Non collider experiments results on Dark Matter

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Properties of the Dark Matter (particles)

Assuming DM is made of **particles:**

- **Non baryonic** (from CMB properties)
- **Neutral** (no interactions with photons, otherwise visible)
- **Weak** interaction
- **Stable** (or extremely long-lived, otherwise decayed)

→ no candidates in the Standard Model

Other hypotheses include also macroscopic objects (black holes) or modified gravitation (MOND) theories
Dark matter candidates

- Possible candidates over a wide range of masses
- Need a diversified approach to probe all scenarios
- Complementarity (and, in some cases, independent test of the same parameter space) is the way

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A theoretical framework is key to interpret results and compare them across different fields.
Direct detection principle (WIMP)

- Dark matter elastic scattering off target nuclei (or e for light dark matter)
- Detection → measure the recoil

The recoil energy is 1-100 keV for a 1-100 GeV WIMP

\[ E_{NR} = \frac{q^2}{2m_N} = \frac{(m_{DM}v)^2}{2m_N} \geq E_{\text{threshold}} \sim \text{keV} \]

\[ \phi = \frac{\rho_\chi}{m_\chi} < \nu > \quad \text{WIMP flux on Earth} \sim 10^5 \text{ cm}^{-2} \text{ s}^{-1} \]

\[ \rho_\chi = 0.3 \text{ GeV/cm}^3 \]
Dark matter expected rate (WIMP)

\[ R \propto N \frac{\rho}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle \]

**Astrophysics**
- \(\rho\): Local dark matter density in the Milky Way: \(~0.3\) GeV/cm\(^3\)
- \(\langle v \rangle\): WIMP average velocity \(~220\) km/s
- \(m_\chi\): WIMP mass (\(~1\) to \(1000\) GeV)
- \(\sigma_{\chi N}\): WIMP-nucleus elastic scattering cross section

**Particle Physics**
- Expected DM rate: Mass = 20 GeV, \(\sigma_{N,SI} = 10^{-45}\) cm\(^2\)
- One event / kg / year

**Rare interactions** → Experimental challenge: detect tiny signal over large background

~100 event/kg / s
Techniques for direct searches (WIMP)

**Phonons**
- Ge, Si: SuperCDMS, EDELWEISS
- CaWO₄, NaI: CRESST, COSINUS

**Ionization**
- CₓFᵧ: PICO
- Ge: CDEX
- Si: DAMIC, SENSEI
- Ar, Ne: TREX-DM
- He:SF₆/CH₄: CYGNUS
- Ag, Br, C: NEWSdm
- H, He, Ne: NEWS-G

**Scintillation**
- Xe: LZ, PandaX-4T, XENONnT, DARWIN
- Ar: DarkSide-50, DarkSide-20k, ARGO
- He: ALETHEIA, HeRALD (R&D)

**New initiatives:**
- quantum sensors for DM detection; super fluid LHe;
- molecular excitations and IR photon detection with SC nano-wires; graphene...
Current status WIMP searches

- Enormous effort in the last decades, sensitivity improved of orders of magnitude
- Low mass region (<10 GeV) less constrained so far

Long-standing annual modulation measured by DAMA/LIBRA need to be independently verified using NaI(Tl)

DAMA/LIBRA 12σ modulation
Perspectives of WIMP searches

- low mass WIMP: cryogenic detectors - gas TPC → but hard to scale to large masses

- M>10 GeV region will be eventually covered by next generation LAr/LXe exp
- Space for new ideas in the low mass region
- Directionality needed to overcome neutrino floor

WIMP M>10 GeV with ton-scale noble liquids (XENON nT, Darkside-20k) → neutrino floor intrinsic limit
Indirect searches (WIMP)

- WIMP particles annihilation in overdense regions of the Universe (galactic center, Sun, dwarf galaxies, ...)

- Products of annihilation:
  - **Gamma flux** (FERMI-LAT, HESSE, MAGIC, ...)
    - neutral → point back to sources
    - large backgrounds
  - **Neutrino flux** (ICECUBE, ANTARES, KM3NET, ...)
    - neutral → point back to sources
    - weak interaction
  - **Charged cosmic rays** (PAMELA, AMS, DAMPE)
    - do not point to source
    - low background for anti-matter
Current status of ID (WIMP)

- Model-independent UL on annihilation cross-section for a given final state
- Total cross-section sets **relic abundance**

- Fermi gamma rays telescope → strongest bounds on annihilation to hadronic final states
- AMS-02 positron fluxes → best limits to annihilation to leptons
- CMB → strongest limits for low dark matter masses

- Combining all the data in the context of the generic thermal WIMP → **allowed window between 20 GeV-100 TeV**
- Great experimental progress at multiple wavelengths/messengers (LOFAR, SKA, CTA, etc) → access to uncharted portions of the DM parameter space
Complementarity with collider searches

Comparisons are **model-dependent**

Parameters: $m_{\text{DM}}$, $m_{\text{med}}$, $g_q$, $g_{\text{DM}}$

- Collider results often expressed in terms of 2D at fixed couplings in plane $m_{\text{DM}}$ vs $m_{\text{med}}$

- Results can be translated in DM-nucleon cross section vs $m_{\text{DM}}$ plane
Complementarity with collider searches

**Spin independent** xsec (vector med)  
→ comparison with DD

**Spin dependent** xsec (axial-vector med)  
→ comparison with DD and ID

(see Talk by O. Brandt @LHCP)

All DM summary plots by Atlas and CMS
Ultra-light DM: axions

Search for axions is well motivated:
1. Solution for strong CP problem
2. "Axion-like" particles are compatible with SUSY, GUTs and String Theories
3. Also a Dark Matter candidate

Experiments measure the couplings with photons ($g_{a\gamma}$)
- an axion may interact with a strong B field
- oscillating E field at specific frequency ($\rightarrow$ axion mass)

Haloscopes $\rightarrow$ resonant cavities sensitive to $m_a \sim 1$-100 $\mu$eV
Current status axions searches

Axion parameter space
- Coupling $g_{a\gamma}$ VS mass $m_a$ with known density and velocity distribution throughout the galactic halo
- yellow/white regions not probed
- yellow = QCD axion (only method for reaching QCD band is with haloscope)
Conclusions

- DM is a big open question in modern physics
  → strong evidences
  → no direct measurements (yet) but a extraordinary effort worldwide using **different and complementary approaches**

- Next generation DD experiments approaching neutrino floor
- Collider results excluding large parts of the phase space for different DM scenarios
- New ID experiments will reach sensitivity to relic cross section
- Present technology is reaching its limits, **new ideas and developments needed**

**Exciting times to hunt Dark Matter!**
Background rejection (WIMP)

- Ambient neutrons/gammas
  (radioactivity of the laboratory)
- "Radiogenic" neutrons/gammas
  (radioactive materials in setup)
- Cosmogenically activated isotopes
  (activation from cosmic rays)
- Cosmogenic neutrons
  (cosmic muons interactions)

Passive/active shieldings
Careful choice of low radioactivity materials
Underground laboratories
Detection strategy (WIMP): counting experiment

Discern between ER and NR

Fiducialization: most background NR from superficial radioactivity

Operate with zero-background → exclusion limits
Detection strategy (WIMP): annual modulation

- Expected rate in an Earth-based detector is modulated
- Small modulation fraction $S_m/S_0 = O(\text{few } \%)$

\[ R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right) \]
Detection strategy (WIMP): directionality

- **Dark matter** particles arrive from a precise direction in the sky (Cygnus)
- Radioactivity neutron background → no preferred direction
- Solar neutrinos → Sun never in the same position of the Cygnus

**Directionality** → important **handle to discover DM** and overcome neutrino floor
Current status of ID (WIMP)

Conservative limits on s-wave $2 \rightarrow 2$ GeV dark matter annihilation to various final states. Left: Limits from the CMB. Middle: Limits arising from Fermi measurements of gamma rays from dwarf spheroidal galaxies. Right: Limits from positron flux measurements with AMS. Relic cross section is the dashed line.

Current status of ID (WIMP)

Upper limits and projected sensitivity from CTA on the pair-annihilation rate versus the DM mass from gamma-ray and CMB observations

Status and perspectives on DM limits from annihilation to neutrinos

Detection principle (axions)

- **Cavity haloscopes**: ADMX, HAYSTAC, QUAX
  - Single cavity can explore ~1-70 \( \mu \text{eV} \) mass range
  - Sensitivity scales with volume and Q-factor of the cavity

- **Helioscopes**: detect axions produced thermally in the Sun (CAST, IAXO)
  - Sensitive to \( g_{\gamma} \) and \( g_{\alpha e} \)
  - Limits up to \( m_a \sim \text{keV} \)

- **Light-shining-through-the-wall (LSW)** experiments (ALPS, OSQAR)
  - Limits to masses < meV

**Note**: only haloscopes are direct detection experiments