Searching for Dark matter

• Direct detection
  – Elastic scattering of WIMPs off nucleons in a large detector
  – Xenon, CDMS, Dama/Libra

• Indirect detection
  – WIMPs annihilation in galaxy, observe decay products
  – e, p, γ: Pamela, Fermi, Hess
  – Neutrinos: IceCube, Km3Net

• Collider searches
  – Indirect + Direct searches: Tevatron, LHC, ILC
Cosmology-(astro)particle-colliders

Cosmology
Evidence for dark matter

Colliders
Search for dark matter

Theory:
- SUSY
- Extra-Dimensions
- Scalars

Astrophysics: evidence DM
Astroparticle: hints for DM

Tevatron
LHC (2009)
ILC (?)

Where to look

Precision measurements

How much dark matter
- WMAP (2003)
- PLANCK (2009)

Dark matter a new particle?

AMS, Egret, PAMELA, Fermi, Hess...
CDMS, Xenon, DAMA, Kims...
Direct detection

• Elastic scattering of WIMPs off nuclei in a large detector
• Measure nuclear recoil energy, $E_R$

• Best way to prove that WIMPs form DM

• Small transfer momentum – typically 100MeV
  – $E_R = \frac{q^2}{2m_N}$  $q$: transfer momentum
  – $E_R = \mu^2 \frac{v^2(1-\cos \theta)}{m_N}$
  – $\mu = \frac{m_\chi m_N}{(m_\chi + m_N)}$: reduced mass
  – 100GeV WIMP, $v=220$km/s $\rightarrow$ $E_R<27$keV
Direct detection

- Two types of scattering
  - Coherent scattering on $A$ nucleons in nucleus, for spin independent interactions
    - Dominant for heavy nuclei
  - Spin dependent int – only one unpaired nucleon
    - Dominant for light nuclei

Galactic WIMP Halo
($\rho = 0.3$ GeV/cm$^3$)

$\langle V \rangle = 220$ km/s

Recoil Nucleus
$\sim 10-100$ keV or less
Steps to compute nucleus recoil energy

• Wimp-quark/gluon scattering: depend on particle physics model, compute from Feynman diagrams
• Relate WIMP-quark to WIMP-nucleon – quark coefficients in nucleons – determined from first principle + experiments
• WIMP-nucleon → WIMP nucleus : form factor
• Take into account velocity distribution of WIMP
• Recoil energy for WIMP scattering on nucleus
• Experimental results are presented in sigma WIMP-proton vs DM mass : easy comparison between exp.
WIMP- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude \textit{at small momentum},
- Generic form for a Majorana fermion

\[ \mathcal{L}_F = \lambda_N \bar{\psi}_X \psi_X \bar{\psi}_N \psi_N + i \kappa_1 \bar{\psi}_X \gamma_5 \psi_X \bar{\psi}_N \psi_N + i \kappa_2 \bar{\psi}_X \gamma_5 \psi_X \bar{\psi}_N \gamma_5 \psi_N + \kappa_3 \bar{\psi}_X \gamma_5 \psi_X \bar{\psi}_N \gamma_5 \psi_N + \kappa_4 \bar{\psi}_X \gamma_\mu \psi_X \bar{\psi}_N \gamma_\mu \psi_N + \xi_N \bar{\psi}_X \gamma_\mu \gamma_5 \psi_X \bar{\psi}_N \gamma_\mu \gamma_5 \psi_N \]

- For Majorana fermion only 2 operators survive at small \( q^2 \)

- First need to compute the WIMP quark amplitudes
  - Computed from Feynman diagrams + Fierz
  - depends on details of particle physics model
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon
Direct detection

- Typical diagrams
- Higgs exchange often dominates

For Dirac fermions Z exchange contributes to SI and SD
Spin independent interactions

• The case of Majorana fermion
  \[ \mathcal{L}^{SI} = \lambda_N \bar{\psi}_X \psi_X \bar{\psi}_N \psi_N \]

• Matrix element squared
  \[ |A_N^{SI}|^2 = 64 \left( \lambda_N M_X M_N \right)^2 \]

• Summing over photons and neutrons
  \[ |A_A^{SI}|^2 = 64 M_X^2 M_A^2 (\lambda_p Z + \lambda_n (A - Z))^2 \]

• Cross section for scattering on point like nucleons
  \[ \sigma_0^{SI} = \frac{4 \mu_X^2}{\pi} \left( \lambda_p Z + \lambda_n (A - Z) \right)^2 \]
  \[ \mu_X = m_{\tilde{\chi}} M_A / (m_{\tilde{\chi}} + M_A) \]
WIMP-quark to WIMP-nucleon

- Coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Scalar, vector, pseudovector, tensor
  - Extracted from experiments
  - Source of theoretical uncertainties
- Example, scalar coefficients, contribution of q to nucleon mass (heavy quark contribution expressed in terms of gluonic content)

\[
\langle N| m_q \bar{\psi}_q \psi_q |N\rangle = f_q^N M_N
\]

\[
\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}
\]

\[
f_Q^N = \frac{2}{27} \left( 1 - \sum_{q\leq3} f_q^N \right)
\]
• Scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and $\sigma_0$ (size of SU(3) breaking effect)

$$\sigma_{\pi N} = m_i \langle p | \bar{u}u + \bar{d}d | p \rangle$$

$$\sigma_0 = m_i \langle p | \bar{u}u + \bar{d}d - 2\bar{s}s | p \rangle$$

• Large uncertainty in s-quark contribution

$$\sigma_{\pi N} = 55 - 73 \text{ MeV} \quad \text{and} \quad \sigma_0 = 35 \pm 5 \text{ MeV}$$

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>$f_{Tu}$</th>
<th>$f_{Td}$</th>
<th>$f_{Ts}$ [24]</th>
<th>$f_{Ts}$ [25]</th>
<th>$f_{Ts}$ [20, 26]</th>
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<td>n</td>
<td>0.023</td>
<td>0.034</td>
<td>0.08</td>
<td>0.14</td>
<td>0.46</td>
</tr>
<tr>
<td>p</td>
<td>0.019</td>
<td>0.041</td>
<td>0.08</td>
<td>0.14</td>
<td>0.46</td>
</tr>
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</table>

• 2011: Lattice calculations give new estimates of those coefficients – get s-quark content lower than previously thought (~0.02)

• The value of the quark coefficient a large impact on the scattering rate - varying coefficients within the range above can in the MSSM lead to almost order of magnitude change in cross section

WIMP-nucleon to WIMP-nucleus

• To get rate as a function of the recoil energy must take into account nuclear form factor + velocity distribution

• Ignoring form factor effect expect isotropic scattering in CMS frame - - in lab frame for velocity v get constant distribution over recoil energy in interval 0<E<E_{\text{max}}

\[ E_{\text{max}}(v) = 2 \left( \frac{v^2 \mu^2}{M_\chi} \right) \]

• For fixed v, recoil energy distribution

\[ \frac{d\sigma^S_I}{dE} = \sigma_0^S I \frac{E_{\text{max}}(v) - E}{E_{\text{max}}(v)} \frac{F_A^2(q)}{E_{\text{max}}(v)} \]

\[ q = \sqrt{2E M_A}. \]

• \( F_A(q) \) : form factor (Woods-Saxon form factor)

\[ F_A(q) = \int e^{-iqx} \rho_A(x) d^3x \]

\[ \rho_A(r) = \frac{c_{\text{norm}}}{1 + \exp((r - R_A)/a)} \]

\[ R_A = 1.23A^{\frac{1}{3}} - 0.6 \text{fm} \]

\[ a = 0.52 \text{fm} \] (extracted from muon scattering data)
• DM have velocity distribution $f(v)$
• Integrating over incoming velocities -> distribution of number of events over the recoil energy

$$\frac{dN^{SI}}{dE} = \frac{2M_{\text{det}}}{\pi} \frac{\rho_0}{M_\chi} F_A^2(q) (\lambda_pZ + \lambda_n(A-Z))^2 I(E)$$

$\rho_0$: DM density near Earth

• $M_{\text{det}}$: detector mass
• $T$: exposure time

$$I(E) = \int_{v_{\text{min}}(E)}^{\infty} \frac{f(v)}{v} dv$$

$$v_{\text{min}}(E) = \left( \frac{EM_A}{2\mu^2_\chi} \right)^{1/2}$$

$$f(v) dv = \frac{4v^2}{v_0^3 \sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$
WIMP-nucleon to WIMP-nucleus

- Rates (SI and SD) depend on nuclear form factors and velocity distribution of WIMPs + local density

\[
\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi} \frac{\rho_0}{M_\chi} F_A^2(q) (\lambda_p Z + \lambda_n (A - Z))^2 I(E)
\]

- Nuclear form factors
- Particle physics + quark content in nucleon
- DM velocity distribution

\[
I(E) = \int_{v_{\text{min}}(E)}^{\infty} \frac{f(v)}{v} dv
\]

\[
v_{\text{min}}(E) = \left( \frac{EM_A}{2\mu_X^2} \right)^{1/2}
\]
Spin dependent

- Effective Lagrangian for Majorana fermion
  \[ \mathcal{L}^{SD} = \xi_N \bar{\psi}_X \gamma_5 \gamma_\mu \psi_X \bar{\psi}_N \gamma_5 \gamma_\mu \psi_N \]
  \[ |A_N^{SD}|^2 = 192(\xi_N S_N M_X M_N)^2 \]
- Sum spin currents produced by p and n separately
- \( \psi_0 \) component vanish \( \rightarrow \) 3dim vector current proportional to angular momentum
  \[ \vec{J}_N^A = S_N^A \vec{J}_A / |J_A| \]
- \( S_p = S_n = 1/2 \)
- Non trivial summation over spins
  \[ \sum_{s_X, s'_X} \sum_{s_A, s'_A} \sum_{1 \leq k, l \leq 3} \langle s_X | J^k_X | s'_X \rangle \langle s'_X | J^l_X | s_X \rangle \langle s_A | J^k_A | s'_A \rangle \langle s'_A | J^l_A | s_A \rangle \]
  \[ = \sum_{1 \leq k, l \leq 3} tr(J^k_X J^l_X) tr(J^k_A J^l_A) = (2J_X + 1) J_X (J_X + 1) \cdot (2J_A + 1) J_A (J_A + 1)/3 \]
- After average over initial polar, \( (2J_X+1)(2J_A+1) \) cancels out
• WIMP-nucleus amplitude squared

\[ |A^{SD}|^2 = 256 \frac{J_A + 1}{J_A} \left( \xi_p S_p^A + \xi_n S_n^A \right)^2 \frac{M^2_\chi M^2_A}{M_X^2 M_A^2} \]

• Cross section at rest for point-like nucleus

\[ \sigma^{SD}_0 = \frac{\mu^2_\chi}{\pi} \frac{J_A + 1}{J_A} \left( \xi_p S_p^A + \xi_n S_n^A \right)^2 \]

• \( S^A_N \) are obtained from nuclear calculations or from simple nuclear model \(~0.5\) for nuclei with odd nb of p or n \(~0\) for even nuclei

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>( \langle S_p \rangle_{OGM} )</th>
<th>( \langle S_n \rangle_{OGM} )</th>
<th>( \langle S_p \rangle )</th>
<th>( \langle S_n \rangle )</th>
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<tr>
<td>(^{19}\text{F})</td>
<td>0.46</td>
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<tr>
<td>(^{27}\text{Al})</td>
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<tr>
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<td>(^{73}\text{Ge})</td>
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</tr>
<tr>
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<td>-0.166</td>
<td>-0.041</td>
<td>-0.236</td>
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</table>
Axial vector quark coefficients

• Axial vector current counts the total spin of quarks and antiquarks in nucleon

• Operators for A-V interactions in nucleon related to those in quarks

\[ \xi_{N,s} = \sum_{q=u,d,s} \Delta q^N \xi_{q,s} \]

\[ 2s_\mu \Delta q^N = \langle N | \bar{\psi}_q \gamma_\mu \gamma_5 \psi_q | N \rangle \]

• \( \Delta q^N \) extracted from lepton-proton scattering, in particular strange contribution to spin of nucleon (measured first by EMC) much larger than expected in naïve quark model

\[ \Delta^p_u = 0.842 \pm 0.012, \quad \Delta^p_d = -0.427 \pm 0.013, \quad \Delta^p_s = -0.085 \pm 0.018 \]

\[ \Delta^n_u = \Delta^p_u, \quad \Delta^n_d = \Delta^p_u, \quad \Delta^n_s = \Delta^p_s \]
Dirac fermion

• Fermions

\[ \mathcal{L}_F = \lambda_{N,e} \bar{\psi}_X \psi_X \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_X \gamma_\mu \psi_X \bar{\psi}_N \gamma^\mu \psi_N + \xi_{N,e} \bar{\psi}_X \gamma_5 \gamma_\mu \psi_X \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_X \sigma_{\mu \nu} \psi_X \bar{\psi}_N \sigma^{\mu \nu} \psi_N \]

\[ \lambda_N = \frac{\lambda_{N,e} \pm \lambda_{N,o}}{2} \quad \text{and} \quad \xi_N = \frac{\xi_{N,e} \pm \xi_{N,o}}{2} \]

• Vector current \( \bar{\psi}_q \gamma_\mu \psi_q \) is responsible for the difference between \( \chi^N \) and \( \chi^N \) interactions. It counts the number of quarks minus antiquarks in the nucleon (valence quarks)
  - no uncertainties.

\[ \lambda_{N,p} = \sum_{q=u,d} f_{Vq}^N \lambda_{q,p} \quad f_{Vu}^p = 2, \quad f_{Vd}^p = 1, \quad f_{Vu}^n = 1, \quad f_{Vd}^n = 2 \]
Scalar and vector DM

- **Complex scalar**
  - Only spin independent interactions

\[
\mathcal{L}_S = 2\lambda_{N,e} M_X \phi_X \phi_X^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_X \phi_X^* - \phi_X \partial_\mu \phi_X^*) \bar{\psi}_N \gamma_\mu \psi_N
\]

- **Complex vector (SI and SD)**

\[
\mathcal{L}_V = 2\lambda_{N,e} M_X A_{X,\mu} A_{X,\mu}^* \bar{\psi}_N \psi_N + \lambda_{N,o} i(A_{X,\alpha}^* \partial_\mu A_{X,\alpha} - A_{X,\alpha} \partial_\mu A_{X,\alpha}^*) \bar{\psi}_N \gamma_\mu \psi_N \\
+ \sqrt{6} \xi_{N,e} (\partial_\alpha A_{X,\beta}^* A_{X,\gamma} - A_{X,\beta}^* \partial_\alpha A_{X,\gamma}) \epsilon^{\alpha \beta \gamma \mu} \bar{\psi}_N \gamma_5 \gamma_\mu \psi_N \\
+ \frac{i}{\sqrt{3}} \xi_{N,o} (A_{X,\mu} A_{X,\nu}^* - A_{X,\mu}^* A_{X,\nu}) \cdot \bar{\psi}_N \sigma_{\mu \nu} \psi_N
\]
World Wide Wimp searches

In this talk: only recent results (2007-2008) and status of near future projects
Direct detection - results

• For easy comparison between experiments – extract $\sigma_{\chi p}$

$$\sigma_p^{SI} = \lim_{m_\chi \to \infty} \sigma \{ m_N = m_p, m_\chi \}$$

• Assume velocity distribution

• Limits are improving every year
  – Best limits Xenon (2012)
  – DAMA confirm their annual modulation signal
Direct Detection

- DAMA: signal in annual modulation compatible with light DM (8.9σ)
- Recently CoGent, CDMS, CRESST also reported some signals compatible with ‘light’ DM
- Some of the favoured regions are excluded by Xenon10, Xenon100, CDMS
  - theoretical uncertainties

DM proton scattering cross section:
experimental results

Akerib et al, CDMS, 1010.4290
Spin dependent

- Also KIMS 1204.2646

Coupp : 1204.3094
Indirect detection

• Annihilation of pairs of DM particles into SM: decay products observed

• Searches for DM in 4 channels
  – Antiprotons and
  – Positrons from galactic halo/center
  – Photons from galactic halo/center
  – Neutrinos from Sun

• Rate for production of $e^+, p, \gamma$
  – Dependence on the DM distribution ($\rho$) – not well known in center of galaxy

• Typical annihilation cross section at freeze-out

$$Q(x, E) = \frac{<\sigma v>}{2} \left(\frac{\rho(x)}{m_\chi}\right)^2 \frac{dN}{dE}$$

$$<\sigma v> = 3 \times 10^{-26} \text{cm}^3/\text{sec}$$
\[ \frac{dN}{dE} \]

- Spectrum depends
  - mass of DM
  - primary annihilation channels
Propagation of cosmic rays

- For Charged particle spectrum detected different than spectrum at the source

- Charged cosmic rays are deflected by irregularities in the galactic magnetic field
  - For strong magnetic turbulence, MC simulations show that effect similar to space diffusion

- Energy losses due to interactions with interstellar medium

- Convection driven by galactic wind

- Reacceleration due to interstellar shock wave
Antiprotons and positrons from DM annihilation in halo

\[
\frac{\partial N}{\partial t} - \nabla \cdot [K(x, E) \nabla N] - \frac{\partial}{\partial E} [b(E) N] = q(x, E)
\]

diffusion \hspace{1cm} \text{Energy losses} \hspace{1cm} \text{Source}
Indirect detection

- For charged particles: solve propagation equation
  \[ \frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E) \nabla N] - \frac{\partial}{\partial E} \left[ b(E) N \right] = q(\mathbf{x}, E) \]

- Theoretical computation of spectrum of secondary charged particle and from DM annihilation
  - GALPROP – Strong and Moskalenko
  - T. Delahaye, P. Salati et al

- Background spectrum
  - Astro sources: supernova explosions, interaction between cosmic ray nuclei in interstellar medium
Indirect DM searches

Payload for Anti Matter Exploration and Light nuclei Astrophysics

Ground base large array gamma ray telescope
Excess in positron fraction at high energies
DM indirect detection

- Results on total electron positron spectrum
  - Higher energies than PAMELA
  - Excess over background

- Fit Pamela, Fermi, Hess with e.g. heavy DM (2TeV) annihilating into taus

- Careful investigation of secondary spectrum
- Astro sources (pulsars) give similar signal

Fermi-LAT 0905.0025

Strumia, Papucci.. arXiv:0905.0480
DM in antiprotons - example

WW channel

O. Adriani, 0810.4994

O. Adriani 0810.4995
Photons

- Flux calculation
  \[
  \Phi_{\gamma,\nu} = \frac{1}{8\pi} \frac{\langle \sigma_{\text{ann}} \nu \rangle}{m_{\chi}^2} \sum_{\text{f.s.}} \left( \frac{dN_{\gamma,\nu}}{dE} \right)_{\text{f.s.}} \int_{\text{l.o.s.}} \rho_s^2
  \]

- Photon production
  - In decay of SM particles
  - Monochromatic gamma rays (\(\gamma\gamma, \gamma Z\))
  - Internal bremsstrahlung

- Integral over line of sight depends strongly on the galactic DM distribution
Dark matter profile

• Dark matter profile

\[ \rho_s(r) = \rho_\odot \left[ \frac{r_\odot}{r} \right]^\gamma \left[ \frac{1 + (r_\odot/a)^\alpha}{1 + (r/a)^\alpha} \right]^{\frac{\beta - \gamma}{\alpha}} \]

- \( r_\odot = 8 \text{ kpc} \)
- \( \rho_\odot = 0.3 \text{ GeV.cm}^{-3} \)

• N-body simulation

• Different halo profile rather similar except in center of galaxy

<table>
<thead>
<tr>
<th>Halo model</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>a (kpc)</th>
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<td>0</td>
<td>4</td>
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<tr>
<td>NFW</td>
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<tr>
<td>Moore</td>
<td>1.5</td>
<td>3</td>
<td>1.5</td>
<td>28</td>
</tr>
</tbody>
</table>
Photons from dwarf galaxies

- Dwarf galaxies are dominated by DM – good probe
- Not as strong dependence on the density profile (profiles differ strongly only in Galactic center)
- Fermi has derived limits on photon flux and DM cross section for different channels
- Low masses probe the relic density favoured value
Impact of DM profile on rate

A SUSY example

Roszkowski, Ruiz, Silk & Trotta (2007)

$\Phi_\gamma$ from GC

$\Delta \Omega = 10^{-5} \text{ sr}$

$E_{\text{thr}} > 1 \text{ GeV}$

$\log[\Phi_\gamma \text{ (cm}^{-2} \text{s}^{-1})]$
Summary

• A number of direct and indirect detection offer good prospects to probe dark matter (probe $\sigma v$ and $M_{DM}$)
• Photons and antiprotons sensitive to light DM with expected cross section
• Direct detection can probe both SI and SD interactions in protons and neutrons using different detectors
• Already constrain some favoured models
• Theoretical uncertainties are important
• Hints of signals, not clear it is DM: DAMA, Pamela, Fermi gamma-ray line
• Extra notes
Velocity distribution of DM

• Nuclear recoil energy measured depends on WIMP velocity distribution in rest frame of detector → distribution in rest frame of galaxy + Earth velocity in this frame

\[ v_0 = 220 \pm 20 \text{km/s} \]

• Velocity of rotation in LSR

• Peculiar velocity of the Sun

• Earth velocity in Galactic frame: \( v_1 = v_0 + v_{\text{pec}} + v_{\text{E}} \) (Earth in solar system)

\[ \vec{v}_e = v_e(-\sin(2\pi t), \sin \gamma \cos(2\pi t), \cos \gamma \cos(2\pi t)) \]

• Velocity of DM particles on Earth = obtained from velocity of DM particles in Galactic Rest Frame

\[ f(v) = \int \delta(v - |\vec{V}|) F_{GRF}(\vec{V} - \vec{v}_0 - \vec{v}_{\text{pec}} - \vec{v}_e) d^3\vec{V} \]

• Mass Galaxy is finite \( 498 \text{km/s} < v_{\text{max}} < 608 \text{km/s} \) for which \( F_{GRF} \neq 0 \)
• Several DM velocity distribution, they are correlated with DM density distribution

• Simplest: isothermal sphere model

\[ F_{GRF}(\vec{V}) \sim \exp(-|\vec{V}|^2/\Delta V^2) \Theta(v_{max} - |\vec{V}|) \]

• Lead to

\[ f(v) = c_{\text{norm}} \left[ \exp \left( -\frac{(v - v_1)^2}{\Delta V^2} \right) - \exp \left( -\frac{\min(v + v_1, v_{max})^2}{\Delta V^2} \right) \right] \]

\[ \Delta V = v_0 \]

• Note: Earth motion around Sun leads to 7% modulation effect of \( v_1 \) and to modulation of signal in DD experiments

• DM velocity distribution near the sun could be quite different