A halo independent comparison of direct dark matter searches

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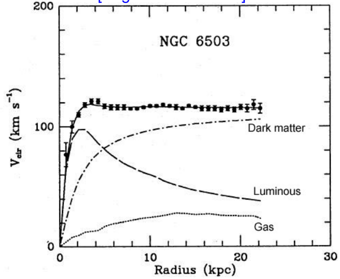
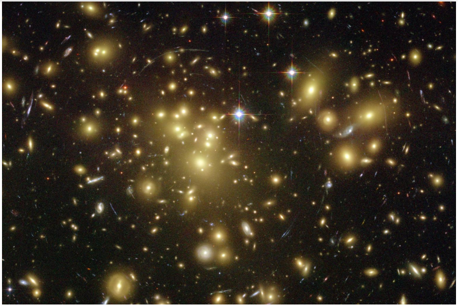
28.09.2016

Paper in preparation
In collaboration with A.Ibarra

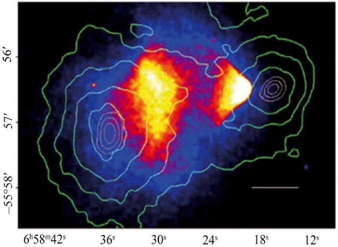
Evidence for dark matter

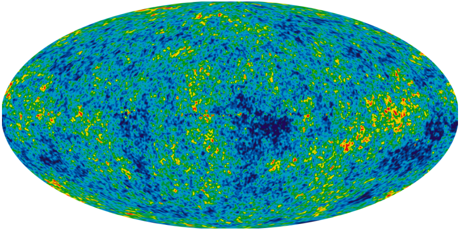
[Begeman et. al. '91]



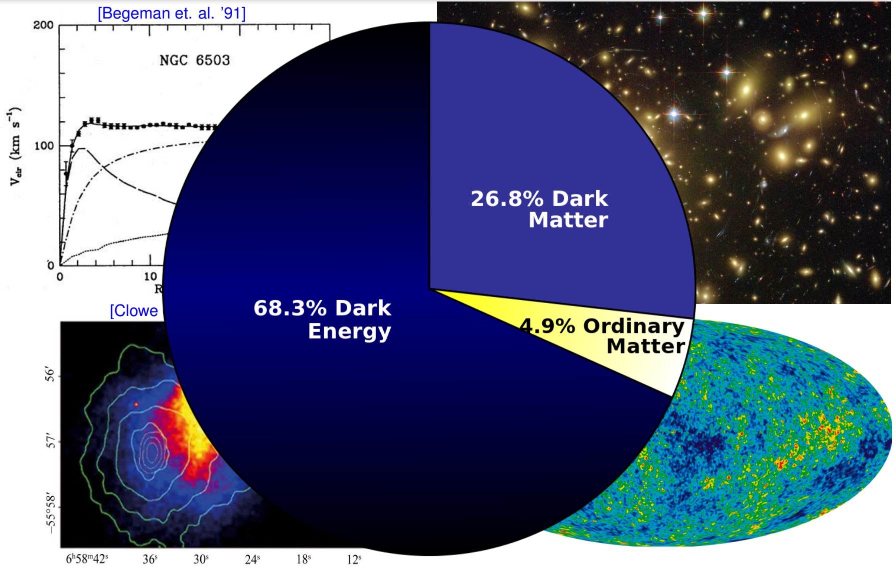


[Clowe et. al. '06]

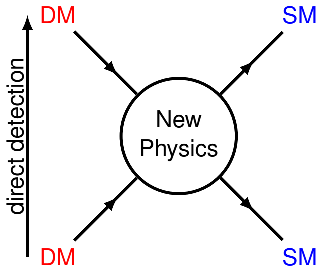


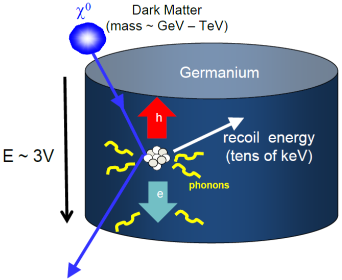


Evidence for dark matter



Direct detection of dark matter





- Dark matter interacts with nuclei inside the target

$$\text{DM} + \text{nucleus (at rest)} \to \text{DM} + \text{nucleus } (E_R \sim \text{keV})$$

- Huge experimental effort (LUX, DAMA, PandaX, CDMS, ...)
- No conclusive signal, although some experiments have reported detection (DAMA, CoGeNT,...).

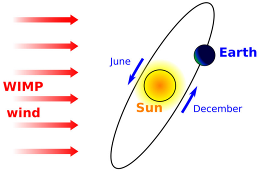
Direct Detection of dark matter

Observable: Number of recoil events

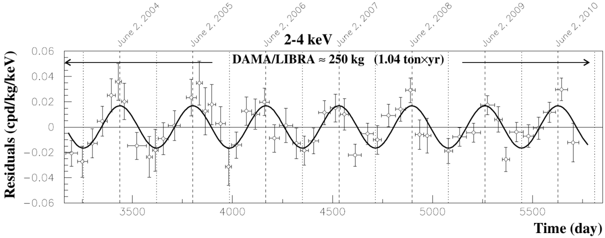
$$R = \sum_i \frac{\epsilon \cdot \rho_{loc} \cdot \xi_i}{m_{N_i} \cdot m_{DM}} \int_{E_{th}}^{E_{max}} dE_R \cdot \epsilon(E_R) \cdot \int_{v_{min}} dv^3 \cdot v \cdot f(\vec{v} + \vec{v}_{obs}) \cdot \frac{d\sigma_i}{dE_R}$$

- Particle Physics of dark matter
  - m_{DM}: Between 1 GeV and 100 TeV for WIMPs.
  - $\frac{d\sigma_i}{dE_R}$: Usually spin-independent and spin-dependent scattering.
- Astrophysics of dark matter
  - ρ_{loc}: local dark matter density.
  - $f(\vec{v})$: local velocity distribution of dark matter in the rest frame of the sun.

Direct detection of dark matter



[Freeze et. al. 1209.3339]



[Bernabei et. al. 1308.5109]

- The movement of the earth around the sun causes a modulation of the recoil rate.
- DAMA puzzle: The collaboration reports a signal with more than 9σ confidence although no other experiment claims to see a signal.
  - $\rightarrow$ Up to now there are no background processes known which can mimic an annual modulation signal.

Direct Detection of dark matter

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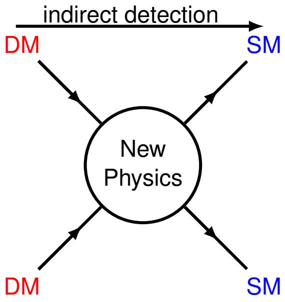
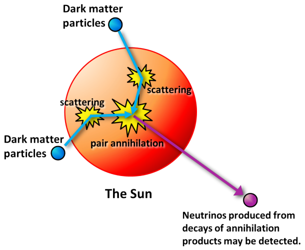
Observable: Modulation amplitude in the energy bin $[E_+, E_-]$

$$S_{[E_-,E_+]} = \frac{1}{E_+ - E_-} \cdot \frac{1}{2} \cdot \left\{ R_{[E_-,E_+]}\big|_{June\ 1st} - R_{[E_-,E_+]}\big|_{Dec\ 1st} \right\}$$

- $R_{[E_-,E_+]}$ is the number of expected recoil events with $E_{th} = E_-$ and $E_{max} = E_+$.
- It depends in exactly the same way on unknown Particle Physics and Astrophysics as the number of recoil events R.

Neutrino telescopes





- Dark matter can be captured by the sun via scattering off the nuclei inside the sun.
- Captured dark matter particles gather in the core of the sun and start to annihilate.
  - → Final state neutrinos can escape the sun and are detected by neutrino telescopes like IceCube or Super Kamiokande.

Neutrino telescopes

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Observable: Capture rate inside the sun

$$C = \sum_i \int_0^{R_\odot} dr\, 4\pi r^2\, \eta_i(r)\, \frac{\rho_{loc}}{m_{DM}} \int_0^{u_{max}(r)} du^3\, \frac{f(\vec{u})}{u}\, (u^2 + v_{esc}(r)^2) \times \int_{E_{min}}^{E_{max}} dE_R\, \frac{d\sigma_i}{dE_R}$$

- We assume equilibrium of capture and annihilation of dark matter.
- This time the velocity integral has an upper limit $u_{max}(r)$.

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All of these three detection techniques depend on the dark matter velocity distribution $f(\vec{v})$ in the same way. But they probe different parts of the velocity space.

Standard approach

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Direct detection	Annual modulation	Neutrino telescope
Upper limit on R	Modulation signal	Upper limit on C
↓	↓	↓
Assume Maxwell-Boltzmann velocity distribution	Assume Maxwell-Boltzmann velocity distribution	Assume Maxwell-Boltzmann velocity distribution
↓	↓	↓
Upper limit on $\sigma^{\mathrm{SI/SD}}$	allowed regions in parameter space	Upper limit on $\sigma^{\mathrm{SI/SD}}$

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But we do not know the true velocity distribution of dark matter.
$\rightarrow$ This talk: halo independent upper limits.

Step 1: $f(\vec{v})$ **as superposition of streams**

Following [Feldstein et. al. 1403.4606], we decompose the velocity distribution into a set of streams. Then, we discretise the integral:

$$f(\vec{v}) = \int \mathrm{d}v_0^3 \, f(v_0) \, \delta(v - v_0) \rightarrow \sum_i a_i \, \delta(\vec{v} - \vec{v}_i)$$

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$\rightarrow$ The observables become linear equations:

$$\mathrm{R} = \sum_i \mathrm{a}_i \, \mathrm{R}_{\vec{v}_i}$$

$$\mathrm{S}_{[\mathrm{E}_-,\mathrm{E}_+]} = \sum_i \mathrm{a}_i \, \mathrm{S}_{[\mathrm{E}_-,\mathrm{E}_+],\vec{v}_i}$$

$$\mathrm{C} = \sum_i \mathrm{a}_i \, \mathrm{C}_{\vec{v}_i}$$

Step 2: Calculating minima and maxima

We choose one experiment (let's call it A) and calculate the minimal and maximal value of the observable (Number of events, capture rate, ...) compatible with constraints from other experiments.

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- Since all equations are linear, we can perform this optimization with existing methods of linear programming.
- We impose the normalization condition on the velocity distribution:

$$\int dv^3 \, f(\vec{v}) = 1 \to \sum_i a_i = 1$$

Applications

(i) Upper limits on the cross section from null searches.

→ For a fixed dark matter mass, we increase the cross section until

$$\min\{N_A(\sigma, m_{DM})\} = N_A^{u.l.}.$$

(ii) Confronting a detection claim with null searches.

→ We scan the parameter space and look for regions where

$$\min\{N_A(\sigma, m_{DM})\} \leq N_A^{u.l.}.$$

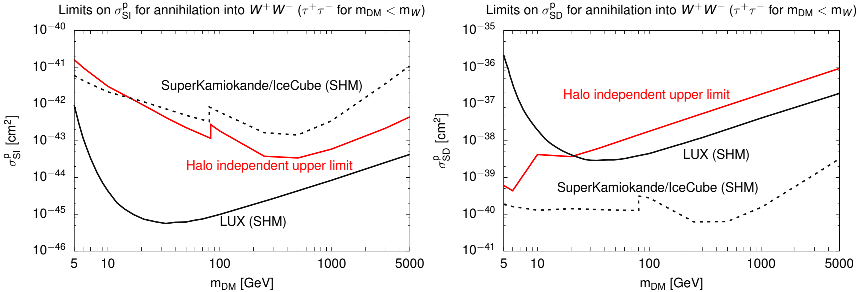
(iii) Prospects for future experiments.

→ From given experimental results, we can forecast the region where a future experiment will be sensitive by scanning the parameter space and requiring

$$\max\{N_A(\sigma, m_{DM})\} \geq 1.$$

Preliminary results

- Combining null results from direct detection and neutrino telescopes:



- The limits are remarkably strong.
- We could further improve the halo independent limits of [Ibarra et. al. 1506.03386] by up to a factor 2.

Conclusions

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- Standard upper limits are only valid for one specific choice of velocity distribution.
- We derived a new method for setting halo independent limits on $\sigma^{\text{SI/SD}}$.
  - $\rightarrow$ It is based on the decomposition of the velocity distribution into streams from [Feldstein et. al. 1403.4606].
  - $\rightarrow$ It has a wide range of applications.
  - $\rightarrow$ The limits presented here are valid for all kinds of velocity distributions including anisotropic distributions, streams, dark disks, ...
- We improve with this method previous halo independent limits on the cross-section.