The missing 95%: Theory and Phenomenology of Dark Matter and Dark Energy

Joachim Kopp

DPG Spring Meeting Göttingen, March 2012
Outline

1. Evidence for dark matter

2. Finding dark matter
   - Direct detection
   - Indirect detection
   - Production at colliders

3. Modelling dark matter

4. Dark energy
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Celestial mechanics

Stellar/galactic dynamics relates:

- The mass distribution  
  (inferred from brightness)
- Kinetic energy  
  (inferred from Doppler shifts)

Fritz Zwicky  
1898–1974

Vera Rubin  
1928–

Observations of rotational velocities in galaxies show:  
Rubin 1975

The gravitational pull on peripheral stars is stronger than predicted from the mass of the luminous matter $M$

$$m \frac{v^2}{r} = G_N \frac{mM}{r^2} \quad \text{at } r \to \infty$$

M33 Rotation Curve
Collisions of galaxy clusters

Artist’s rendering (Image: NASA)

red = gas (from x-ray observations)
blue = (dark) matter distribution (from gravitational lensing)
Collisions of galaxy clusters

Image: NASA (Chandra [x-ray], ESO WFI [lensing], HST [optical])

red = gas (from x-ray observations)

blue = (dark) matter distribution (from gravitational lensing)
The Cosmic Microwave Background (CMB)

WMAP’s observation of the CMB: A fingerprint of the universe at $t \sim 300,000$ yrs (when electrons and protons first combined to form atoms).

red = overdense, hot regions ($0 \ldots +200 \ \mu K$)
blue = underdense, cold regions ($-200 \ldots 0 \ \mu K$)

Image credit: NASA
The Cosmic Microwave Background (CMB)

WMAP’s observation of the CMB: A fingerprint of the universe at $t \approx 300\,000$ yrs (when electrons and protons first combined to form atoms).

More useful: The CMB fluctuation power spectrum

Image credit: NASA
The Cosmic Microwave Background (CMB)

WMAP’s observation of the CMB: A fingerprint of the universe at $t \approx 300,000 \text{ yrs}$ (when electrons and protons first combined to form atoms).

Image credit: NASA

red curve = theory prediction
black points = WMAP data
The Cosmic Microwave Background (CMB)

WMAP’s observation of the CMB: A fingerprint of the universe at \( t \approx 300,000 \) yrs (when electrons and protons first combined to form atoms).

too little DM \((0.04\rho_c)\)  right amount of DM \((0.22\rho_c)\)  too much DM \((0.74\rho_c)\)

Image credit: NASA
What is this stuff?

- **Modified laws of gravity?**
  - Hard to explain all observations

- **MACHOs (Massive Compact Halo Objects)?**
  - Planets, Brown dwarfs, neutron stars, . . .
  - Ruled out as dark matter in the mass range $0.6 \times 10^{-7} M_\odot < M < 15 M_\odot$ by searches for gravitational microlensing
  - Searches for candidate objects yield too few of them

- **Hot (relativistic) Dark Matter (neutrinos or other relativistic particles)?**
  - Cannot explain large scale structure of the universe (hot dark matter would smoothen the galaxy distribution)

- **Cold or Warm Dark Matter**
  - **Axions**
    - Ultra-light, but non-relativistic due to non-thermal production
  - **Gravitinos**
    - Only gravitational couplings → bad for direct/indirect/collider detection
  - **WIMPs (Weakly Interacting Massive Particle)**
    - New, heavy, stable particles
    - Should have some non-gravitational interaction with SM particles for production in the early universe
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Direct Dark Matter detection

Idea: A WIMP (Weakly Interacting Massive Particle) can scatter on an atomic nucleus.

Strategy: Look for feeble nuclear recoil

Problem: Many background processes (radioactive decays, cosmic rays, ...) can mimic the signal
Direct DM detection — The experimental challenge
Direct DM detection — The experimental challenge
Direct detection results

Assumptions here: Elastic DM scattering $\propto$ target mass (often realized in SUSY)
Direct detection phenomenology of alternative models

- Previous slide: Elastic dark matter ($\chi$) scattering through scalar current \[ (\bar{q}q)(\bar{\chi}\chi) \] or vector current \[ (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu \chi) \] assumed
  \[ \Rightarrow \text{Cross section } \propto \text{target mass} \]

- In models with different coupling structure, the relative detection efficiencies of different experimental technologies may be different
Direct detection phenomenology of alternative models

- Spin-dependent couplings
  - E.g. coupling through axial vector current \[ (\bar{q} \gamma^\mu \gamma^5 q)(\bar{\chi} \gamma^\mu \gamma^5 \chi) \]
  - Cross section \( \propto \) target spin
  - Cannot explain DAMA, CoGeNT, CRESST results
Direct detection phenomenology of alternative models

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**Inelastic dark matter** Tucker-Smith Weiner hep-ph/0101138
- There may be two DM states \( \chi \) and \( \chi' \) with \( m'_\chi = m_\chi + \delta \) (\( \delta \sim 100 \) keV)
- Scattering \( \chi N \rightarrow \chi' N \Rightarrow \) heavy target nuclei kinematically preferred
- Could explain CRESST, but not DAMA JK Schwetz Zupan 1110.2721
Direct detection phenomenology of alternative models

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- **Leptophilic dark matter**
  - Bernabei et al. 0712.0562; Fox Poppitz arXiv:0811.0399; JK Niro Schwetz Zupan arXiv:0907.3159
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- **Isospin-violating dark matter** Feng Kumar Marfatia Sanford 1102.4331
Direct detection phenomenology of alternative models

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- ... 

**Conclusion:** Hard to explain all data simultaneously
Direct detection uncertainties

- Large uncertainty in local DM density

Scattering rate depends strongly on DM velocity

- DM streams?
- Debris flow?

Predicting WIMP–nucleus cross sections is difficult

- Models predict WIMP–quark cross section
- Need to know quark content of the nucleon
- Especially problematic for Higgs-mediated scattering: coupling \( \propto \) quark mass \( \Rightarrow \) sea quarks dominate
- Need to know nuclear form factor especially difficult for spin-dependent scattering
Direct detection uncertainties

- Large uncertainty in local DM density
- Large uncertainties in DM velocity distribution
  - Scattering rate depends strongly on DM velocity
  - DM streams?
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Maxwell-Boltzmann  Debris Flows  Streams

\[ y \]

\[ x \]

\[ v_y \]

\[ v_x \]

\[ v_y \]

\[ v_x \]

\[ v_y \]

\[ v_x \]

Fully Virialized  \(-\)  Not Virialized

Kuhlen Lisanti Spergel arXiv:1202.0007, graphics courtesy of Mariangela Lisanti

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Dark Matter and Dark Energy
Direct detection uncertainties

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- Large uncertainties in DM velocity distribution
  - Scattering rate depends strongly on DM velocity
  - DM streams?
  - Debris flow?
- Predicting WIMP–nucleus cross sections is difficult
  - Models predict WIMP–quark cross section
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    especially difficult for spin-dependent scattering
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Indirect Dark Matter detection

Idea: WIMPs (Weakly Interacting Massive Particles) $\chi$ can annihilate (or decay) into Standard Model particles ($f$) in an astrophysical environment.

Strategy: Look for annihilation products in cosmic rays

Problems:
- Many other sources of cosmic rays
- Propagation of charged particles in the galaxy poorly understood

Advantage:
- Many sources to look at
Indirect DM detection — The experimental challenge
Indirect DM detection — The experimental challenge

look at many sources
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Indirect DM detection — The experimental challenge
Indirect DM detection — Examples

**γ-rays from dwarf galaxies**

**Idea:**
Look for anomalous γ-ray flux

**Pro:**
Few stars ⇒ few backgrounds

**Con:**
- Relatively low DM density
- Results model-dependent
- Large astrophysical uncertainties

Other indirect DM searches:
- Cosmic anti-matter ($e^+$, $\bar{p}$, ...) — PAMELA, Fermi-LAT, ...
- γ-rays from the galactic center — Hooper et al.
- High-energy neutrinos from the Sun — IceCube, SuperKamiokande, ...
Indirect DM detection — Examples

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Indirect DM detection — Examples

\( \gamma \)-rays from dwarf galaxies

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Look for anomalous \( \gamma \)-ray flux

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\begin{center}
\begin{tabular}{l}
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Dark matter at colliders
Dark matter at colliders

make your own needles!
Generic collider searches for dark matter

Idea:
- **Produce** WIMPs in collisions of Standard Model particles
- WIMPs can **recoil** against a **jet** or a **photon** from initial state radiation

**Experimental signatures:** Mono-jets $+ \slashed{E}_T$ and mono-photons $+ \slashed{E}$
LHC limits on DM–quark couplings

Assumptions here:

- Effective field theory approach valid (limits may be better or worse if EFT not valid)
- Equal coupling to all quark flavors

Extremely competitive limits for

- Light dark matter (below direct detection threshold)
- DM coupled to gluons (high gluon luminosity at the LHC)
- Spin-dependent DM interactions (DD suffers from loss of coherence)
Model-dependent collider searches: SUSY-DM

Idea:
- In many models, DM is produced in the decay of heavy, strongly interacting particles (for instance squarks and gluinos in SUSY)
- Experimental signature: something + missing energy
- Example: $pp \rightarrow (\tilde{g} \rightarrow jZ\chi^0)(\tilde{q} \rightarrow jjW\chi^0)$

- Advantage: Very sensitive
- Problem:
  - Minor modifications to the model may drastically change the phenomenology
- Problem (all collider searches):
  - Collider can only find DM candidate(s)
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Electroweak-scale DM? — The “WIMP Miracle”

- In the early universe, DM is in chemical equilibrium with other particles.
Electroweak-scale DM? — The “WIMP Miracle”

- In the early universe, DM is in chemical equilibrium with other particles.
- As the temperature drops, DM begins to annihilate away: $\bar{\chi}\chi \rightarrow \bar{f}f$

Conclusion: If dark matter originates from electroweak-scale new physics, it automatically has the right abundance.
In the early universe, DM is in chemical equilibrium with other particles. As the temperature drops, DM begins to annihilate away: $\bar{\chi}\chi \rightarrow \bar{f}f$

When the annihilation rate $\Gamma(\bar{\chi}\chi \rightarrow \bar{f}f)$ drops below the Hubble expansion rate $H$, annihilations cease

$\Rightarrow$ DM abundance remains constant ("thermal freeze-out")
In the early universe, DM is in chemical equilibrium with other particles. As the temperature drops, DM begins to annihilate away: \( \bar{\chi} \chi \to \bar{f} f \). When the annihilation rate \( \Gamma(\bar{\chi} \chi \to \bar{f} f) \) drops below the Hubble expansion rate \( H \), annihilations cease. \( \Rightarrow \) DM abundance remains constant ("thermal freeze-out"). From this requirement, and from the observed DM abundance today, cosmology predicts the DM annihilation cross section

\[
\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}
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- From this requirement, and from the observed DM abundance today, cosmology predicts the DM annihilation cross section
  $\langle \sigma v \rangle \simeq 3 \times 10^{-26}$ cm$^3$/s
- Consider generic DM coupling:
  $\mathcal{L} \supset \frac{g^2}{M^2}(\bar{\chi}\chi)(\bar{f}f)$

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The Wimp Miracle

Joachim Kopp
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$$\mathcal{L} \supset \frac{g^2}{M^2} (\bar{\chi}\chi)(\bar{f}f)$$

For typical coupling $g \sim 0.1$, suppression scale $M \sim 100 \text{ GeV}$, DM mass $m_\chi \sim 100 \text{ GeV}$, this yields the right value for $\langle \sigma v \rangle$. The "WIMP Miracle"
Electroweak-scale DM? — The “WIMP Miracle”

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- Conclusion: If dark matter originates from electroweak-scale new physics, it automatically has the right abundance

The **Wimp Miracle**
Relating the DM and baryon abundances

Motivation: The DM and baryon energy densities in the universe are similar

$$\Omega_{DM} \approx 5 \Omega_b$$

($$\Omega$$ = energy density as fraction of “critical density” for flat universe)
Motivation: The DM and baryon energy densities in the universe are similar

\[ \Omega_{DM} \approx 5 \Omega_b \]

(\( \Omega \) = energy density as fraction of “critical density” for flat universe)

If the DM and baryon number densities are similar and

\[ m_{DM} \sim 5m_p - 10m_p \sim 5\text{–}10 \text{ GeV} , \]

this is quite natural.
Relating the DM and baryon abundances

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- This is precisely the mass range where the direct detection hints (DAMA, CoGeNT, CRESST) have been observed!
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- Baryon density \( \Omega_b \) generated by *yet unknown* dynamics behind the particle–antiparticle asymmetry of the universe (not by thermal freeze-out)
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Baryon density \( \Omega_b \) generated by yet unknown dynamics behind the particle–antiparticle asymmetry of the universe (not by thermal freeze-out)

Assume dark matter (\( \chi \)) density is also determined by \( \bar{\chi} - \chi \) asymmetry \( \Rightarrow \) Asymmetric dark matter
Models of asymmetric dark matter

Example 1

- $B - L$ asymmetry generated at high $T$ (e.g. via Leptogenesis)
- Effective superfield operator

$$\mathcal{L} \supset \frac{1}{M} \bar{X}^2 L H_u$$

Transfers $B - L \leftrightarrow 2X$, e.g. via

Final $X$ (DM number) asymmetry depends on # of SM species contributing to (*) at freeze-out.
Models of asymmetric dark matter

**Example 1**

*Kaplan Luty Zurek, arXiv:0901.4117*

- **$B - L$ asymmetry generated at high $T$** (e.g. via Leptogenesis)
- **Effective superfield operator**

\[ \mathcal{L} \supset \frac{1}{M} \bar{X}^2 L H_u \]  

(*)

transfers $B - L \leftrightarrow 2X$, e.g. via

![Diagram showing particle interactions](image)

- **Final $X$ (DM number) asymmetry depends on # of SM species contributing to (*) at freeze-out**

**Example 2**

*Buckley Randall 1009.0270  
Blennow et al. 1009.3159*

- **Generate $X$ asymmetry in hidden sector**
- **Transfer to $B - L$ asymmetry in the SM sector**
  - via $B - L$ violating interactions (e.g. (*)
  - via sphaleron processes**
Models of asymmetric dark matter

Example 1

- \(B - L\) asymmetry generated at high \(T\) (e.g. via Leptogenesis)
- Effective superfield operator

\[
\mathcal{L} \supset \frac{1}{M} \bar{X}^2 LH_u \quad (*)
\]

transfers \(B - L \leftrightarrow 2X\), e.g. via

\[
\begin{array}{cccc}
X & \bar{X}^0 & X \\
\bar{\nu} & \nu & \bar{\nu} & \nu
\end{array}
\]

Final \(X\) (DM number) asymmetry depends on # of SM species contributing to (*) at freeze-out

Example 2

- Generate \(X\) asymmetry in hidden sector
- Transfer to \(B - L\) asymmetry in the SM sector
  - via \(B - L\) violating interactions (e.g. (*)
  - via sphaleron processes

Example 3

- New heavy particles decay partly into DM, partly into SM particles
- \(B - L - X\) is conserved
- DM \((X)\) does not participate in SM sphaleron processes
  ⇒ Asymmetry frozen in
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Evidence for dark energy: Type Ia Supernovae

- When a white dwarf accretes matter from a companion star, it becomes unstable once it reaches $\sim 1.4M_\odot$
  - Re-ignition of nuclear fusion
  - Thermonuclear explosion
- Since the progenitor mass is always $\sim 1.4M_\odot$, all Type Ia Supernovae are very similar
  - Energy release precisely known
  - SN Ia are standard candles
- Measurement:
  - Apparent brightness $\rightarrow$ distance
  - Redshift $\rightarrow$ velocity
- Result:
  - Long ago (very distant SN Ia, low brightness), the universe was expanding more slowly than we thought!
  - It must be accelerating
- CMB and Large Scale Structure observations confirm this

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Dark Matter and Dark Energy
What is accelerating the Universe?

- A cosmological constant?
  - An ad-hoc addition to the Einstein equations
    \[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R^\alpha_{\alpha} = 8\pi G T_{\mu\nu} + g_{\mu\nu}\Lambda \]
  - Observations require \( \Lambda \sim (10^{-12} \text{ GeV})^4 \)
  - Extra source of energy with negative pressure
What is accelerating the Universe?

- **A cosmological constant?**
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    \]
  - Observations require \( \Lambda \sim (10^{-12} \text{ GeV})^4 \)
  - Extra source of energy with negative pressure

- **QFT vacuum energy?**
  - A vacuum expectation value (vev) or condensate of a quantum field behaves like a cosmological constant
  - **Problem:** All known condensates/vevs are way too large!
    (We expect \( \Lambda \sim M_{\text{Pl}}^4 \sim (10^{19} \text{ GeV})^4 \))
What is accelerating the Universe? (cont’d)

- **Quintessence**: A new, slowly rolling scalar field
  - Introduce new scalar field $\phi$ slowly rolling down its potential $V(\phi)$
  - Lagrangian:
    \[
    \mathcal{L}_\phi = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)
    \]
  - Energy and pressure:
    \[
    \rho = \frac{1}{2} \dot{\phi}^2 + V(\phi), \quad p = \frac{1}{2} \dot{\phi}^2 - V(\phi)
    \]
  - A cosmological constant corresponds to $\rho = -p \Rightarrow$ require $\dot{\phi}^2 \ll V(\phi)$

---

for a review see Caldwell Kamionkowski 0903.0866
What is accelerating the Universe? (cont’d)

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- Extensions of general relativity
  - Scalar-tensor gravity: Modified Einstein-Hilbert action
    \[
    S = \frac{1}{16\pi G} \int \sqrt{-g} \, d^4x \, R \rightarrow S = \frac{1}{16\pi G} \int \sqrt{-g} \, d^4x \, f(\phi) \times R
    \]
  - A special case: $f(R)$ gravity:
    \[
    S = \frac{1}{16\pi G} \int \sqrt{-g} \, d^4x \, f(R)
    \]

for a review see Caldwell Kamionkowski 0903.0866
Summary

- **Overwhelming evidence** for dark matter
- **A lot of data available**
  - **Direct detection**
    - Difficult to reconcile possible evidence with null results
  - **Indirect searches**
    - Strong exclusion limits
    - Suffers from poorly understood astrophysical backgrounds
  - **Collider searches**
    - Generic searches (monojets + $E_T$, mono-$\gamma + E$) and model-specific searches (cascade decays) are underway full-steam

- **Dark matter models**
  - Dark matter from electroweak scale new physics:
    - Correct cosmic abundance due to WIMP Miracle
  - Light (10 GeV) dark matter:
    - Correct cosmic abundance if related to baryon–antibaryon asymmetry

- **Dark energy**
  - Accelerated expansion of the Universe well-established
  - So far, a cosmological constant is the leading explanation
Thank you!
Bonus material
Spin-dependent DM couplings?

- Previous slide: Dark matter ($\chi$) couplings through scalar current $[(\bar{q}q)(\bar{\chi}\chi)]$ or vector current $[(\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu \chi)]$ assumed
  ⇒ Cross section $\propto$ target mass
- Alternative: Axial vector $[(\bar{q}\gamma_\mu \gamma^5 q)(\bar{\chi}\gamma_\mu \gamma^5 \chi)]$ interaction
  ⇒ Cross section $\propto$ target spin

Note: CoGeNT & CRESST have very low sensitivity to spin-dependent DM scattering.
Inelastic dark matter?

Idea: There may be two DM states $\chi$ and $\chi'$ with

$$m_{\chi'} = m_\chi + \delta$$

Scattering proceeds via

$$\chi + N \rightarrow \chi' + N$$

- Modified kinematics compared to elastic scattering
- Affects different target nuclei differently
Inelastic dark matter?

**Idea:** There may be two DM states $\chi$ and $\chi'$ with

$$m_{\chi'} = m_\chi + \delta$$
**Isospin-violating dark matter?**

**Idea:** Dark matter could couple differently to protons and neutrons

⇒ Detection efficiencies of different target materials change

\[ \frac{A_{\text{eff}}^2}{\hat{A}^2} \quad \text{vs.} \quad \frac{f_n}{f_p} \]

- $f_n$, $f_p$: DM couplings to protons and neutrons
- $A_{\text{eff}}$: Effective nuclear mass for DM scattering

Plot from JK Schwetz Zupan 1110.2721
Isospin-violating dark matter?

Idea: Dark matter could couple differently to protons and neutrons ⇒ Detection efficiencies of different target materials change
Leptophilic dark matter?

**Idea:** DM could couple only to leptons at tree level

- DAMA and CoGeNT do not reject electron-recoils as background
- But: Electron recoils above threshold ($\gtrsim 1$ keV) strongly suppressed
  (electron needs large initial momentum $\rightarrow$ probe high-$p$ tail of wave functions)
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- DAMA and CoGeNT do not reject electron-recoils as background
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- Thus: DM–nucleus scattering dominates, even if loop-induced
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- But: Loop diagrams forbidden for some models
  e.g. axial vector couplings $g^2/M^2 (\tilde{\chi} \gamma_\mu \gamma_5 \chi)(\bar{f} \gamma^\mu \gamma_5 f)$
Leptophilic dark matter?

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- Thus: DM–nucleus scattering dominates, even if loop-induced
- But: Loop diagrams forbidden for some models
- Problems then:
  ▶ Very large couplings needed to compensate wave function suppression
  ▶ Poor fit to DAMA and CoGeNT energy spectra

![Graph](image)
Indirect DM detection — where to look

The Galactic Center

Pros:
- Highest DM density

Cons:
- DM distribution uncertain
- Many background sources

Dwarf Galaxies

Pros:
- Few backgrounds

Cons:
- Relatively low DM density
Indirect DM detection — where to look

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Fermi-LAT, 1108.3546
see also Geringer-Sameth Koushiappas 1108.2914
Indirect DM detection — where to look (2)

Cosmic antimatter

Pros:
- Few background sources

Cons:
- Backgrounds uncertain
- Propagation of charged particle has large uncertainties
- Non-directional
Indirect DM detection — where to look (2)

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PAMELA collaboration, 0810.4995
Cosmic antimatter

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High-energy neutrinos

Idea:
- DM capture/annihilation in the Sun
- Flux dominated by capture rate

Pros:
- Few backgrounds

Cons:
- Low neutrino cross sections
Indirect DM detection — where to look (2)

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What is a sphaleron?

- **SU(2)** gauge field vacuum configurations are classified according to their winding number (or Chern-Simons number)

\[
N_{CS} = \frac{1}{16\pi^2} \int_0^t dt \int d^3 x \, \text{tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu}
\]

Configurations with **different winding number** cannot be continuously transformed into each other.
What is a sphaleron?

- **SU(2)** gauge field vacuum configurations are classified according to their winding number (or Chern-Simons number) \( N_{CS} = \frac{1}{16\pi^2} \int_0^t dt \int d^3 x \, \text{tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu} \)

- Sphalerons are processes (with \( E > 0 \)) that change the winding number. Their energy is of order \( m_H \), the symmetry breaking scale (100 GeV)
What is a sphaleron?

- \( SU(2) \) gauge field vacuum configurations are classified according to their winding number (or Chern-Simons number) \( N_{CS} = \frac{1}{16\pi^2} \int_0^t dt \int d^3 x \text{ tr } F_{\mu\nu} \tilde{F}^{\mu\nu} \)

- Sphalerons are processes (with \( E > 0 \)) that change the winding number

- In the SM, a change in winding number corresponds to a change in \( B + L \). In fact, considering only left-handed \( (SU(2)_L\)-charged) fermions:

\[
j^{\mu}_{B+L} = \sum_{\psi=q,\ell} \frac{1}{2} \bar{\psi} \gamma^\mu (1 - \gamma^5) \psi
\]

A change in \( B + L \) is equivalent to a change in \( N_{CS} \):

\[
\partial_t \int d^3 x j^0_{B+L} \equiv \int d^3 x \frac{1}{2} \partial_\mu \bar{\psi} \gamma^\mu \gamma^5 \psi
\]

\[
= -\frac{1}{16\pi^2} \int d^3 x \text{ tr } F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{(since } \partial_\mu \bar{\psi} \gamma^\mu \psi = 0)\]

\[
= -\partial_t N_{CS} \quad \text{(chiral anomaly)}
\]