Lecture on
Direct Dark Matter Detection Phenomenology

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I. Evidence and candidates for Dark Matter
   Evidence for Dark Matter
   Candidates for Dark Matter

II. Direct Dark Matter detection experiments
   Overview
   Direct detection phenomenology
   Direct detection techniques
   Backgrounds and background discriminations
Part I:
Evidence and candidates for Dark Matter
Evidence for Dark Matter
Evidence for Dark Matter

- Dark: interacts at most very weakly with EM radiation
- The observational evidence for the existence of Dark Matter is gravitational.
- Clusters of galaxies (1930s)
- Rotation curves of spiral galaxies (1970s)
- The observed luminous objects cannot have enough mass to support the observed gravitational effects.

- Modified Newtonian Dynamics/Modified Gravity
Evidence for Dark Matter

- Clusters of galaxies (1930s)

[https://insidetheperimeter.ca/what-we-know-and-what-we-dont-about-dark-matter/]

[Coma cluster of galaxies; F. Zwicky (1933)]
Evidence for Dark Matter

- Rotation curves of spiral galaxies (1970s)

[https://insidetheperimeter.ca/what-we-know-and-what-we-dont-about-dark-matter/]

Evidence for Dark Matter

- Galaxy NGC1052–DF2 (2018)

[P. van Dokkum et al., Nature 555, 629 (2018)]
Evidence for Dark Matter

- Collision of two clusters of galaxies (Bullet Cluster, 1E 0657-56)

[http://chandra.harvard.edu/photo/2006/1e0657/]

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Evidence for Dark Matter

- Anisotropy of the cosmic microwave background radiation (CMBR)

[NASA/WMAP Science Team (full sky map in 1965)]
Evidence for Dark Matter

- Anisotropy of the cosmic microwave background radiation (CMBR)

Evidence for Dark Matter

- Anisotropy of the cosmic microwave background radiation (CMBR)

\[ \Omega_0 > 1 \quad \Omega_0 = 1 \quad \Omega_0 < 1 \]

Closed \quad Flat \quad Open Universe

[NASA/WMAP Science Team, WMAP 5-year result (2008)]
Evidence for Dark Matter

- Anisotropy of the cosmic microwave background radiation (CMBR)

[Image: Map of the cosmic microwave background radiation with arrows indicating more and fewer (primordial) baryonic matter.]

[NASA/WMAP Science Team, WMAP 5-year result (2008)]
Evidence for Dark Matter

- Anisotropy of the cosmic microwave background radiation (CMBR)

Evidence for Dark Matter

- Abundances of the light elements: D, $^3$He, $^4$He, $^7$Li

[Review of Particle Physics 2016, 24. Big-Bang Nucleosynthesis]
Evidence for Dark Matter

- Supernovae type Ia (SNe Ia) at high-redshift
Evidence for Dark Matter

- Astronomical measurements
  - Cosmic microwave background (CMB)
  - Anisotropy of the CMB radiation (CMBR)
  - Present expansion rate of the Universe: Hubble constant
  - Age of the Universe
  - Abundances of the light elements: D, $^3$He, $^4$He, $^7$Li
  - Opacity of the Lyman-$\alpha$ forest toward high-redshift quasars
  - Gas-to-total mass ratio
  - Mass-to-light ratio
  - Peculiar velocities of galaxies
  - Shape of the present power spectrum of density perturbations
  - Supernovae type Ia (SNe Ia) at high-redshift
Evidence for Dark Matter

- A large fraction of the mass/energy in our Universe is dark!

  ▲ Dark Energy: $\Omega_\Lambda = 0.692 \pm 0.012$
  
  ▲ (Cold) Dark Matter: $\Omega_{CDM} = 0.258 \pm 0.011$
  
  ▲ Baryonic matter: $\Omega_b = 0.0484 \pm 0.0010$
  
  ▲ Luminous matter: $\Omega_{lum} \simeq (3.5398 \pm 0.0470) \times 10^{-5}$
  
  ▲ Stars: $0.002 \lesssim \Omega_* \lesssim 0.003$
  
  ▲ Neutrinos: $0.0012 \leq \Omega_\nu < 0.016$
  
  ▲ CMB photons: $\Omega_\gamma = 5.38(15) \times 10^{-5}$

[†: Review of Particle Physics 2016, 2. Astrophysical Constants and Parameters]

[‡: Review of Particle Physics 2016, 24. Big-Bang Nucleosynthesis]

[§: Review of Particle Physics 2016, 22. Big-Bang Cosmology]
Candidates for Dark Matter
Candidates for Dark Matter

- Non-luminous, non-baryonic, non-relativistic (cold), collisionless elementary particles which have not yet been discovered.

  ▲ Dark Matter should move non-relativistically in the early Universe in order to allow it to merge to galactic scale structures.

  ▲ So far we can observe (or “feel”) the existence of Dark Matter only through its gravitational effects.

  ▲ Dark Matter forms halos with an approximately spherical distribution around galaxies.

  ▲ Dark Matter must be stable on the cosmological time scale.

  ▲ Dark Matter must have the right relic cosmological density.
Candidates for Dark Matter

- **Cold Dark Matter (CDM)**
  - moved non-relativistically when galaxies could just start to form (matter-radiation decoupling time).
  - would form some small galactic scale structures due to their relatively slower velocities (bottom-up).

- **Hot Dark Matter (HDM)**
  - moved relativistically at the matter-radiation decoupling time.
  - would cover great(er) distances and form some very large scale structures (top-down).

- **Warm Dark Matter (WDM)**

- **Dark baryons**
Candidates for Dark Matter

Particles of the Standard Model

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>u (Up quark)</td>
<td>$\approx 2.3$ MeV/c^2</td>
<td>$2/3$</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>c (Charmed quark)</td>
<td>$\approx 1.275$ GeV/c^2</td>
<td>$2/3$</td>
<td>1/2</td>
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<tr>
<td>t (Top quark)</td>
<td>$\approx 173.07$ GeV/c^2</td>
<td>$2/3$</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>g (Gluon)</td>
<td>$\approx 126$ GeV/c^2</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>H (Higgs boson)</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>e (Electron)</td>
<td>$\approx 0.511$ MeV/c^2</td>
<td>-1</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>μ (Muon)</td>
<td>$\approx 105.7$ MeV/c^2</td>
<td>-1</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>τ (Tau)</td>
<td>$\approx 1.777$ GeV/c^2</td>
<td>-1</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>Z (Z boson)</td>
<td>$\approx 91.2$ GeV/c^2</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>W (W boson)</td>
<td>$\approx 80.4$ GeV/c^2</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e (Electron neutrino)</td>
<td>$\approx 0.017$ MeV/c^2</td>
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<td>1/2</td>
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<tr>
<td>ν_μ (Mu neutrino)</td>
<td>$\approx 0.17$ MeV/c^2</td>
<td>0</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>ν_τ (Tau neutrino)</td>
<td>$\approx 15.5$ MeV/c^2</td>
<td>0</td>
<td>1/2</td>
<td></td>
</tr>
</tbody>
</table>

## Candidates for Dark Matter

**Particles of the Standard Model**

<table>
<thead>
<tr>
<th>SM particles</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Name</td>
<td>Symbol</td>
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<tr>
<td>up-quarks</td>
<td>u, c, t</td>
</tr>
<tr>
<td>down-quarks</td>
<td>d, s, b</td>
</tr>
<tr>
<td>leptons</td>
<td>e, µ, τ</td>
</tr>
<tr>
<td>neutrinos</td>
<td>ν_e, ν_µ, ν_τ</td>
</tr>
<tr>
<td>gluons</td>
<td>g</td>
</tr>
<tr>
<td>photon</td>
<td>γ</td>
</tr>
<tr>
<td>Z boson</td>
<td>Z⁰</td>
</tr>
<tr>
<td>Higgs boson</td>
<td>H</td>
</tr>
<tr>
<td>W bosons</td>
<td>W⁺⁻</td>
</tr>
</tbody>
</table>
**Candidates for Dark Matter**

Particles of typical *supersymmetric* models

<table>
<thead>
<tr>
<th>Normal particles</th>
<th>SUSY partners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Symbol</strong></td>
</tr>
<tr>
<td>up-quarks</td>
<td>u, c, t</td>
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<tr>
<td>down-quarks</td>
<td>d, s, b</td>
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<td>leptons</td>
<td>e, μ, τ</td>
</tr>
<tr>
<td>neutrinos</td>
<td>νe, νμ, ντ</td>
</tr>
<tr>
<td>gluons</td>
<td>g</td>
</tr>
<tr>
<td>photon</td>
<td>γ</td>
</tr>
<tr>
<td>Z boson</td>
<td>Z0</td>
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<tr>
<td>light scalar Higgs</td>
<td>h0</td>
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<tr>
<td>heavy scalar Higgs</td>
<td>H0</td>
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<tr>
<td>pseudoscalar Higgs</td>
<td>A0</td>
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<tr>
<td>charged Higgs</td>
<td>H±</td>
</tr>
<tr>
<td>W bosons</td>
<td>W±</td>
</tr>
<tr>
<td>graviton</td>
<td>G</td>
</tr>
<tr>
<td>axion</td>
<td>a</td>
</tr>
</tbody>
</table>
Candidates for Dark Matter

- Weakly Interacting Massive Particles (WIMPs) $\chi$
  - Dark Matter relic density
    \[
    \Omega_{\text{CDM}} h^2 = 0.1186 \pm 0.0020^\dagger \approx \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_{\text{anni}} v \rangle}
    \]
    

  - $\sigma_{\text{anni}} \approx 10^3 \text{ pb}$
  - Weak interaction
    ⬡
  - Gravitational, EM, strong interactions
  - Mass ranges roughly between 10 GeV and a few TeV.
    - $v_{\text{CDM}} \sim 10^{-3} c \Rightarrow Q \sim \left( \frac{10^{-6}}{2} \right) m_\chi c^2$
      ⬡

- Gravitino, axion, axino
Candidates for Dark Matter

- The lightest neutralino $\tilde{\chi}_1^0$
  - The lightest SUSY particle (LSP)
  - Linear combinations of photino, Z-ino and neutral higgsinos
- The lightest Kaluza-Klein (KK) particle (LKP) in Universal Extra Dimensions (UED) models
- The lightest T-odd particle (LTP) in Little Higgs (LH) models

Other candidates:
Summary
Summary

- Astronomical observations and measurements indicate the existence of Dark Matter
  - Rotation curves of spiral galaxies
  - Anisotropy of the CMB radiation

- Models in particle physics offer candidates for Dark Matter
  - the lightest neutralino in SUSY models
  - the lightest Kaluza-Klein (KK) particle in UED models
  - the lightest T-odd particle in Little Higgs models

- We are searching for Dark Matter by
  - producing new particle(s) at colliders
  - indirect detection of secondary products of WIMP annihilation/decay
  - direct detection through elastic WIMP-nucleus scattering
Thank you very much for your attention!
Part II:
Direct Dark Matter detection experiments
Dark Matter searches
Dark Matter searches

DM should have small, but non-zero interactions with ordinary matter.

⇒ Three different ways to detect DM particles

Colliders

Indirect detection

Direct detection
Direct Dark Matter detection
Direct Dark Matter detection: elastic WIMP-nucleus scattering

- WIMPs could scatter elastically off target nuclei and produce nuclear recoils which deposit energy in the detector.

  ▲ The event rate depends on
  - the WIMP density near the Earth $\rho_0$
  - the WIMP-nucleus cross sections $\sigma_{0}^{\text{SI}}$ and $\sigma_{0}^{\text{SD}}$
  - the WIMP mass $m_\chi$
  - the velocity distribution of incident WIMPs $f_1(v)$

  ▲ The **WIMP-nucleus** cross section is about $10^{-3} \sim 10^{-6}$ pb
  - the optimistic expected event rate is $\sim 0.1$ events/(100 kg–100 day)
  - but could be $< 1$ event/ton-yr

  ▲ An **exponential-like** recoil energy spectrum
  - Most events would be with energies less than a few tens keV

  ▲ Typical background events due to cosmic rays and ambient radioactivity: signals $\approx \mathcal{O}(10^6) : 1 \rightarrow \text{bg discrimination} \Rightarrow \sim 1 : 1.x$
Direct Dark Matter detection: elastic WIMP-nucleus scattering

- Time-dependence of the scattering event rate

  ▲ Annual modulation of the event rate

- Due to the orbital motion of the Earth around the Sun

- A cosinusoidal function with a one-year period, a peak around June 2nd, and an amplitude of \( \sim 5\% \) (recoil-energy dependent)

- The peak could be shifted by \( \sim 3 \) weeks!

- The nuclear recoil (signal) identification should be performed!


Direct Dark Matter detection: elastic WIMP-nucleus scattering

- Time-dependence of the scattering event rate
  - Annual modulation of the event rate

Results of the DAMA/NaI and DAMA/LIBRA experiments


[R. Bernabei et al., Nucl. Instrum. Meth. A742, 177 (2014)]
Direct Dark Matter detection: elastic WIMP-nucleus scattering

- Time-dependence of the scattering event rate
  - **Diurnal modulation** of the event rate

Due to the rotation of the Earth
- **Directionality of the WIMP wind**
- **Shielding of the incident WIMP flux** by the Earth
- **CYGNUS International Workshop on Directional Detection of Dark Matter**


http://www.tir.tw/conf/cygnus2017/
Direct Dark Matter detection phenomenology
Direct Dark Matter detection phenomenology

- Astrophysical and particle parameters
  - (One-dimensional) velocity distribution function $f_1(v)$ or $f(v)$
    - The Solar orbital speed around the Galactic center $v_0$
    - Escape and 1-D maximal cut-off velocities $v_{esc}$ and $v_{max}$
    - The Earth’s motion in the Galactic frame
  - Local density $\rho_0$ or halo density distribution $\rho(r)$
  - WIMP mass $m_\chi$
  - WIMP-nucleon (proton/neutron) couplings
    - SI scalar couplings $f_{(p,n)}$
    - SI vector couplings $b_{(p,n)}$
    - SD axial-vector couplings $a_{(p,n)}$
Direct Dark Matter detection phenomenology

- Target material dependence

  ▲ (WIMP-nucleus) scattering form factors $F_{SI,SD}^2(Q)$

  ▶ For nuclei with $A \gtrsim 30$, the SI scalar interaction ($\propto A^2$) would almost always dominate over the SD interaction (in SUSY models).

  ▶ In e.g. UED models, the SI and SD interactions are comparable.

  ▲ Minimal and (kinematic) maximal cut-off energies $Q_{(\text{min, max})}$ and $Q_{\text{max, kin}}$

  ▲ Detector materials

    ▶ Ge $\Leftrightarrow$ Si
    ▶ Xe $\Leftrightarrow$ Ar
    ▶ I $\Leftrightarrow$ F
Direct Dark Matter detection phenomenology

- Works include
  - developing data analysis procedures
  - comparing different models on the $m_\chi - \sigma_{\chi(p/n)}^{\text{SI}} - \sigma_{\chi(p/n)}^{\text{SD}}$ space
  - constraining/distinguishing particle/astrophysical halo models
  - reconstructing WIMP properties
  - combining with and being complementarity of indirect Dark Matter detection and collider experiments
  - building packages for Monte Carlo simulations and/or (real) data analyses

- Phenomenologists $\implies$ Data analysts $\implies$ Code programmers
Direct Dark Matter detection phenomenology

- Constraints in parameter space
  
  ▲ Exclusion limits on the (predicted) $\sigma^{\text{SI}}_{\chi p}$ vs. $m_\chi$ plane

![Image of exclusion limits plot]

[http://dmtools.berkeley.edu/limitplots/]
Direct Dark Matter detection phenomenology

- Constraints in parameter space

  ▲ Exclusion limits on the $\sigma_{\chi p}^{SD}$ vs. $m_\chi$ plane

[http://dmtools.berkeley.edu/limitplots/]
Direct Dark Matter detection phenomenology

- Constraints in parameter space
  - Exclusion limits on the $\sigma^{SD}_{\chi n}$ vs. $m_\chi$ plane

[http://dmtools.berkeley.edu/limitplots/]
Direct Dark Matter detection phenomenology

- Constraints in parameter space
  ▲ Constraints on the $a_n$ vs. $a_p$ plane

[ZPLIN-III Collab., V. N. Lebedenko et al., PRL 103, 151302 (2009)]
Direct Dark Matter detection techniques
Direct Dark Matter detection techniques

- Induced signals
  - Ionization (charges)
  - Scintillation (light)
  - Heat (phonons)
- Quenching factor
  - Nuclear recoil relative efficiency
  - Measured (electron equivalent) recoil energy $\text{keV}_{ee}$
    $\iff$ true nuclear recoil energy $\text{keV}_r$
- Raw/total mass/exposure
  $\iff$ fiducial mass/exposure
- Combinations of two signals
  - Event-by-event background discrimination
  - Down to 5 to 10 keV recoil energy
Direct Dark Matter detection techniques

- **Semiconductor/scintillator detectors**

  ▲ **ANAIS**
  NaI(Tl), Laboratorio Subterráneo de Canfranc (LSC), Spain.

  ▲ **CDEX**
  Ge, China Jin-Ping Laboratory (CJPL), China.

  ▲ **CDMS → SuperCDMS**
  Ge and Si, Soudan Undergd. Lab., USA; Sudbury Neutrino Observatory (SNOLAB), Canada.

  ▲ **CoGeNT → C-4**
  Ge, Soudan Underground Laboratory, USA.

  ▲ **CRESST → EURECA**
  Al₂O₃/CaWO₄, Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  ▲ **DAMA/NaI → DAMA/LIBRA**
  NaI(Tl), Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  ▲ **DM-Ice → COSINE**
  NaI(Tl), South Pole.

  ▲ **EDELWEISS (EDW) → EURECA**
  Ge, Laboratoire Souterrain de Modane (LSM), France.

  ▲ **KIMS → COSINE**
  CsI(Tl), Yangyang Laboratory (Y2L → CUNP), South Korea.

  ▲ **NaIAD**
  NaI(Tl), Boulby Underground Laboratory, UK.

  ▲ **SABRE**
  NaI(Tl), Stawell Underground Physics Laboratory (SUPL), Australia.
Direct Dark Matter detection techniques

- **Semiconductor/scintillator detectors**
  - CDMS, CRESST and EDELWEISS detectors

Direct Dark Matter detection techniques

- **Semiconductor/scintillator** detectors
  - Working principle of a **CDMS** detector

[https://www.slac.stanford.edu/exp/cdms/]
Direct Dark Matter detection techniques

- **Liquid noble gas detectors**

  - **ArDM**
    Dual-phase Ar, Laboratorio Subtarráneo de Canfranc (LSC), Spain.

  - **DarkSide**
    Dual-phase Ar, Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  - **DARWIN**
    Dual-phase Ar and Xe, Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  - **DEAP/CLEAN**
    Single-phase Ar and Ne, Sudbury Neutrino Observatory (SNOLAB), Canada.

  - **LUX → LZ**
    Dual-phase Xe, Sanford Underground Research Facility (SURF), USA.

  - **NEWS-G**
    Ne and CH$_4$, Laboratoire Souterrain de Modane (LSM), France.

  - **PandaX**
    Dual-phase Xe, China Jin-Ping Laboratory (CJPL), China.

  - **WARP**
    Dual-phase Ar, Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  - **XENON**
    Dual-phase Xe, Laboratori Nazionali del Gran Sasso (LNGS), Italy.

  - **XMASS**
    Single-phase Xe, Kamioka Observatory, Japan.

  - **ZEPLIN → LZ**
    Single-/dual-phase Xe, Boulby Underground Laboratory, UK.
Direct Dark Matter detection techniques

- Liquid noble gas detectors
  - XENON1T and XMASS detectors

Direct Dark Matter detection techniques

- Liquid noble gas detectors
  - Working principle of the XENON1T detector

Direct Dark Matter detection techniques

- Liquid noble gas detectors
  - Working principle of the XENON1T detector

Direct Dark Matter detection techniques

- **Superheated droplet/gas detectors (with directional sensitivity)**
  
  ▲ **COUPP → PICO**  
  CF$_3$I, C$_3$F$_8$, and C$_4$F$_{10}$, Sudbury Neutrino Observatory (SNOLAB), Canada.  

  ▲ **PICASSO → PICO**  
  C$_4$F$_{10}$, Sudbury Neutrino Observatory (SNOLAB), Canada.  

  ▲ **SIMPLE**  
  C$_2$ClF$_5$ and CF$_3$I, Laboratoire Souterrainá Bas Bruit (LSBB), France.  

  ▲ **TREX-DM**  
  Ar and Ne, Laboratorio Subterráneo de Canfranc (LSC), Spain.  

  ▲ **D3 → CYGNUS**  
  SF$_6$ + $^4$He, USA.  

  ▲ **DMTPC**  
  CF$_4$, Sudbury Neutrino Observatory (SNOLAB), Canada.  

  ▲ **DRIFT → CYGNUS**  
  73% CS$_2$ + 25% CF$_4$ + 2% O$_2$, Boulby Underground Laboratory, UK.  

  ▲ **MIMAC**  
  70% CF$_4$ + 28% CHF$_3$ + 2% C$_4$H$_{10}$, Laboratoire Souterrain de Modane (LSM), France.  

  ▲ **NEWAGE → CYGNUS**  
  CF$_4$, Kamioka Observatory, Japan.  

  ▲ **NEWSdm**  
  AgBr(I), Laboratori Nazionali del Gran Sasso (LNGS), Italy.
Direct Dark Matter detection techniques

- **Superheated droplet/gas detectors (with directional sensitivity)**
  - COUPP detector (bubble chamber)

[COUPP Collab., E. Behnke et al., Science 319, 933 (2008)]
Direct Dark Matter detection techniques

- **Directional** Direct detection experiments
  - Recoil track (3D) reconstruction
  - Sense (head-tail) recognition

- **Detector techniques**
  - (Low pressure) gaseous time-projection chamber (TPC)
  - Micromegas
  - Gas electron multiplier (GEM)
  - Nuclear emulsion

- **Materials**
  - CF₄, C₃F₈, C₄F₁₀
  - CF₃I, CHF₃, C₂ClF₅
  - CS₂, CH₄
  - SF₆
Direct Dark Matter detection techniques

- **Directional** Direct detection experiments

  ▲ Working principle of the **MIMAC μTPC** detector

  ![Diagram of MIMAC μTPC detector](image)

  [Q. Riffard et al., J. Inst. 12, P06021 (2017)]
Direct Dark Matter detection techniques

- **Directional** Direct detection experiments
  - Working principle of the MIMAC $\mu$TPC detector

[Q. Riffard et al., J. Inst. 11, P08011 (2016)]
Direct Dark Matter detection techniques

- **Directional** Direct detection experiments
  - Working principle of the MIMAC $\mu$TPC detector

![Diagram of MIMAC $\mu$TPC](image)

**Scheme of a MIMAC $\mu$TPC**

**Evolution of the collected charges on the anode**

[Q. Riffard et al., J. Inst. 11, P08011 (2016)]
Backgrounds and background discriminations
Backgrounds and background discriminations

- Backgrounds
  - Cosmic muons
  - External natural radioactivity
  - Internal natural radioactivity
  - Fast neutrons
  - Multiple-scatter events
  - Electron recoils
  - Surface events
  - Incomplete charge collection
  - Neutron-induced nuclear recoils
Backgrounds and background discriminations

- Cosmic muons
  - Induce fast neutrons
  - $\mathcal{O}(10^{10})$ cosmic muons/m$^2$ Earth’s surface/yr
  - Go deep underground (reduced by a factor of $10^5$ to $10^8$)

Backgrounds and background discriminations

- **External natural radioactivity**
  - Radioactive isotopes in the rock/walls
  - Passive shielding:
    - high-Z materials (e.g., lead) for MeV $\gamma$-ray,
    - low-Z materials for $\alpha$, $\beta$, and low energy $\gamma$-rays

- **Internal natural radioactivity**
  - Radioactive isotopes contamination in the outer shielding, equipment around the detector, and detector material
  - Radiopure materials

- **Fast neutrons**
  - Induced by cosmic-ray in the inner lead shielding
  - Water tank or polyethylene (PE)
    (materials with high density of hydrogen)
Backgrounds and background discriminations

- Multiple-scatter events
  - Mean free path of WIMP-induced events $\sim O$ (light year)
  - Array of detectors
  - CDMS ZIP-detector cryostat and tower

[http://cdms.berkeley.edu/; P. Cushman, JPCS 39, 63 (2006)]
Backgrounds and background discriminations

- **Electron recoils**
  - Ionization yield
  - Ionization (S2)/primary scintillation (S1)
  - CDMS-II calibration

[CDMS Collab., Z. Ahmed et al., Science 327, 1619 (2010)]
Backgrounds and background discriminations

- **Surface events/incomplete charge collection**
  - Rising time of phonon pulses
  - Self-shielding
  - CDMS-II calibration

[CDMS Collab., Z. Ahmed et al., Science 327, 1619 (2010)]
Backgrounds and background discriminations

- Surface events/incomplete charge collection
  - Rising time of phonon pulses
  - Self-shielding
  - XENON10 result

[XENON10 Collab., J. Angle et al., PRL 100, 021303 (2008)]
Backgrounds and background discriminations

- Neutron-induced nuclear recoils
  - Mimic WIMP-induced nuclear recoils
  - Scintillating reflector
  - CRESST-II calibration

[CRESST Collab., R. F. Lang et al., Astropart. Phys. 33, 60 (2010)]
Summary
Summary

- **Direct WIMP Dark Matter searches** depend on
  - the local WIMP density $\rho_0$
  - the velocity distribution of halo WIMPs $f_1(v)$
  - the WIMP mass $m_\chi$
  - the SI and SD WIMP-nucleon couplings $f_{(p,n)}, b_{(p,n)}$, and $a_{(p,n)}$
  - the nucleon group spins $\langle S_{p,n} \rangle$
  - the nuclear form factors $F_{SI,SD}^2(Q)$
  - the mass of target nucleus $m_N$
  - the total/fiducial detector mass $m_{det}$
  - the minimal and (kinematic) maximal cut-off energies $Q_{(min,max)}$ and $Q_{max,kin}$
  - the quenching factor $Q_{ee} \rightarrow Q_r$
  - the background discrimination techniques/ability
Summary

- **Background discrimination techniques**
  - Underground laboratories
  - Muon vetos
  - Passive shielding
  - Radiopure materials
  - Water tank or polyethylene (PE)
  - Array of detectors
  - Ionization to heat/scintillation ratios
  - Rising time/shape of phonon pulses
  - Self-shielding
  - Scintillating reflector
  - ...

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Thank you very much for your attention!