Dark Matter Phenomenology

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Outline

Lecture 1: Evidence for dark matter.
Lecture 2: Dark matter production.
Lecture 3: Indirect detection
Lecture 4: Indirect detection (cont.)
Lecture 5: Direct detection, collider signals
Direct Dark Matter Searches
Direct dark matter searches

The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

$\text{Sun} \quad v \approx 200 \text{ km/s}$

$\text{WIMPs} \quad v \approx 200 \text{ km/s}$
Direct dark matter searches

The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

\[ v \approx 200 \text{ km/s} \]

Once in a while a dark matter particle will interact with a nucleus. The nuclear recoil can be interpreted as a dark matter signal.

\[ v \approx 200 \text{ km/s} \]
Simple idea ...

... but very challenging in practice!
Challenges in direct dark matter detection

- Expected scattering cross section

Assume that the DM interacts with a proton via a weak interaction

$$\sigma \sim \frac{1}{32\pi} G_F^2 \mu^2$$

$$\mu = \text{reduced mass} = \frac{m_{DM} m_p}{m_{DM} + m_p} \simeq m_p$$

$$\sigma \sim 5 \times 10^{-4} \text{ pb}$$
Challenges in direct dark matter detection

- Expected scattering cross section
  Assume that the DM interacts with a proton via a weak interaction
  \[ \sigma \sim \frac{1}{32\pi} G_F^2 \mu^2 \]
  \[ \mu = \text{reduced mass} = \frac{m_{DM} m_p}{m_{DM} + m_p} \approx m_p \]
  \[ \sigma \sim 5 \times 10^{-4} \text{ pb} \]

- Expected flux
  \[ \text{Flux} = \text{density} \times \text{velocity} \]
  \[ \rho_{DM} = 0.38 \text{ GeV/cm}^3 \]
  \[ n = 3.8 \times 10^{-3} \text{ WIMPs/cm}^3 \]
  \[ \text{flux} \sim 10^5 \text{ WIMPs/cm}^2 \text{ s} \]
  (For \( m = 100 \text{ GeV} \))
Challenges in direct dark matter detection

- Expected interaction rate

\[
\text{Rate} = \text{flux} \times \text{number of targets} \times \text{cross section}
\]

\[10^5 \text{ cm}^{-2} \text{ s}^{-1}\]

For a 70 kg person, \(10^{29}\) protons

\[5 \times 10^{-40} \text{ cm}^{-2}\]

Rate \(\sim 1\) interaction per day, producing nuclear recoils

However, cosmic ray interactions and the natural radioactivity also produce nuclear recoils, with a much much larger rate. How to distinguish the signal events from the background events?
Reducing backgrounds

1) Take experiments deep underground

2) Shield the detector against natural radioactivity in the laboratory.

3) Devise techniques to further reduce residual backgrounds
Direct dark matter searches
Direct dark matter searches

No evidence for DM-induced nuclear recoils
Theoretical interpretation of the experimental results
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Important: the momentum transferred in the scattering to the target is small:

Typical kinetic energy of a DM particle at the location of the Earth:

\[ E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v^2 \sim 30 \text{ keV} \]

\[ m_{\text{DM}} = 100 \text{ GeV} \]

⇒ Momentum transferred < \( E_{\text{kin}} \sim 30 \text{ keV} \)

⇒ The DM cannot “see” the constituents of the nucleus

~~⇒ Coherent scattering with the whole nucleus.
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Assume for the moment that all DM particles have the same velocity $v$

Interaction rate with one nucleus in the detector $= \text{flux} \times \text{cross section}$

$$R = \frac{\rho_{DM}}{m_{DM}} v \sigma_{DM,N}(v, E_R)$$
Implications for Particle Physics

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Differential event rate

$$\frac{dR}{dE_R} = \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \; v \frac{d\sigma_{\text{DM},N}}{dE_R}(v, E_R)$$
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$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_{DM}} \, v \, \frac{d\sigma_{DM,N}}{dE_R}(v, E_R)$$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_{DM} m_N} \, v \, \frac{d\sigma_{DM,N}}{dE_R}(v, E_R)$$
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_{DM} m_N} \int_{v_{min}}^{\infty} d^3v \, v \, f(\tilde{v}) \, \frac{d\sigma_{DM,N}}{dE_R}(\nu, E_R)$$

(units: counts/kg/day/keV)
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution $f(v)$.

Differential event rate normalized by the mass of the target nucleus:

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{m_{DM} m_N} \int_{v_{\min}}^{\infty} d^3v \; v f(\vec{v}) \frac{d\sigma_{DM,N}}{dE_R}(v, E_R)$$

Local DM density

ASTROPHYSICS

dark matter Velocity distribution (Maxwellian?)
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

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PARTICLE PHYSICS (and nuclear physics)
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

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DETECTOR CHARACTERISTICS

Target nucleus mass
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution $f(v)$.

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\text{DM}}}{m_{\text{DM}} m_N} \int_{v_{\text{min}}}^{\infty} d^3v \, v \, f(\vec{v}) \frac{d\sigma_{\text{DM},N}}{dE_R}(v, E_R)$$

Minimum DM velocity to produce a recoil with energy $E_R$.

PARTICLE PHYSICS+DETECTOR

$$v_{\text{min}} = \sqrt{\frac{m_N E_R}{2 \mu_N^2}}$$

$$\mu_N = \frac{m_{\text{DM}} m_N}{m_{\text{DM}} + m_N}$$
Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the model parameters?

Dark matter particles in the Solar System have a velocity distribution \( f(v) \)

Event rate is calculated by integrating over all possible recoil energies

\[
R = \int_{E_T}^{\infty} \frac{\rho_0}{m_{DM} m_N} \int_{v_{\text{min}}(E_R)}^{\infty} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma_{\text{DM},N}}{dE_R}(v, E_R)
\]

threshold energy of the detector. Typically a few keV.
From partons to nuclei

From the fundamental point of view, the relevant quantity is the dark matter – parton cross section.

Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

$$\mathcal{L}_{\text{eff}} = \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{q} \gamma_\mu (\alpha_1 + \alpha_2 \gamma_5) q + \alpha_3 \bar{\chi} \chi \bar{q} q + \alpha_4 \bar{\chi} \gamma_5 \chi \bar{q} \gamma_5 q + \alpha_5 \bar{\chi} \chi - q \gamma_5 q + \alpha_6 \bar{\chi} \gamma_5 \chi \bar{q} q$$
From partons to nuclei

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Velocity dependent in the non-relativistic limit. Negligible.
From partons to nuclei

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Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

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CP violating
From the fundamental point of view, the relevant quantity is the dark matter – parton cross section.

Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

\[ \mathcal{L}_{\text{eff}} = \overline{\chi} \gamma^\mu \gamma_5 \chi \overline{q} \gamma_\mu \left( \alpha_1 + \alpha_2 \gamma_5 \right) q + \alpha_3 \overline{\chi} \chi \overline{q} q + \alpha_4 \overline{\chi} \gamma_5 \chi \overline{q} \gamma_5 q + \alpha_5 \overline{\chi} \chi \gamma_5 q + \alpha_6 \overline{\chi} \gamma_5 \chi \overline{q} q \]

\[ \mathcal{L} \supset \alpha^A (\overline{\chi} \gamma^\mu \gamma_5 \chi) (\overline{q} \gamma_\mu \gamma_5 q) \quad \text{Axial-vector coupling} \]

\[ \mathcal{L} \supset \alpha^S \overline{\chi} \chi \overline{q} q \quad \text{Scalar coupling} \]
Spin independent term \[ \mathcal{L} \supset \alpha^S_q \bar{\chi} \chi \bar{q}q \]

The matching from the parton level to the hadronic level is described by means of form factors:

\[ \langle p | m_q \bar{q}q | p \rangle \equiv m_p f^{p}_{Tq} \]

Experimentally, for the proton

\[ f^{p}_{Tu} = 0.020 \pm 0.004, \quad f^{p}_{Td} = 0.026 \pm 0.005, \quad f^{p}_{Ts} = 0.118 \pm 0.062 \]

(and for the neutron \( f^{n}_{Tu} = f^{p}_{Td}, \quad f^{n}_{Td} = f^{p}_{Tu}, \) and \( f^{n}_{Ts} = f^{p}_{Ts} \))
The spin independent cross section between the WIMP and all the individual protons and neutrons is:

\[ \sigma_{SI} = \frac{4\mu_N^2}{\pi} \left[ Z f^p + (A - Z) f^n \right]^2 \]

\[ \frac{f^p}{m_p} = \frac{\sum q=u,d,s \alpha^S_q f^p_{Tq}}{m_q} + \frac{2}{27} f^p_{TG} \sum q=c,b,t \alpha^S_q \]

Coupling to quarks

Coupling to gluons

\[ m_p f^p_{Tq} \equiv \langle p | m_q \bar{q} q | p \rangle \]

\[ f^p_{TG} = 1 - \sum q=u,d,s f^p_{Tq} \]
Lastly, the total differential cross section between the WIMP and the nucleus should take into account the internal structure of the nucleus → **Nuclear form factor**

\[
\left( \frac{d\sigma_{DM,N}}{dE_R} \right) = \frac{m_N \sigma_{SI} F^2(E_R)}{2\mu_N^2 v^2}
\]

The nuclear form factor is usually parametrized as:

\[
F^2(q) = \left( \frac{3j_1(qR_1)}{qR_1} \right)^2 \exp \left[ -q^2 s^2 \right]
\]

\[R_1 = \sqrt{R^2 - 5s^2} \quad R \simeq 1.2 A^{1/2} \text{ fm.}\]
\[s \simeq 1 \text{ fm}\]
\[ \mathcal{L} \supset \alpha_q^S \bar{\chi} \chi \bar{q} q \]

\[ \sigma_{SI} = \frac{4 \mu_N^2}{\pi} \left[ Z f^p(\alpha_q^S) + (A - Z) f^n(\alpha_q^S) \right]^2 \]

\[ \left( \frac{d\sigma_{DM,N}}{dE_R} \right) = \frac{m_N \sigma_{SI} F^2(E_R)}{2 \mu_N^2 v^2} \]

\[ R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} dv v f(v) \frac{d\sigma_{DM,N}}{dE_R} \]
Many unknowns...

Scattering rate:

\[
R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} dv \, v \, f(v) \frac{d\sigma_{DM,N}}{dE_R}
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\]

Standard strategy:

- Fix the form factors
Many unknowns...

Scattering rate:

\[ R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} dv v f(v) d\sigma_{DM,N}^{\text{SI}}(E_R) \]

\[ \left( \frac{d\sigma_{DM,N}}{dE_R} \right) = \frac{m_N \sigma_{SI} F^2(E_R)}{2 \mu_N^2 v^2} \]

Standard strategy:

- Fix the form factors

i.e. one assumes that the nuclear physics is understood.
Many unknowns...

Scattering rate:

\[ R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} dv \, v \, f(v) \frac{d\sigma_{DM,N}}{dE_R} \]

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Standard strategy:

- Fix the form factors
- Fix the local DM density, \( \rho_0 = 0.3 \) GeV/cm\(^3\)
- Fix the velocity distribution to a Maxwell-Boltzmann distribution
Many unknowns...

Scattering rate:

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Standard strategy:

- Fix the form factors
- Fix the local DM density, \( \rho_0 = 0.3 \) GeV/cm\(^3\)
- Fix the velocity distribution to a Maxwell-Boltzmann distribution
  i.e. one assumes that the astrophysics is understood.
Many unknowns...

Scattering rate:

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R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} d\nu \nu f(\nu) \frac{d\sigma_{DM,N}}{dE_R}
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\]

Standard strategy:

- Fix the form factors
- Fix the local DM density, \( \rho_0 = 0.3 \) GeV/cm\(^3\)
- Fix the velocity distribution to a Maxwell-Boltzmann distribution
- Leave the DM mass and DM-nucleon cross section as free parameters
Experimental results. SI interaction

![Graph showing WIMP-nucleon cross-section vs. WIMP mass]
Spin dependent interaction

\[ \mathcal{L} \supset \alpha^A_q (\bar{\chi} \gamma^\mu \gamma_5 \chi)(\bar{q} \gamma_\mu \gamma_5 q) \]

\[ \sigma_{SD} = \frac{32}{\pi} G^2_F \mu_N^2 \Lambda^2 J(J + 1) \]

\[ \left( \frac{d\sigma_{DM,N}}{dE_R} \right) = \frac{16 m_N}{\pi v^2} \Lambda^2 G^2_F J(J + 1) \frac{S(E_R)}{S(0)} \]

\[ R = \int_{E_T}^\infty dE_R \frac{\rho_0}{m_N m_{DM}} \int_{v_{min}}^{\infty} dv v f(v) \frac{d\sigma_{DM,N}}{dE_R} \]
Experimental results. SD interaction

PICO coll.'17
Astrophysical uncertainties?

It is assumed a local DM density of 0.3 GeV/cm$^3$ and a Maxwell-Boltzmann velocity distribution.

… However, the value of the local DM density is inferred from observations far away from the Solar System.
Astrophysical uncertainties?

It is assumed a local DM density of 0.3 GeV/cm$^3$ and a Maxwell-Boltzmann velocity distribution.

… and the Maxwell-Boltzmann distribution is justified only when the density distribution follows a singular isothermal sphere profile.
Astrophysical uncertainties?

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Hydrodynamical simulations (DM+baryons).
Astrophysical uncertainties?

\[ \left| \frac{f(\bar{v}) - f_{MB}(\bar{v})}{f_{MB}(\bar{v})} \right| \leq \Delta \]

Dependence of the Xenon1T limits on \( \Delta \) at 90% C.L.

AI, Kavanagh, Rappelt'18
Bright future in direct dark matter searches
Bright future in direct dark matter searches

\[ \sigma \sim 10^{-40} \text{ cm}^2 \]
Bright future in direct dark matter searches

$$\sigma \sim 10^{-40} \text{ cm}^2$$

\[ \text{WIMP-nucleon } \sigma \text{ [cm}^2] \]
\[ \text{WIMP mass [GeV/c}^2] \]
Bright future in direct dark matter searches

Tree-level Z-exchange

\[ \sigma \sim 10^{-40} \text{ cm}^2 \]
Bright future in direct dark matter searches

Tree-level Z-exchange

$\sigma \sim 10^{-40} \text{ cm}^2$

$\sigma \sim 10^{-45} \text{ cm}^2$

![Graph showing WIMP-nucleon cross-section versus WIMP mass]
Bright future in direct dark matter searches

Tree-level Z-exchange

\[ \sigma \sim 10^{-40} \text{ cm}^2 \]

One-loop Z-exchange

\[ \sigma \sim 10^{-45} \text{ cm}^2 \]
Bright future in direct dark matter searches

Tree-level $Z$-exchange

$\sigma \sim 10^{-40} \text{cm}^2$

One-loop $Z$-exchange

$\sigma \sim 10^{-45} \text{cm}^2$

Tree level Higgs exchange

$\sigma \lesssim 10^{-45} \text{cm}^2$

WIMP-nucleon cross section $\sigma$ [cm$^2$]

WIMP mass [GeV/c$^2$]
Collider Searches
Collider searches

Differential cross-section for the final state of interest $Y$

$$d\sigma(p(P_1) + p(P_2) \rightarrow Y + X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1, i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(x_1 P_1) + i_2(x_2 P_2) \rightarrow Y)$$
Collider searches

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Fraction of the momenta of the proton carried by the parton $i$
**Collider searches**

Differential cross-section for the final state of interest $Y$

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**Parton distribution functions**

[Graphs depicting parton distribution functions with labels for different partons like $u$, $d$, $s$, $c$, $b$, and $g$.]

Ball et al'17
Collider searches

Differential cross-section for the final state of interest $Y$

$$d\sigma(p(P_1) + p(P_2) \to Y + X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1, i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(x_1 P_1) + i_2(x_2 P_2) \to Y)$$

Cross-section for the partonic process

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<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M_Z^2} \chi^\dagger \chi \bar{q} q$</td>
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<tr>
<td>C5</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M_Z^2} \chi^\dagger \chi \alpha_s (G_{\mu\nu}^a)^2$</td>
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<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M_Z^2} \chi \bar{q} q$</td>
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<tr>
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<tr>
<td>D8</td>
<td>$qq$</td>
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<td>$\frac{1}{M_Z^2} \chi \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$</td>
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<tr>
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<td>tensor</td>
<td>$\frac{1}{M_Z^2} \chi \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
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<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M_Z^2} \chi \bar{q} \chi \alpha_s (G_{\mu\nu}^a)^2$</td>
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</tbody>
</table>
Collider searches

Monojet + missing $E_T$
Collider searches

Monojet + missing $E_T$
Collider searches

Monojet + missing $E_T$

ATLAS
$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

Expected limit (±1σ±2σ)

Observed limit

Thermal relic

Truncated, max coupling

WIMP mass $m_{\chi}$ [GeV]
Collider searches

Monojet + missing $E_T$

Mediator production
Complementarity of DM search strategies
Many possible realizations of the effective interaction
Many possible realizations of the effective interaction

- Which dark matter particle?
- Which mediator (if any)?
- What is the role of the mediator in the phenomenology?
Many possible realizations of the effective interaction

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Many possible realizations of the effective interaction

Which dark matter particle?

Which mediator (if any)?

What is the role of the mediator in the phenomenology?

Three parameters:
- DM mass, $m_\chi$
- Mediator mass, $m_\eta$
- Coupling constant, $\gamma$
Many possible realizations of the effective interaction

Which dark matter particle?
Which mediator (if any)?
What is the role of the mediator in the phenomenology?

Three parameters:
- DM mass, $m_\chi$
- Mediator mass, $m_\eta$
- Coupling constant, $y$

Fixed by the requirement of reproducing the correct DM abundance.
Parameter space of the model spanned by $m_\chi$ and $m_\eta$.
Complementarity of searches

Impact for dark matter produced via thermal freeze-out

DM coupling to $u$–quark

![Graph showing complementarity of searches and impact for dark matter produced via thermal freeze-out. The graph includes regions for ATLAS, jets+ETmiss, XENON100, LUX, ATLAS Monojet, underproduction, and overproduction/non-pert.](image)
Complementarity of searches

Impact for dark matter produced via thermal freeze-out
List of conclusions

End of list
Concluding remarks

1- Zwicky's observations of 1933
Concluding remarks

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3- BUT, the dark matter particle could not be a WIMP. Or perhaps the astronomical observations of galaxies, clusters of galaxies, etc. are explained by something completely different (not yet proposed). Keep an open mind.
Thank you for your attention!