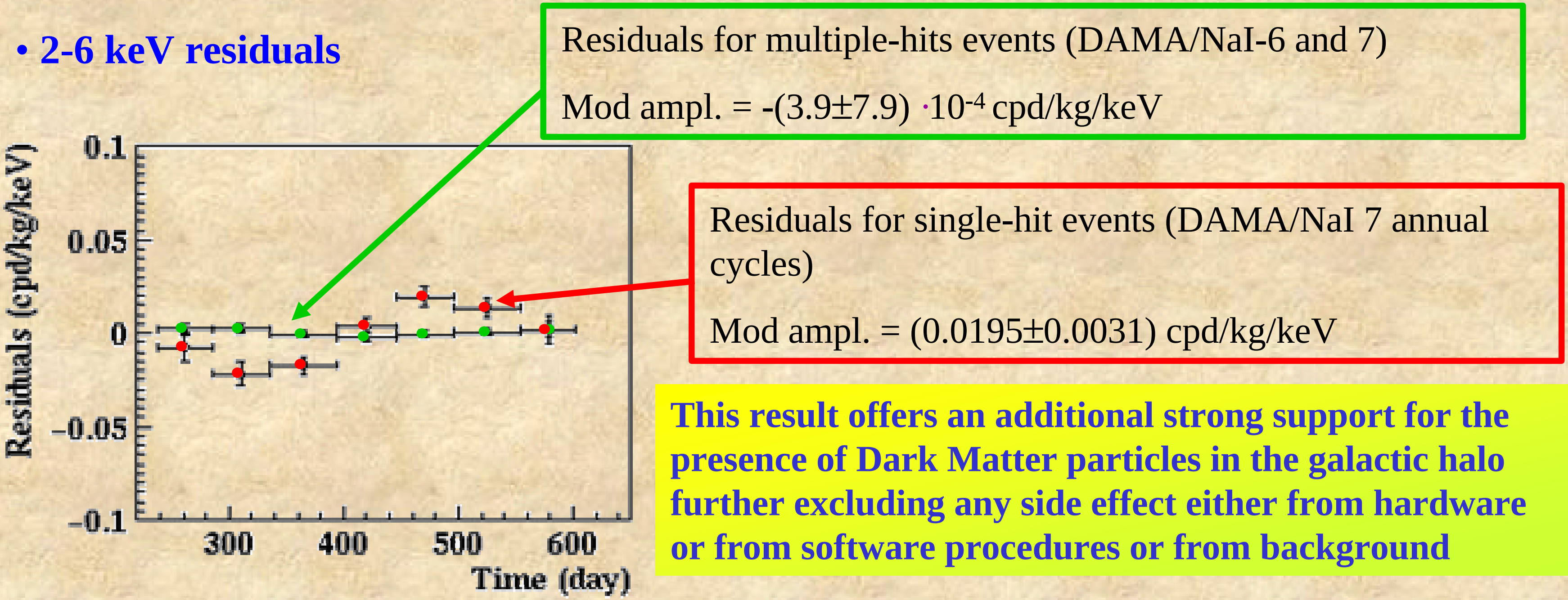
Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

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: recoils 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) ·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 DAMA/NaI *Model Independent* result

- Presence of modulation over 7 annual cycles at ~6.3s CL with the proper distinctive features for a Dark Matter particle induced effect
- The deep investigation has shown absence of known sources of possible systematics and side processes able to account for the observed effect
- All the signature features satisfied by the data over 7 independent experiments of 1 year each one

corollary quest for a candidate

To investigate the nature and coupling with ordinary matter of the Dark Matter candidate particle, an effective energy and time correlation analysis of the events has to be performed within model frameworks

THUS
uncertainties on models and comparisons

?

rw;
Dark Matter particles velocity distribution and its parameters;
coupling: SI, SD, mixed SI&SD,
preferred inelastic (PRD64(2001)043502,hep-ph/0402065) , ...;
new contributions to WIMP-nucleus scattering? (see e.g. astro-ph/0309115);
scaling laws on cross sections;
form factors and related parameters;
spin factors;
etc.

They can affect not only the corollary estimated regions following a positive effect from the annual modulation signature, but also results given as exclusion plots

\+

experimental parameters (typical of each experiment)

comparison within particle models

WIMP-nucleus elastic scattering

SI+SD differential cross sections:

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

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

$g_{p,n}$($a_{p,n}$) effective WIMP-nucleon couplings

<$S_{p,n}$> nucleon spin in the nucleus

$F^2(E_R)$ nuclear form factors

m_{Wp} reduced WIMP-nucleon mass

Generalized SI/SD WIMP-nucleon cross sections:

$$\sigma_{SI}=\frac{4}{\pi}G_F^2 m_{Wp}^2 g^2 \qquad \sigma_{SD}=\frac{32}{\pi}\frac{3}{4}G_F^2 m_{Wp}^2 \bar{a}^2$$

where:

$$\begin{cases} g=\dfrac{g_p+g_n}{2}\bullet\left[1-\dfrac{g_p-g_n}{g_p+g_n}\left(1-\dfrac{2Z}{A}\right)\right] \\ \bar{a}=\sqrt{a_p^2+a_n^2} \qquad tg\theta=\dfrac{a_n}{a_p} \end{cases}$$

g: independent on the used target nucleus since Z/A nearly constant for the nuclei typically used in WIMP direct searches

Differential energy distribution:

$$\frac{dR}{dE_R}=N_T\frac{\rho_W}{m_W}\int_{v_{\min}(E_R)}^{v_{\max}}\frac{d\sigma}{dE_R}(v,E_R)vf(v)dv=N_T\frac{\rho_W m_N}{2m_W m_{Wp}^2}\cdot\Sigma(E_R)\cdot I(E_R)$$

$$\Sigma(E_R)=\left\{A^2\sigma_{SI}F_{SI}^2(E_R)+\frac{4}{3}\frac{J+1}{J}\sigma_{SD}\left[\langle S_p\rangle\cos\theta+\langle S_n\rangle\sin\theta\right]^2 F_{SD}^2(E_R)\right\}$$

$$I(E_R)=\int_{v_{\min}(E_R)}^{v_{\max}}\frac{f(v)}{v}dv \qquad v_{\min}=\sqrt{\frac{m_N E_R}{2m_{WN}^2}}$$

minimal velocity providing E_R recoil energy

N_T: number of target nuclei

f(v): WIMP velocity distribution in the Earth frame (**it depends on v_e**)

$v_e=v_{sun}+v_{orb}\cos\omega t$

v_{max}: maximal WIMP velocity in the Earth frame

The inelastic WIMP – nucleus interaction: W + N ® W* + N

- **WIMP candidate suggested by D. Smith and N. Weiner (PRD64(2001)043502)**
- **Two mass 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

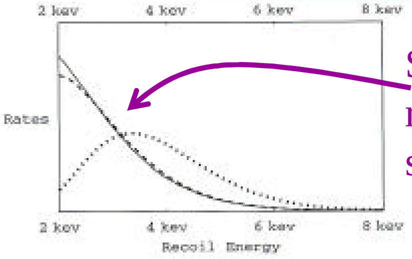
Differential energy distribution for SI interaction:

$$\frac{ds}{d\Omega^*} = \frac{G_F^2 m_{WN}^2}{p^2}\left[Zg_p + (A-Z)g_n\right]^2 F_{SI}^2(q^2)\cdot\sqrt{1-\frac{v_{thr}^2}{v^2}}$$

g$_{p,n}$ effective WIMP-nucleon couplings

dΩ* differential solid angle in the WIMP-nucleus c.m. frame

q^2 = squared threee-momentum transfer



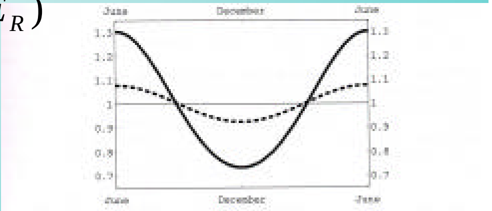
Normalized modulation (S_m) as a function of energy for ordinary WIMP scenario (solid), inelastic WIMP scenario with $\delta = 100$keV (dashed), and inelastic WIMP scenario with $\delta = 150$keV (dotted), all with $m_\chi = 60$GeV.

S$_m$/S$_0$ enhanced with respect to the elastic scattering case

Nucleus recoil energy:

$$E_R = \frac{2m_{WN}^2 v^2}{m_N}\cdot\frac{1-\frac{v_{thr}^2}{2v^2}-\sqrt{1-\frac{v_{thr}^2}{v^2}}\cdot\cos q^*}{2}$$

$$\frac{ds}{dE_R} = \frac{2G_F^2 m_N}{pv^2}\left[Zg_p + (A-Z)g_n\right]^2 F_{SI}^2(E_R)$$



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.

Differential energy distribution:

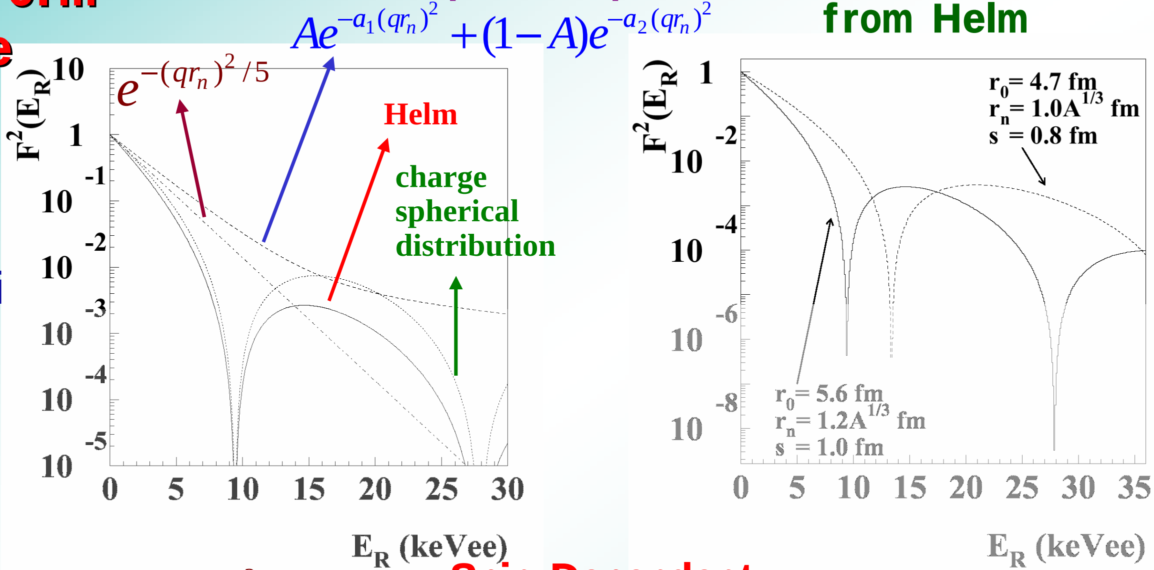
$$\frac{dR}{dE_R} = N_T\frac{r_W}{m_W}\int_{v_{\min}}^{v_{\max}}\frac{ds}{dE_R}(v,E_R)vf(v)dv \qquad v_{\min}(E_R) = \sqrt{\frac{m_N E_R}{2m_{WN}^2}}\cdot\left(1+\frac{m_{WN}d}{m_N E_R}\right)$$

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

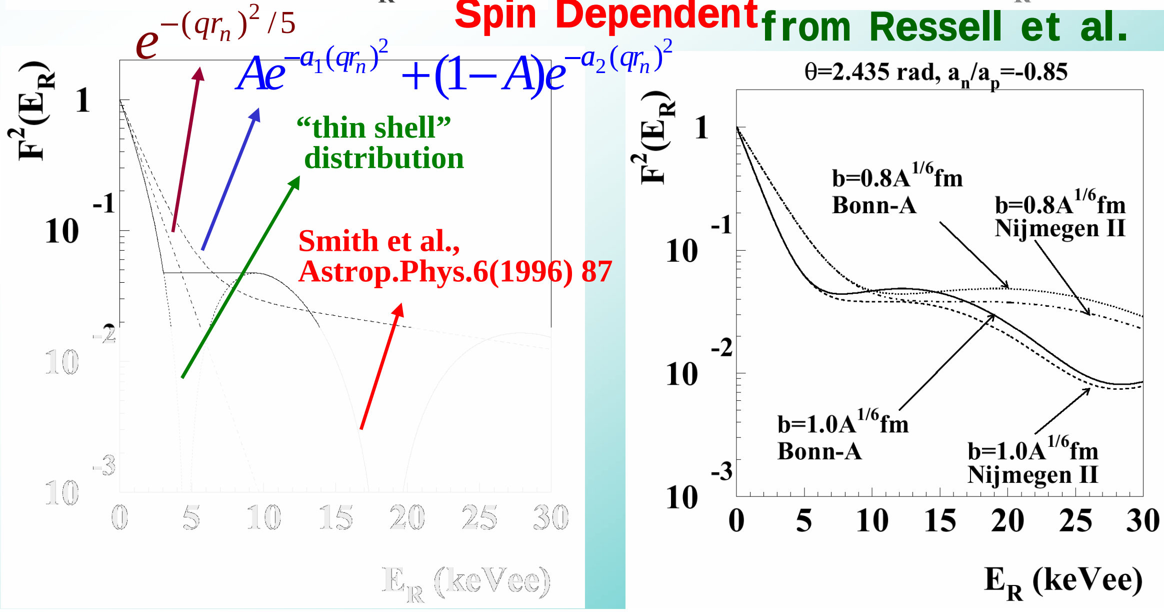
- Take into account the structure of target nuclei
- In SD form factor: no decoupling between nuclear and Dark Matter particles degrees of freedom; dependence on nuclear potential.

Similar situation for all the target nuclei considered in the field

Spin Independent

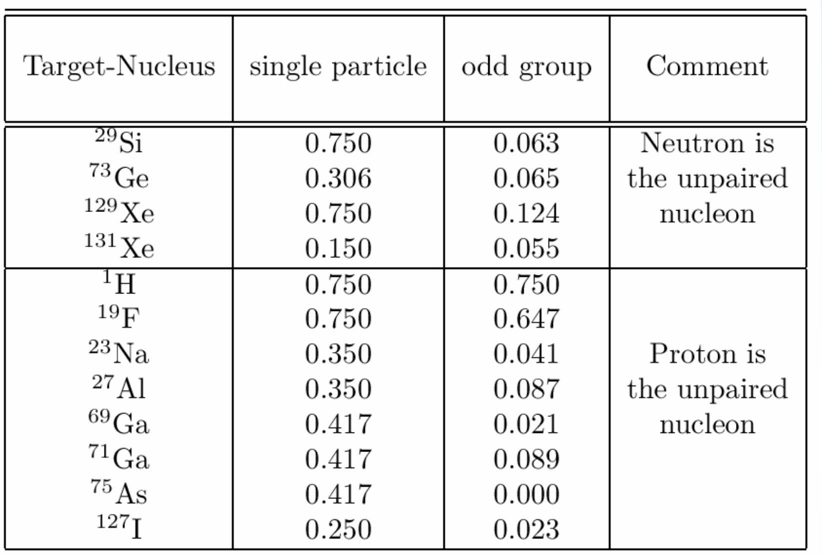


Spin Dependent



The Spin Factor

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

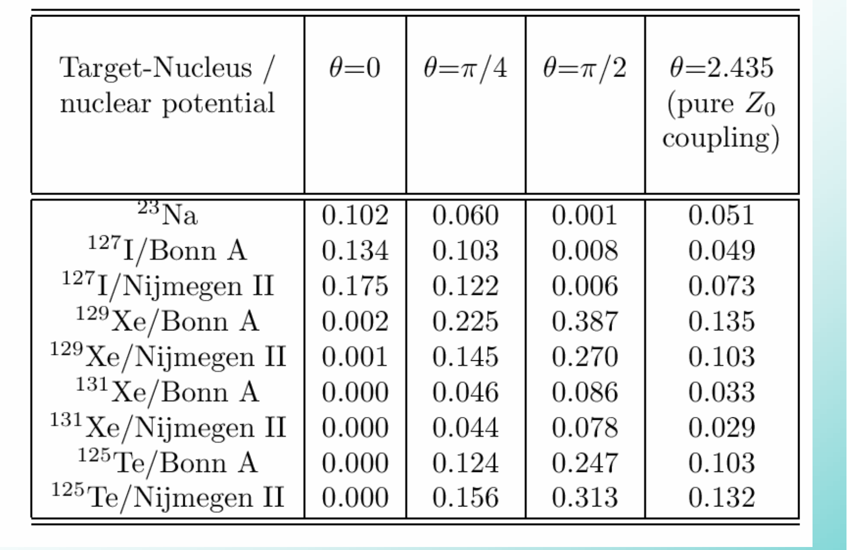


Target-Nucleus	single particle	odd group	Comment
^{29}Si	0.750	0.063	Neutron is the unpaired nucleon
^{73}Ge	0.306	0.065	
^{129}Xe	0.750	0.124	
^{131}Xe	0.150	0.055	
^{1}H	0.750	0.750	Proton is the unpaired nucleon
^{19}F	0.750	0.647	
^{23}Na	0.350	0.041	
^{27}Al	0.350	0.087	
^{69}Ga	0.417	0.021	
^{71}Ga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

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

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

Spin Factors calculated on the basis of Ressell et al. for some of the possible q 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 = $L^2J(J+1)/\bar{a}^2$

Large differences in the measured countingt rate can be expected:

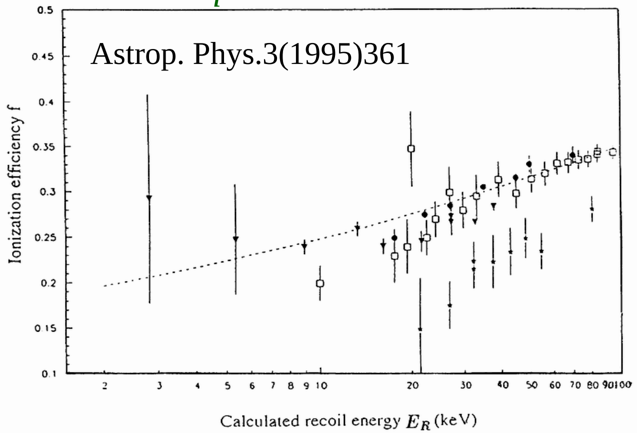
- **when using target nuclei sensitive to the SD component of the interaction (such as e.g. ^{23}Na and ^{127}I) with the respect to those largely insensitive to such a coupling (such as e.g. ^{nat}Ge, ^{nat}Si, ^{nat}Ar, ^{nat}Ca, ^{nat}W, ^{nat}O);**

- **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

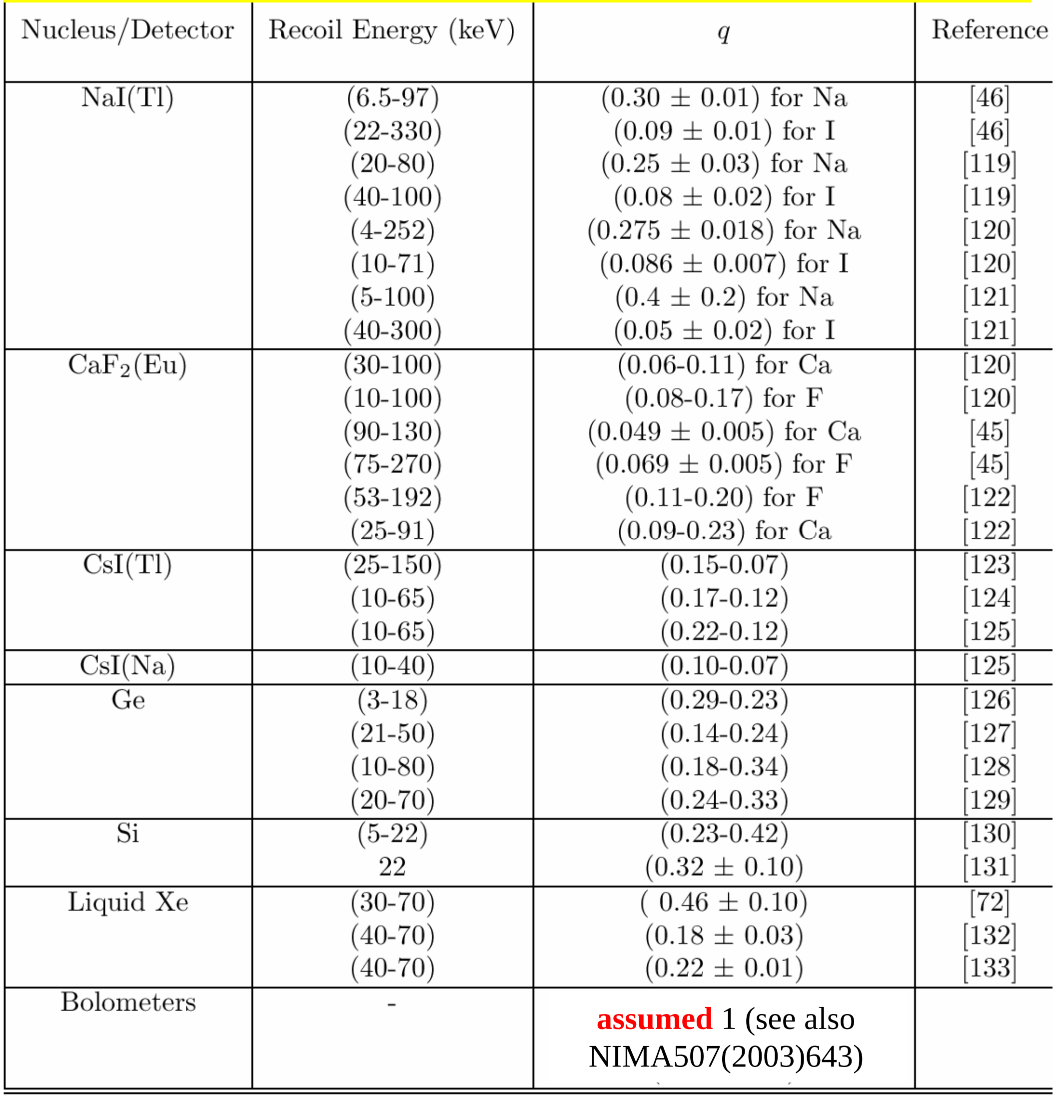
Quenching factors, *q*, measured by neutron sources or by neutron beams for some detectors and nuclei

Ex. of different *q* determinations for Ge


Astrop. Phys.3(1995)361

- **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)**

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 Þ 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 $\rho_0 = \rho_{DM}(R_0 = 8.5\ \mathrm{kpc})$

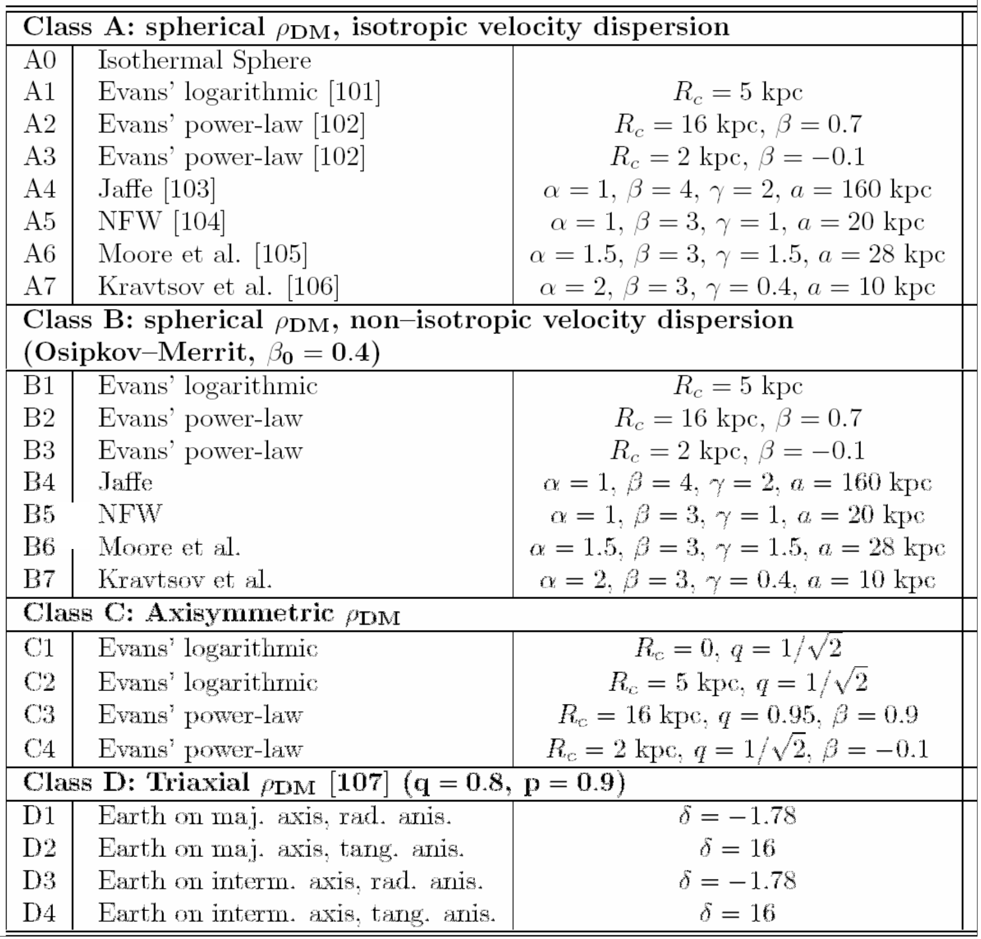
→ local velocity $v_0 = v_{rot}(R_0 = 8.5\mathrm{kpc})$

→ velocity distribution $f(\vec{v})$

- **Allowed ranges of r_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:**

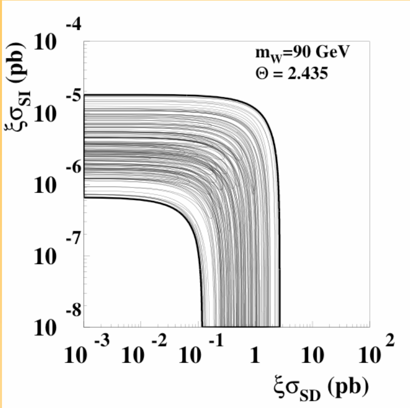
$$v_0 = (220 \pm 50) km \cdot s^{-1}$$
$$1 \cdot 10^{10} M_\oplus \le M_{vis} \le 6 \cdot 10^{10} M_\oplus$$
$$0.8 \cdot v_0 \le v_{rot}(r = 100kpc) \le 1.2 \cdot v_0$$

NOT 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.	$\delta = 16$

Model dependent scenarios investigated by DAMA/NaI (others under investigation)



Main topics (for details see Riv. N. Cim. 26 n.1. (2003) 1-73, astro-ph/0307403)

- Several halo models considered
- Helm FF for SI coupling
- Ressel FF (Nijmengen II nuclear potential) for SD calculated for χ
- Some of the uncertainties included
- Assumed scaling laws: σ_{SI} proportional to $\mu^2 A^2$;
- σ_{SD} proportional to $\mu^2 \Lambda^2$ J(J+1)

For simplicity, the results are given in terms of allowed regions obtained as superposition of the configurations 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 considered here.

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

For each model the likelihood function requires:

1. the agreement of the expectations for the **modulated part of the signal** with the measured modulated behaviour for each detector and for each energy bin;
2. the agreement of the expectations for the **unmodulated component of the signal** with the respect to the measured differential energy distribution and with the bound on recoils obtained by pulse shape discrimination in the devoted **DAMA/NaI-0** period. The latter one acts - by the fact - as an experimental upper bound in the determination of the unmodulated component of the signal and, thus, implies a lower bound on the constant (see elsewhere) background contribution to the measured differential energy distribution.

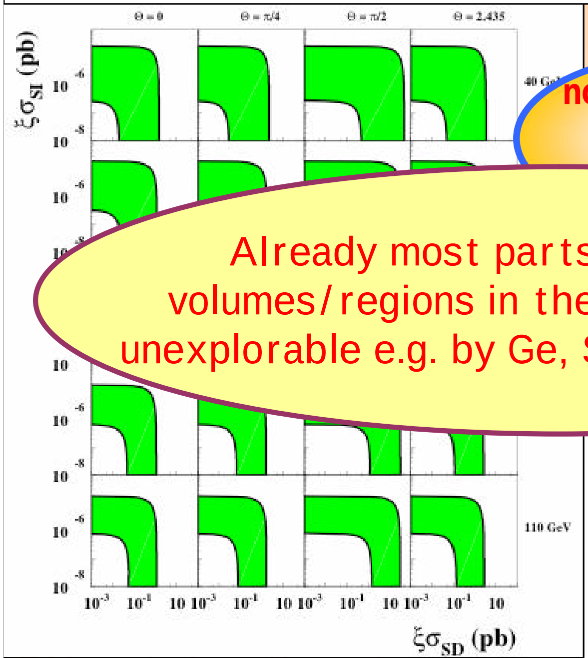
Thus, the quoted C.L.'s already account for compatibility with the measured differential energy spectrum and with the measured upper bounds on recoils.

Few Examples of corollary quests for the candidate particle

(Riv. N.Cim. vol.26 n.1. (2003) 1-73 and ref. therein for more)

General case: DM particle with SI&SD couplings (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 $0=\theta<\pi$) and m_W

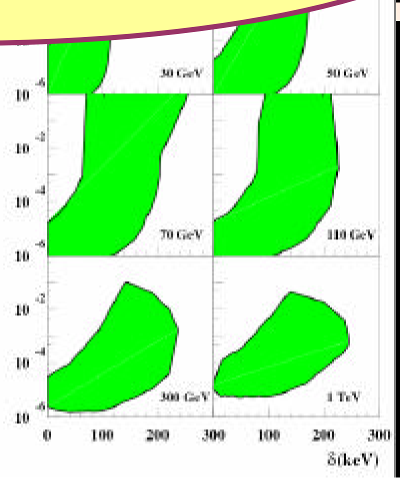


not exhaustive

+ different

Already most parts of the allowed volumes/regions in these frameworks are unexplorable e.g. by Ge, Si, Xe, $CaWO_4$ targets

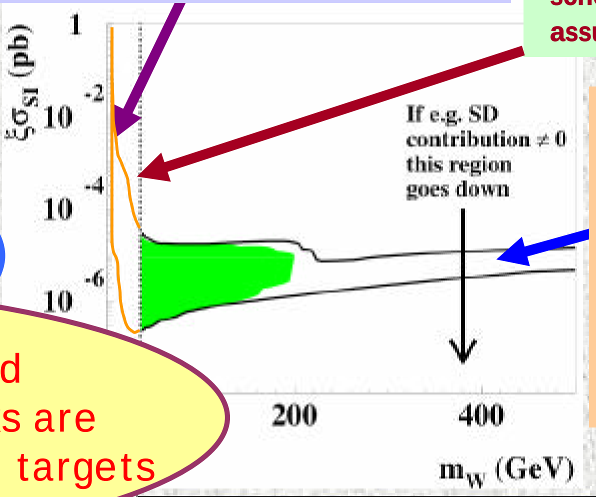
DM particle with preferred inelastic interaction: $W + N \rightarrow W^* + N$ (S_m/S_0 enhanced): examples of slices of the allowed volume in the space ($\xi\sigma_p$, m_W, δ) [e.g. Ge disfavoured]



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

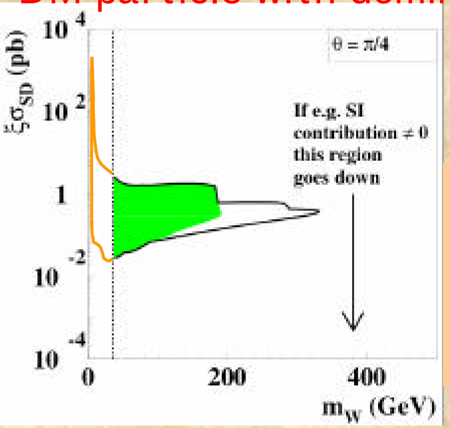
Model dependent lower bound on neutralino mass as derived from LEP data in supersymmetric schemes based on GUT assumptions (DPP2003)



If e.g. SD contribution ≠ 0 this region goes down

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 set A

DM particle with dominant SD coupling



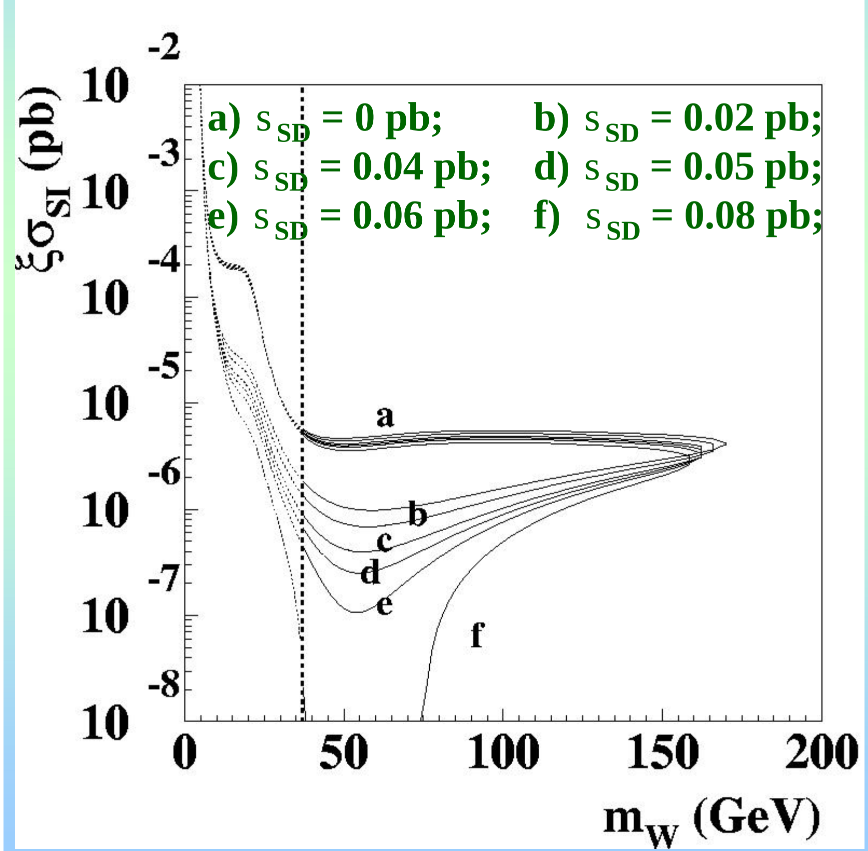
If e.g. SI contribution ≠ 0 this region goes down

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

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 Þ drastically moves the allowed region in the plane (m_W, x s$_{SI}$) towards lower SI cross sections (x s$_{SI}$ < 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 q » 0 or q » p.**

Supersymmetric expectations in MSSM

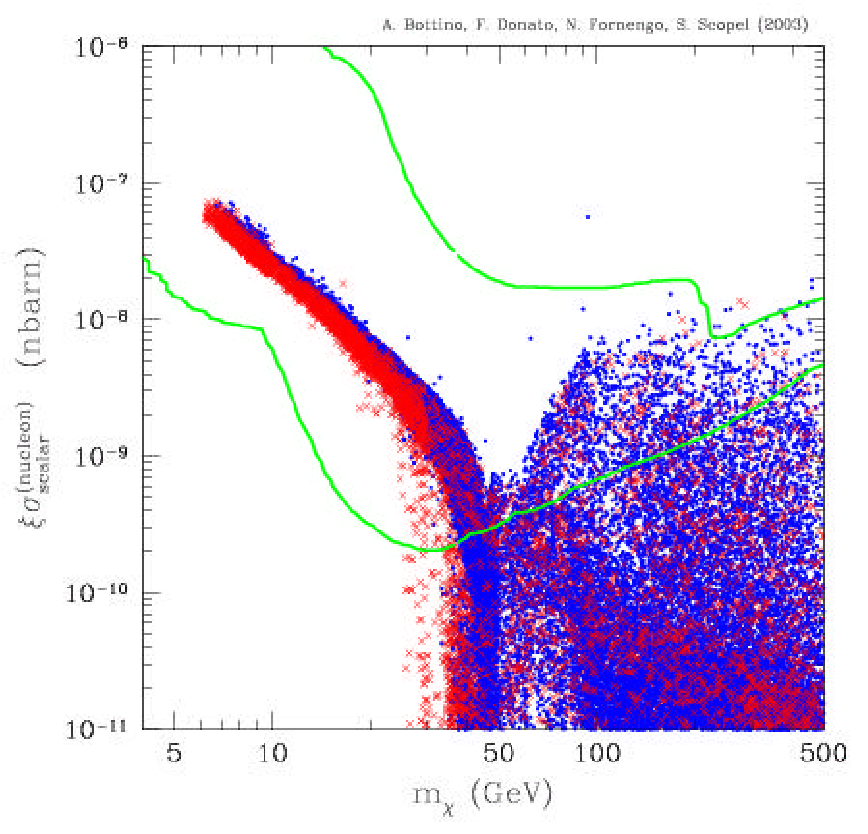
- Assuming for the neutralino a dominant purely SI coupling

- 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



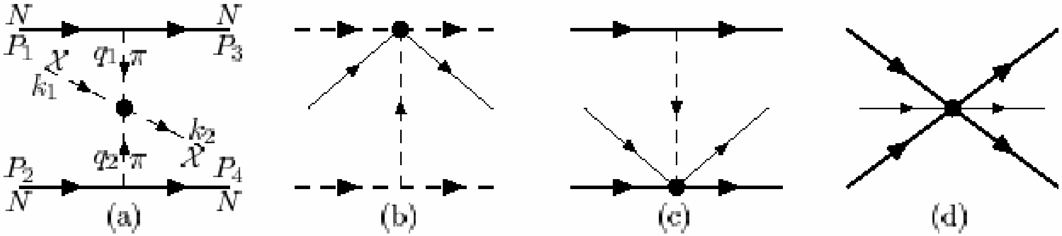
scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line);
figure taken from PRD69(2004)037302

(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.



(a) (b) (c) (d)

"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

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

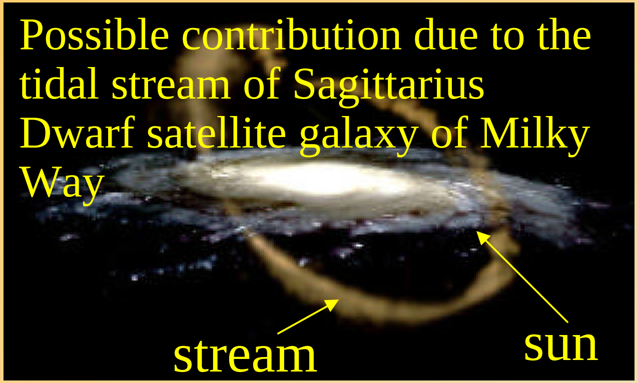
$\varepsilon_A = 0$ "usually"

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

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

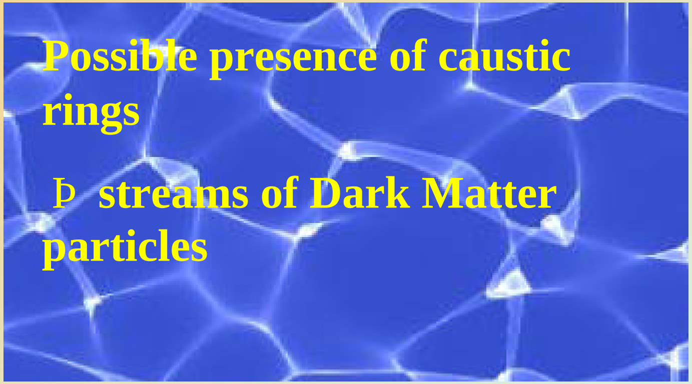
… other astrophysical scenarios?

Possible non-thermalized multicomponent galactic halo? **In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected :**



Possible contribution due to the tidal stream of Sagittarius Dwarf satellite galaxy of Milky Way

K.Freese et al. astro-ph/0309279



Possible presence of caustic rings

Þ streams of Dark Matter particles

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?

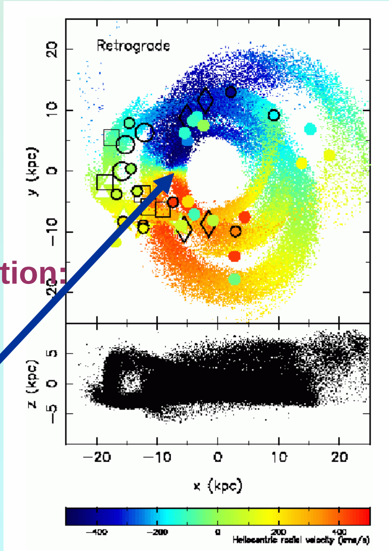
Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

.....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



DAMA/NaI vs some others

	DAMA/NaI	CDMS-II	Edelweiss-I	Zeplin-I	Cresst-II
• Signature	annual modulation	none	none	none	none
• Targets	^{23}Na, ^{127}I	^{nat}Ge	^{nat}Ge	^{nat}Xe	CaWO$_4$
• Technique	widely known	poorly experienced (known just by Edelweiss)	poorly experienced (known just by CDMS)	liq/gas optical interface (light collected from top)	poorly experienced (known just by themselves)
• Target mass	» 100 kg	0.75 kg	0.32 kg	» 3 kg	» 0.6 kg
• Used exposure	~(1.1 ´ 10^5) kg ´ day (RivNCim 26 n1(2003)1-73)	19.4 kg ´ day (astro-ph/0405033)	30.5 kg ´ day (NDM03)	280 kg ´ day (Moriond03)	20.5 kg x day (astro-ph/0408006)
• Expt. depth	1400 m	780 m	1700 m	1100 m	1400 m
• Neutron shield	~1m of concrete + 10/40 cm polyethylene/paraffin + 1.5 mm Cd	50 cm polyethylene	30 cm paraffin	---	none
• Energy threshold	2 keVee (5.5 – 7.5 p.e./keV)	10 keVee	20 keVee	2 keVee (but: s /E=100% and 1 p.e./keVee!!!; IDM02) (2.5 p.e./keVee; Moriond03)	12 keVee
• Quenching factor	measured	assumed 1	assumed 1 (see also NIMA507(2003)643)	measured	assumed 1
• Measured evt rate in low energy range	~1 cpd/kg/keV	?? (claimed g > than CDMS-I where ~60 cpd/kg/keV, 10^5 events)	~ 10^4 events total	~100 cpd/kg/keV (IDM02)	(??) 6 cpd/kg/keV above 35 keVee
• Claimed evts after rejection procedures		0 o 1	2 (claimed taken in a noisy period!)	~20-50 cpd/kg/keV after filtering (?) and ?? after PSD (Moriond03, IDM02)	16
• Evts satisfying the signature in DAMA/NaI	modulation amplitude integrated over the given exposure some 10^3 evts	insensitive	insensitive	insensitive	insensitive
• Expected number of evts from DAMA/NaI effect		from few down to zero depending on the model frameworks (and on quenching factor)	from few down to zero depending on the model framework (and on quenching factor)	depends on the model framework, also zero	from few down to zero depending on the model framework (and on quenching factor)

1kg stage of EDELWEISS I : 3 * 320 g Ge.

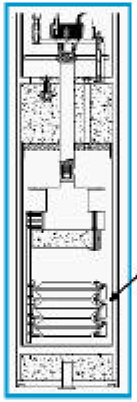
Cu screens without Roman Pb lateral shield

1st data taking: Fall 2000, 1 detector mounted and used – 3kg.d

2nd data taking : Spring 2002, 1 detector used out of 3 – 8.6 kg.d

3rd data taking : October 2002 - March 2003, 3 detect. - 19 kg.d

Exposure about 10^4 times smaller than DAMA/NaI



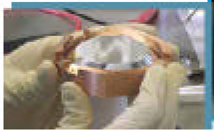
4th data taking : April -Nov 2003, 3 detectors - 30 kg.d

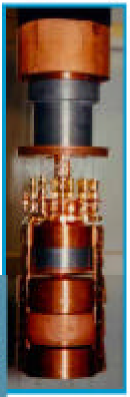
Archeological lead

3 * 320 g Ge detectors

May 2002
GGA1,GeAl9,GeAl10
October 2002
GGA3, GSA1, GSA3

320 g detector





But: quenching factor assumed 1 (the only measured value in NIMA507(2003)643 is compatible with all: 0.87±0.10%(stat) ± 10%(syst). What about if less?

Also for future claimed sensitivities: which is the limit from systematics of this approach?

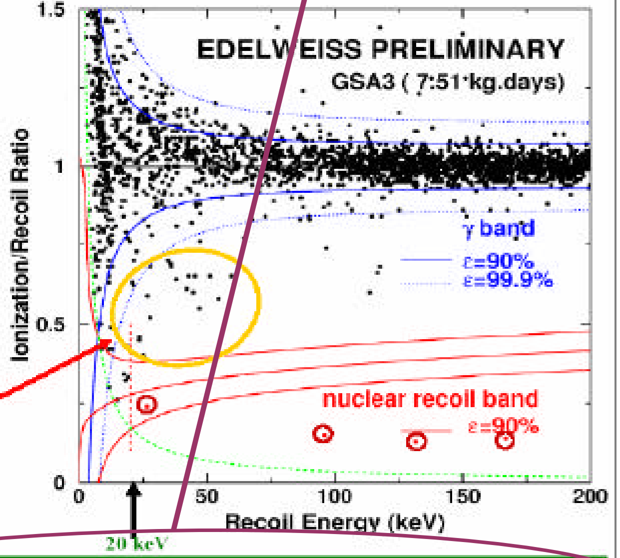
FEW COMMENTS:

- **very small exposure released with respect to several years of the experiment**
- **bckg rejection technique and associated uncertainties full under control (e.g. bulk response, pre-rejection of so-called surface electrons, quenching factors,..)? Are the two sensitive volumes (for ionization and bolometer signals) exactly identical?**
- **What about the needed continuous monitoring of rejection windows stability, energy scale and threshold, overall detection efficiency, calibration..?**
- **Set-up activation during neutron calibration**
- **Starting from a high background level**

- « Noisy » episode ?

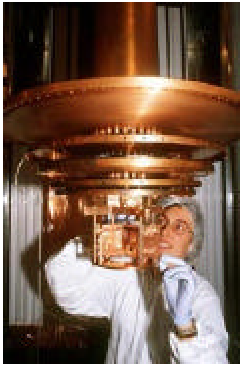
-Events in red (1 inside and 3 outside the neutron zone) all arriving within an interval of a few days out of 90 days total acq time

What about spilling of these events with 10 times more exposure ?

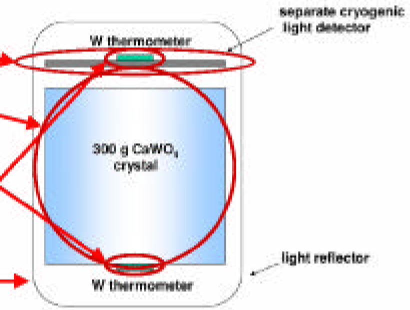


NB : 100 % efficiency at true nuclear recoil energy threshold

Cresst-II



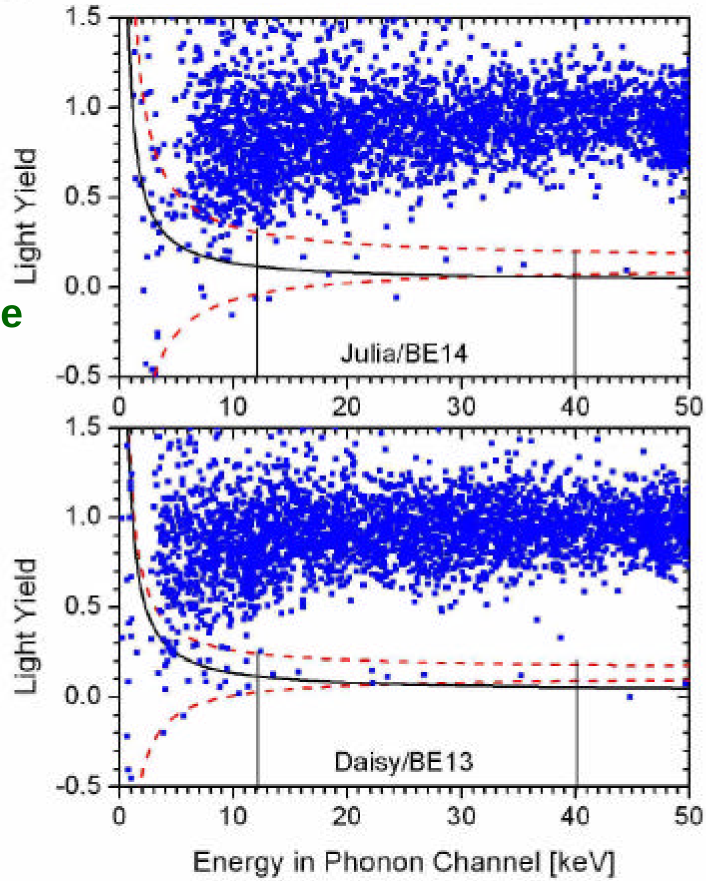
- Light detector
- $(CaWO_4)$ absorber crystal
- Two Tungsten Superconducting Phase Transition Thermometers (W-SPT)
- Light reflector



astro-ph/0408006

Exposure about 10^4 times smaller than DAMA/NaI

20.5 kg d exposure



FEW COMMENTS:

- Scintillation efficiencies at mK, light collection, absorption, efficiency for the coincidence of two signals …?
- Bckg rejection technique and associated uncertainties, q.f. etc.?
- Rejection window stability?
- Some other comments as for ionization / phonons detectors.

Also for future claimed sensitivities: which is the limit from systematics of this approach?

FAQ:
… DAMA/NaI "excluded" by CDMS-II (and others)?

OBVIOUSLY NO

They give a single <u>model</u> <u>dependent</u> result using ^{nat}Ge 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 give them …

- **In general? OBVIOUSLY NO**

The different sensitivities to the various kinds of candidates, interactions and particle mass, the accounting for realistic and consistent halo models and accounting for existing parameters uncertainties, FFs and/or SF and existing uncertainties on related parameters, different scaling laws than assumed (possible even for the neutralino candidate), their proper accounting for experimental parameters and related uncertainties, the many possible scenarios, etc. fully "decouple" the results.

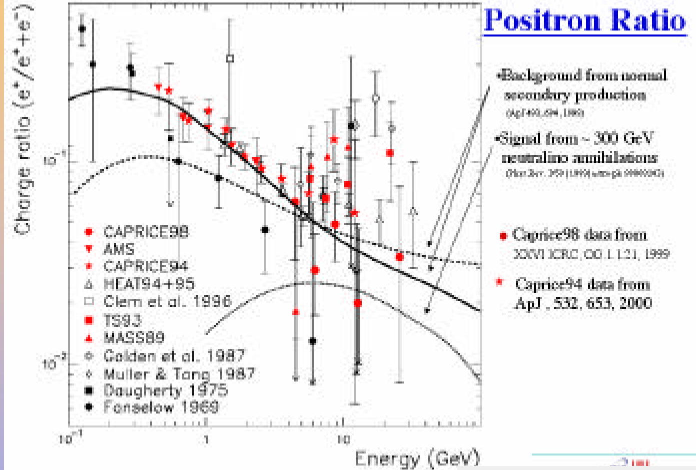
- **At least in the purely SI coupling they only consider? OBVIOUSLY NO**

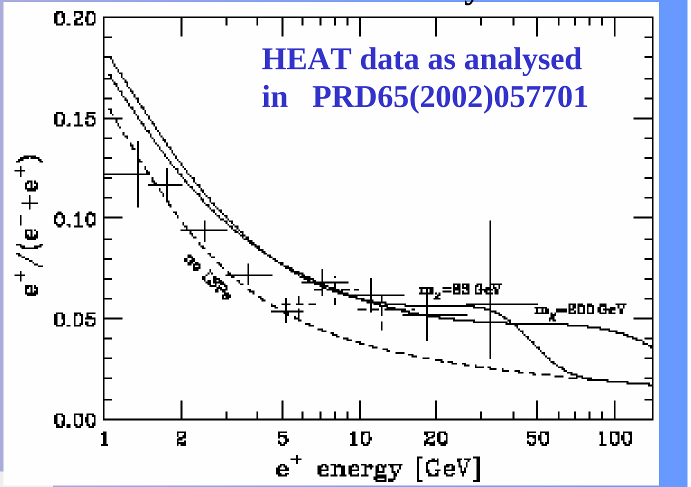
they give a single result fixing all the astrophysical, nuclear and particle physics assumptions and all the expt. and theor. parameters values….; moreover, they usually quote in an uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent result…; see above, etc.

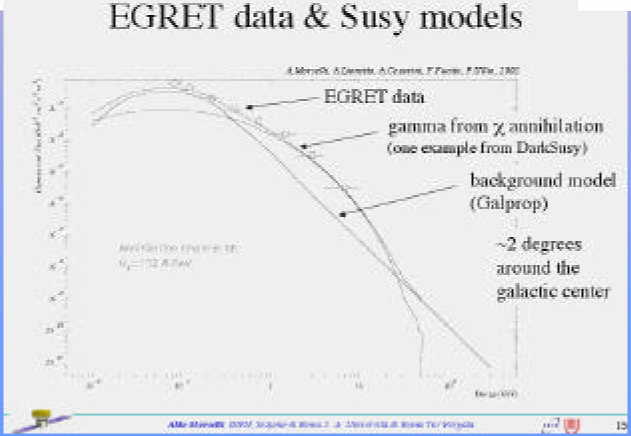
(see also in Riv. N. Cim. 26 n. 1(2003)1-73, astro-ph/0307403 and IJMPD to appear (astro-ph/0501412) and various papers in literature)

Some positive hints from indirect searches not in conflict with DAMA/NaI result

Some measurements performed by indirect search experiments have pointed out the presence of antiparticles and photons which can be ascribed to Dark Matter particles annihilations in the Galaxy







Note: interpretations, evidence itself, derived WIMP mass and cross section depend e.g. on bckg modeling, on WIMP spatial/velocity distribution in the galactic halo, etc.

In next years new data from DAMA/LIBRA and for indirect searches from Agile, Glast, Ams2, Pamela, ...

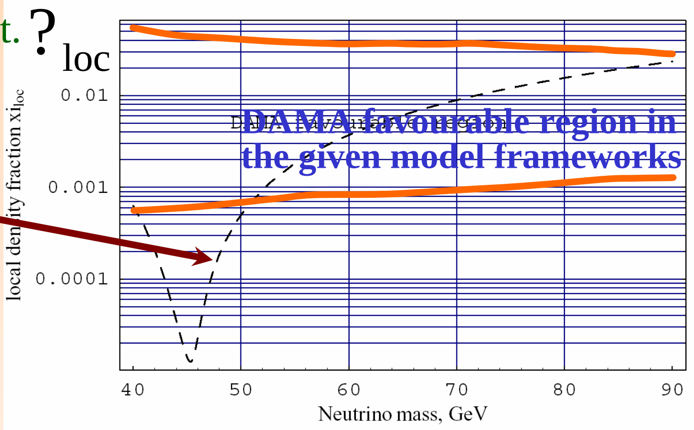
Primordial heavy n's of 4th family

from Belotsky, Fargion, Khlopov et al. (hep-ph/0411093)

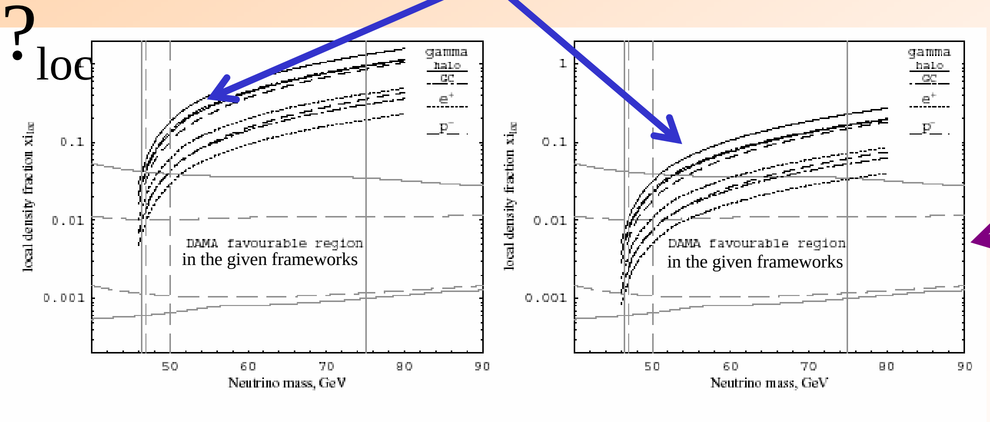
Scenario of multi-component DM consisting of a subdominant heavy neutrino component and a sterile dominant component.

$$x_{loc} = \frac{r_{loc,n}}{r_{loc}} \approx \frac{\Omega_n}{\Omega_{CDM}}; \quad \Omega_n << \Omega_{CDM}$$

for $\Omega_{CDM} = 0.3$



best-fit density parameters deduced from results on indirect detection



Including effect of possible neutrino clumpiness

Large allowable range of the 4th family neutrino mass

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

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)

PMT +HV divider

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

etching staff at work in clean room

storing new crystals

improving installation and environment

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

installing LIBRA de

assembling a DAMA/ LIB

DAMA/LIBRA running since March 2003
Waiting for a larger exposure than DAMA/NaI

detectors during installation; in
he central and right up detectors
the new shaped Cu shield
g light guides (acting
ptical windows) and
Ts was not yet applied

filling the inner Cu box with further shield

closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

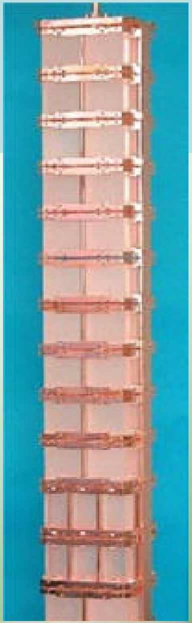
Some of the other perspectives for direct detection experiments

Bolometers:

- double read-out

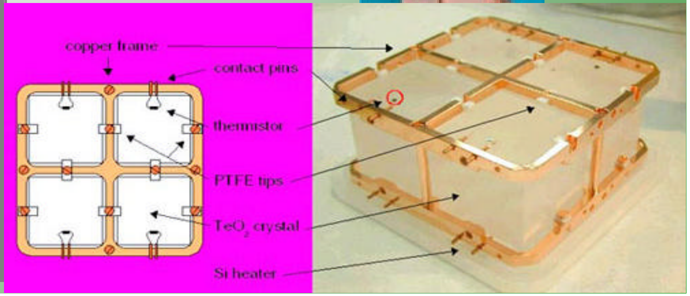
Present difficulties and uncertainties (see above) may be fixed in near future? Duty cycle?cost/benefits?Asymptotic limit in the discrimination from systematics ? → wait for more...

- low-background with single read-out : → wait for CUORE



Large Xenon set-ups?

- very expensive
- Kr-free Xe mandatory
- high gas purification in large volumes difficult to achieve and maintain at fixed level
- light and charge collection critically depend e.g. on thermodynamical parameters and phases interfaces
- cryogenic system complexity
- safety problems
- less competitive duty cycle
- difficult noise rejection →higher threshold
- each liquefaction re-builds the sensitive detector part (reproducibility at the needed level for claimed reachable sensitivities?)
- most of physical quantities depend on the specific features of the set-up (light response, light attenuation lenght, quenching factor, etc.; values strongly depend on the specific technical realization, see literature)
- Asymptotic limit in the discrimination from systematics ?
- etc. etc. → New R&Ds ?



Summary

Particle Dark Matter investigation can offer complementary information on cosmology and particle Physics

- ✓ Annual modulation signature very effective method successfully exploited by DAMA/NaI over 7 annual cycles (~ 1.1 x 10^5 kg day) obtaining a 6.3 σ C.L. model independent evidence for the presence of a Dark Matter particle component in the galactic halo
- ✓ The complexity of model dependent results (either exclusion plots or allowed regions) and of model dependent comparisons pointed out
- ✓ **DAMA/LIBRA (~250 kg NaI(Tl)) now running since march 2003**

… wait for an exposure larger than that of DAMA/NaI

…and beyond?

- ***multi-purpose NaI(Tl) ton set-up (R. Bernabei, IDM96)***
- ***new ideas to fully exploit signal peculiarities and halo features***

Many other complementary developments in progress

@LNGS: GENIUS-TF running, CUORE and WARP in developments

Some different kinds of approaches can offer complementary results