Dark matter searches

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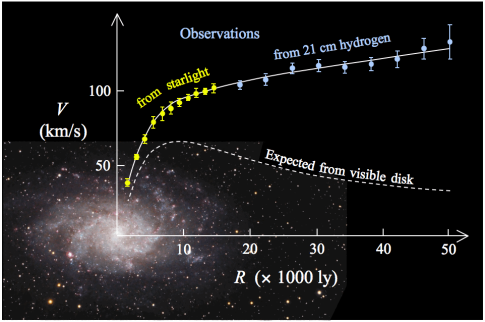
Introduction

- The existence of dark matter is confirmed via multiple independent observations:
  - Galactic rotation curves and velocity dispersions.
  - Gravitational lensing of galaxy clusters.
  - CMB power spectrum.
  - Structure formation.
- All of these observations are based on the **gravitational** interactions between DM and visible matter.



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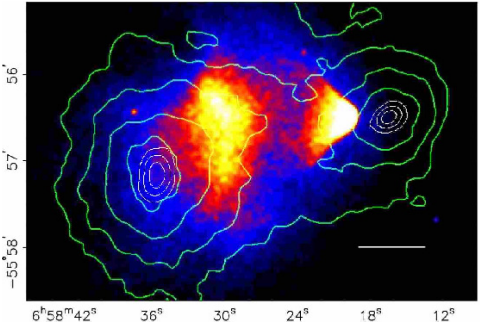

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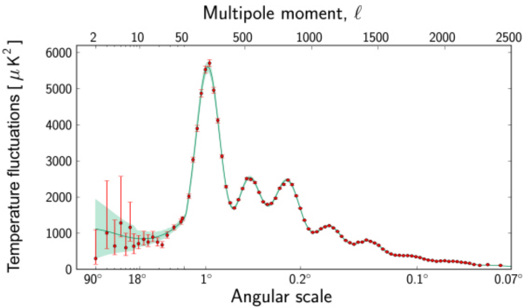

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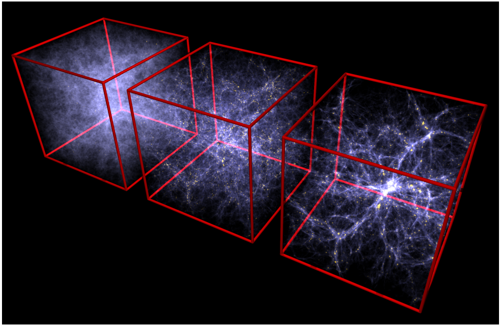
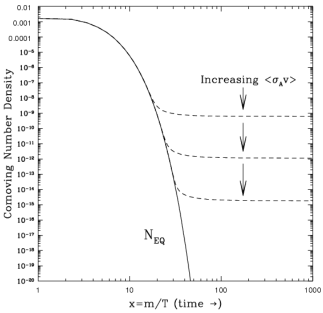
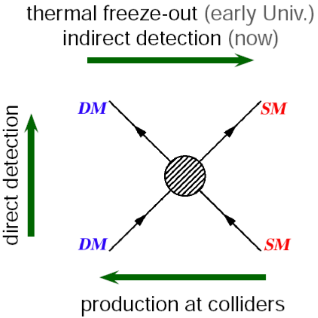


Introduction

- To understand the role of the DM particle in the context of particle physics theory, we would like to know something about its **non-gravitational** interactions.
- A nice feature of WIMPs is that their abundance is determined via their scattering with the SM particles.
- Therefore WIMPs should be observable with direct detection, indirect detection and collider experiments.



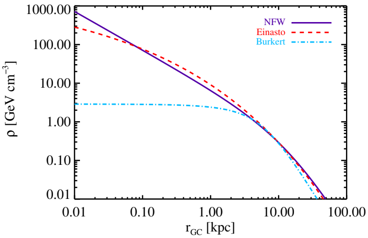


Indirect detection

- Indirect detection refers to the attempts to observe the annihilation products of DM particles.
- For WIMPs the annihilation cross section σ_A determines the abundance, so the indirect detection signal is directly linked to the production of DM in the early universe:

$$\Omega_\chi h^2 \sim \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{\mathrm{fo}}}$$

$$\frac{dN}{dA\, dt\, d\Omega\, dE} = \frac{\langle \sigma_A v \rangle_0}{2 m_\chi^2} \frac{dN_x}{dE} \frac{1}{4\pi} J_A(\psi), \qquad J_A(\psi) = \int_{\mathrm{los}} \rho_\chi^2(\psi, \ell) d\ell.$$



Indirect detection

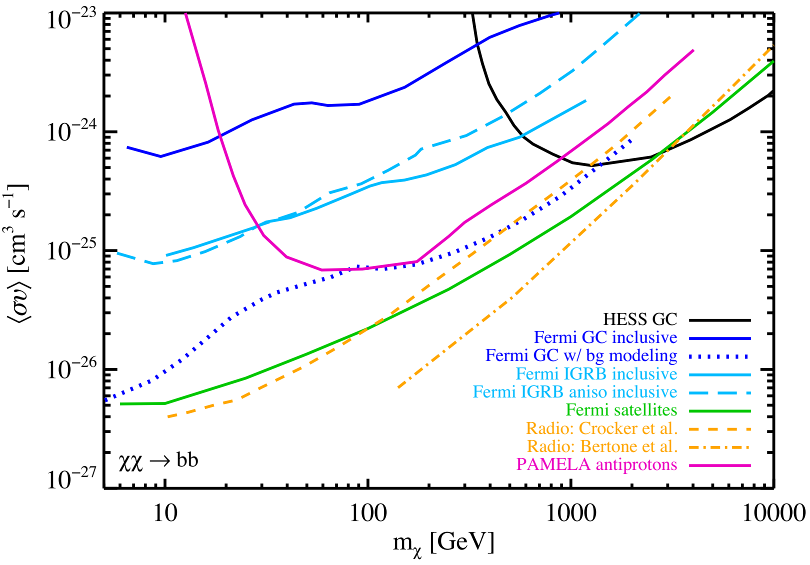
Indirect detection experiments search for gamma-ray photons, neutrinos, or cosmic rays (charged particles).

Particle	Experiments	Advantages	Challenges
Gamma-ray† photons	Fermi LAT, GAMMA-400, H.E.S.S.(-II), MAGIC, VERITAS, HAWC, CTA	point back to sources, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube/DeepCore/PINGU, ANTARES/KM3NET, BAIKAL-GVD, Super-Kamiokande/Hyper-Kamiokande	point back to sources, spectral signatures	backgrounds, low statistics
Cosmic rays	PAMELA, AMS-02, ATIC, IACTs, Fermi LAT, Auger, CTA, GAPS	spectral signatures, low backgrounds for antimatter searches	diffusion, do not point back to sources

There have been some excess signals, but not definite observations:

- Fermi LAT Galactic center excess ('Hooperon', $\chi\chi \to b\bar{b}$, $m_\chi \sim 50$ GeV)
- 3.5 keV X-rays. (Decaying DM, $m_\chi \sim 7$ keV.)
- AMS antiprotons. (Could fit with 'Hooperon')
- ...

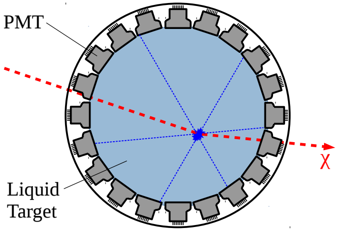
Indirect detection limits

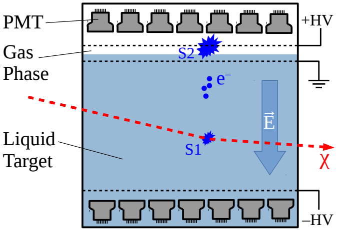


Direct detection

- Direct detection experiments look for DM scattering off the nucleus of the target material, by detecting the nuclear recoil (typically via scintillation light, electric signal or phonons).
- The event rate depends on the DM-nucleus scattering cross section, and the velocity distribution of DM:

$$\frac{dR}{dE_r} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\rm min}}^{v_{\rm esc}} v f(v) \frac{d\sigma}{dE_r} dv, \qquad v_{\rm min} = \sqrt{\frac{E_r m_N}{2\mu_{N\chi}^2}}.$$





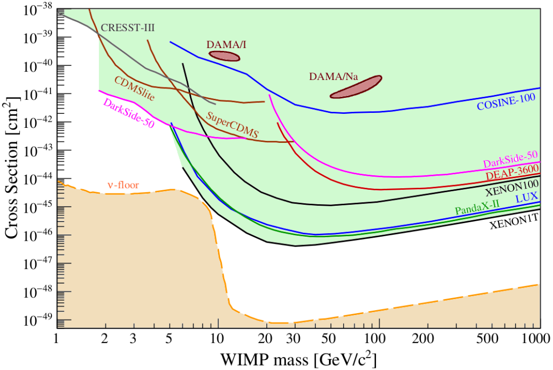
Direct detection experiments

Experiment	Type	Target	Mass [kg]	Laboratory
ANAIS-112	Crystal	NaI	112	Canfranc
CDEX-10	Crystal	Ge	10	CJPL
CDMSLite	Cryogenic	Ge	1.4	Soudan
COSINE-100	Crystal	NaI	106	YangYang
CRESST-II	Cryogenic	$CaWO_4$	5	LNGS
CRESST-III	Cryogenic	$CaWO_4$	0.024	LNGS
DAMA/LIBRA-II	Crystal	NaI	250	LNGS
DarkSide-50	TPC	Ar	46	LNGS
DEAP-3600	Single phase	Ar	3300	SNOLAB
DRIFT-II	Directional	CF_4	0.14	Boulby
EDELWEISS	Cryogenic	Ge	20	LSM
LUX	TPC	Xe	250	SURF
NEWS-G	Gas Counter	Ne	0.283	SNOLAB
PandaX-II	TPC	Xe	580	CJPL
PICASSO	Superheated Droplet	C_4F_{10}	3.0	SNOLAB
PICO-60	Bubble Chamber	C_3F_8	52	SNOLAB
SENSEI*	CCD	Si	9.5×10^{-5}	FNAL
SuperCDMS*	Cryogenic	Si	9.3×10^{-4}	above ground
XENON100	TPC	Xe	62	LNGS
XENON1T	TPC	Xe	1995	LNGS
XMASS	Single phase	Xe	832	Kamioka

Direct detection

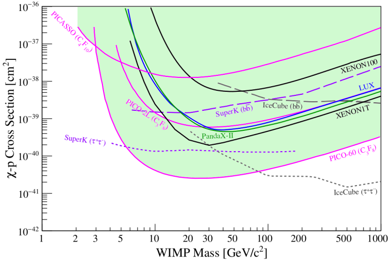
- The exclusion limit is typically presented in the $(m_\chi, \sigma_{\chi n})$-plane, where the cross section refers to a given scattering operator.
- The simplest operator is the scalar (Spin-Independent) operator. Arising from e.g. $\bar{\chi}\chi\bar{q}q$.

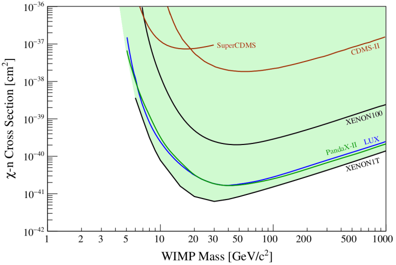
$$\frac{d\sigma}{dE_r} = \sigma_{\chi n}\frac{A^2 m_N}{2v^2\mu_{n\chi}^2}F^2(E_r)$$



Direct detection

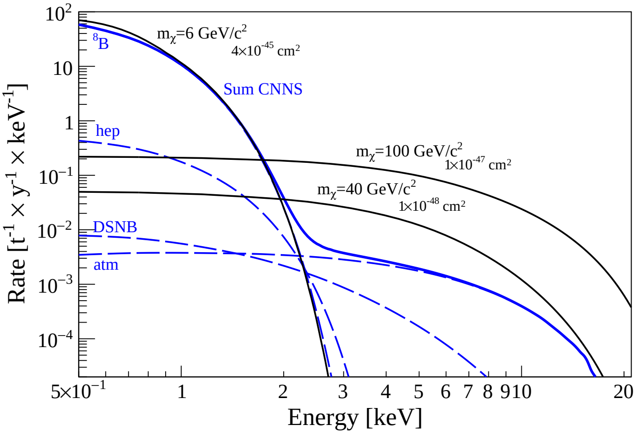
Limits for spin-dependent couplings can be extracted separately for $\chi - p$ and $\chi - n$ scattering cross sections





The neutrino floor

- Solar and cosmic neutrinos form an irreducible background for the standard direct detection experiments.
- DM-nucleon cross sections below the neutrino floor can not be probed with simple counting experiments.

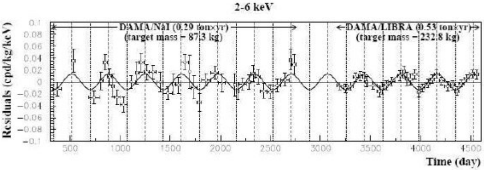


Modulation experiments

- To reach below the neutrino floor, the DM signal must somehow be differentiated from the neutrino background.
- The separation can be achieved via the modulation of the DM scattering event rate due to the motion of the earth in the Galactic rest frame.

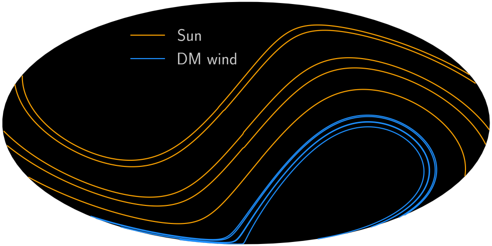
$$\vec{v}_{\rm lab} = \vec{v}_{\rm circ} + \vec{v}_{\rm sol} + \vec{v}_{\rm rev} + \vec{v}_{\rm rot}\,,$$

  $v_{\rm circ} \sim 220\,{\rm km\,s^{-1}}$, $v_{\rm sol} \sim 18\,{\rm km\,s^{-1}}$, $v_{\rm rev} \sim 30\,{\rm km\,s^{-1}}$, $v_{\rm rot} \sim 0.5\,{\rm km\,s^{-1}}$.
- Annual modulation (of order $\sim 5\%$) is expected due to the variation in $v_{\rm lab}$ as $\vec{v}_{\rm rev}$ and $\vec{v}_{\rm circ}$ are aligned/antialigned during the year.



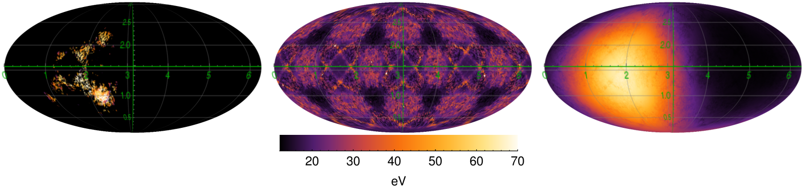
Daily modulation

- The rotation speed $v_{\rm rot}$ is small compared to the other components, and the daily modulation induced by the variation of $v_{\rm lab}$ due to $v_{\rm rot}$ is negligible.
- However, the rotation changes the direction of $\vec{v}_{\rm lab}$ significantly during the day.

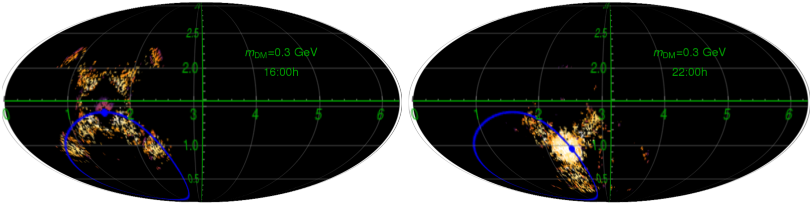


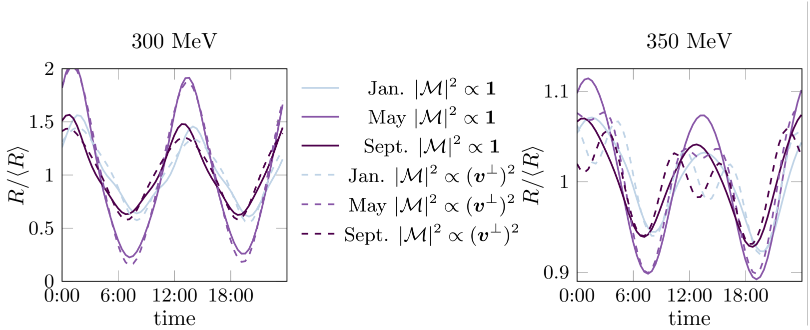
Daily modulation

- If the DM scattering rate depends on the recoil direction, as is generally the case in crystalline materials, the rotation of the 'DM wind' induces a daily modulation in the event rate.
- The dependence on the scattering rate is a threshold effect: the creation threshold for an observable signal depends on the recoil direction with respect to the crystal lattice.
- For heavy DM particles the effect is small, since the event rate is dominated by events far above the threshold.



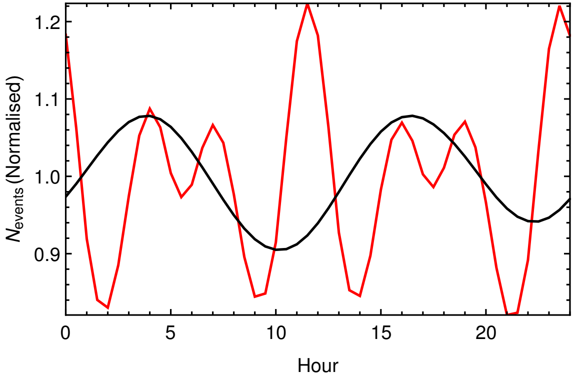
Daily modulation





Daily modulation

As the direction to the sun in the lab-frame varies during the day, the solar neutrino background will also exhibit a daily modulation signal: However, the structure and phase of the neutrino modulation differs from the DM signal: (PRELIMINARY RESULTS)



DM-electron scattering

- For very light DM, nuclear recoils become inefficient due to the energy threshold.
- DM-electron scattering could allow probing DM well below the GeV-scale.
- The electron band structure in a crystal is not spherically symmetric, resulting in daily modulation as discussed above.
- Various materials have been proposed for targets of DM-electron scattering: semiconductors, graphene, nanowires, dirac metals...
- Feasibility for large scale experiments still to be demonstrated.

Conclusions

- Direct and indirect DM searches are effectively closing the WIMP-window for $m_\chi \sim$ few GeV - few hundred GeV.
- For light DM $m_\chi \lesssim 10$ GeV the constraints are less severe. (But the neutrino floor is higher).
- Daily modulation due to directional threshold effects could allow to probe light DM below the neutrino floor.
- Theoretical studies underway, no serious daily modulation experiments yet running.