Heavy Scalar Dark Matter

in collaboration with T. Hambye, L. Lopez-Honorez, J. Rocher

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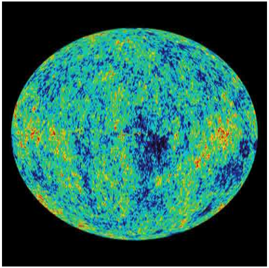
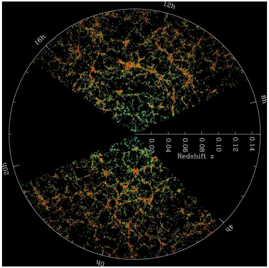
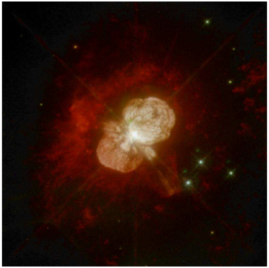
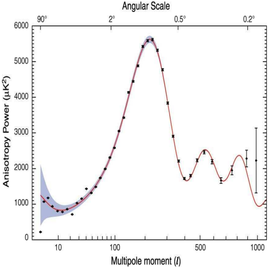
Outline

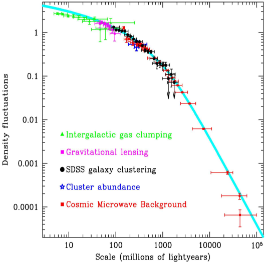
Observational cosmology

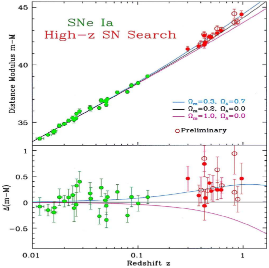




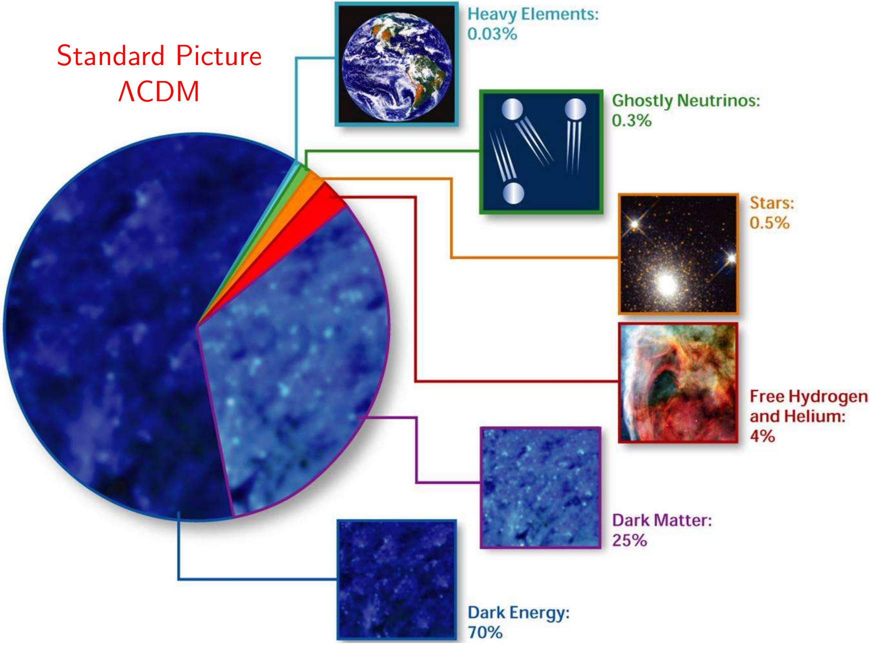




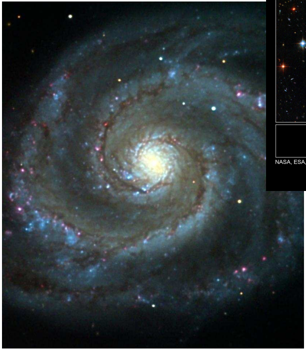


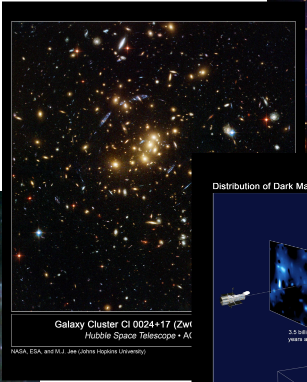


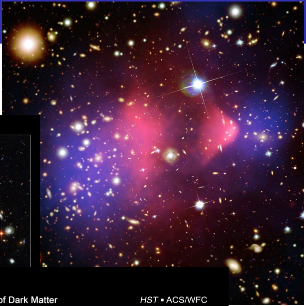
Standard Picture
ΛCDM

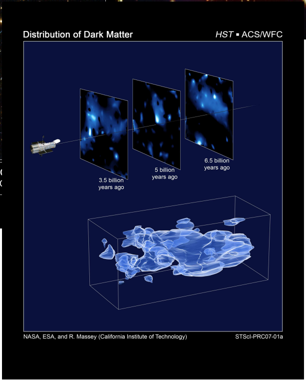


Evidence for Dark Matter



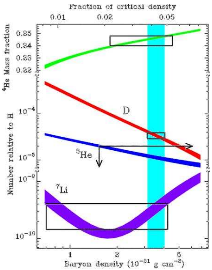


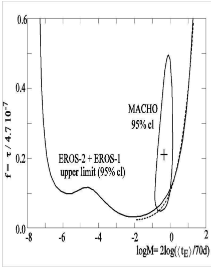


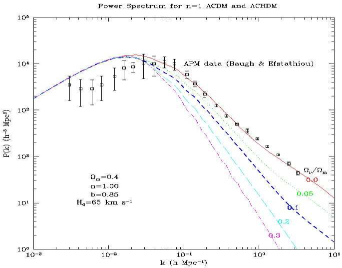


!!WANTED!! : Dark Matter

- Non-baryonic
  from BBN and MACHOs microlensing surveys
- Neutral
- Cold
  not neutrinos for structure formation
- Stable or very long-lived
  parity symmetry
- Weakly interacting
  new physics at TeV scale

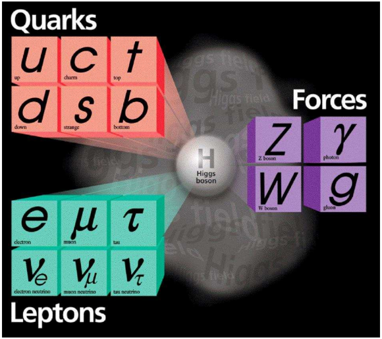






Minimalistic approach to the question of DM

Standard Model



$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Dark matter

- Renormalisable theory
- Perturbativity
- Vacuum stability
- Relic abundance
  $\Omega_{DM} h^2 = 0.1131 \pm\ 0.0034$
- EWPT constraints
- Avoid FCNC
- Direct Detection limits

Fermionic Minimal Dark Matter

M. Cirelli, N. Fornengo, A. Strumia (2006)

- Only gauge interactions
- Mass spectrum Degenerate at tree-level. At one-loop,

$$m_Q - m_0 \simeq Q(Q + \frac{Y}{2\cos\theta_W})166\ MeV$$

- Y=0 to avoid coupling with the Z
- Relic density determines DM mass
- Perturbativity $n \leq 8$. $n = 5$ automatically stable

Higgs portal : Singlet Scalar Dark Matter

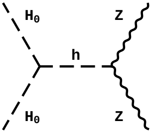
Potential

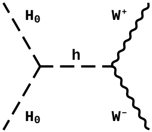
$$V = \mu_1^2|H_1|^2 + \frac{1}{2}\mu_2^2 H_0^2 + \lambda_1|H_1|^4 + \frac{\lambda_2}{8}H_0^4 + \frac{\lambda_3}{2}|H_1|^2 H_0^2$$

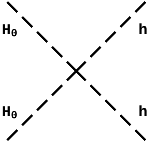
$$H_1 = \begin{pmatrix} h_W^+ \\ \frac{1}{\sqrt{2}}(v_0 + h + ih_Z) \end{pmatrix}$$

- Z_2 symmetry $\quad H_1 \to H_1,\ H_0 \to -H_0$
- Vacuum stability $\quad \lambda_1,\ \lambda_2 > 0,\ \lambda_3 > -\sqrt{2\lambda_1\lambda_2}$
- EWSB $\quad \mu_1^2 < 0$
- Mass $\quad m_0^2 = \mu_2^2 + \lambda_3 v_0^2/2$
- $H_0 - h$ quartic coupling $\quad \lambda_3$

- $H_0 H_0 \to ZZ$
- $H_0 H_0 \to W^+ W^-$
- $H_0 H_0 \to hh$



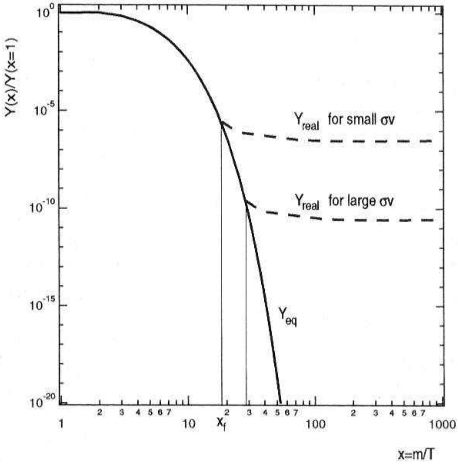




$$\sigma_Z v = \frac{\lambda_3^2}{64\pi m_0^2} \qquad \sigma_W v = \frac{\lambda_3^2}{32\pi m_0^2} \qquad \sigma_h v = \frac{\lambda_3^2}{64\pi m_0^2}$$

$$\sigma v = \frac{\lambda_3^2}{16\pi m_0^2} \qquad \text{WMAP} : \lambda_3 \simeq 0.33 \left(\frac{m_0}{1\ TeV}\right)$$

Thermal abundance of Dark Matter



$$\Omega h^2 \sim \frac{1}{\langle \sigma_A v \rangle}$$

Ω_{WMAP} :

$$\langle \sigma_A v \rangle \simeq 0.8 \text{ pb}$$

Scalar Dark Matter with $SU(2)_L$ interactions

Lagrangian

$$\mathcal{L} = (D_\mu H_n)^\dagger (D^\mu H_n) - V(H_n, H_1)$$

$$D_\mu \equiv \partial_\mu - ig\tau_a^{(n)} W_\mu^a - ig_Y \frac{Y}{2} B_\mu$$

Potential in the doublet case

$$\begin{aligned} V &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\ &\quad + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + h.c. \right] \end{aligned}$$

Potential for higher multiplets

$$\begin{aligned} V(H_n, H_1) &= V_1(H_1) + \mu^2 |H_n|^2 + \frac{\lambda_2}{2} |H_n|^4 + \lambda_3 |H_1|^2 |H_n|^2 \\ &\quad + \frac{\lambda_4}{2} (H_n^\dagger \tau_a^{(n)} H_n)^2 + \lambda_5 (H_1^\dagger \tau_a^{(2)} H_1)(H_n^\dagger \tau_a^{(n)} H_n) \end{aligned}$$

Scalar Dark Matter with $SU(2)_L$ interactions

Lagrangian

$$\mathcal{L} = (D_\mu H_n)^\dagger (D^\mu H_n) - V(H_n, H_1)$$

$$D_\mu \equiv \partial_\mu - i g \tau_a^{(n)} W_\mu^a - i g_Y \frac{Y}{2} B_\mu$$

Potential in the doublet case

$$\begin{aligned} V \quad = \quad & \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\ & + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + h.c. \right] \end{aligned}$$

Potential for a real multiplet

$$V(H_n, H_1) = V_1(H_1) + \mu^2 |H_n|^2 + \frac{\lambda_2}{2} |H_n|^4 + \lambda_3 |H_1|^2 |H_n|^2$$

Inert Doublet Model

Inert Doublet Model

$$H_1 = \begin{pmatrix} h_W^+ \\ \frac{1}{\sqrt{2}}(v_0 + h + ih_Z) \end{pmatrix} , \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix}$$

Mass spectrum at tree-level

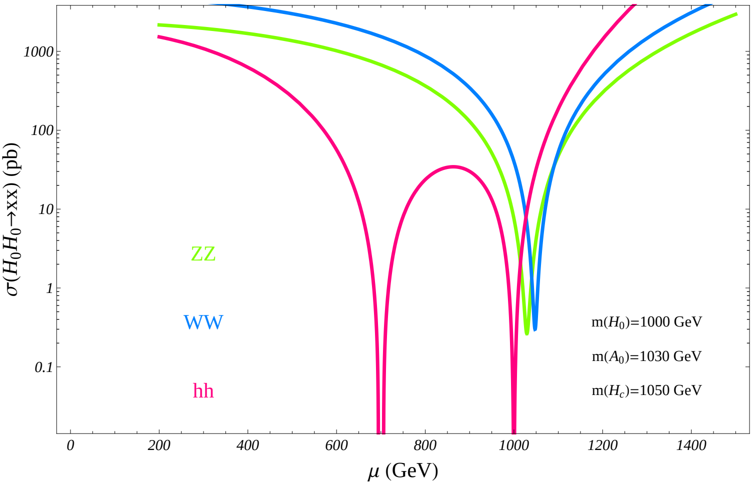
$$\begin{aligned} m_h^2 &= 2\lambda_1 v_0^2 \\ m_{H_0}^2 &= \mu_2^2 + \lambda_{H_0} v_0^2 \\ m_{A_0}^2 &= \mu_2^2 + \lambda_{A_0} v_0^2 \\ m_{H^+}^2 &= \mu_2^2 + \lambda_{H_c} v_0^2 \end{aligned}$$

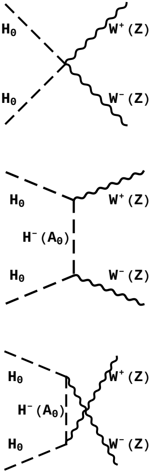
$$\begin{aligned} \lambda_{H_0} &= (\lambda_3 + \lambda_4 + \lambda_5)/2 \\ \lambda_{A_0} &= (\lambda_3 + \lambda_4 - \lambda_5)/2 \\ \lambda_{H_c} &= \lambda_3/2 \end{aligned}$$

Scalar Interactions with Higgs particle

$$V_{h-H} = \frac{1}{2}\left(\lambda_{H_0} H_0^2 + \lambda_{A_0} A_0^2 + 2\lambda_{H_c} H^+ H^-\right)\left(2v_0 h + h^2\right)$$

Annihilation cross-sections



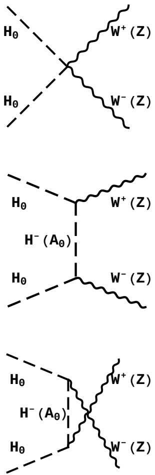


$$\mathcal{M}_T \equiv \mathcal{M}(H_0 H_0 \to Z_T i Z_T i) \simeq \frac{g^2}{2c_w^2}$$

$$\mathcal{M}_L \equiv \mathcal{M}(H_0 H_0 \to Z_L Z_L) \simeq \frac{g^2}{4c_w^2} \cdot \frac{m_Z^2}{m_{H_0}^2}$$

$$\rightsquigarrow \quad \sigma_0(H_0 H_0 \to ZZ)v \simeq \frac{\alpha_2^2}{128\pi c_w^4 m_{H_0}^2}$$

With or without Scalar Quartic Couplings ?



$$\mathcal{M}_T \equiv \mathcal{M}(H_0 H_0 \to Z_T i Z_T i) \simeq \frac{g^2}{2c_w^2}$$

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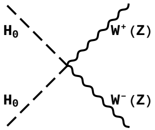
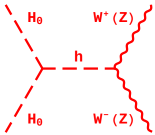
$$\rightsquigarrow \quad \sigma_0(H_0 H_0 \to ZZ)v \simeq \frac{\alpha_2^2}{128\pi c_w^4 m_{H_0}^2}$$

Effect of the quartic couplings :

- $\mathcal{M}_L^\lambda \simeq \frac{g_2^2}{2c_w^2} \cdot \frac{m_{H_0}^2}{m_Z^2} \cdot \frac{m_{A_0}^2 - m_{H_0}^2}{m_{H_0}^2}$

With or without Scalar Quartic Couplings ?





$$\mathcal{M}_T \equiv \mathcal{M}(H_0 H_0 \to Z_T i Z_T i) \simeq \frac{g^2}{2c_w^2}$$

$$\mathcal{M}_L \equiv \mathcal{M}(H_0 H_0 \to Z_L Z_L) \simeq \frac{g^2}{4c_w^2} \cdot \frac{m_Z^2}{m_{H_0}^2}$$

$$\rightsquigarrow \quad \sigma_0(H_0 H_0 \to ZZ)v \simeq \frac{\alpha_2^2}{128\pi c_w^4 m_{H_0}^2}$$

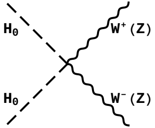
Effect of the quartic couplings :

- $\mathcal{M}_L^\lambda \simeq \frac{g_2^2}{2c_w^2} \cdot \frac{m_{H_0}^2}{m_Z^2} \cdot \frac{m_{A_0}^2 - m_{H_0}^2}{m_{H_0}^2}$
- $\mathcal{M}_L^\lambda \simeq \frac{g_2^2}{2c_w^2} \cdot \frac{m_{H_0}^2}{m_Z^2} \cdot \frac{\lambda_{H_0} v_0^2}{m_{H_0}^2}$

$\rightsquigarrow \mathcal{M}_L^\lambda \simeq 2\lambda_{A_0}$

$$\rightsquigarrow \quad \sigma_\lambda(H_0 H_0 \to ZZ)v \simeq \frac{\lambda_{A_0}^2}{16\pi m_{H_0}^2}$$

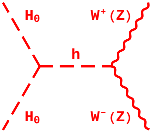
With or without Scalar Quartic Couplings ?



$$\mathcal{M}_T \equiv \mathcal{M}(H_0 H_0 \to Z_T i Z_T i) \simeq \frac{g^2}{2c_w^2}$$

$$\mathcal{M}_L \equiv \mathcal{M}(H_0 H_0 \to Z_L Z_L) \simeq \frac{g^2}{4c_w^2} \cdot \frac{m_Z^2}{m_{H_0}^2}$$

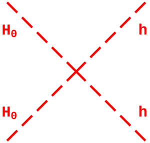
$$\rightsquigarrow \quad \sigma_0(H_0 H_0 \to ZZ)v \simeq \frac{\alpha_2^2}{128\pi c_w^4 m_{H_0}^2}$$



<u>*Effect of the quartic couplings*</u> :

- $\mathcal{M}_L^\lambda \simeq \frac{g_2^2}{2c_w^2} \cdot \frac{m_{H_0}^2}{m_Z^2} \cdot \frac{m_{A_0}^2 - m_{H_0}^2}{m_{H_0}^2}$
- $\mathcal{M}_L^\lambda \simeq \frac{g_2^2}{2c_w^2} \cdot \frac{m_{H_0}^2}{m_Z^2} \cdot \frac{\lambda_{H_0} v_0^2}{m_{H_0}^2}$

$$\rightsquigarrow \mathcal{M}_L^\lambda \simeq 2\lambda_{A_0}$$



$$\rightsquigarrow \quad \sigma_\lambda(H_0 H_0 \to ZZ)v \simeq \frac{\lambda_{A_0}^2}{16\pi m_{H_0}^2}$$

- $\sigma_\lambda(H_0 H_0 \to hh)v \simeq \frac{\lambda_{H_0}^2}{16\pi m_{H_0}^2}$

Relic density in the high-mass regime

Effective Boltzmann equation

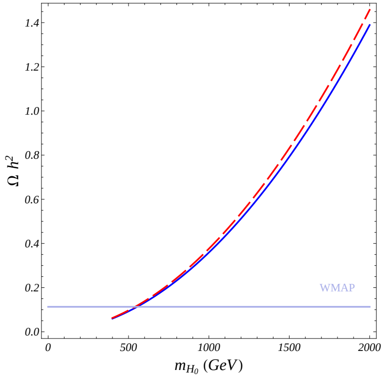
$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{eff} v \rangle (n^2 - n^{\mathrm{eq}\,2})$$

$$\langle \sigma_{eff} v \rangle = \sum_{i,j} \langle \sigma^{ij} v \rangle \frac{n_i^{\mathrm{eq}}}{n^{\mathrm{eq}}} \frac{n_j^{\mathrm{eq}}}{n^{\mathrm{eq}}}$$

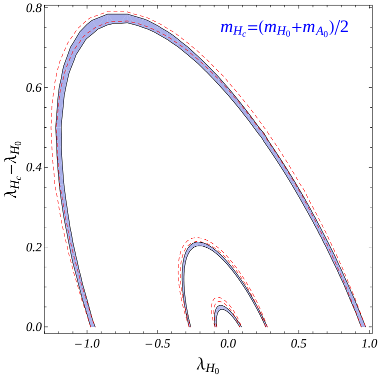
- Coannihilating species contribution to the relic density is important. Coannihilations can also be sizable. $\langle \sigma_{eff} v \rangle \neq \langle \sigma^{00} v \rangle$
- Scalar couplings not negligible compared to gauge couplings
- Parameters $\{\mu_2,\, m_{H_0},\, m_{A_0},\, m_{H_c}\}$ or $\{m_{H_0},\, \lambda_{H_0},\, \lambda_{A_0},\, \lambda_{H_c}\}$

Relic density

Pure gauge limit



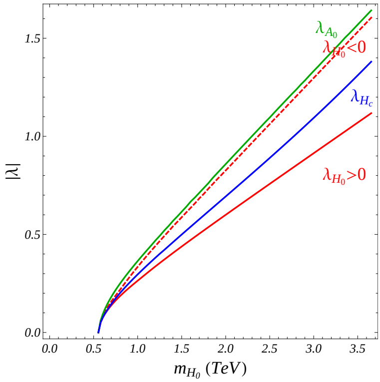
With quartic couplings



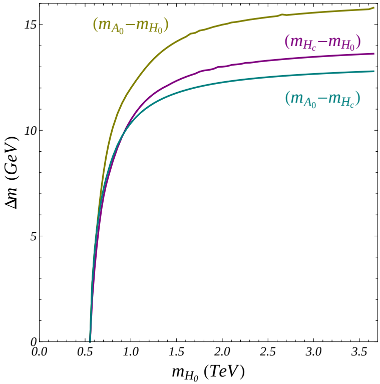
$m_{H_0} = 600, 1000, 3000$ GeV

Relic density constraints

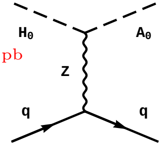
Quartic couplings



Mass splittings

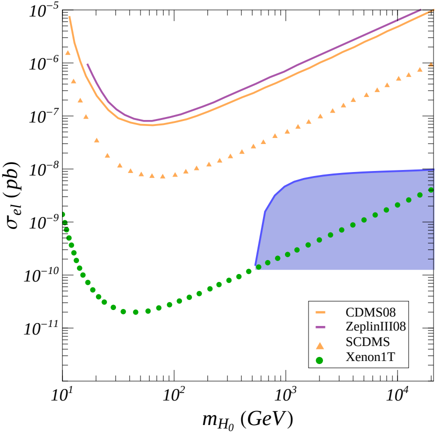


- $m_{A_0} = m_{H_0}$

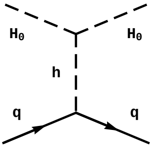


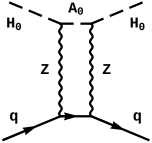
$\sigma^Z_{DM-n} \sim G_F^2 \simeq 10^{-2}$ pb

Excluded !

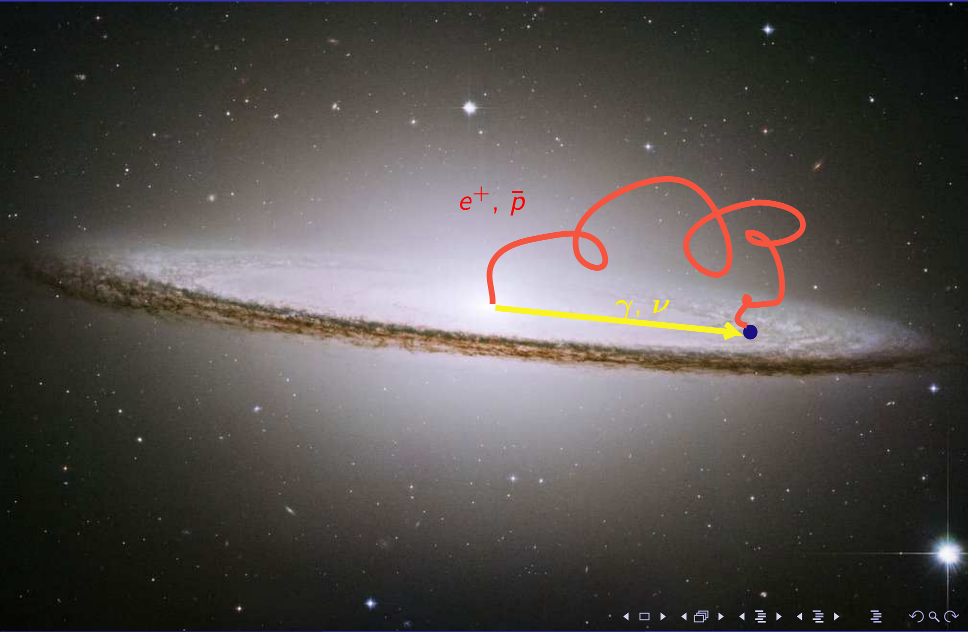


- $m_{A_0} - m_{H_0} \simeq 100$ keV
  Z exchange becomes inelastic (DAMA)
- $m_{A_0} - m_{H_0} \gg 100$ keV





Indirect detection



H_0 annihilation cross-sections

- $H_0 H_0 \to ZZ$
- $H_0 H_0 \to W^+ W^-$
- $H_0 H_0 \to hh$

$$\sigma_Z^0 v = \frac{g^4}{128\pi c_W^4 m_{H_0}^2} \qquad \sigma_W^0 v = \frac{g^4}{64\pi c_W^4 m_{H_0}^2} \qquad \sigma_h^0 v = 0$$

$$\sigma_Z^\lambda v = \frac{\lambda_{A_0}^2}{16\pi m_{H_0}^2} \qquad \sigma_W^\lambda v = \frac{\lambda_{H_c}^2}{8\pi m_{H_0}^2} \qquad \sigma_h^\lambda v = \frac{\lambda_{H_0}^2}{16\pi m_{H_0}^2}$$

$\sigma v \simeq 3 \text{ pb}$ WMAP : $\sigma v \simeq 0.8 \text{ pb}$

Gammas and Neutrinos from GC

$$\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\,\rho_0^2\,R_0}{4\pi}\,\bar{J}(\Delta\Omega)$$

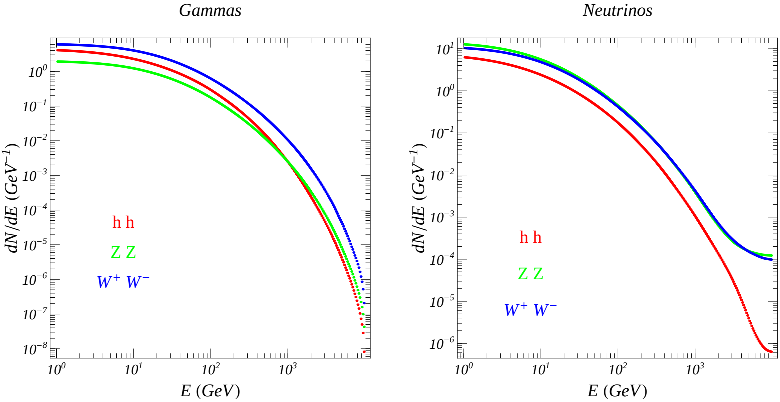
Gammas and Neutrinos from GC

$$\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle \sigma v \rangle}{2 m_{DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\, \rho_0^2\, R_0}{4\pi} \bar{J}(\Delta\Omega)$$

$$\begin{aligned} N_{\gamma,\nu} &= \int_{E_{min}}^{E_{max}} \sum_i \frac{dN^i_{\gamma,\nu}}{dE} BR_i \\ \bar{J}(\Delta\Omega) &= \frac{BF}{\Delta\Omega\, \rho_0^2\, R_0} \int \rho^2 \; dl\, d\Omega \end{aligned}$$

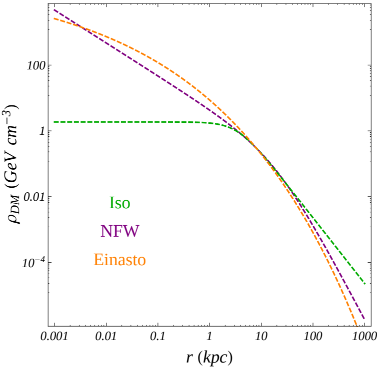
Gammas and Neutrinos from GC

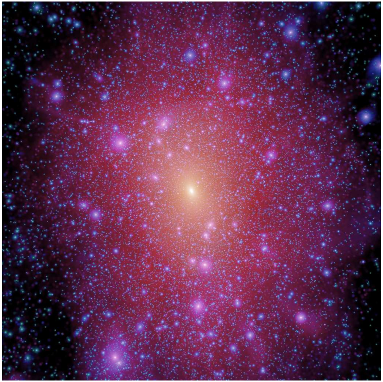
$$\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\,\rho_0^2\,R_0}{4\pi}\,\bar{J}(\Delta\Omega)$$



Gammas and Neutrinos from GC

$$\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle \sigma v \rangle}{2 m_{DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\, \rho_0^2\, R_0}{4\pi} \bar{J}(\Delta\Omega)$$





Gammas and Neutrinos from GC

$$\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle \sigma v \rangle}{2 m_{DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\, \rho_0^2\, R_0}{4\pi} \bar{J}(\Delta\Omega)$$

Gammas

$$\Phi_\gamma(\Delta\Omega = 10^{-3}) \simeq \mathcal{O}(1) \times 2.3 \cdot 10^{-10} \left(\frac{m_{DM}}{1\ TeV}\right)^{-2} \quad [\mathrm{ph\, cm^{-2}\, s^{-1}}]$$

Visible with FERMI-LAT !

Neutrinos

(for $m_{H_0} = 10$ TeV)

$$\Phi_\nu(\Delta\Omega = 10^{-3}) \simeq \mathcal{O}(1) \times 1.5 \cdot 10^{-12} \left(\frac{E_\nu^{min}}{100\ GeV}\right)^{-1} \quad [\nu\, \mathrm{cm^{-2}\, s^{-1}}]$$

Challenging ! ... even with KM3net

Charged cosmic rays e^+ and $\bar{p}$

Transport equation

$$\vec{\nabla}\left[K(E)\vec{\nabla}\mathcal{N}_{\rm cr} - \vec{V}_{\rm conv}\mathcal{N}_{\rm cr}\right] + \frac{\partial}{\partial E}\left[b(E)\mathcal{N}_{\rm cr} + K_{EE}\frac{\partial}{\partial E}\mathcal{N}_{\rm cr}\right] + \Gamma(E)\mathcal{N}_{\rm cr} + \mathcal{Q} = 0$$

Differential flux

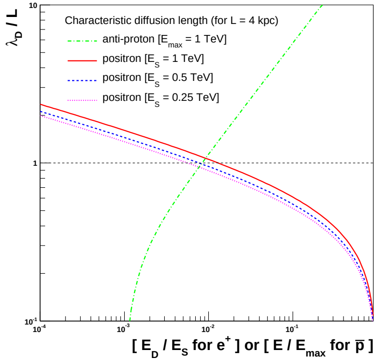
$$\frac{d\phi_{\rm cr}(E)}{dE} \equiv \frac{v_{\rm cr}}{4\pi} \times \frac{\langle\sigma v\rangle\rho_0^2}{2m_{DM}^2} \times \int_{\rm slab} d^3\vec{x}_S\ \tilde{\mathcal{G}}(E;\vec{x}_\odot \leftarrow \vec{x}_S) \times \mathcal{Q}(\vec{x}_S)$$

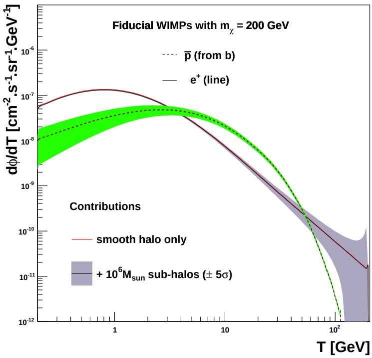
Positrons : IC energy losses

Antiprotons : Convective wind & spallation

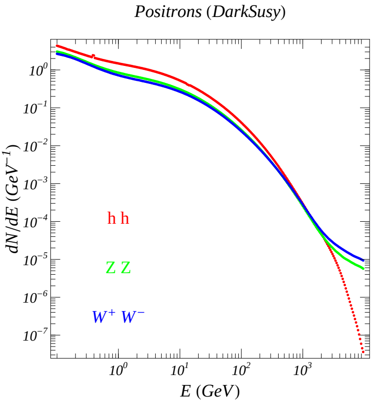
Diffusion length & Clumpiness

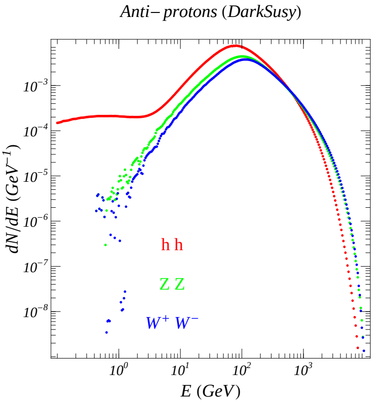
J. Lavalle et al. (2008)



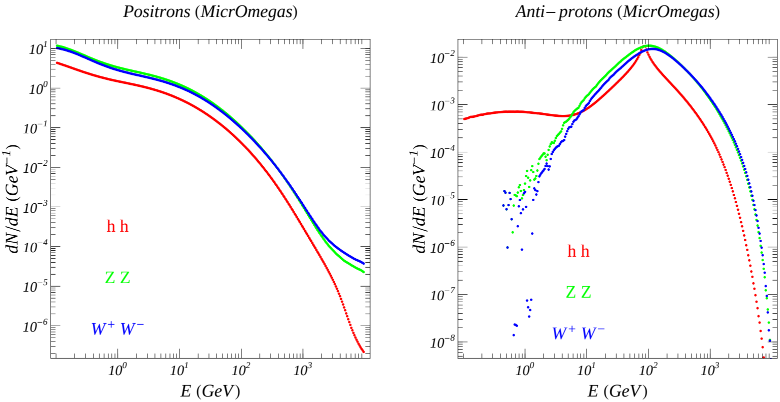


Differential spectrum

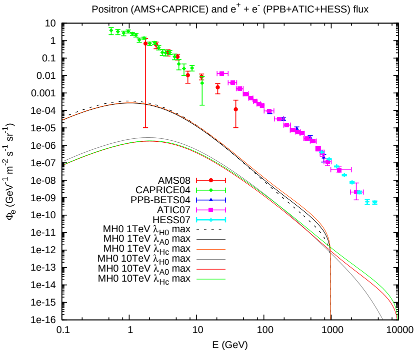


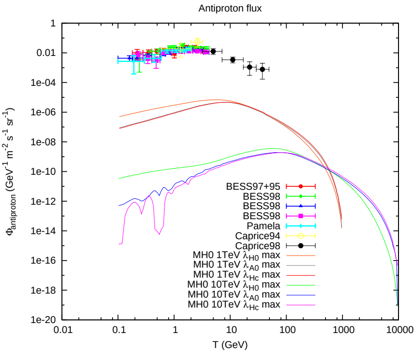


Differential spectrum



Differential fluxes





Higher Multiplets

Higher Multiplet Models

Lagrangian

$$\mathcal{L} = (D_\mu H_n)^\dagger (D^\mu H_n) - V(H_n, H_1)$$

$$D_\mu \equiv \partial_\mu - ig\tau_a^{(n)} W_\mu^a - ig_Y \frac{Y}{2} B_\mu$$

$$H_n = \begin{pmatrix} \Delta^{(Q_{max})} \\ \dots \\ \Delta^{(Q_{min})} \end{pmatrix} \qquad Q = T_3 + \frac{Y}{2}$$

Higher Multiplet Models

$SU(2)$ generators

$$[\tau_a^{(n)}, \tau_b^{(n)}] = i\epsilon_{abc}\tau_c^{(n)}$$

$$\begin{aligned}
\tau_3^{(n)} &= \mathrm{diag}(j_n, j_n - 1, \ldots, -(j_n - 1), -j_n) \\
\tau_\pm^{(n)} &= \tau_1^{(n)} \pm i\tau_2^{(n)} \\
\tau_+^{(n)}|e_k^{(n)}\rangle &= \begin{cases} -[(j_n - k)(j_n + k + 1)]^{1/2}|e_{k+1}^{(n)}\rangle & , \quad k \geq 0 \\ [(j_n - k)(j_n + k + 1)]^{1/2}|e_{k+1}^{(n)}\rangle & , \quad k < 0 \end{cases}
\end{aligned}$$

$$\tau_1^{(3)} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -1 & 0 \\ -1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \tau_2^{(3)} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & i & 0 \\ -i & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \tau_3^{(3)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Higher Multiplet Models

$SU(2)$ generators

$$[\tau_a^{(n)}, \tau_b^{(n)}] = i\epsilon_{abc}\tau_c^{(n)}$$

Charge conjugation

$$\begin{aligned} T_n \tau_a^{(n)} T_n^{-1} &= -\tau_a^{(n)*} \\ \tilde{H}_n &= T_n \cdot H_n^* \end{aligned}$$

Real multiplet : $H_n = \tilde{H}_n$

Complex multiplet : $H_n \neq \tilde{H}_n$

$$T_3 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad H_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ \\ \Delta^0 \\ \Delta^- \end{pmatrix}$$

Higher Multiplet Models

Lagrangian

$$\mathcal{L} = (D_\mu H_n)^\dagger (D^\mu H_n) - V(H_n, H_1)$$

Potential

$$V(H_n, H_1) = V_1(H_1) + \mu^2 H_n^\dagger H_n + \frac{\lambda_2}{2}(H_n^\dagger H_n)^2 + \lambda_3 (H_1^\dagger H_1)(H_n^\dagger H_n)$$
$$+ \frac{\lambda_4}{2}(H_n^\dagger \tau_a^{(n)} H_n)^2 + \lambda_5 (H_1^\dagger \tau_a^{(2)} H_1)(H_n^\dagger \tau_a^{(n)} H_n)$$

$\rightsquigarrow$ No term analogous to $\mathrm{Re}[(H_1^\dagger H_2)^2]$

$\rightsquigarrow$ DD constraints require that $Y = 0$

Real Multiplet with $Y = 0$

Potential

$$V(H_n, H_1) = V_1(H_1) + \mu^2 H_n^\dagger H_n + \frac{\lambda_2}{2}(H_n^\dagger H_n)^2 + \lambda_3 (H_1^\dagger H_1)(H_n^\dagger H_n)$$
$$+ \frac{\lambda_4}{2}(H_n^\dagger \tau_a^{(n)} H_n)^2 + \lambda_5 (H_1^\dagger \tau_a^{(2)} H_1)(H_n^\dagger \tau_a^{(n)} H_n)$$

Real Multiplet with $Y = 0$

Potential

$$V(H_n, H_1) = V_1(H_1) + \mu^2 H_n^\dagger H_n + \frac{\lambda_2}{2}(H_n^\dagger H_n)^2 + \lambda_3 (H_1^\dagger H_1)(H_n^\dagger H_n)$$

- Tree-level mass $m_0^2 = \mu_2^2 + \lambda_3 v_0^2/2$
- One-loop mass splitting $m_Q - m_0 = Q^2 \times 166$ MeV
- Vacuum stability $\lambda_1, \lambda_2 > 0,\ \lambda_3 > -\sqrt{2\lambda_1\lambda_2}$
- Perturbativity $\rightsquigarrow n \leq 8$
- Z_2 symmetry not necessary for $n = 7$

Only 3 cases : $n = 3, 5, 7$

Relic density

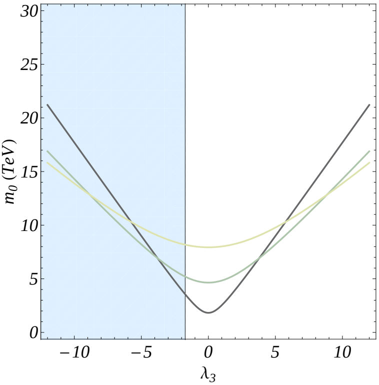
Effective cross-section :

$$\sigma_0^{(n)} v = \frac{(n^2-1)(n^2-3)}{n} \frac{g^4}{128\pi\ m_0^2}$$

$$\sigma_\lambda^{(n)} v = \frac{1}{n} \frac{\lambda_3^2}{16\pi\ m_0^2}$$

Threshold masses (TeV) :

Triplet	1.826 ± 0.028
Quintuplet	4.642 ± 0.072
Eptaplet	7.935 ± 0.12



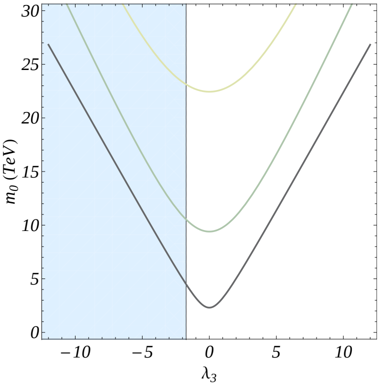
Effective cross-section :

$$\sigma_0^{(n)} v = \frac{(n^2-1)(n^2-3)}{n} \frac{g^4}{128\pi\ m_0^2}$$

$$\sigma_\lambda^{(n)} v = \frac{1}{n} \frac{\lambda_3^2}{16\pi\ m_0^2}$$

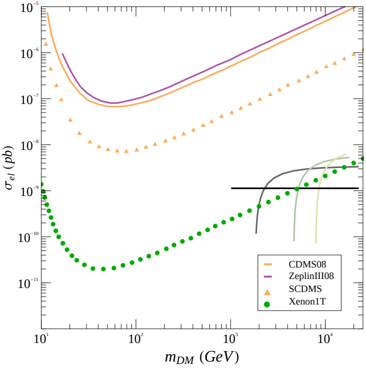
Threshold masses with SE (TeV) :

Triplet	~ 2.5
Quintuplet	~ 9.4
Eptaplet	~ 25

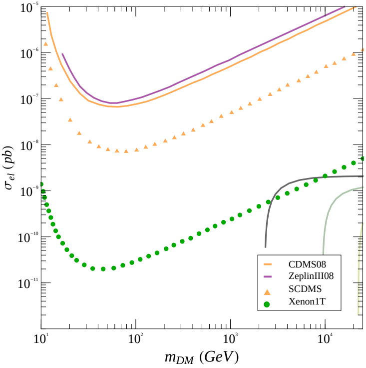


Direct detection

Without Sommerfeld



With Sommerfeld



Indirect detection

- $H_0 H_0 \to ZZ$

$$\sigma_Z^0 v = 0$$

$$\sigma_Z^\lambda v = \frac{\lambda_3^2}{64\pi m_0^2}$$

- $H_0 H_0 \to W^+ W^-$

$$\sigma_W^0 v = \frac{(n^2-1)^2 g^4}{256\pi m_0^2}$$

$$\sigma_W^\lambda v = \frac{\lambda_3^2}{32\pi m_0^2}$$

- $H_0 H_0 \to hh$

$$\sigma_h^0 v = 0$$

$$\sigma_h^\lambda v = \frac{\lambda_3^2}{64\pi m_0^2}$$

$\rightsquigarrow$ $W^+ W^-$ annihilation channel dominant.

Summary

Summary (1)

- Scalar particles with a mass in the multi-TeV range and $SU(2)_L$ quantum numbers offer a variety of viable DM candidates.
- Scalar quartic couplings play a key role as they *enhance* (co)annihilations into gauge bosons. They can only increase the (co)annihilation cross-sections.
- The desired relic abundance can be obtained for any mass above the pure gauge threshold, with an sizable contribution from the multiplet companions. Coannihilations are not negligible. In the doublet case, mass splittings are limited.
- Higher multiplet : $Y = 0$, degenerate masses at tree-level, only one relevant scalar quartic coupling, similar to a simple Higgs portal model.

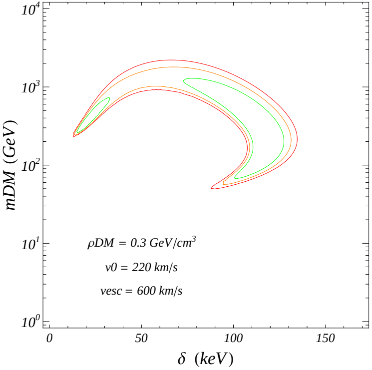
Summary (2)

- Direct detection through spin independent elastic scattering. Needs a ton $\times$ year sensitivity. Possibility for inelastic scattering in the doublet case.
- Indirect detection mainly through annihilation into W^+W^-, ZZ, hh.
  - gamma from GC : cuspy DM profile required for FERMI
  - neutrinos from GC : difficult
  - neutrinos from Sun or Earth capture : negligible
  - charged cosmic rays : well below background
- Sommerfeld effect increases with the multiplet dimension. SE pushes viable DM candidates towards higher masses. Direct detection is decreased. Indirect detection can be boosted.

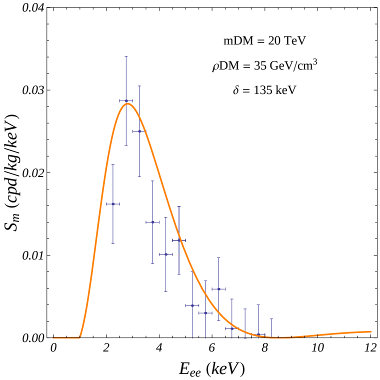
Backup slides

IDM vs. DAMA

Standard Maxwellian Halo

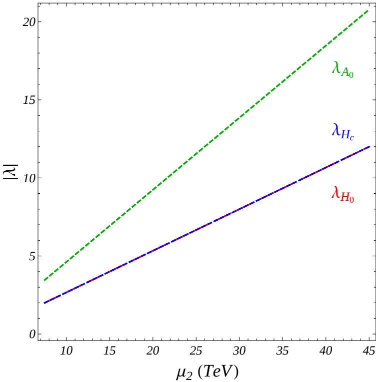


Local Overdensity

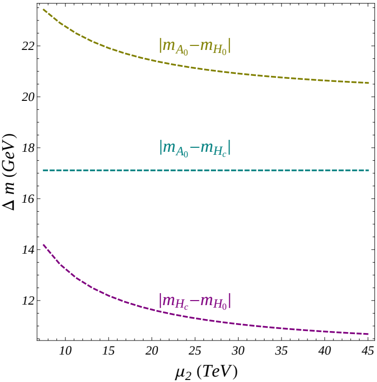


IDM : Freeze-out before EW phase transition

Quartic couplings



Mass splittings



Corrections to EW precision tests

R. Barbieri, L.J. Hall, V.S. Rychkov (2006)

$$\Delta T \approx \frac{1}{12\pi^2 \alpha v^2}(m_{H^+} - m_{A_0})(m_{H^+} - m_{H_0})$$