Dark Matter searches

7th School on non-accelerator Astroparticle Physics

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Interdisciplinary field: Particle Cosmology

Particle Physics
studies on nature
at smallest scale

Cosmology
studies on nature
at largest scale

to investigate the initial condition when the fundamental particles and forces produced the perturbation in the cosmic density field

⟷

to investigate the origin and the evolution of the largest-scale structure

Possibility to investigate physics beyond the Standard Model

Early Universe → **Ultimate particle accelerator?**

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

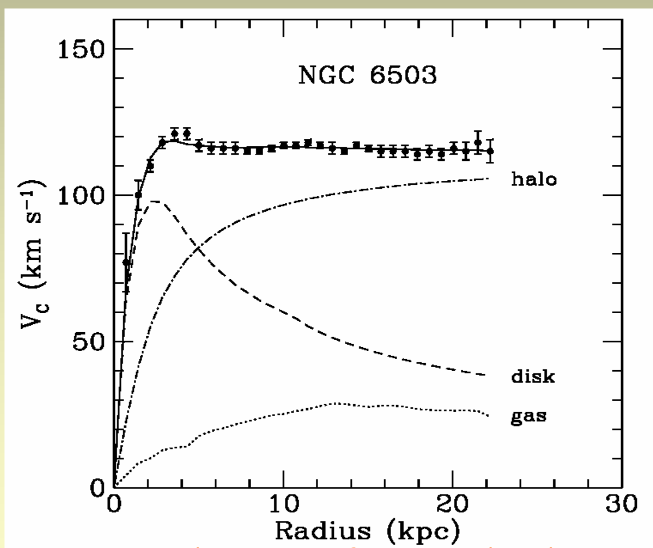
COMA Cluster

First evidence and confirmations:

1933 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

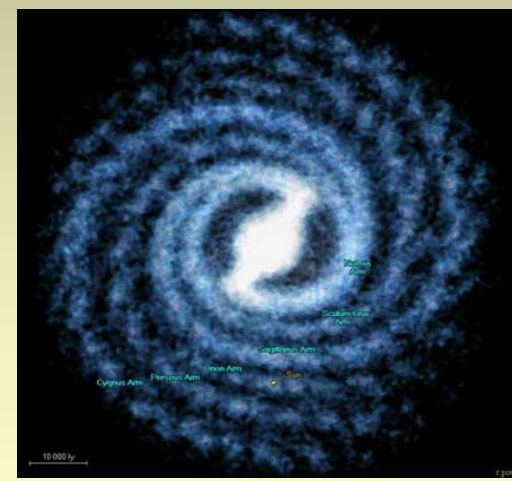
1974 two groups: systematical analysis of mass *density* vs *distance from center* in many galaxies



Rotational curve of a spiral galaxy

Other experimental evidences

- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters



Milky Way

$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ $\Rightarrow$ about 90% of the mass is DARK

From cosmology...

Standard cosmology + Standard inflationary scenario $\Rightarrow$ $\Omega = \rho/\rho_c = 1$

$$\rho_c = \frac{3H_0^2}{8\pi G} = 1.88 \cdot h^2 \cdot 10^{-29} g/cm^3$$

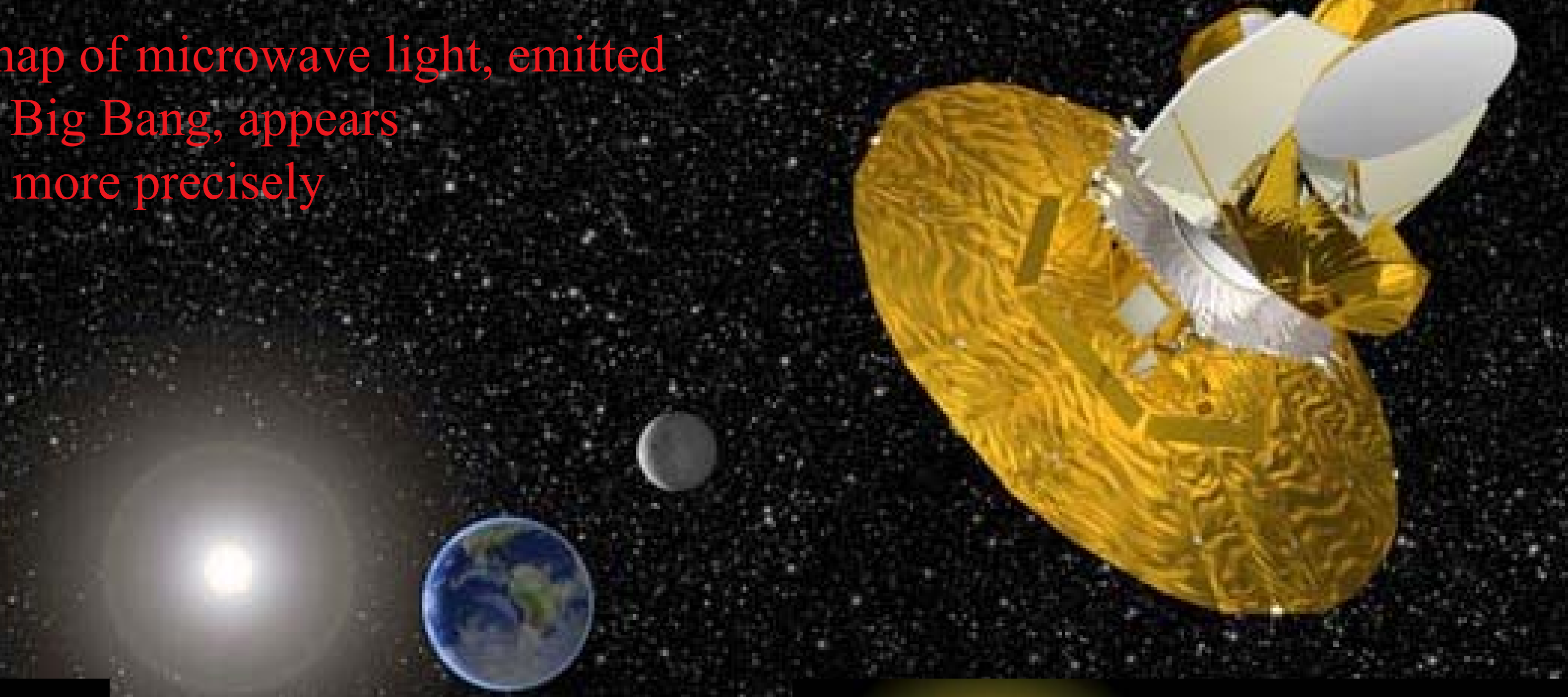
Cosmological Constant $\Lambda \neq 0$ $\Rightarrow$ Ω (Luminous+Dark Matter) **= 0.5 - 0.1**

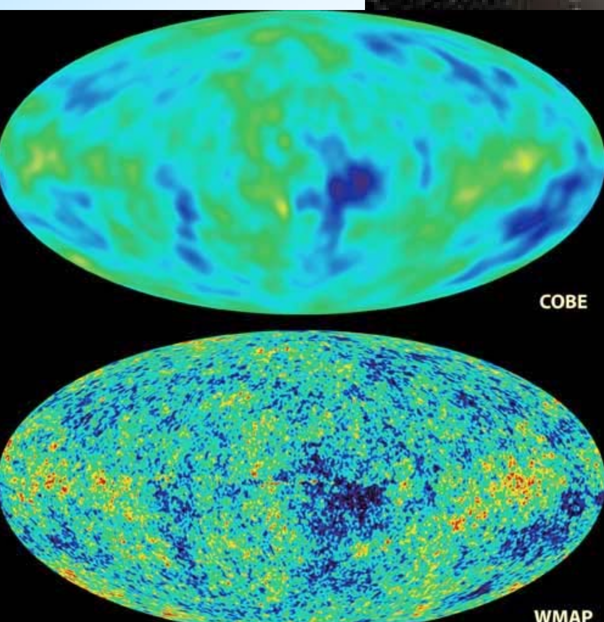
...and from observations

	R (kpc)	$\Omega = \rho/\rho_c$
•Visible part of galaxies	10	~0.007
•Galactic haloes	50 - 100	~0.02 - ~0,2
•Clusters	10^3 - 10^4	~0.2
•Collapse on Virgo cluster	10^4	~0.2
•Collapse on large scale	$3 \cdot 10^4$	~ 0.2 - ~1
•IRAS measurements on large scale velocity flow	10^5	~1

Wilkinson Microwave Anisotropy Probe (WMAP)

New high-resolution map of microwave light, emitted 380000 years after the Big Bang, appears to define our Universe more precisely

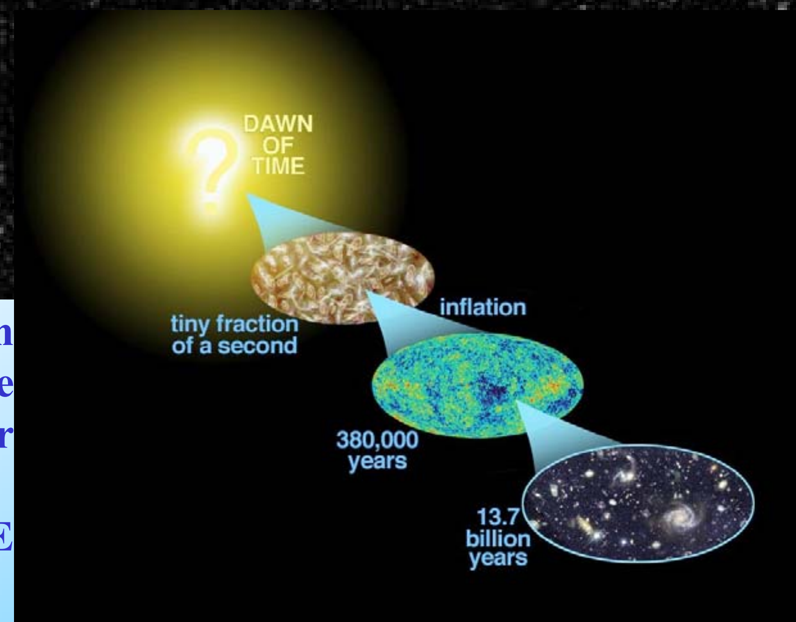




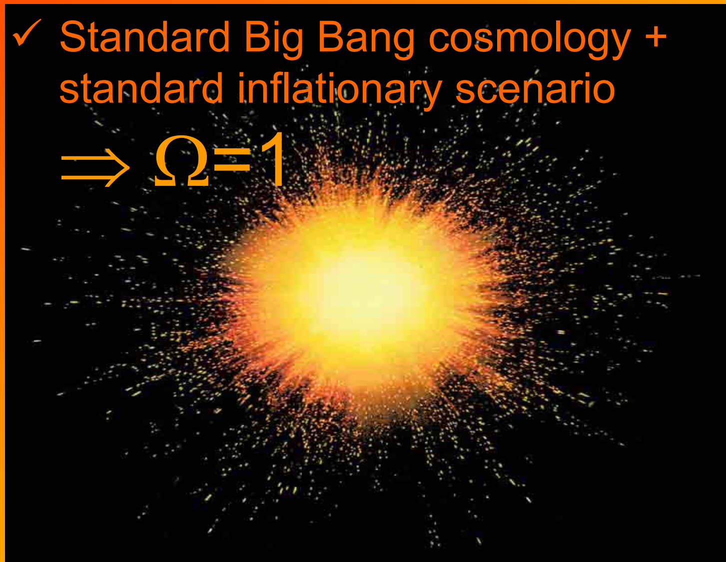
An all-sky image of the infant Universe 380000 years after the Big Bang.

In 1992, NASA's COBE mission firstly detected tiny temperature fluctuations (shown as color variations).

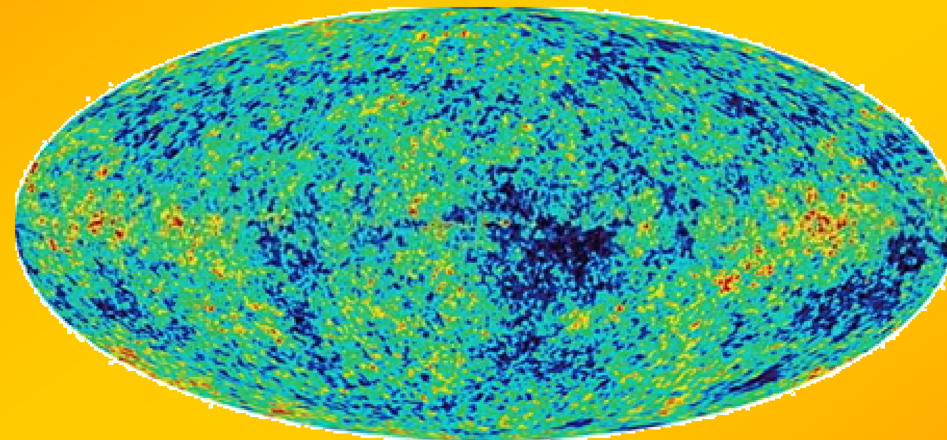
The WMAP image brings the COBE image into sharp focus.



... and support from cosmology

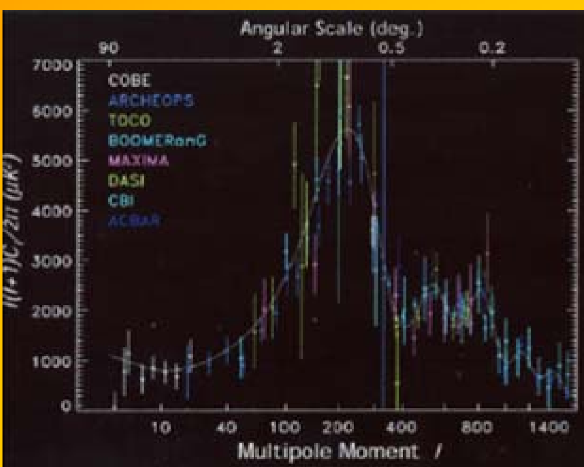


Power Spectrum: CMB measurements

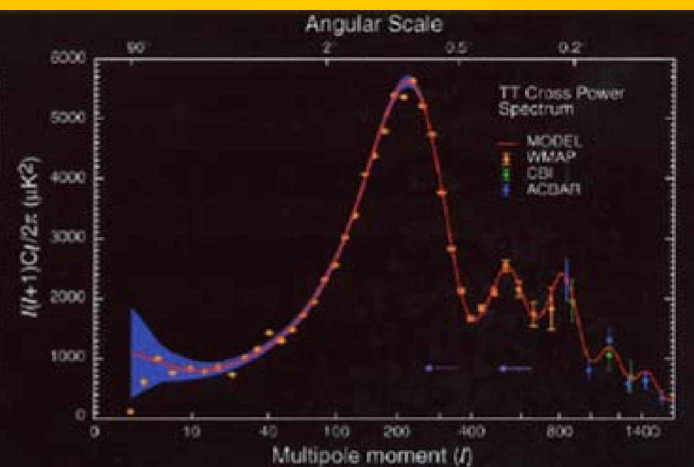


The dynamical evolution of the Universe depends on the quantity and kind of mass and energy densities. The curvature radius of the Universe is related to Ω .

before WMAP



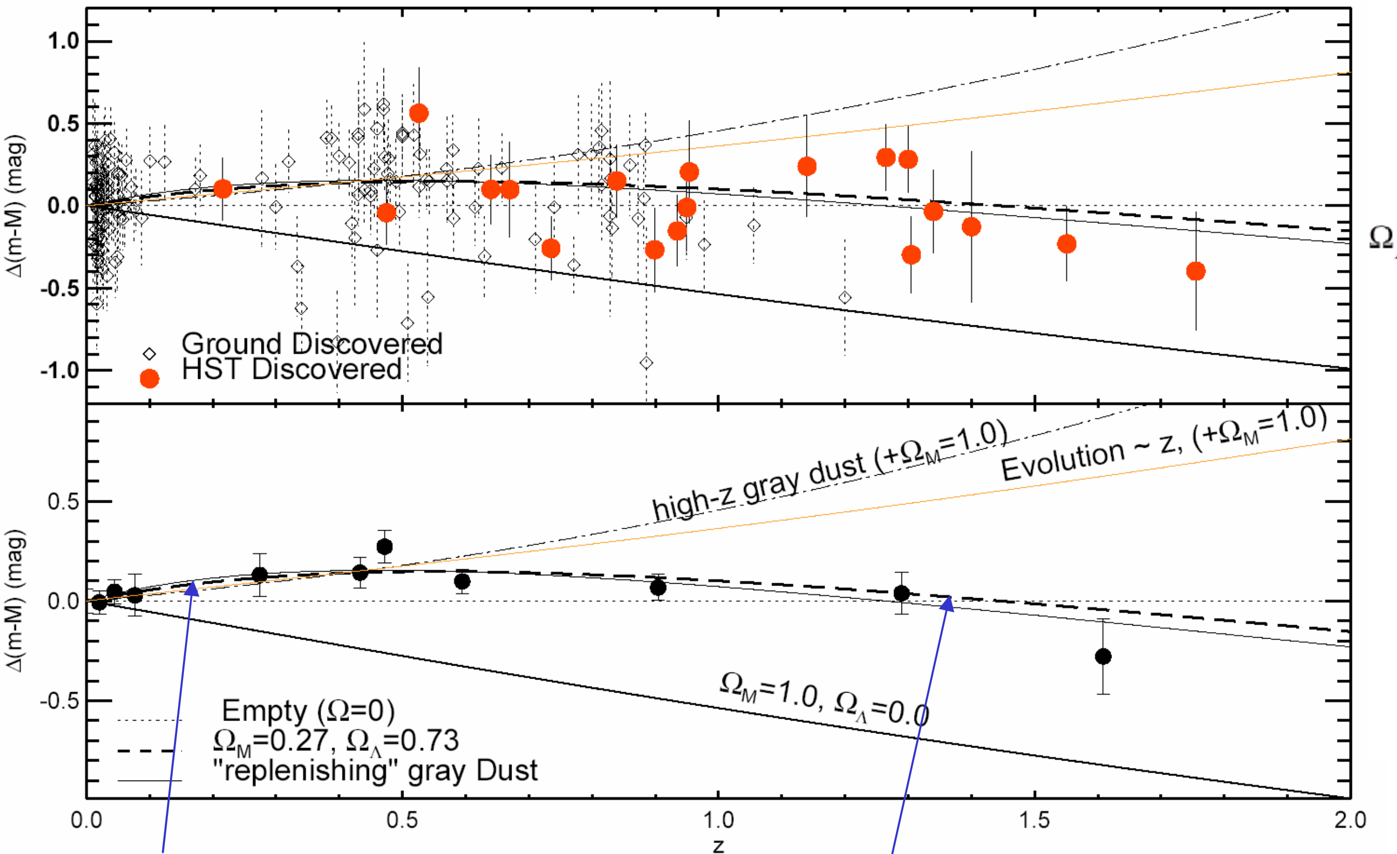
WMAP data

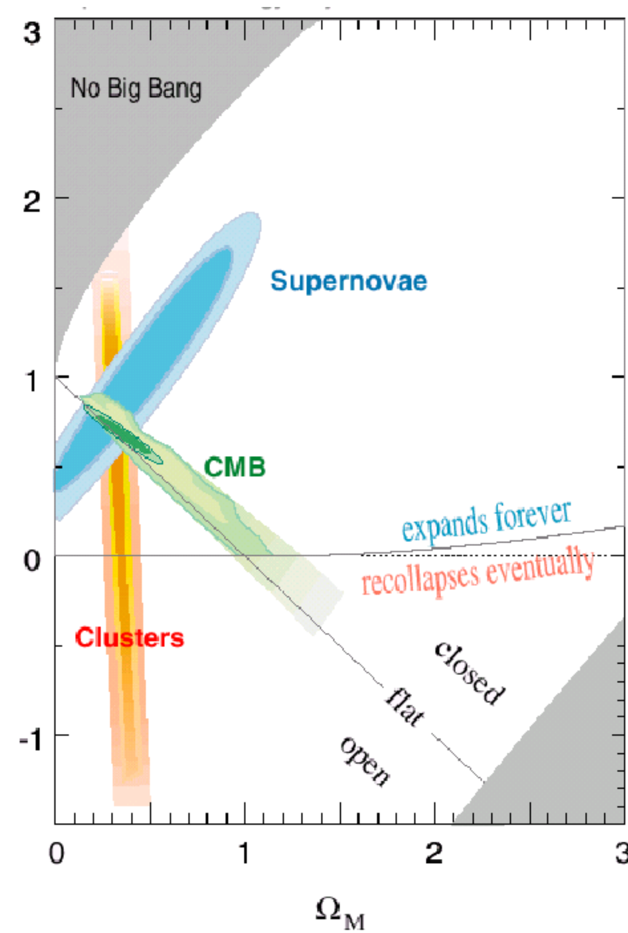


A significant presence of Cold Dark Matter ($\Omega_{CDM} \approx 0.23$) is necessary to reproduce the present cosmological observation

COSMOLOGICAL CONSTANT?

SN Ia standard candle





Accelerating Universe dominated by Λ

Decelerating Universe dominated by (dark) matter

$$\Omega_\Lambda \approx 0.73; \quad \Omega_M \approx 0.27$$

~ 90% of the matter in the Universe is non barionic

A cosmological constant?

Quantum gravity would predict its value to be 10^{120} times the observed value, perhaps it could be zero only in the presence of an unknown symmetry.
A vacuum energy? Does it evolve with time? A quintessence field?

The dark energy? A mystery

Cosmology

About it :

1) It should emit/absorb no light
2) It should have negative pressure, with magnitude comparable to its energy density in order to produce accelerated expansion
3) It should be "approximately" homogeneous
4) It should not interfere with production of structure but it could decide the future of Universe

Particle physics

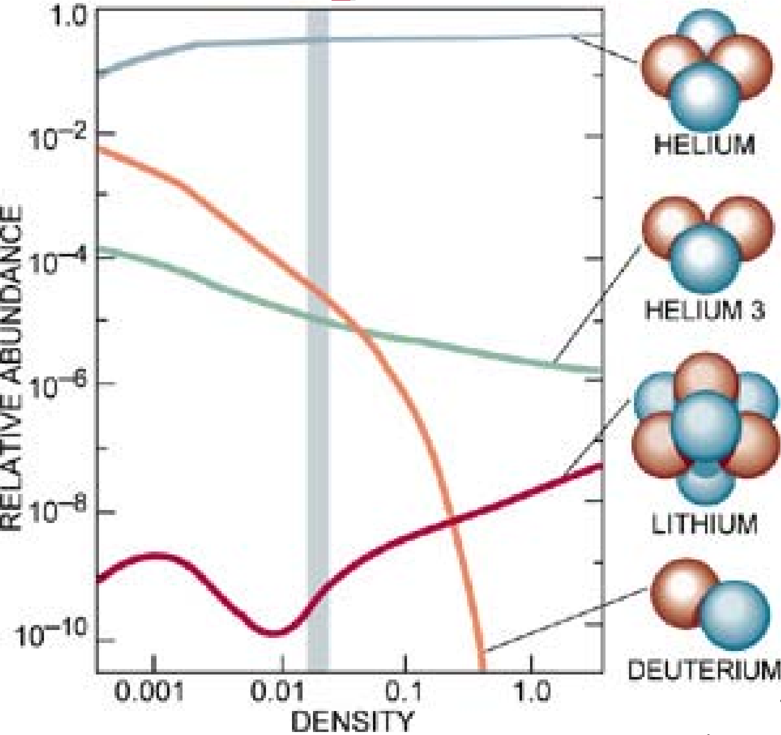
A direct remnant of string theory ??

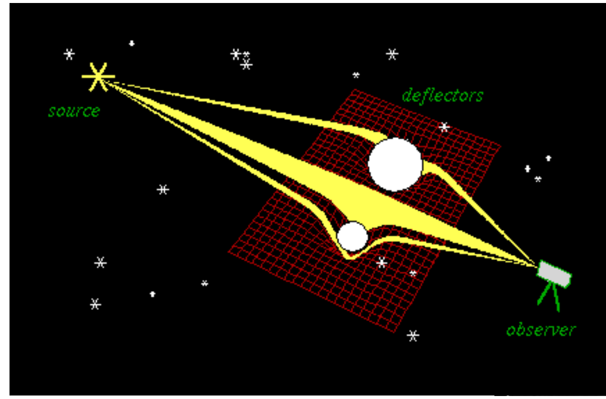
Are dark matter and dark energy connected through axion physics?

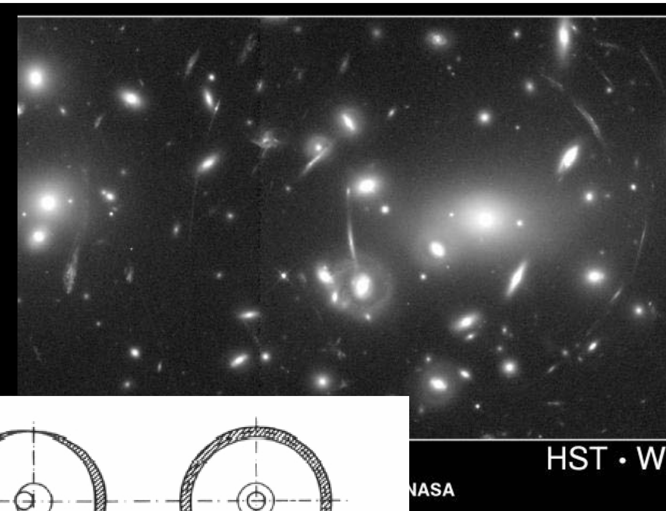
Is there a case of "vacuum energy" or "quintessence" in particle physics?

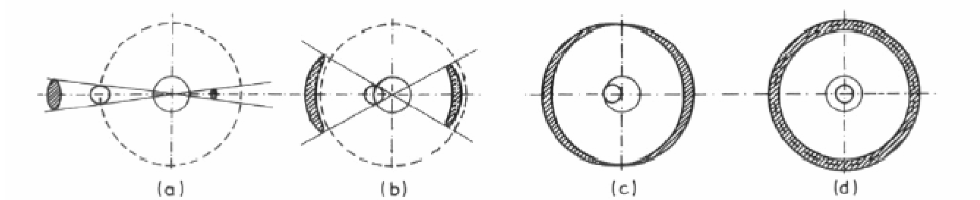
If elementary particles could couple to quintessence field , there could be exotic signatures detectable at accelerator and by astrophysical experiments

Nucleosynthesis + searching for barionic D.M.



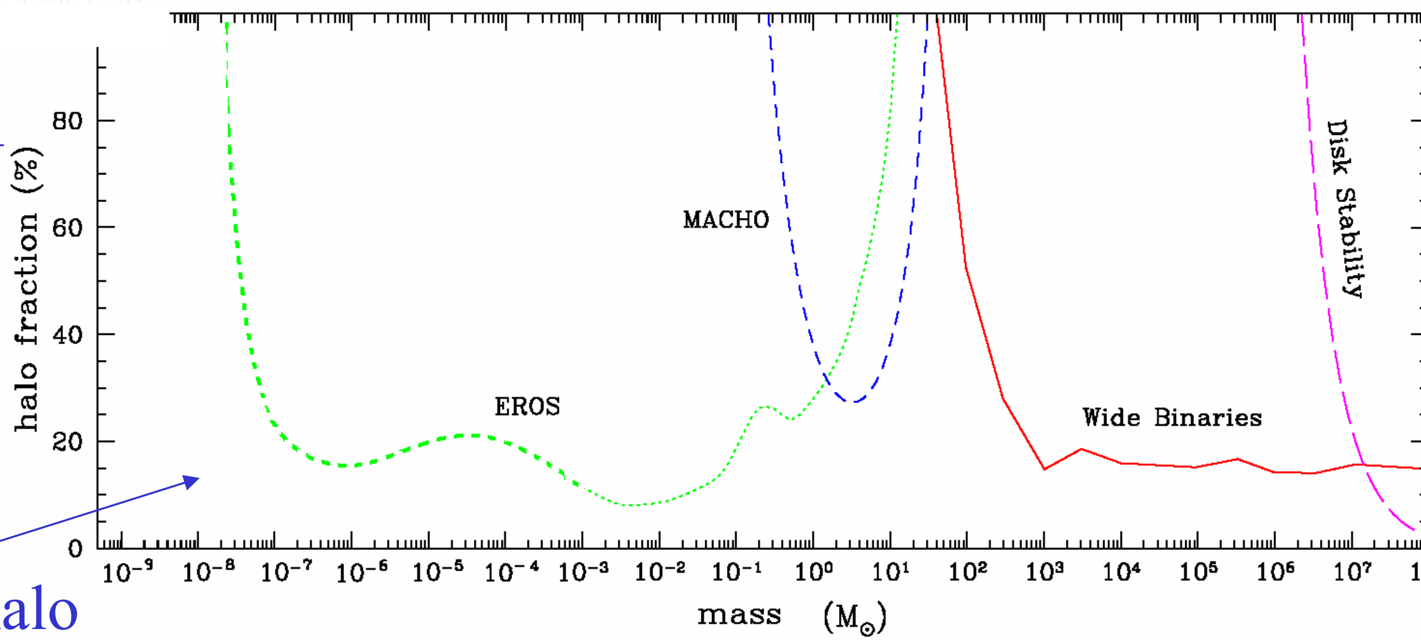






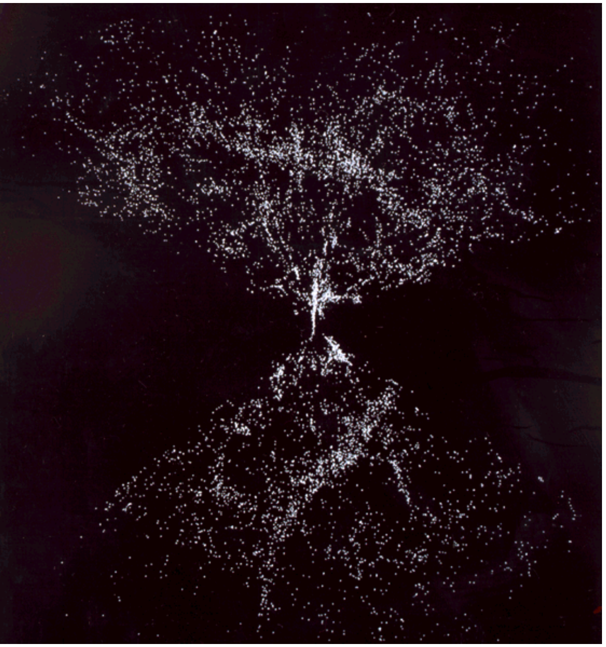
$$\Omega_b h^2 \approx 0.02$$

MACHOs: non luminous astrophysical compact objects (brown dwarf, faint stairs, planets)

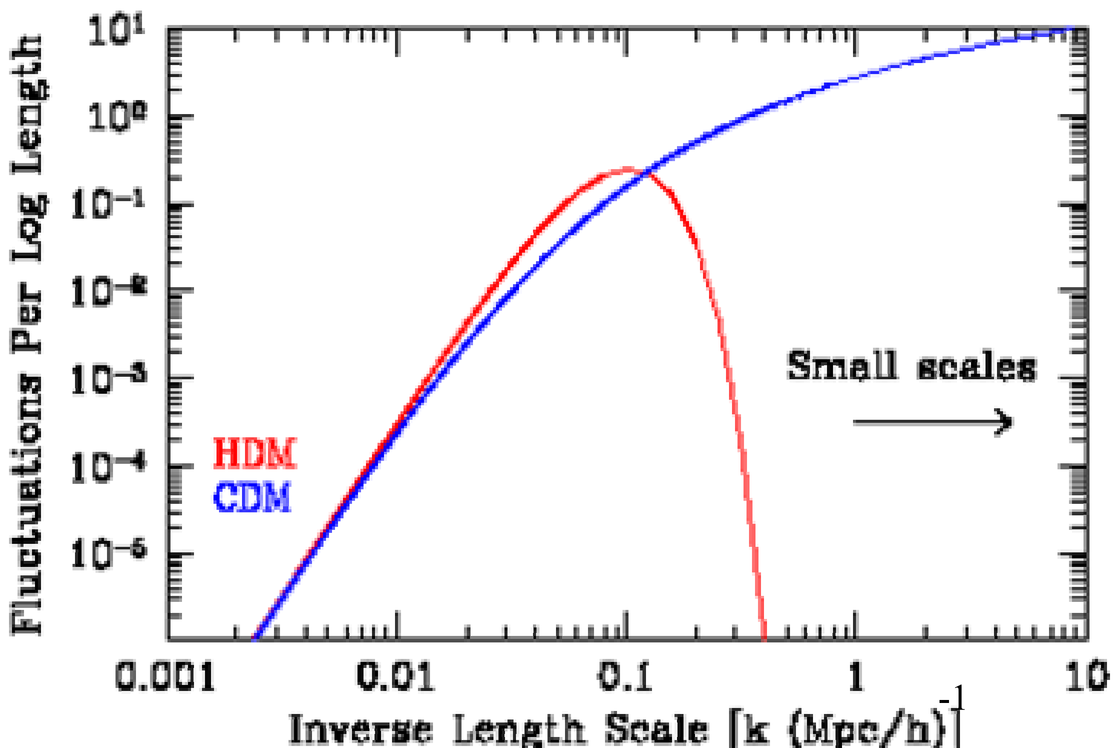


< 10% of the galactic halo

Structure formation in the Universe and nature of the non baryonic D.M.



To obtain the pattern of the present large scale structures from the evolution of the primordial perturbations is necessary to assume the existence of non baryonic D.M., that is of particles relicts from Big-Bang. In this scenario, the structures observed at present have been originated by the "gravitational trapping" of the baryonic matter by the non baryonic D.M. (seed)



HDM scenario (light massive ν …): particles relativistic at decoupling time

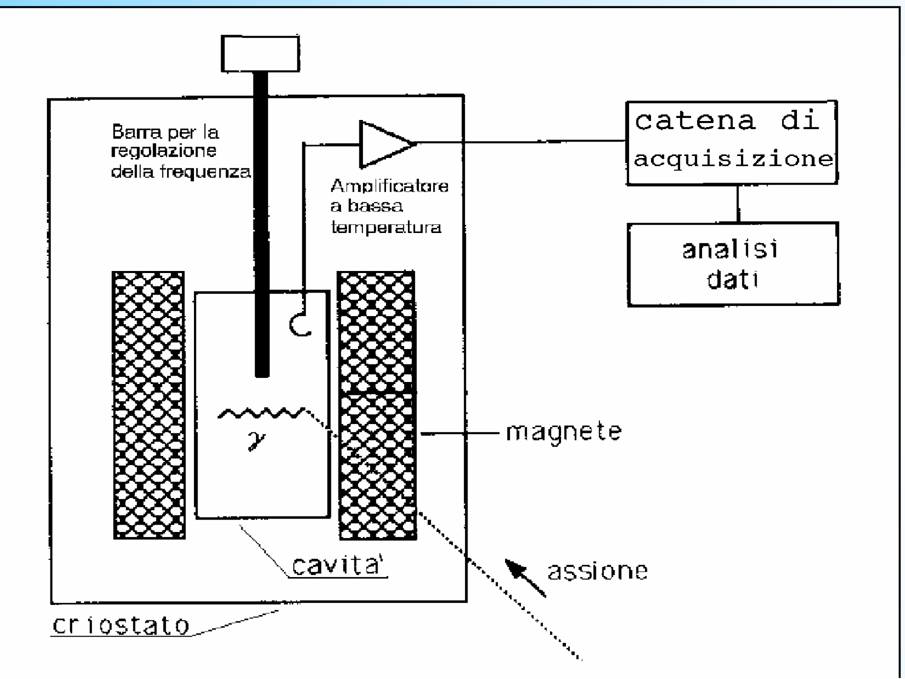
CDM scenario (WIMPs, axions ..): particles non-relativistic at decoupling time

But HDM does not produce small scale structure !

Axions

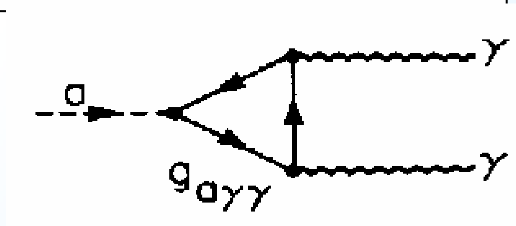
- In 1977 the axion was introduced as the Nambu-Goldstone pseudo-boson of the R.D.Peccei and H.Quinn symmetry [$U_{PQ}(1)$] proposed to explain CP conservation in QCD. The axion mass, m_a, and the coupling constants are proportional to $1/f_{PQ}$; (the inverse of the scale breaking of $U_{PQ}(1)$ symmetry)

Relic axions searches



- By resonant cavity.
- In the cavity a static magnetic field of several Tesla is present.
- The temperature of the cavity is few Kelvin
- The resonant frequency can be tuned to the (unknown) axion mass by moving dielectric bars. The resonant condition yields enhanced conversion of axions into photons in the static magnetic field of the cavity.

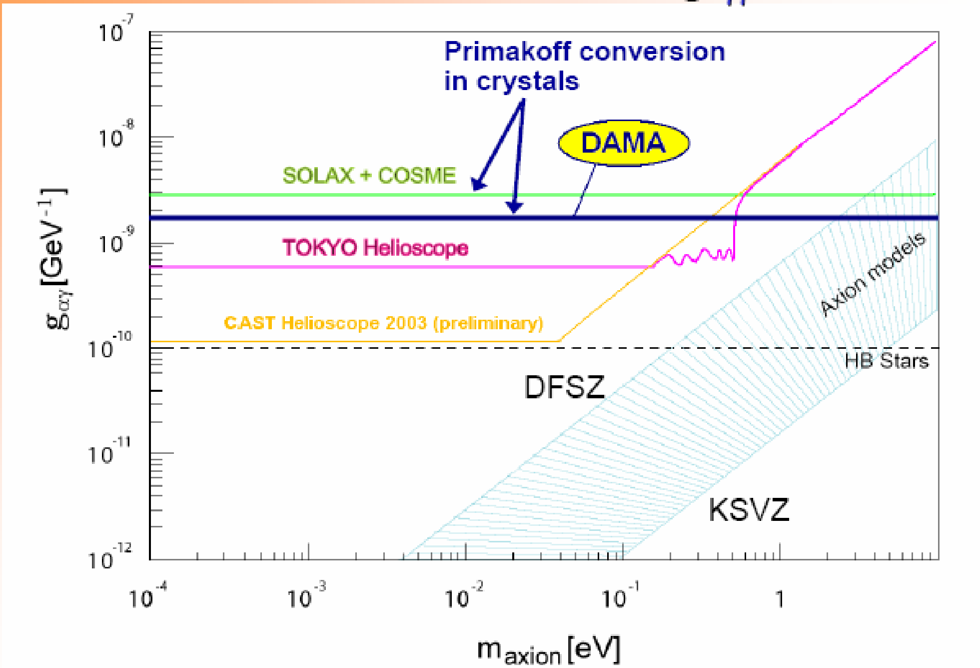
Typical diagram:



observed photon

static magnetic field (virtual photon)

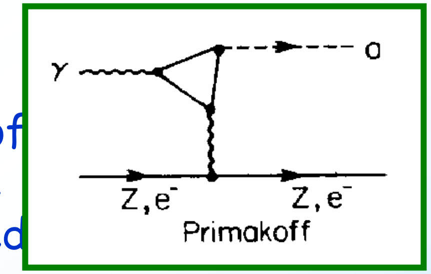
Searches by RBF, UF, LLNL down to m_a of order of few μeV



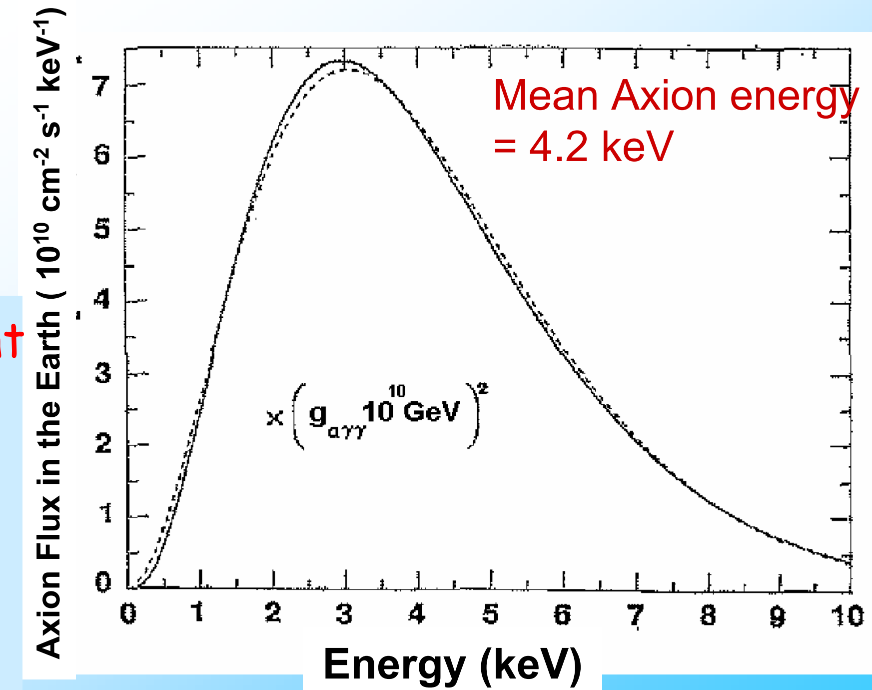
Solar axions' searches

- DAMA limit is the most stringent for Primakoff conversion in crystals
- It is independent on the axion mass m_a
- For $m_a > 0.3$ eV is the best limit obtained by direct search
- Exclude the KSVZ model for $m_a > 4.6$ eV (but exist a region allowed for $m_a \approx$ eV)

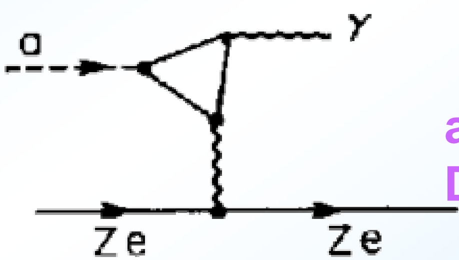
Inside the sun axions are produced by Primakoff conversion of thermal photons in the electric field generated by the particles of the solar plasma (T ~ 1.3 keV).



$$L_{a\gamma\gamma} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



Solar axion's searches by Primakoff coherent conversion of axions in crystal detector



approach followed by DAMA/NaI (PLB515(2001)6)

The WIMPs

relic CDM particles from primordial Universe

- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time
- $<\sigma_{ann} \cdot v> \sim 10^{-26}/\Omega_{WIMP}h^2 \ cm^3 s^{-1}$ → $\sigma_{ordinary\ matter} \sim \sigma_{weak}$
- Expected flux: $\Phi \sim 10^7 \cdot (GeV/m_W)\ cm^{-2}\ s^{-1}$ $(0.2 < \rho_{halo} < 0.7\ GeV\ cm^{-3})$
- Form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}c$)

Searching for a candidate

✓ neutral
✓ stable (or with τ ~ age of Universe)
✓ massive
✓ weakly interacting

the sneutrino in the Smith and Weiner scenario

SUSY
R-parity conserved → LSP is stable
LSP (neutralino, sneutrino,gravitino, axino)

mirror dark matter

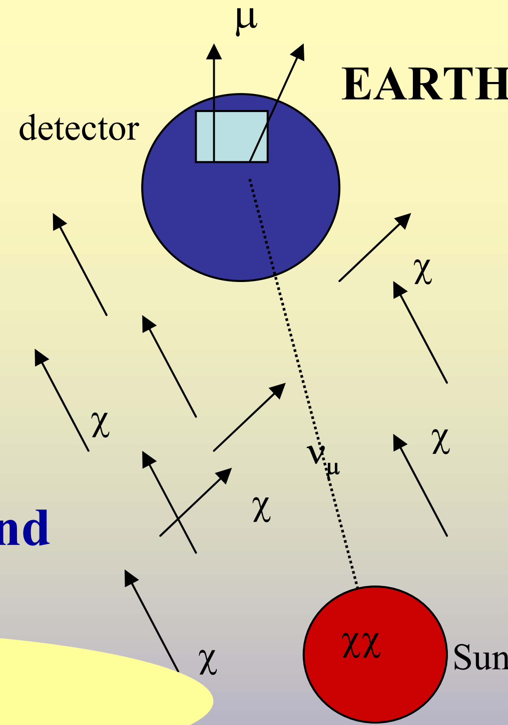
a heavy ν of the 4-th family

&

Kaluza-Klein particles

even a particle not yet foreseen by theories

Indirect detection



WIMPs may accumulate in Sun/Earth, in galactic halo

↓

annihilate

↓

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

↓

Search for an excess over the (largely unknown) background

e^+ signature

- **Search for positron excess in cosmic rays**
- **space detectors**

ν_μ signature

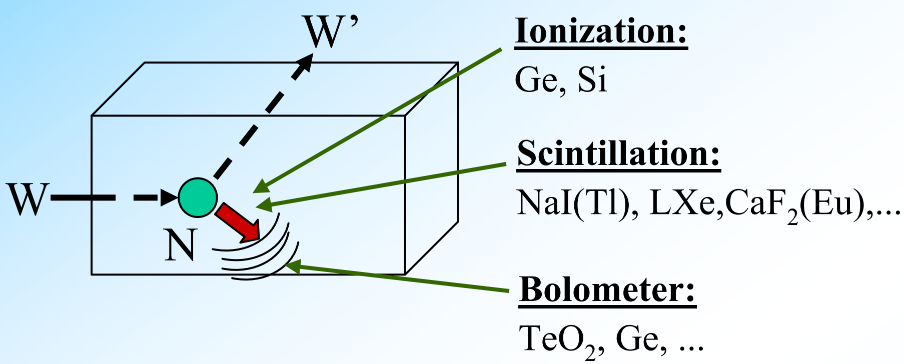
- **Best signature from ν_μ producing up-ward going μ**
- **Underground, underwater, underice detectors**

... either in the space to search for anti-matter and monoenergetic γ's
... or with very large EAS detectors at surface

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

WIMP direct detection strategies

- **Direct detection:** different techniques applied mostly giving only a model dependent result and several still at R&D stage



	Experiment	Site	Target
Ionization	UCSB-UCB-LBL(+Saclay in Si) Neuchatel-Caltech-PSI USC-PNL-Zaragoza IGEX H/M-HDMS (Heidelberg-Moscow) GENIUS-TF	Oroville St. Gottard Canfranc Canfranc,Baksan Gran Sasso Gran Sasso	Ge,Si Ge Ge Ge Ge Ge
Scintillation	DAMA DAMA/LIBRA (250 kg) ANAIS ELEGANT V ELEGANT IV UKDMC(IC-Sheffield-RAL) ZEPLIN-I	Gran Sasso Gran Sasso Canfranc Oto Oto Boulby Boulby	Na,I,,Xe,Ca, F Na,I Na,I Na,I Ca,F Na,I Xe
Bolometers	Mi-Beta CUORICINO 42 kg CRESST-I ROSEBUD Japan coll.	Gran Sasso Gran Sasso Gran Sasso Canfranc Kamioka	TeO_2 TeO_2 sapphire sapphire LiF
Bolometers/ Ionization	EDELWEISS-I, II CDMS-I	Frejus Shallow depht	Ge Ge,Si
Bolometers/ light	CRESST-II ROSEBUD-II	Gran Sasso Canfranc	Ca,W,O Ca,W,O,BGO
In construction, R&D,proposal etc	ORPHEUS, PICASSO, SIMPLE, CUORE, GENIUS, GEDEON, DRIFT, ZEPLINII, XMASS, CDMS-II, CsI (Korea),Warp		

More widely considered detectors for WIMP direct search

Scintillators (NaI(Tl)):

- → conversion of recoil energy in light, collected by PMT
- → Very good light output ($\approx 4 \times 10^4$ photons @ 1MeV)
- → linear response for a wide range of energy
- → pulse decay time ≈ 230 ns
- → refraction index 1.85
- → $\lambda_{max} = 415$ nm

Semiconductors:

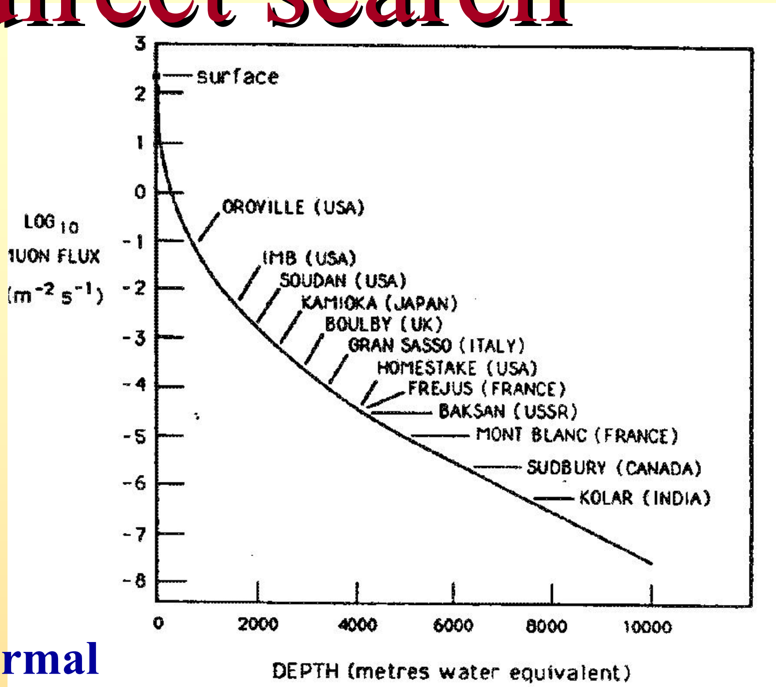
- → p-n junction
- → production and consequently collection of electron and hole pair produced by energy absorbtion
- → ≈3 eV to produce 1 electron-hole pair ⇒ high energy resolution
- → cryogenic system for Germanium detector

Cryogenic Microcalorimeters or Bolometers:

- → increase in temperature (production of phonons) due to energy absorbtion from incident radiation
- → heat capacity (C_p) of dielectric materials or crystals $\propto T^3$
- → electrical signal provided by thermistor or superconducting film
- → pulse height: $\Delta T = \Delta E / C_p$
- → phonons energy ≈ meV ⇒ good energy resolution but noise due to thermodynamic fluctuations (f_{th}) at phonon level, $f_{th} \propto T^5$
- → random variations in the flow of phonons across the thermal coupling between the absorber and the sorrounding materials
- → material: silicon, germanium, TeO_2, Al_2O_3, $CaWO_4$

Goals for the WIMP direct search

- Underground site
- Low bckg hard shields against γ's, neutrons
- Lowering bckg: selection of materials, purifications, growing techniques, ...
- Rn removal systems



Background sources

- Background at LNGS:

muons → **$0.6\ \mu/(m^2h)$**

neutrons → **$1.08 \cdot 10^{-6}\ n/(cm^2s)$ thermal**

$1.98 \cdot 10^{-6}\ n/(cm^2s)$ epithermal

$0.09 \cdot 10^{-6}\ n/(cm^2s)$ fast (>2.5 MeV)

Radon in the hall → **$\approx 30\ Bq/m^3$**

- Internal Background:

selected materials (Ge, NaI, AAS, MS, ...)

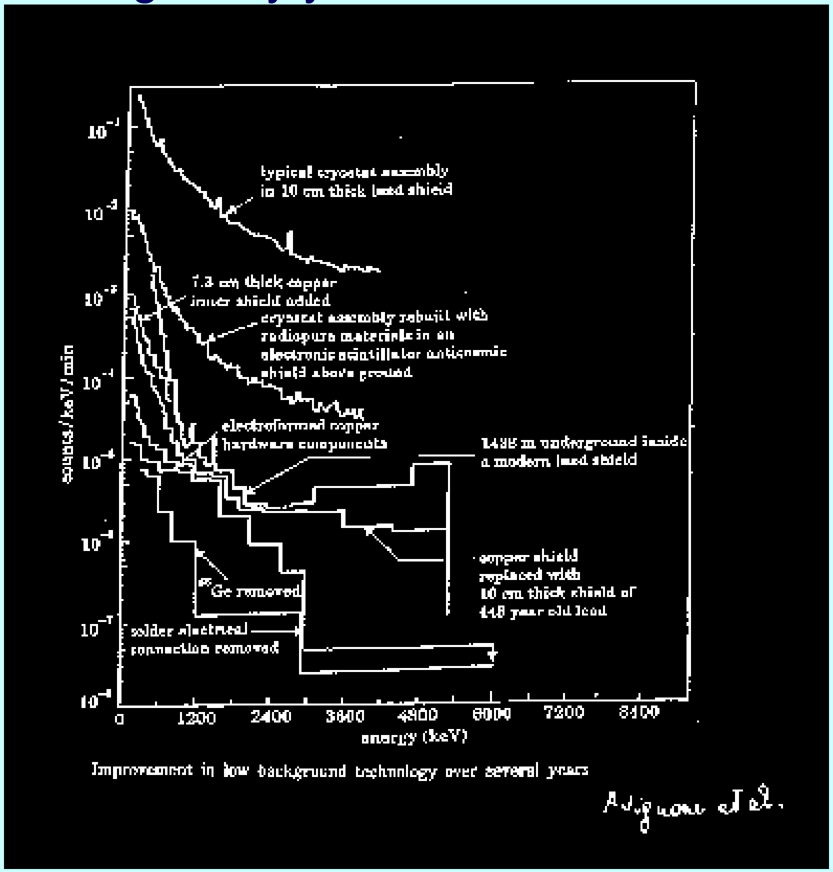
Shielding

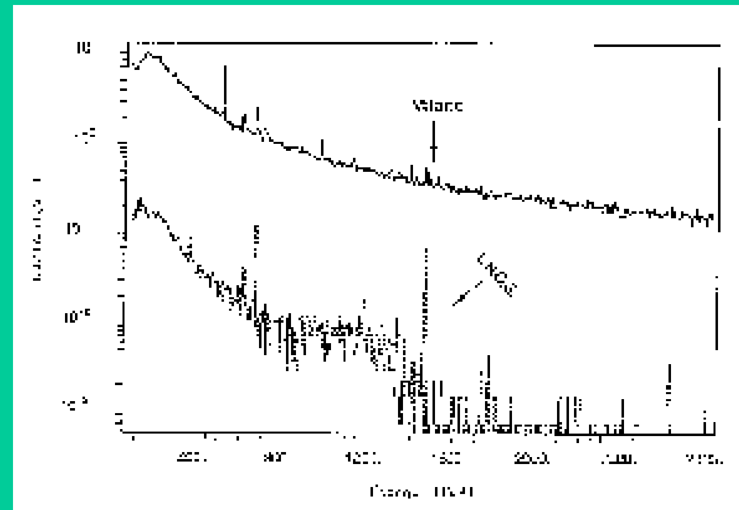
Passive shield: Lead (Boliden [< 30 Bq/kg from ^{210}Pb], LC2 [<0.3 Bq/kg from ^{210}Pb], lead from old roman galena), OFHC Copper, Neutron shield (low A materials, n-absorber foils)

Active shield: Low radio-activity NaI(Tl) surrounding the detectors

Lowering the background

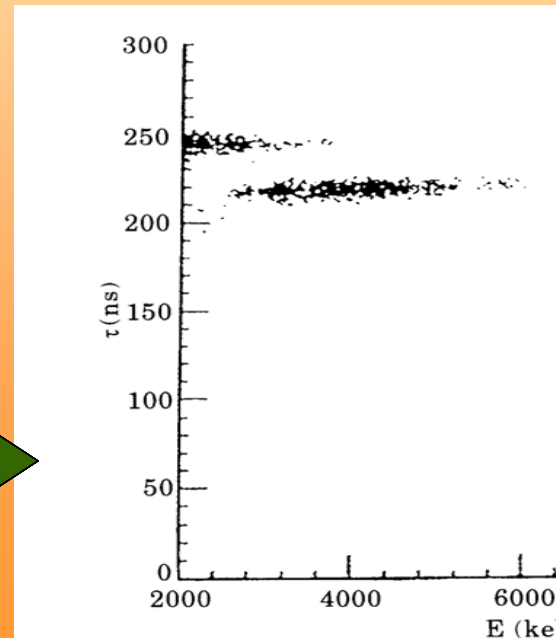
Example of background reduction during many years of work





Reduction from the underground site

U/Th residual contamination in the ≈100 kg NaI(Tl) DAMA set-up



Detector	U + Th (ppt)
1	6.5
2	8.8
3	8.2
4	11.6
5	9.9
6	11.3
7	15.3
8	3.8
9	3.8

Now, improvements from chemical/physical purification of the powders (see DAMA/LIBRA, 250 kg NaI(Tl))

Limitations of electromagnetic background rejection approaches

1. Pulse Shape Discrimination (τ of the pulse depends on the particle) in scintillators (NaI(Tl), LXe,…)

2. Heat/Ionization (Ge,Si)

3. Heat/Scintillation (CaF_2(Eu), $CaWO_4$)

1. Limitations in PSD in scintillators from temperature (+possible systematics peculiar of the given expt)

2. Limitations in bolometers from the identification of the two sensitive volumes, efficiency of the required coincidences, stability of the selection windows, quenching factors, etc. (+possible systematics peculiar of given expt)

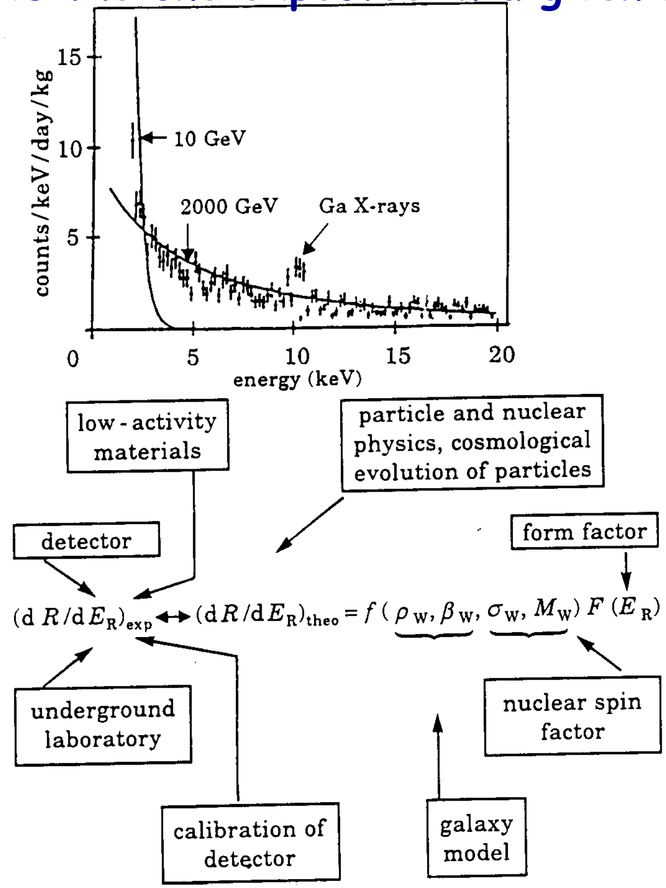
In all kinds of techniques: end-range α's, unshielded environmental neutrons, fission fragments, etc. can mimic the WIMP recoils

⬇

Always not a WIMP signature!

The "traditional" approach

- Experimental energy distribution (with or without bckg rejection) vs the one expected in a given model framework

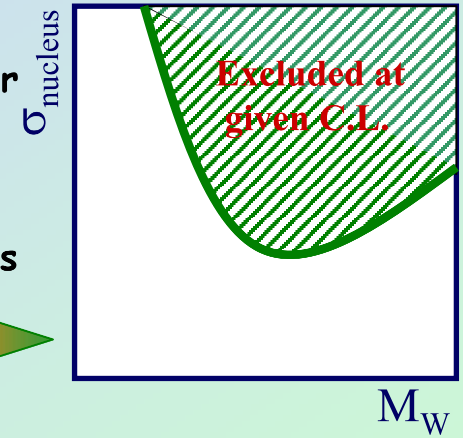


several assumptions and modeling required

+

experimental and theoretical uncertainties generally not included in calculations

Exclusion plot for a fixed set of assumptions and of expt and theor.parameters values



by additional model: σ_p

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

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

- No discovery potentiality
- Uncertainties in the exclusion plots and in their comparison
- Warning: limitations in the recoil/background discrimination

A WIMP model independent signature is needed

Directionality Correlation of nuclear recoil track with Earth's galactic motion due to the distribution of WIMP 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 WIMPs
only for high σ

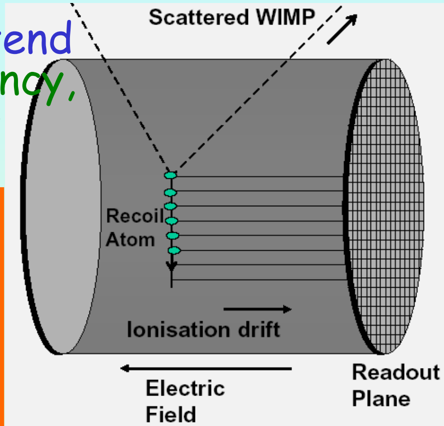
Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun.
at present the only feasible one

Which signature for WIMPs?

- Directionality
- Correlation of the track of the nuclear recoil with Earth's motion in the Galactic halo

- Hard to realize if the track has to be detected: e.g. in low pressure TPC (old Saclay R&D).

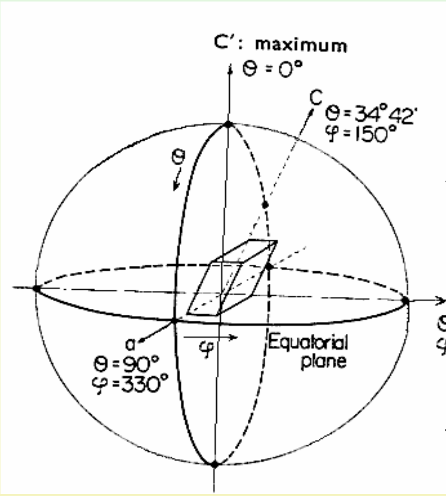
DRIFT at Boulby: TPC + ion drift with CS_2 low pressure (<100 Torr) to extend recoil range to few mm. But: reachable energy threshold, detection efficiency, radiopurity, stability with time of the overall performances? etc. **Wait for more ...**



A directional WIMP detector with organic anisotropic scintillator?

DAMA, N.Cim.15C(1992)475, EPJC28 (2003)203 (some tests also by UKDMC,Tokyo)

Crystals as anthracene, $C_{14}H_{10}$ and stilbene $C_{14}H_{12}$



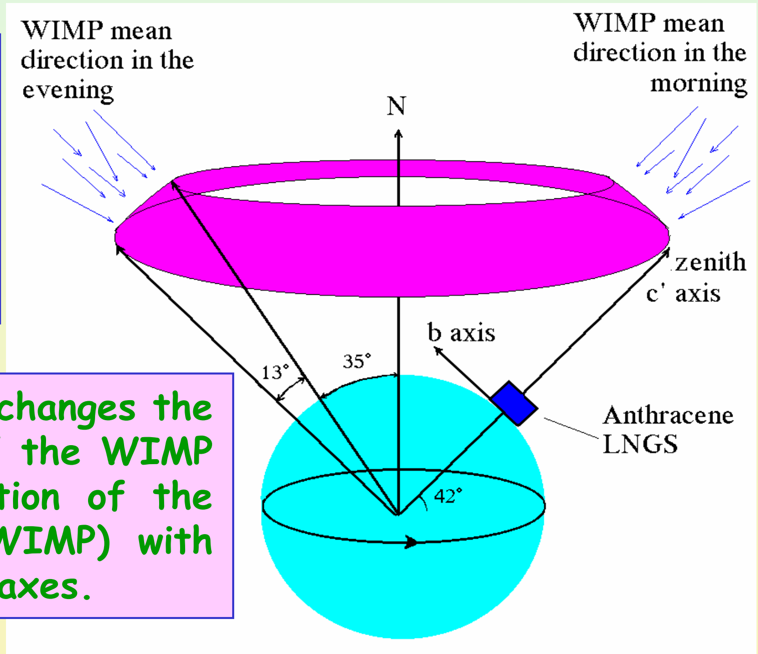
$$\frac{q^{c'}}{q^{b}} \approx 1.5$$

$$\frac{q^{c'}}{q^{a}} \approx 1.2$$

- light anisotropy for recoil nuclei and no anisotropy for electrons;
- anisotropy greater at low energy.

Example: Light response of anthracene relative to heavy ionizing particles depends on their impinging direction with respect to the crystal axes.

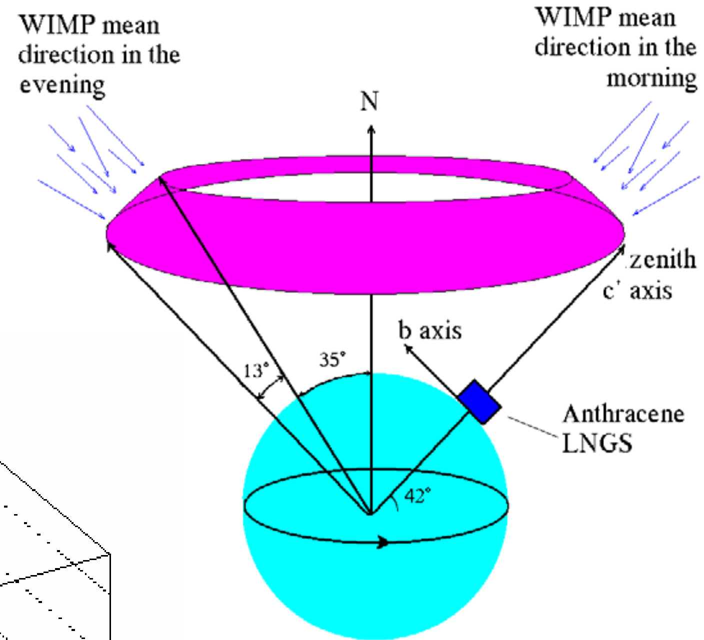
The diurnal Earth rotation changes the mean impinging direction of the WIMP flux (and the mean direction of the recoil nuclei induced by WIMP) with the respect to the crystal axes.

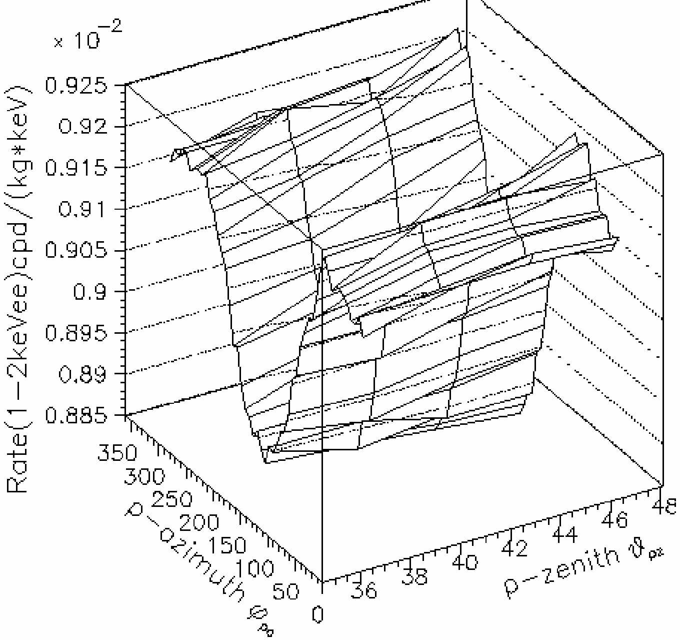


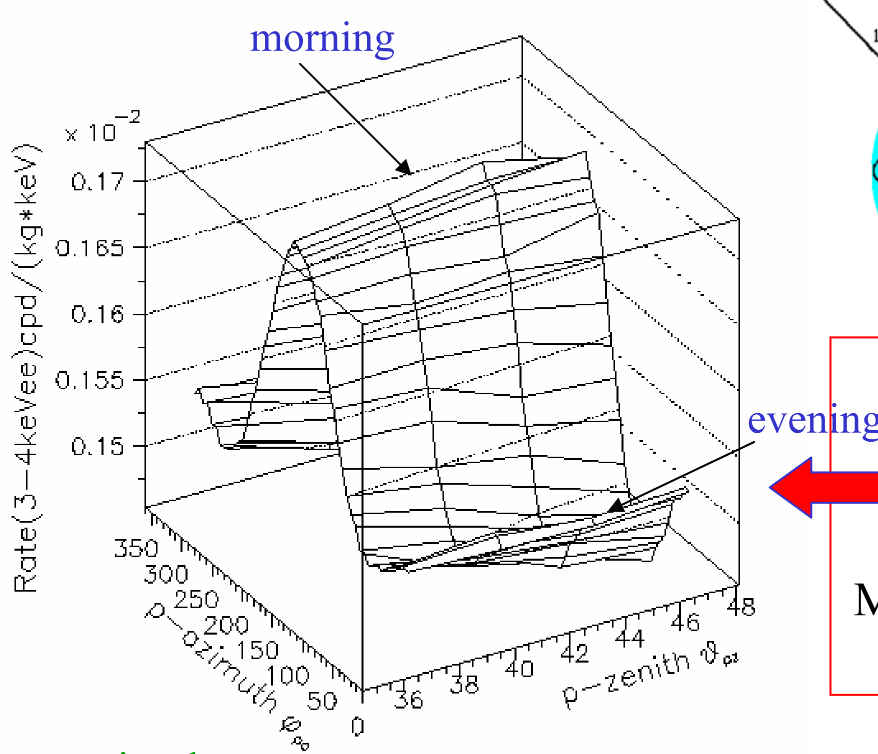
an hypothetical experimental configuration:

EPJC28 (2003)203

$$t \underset{(\vec{v}_d(t))}{\Longleftrightarrow} \left(\theta_{pz}(t), \varphi_{pa}(t)\right)$$







Example of rate expectations in a given model:

Model: m_w= 50 GeV, SI, isothermal halo, ecc..

A diurnal variation of the counting rate in the selected energy windows is expected; this is due to the different WIMP mean impinging direction on the detector during in the daily Earth rotation.

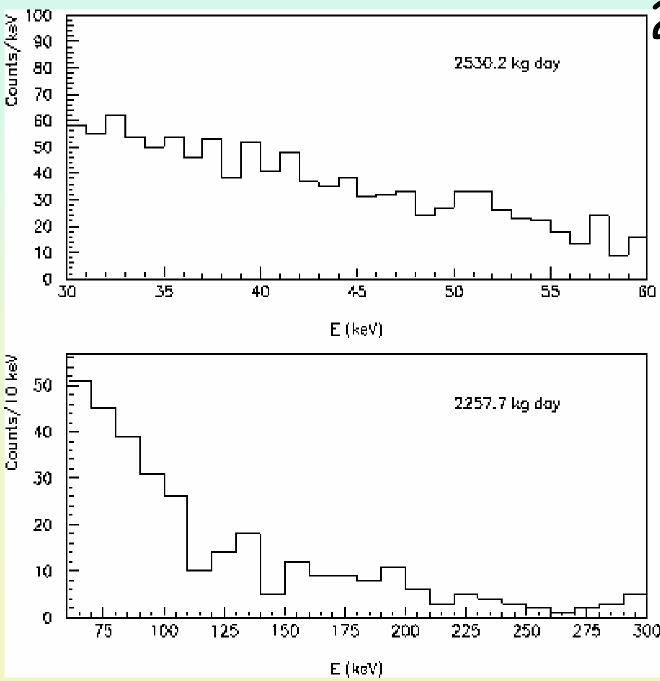
For an immovable anthracene detector, a suitable configuration at LNGS latitude is to put the b axis towards north and c' axis towards the vertical. During the day, the mean WIMP impinging direction passes from the b axis to c'axis (12 hours later) with maximal variation amplitude.

Which signature for WIMPs?

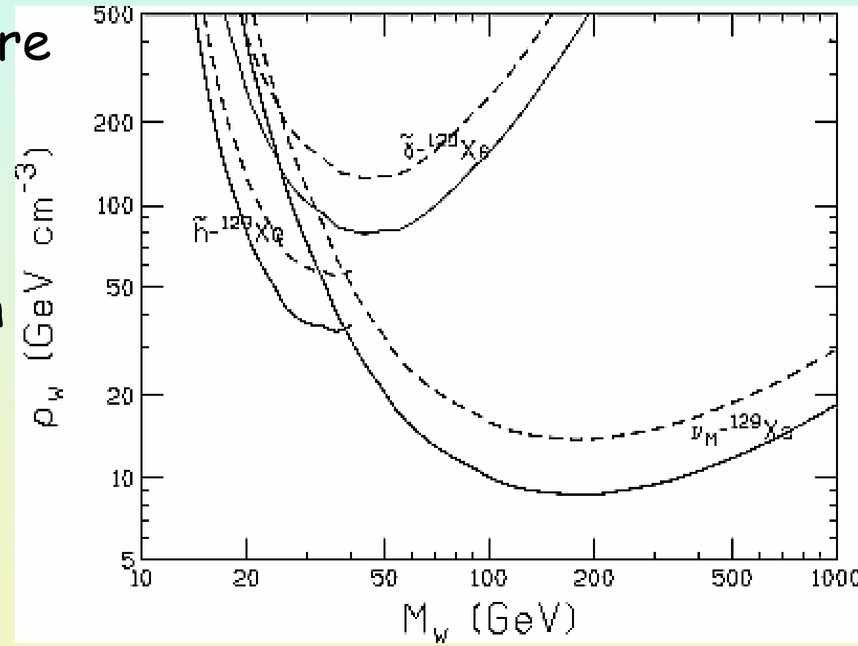
- Nuclear-inelastic scattering: $W+N \rightarrow W+N^*$
  $\rightarrow N+\gamma$
- Signature: detection of γ's emitted by excited nucleus after a WIMP-nucleus inelastic scattering + N^* Recoil energy

DAMA- LXe: looking for 39.6 keV γ's
2530.2 kg day exposure

(New J. of Phys. 2(2000)15.1)



a possible model dependent implication



Also Eijiri et al. with NaI(Tl) but large MC subtraction

hardly effective

Very low counting rates expected

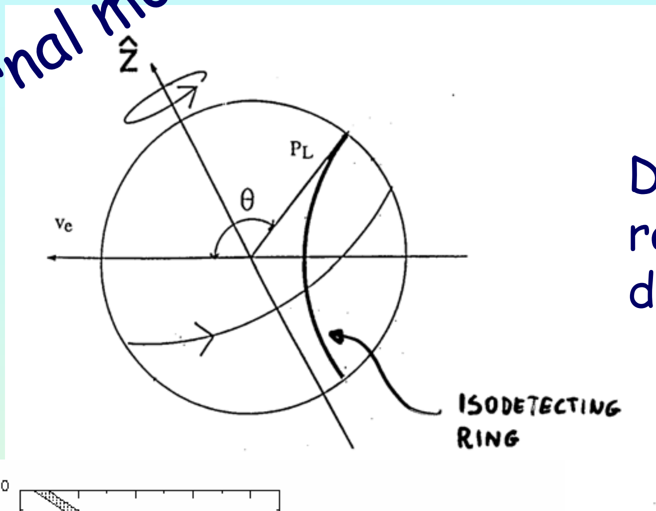
⇓

Very large exposure needed

Which signature for WIMPs?

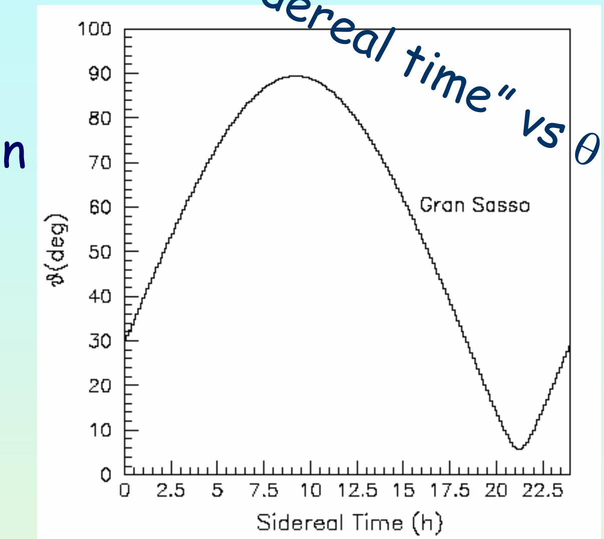
Diurnal modulation

Collar et al., PLB275(1992)181

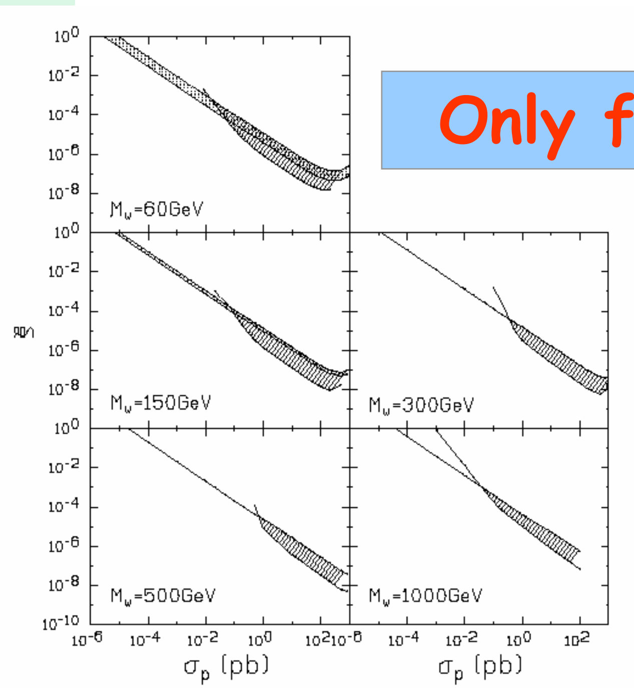


Daily variation of the interaction rate due to different Earth depth crossed by the WIMPs

"Sidereal time" vs θ



Only for large cross sections



An example: investigation of possible diurnal modulation in DAMA/NaI-2 data (N.Cim. A112(1999)1541): 14962 kg d

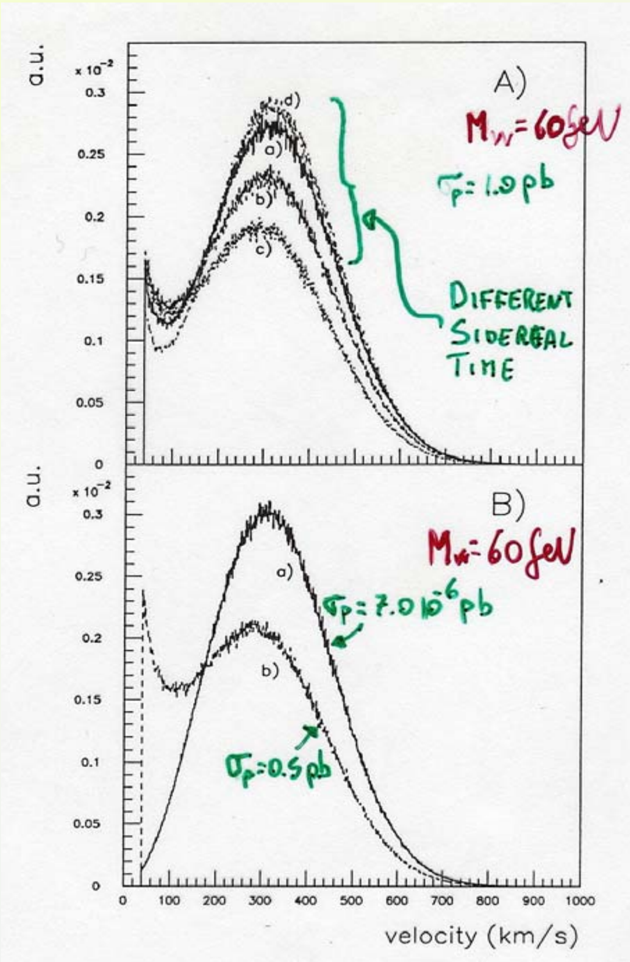
Absence of rate diurnal variation excludes the presence of:

- high σ_p WIMP component (with small ξ)
- spurious effects correlated with diurnal sidereal and solar time

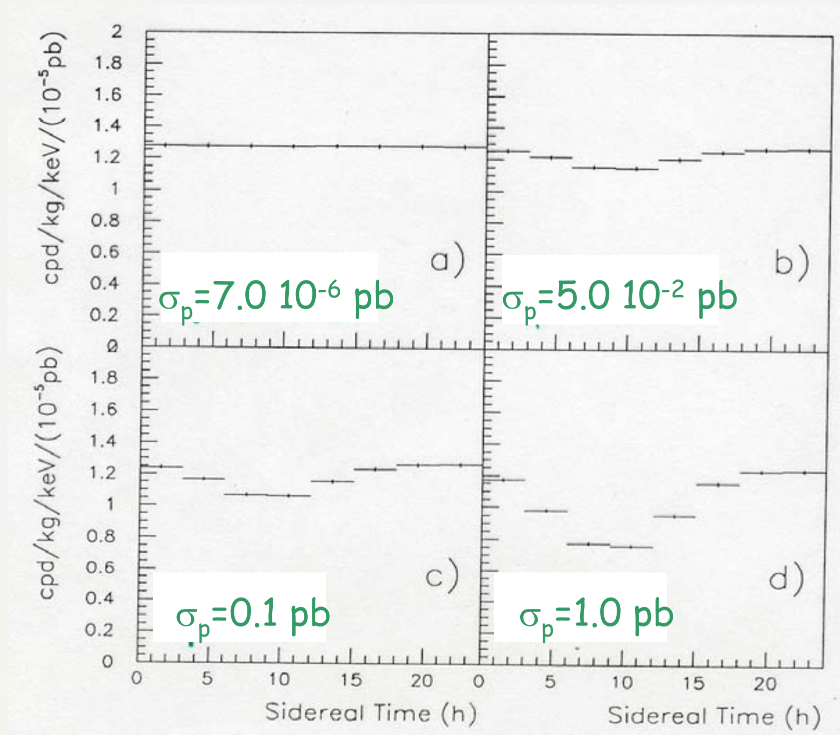
Limits on halo fraction (ξ) vs σ_p for SI case in the given model

For a given simplified model

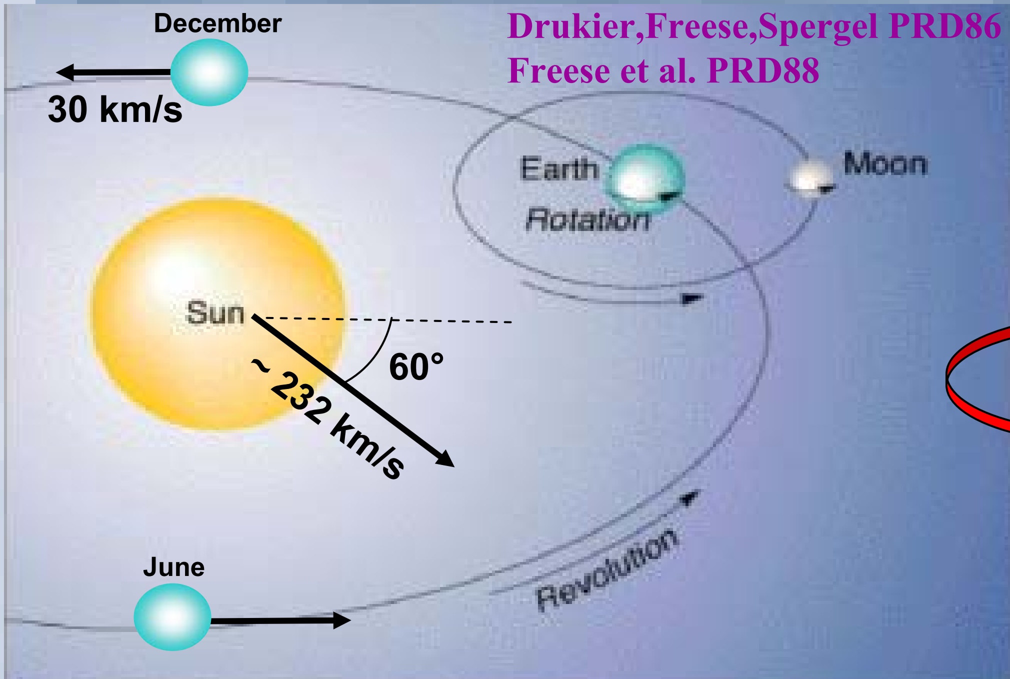
Velocity distributions (MonteCarlo)



Example of expected rate [2,6] keV for the particular case of M_w=60 GeV and $\xi\sigma_p=10^{-5}$ pb



Investigating the presence of a WIMP component in the galactic halo by the model independent WIMP 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)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ 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 in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity $\lesssim$ 7% (larger for WIMP 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 satisfy contemporaneously all these 6 requirements

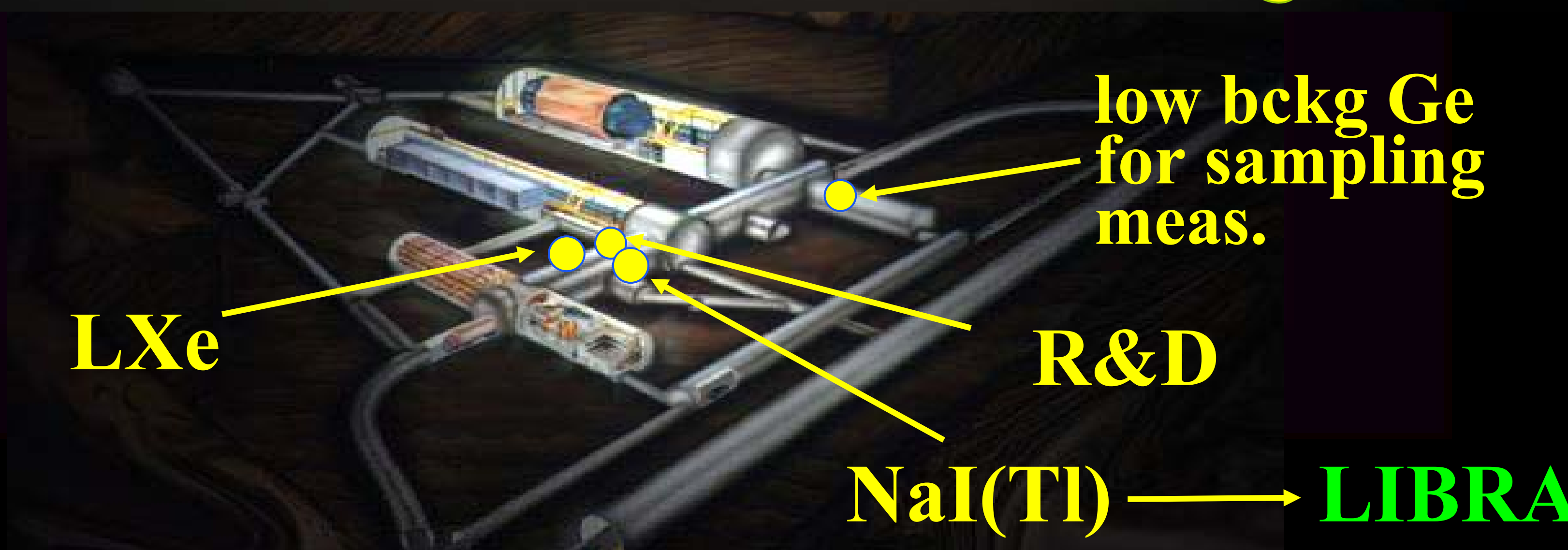
Competitiveness of NaI(Tl) set-up

- **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

DAMA: an observatory for rare processes @LNGS



The DAMA experiment

- ✓ Proposal by R. Bernabei, P.Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prosperi on large mass NaI(Tl) and liquid Xenon experiments for Dark Matter search and first funding on 1990.
- ✓ The chinese colleagues joined the project on 1992
- ✓ Several results since the beginning
- ✓ the ~ 100 kg NaI(Tl) experiment:
  - First experimental result on 1996 (DAMA coll., PLB389(1996)757).
  - First result on WIMP annual modulation signature: TAUP97
  - Data from 4 annual cycles released and published (1998, 1999, 2000)
  - Several other rare processes investigated
  - New electronics and DAQ in summer 2000.
  - Out of operation in July 2002 (to allow the mounting of DAMA/LIBRA)
  - Full result on the WIMP annual modulation signature (7 annual cycles) published on July 2003
- ✓ The ~ 6.5 kg liquid Xenon experiment:
  - from the former Xelidon expt in 80's on LXe detectors R&D
  - Set-up deeply upgraded in fall 1995 and in summer 2000
  - Many rare processes investigated -- Running
- ✓ The R&D experiment: Small scale expts with various scintillators (e.g. CaF_2(Eu), BaF_2, CeF_3, ...) + prototypes tests -- Running
- ✓ The low background Ge: Installed beginning of 90's; sample measurements continuously carried out

Now the new ~ 250 kg more radiopure NaI(Tl) set-up named LIBRA running

... and looking forward: **a new R&D for further radiopurifications started toward 1 ton set-up we proposed in 1996**

DAMA/LXe experiment: results on rare processes

NIMA482(2002)728

DARK MATTER investigation ...

- Limits on recoils investigating the WIMP-^{129}Xe elastic scattering by means of Pulse Shape Discrimination PLB436(1998)379
- Limits on WIMP-^{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 → comparing SD *vs* SI signal to increase the sensitivity on the SD component foreseen/in progress

... other rare processes

- Nuclear level excitation of ^{129}Xe during CNC processes
  $\tau > 1.1\times10^{24}$ y at 90% C.L PLB465(1999)315
- Nucleon and di-nucleon decay into invisible channels in ^{129}Xe PLB493(2000)12
  $\tau > 1.9\times10^{24}$ y 90% C.L. (p→invisible channel),
  $\tau > 5.5\times10^{23}$ y 90% C.L. (pp→invisible channel),
  $\tau > 1.2\times10^{25}$ y 90% C.L. (nn→invisible channel)
- Electron decay $e^- \rightarrow \nu_e\gamma$ PRD61(2000)117301
  $\tau > 2.0\times10^{26}$y at 90% C.L.
- 2β decay in ^{136}Xe $T_{1/2} > 7.0\times10^{23}$y (90% CL) 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 INFN/EXP-08/03
  $\tau > 1.3\times10^{23}$y at 90% C.L.
- Nucleon and di-nucleon decay into invisible channels in ^{136}Xe INFN/EXP-08/03

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

WIMPs:

- WIMP search with $CaF_2(Eu)$ NPB563(1999)97, Astrop.Phys.7(1997)73

Other rare process:

- 2β decay in ^{136}Ce and in ^{142}Ce Il Nuov.Cim.A110(1997)189
- 2EC2ν ^{40}Ca decay using $CaF_2(Eu)$ scintillator 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 and 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

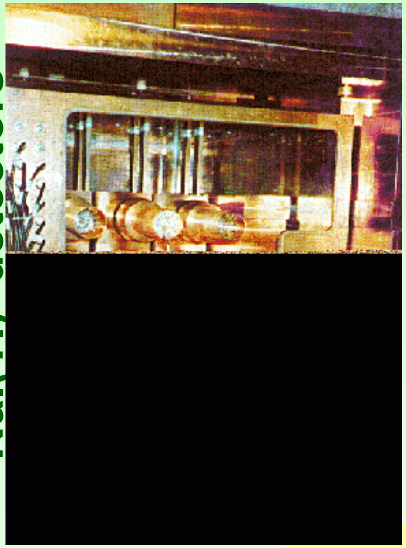
The R&D shield closed

The R&D shield open

Fulfilling the inner Cu box

~100 kg NaI(Tl) DAMA set-up: data taking completed on July 2002

NaI(Tl) detectors



Glove-box for calibration

Performances: N.Cim.A112(1999)545-575, 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

Results on WIMPS:

- 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**

during installation

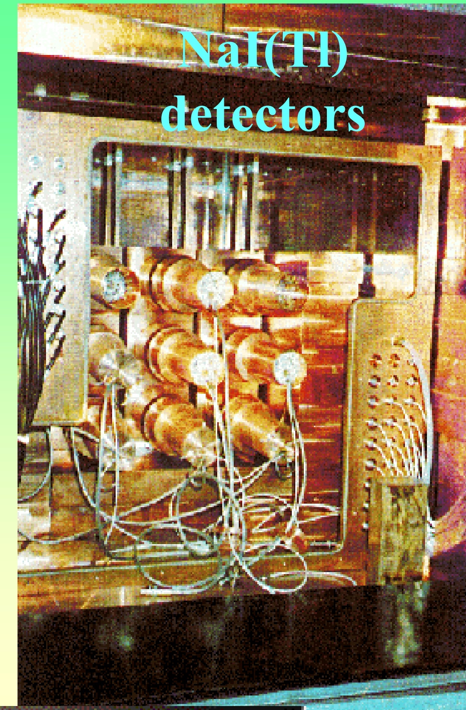
2003: total exposure collected during 7 annual cycles released: 107731 kg·d

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

DAMA @ LNGS
The ~100 kg NaI(Tl) set-up

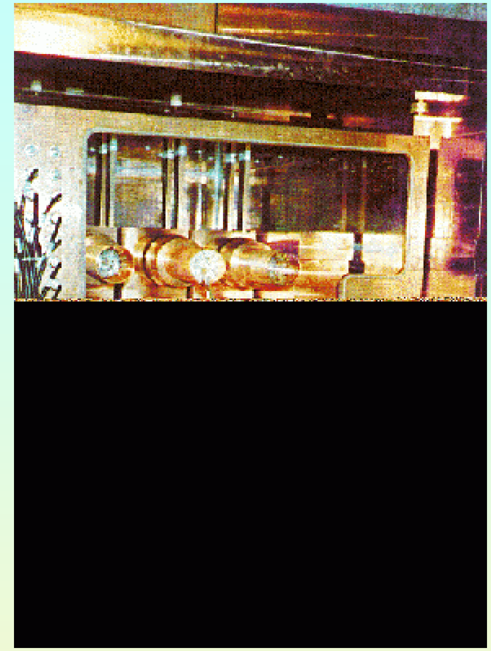
Glove-box for calibration

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



Main Features of DAMA/NaI

(Il Nuovo Cim. A112 (1999) 545-575,
Riv. N. Cim. 26 n.1 (2003)1-73)



•Reduced standard contaminants (e.g. U/Th of order of some ppt) by material selection and growth/handling protocols.

•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 copper, 15 cm of lead + shield from neutrons: Cd foils + 10/40 cm polyethylene/paraffin + ~ 1 m concrete moderator largely surrounding the set-up**

•A plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure

•Installation in air conditioning + huge heat capacity of shield

•Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm^2/s permeability).

•Calibration using the upper glove-box (equipped with compensation chamber) in HP Nitrogen atmosphere in slight overpressure calibration → in the same running conditions as the production runs.

•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)

•Pulse shape recorded over 3250 ns by Transient Digitizers.

•Monitoring and alarm system continuously operating by self-controlled computer processes.

•Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy.

+ electronics and DAQ fully renewed in summer 2000

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

- data taking of each annual cycle starts from autumn/winter (when $\cos\omega(t-t_0)\approx0$) toward summer (maximum expected).
- routine calibrations for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration 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.

Advantage of the ~100 kg NaI(Tl) expt

- **Knowledge of the physical energy threshold**

  (external keV range sources + low energy Compton electrons)

- **Noise identification**

  (high # ph.el./keV + pulse time structures)

- **Measurability of the software cut efficiencies**

  (by irradiating the crystal with γ sources and Compton e^-)

- **Knowledge of the needed efficiencies**

- **Knowledge of the sensitive volume**

- **Quenching factors measured**

  (by irradiating a detector from the same growth with neutrons,
  inducing recoils in the whole sensitive volume)

100 kg DAMA/NaI data takings

PERIOD	STATISTICS (kg · day)	REFERENCES
DAMA/NaI-0 (PSD)	4123	PLB389(1996)757
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
Cumulative 1-4	57986	idem +EPJ C18(2000)283 +PLB509(2001)197+ EPJ C23(2002)61+PRD66(2002)043503
DAMA/NaI-5	15911 ~ August to end of July	
	electronics and DAQ fully renewed)	
DAMA/NaI-6	16608 ~ November to end of July	
DAMA/NaI-7	17226 ~ August to end of July	

DAMA/NaI-0 to DAMA/NaI-1: partially overlapped

DAMA/NaI-5 to DAMA/NaI-7: Riv. N.Cim. 26 n.1 (2003) 1-73 (astro-ph/0307403)

TOTAL EXPOSURE 107731 kg·day

The model independent result

Annual modulation of the rate: DAMA/NaI-1 to -7

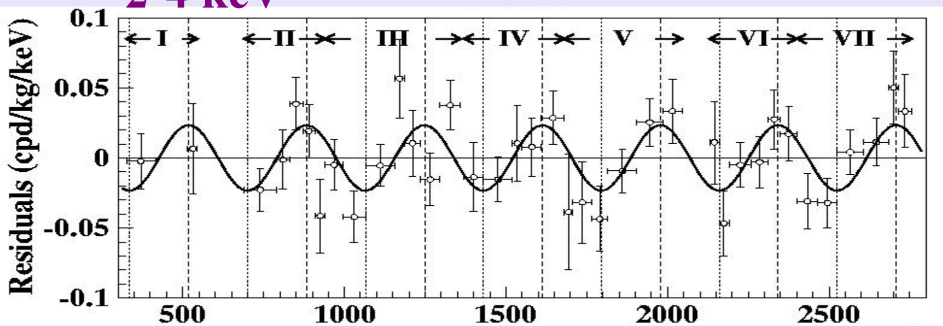
Riv. N. Cim. 26 n.1. (2003) 1-73
(astro-ph/0307403)

single-hit residuals rate vs time and energy

107731 kg · d

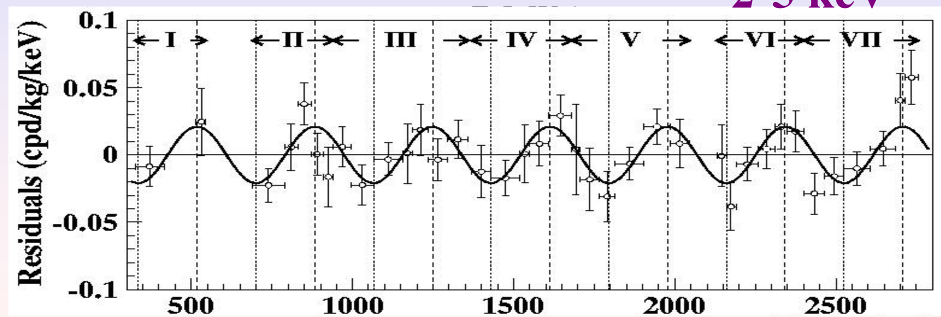
$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV



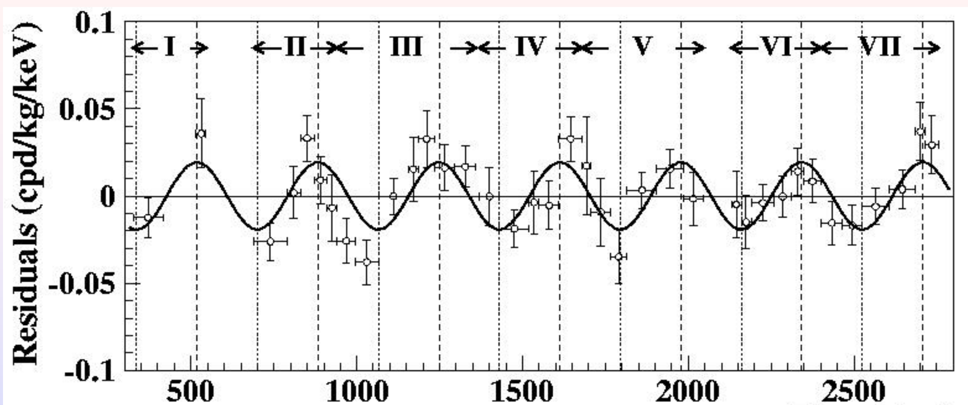
fit: A=(0.0233 ± 0.0047) cpd/kg/keV

2-5 keV



fit: A = (0.0210 ± 0.0038) cpd/kg/keV

2-6 keV



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;

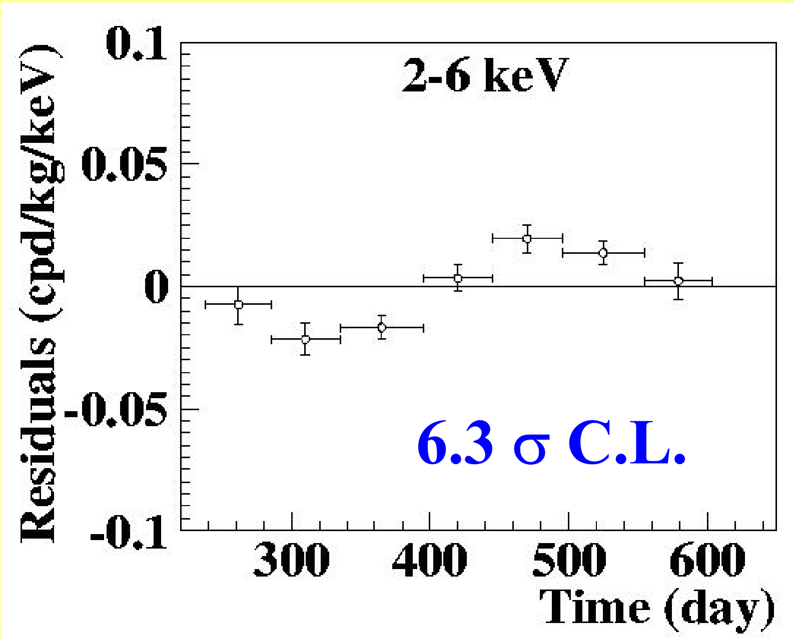
t_0 = (140 ± 22) d ; T = (1.00 ± 0.01) y

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

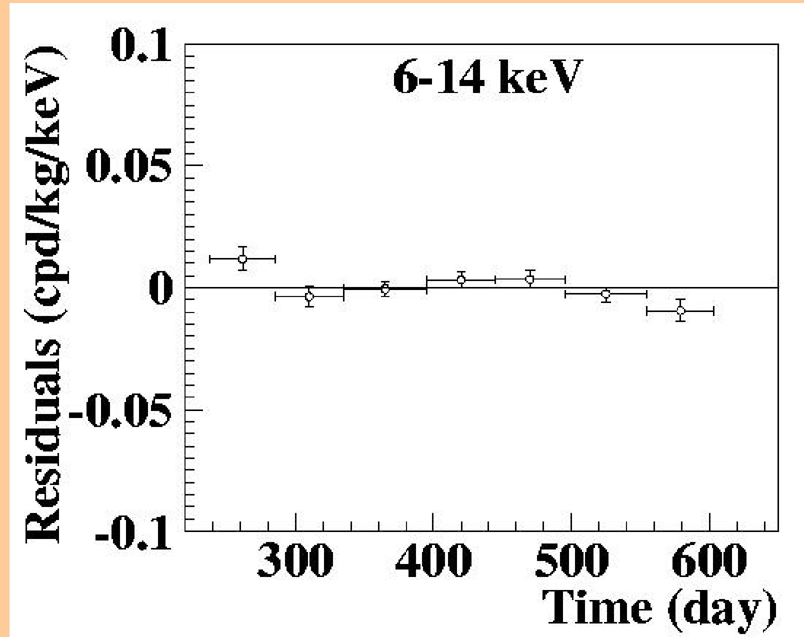
Model-independent single-hit residual rate in a single annual cycle

DAMA/NaI-1 to -7: Total Exposure: 107731 kg · d

- **Initial time 7th August**



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



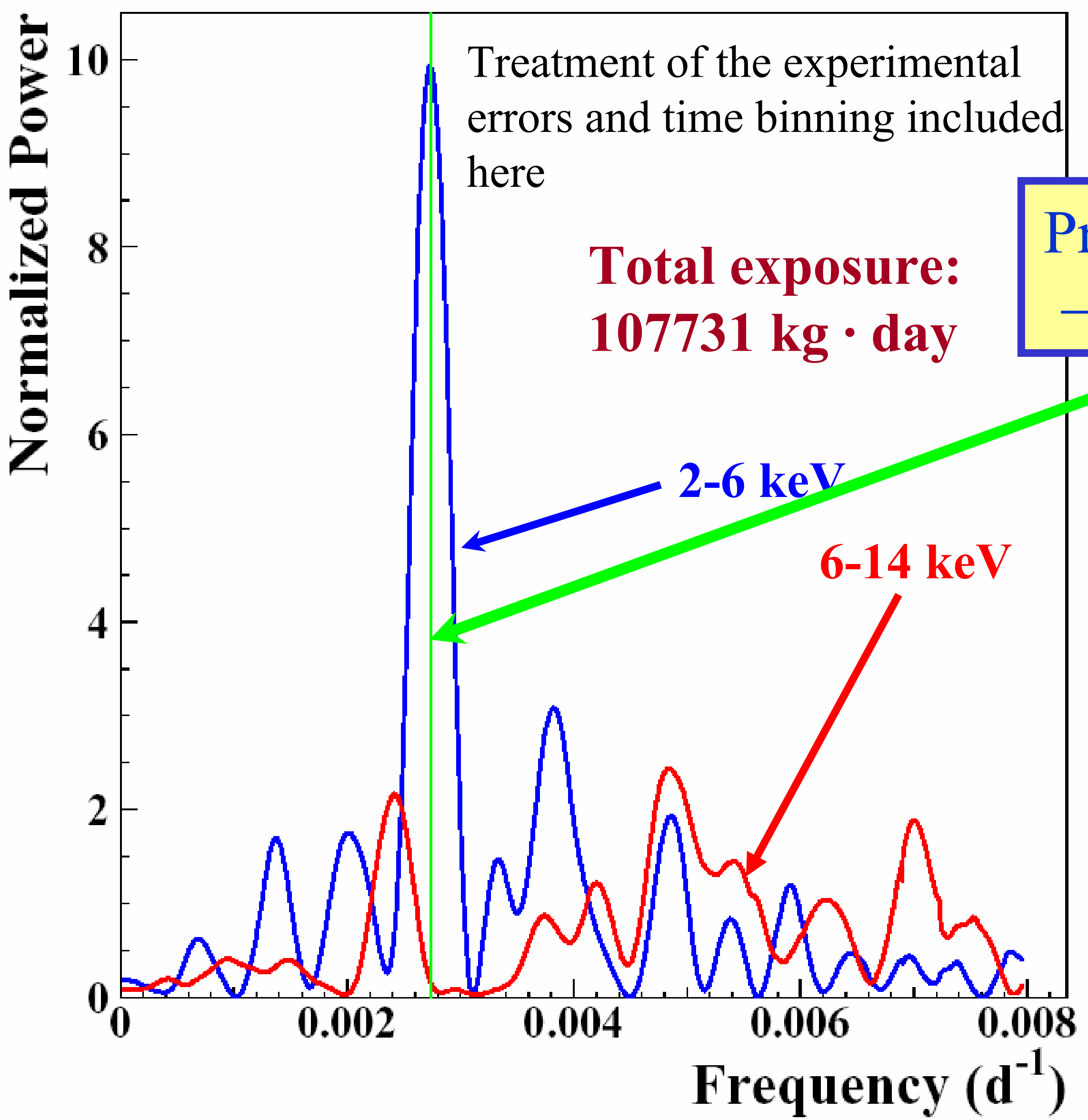
for t_0 = 152.5 d and T = 1.00 y:
A = -(0.0009 ± 0.0019) cpd/kg/keV

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

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

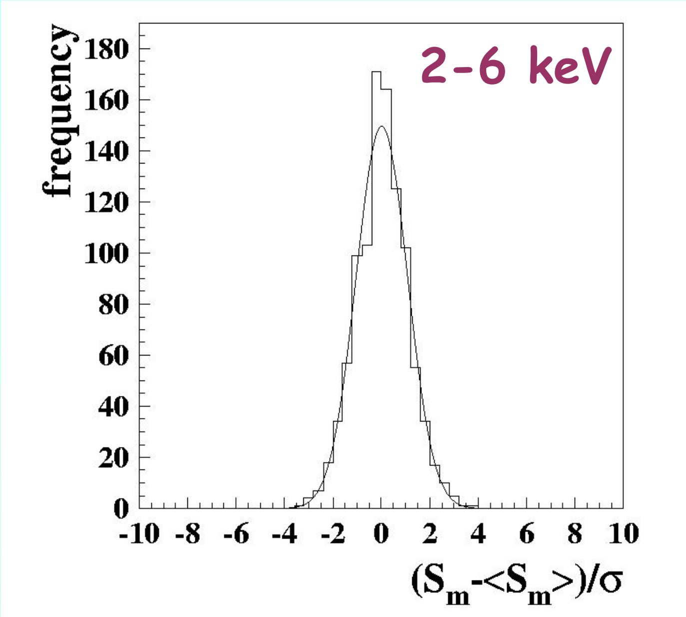


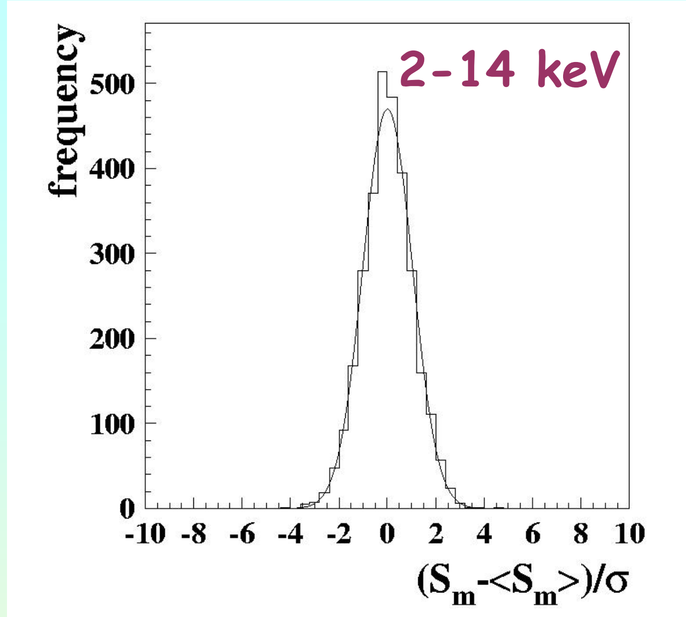
Principal mode in the 2-6 keV region → $2.737 \cdot 10^{-3}$ d^{-1} ≈ 1 y^{-1}

+

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

Statistical distribution of the modulation amplitudes (S_m)





a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

b) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = error associated to the S_m

Individual S_m values follow a normal distribution since **$(S_m - \langle S_m \rangle)/\sigma$** is distributed as a Gaussian with a unitary standard deviation

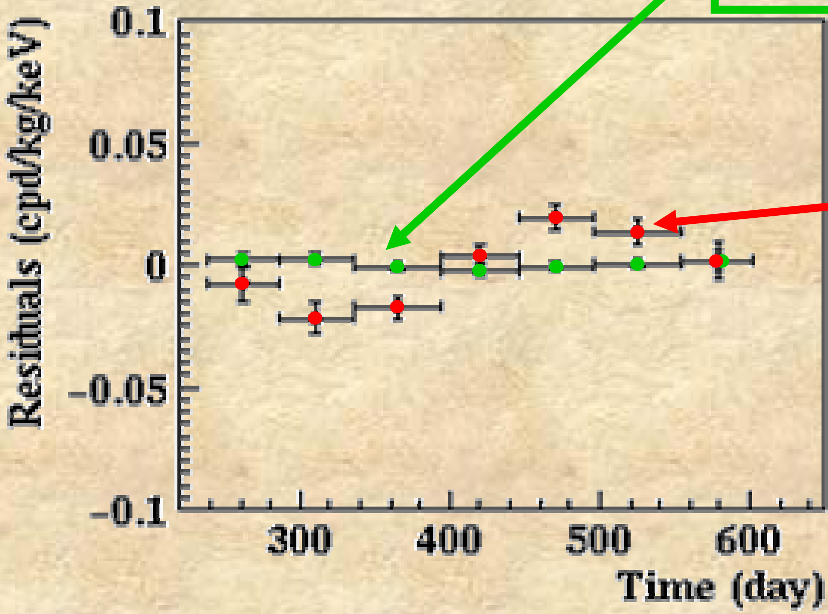
S_m statistically well distributed in all the crystals, in all the data-taking periods and energy bins

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 WIMPs do not belong to this class of events, that is: multiple-hits events = WIMPs events "switched off"

- **2-6 keV residuals**



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

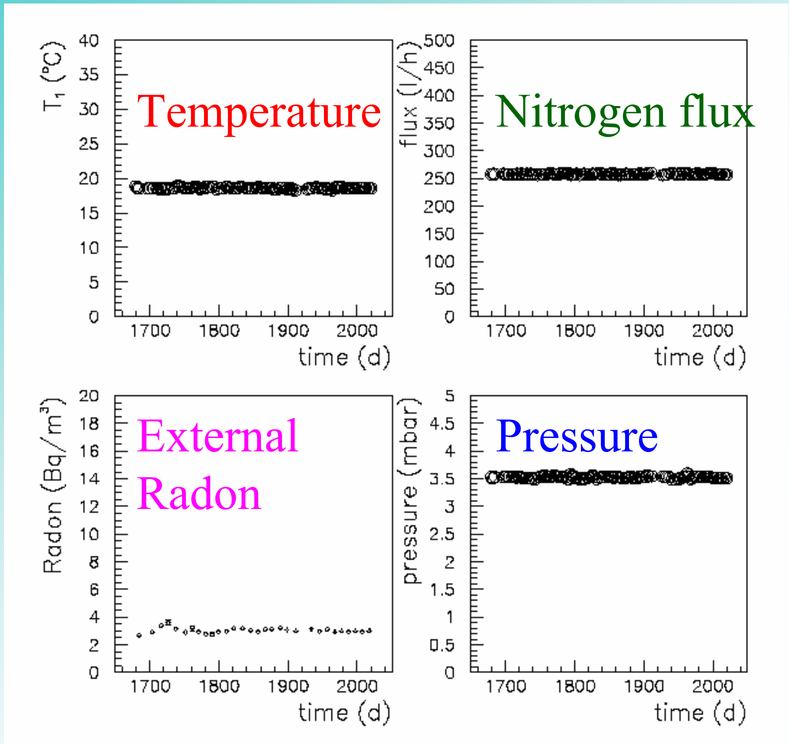
Mod ampl. = $-(3.9 \pm 7.9) \cdot 10^{-4}$ cpd/kg/keV

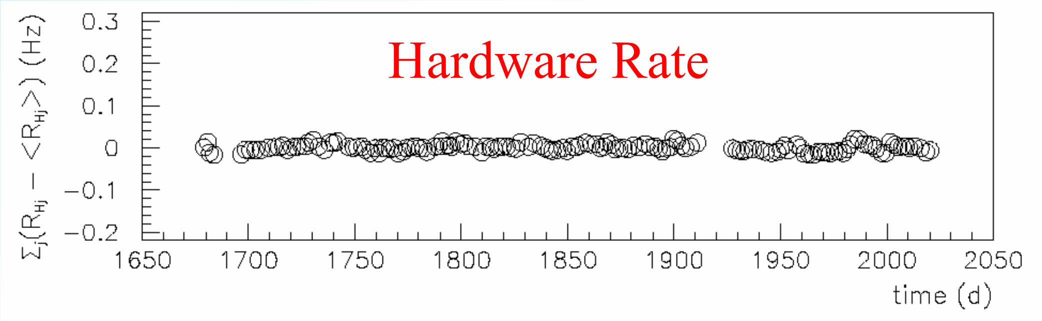
Residuals for single-hit events (DAMA/NaI-1 to 7)

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

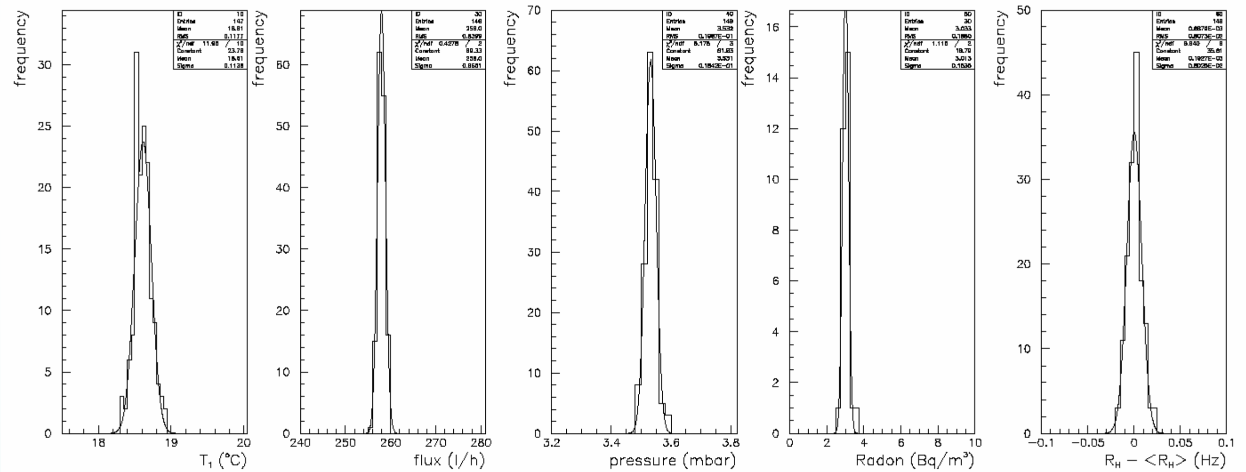
Few examples of the Stability Parameters: DAMA/NaI-7





Running conditions stable at level < 1%

Parameters distribution



All amplitudes well compatible with zero

+ no effect can mimic the annual modulation

The Stability Parameters

Time behaviour

modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a WIMP-like modulation

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

Running conditions stable at a level better than 1%

All the measured amplitudes well compatible with zero

+ no effect can mimic the annual modulation

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

(for the other annual cycles see DAMA/NaI references)

Summary of the results obtained by the investigation of possible systematics or side reactions

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

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere	$<0.2\%\ S_m^{obs}$
TEMPERATURE	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 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 6 requirements of annual modulation signature

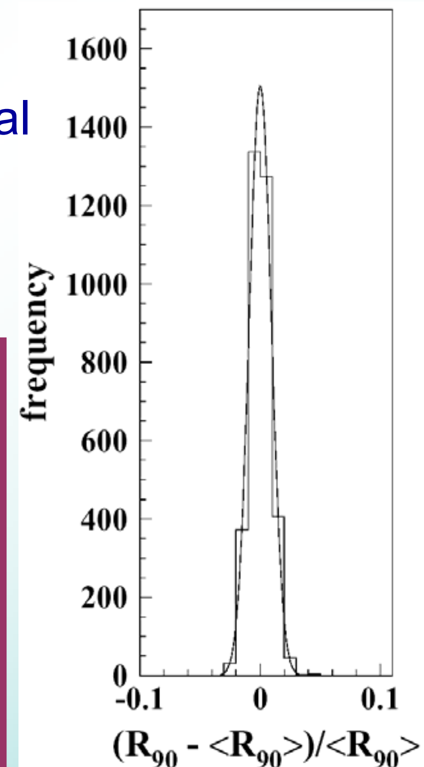
Thus, they can not mimic the observed annual modulation effect

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 WIMPs:

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

→ consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

Energy regions closer to that where the effect is observed e.g.:

Mod. Ampl. (6-10 keV): -(0.0076 ± 0.0065), (0.0012 ± 0.0059) and (0.0035 ± 0.0058) cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; → they can be considered statistically consistent with zero

In the same energy region where the effect is observed:

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

No modulation in the background:

these results also account for the bckg component due to neutrons

The order of magnitude of the neutron flux @ LNGS known since ~ 20 years: example of some measurements

Energy (MeV)	Flux(10^{-6} cm^{-2} s^{-1})	Reference
1.0-2.5	0.14 ± 0.12	F. Arneodo et al. (for ICARUS expt.), Il Nuov. Cim. A8 (1999) 819 (liquid scintillator PSD)
2.5-5.0	0.13 ± 0.04	
5.0-10.0	0.15 ± 0.04	
10.0-15.0	$(0.4 \pm 0.4)\cdot 10^{-3}$	
> 2.5	0.09 ± 0.06	M. Cribier et al. (for Gallex expt.), Astrop. Phys. 4 (1995) 23 (radiochemical)
Thermal	1.08 ± 0.02	P. Belli et al. (for Gallex expt.), Il N. Cim. A101 (1989) 959 (BF_3+various shields)
Epithermal	1.98 ± 0.05	
Fast (> 2.5 MeV)	(0.23 ± 0.07)	
1.0-2.5	0.38 ± 0.01	A. Rindi et al., LNGS report LNF-88/01(P) (1988) (high pressure ^{3}He)
2.5-5.0	0.27 ± 0.14	
5.0-10.0	0.05 ± 0.01	
10.0-15.0	$(0.6 \pm 0.2)\cdot 10^{-3}$	

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

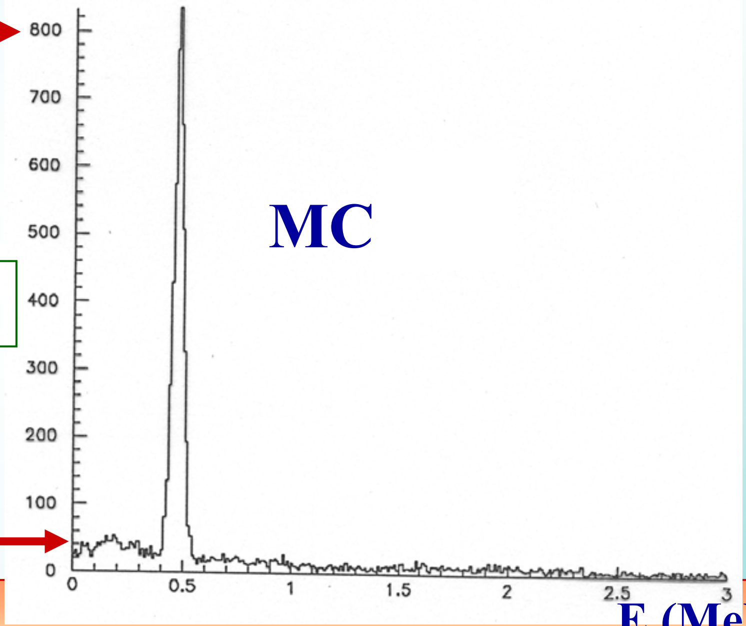
capture rate = $\Phi_n \sigma_n N_T$ = 0.17 captures/d/kg • $\Phi_n/(10^{-6}$ n cm^{-2} s$^{-1})$

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

1.4 x 10^{-3} cpd/kg/keV

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

7 x 10^{-5} cpd/kg/keV



Thermal neutron flux @ LNGS:

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

$\Phi_n < 5.9\ 10^{-6}$ 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: ⇒ $S_m^{(\text{thermal n})} < 10^{-5}$ cpd/kg/keV ($< 0.05\%\ S_m^{\text{observed}}$)

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**

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 (outside the barrack) the passive shield

Elastic scatterings: recoil nuclei

capture rate = $\Phi_n \sigma_n N_T$

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

By MC: differential counting rate above 2 keV ≈ 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

Can the μ modulation measured by MACRO account for the observed effect?

Case of fast neutrons produced by muons

Φ_μ @ LNGS ≈ 20 μ m^{-2} d^{-1} (±2% modulated)
Neutron Yield @ LNGS: Y=1÷7 10^{-4} n /μ /(g/cm²) (hep-ex/0006014)
R_n = (fast n by μ)/(time unit) = Φ_μ Y M_{eff}

Annual modulation amplitude at low energy due to μ modulation:

$$S_m^{(\mu)} = R_n\, g\, \varepsilon\, f_{\Delta E}\, f_{single}\, 2\% /(M_{setup}\, \Delta E)$$

where:
- g = geometrical factor
- ε = detection efficiency by elastic scattering
- $f_{\Delta E}$ = energy window (E>2keV) efficiency
- f_{single} = single hit efficiency

Hyp.: M_{eff} = 15 tons
$g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)

Knowing that: M_{setup}=100kg and ΔE=4keV

⇒ $S_m^{(\mu)}$ < (1÷7) 10^{-5} cpd/kg/keV (< 0.3% $S_m^{observed}$)

NO

Moreover, this modulation also induces a variation in other parts of the energy spectrum

Excluded by R_{90} analysis

Summary of the
DAMA/NaI *Model Independent* result

- Presence of modulation for 7 annual cycles at ~6.3σ CL with the proper distinctive features for a WIMP induced effect
- The deep investigation has shown absence of known sources of possible systematics and side processes able to account for the observed modulation amplitude and to contemporaneously satisfy the several peculiarities of the signature as well.
- All the signature features satisfied by the data over 7 independent experiments of 1 year each one
- No other experiment whose result can be directly compared in model independent way with this one is available so far

corollary quest for a candidate

to investigate the nature and coupling with ordinary matter of a Dark Matter candidate particle → analyses within given model frameworks

Some (of the many possible) corollary quests for the candidate particle

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

THUS
uncertainties on models
and comparisons

ρ_W

WIMP velocity distribution and its parameters

coupling: SI, SD, mixed SI&SD, preferred inelastic, ...

new contributions to WIMP-nucleus scattering?
(see e.g. PRL91(2003)231301)

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 WIMP annual modulation signature, but also results given e.g. 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

$\langle S_{p,n}\rangle$ 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:

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

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

where:

$$g = \frac{g_p + g_n}{2} \bullet \left[1 - \frac{g_p - g_n}{g_p + g_n}\left(1 - \frac{2Z}{A}\right)\right]$$

$$\bar{a} = \sqrt{a_p^2 + a_n^2} \qquad tg\theta = \frac{a_n}{a_p}$$

Differential energy distribution:

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

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

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

minimal velocity providing E_R recoil energy

N_T: number of target nuclei

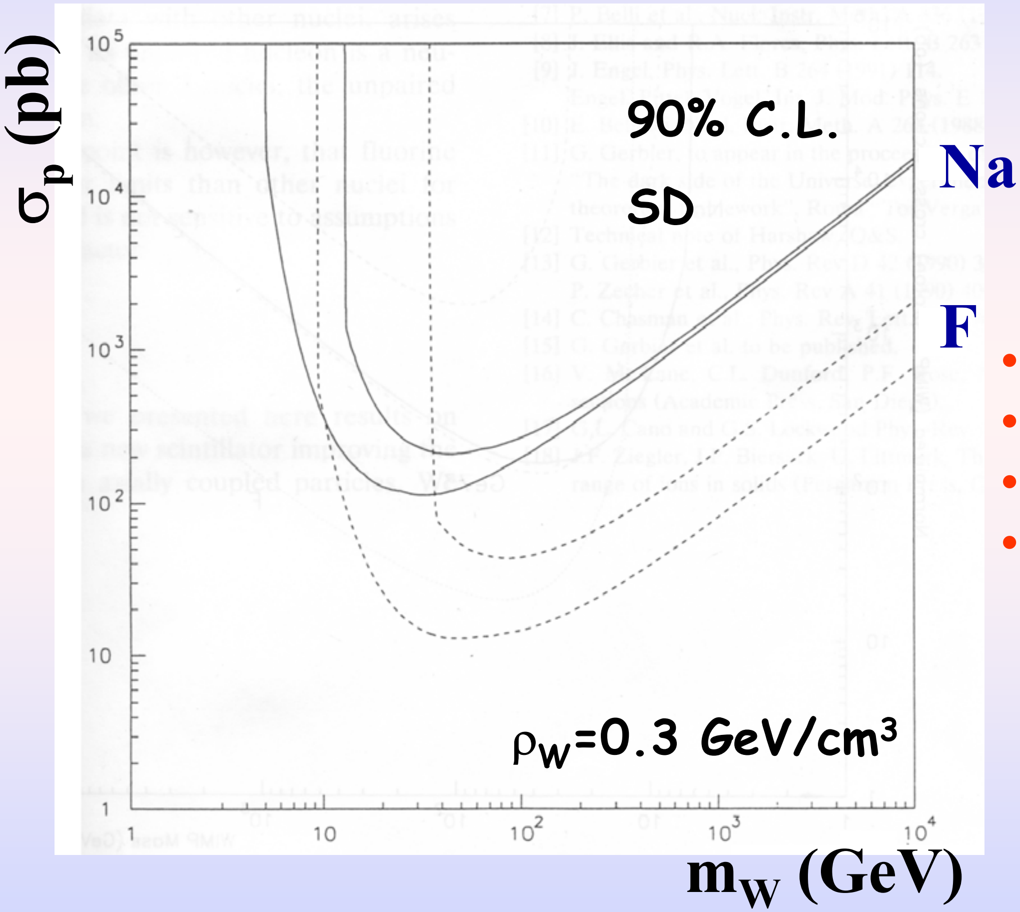
f(v): WIMP velocity distribution in the Earth frame (**it depends on v_e**)

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

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

Example

exclusion plots variations even when changing the value of a single parameter (inside its allowed range) within the assumed model framework



Astrop. Phys. 2 (1994) 117

- 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

Variations are found for whatever nucleus and interaction type when changing assumptions and/or used values for expt/theoretical parameters

The inelastic WIMP – nucleus interaction: $W + N \rightarrow W^* + N$

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

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

Ex. m_W =100 GeV

m_N	μ
70	41
130	57

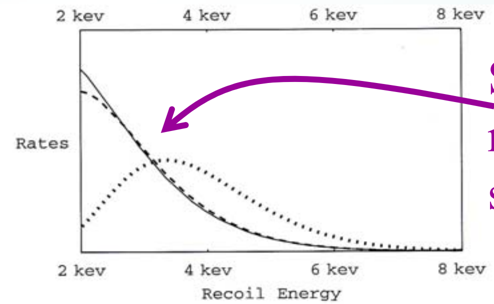
Differential energy distribution for SI interaction:

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

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

$d\Omega^*$ differential solid angle in the WIMP-nucleus c.m. frame

q^2 = squared threee-momentum transfer



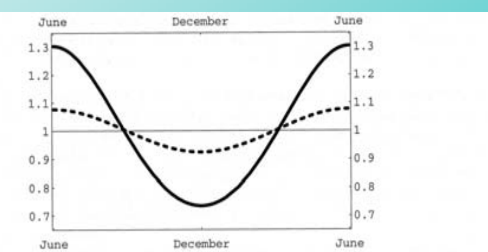
Normalized modulation (S_m) as a function of energy for ordinary WIMP scenario (solid), inelastic WIMP scenario with δ = 100keV (dashed), and inelastic WIMP scenario with δ = 150keV (dotted), all with m_χ = 60GeV.

S_m/S_0 enhanced with respect to the elastic scattering case

Nucleus recoil energy:

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

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



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

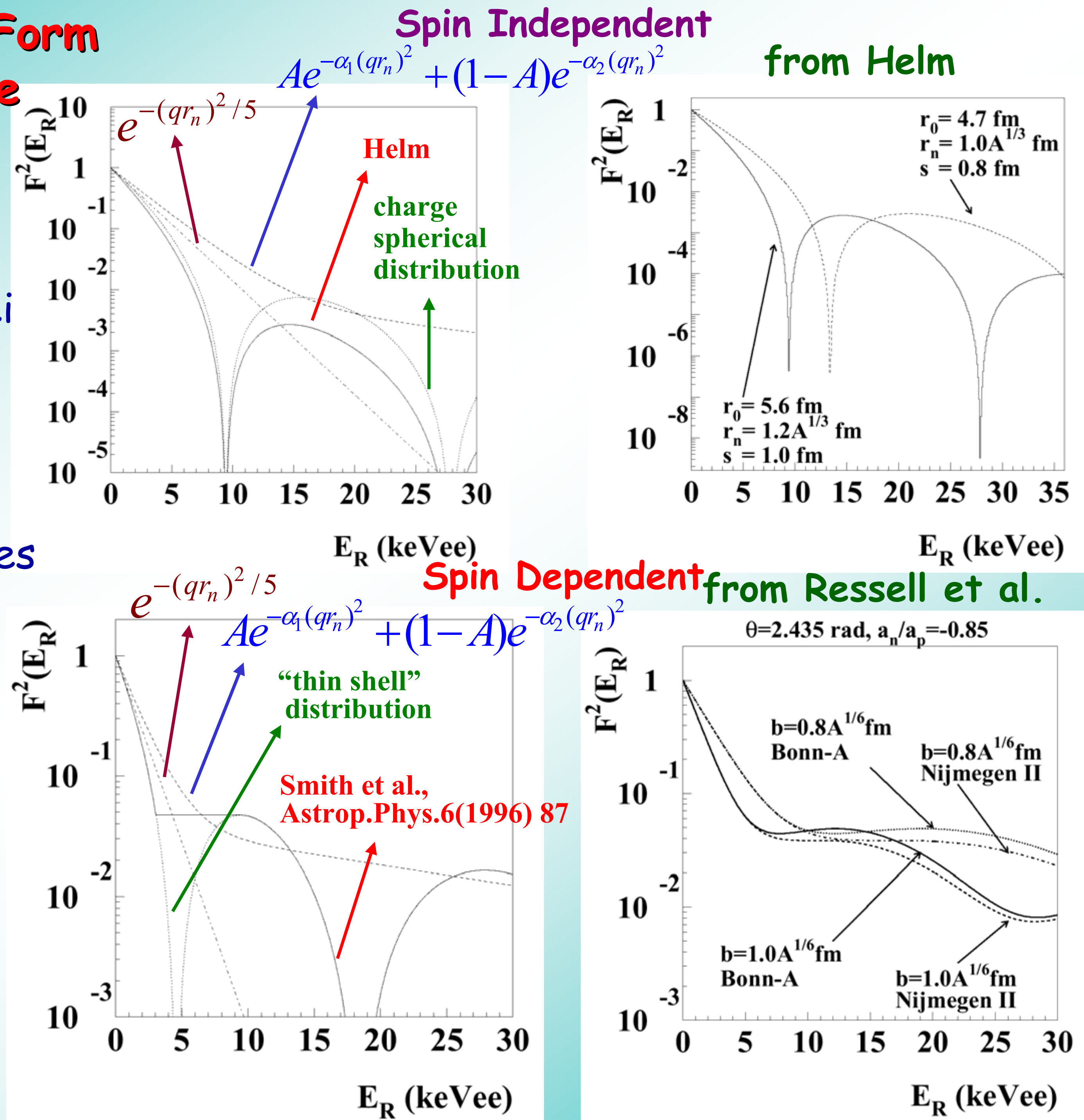
Differential energy distribution:

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

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 WIMP degrees of freedom; dependence on nuclear potential.

Similar situation for all the target nuclei considered in the field



The Spin Factor

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

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

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

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

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

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

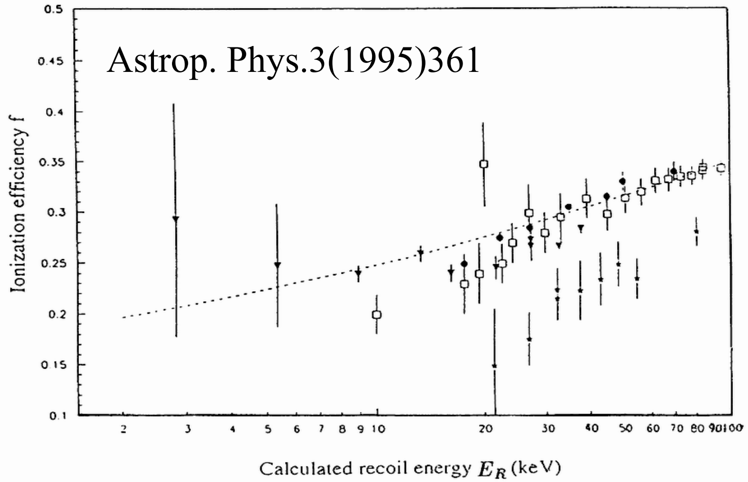
Spin factor = $\Lambda^2 J(J+1)/\bar{a}^2$

Quenching factor

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

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

Ex. of different *q* determinations for Ge



- **differences are often present in different experimental determinations of q for the same nuclei in the same kind of detector**
- **e.g. in doped scintillators q depends on dopant and on the impurities/trace contaminants**
- **Some time increases at low energy in scintillators (dL/dx)**

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)	

Halo modeling

- **Needed quantities for Dark Matter direct searches:**

  → DM local density $\rho_0 = \rho_{DM}(R_0 = 8.5\ \text{kpc})$

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

  → velocity distribution $f(\vec{v})$

Isothermal sphere: the most widely used (but not correct) model

density profile: $\rho_{DM}(r) \propto r^{-2}$ gravitational potential: $\Psi_0 \propto \log(r^2)$

→ Maxwellian velocity distribution

Axisymmetric ρ_{DM} → q flatness

$$\Psi_0(r,z) = -\frac{v_0^2}{2}\log\left(R_c^2 + r^2 + \frac{z^2}{q^2}\right)$$

Spherical ρ_{DM}, isotropic velocity dispersion

Evans' logarithmic

$$\rho_{DM}(r) = \frac{v_0^2}{4\pi G}\frac{3R_c^2 + r^2}{(R_c^2 + r^2)^2} \qquad \Psi_0(r) = -\frac{v_0^2}{2}\log(R_c^2 + r^2) \qquad v_{rot}^2(r) = v_c^2\frac{r^2}{(R_c^2 + r^2)}$$

Evans' power-law

$$\rho_{DM}(r) = \frac{\beta\Psi_a R_c^\beta}{4\pi G}\frac{3R_c^2 + r^2(1-\beta)}{(R_c^2 + r^2)^{(\beta+4)/2}} \qquad \Psi_0(r) = \frac{\Psi_a R_c^\beta}{(R_c^2 + r^2)^{\beta/2}}, (\beta \neq 0) \qquad v_{rot}^2(r) = \frac{\beta\Psi_a R_c^\beta r^2}{(R_c^2 + r^2)^{(\beta+2)/2}}$$

Others:

$$\rho_{DM}(r) = \rho_0\left(\frac{R_0}{r}\right)^\gamma\left[\frac{1 + (R_0/a)^\alpha}{1 + (r/a)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Triaxial ρ_{DM} → p, q, δ

$$\Psi_0(x,y,z) = -\frac{v_0^2}{2}\log\left(x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2}\right)$$

δ = free parameter → in spherical limit (p=q=1) quantifies the anisotropy of the velocity dispersion tensor

$$\frac{\overline{v}_\phi^2}{\overline{v}_r^2} = \frac{2+\delta}{2}$$

Spherical ρ_{DM} with non-isotropic velocity dispersion → $\beta_0 = 1 - \frac{\overline{v}_\phi^2}{\overline{v}_r^2}$

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

Consistent Halo Models

- Isothermal sphere ⇒ very simple but unphysical halo model
- Several 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 astroph/0203293.

•Large number of self-consistent halo models constrained by astrophysical observations (PRD66(2002)043503)

Models accounted in the following

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.	$\delta = 16$

The allowed local density values

- **Allowed intervals of ρ_0 (GeV/cm^3) for v_0=170,220,270 km/s, for the halo models considered in the model dependent analyses given in the following**

PRD66(2002)043503

	$v_0 = 170$ km s^{-1}		$v_0 = 220$ km s^{-1}		$v_0 = 270$ km s^{-1}	
Model	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}
A0	0.18	0.28	0.30	0.47	0.45	0.71
A1 , B1	0.20	0.42	0.34	0.71	0.62	1.07
A2 , B2	0.24	0.53	0.41	0.89	0.97	1.33
A3 , B3	0.17	0.35	0.29	0.59	0.52	0.88
A4 , B4	0.26	0.27	0.44	0.45	0.66	0.67
A5 , B5	0.20	0.44	0.33	0.74	0.66	1.11
A6 , B6	0.22	0.39	0.37	0.65	0.57	0.98
A7 , B7	0.32	0.54	0.54	0.91	0.82	1.37
C1	0.36	0.56	0.60	0.94	0.91	1.42
C2	0.34	0.67	0.56	1.11	0.98	1.68
C3	0.30	0.66	0.50	1.10	0.97	1.66
C4	0.32	0.65	0.54	1.09	0.96	1.64
D1 , D2	0.32	0.50	0.54	0.84	0.81	1.27
D3 , D4	0.19	0.30	0.32	0.51	0.49	0.76

Intervals evaluated considering the density profile and the astrophysical constraints

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

PRIORS

- Measured upper limits on the recoil fractions in the DAMA/NaI-0 running period, especially devoted to this investigation

- Model dependent mass limit for supersymmetric candidates by accelerator experiments:

  – $m_W > 30$ GeV from lower bound on neutralino mass as derived from LEP data in supersymmetric schemes based on GUT assumptions (from DPP2003)

  but other model assumptions are possible and would imply significant variations of the accelerators bounds as shown in literature also recently e.g. for the case when the gaugino-mass unification at GUT scale is released

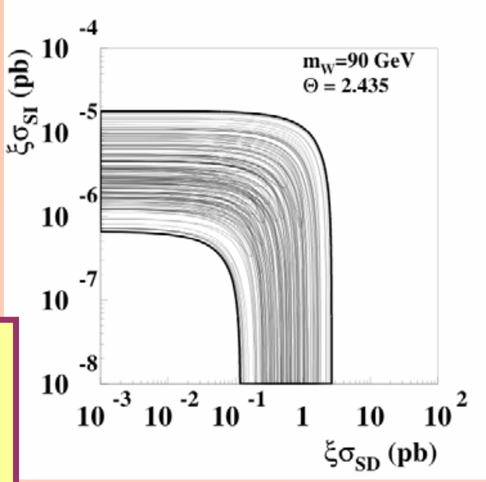
  + candidates other than neutralino are possible.

  e.g.:
  - an heavy neutrino of the 4-th family;
  - the sneutrino in the Weiner and Smith scenario;
  - even whatever suitable particle not yet foreseen by theory
  - mirror dark matter, Kaluza-Klein particles

Model dependent scenarios investigated here (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



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.

The allowed regions take into account the time and energy behaviours of the experimental 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**. 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 above) 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.

Model dependent scenarios investigated here (others under investigation)

Main topics:

Halo models as in PRD66(2002)043503
Helm FF for SI coupling
Ressel FF (Nijmengen II nuclear potential) calculated for χ

Case A: **FF parameters at fixed values and quenching factors at mean measured values**

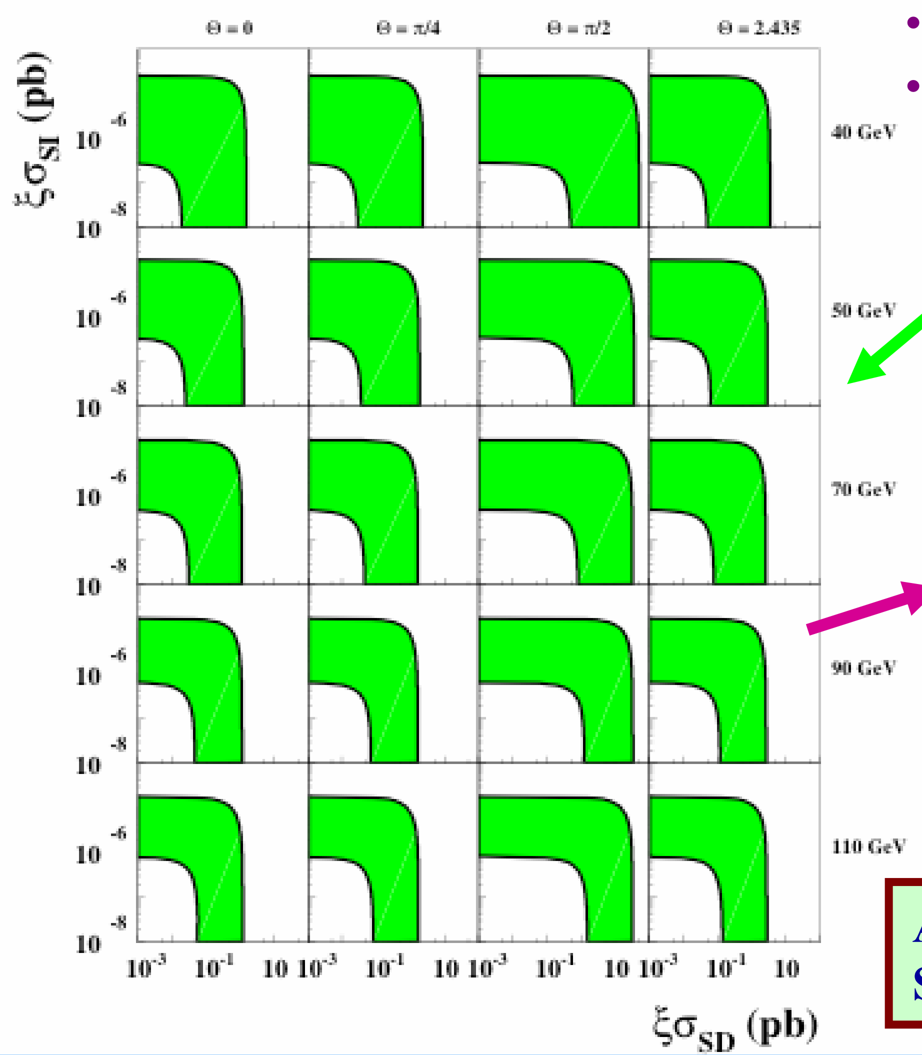
+

Case B: **i) ^{23}Na and ^{127}I quenching factors from mean values up to +2 times the errors; ii) nuclear radius, *r*, and nuclear surface thickness parameter, *s*, in the SI FF from fixed values down to 20%; iii) *b* parameter in the considered SD FF from fixed value down to 20%.**

Case C: **one of the possible more extreme cases where the Iodine nucleus parameters are fixed at values of case B, while for Sodium nucleus one considers: i) ^{23}Na quenching factor at the lowest value available in literature (see Table); ii) nuclear radius, r_n, and nuclear surface thickness parameter, *s*, in the used SI FF from central values up to +20%; iii) *b* parameter in the considered SD FF from fixed value up to +20%.**

General case: WIMP with SI & SD couplings (Na and I are fully sensitive to SD interaction, on the contrary of e.g. Ge and Si,)

- The result is an allowed volume in the space ($\xi\sigma_{SI}$, $\sigma\xi_{SD}$, m_W) for each possible θ ($tg\theta = a_n/a_p$, with $0 \leq \theta < \pi$)
- $\xi = \rho_W / \rho_0$, $\xi \leq 1$ fraction of amount of local WIMP density
- Several consistent halo models including halo rotation (see before)
- Cases A, B and C



- $\theta=0$ ($a_n=0$, $a_p \neq 0$)
- $\theta=\pi/4$ ($a_n=a_p$)
- $\theta=\pi/2$ ($a_n \neq 0$, $a_p=0$)
- $\theta=2.435$ ($a_n/a_p= -0.85$, Z_0 coupl.)

Example of slices of the allowed volume for some given m_W and θ values

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

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

The use e.g of more favourable form factors than those we considered here alone would move the region towards lower cross sections

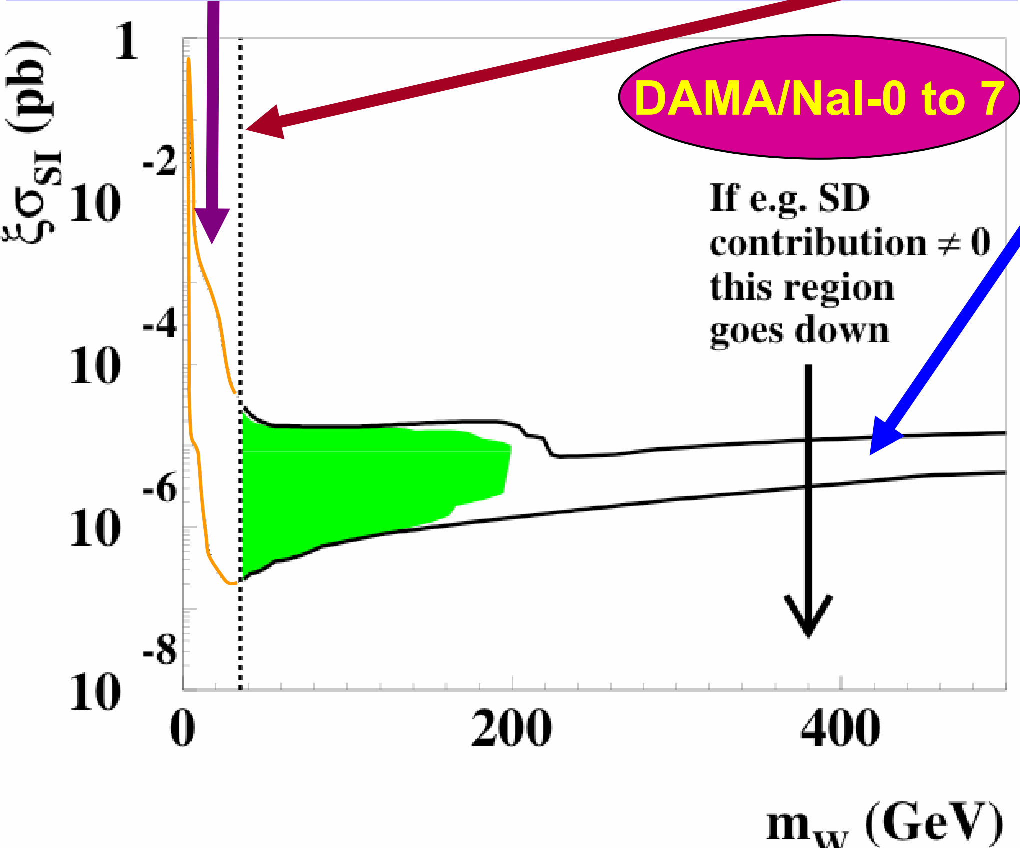
At present either a purely SI or a purely SD or a mixed SI&SD configurations are supported by the data

WIMP with dominant SI coupling

- $\xi = \rho_W / \rho_0$, $\xi \leq 1$ fraction of amount of local WIMP density
- Several consistent halo models including halo rotation (see before)
- Cases A, B and C

Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for “generic” WIMP

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 set A

Best-fit values of cross section and WIMP mass span over a large range depending on the model framework.

Just as an example: triaxial D2, max ρ_0, low v_0 and parameters case C: $m_W=(74^{+17}_{-12})$ GeV and $\xi\sigma_{SI}=(2.6\pm0.4)\ 10^{-6}$ pb

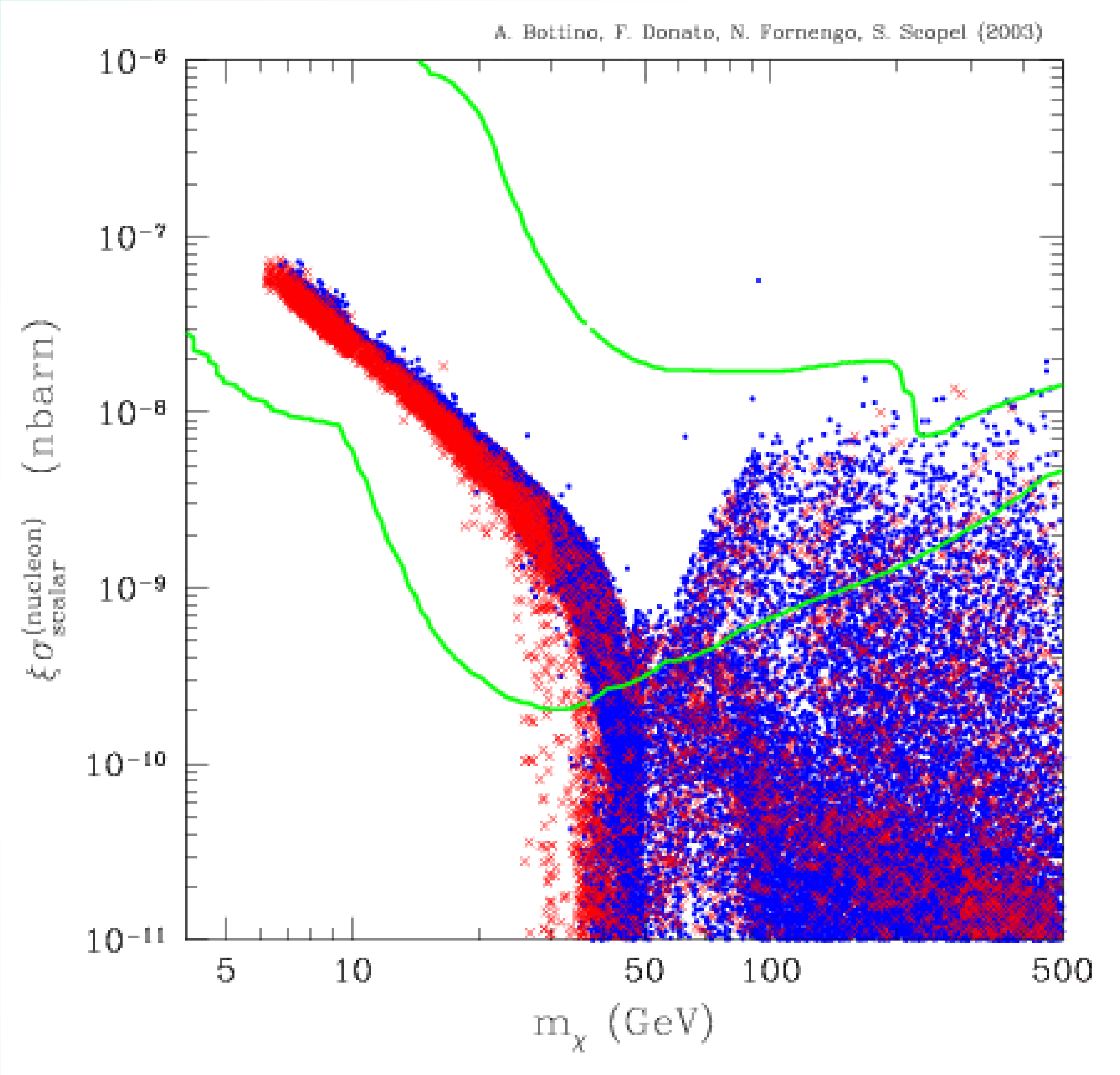
The inclusion of other existing uncertainties on parameters and models would further extend the region: e.g. the use of more favourable FF than those considered here alone would move the region towards lower cross sections

Supersymmetric expectations in MSSM

- purely SI coupling
- mass below 50 GeV obtained when releasing the gaugino mass unification at GUT scale:

  $M_1/M_2 \neq 0.5$ (<);

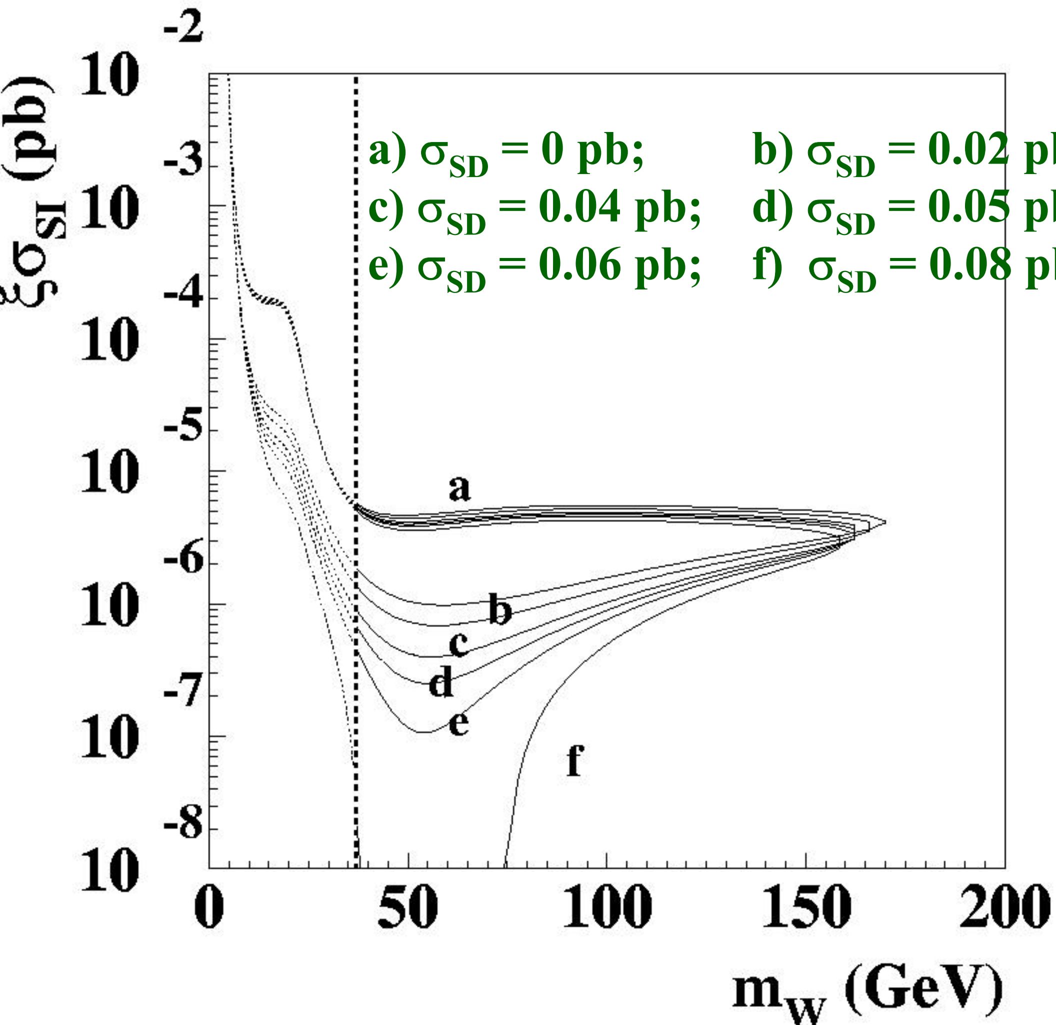
  (where M_1 and M_2 U(1) and SU(2) gaugino masses)



scatter plot of theoretical configurations (A. Bottino et al., hep-ph/0304080, hep-ph/0307303)

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 and parameters of set A
- The different regions refer to different SD contributions with θ=0

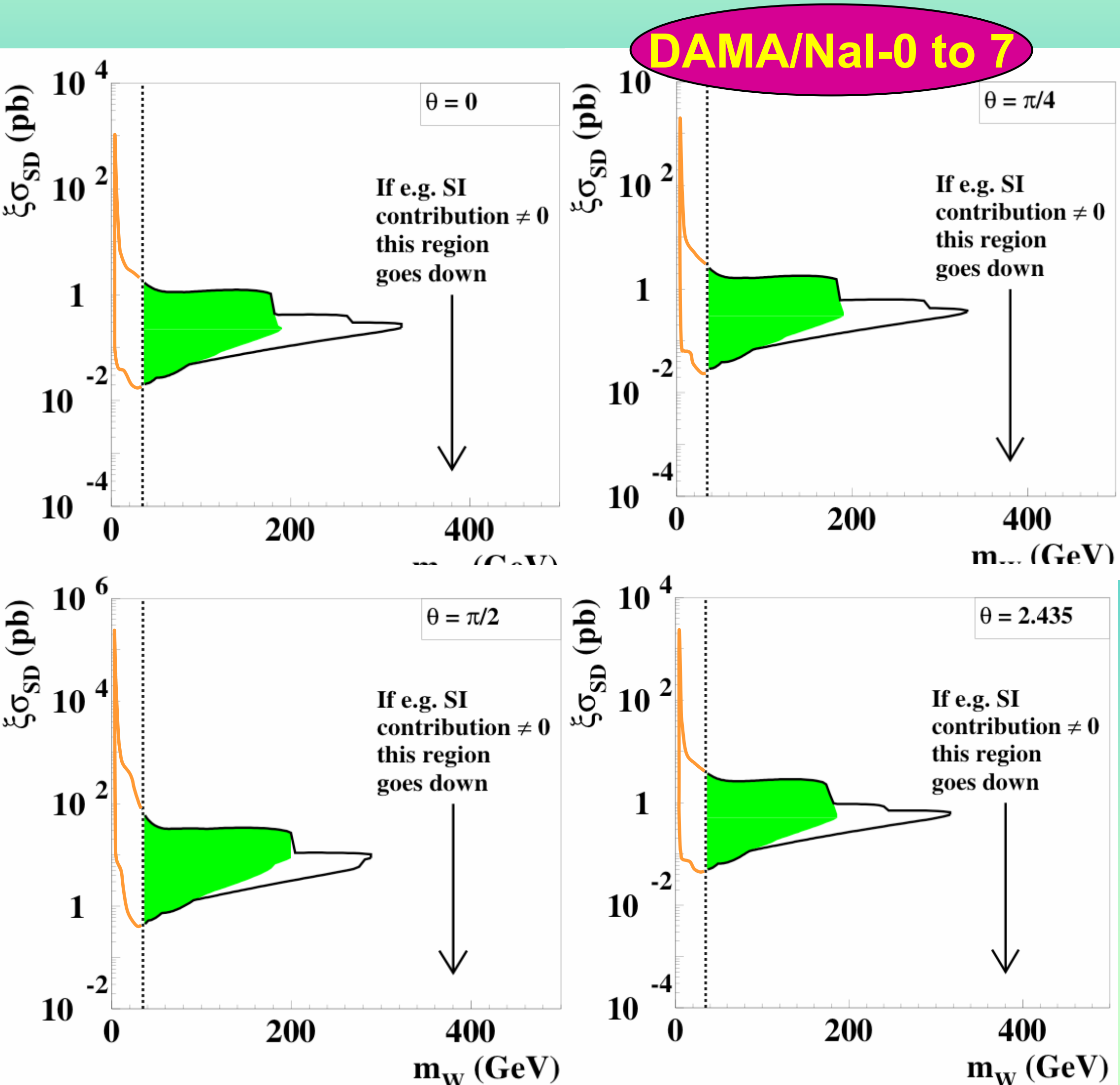


A small SD contribution ⇒ drastically moves the allowed region in the plane (m_W, $\xi\sigma_{SI}$) towards lower SI cross sections ($\xi\sigma_{SI} < 10^{-6}$ pb)

- 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 $\theta \approx \pi$.

WIMP with dominant SD couplings

- Region allowed in the space $(m_W, \xi\sigma_{SD}, \theta)$
- Here example of slices for only 4 (θ=0, $\pi/4$, $\pi/2$, 2.435) values of θ (which can range from 0 to π)
- Several consistent halo models including halo rotation (see before)
- Cases A, B and C + see previous transparencies



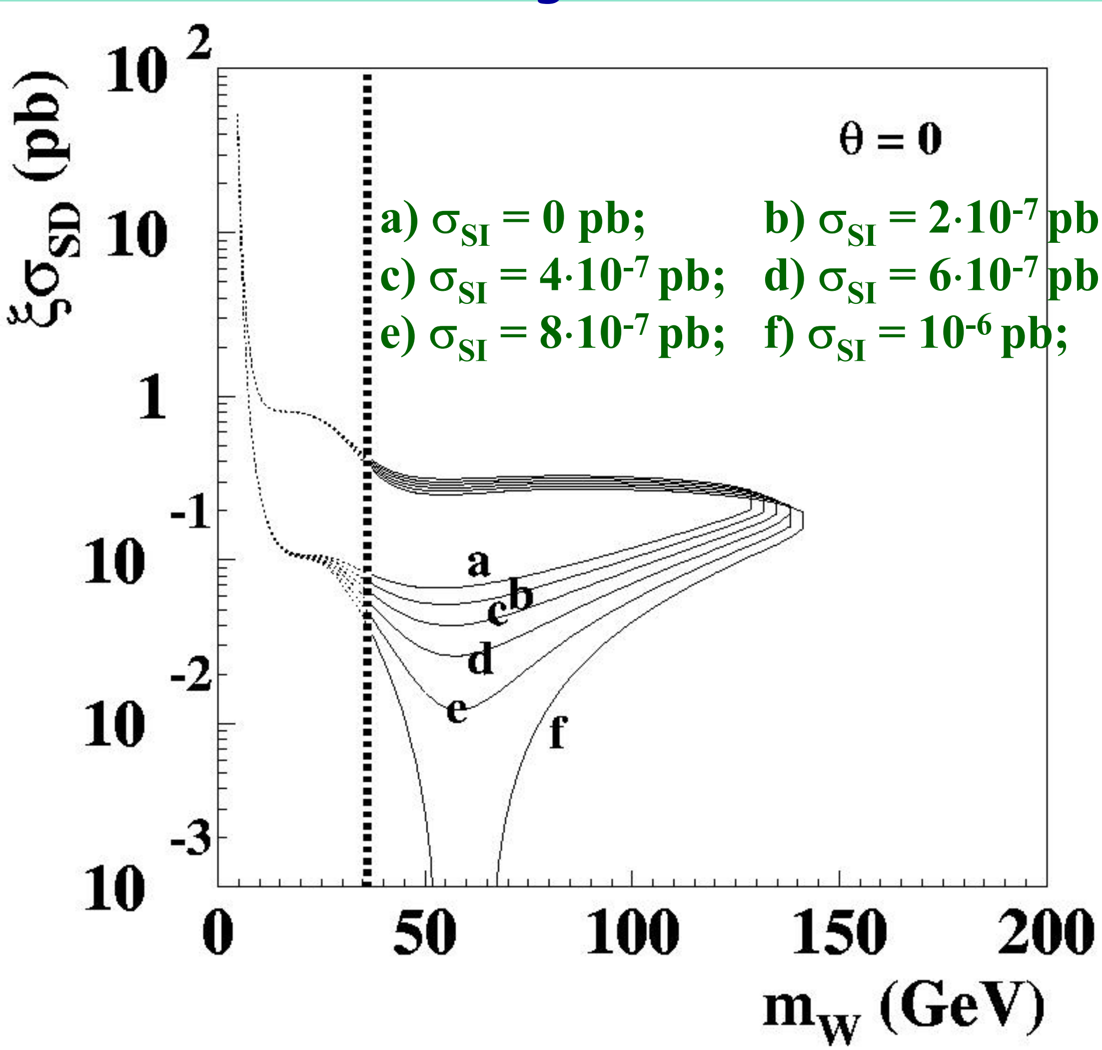
Regions above 200 GeV allowed for low v_0, for every set of parameters' values and for Evans' logarithmic C2 co-rotating halo models

Best-fit values of cross section and WIMP mass span over a large range depending on the model framework

The inclusion of other existing uncertainties on parameters and models would further extend the region: e.g. the use of more favourable FF than those we considered here alone would move the region towards lower cross sections

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

- Example obtained considering Evans' logarithmic axisymmetric C2 halo model with v_0 = 170 km/s, ρ_0 max and parameters of set A for θ=0.
- The different regions refer to different SI contributions

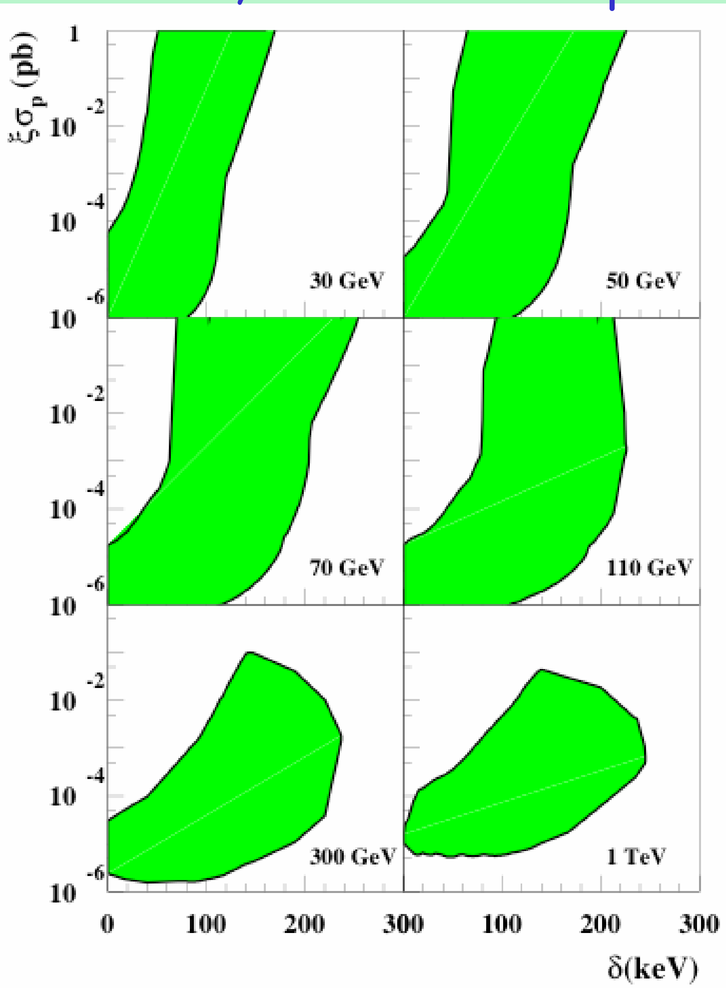


A small SI contribution ⇒ drastically moves the allowed region in the plane (m_W, $\xi\sigma_{SD}$) towards lower SD cross sections ($\xi\sigma_{SD}$ < 0.1 pb)

The accounting for the uncertainties, e.g., on the spin factors, different SD form factors would extend the region allowed and move it towards lower $\xi\sigma_{SD}$ values

WIMP with preferred SI inelastic interaction: $W + N \rightarrow W^* + N$

- Region allowed in the space $(m_W, \xi\sigma_p, \delta)$
- $\xi = \rho_W/\rho_0$, $\xi \leq 1$ fraction of amount of local WIMP density
- Here examples of slices for some m_W values
- Several consistent halo models including halo rotation (see before)
- Cases A, B and C + see previous transparencies



v_{esc} fixed but its uncertainties can play an important role, extending the allowed regions

region largely lies in δ regions where e.g. Ge is disfavoured

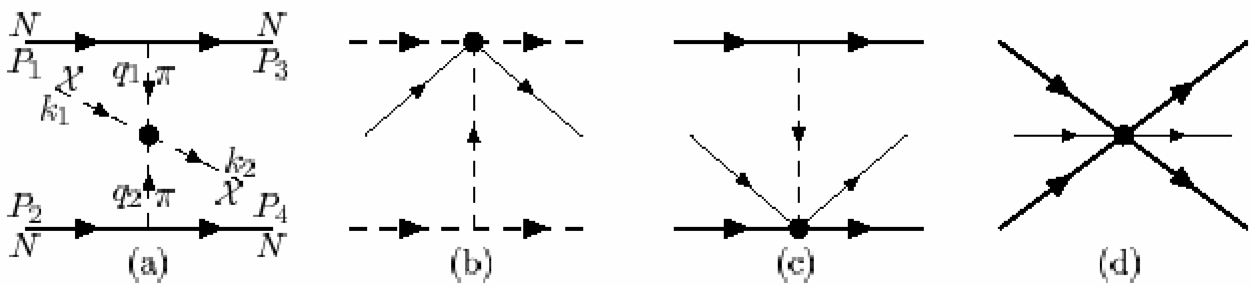
Best-fit values of cross section and δ for given m_W span over a large range depending on the model framework. Just as an example: $m_W = 70$ GeV in NFW B5 halo model with low v_0, max ρ_0 and parameters as in case B: $\delta = (86^{+6}_{-8})$ keV, $\xi\sigma_p = (1.2 \pm 0.2)\ 10^{-5}$ pb

The inclusion of other existing uncertainties on parameters and models would further extend the region: e.g. the use of a more favourable SI form factor for iodine would move the regions towards lower cross-sections

... either other uncertainties or new models?

Two-nucleon currents from pion exchange in the nucleus:

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



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

Marc Kamionkowski, Petr Vogel et al., astro-ph/0309115

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

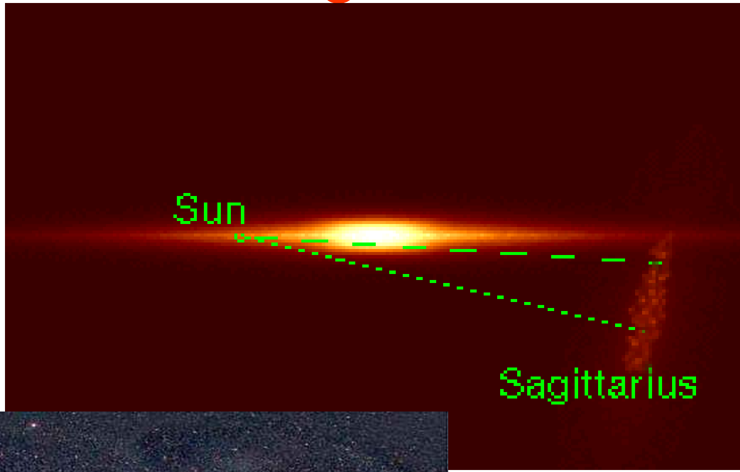
$\varepsilon_A = 0$ "usually"

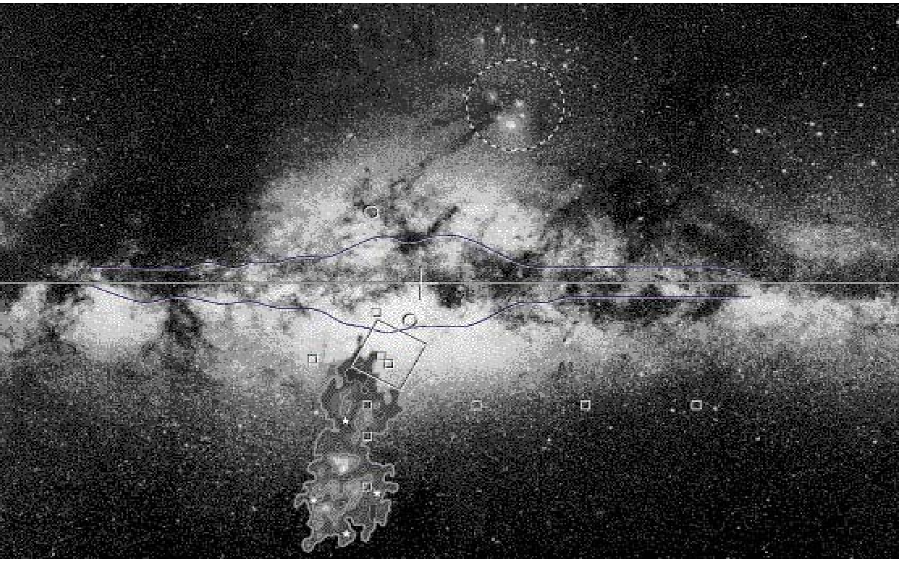
$\varepsilon_A \approx \pm 1$ here in some nuclei?

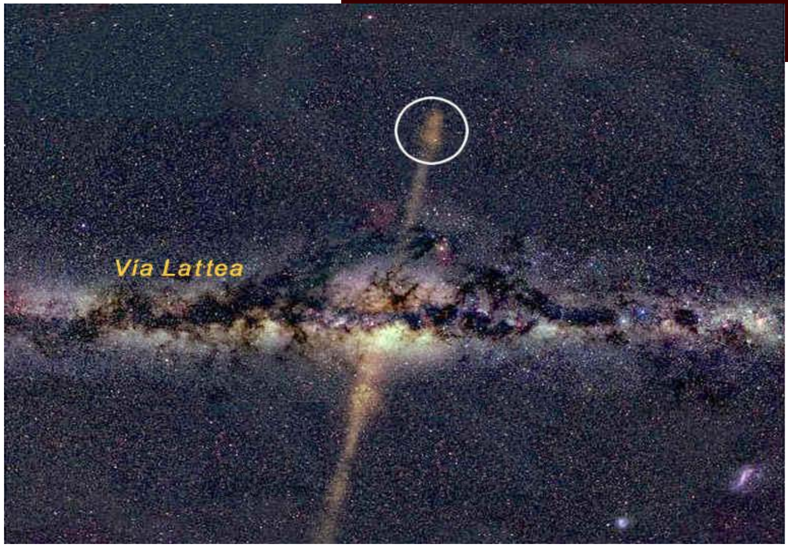
New scaling laws even in the pure SI case for χ in MSSM?

The Sagittarius Dwarf Elliptical Galaxy and the Dark Matter galactic halo

In 1994 –1995 a new object: the "Sagittarius Dwarf Elliptical Galaxy", has been observed in the vicinity of the Milky Way, in the direction of the galactic center and in the opposite position with respect to the solar system.



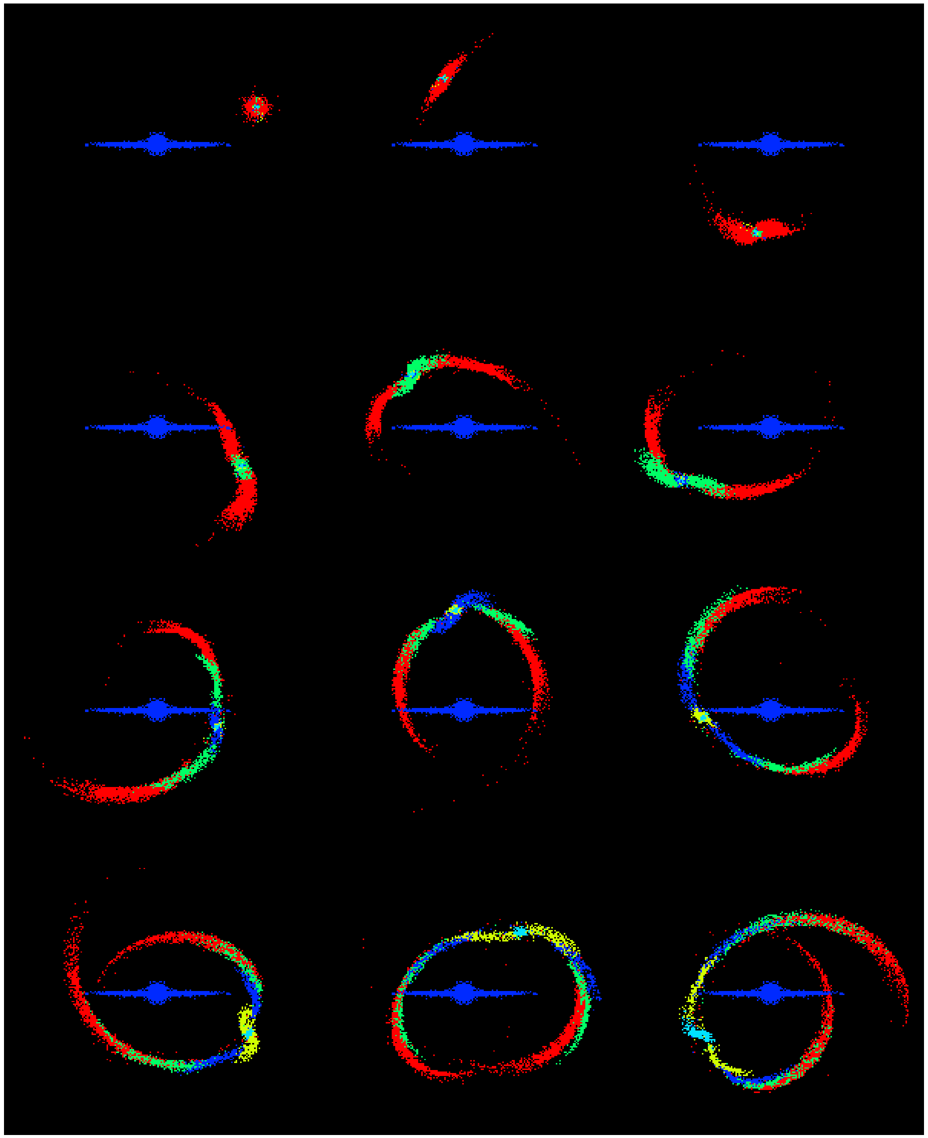




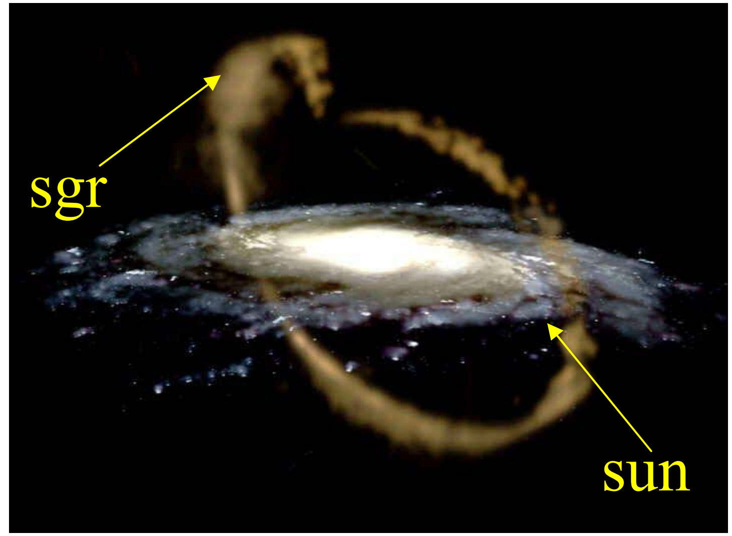
The motion direction of the Sagittarius DEG was well different than that of the other luminous objects in the Milky Way and, thus, it has been discovered that the observed stars belong to this dwarf galaxy satellite of the Milky Way, which is going to be captured.

This dwarf galaxy has a very long shape because of the tidal strengths suffered during about 10 revolutions around the Milky Way.

Simulation of the deformation of the SagDEG due to the tidal strengths during its revolutions around the Milky Way



The Sun is at about 2 kiloparsec from the center of the main tail



A particle Dark Matter flux from the dark halo of SagDEG, with a velocity of about 300 km/s perpendicular to our galactic plane, is expected.

Estimated density: [1 - 80] 10^{-3} GeV/cm^3

that is (0.3-25)% of the local density.

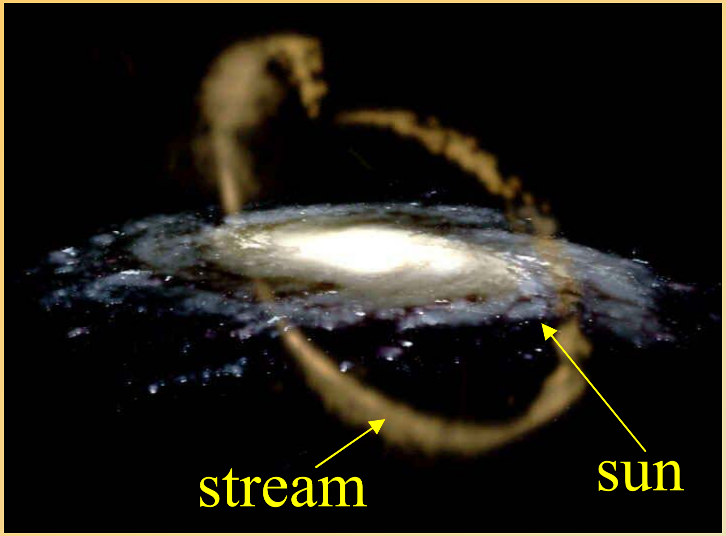
A multi-component Dark Matter galactic halo?

Other contributing satellite DEGs may exist?

… other astrophysical scenarios?

possible contribution in the halo from Sagittarius Dwarf Tidal Stream?

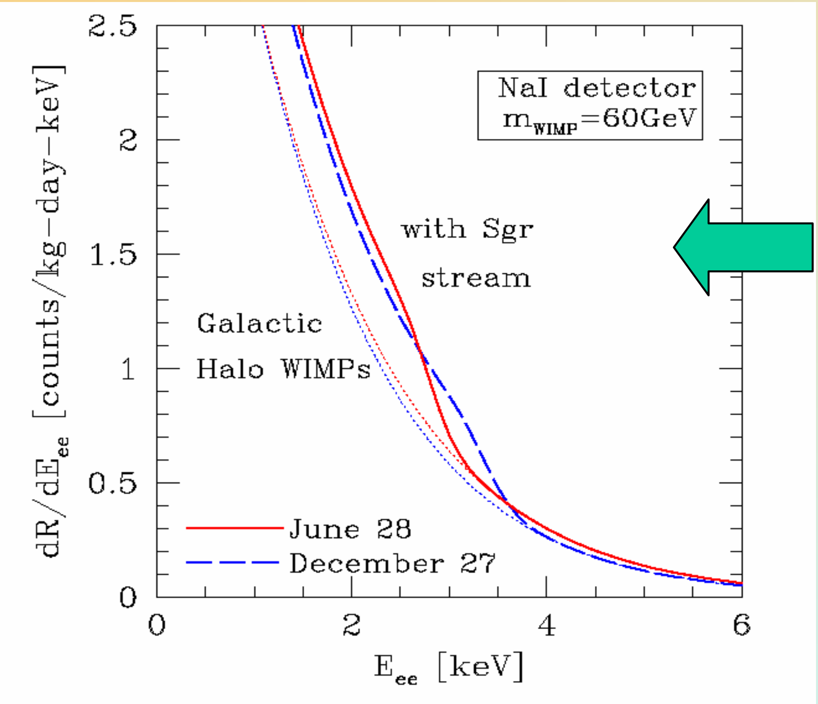
K.Freese et. al. astro-ph/0309279



Tidal streams of Sagittarius dwarf spheroidal galaxy may be showering dark matter onto the Solar System. The Sagittarius WIMPs stream could contribute to (0.3-25)% of the local density of our galactic halo, and the velocity is estimate to be ~300 km/s in direction of the stream (about perpendicular to the galactic plane).

e.g.:

Example of expected differential counting rate for a given model and parameters assumptions.



Does $|S_m/S_o|$ ratio drastically change with respect to "usually" adopted halo models?

Interesting scenario for DAMA work under development

DAMA/NaI vs others

	DAMA/NaI	CDMS-II	Edelweiss-I	UKLXe (Zeplin-I)
• Signature	annual modulation	none	none	none
• Target	^{23}Na, ^{127}I	^{nat}Ge	^{nat}Ge	^{nat}Xe
• Technique	widely known	poorly experienced	poorly experienced	liq/gas optical interface (light collected from top)
• Target mass	≈ 100 kg	0.75 kg	0.32 kg	≈ 3 kg
• Used statistics	~(1.1 × 10^5) kg × day (Riv.N.Cim.26 n.1 (2003)1-73)	19.4 kg × day (astro-ph/0405033)	30.5 kg × day (NDM03)	280 kg × day (Moriond03)
• Expt. depth	1400 m	780 m	1700 m	1100 m
• Energy threshold	2 keVee	10 keVee	20 keVee	2 keVee (but: σ/E=100% and 1 p.e./keVee!!!; IDM02) (2.5 p.e./keVee; Moriond03)
• Quenching factor	measured	assumed 1	assumed 1 (see also NIMA(507(2003)643)	measured
• Measured evt rate in low energy range	~1 cpd/kg/keV	?? (said gammas > than CDMSI where ~60 cpd/kg/keV)	~ 10^4 events total	~100 cpd/kg/keV (IDM02)
• 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)
• Evts satisfying the signature in DAMA/NaI	modulation amplitude integrated over the given exposure some 10^3 evts	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

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

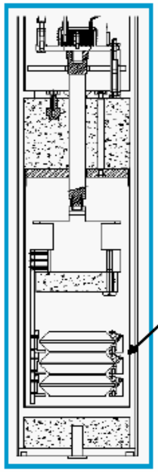
Cu screens without Roman Pb lateral shield

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

Future:

larger mass

different target nuclei?

COMMENTS:

- **data "selection" and "handling"?**

  (very small exposure released with respect to several years of the experiment)

- **bckg rejection technique and associated uncertainties full under control?**

- **What about the needed continuous monitoring of rejection windows stability, energy scale and threshold, overall detection efficiency, calibration..?**

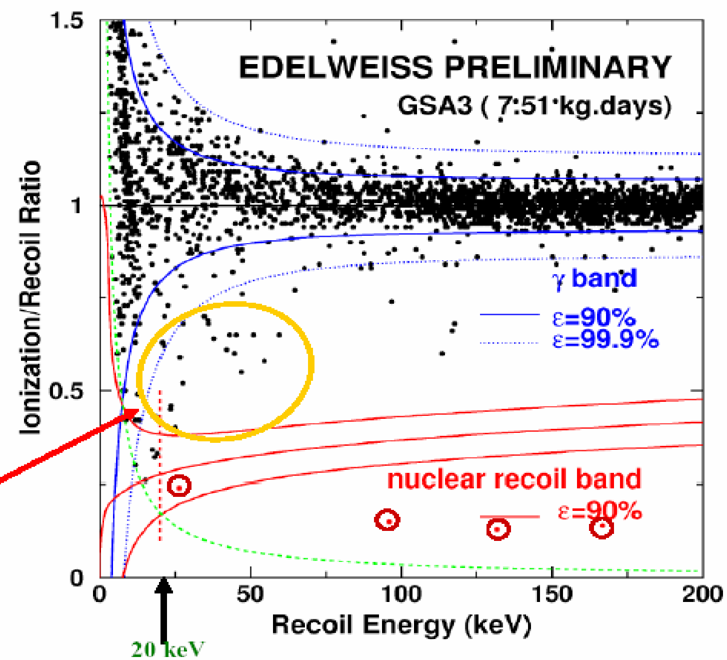
- **Are the two sensitive volumes (for ionization and bolometer signals) exactly identical?**

- **Bulk response, quenching factors, ….**

- **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

CDMS II at Soudan

astro-ph/0405033

Exposure about 10^4 times smaller than DAMA/NaI

See comments in the slide on Edelweiss

19.4 kg d exposure

3 x 250 g crystals

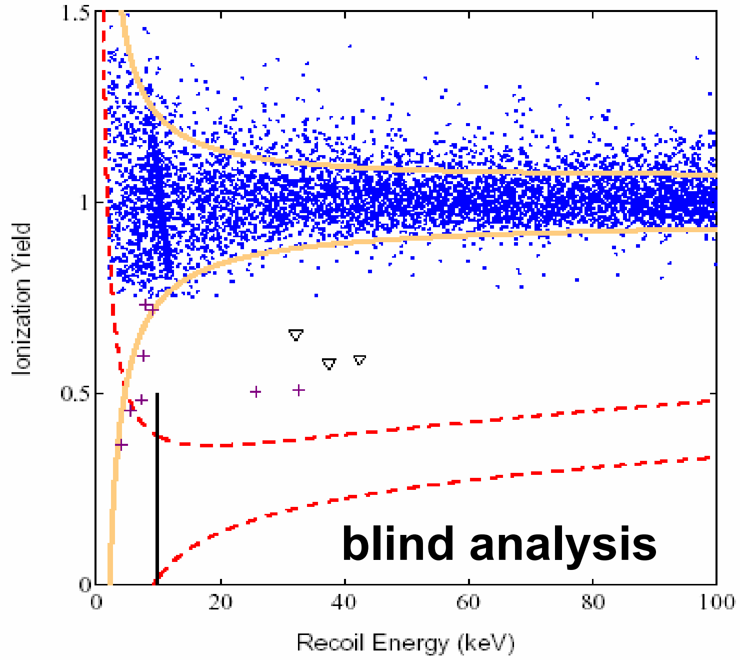
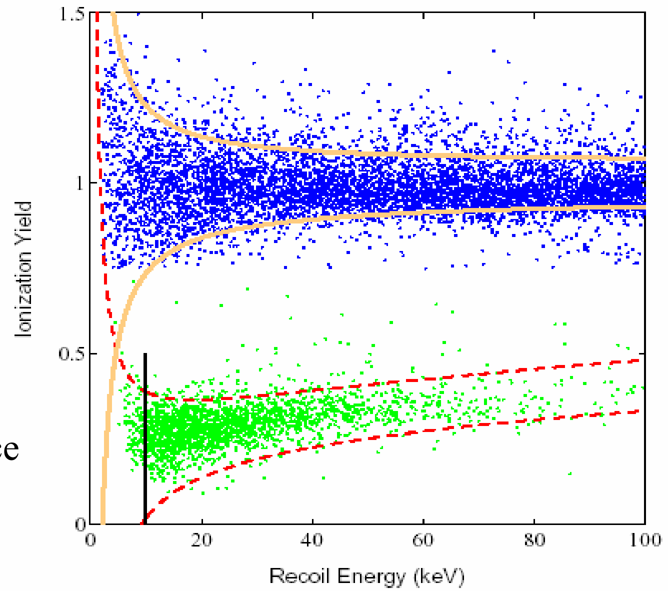


FIG. 4: Ionization yield versus recoil energy for WIMP-search data from Z2 (triangle), Z3, and Z5 (+) in Tower 1, using the same yield-dependent cuts and showing the same curves as in Fig. 1. Above an ionization yield of 0.75, the events from all three detectors are drawn as identical points in order to show the 10.4 keV Ga line from neutron activation of Ge.

source



Non-blind analysis: 1 nuclear event candidate

... DAMA/NaI "excluded" by CDMS-II (and friends)?

OBVIOUSLY NOT!

CDMS-II gives only a single model dependent result using ^{nat}Ge target nuclei!

DAMA/NaI gives a model independent result using ^{23}Na and ^{127}I target nuclei!

No direct model independent comparison possible

Taking their results as they gave:

•In general ? **OBVIOUSLY NOT!**

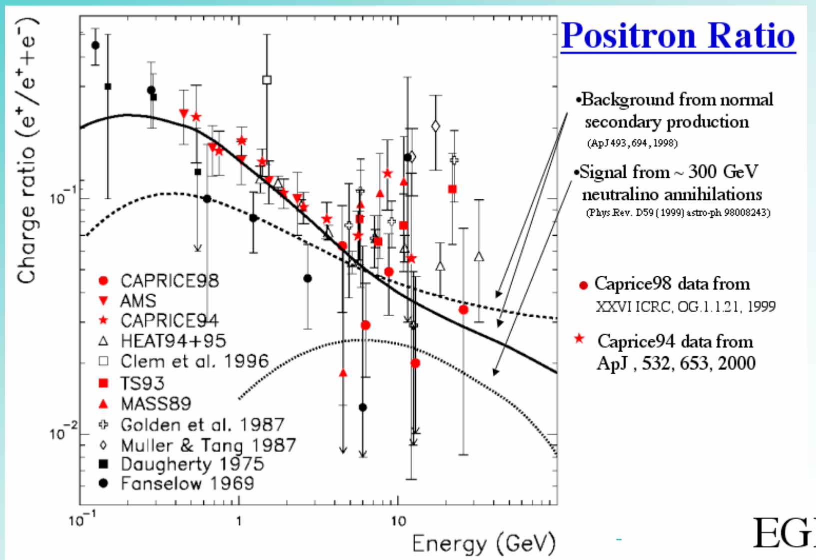
Different sensitivity to the different kinds of interactions, different more realistic and consistent halo models, alternative FF and/or SF and existing uncertainties on related parameters, different scaling laws (possible even for the neutralino candidate itself), proper accounting for experimental parameters (e.g. q.f.) and related uncertainties, priors, etc. can fully "decouple" the results.

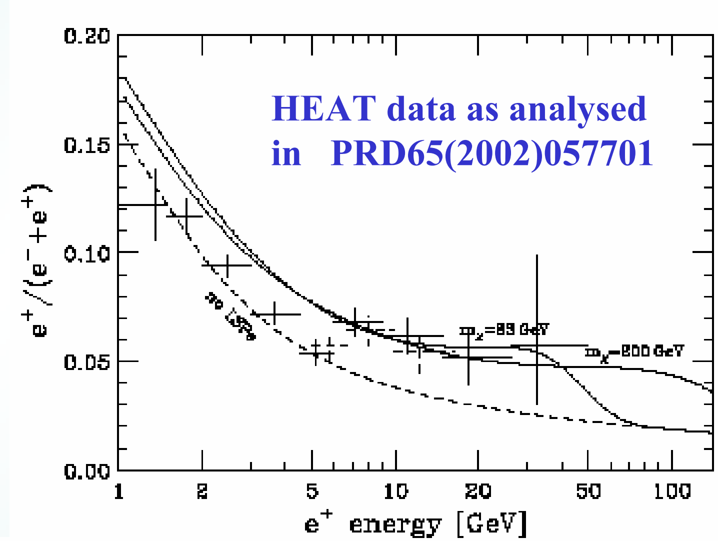
•At least in the purely SI coupling they only consider? **OBVIOUSLY NOT!**

they give a single result fixing all the astrofisical, nuclear and particle physics assumptions and expt. and theor. Parameters values. Then, they compare what they obtain in this particular case with a region also calculated under some fixed assumptions they choose in an old reference (the 1-4) among the regions calculated there for a small set of possibilities. This region was even not the one endorsed by DAMA/NaI for the limited scenarios considered for that partial exposure (see **PLB480(2000)23, EPJ C18(2000)283, PLB509(2001)197, EPJ C23 (2002)61, PRD66(2002)043503**). Thus they exclude what DAMA/NaI does not support: this is OK.

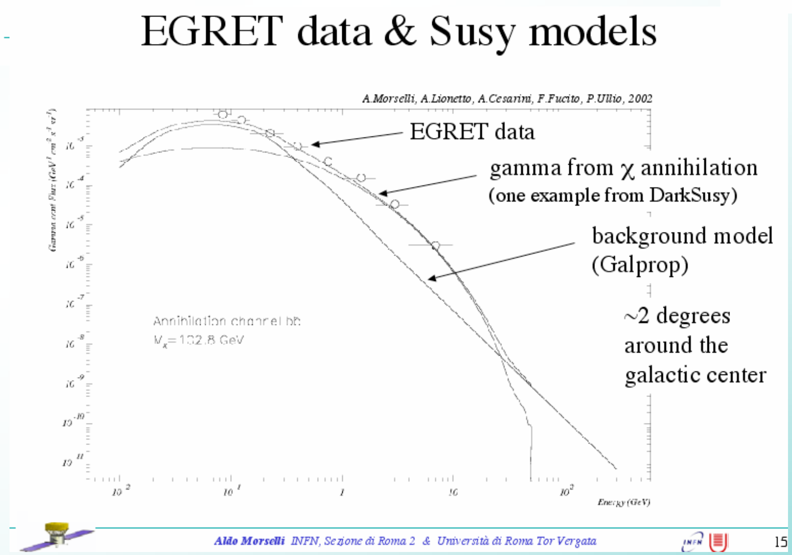
More complete calculations, accounting for uncertainties and for updated results on 7 cycles from DAMA/NaI (**Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403**), etc, exist for Na, I and ^{nat}Ge which show results from the two expts not in contradiction at all even for purely SI coupling as also commented by various authors.

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





A. Morselli et al., astro-ph/0211286



Note interpretation, derived WIMP mass and cross section depend e.g. on bckg modelling, on spatial/velocity WIMP distribution in the galactic halo, etc.

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

DAMA/NaI out of operation

The switching off of the ~100kg NaI(Tl) set-up at end of July 2002

Opening the shield

Dismounting the ~100kg NaI(Tl) set-up in August 2002 in HP N_2 atmosphere

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 new R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques

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

improving installation and environment

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

etching staff at work in clean room

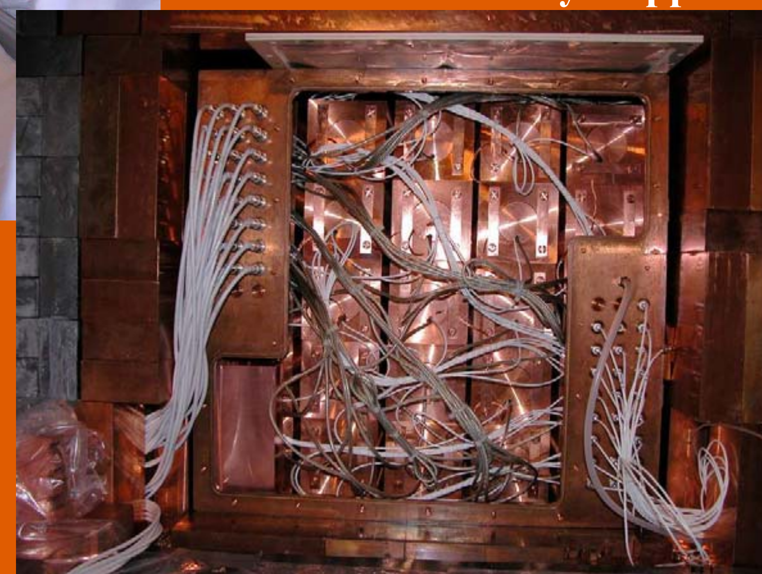
(all operations involving crystals and PMTs -including photos- in HP N_2 atmosphere)

installing LIBRA detectors

assembling a DAMA/ LIBRA detector

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

filling the inner Cu box with further shield

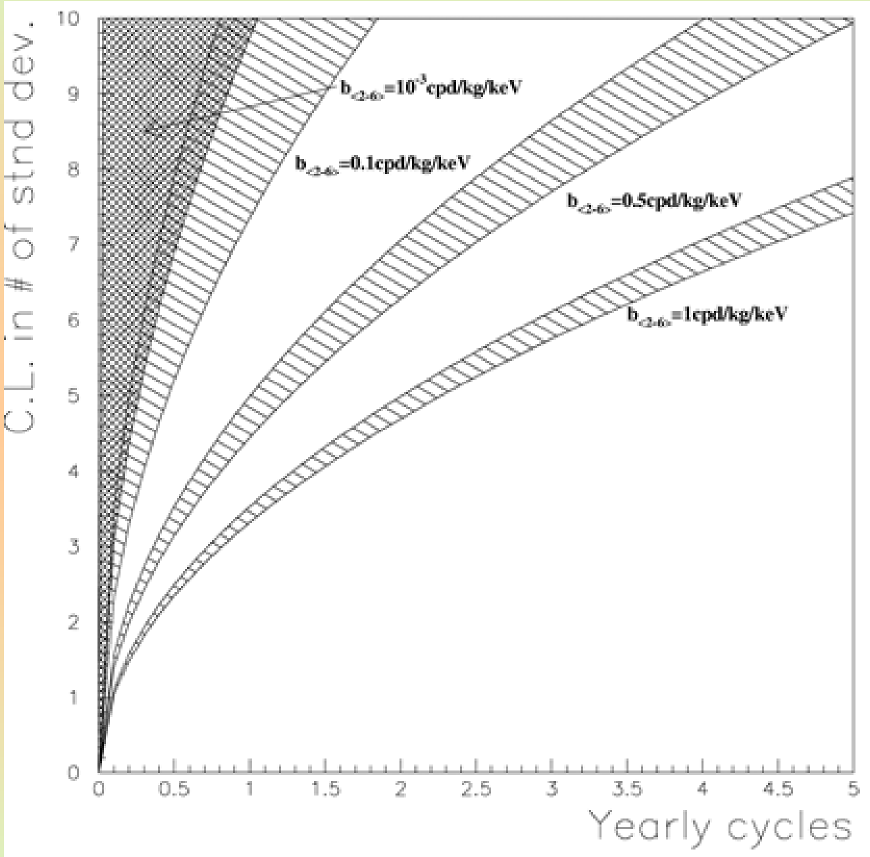


closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

An example on sensitivity in a simplified scenario

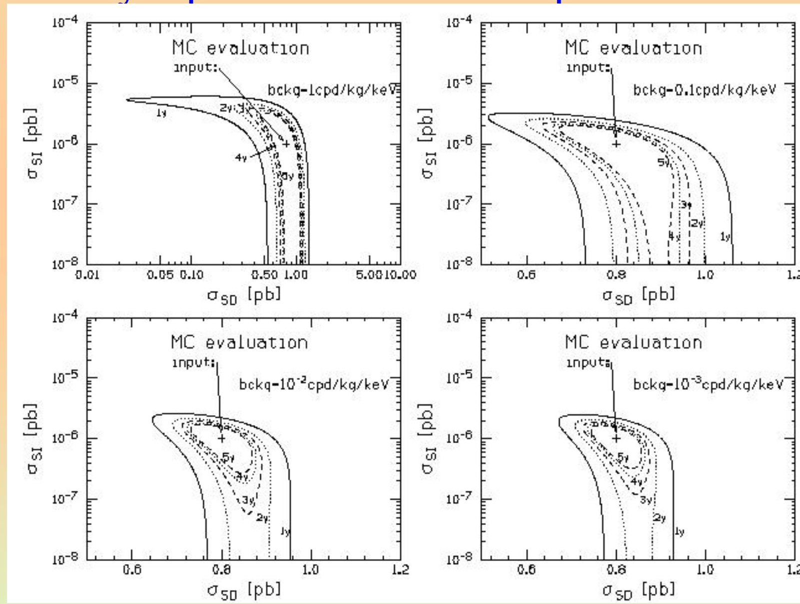
Model Independent approach



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

Model Dependent approaches

An example in a simple scenario: role of the increase of statistics and of the improvement in the bckg rate to identify a possible SI/SD coupled WIMP



Assumptions:

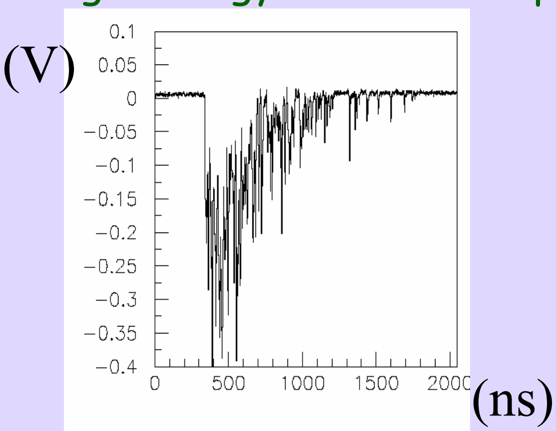
- 1σ C.L.
- v_0=220km/s, fixed params
- isothermal spherical halo, ecc

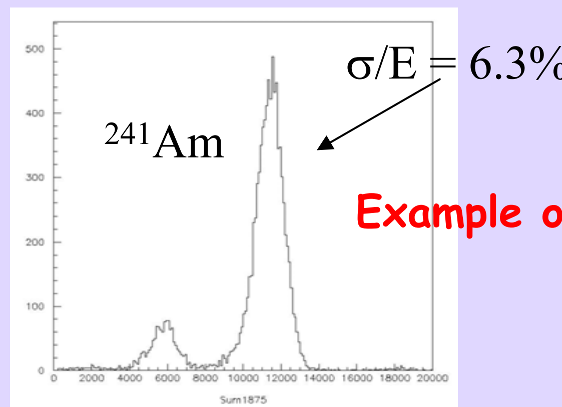
- Allowed regions evaluated by simulating the response of the ~250kg NaI(Tl) set-up to a WIMP having m_W=60GeV, $\sigma_{SI}=10^{-6}$ pb, σ_{SD}=0.8 pb and θ=2.435rad in the given simplified model framework
- Various exposure times are considered (from 1 to 5y).
- In each panel different bckg rate.

Further on LIBRA installation

upper glove box for calibration; the same as for ~100kg set-up (old photo)

first high energy scintillation pulse

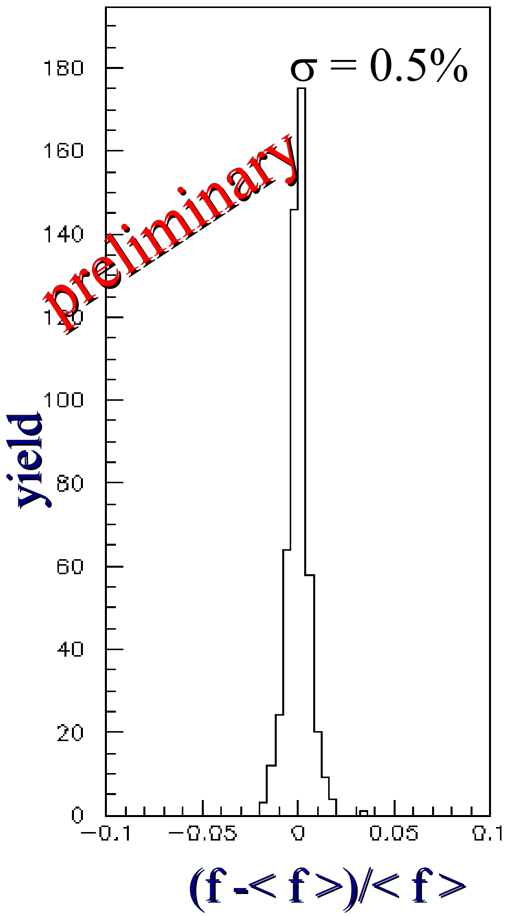




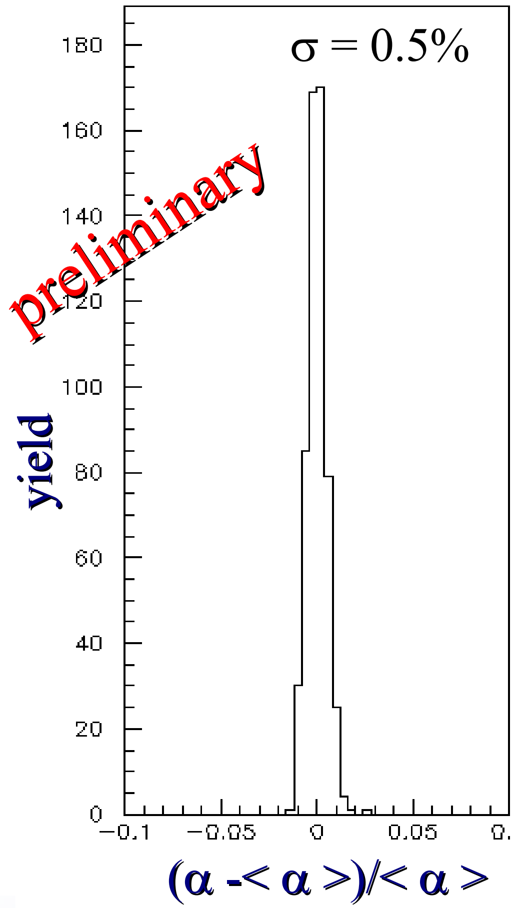
Example of energy resolution

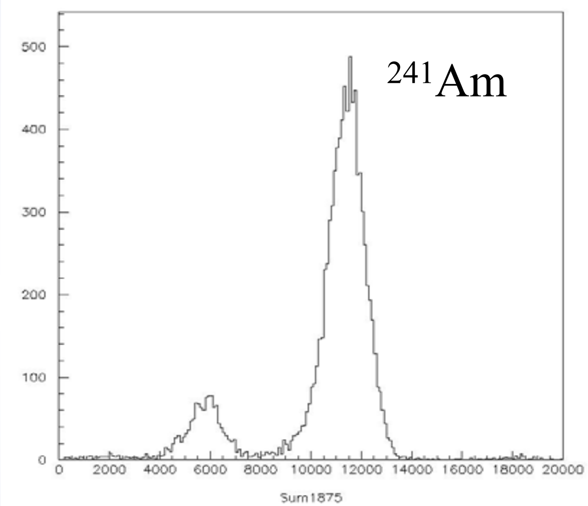
Stability of energy calibration factor in more than 1 year of data taking with DAMA/LIBRA set-up

Calib. factor (f)



Ratio (α) of the peaks' positions





Towards:

- higher C.L. for the signal in shorter time
- possibility to disantangle among some of the different astrophysical, nuclear and particle physics models

...waiting for an exposure larger than DAMA/NaI

... and beyond?

1996 (INFN comm. and IDM96) R. Bernabei discussed "Competitiveness of a very low radioactive ton scintillator for particle Dark Matter search"

LXE?

- 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 on thermodynamical parameters and phases interfaces
- cryogenic system complexity and safety problems
- less competitive duty cycle
- difficult noise rejection →higher threshold
- Unsuitable to investigate effects which require long time and high stability and reproducibility of the running condition
- each liquefaction re-builds the sensitive detector part (reproducibility?)
- etc.

→ NO

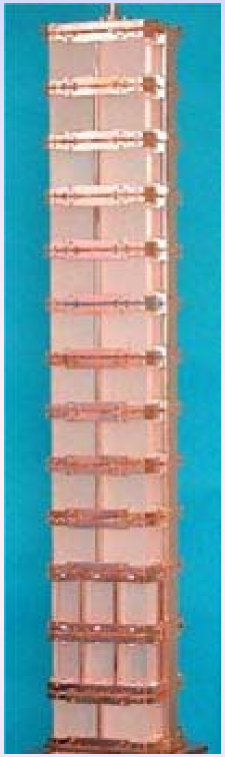
NaI(Tl)?

- cheap
- well known technology
- low energy threshold reachable
- efficient noise rejection
- techniques for high radiopurification exist
- the highest duty cycle
- efficient monitoring and control of running condition possible
- easy to operate over many years
- etc.

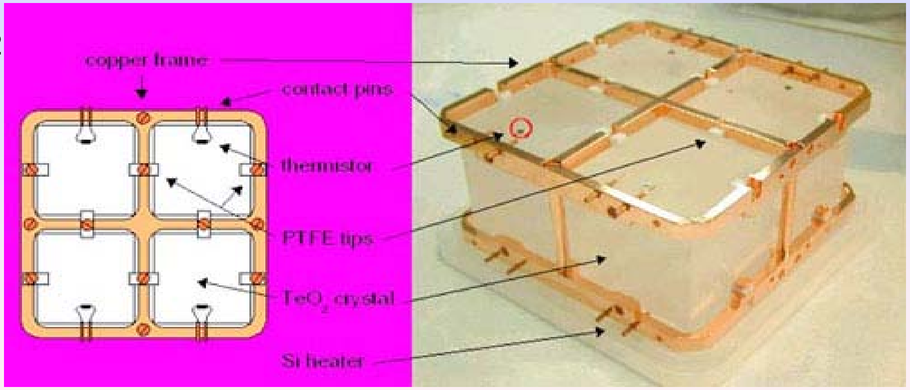
→ YES

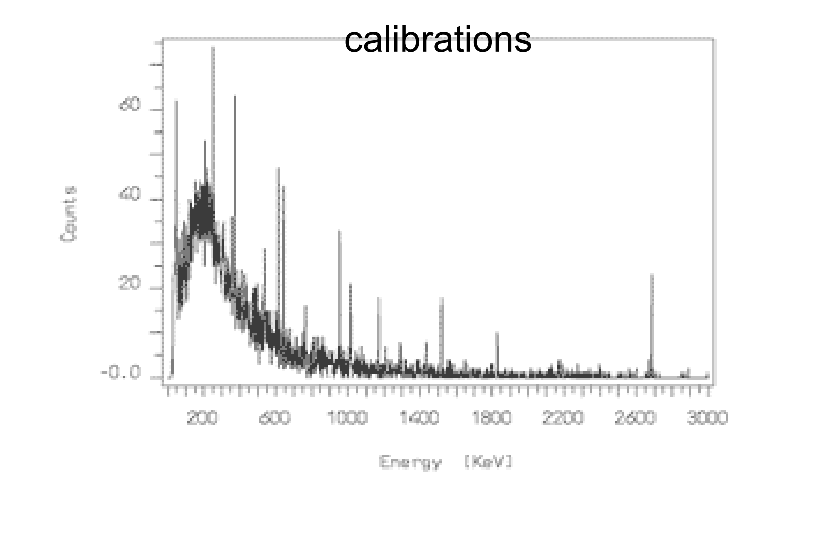
A new R&D for ultra-low background NaI(Tl) funded and in progress

CUORICINO/CUORE
(mainly devoted to double beta decay investigations)

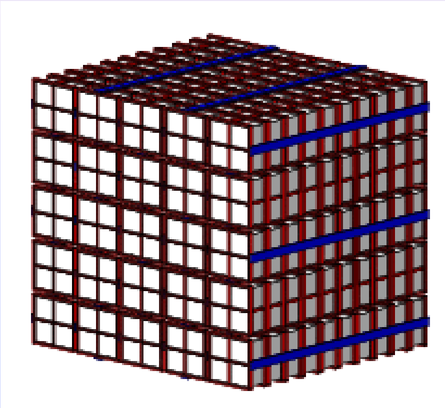


- **CUORICINO** consists in an array of 62 TeO_2 bolometers assembled in a tower structure, with a total mass of TeO_2 of ~ 40 kg, the array will be mounted inside the same dilution refrigerator used in MiDBD experiment.
- The design of the detector is very similar to that of the single CUORE tower. Cuore plans to have a mass of about a ton.
- **CUORICINO** is not only a test bed for CUORE but also a self consistent experiment that plans to explore the present sensitivity for < m_ν > obtained with isotopically enriched Ge detectors.

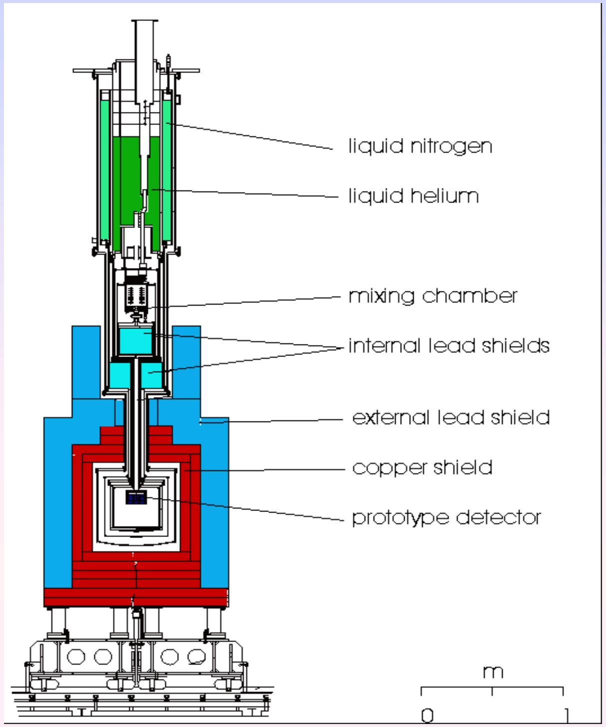




CUORE schematic view

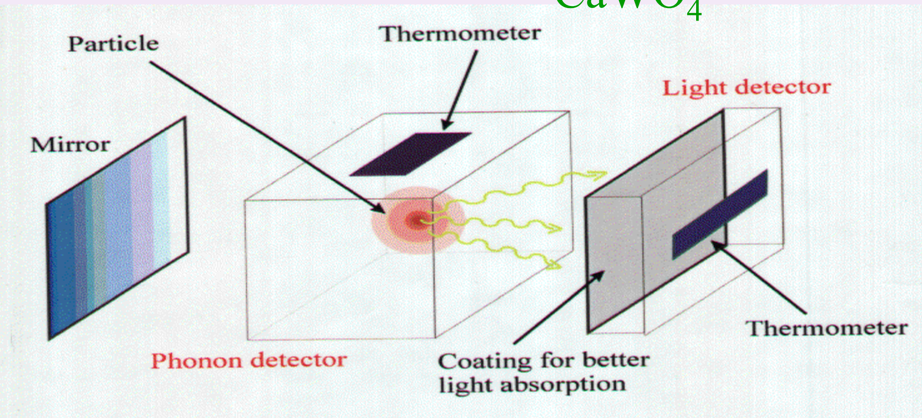


CRESST

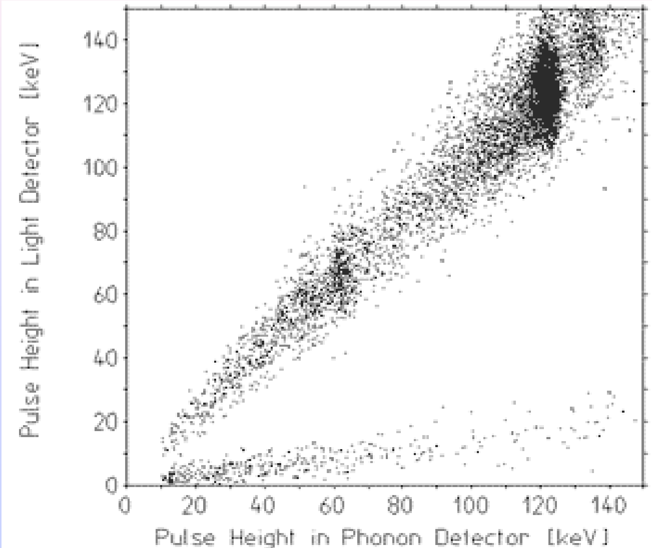


- CRESST first stage: sapphire detectors with a mass of 262g
- CRESST second phase, CRESST II: $CaWO_4$ crystals, with simultaneous measurement of scintillation light and phonons. The mass of a single detector module is about 300g.
- Only in 2003 CRESST installed a neutron shield and a muon veto and started measurements with a mass of about 3 kg which will be upgraded to 10 kg in 2004.

Phonons vs light: $CaWO_4$

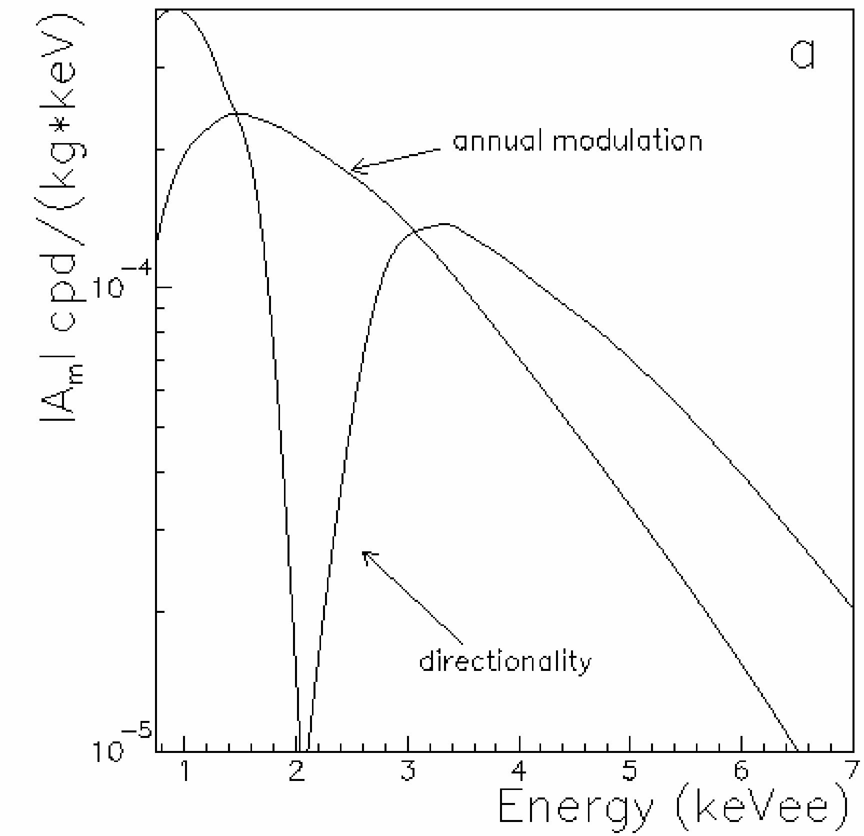


- q.f. for $CaWO_4$ bolometer signal ?
- Ca, W, O light q.f. in $CaWO_4$?
- "light collection" efficiency?
- Bulk response?
- Stability?



A possible goal in future with scintillators?

Signatures cooperation: annual modulation + directionality



An example of signature amplitude expectations in a given simplified single model framework

(EPJC28 (2003)203

For anisotropic scintillator (as e.g. anthracene) both signatures are effective.

...working for new anisotropic scintillators with high Z, high light response, stronger anisotropy coefficients

Wait for more...

Summary

- ✓ Particle Dark Matter investigation offers complementary informations on cosmology and particle Physics
- ✓ Several complementary approaches possible
- ✓ 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*

+ Some different kinds of approaches can offer complementary results