Changing Dark Matter

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Outline

- Evidence and Recent Hints of DM
  - Gravitational Evidence for DM
  - Direct Detection: CDMS, XENON, DAMA, ...
  - Indirect Detection: PAMELA, ATIC, INTEGRAL, ...
  - LHC Prospects

- Changing DM
  - A late-time phase transition after freeze-out
  - Effects on the DM
  - Phenomenology of the PT
Evidence and Recent Hints of Dark Matter
Dark Matter ...
...not so Dark

[Corbelli et al.]
Dark Matter Evidence from Gravity

- WMAP and other CMB probes have precisely determined the average dark matter density in the universe:

\[ \Omega_{DM} h^2 = 0.104^{+0.0073}_{-0.0128}. \]

- This value is consistent with estimates of structure formation and gravitational lensing.

- It is also about what we would expect from the thermal freeze-out of a stable WIMP:

\[ \Omega h^2 \sim \left( \frac{T_0}{M_{Pl}} \right)^3 \frac{1}{3H_0^2} \left( \frac{m}{T_{fo}} \right) \frac{1}{\langle \sigma v \rangle_{fo}}. \]
Other Possible Dark Matter Signals

- Dark matter around us can be detected directly by its scattering off nuclei.

- Dark matter in the galaxy can annihilate producing particle fluxes.

- Dark matter captured in the sun can annihilate and generate a neutrino signal.

- If the DM particle is related to a sector that stabilizes the electroweak scale, we may discover it at the LHC.
DM in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo:

\[ \mathbf{v}_{us} \simeq (220 \text{ km/s}) + (30 \text{ km/s}) (0.51) \cos(2\pi t/\text{yr}). \]

- \( \mathbf{v}_{DM} = \) Maxwell distribution with \( \langle \mathbf{v} \rangle \simeq 250 \text{ km/s}. \)
Direct DM Detection

- We encounter a DM “wind” from our motion with the galactic disk.
- This DM flux can scatter off nuclei.
  \[\rightarrow\text{look for nuclear recoils }\sim 100\text{ keV}\]
Experimental Limits (Low Background)

- WIMP mass [GeV/c²]
- Spin-independent cross section [cm²]

- Baltz Gondolo 2004
- Roszkowski et al. 2007 95% CL
- Roszkowski et al. 2007 68% CL
- CDMS II 1T+2T Ge Reanalysis
- XENON10 2007
- CDMS II 2008 Ge
- CDMS II Ge combined

[CDMS '08]
Annual Modulation - DAMA

- The DM flux changes due to the annual motion of the Earth relative to the galactic rotation.

[Drukier,Freese,Spergel '86]

- DAMA looked for scattering off $NaI$ with little background rejection to find an annual modulation signal ($\gtrsim 8 \sigma$).

### 2-6 keV

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DAMA/NaI (0.29 ton×yr) (target mass = 87.3 kg)

DAMA/LIBRA (0.53 ton×yr) (target mass = 232.8 kg)
DAMA vs. Other Searches

- DAMA seems to be inconsistent with CDMS, . . . .
  
  [Chang, Pierce, Weiner ’08]

- Non-standard (inelastic) DM can still fit.
  
  [Tucker-Smith+Weiner ’08]
Indirect Detection

- Dark matter annihilation in our galaxy can give rise to particle fluxes, especially from the galactic center.

Possible Hints:

- PAMELA, ATIC, PPB-BETS see an excess $e^+$ and $e^-$.  
- WMAP Haze: too much synchrotron radiation from the galactic center. [Finkbeiner '04]
- INTEGRAL 511 keV line from around the galactic center.

Signals from DM annihilating into leptons?
Excess Cosmic Ray Positrons and Electrons

- PAMELA observes a cosmic ray positron excess.

- ATIC, PPB-BETS also see an excess \((e^+ + e^-)\) flux.
• Energies are consistent with DM of mass $\gtrsim 500$ GeV.

• Plots from [Cirelli, Kadastik, Raidal, Strumia '08]:

(Preliminary Data!!!)
• Injected electrons will circulate in the galactic magnetic field and emit synchrotron radiation.
  → WMAP haze [Finkbeiner '04]

• Soft $e^+$ injected near the galactic center will annihilate.
  → INTEGRAL 511 keV line [Hooper et al. '04]

• GLAST/Fermi should test these hints by looking for hard photons from inverse Compton scattering off the CMB.
DM at the LHC

- DM from new physics stabilizing the electroweak scale?
- It may be possible to deduce the DM mass and couplings from data.

[Baltz et al. '06]
Reconstructing the Relic Density

• If these various probes allow us to deduce the DM mass and couplings we can reconstruct $(\Omega h^2)_{obs}$.
  → DM relic density assuming a standard thermal history.

• If $(\Omega h^2)_{obs} \neq \Omega_{DM} h^2$ we learn about cosmology.

• $(\Omega h^2)_{obs} > \Omega_{DM} h^2$
  → dilution by entropy production

• $(\Omega h^2)_{obs} < \Omega_{DM} h^2$
  → non-thermal production, another source of DM, . . .

• Another possibility for either direction is Changing DM.
Changing Dark Matter
Changing DM

- All these probes measure DM today.

- What if the DM properties changed since the time its density was formed?

- Idea: a late phase transition that modifies the DM.

- Does this have any generic features?

  Is it even possible?
WIMP Thermal Freeze-Out

- \( n_{DM} \propto e^{-m/T} \) for \( T < m \) in equilibrium.

- \( \Gamma_{\text{ann}} = \langle \sigma v \rangle_{\text{ann}} n_{DM} \) falls below \( H^{-1} \) at \( T = T_{fo} \).

\[ \Rightarrow n_{DM}/s \text{ remains constant for } T < T_{fo} \]
DM-Changing Phase Transition after Freeze-Out?

- Suppose $P$ develops a VEV at $T_{PT} < T_{fo}$,
  
  $v_P = \langle P \rangle$ changes the properties of the DM.

- $T_{fo} \lesssim m_{DM}/20$ for WIMP DM.

  We typically want $v_P \sim m_{DM}$ for a large effect.

  $\Rightarrow T_{PT} < T_{fo} \ll v_P \sim m_{DM}$

- Electroweak PT: $v \sim T_{PT}$ with $T_{PT}$ too large.

- QCD PT: $\Lambda_{QCD} \sim T_{PT}$ with $\Lambda_{QCD}$ too small.
A New Phase Transition Sector (Toy Model)

- New singlet field $P$ with potential

\[ V_P = -\frac{1}{2} m_P^2 P^2 + \frac{\lambda_P P^4}{4!} \]

\[ \Rightarrow v_P = \sqrt{6m_P^2/\lambda_P} \]

- $N_Q$ sets of massless fermions with $-\mathcal{L} \supset \lambda_{PQ} P \bar{Q}Q$.

- At finite temperature ($P \sim 0$),

\[ V_P \simeq -\frac{1}{2} \left( m_P^2 P^2 - \frac{N_Q}{6} \lambda_{PQ} T^2 \right) + \frac{\lambda_P P^4}{4!} \]

- The $Q$'s trap $P$ at the origin independently of $\lambda_P$. 
• At $T = 0$

$$v_p = \sqrt{\frac{6m_P^2}{\lambda_P}}.$$ 

• The phase transition occurs at

$$T_{PT} = \sqrt{\frac{6m_P^2}{NQ\lambda_{PQ}^2}}.$$ 

• A hierarchy $v_P \gg T_{PT}$ arises for $N_Q\lambda_{PQ}^2 \gg \lambda_P$.

• Note that $Q$ loops induce

$$\Delta \lambda_P \sim N_Q \frac{\lambda_{PQ}^4}{16\pi^2}.$$
$T > v_p$

$T \sim m_p$

$T << m_p$
The Final DM Relic Density

• If this PT changes the DM mass and couplings after freeze-out, the resulting relic density is

\[ \Omega_{DM} h^2 = D \left( \frac{m_{vP \neq 0}^{vP \neq 0}}{m_{vP = 0}^{vP = 0}} \right) \Omega_{DM}^{vP = 0} h^2. \]

\( \Omega_{DM} h^2 \) is the actual value of the relic density.

\( \Omega_{DM}^{vP = 0} h^2 \) is the value obtained without a PT.

\( D \leq 1 \) is a dilution factor from thermal inflation.

\[ D = \frac{g_{*}^{PT} T_{PT}^3}{g_{*}^{RH} T_{RH}^3}. \]

(We focus on cases where \( D \sim 1 \).)
Temperature Timeline

\[ T \]

\[ fo \quad PT \quad RH \quad t \]
A Sample Dark Matter Sector

- Higgsino-Singlino system with a \( \mathbb{Z}_2 \) symmetry:
  
  \( SU(2)_L \) chiral doublets: \( \Psi_L, \Psi_{\bar{L}} \)
  
  Singlet chiral fermion: \( \Psi_s \)
  
  \( -\mathcal{L} \subset \lambda_s P \Psi_s \Psi_s \)

- Neutral Mass Matrix:
  
  \[
  \mathcal{M} = \begin{pmatrix}
  0 & \mu & -\lambda_1 v_H/\sqrt{2} \\
  \mu & 0 & \lambda_2 v_H/\sqrt{2} \\
  -\lambda_1 v_H/\sqrt{2} & \lambda_2 v_H/\sqrt{2} & 2(\mu_s + \lambda_s v_P)
  \end{pmatrix}
  \]

- Choose parameters such that the lightest state is:
  
  \( v_P = 0 \Rightarrow \text{mostly doublet} \)
  
  \( v_P \neq 0 \Rightarrow \text{mostly singlet} \)
**Actual and Apparent Relic Densities**

- “Higgsino” DM annihilates into $W^+W^-$ with

  \[ \Omega_{DM}^{\nu_P=0} h^2 \approx (0.1) \left( \frac{m_{DM}^{\nu_P=0}}{\text{TeV}} \right)^2 . \]

- Actual relic density after the phase transition:

  \[ \Omega_{DM} h^2 \approx (0.1) \left( \frac{m_{DM}^{\nu_P=0}}{\text{TeV}} \right)^2 D \left( \frac{m_{DM}^{\nu_P \neq 0}}{m_{DM}^{\nu_P=0}} \right) . \]
• The DM particle at $T = 0$ is mostly singlet.

• If the DM properties at $T = 0$ were measured, the apparent annihilation mode would be through an $s$-channel $P$ to $Q\bar{Q}$:

$$ (\Omega h^2)_{obs} \sim \frac{0.05}{N_Q(\lambda_{PQ}\lambda_s)^2} \left( \frac{m_{vP\neq0}}{\text{TeV}} \right)^2. $$

• It is easy to obtain $(\Omega h^2)_{obs} \gg \Omega_{DM} h^2$.

• $s$-channel $P$ exchange also dominates the rate of annihilation in the galaxy today.
• Getting $(\Omega h^2)_{\text{obs}} \ll \Omega_{DM} h^2$ is more difficult.

• Need $\langle \sigma v \rangle_{vP \neq 0} \gg \langle \sigma v \rangle_{vP=0}$.
  
  $\rightarrow$ modified $v_P \neq 0$ DM tends to recouple after the PT

• Non-recoupling $\Rightarrow n_{DM}^{PT} \langle \sigma v \rangle_{vP \neq 0} \leq 1.66 (g_*^{RH})^{1/2} \frac{T_{RH}^2}{M_{Pl}}$.

• Model-independent bound:

\[
\frac{(\Omega h^2)_{\text{obs}}}{\Omega_{DM} h^2} \gtrsim \sqrt{\frac{g_*^{RH}}{g_*^{vP=0}}} \frac{T_{RH}}{T_{f^0_{vP \neq 0}}}.
\]
Related Phenomenology

- A late phase transition generically requires a light scalar:

\[ T_{PT} < T_{fo} \lesssim 50 \text{ GeV} \left( \frac{m_{DM}}{\text{TeV}} \right) \]

\[ T_{PT} = \sqrt{\frac{m_p^2}{N_Q \lambda_{PQ}^2}} \]

\[ m_P \sim \text{mass of the scalar excitation } \phi_P = P - v_P. \]

- “Higgs Portal” mixing:

\[ -\mathcal{L} \supset \frac{\lambda_{PH}}{2} P^2 |H|^2 \]

- Mixing Angle \( \theta \):

\[ \tan 2\theta = \frac{\lambda_{PH} v_P v_H}{\lambda_{P}^2 v_P^2 - \lambda_{H}^2 v_H^2} \]
Bounds on $\phi_P$

- Heavier masses: $m_P \gtrsim 9.5$ GeV
  $\Rightarrow \theta < 0.14$ from $Z^0 h^0$ searches at LEP

- Intermediate masses: $5.5$ GeV $\lesssim m_P \lesssim 9.5$ GeV
  $\Rightarrow \theta \lesssim 0.3$ from $\gamma \rightarrow \phi_P \gamma$ with $\phi_P \rightarrow \tau \bar{\tau}$

- Lighter masses: $m_P \lesssim 5.5$ GeV
  $\Rightarrow \theta \lesssim 10^{-4}$ from $B^0$ decays ($b \rightarrow s \phi_P$)

- $h^0 Z^0 \rightarrow \phi_P \phi_P Z^0 \rightarrow 4b Z^0$ at the LHC?

[Carena, Han, Huang, Wagner '07]
Other Possibilities

- Our phase transition sector appears to be fairly generic. Use the EW PT by modifying the Higgs sector?

- Other possibilities for the DM sector:

  - Move $m_{DM}$ on or off of an $s$-channel resonance.

  - Change the mass of another particle that coannihilates with the DM.

  - ...

Summary and Hints

- Lots of gravitational evidence for DM. New data may be non-gravitational hints for DM: DAMA, PAMELA, INTEGRAL, WMAP haze.

- Current and upcoming experiments stand a good chance of measuring the properties of the DM.

- DM properties can change after freeze-out.

- DM for PAMELA: $\langle \sigma_{\text{ann}} v \rangle \sim 10^{-24} \text{cm}^3/\text{s}$
  with $v \sim 10^{-3}$.

- DM for thermal freeze-out: $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$
  with $v \sim 0.05$. 