Leak-in Dark Matter

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JAE, Gaidau, Shelton – in progress
Dark matter exists... but where did it come from?

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Leak-in Dark Matter
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Thermal Freezeout in the Early Universe

- After reheating, universe expands and cools adiabatically,

Expansion rate: \( H \propto \frac{T^2}{M_{pl}} \)
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- Rapid collisions keep SM in equilibrium

- Thermodynamics dictates properties,
  
  \[ n_{\text{relativistic}} \propto T^3, \quad n_{\text{massive}} \propto (mT)^{3/2} e^{-\frac{m}{T}} \]
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For Dark Matter, \( \chi \) (any state with approximate \( Z_2 \)):

- Falling \( n_\chi \Rightarrow \Gamma_{\Delta \#} = n_\chi \langle \sigma v \rangle_{\chi \bar{\chi} \rightarrow \text{SM}} \lesssim H \)

- Number changing ceases, and \( \chi \) departs chemical equilibrium
WIMP Miracle

*Dark matter freezeout* gives observed relic dark matter abundance for

\[
\langle \sigma v \rangle_{\chi \bar{\chi} \rightarrow SM} \approx 1 \text{ pb} \cdot \text{c}
\]

**Comoving Number Density**

\[
<\sigma v> \sim 1 \text{ pb c} \\
<\sigma v> \sim 0.1 \text{ pb c} \\
<\sigma v> \sim 10 \text{ pb c}
\]

Too much DM

Not enough DM

**Equilibrium Density**

\[
x = \frac{m_{DM}}{T}
\]
WIMP Miracle

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WIMP miracle:

$$\langle \sigma v \rangle_{\chi \bar{\chi} \rightarrow SM} \approx \frac{\alpha_{\text{weak}}^2}{\Lambda_{\text{weak}}^2} \approx 1 \text{ pb} \cdot \text{c}$$

TeV scale mass and SU(2)$_L$ interaction can provide our dark matter!
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TeV scale mass and SU(2)_L interaction can provide our dark matter!

Natural models like SUSY have perfect candidates (neutralino)!
No evidence of SUSY (or top partners or anything else)

SUSY WIMP parameter space remains, but outlook not great
WIMP Schmiracle

<table>
<thead>
<tr>
<th>Dark Matter</th>
<th>$Z$, Higgs Coupling</th>
<th>Direct</th>
<th>Status</th>
<th>XENON1T</th>
<th>Indirect ($10^{-26}$ cm$^3$/s)</th>
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<tbody>
<tr>
<td>Majorana Fermion</td>
<td>$\tilde{\chi}^\mu \gamma_5 \tilde{\chi} Z_\mu$</td>
<td>$\sigma_{SD} \sim 1$</td>
<td>$m_X \sim m_Z/2$ or $m_X \gtrsim 190$ GeV</td>
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<td></td>
<td></td>
<td></td>
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<td>Up to 440 GeV</td>
<td>$\sigma v \sim 2.1 - 2.3$</td>
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<td>$\tilde{\chi}^\mu \chi Z_\mu$</td>
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Renormalizable minimal models are heavily constrained
Some territory remains, but not much for long
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Perhaps the WIMP miracle is a red herring?
WIMPless Freezeout

Minimal idea – keep thermal freezeout, lose the weak scale

The WIMP next door: one step more complex than standard WIMP

Hidden sector freezeout $\chi \bar{\chi} \rightarrow VV/\phi\phi$
WIMPless Freezeout

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$m_\chi > m_V, m_\phi$

g_D, y_D sets relic abundance

$\epsilon$ thermalizes with SM & dumps entropy back to SM

Pospelov, Ritz, Voloshin – 07; Feng, Kumar – 08; Feng, Tu, Yu – 08; ...; JAE, Gori, Shelton – 17
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Thermalizing a Hidden Sector

Minimal Hidden Sector Vector Model ($\epsilon \ll 1$):

$$\mathcal{L}_{Z_D} = g_D Z_{D,\mu} \bar{\chi} \gamma^\mu \chi + \frac{1}{2} m_{Z_D}^2 Z_D^\mu Z_{D\mu} + m_\chi \bar{\chi} \chi + \frac{\epsilon}{2 \cos \theta} Z_{D\mu \nu} B^{\mu \nu}$$

Free parameters: $m_\chi$, $m_{Z_D}$, $\epsilon$, $g_D \leftarrow$ fixed by relic abundance
Thermalizing a Hidden Sector

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Free parameters: $m_{\chi}$, $m_{Z_D}$, $\epsilon$, $g_D \leftarrow$ fixed by relic abundance

In Thermal Equilibrium During Freeze-Out

Never in Thermal Equilibrium

$\Gamma(T) = H(T)$

Equilibration floor
Thermalizing a Hidden Sector

Consider two objects with temperatures $T$ and $\tilde{T}$

$T$

$\tilde{T}_0 \ll T$
Thermalizing a Hidden Sector

Consider two objects with temperatures $T$ and $\tilde{T}$.

- $T$
- Heat capacity: $C_T$
- Thermal conductance: $k$
- $\tilde{T}_0 \ll T$
- $\tilde{C}_T$

How long until $\tilde{T} \approx T$?
Thermalizing a Hidden Sector

Consider two objects with temperatures $T$ and $\tilde{T}$.

Thermal conductance: $k$

How long until $\tilde{T} \approx T$?
Thermalizing a Hidden Sector

Consider two objects with temperatures $T$ and $\tilde{T}$

$T$ is cooling

Thermal conductance: $k$

Heat capacity: $C_T$

$\tilde{T}_0 \ll T$

$\tilde{C}_T$

Will $\tilde{T} \approx T$ before some $T_c$?
Thermalizing a Hidden Sector

Consider two objects with temperatures $T$ and $\tilde{T}$

heat capacity: $C_T$

Thermal conductance: $k$

$\tilde{T}_0 \ll T$

$\tilde{C}_T$

Will $\tilde{T} \approx T$ before some $T_c$?

What $k$ is needed for $\tilde{T}$ to reach $T_c$?

$T$ is cooling
Thermalizing a Hidden Sector

Consider two sectors with temperatures $T$ and $\tilde{T}$

![Diagram]

- **Portal coupling:** $\epsilon$
- **Heat capacity:** $g_{*,sm}$
- **Thermal conductance:** $k$
- **Heat capacity:** $g_{*,hs}$

Will $\tilde{T} \approx T$ before some $T_f$?

What $\epsilon$ is needed for $\tilde{T} \approx T = T_f$?

$T$ is cooling due to Hubble
Thermalizing a Hidden Sector

\[ \Gamma(T) < H(T) \]

\[ (\Gamma \propto T, \ H \propto T^2) \]

What happens below the floor?

\[ \epsilon \]
Thermalizing a Hidden Sector

\[ \Gamma(T) < H(T) \]

\( (\Gamma \propto T, H \propto T^2) \)

What happens below the floor?

Leak-in Dark Matter
Life Below the Equilibration Floor

Consider two sectors with temperatures $T$ and $\tilde{T}$.

Some energy “leaks in” from SM

Portal coupling: $\epsilon < \epsilon_{eq}$

$T$ is cooling due to Hubble

$\tilde{T} \ll T$

$\tilde{T} \neq T$

Does a dark matter hidden sector freezeout solution exist at all?
A Toy Leak-in Model

$\tilde{T} \ll T$

$\dot{\rho} + 4H\tilde{\rho} = -C_E[\rho, \tilde{\rho}]$

$\dot{\rho} + 4H\rho = C_E[\rho, \tilde{\rho}]$

$H \approx c_3' \frac{\sqrt{\rho}}{M_{pl}} = c_3 \frac{T^2}{M_{pl}}$

$\rho = c_1 g_* T^4 = \text{SM energy density}$

$\tilde{\rho} = c_1 \tilde{g}_* \tilde{T}^4 = \text{HS energy density}$

$C_E \equiv c_2 \epsilon^2 T^5 = \text{energy transfer rate}$

$\frac{d}{dt} \approx -TH \frac{d}{d\tilde{T}}$ (from $S$ conservation)
A Toy Leak-in Model
($\tilde{T} \ll T$)

\[ \dot{\rho} + 4H\tilde{\rho} = -C_E[\rho, \tilde{\rho}] \]

\[ \dot{\rho} + 4H\rho = C_E[\rho, \tilde{\rho}] \]

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\[ C_E \equiv c_2 \epsilon^2 T^5 = \text{energy transfer rate} \]

\[ \frac{d}{dt} \approx -TH \frac{d}{dT} \text{ (from S conservation)} \]

\[ \frac{d\tilde{T}^4}{dt} \approx -\epsilon^2 T^5 \Rightarrow \frac{d\tilde{T}}{dT} \tilde{T}^{-3} \approx \epsilon^2 M_{pl} T^2 \]
A Toy Leak-in Model

\( \tilde{T} \ll T \)

\[
\begin{align*}
\dot{\tilde{\rho}} + 4H\tilde{\rho} &= -C_E[\rho, \tilde{\rho}] \\
\dot{\rho} + 4H\rho &= C_E[\rho, \tilde{\rho}] \\
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\tilde{\rho} &= c_1 \tilde{g}_* \tilde{T}^4 = \text{HS energy density} \\
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\end{align*}
\]

\[
\frac{d\tilde{T}^4}{dt} \approx -\epsilon^2 T^5 \Rightarrow \frac{d\tilde{T}}{dT} \tilde{T}^3 \approx \epsilon^2 M_{pl} T^2
\]

\[
\tilde{T} \propto M_{pl}^{1/4} \epsilon^{1/2} T^{3/4}
\]

This temperature evolution is generic to the leak-in mechanism
A Toy Leak-in Model

$(\tilde{T} \ll T)$

\[ \tilde{T} \propto M_{pl}^{1/4} \epsilon^{1/2} T^{3/4} \]

A few major consequences:
A Toy Leak-in Model

\( \tilde{T} \ll T \)

\[ \tilde{T} \propto M_{pl}^{1/4} \epsilon^{1/2} T^{3/4} \]

A few major consequences:

- \( \tilde{\rho} \propto \tilde{T}^4 \propto T^3 M_{pl} \leftarrow \text{energy density redshifts like matter!} \)
A Toy Leak-in Model

(A Toy Leak-in Model)

\( \tilde{T} \ll T \)

\[ \tilde{T} \propto M_{pl}^{1/4} \epsilon^{1/2} T^{3/4} \]

A few major consequences:

- \( \tilde{\rho} \propto \tilde{T}^4 \propto T^3 M_{pl} \Leftarrow \) energy density redshifts like matter!

- \( \tilde{T} = \left( \frac{\epsilon}{\epsilon_{\text{crit}}} \right)^{1/2} T \)

\[ \epsilon = 0.01 \epsilon_{\text{crit}} \]
\[ \tilde{T} = 0.1 T \]
A Toy Leak-in Model

\( \tilde{T} \ll T \)

\[ \tilde{T} \propto M_{pl}^{1/4} \epsilon^{1/2} T^{3/4} \]

A few major consequences:

- \( \tilde{\rho} \propto \tilde{T}^4 \propto T^3 M_{pl} \) \( \Leftarrow \) energy density redshifts like matter!

- \( \tilde{T} = \left( \frac{\epsilon}{\epsilon_{\text{crit}}} \right)^{1/2} T \)

- \( \tilde{n} \approx \frac{m^2}{2\pi^2} \tilde{T} K_2 \left( \frac{m}{\tilde{T}} \right) \) \( \Rightarrow \)

\[ \tilde{n} \propto T^{9/8} e^{-m/T^{3/4}} \quad \text{non-relativistic} \]

\[ \tilde{n} \propto T^{9/4} \quad \text{relativistic} \]

\( \tilde{n}_\chi \) has strange scaling
Dark Matter Densities Below the Equilibration Floor

Comoving Number Density

$m = 1 \text{ TeV}; -\log_{10}[\epsilon] = 8 \ 9 \ 10 \ 11 \ 12 \ 13$

Equilibrated Sector

Relic Density

$x = m/T$

$m = 1 \text{ TeV}$

Leak-in Dark Matter

Evans (Cincinnati)
Dark Matter Densities Below the Equilibration Floor

\[ m = 1 \text{ TeV}; \log_{10}[\epsilon] = 8, 9, 10, 11, 12, 13 \]

\[ x = m/T \]

Comoving Number Density

\[ \tilde{T} \sim m_{DM}/(2 - 3) \]
Dark Matter Densities Below the Equilibration Floor

\[ m = 1 \text{ TeV}; \quad -\log_{10}[\epsilon] = 8 \ 9 \ 10 \ 11 \ 12 \ 13 \]

Equilibrated Sector

\[x = \frac{m}{T}\]

Comoving Number Density

Relic Density →

Never reach a density for right relic abundance!

\[ T \sim \frac{m_{\text{DM}}}{(2^{-3})} \]

\[ T \sim 3 \text{ TeV} \]

\[ T \sim 50 \text{ TeV} \]

\[ T \sim 2 \text{ PeV} \]
Dark Matter Densities Below the Equilibration Floor

$m = 1$ TeV; $-\log_{10}[\epsilon] = 8 9 10 11 12 13$

smaller $\epsilon \Rightarrow$ smaller $\langle \sigma v \rangle$

to depart from leak-in quasi-static solution earlier
Life Below the Equilibration Floor
Vector Portal Model

PRELIMINARY

Equilibrated

Non-perturbative

No solution

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Leak-in Dark Matter
Oct 6, 2018 14 / 15
Life Below the Equilibration Floor
Vector Portal Model

PRELIMINARY

Equilibrated

Non-perturbative

$\log_{10} \sigma v (\text{pb} \cdot \text{c})$

$\log_{10} m_{\chi} / \text{GeV}$

No solution
Life Below the Equilibration Floor
Vector Portal Model

PRELIMINARY

Equilibrated

Non-perturbative

Log_{10} \sigma_v (pb \cdot c)

Log_{10} m_\chi/GeV

Log_{10} \epsilon

No solution

subMeV DM

> PeV DM

Evans (Cincinnati)

Leak-in Dark Matter

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14 / 15
Summary

- **Disclaimer:** This talk is only a brief introduction to this rich subject.
- The leak-in mechanism is simply how a cold sector gets populated.
- Leak-in DM is freezeout during this non-adiabatic phase.
- Leak-in DM is a simple, plausible origin for dark matter.
- The vector portal model is very minimal and predictive.
- Leak-in DM parameter space is bounded.
- Direct / indirect detection probes parts of parameter space now!
- Also, interesting cosmological and astrophysical consequences.
- A lot of opportunities for future experiments to access this sector.