Future goals for the possible DAMA/1ton, now at R&D stage

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Vulcano Workshop
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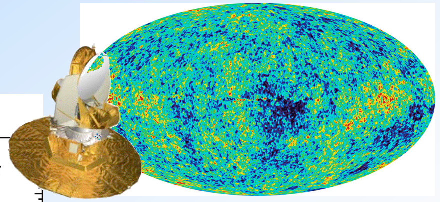
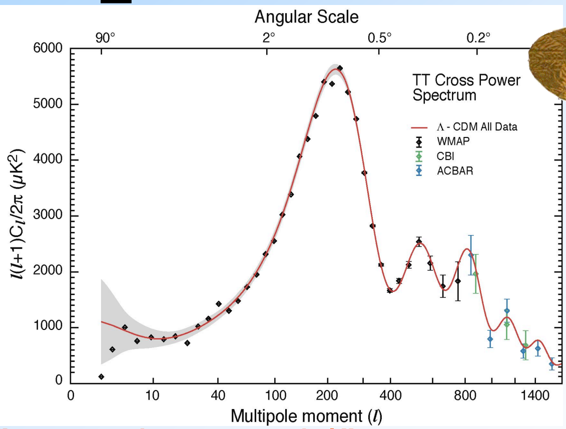
Dark Matter in the Universe

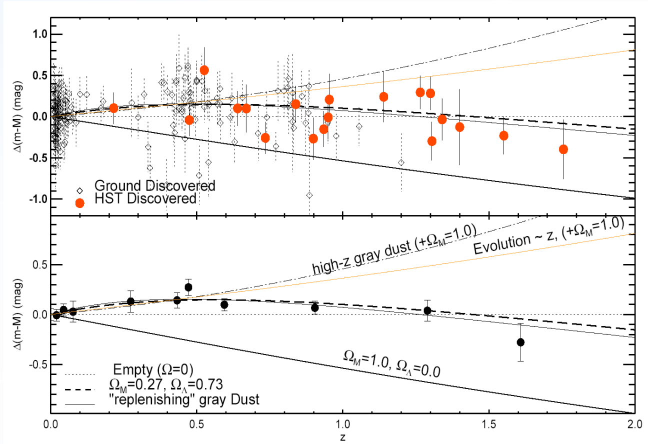
CMB measurements shows that the Universe is flat:

$$\Omega = 1.02 \pm 0.02$$

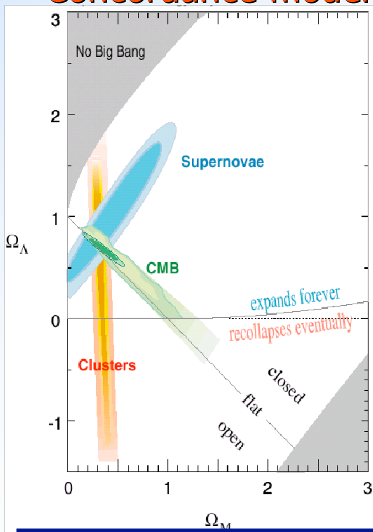




Current acceleration of the Universe from the measurement of the luminosity distances of Supernovae IA



"Concordance model":



$$\Omega_\Lambda \approx 0.73$$

$$\Omega_M \approx 0.27$$

From BBN + theories of structure formation and observations on light nuclei abundance, microlensings, visible light:

small baryons contribution $\Omega_b \approx 4\%$

dominant Non baryonic Cold Dark Matter component $\Omega_{CDM} \approx 23\%$, $\Omega_{HDM,\nu} < 1\%$

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

⇒ 90% of the matter in the Universe is non baryonic
A large part of the Universe is in form of non baryonic Dark Matter particles

Relic particles from primordial Universe

- Heavy or Light candidate
- Single or multiple component in the Galaxy

CDM particle candidates

- SUSY (R-parity conserved □ LSP is stable): neutralino or sneutrino
- the sneutrino in the Smith and Weiner scenario
- a heavy □ of the 4-th family
- etc., etc.

&

- self-interacting dark matter
- mirror dark matter
- Kaluza-Klein particles (LKK)
- heavy exotic canditates, as "4th family atoms", ...
- axion-like (light pseudoscalar and scalar candidate)
- etc., etc.

- even a suitable particle not yet foreseen by theories

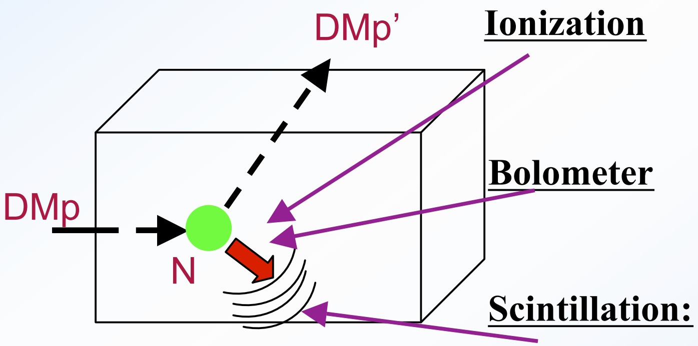
Direct detection:

- ✓ Various approaches and techniques (many still at R&D stage)
- ✓ Various different target nuclei
- ✓ Various different experimental site depths

Direct detection processes:

- scatterings on nuclei

  ⇒ detection of nuclear recoil energy



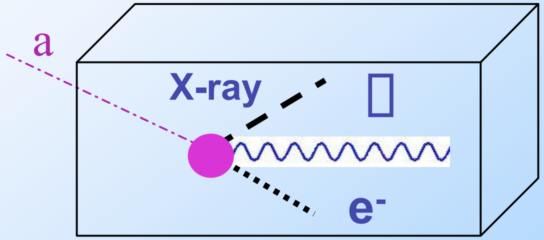
- excitation of bound electrons in scatterings on nuclei

  ⇒ detection of recoil nuclei + e.m. radiation

- etc......

- conversion of particle into electromagnetic radiation

  ⇒ detection of γ, X-rays, e^-

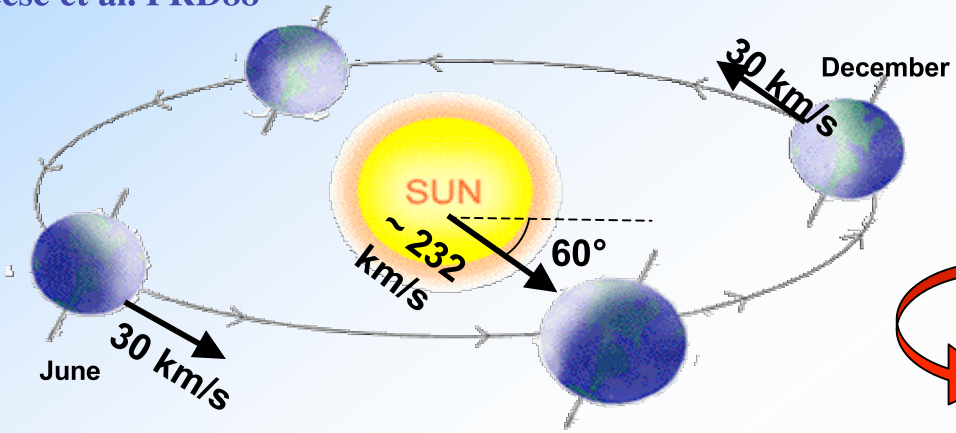


NOTE: signals from these candidates are lost in experiments based on rejection procedures of the electromagnetic contribution to the counting rate

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

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

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

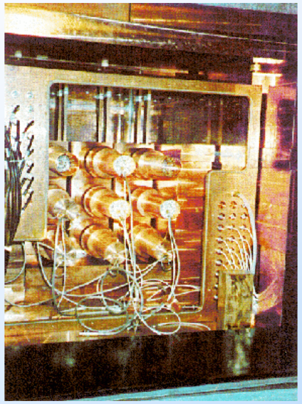
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

DAMA experiment: development and use of ultra-radiopure NaI detector for Dark Matter

- ✓ Proposed and first funded on 1990
- ✓ 1992 chinese colleagues joined the project

Several results since the beginning
and various test/preliminary set-ups

The high radiopure ~ 100 kg DAMA/NaI set-up:



- ✓ First experimental result published on 1996 (PLB389(1996)757)
- ✓ First result on WIMP annual modulation signature presented at TAUP97
- ✓ New electronics and DAQ in summer 2000
- ✓ Data from 7 annual cycles released and published
- ✓ Several rare processes investigated
- ✓ Out of operation in July 2002 to install the new ~ 250 kg DAMA/LIBRA

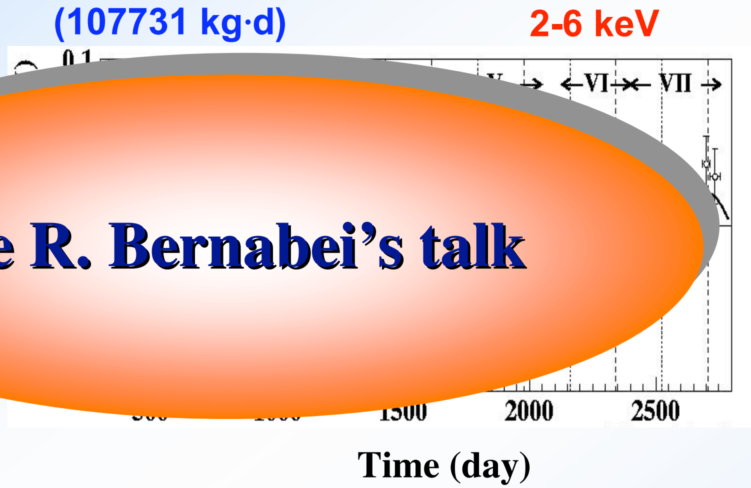
JULY 2003: RELEASE OF THE CUMULATIVE
7 ANNUAL CYCLES EXPOSURE (107731 kg day)
... still producing results

The ~ 250 kg new DAMA/LIBRA set-up:

- ✓ 2^{nd} generation R&D for highly radiopure new NaI(Tl) set-up
- ✓ new detectors, re-newed installation, new electronics and DAQ
- ✓ improvement in the shield
- ✓ in measurement since March 2003

DAMA/NaI (~100 kg NaI(Tl)) experimental result: model independent evidence for Dark Matter particle in galactic halo by annual modulation signature at 6.3σ C.L.

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



see R. Bernabei's talk

P(A=0) = 7·10^{-4}
Solid line: t_0 = 152.5 days, T = 1.00 years
from the fit:
A = (0.0192 ± 0.0031) cpd/kg/keV

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

- The several peculiar features of the signature satisfied. No systematics or side reactions able to mimic it
- Some of the many possible model frameworks investigated in the corollary quests for a candidate

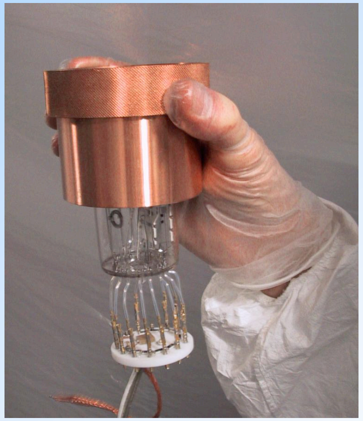
Corollary quest for a candidate:

- WIMP candidate (SI, SD, SI&SD)
- Inelastic WIMP
- bosonic DM
- effect for halo properties
- …etc. etc.

Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD 13 (2004) 2127, IJMPA 21 (2006) 1445, EPJC to appear. + in preparation

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 further purification of NaI(Tl) by exploiting new chemical/physical radiopurification techniques



PMT
+HV
divider

etching staff at work
in clean room

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

installing LIBRA detectors

view at end of detectors' installation in the Cu box

LIBRA (~250kg NaI(Tl)) is data taking …waiting for a larger exposure than that released by DAMA/NaI before first data release

Warnings for a possible ton generation experiment

1) Exploit the annual modulation with its unique features as a signature to investigate the Galactic Dark Matter particle component with a model independent approach

2) Note that experiments based on rejection of electromagnetic events are not sensitive to all kinds of candidates and possible interaction processes + claimed rejection factors for recoiling events up to 10^7-10^8 (asymptotic systematics?) + general huge data selection (few kg d in more than 10 years of operation) + multiple rejection procedure + only model-dependent results + recoil/recoil-like indistinguishable + etc.

3) Bet on experiments:
- with very high radiopurity
- sensitive to the various existing kinds of candidates and couplings (mixed SI&SD, pure SI, pure SD, various SD interaction depending on the effective coupling on proton and neutron, preferred inelastic, axion-like, neutrinos, etc.)

Advantages of NaI detector for Dark Matter

- Well known technology
- Very high duty cycle
- *"Ecological clean"* set-up; no safety problems
- Cheaper than other techniques considered in the field
- Neither re-purification procedure 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)
- High radiopurity by selections, chem./phys. purifications, protocols
- Well controlled operational condition feasible
- Routine calibrations feasible down to keV range
- Feasibility proved up to 250 kg +RDIII in progress
- Nominal sensitivity (calculated - as usual - assuming absence of signal) e.g. for SI particle: $\sigma_p < 10^{-10}$ pb
- Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-materials
- Sensitive to both high (by Iodine target) and low mass (by Na target) candidates
- PSD feasible at reasonable level
- Effective investigation of the annual modulation signature feasible
- Feasible in few years
- Small underground space needed
- etc. etc. etc.

Aims of DAMA/1 ton for Dark Matter

Goals of 1 ton NaI detector:

- Extremely high C.L. for the model independent signal observed by DAMA/NaI
- Model independent investigation on other peculiarities of the signal
- High statistics for the investigation and test of different astrophysical, nuclear and particle physics models

- Investigation on the Dark Matter candidate (neutralino, bosonic DM, mirror DM, inelastic DM, neutrino of 4th family, etc.):

  high exposure can allow to disantangle among different astrophysical, nuclear and particle physics models (nature of the candidate, candidate couplings, inelastic interaction, particle conversion processes, ….., form factors, spin-factors and more on new scenarios)

  scaling laws and cross sections

+

- Investigation on astrophysical models:

  velocity and position distribution of DM particles in the galactic halo

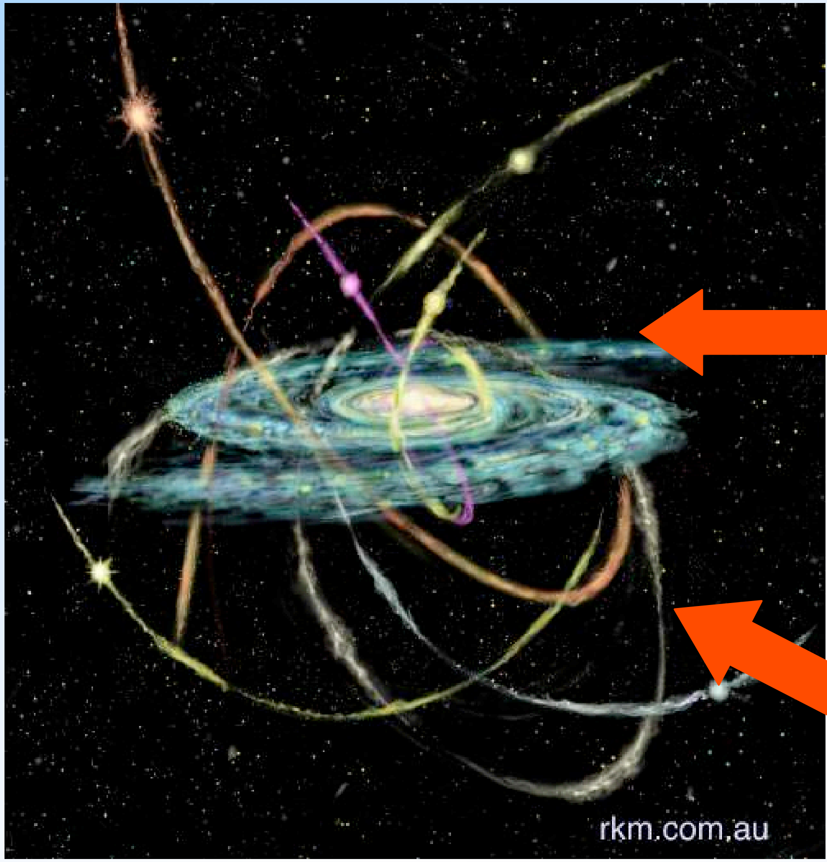
  effects on such distribution due to satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal “streams”

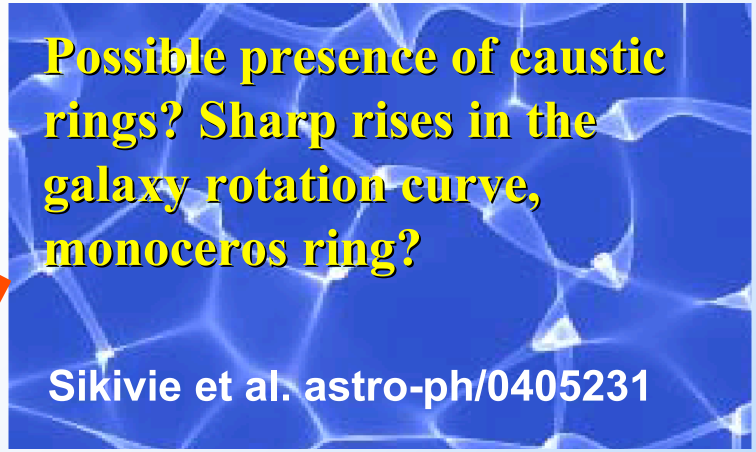
  effects due to clumpiness, caustics in the halo and possible distorsion due to the Sun gravitational field

Some open scenarios on astrophysical aspects

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

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



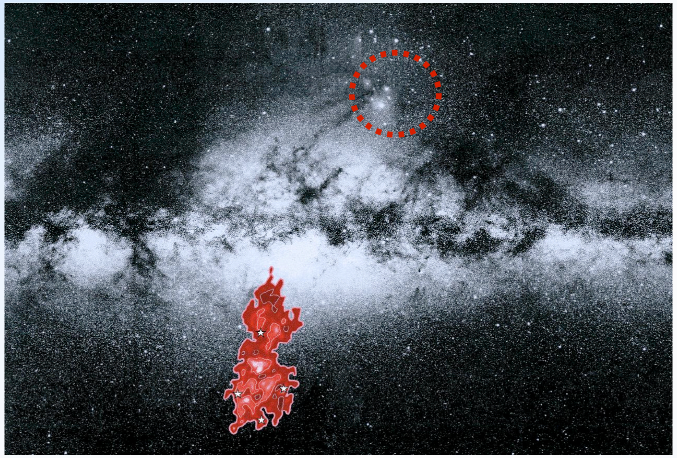


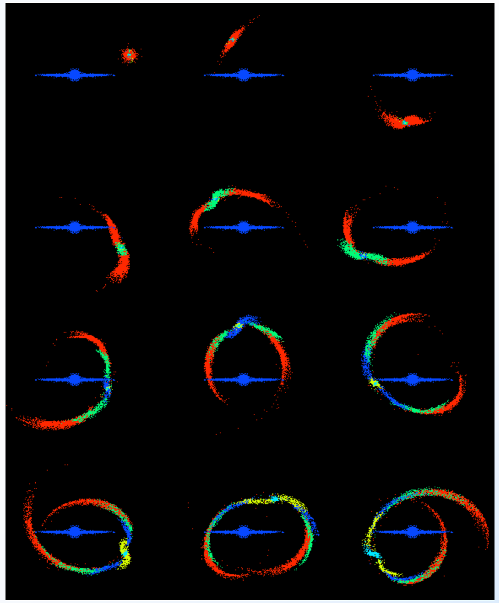
BOTH scenarios foreseen streams of Dark Matter particles with low velocity dispersion, very interesting for direct detection: S_m/S_0 enhanced in A.M., new signature for streams

Ex. the Sagittarius dwarf spheroidal galaxy: a disrupting satellite of the Milky Way

(Ibata et al. 1994)

Some models of the galactic gravitational potential foreseen a leading tail in the Solar neighborhood…





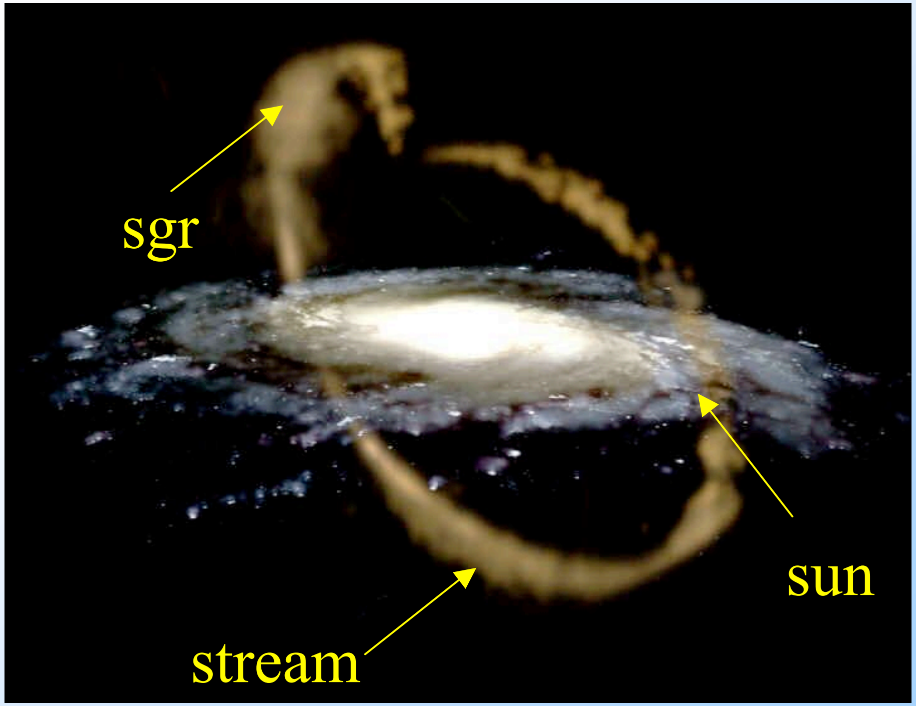
Considering from astro-ph/0309279:

Expected density:

[1 -- 80] 10^{-3} GeV/cm^3 (0.3-25)% of ρ_{halo}

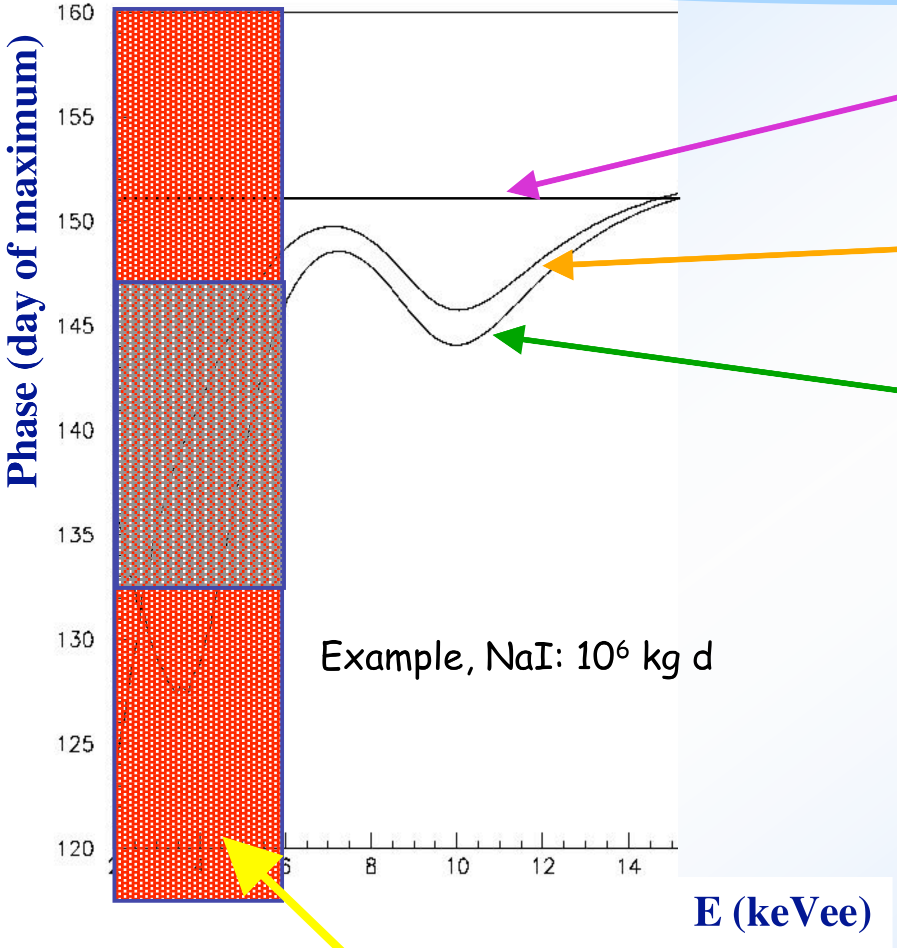
8 local stars hypotesized in the Sgr tail :
(290±26) km/s in the direction (l,b)=(116,-59):
(V_x,V_y,V_z)=(-65±22, 135±12,-249±6)km/s

Velocity dispersion:
$(\sigma_{vx},\sigma_{vy},\sigma_{vz})$=(63,33,17)km/s



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

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



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

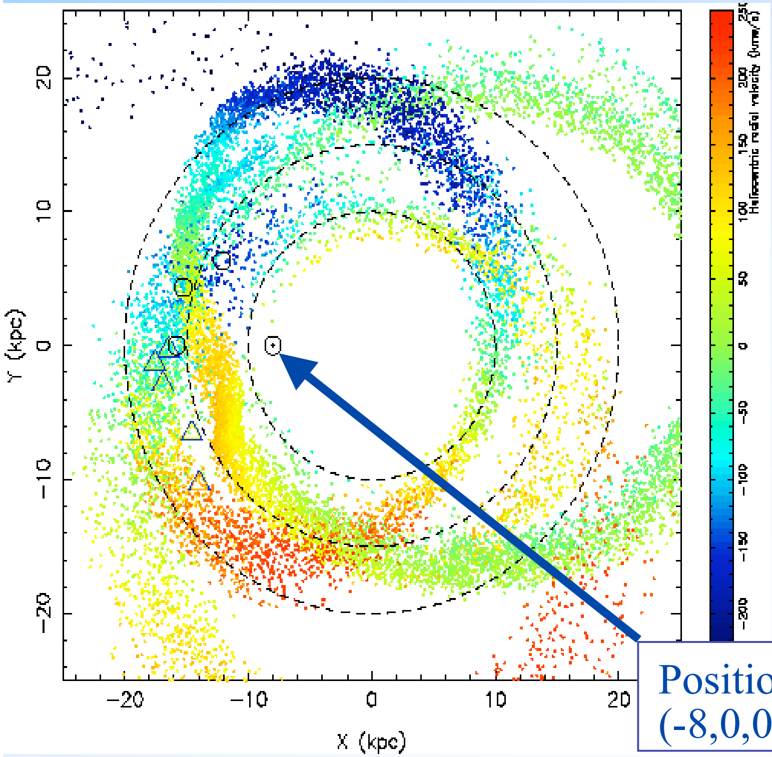
Evans'log axisymmetric non-rotating,
V_0=220km/s, R_c= 5kpc, $\_{0}$ max + 4% Sgr

NFW sferical isotropic non-rotating,
V_0=220km/s, $\_{0}$ max + 4% Sgr

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

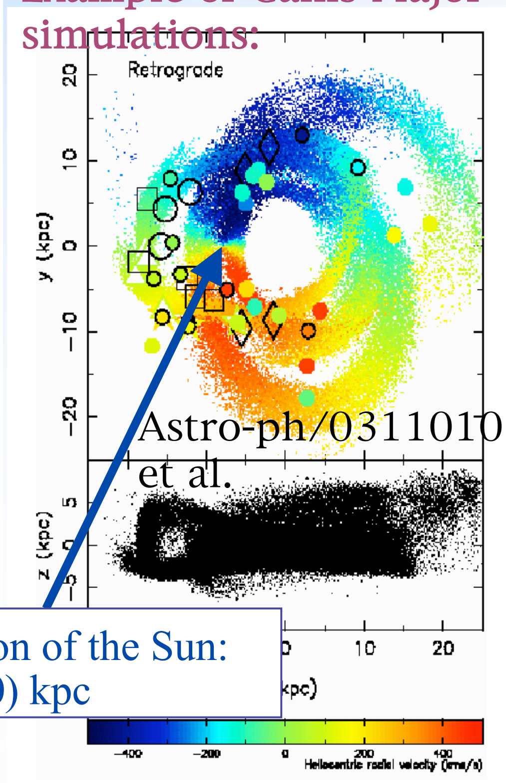
DAMA/NaI results:
(2-6) keV t_0 = (140 ± 22) d

Canis Major structure: the parent galaxy of the Monoceros Ring?



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

Example of Canis Major simulations:



Astro-ph/0311010 Ibata et al.

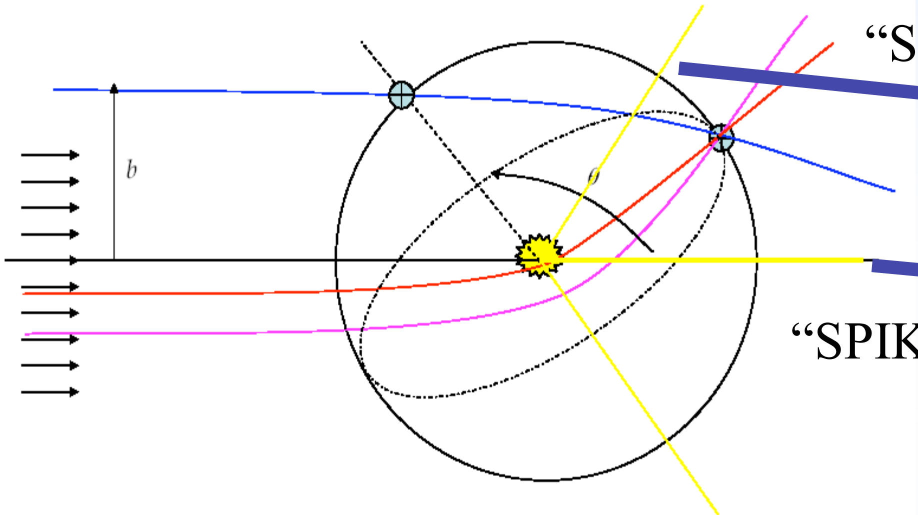
For a satellite galaxy embedded in the Milky way disk: the same t_0 is expected for the annual modulation signature but S_m/S_0 can be enhanced

There is general consensus on the PRESENCE of the structure, not jet on its NATURE:

1) It is the remnant of an accreted dwarf galaxy?
   (Martin et al. 2004a,b; Bellazzini et al. 2004; Martin et al. 2005, Bellazzini et al. 2005)
2) It is due to a deformation of the Galactic disc (warp)?
   (Momany et al. 2004, A&A, 421, L29)
3) It is part of a larger remnant: Argo?
   (Rocha-Pinto et al 2005, astro-ph/0504122)
4) There is a caustic ring at R~20 kpc?
   (Sikivie 2003, astro-ph/0309627)

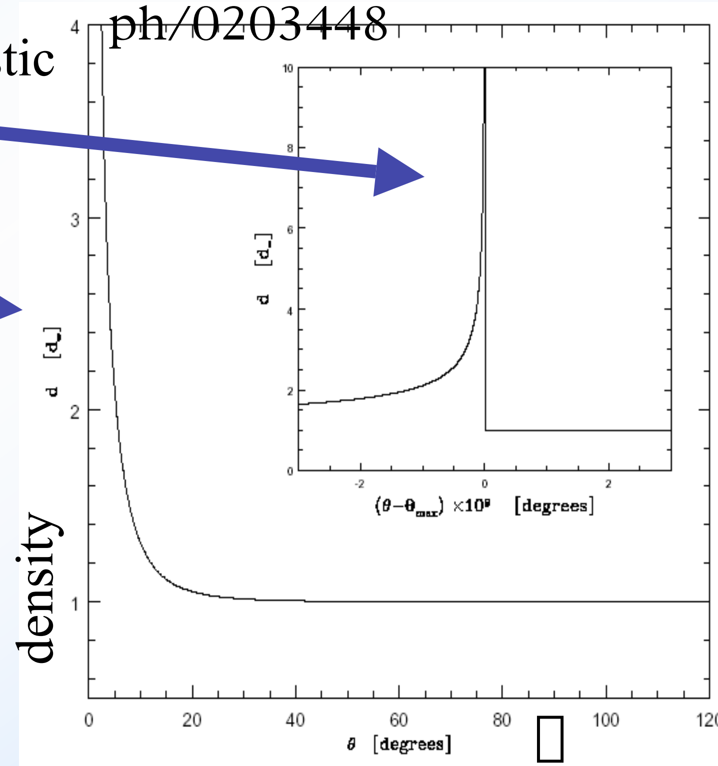
Example of a viable signature for DM streams in the solar neighborhood...

Sikivie et al. Astro-ph/0203448



"SKIRT" caustic

"SPIKE" caustic



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

an example:

V_{flux} ~ 300 km/s ; □$_V$ □70km/s

Earth orbit within 10° from "spike"

sensibility to $_{flux}$ > few % $_0$

Beyond the Dark Matter investigation by means of a 1 ton NaI(Tl) set-up

- **Possible PEP violating processes** maximal reachable sensitivity: ~ 3×10^{27} y
- **Possible CNC processes in ^{23}Na, ^{127}I**

  in case of a rate ~ 0.1 cpd/kg/keV in the region

  of interest and of the same duty cycle as at present:

  a) reachable sensitivity for CNC EC 10^{24}y 90%C.L. (or higher depending on r)

  b) reachable sensitivity for e^- disappearance 10^{25}y at 90%C.L.(or higher depending on r)
- **Nucleon and di-nucleon decay** maximal reachable sensitivity: τ_h -> 10^{27}y
- **SIMP investigation** maximal explorable mass: above 10^{17} GeV
- **Neutral nuclearities** maximal explorable flux: $\sim5\times10^{-12}s^{-1}cm^{-2}ster^{-1}$
- **Investigation on inelastic scattering** reachable sensitivity for r~ 0.1 cpd/kg/keV in the region of interest and the same duty cycle as at present 5 GeV/cm^3; lower rate can allow to explore physical regions
- **Solar axion investigation** maximal reachable sensitivity: $g_{a\gamma\gamma}\sim10^{-10}$ GeV^{-1}

… and beyond (e.g. $\beta\beta$ decays with passive and active sources, tests for ν physics with artificial ν source, neutrino magnetic moment measurement, solar neutrino spectroscopy, etc. etc

Towards DAMA/1ton

1) Proposed since 1996 (LIBRA intermediate step)
2) Technology largely at hand (do not waste experience and costs)
3) Possible further improvement in low-background characteristcs of the set-up (NaI(Tl) crystals, PMTs, shield, etc.)
4) 1 ton detector: the cheapest, the highest duty cycle, the fastest realization

It will have an extremely competitive "nominal sensitivity" because of e.g. the uncomparably higher duty cycle with the respect to all the proposals available so far + will be able to effectively investigate second order effects in the Dark Matter component in the galactic halo and several other rare process with high competitivity

Strong merit of highly radiopure NaI(Tl) (see elsewhere)

+ No experiment proposed so far exists:

- ✓ **with really new well proved technology**
- ✓ **able to effectively explore the same identical "physical" window (different target nuclei, different approaches, different radiopurity, different locations, different sensitivities to different scenarios, etc....)**
- ✓ **... and more**

Plans:

to complete RD-III in 2006-2007, if positive submit an updated operative report in 2007-2008 and possibly start detectors production in fall 2008.

Schema of the new R&D-III on ultra low background NaI(Tl)

1. NaI:
new NaI purification process starting from standard materials and measurements on powder

2. Thallium :
new source of raw material and research on new purification method and measurements on powder

3. Housing:
investigation on possible new housing materials and low-background welding technique + measurements

4. Production procedures:
investigation of new protocols for production and materials handling and measurements

5. Production of 1 NaI(Tl) - 3" x 3" - prototype
using the output of items 1, 2 and selected materials and procedure from 3 and 4 fixing a devoted protocol + measurements

6. Production of 1 NaI(Tl) - 3" x 3" - prototype
using the best identified procedures and materials from points 2,3,4 + previous experience. New devoted protocol will be fixed + measurements

→ **first new purified powders already produced**

LIBRA

N.Cim.A112(1999)545

detectors	^{nat}K< 50 ppb	U/Th several ppt

MS ISPRA AAS	^{nat}K (ppm)	^{238}U (ppb)	^{232}Th (ppb)
Old NaI powder	<0.8	0.56±0.04	0.21±0.01
New NaI purified powder	<0.1	0.02	0.02

New radiopure detectors by chemical/physical purification of the NaI and TlI powders: result of a dedicated second generation R&D

Intermediate test prototype	^{nat}K< 5 ppb	U/Th □ 1 ppt

In the final detectors' realization improved owen, crucible and protocol: features will be published in a devoted paper

Kyropoulos crystallization process (in platinum crucible when growing for final detectors) acts as an additional considerable purification step

PMTs

Current PMT in running set-up

- 3” window PMTs
- 3” diameter and 10 cm long UV Tetrasil-B light guides used, acting also as optical windows of the detectors.
- Flying leads directly connected to voltage dividers made of miniaturized SMD components mounted on thin teflon sockets (all selected for low bckg)
- solders performed by low radioactive Boliden lead and low radiactive resin
- The residual contaminants in the PMTs mounted on the DAMA/NaI detectors were already published in: Il Nuovo Cim. 112 A (1999) 545

  ^{nat}K: (60±15) ppm; ^{232}Th: (30±10) ppb; ^{238}U: (30±20) ppb.

- PMT shielding: in DAMA/NaI low radioactivity Cu (housing + bricks); in DAMA/LIBRA low radioactivity Cu (new shaped shield +housing) for the whole PMT body

Example of some new prototype developments without any glass and ceramics:

The residual contaminants in the first PMTs prototypes:

prototype no.1:	prototype no.2:
^{40}K < 0.12 ppb	^{40}K < 10 ppt
^{238}U: (5 ±1) ppb	^{238}U: (20 ±1) ppb
^{232}Th: (0.9 ± 0.2) ppb	^{232}Th: (2.2 ± 0.2) ppb

- ... But improvements on electronic part necessary, possible?
- … other more “traditional” solutions also in progress

Conclusion

- Dark Matter investigation is a crucial challenge in the incoming years for cosmology and for physics beyond the standard model

  - DAMA/NaI observed the first model independent evidence for the presence of a Dark Matter component in the galactic halo at 6.3□ C.L. with a total exposure 107731 kg·d

    - DAMA/LIBRA the 2nd generation NaI(Tl) detector (~250 kg) is in measurement

A possible ultimate NaI(Tl) multi-purpose set-up DAMA/1 ton proposed by DAMA since 1996 is at present at R&D phase

to deep investigate Dark Matter phenomenology at galactic scale