

Dipolar Dark Matter

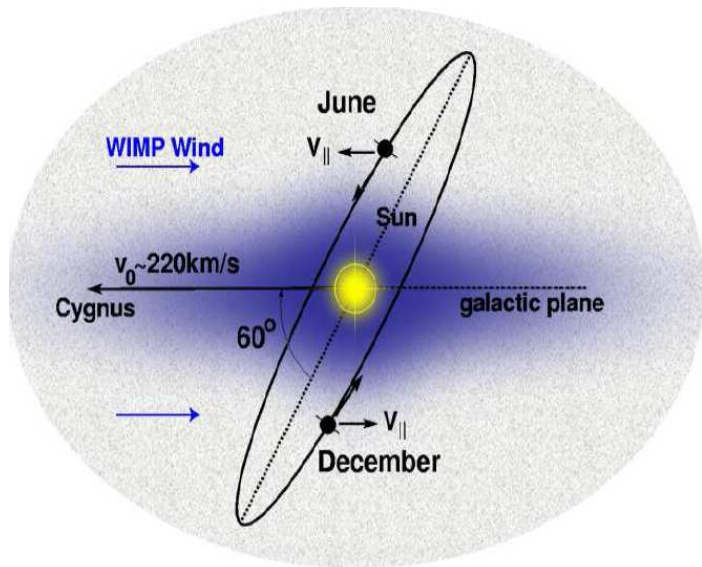
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- Experimental observations of dynamics of spiral galaxies and galaxy clusters indicate existence of Dark matter
- Cosmological observations show bulk of it must be non-baryonic
- Direct detection of DM - elastic scattering of DM by target nuclei
Measure recoil energies of the target nucleus
- Several experiments like DAMA, CDMS, COGENT, XENON etc.
- Only DAMA sees positive signal (recently COGENT also)
- Propose dipolar interactions of DM to explain direct detection results (Sigurdson et al, Pospelov et al)
- Reconcile null results of CDMS, XENON with DAMA and constrain DM dipole moments

Annual Modulation

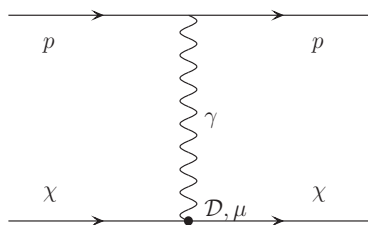


DAMA and other experiments

Experiment	Target nucleus	Quenching factor(Q)	Energy interval [keVee]
DAMA	Na	0.3	2-14
	I	0.09	
CDMS	Ge	1	10-100
XENON	Xe	1	4.5-45
COGENT	Ge	0.2	0.338-0.661

- Only electromagnetic interactions with the nucleus measured in DAMA - no heat or phonons detected
- Quenching : $E_R = Q \times E_{ee}$
- Channeling effect removes quenching factor or sets $Q = 1$
- CDMS measures both phonons and electromagnetic interactions of the nucleus - no quenching/channeling

Dipole interactions



- DM couples to photons through loops in the form of electric and magnetic dipole moments

$$\mathcal{L}_{elast} = -\frac{i}{2} \bar{\chi} \sigma_{\mu\nu} (\mu + \gamma_5 \mathcal{D}) \chi \mathcal{F}^{\mu\nu}$$

- Majorana DM has non-zero transition moments between different mass eigenstates

$$\mathcal{L}_{inel} = -\frac{i}{2} \bar{\chi}_2 \sigma_{\mu\nu} (\mu_{12} + \gamma_5 \mathcal{D}_{12}) \chi_1 \mathcal{F}^{\mu\nu} + \text{h.c.}$$

- Majorana DM scatters inelastically to a heavier mass eigenstate

Kinematics of Scattering

- Elastic Scattering : $\chi N \rightarrow \chi N$

$$\text{Energy transferred to detector : } E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v^2 (1 - \cos \theta)}{m_N}$$

$$\text{Minimum Wimp velocity : } v_{min} = \sqrt{\frac{m_N E_{Rmin}}{2\mu_N^2}}$$

- Inelastic Scattering : $\chi_1 N \rightarrow \chi_2 N$

$$\text{Minimum Wimp velocity : } v_{min} = \sqrt{\frac{1}{2m_N E_{Rmin}} \left(\frac{m_N E_{Rmin}}{\mu_N} + \delta \right)}$$

$$\text{Differential cross section : } d\sigma_{inelastic}/dE_R = d\sigma_{elastic}/dE_R$$

Event Rates for dipolar interaction

- Differential event rate :

$$\frac{dR}{dE_R} = N_T \frac{\rho_X}{m_X} \int_{v > v_{min}} f(v) v \frac{d\sigma}{dE_R} dv$$

- Event Rate :

$$R = \int_{E_1/Q}^{E_2/Q} dE_R \epsilon(QE_R) \frac{dR}{dE_R}$$

$Q \equiv$ Quenching factor

$\epsilon(QE_R) \equiv$ Efficiency of detector

- Differential scattering cross sections:

$$\text{EDM} : \frac{d\sigma}{dE_R} = \frac{Z^2 e^2 \mathcal{D}^2}{4\pi v^2 E_R}$$

$$\mu\text{DM} : \frac{d\sigma}{dE_R} = \frac{e^2 \mu^2}{4\pi E_R} \left(1 + \frac{E_R}{2\mu_N v^2} \right)$$

Relic density from dipolar interaction

■ Parametrization of σv

$$\langle \sigma v_{rel} \rangle \equiv \sigma_0 \left(\frac{T}{m_\chi} \right)^n \quad (1)$$

$$\text{Magnetic Dipole: } \sigma_0 = \frac{e^2 \mu^2}{4\pi}, \quad n = 0 \quad (2)$$

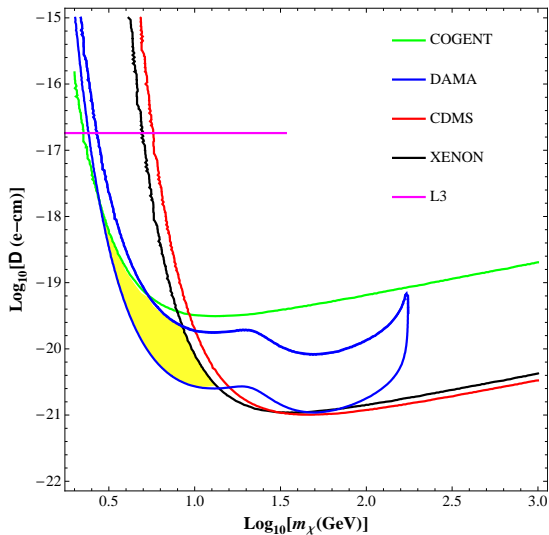
$$\text{Electric Dipole: } \sigma_0 = \frac{3e^2 \mathcal{D}^2}{48\pi}, \quad n = 1 \quad (3)$$

■ DM relic density :

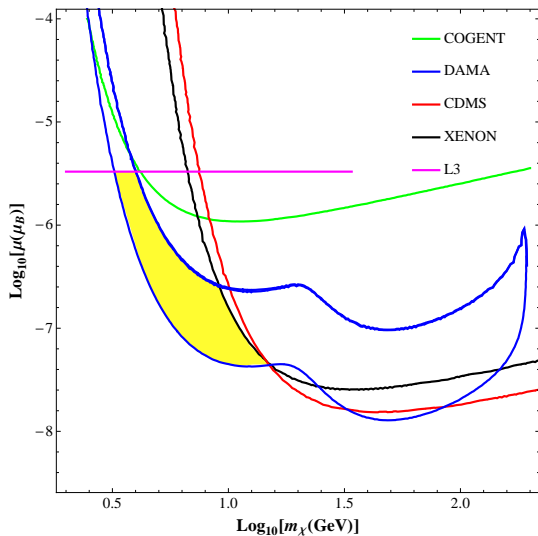
$$\Omega h^2 = 0.34 \left(\frac{(n+1) x_f^{n+1}}{(g_{*s}/g_*^{1/2})} \right) \frac{10^{-37} \text{cm}^2}{\sigma_0}$$

■ For correct relic density : $\mu \sim 10^{-5}$ and $\mathcal{D} \sim 2.5 \times 10^{-16}$

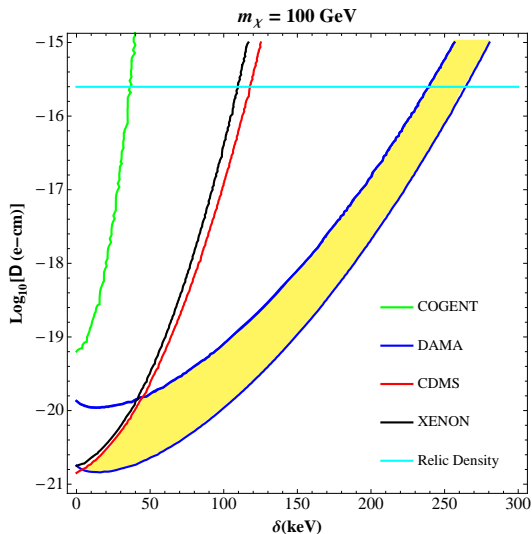
Results : Elastic EDM



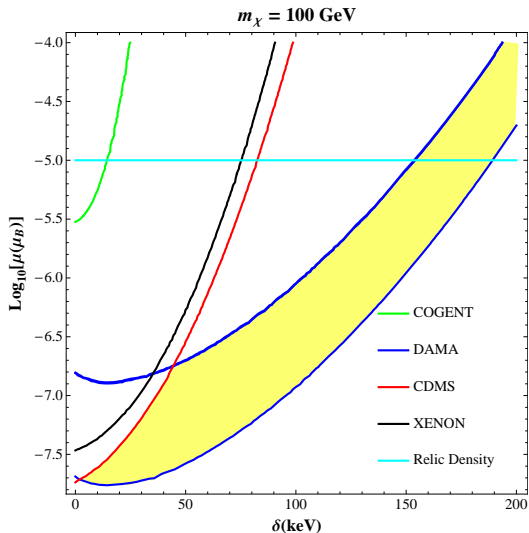
Results : Elastic μ DM



Results : Inelastic EDM



Results : Inelastic μ DM



Conclusions

- Direct Dipole moments give a low mass window for Wimps (3 – 15) GeV with $\mathcal{D} \sim 2.5 \times 10^{-20}$ e-cm and $\mu \sim 3.2 \times 10^{-7} \mu_B$
- Bounds from direct dipole moments much lower than dipole moments required to explain relic density
- Transition dipole moments allow masses upto 200 GeV which can have mass splittings upto 200 keV.
- Transition dipole moments offer a large parameter space where results from DAMA, null experiments and relic density are all consistent