The four basic ways of creating dark matter through a portal

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Work in collaboration with Xiaoyong Chu and Michel Tytgat
Gravitational evidences of dark matter

- At galactic scale: velocity distribution of stars
- At galaxy cluster scale: velocity distribution of galaxies
  - bullet cluster
- At cosmological scales: CMB data (WMAP), supernovae,....

lead consistently to: $\Omega_{DM} \simeq 0.229 \pm 0.015\%$

DM is neutral, stable ($\tau_{DM} > 10^{26}$ sec), cold, $\Omega_{DM} \simeq 23\%$, has constrained cross section on Nucleon, produces constrained fluxes of cosmic rays, BBN, ....

but this still leaves an enormous freedom for the DM particle (mass, spin, interactions, stabilization mechanism, ...
The WIMP freeze-out mechanism

Relic density from annihilation freeze out:

down to $T \sim m_{DM}$ DM is thermal equilibrium for $T \lesssim m_{DM}$ Boltzmann suppression of $n_{DM}^{eq}$

freeze-out of annihilation

$\Omega_{DM} \propto 1/\langle \sigma_{\text{annih}} v \rangle$

if $m_{DM} \sim 1$ GeV $- 10$ TeV and $\lambda \sim 1$ $\Rightarrow$ $\Omega_{DM} \sim 23\%$

$\sigma_{\text{annih}} v \simeq 10^{-26}$ cm$^3$/sec

most straightforward/natural mechanism but not at all the only possible/simple one
A general visible sector/hidden sector/mediator DM setup

VISIBLE SECTOR

with its own
gauge groups

mediator

HIDDEN SECTOR

with its own
gauge groups

including DM stabilization mechanism

such a structure gives 4 regimes to get the observed relic density
A very simple light mediator model

VISIBLE SECTOR

with its own
gauge groups

mediator

HIDDEN SECTOR

with its own
gauge groups

including DM stabilization mechanism
A very simple light mediator model

VISIBLE SECTOR  mediator  HIDDEN SECTOR

Standard Model  with its own gauge groups

including DM stabilization mechanism
A very simple light mediator model

VISIBLE SECTOR \[\text{Standard Model}\] \[\text{mediator}\] HIDDEN SECTOR

\[\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not\!\!\!D' - m_\psi)\psi'\]

- a $U(1)'$ gauge symmetry and the lightest particle charged under it
- a fermion: $e'$
A very simple light mediator model

VISIBLE SECTOR

Standard Model

HIDDEN SECTOR

a $U(1)'$ gauge symmetry and the lightest particle charged under it

a fermion: $e'$

mediator

kinetic mixing

$$\mathcal{L} \ni - \frac{\varepsilon}{2} F_Y^{\mu\nu} F'^{\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(iD' - m_\psi)\psi'$$

Feldman, Kors, Nath 06'

Pospelov, Ritz, Voloshin 08'

for a massive $Z'$
A very simple light mediator model

Standard Model \rightarrow \text{mediator} \rightarrow \gamma'

\text{kinetic mixing}

\mathcal{L} \equiv -\frac{\varepsilon}{2} \mathcal{F}_Y^{\mu\nu} \mathcal{F}'_{\mu\nu}

\text{HIDDEN SECTOR}

\text{a } U(1)' \text{ gauge symmetry and the lightest particle charged under it}

\text{a fermion: } e'

\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\gamma'\not{D}' - m_{\psi})\psi'

\Rightarrow \text{a good DM candidate based on 3 parameters: } m_{DM}, \alpha', \epsilon

\Rightarrow m_{e'}

Feldman, Kors, Nath 06'
Pospelov, Ritz, Voloshin 08'
f for a massive Z'
Motivations for such a Hidden sector gauge structure

- UV......
- simplicity
- the stability of the DM particle is a fundamental issue! 
  \( \tau_{DM} > 10^{26} \text{ sec} \)
- not that many stabilization mechanisms
- one of the simplest: the lightest charged particle under a new gauge group
- visible sector = Standard Model \( \Rightarrow \) mass and interactions of source particles are known
- new DM long range force from \( \gamma' \) \( \Rightarrow \) rich cosmological phenomenology
  studied in details in: Ackerman, Buckley, Carroll, Kamionkowski 08’
  Feng Kaplinghat, Tu, Yu 09’
  Feng, Tu , Yu 08
  see also Foot at al. 06’-10’
- prototype of visible sector/hidden sector/mediator structure
- with such a structure: not only freeze-out and freeze-in but 4 DM production regimes
Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime

Freeze-in regime

Connector freeze-out regime

Observed relic density: "square” or “mesa” shape

in each regime $\Omega_{DM}$ depends essentially on one coupling characteristic of the visible sector/hidden sector/mediator structure

$\Omega_{DM} \sim 23\%$

$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha}$
Relevant processes

Connector processes:

\[\bar{f}, W^- \rightarrow \gamma, \gamma', e'\]

\[f, W^+ \rightarrow \bar{e}'\]

\[\mathcal{L} \equiv -\frac{\varepsilon}{2} F_{\mu\nu} F'_{\mu\nu}\]

Hidden sector process:

\[e' \rightarrow \gamma'\]

\[\gamma' \rightarrow e'\]

\[e' \rightarrow \gamma'\]

convenient to go in a $\gamma - \gamma'$ basis where kinetic terms are canonical (i.e. no $\gamma - \gamma'$ mixing)

basis where $\gamma'$ couples to $f$

$\gamma$ couples to $e'$ and $f$

\[\sigma(SMSTM \rightarrow e'\bar{e}') \propto \alpha^2 \kappa^2\]

\[\kappa \equiv \epsilon \sqrt{\alpha'}/\alpha\]

\[\kappa \equiv \epsilon \sqrt{\alpha'}/\alpha\]

\[\sigma(e'\bar{e}' \rightarrow \gamma'\gamma') \propto \alpha'^2\]
Boltzmann equation

in terms of the usual $\langle \sigma v \rangle$:

\[
\frac{z}{s} \frac{H}{s} \frac{dY}{dz} = \sum_i \langle \sigma_{\text{connect}} v \rangle_i \left( Y_{eq}^2(T) - Y^2 \right) + \langle \sigma_{HS} v \rangle \left( Y_{eq}^2(T') - Y^2 \right)
\]

\[
z = \frac{m_{DM}}{T}
\]

\[
Y = \frac{n_{e'}}{s} \quad (= Y_{DM}/2)
\]
Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime

Freeze-in regime

Connector freeze-out regime

we consider a HS negligible at high temperature

likely that DM production from inflaton decay negligible if reheating occurs mostly in one of the feebly coupled sectors

can be tested if the DM mass and coupling measured are the ones which give the right relic density

\[ \Omega_{DM} \sim 23\% \]

\[ \kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \]

\[ Y_{DM} \sim 0 \]

\[ \rho' \sim 0 \]

HS energy density
\( \kappa \) and \( \alpha' \) are small \( \implies \) freeze-in regime

\( \text{if } \kappa \text{ and } \alpha' \text{ small: } SMSM \leftrightarrow DMDM \text{ does not thermalize} \)

\( DMDM \leftrightarrow \gamma'\gamma' \text{ does not thermalize} \)

\[
\frac{H}{s} \frac{dY}{dz} = \sum_i \langle \sigma_{\text{connect}} v \rangle_i (Y_{eq}^2(T) - Y_{eq}'^2) + \langle \sigma_{H S} v \rangle (Y_{eq}^2(T') - Y_{eq}'^2)
\]

\( SM_i SM_i \rightarrow DMDM \)

\( \gamma'\gamma' \rightarrow DMDM \)

\( DMDM \rightarrow SM_i SM_i \)

\( DMDM \rightarrow \gamma'\gamma' \)

only \( SMSM \rightarrow DMDM \) is relevant because only \( Y_{eq}^{SM} \) is large

freeze-in regime:

\[
Y_{DM} \equiv \frac{n_{DM}}{s} \propto \frac{1}{T} \quad \text{down to } \quad T \sim m_{DM} \quad \text{where } \quad n_{A}^{eq}
\]

becomes Boltz. suppressed

\( DM \text{ production IR dominated} \)

\( m_{DM} \)

\( \Omega_{DM} \)

\( \kappa \sim 10^{-10} \quad \kappa \sim 1 \)

thermalization point

\( 0.23 \)
Relic density phase diagram

- Reannihilation regime
- Freeze-in regime
- Hidden sector freeze-out regime
- Connector freeze-out regime

Phase diagram $\log_{10}[\Omega_{DM}]$ ($m_{DM}=0.1\text{GeV}$)

$\Omega_{DM} \sim 23\%$
Reannihilation regime

if one increases $\kappa \Rightarrow$ more DM created
if one increases $\alpha' \Rightarrow \langle \sigma_{HSv} \rangle$ increases

both favor thermalization of $\langle \sigma_{HSv} \rangle$

\[ \Gamma_{annih} > H \quad \Gamma_{annih} = n_{e'} \langle \sigma_{HSv} \rangle \]

\[ n_{eq}(T) \langle \sigma_{effv} \rangle > H \]

\[ \langle \sigma_{effv} \rangle \equiv \sqrt{\langle \sigma_{HSv} \rangle \langle \sigma_{connectv} \rangle} \]

we can define a HS temperature $T'$

\[ n_{\gamma'} = n_{eq}(T') \sim g_{\gamma'} T'^3 \]

\[ \rho' \sim g_{*}^{HS} T'^4 \]

necessary to know the number of $\gamma'$, i.e. the $\gamma'\gamma' \rightarrow DMDM$ rate

\[ z \frac{H}{s} \frac{dY}{dz} = \sum_{i} \langle \sigma_{connectv} \rangle_i (Y_{eq}^2(T) - Y^2) + \langle \sigma_{HSv} \rangle (Y_{eq}^2(T') - Y^2) \]

we need to calculate the HS energy density $\rho'$ in order to determine $T'$
Calculation of the energy transfer from the SM to the HS

energy transfer Boltzmann equation

\[ \frac{d\rho'}{dt} + 3H(\rho' + \rho) = \int \prod_{i=1}^4 d^3 \vec{p}_i \cdot g_i f_1(\vec{p}_1) f_2(\vec{p}_2) |i_{M_12 \leftrightarrow 34}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \Delta E_{tr} \]

\[ \frac{d(\rho'/\rho)}{dT} = -\frac{1}{H(T)T\rho} \frac{g_1 g_2}{32\pi^4} \int ds \cdot \sigma_{\text{connect}}(s)(s - 4m^2)sTK_2\left(\frac{\sqrt{s}}{T}\right) \]

\[ SM_i SM_i \rightarrow DM DM \]

\[ m_{DM} = m_e \]
\[ m_{DM} = 0.1 \text{ GeV} \]
\[ m_{DM} = 10 \text{ GeV} \]
\[ m_{DM} = 1 \text{ TeV} \]

\[ \rho'/\rho \text{ saturates when } T' \text{ reaches } T \]
\[ \rho'/\rho \sim 1/T \text{ for } T > m_{DM} \]
\[ \rho'/\rho \sim \text{const for } T < m_{DM} \]
Reannihilation regime: Boltzmann equation

\[ z \frac{H}{s} \frac{dY}{dz} = \sum_i \langle \sigma_{\text{connect}} v \rangle_i (Y_{eq}^2(T') - X^2) + \langle \sigma_{HS} v \rangle (Y_{eq}^2(T') - Y^2) \]

\[ \text{SM}_i \text{SM}_i \rightarrow \text{DMDM} \]
\[ \text{DMDM} \rightarrow \text{SM}_i \text{SM}_i \]
\[ \gamma' \gamma' \rightarrow \text{DMDM} \]
\[ \text{DMDM} \rightarrow \gamma' \gamma' \]

after thermalization \( Y \) follows \( Y_{eq}(T') \)

at \( T' \lesssim m_{DM} \): \( Y_{eq}(T') \) becomes Boltzmann suppressed

\( \text{SMSM} \rightarrow \text{DMDM} \) rate (which decouples only at \( T \lesssim m_{DM} \))

gets larger than the \( \gamma' \gamma' \rightarrow \text{DMDM} \) rate (which
decouples already at \( T' \lesssim m_{DM} \)) \( \Rightarrow \) reannihilation

at \( T \lesssim m_{DM} \) the \( \text{SMSM} \rightarrow \text{DMDM} \) source term

gets Boltzmann suppressed \( \Rightarrow \) freezes

\[ \Gamma_{\text{annih}} = H \leftrightarrow Y = Y_{\text{crit}} \equiv H/\langle \sigma_{HS} v \rangle \]
Reannihilation regime: Boltzmann equation

When the $\gamma' \gamma' \rightarrow \text{DMDM} \propto Y_{eq}^2(T')$ rate goes below the $\text{SM SM} \rightarrow \text{DMDM} \propto Y_{eq}^2(T)$ rate:

- In thermal equilibrium
- Out of thermal equilibrium

\[
\frac{H}{s} \frac{dY}{dz} = \sum_i \langle \sigma_{\text{connect}} v \rangle_i (Y_{eq}^2(T) - Y^2) + \langle \sigma_{\text{HS}} v \rangle (Y_{eq}^2(T') - Y^2)
\]

- $\text{SM}_i \text{SM}_i \rightarrow \text{DMDM}$
- $\gamma' \gamma' \rightarrow \text{DMDM}$
- $\text{DMDM} \rightarrow \text{SM}_i \text{SM}_i$
- $\text{DMDM} \rightarrow \gamma' \gamma'$

\[
\frac{dY}{dz} = \frac{\langle \sigma_{\text{connect}} v \rangle_s}{H} Y_{eq}^2(T) - \frac{Y^2}{Y_{crit}}
\]

- Period of Quasi Static Equilibrium where both terms compensates each other

\[
Y = Y_{QSE} \equiv \sqrt{Y_{crit} \frac{\langle \sigma_{\text{connect}} v \rangle_s}{H} Y_{eq}^2(T)}
\]

- Until $Y = Y_{QSE} = Y_{crit}$ where $Y$ freeze at $T \equiv T_f$

- Simultaneous freezing of both connector source term and HS reannihilation term
Reannihilation regime: analytical result

in practice: if the HS thermalize but the connector does not
one has always a period of reannihilation

Freeze-out equation to determine $T_f$:

$$n_{eq}(T_f)\langle \sigma_{eff} v \rangle = H(T_f)$$

ordinary freeze-out equation but with another cross section: $\langle \sigma_{eff} v \rangle$

$$x_f = \log[0.038 \frac{g_{e'} m_{Pl} m_{DM} \langle \sigma_{eff} v \rangle c(c + 2)}{\sqrt{g^*_{eff}}}]$$

$$-\frac{1}{2} \log[\log[0.038 \frac{g_{e'} m_{Pl} m_{DM} \langle \sigma_{eff} v \rangle c(c + 2)}{\sqrt{g^*_{eff}}}]$$

$$Y(T_f) \equiv Y_{QSE}(T_f) = \frac{1}{\langle \sigma_{HS} v \rangle} \frac{3.79 x_f}{(g_{s}/\sqrt{g^*_{eff}})} m_{Pl} m_{DM}.$$
Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime

Freeze-in regime

\( \Omega_{DM} \sim 23\% \)

Connector freeze-out regime

\[ \text{phase diagram } \log_{10}[y_{DM}] \ (m_{DM}=0.1\text{GeV}) \]
Hidden sector freeze-out regime

starting from a reannihilation situation
if one increases $\kappa$ further $\Rightarrow$ the connector interaction thermalizes: $T' = T$

$SM \leftrightarrow DM$

one enters a regime where even if the connector thermalizes
the HS interaction thermalizes much more $\langle \sigma_{HS} v \rangle > \langle \sigma_{connect} v \rangle$

standard freeze-out (only one temperature) dominated by the HS interaction

$\Omega_{DM} \propto \frac{1}{\langle \sigma_{HS} v \rangle} \propto \frac{1}{\alpha'^2}$
Connector freeze-out regime

if one increases $\kappa$ further $\Rightarrow$ the connector not only thermalizes but dominates the freeze-out process $\langle \sigma_{\text{connect}} u \rangle > \langle \sigma_{HS} u \rangle$

$\Omega_{DM} \propto \frac{1}{\langle \sigma_{\text{connect}} u \rangle} \propto \frac{1}{\kappa^2}$

$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \Rightarrow$ if $\kappa$ big $\Rightarrow \epsilon$ non perturbative
Relic density phase diagram

\[ m_{DM} = m_e \]

\[ m_{DM} = 0.1 \text{GeV} \]

\[ m_{DM} = 10 \text{GeV} \]

\[ m_{DM} = 1 \text{TeV} \]
Generality of the “mesa” phase diagram: the Higgs portal example

VISIBLE SECTOR \[\rightsquigarrow\] Standard Model \[\rightsquigarrow\] couplced through the Higgs portal \[\uparrow\]

\[\mathcal{L} \ni - \lambda_m \phi \phi^\dagger HH^\dagger\]

HIDDEN SECTOR \[\leftarrow\]

a \[U(1)'\] gauge symmetry and the lightest particle charged under it

\[\uparrow\]

a scalar: \(\phi\)

\[\mathcal{L} \ni \mathcal{L}_{SM} + D'_{\mu} \phi^\dagger D'^\mu \phi - \mu_{\phi}^2 \phi \phi^\dagger - \lambda_{\phi}(\phi \phi^\dagger)^2\]
Generality of the “mesa” phase diagram: the Higgs portal example

$m_{DM} = m_e$

$m_{DM} = 0.1 \text{ GeV}$

$m_{DM} = 10 \text{ GeV}$

$m_{DM} = 1 \text{ TeV}$

same general structure despite of important differences: the mediator is massive

production through \( m_h \to \phi\phi^\dagger \) decay if \( m_{DM} < m_h/2 \)

visible/hidden sector communication cut-off at \( T \sim \text{Max}[m_h, m_{DM}] \)

\( m_h \approx 120 \text{ GeV} \)

if the HS thermalizes but not the connector: both reannihilation and HS freeze-out possible
Test of meso phase diagrams for kinetic mixing: direct detection

DM elastic cross section on Nucleon

\[ d\sigma \frac{dE_r}{E_r} = \frac{1}{E_r} \frac{1}{v^2} \frac{2\pi \kappa^2 Z^2 \alpha^2}{m_A} F_A^2(q r_A) \]

\[ E_r \sim \text{few KeV} \]

huge enhancement

direct detection sensitive to very small \( \kappa \) values
Test of mesa phase diagrams for kinetic mixing: direct detection

Xenon-100kg: excludes all regimes for $m_{DM} > \text{few GeV}$ except freeze-in and part of reannihilation

Xenon-1T: will test freeze-in for

- $50 \text{ GeV} < m_{DM} < 140 \text{ GeV} \quad \leftarrow 1 \text{T/year}$
- $40 \text{ GeV} < m_{DM} < 600 \text{ GeV} \quad \leftarrow 4 \text{T/year}$

characteristic $\sim \frac{1}{E_r^2}$ spectrum to be observed!!
Cosmological constraints

- BBN
- bullet cluster
- galactic dynamics
- ... DM Rutherford scattering may affect formation of DM halo
- ellipticity of galaxies: \[ \alpha' \lesssim 10^{-7} \left( \frac{m_{DM}}{\text{GeV}} \right)^{3/2} \]

Ackerman, Buckley, Carroll, Kamionkowski 08'
Feng Kaplinghat, Tu, Yu 09'
Feng, Tu, Yu 08
Ellipticity and relic density constraints combined

\[ \kappa \]

\[ \log_{10}[\alpha'] \quad \text{HDM} = 0.11 \]

Reannihilation allowed for:

\[ m_{DM} > \sim \text{few 100 GeV} \]

Freeze-in always allowed
Ellipticity constraint for the case of a slightly massive $\gamma'$

if we break the $U(1)'$ slightly with $m_{\gamma'} << m_{DM}$

- the relic density plot doesn't change
- the lightest charged fermion remains stable
- but the cosmological constraints change a lot

![Graph showing ellipticity bounds](image-url)
Depletion of DM in galactic disk

- the DM feels the galactic magnetic field via $\kappa$
- sufficient for a DM coming off the disk not to enter in the disk
- only freeze-in regime is allowed for $m_{DM} \lesssim 100 \text{ GeV}$ but the constraint vanishes as soon as the $\gamma'$ becomes slightly massive

![Diagram showing the allowed regions for dark matter properties under different conditions.]
Summary

- Visible/hidden sectors/mediator structure:
  the observed relic density can be produced through characteristic 4 regimes
  “mesa” phase diagram...
  natural “analytic prolongation” of the usual freeze-out regime towards small coupling values

- Kinetic mixing portal:
  - all 4 regimes can be tested from direct detection, even the freeze-in one
  - rich cosmological phenomenology (which strongly depends on the mass of the $\gamma'$)
Backup
Figure 10. Summary of astrophysical, cosmological and laboratory constraints for hidden photons (kinetic mixing $\chi$ vs. mass $m_{\gamma'}$). At higher mass we have electroweak precision measurements (EW), bounds from upsilon decays ($\Upsilon_{3S}$) and fixed target experiments (EXXX)). Areas that are especially interesting are marked in light orange. Compilation from Ref. [93].
Figure 5: DM relic abundance $Y_{DM}$ as a function of the connector parameter $\kappa$ for different DM masses $m_{DM}$ and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7$ (bottom-up).
Figure 18: Phase diagram for the kinetic mixing portal and $m_{DM} = 10$ GeV separating explicitly the reannihilation regimes dominated by the decay (IIA) and by the $\gamma$ mediated scattering (IIB).
Figure 6: Values of $\alpha'$ required to get the WMAP relic density as a function of $m_{DM}$ assuming no connector between the hidden sector and the SM sector, for different values of the temperature ratio $\xi \equiv T'/T = 0.01, 0.1, 1$ (bottom-up).
Figure 12: Evolution of the ratio of the visible and hidden sectors energy densities, for a range of connector parameter, $\lambda_m = 10^{-6}, -7, -8, -9, -10$ (from up to down), and for various DM masses.
$m_{DM} = m_e$

$m_{DM} = 10\text{GeV}$

$m_{DM} = 0.1\text{GeV}$

$m_{DM} = 10000\text{GeV}$

Figure 14: DM relic abundance $Y_{DM}$ as a function of the connector parameter $\lambda_m$ for different DM masses $m_{DM}$ and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7, -9$, bottom-up (the last two lines are the same for $m_{DM} = 10 \text{ GeV}$, as well as for $m_{DM} = 1 \text{ TeV}$).
Figure 14: Higgs portal parameter required to get the observed DM relic density through freeze-in (\(\alpha' = 0\)).
For large values of $\lambda$, the usual behavior is inversely proportional to $\sim 20$. A little bit later after that, the equation can be found in Refu [z]. Taking into account the fact that the first example corresponds to a case of hidden sector interaction freezeout without thermalization, the connector source term gets suppressed.

Region II ($m_{DM} = 10\text{GeV}, \lambda_m = 10^{-8}, \alpha' = 10^{-4}$)

Region II ($m_{DM} = 10\text{GeV}, \lambda_m = 10^{-11}, \alpha' = 10^{-4.7}$)
The freeze-in mechanism

DM couples only feebly to the SM particles production through out-of-equilibrium $AA \rightarrow DMDM$ or $A \rightarrow DMB$ processes

example: $A \rightarrow DMB$

at $T > m_A$

$$\frac{dn_{DM}}{dt} = n^e_A(T)\Gamma_{A\rightarrow DMB}(T)$$

$Y_{DM} \equiv \frac{n_{DM}}{s}$

$$dY_{DM} = \frac{n^e_A(T)\Gamma_{A\rightarrow DMB}(T)}{TH(T)s(T)} \propto \frac{1}{T^2}$$

$Y_{DM} \propto \frac{1}{T}$ down to $T \sim m_A$

DM production IR dominated

$z = \frac{m_A}{T}$

where $n^e_A$ becomes Boltzmann suppressed

Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09'
The freeze-in mechanism

\[ Y_{DM}(T << m_A) \approx \frac{n_{eq} \Gamma_{A \rightarrow DM B}}{s} \frac{1}{H} \bigg|_{T=m_A} \]

freeze-in is “thermal” in the sense that DM is produced by a particle in thermal equilibrium

\[ Y_{DM} \text{ produced depends only on mass and interactions of particles at freezing} \]

\[ \Omega_{DM} \sim 23\% \text{ requires tiny coupling } \sim 10^{-10} \]

\[ \Rightarrow \text{ for a } AA \rightarrow DM DM \text{ scattering production process:} \]

\[ \sigma(AA \rightarrow DM DM) \propto \lambda^2 \]

Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09’
Freeze-in issues

- what about a primordial DM density?
  - not washed-out by (out-of-equil.) DM production process
    - negligible if reheating occurs mostly in one of the feebly coupled sectors
  - can be tested if the DM mass and coupling measured are the ones which give the right relic density

- what about testing the freeze-in mechanism?
  - one possibility: \( A \rightarrow DMB \) decay very slow \( \Rightarrow \) displaced vertex at colliders
    - requires:
      - \( A \) and \( B \) couple sizably to the SM
      - sym. which stabilizes the DM particle also shared by visible sector
        - e.g. \( A \) and \( DM \) odd under a \( Z_2 \)
  - \( \lambda \sim 10^{-10} !! \)

Cheung, Elor, Hall, Kumar 10'

\( \Rightarrow \) rich phenomenology at LHC
\( \kappa \) and \( \alpha' \) are small \( \rightarrow \) freeze-in regime

we consider a HS negligible at high temperature

\( Y_{DM} \sim 0 \)
\( \rho' \sim 0 \)

HS energy density

if \( \kappa \) and \( \alpha' \) small: \( SM SM \leftrightarrow DM DM \) does not thermalize
\( DM DM \leftrightarrow \gamma' \gamma' \) does not thermalize

only \( SM SM \rightarrow DM DM \) is relevant because only \( Y_{SM}^{eq} \) is large

freeze-in: \( Y \sim \left( \frac{\sigma_{\text{connect}} v}{s H} \right) n_{SM}^2 \bigg|_{T=m_{DM}} \propto \kappa^2 \)

\( \kappa \sim 3 \cdot 10^{-11} \)

dominated by \( m_{SM_i} < m_{DM} \) channels
Test of mesa phase diagrams for kinetic mixing: direct detection

DAMA-CoGeNT: small threshold
Xenon: higher threshold

$\sim \frac{1}{E_T^2}$ gives much better agreement
Test of mesa phase diagrams for kinetic mixing: direct detection

DAMA-CoGeNT: small threshold
Xenon: higher threshold

\( \sim \frac{1}{E_T^2} \) gives much better agreement

but not compatible anymore