DAMA: an observatory for rare processes @LNGS

DAMA/LXe → DAMA/NaI(Tl) → DAMA/LIBRA

DAMA/low bckg Ge for sampling meas.
DAMA/R&D

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Corso di Fisica Nucleare e Subnucleare II
Prof. Carlo Dionisi
The Universe is flat

\[ \Omega = \Omega_M + \Omega_\Lambda = 1.02 \pm 0.02 \]

\[ \Omega_\Lambda \approx 0.73; \quad \Omega_M \approx 0.27; \]

Observations on:
- light nuclei abundance
- microlensings
- rotational curves
- visible light.

Primordial Nucleosynthesis

Structure formation in the Universe

The baryons give “too small” contribution

Non baryonic Cold Dark Matter is dominant

\[ \Omega_b \sim 4\% \]

\[ \Omega_{CDM} \sim 23\%, \quad \Omega_{HDM,\nu} < 1\% \]

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

A large part of the Universe is in form of non baryonic Cold Dark Matter particles
**Relic CDM particles from primordial Universe**

**Light candidates:** axion, axion-like produced at rest

**Heavy candidates:**
- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time (that is, COLD dark matter)
  \[ <\sigma_{\text{ann}} \cdot v> \sim 10^{-26}/\Omega_{\text{WIMP}} h^2 \text{ cm}^3\text{s}^{-1} \rightarrow \sigma_{\text{ordinary matter}} \sim \sigma_{\text{weak}} \]
- Expected flux: \( \Phi \sim 10^7 \cdot (\text{GeV/m}_W) \text{ cm}^2 \text{ s}^{-1} \) \( (0.2 < \rho_{\text{halo}} < 1.7 \text{ GeV cm}^{-3}) \)
- Form a dissipationless gas trapped in the gravitational field of the Galaxy \( (v\sim10^{-3}\text{c}) \)
  - neutral
  - stable (or quasi-stable with half life ~ age of Universe)
  - massive
  - weakly interacting

- **SUSY**
  - (R-parity conserved \( \rightarrow \) LSP is stable)
  - neutralino or sneutrino
  - a heavy \( \nu \) of the 4-th family
  - even a particle not yet foreseen by theories

- **the sneutrino in the Smith and Weiner scenario**
- **self-interacting dark matter**
- **mirror dark matter**
- **Kaluza-Klein particles**
- **heavy exotic candidates, as “4th family atoms”, ...**
For the DM 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 $\rightarrow 0.6 \, \mu/(m^2h)$
  - neutrons $\rightarrow 1.08 \cdot 10^{-6} \, n/(cm^2s)$ 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 $\rightarrow \approx 30 \, Bq/m^3$

- 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 activity NaI(Tl) surrounding the detectors
Experimental vs Expected spectra (with or without bckg rejection)

- Several assumptions and modeling required
- Experimental and theoretical uncertainties generally not included in calculations

No discovery potentiality

Uncertainties in the exclusion plots and in their comparison

Warning: limitations in the recoil/background discrimination (always not event by event): PSD (τ of the pulse depends on the particle) in scintillators (NaI(Tl), LXe), Heat/Ionization (Ge), Heat/Scintillation (CaF$_2$(Eu), CaWO$_4$).

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

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

**Direct search:**

- **Directionality** Correlation of nuclear recoil track with Earth's galactic motion due to the distribution of DM particle velocities very hard to realize.
- **Nuclear-inelastic scattering** Detection of $\gamma$'s emitted by excited nucleus after a nuclear-inelastic scattering. Very large exposure and very low counting rates hard to realize.
- **Annual modulation** Annual variation of the interaction rate due to Earth motion around the Sun. At present the only feasible one.
- **Diurnal modulation** Daily variation of the interaction rate due to different Earth depth crossed by the DM particle. Only for high $\sigma$. 
Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

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

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

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

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

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7\% (larger for DM particles with preferred inelastic interaction, PRD64 (2001)043502, or if contributions from Sagittarius, astro-ph/0309279)

To mimic this signature, spurious effects and side reactions must not only obviously be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all these 6 requirements.
The investigation on the annual modulation signature is model independent. If all the signature’s features are satisfied by the data, this points out the presence of DM particles in the galactic halo at a certain C.L.

To investigate the nature and coupling with ordinary matter of the possible DM candidate, an effective energy and time correlation analysis of the events has to be performed within given model frameworks. Thus, uncertainties on models and comparisons can affect not only the corollary estimated regions following a positive effect from the DM annual modulation signature, but also results given as exclusion plots.

First STEP

- The investigation on the annual modulation signature is model independent.
- If all the signature’s features are satisfied by the data, this points out the presence of DM particles in the galactic halo at a certain C.L.

Second STEP

Corollary quest for a candidate

DM particle’s velocity distribution and its parameters

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

New contributions to DM particle-nucleus scattering?

(see e.g. astro-ph/0309115 )

Scaling laws on cross sections

Form factors and related parameters

Spin factors etc.

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

Experimental parameters (typical of each experiment)

Comparison within particle models
**Results on rare processes:**

- Possible Pauli exclusion principle violation
- Nuclear level excitation of $^{127}$I and $^{23}$Na during CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Exotic Dark Matter search
- Search for solar axions by Primakoff effect in NaI(Tl) crystals
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

**Results on WIMPS:**

- PSD: PLB389(1996)757

**Total exposure collected during 7 annual cycles:**

$107731 \text{ kg \cdot d}$

**Performances:**


NaI(Tl) well suitable to investigate the annual modulation signature of DM particle

- Well known technology
- Large mass possible
- 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)(e.g. Xe has 1 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
- High duty cycle
- 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
The model independent result

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

Experimental single-hit residuals rate vs time and energy

Acos[ω(t-t₀)]; continuous lines: t₀ = 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

fit: A = (0.0192 ± 0.0031) cpd/kg/keV

Absence of modulation? No

χ²/dof=71/37 → P(A=0)=7·10⁻⁴

fit (all parameters free):

A = (0.0200 ± 0.0032) cpd/kg/keV ;

t₀ = (140 ± 22) d ; T = (1.00 ± 0.01) y

The data favour the presence of a modulated behaviour with proper features at 6.3σ C.L.
These residual rates are calculated from the measured rate after subtracting the constant part (the weighted mean of the residuals must obviously be zero over each period):

\[
\left\langle r_{ijk} - \text{flat}_{jk} \right\rangle_{jk}
\]

There the \( r_{ijk} \) is the rate in the considered i-th time interval for the j-th detector in the k-th considered energy bin, while \( \text{flat}_{jk} \) is the rate of the j-th detector in the k-th energy bin averaged over the cycles. The average is made on all the detectors (j index) and on all the energy bins in the considered energy interval.
Model-independent residual rate for single hit events

Results of the fits keeping all parameters free:

(2-4) keV
A = (0.0252 ± 0.0050) cpd/kg/keV
\( t_0 = (125 \pm 30) \) d
T = (1.01 ± 0.02) y

(2-5) keV
A = (0.0215 ± 0.0039) cpd/kg/keV
\( t_0 = (140 \pm 30) \) d
T = (1.01 ± 0.02) y

(2-6) keV
A = (0.0200 ± 0.0032) cpd/kg/keV
\( t_0 = (140 \pm 22) \) d
T = (1.00 ± 0.01) y
Power spectrum of single-hit residuals

2-6 keV vs 6-14 keV

Total exposure: 107731 kg · day

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

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

Treatment of the experimental errors and time binning included here

Single-hit residual rate as in a single annual cycle

DAMA/NaI 7 annual cycles: 107731 kg × day

Initial time August, 7

for $t_0 = 152.5$ day and $T = 1.00$ y:
$A = (0.0195 \pm 0.0031)$ cpd/kg/keV

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

Initial time August, 7

for $t_0 = 152.5$ d and $T = 1.00$ y:
$A = -(0.0009 \pm 0.0019)$ cpd/kg/keV
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: \textit{multiple-hits events = DM particle 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 7 annual cycles)
Mod ampl. = (0.0195\(\pm\)0.0031) cpd/kg/keV

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background
Summary of the results obtained in the investigation of possible systematics or side reactions

<table>
<thead>
<tr>
<th>Source</th>
<th>Main comment</th>
<th>Cautious upper limit (90%C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADON</td>
<td>Sealed Cu box in HP Nitrogen atmosphere</td>
<td>&lt;0.2% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>The installation is air- conditioned+ detectors in Cu housings directly in contact with multi-ton shield $\rightarrow$ huge heat capacity + T continuously recorded</td>
<td>&lt;0.5% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective noise rejection</td>
<td>&lt;1% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Periodical calibrations+ continuous monitoring of $^{210}$Pb peak</td>
<td>&lt;1% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>&lt;1% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>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</td>
<td>&lt;0.5% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured by MACRO</td>
<td>&lt;0.3% $S_m^{\text{obs}}$</td>
</tr>
</tbody>
</table>

 Thus, they can not mimic the observed annual modulation effect. Even if larger they can not satisfy all the 6 requirements of annual modulation signature.
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 DM 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
- No other experiment whose result can be directly compared in model independent way with this one is available so far

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 to be performed within given model frameworks

**THUS uncertainties on models and comparisons**

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

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

**corollary quest for a candidate**

experimental parameters (typical of each experiment)

comparison within particle models
Few Examples of corollary quests for the candidate particle


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

Examples of slices of the allowed volume in the space \((\xi_{\text{SD}}, \xi_{\text{SD}}, m_W, \theta)\) for some of the possible \(\theta\) (\(\text{tg}\theta = a_n/a_p\), with \(0 \leq \theta < \pi\)) and \(m_W\)

DM particle with dominant SI coupling

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

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

higher mass region allowed for low \(v_0\), every set of parameters’ values and the halo models: Evans’ logarithmic C1 and C2 co-rotating, triaxial D2 and D4 non-rotating, Evans power-law B3 in set A

DM particle with preferred inelastic interaction: \(W + N \rightarrow W^* + N\) (\(S_m/S_0\) enhanced): examples of slices of the allowed volume in the space \((\xi_{\text{SD}}, m_W, \delta)\) [e.g. Ge disfavoured]

not exhaustive + different scenarios?

DM particle with dominant SD coupling

Volume allowed in the space \((m_W, \xi_{\text{SD}}, \theta)\); here example of a slice for \(\theta = \pi/4\) \(0 \leq \theta < \pi\).

Regions above 200 GeV allowed for low \(v_0\), for every set of parameters’ values and for Evans’ logarithmic C2 co-rotating halo models
Summary

Particle Dark Matter investigation can offer complementary information on Cosmology and Particle Physics beyond the standard model.

Annual modulation signature very effective method successfully exploited by DAMA/NaI over 7 annual cycles (~ 1.1 x 10^5 kg day) obtaining a 6.3σ 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 have been pointed out not exhaustive at all – many other possibilities under investigations
+ different scaling laws?
+ different scenarios?
+ different Dark Matter distributions? non-thermal contributions?
  existence of streams? either caustics or clumpiness? ... and more

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
Supersymmetric expectations in MSSM

• Assuming for the neutralino a dominant purely SI coupling

• when releasing the gaugino mass unification at GUT scale: \( M_1/M_2 \neq 0.5 (<) \);

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

low mass configurations are obtained

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

figure taken from PRD69(2004)037302 (for previous DAMA/NaI partial exposure see PRD68(2003)043506)
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 N₂ atmosphere
**DM particle-nucleus elastic scattering**

**SI+SD differential cross sections:**

\[
\frac{d\sigma}{dE_R}(v, E_R) = \left( \frac{d\sigma}{dE_R} \right)_{SI} + \left( \frac{d\sigma}{dE_R} \right)_{SD} = \frac{2G_F^2 m_N}{\pi v^2} \left\{ \left[ Zg_p + (A-Z)g_n \right] F_{SI}^2(E_R) + 8 \frac{J+1}{J} \left[ a_p \left< S_p \right> + a_n \left< S_n \right> \right]^2 F_{SD}^2(E_R) \right\}
\]

\(g_{p,n}(a_{p,n})\) effective DM particle-nucleon couplings \(\langle S_{p,n} \rangle\) nucleon spin in the nucleus

\(F^2(E_R)\) nuclear form factors

\(m_{wp}\) reduced DM particle-nucleon mass

**Generalized SI/SD DM particle-nucleon cross sections:**

\[\sigma_{SI} = \frac{4}{\pi} G_F^2 m_{wp}^2 g^2 \quad \sigma_{SD} = \frac{32}{\pi} \frac{3}{4} G_F^2 m_{wp}^2 \bar{a}^2\]

where:

- \[g = \frac{g_p + g_n}{2} \left[ 1 - \frac{g_p - g_n}{g_p + g_n} \left( 1 - \frac{2Z}{A} \right) \right]\]
- \[\bar{a} = \sqrt{a_p^2 + a_n^2}\]
- \[\tan \theta = \frac{a_n}{a_p}\]

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

**Differential energy distribution:**

\[
\frac{dR}{dE_R} = N_T \frac{\rho_w}{m_w} \int_{v_{min}(E_R)}^{v_{max}} \frac{d\sigma}{dE_R}(v, E_R)vf(v)dv = N_T \frac{\rho_w m_N}{2 m_w m_{wp}} \cdot \Sigma(E_R) \cdot I(E_R)
\]

where:

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

\[I(E_R) = \int_{v_{min}(E_R)}^{v_{max}} \frac{f(v)}{v} dv\]

**Notes:**

- \(N_T\): number of target nuclei
- \(f(v)\): DM particle velocity distribution in the Earth frame (it depends on \(v_e\))
- \(v_{max}\): maximal DM particle velocity in the Earth frame
- \(v_{min} = \sqrt{\frac{m_N E_R}{2 m_{wp}^2}}\): minimal velocity providing \(E_R\) recoil energy

**Equations:**

\[v_e = v_{sun} + v_{orb} \cos \omega t\]
**Halo modeling**

- **Needed quantities for Dark Matter direct searches:**
  - DM local density \( \rho_0 = \rho_{DM} (R_0 = 8.5 \text{ kpc}) \)
  - local velocity \( v_0 = v_{\text{rot}} (R_0 = 8.5 \text{ kpc}) \)
  - velocity distribution \( f(\vec{v}) \)

**Spherical \( \rho_{DM} \) isotropic velocity dispersion**

- Evans’ logarithmic
  \[
  \rho_{DM}(r) = \frac{v_0^2}{4\pi G} \frac{3R_e^2 + r^2}{(R_e^2 + r^2)^2} \]
  \[
  \Psi_0(r) = -\frac{v_0^2}{2} \log(R_e^2 + r^2) \]
  \[
  v_{rot}^2(r) = \frac{r^2}{(R_e^2 + r^2)} \]

- Evans’ power-law
  \[
  \rho_{DM}(r) = \frac{\beta \Psi_a R_c^\beta}{4\pi G} \frac{3R_e^2 + r^2(1 - \beta)}{(R_e^2 + r^2)^{\beta+4/2}} \]
  \[
  \Psi_0(r) = \frac{\beta \Psi_a R_c^\beta}{(R_e^2 + r^2)^{\beta+2/2}} (\beta \neq 0) \]

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

**Isothermal sphere**: the most widely used model only in the WIMP direct search (but not correct)

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

- Maxwellian velocity distribution

**If spherical \( \rho_{DM} \) with non-isotropic velocity dispersion**

- \( \beta_0 = 1 - \frac{\bar{v}_\phi^2}{\bar{v}_r^2} \)

**If Axisymmetric \( \rho_{DM} \)**

- \( q \) flatness
  \[
  \Psi_0(r,z) = -\frac{v_0^2}{2} \log(R_e^2 + r^2 + \frac{z^2}{q}) \]

**Triaxial \( \rho_{DM} \)**

- \( p,q,\delta \)
  \[
  \Psi_0(x,y,z) = -\frac{v_0^2}{2} \log \left( x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2} \right) \]
  \[
  \frac{\bar{v}_\phi^2}{\bar{v}_r^2} = \frac{2 + \delta}{2} \]

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

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

**Constraining the models**
• Isothermal sphere ⇒ very simple but unphysical halo model; generally not considered

Models accounted in the following


• Needed quantities
  → DM local density \( \rho_0 = \rho_{DM}(R_0 = 8.5\, \text{kpc}) \)
  → local velocity \( v_0 = v_{\text{rot}}(R_0 = 8.5\, \text{kpc}) \)
  → velocity distribution

• Allowed ranges of \( \rho_0 \) (GeV/cm\(^3\)) have been evaluated for \( v_0 = 170,220,270 \, \text{km/s} \), for each considered halo density profile and taking into account the astrophysical constraints:

\[
\begin{align*}
\nu_0 &= (220 \pm 50) \, \text{km} \cdot \text{s}^{-1} \\
1 \cdot 10^{10} \, M_{\odot} &\leq M_{\text{vir}} \leq 6 \cdot 10^{10} \, M_{\odot} \\
0.8 \cdot v_0 &\leq v_{\text{rot}}(r = 100\, \text{kpc}) \leq 1.2 \cdot v_0
\end{align*}
\]

Consistent Halo Models

Class A: spherical \( \rho_{DM} \), isotropic velocity dispersion

<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>( R_c ) (kpc)</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Isothermal Sphere</td>
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<tr>
<td>A1</td>
<td>Evans’ logarithmic [101]</td>
<td></td>
<td></td>
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<tr>
<td>A2</td>
<td>Evans’ power-law [102]</td>
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<tr>
<td>A3</td>
<td>Evans’ power-law [102]</td>
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<td>A4</td>
<td>Jaffe [103]</td>
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<td>A5</td>
<td>NFW [104]</td>
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<tr>
<td>A6</td>
<td>Moore et al. [105]</td>
<td></td>
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<tr>
<td>A7</td>
<td>Kravtsov et al. [106]</td>
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</tbody>
</table>

Class B: spherical \( \rho_{DM} \), non–isotropic velocity dispersion

(Osipkov–Merritt, \( \rho_0 = 0.4 \))

<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>( R_c ) (kpc)</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Evans’ logarithmic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Evans’ power-law</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>Evans’ power-law</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>Jaffe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>NFW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>Moore et al.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B7</td>
<td>Kravtsov et al.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Class C: Axisymmetric \( \rho_{DM} \)

<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>( R_c ) (kpc)</th>
<th>( q ), ( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Evans’ logarithmic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>Evans’ logarithmic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>Evans’ power-law</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>Evans’ power-law</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Class D: Triaxial \( \rho_{DM} \) [107] (\( q = 0.8 \), \( p = 0.9 \))

<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Earth on maj. axis, rad. anis.</td>
<td>( \delta = -1.78 )</td>
</tr>
<tr>
<td>D2</td>
<td>Earth on maj. axis, tang. anis.</td>
<td>( \delta = 16 )</td>
</tr>
<tr>
<td>D3</td>
<td>Earth on intern. axis, rad. anis.</td>
<td>( \delta = -1.78 )</td>
</tr>
<tr>
<td>D4</td>
<td>Earth on intern. axis, tang. anis.</td>
<td>( \delta = 16 )</td>
</tr>
</tbody>
</table>

NOT YET EXHAUSTIVE AT ALL
The allowed local density values

- Allowed intervals of $\rho_0$ (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

<table>
<thead>
<tr>
<th>Model</th>
<th>$v_0 = 170$ km s$^{-1}$</th>
<th>$v_0 = 220$ km s$^{-1}$</th>
<th>$v_0 = 270$ km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho_0^{\text{min}}$</td>
<td>$\rho_0^{\text{max}}$</td>
<td>$\rho_0^{\text{min}}$</td>
</tr>
<tr>
<td>A0</td>
<td>0.18</td>
<td>0.28</td>
<td>0.30</td>
</tr>
<tr>
<td>A1 , B1</td>
<td>0.20</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td>A2 , B2</td>
<td>0.24</td>
<td>0.53</td>
<td>0.41</td>
</tr>
<tr>
<td>A3 , B3</td>
<td>0.17</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>A4 , B4</td>
<td>0.26</td>
<td>0.27</td>
<td>0.44</td>
</tr>
<tr>
<td>A5 , B5</td>
<td>0.20</td>
<td>0.44</td>
<td>0.33</td>
</tr>
<tr>
<td>A6 , B6</td>
<td>0.22</td>
<td>0.39</td>
<td>0.37</td>
</tr>
<tr>
<td>A7 , B7</td>
<td>0.32</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>C1</td>
<td>0.36</td>
<td>0.56</td>
<td>0.60</td>
</tr>
<tr>
<td>C2</td>
<td>0.34</td>
<td>0.67</td>
<td>0.56</td>
</tr>
<tr>
<td>C3</td>
<td>0.30</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>C4</td>
<td>0.32</td>
<td>0.65</td>
<td>0.54</td>
</tr>
<tr>
<td>D1 , D2</td>
<td>0.32</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>D3 , D4</td>
<td>0.19</td>
<td>0.30</td>
<td>0.32</td>
</tr>
</tbody>
</table>

$\nu_0 = (220 \pm 50) km \cdot s^{-1}$

$1 \cdot 10^{10} M_\odot \leq M_{\text{vis}} \leq 6 \cdot 10^{10} M_\odot$

$0.8 \cdot \nu_0 \leq \nu_{\text{rot}} (r = 100 kpc) \leq 1.2 \cdot \nu_0$

Intervals evaluated considering the density profile and the astrophysical constraints

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